Physics at a future e^+e^- collider

J. List (DESY)

IFT Seminar, Madrid, 17th of January 2022

Outline

- Introduction
- Higgs
- Z, W & Top
- High energies
- Conclusion & ECFA study

An e^+e^- Higgs factory is the highest-priority next collider

- accelerator R&D, in particular high-field magnets
- investigate technical & financial feasibility of 100 TeV pp collider at CERN, with posssible e+e- first stage
- timely realisation of ILC in Japan would be compatible and European particle physics would wish to collaborate

https://europeanstrategyupdate.web.cern.ch/welcome

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High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

• ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

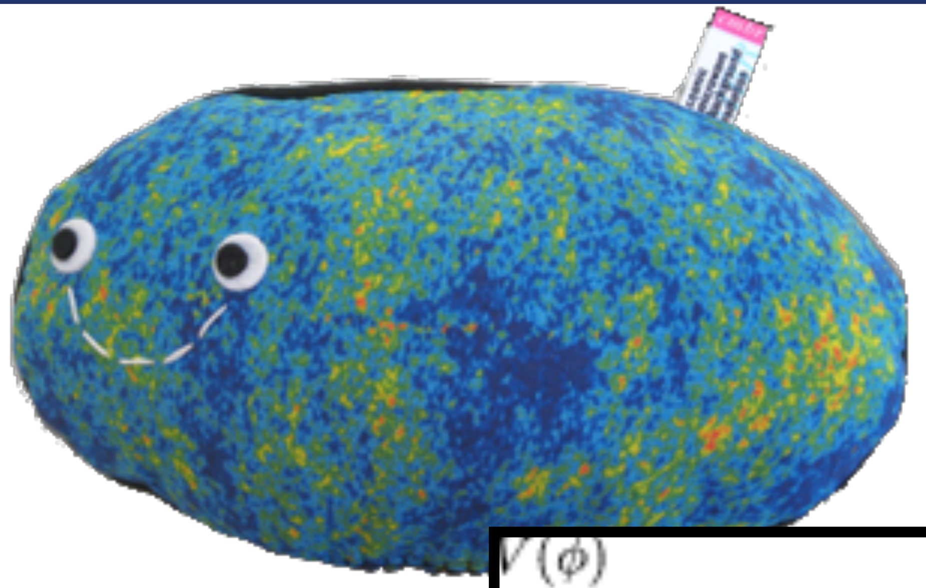
• ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

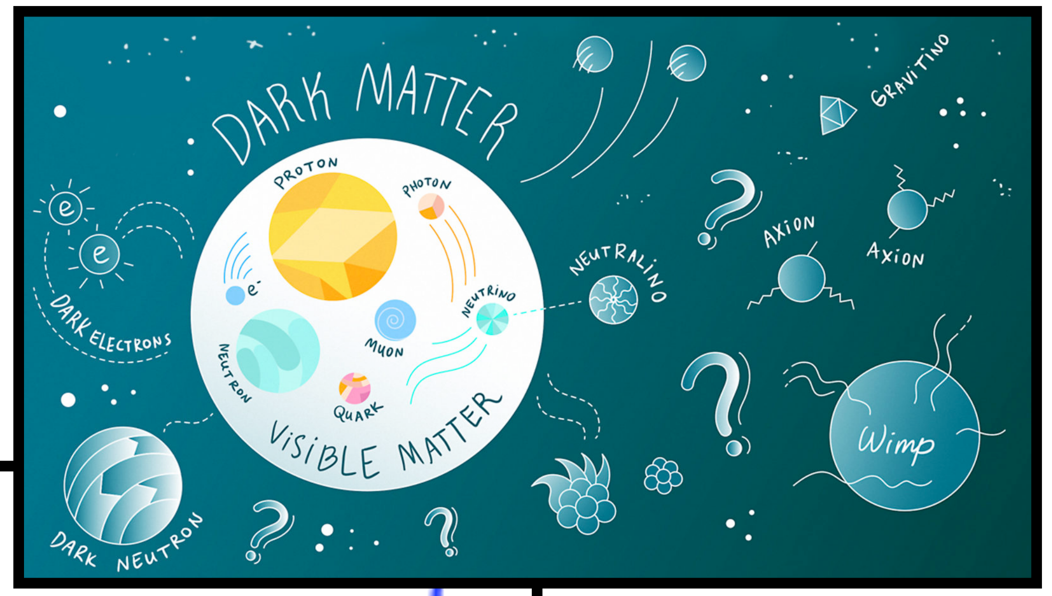
The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

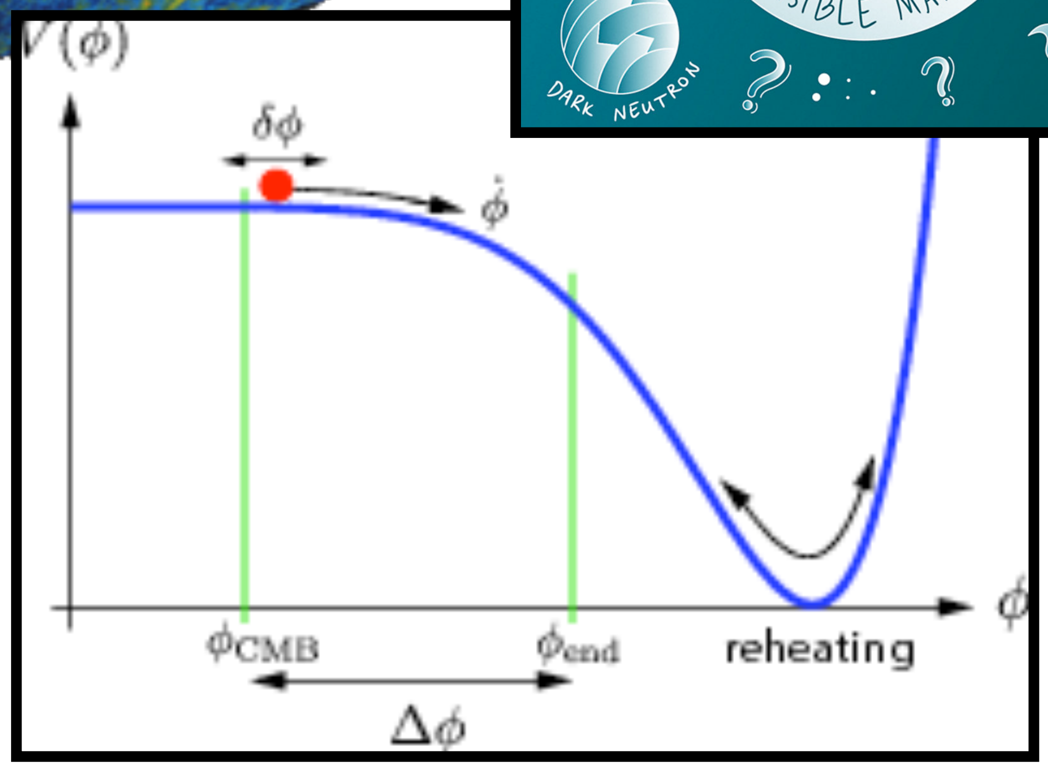
The big questions for future colliders….

What we’d really like to know

- How can the Higgs boson be so light?
- What is the mechanism behind electroweak symmetry breaking?
- What is Dark Matter made out of?
- What drives inflation?
- Why is the universe made out of matter?
- What generates Neutrino masses?
- …







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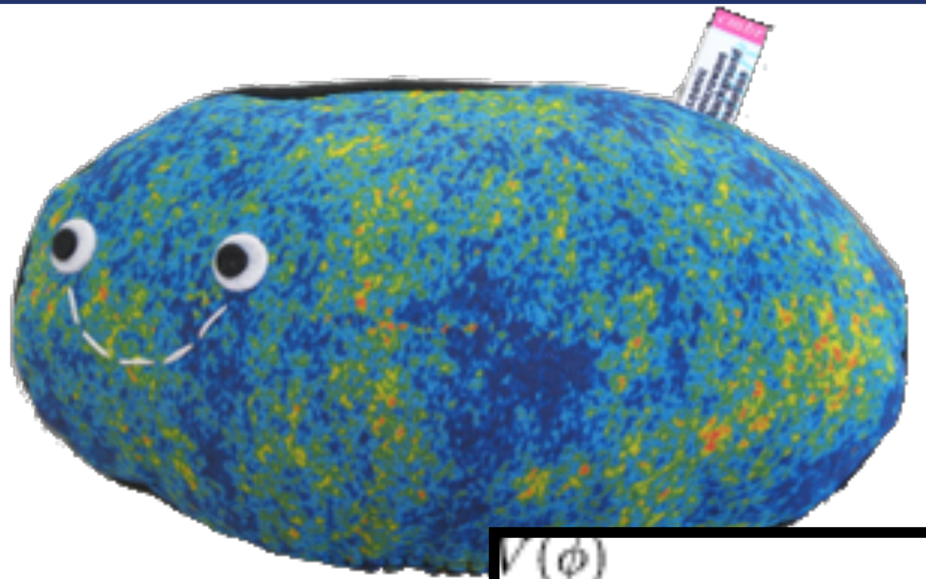
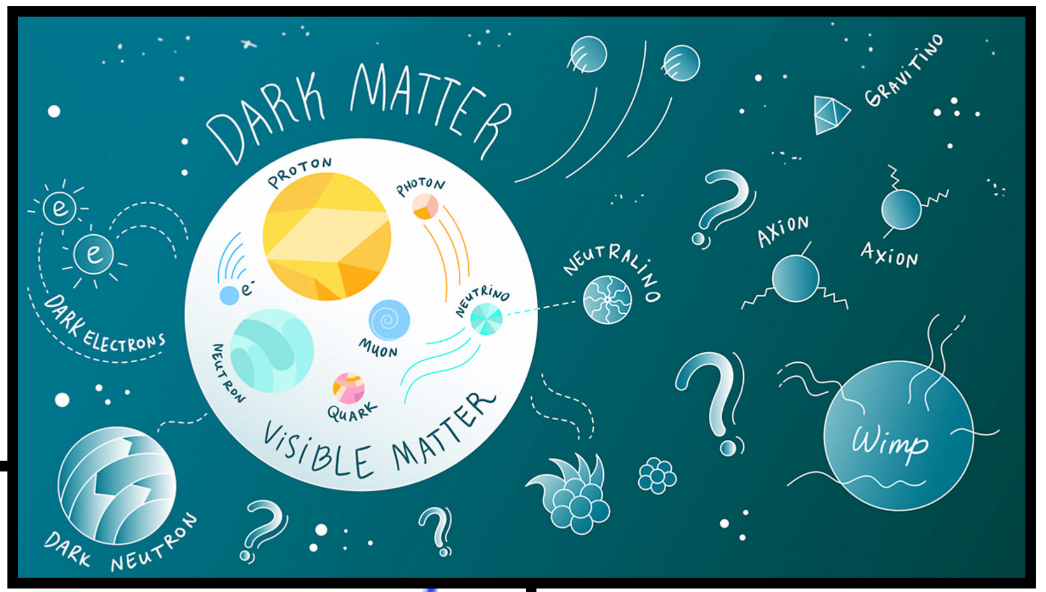
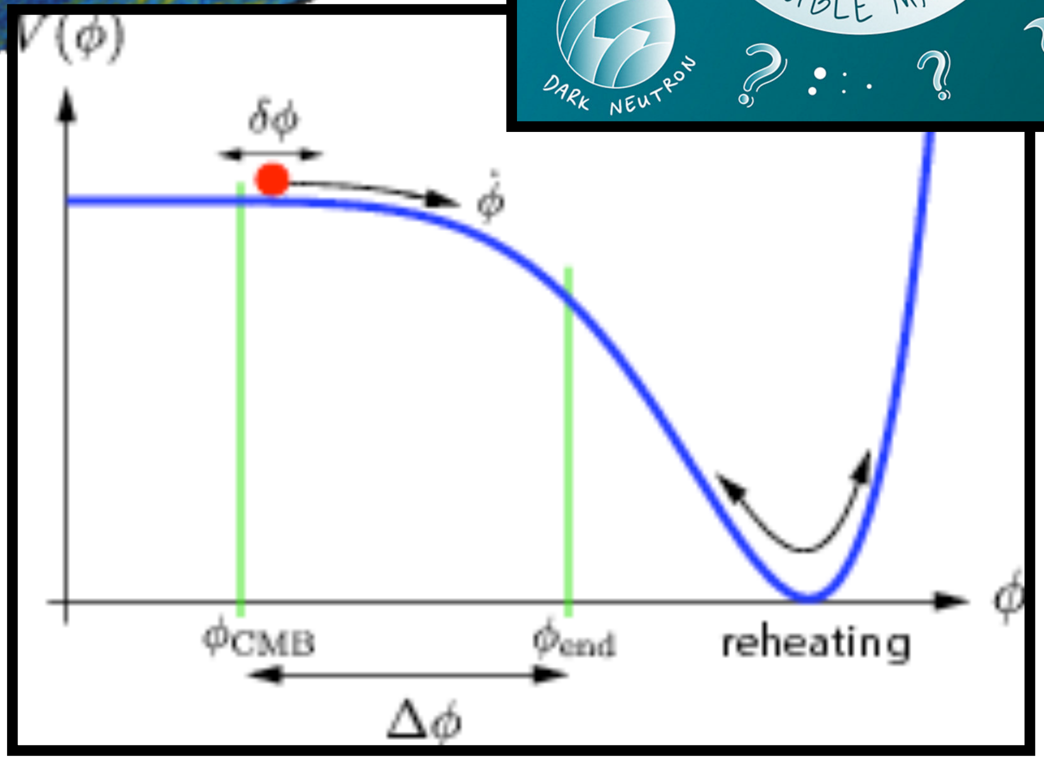
Answers can only be found *outside* of the Standard Model of particle physics







