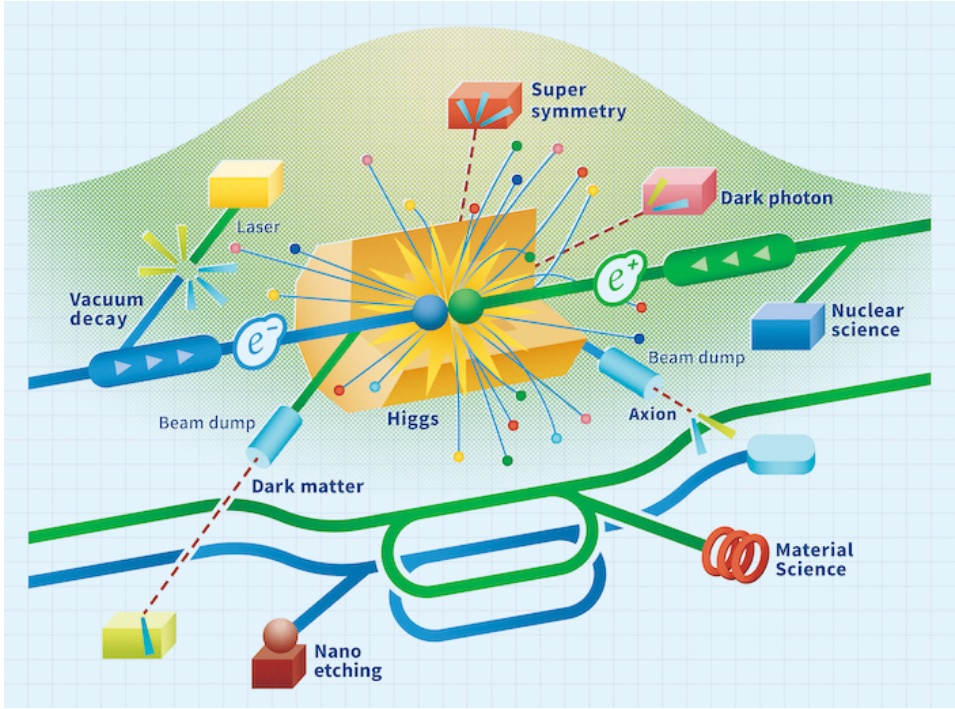
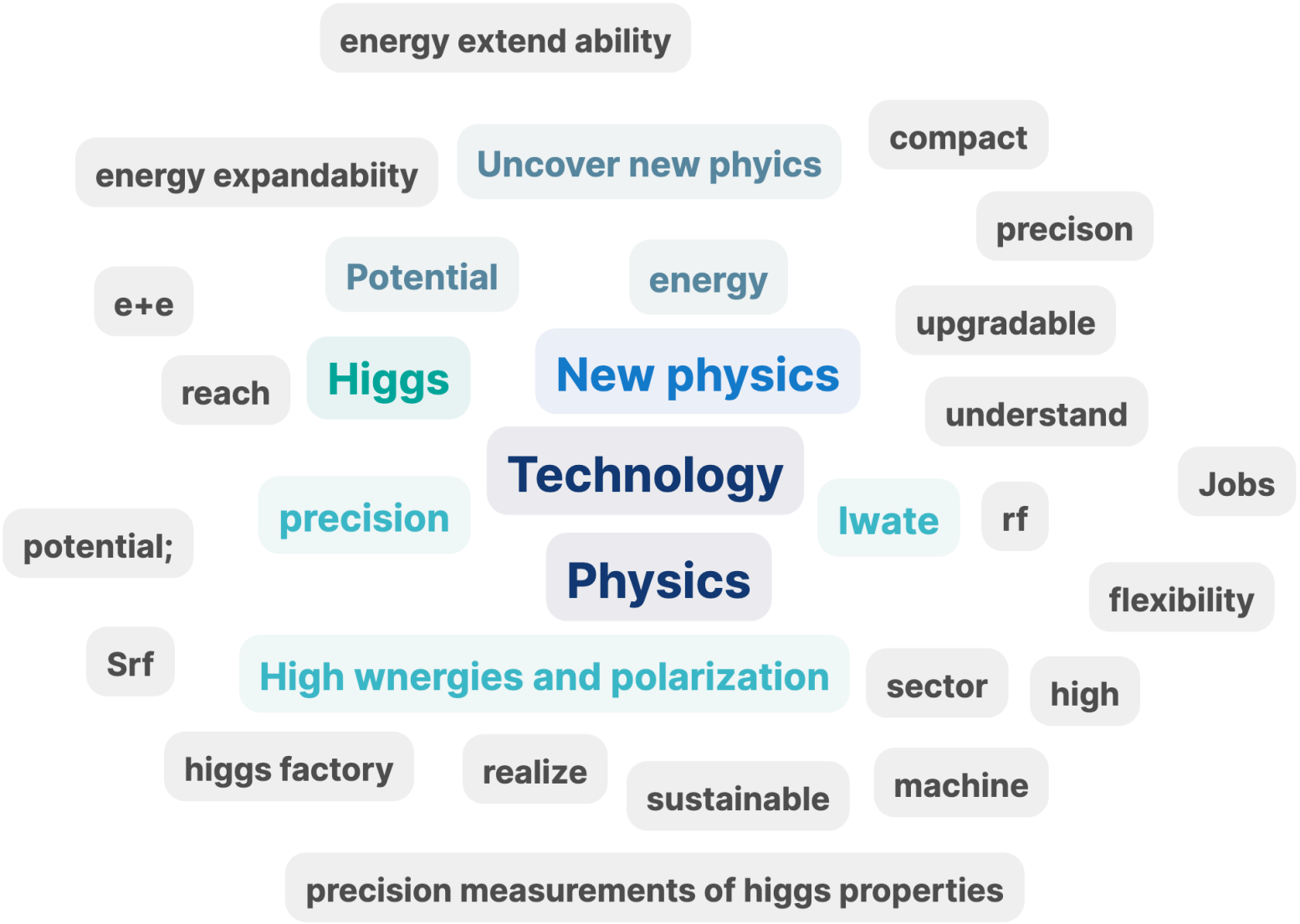
A Global Vision for a Linear Collider Facility



LCWS 2024
Tokyo University
July 10, 2024

LC Vision Team: T. Barklow, T. Behnke, M. Demarteau, A. Faus-Golfe, B. Foster, M. Hogan, M. Ishino, D. Jeans, B.List, J.List, V. Litvinenko, S. Michizono, T. Nakada, E. Nanni, M. Nojiri, M. Peskin, R. Patterson, R. Pöschl, A. Robson, D. Schulte, S. Stapnes, T.Suehera, C. Vernieri, M. Wenskat, J. Zhang

From discussion session: What makes you enthusiastic about Linear Colliders?



From discussion session & poll: Comments on LC vision

- **clear majority of responses very supporting**
- **some specific comments:**
  - please include 2nd BDS & 2nd interaction region!
  - More cost effective, sustainable, while still retaining physics reach. More potential for beyond collider experiments e.g. strong field QED!!!
  - specify the impact to detector and physics of HALHF energy asymmetry
- **some questions on the overall strategy to put forward a joint LC vision - in general and for CERN:**
  - how do we convince the wider particle physics community that the LC Vision of an initial-stage Higgs factory, upgradeable, is the best path for the field?
  - What do you consider a realistic "way out" of the currently "stuck" future collider situation? (FCC likely not affordable, uncertainty on CEPC, LC politics)
  - How seriously is ILC at CERN being discussed, while CERN seems currently willing to go for FCCee?

=> formulating the LC vision more precisely & coherently is a first step to address these!

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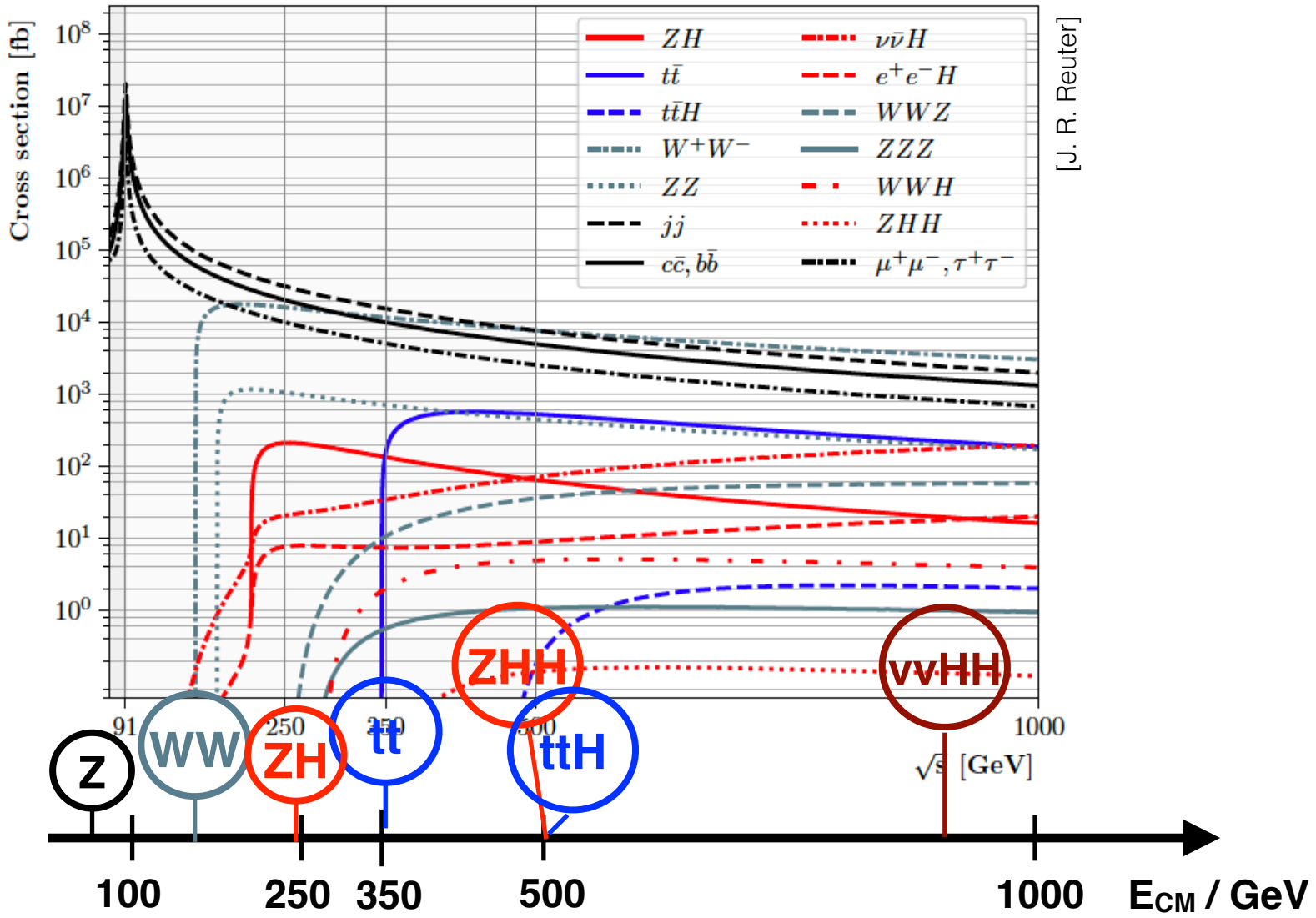
And base it on science!

e+e- Physics at a Linear Collider Facility

Electron-Positron Physics Menu



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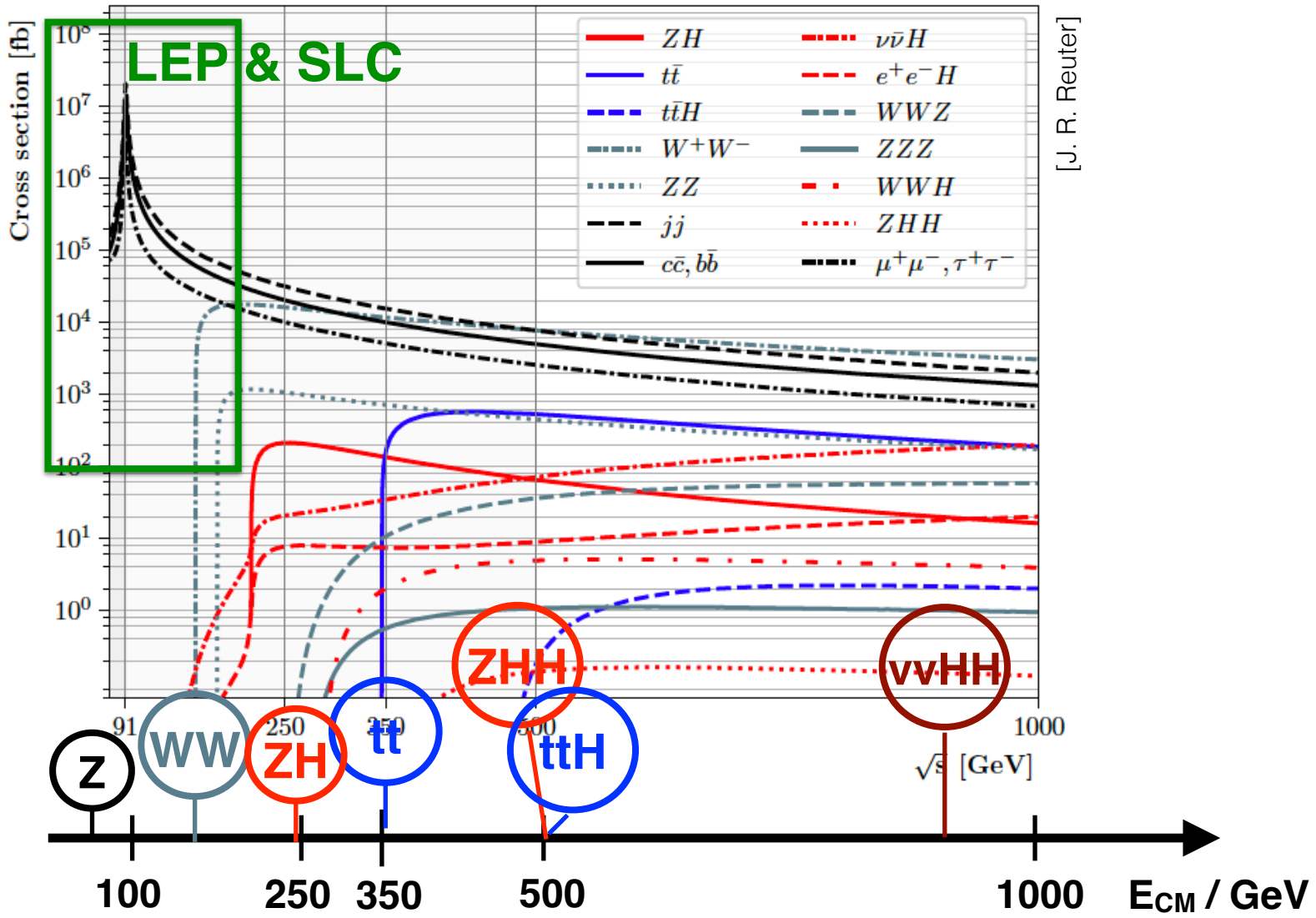
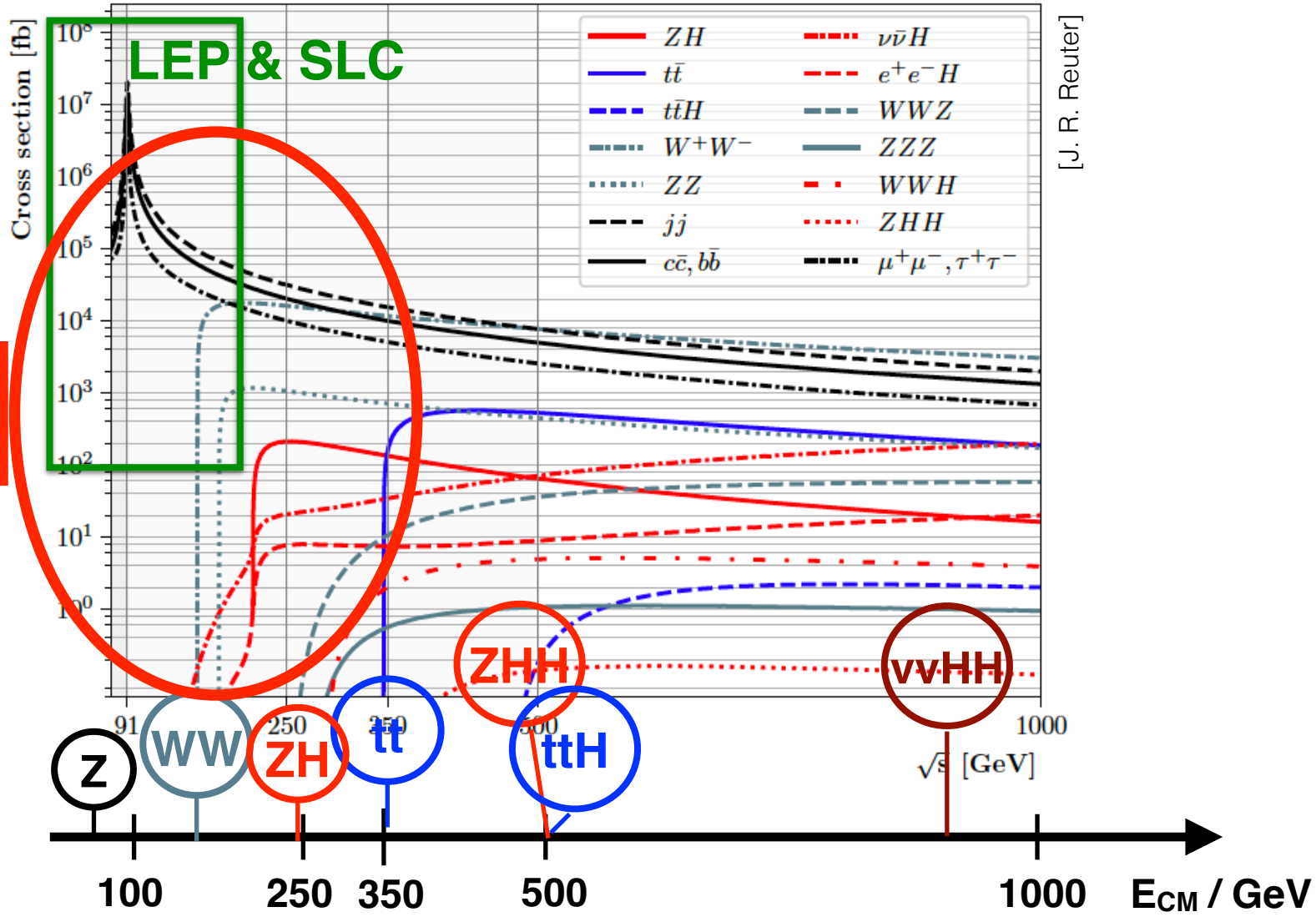


