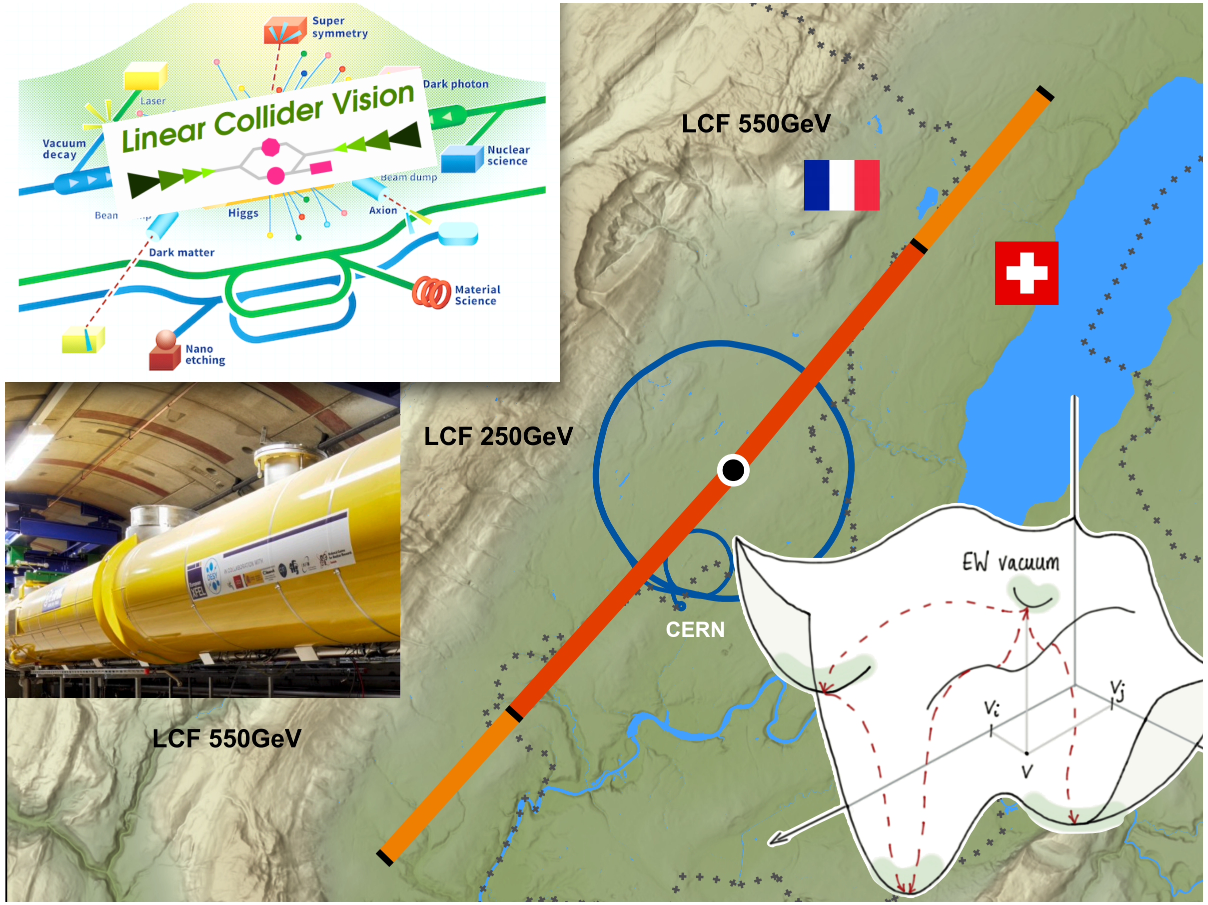
The Linear Collider Facility for CERN

CEPC-Europe Workshop
Barcelona
June 16, 2025

Jenny List
on behalf of the LCVision Team

Outline:

- Introduction
- LCF@CERN
- Conclusions & Invitation

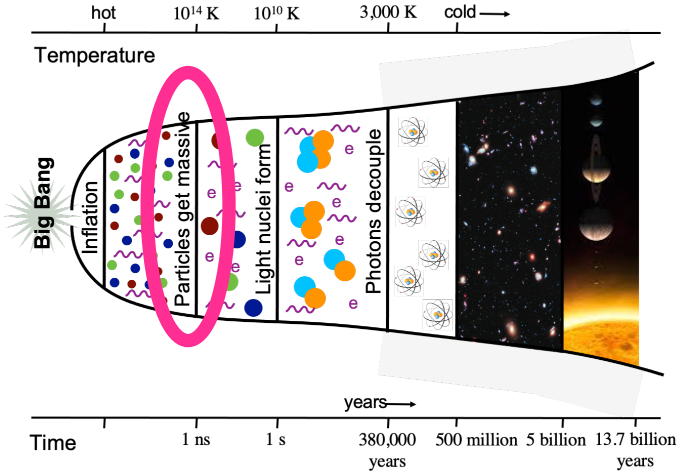


Introduction

Particle Physics in 2025

Towards 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
- we must continue beyond HL-LHC to scrutinize the place where new physics is most likely to be found:
  in precision measurements of the Higgs boson!



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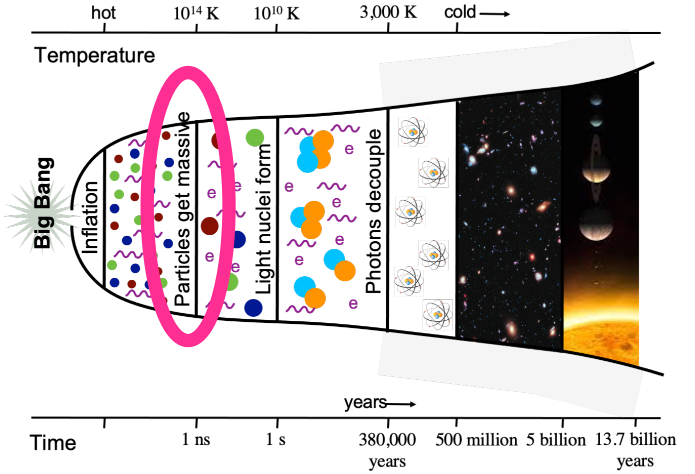
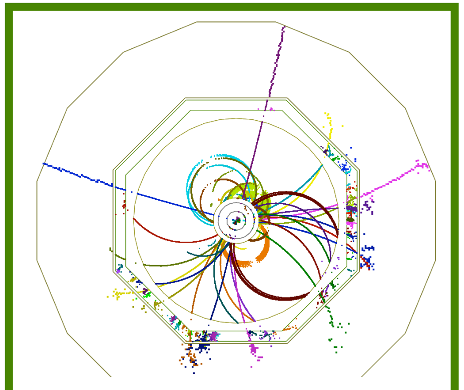


an e+e- collider is the ideal place to do this:
collides elementary, electroweak particles
=> clean experiments & precise predictions



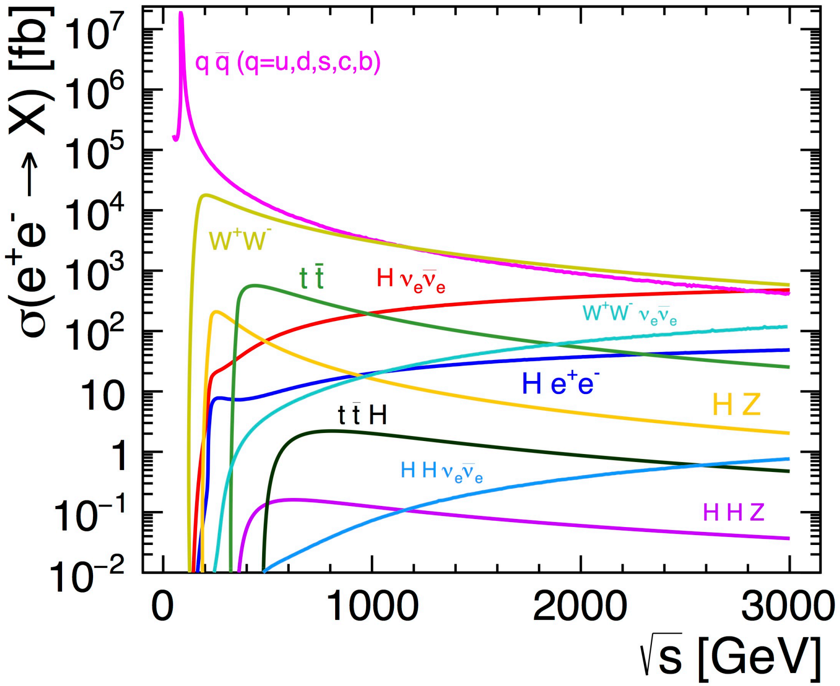
$e^+e^- \to \mu^+\mu^- H \to \mu^+\mu^-$ bb in ILD

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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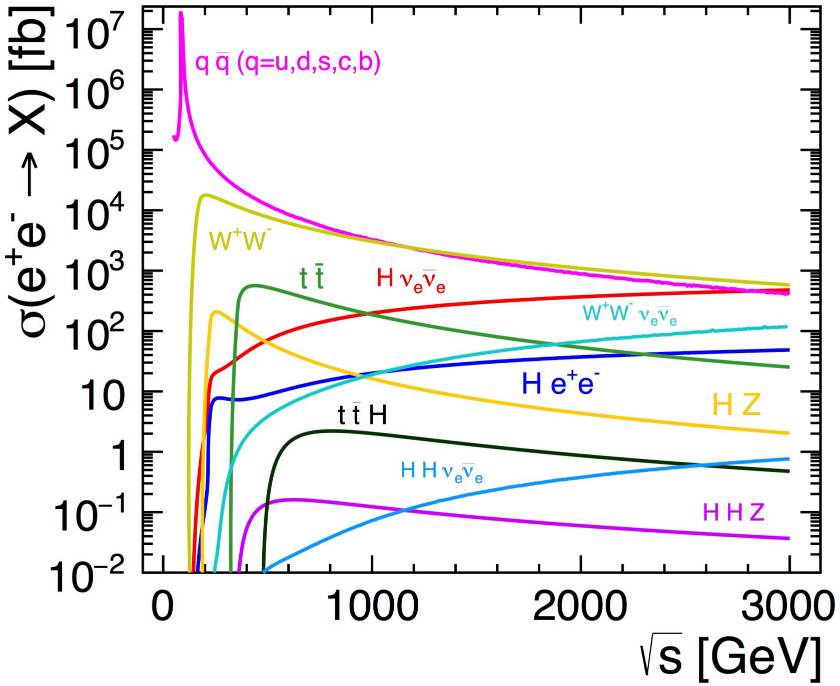

the full Higgs / top / electroweak program requires polarised beams & E_{CM} up to at least 1 TeV

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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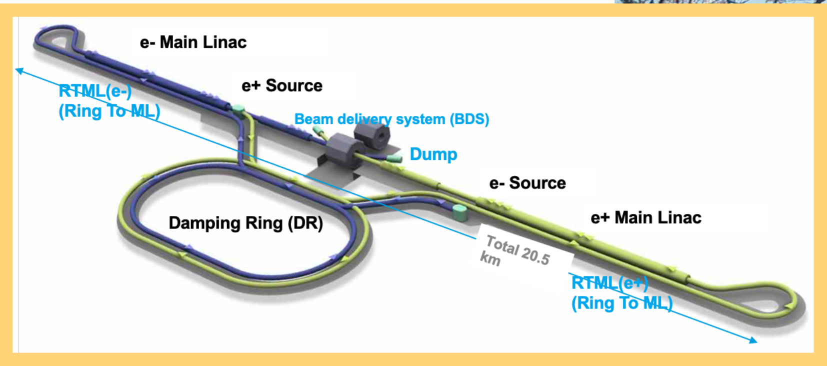

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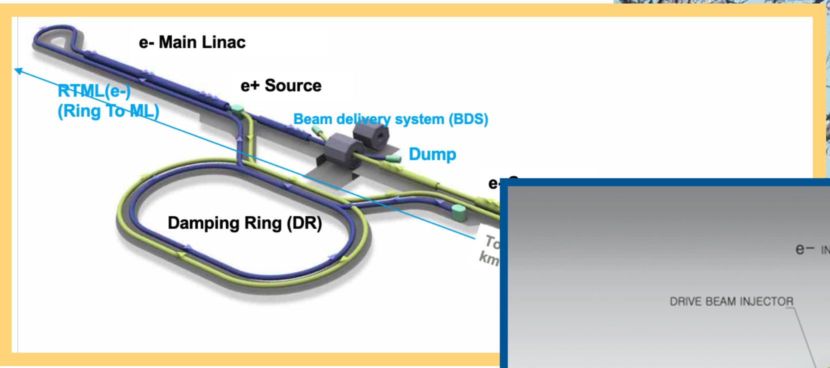

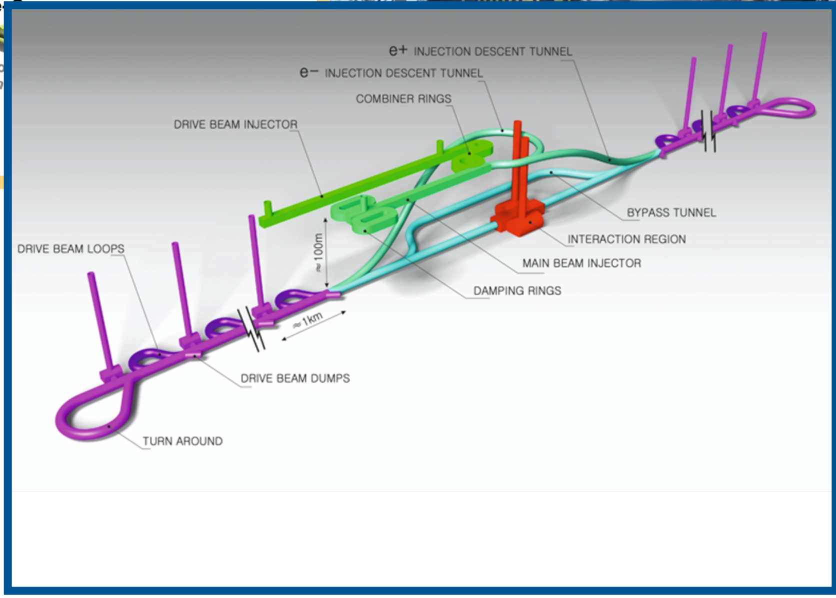

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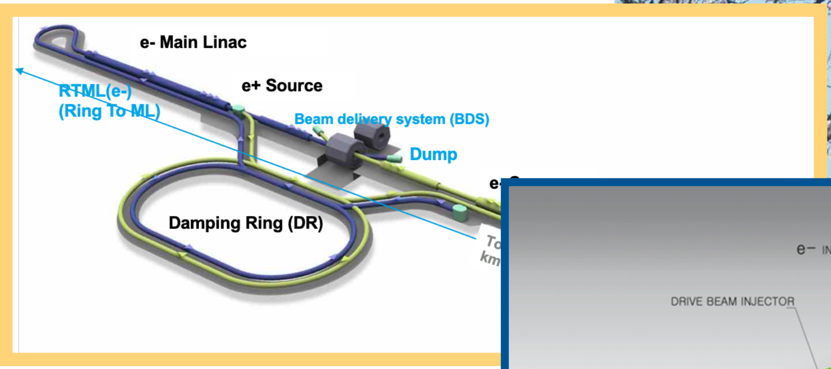

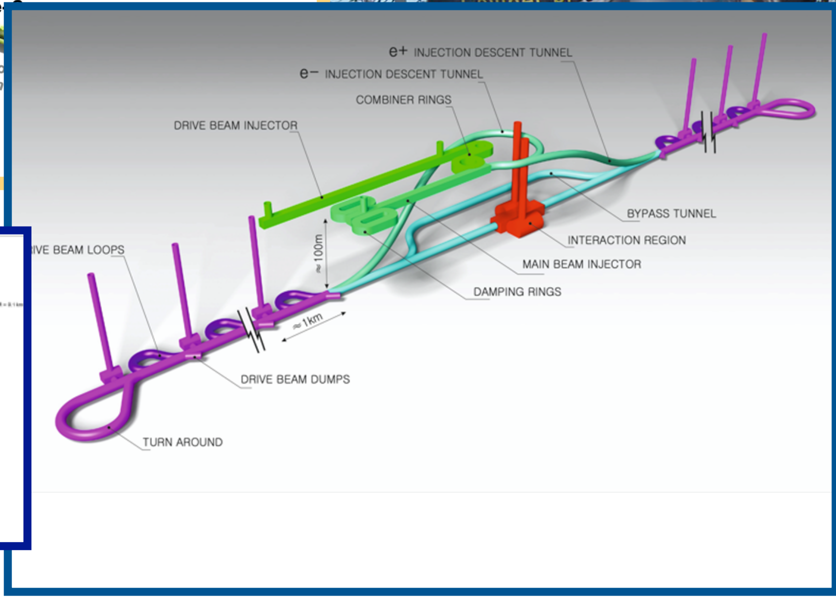

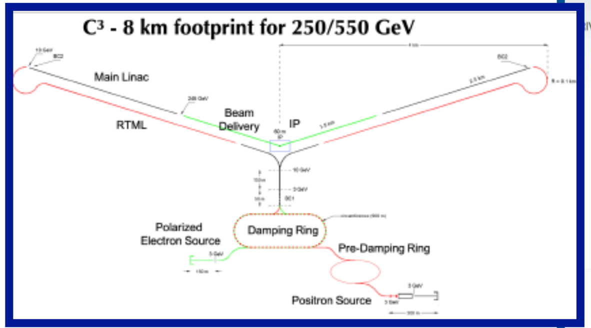

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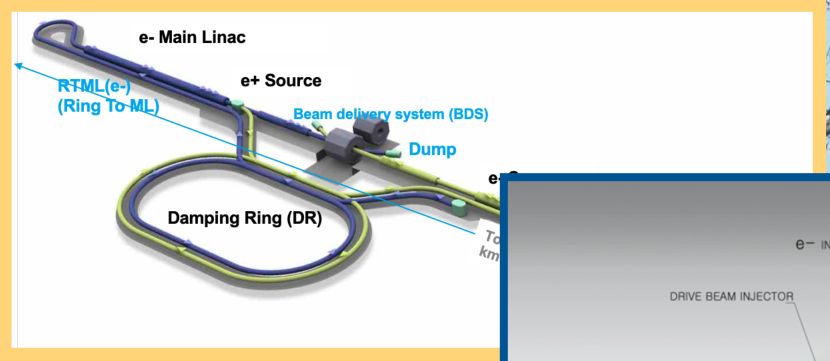

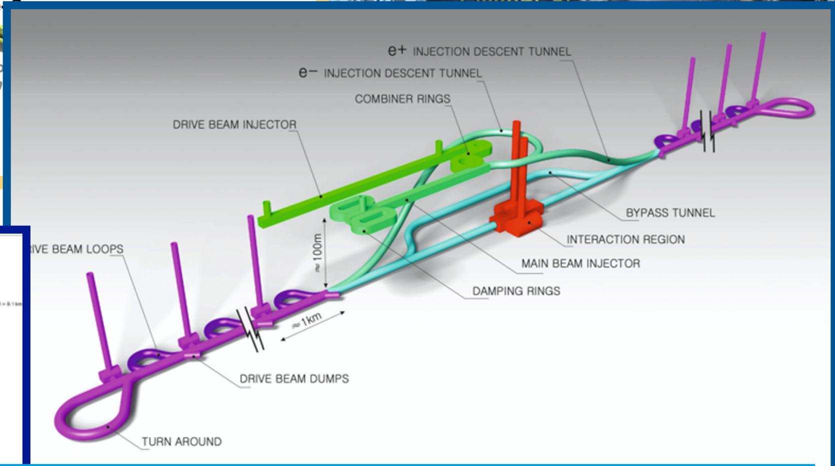

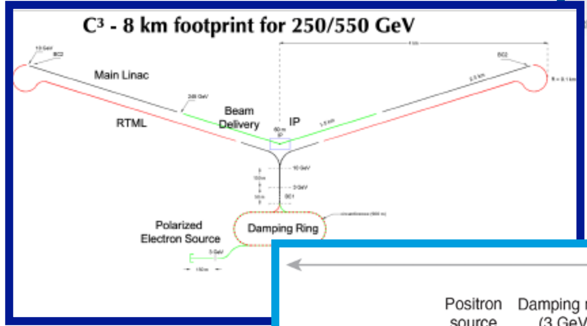

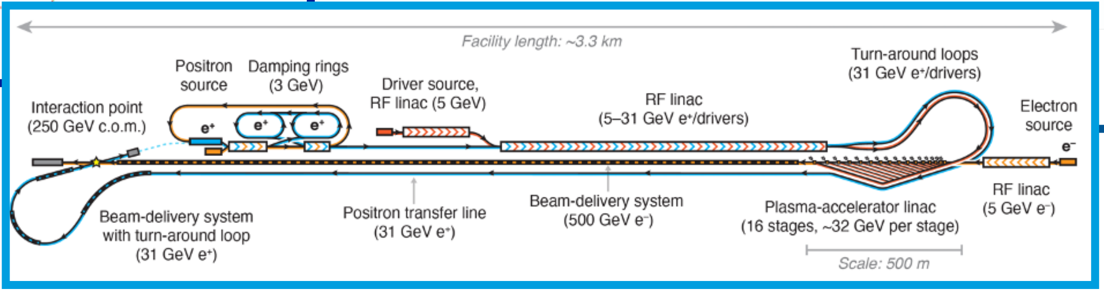

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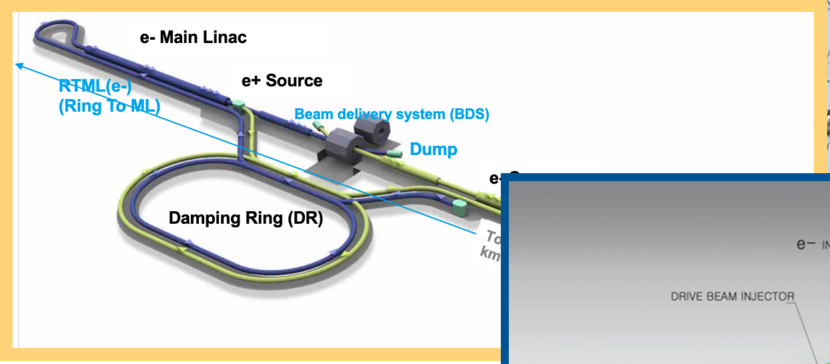
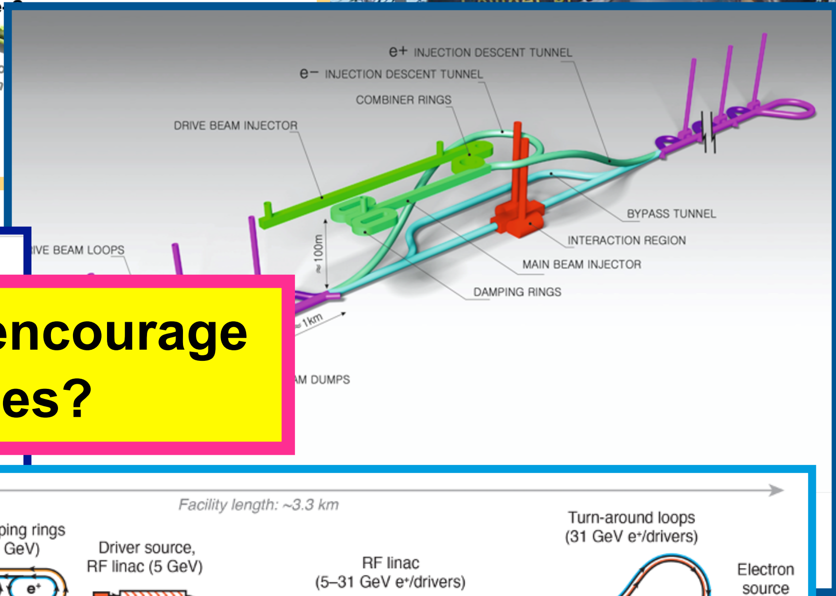
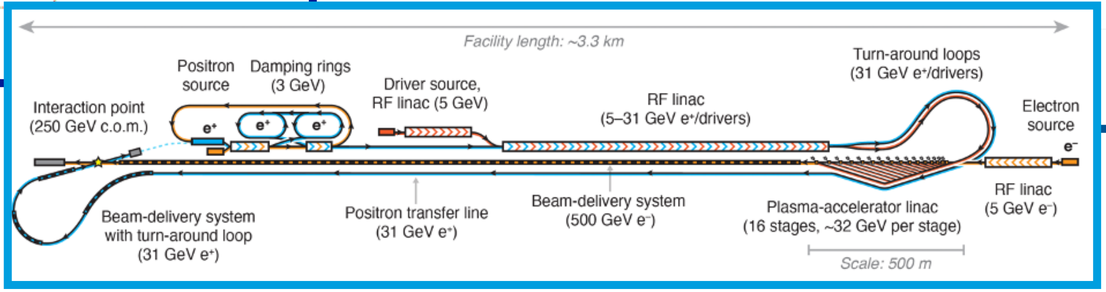




Can we start with ILC-technology NOW — but encourage later upgrades with advanced technologies?



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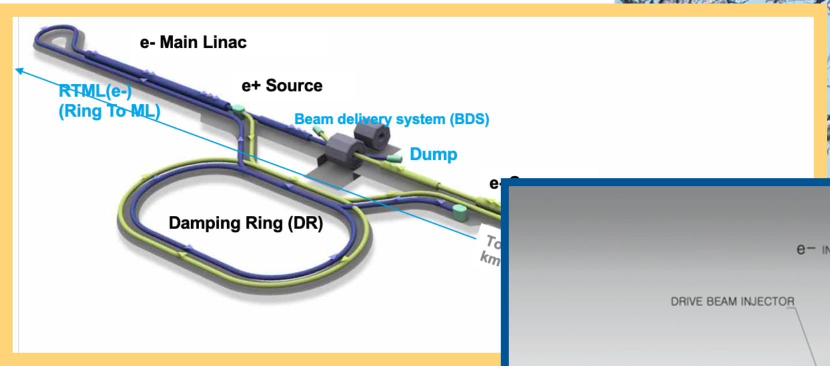
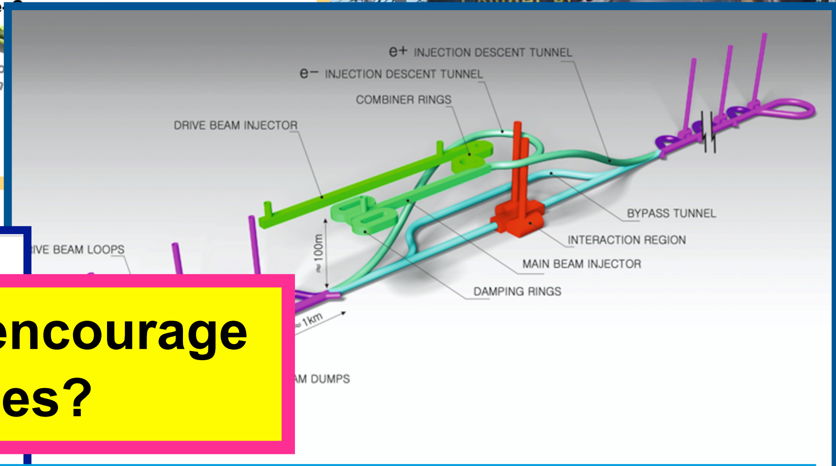
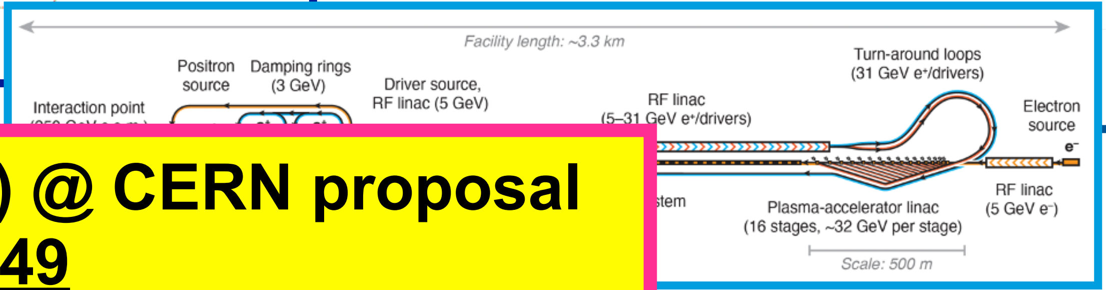






Can we start with ILC-technology NOW — but encourage later upgrades with advanced technologies?

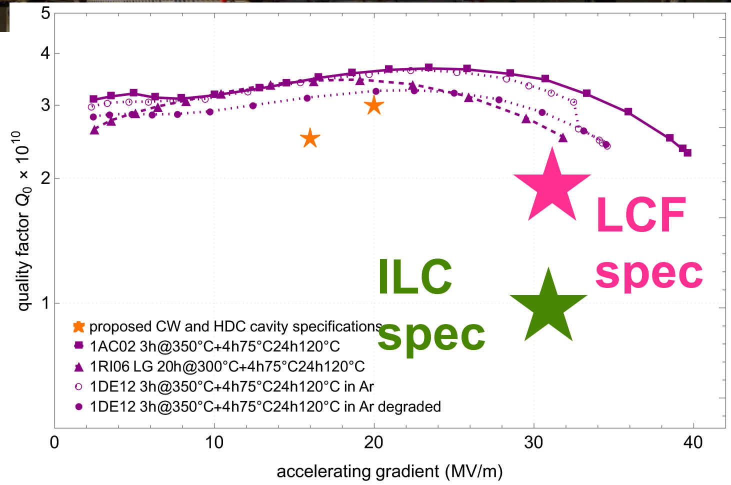
=> Linear Collider Facility (LCF) @ CERN proposal
arxiv:2503.24049

The LCF@CERN Proposal

General Considerations

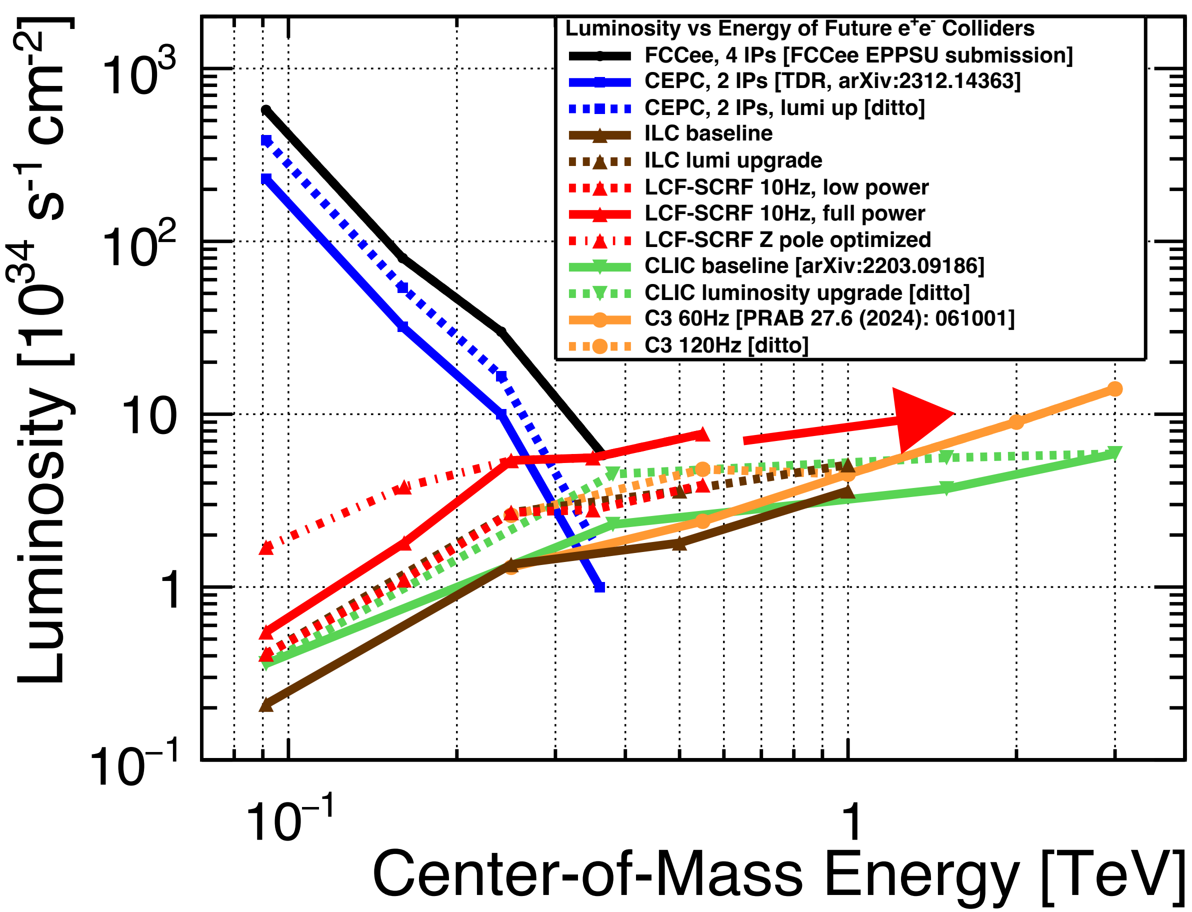
for the LCF@CERN

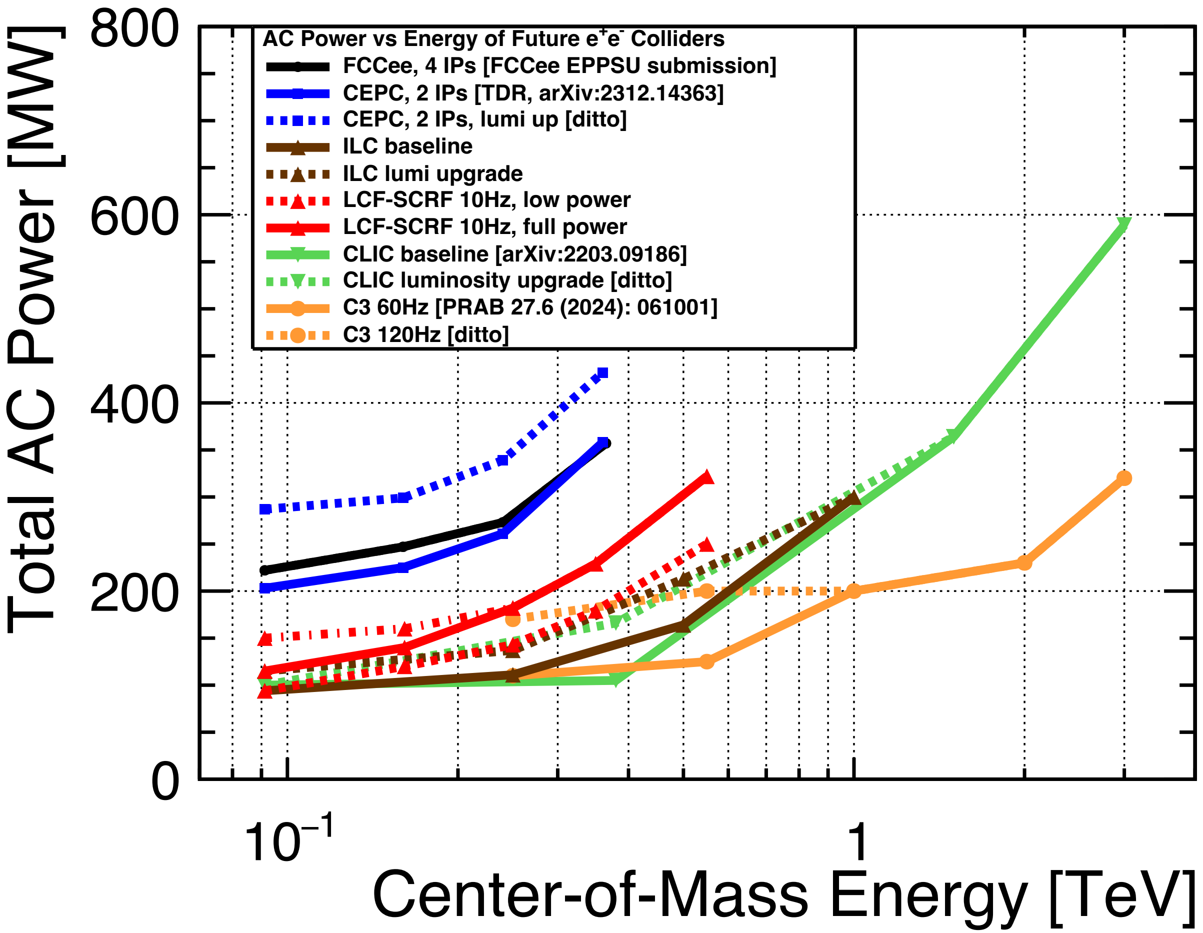
- Philosophy:
  - leverage all the excellent work done for ILC & CLIC in the past
    - reliable costing etc
    - “ready to build”
  - gently modernize to turn into true flagship project for CERN
- Superconducting RF technology (like ILC)
  - successful construction & operation of Eu.XFEL, LCLS-II…
    => 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
  - 2-4x higher luminosity than ILC (power calc. assumes Q_0=2E10)
  - add-on facilities (Beyond Collider, R&D / irradiation facilities)
  - attaractive upgrade perspectives with advanced technologies
  - but stay affordable (constr. and op.) wrt to CERN budget



Luminosity and Power Consumption

For LCF-SCRF and other e+e- colliders





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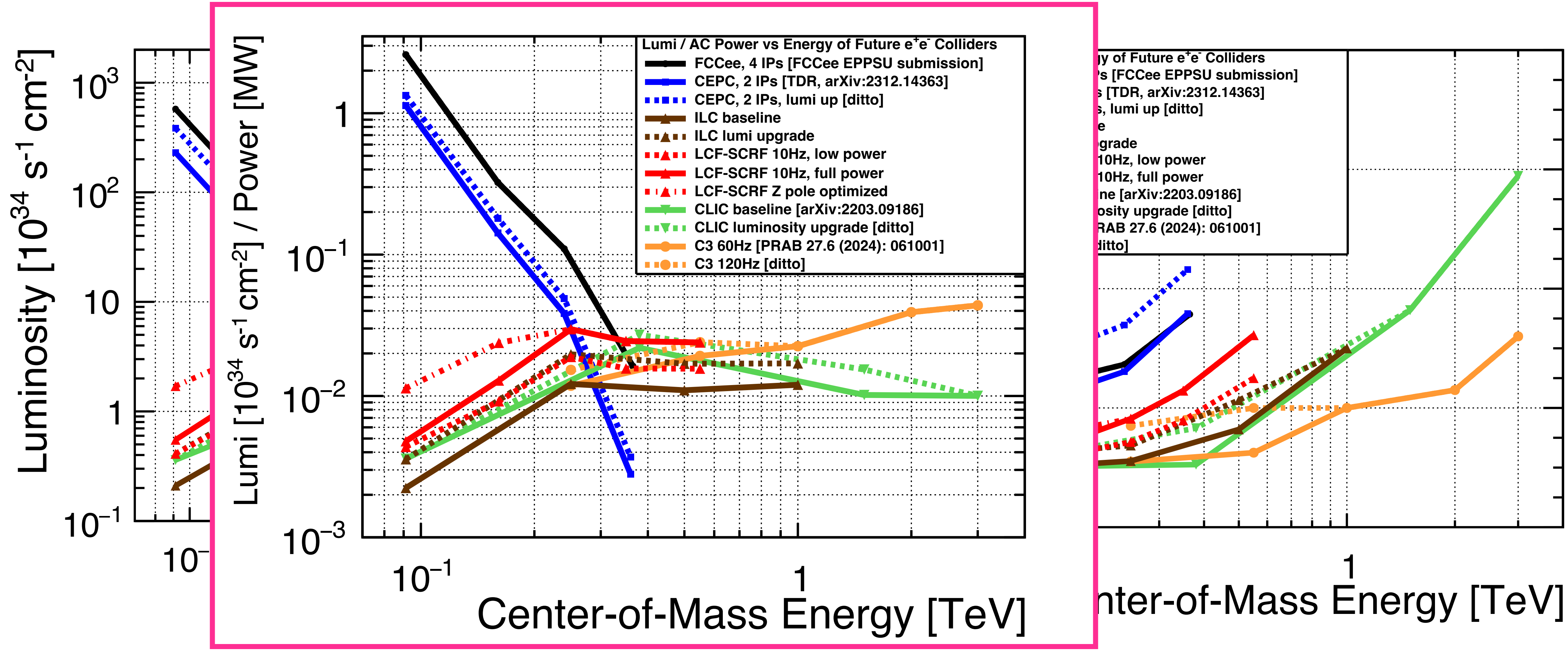
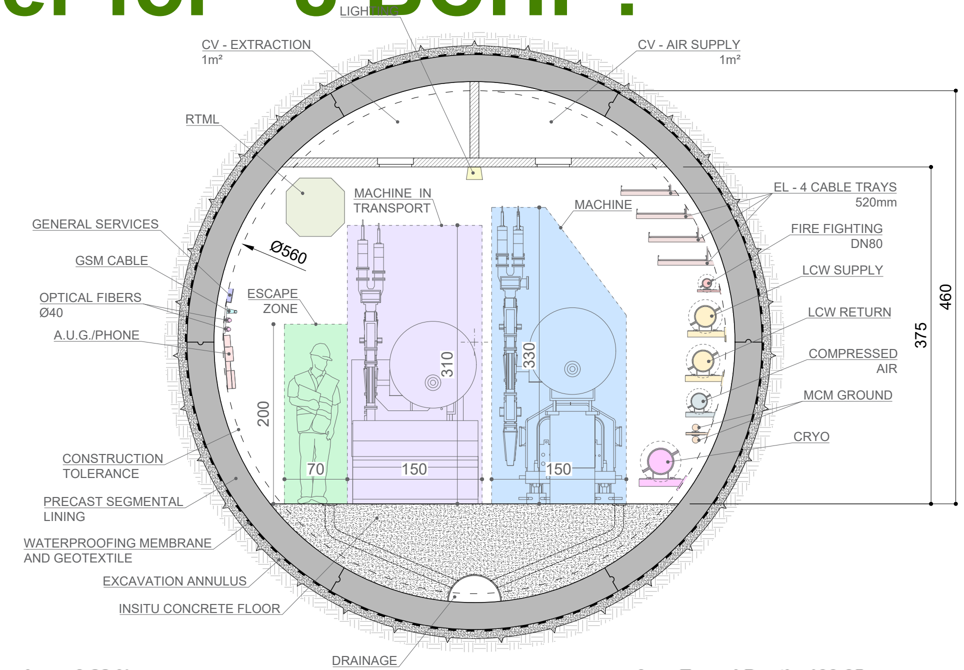
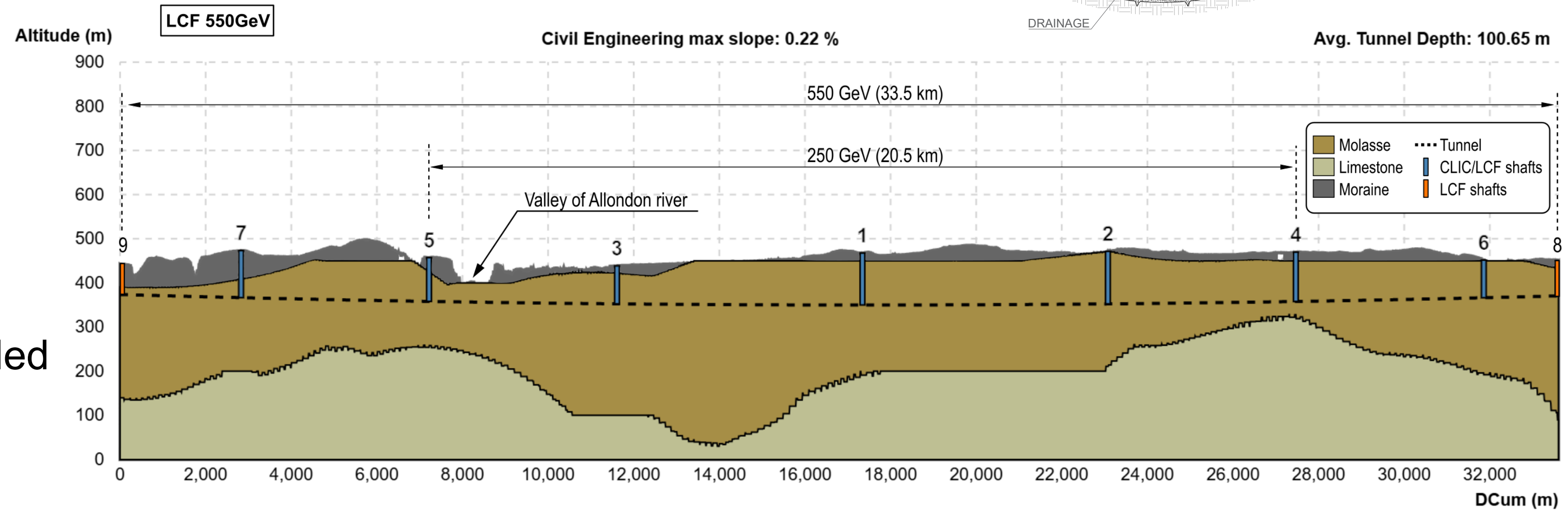


The first stage - or what can LCF offer for ~8 BCHF?

