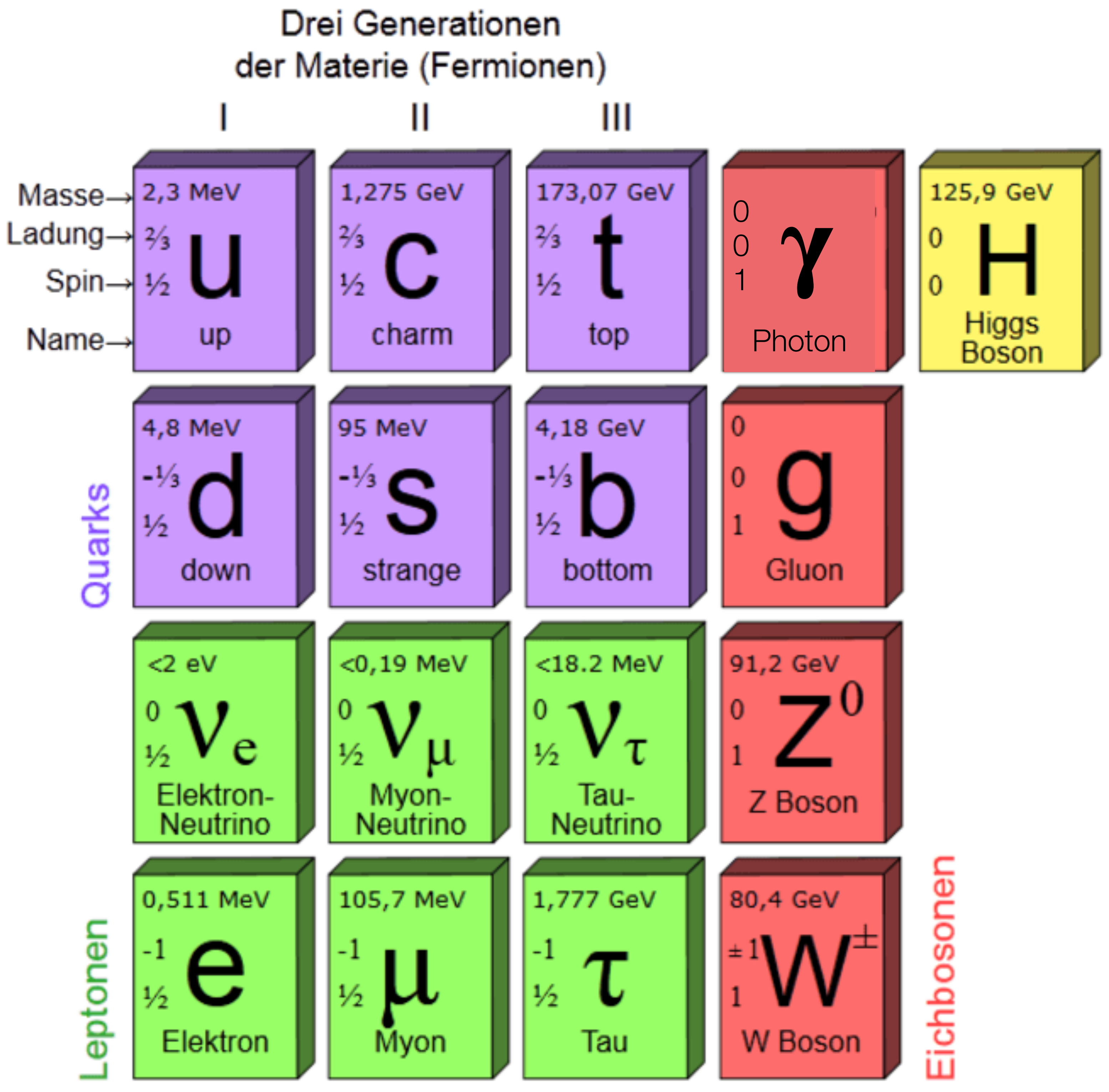
Straight to the Future: Physics Program and Status of the ILC

J. List (DESY/CERN)

International Conference on the Physics of Two Infinities, Kyoto, March 27-30, 2023

The Higgs Boson and the Standard Model of Particle Physics

A discovery which is only the beginning …



The Standard Model of Particle Physics

- describes (nearly) all measurements down to the level of quantum fluctuations
- based on only a few fundamental ideas:
  - special relativity
  - quantum mechanics
  - invariance under local gauge transformations: $SU(3) \times SU(2)_L \times U(1)_Y$

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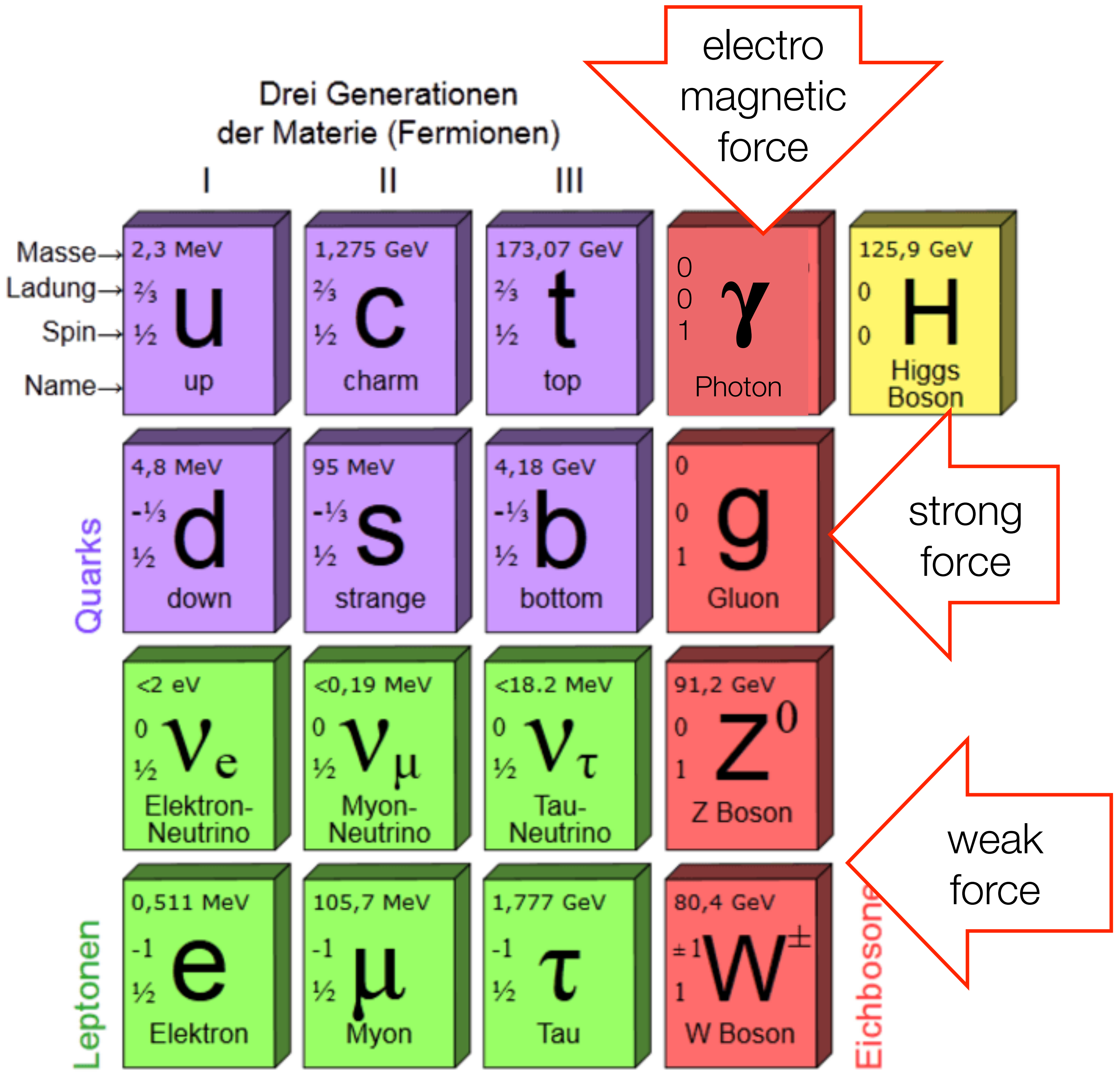

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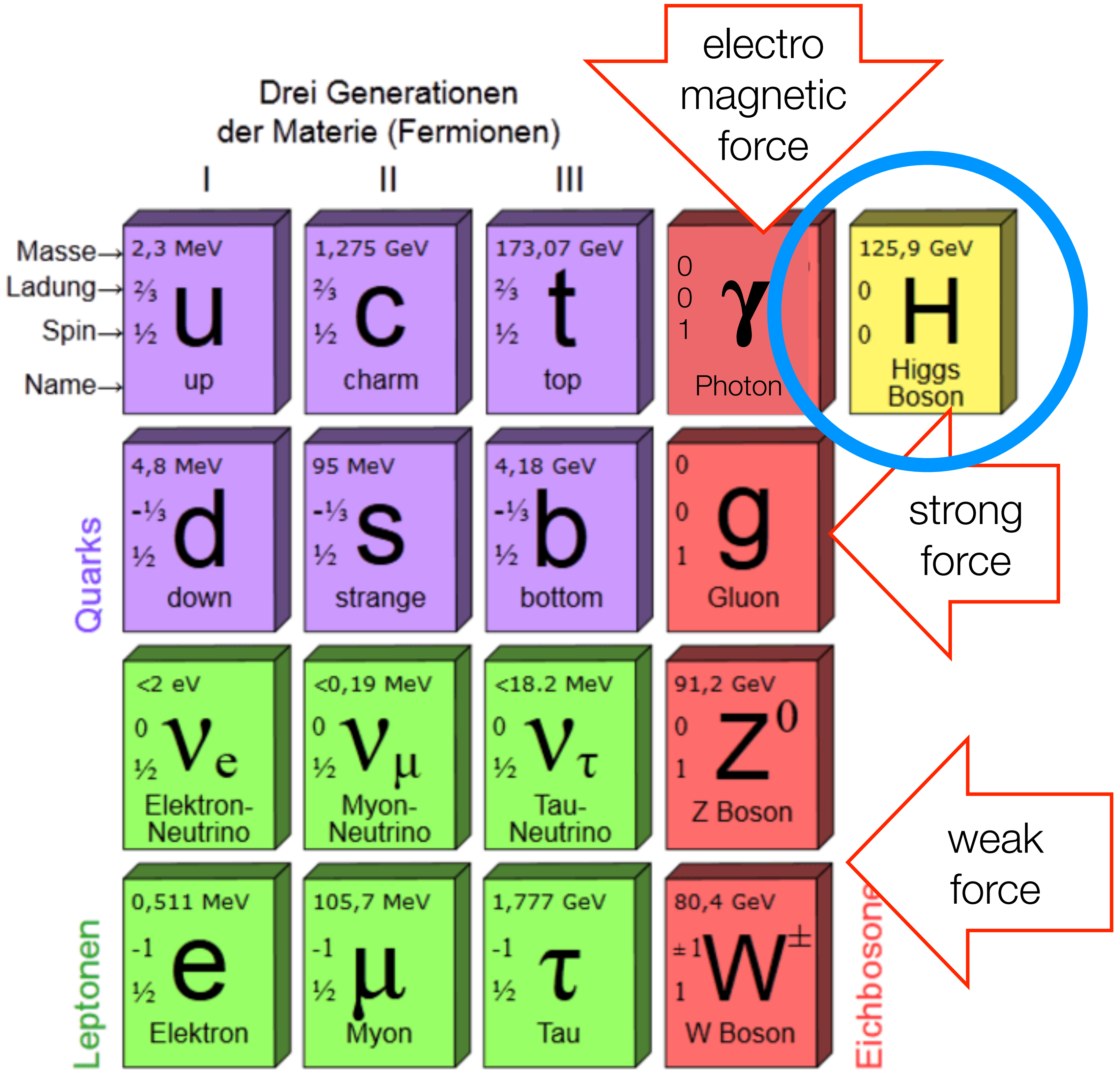

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2012: Discovery of a Higgs bosons at the LHC!

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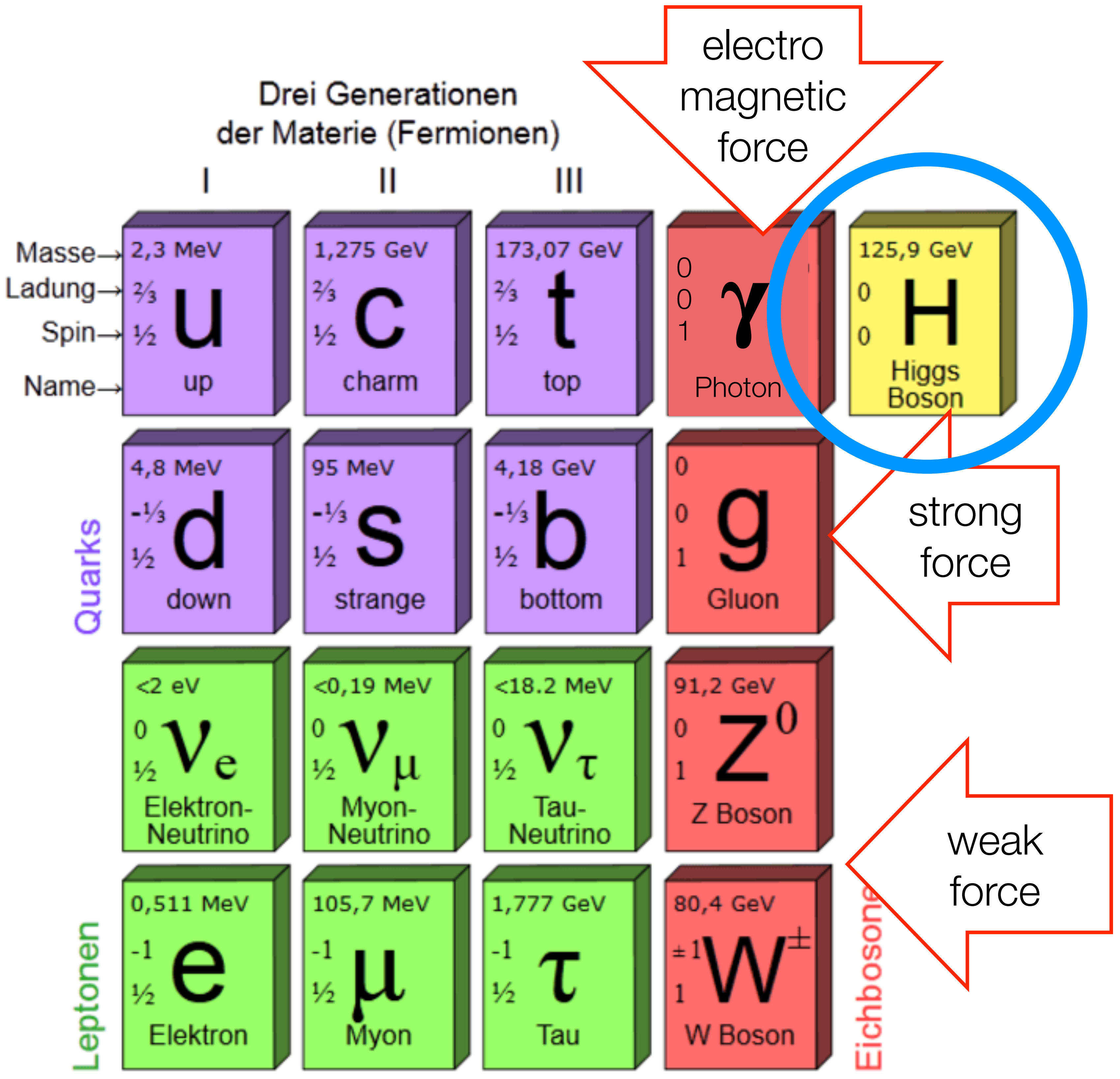

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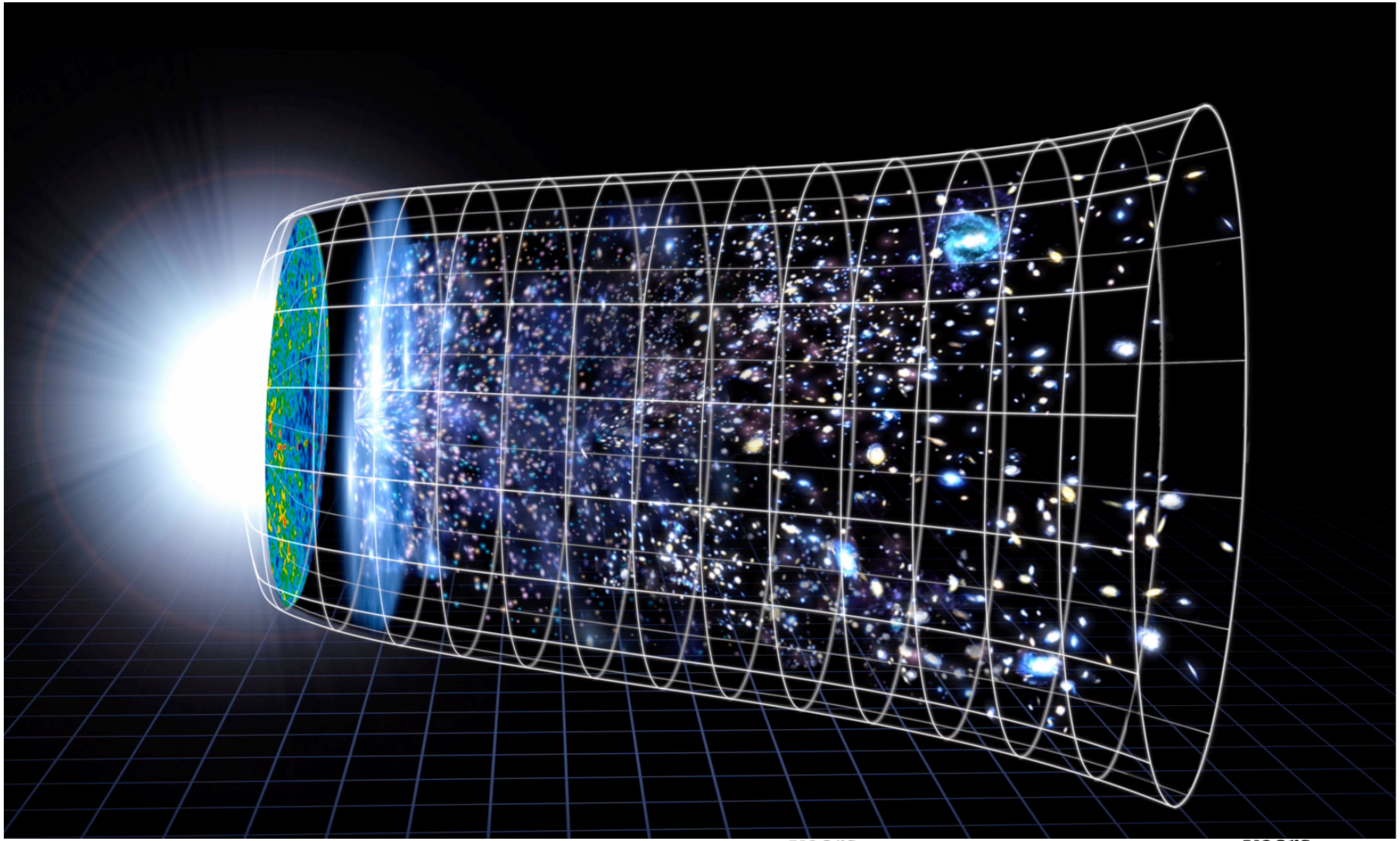
Are we done? — No! — The Higgs Boson is

1. **a mystery in itself: how can an elementary spin-0 particle exist and be so light?**
2. **intimately connected to cosmology => precision studies of the Higgs are a *new* messenger from the early universe!**

A new messenger from the early universe

see talk by Roberto Salerno for many more details!



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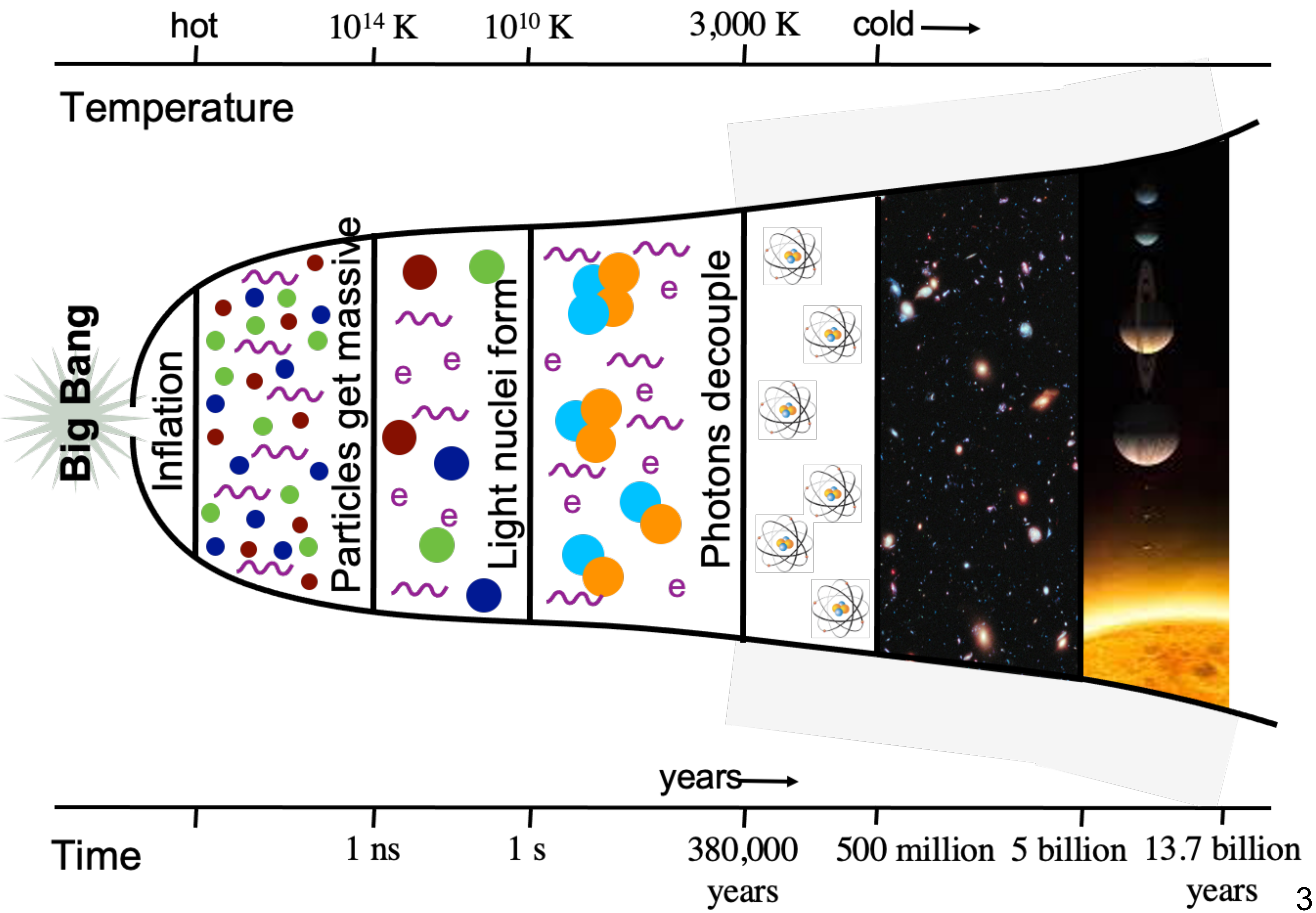

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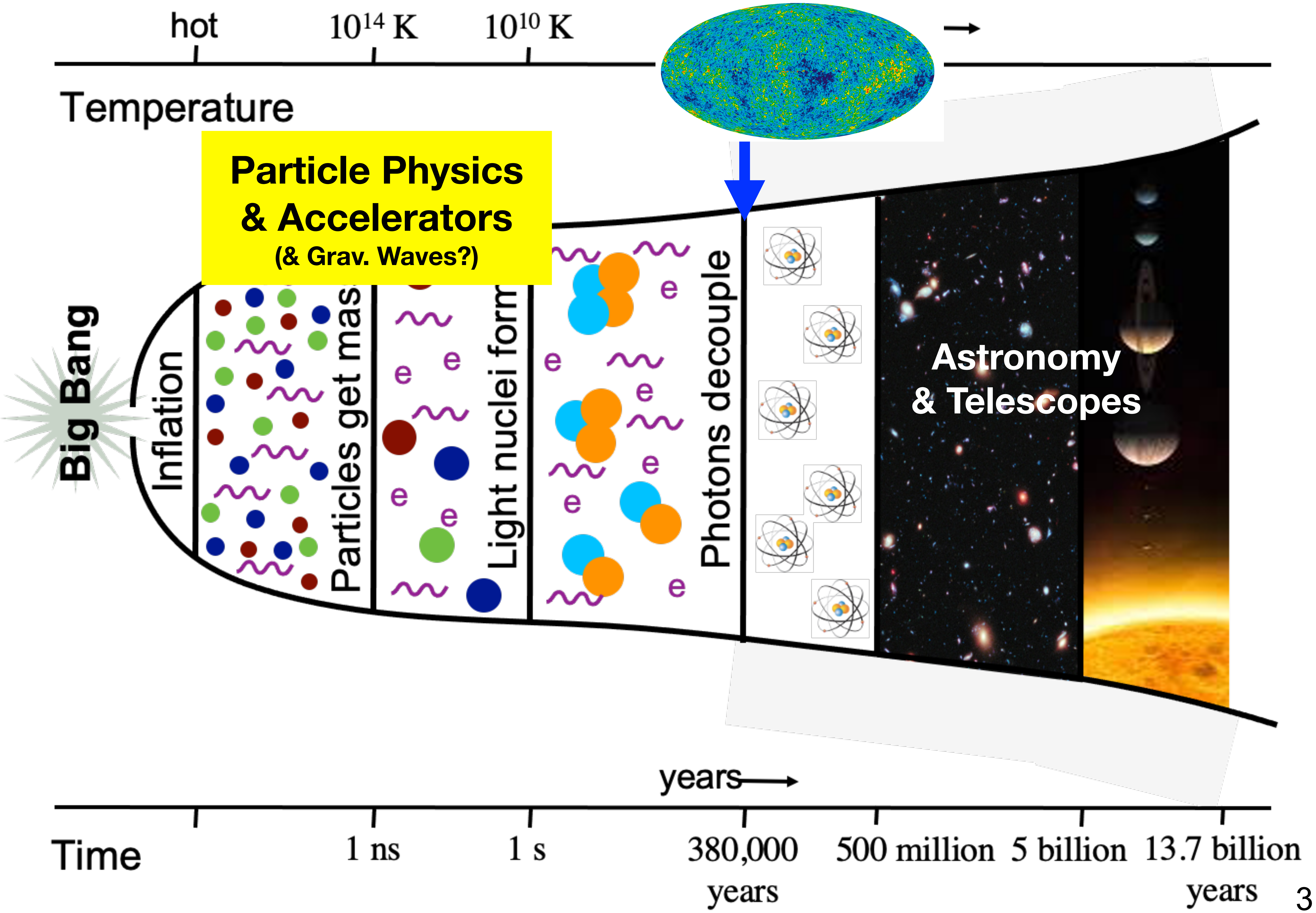

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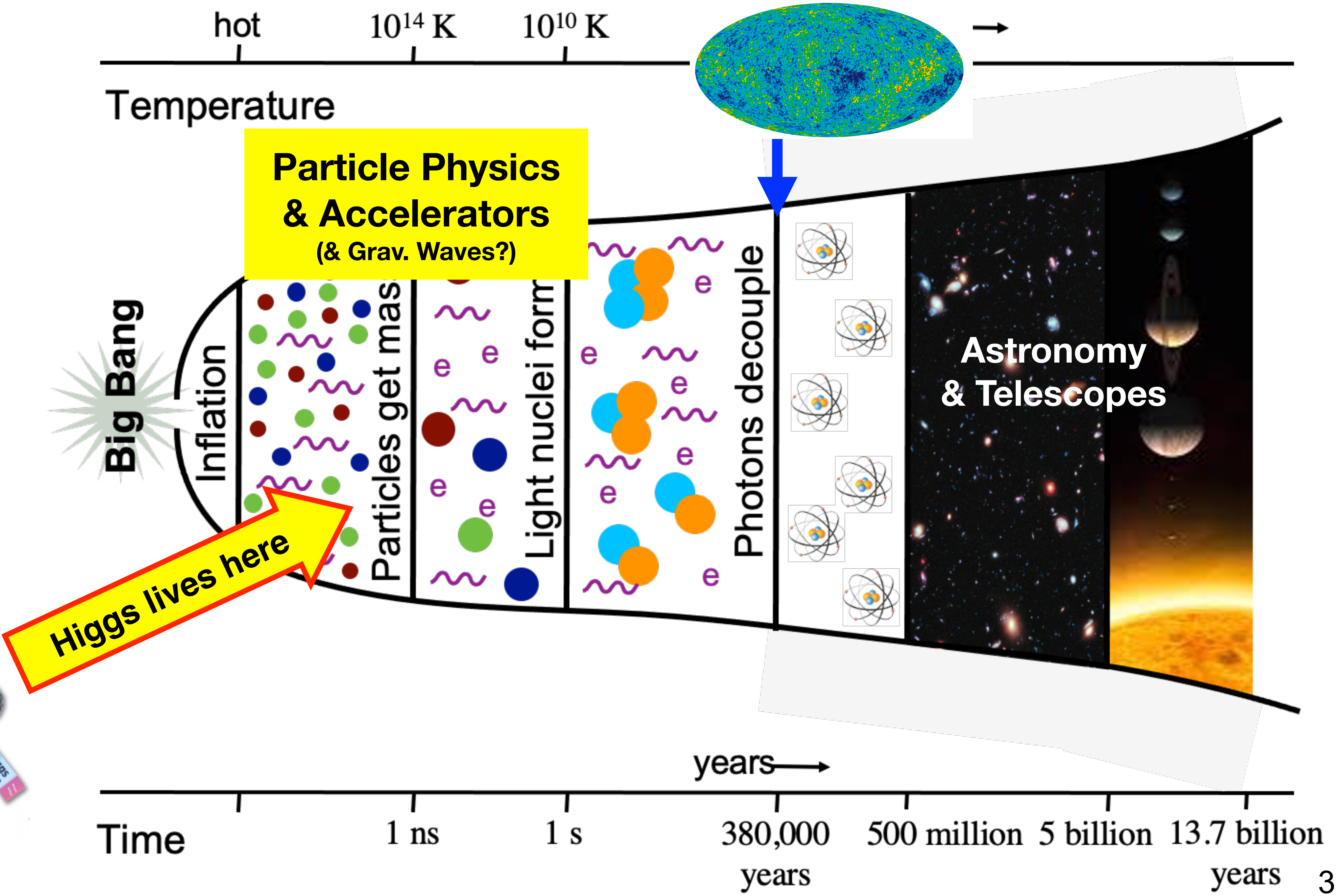

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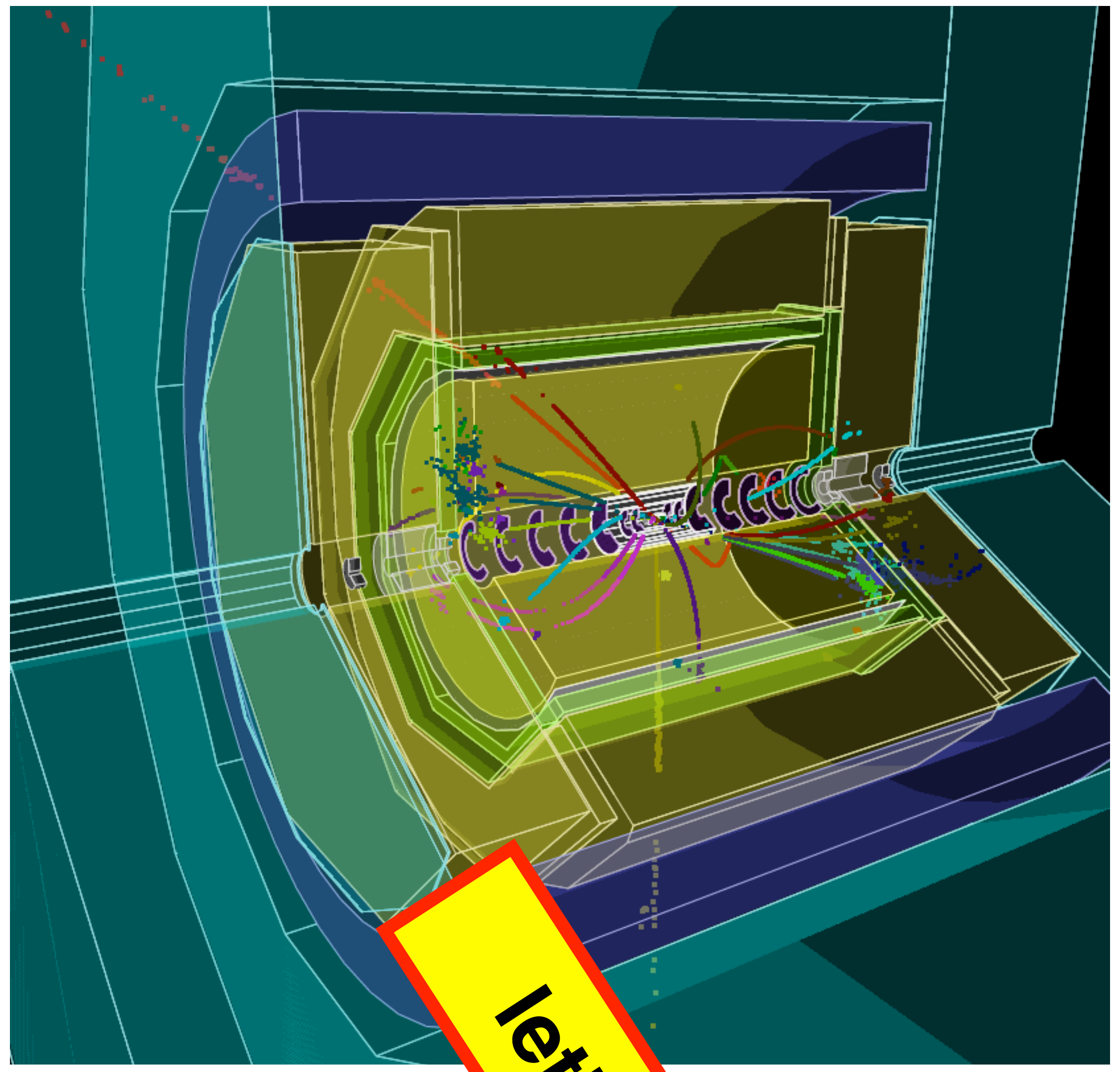
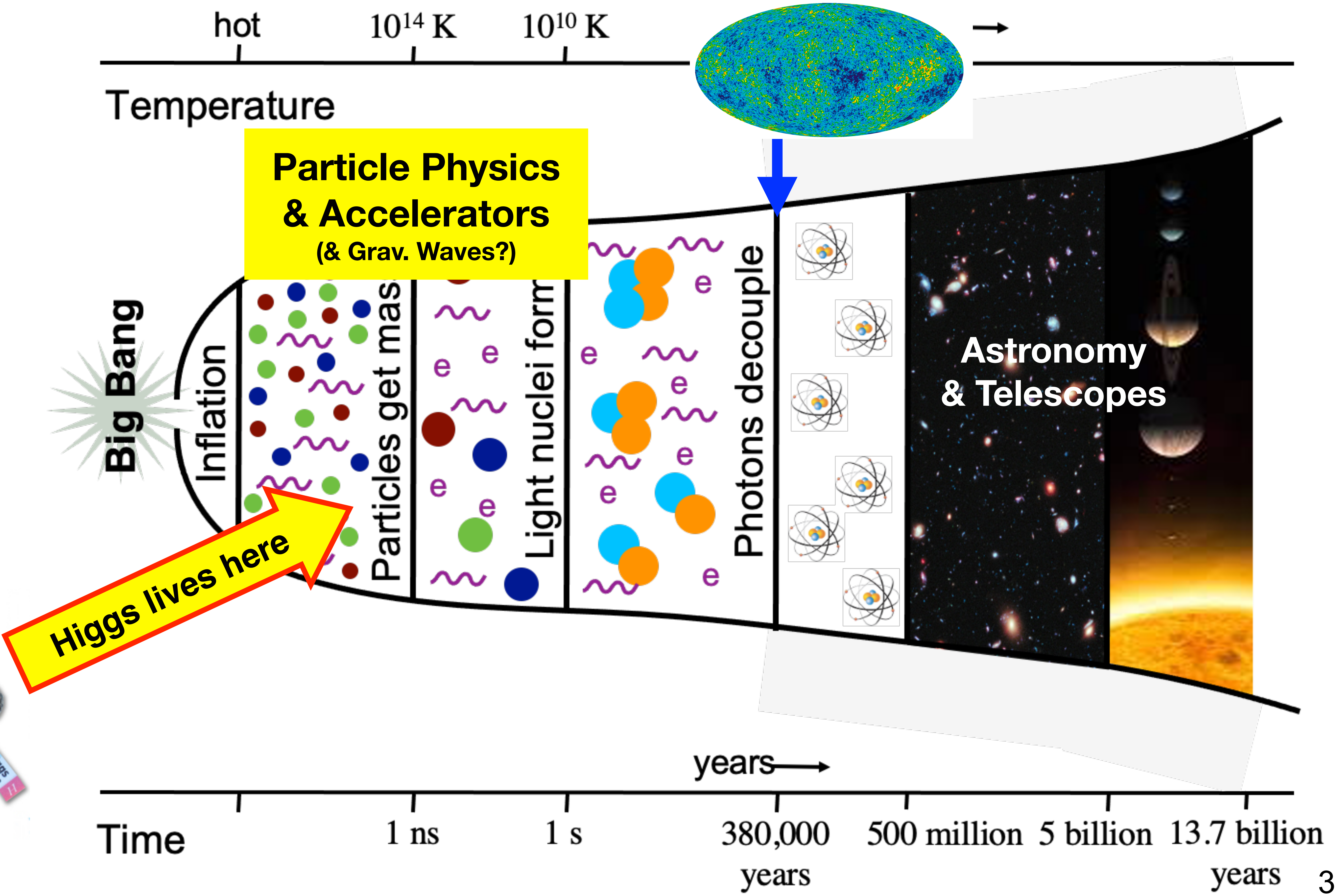
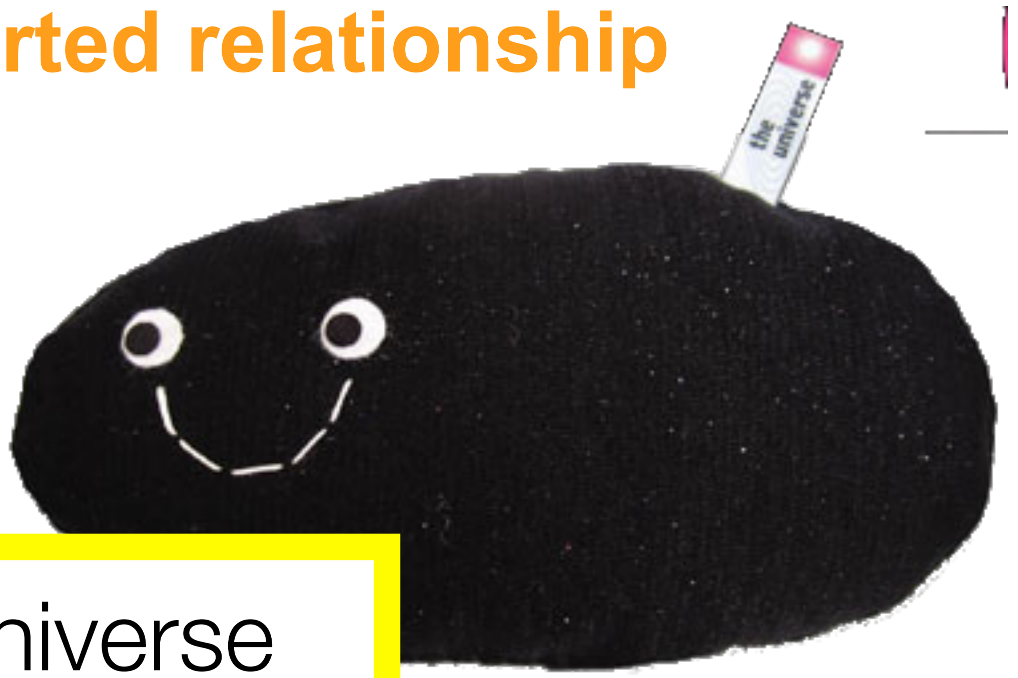




The Higgs Boson and the Universe

Exploration of an uncharted relationship



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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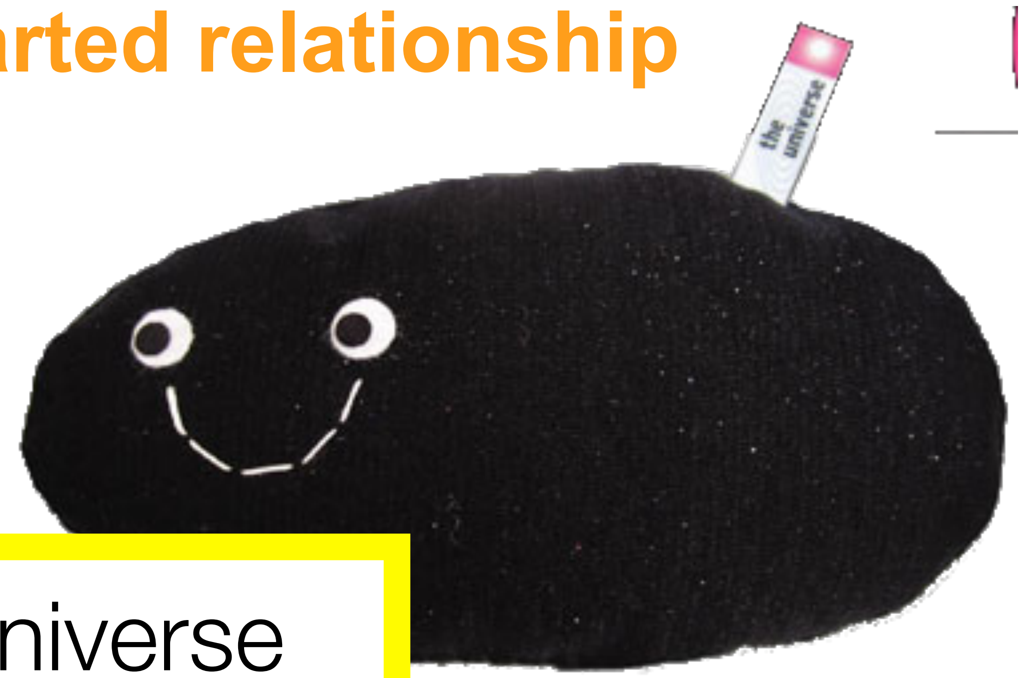

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Is the Higgs the portal to the Dark Sector?

- 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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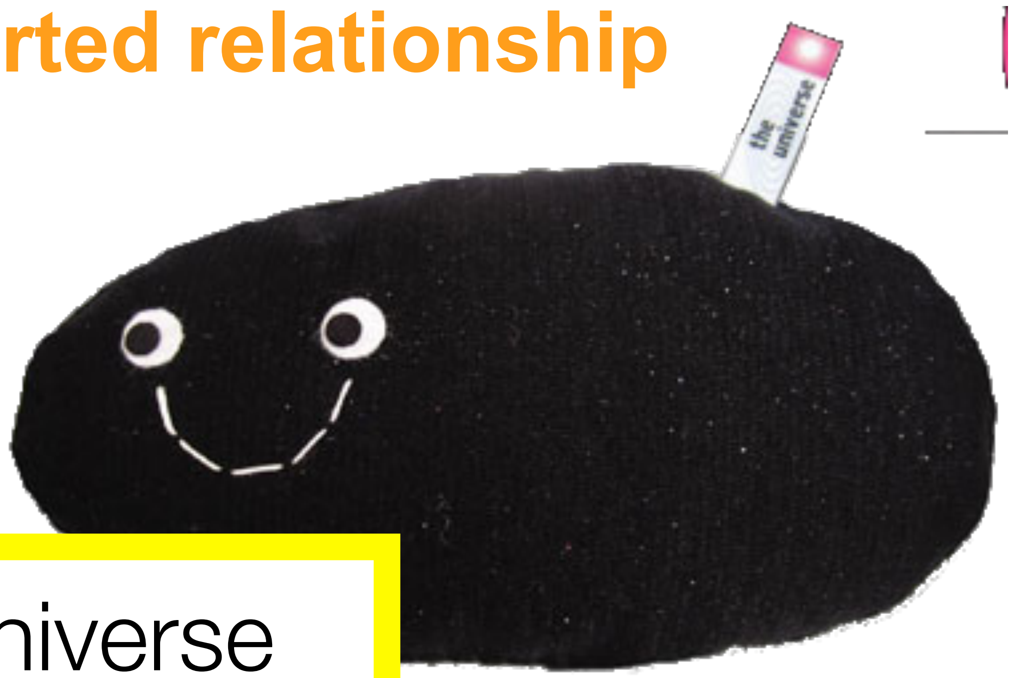

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Is the Higgs the portal to the Dark Sector?

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

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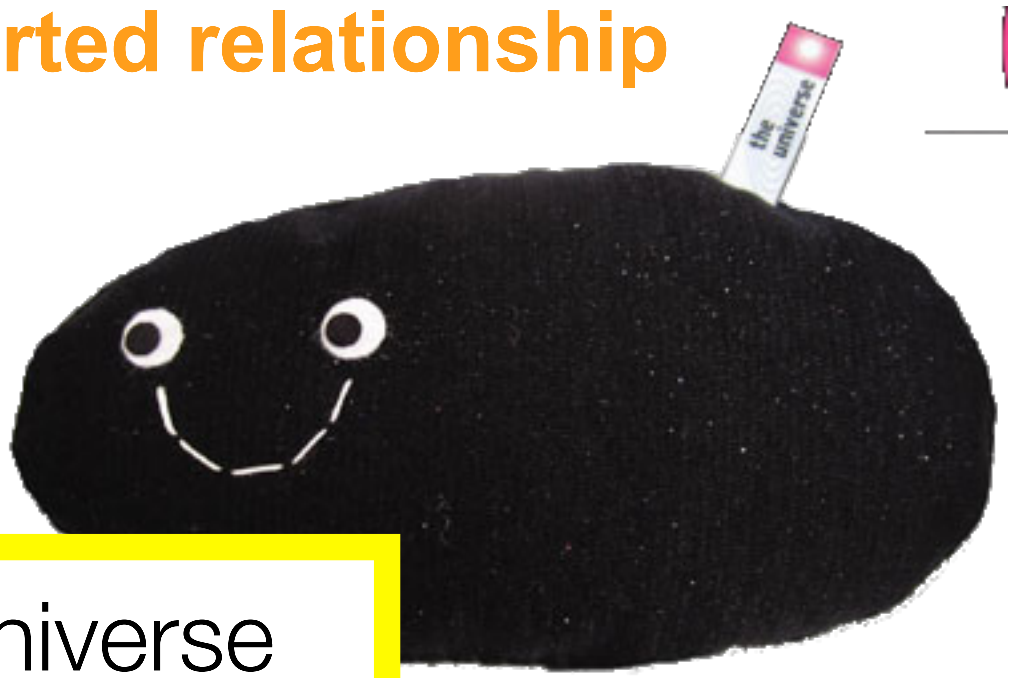

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Why is the Higgs-fermion interaction so different between the species?

- 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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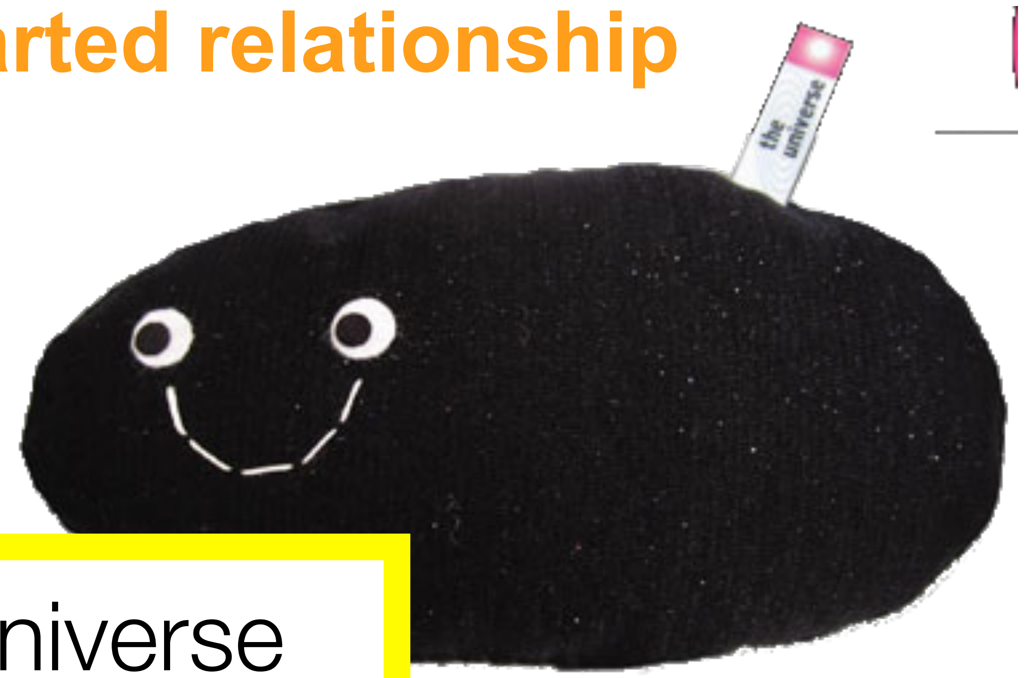

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Does the Higgs sector contain additional CP violation?

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

=> small contributions -> need precise measurements!

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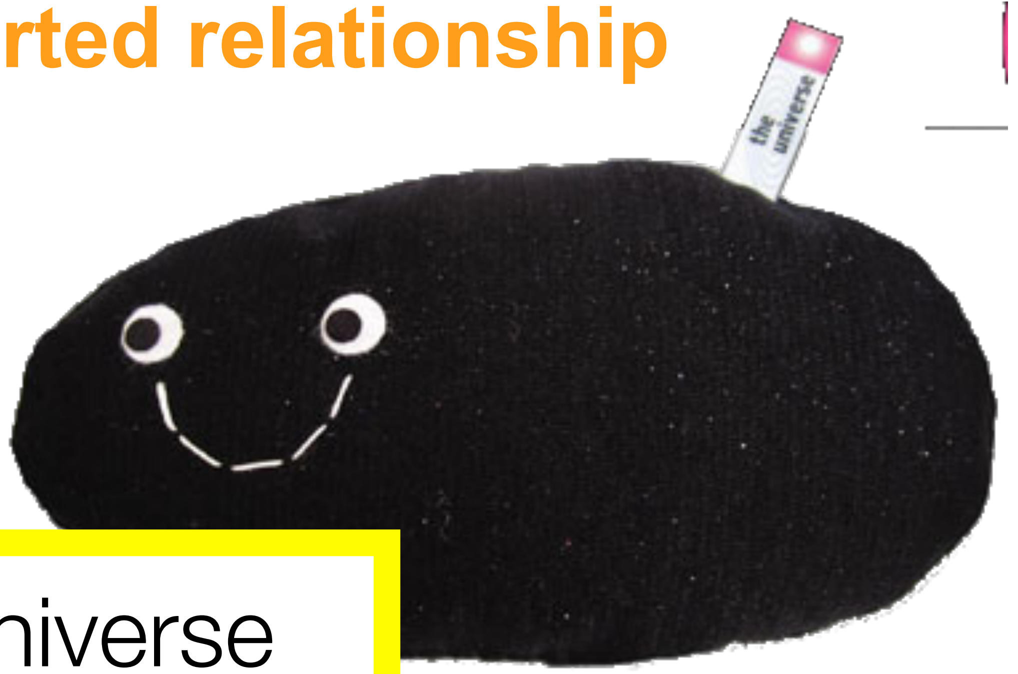

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What is the shape of the Higgs potential, and its evolution?

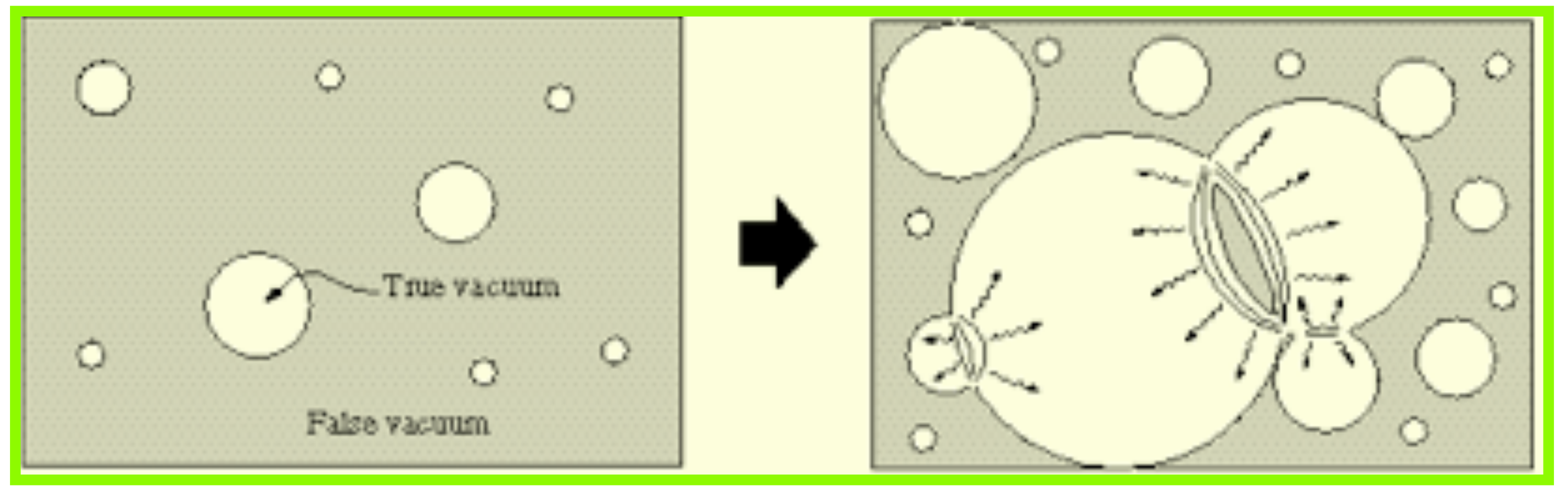
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

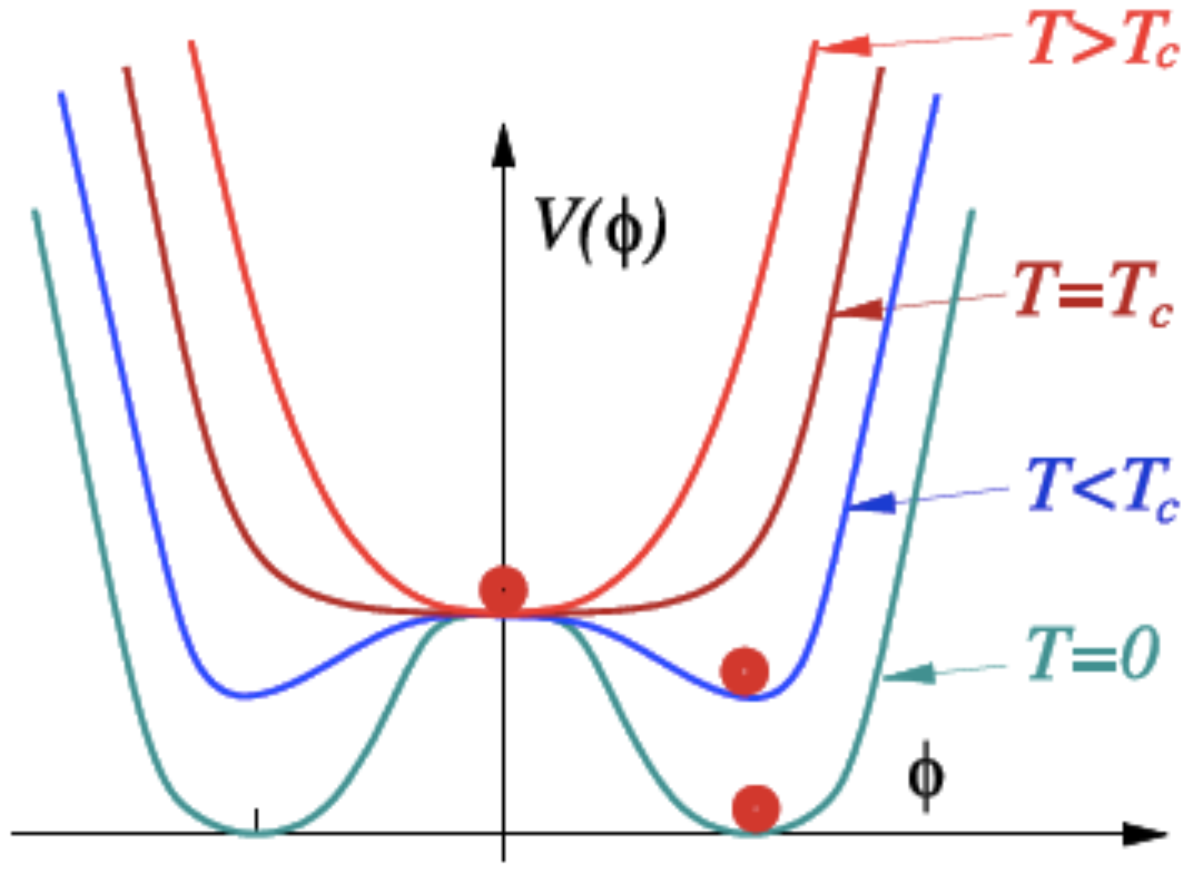
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

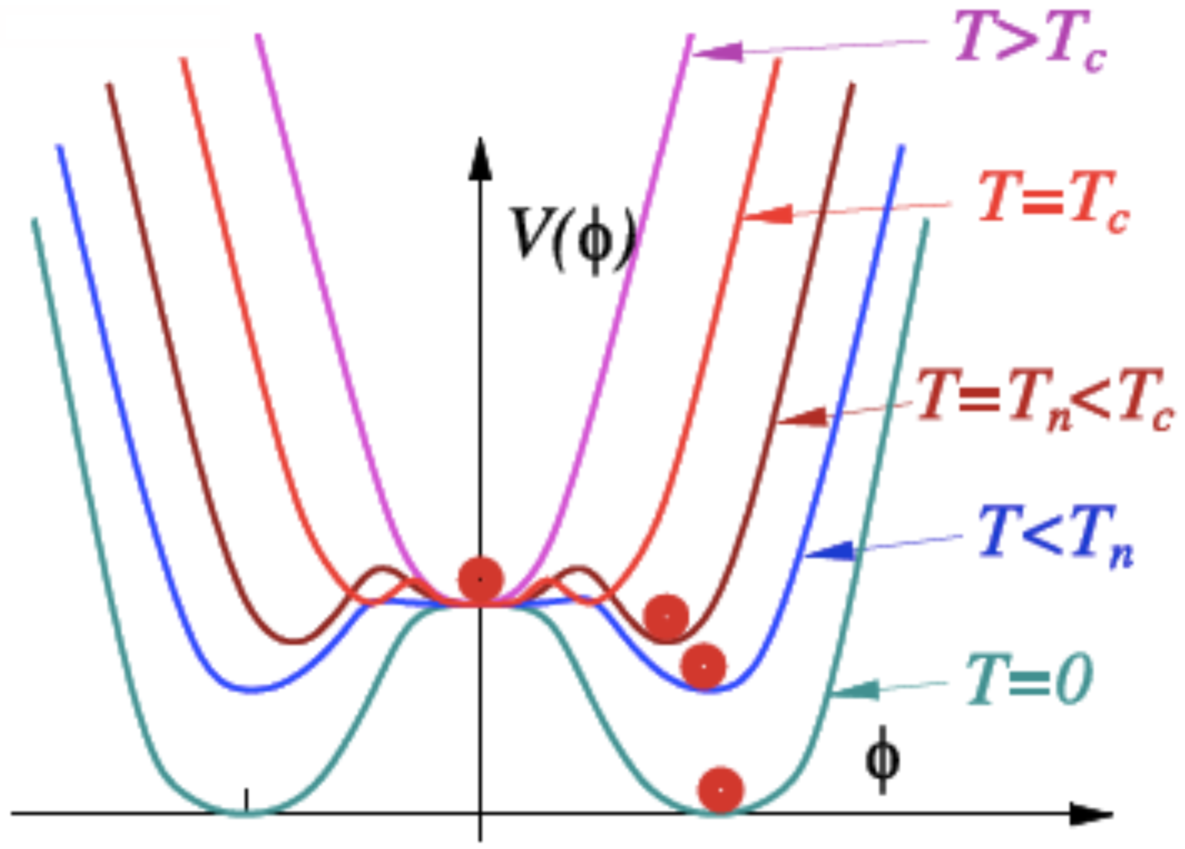
1st vs 2nd order phase transition

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





2nd order



1st order, requirement for EW baryogenesis

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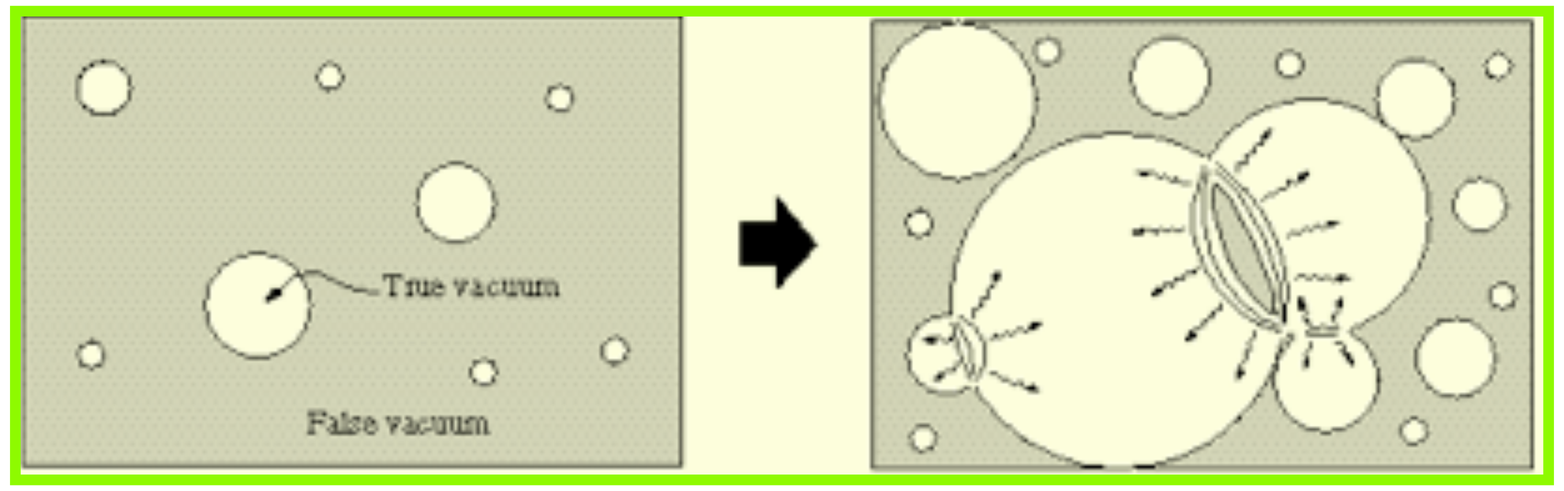

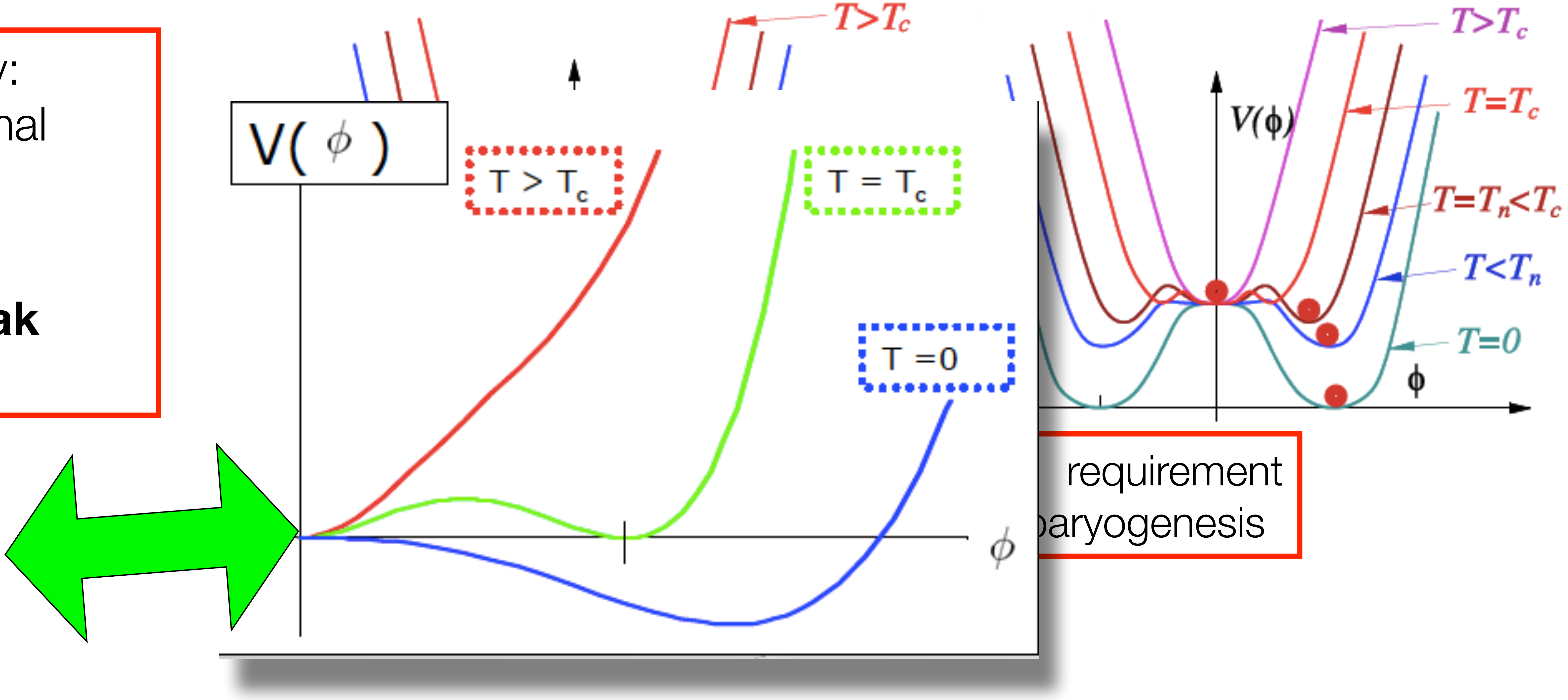

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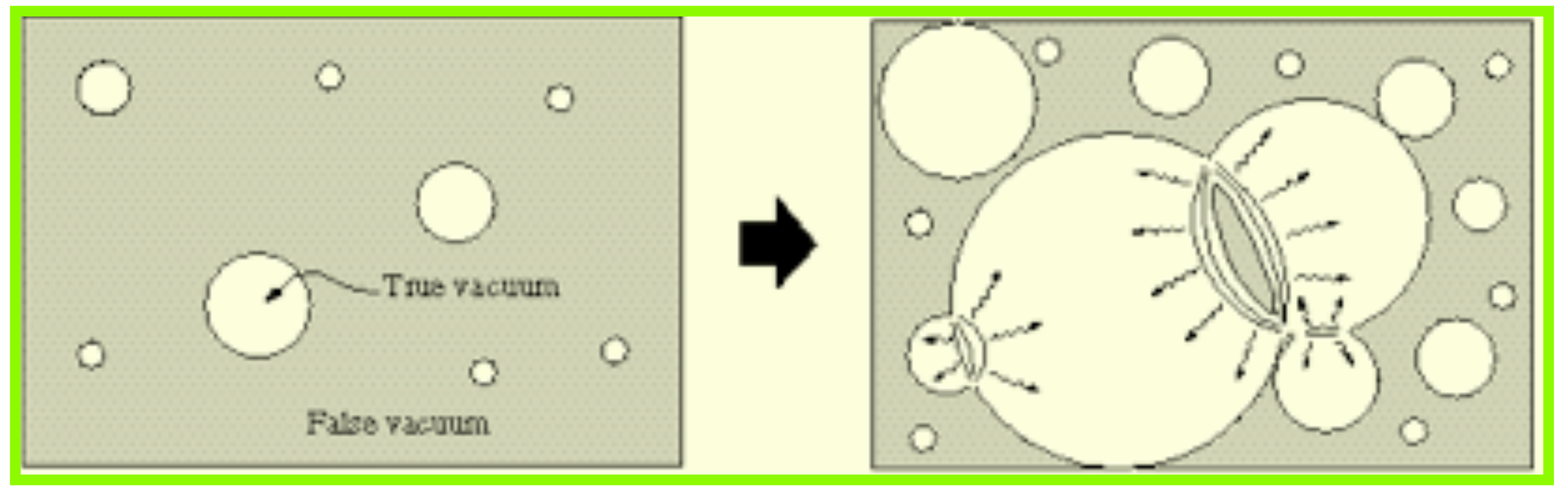

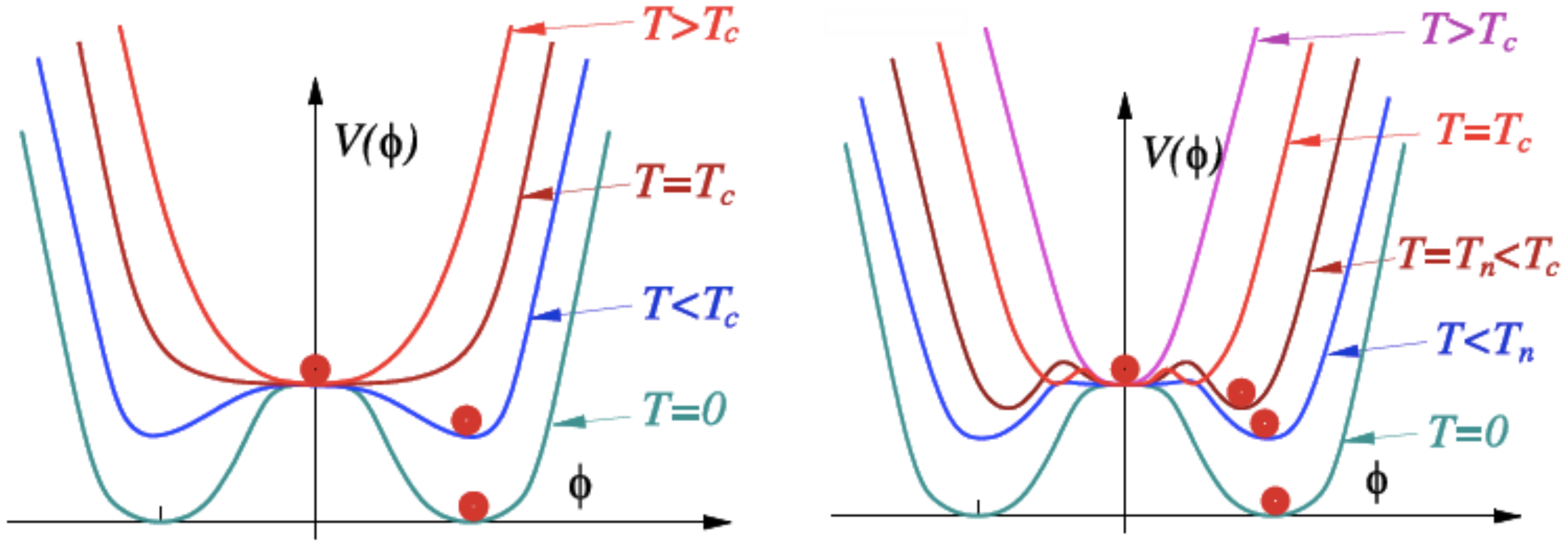

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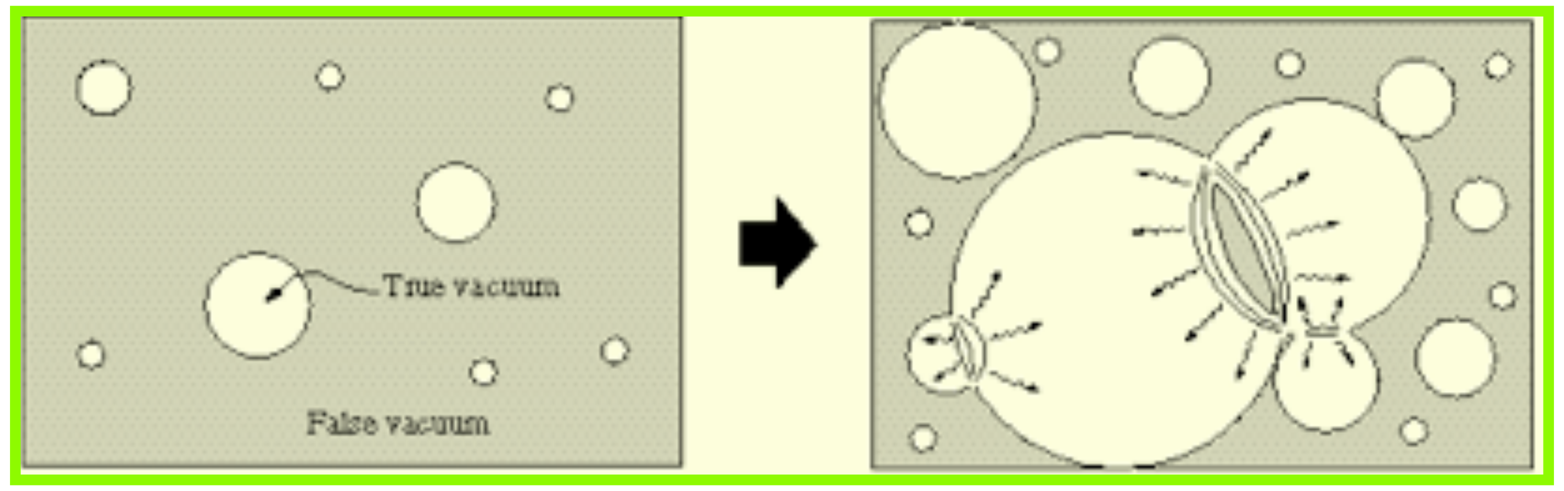

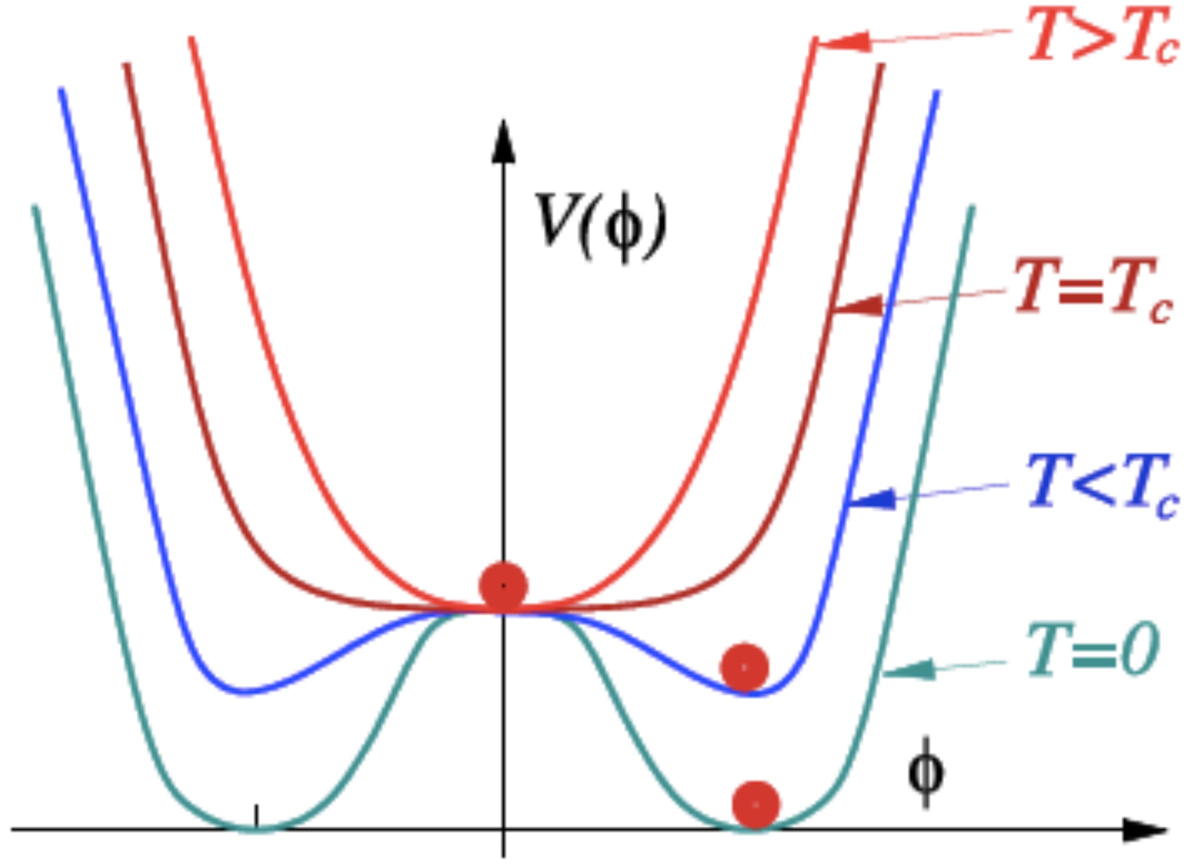

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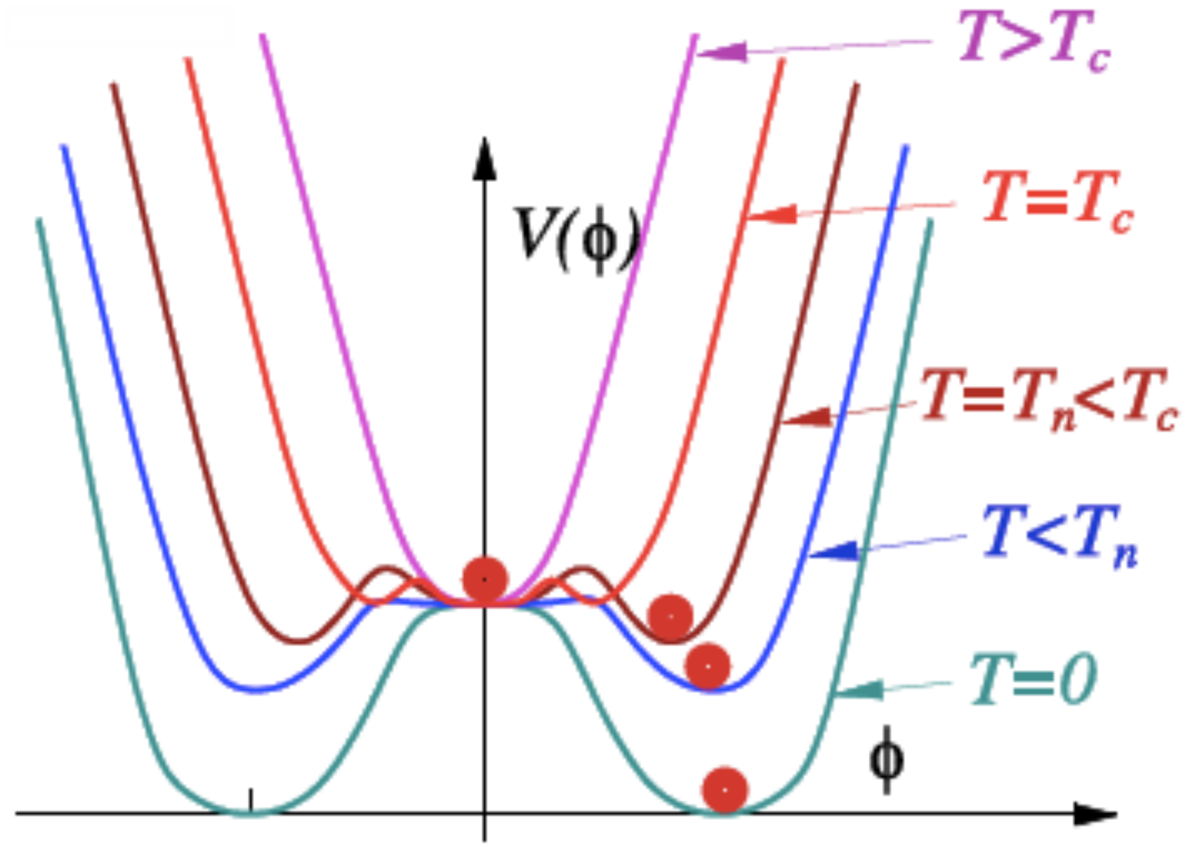

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- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
- electroweak baryogenesis possible in BSM scenarions with $\lambda > \lambda_{SM}$ (e.g. 2HDM, NMSSM, …)

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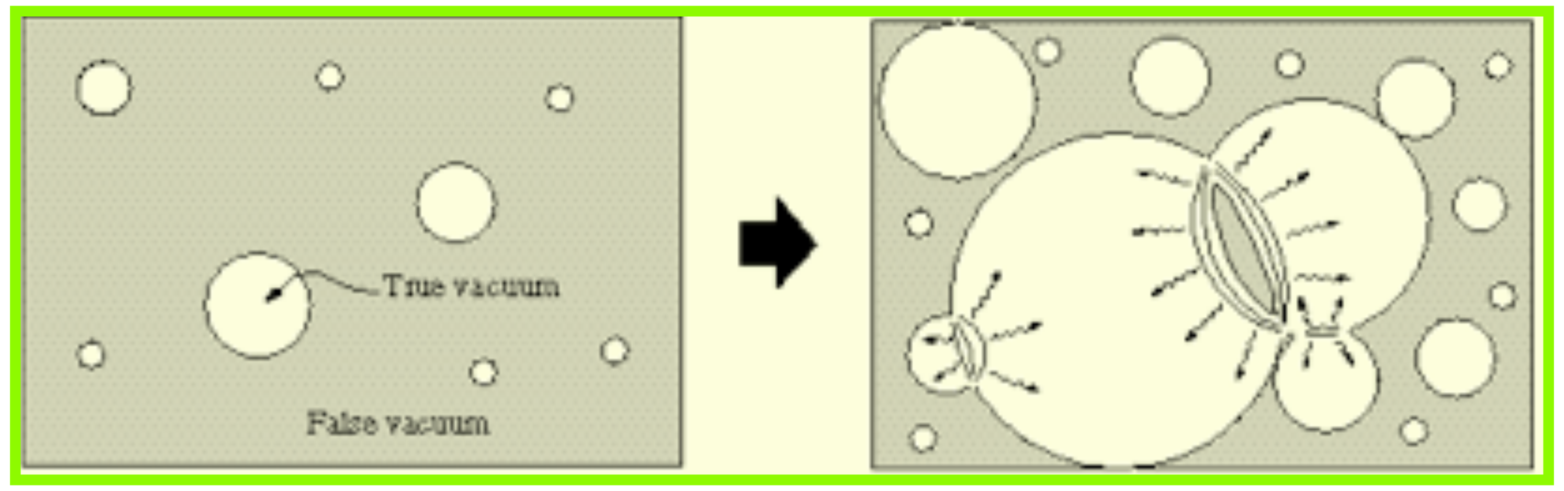

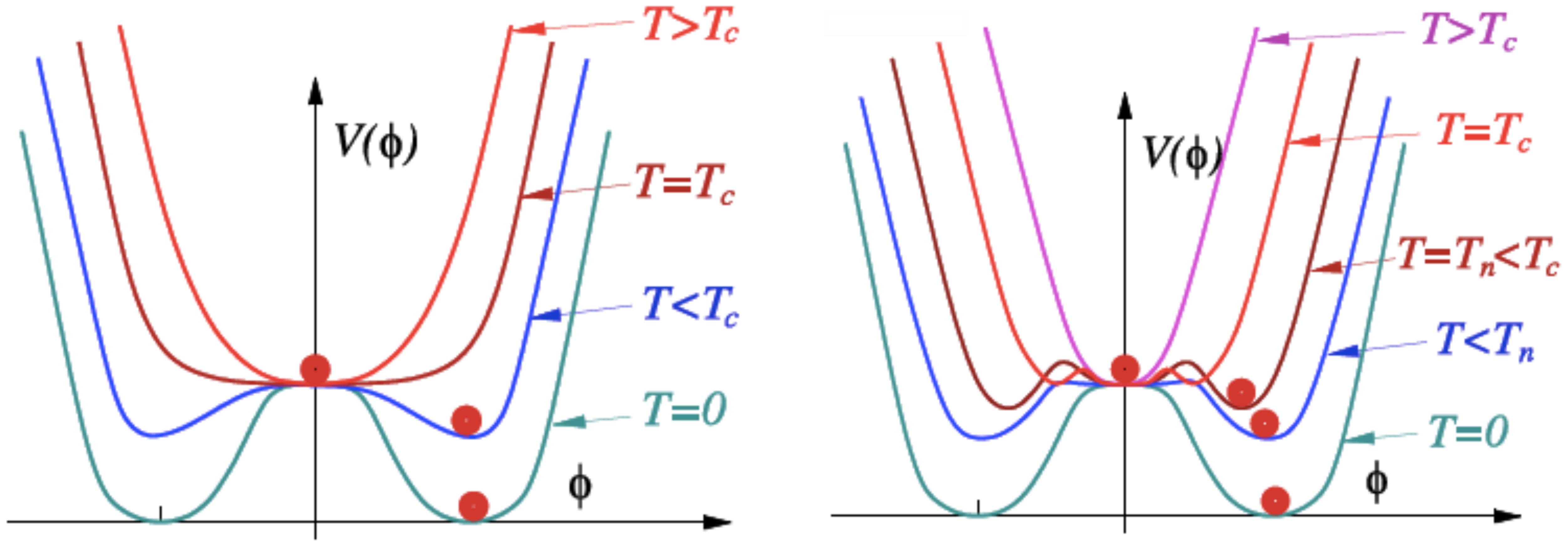

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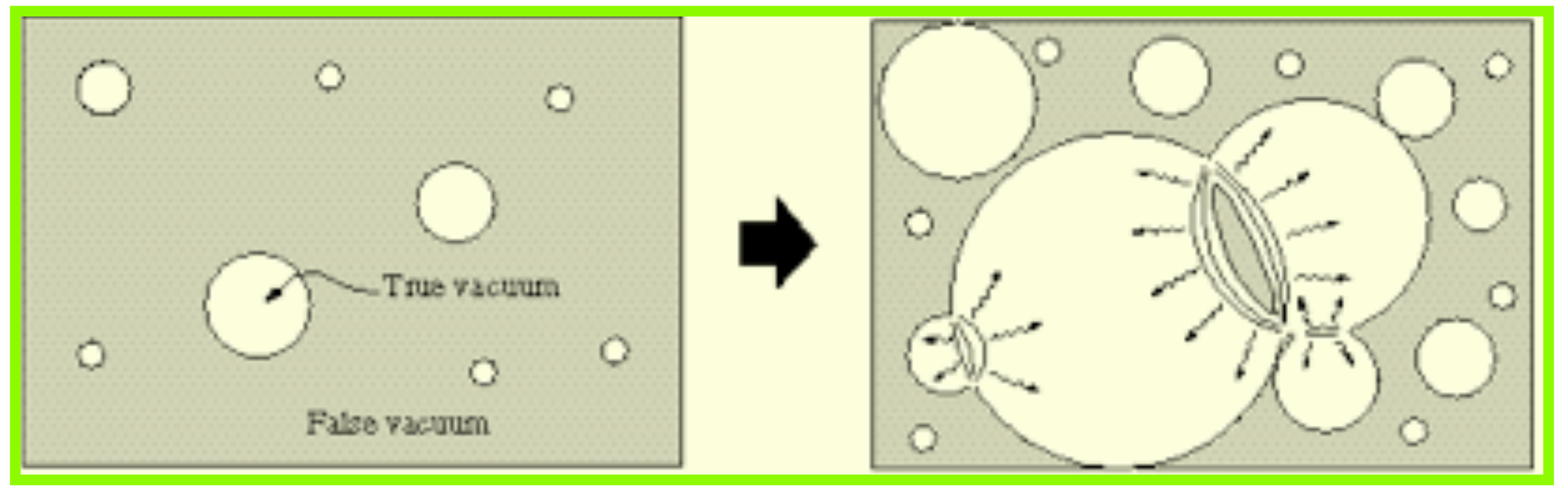

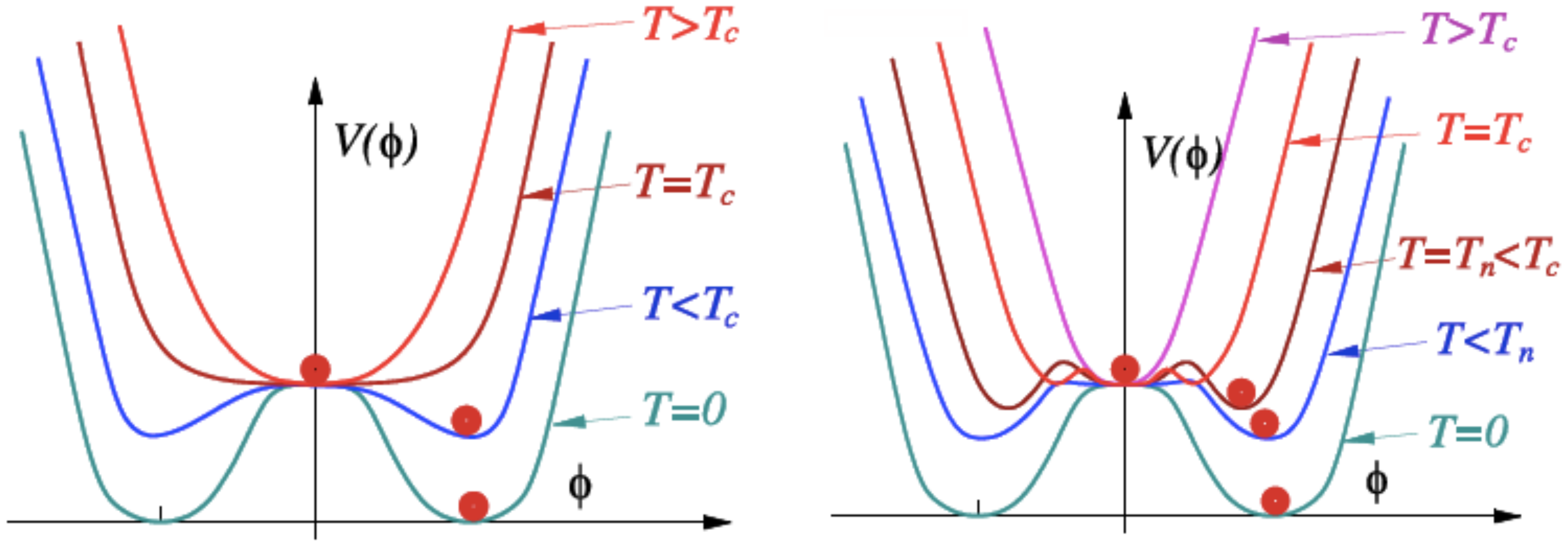

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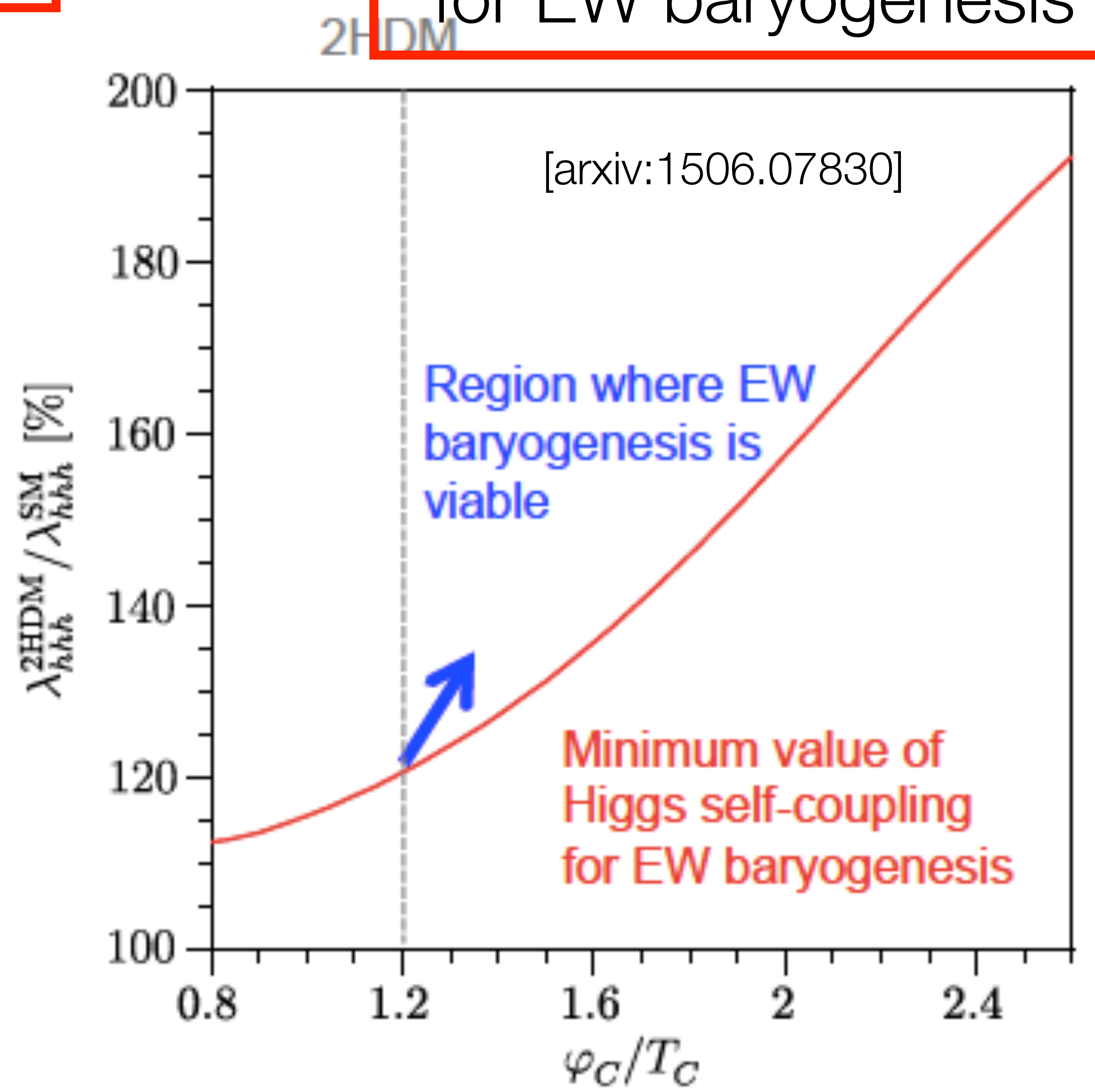