Electron-Positron Physics Menu

all proposed
e+e- projects



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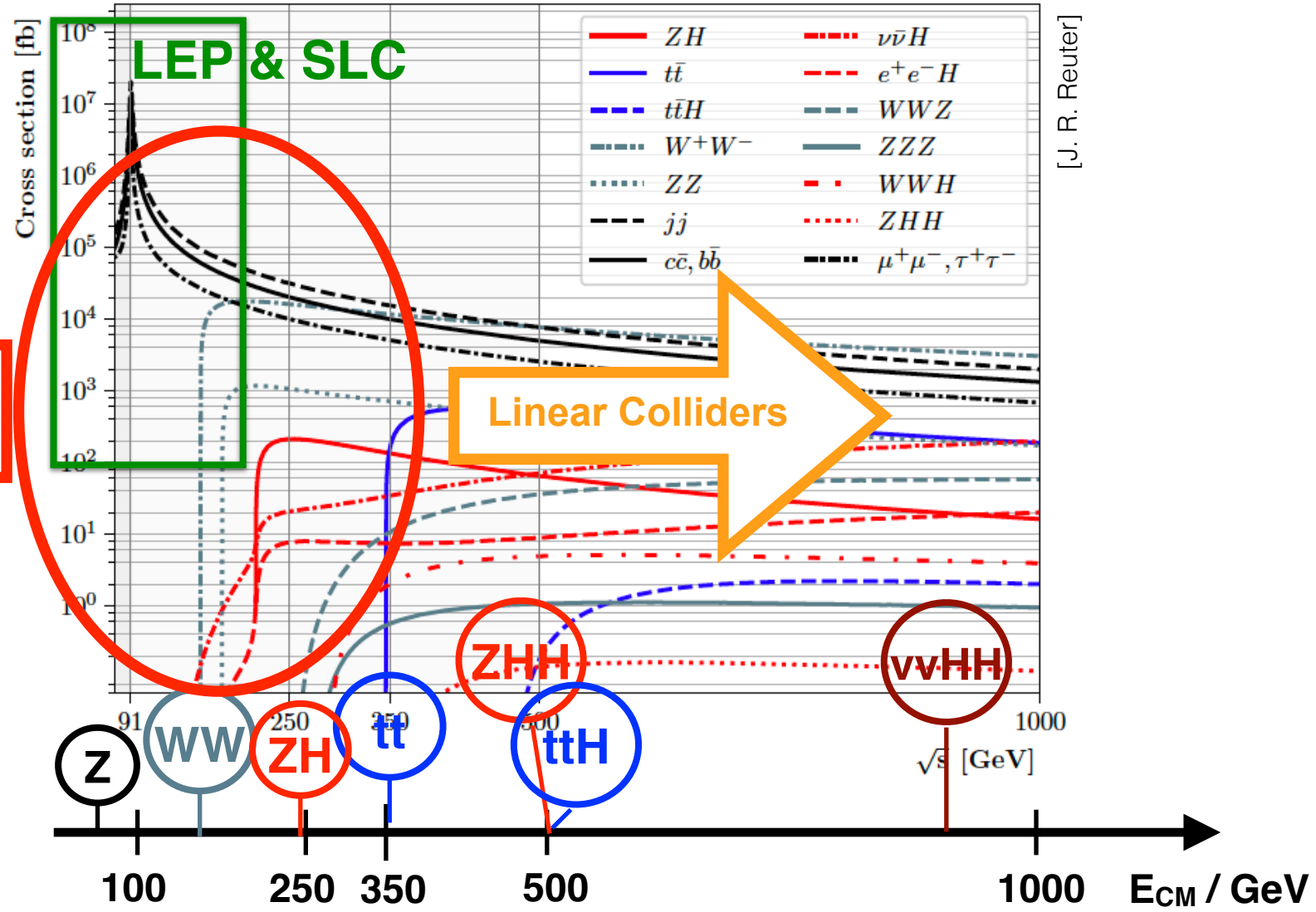
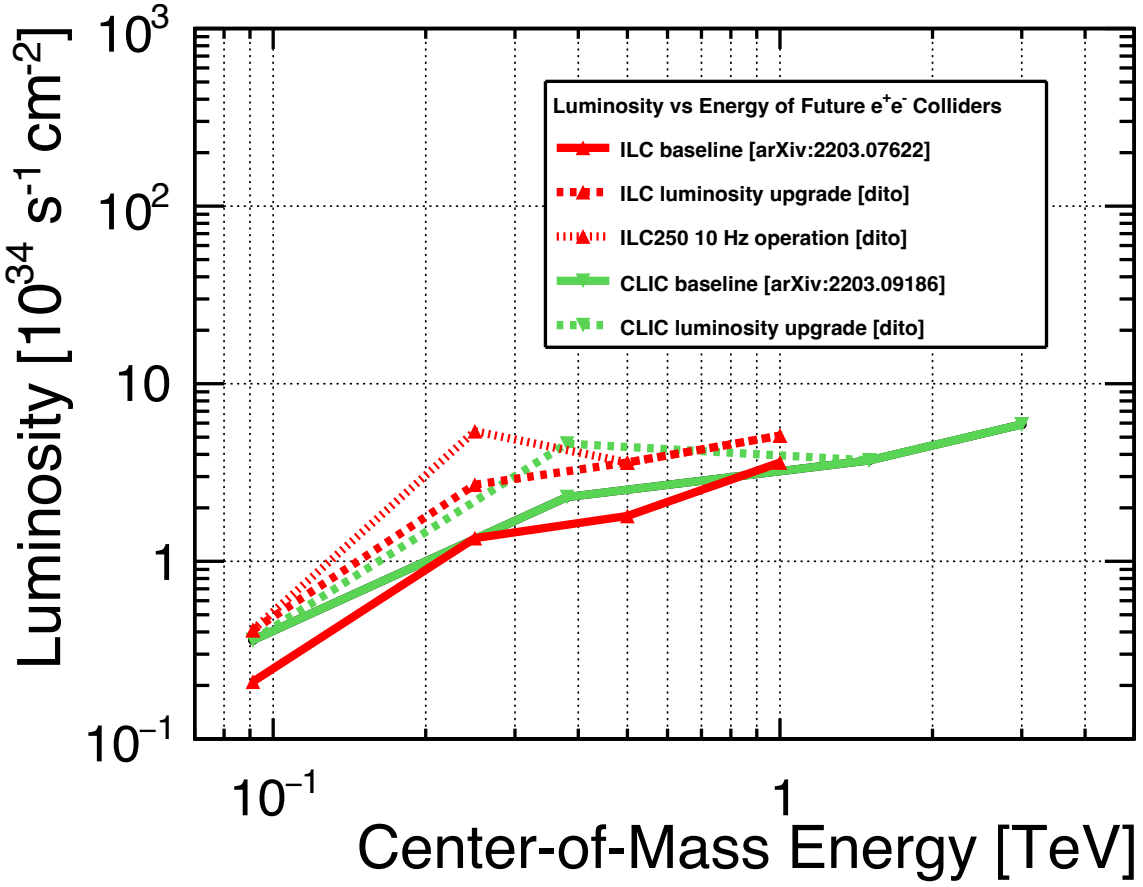


A physics-driven, polarised operating scenario for a Linear Collider

- **250 GeV, ~2ab-1:**
  - precision Higgs mass and total ZH cross-section
  - Higgs -> invisible (Dark Sector portal)
  - basic ffbar and WW program
  - optional: WW threshold scan
- **Z pole, few billion Z's: EWPOs 10-100x better than today**
- **350 GeV, 200 fb-1:**
  - precision top mass from threshold scan
- **500…600 GeV, 4 ab-1:**
  - **Higgs self-coupling in ZHH**
  - **top quark ew couplings**
  - **top Yukawa coupling incl CP structure**
  - improved Higgs, WW and ffbar
  - probe Higgsinos up to ~300 GeV
  - probe Heavy Neutral Leptons up to ~600 GeV
- **800…1000 GeV, 8 ab-1:**
  - Higgs self-coupling in VBF
  - further improvements in tt, ff, WW, ….
  - probe Higgsinos up to ~500 GeV
  - **probe Heavy Neutral Leptons up to ~1000 GeV**
  - searches, searches, searches, …

Based on classic ILC/CLIC luminosity assumptions
limited by self-allowed power budget



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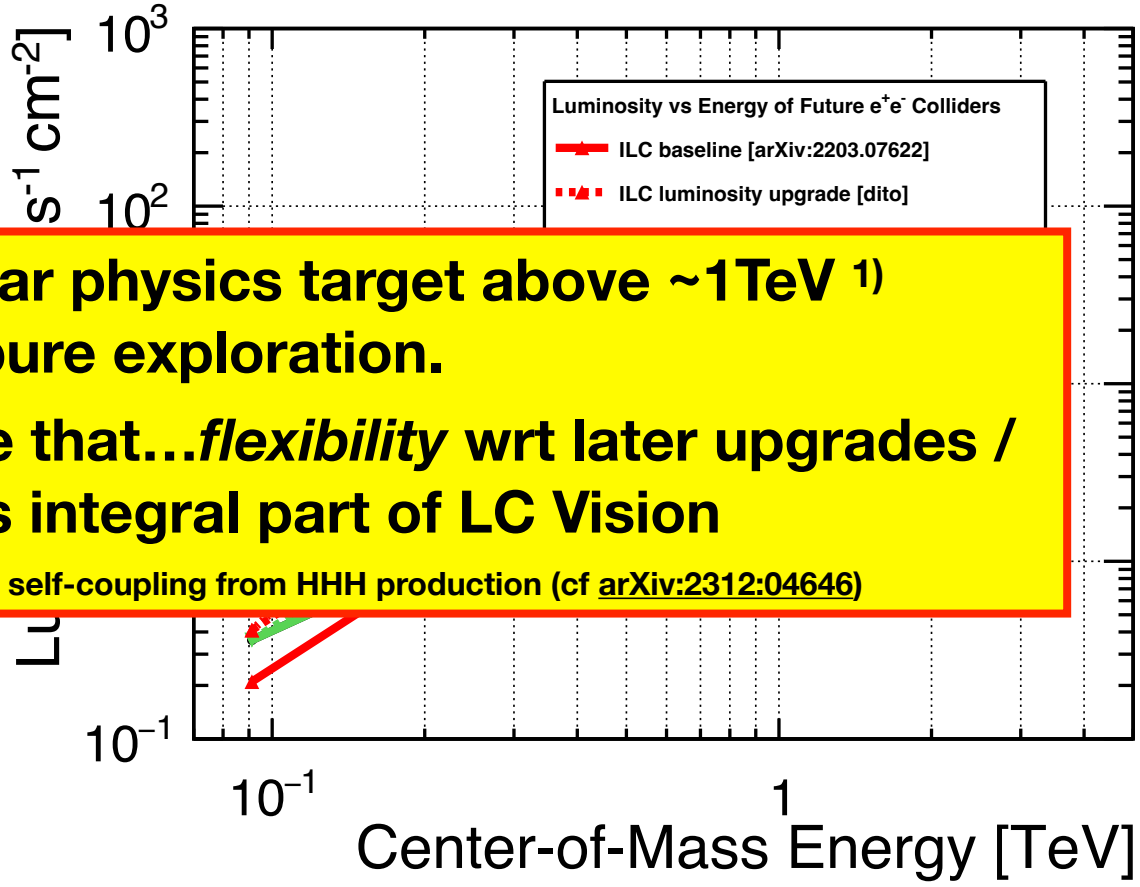
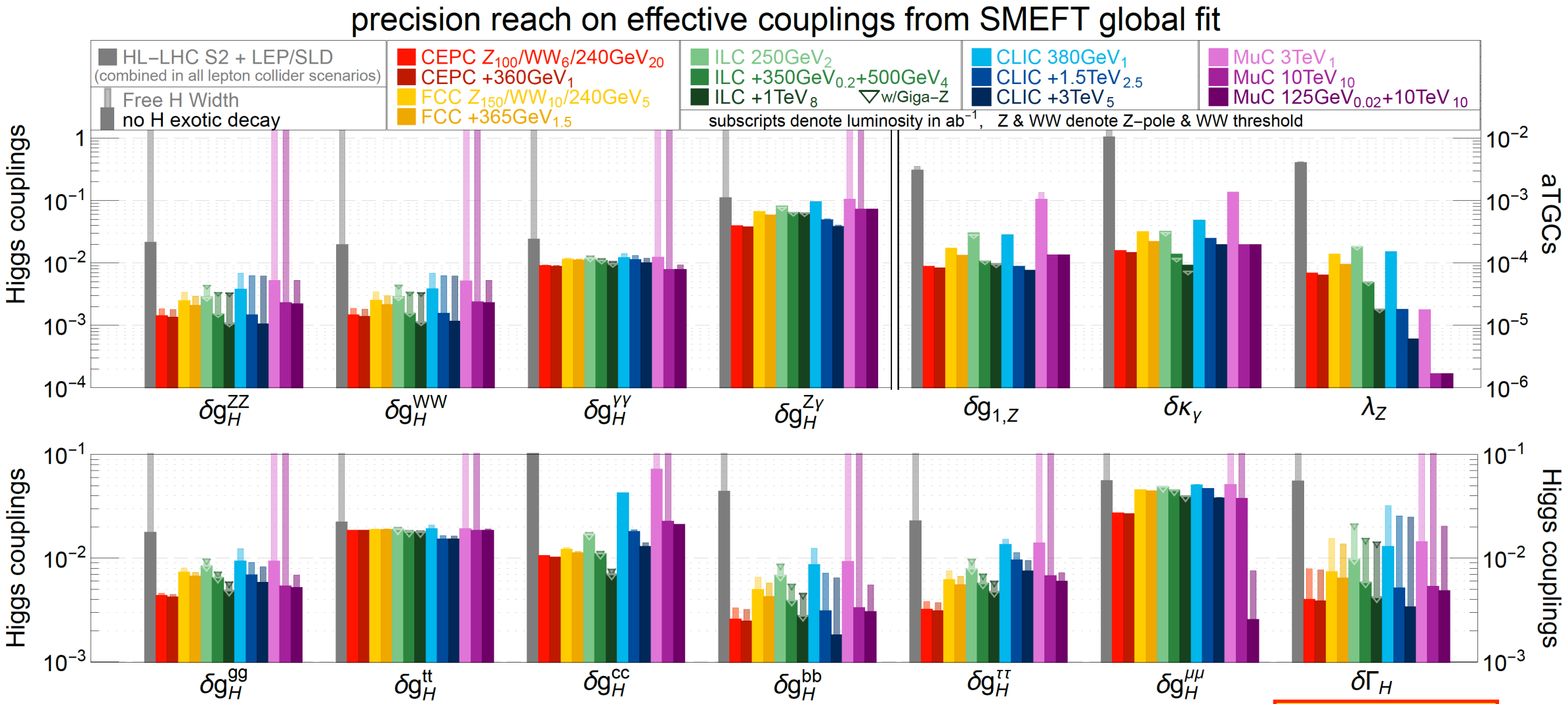


As of today, there's no very clear physics target above ~1TeV [1)]
— apart from pure exploration.

However HL-LHC might still change that…*flexibility* wrt later upgrades / choice of 10 TeV pCoM is integral part of LC Vision

1) 3-10 TeV with 5-10 ab-1 might give access to quartic self-coupling from HHH production (cf arXiv:2312:04646)

All e+e- colliders deliver the basic single-Higgs program



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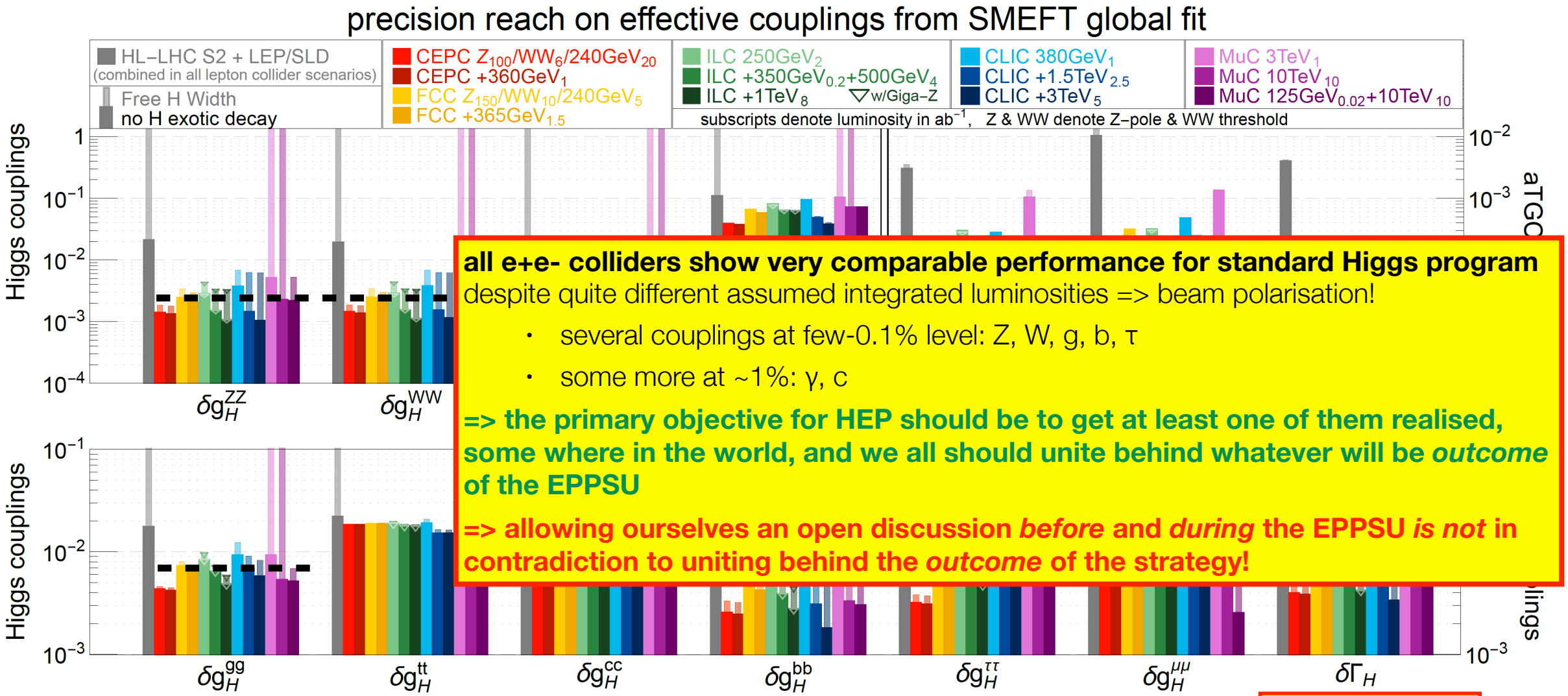

all e+e- colliders show very comparable performance for standard Higgs program
despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

=> the primary objective for HEP should be to get at least one of them realised, some where in the world, and we all should unite behind whatever will be *outcome* of the EPPSU

=> allowing ourselves an open discussion *before* and *during* the EPPSU *is not* in contradiction to uniting behind the *outcome* of the strategy!