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} / cm² / 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

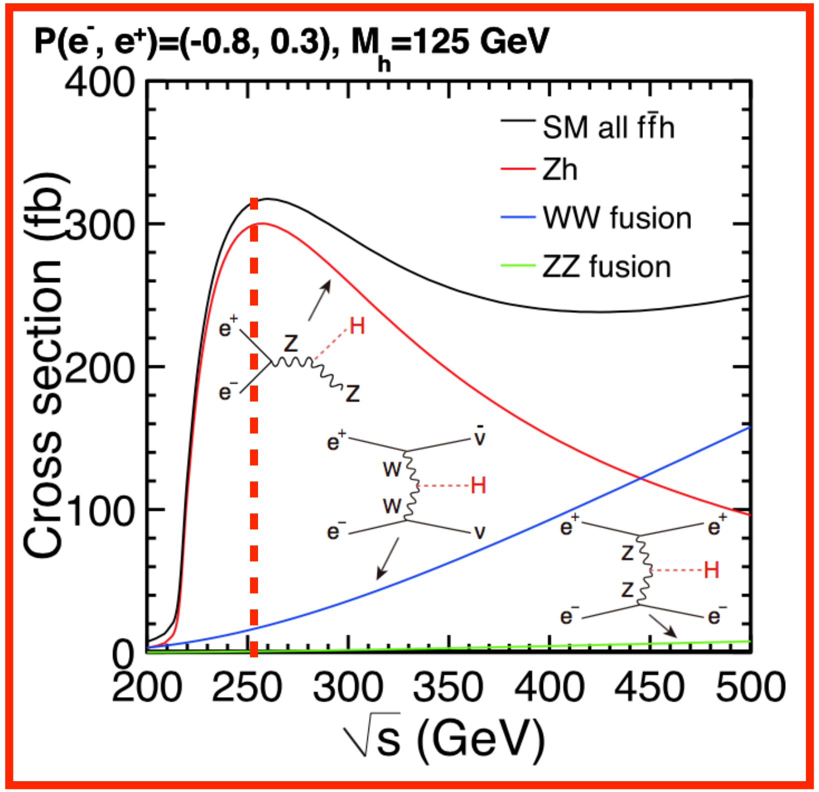




The first stage

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)



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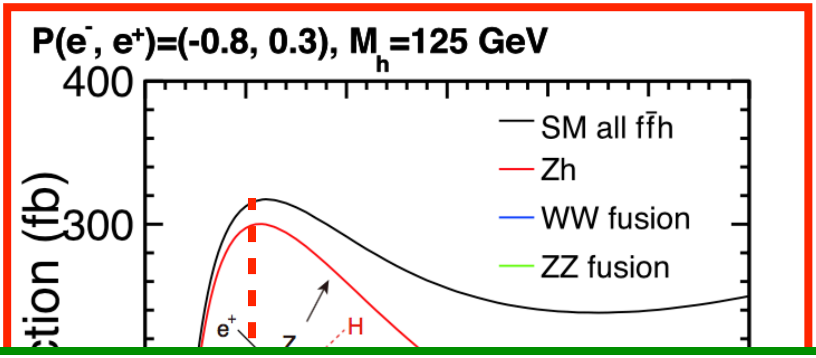
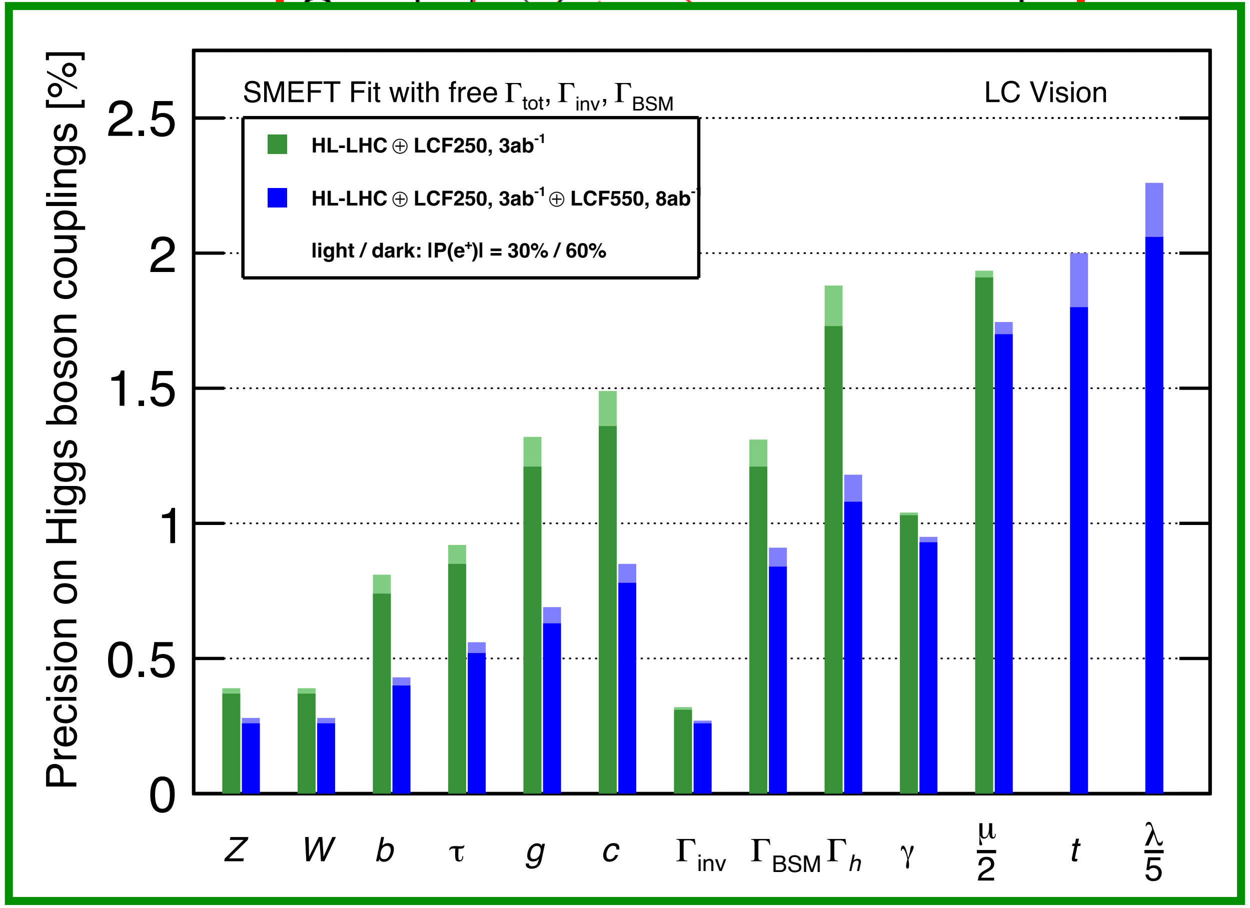


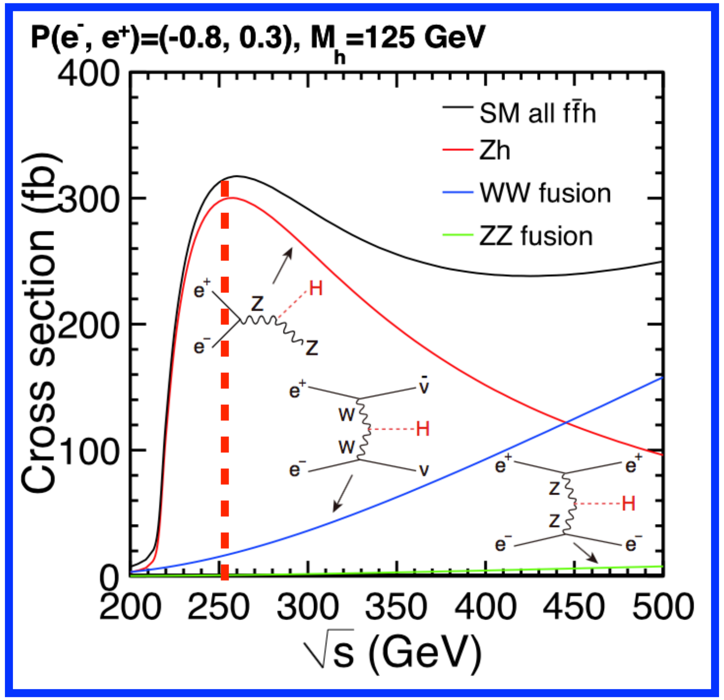


The second stage

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

      - for any value of λ !



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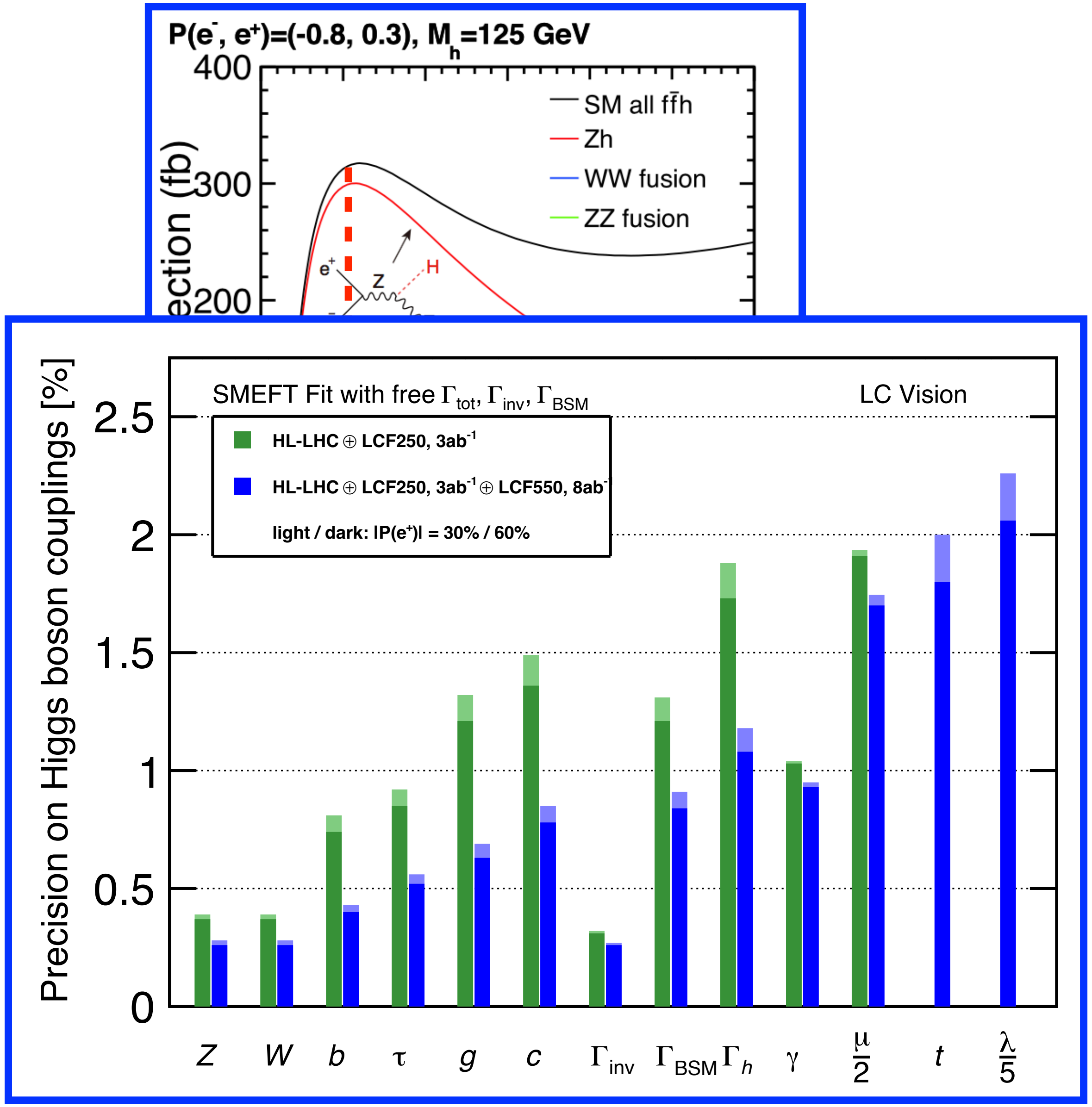


Di-Higgs Production

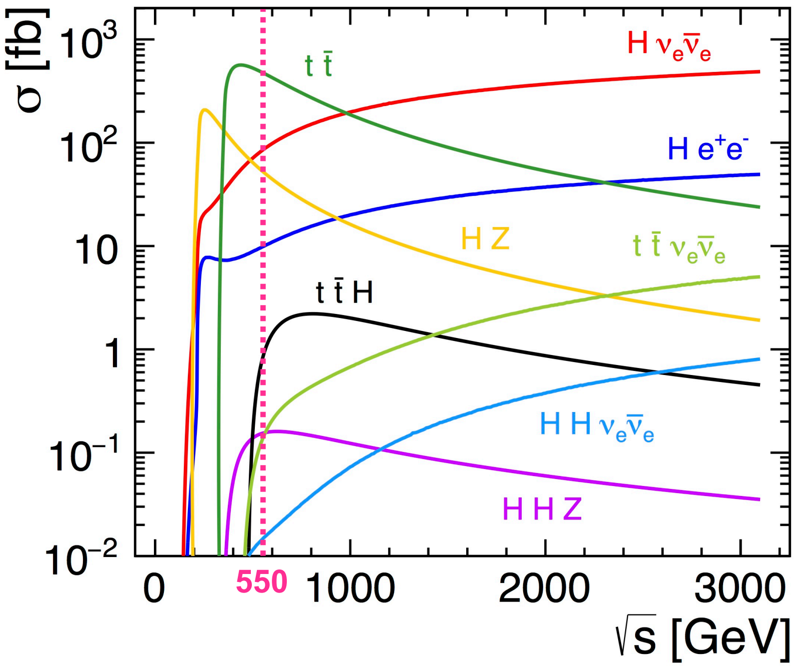
tree-level access to self-coupling

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

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

- **1-3 TeV:** **vvHH** becoming dominant
  - $\Delta\kappa_\lambda$ = **0.04** (8ab-1) over wide range of κ_λ (except κ_λ ~ 1.5)

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



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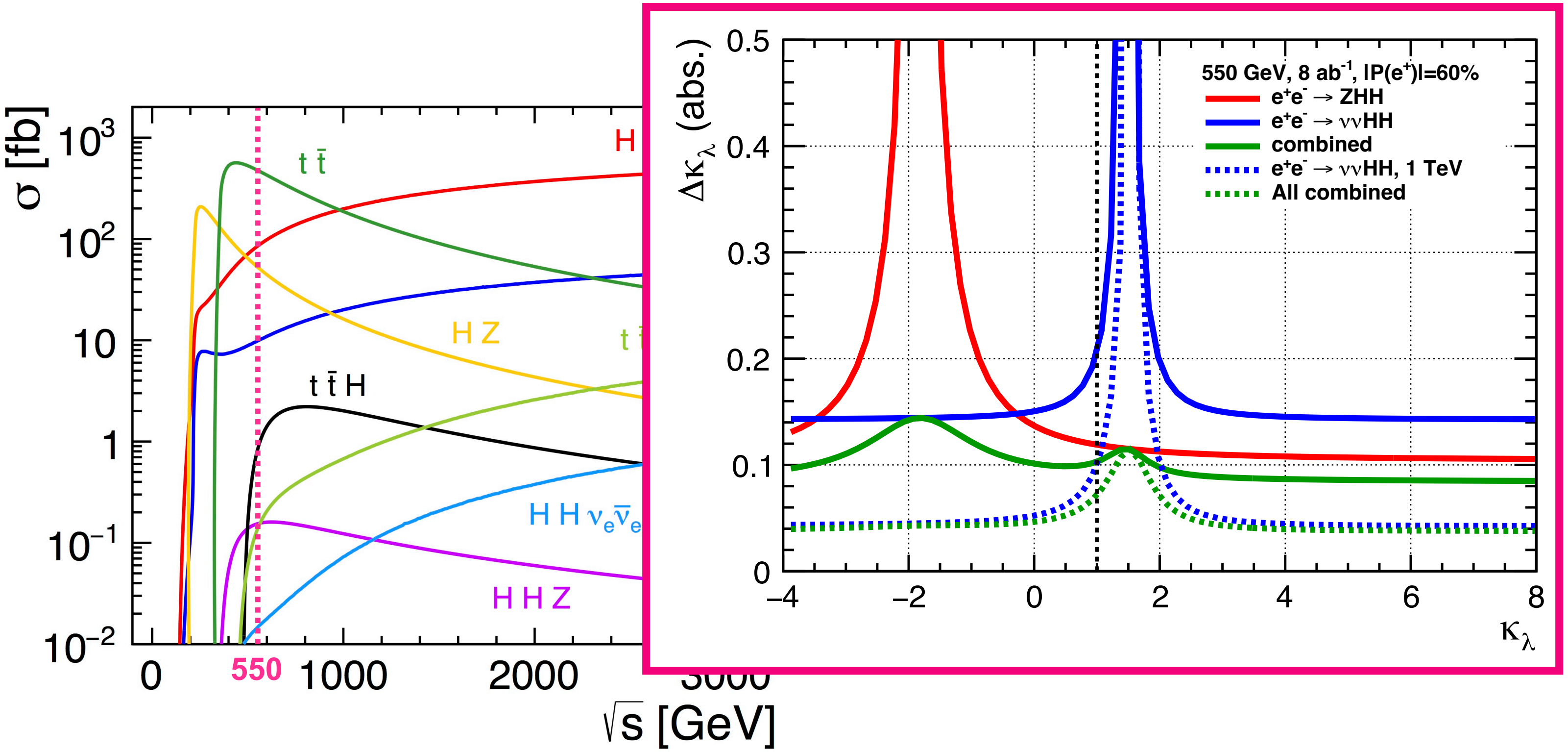

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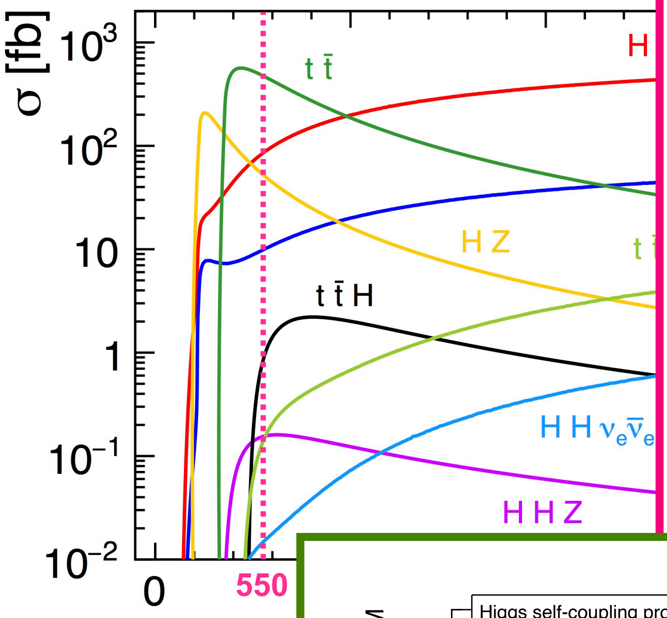

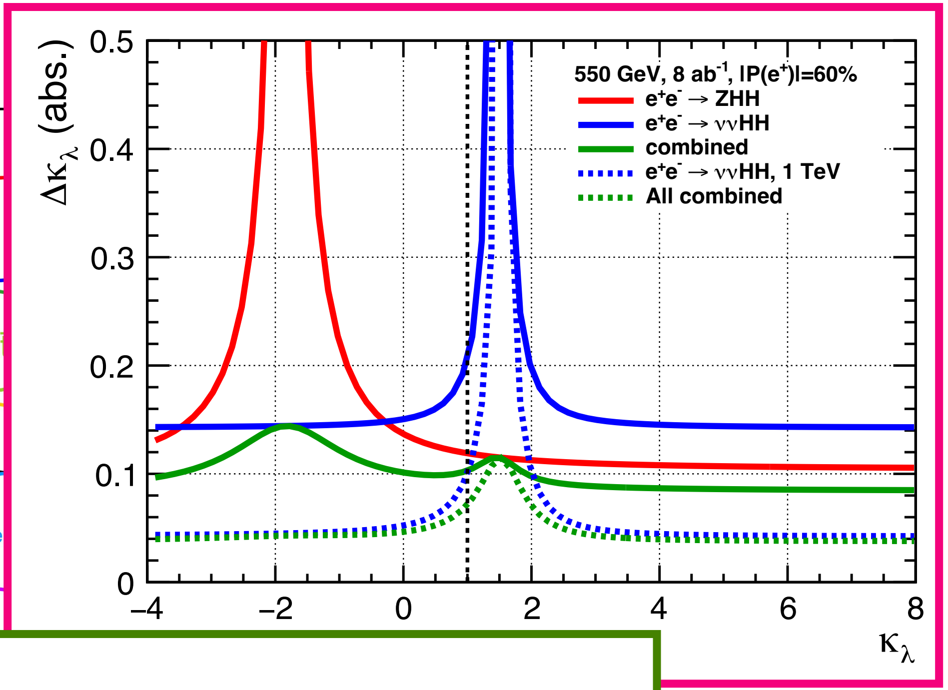

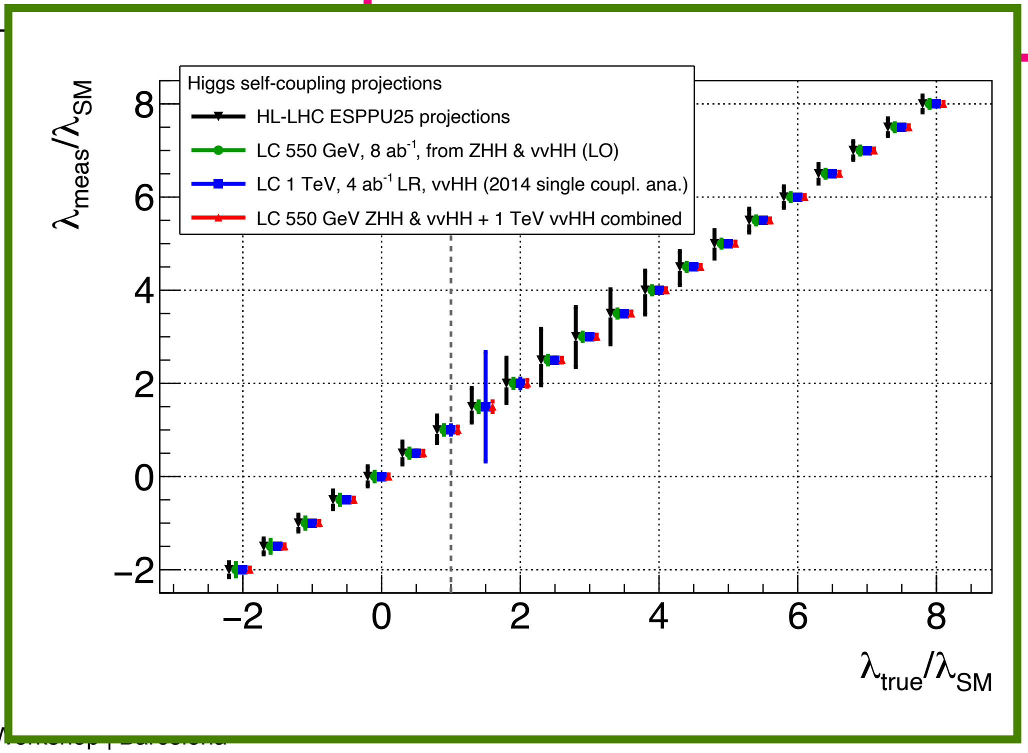

Di-Higgs Production

tree-level access to self-coupling

- **550 GeV**
  - ~ peak of **ZHH** cross-section
  - **ννHH** becomes just about visible
  - together for SM case: $\Delta\kappa_\lambda$ = **11%** (15%) for **8ab^{-1}** (4ab^{-1})
- **dependence on λ:**
  - **ZHH**: **constructive** interference
  - **ννHH**: **destructive** interference
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- **1-3 TeV:** **ννHH** becoming dominant
  - $\Delta\kappa_\lambda$ = **0.04** (8ab-1) over wide range of κ_λ (except κ_λ ~ 1.5)
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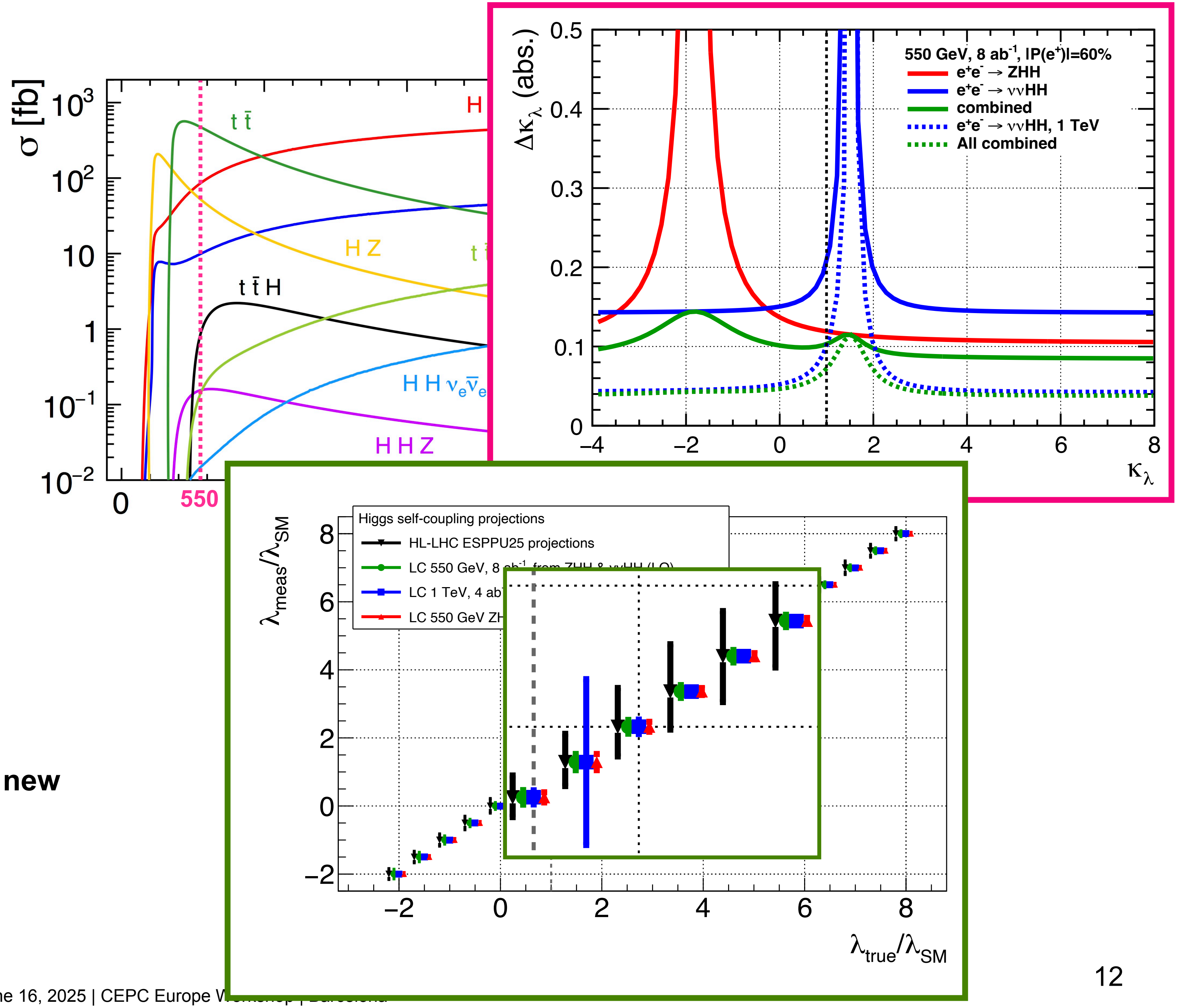

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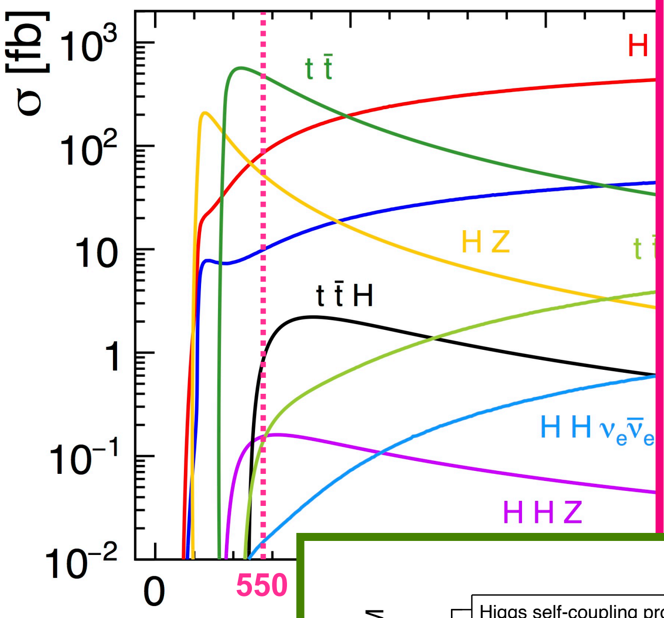

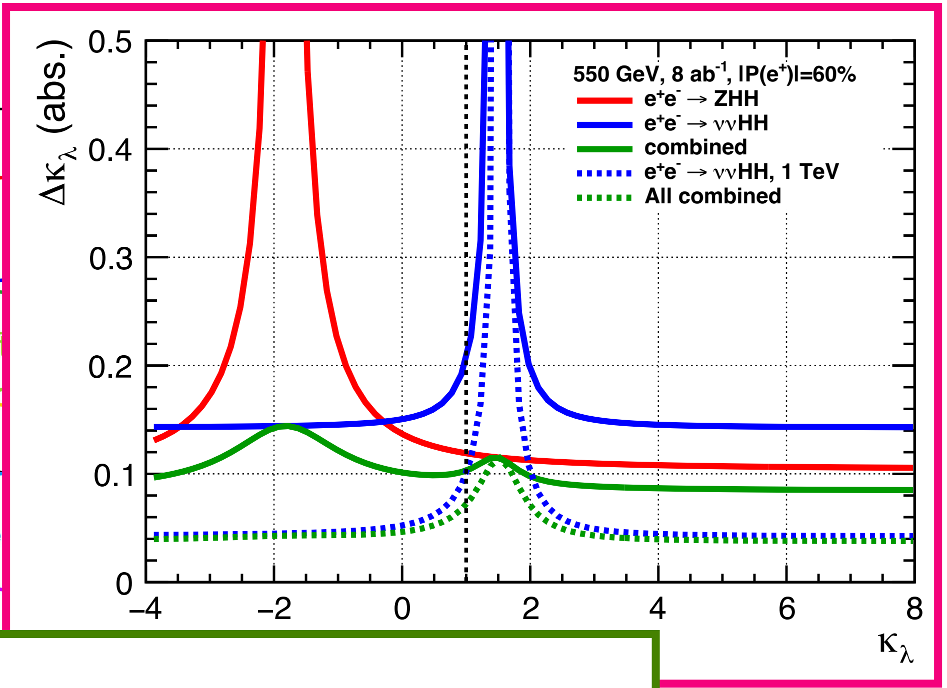

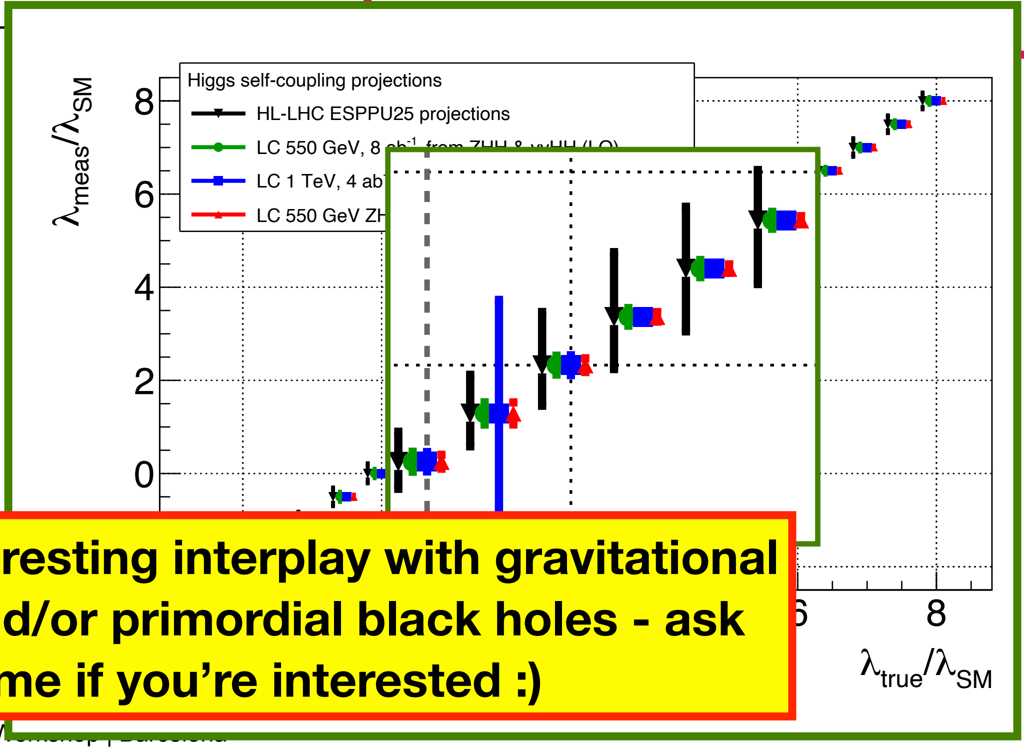

EWPT: Interesting interplay with gravitational waves and/or primordial black holes - ask me if you're interested :)

Higher energies offer so much more

Example: top physics

- **tt threshold ~350 GeV:**
  - threshold mass => exp. stat. uncetainty negligible after ~100fb^{-1}
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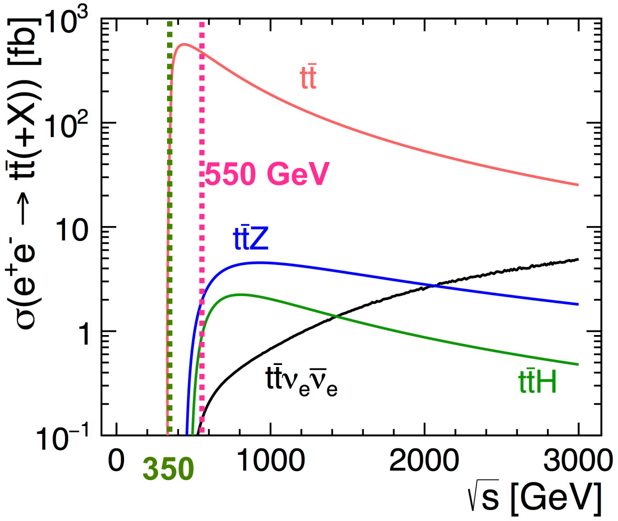

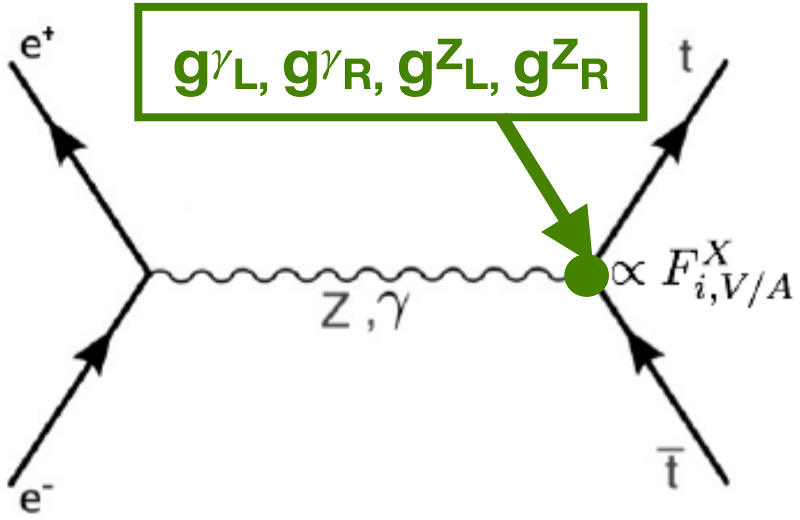

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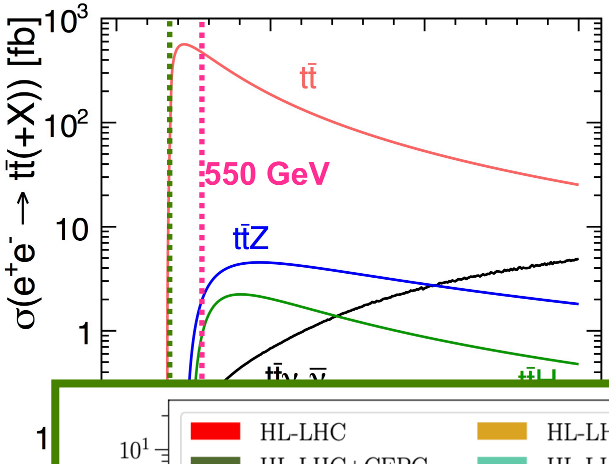

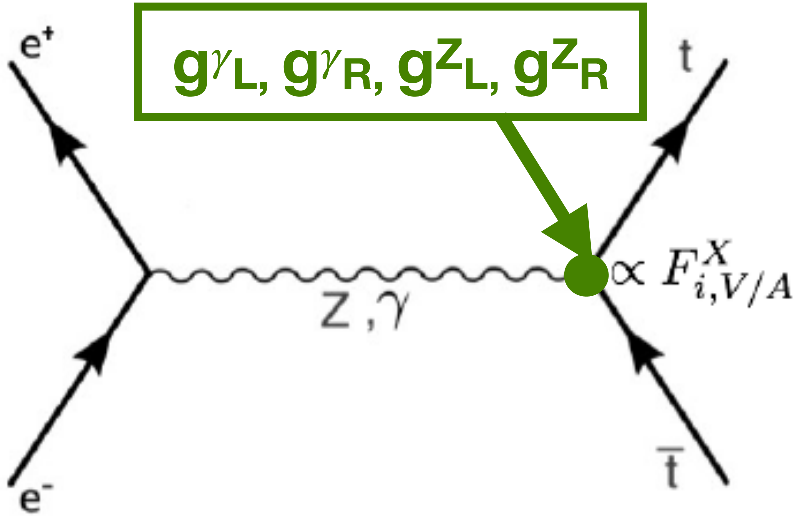

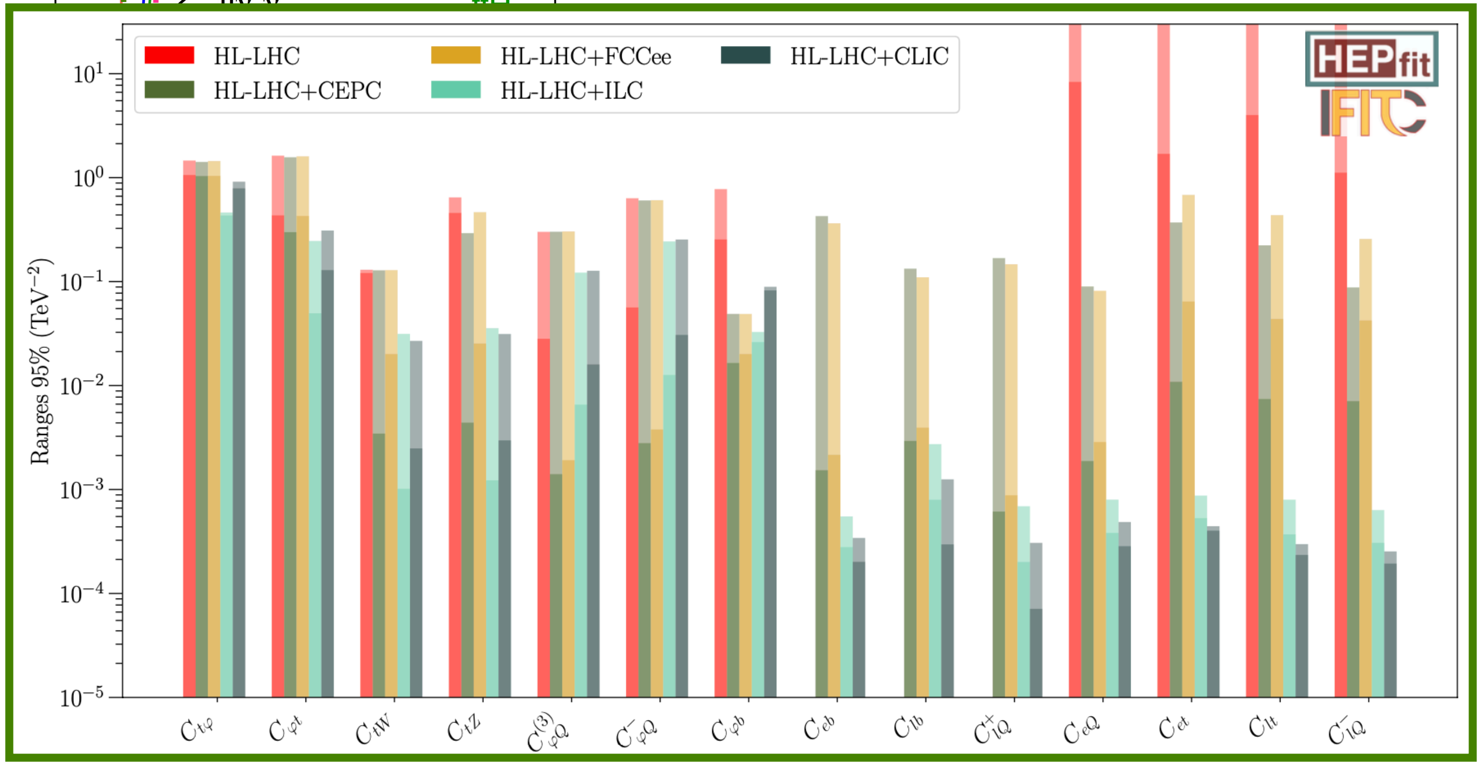

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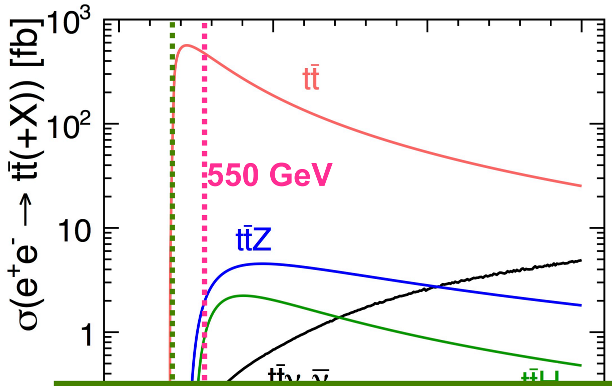