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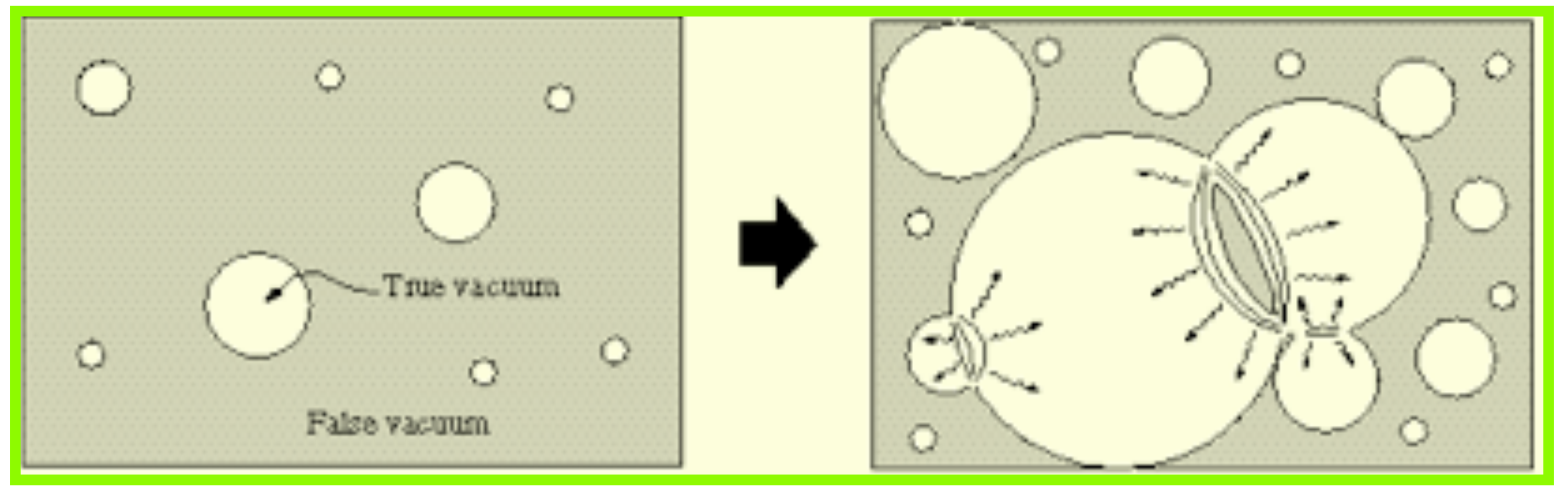

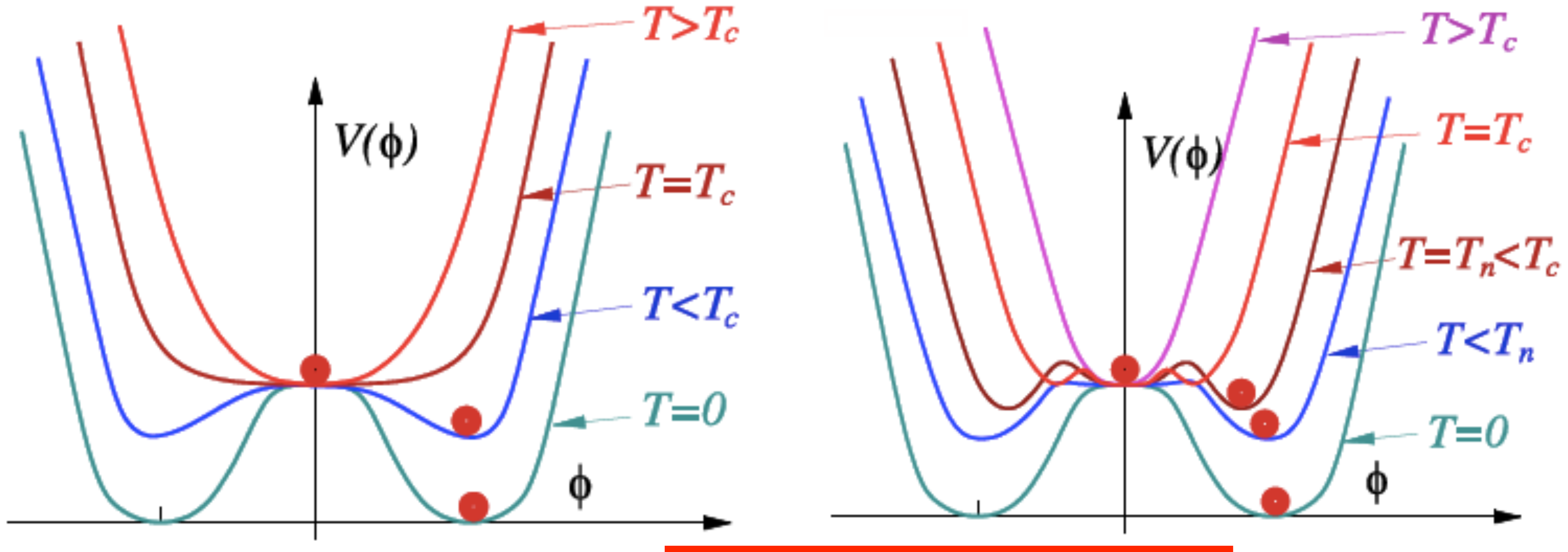

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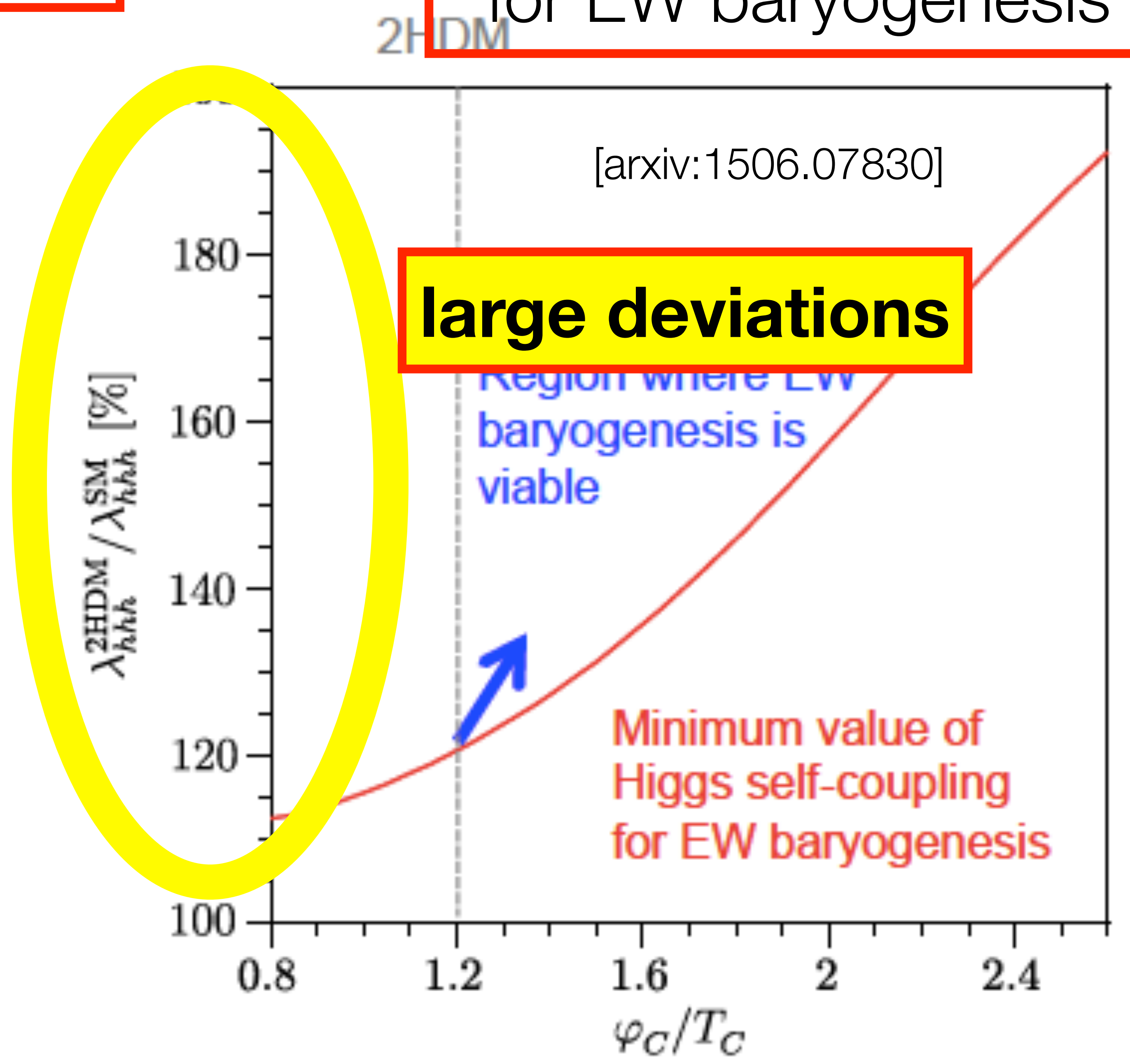

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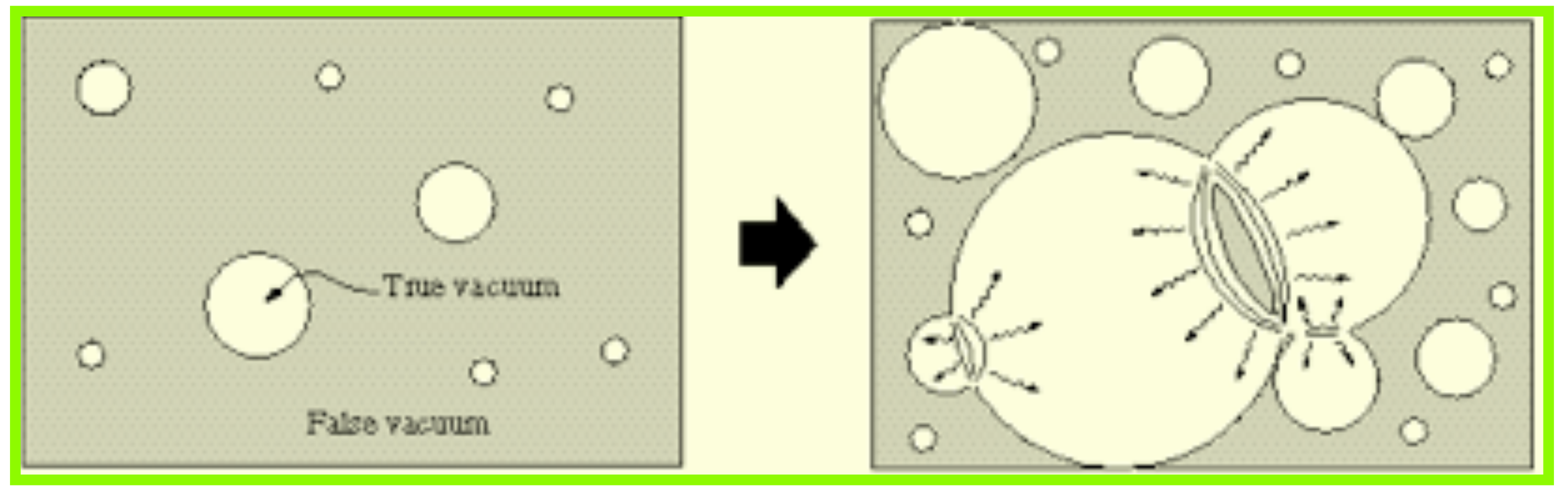

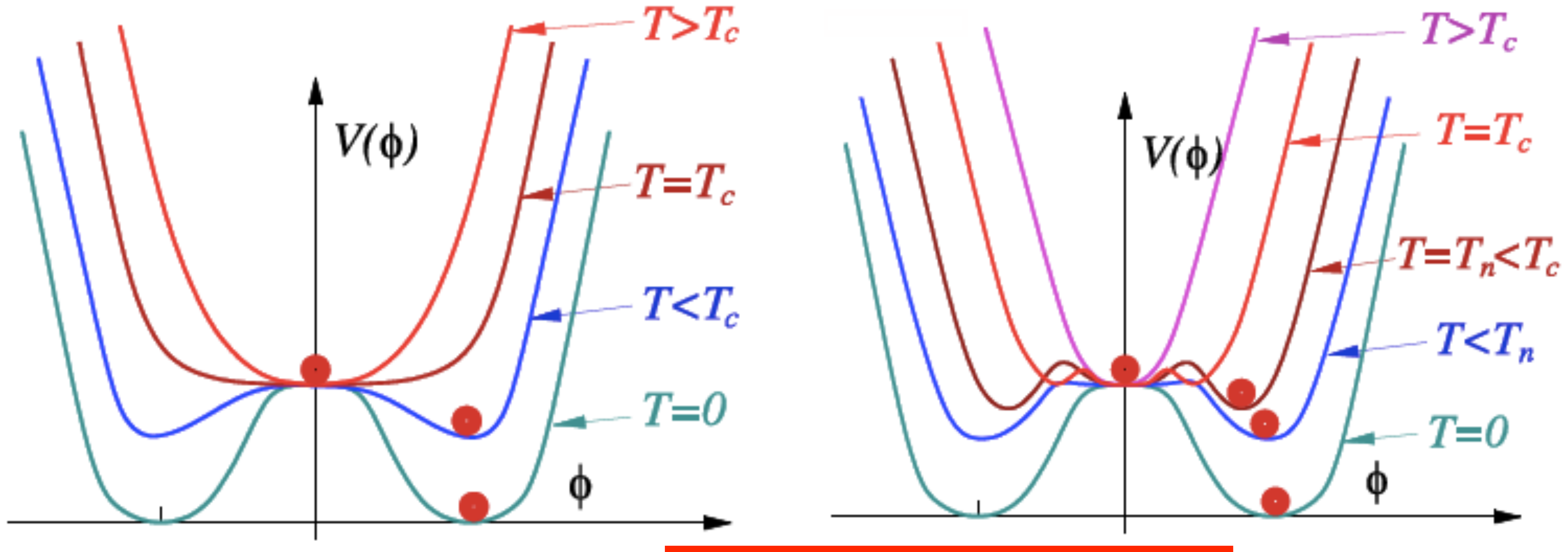

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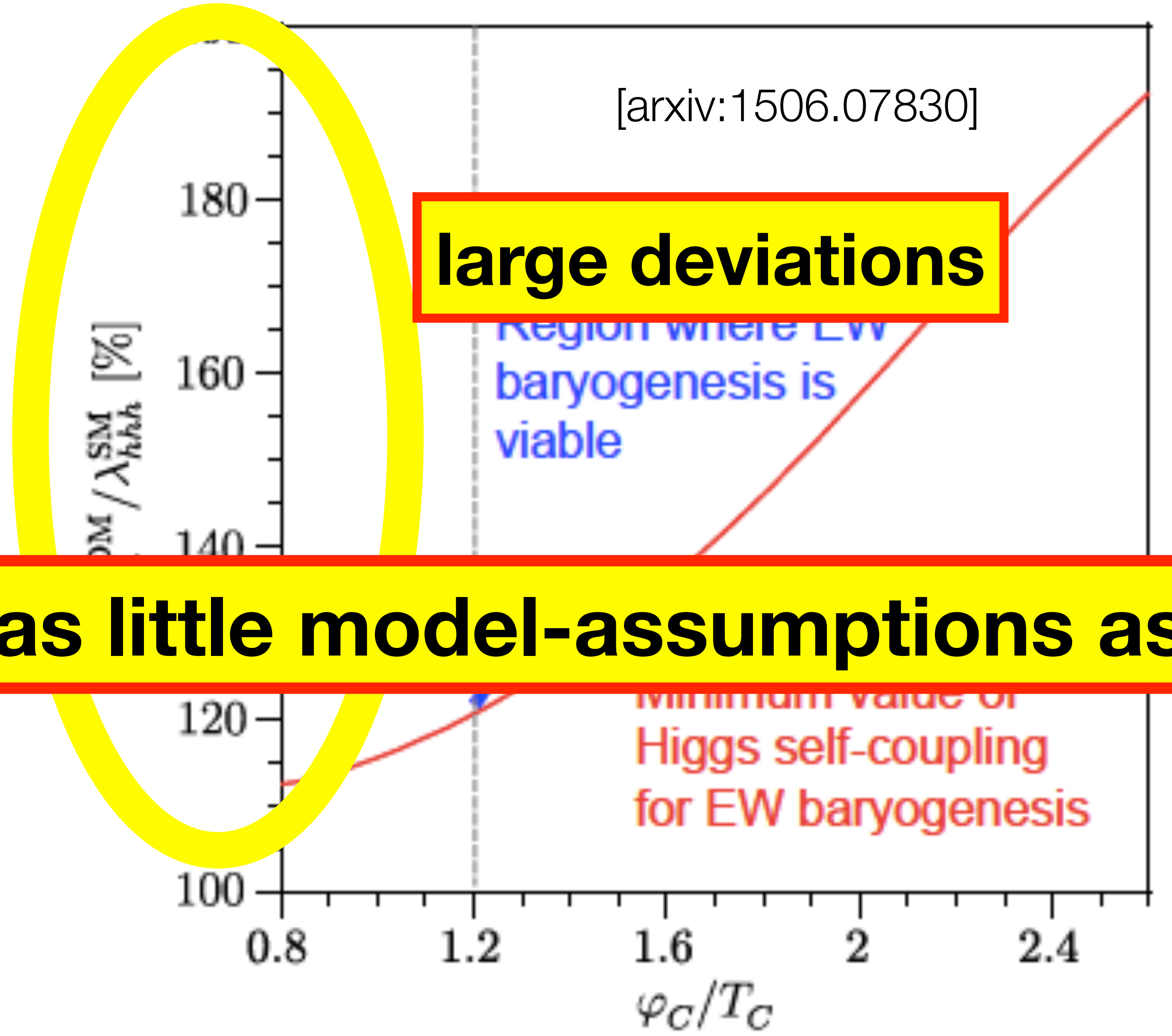

large deviations

=> measure λ, with as little model-assumptions as possible!

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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=> 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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- clean events
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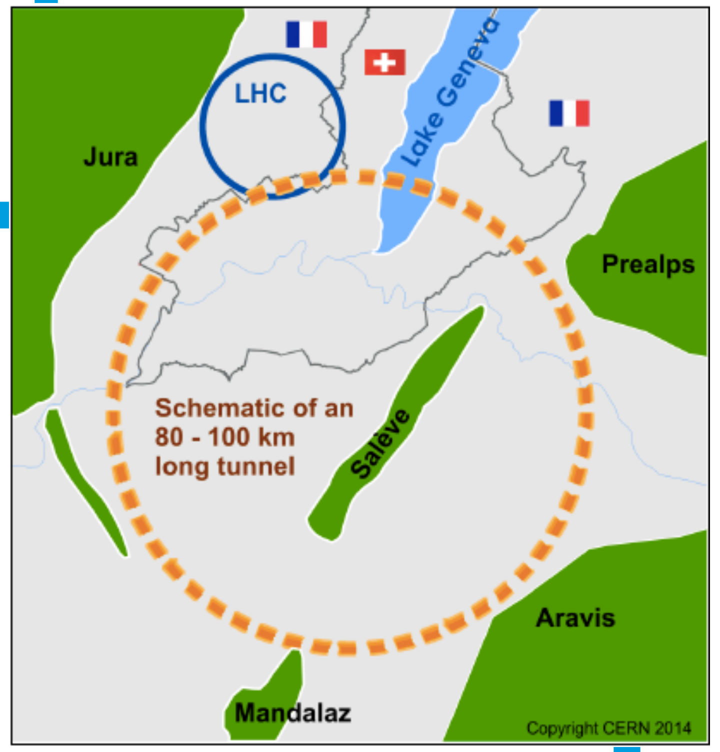
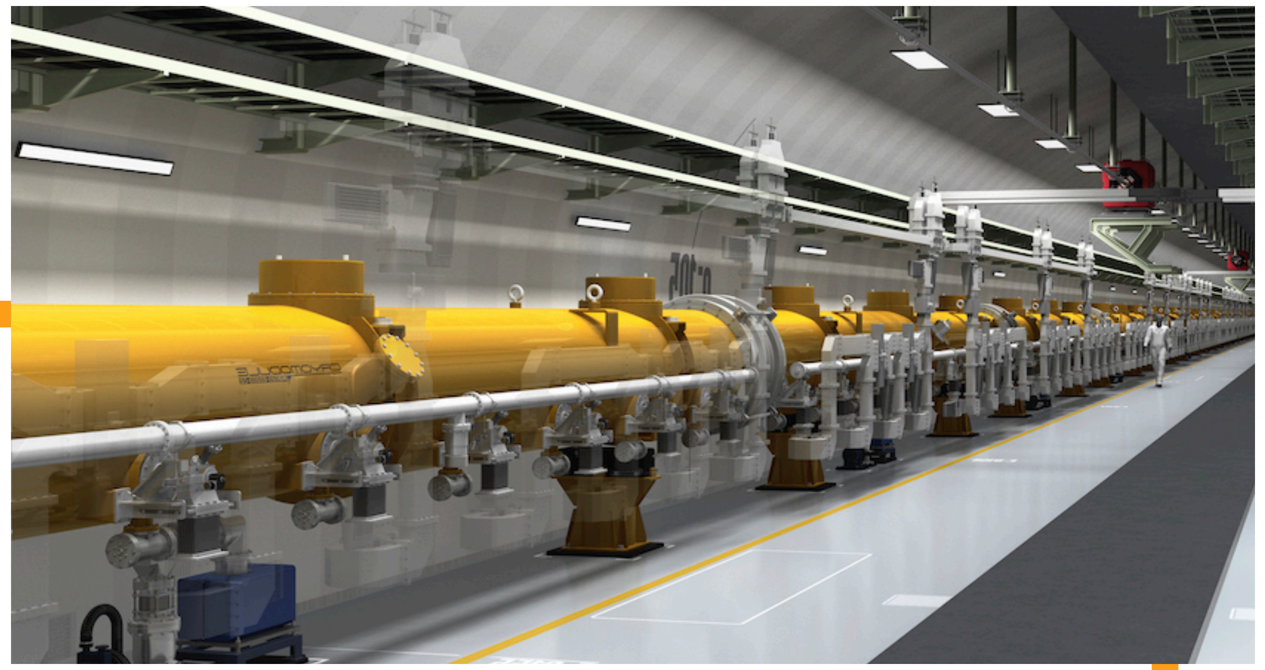
There are several proposed Higgs factories

Each have their advantages



Circular e+e- Colliders

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



Linear Colliders

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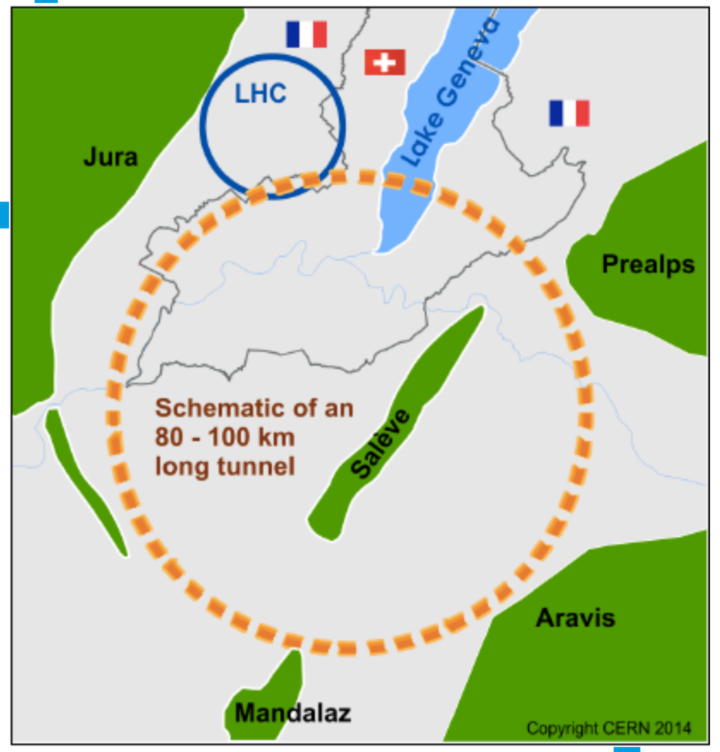

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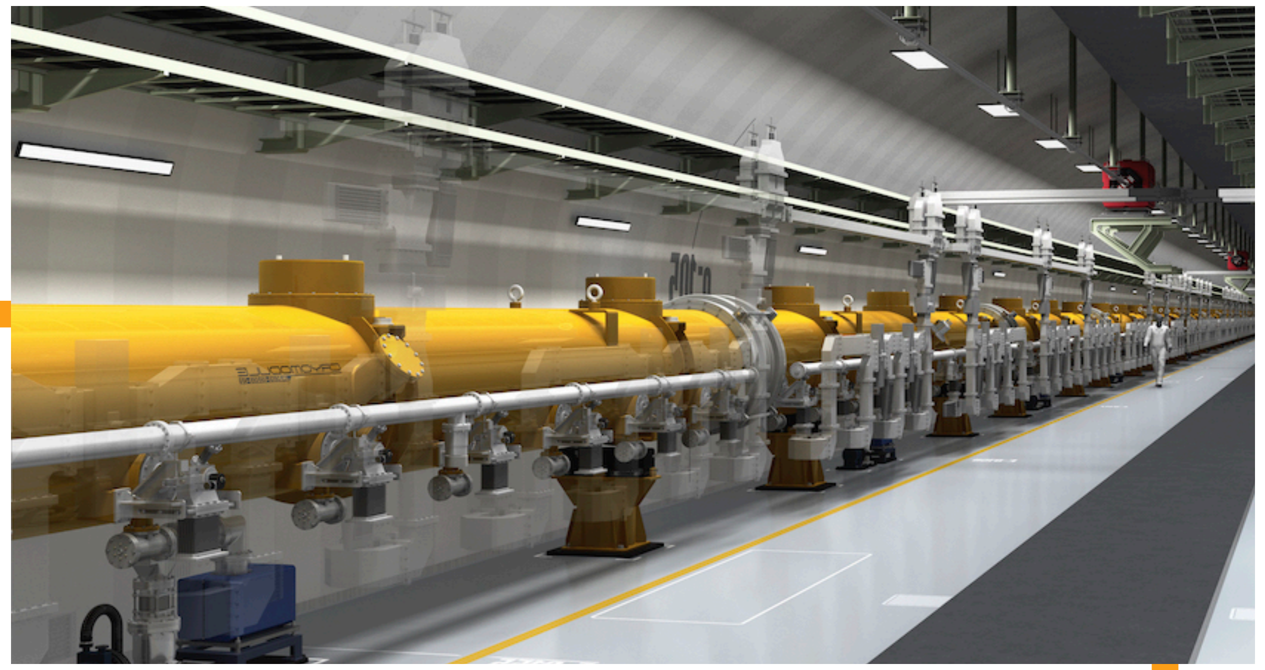

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Long-term vision: re-use of tunnel for pp collider

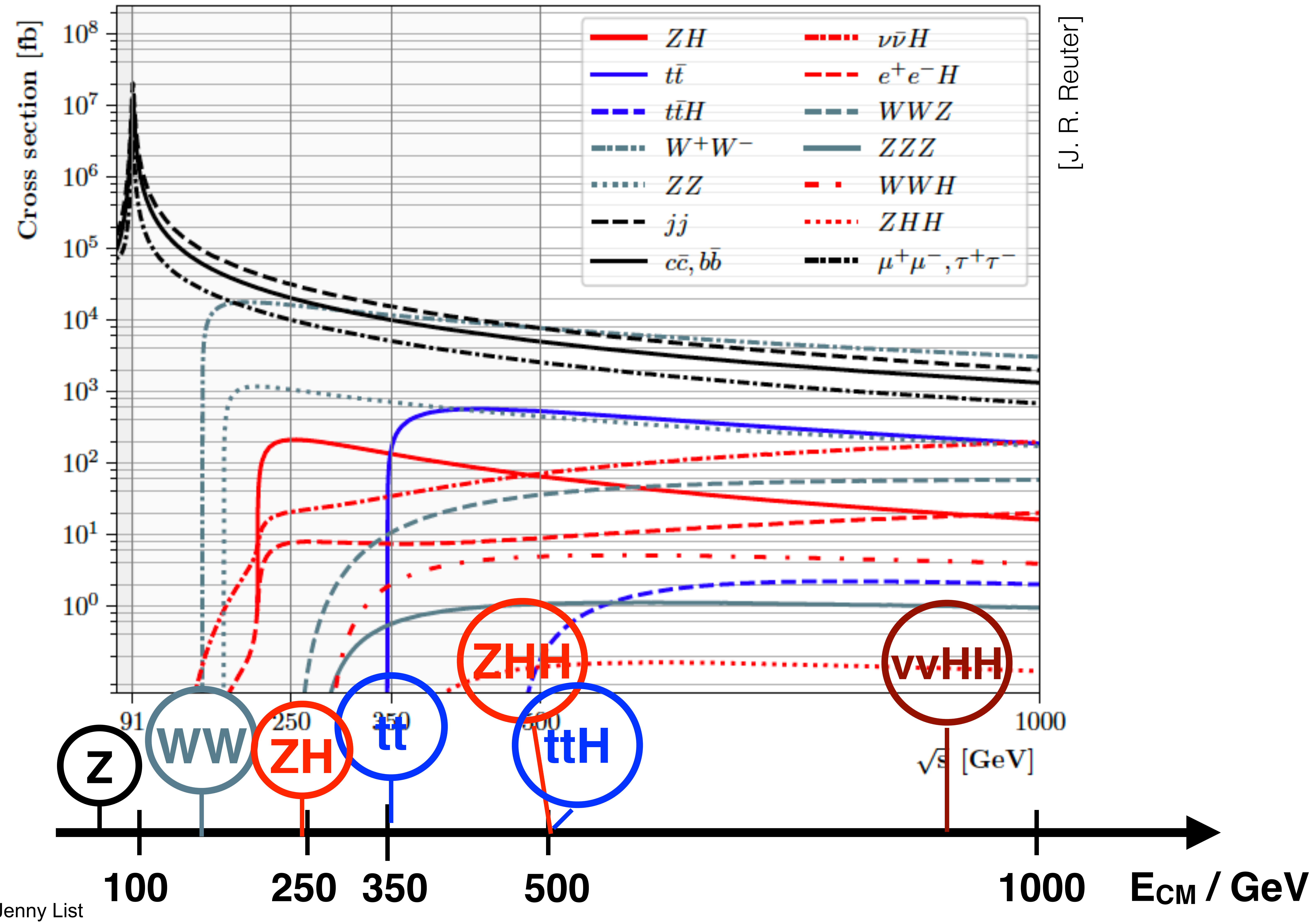
- technical and financial feasibility of required magnets still unclear

Long-term upgrades: energy extendability

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

Particle production thresholds in e+e- collisions

Production rates vs collision energy



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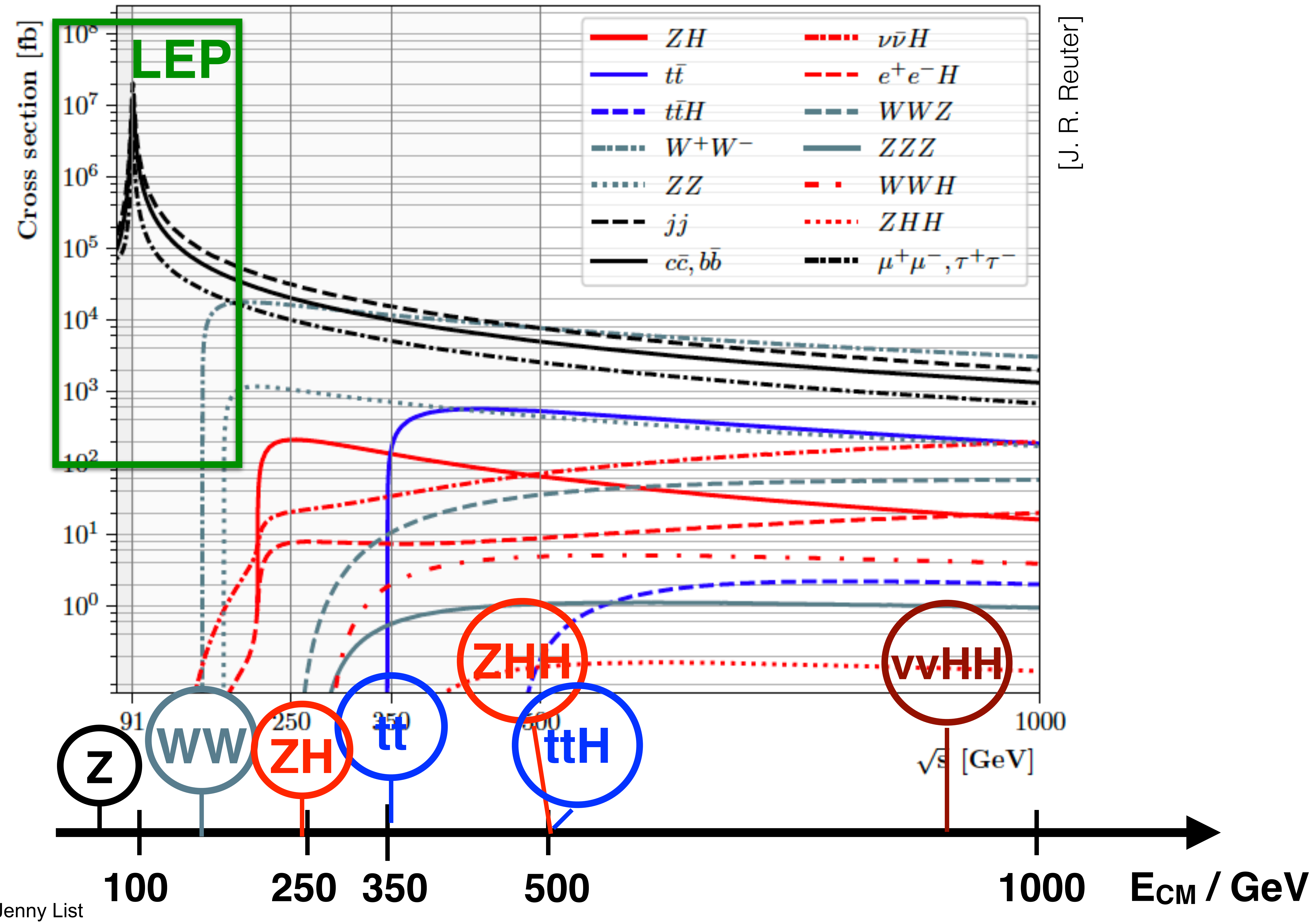
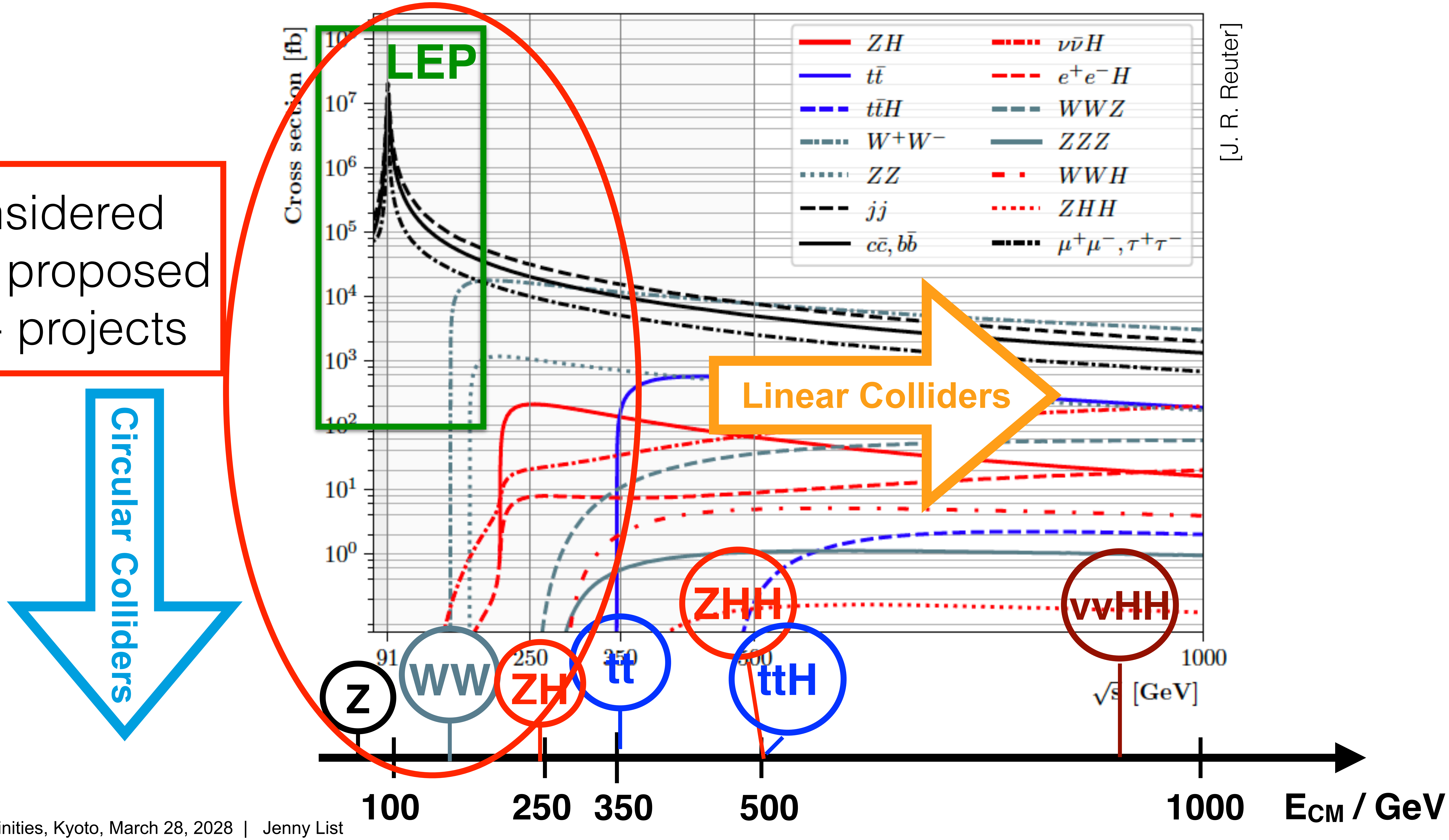


Particle production thresholds in e+e- collisions

Production rates vs collision energy

considered
by all proposed
e+e- projects



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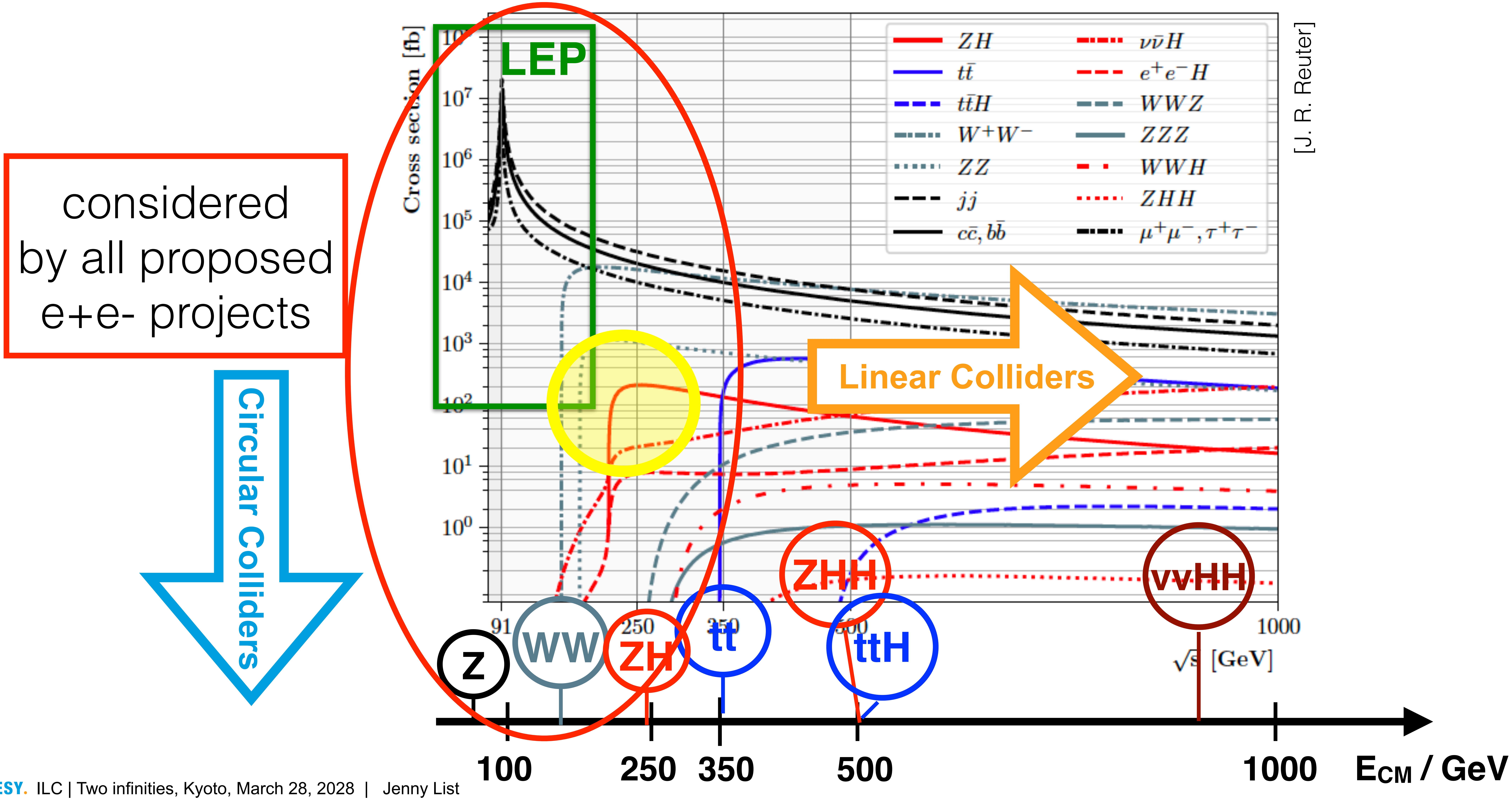


Absolute Higgs Production Rate

Absolute normalisation of Higgs couplings & total decay width

- Higgs factory at 250 GeV: **e+e- → ZH**
- **can measure its total cross section: *the key*** to model-independent determination of **absolute** couplings
- measurable independently of Higgs decays modes via **recoil technique**
- only possible at e+e- collider due **to known momentum of colliding particles**
- **enables a plethora of further precision measurements**

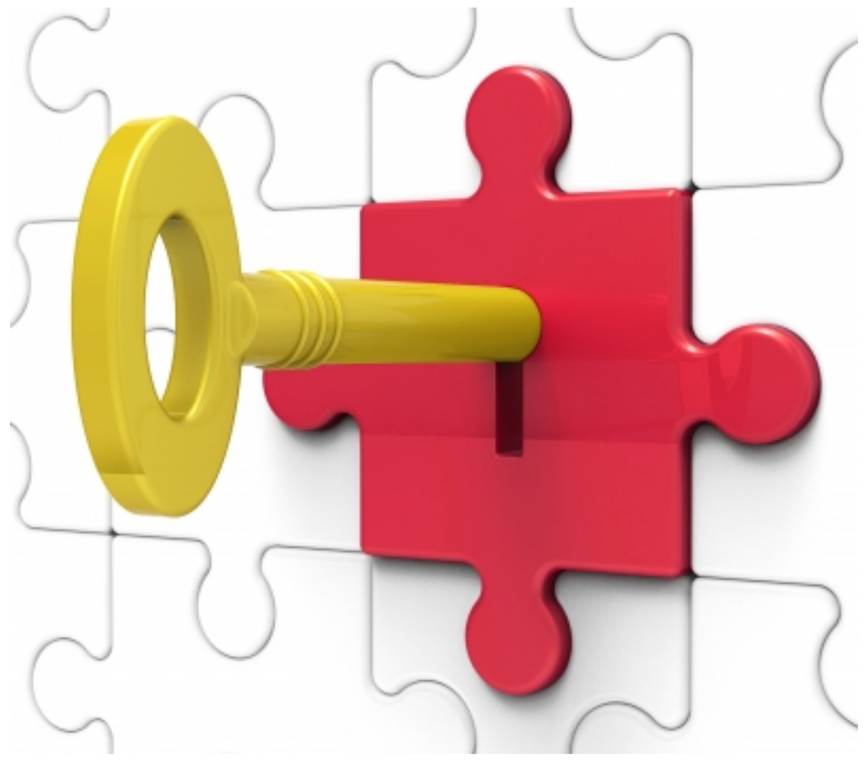
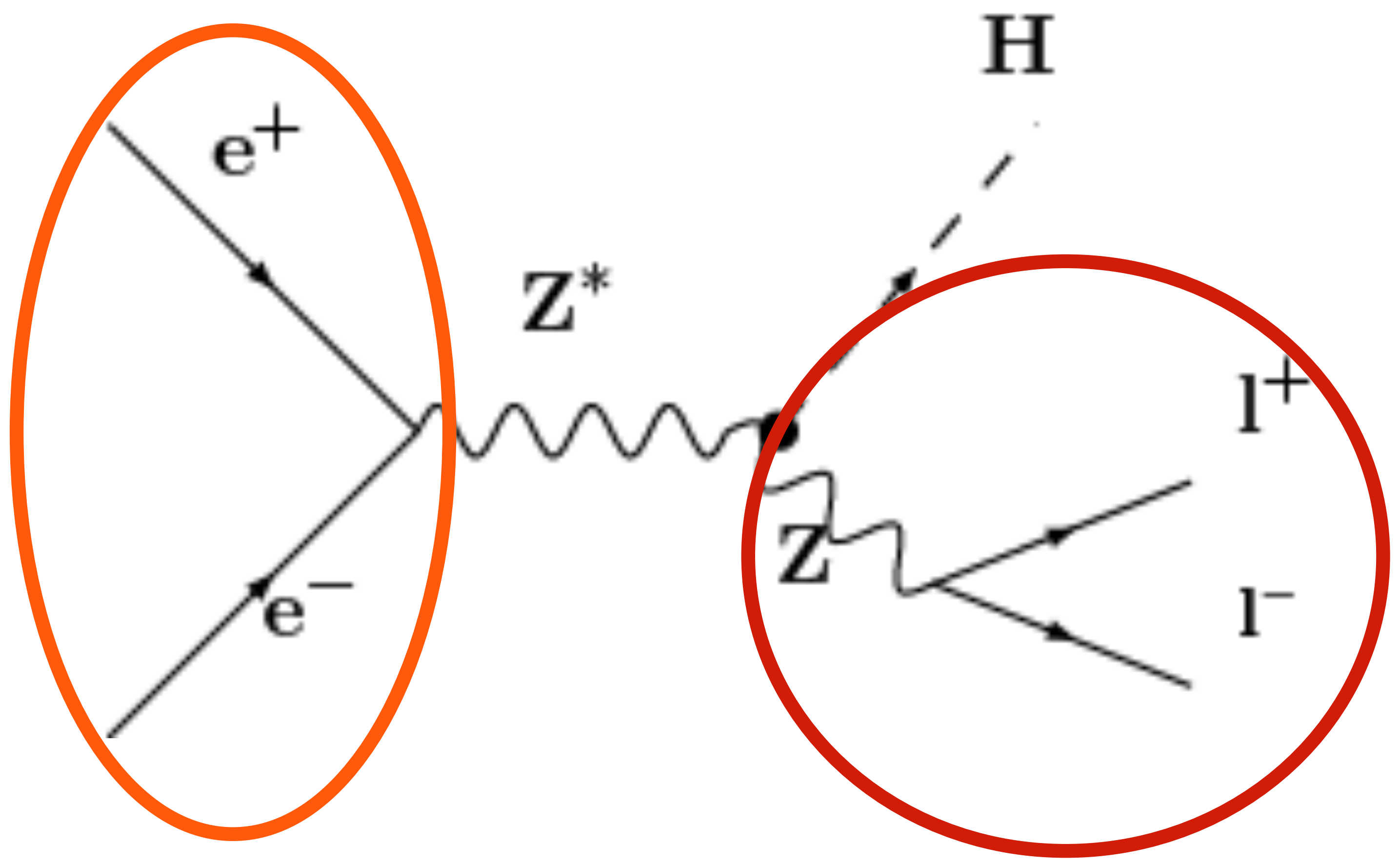
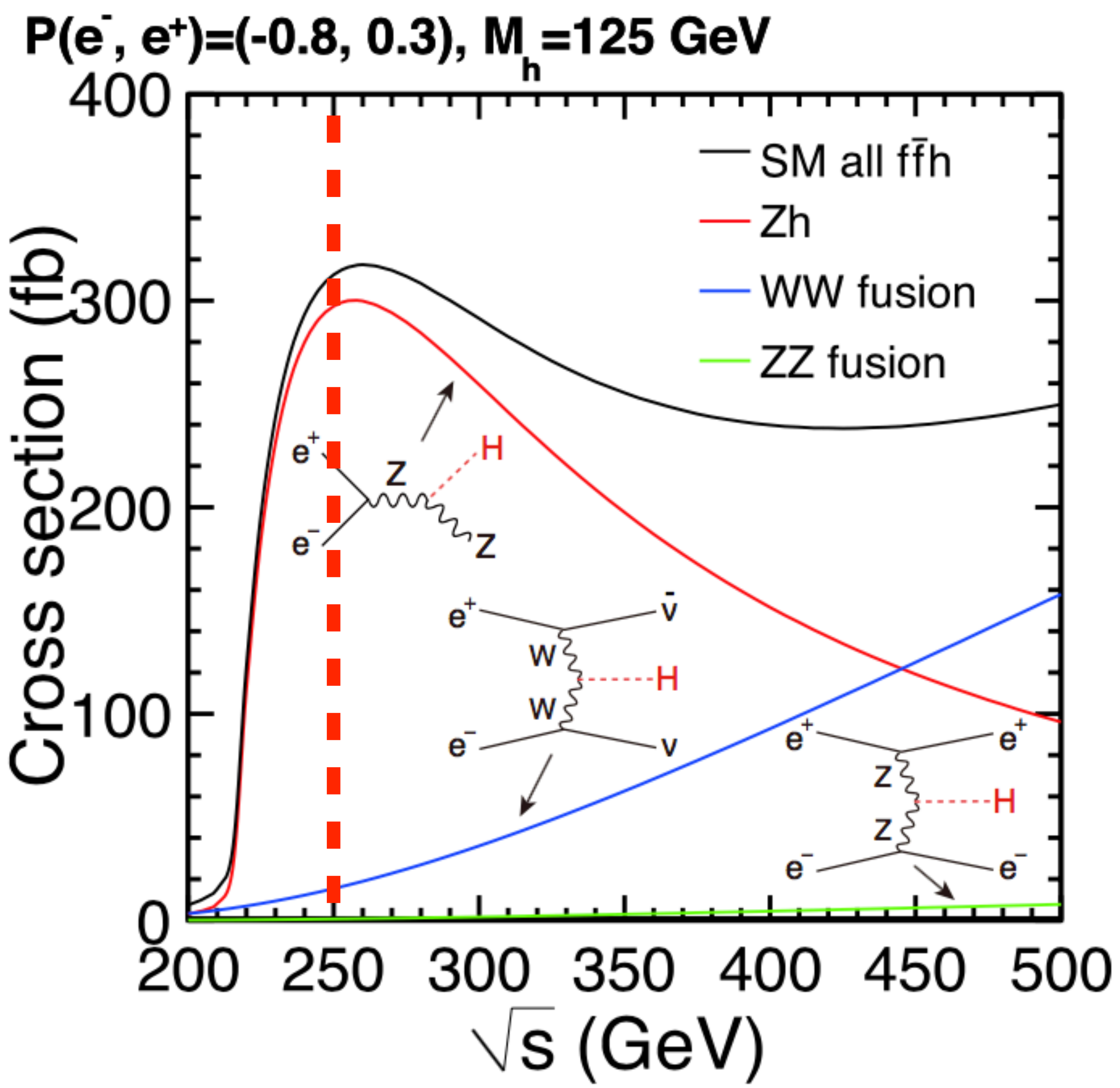


Image courtesy of Stuart Miles at FreeDigitalPhotos.net



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



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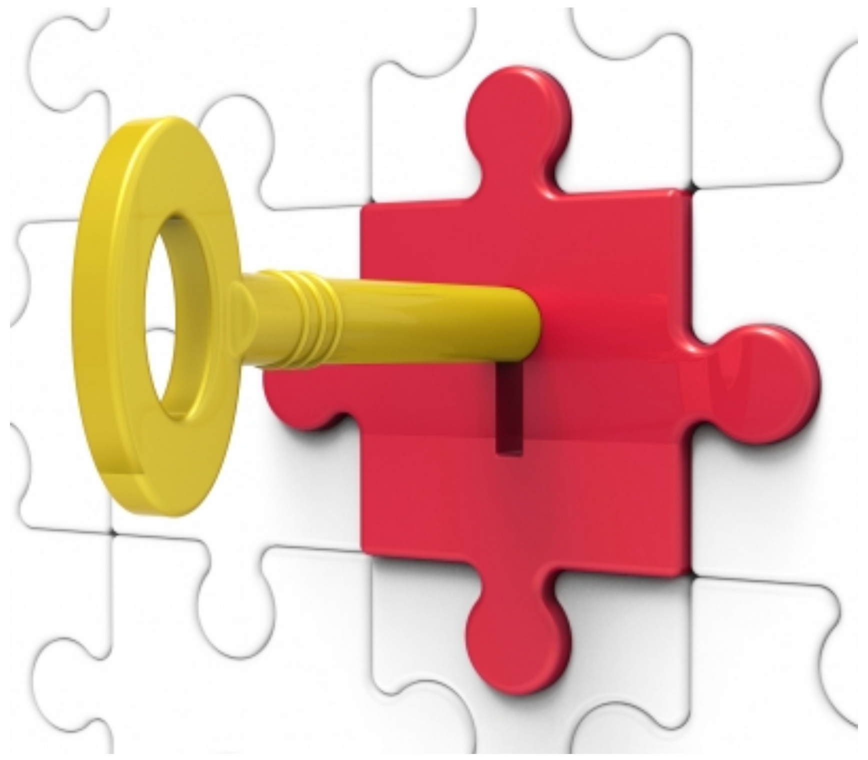

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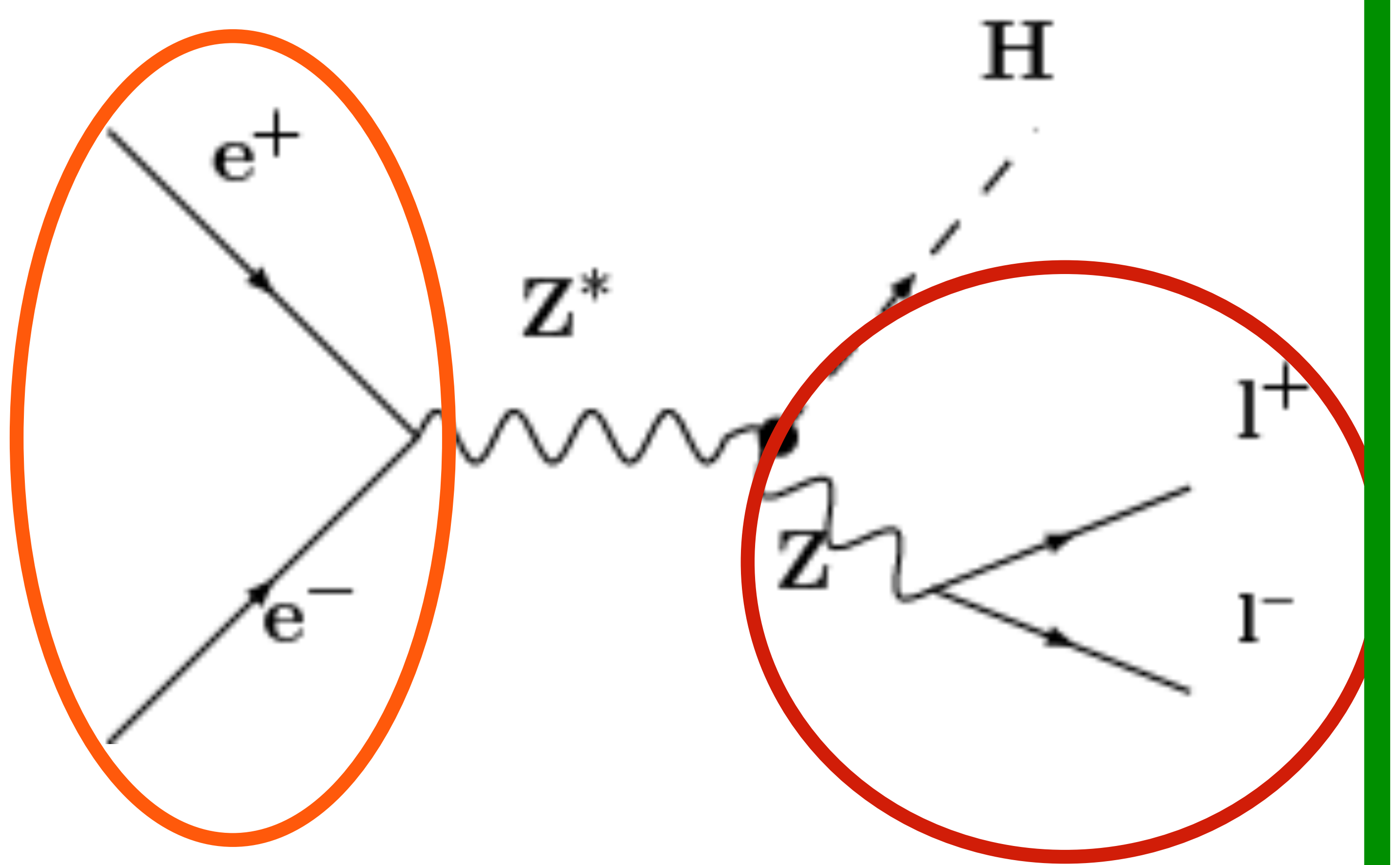
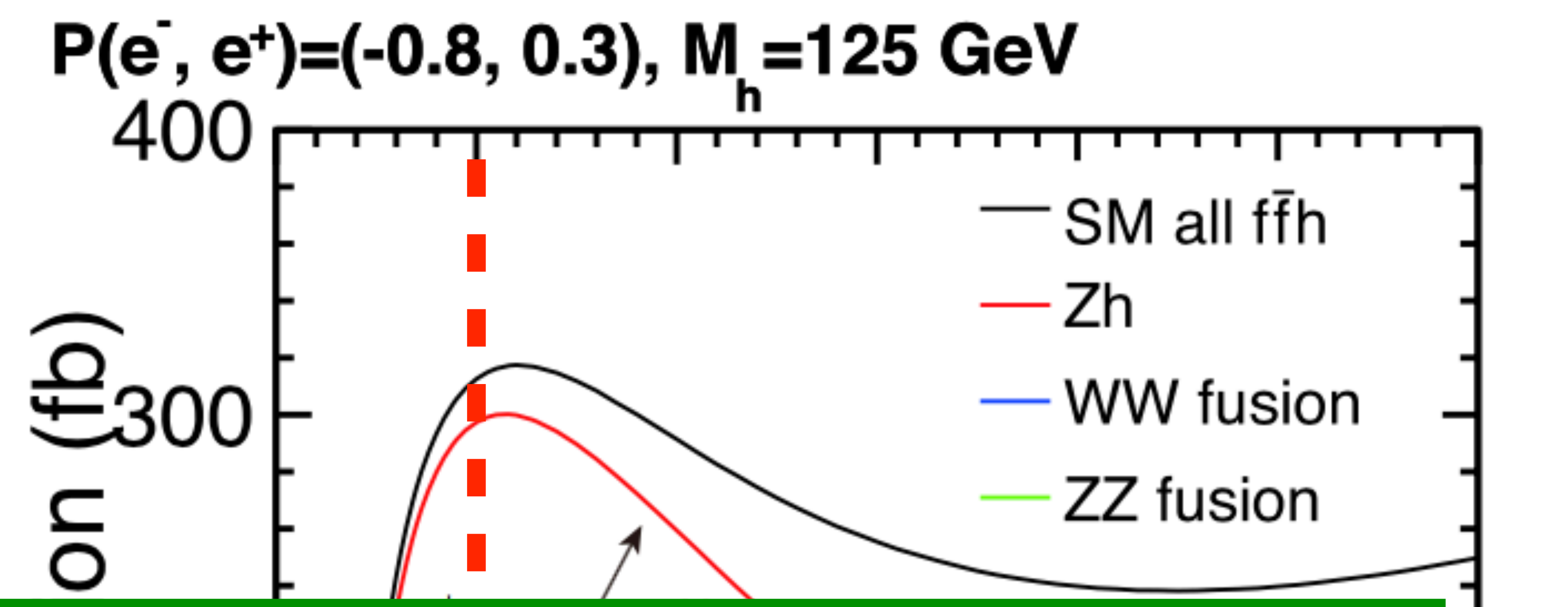
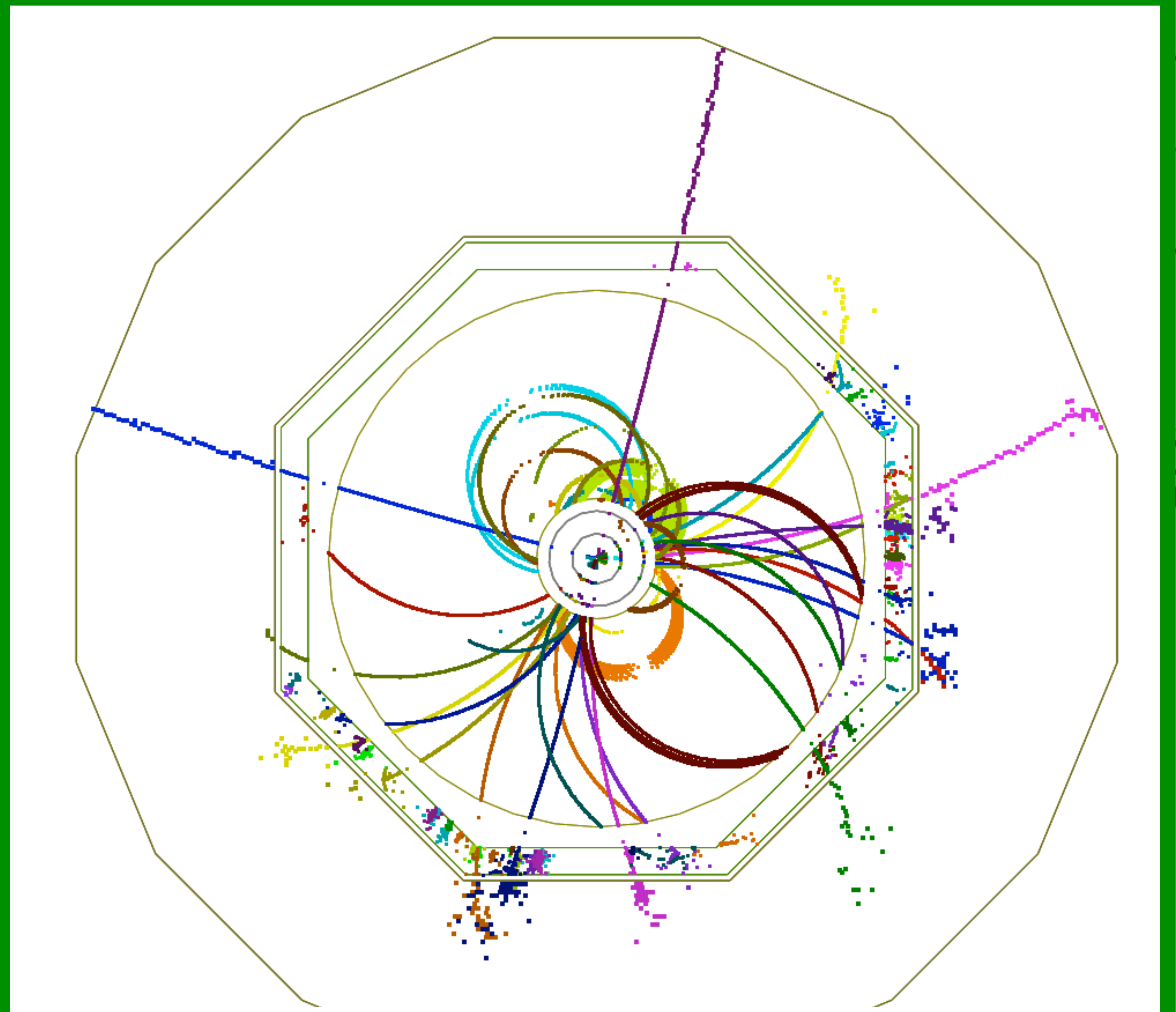


$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E$$





e⁺e⁻ → μ⁺μ⁻H → μ⁺μ⁻ bb in ILD detector

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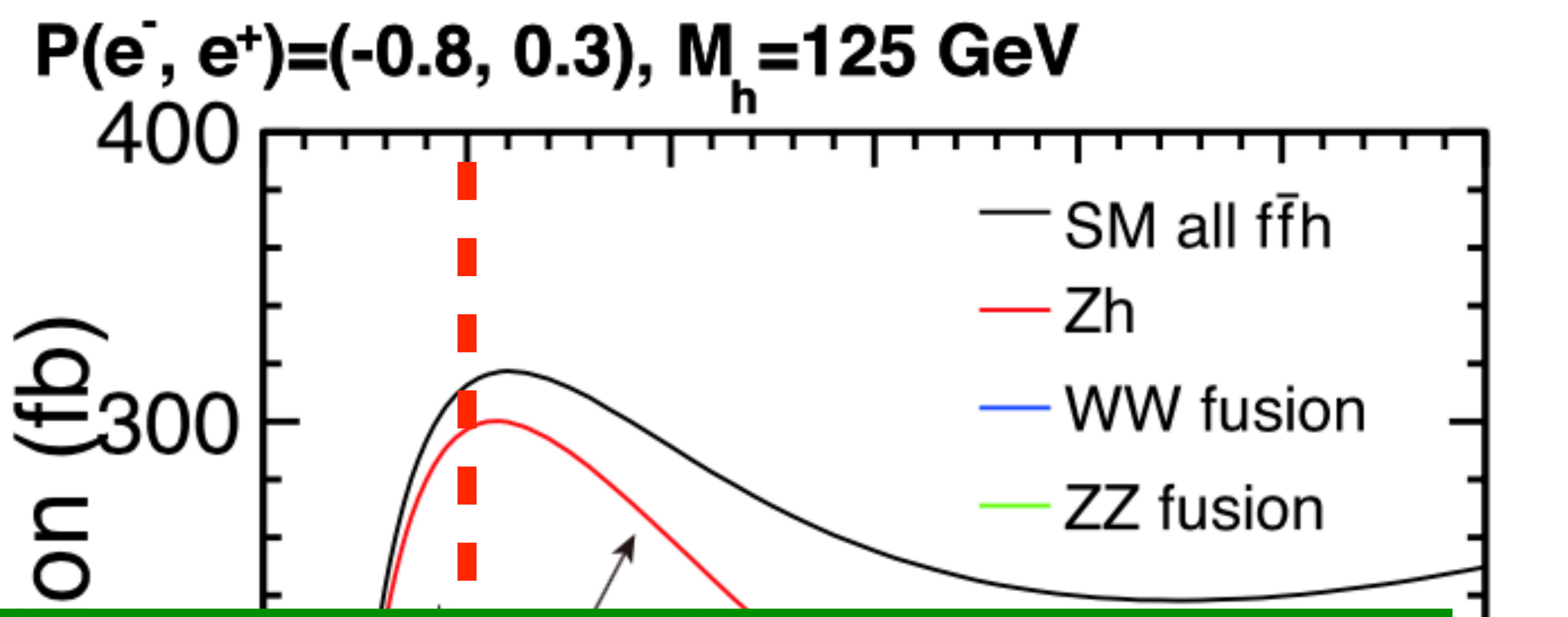

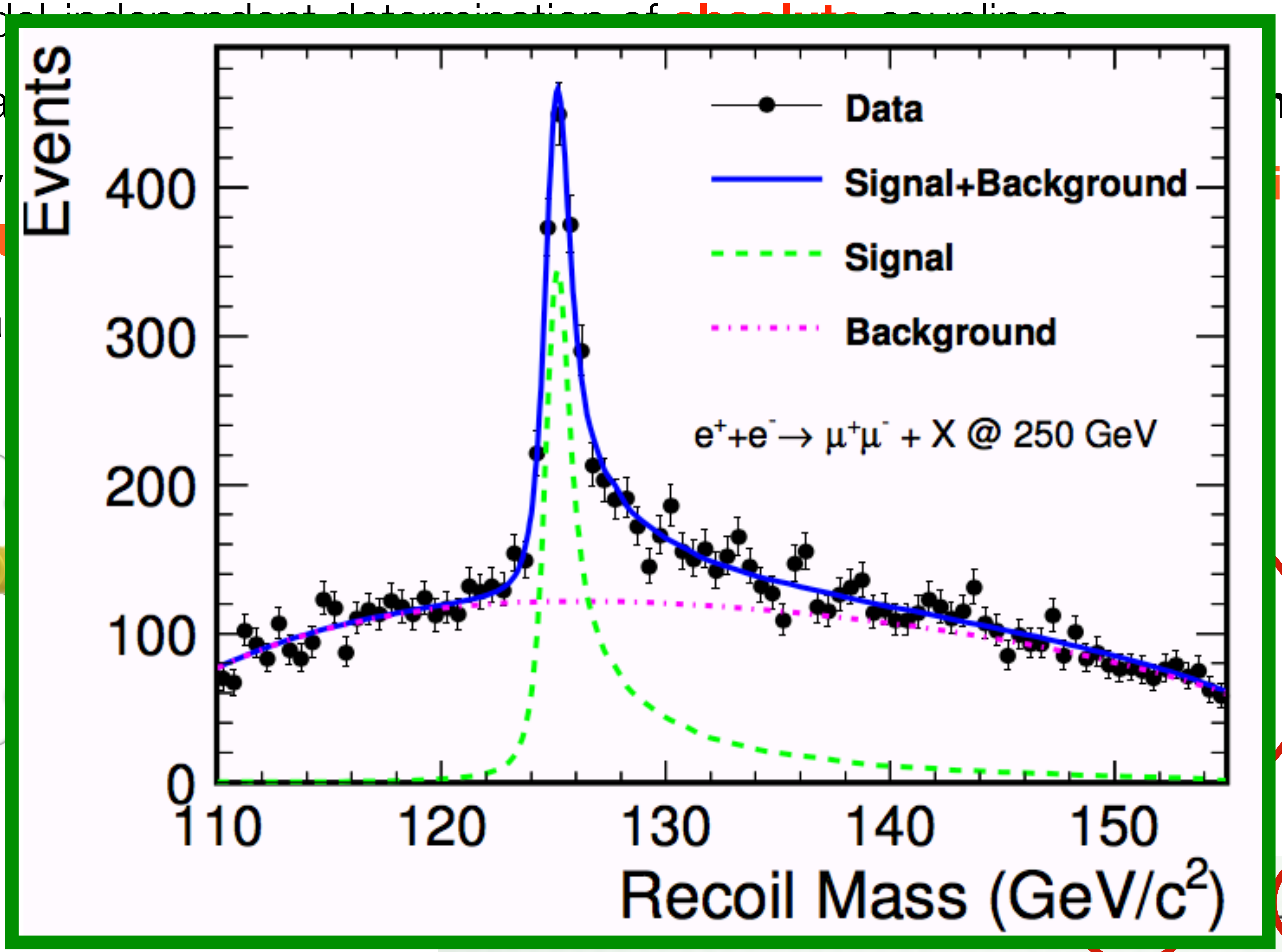

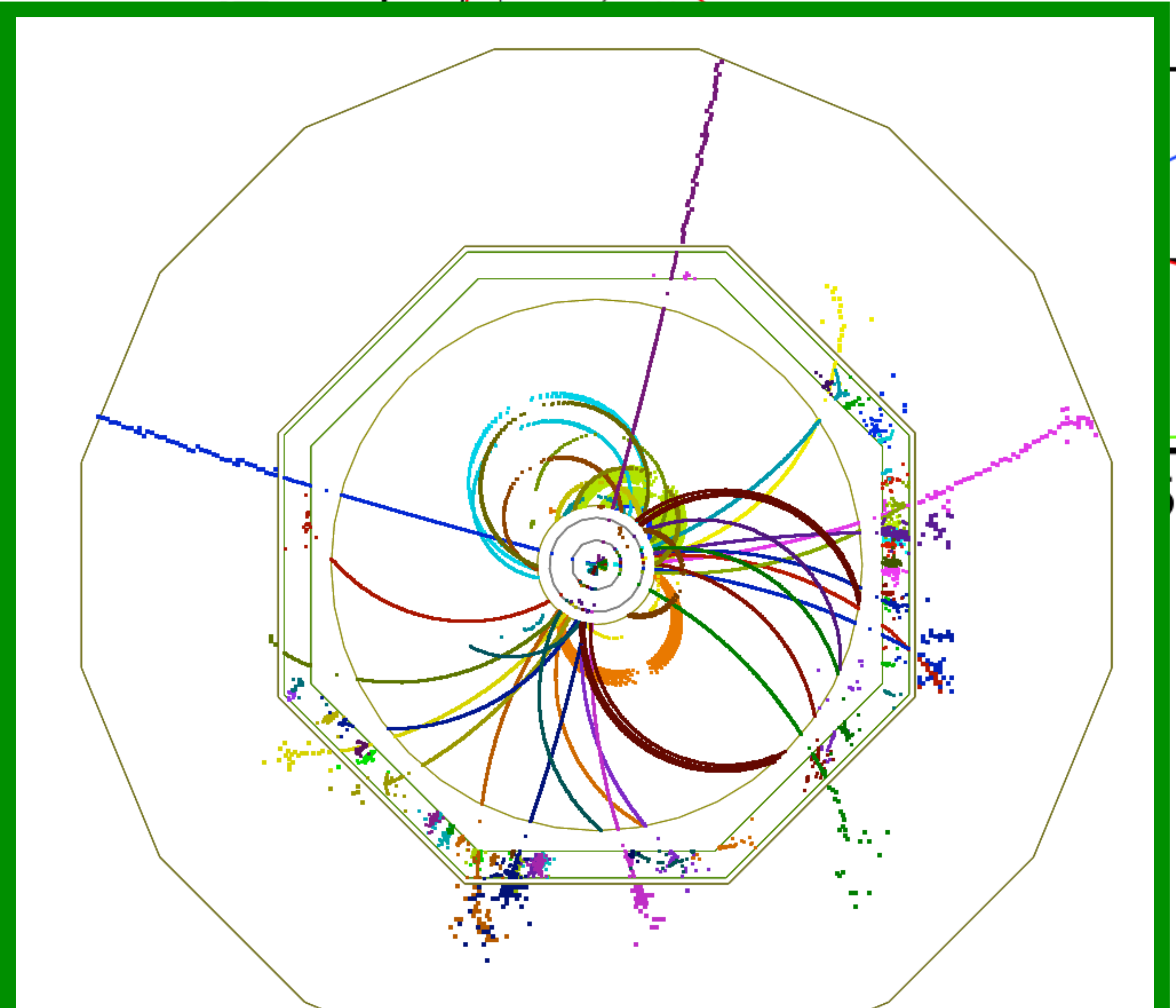

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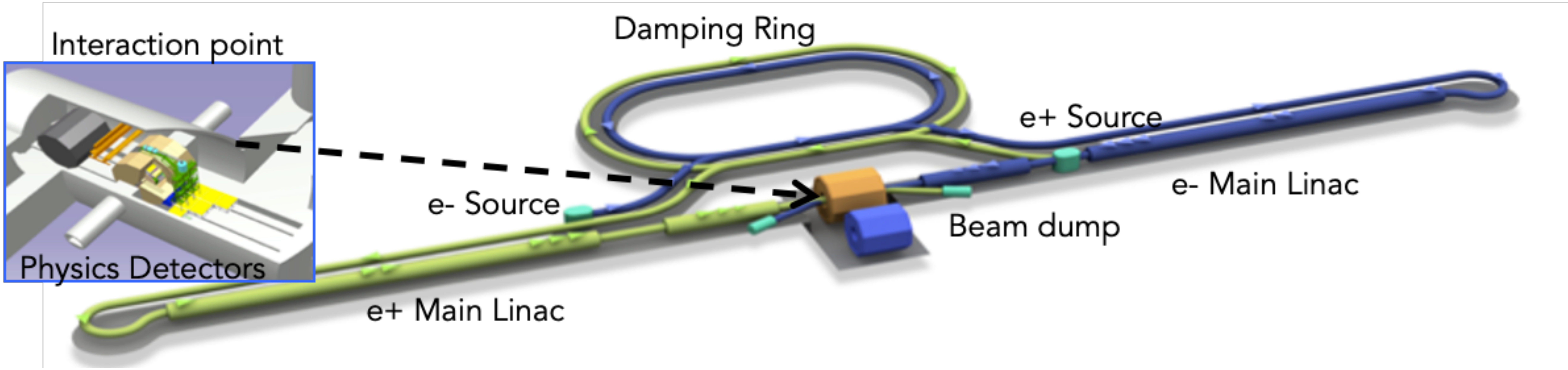
The International Linear Collider Facility

An overview - all up-to-date information in https://arxiv.org/abs/2203.07622

- **based on superconducting radio-frequency cavities => well established technology (EuXFEL, ESS, LCLS-II, …)**, with potential for continuous improvement by R&D
- **total length (250 GeV / ~500 GeV / ~1 TeV): 20.5 km / 30 km / 50 km** (with established technology)
- **construction in staged approach, starting from 250 GeV** (“Higgs factory”, incl. Z pole / WW threshold)
- **further stages can be chosen according to physics needs and technological developments**
- **2 detectors in push-pull mode => complementarity, cross-checks, competition!**



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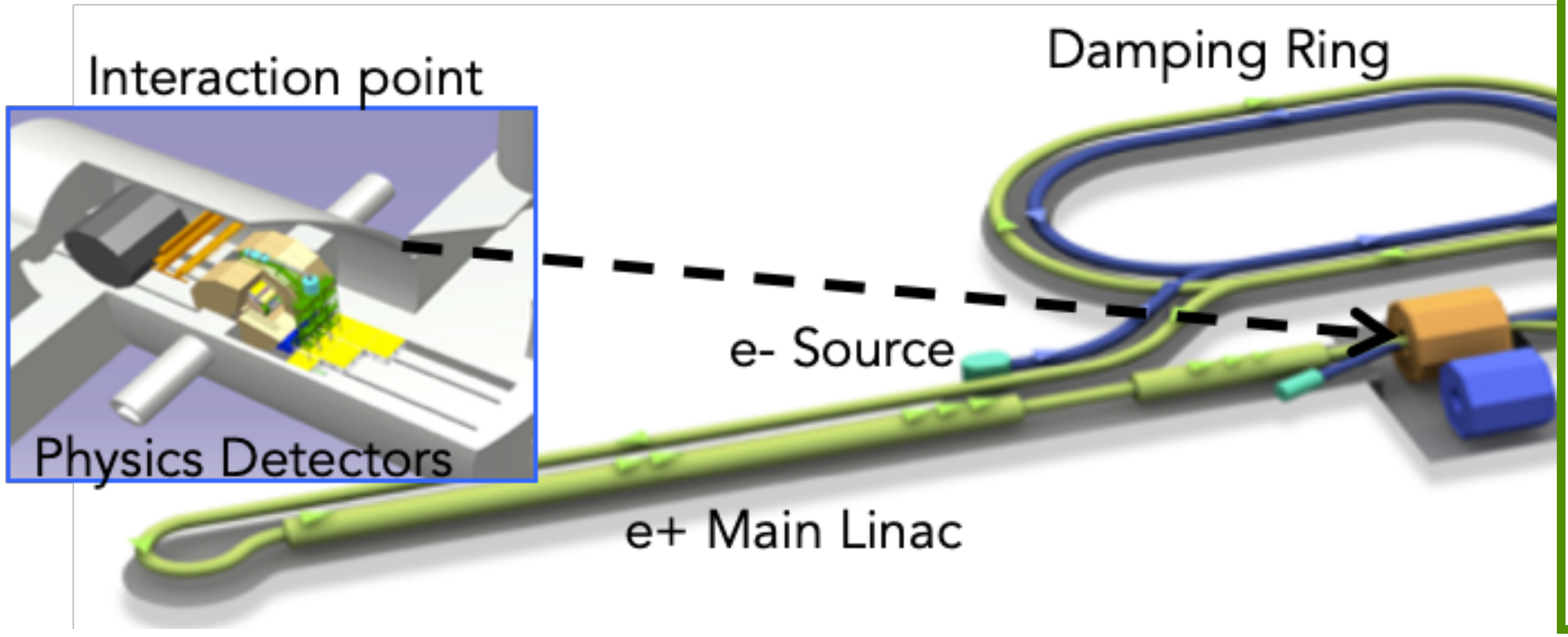

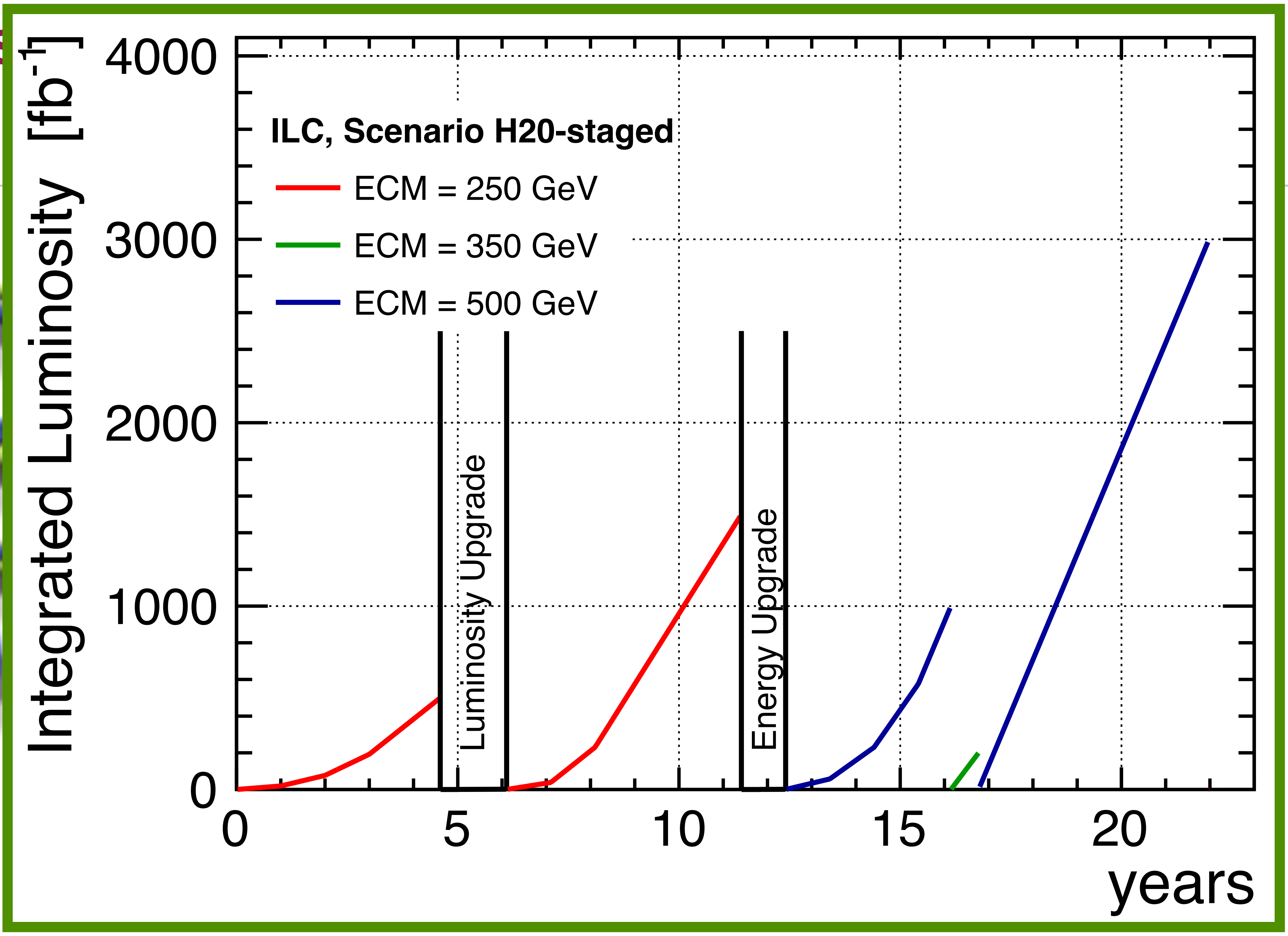

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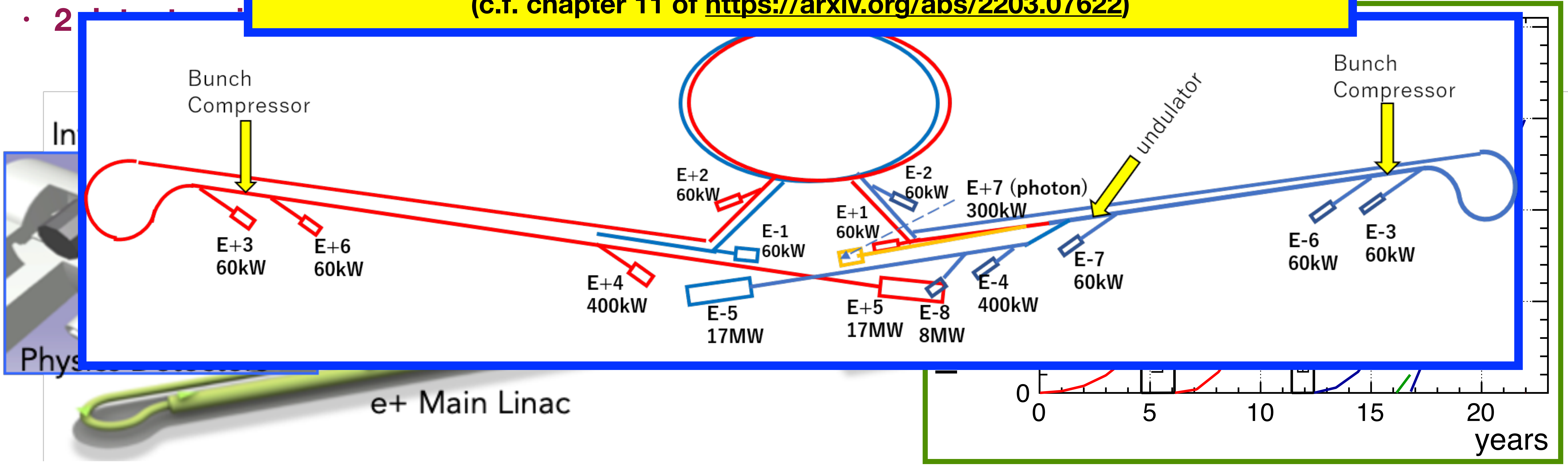
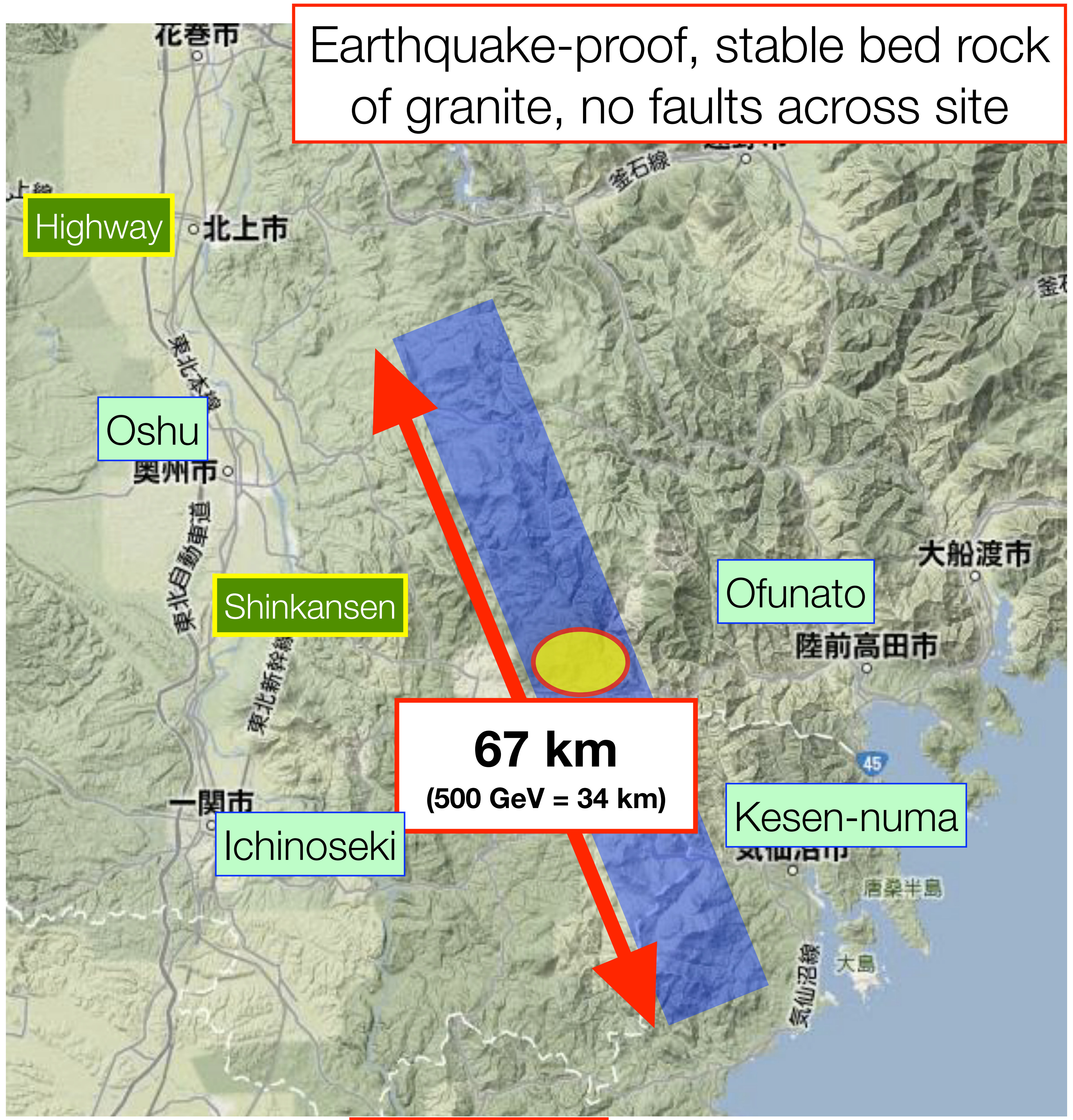
- **further stage** … **ents**
- **2** …