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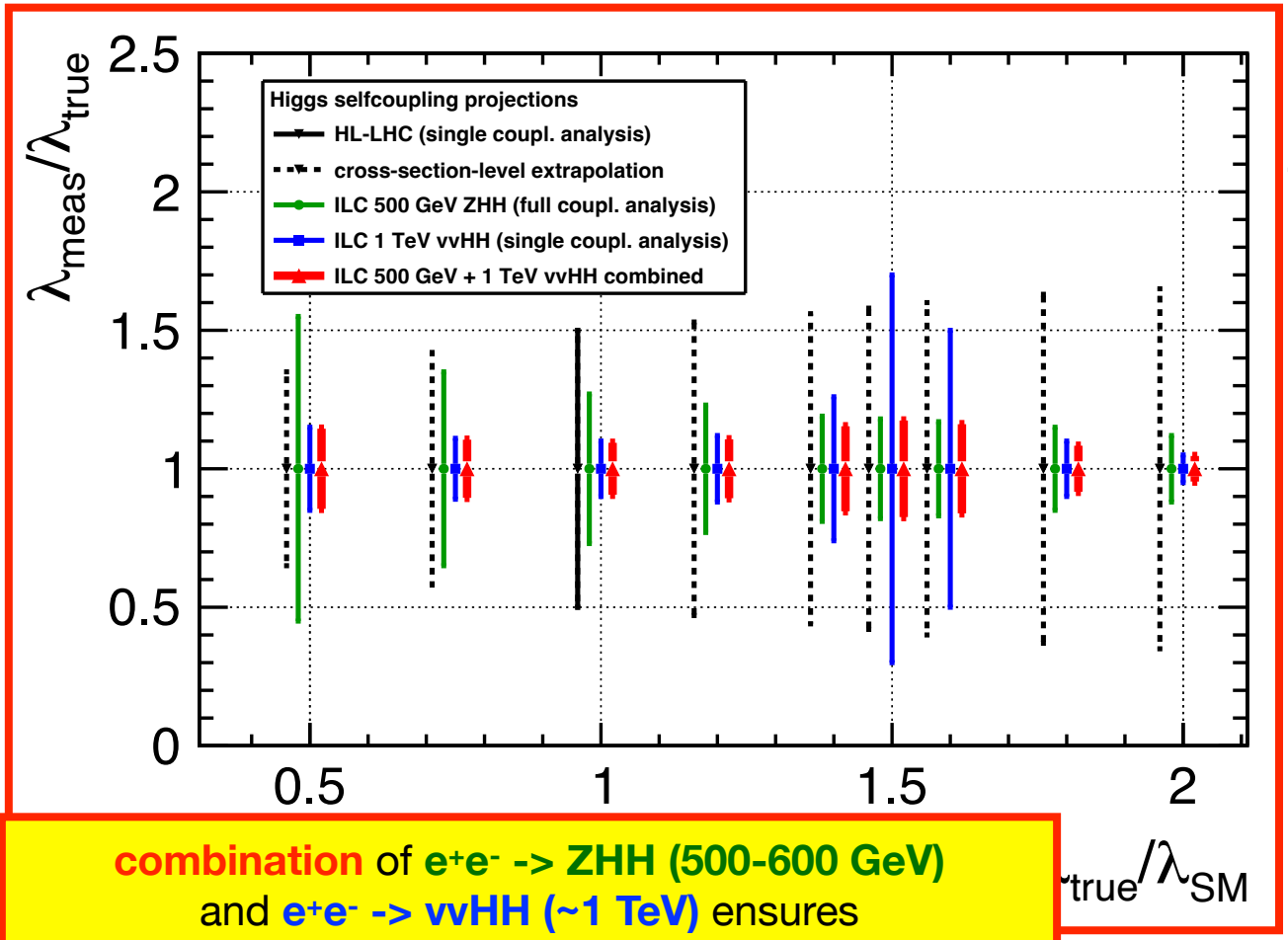
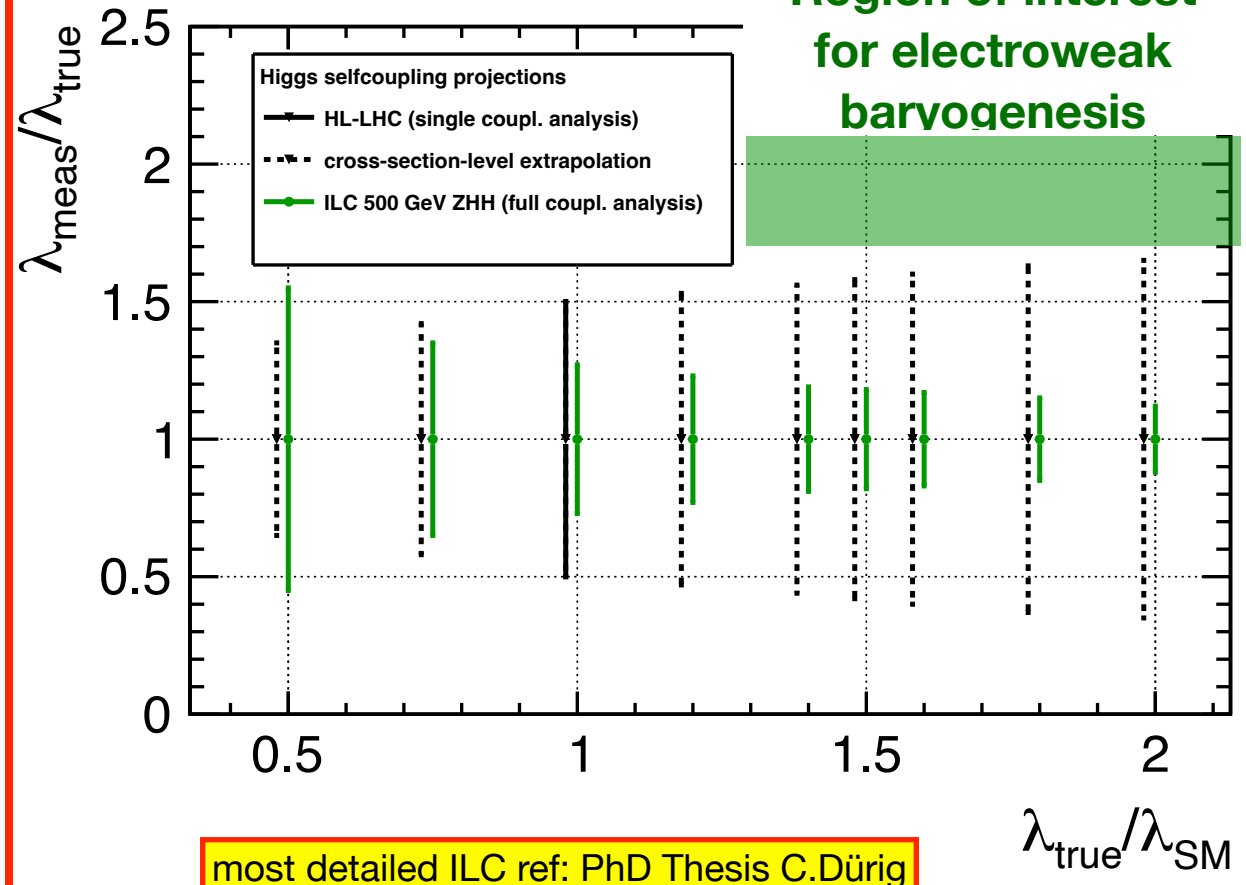
Higgs self-coupling beyond the SM



combination of **e^+e^- -> ZHH (500-600 GeV)**
and **e^+e^- -> vvHH (~1 TeV)** ensures
at least 10-15% precision for all λ

Region of interest for electroweak baryogenesis

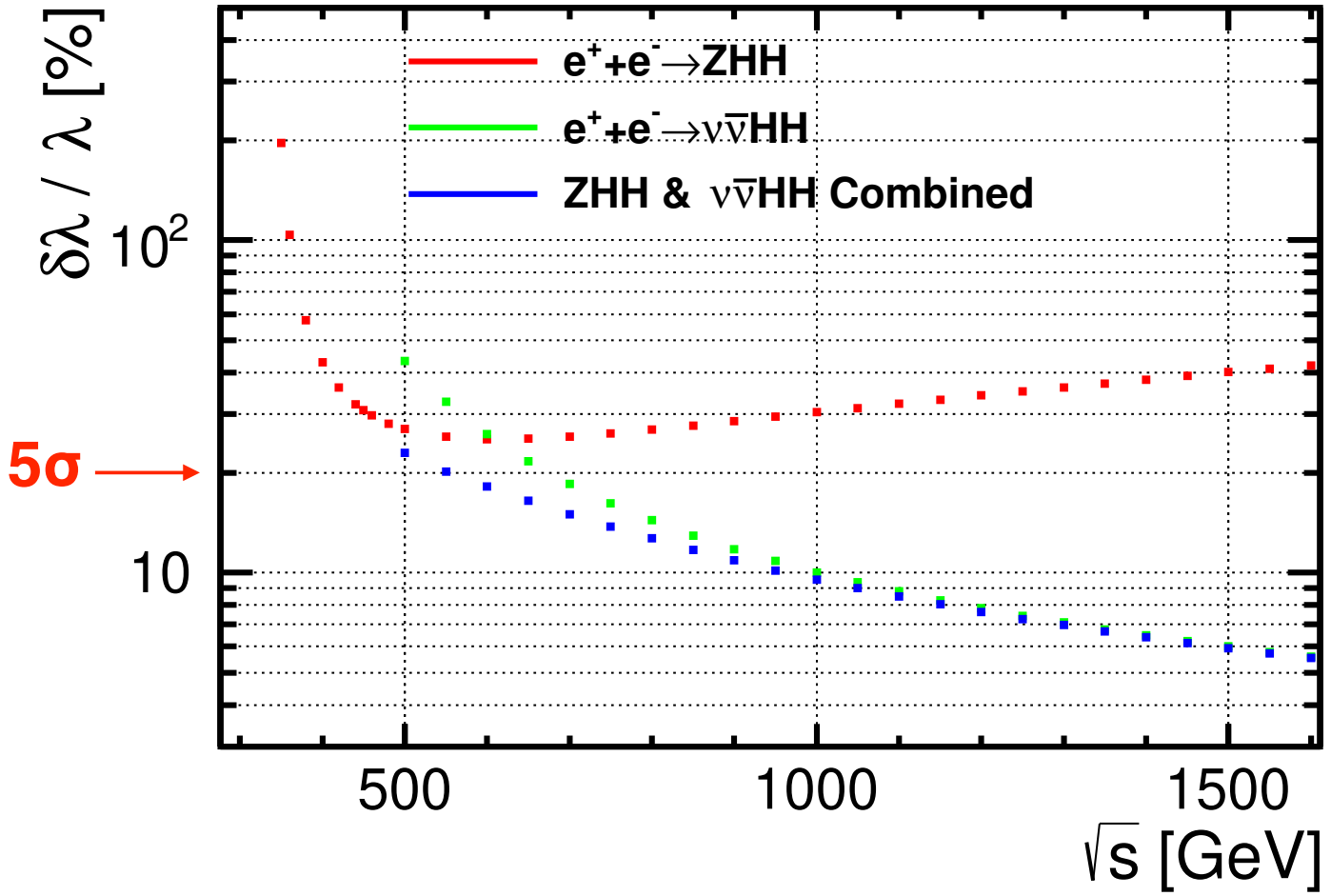


most detailed ILC ref: PhD Thesis C.Dürig
Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING

Higgs self-coupling beyond the SM

- two production channels **combined** at all √s: WW-fusion channel rapidly becomes useful just a little above 500 GeV
- luminosity now also scaled **proportionally** to √s

J.Tian, this workshop



Discovery can be guaranteed

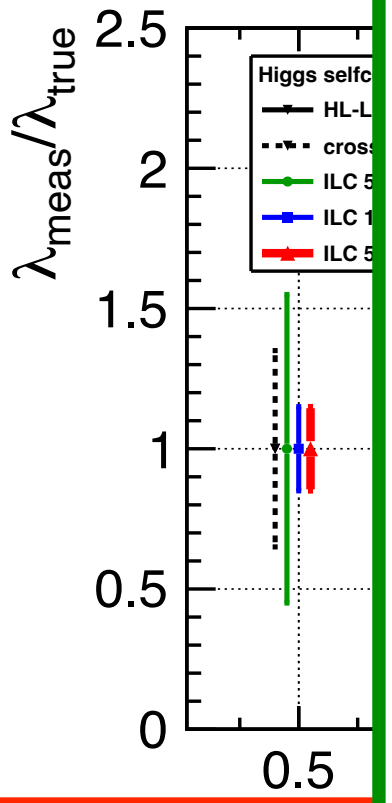
ILC500: 23%

ILC550: 20%

ILC600: 18%

note: this is based on old DBD analysis; large room from new analysis

16



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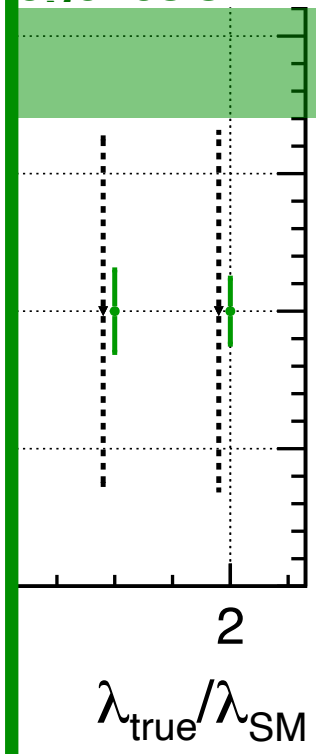

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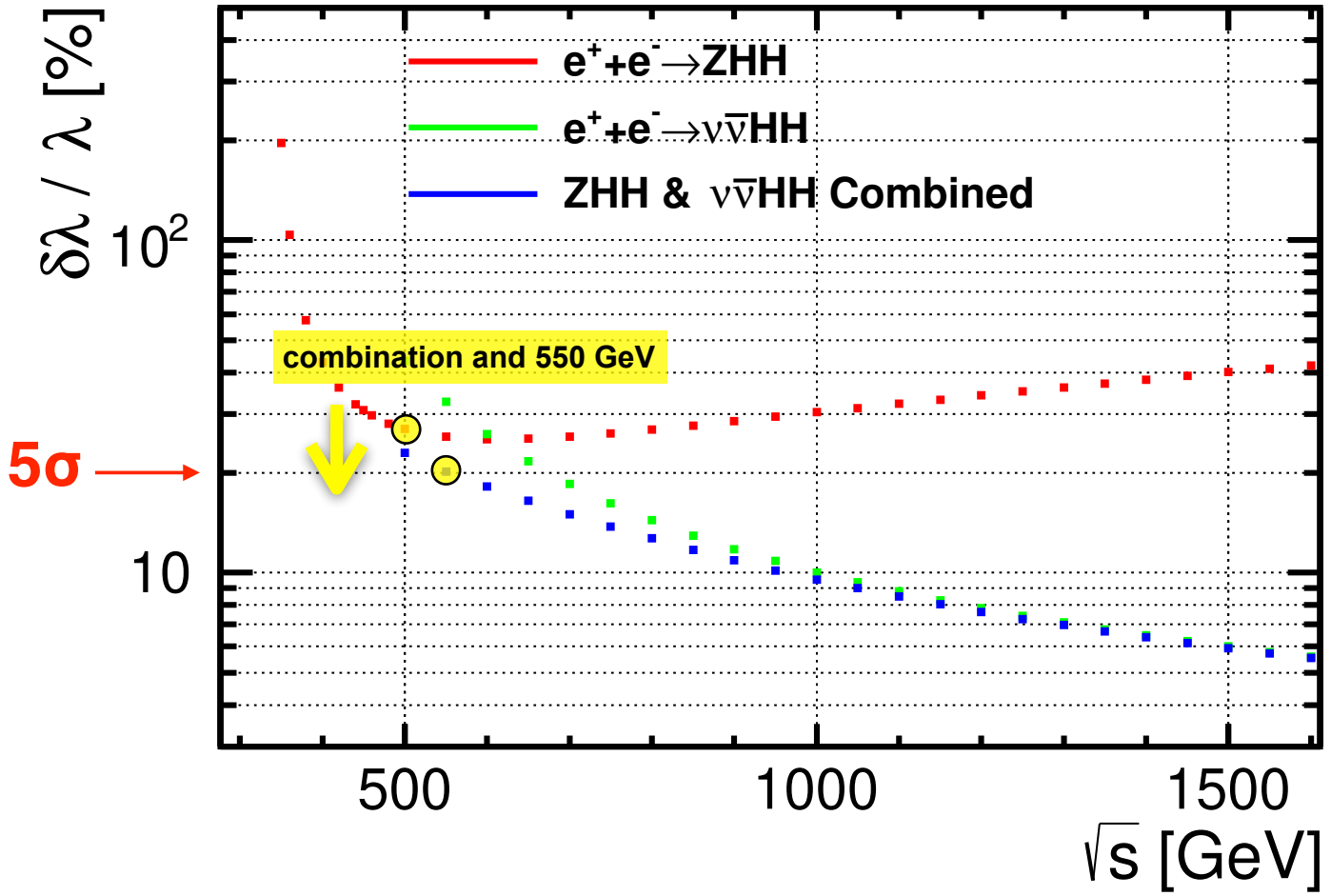