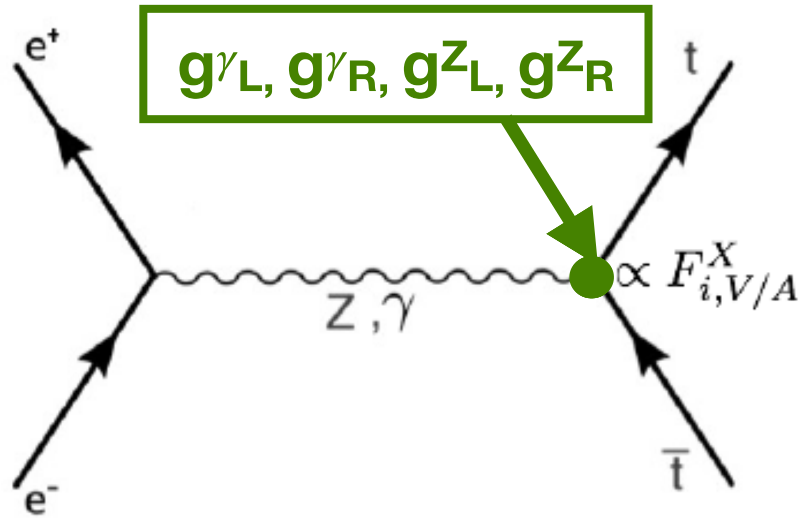

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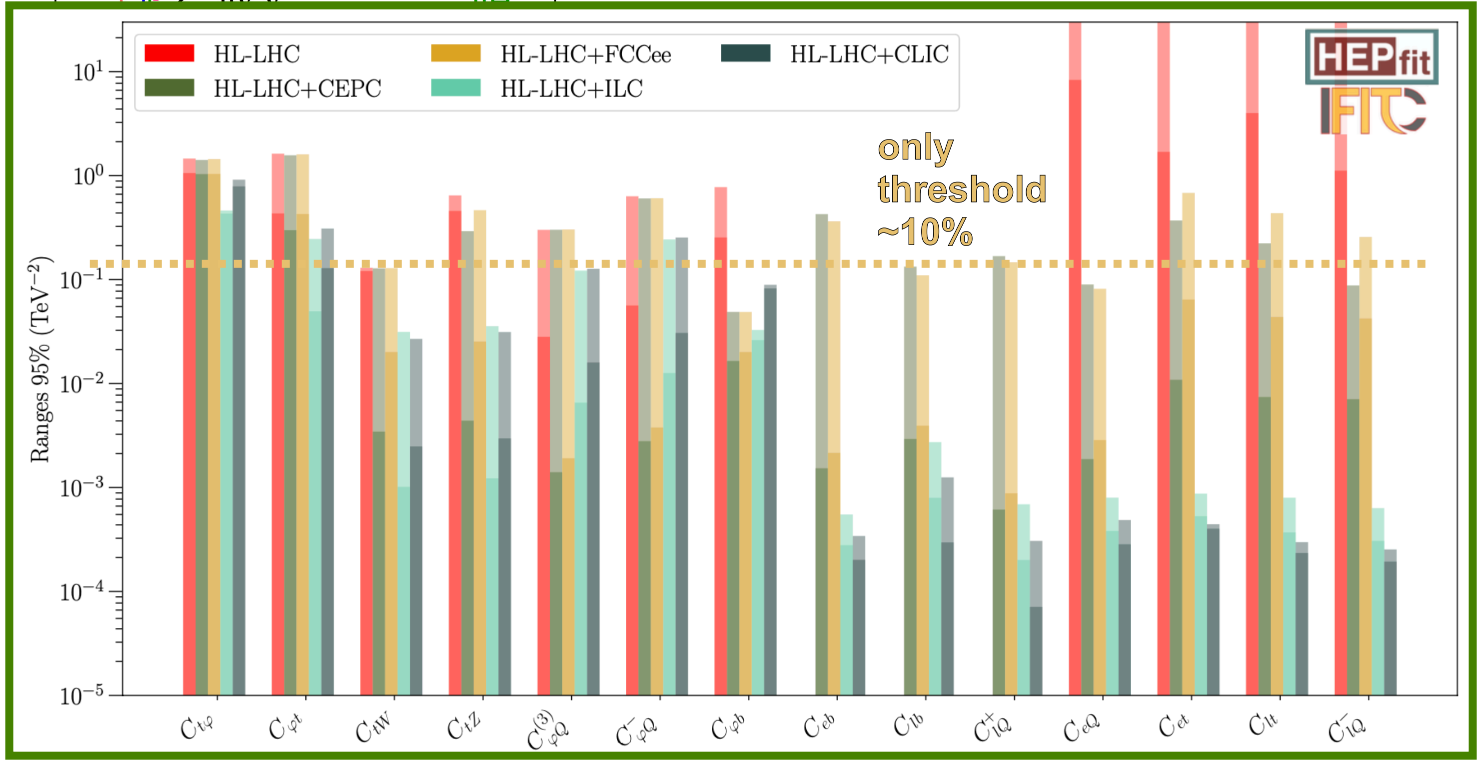

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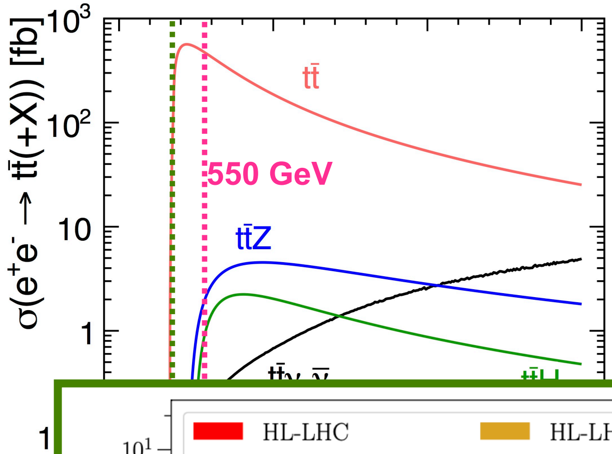
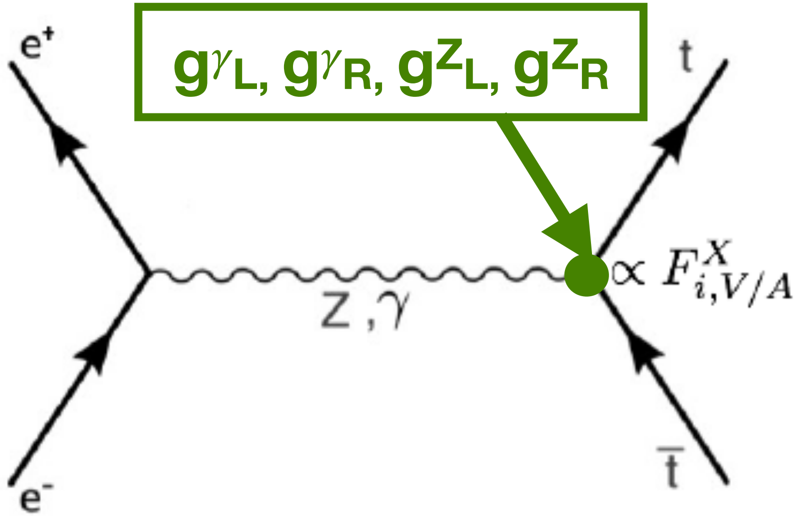
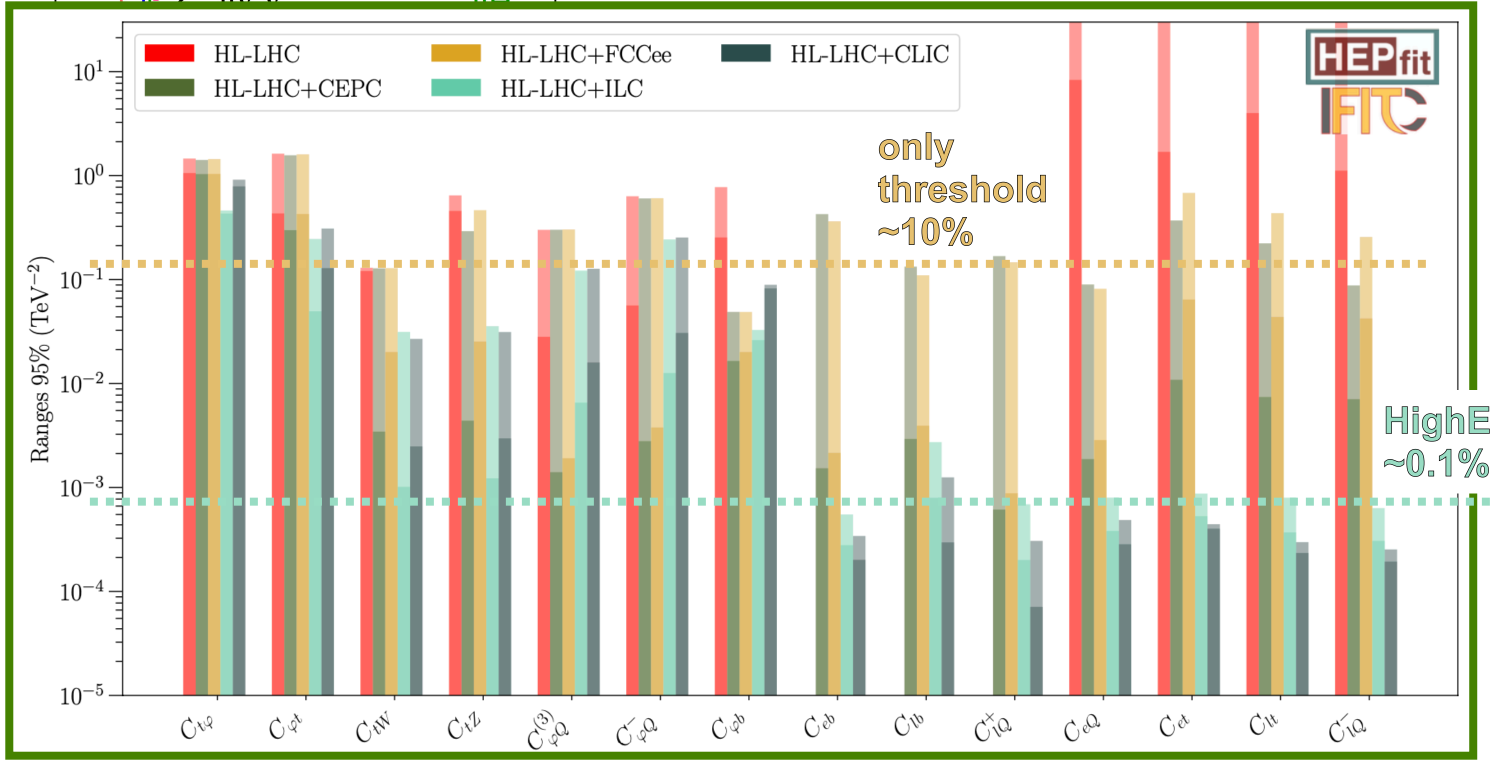




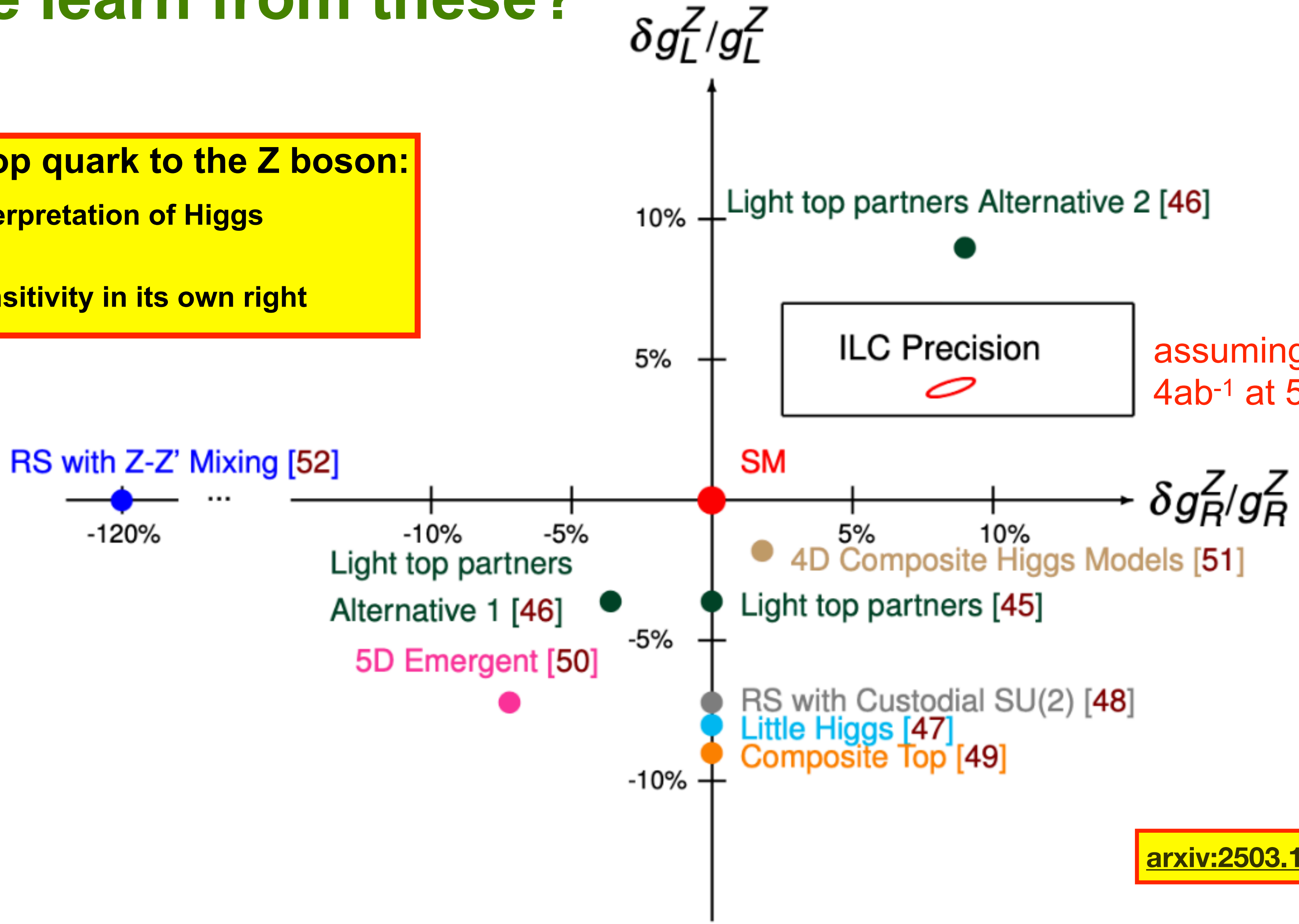


What do we learn from these?

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**

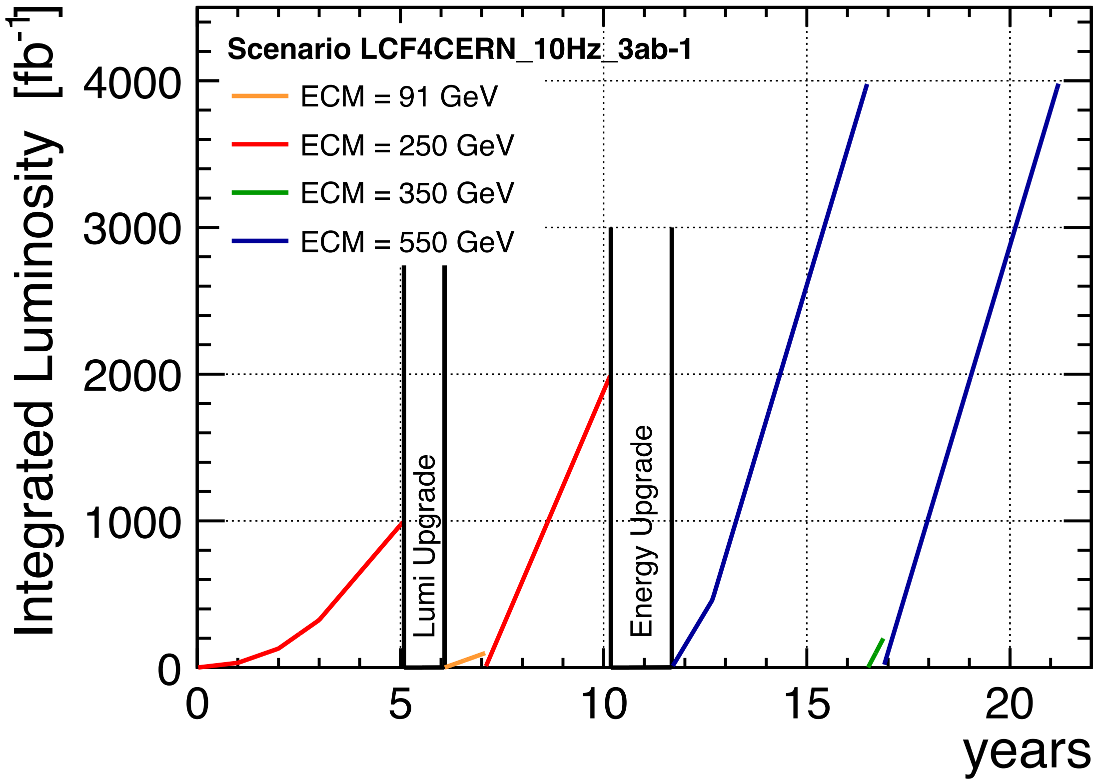


assuming only $4ab^{-1}$ at 500 GeV

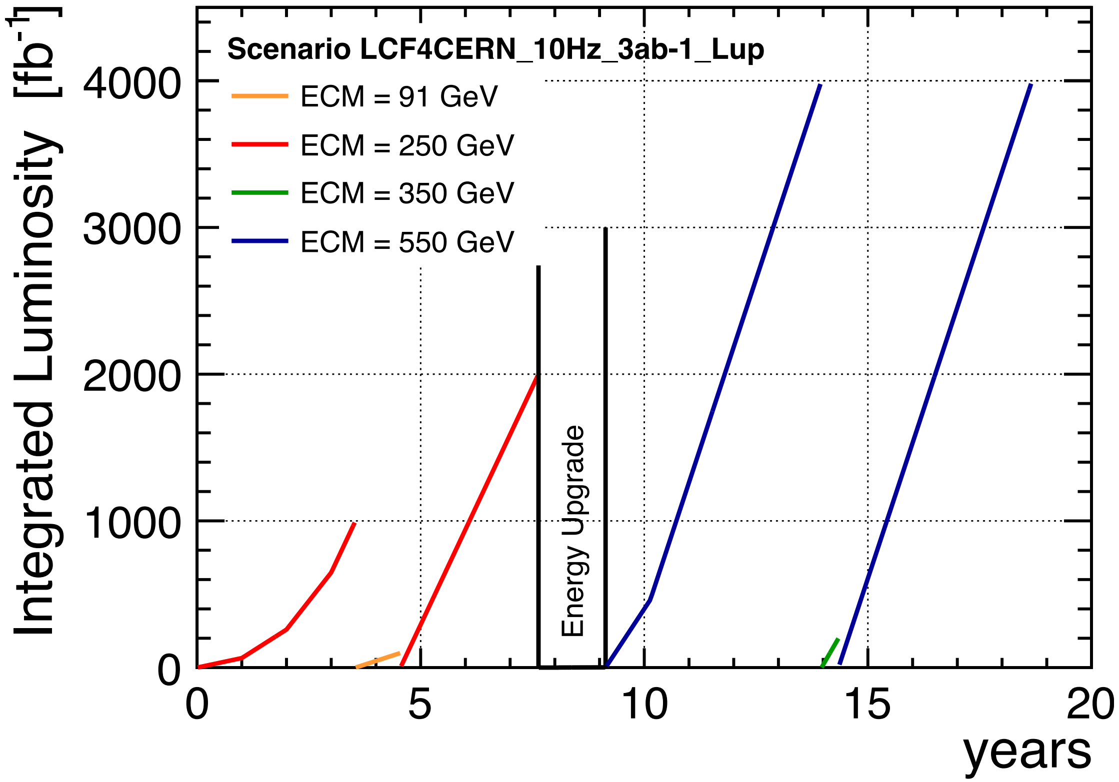
arxiv:2503.19983

Running Scenarios up to 550 GeV

baseline



start immediately with full power



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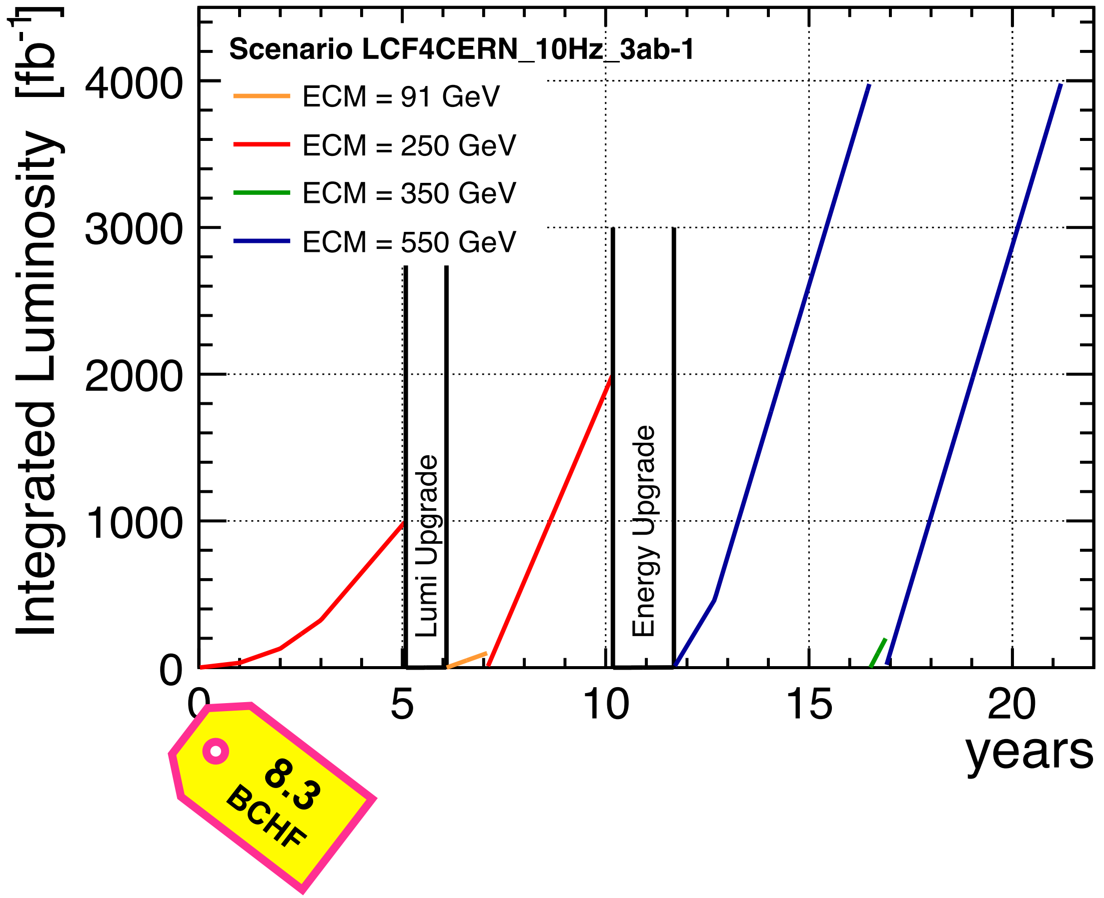

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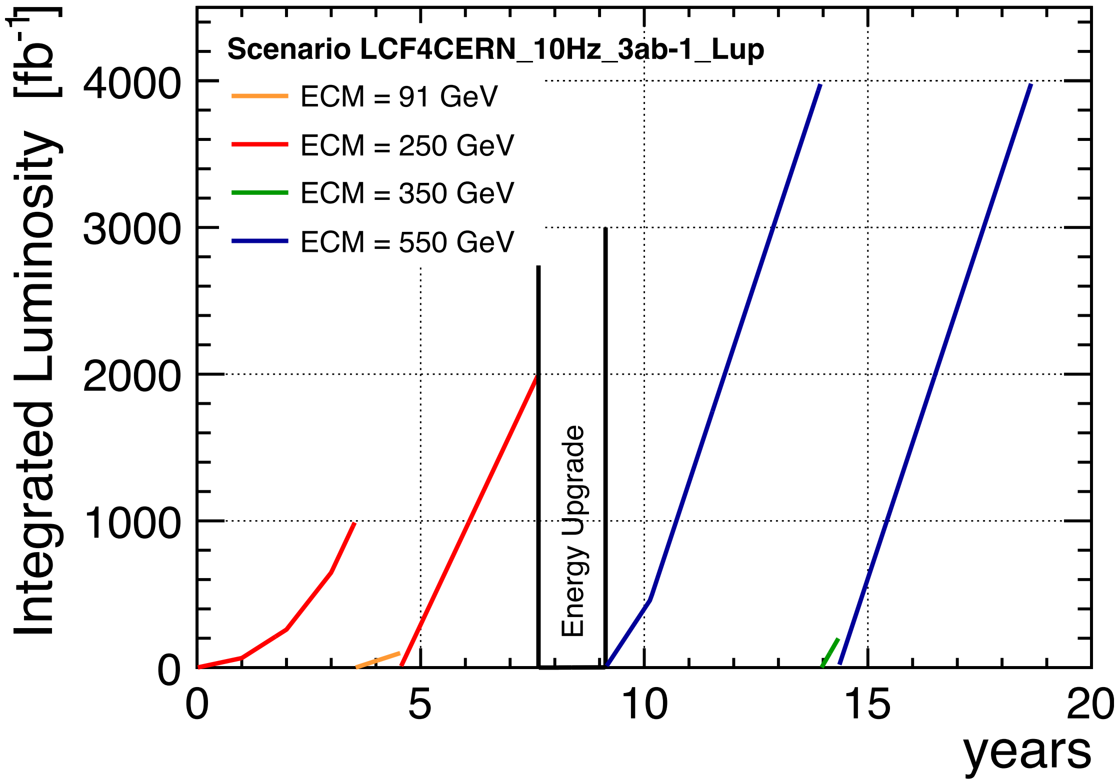

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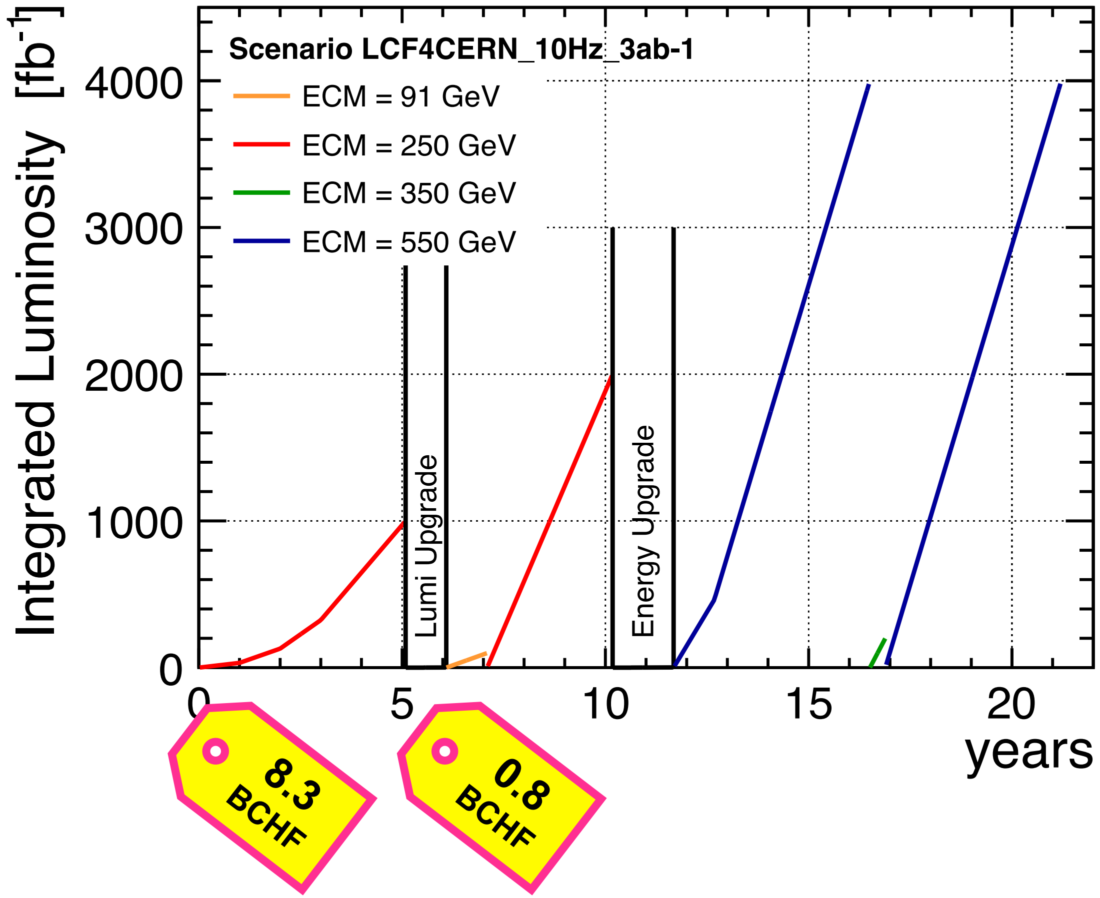

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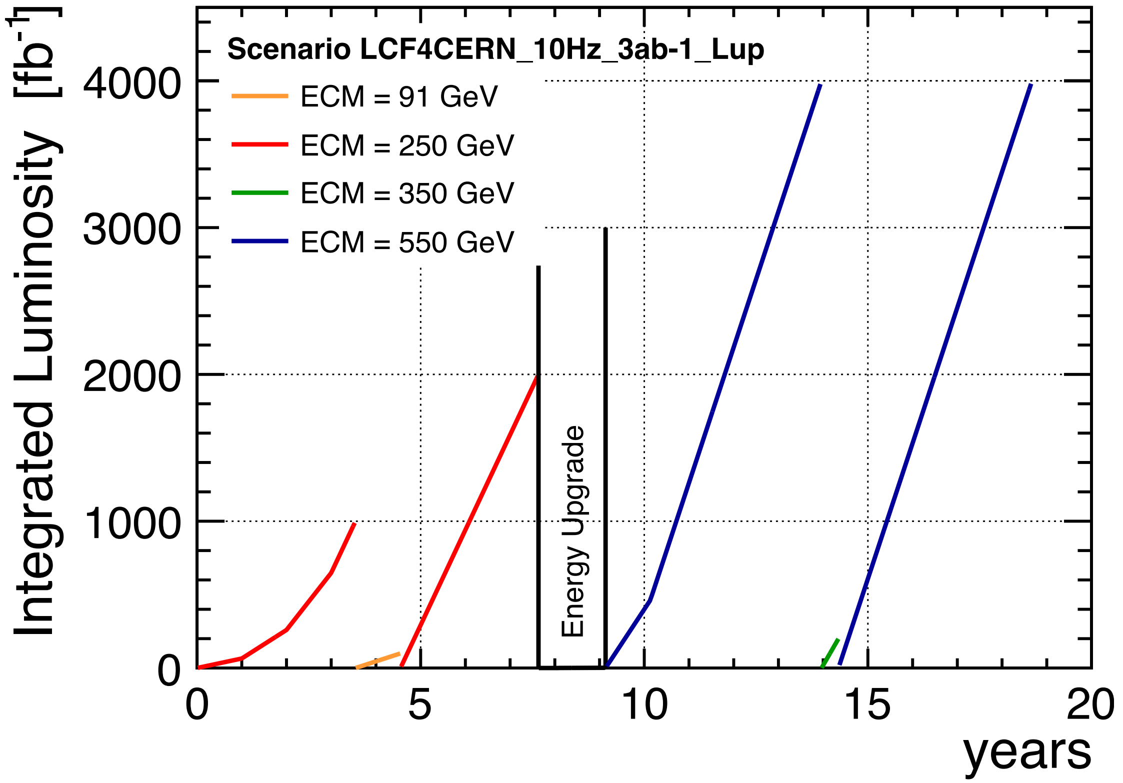

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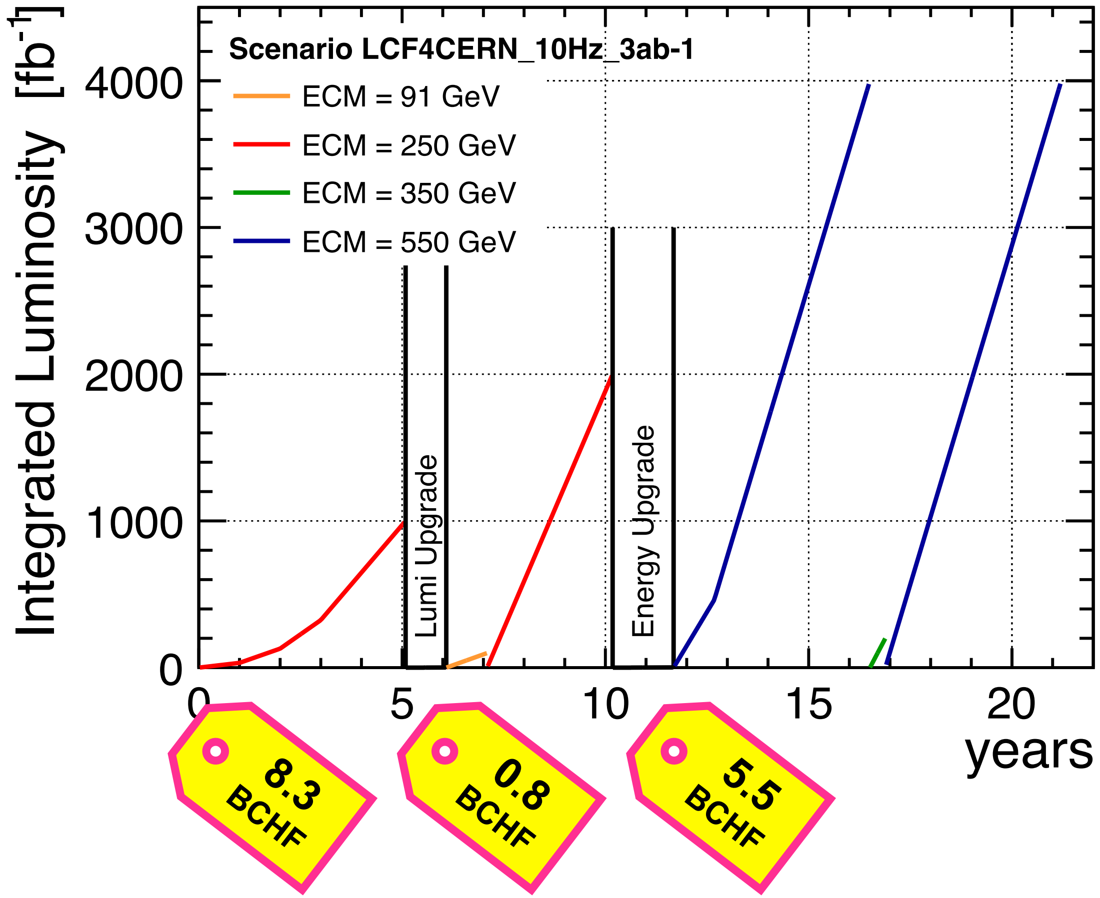

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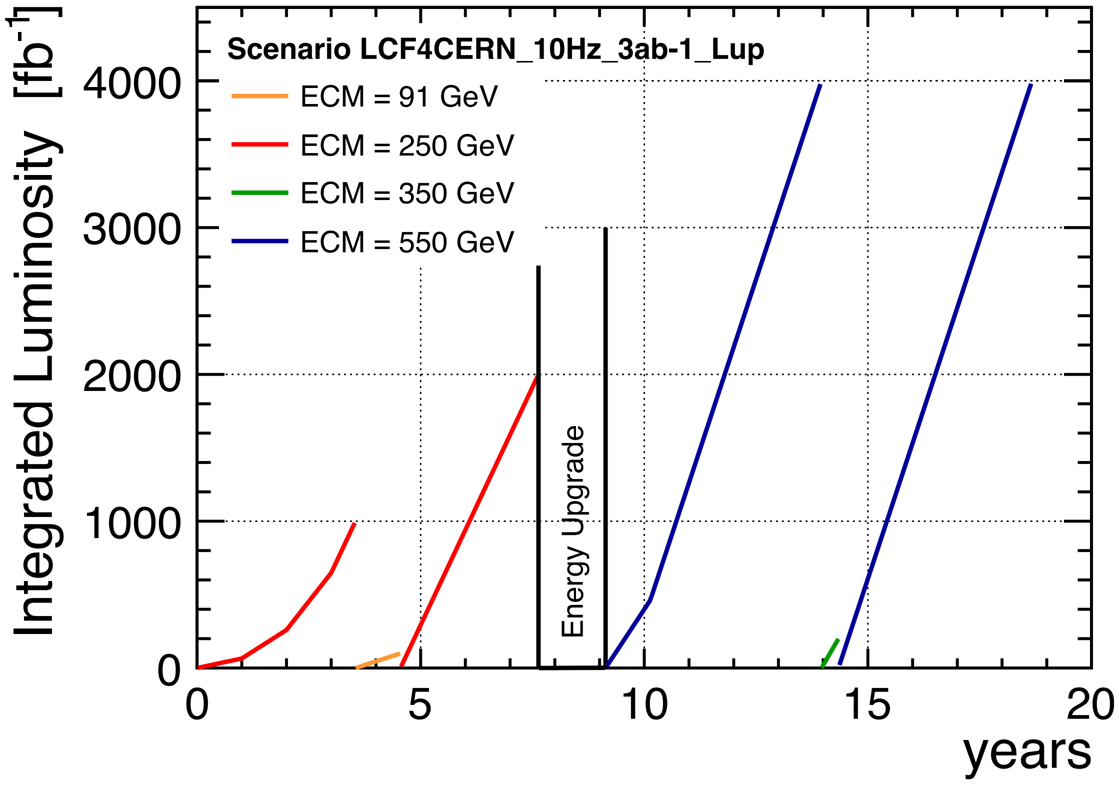

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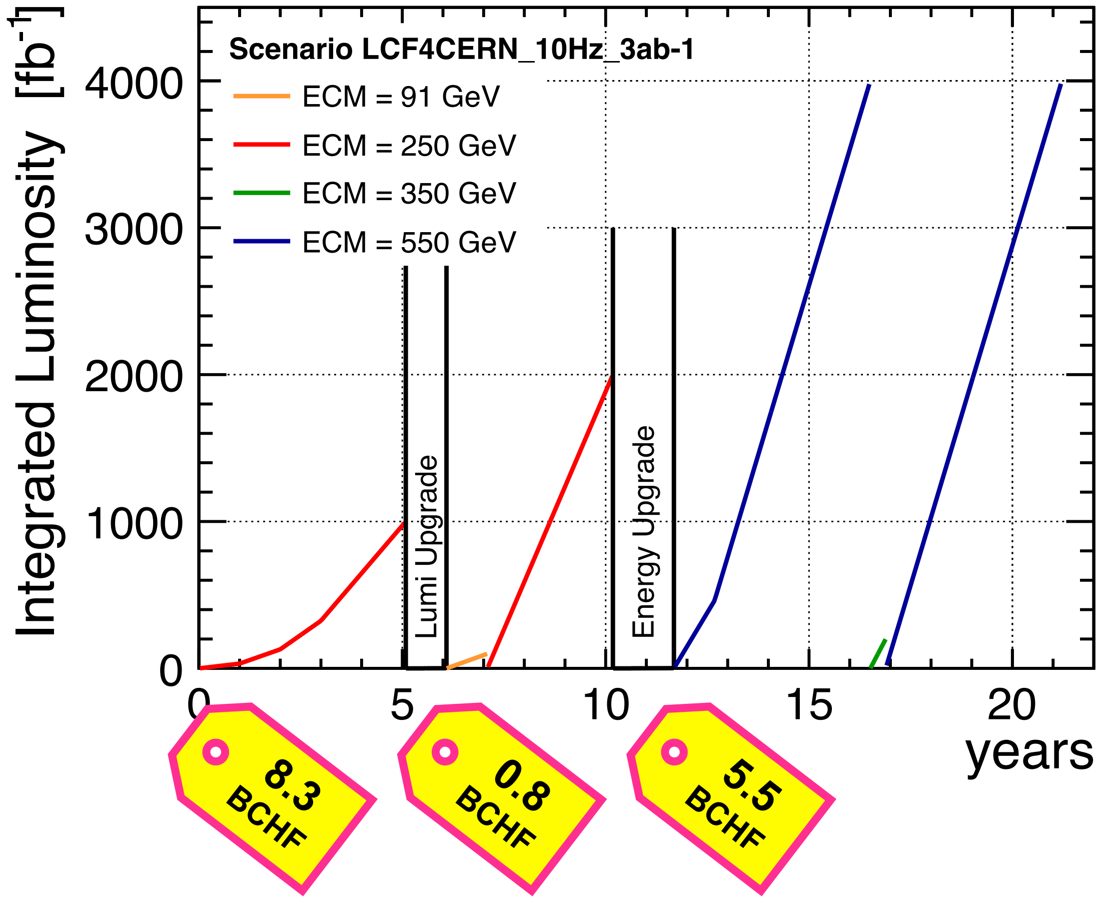

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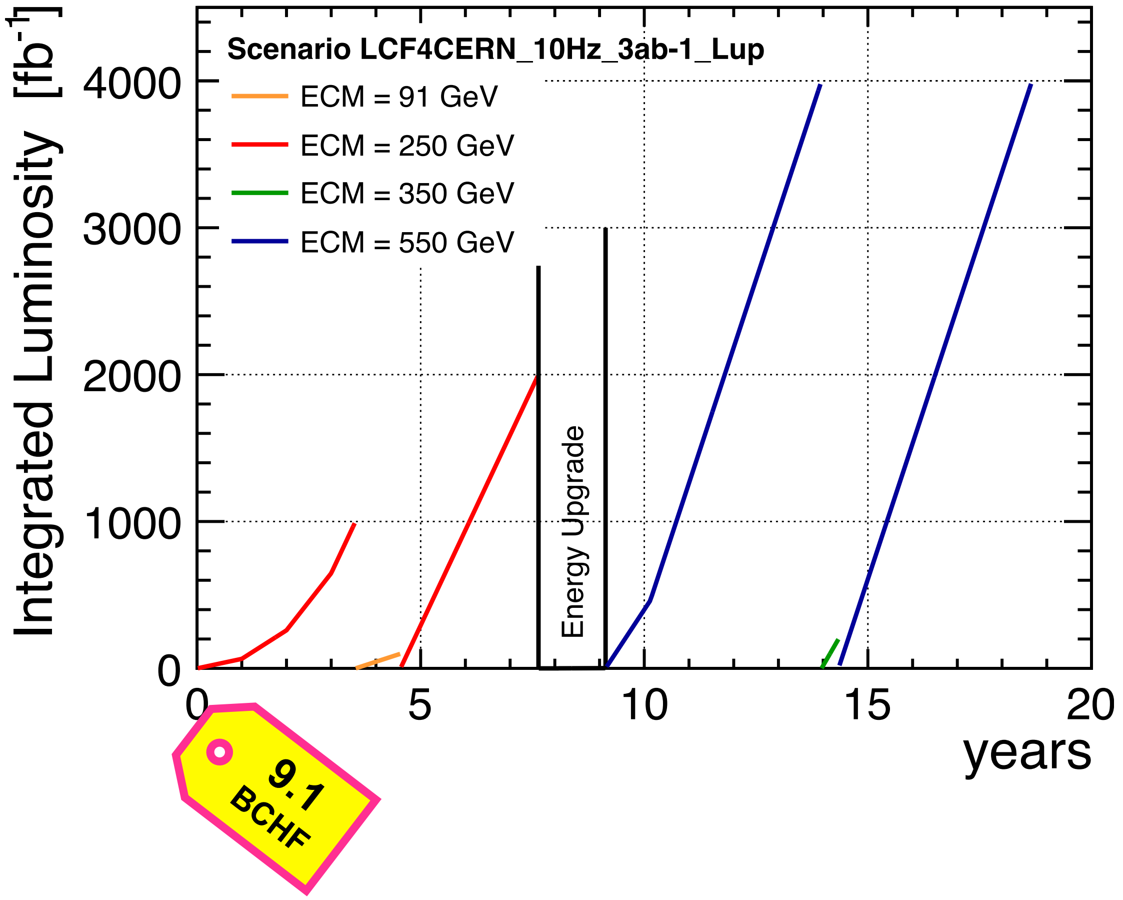

