

Beyond HL-LHC: The next big things in particle physics — opportunities & challenges

J. List (DESY)

Colloquium, PUC, Rio de Janeiro, October 1 2026

Outline

Today's menu

- Introduction: Particle physics, the Universe and all that
- From the HL-LHC to electron-positron colliders
- FCC-ee as the next flagship collider for CERN
- A complementary vision: Linear Colliders
- Conclusions



Many thanks to all who contributed material!
(with and without being asked ;)

Introduction:
Particle physics, the Universe and all that

Particle Physics - why?

A personal motivation

- Connects the **smallest** and the **largest** objects we can imagine
- Aims for nothing less than a **description of Nature** at the fundamental, microscopic level of **Quantum Theory**
- **Particle properties** have consequences for our world:
  - Exact value of the **electron mass** has huge impact — only small window for “chemistry as we know it”
  - **Down quark is a bit heavier than up quark**
    => essential for stable proton
  - Exact value of **W boson mass**
    => nuclear fusion as energy source of the sun

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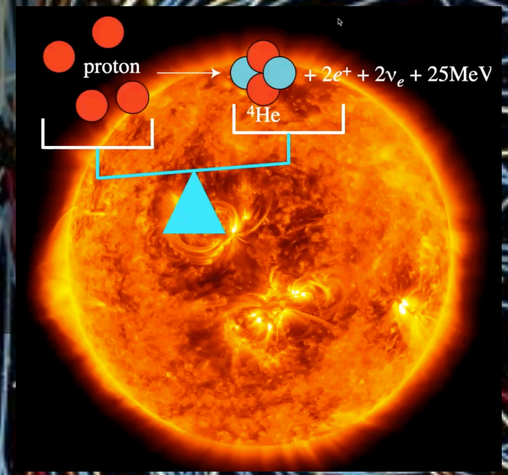

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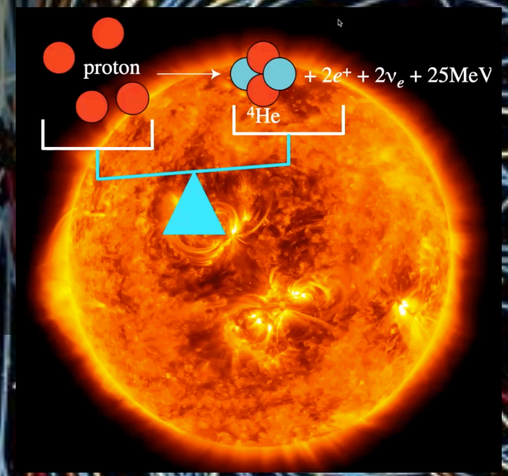
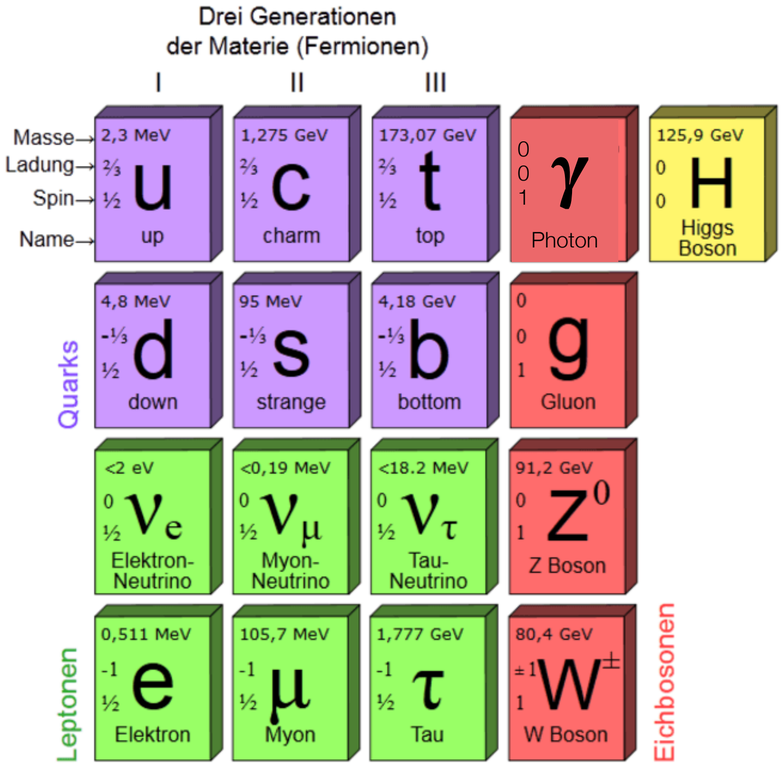


Answers to BIG questions often lie in *precision*!

The Standard Model of Particle Physics and the Higgs Boson

A discovery which is only the beginning …



The Standard Model of Particle Physics

- **describes measurements down to the level of quantum fluctuations**
- **based on only a few fundamental ideas:**
  - **special relativity**
  - **quantum mechanics**
  - **invariance under local gauge transformations: $SU(3)xSU(2)_LxU(1)_Y$**

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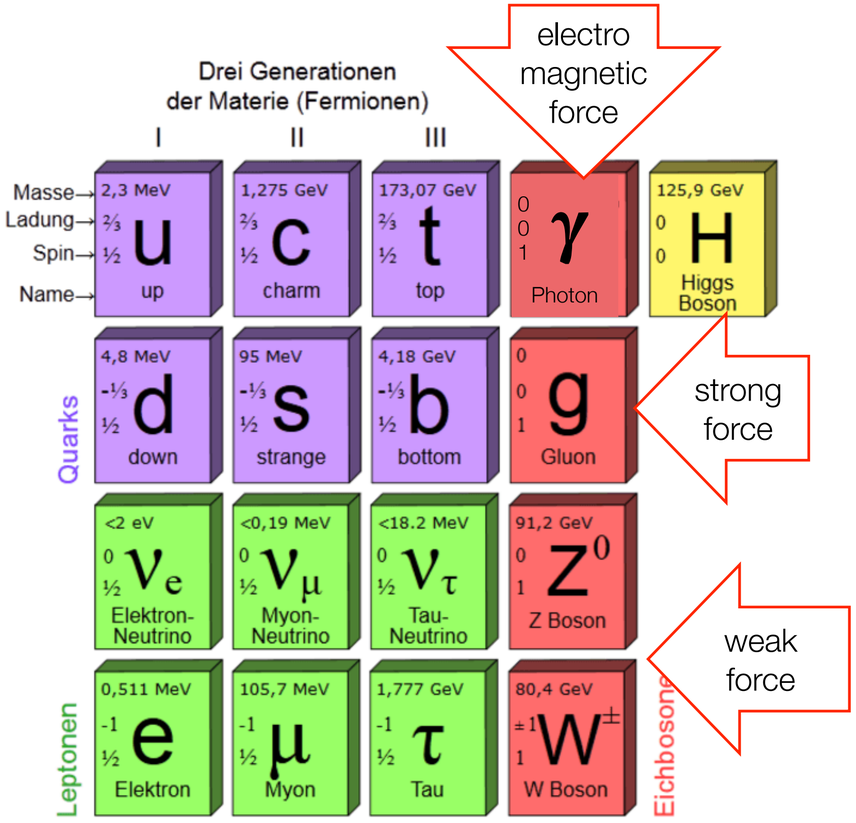

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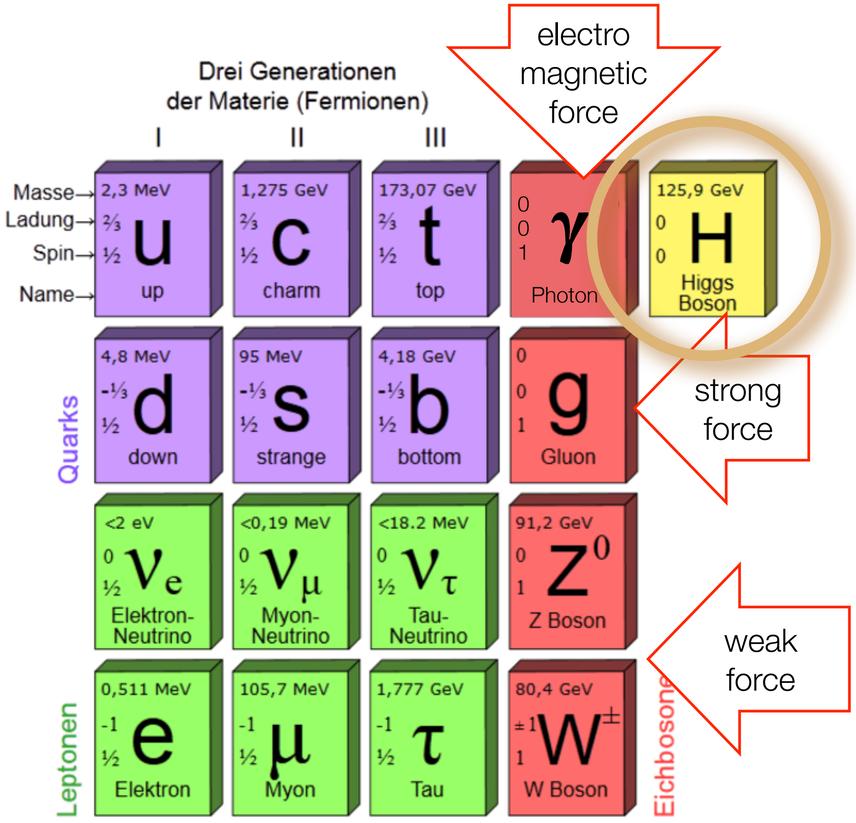

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2012: Discovery of a Higgs bosons at the LHC!

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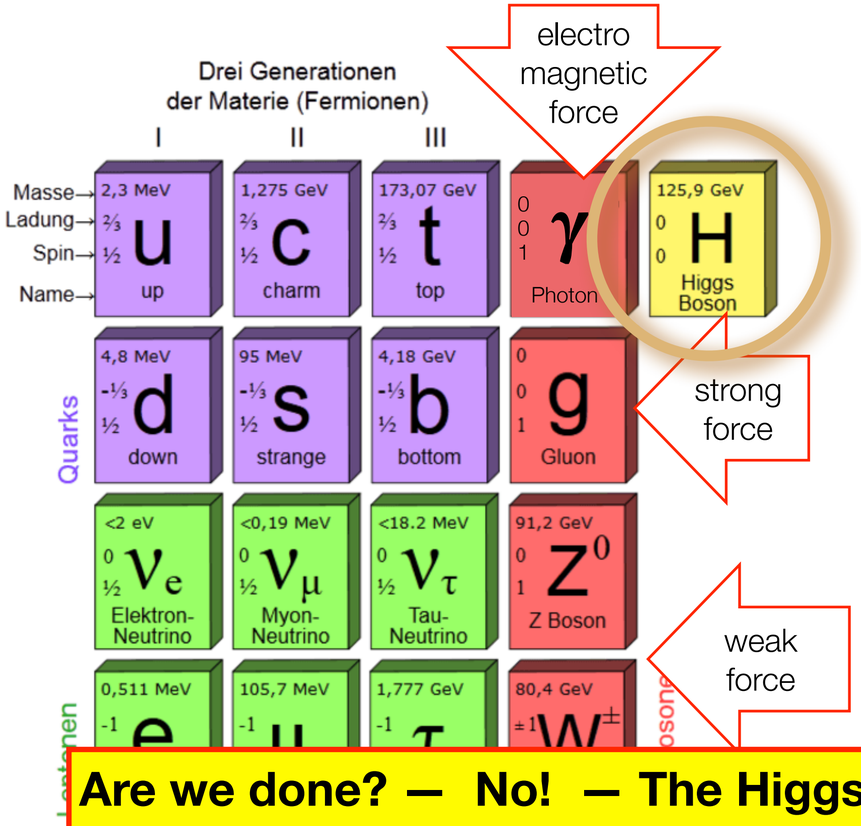

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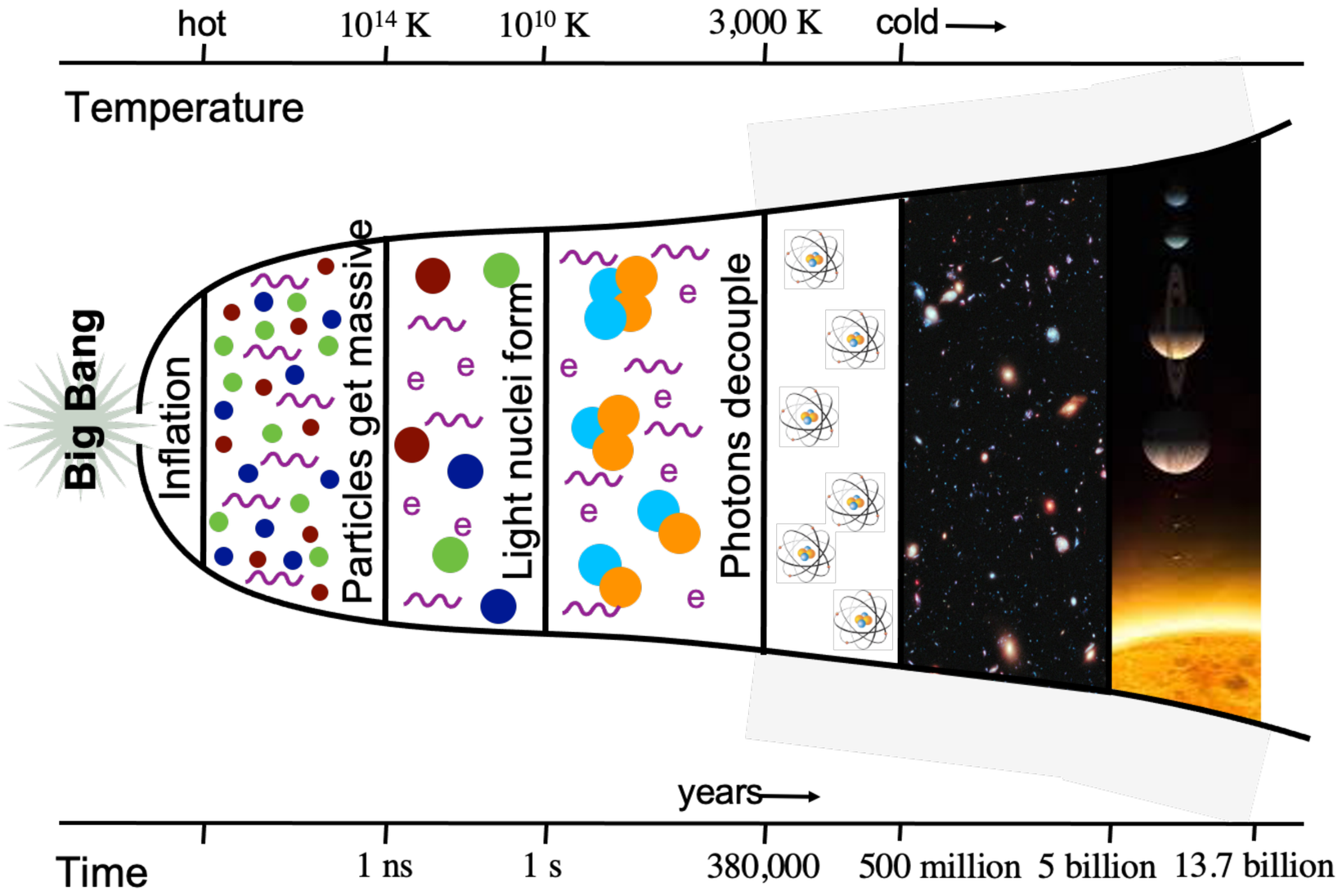
Are we done? — No! — The Higgs Boson is

1. **a mystery in itself: how can an elementary spin-0 particle exist and be so light?**
2. **giving masses to particles — really? And why the values we observe?**
3. **intimately connected to cosmology => the Higgs boson is a *new* messenger from the early universe!**

A new messenger from the early universe

The Higgs Boson



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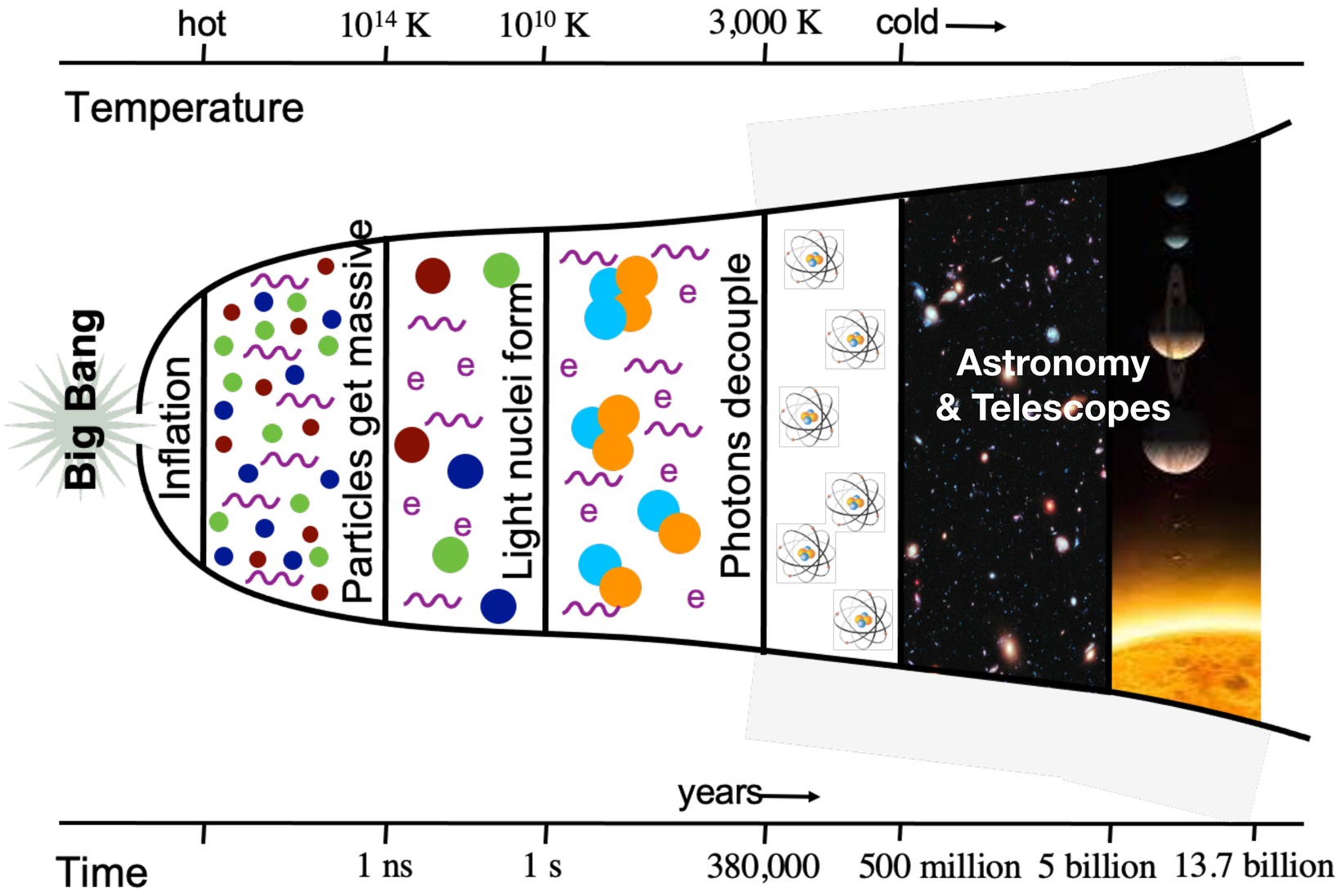

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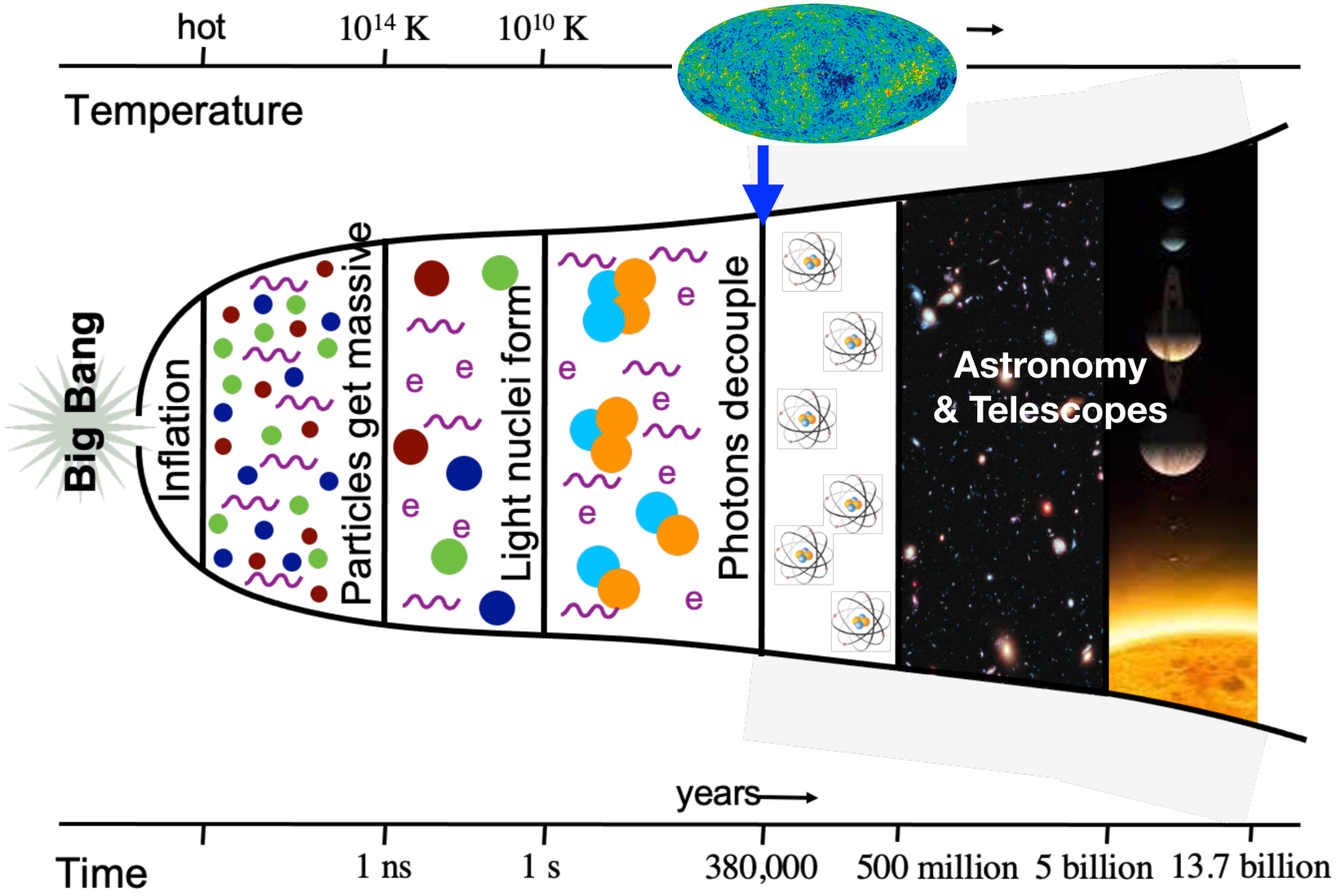

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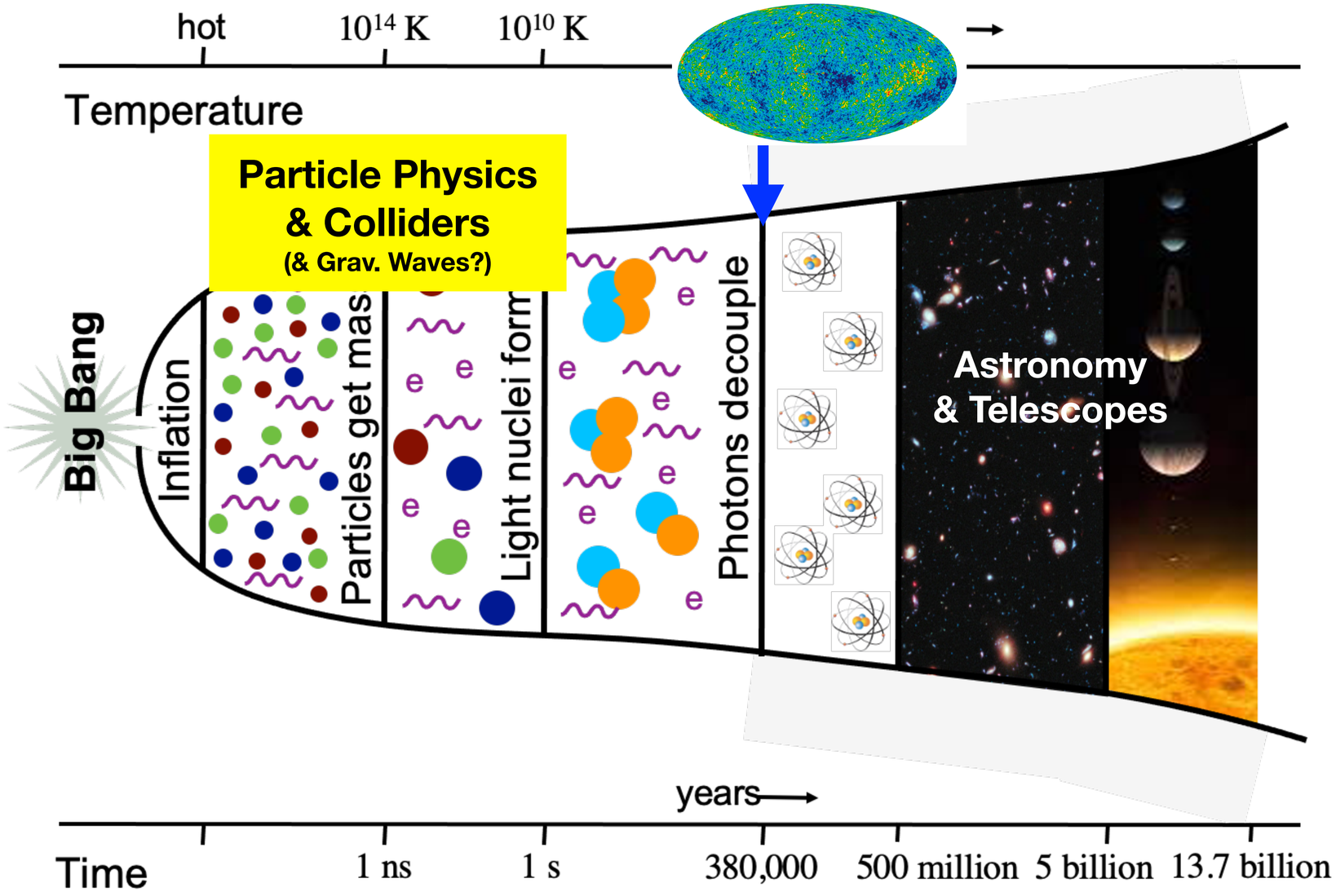

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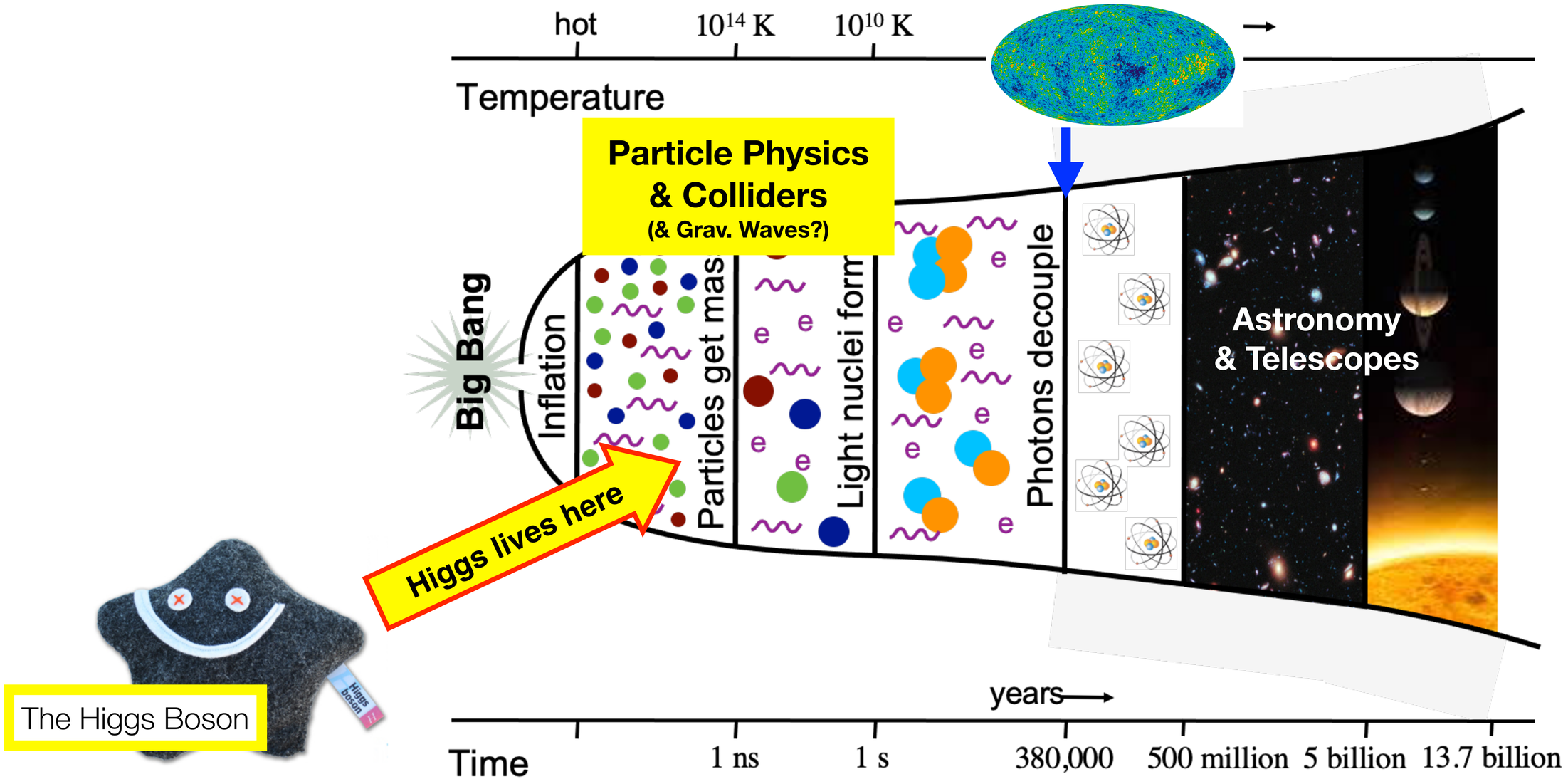

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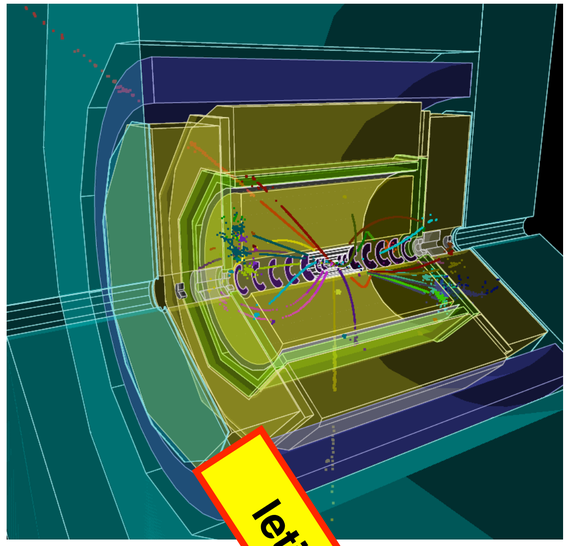


let's ask it!



The Higgs Boson

Higgs lives here

hot
10^{14} K
10^{10} K
Temperature

Particle Physics & Colliders
(& Grav. Waves?)

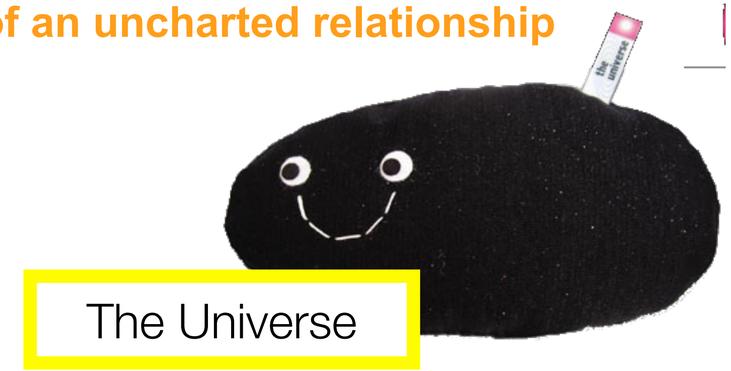
Big Bang
Inflation
Particles get mas
Light nuclei form
Photons decouple

Astronomy & Telescopes

years
Time
1 ns
1 s
380,000 years
500 million years
5 billion years
13.7 billion years

The Higgs Boson and the Universe

Exploration of an uncharted relationship



The Universe



The Higgs Boson

What we'd really like to know

- What is Dark Matter made out of?
- What drove cosmic inflation?
- What generates the mass pattern in quark and lepton sectors?
- What created the matter-antimatter asymmetry?
- What drove electroweak phase transition?
  - **and could it play a role in baryogenesis?**
- …

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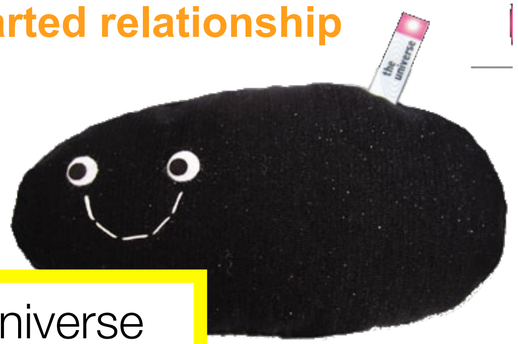

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Is the Higgs the portal to the Dark Sector?

- does the Higgs decays "invisibly", i.e. to dark sector particles?
- does the Higgs have siblings in the dark (or the visible) sector?

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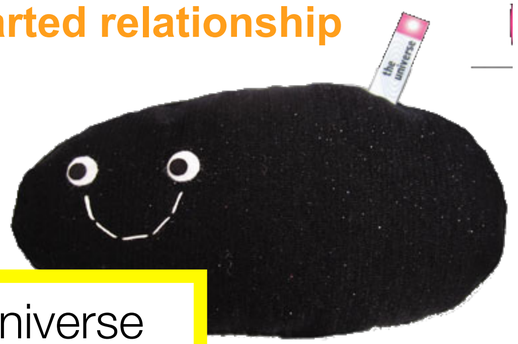

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Is the Higgs the portal to the Dark Sector?

- **The Higgs could be first "elementary" scalar we know -**
  - is it really elementary?
  - is it the inflaton?
  - even if not - it is the best "prototype" of a elementary scalar we have

=> study the Higgs properties precisely and look for siblings

The Higgs Boson and the Universe

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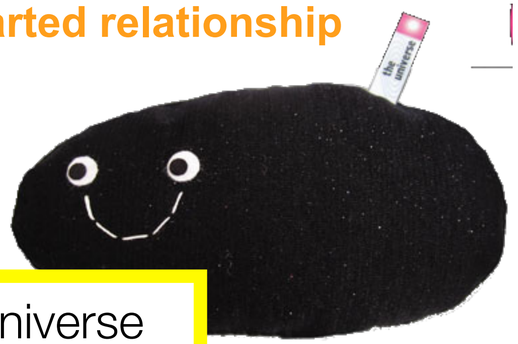

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Why is the Higgs-fermion interaction so different between the species?

- does the Higgs generate all the masses of all fermions?
- are the other Higgses involved - or other mass generation mechanisms?
- what is the Higgs' special relation to the top quark, making it so heavy?
- is there a connection to neutrino mass generation?

=> study Higgs and top - and search for possible siblings!

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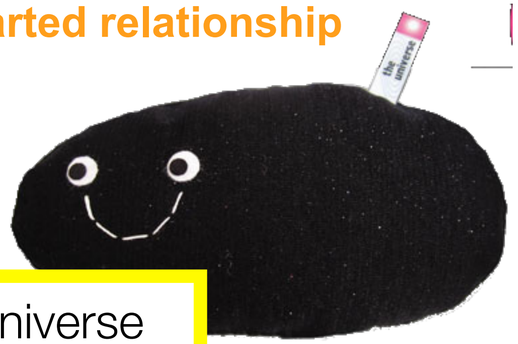

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Does the Higgs sector contain additional CP violation?

- in particular in couplings to fermions?
- or do its siblings have non-trivial CP properties?

=> small contributions -> need precise measurements!

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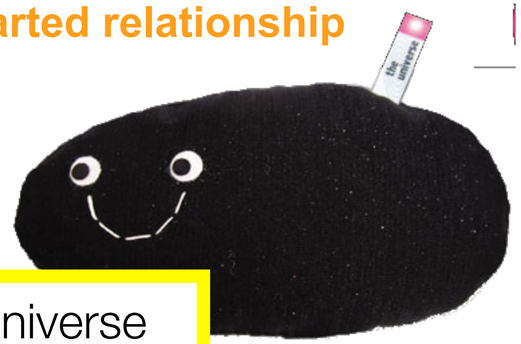

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What is the shape of the Higgs potential, and its evolution?

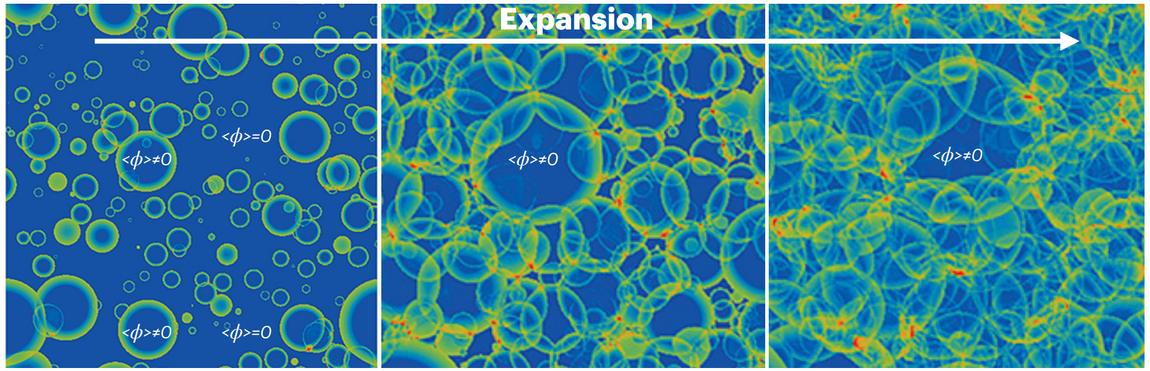
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

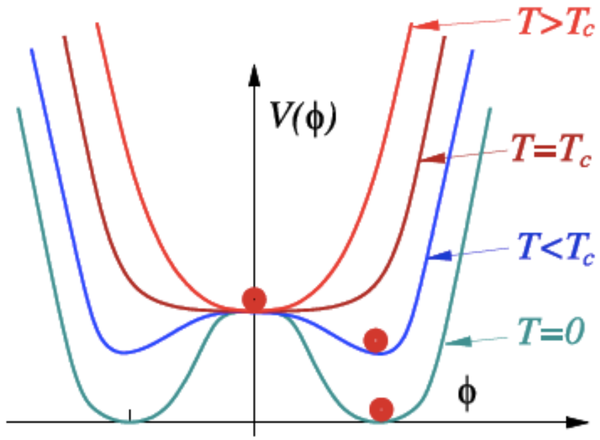
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

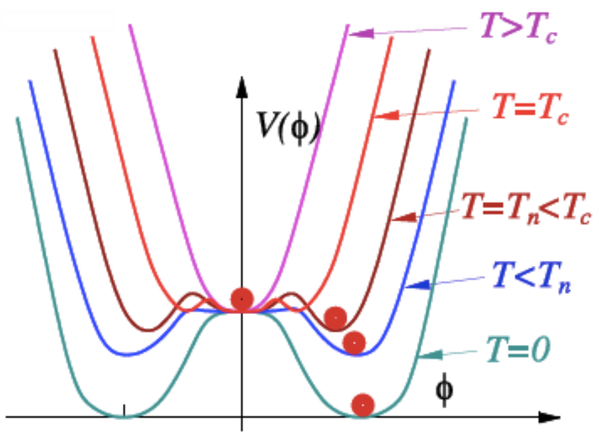
1st vs 2nd order phase transition

- origin of matter-antimatter asymmetry: universe must have been out of thermal equilibrium => 1.order phase transition
- **Electroweak phase transition?**





2nd order



1st order, requirement for EW baryogenesis

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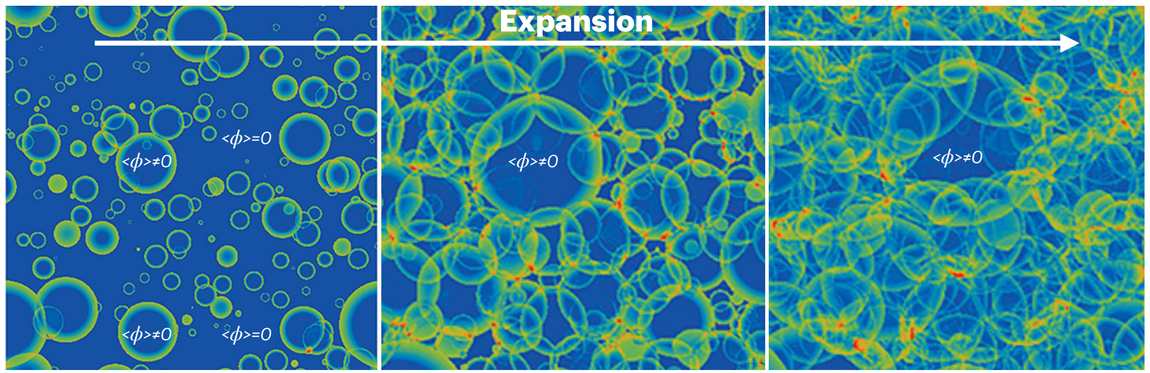

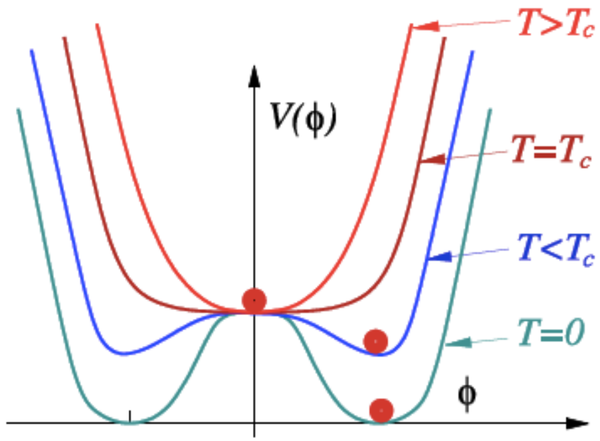

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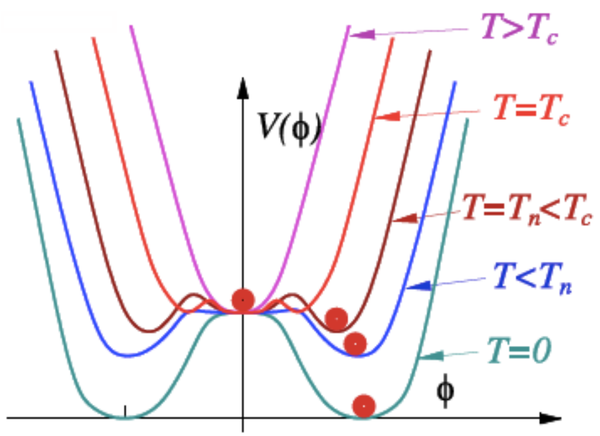

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- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
- electroweak baryogenesis possible in BSM scenarions with $\lambda > \lambda_{SM}$ (e.g. 2HDM, NMSSM, …)

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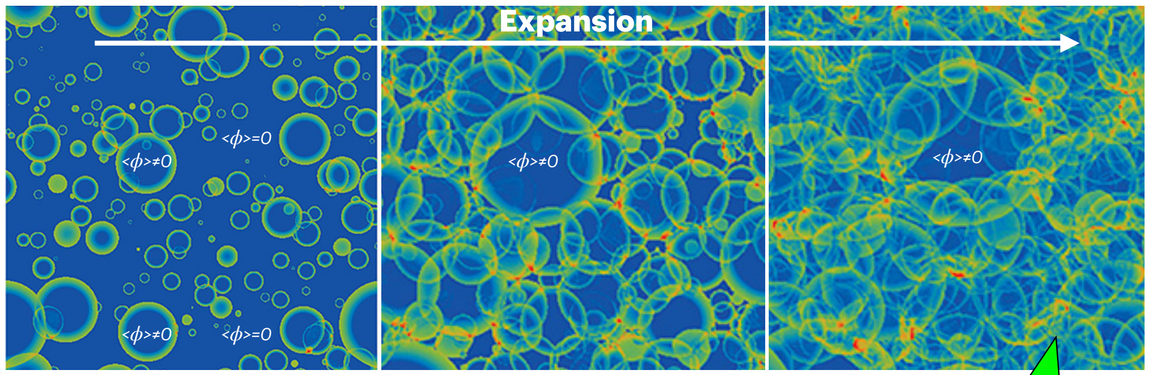

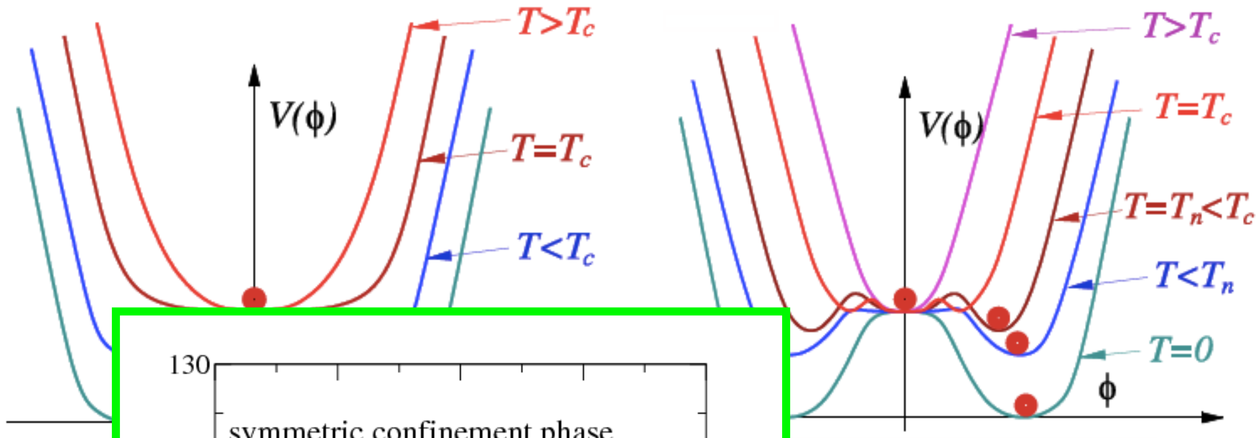

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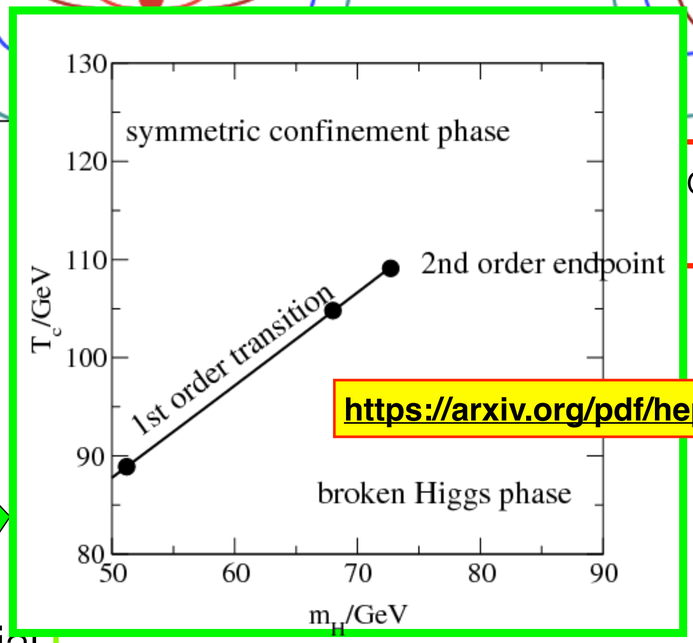

https://arxiv.org/pdf/hep-ph/0010275

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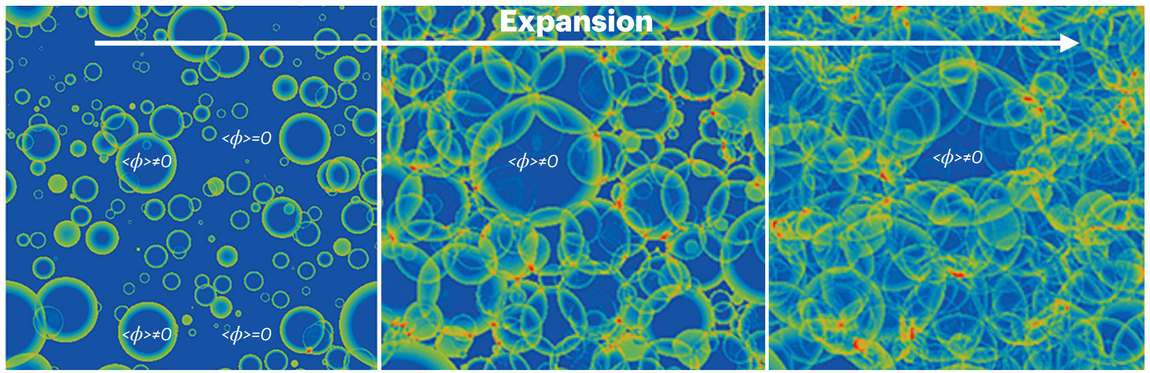

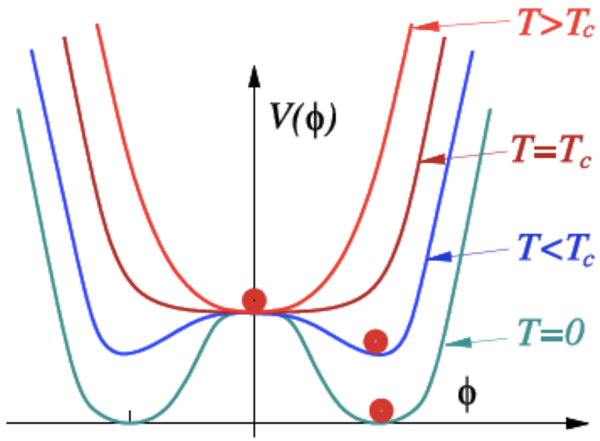

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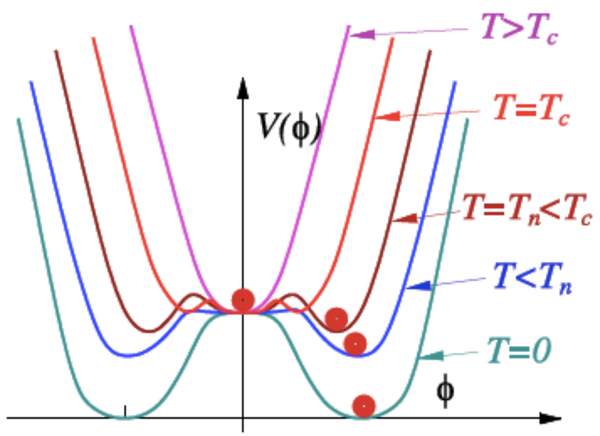

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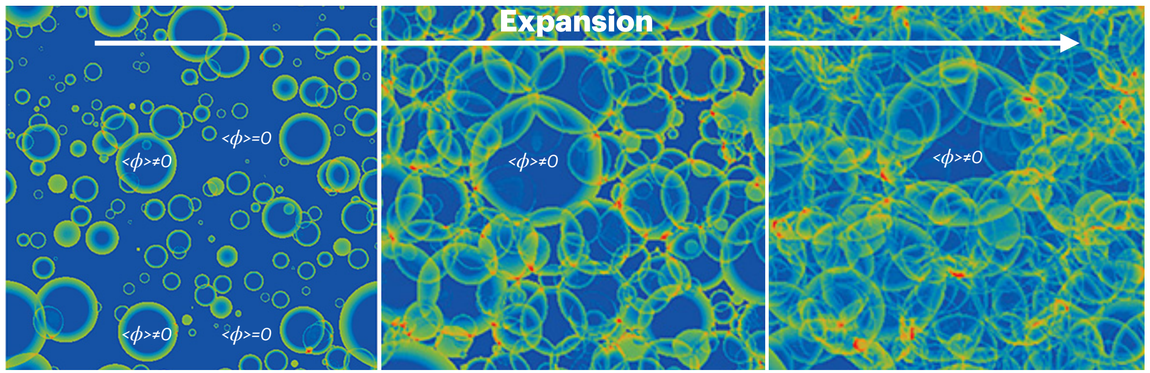

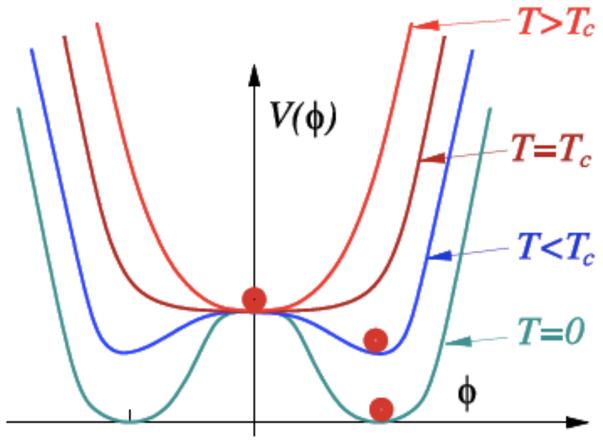

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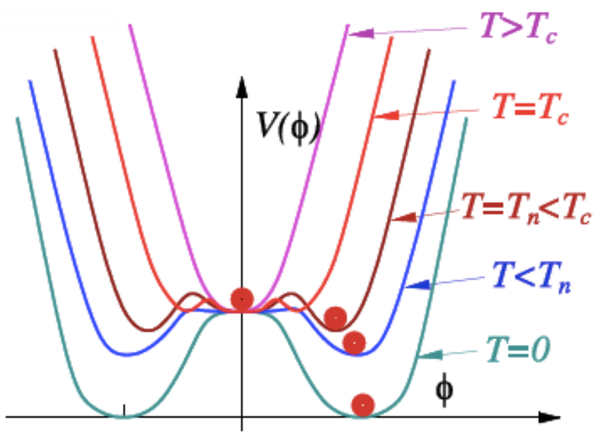

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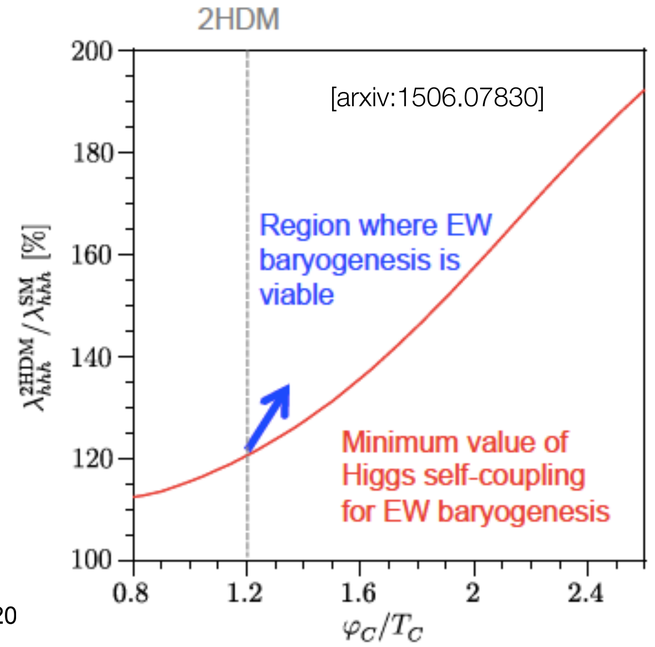

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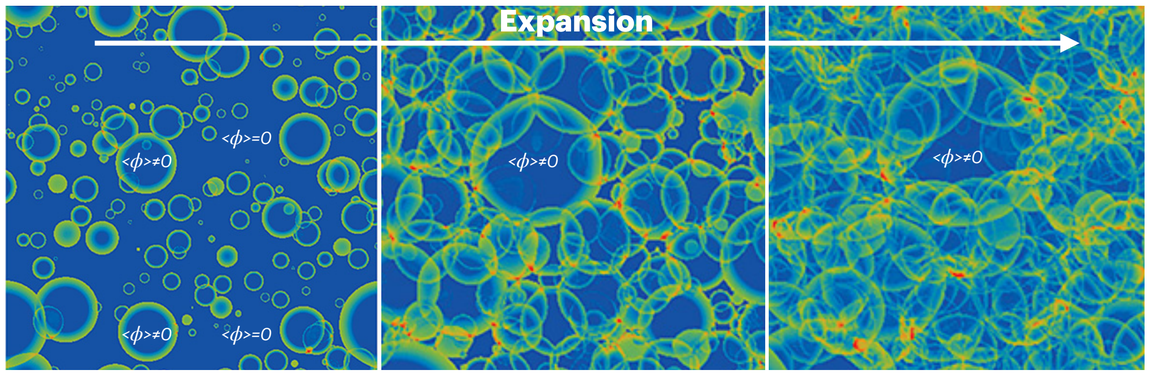

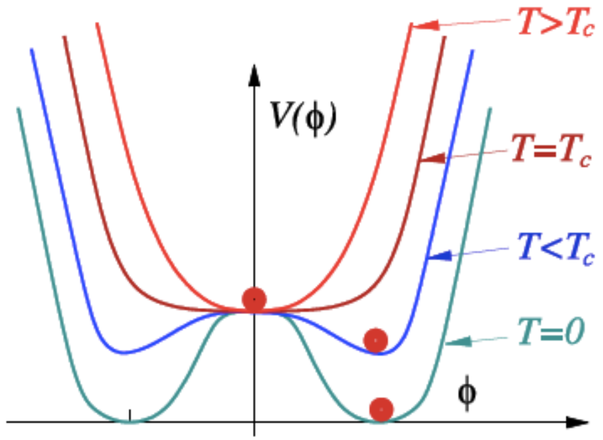

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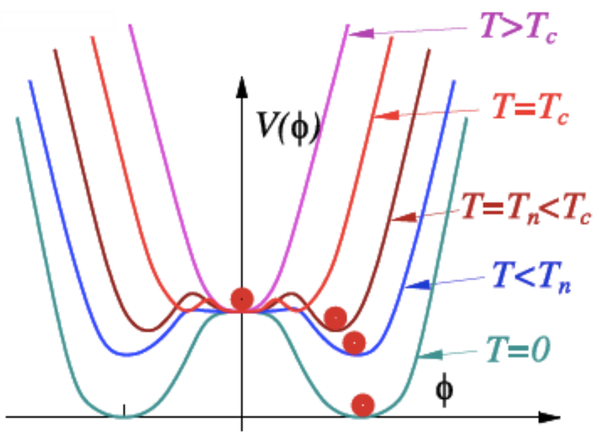
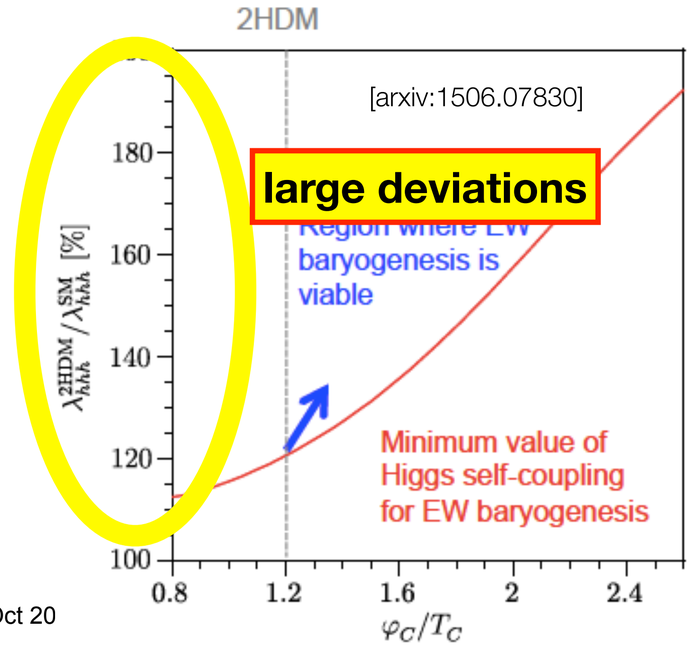


1st order, requirement for EW baryogenesis

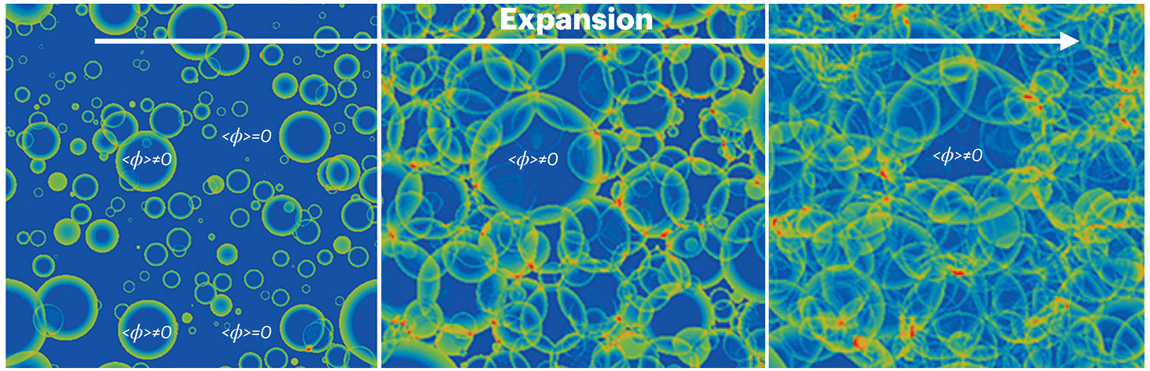
- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
- electroweak baryogenesis possible in BSM scenarions with $\lambda > \lambda_{SM}$ (e.g. 2HDM, NMSSM, …)

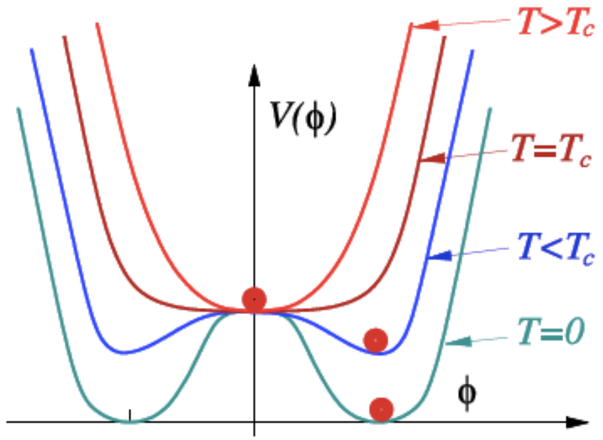


The Higgs potential, the Higgs self-coupling and Baryogenesis

1st vs 2nd order phase transition

- origin of matter-antimatter asymmetry: universe must have been out of thermal equilibrium
  => 1.order phase transition
- **Electroweak phase transition?**





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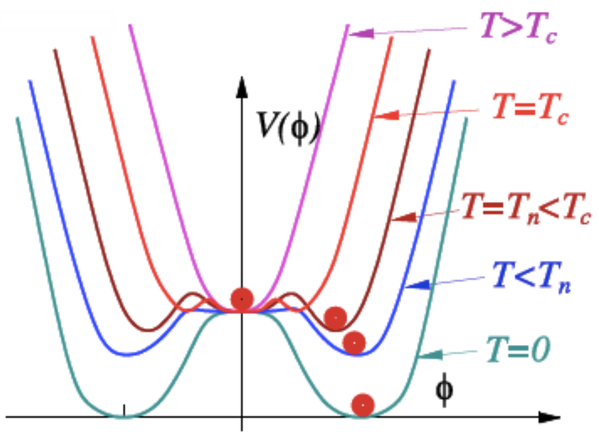

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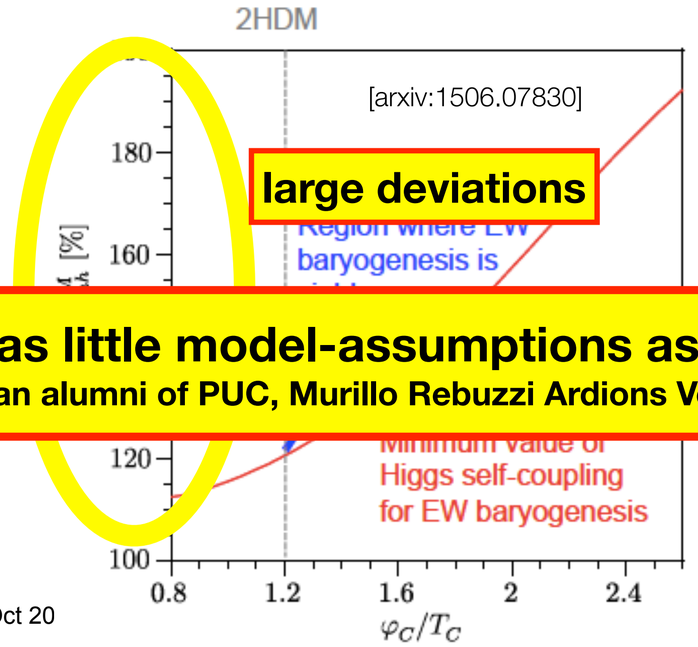
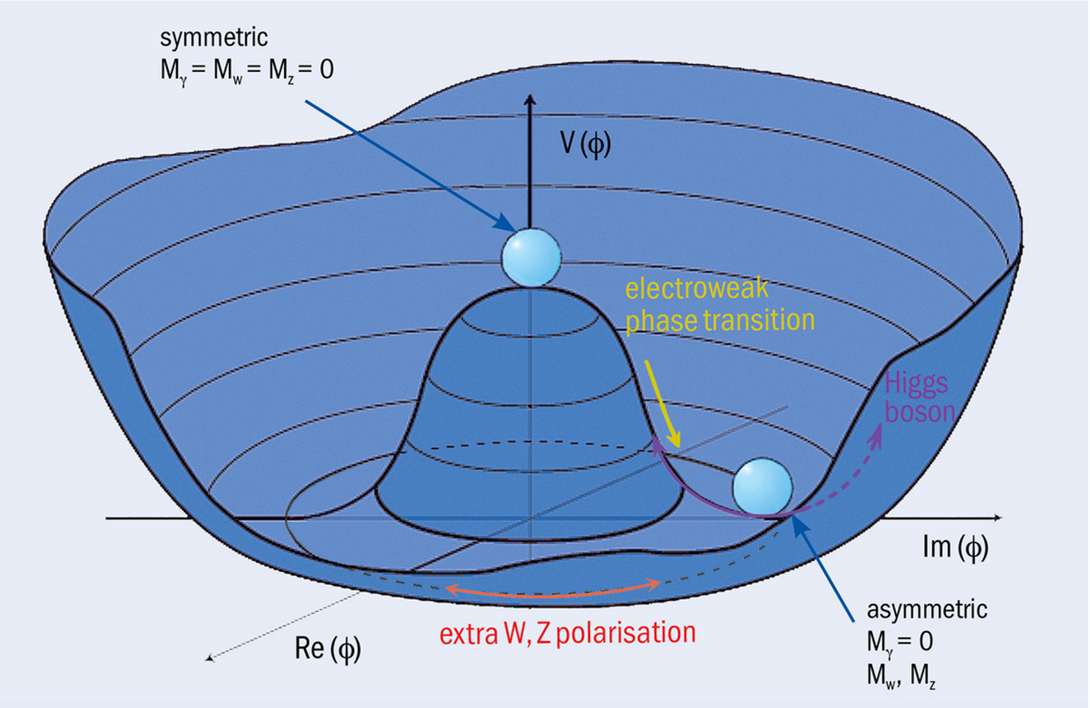


=> measure λ, with as little model-assumptions as possible!
(Working on this with an alumni of PUC, Murillo Rebuzzi Ardions Vellasco)

Higgs potential in extended Higgs Sectors

“Mexican hat” turns into complex landscape

- more Higgs fields => much more complex potential “landscape” (even at zero-temperature)
- extra Higgs bosons
- several triple-Higgs couplings among them
- several minima
- EW vaccuum not necessarily global minimum => vacuum stability?