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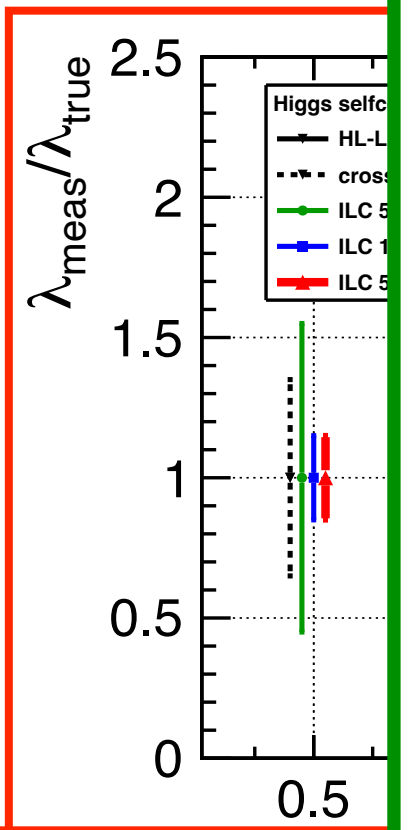

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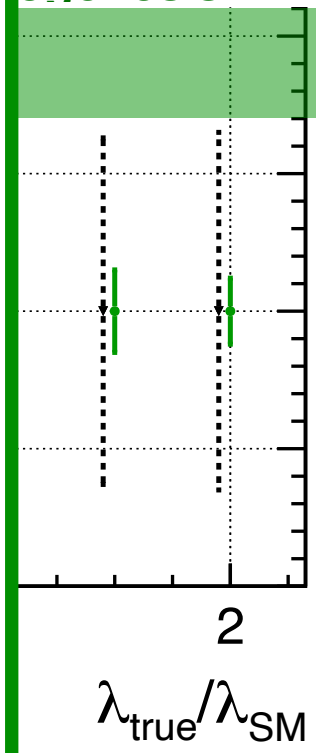

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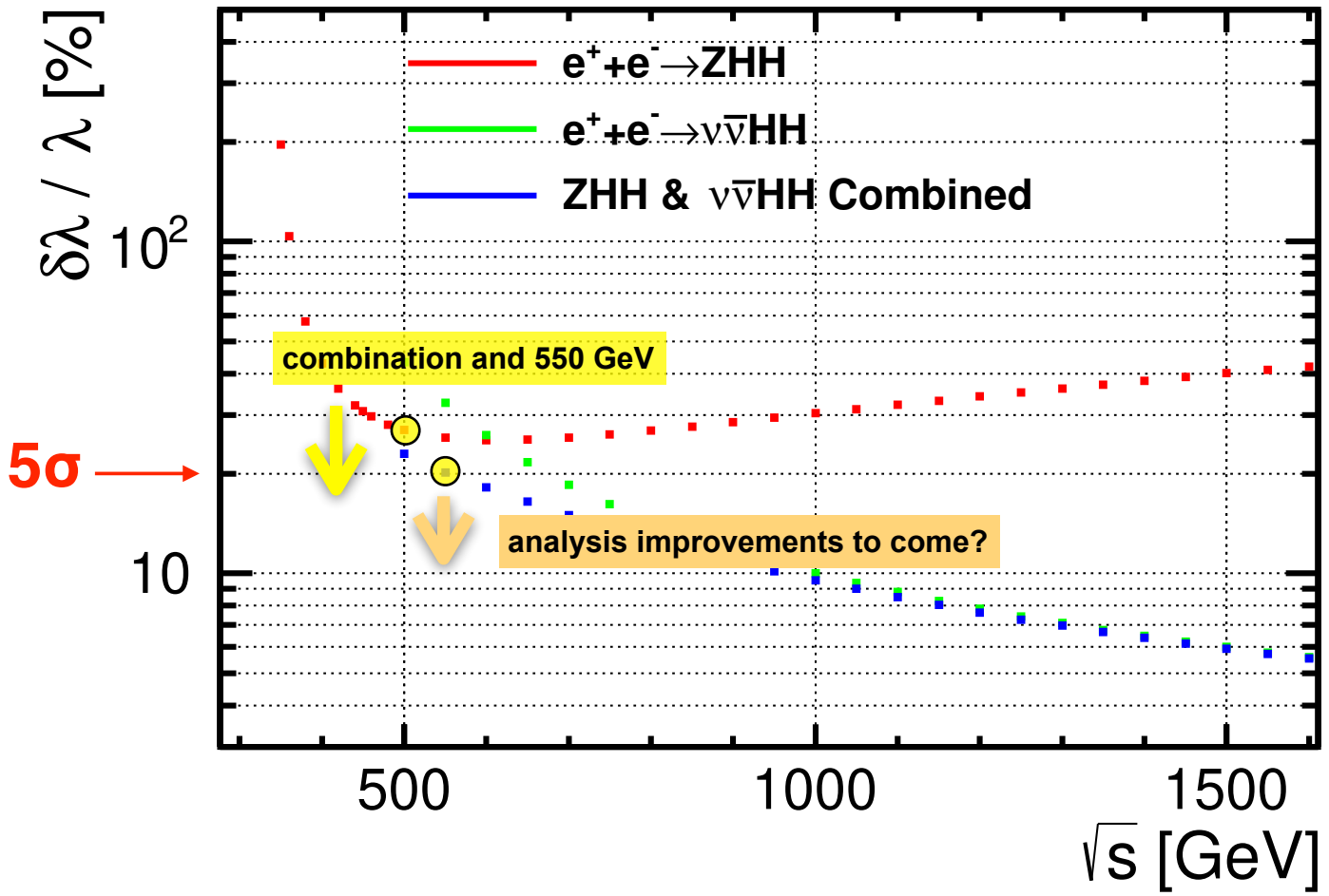

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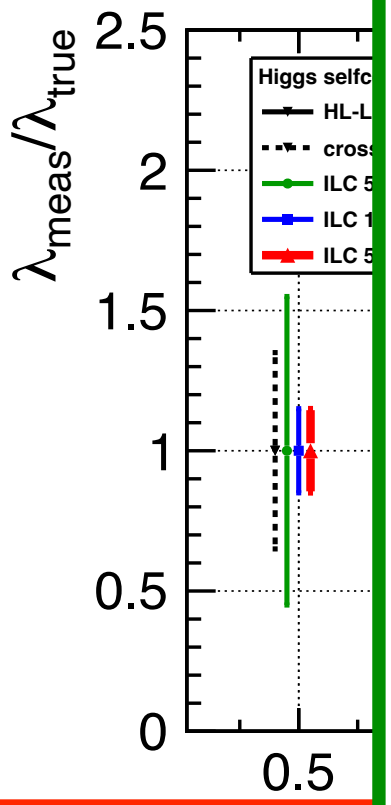

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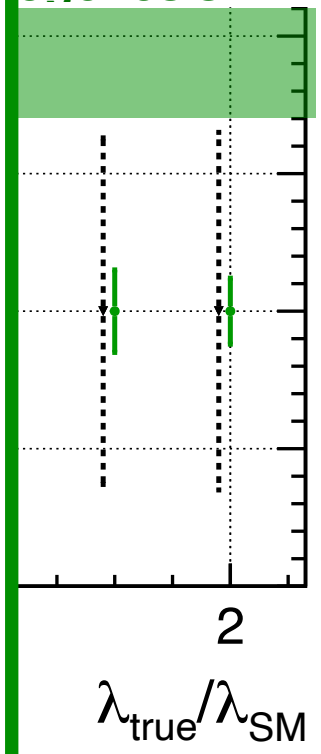
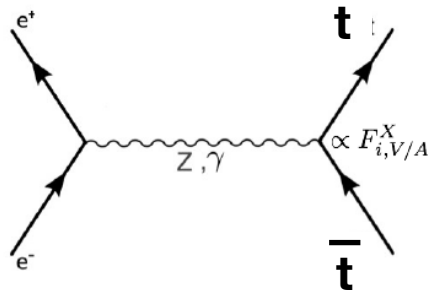
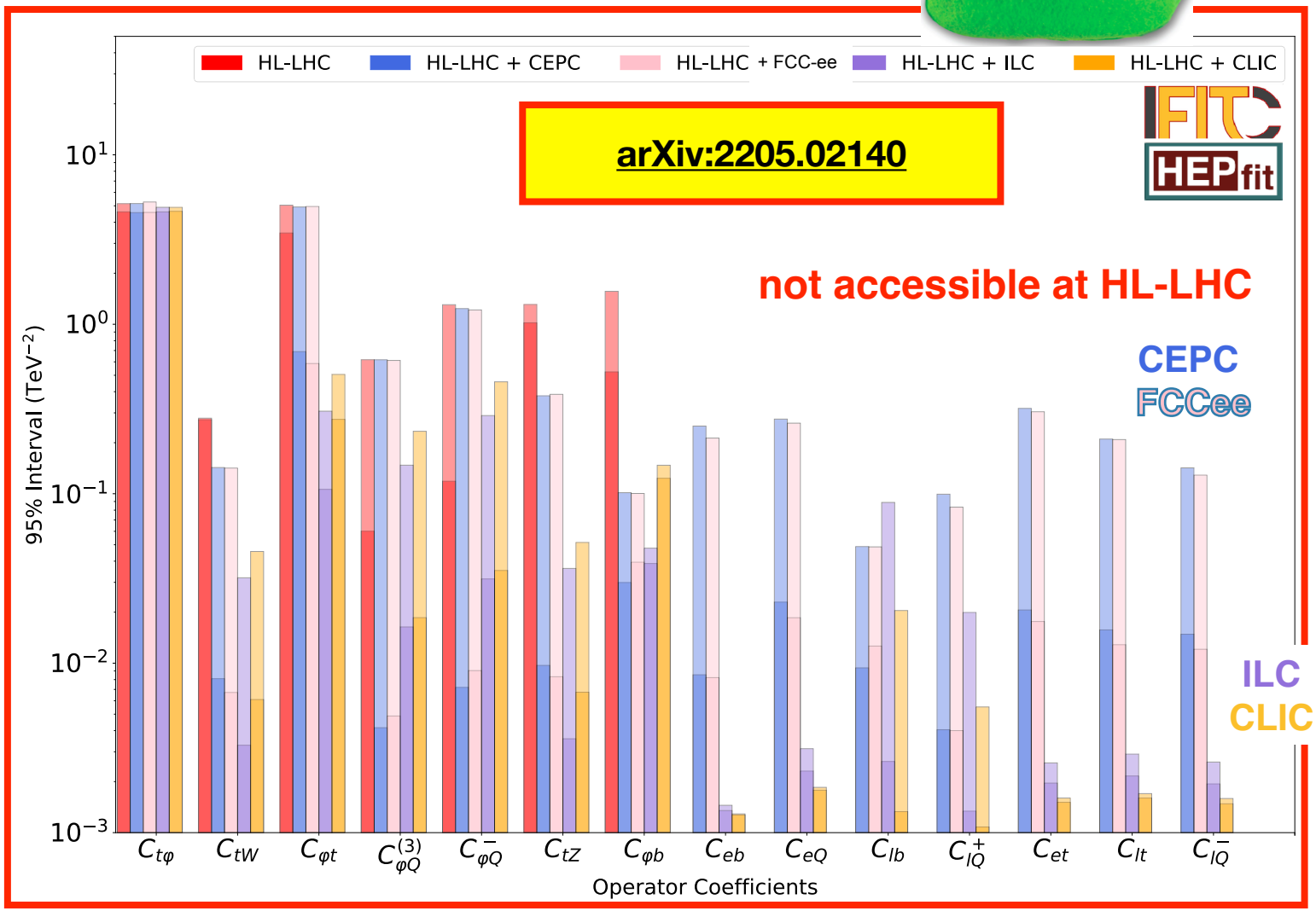


Full SMEFT analysis of Top Quark sector



- expected precision on Wilson coefficients for HL-LHC alone and combined with various e+e- proposals
- e+e- at **high center-of-mass energy** with **polarised beams** lifts degeneracies between operators



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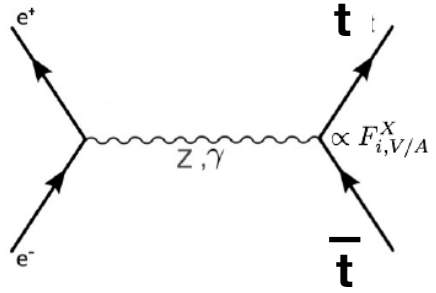

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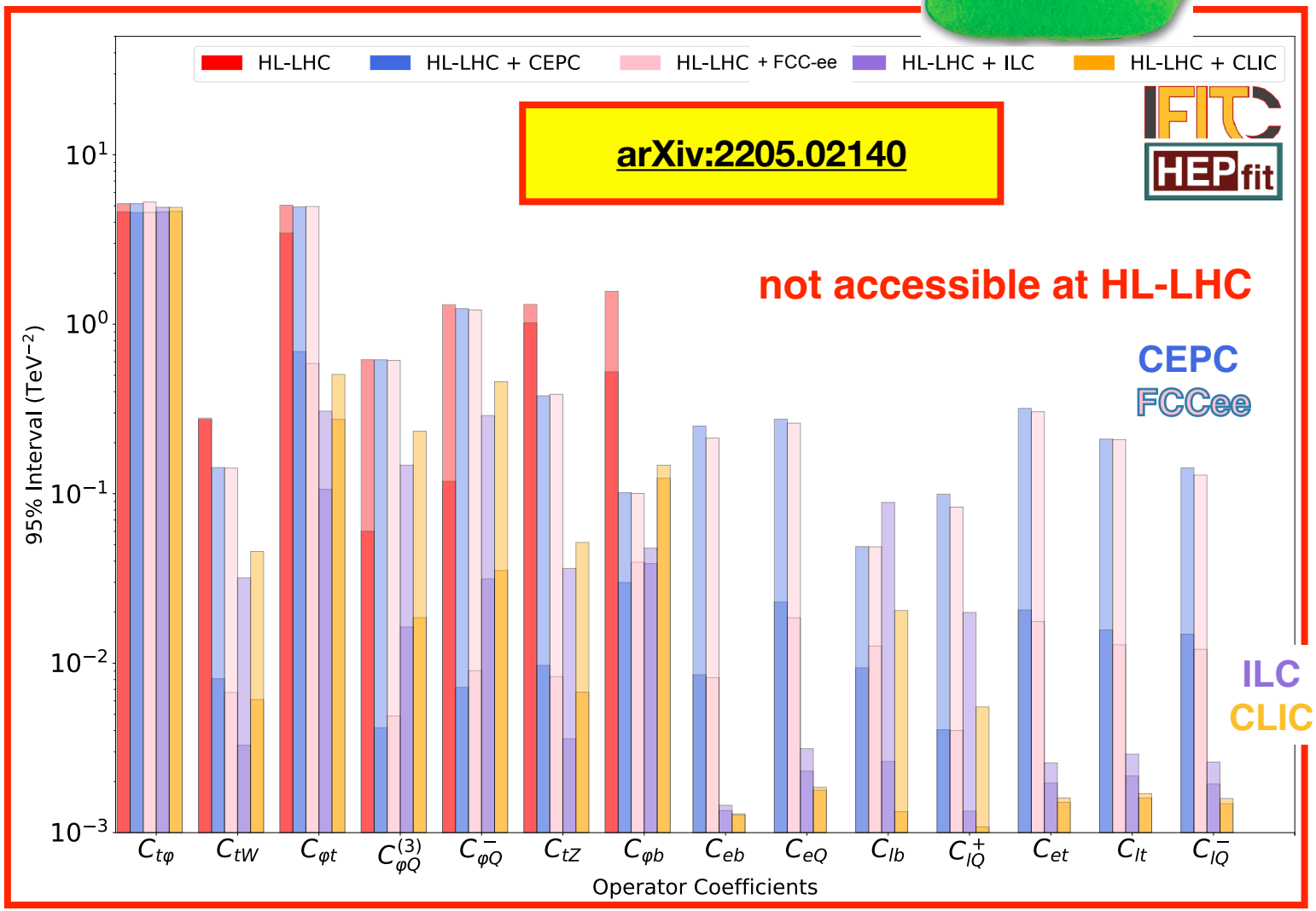
full top-quark physics requires ≥ 500 GeV AND *polarised beams*

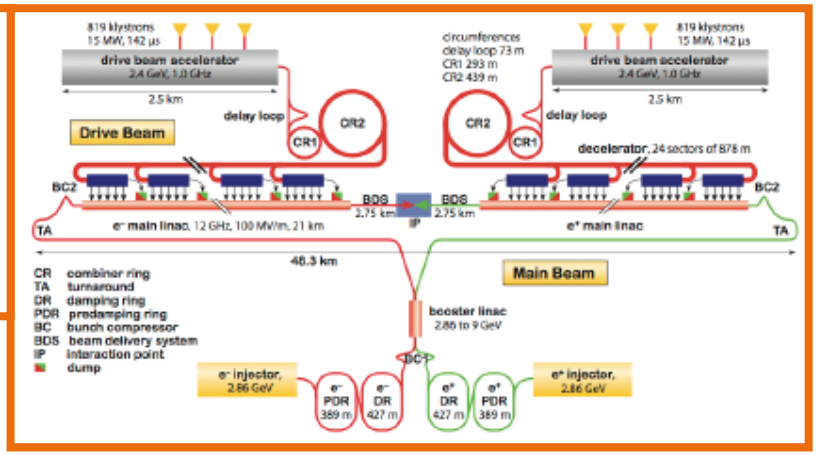


Implementation of a Linear Collider Facility

A Linear Collider Facility — at CERN or in Japan

- **What could be the initial technology for an LCF at CERN? (Japan=ILC)**
  - For many years, CERN pioneered CLIC — from 380 GeV to 3 TeV
    - drive beam technology demonstrated
    - detailed design and costing
      => first stage can be built within CERN budget
      (shown in CLIC Project Implementation Plan, 2018)
- **However could also consider to start out with a linear collider based superconducting RF**
  - proven and *industrialised* technology
  - strong general interest in technology around the world
  - significant industrial production capacities in Europe (and elsewhere)
  - strong lab expertise *outside* of CERN
    => could take significant load off CERNs shoulders while still busy with / paying off HL-LHC
  - CERN site actually been studied for ILC TDR…

CLIC: e^+e^- @ 0.38, 1.5, 3 TeV
Conceptual Design **2012**
Updated Baseline in **2017 & 2021** for Snowmass
2-beam acceleration