More than a collider:
ample opportunities for extra beamlines, fixed-target & beam-dump experiments!
(c.f. chapter 11 of https://arxiv.org/abs/2203.07622)

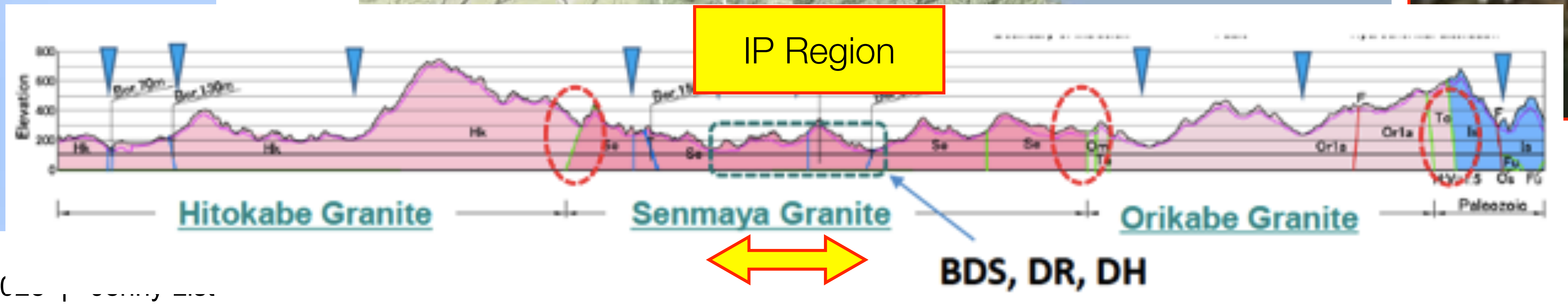


Candidate Site in Japan

Kitakami Mountains



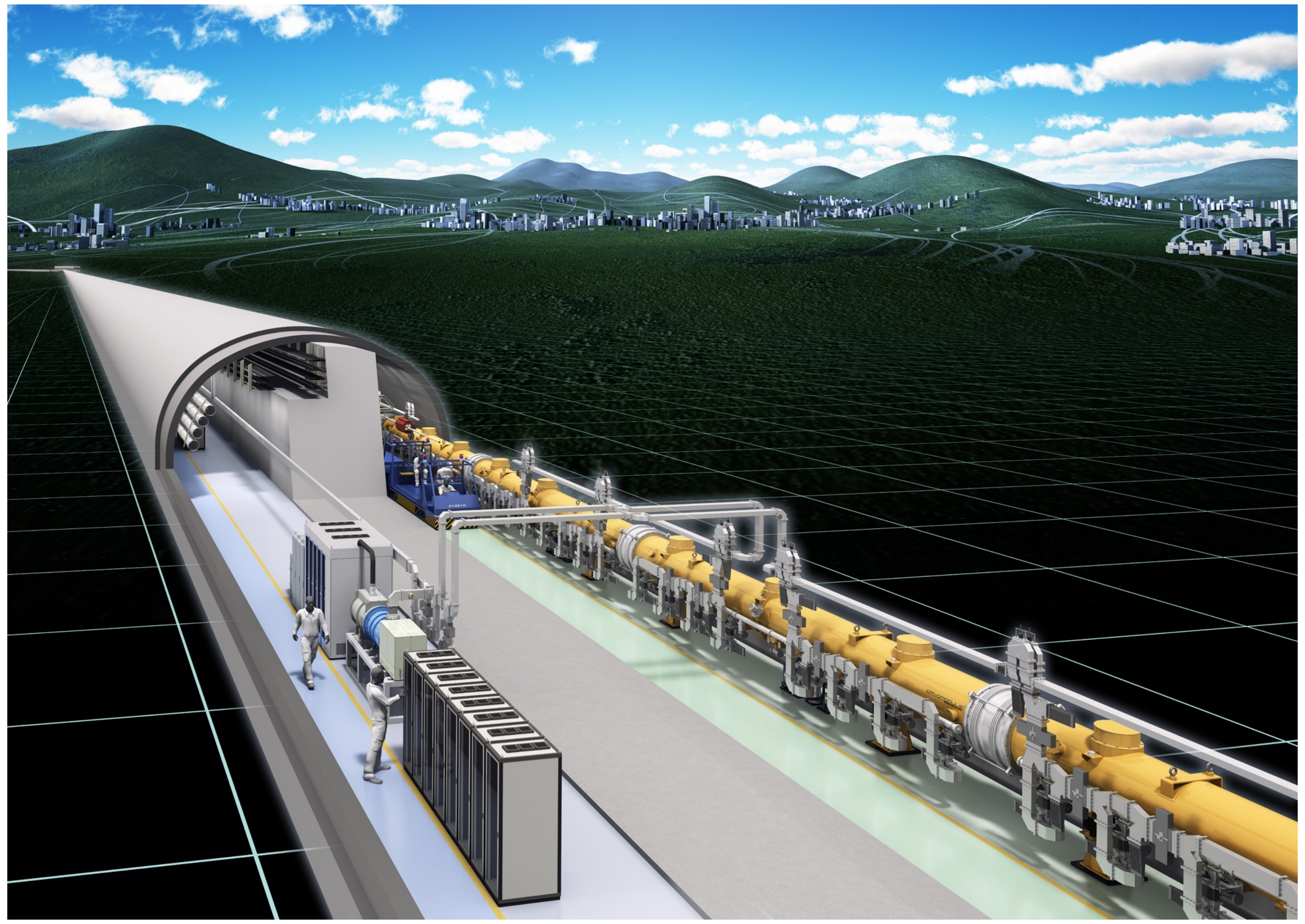
Earthquake-proof, stable bed rock of granite, no faults across site



ILC Political Status

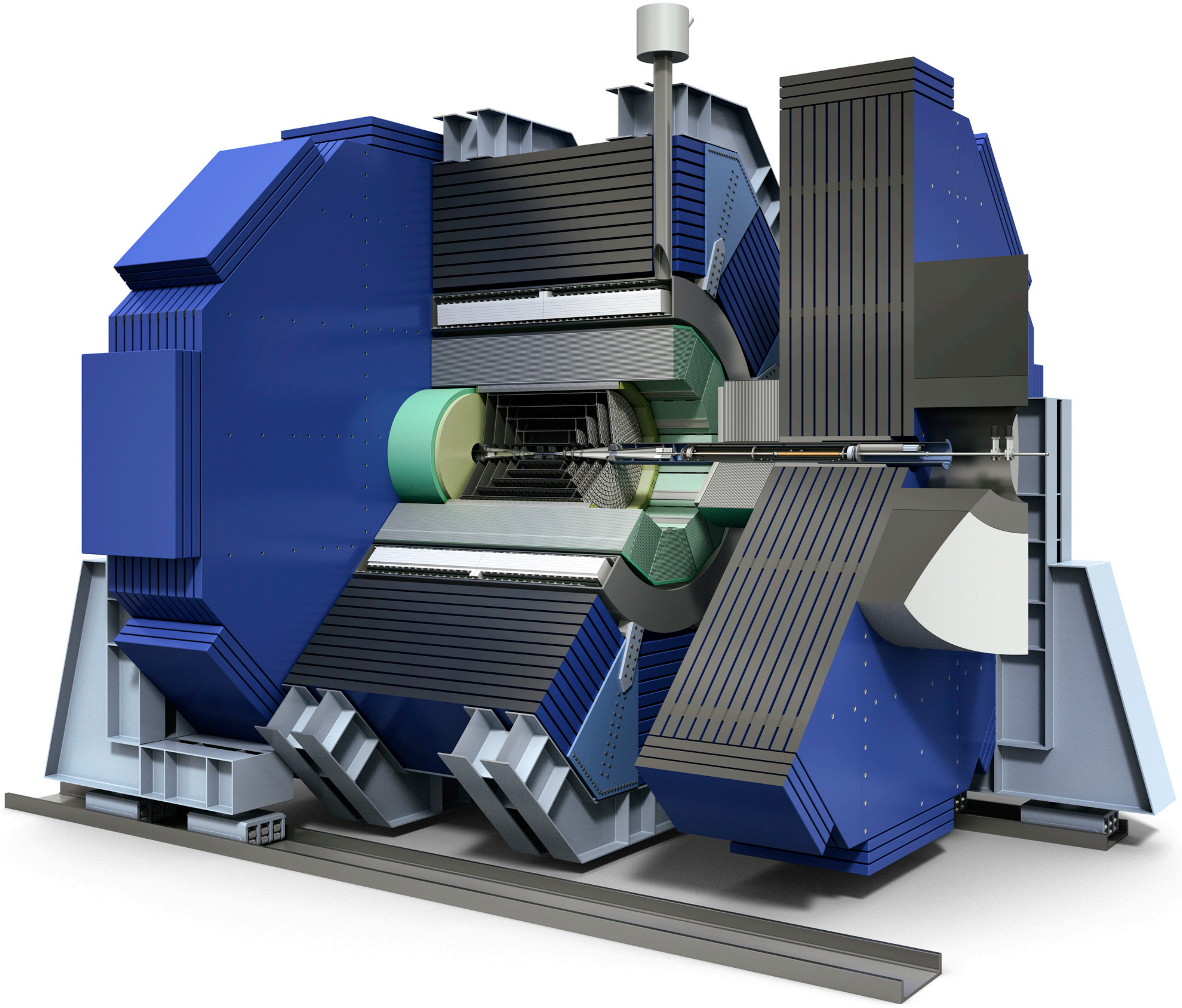
The International Development Team (IDT)

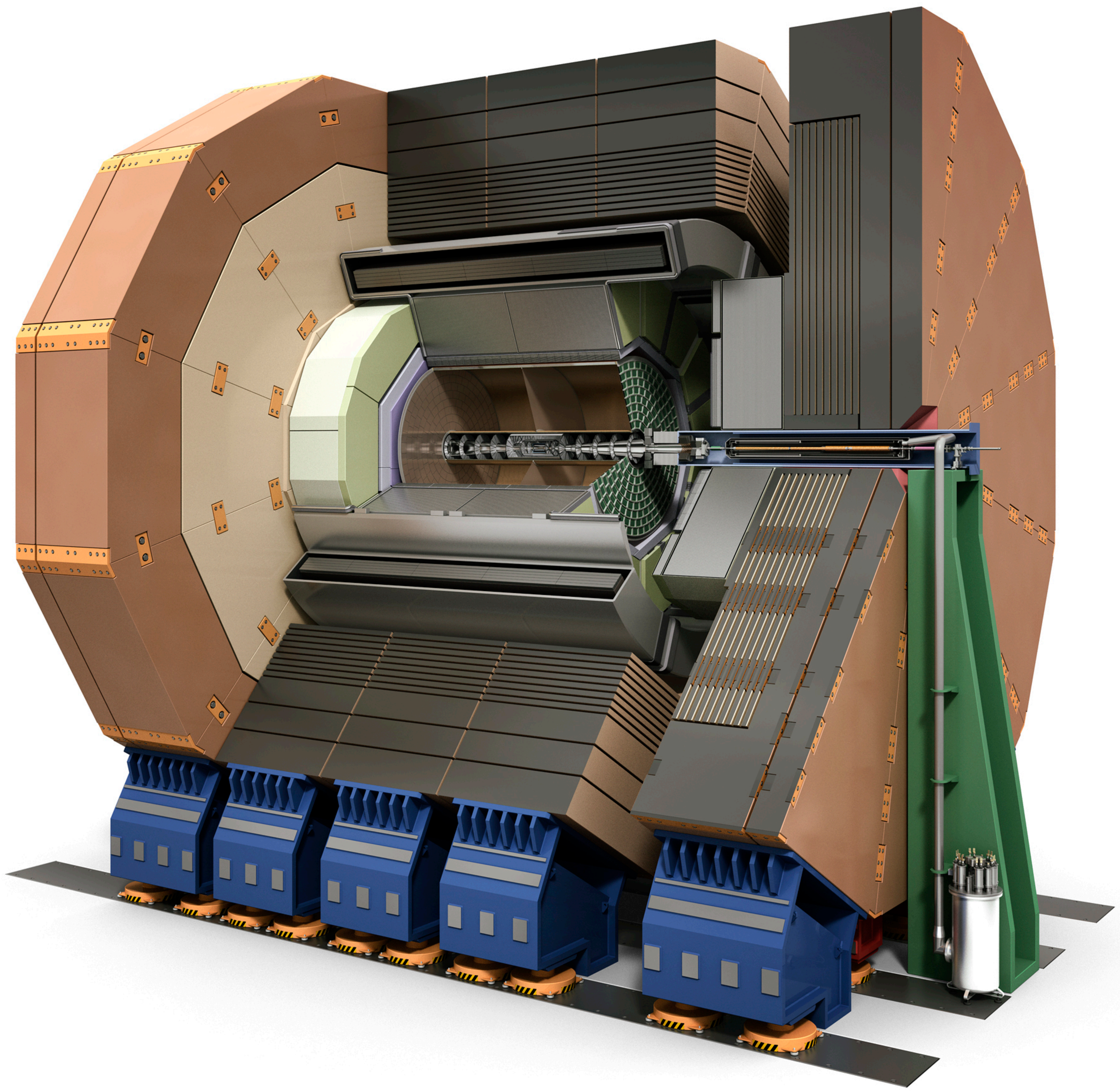
- **ILC project run by the International Development Team (IDT) mandated by ICFA**
- 2020: The IDT – created by ICFA and hosted by KEK – prepared the ILC Preparation Phase plan ("Pre-lab"), which would over a ~4 year period, lead to a complete Engineering Design as needed to start construction of the ILC.
- Late 2020 - early 2021: The plan was reviewed by a MEXT appointed panel and deemed premature, referring to that the prospects for an international cost sharing for ILC were not clear. However increased support for technical developments and accelerator R&D was recommended.
- During 2021- early 2022: Within the IDT a subset of the technical activities of the full preparation phase programme has been identified as priorities, to be addressed with an international effort. The required resources are at ~1/3 level of the original plans. The activities planned are foreseen to take 2-4 years.
- second half of 2022: These plans were included MEXT budget request and has been approved by the Finance Ministry. The funding can become available in May 2023 (DIET approval needed). It will double the KEK resourced available for ILC preparation, and in particular provides important new funding for ILC relevant hardware developments. Some parts of this funding can be used to foster international collaboration and efforts. The budget needs to be approved yearly, but the programme is set up for five years.
- We call this pre-preparation program the **ILC Technology Network (ITN)**
  Start: NOW



ILC Detectors

SiD & ILD





ILC Detectors

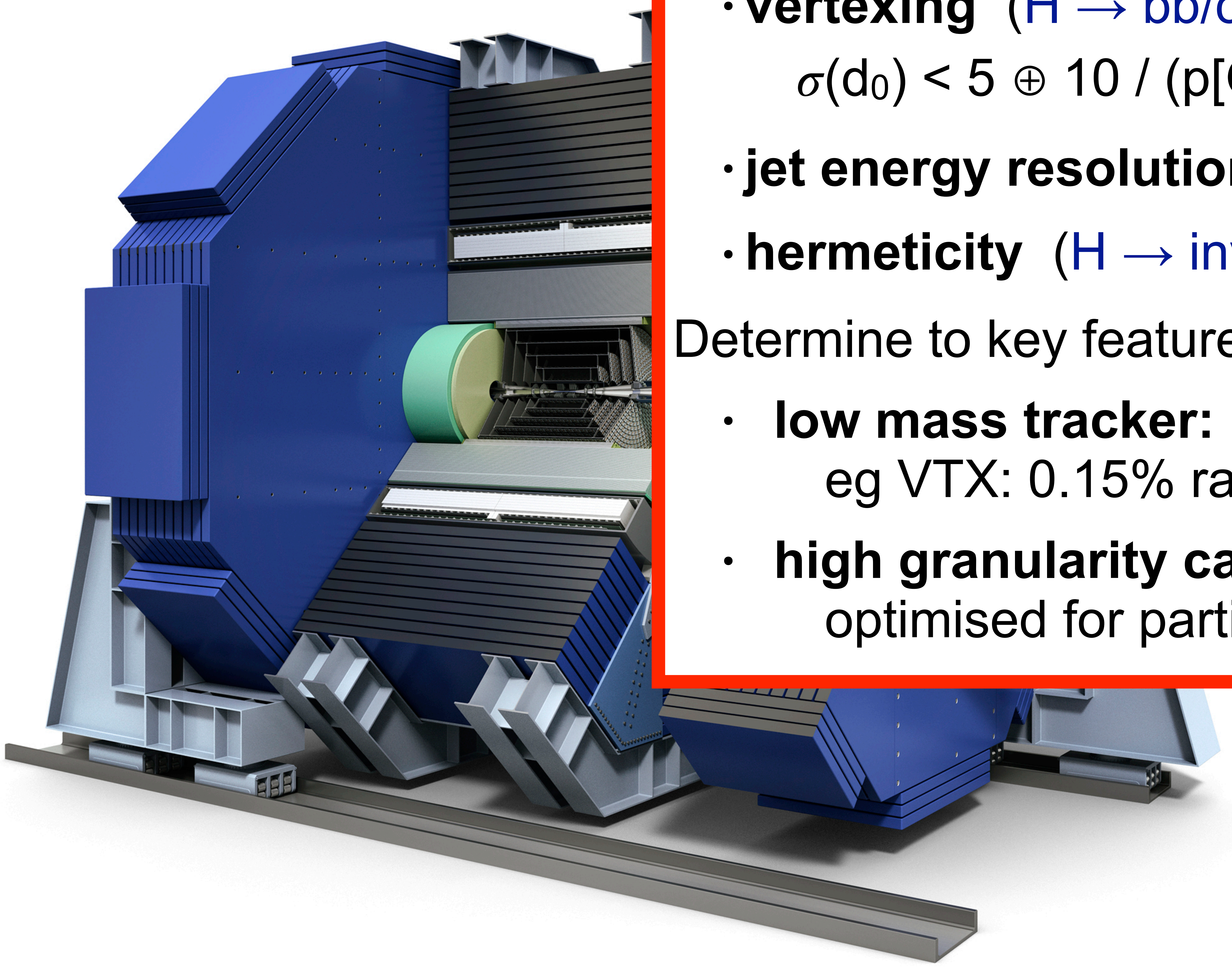
SiD & ILD

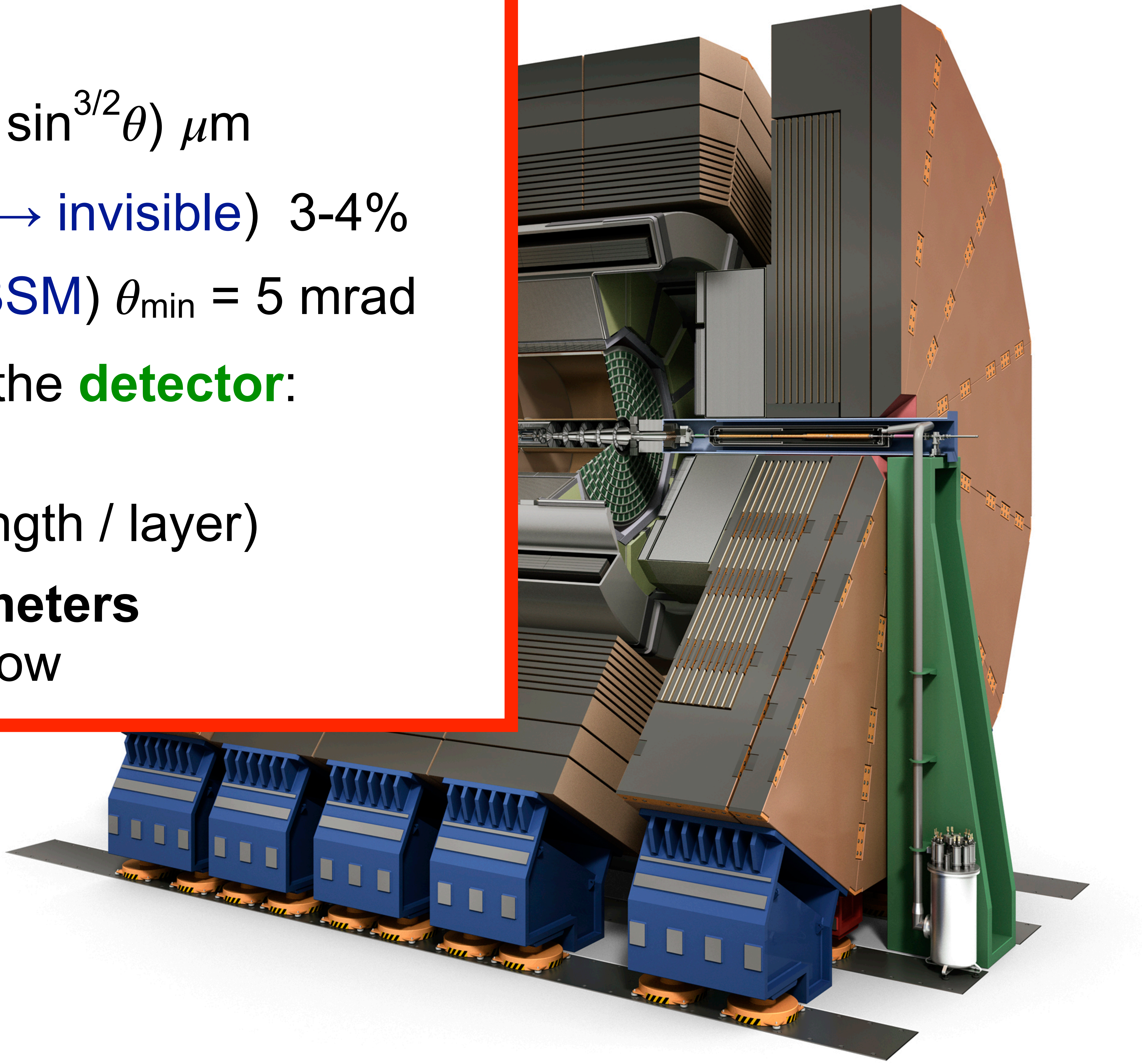
Key requirements from physics:

- **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** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) $\theta_{min} = 5$ mrad

Determine to key features of the detector:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow





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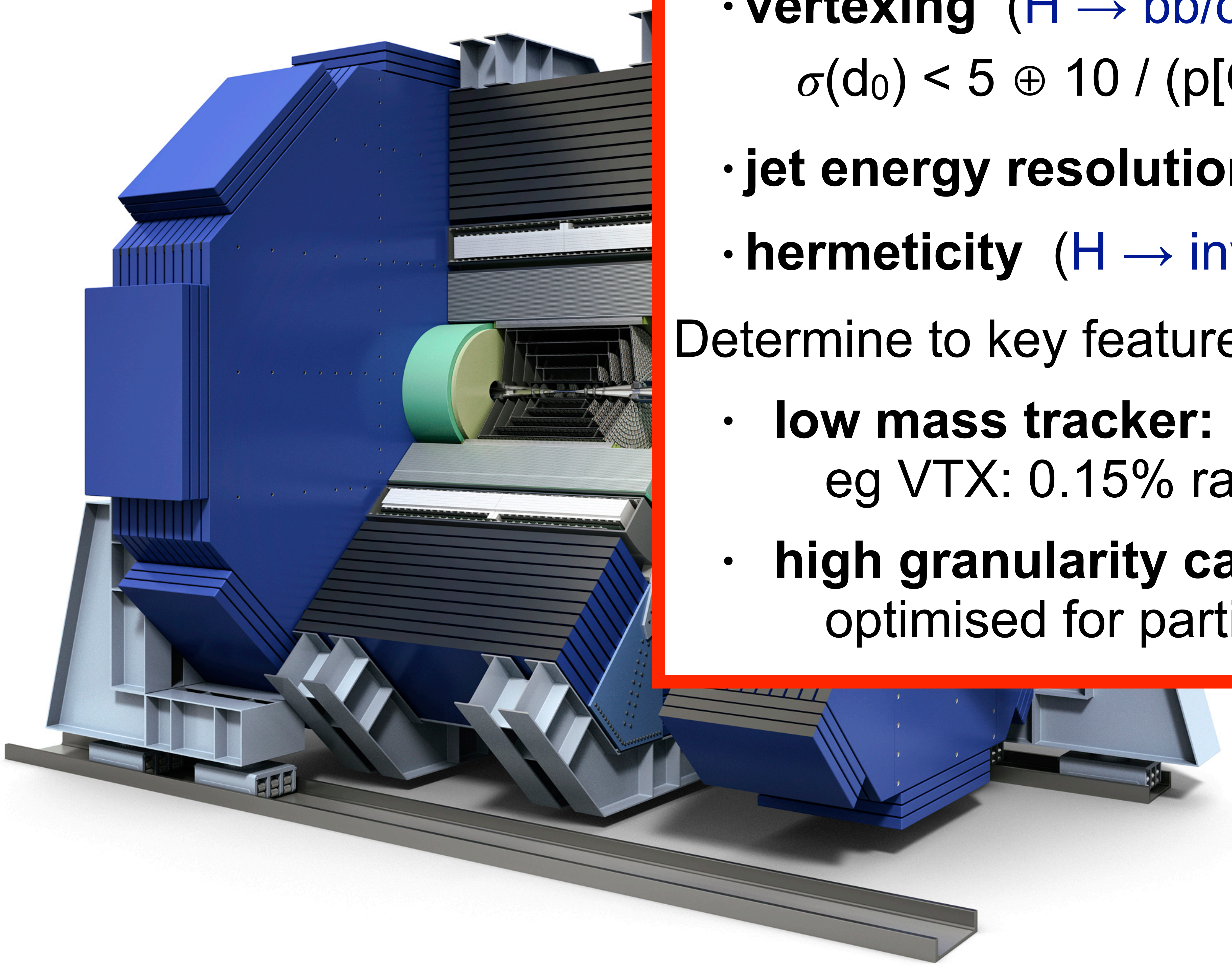

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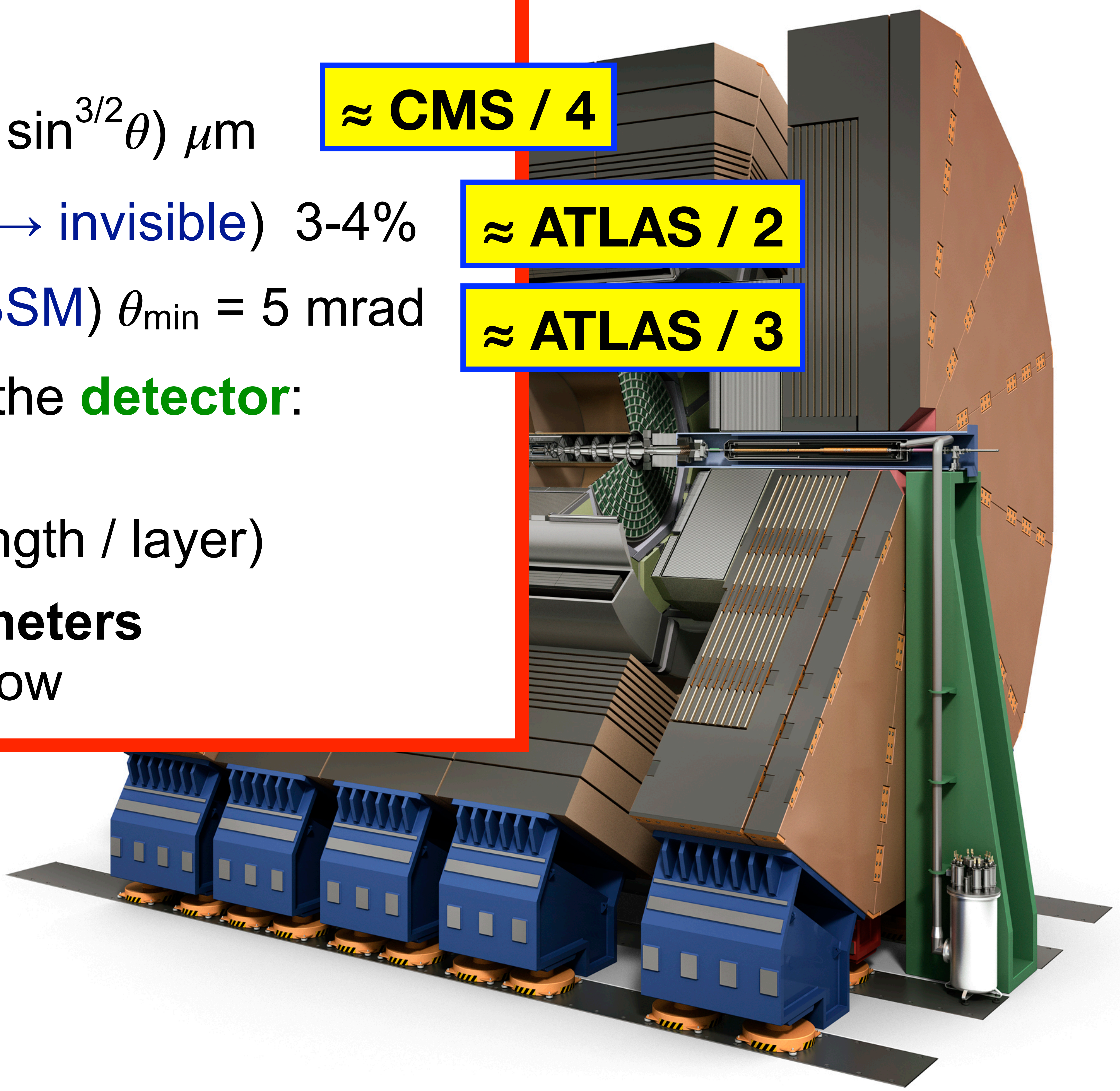

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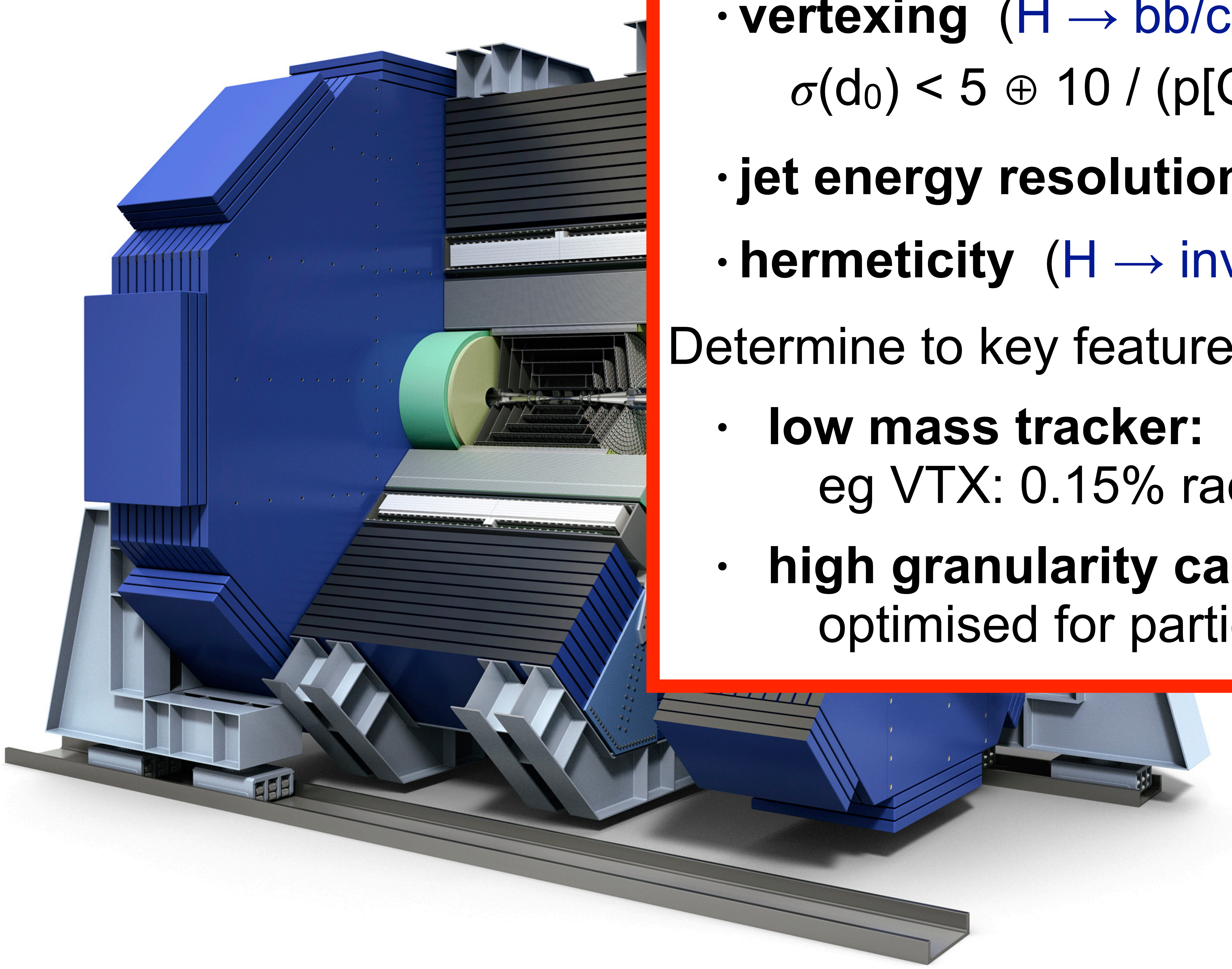

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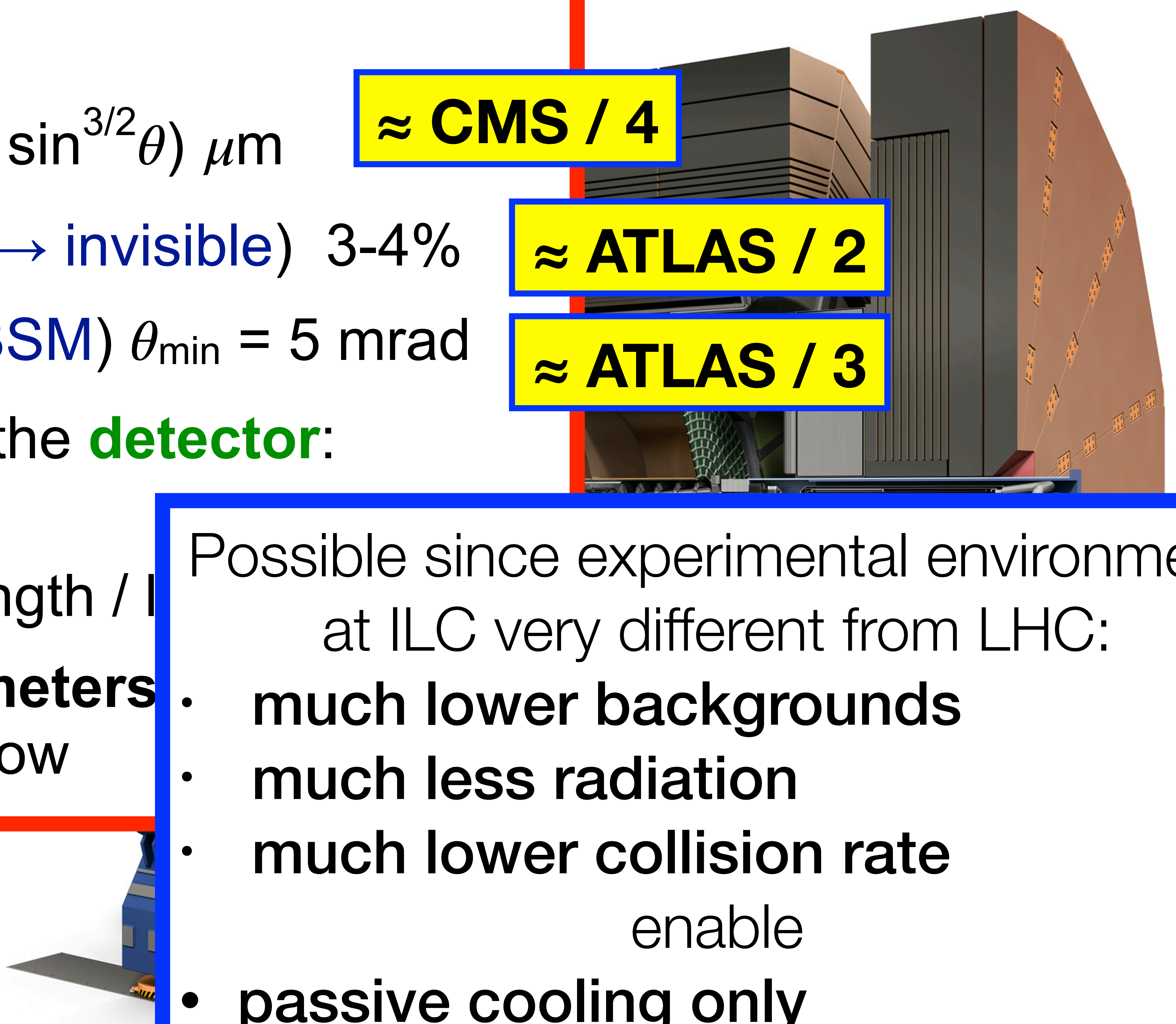
≈ CMS / 40

≈ CMS / 4

≈ ATLAS / 2

≈ ATLAS / 3



Possible since experimental environment at ILC very different from LHC:

- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**

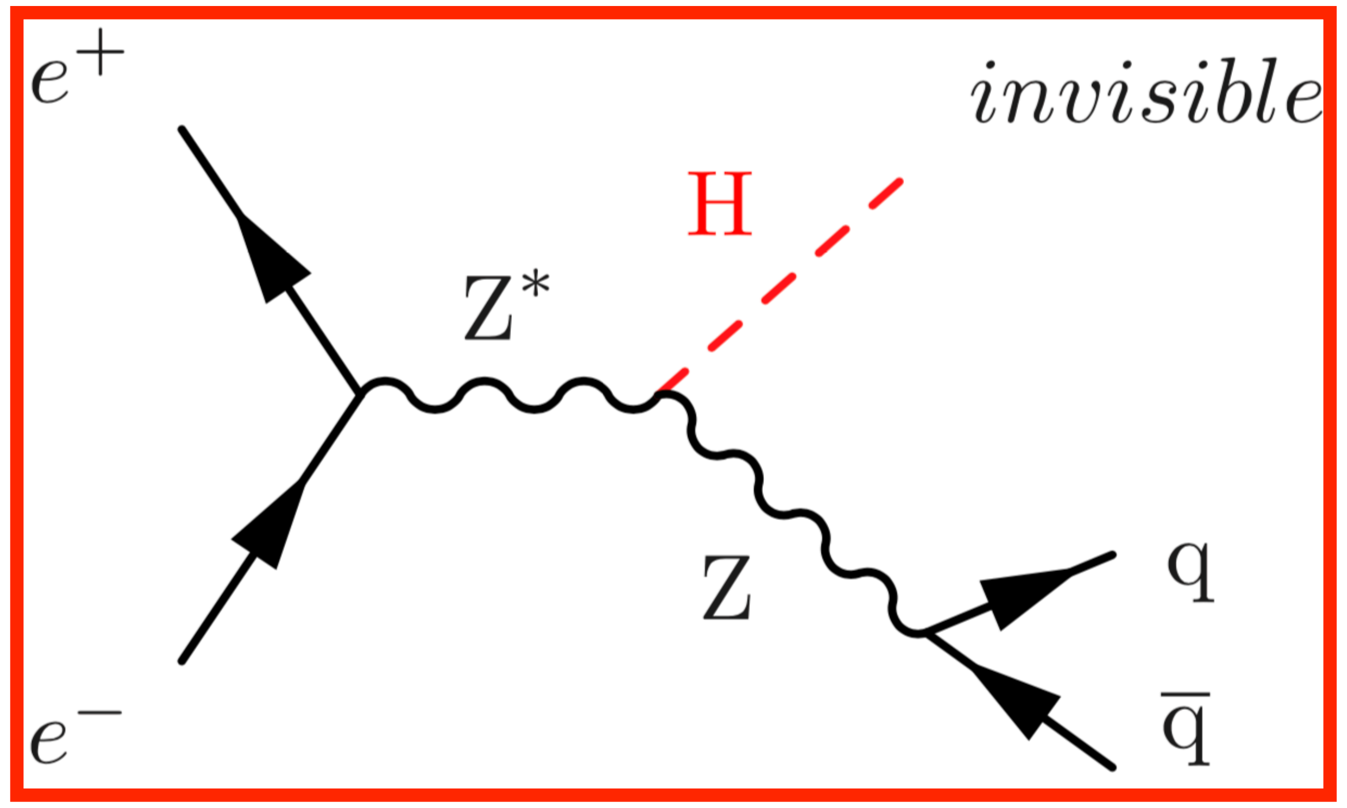
enable

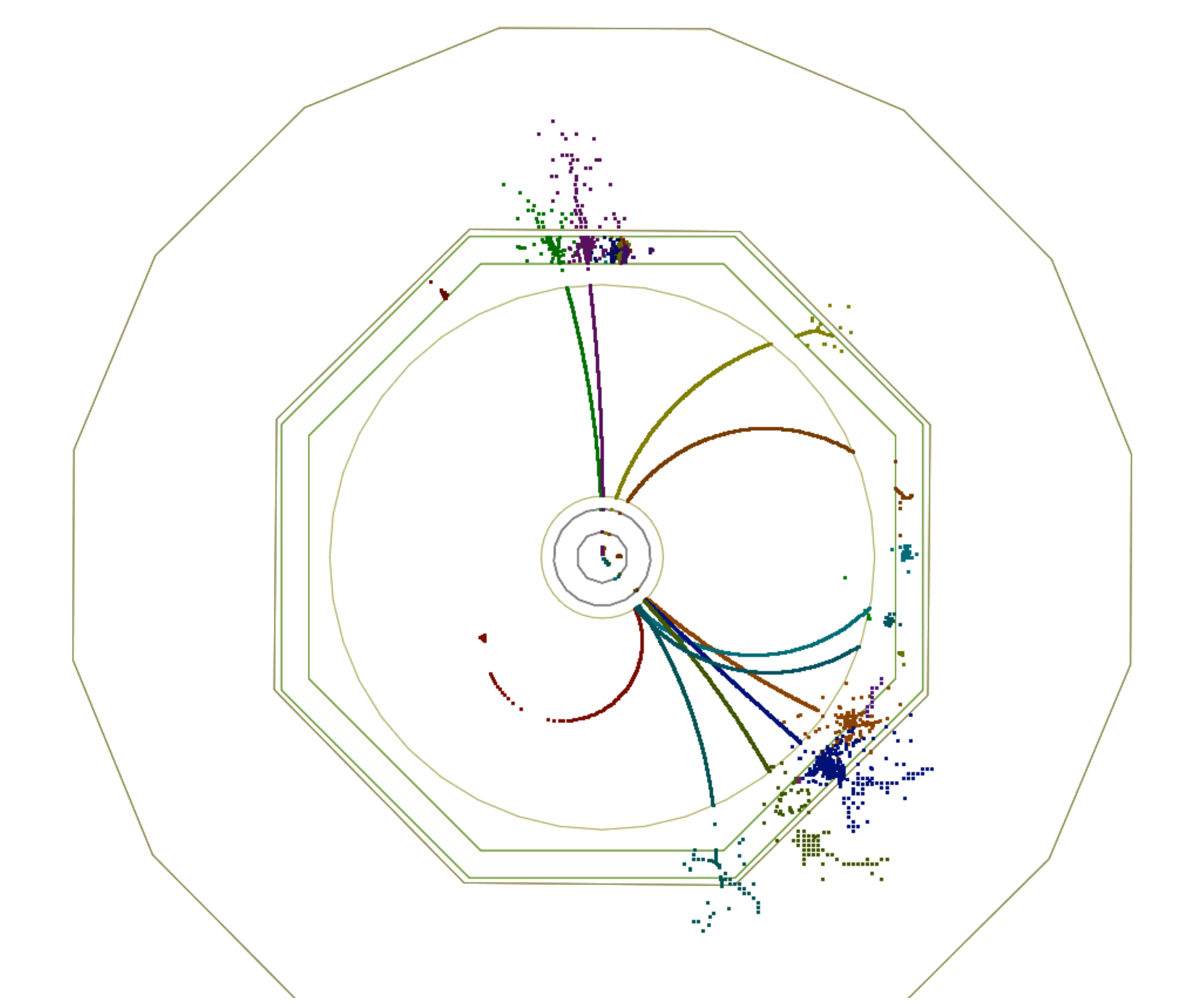
- **passive cooling only**
  => low material budget
- **triggerless operation**

Example: Higgs decay to “invisible”

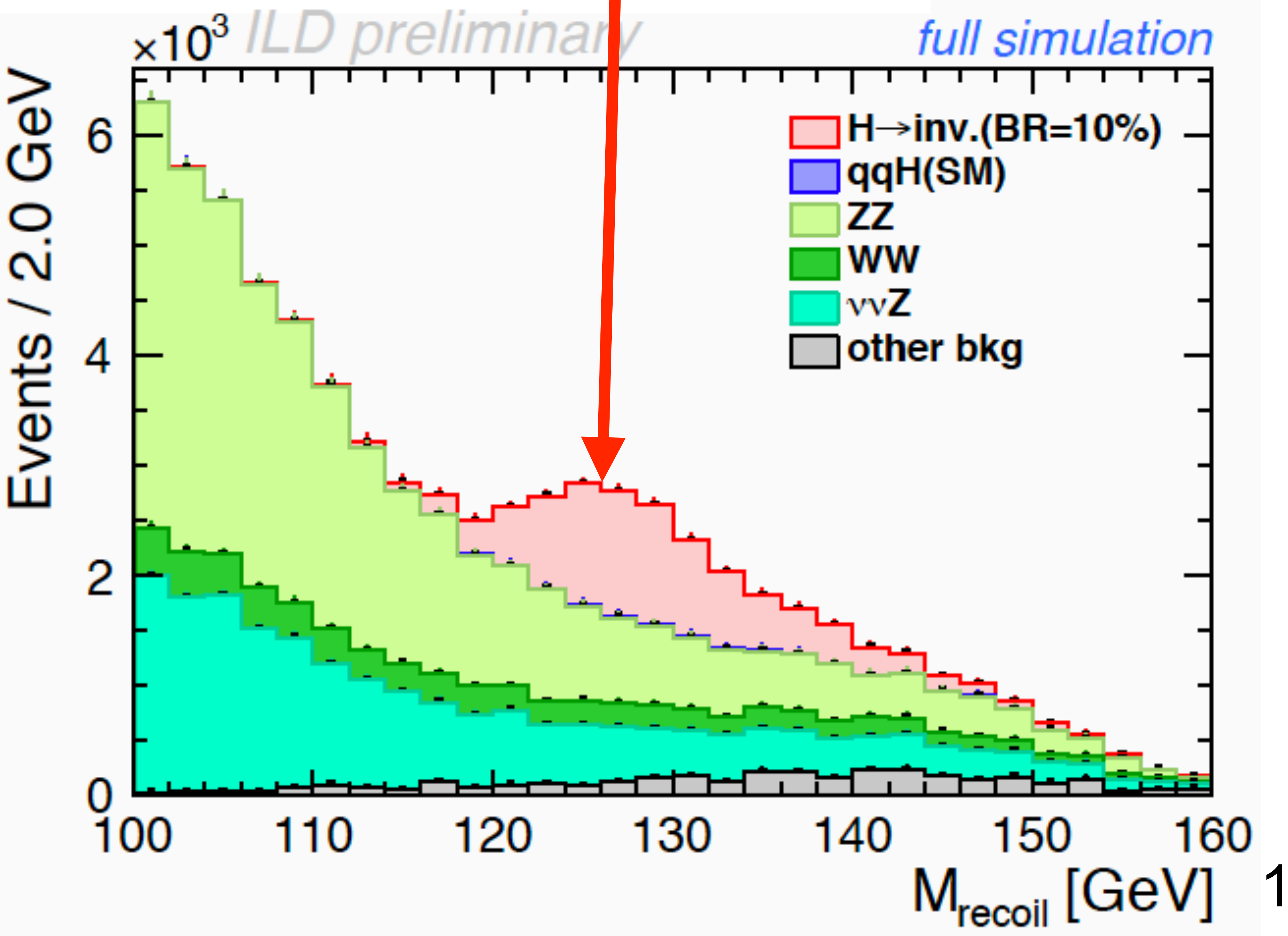
Dark Sector Portal?

- use $e^+e^- \to$ **Z h** process
- select a **visible final state (qq, ee, μμ) compatible with a Z decay**
- **recoiling against “nothing”**
- **if signal observed at ILC: discovery! Of Dark Matter?**
- **if no signal observed at ILC250: exclude BF > 0.16% at 95% CL (HL-LHC expectation: 2.5%, SM prediction: 0.1%)**





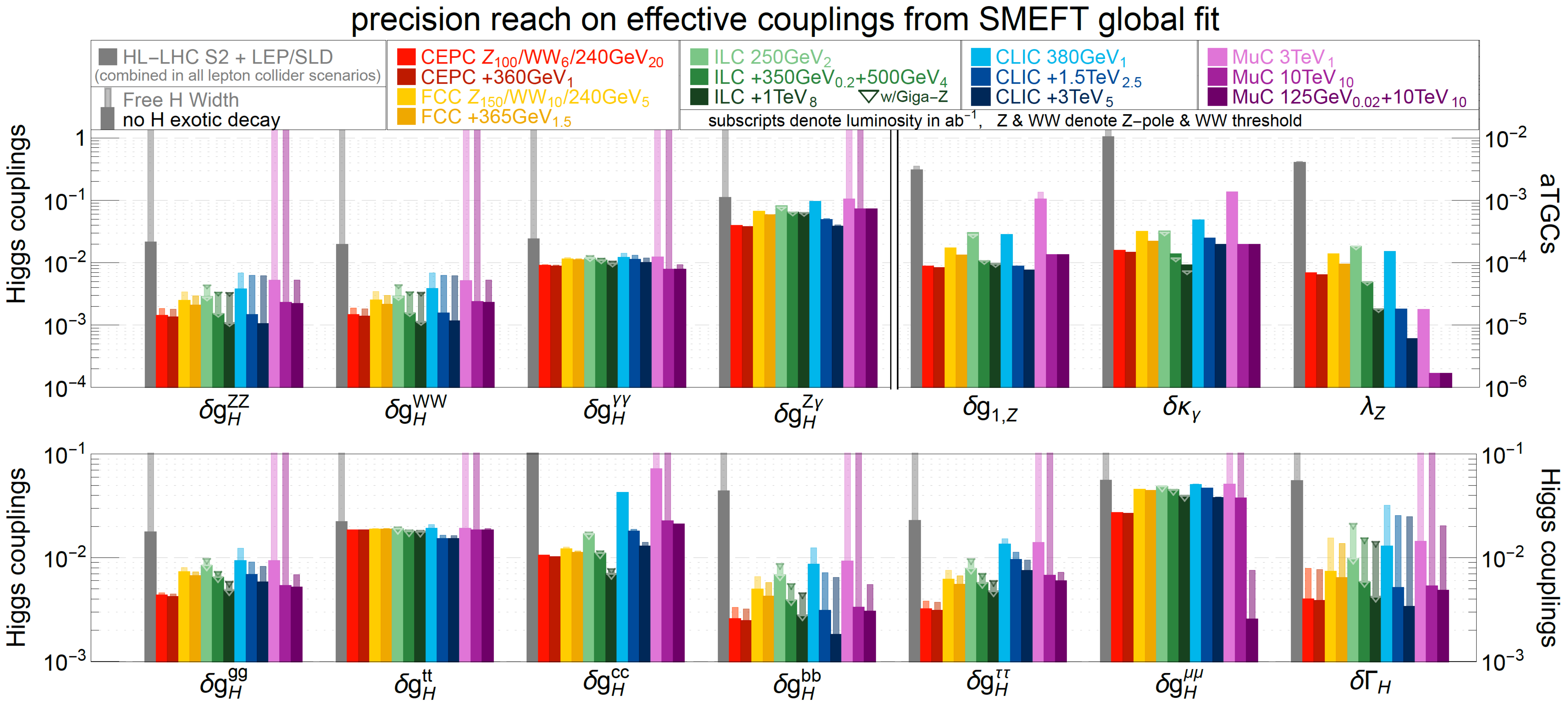
$e^+e^- \to q\bar{q}H \to qq$ inv in ILD detector



arXiv:2203.08330 (SiD) &
***PoS* EPS-HEP2019 (2020) 358 (ILD)**

The new Snowmass SMEFT fit

Rainbow-Manhattans



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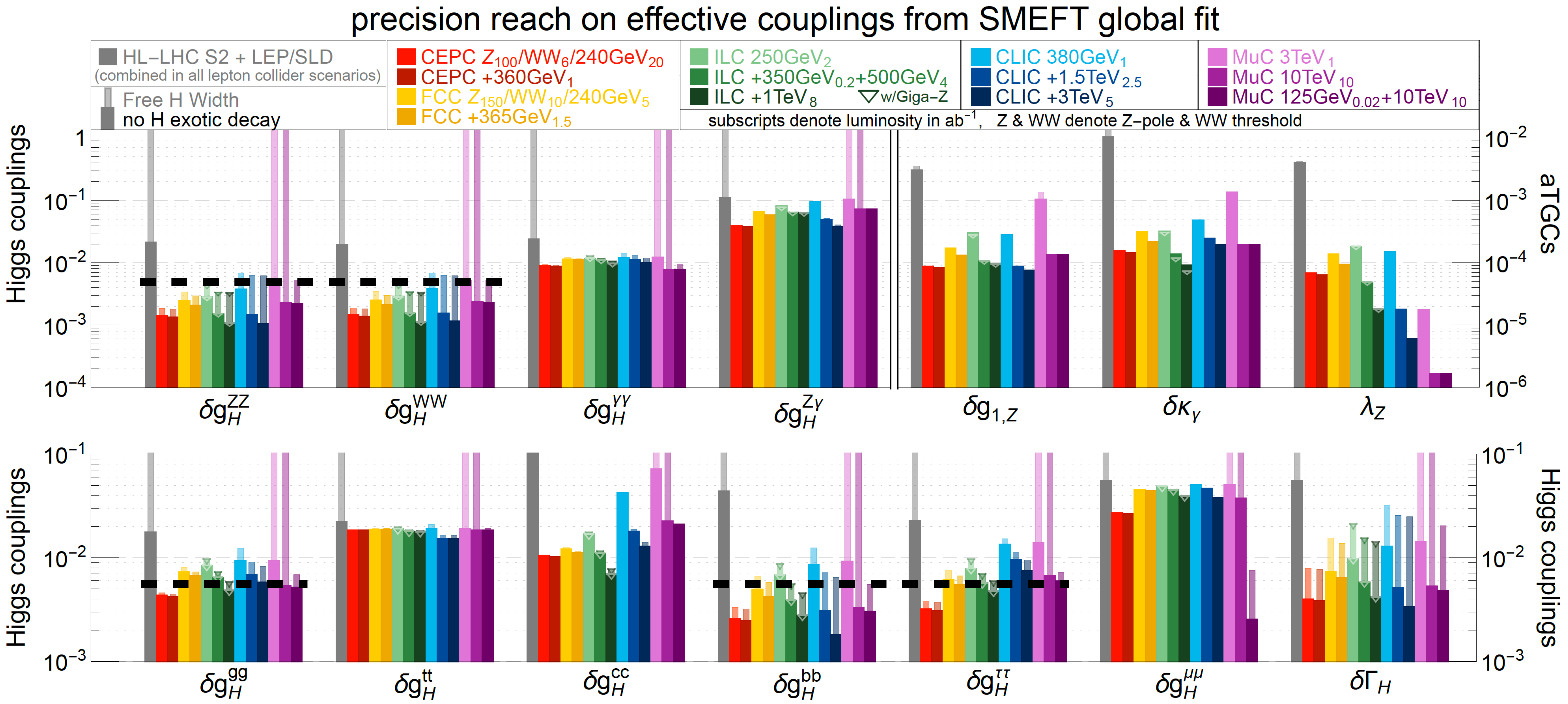

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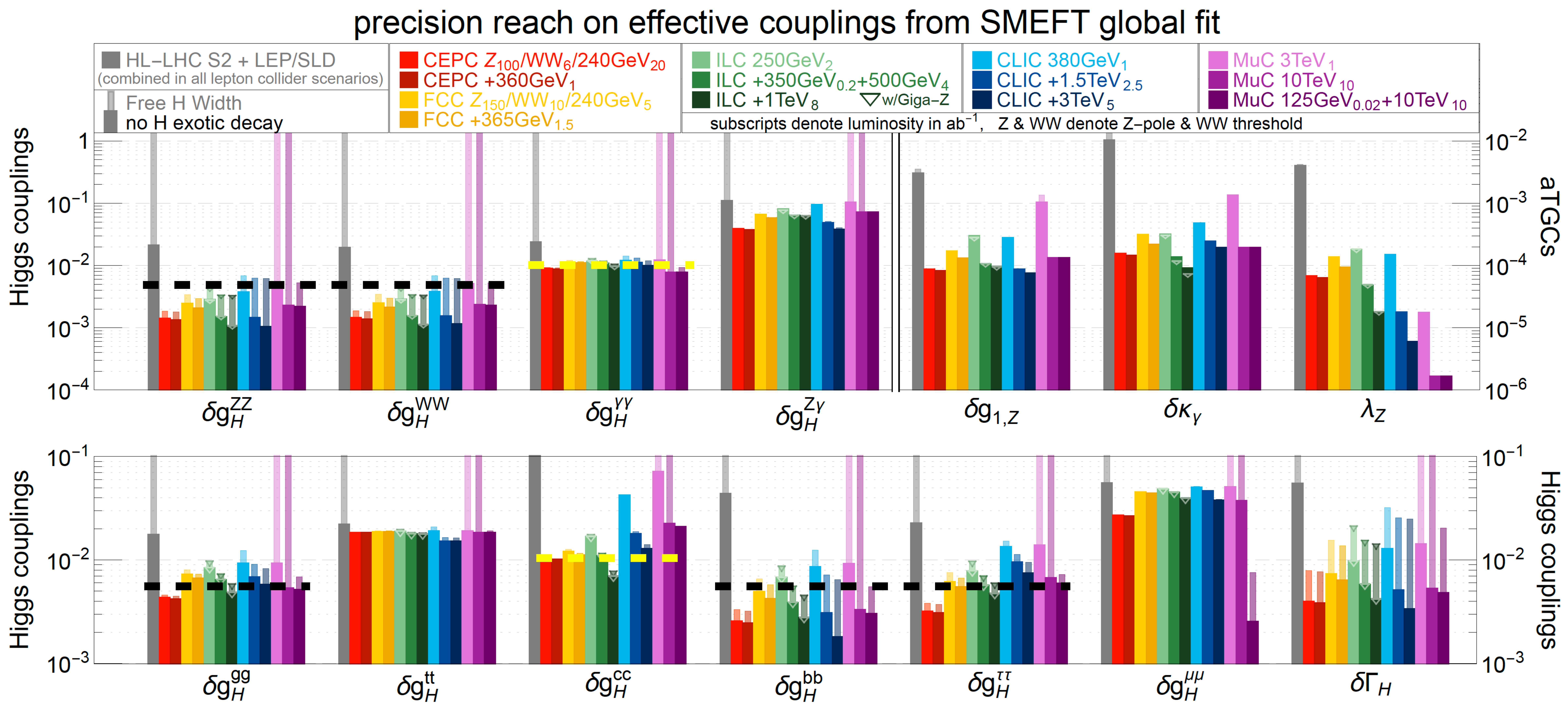

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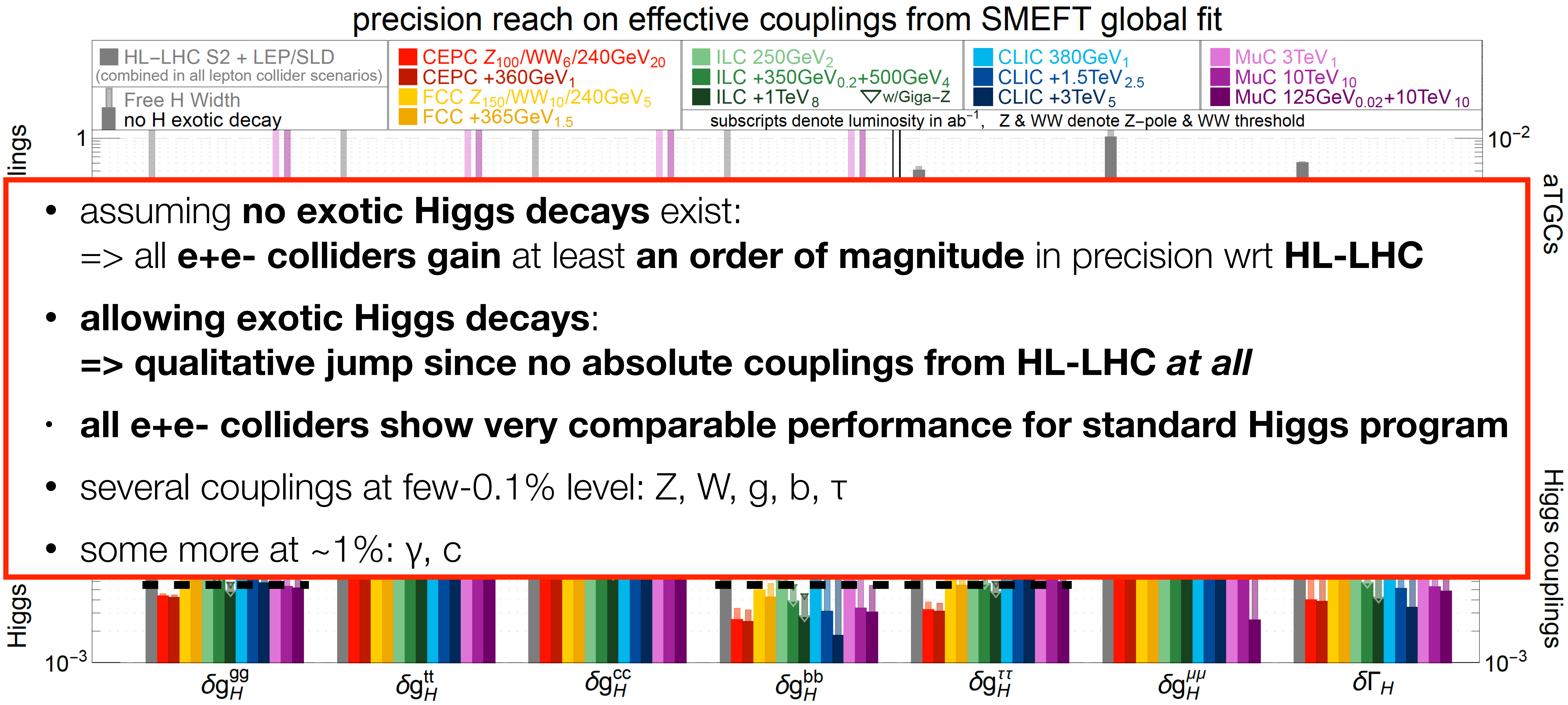


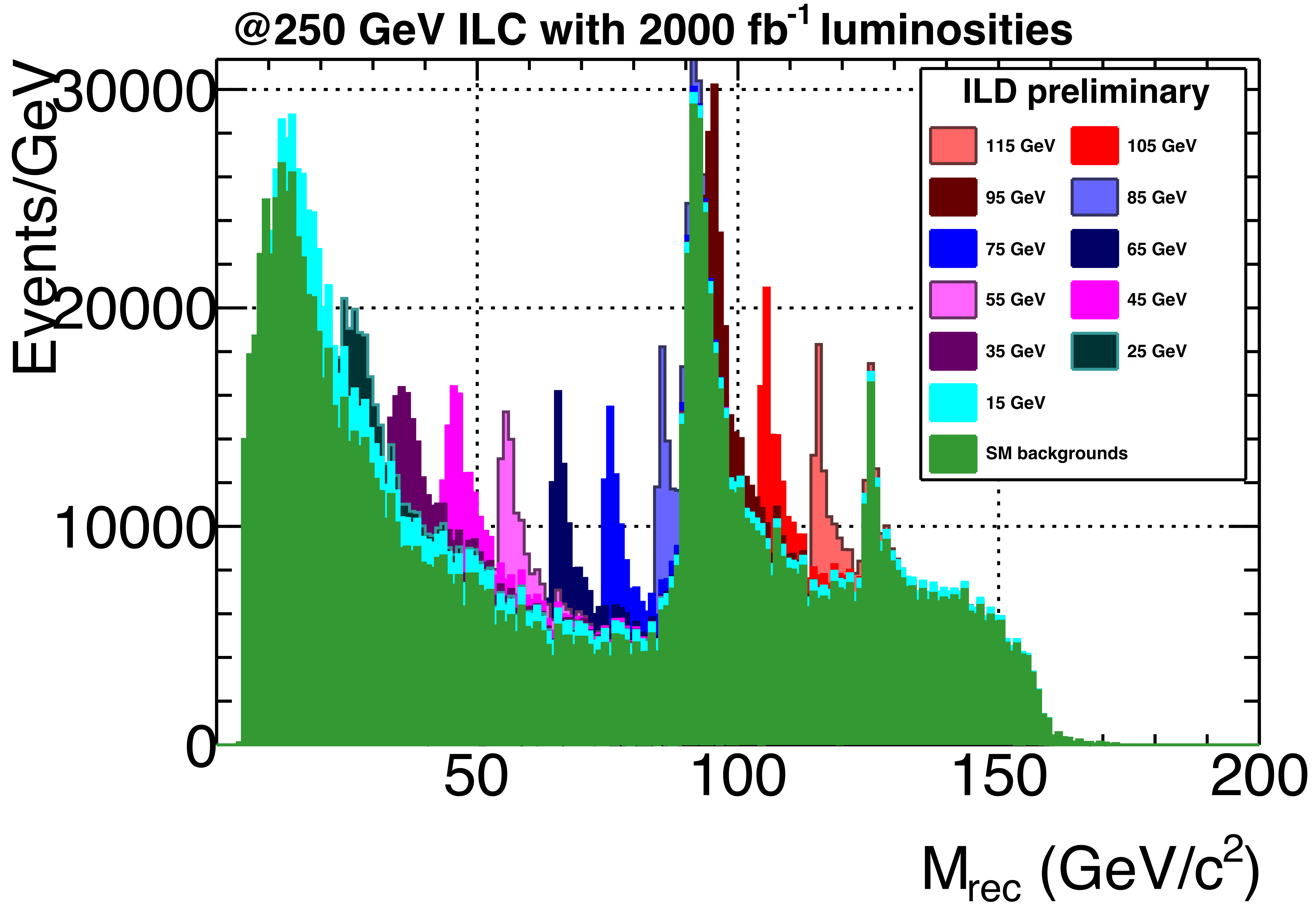
- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**:
  => qualitative jump since no absolute couplings from HL-LHC *at all*
- **all e+e- colliders show very comparable performance for standard Higgs program**
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

Extra Higgs Bosons ?

Siblings of the Higgs

- must "share" coupling to the Z with the 125-GeV guy:
  - $g_{HZZ}^2 + g_{hZZ}^2 \leq 1$
  - 250 GeV Higgs measurements:
    $g_{hZZ}^2 < 2.5\%\ g_{SM}^2$ excluded at 95% CL
- probe smaller couplings by ***recoil* of h against Z**

=> decay mode independent!



ILD full detector simulation @ ILC 250 GeV & 500 GeV, arxiv:2005.06265

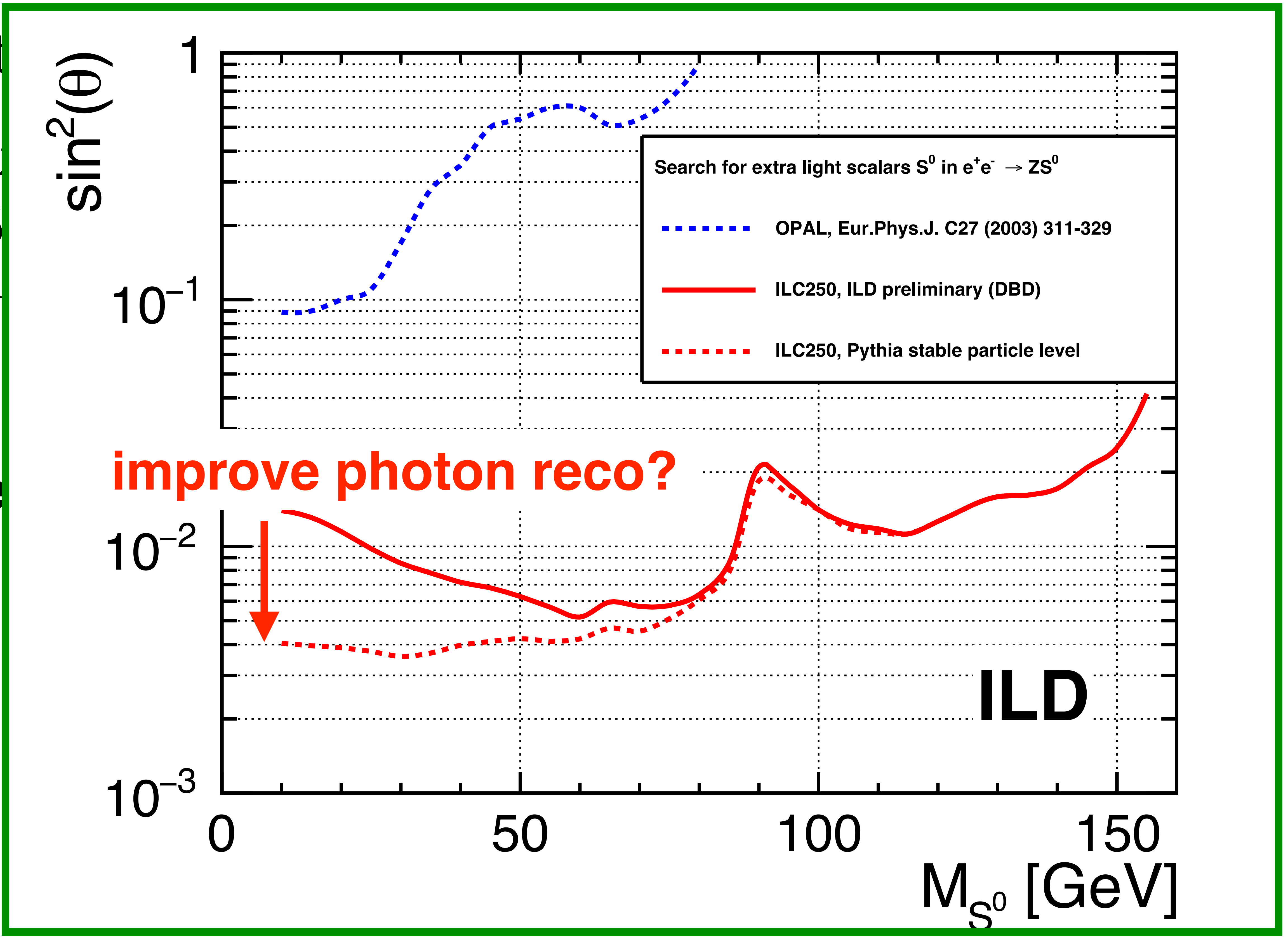
- **fully complementary to measurement of ZH cross section**
- **other possibility: ee -> bbh (via Yukawa coupling)**

Extra Higgs Bosons ?

Siblings of the Higgs

- must
  - g_H
  - 25
    g_h
- prob

=> de



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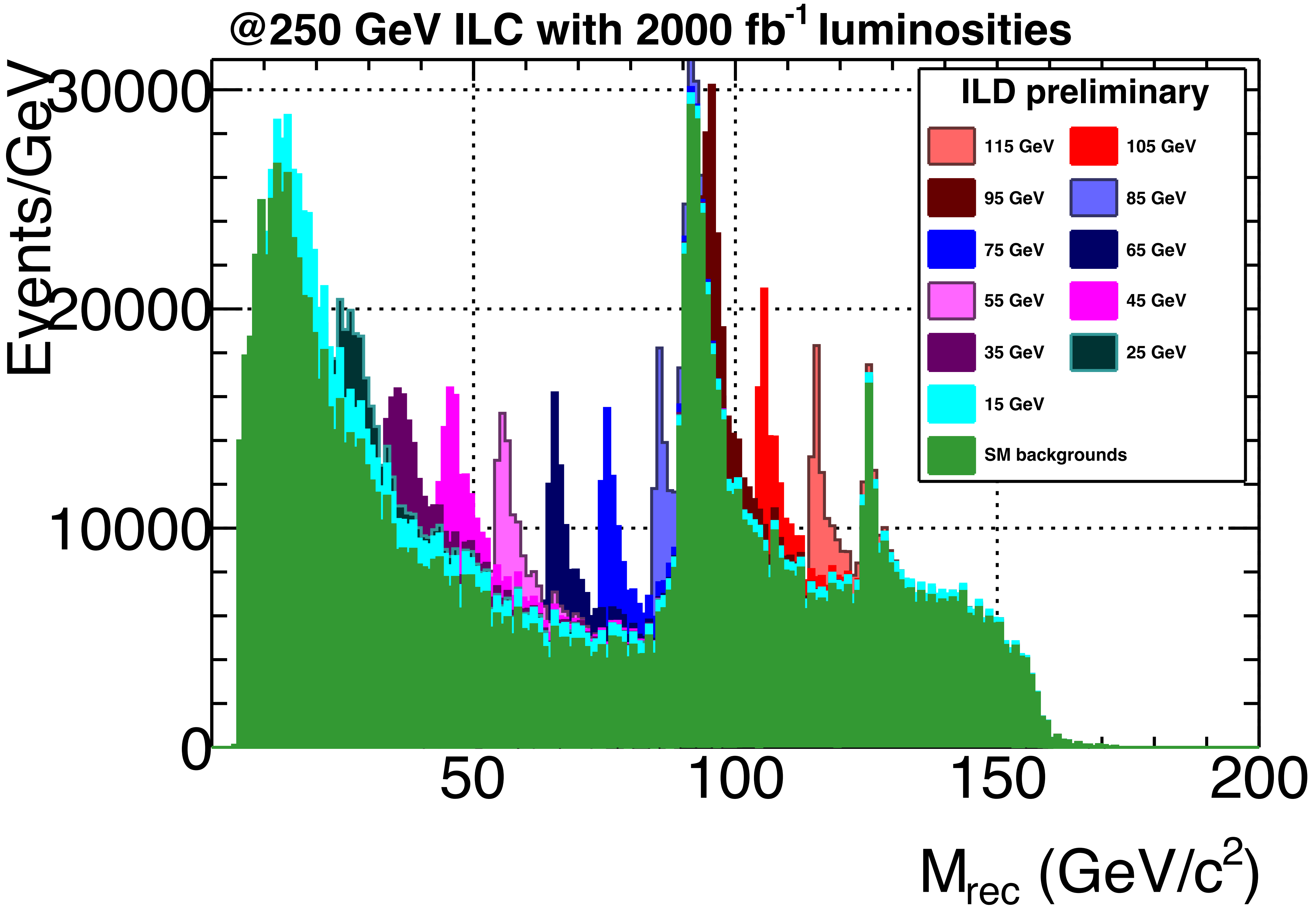

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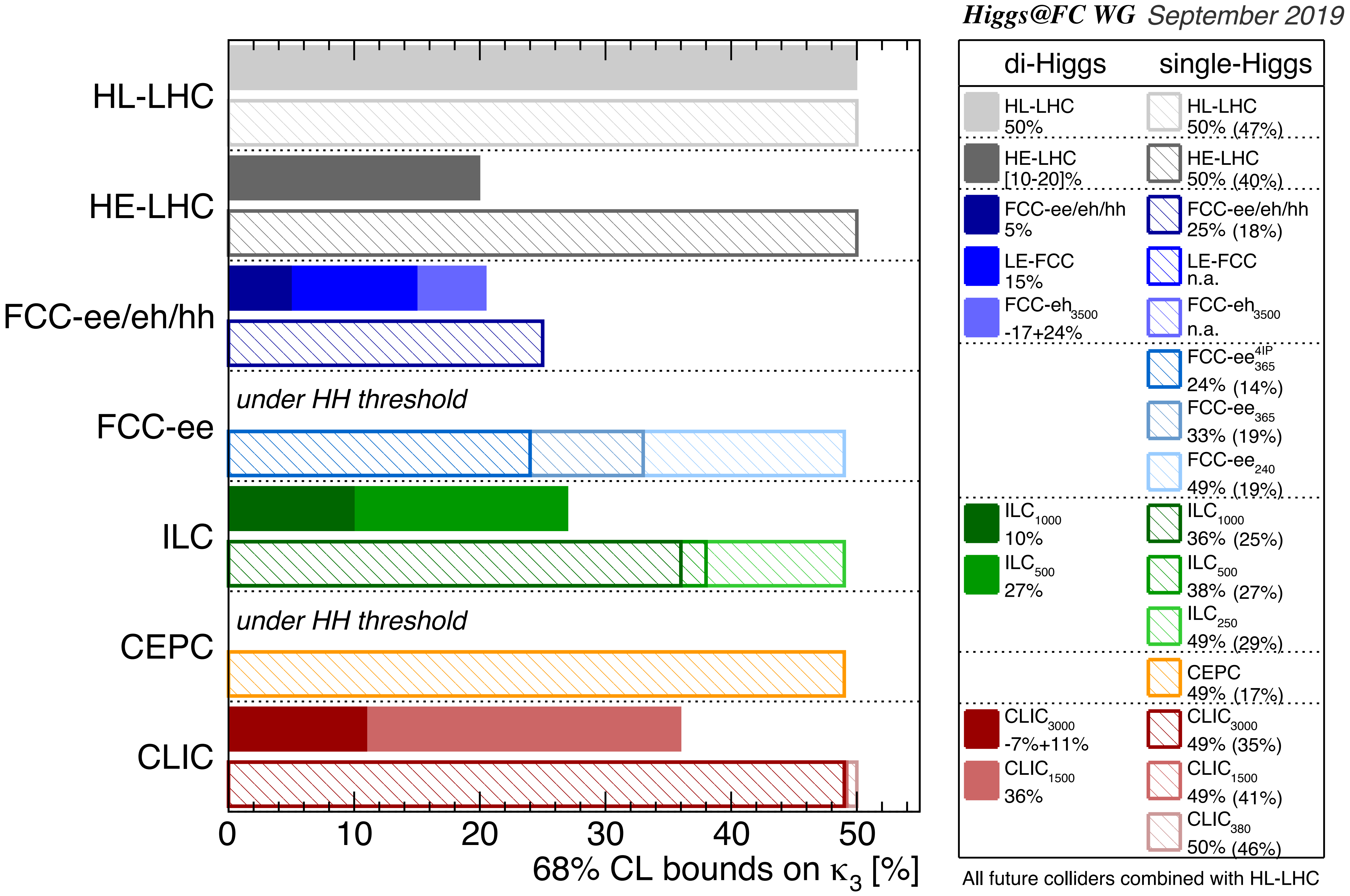
Higgs self-coupling

Electroweak Baryogenesis?



most detailed ILC ref: PhD Thesis C.Dürig
Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

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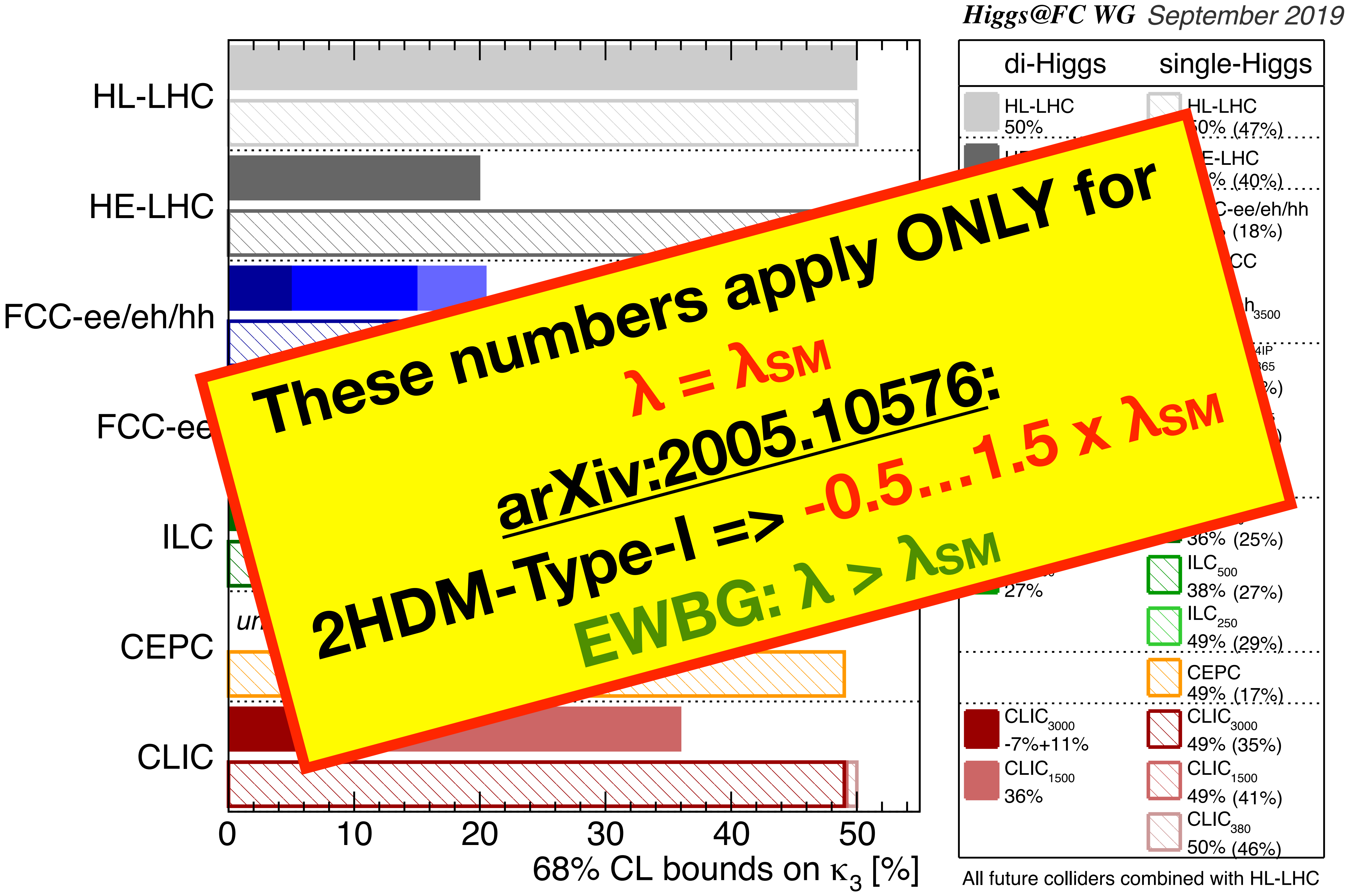

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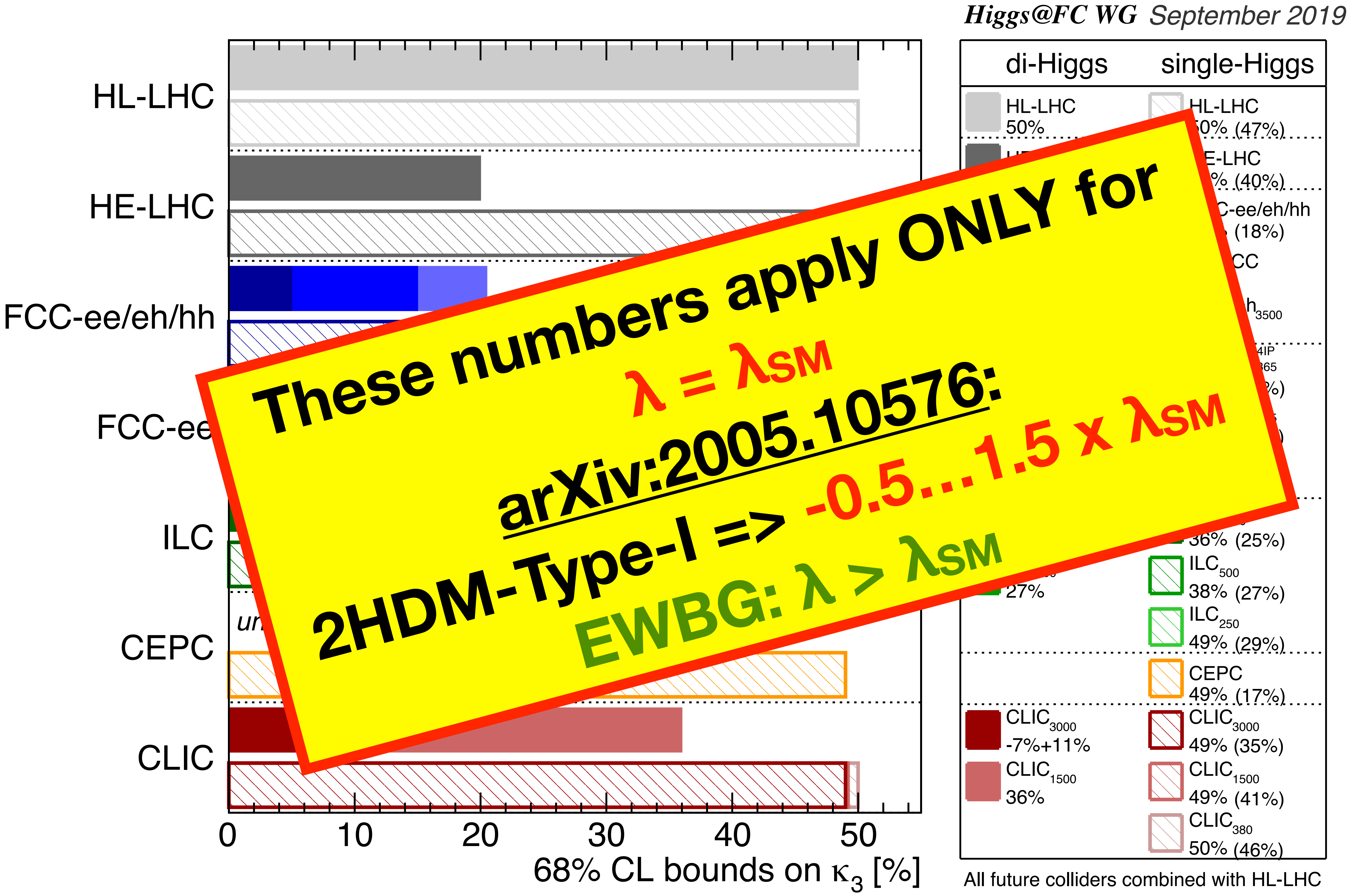

These numbers apply ONLY for $\lambda = \lambda_{SM}$

arXiv:2005.10576:

2HDM-Type-I => $-0.5 \dots 1.5 \times \lambda_{SM}$

EWBG: $\lambda > \lambda_{SM}$

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- **pp cross section drops**
- **ee cross section rises**

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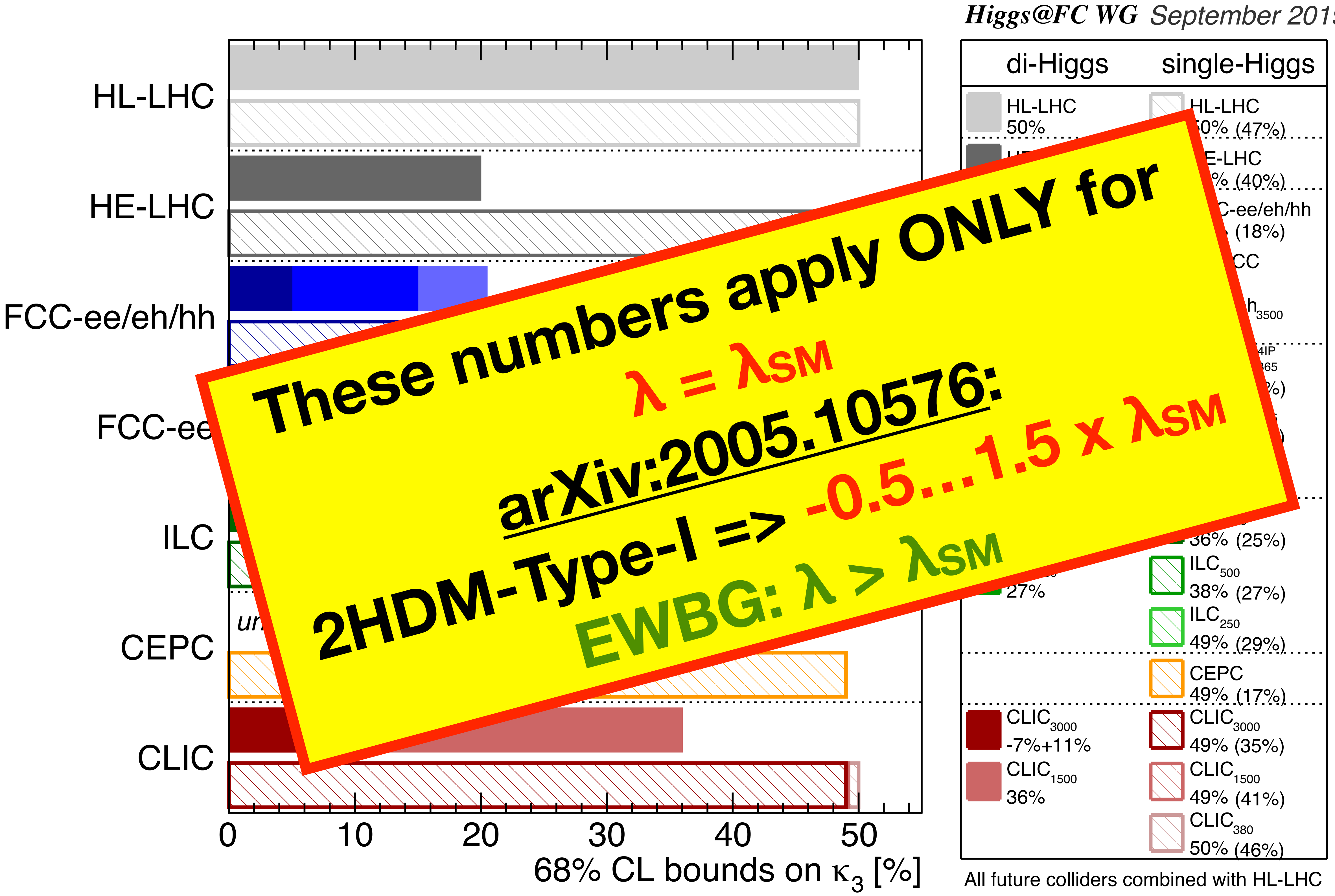

