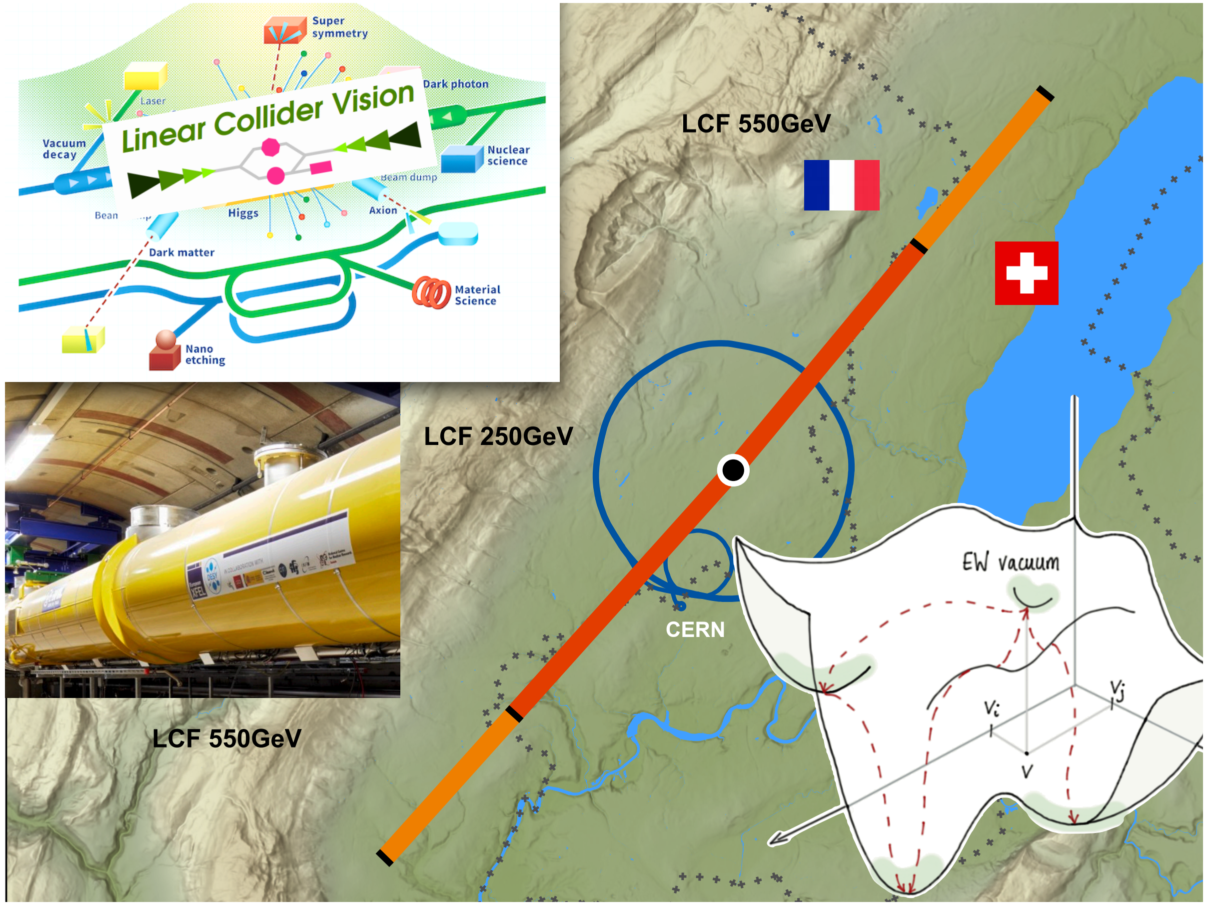
A Linear Collider Vision for CERN

Séminaires LLR
June 2, 2025

[Jenny List](#)
on behalf of the LCVision Team

Outline:

- Introduction
- LCVision
- LCF@CERN
- Conclusions & Invitation

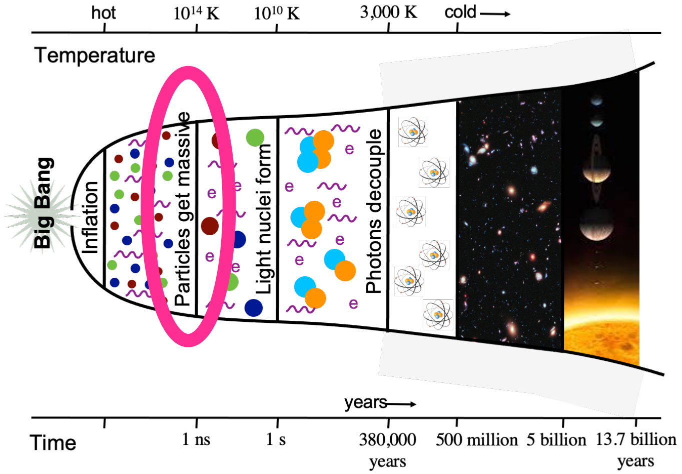


Introduction

Particle Physics in 2025

At the dawn of the Update of the European Strategy for Particle Physics (EPPSU)

- **the discovery of a Higgs boson at the LHC in 2012 was a huge triumph**
- so far, the Standard Model of particle physics gives an excellent description of all particles and interactions probed at the LHC
- yet, the SM is manifestly incomplete:
  - dark matter, dark energy, gravity, …
  - fermion masses and pattern, stabilisation of the Higgs mass, the origin of electroweak symmetry breaking …
- actual dynamical explanations for these features must come from new interactions and particles that couple to the Higgs boson
- now is the time for a concerted effort to discover new physics in the place where it is most likely to be found:
  in precision measurements of the Higgs boson!



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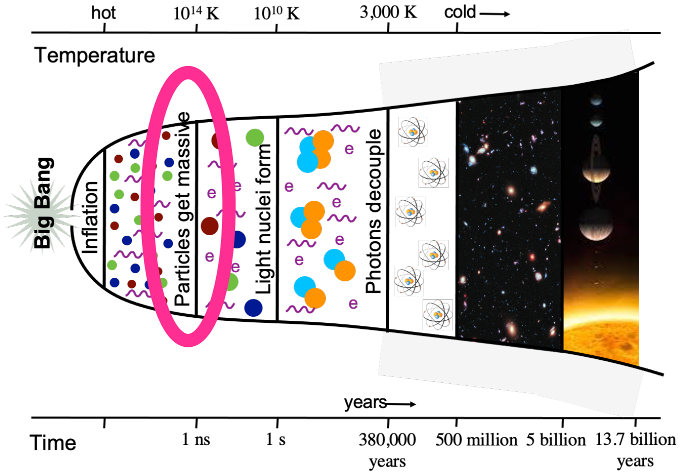
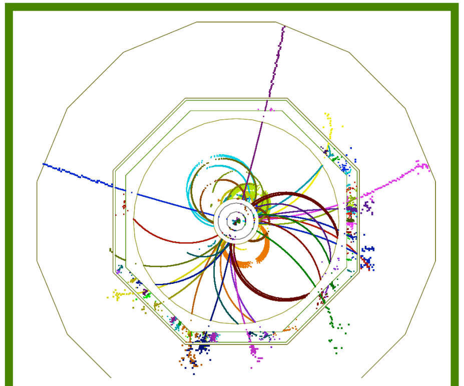


an e+e- collider is the ideal place to do this:
collides elementary, electroweak particles
=> clean experiments & precise predictions



$e^+e^- \to \mu^+\mu^- H \to \mu^+\mu^- b\bar{b}$ in ILD

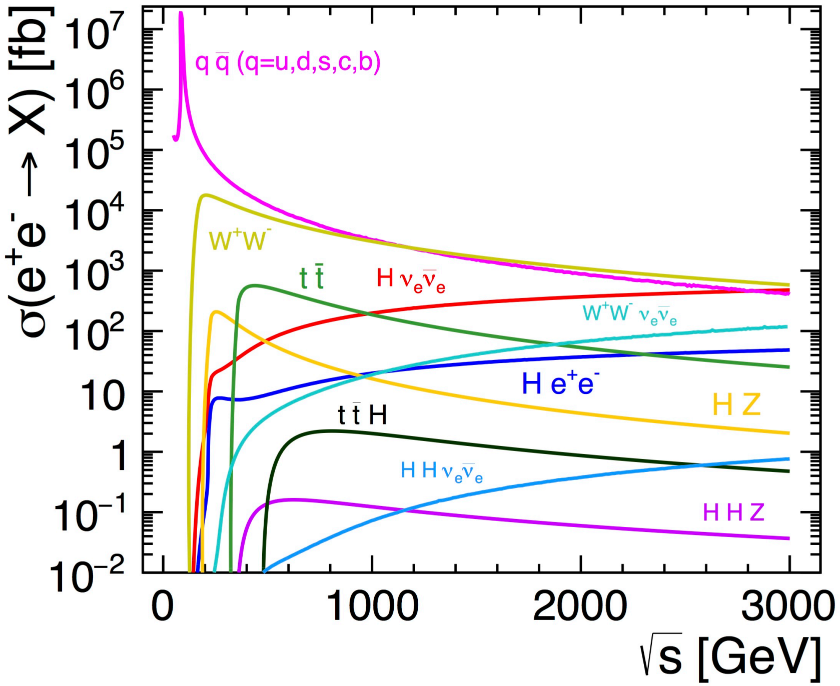
Linear Collider Vision

A Linear Collider re-doubles these advantages

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

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

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



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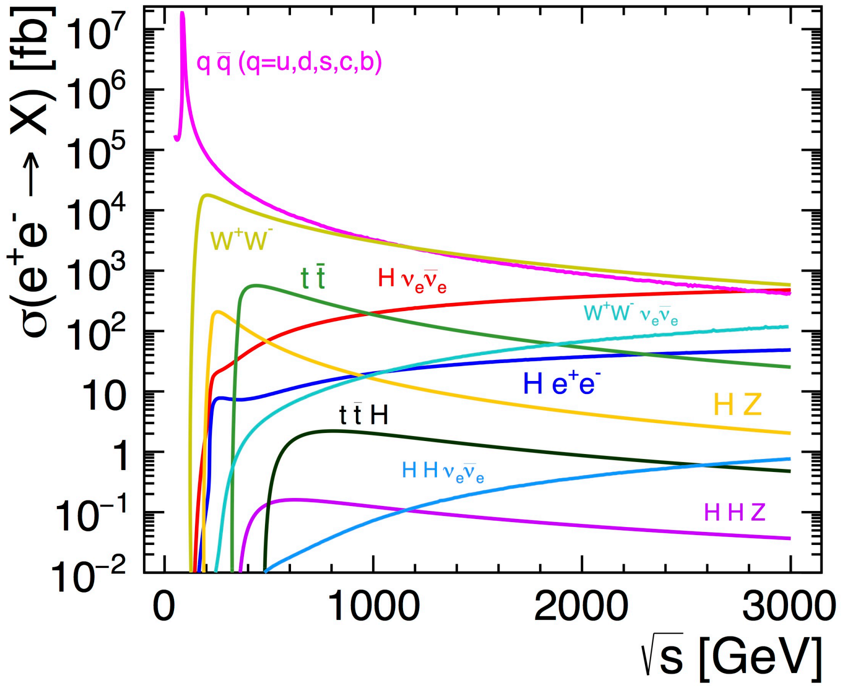

the full Higgs / top / electroweak program requires polarised beams & E_{CM} up to at least 1 TeV

Linear Colliders

from construction-ready to advanced accelerator R&D

- **the most mature proposal: the ILC**
  - superconducting RF 31-35 MV/m
  - proven technology: Eu.XFEL, LCLS-II, SHINE, …
  - up to 1 TeV, both beams polarised
  - since 2012 considered for construction in Japan!
- **Compact Linear Collider (CLIC):**
  - beam-driven warm copper RF, 70-100 MV/m
  - up to 3 TeV, electrons polarised
- **a vast number of other ideas / R&D programs**
  - C3: cool copper collider up 150 MV/m
  - HELEN: advanced SCRF up to 70 MV/m
  - ReLiC / ERLC: energy & particle recovery
  - HALHF: hybrid asymmetric linear Higgs factory
  - ALEGRO: 10 TeV PWA ee / $\gamma\gamma$
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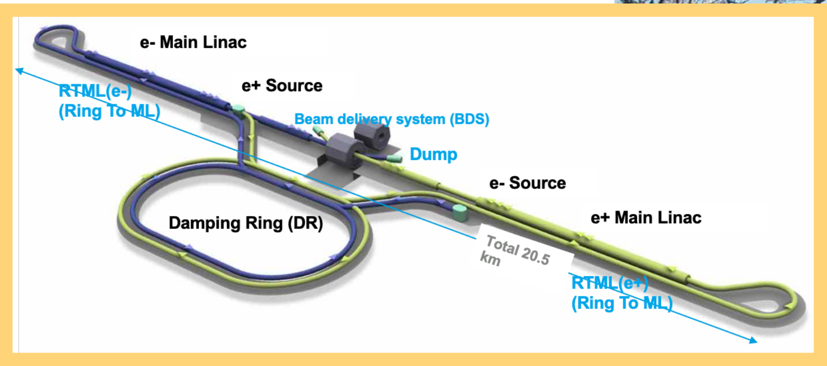

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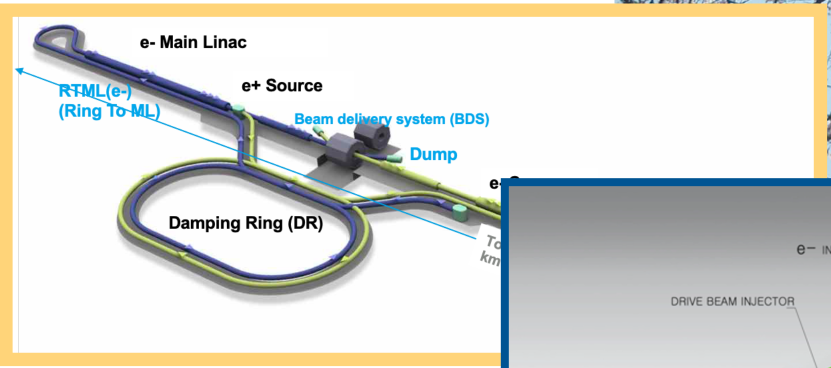

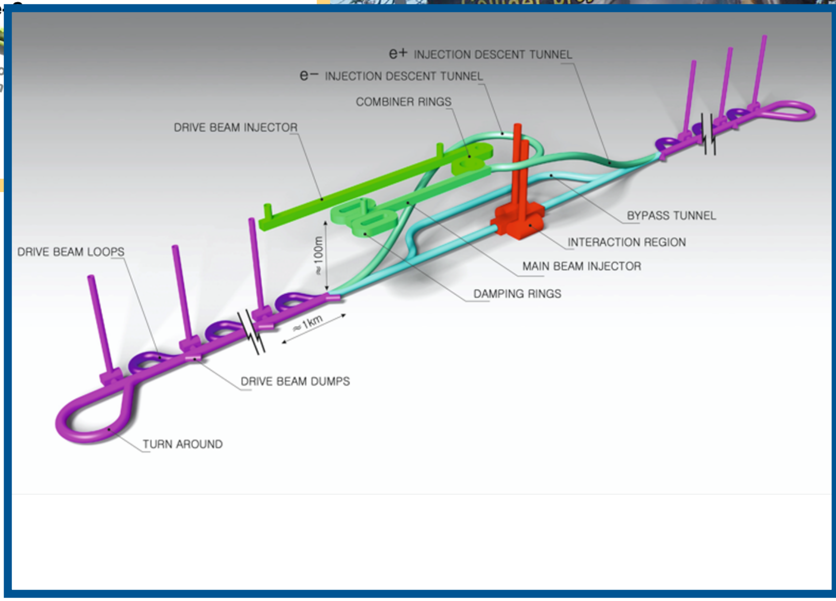

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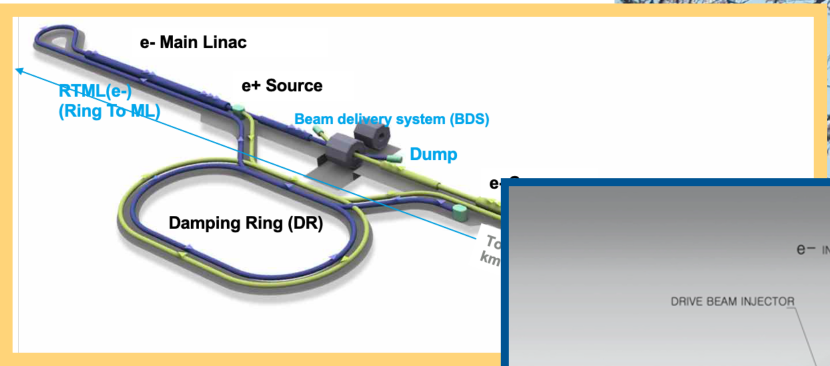

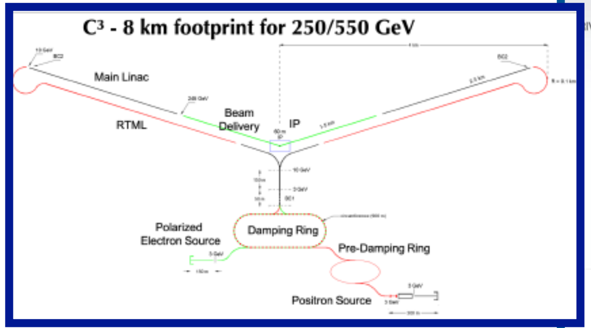

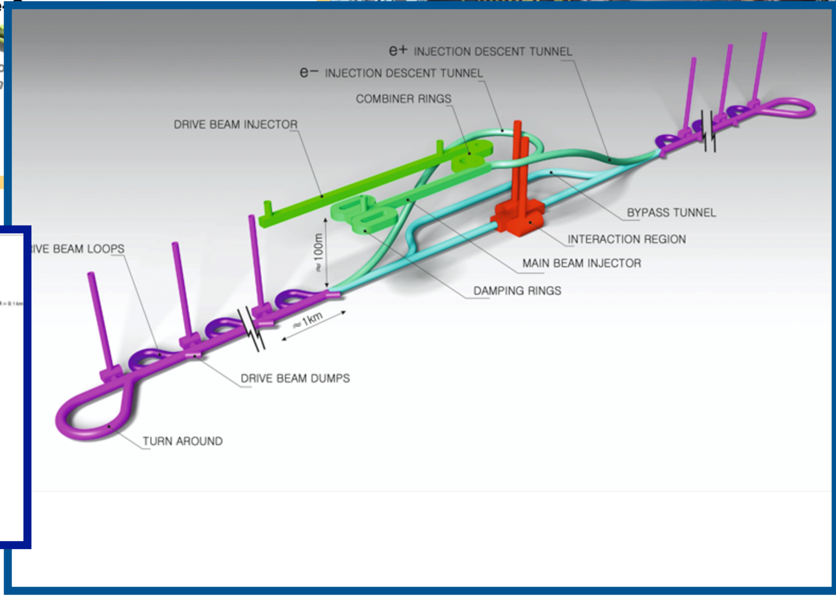

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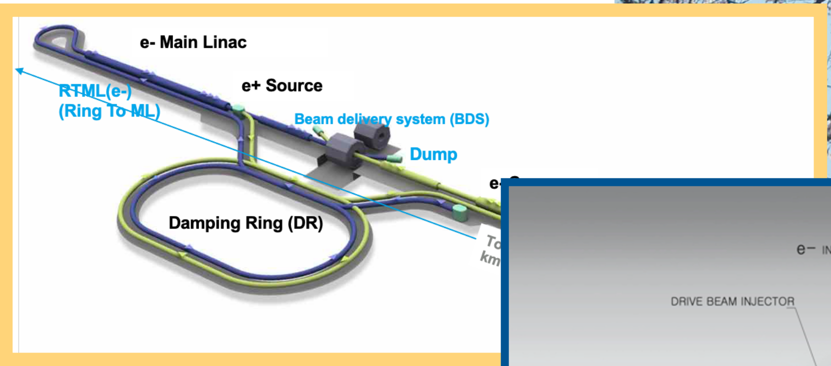

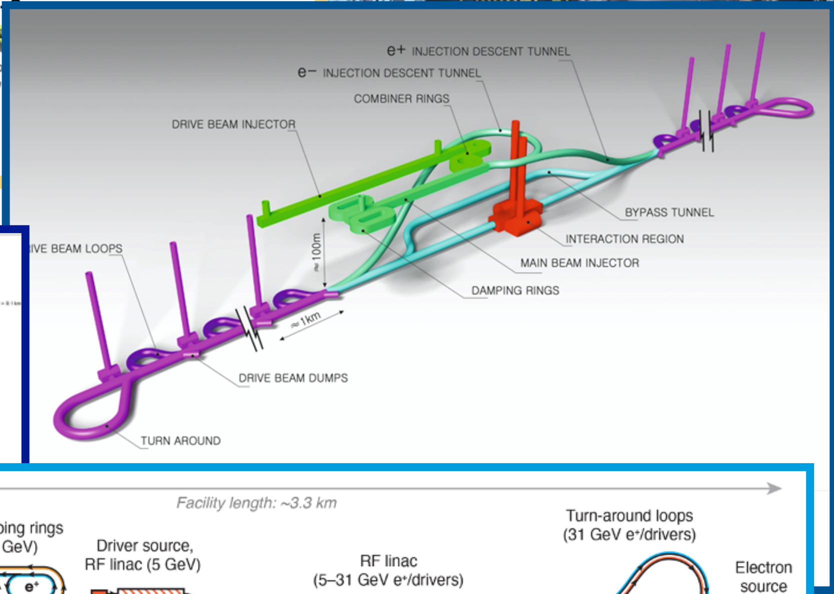

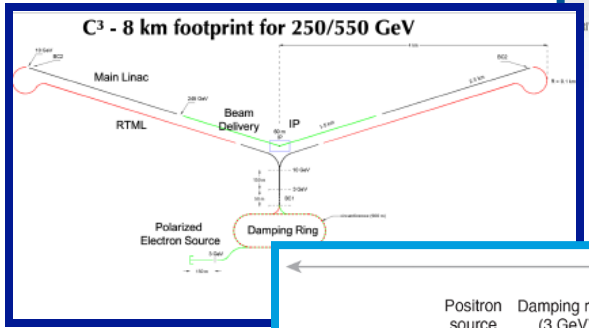

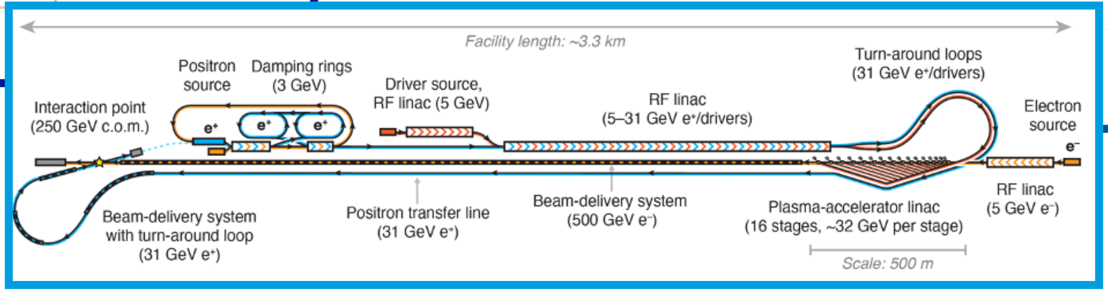

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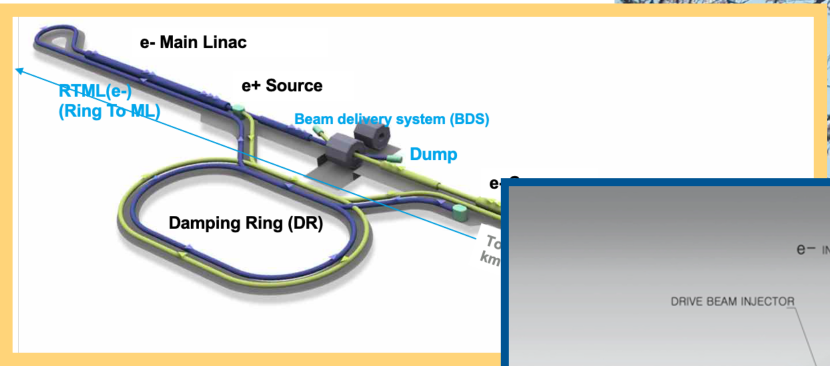

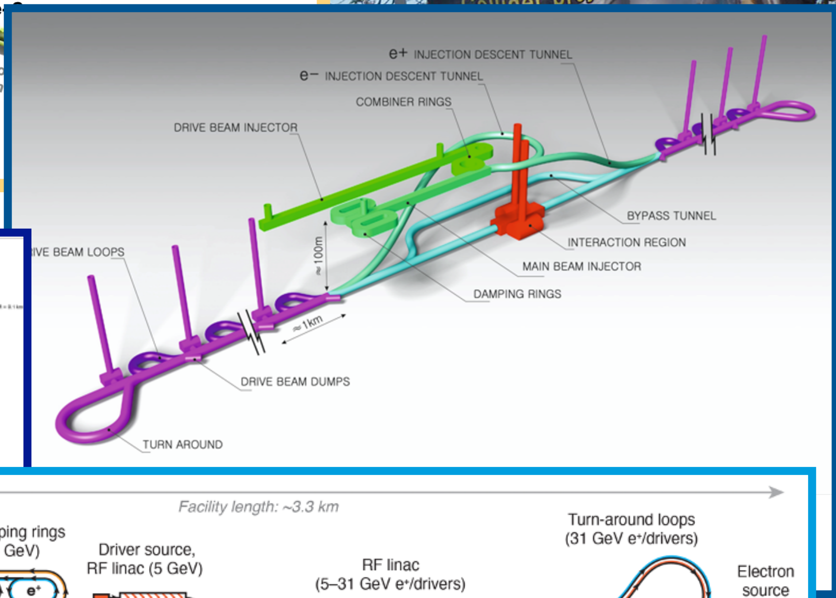

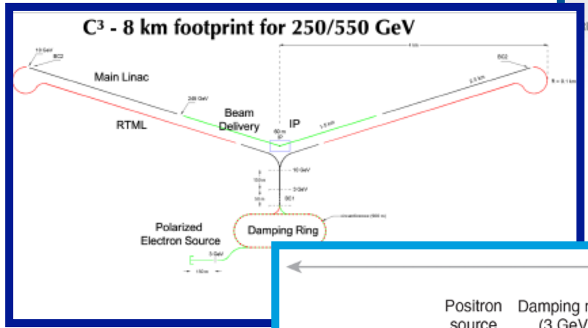

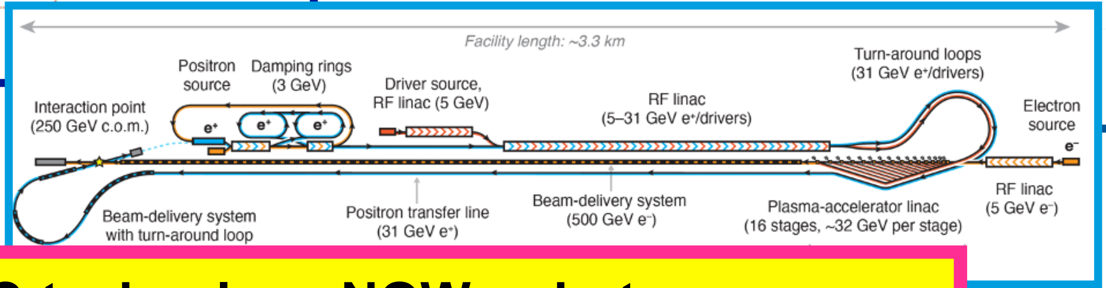

Can we start with ILC-technology NOW — but encourage later upgrades with advanced technologies?

LCVision

LCVision: a united approach

LCWS2024: Linear Colliders teaming up in view of the upcoming EPSSU

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

LCVision and the EPPSU

from the remit of the European Strategy Group

- The aim of the Strategy update should be
  - **to develop a visionary and concrete plan**
  - that **greatly advances human knowledge in fundamental physics**
  - through the realisation of **the next flagship project** at CERN**.**
- The Strategy update should include
  - **the preferred option for the next collider** at CERN
  - **and prioritised alternative options** to be pursued if the chosen preferred plan turns out **not to be feasible or competitive.**

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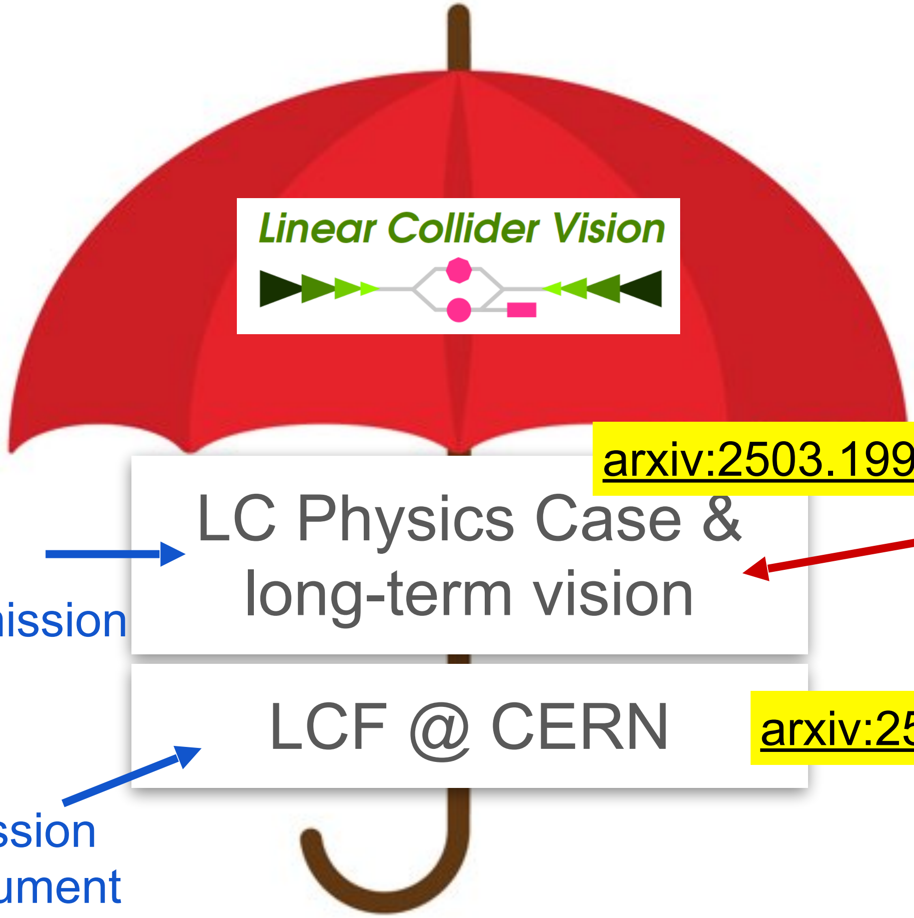
In order to receive full attention for the LCVision idea:
complement a generic, site-independent concept with
a concrete proposal for a
Linear Collider Facility (LCF) @ CERN

LCVision EPPSU documents

… and relation to other inputs



Linear Collider Vision

LC Physics Case & long-term vision — arxiv:2503.19983

arxiv paper & EPPSU submission

LCF @ CERN — arxiv:2503.24049

EPPSU submission & back-up document

Technologies and upgrades

- ILC in Japan (IDT) — arxiv:2504.11292
- CLIC at CERN — arxiv:2503.24168, arxiv:2503.21857
- C^3 — arxiv:2503.20829
- HALHF — arxiv:2503.23489, arxiv:2503.19880
- 10 TeV Wakefield — arxiv:2503.20214, arxiv:2504.01434
- Beyond Collider — https://cds.cern.ch/record/2927631

LCVision EPPSU documents

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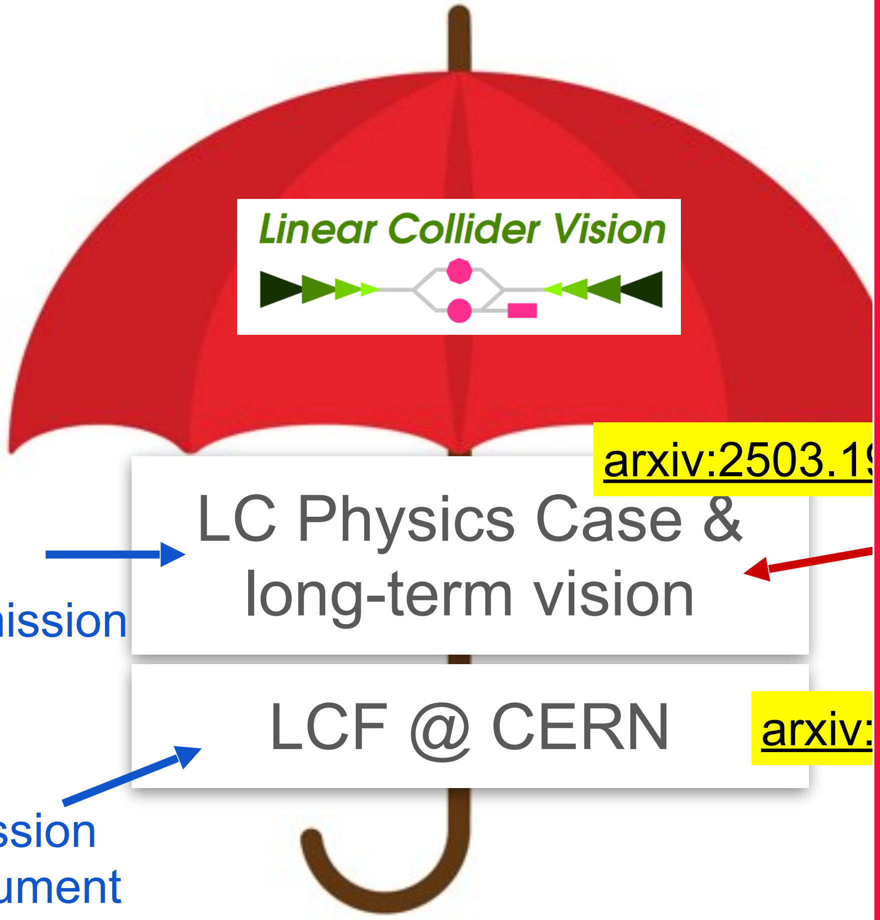

arxiv paper & EPPSU submission

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09:00	**FCC-ee (incl. common infrastructure)** *Sala Perla, Palazzo del Casinò*	*Michael Benedikt (CERN)*	09:00 - 09:40
	FCC-hh *Sala Perla, Palazzo del Casinò*	*Frank Zimmermann (CERN)*	09:40 - 10:10
10:00	**A Linear Collider at CERN (ILC, CLIC)** *Sala Perla, Palazzo del Casinò*	*Steinar Stapnes (CERN)*	10:10 - 10:50
	Coffee-Break *Sala degli Specchi, Palazzo del Casinò*		10:50 - 11:20
11:00	**LEP3** *Sala Perla, Palazzo del Casinò*	*Tejinder Virdee (Imperial College London)*	11:20 - 11:45
	LHeC *Sala Perla, Palazzo del Casinò*	*Jorgen D'Hondt (Nikhef)*	11:45 - 12:10
12:00	**Muon Collider** *Sala Perla, Palazzo del Casinò*	*Daniel Schulte (CERN)*	12:10 - 12:35
	Linear Collider Vision (C3, HALHF, wake-field acceleration) *Sala Perla, Palazzo del Casinò*	*Jenny List DESY)*	12:35 - 13:00
13:00	**Lunch Break**		

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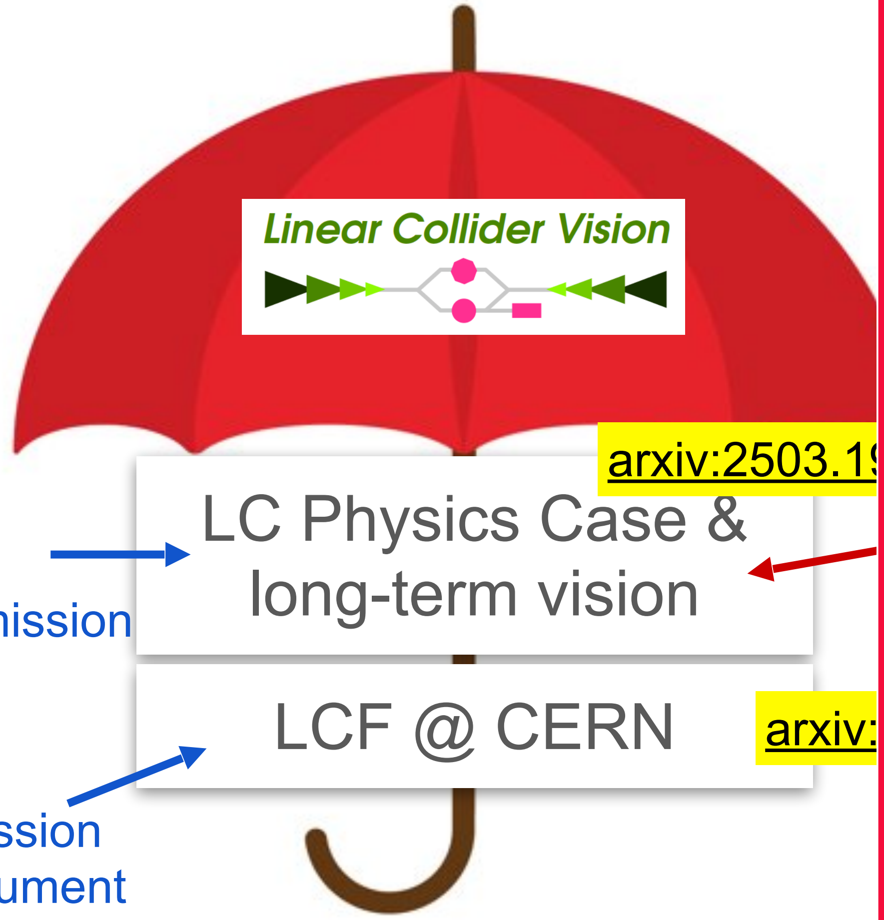

arxiv:2503.19

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LCF @ CERN

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The LCF@CERN Proposal

General Considerations

for the LCF@CERN

- Philosophy:
    - leverage all the excellent work done for ILC & CLIC in the past
        - reliable costing etc
        - "ready to build"
    - gently modernize to turn into true flagship project for CERN
- Superconducting RF technology (like ILC)
    - successful construction & operation of Eu.XFEL, LCLS-II…
      => no large-scale demonstrator step needed
    - lab experience and production capacities in industry globally
      => opportunity to take burden off CERN's shoulders
    - choice for fastest implementation
- Scope project to be a flagship project for CERN
    - 2 interaction regions
    - 2-4 higher luminosity than ILC (possible due to Q_0=**2**E10)
    - add-on facilities (Beyond Collider, R&D / irradiation facilities)
    - attaractive upgrade perspectives with advanced technologies
    - but stay affordable, wrt to CERN budget

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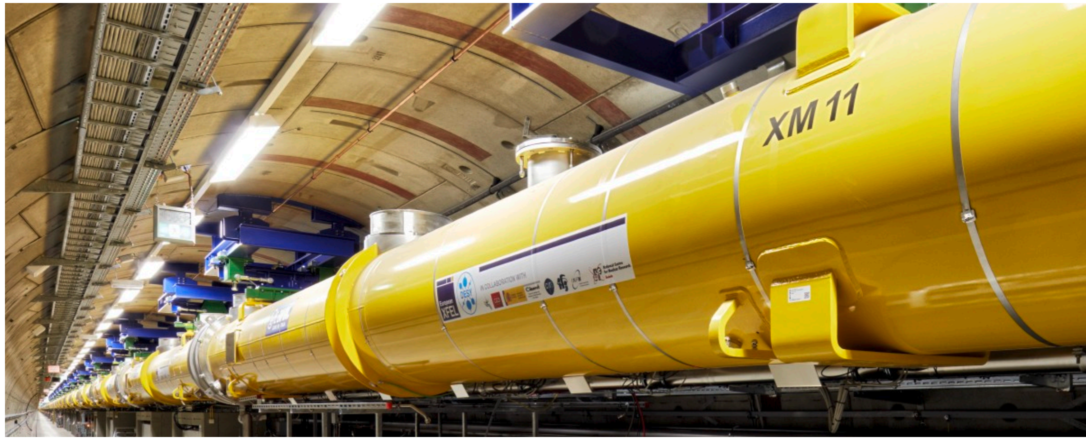

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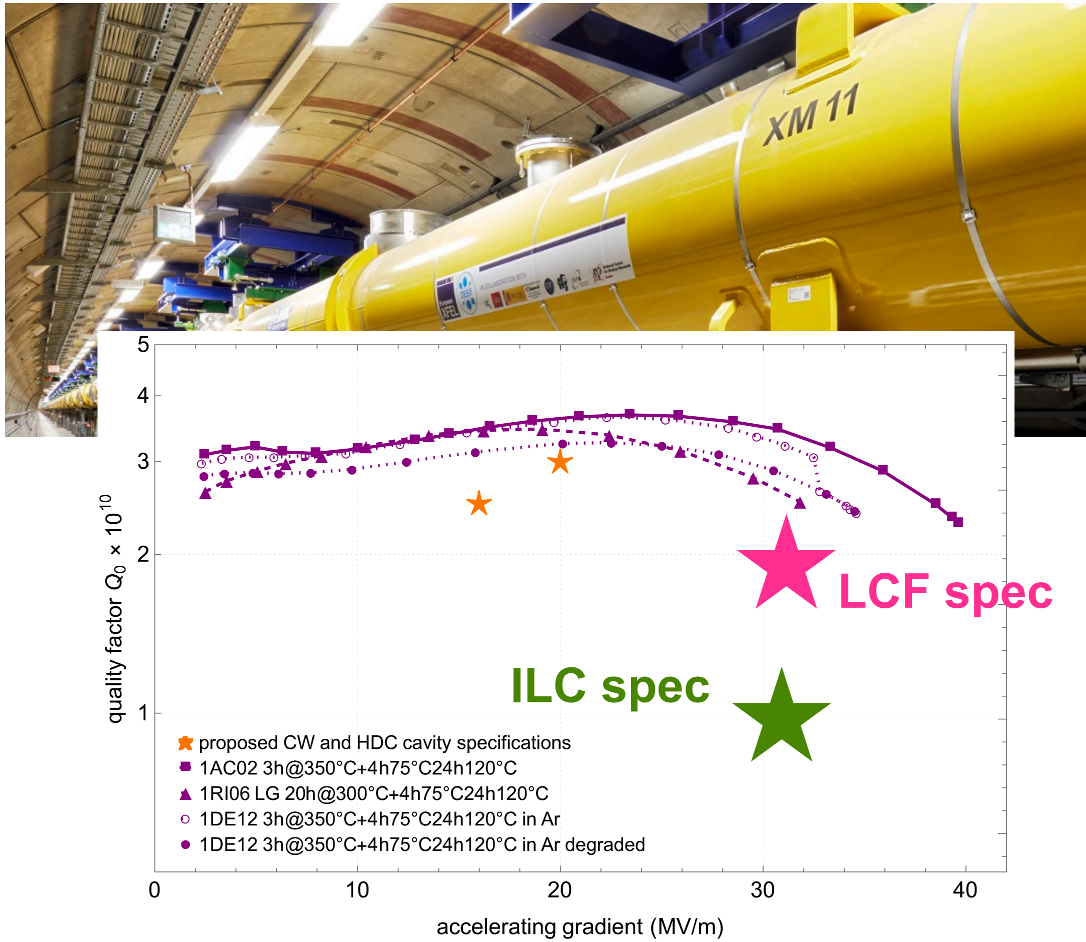
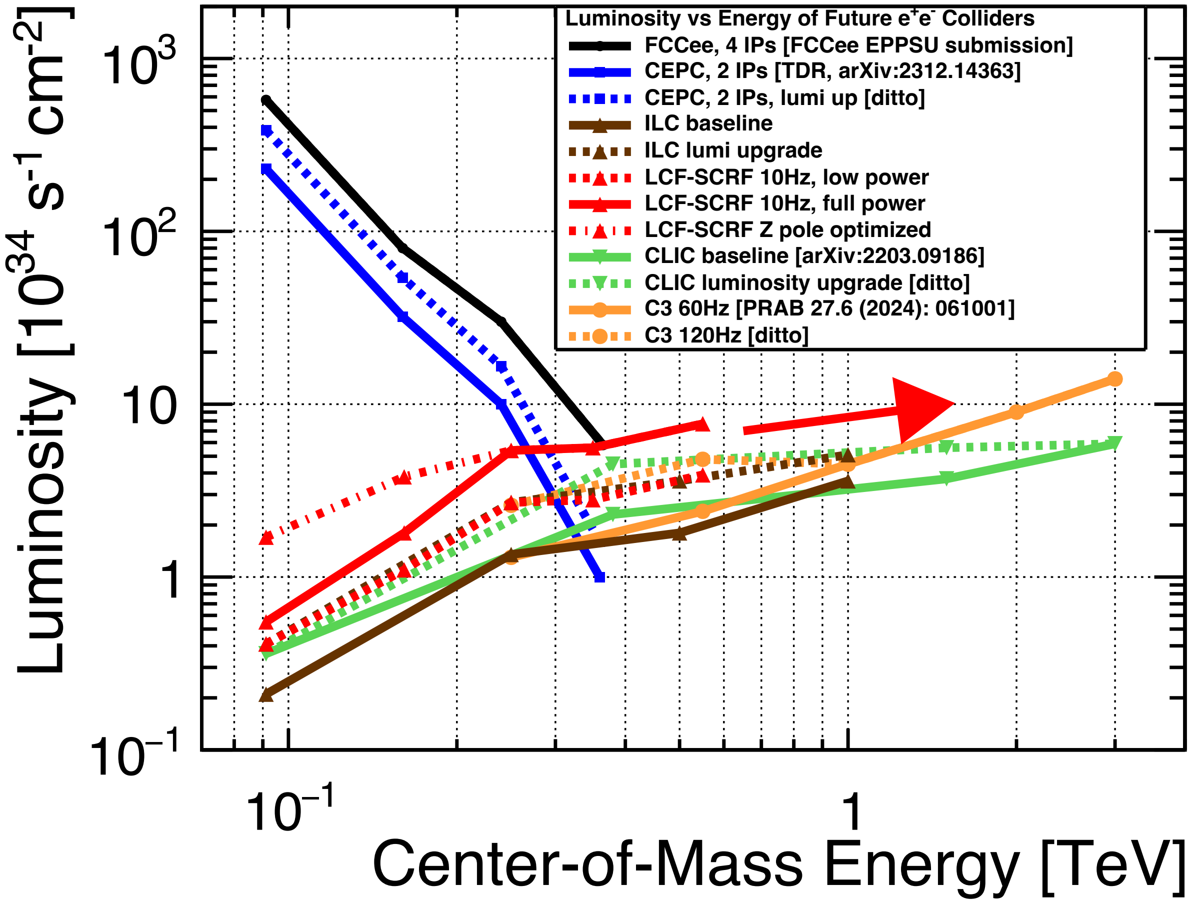
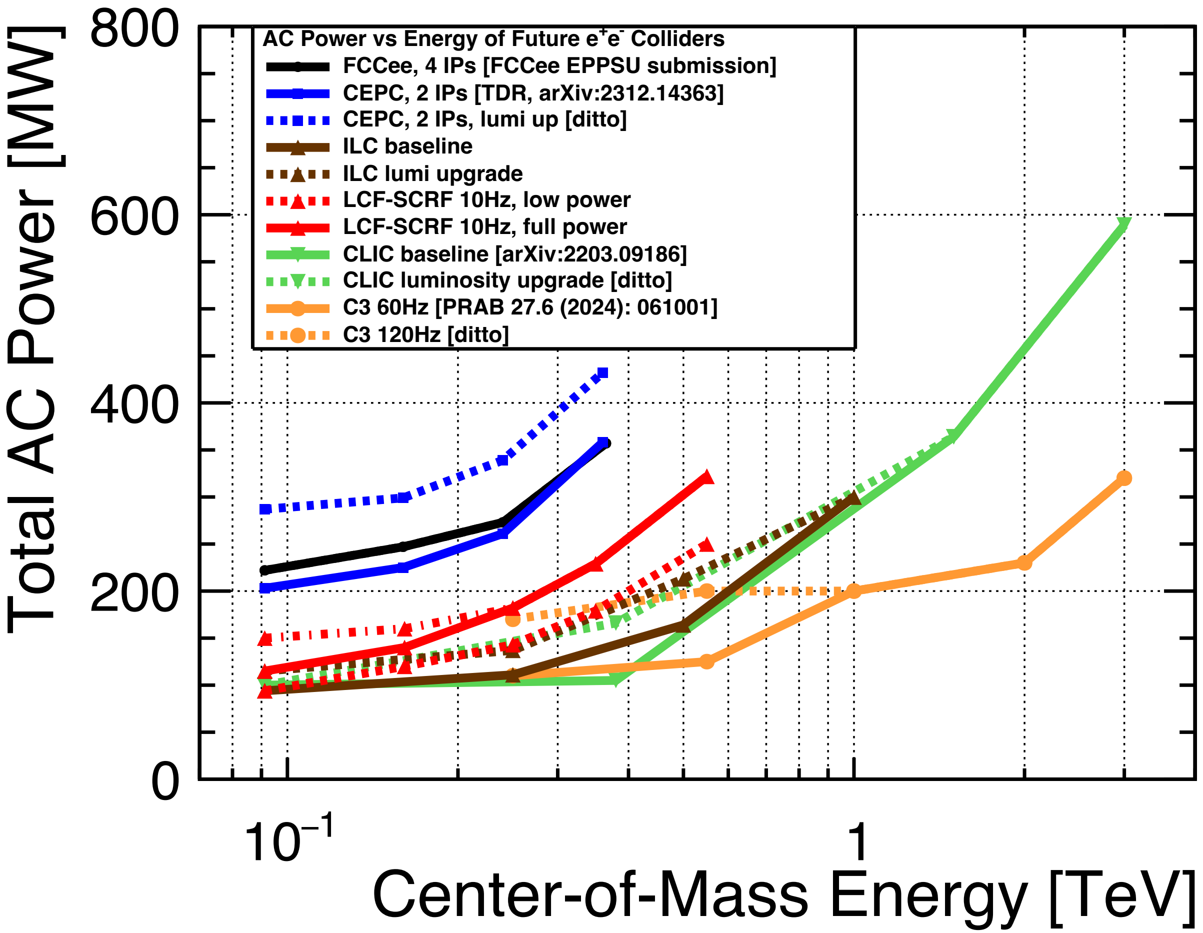