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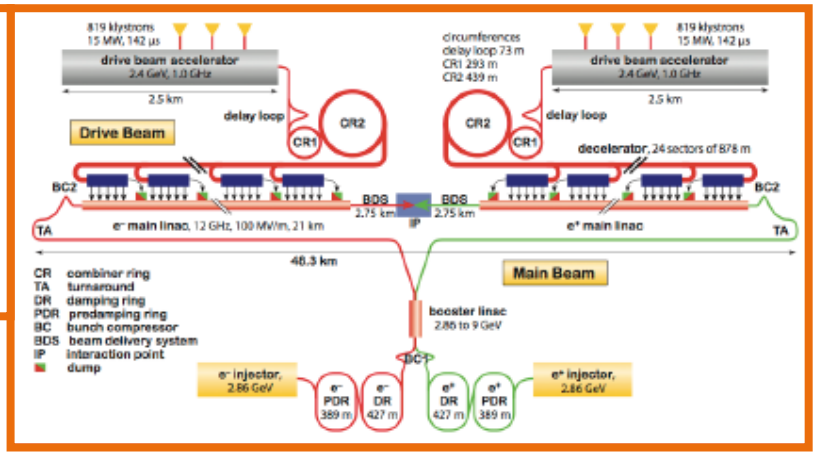
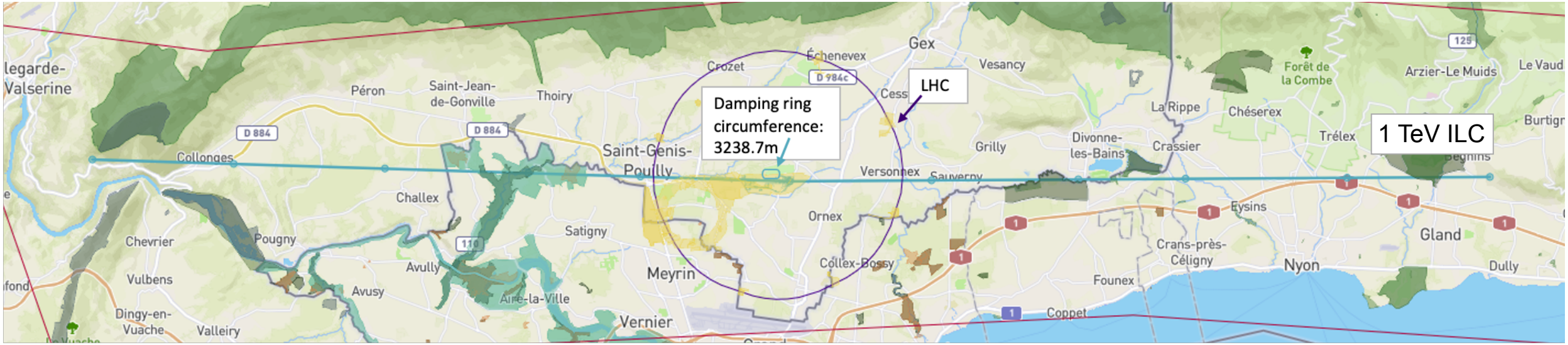


ILC in Japan — or LCF@CERN starting with ILC technology — minimize time til next project
=> crucial for next generation of our community!

Revisiting siting of ILC-like machine at CERN

- **revisiting ILC siting at CERN from TDR and CLIC siting**
  - updating / merging existing material, incl. CERN-specific CFS costing for an “ILC-like” machine
  - extending the CLIC&ILC life-cycle-assessment (“ARUP study”) from civil construction to full project
- **currently ongoing @global LC community:**
  - updating the costing for 250 GeV and 550 (!) GeV SCRF collider



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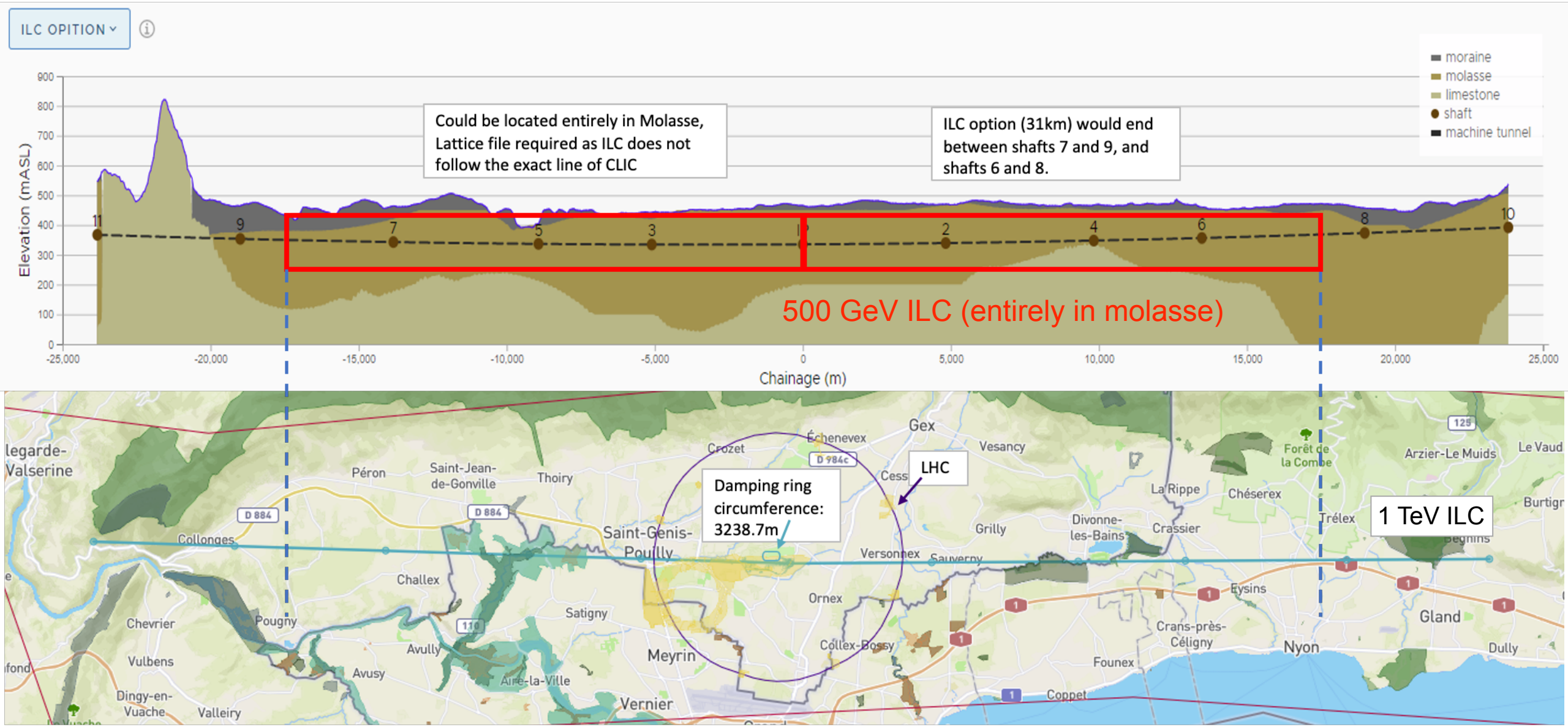
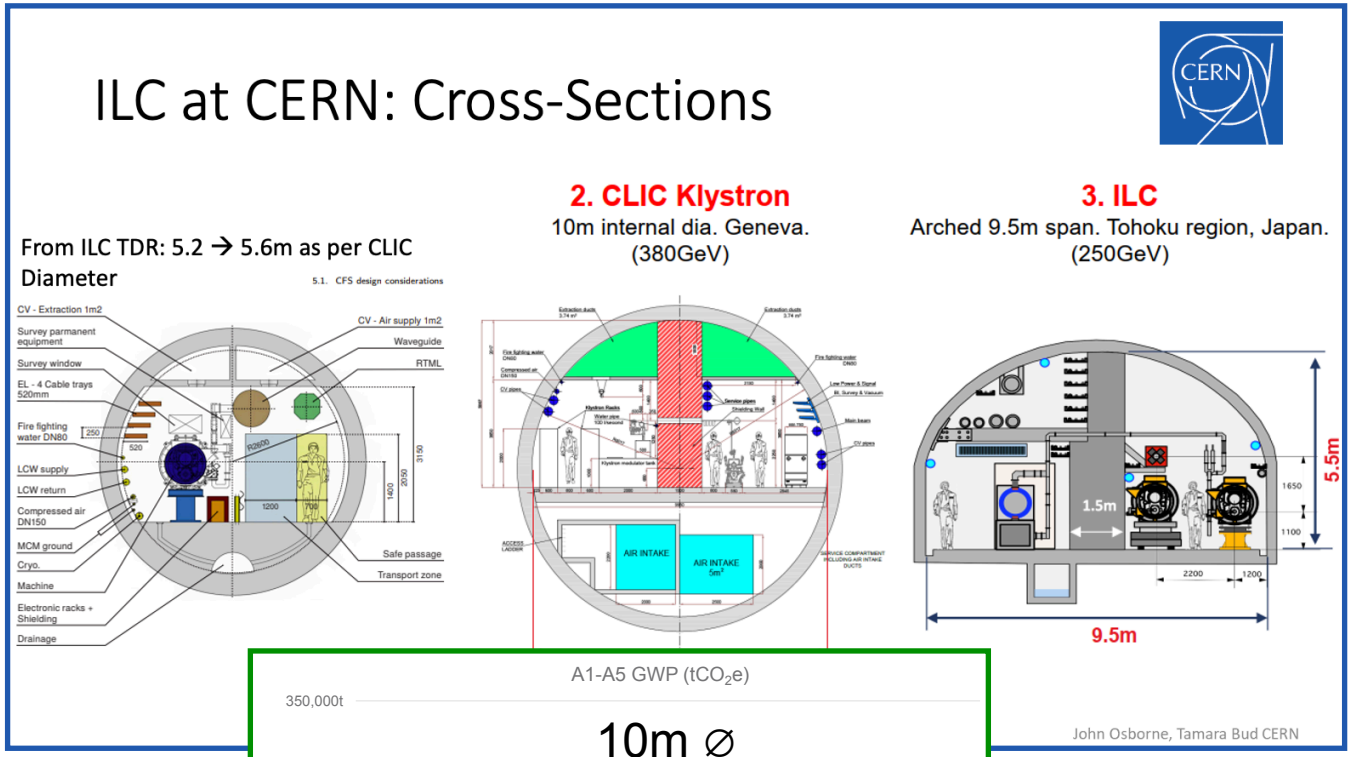
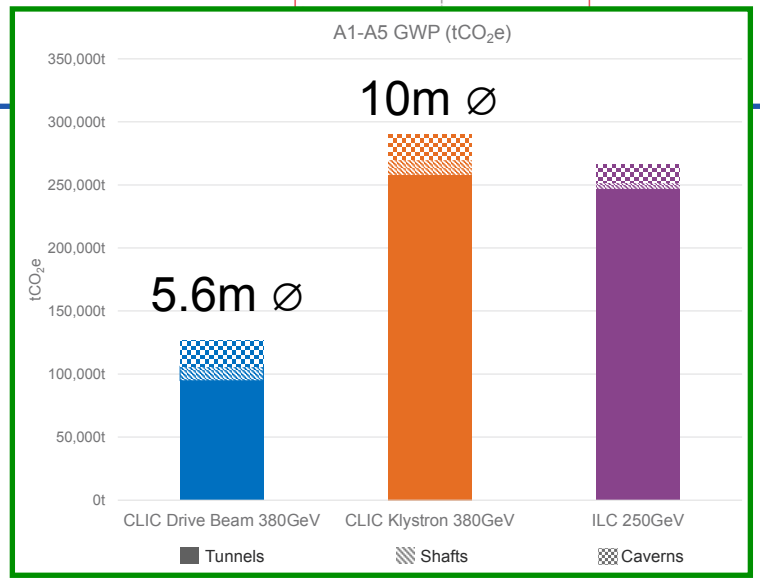


Tunnel Geometry and Global Warming Potential

- Linear Collider Facility at CERN:
  - **round tunnel like for XFEL (5.2m) or CLIC (5.6m)**
  - diameter, wall thinkness to be optimised
- ARUP study for CLIC/ILC tunnels:
  - **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
  - green house gas emission plus 13 more impact categories
  - showed room for 40% reduction of GWP
  - **new**: being extended to “content” of tunnels & halls

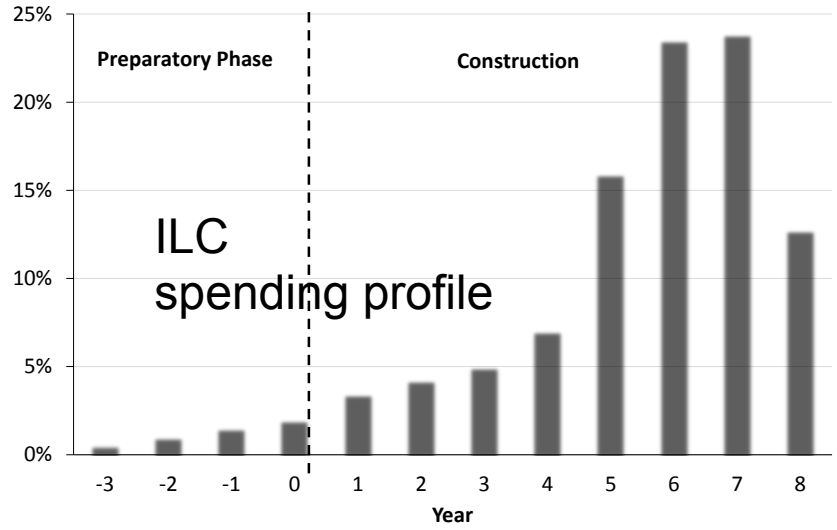
https://edms.cern.ch/document/2917948/1

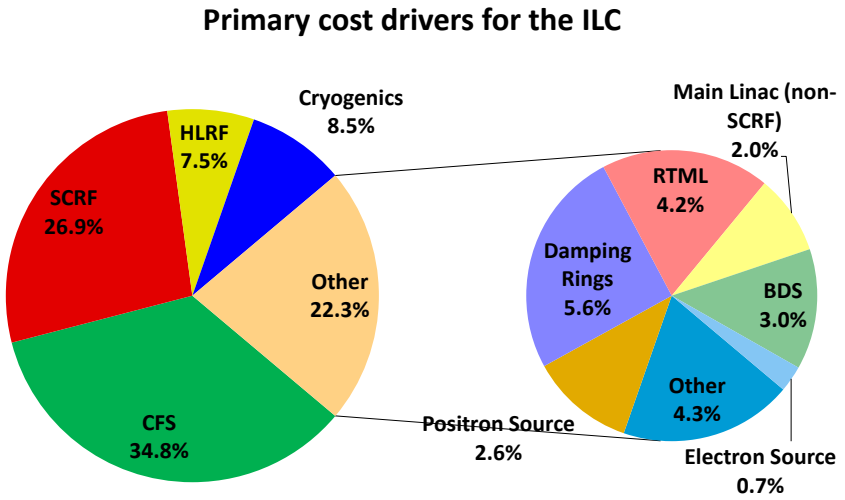


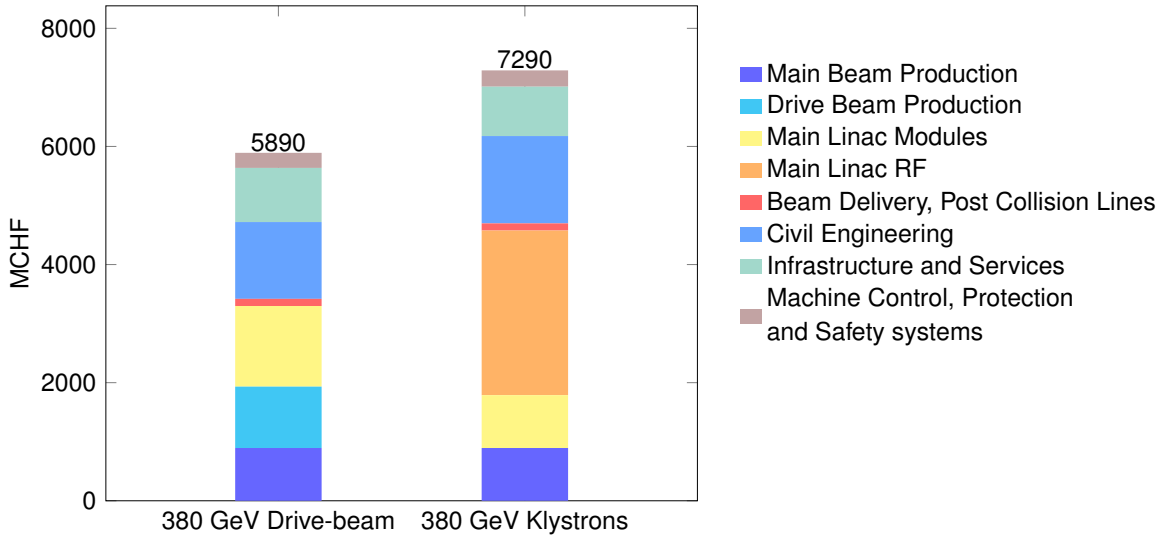


Cost estimates…

- **Cost estimates are being updated - stay tuned….**
- **old (!)** existing costings (European accounting):
  - CLIC500 (CDR, 2010): **7.4 BCHF**
  - ILC500 (TDR, 2012): **8 BILCU** (ILCU = US$ in 2012)
  - CLIC380 (drive-beam / klystron, EPPSU 2018): **5.9 / 7.3 BCHF**
  - ILC250 (EPPSU 2018): **5 BILCU**
- **CLIC380 has been shown to be financiable from CERN budget over construction time** (CLIC Project Implementation Plan 2018)