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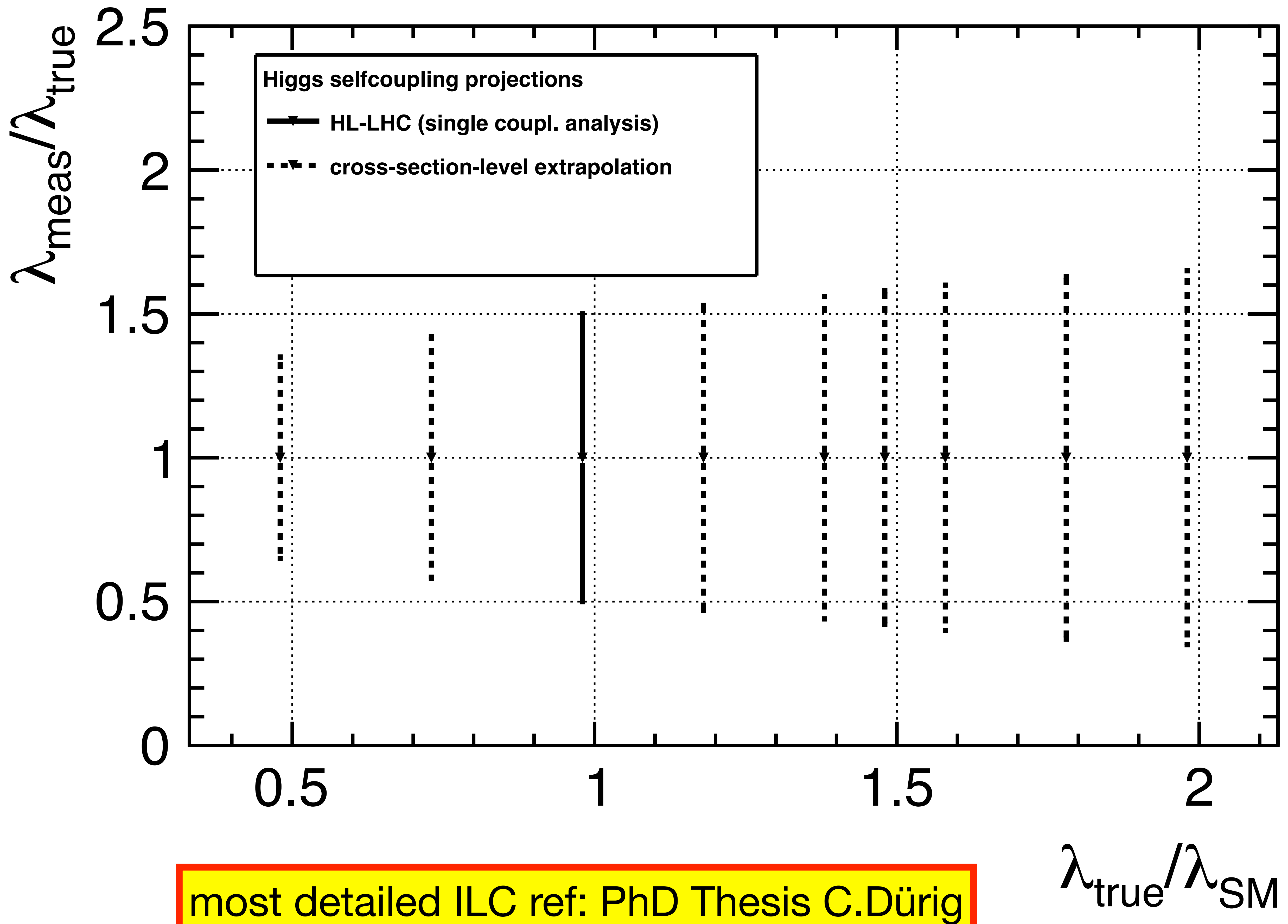

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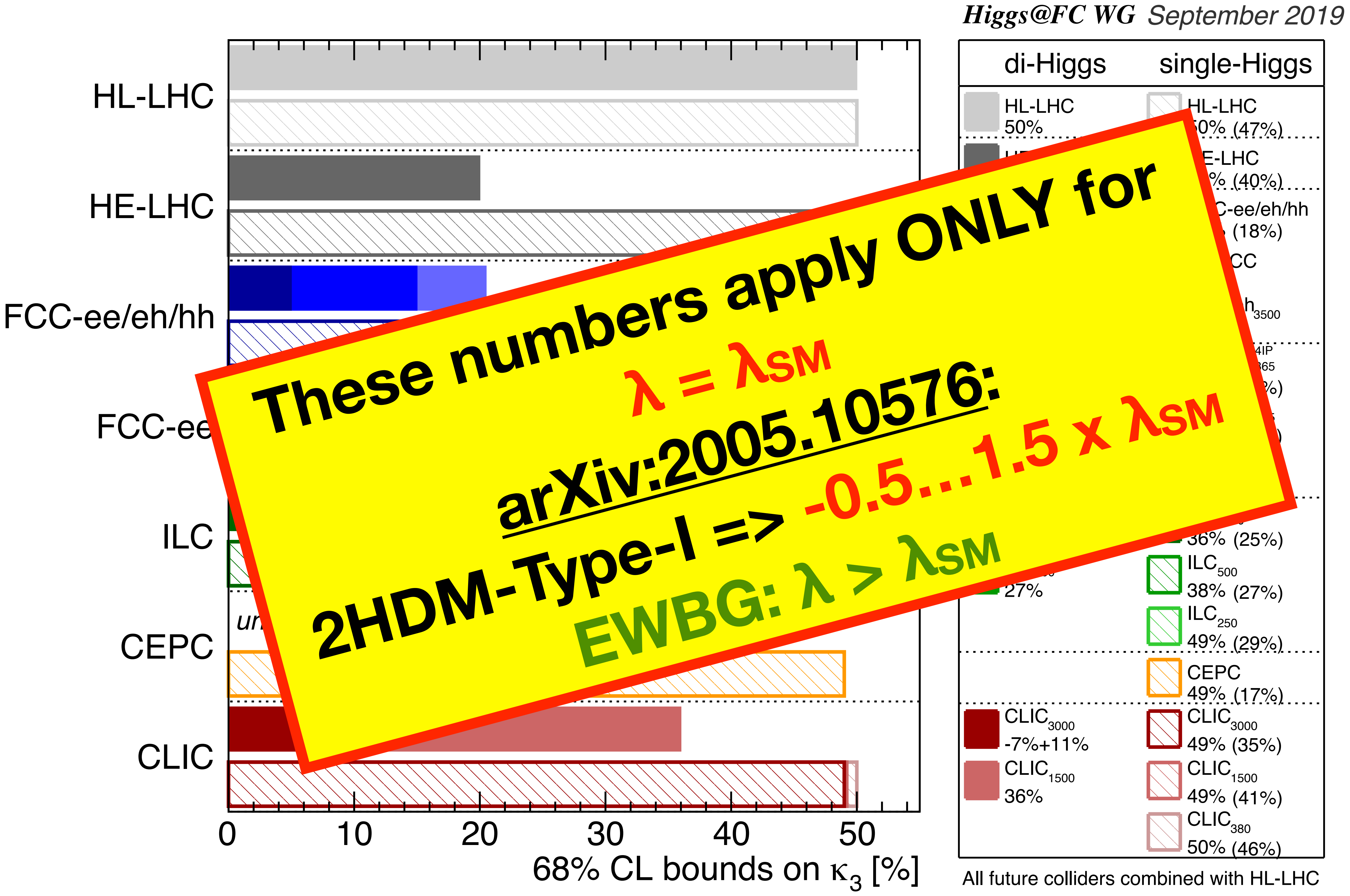

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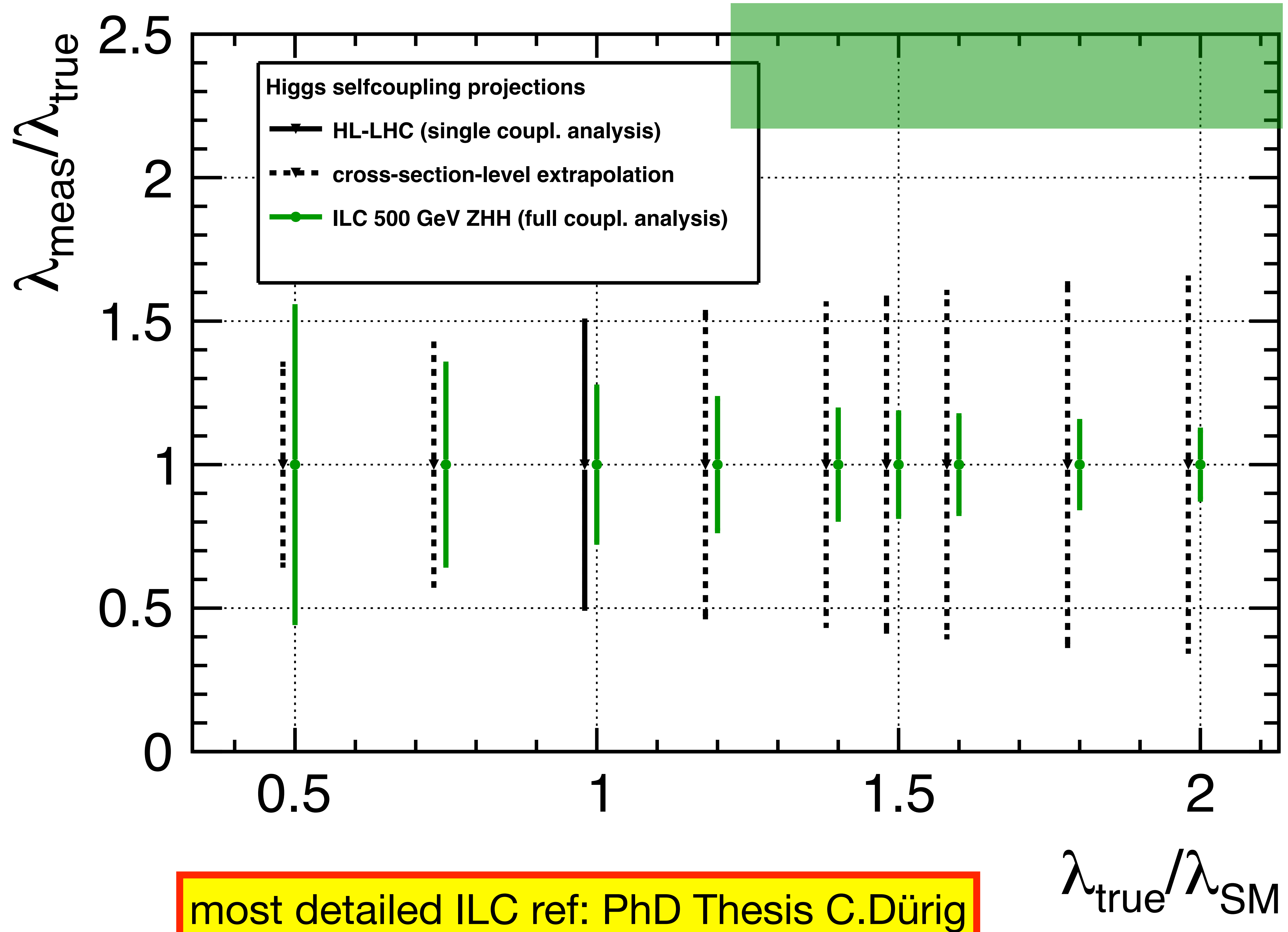
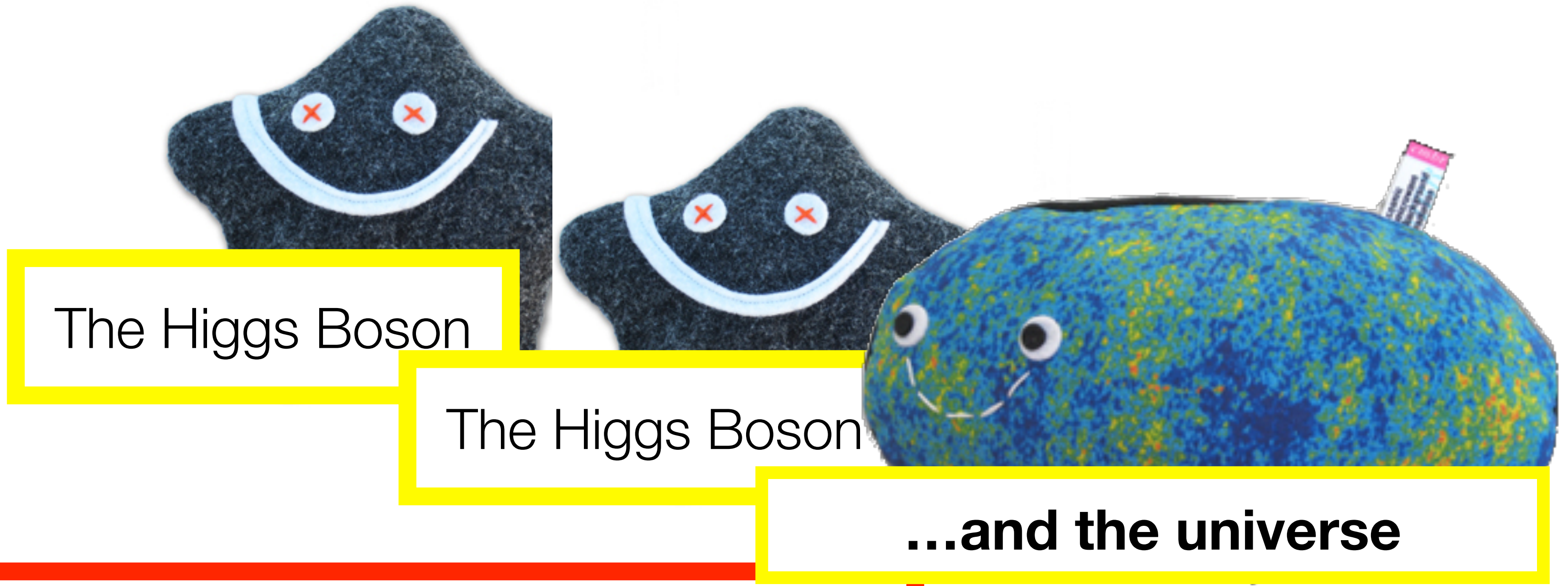
Region of interest for electroweak baryogenesis

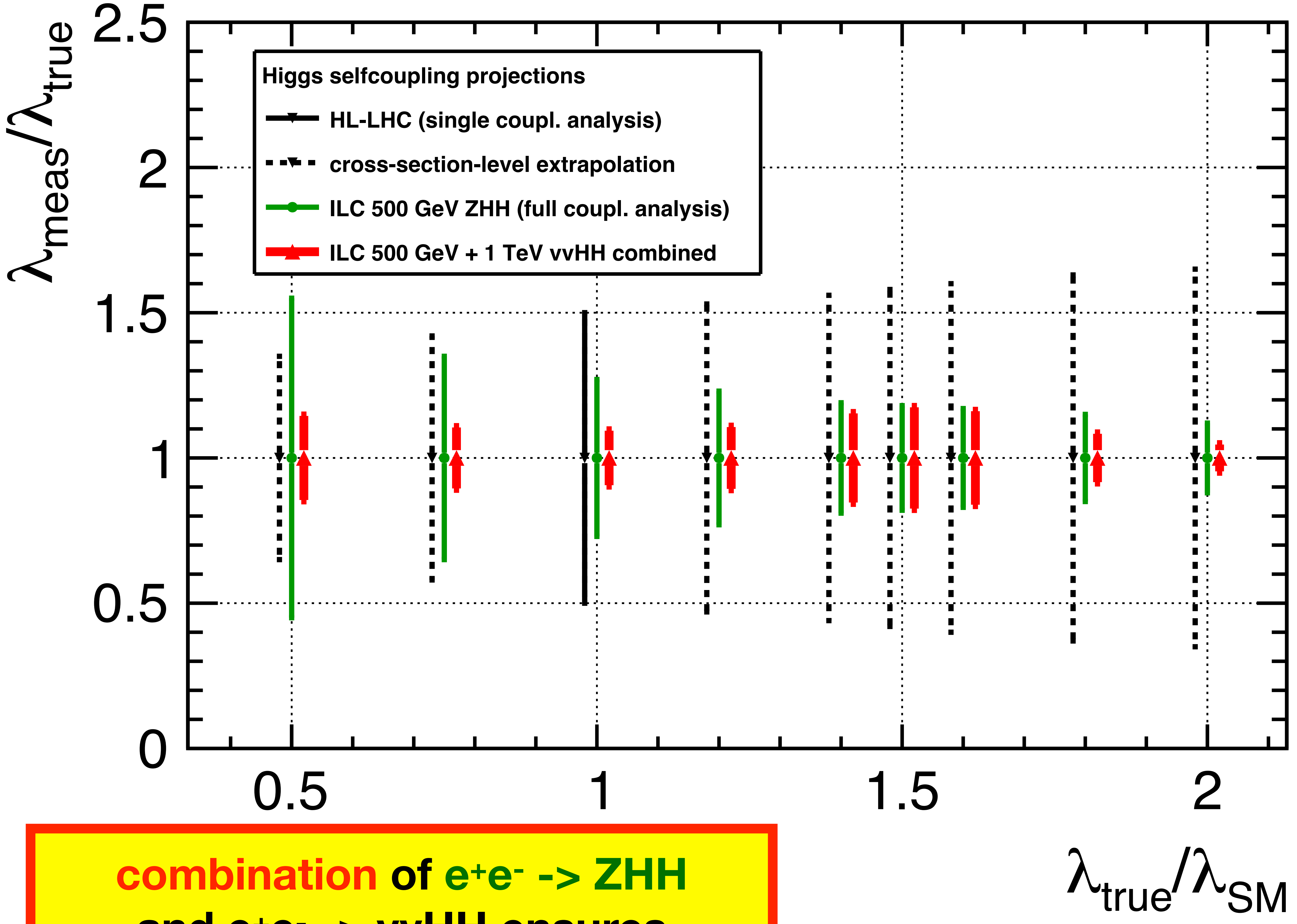


most detailed ILC ref: PhD Thesis C.Dürig Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

Higgs self-coupling

Electroweak Baryogenesis?





combination of e^+e^- -> ZHH and e^+e^- -> ννHH ensures at least 10-15% precision for all λ

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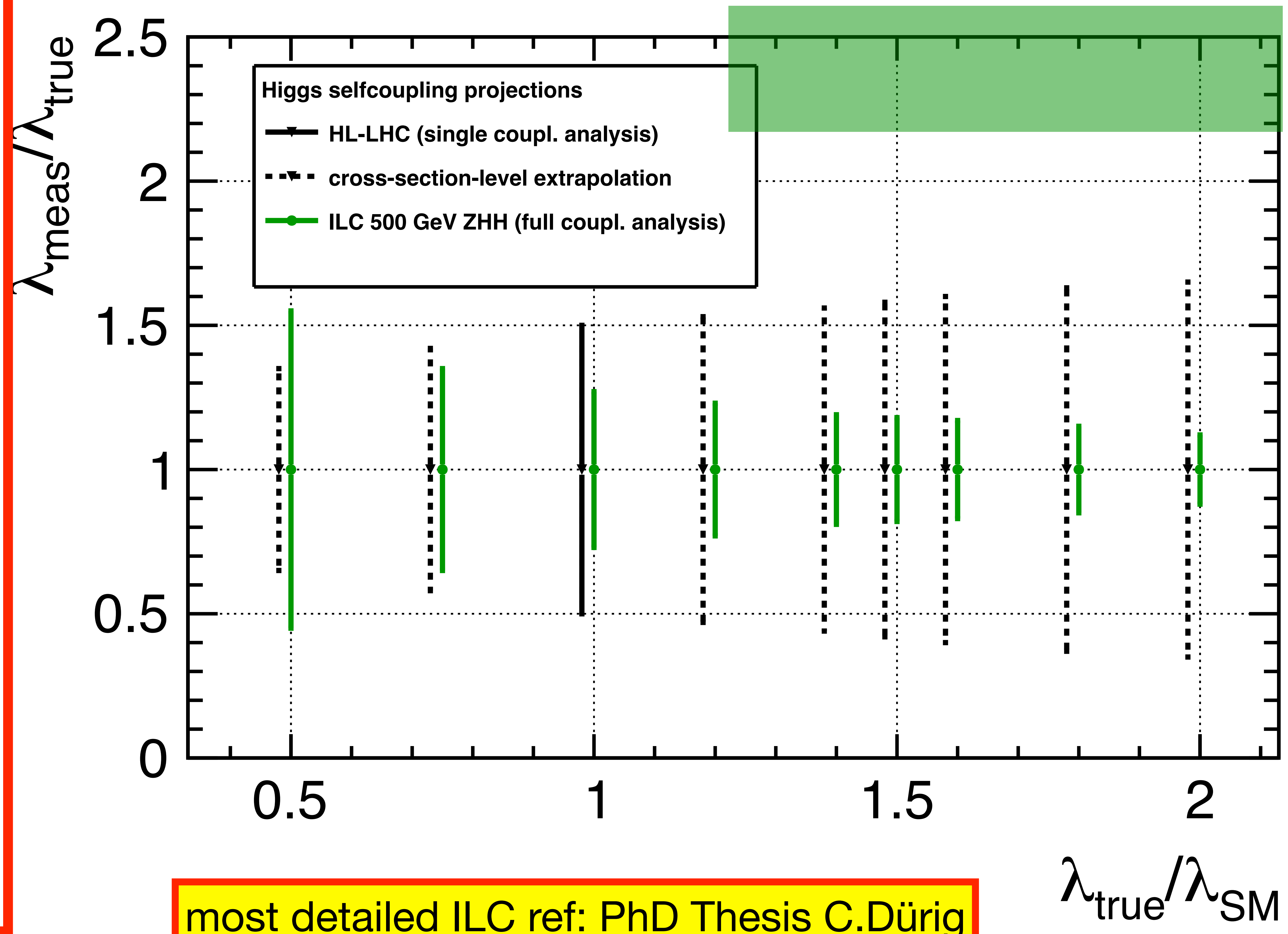

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And finally a word on Leptogenesis

Comprehensive exploration by neutrino physics…

- … but there are cases where colliders can make discoveries and give decisive input
- e.g. Leptogenesis and Gravitino Dark Matter [Buchmüller (2018)]:
  - leptogenesis implies upper bound on SUSY masses since thermal production of light gravitinos ~ m^2
  - then typically gravitino is LSP, "NLSP" is a low-ΔM-triplet of Higgsinos
- full detector simulation for two leptogenesis-motivated benchmark points ☆★ and extrapolation to full plane
- conclusions:
  - loop-hole free discovery / exclusion potential up to ~ half E_{CM}
  - even in most challenging cases few % precision on masses, cross-sections etc
  - SUSY parameter determination, cross-check with cosmology

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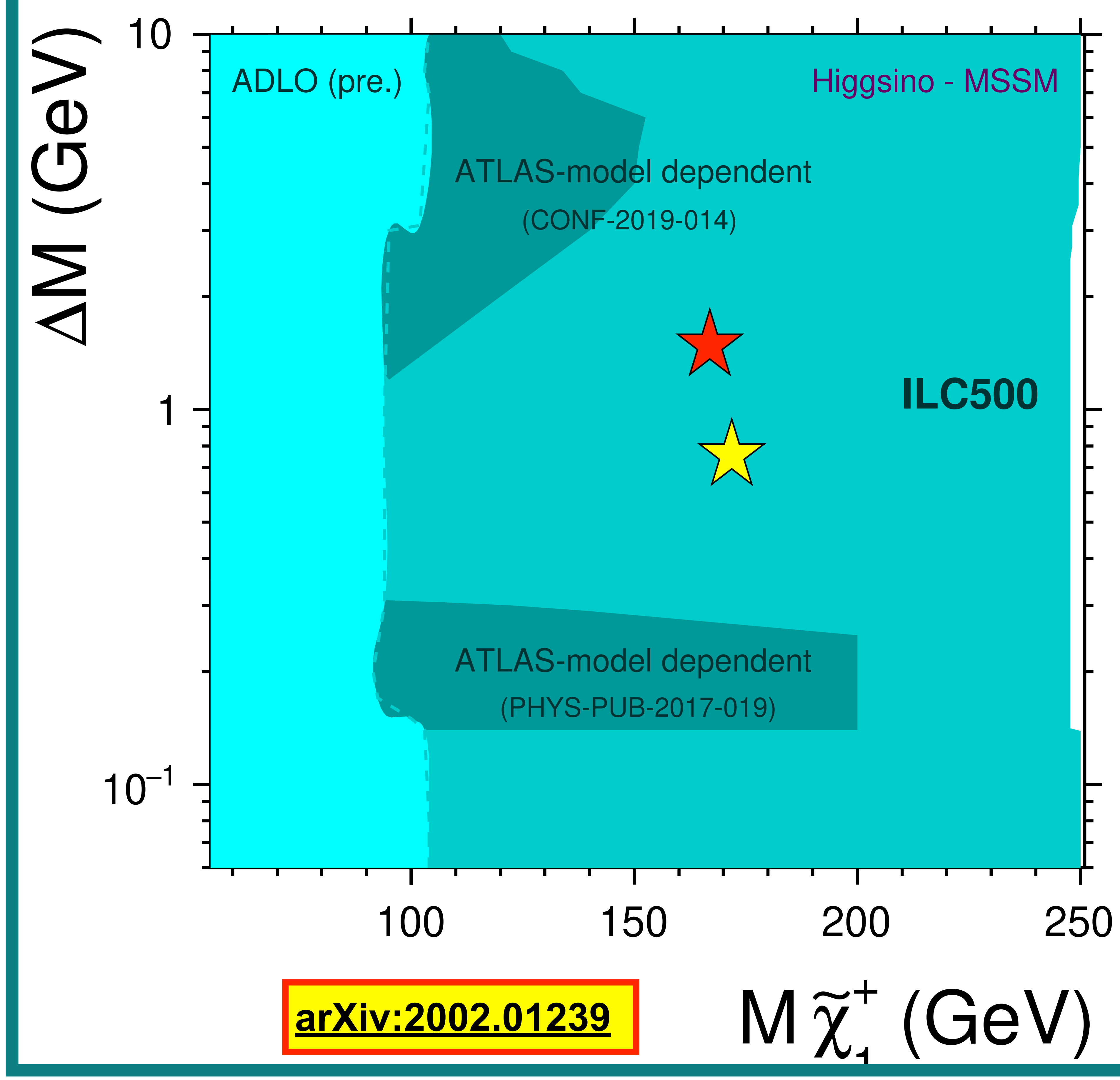

arXiv:2002.01239

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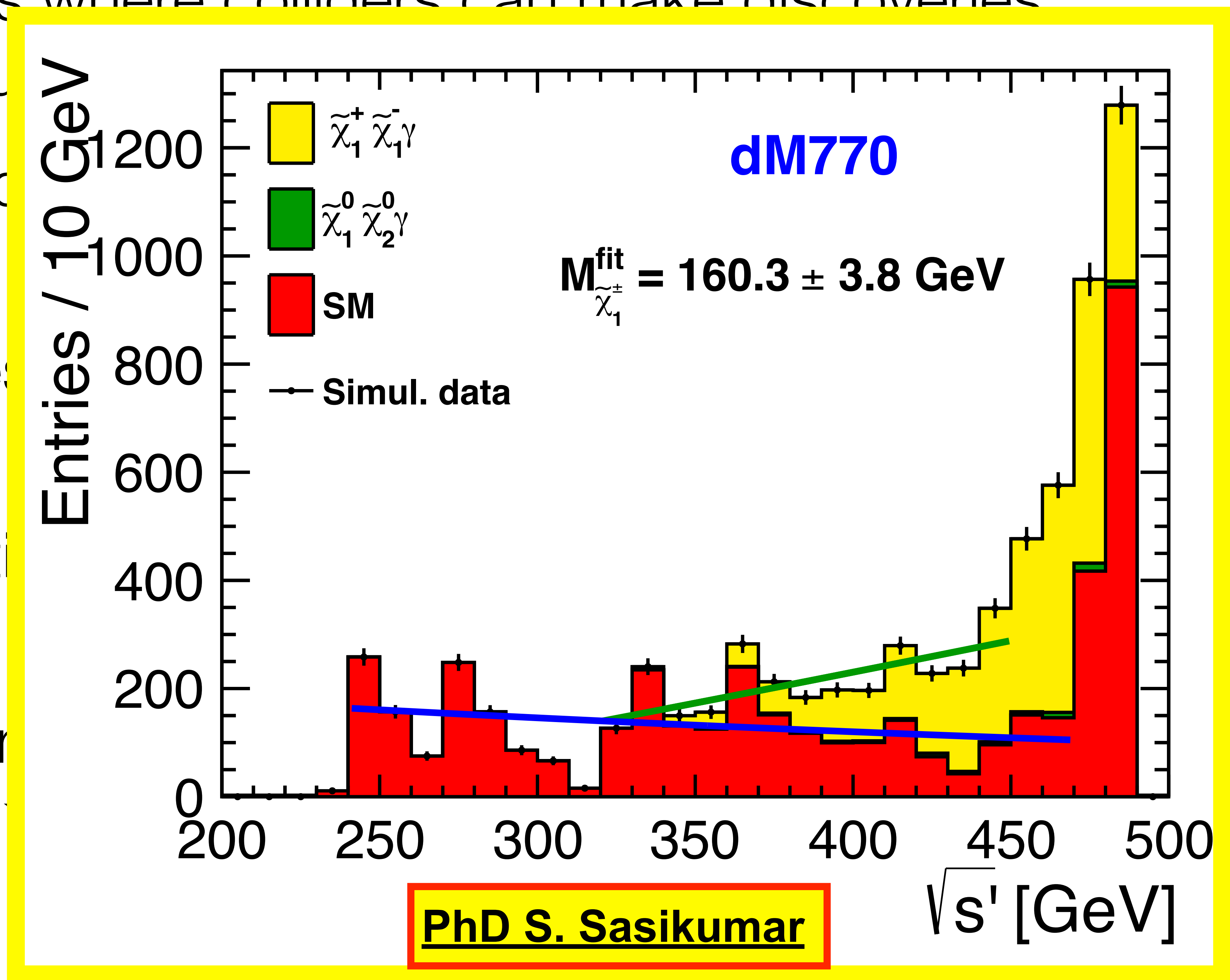

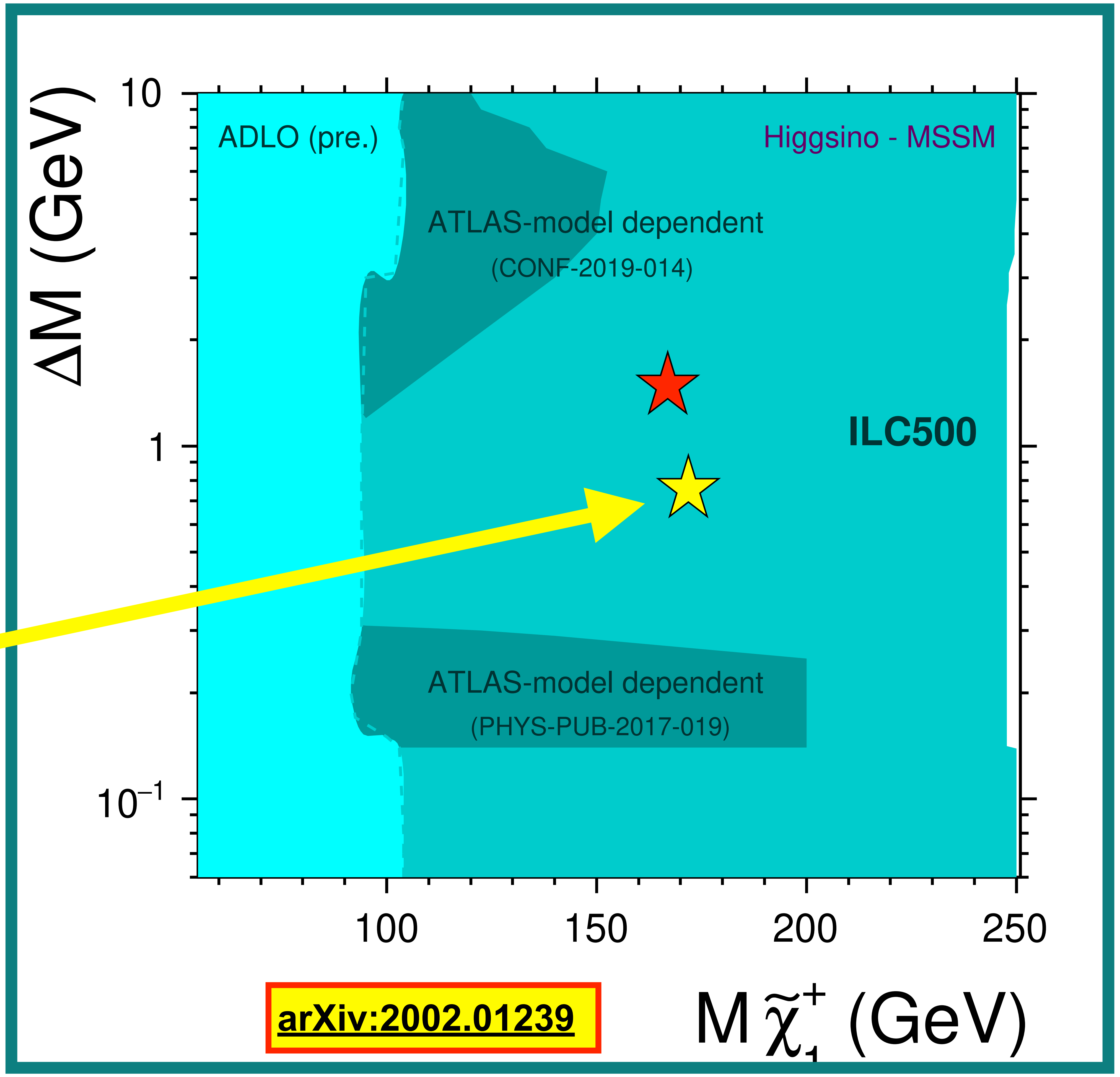

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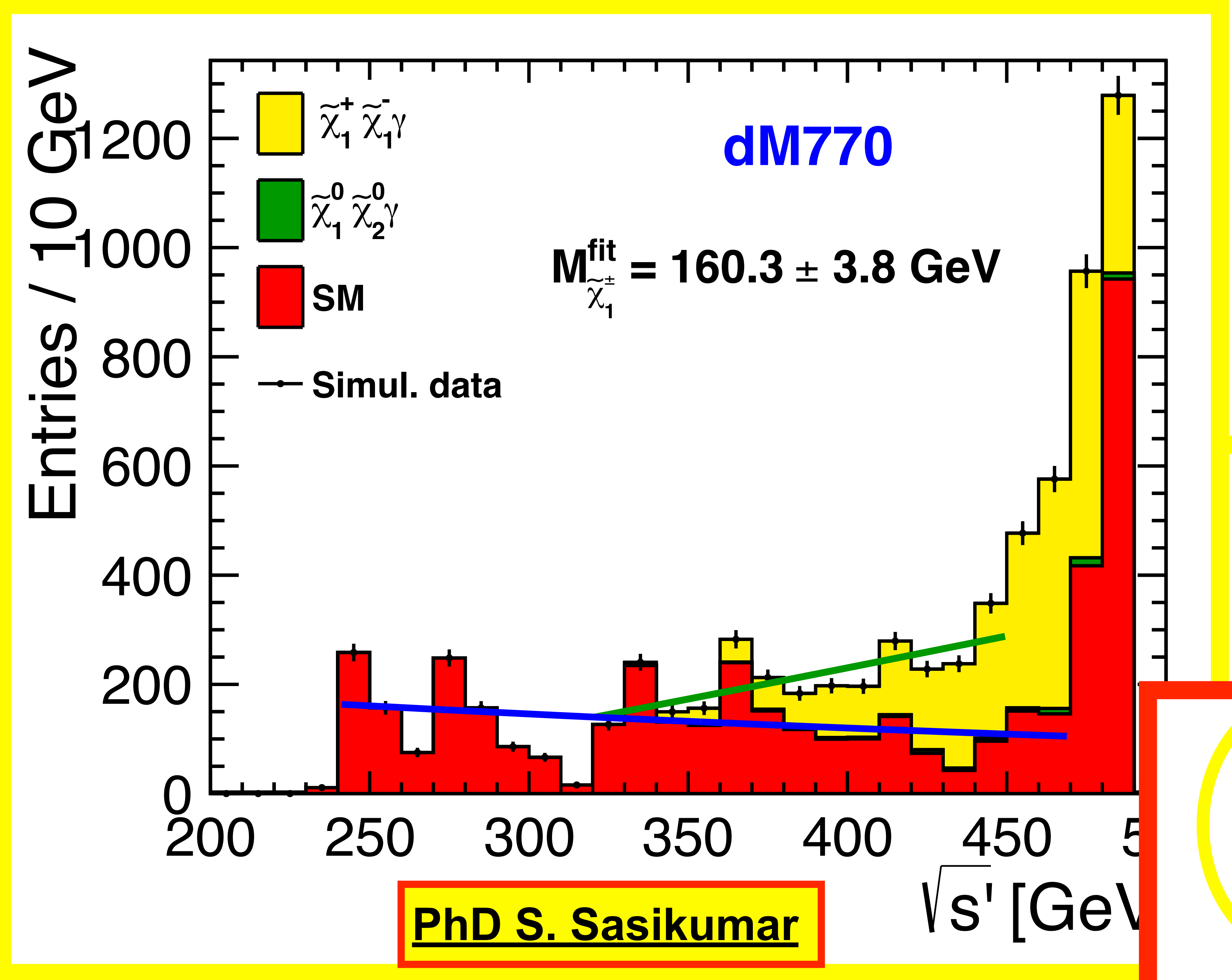

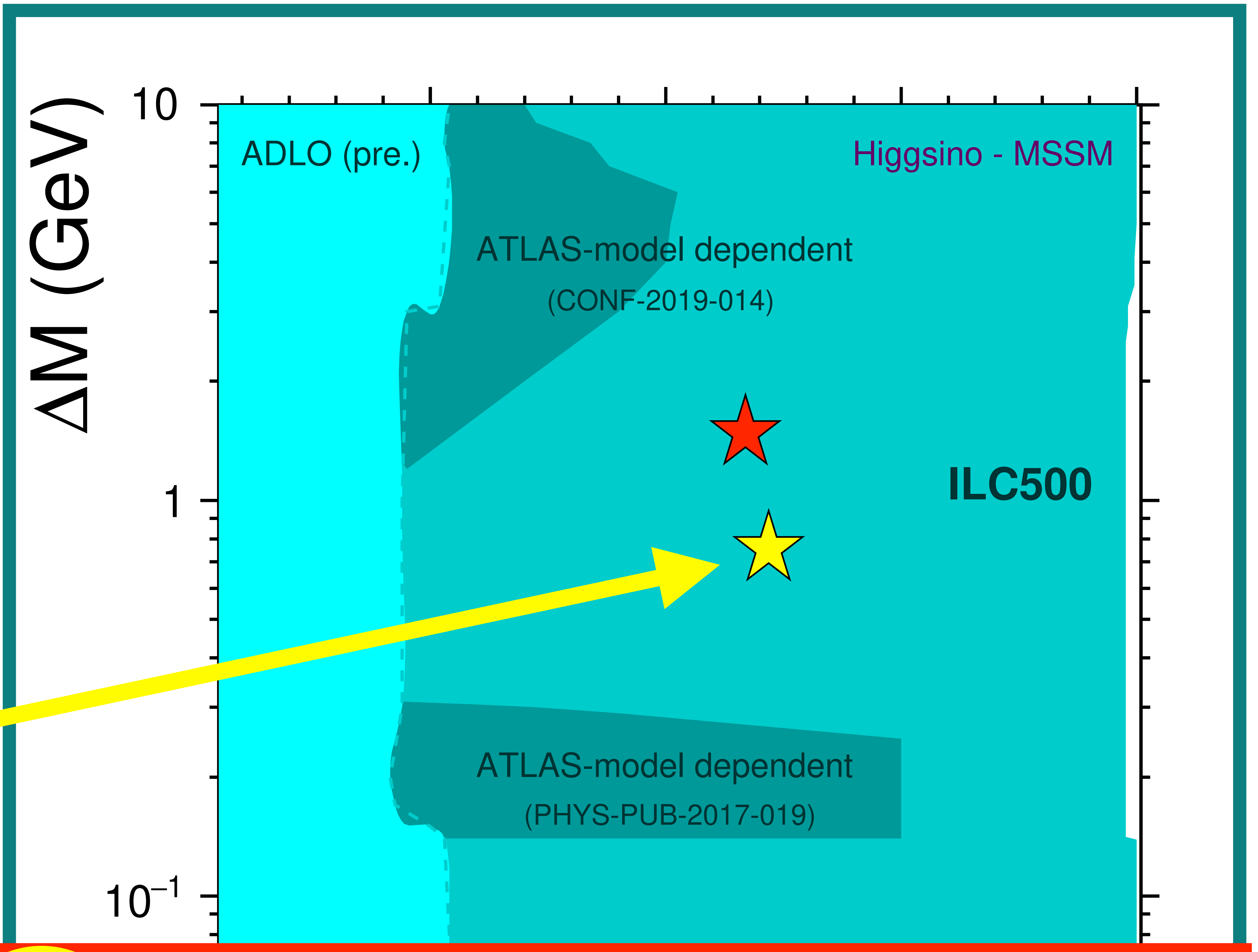

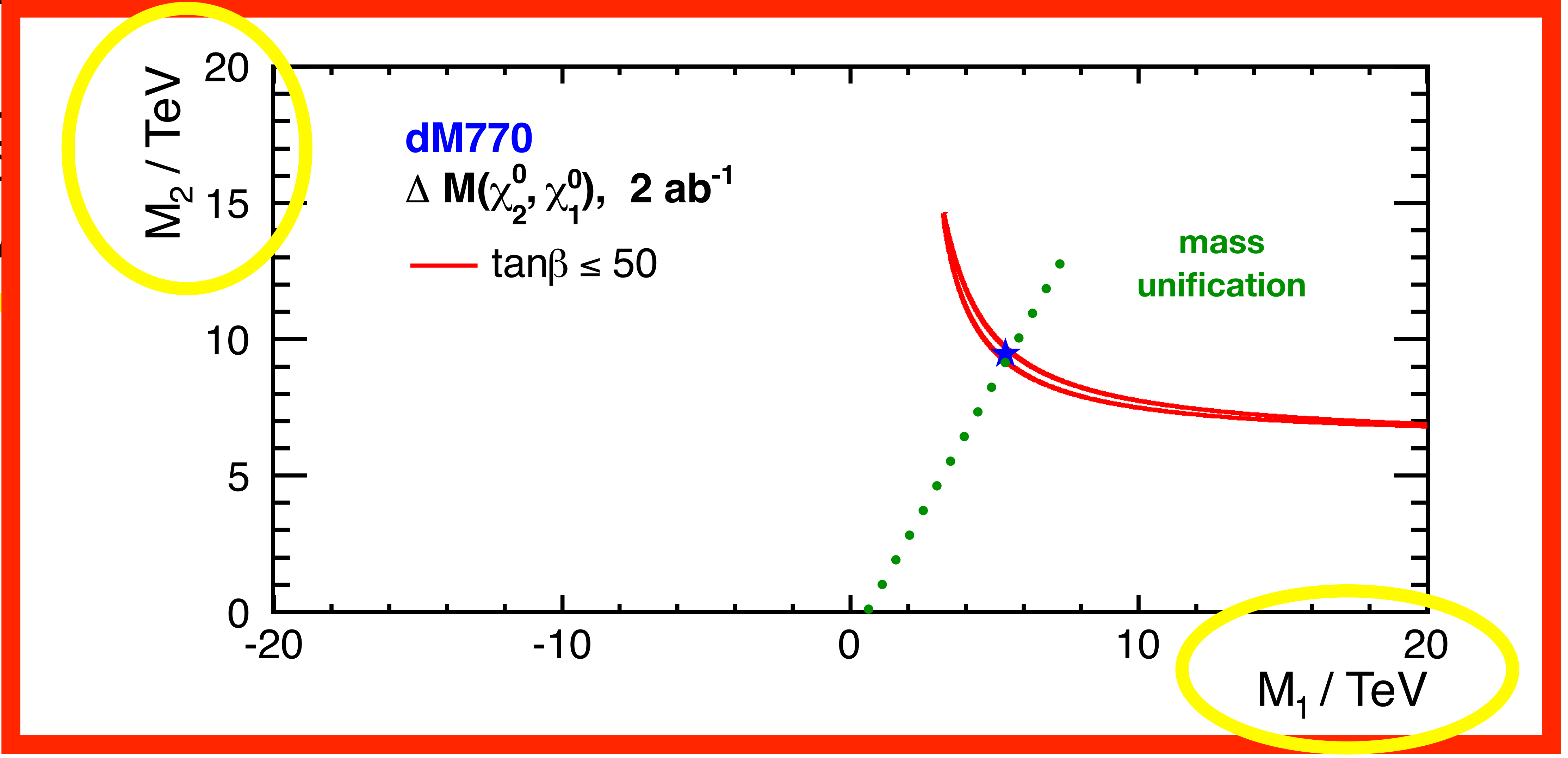

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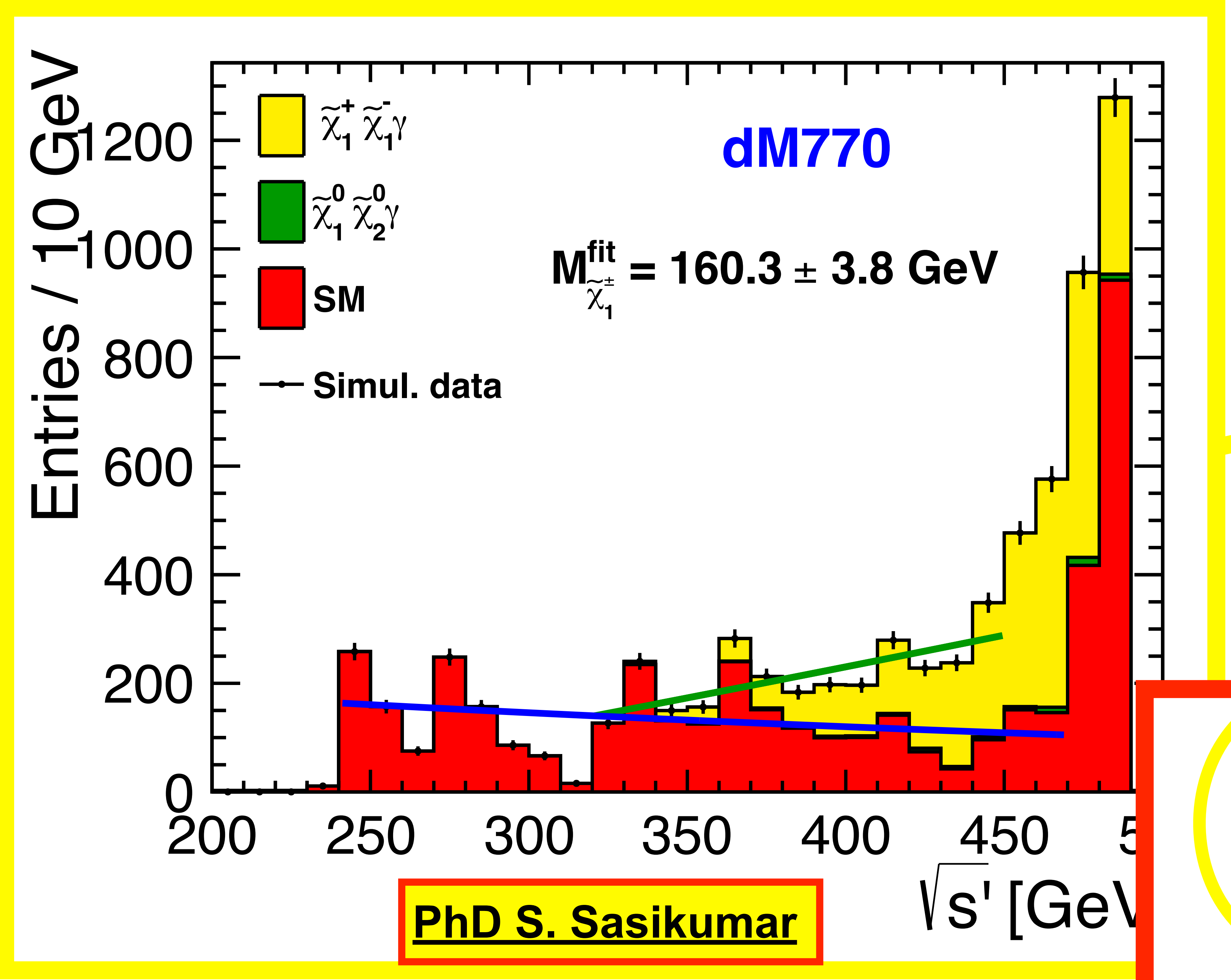
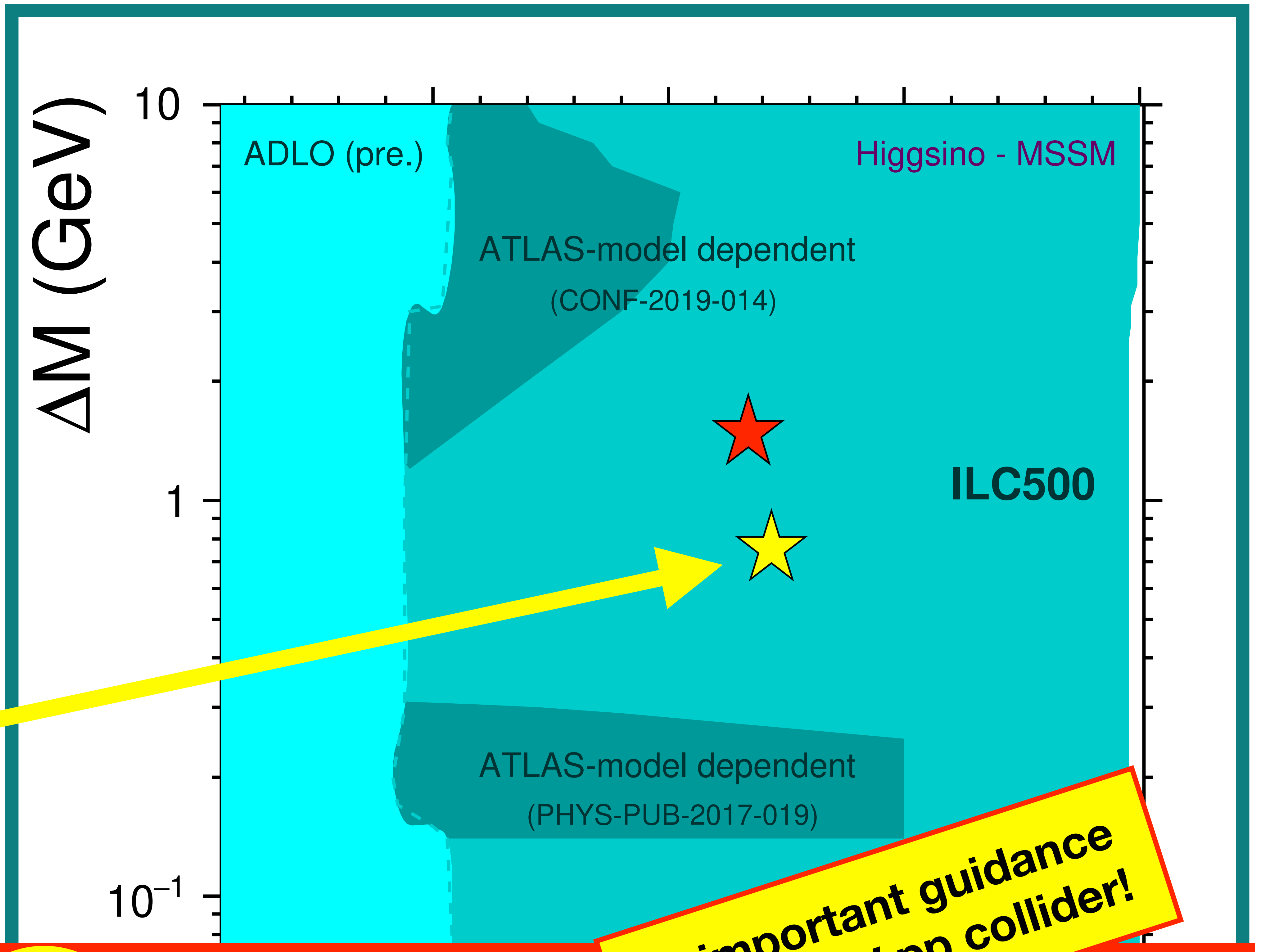
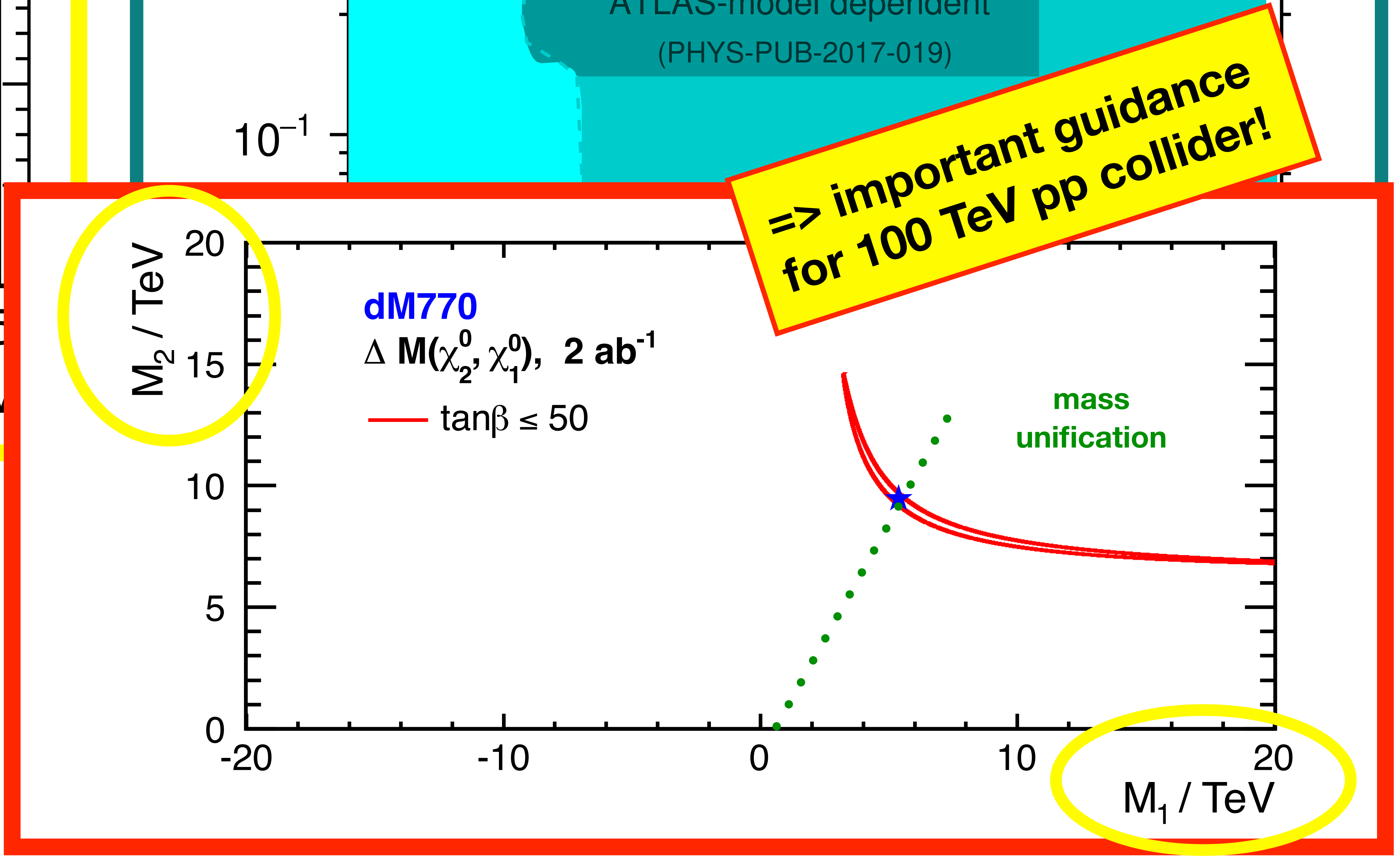


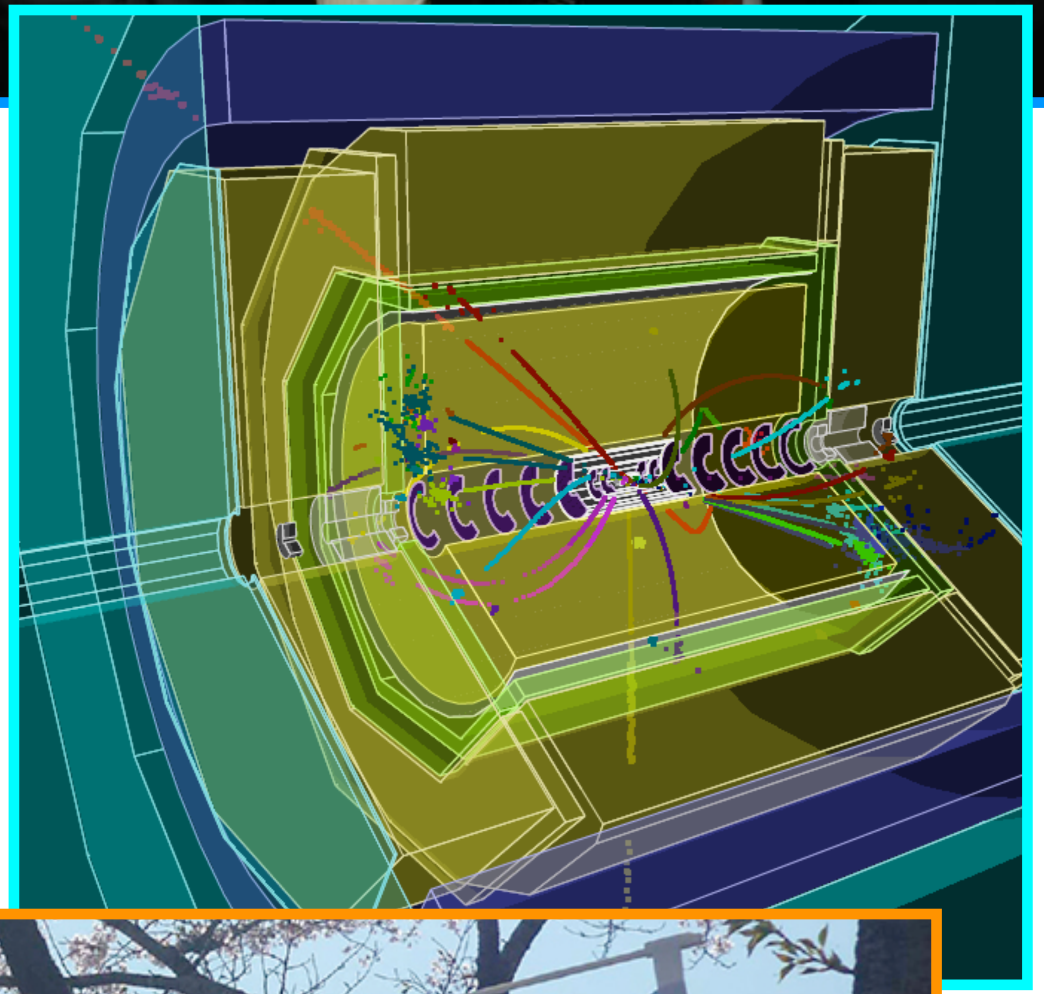




Conclusions

and outlook

- The discovery of the Higgs boson has provided us a new messenger from the early universe => an e+e- Higgs factory is needed in order to let this messenger speak to us!
- Several e+e- projects have been proposed
  - All provide similar performance for exploring single-Higgs production at E_{CM} = ~250 GeV and/or ~350 GeV;
  - Only linear colliders like ILC are upgradable to higher energies ≥ 500 GeV for complete exploration of the Higgs (self-coupling!), the top quark and their possible - visible or “dark” - siblings
- The ILC is just NOW starting into a new phase, the ILC Technology Network, in which laboratories around the world will team up to advance the R&D, and work towards an engineering design - and a scientific and political consensus
- Interested to explore yourself what one can learn about the universe at a future e+e- collider in general - or specifically at ILC ?
  => Get in touch jenny.list@desy.de

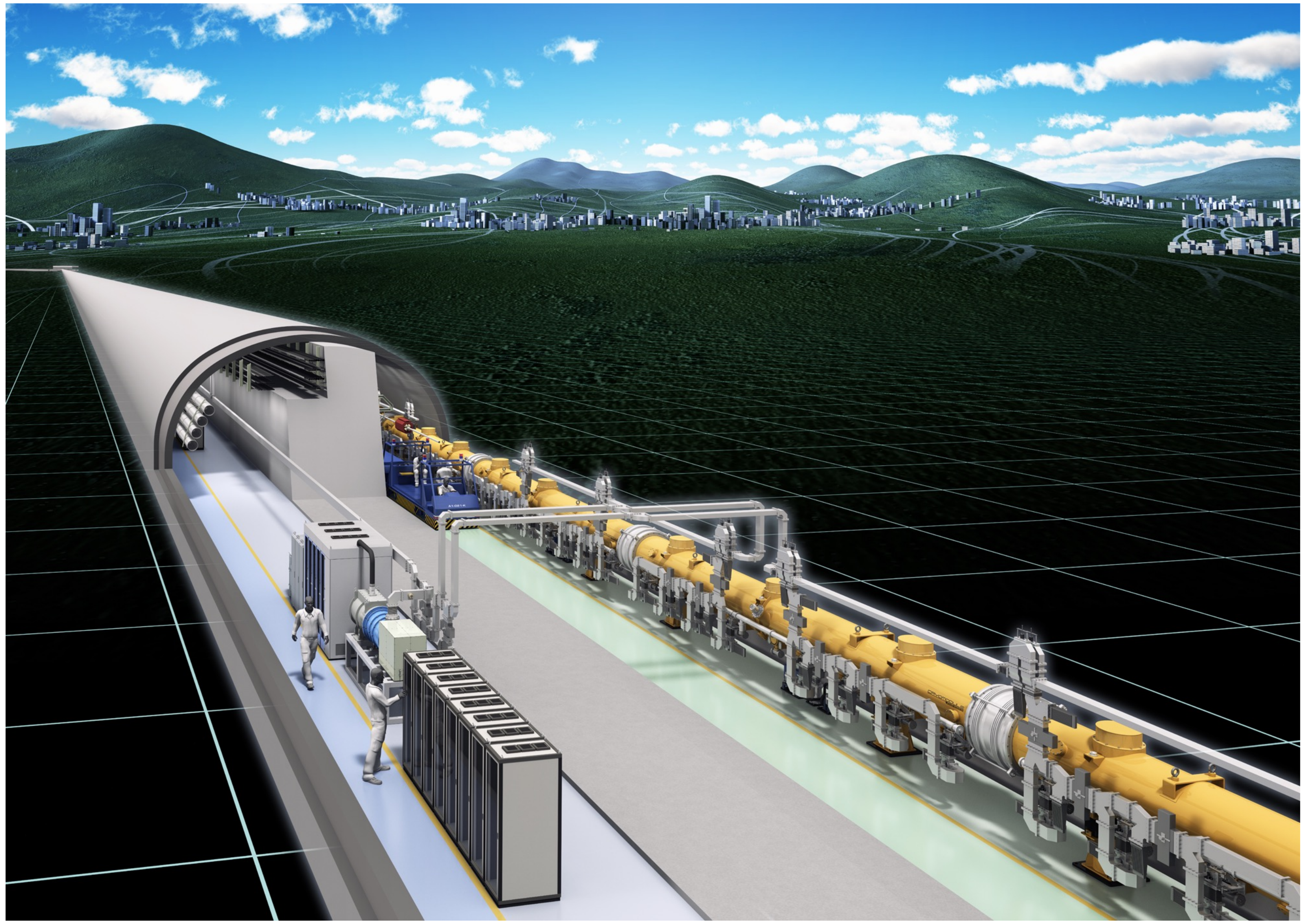


Backup

Currently Envisioned Location

Kitakami Mountains

- **e+e- centre-of-mass energy**
  - first stage: 250 GeV
  - tunable
  - upgrades: 500 GeV, 1 TeV
  - further options:
    running at Z pole & WW threshold
- **luminosity at 250 GeV**
  - 1.35 x 10^{34} /cm^2 /s
  - upgrade 2.7 x 10^{34} /cm^2 /s (cheap)
  - upgrade 5.4 x 10^{34} /cm^2 /s (expensive)
- **beam polarisation**
  - $P(e_-) \geq \pm 80\%$
  - $P(e_+) = \pm 30\%$,
    at 500 GeV upgradable to 60%
- **total length (250 GeV): 20.5 km**
- **total site power consumption (250 GeV): 100 MW**



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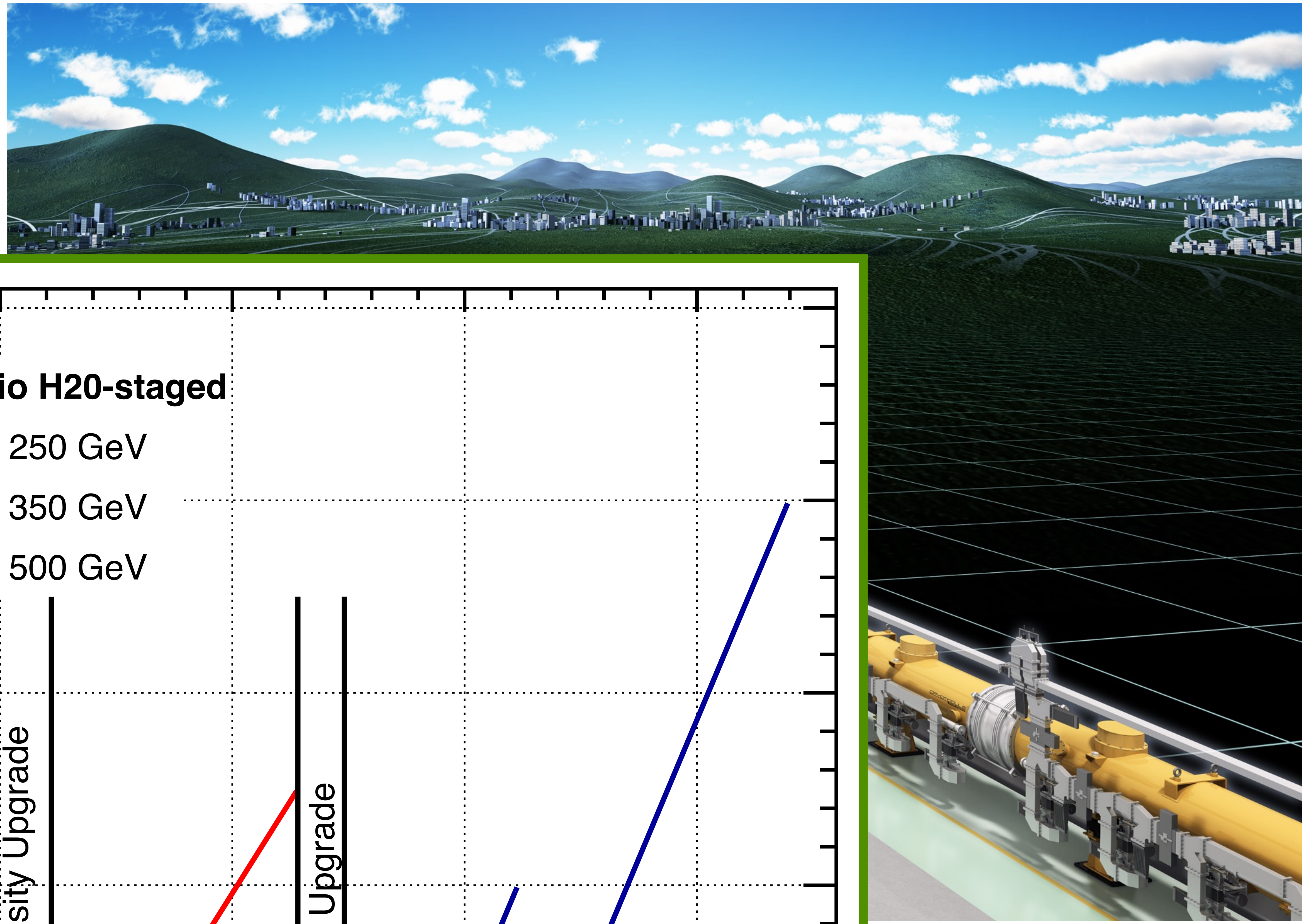

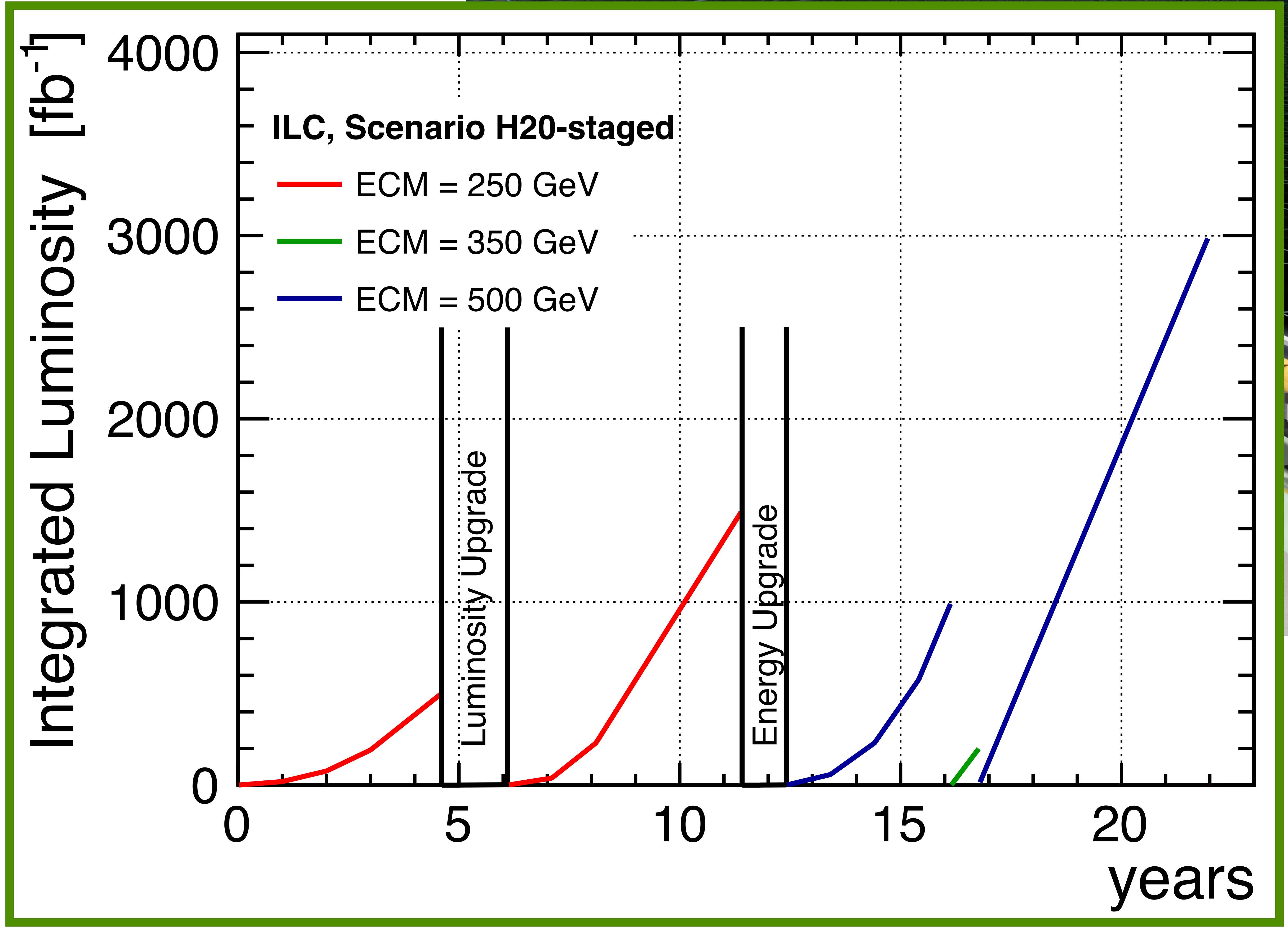

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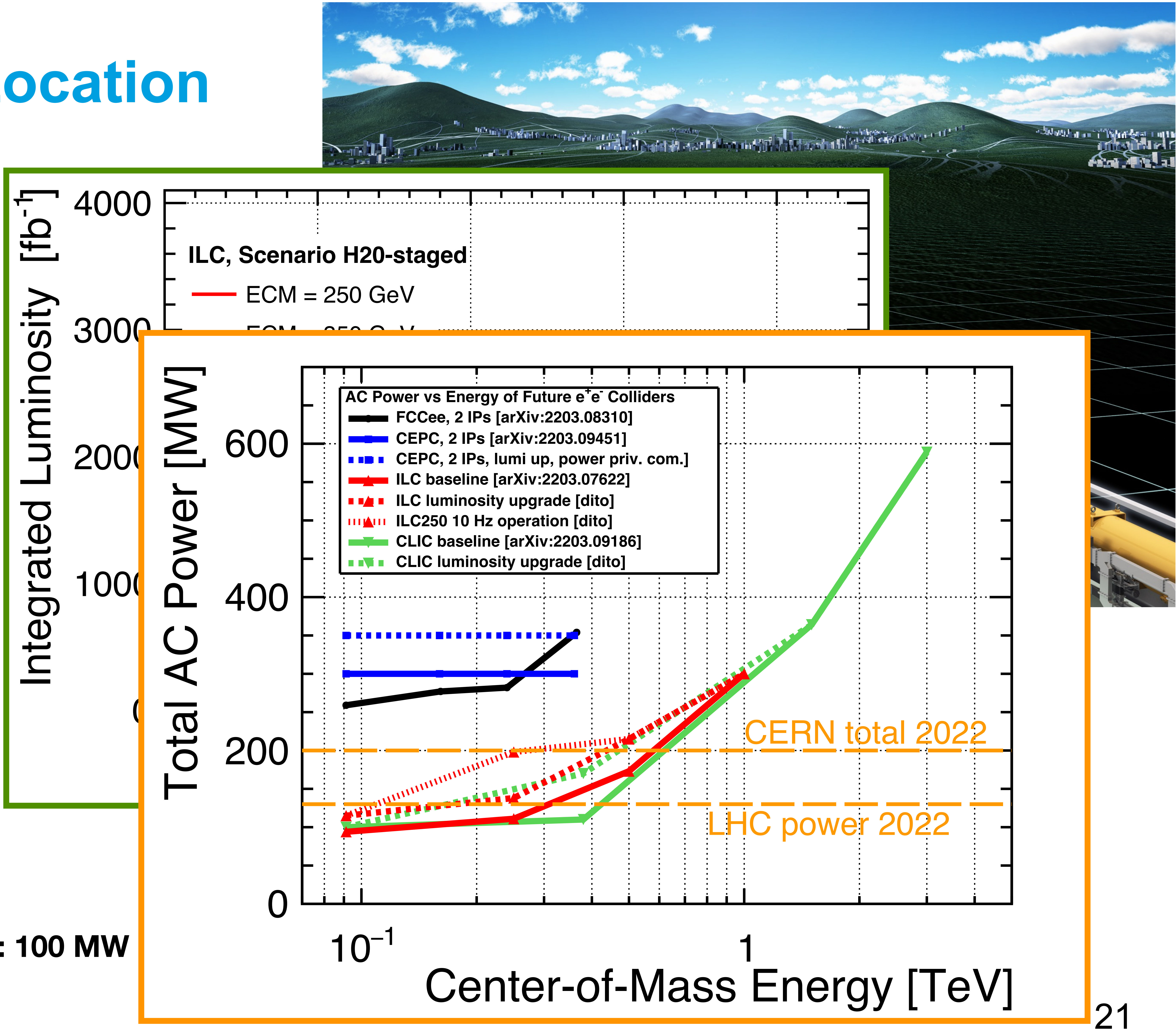
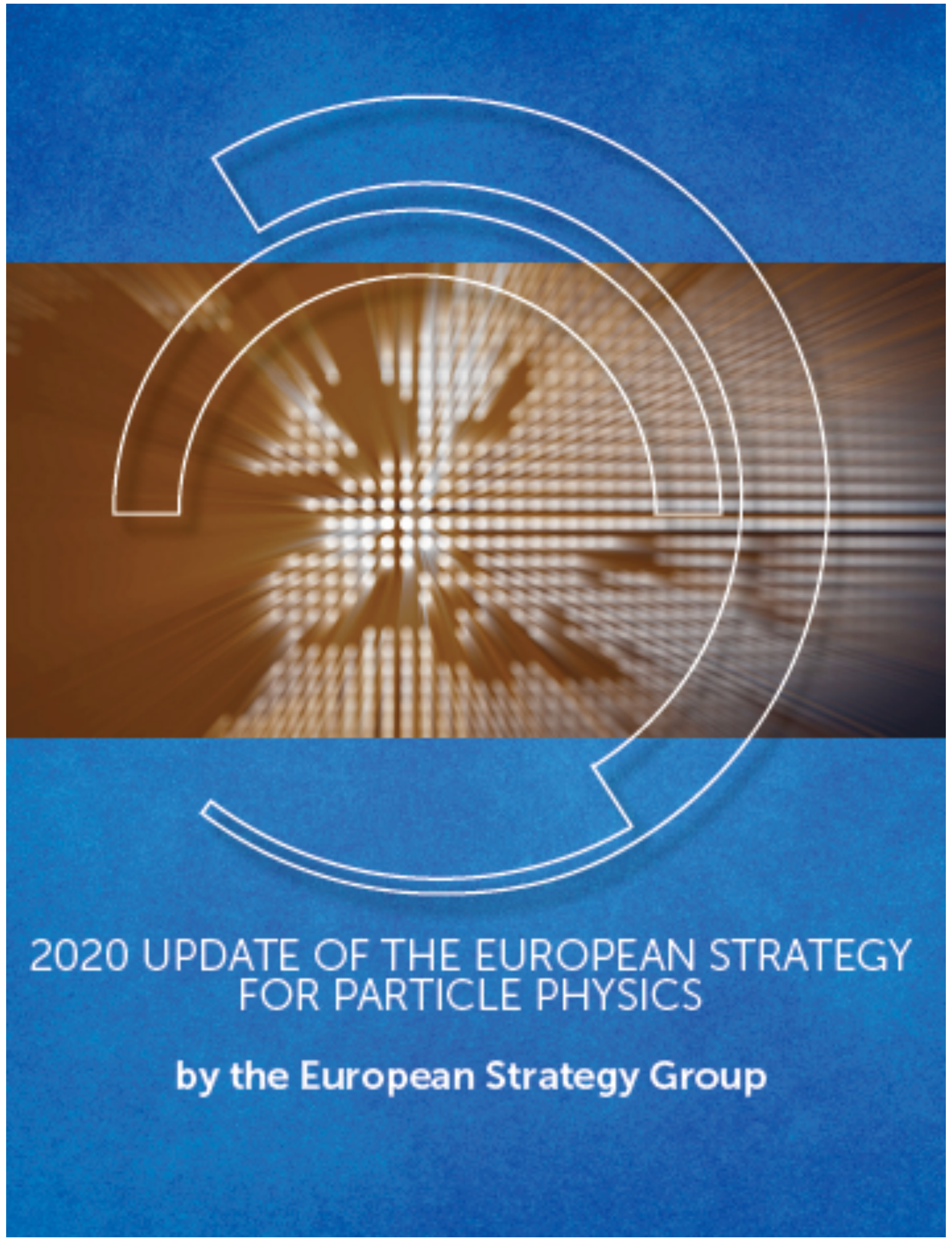


European Strategy for Particle Physics

2020 Update - Future Colliders

"An electron-positron Higgs factory is the highest-priority next collider."



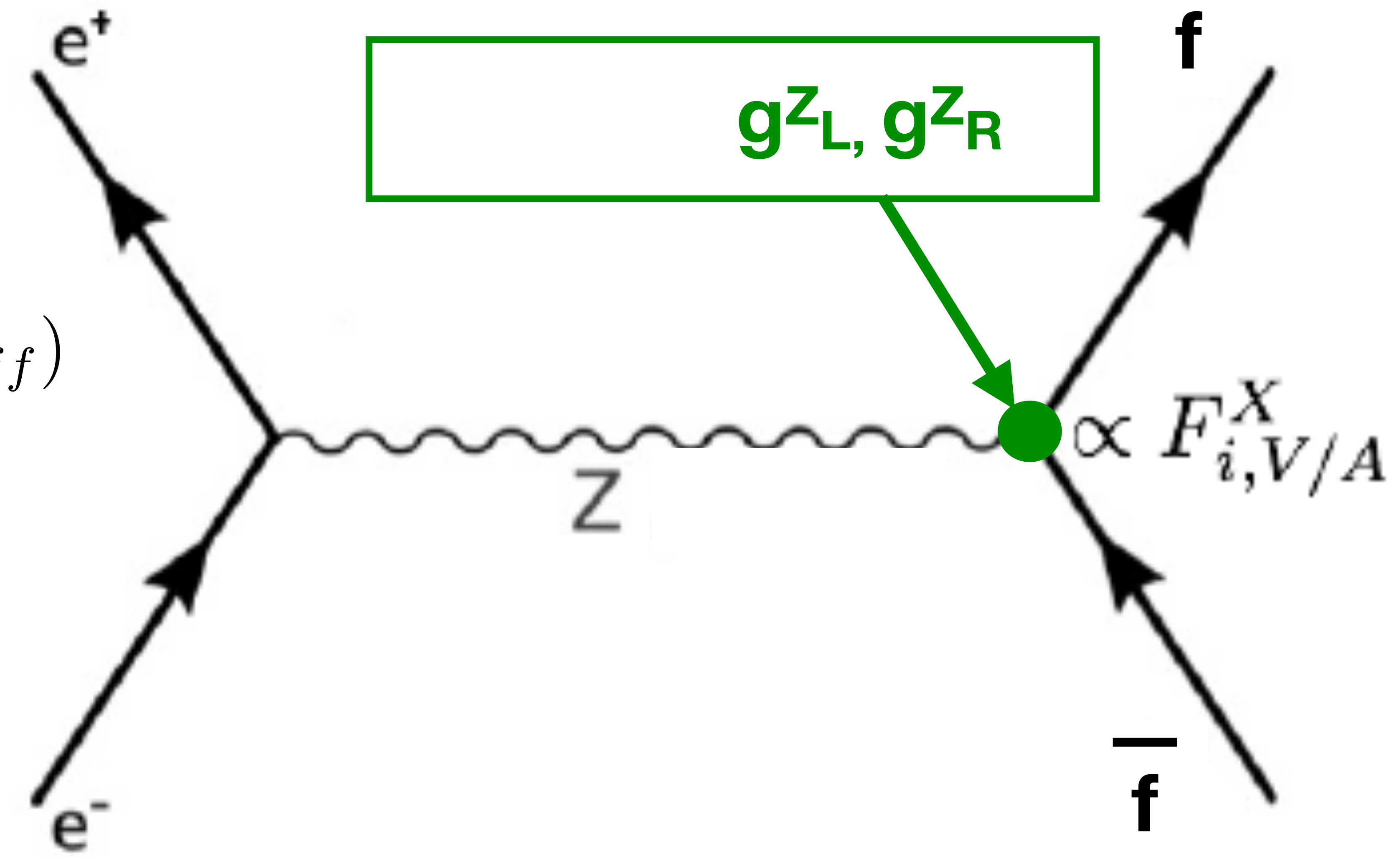
Polarisation & Electroweak Physics

let's first recall at the Z pole situation

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

=> $$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

specifically for the electron: $$A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$$



at an *unpolarised* collider:

$$A^f_{FB} \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f$$

=> no direct access to A_e,
only via tau polarisation

While at a ***polarised*** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}$$

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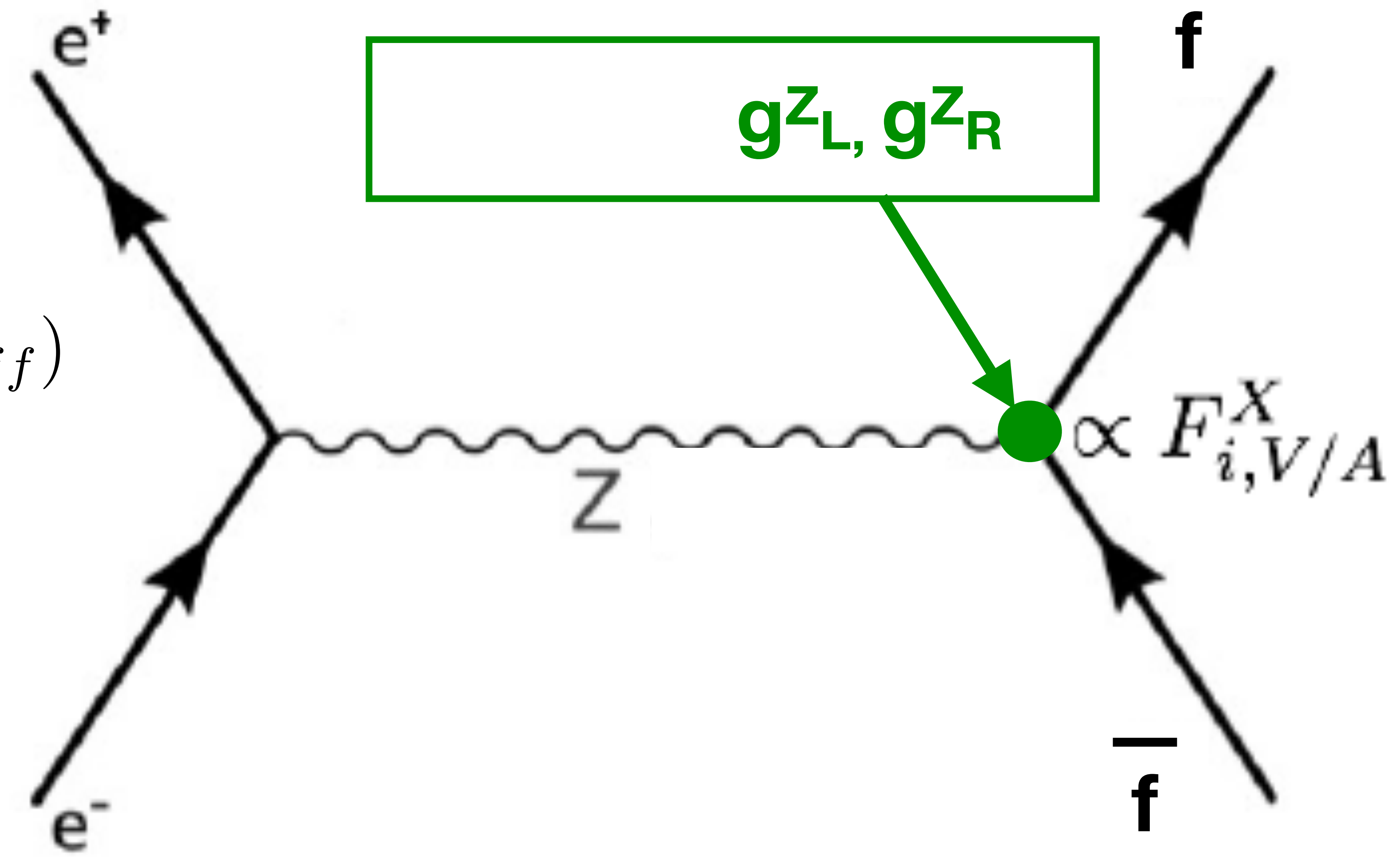

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trading theory uncertainy:

the **polarised** $A_{FB,LR}^f$ receives 7 x smaller radiative corrections than the **unpolarised** A_{FB}^f !