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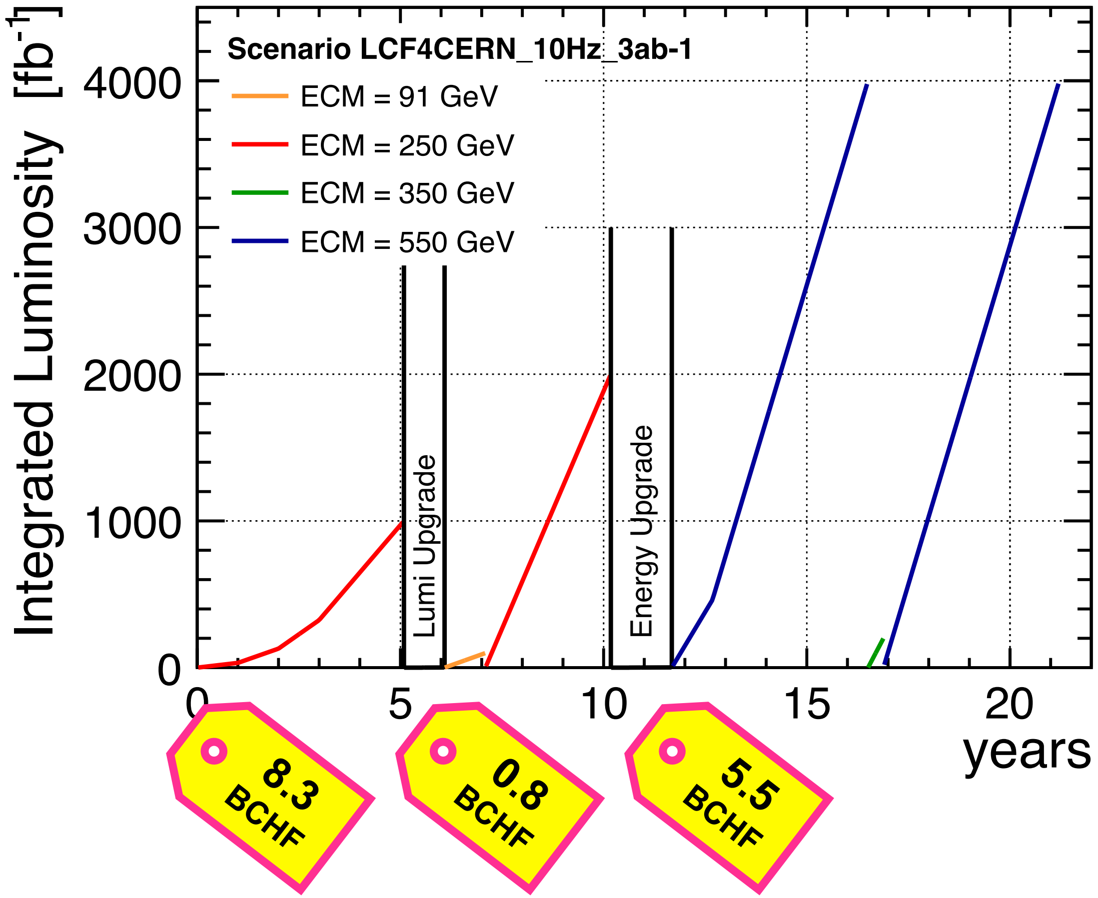

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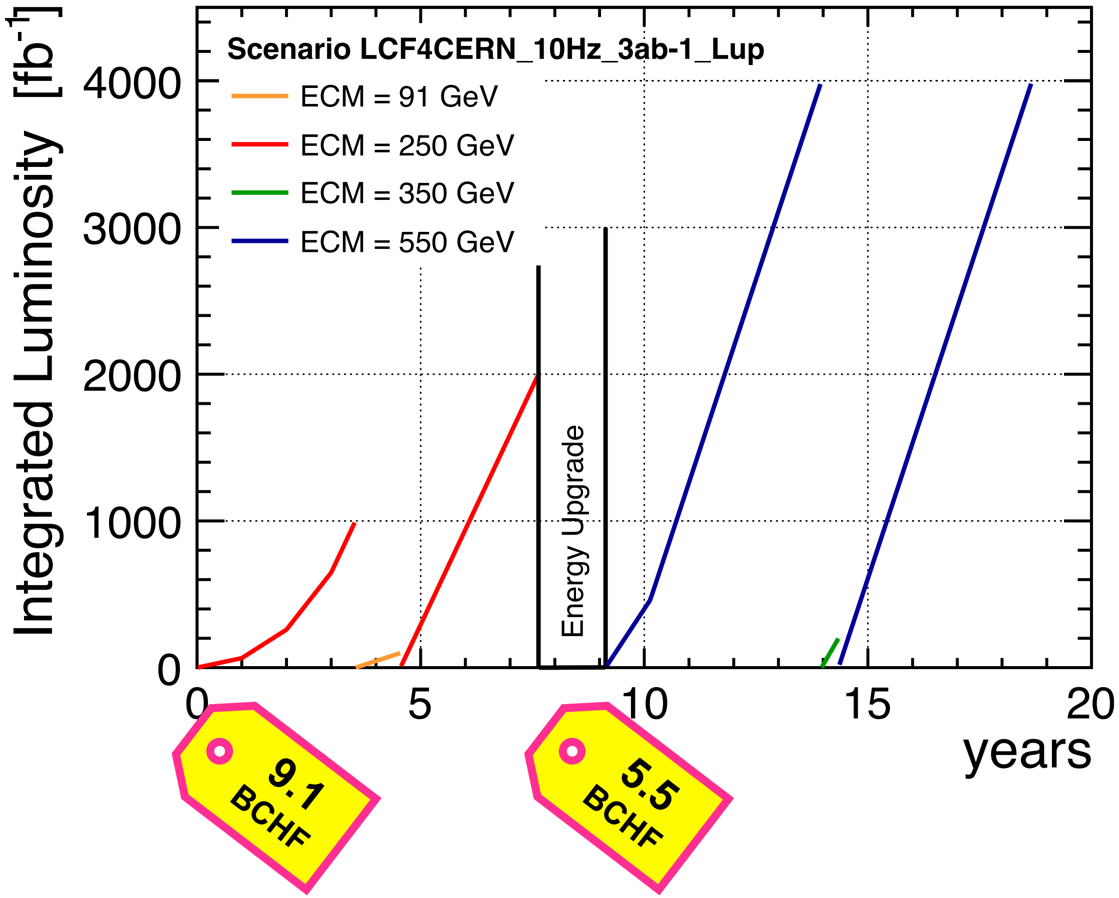
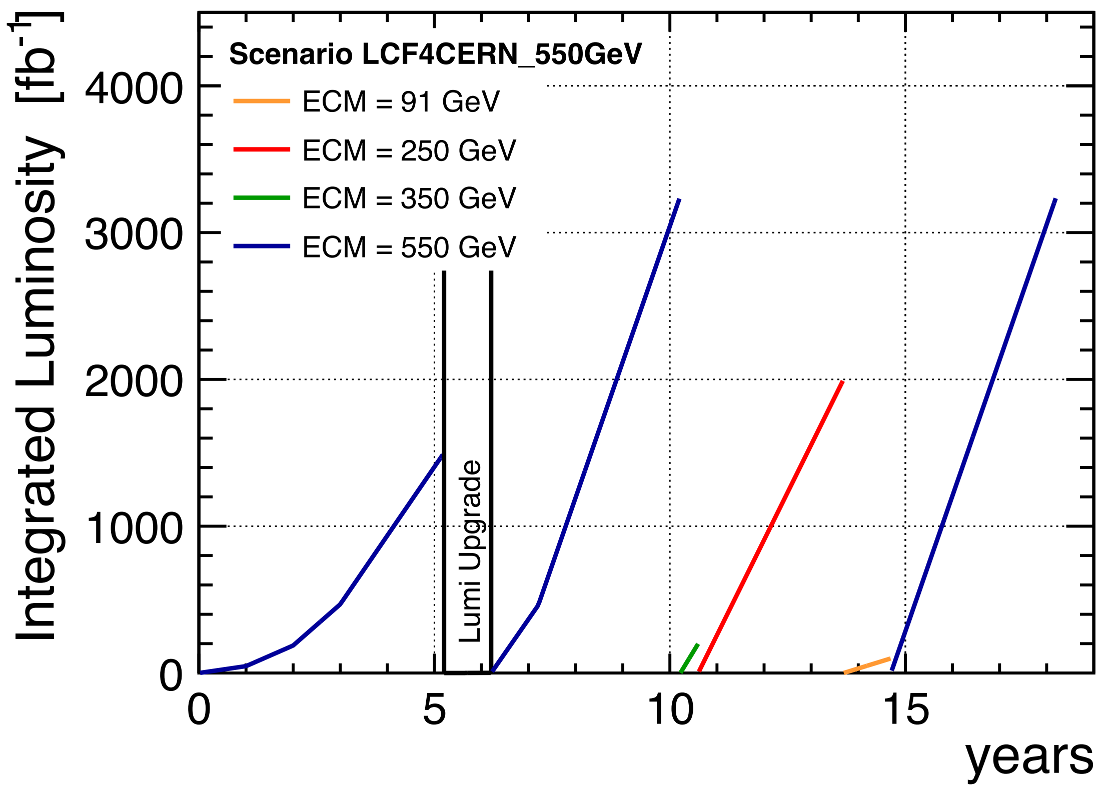
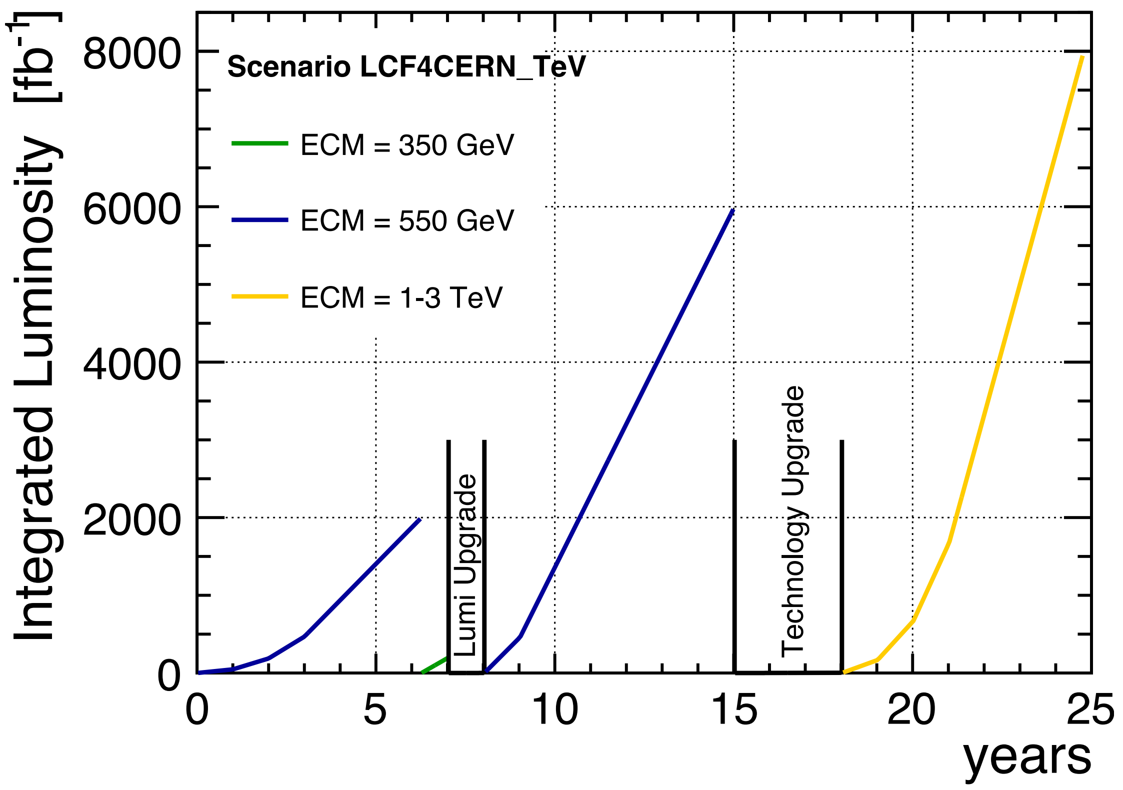


Running Scenarios - starting at 550 GeV - e.g. if CEPC goes ahead!

take some polarised data at lower energies



or go more quickly to TeV range



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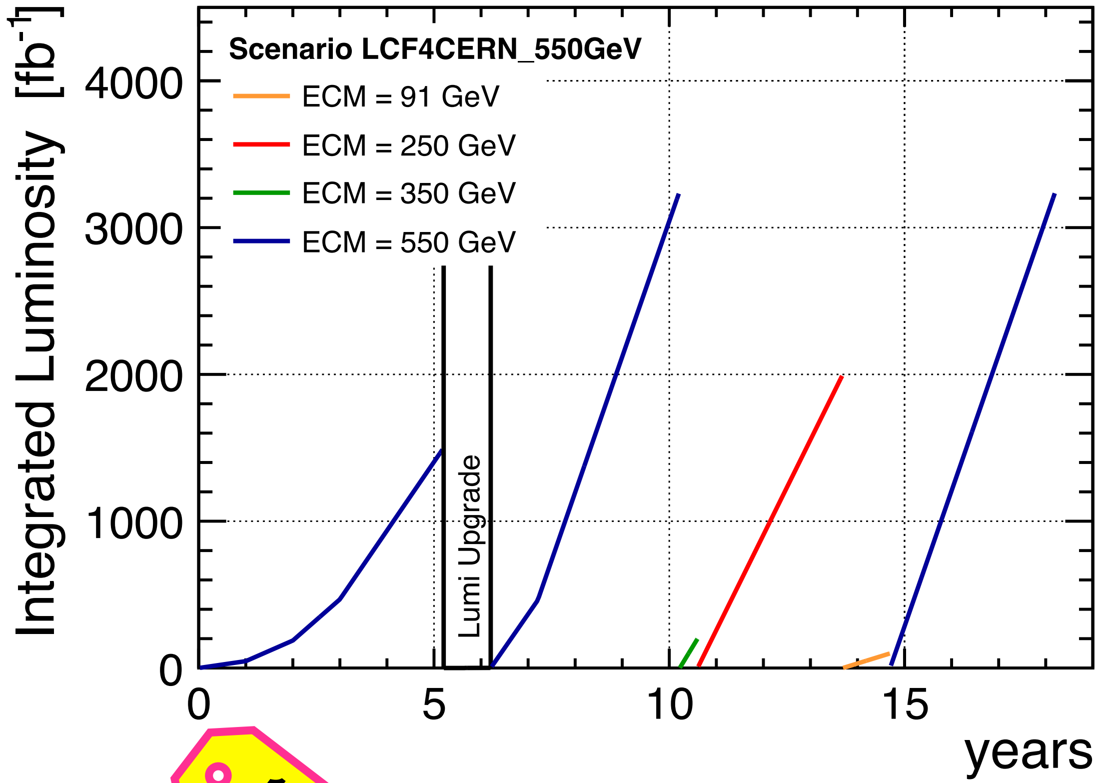

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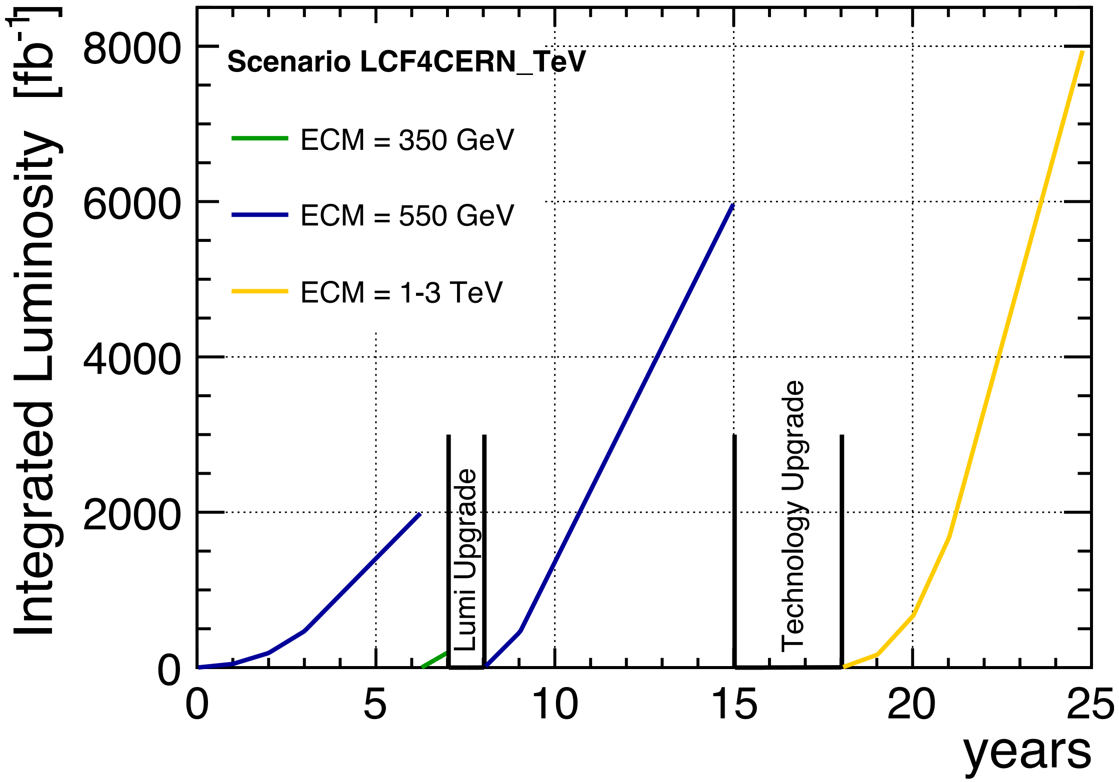

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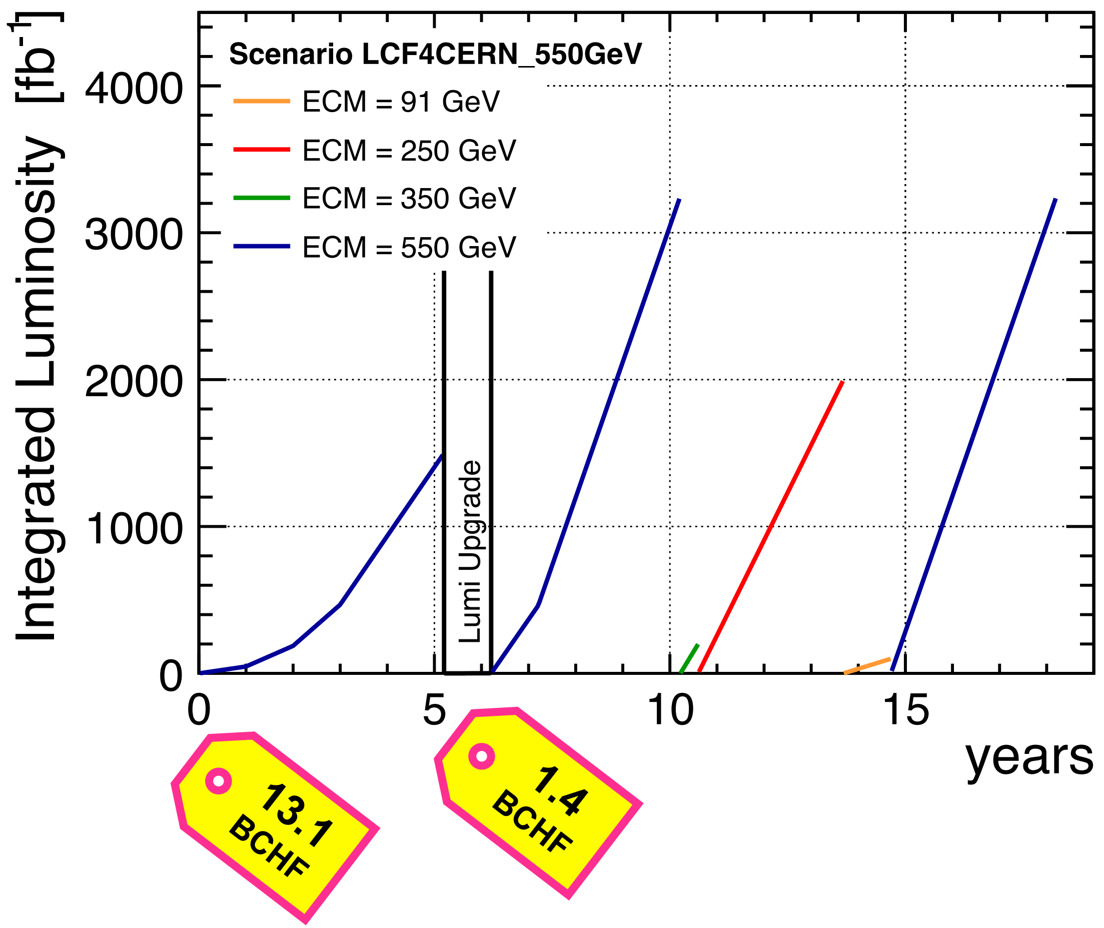

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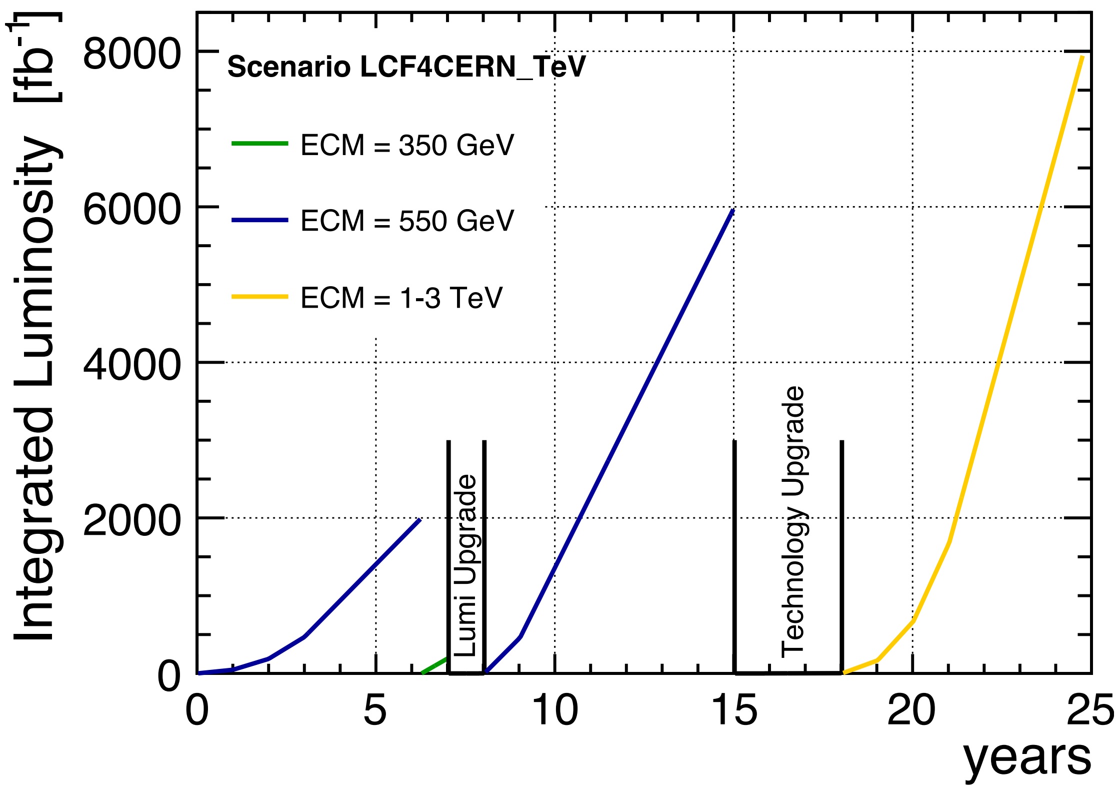
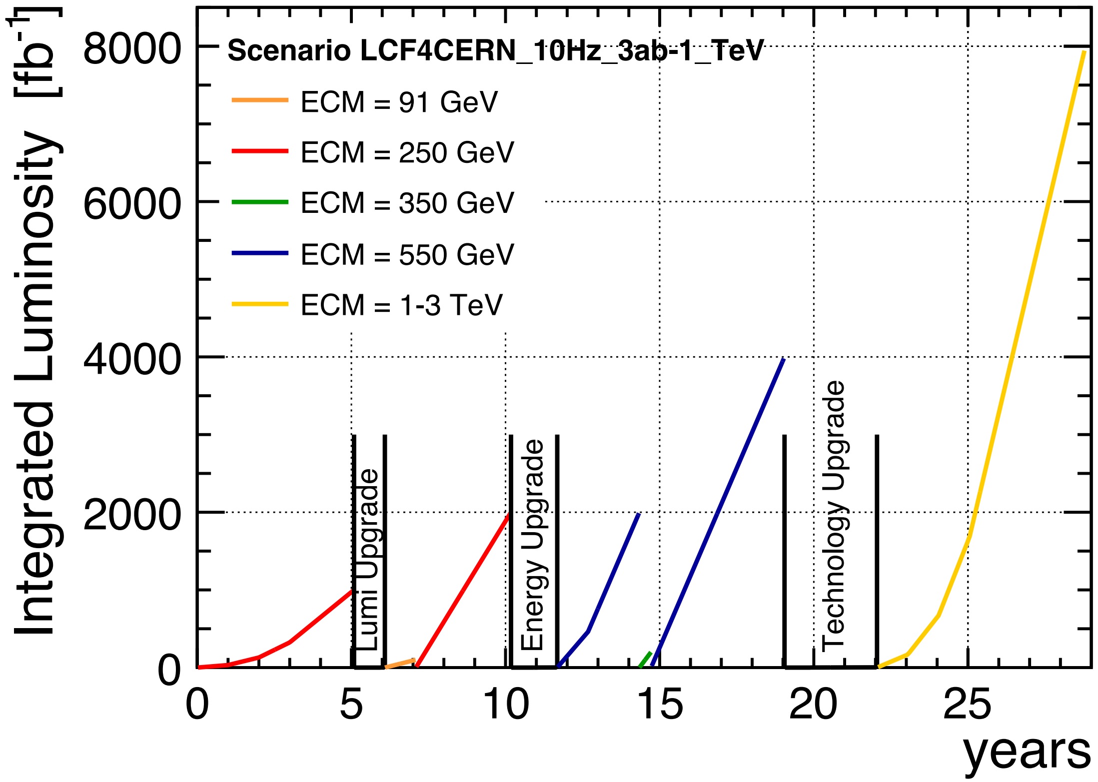
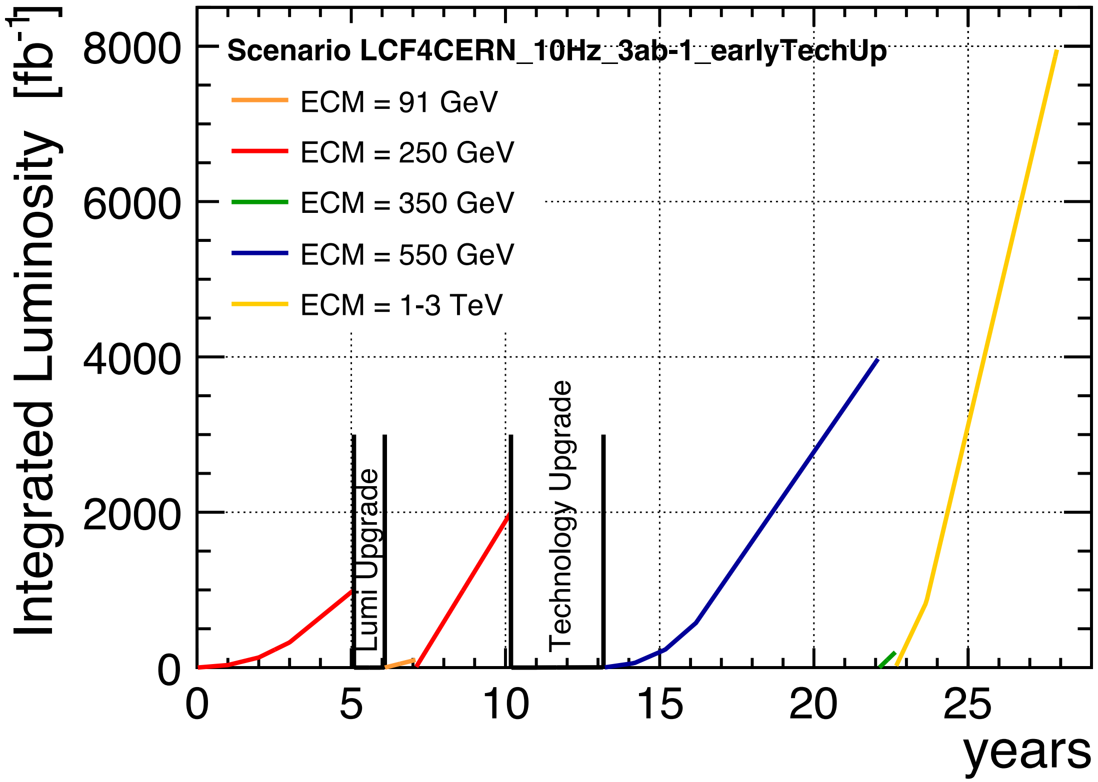


Running Scenarios - shortening 550 GeV in favour of TeV

Tech upgrade after 550 GeV



Tech upgrade after 250 GeV



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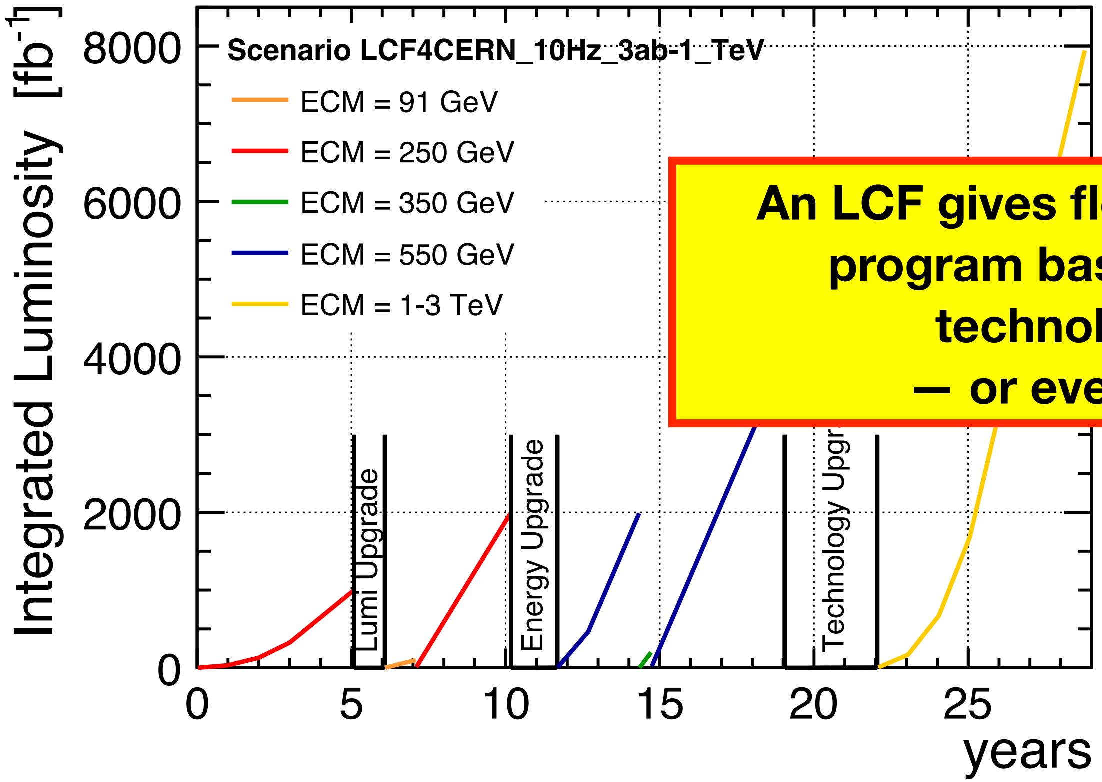

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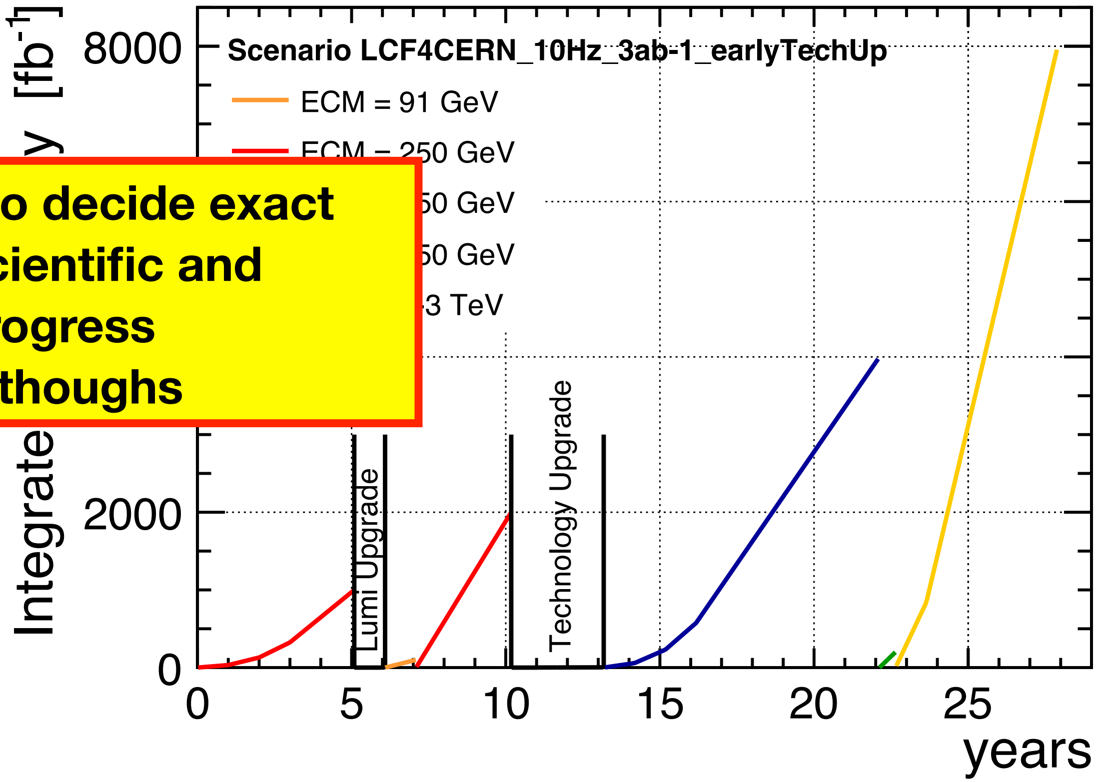
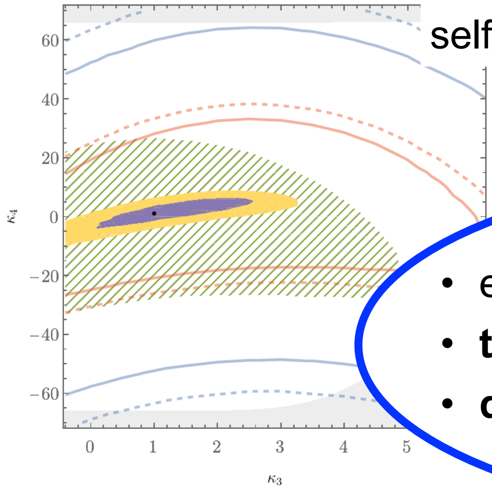
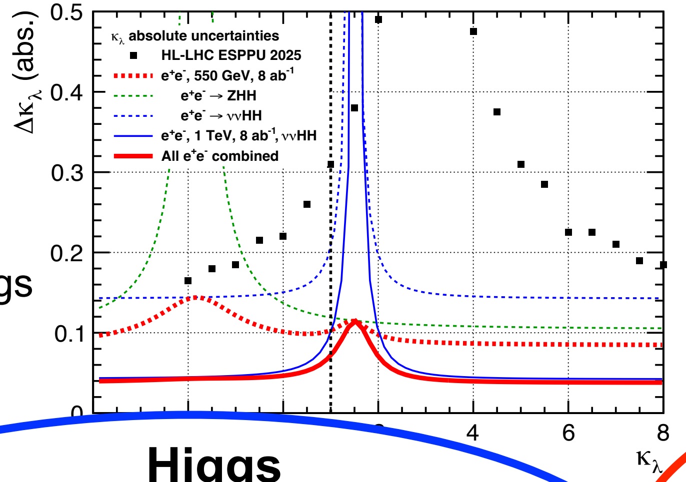


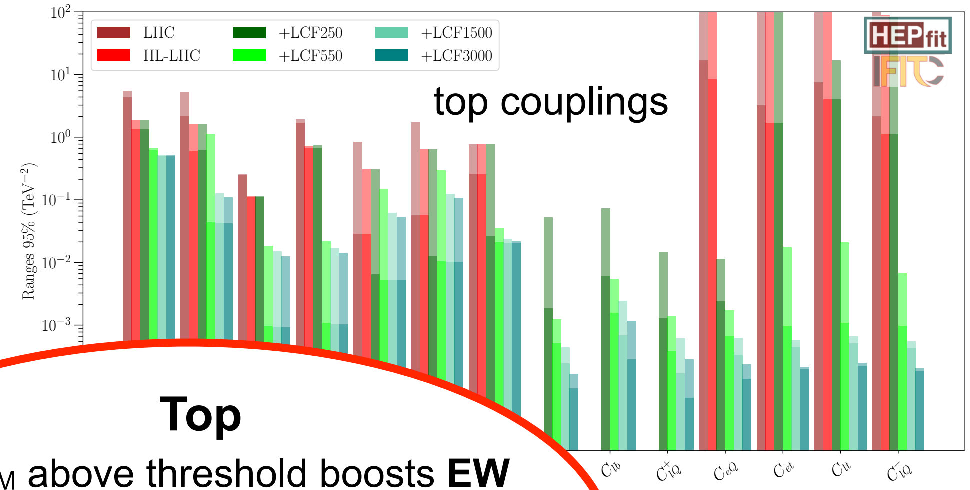
An LCF gives flexibility to decide exact program based on scientific and technological progress — or even break-thoughs

Why ≥ 1 TeV?

Targets of e+e- at 1-3 TeV





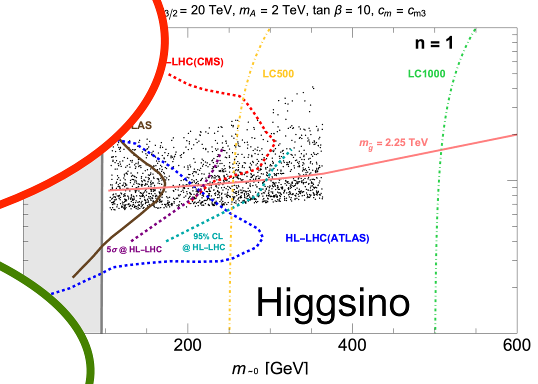


Higgs

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

Top

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

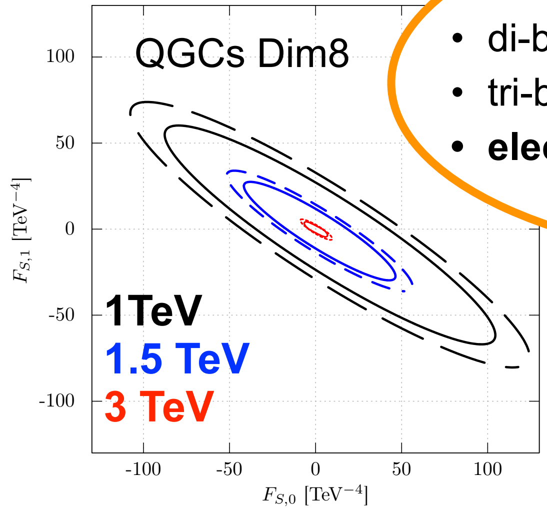


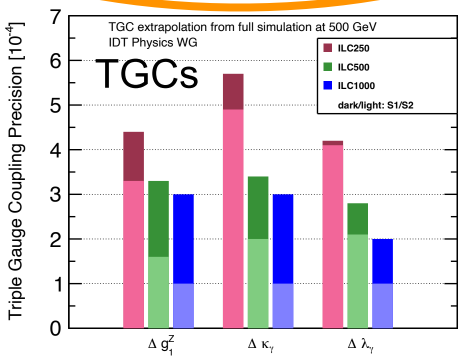
Vector Bosons

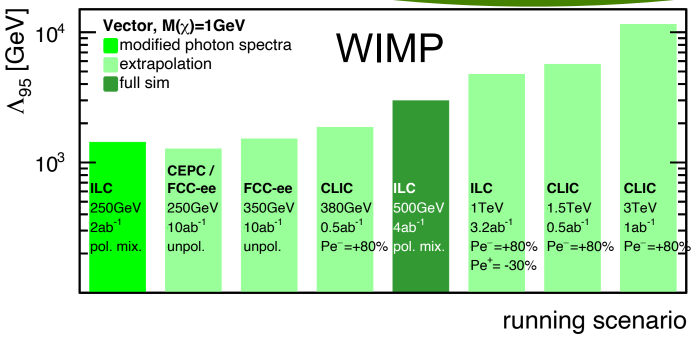
- di-bosons & **triple gauge couplings**
- tri-bosons and **quartic couplings**
- **electro-weak jets**

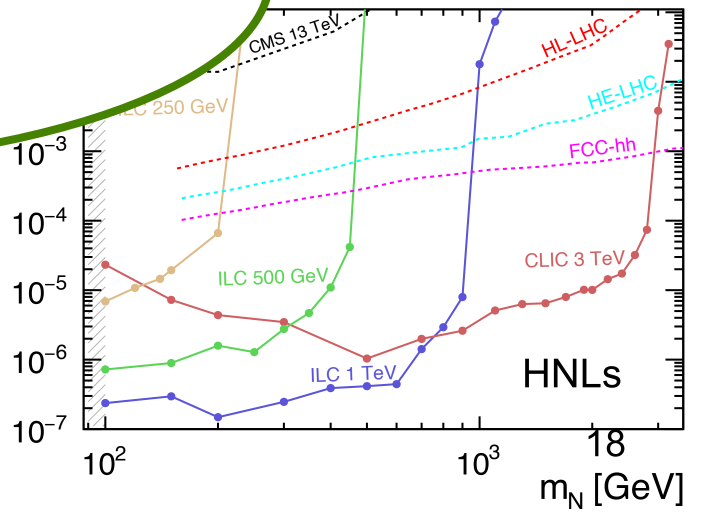
Direct New Particles

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









Linear Collider Vision

The Linear Co

Energy Upgrades beyond 550 GeV

1 TeV and beyond

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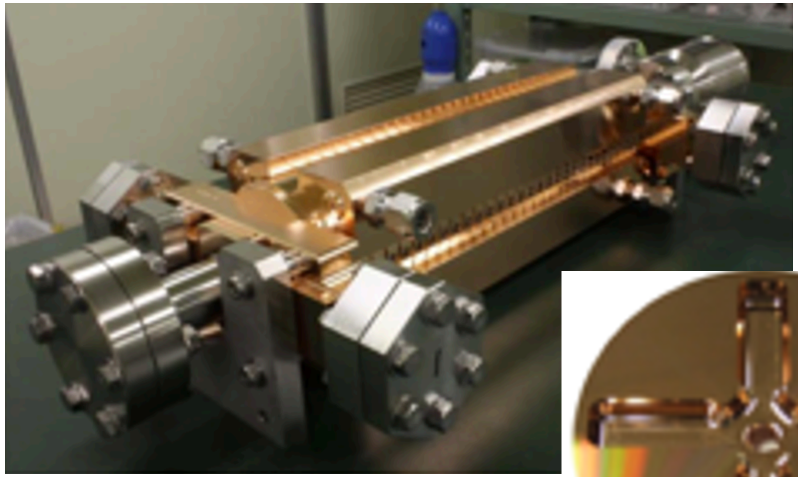

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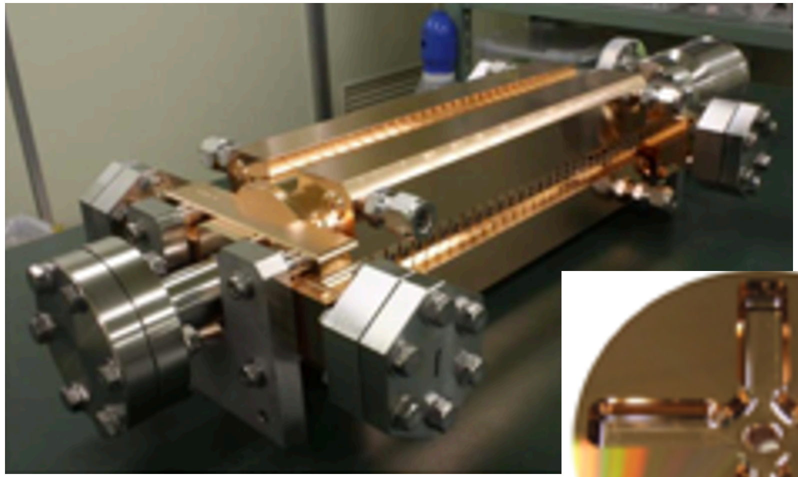