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  - ILC250 (EPPSU
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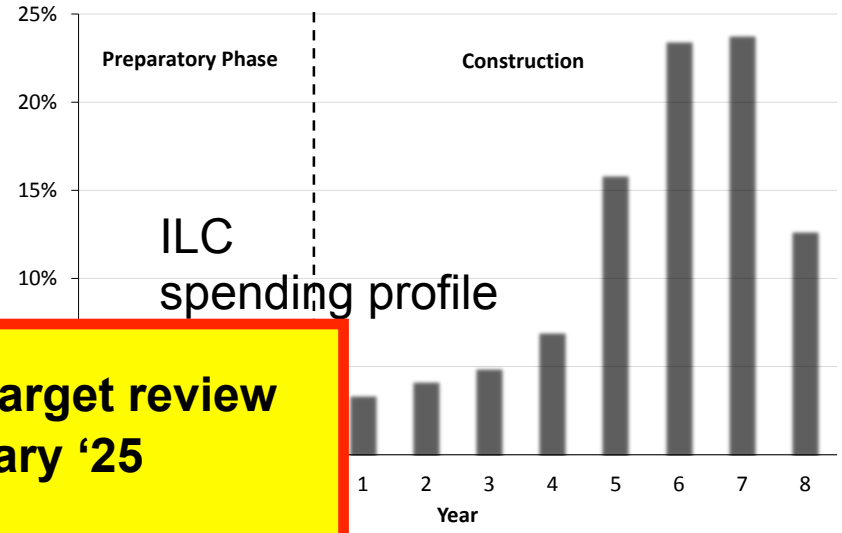
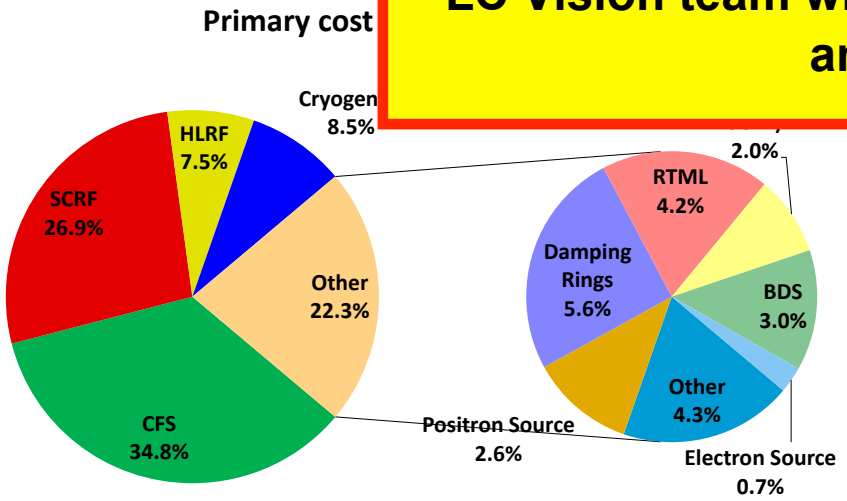
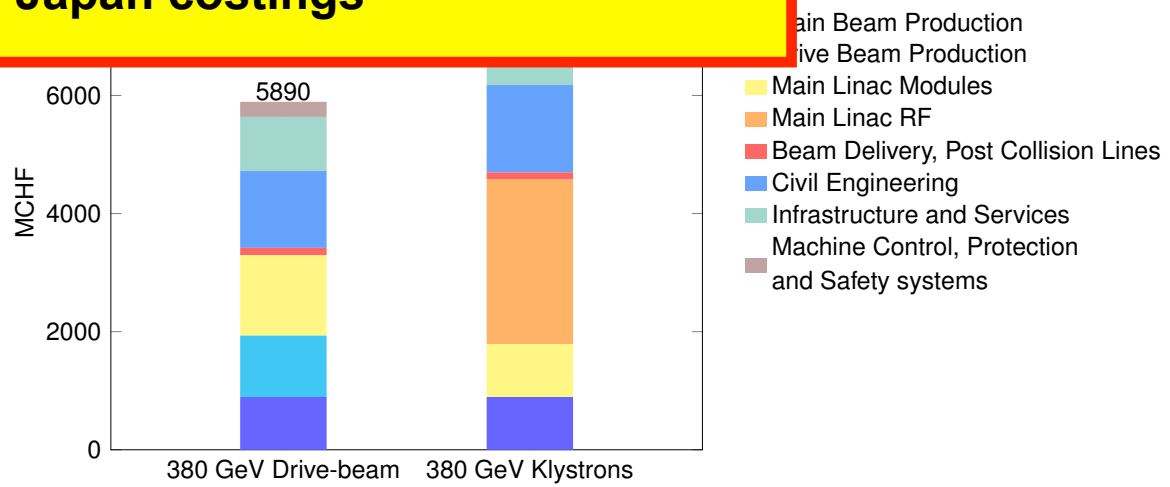
  construction time (

ILC (in Japan) cost update underway by IDT, target review in December ’24, public release in January ‘25

LC Vision team will estimate ILC@CERN with help of CLIC and ILC in Japan costings

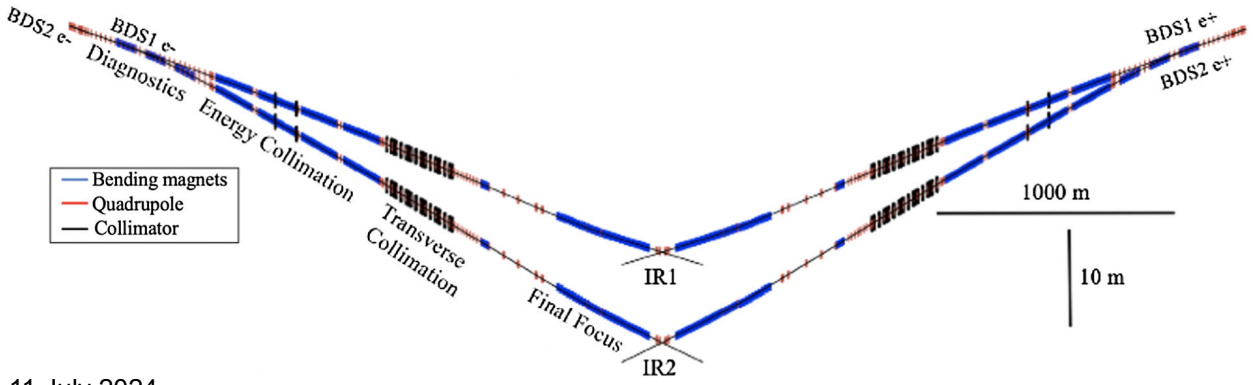


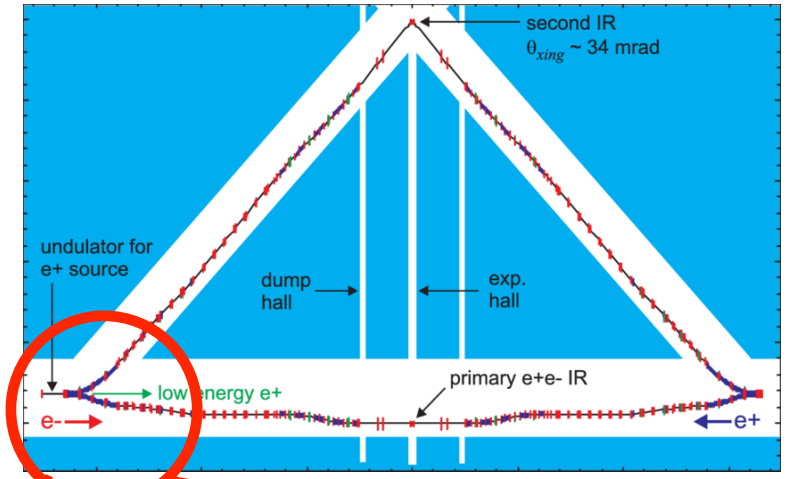


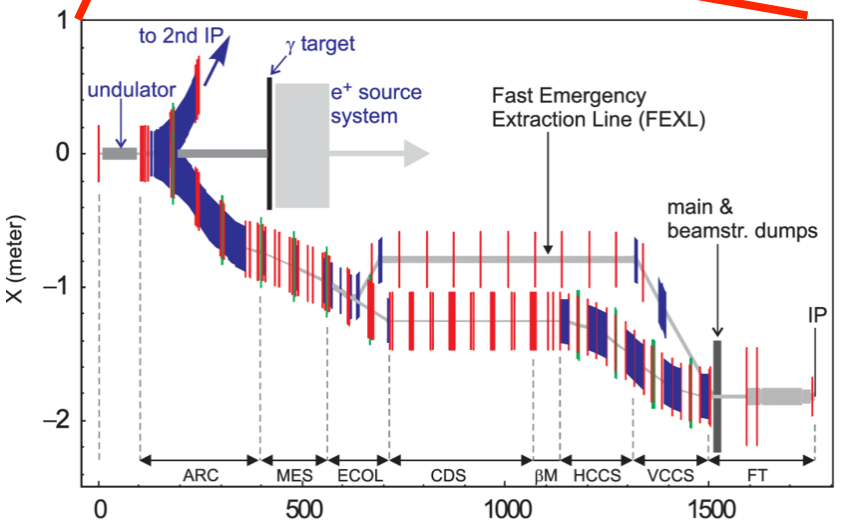


2nd Interaction Region — for 2nd e+e- detector — or γγ / eγ / e-e- ?

- **2nd Beam Delivery System (BDS) to 2nd Interaction Region,** served "quasi-concurrently", by switching on train-by-train basis have been **designed for ILC & CLIC**
- eliminating it from ILC baseline "saved" **O(0.5) BILCU — could reinstantiate for a Linear Collider Facility**
- **2 IRs are important for**
  - 2 detectors for redundancy, technological complementarity, systematic cross-checks, competition
  - special collision modes: e-e- / γe / $\gamma\gamma$, each adding specialized, unique physics opportunities
  - …but do of course *not* double the e+e- luminosity







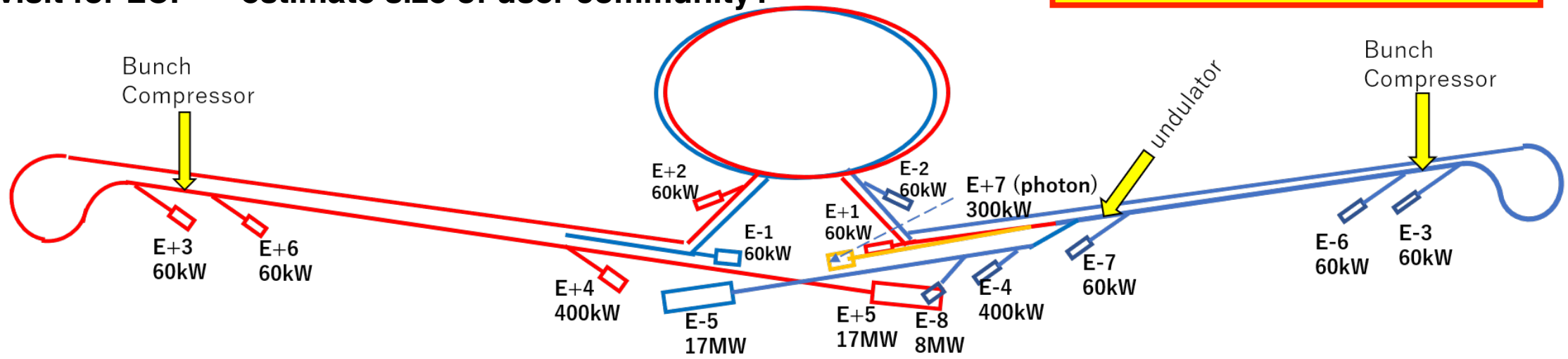
Beyond e+e- Collisions - Beam Dump / Fixed Target Experiments

- **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 4×10^{21} eot/a (SHIP: 10^{20} pot in 5 years)
    - **super-SHIP, generic dark photon and ALP searches**

      => together with e+e- cover all Dark Sector portals
- **Studied for ILC around 2021**
- **Revisit for LCF — estimate size of user community?**

ILCX workshop | **Chap 11 of arXiv:2203.07622**

and talks at this LCWS!



Beyond e+e- Collisions - Test and R&D Facilities

- **low-emittance, mono-energetic beams ideal for**
  - high-rate detector and beam instrumentation tests

ILCX workshop

  - 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**
- **impact on e+e- luminosity?**
  - ILC: ~1300 / ~2600 bunches per train
  - **extracting 10 bunches per train is few-permille loss in luminosity**

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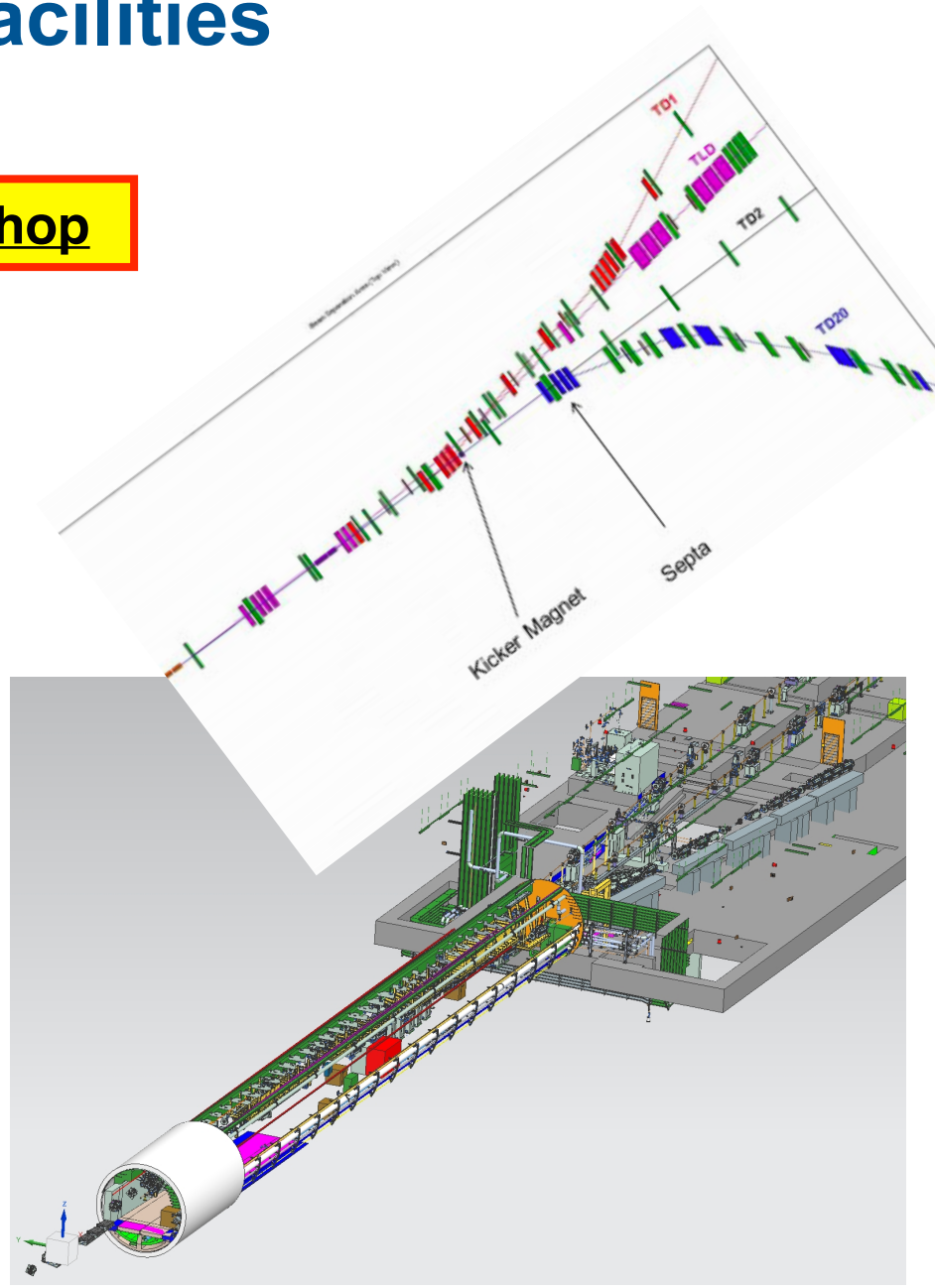


Pioneering this *now* at DESY / Eu.XFEL with ELBEX facility (beam extraction for LUXE & other applications)

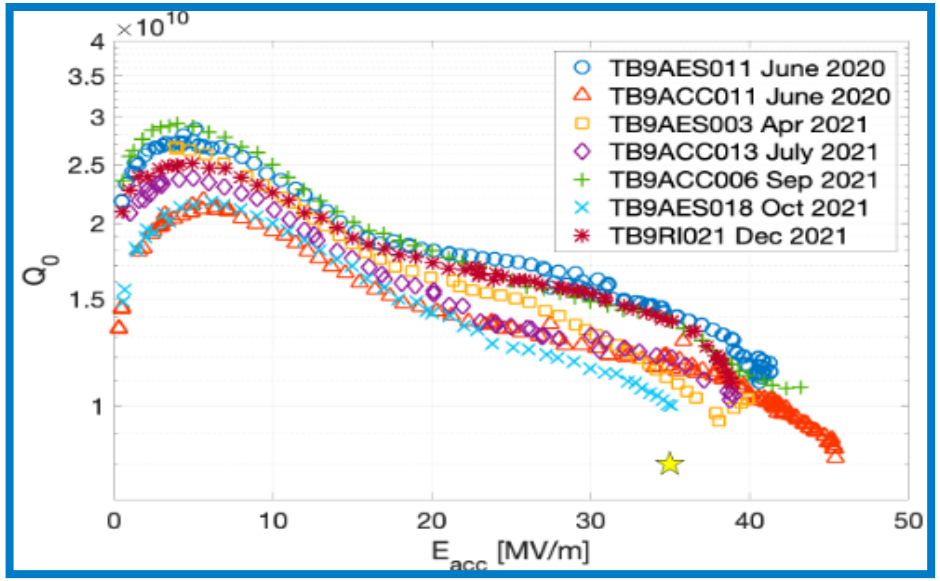
Upgrade Options - Higher Energy "conventional"

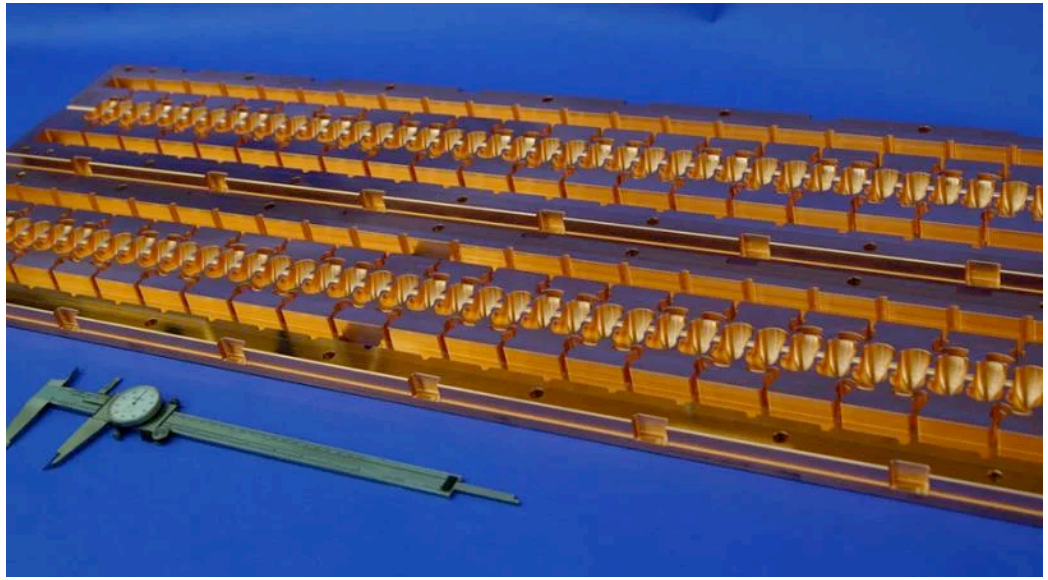
Chap 15 of arXiv:2203.07622

- **ILC TDR: upgrade of SCRF machine up to ~1 TeV**
  - extend tunnel to ~50 km, upgrade power to 300 MW