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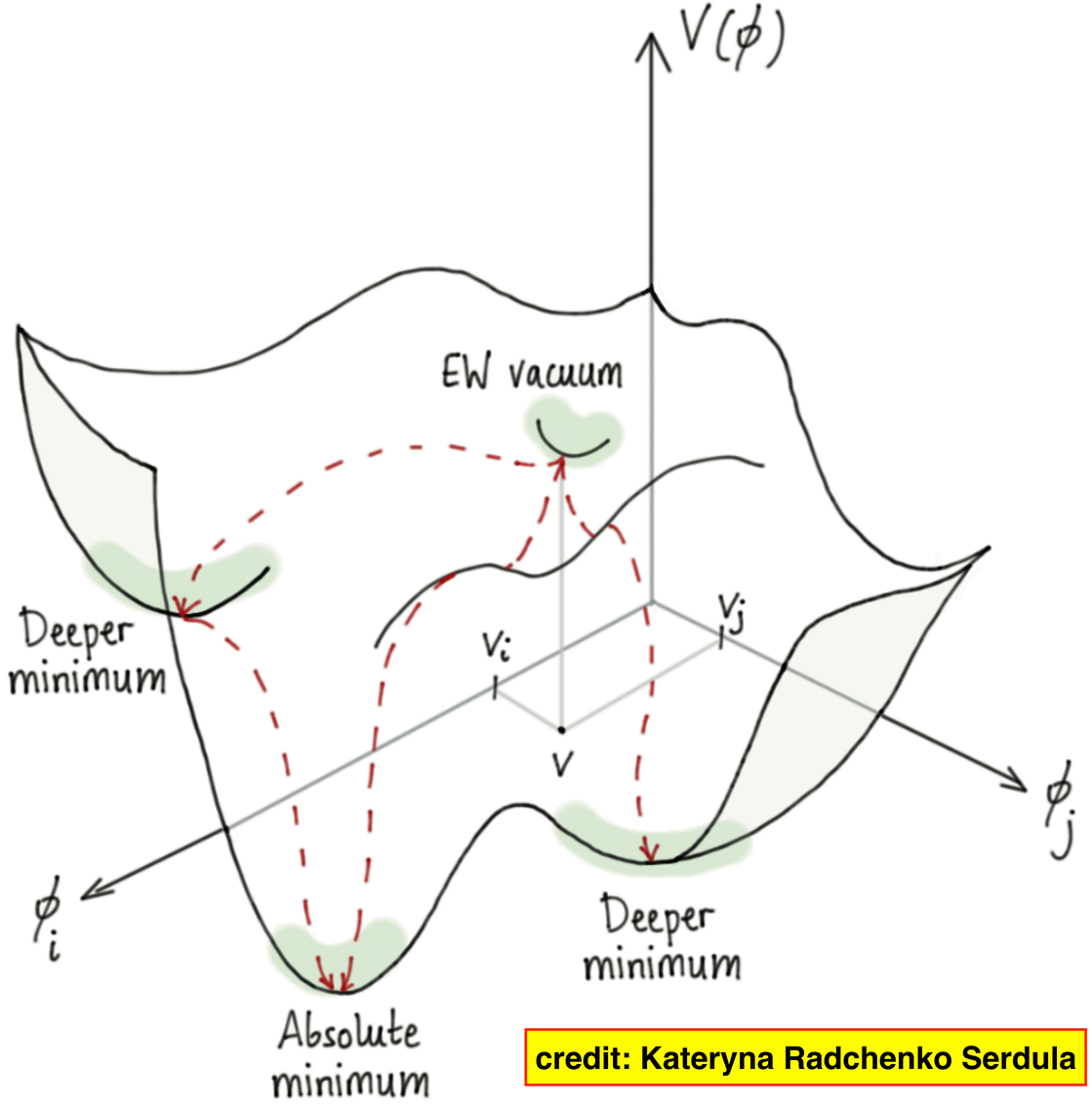

credit: Kateryna Radchenko Serdula

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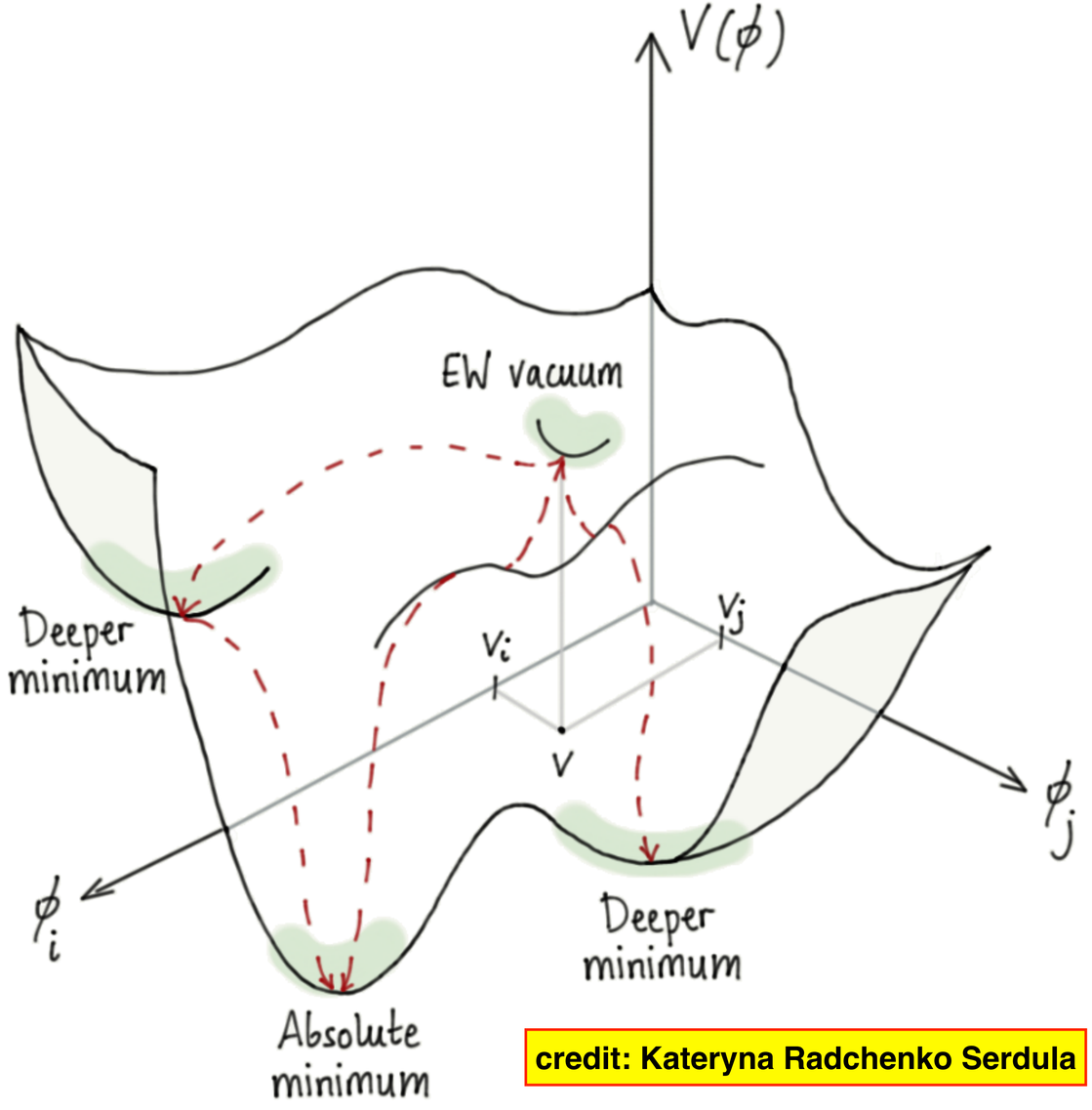
Interesting interplay with gravitational waves: detect direct remnants of the phase transition? => ask me if interested…



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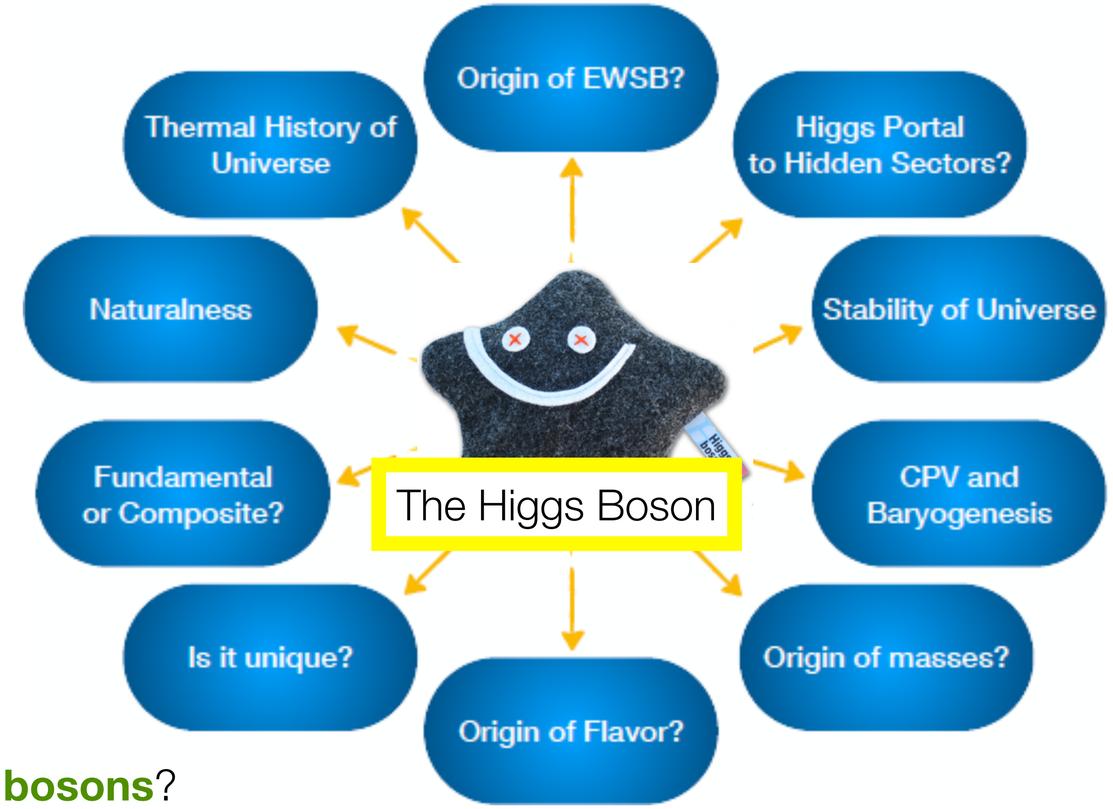
The Higgs Boson Mission

Why we need a Higgs Factory



- **Find out as much as we can about the 125-GeV Higgs**
  - Basic properties:
    - **total production rate**, total width
    - decay rates to known particles
    - **invisible decays**
    - search for “exotic decays”
  - CP properties of couplings to gauge bosons and fermions
  - **self-coupling**
  - Is it the only one of its kind, or are there **other Higgs (or scalar) bosons**?
- **To interprete these Higgs measurements, also need**
  - top quark: mass, Yukawa & electroweak couplings, their CP properties…
  - Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP…
- **Search for direct production of new particles - and determine their properties**
  - Dark Matter? **Dark Sector?**
  - Heavy neutrinos?
  - SUSY? **Higgsinos?**
  - The **UNEXPECTED** !

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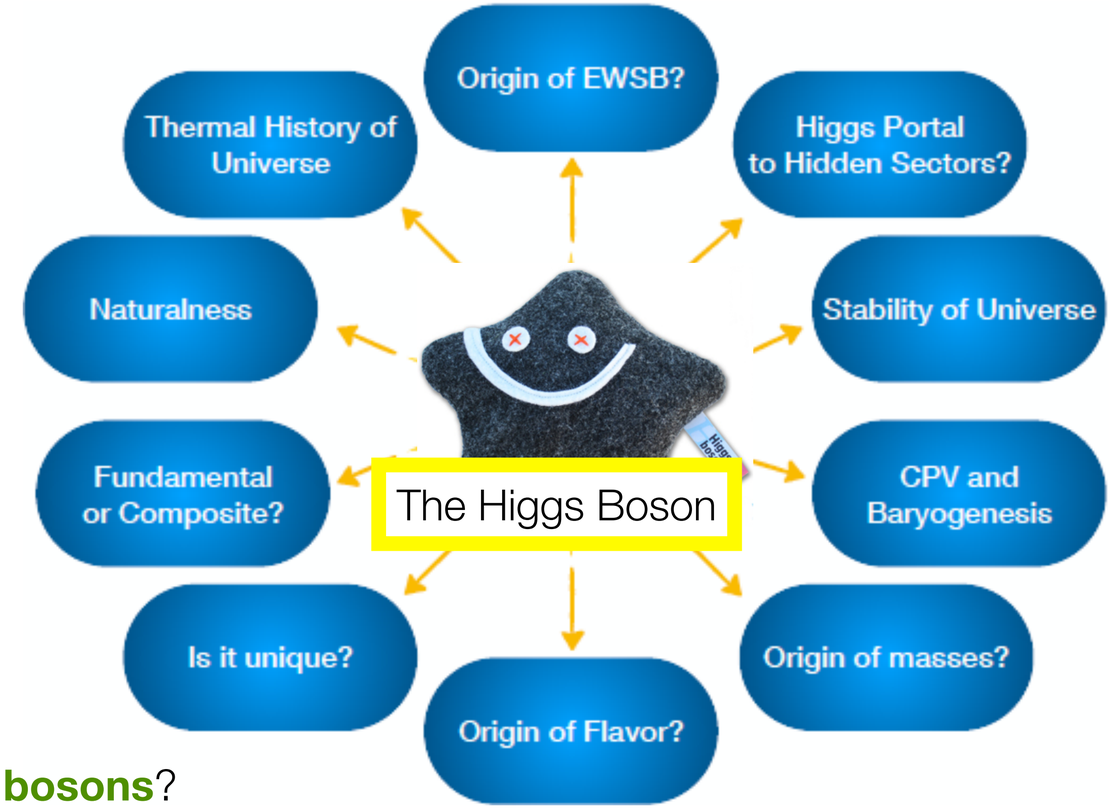

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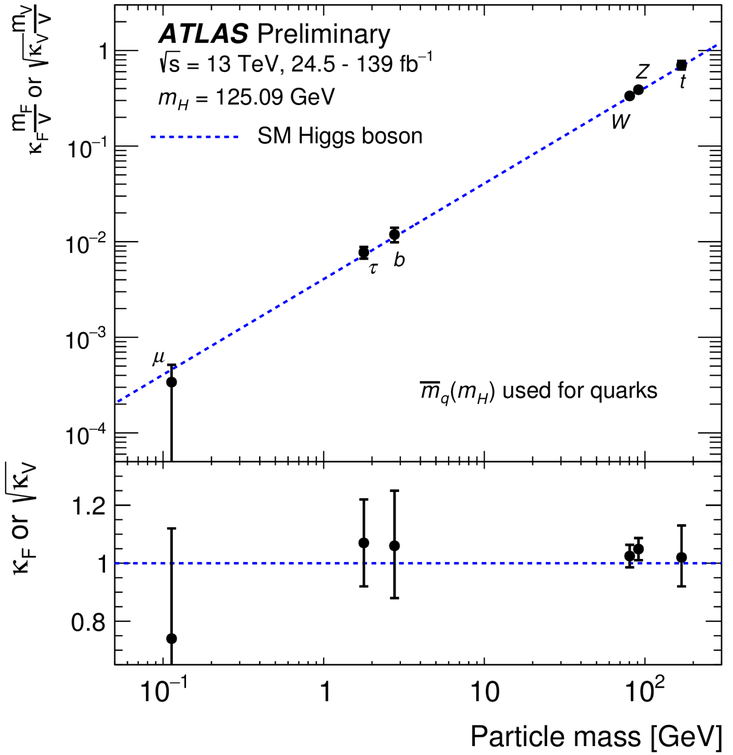
  - The **UNEXPECTED** !

Conditions at e+e- colliders very complementary to LHC:
- in particular low backgrounds
- clean events
- triggerless operation (LCs)

What will we still learn from HL-LHC?

…and other ongoing experiments

- **LHC discovered the 125-Higgs!**
  - Since then many properties measured with increasing precision
  - But need >10x better to detect deviations expected from BSM
  - No absolute coupling measurement possible, no total width
  - Self-coupling to 25..30% in SM case
    - not bad, but would like 10% for SM and BSM case
- **Will (HL-)LHC discover more new particles?**
  - Maybe!
- **Many more discovery opportunities…**
  - LZ?
  - FermiLAT?
  - …?



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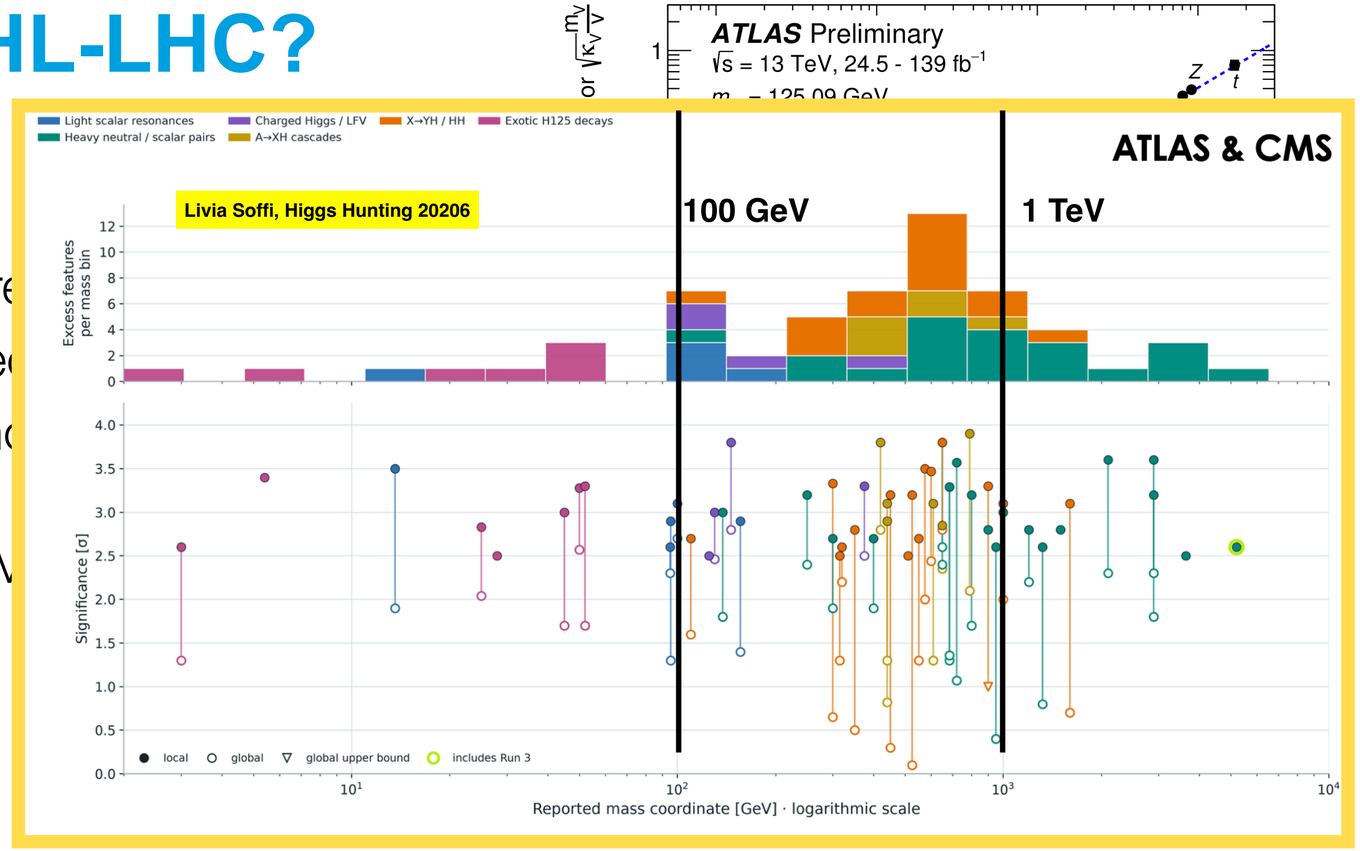

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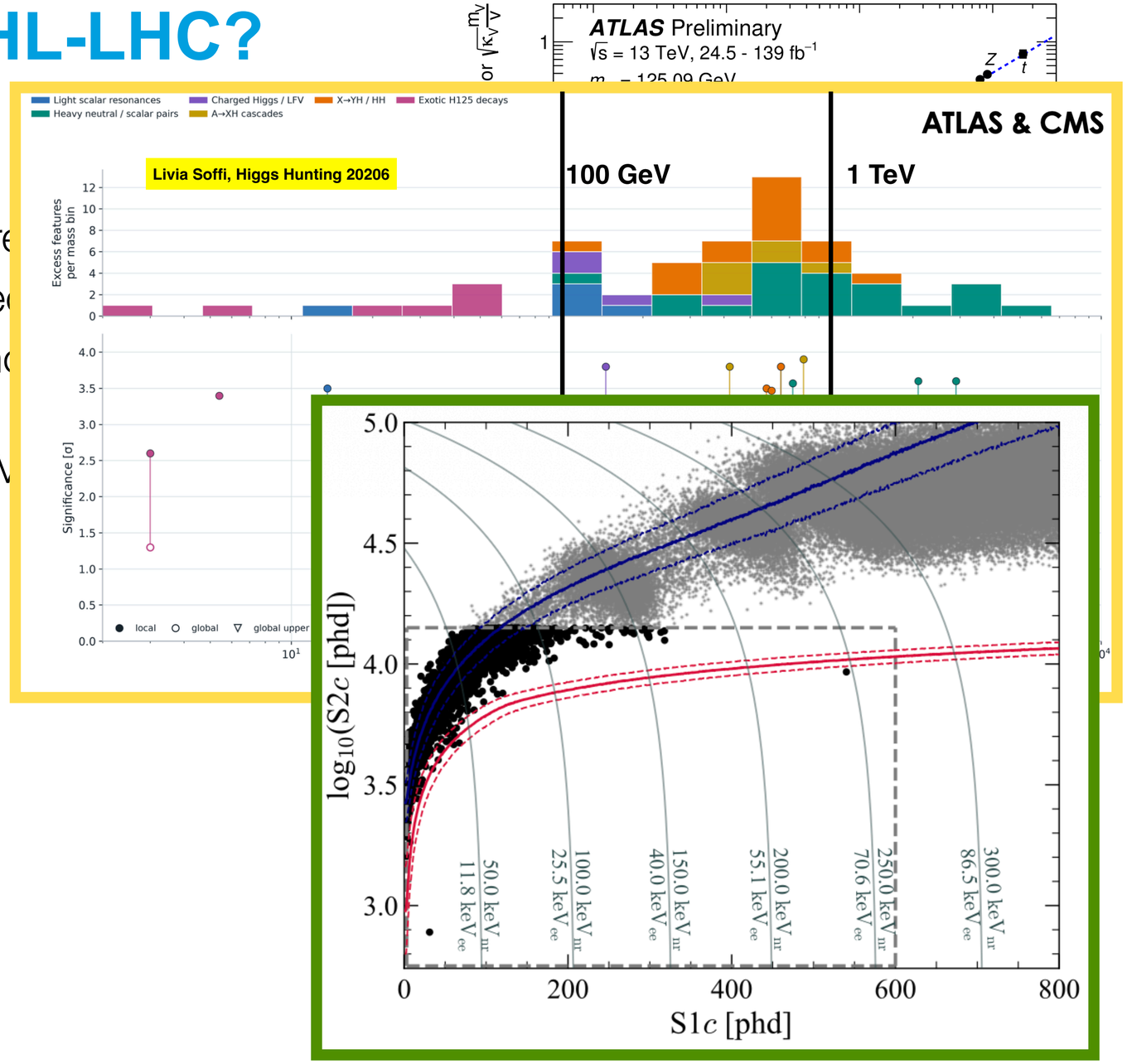

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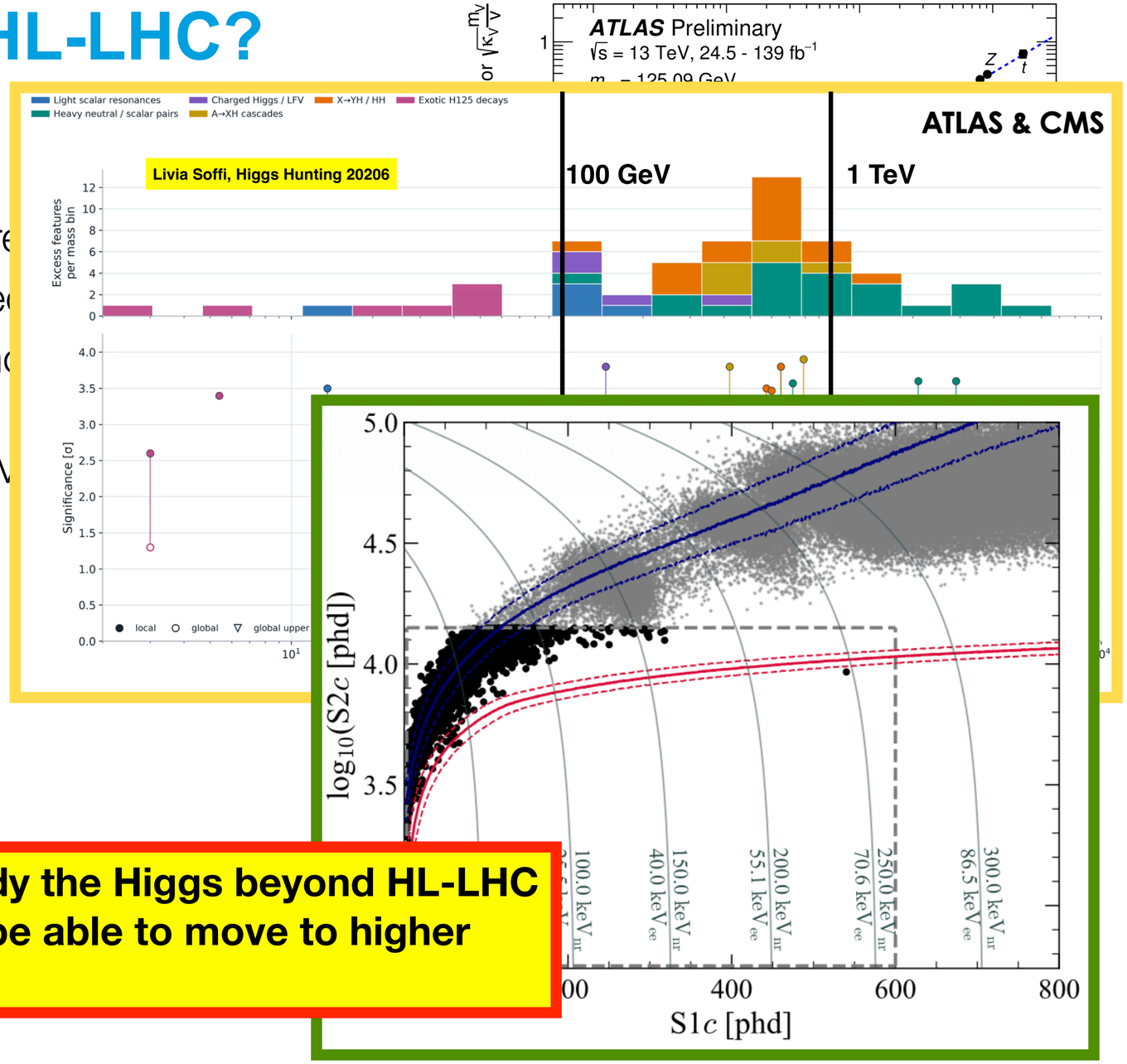
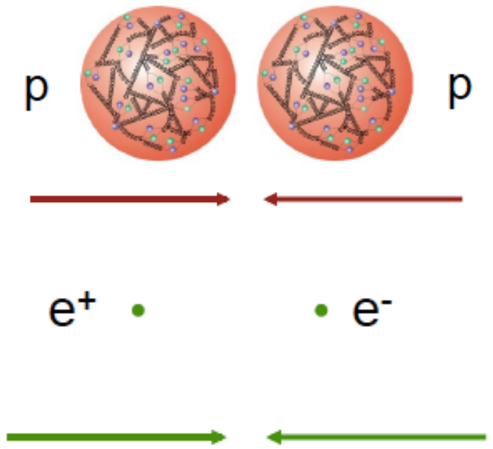


- ***For sure* need new collider to study the Higgs beyond HL-LHC**
- ***If* new particle emerges, need to be able to move to higher energy — don't know yet which…**

From the HL-LHC to electron-positron colliders

From pp to e+e-

Complementary tools



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From pp to e+e-

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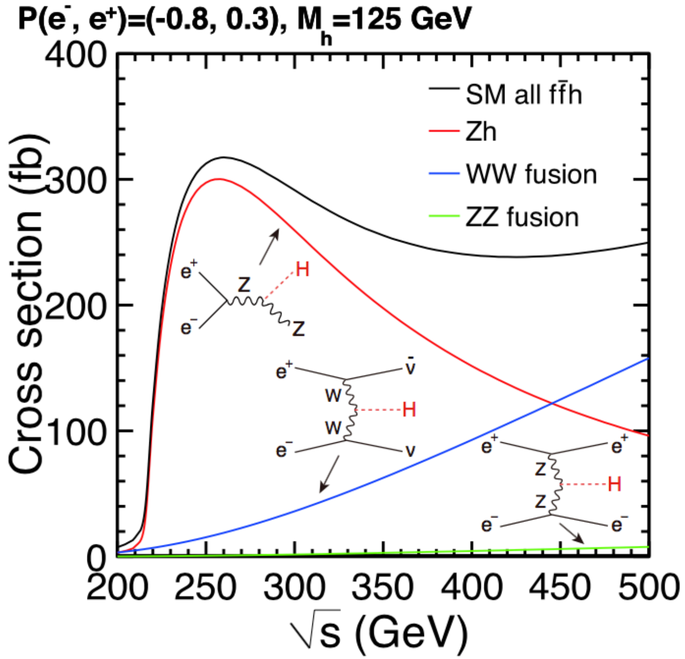

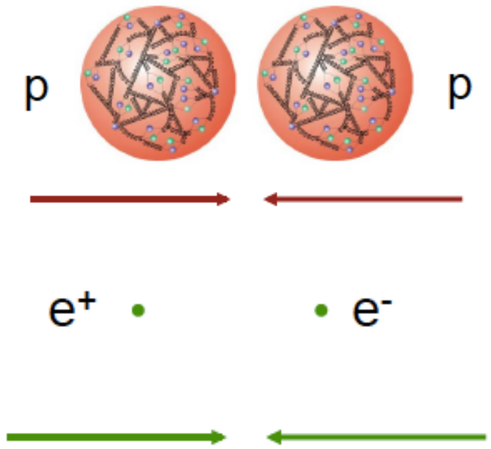

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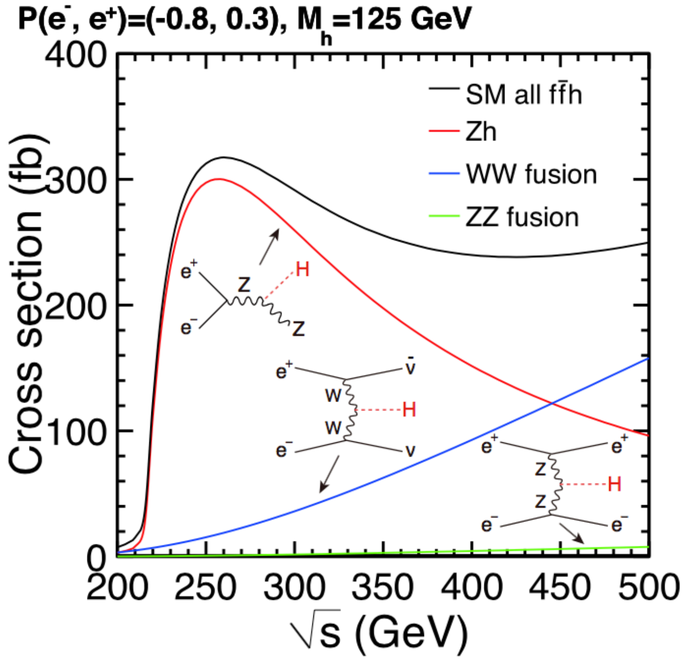

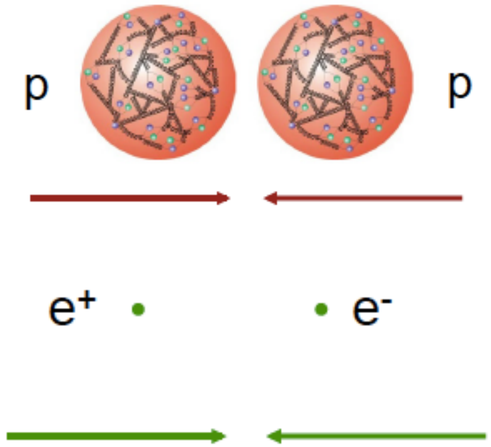

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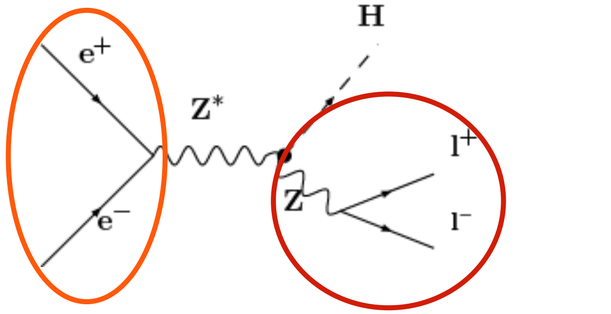

$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

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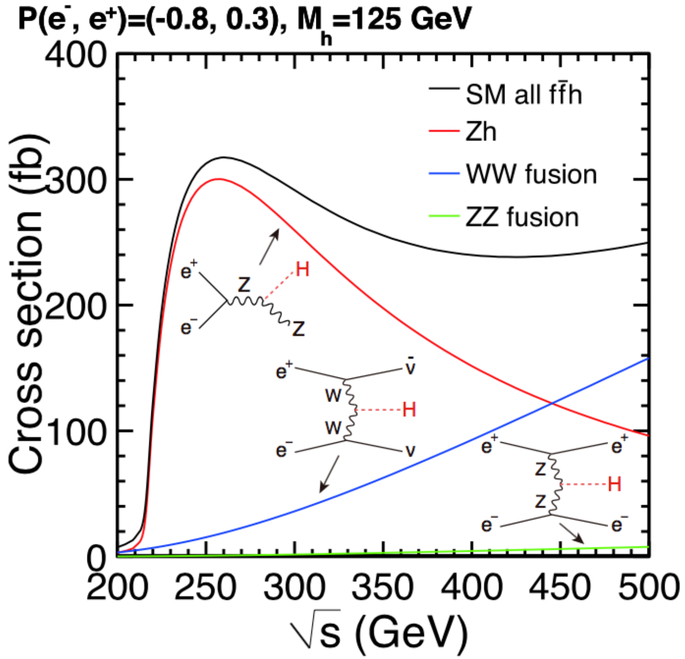

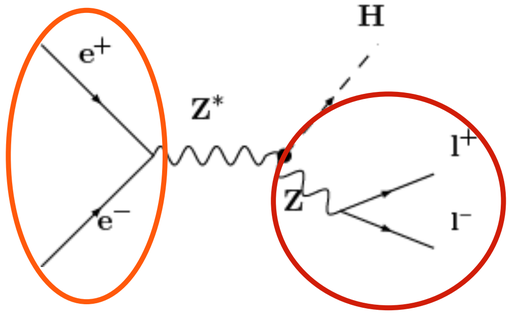

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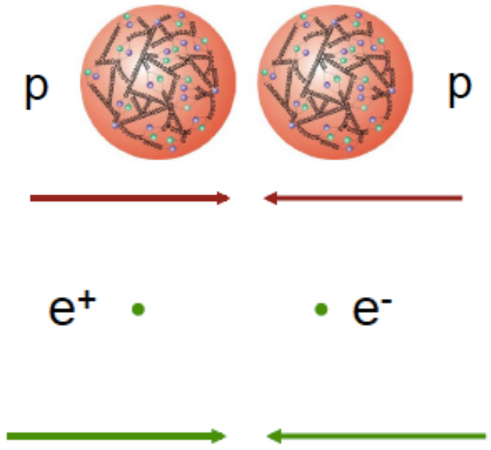

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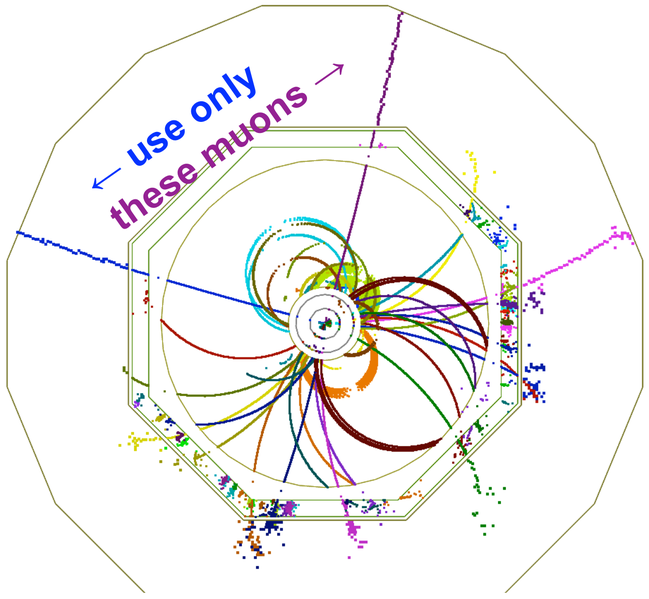

$e^+e^- \rightarrow \mu^+\mu^- H \rightarrow \mu^+\mu^-$ bb in ILD

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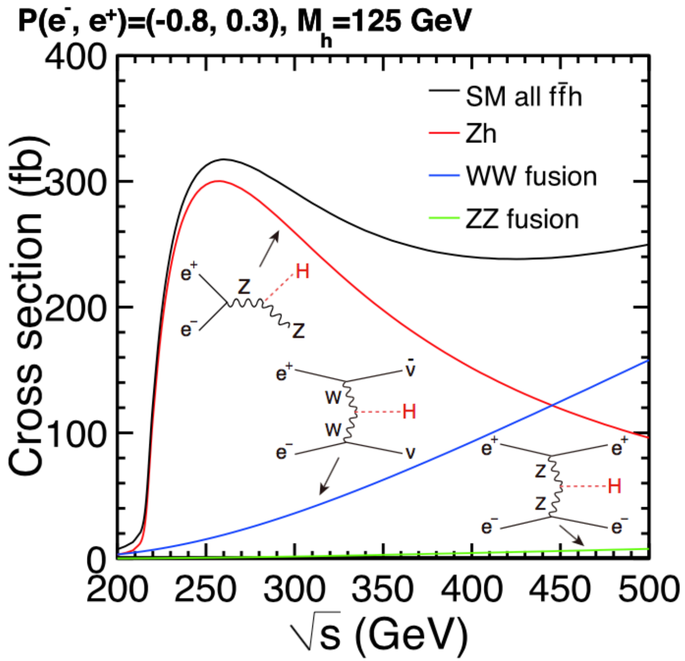

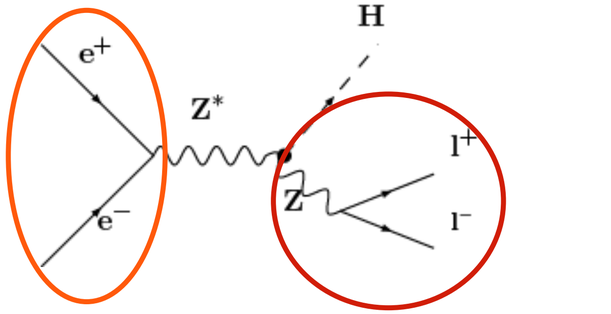

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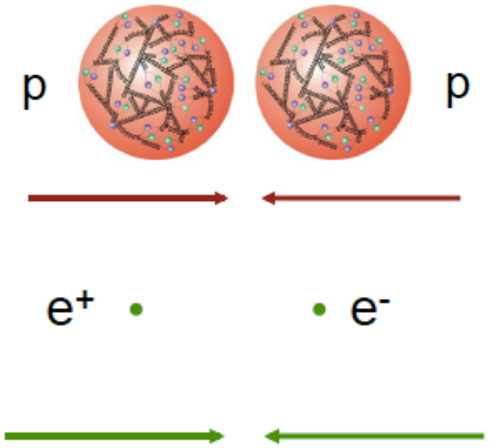

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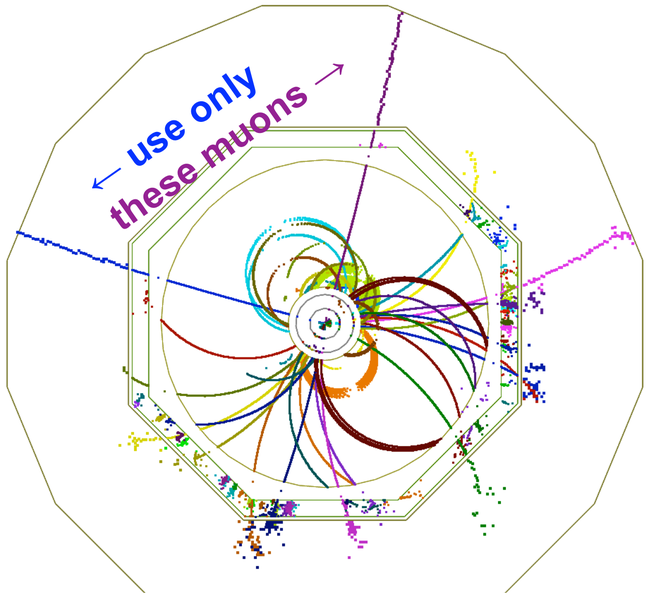

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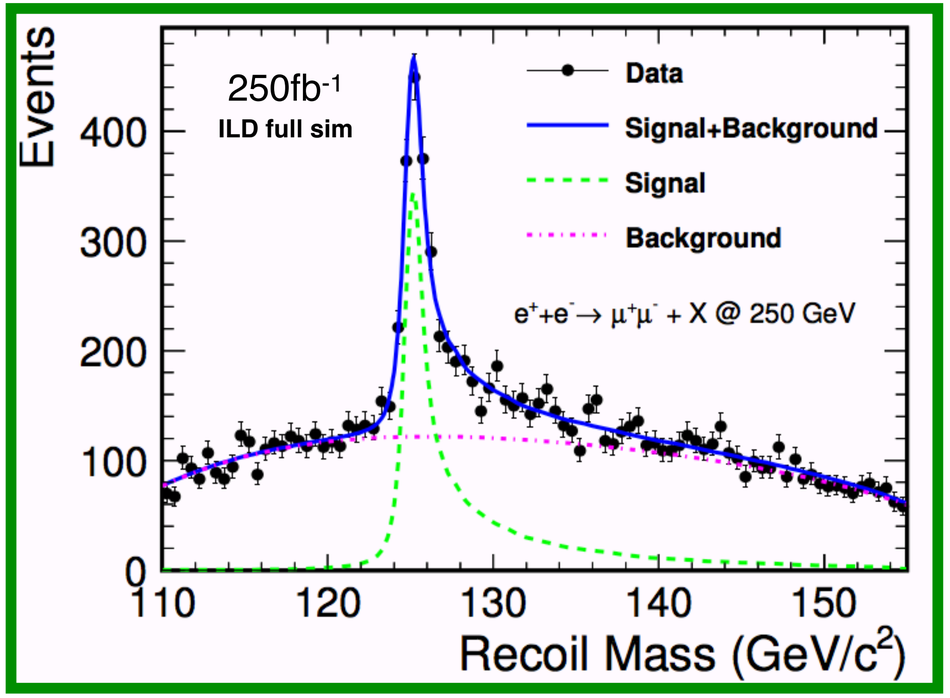

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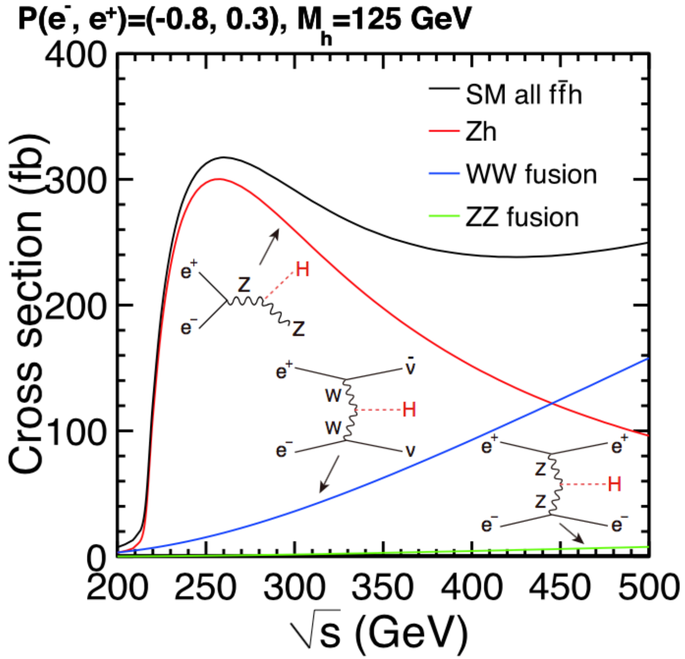

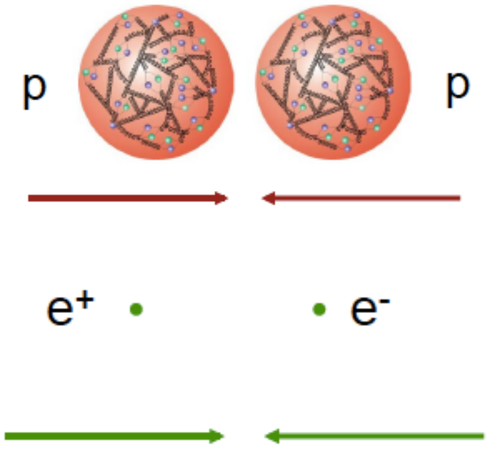

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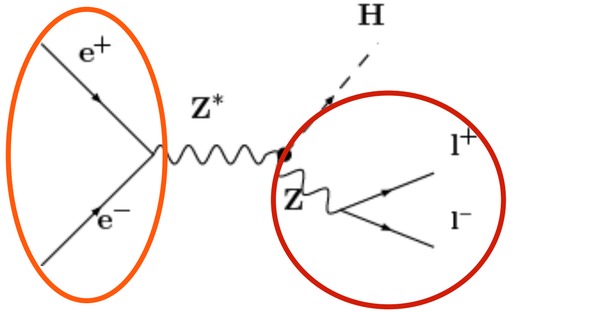

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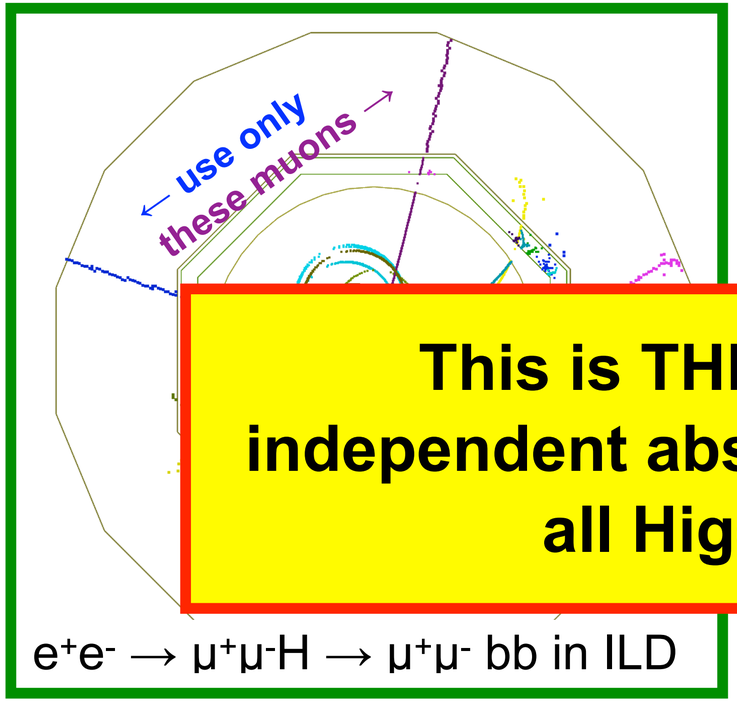

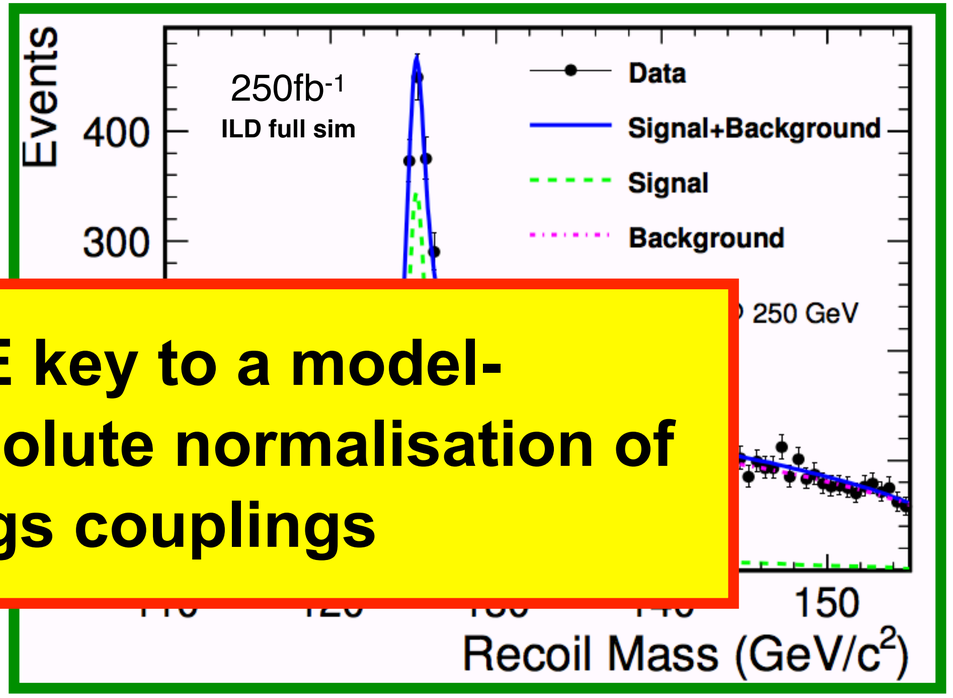

This is THE key to a model-independent absolute normalisation of all Higgs couplings

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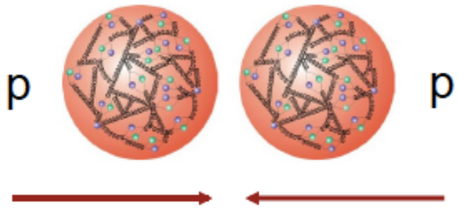

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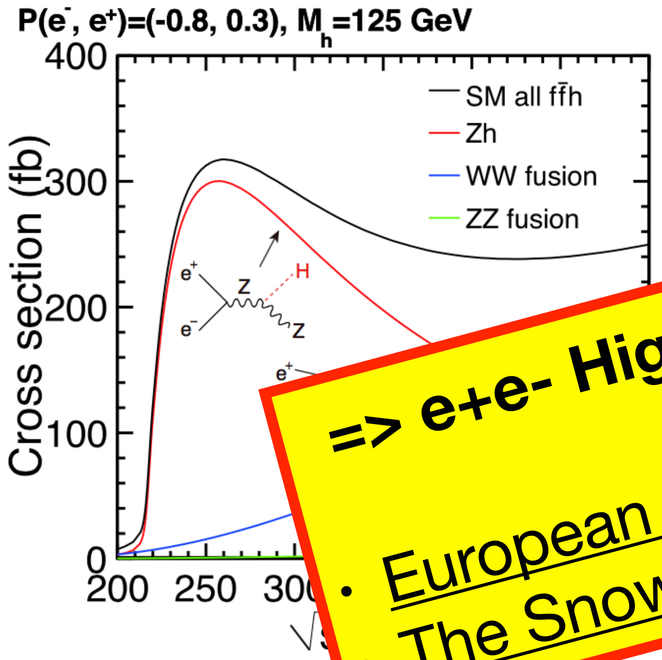
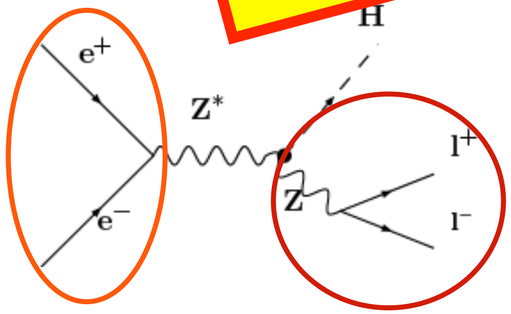


=> e+e- Higgs factory identified as the highest priority next collider by

- European Strategy for Particle Physics (2020)
- The Snowmass process in the US (2022)



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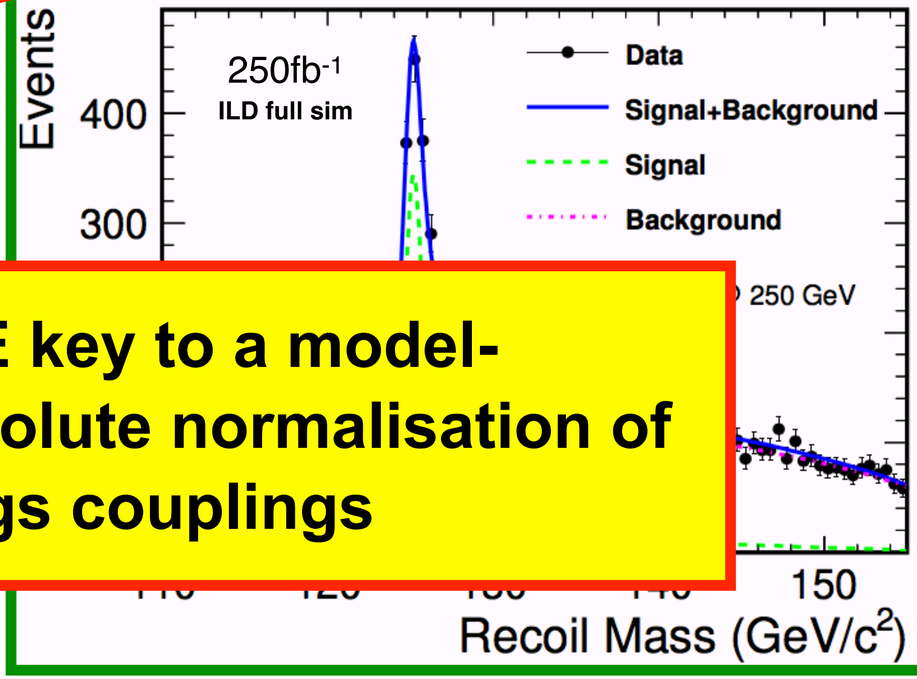

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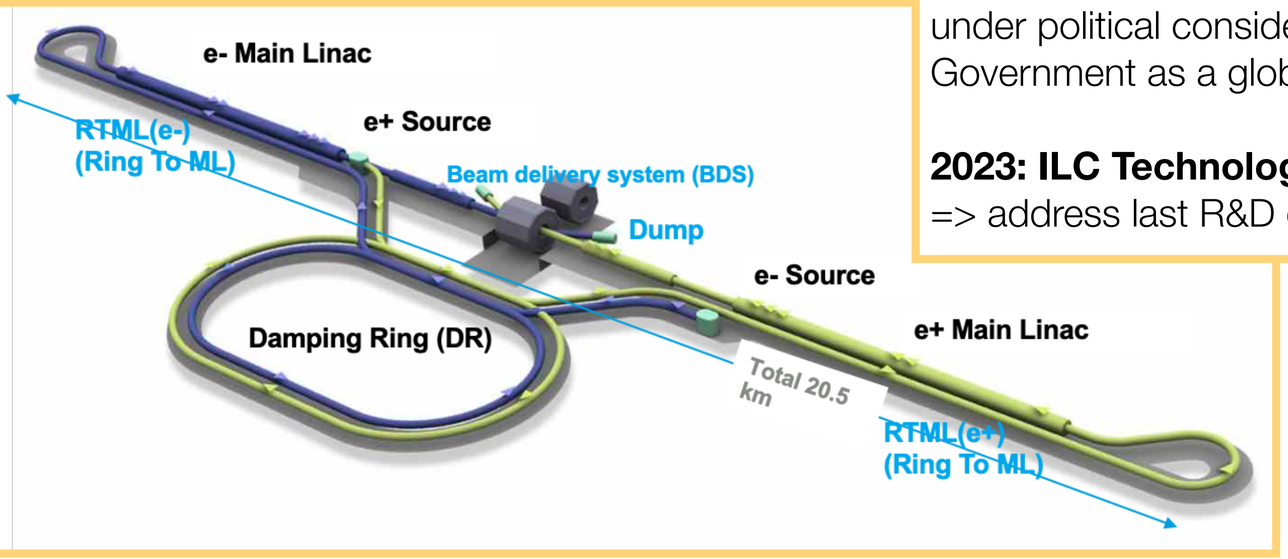
The key contenders

Status overview



ILC: e^+e^- **@** 90, 160**, 250,** 350**, 500 GeV, 1TeV**
TDR in **2012; 2017:** staged start at **250 GeV**
Superconducting RF

under political consideration by Japanese Government as a global project

2023: ILC Technology Network
=> address last R&D questions on accelerator

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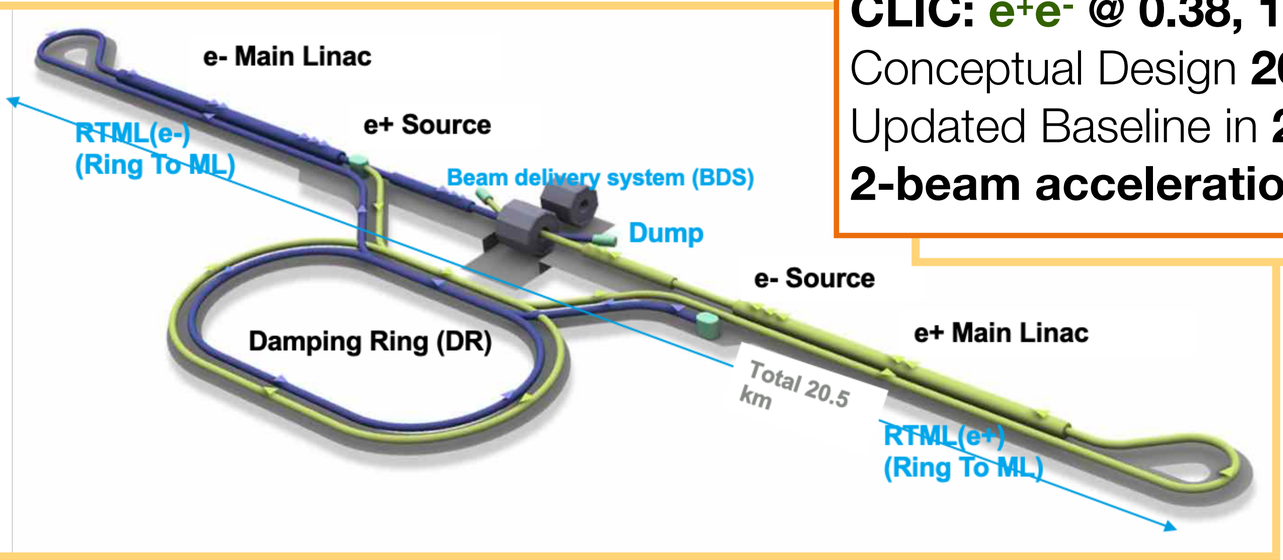

CLIC: e^+e^- @ 0.38, 1.4, 3 TeV
Conceptual Design **2013**
Updated Baseline in **2017**
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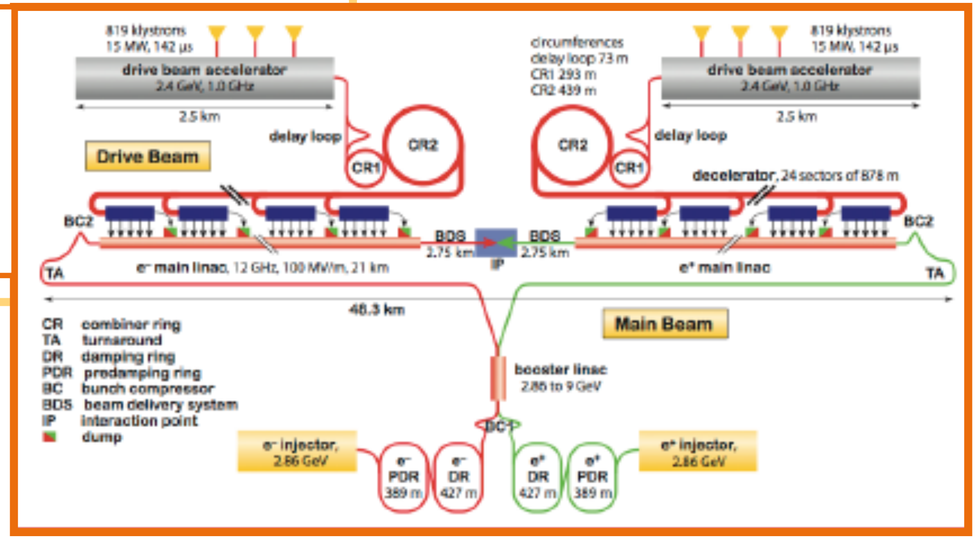

The key contenders

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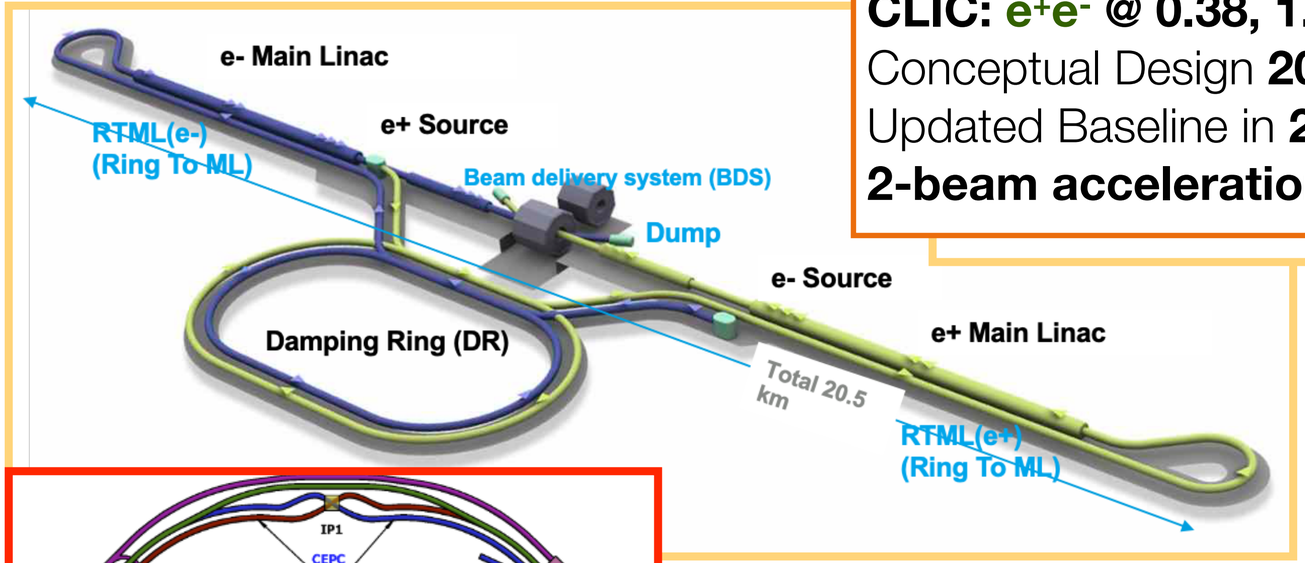

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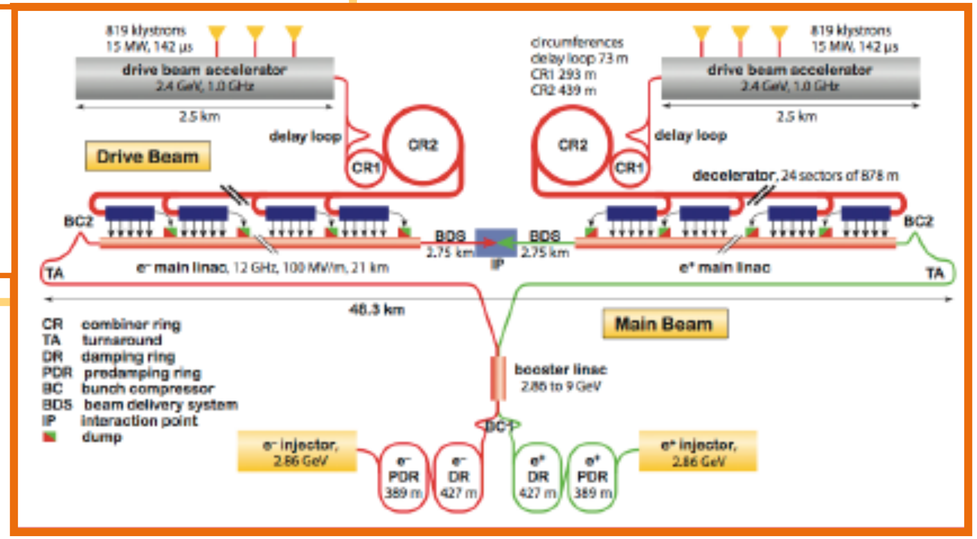

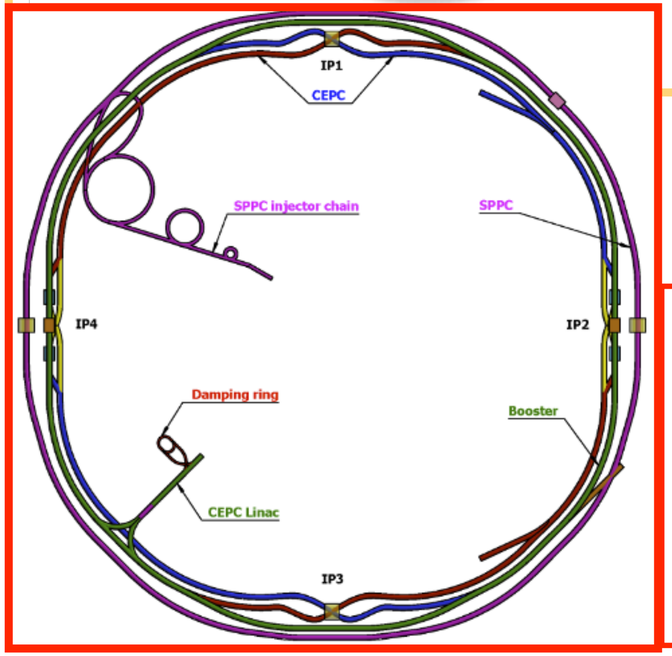

CEPC: e^+e^- @ 90-365 GeV

CDR published 2018
TDR in preparation, incl. cost review (Sep)
aiming for approval in next 5-year-plan (2025)
ranked 1st in HEP preselection

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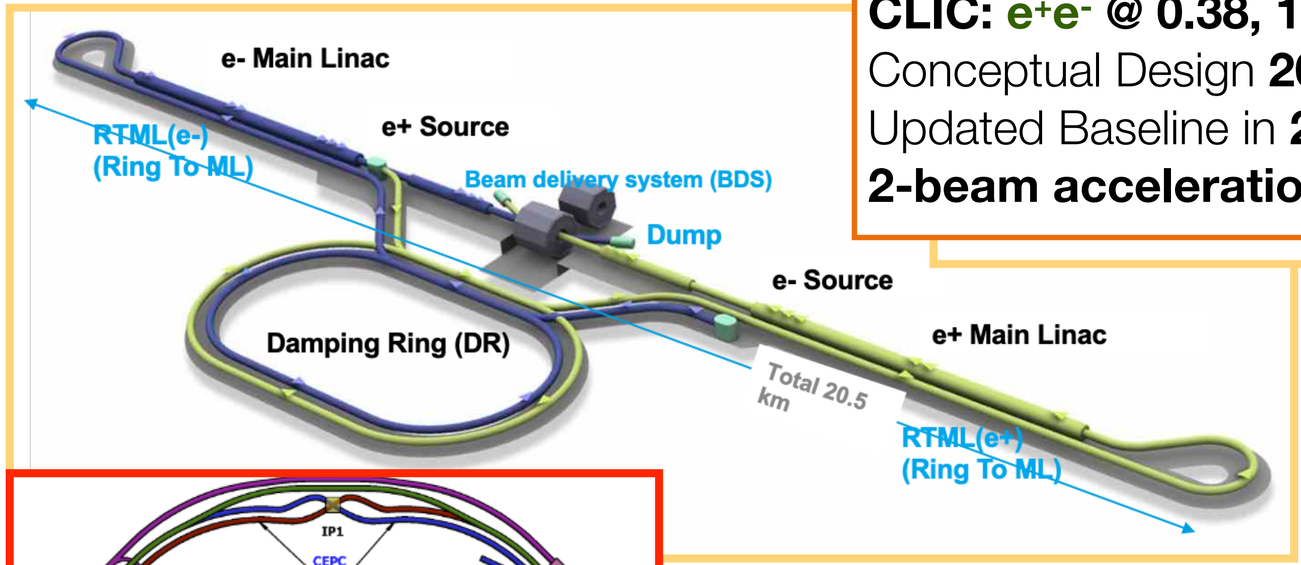

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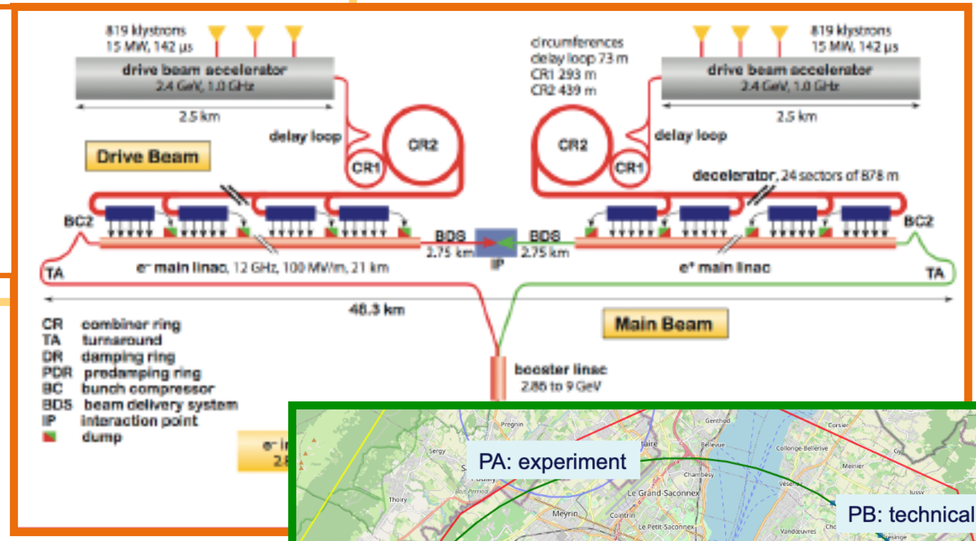

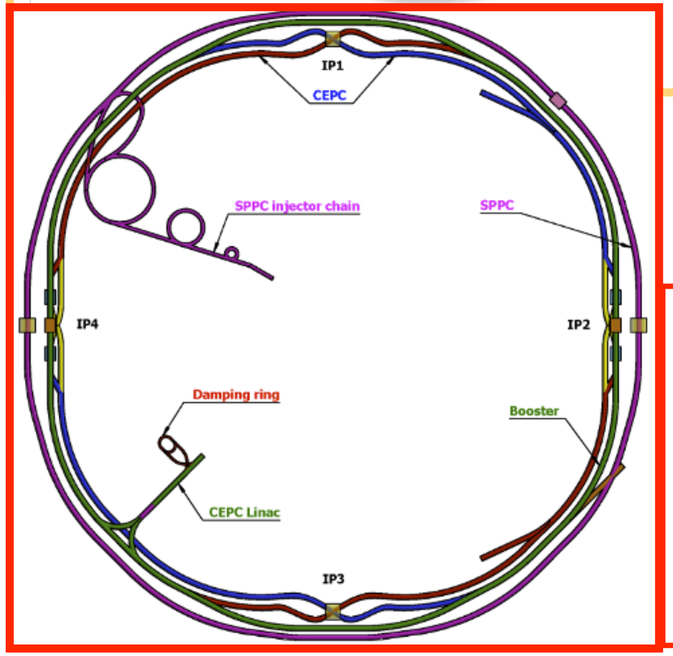

CEPC

CDR p
TDR i
aimin
ranke

FCC-ee e^+e^- @ 90-365 GeV
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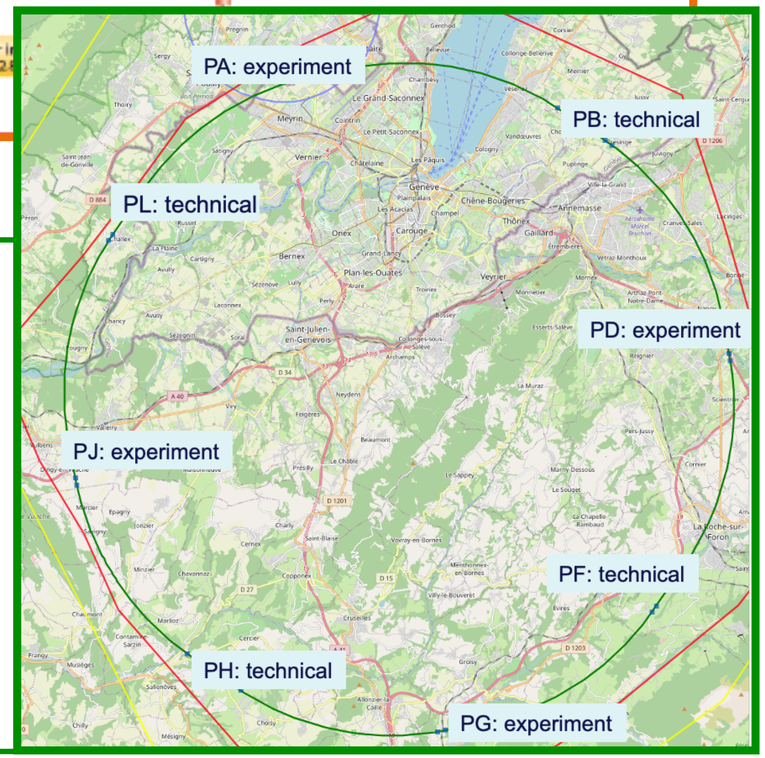
Since 2021: FCC Feasibility Study
(implementation scenario, environmental analysis, high-field magnets, ..)
=> FCC Feasibility Study report in 2025

next flagship collider for CERN!