Luminosity and Power Consumption

For LCF-SCRF and other e+e- colliders





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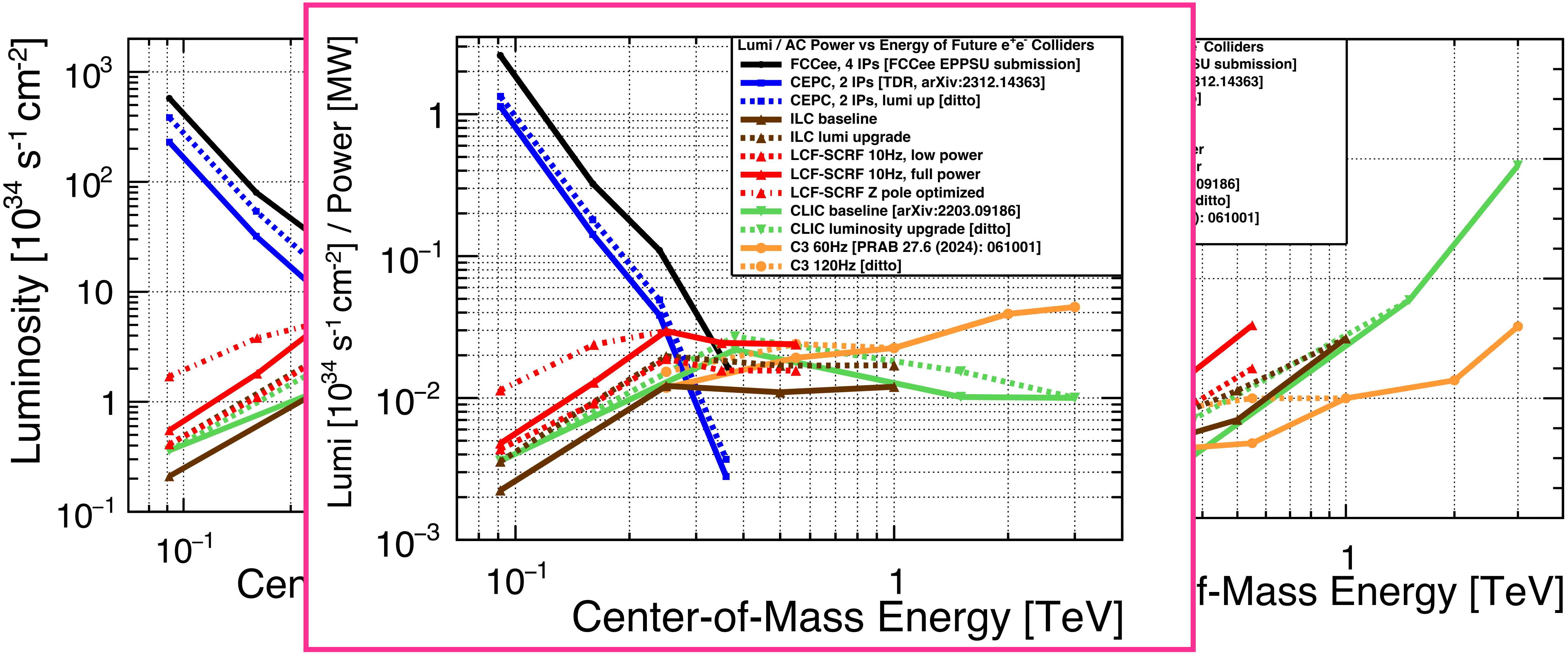
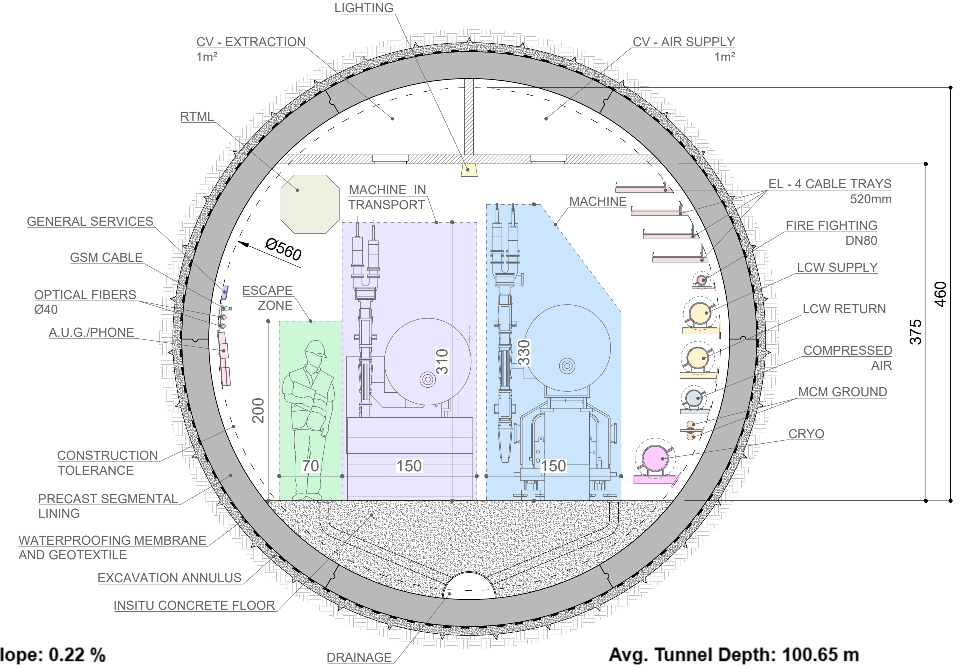
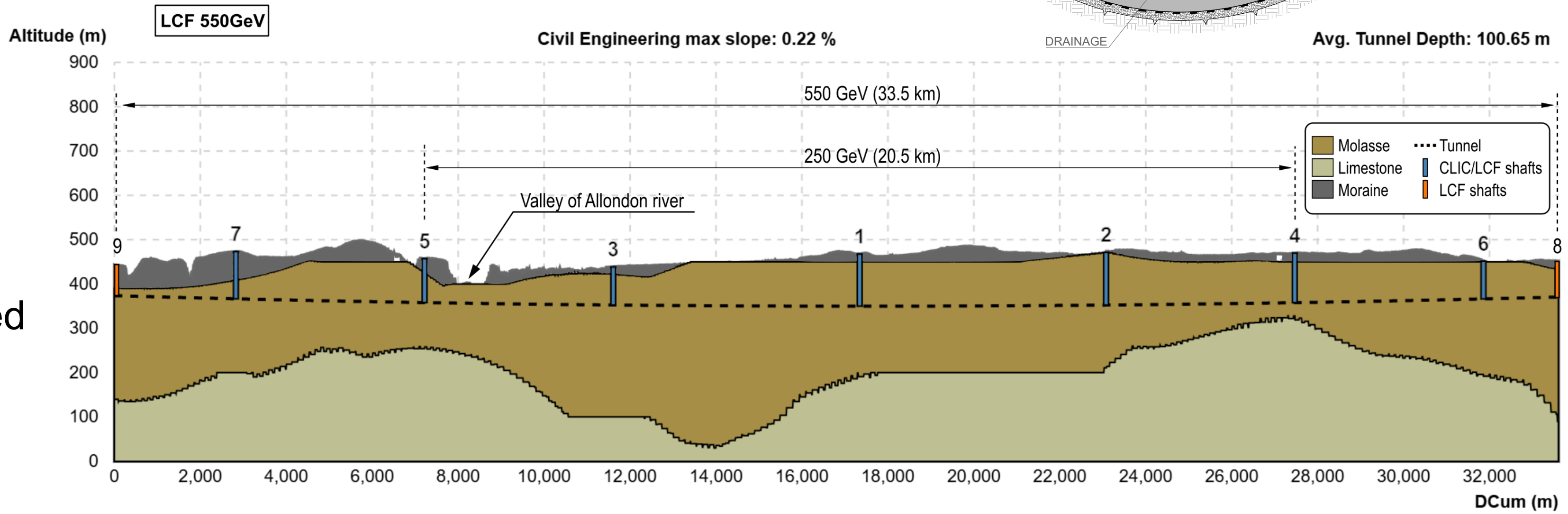


The first stage - or what can LCF offer for ~8 BCHF?

250 GeV incl Z pole - facility

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

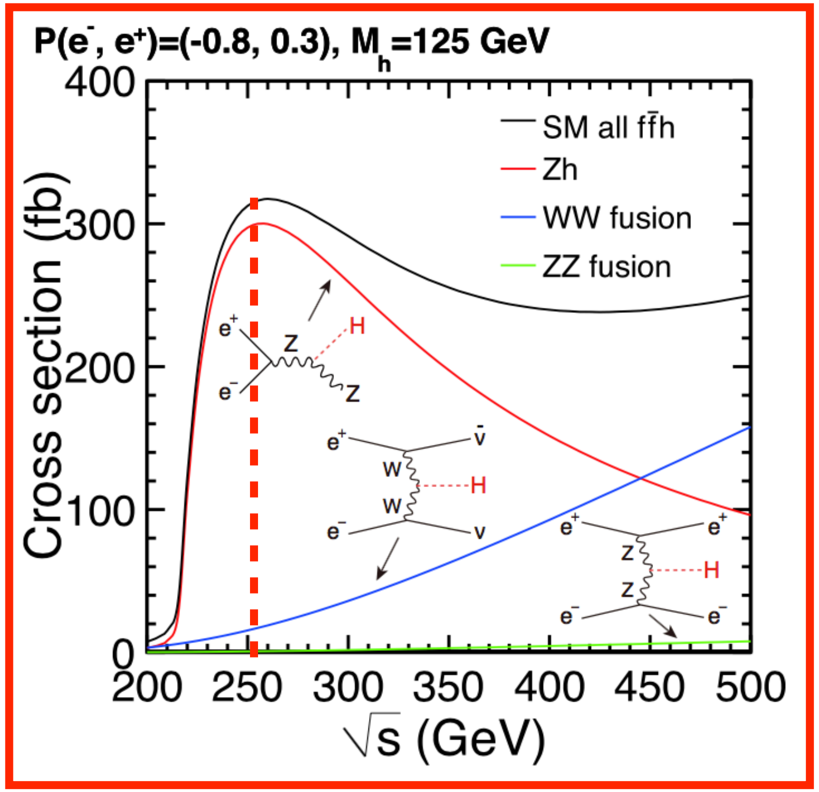




The first stage

250 GeV incl Z pole - physics

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



The first stage

250 GeV incl Z pole - physics

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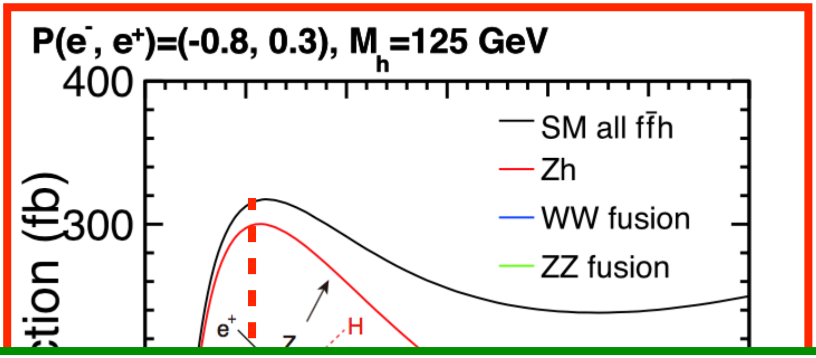
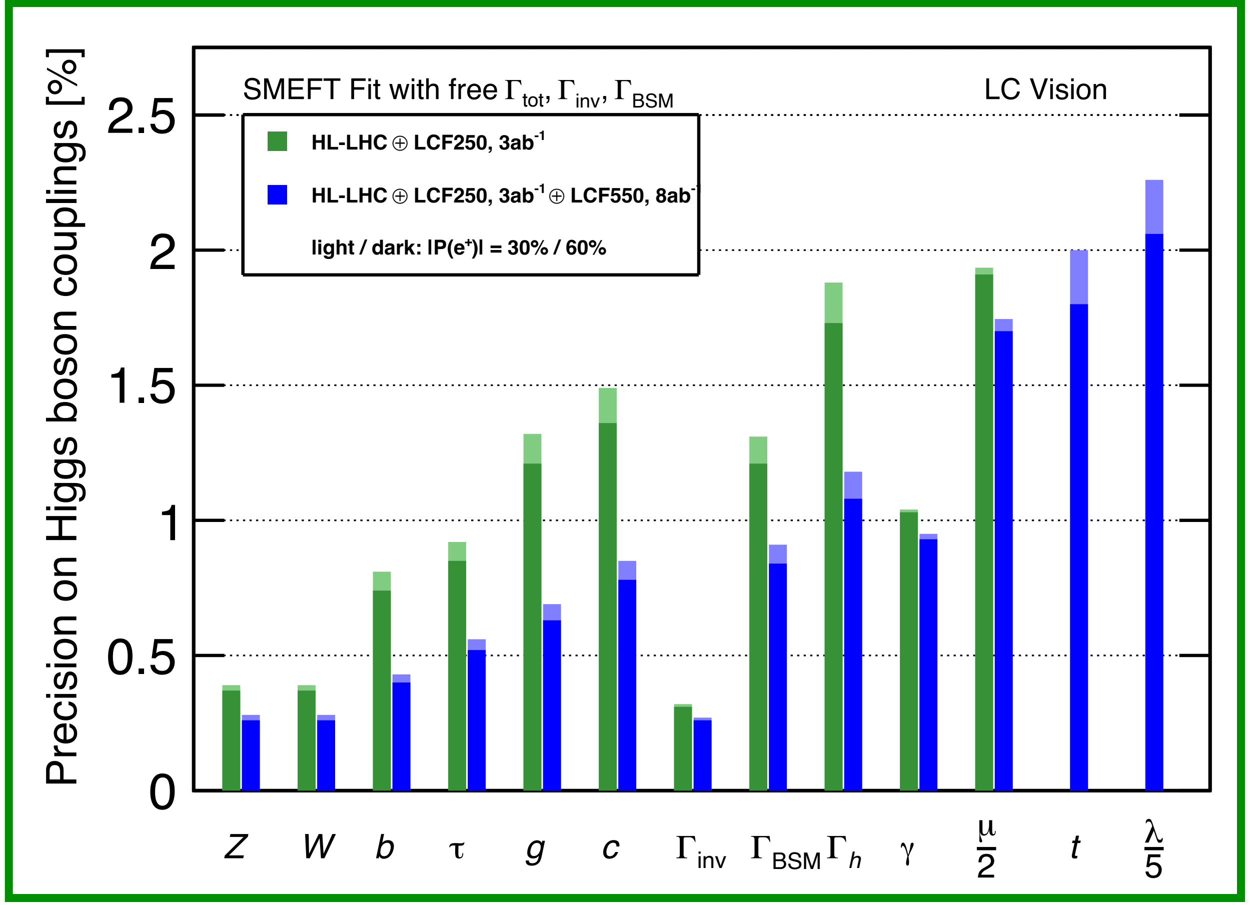


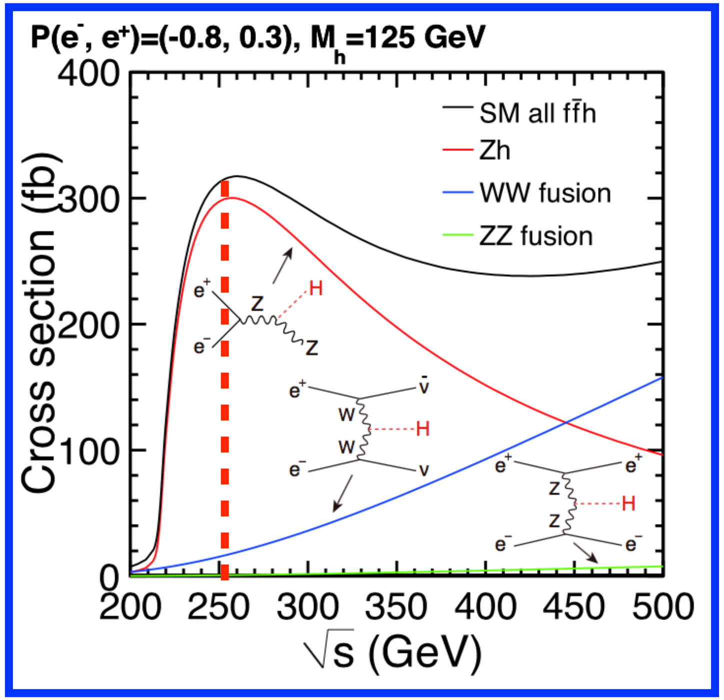


The second stage

550 GeV incl ttbar theshold

- Upgrade
  - equipping the additional tunnel with SCRF
  - **+ 5.46 BCHF**
  - 10 Hz trains of 2625 bunches => 7.7 x 10^{34} / cm^2 / s
  - **AC power 322 MW**
  - target 8 ab^{-1}
- **Higgs physics at 550 GeV and beyond:**
  - now **WW fusion** dominant => **independent, complementary set of observables**
  - **ttH, ZHH and even vvHH become observable:**
    - **ttH:** tree-level sensitivity to top-Yukawa ~2%
    - **di-Higgs production: tree-level sensitivity of ~10% to self-coupling λ**

      - for any value of λ !



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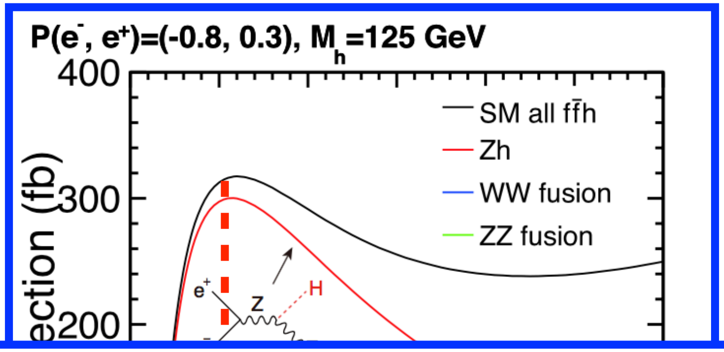

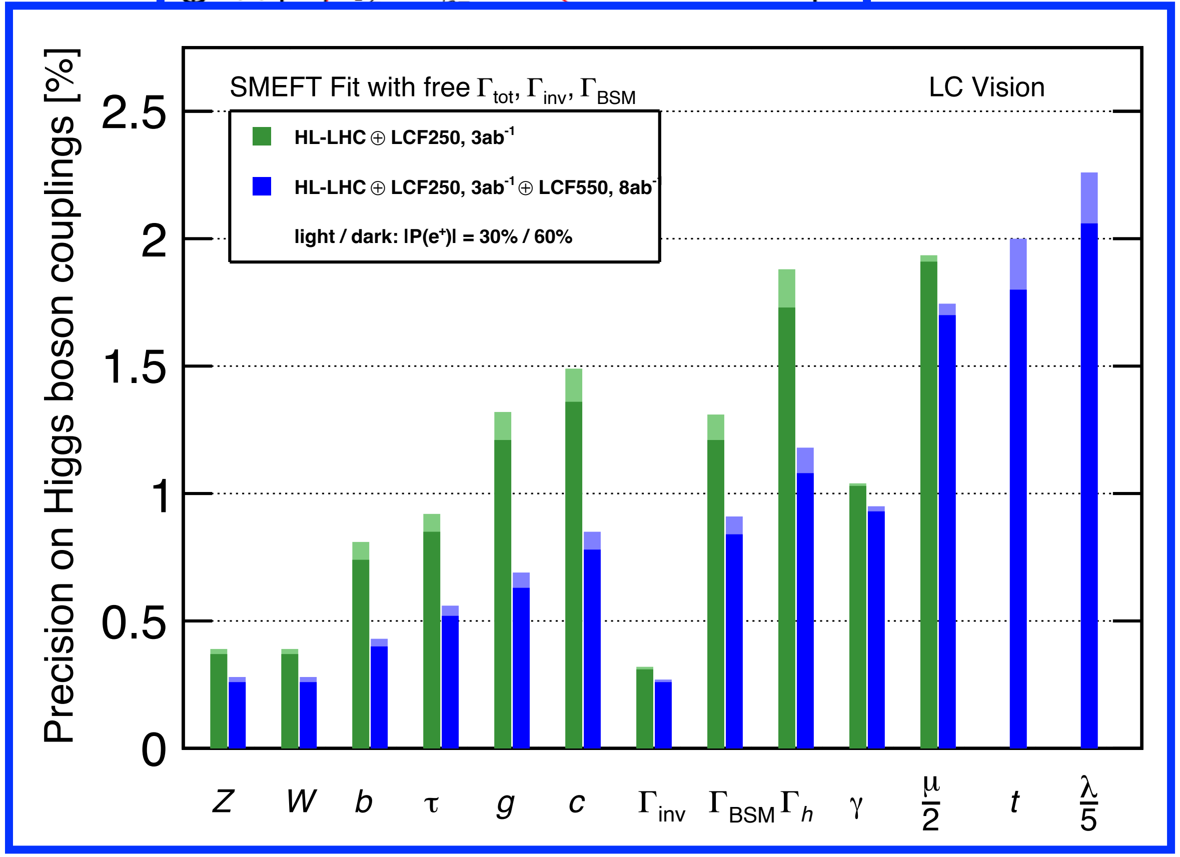

Di-Higgs Production

tree-level access to self-coupling

- **550 GeV**
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  - **vvHH** becomes just about visible
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    $\Delta\kappa_\lambda$ **=** **11%** (15%) for **8ab^{-1}** (4ab^{-1})
- **dependence on λ:**
  - **ZHH**: **constructive** interference
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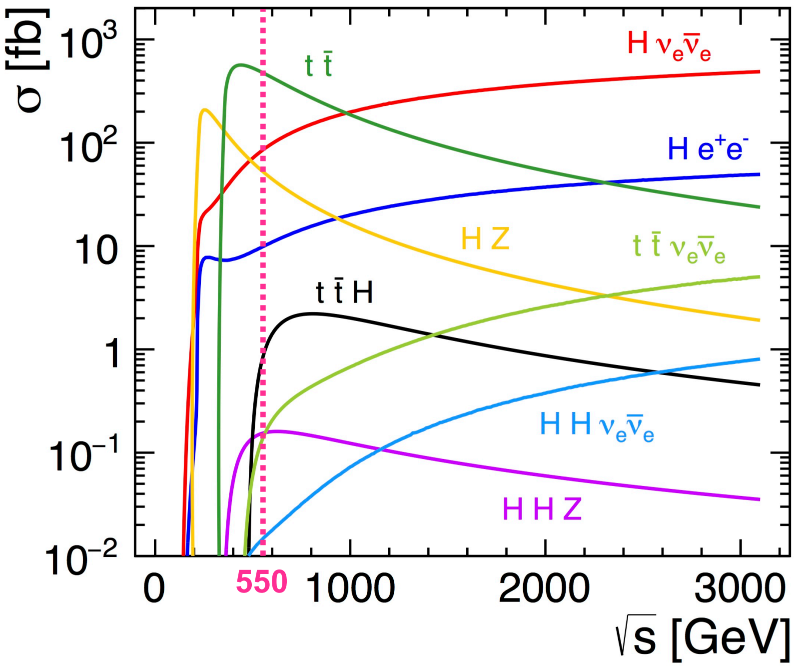
  - **together**: ~const absolute precision as function of λ
- **1-3 TeV:** **vvHH** becoming dominant
  - $\Delta\kappa_\lambda$ **= 0.04** (8ab-1) over wide range of κ_λ (except κ_λ ~ 1.5)
- **quantitative improvement and qualitatively new information wrt HL-LHC**



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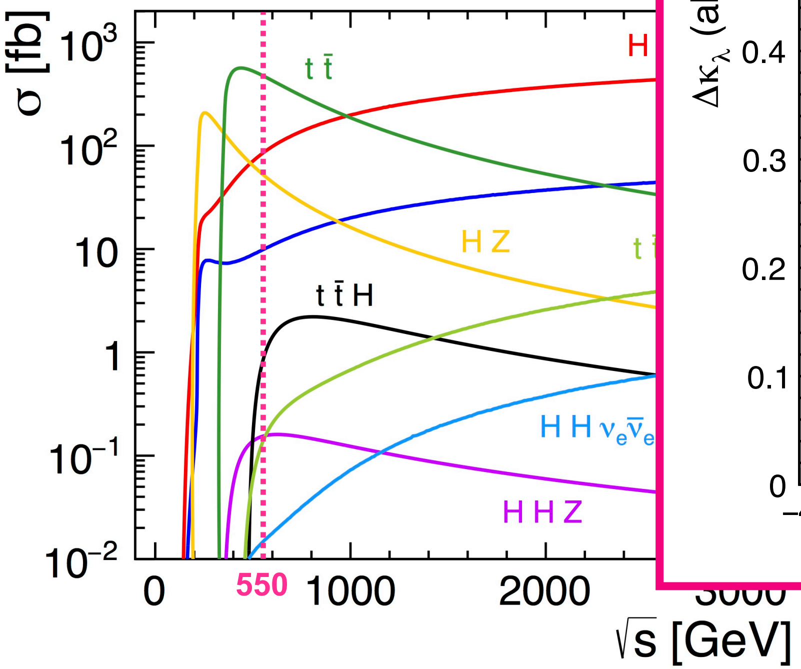

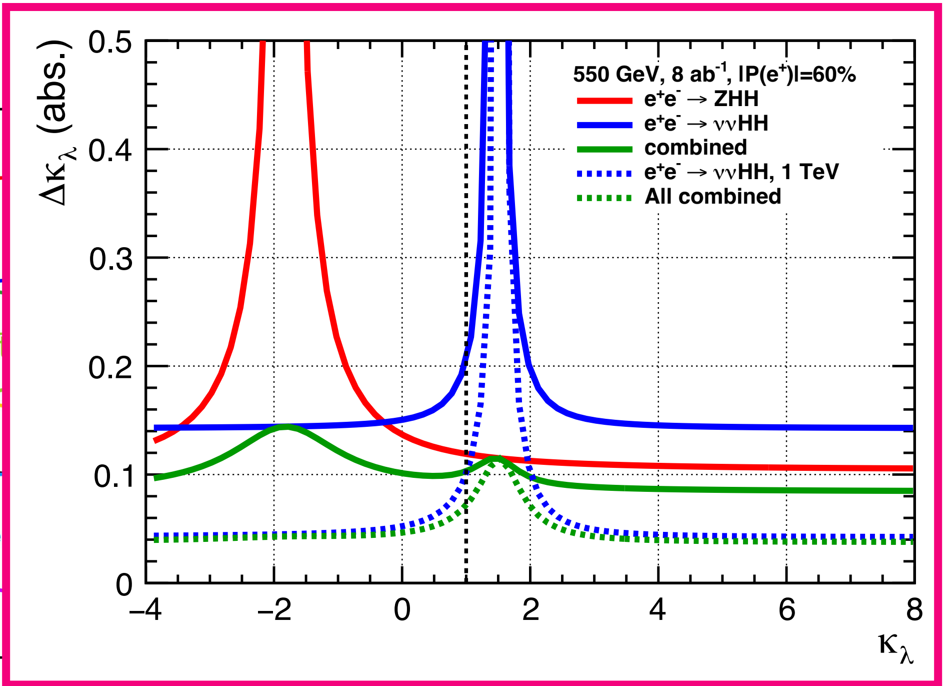

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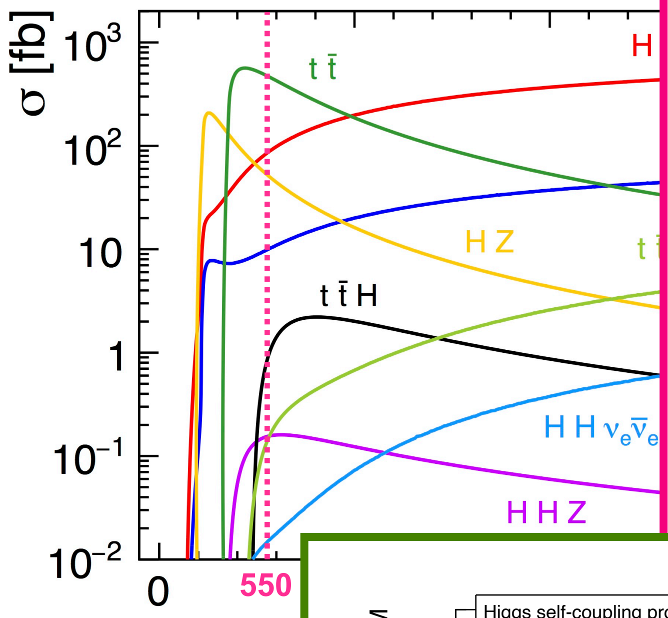

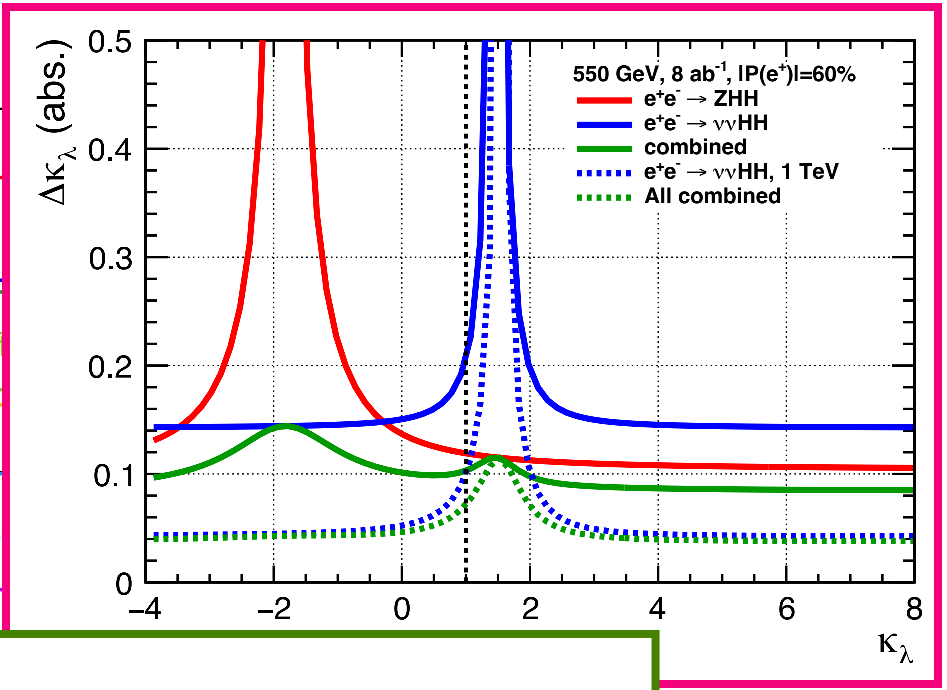

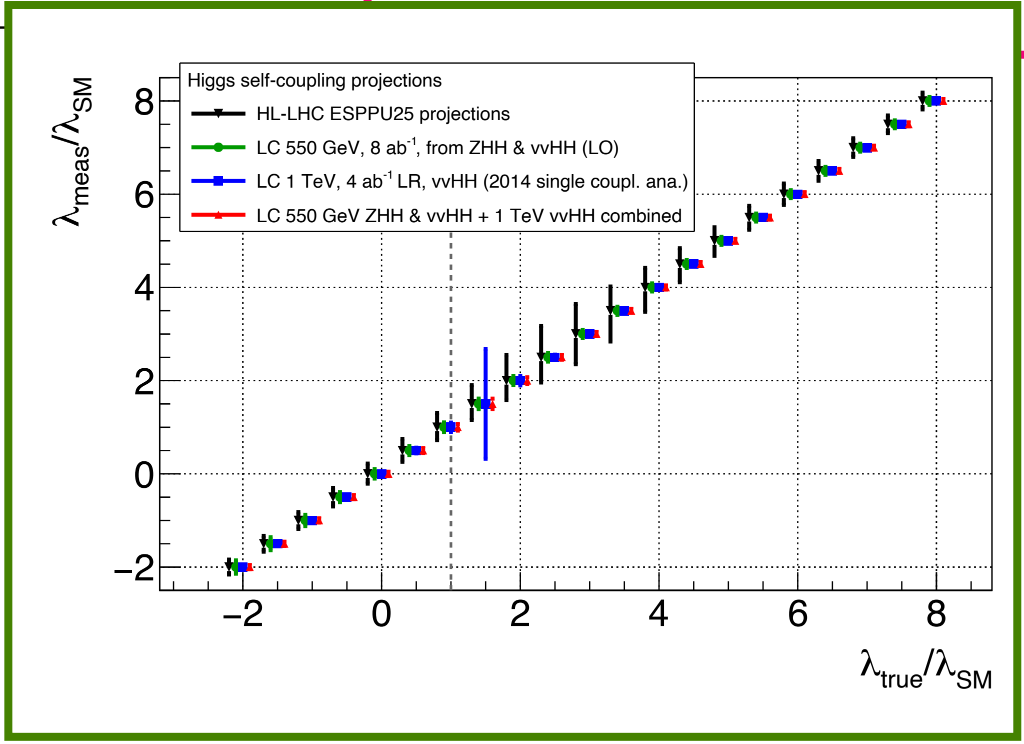

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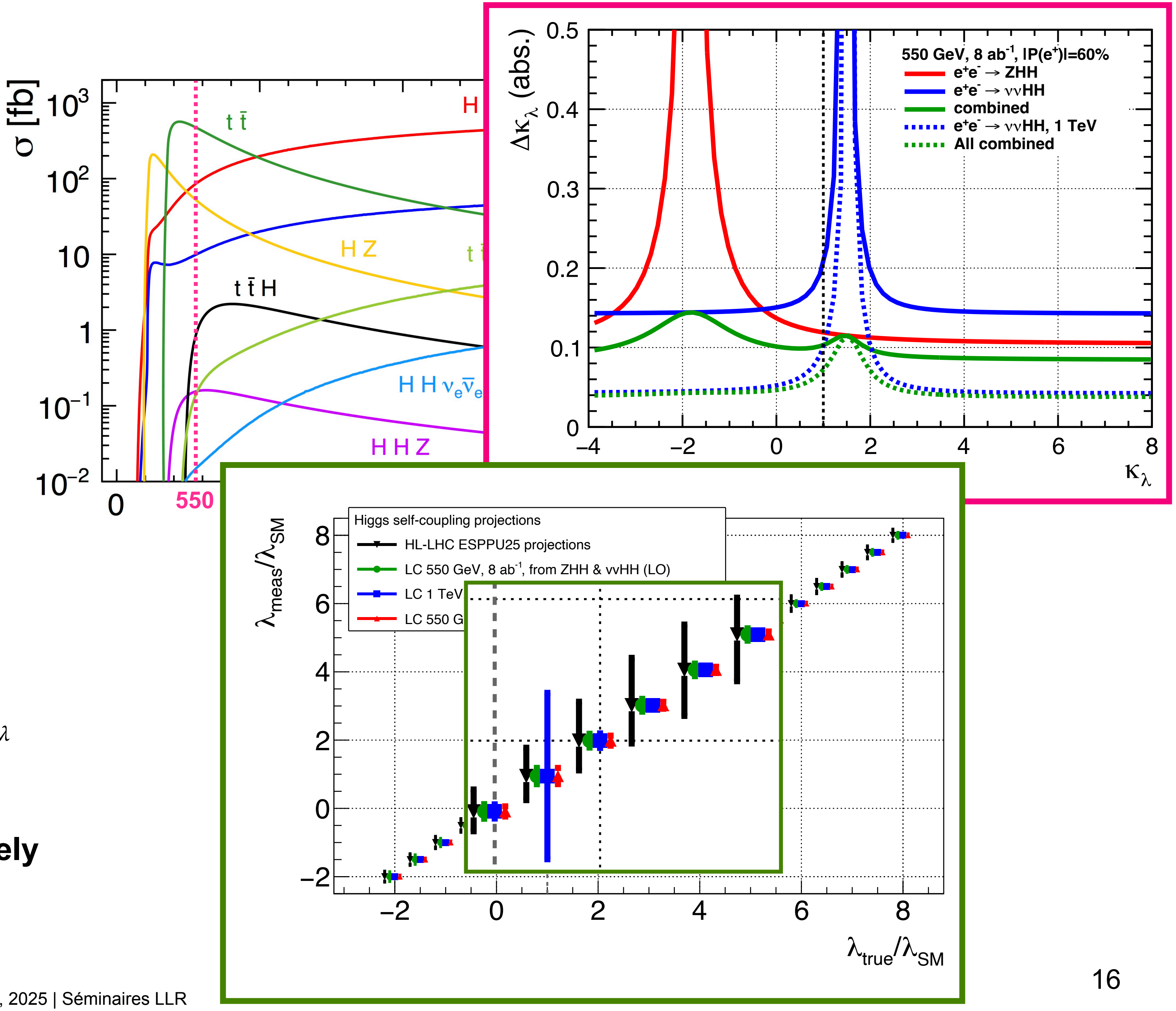

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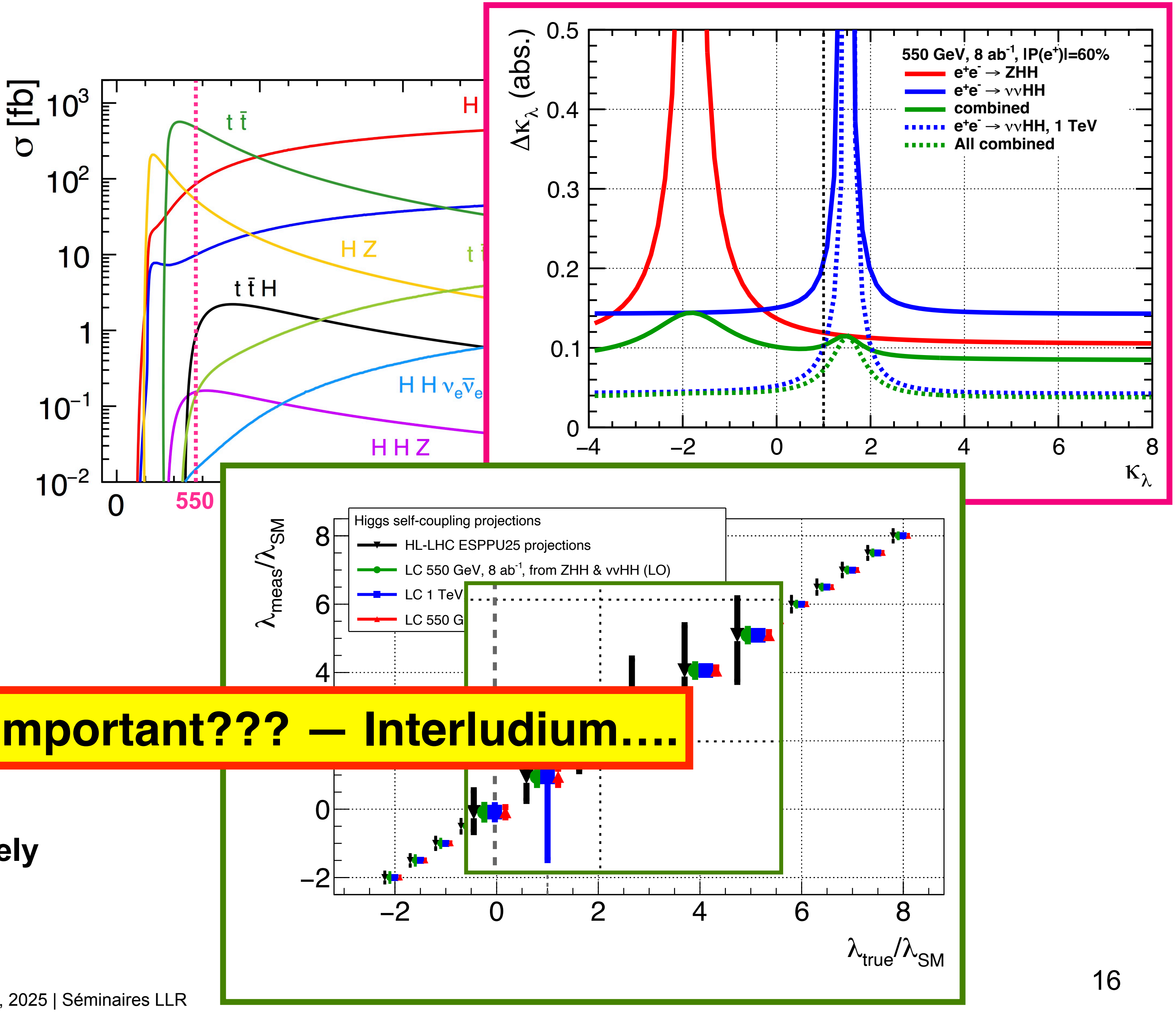
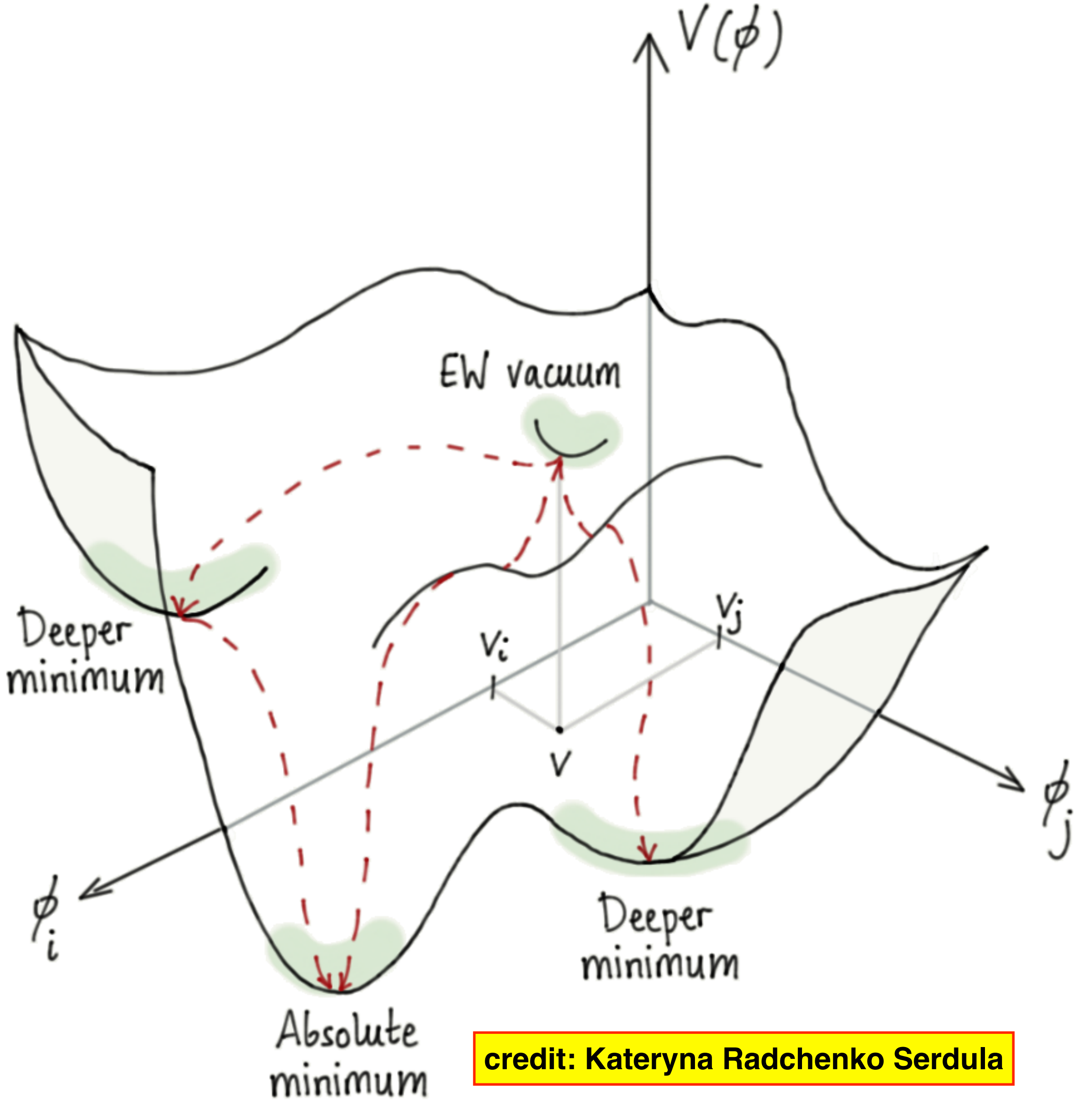


Why is this so important??? — Interludium….