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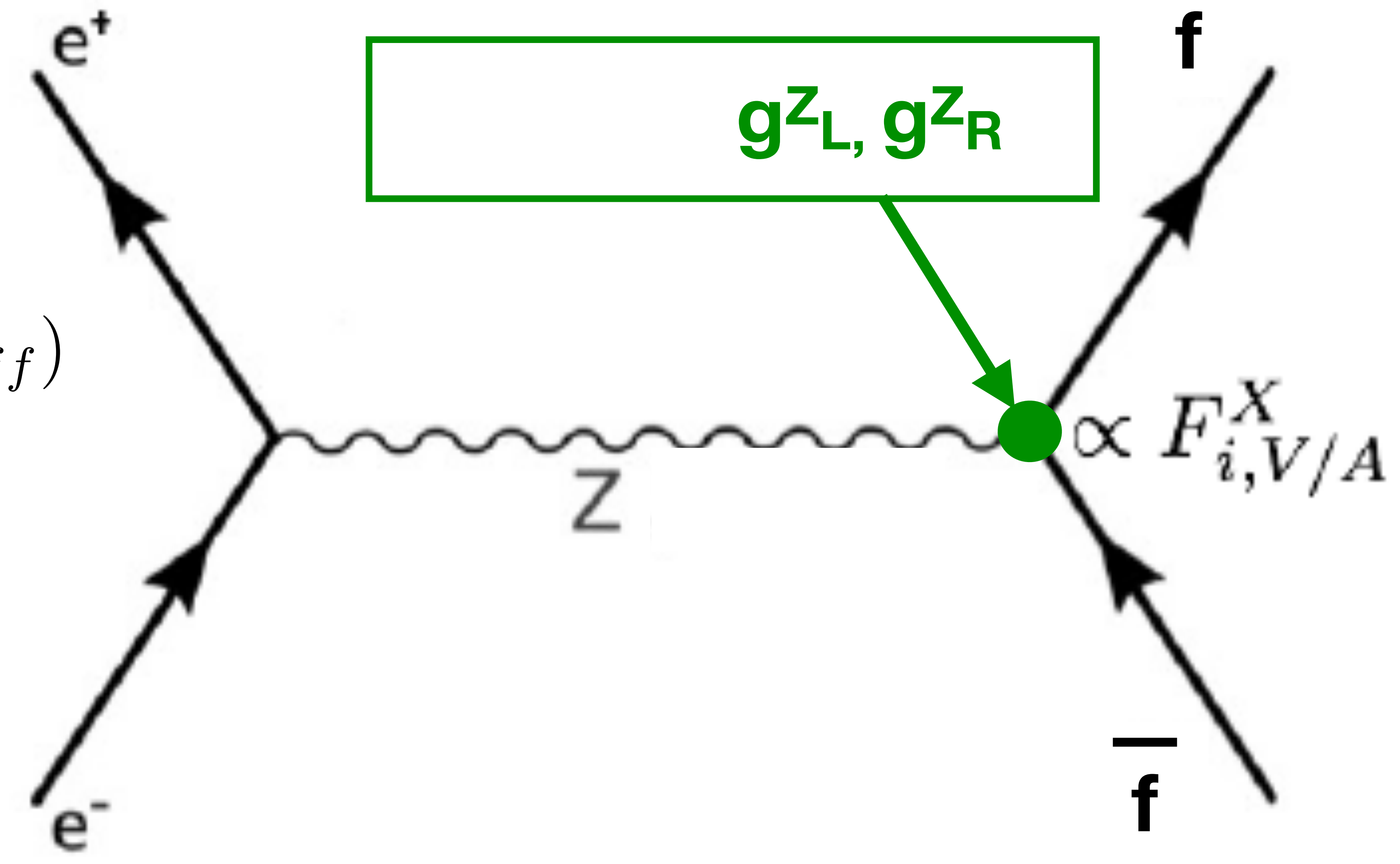

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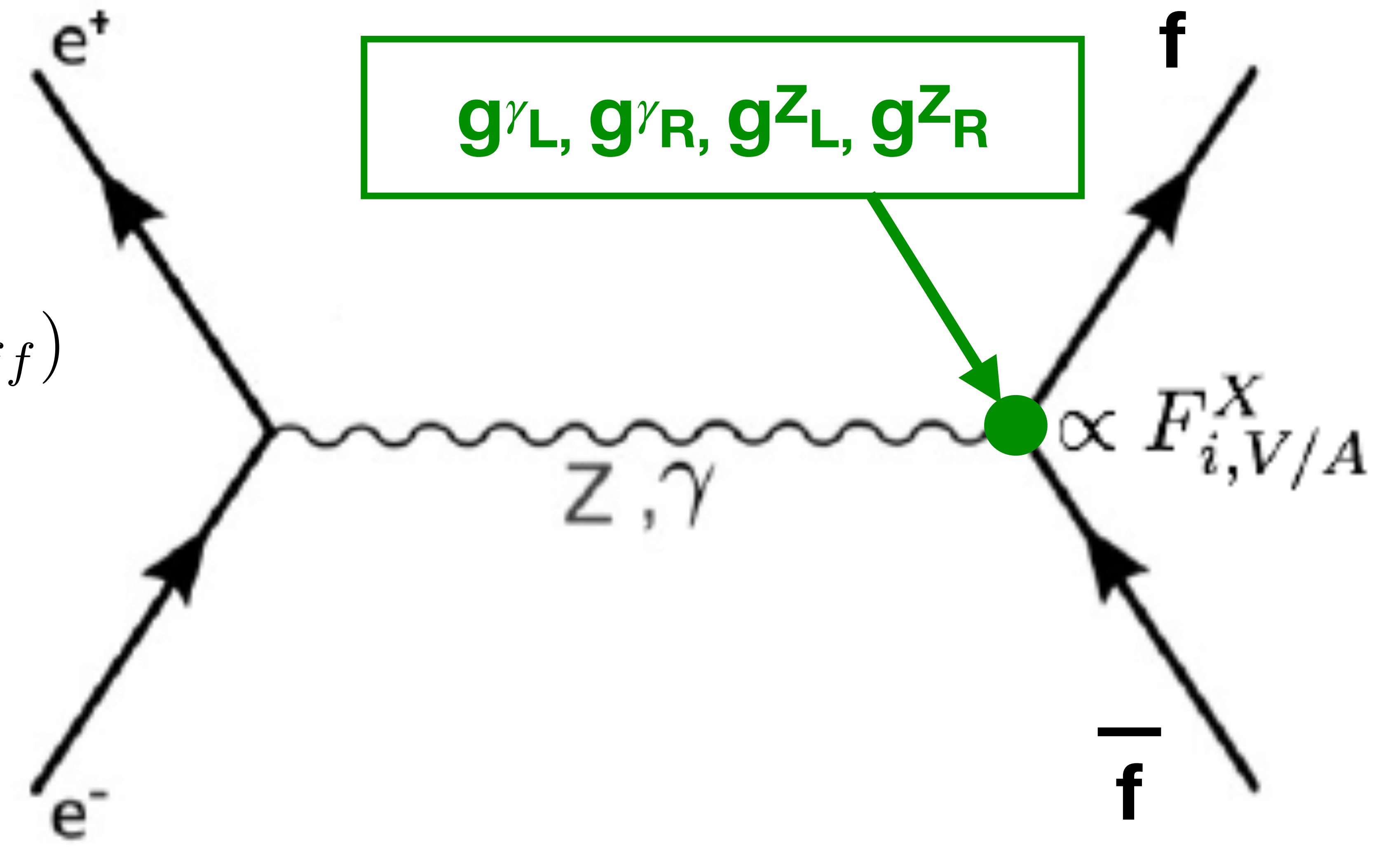

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Polarisation & Electroweak Physics at the Z pole

LEP, ILC, FCCee

new detailed studies by ILD@ILC:

- at least factor 10, often ~50 improvement over LEP/SLC
- note in particular:
  - **A_c nearly 100 x better** thanks to excellent charm / anti-charm tagging:
    - excellent vertex detector
    - tiny beam spot
    - Kaon-ID via dE/dx in ILD's TPC

polarised "GigaZ" typically only factor 2-3 less precise than FCCee's unpolarised *TeraZ*
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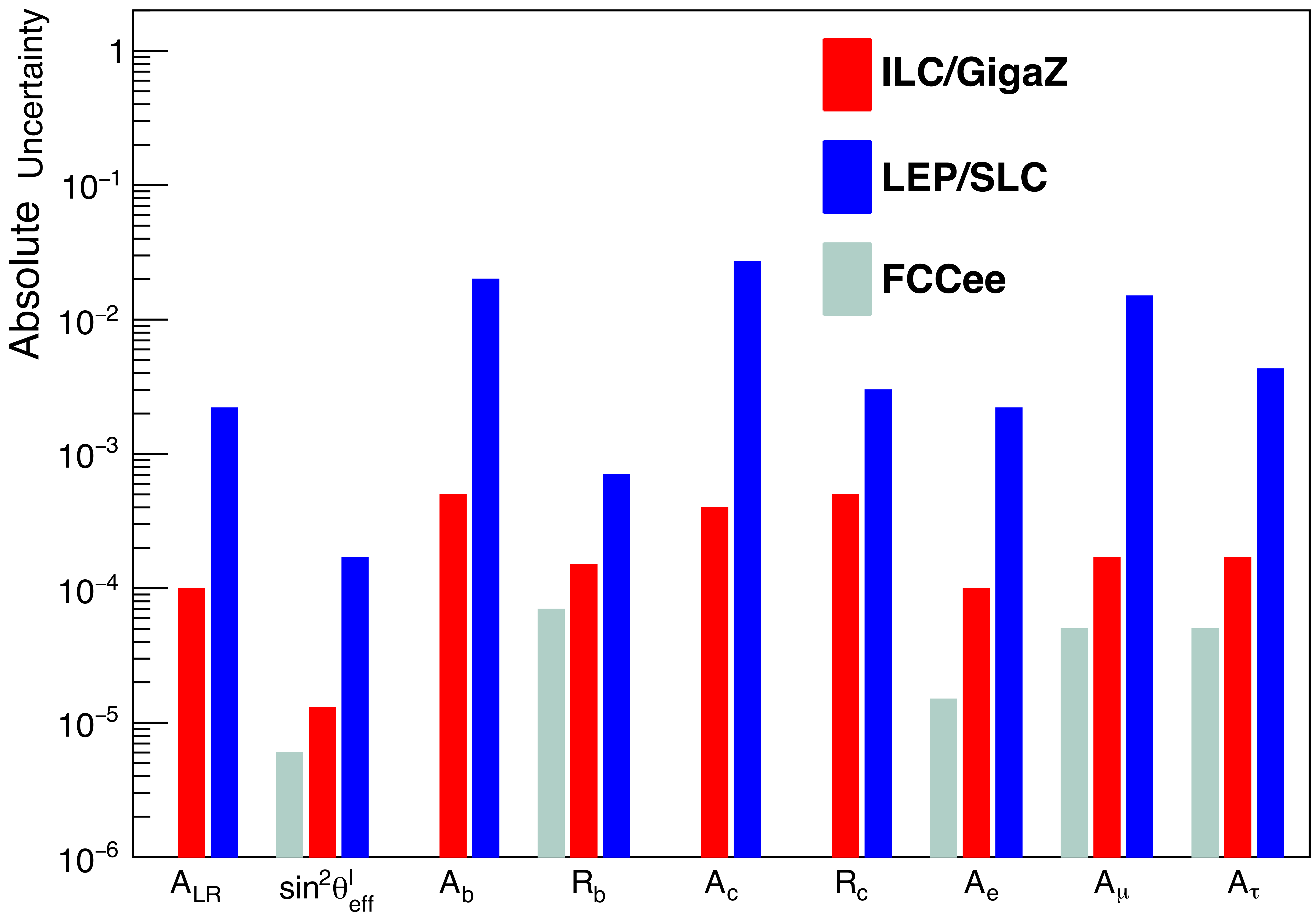

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arXiv:1908.11299

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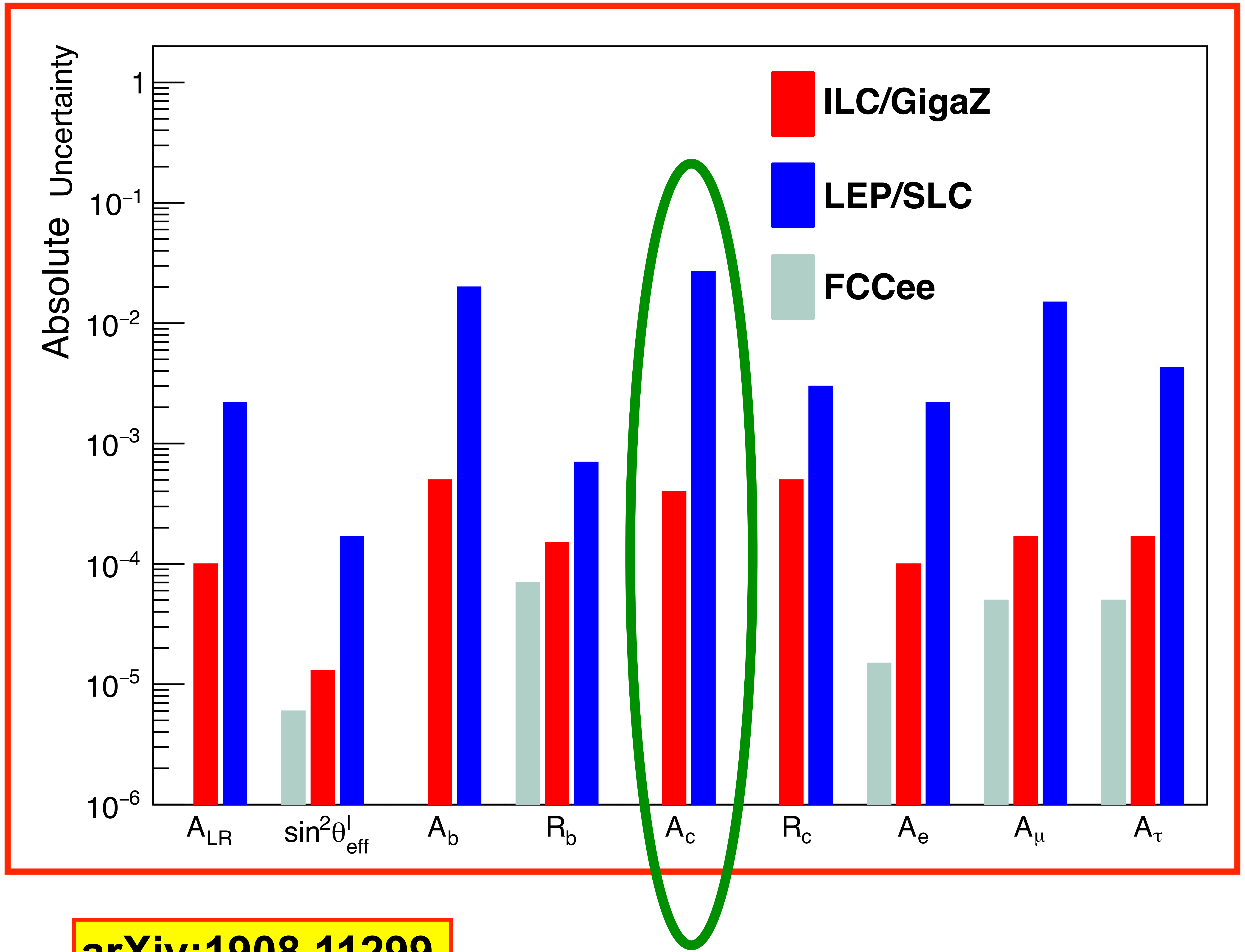

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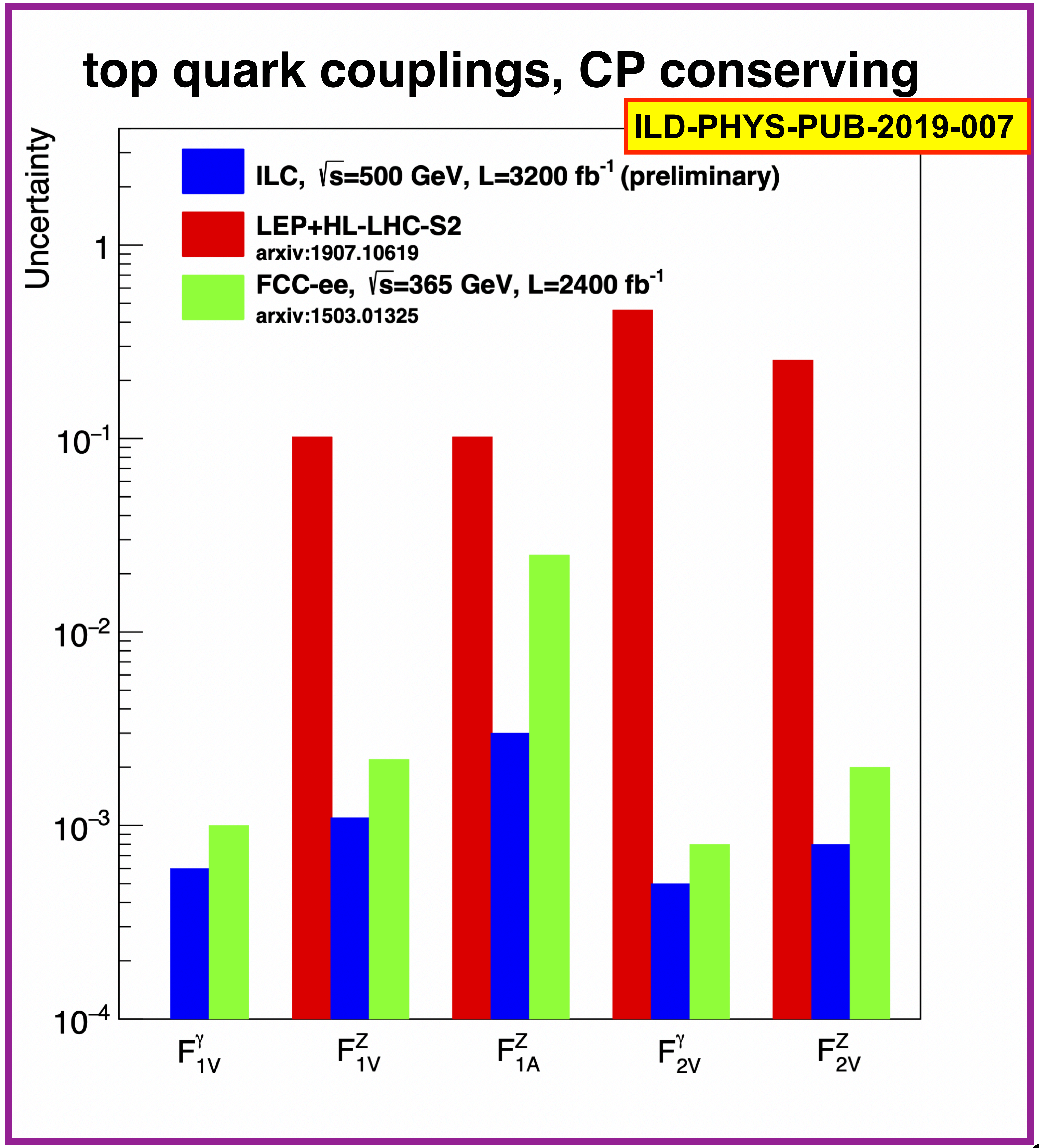
Polarisation & Electroweak Physics at high energies

e+e- at 500 GeV and 1 TeV

- ex1: top quark pair production - disentangle Z / γ:
  - unpolarised case: from final-state analysis only
  - polarised case: direct access
    - final state analysis can be done in addition
    => redundancy, control of systematics
- ex2: oblique parameters for 4-fermion operators
  - beam polarisation essential to disentangle Y vs W
  - ILC 250 outperforms HL-LHC
  - ILC 500 outperforms unpolarised e^+e^- machines



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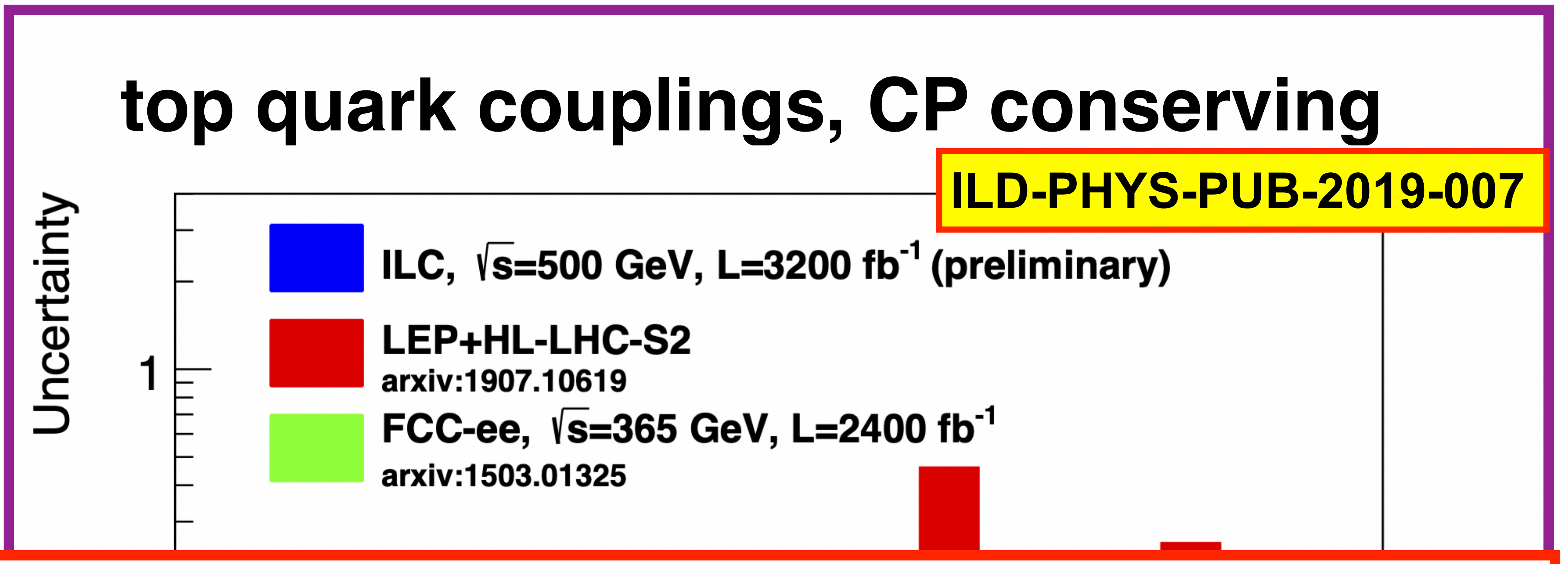
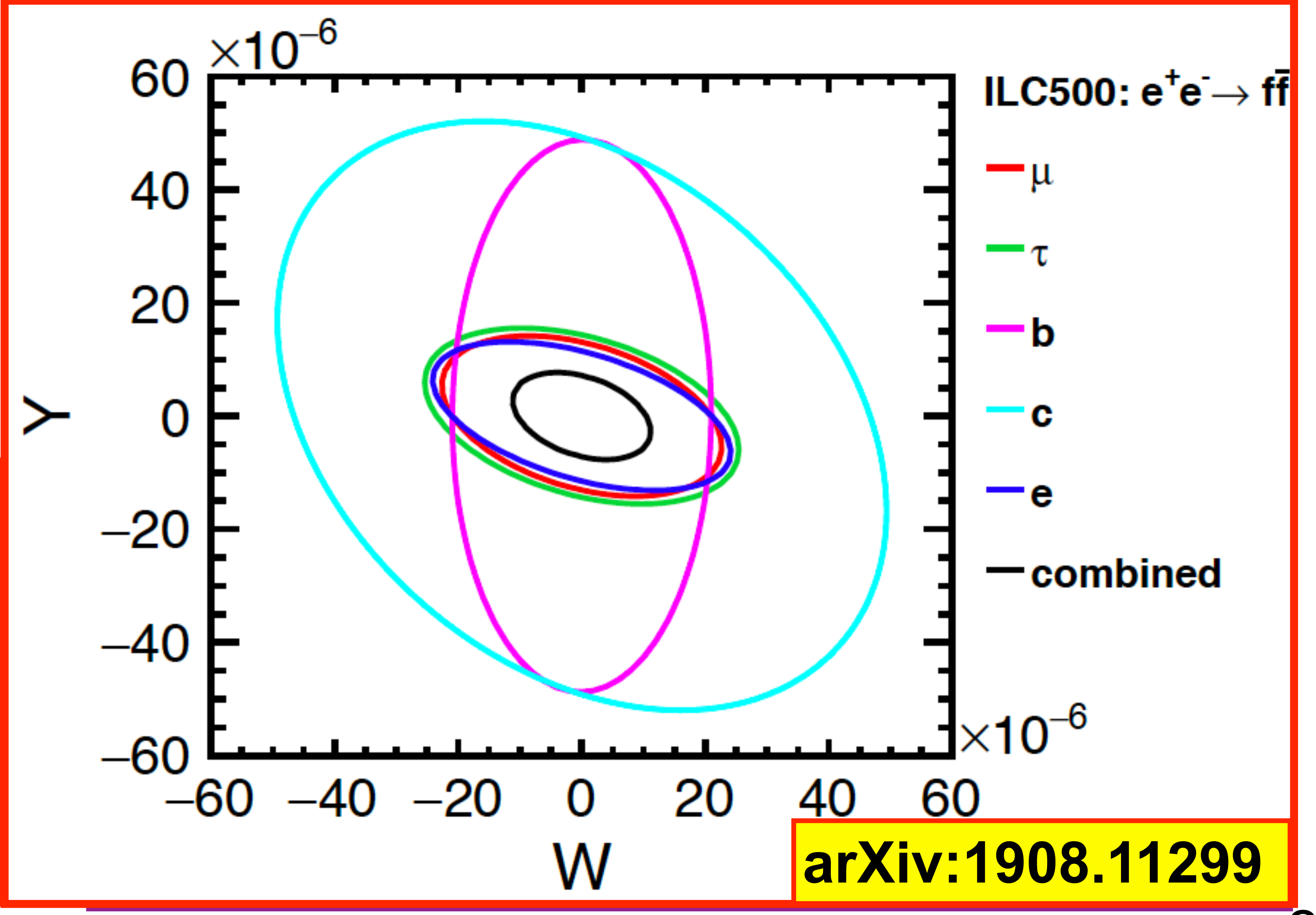


$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

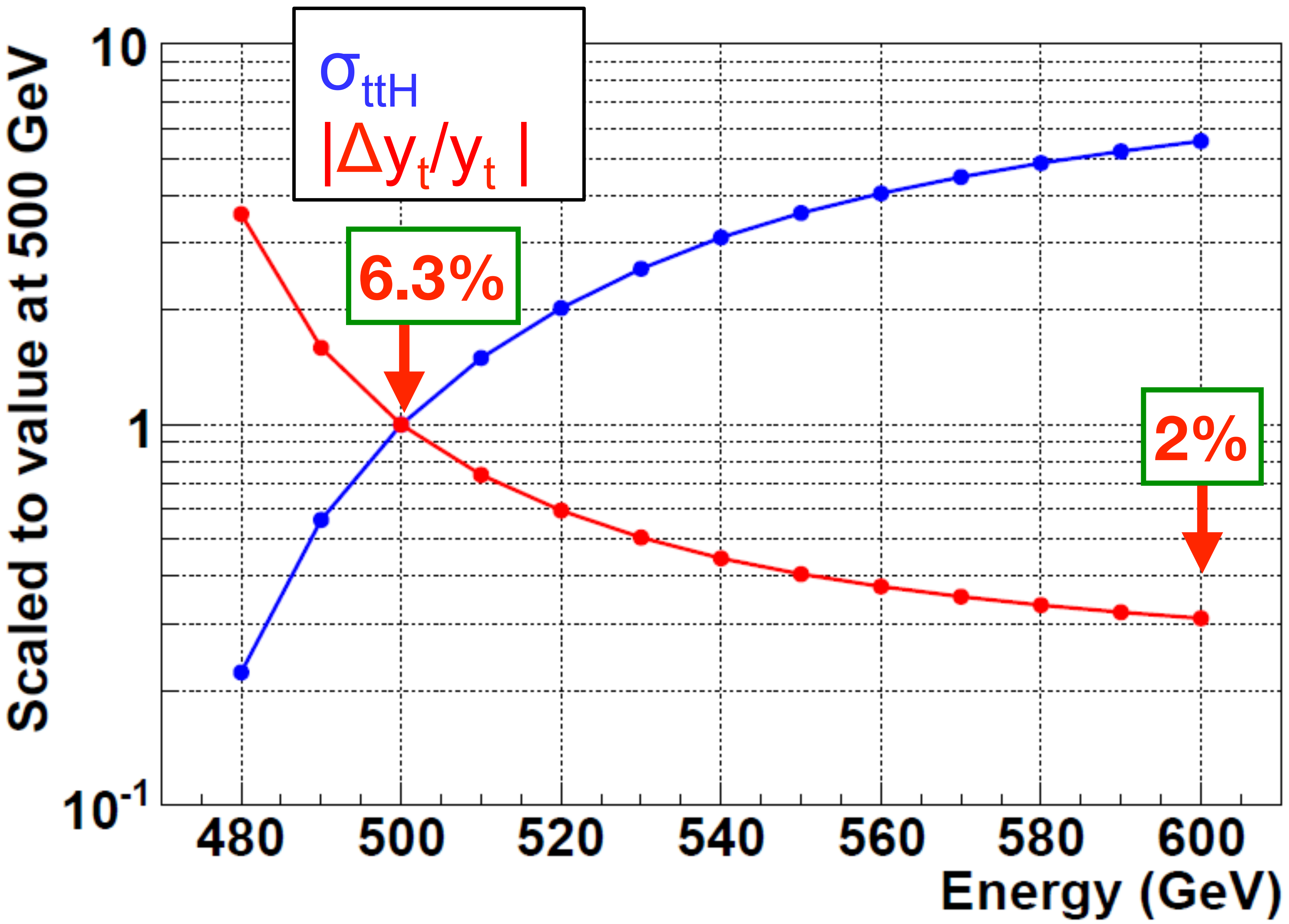


Top Yukawa coupling

The Higgs and the Top

- **absolute size of $|y_t|$:**
  - **HL-LHC:**
    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in $SMEFT_{ND}$**
  - **ILC:**
    - current full simulation achieved **6.3% at 500 GeV**
    - ***strong dependence*** on exact choice of E_{CM}, e.g. **2% at 600 GeV**
    - *not* included:
      - experimental improvement with higher energy (boost!)
      - other channels than H->bb

[Phys.Rev. D84 (2011) 014033 & arXiv:1506.07830]



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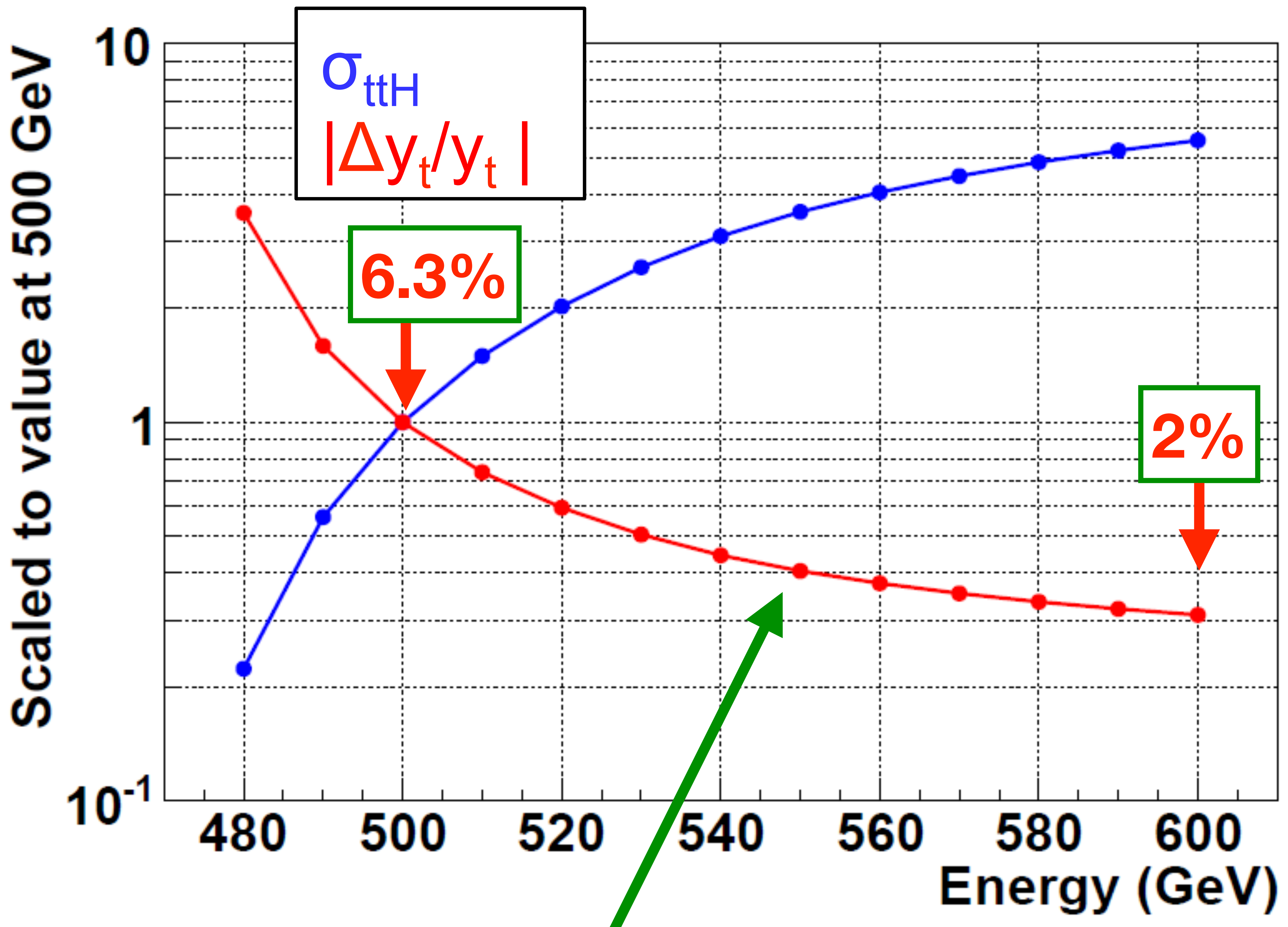

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Note: C³ proposes 550 GeV

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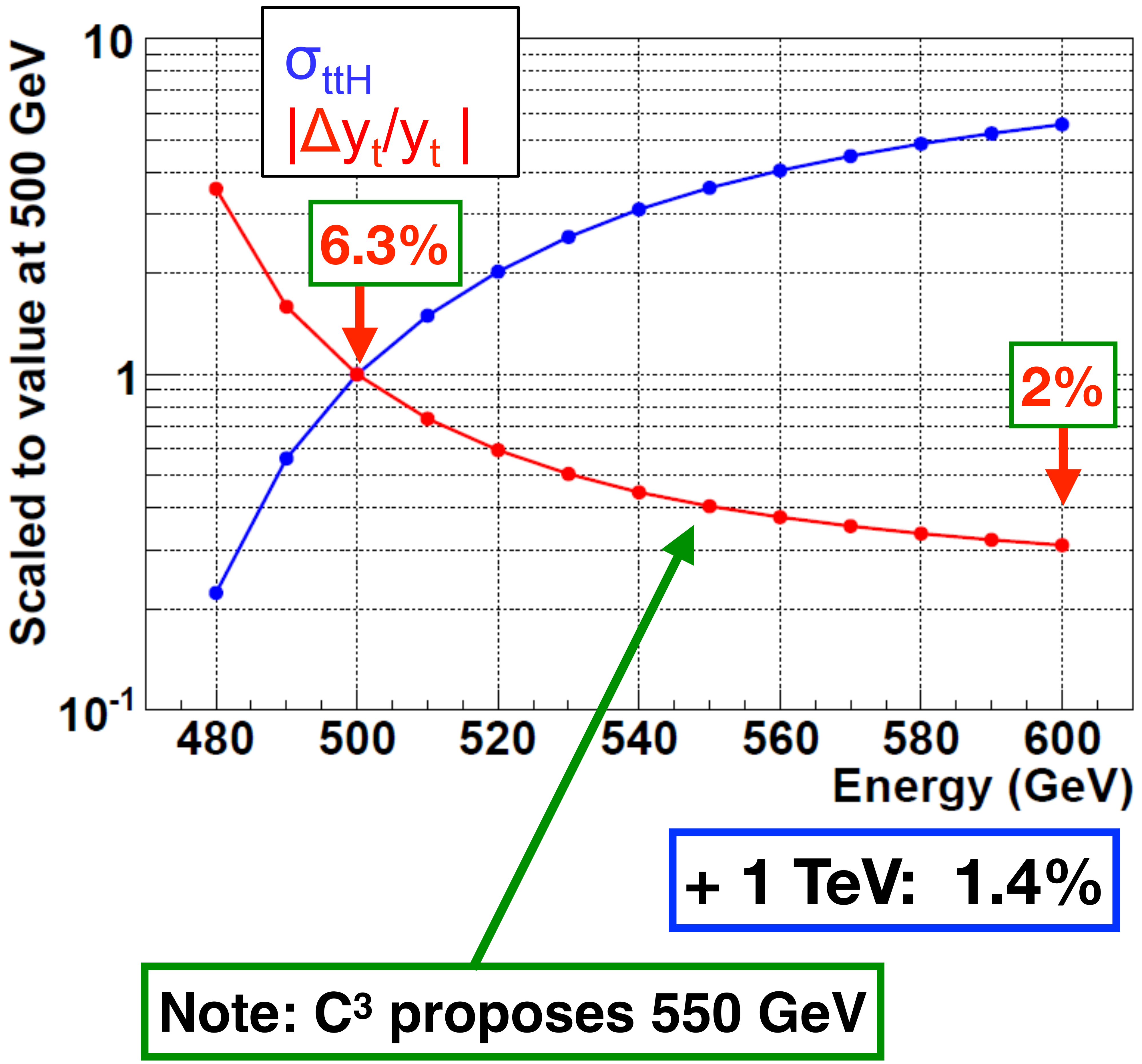
- **full coupling structure** of tth vertex, incl. CP:
  - **e^+e^- at E_{CM} ≥ ~600 GeV**
    => ***few percent sensitivity to CP-odd admixture***
  - **beam polarisation essential!**

[Eur.Phys.J. C71 (2011) 1681]

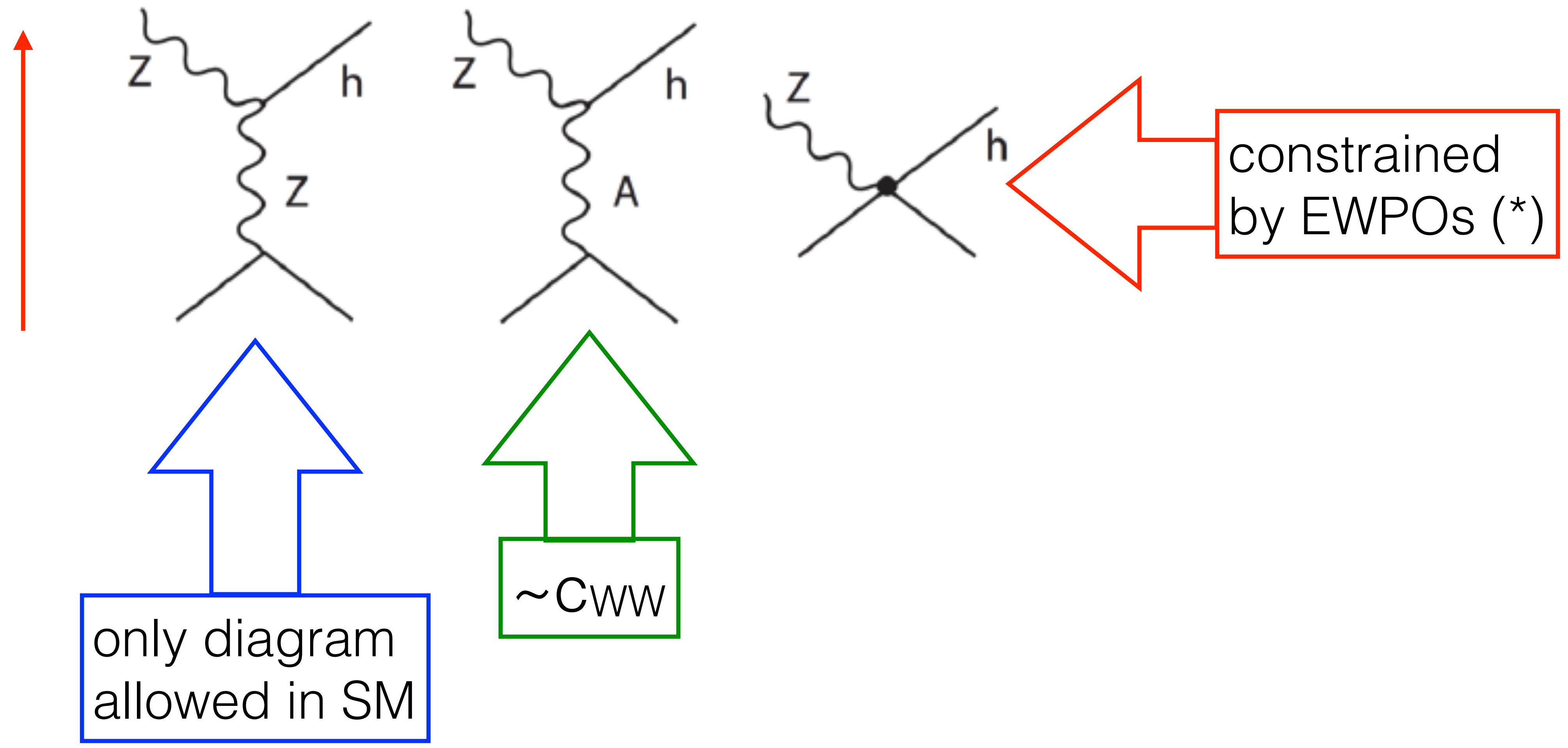
[Phys.Rev. D84 (2011) 014033 & arXiv:1506.07830]



Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

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



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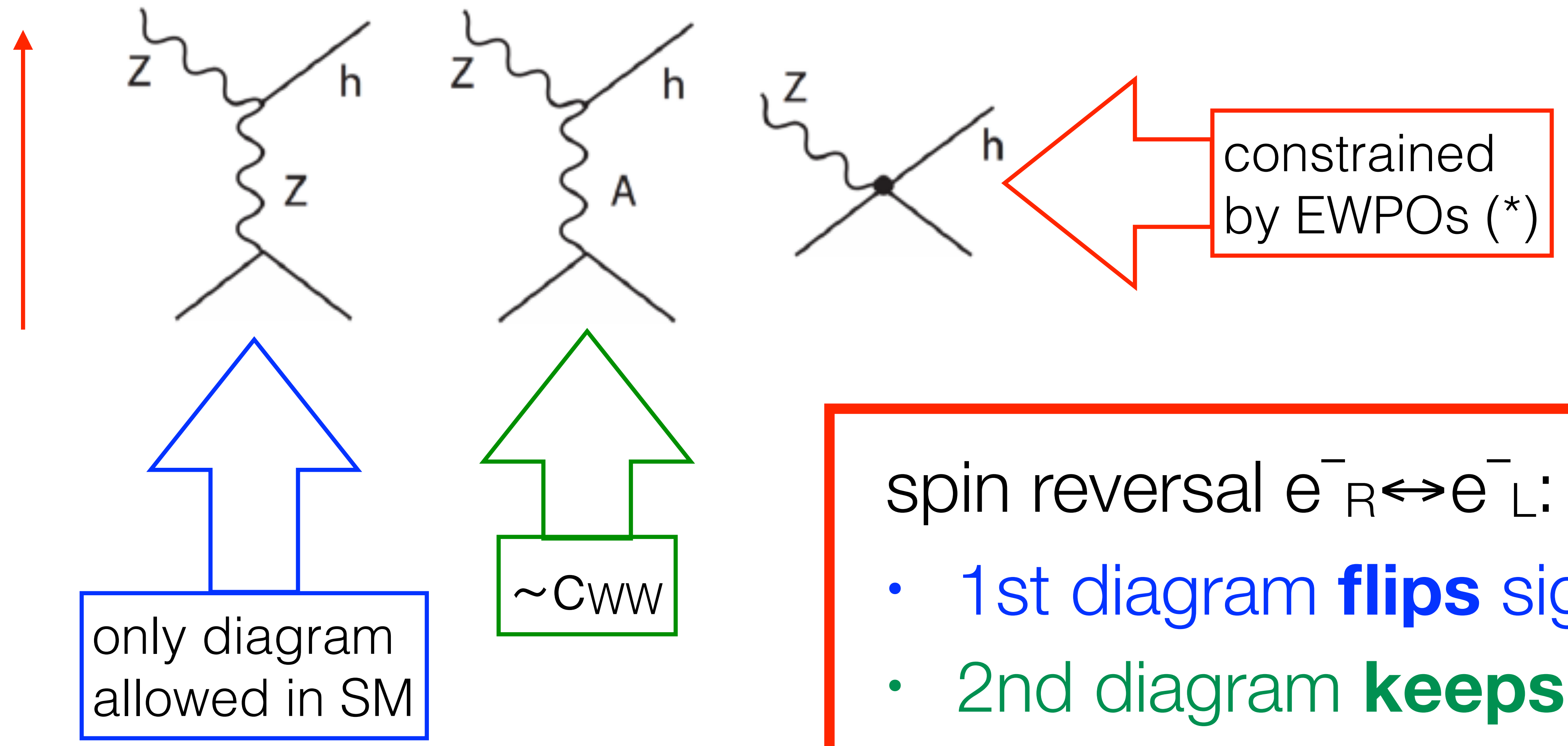

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

⇒ A_{LR} lifts degeneracy between operators!

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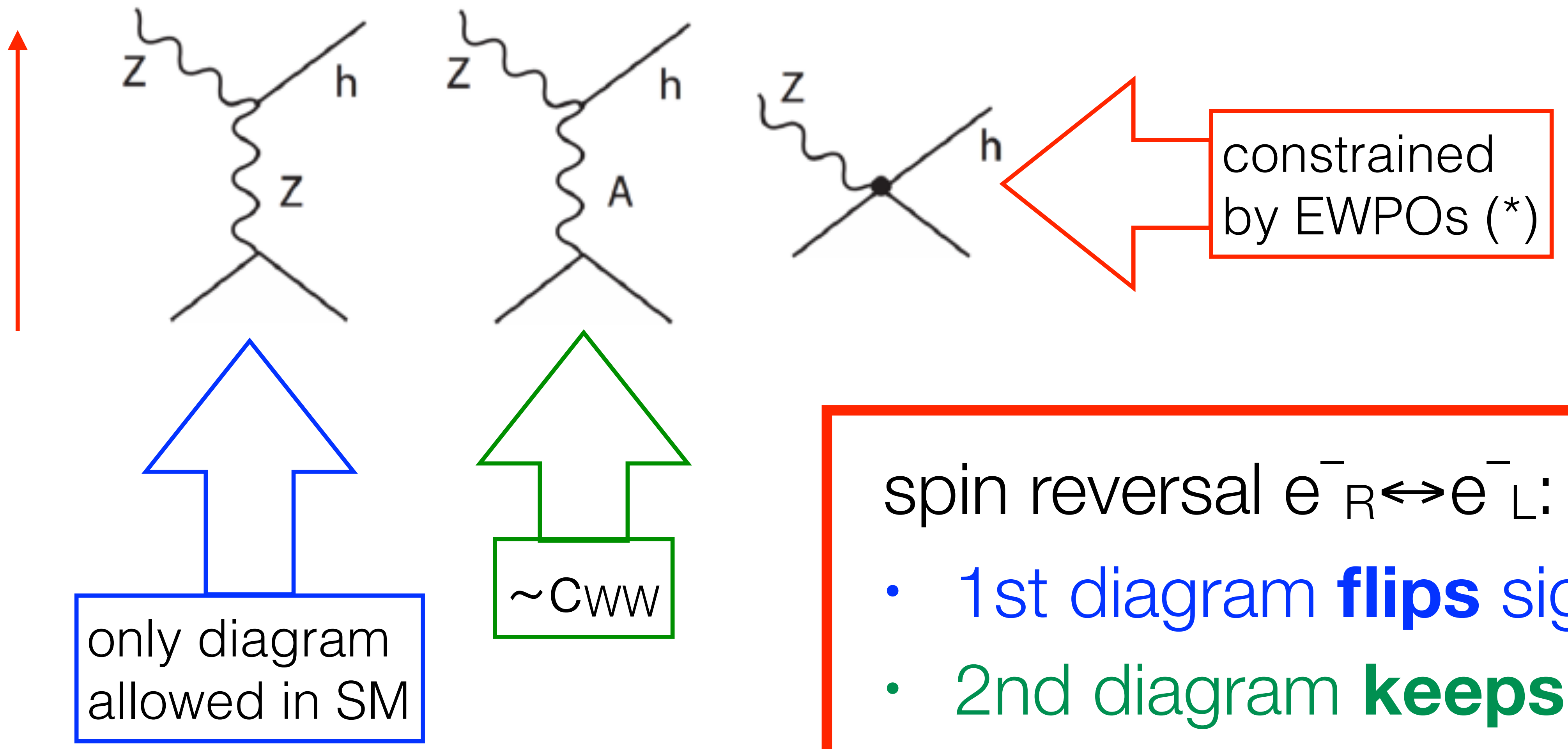

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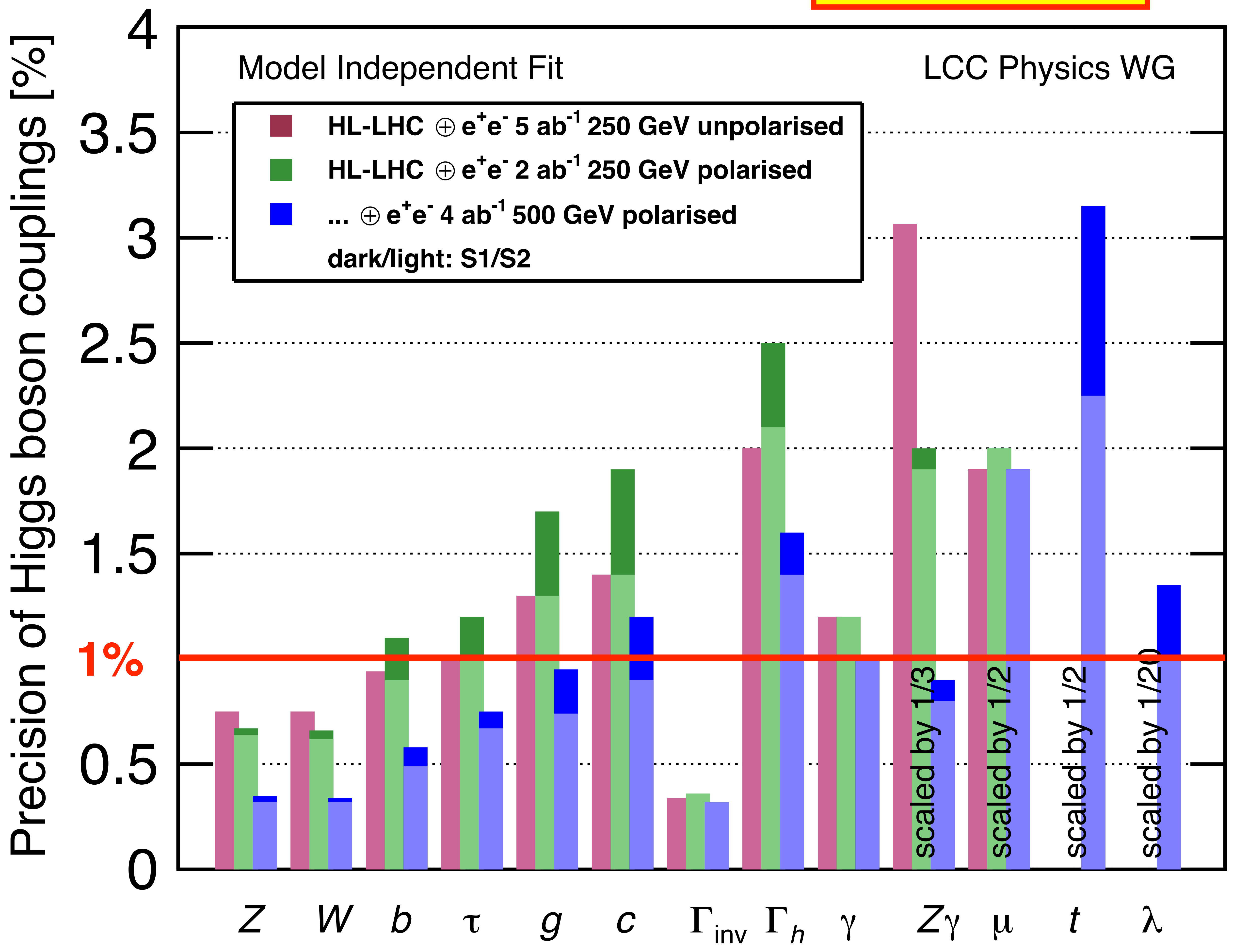
arXiv:1903.01629



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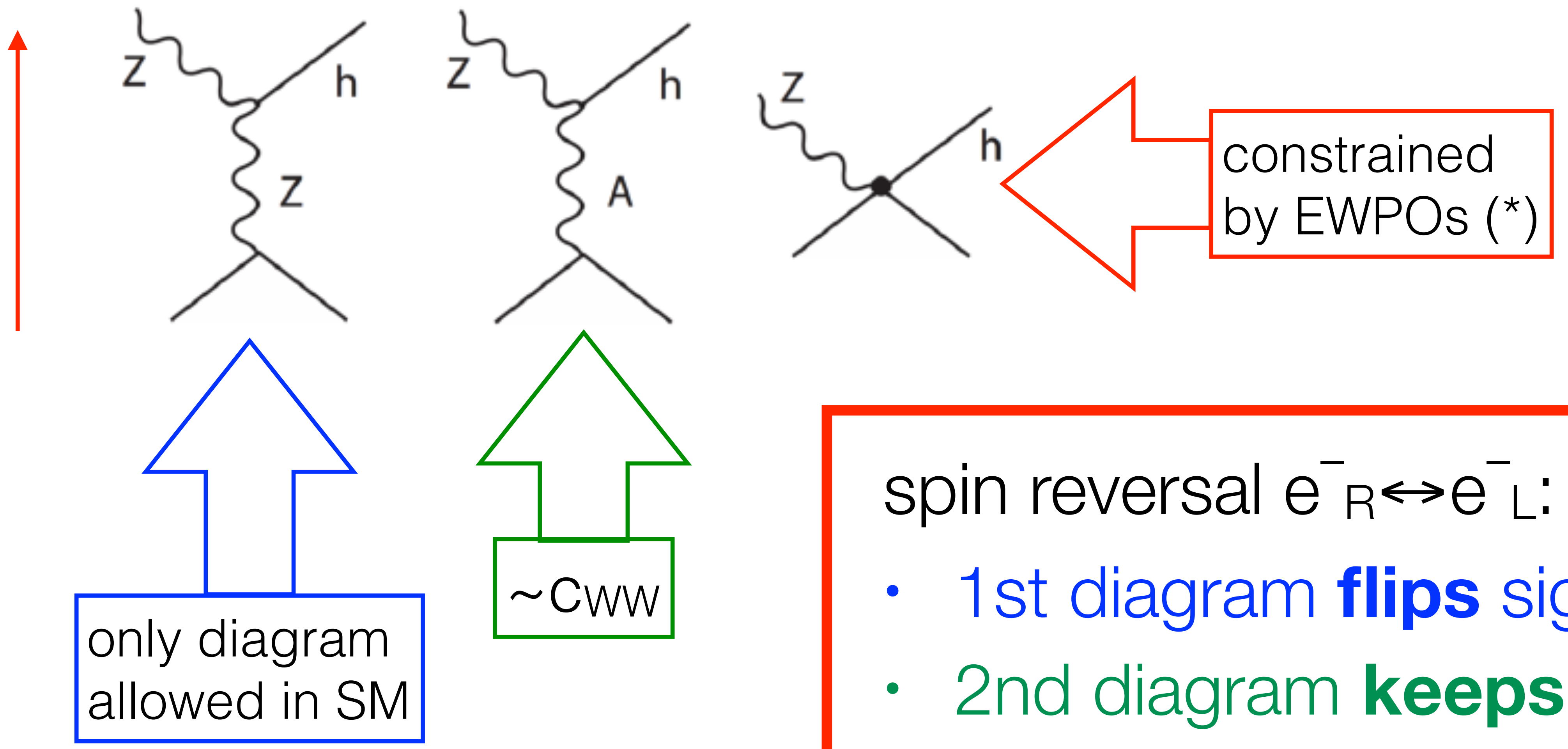

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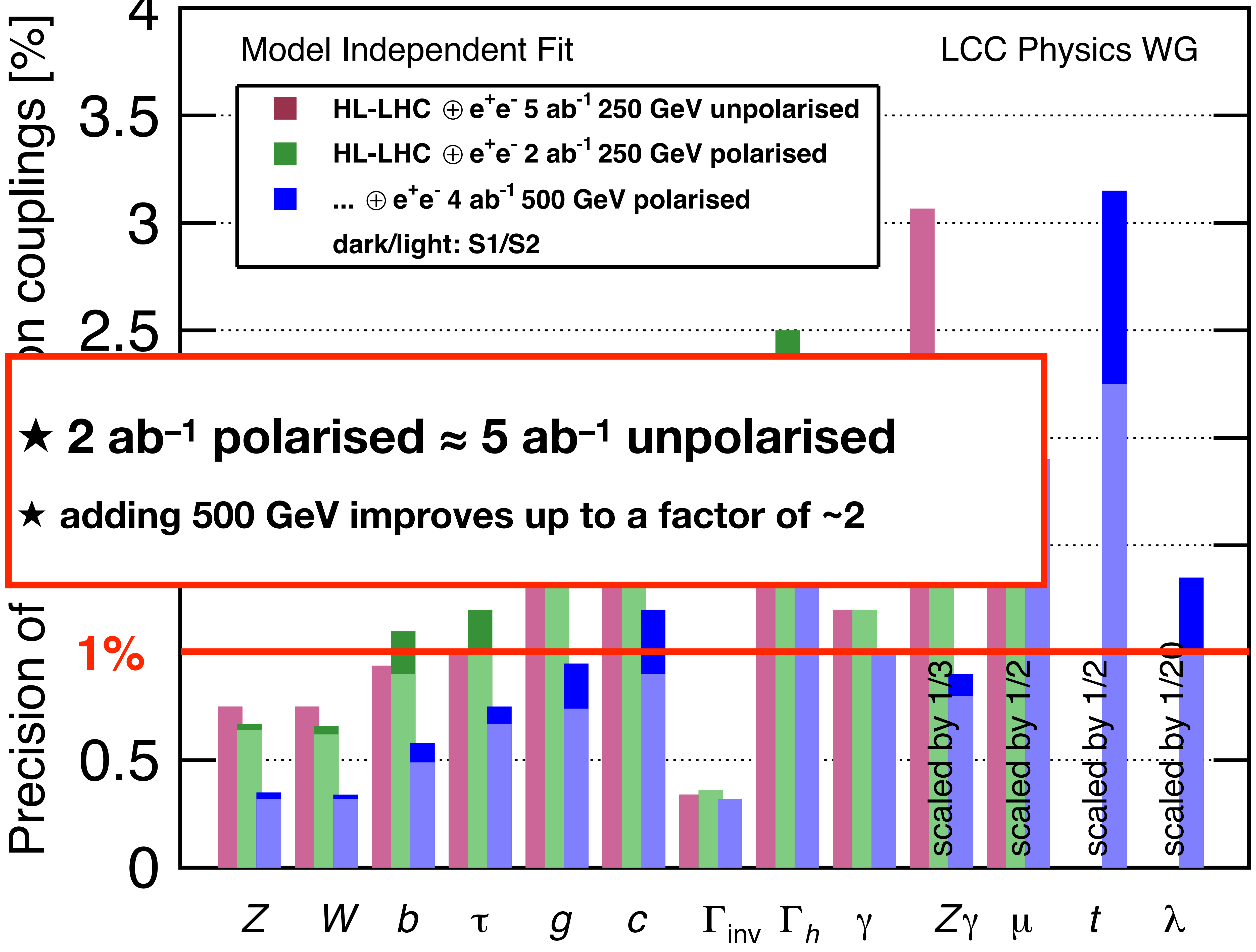


★ **2 ab⁻¹ polarised ≈ 5 ab⁻¹ unpolarised**

★ **adding 500 GeV improves up to a factor of ~2**

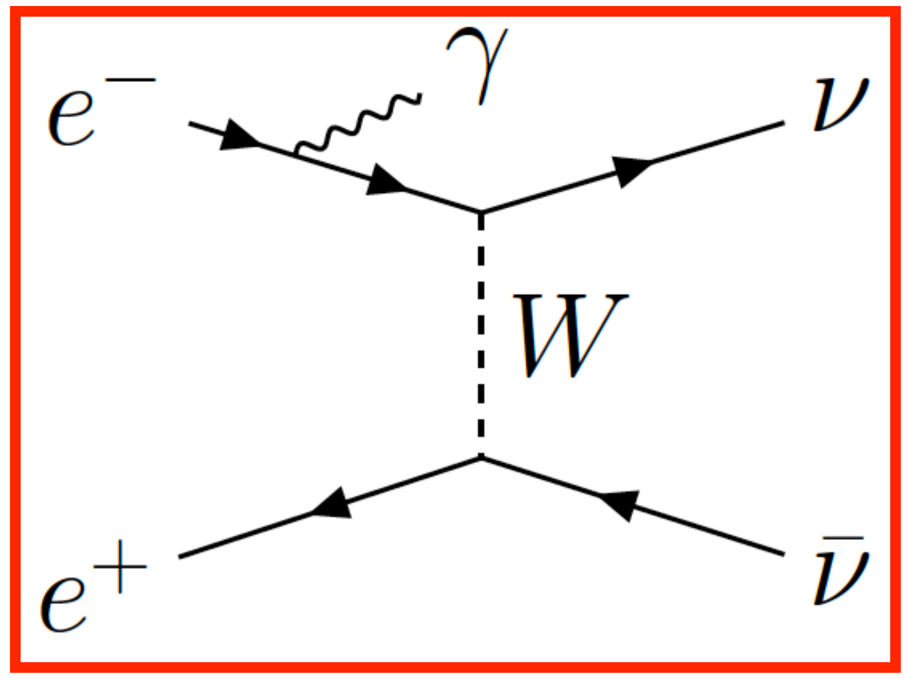
Physics benefits of polarised beams

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

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

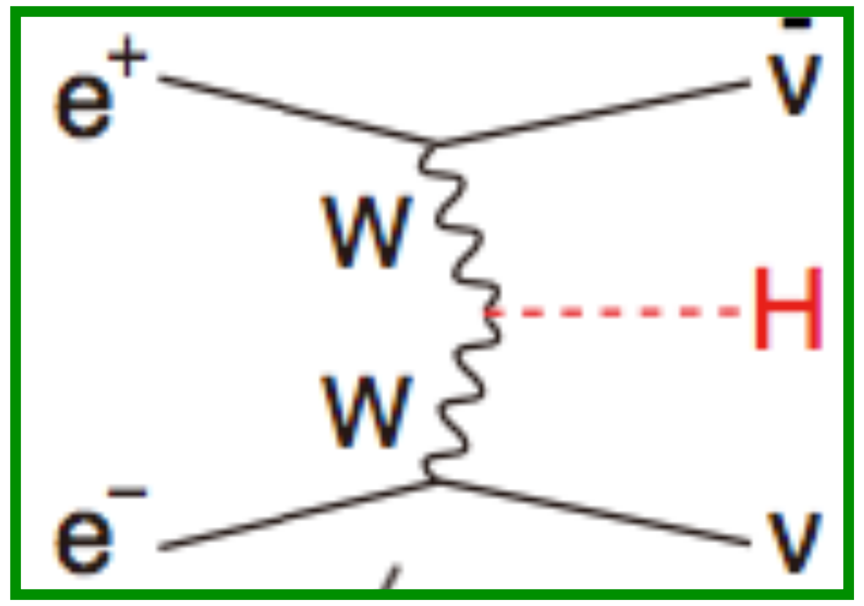
background suppression:

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



signal enhancement:

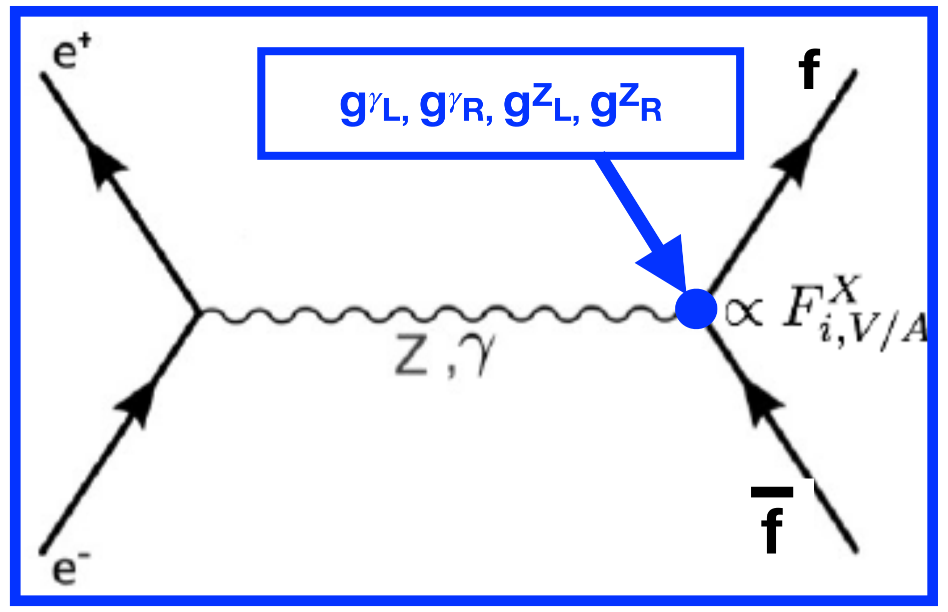
- Higgs production in WW fusion
- many BSM processes



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!

… and how to tackle them at colliders

electron-positron & proton-proton

Our tools:

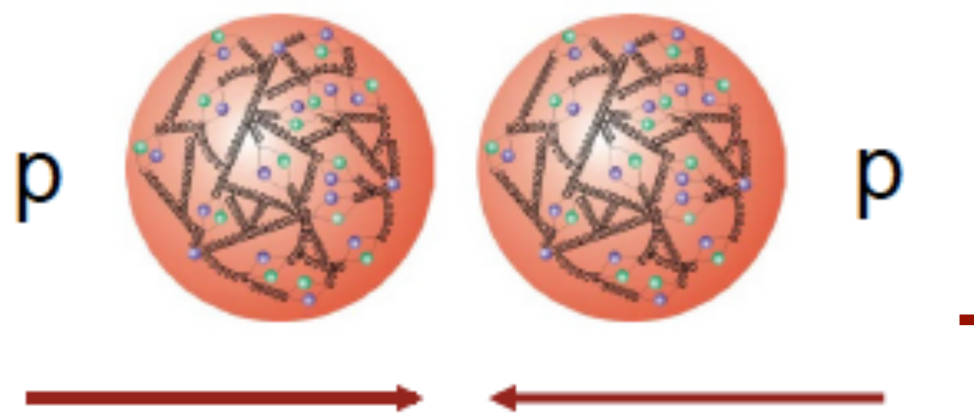
The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

Discoveries of new particles ?

- elementary particles
- different E_{CM} via accelerator operation
- E_{CM} known on event-by-event level



- proton structure
- E_{CM} of “hard” interactions cover all energies < pp E_{CM}
- not known on event-by-event level

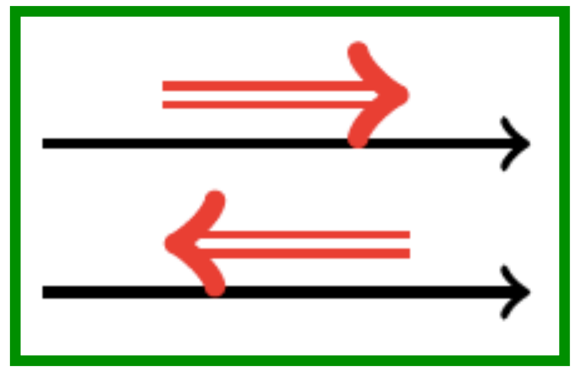
Other important parameters in e^+e^- collisions

Luminosity

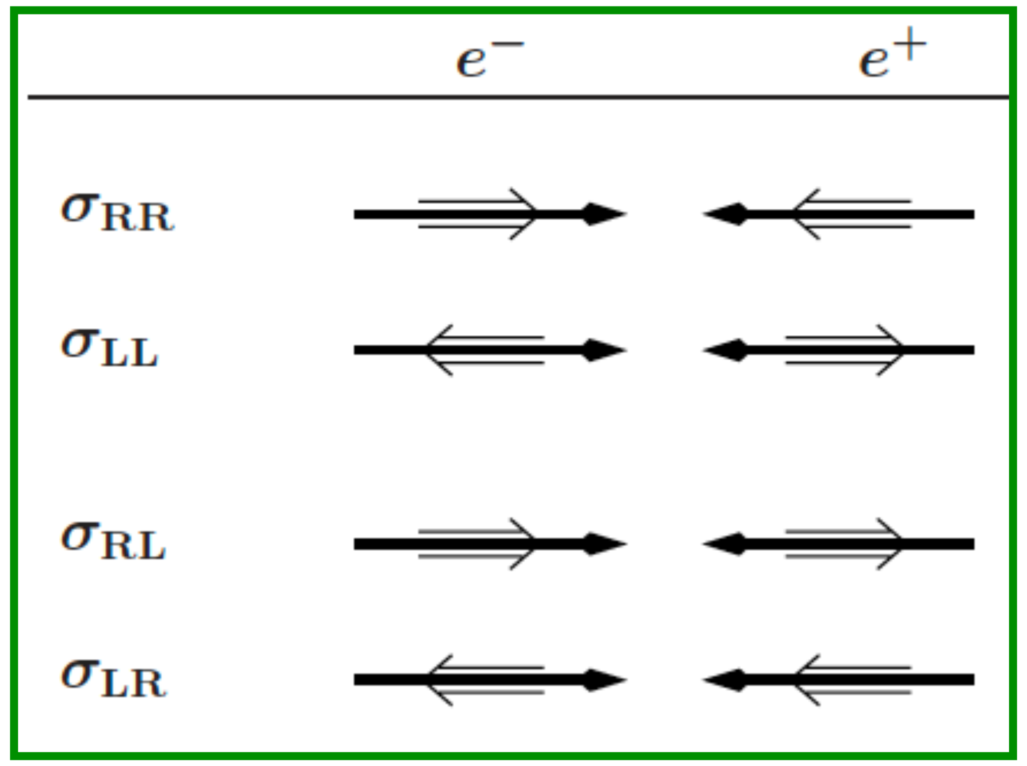
- Defines event rate => size of data set
- Future e^+e^- colliders aim for $10^3..10^6$ larger data sets than LEP
- Depends strongly on invest costs and power consumption => be careful to compare apples to apples!
- Are there fundamental boundaries *beyond* statistics?
  (e.g. theory & parametric uncertainties, detector resolution, …)

Beam polarisation:

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



- Electroweak interactions highly sensitive to chirality of fermions: $SU(2)_L \times U(1)$
- both beams polarised => “four colliders in one”:



Interlude: Chirality in Particle Physics

- 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!

The minimal Higgs program

The Higgs Boson couplings

How big can BSM effects be?

- low scale new physics
  => modification of Higgs properties!
- different *patterns* of deviations from SM prediction for different NP models
- *size* of deviations depends on NP scale
  typically few percent on tree-level:
  - MSSM, eg: $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$
  - Littlest Higgs, eg m_T=1TeV: $$\frac{g_{hgg}}{g_{h_{SM}gg}} = 1 - (5\% \sim 9\%)$$ $$\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} = 1 - (5\% \sim 6\%),$$
  - Composite Higgs, eg: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}) \end{cases}$$

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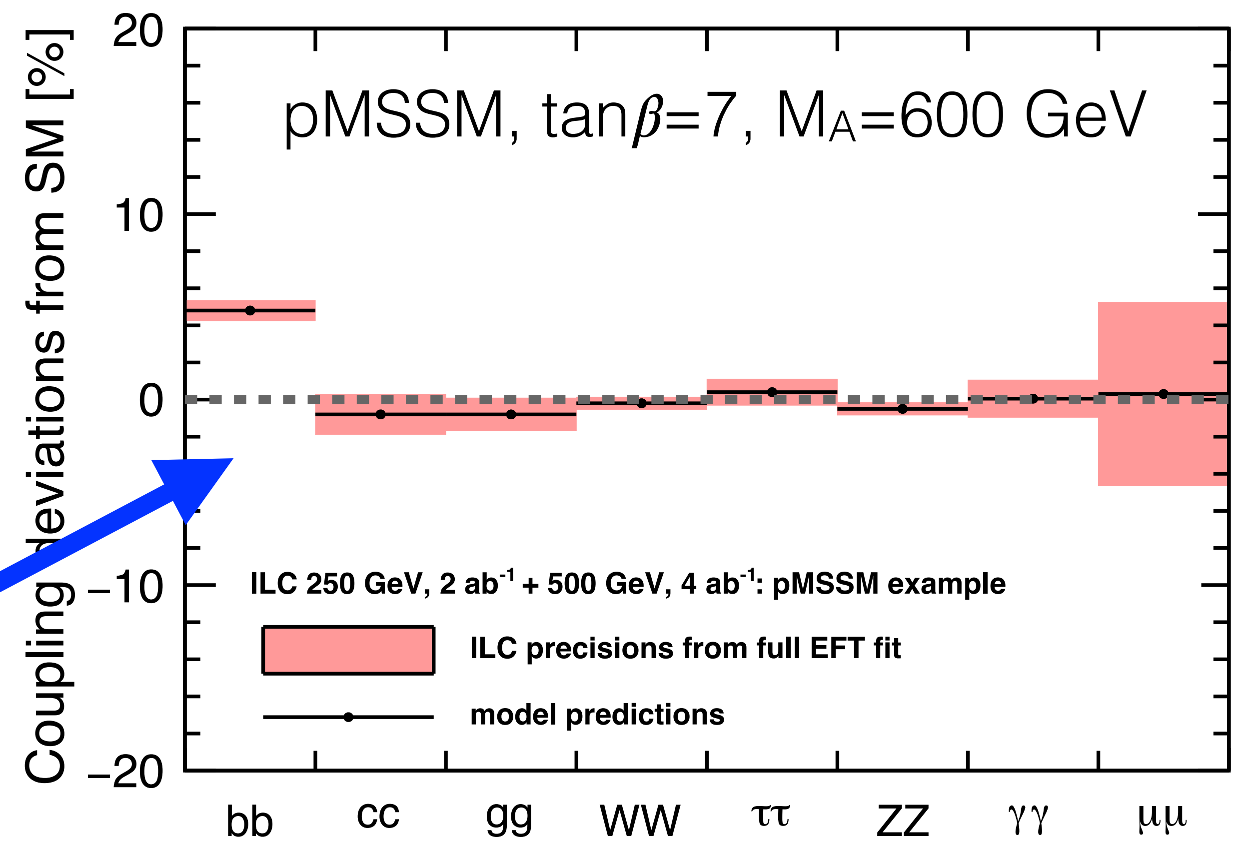

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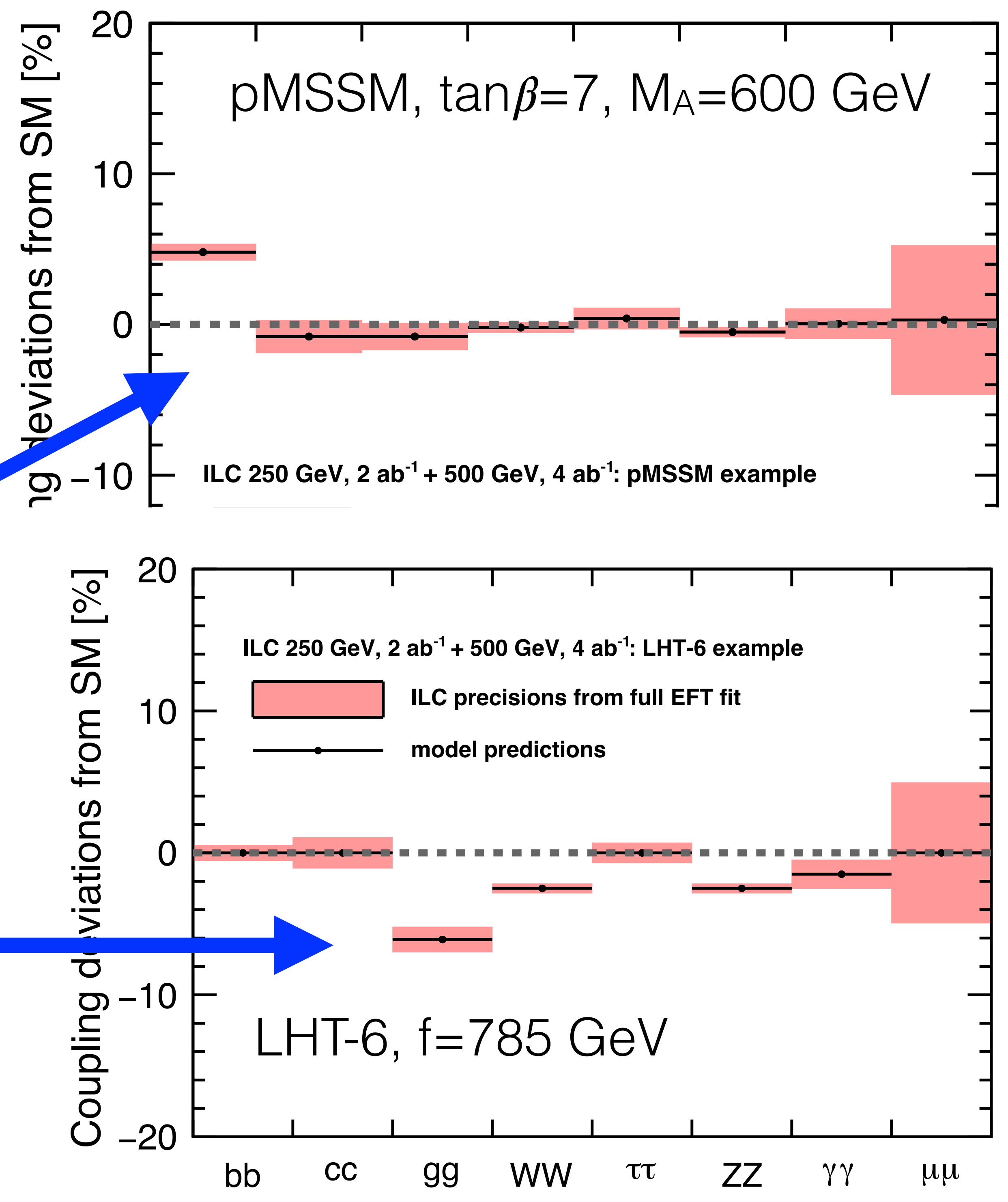

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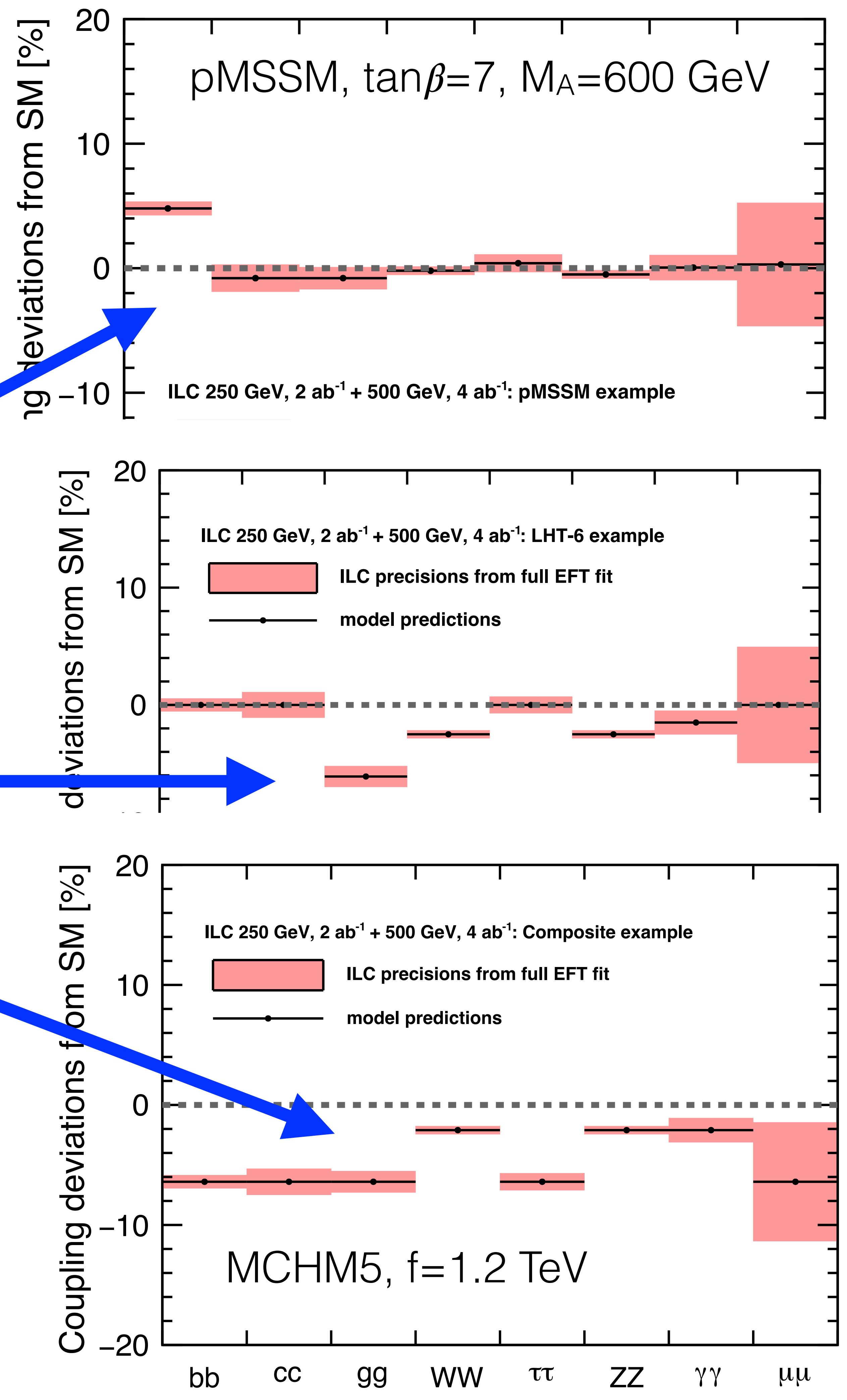

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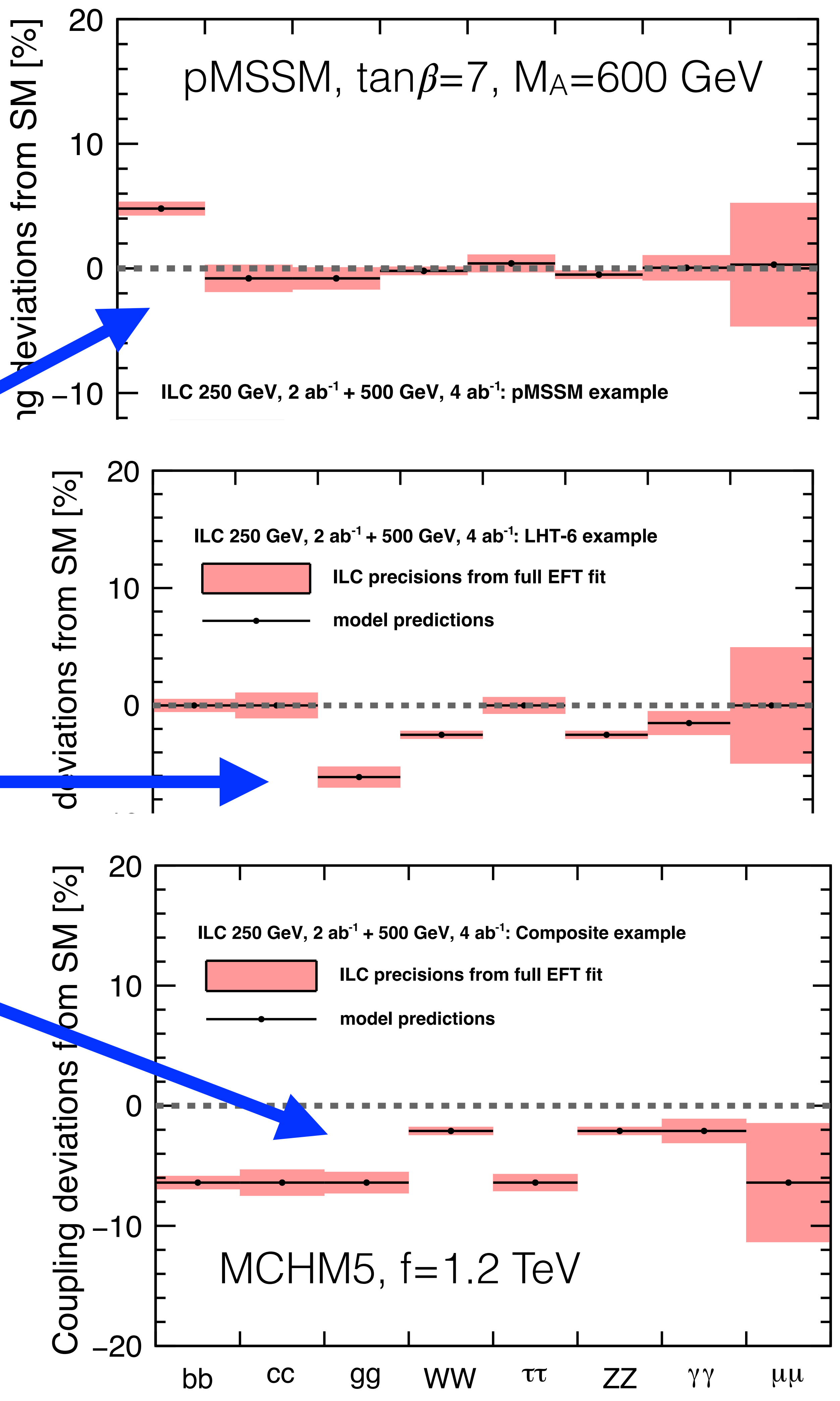
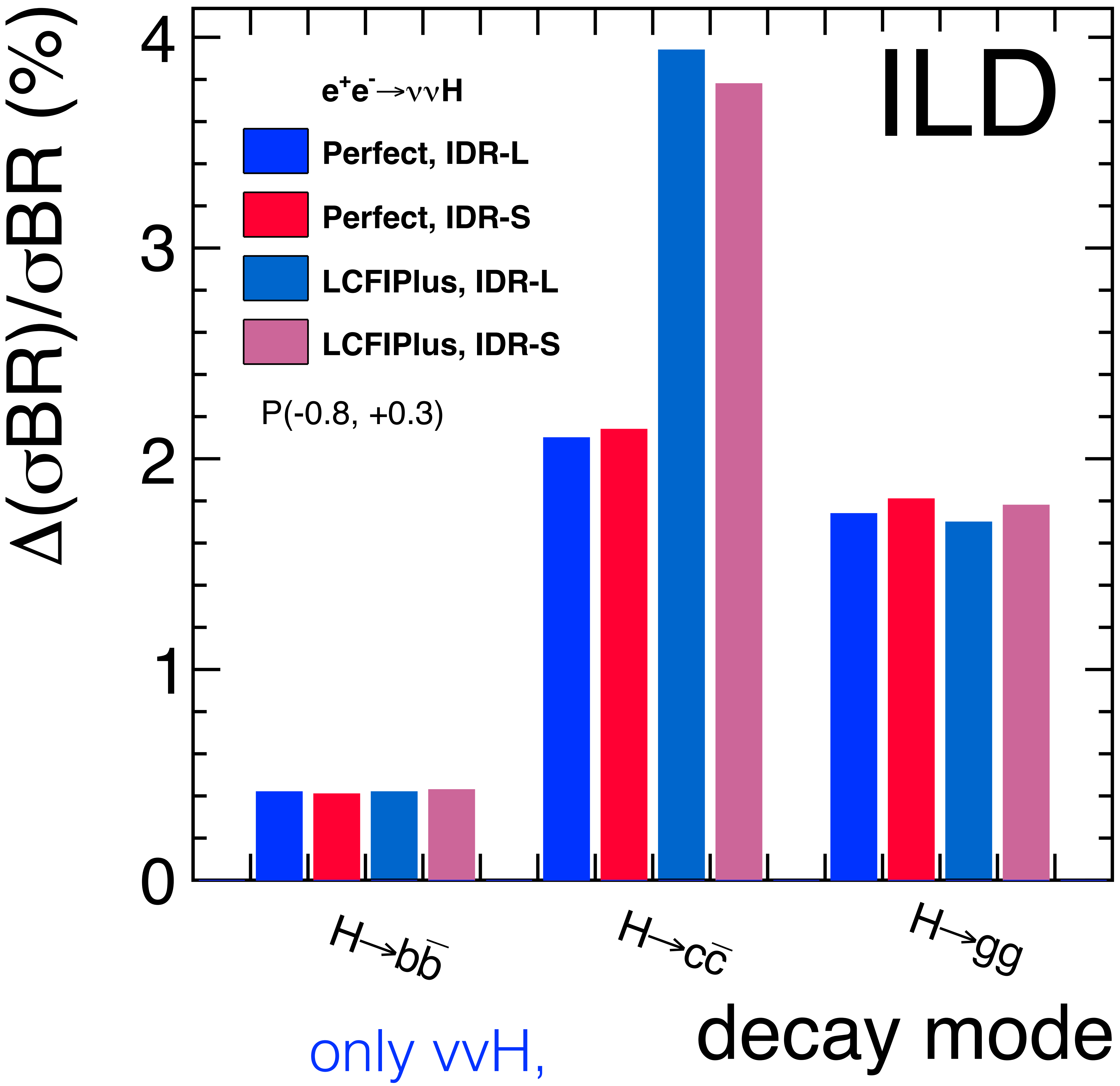


At least percent-level precision required!

Higgs decay to jets

...the experimental situation

- use all visible decay modes of Z and ννH
- H->jets and Z->jets play important role!
- Example from ILD IDR:
  - **σxBR(bb) to ~0.4%**
    from one channel & data set alone
  - σxBR(cc) shows lot of room for improvement by smarter flavour tag algorithm



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1.6ab-1
P(-0.8,+0.3)
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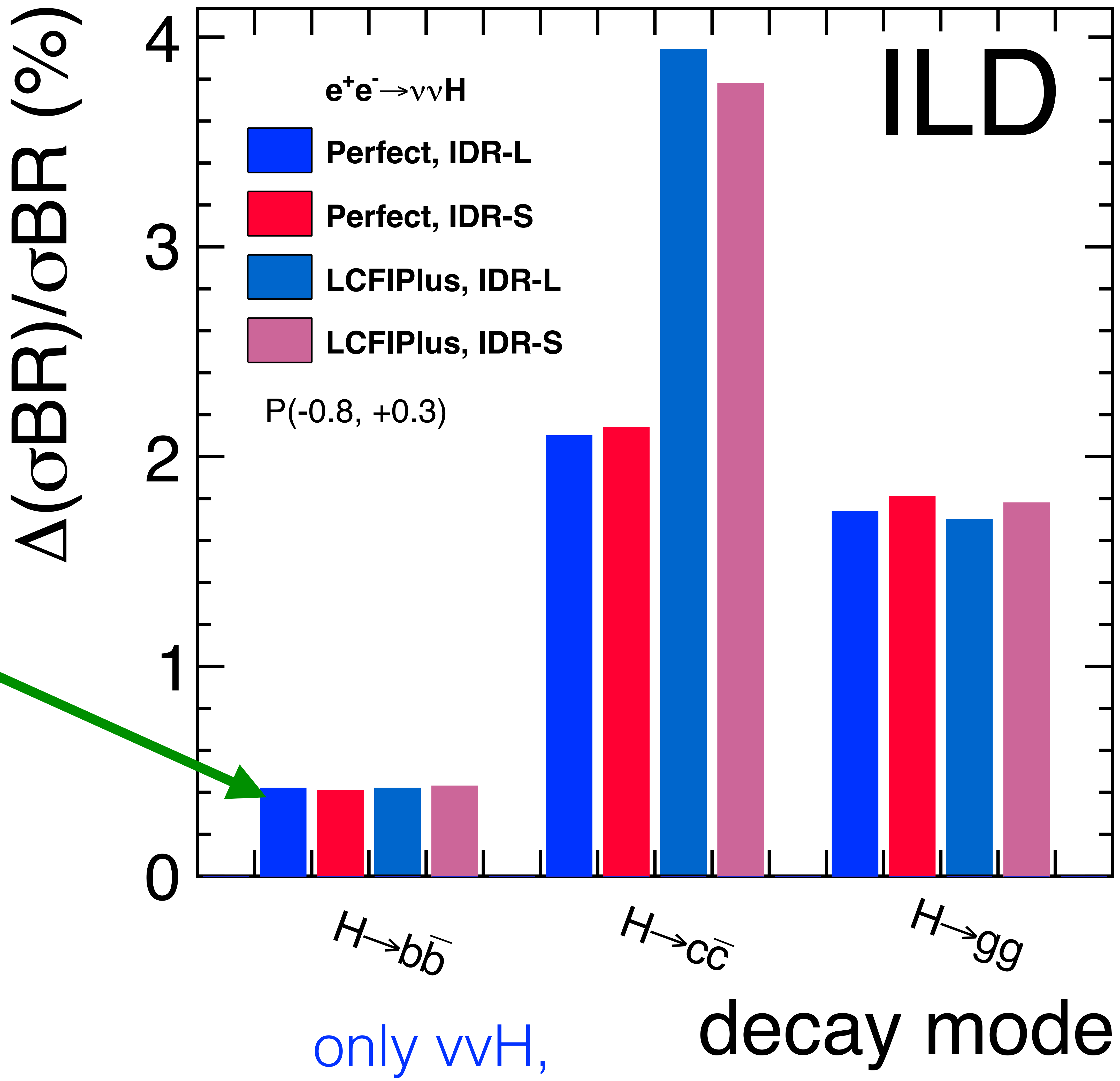

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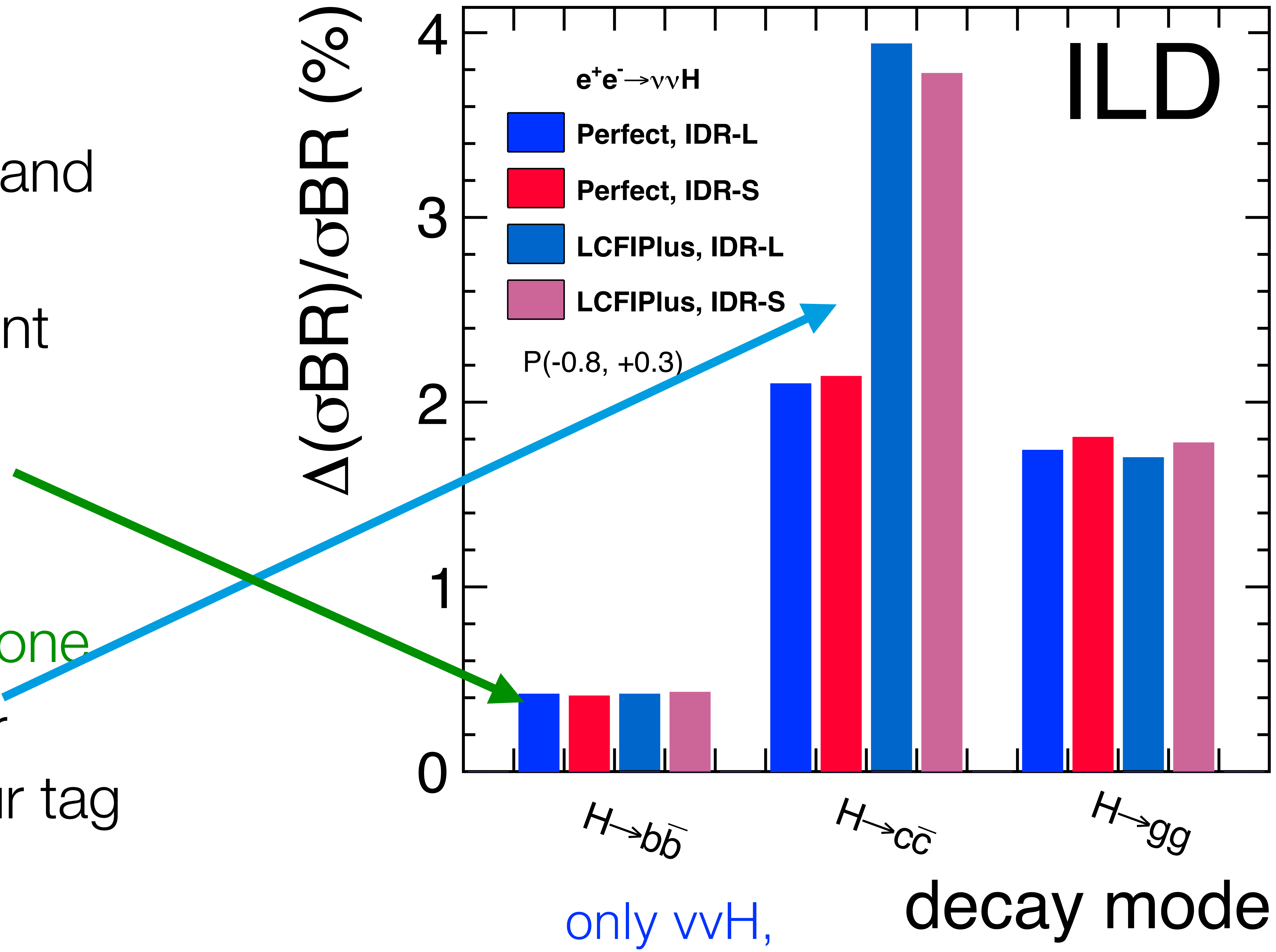

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Illustrating the principle - based on older fit!

Test various example BSM points - all chosen such that no hint for new physics at HL-LHC

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2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
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Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era ($3\,\text{ab}^{-1}$ of integrated luminosity). From [15].