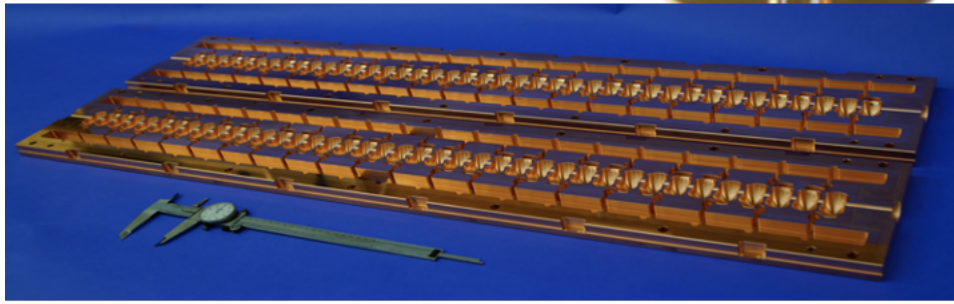

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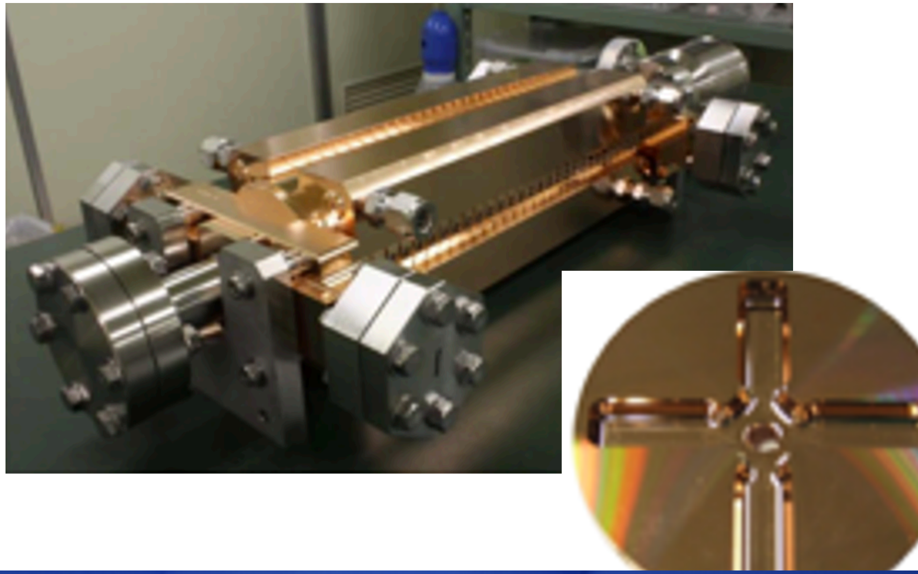

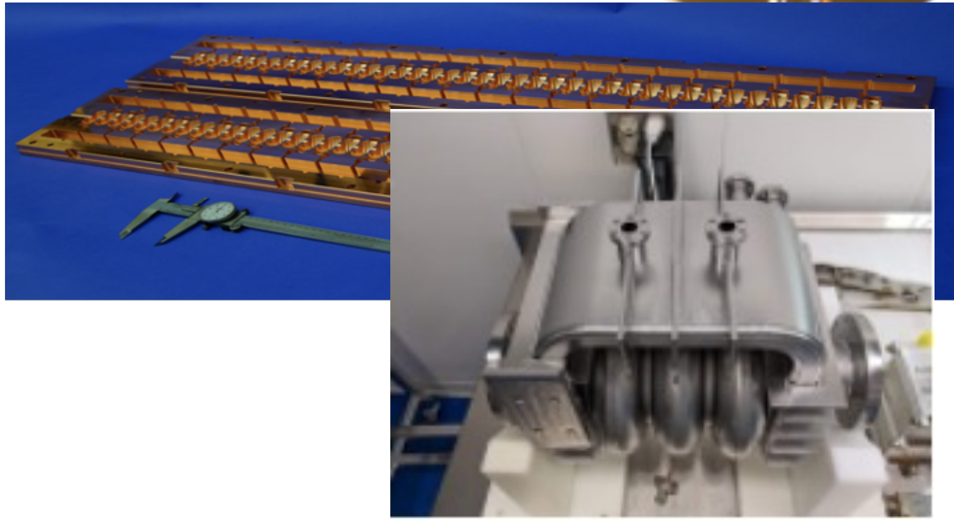

Energy Upgrades beyond 550 GeV

1 TeV and beyond

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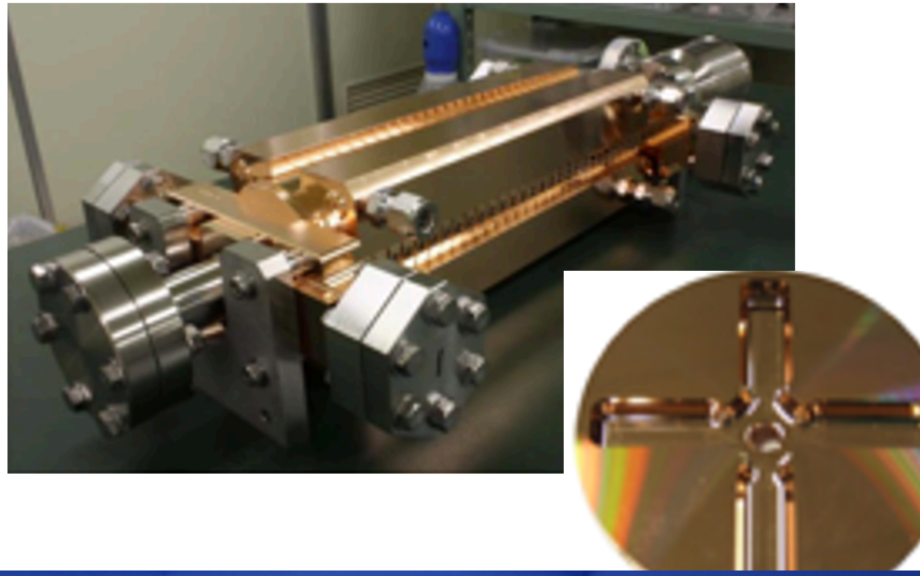

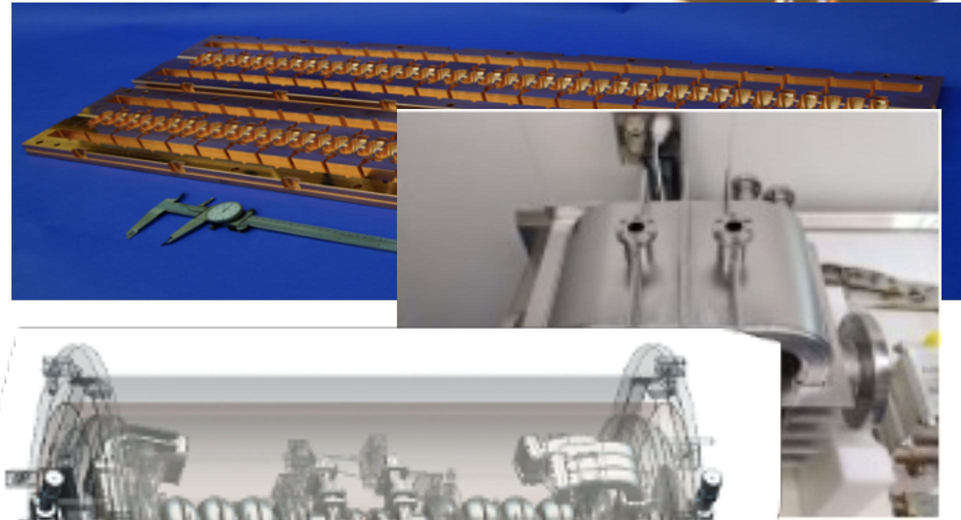

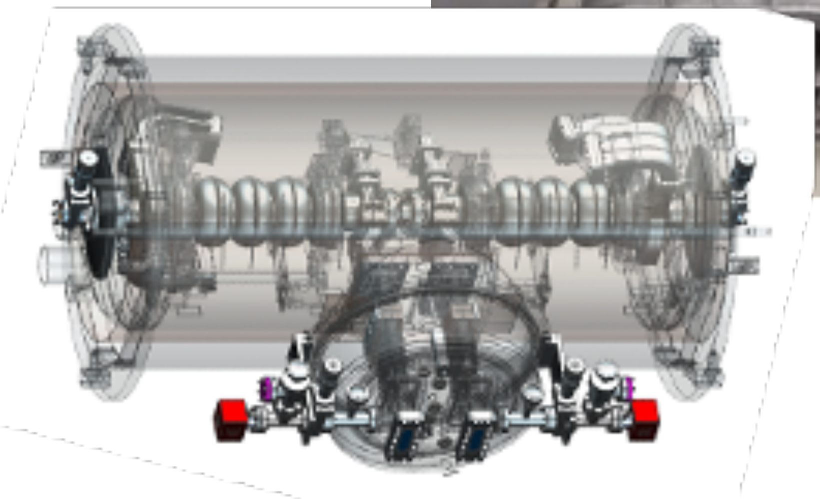

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for each of the options how it
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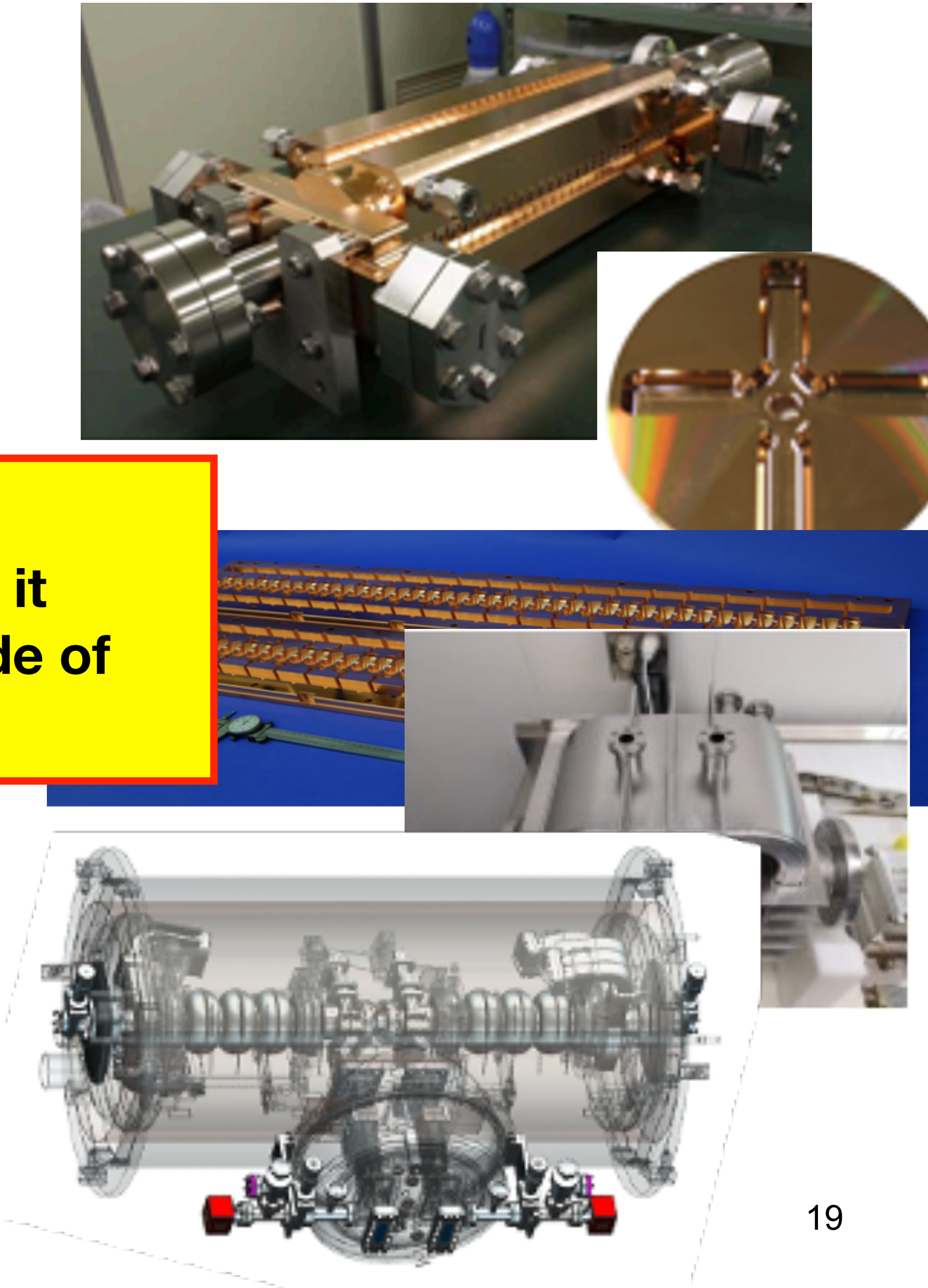
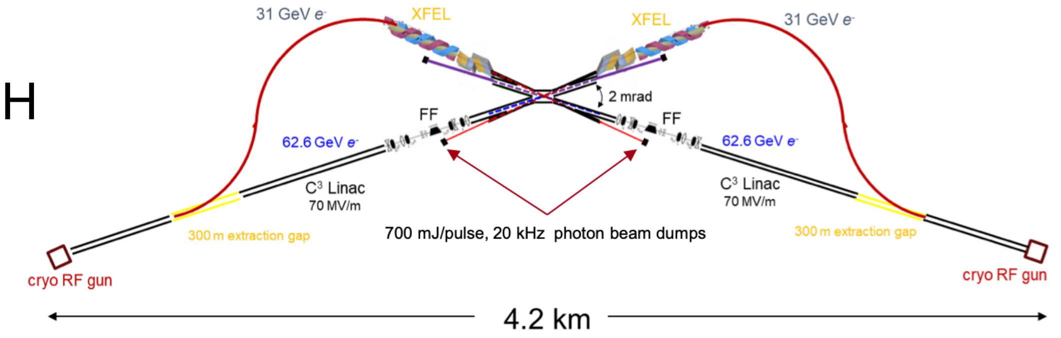
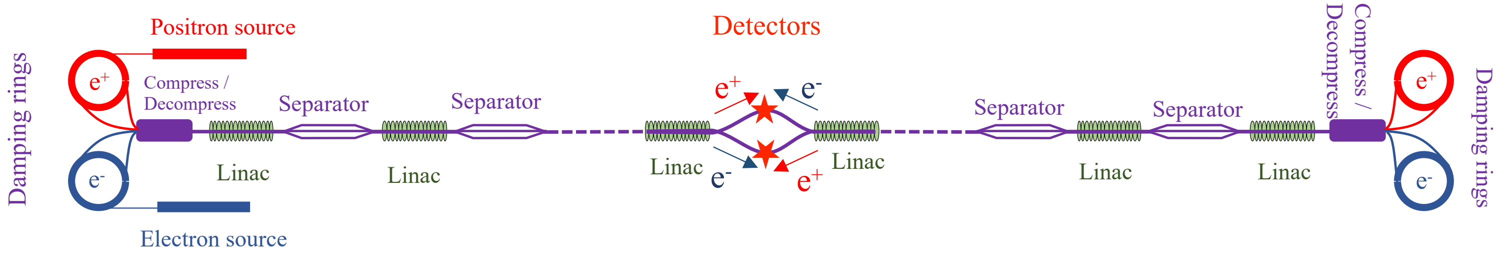


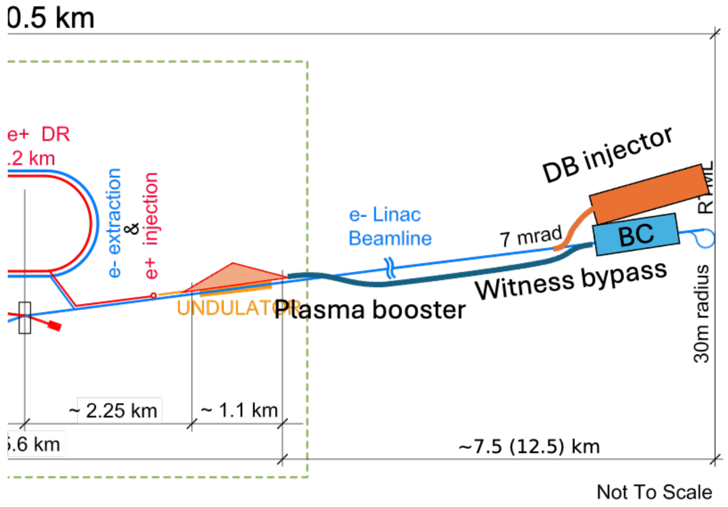
Additional Upgrade Paths

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
  - either only for e-, asymmetric collisions a la HALHF
  - or e- and e+, paving the way towards 10 TeV $\gamma\gamma$ or e+e-







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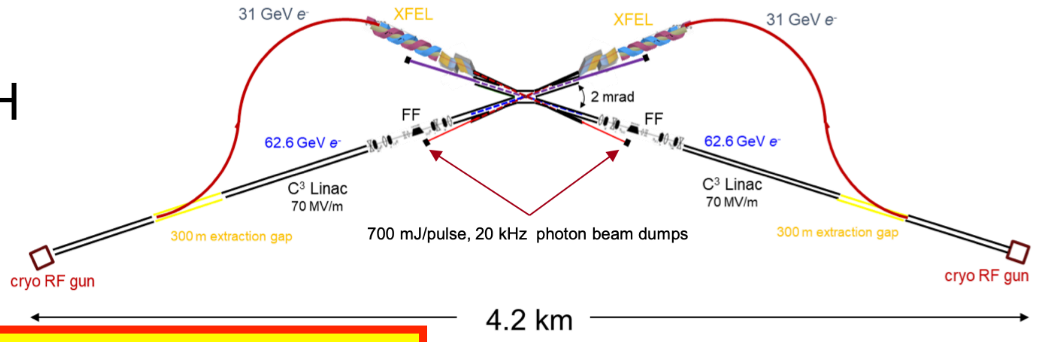

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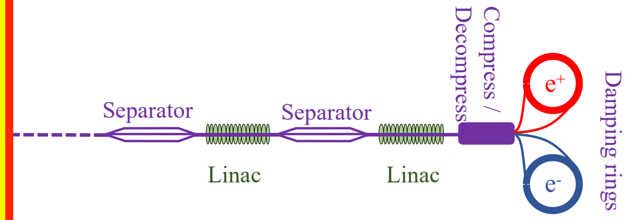

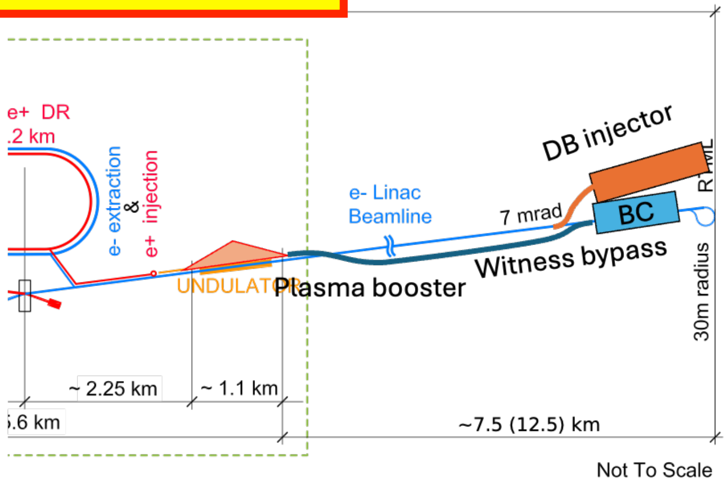

The Linear Collider Facility @ CERN and beyond

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: 2-phase preparatory period**
  - ideally starting after conclusion of EPPSU in mid-2026
  - prior to construction start in 2034 (to avoid overlap of beam-commissioning with HL-LHC operation)
- **Phase 1 (~35 MCHF + 180FTEy over 3 years)**
  - in parallel to ILC Technology Network
  - placement study at CERN, review with stakeholders (local region / host states / ..)
  - 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 over 5 years)**
  - 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

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Strategic Considerations for Europe

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 E_{CM} 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
- stays affordable, in parallel to HL-LHC, SuperKEKB, smaller experiments - and R&D towards the 10-TeV pCoM scale
- the ESPPU is discussing the preferred flagship collider projects 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

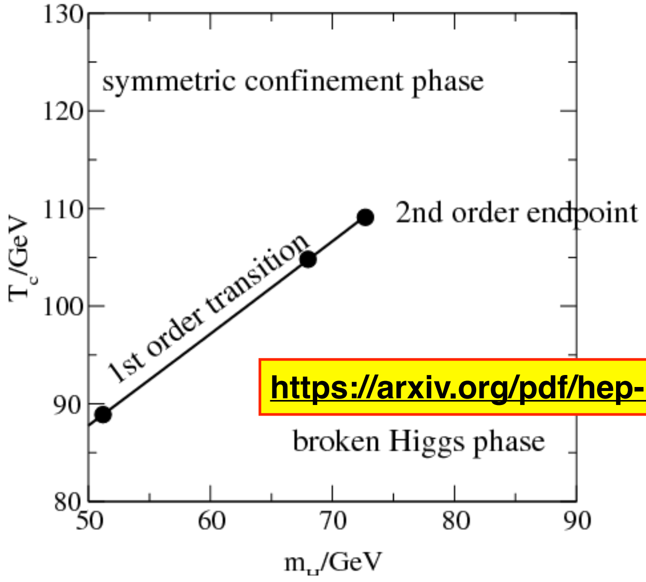
- **mark your calendars for LCWS2025: October 20-24 in Valencia, Spain**

Any Questions?

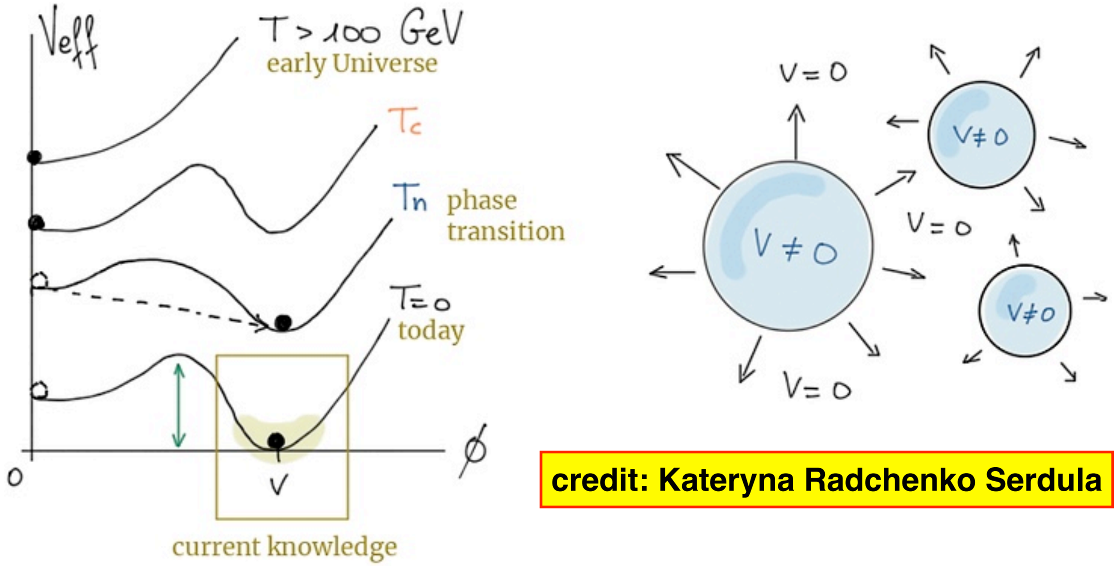
Recap: Electroweak Symmetry Breaking and Baryogenesis

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



credit: Kateryna Radchenko Serdula

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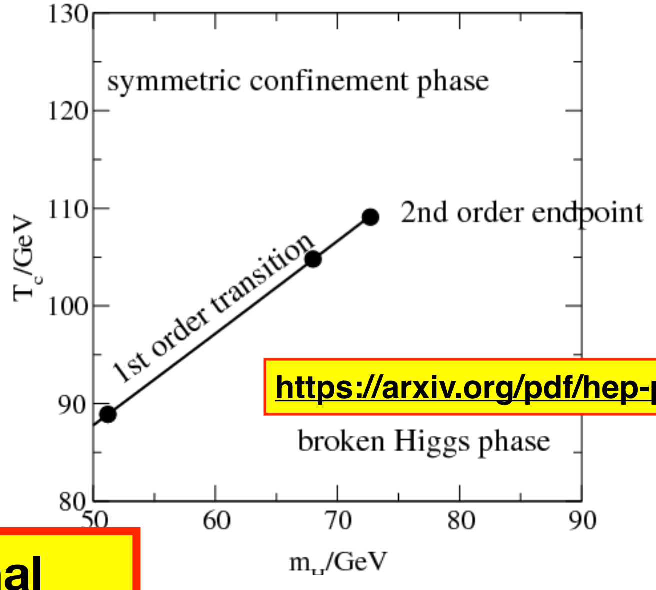
Interesting interplay with gravitational waves: detect direct remnants of the phase transition?



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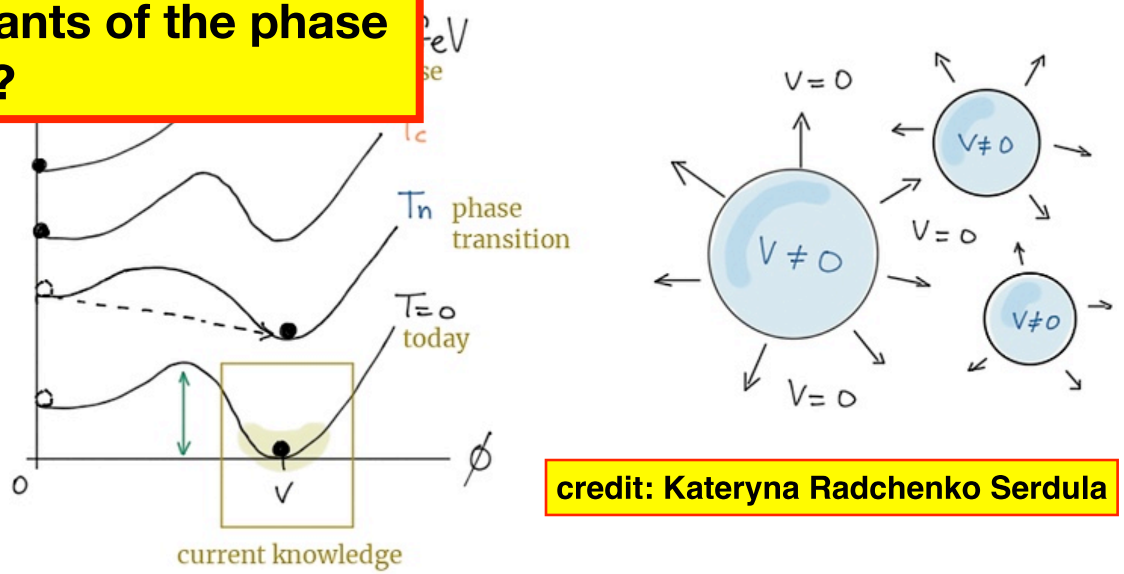

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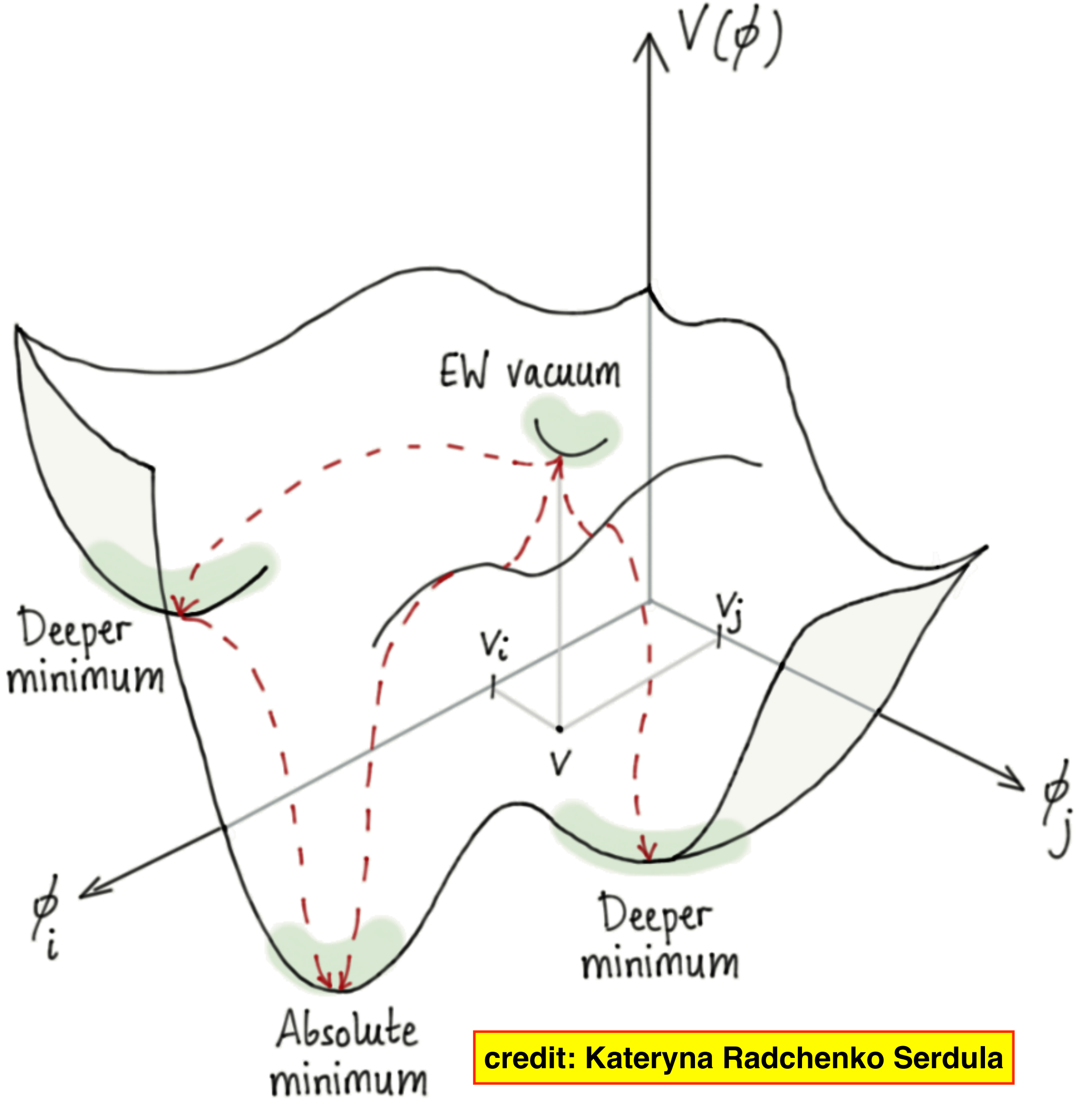
Higgs potential in extended Higgs Sectors

"Maxican hat" turns into complex landscape

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



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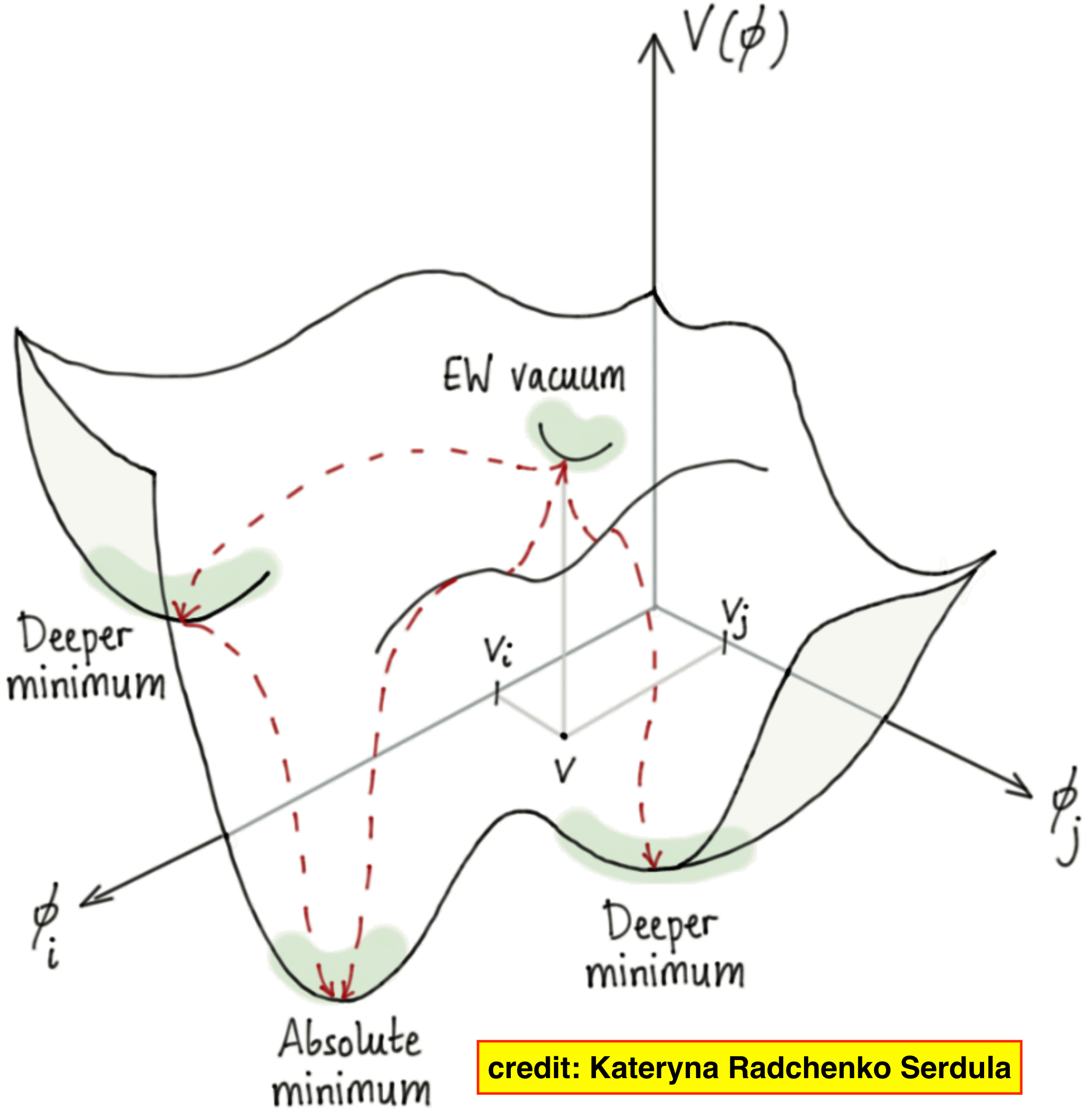
measure as many physical observables with least model-assumptions to explore this landscape - just assuming everything is like in the SM and extract one value is not sufficient!



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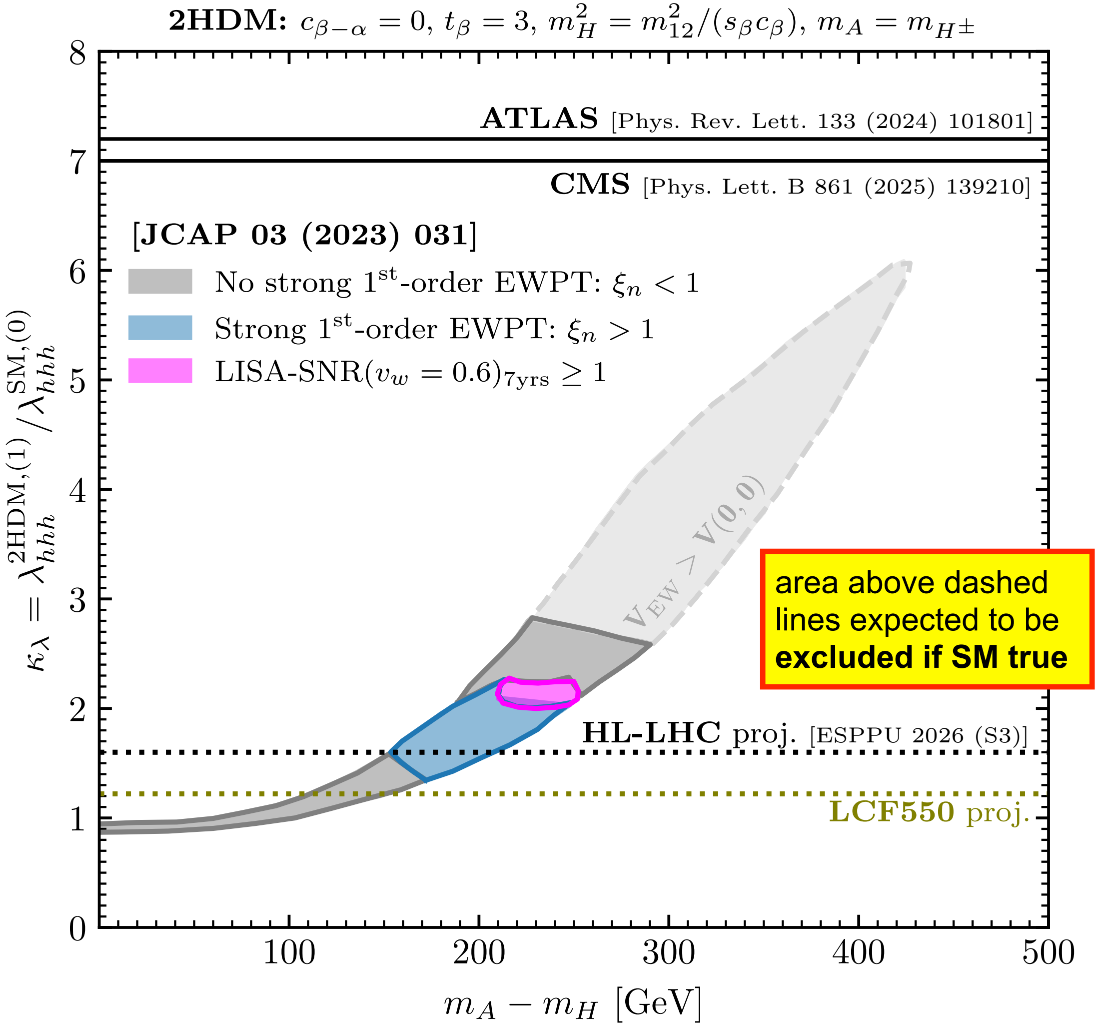
Interplay with Gravitational Wave detection

Need to assume specific extended Higgs sector to quantify effects

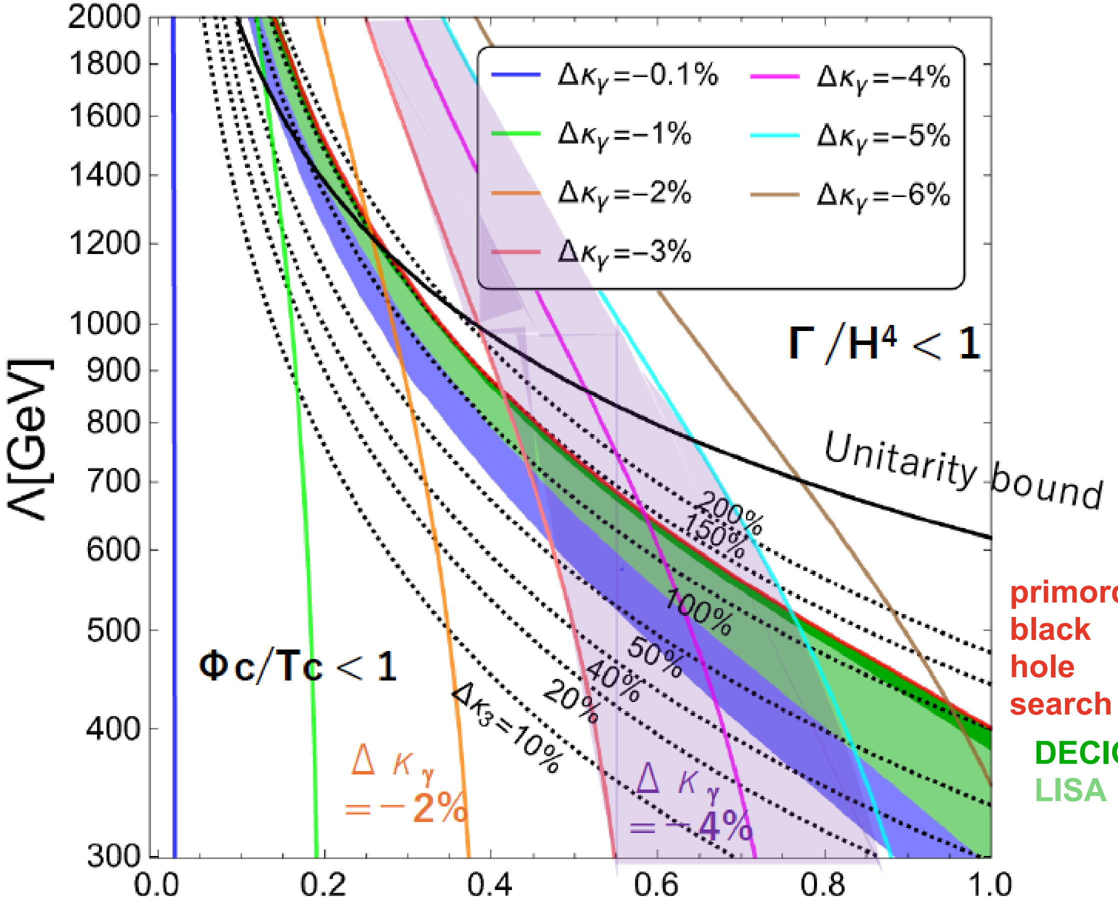


area above dashed lines expected to be **excluded if SM true**

aligned Higgs EFT

n_0=2, n_+=1, n_{++}=0

$\kappa_0=4$



primordial black hole search

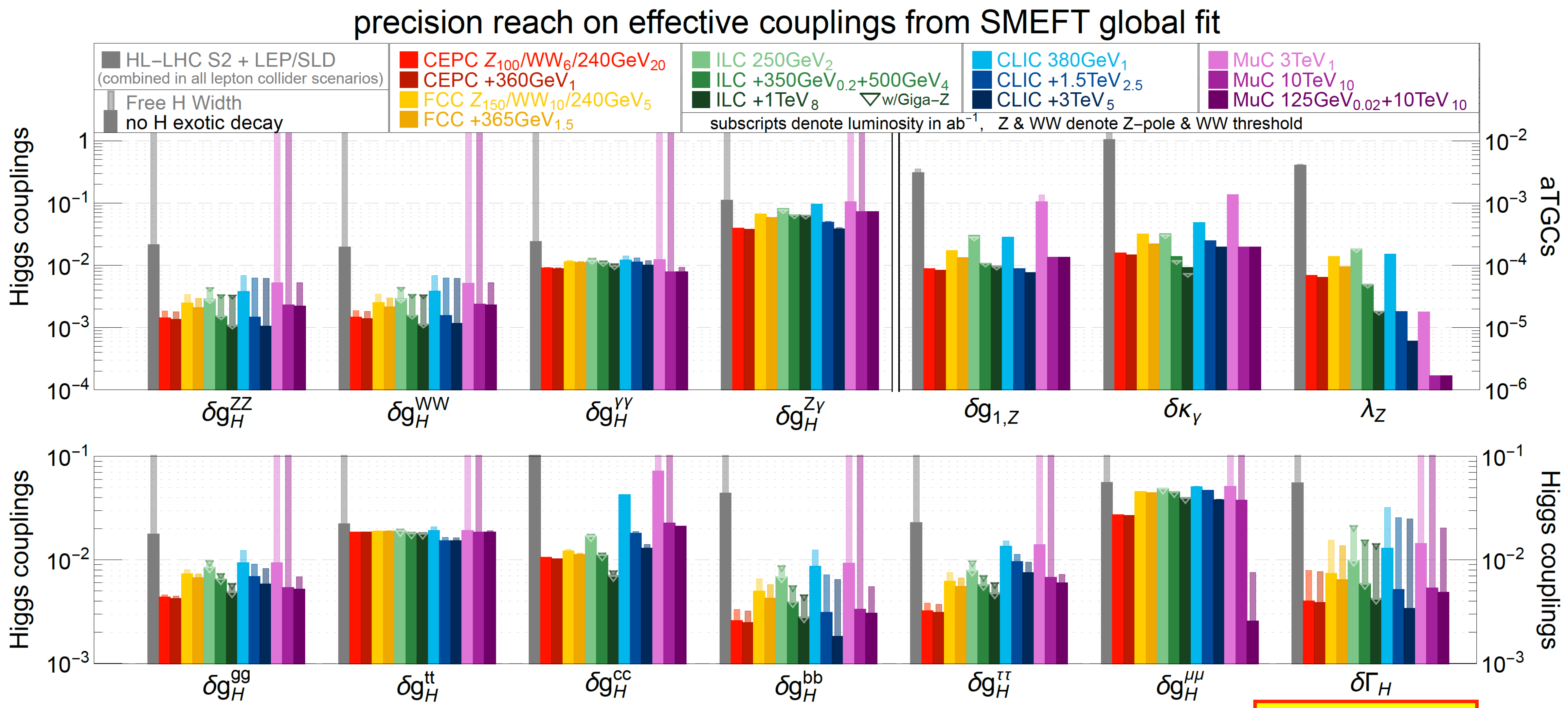
DECIGO/ LISA

FOEWPT only testable via Higgs

Phys.Lett.B 856 (2024) 138940

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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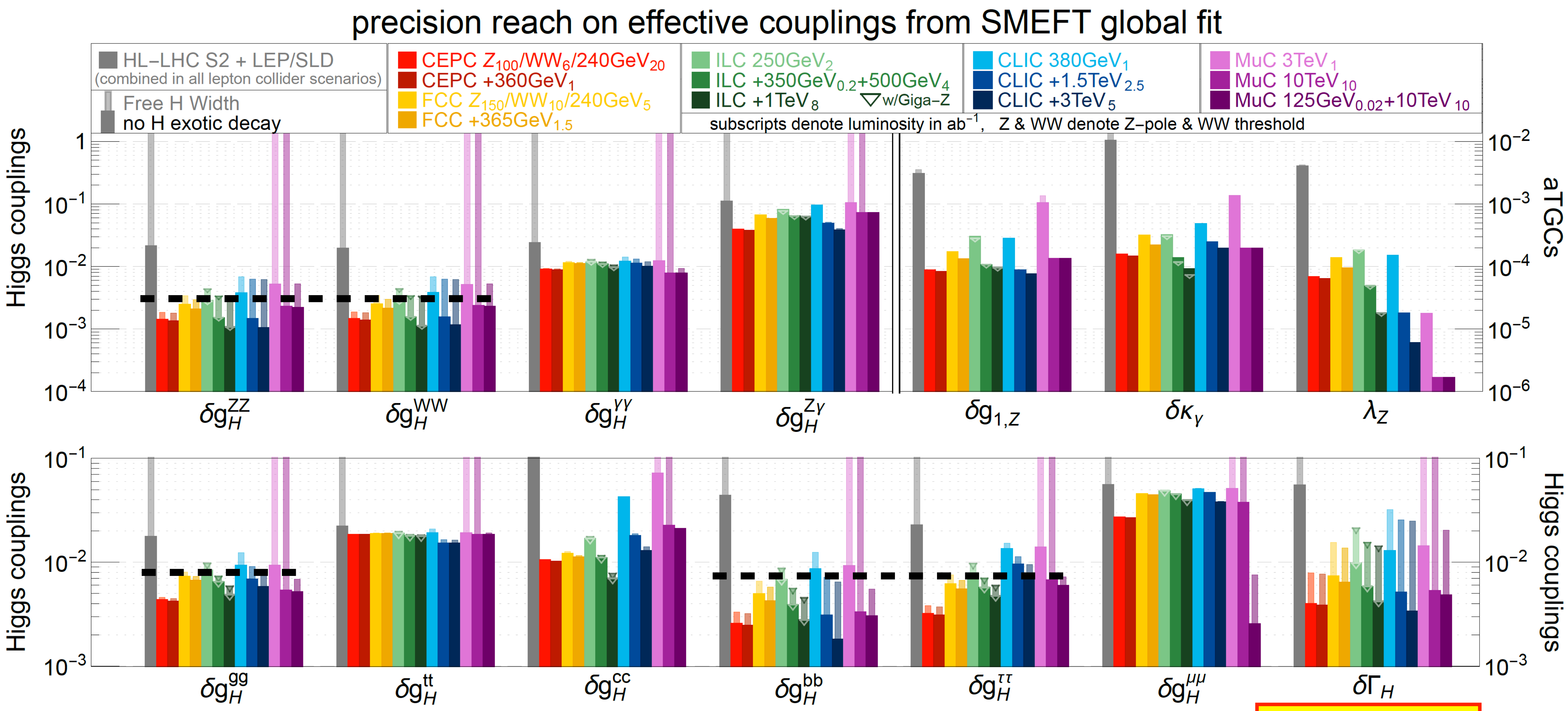