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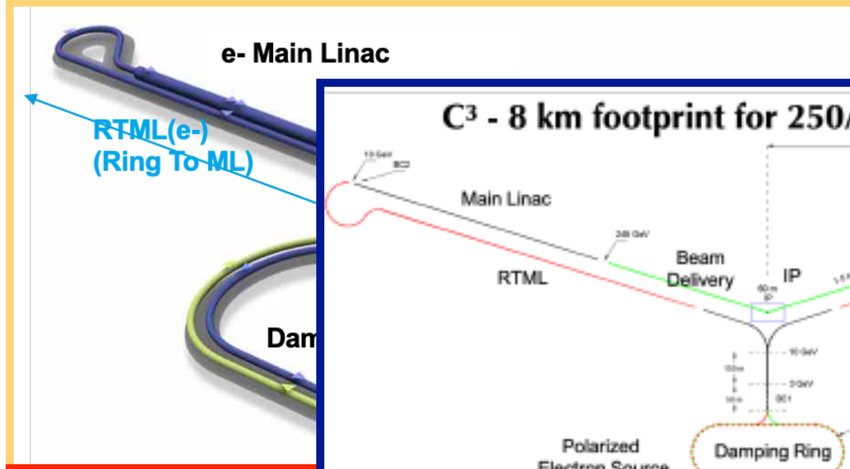

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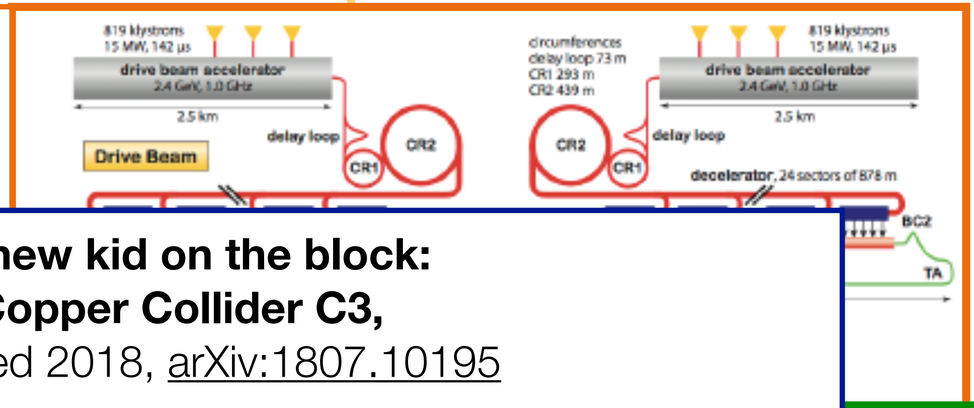
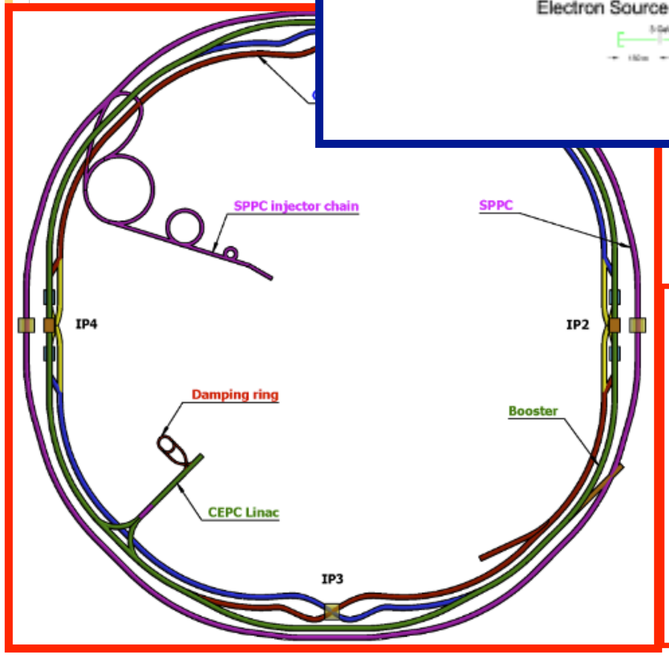


…and the new kid on the block:
the Cool Copper Collider C3,
first proposed 2018, arXiv:1807.10195

4km, time structure compatible with ILC detectors
hoping for support by P5 for 5-year R&D program



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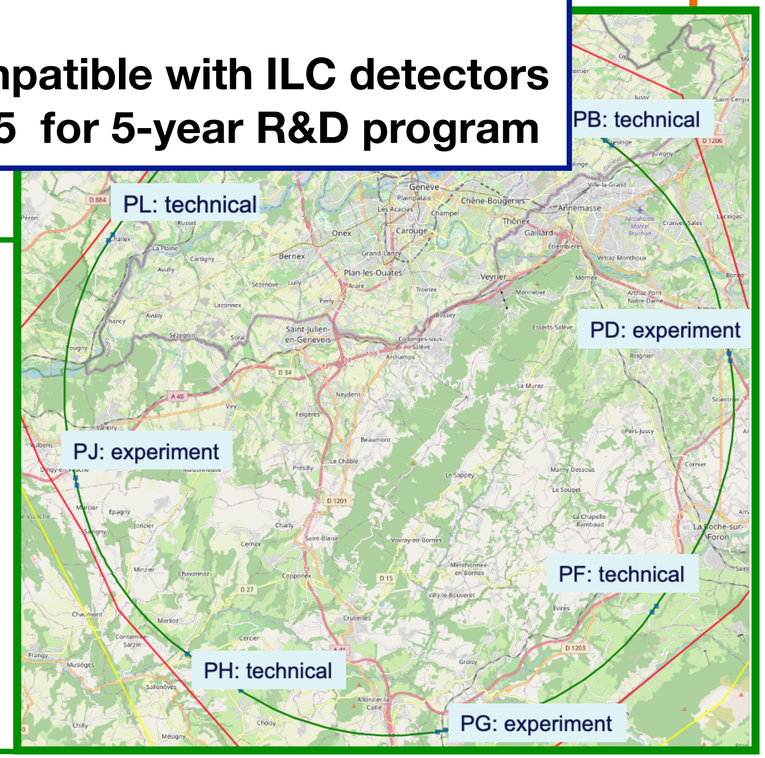

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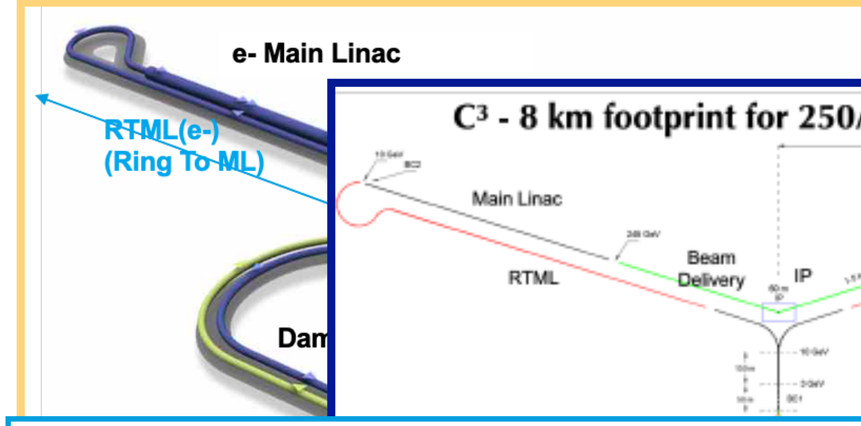

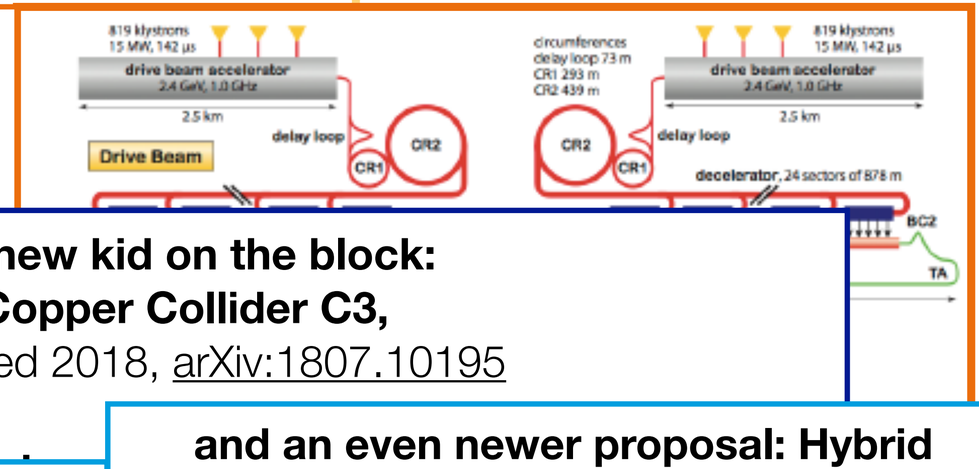

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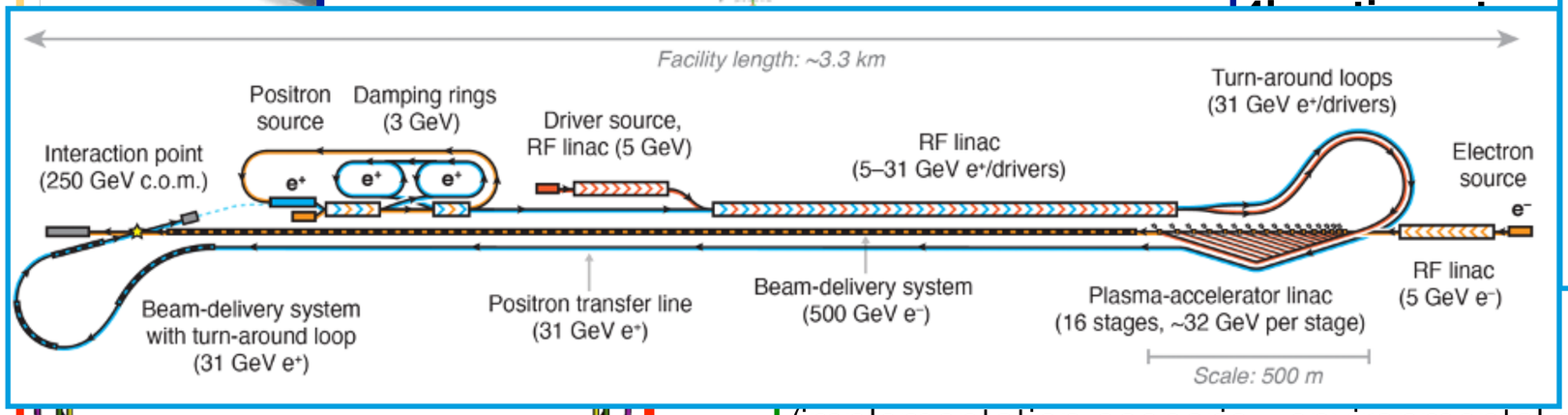
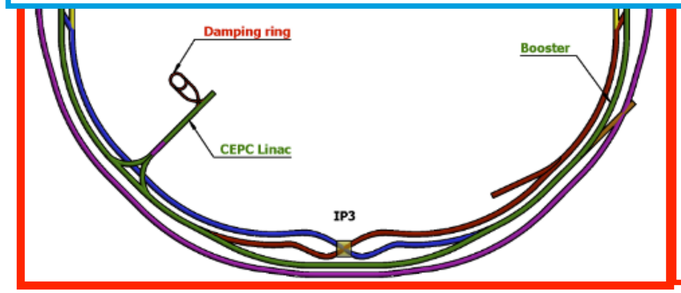


and an even newer proposal: Hybrid Asymmetric Linear Higgs Factory HALHF, arxiv:2303.10150

some first studies on detector / physics
estimated ~10 years of R&D for PWFA part



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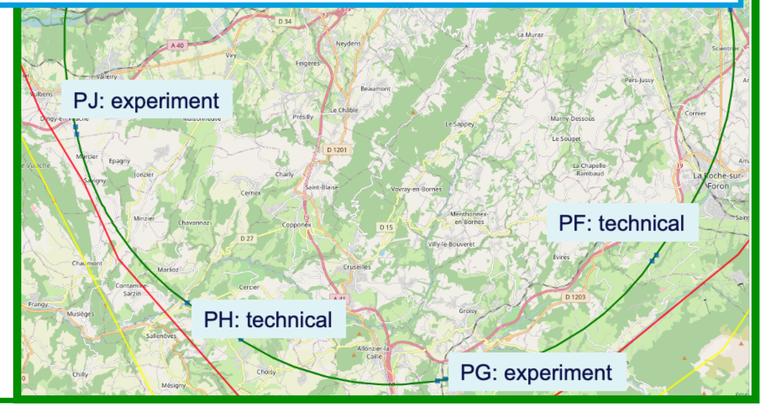

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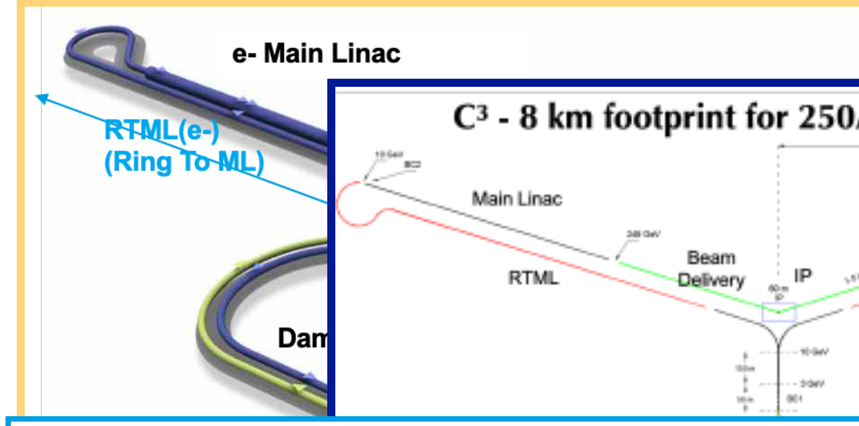

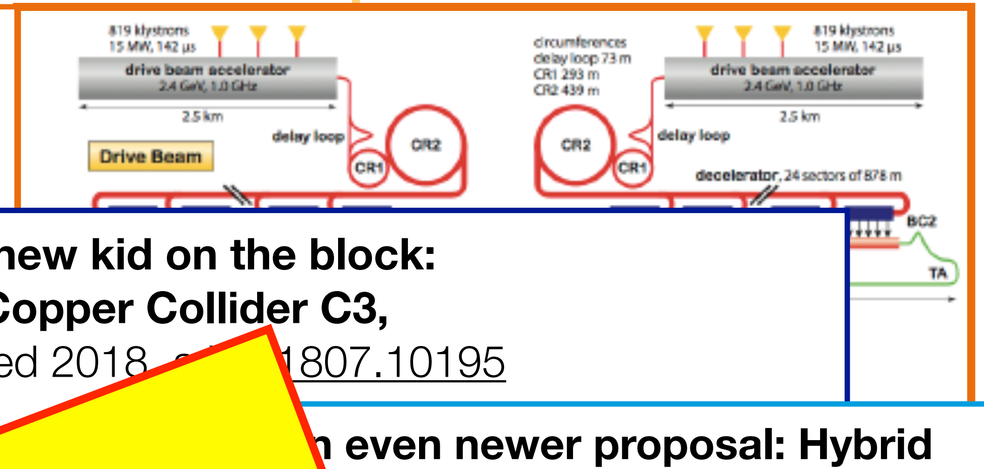

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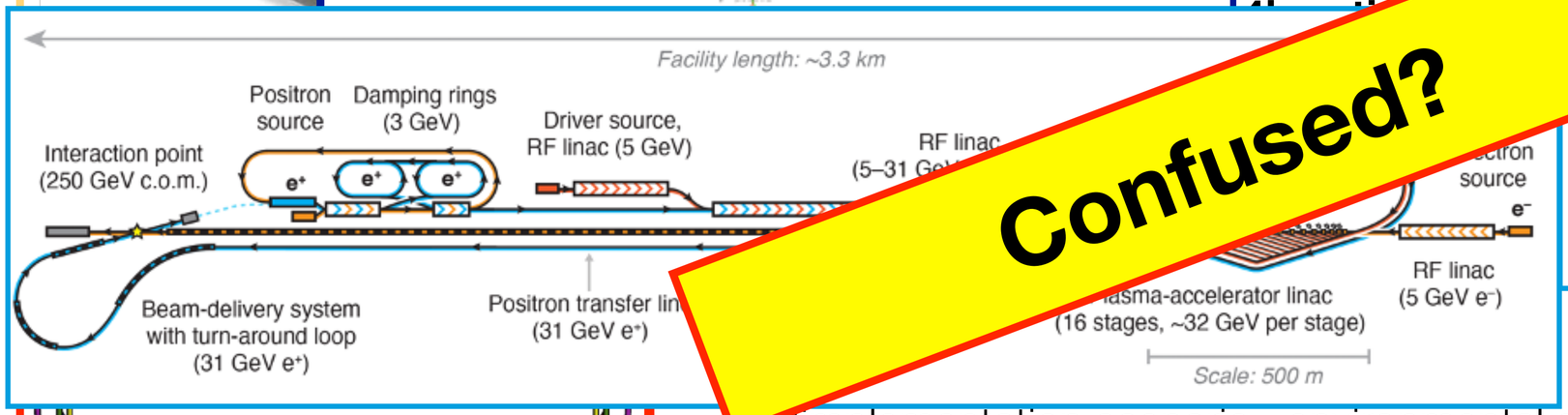

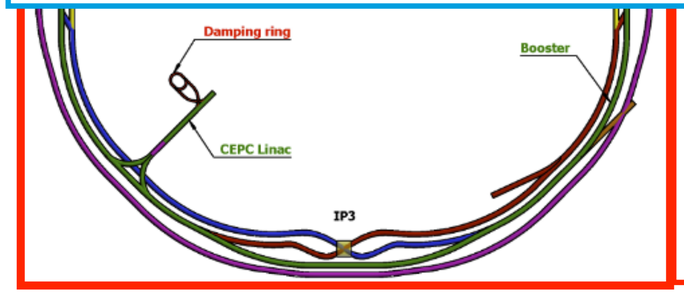

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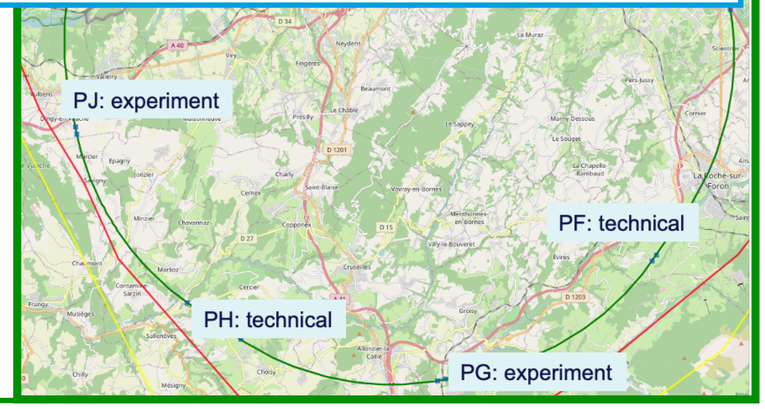
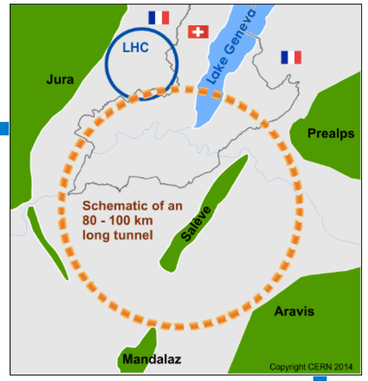


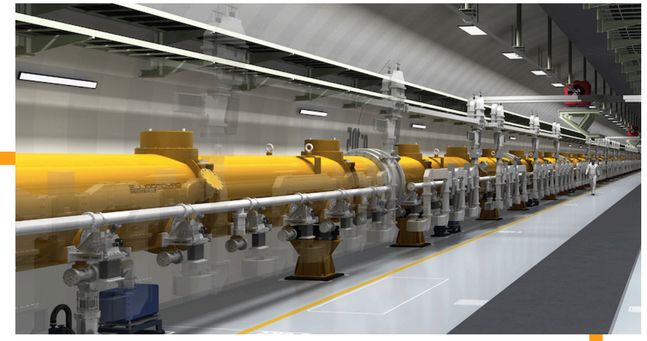
They fall into two classes

Each have their advantages



Circular e+e- Colliders

- FCCee, CEPC
- length 250 GeV: 90…100km
- high luminosity & power efficiency at **low energies**
- **multiple interaction regions**
- very clean: little beamstrahlung etc



Linear Colliders

- ILC, CLIC, C^3, …
- length 250 GeV: 4…11…20 km
- high luminosity & power efficiency at **high energies**
- **longitudinally spin-polarised beam(s)**

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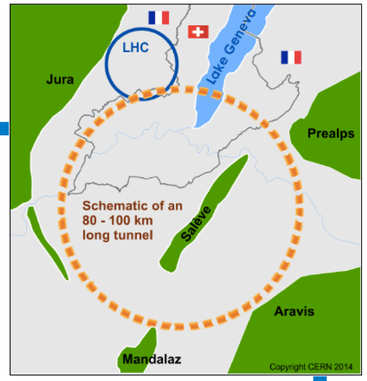

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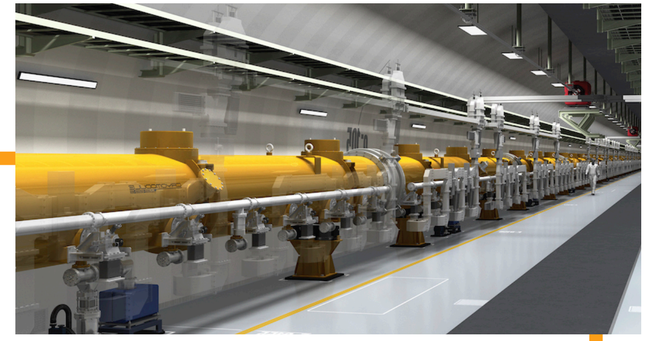

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Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge

Long-term upgrades: energy extendability

- same technology: by increasing length
- **or by replacing accelerating structures with advanced technologies**
  - RF cavities with high gradient
  - plasma acceleration ?

Luminosity vs Energy - a long debate…

Reminder: accelerated charges radiate

- **Synchrotron radiation ~ operation cost:**
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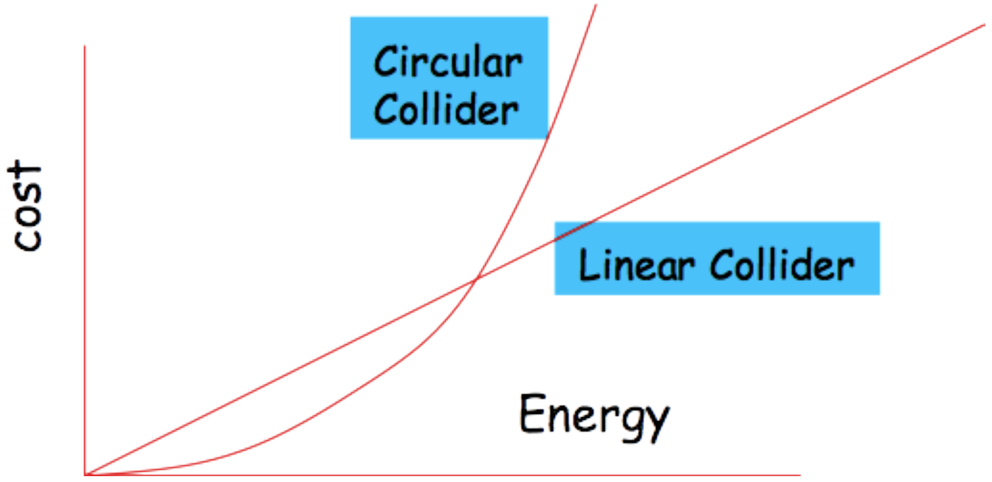

LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND LINEAR COLLIDING BEAM SYSTEMS AT HIGH ENERGY

1978[1)]

J.-E. Augustin*, N. Dikanski†, Ya. Derbenev†, J. Rees‡,
B. Richter‡, A. Skrinski†, M. Tigner**, and H. Wiedemann‡

Introduction

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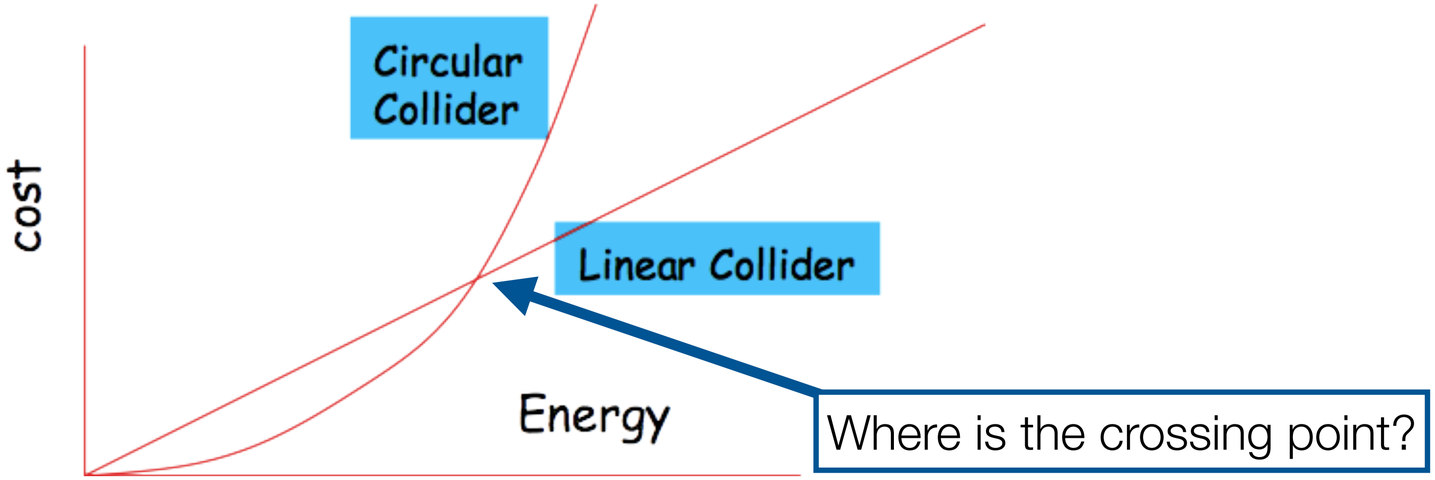

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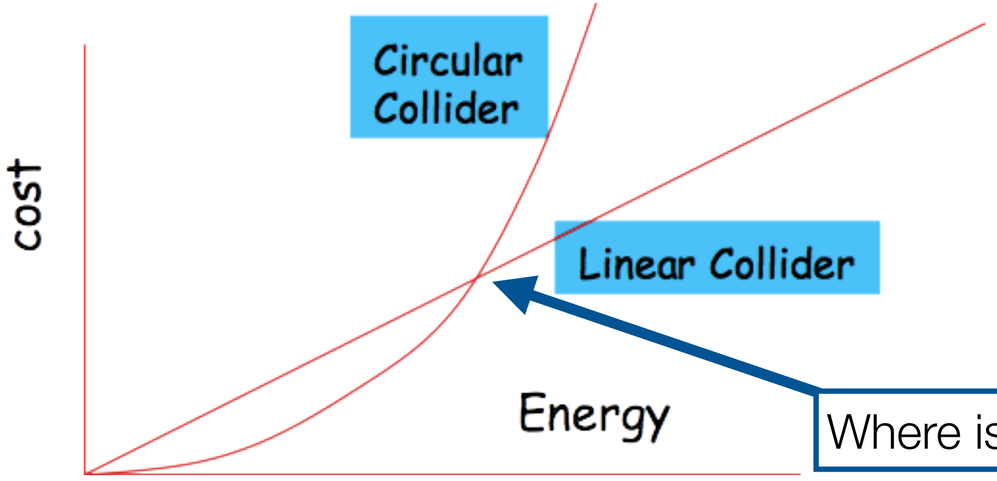
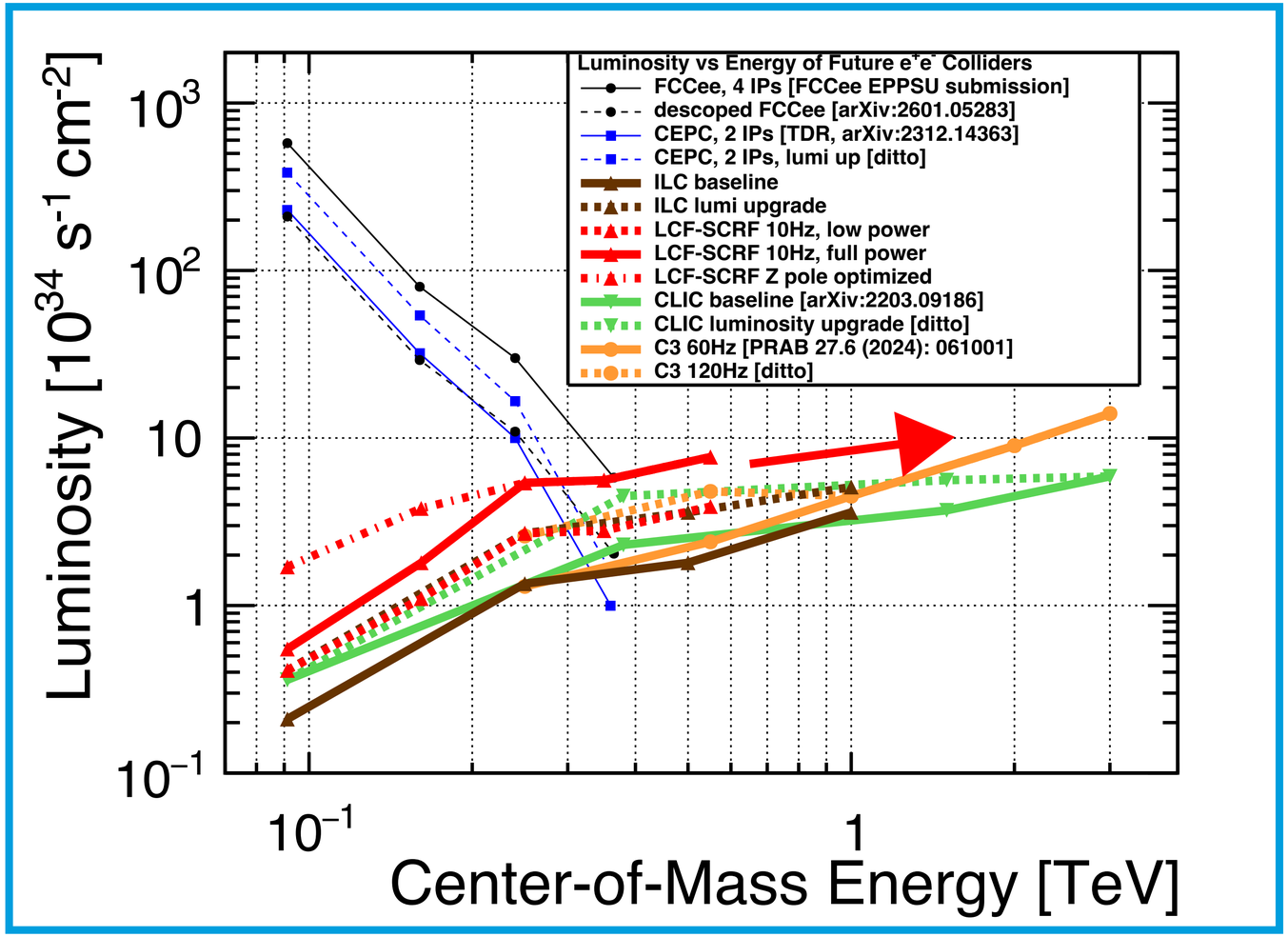


Where is the crossing point?



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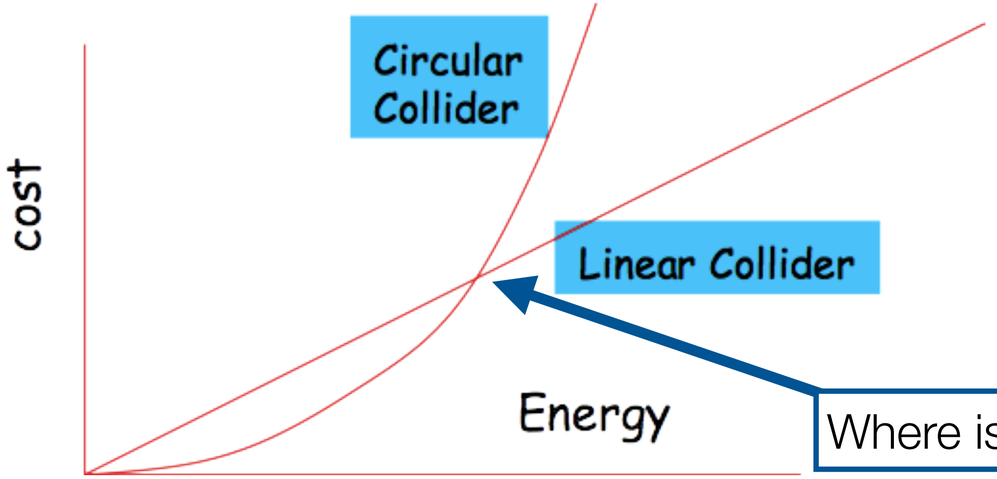

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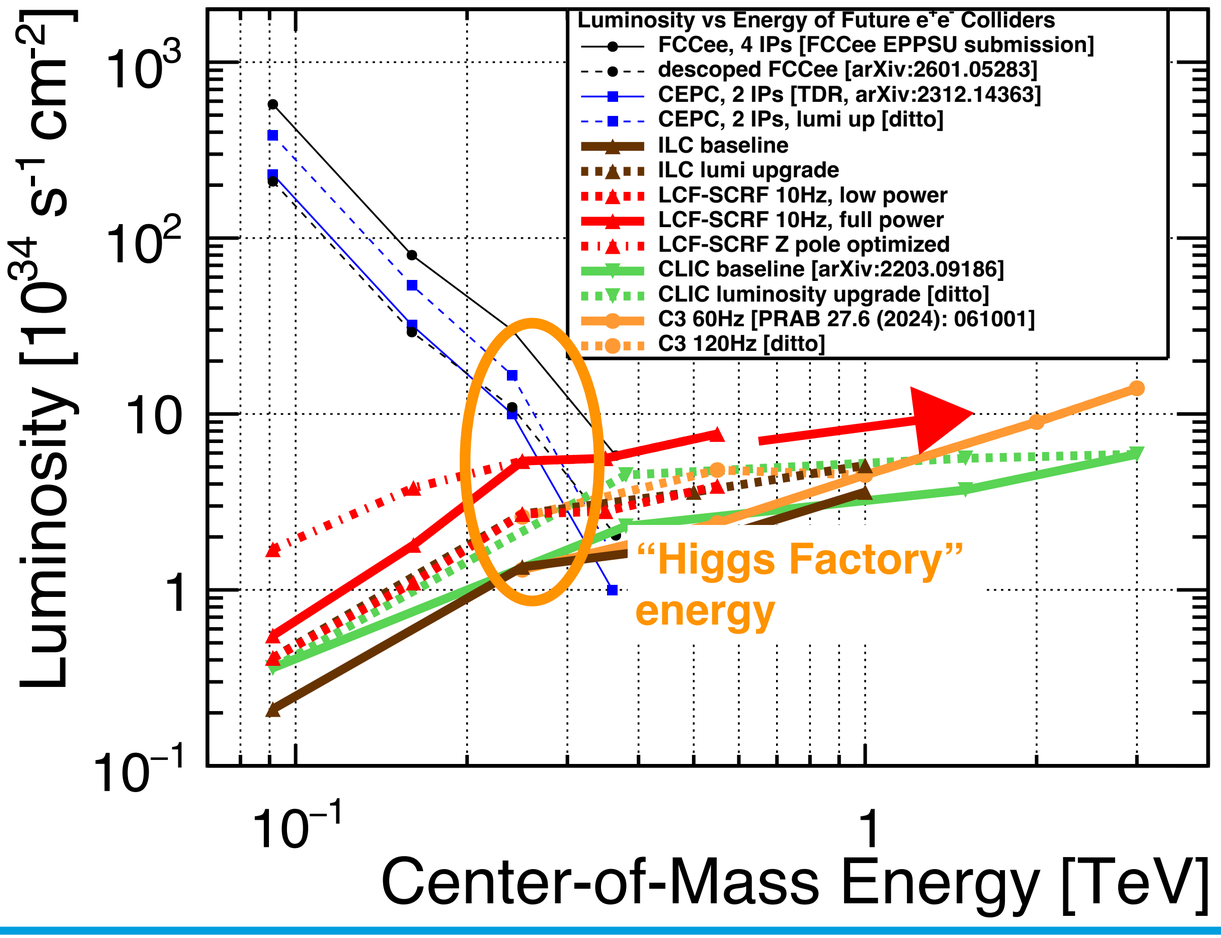

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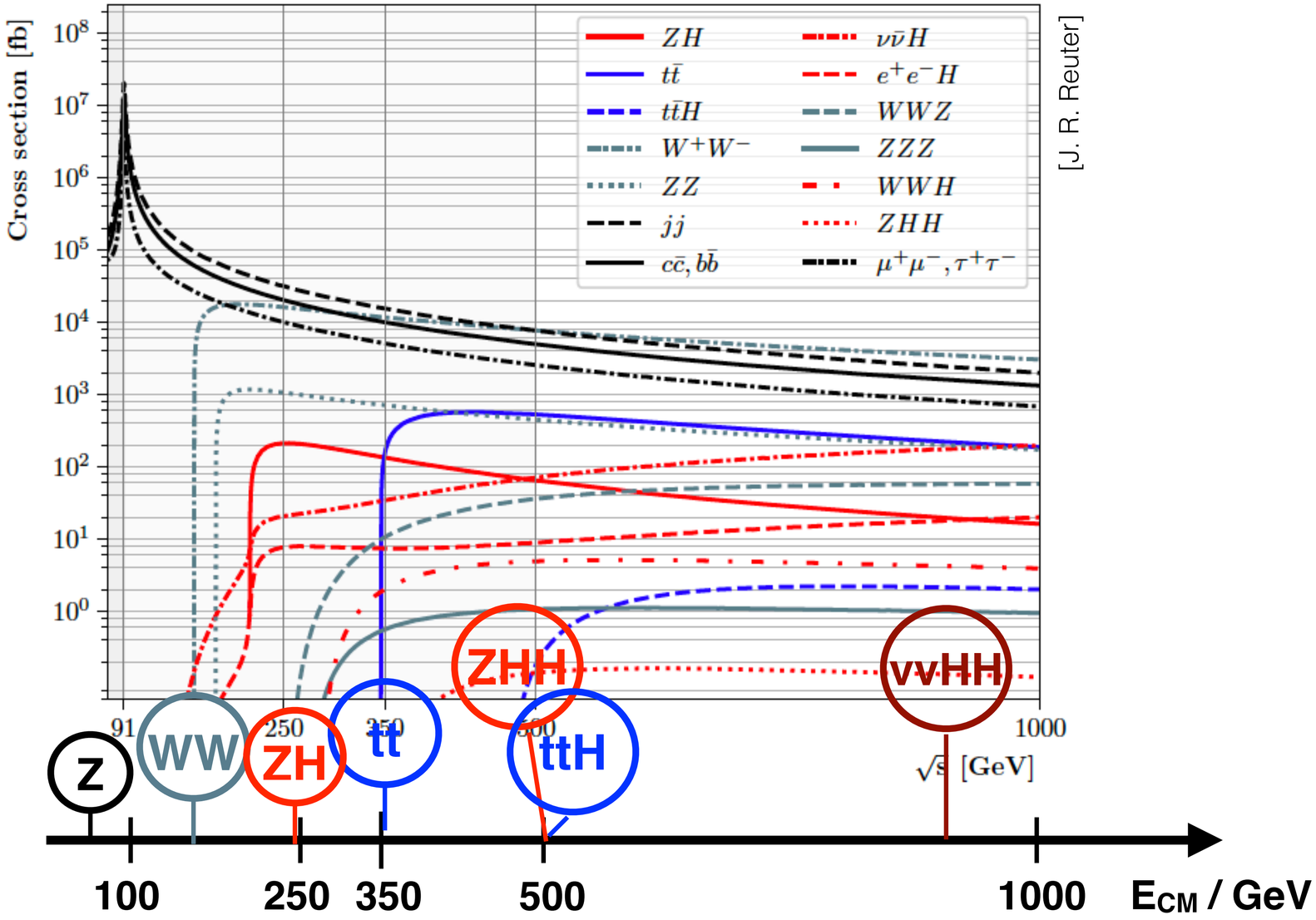
The key physics at a Higgs Factory

Production rates vs collision energy



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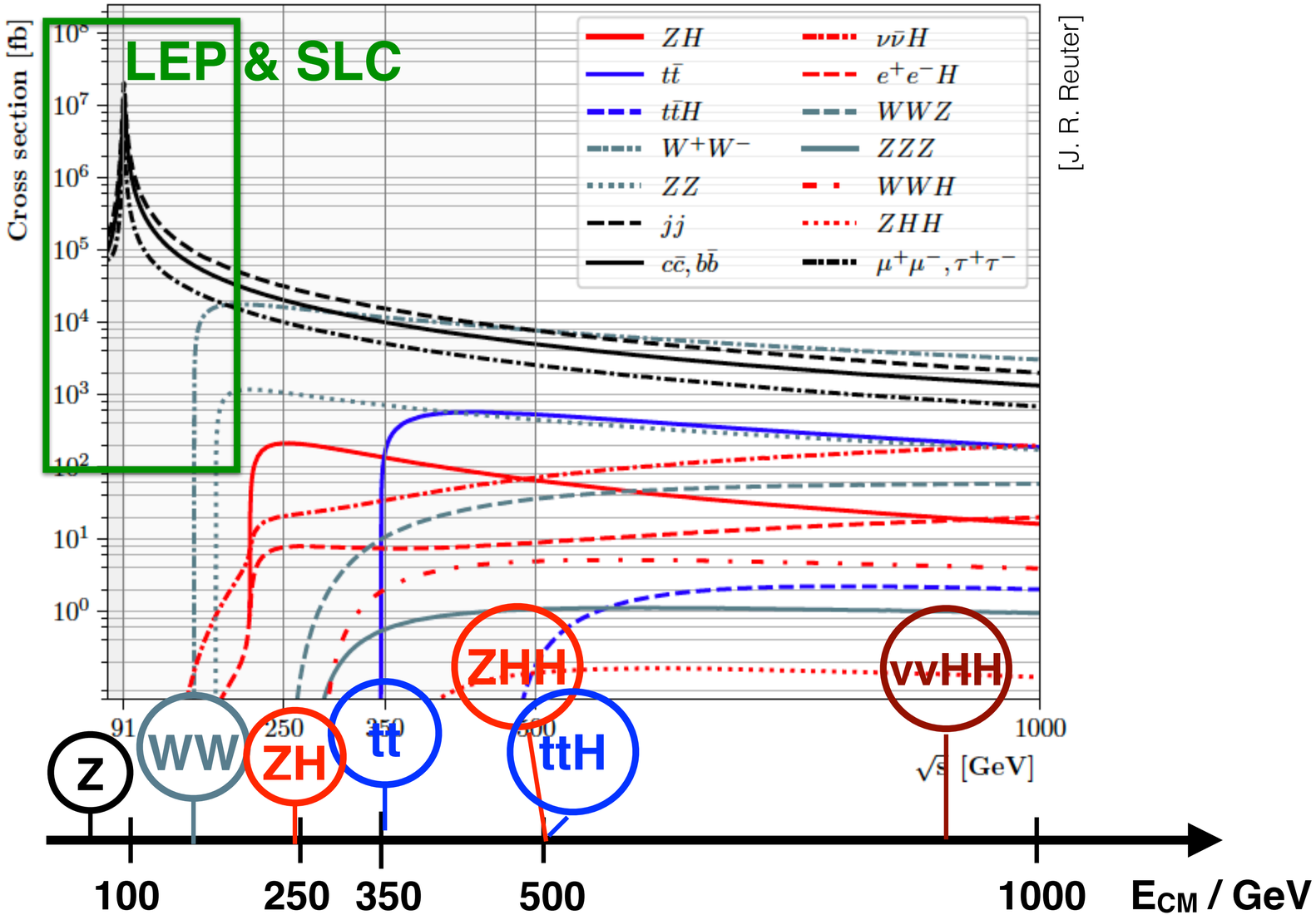

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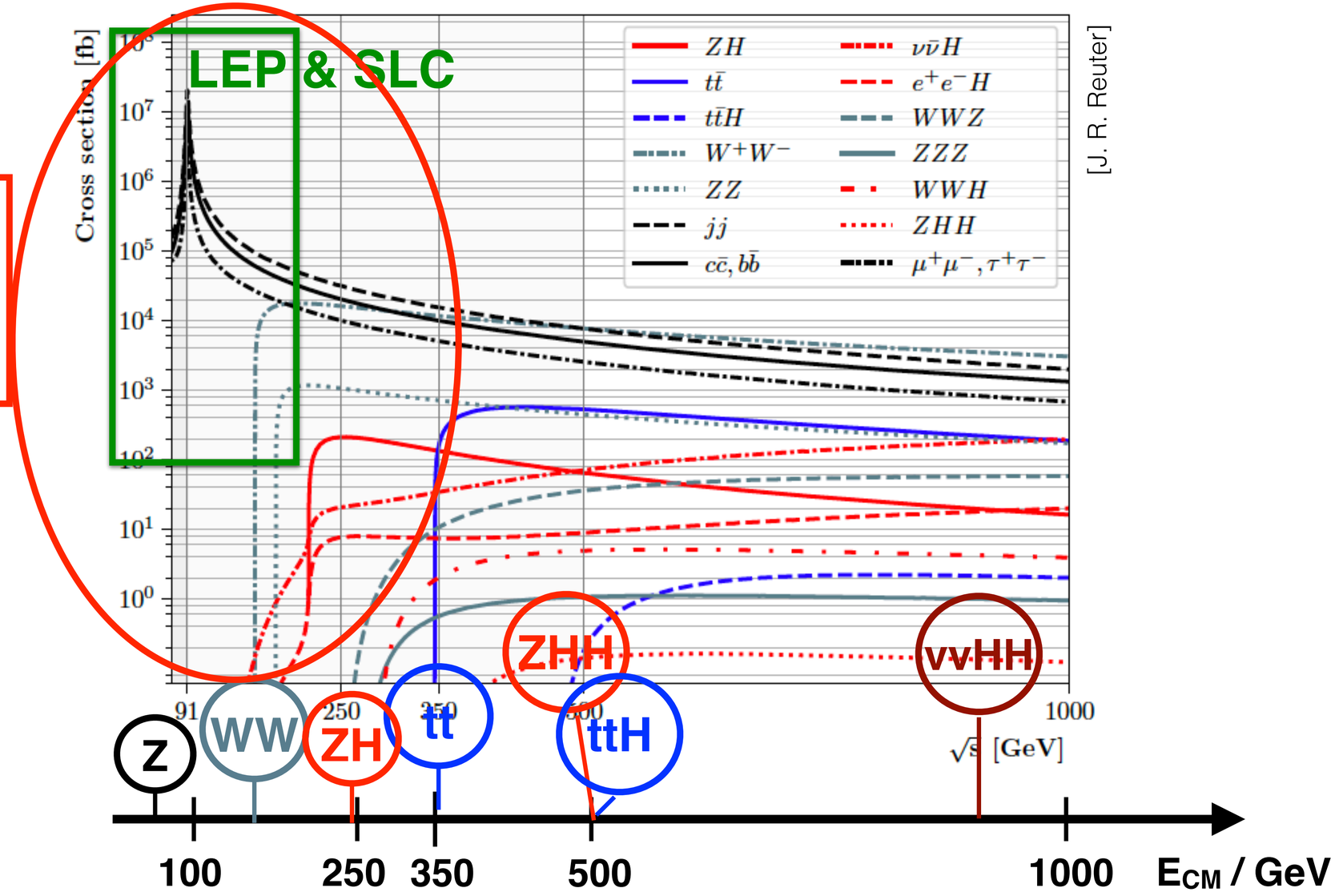

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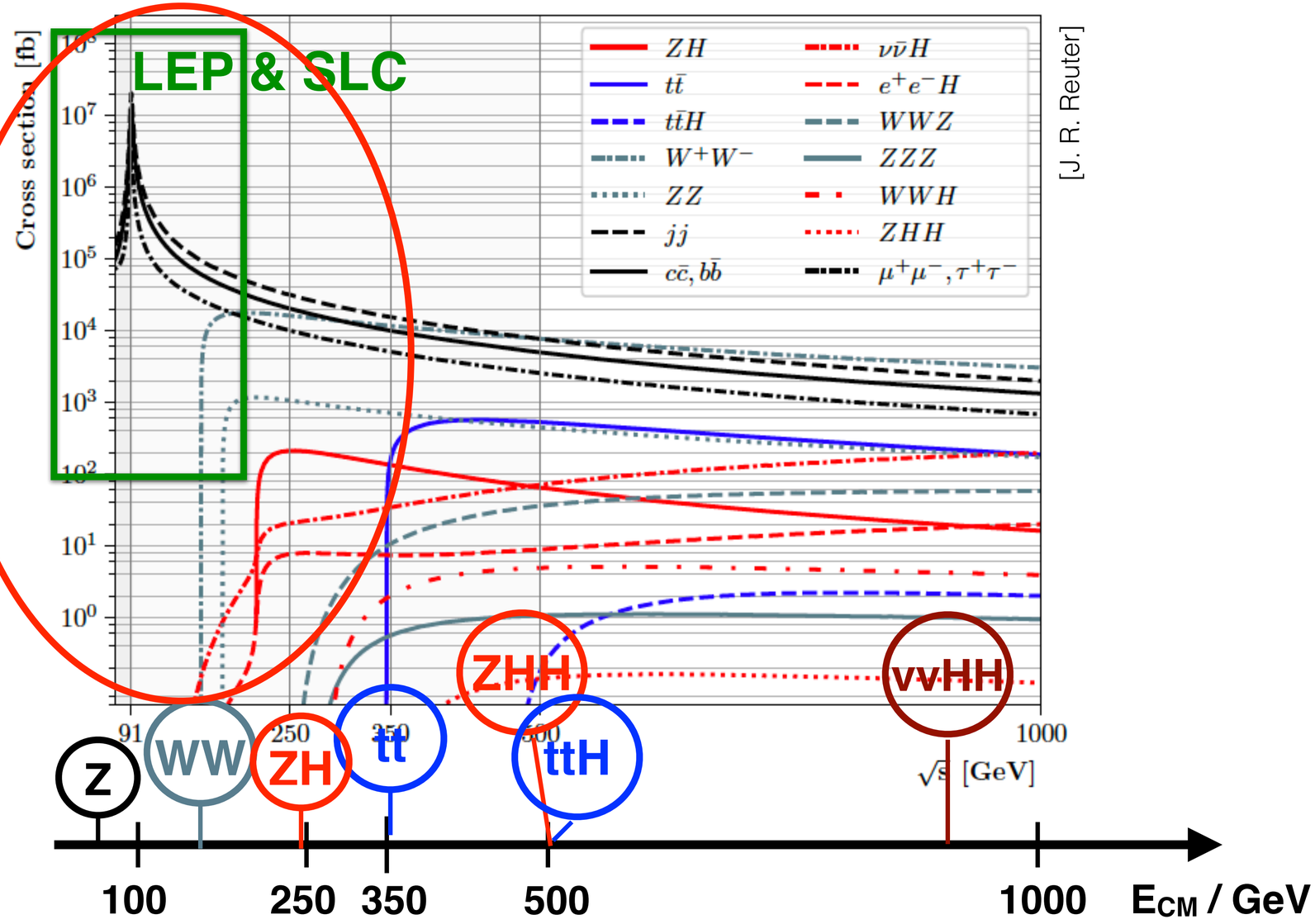

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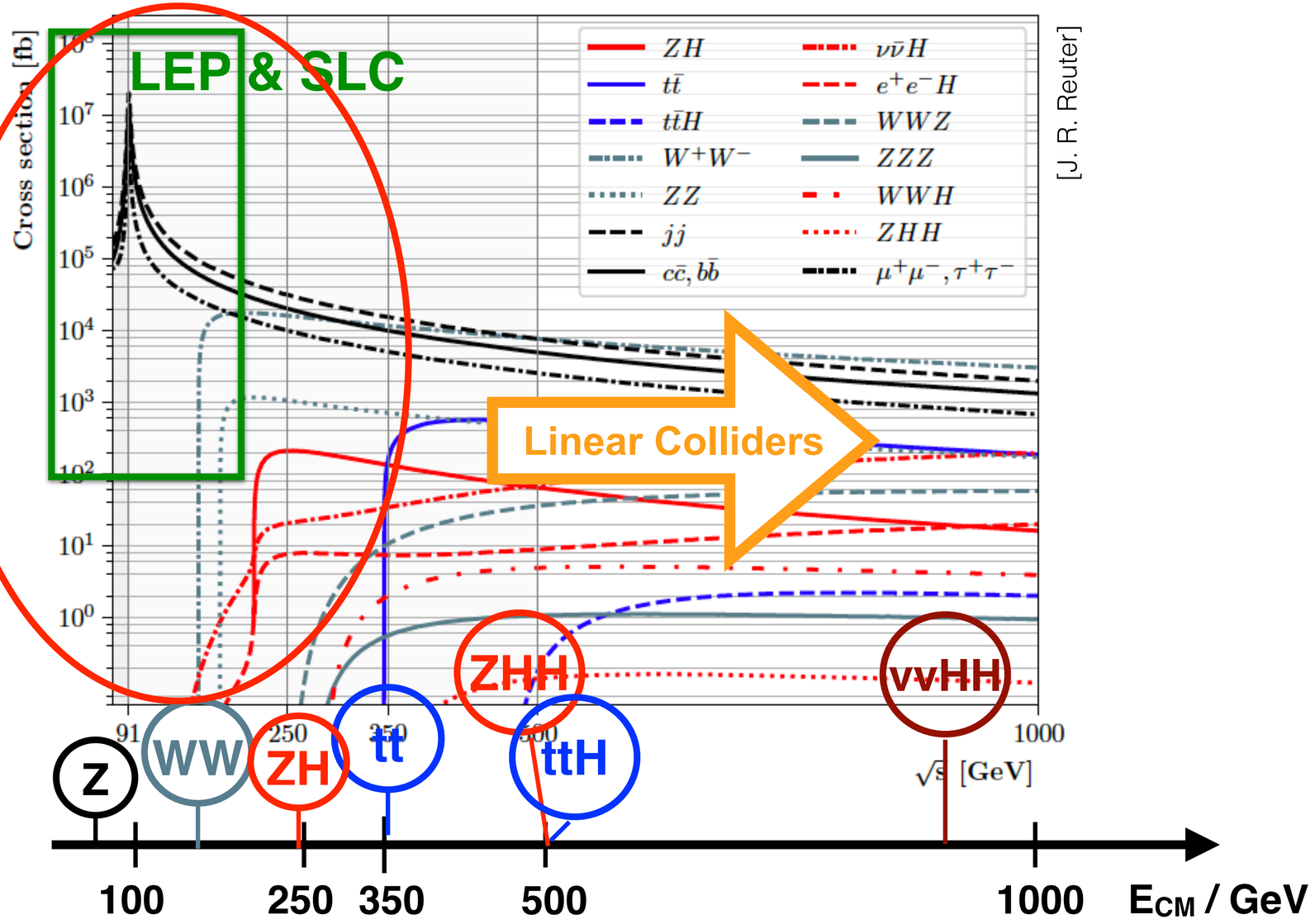

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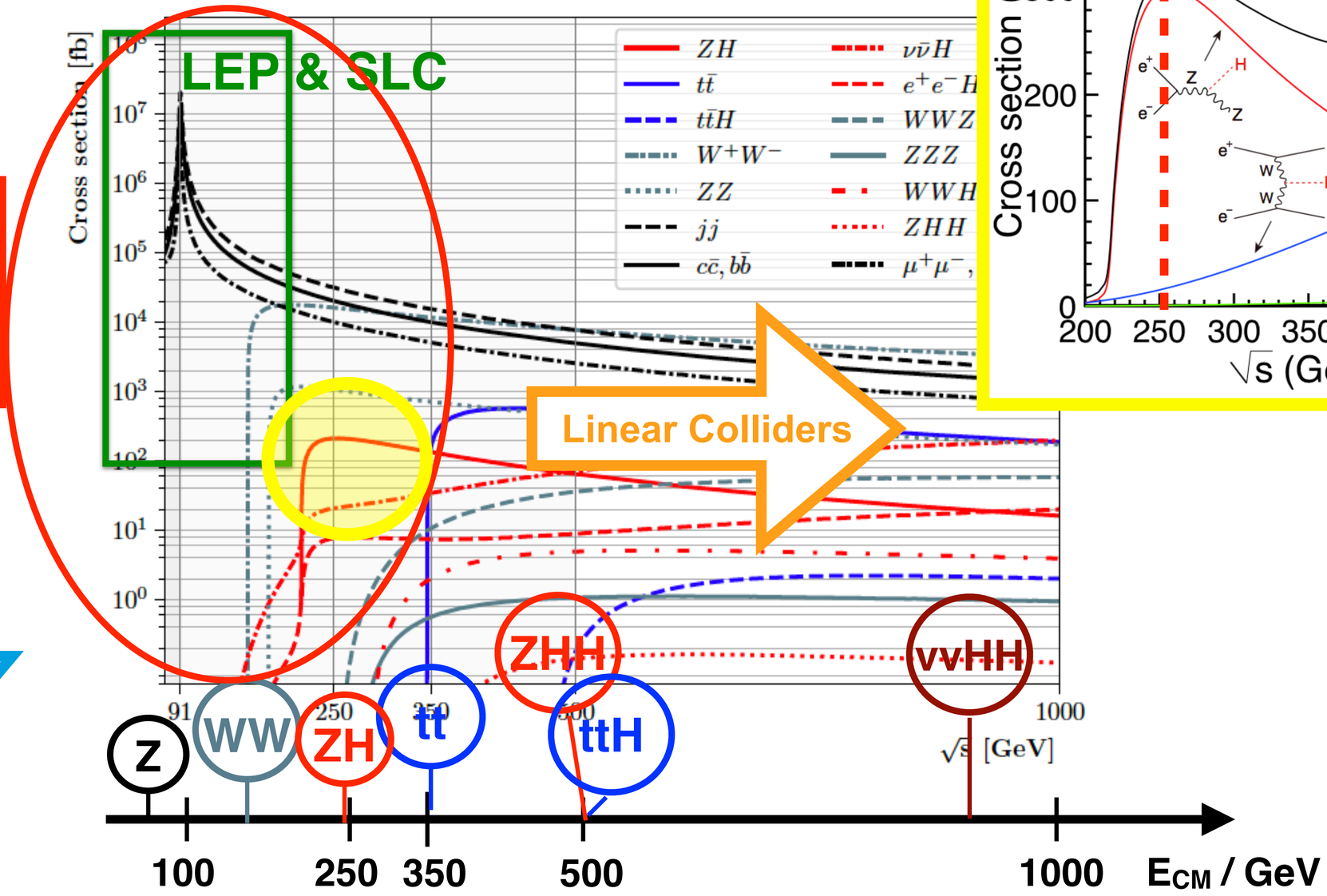
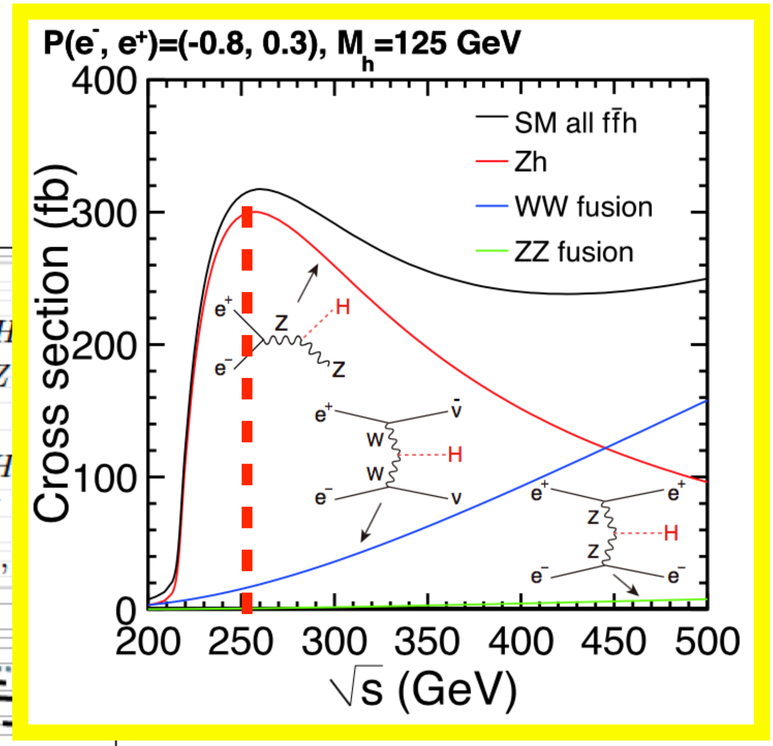
considered by all proposed e+e- projects

Circular Colliders





Interlude: Chirality in Particle Physics

Just a quick reminder…



- Gauge group of weak x electromagnetic interaction: $SU(2)_L$ x U(1)
- L: left-handed, spin anti-|| momentum*
  R: right-handed, spin || momentum*
- **left-handed particles are fundamentally different from right-handed ones:**
  - only left-handed fermions (e^-) and right-handed anti-fermions (e^+) take part in the charged weak interaction, i.e. couple to the W bosons
  - there are (in the SM) no right-handed neutrinos
  - right-handed quarks and charged leptons are singlets under $SU(2)_L$
  - also couplings to the Z boson are different for left- and right-handed fermions

$$P = \frac{N_R - N_L}{N_R + N_L}$$

- **checking whether the differences between L and R are as predicted in the SM is a very sensitive test for new phenomena!**

* for massive particles, there is of course a difference between chirality and helicity, no time for this today, ask at the end in case of doubt!

Physics benefits of polarised beams

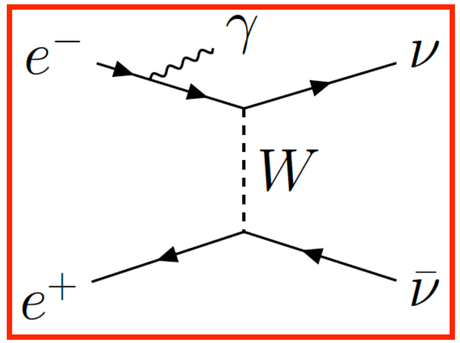
Much more than statistics!