Higgs potential in extended Higgs Sectors

“Mexican hat” turns into complex landscape

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



credit: Kateryna Radchenko Serdula

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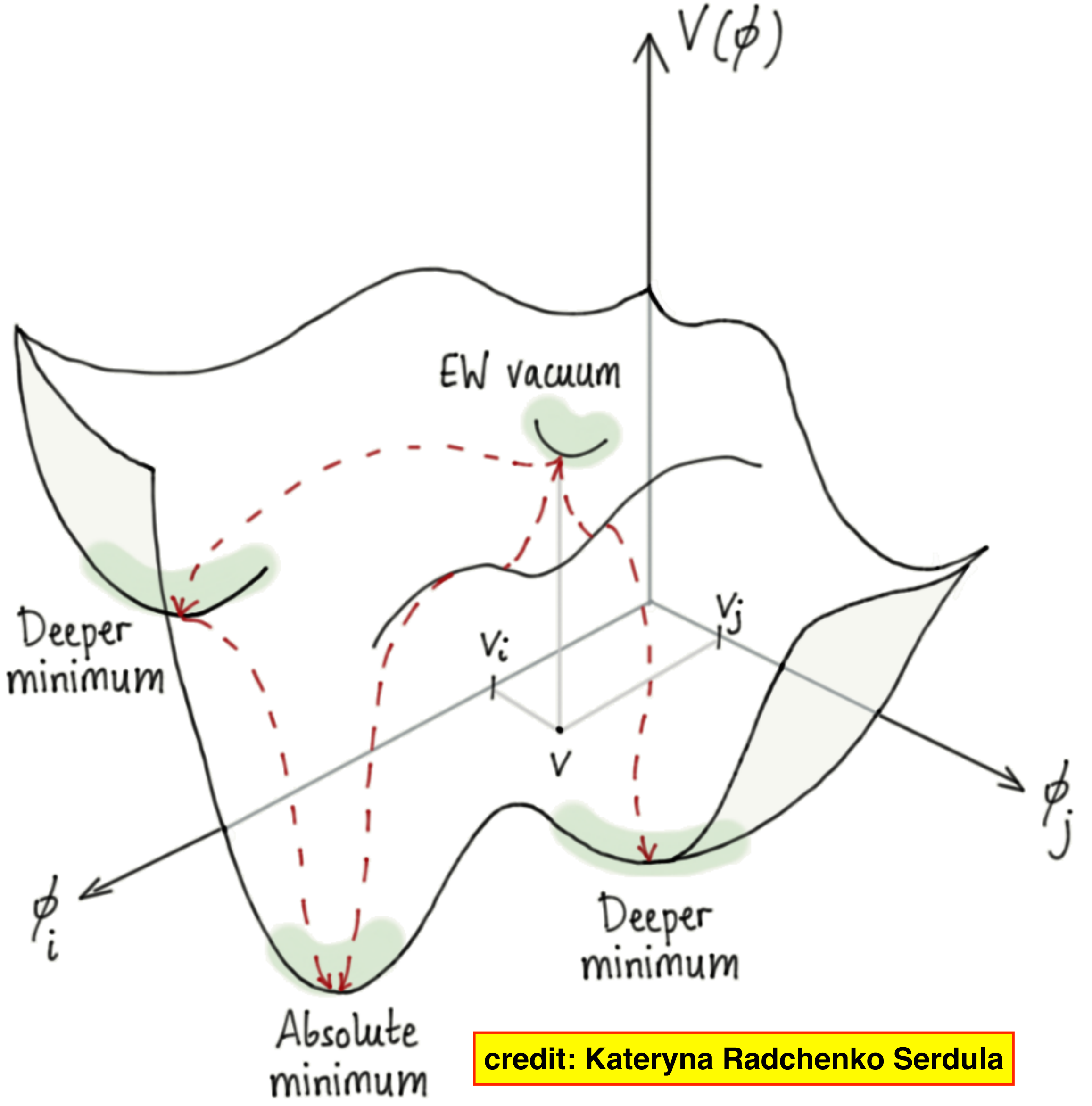
measure as many physical observables with least model-assumptions to explore this landscape - just assuming everything is like in the SM and extract one value is not sufficient!



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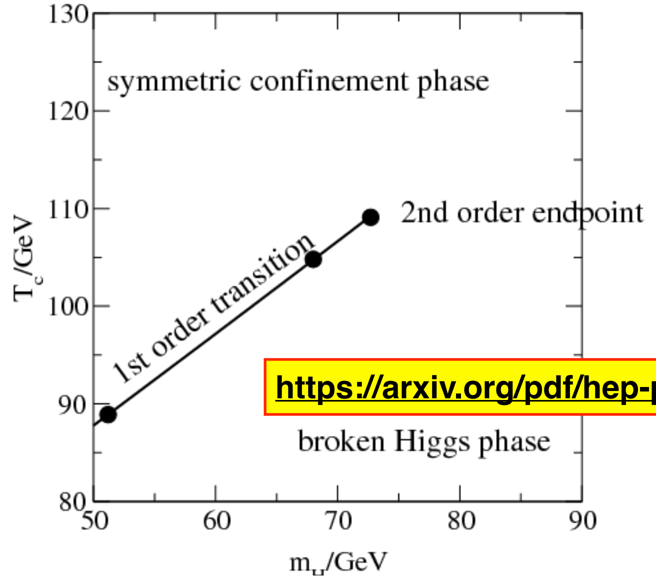
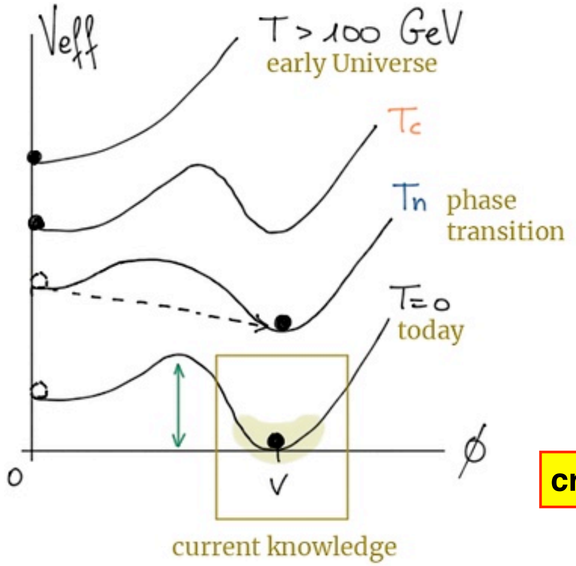
Electroweak Symmetry Breaking and Baryogenesis

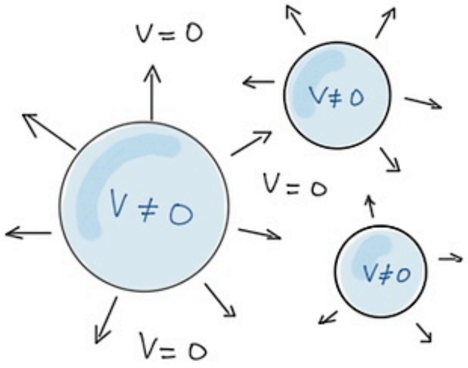
Evolution of the universe

- temperature evolution of Higgs potential ?
- phase diagram of the SM!
- for M_H > 75 GeV, there is no phase transition in the SM
- thus in SM no out-of-equilibrium state of the early universe for baryogenesis (requires 1st order phase transition, cf Sacharov conditions)
- in many **extended Higgs sectors**, 1st order phase transition for $\lambda_3 > \lambda_{SM}$
- need to
  - **measure** whether self-coupling λ_3 = 0.13 as predicted by SM - with the least possible prejudice! (eg “everything else” SM-like)
  - **check** whether Higgs field is indeed just one $SU(2)_L$ doublet



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





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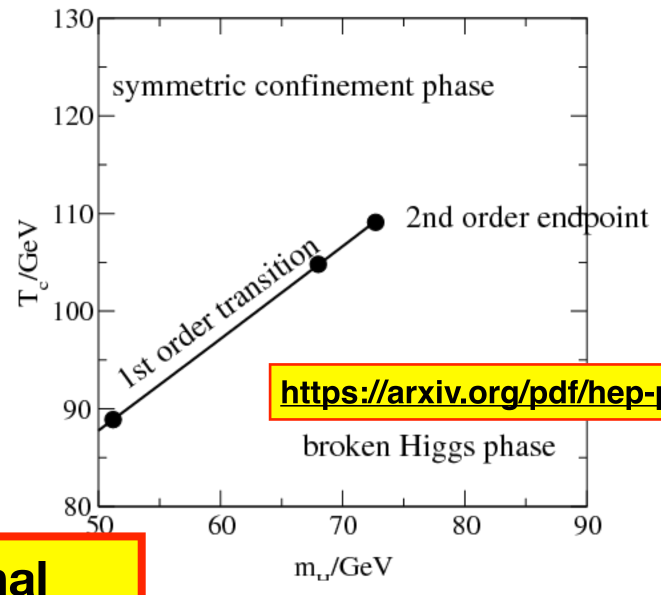

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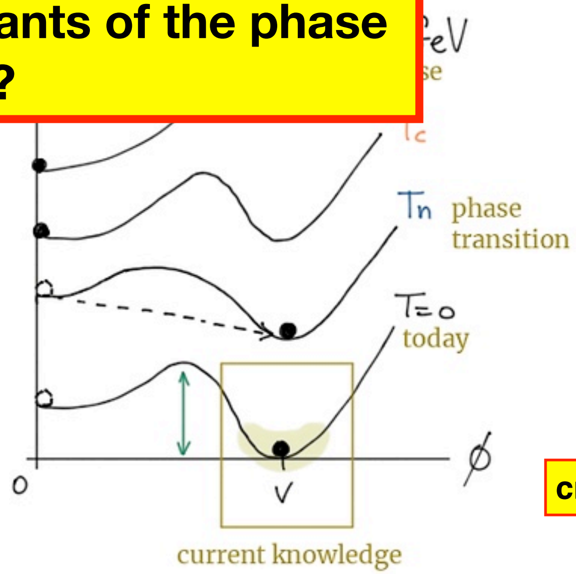
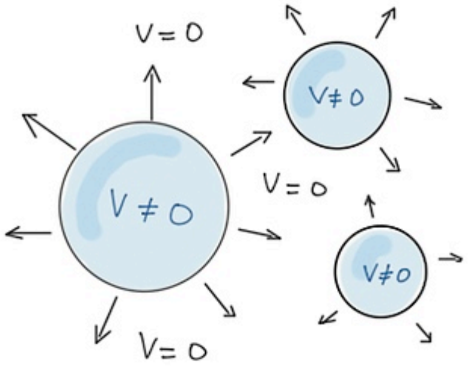
Interesting interplay with gravitational waves: detect direct remnants of the phase transition?





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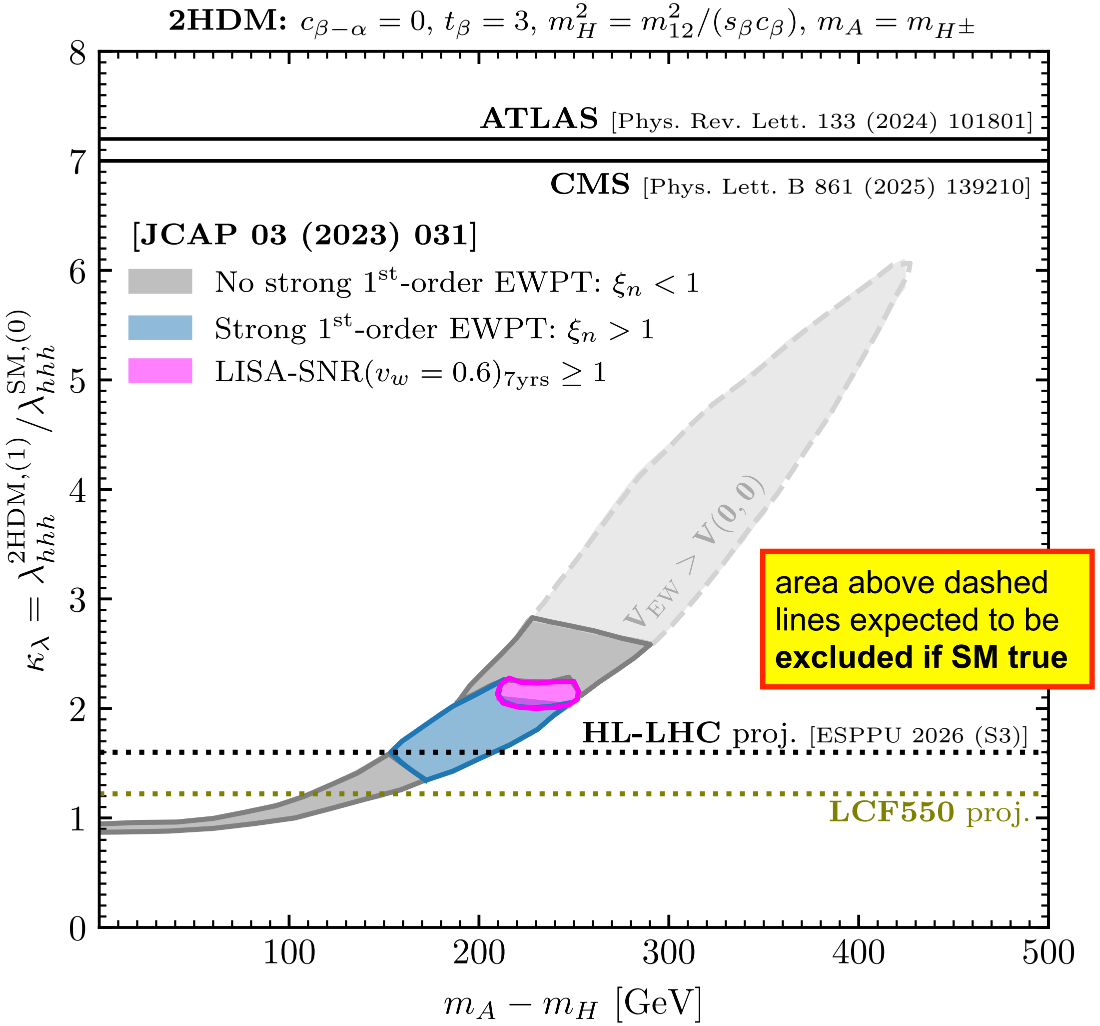
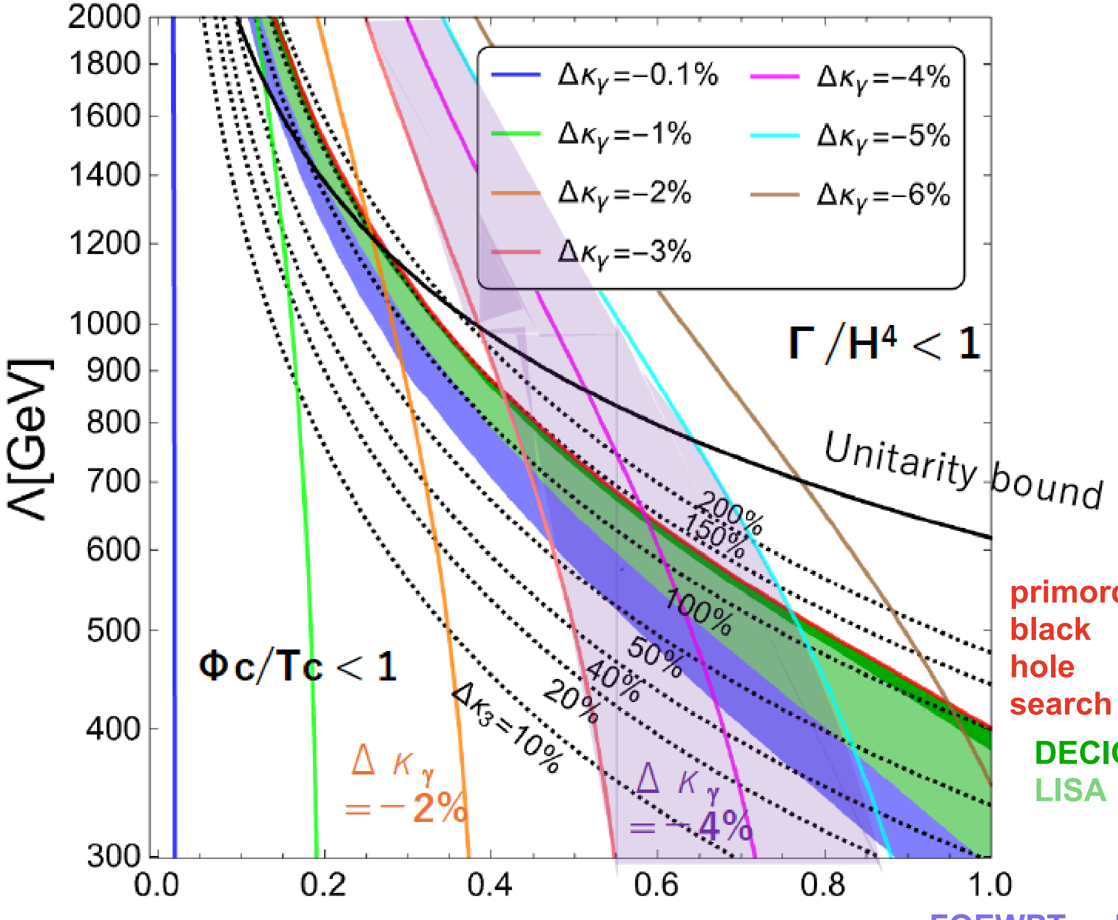
Interplay with Gravitational Wave detection

Need to assume specific extended Higgs sector to quantify effects



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



Phys.Lett.B 856 (2024) 138940

FOEWPT only testable via Higgs

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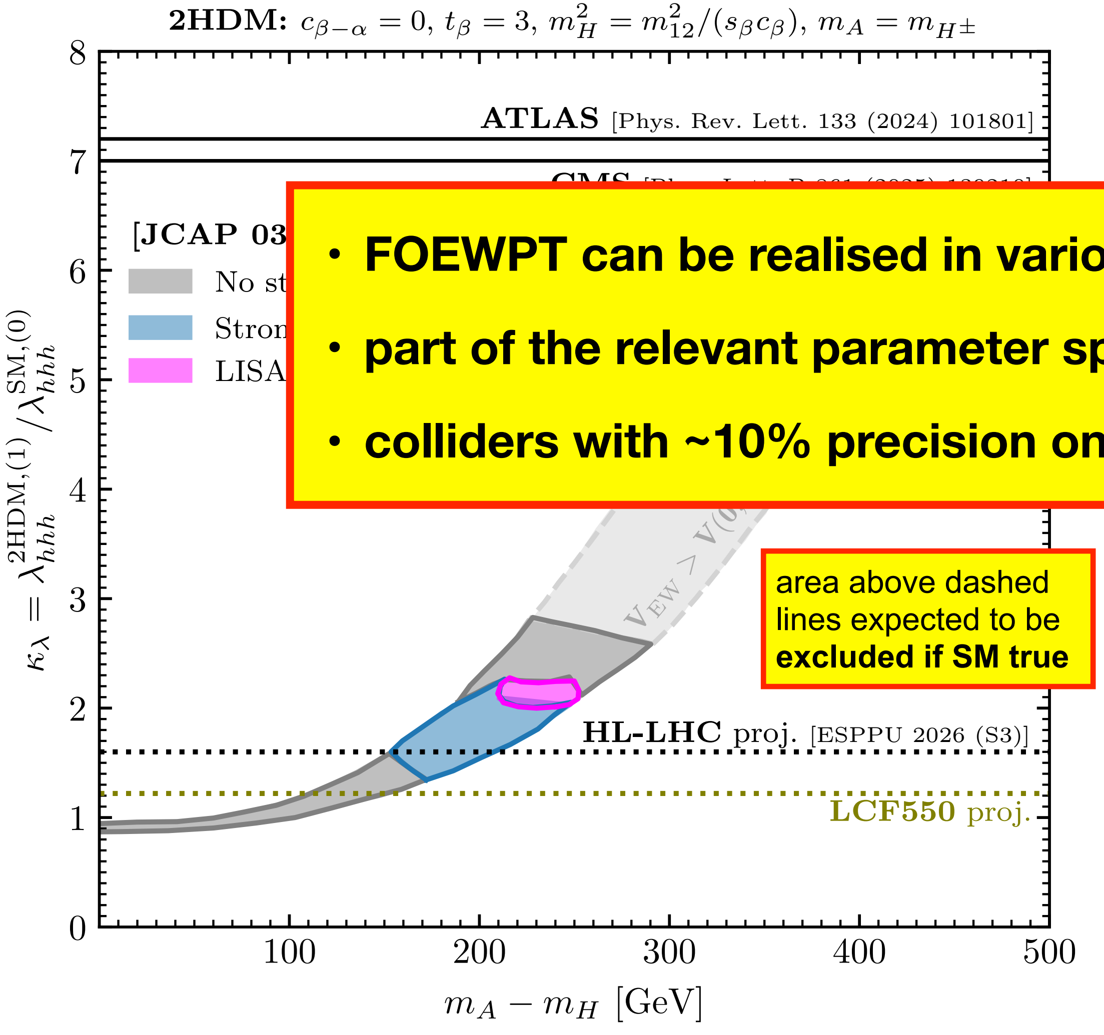

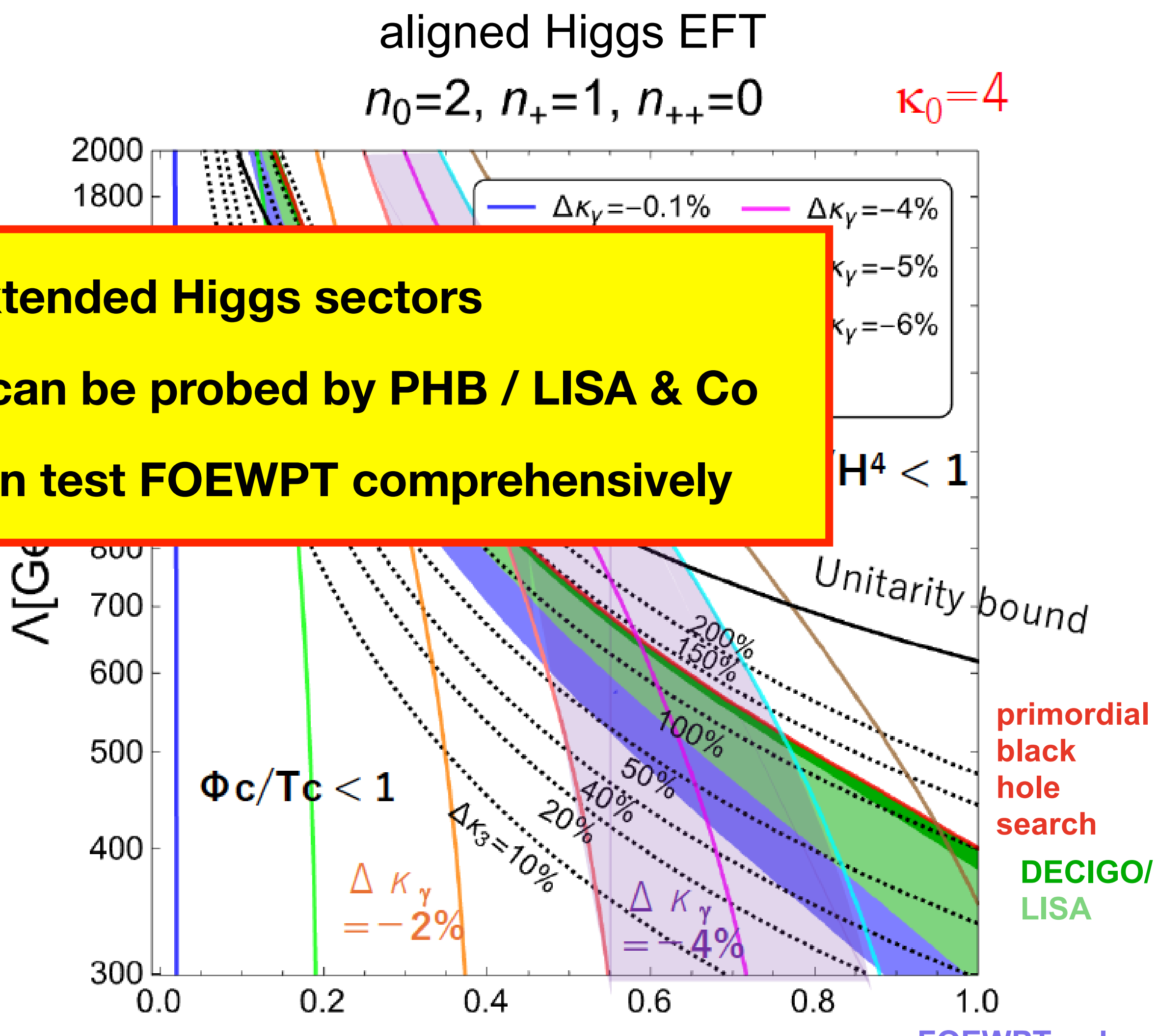

- **FOEWPT can be realised in various extended Higgs sectors**
- **part of the relevant parameter space can be probed by PHB / LISA & Co**
- **colliders with ~10% precision on κ_λ can test FOEWPT comprehensively**

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FOEWPT only testable via Higgs

Higher energies offer so much more

Example: top physics

- **tt threshold ~350 GeV:**
  - threshold mass => exp. stat. negligible after ~100fb^{-1}
- **electroweak couplings need higher energies and polarised beams**
  - polarisation disentangles couplings to Z from couplings to photon
  - sensitivity to "axial-vector"-type of couplings grows with energy
  - dim-6 SMEFT:
    - need measurements at two energies above tt threshold to resolve degeneracies between operators
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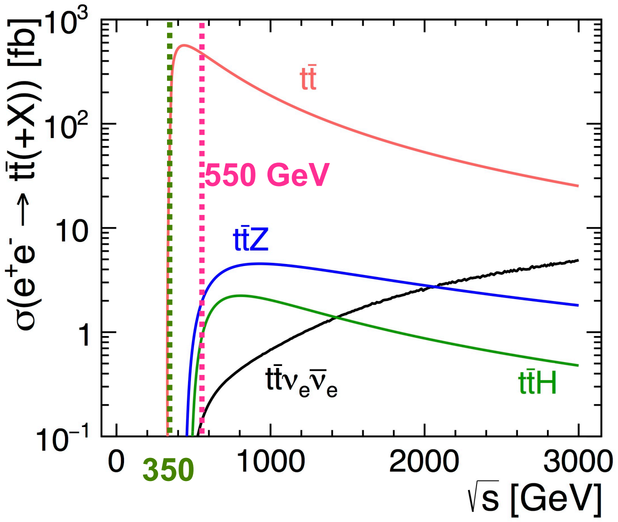
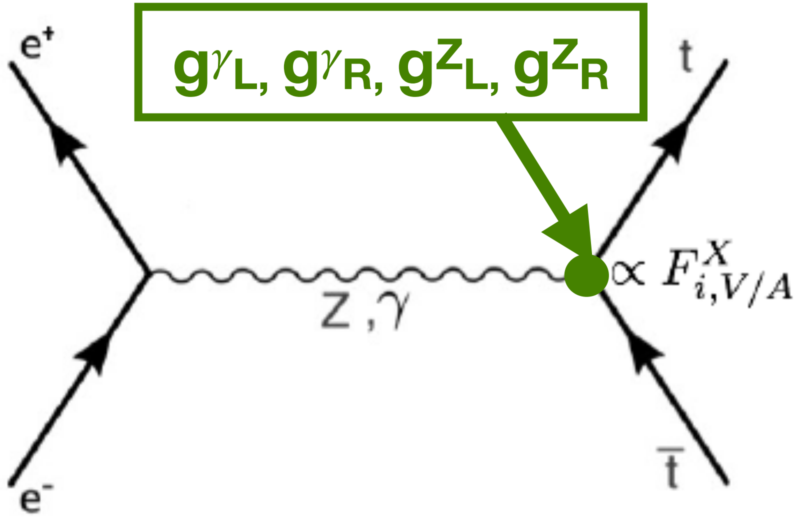
  - constrain 4-fermion operators to < 0.1%
  - incl. eett operators (entering ZH @ NLO)





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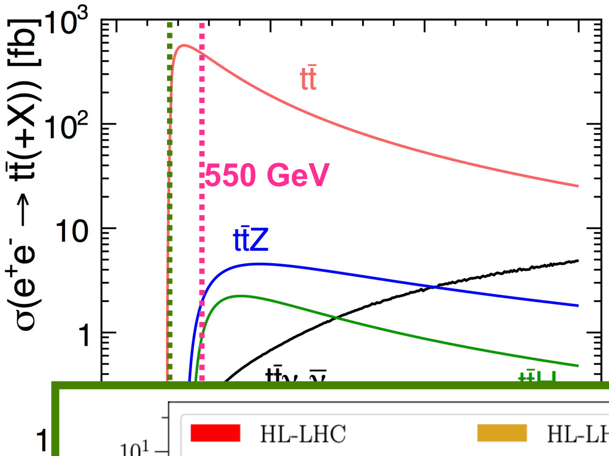

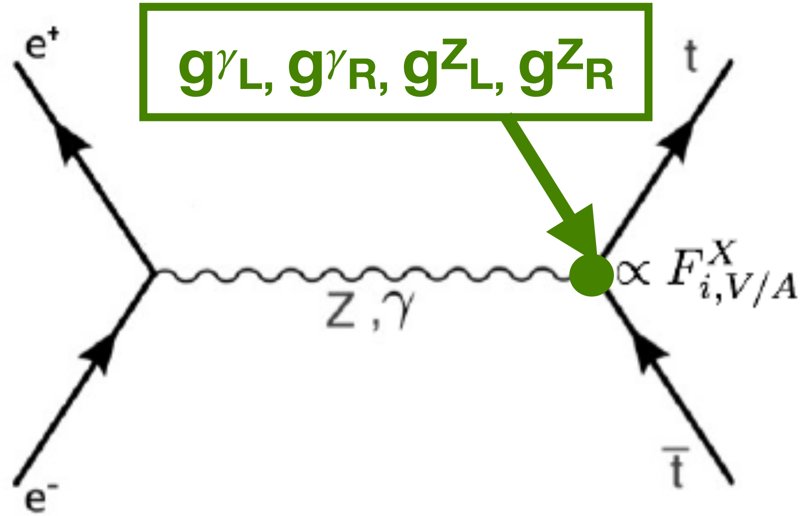

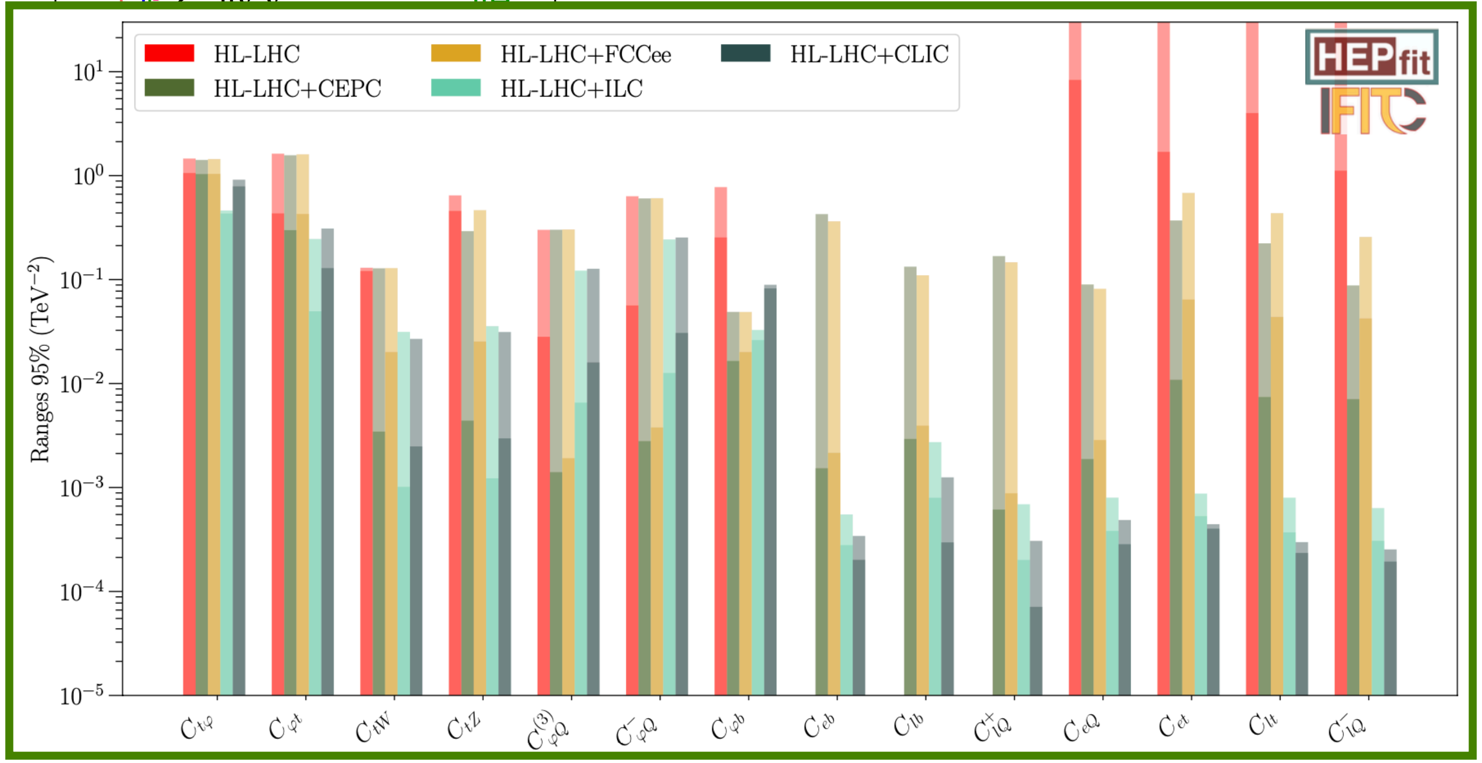

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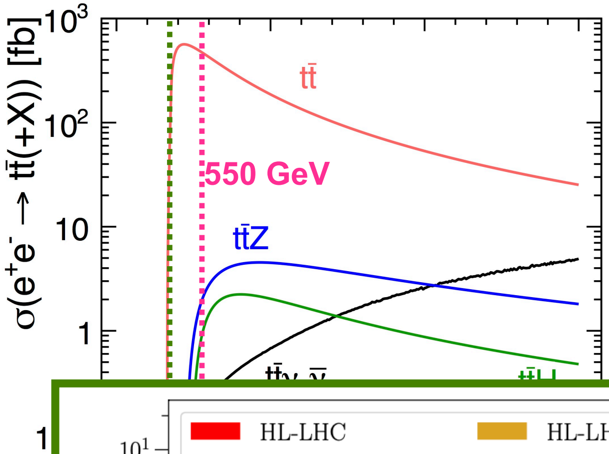

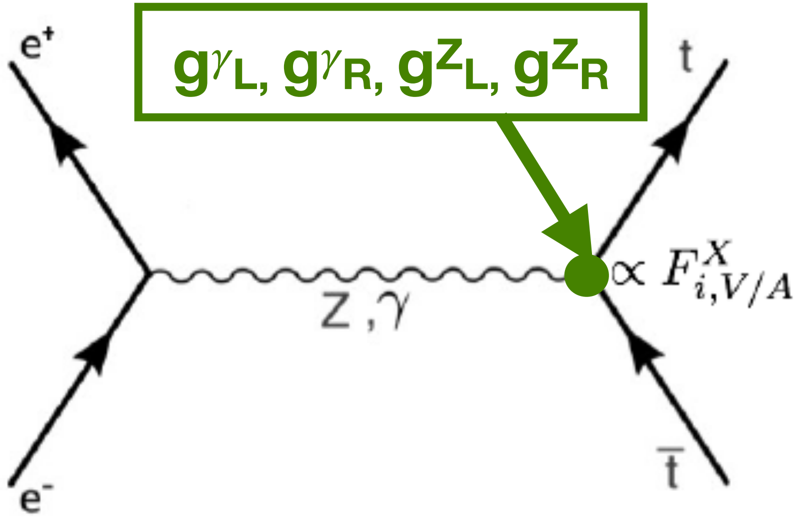

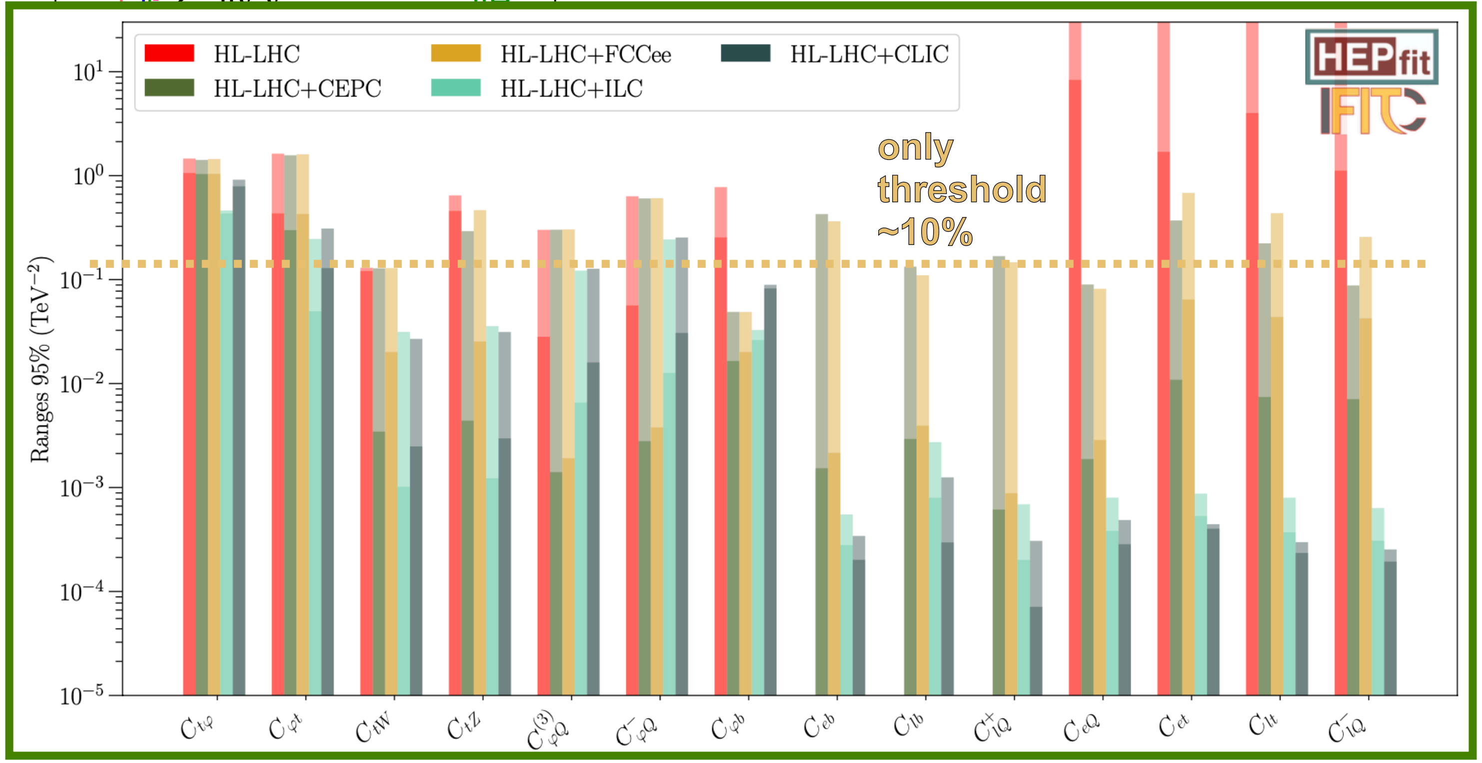

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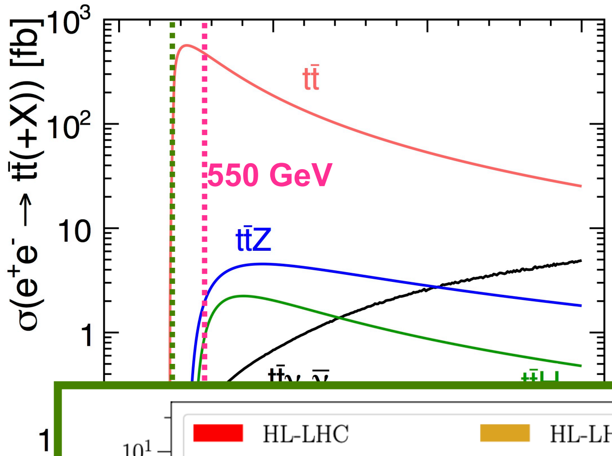
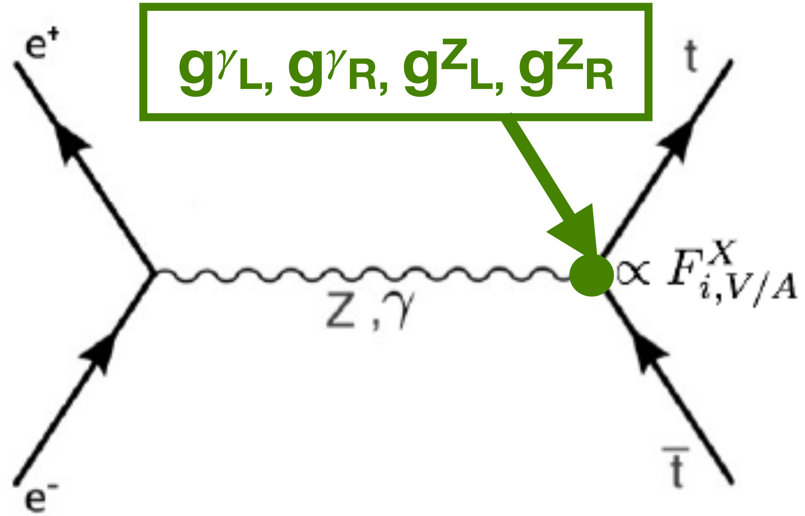
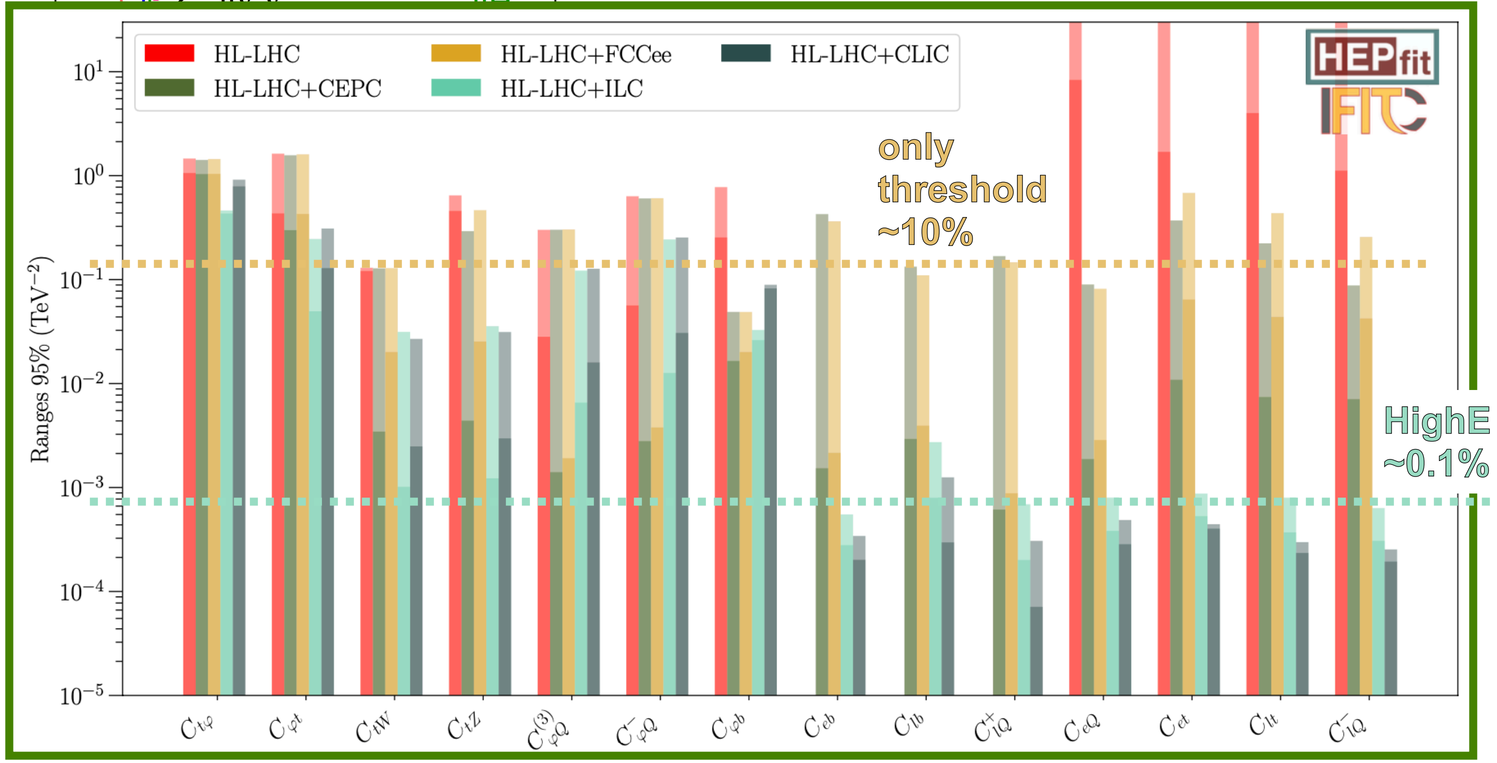




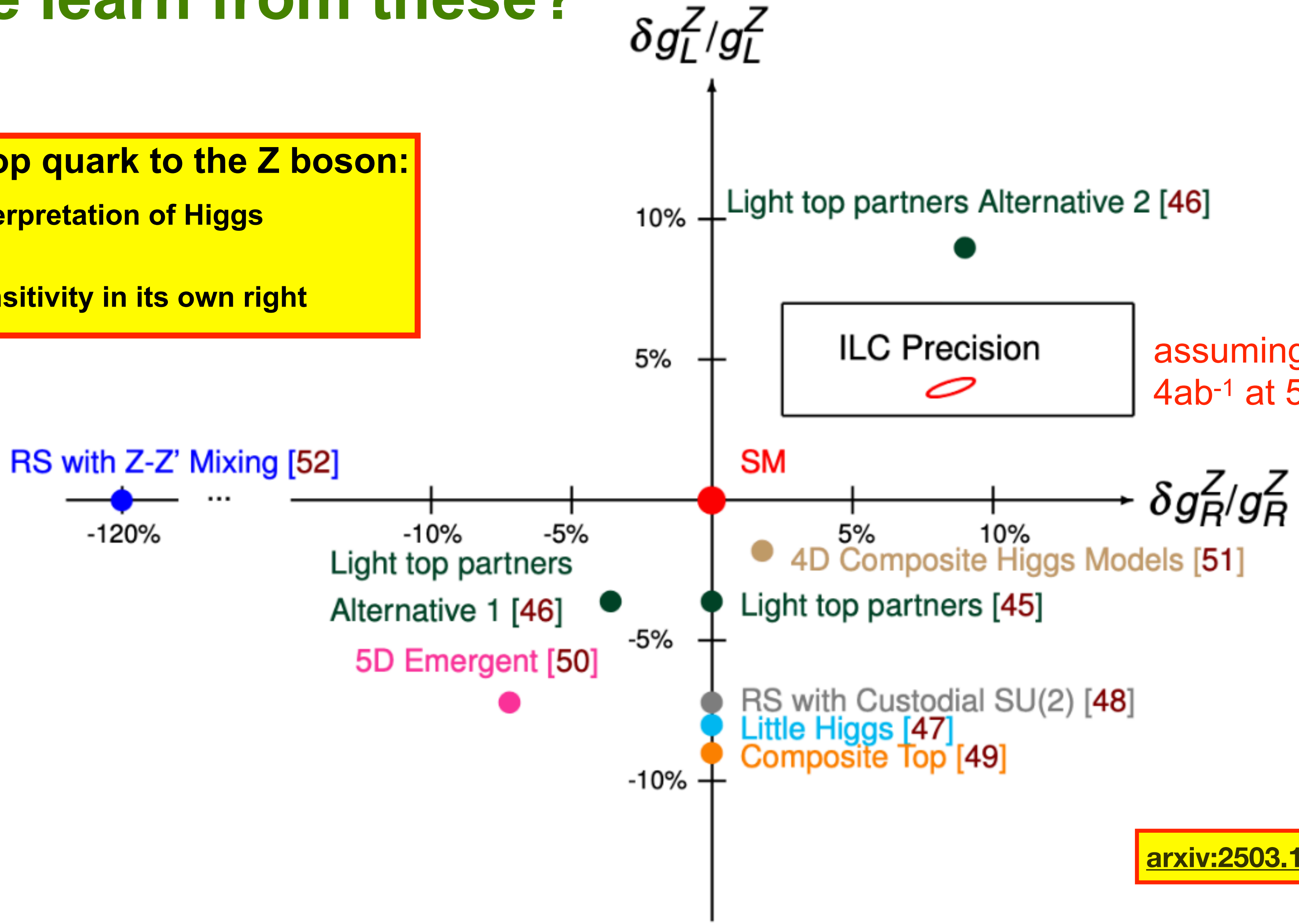


What do we learn from these?