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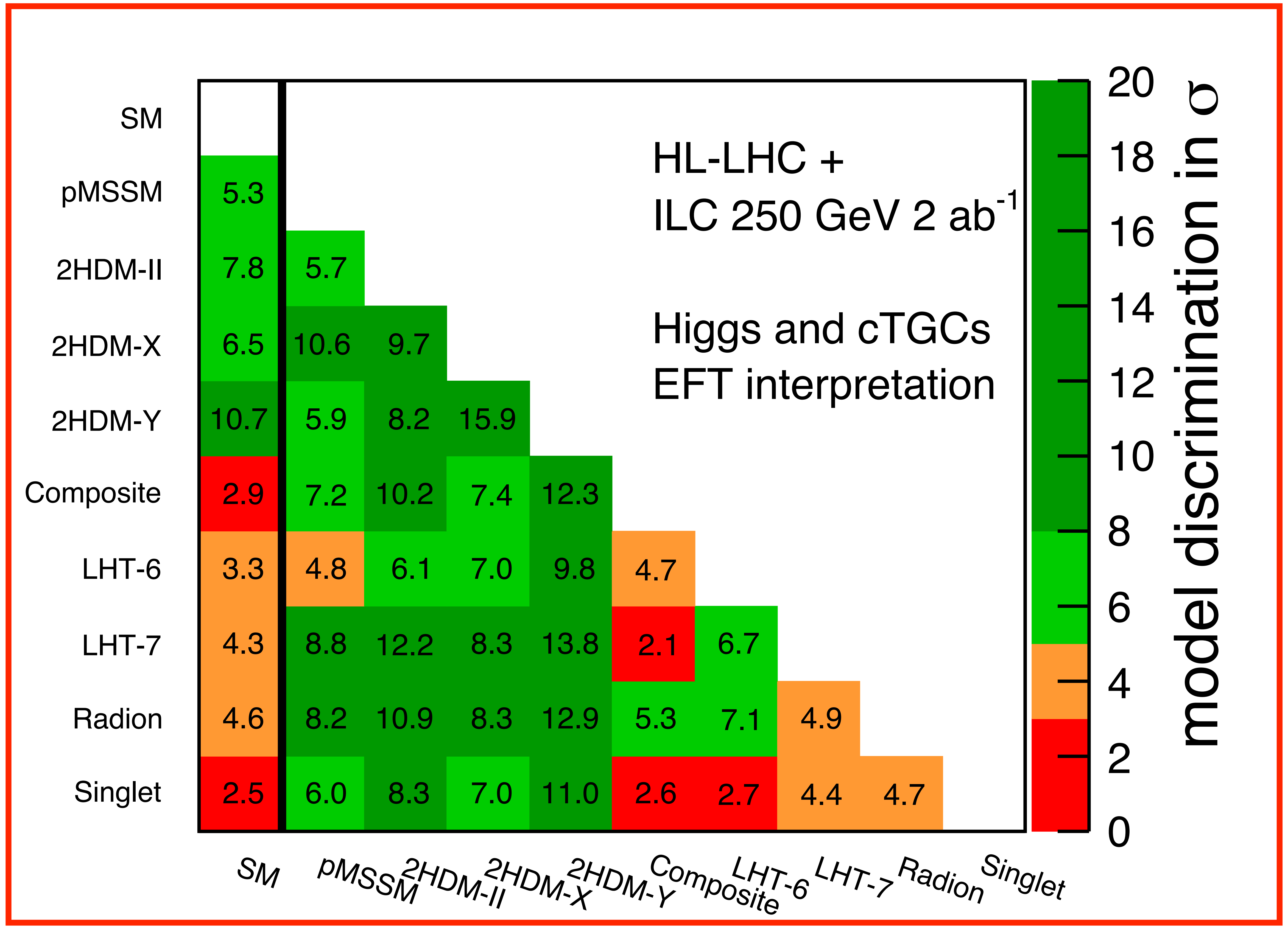

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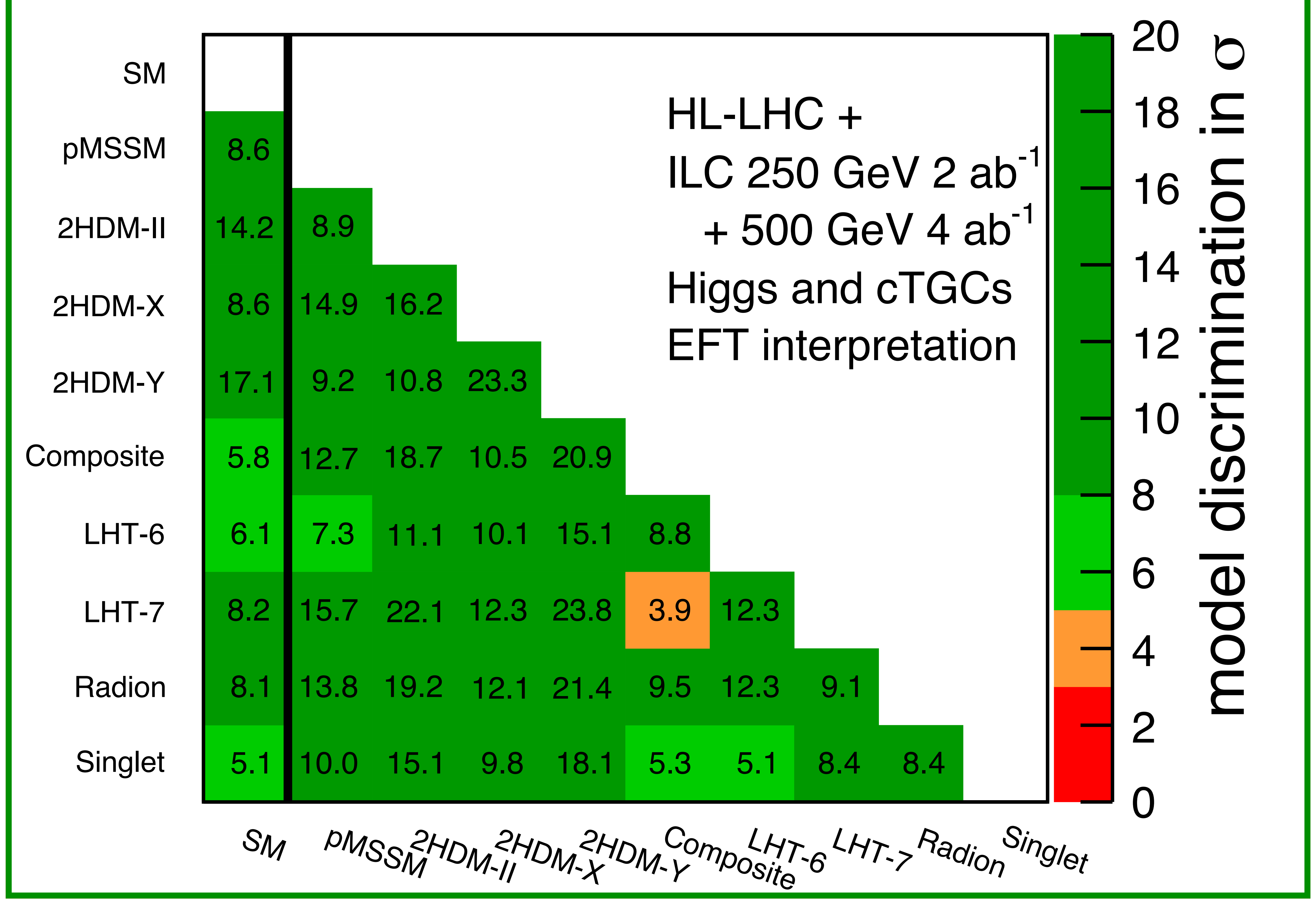

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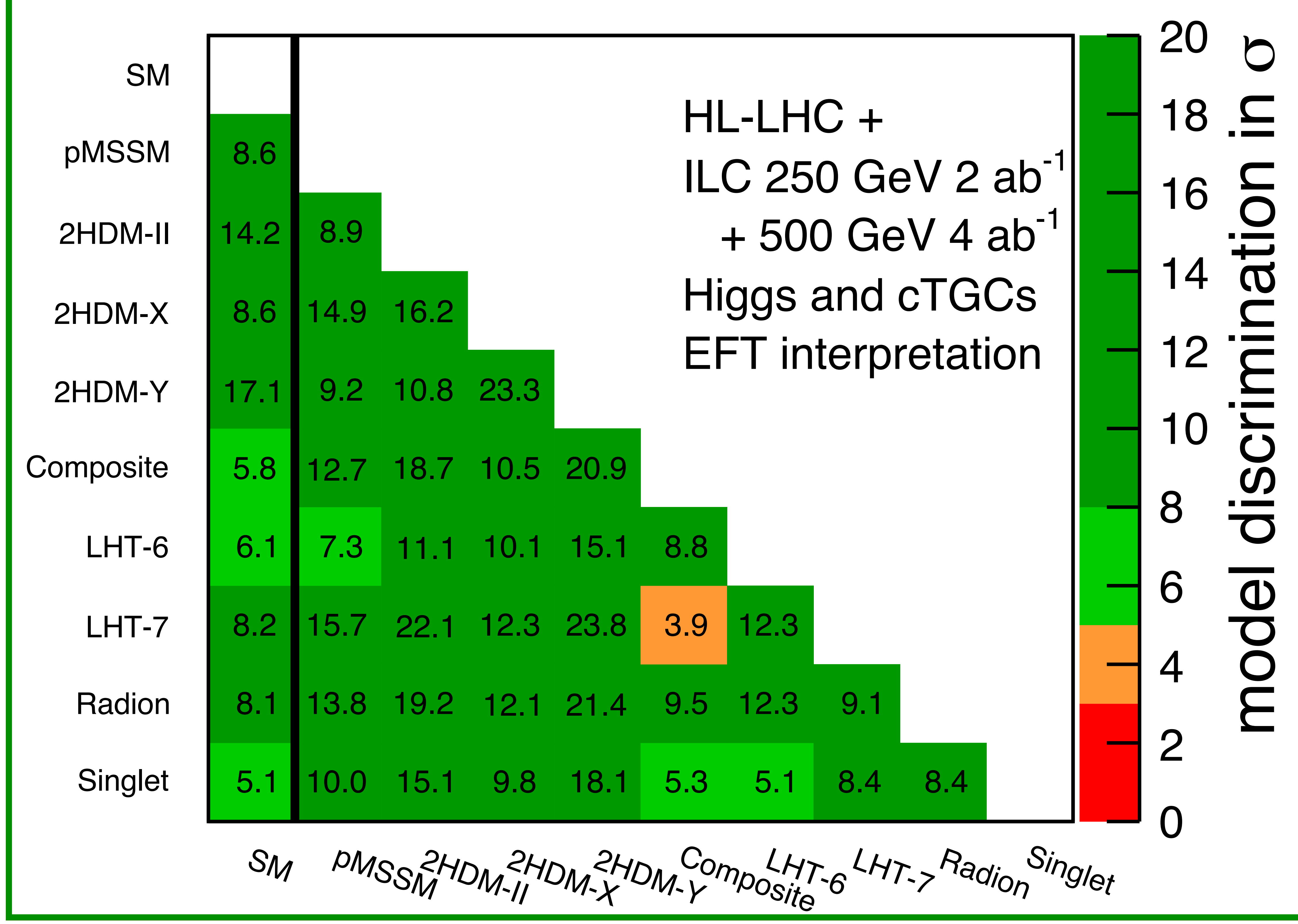
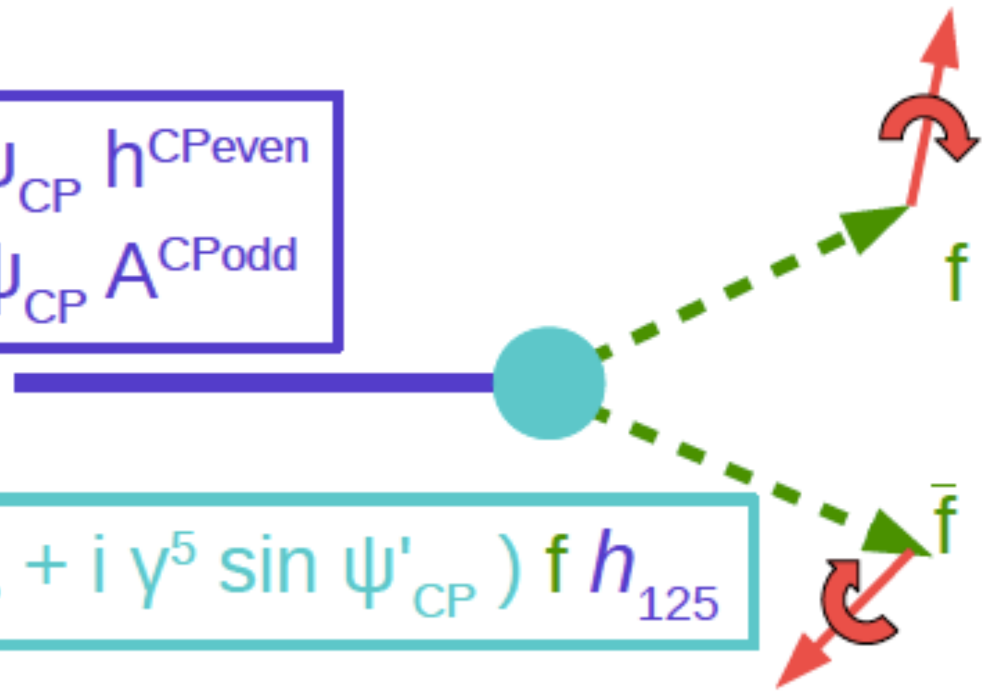


illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

CP properties in h->$\tau\tau$

ZH production ideal

$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$



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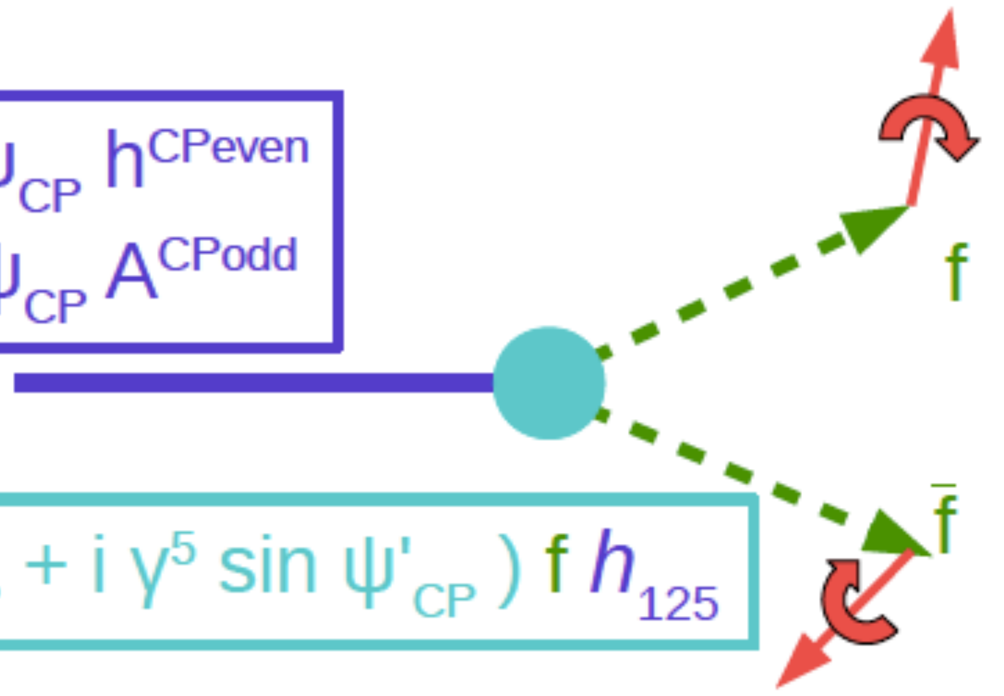

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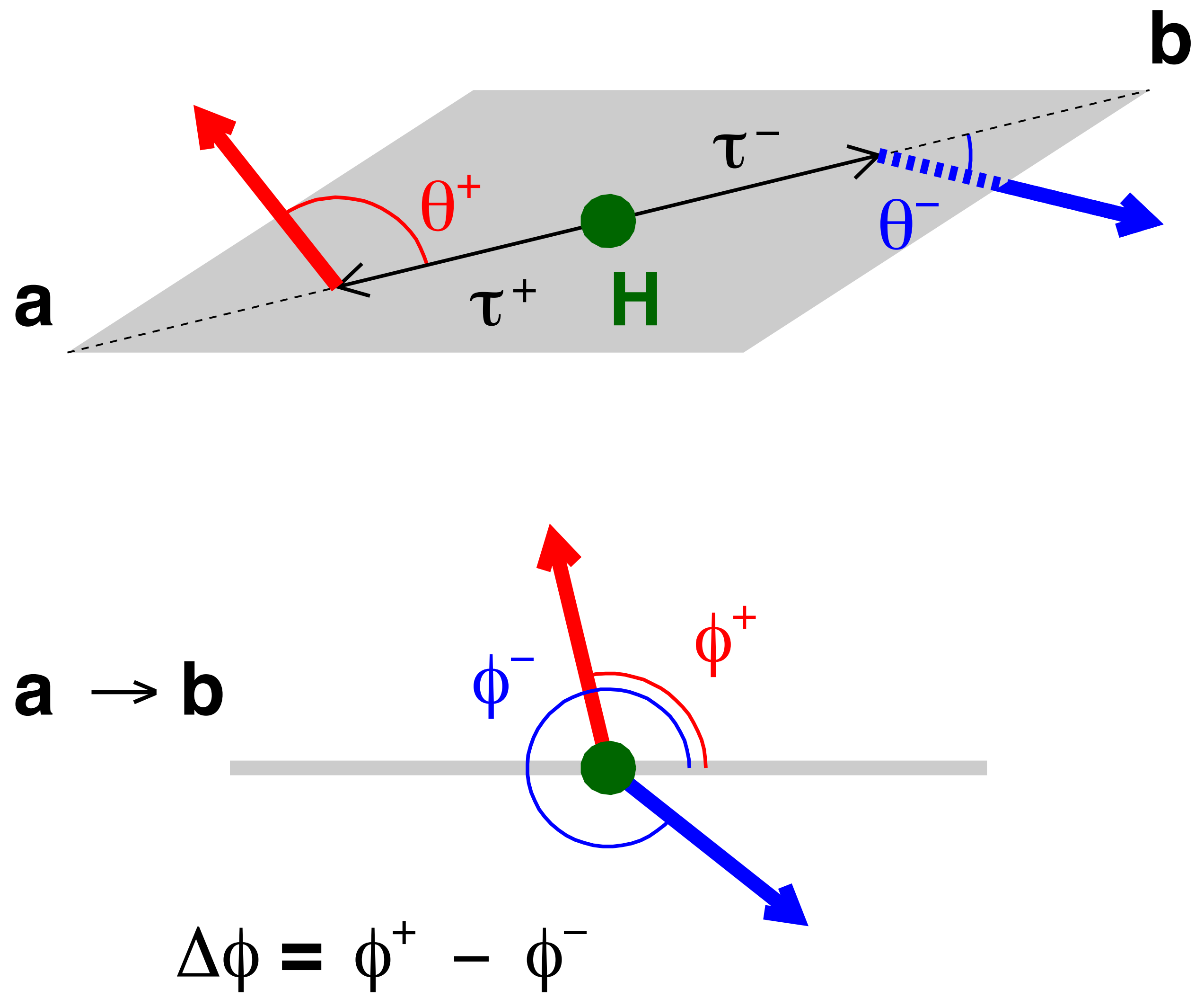

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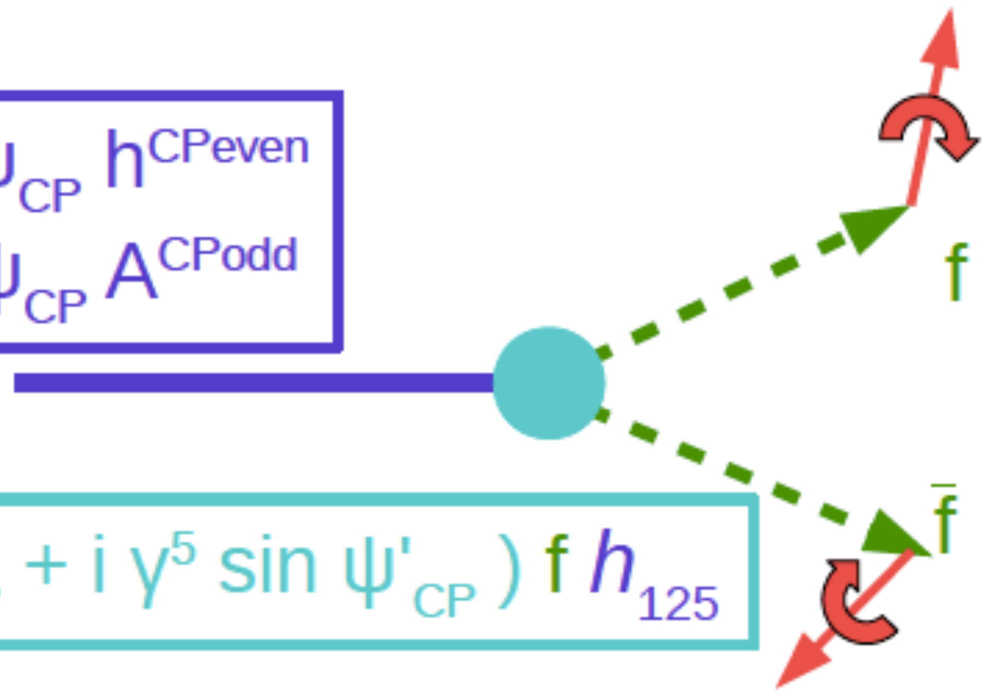

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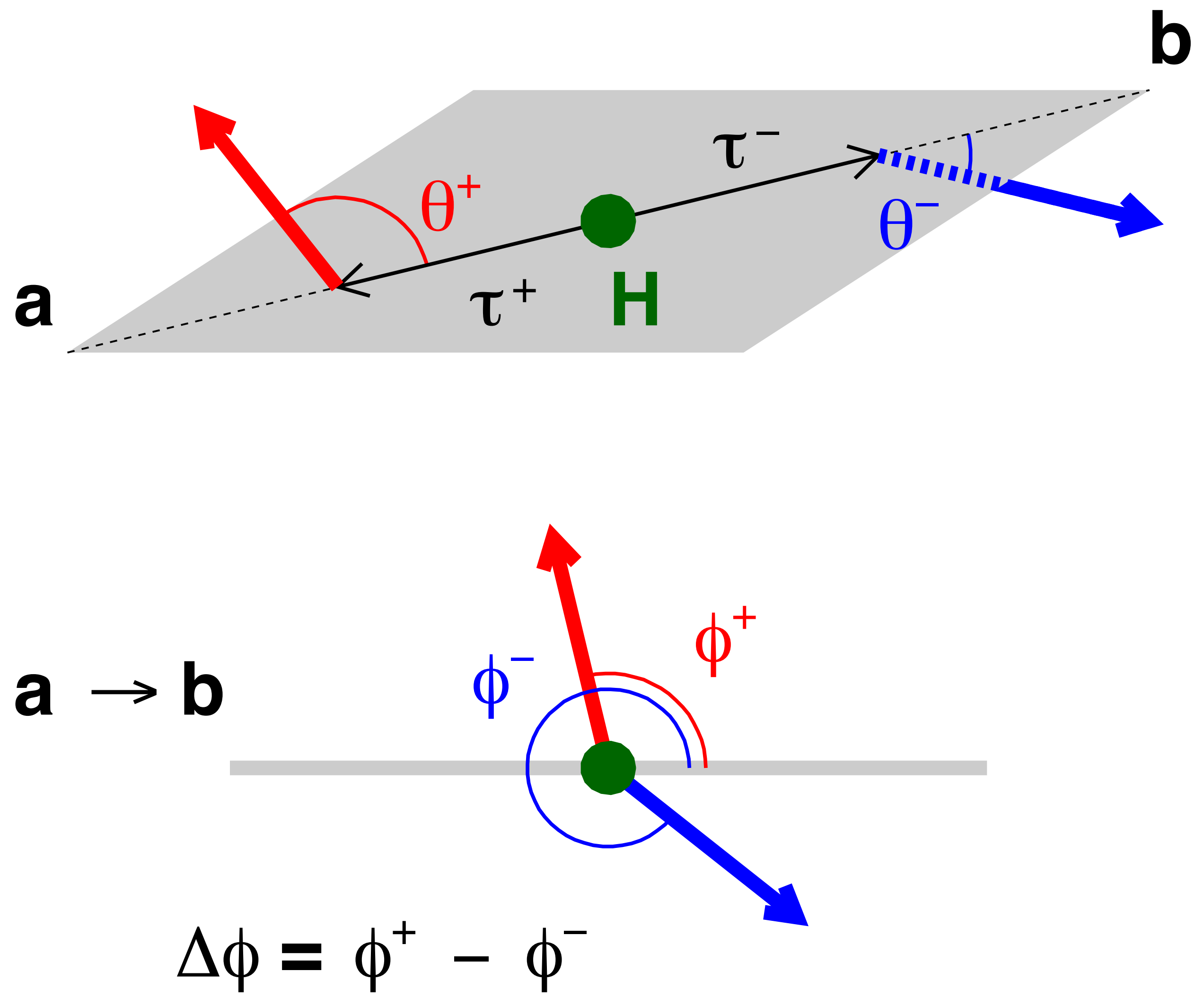

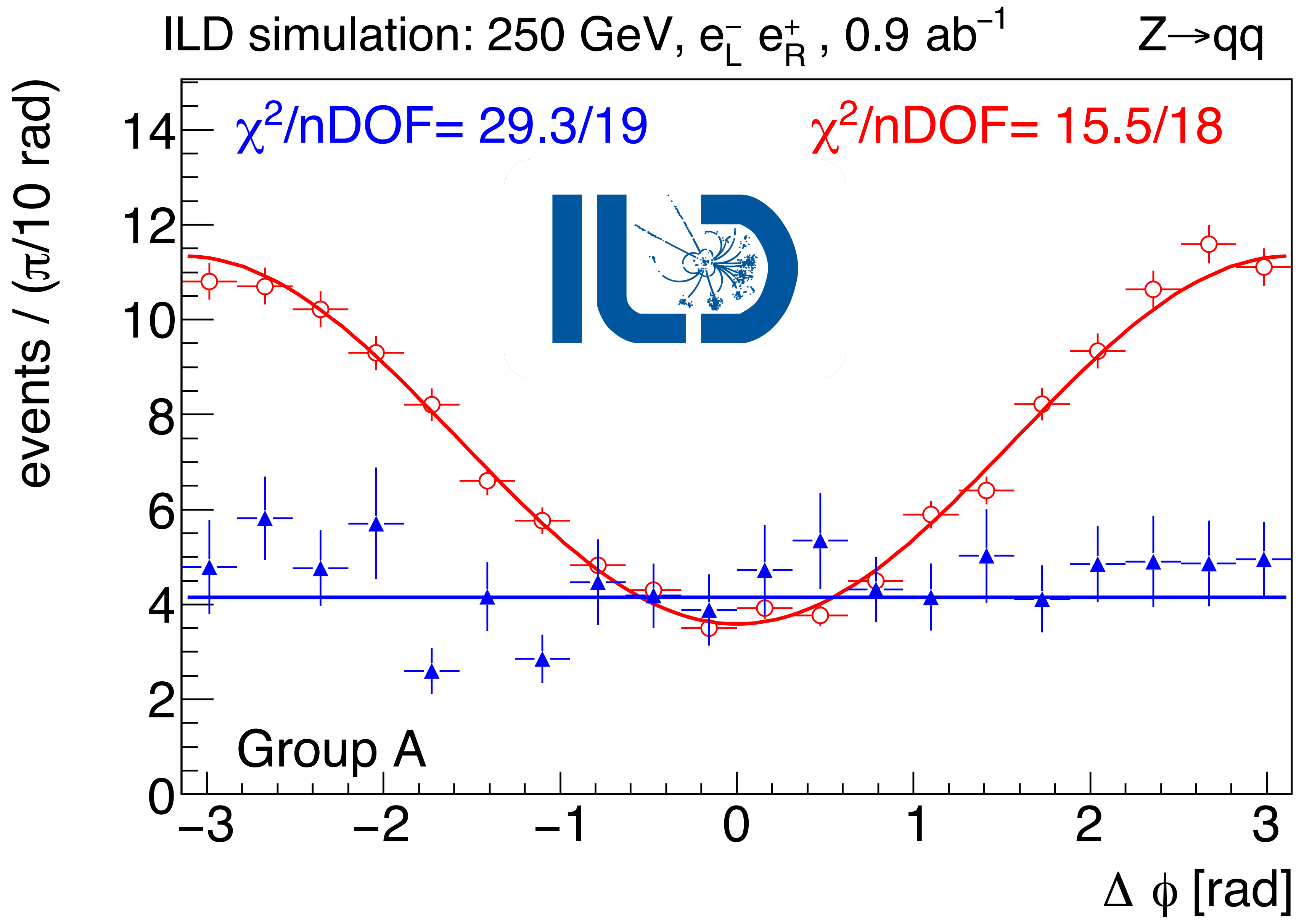

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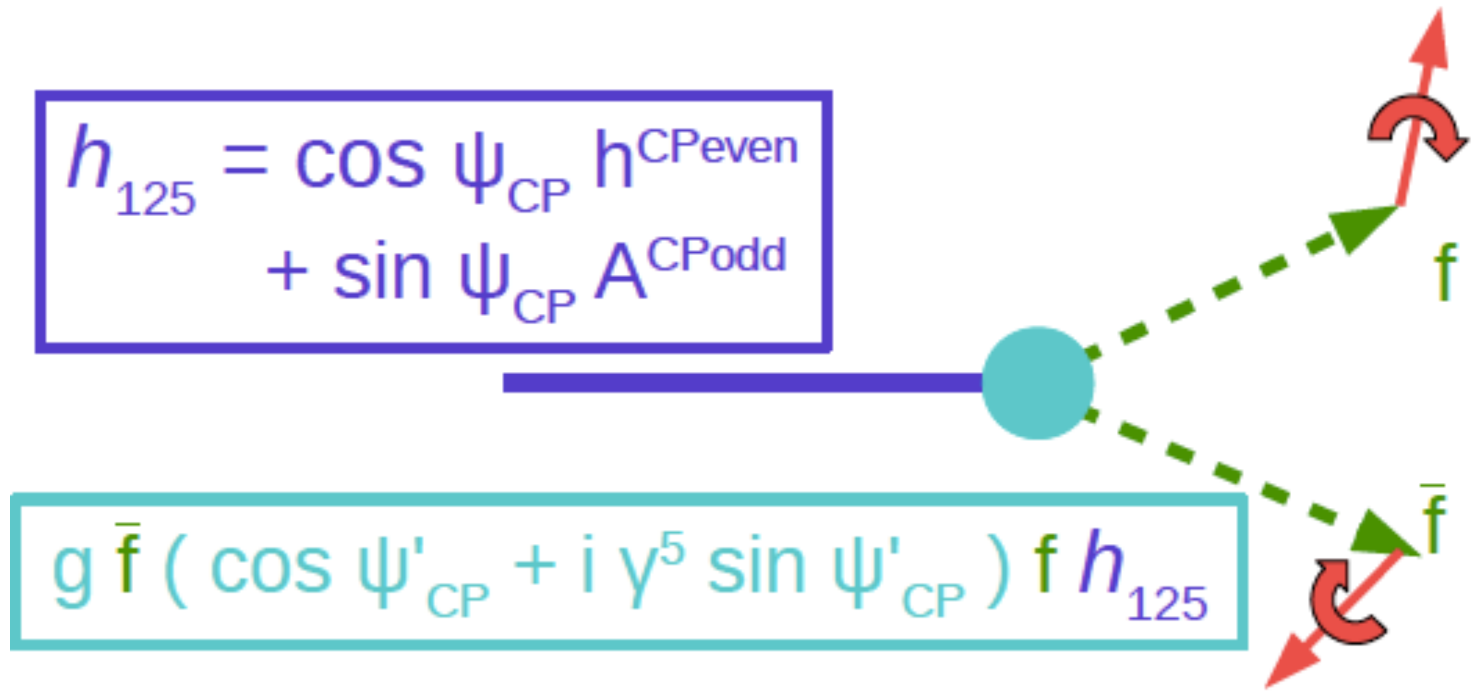

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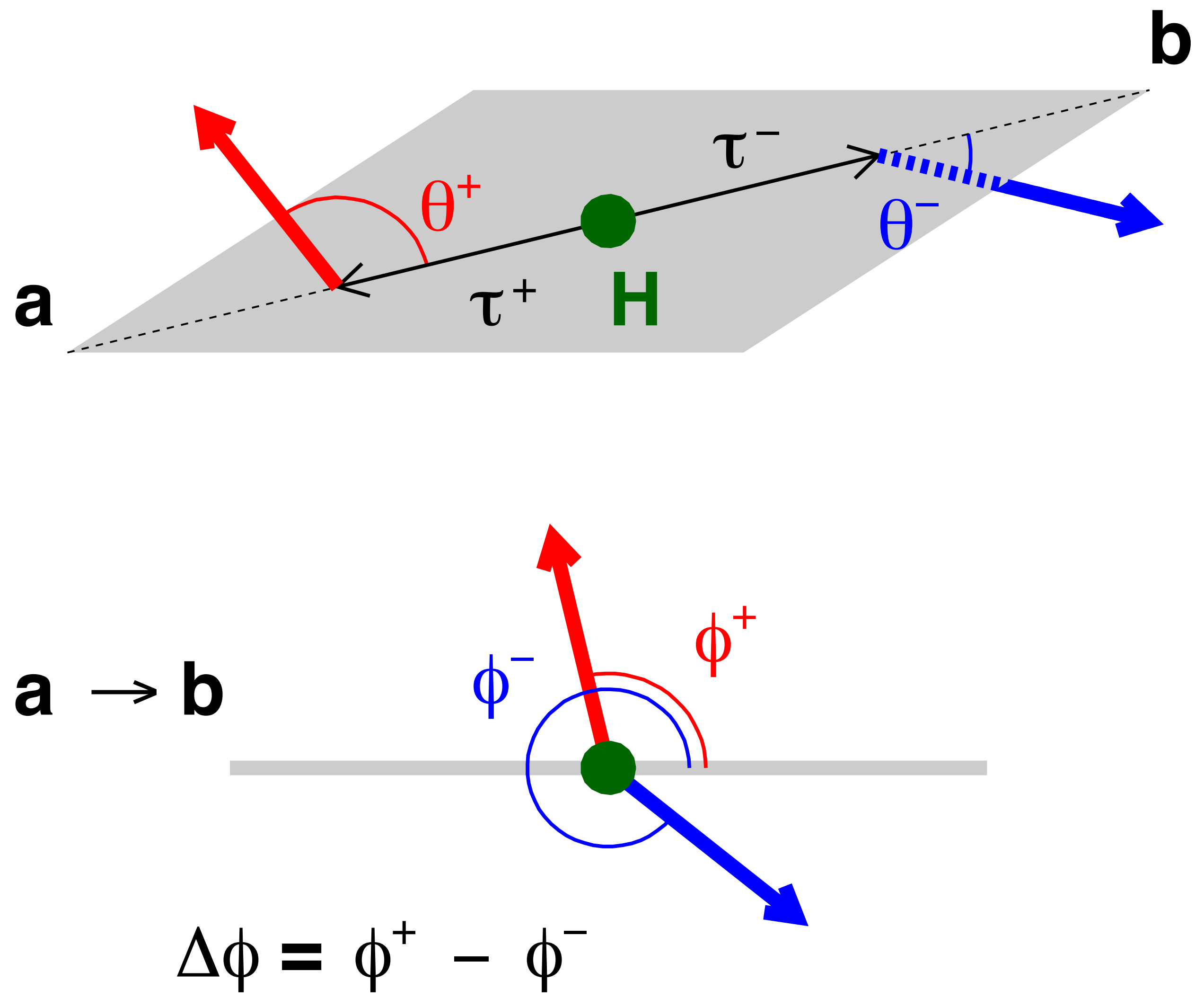

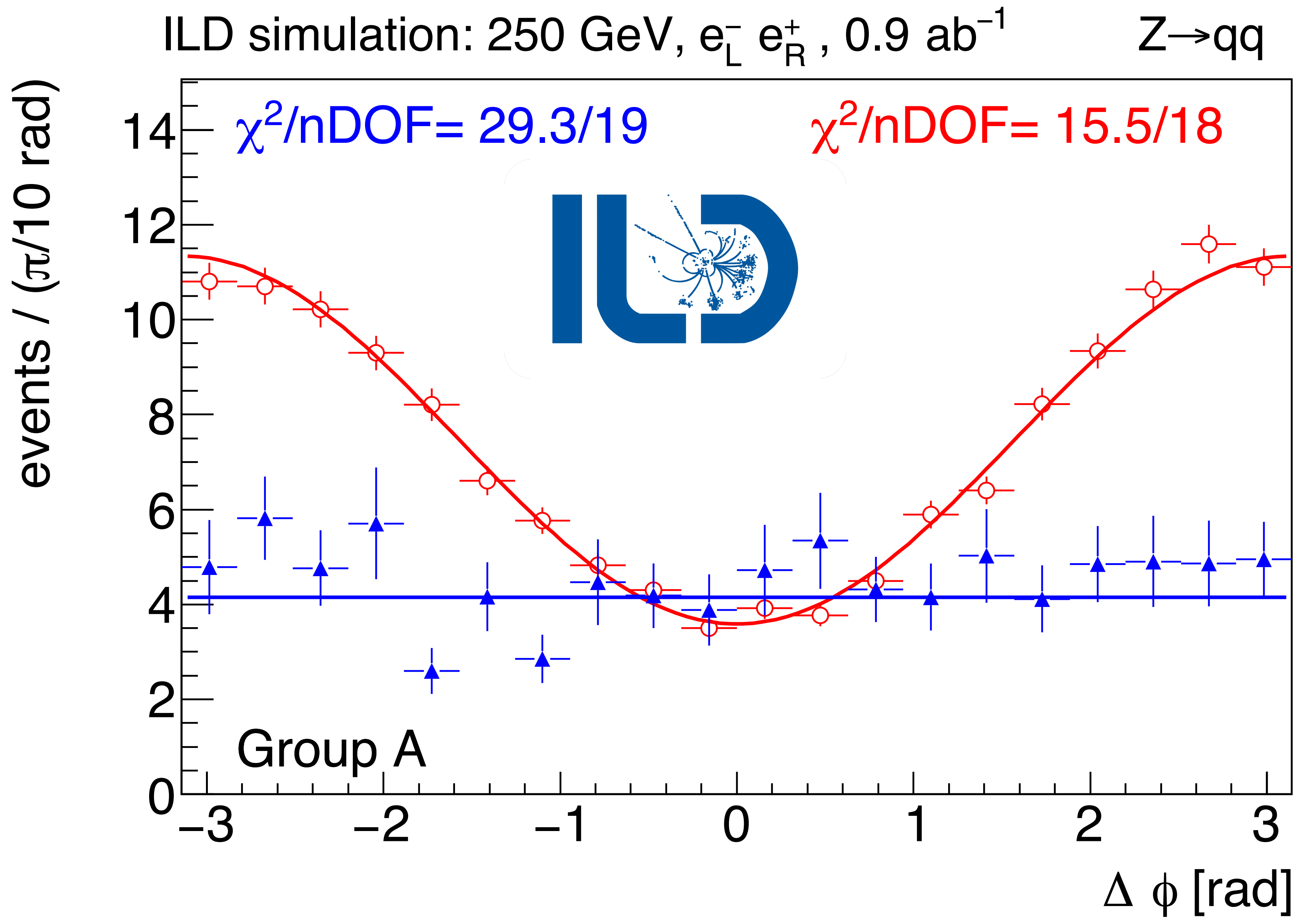

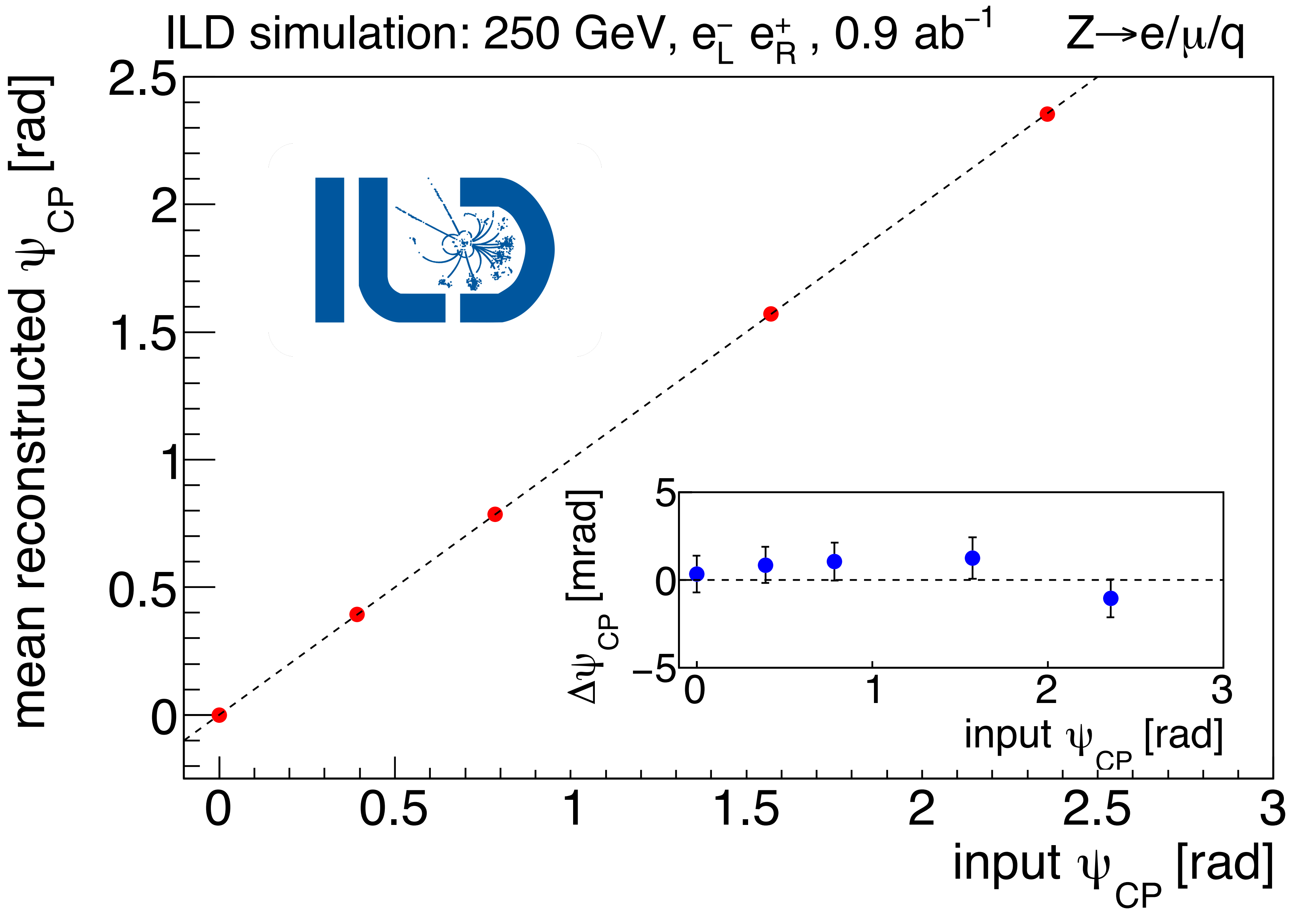

arxiv:1804.01241

based on NIM A810 (2016) 51-58

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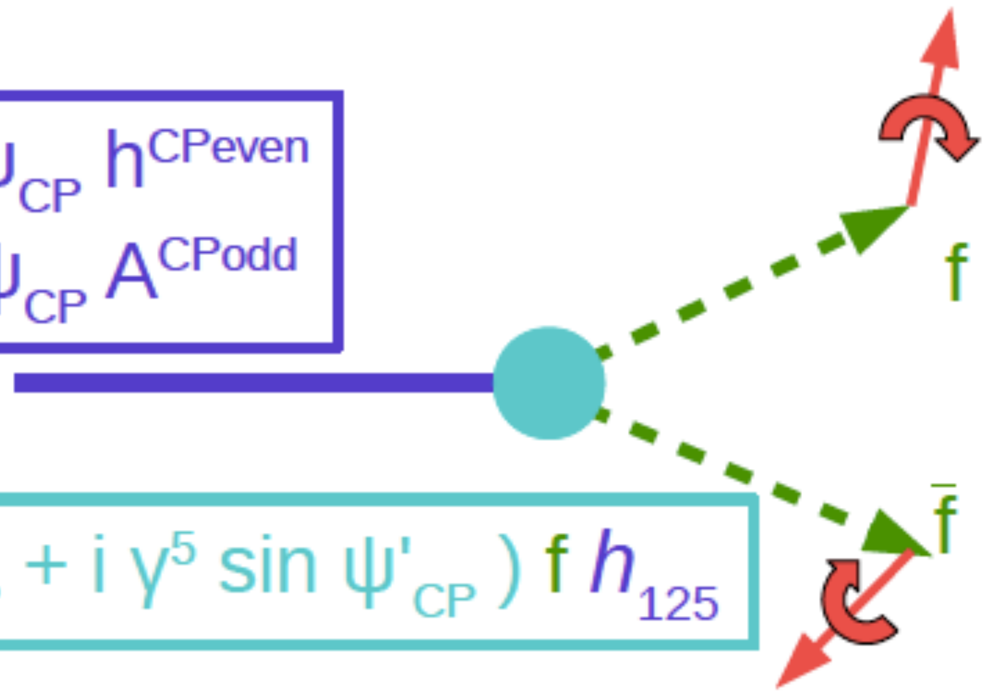

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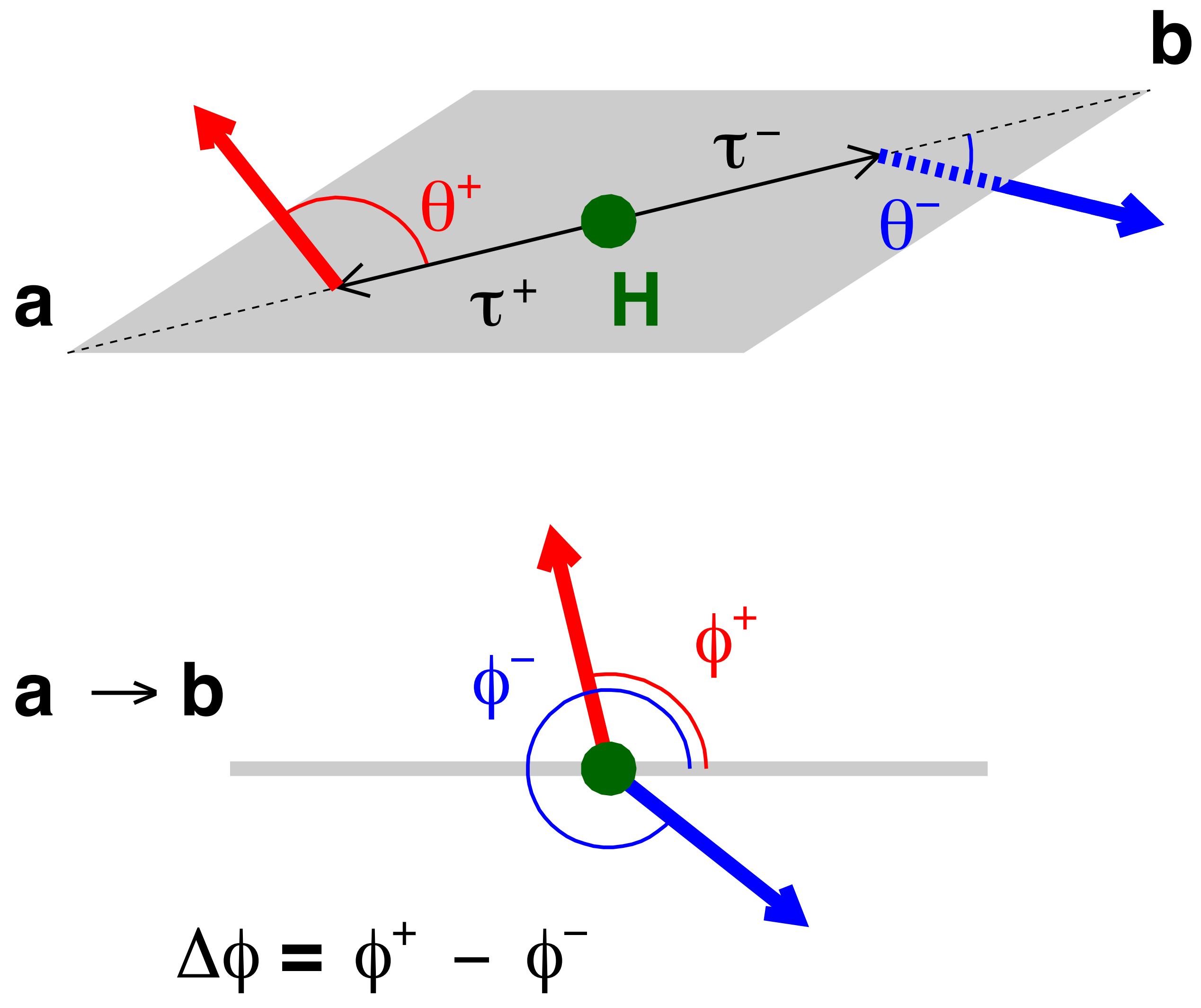

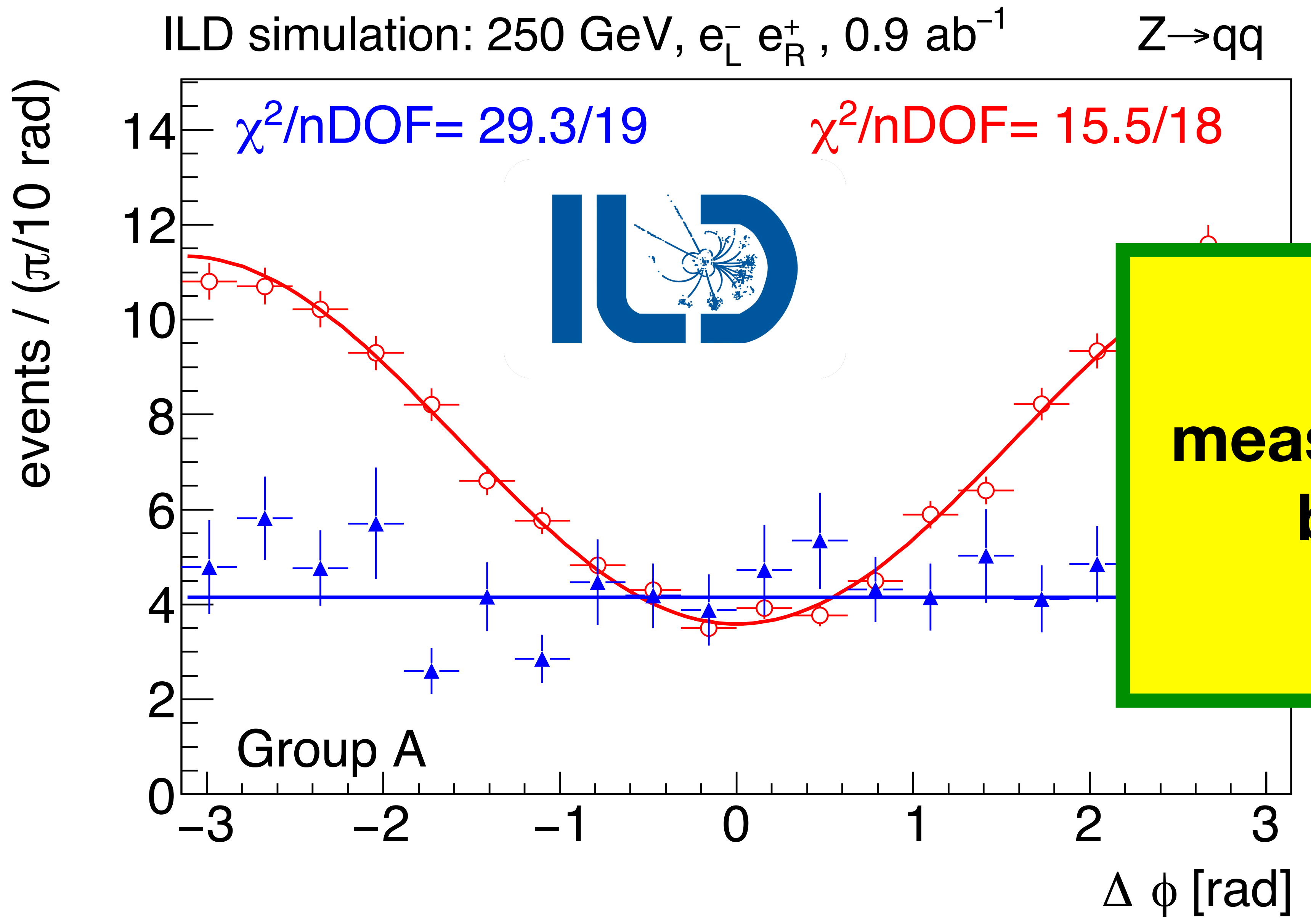

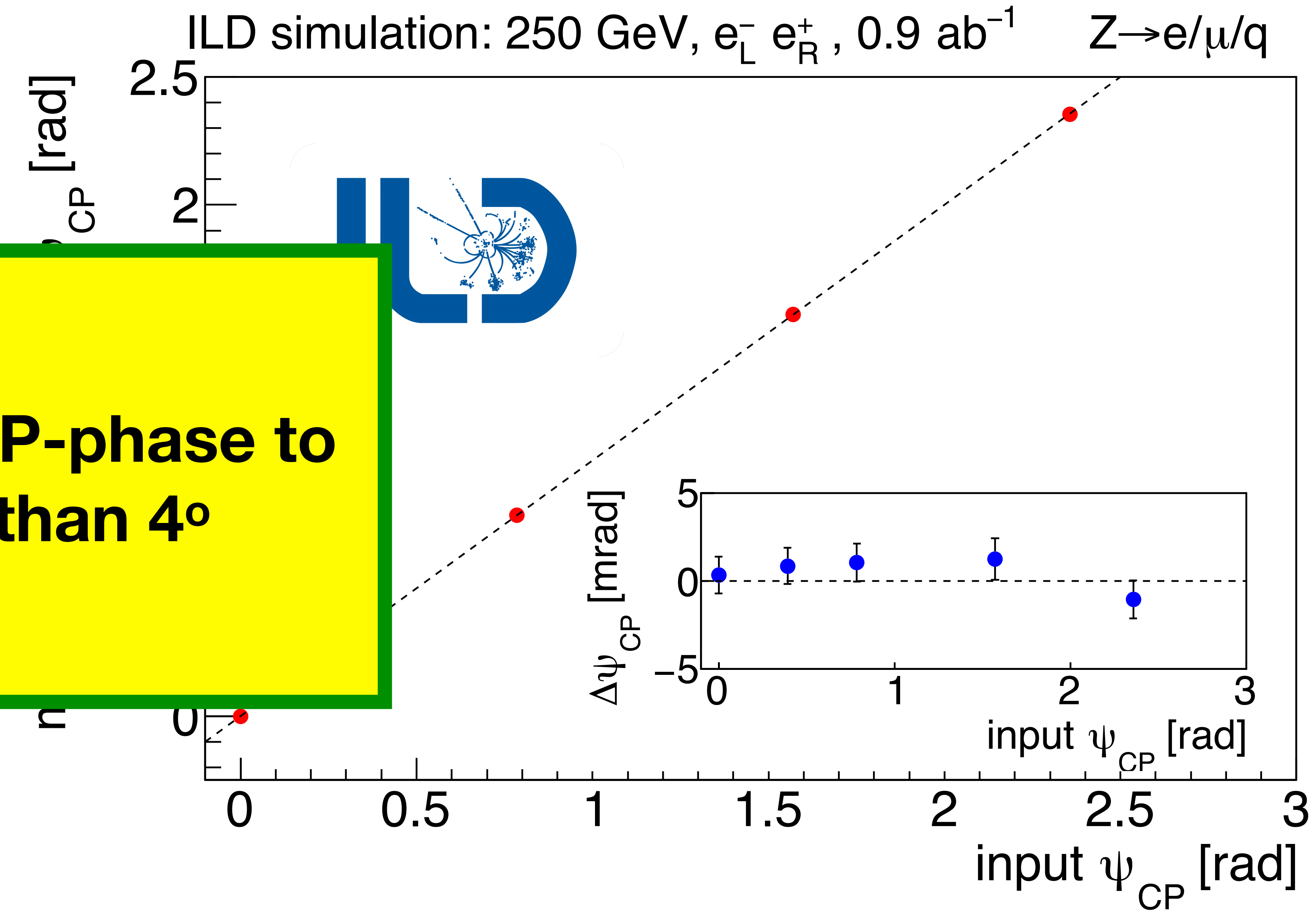

measure CP-phase to better than 4°

arxiv:1804.01241

based on NIM A810 (2016) 51-58

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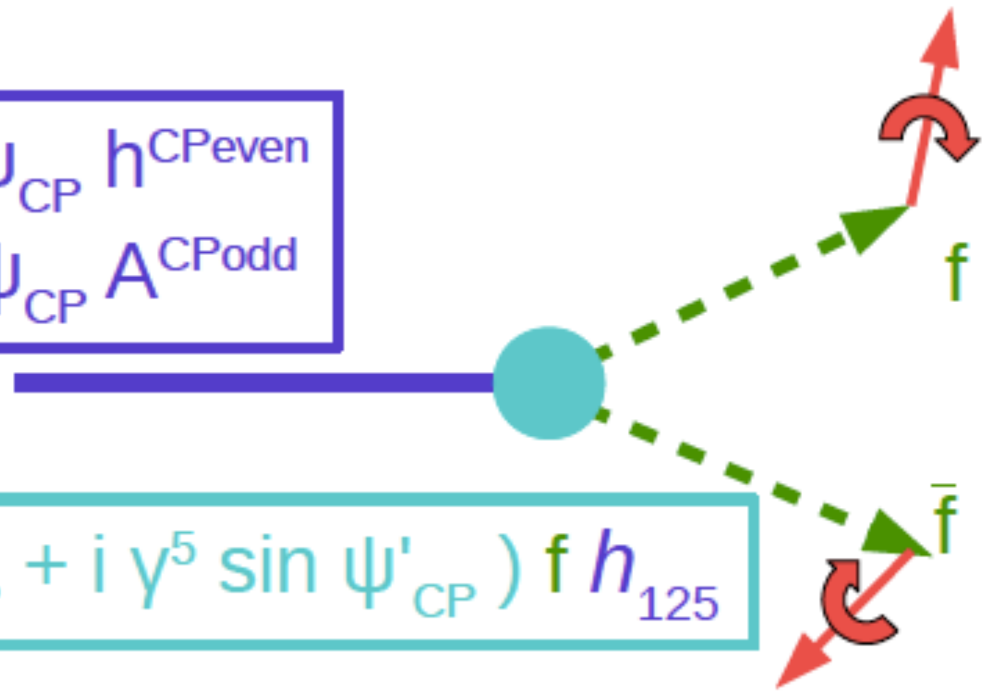

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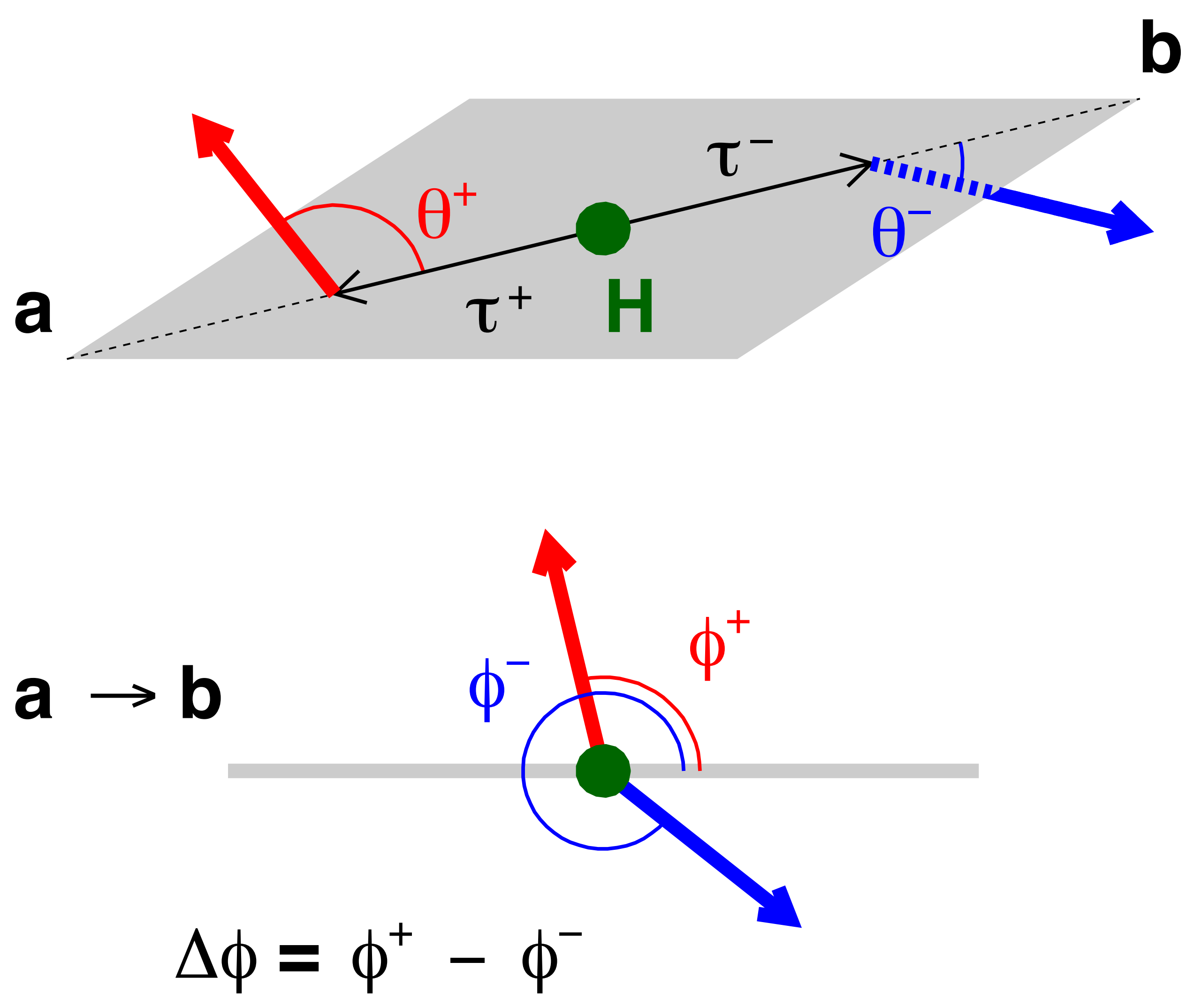
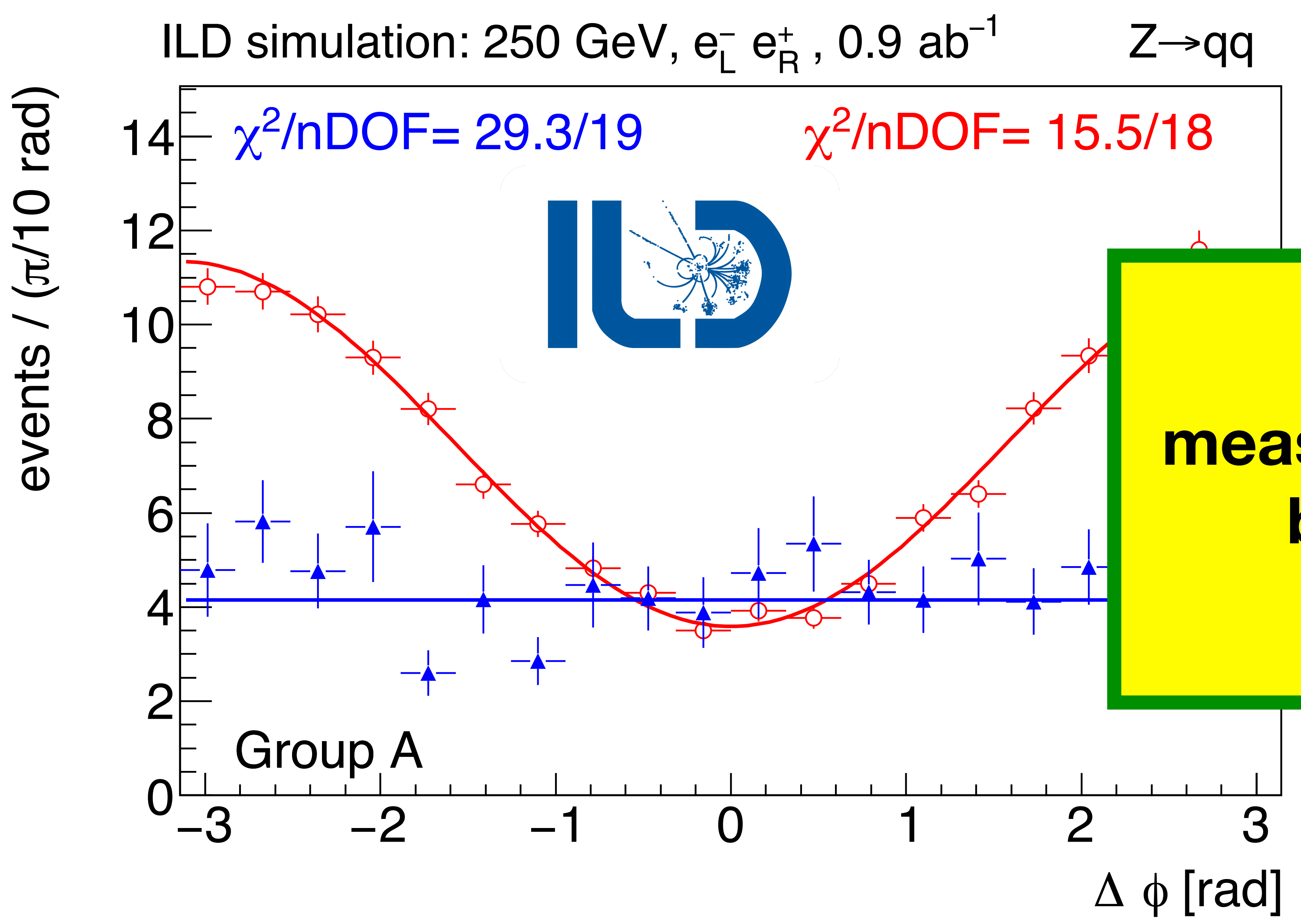
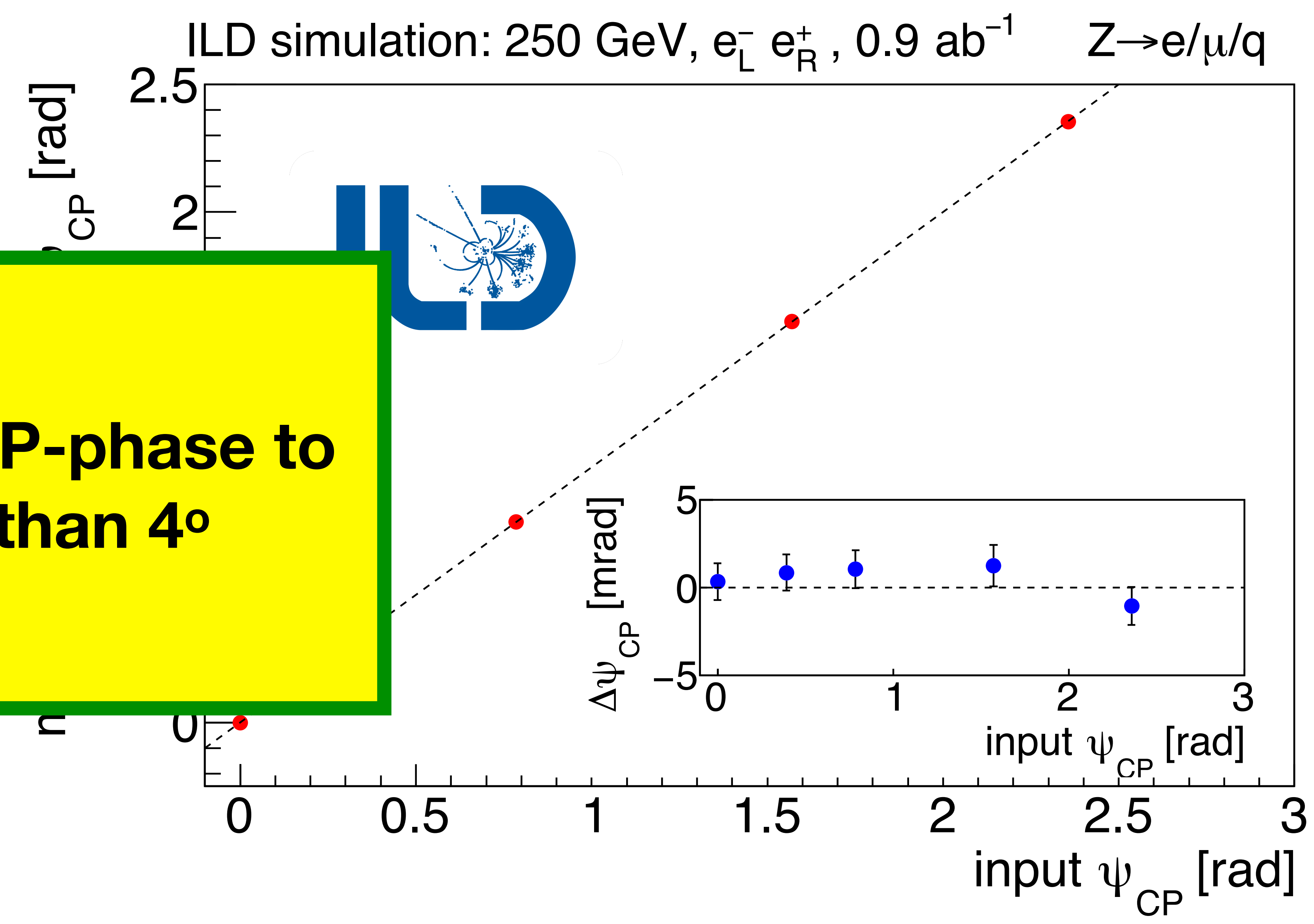






measure CP-phase to better than 4°

..and CPV in Zh coupling:

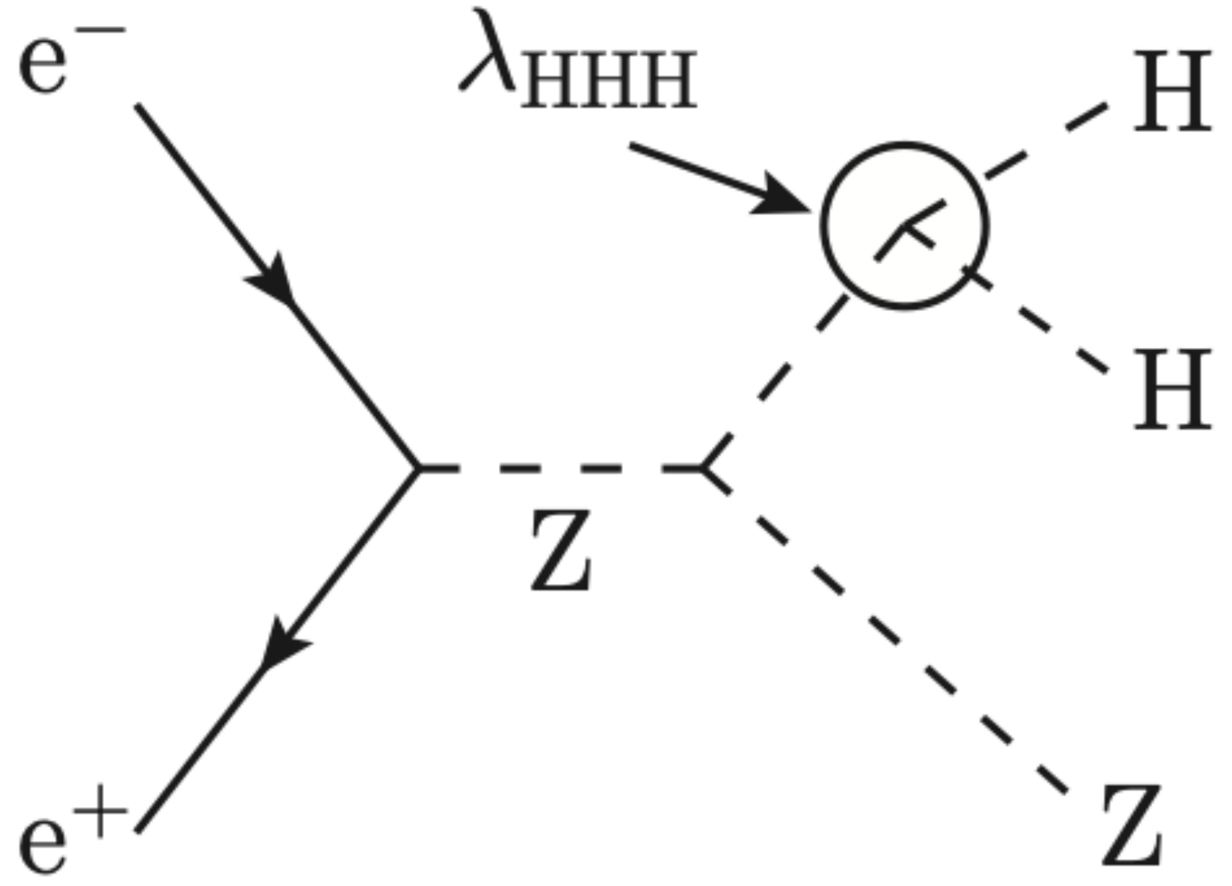
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

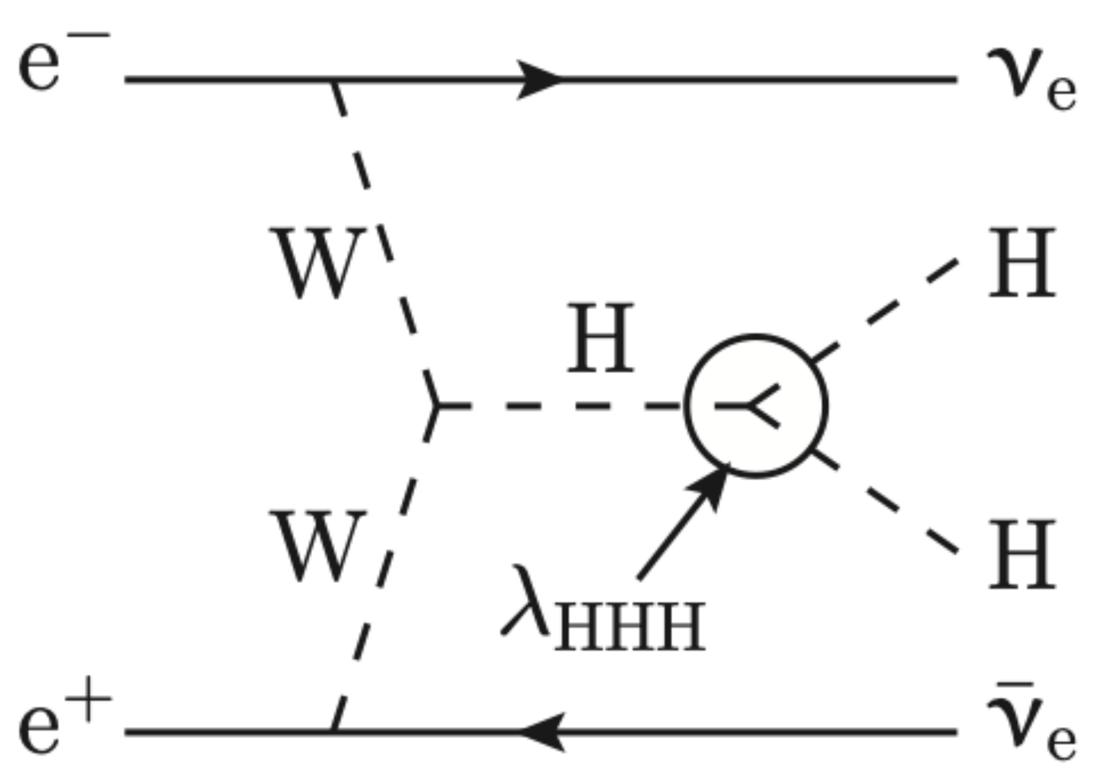
=> $\tilde{b}$ **to ±0.005**

arxiv:1804.01241

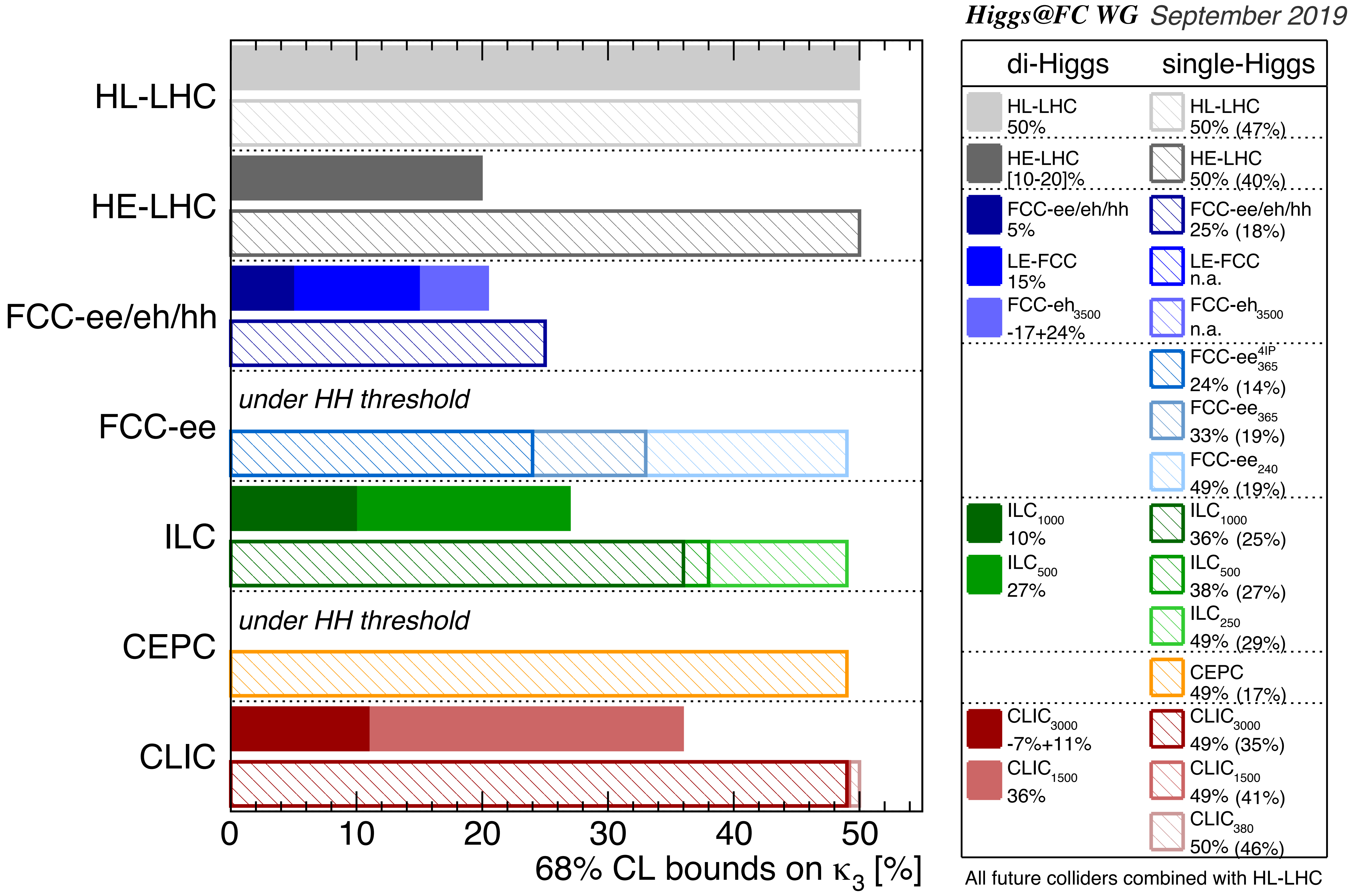
based on NIM A810 (2016) 51-58

Higgs measurements only possible at 500 GeV and above: di-Higgs and ttH production





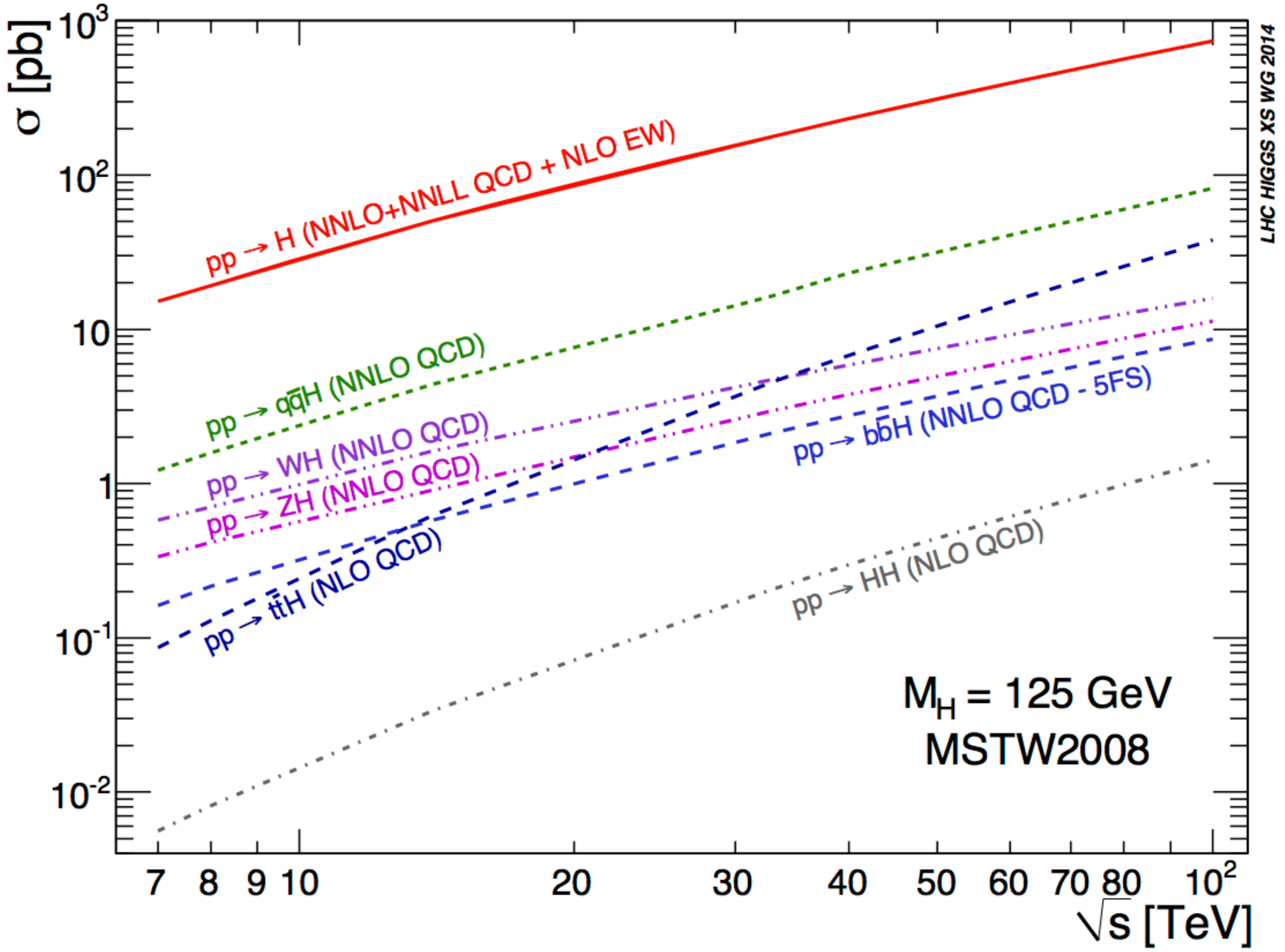
The ECFA Higgs@Future Report



At lepton colliders, double Higgs-strahlung, $e+e- \to ZHH$, gives stronger constraints on positive deviations ($\varkappa 3 > 1$), while VBF is better in constraining negative deviations, ($\varkappa 3 < 1$). While at HL-LHC, values of $\varkappa 3 > 1$, as expected in models of strong first order phase transition, result in a smaller double-Higgs production cross section due to the destructive interference, at lepton colliders for the *ZHH* process they actually result in a larger cross section, and hence into an increased precision. For instance at ILC_{500}, the sensitivity around the SM value is 27% but it would reach 18% around $\varkappa_3 = 1.5$.

This figure applies ONLY for $\lambda = \lambda_{SM}$
no studies of BSM case apart from ILC

Di-Higgs Production Cross sections - pp



dependence on ECM:
14 TeV -> 100 TeV : ~40 x larger cross section
14 TeV -> 38 TeV: ~8 x larger cross section

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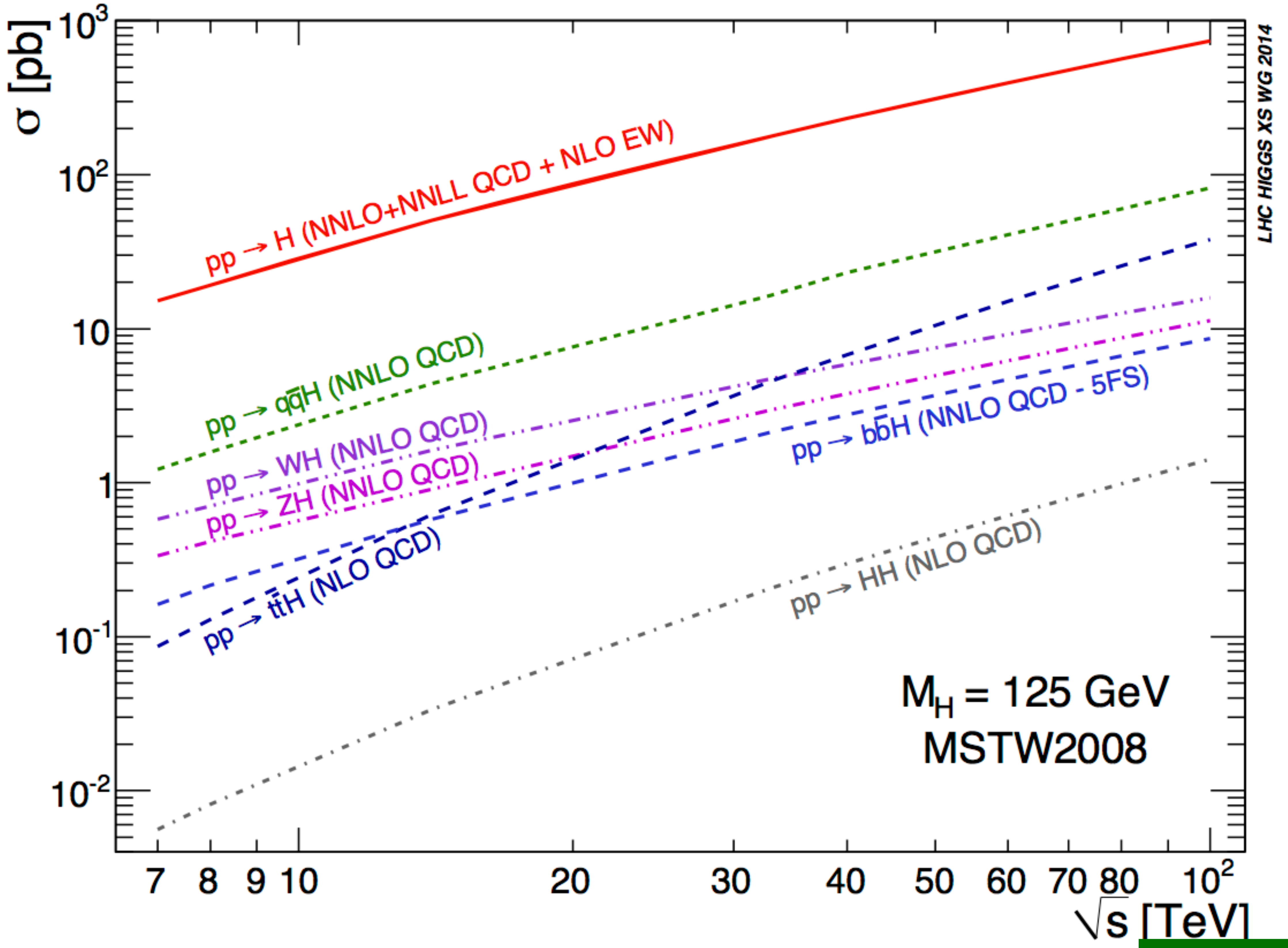

differential distributions!