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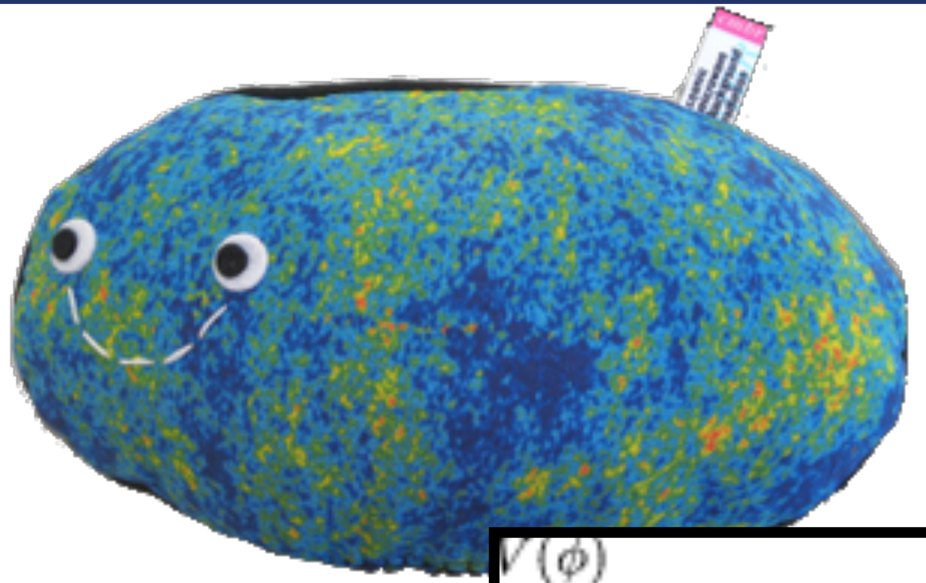

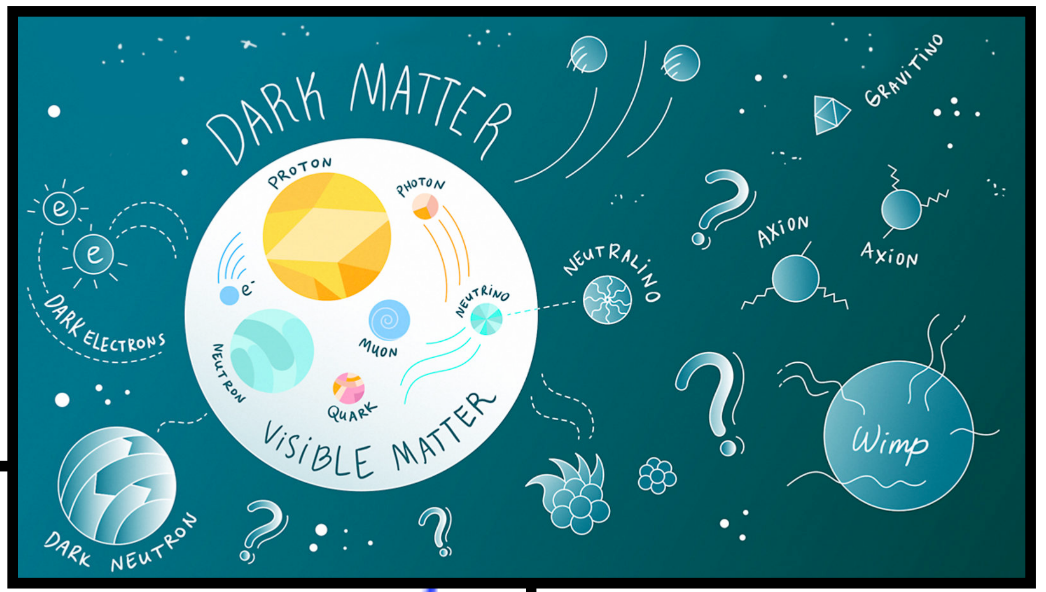

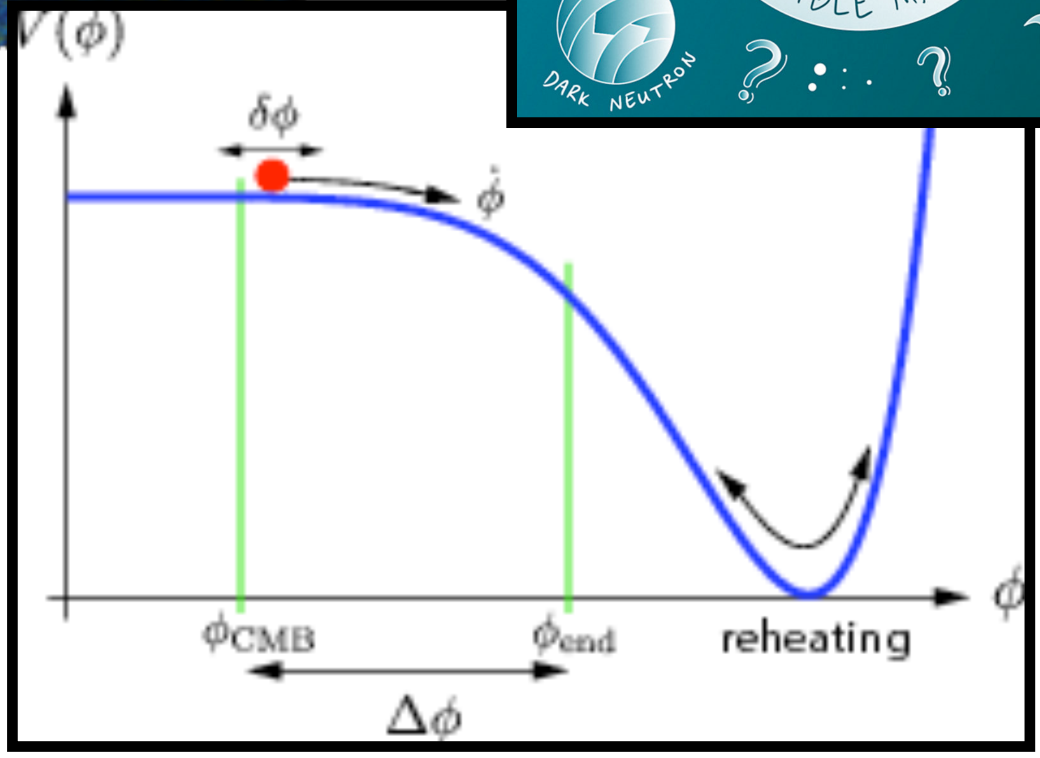

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- **most hints for BSM come out of the electroweak sector, incl. Higgs**

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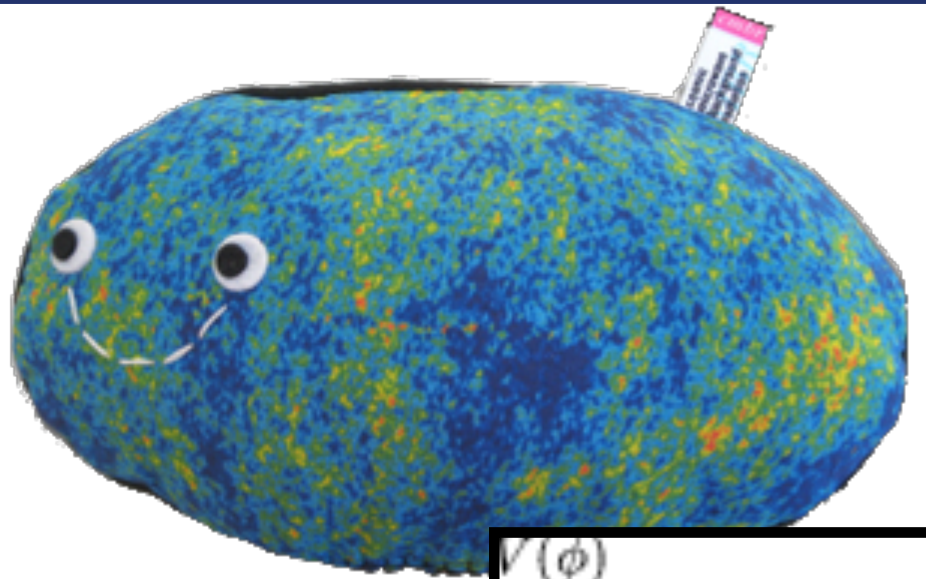

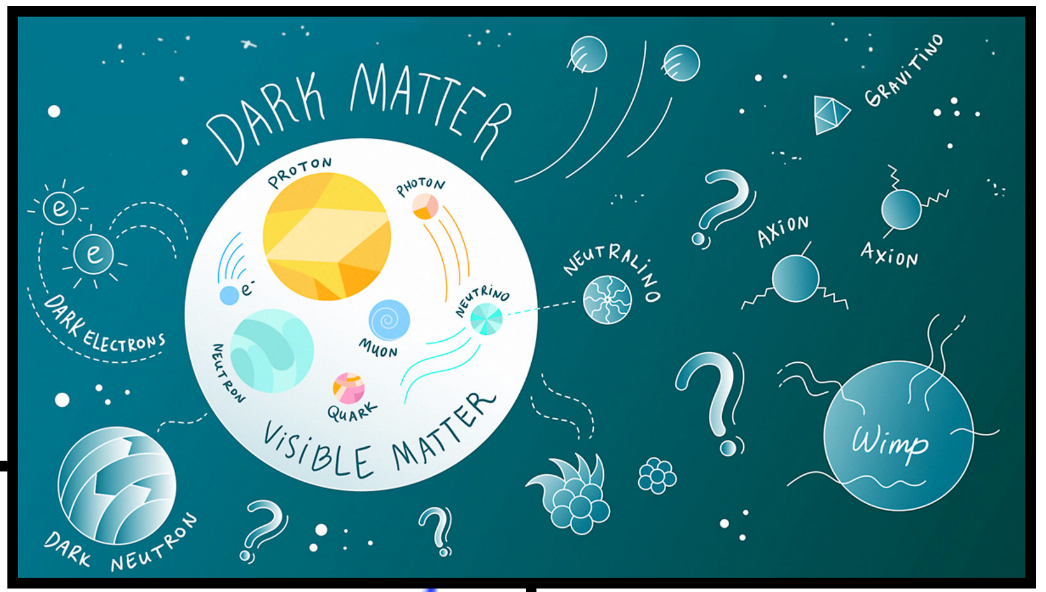

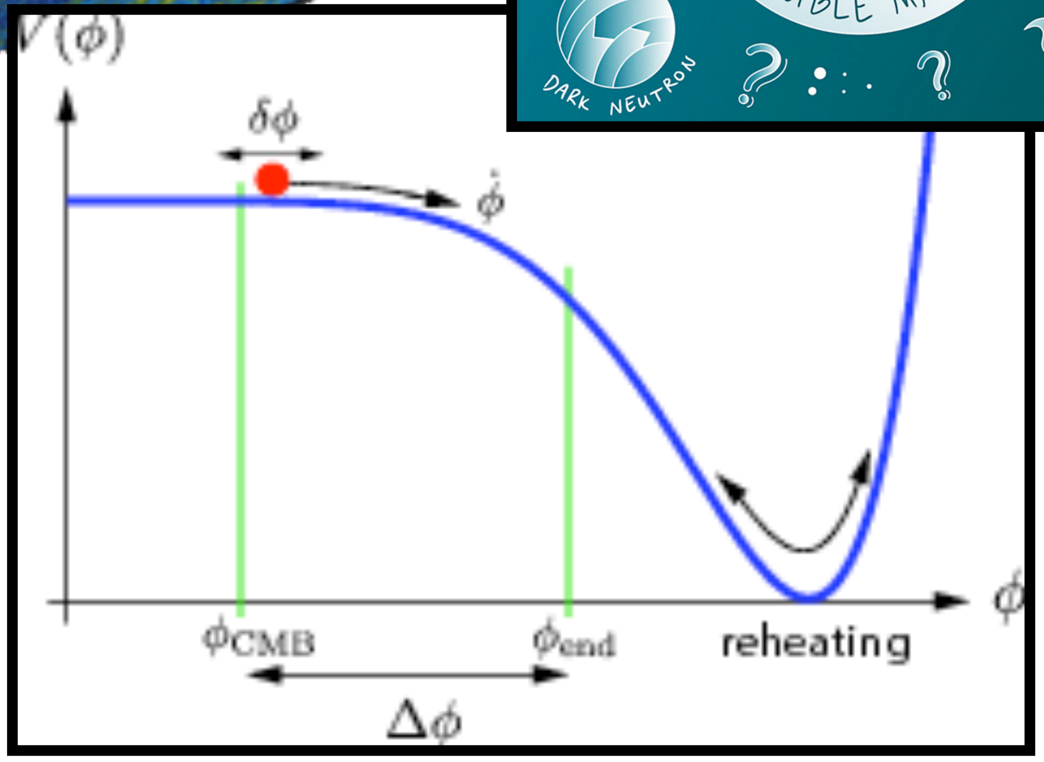

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What we don't know:

- participation in strong interaction?
- energy scale of new particles

=> no guarantee for direct production of new particles

=> need to explore different, complementary experimental approaches

… and how to tackle them at colliders

Our tools:

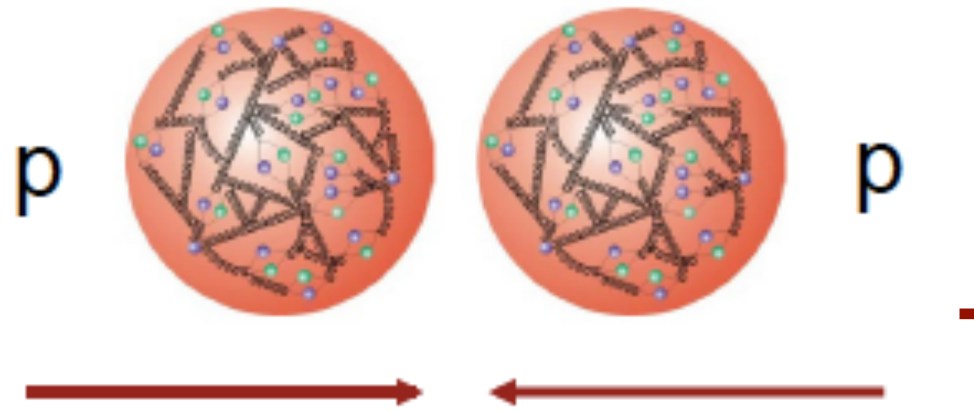
The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