Top and BSM

Couplings of the Top quark to the Z boson:

- **essential for NLO interpretation of Higgs measurements**
- **tremendous BSM sensitivity in its own right**

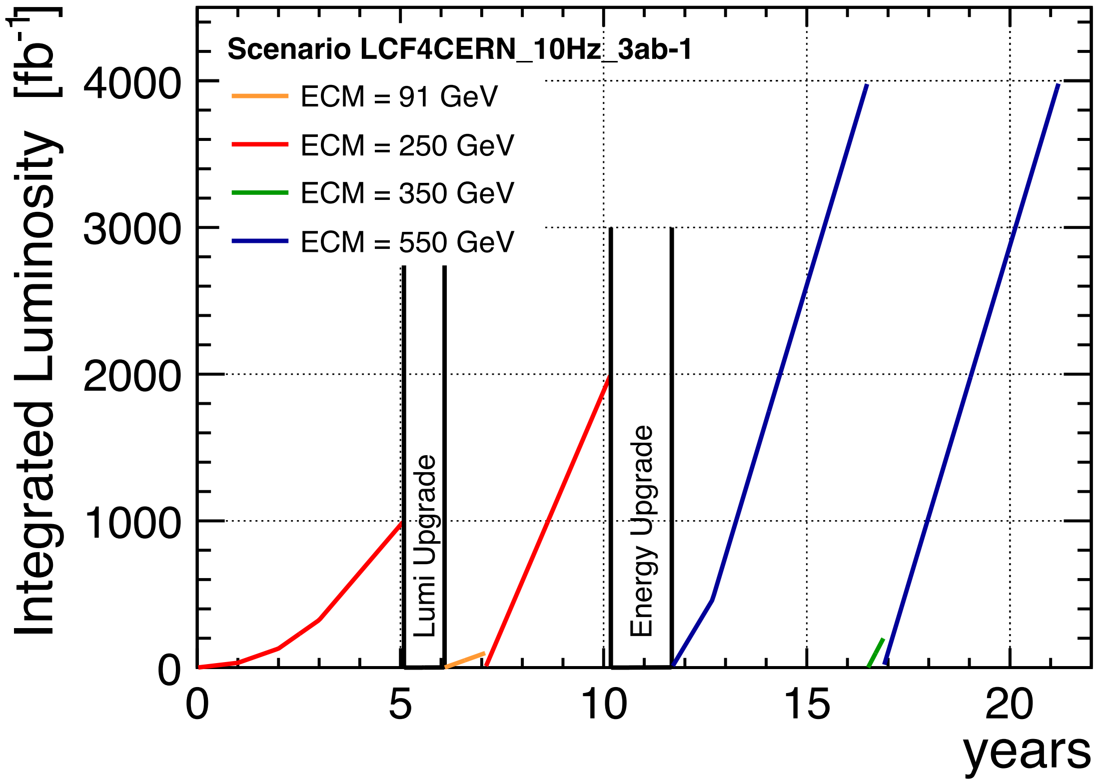


assuming only $4ab^{-1}$ at 500 GeV

arxiv:2503.19983

Running Scenarios up to 550 GeV

baseline



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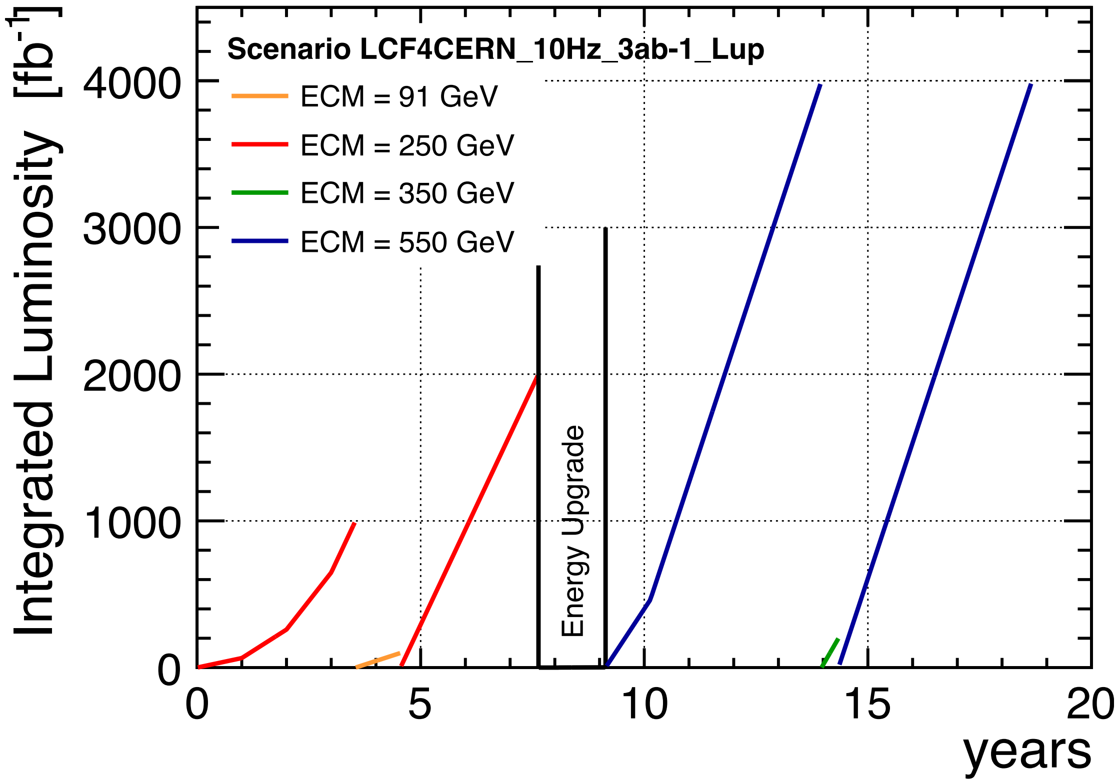

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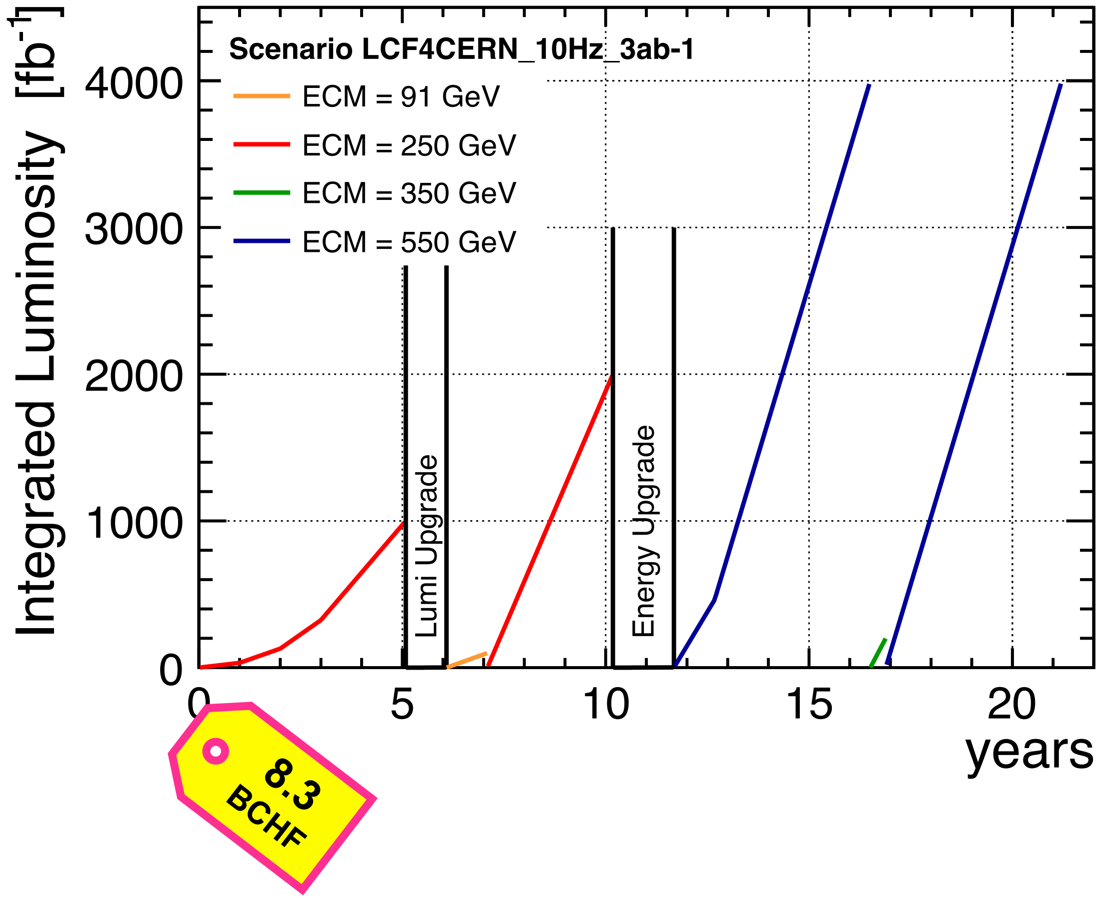

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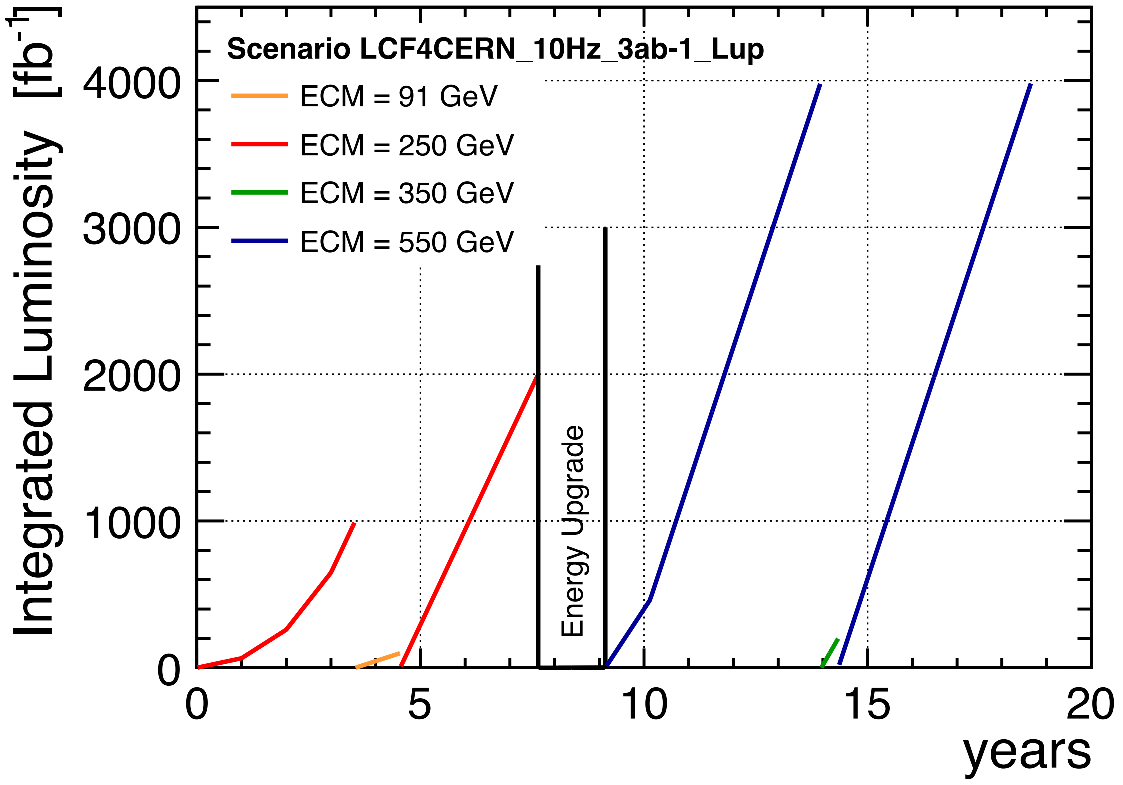

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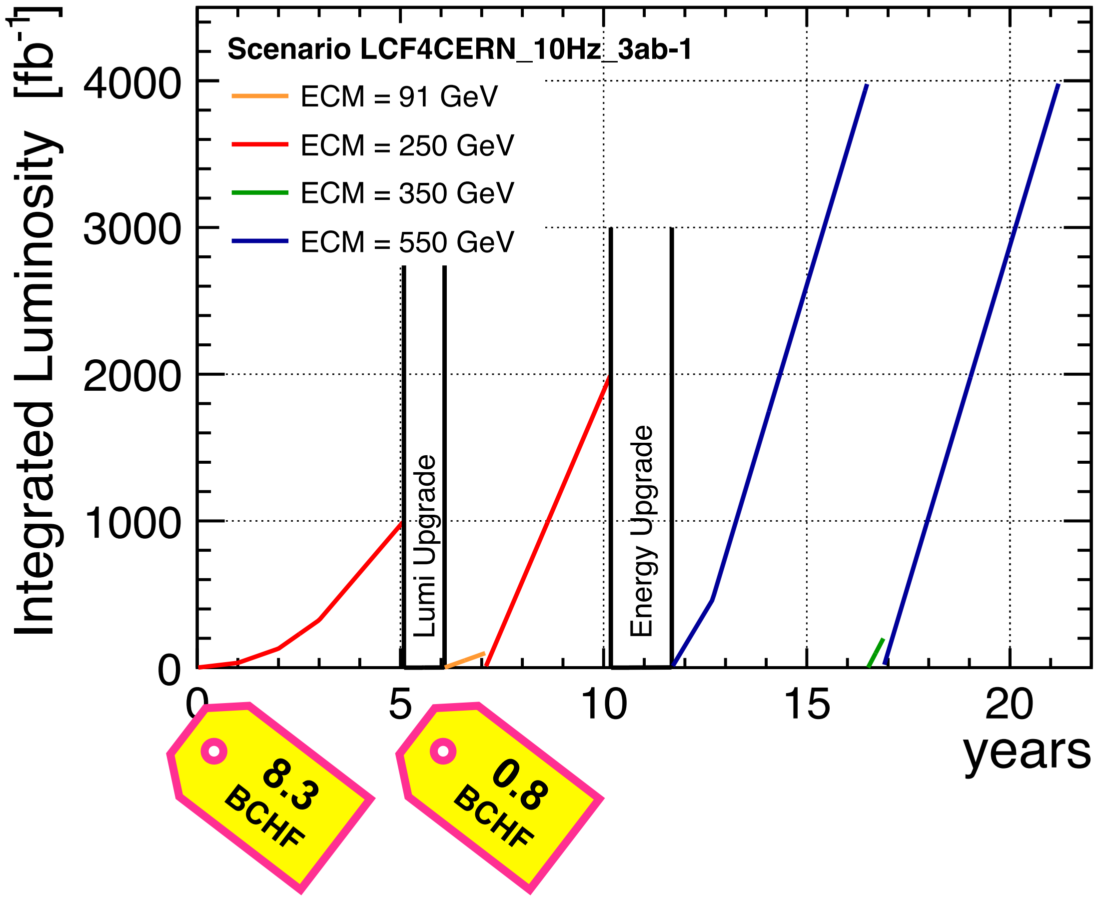

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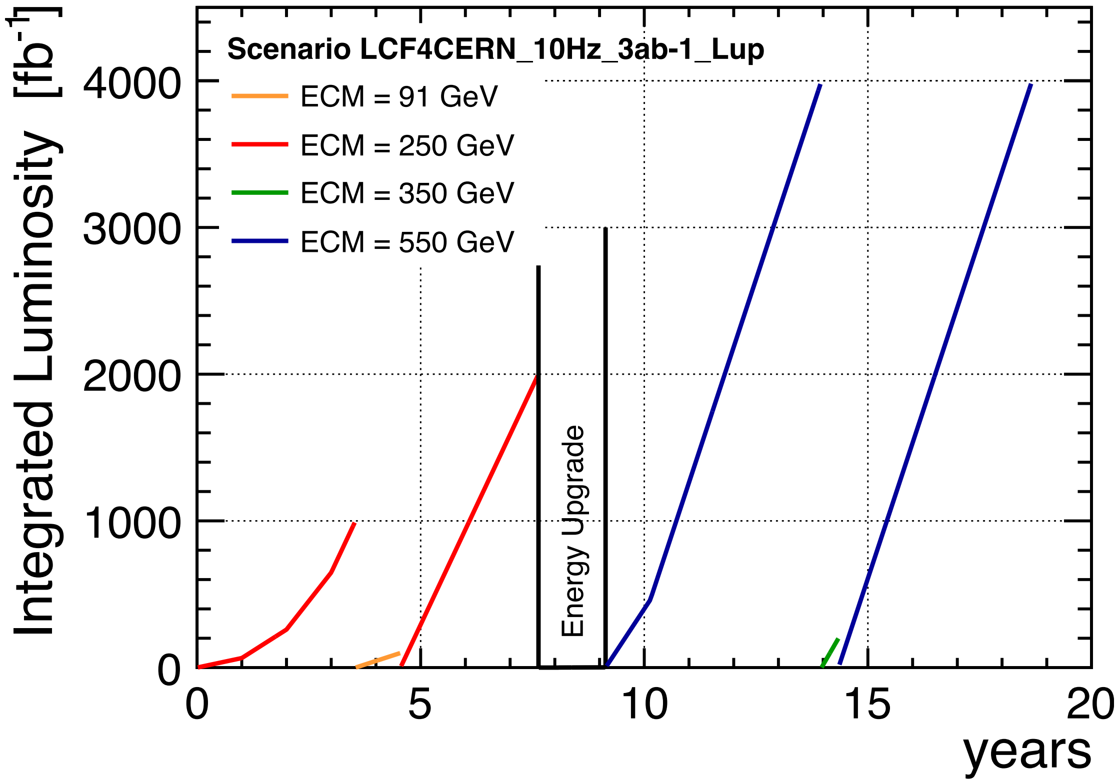

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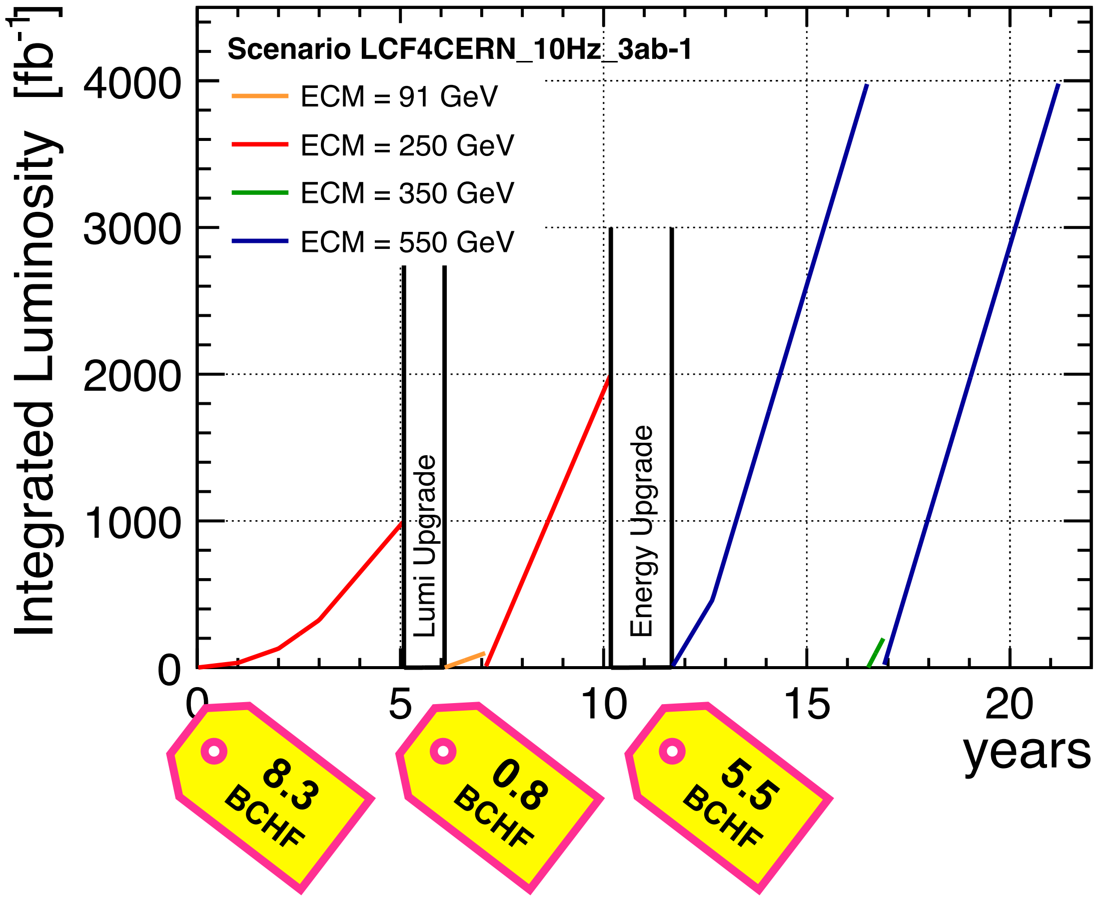

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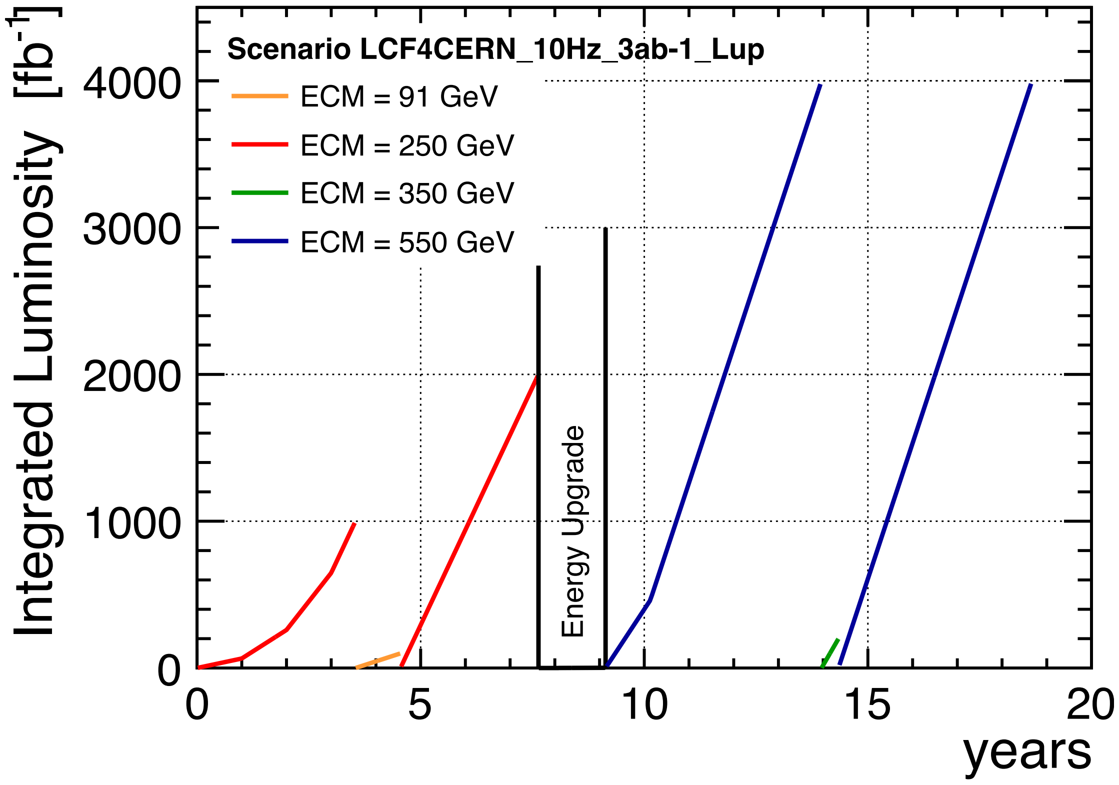

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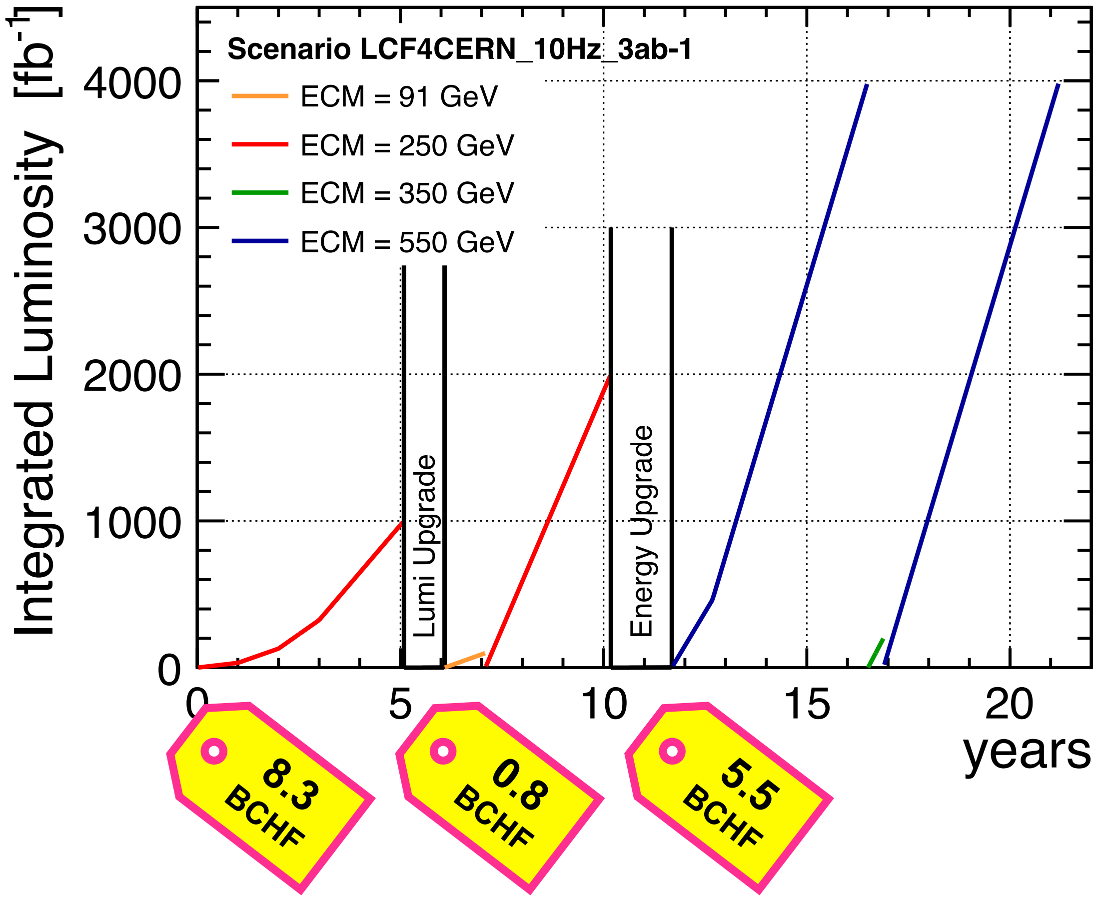
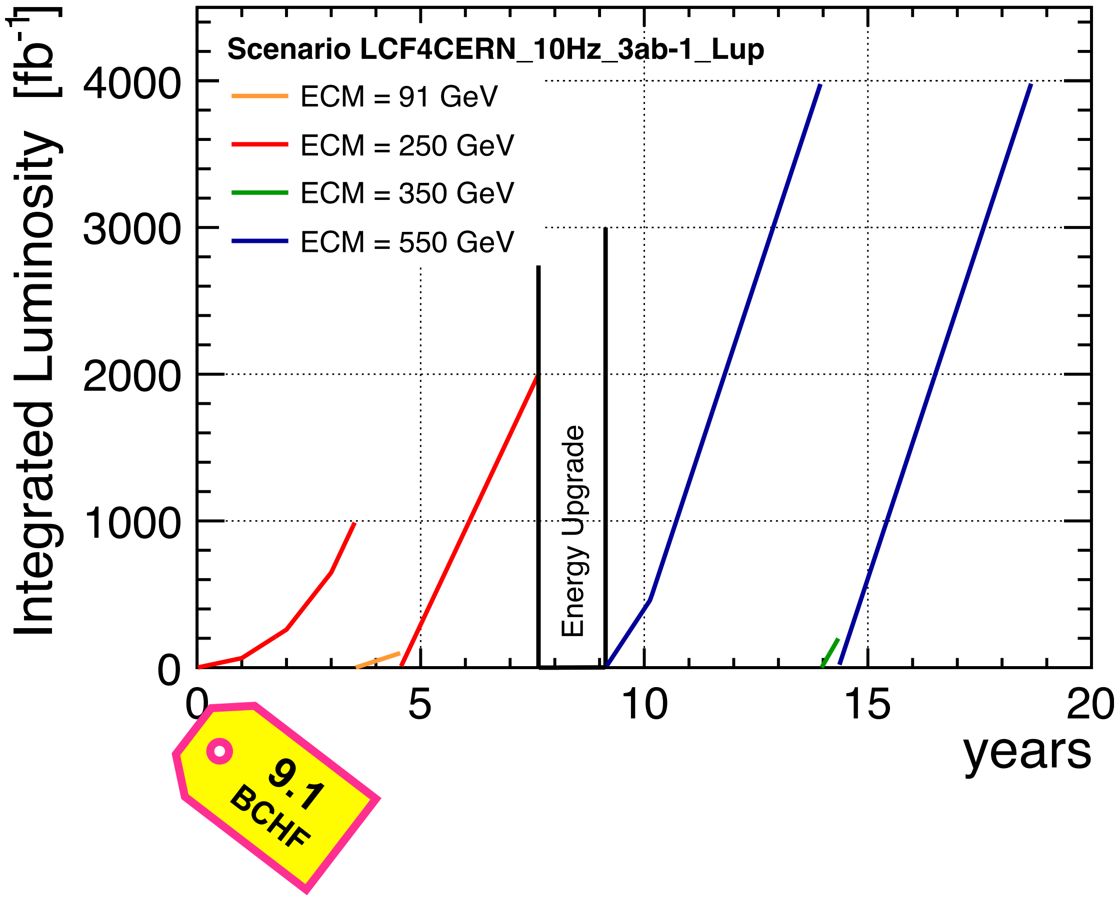
baseline



start immediately with full power



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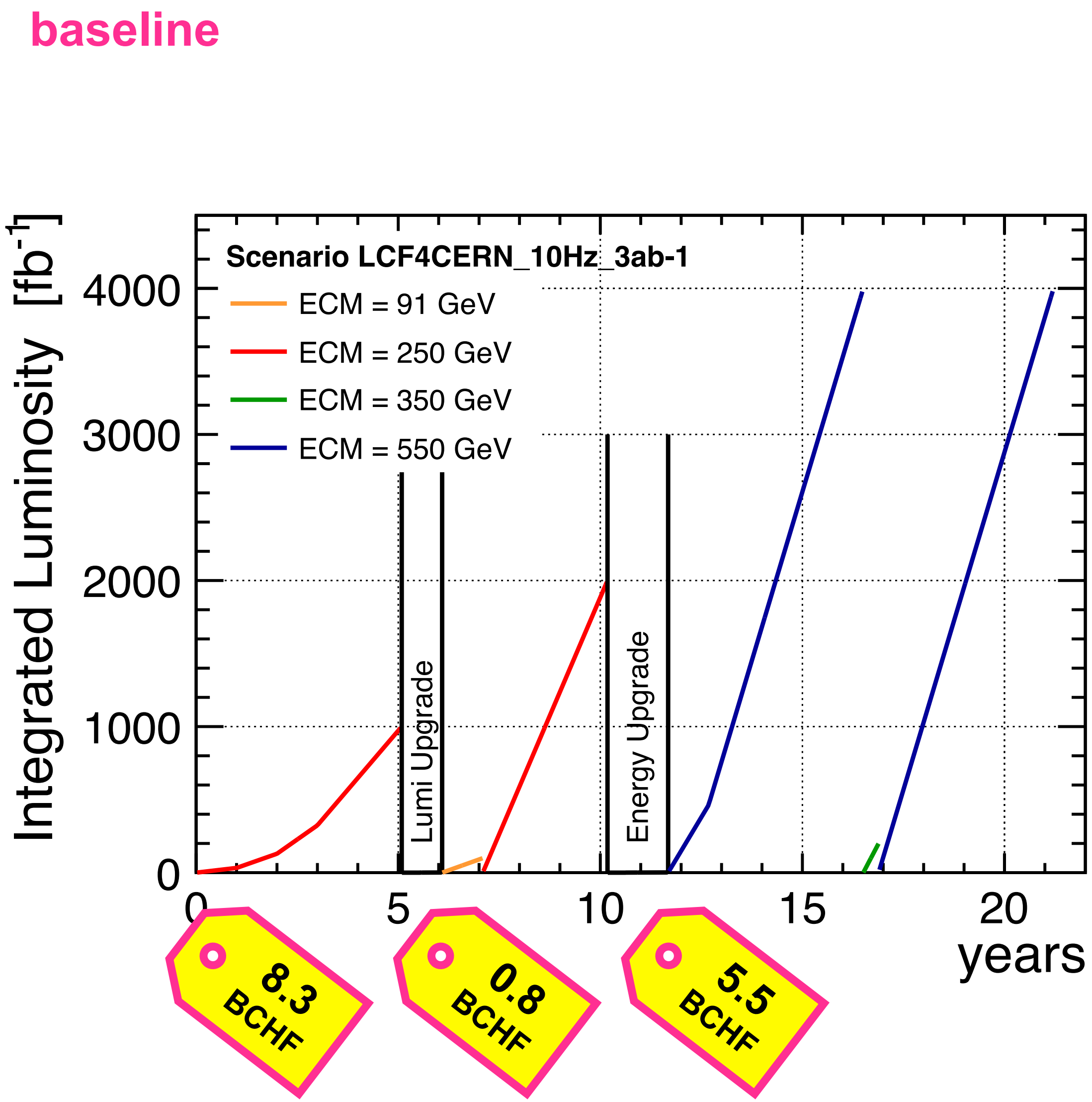
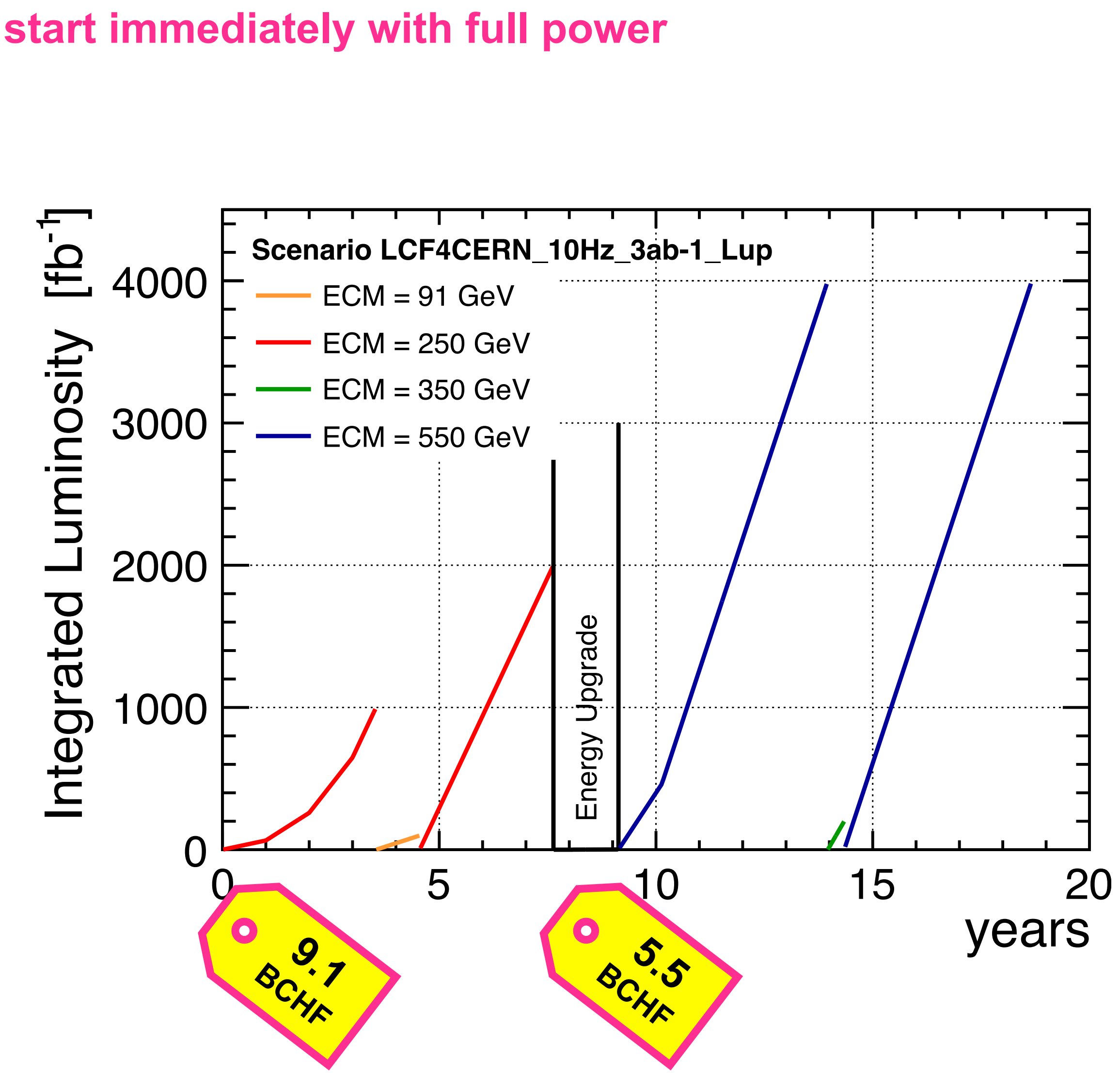
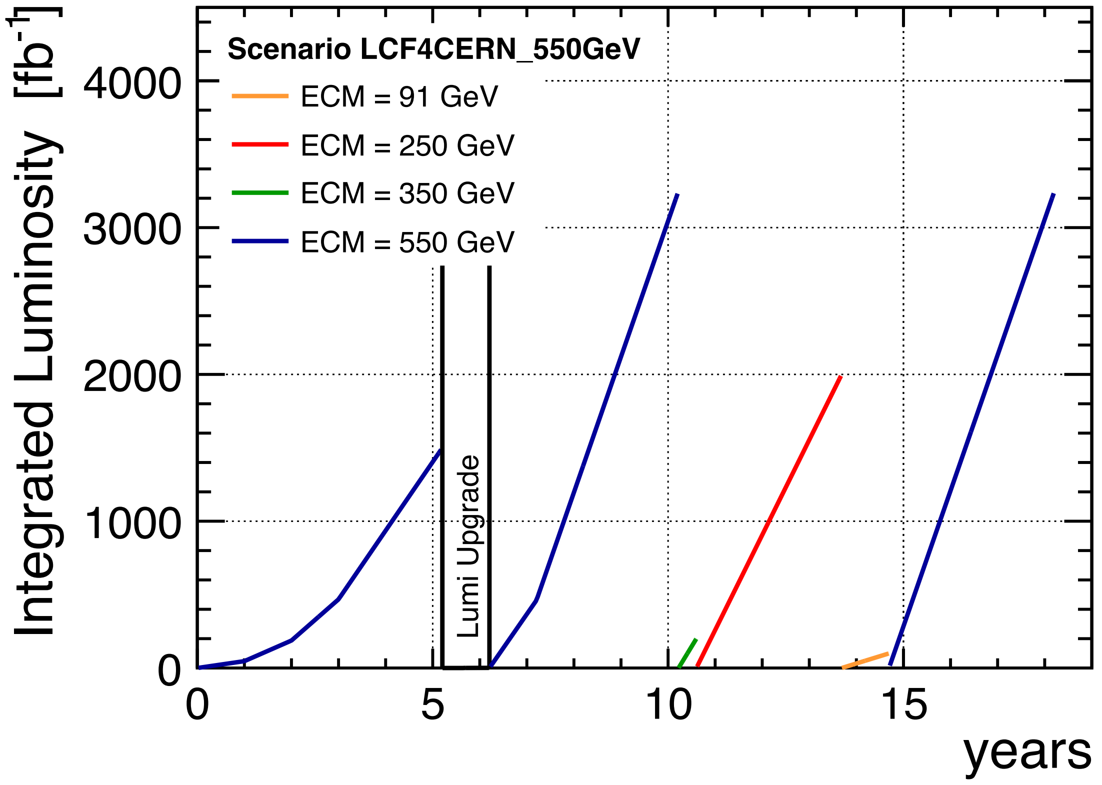


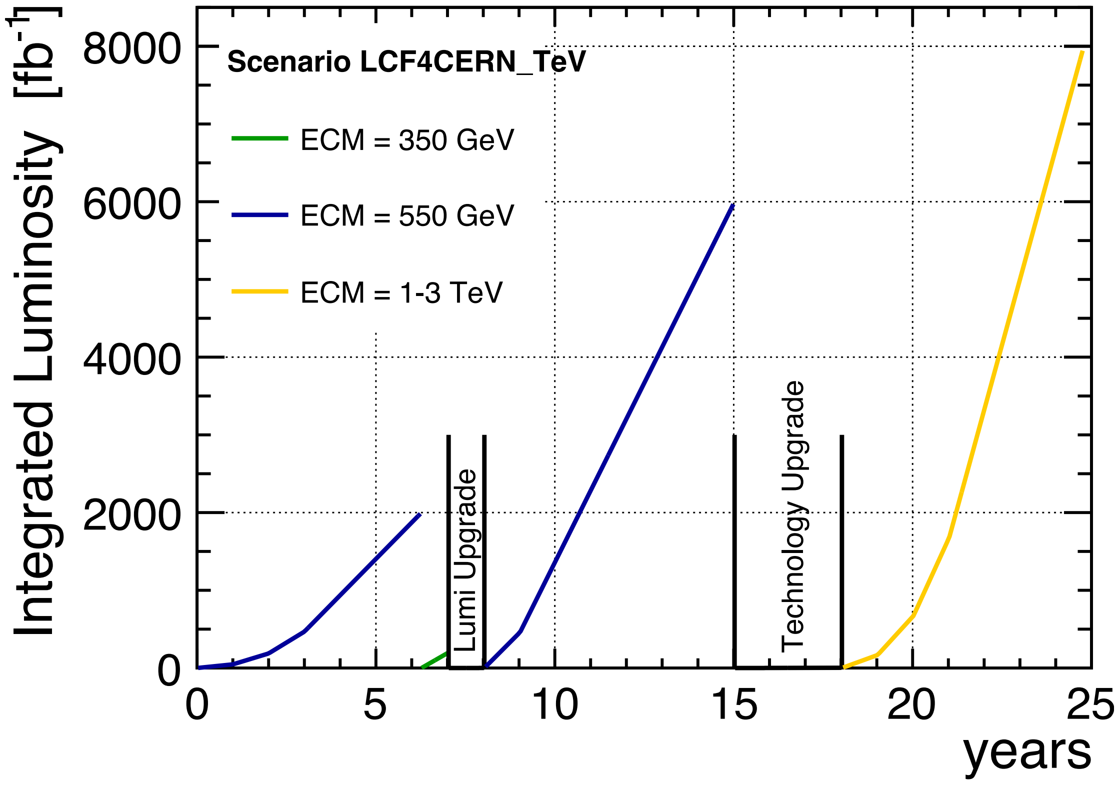


Running Scenarios - starting at 550 GeV

take some polarised data at lower energies



or go more quickly to TeV range



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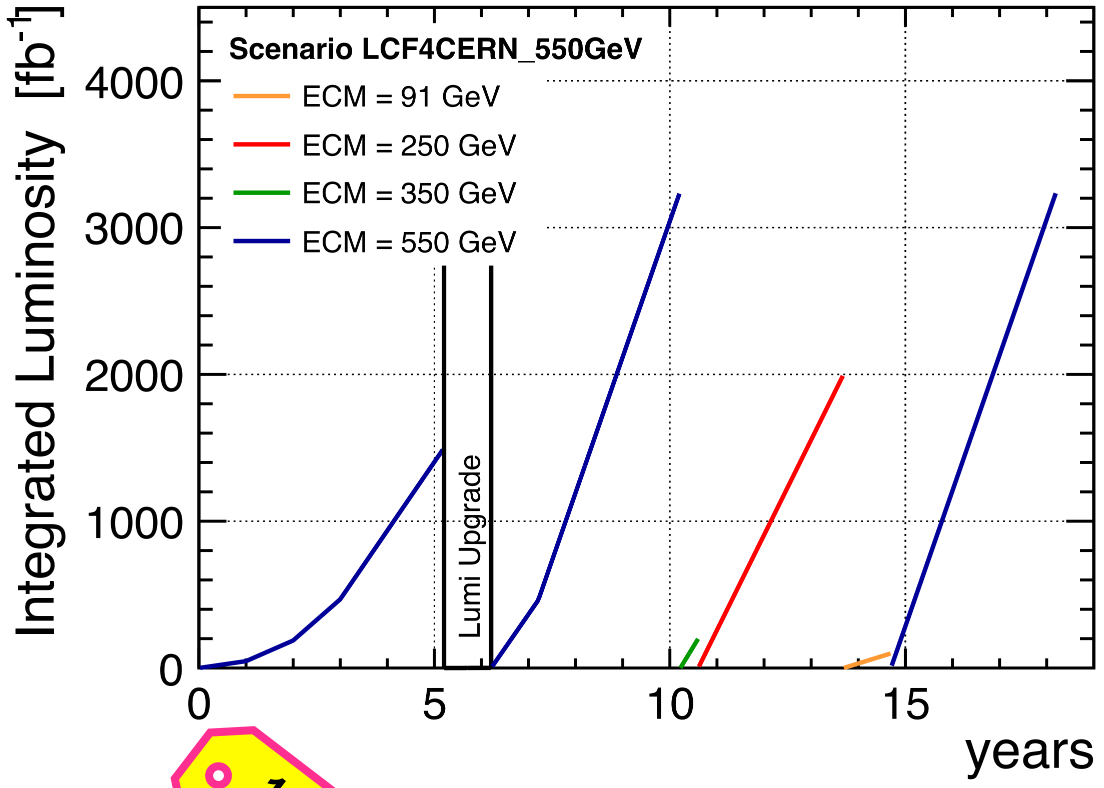