General references on polarised e^+e^- physics:

- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

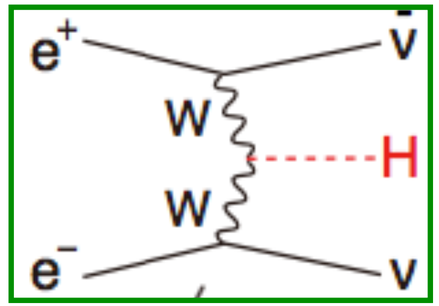
background suppression:

- $e^+e^- \rightarrow WW$ / $\nu_e\nu_e$ strongly P-dependent since t-channel only for $e^-_L e^+_R$



signal enhancement:

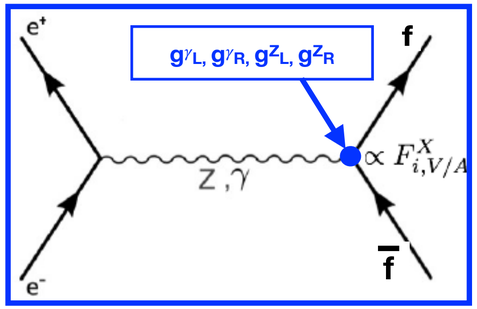
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions
- BSM: chiral structure unknown, needs to be determined!



redundancy & control of systematics:

- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

The Update of the European Strategy for Particle Physics

Reference: various presentations by K.Jakobs

- *The **European Strategy for Particle Physics** is a cornerstone of Europe's decision-making process for the long-term future of the field.*
- *Mandated by the CERN Council, the Strategy is formed through a broad consultation of the particle physics communities in the CERN Member and Associate Member States, and beyond.*
- *In the Strategy process recommendations are developed which will be submitted to the CERN Council for an update of the Strategy.*

The European Strategy for Particle Physics is not a project approval process. Projects are approved by the CERN Council through a separate decision process, taking the Strategy recommendations into account.

Original Strategy (2006):	LHC, mooting of luminosity upgrade of LHC, R&D in accelerator technologies, coordination with a potential ILC project
1st Update (2013):	High Luminosity LHC, need for a post-LHC programme
2nd Update (2020):	FCC feasibility study
3rd Update (2026):	→ recommendation for the next large-scale accelerator project at CERN (reach consensus on the preferred option and possible alternatives)

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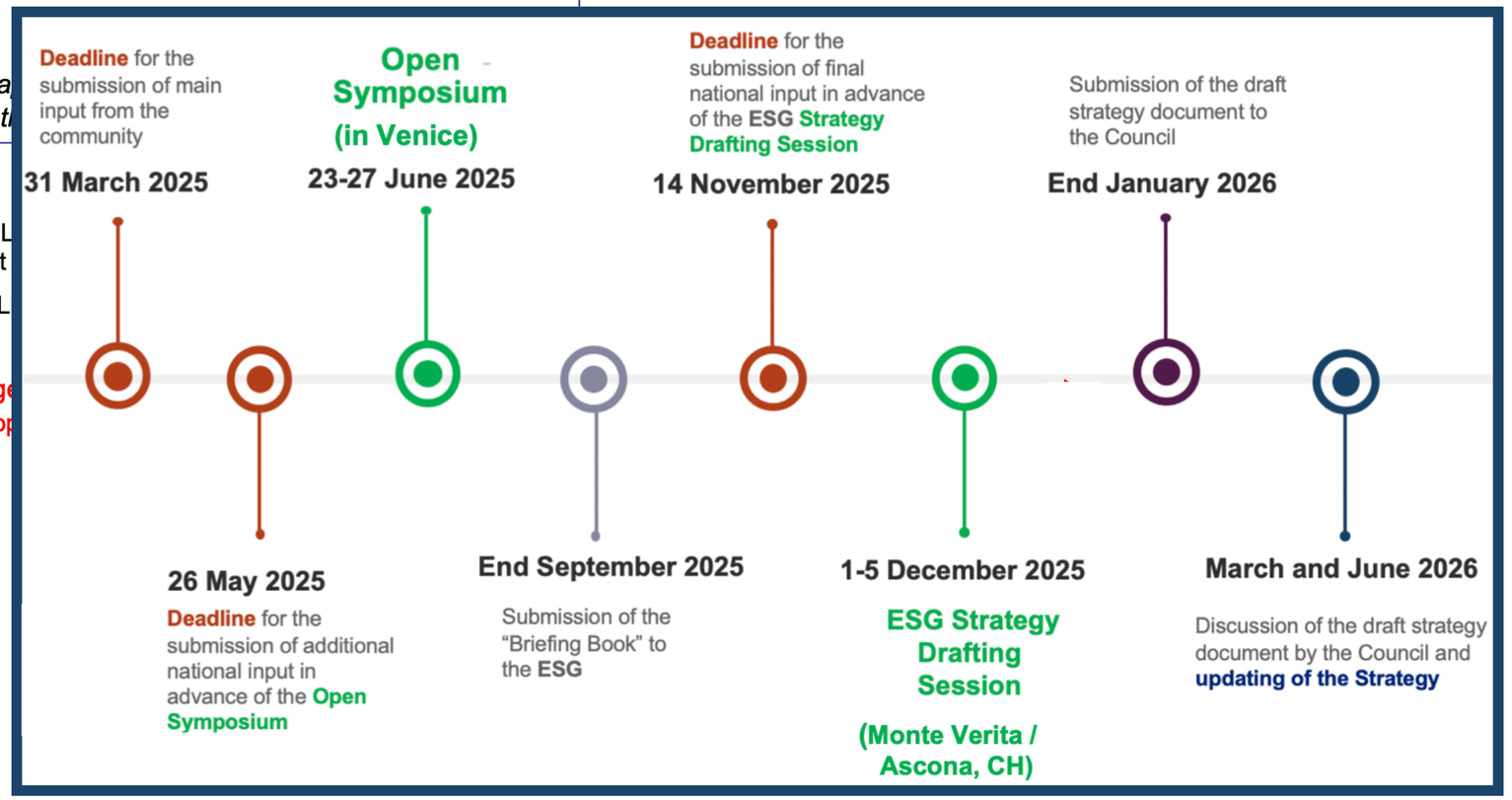


FCC-ee as the next flagship collider for CERN

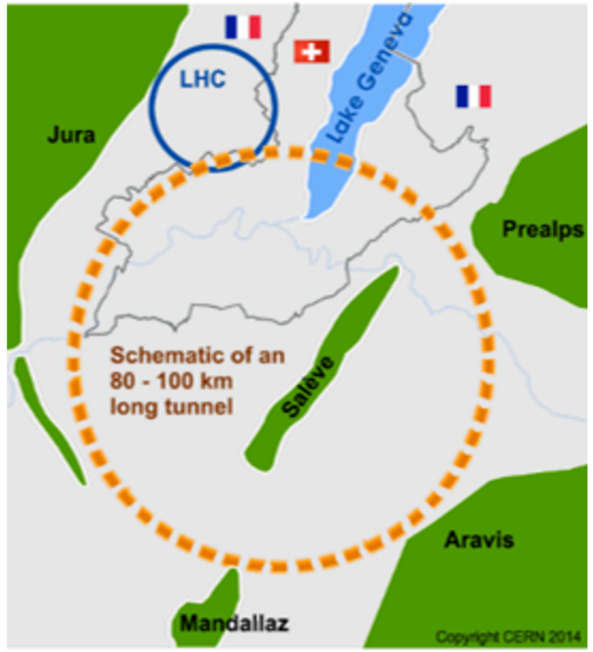
Future Circular Collider – scope

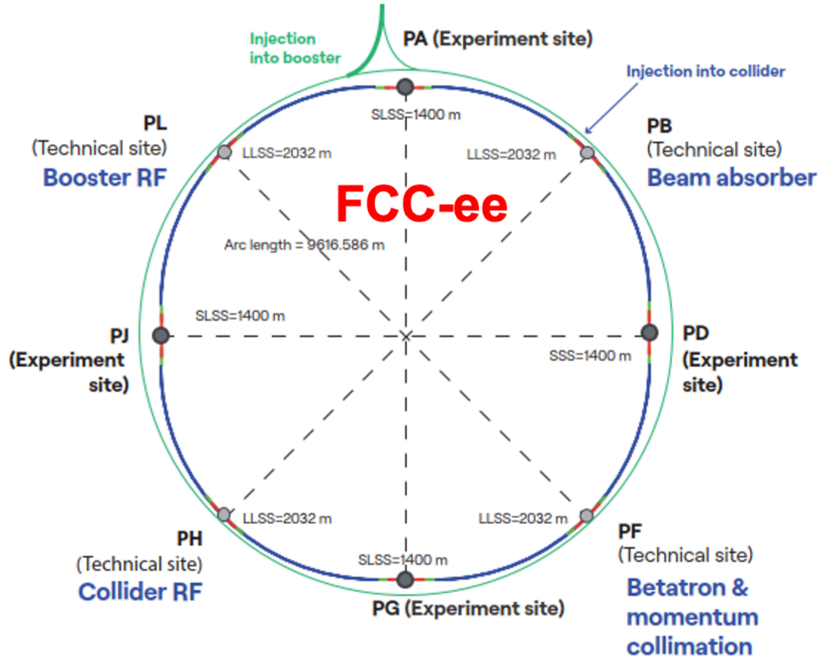
Reference: various presentations by M.Benedikt

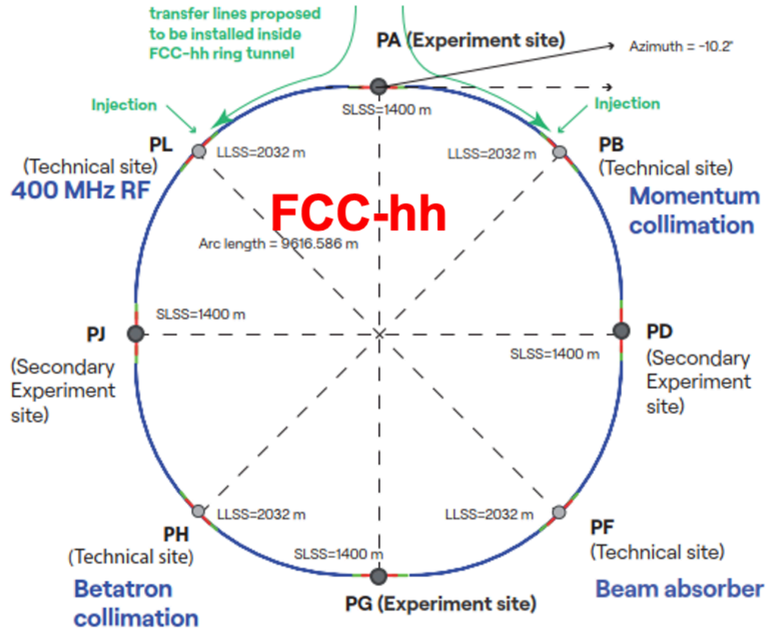
FCC-ee (Z, W, H, $t\bar{t}$): Higgs factory, electroweak & top factory at highest luminosities

FCC-hh (~100 TeV) as potential second step: energy frontier, pp & AA collisions; e-h option

- focus on implementation of FCC-ee as first step ; possible pathway to FCC-hh to be decided later
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- highly synergetic and complementary physics programme maximising the physics opportunities
- FCC-ee project would allow the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2045 | **2048 - 2062** | **~2075 ?**

Reference layout and implementation: PA31 - 90.7 km

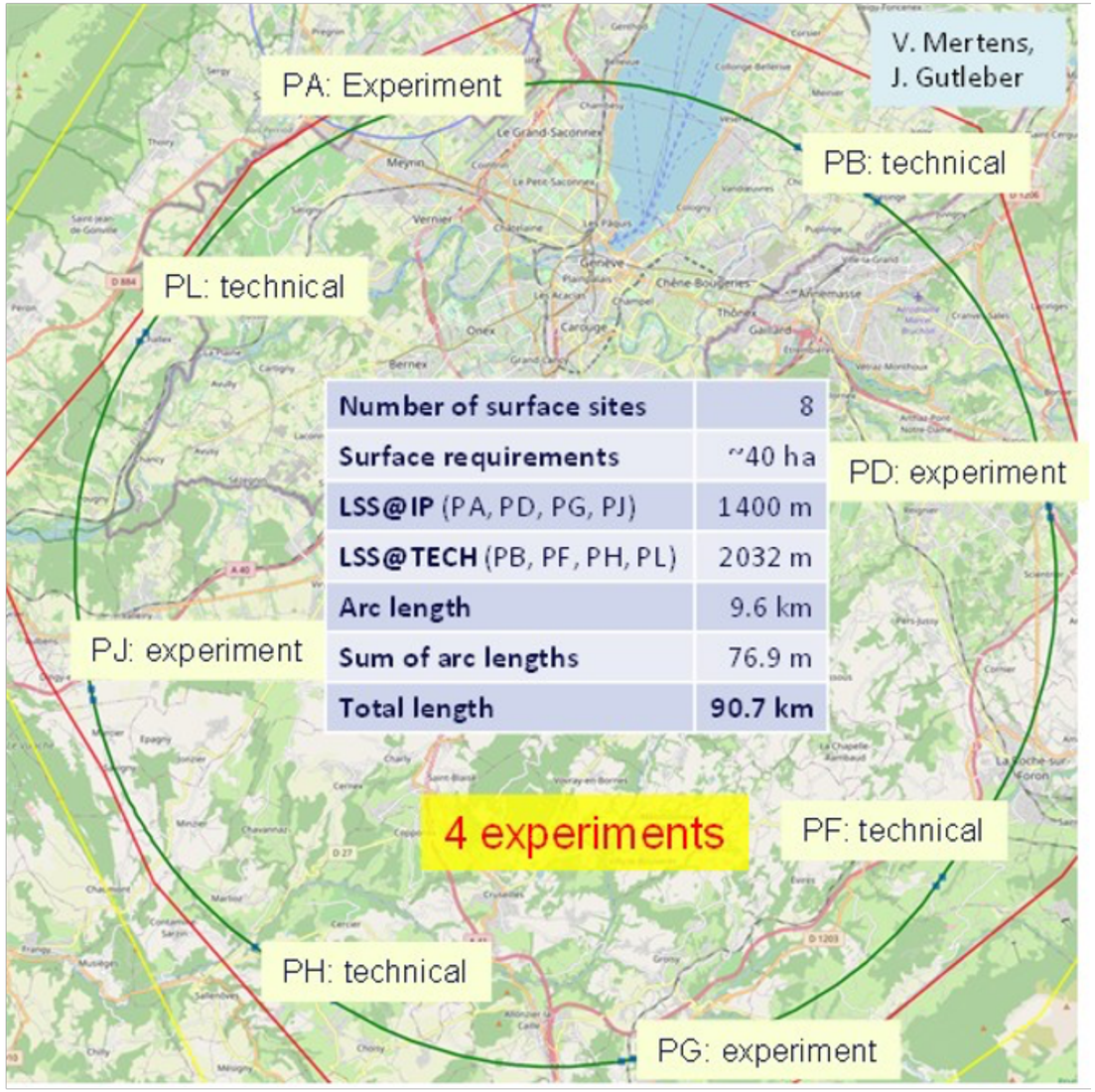
Reference: various presentations by M.Benedikt

Layout chosen out of ~ 100 initial variants, based on several criterias:

- **geology,**
- **surface constraints** (land availability, urbanistic, etc.),
- **environment** (protected zones),
- **infrastructure** (electricity, transport),
- **machine performance**

“Avoid-reduce-compensate” principle of EU and French regulations.

Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold superperiodicity & symmetry

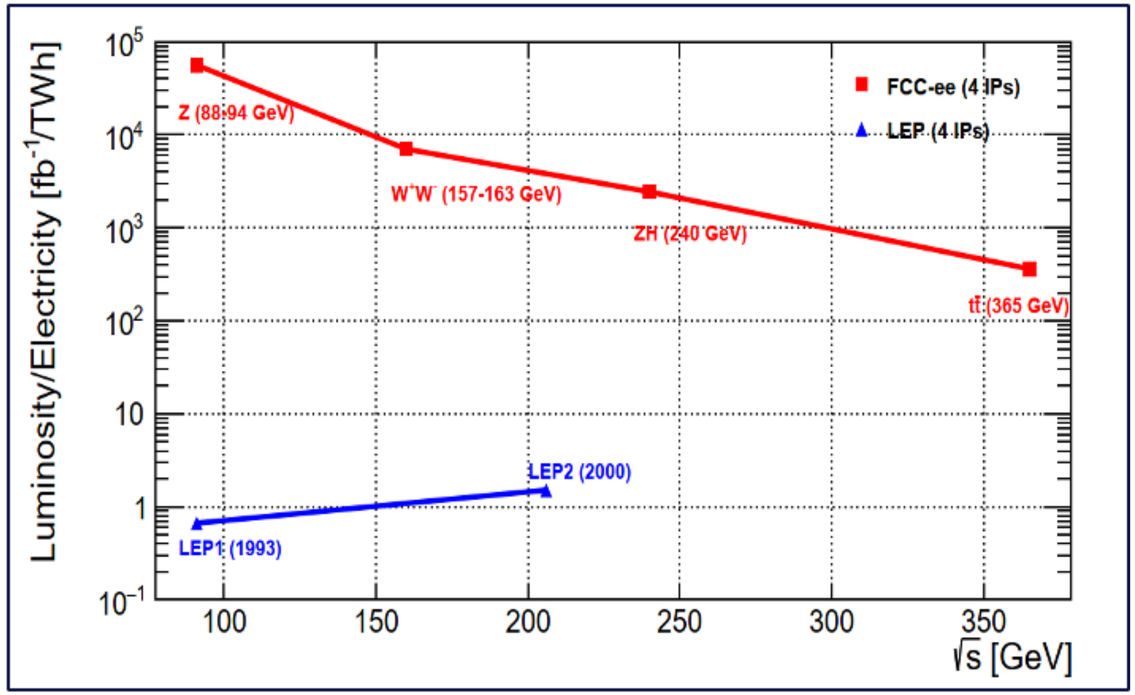


FCC-ee parameters and design aspects

Reference: various presentations by M.Benedikt

→10^4–10^5x luminosity/el.energy of LEP

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
beam lifetime [min]	21	13	9	10
	4 years 272 ab^{-1} (4ext's) 6 x 10^{12} Z LEP x 10^5	2 years 19.8 ab^{-1} (4exp's) > 10^8 WW LEP x 10^4	3 years 10.8 ab^{-1} (4exp's) > 2x10^6 H	5 years 3.4 ab^{-1} (4exp's) 2 x 10^6 tt pairs



- **Double ring** e^+e^- collider, allowing many bunches, high current, like LHC and B factories, different from LEP
- **Synchrotron radiation power 50 MW/beam** at all beam energies. Energy loss ΔE per turn:

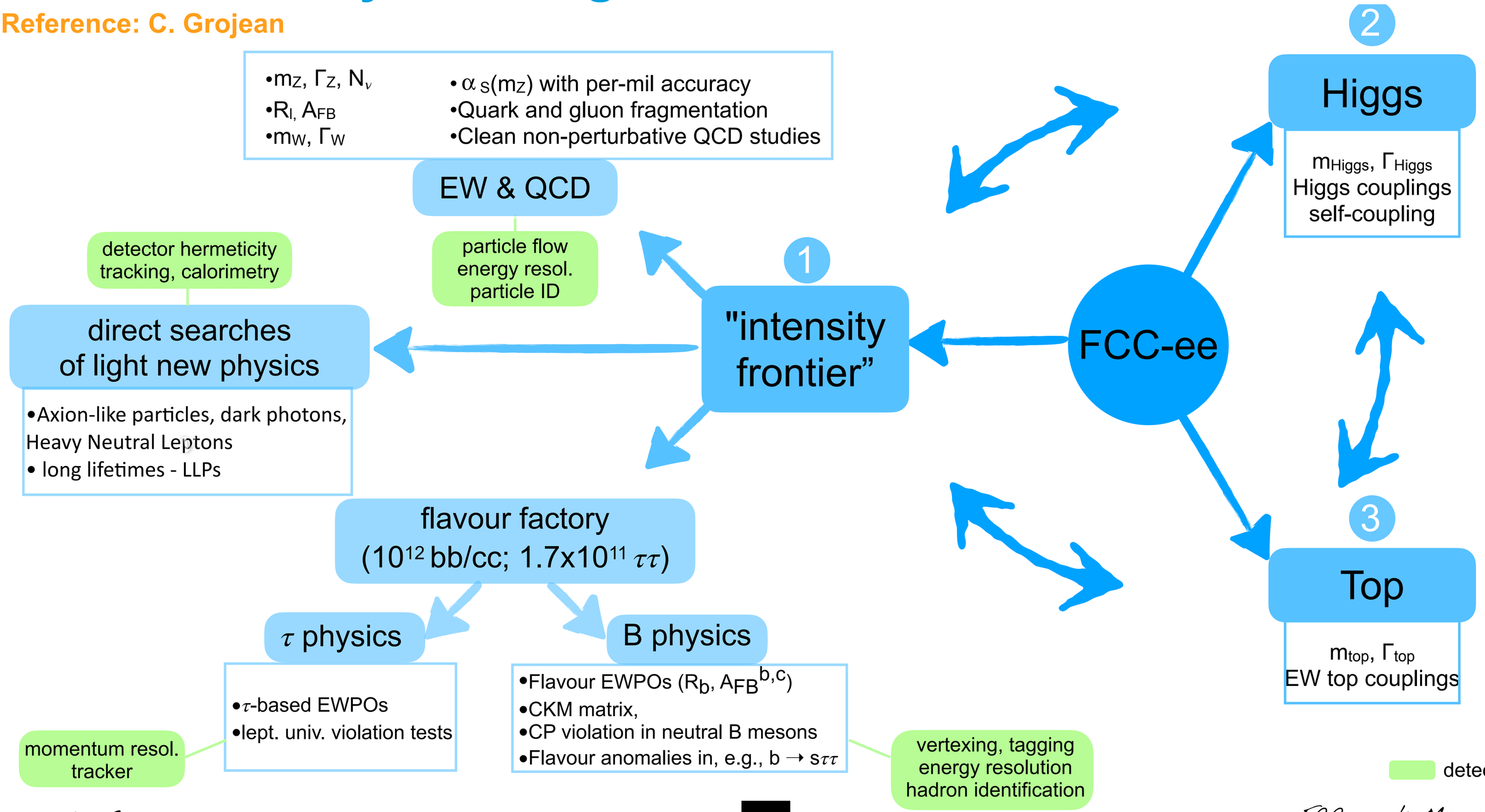
$$\Delta E \sim \gamma^4/\rho = (E/m_0)^4/\rho$$

- **Top-up injection** scheme as at modern light sources (APS, SLS,…) and as at recent e^+e^- colliders, PEP-II (USA), KEKB & SuperKEKB (Japan), BEPCII (China), requires **booster synchrotron in collider tunnel**

No beam polarisation for collisions

The FCC-ee Physics Programme

Reference: C. Grojean



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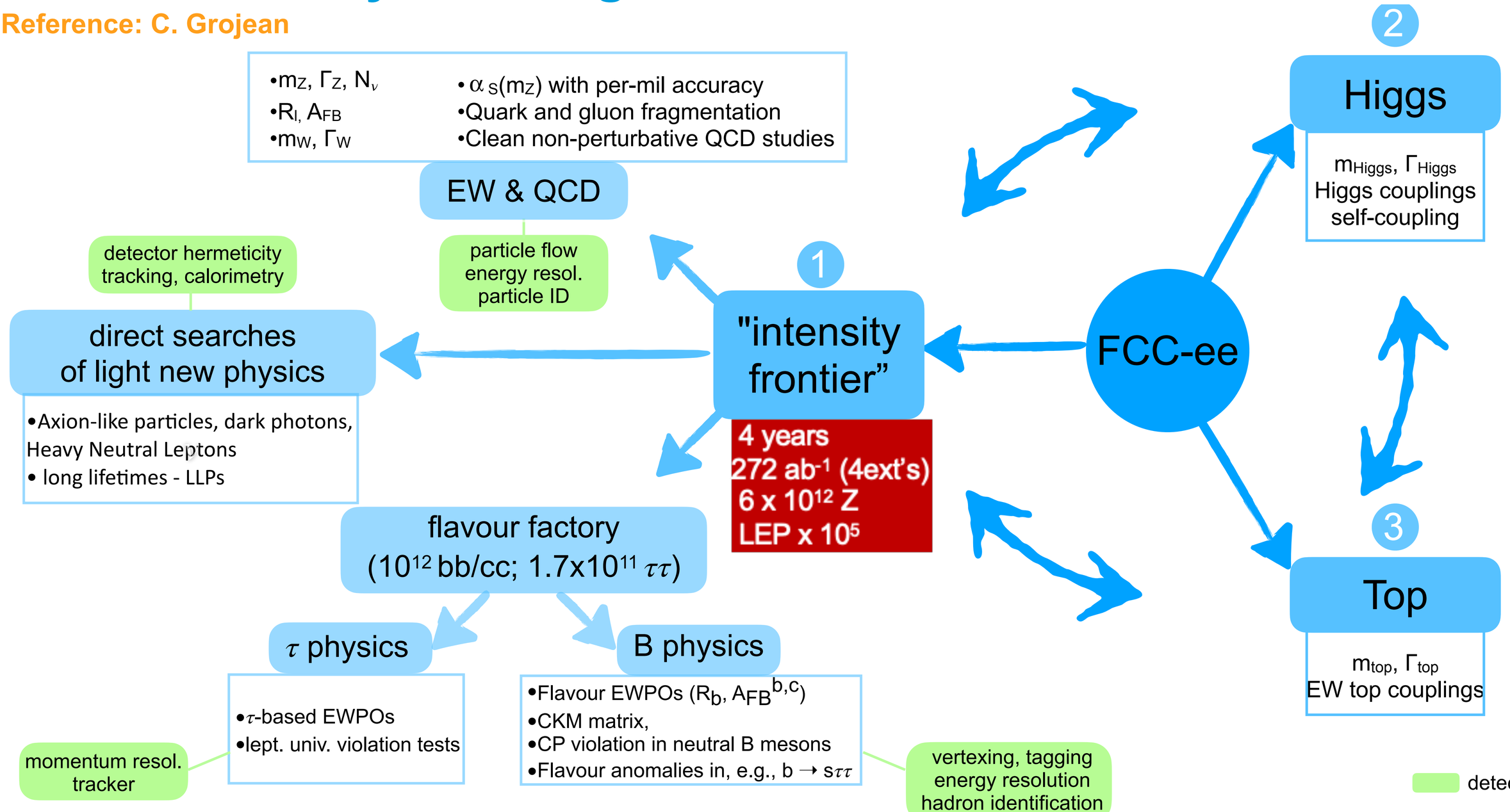

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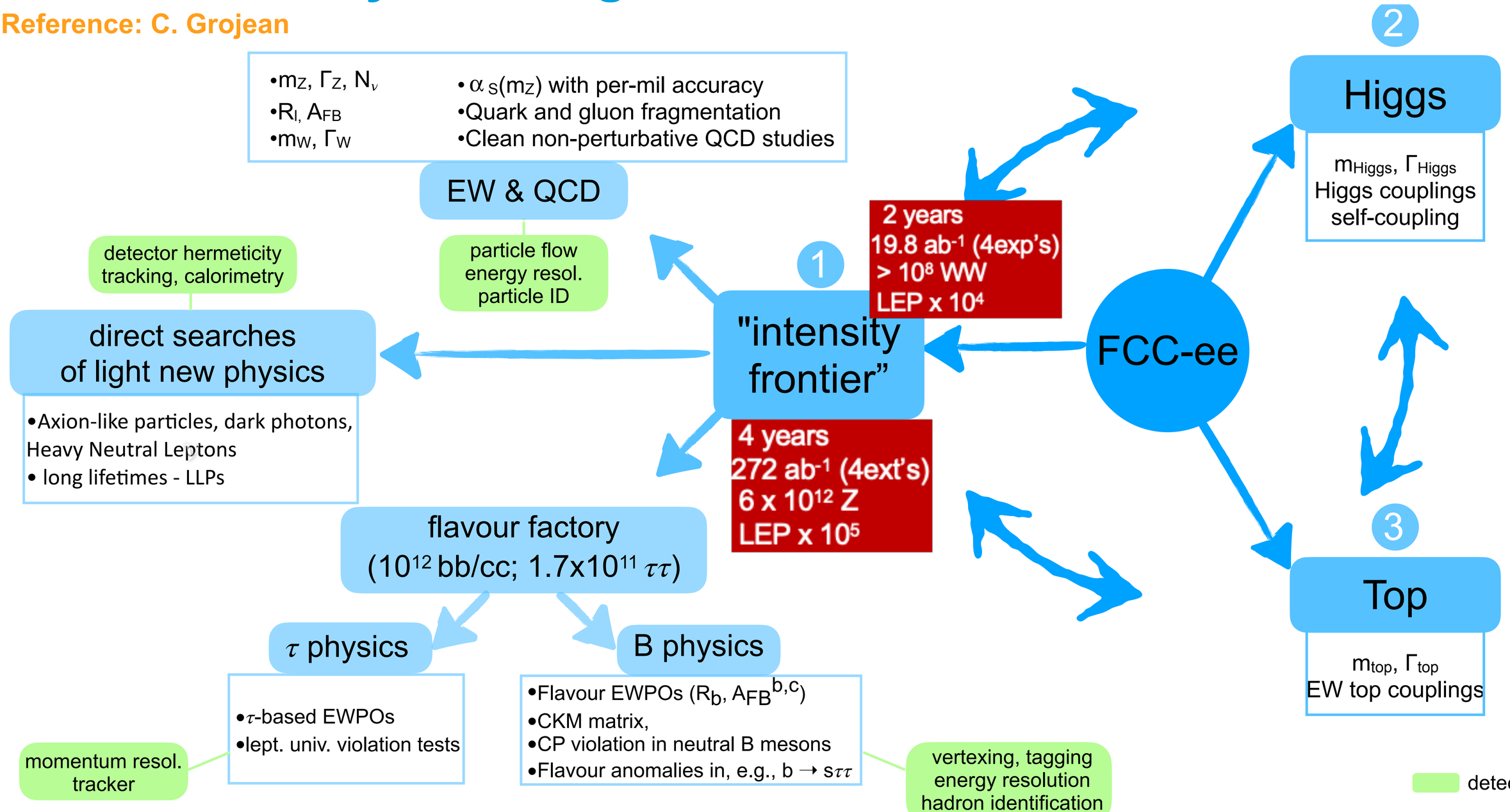

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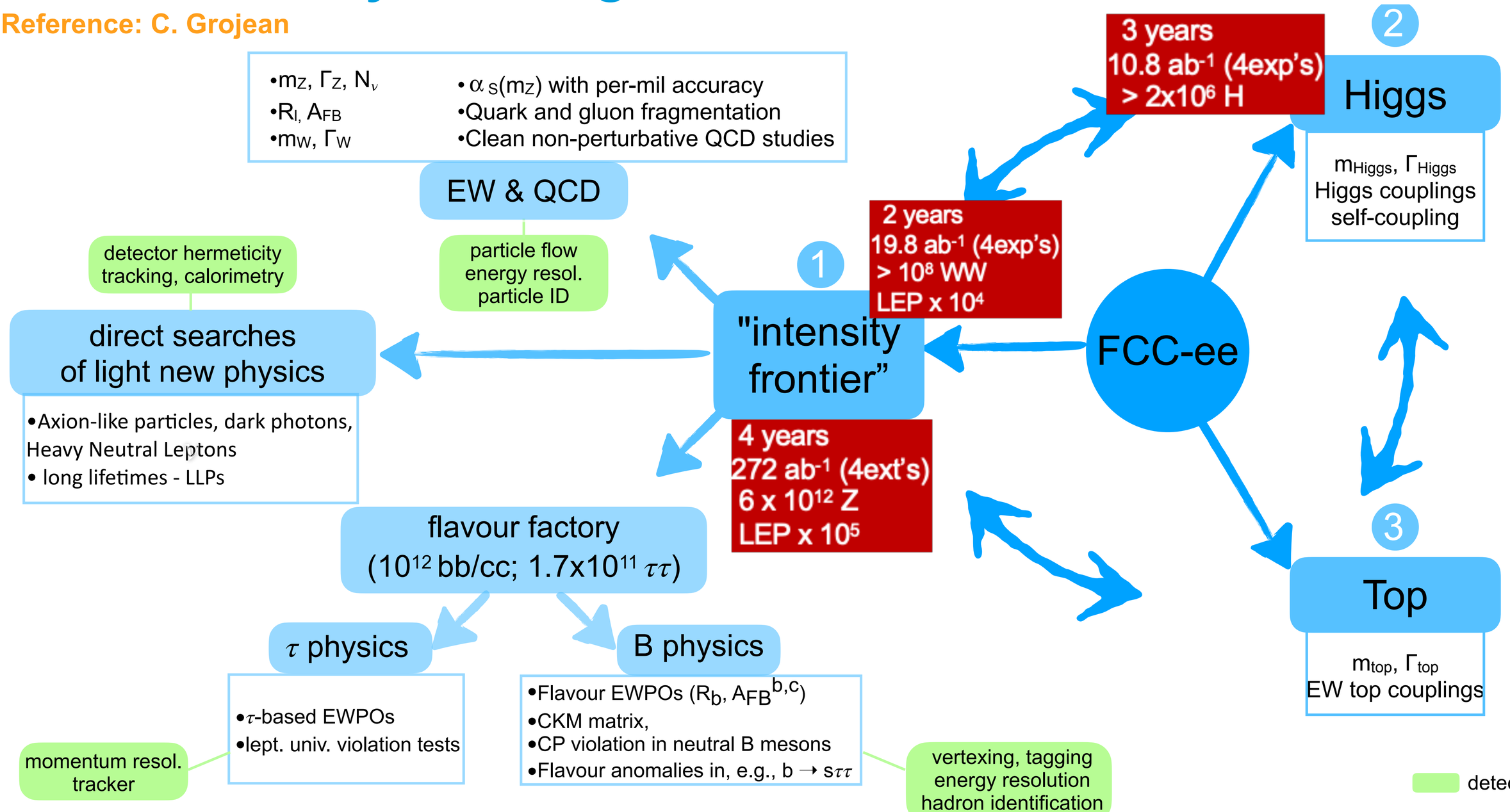

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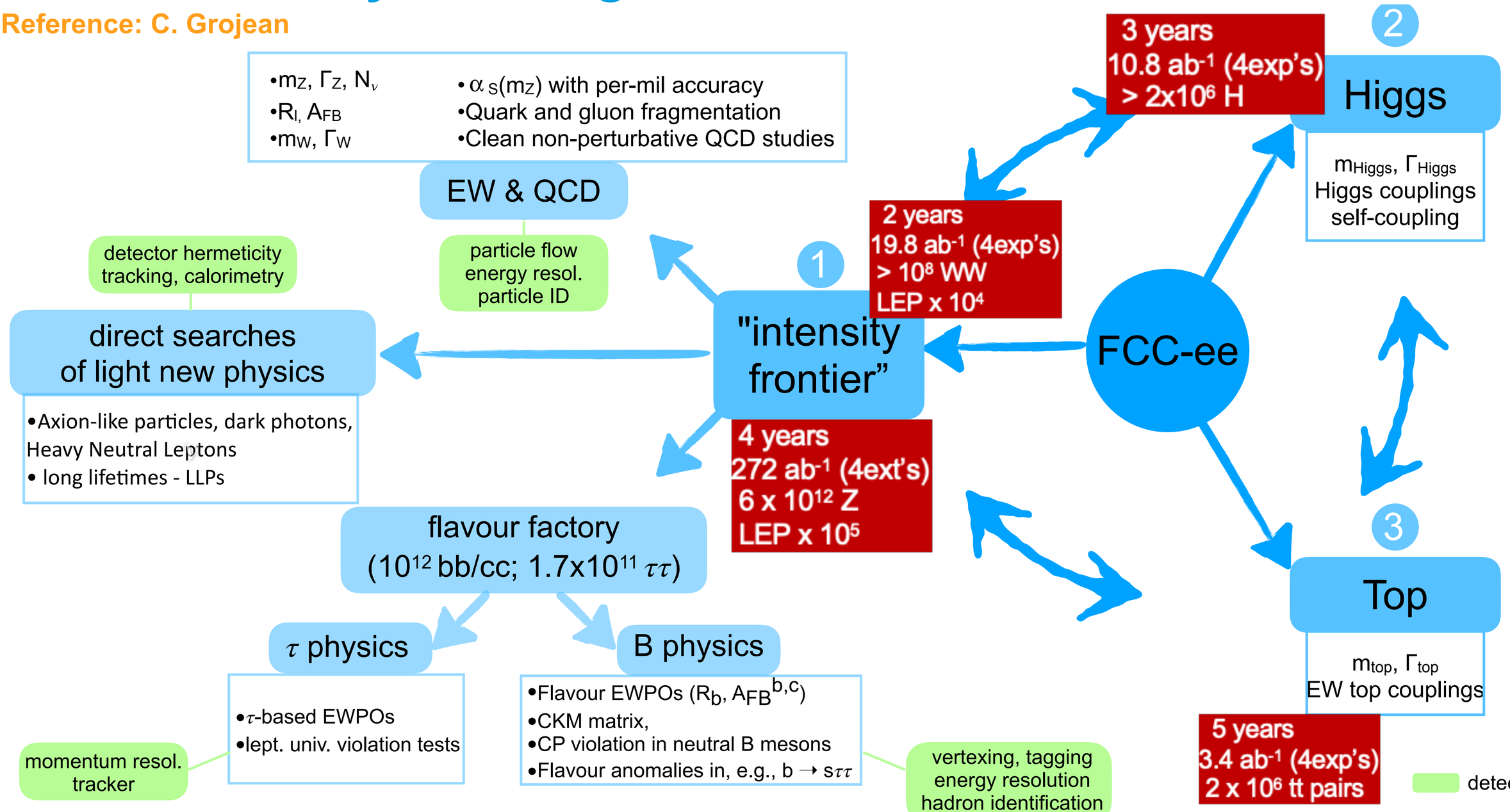

FCC-ee is a giant leap for Higgs couplings & Co

Compared to HL-LHC

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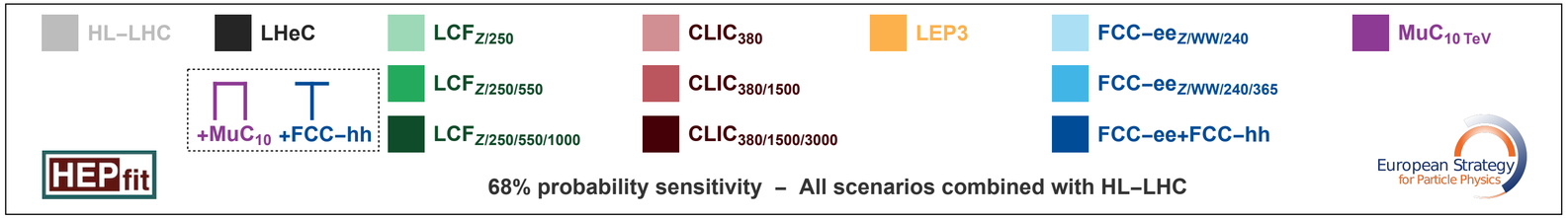

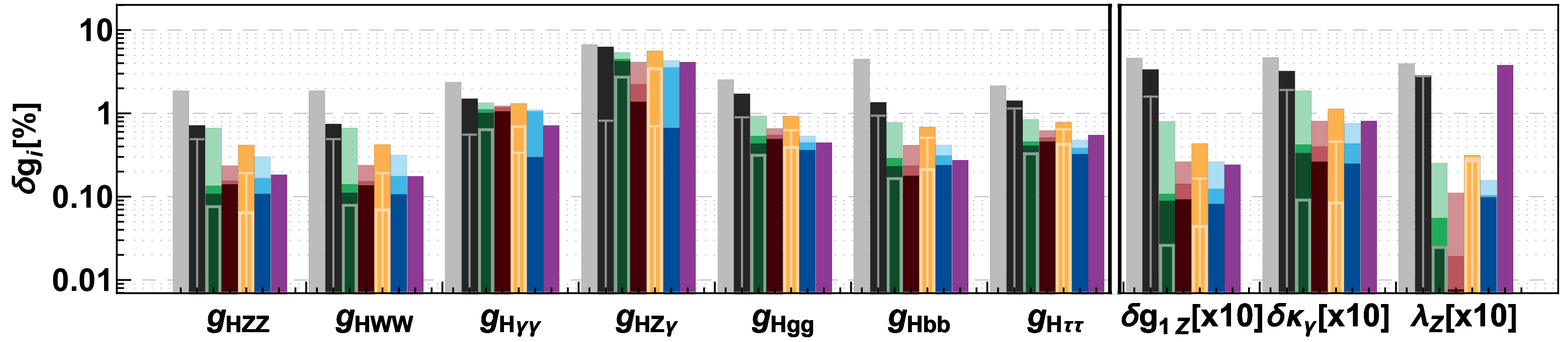

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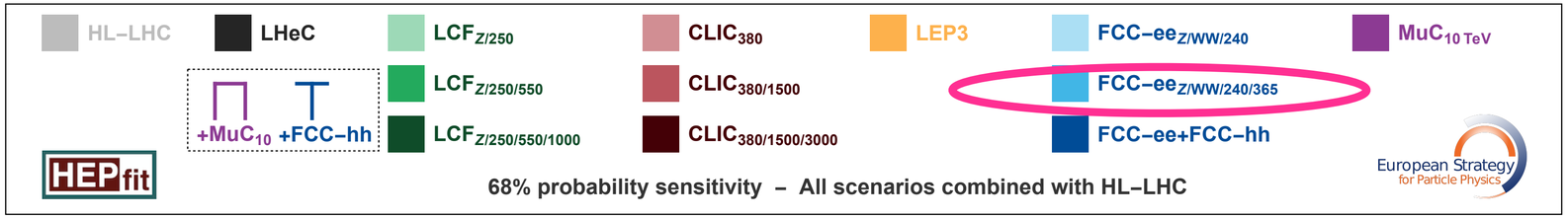

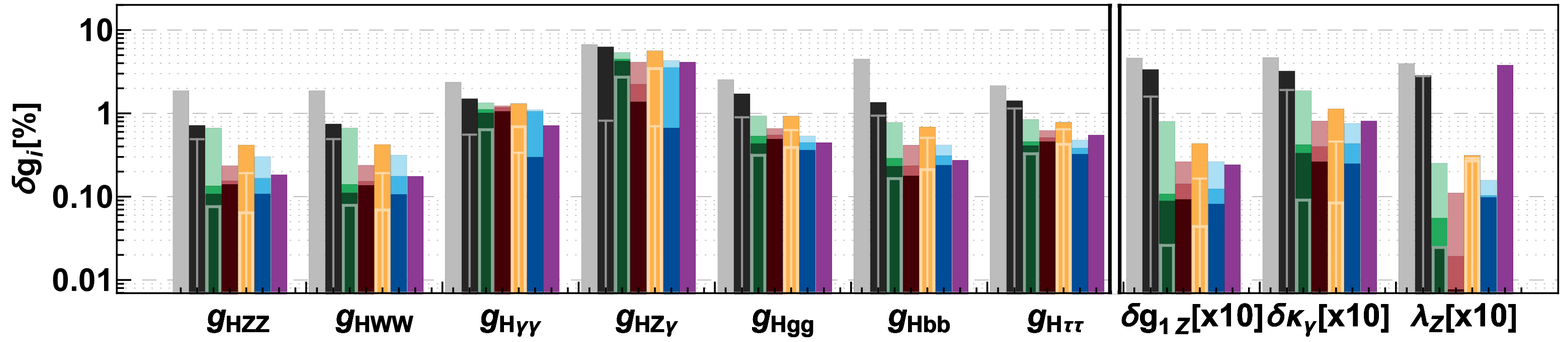

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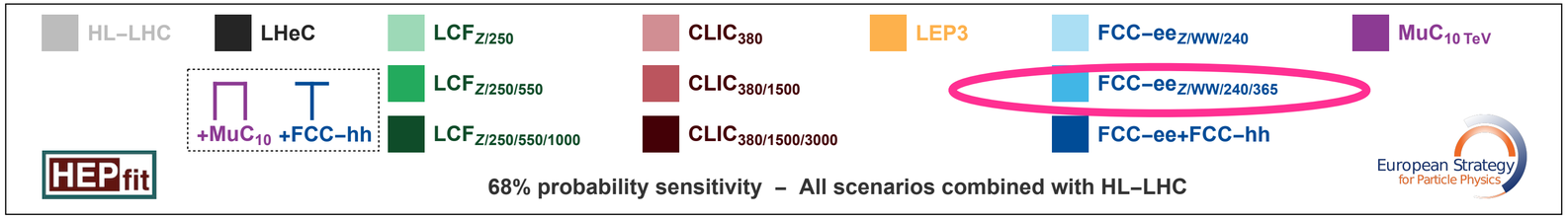

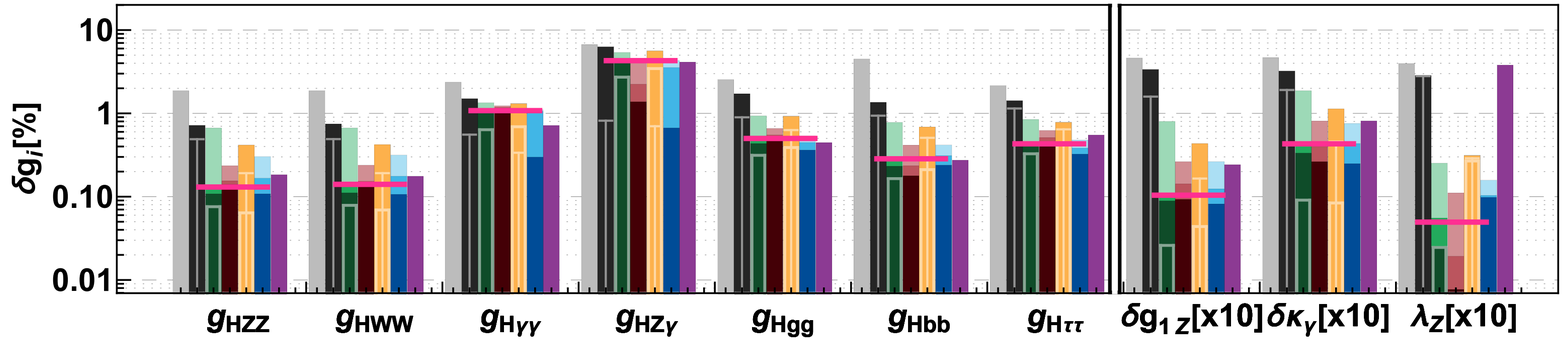

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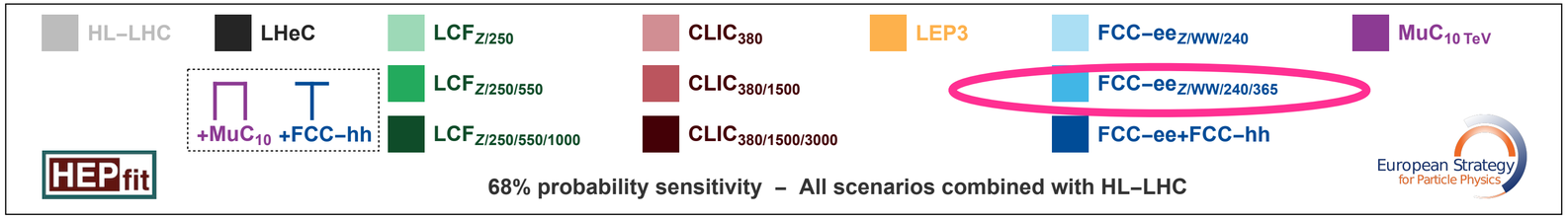

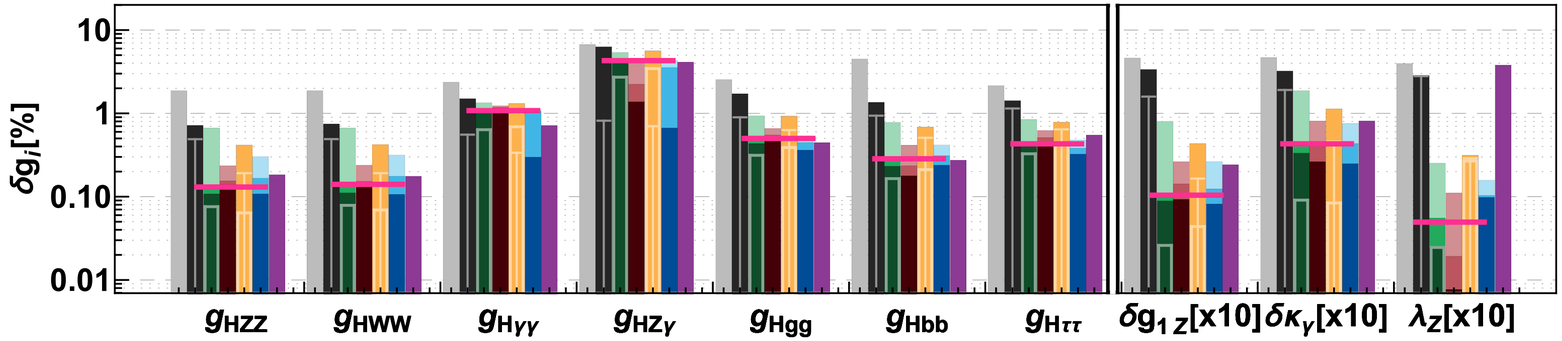

And the Higgs self-coupling ?

FCC-ee is a giant leap for Higgs couplings & Co

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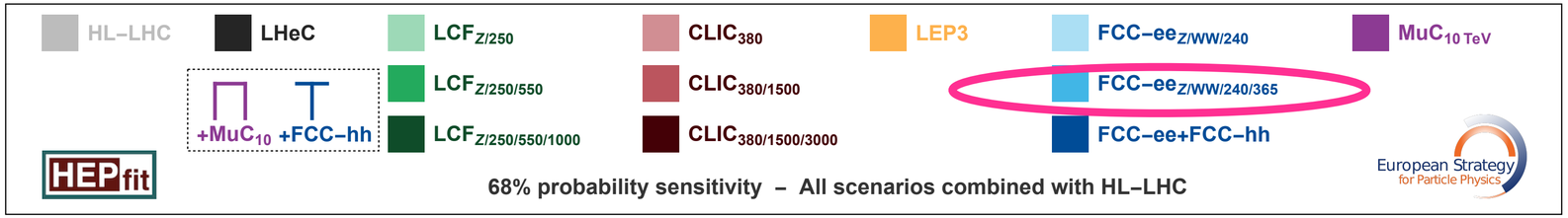

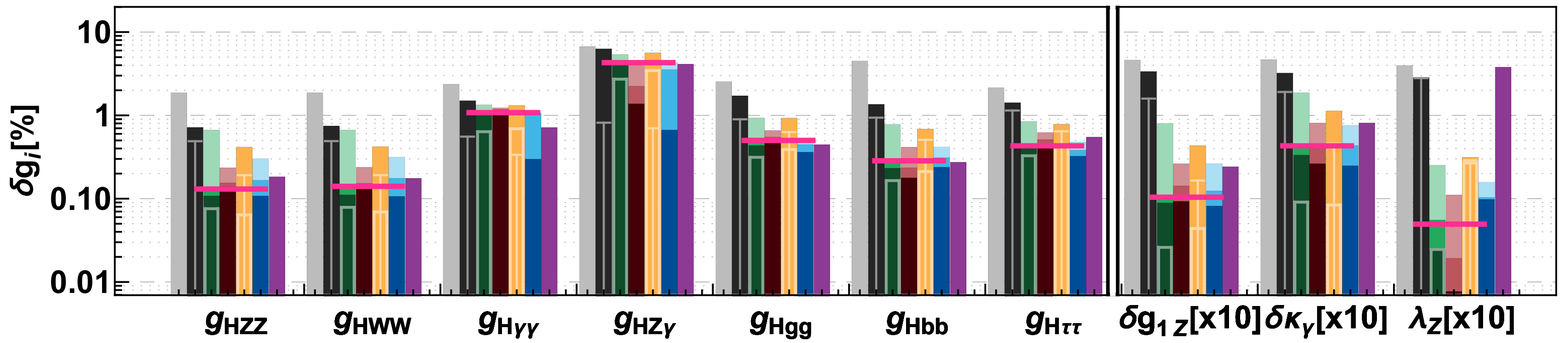

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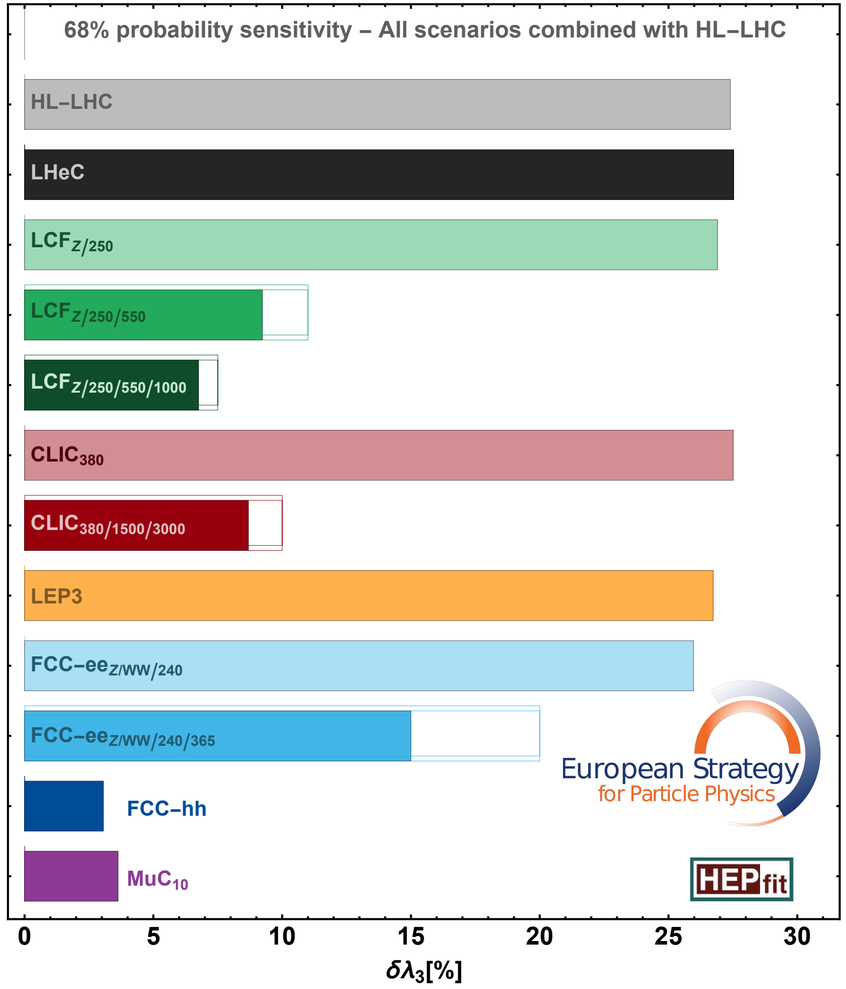

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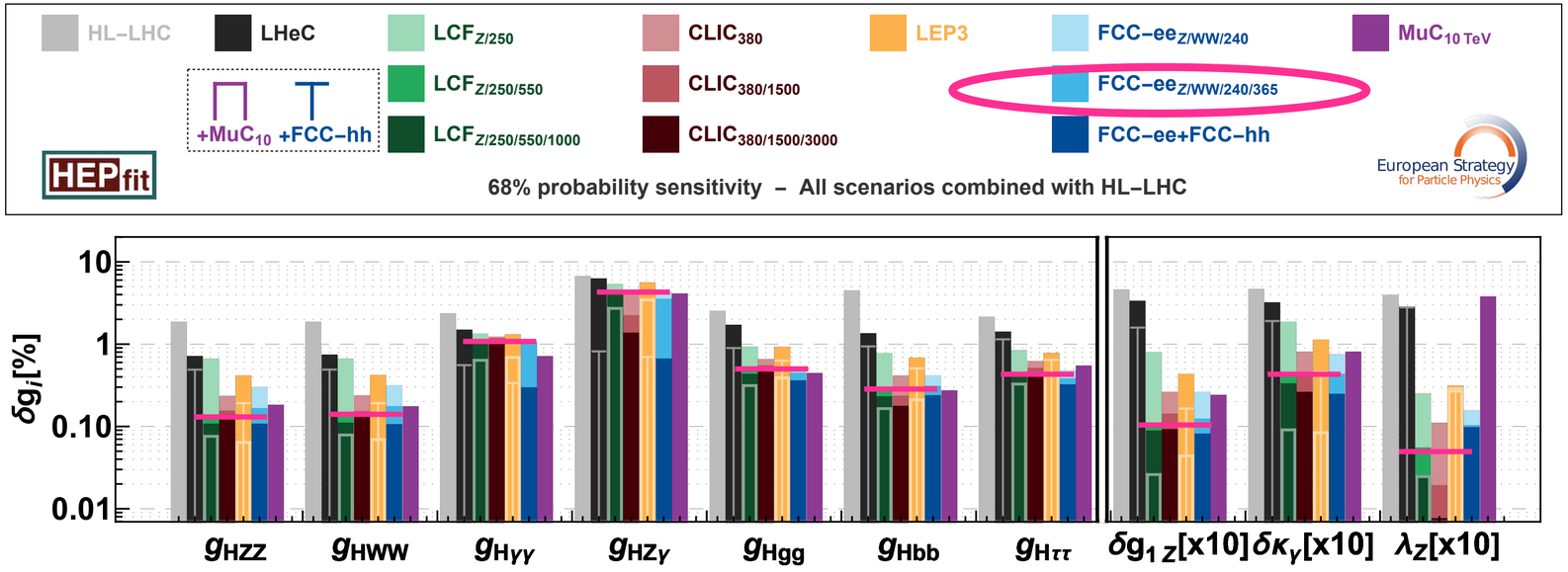

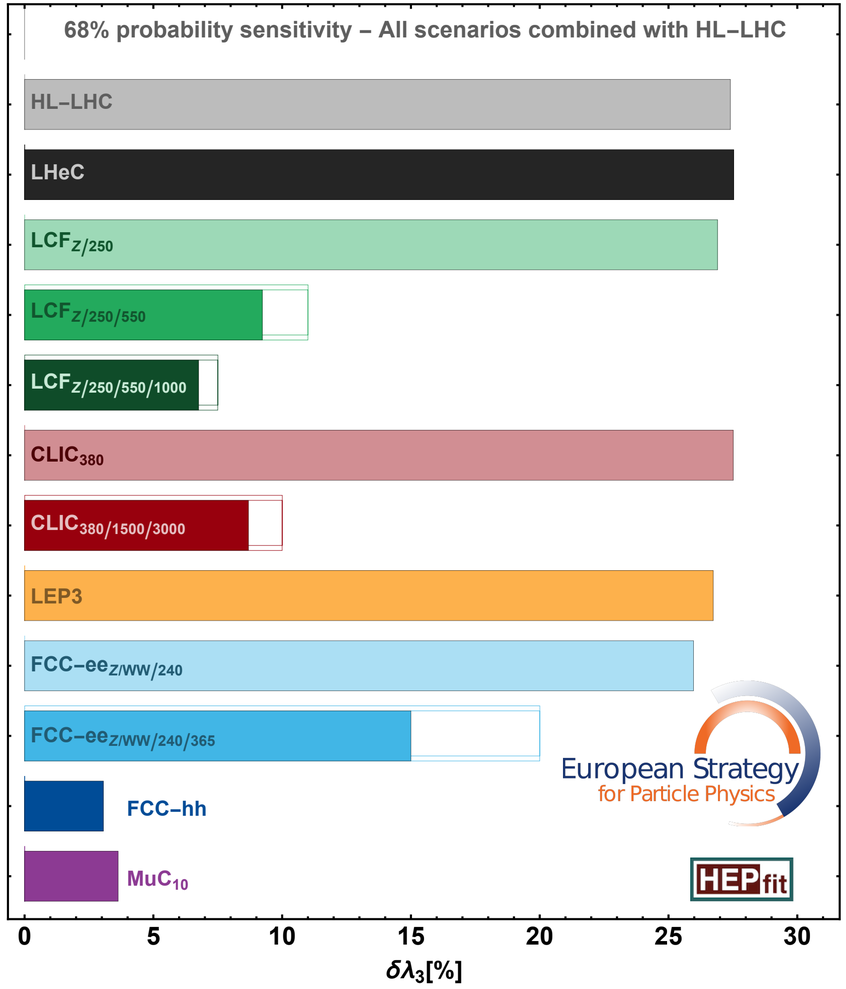

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- At FCC-ee only accessible via loop corrections to ee->ZH
- Requires ZH cross-section measurement at min. 2 energies
- Large model uncertainties (open bars)
- FCC approach: leave this for a future hadron collider!

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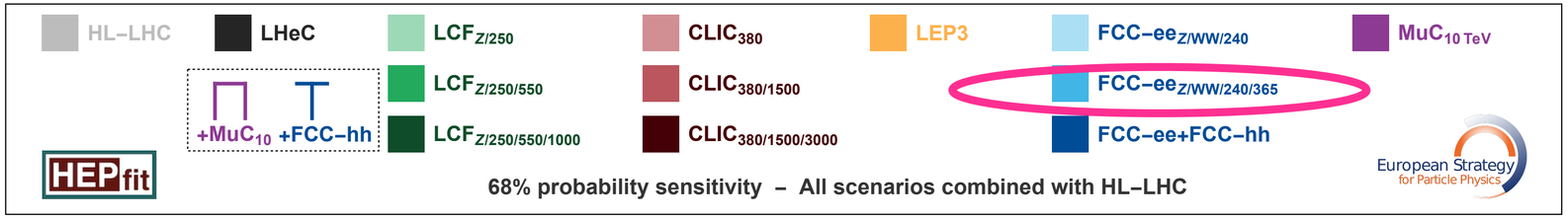

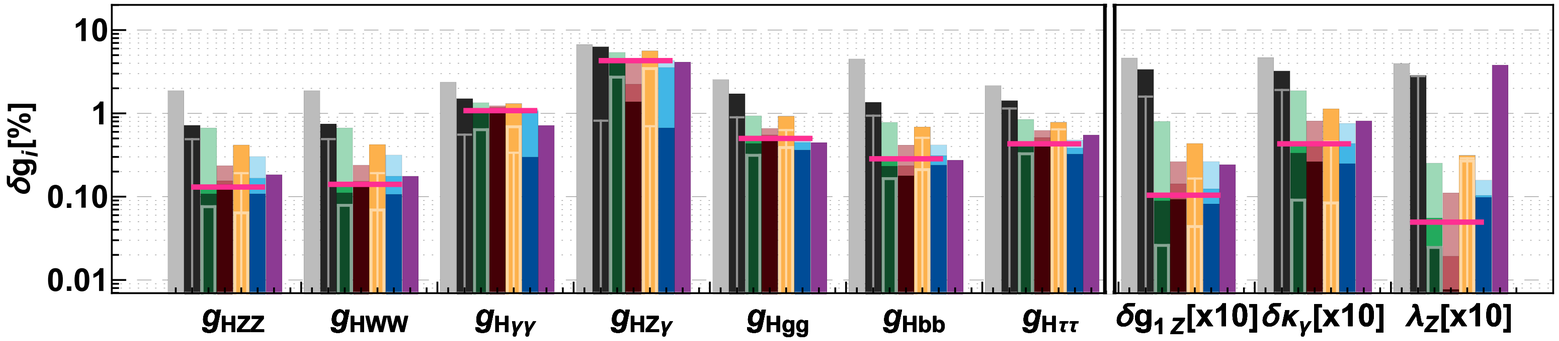

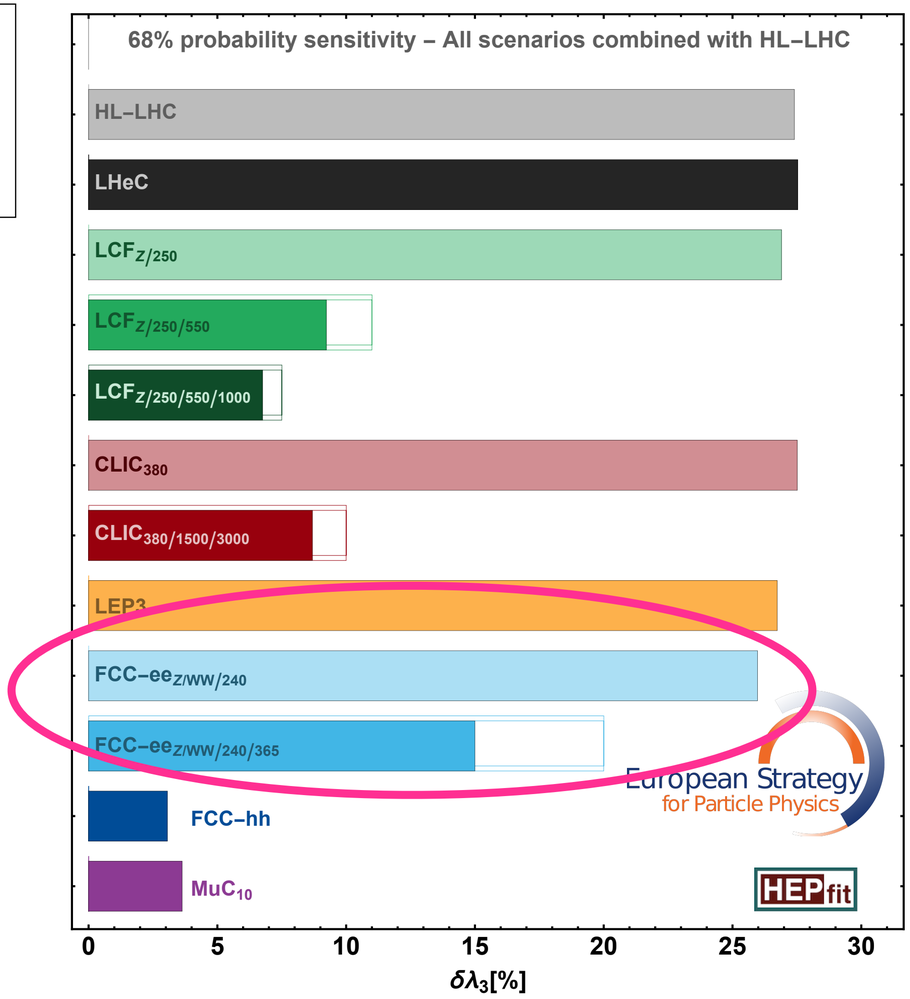

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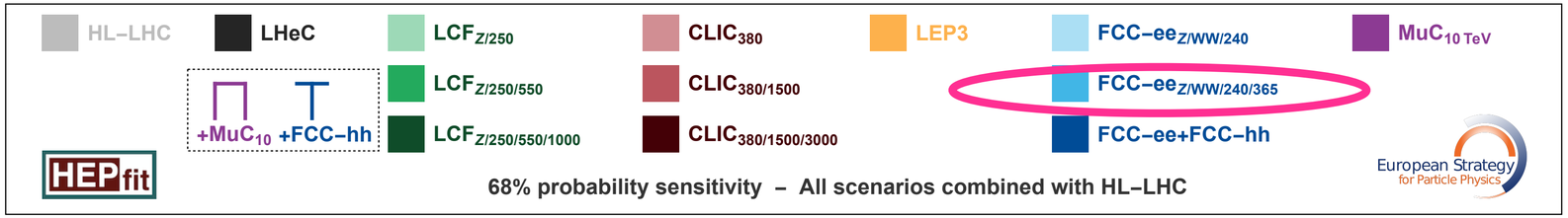

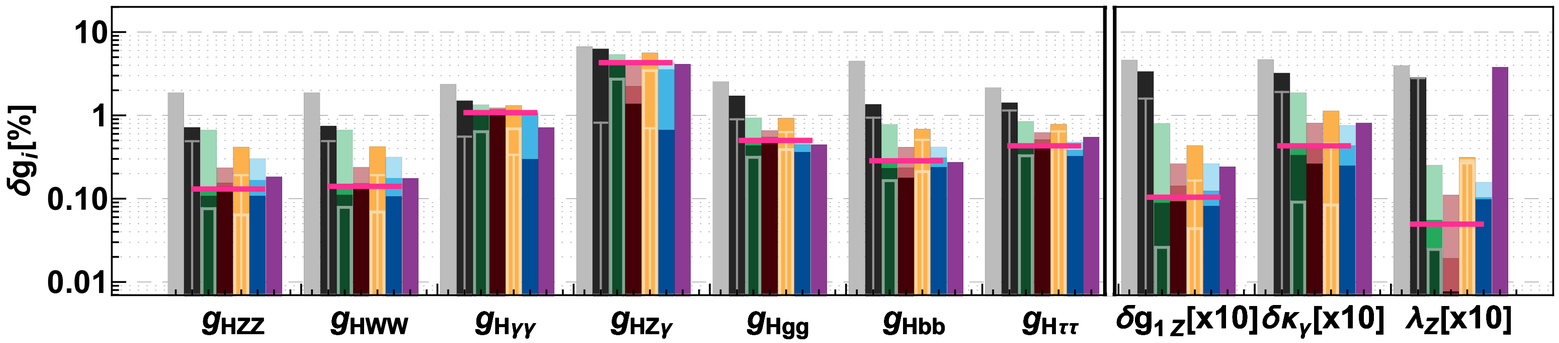

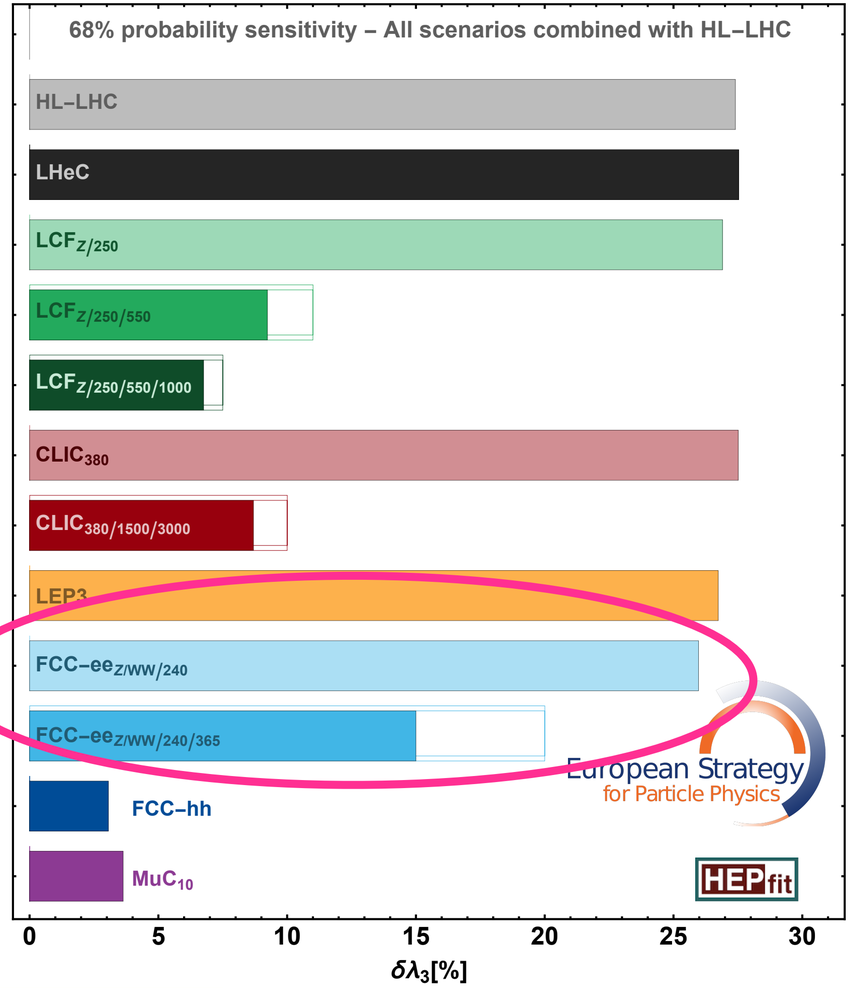

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HL-LHC discovery > 180 GeV? => leave this for a future hadron collider as well

FCC-ee cost estimate (FSR 2025)

Reference: F.Zimmermann, HKUST

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for $t\bar{t}$ operation corresponds to additional cost of 1,260 MCHF.