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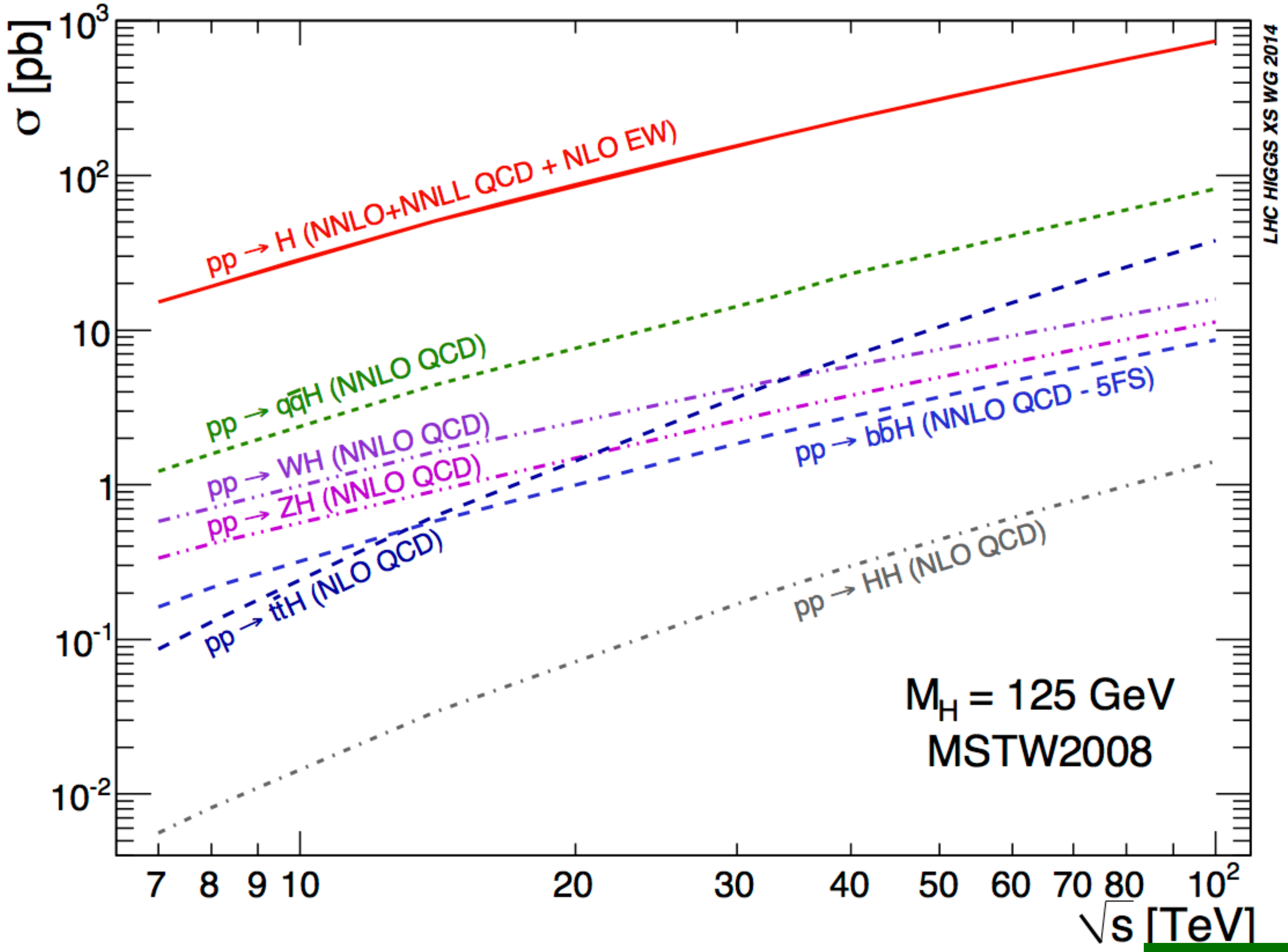

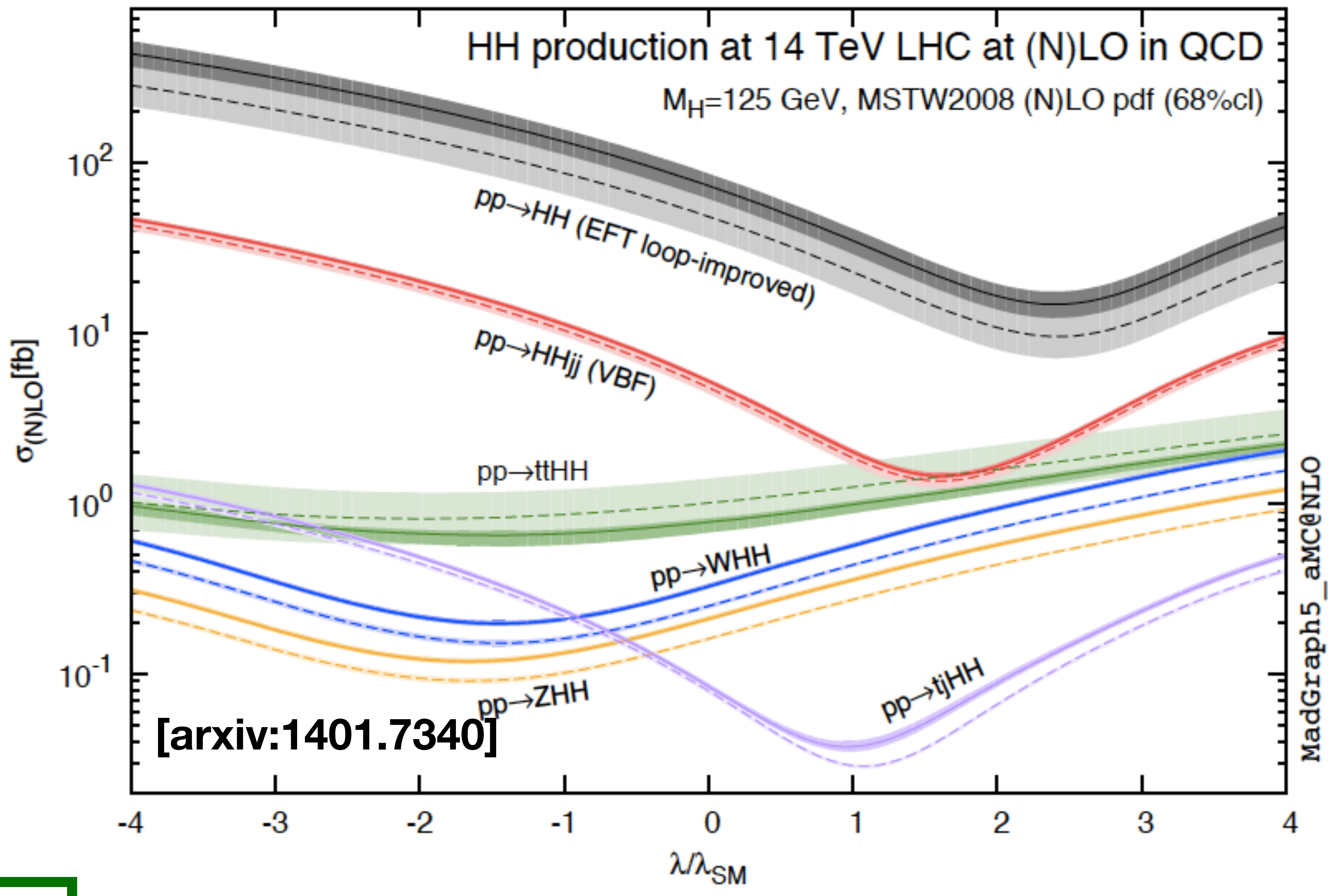

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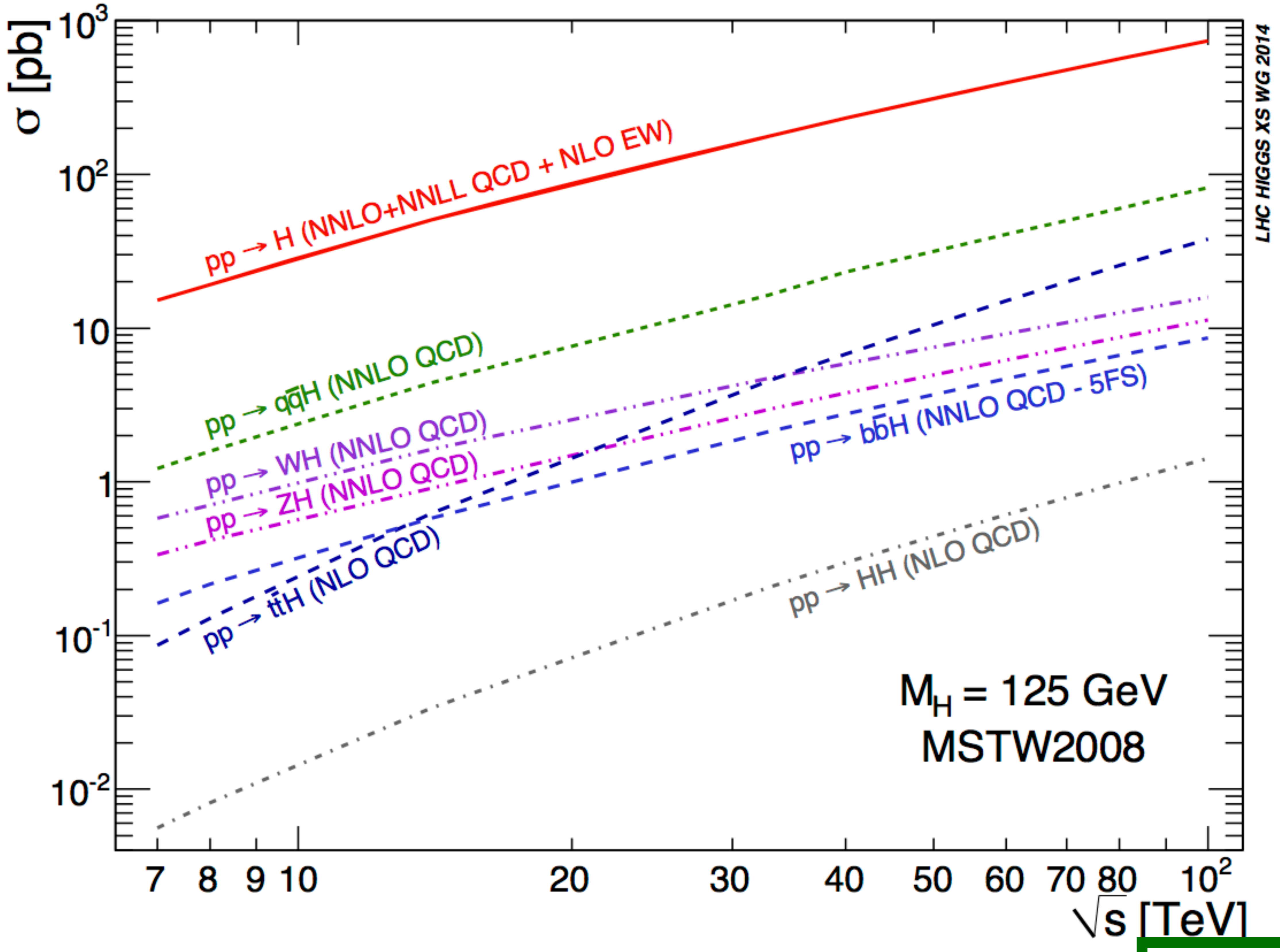

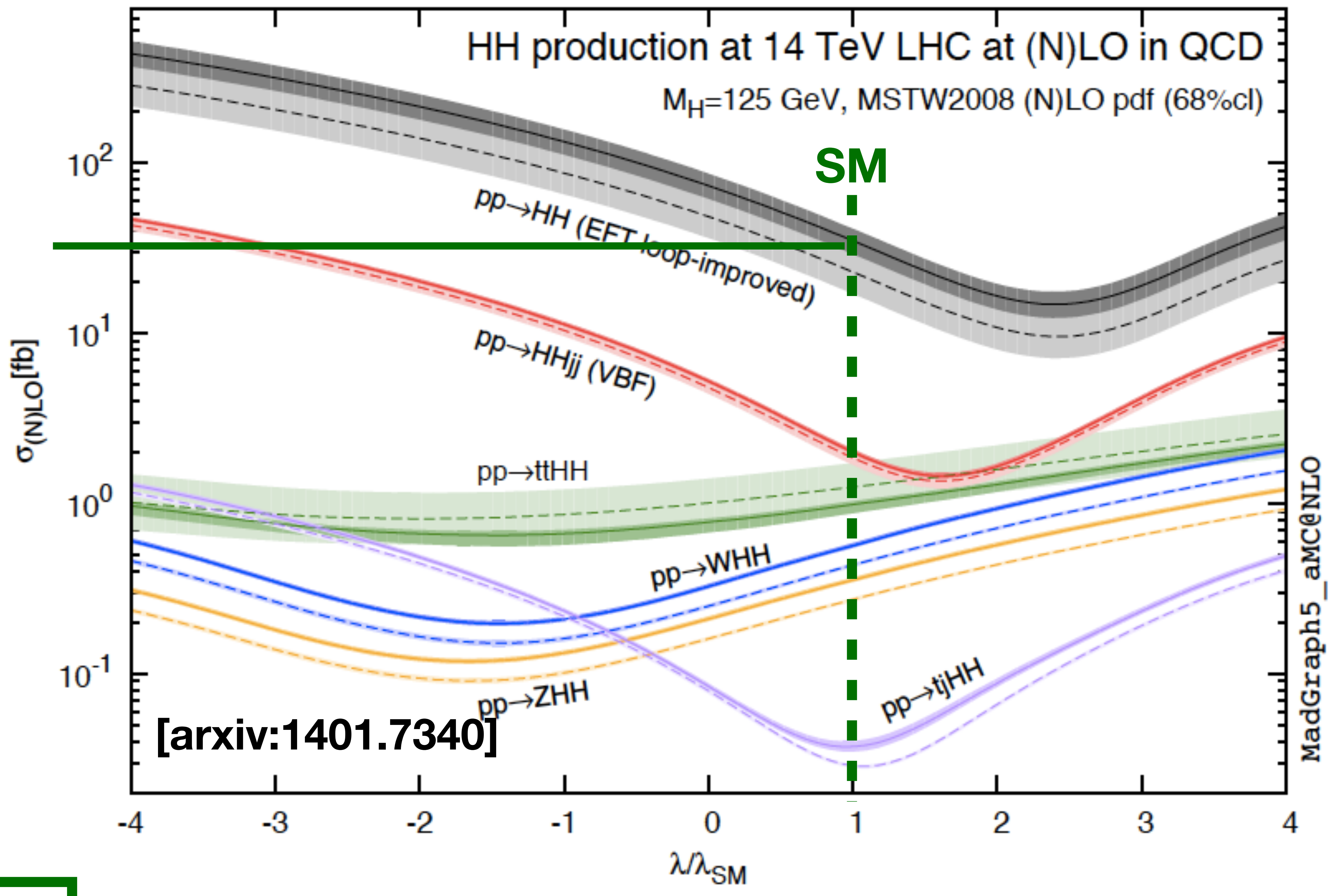

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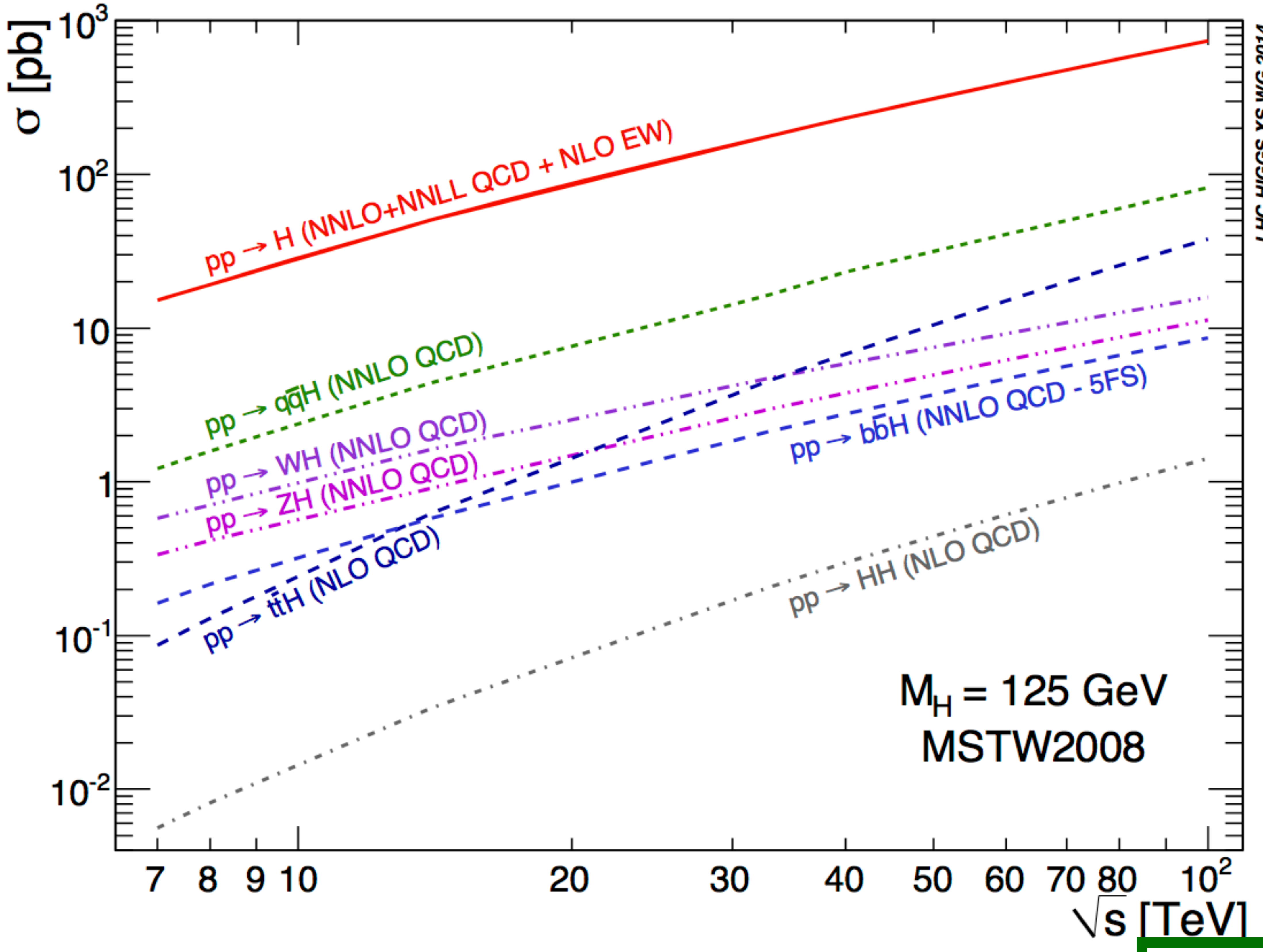

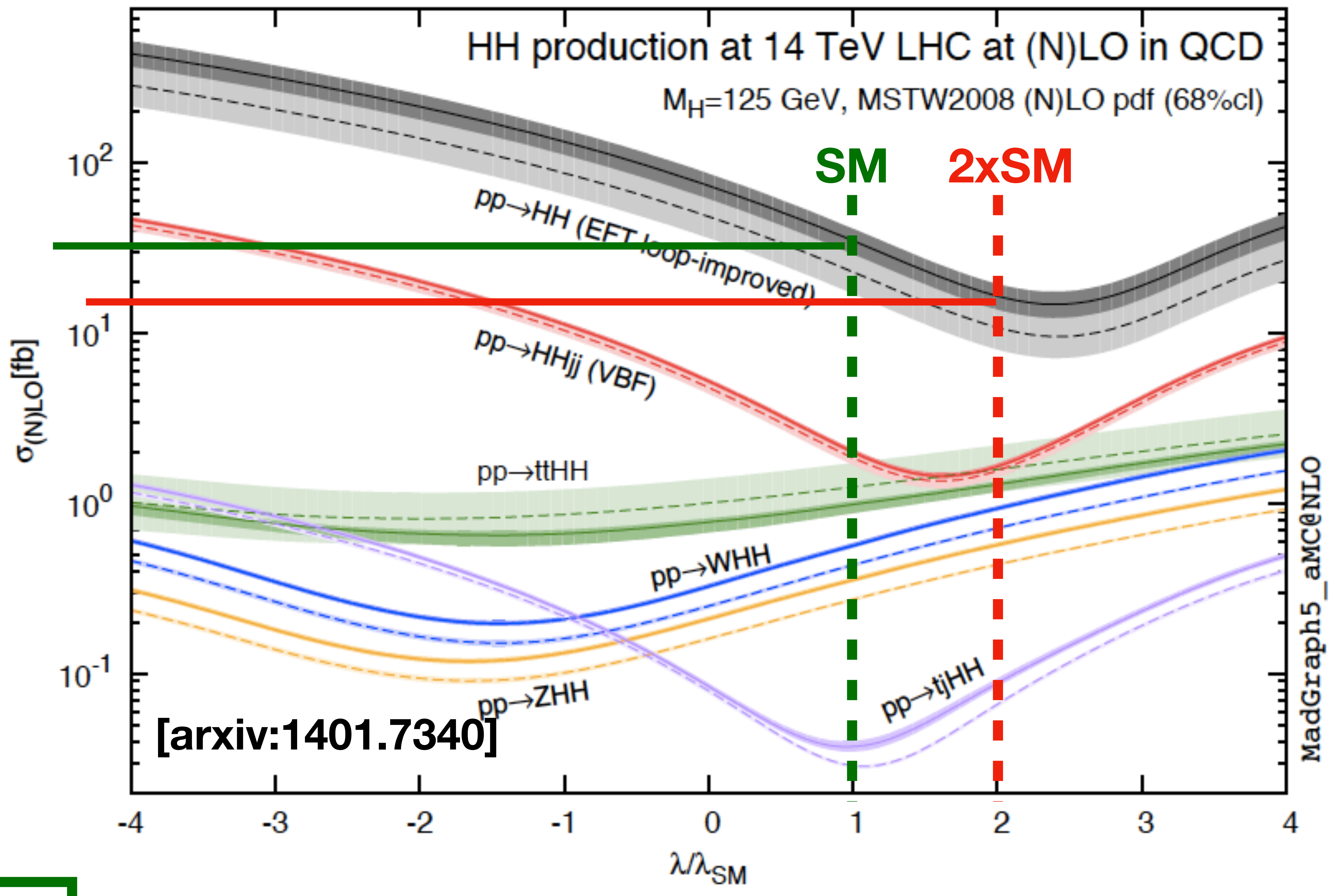

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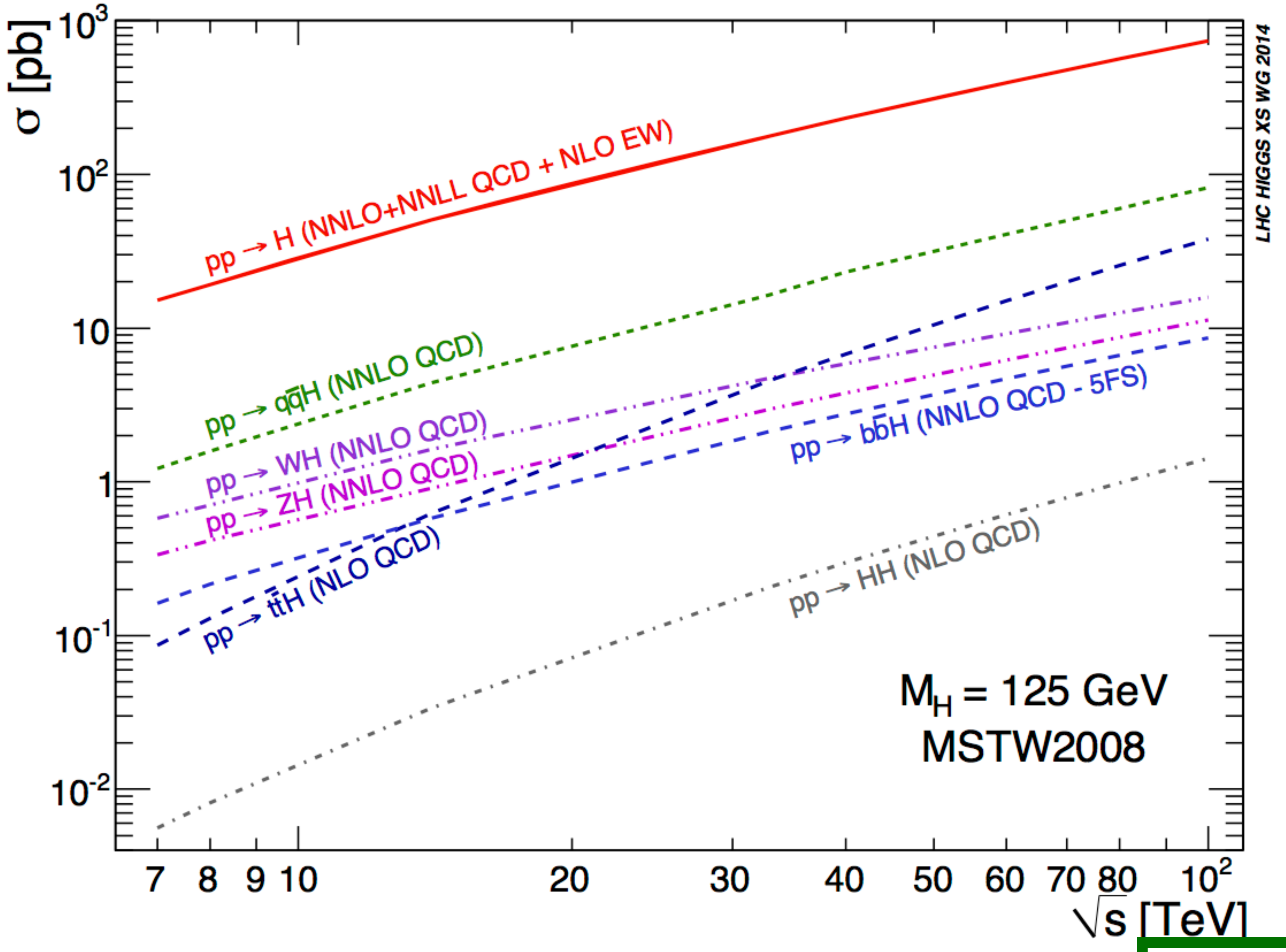

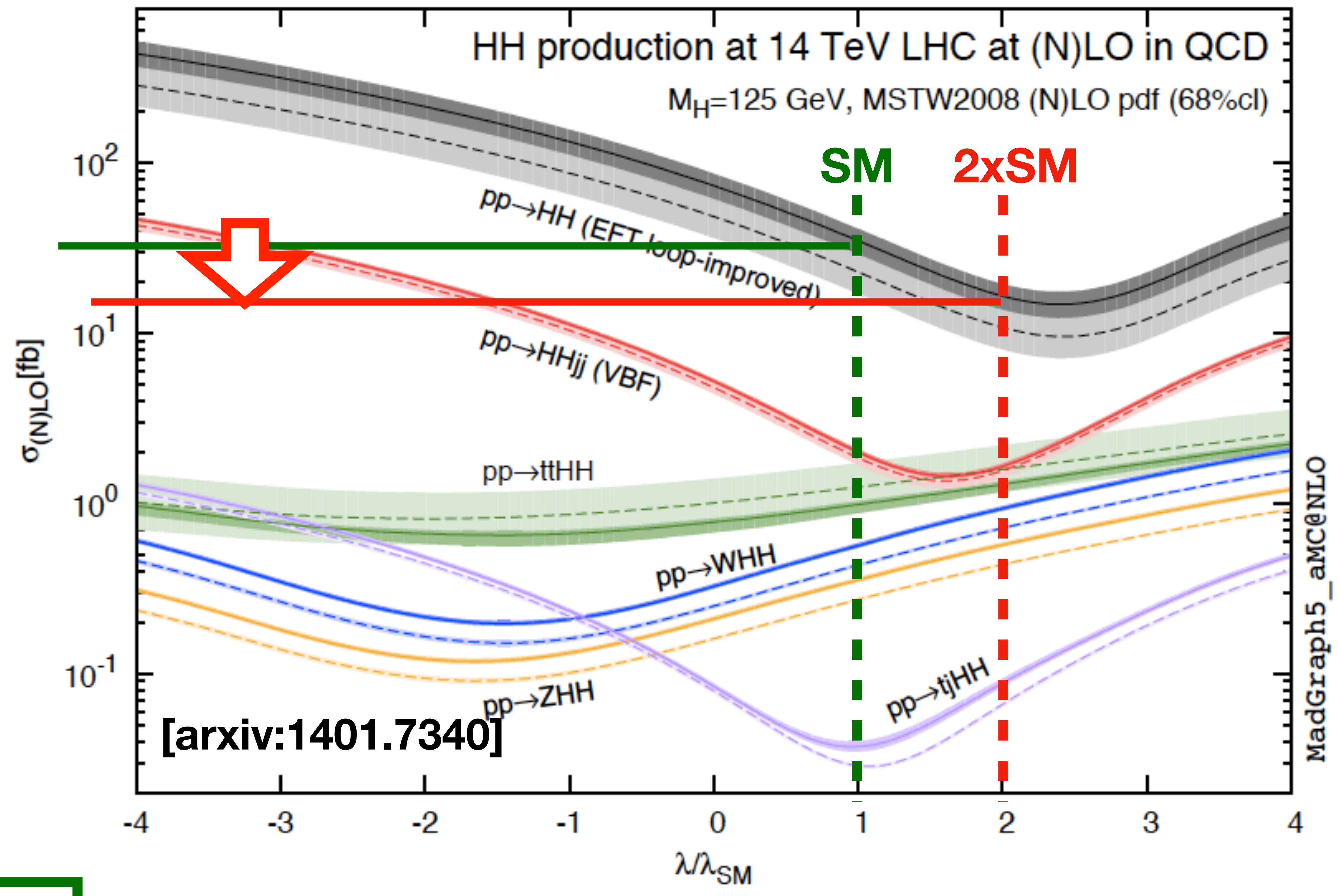

differential distributions!

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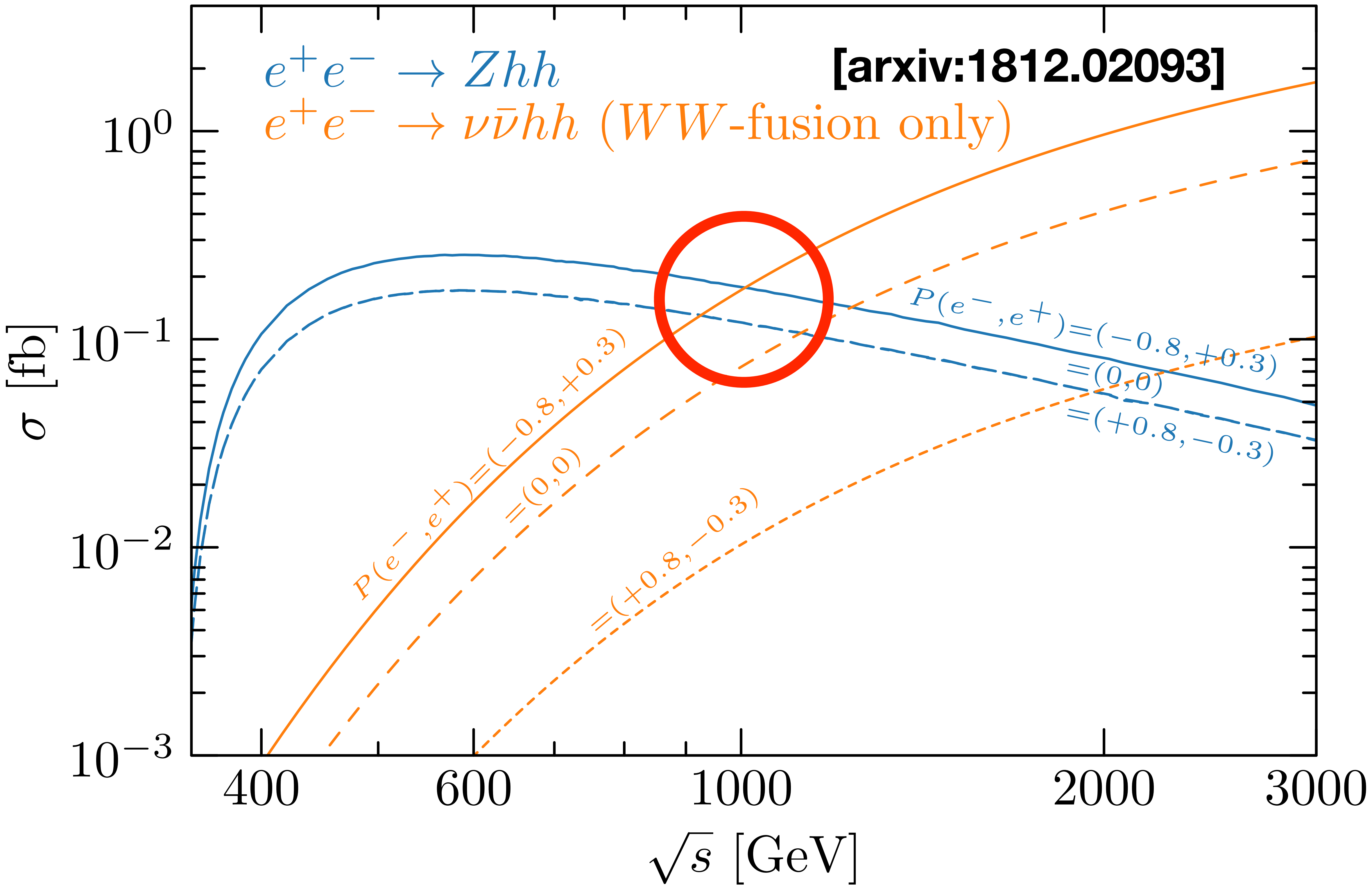
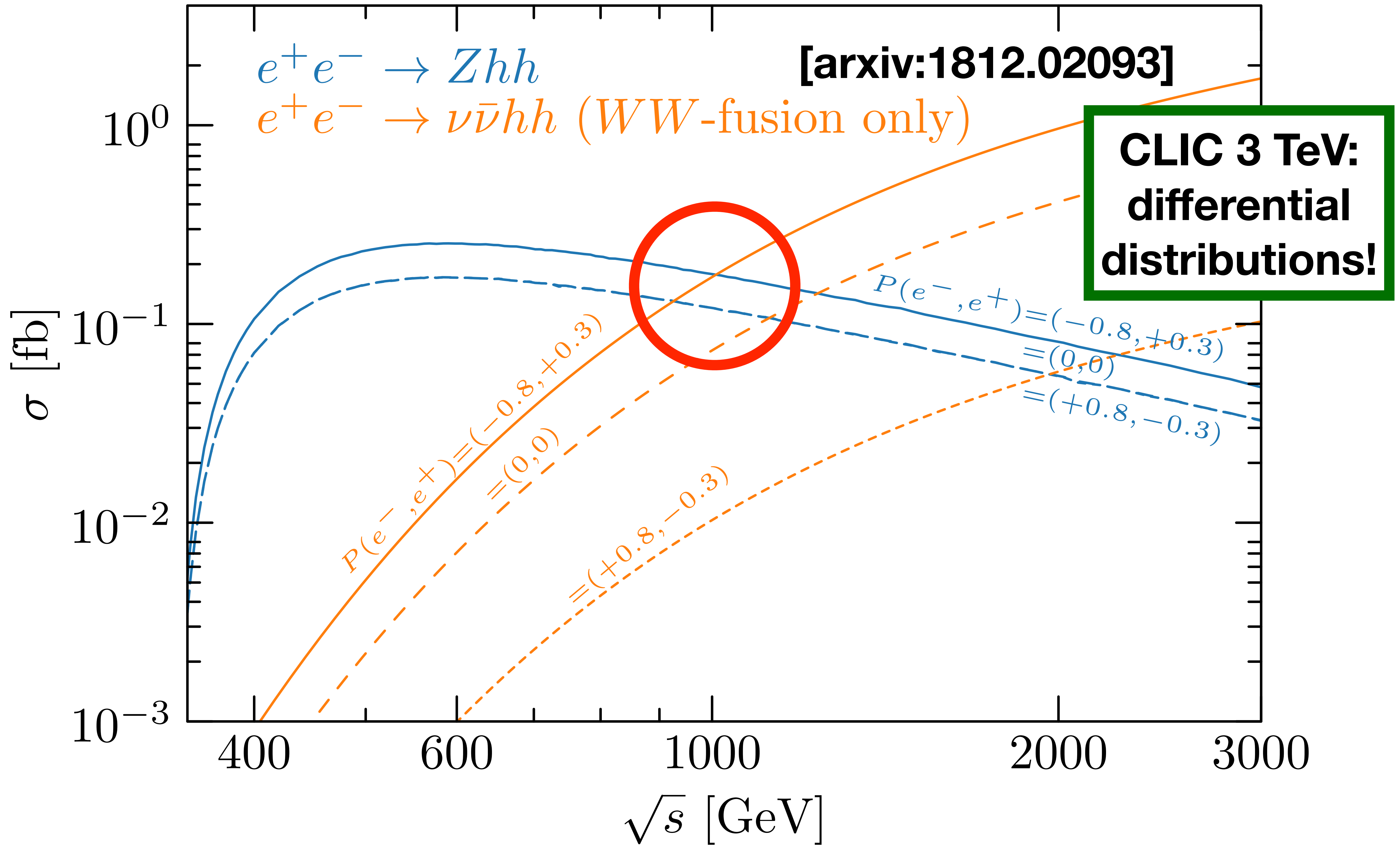
dependence on λ:
$\lambda > \lambda_{SM}$: cross section drops,
i.e. by factor ~2 for $\lambda = 2\,\lambda_{SM}$

Di-Higgs Production Cross sections - ee



ZHH: P(-80%,+30%) and P(+80%,-30%)
give about equal sensitivity
vvHH (fusion): effectively only P(-80%) counts

Di-Higgs Production Cross sections - ee



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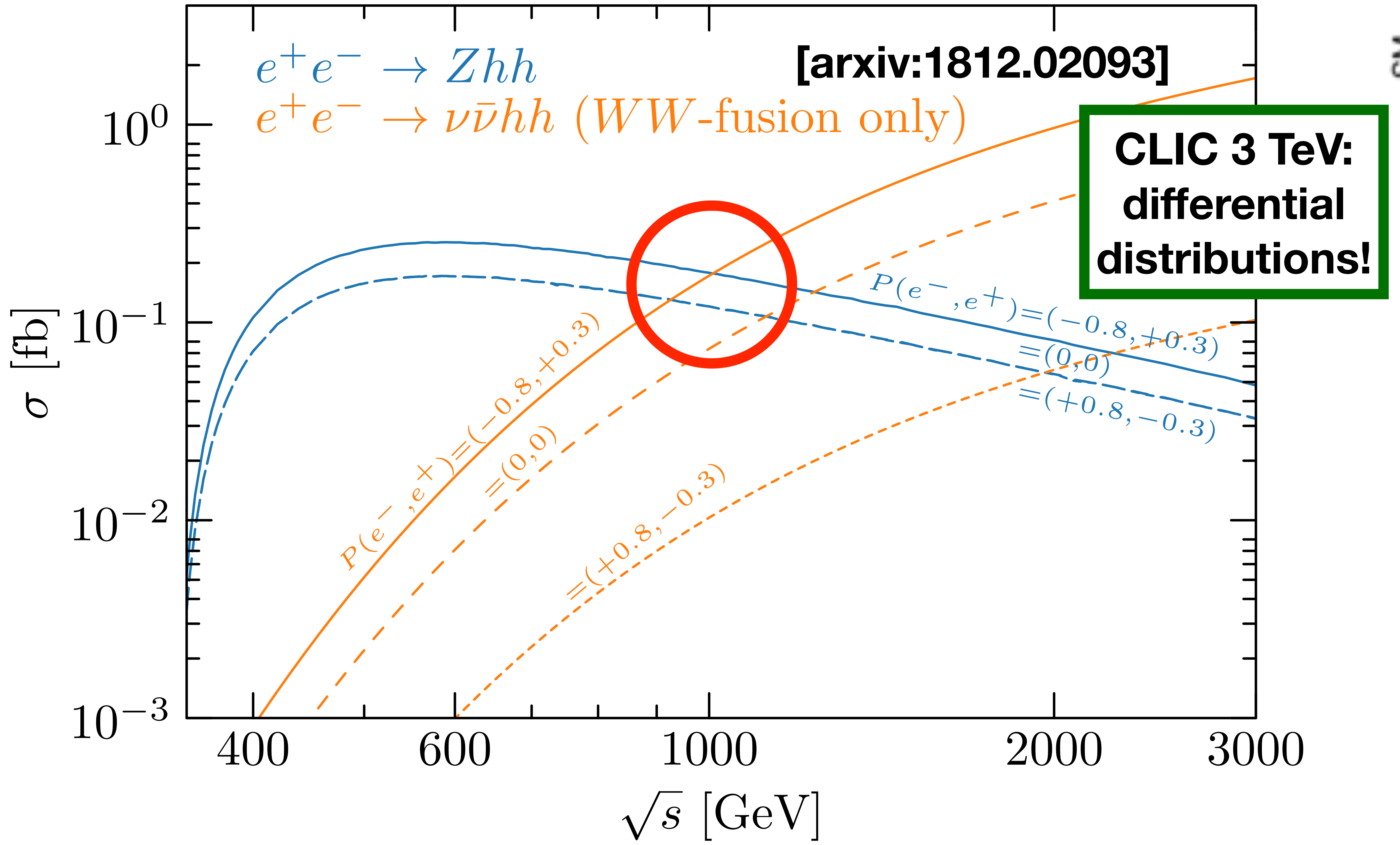
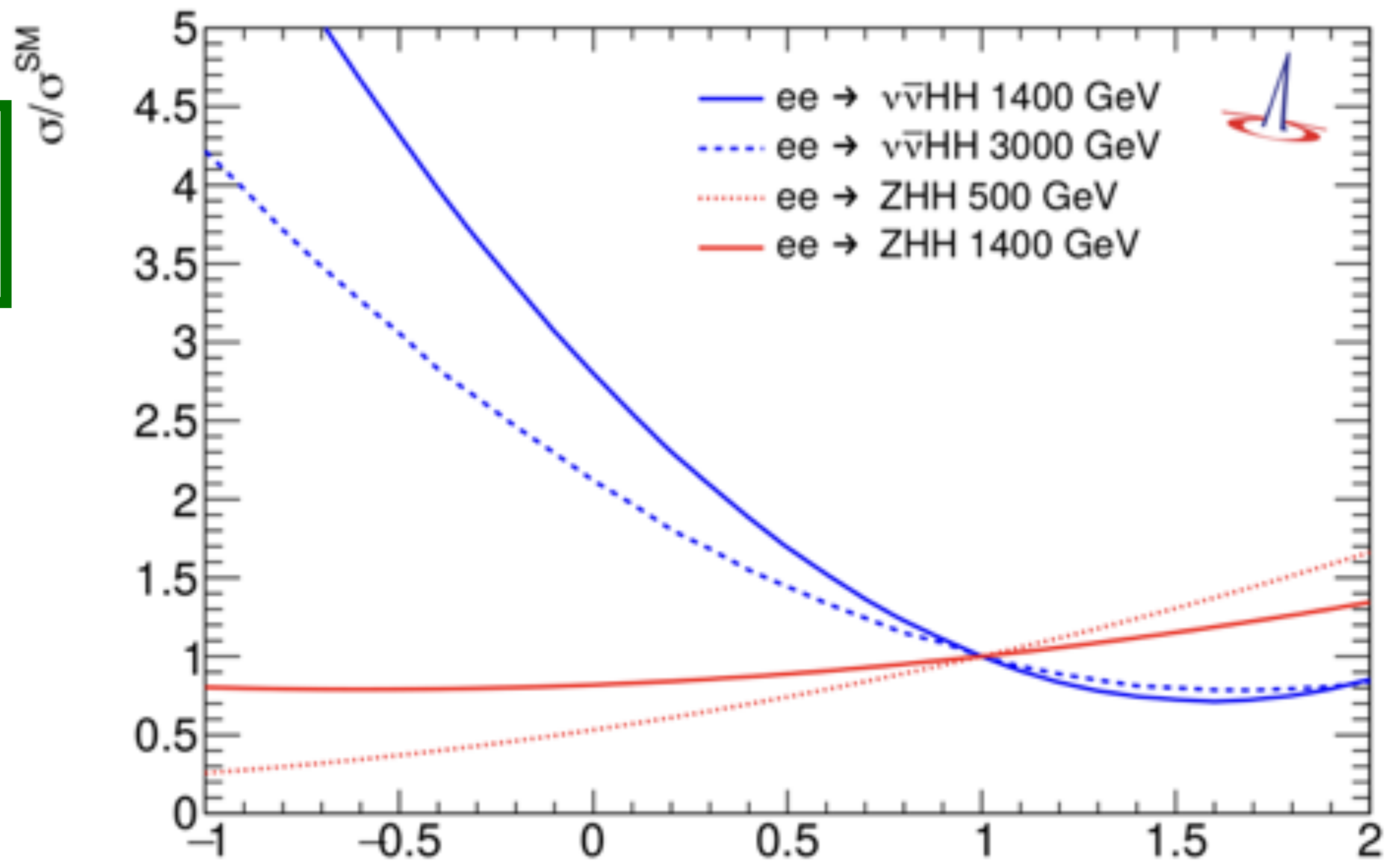


[J.Reuter]



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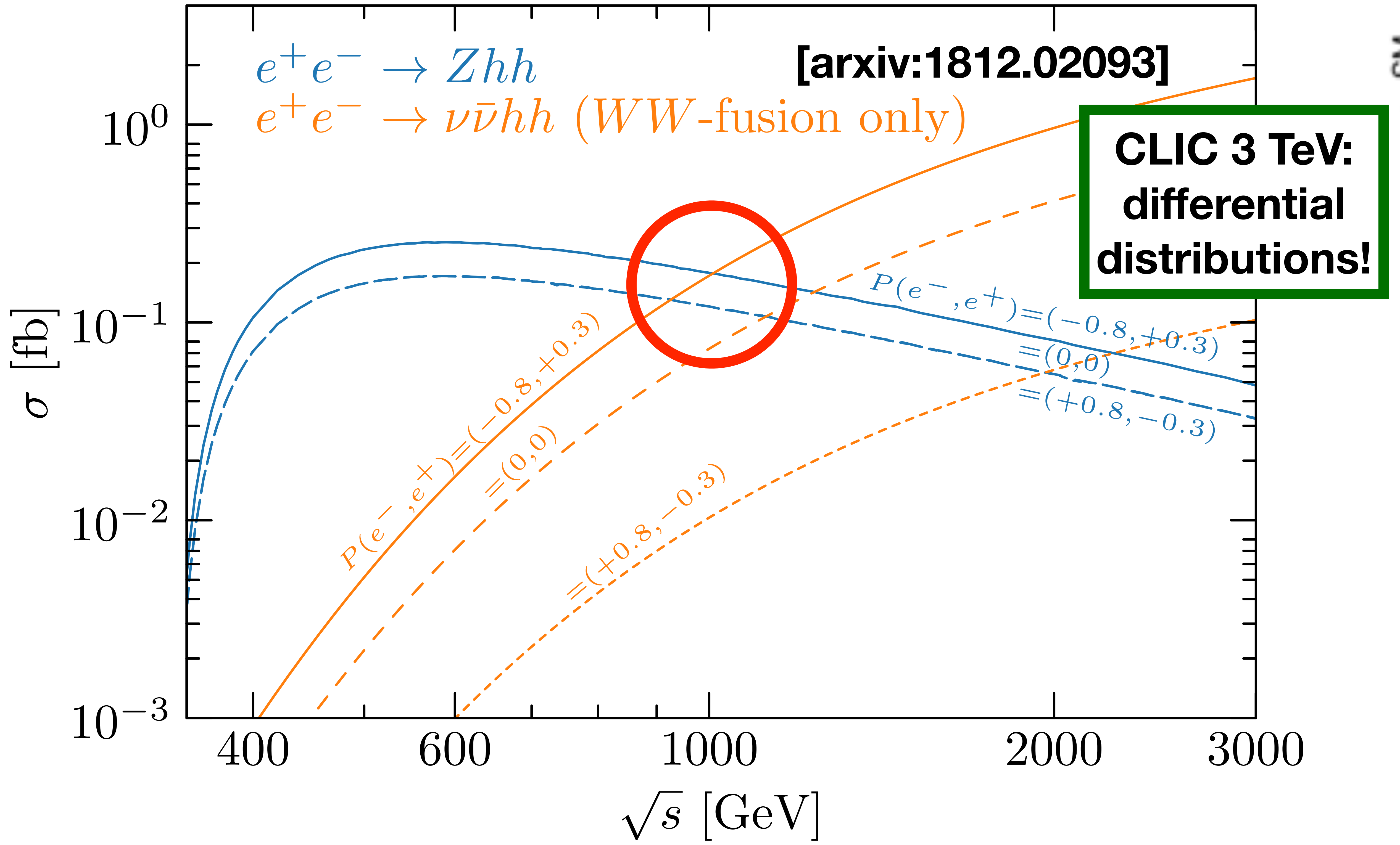

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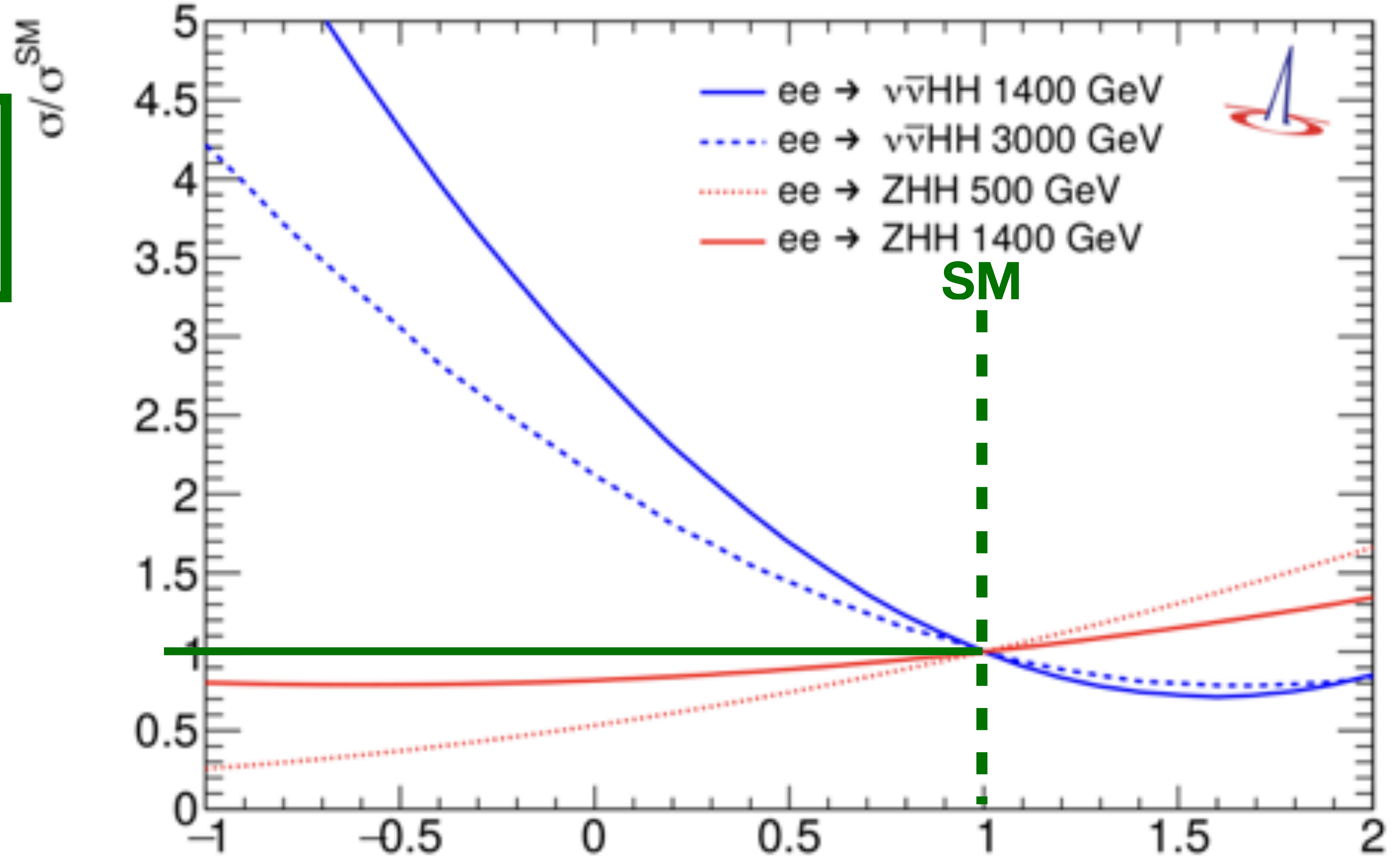

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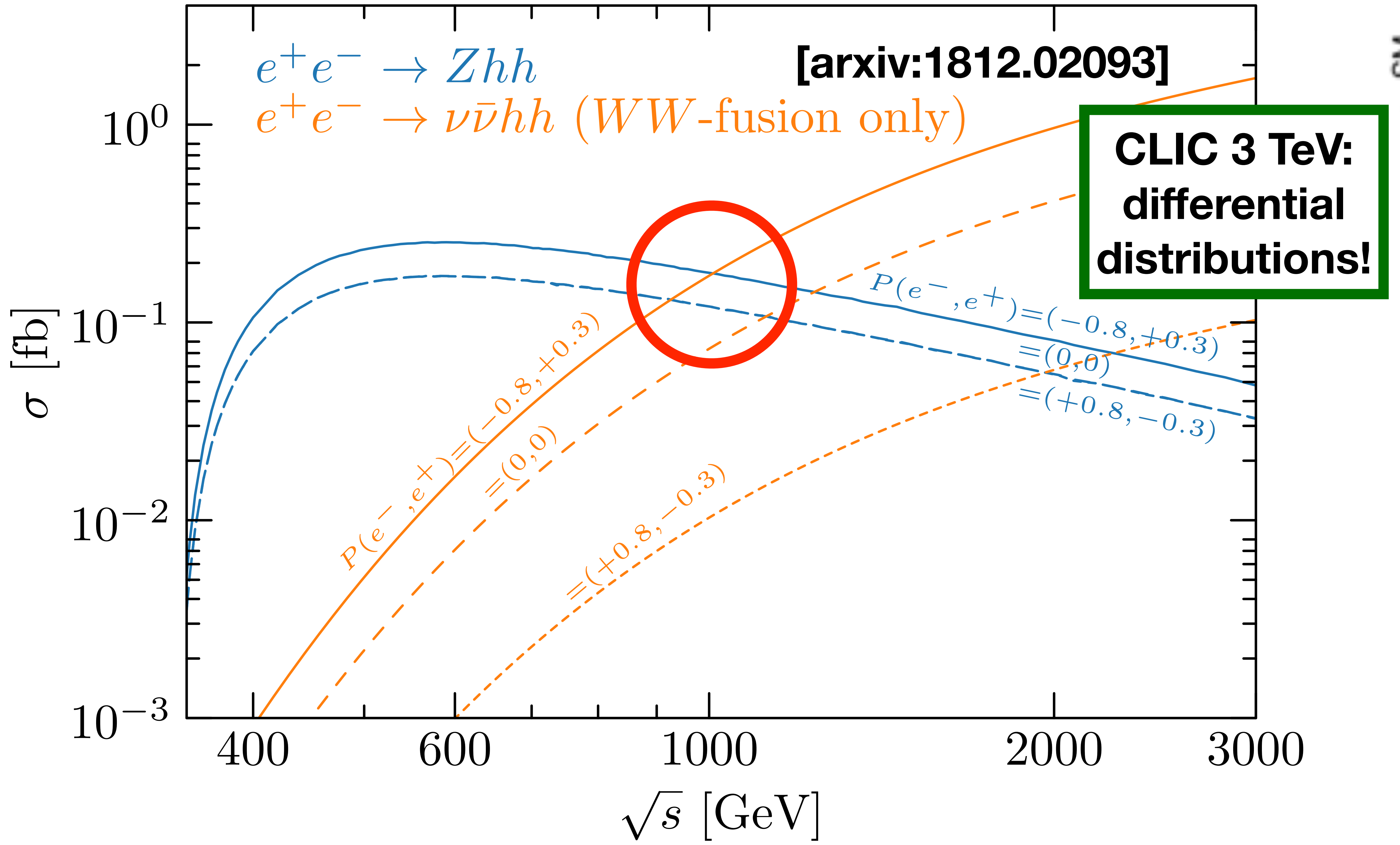

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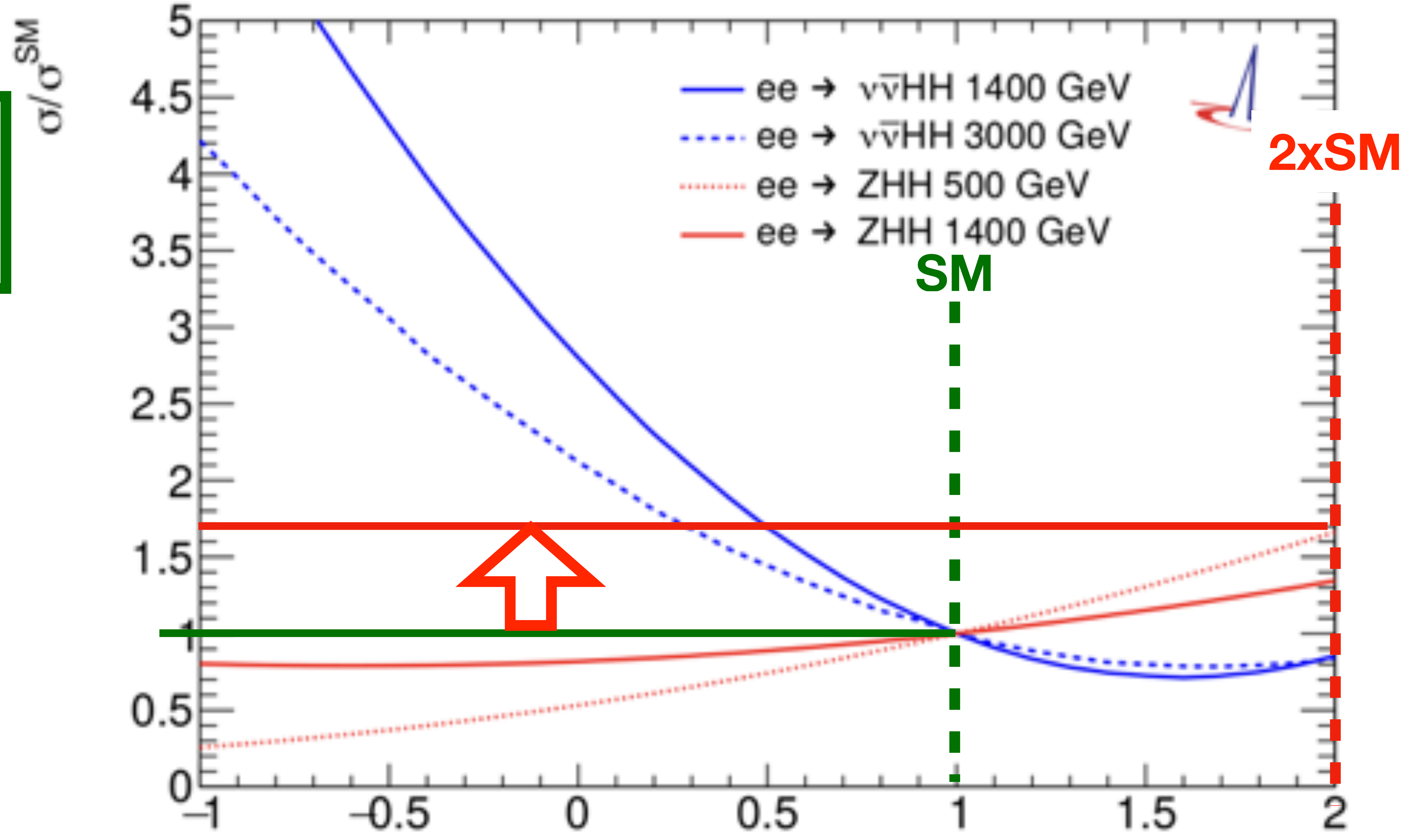

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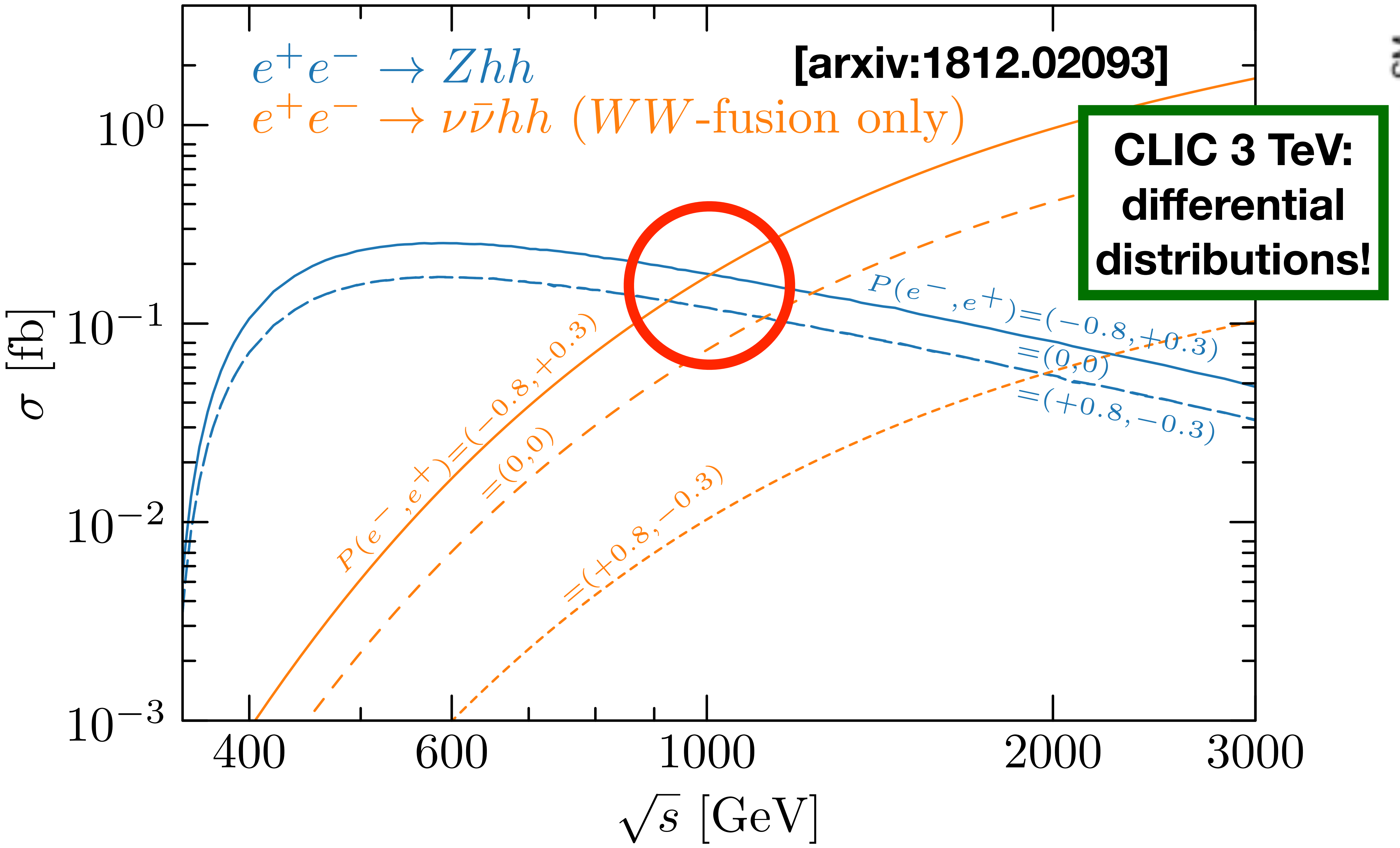

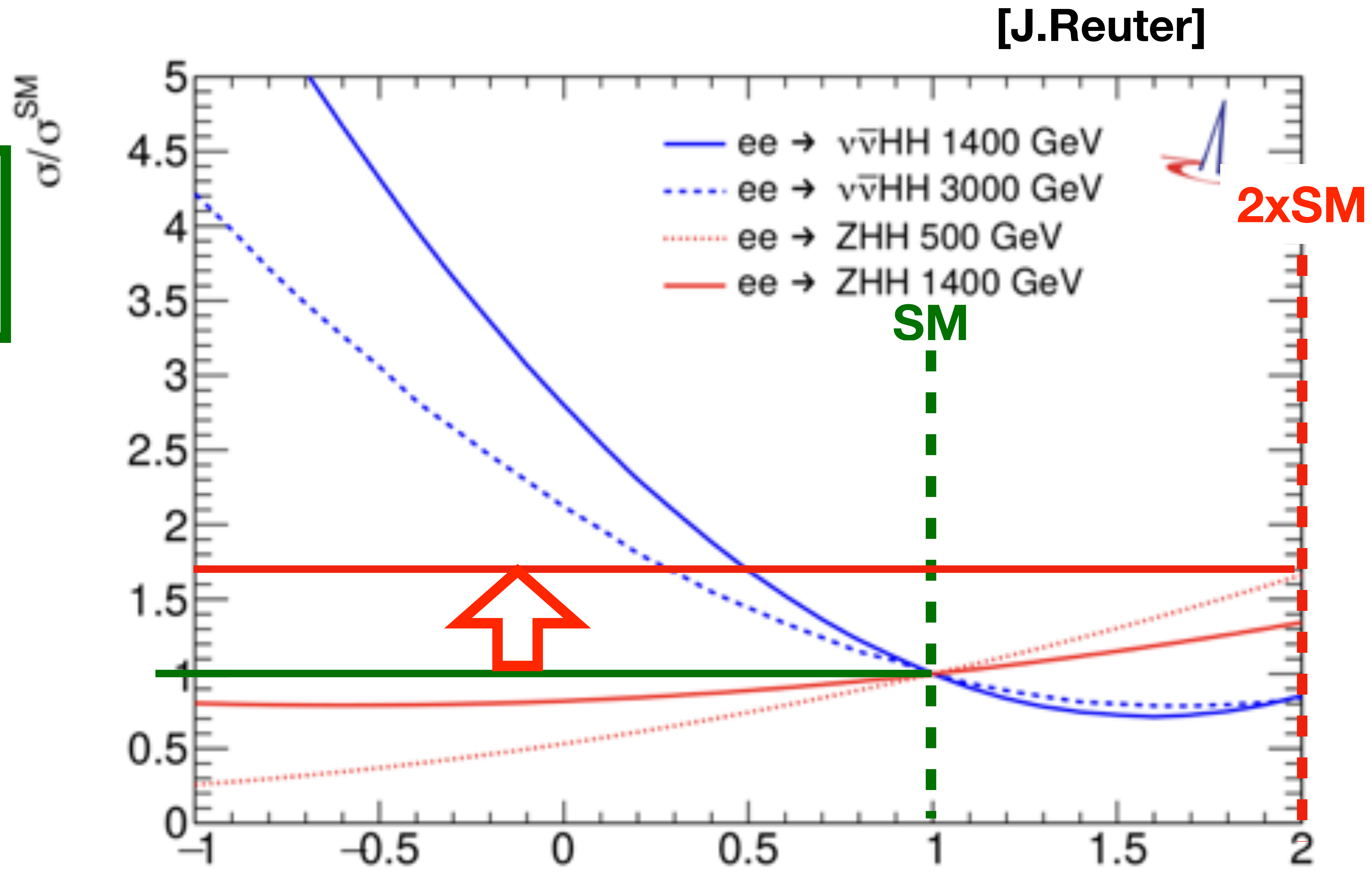

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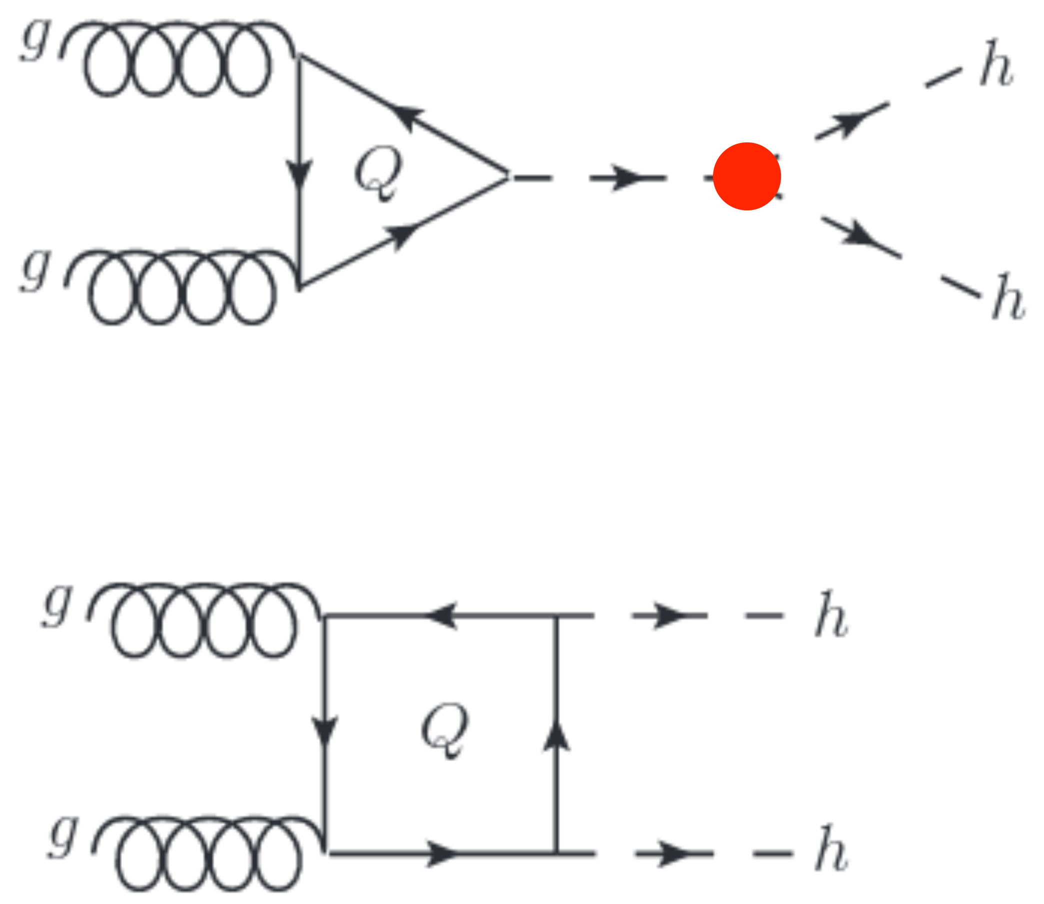
=> VBF(ee/pp)- and Higgsstrahlung (ee) di-Higgs production have orthogonal BSM behaviour

From di-Higgs production to λ

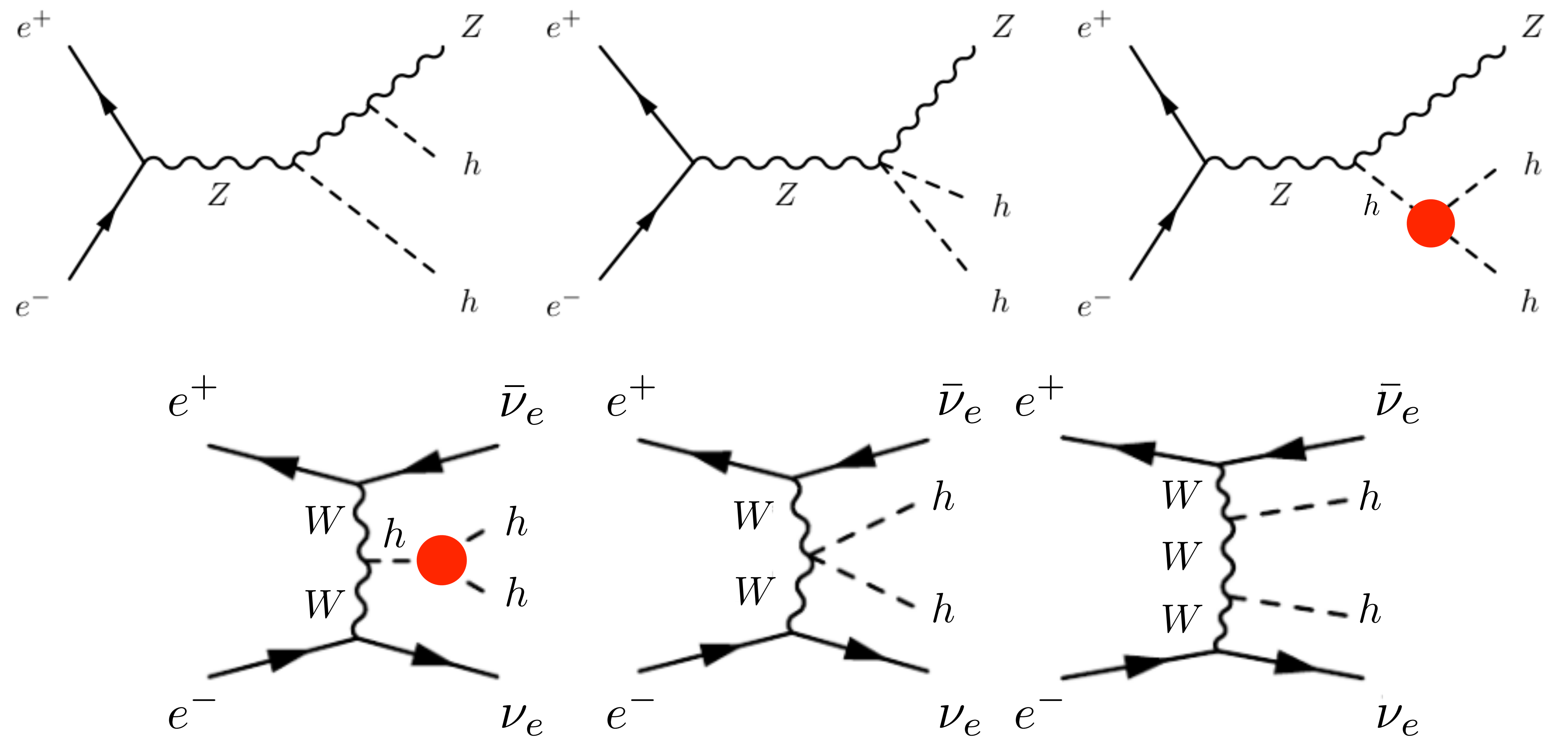
1. Discover di-Higgs production
2. Measure cross section (total and differential!)
3. Extract λ

- Interference of diagrams with / without triple Higgs vertex
  => **k:= (δλ/λ)/(δσ/σ) > 1/2**
- k can be "improved" by using *differential* information
- **k depends on: process, *value of λ* and *E_{CM}***

Hadron collider



Lepton collider



ILC Sensitivity vs Lambda

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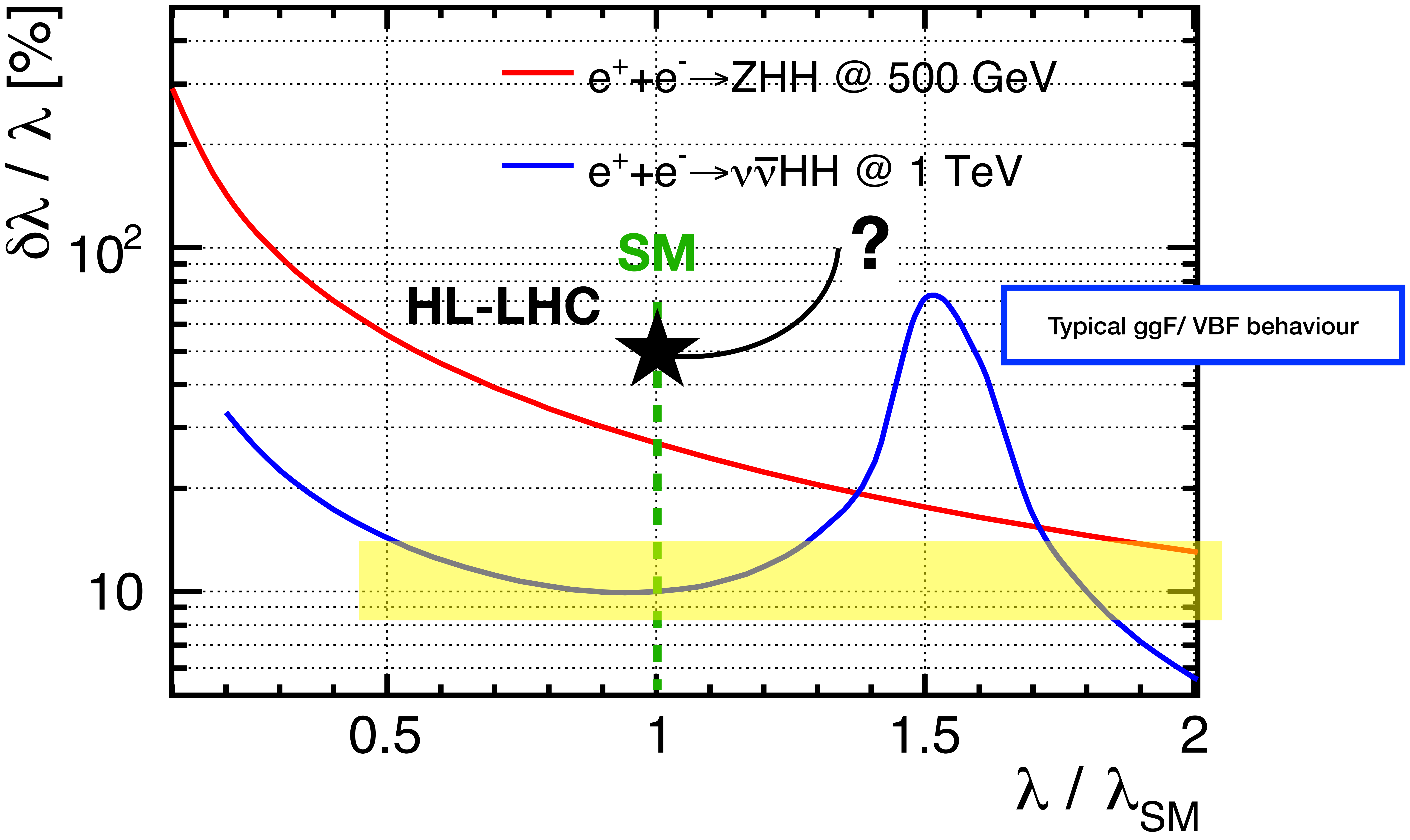
[J.Tian, C.Duerig]



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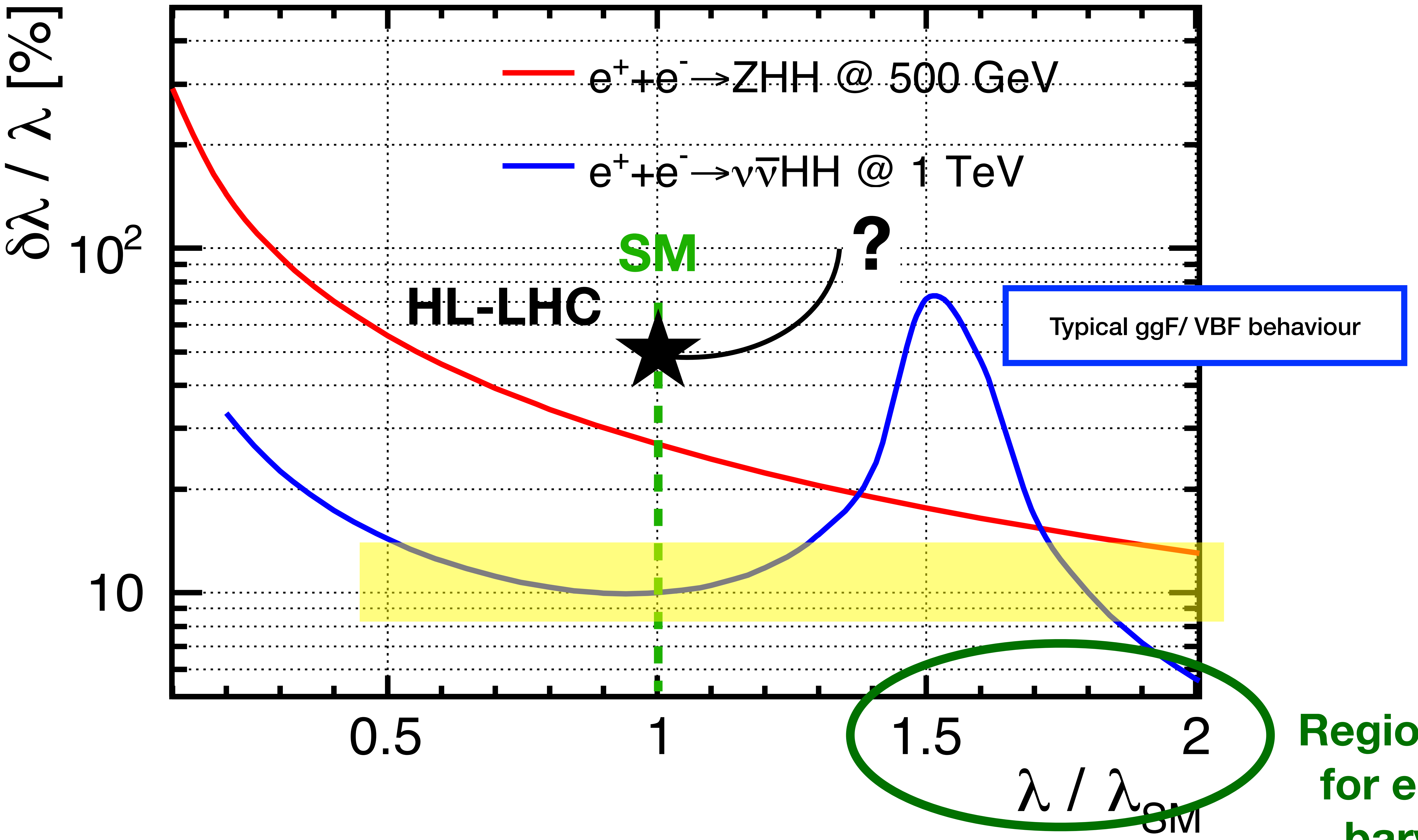
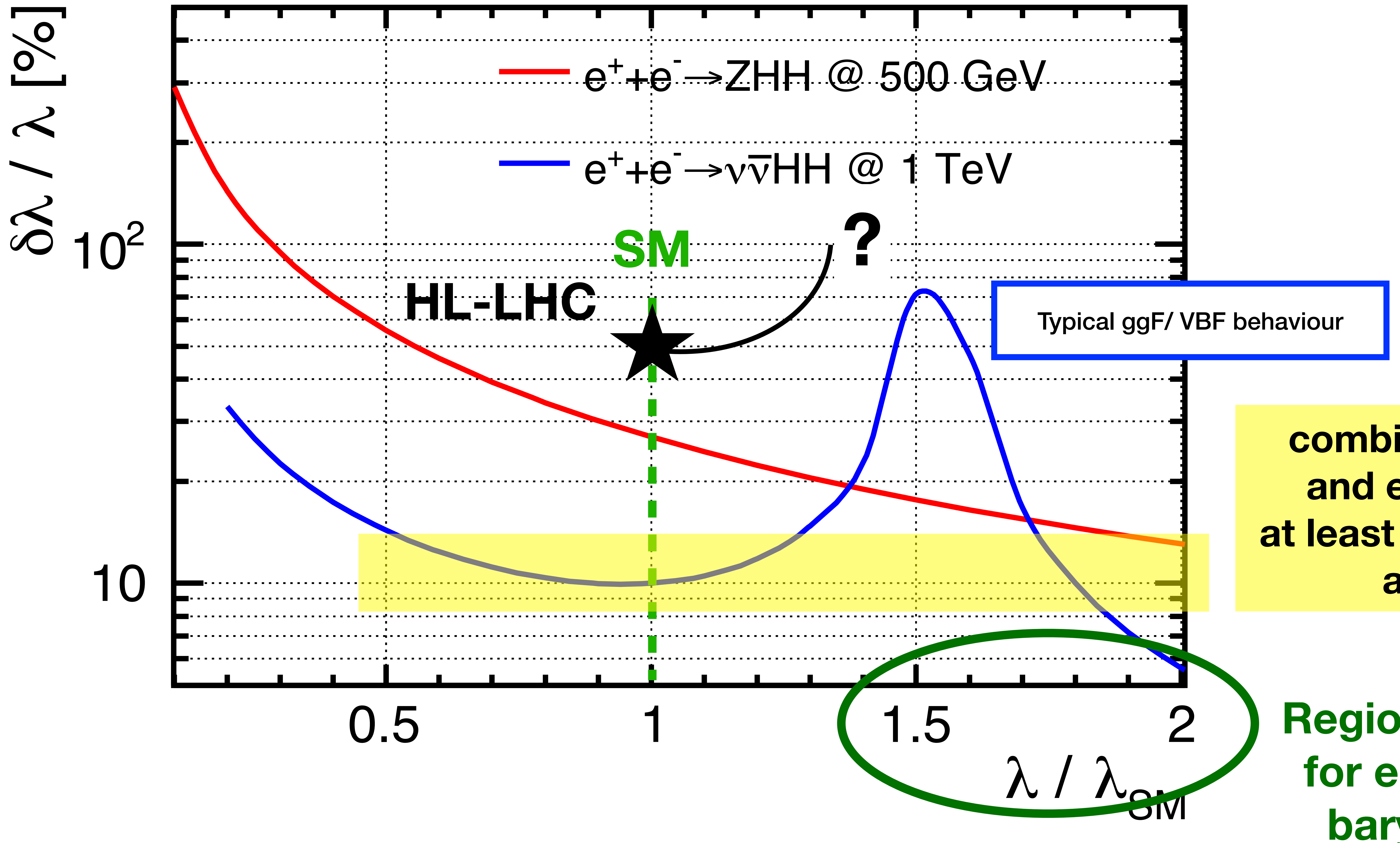


Region of interest for electroweak baryogenesis

ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]

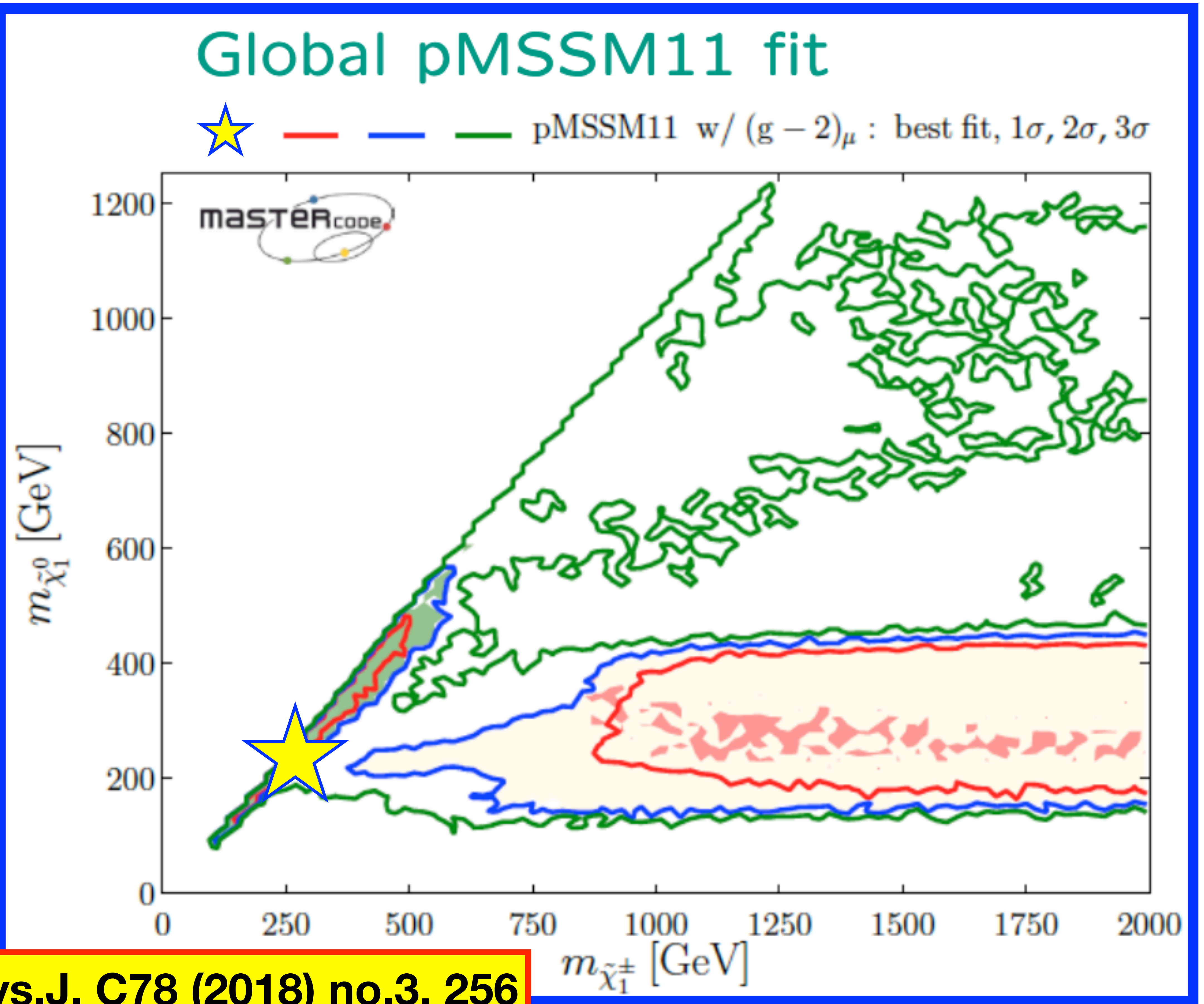


combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision over a wide range in λ

Region of interest for electroweak baryogenesis

Higgsinos ?

- **lowish ΔM is THE region preferred by data, e.g. for charginos & neutralinos**
  => no *general* limit above LEP



Eur.Phys.J. C78 (2018) no.3, 256

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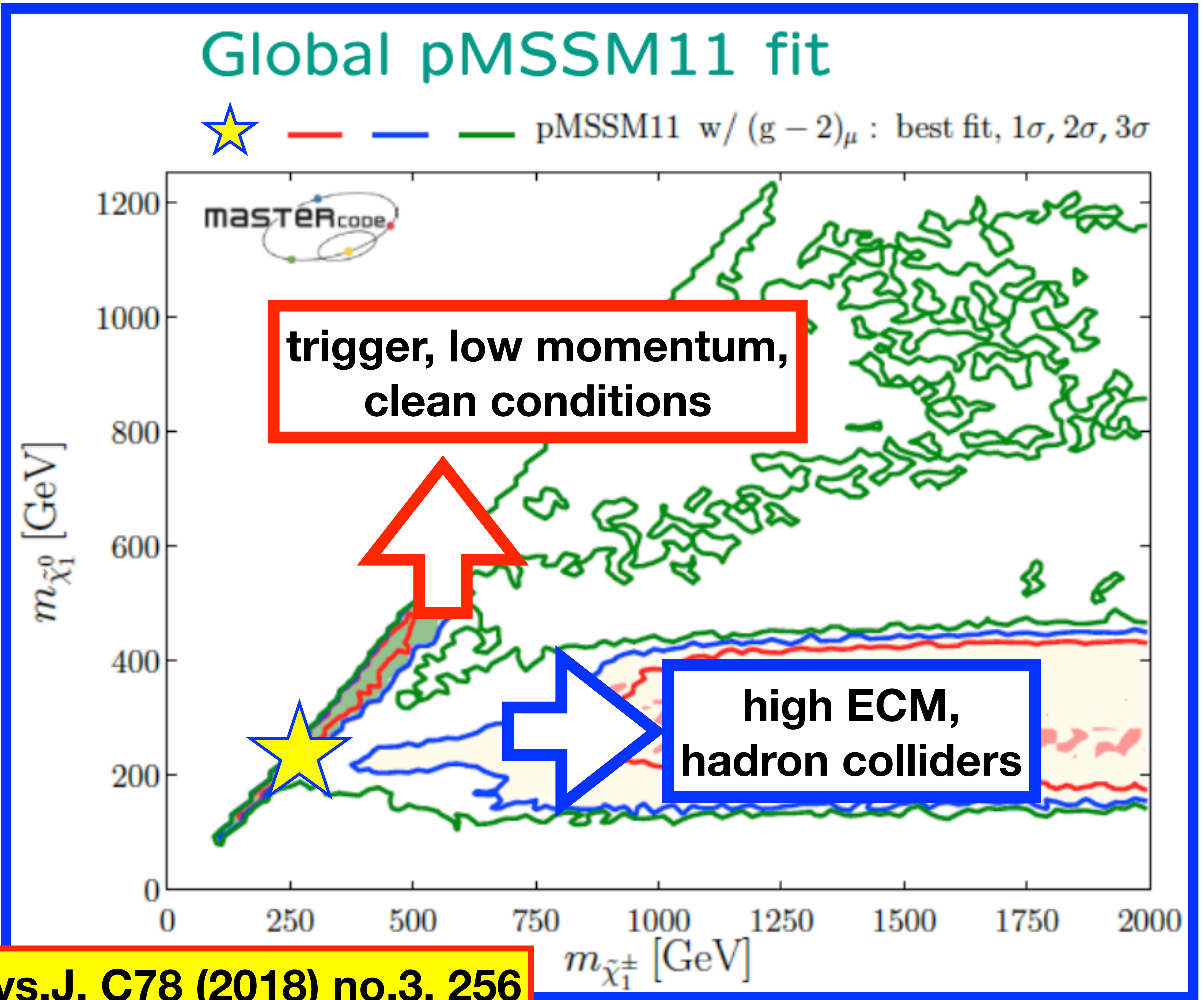

Eur.Phys.J. C78 (2018) no.3, 256

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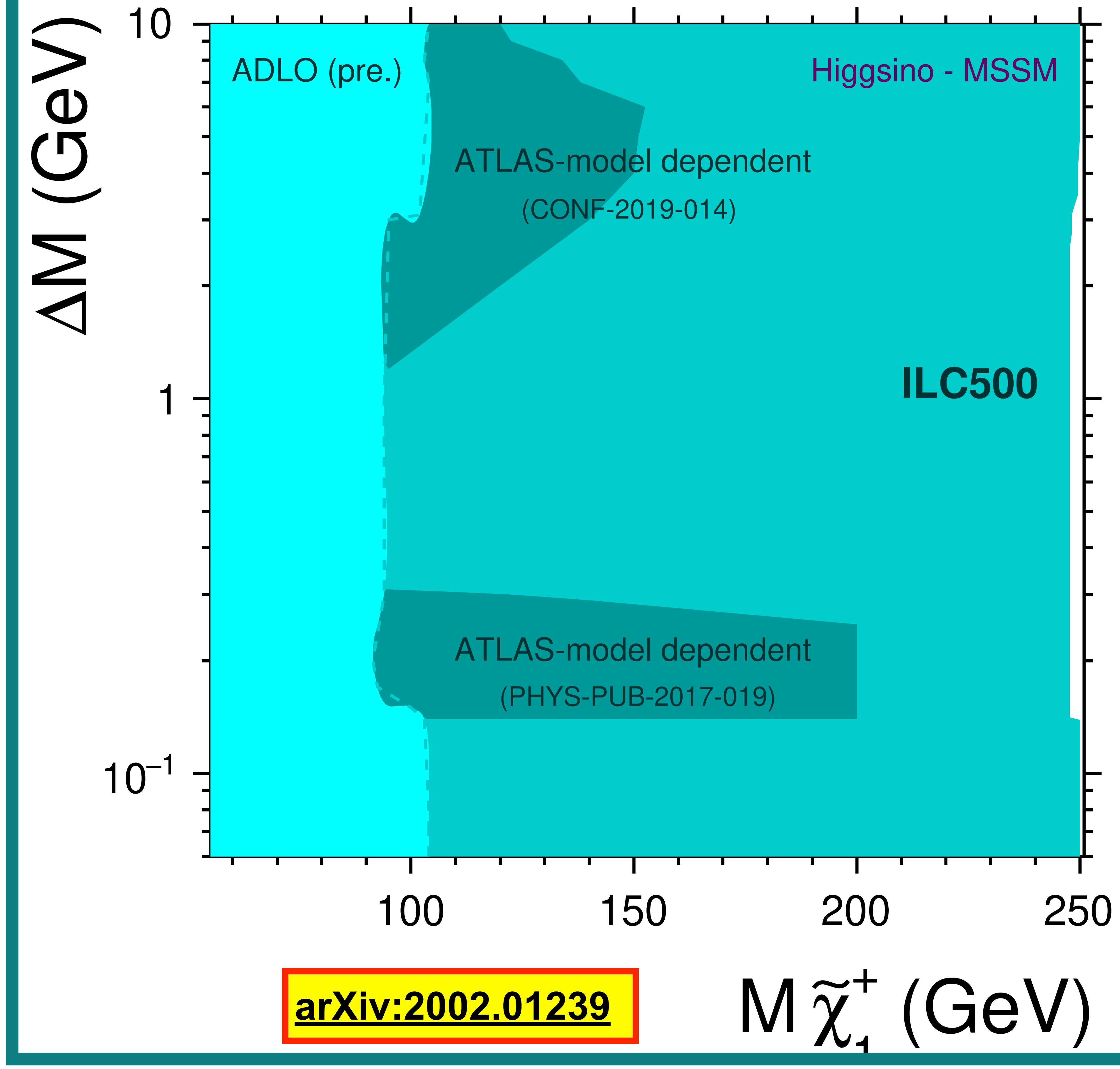
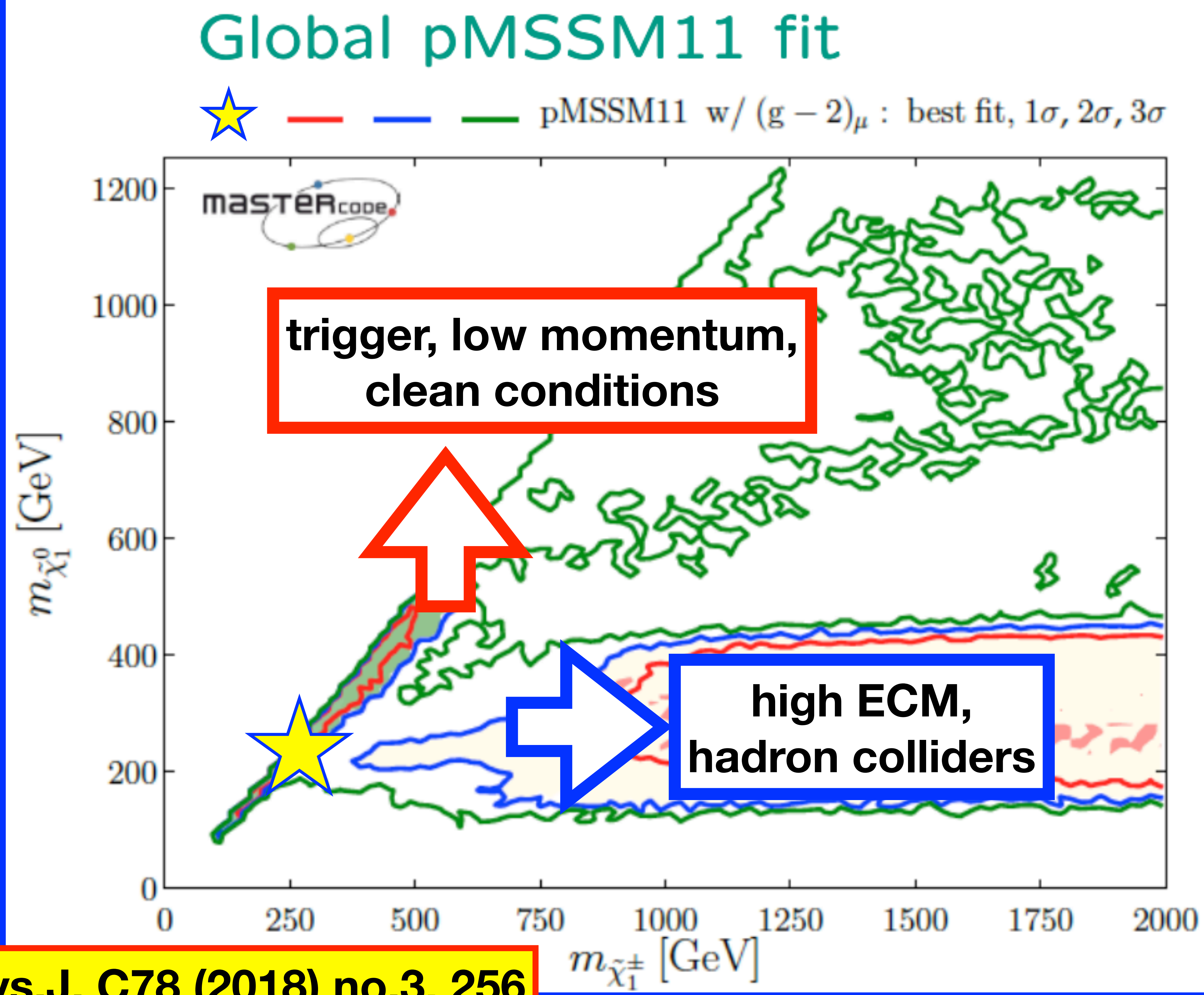


arXiv:2002.01239



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Join the Team!