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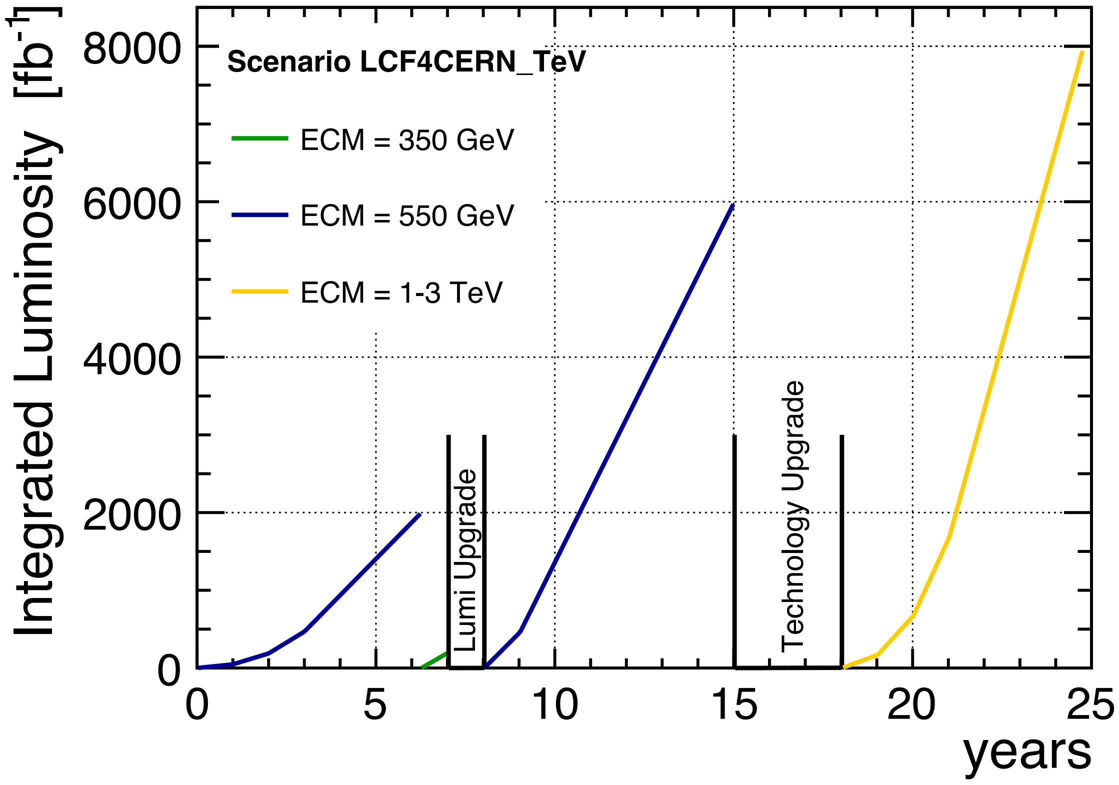

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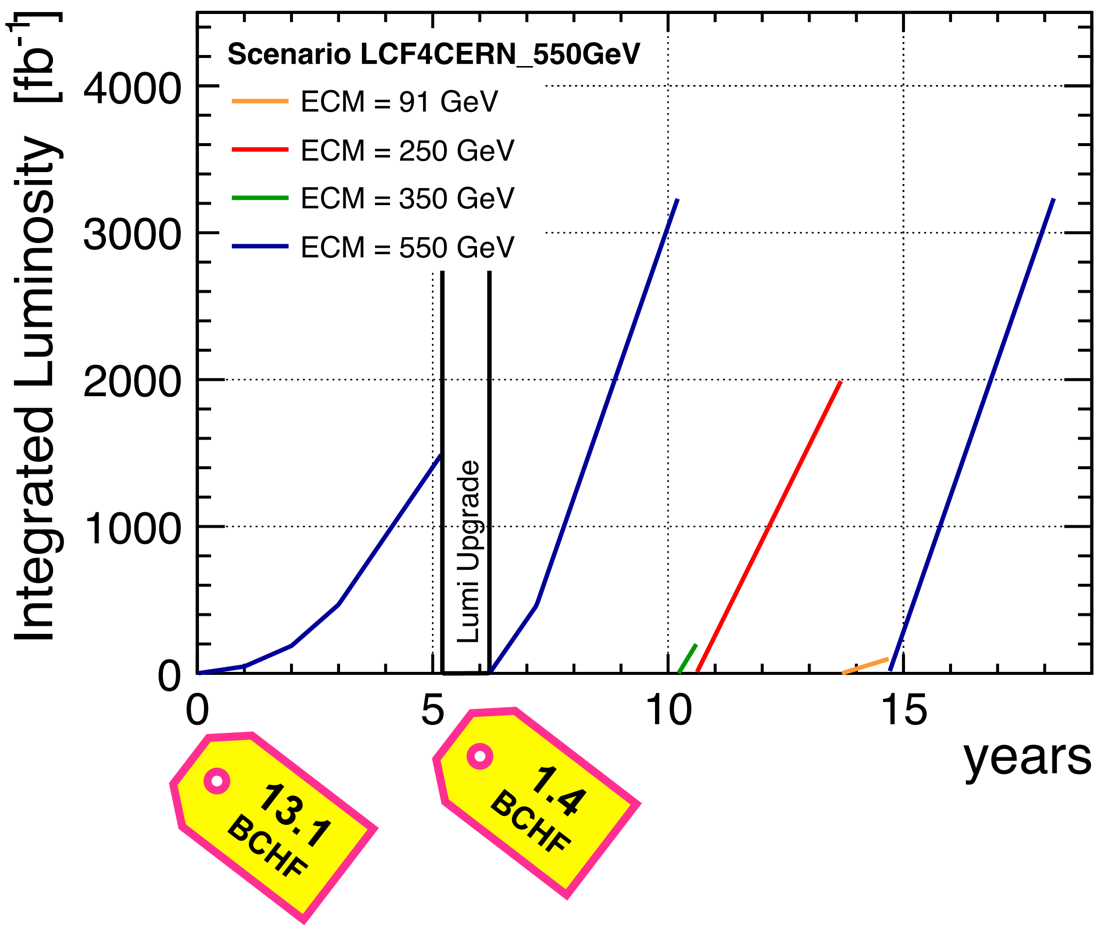

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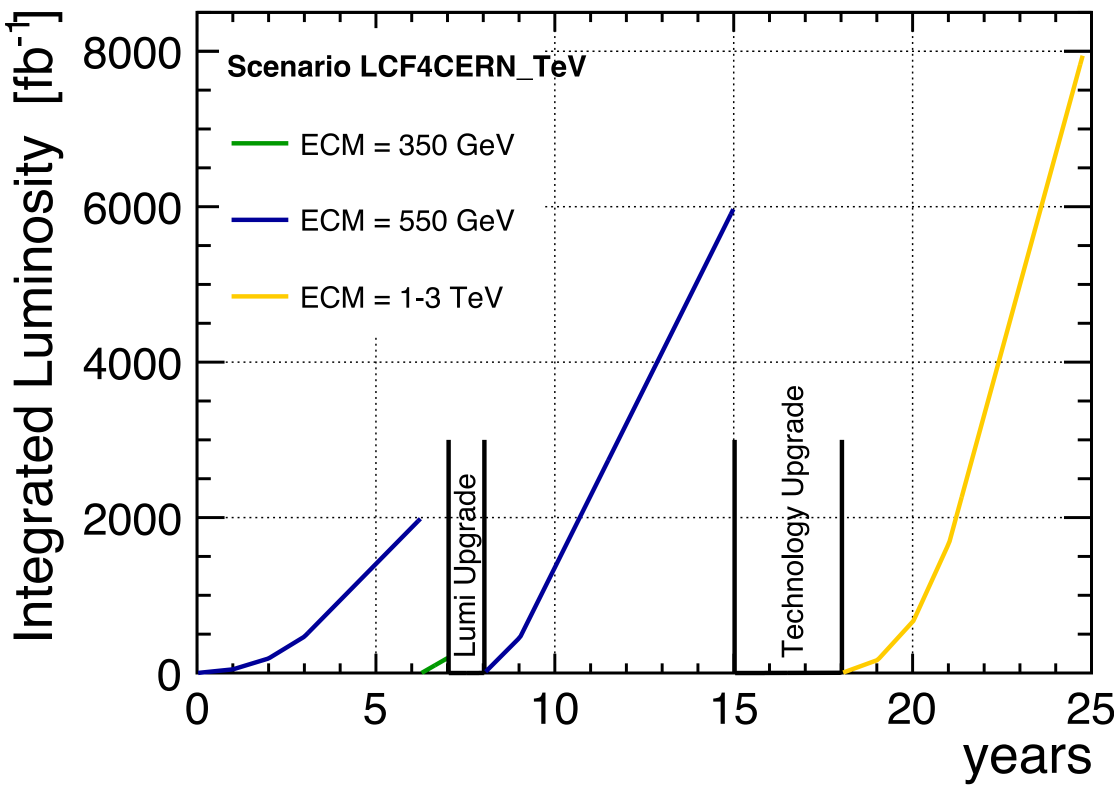
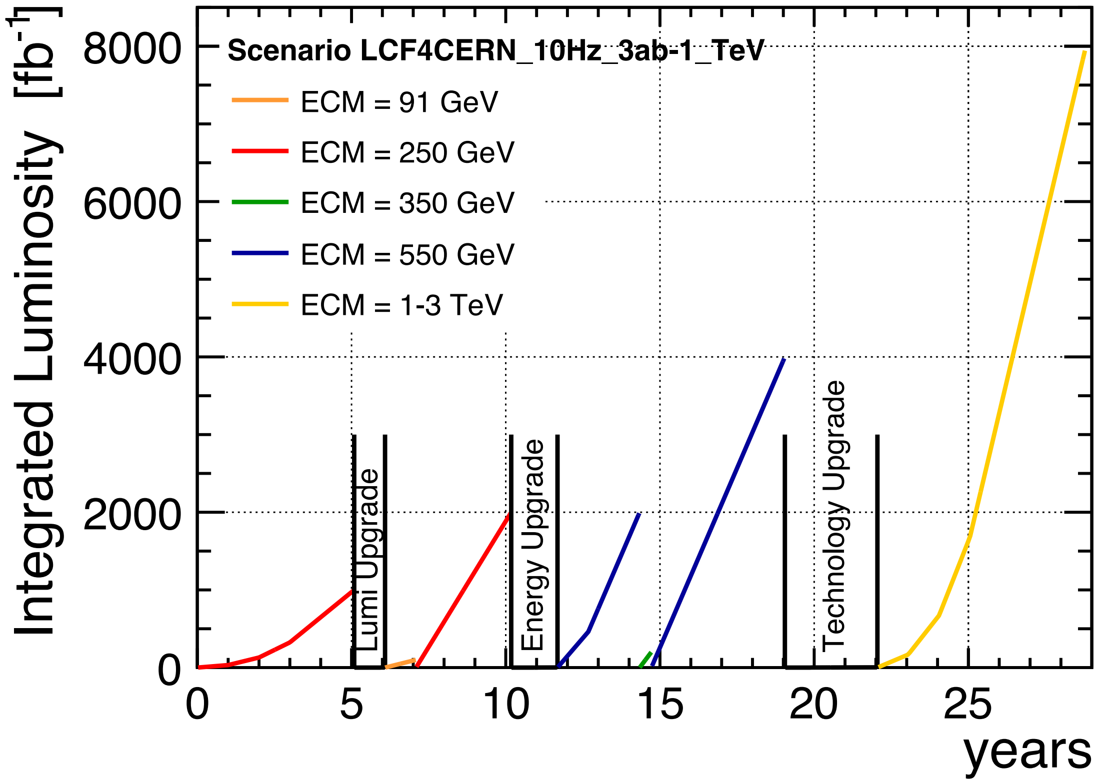
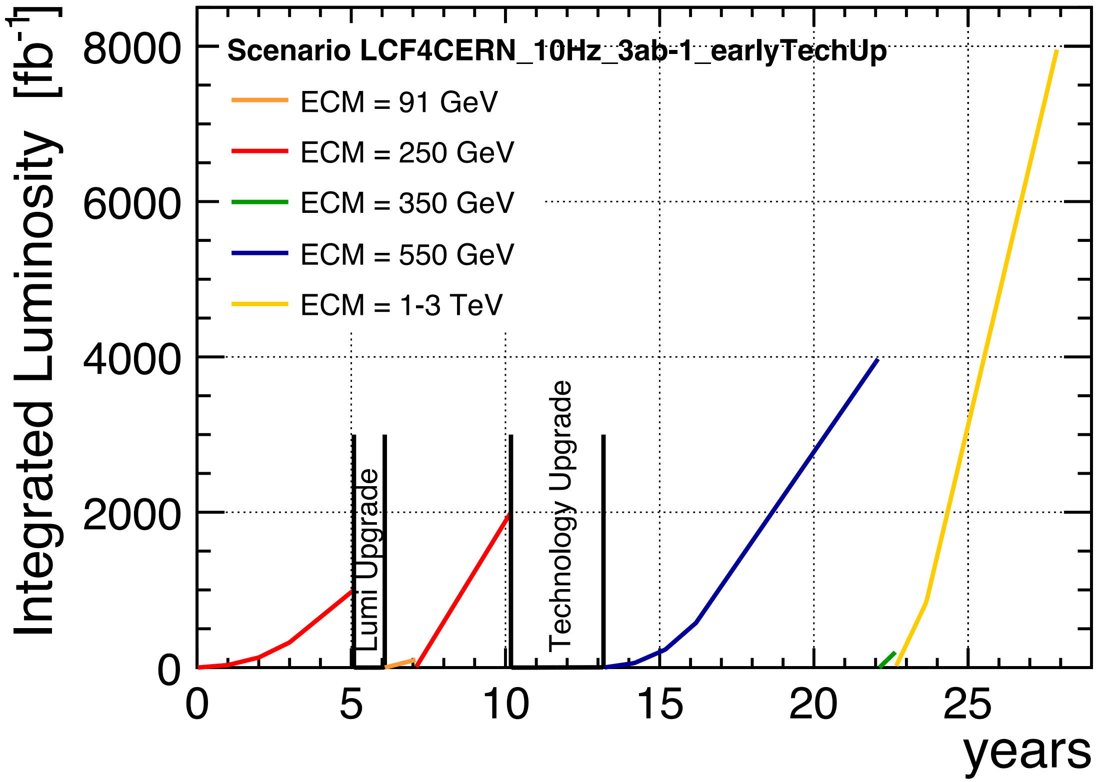


Running Scenarios - shortening 550 GeV in favour of TeV

Tech upgrade after 550 GeV



Tech upgrade after 250 GeV



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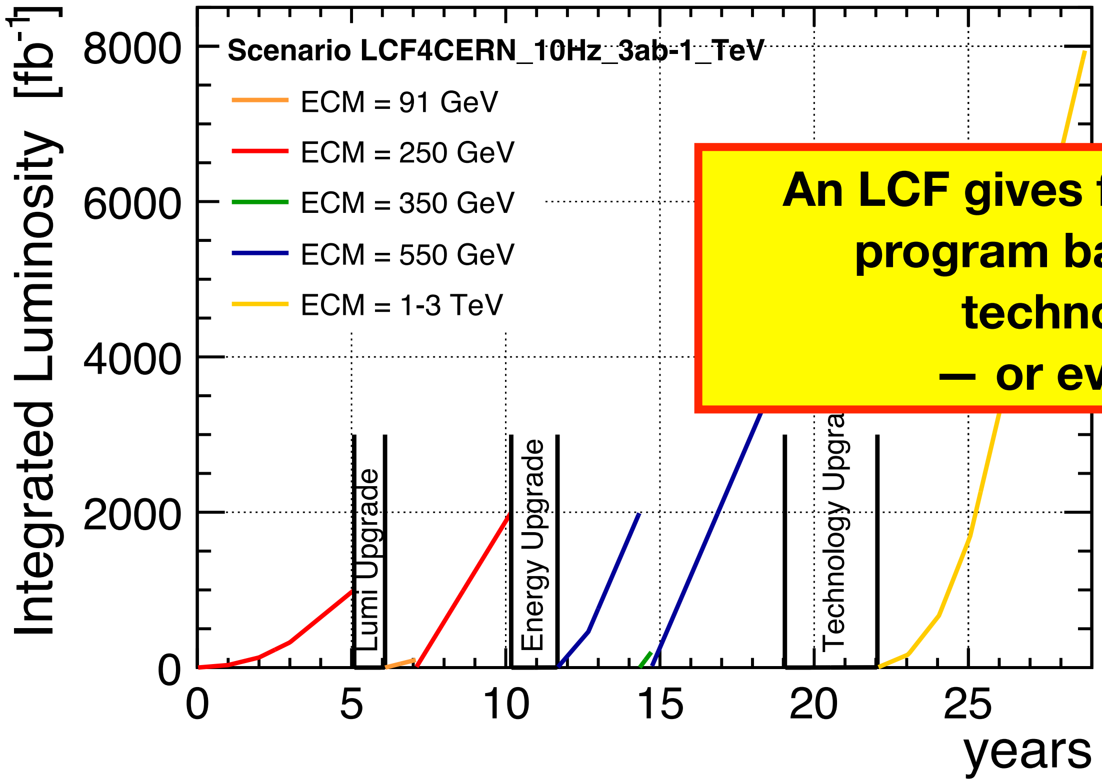

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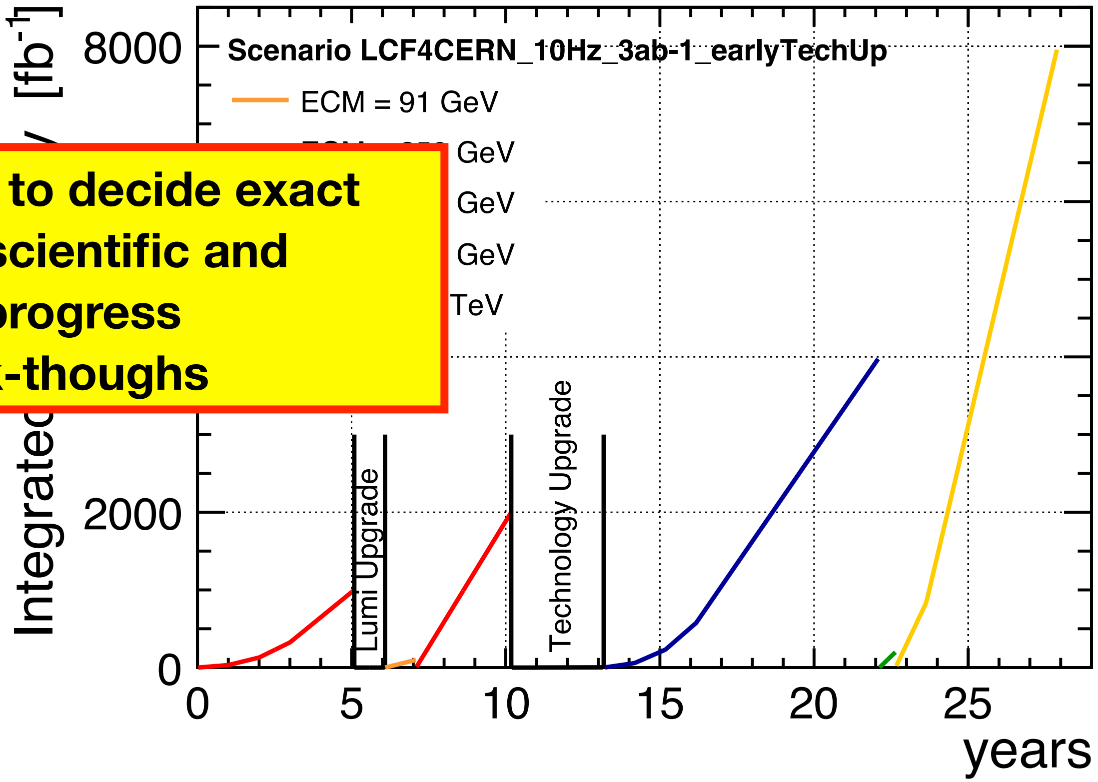

An LCF gives flexibility to decide exact program based on scientific and technological progress — or even break-thoughs

Energy Upgrades beyond 550 GeV

1 TeV and beyond

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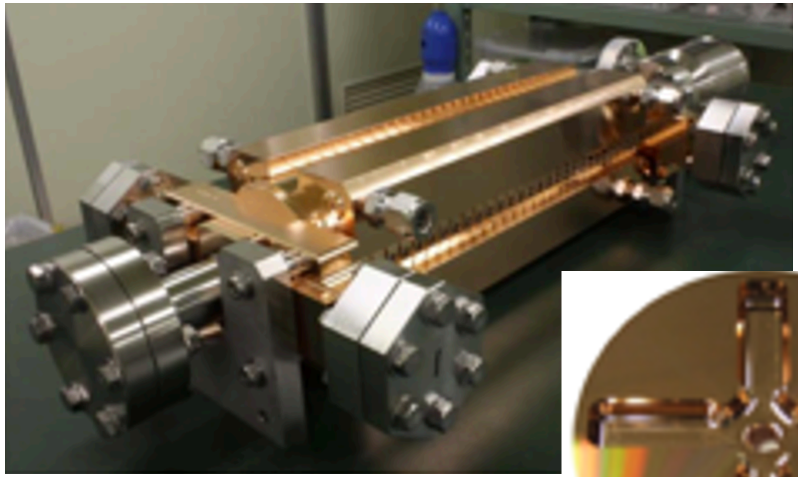

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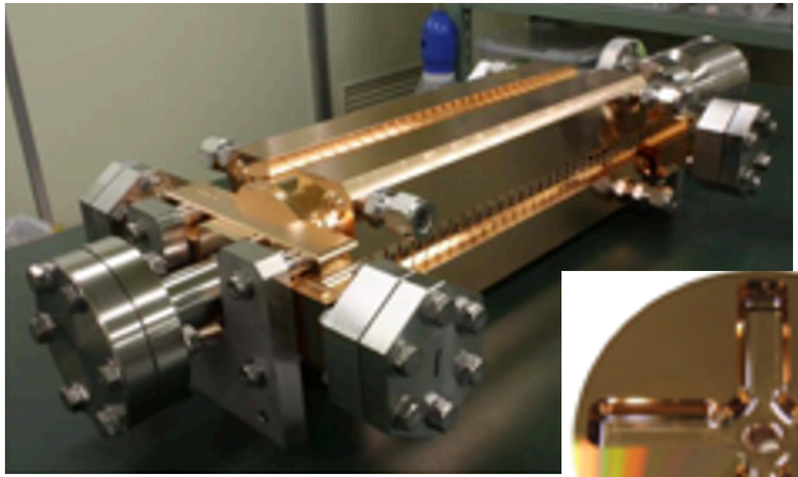

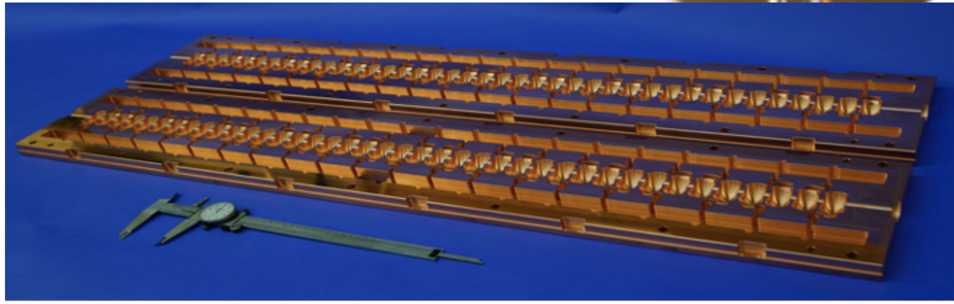

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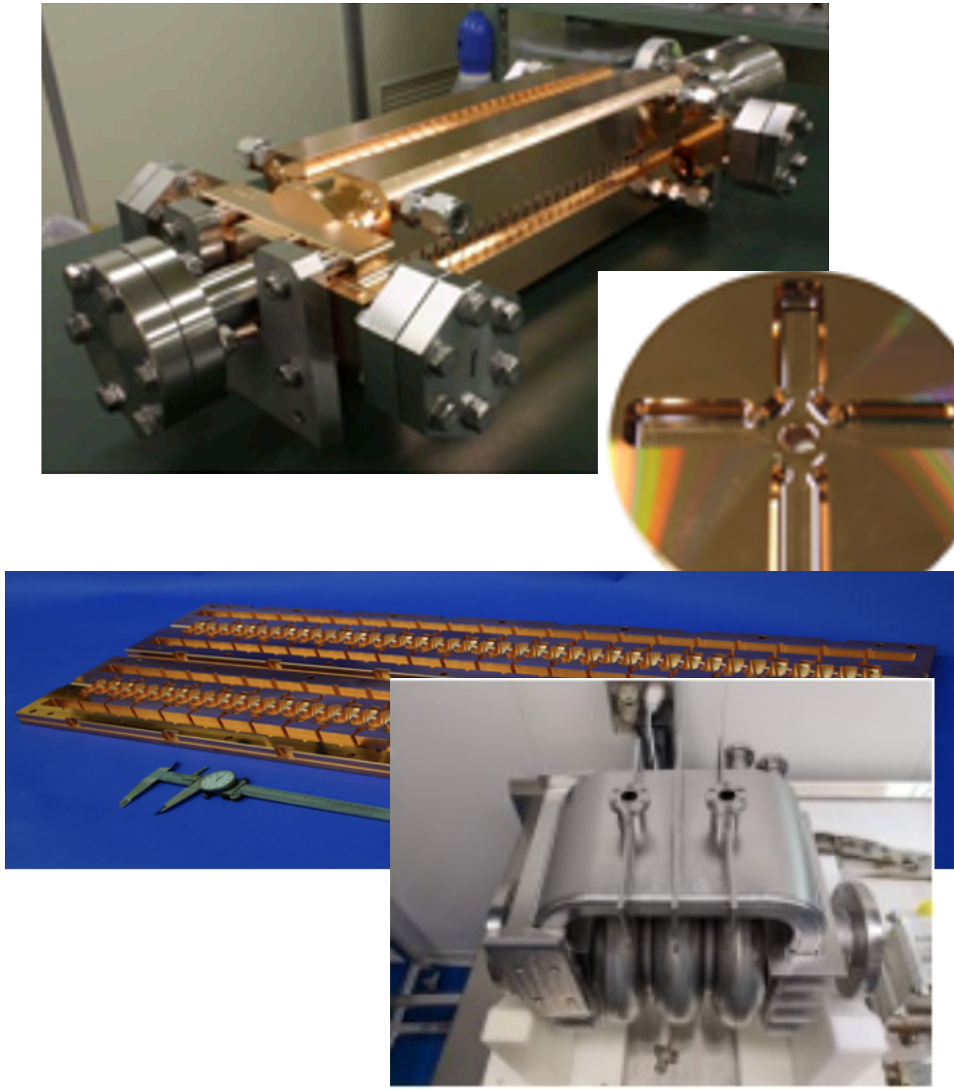

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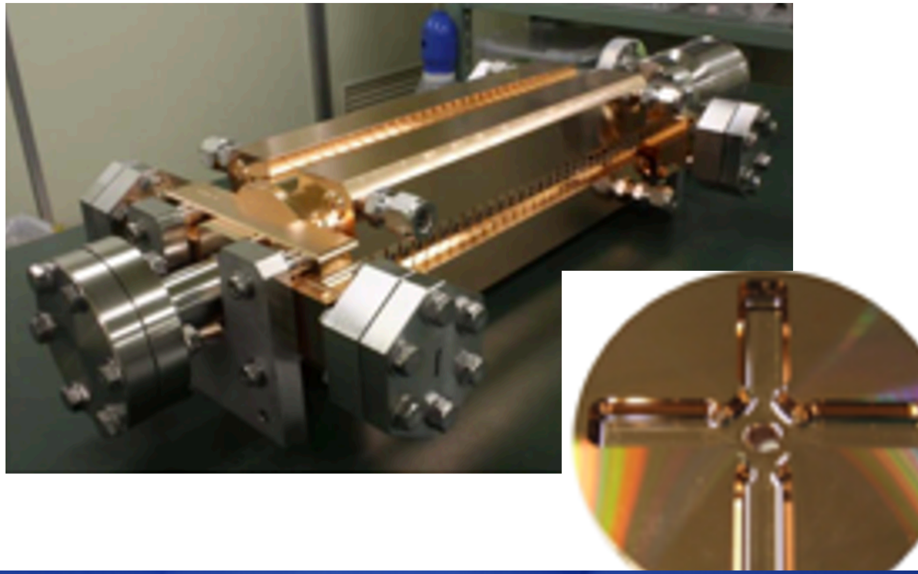

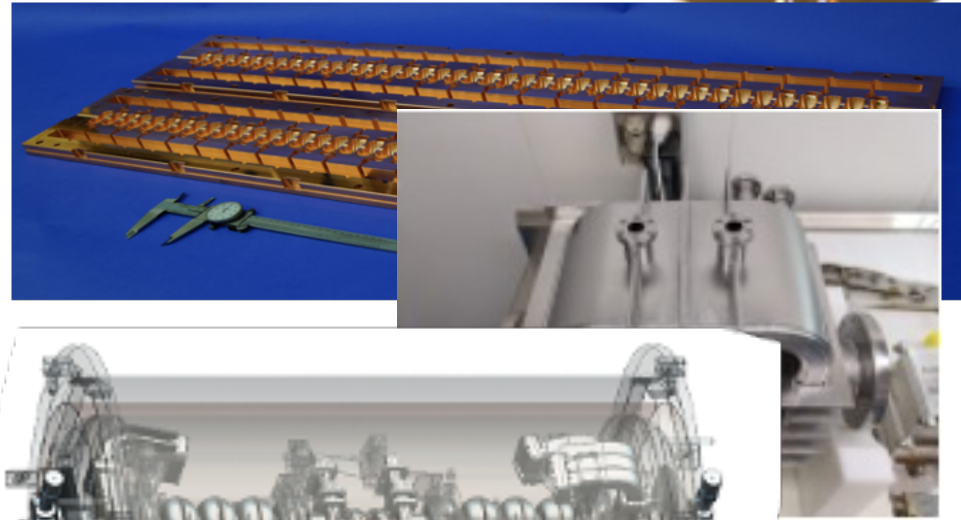

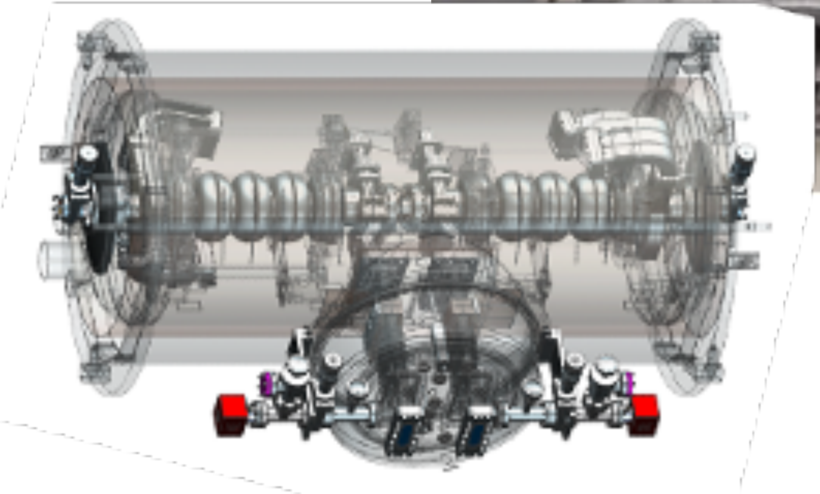

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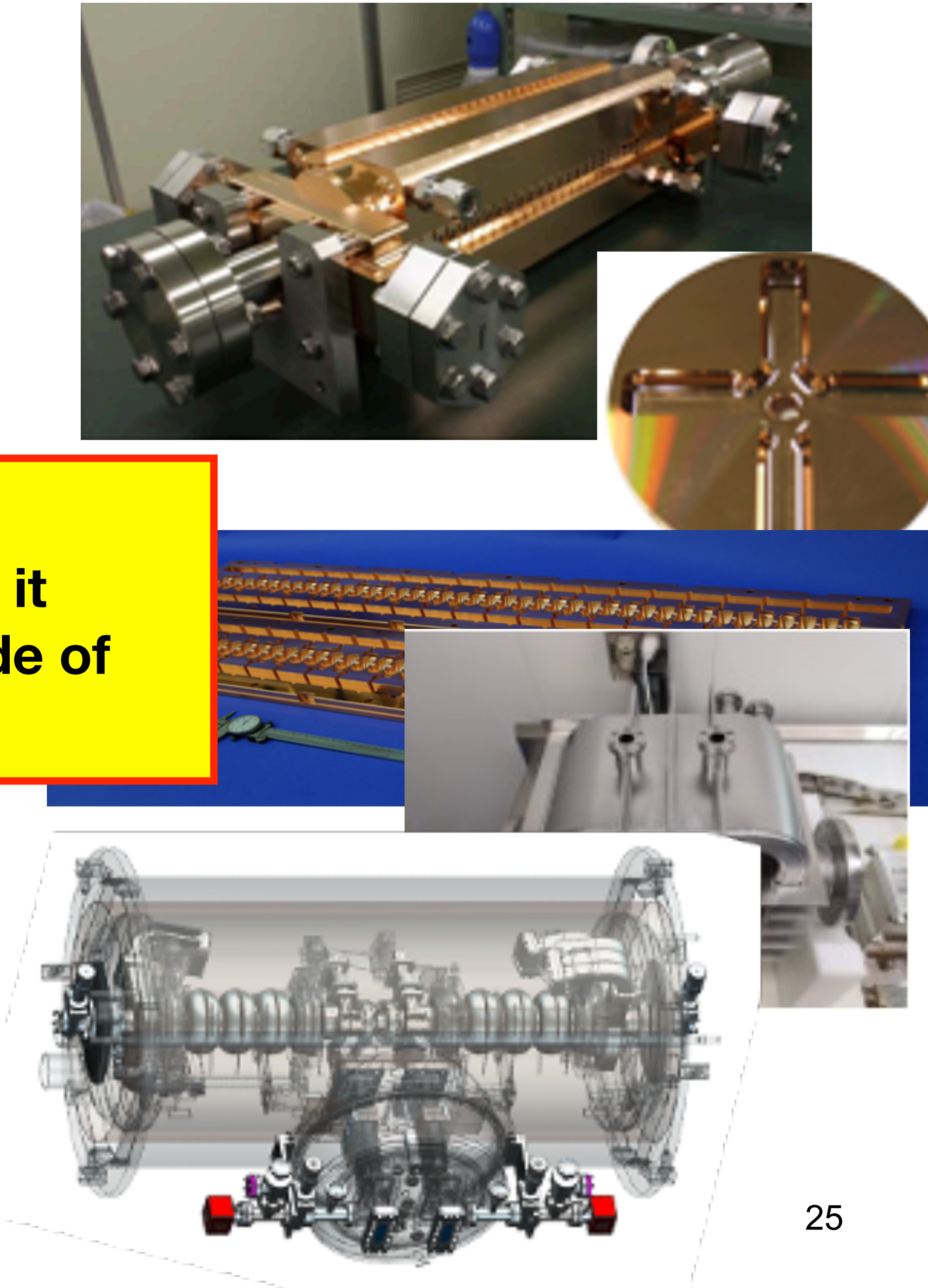
LCVision reviewed for each of the options how it could be embedded as upgrade of initial facility



Additional Upgrade Paths

Photon Collider / higher luminosity / towards 10 TeV

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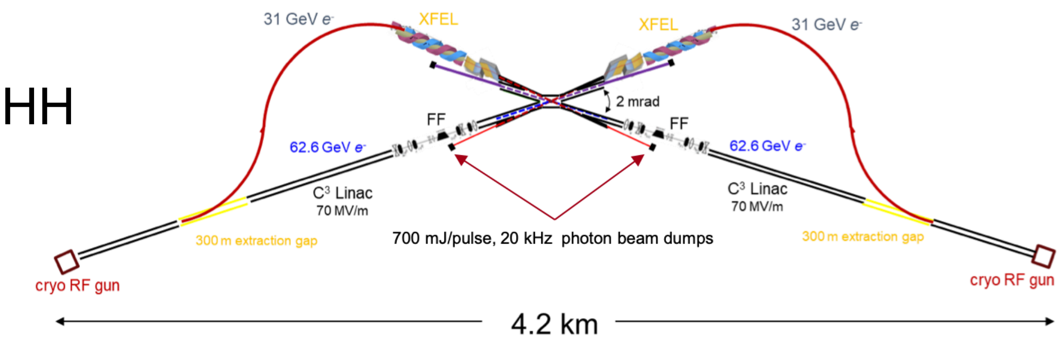

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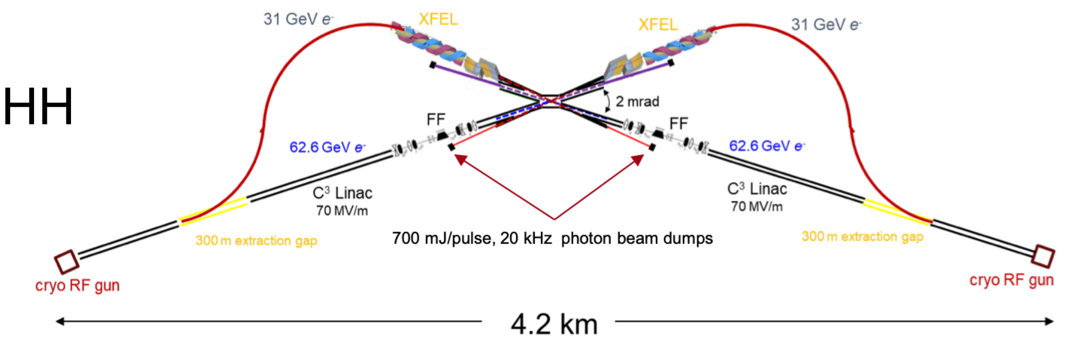

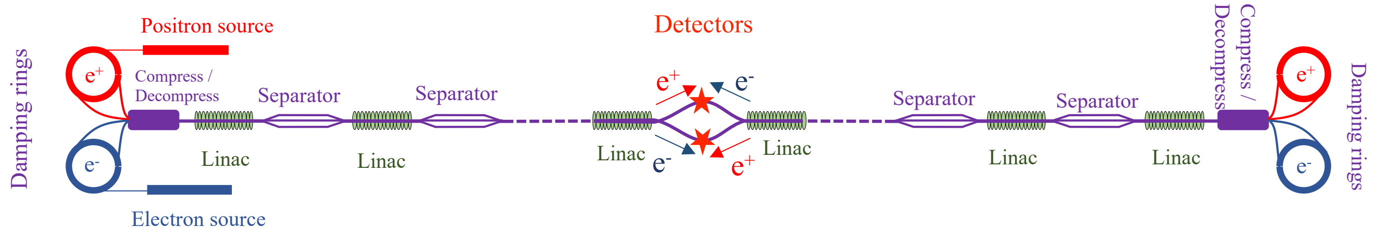

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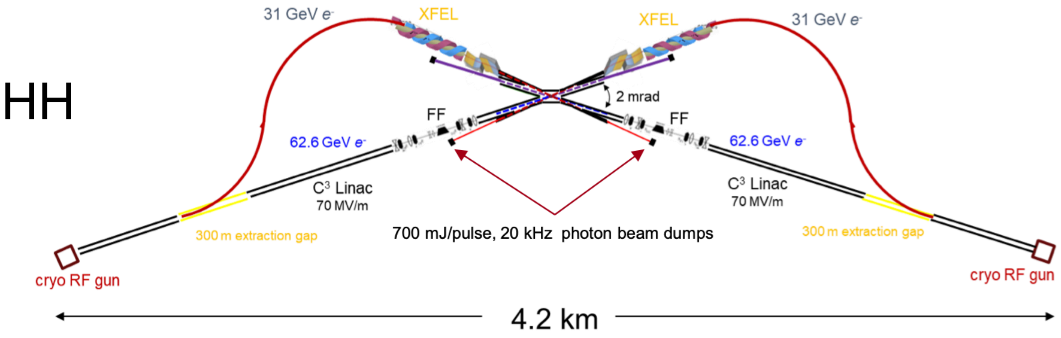

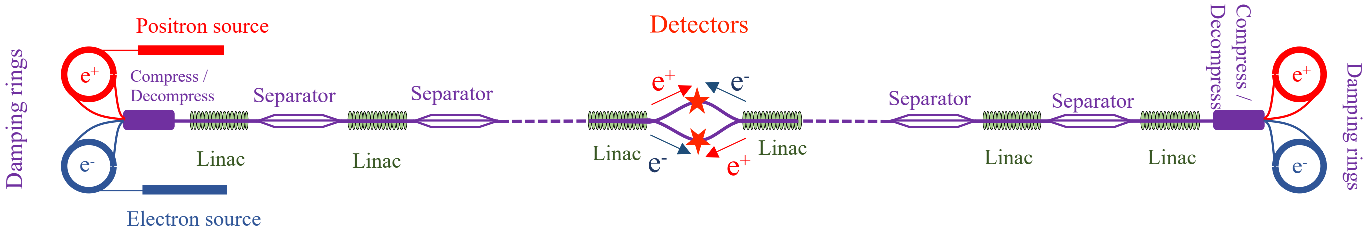

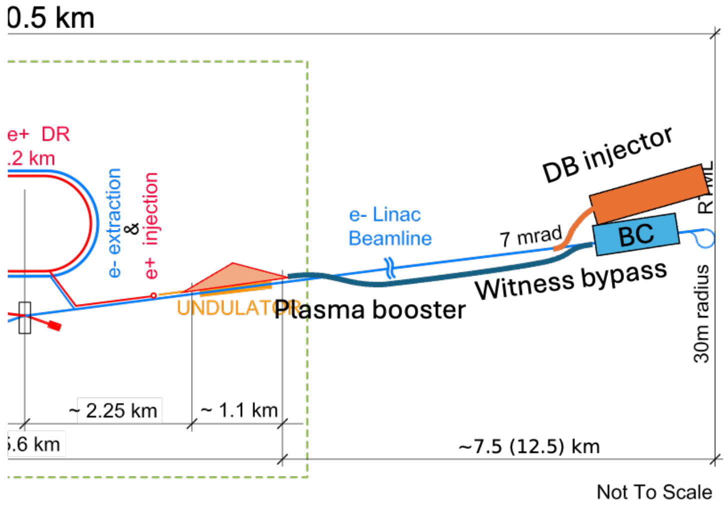

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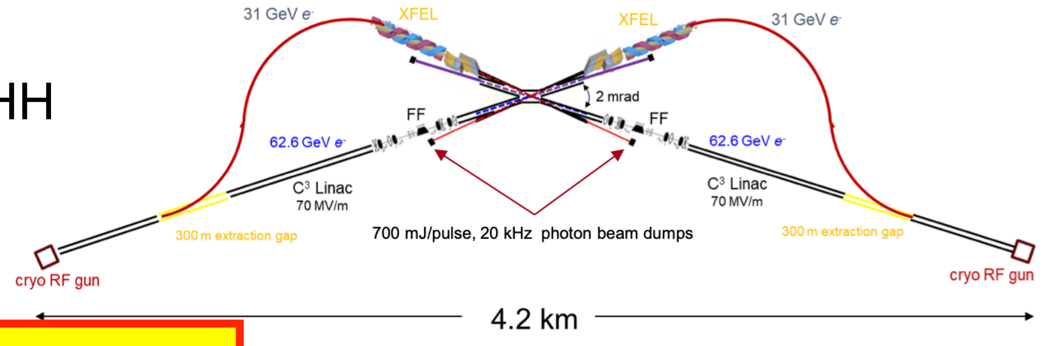

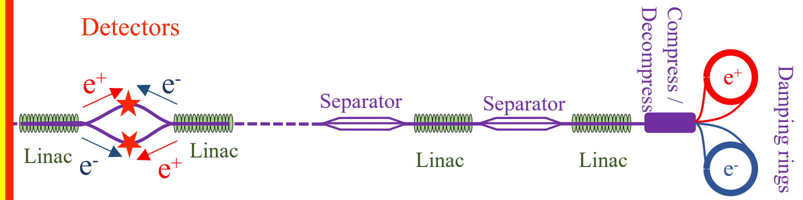

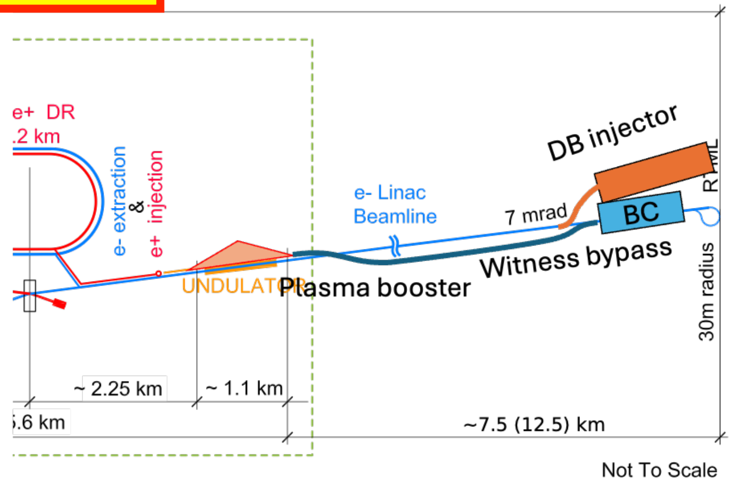

The Linear Collider Facility @ CERN and beyond

General considerations

- **Robust planning:**
  - costs (construction and operation), CFS design, environmental impact etc assessed in a consistent way between all projects proposed for CERN
  - accelerator cost well known thanks to the 2024 update of the ILC costing, to a large extent based on new quotes from industry
- **Timing is important:**
  - current young researchers are key to both the HL-LHC program and the future Higgs factory
  - prolonged uncertainly or delays in decision making discourage ECRs => loss of talent
  - clear and timely transition from HL-LHC to next collider will provide long-term research opportunities
- **Higgs factory and intensified R&D:**
  - eventually, we need to explore the 10-TeV pCoM energy scale
  - we don't have an affordable technology today
  - all routes (pp = HFM; $\mu\mu$ = cooling; ee/$\gamma\gamma$ = PWA) need expensive R&D and demonstrators
  - costs need to be shared globally, a staged and flexible Higgs factory aligns best with R&D needs

Next Steps towards a Linear Collider Facility @ CERN

Short-term investment needed

- **project implementation: 8-year preparatory period**
  - ideally starting after conclusion of EPPSU in mid-2026
  - split into a 3-year and a 5-year phase
  - prior to construction start in 2034
- **Phase 1 (~35 MCHF + 180 FTEy)**
  - in parallel to ILC Technology Network
  - placement study at CERN
  - design and technical studies to determine and confirm the LCF parameters
  - moderate investment from CERN, could be pursued in even parallel to FCC
- **Phase 2 (~120 MCHF + 420 FTEy)**
  - only after decision to go ahead with LCF
  - pre-series production
  - engineering design
  - more substancial investment by CERN
- **world-wide expertise in SCRF-based XFELs and ILC R&D => significant contributions from outside CERN?**
- **in parallel: set-up detector collaborations, build on exiting concepts, but embrace new ideas**

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=> ready for construction start in 2034

Strategic Considerations

Resources & competition

- with ~8 BCHF, the LCF is **affordable for CERN without major external contributions**
  - CERN council could decide for this project without a (potentially lengthy) period of international negociations
  - fast & robust way forward

- nevertheless **excellent opportunities for additional contributions**
  - e.g. lumi-upgrade (2x for ~0.8 BCHF)
  - contributions of more SCRF cryomodules to reach higher energies faster can be incorporated **anytime** - either “cash” - **or in-kind** (more attractive for local industry etc)
  - **but start of project independent of these under CERN council’s control**

- **scientific flexibility**
  - should scientifc developments point to going to higher ECM faster - e.g. LHC discovery or competition at low energies - **this can be done any time**, depending on resources

Conclusions & Invitation

Conclusions

As submitted on March 31

- **we need a new e+e- collider to study the Higgs - now**
- a **Linear Collider has decisive physics advantages: polarisation & high-energy reach**
  - required to do the full Higgs and Top program
  - with sufficient redundancies and complementarities to truely enable discovery via precision measurements
  - supports **flexible upgrades with advanced accelerator technologies**
- a well-understood technology and a staged approach allows a fast start
- **a Higgs factory must not saturate our field** - but stay affordable, in parallel to HL-LHC, SuperKEKB, smaller experiments - and R&D towards the 10-TeV pCoM scale
- the EPPSU shall determine the next flagship collider project for CERN
- **LCVision team**
  - **contributed the physics and technology case for Linear Colliders in general**
  - **and proposed a Linear Collider Facility @ CERN as the next flagship project**

Invitation to participate in LCVision

What you can do

- sign-up for LCVision mailing list (CERN e-group): **http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=LCVision-General**

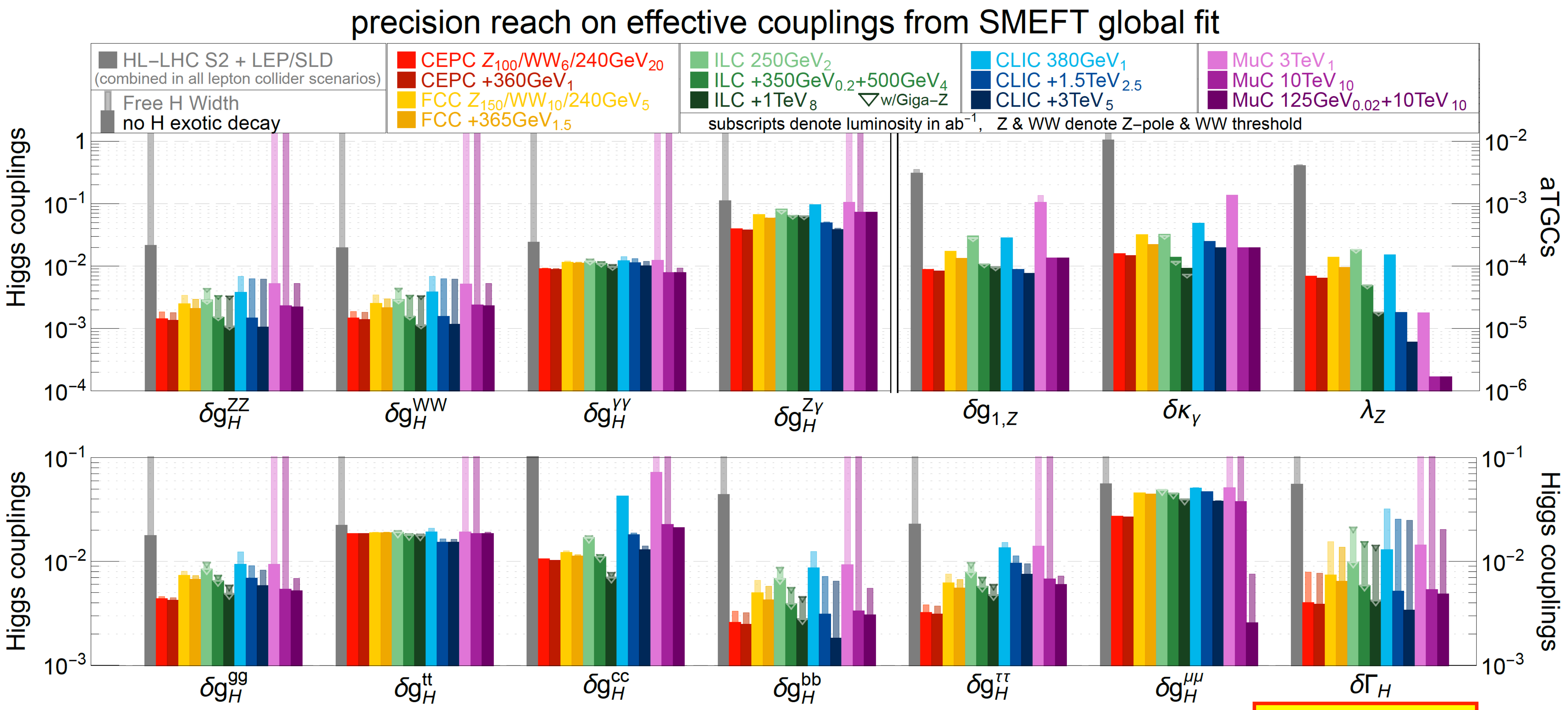
- **sign up on supporter list for the LCVision documents:**
  - either following link on https://agenda.linearcollider.org/event/10624/program
  - or directly on https://www.ppe.gla.ac.uk/LC/LCVision/index.php?show=instadmin&skey=etUI1visTy25

- **mark your calendars for LCWS2025: October 20-24 in Valencia, Spain**

Any Questions?