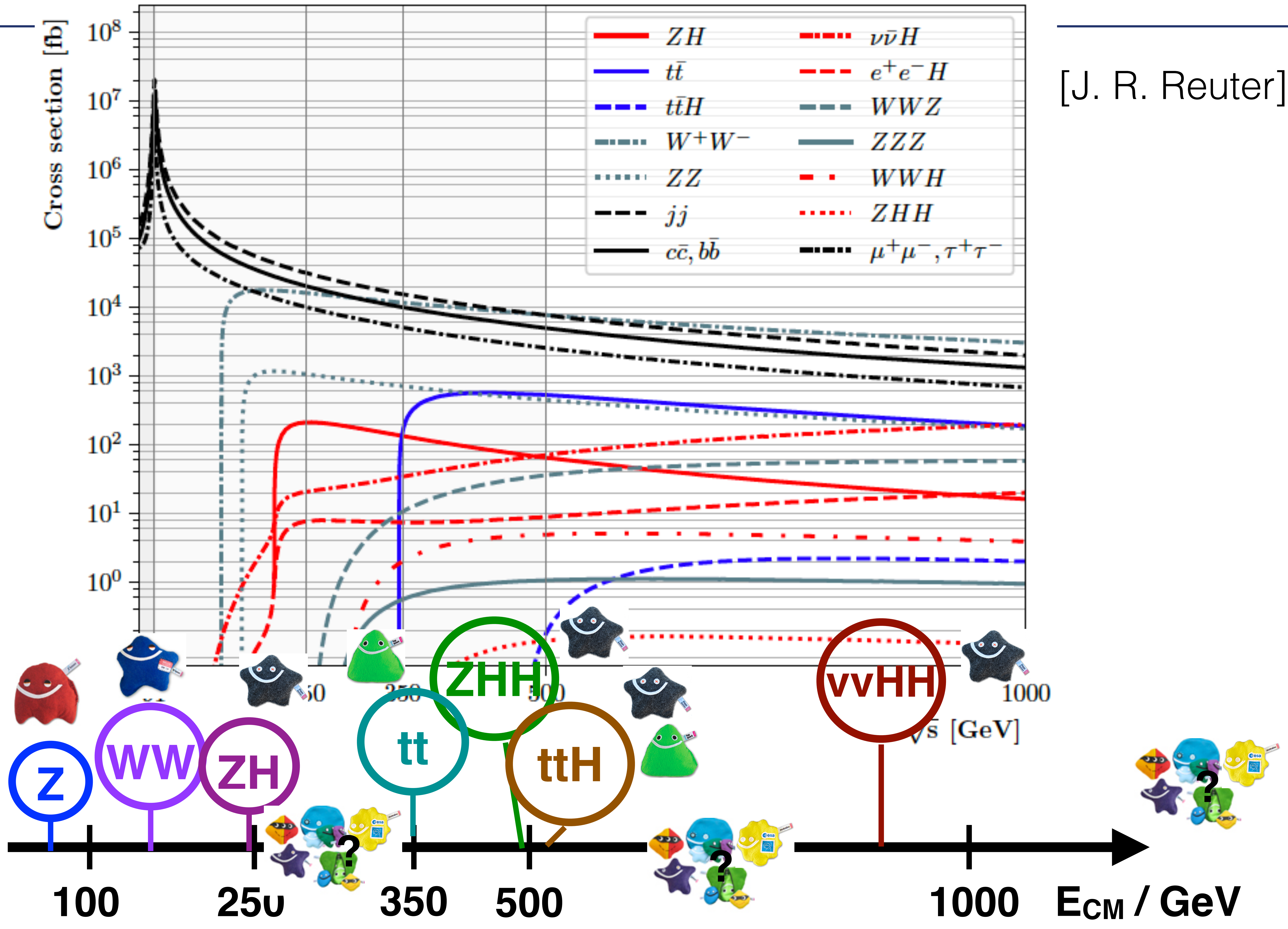
Discoveries of new particles ?

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



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

Energy thresholds in e+e- collisions



[J. R. Reuter]

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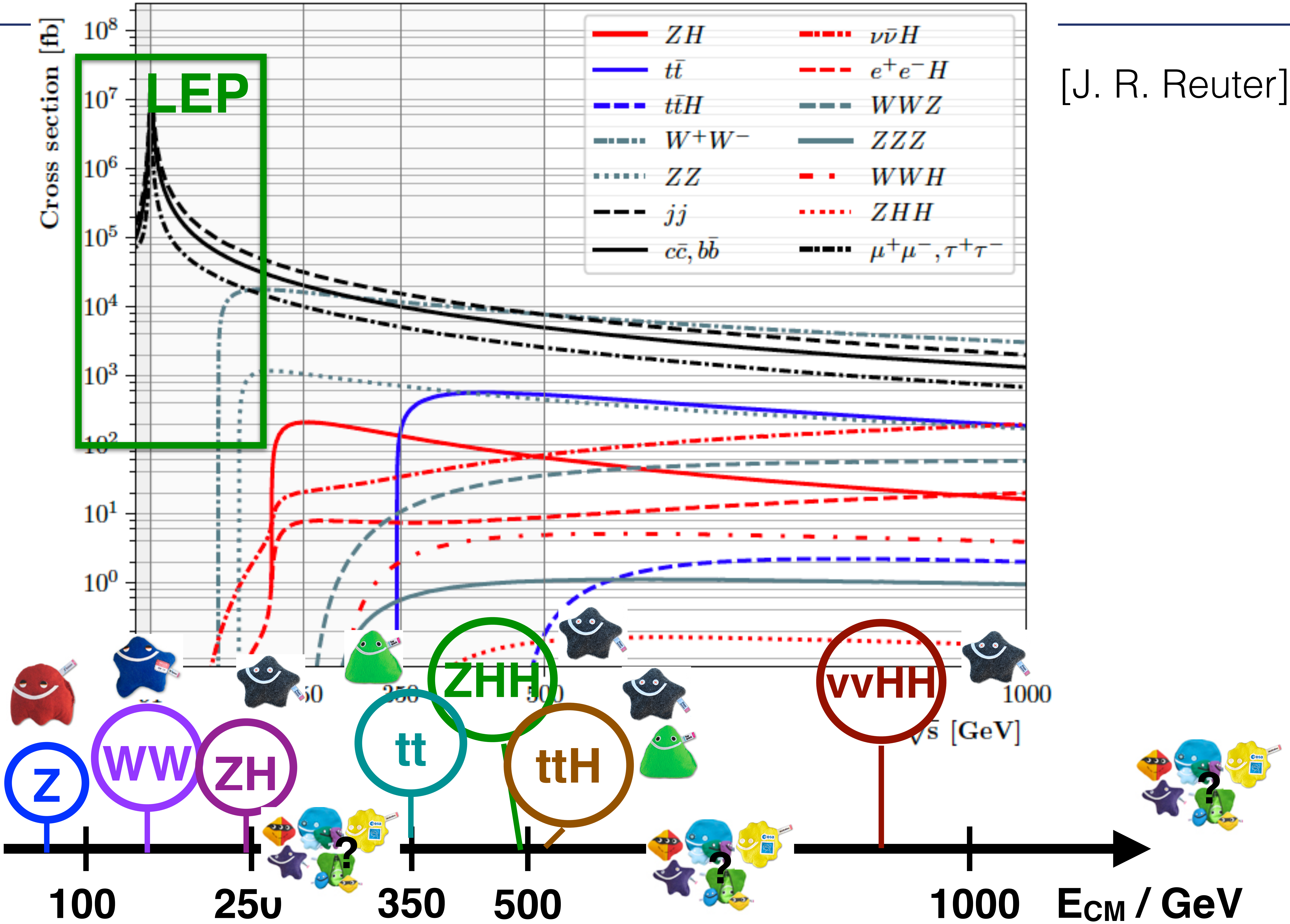
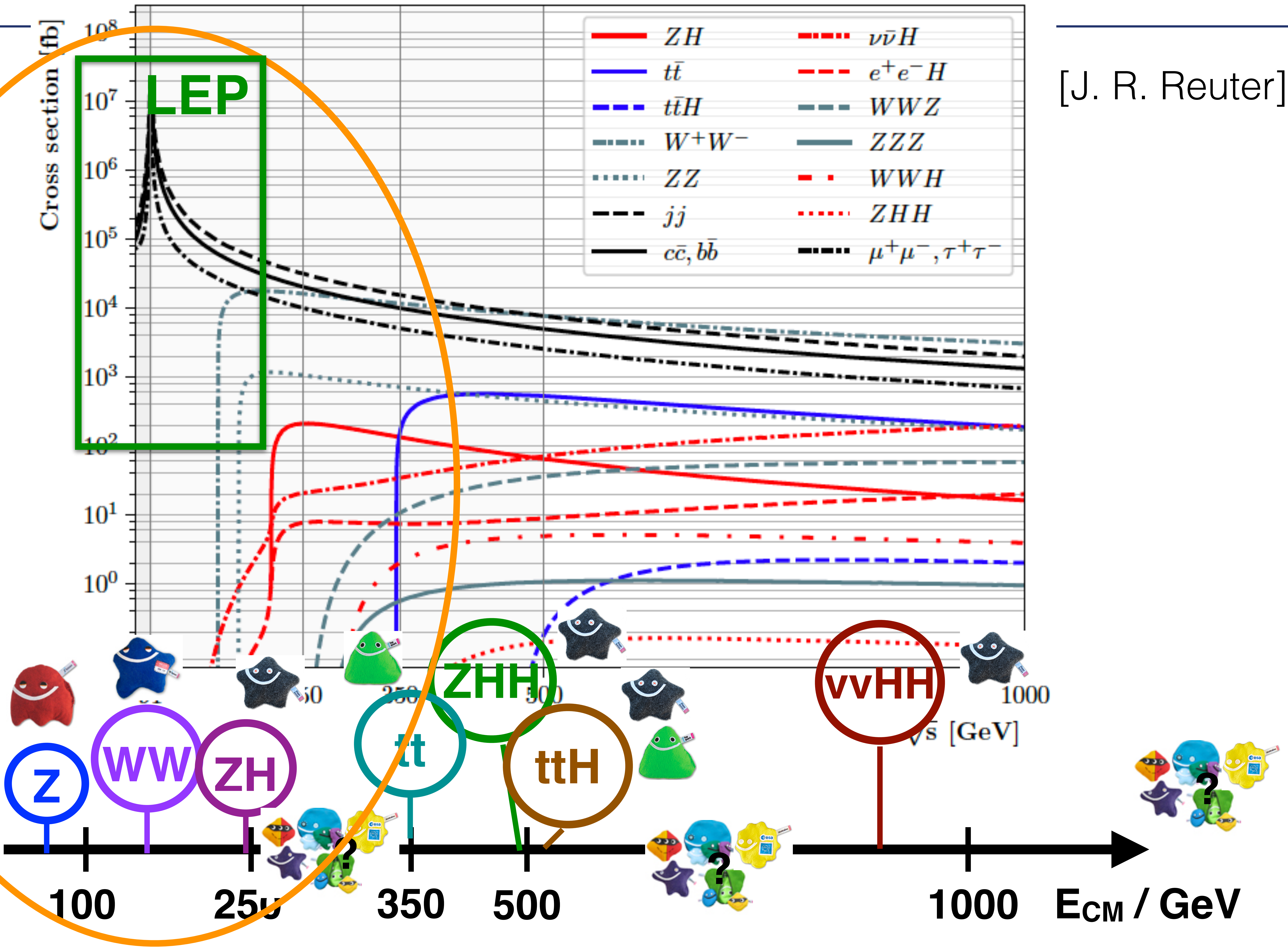


Energy thresholds in e+e- collisions

[J. R. Reuter]

considered by ~all proposed e+e- projects



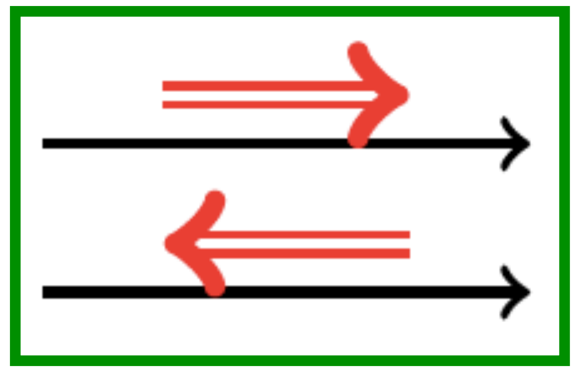
Other important parameters in e^+e^- collisions