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16.6 BCHF incl. ttbar threshold and 4 experiments

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FCC-ee decision process

Reference: M.Thomson & M.Benedikt, FCC week 2026

To be ready for a decision in mid-2028

- The next two years will be critical
  - **need to focus** the next efforts on areas that will be key for the decision-making process
- CERN has established a new FCC Project Office (see MB's talk) to steer the process of developing the necessary design and Reference Design documentation to make the technical case
- In parallel, CERN and the international community, will need to work together on the delivery / partnership model for the FCC-ee itself

Reference Design Documentation by Q1 2028 to enable decision on project realisation:

- Integrated technical baseline
- Resource-loaded project master schedule
- Updated cost estimate with uncertainty
- Project-wide risk register
- Procurement strategy (incl. in-kind contribution opportunities)

In making the case for FCC-ee, we will need to present an "options analysis"

- This is *required* by some CERN Member States – and is a normal part of an investment decision process
- In the update of the ESPP, the scientific assessment of options has been done already – **the answer is clear: FCC-ee then descoped FCC-ee**
- To support the decision-making process on FCC-ee, CERN will coordinate the preparation of documentation (for LEP3 and one LC concept) on technical readiness, cost, risks, future R&D needs **and the scientific and strategic reasons why these are not identified as CERN's future flagship project**

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In case the answer on FCC-ee is "no" in 2028, a new "light-weight" strategy process is envisioned

A complementary vision: Linear Colliders

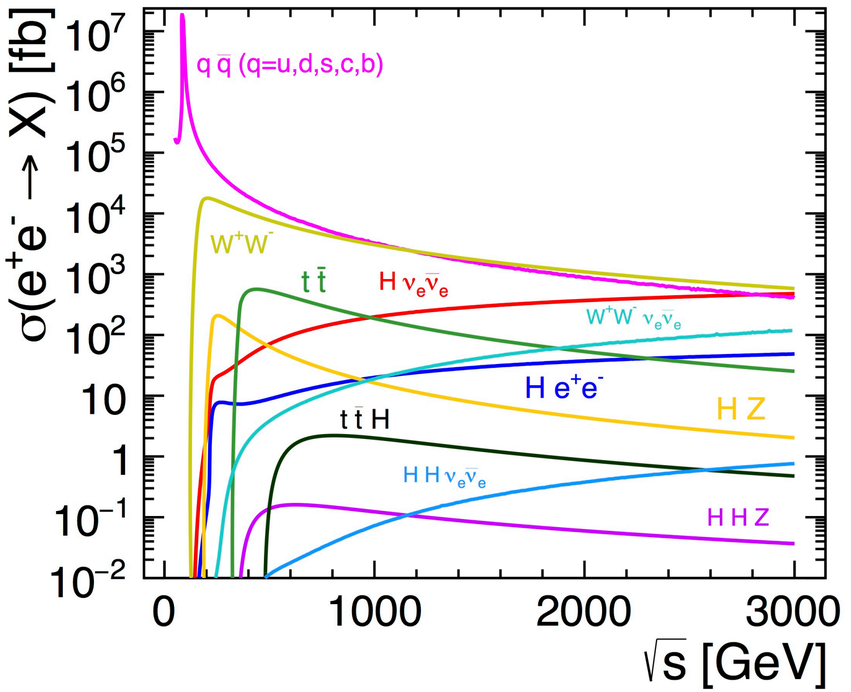
A Linear Collider is quite complementary to a Circular Collider

Beam polarisation & high energy: let's get it straight!

- electroweak physics is intrinsically chiral:
  - left- and right-handed e.g. electrons give different information
  - Linear Colliders offer polarised beams => new observables
    or: "four colliders in one"



- like at LHC, Higgs bosons are produced in e+e- in different reactions complementing each other:
  - ee->HZ, ee->WWvv->Hvv, ee->ZZee->Hee, ee->HHZ, ee->WWvv->HHvv, ee->ttH, …
  - to explore them all, a large span in E_{CM} is needed
- likewise for the closest relatives of the Higgs
  - top quark, multi-gauge boson processes, …



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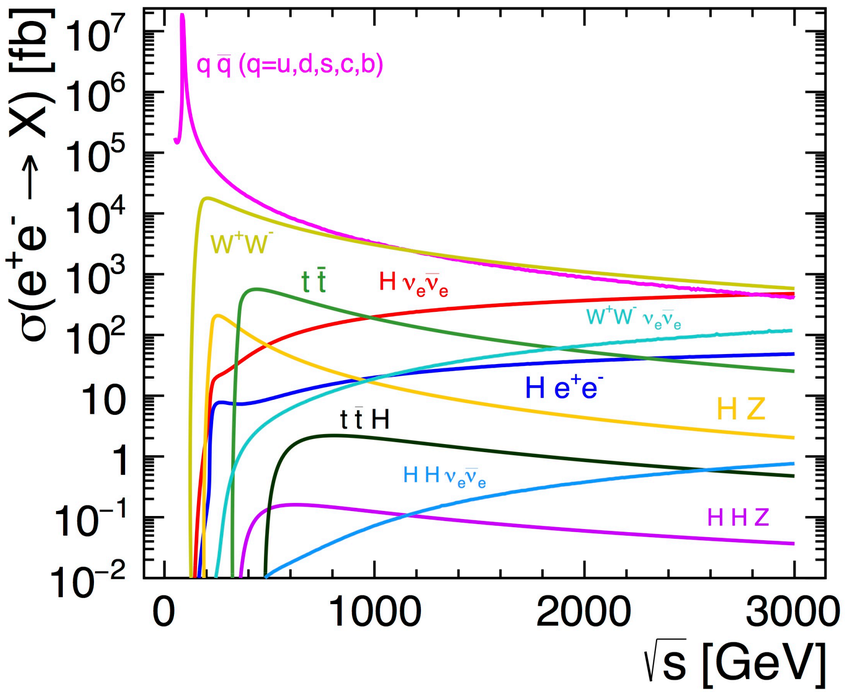

the full Higgs / top / electroweak program requires polarised beams & E_{CM} up to at least 1 TeV

LCVision: a bottom-up community organisation

started at LCWS2024: Linear Colliders in view of the ESPPU



- **all linear colliders share the same scientific goals:**
  - formulate a coherent physics program
  - define energy stages etc science-driven
- **beyond an individual technology:**
  - design a linear collider *facility*
  - infrastructure compatible with various technologies
  - plus beam-dump / fixed-target exp's / R&D facilities
- **study the Higgs in e+e- now - but maintain flexibility for the future:**
  - start now with an *affordable* project
  - maintain scientific diversity
  - strengthen accelerator R&D towards 10 TeV pCM collider
  - **decide on upgrades / new projects based on future developments - or even break-throughs:**
    - **scientifically: a discovery at HL-LHC or elsewhere**
    - **technologically: higher gradients / muon cooling / high-field magnets**

General Considerations

A Linear Collider Vision

LCVision philosophy:

- an affordable “Higgs factory” in mature technology
- with a well-defined upgrade to explore the Higgs self-coupling to < 10%
- and a flexible long-term future leveraging advanced accelerator technologies

Linear Collider Vision



Superconducting RF technology (like ILC):

- successful construction & operation of Eu.XFEL, LCLS-II…
  => no large-scale demonstrator step needed
- lab experience and production capacities in industry globally
- **choice for fastest implementation & most attractive for global (in-kind) contributions**
- **with today’s technology,**
  need ~33 km for 550 GeV (di-Higgs production)



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Linear Collider Vision

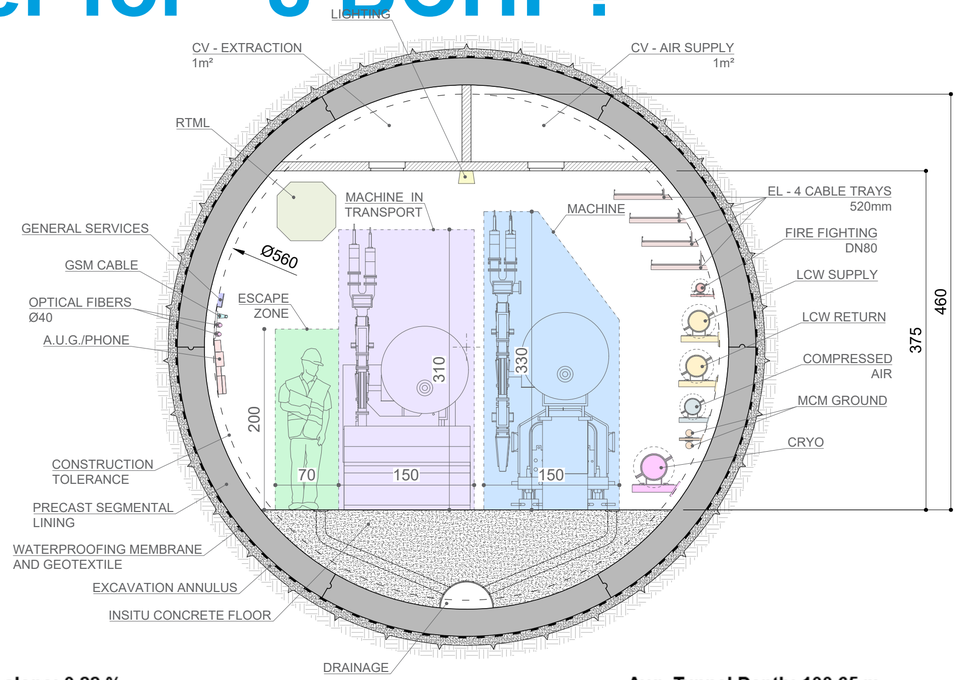


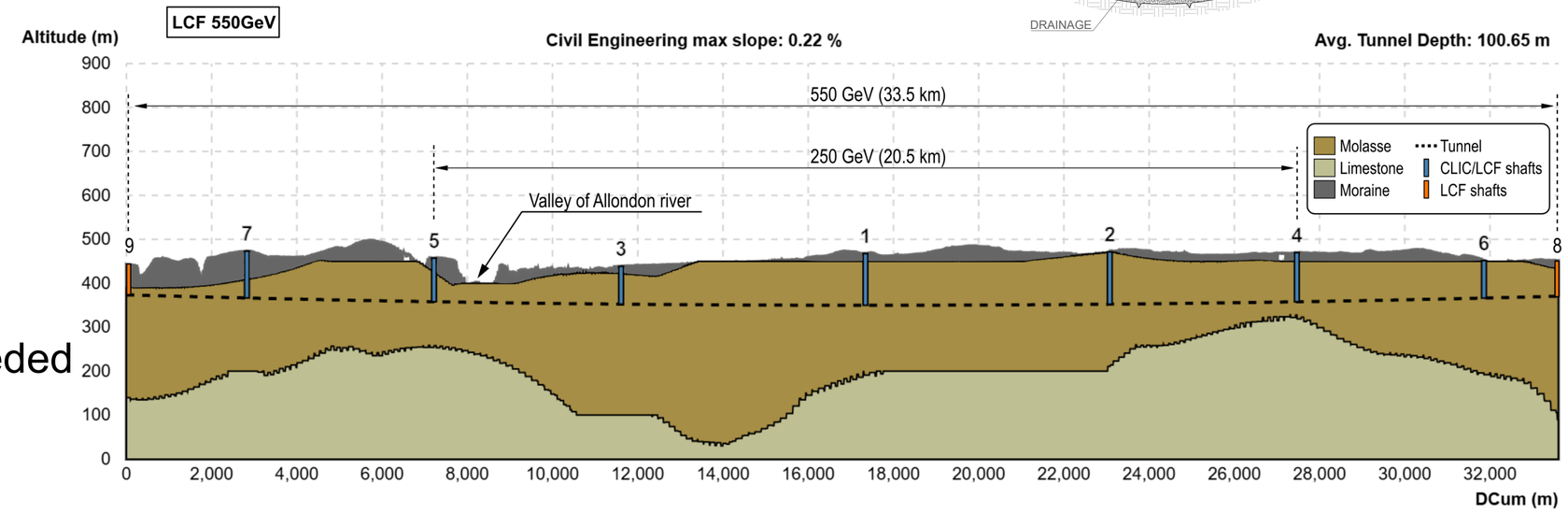
=> Linear Collider Facility (LCF) proposal for ESPPU
arxiv:2503.24049

The first stage - or what can LCF offer for ~8 BCHF?

250 GeV incl Z pole - facility

- **33.5 km long tunnel => reach 550 GeV with 31.5 MV/m SCRF**
- **∅ 5.6m, two IPs**
- **equipped with SCRF for 250 GeV**
- **10Hz trains of 1312 bunches => L = 2.7 x 10^{34} / cm^2 / s**
- **construction cost: 8.29 BCHF** (comparison TF: +0.3 spoil removal +0.8 detectors)
- **AC power: 143 MW**
- optionally: beam-dump / fixed-target
- upgrade: double luminosity 2625 bunches / train: +0.77 BCHF + 39MW
- **both beams polarised:**
  - **e-: 80%**
  - **e+: 30%**
- **3ab-1 @ 250 GeV**
- operation at Z pole (eg 100fb^{-1}) WW theshold (eg 500fb^{-1}) as needed





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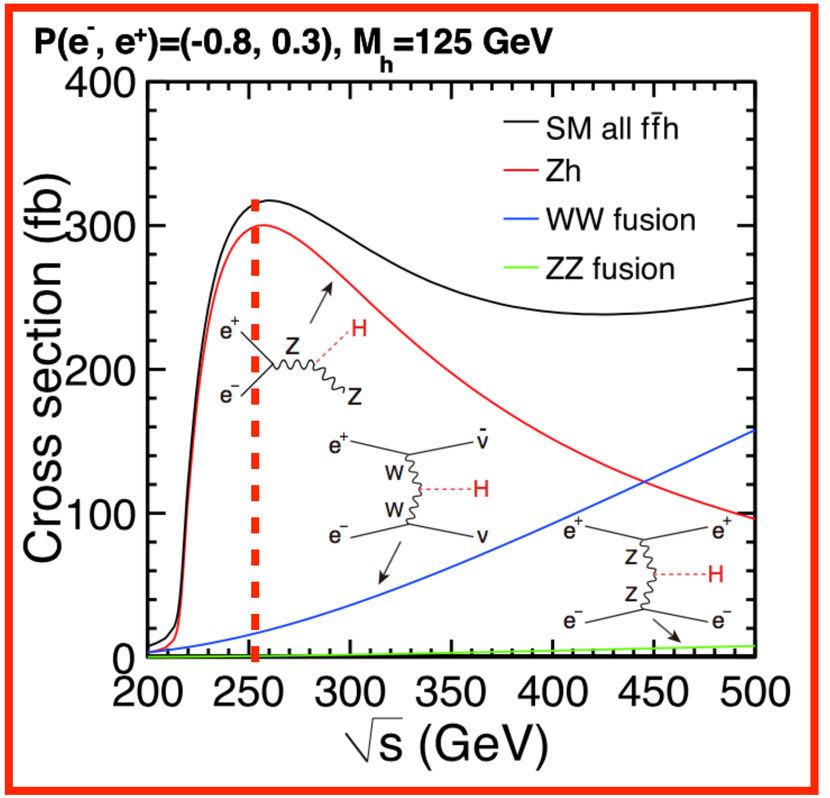
The first stage

250 GeV incl Z pole - physics

- **Higgs:**
  - production via **ee->ZH** dominant
  - **σ_{tot} to ~1% => absolute couplings**
  - **branching fractions to ~1%**
  - mass to 10^{-4}
  - search for invisible / exotic decays to 10^{-3}
- WW:
  - non-linear interactions (10x better than LEP)
  - mass to ~2 MeV (threshold: ~1.4 MeV)
  - CKM matrix elements (e.g. V_{cs}, V_{cb})
- f fbar:
  - precision measurements at 250 GeV
  - and Z pole
    => polarisation: huge increase EWPO sensitivity
    (~10-100x improvement over LEP/SLC)



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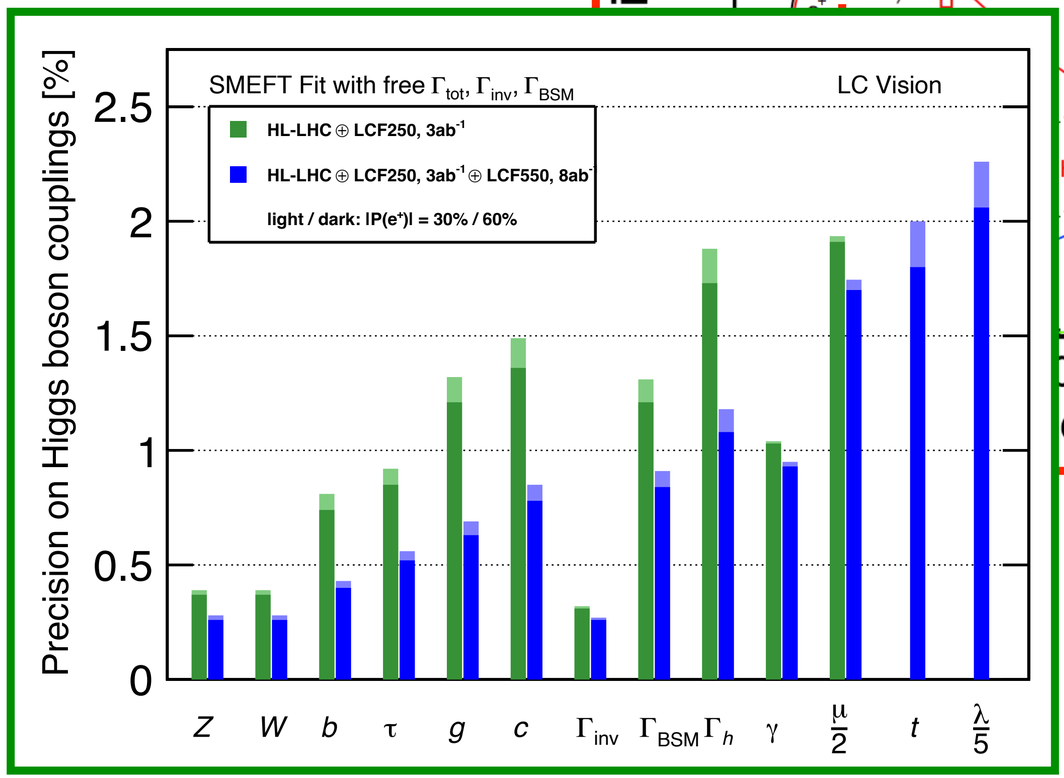

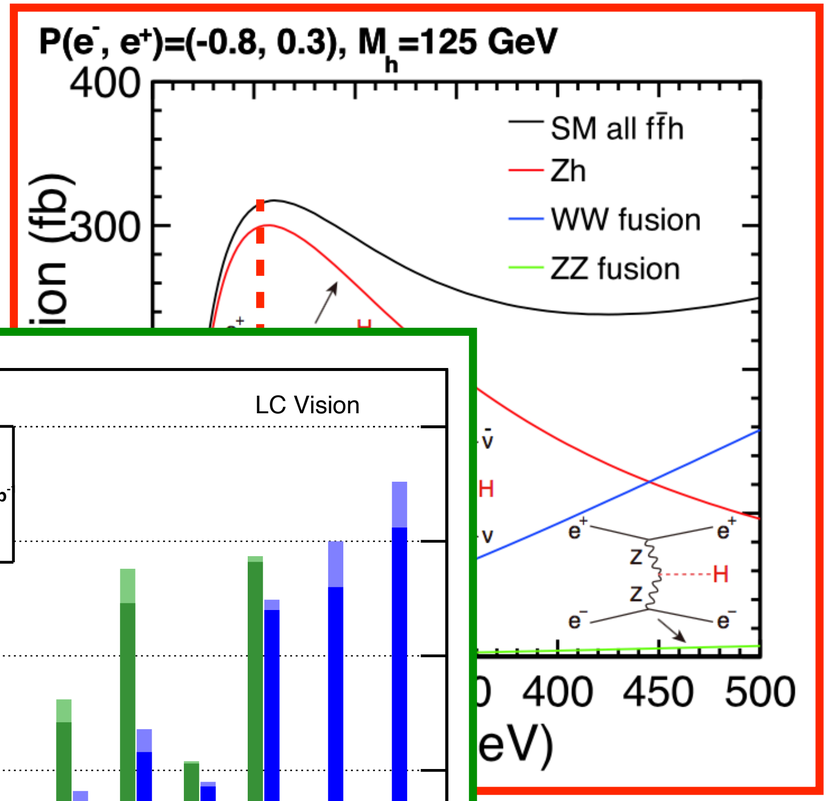

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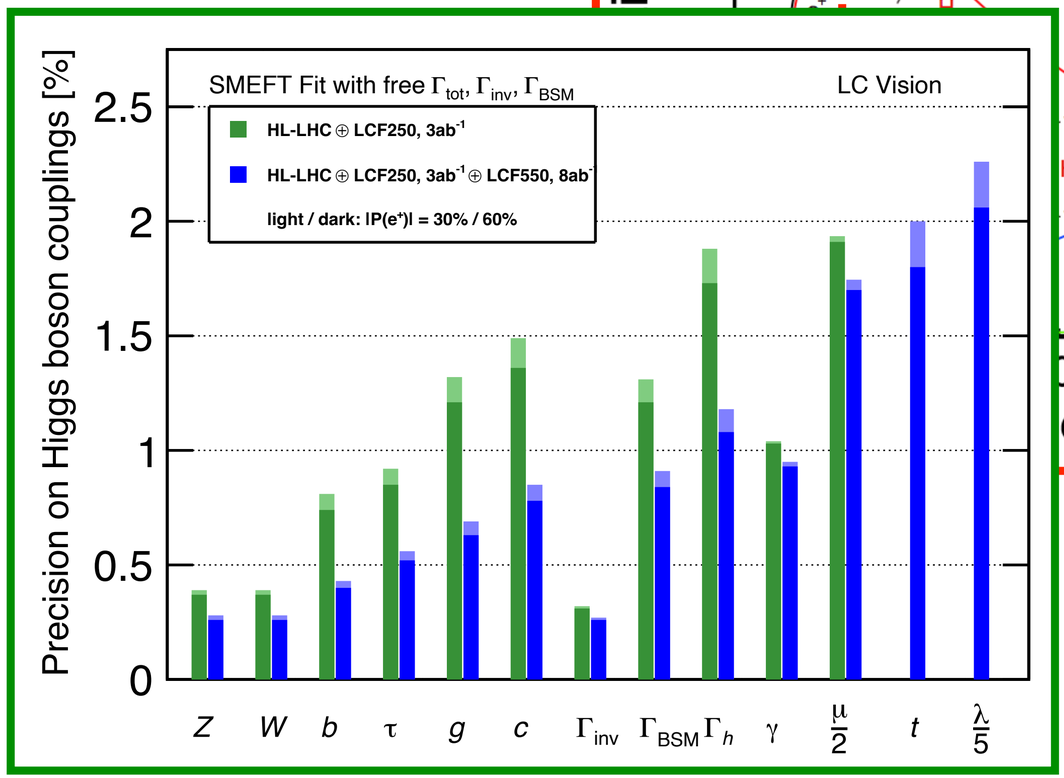
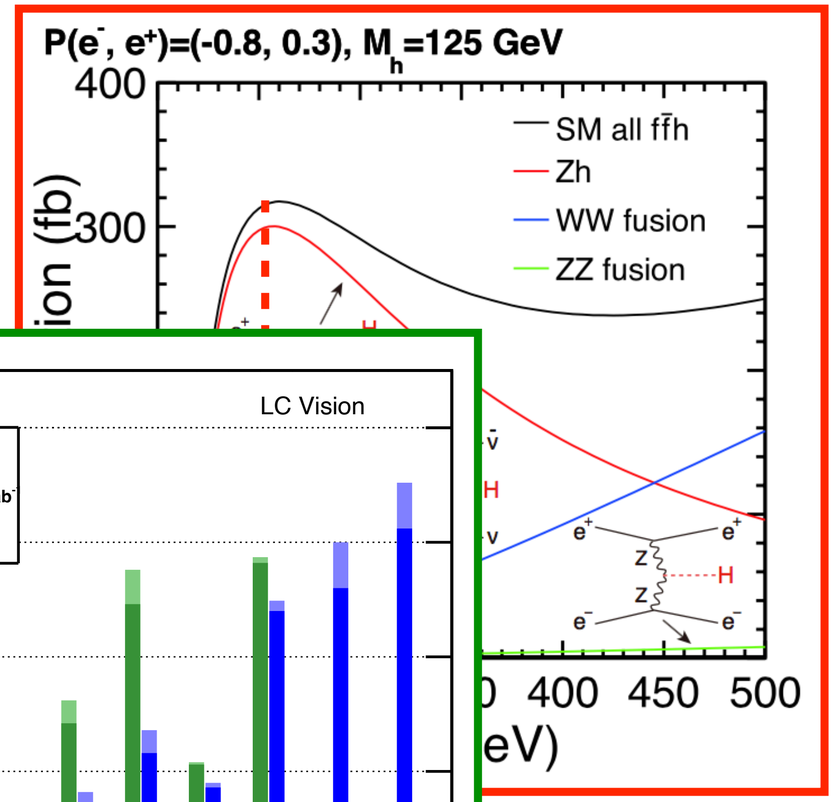




What LCF cannot do: Flavour & QCD at the Z pole (however 9.4 vs 15.3 BCHF)

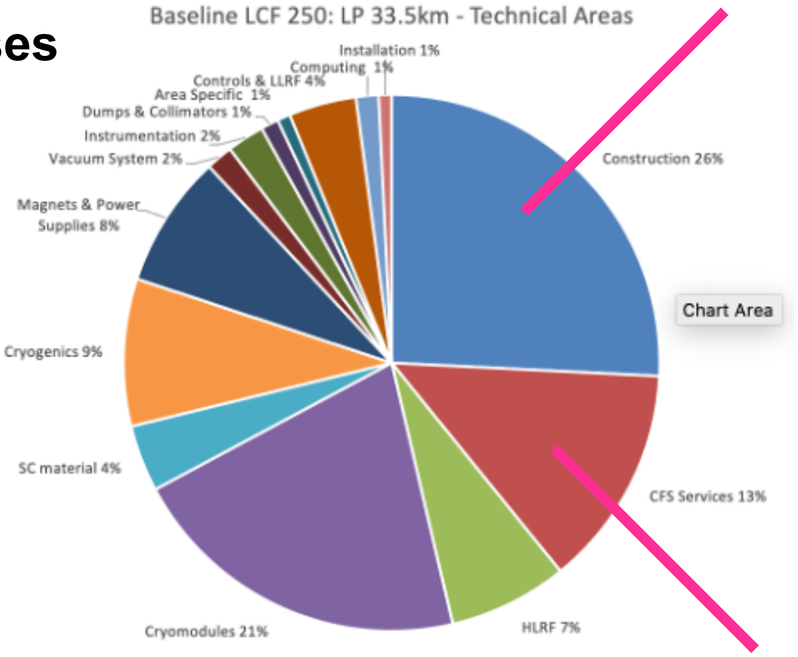
Main components of cost estimate

for ESPPU costing

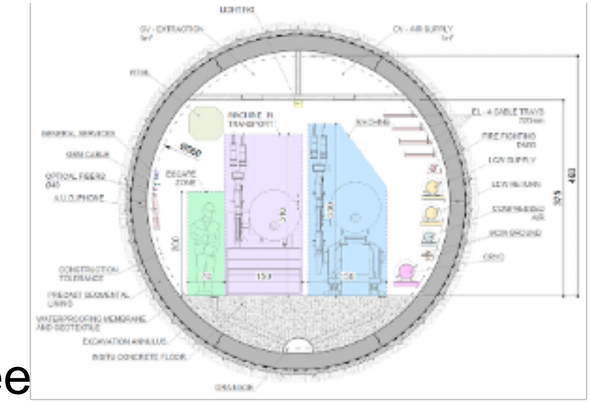
Accelerator
- 5044 MCHF ±27%
- **AACE class 2-3**
  - componentwise
  - **industry quotes & purchases**
  - SCRF: updated 2024 prices

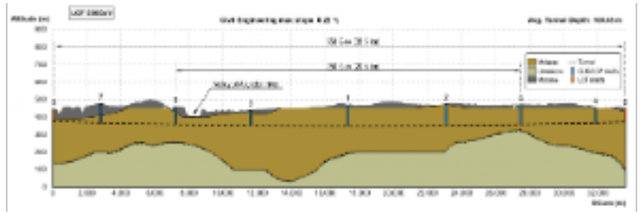




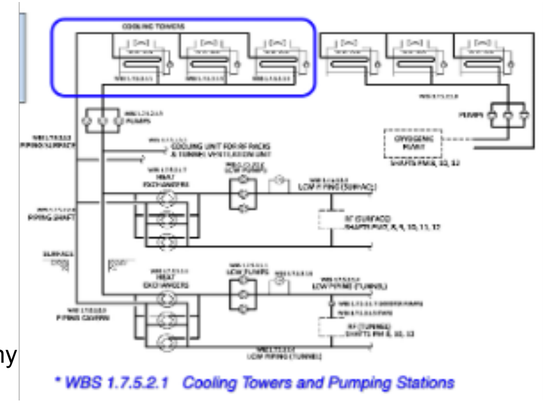


Civil construction
- 2138 MCHF ±30%
- AACE class 4
- CERN study 2024
- unit prices like FCC-ee



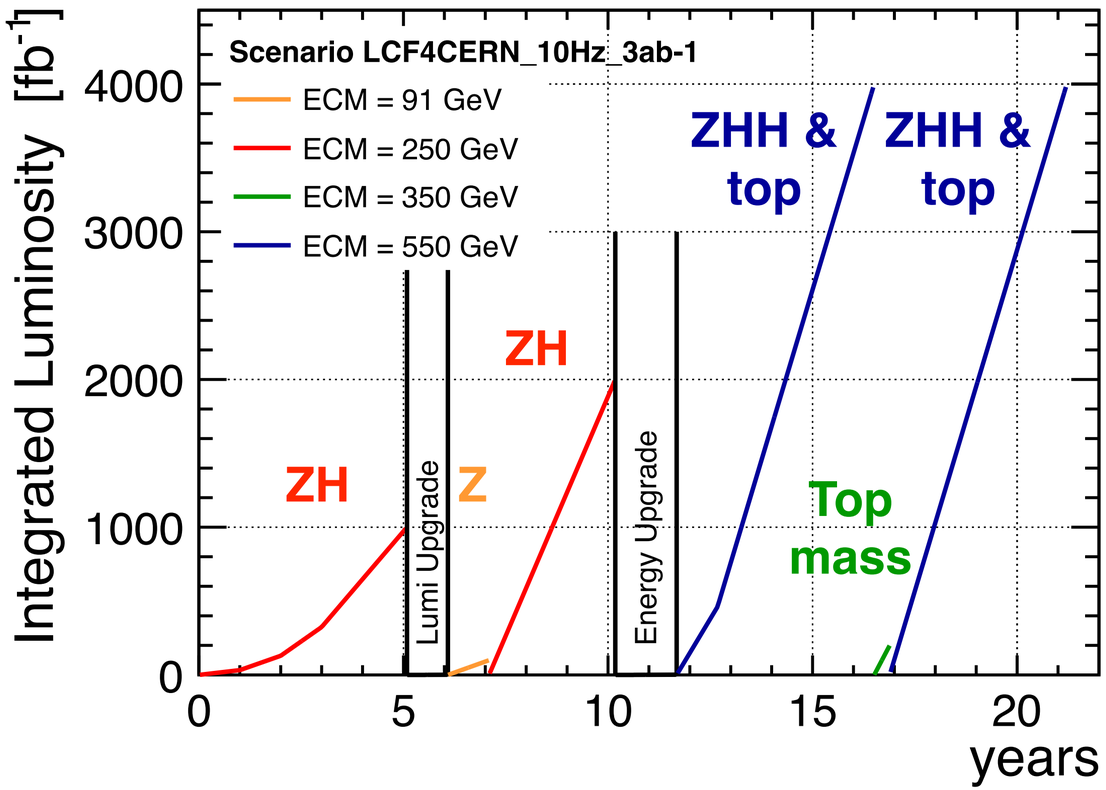


Infrastructure
- 1109 MCHF ±33%
- AACE class 4
- cost base 2012 + inflation
- US design



Running and Spending Scenarios

LCF250 -> 550 baseline scenario



Incl. detectors - 0.4 BCHF / experiment

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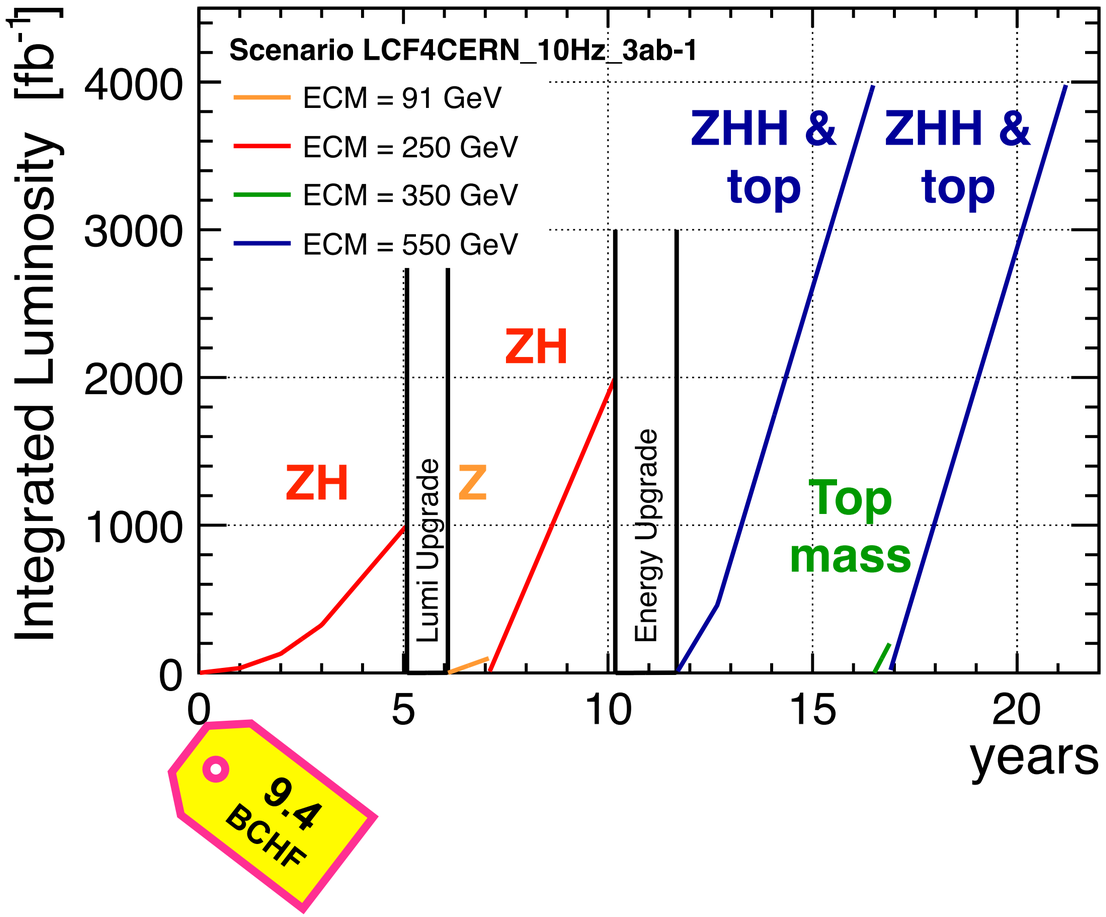

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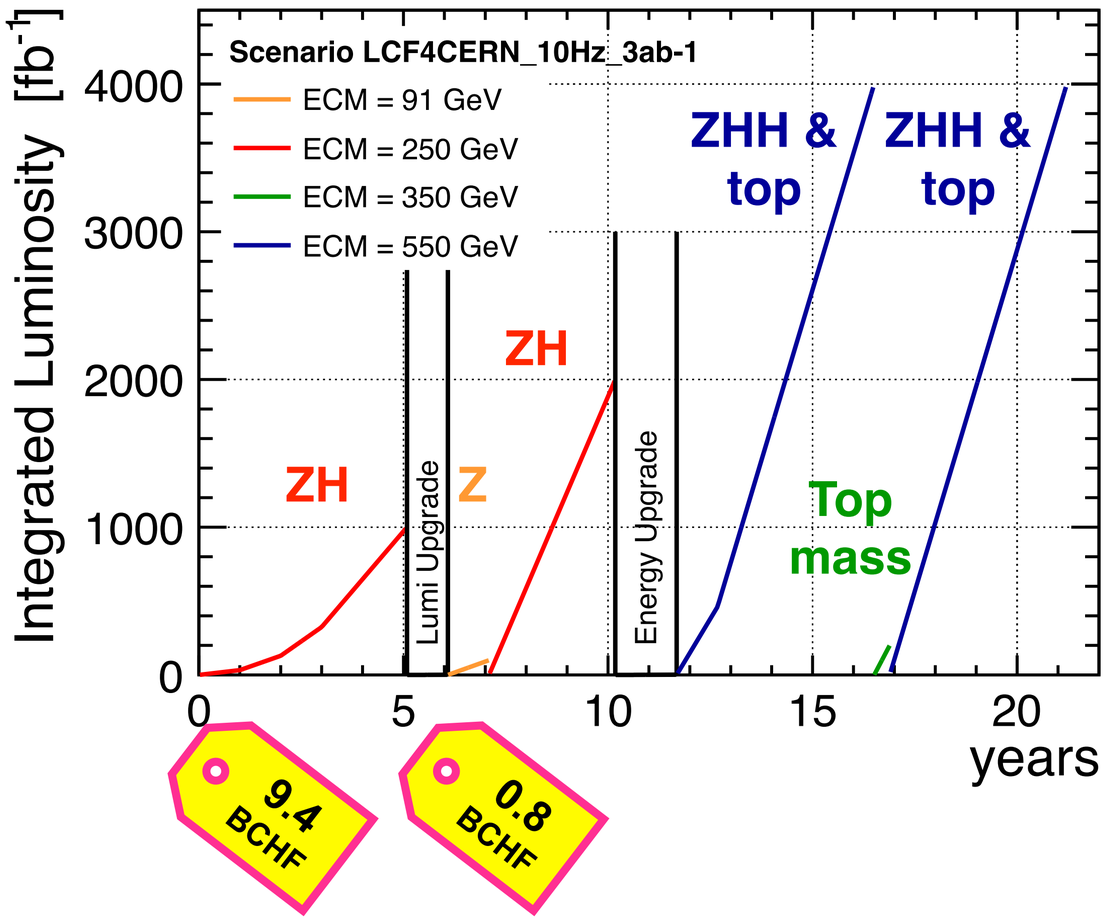

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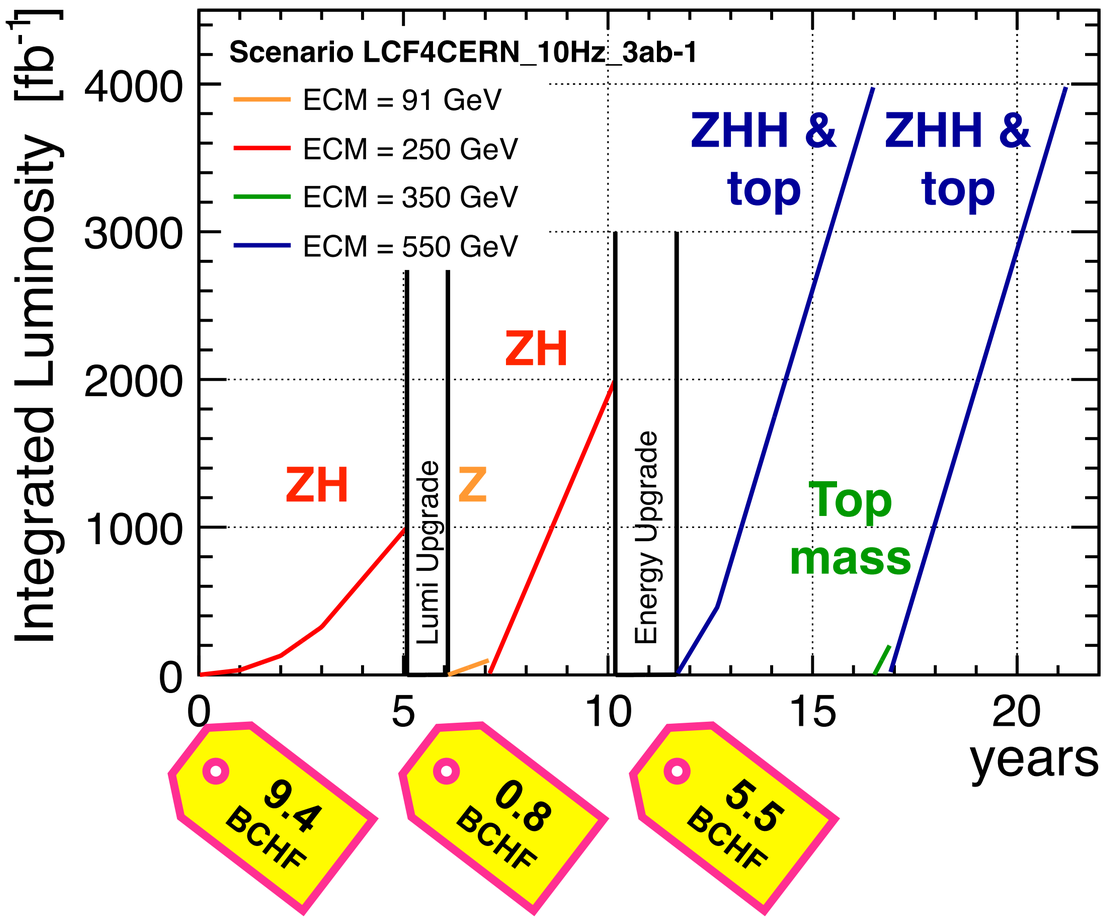

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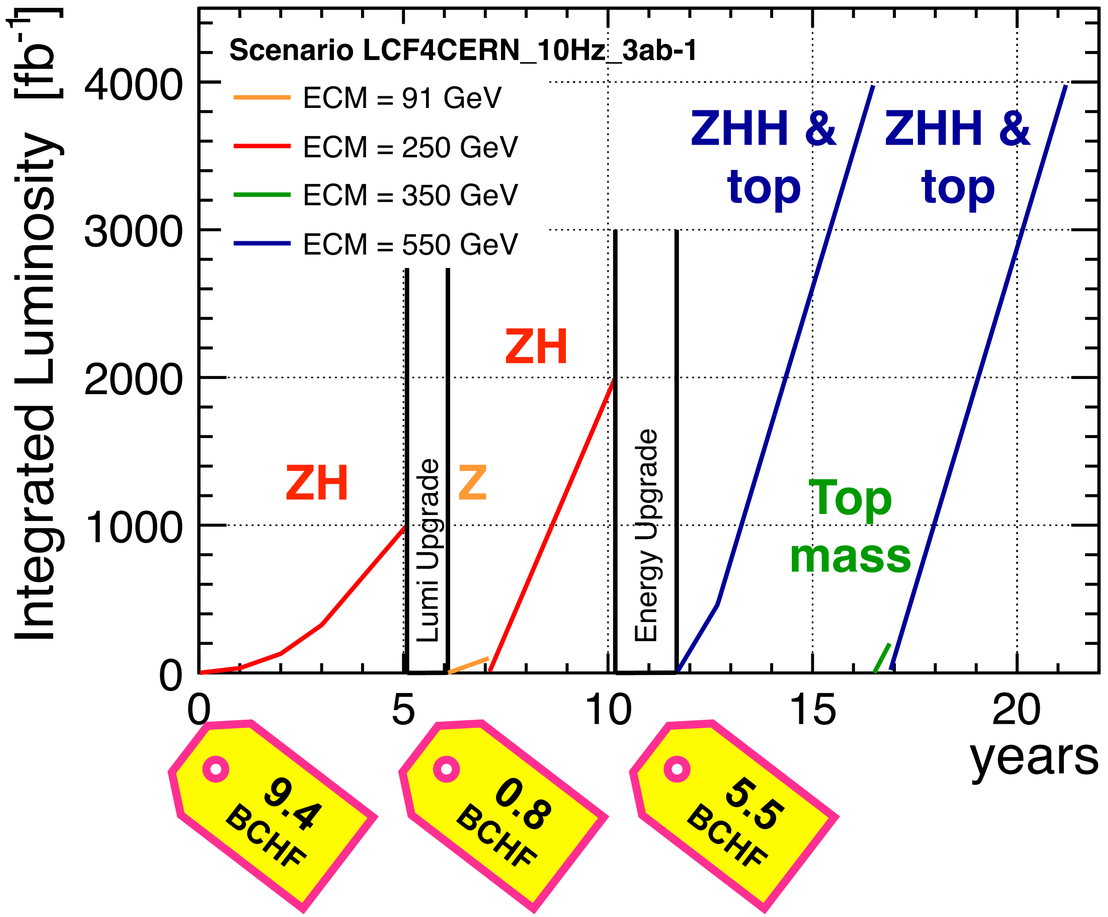

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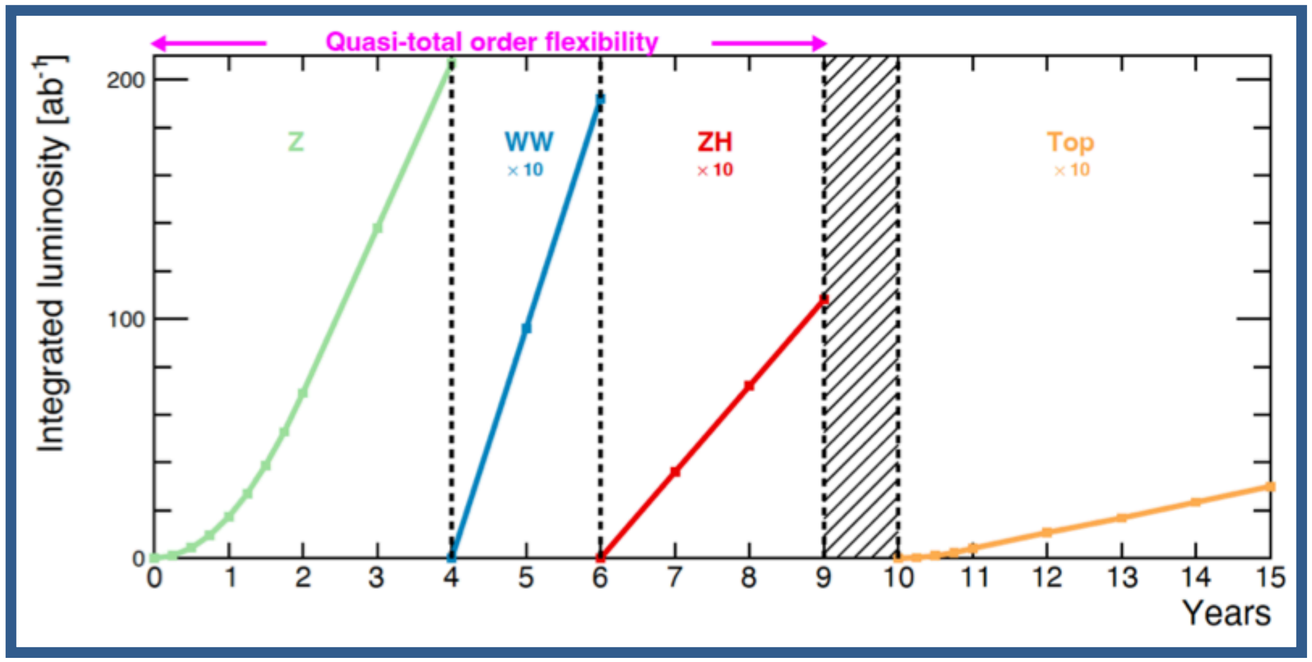

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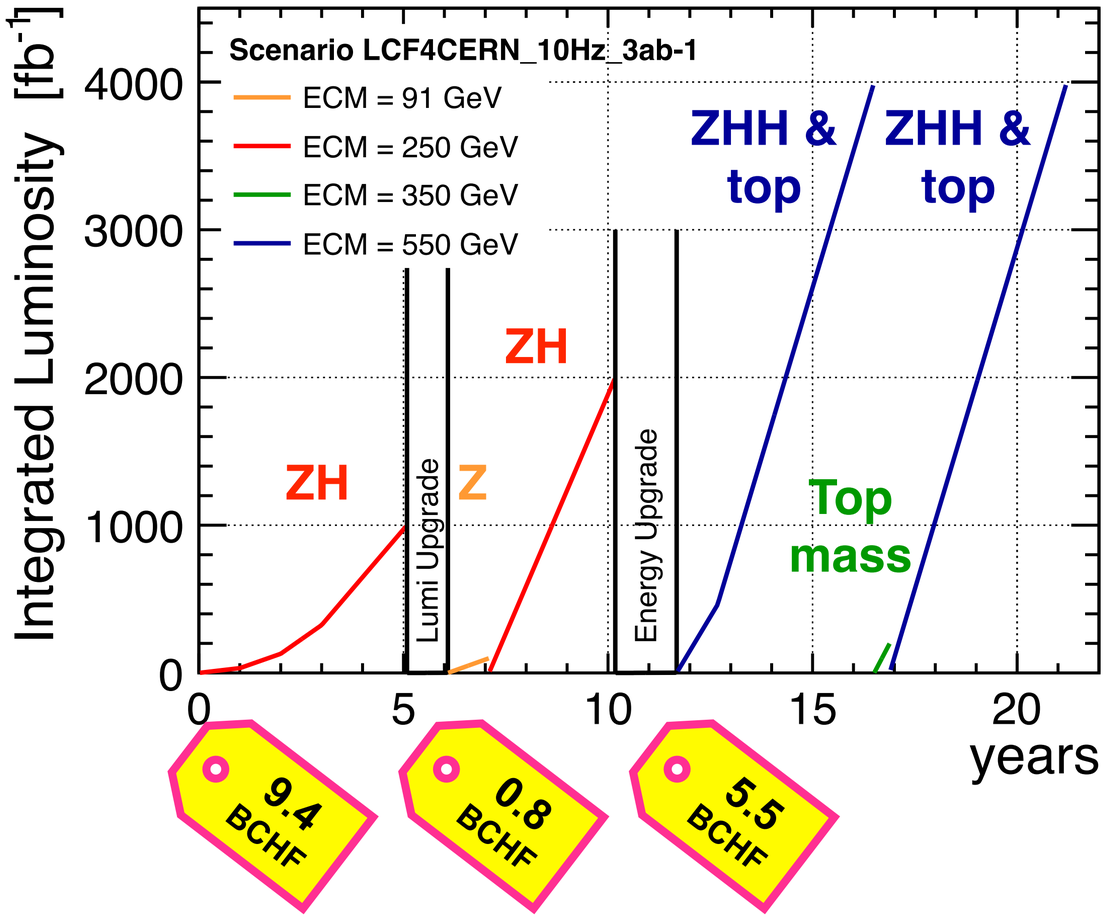

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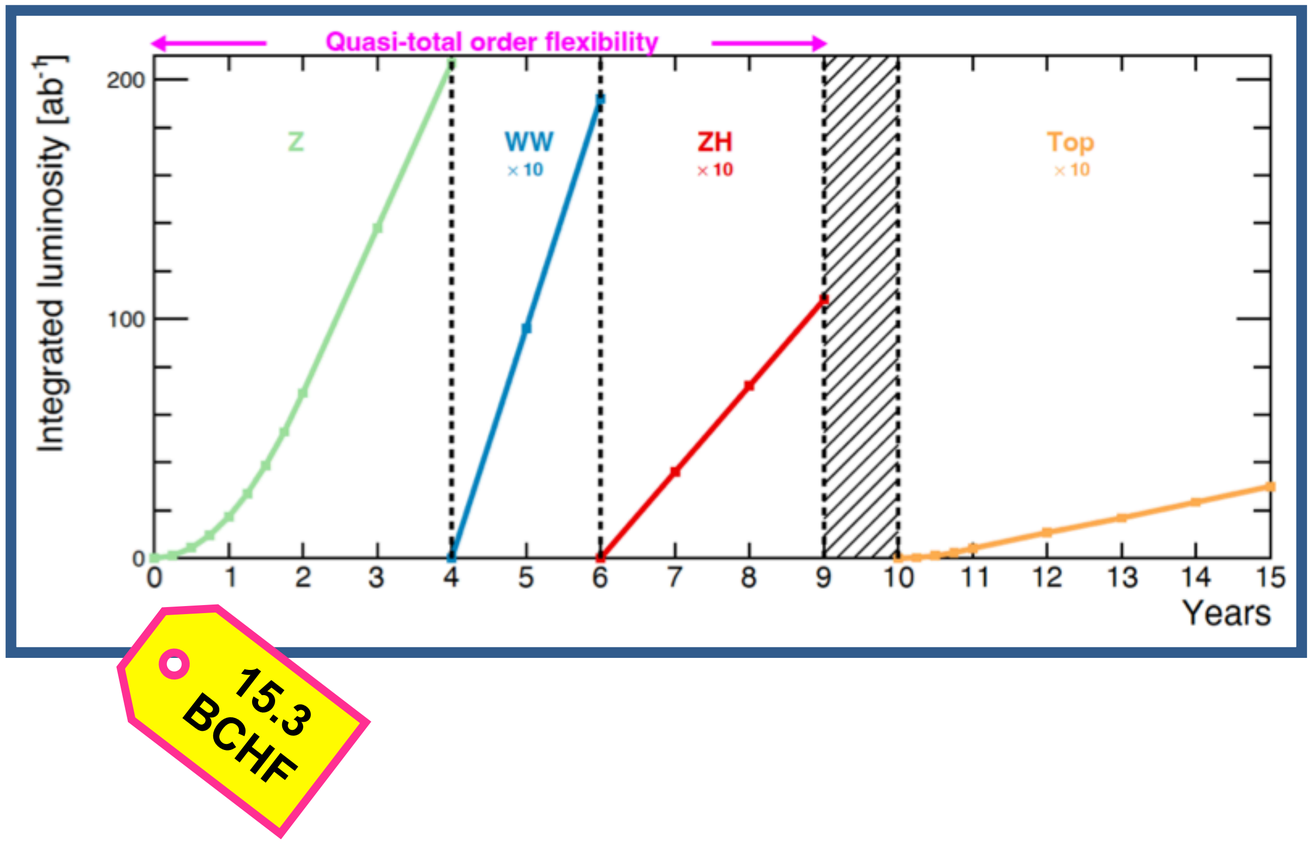

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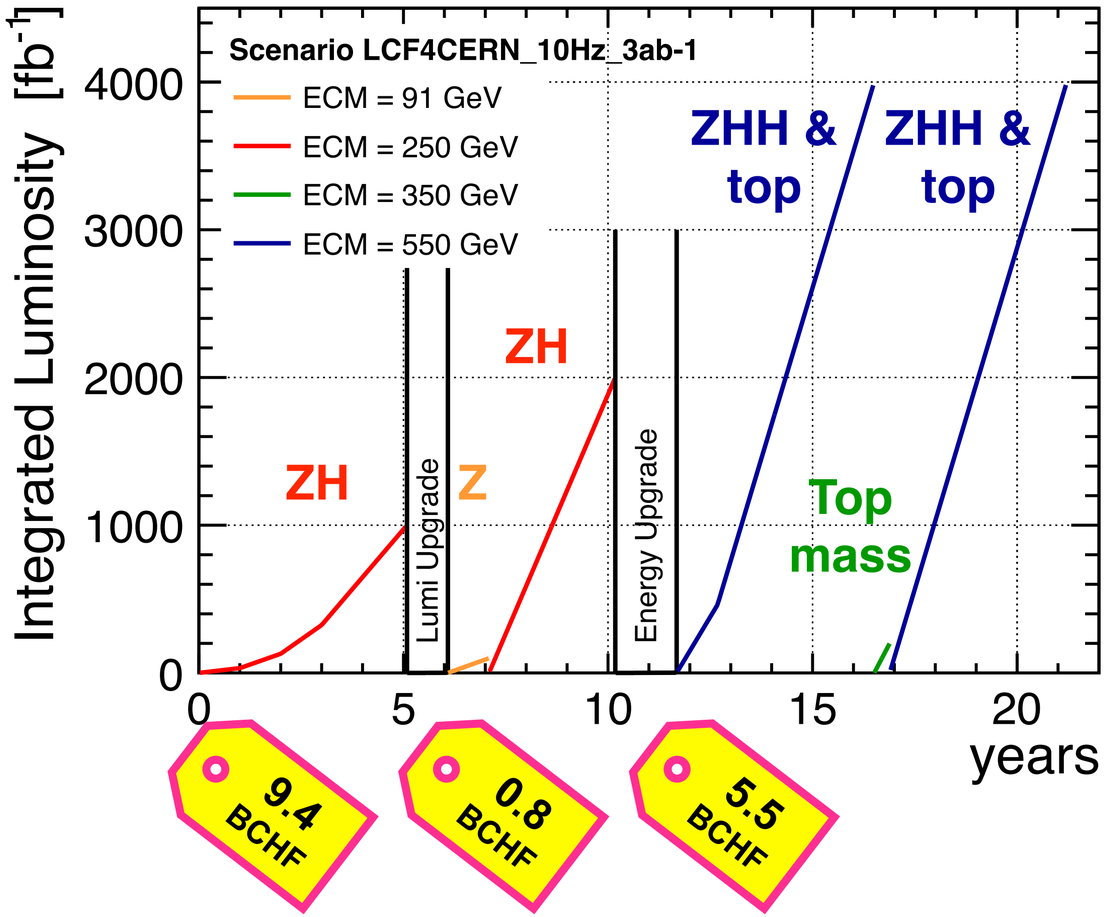

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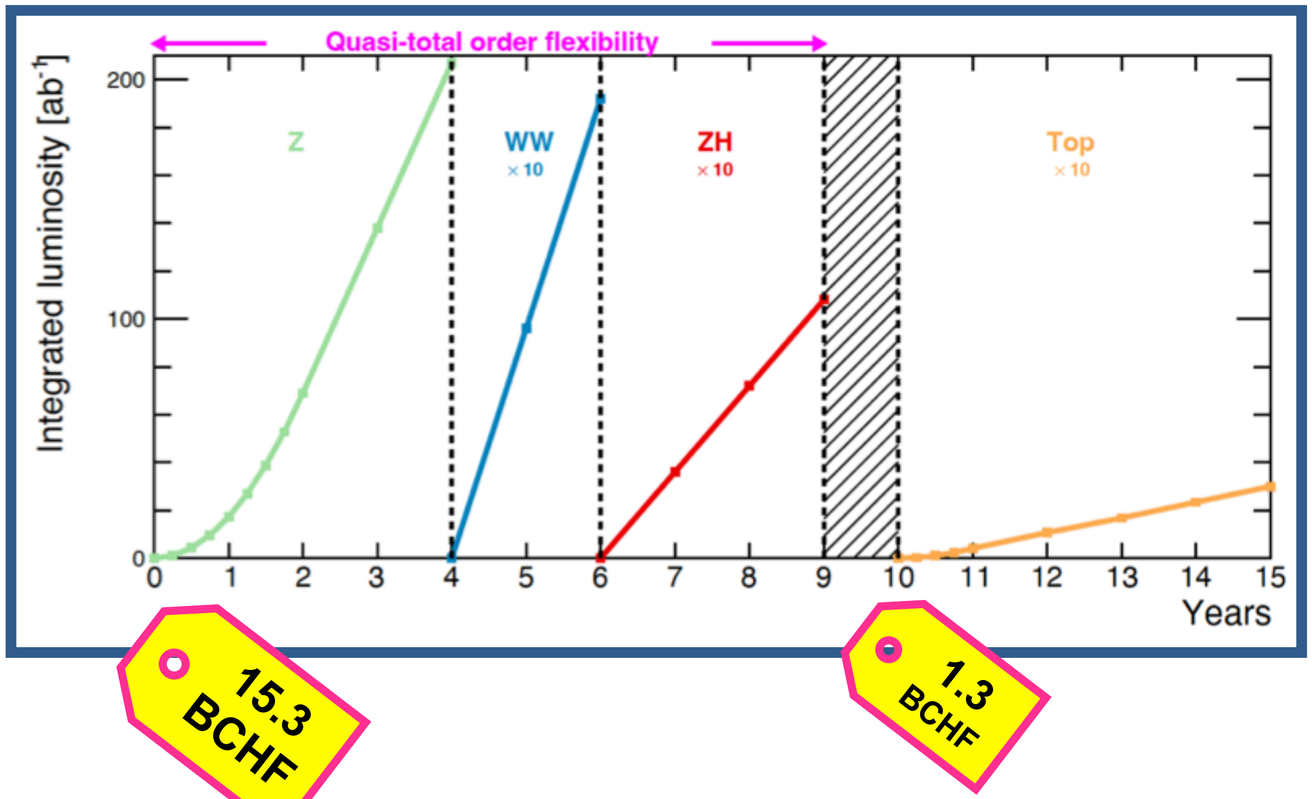

Incl. detectors - 0.4 BCHF / experiment

The second stage

550 GeV incl ttbar theshold

equipping the additional tunnel with SCRF

- **+ 5.46 BCHF**
- 10 Hz trains of 2625 bunches
  => 7.7 x 10^{34} / cm^2 / s
- **AC power 322 MW**
- target 8 ab^{-1}

important: this can come after a number of years of physics data-taking at lower operating costs
=> can afford the upgrade again!