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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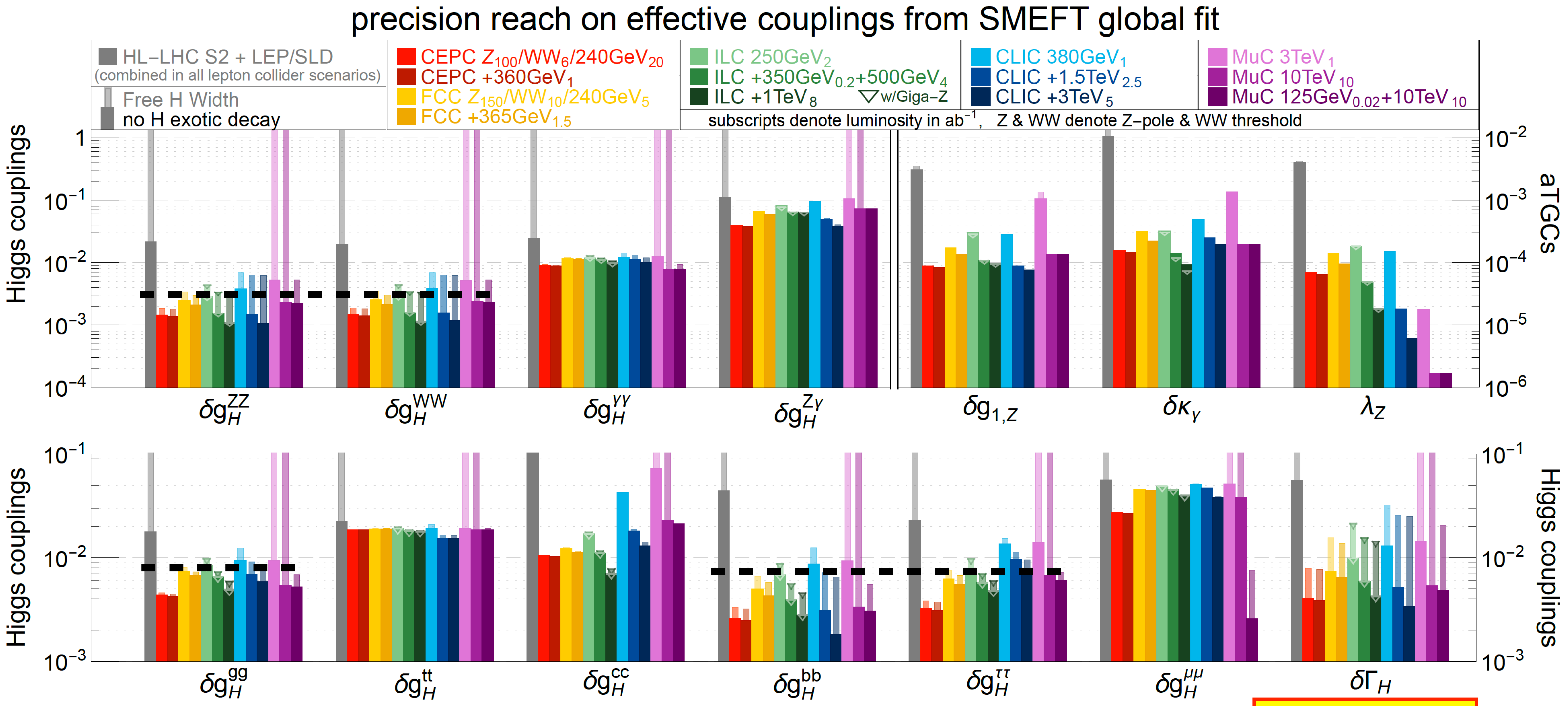

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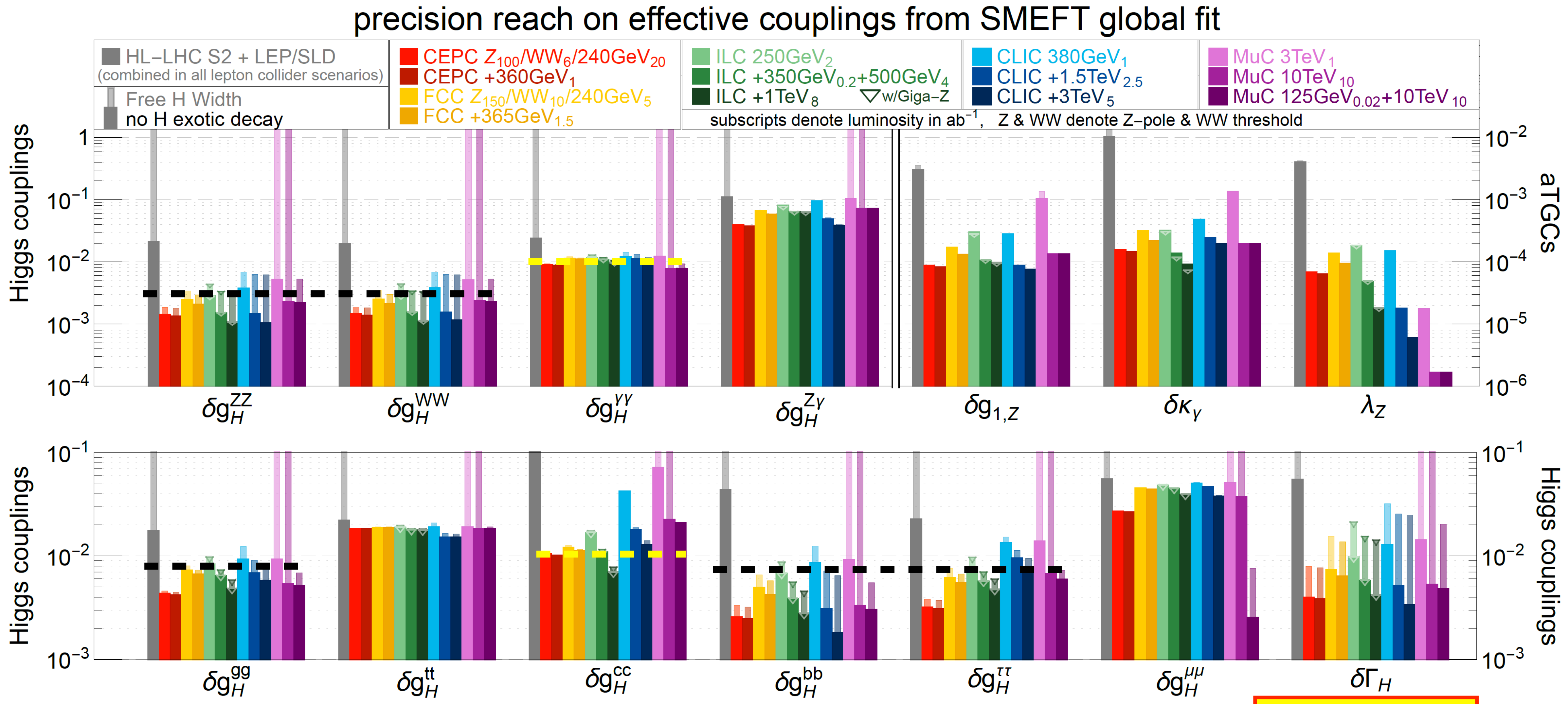

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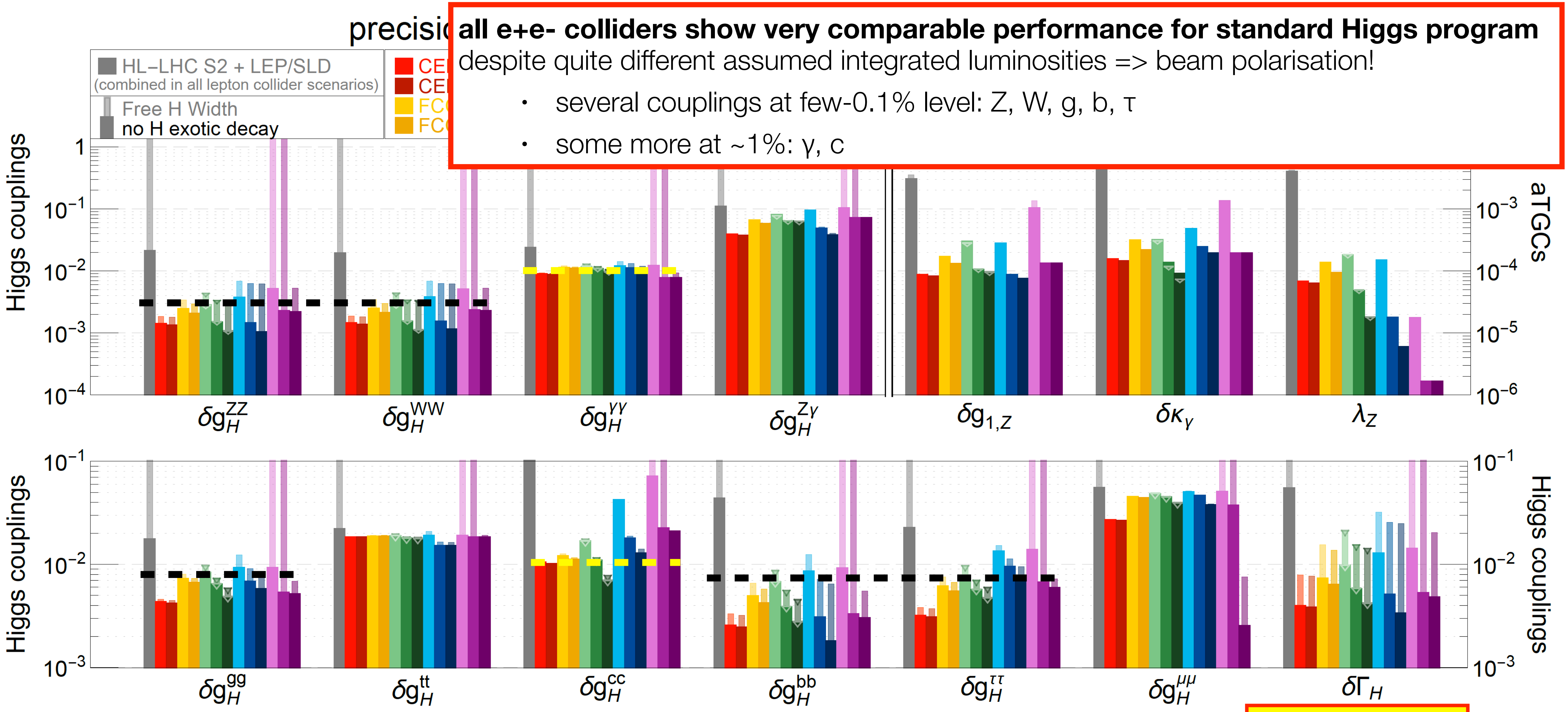

all e+e- colliders show very comparable performance for standard Higgs program

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

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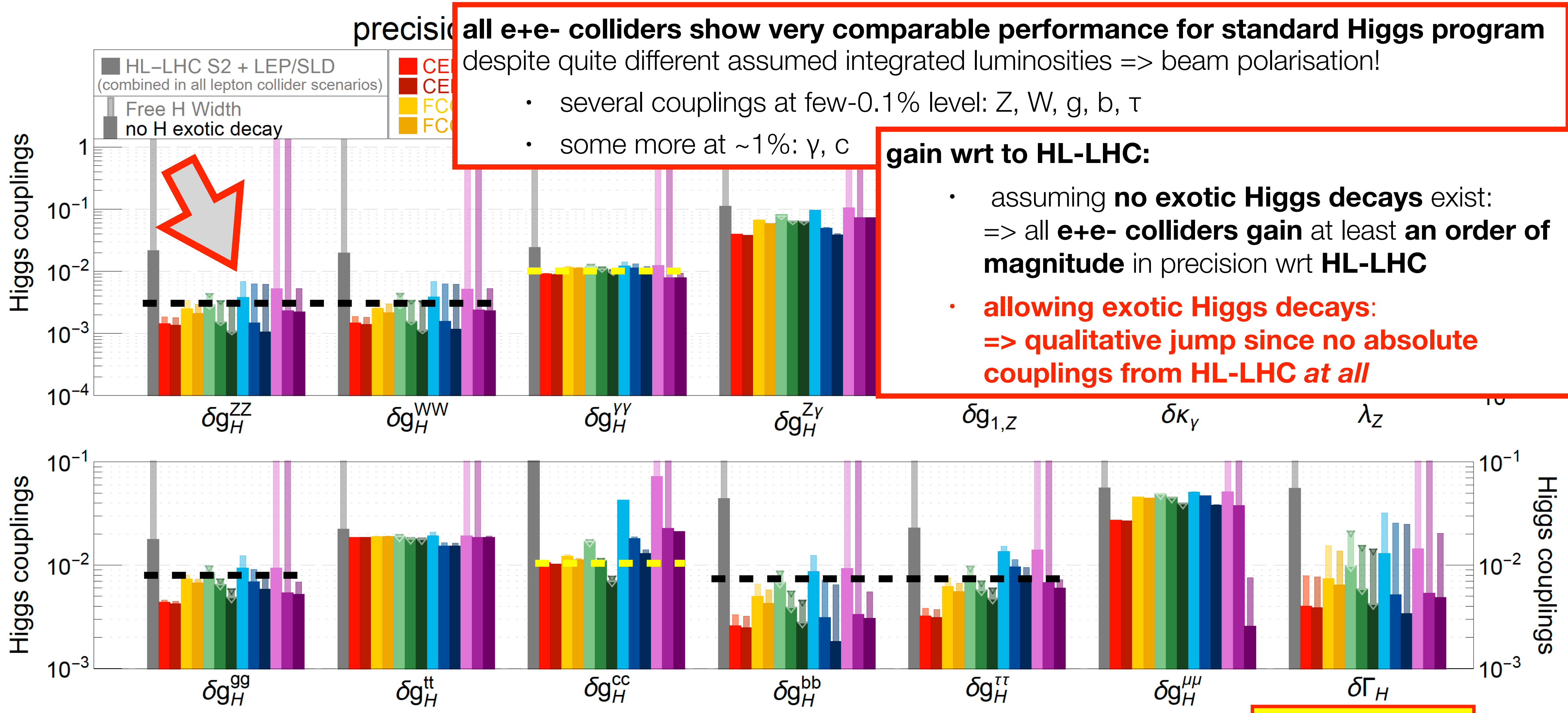

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gain wrt to HL-LHC:

- 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***

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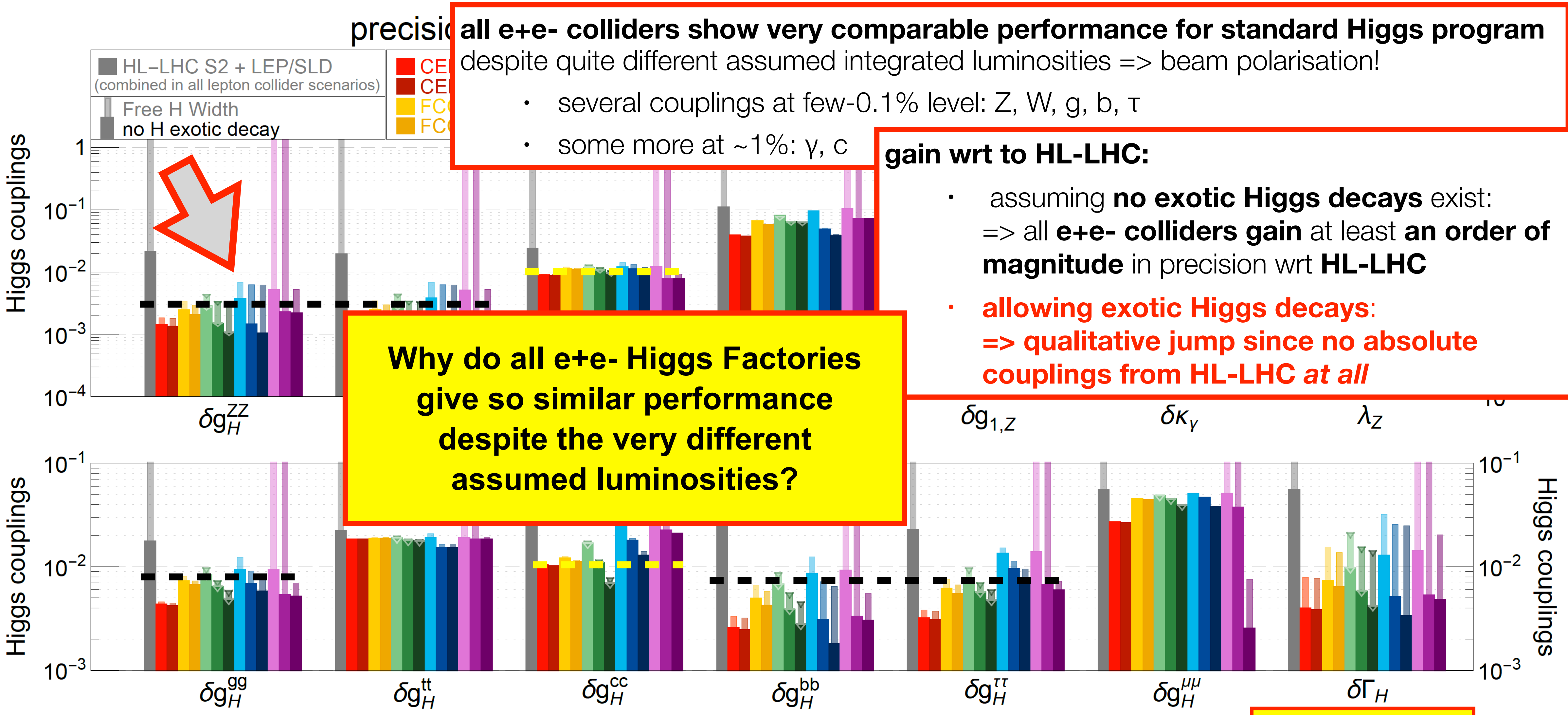

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- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays:**
  => qualitative jump since no absolute couplings from HL-LHC *at all*

Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L$ x U(1)
- L: left-handed, spin anti-|| momentum*
  R: right-handed, spin || momentum*

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

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

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

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

Physics benefits of polarised beams

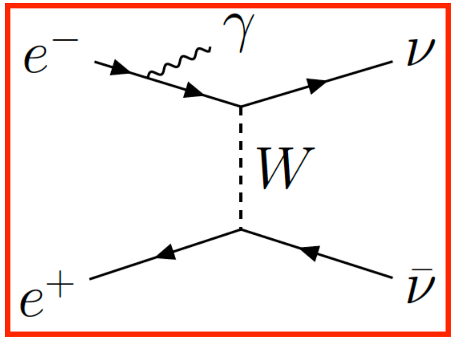
Much more than statistics!

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

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

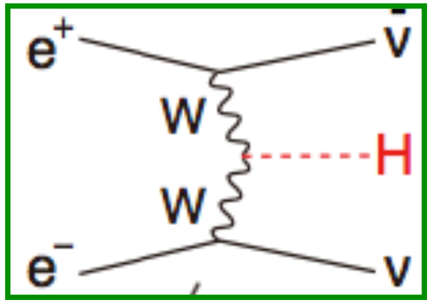
background suppression:

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



signal enhancement:

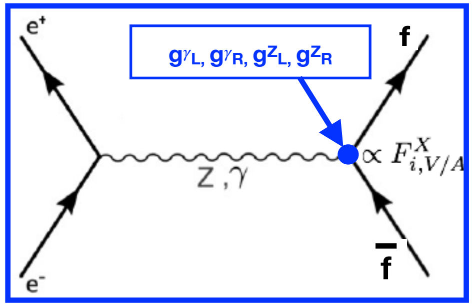
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions



- BSM: chiral structure unknown, needs to be determined!

redundancy & control of systematics:

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

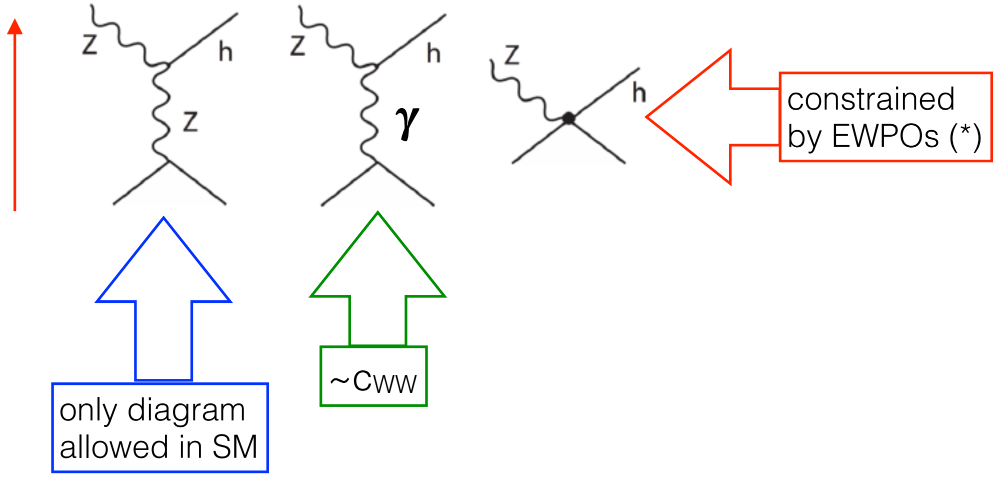
Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

- **THE key process** at a Higgs factory:

  Higgsstrahlung $e^+e^- \rightarrow Zh$

- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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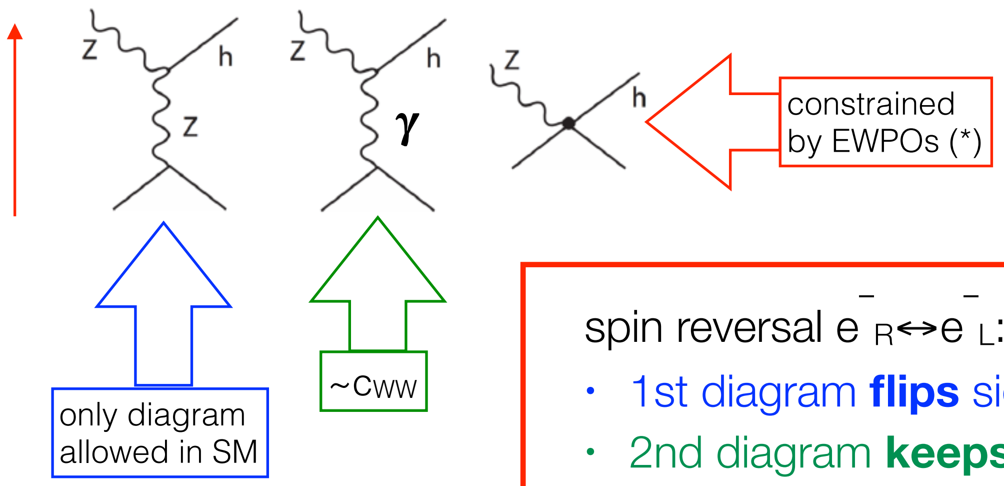

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

⇒ **A_{LR} lifts degeneracy between operators!**

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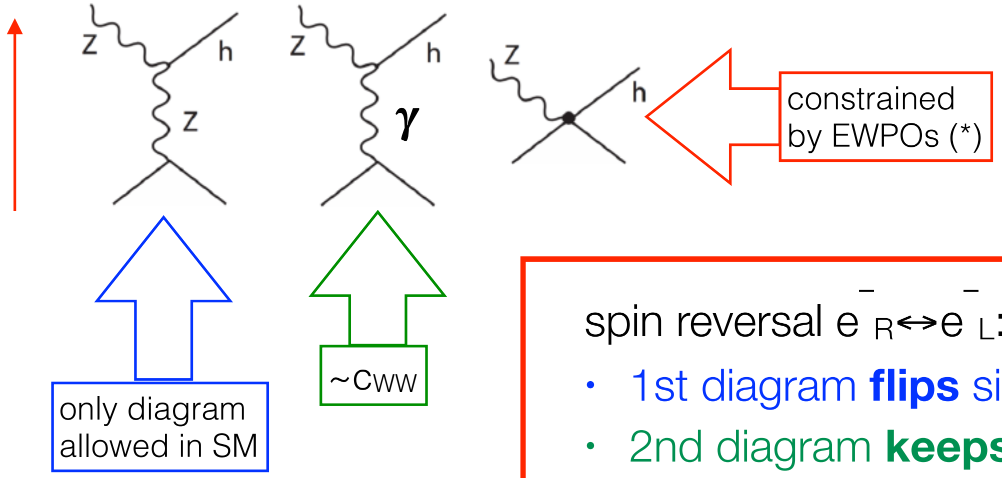

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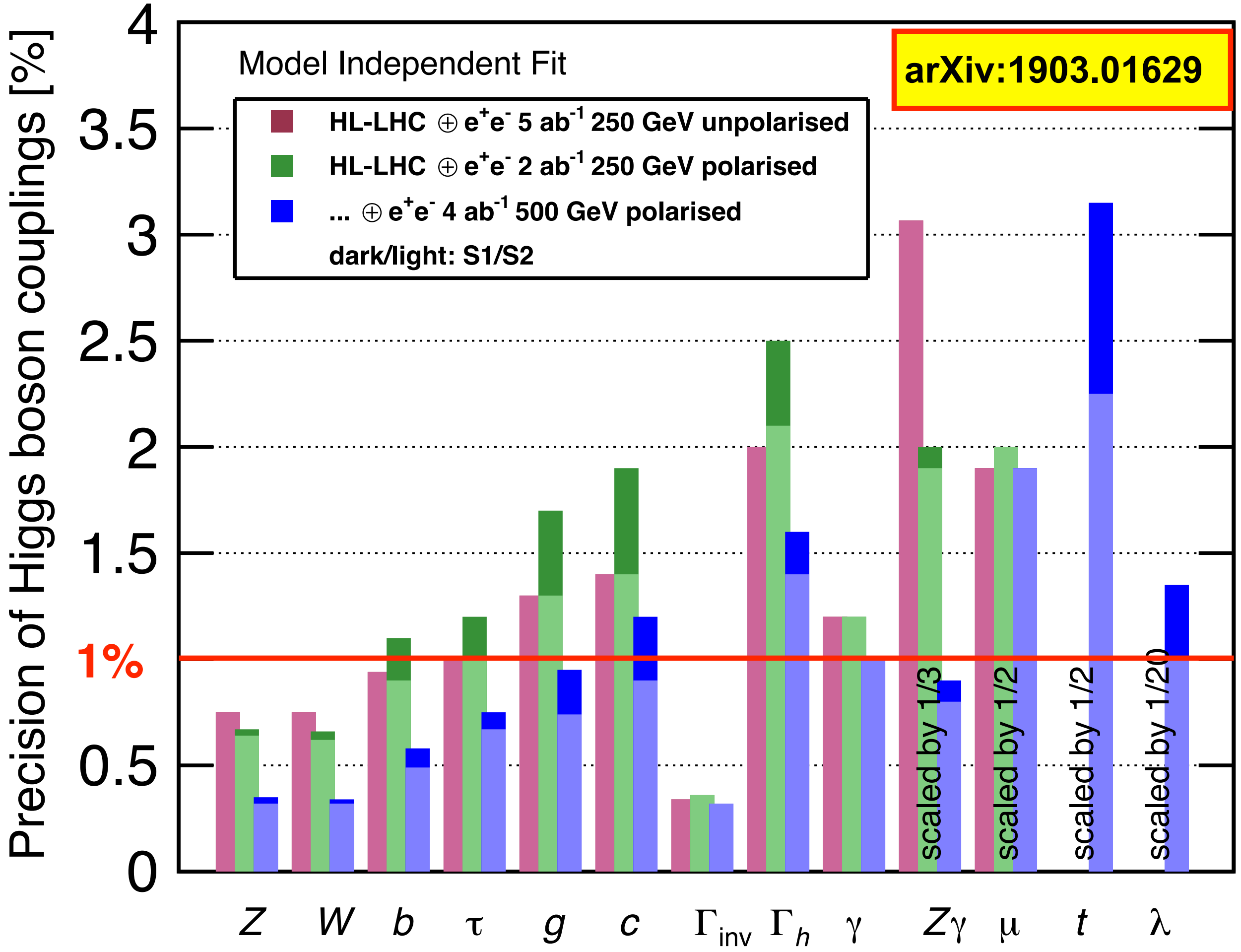

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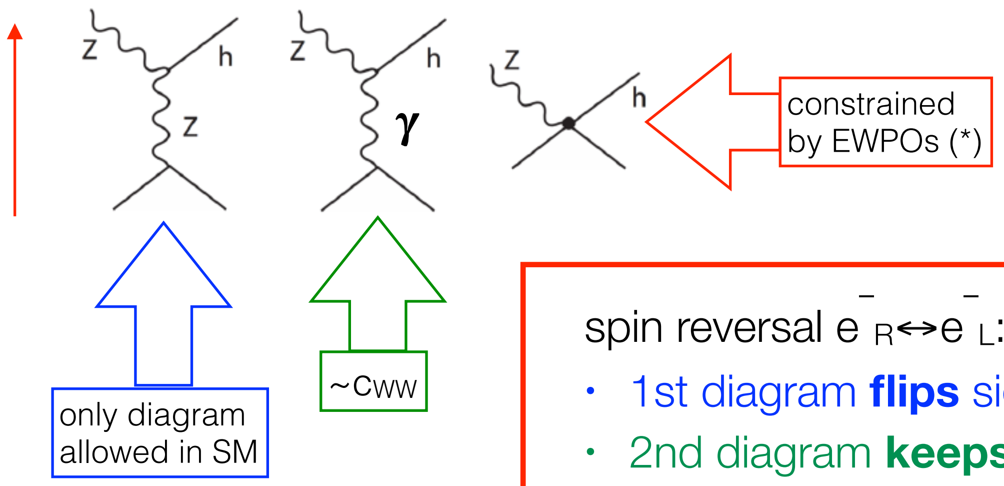

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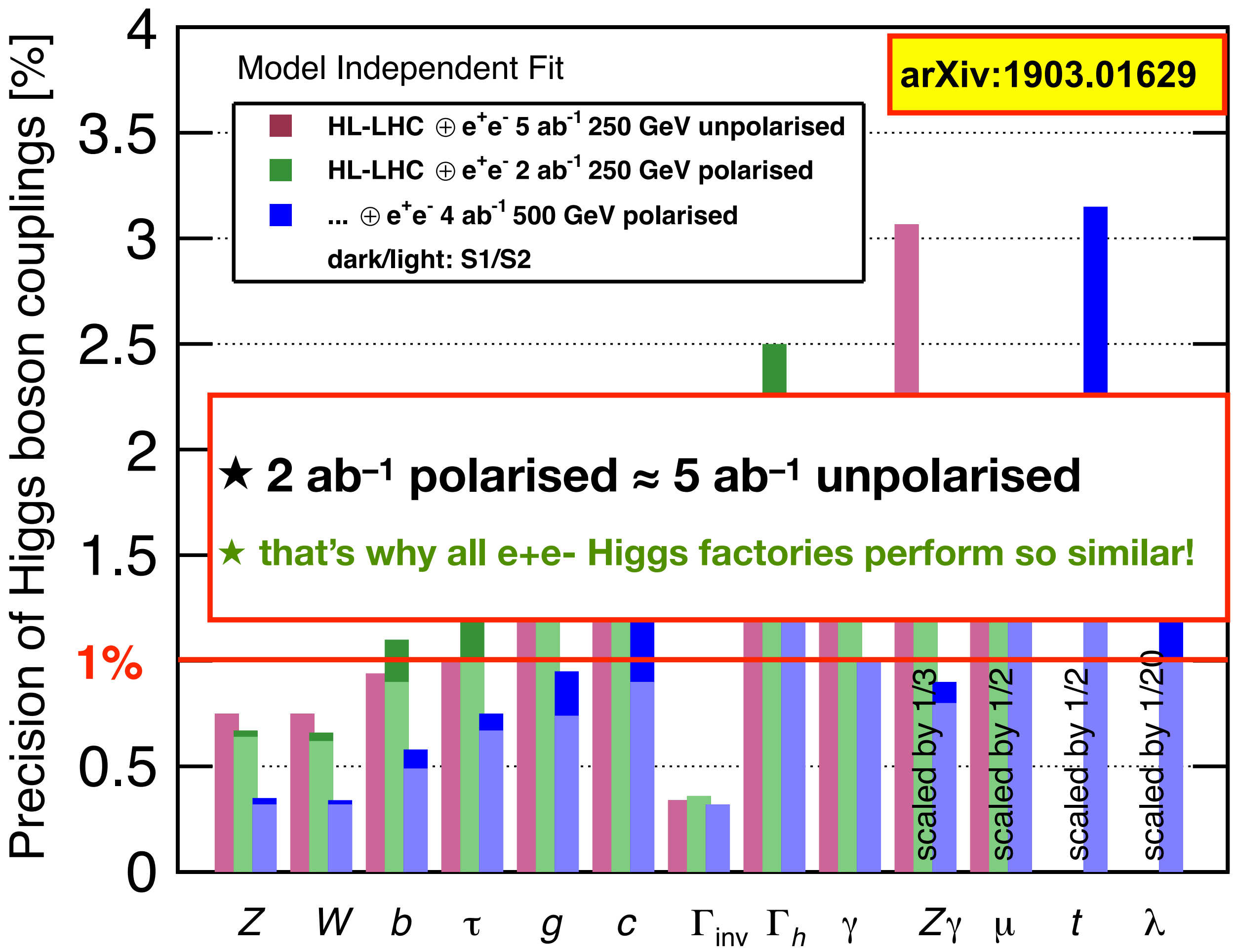
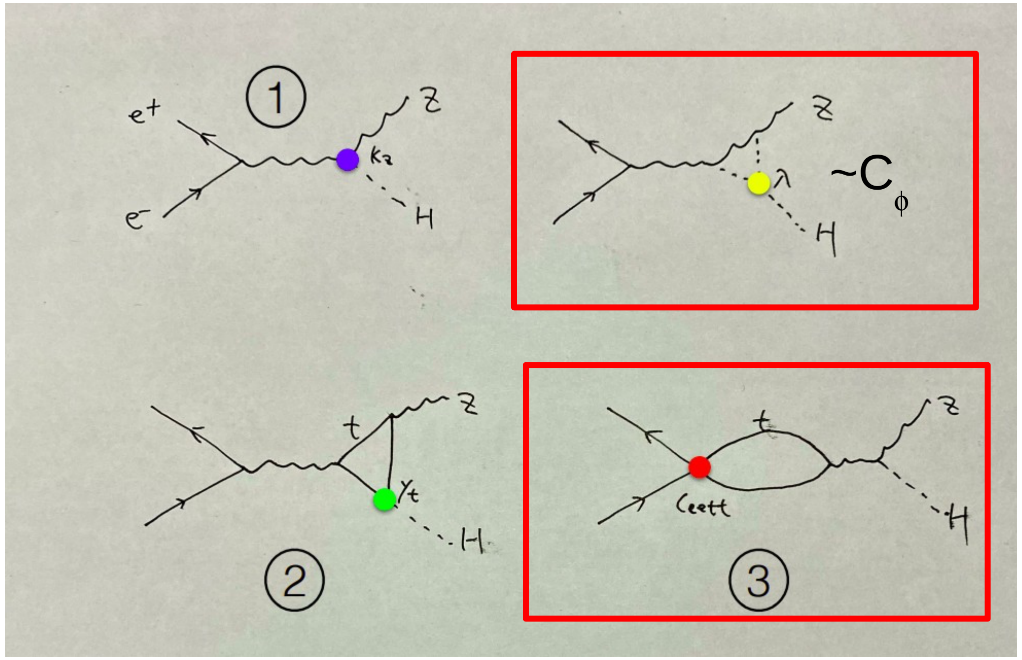


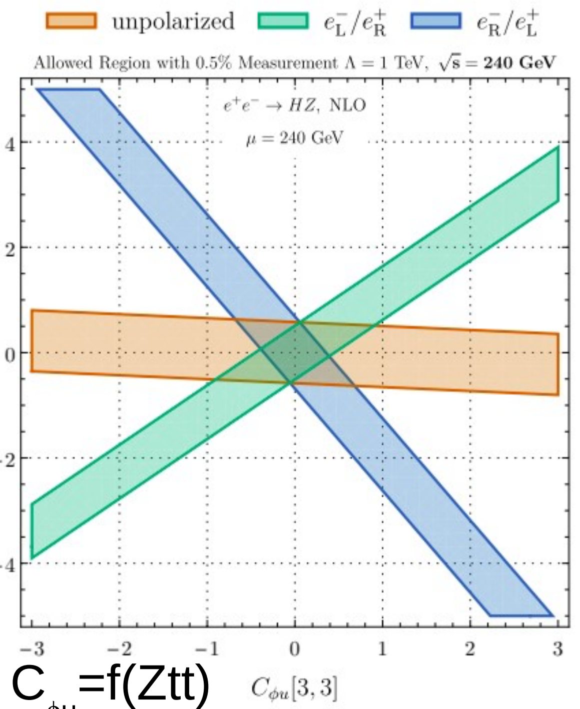
Entanglement - SMEFT NLO

NLO Contributions to ee->HZ



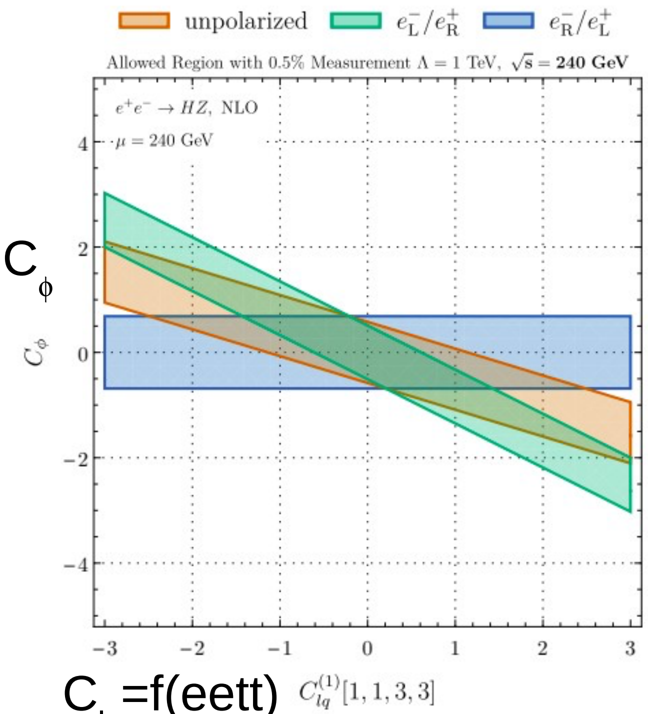
One important contribution is eett Vertex

Correlation C_ϕ to tt-Vertices arxiv:2409.11466



C_ϕ

$C_{\phi u}$=f(Ztt)



C_ϕ

C_{lq}=f(eett)

- NLO SMEFT introduces sensitivity to and constrains C_ϕ and operators involving top vertices
- Disentangling of constraints using beam polarisation
- Final word would come from higher energy measurements
- Note that C_{lq} is strongly energy dependent (-> would benefit from higher energies)

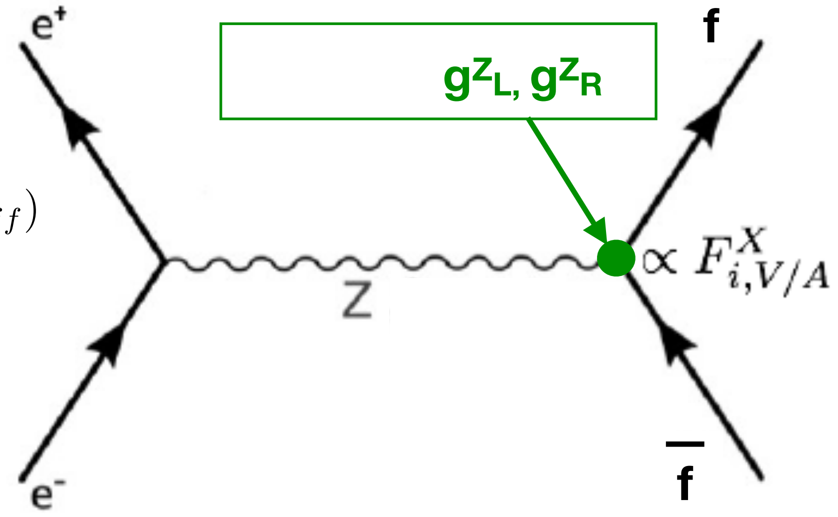
Polarisation & Electroweak Physics

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:

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

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

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

$$\boxed{A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}}$$ and $$\boxed{A_{FB,LR}^f \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f}$$

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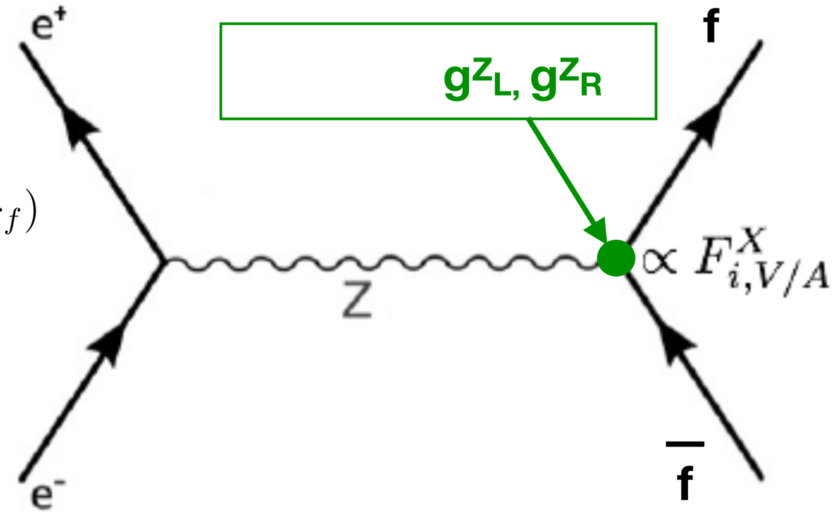

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trading theory uncertainy:

the **polarised** $A^f_{FB,LR}$ receives 7 x smaller radiative corrections than the **unpolarised** A^f_{FB}

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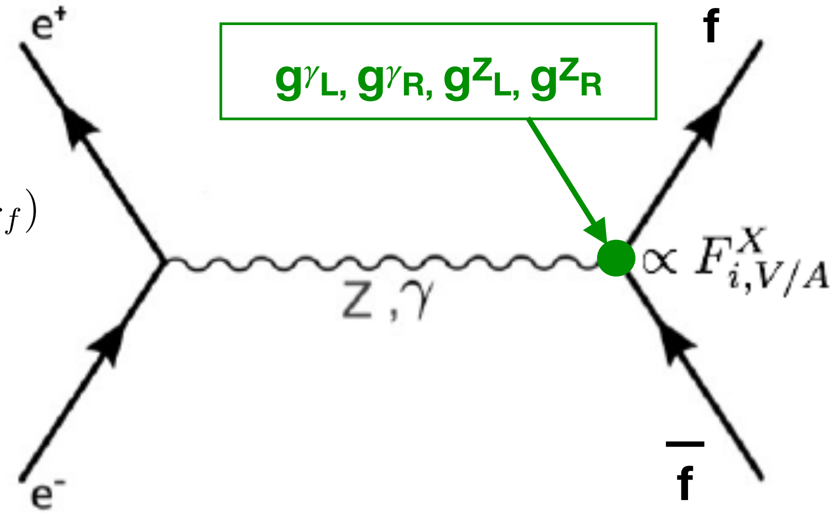

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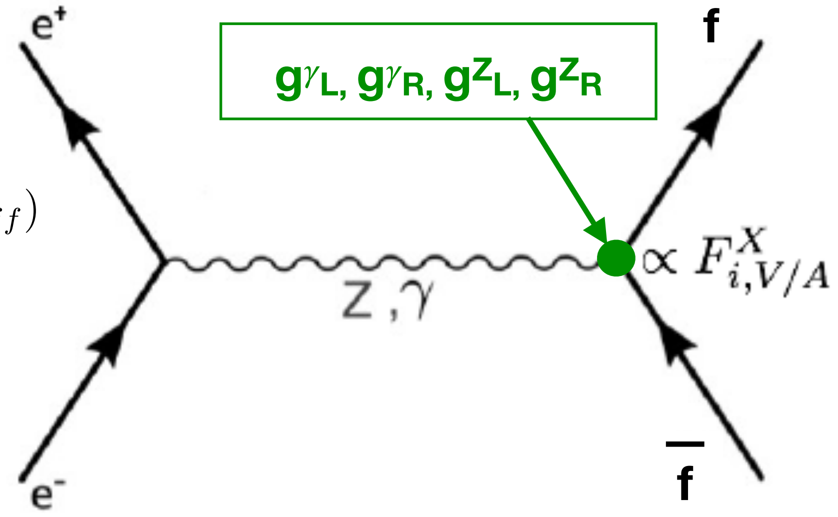