    => huge but unsexy? Still: guaranteed fall-back…
- **Advanced SCRF**
  - higher gradient cavities exist in the lab (45 MV/m vs 31.5 MV/m ILC design), though not yet industrially available

  => upgrade to > 1 TeV — or less new tunnel
- **rip out SCRF and replace by X-band copper cavities (à la CLIC or C3)**
  - 70-150 MV / m **=> double (3x, 4x …?) energy without tunnel extension**
  - sell / donate SCRF modules to build XFELs, irradiation facilities, … all around the world





Upgrade Options - Double ECM by “HALHFing” LCF

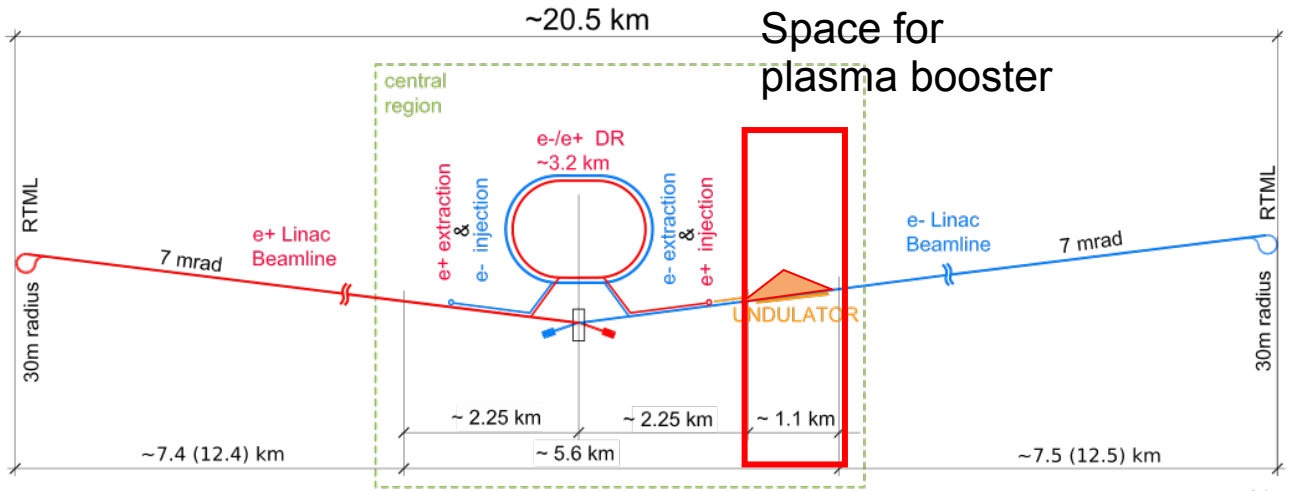
- **Apply HALHF concept to eg 250 GeV ILC:**
  - **plasma-accelerate** e- to 550 GeV
  - keep e+ linac
    (small upgrade 125 -> 137.5 GeV)

⇒ 137.5 GeV on 550GeV ⇒ ECM = 550 GeV

⇒ upgrade Higgs Factory to tt / tth / Zhh factory

- How?
  - Reduce e- linac energy by 4 to 34.4GeV
  - Drive 16 stage plasma accelerator
- Use space between electron ML and BDS to install plasma booster
- Feed boosted electrons into existing BDS (already laid out for $E_{beam} \approx 500$ GeV)

		E- (drive)	E- (Collide)	E+
Beam energy	GeV	34.4	34.4 → 550	137.5
Linac Gradient	MV/m	8.7		35
CoM energy	GeV	550		
Bunch charge	nC	4.3	1.6	6.4
Bunches/pulse		10496	656	656
Rep rate	Hz	5		
Beam power	MW	8.0	0.18 → 2.9	2.9
Lumi (approx.)	$cm^{-2}s^{-1}$	$\sim 1 \cdot 10^{34}$		



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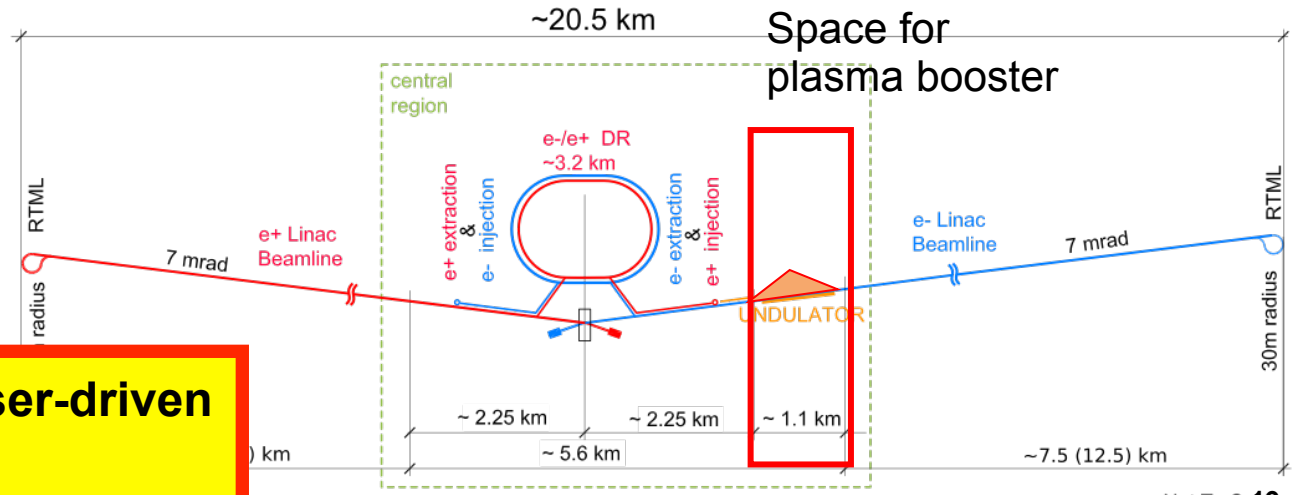
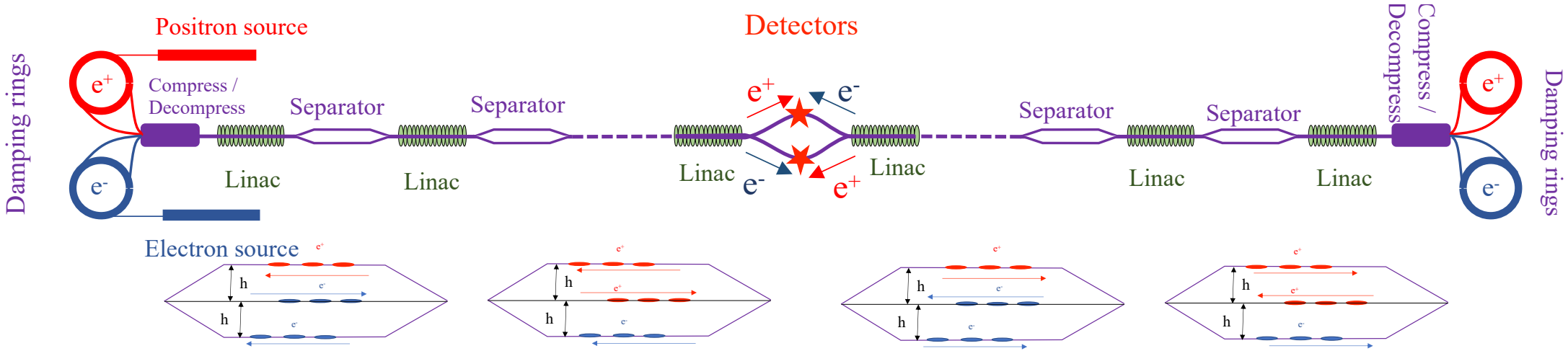


Can we work out a corresponding scheme for laser-driven plasma / ALEGRO-style upgrade?

Upgrade Options - Higher Luminosity à la “ReLiC”

arXiv:2203.06476 [hep-ex]

- **Energy *and* particle recovery by de-celaration and re-cooling**
- Conceptual study indicates up to O(100) higher luminosity than ILC / CLIC conceivable
- Effectively no beamstrahlung **=> even Higgs resonance operation not fundamentally excluded** (conceptual idea exists but needs verification by beam optics study)



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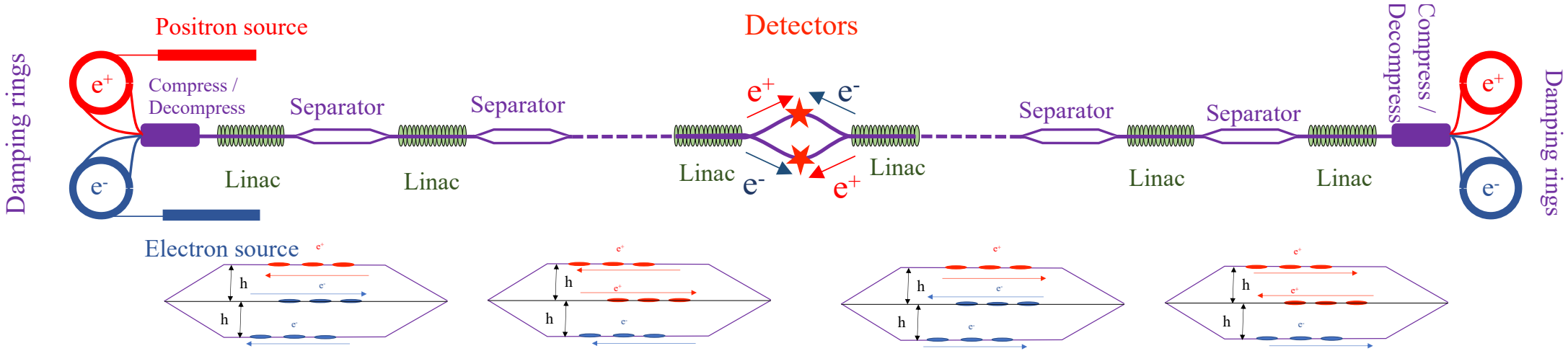
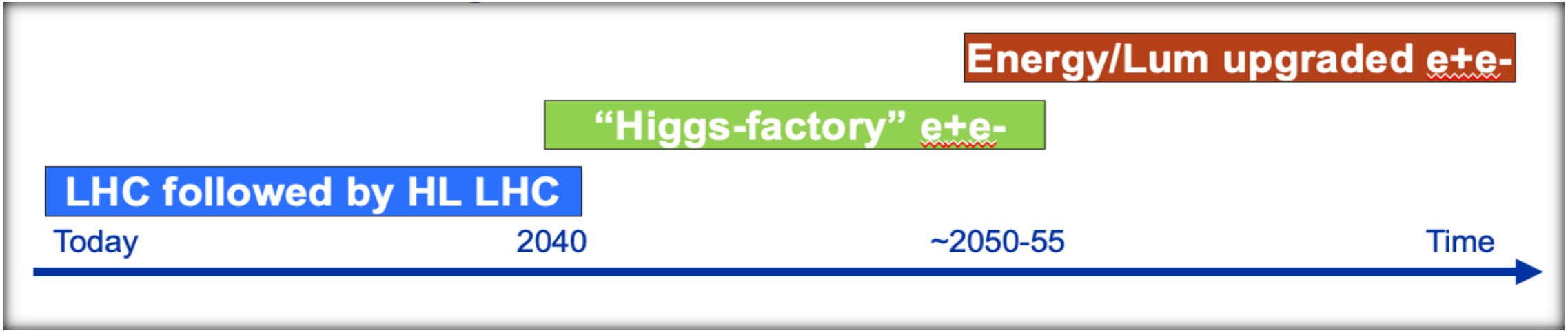
Integrate R&D and demonstrator into initial LCF, upgrade option if successful?



A Linear Collider Facility and the Energy Frontier

Eventually, we want to explore the O(10 TeV)-parton-ECM scale:

- **a Linear Collider Facility does not restrict the choice of how to explore the energy frontier**
  => can choose independently based on scientific and technological developments
- **nor is it coupled to the site:**
  => if technology ready fast, could start building energy frontier machine without stopping e+e- program



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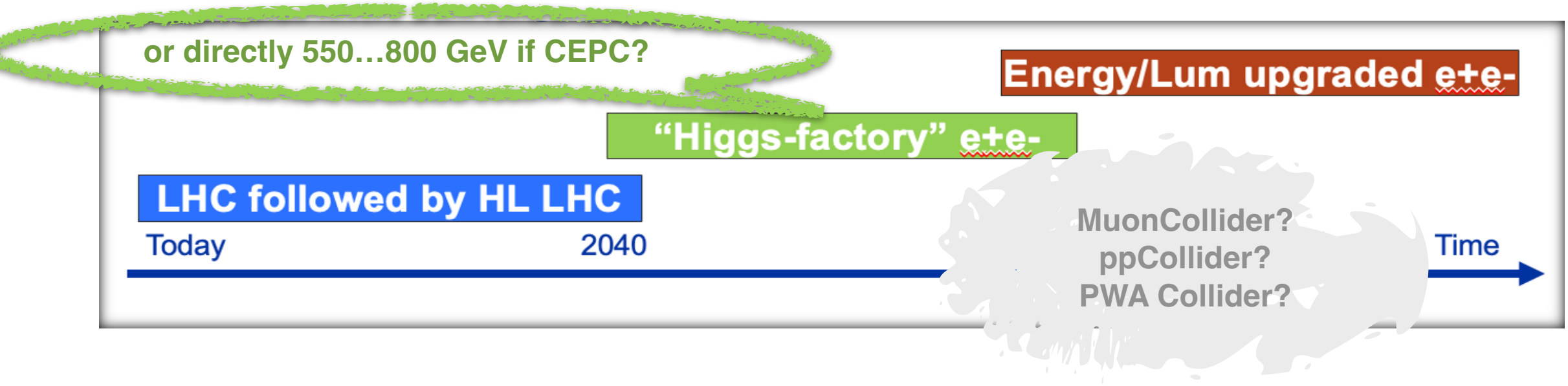

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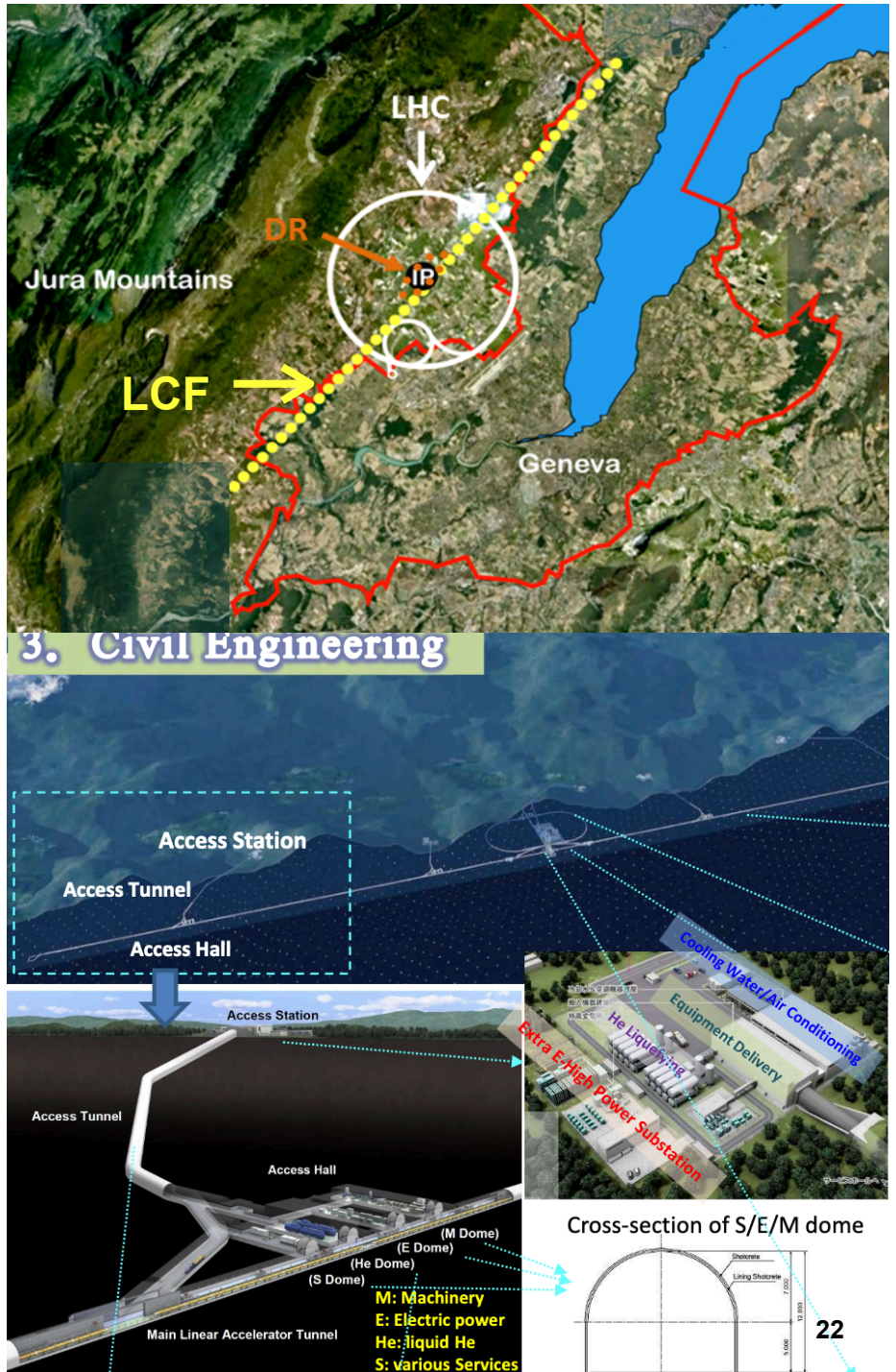
Important: need significant R&D program and demonstrators to bring advanced accelerators to construction readiness - must be part of the over all picture (funding, people, facilities…)