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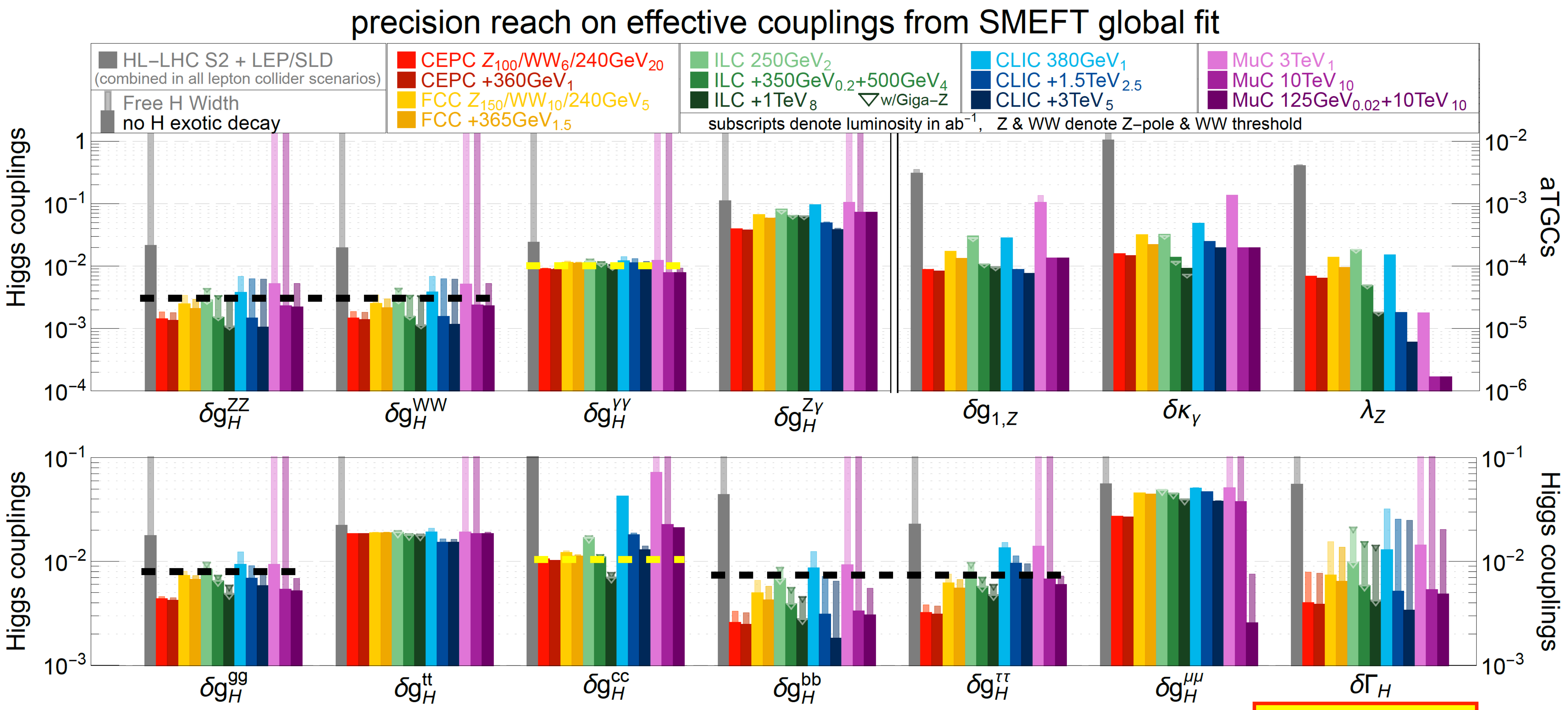

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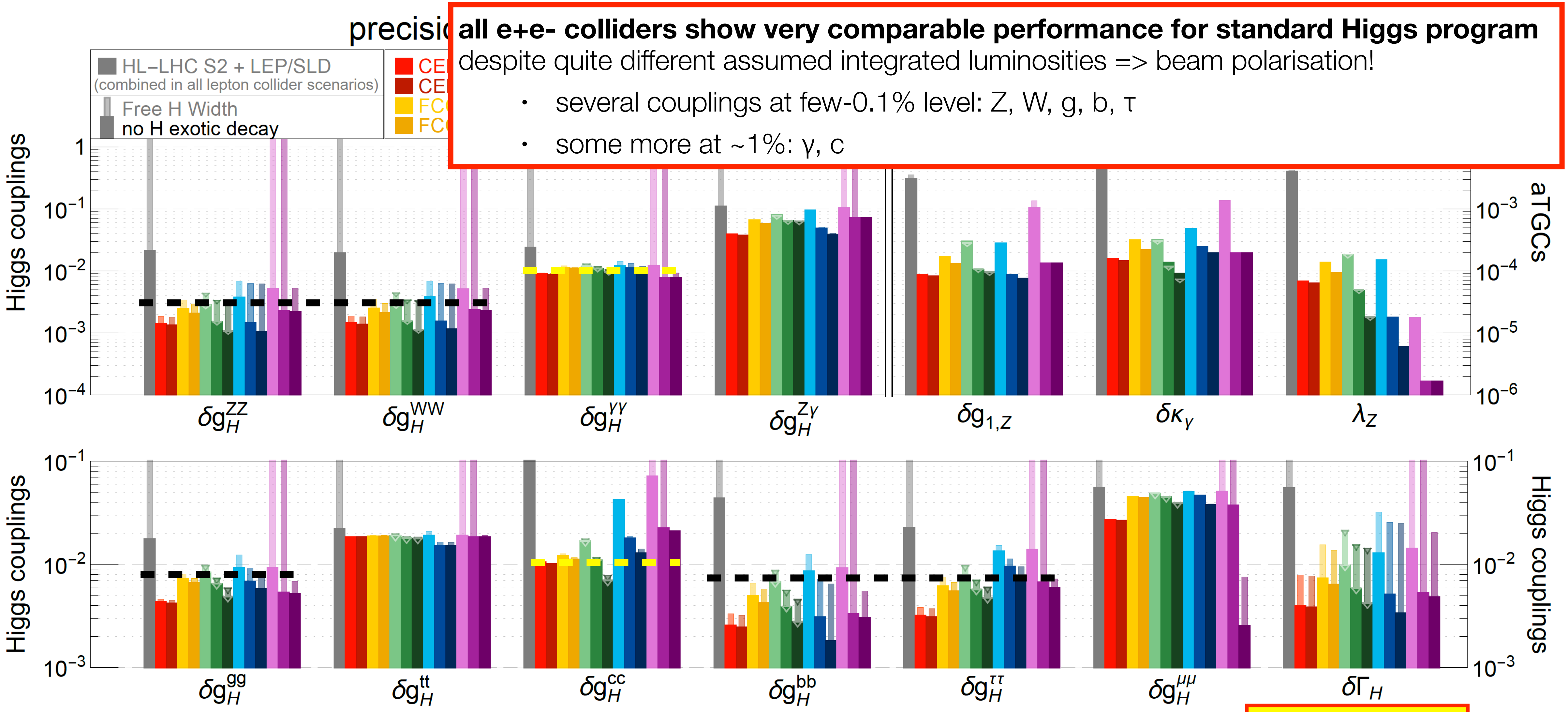
all e+e- colliders show very comparable performance for standard Higgs program

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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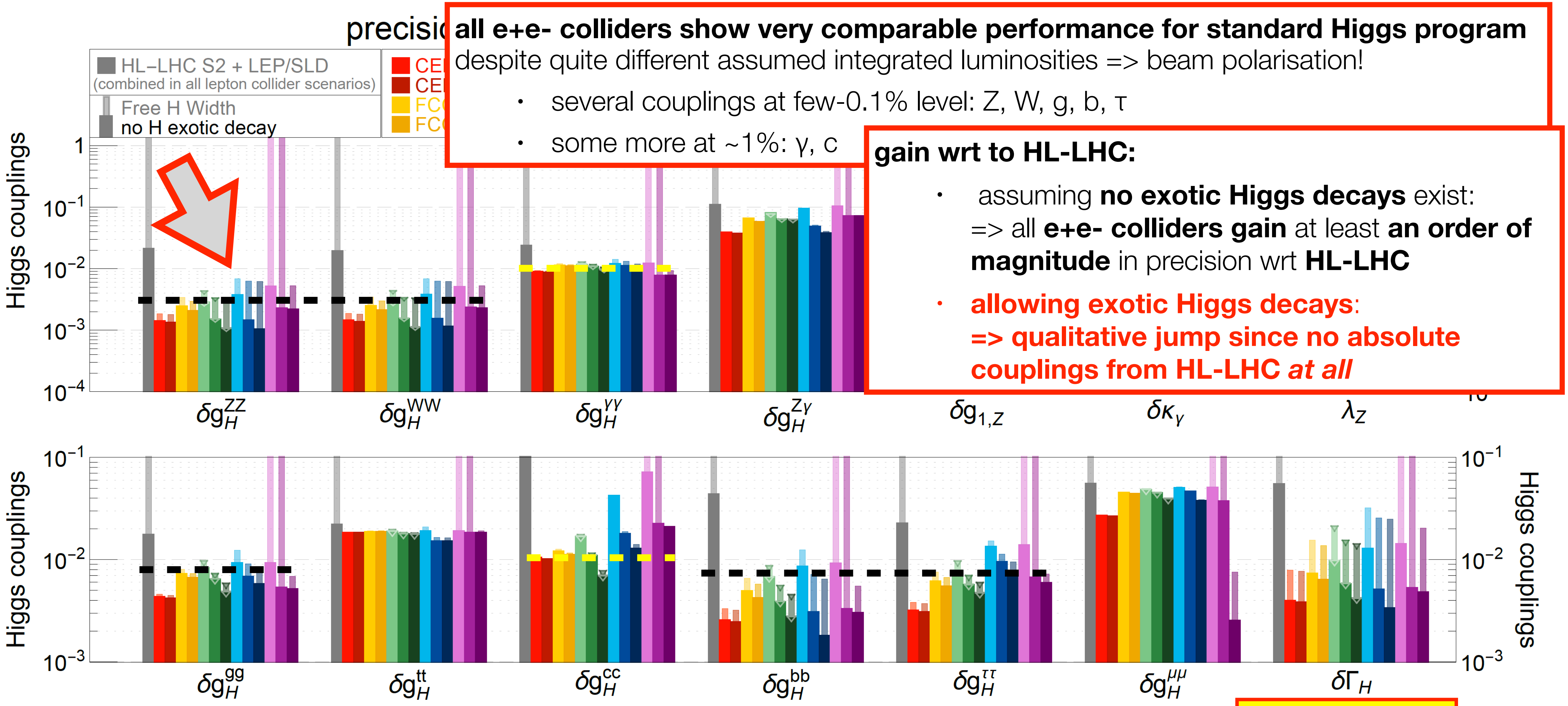

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gain wrt to HL-LHC:

- 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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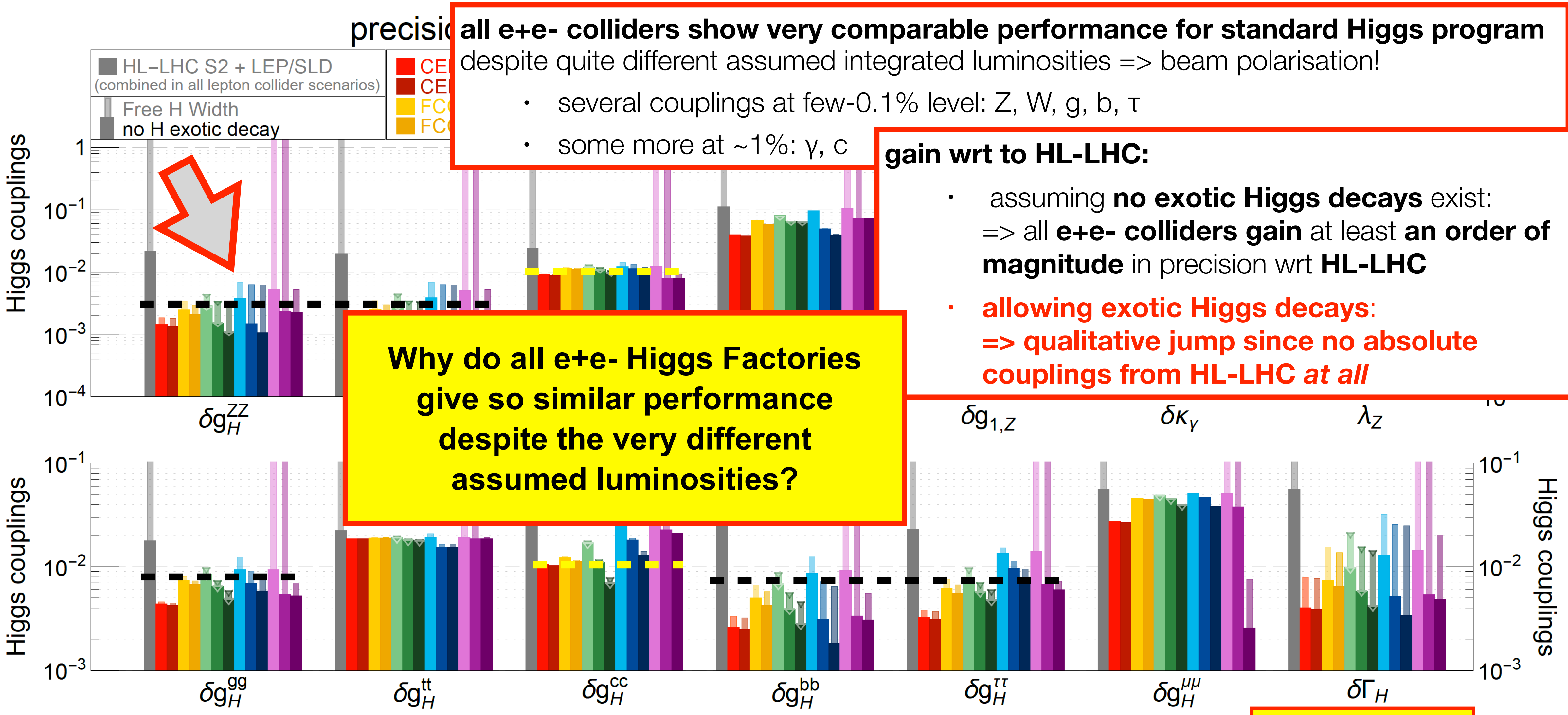

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Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L \times U(1)$
- 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

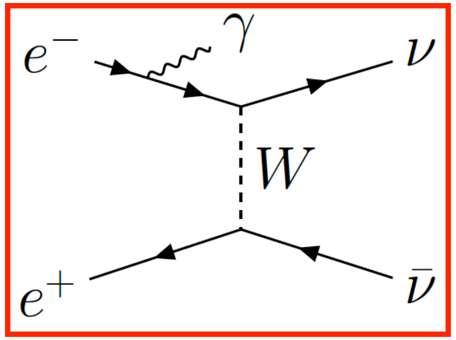
Much more than statistics!

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

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

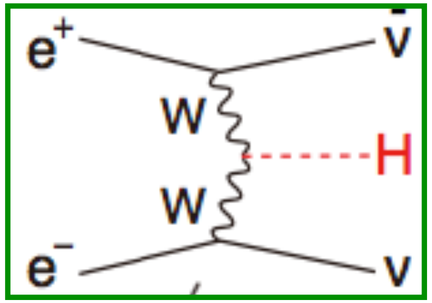
background suppression:

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



signal enhancement:

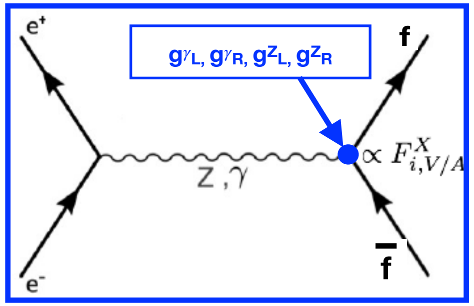
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

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



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

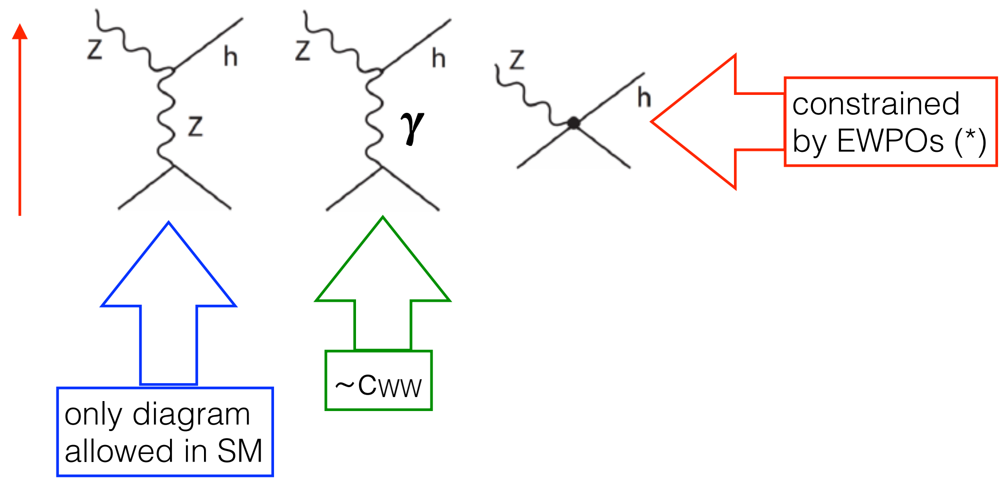
redundancy & control of systematics:

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

Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

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



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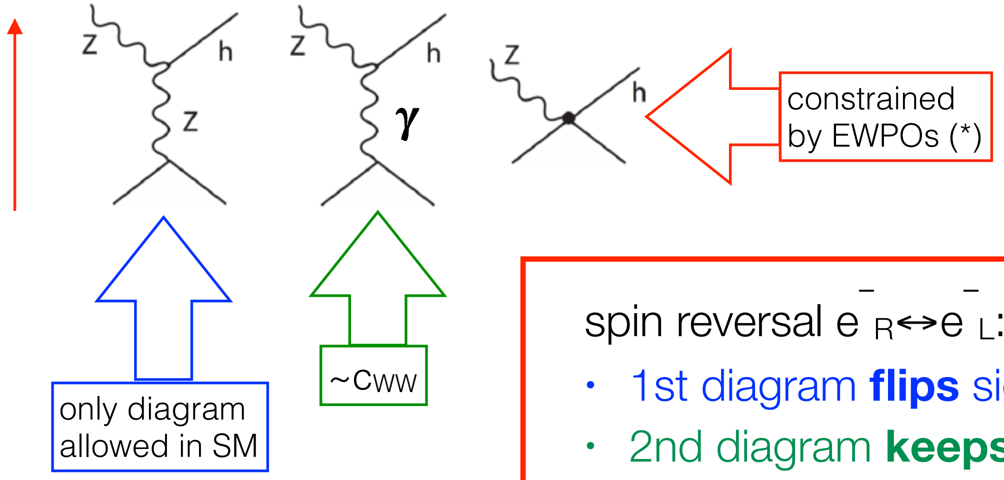

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

⇒ A_{LR} lifts degeneracy between operators!

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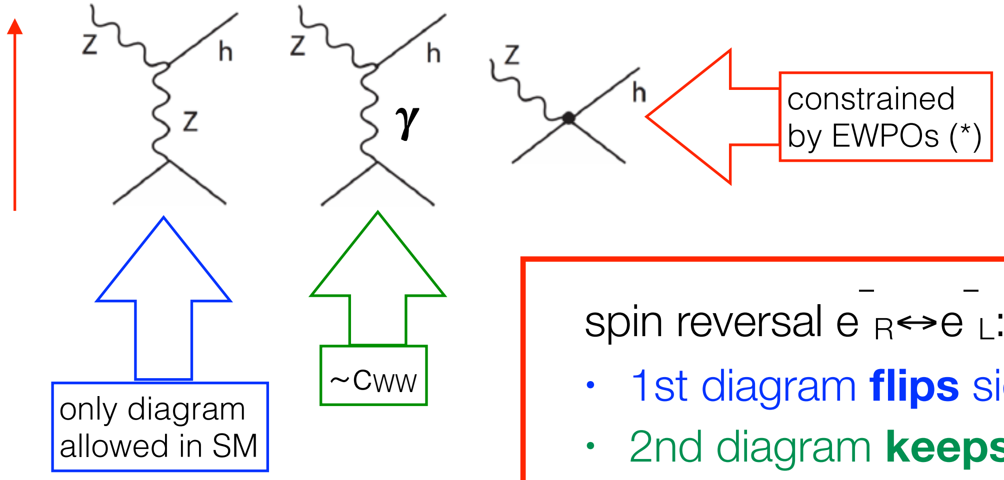

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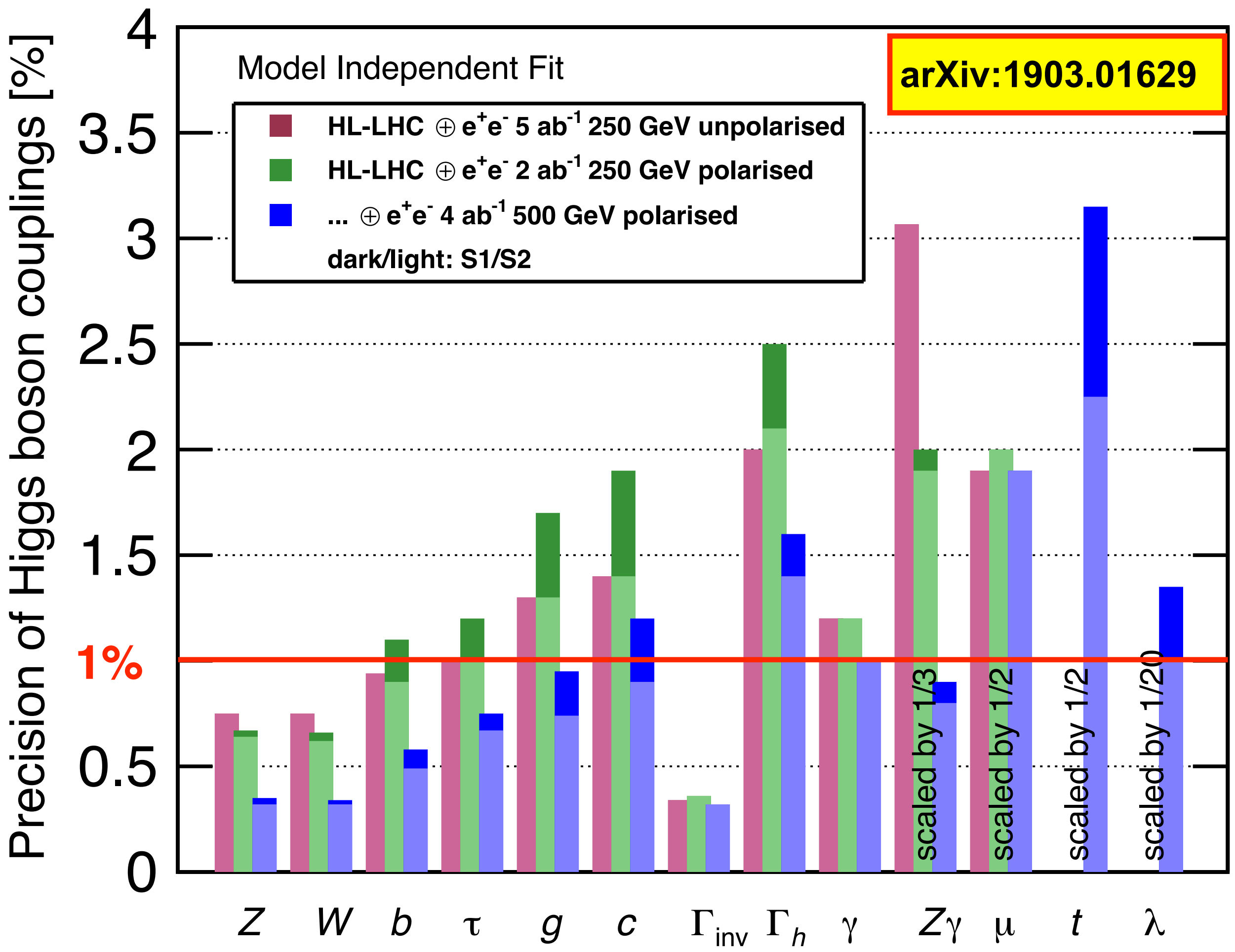

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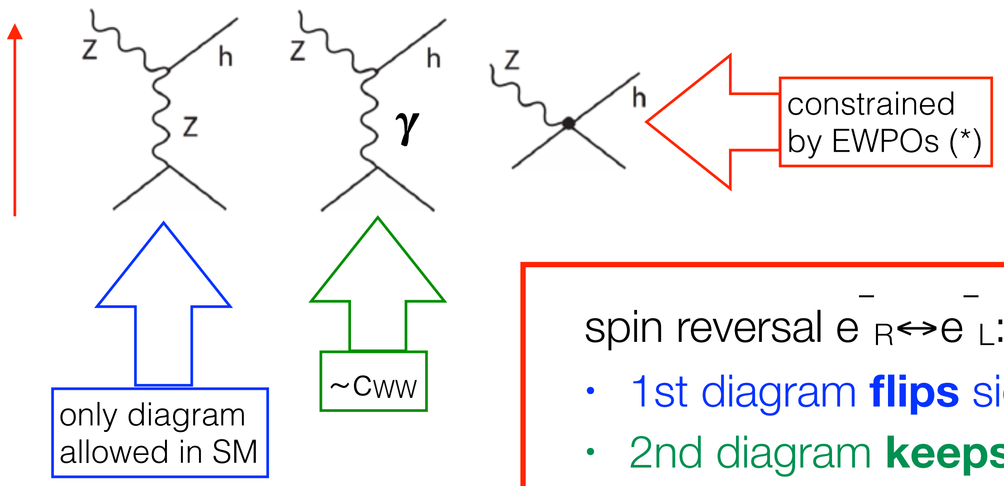
  Higgsstrahlung $e^+e^- \to Zh$

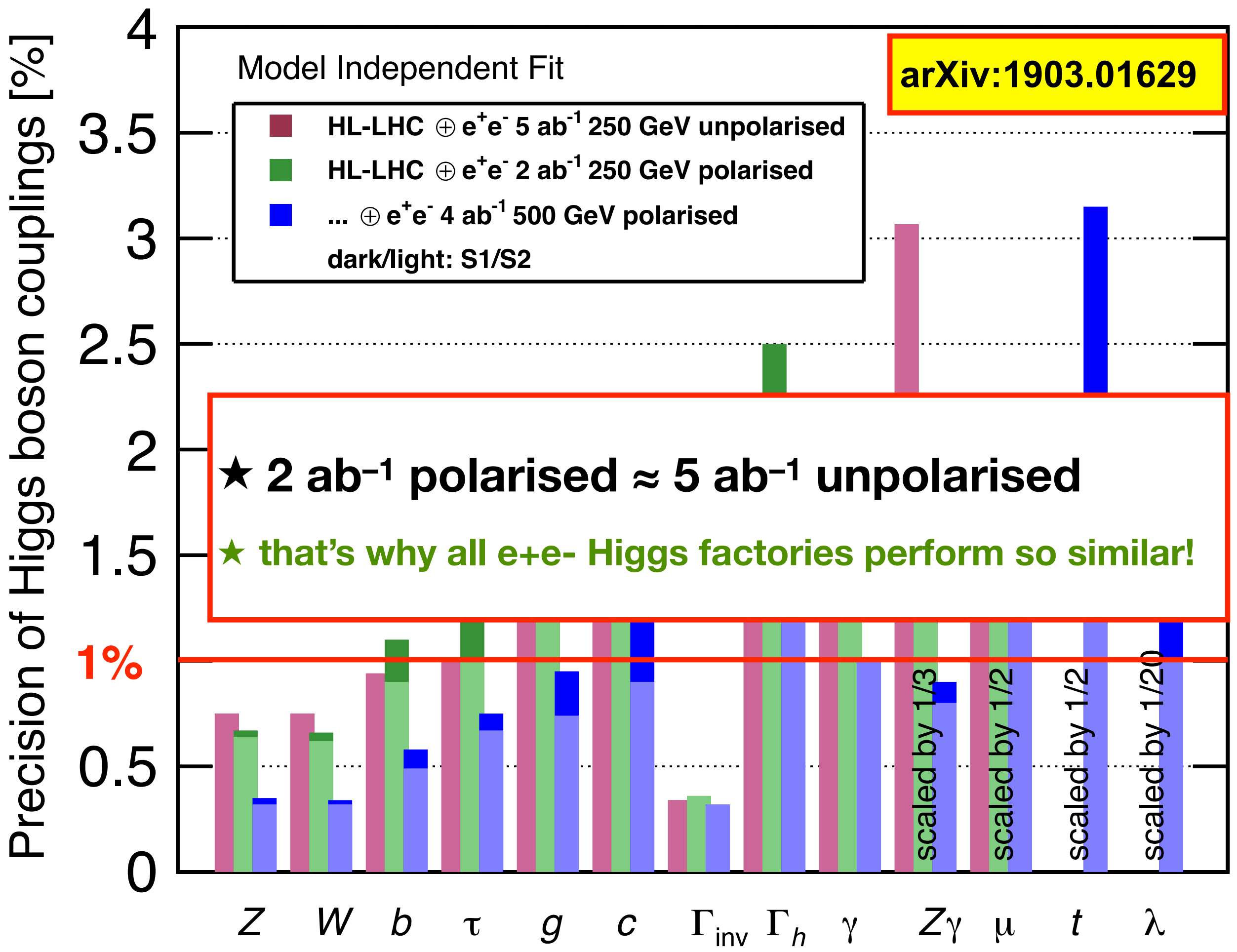
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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

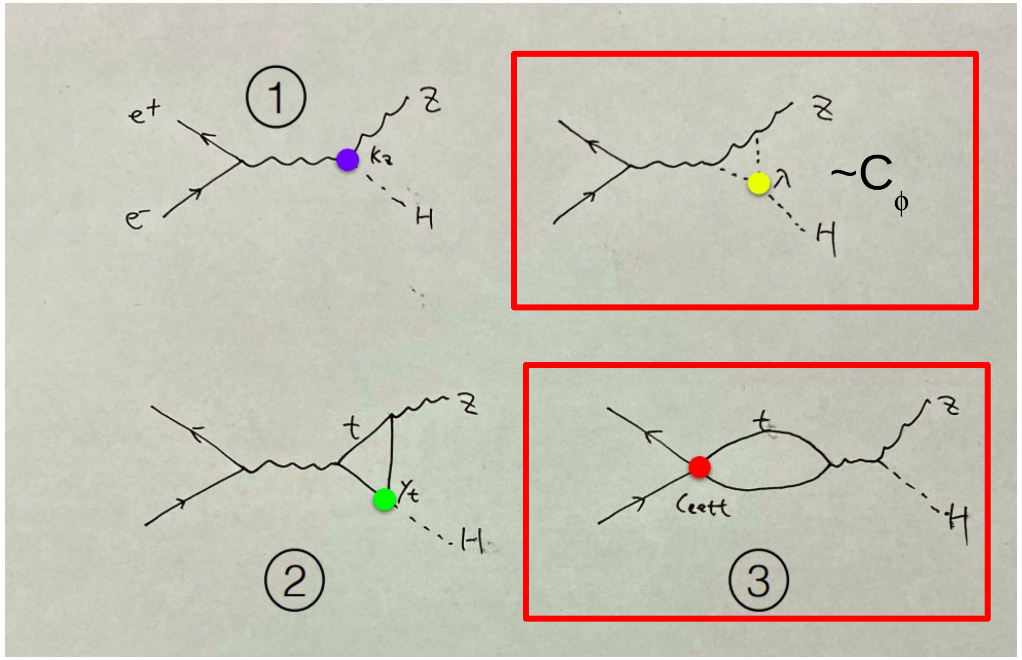
- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

⇒ A_{LR} lifts degeneracy between operators!



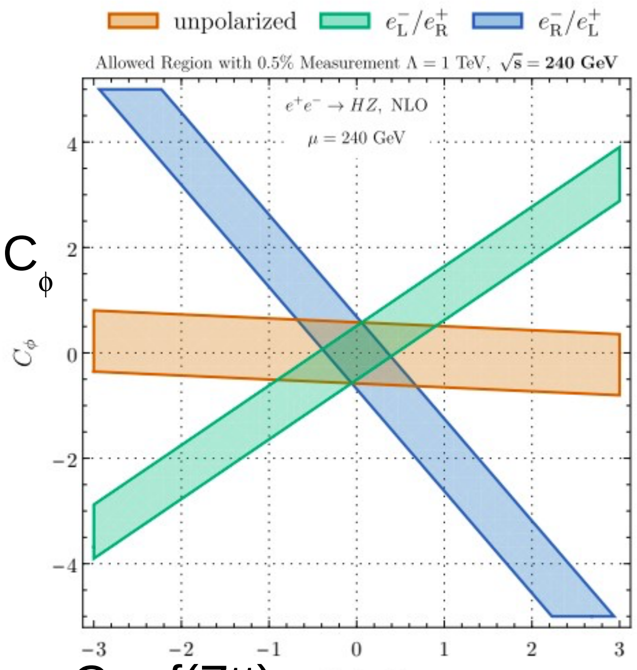
Entanglement - SMEFT NLO

NLO Contributions to ee->HZ



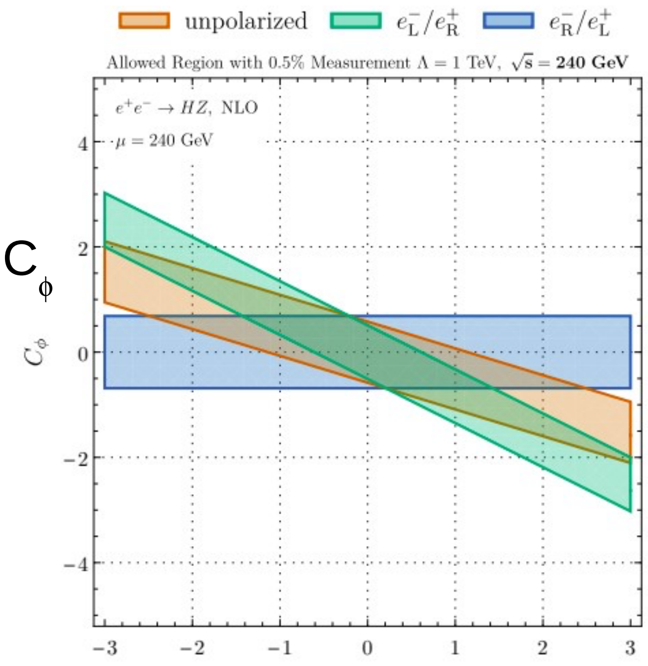
One important contribution is eett Vertex

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)

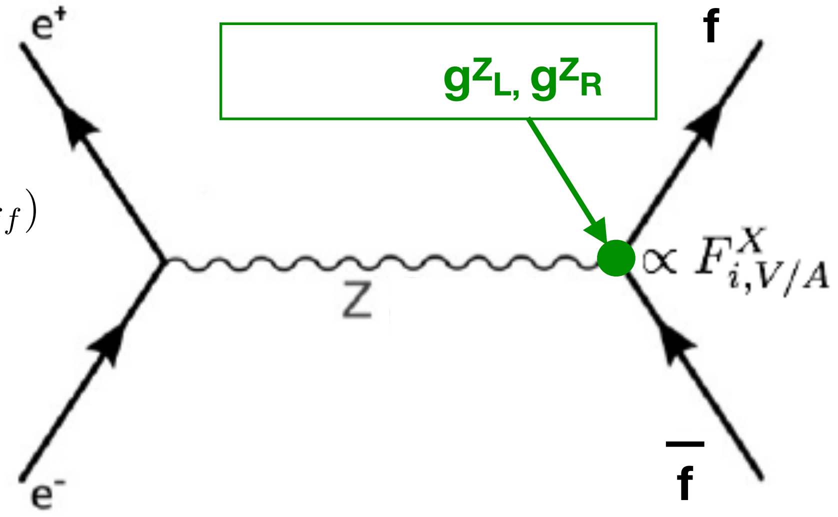
Polarisation & Electroweak Physics

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 *un*polarised collider:

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

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

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

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

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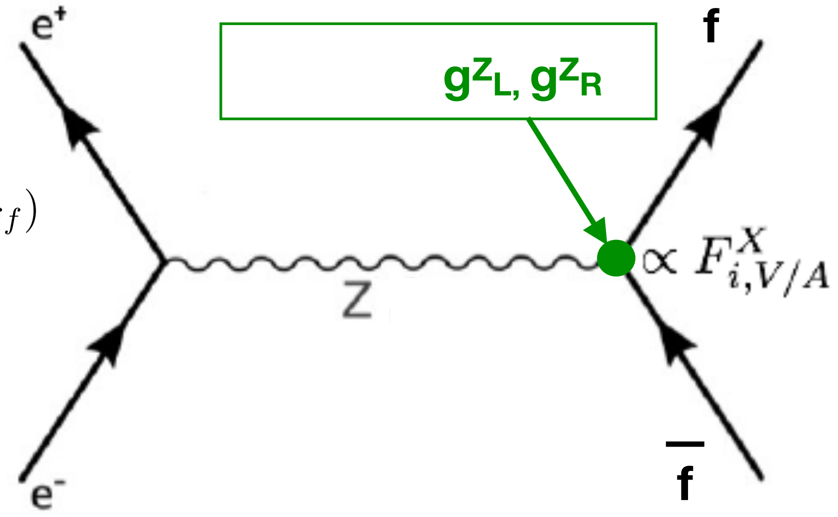

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trading theory uncertainy:

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

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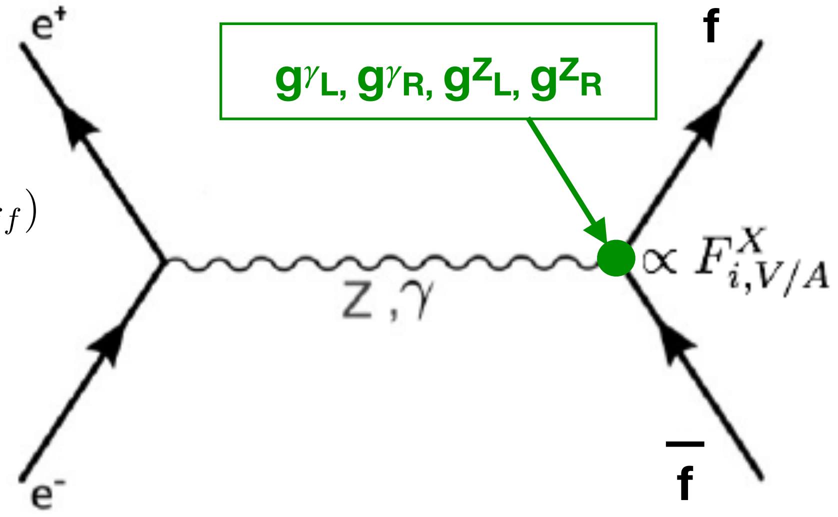

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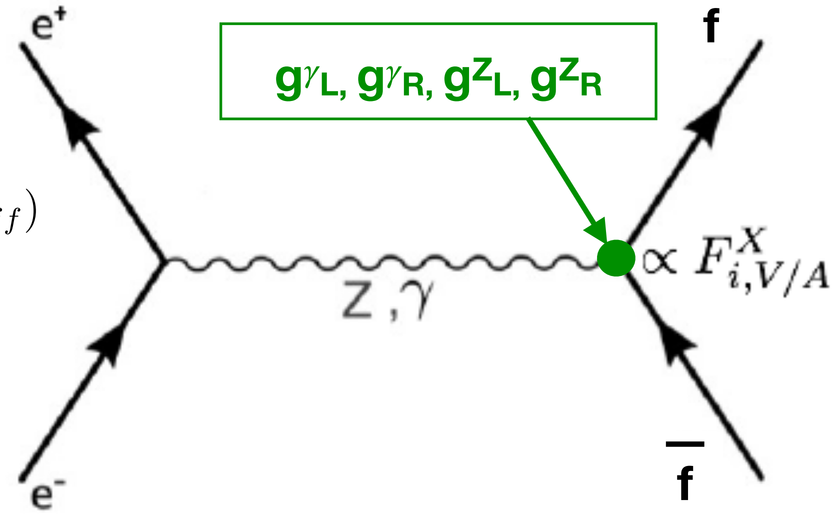