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above Z pole, polarisation essential to disentangle Z / γ exchange in $e^+e^- \rightarrow f\bar{f}$

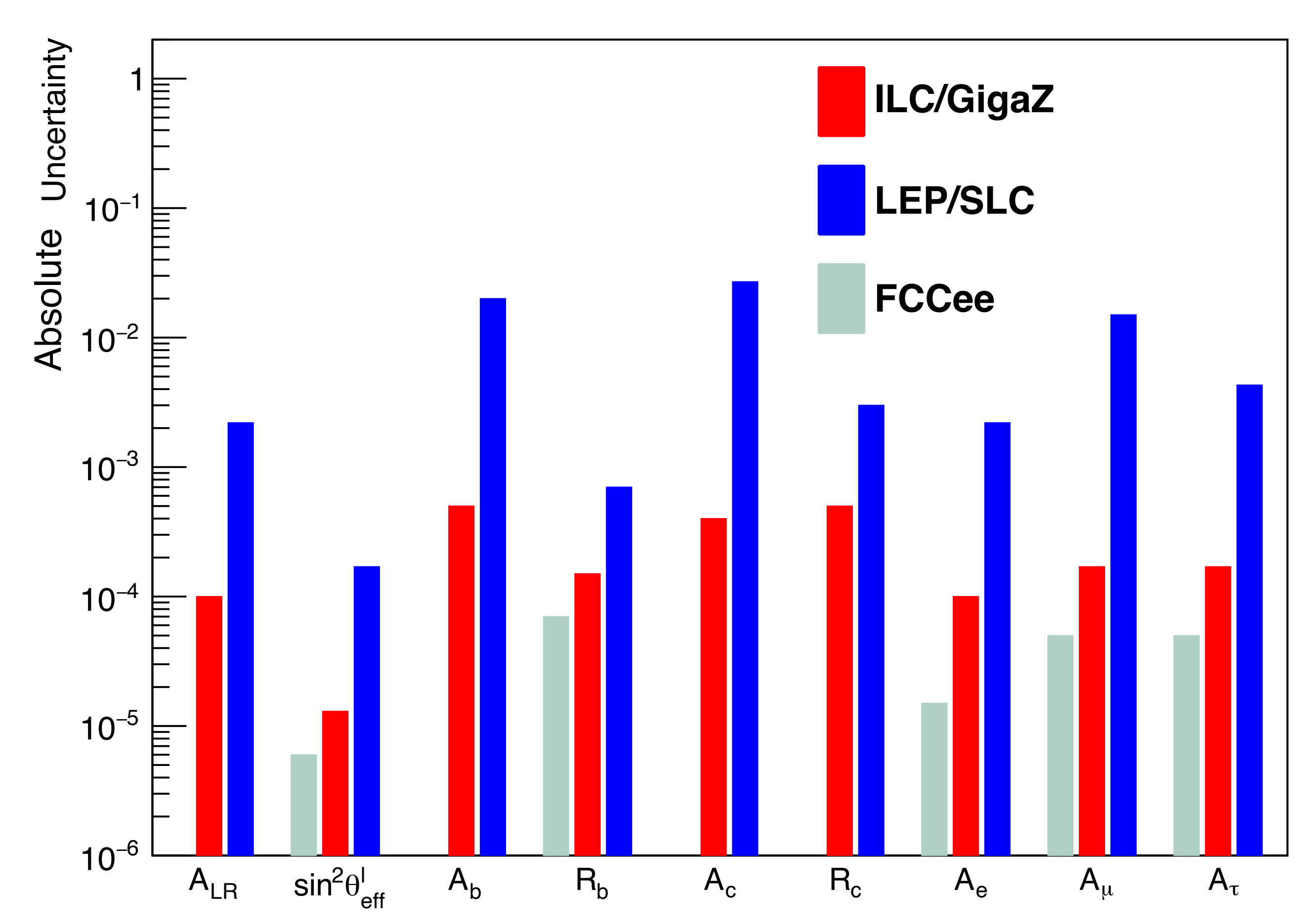
Polarisation & Electroweak Physics at the Z pole

LEP, ILC, FCCee

recent 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*
=> polarisation buys
a factor of ~100 in luminosity



Note: not true for pure decay quantities!

arXiv:1908.11299

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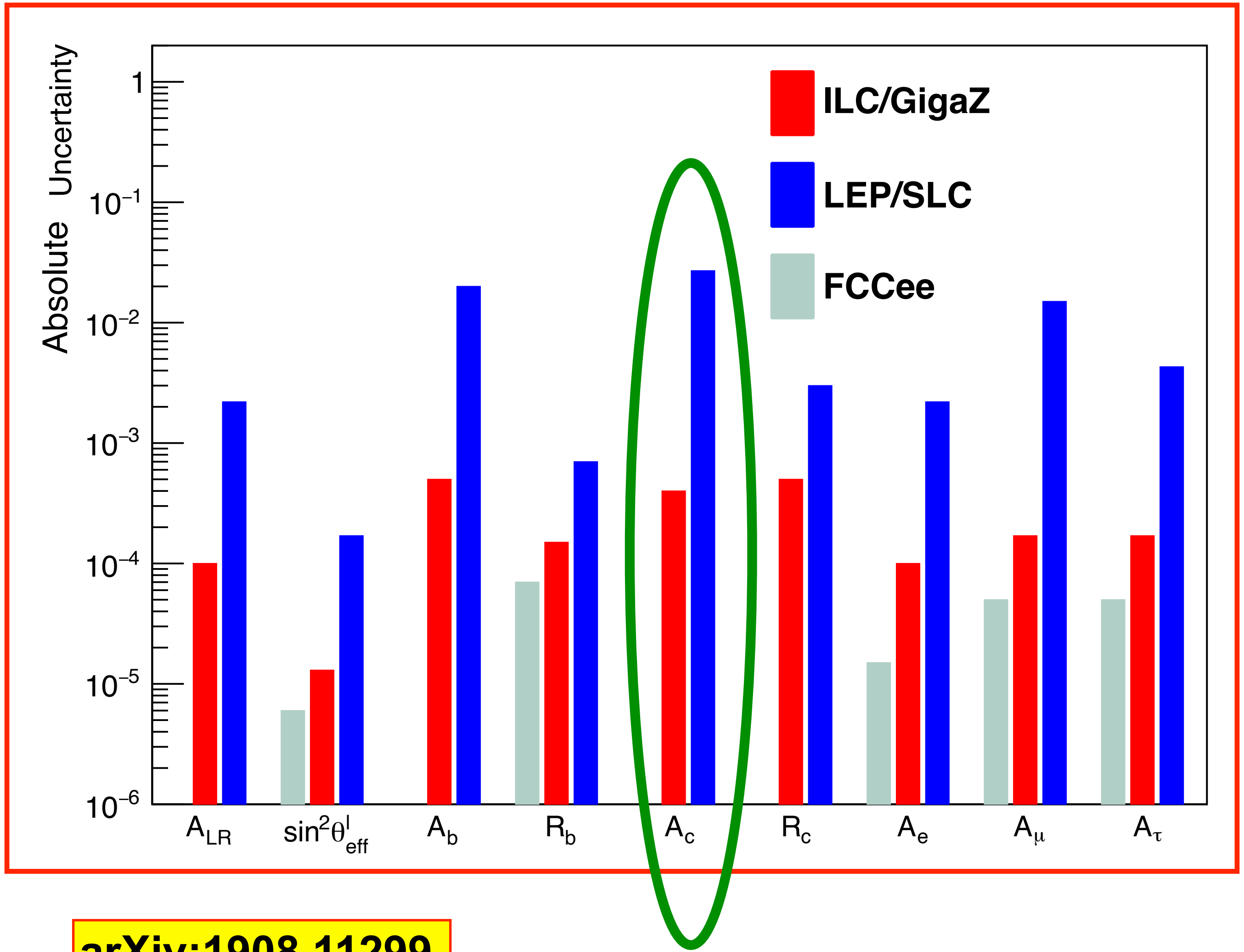

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BSM reach of ee → cc / bb

arXiv:2403.09144

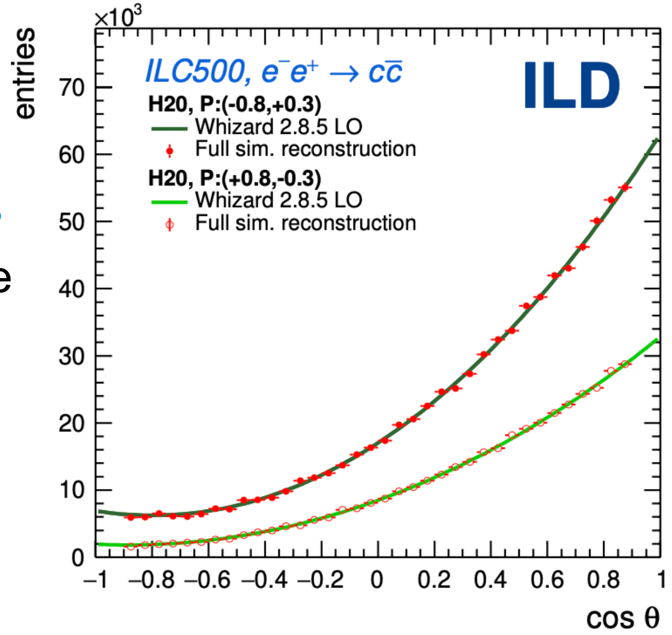
Forward-backward and left-right asymmetries above the Z pole

Study of ee → cc / bb

- full Geant4-based simulation of **ILD**

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
- Z’ as Kaluza-Klein excitations of γ, Z, Z_R
- various model point with $M_{Z'}$ = 7…20 TeV



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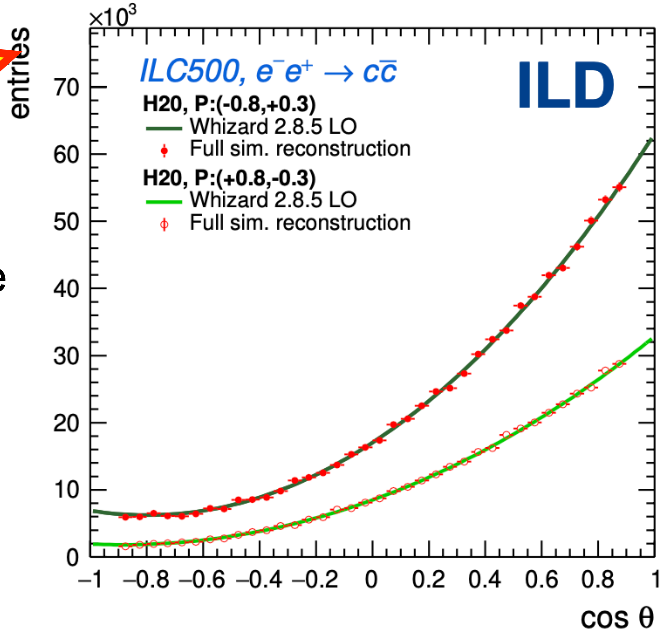

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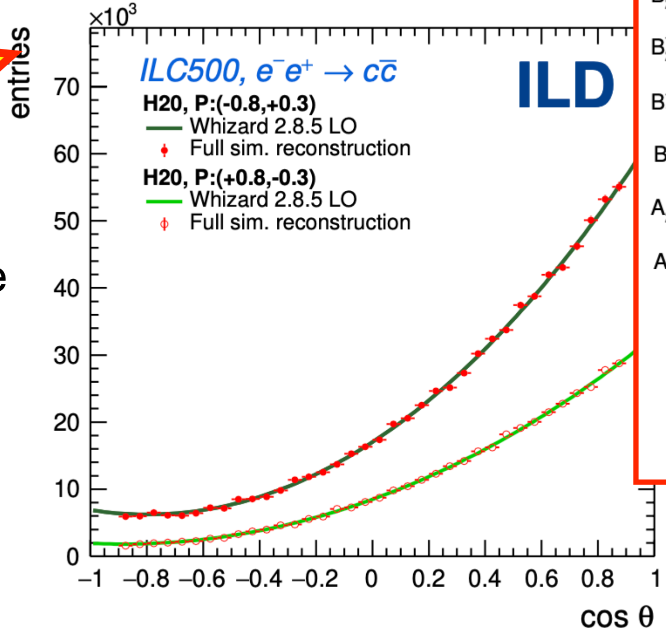

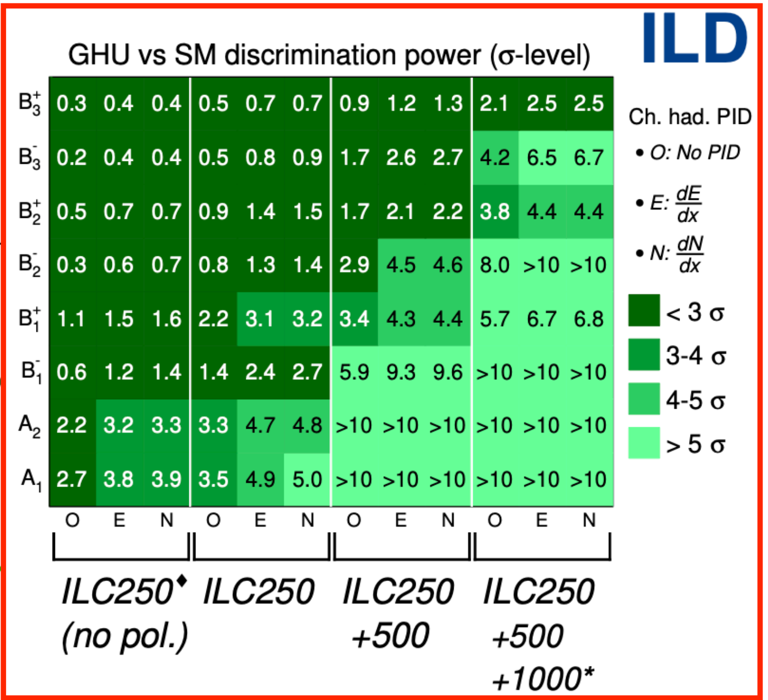

GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.) O	E	N	ILC250 O	E	N	ILC250 +500 O	E	N	ILC250 +500 +1000* O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

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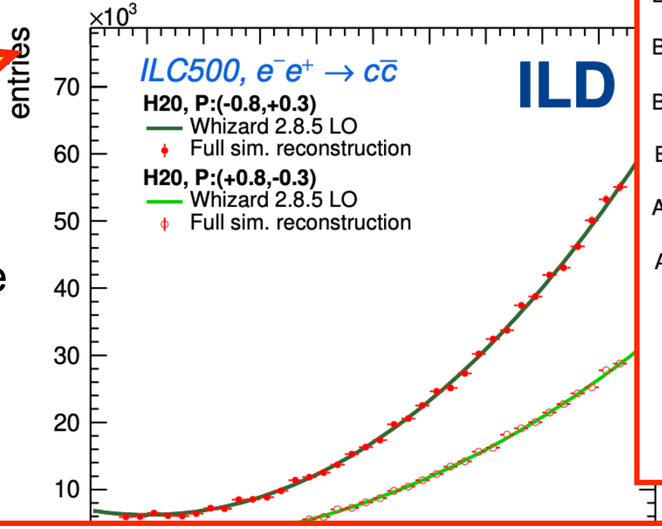

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B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

Ch. had. PID
- O: No PID
- E: $\frac{dE}{dx}$
- N: $\frac{dN}{dx}$

< 3 σ | 3-4 σ | 4-5 σ | > 5 σ

ILD — Between-model discrimination power (σ-level), ILC250♦ (no pol.) (2000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	3.9	3.2	1.5	1.3	0.9	0.4	0.5	
B_3^-	4.1	3.4	1.1	1.4	0.4	0.7		
B_2^+	3.6	2.9	1.6	1.0	1.0			
B_2^-	4.1	3.5	0.7	1.6				
B_1^+	2.7	2.0	1.9					
B_1^-	4.2	3.7						
A_2	0.8							
A_1								

ILD — Between-model discrimination power (σ-level), ILC250 (2000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	5.0	4.7	2.5	2.8	1.4	0.9	0.9	
B_3^-	5.4	5.1	2.1	3.1	0.7	1.4		
B_2^+	4.3	4.1	2.5	2.1	1.7			
B_2^-	5.4	5.1	1.6	3.1				
B_1^+	2.7	2.4	3.4					
B_1^-	5.3	5.1						
A_2	0.5							
A_1								

ILD — Between-model discrimination power (σ-level), ILC250+500 (2000 fb^{-1}+ 4000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	>10	>10	>10	3.9	4.9	1.3	2.9	
B_3^-	>10	>10	7.6	5.1	2.4	3.4		
B_2^+	>10	>10	>10	3.0	5.2			
B_2^-	>10	>10	5.4	6.4				
B_1^+	>10	>10	>10					
B_1^-	>10	>10						
A_2	2.9							
A_1								

ILD — Between-model discrimination power (σ-level), ILC250+500+1000* (2000 fb^{-1}+ 4000 fb^{-1}+ 8000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	>10	>10	>10	5.4	>10	2.7	7.6	
B_3^-	>10	>10	>10	>10	6.7	8.6		
B_2^+	>10	>10	>10	4.1	>10			
B_2^-	>10	>10	>10	>10				
B_1^+	>10	>10	>10					
B_1^-	>10	>10						
A_2	>10							
A_1								

< 3 σ | 4-5 σ | 3-4 σ | > 5 σ

BSM reach of ee → cc / bb

arXiv:2403.09144

Forward-backward and left-right asymmetries above the Z pole

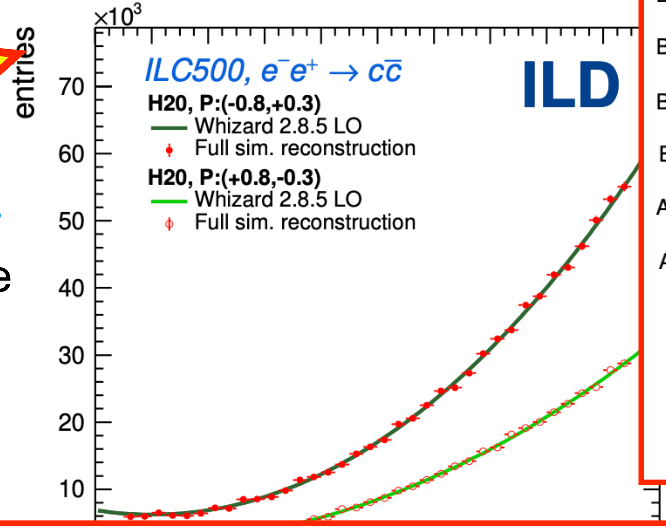
Study of ee → cc / bb

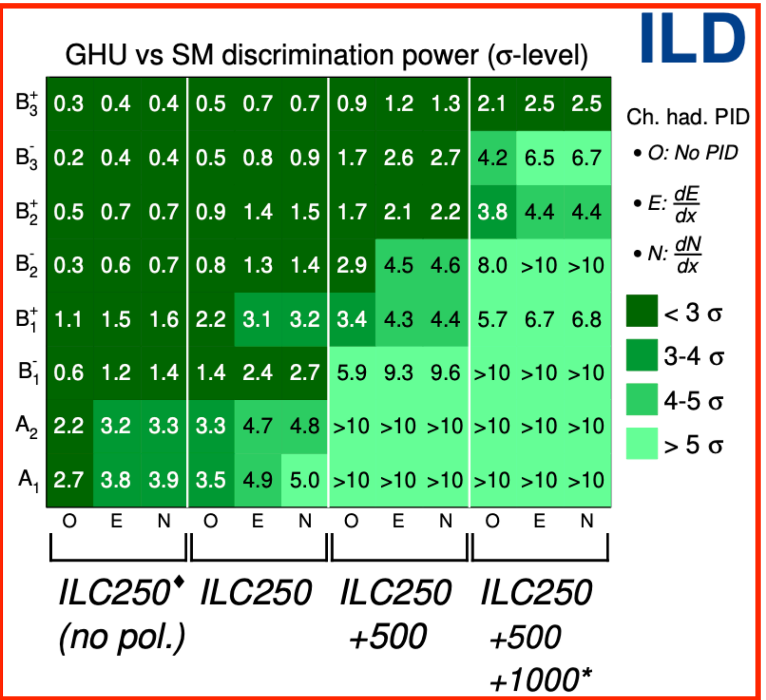
- full Geant4-based simulation of **ILD**

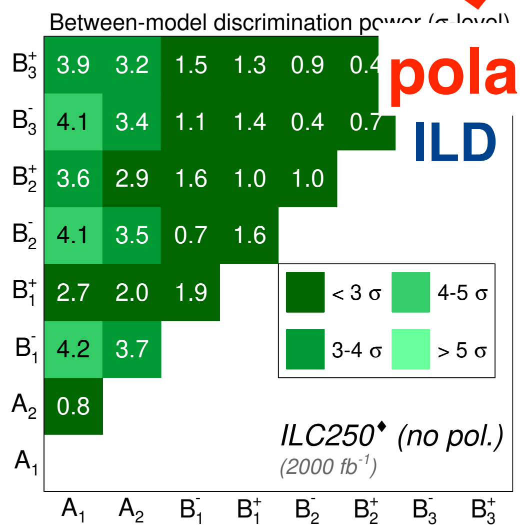
TPC

BSM example: Gauge-Higgs Unification models

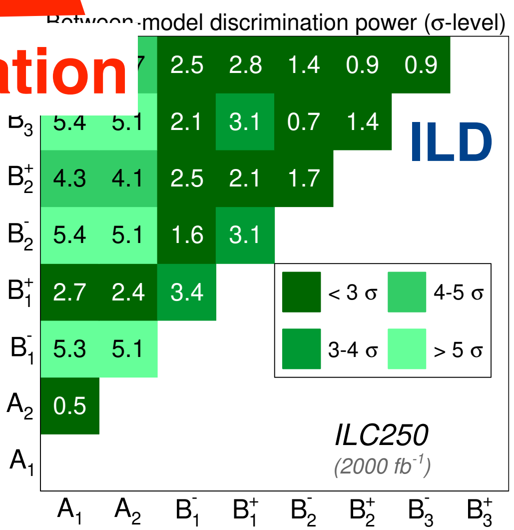
- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
- Z' as Kaluza-Klein excitations of γ, Z, Z_R
- various model point wi… 7…20 TeV

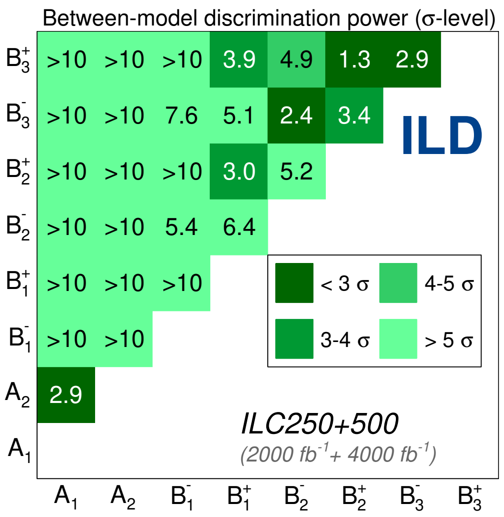


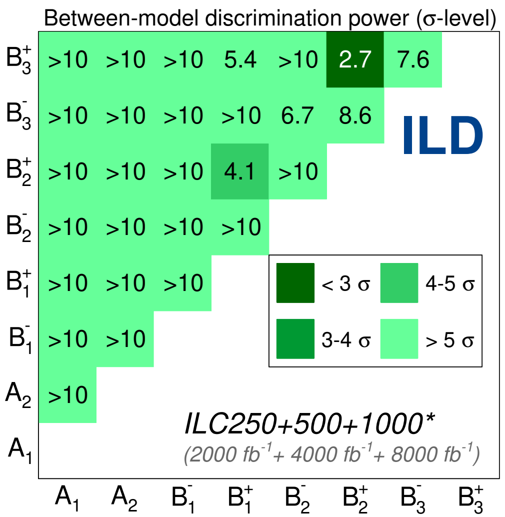




polarisation







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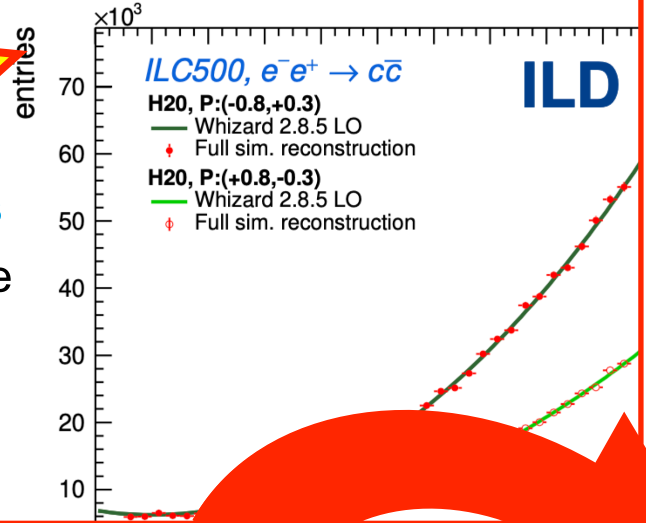
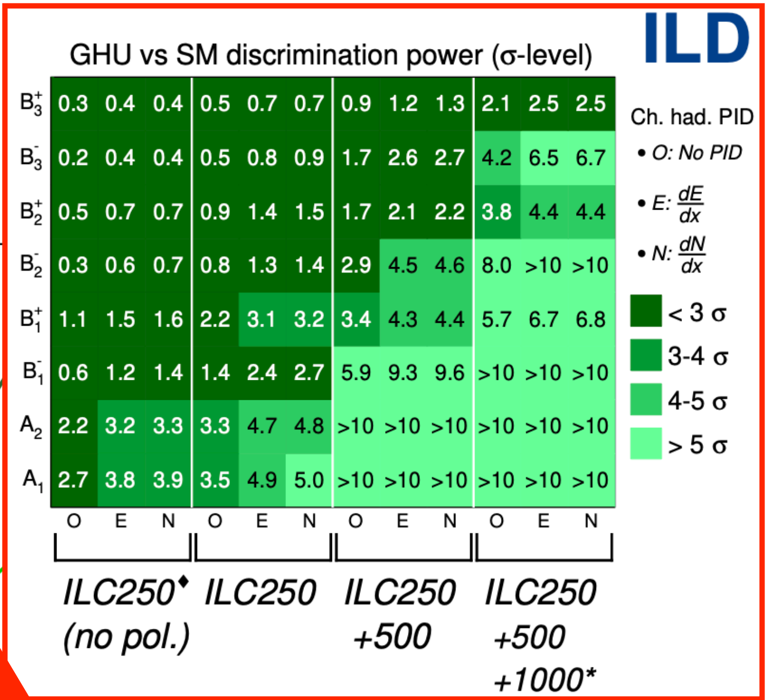
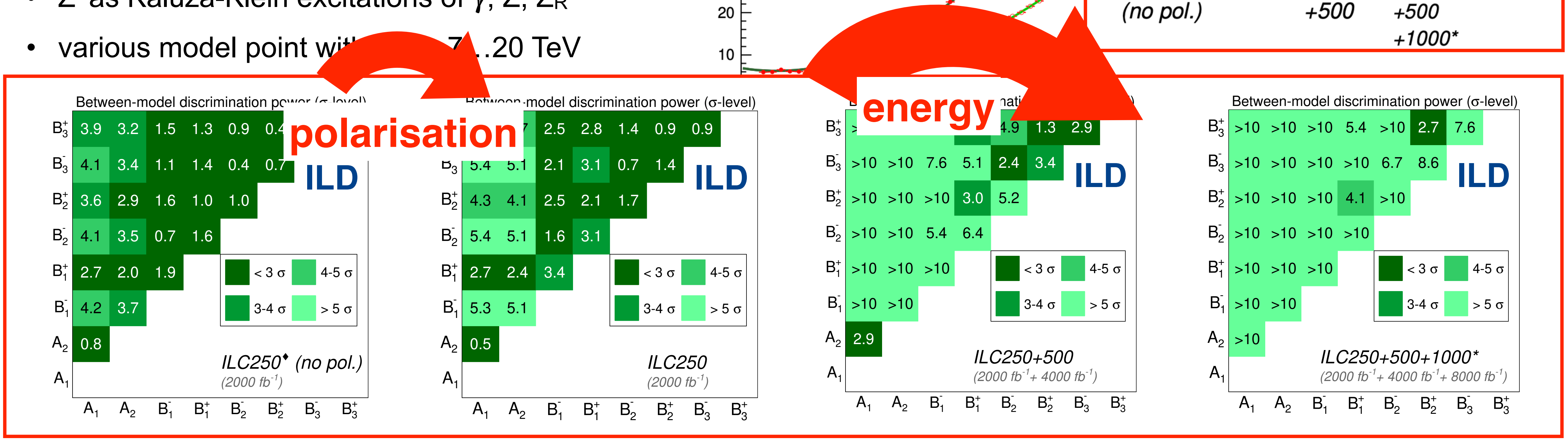




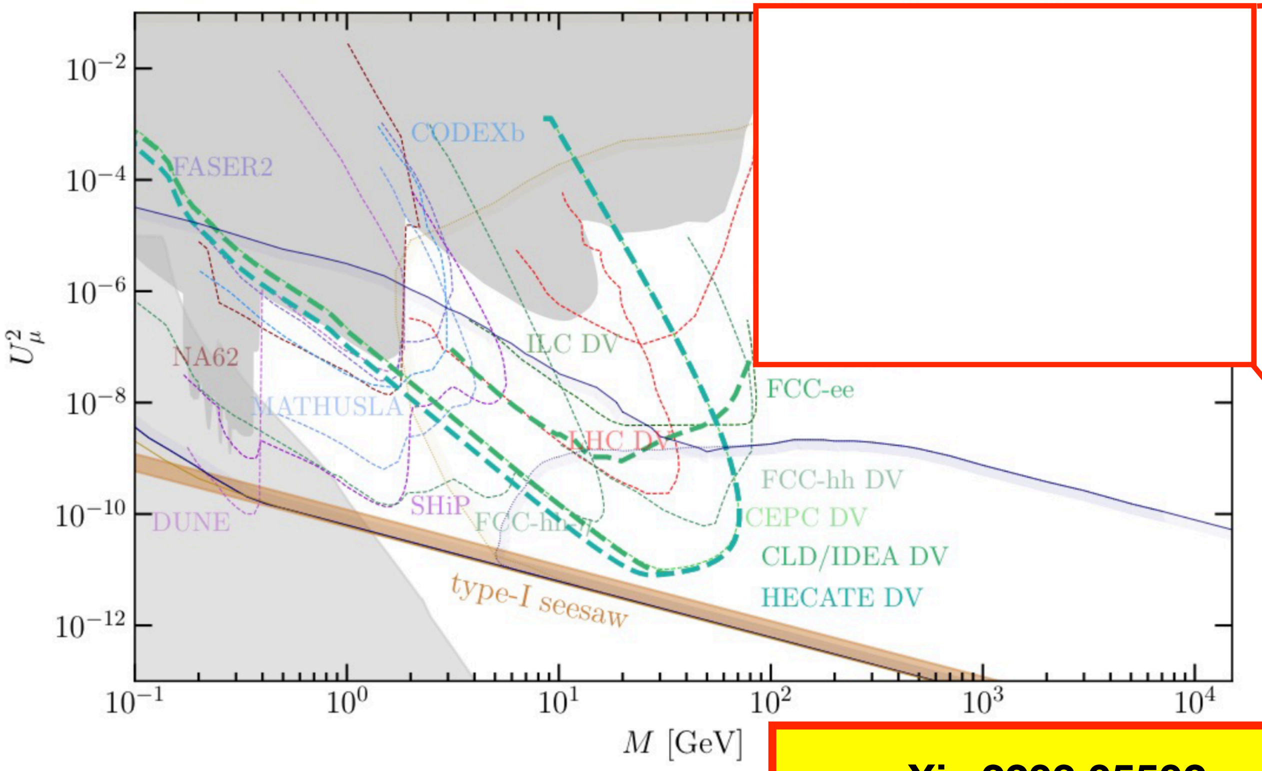


Heavy Neutral Leptons

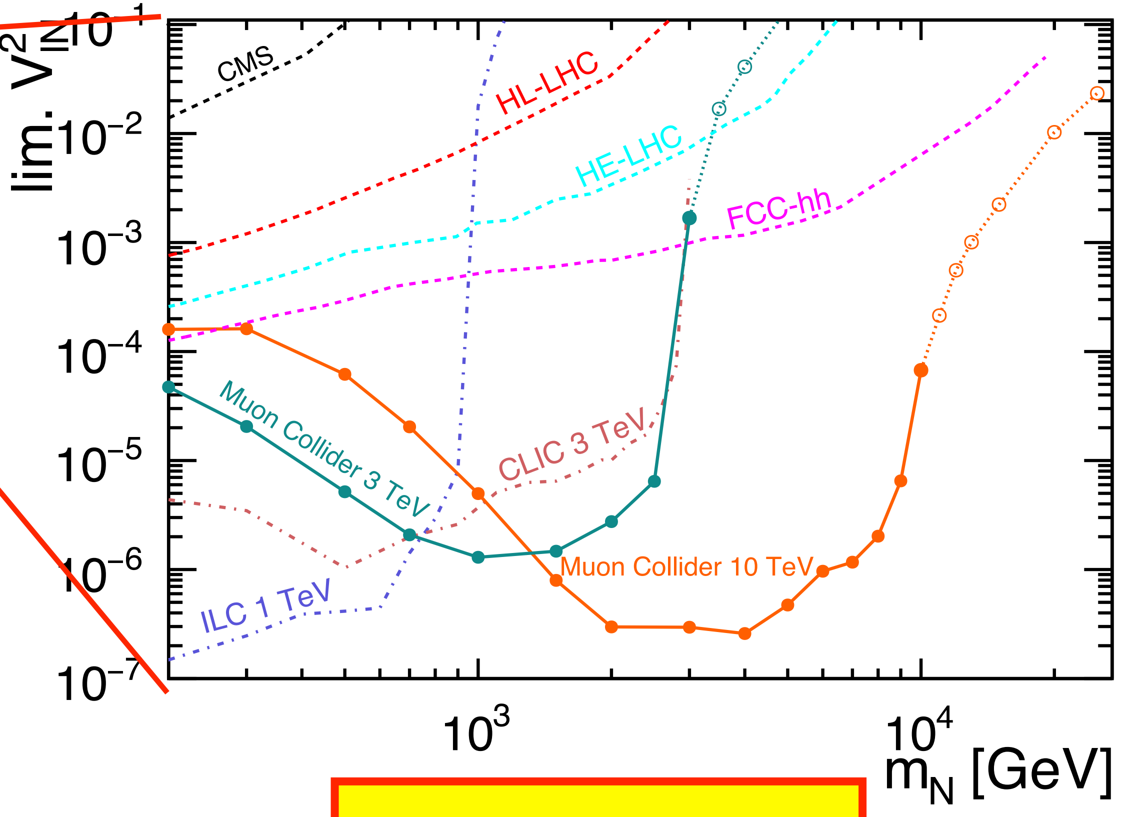
Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices…

…and at high masses in prompt decays



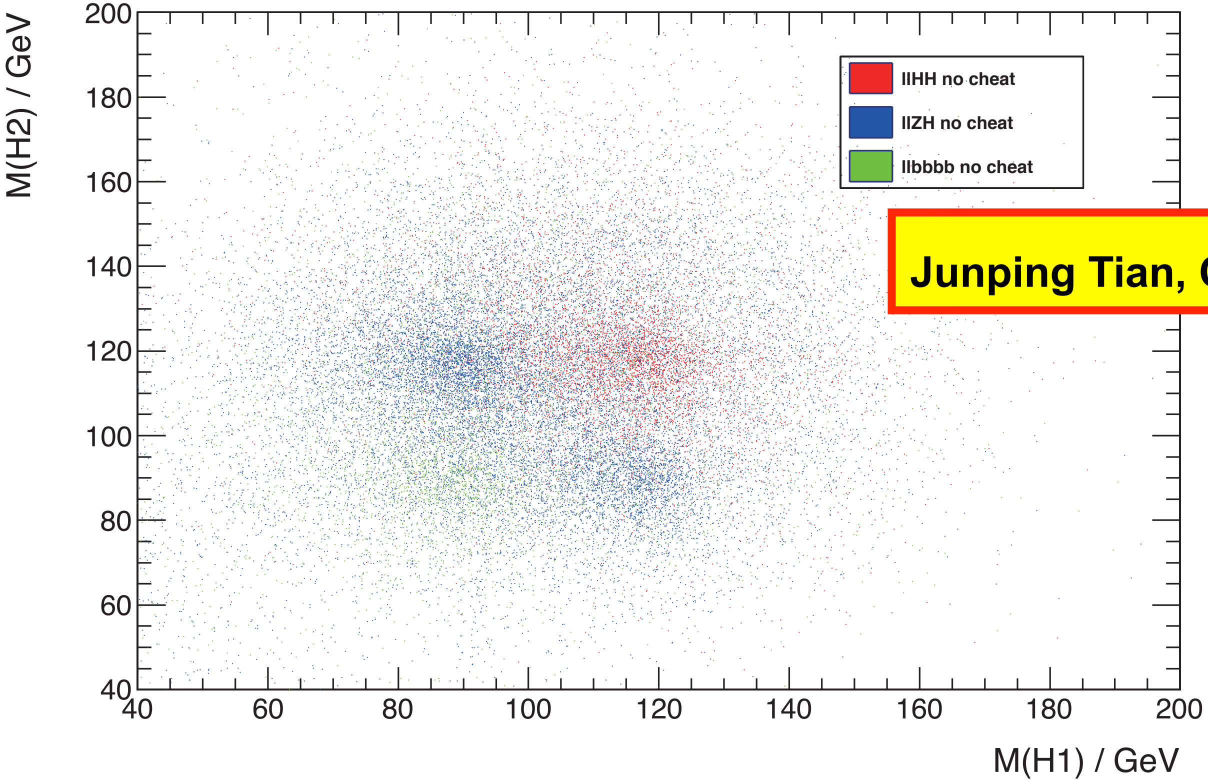
arXiv:2203.05502

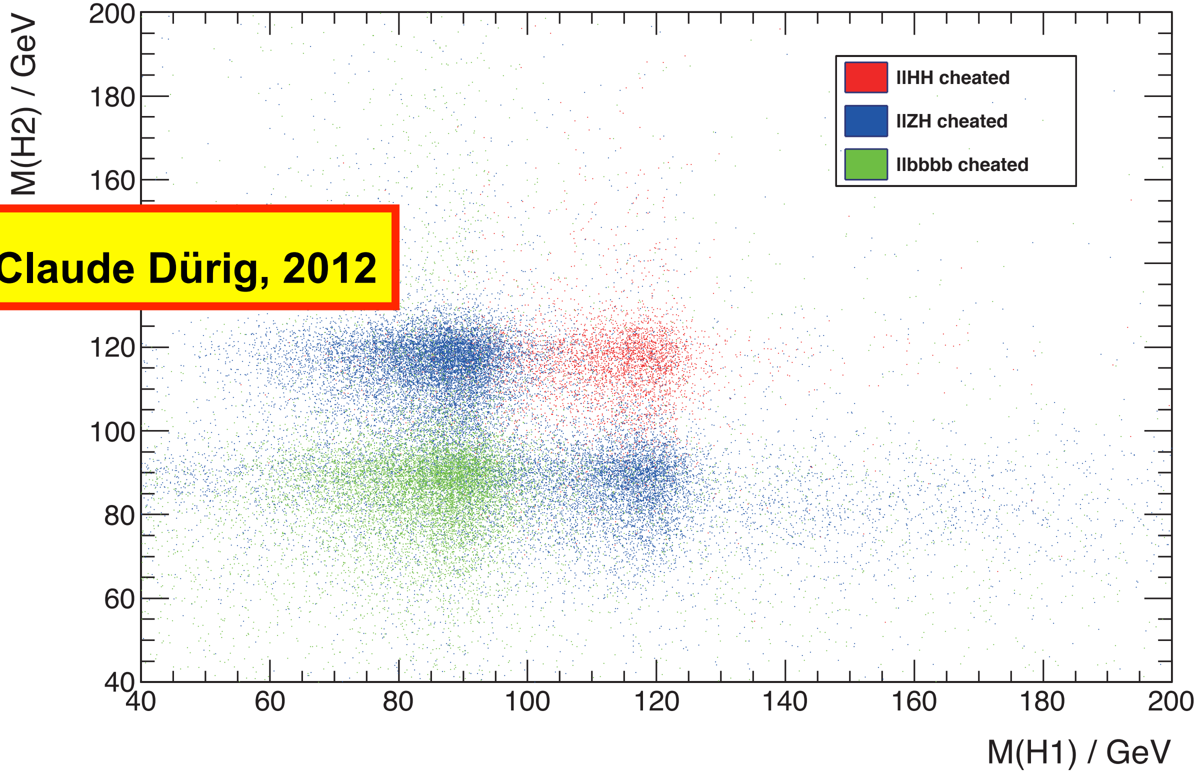


arXiv:2301.02602

Urgently wanted: modern jet clustering

… bottle-neck for Higgs self-coupling precision





Junping Tian, Claude Dürig, 2012

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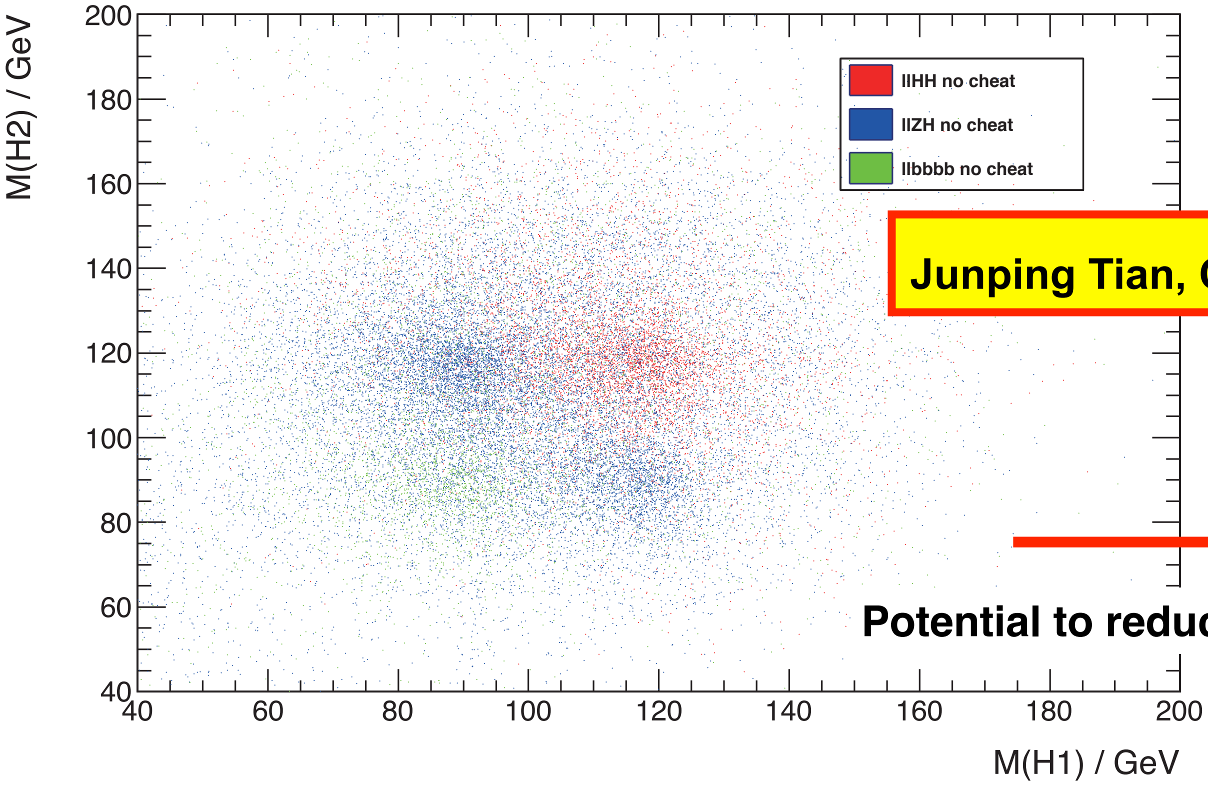

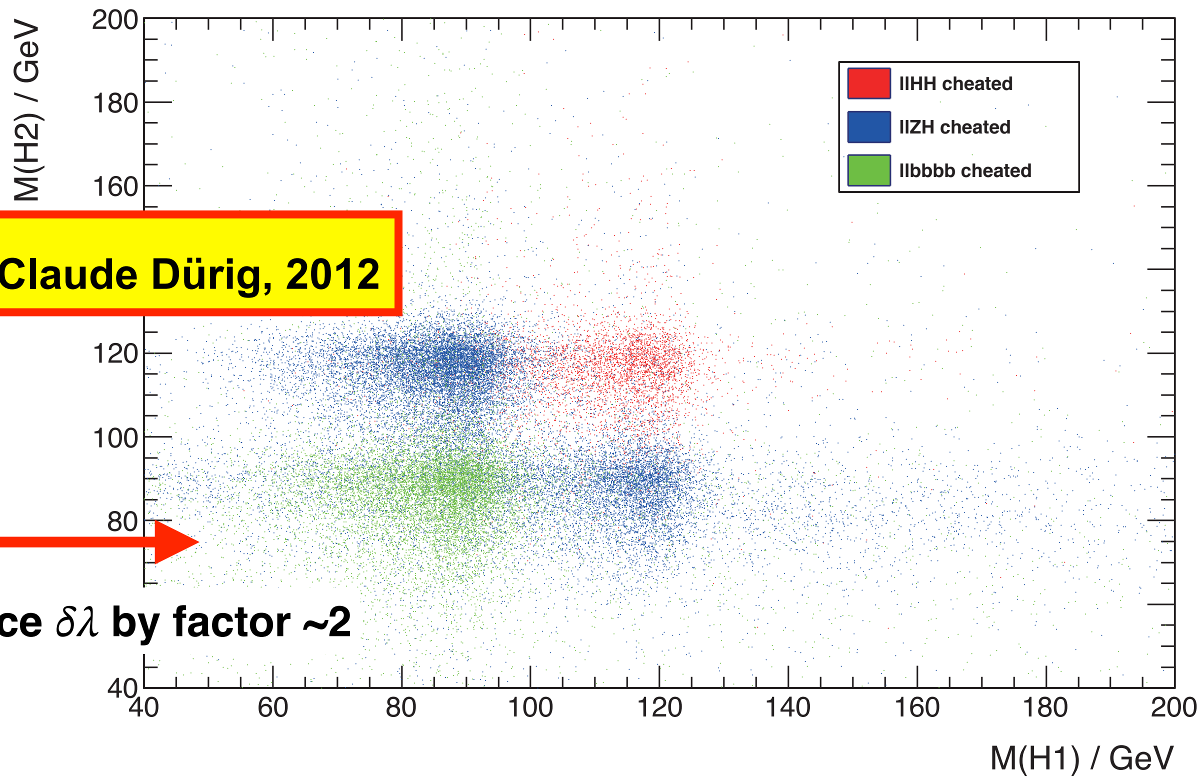

Junping Tian, Claude Dürig, 2012

Potential to reduce $\delta\lambda$ by factor ~2

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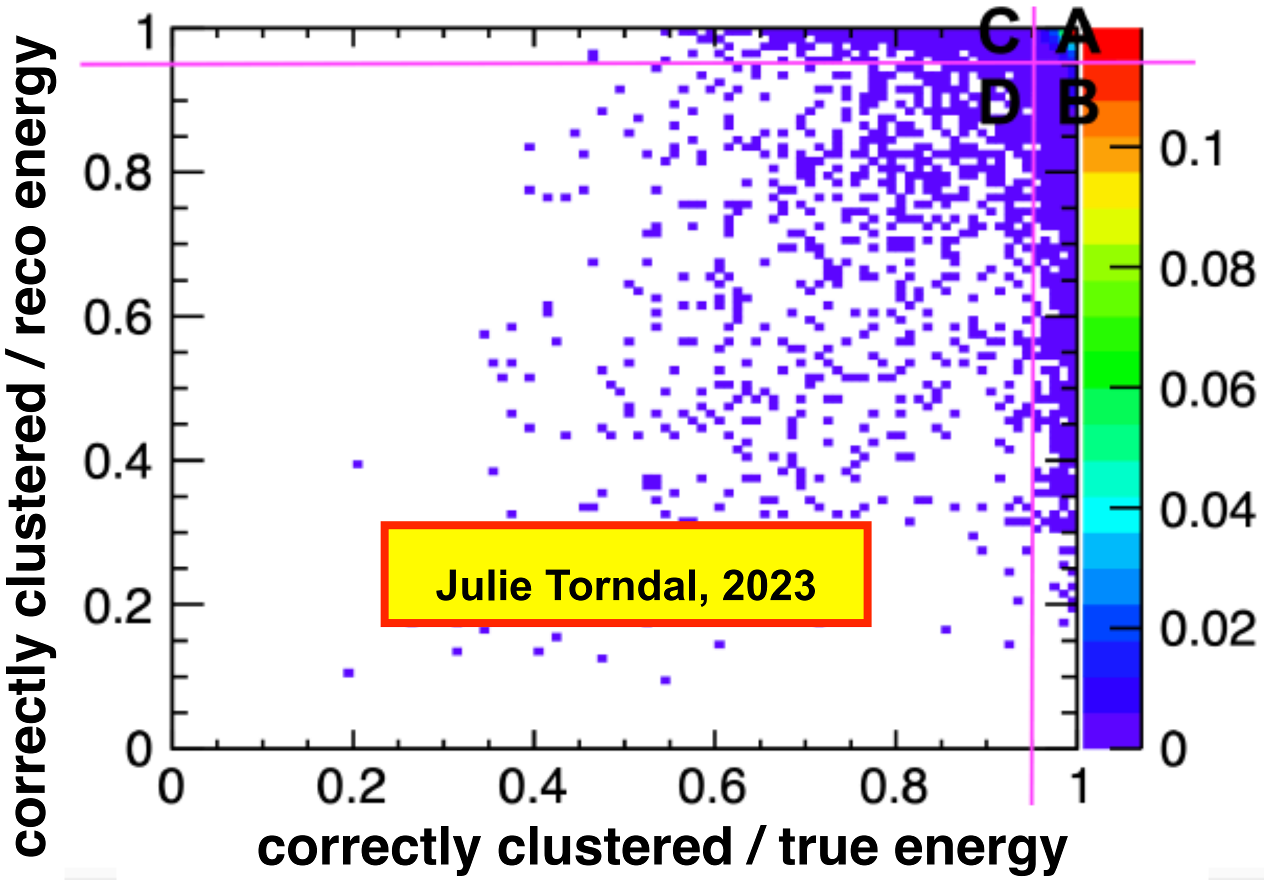