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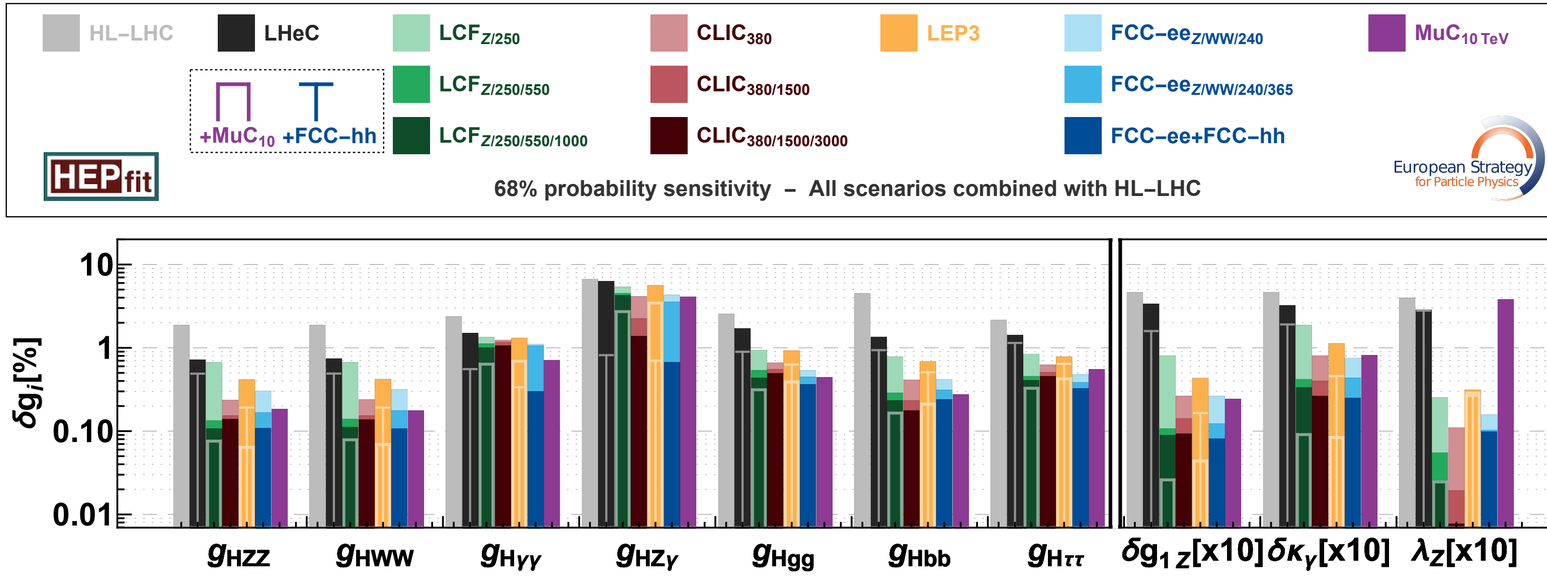

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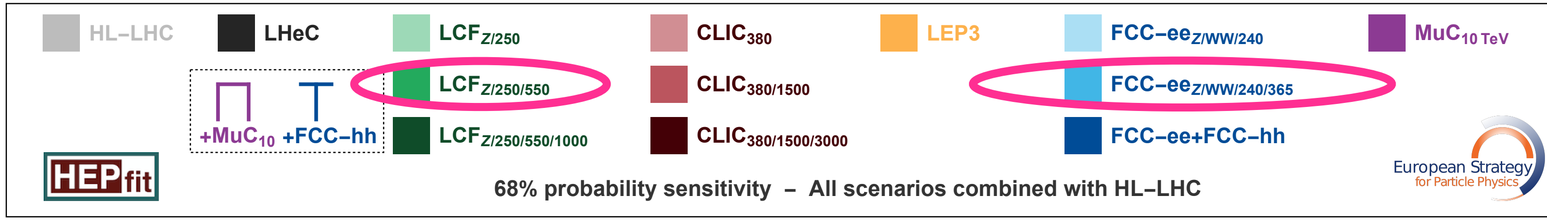

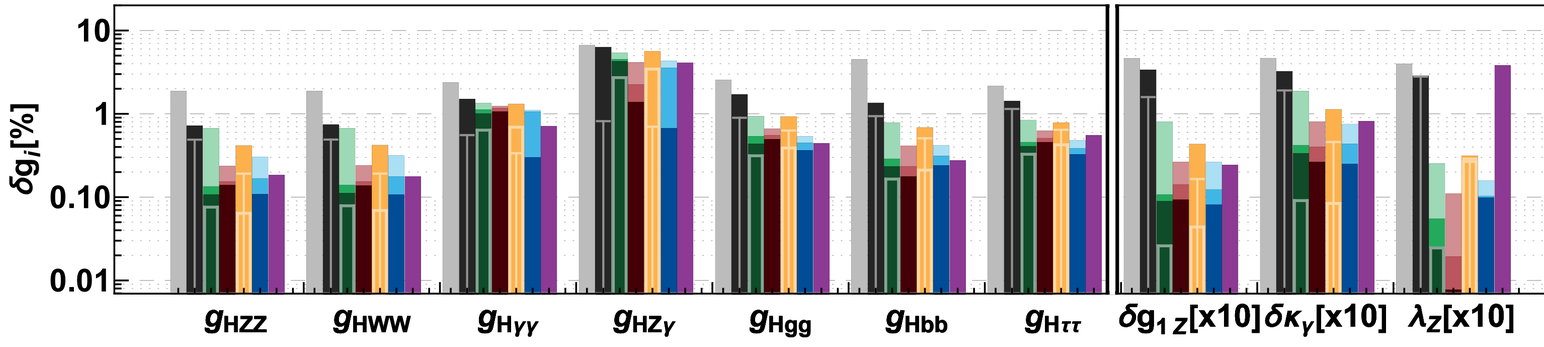

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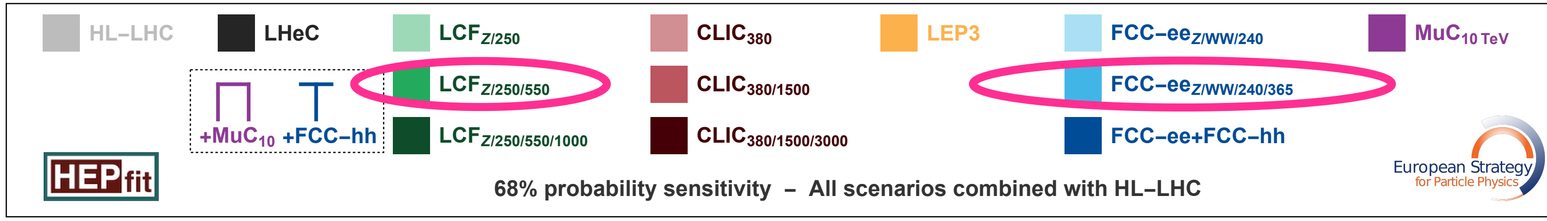

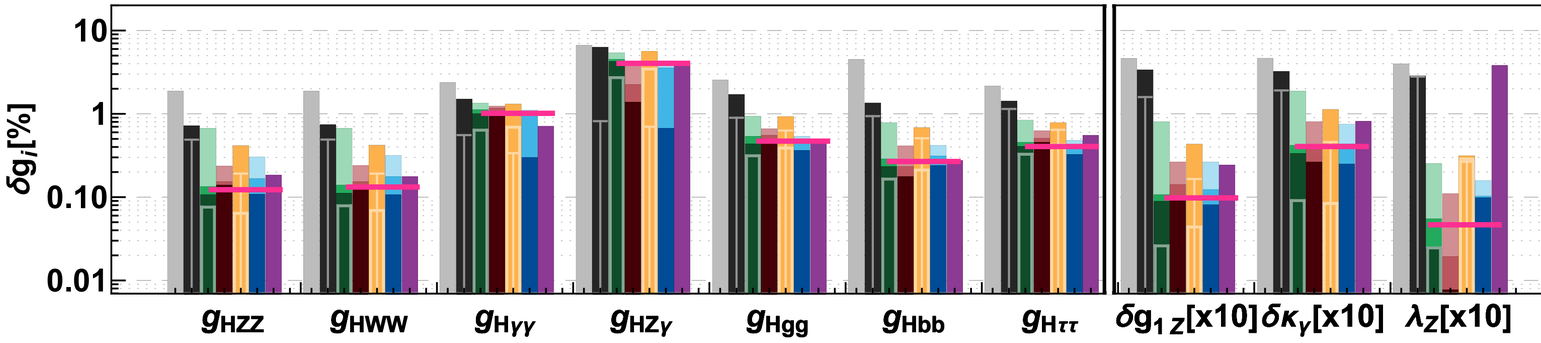

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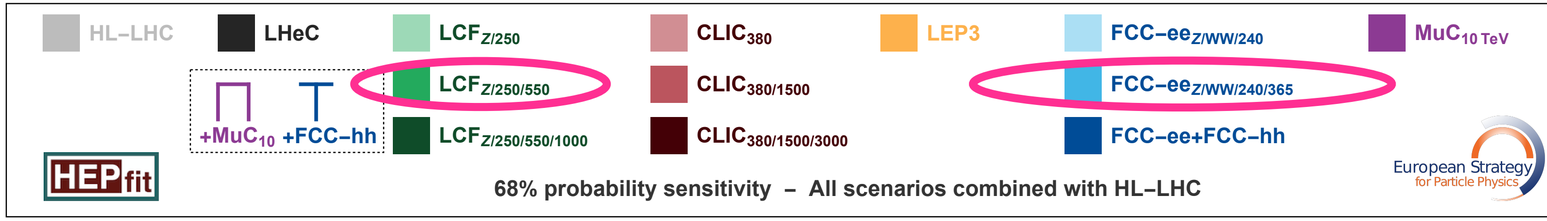

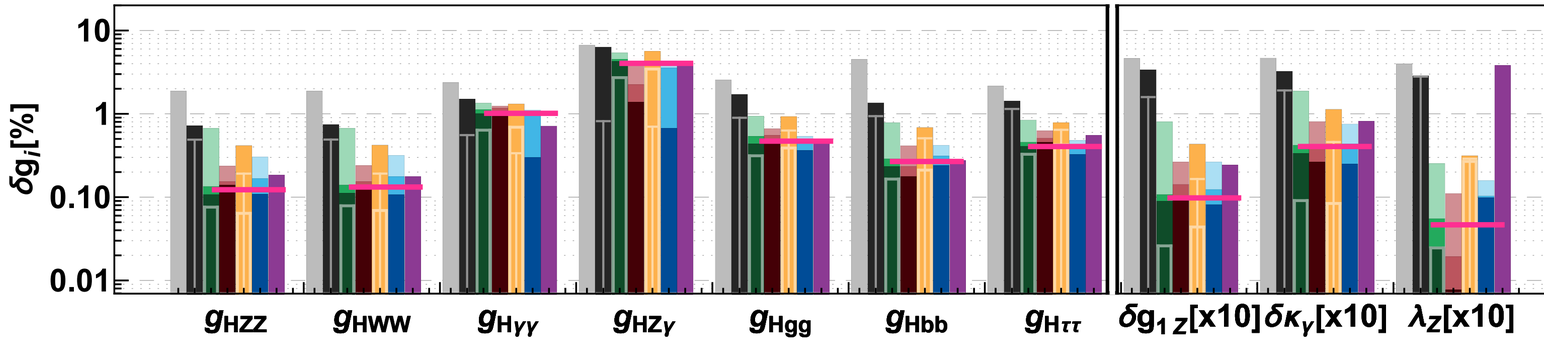

LCF550 and FCCee365 give very similar Higgs precision

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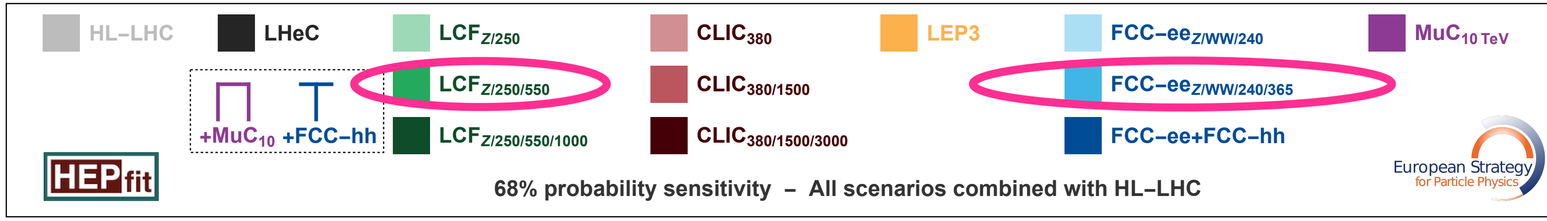

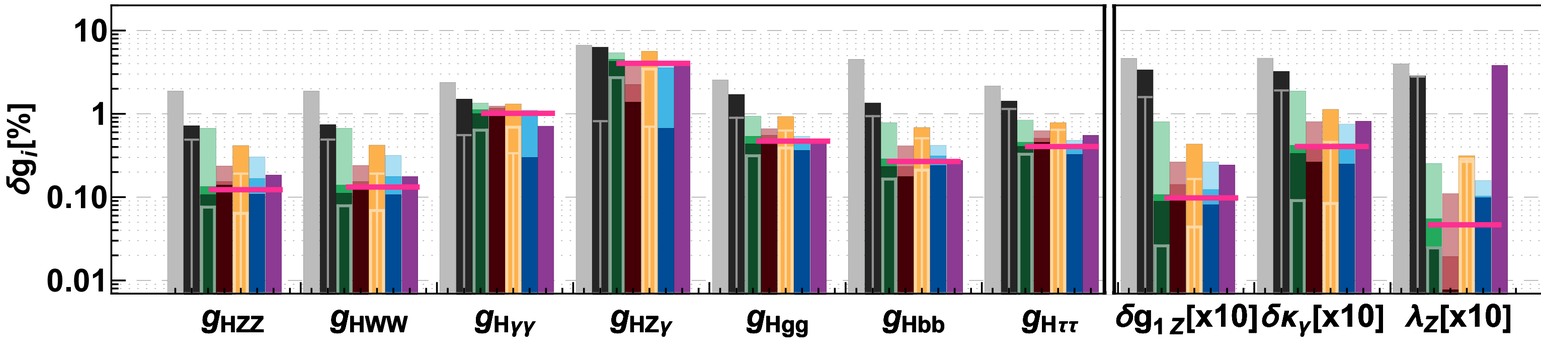

LCF550 and FCCee365 give very similar Higgs precision

Higgs physics at 550 GeV and beyond:

- now **WW fusion** dominant
  => complementary set of observables
  => independent verification of anomalies observed at 250 GeV
- **ttH, ZHH and even vvHH become observable:**
  - **ttH:** tree-level sensitivity to top-Yukawa 1-2%
  - **di-Higgs production: sensitivity of ~10% to self-coupling λ**
    - for any value of λ !

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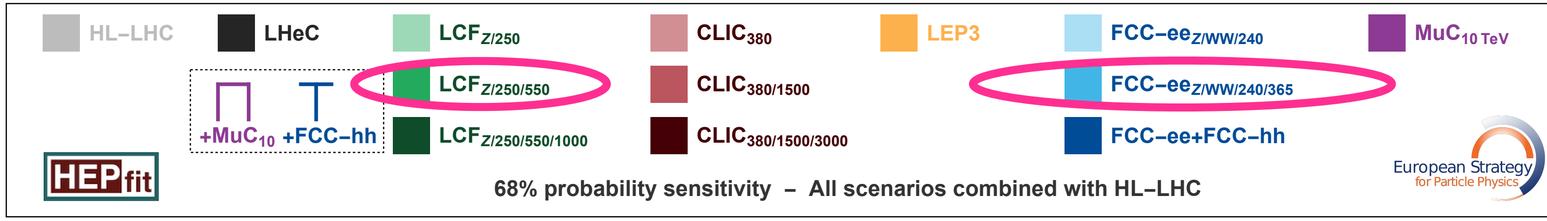

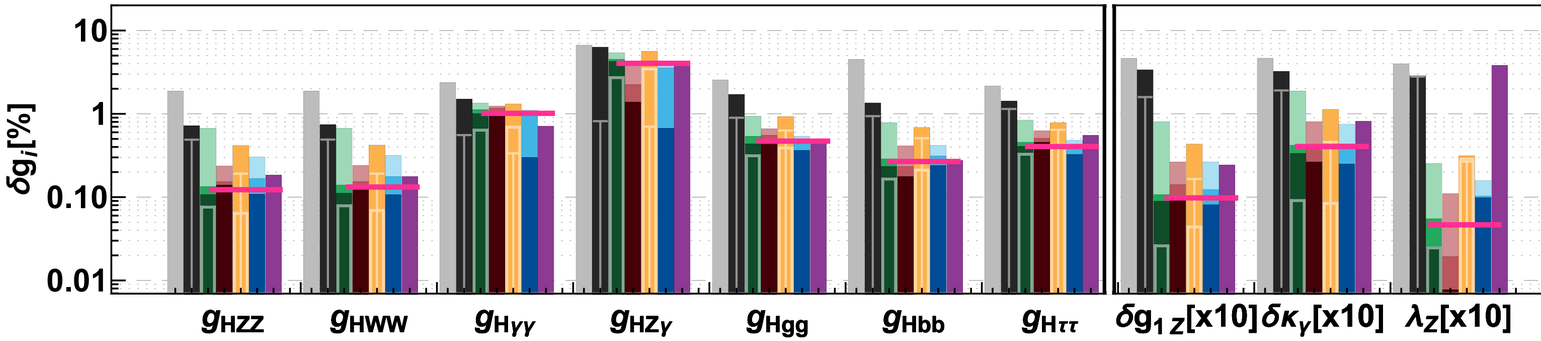

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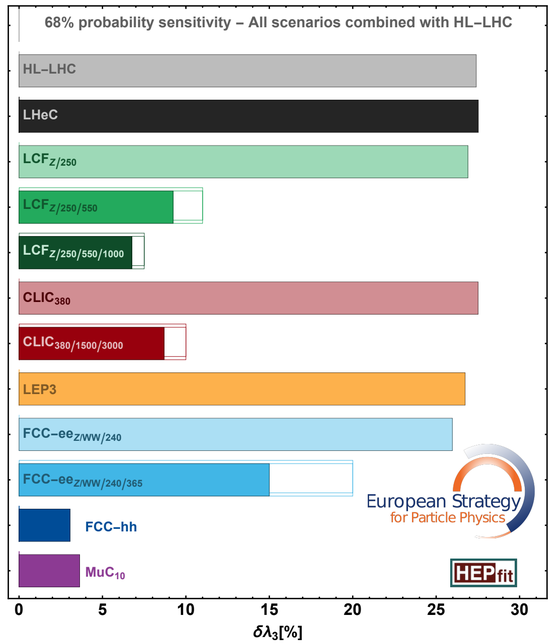

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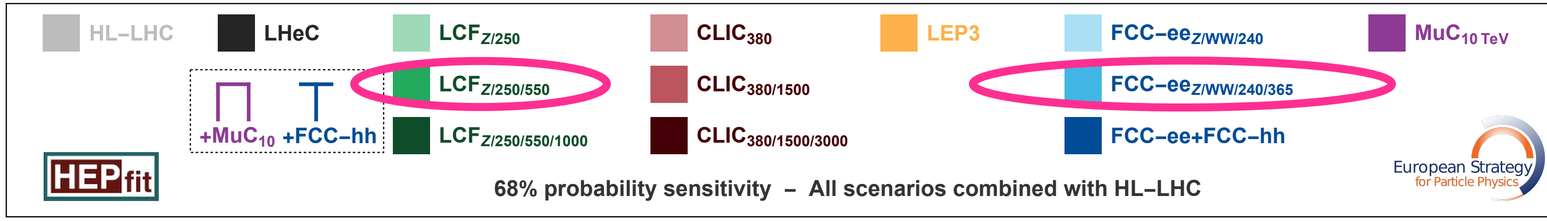
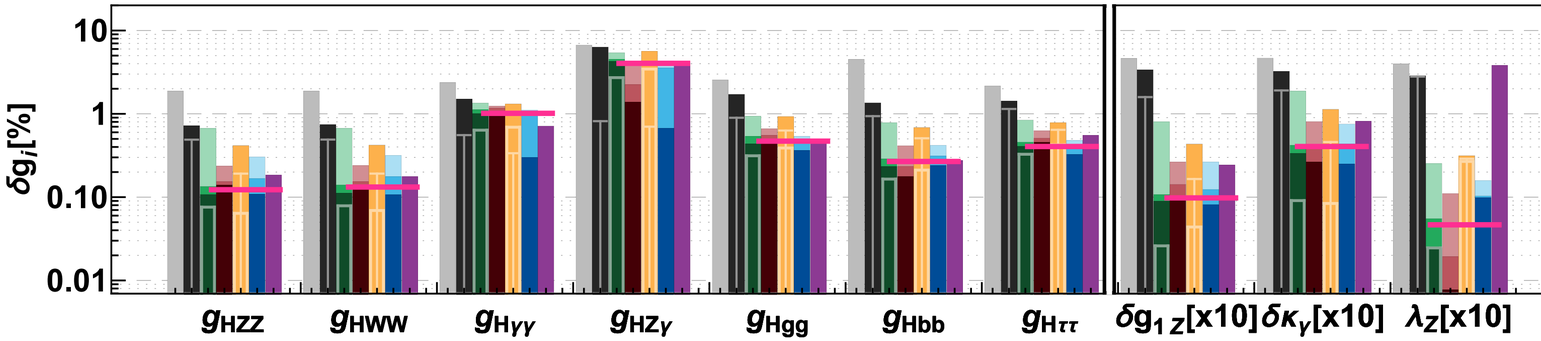
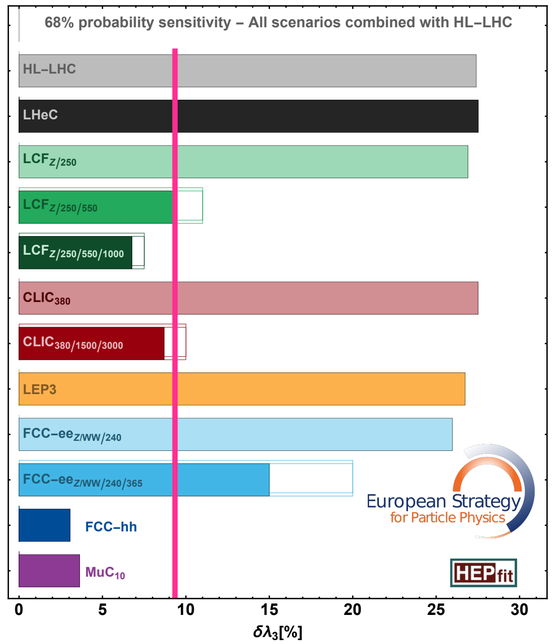




Higgs physics at 550 GeV and beyond:

- now **WW fusion** dominant
  => complementary set of observables
  => independent verification of anomalies observed at 250 GeV
- **ttH, ZHH and even vvHH become observable:**
  - **ttH:** tree-level sensitivity to top-Yukawa 1-2%
  - **di-Higgs production: sensitivity of ~10% to self-coupling λ**
    - for any value of λ !



LCF550 and FCCee365 give very similar Higgs precision

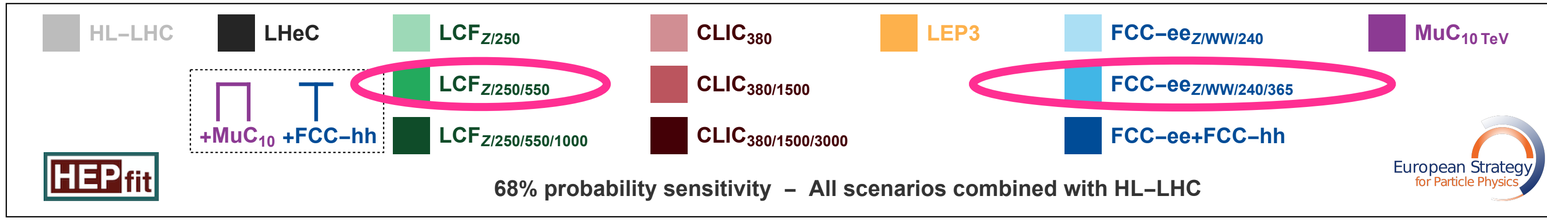
The second stage

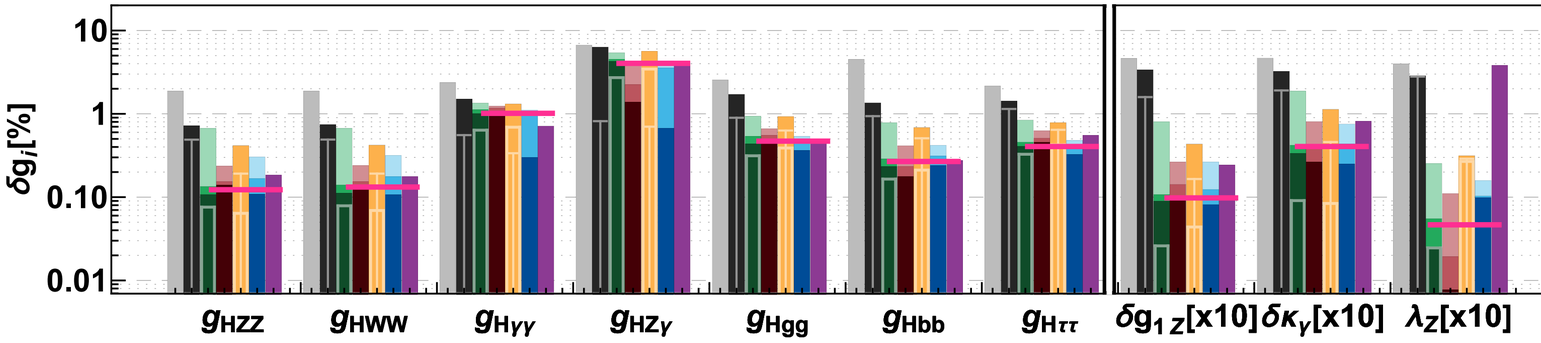
550 GeV incl ttbar theshold

equipping the additional tunnel with SCRF

- **+ 5.46 BCHF**
- 10 Hz trains of 2625 bunches
  => 7.7 x 10^{34} / cm^2 / s
- **AC power 322 MW**
- target 8 ab^{-1}

important: this can come after a number of years of physics data-taking at lower operating costs
=> can afford the upgrade again!





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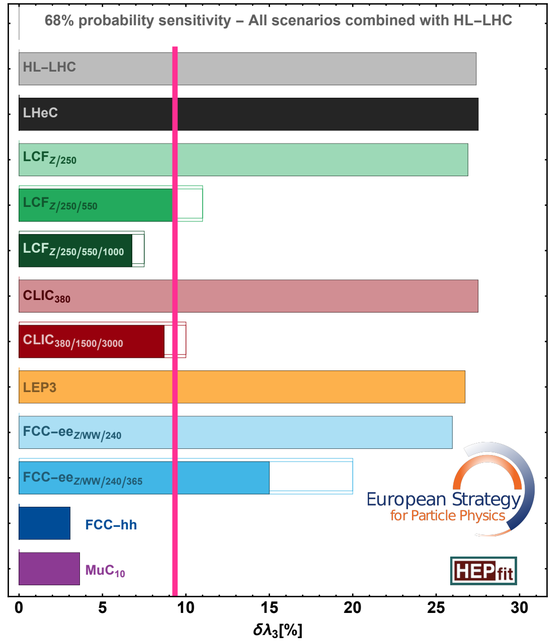

LCF550 and FCCee365 give very similar Higgs precision

assumes SM value of λ_3 , i.e. $\kappa_\lambda = 1$

Higher energies offer so much more

Example: top physics

- **tt threshold ~350 GeV:**
  - threshold mass => exp. stat. uncetainty negligible after ~100fb^{-1}
- **electroweak couplings need higher energies and polarised beams**
  - polarisation disentangles couplings to Z from couplings to photon
  - sensitivity to “axial-vector”-type of couplings grows with energy
  - dim-6 SMEFT:
    - need measurements at two energies above tt threshold to resolve degeneracies between operators
- with highE and polarisation, **Linear Colliders**
  - constrain 4-fermion operators to < 0.001/TeV^2
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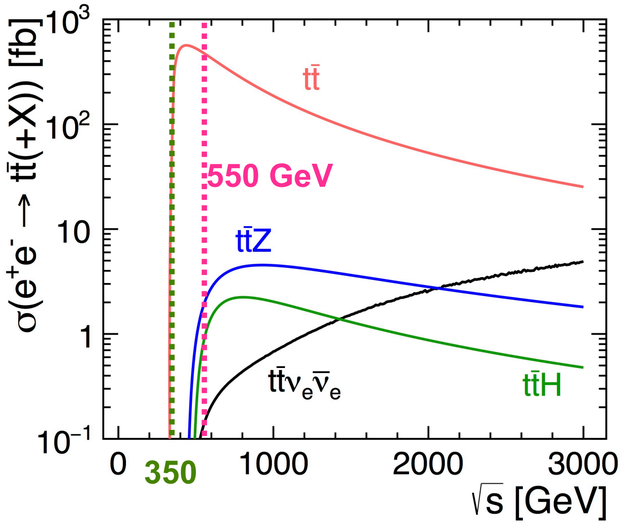

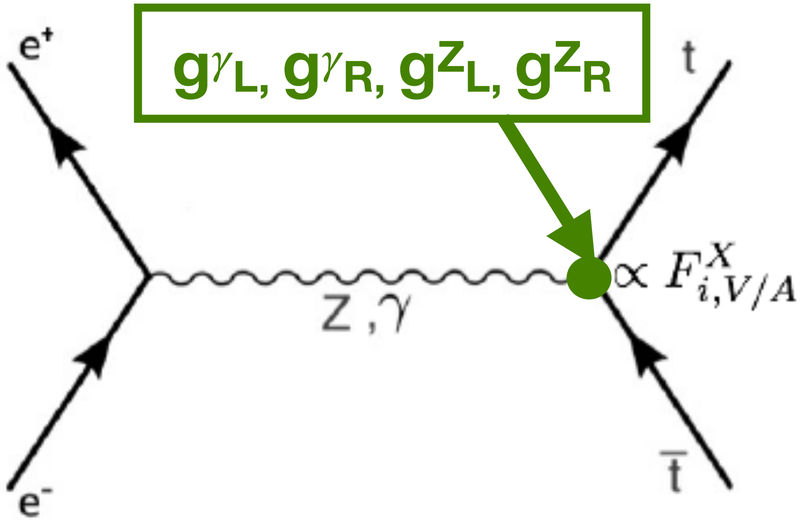

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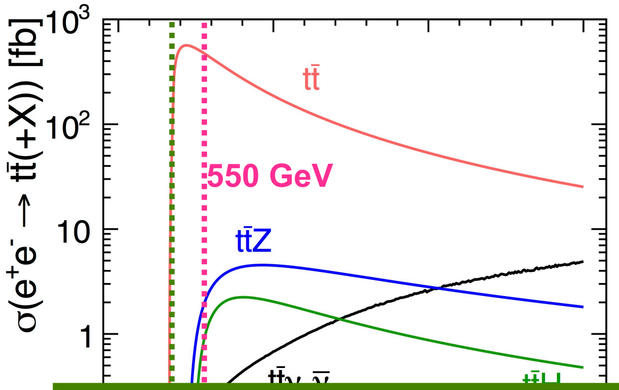

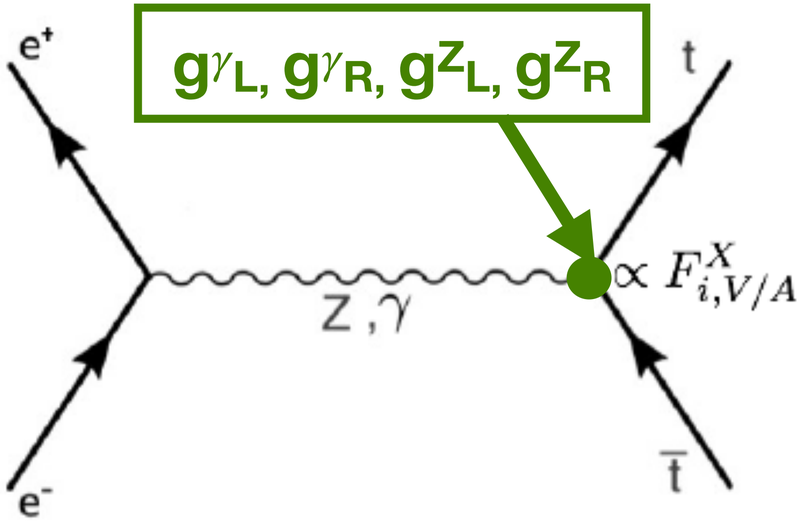

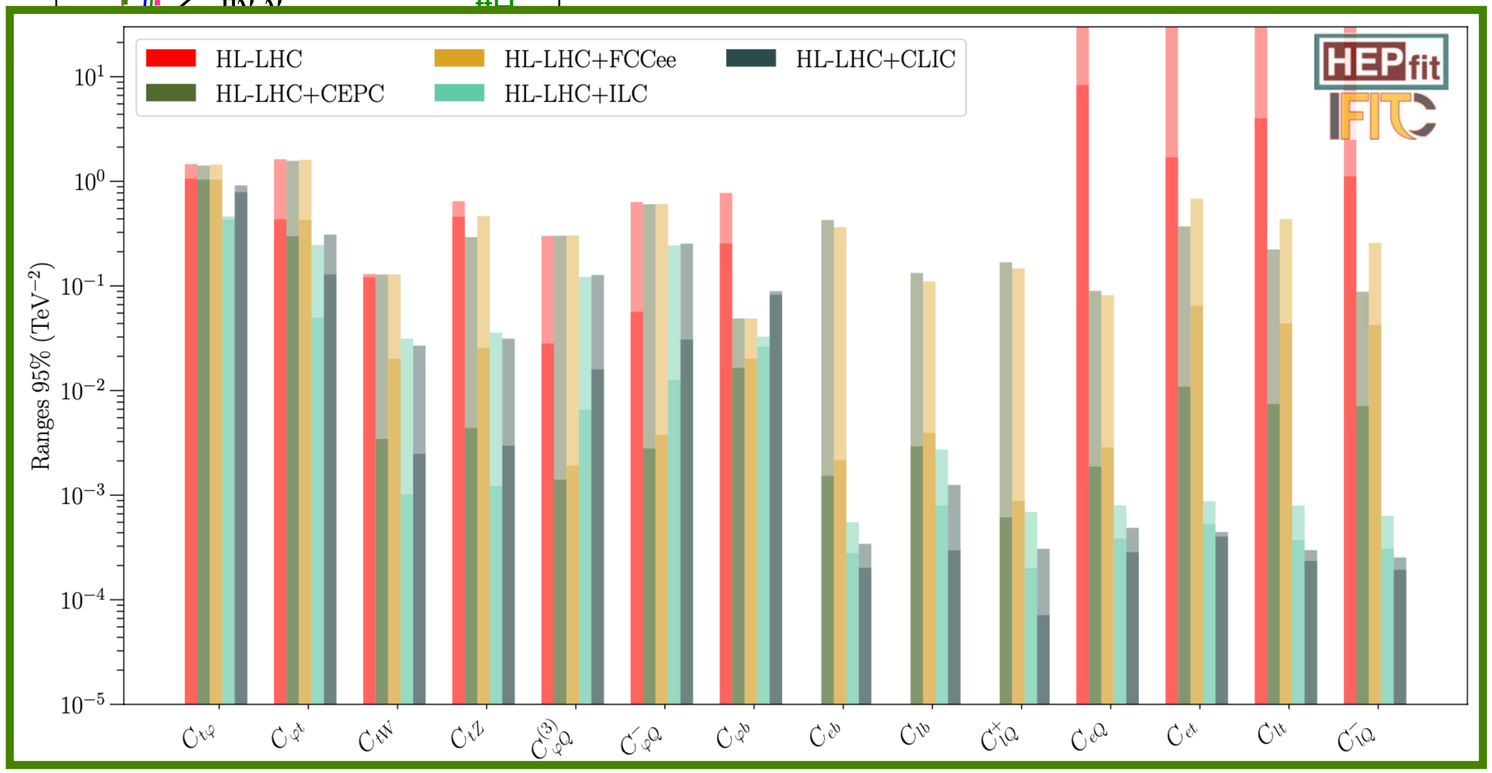

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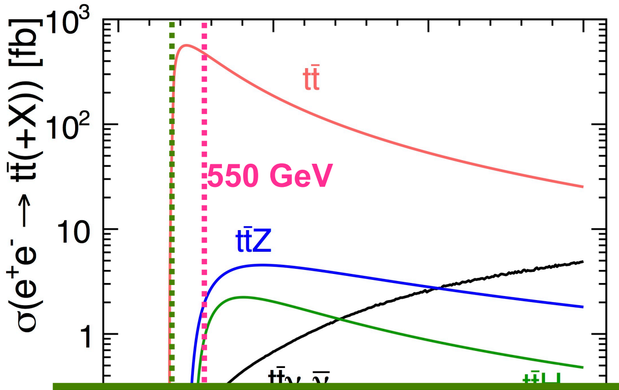

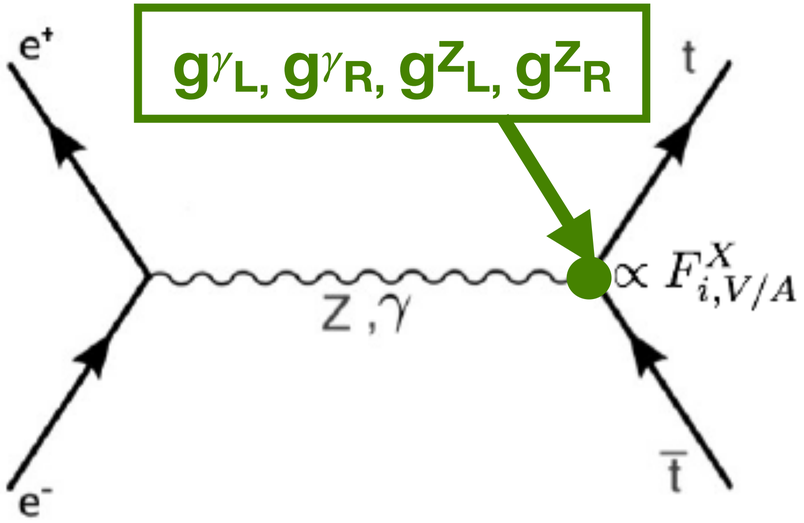

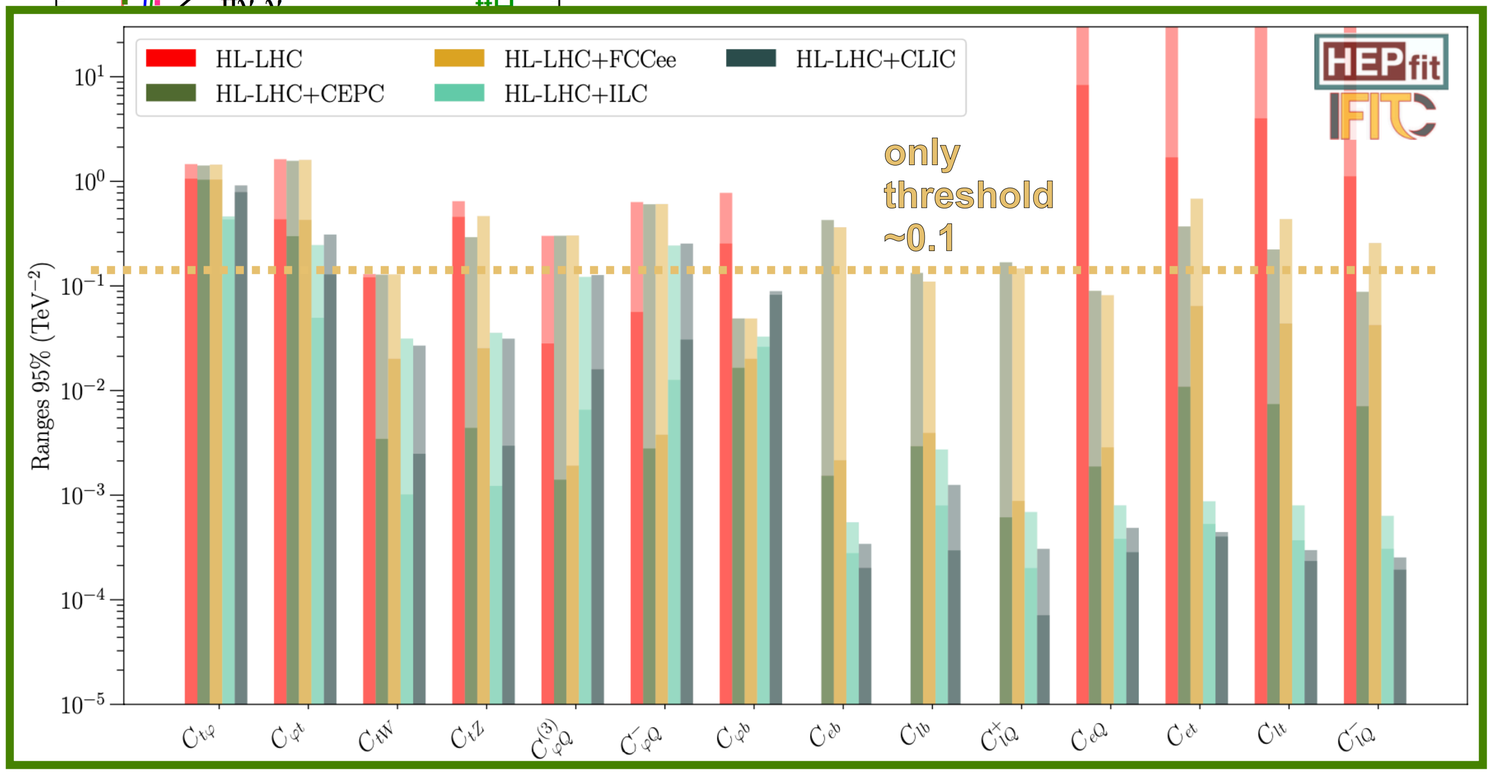

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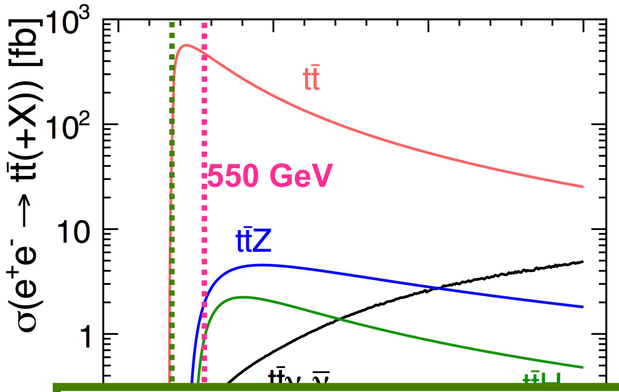

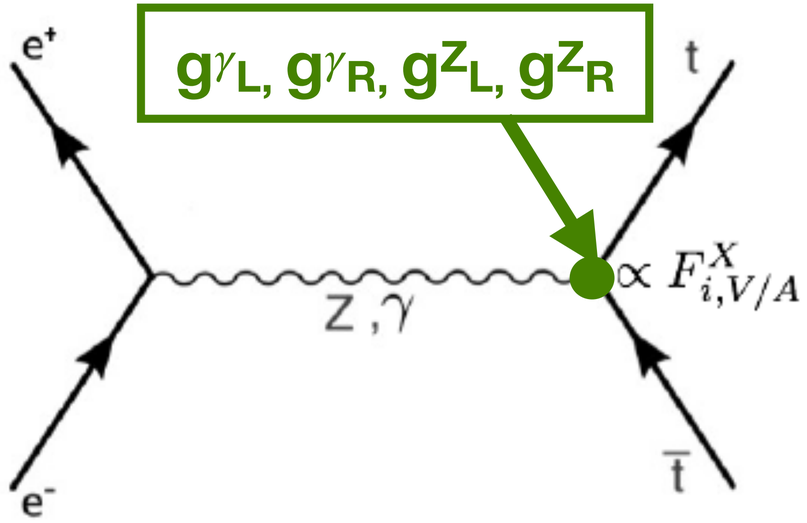

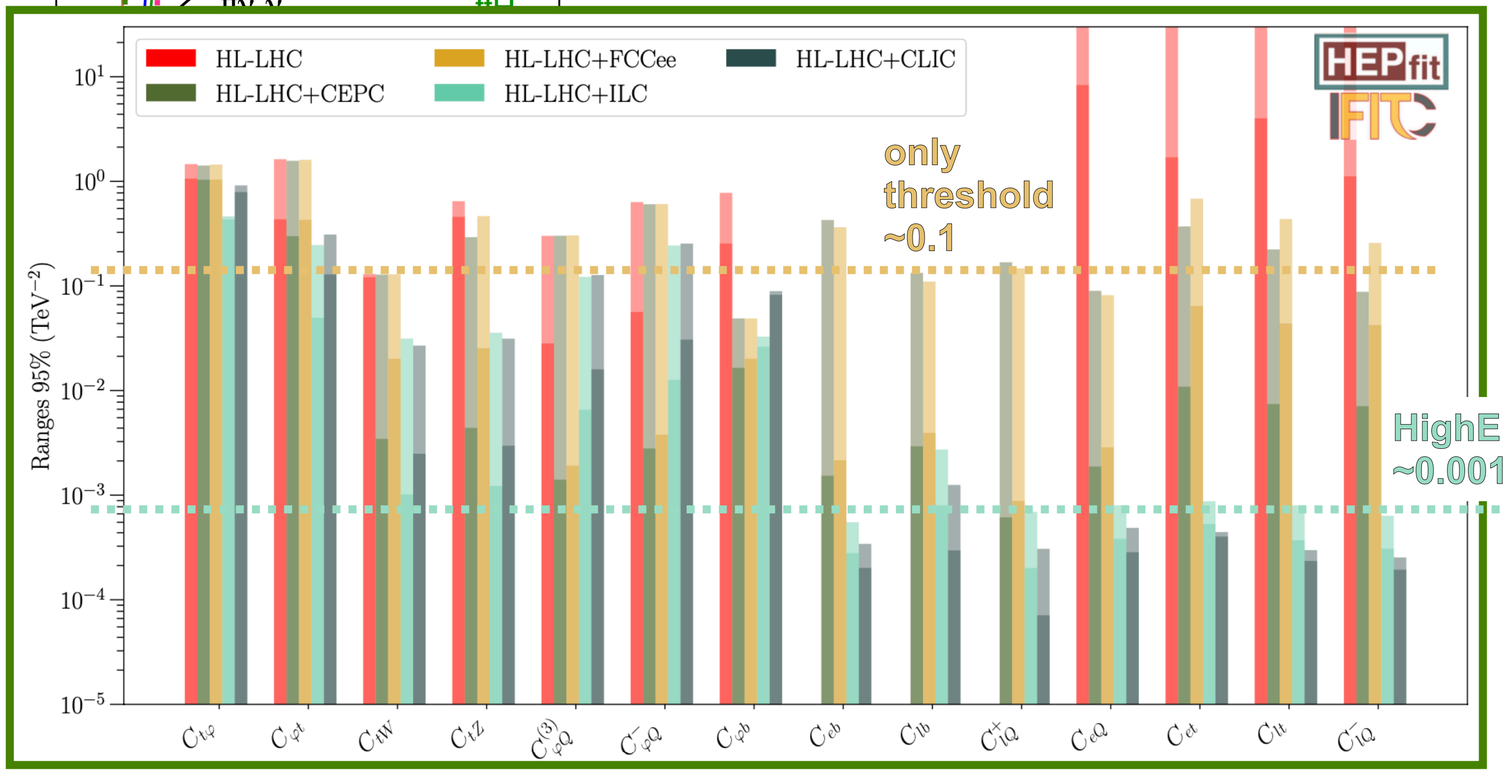

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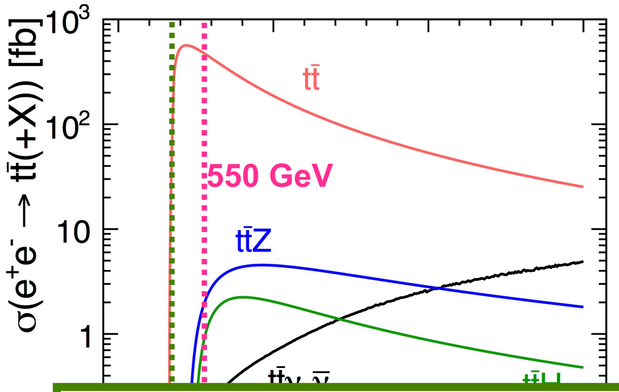
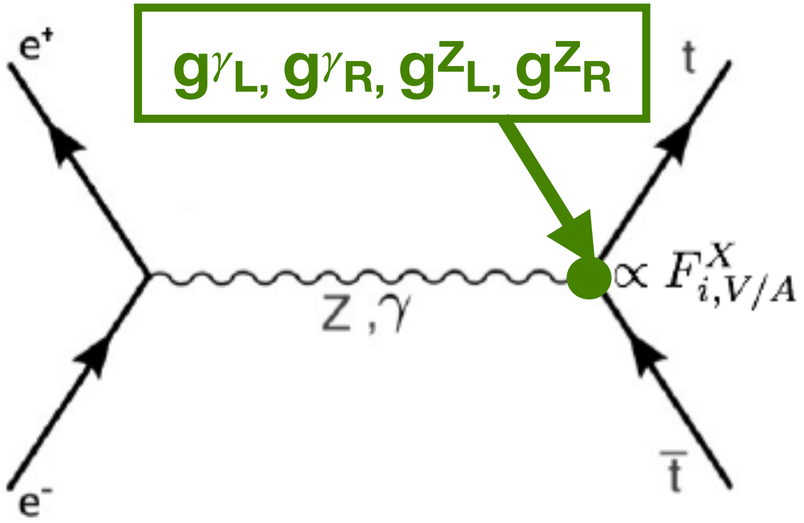
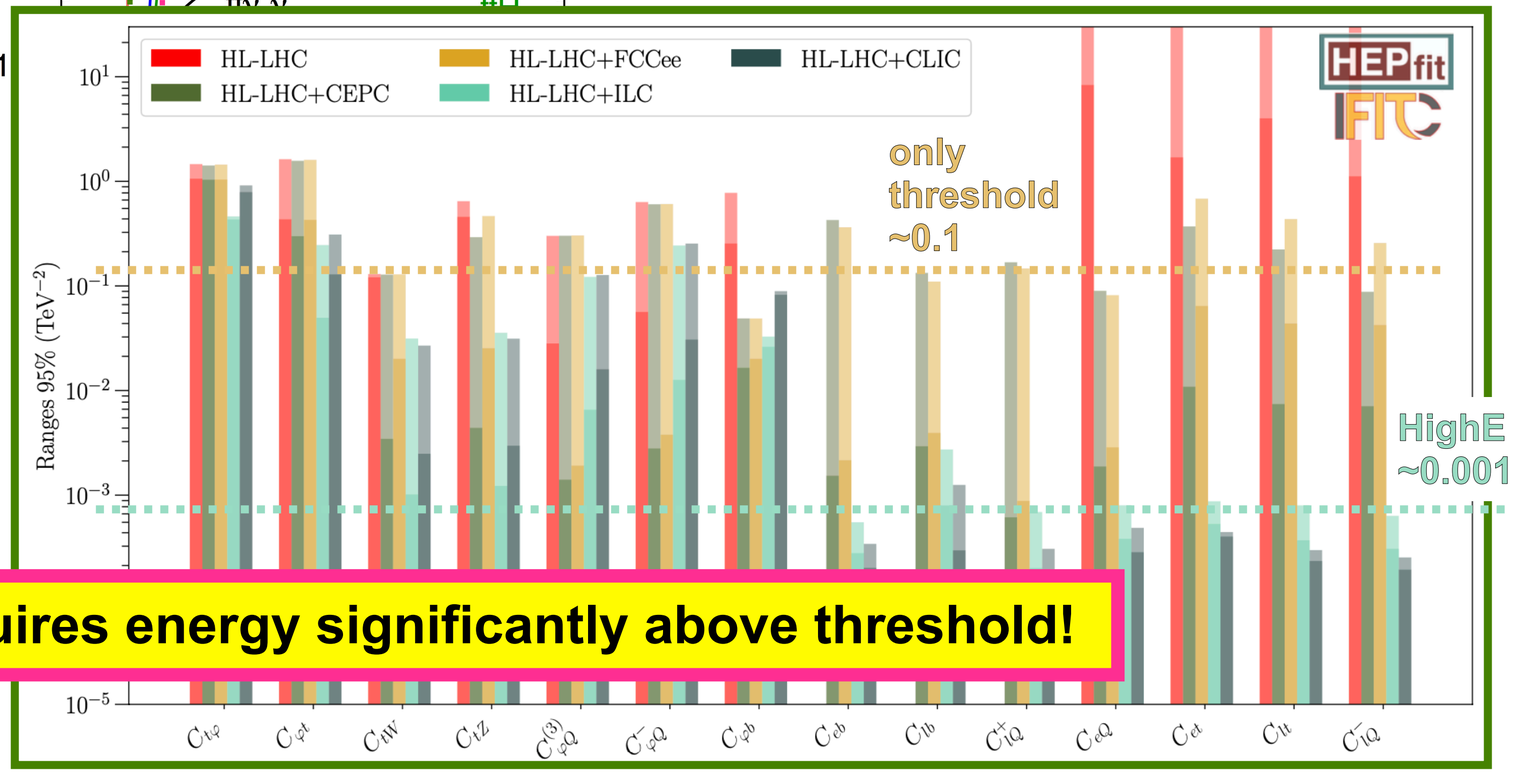






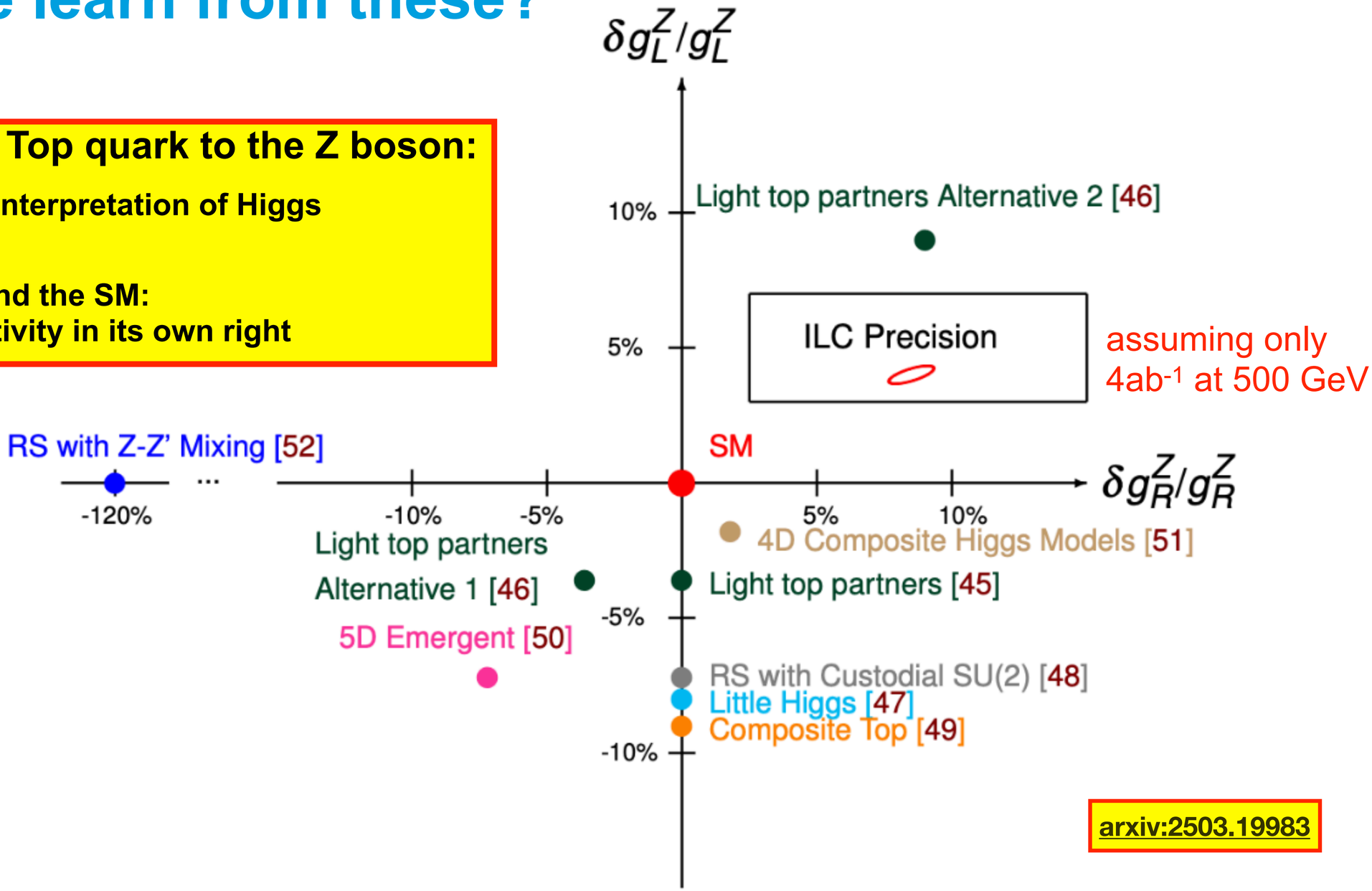
actual top precision program requires energy significantly above threshold!

What do we learn from these?

Top and BSM

Couplings of the Top quark to the Z boson:

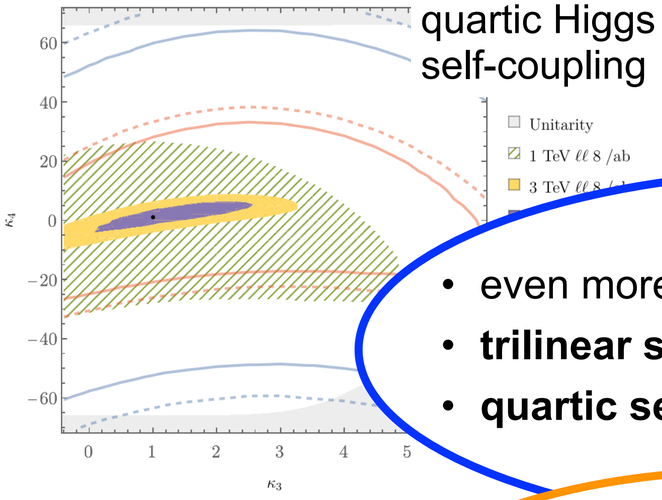
- **essential for NLO interpretation of Higgs measurements**
- **Tomography beyond the SM: tremendous sensitivity in its own right**



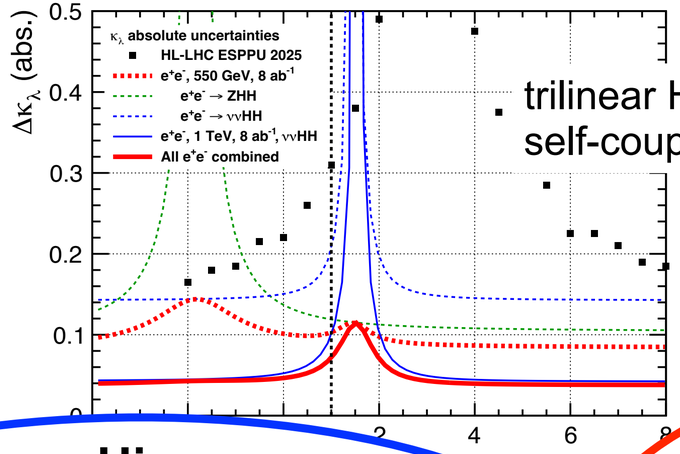
arxiv:2503.19983

Beyond 550 GeV

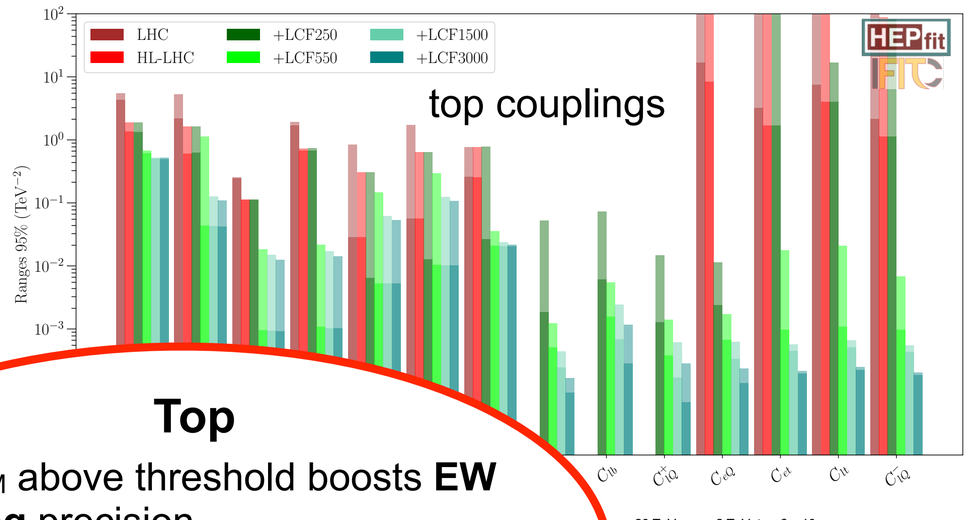
Targets of e+e- at 1-3 TeV



quartic Higgs self-coupling



trilinear Higgs self-coupling

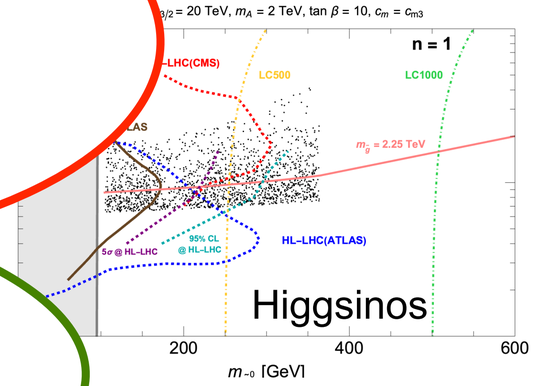


Higgs

- even more single-H
- **trilinear self-coupling** in WW fusion mode
- **quartic self-coupling**

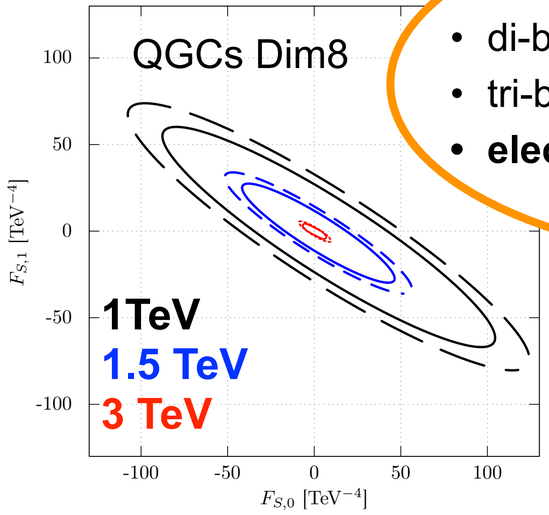
Top

- 2nd E_{CM} above threshold boosts **EW coupling** precision
- **top Yukawa to 1%,**
- **CP analysis of tth vertex**



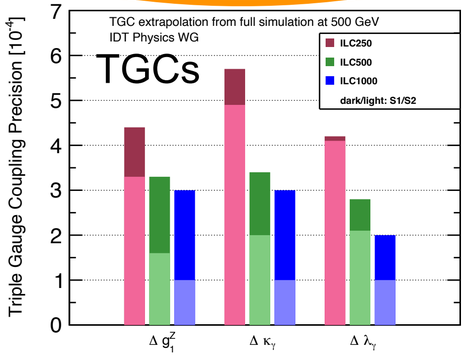
Vector Bosons

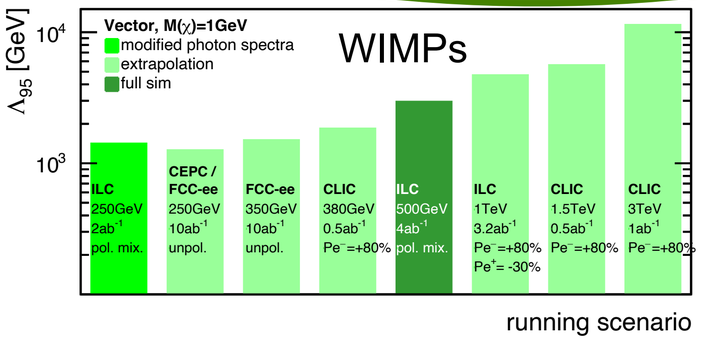
- di-bosons & **triple gauge couplings**
- tri-bosons and **quartic couplings**
- **electro-weak jets**

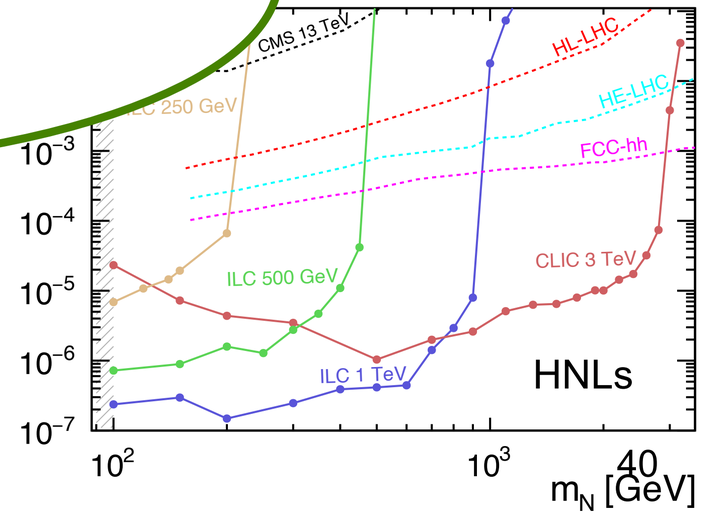


Direct New Particles

- **complementary discovery potential:**
  - **electroweak NP**, **WIMPs** etc up to $E_{CM}/2$ ~w/o fine-print
  - **heavy neutral leptons**
  - additional Higgs bosons
  - …
- follow-up on HL-HLC discoveries!







Looking into the crystal ball…

for the future of a Linear Collider Facility

assume we had a 33.5km straight tunnel…
…with some initial Linear Collider inside, starting to take data mid 2040ies

- **10…20 years later:**
  2050ies - 2060ies => obviously very conceptual now — lots of opportunies!

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  - ReLiC / ERLC
- **go for photon collisions:**
  - with optical lasers or a la XCC
- **beyond-collider opportunities**
  - beam dump / fixed-target / R&D ….

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LCVision reviewed
how these could be embedded as upgrade of initial facility
— obviously each technology could be used for a stand-alone project, too!