Luminosity

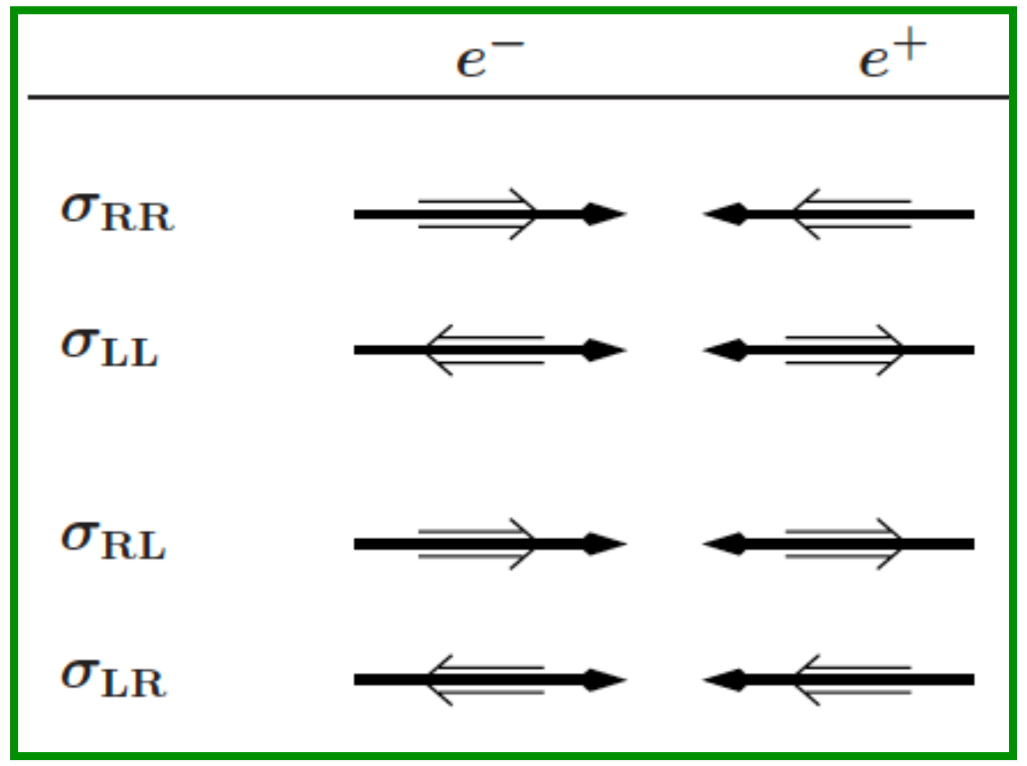
- Defines event rate => size of data set
- Future e^+e^- colliders aim for $10^3..10^6$ larger data sets than LEP
- Depends strongly on invest costs and power consumption => be careful to compare apples to apples!
- Are there fundamental boundaries *beyond* statistics?
  (e.g. theory & parametric uncertainties,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

Beam polarisation:

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



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



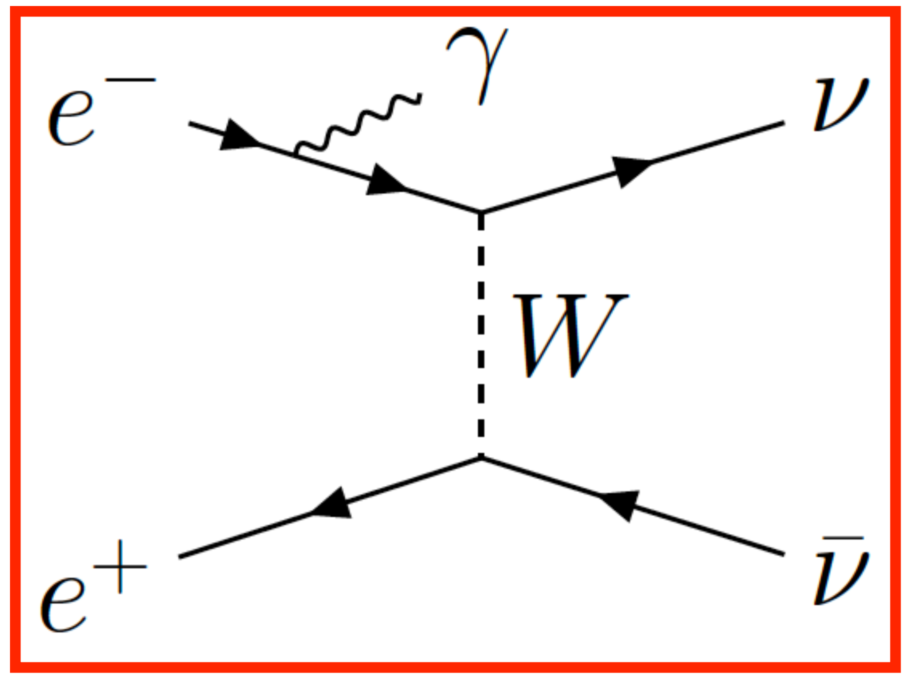
General references on polarised e^+e^- physics:

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

Physics benefits of polarised beams

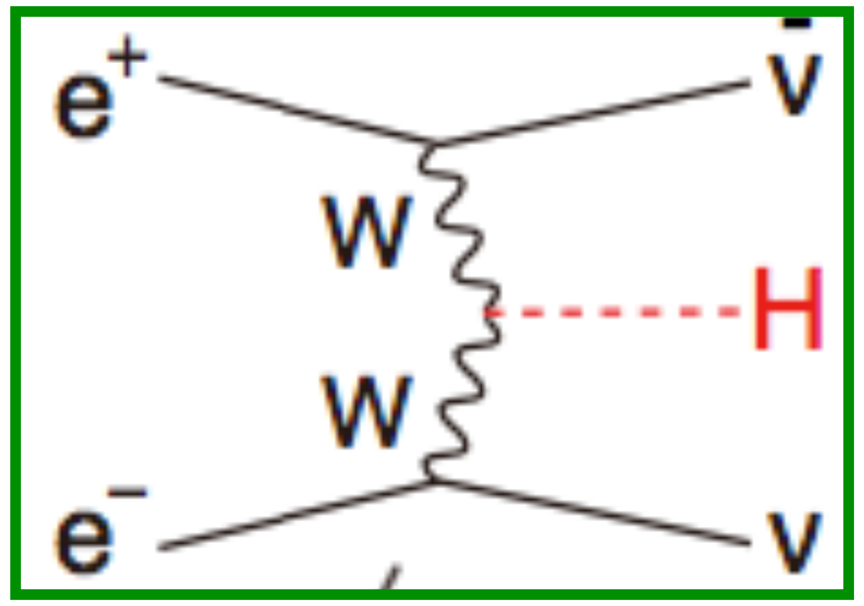
background suppression:

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



signal enhancement:

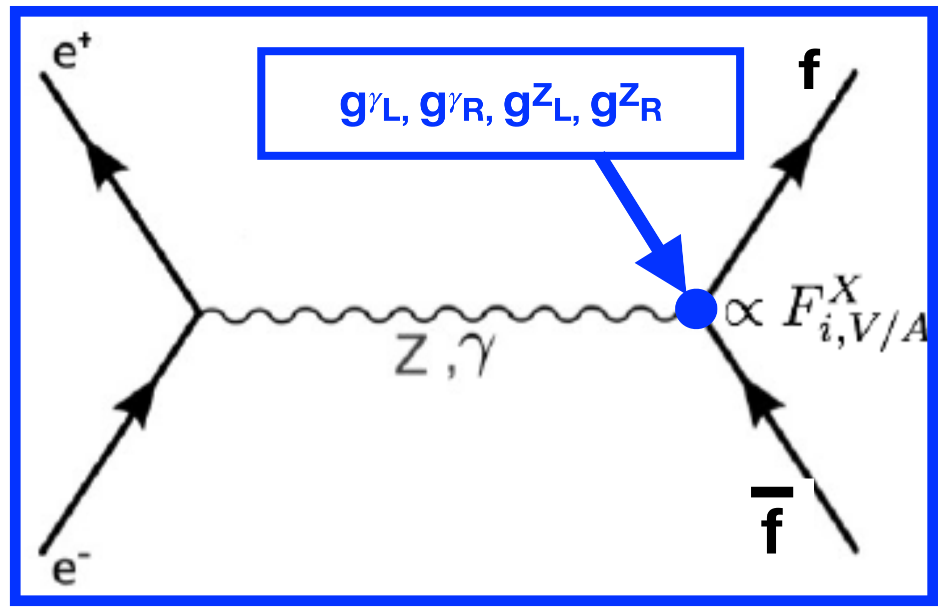
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

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

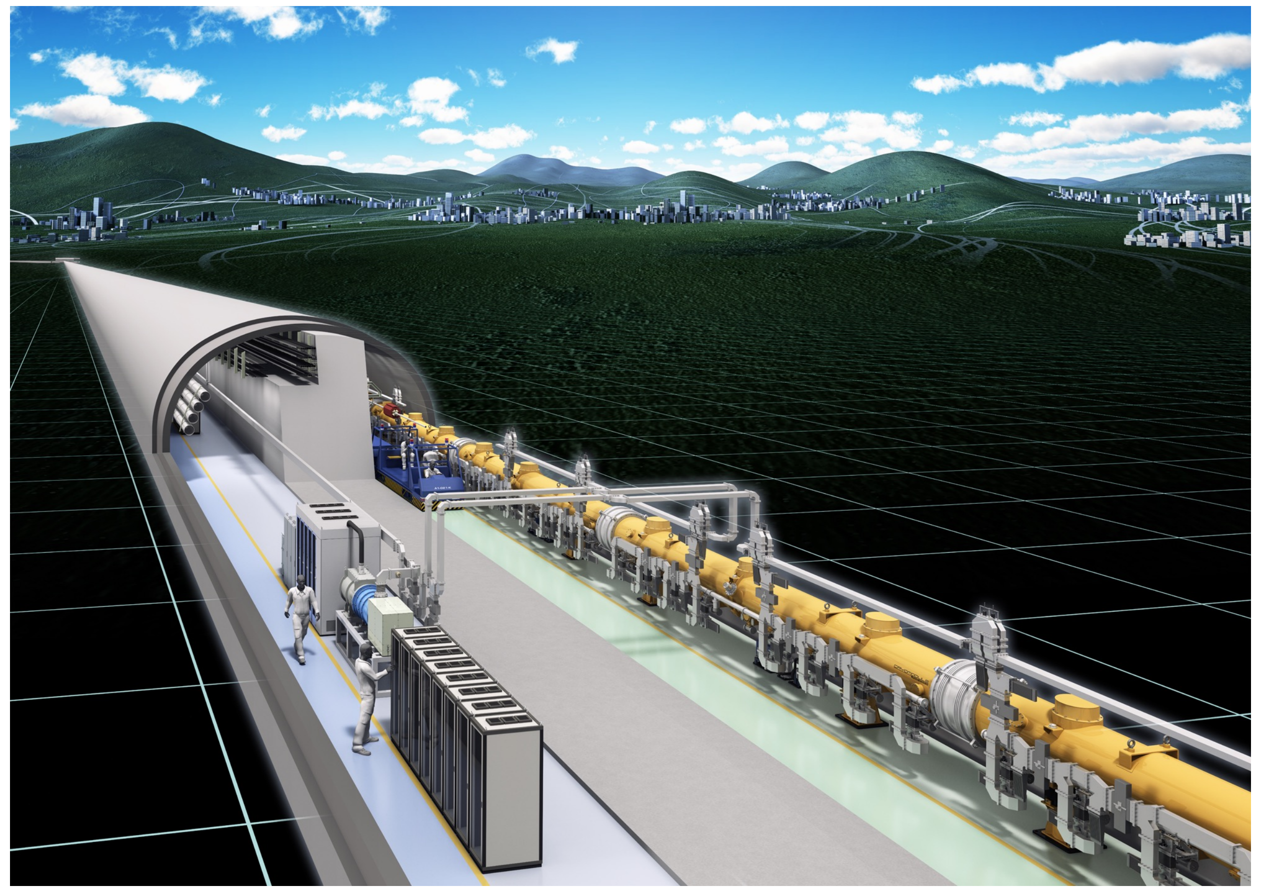


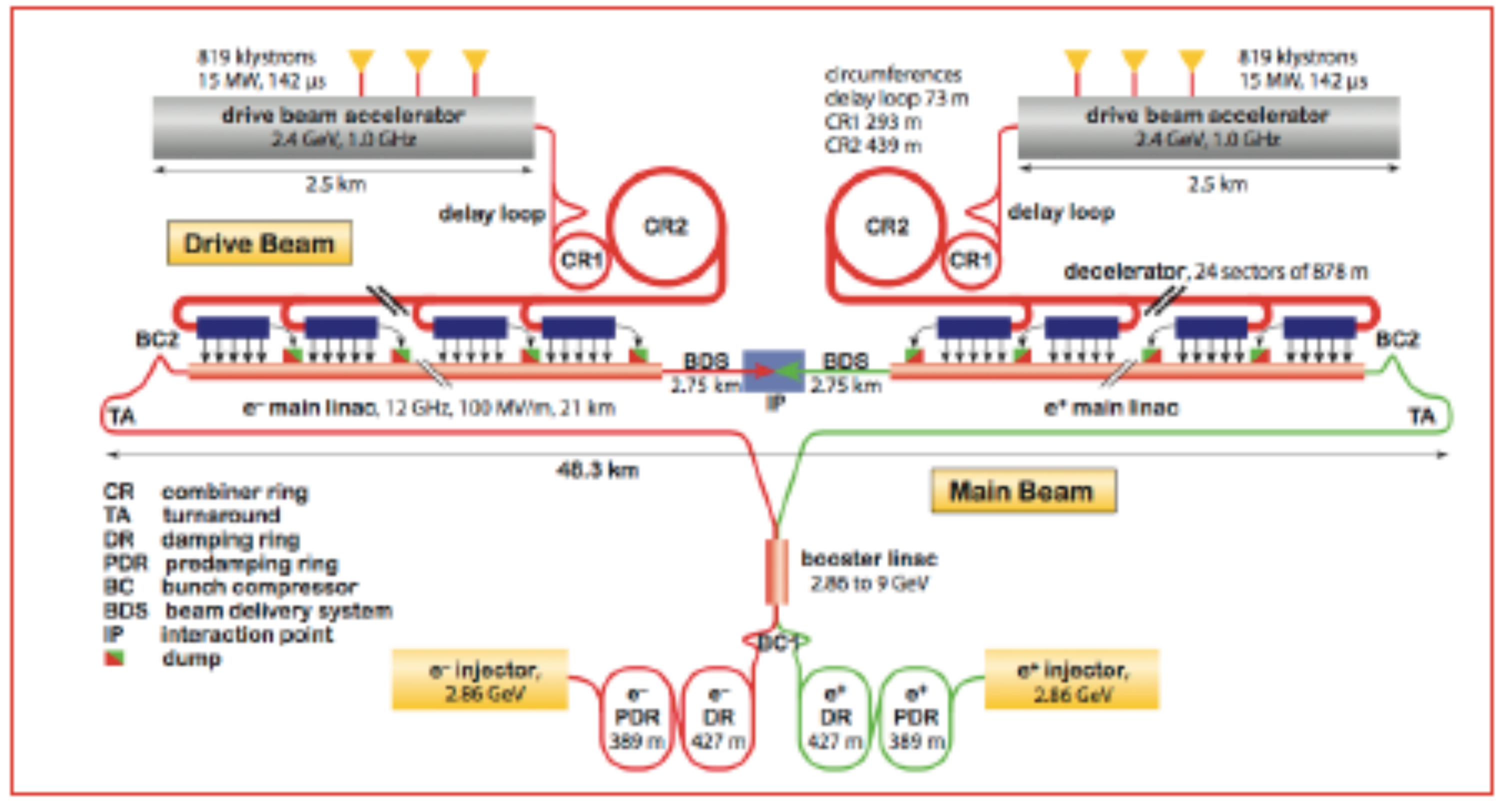
- BSM: chiral structure unknown, needs to be determined!