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above Z pole, polarisation essential to disentangle Z / γ exchange in $e^+e^- \to f\bar{f}$

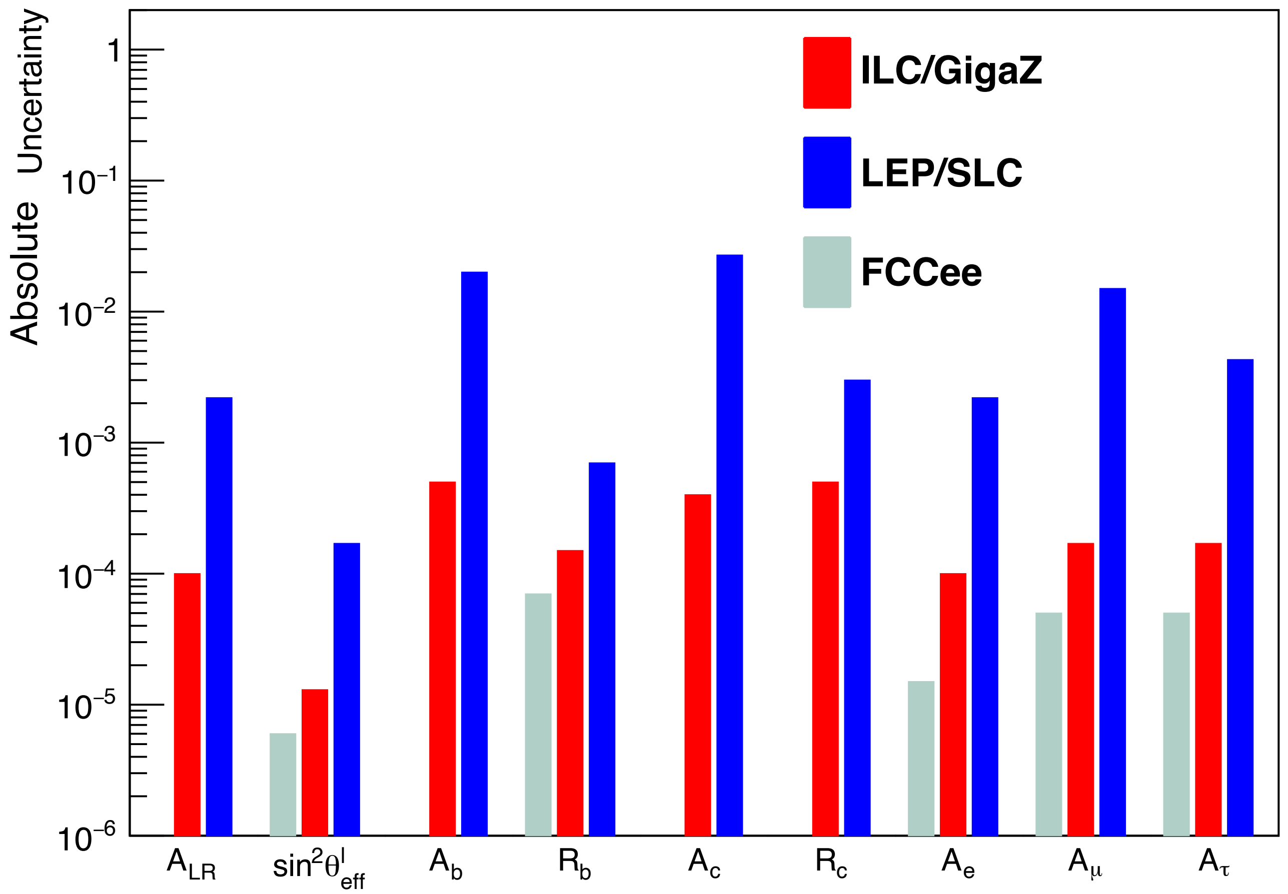
Polarisation & Electroweak Physics at the Z pole

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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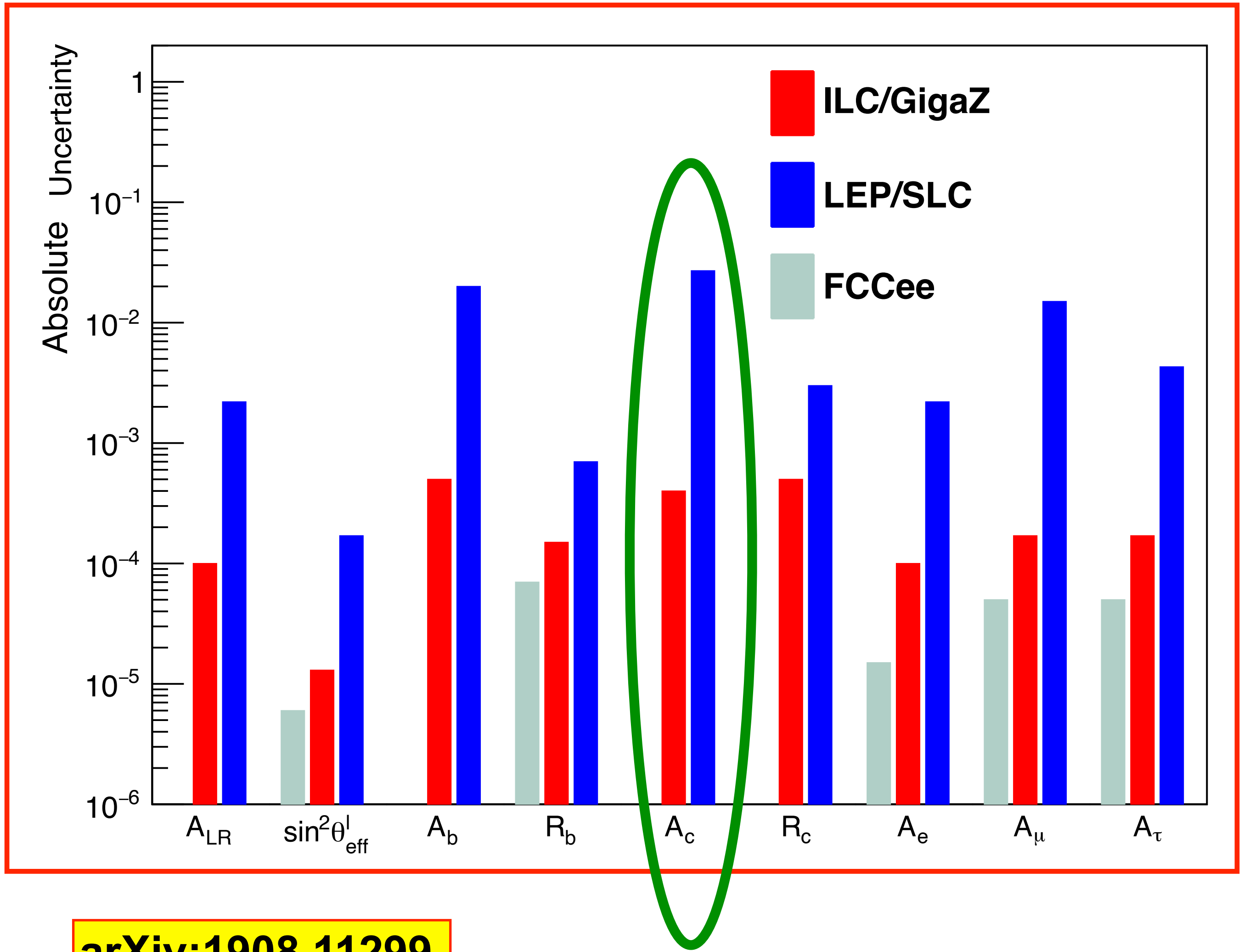

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BSM reach of ee → cc / bb

arXiv:2403.09144

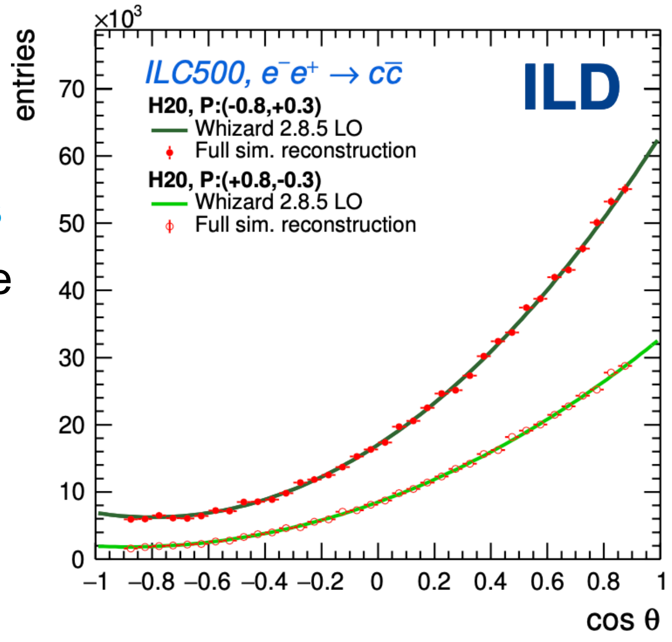
Forward-backward and left-right asymmetries above the Z pole

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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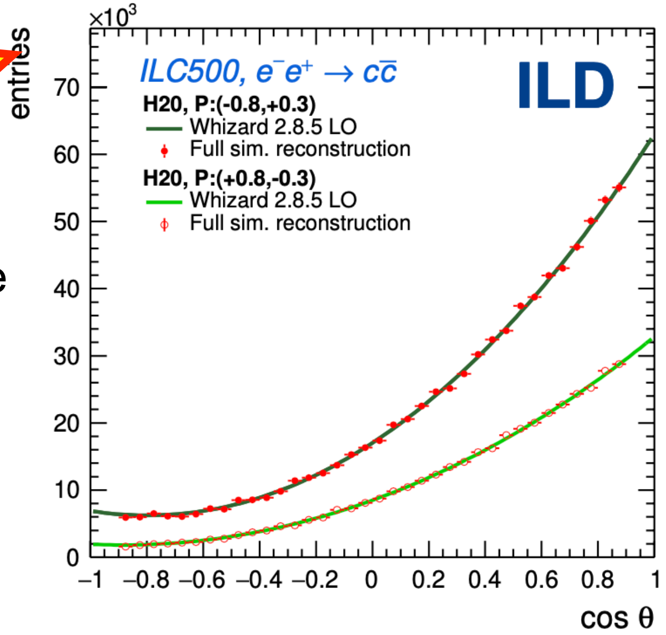

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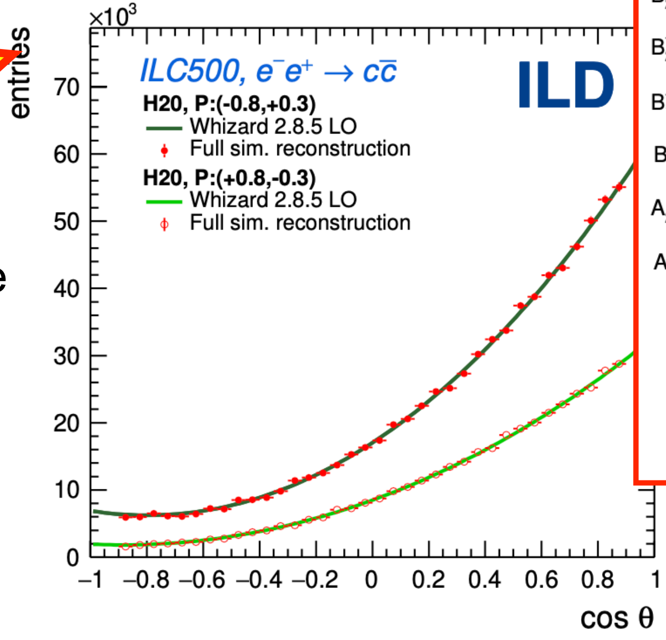

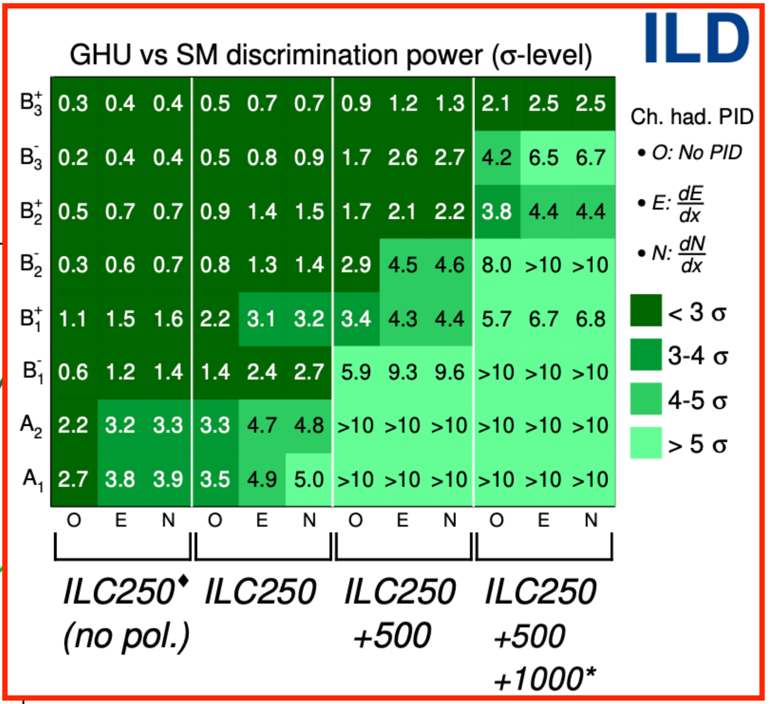

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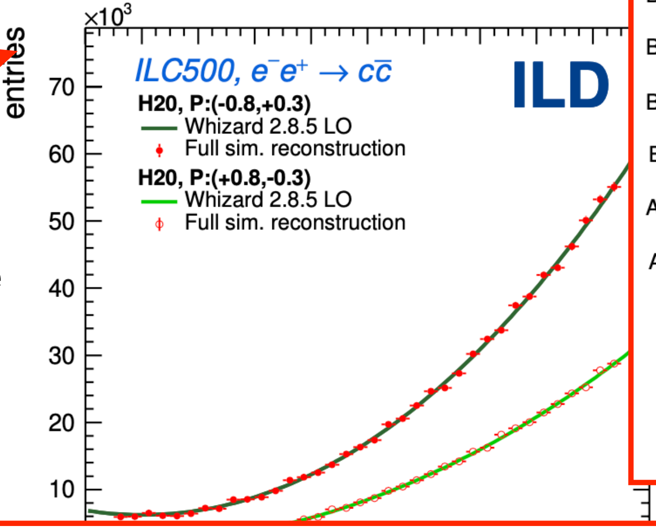

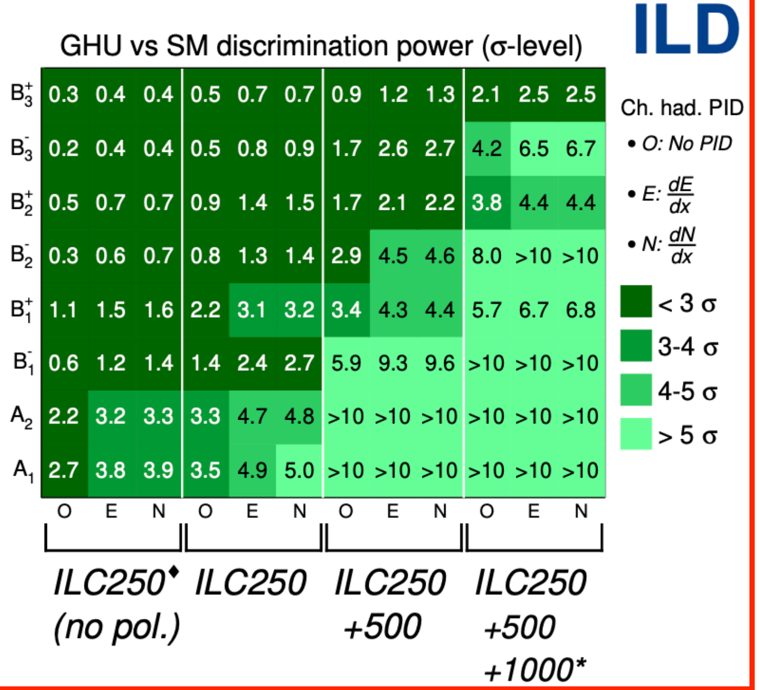

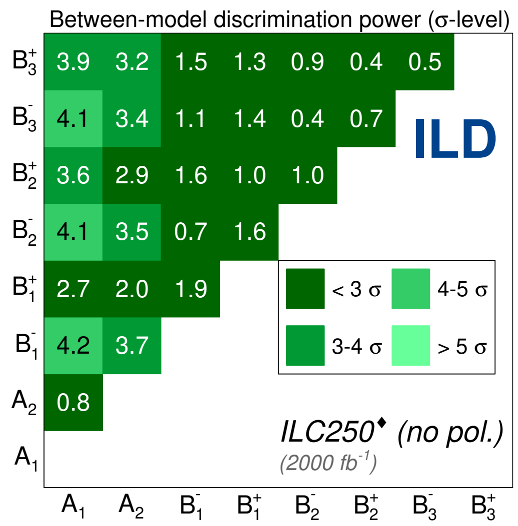

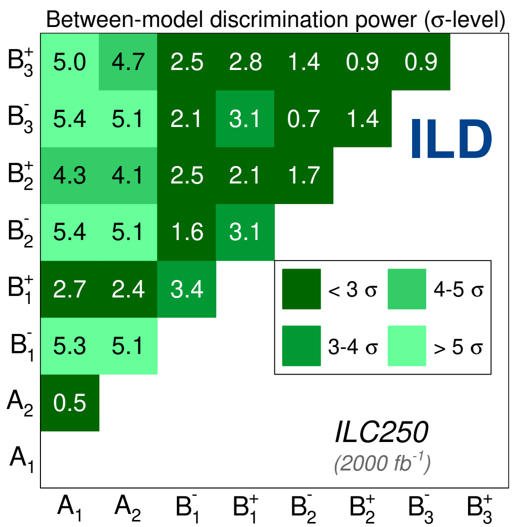

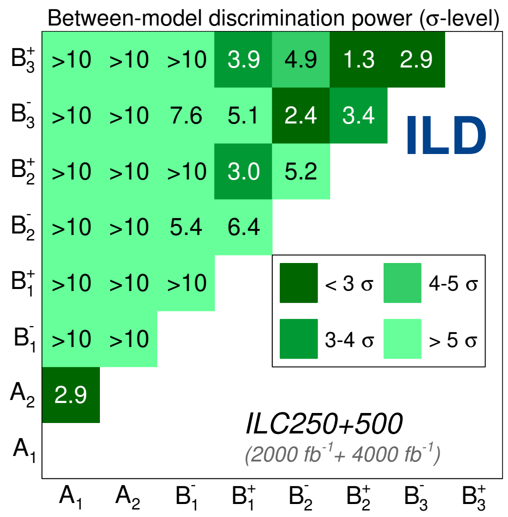

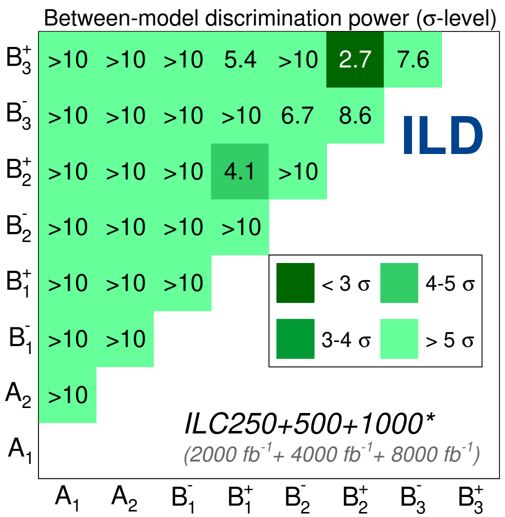

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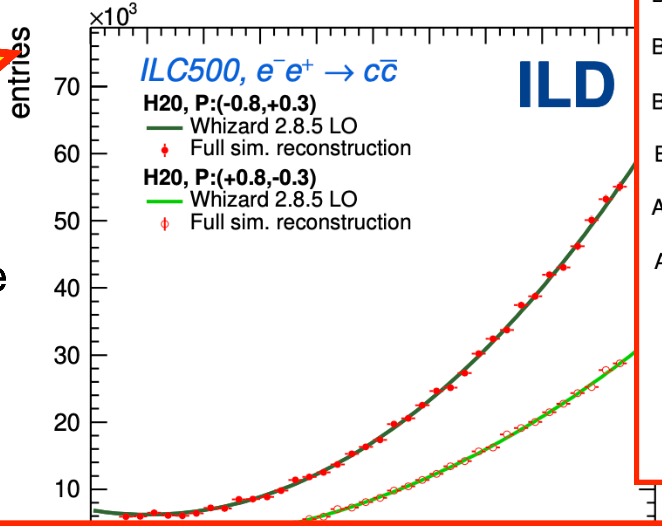

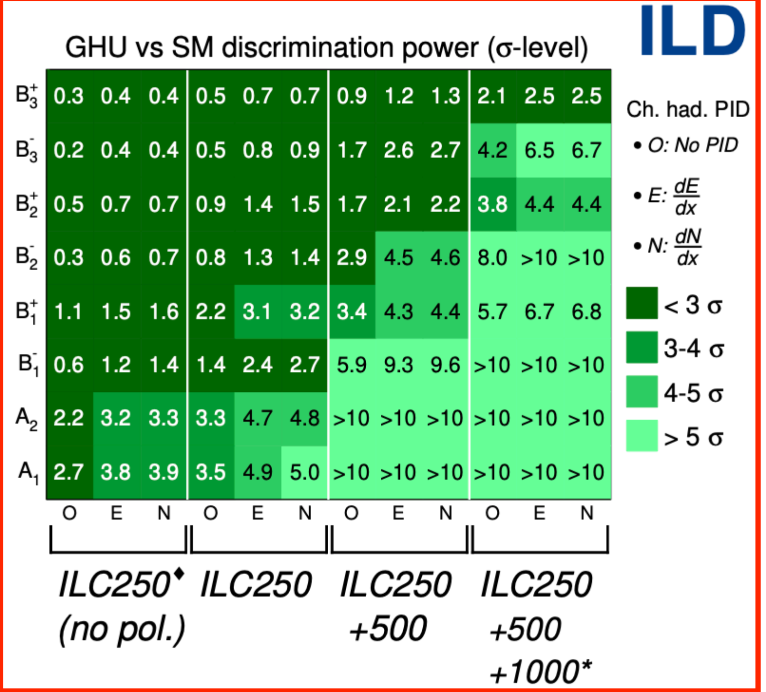

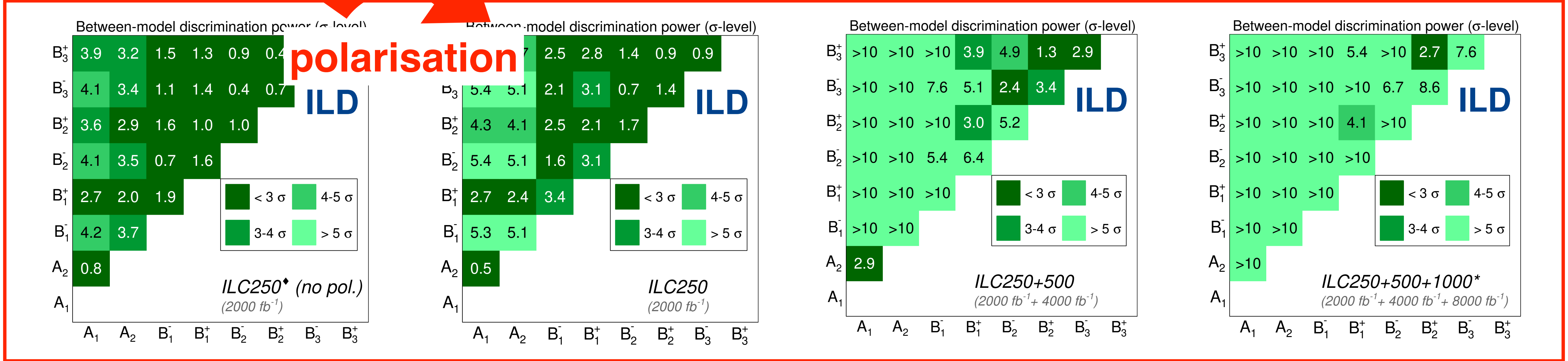

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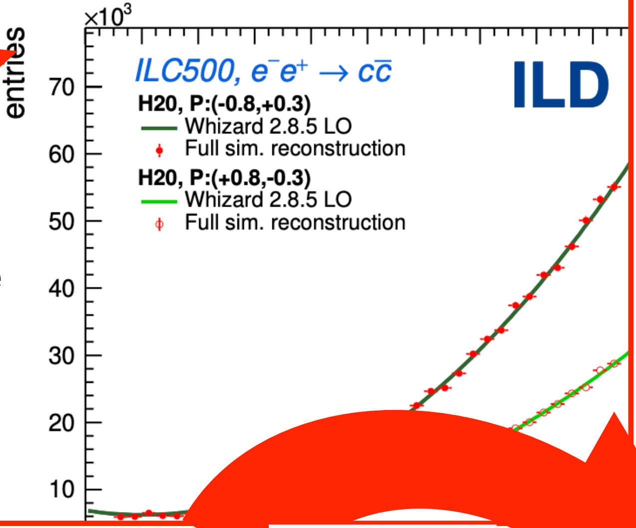
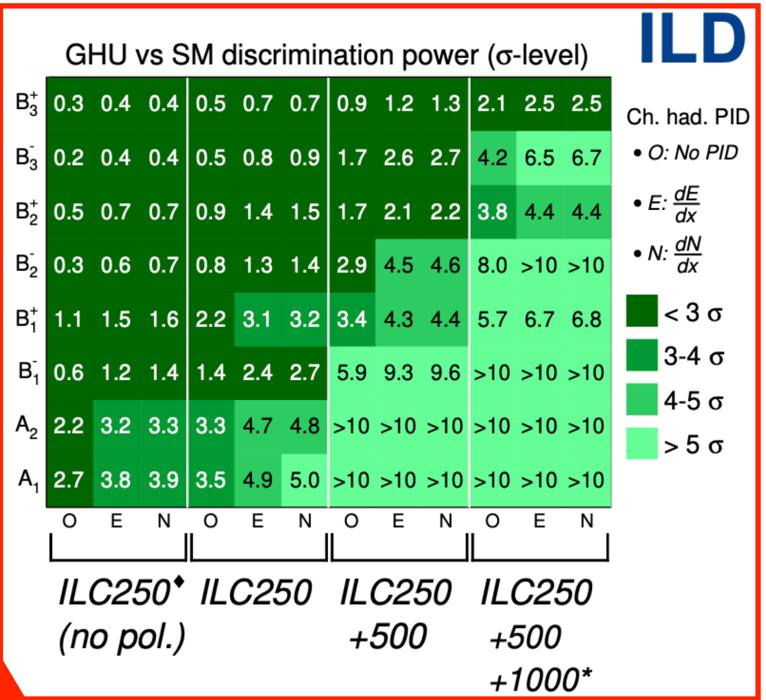
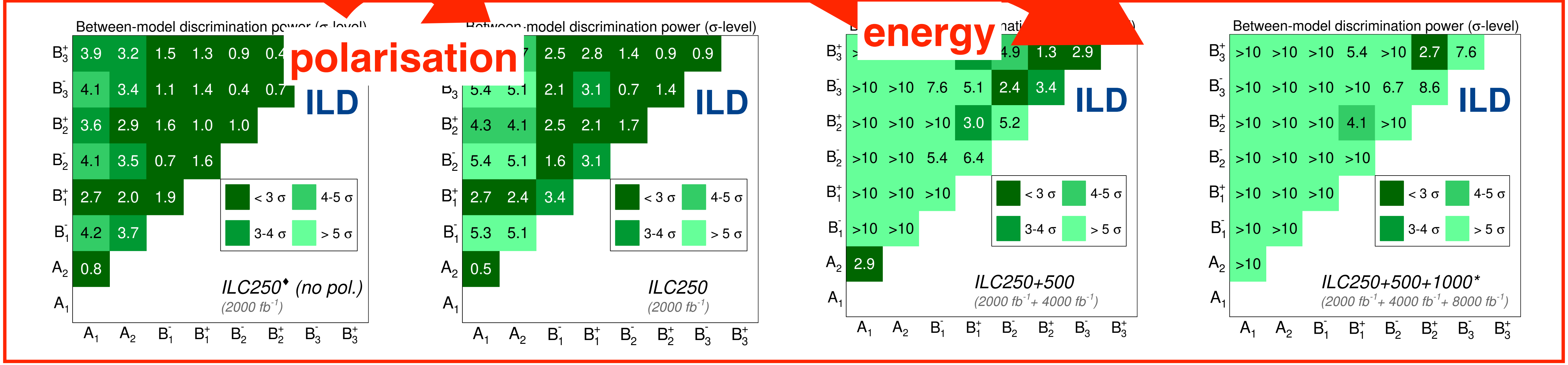


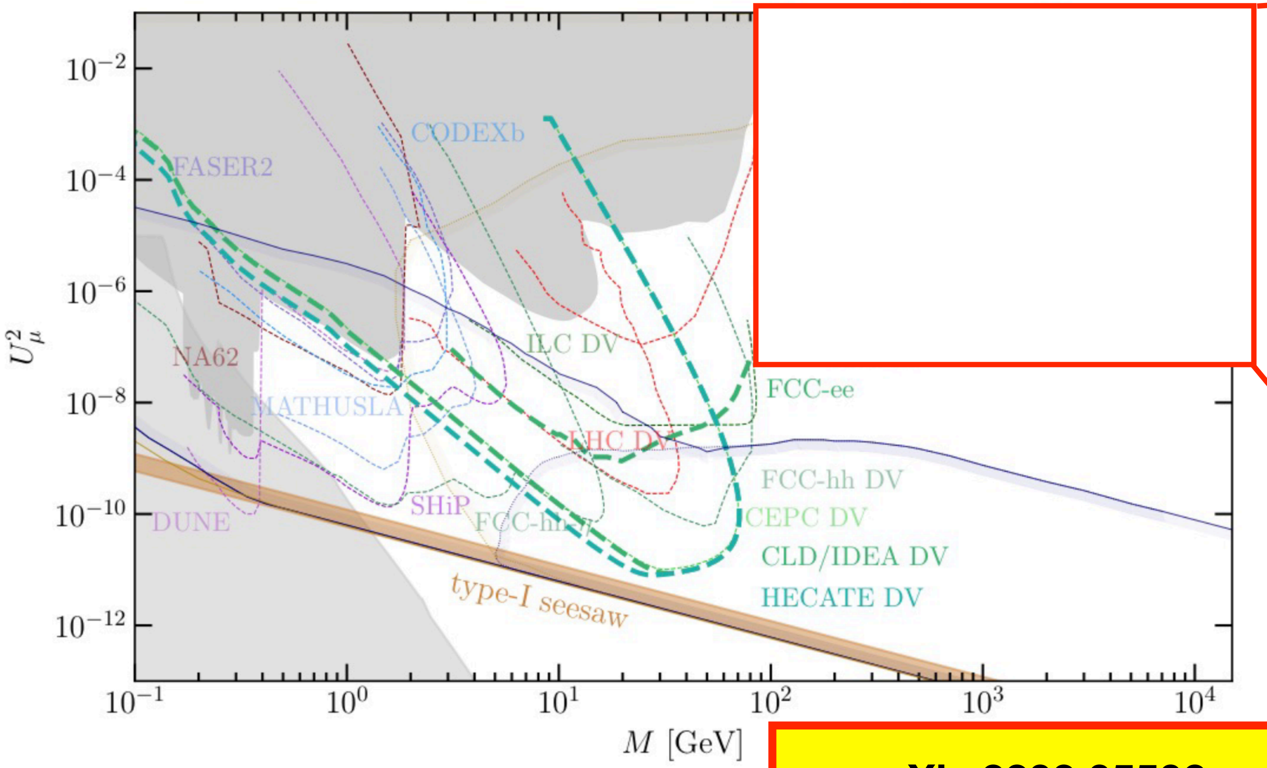




Heavy Neutral Leptons

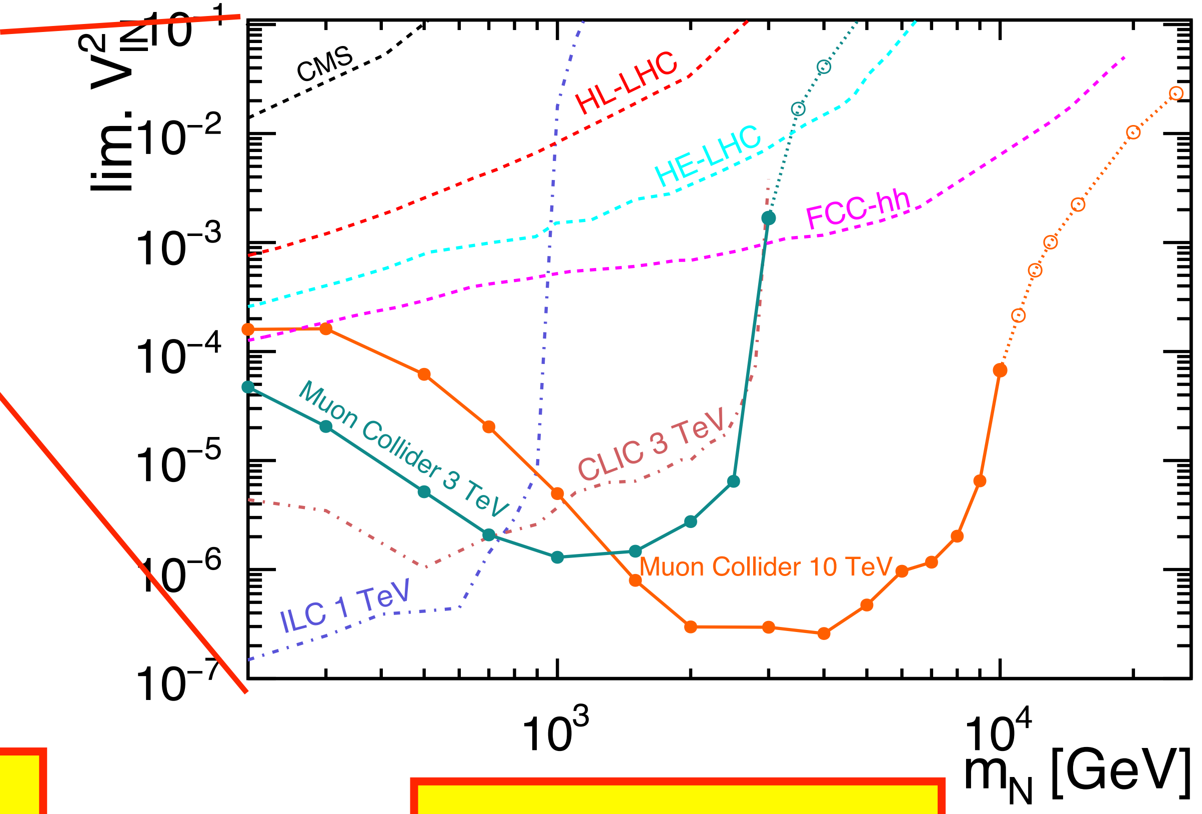
Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices…



arXiv:2203.05502

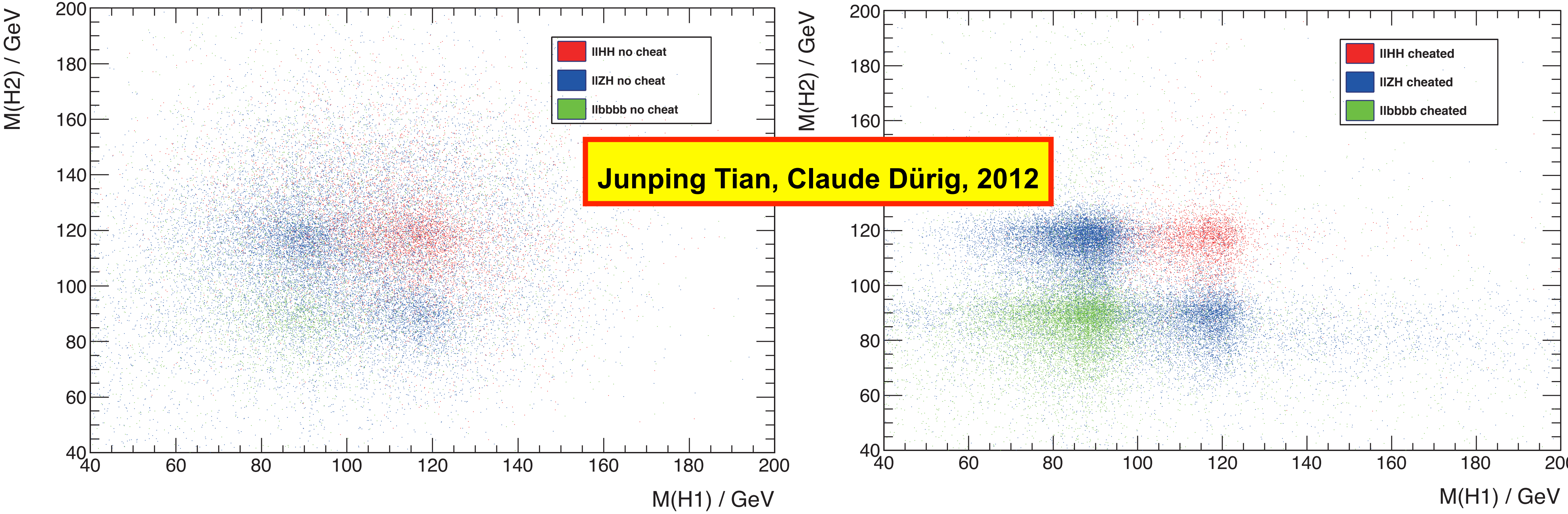
…and at high masses in prompt decays



arXiv:2301.02602

Urgently wanted: modern jet clustering

… bottle-neck for Higgs self-coupling precision



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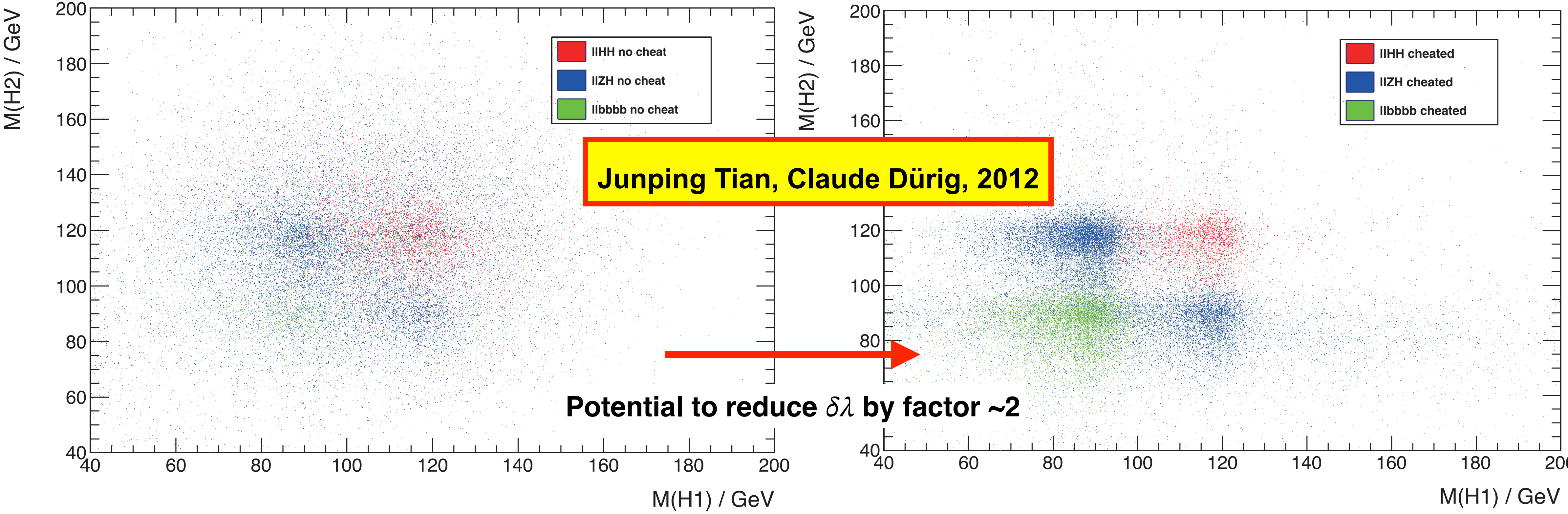

Junping Tian, Claude Dürig, 2012

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

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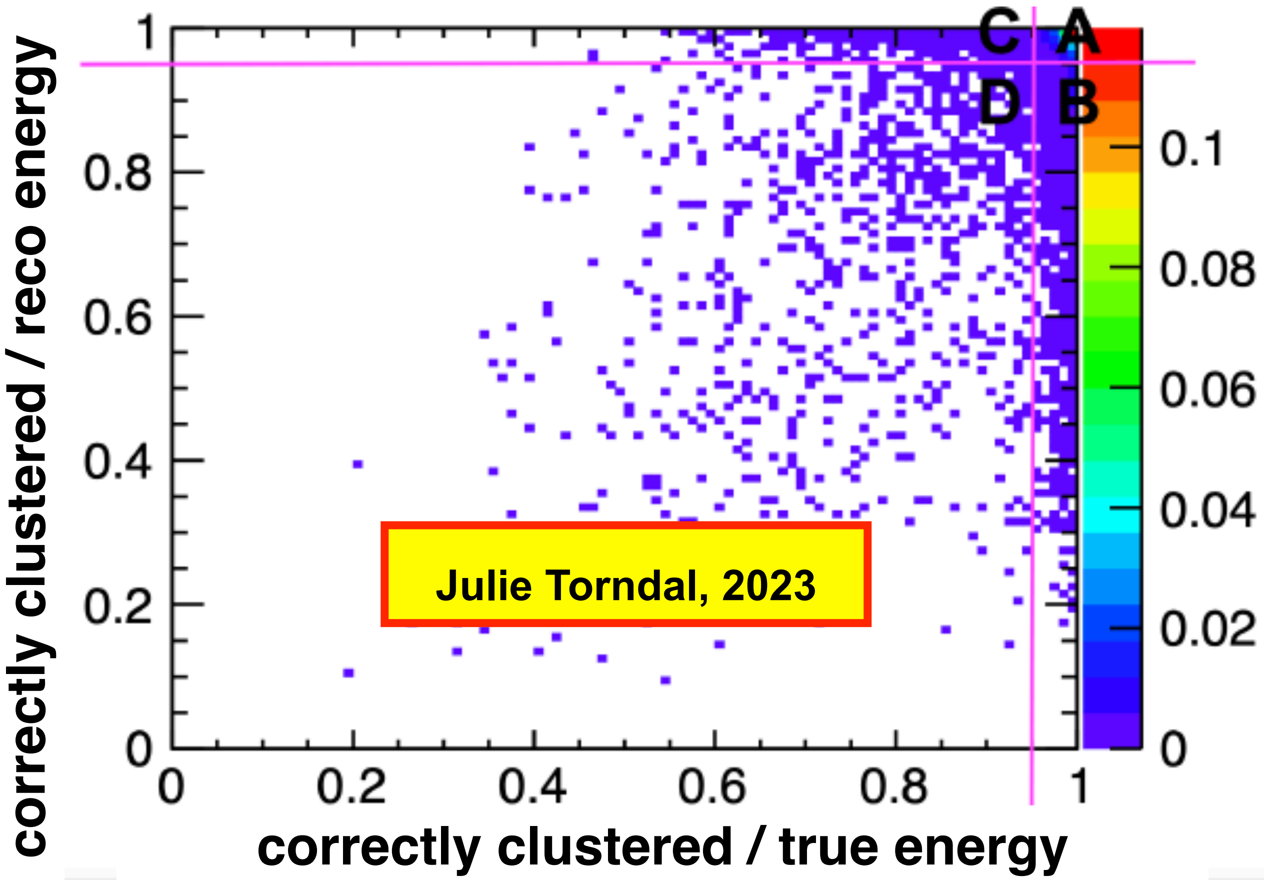