How to contribute

- **want to get involved?**
  - **ECFA set up a workshop series on Physics, Experiments and Detectors at a Higgs, Top and Electroweak factory cf https://indico.cern.ch/event/1044297/**
    - main focus: topics in common between all e^+e^- colliders: theory prediction, assessment of systematic uncertainties, software tools
    - topical workshops, seminar series, tutorials, mailing lists -> will give input to next round of ESU
    - **if you don't won't to commit to a specific collider project / detector concept => this is your way to contribute => get in touch!**
  - **Project specific, eg detector specific questions -> contact e.g. ILC:**
    - ILC Study Questions: arXiv:2007.03650
    - check presentation of the Physics & Detector WG of the ILC International Development Team at LCWS
    - sign-up for the topical group mailing lists: https://agenda.linearcollider.org/event/9154/
- **In either case, you're welcome to drop me an email: jenny.list@desy.de**

ILC running modes - and Z production

ILC e^+e^- collider

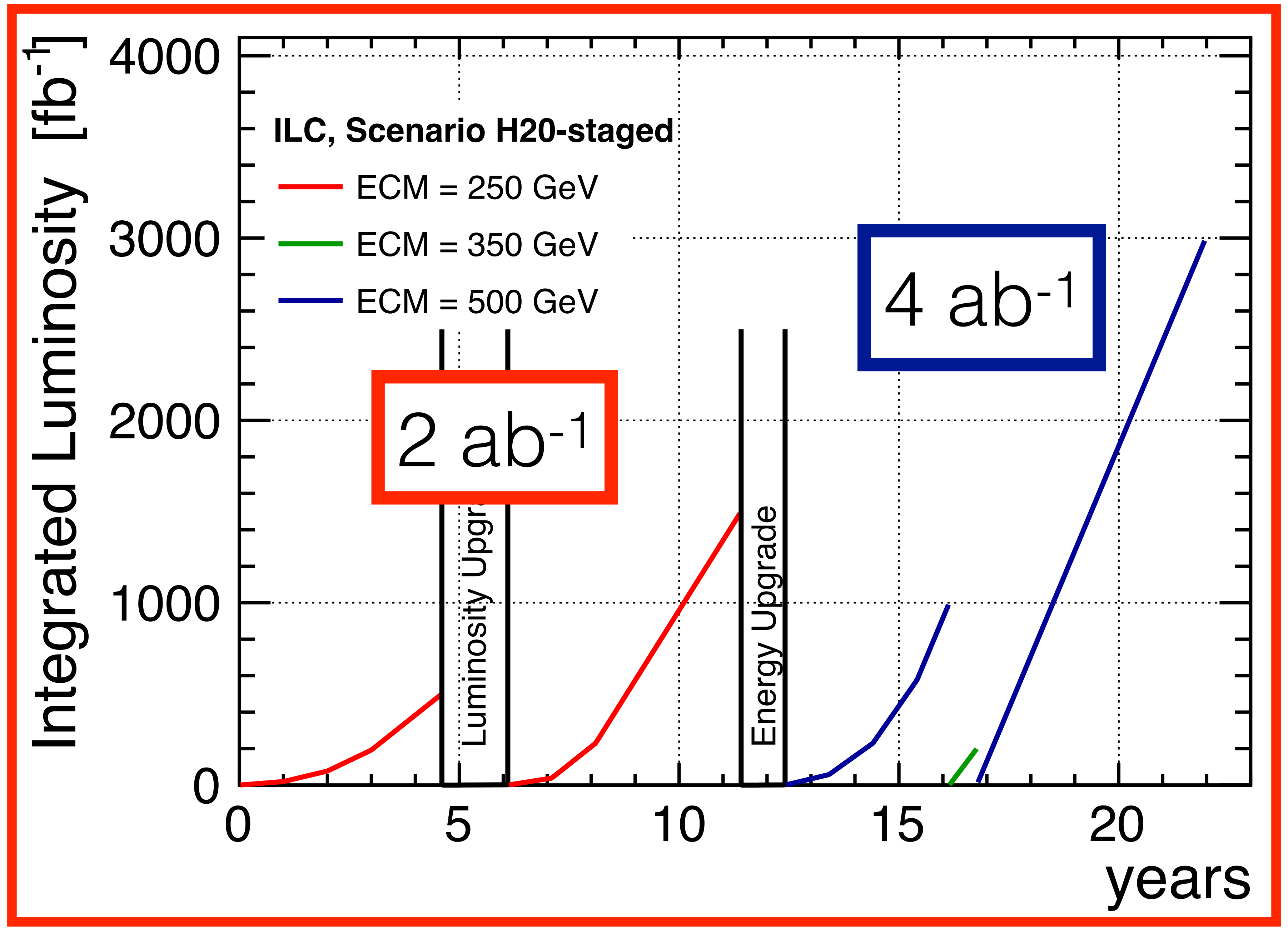
- **first stage: 250 GeV**
- **GigaZ & WW threshold possible**
- upgrades: 500 GeV, 1 TeV

polarised beams

- **$P(e^-) \geq \pm 80\%$,**
- **$P(e^+) = \pm 30\%$,**
  at 500 GeV upgradable to 60%

Since 2015
arXiv:1506.07830

$\sqrt{s}$	$\int \mathscr{L} dt$
250 GeV	2 ab^{-1}
350 GeV	0.2 ab^{-1}
500 GeV	4 ab^{-1}
1 TeV	8 ab^{-1}
91 GeV	0.1 ab^{-1}
161 GeV	0.5 ab^{-1}



(radiative) Z's in 2 ab^{-1} at **250 GeV**:

- ~77 10^6 Z->qq
- ~12 10^6 Z->ll

=> substantial increase over LEP,
….and polarised!

Z's in 0.1ab^{-1} at **91 GeV**:

- ~3.4 10^9 Z->qq
- ~0.5 10^9 Z->ll

~1-2 years of running (after lumi upgrade)

Accelerator implementation - arXiv:1908.08212

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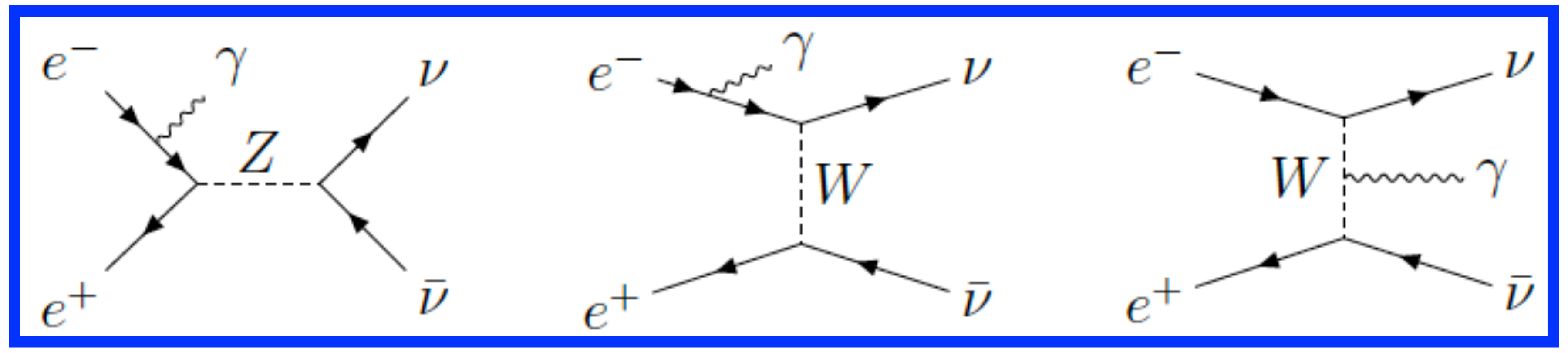
Polarisation & Beyond the SM: Dark Matter

Background reduction & Systematics

- mono-photon search $e^+e^- \rightarrow \chi\chi\gamma$
- main SM background: $e^+e^- \rightarrow \nu\nu\gamma$



reduced ~10x with polarisation

- shape of observable distributions changes with polarisation sign
=> combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
beats down the effect of systematic uncertainties

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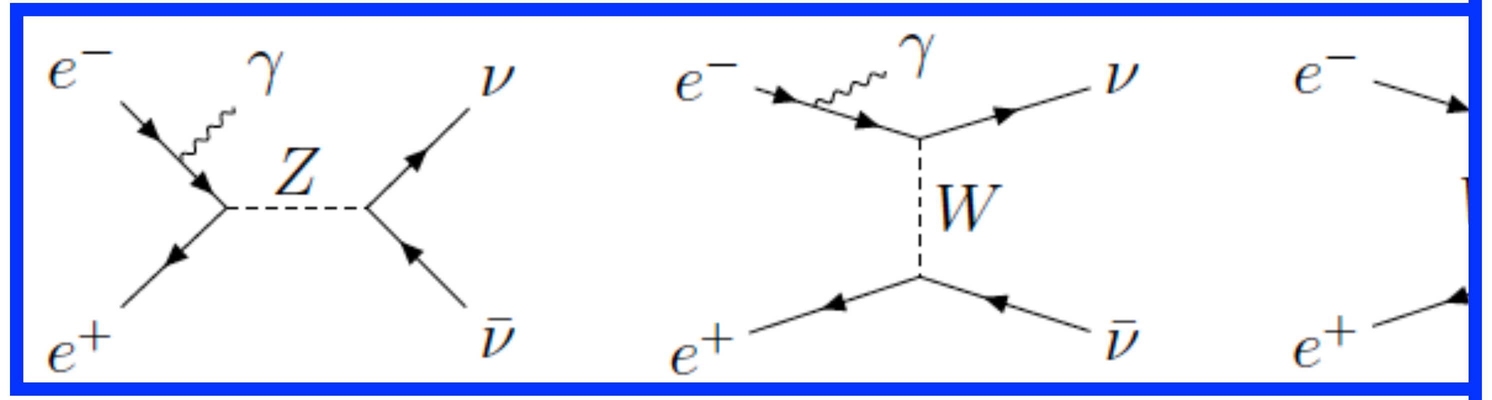

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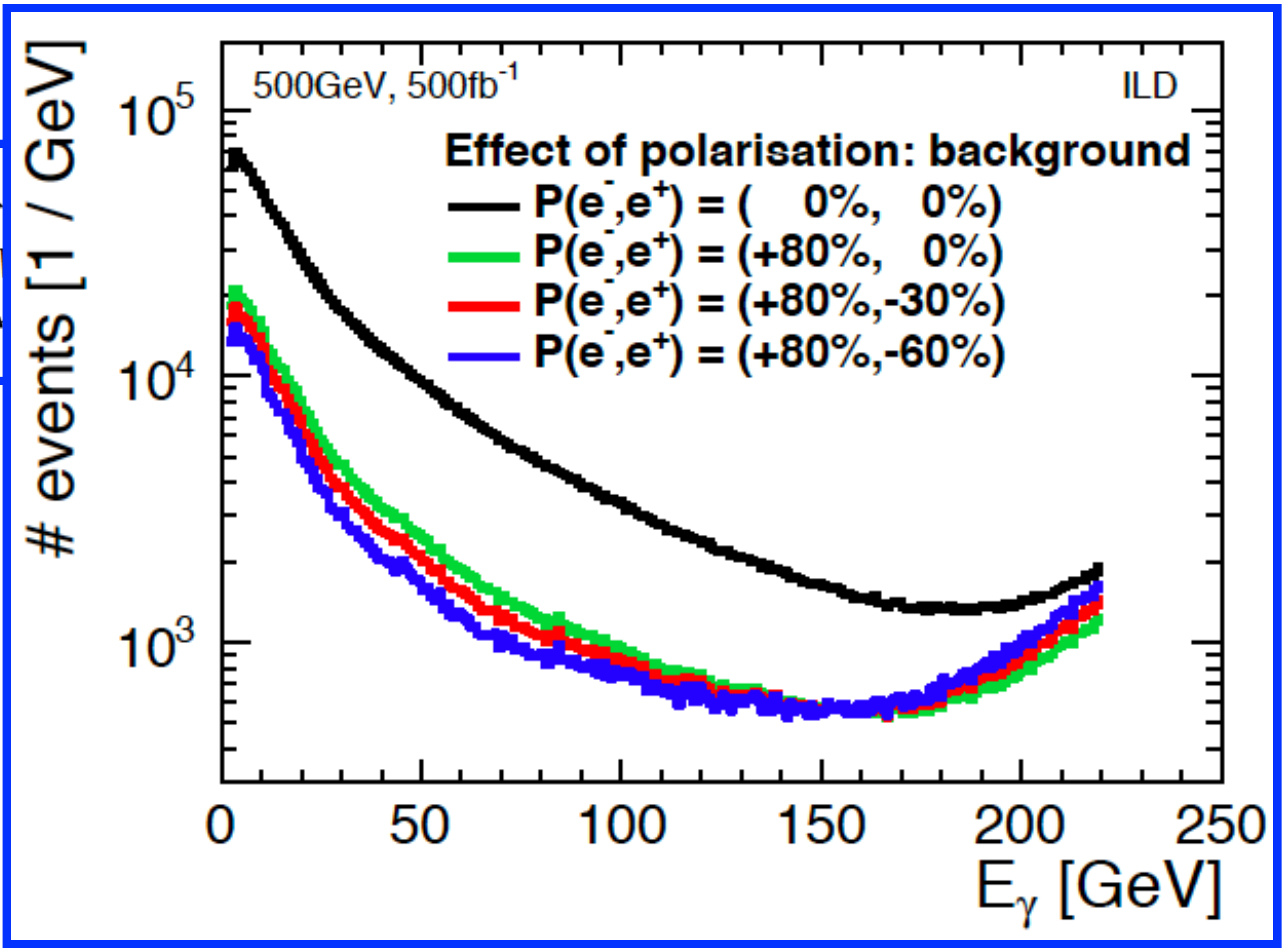

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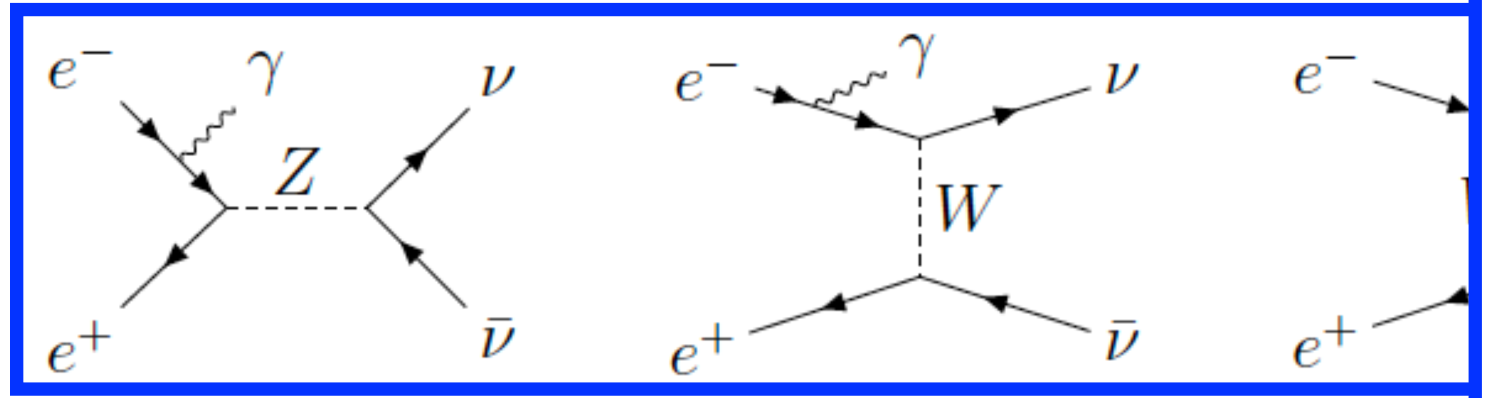
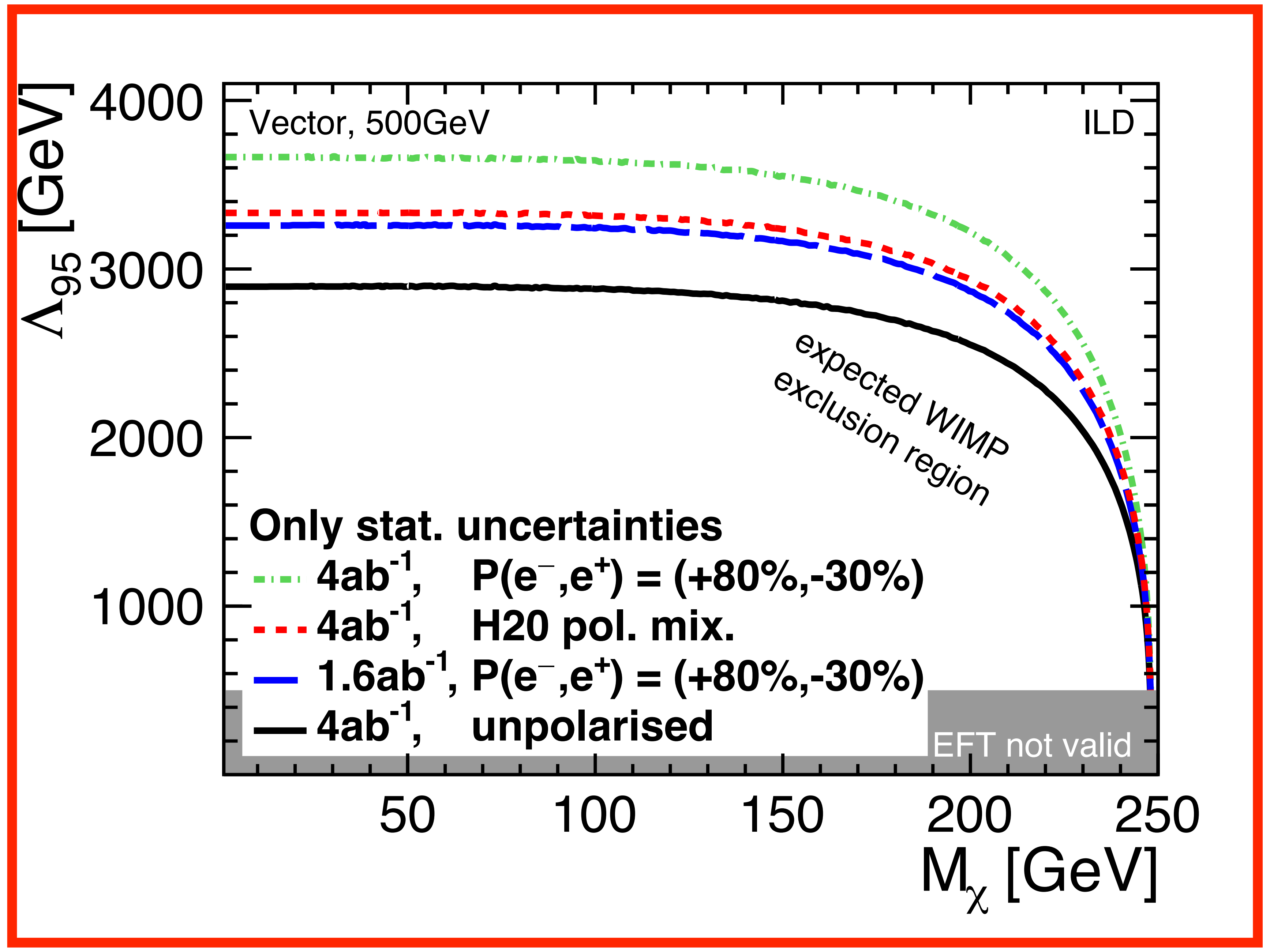
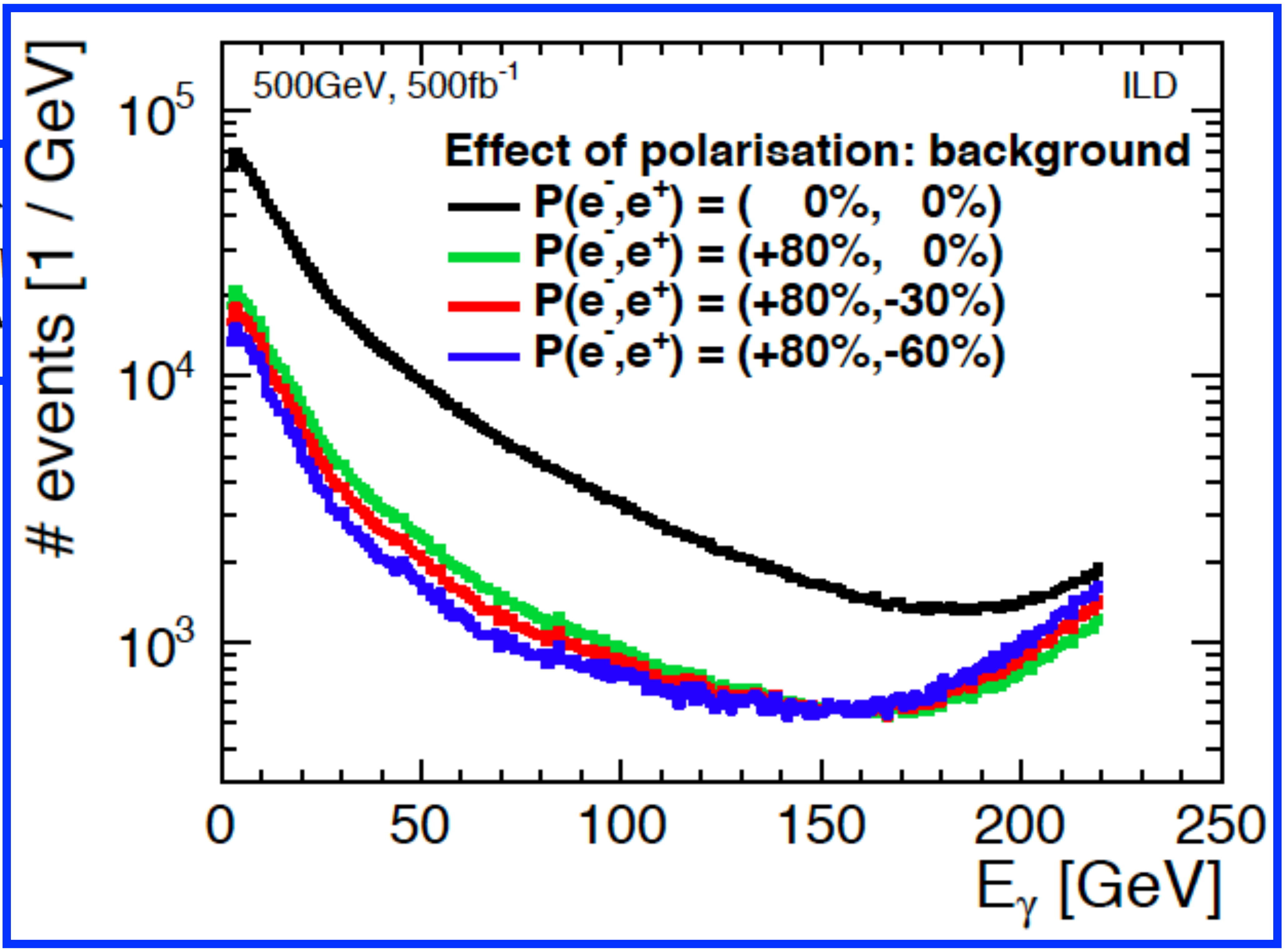


reduced ~10x with polarisation

- shape of observable distributions changes with polarisation sign => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–) beats down the effect of systematic uncertainties





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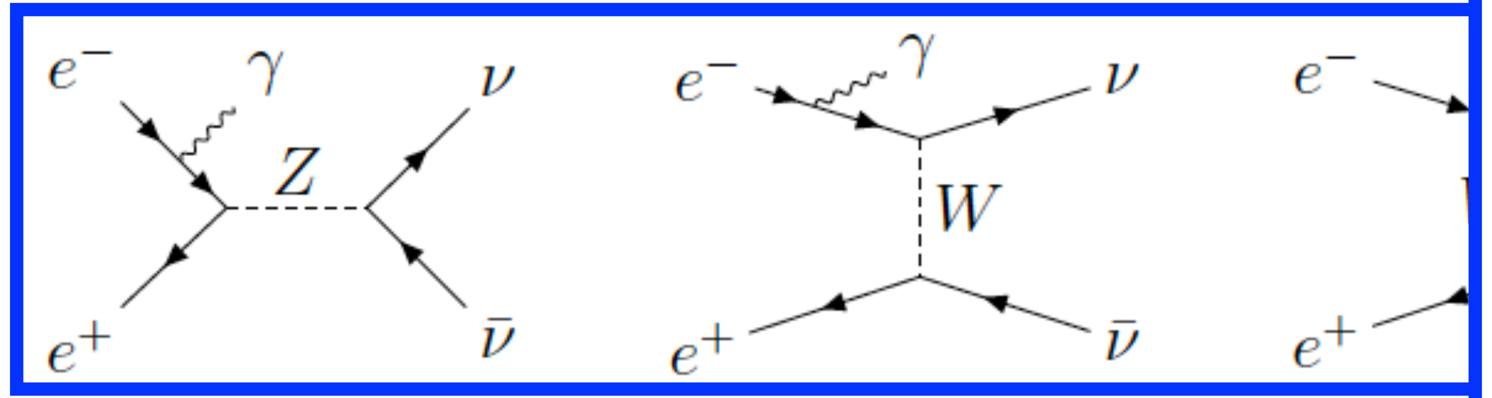

reduced ~10x with polarisation

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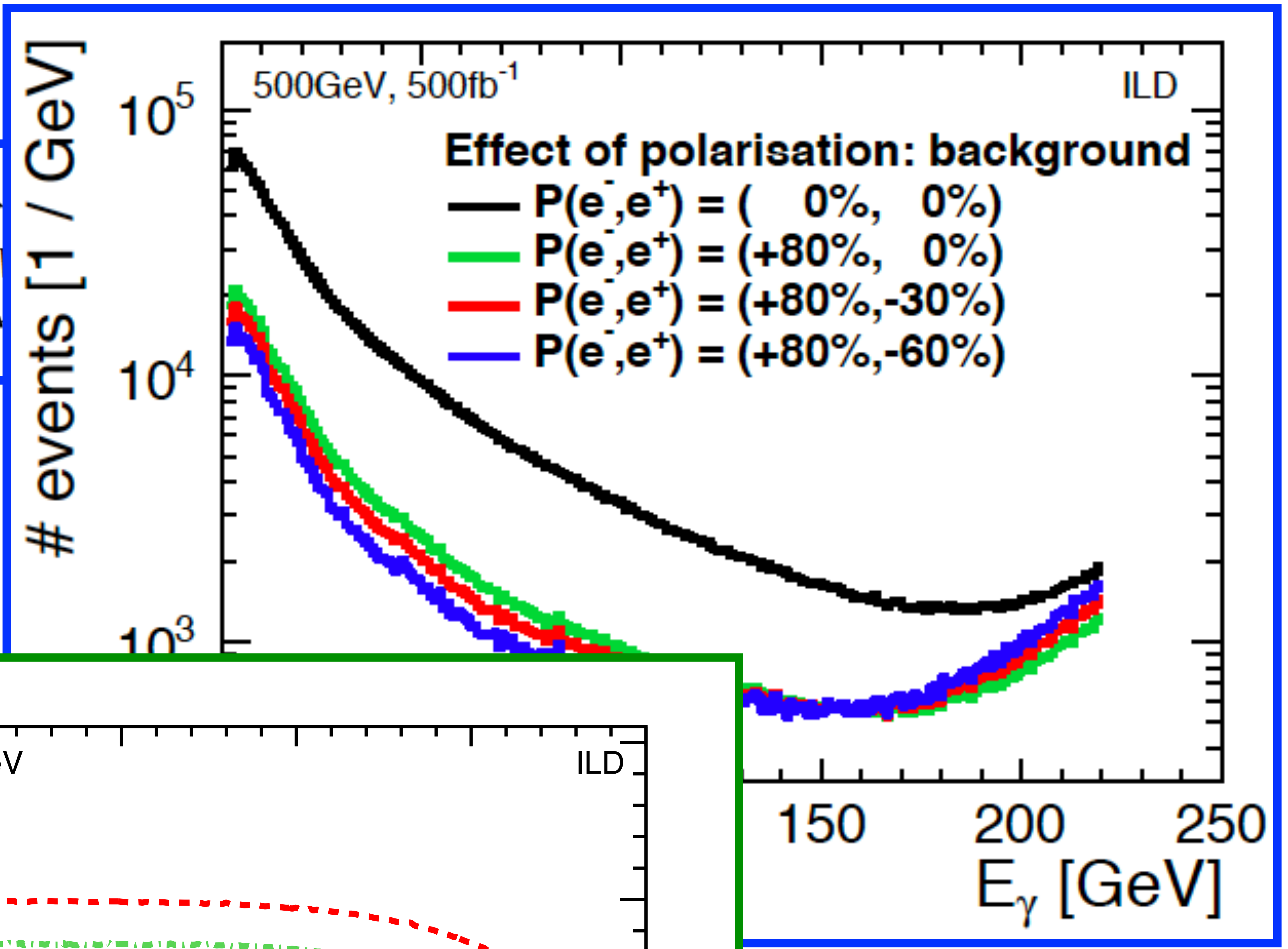

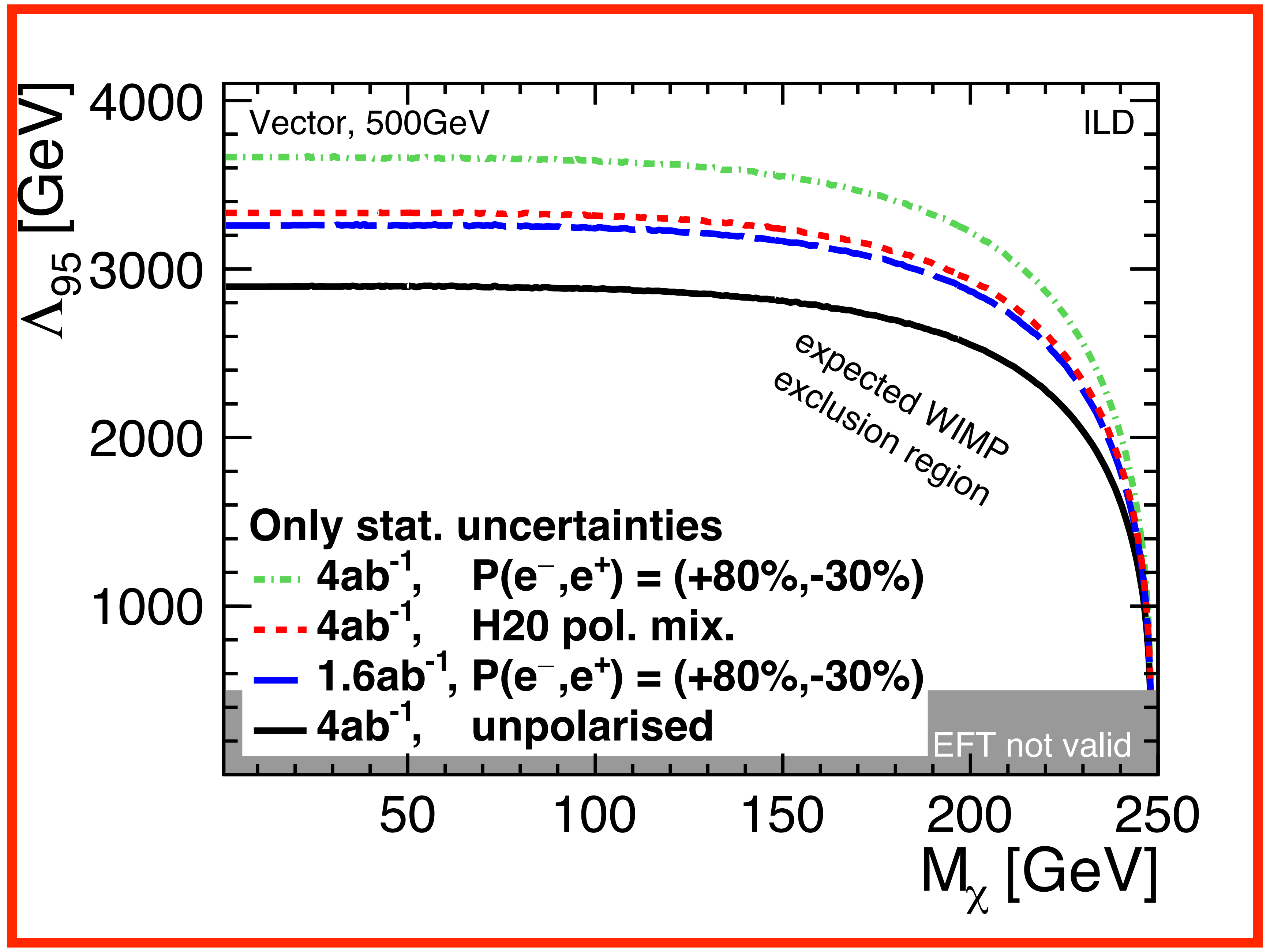

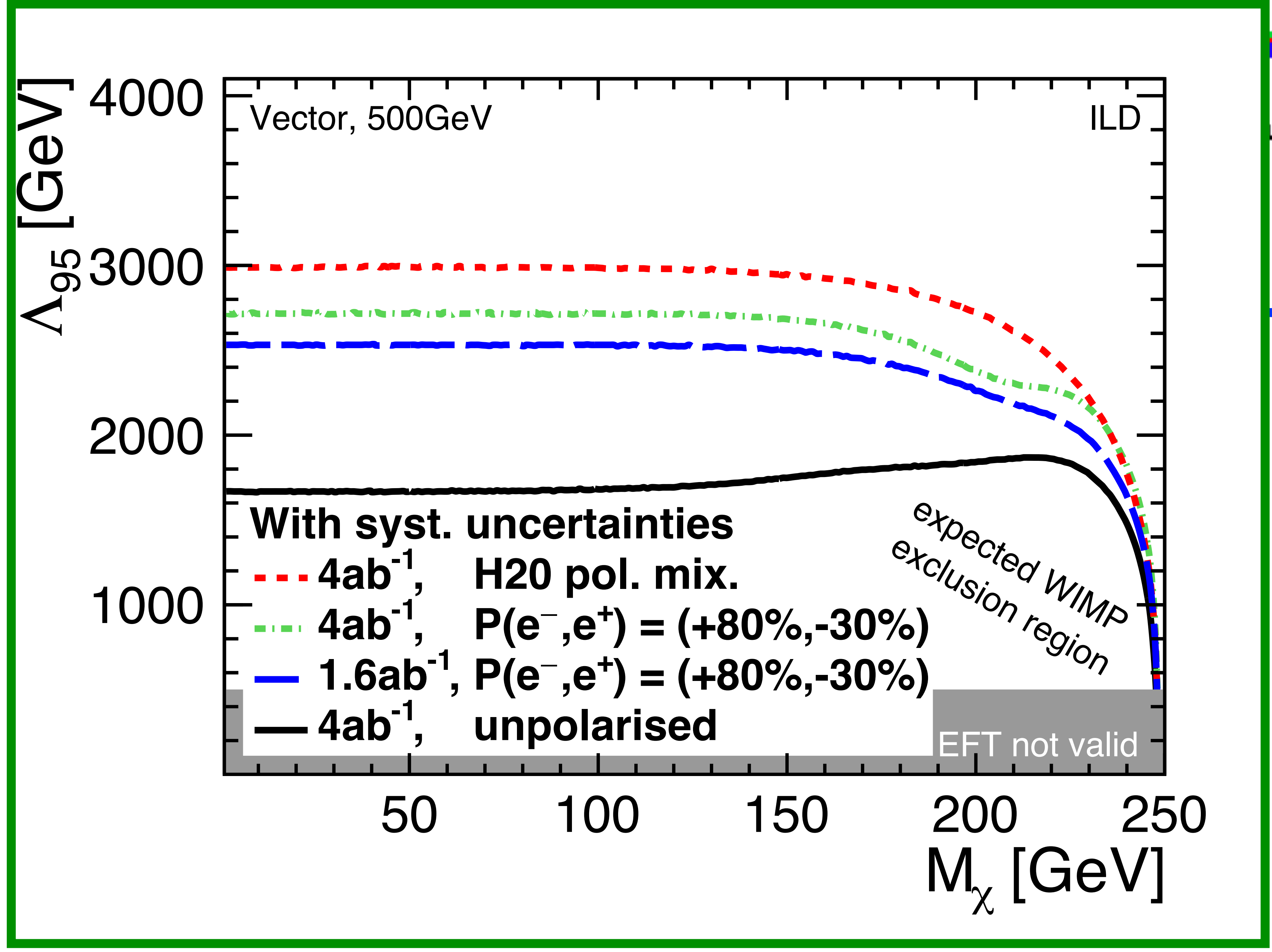

Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

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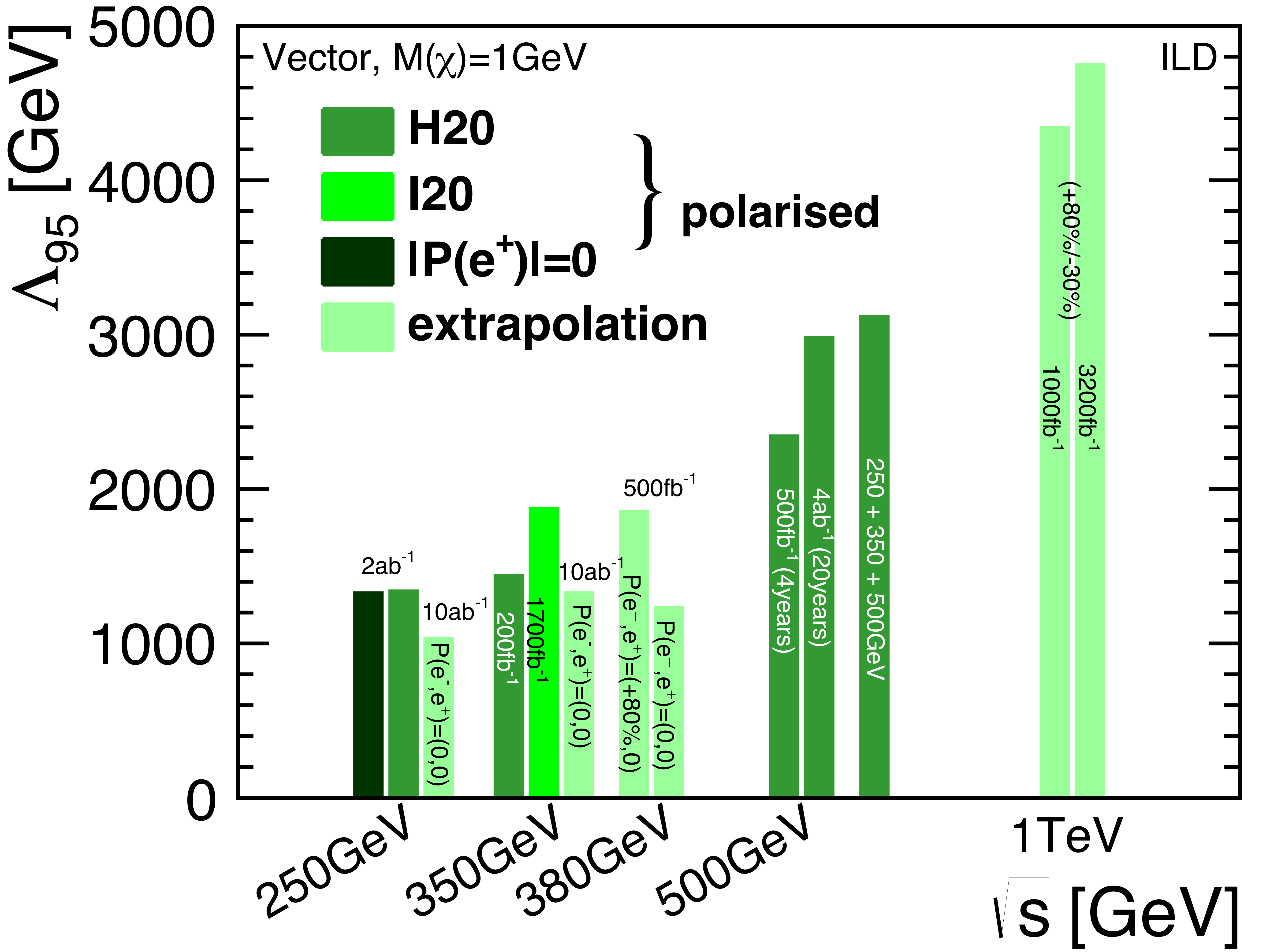
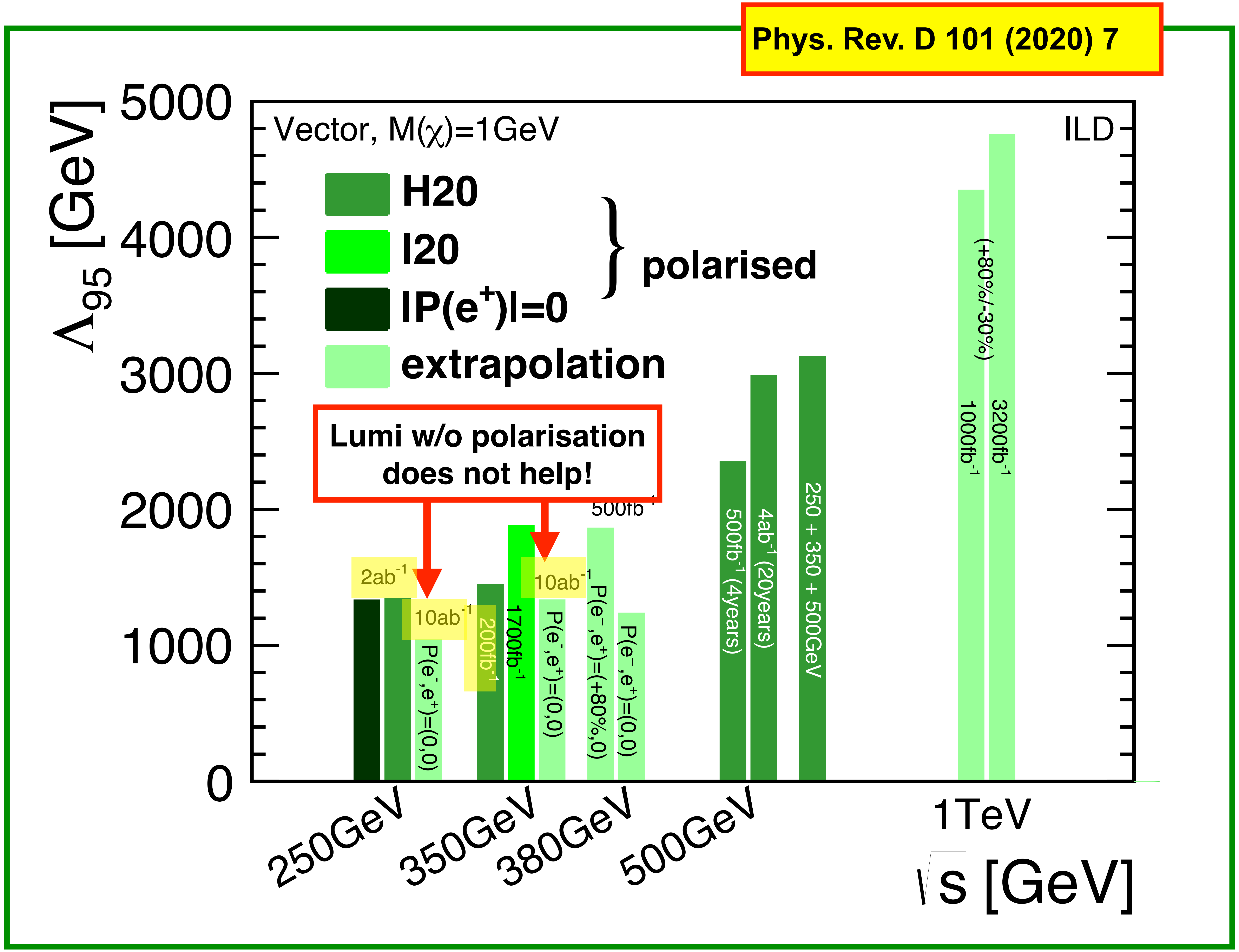


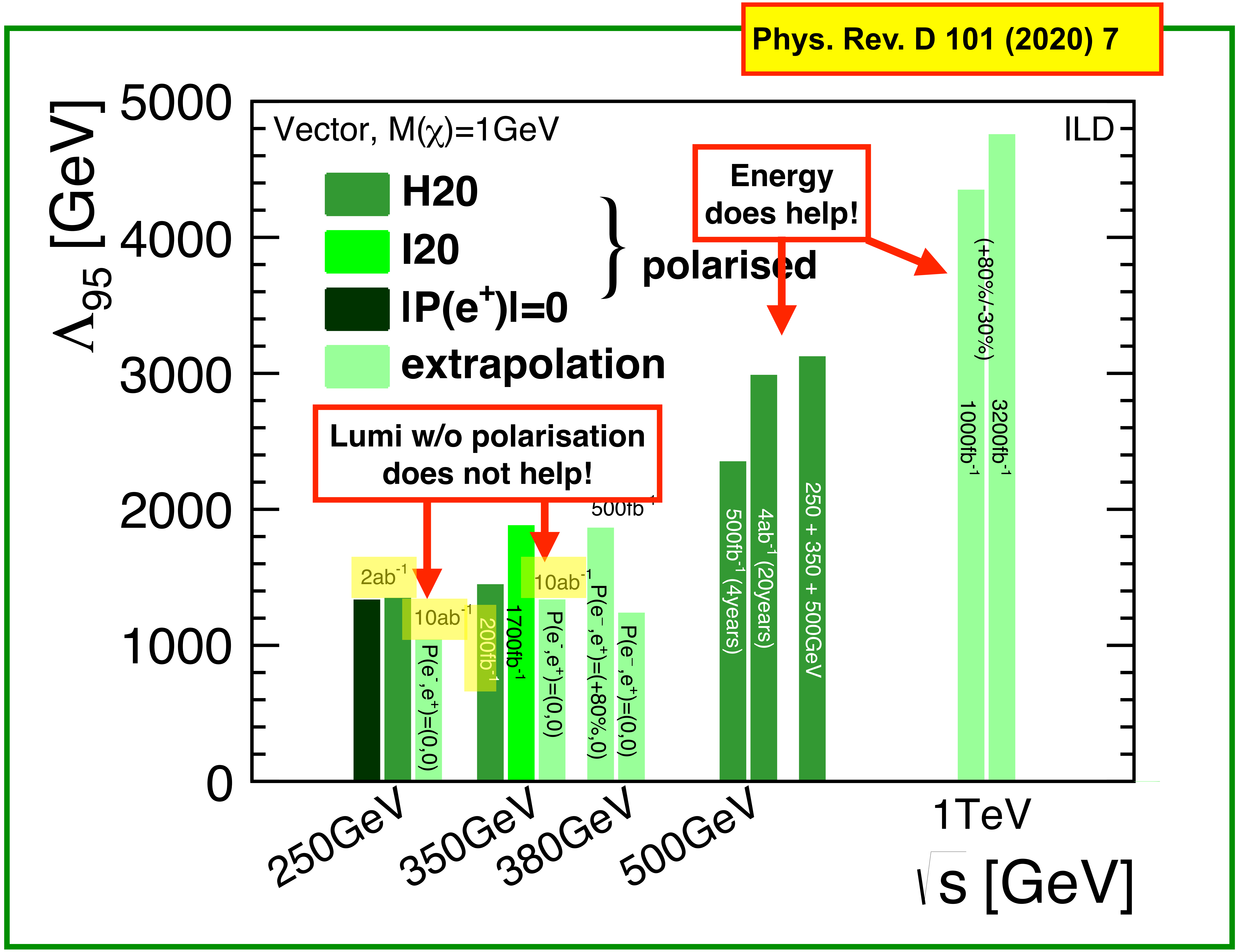
Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case



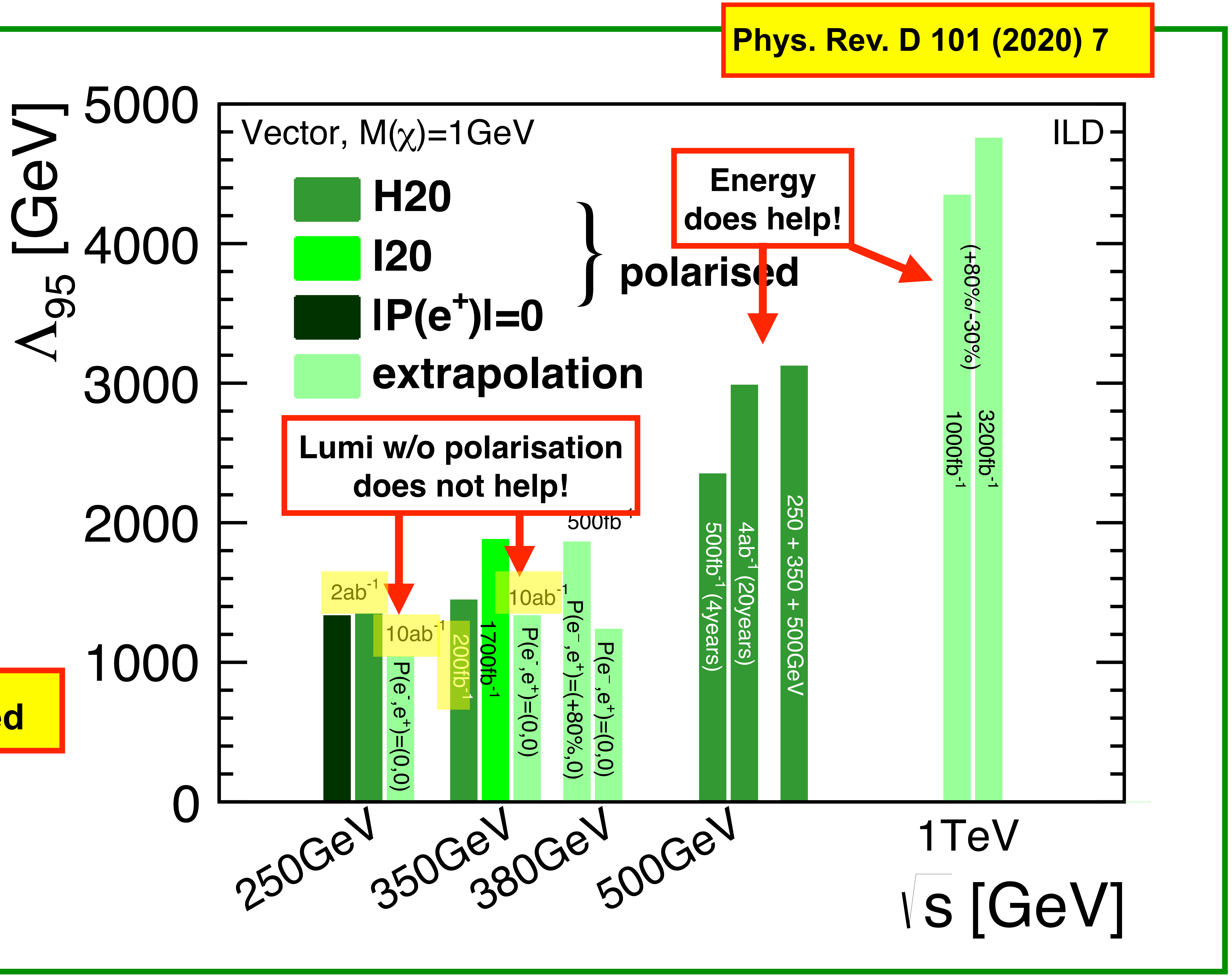
Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case



Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case



200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised

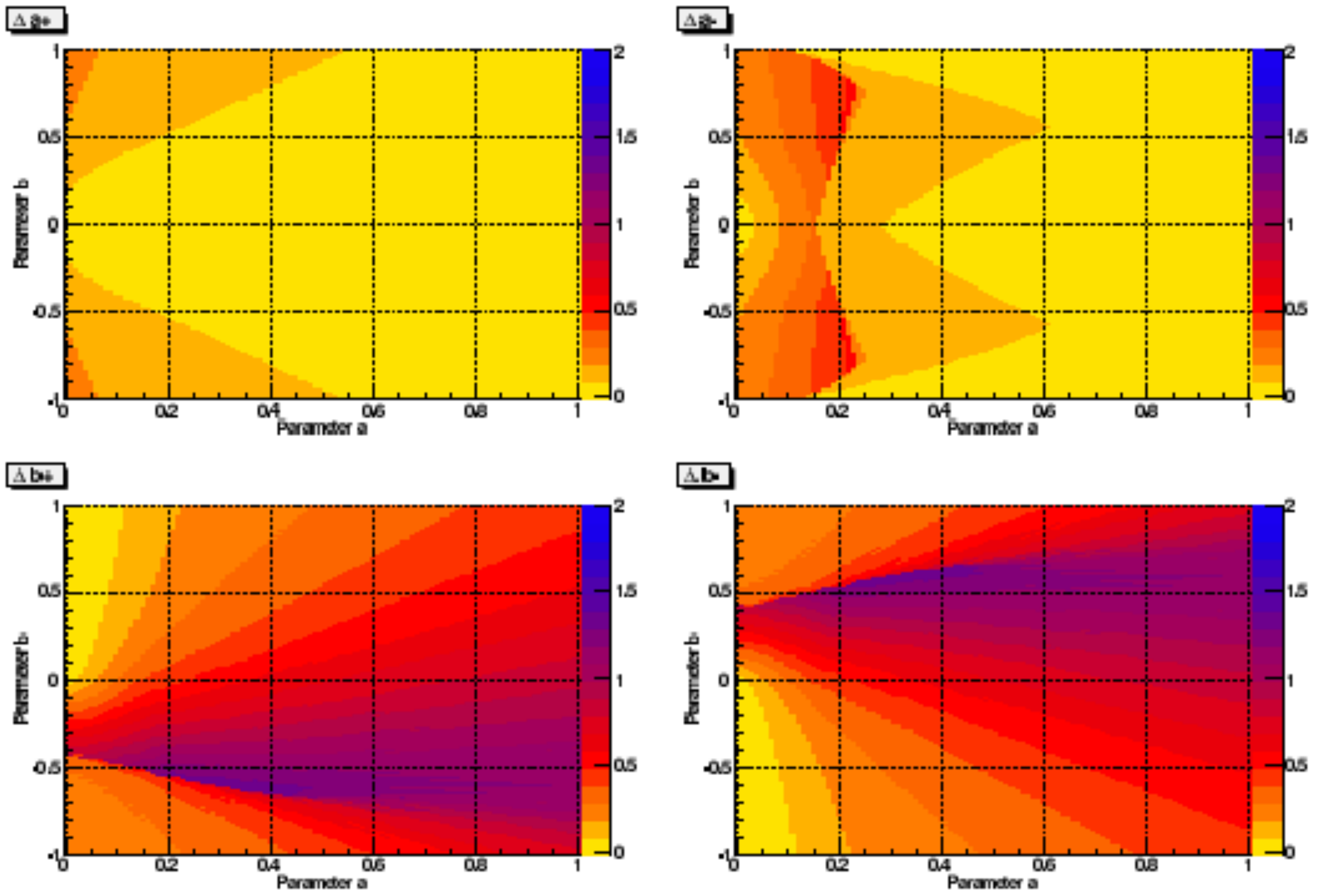
CP odd admixture

∗ coupling of a general CP-mixed state Φ to $t\bar{t}$: $a, b \in [-1, .., 1]$

$$C_{tt\Phi} = -i\frac{e}{\sin\theta_W}\frac{m_t}{2M_W}(a + ib\gamma_5) \equiv -ig_{ttH}(a + ib\gamma_5)$$

Accuracy on a, b from the Combined Observables σ, P_t, A_ϕ

Godbole,Hangst,MMM,Rindani,Sharma



$\sqrt{s} = 800$ GeV, $\int \mathcal{L} = 500$ fb^{-1}, polarised $e^{\pm}$ beams

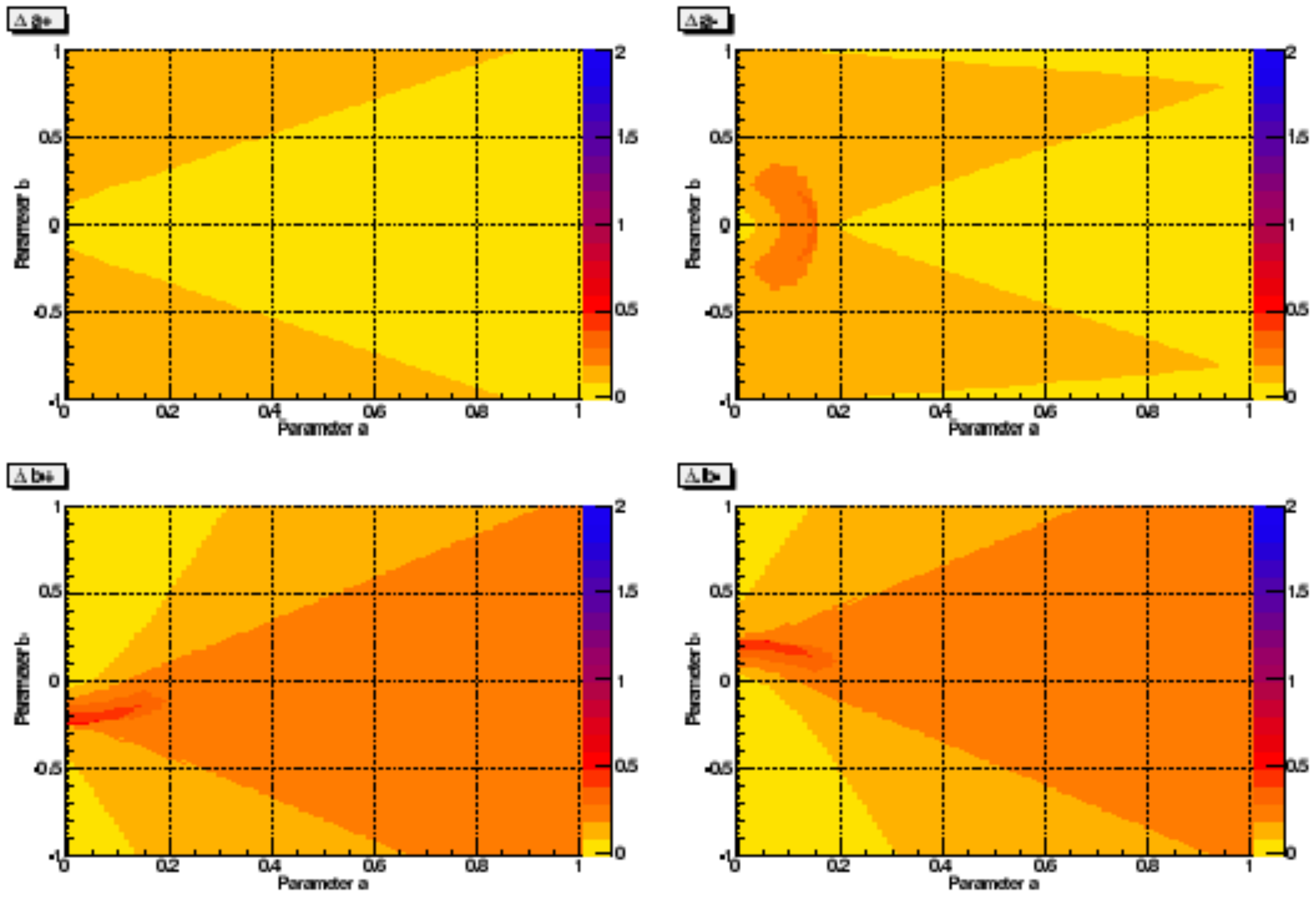
CP odd admixture

$*$ coupling of a general CP-mixed state Φ to $t\bar{t}$: $a, b \in [-1, .., 1]$

$$C_{tt\Phi} = -i \frac{e}{\sin\theta_W} \frac{m_t}{2M_W} (a + ib\gamma_5) \equiv -ig_{ttH}(a + ib\gamma_5)$$

Accuracy on a, b from Combined Observables σ, P_t, A_ϕ – $\sqrt{s} = 3$ TeV

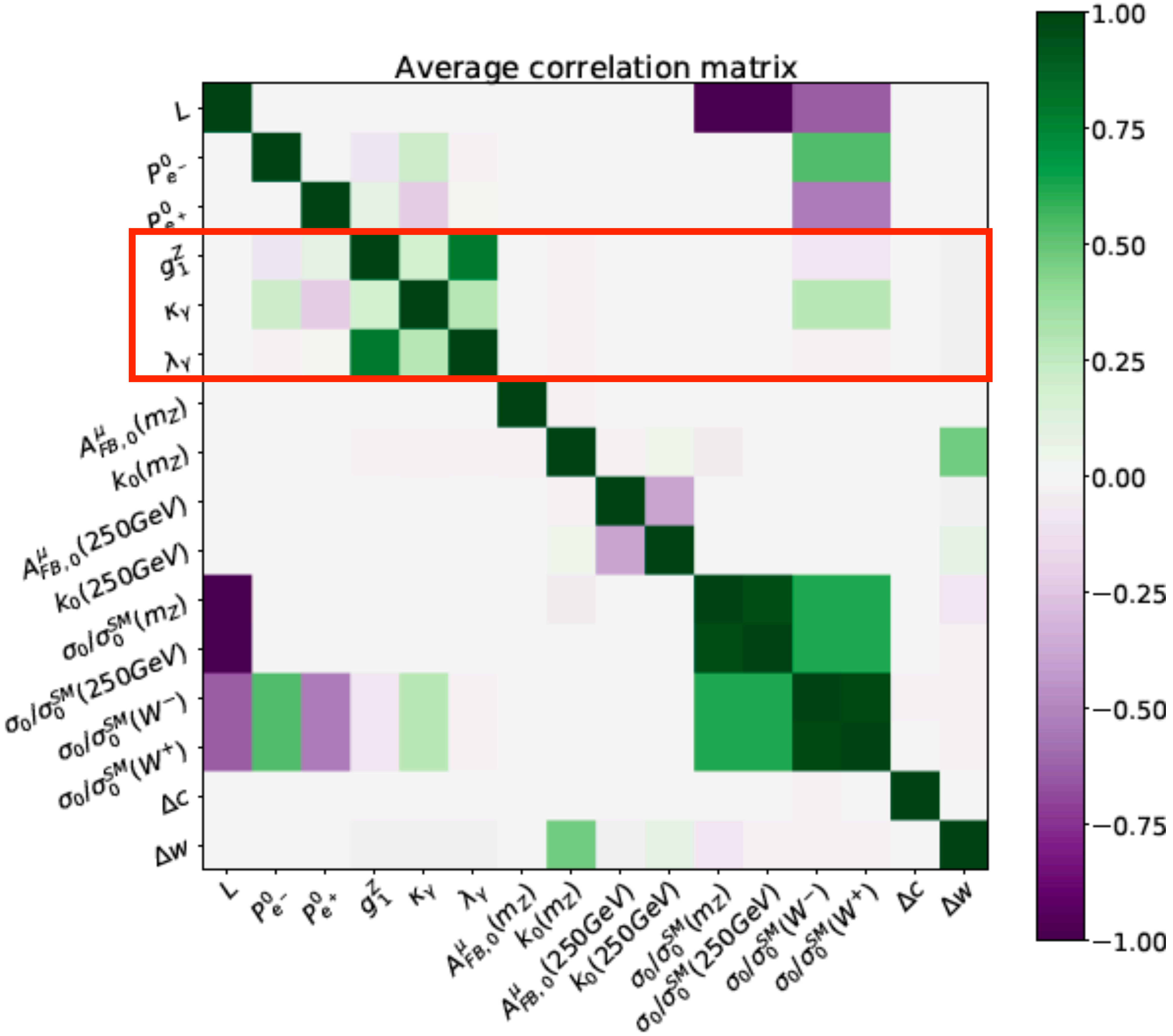
Godbole,Hangst,MMM,Rindani,Sharma

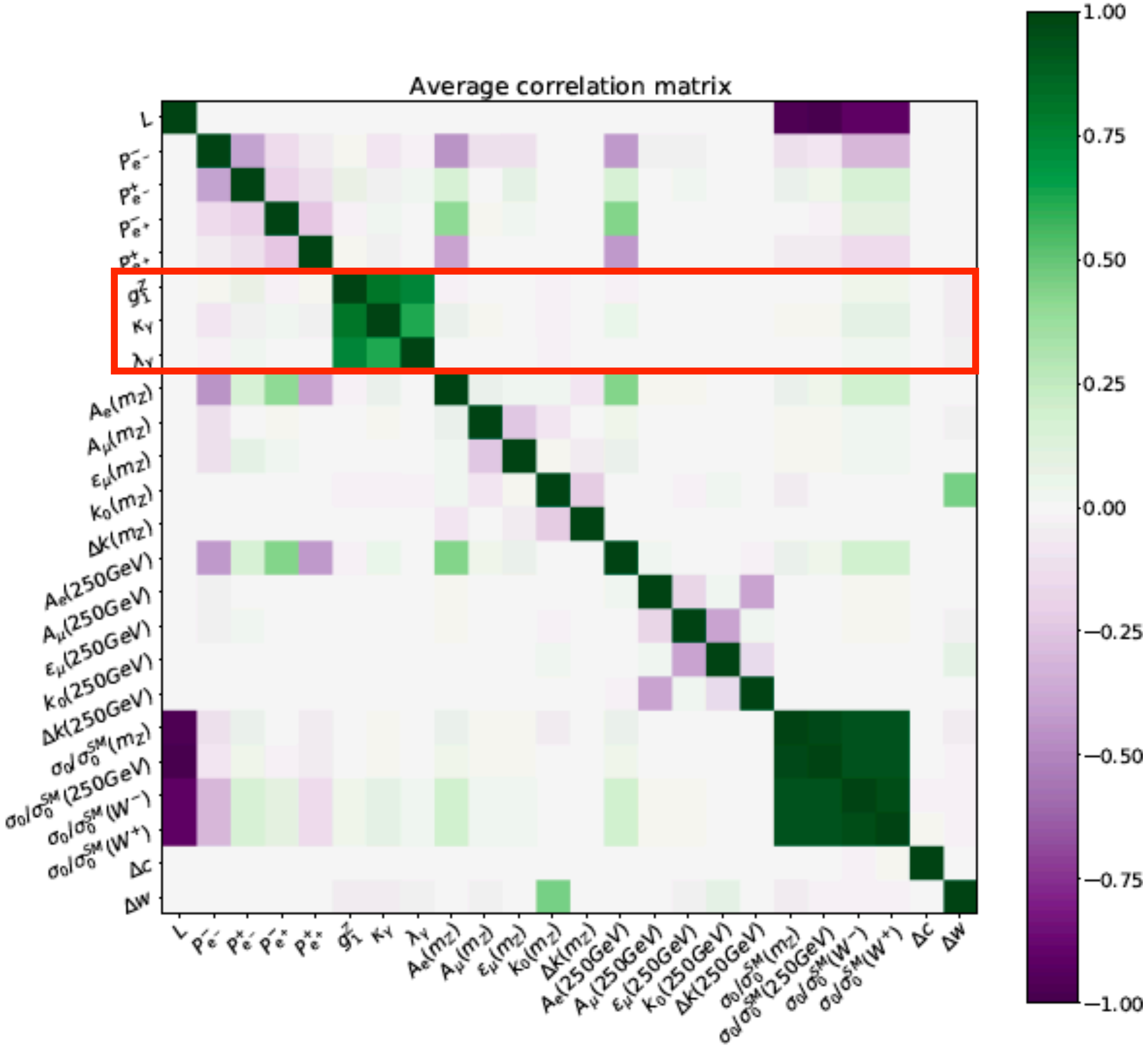


$\sqrt{s} = 3$ TeV, $\int \mathcal{L} = 3$ ab^{-1}, polarised $e^{\pm}$ beams

Can we determine polarisation AND devitions from SM?

P = (0%,0%) vs **P = (±80%, ∓30%)**





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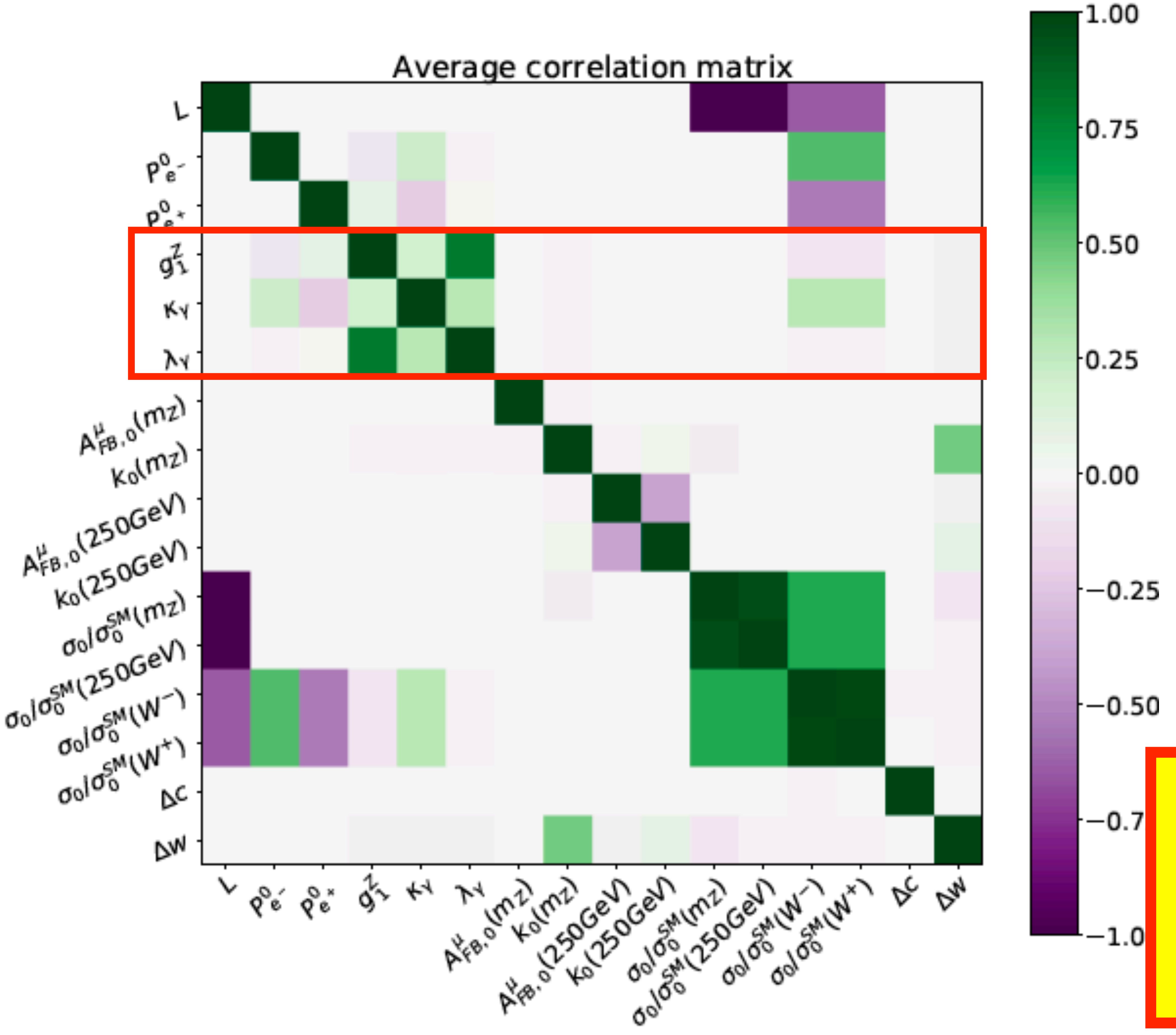

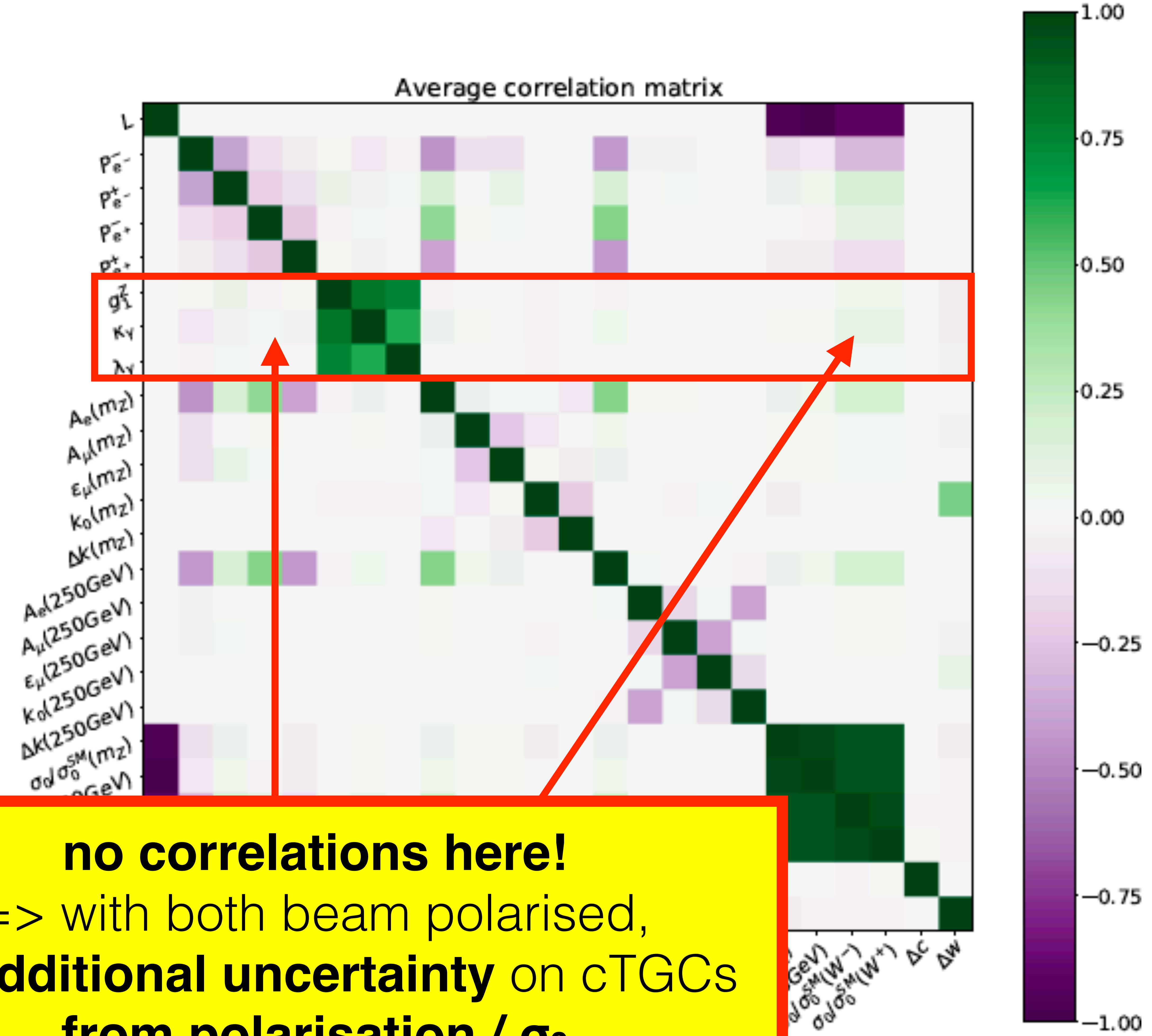

no correlations here!
=> with both beam polarised,
no additional uncertainty on cTGCs
from polarisation / σ0

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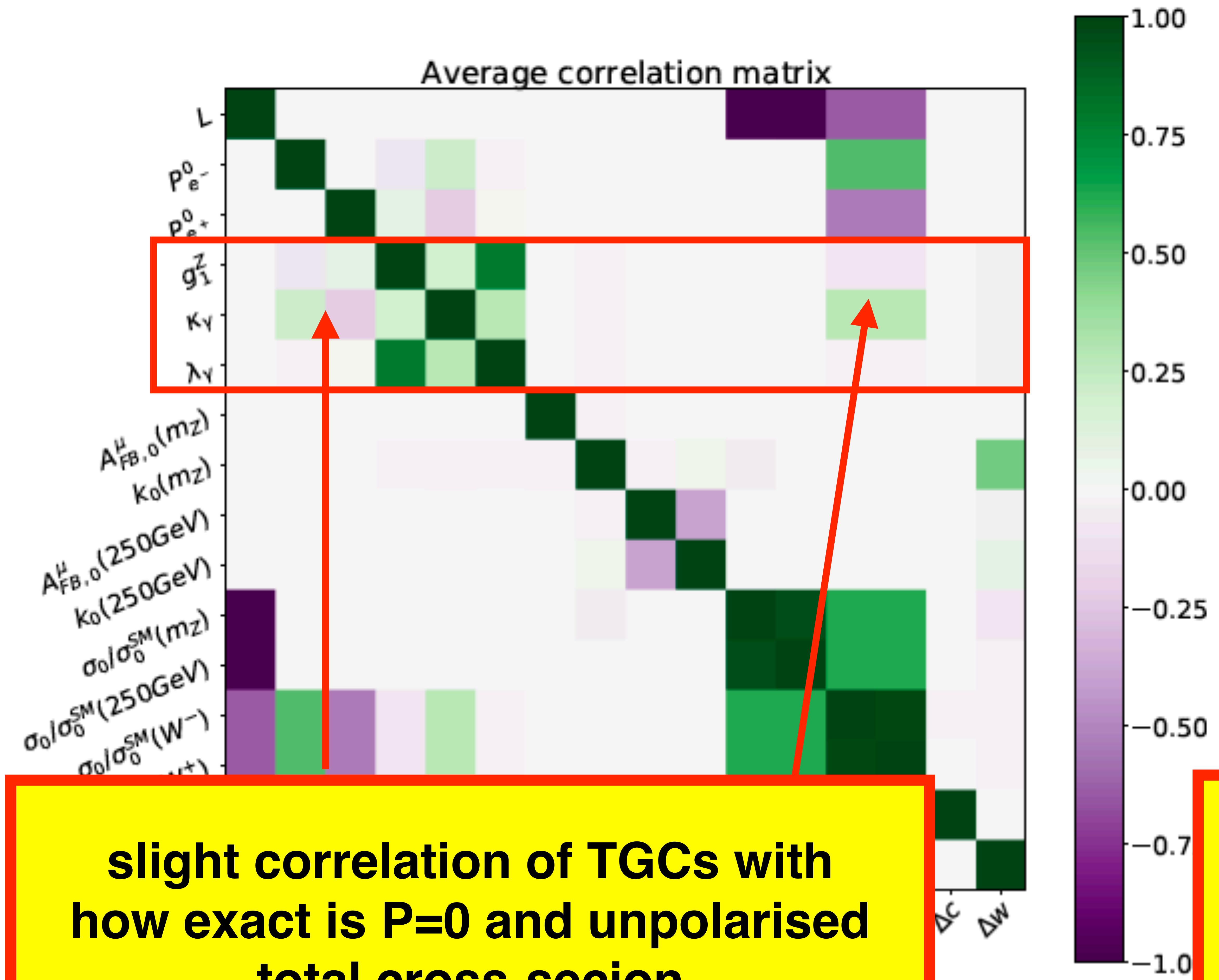
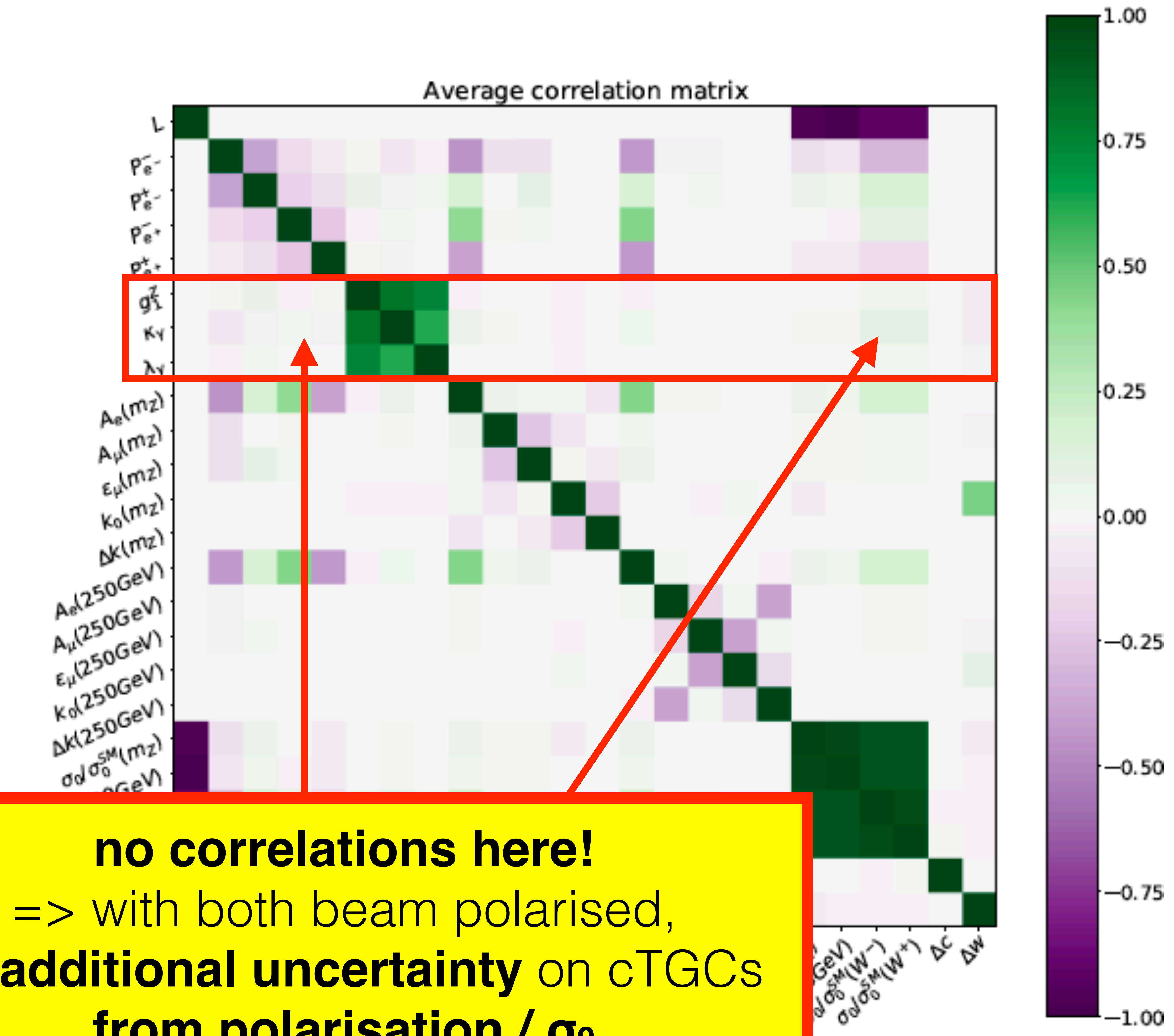


slight correlation of TGCs with how exact is P=0 and unpolarised total cross-secion



no correlations here!
=> with both beam polarised,
no additional uncertainty on cTGCs
from polarisation / σ_0

Impact of A_{LR}(WW)

- same effect seen in HL-LHC projections
- effect even stronger for HE-LHC

=> will require A_q's from lepton collider!

arXiv:1902.04070

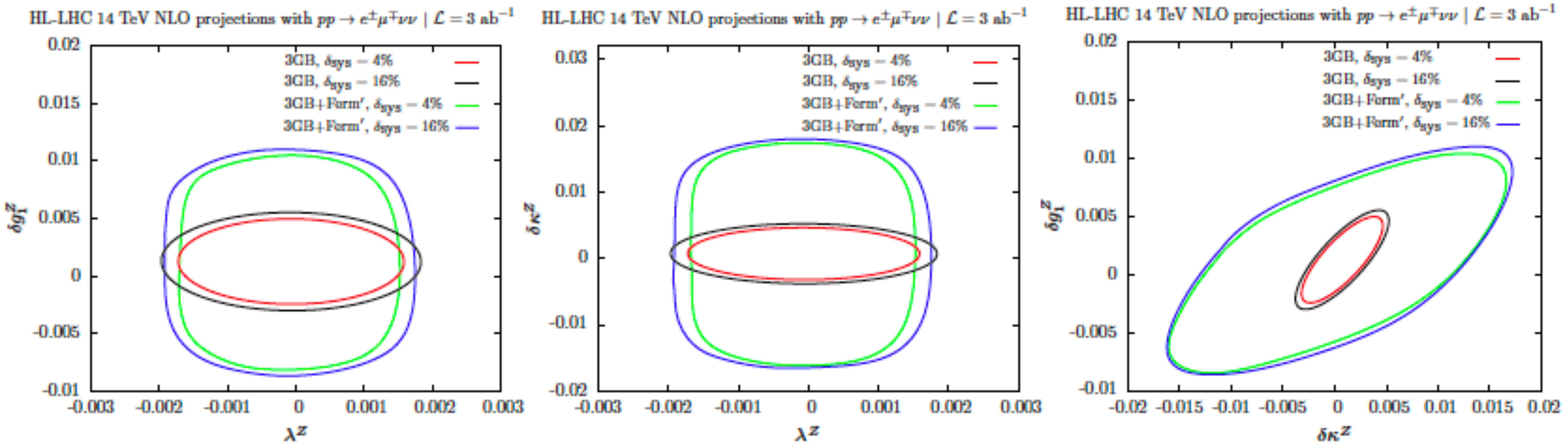


Fig. 40: Projections for 14 TeV with 3 ab^{-1}. $p_{T,cut}$ = 750 GeV, corresponding to δ_{stat} = 16% with δ_{sys} = 4% and δ_{sys} = 16%. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

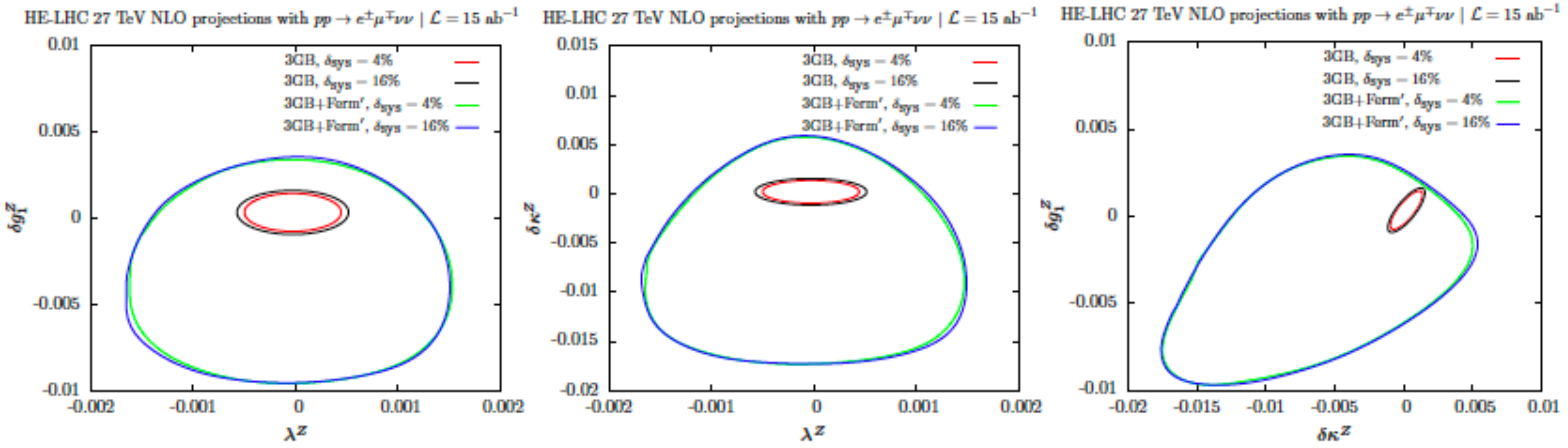


Fig. 41: Projections for 27 TeV with 15 ab^{-1}. $p_{T,cut}$ = 1350 GeV, corresponding to δ_{stat} = 16% with δ_{sys} = 4% and δ_{sys} = 16%. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.