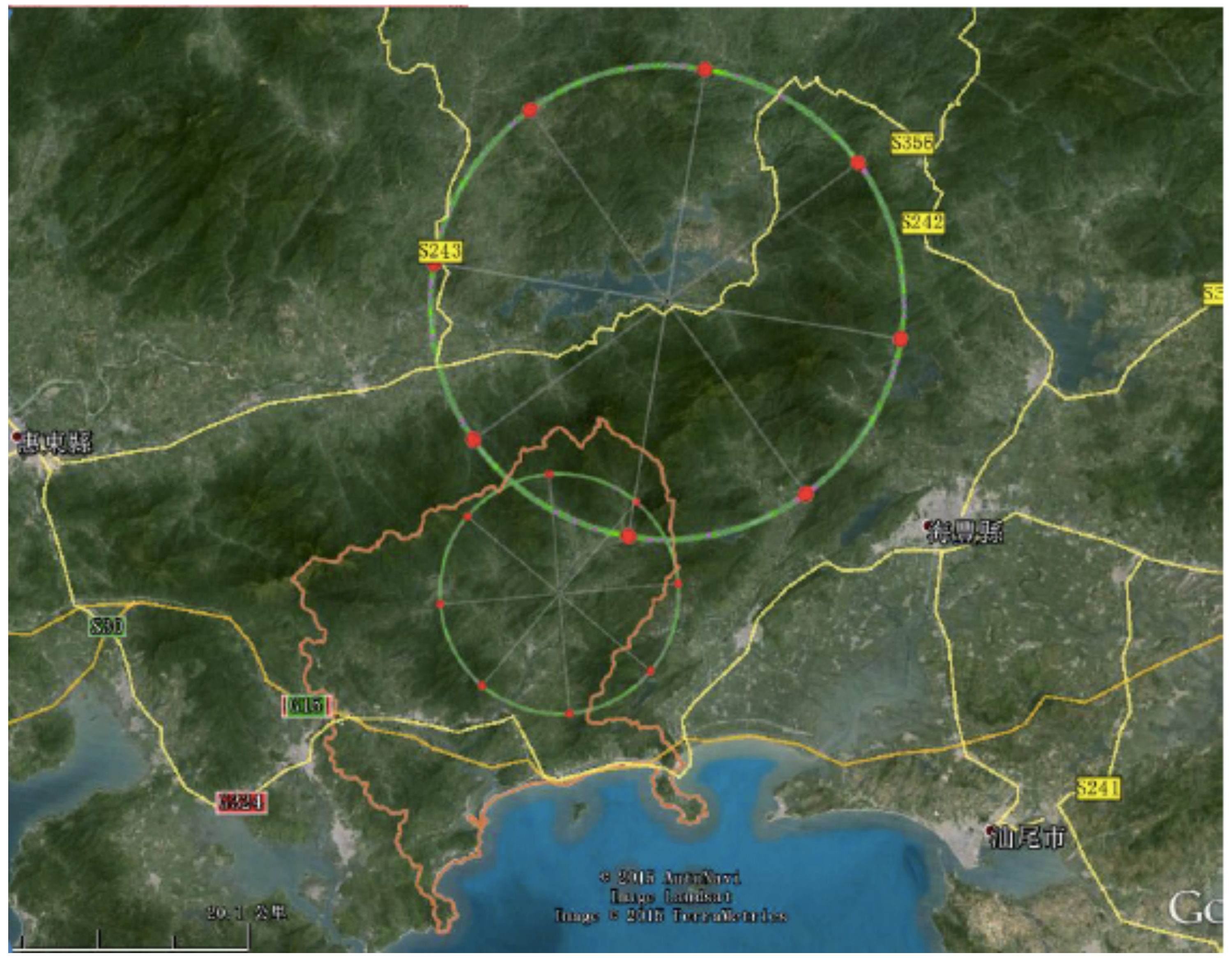
redundancy & control of systematics:

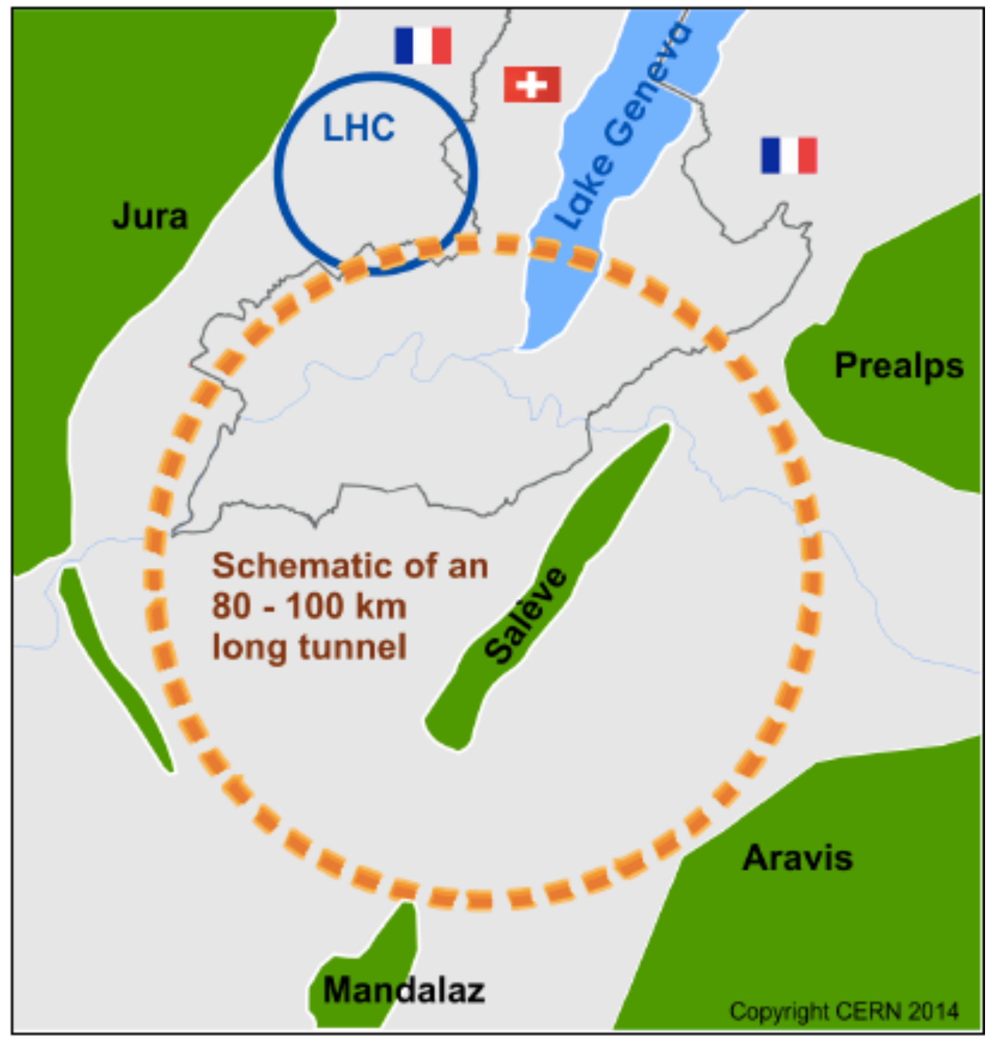
- “wrong” polarisation yields “signal-free” control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

The Key Contenders









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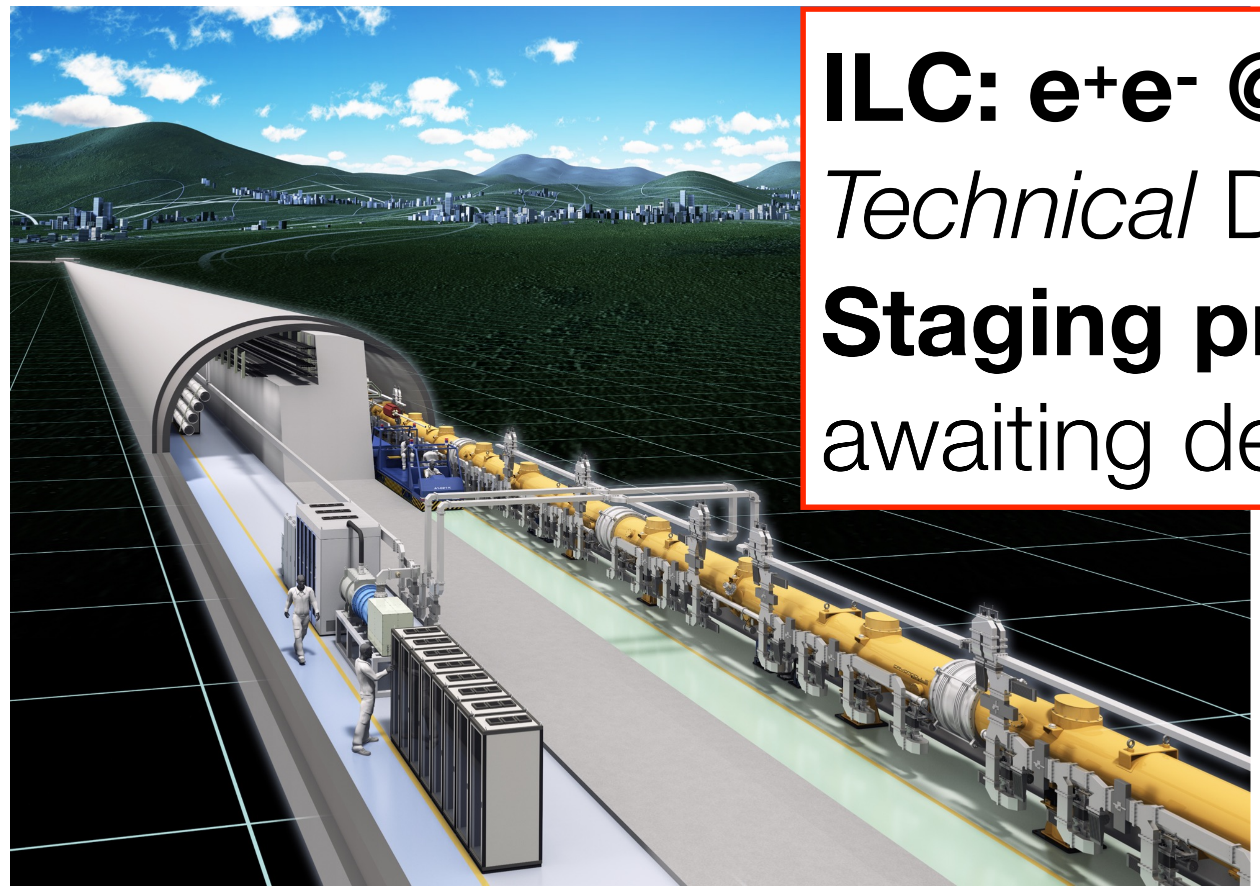

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Technical Design Rep. in **2012**
Staging proposal 2017: start at 250 GeV
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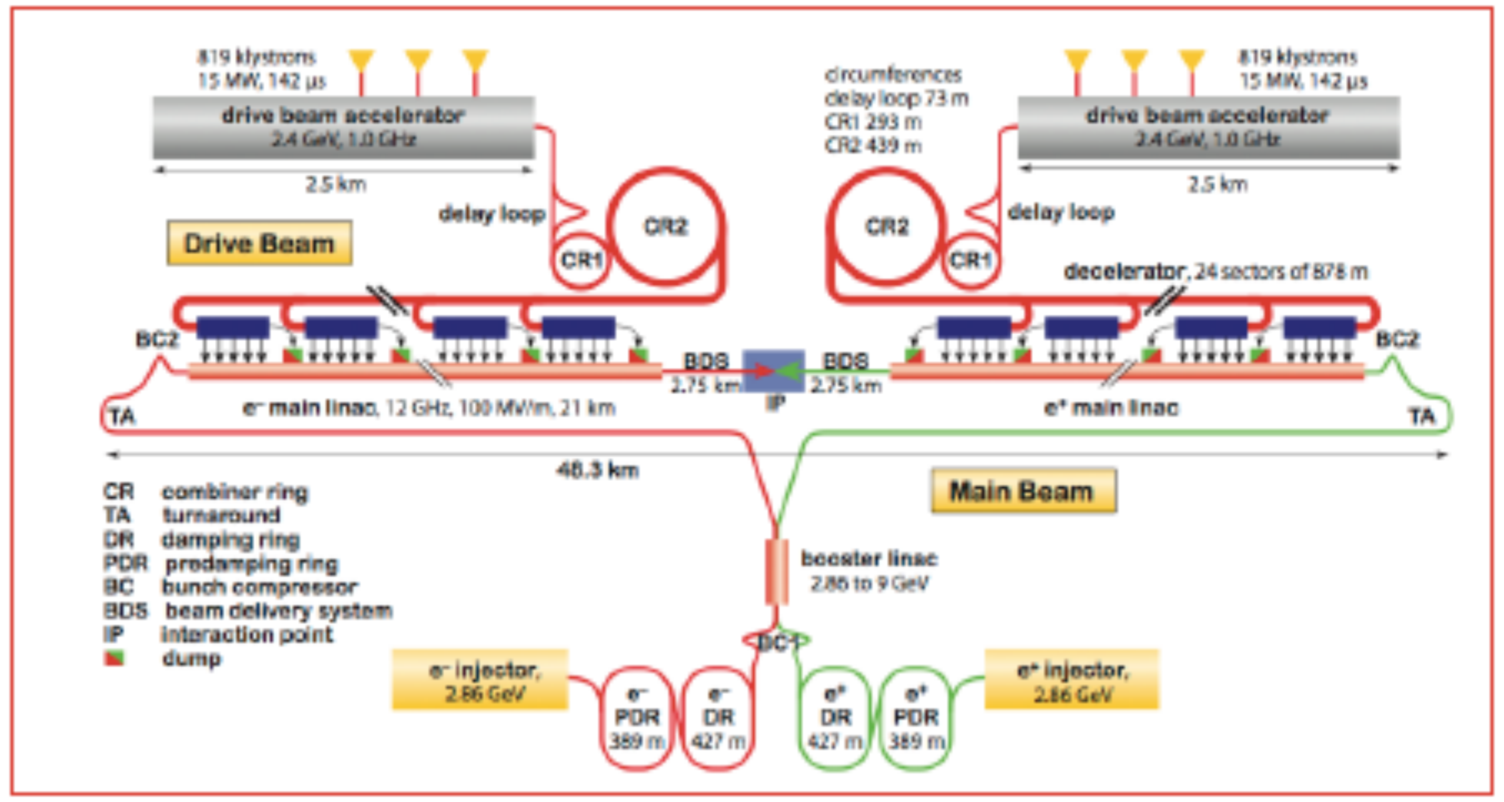