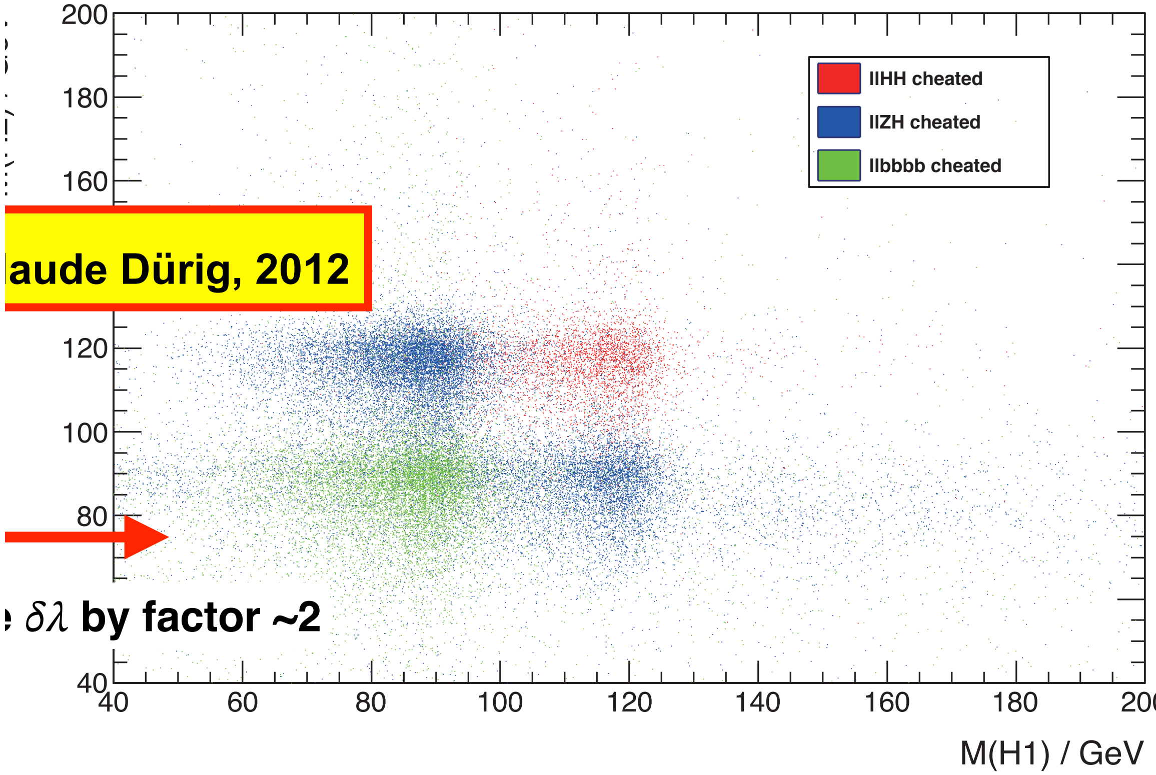

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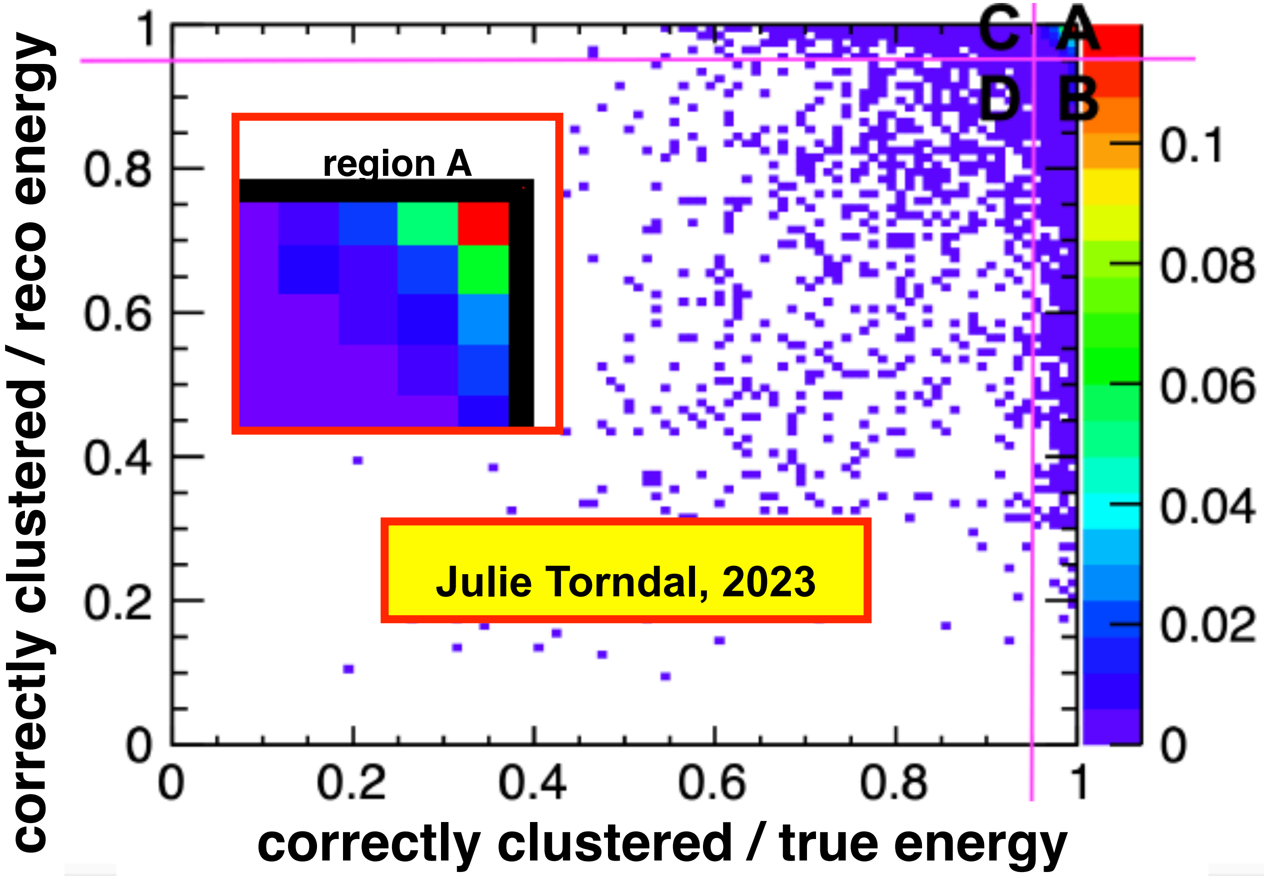

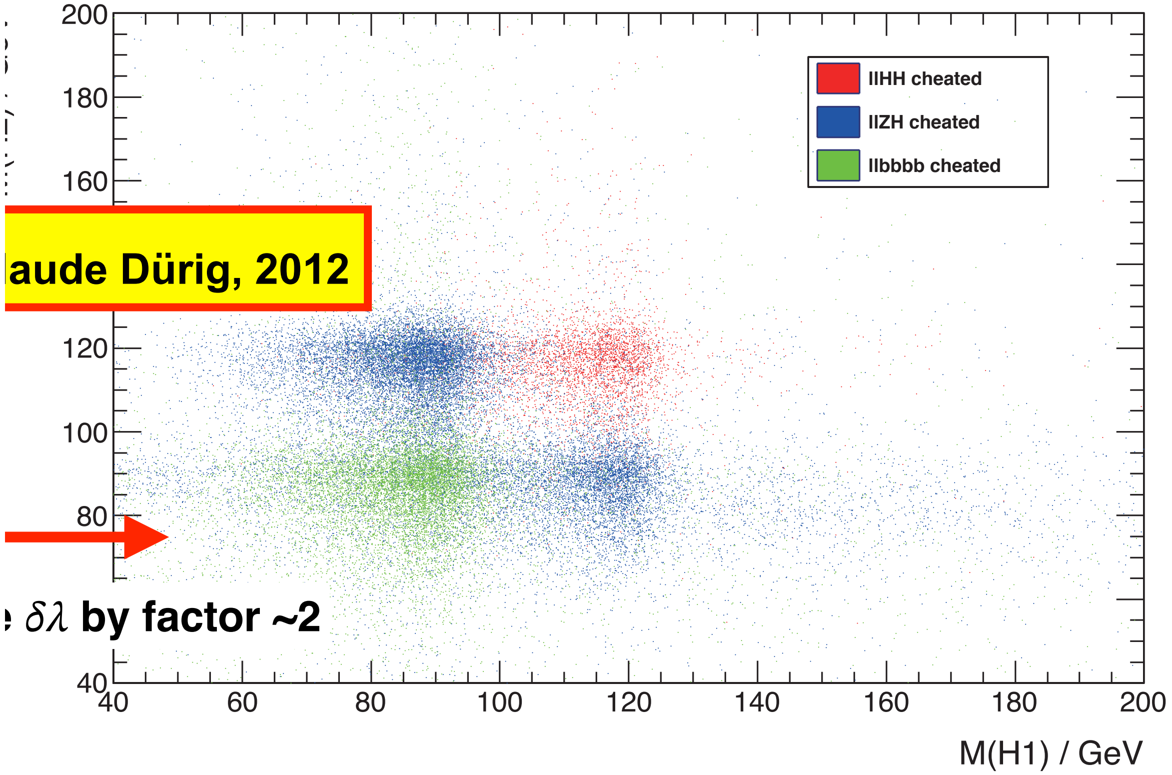

Claude Dürig, 2012

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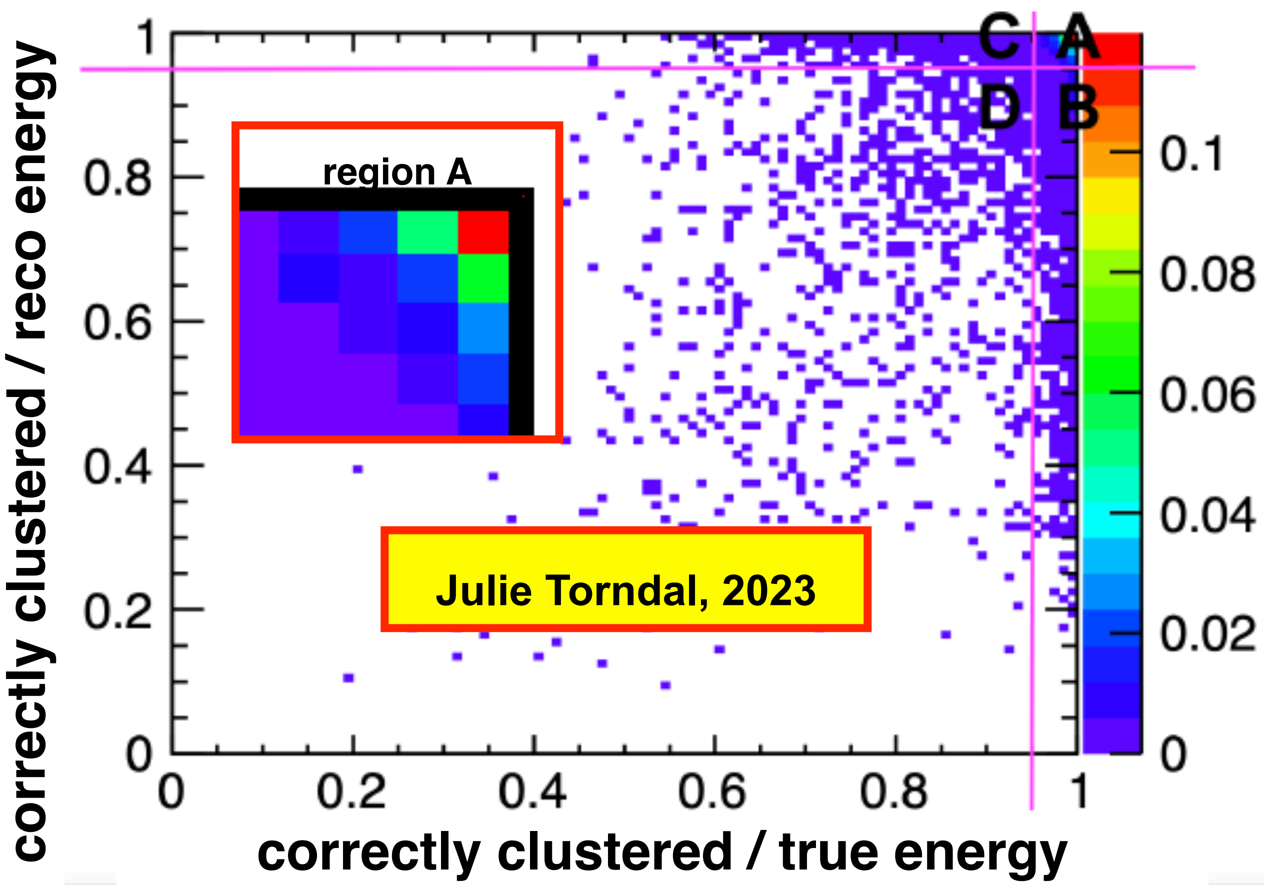

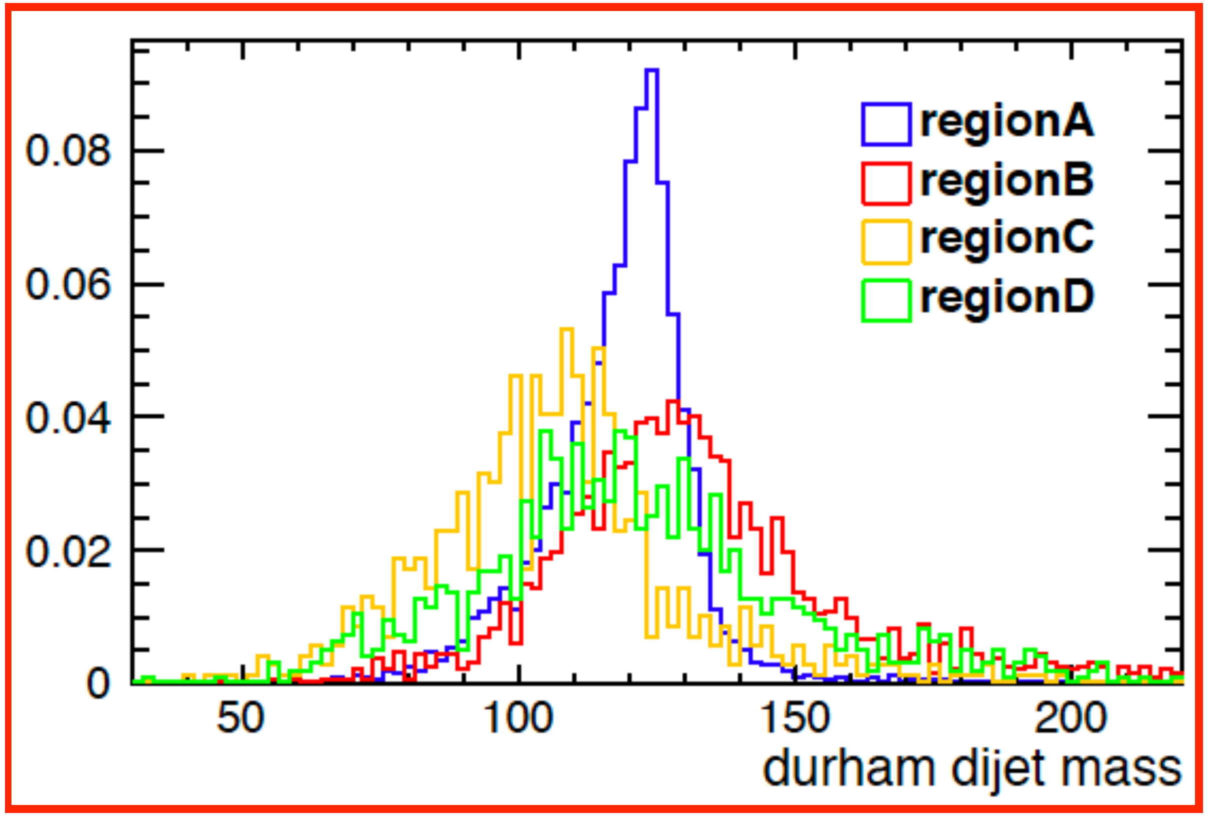

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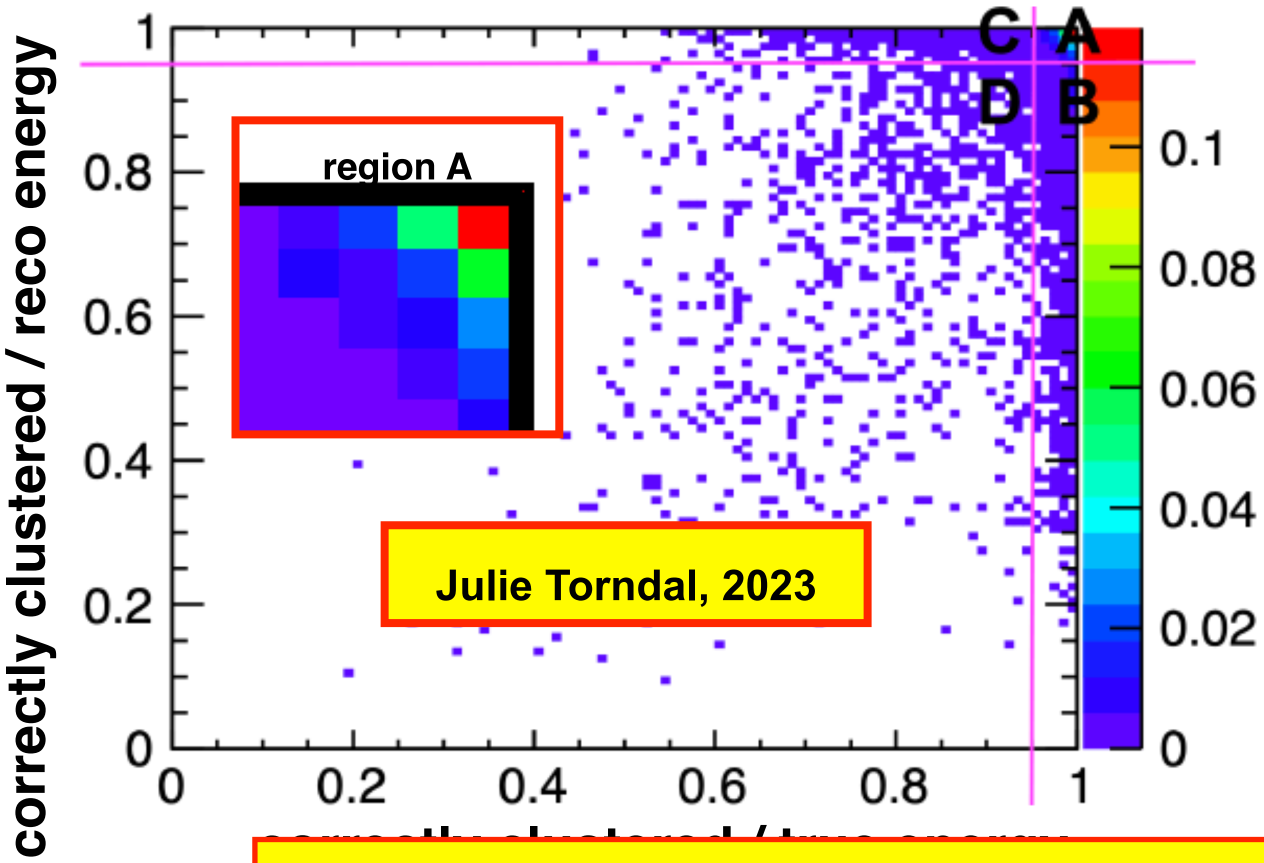
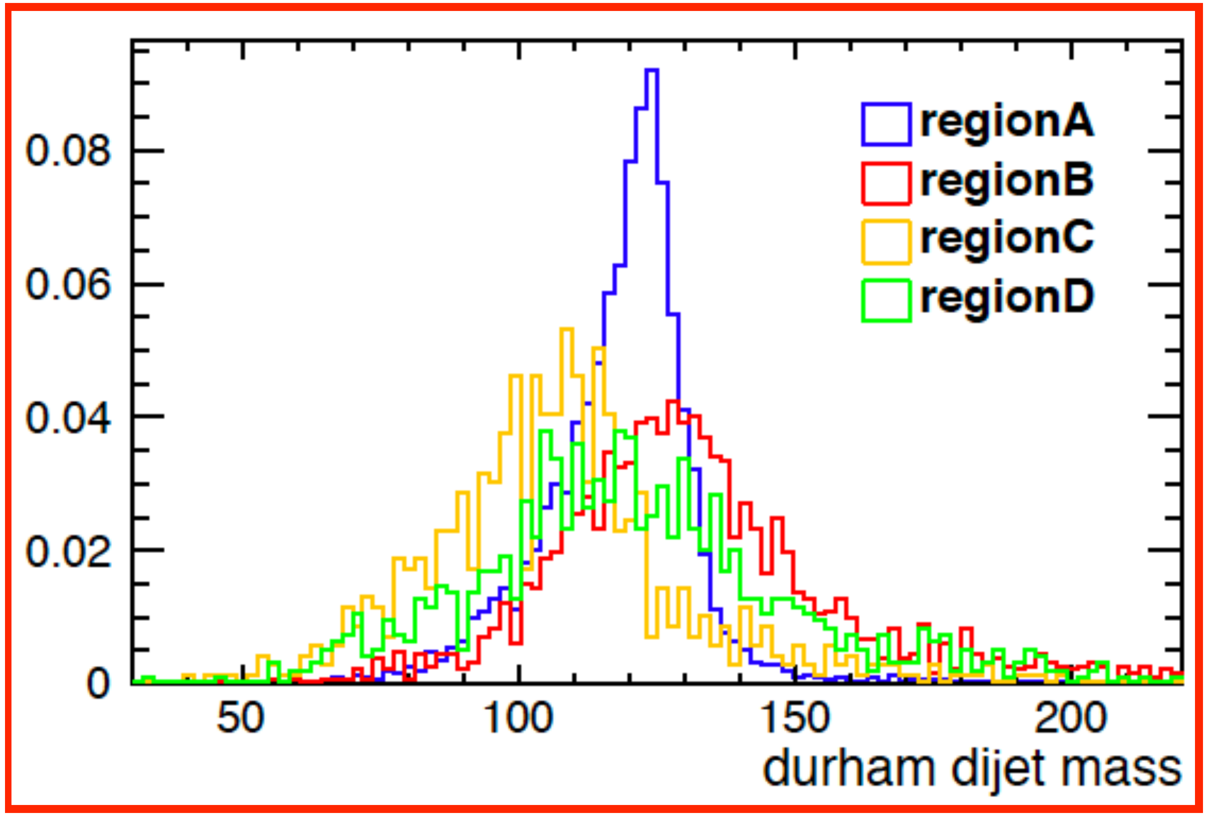




=> Urgently needed: Advanced Jet Clustering, ML, …can we get rid of B, C, D ???

which additional detector information would help?

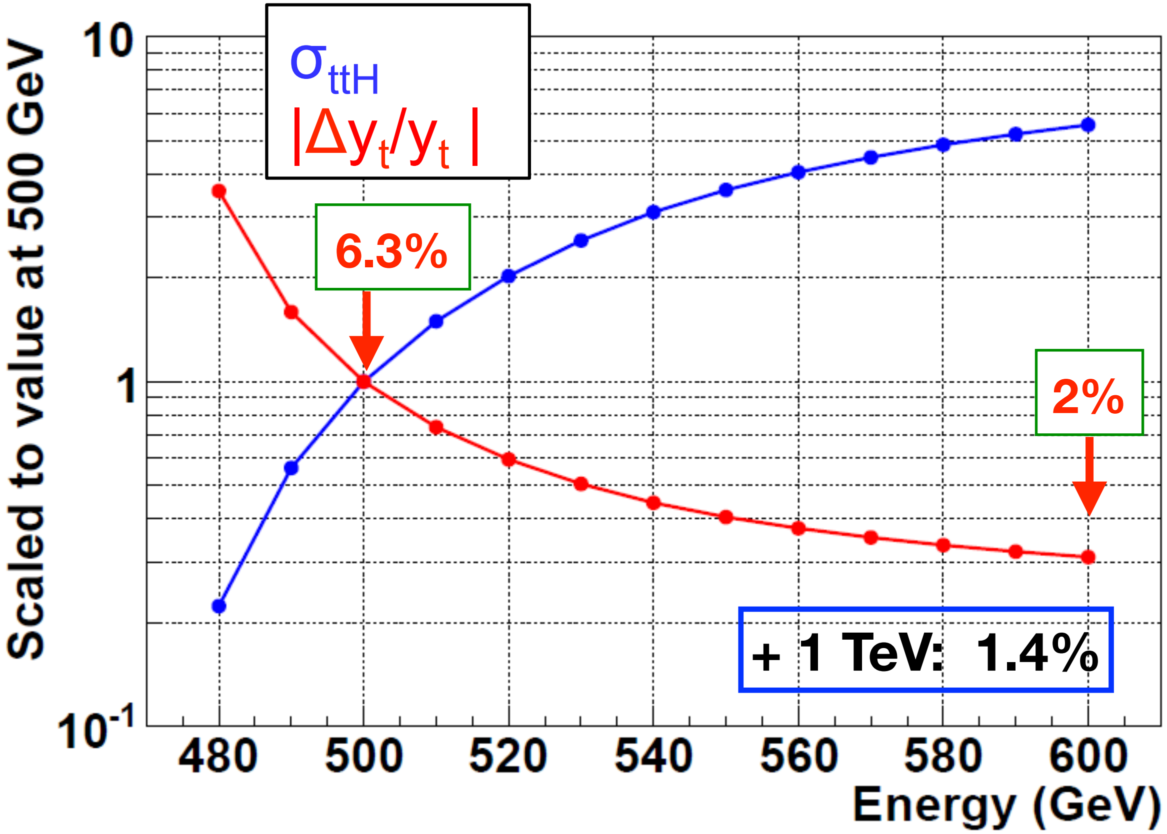
This has the potential to reduce $\delta\lambda/\lambda$(SM) from 20% to 10% !

Top Yukawa coupling

Choosing the right energy

[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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The Higgs and the Top

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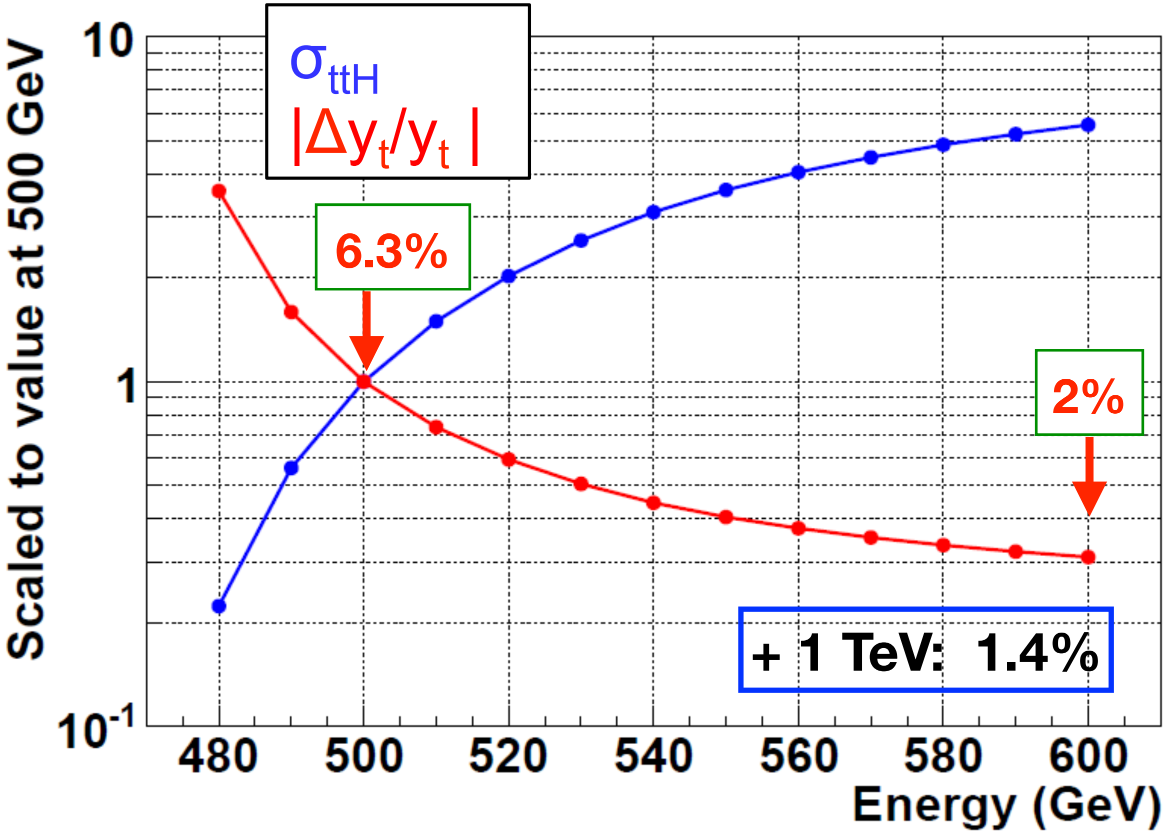


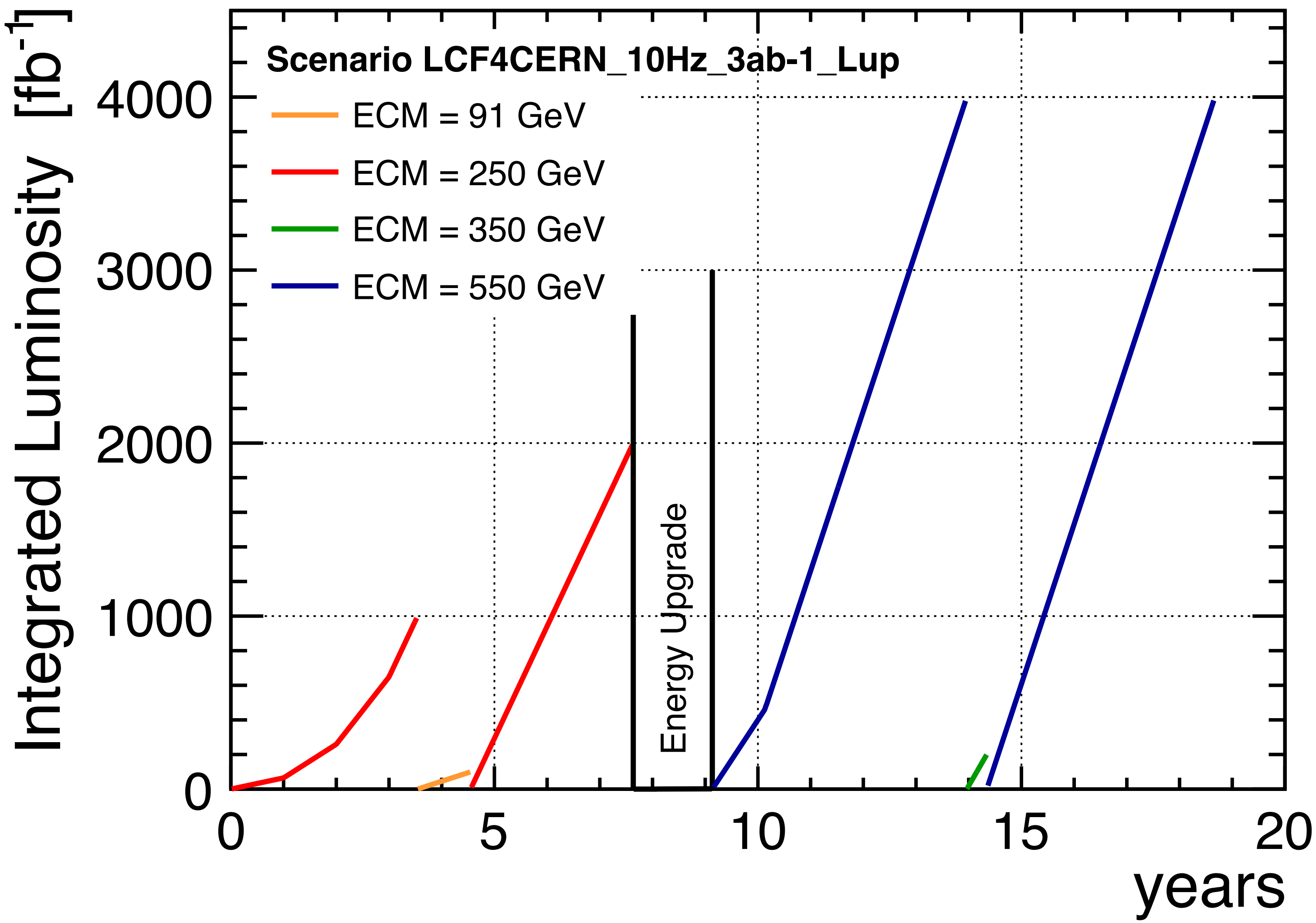
to-do: real, full sim study @ 600 GeV!

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

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

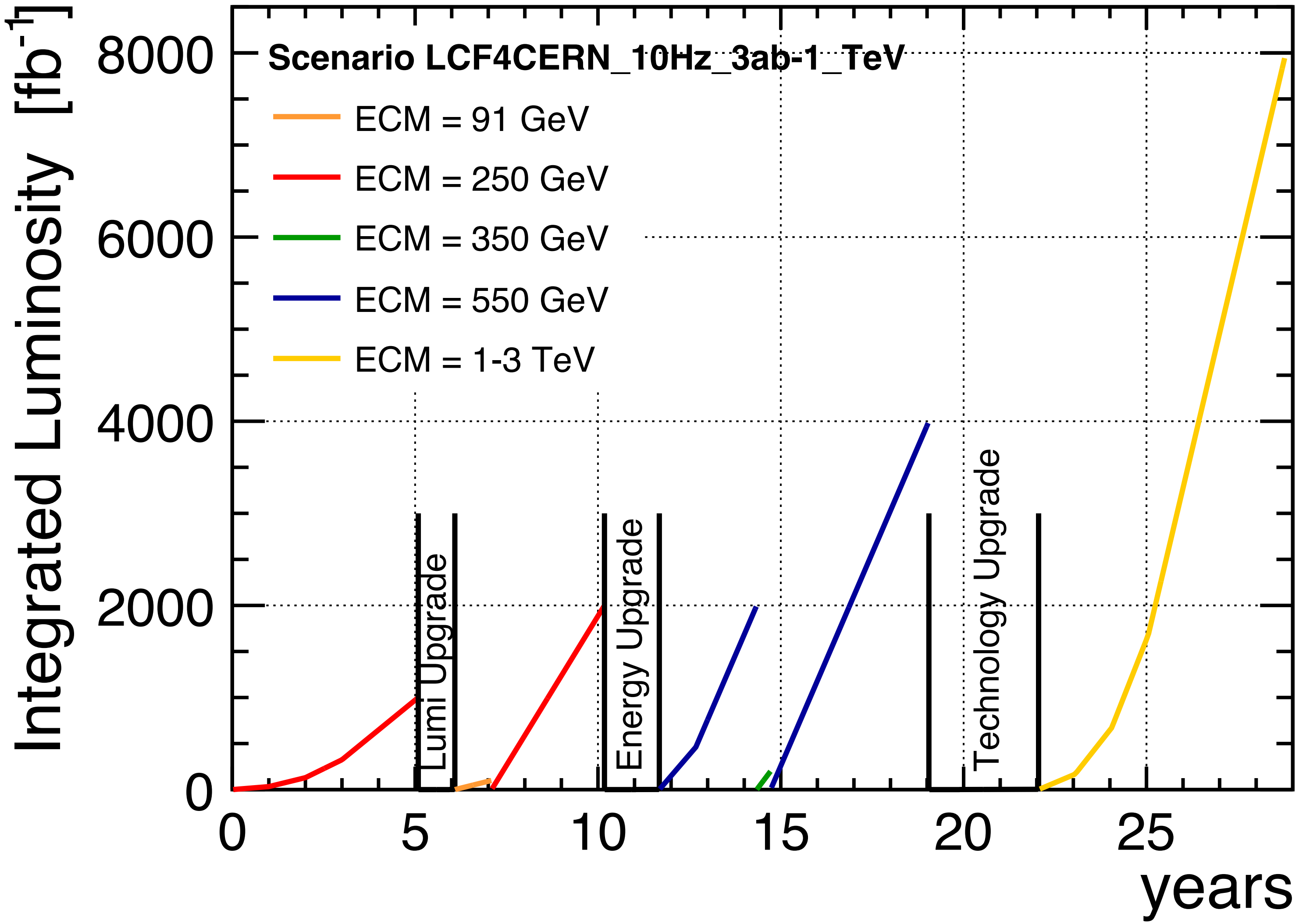
Running Scenarios - illustrating the flexibility

start with full power



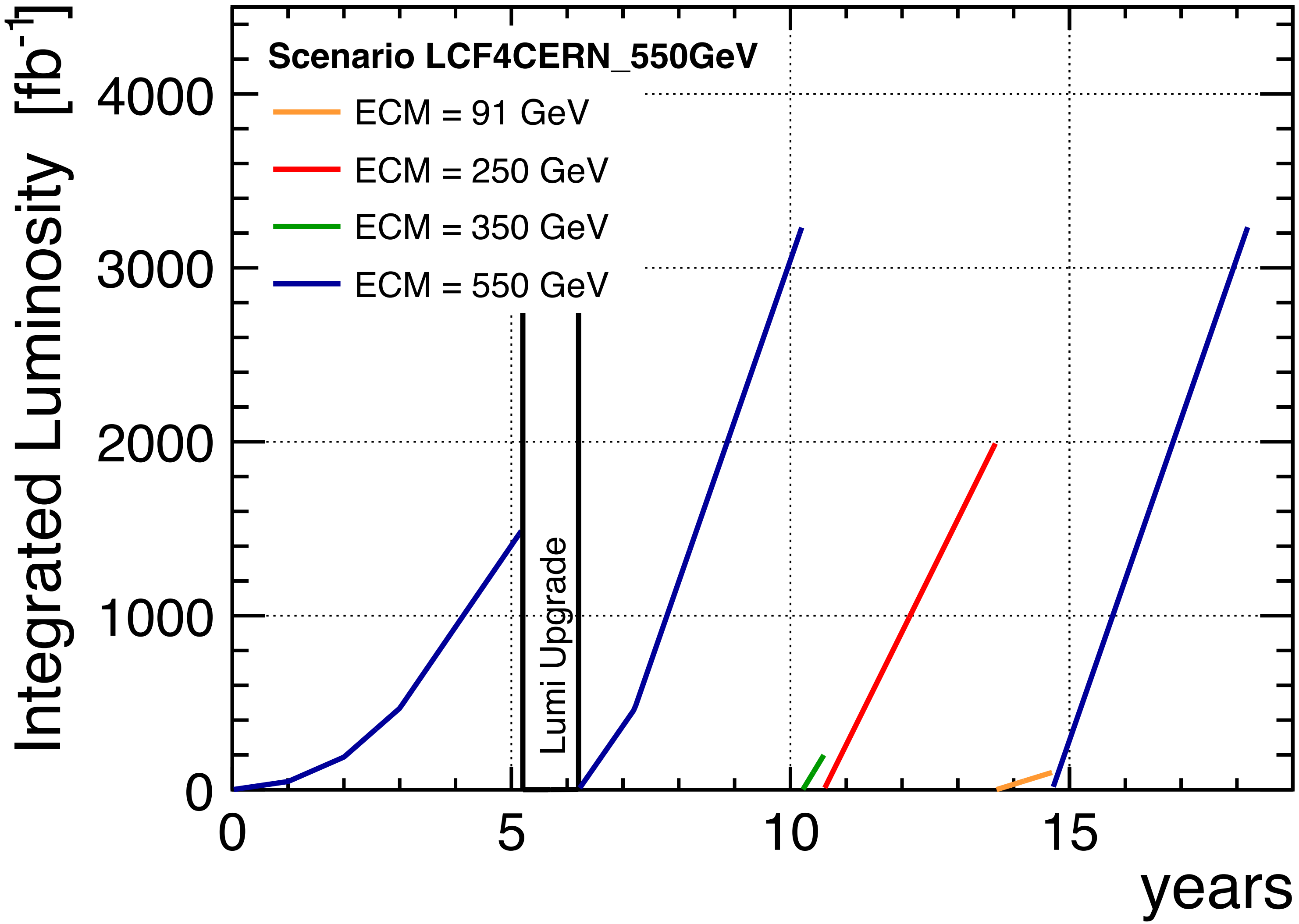
Running Scenarios - illustrating the flexibility

shorten 550 GeV to go to TeV range earlier



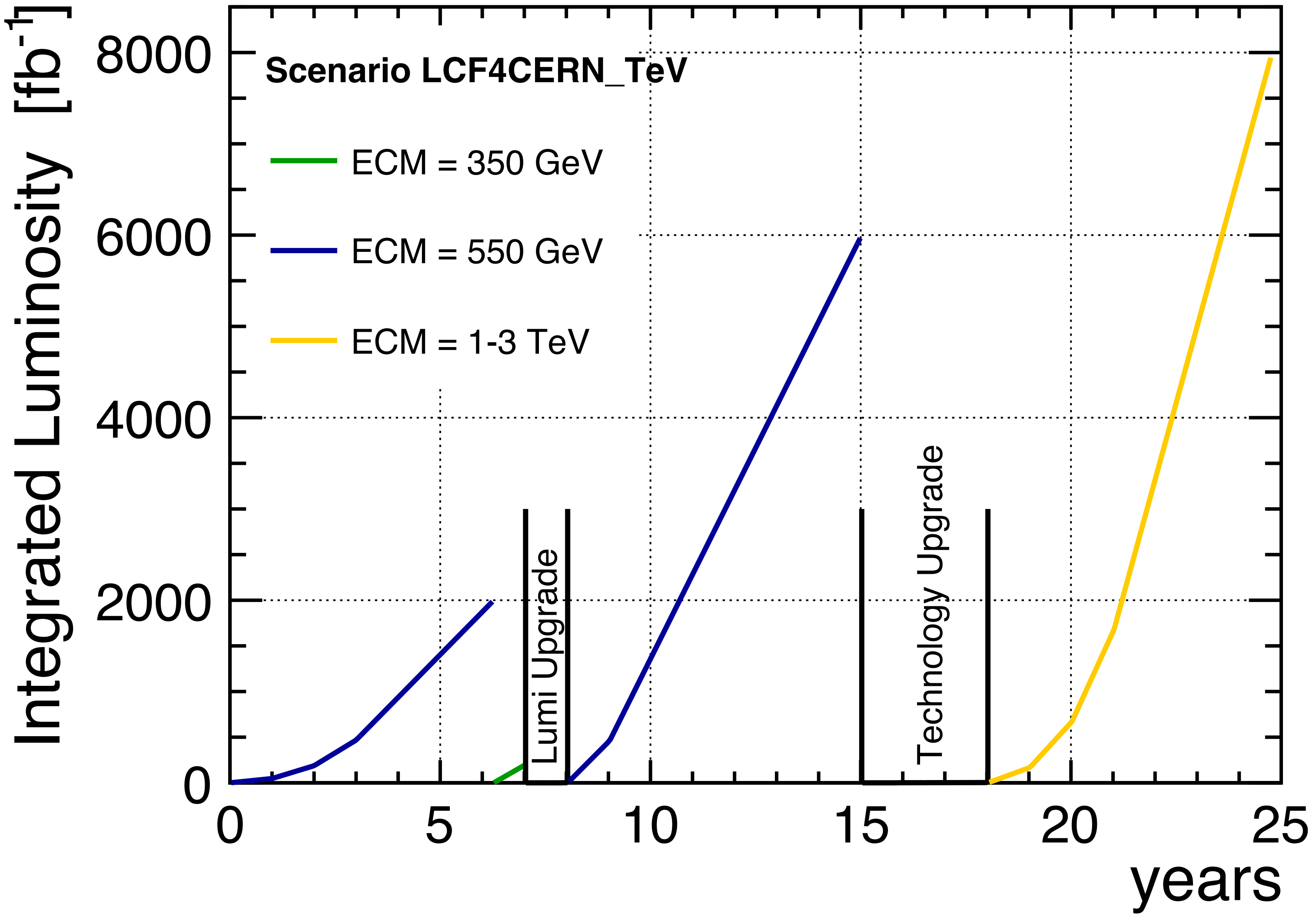
Running Scenarios - illustrating the flexibility

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