Conclusions

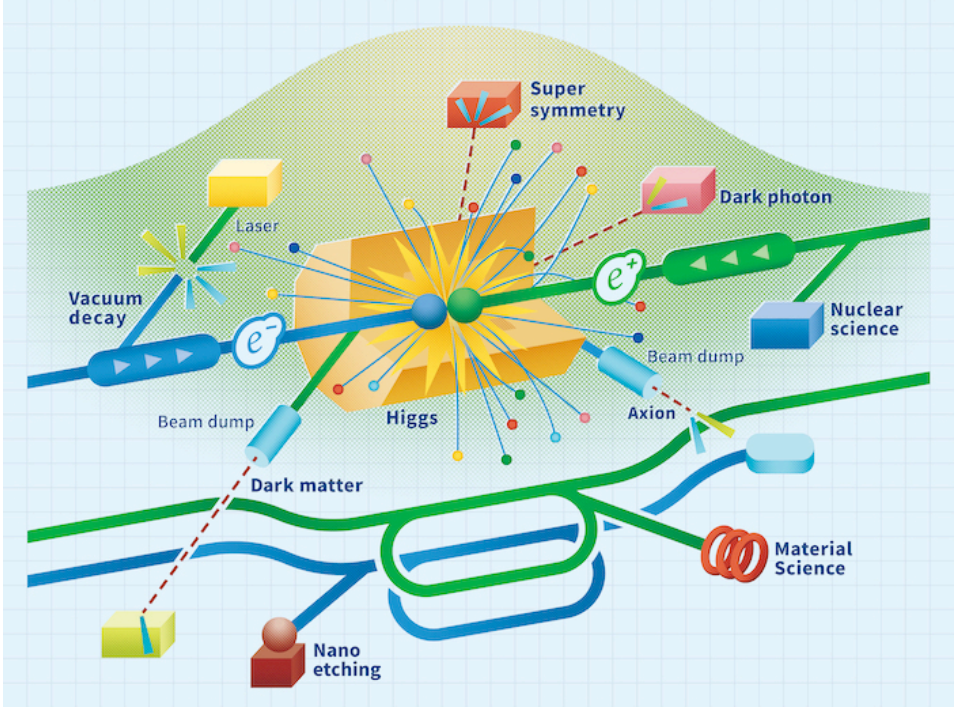
A Linear Collider Facility in Japan, at CERN or whereever

- offers
  - the **full Higgs/top/EW e+e- physics program** from 91 to (at least) 1000 GeV with polarised beams
  - and a rich program of **other collision modes and beyond-collider / R&D opportunities**
- can be built
  - at CERN:
    - ~within the CERN budget (ref CLIC PIP), leaving resources for scientific diversity and investment in R&D / demonstrators
    - **early:** industrialised SCRF production & expertise in other labs minimizes interference with HL-LHC
  - in Japan: **even earlier** if we could overcome political obstacles for funding…
- can be **upgraded** with same - or **advanced accelerator technology** (CLIC, C3, Plasma, ERL, …)
- leaves time to decide on target energy and best technology for exploring the energy frontier based on
  - scientific progress from HL-LHC *and* Higgs Factory
  - technology development



Outlook

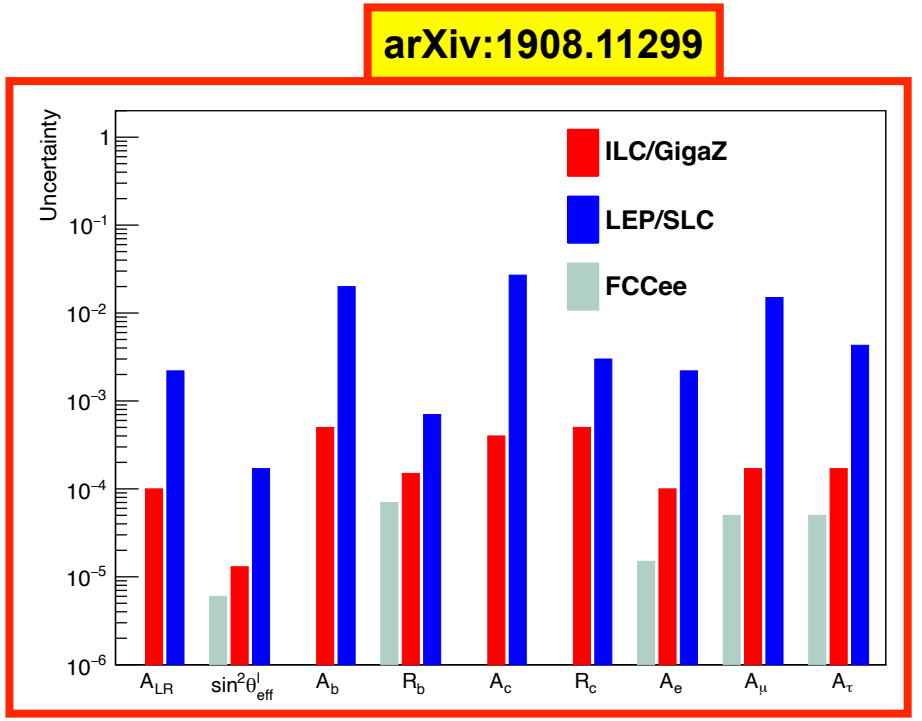
- discussions towards a joint global LC vision just started
- will continue and intensify
- prepare strong contributions to the EPPSU, complementing individual project / detector concept submissions
  - **“Joint LC Vision Document (arXiv)”** (main ed. R.Pöschl) covering
    - physics at a LC from 90 GeV to multi-TeV (use references to existing documents, but highlight specifically
      - need for >= 500 GeV and polarised beams
      - new results since Snowmass
    - a joint strategic vision for a Linear Collider Facility incl. upgrades, beyondcollider etc — at any location in the world
  - **“Joint LC Vision EPPSU submission”** (main ed. M.Peskin) -> executive summary
  - **“LCF@CERN submission”**
- **mailing lists, inner organisation of LC vision to be improved**



BACKUP

Lower Energies at Linear Colliders

- **Z pole: "only" few billion Z's — however: polarized…**
  - **not compatitive with TeraZ for Z pole flavour physics & very low mass searches ("rate only")**
  - **EWPO: improve by at least an order of magnitude (polarisation makes a huge difference!)**
  - schedule as needed after Higgs running incl. "free" Z physics from rad. return
- **Higgs resonance running: not possible with classic Linear Collider** — might change with ERL upgrade???
- **WW threshold scan:** possible if needed after mW from continuum



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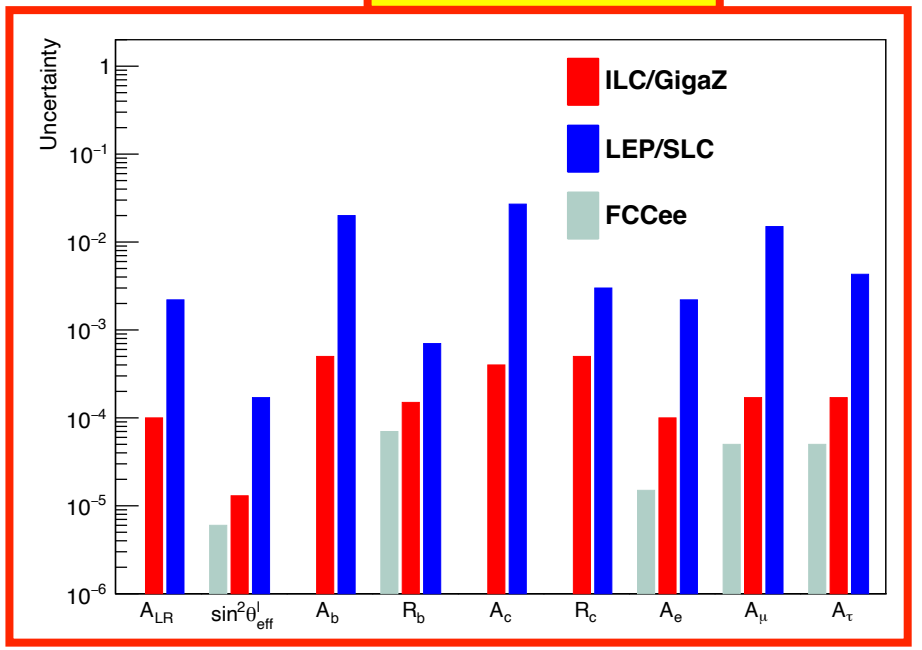
arXiv:1908.11299

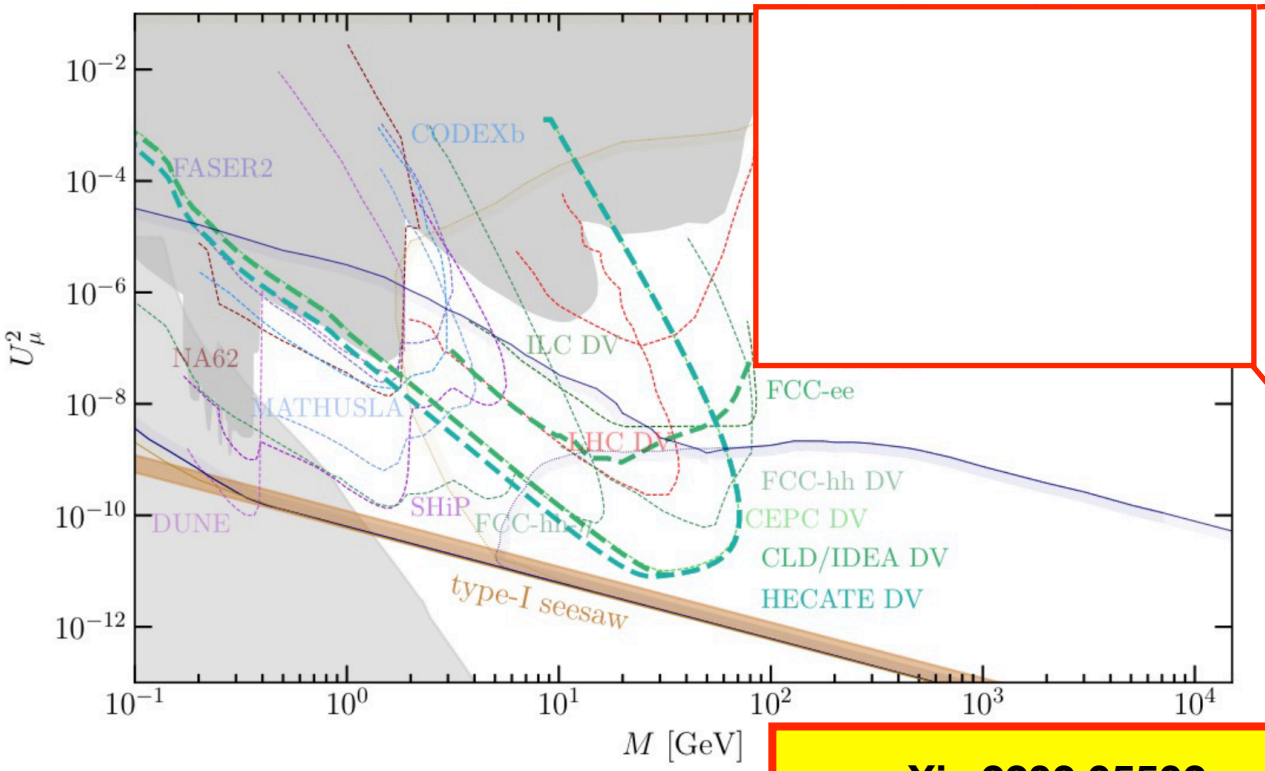


The raison d'être of a Linear Collider Facility are energies ≥ 500 GeV

- **low-E program can be covered with running 500+ GeV machine at lower gradients**
- **as needed after exploring higher energies**
- **start at 250 GeV serves to lower theshold of initial investment as much as possible!**

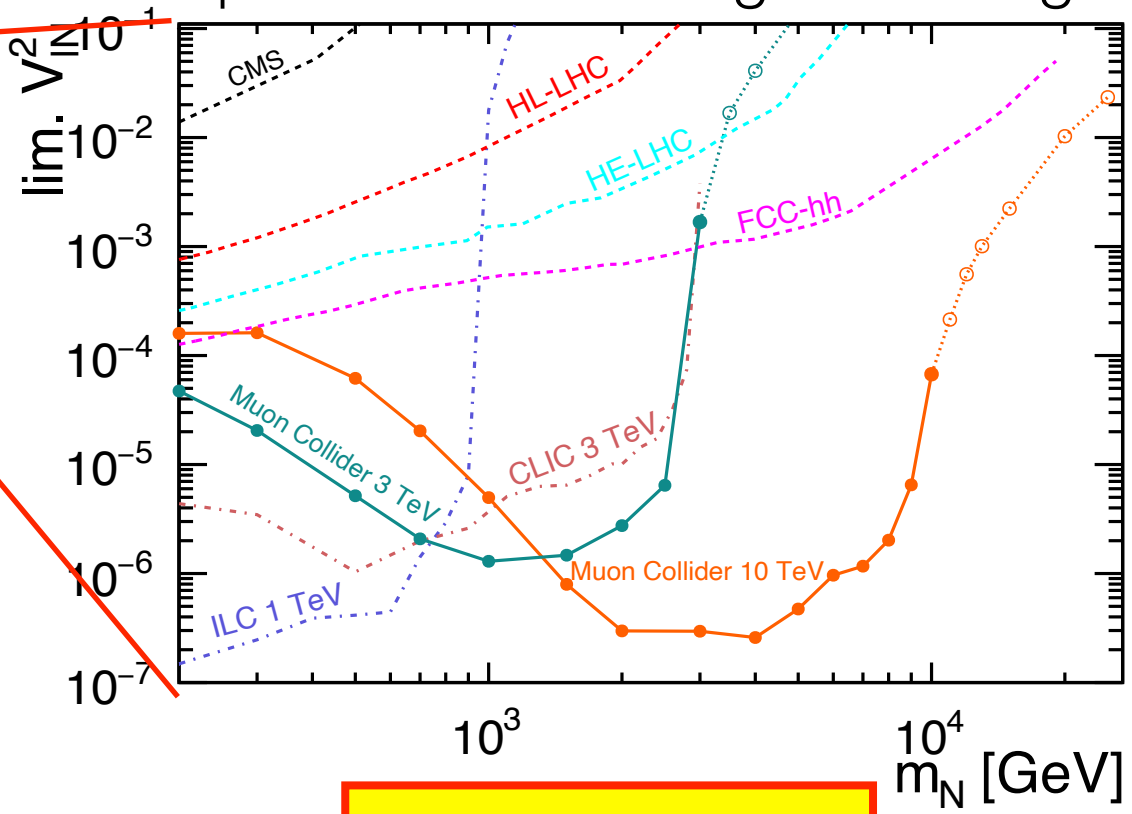
Direct Search Example - Complementarity of Different Approaches
Heavy Neutral Leptons

in Z decays with displaced vertices…
TeraZ excels



arXiv:2203.05502

…and at high masses in prompt decays
from lepton collision at highest energies



arXiv:2301.02602

From ILC@CERN to Linear Collider Facility

- **excellent starting point for a Linear Collider Facility**
- **… but needs to be (re-)augmented to a true "facility"**
- **eg revisit many of the previous cost saving measure….**

ILC Parameters at CERN

- Energy/length: 31km corresponding to 500 GeV
- Crossing angle: 14 mrad
- Entirely laser straight
- Tunnel diameter →The CLIC klystron tunnel is excessive. The European XFEL is 5.2m. There is one klystron every ~40 etc. → conclusion: ~6m estimate
- Push/pull caverns and access points as in the TDR and in the current ILC layout.
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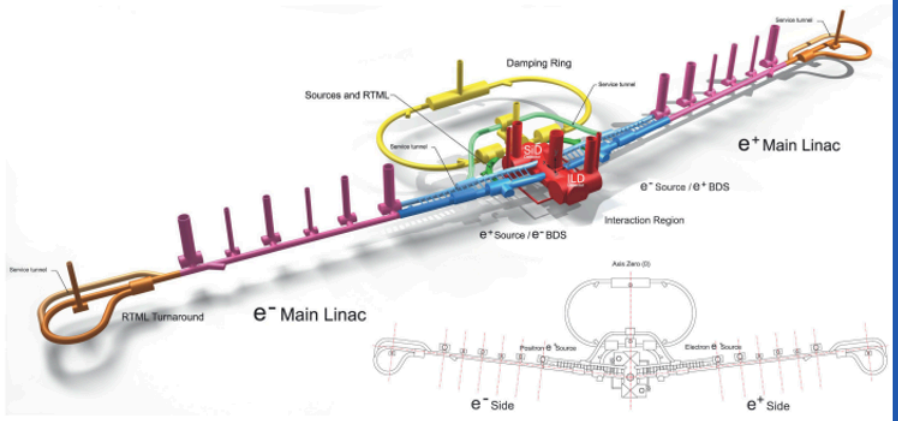

Figure 11.1. ILC tunnel schematic for KCS showing accelerator systems, IR hall and support tunnels.

John Osborne, Tamara Bud CERN

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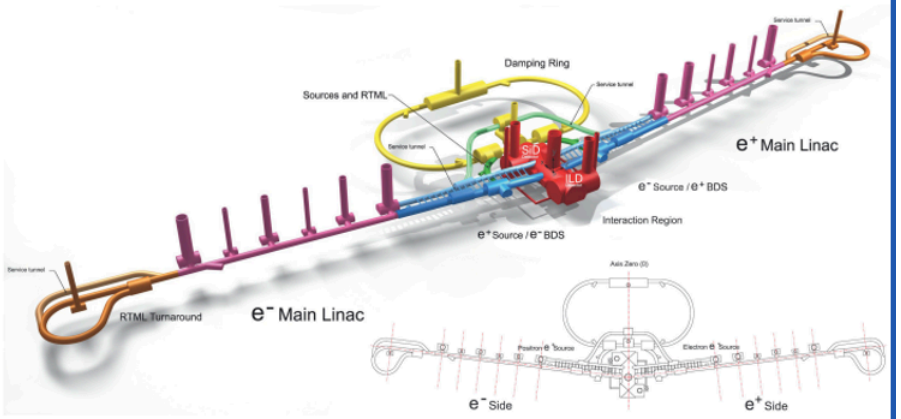

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