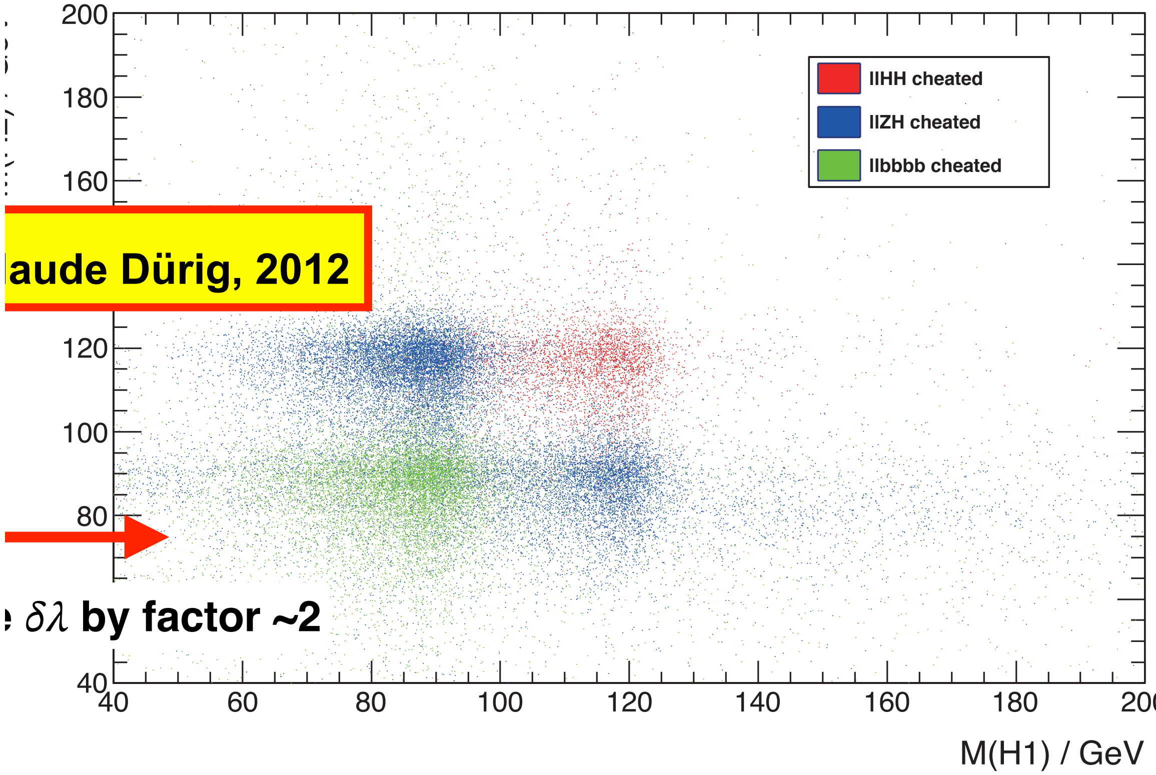

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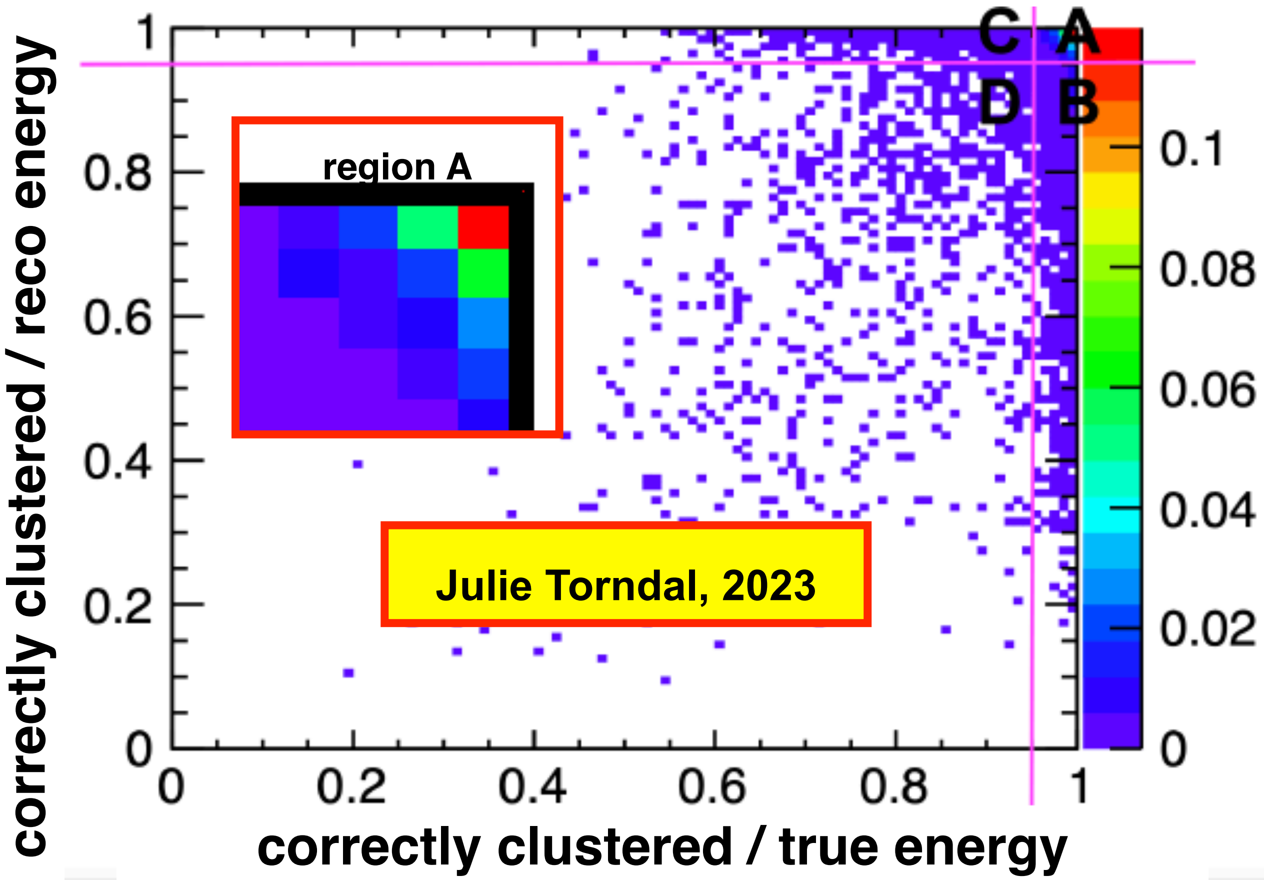

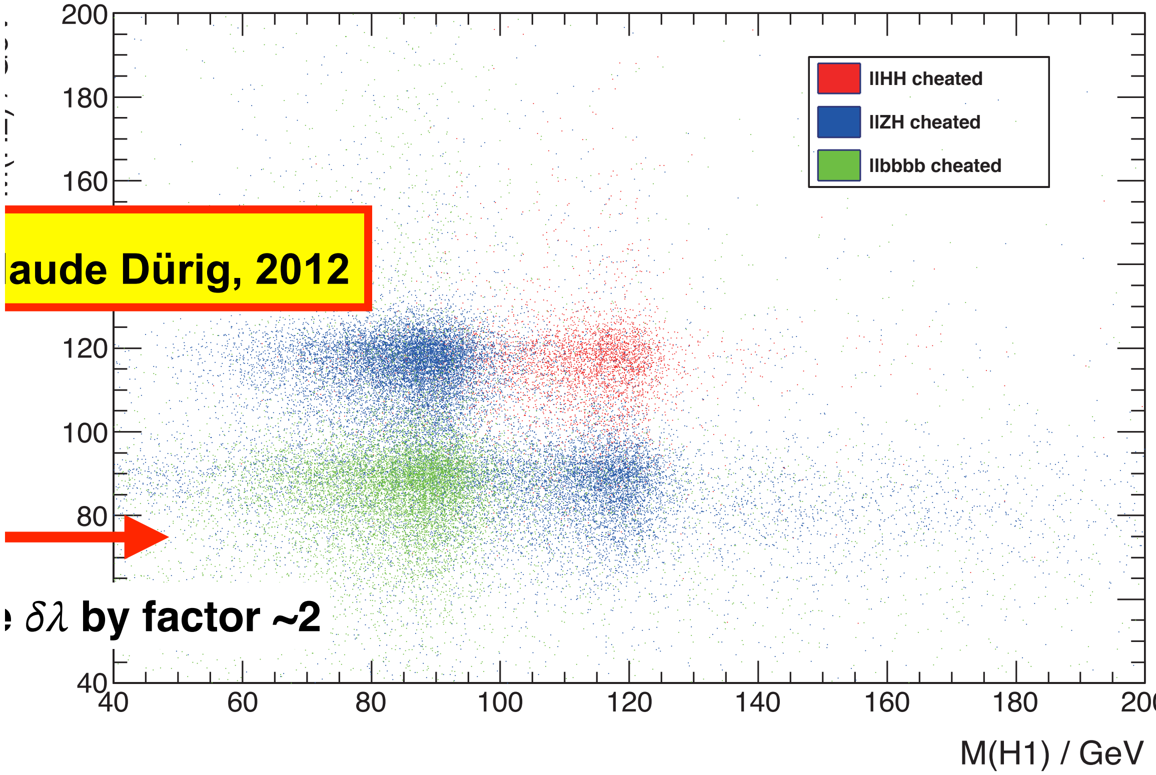

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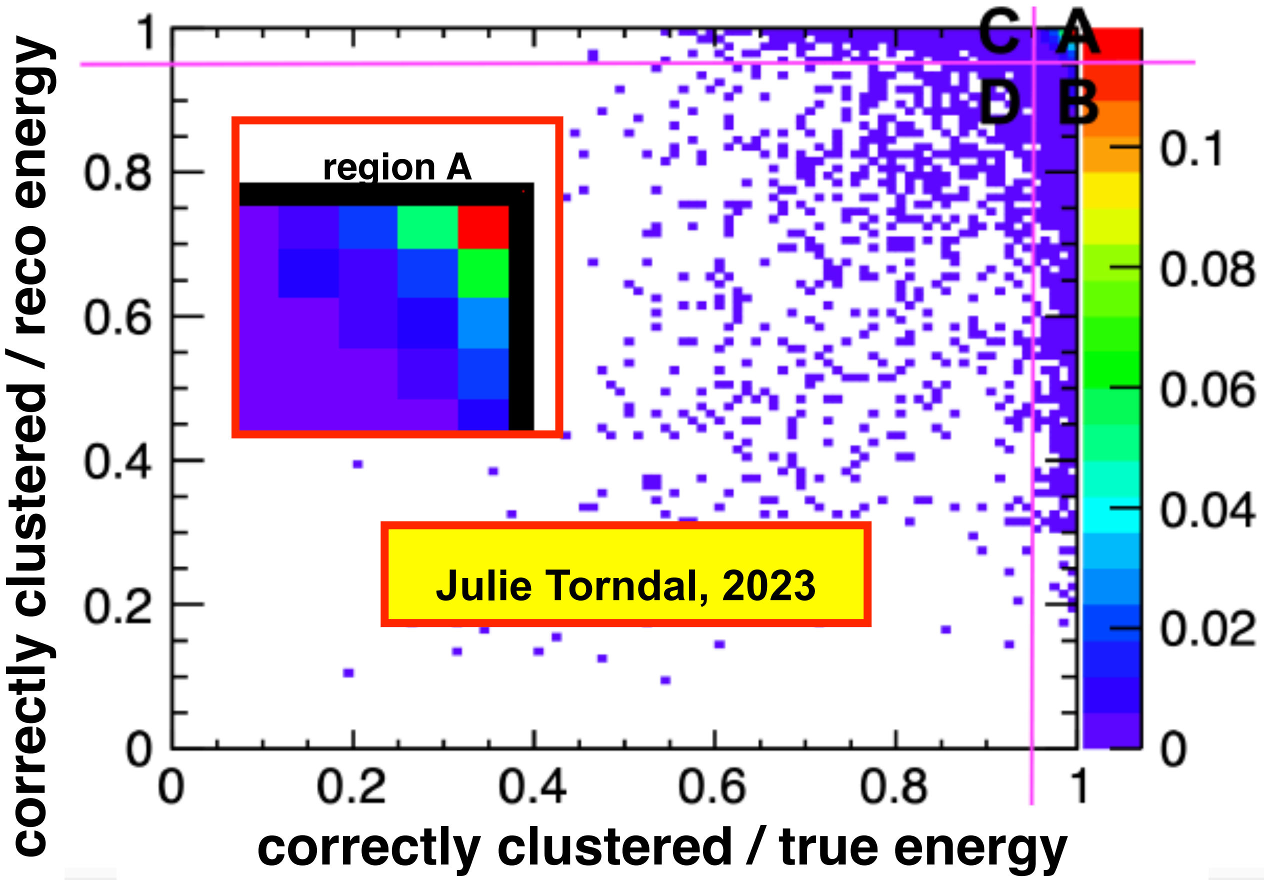

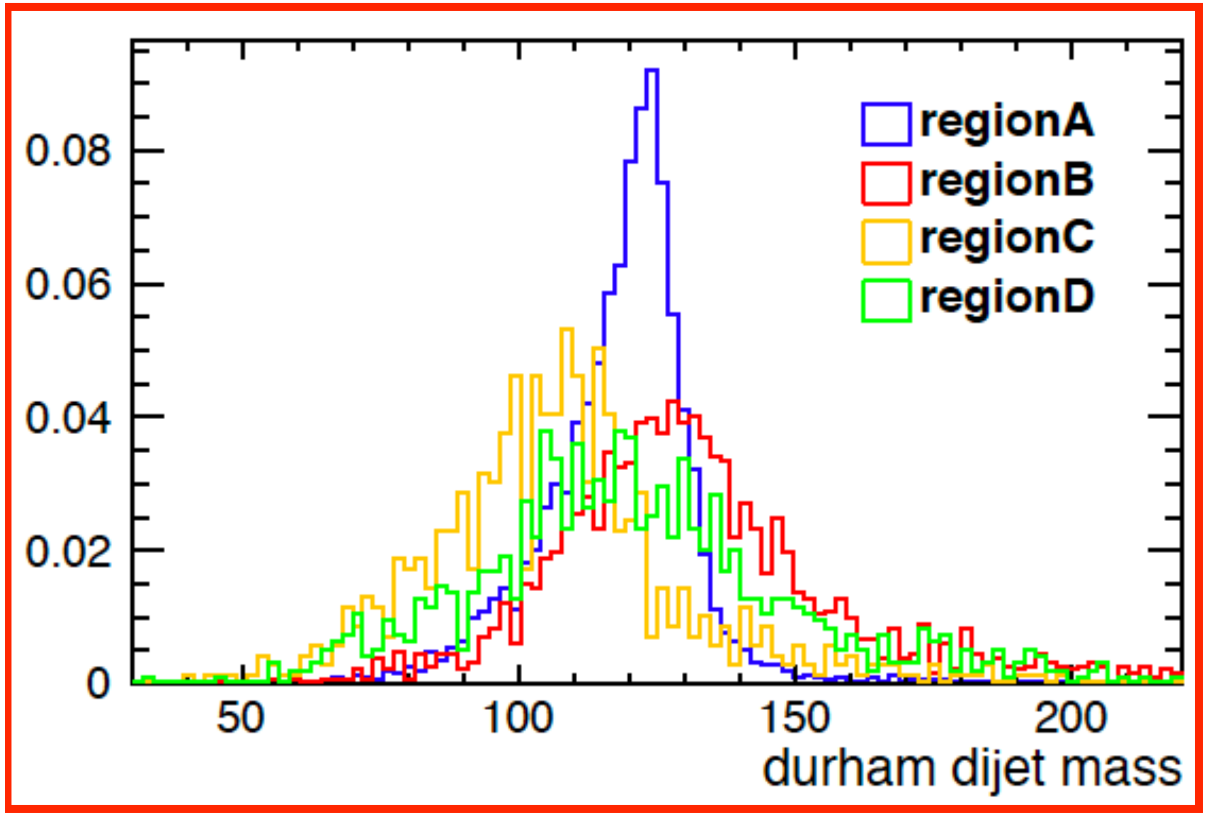

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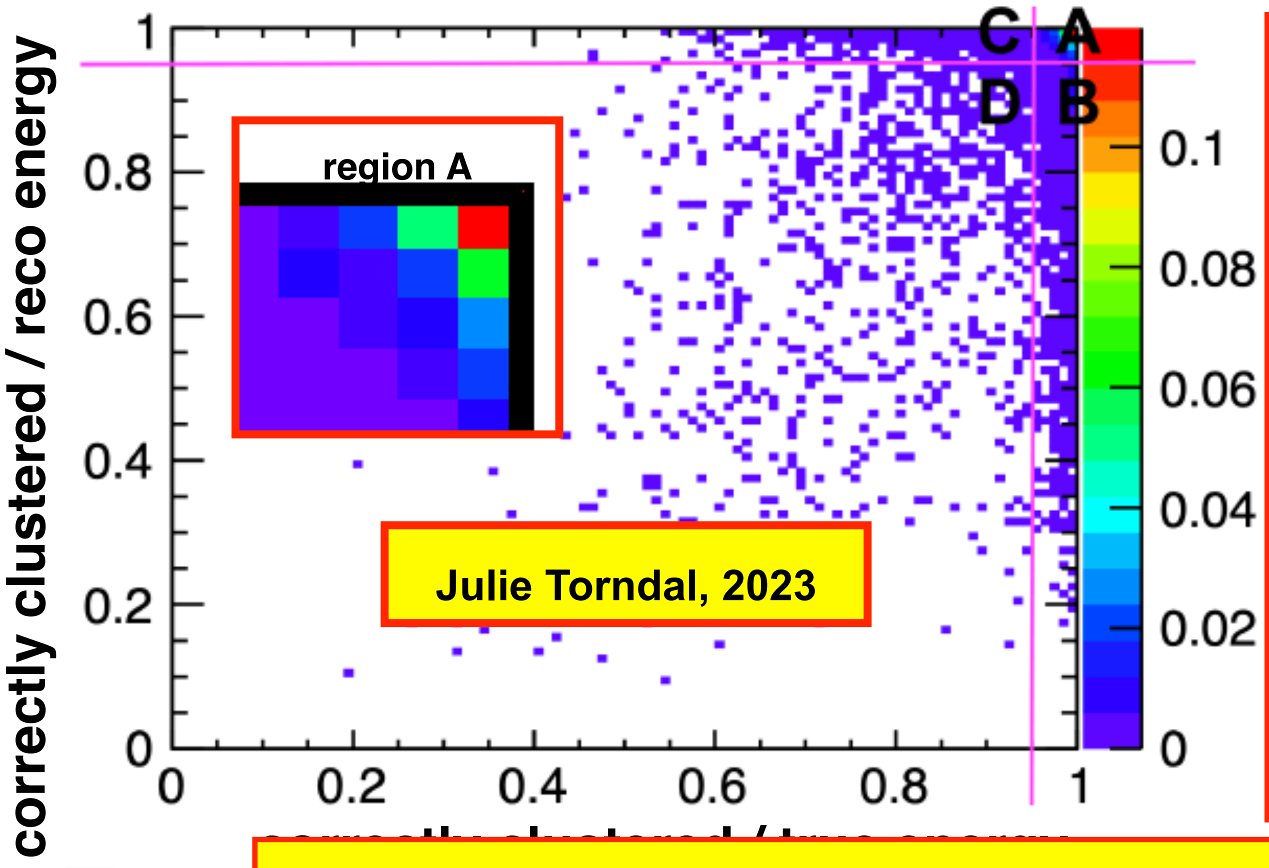
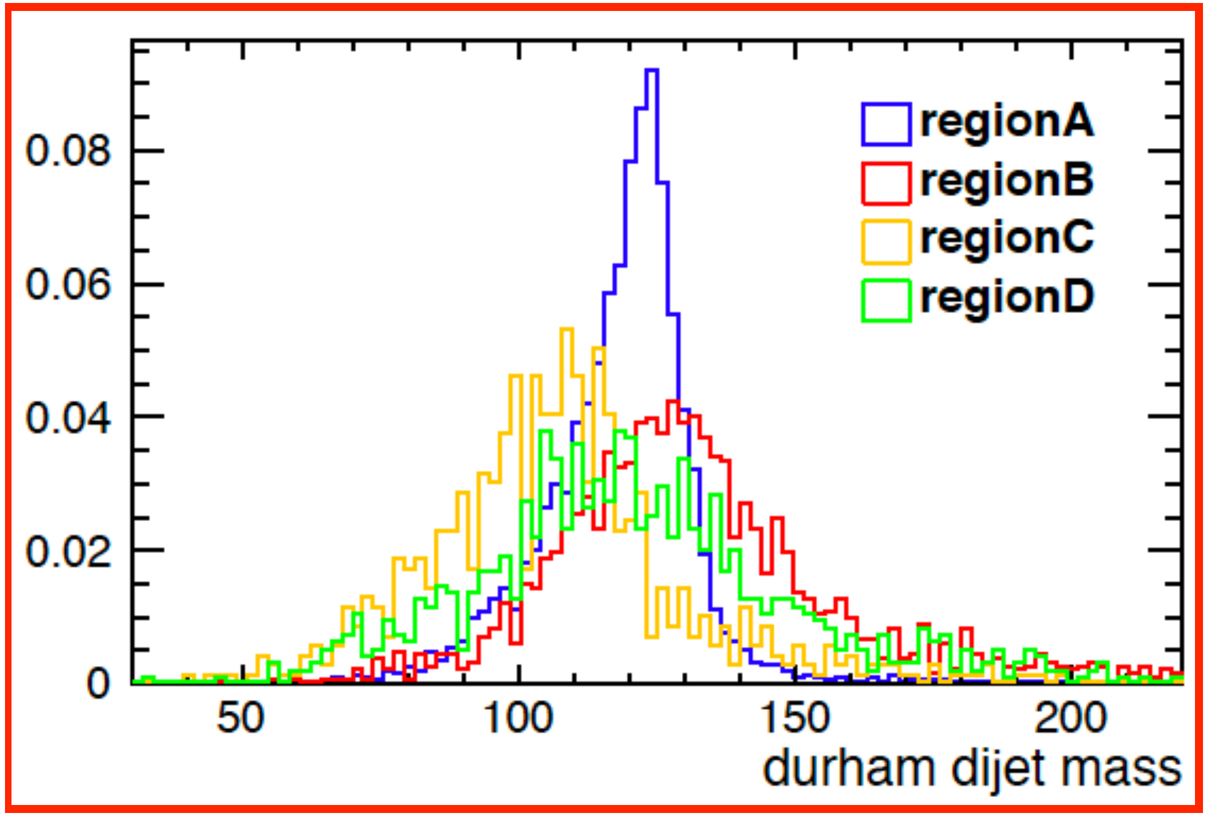




=> Urgently needed: Advanced Jet Clustering, ML, …can we get rid of B, C, D ???

which additional detector information would help?

This has the potential to reduce $\delta\lambda/\lambda$(SM) from 20% to 10% !

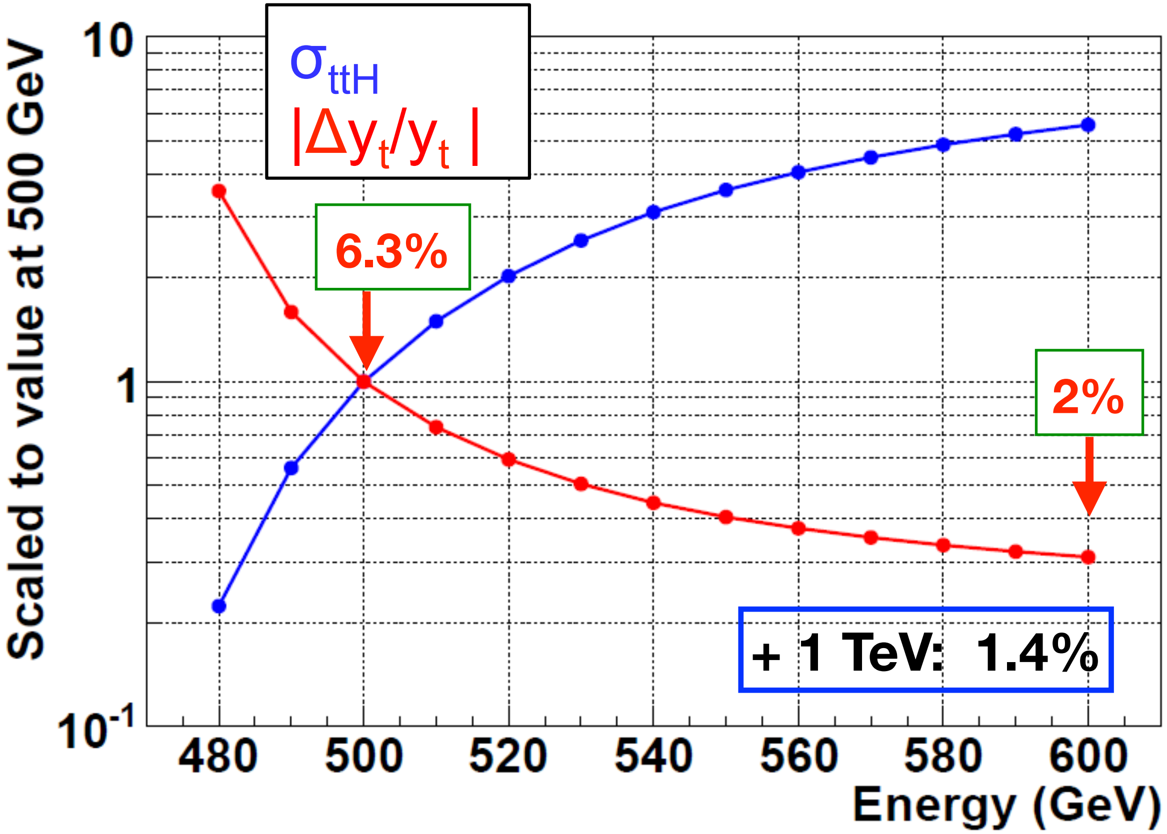
Top Yukawa coupling

Choosing the right energy

The Higgs and the Top

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

- **absolute size of $|y_t|$:**
  - **HL-LHC:**
    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in $SMEFT_{ND}$**
  - **e+e- LC:**
    - 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



to-do: real, full sim study @ 600 GeV!

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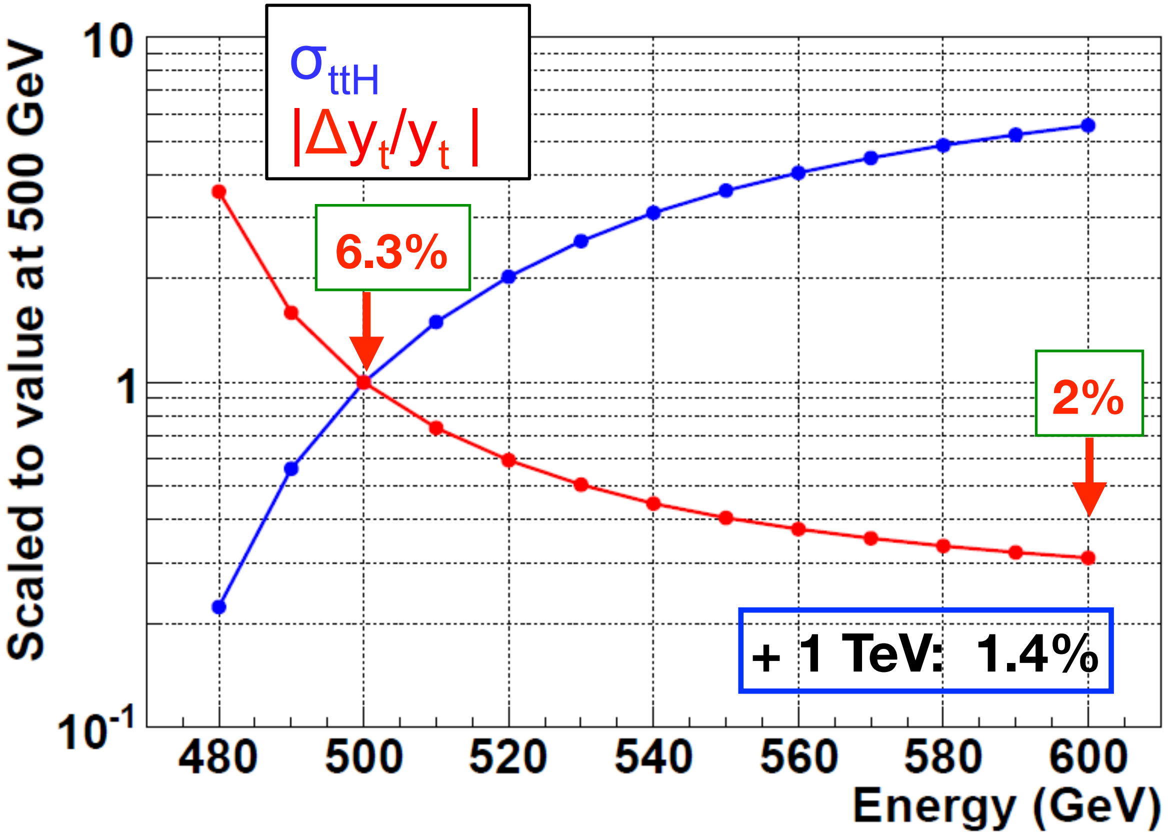


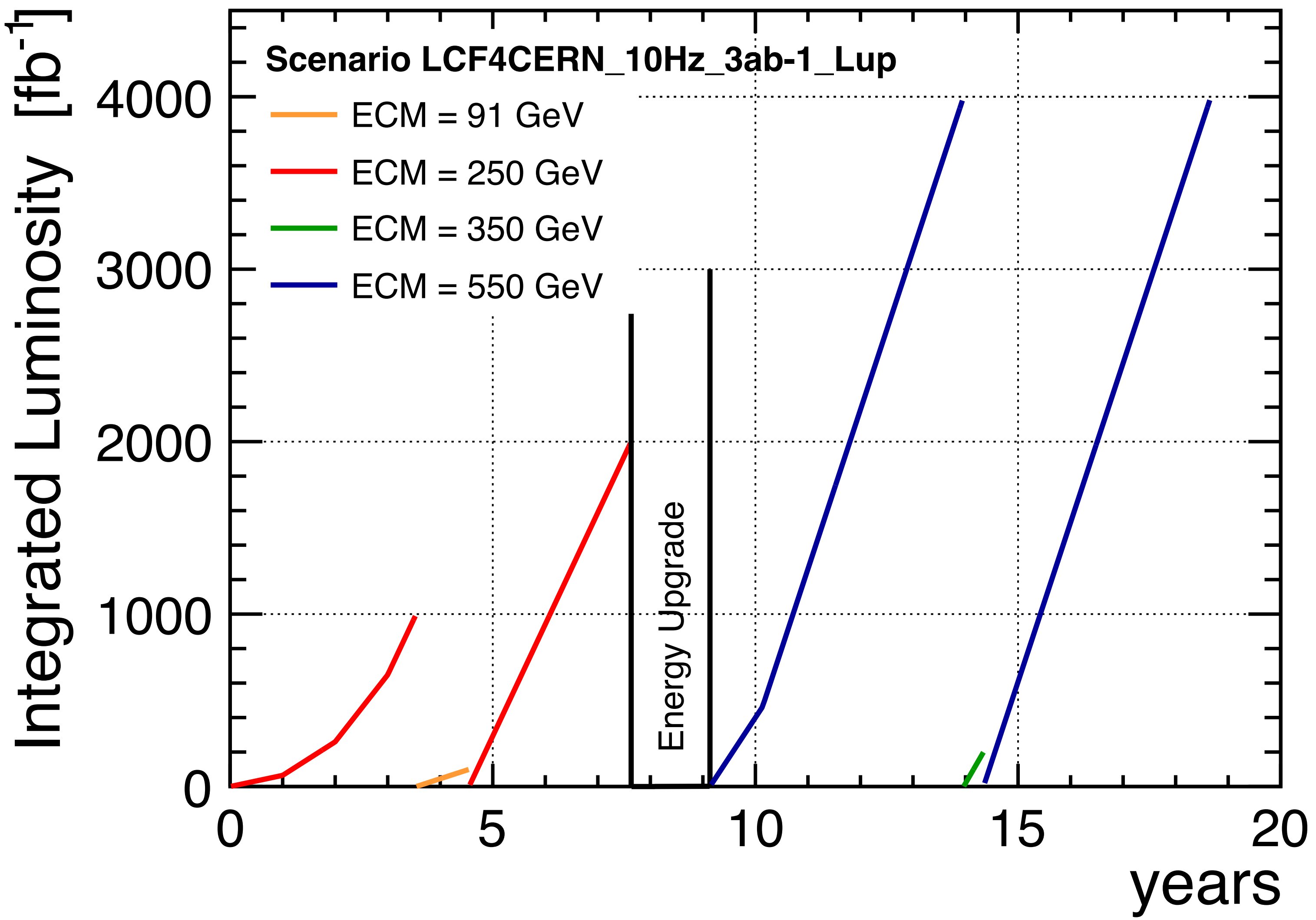
to-do: real, full sim study @ 600 GeV!

- **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]

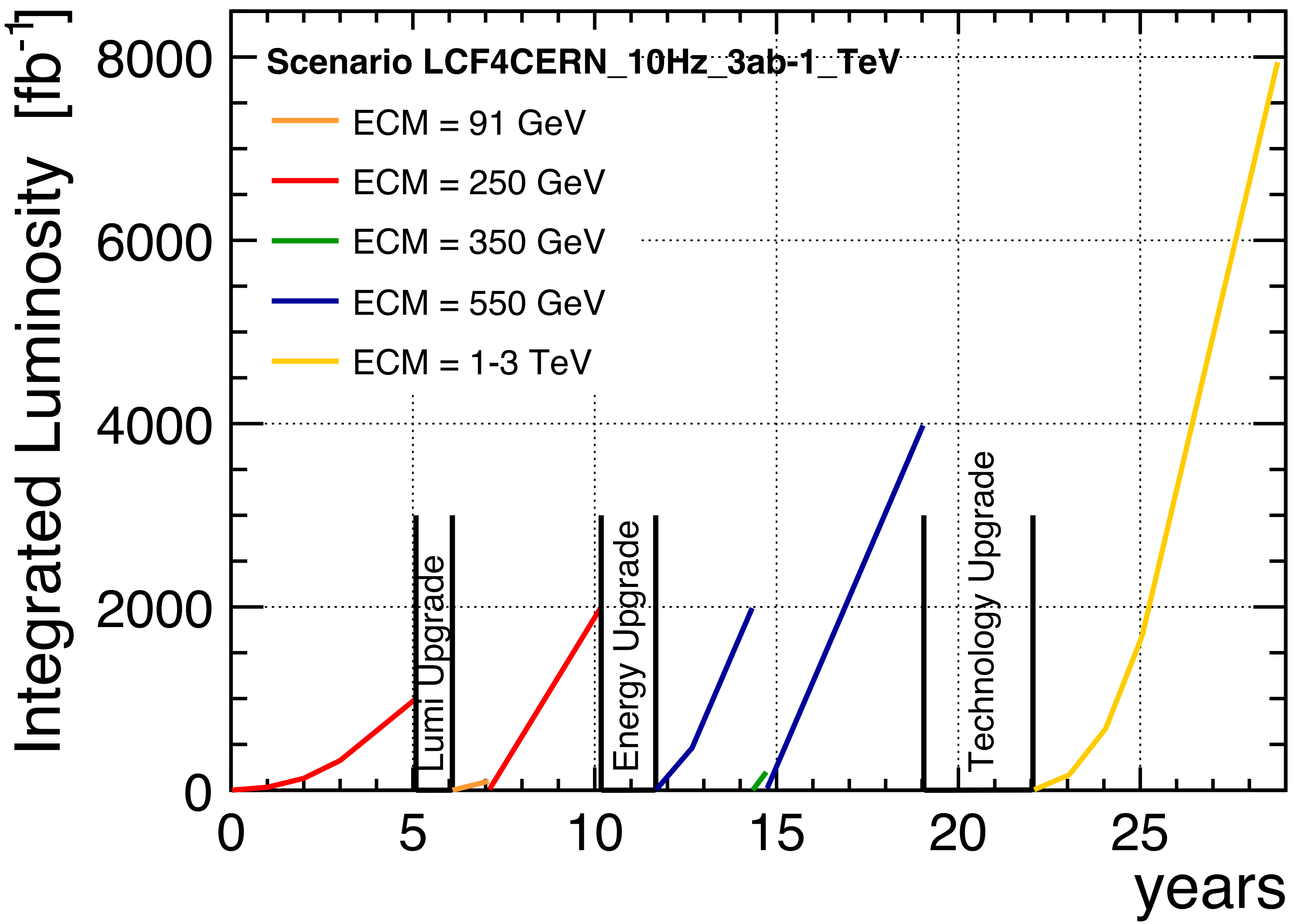
Running Scenarios - illustrating the flexibility

start with full power



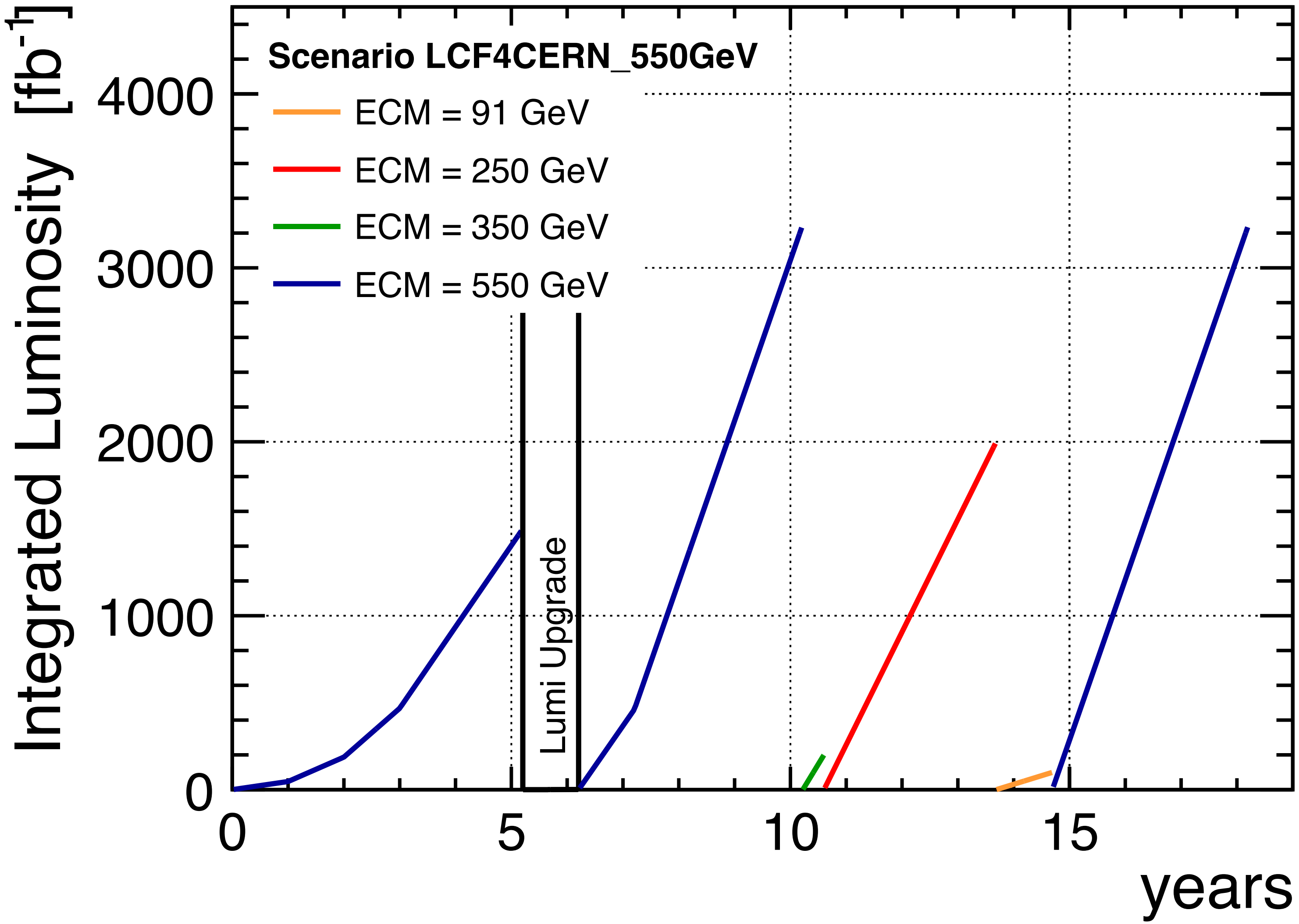
Running Scenarios - illustrating the flexibility

shorten 550 GeV to go to TeV range earlier



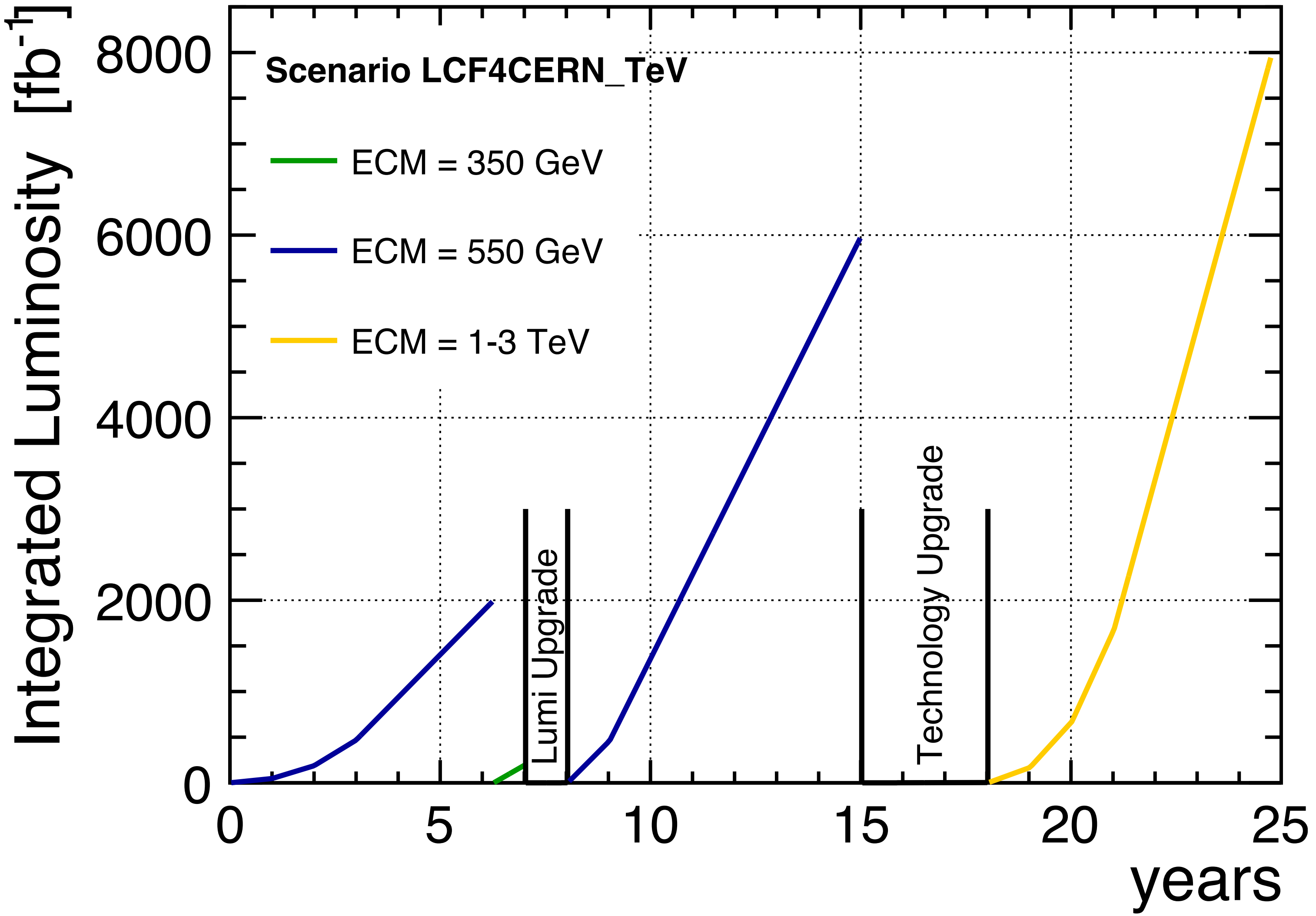
Running Scenarios - illustrating the flexibility

start with 550 GeV - cross-check CEPC with polarised data ?



Running Scenarios - illustrating the flexibility

start with 550 GeV - or go to TeV range earlier



Running Scenarios - illustrating the flexibility

Early Technology upgrade