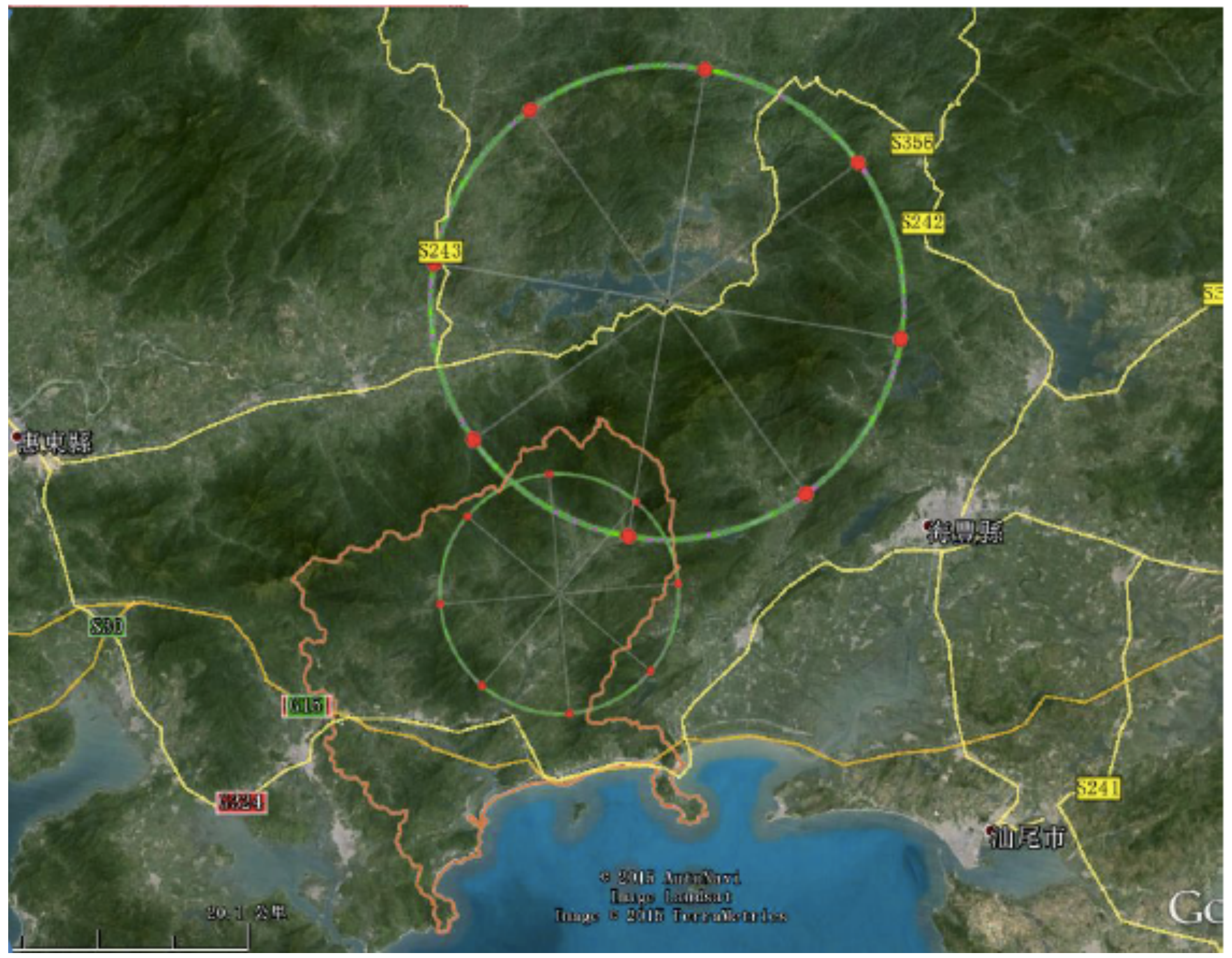

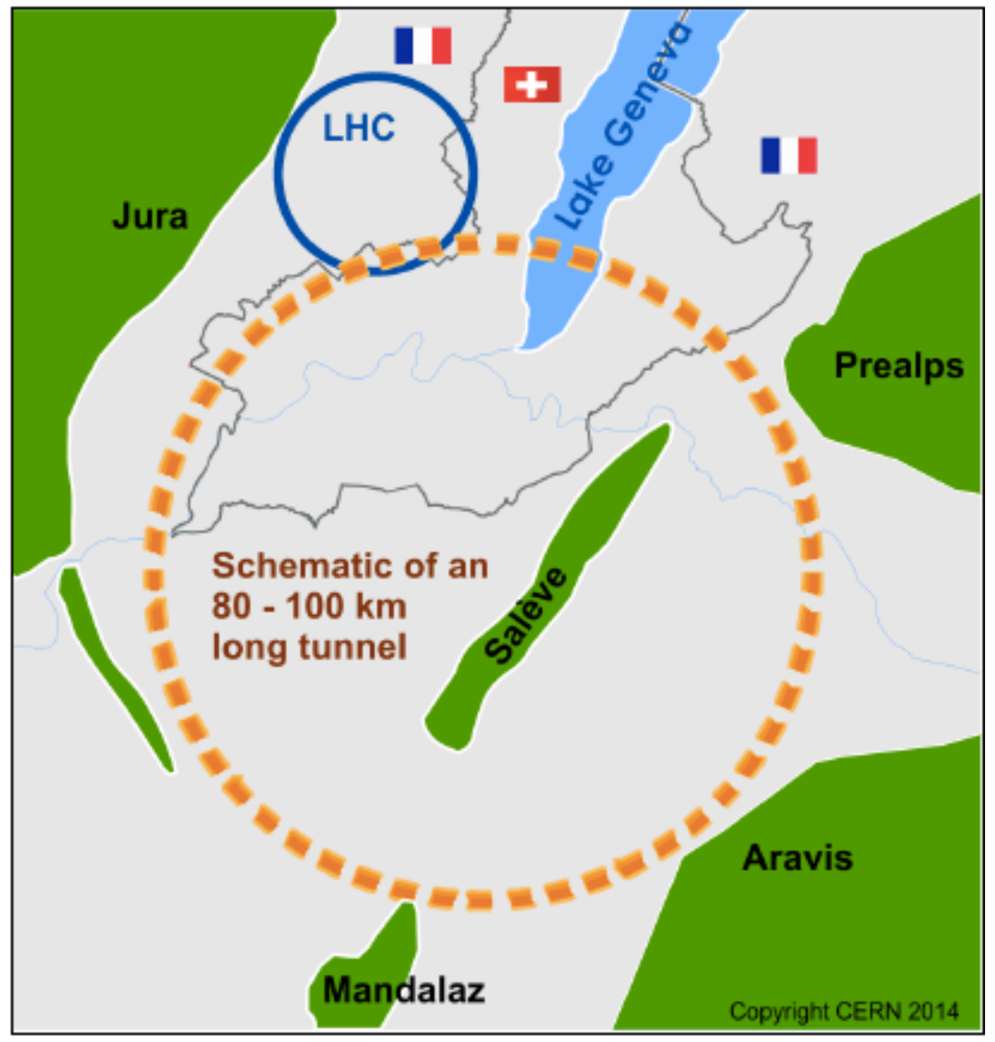

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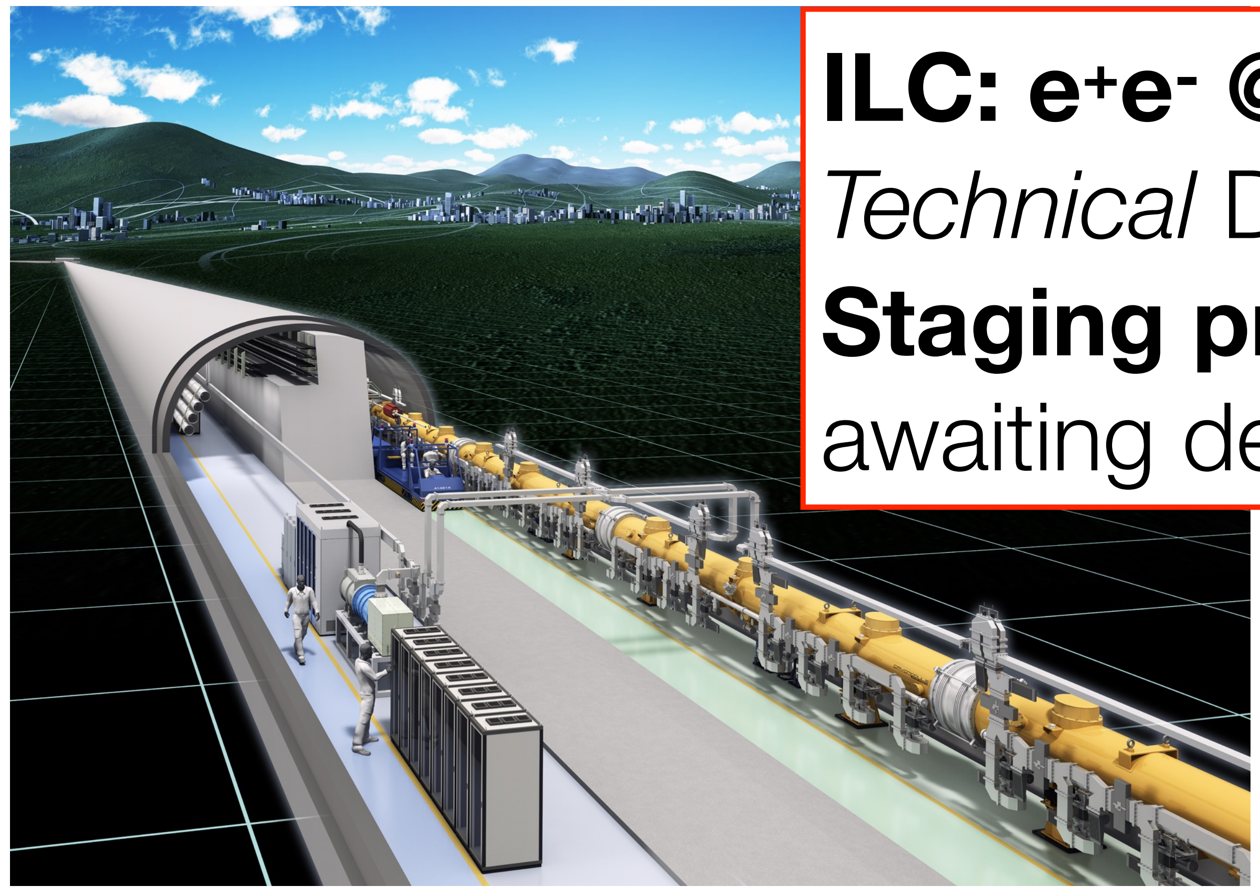