Energy Upgrades beyond 550 GeV

1 TeV and beyond

- **Philosophy: prioritize**
  - **advanced technologies** over more civil construction
  - **flexibility** over a fixed future:
    choices should be made later depending on scientific and technological developments - or even revolutions
- replacing the linacs, re-using as much as possible from initial machine (DRs, BDS, …)
- Example options:
  - **CLIC technology:** 72-100 MV/m warm copper cavities, klystron-driven **=> 1.5 - 2 TeV**
  - **C3 technology:** up to 150 MV/m cool copper cavities **=> 1.5…3 TeV**
  - **HELEN technology:** traveling-wave SCRF with ~70 MV/m **=> at least 1 TeV**
  - **Nb_3Sn or multi-layer cavities:** SCRF with ~100 MV/m **=> 1.5…2 TeV**



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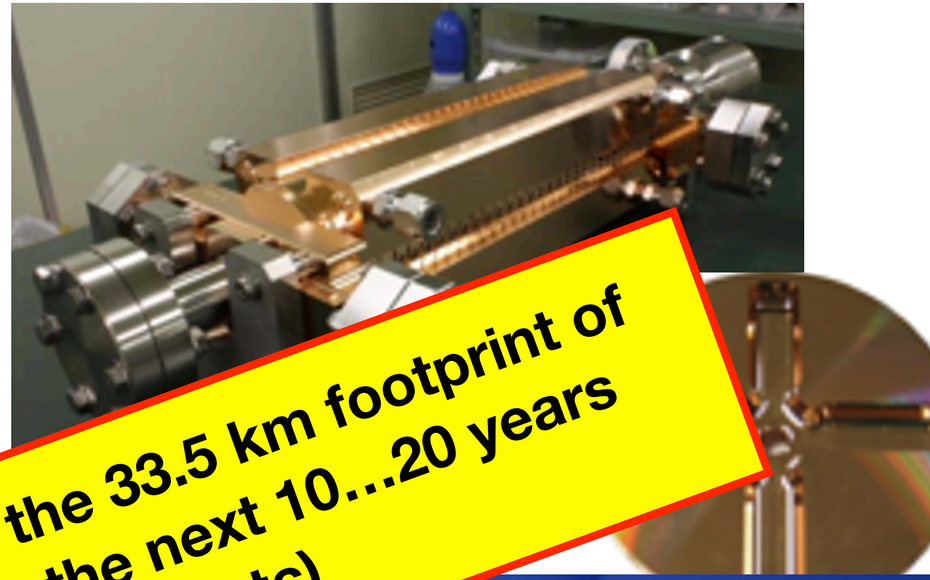
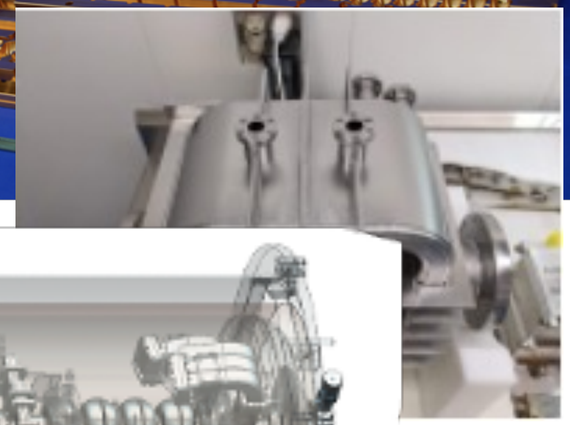
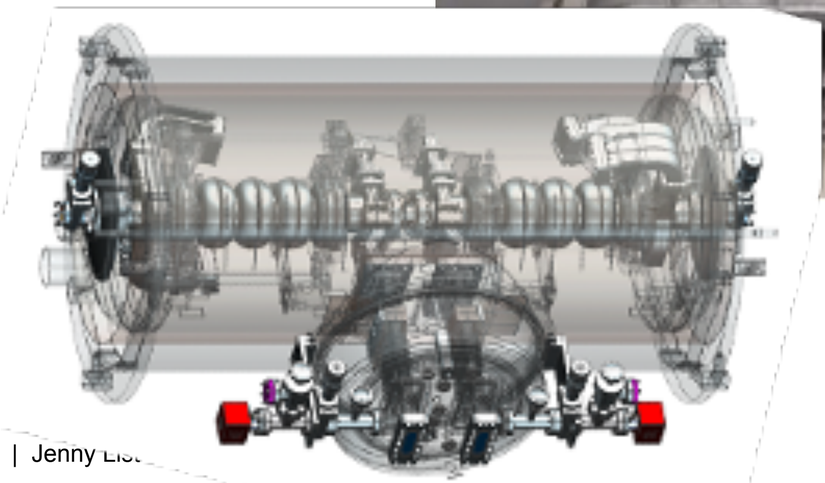
  - **HE… …wave SCRF with ~70 MV/m => a…**
  - **Nb_3S… …-layer cavities:** SCRF with ~100 MV/m **=> 1.5…2 TeV**

Several technologies which could reach 1-3 TeV in the 33.5 km footprint of LCF are expected to become application-ready in the next 10…20 years (e.g. for injectors for light sources, medical etc)





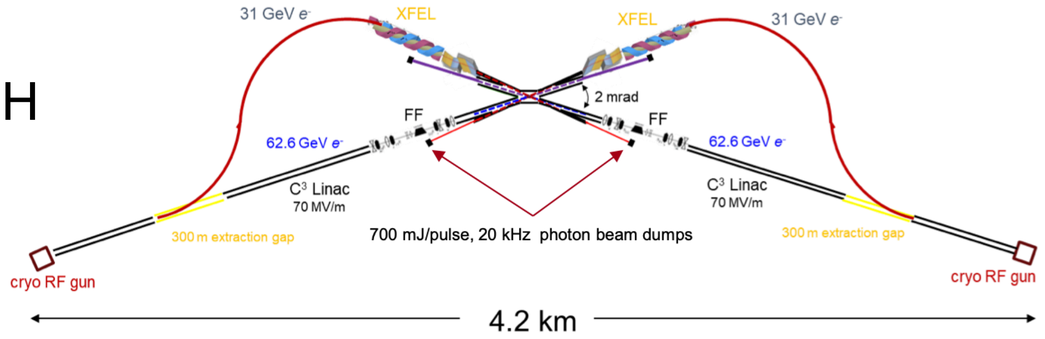




Additional Upgrade Paths

Photon Collider / higher luminosity / towards 10 TeV

- **Photon Collider:**
  - complementary physics case, e.g. self-coupling in $\gamma\gamma$ -> HH with different BSM behaviour than e+e- / pp
  - install in one IP
  - either classic way with optical lasers
  - or XCC-like with X-ray lasers
- **Energy and particle recovery:**
  - boost luminosity up to 10^{36} / cm^2 / s
  - by re-using particles and energy
  - eg a la ReLiC or ERLC or Ghostcollider
- **Plasma or Structure Wakefield Acceleration:**
  - gradients of GV/m
  - either only for e-, asymmetric collisions a la HALHF
  - or e- and e+, paving the way towards 10 TeV $\gamma\gamma$ or e+e-



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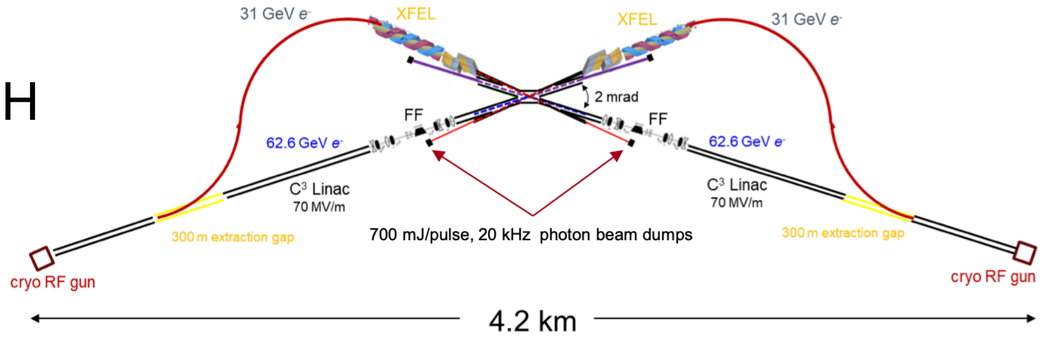

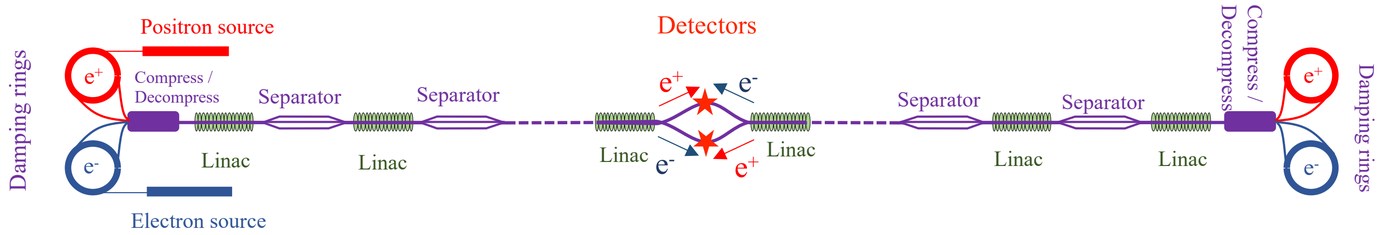

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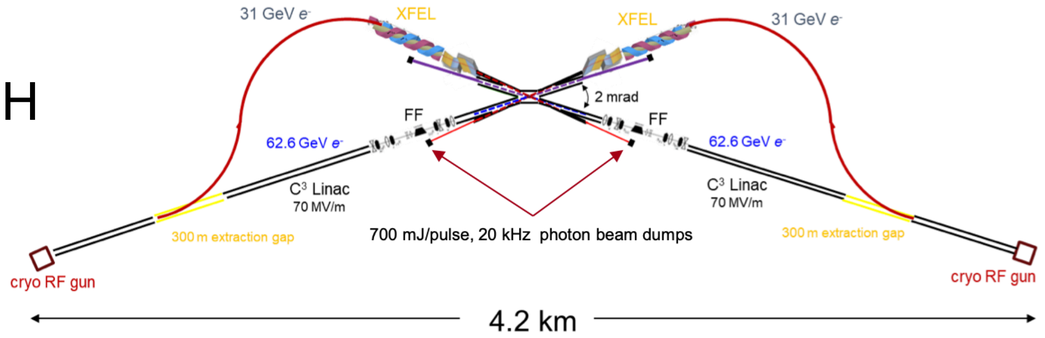
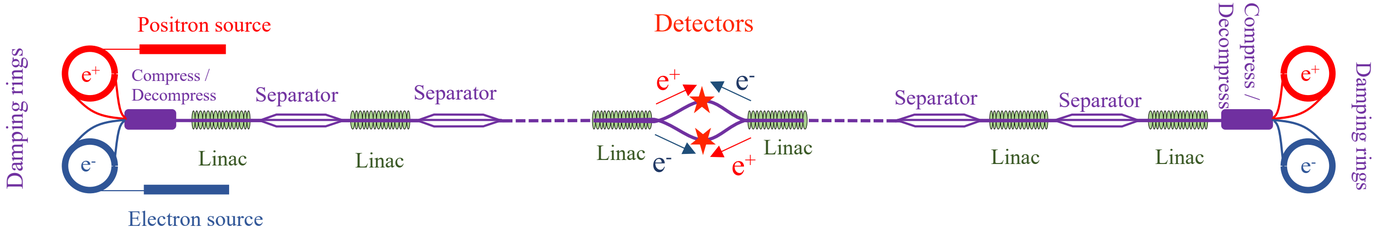
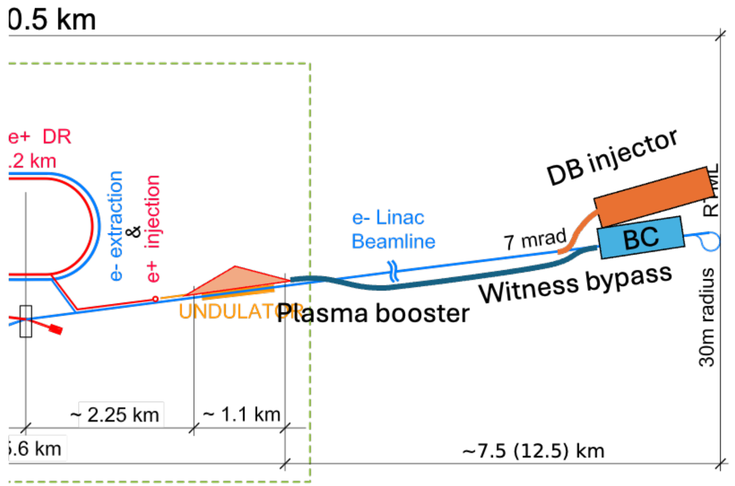




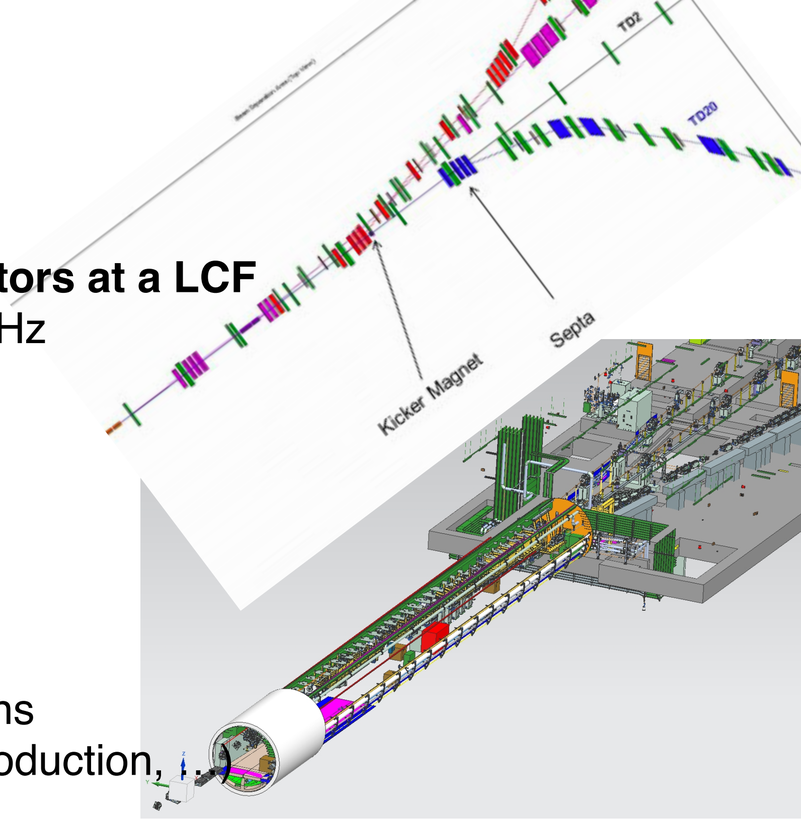


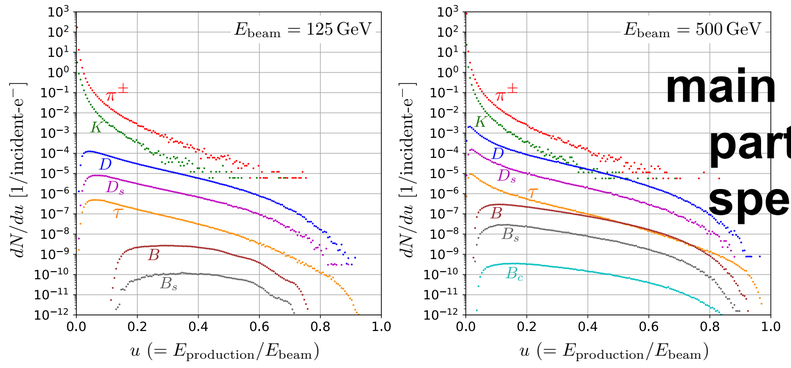
Not To Scale

Beyond a collider

Beam-dump / fixed-target / R&D / irradiation

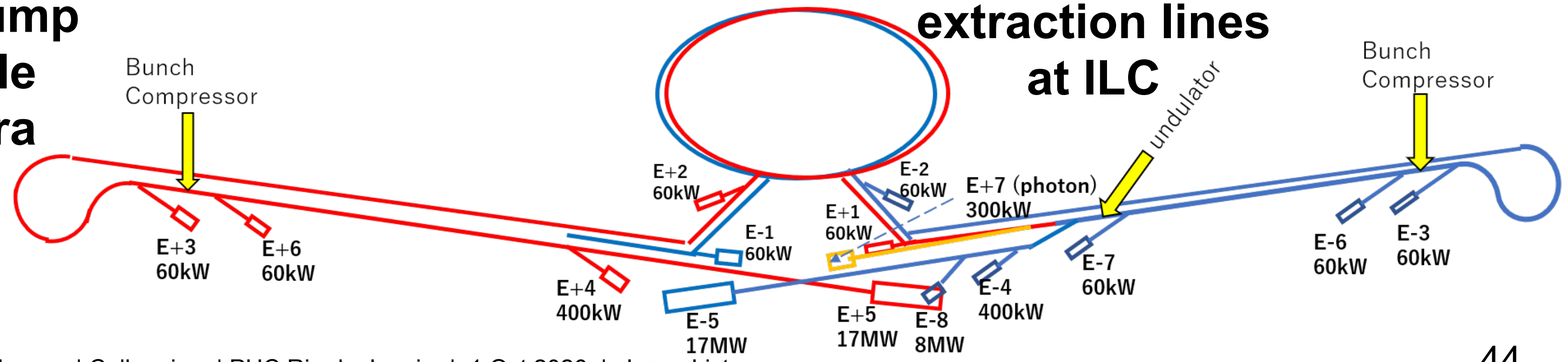
- **Ample opportunities to foresee beam extraction / dump instrumentation / far detectors at a LCF**
  - extraction of bunches before IP -> mono-energetic, extremely stable, few 10^{10} @ 1-10 Hz
    => super-LUXE (SF-QED χ = O(few hundred) & BSM search), super-LDMX, …
  - disrupted beam after IP -> broad energy and highly divergent, but up to 10^{15} eot / s
    super-SHIP, generic dark photon and ALP searches
    => together with e+e- cover all Dark Sector portals
- **Low-emittance, mono-energetic beams ideal for**
  - high-rate detector and beam instrumentation tests
  - creating **low-emittance beams of photons / muons / neutrons** for various applications (hadron spectroscopy, material science, irradiation, tomography, radioactive isotope production, …)
  - **accelerator development:**
    - high-gradient accelerating structures, new final focus schemes, deceleration (for ERLs), beam and laser driven plasma, …
    - from extracted beam to test small setups - **to large-scale demonstrators for upgrades of the main facility**





main dump particle spectra

dumps / extraction lines at ILC



Some personal thoughts

On the future of particle physics

- **FCC-ee is a fantastic project - but also high-risk:**
  - Securing the funding is very challenging (even China (!) considered CEPC too expensive…)
  - Only part of the geology is explored, civil construction will remain a huge (cost) risk
  - A no-go decision for FCC-ee would cause delays, especially if only FCC-ee is studied in the coming years
  - FCC-ee relies heavily on FCC-hh for some important scientific questions
  - What would one do if HL-LHC & Co discover new particles in the few 100 GeV to 1 TeV range?
- **FCC integrated programme (FCC-ee /-hh /-eh) defines the future of CERN for the rest of the century**
  - How can particle physics keep driving (and profiting from) advanced accelerator technologies?
  - How can particle physics react to scientific and technological developments — or even break-throughs?
  - There's no affordable technology for FCC-hh right now => in parallel to funding FCC-ee, would need a massive invest in high-field magnet R&D
- **Is it healthy for particle physics if CERN is the only place operating energy-frontier colliders?**
  - Global cooperation is needed given scale of projects — is the sustainable if all money is spend at CERN?
  - In a more and more multi-polar world, can particle physics become more and more a monopoly of Europe?
  - How can advanced accelerator technologies help to make colliders affordable for more countries worldwide?

Conclusions

Conclusions

And invitation

- **Particle physics has many deep and exciting mysteries to solve**
  - Might - or might not - learn something from HL-LHC, (in-)direct WIMP searches and/or other experiments
  - Next step on the journey: e+e- collider scrutinising the Higgs, the top quark and electroweak gauge bosons
- **The ESPPU and CERN identified FCC-ee as the strongly preferred approach**
  - A fascinating plan with a broad physics programme incl. flavour physics, QCD, …
  - Tunnel could be reused for a hadron collider -> 2075+
  - Very ambitious, with still many risks ahead
  - Decision expected in 2028
- **Linear Colliders provide a complementary approach to the future, more focused on**
  - Higher energies: The Higgs potential, the top quark, new particles
  - Finite resources and sustainability
  - Staged construction and flexible future developments
  - Advanced accelerator technologies

Conclusions

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  - Finite resources and sustainability
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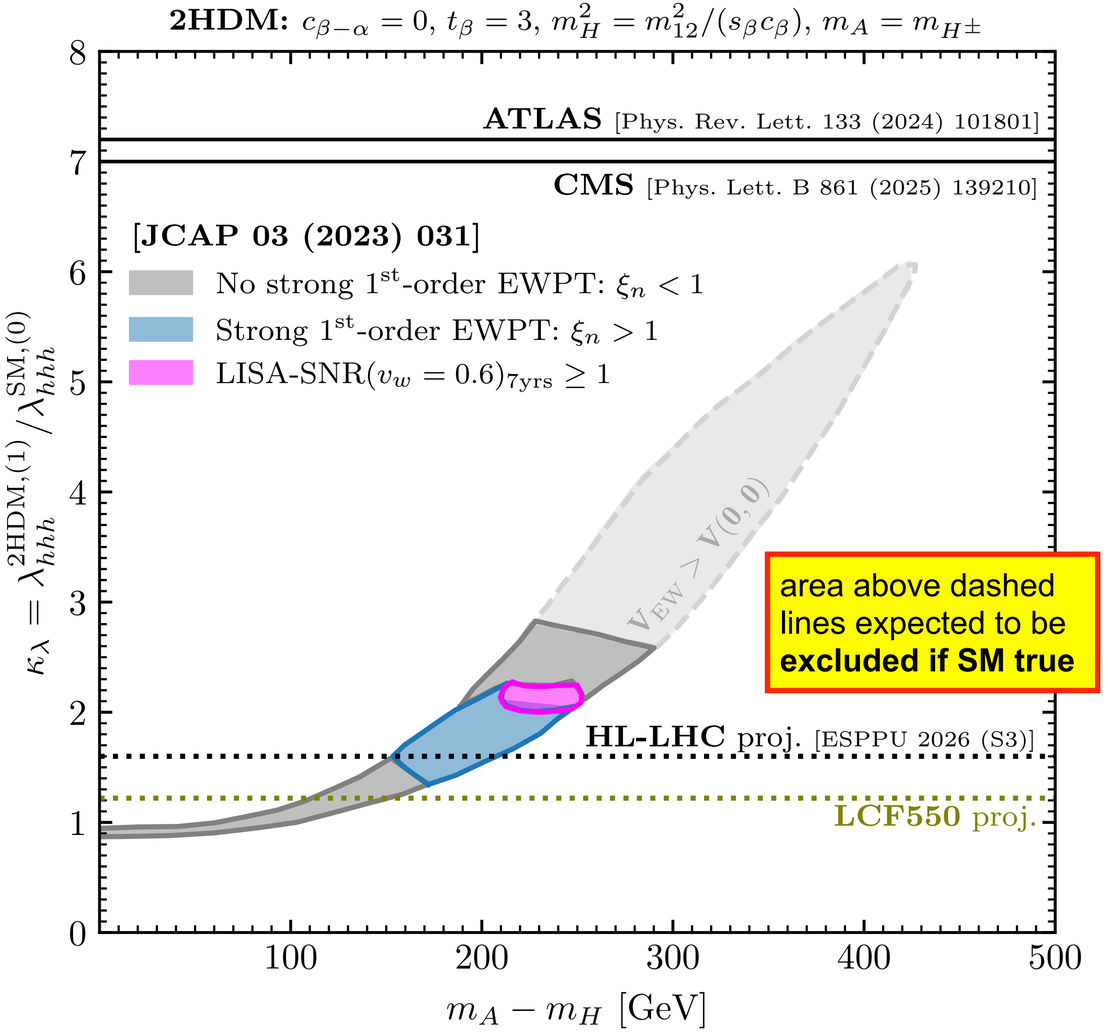
Most importantly:
Any Future Collider can only happen based on broad support within global HEP community
=> get engaged and make it happen!

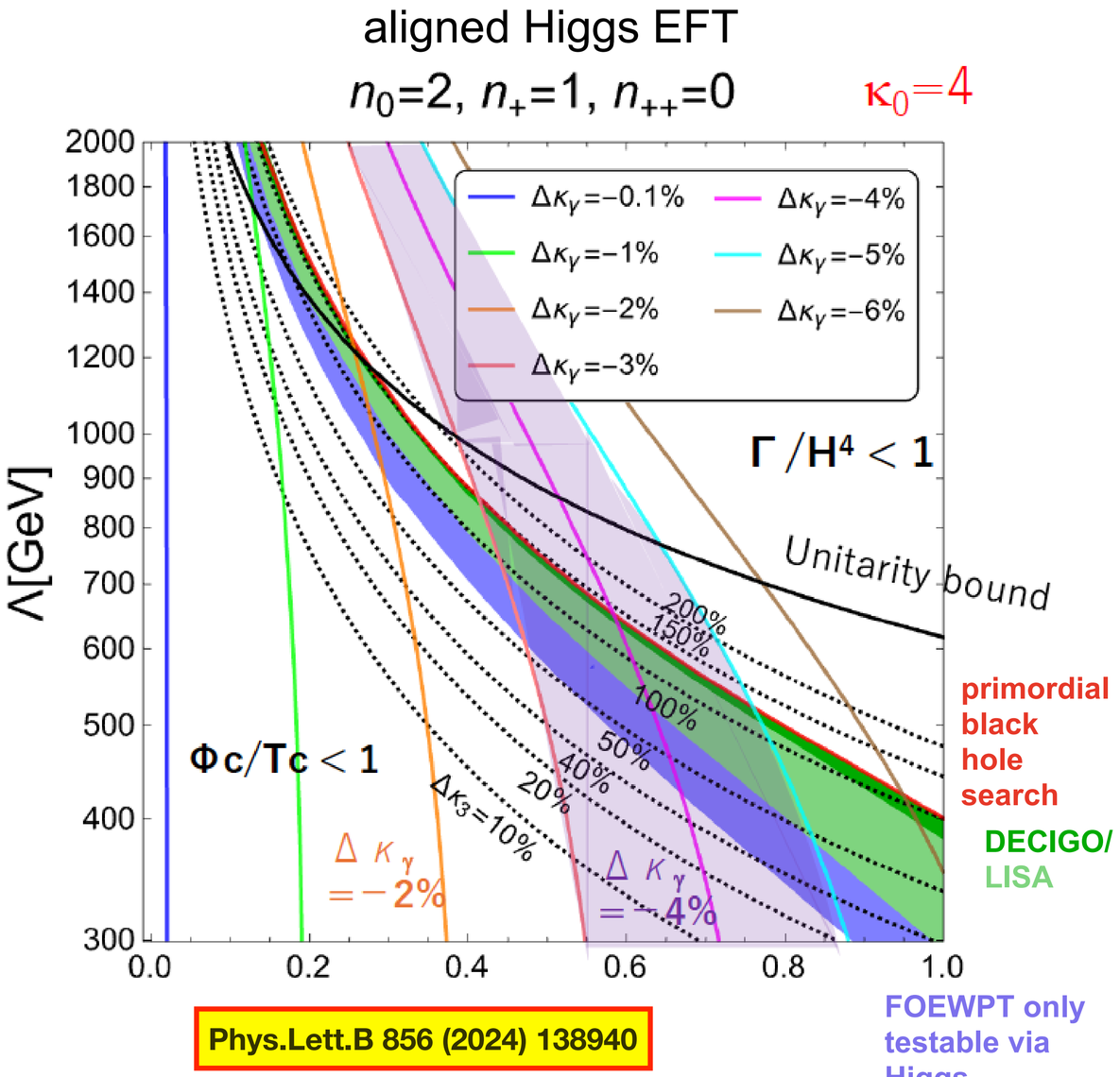
Bonus

Interplay with Gravitational Wave detection

Need to assume specific extended Higgs sector to quantify effects



area above dashed lines expected to be **excluded if SM true**



primordial black hole search

DECIGO/ LISA

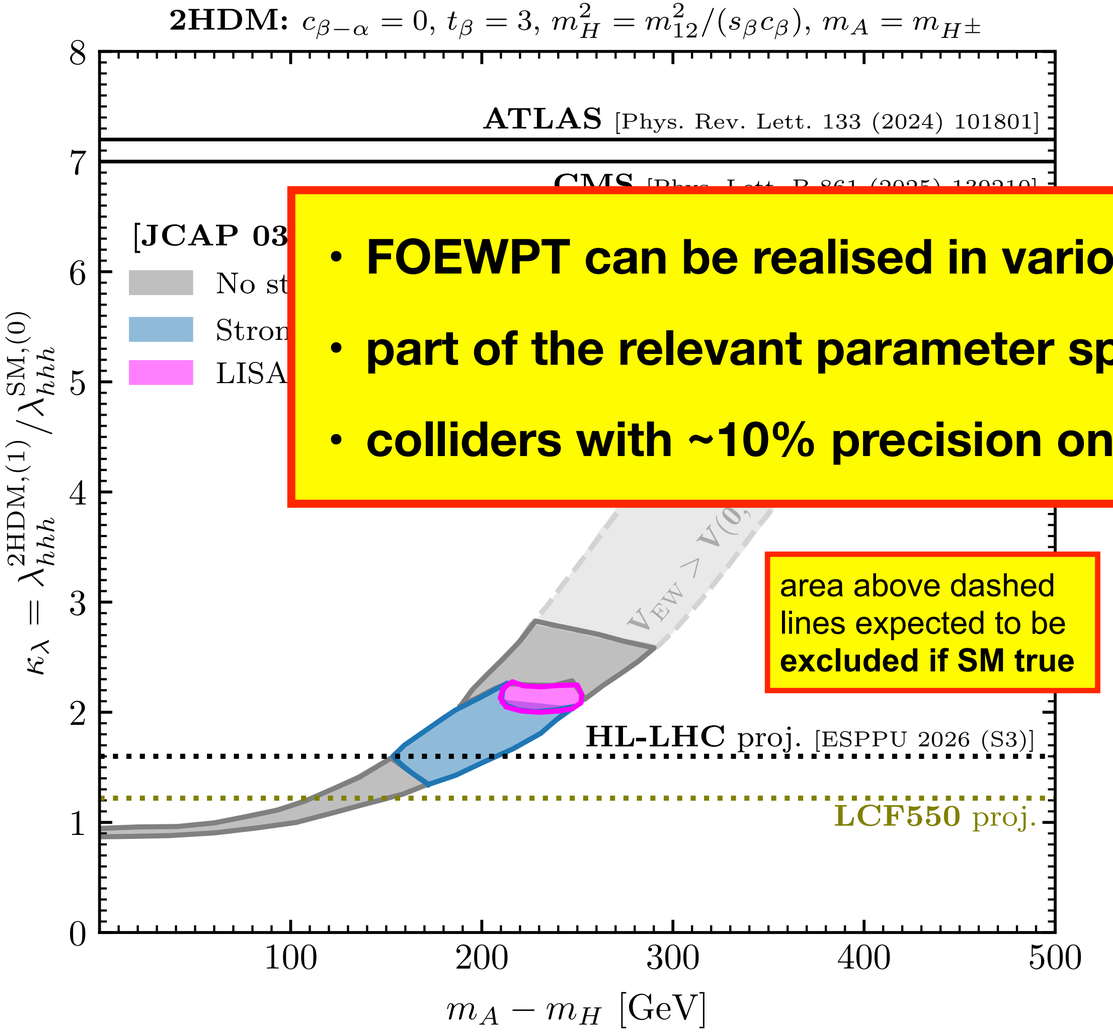
Phys.Lett.B 856 (2024) 138940

FOEWPT only testable via Higgs

Interplay with Gravitational Wave detection

Need to assume specific extended Higgs sector to quantify effects

- **FOEWPT can be realised in various extended Higgs sectors**
- **part of the relevant parameter space can be probed by PHB / LISA & Co**
- **colliders with ~10% precision on κ_λ can test FOEWPT comprehensively**



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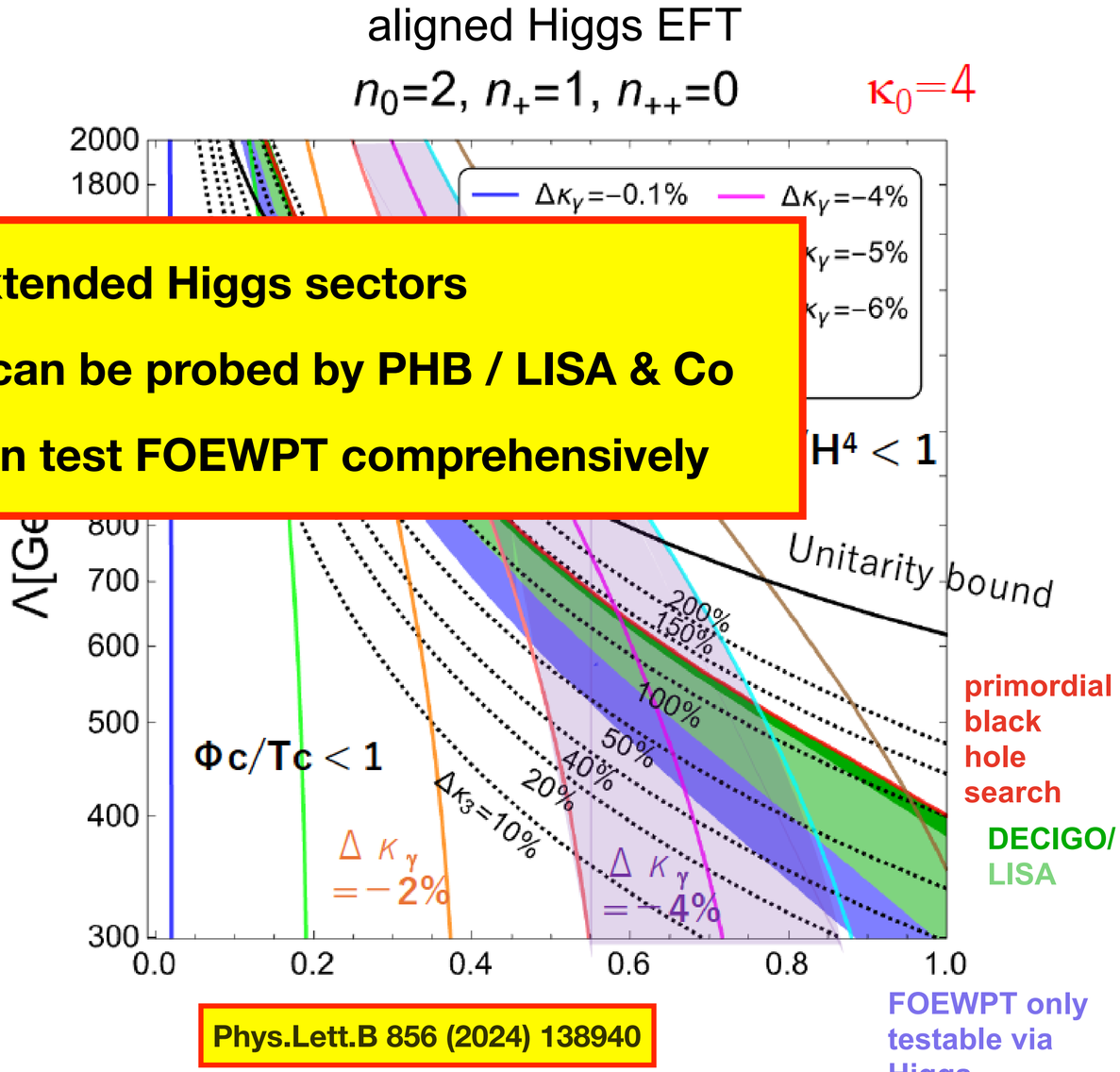

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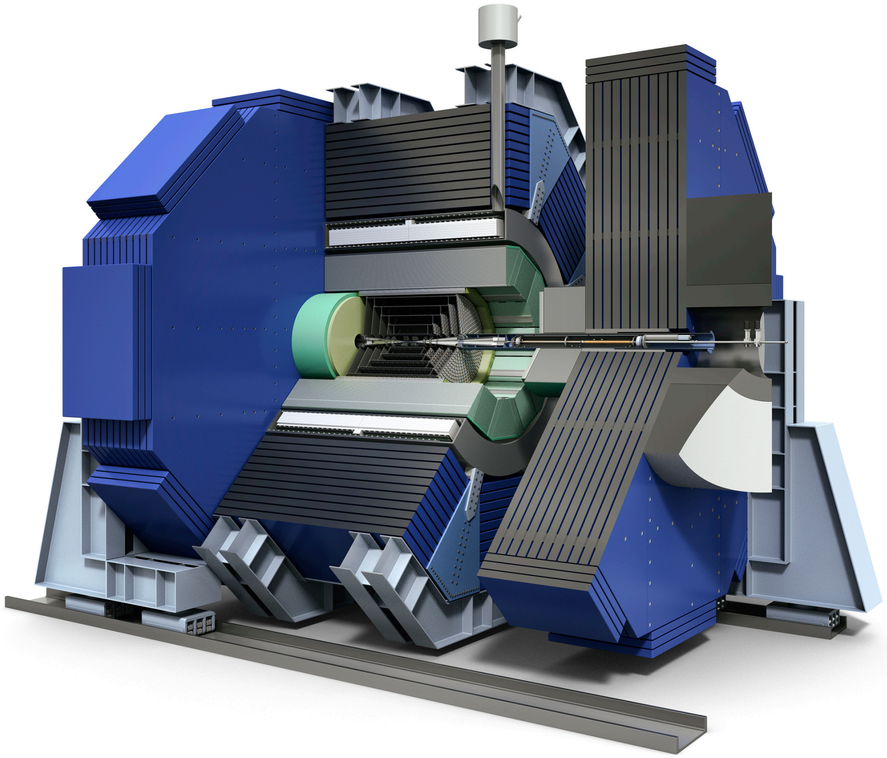
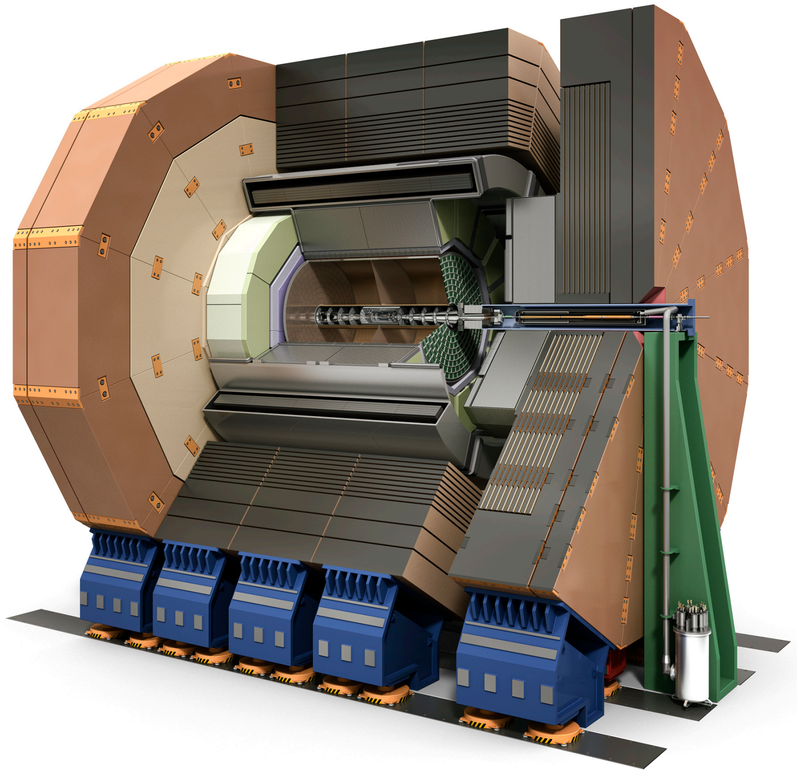
Higgs Factory Detector Concepts

for linear & circular





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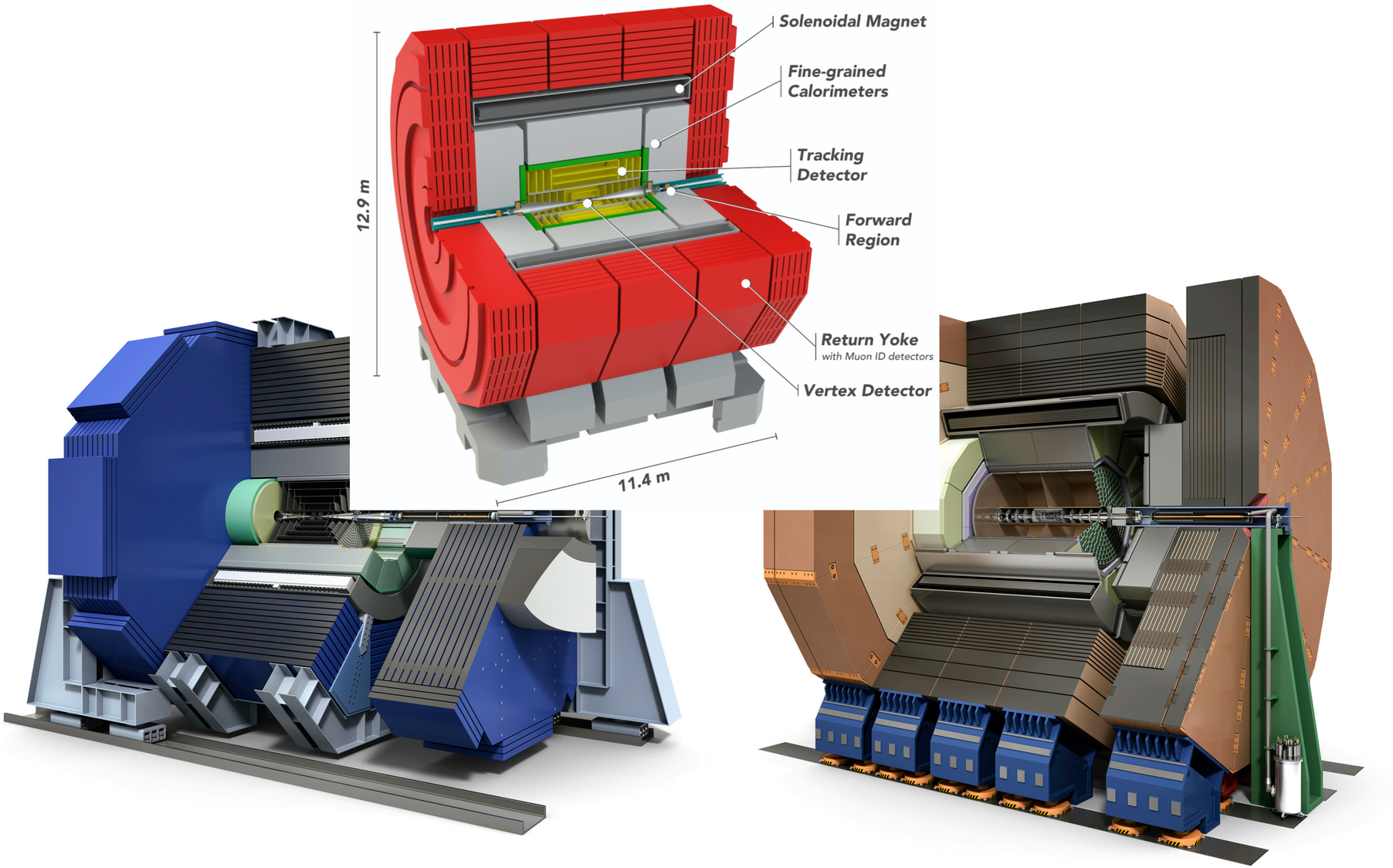

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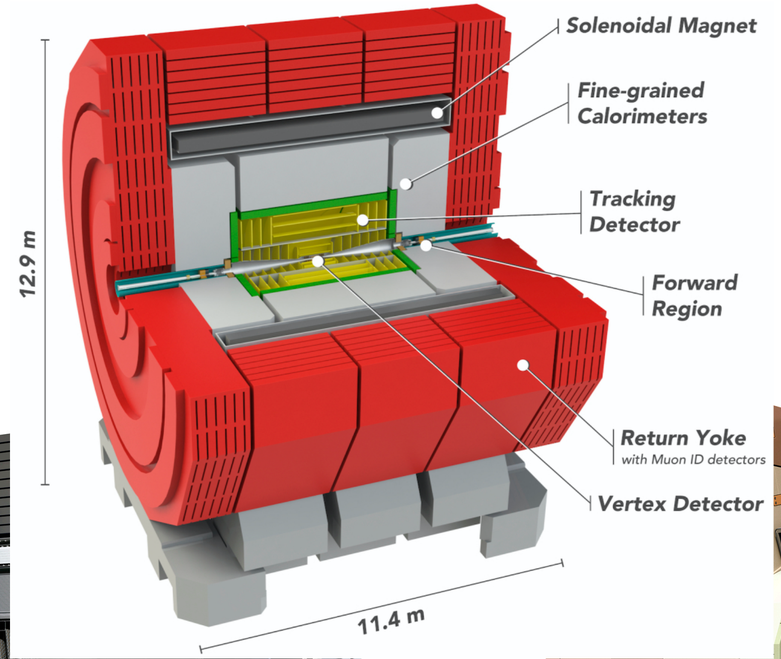

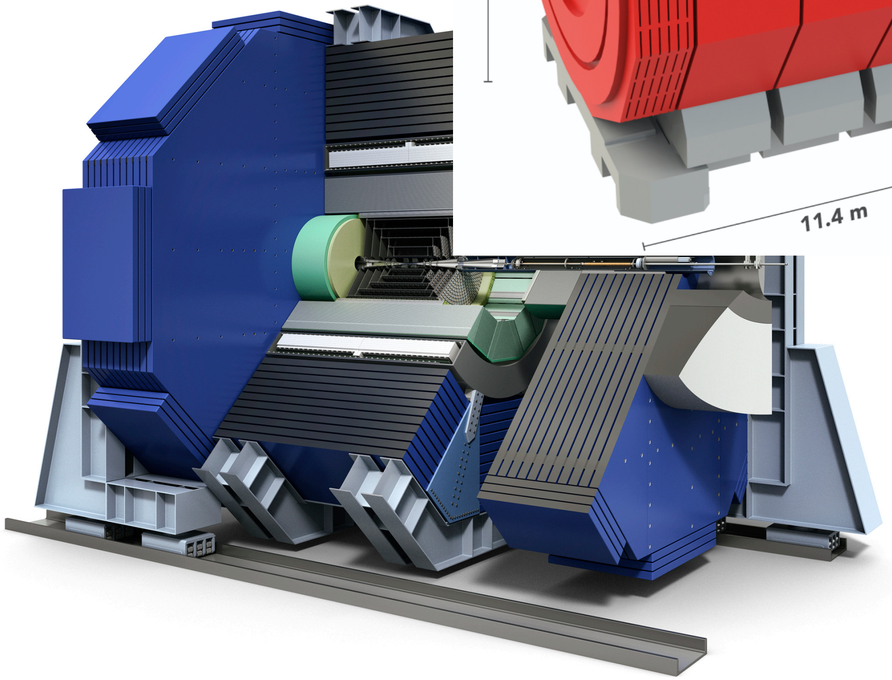



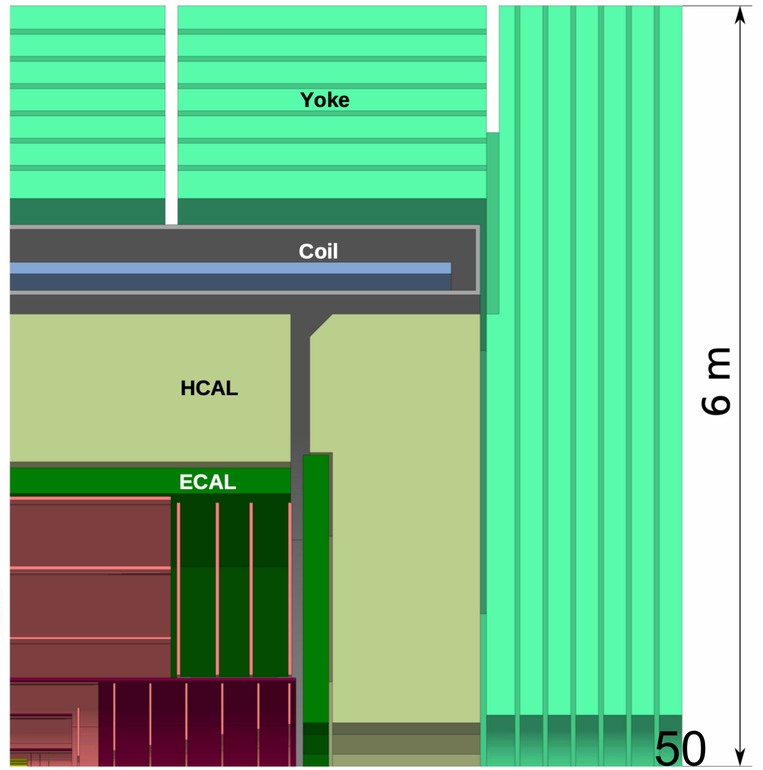

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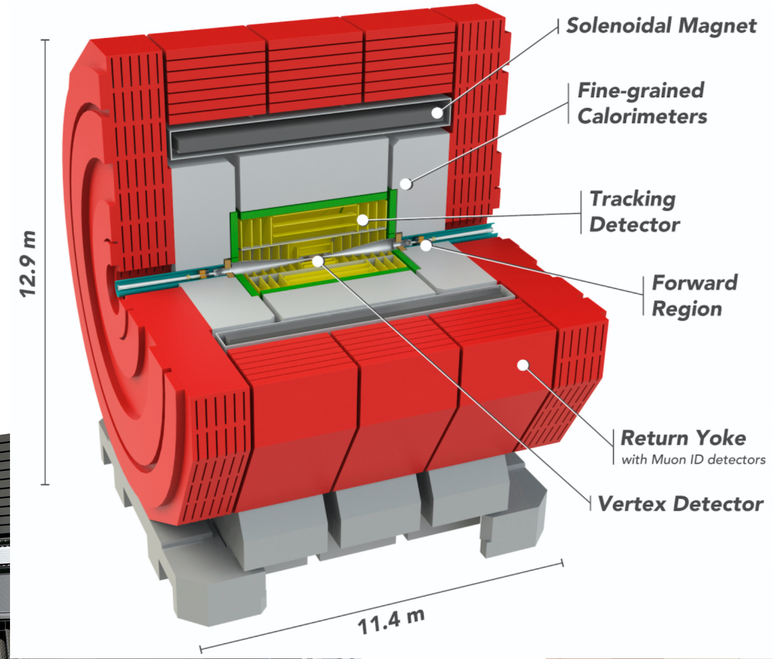

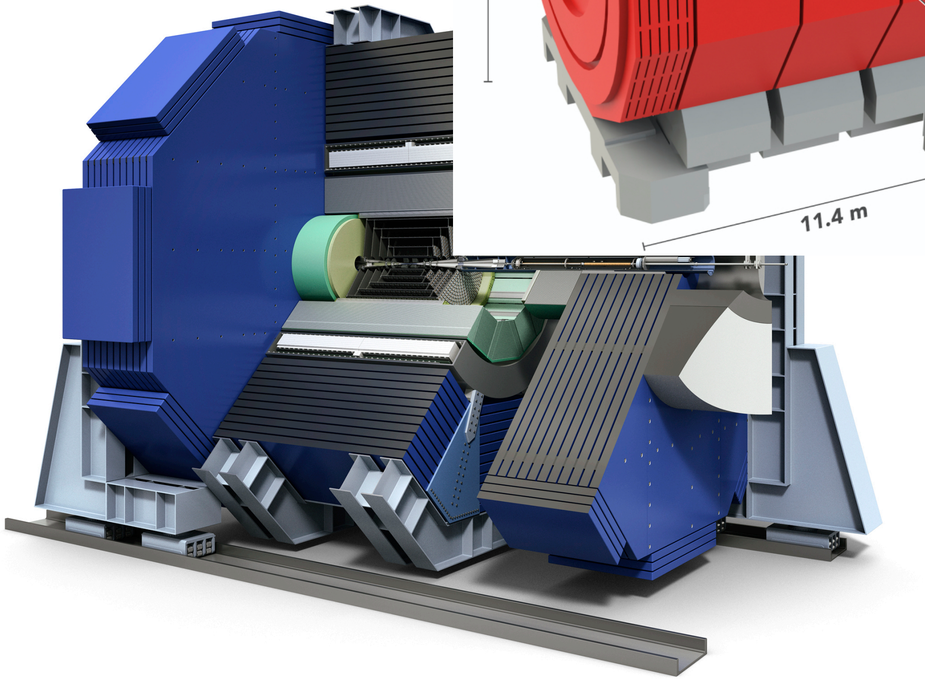



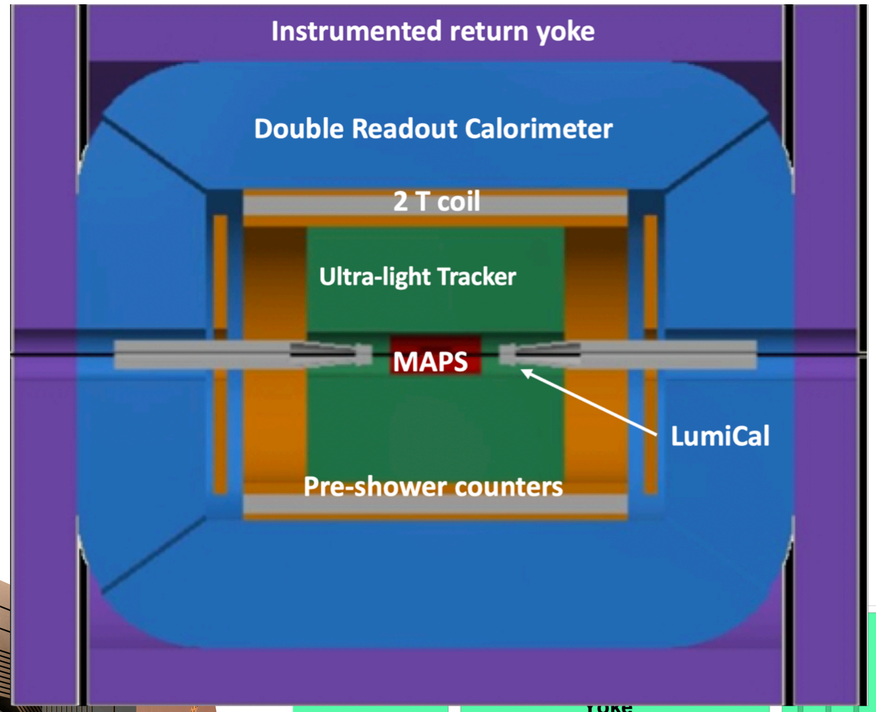

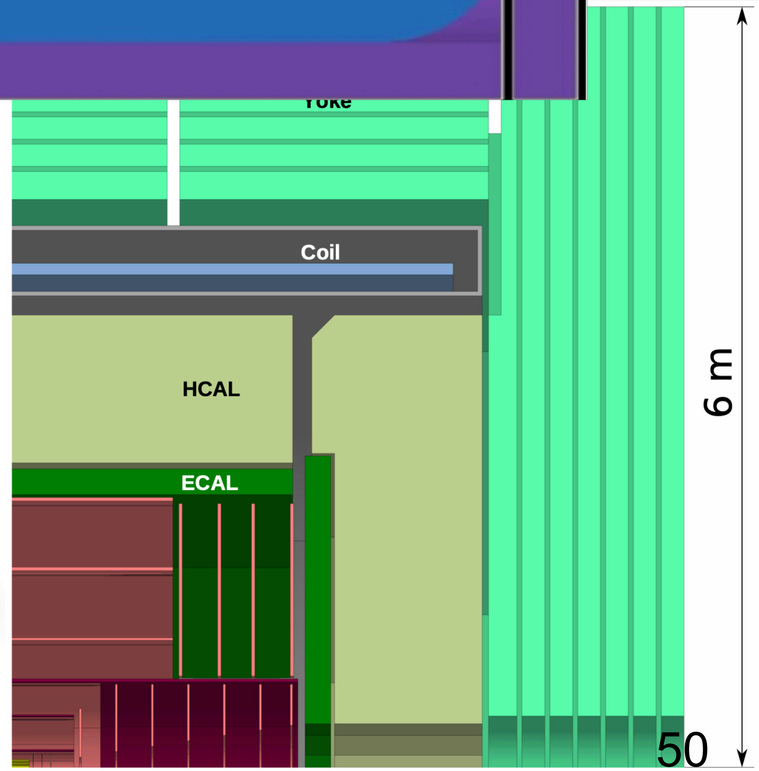

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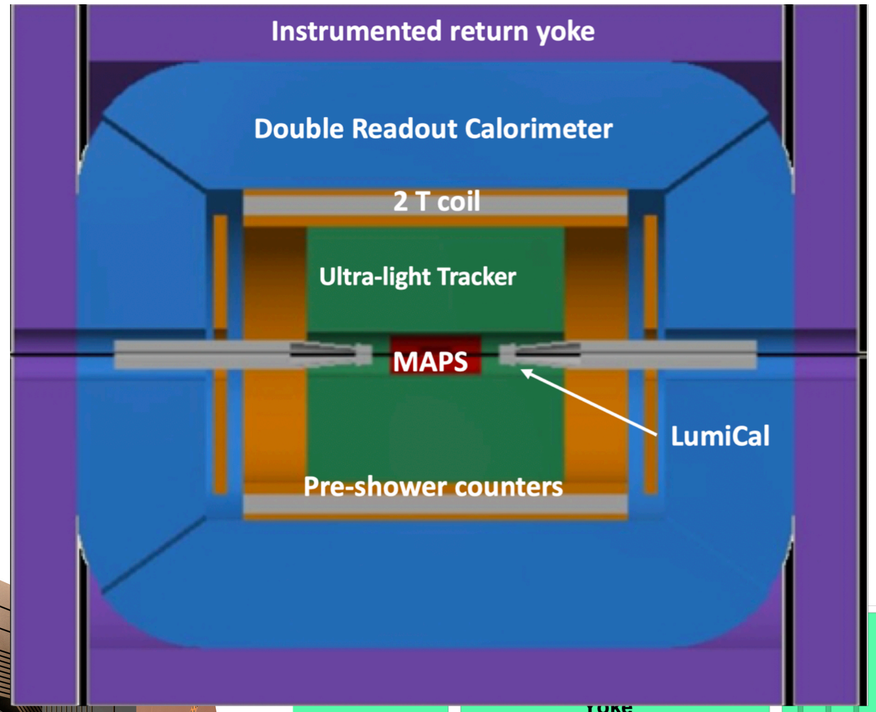

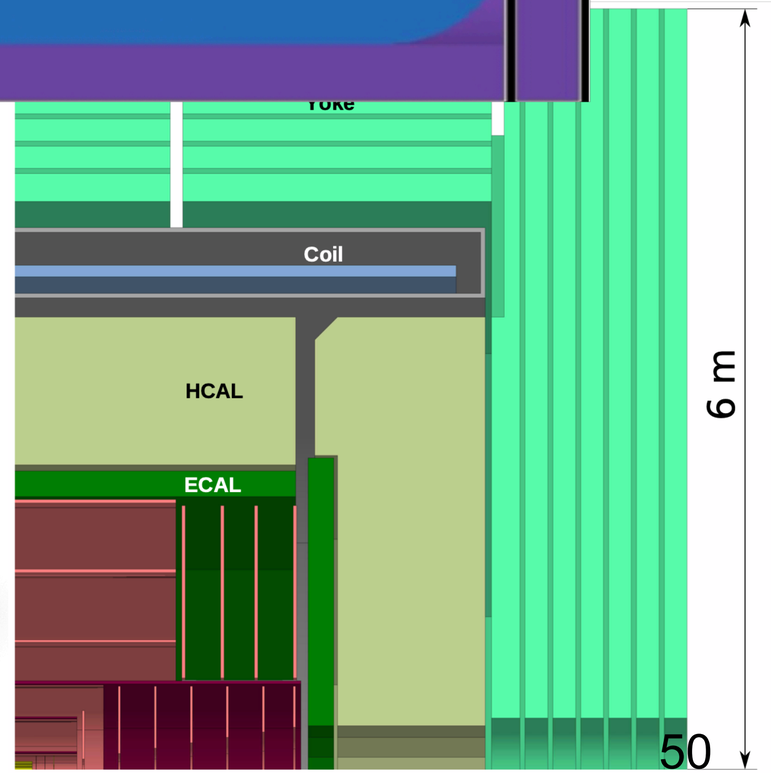

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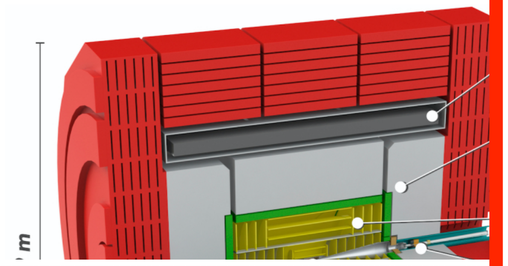

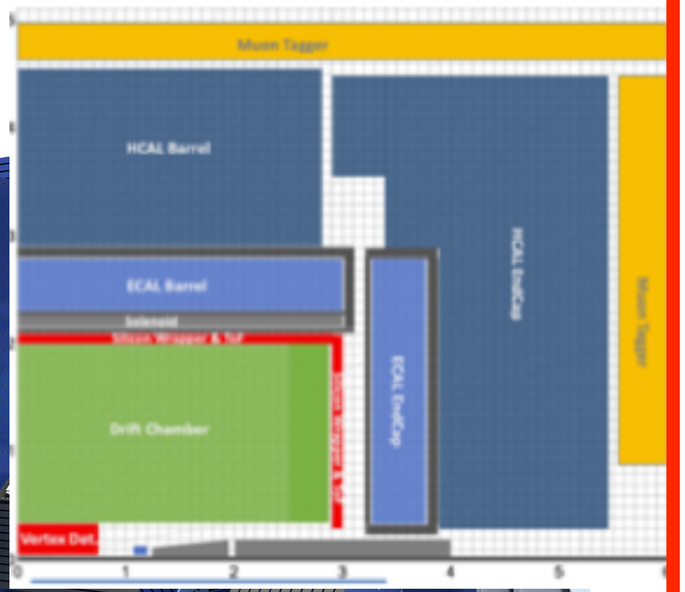

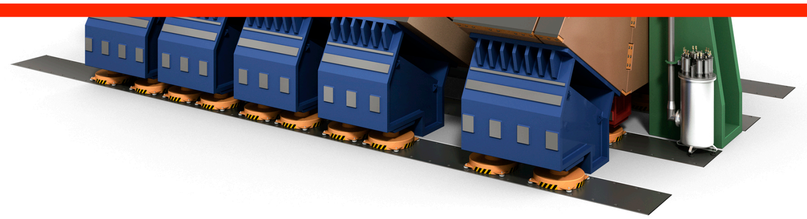

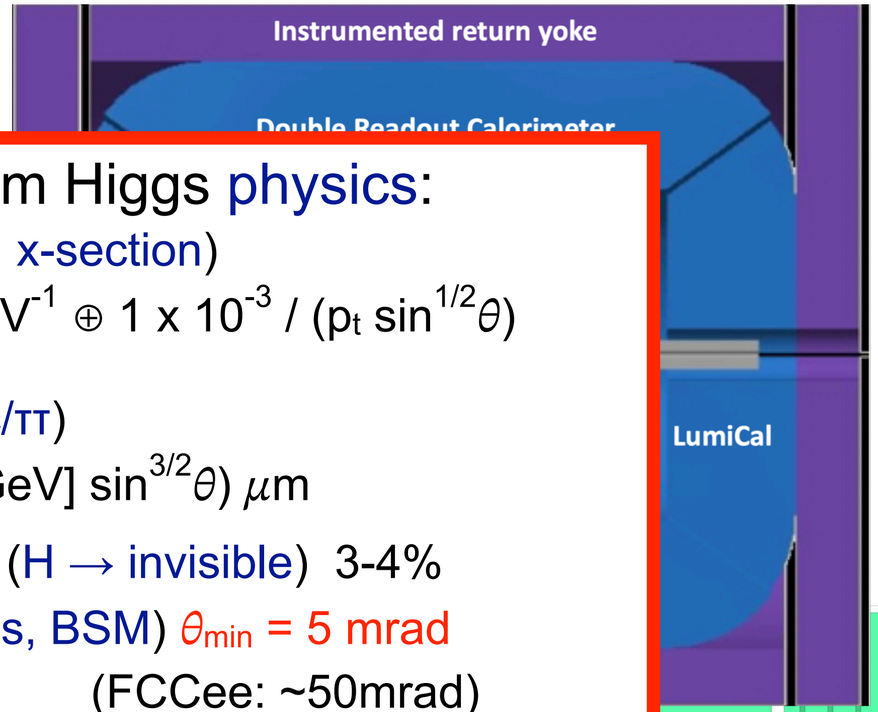

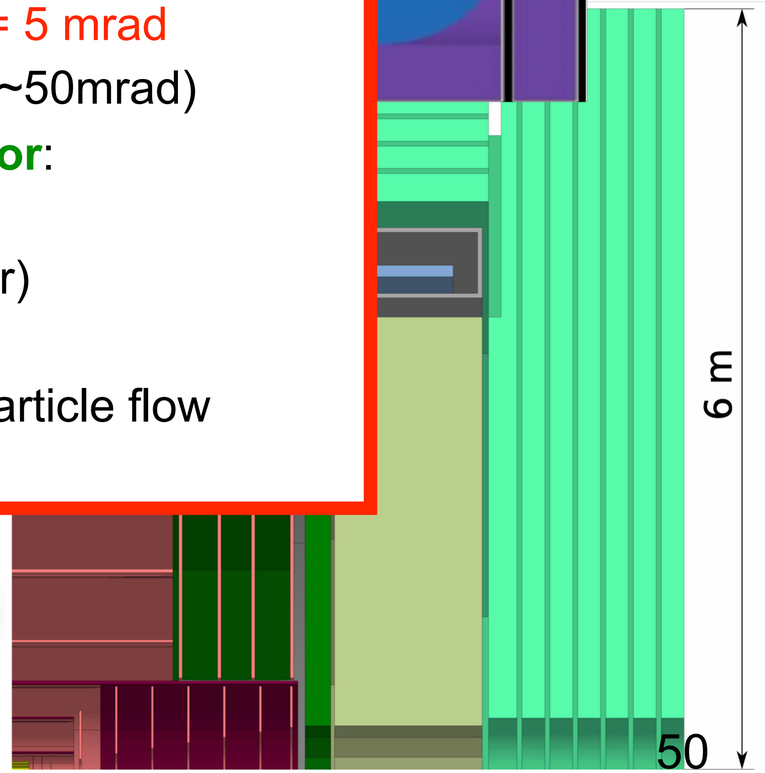

Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)

  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$

- **vertexing** ($H \to bb/cc/\tau\tau$)

  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu\mathrm{m}$

- **jet energy resolution** ($H \to$ invisible) 3-4%
- **hermeticity** ($H \to$ invis, BSM) θ_{min} = 5 mrad

  (FCCee: ~50mrad)

Determine to key features of the **detector**:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **calorimeters**
  - **highly granular,** optimised for particle flow
  - or dual readout, LAr, …

Higgs Factory Detector Concepts

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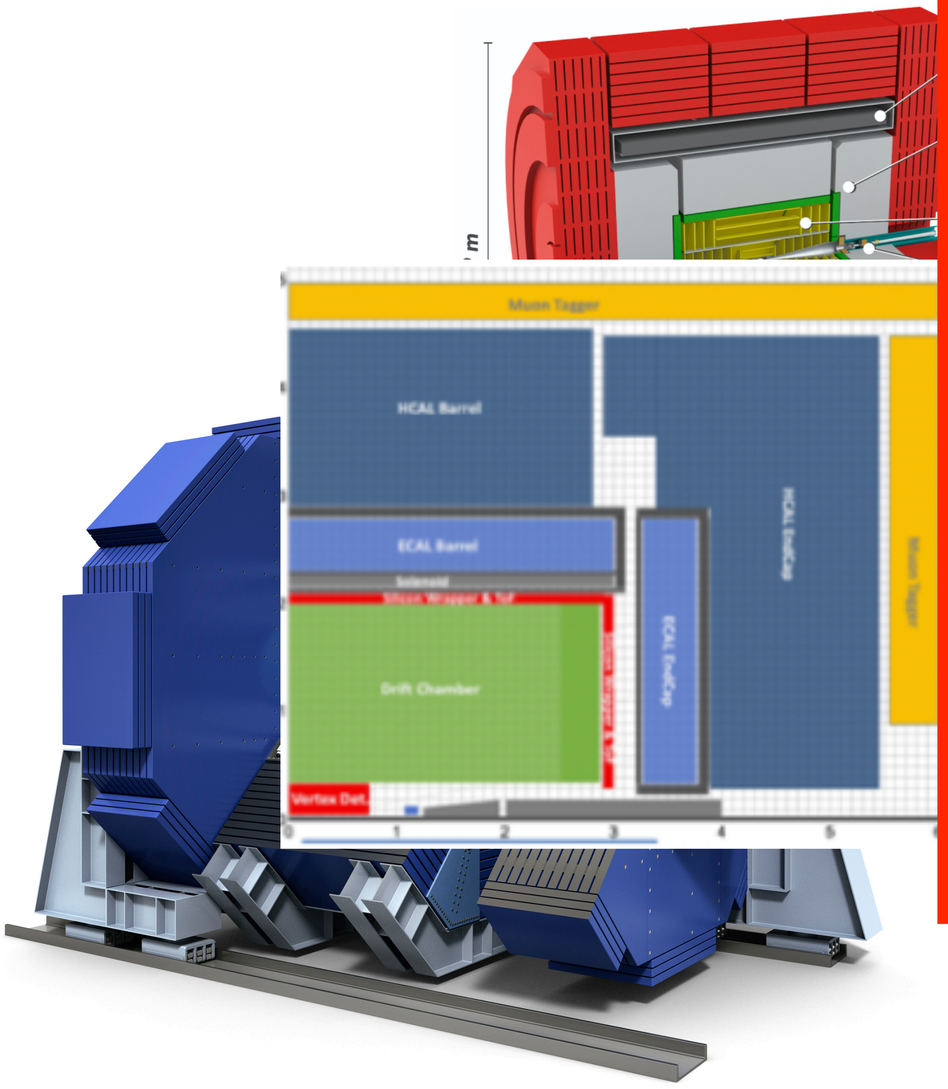

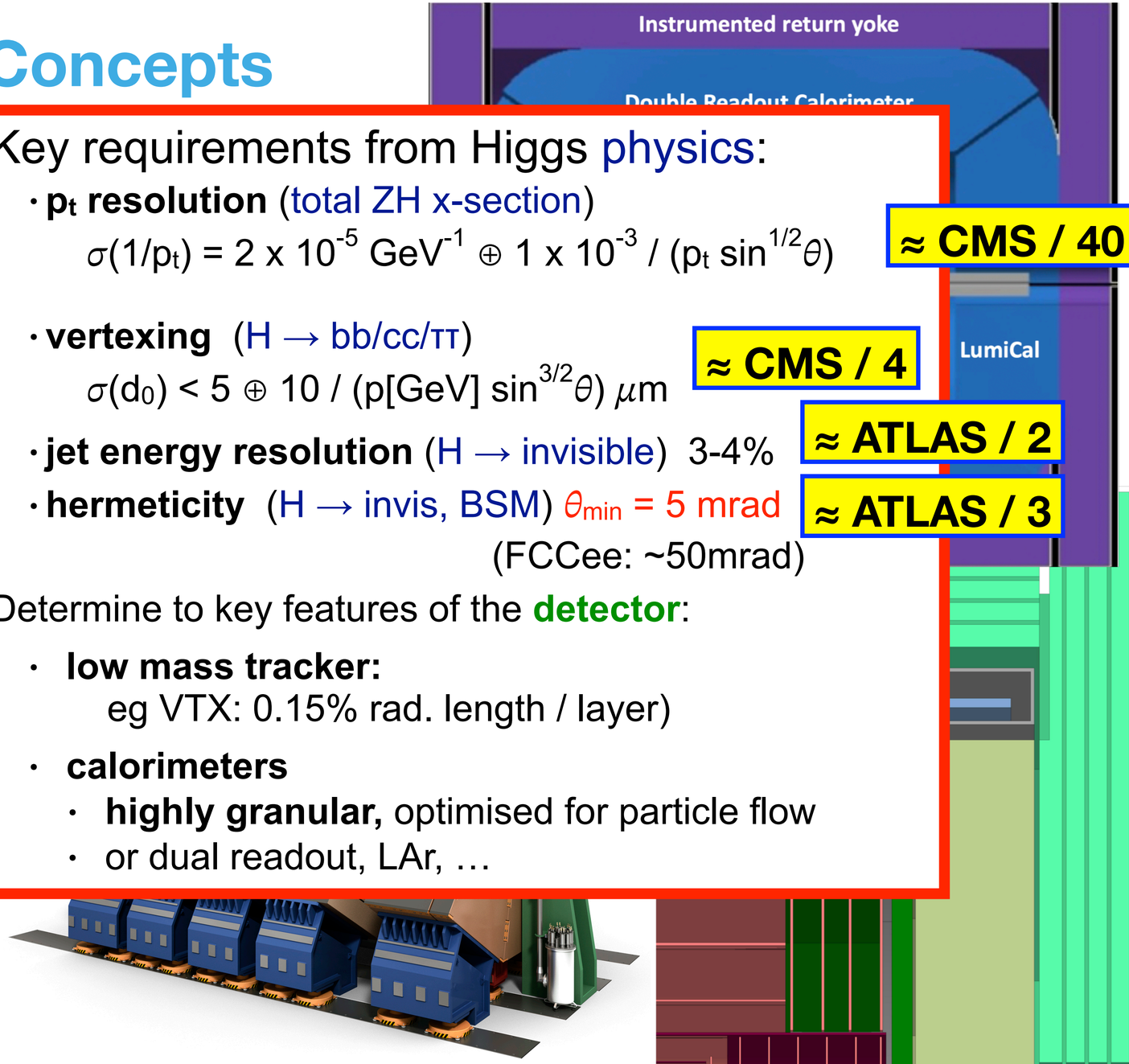

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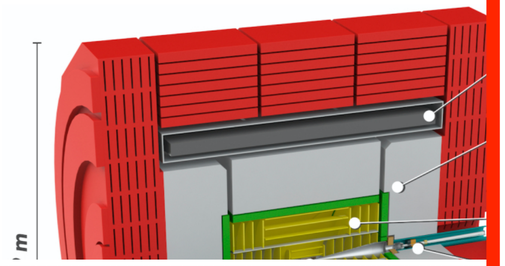

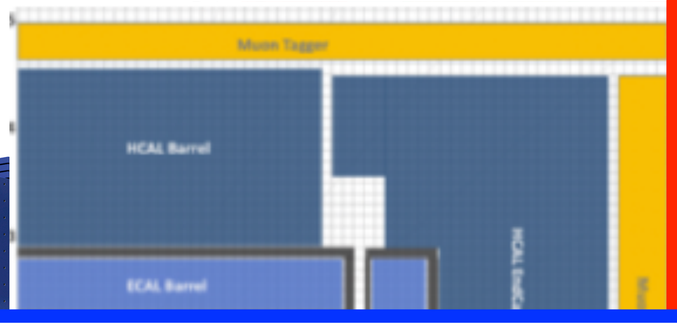

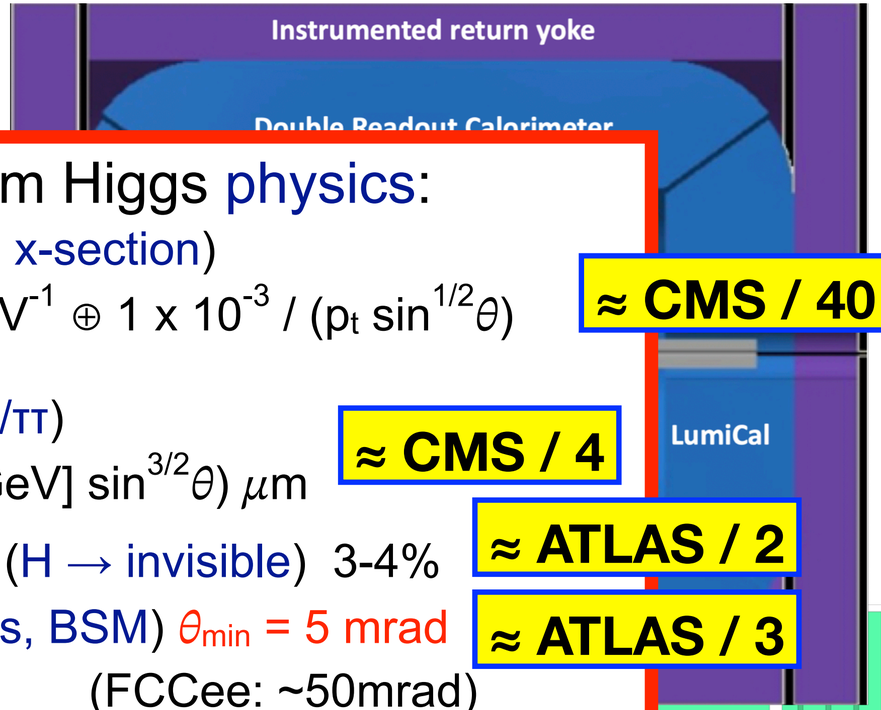

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anular, optimised for particle flow

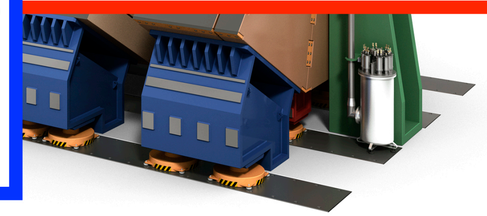
adout, LAr, …

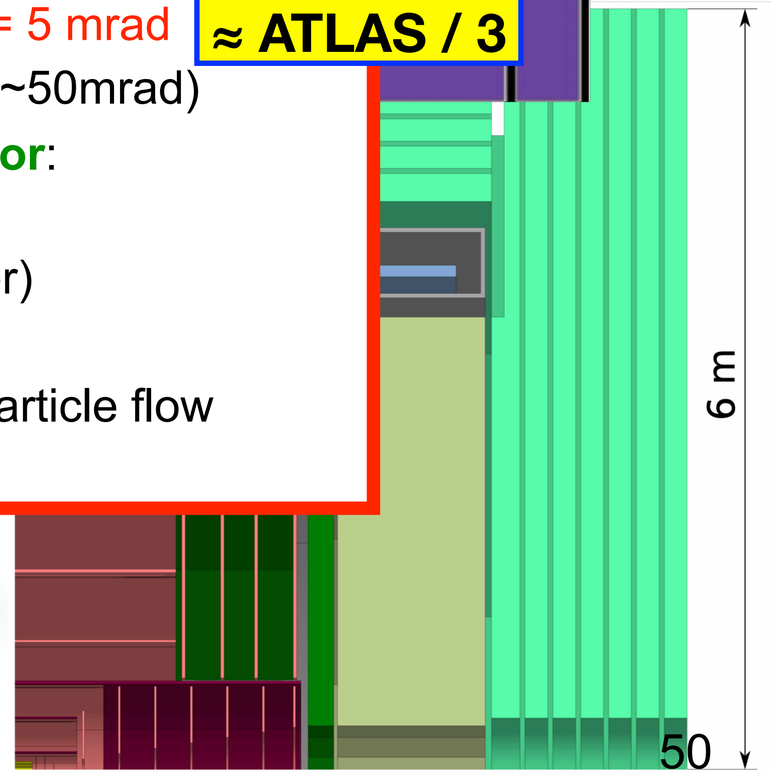
Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

only Linear Colliders: lower collision rate enables

- **passive cooling only => low material budget**
- **triggerless operation**

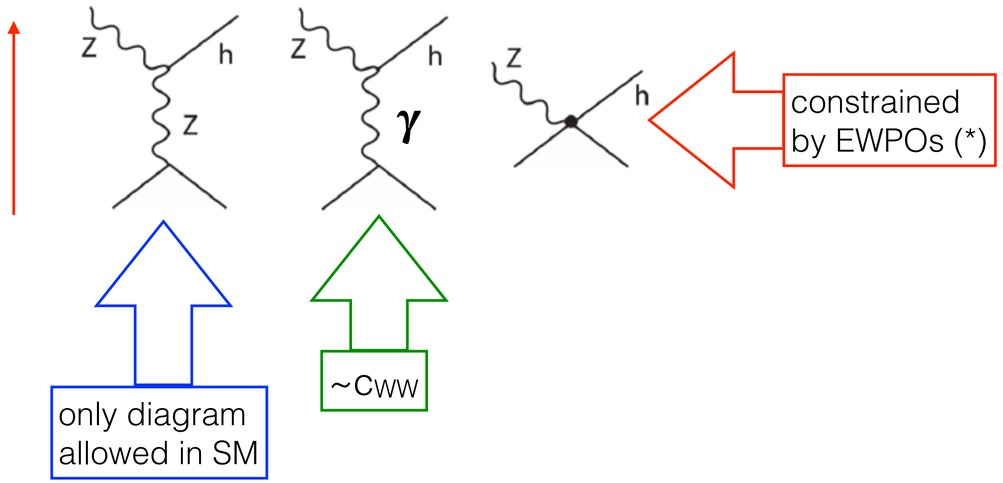




Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

- **THE key process** at a Higgs factory:
  Higgsstrahlung $e^+e^- \rightarrow Zh$
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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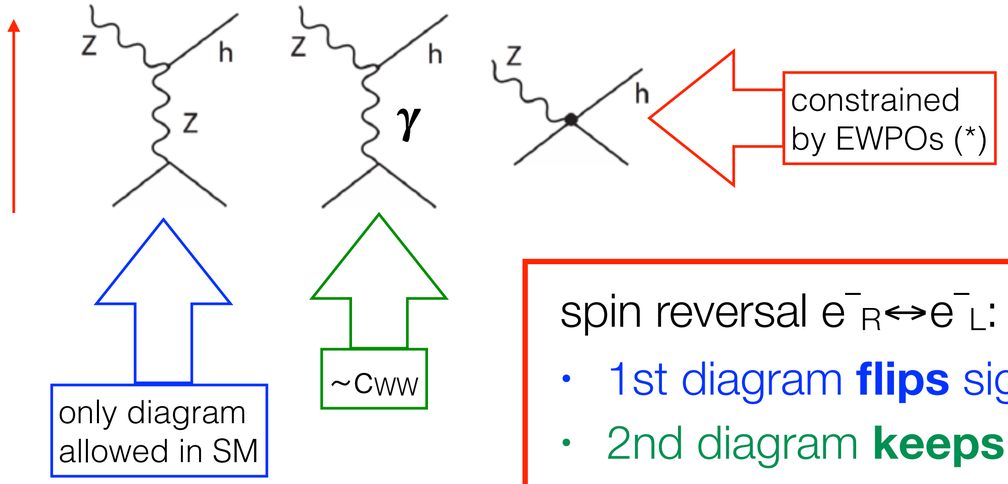

spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

⇒ A_{LR} lifts degeneracy between operators!