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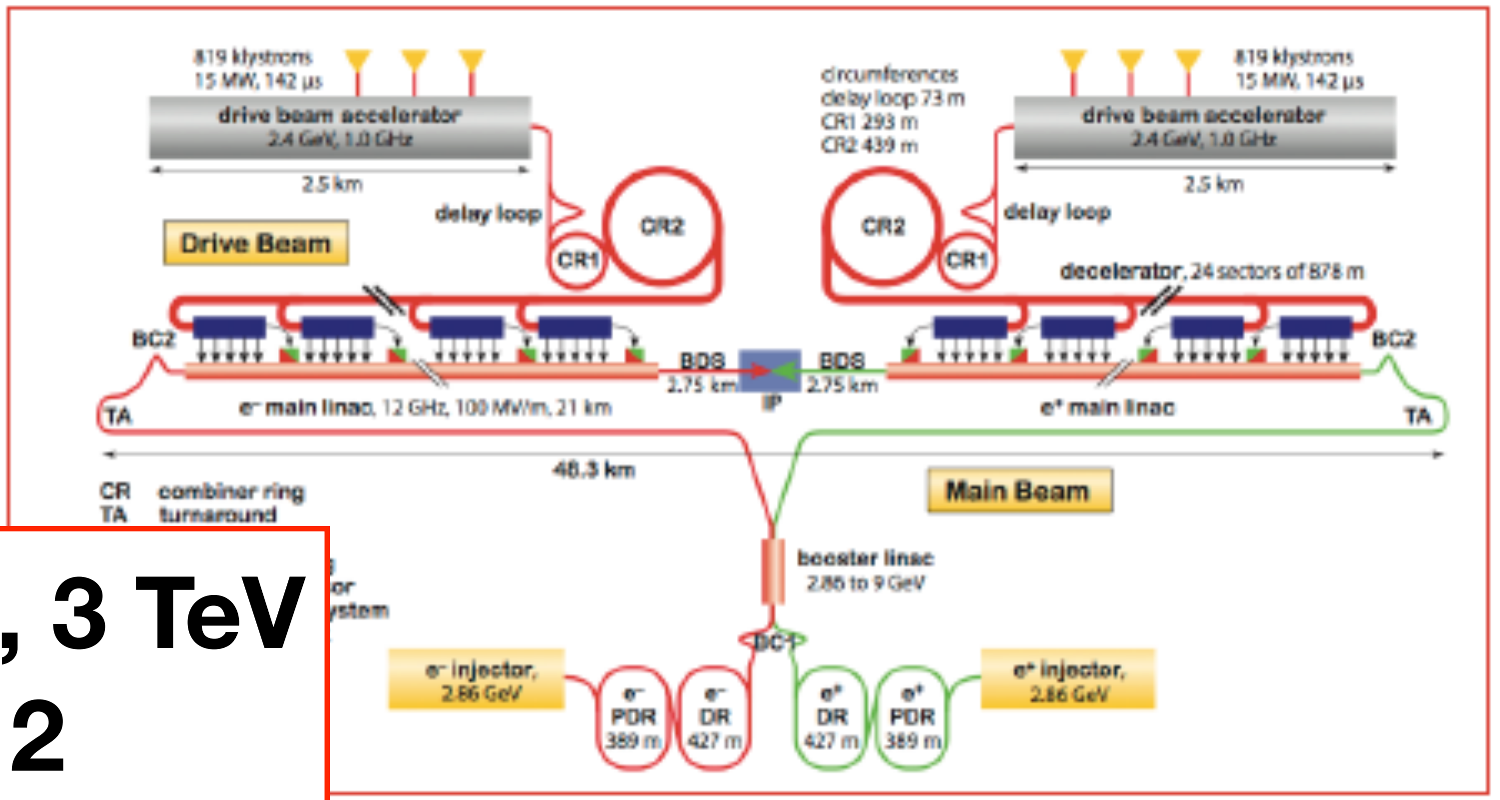

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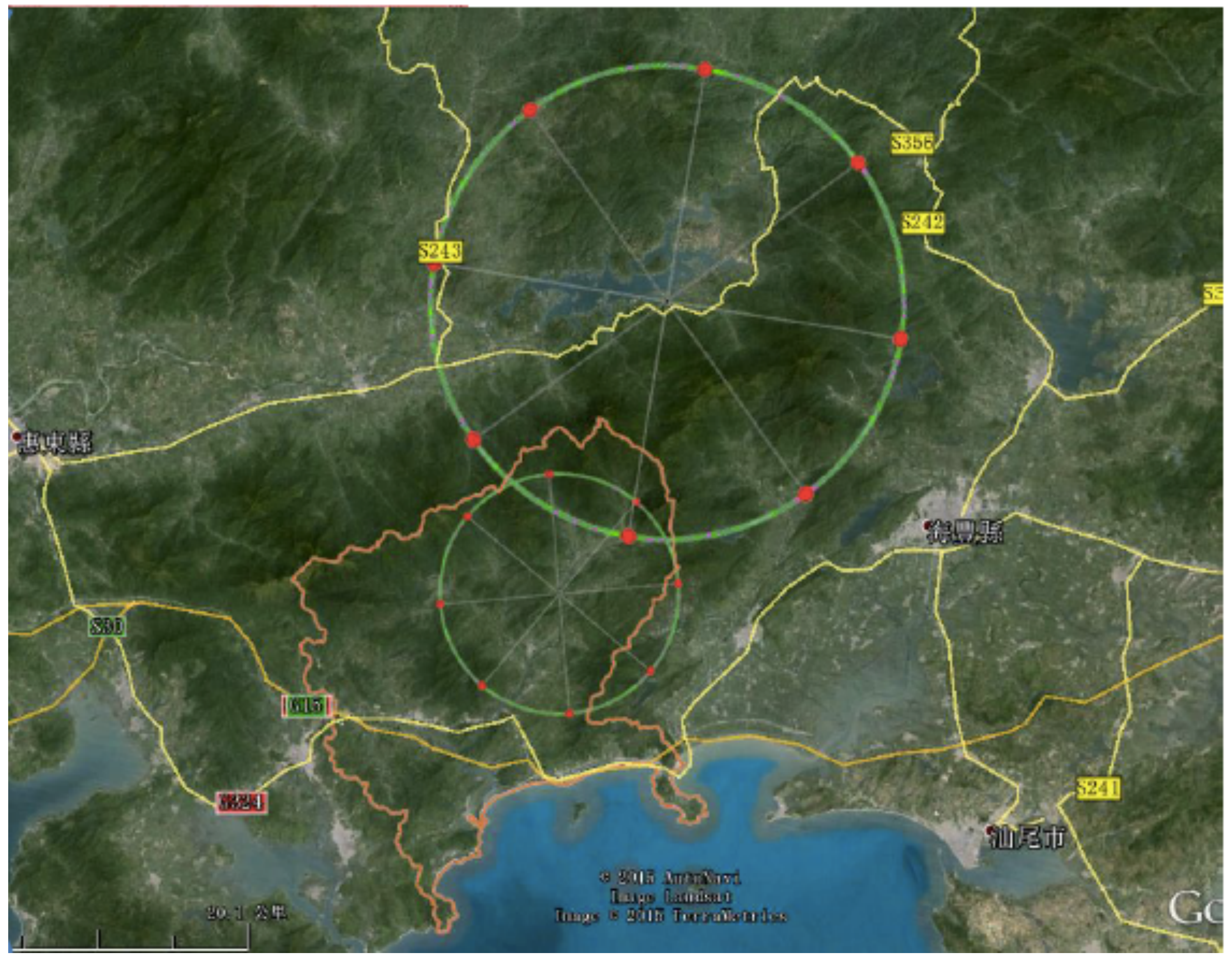

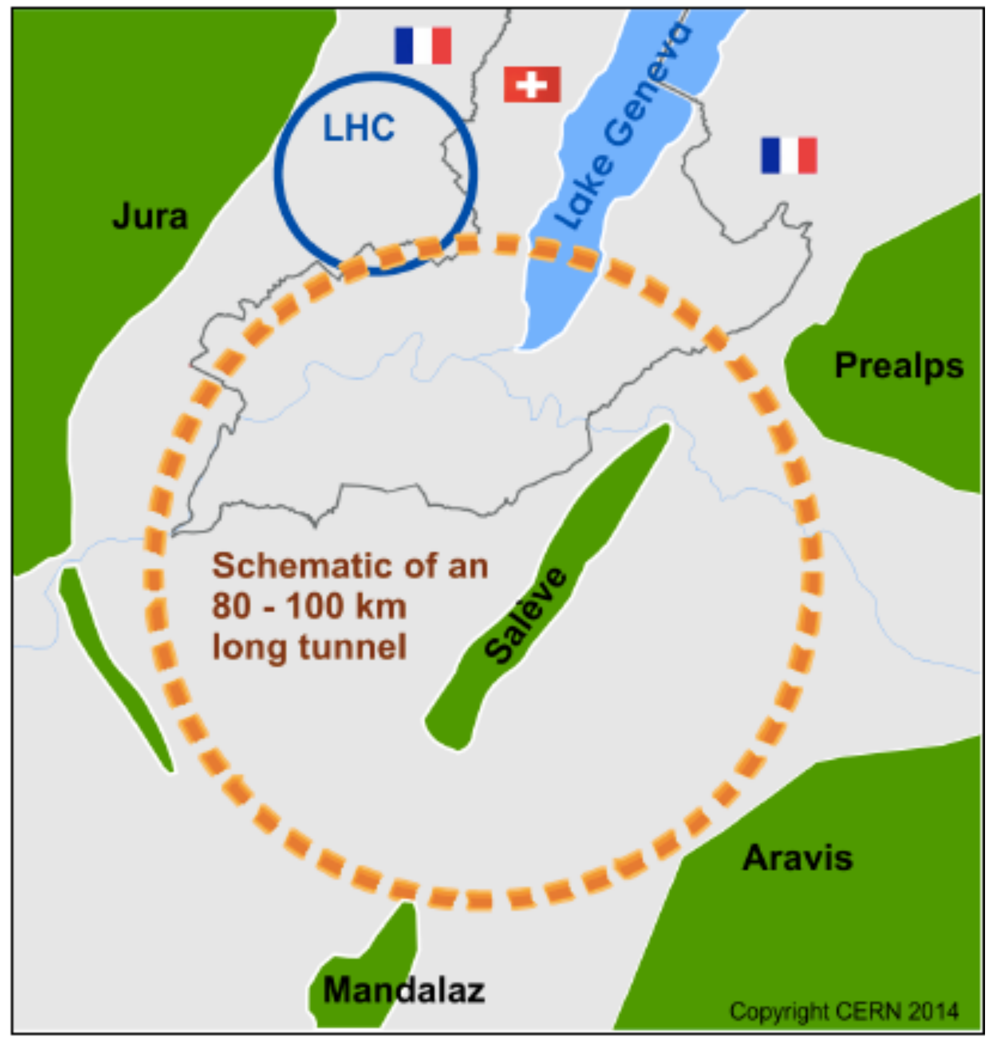

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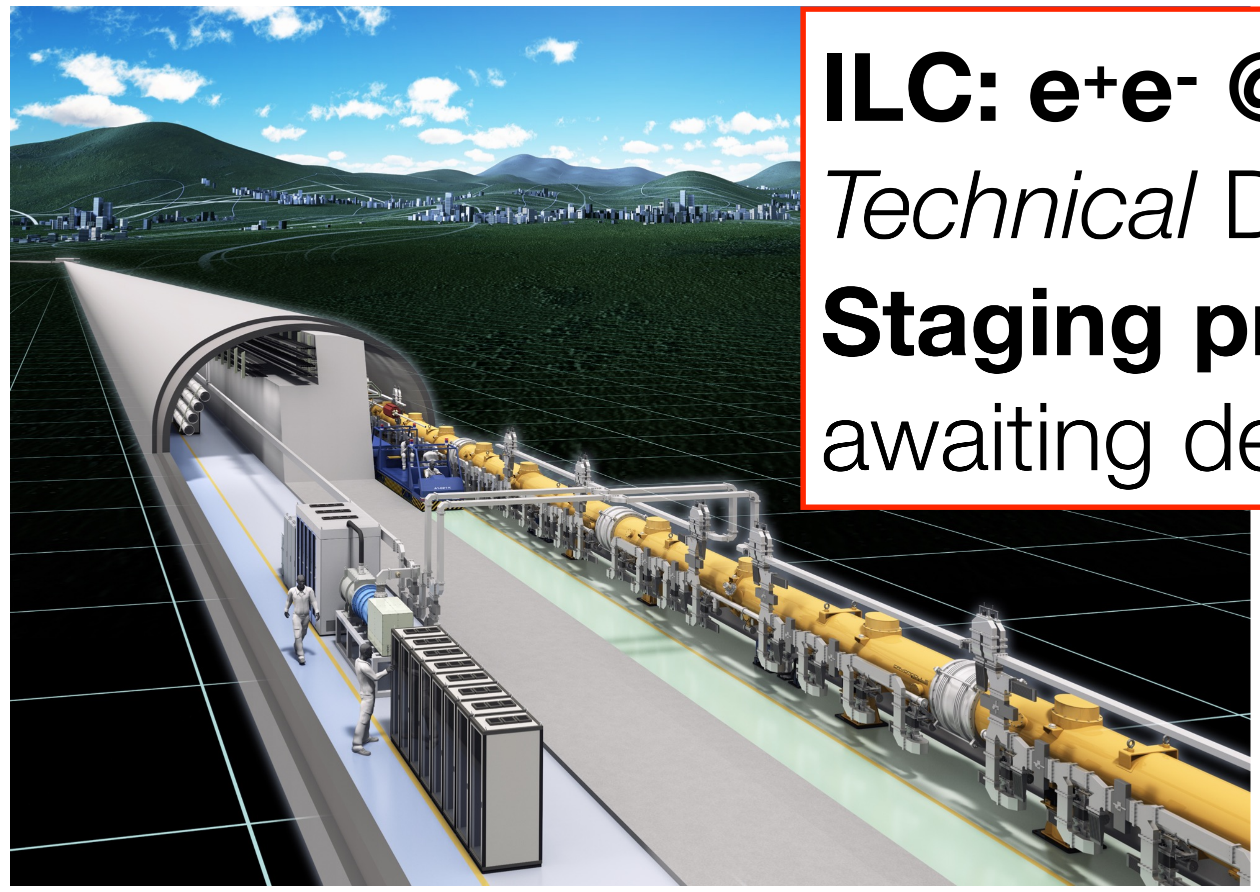