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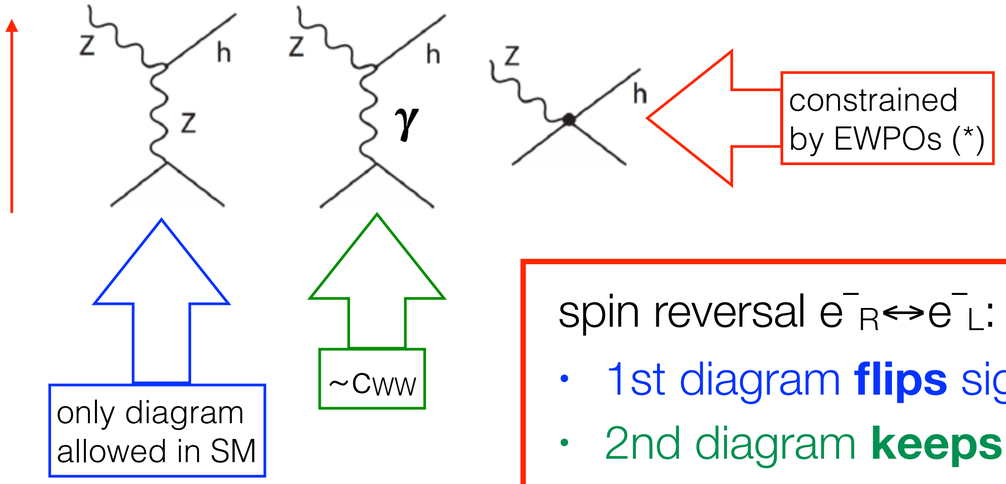

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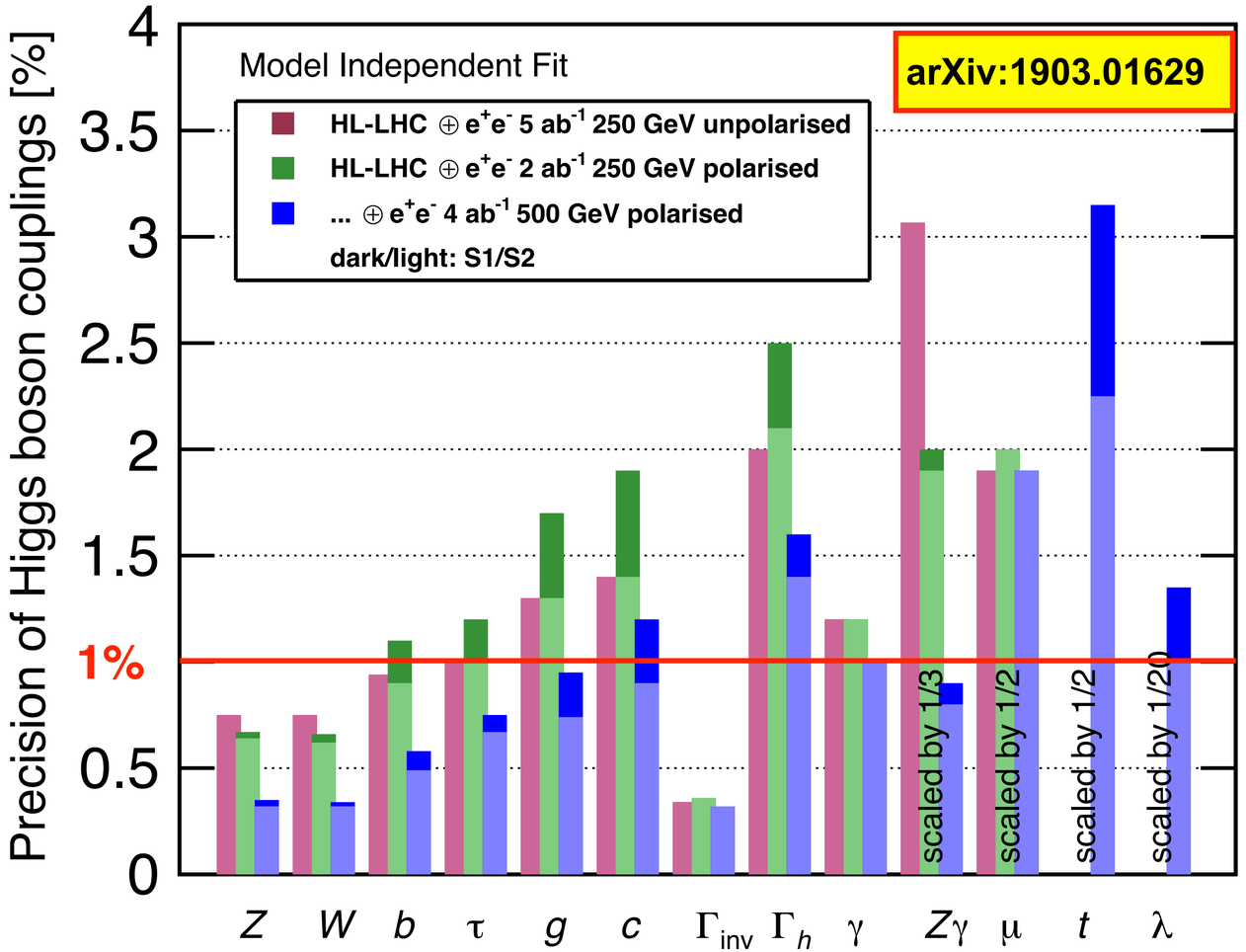

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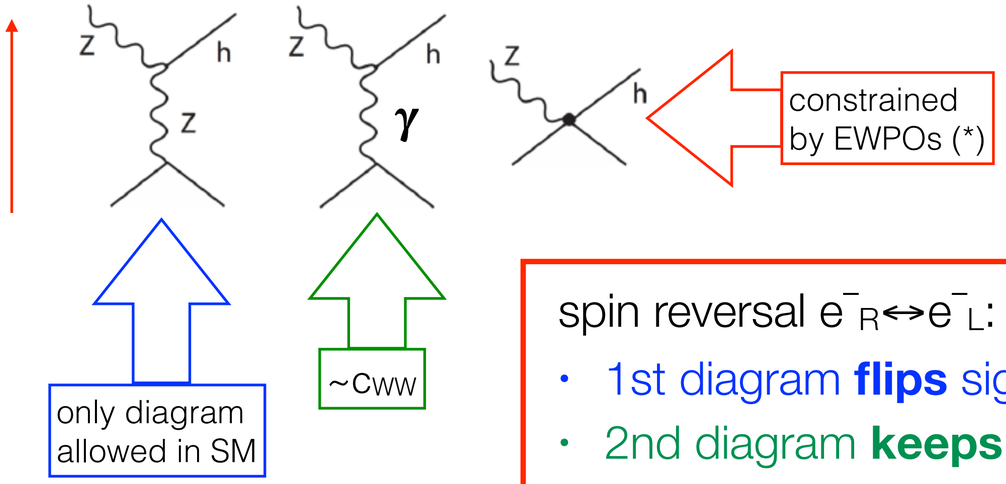

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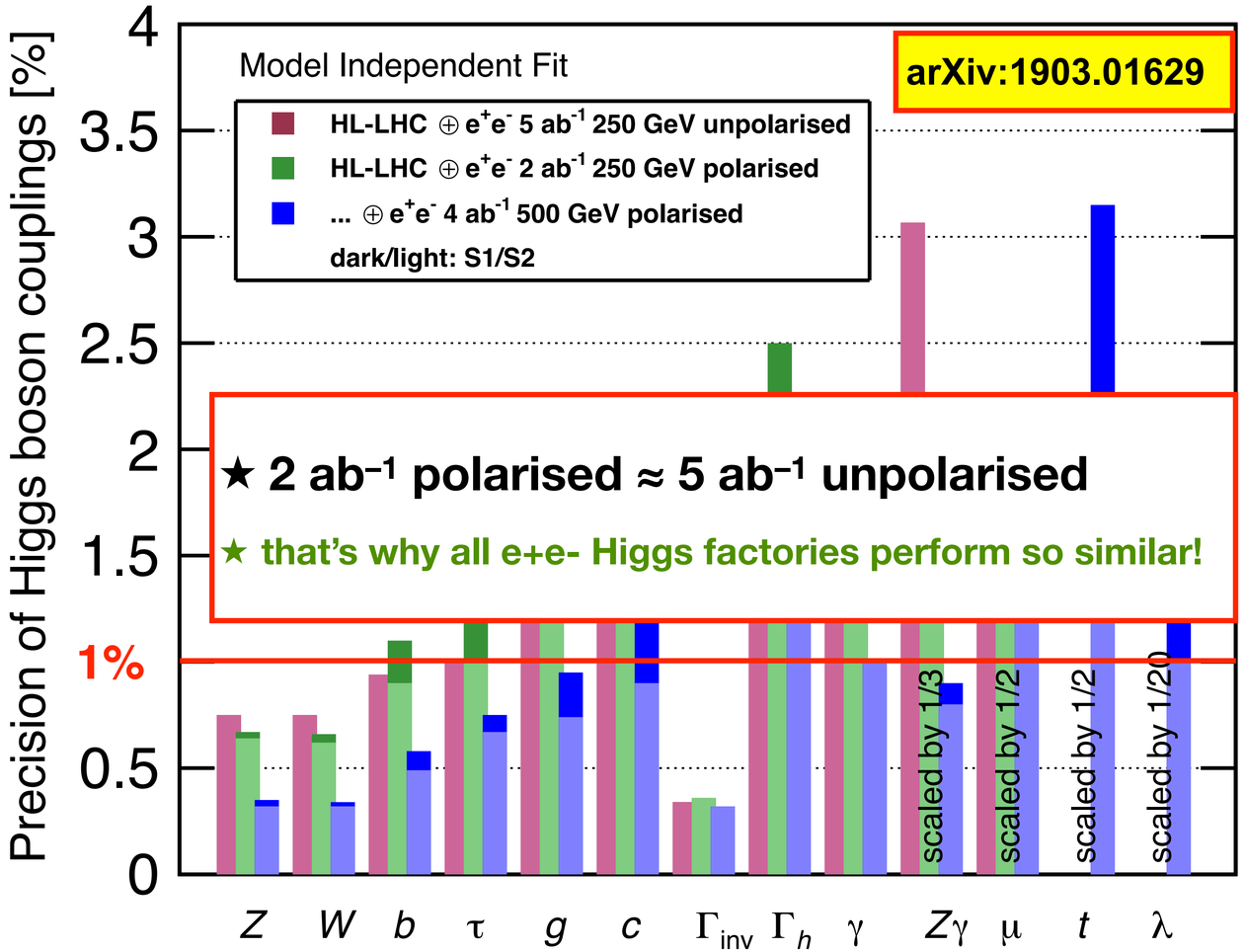
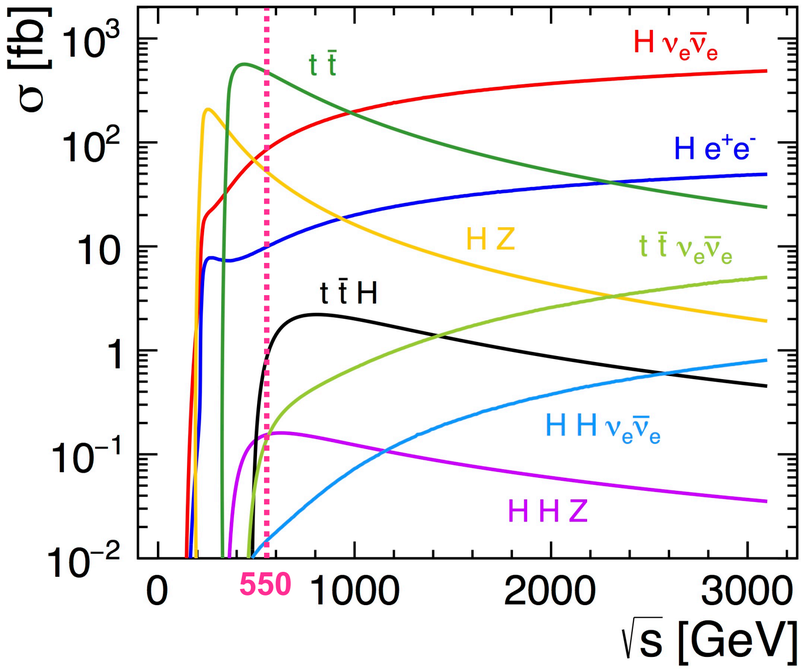


Di-Higgs & BSM

tree-level access to self-coupling

- **550 GeV**
  - ~ peak of **ZHH** cross-section
  - **vvHH** becomes just about visible
  - together for SM case:
    $\Delta\kappa_\lambda$ **= 11%** (15%) for **8ab^{-1}** (4ab^{-1})

- **dependence on λ:**
  - **ZHH**: **constructive** interference
  - **vvHH**: **destructive** interference
  - **together**: ~const absolute precision as function of λ



- **1-3 TeV:** **vvHH** becoming dominant
  - $\Delta\kappa_\lambda$ **= 0.04** (8ab-1) over wide range of κ_λ (except κ_λ ~ 1.5)
  - NB: “old” studies - if improve with ML similar as 550GeV => $\Delta\kappa_\lambda$ **≈0.02**

- **quantitative improvement and qualitatively new information wrt**
  - **HL-LHC**
  - **loop corrections at lower ECM stages**

Di-Higgs & BSM

tree-level access to self-coupling

- **550 GeV**
  - ~ peak of **ZHH** cross-section
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    $\Delta\kappa_\lambda$ **= 11%** (15%) for **8ab^{-1}** (4ab^{-1})
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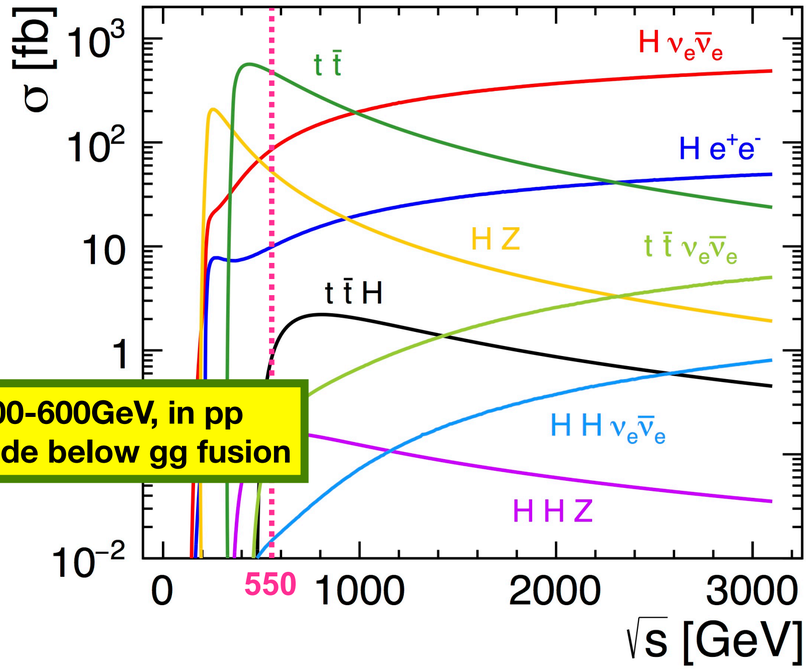

unique to ll@500-600GeV, in pp orders of magnitude below gg fusion

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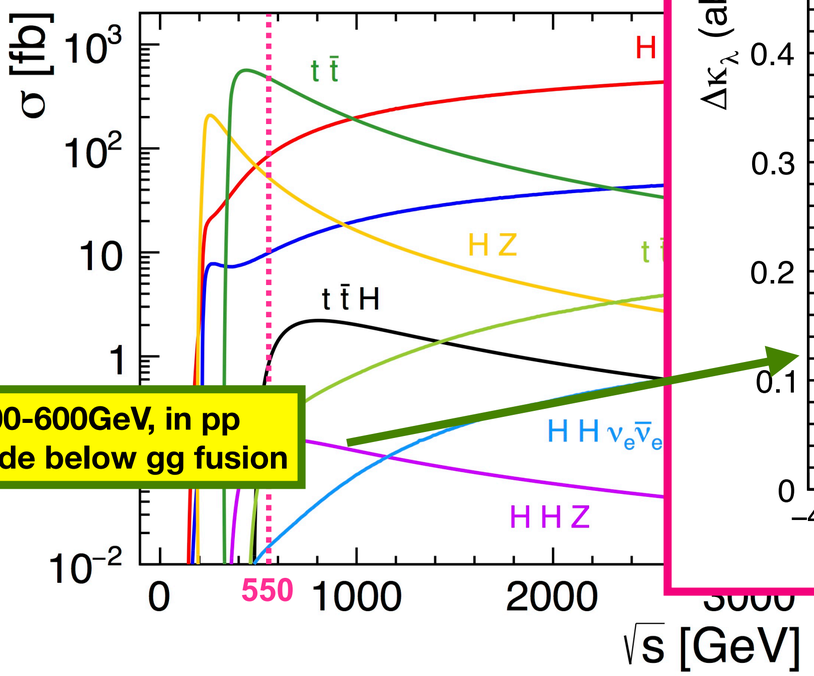

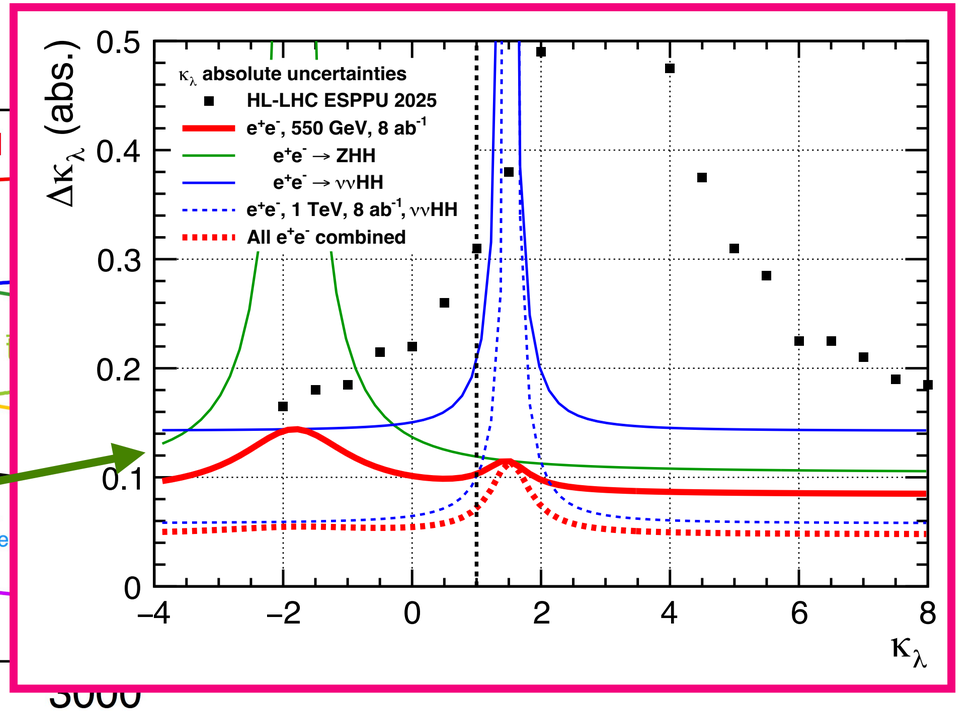

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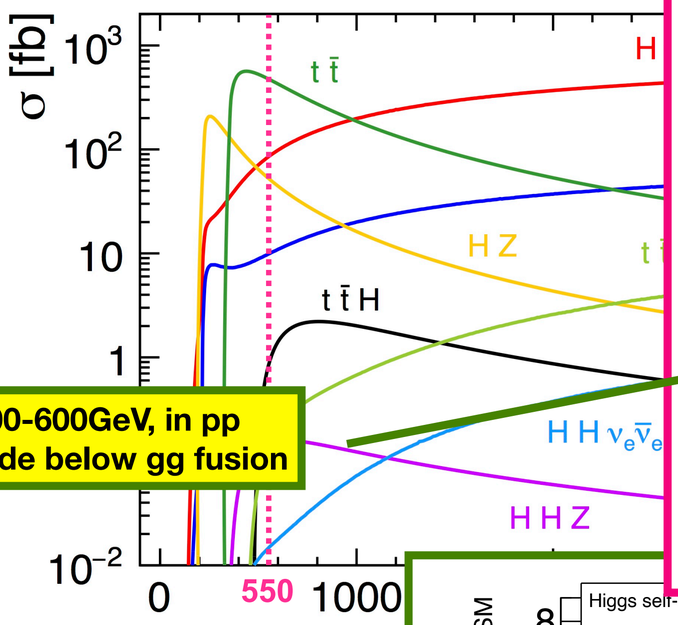

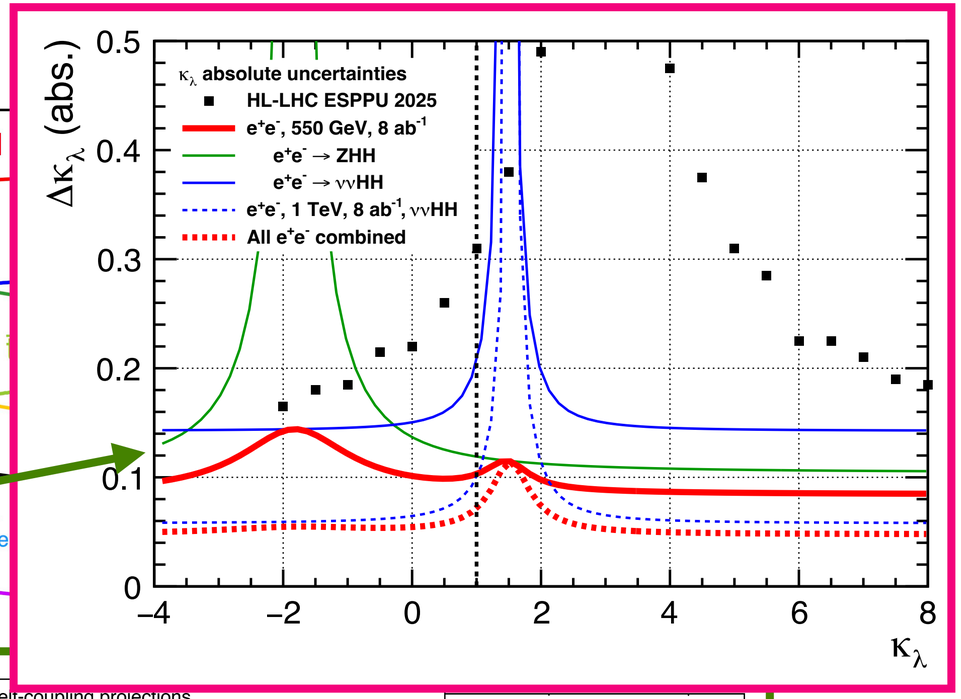

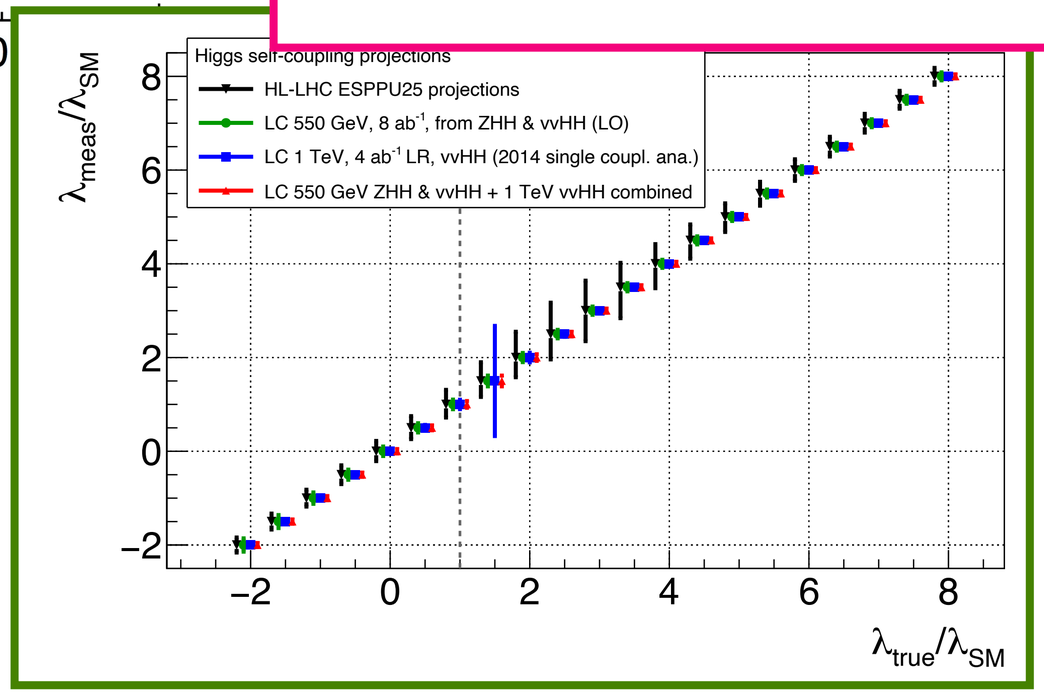

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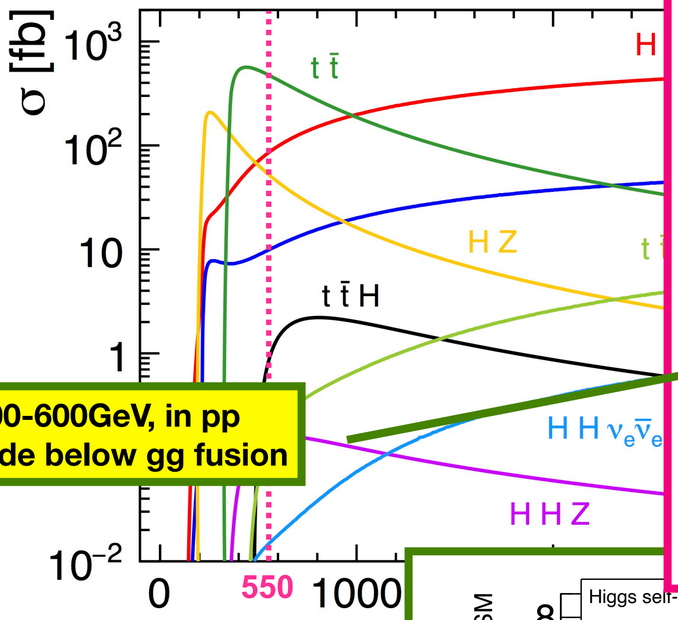
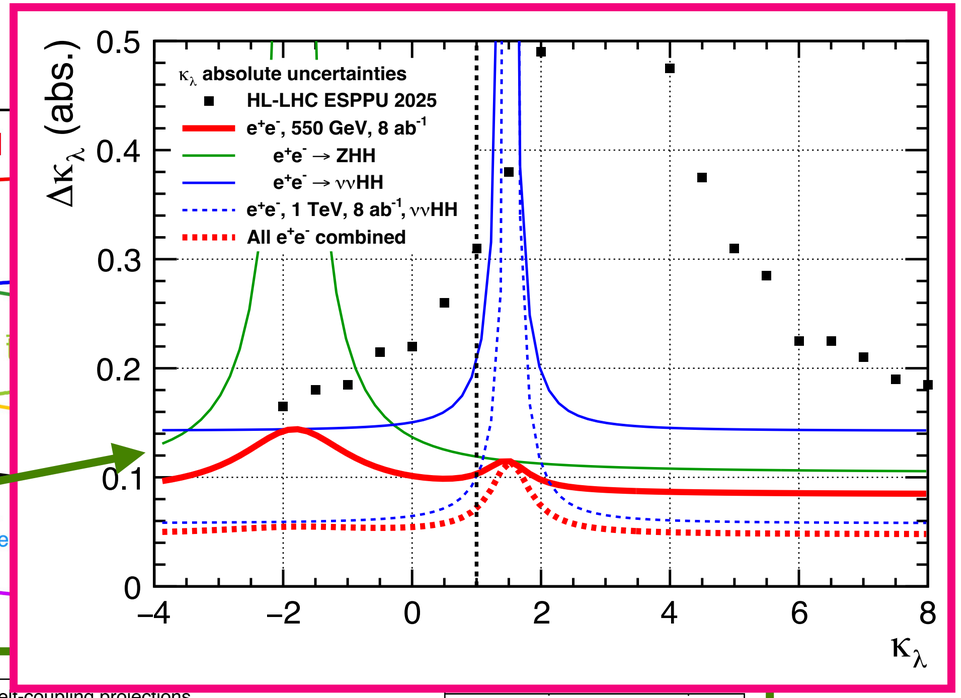
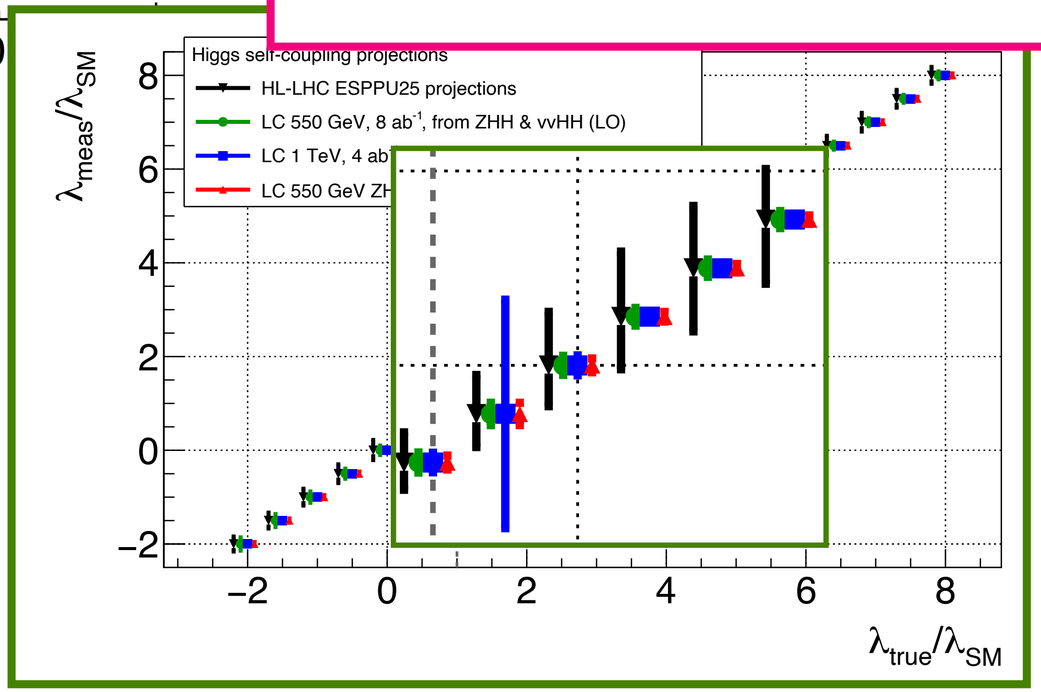






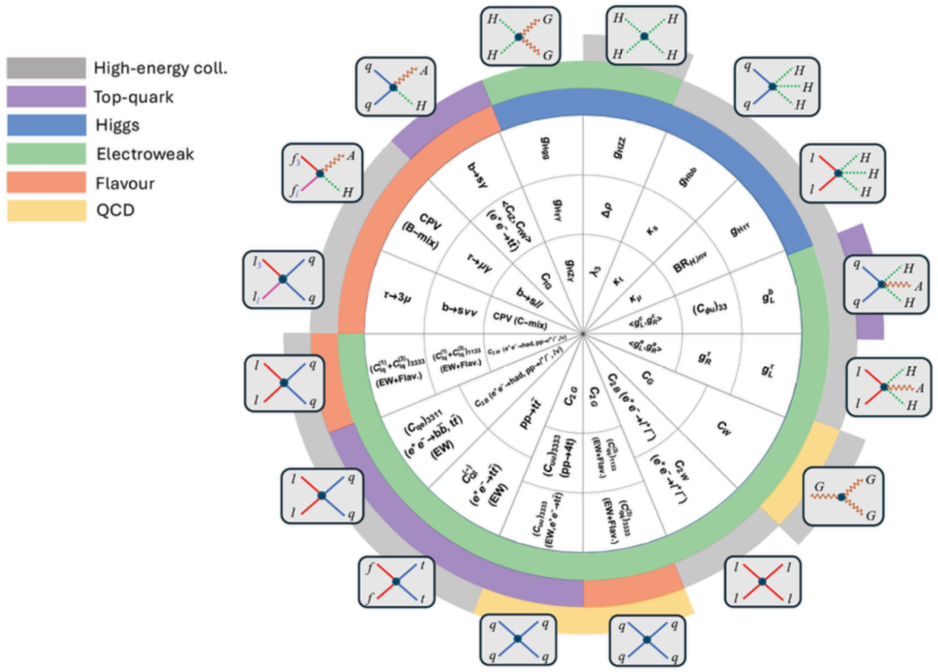
The dartboard plot fine print

Don’t trust your eyes without asking your brain :)

Coverage of the Physics Landscape

(i) Methodology*

effective interactions



- Slice physics landscape in 16 different sectors (adequate representation of the effective interactions among SM fields where new physics can show up)
- Sensitive to: Higgs, el.weak, top, flavour, QCD, high-energy observables

Each sector is subdivided in 2 or 3 rings with increasing measurement challenges

Examples:
- Higgs-only operators ($HZZ, \Delta\rho, \lambda_3$)
- Quark Yukawa (Y_b, Y_s, Y_t)

- Tri-linear gauge operators (el.weak, GGG)
- 4-lepton ops. (W parameter, Y parameter)

- Compare potential of each collider for all sectors/rings
- HL-LHC performance is used as reference
- **Improvement factors** in precision w.r.t. HL-LHC are evaluated and mapped on a log-scale covering the range 1 to 5

HL-LHC: 1 (gray scale 1 = black)
Best collider: 5 (gray scale 5 = white)

22

K.Jakobs, ESPP update at pECFA July

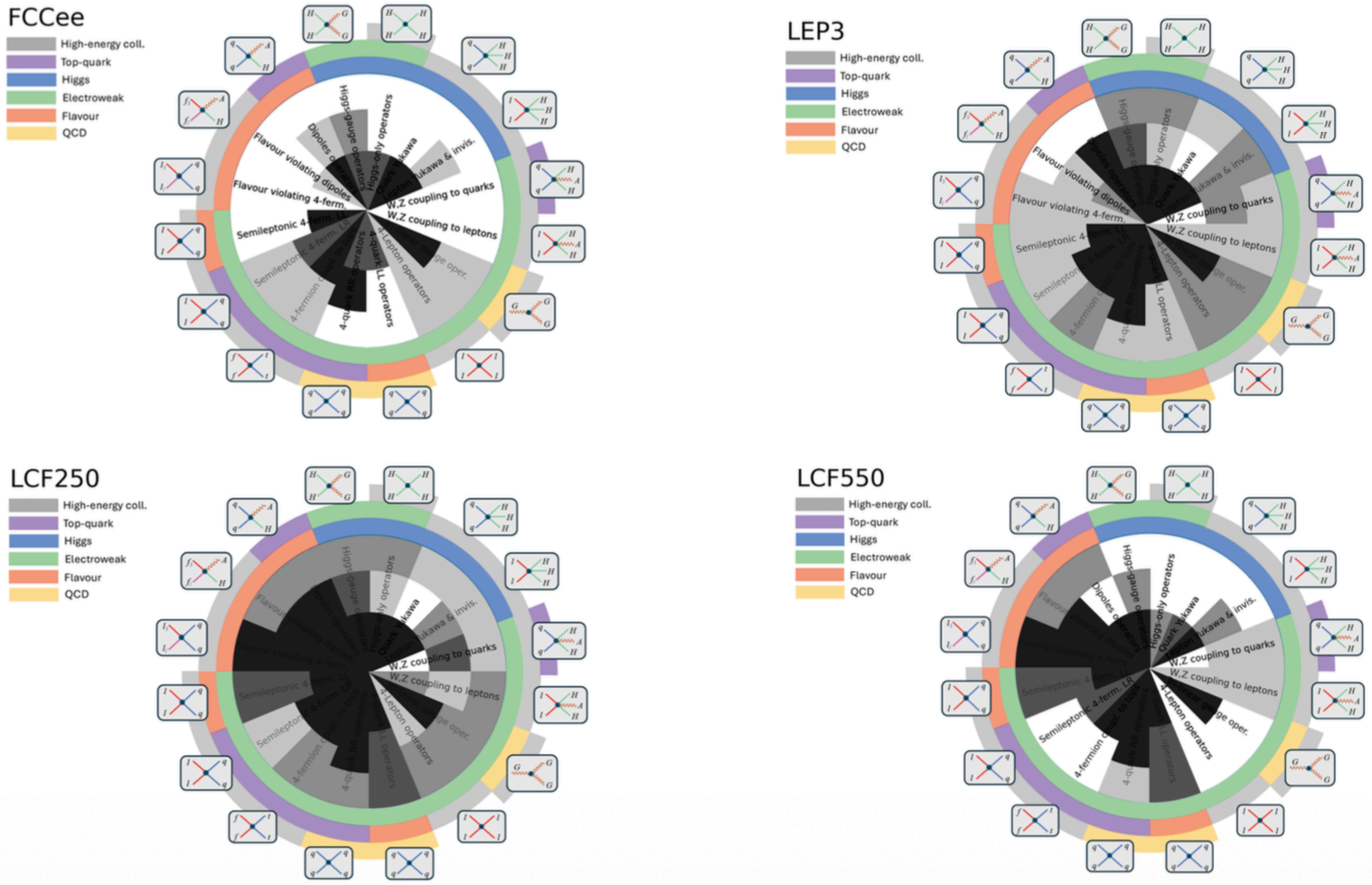
White = good, black = bad

**Thanks to Jorge de Blas, Monica Dunford and Gino Isidori (ESG WG 2b)*

Interlude: an optical deception experiment

Don’t trust your eyes without asking your brain :)

Coverage of first-stage e^+e^- colliders



K.Jakobs, ESPP update at pECFA July

White = good, black = bad

=> FCC-ee has much more white than anybody else, in all physics sectors, right?

=> didn’t we always say they give comparable performance for Higgs, top, EW, And only the b-physics at the Z pole is unique to FC-ee?

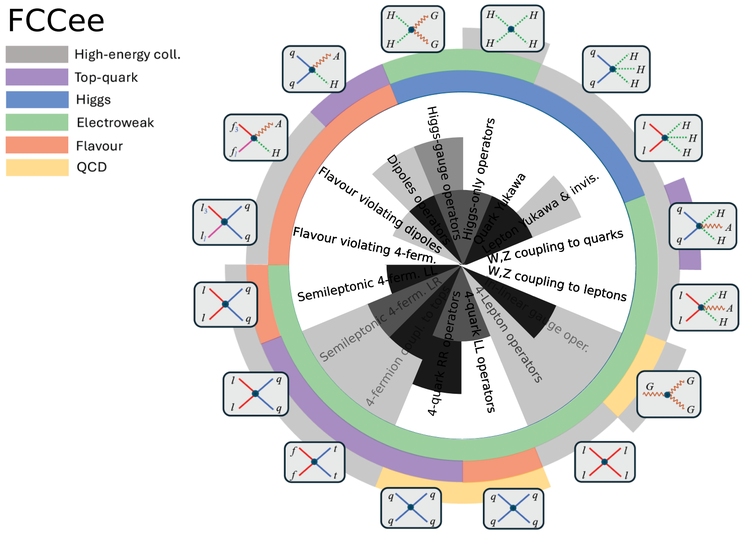
CERN-ESU-2026-006

Interlude: an optical deception experiment

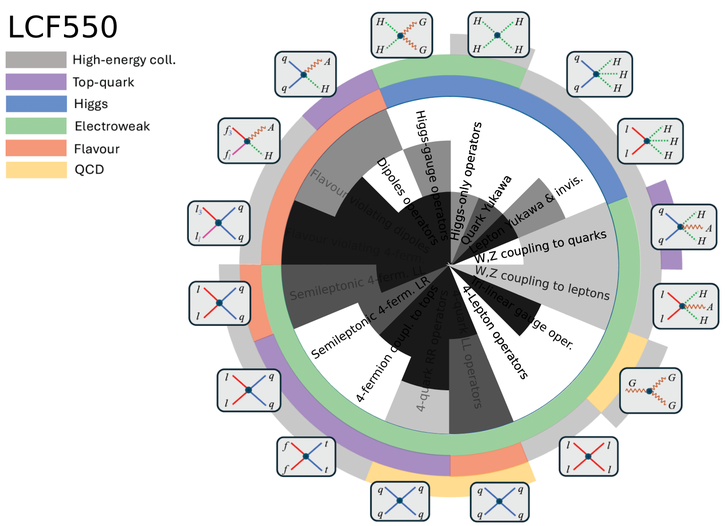
Don’t trust your eyes without asking your brain :)

Originals:

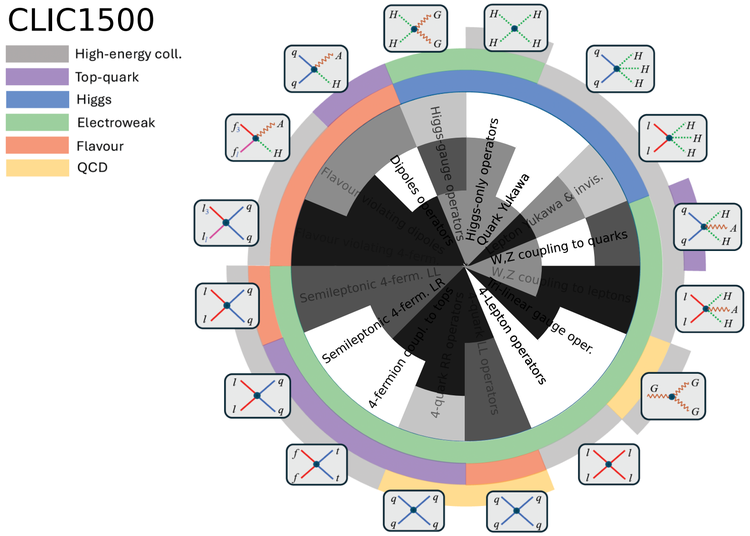
FCCee



LCF550



CLIC1500



Interlude: an optical deception experiment

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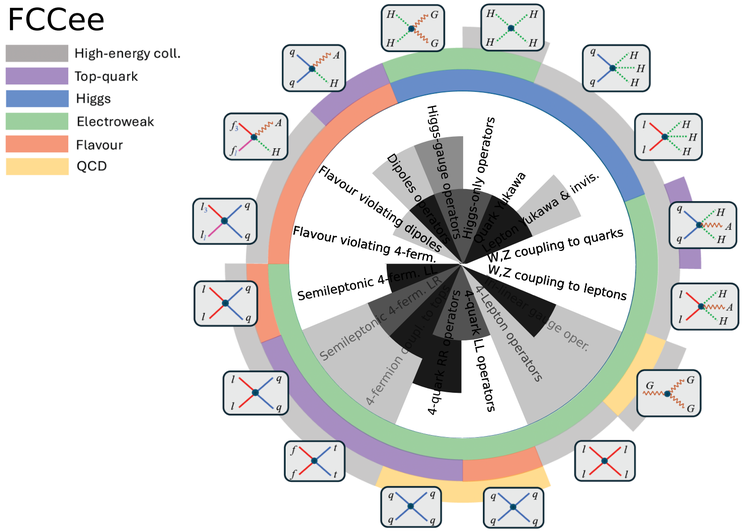
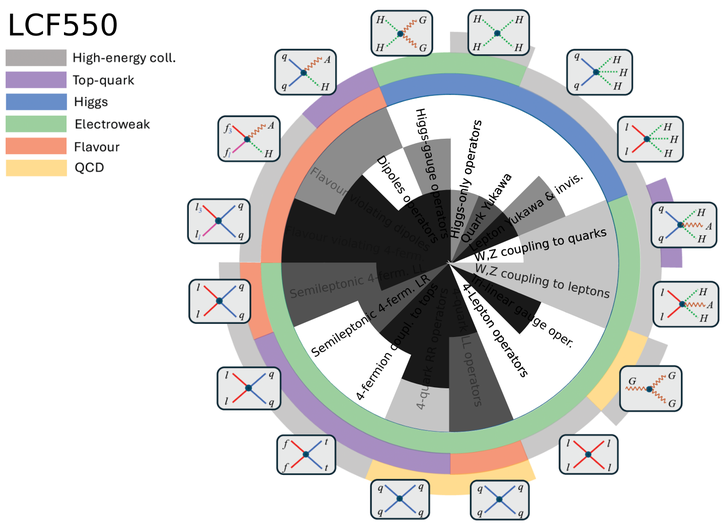
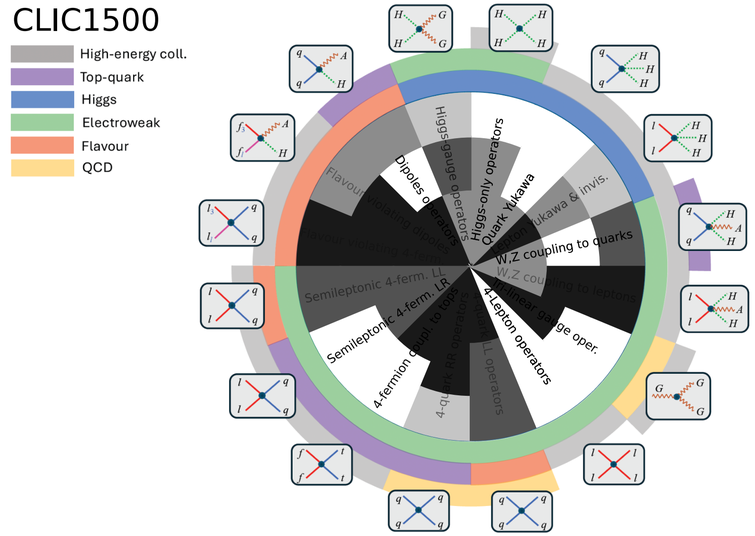


LCF550

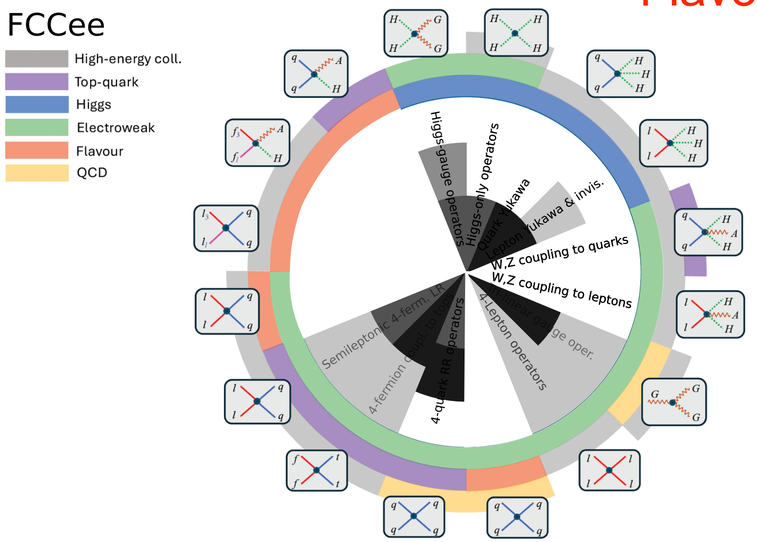


CLIC1500

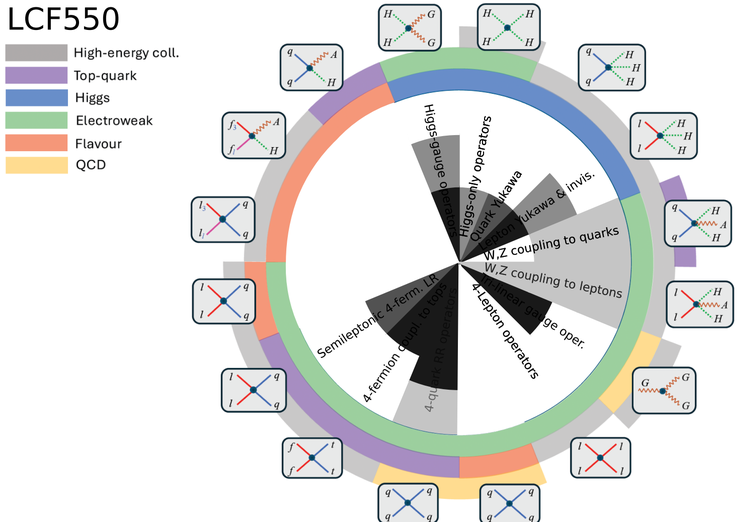


Flavour observables blanked out:

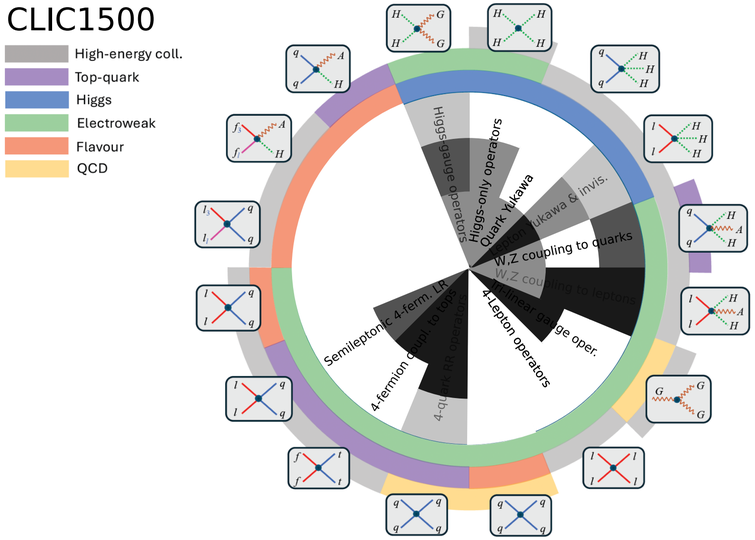
FCCee



LCF550



CLIC1500



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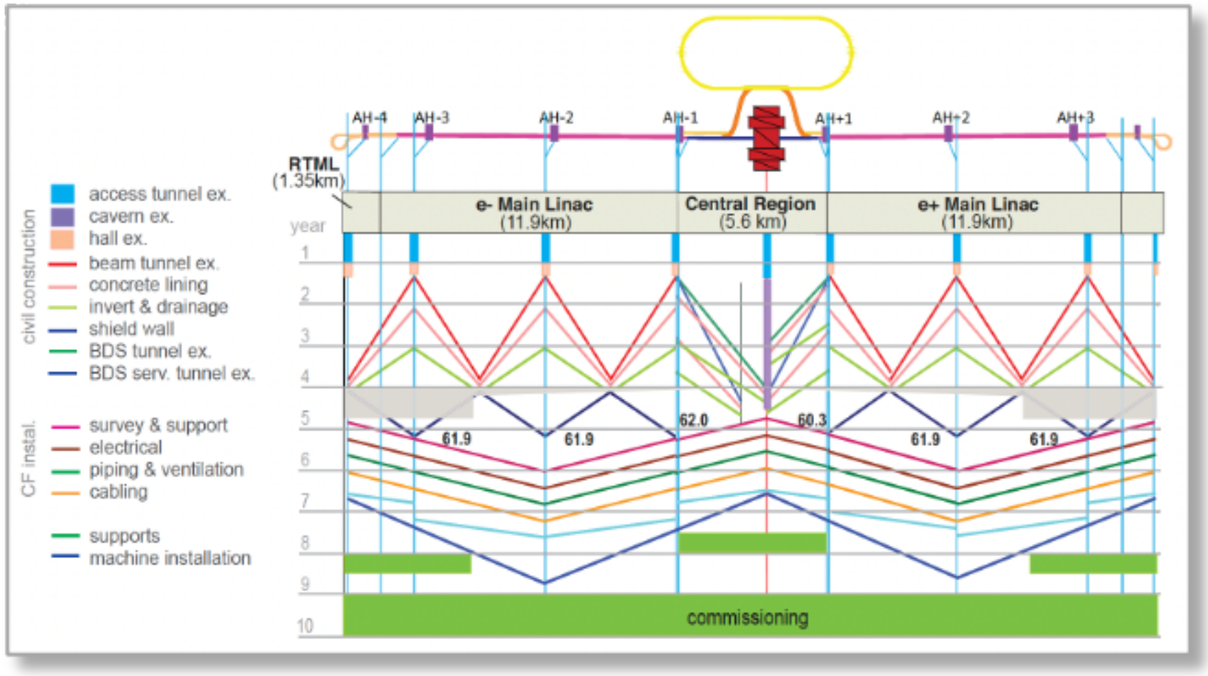
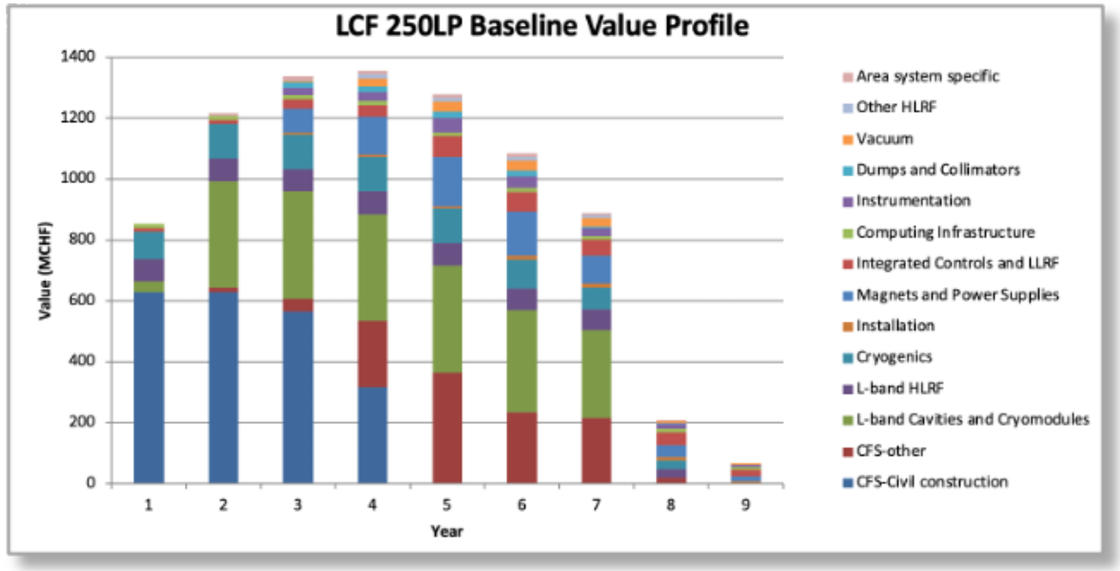
ny List

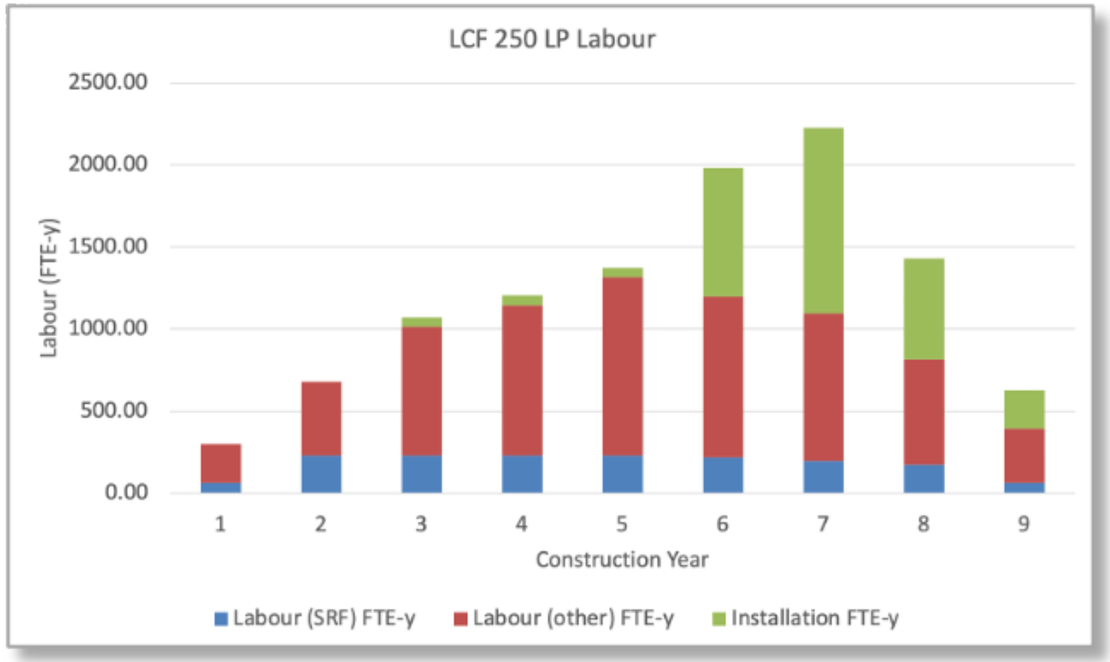
Spending profile

for ESPPU costing

- spending profile for construction phase
  (9 years construction + 1 year commissioning)
  based on detailed ILC studies







Operating costs, personnel & electricity

for ESPPU costing

- operating costs determined by CERN-wide standard
- fixed percentage of invest costs (1-5% depending on category)
- personnel: based on experience with major accelerators
- electricity: CERN-standardized calculation of power consumption and price (80CHF / MWh)

	CLIC 380 GeV	FCC-ee 91.2 – 365 GeV	LCF 250 GeV LP – FP
Maintenance and replacement material cost [MCHF/y]	137	200[a]	170[b]
Electricity cost [MCHF/y]	63	92 – 146	61 – 77
Personnel for operation of the future collider accelerator complex [FTE/y]	650	950	800

[a] Average of the costs for the different energy configurations.
[b] Average of the costs for the LP and FP configurations.

Table 4.12: Annual resource requirements for the operation of the accelerator complex of the proposed e^+e^- colliders at CERN.

OPEX LCF 250 LP

		Inputs										Outputs			
Cost and PPA breakdown			Weights				Raw Factors			Tuned factors			Annual cost MCHF			
Department	System	MCHF (2 IP)	Tech Infr	Fixed Inst	Consum	Others	F1%	F2%	F3%	TF1%	TF2%	TF3%	Tech Infr	Fixed Inst	Consum	Total
	Positron Source	303	0	118	186		5	1	3	5.0	1.0	3.0	0.00	1.18	5.58	6.8
	Electron Source	183	0	61	123		5	1	3	5.0	1.0	3.0	0.00	0.61	3.68	4.3
	Damping Rings	428	0	219	209		5	1	3	5.0	1.0	3.0	0.00	2.19	6.27	8.5
	RTML	612	0	330	282		5	1	3	5.0	1.0	3.0	0.00	3.30	8.46	11.8
	Main Linac	2802	0	1738	1064		5	1	3	5.0	1.0	3.0	0.00	17.38	31.93	49.3
	BDS and IR	449	0	158	291		5	1	3	5.0	1.0	3.0	0.00	1.58	8.73	10.3
	Common Systems	266	0	0	266		5	1	3	5.0	1.0	3.0	0.00	0.00	7.99	8.0
	Air Handling	38	38				5	1	3	5.0	1.0	3.0	1.88	0.00	0.00	1.9
	Cooling Water	289	289				5	1	3	5.0	1.0	3.0	14.43	0.00	0.00	14.4
	Electrical	539	539				5	1	3	5.0	1.0	3.0	26.95	0.00	0.00	26.9
	Handling Equipment	60	60				5	1	3	5.0	1.0	3.0	3.02	0.00	0.00	3.0
	Piped Utilities	19	19				5	1	3	5.0	1.0	3.0	0.93	0.00	0.00	0.9
	Safety Equipment	40	40				5	1	3	5.0	1.0	3.0	1.98	0.00	0.00	2.0
	Survey and Alignment	125	125				5	1	3	5.0	1.0	3.0	6.23	0.00	0.00	6.2
	Civil Construction	2138		214		1924	5	1	3	5.0	1.0	3.0	0.00	2.14	0.00	2.1
Totals		8291	1109	2837	2421	1924							55.4	28.4	72.6	156

A.1 Operational year

A.1.0.1 e^+e^- colliders

The operational parameters (number of days of operation in each phase, and corresponding fraction of the peak power needed) are presented in Table A.1 and Figure A.1.

Operational phase	Number of days	Fraction of the peak power consumption [%]								
		circular				CLIC		LCF		
		Z	W	ZH	$t\bar{t}$	380 GeV	1.5 TeV	250 LP	250 FP	550 FP
Annual shutdown	120	12	12	11	11	6	5	28	18	25
Commissioning	30	58	60	60	62	55	55	77	72	72
Technical stops	10	27	28	27	28	55	55	54	45	44
Machine development	20	39	45	50	61	55	55	77	72	72
Downtime (faults)	46	30	36	42	55	55	55	54	45	44
Data taking	**139**	100								

Table A.1: Breakdown of the operational phases [8,18,23] and of the corresponding fractional electricity consumption [18,23], for the linear and circular e^+e^- colliders. For CLIC the baseline and energy upgrade are considered, and for LCF [25] the baseline and upgrade options are given—Low-Power (LP) at 250 GeV and Full-Power (FP) at 250 GeV and 550 GeV.