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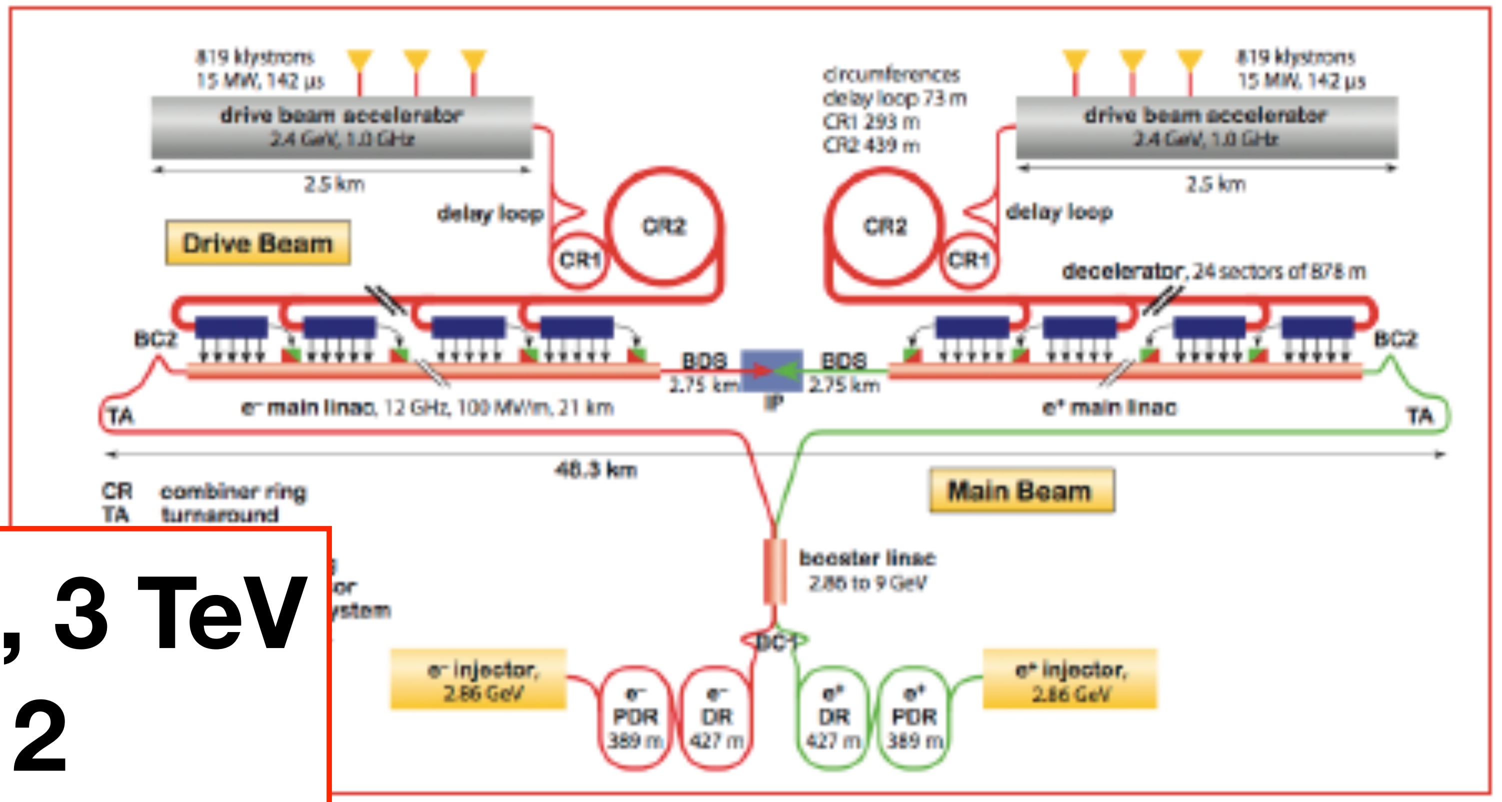

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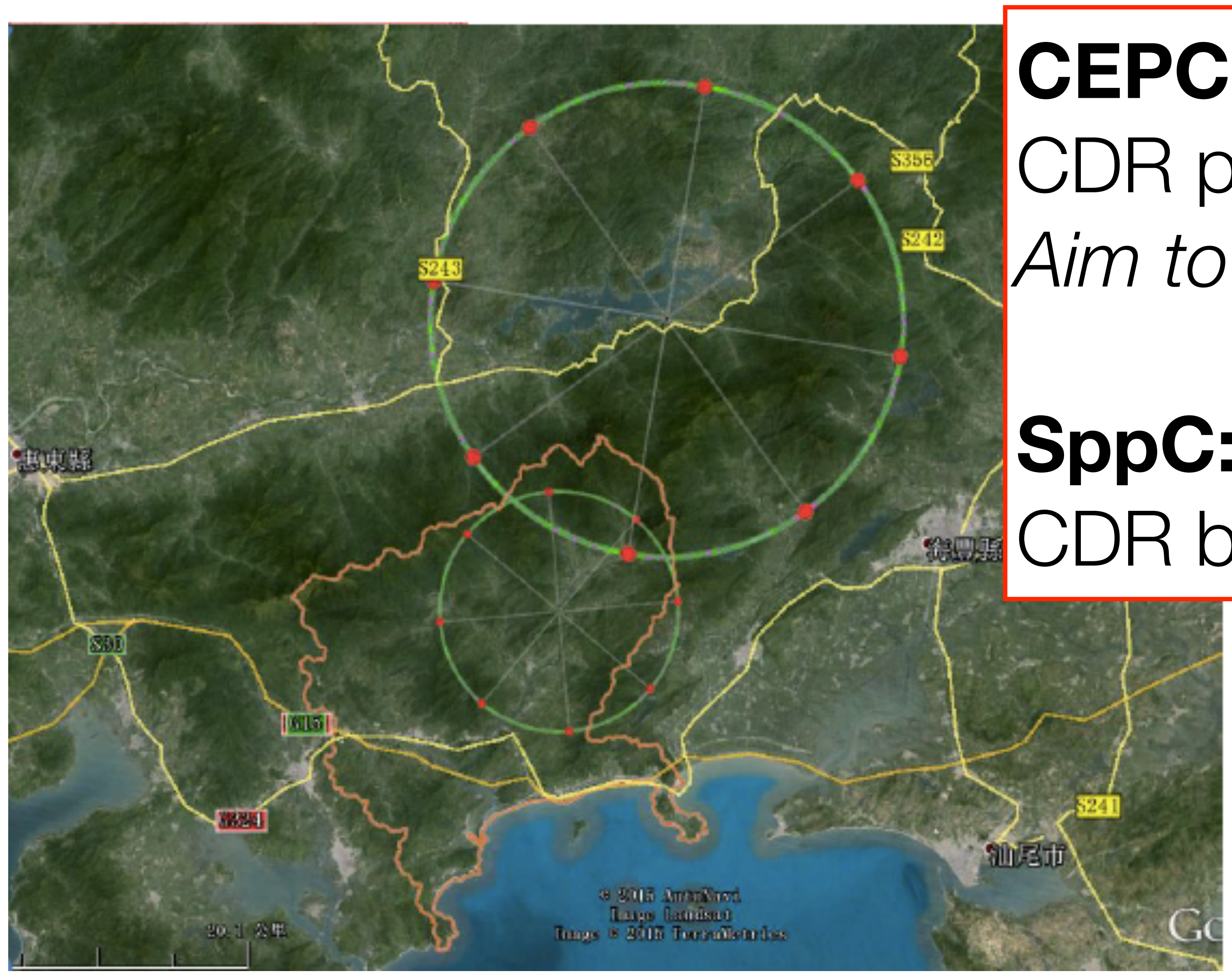
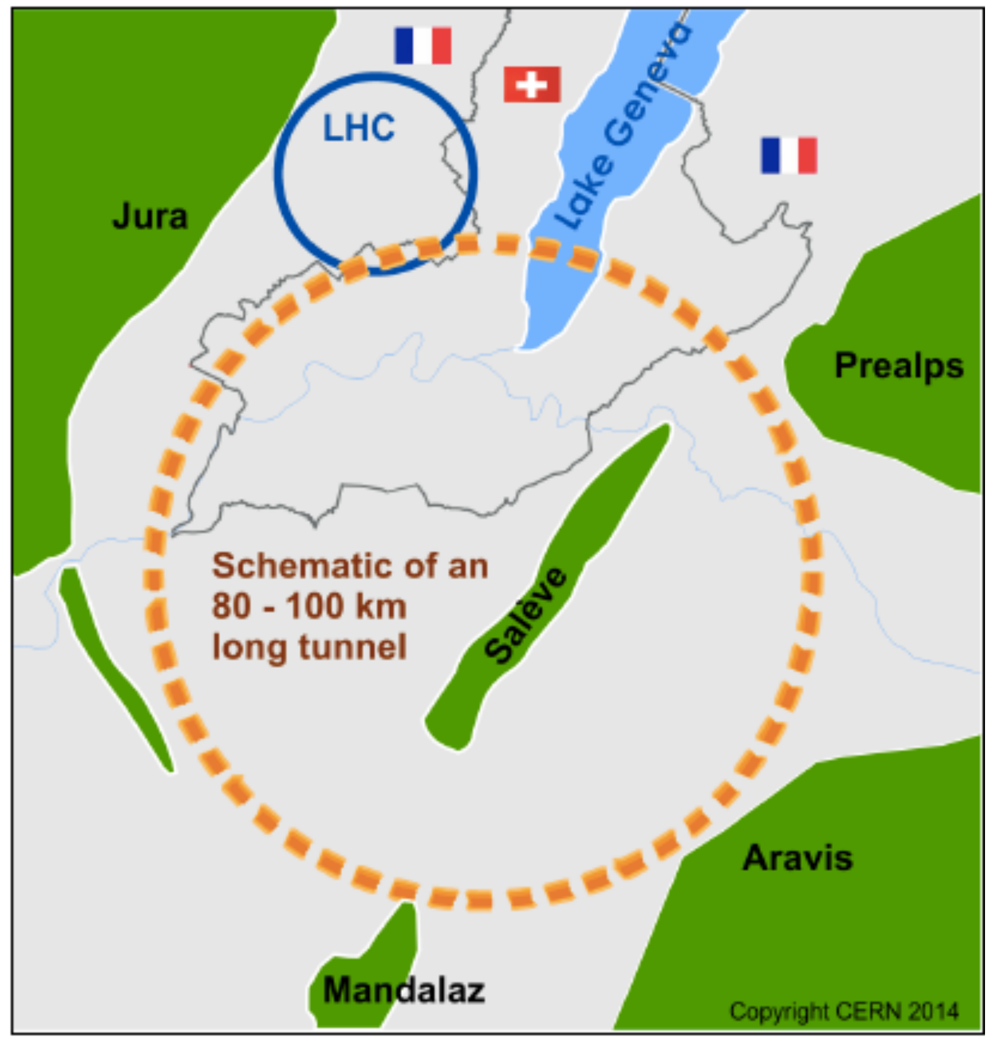


CEPC: e$^+$e$^-$ @ 240 GeV
CDR published in **2018**
Aim to start construction in **2023**

SppC: pp @ 50-70 TeV
CDR by **2035**



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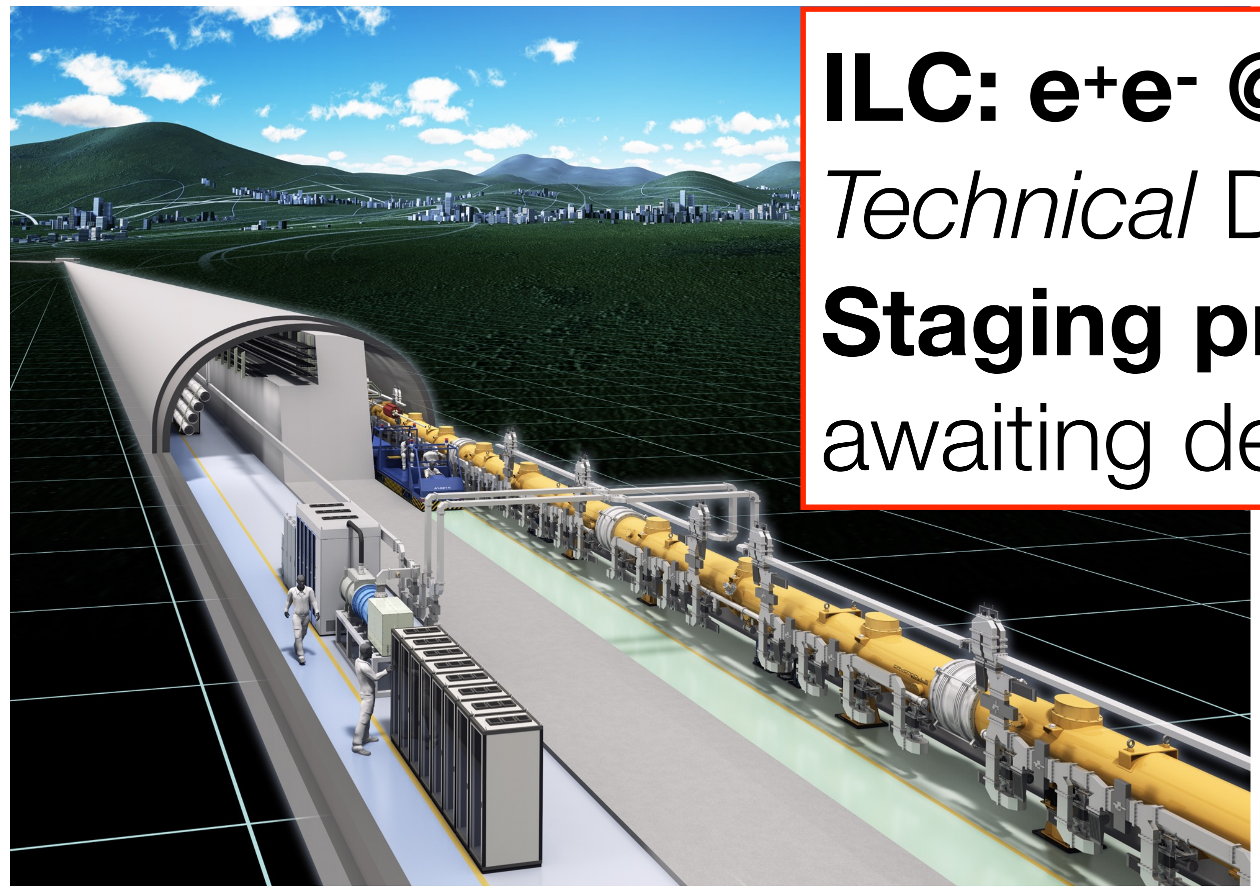

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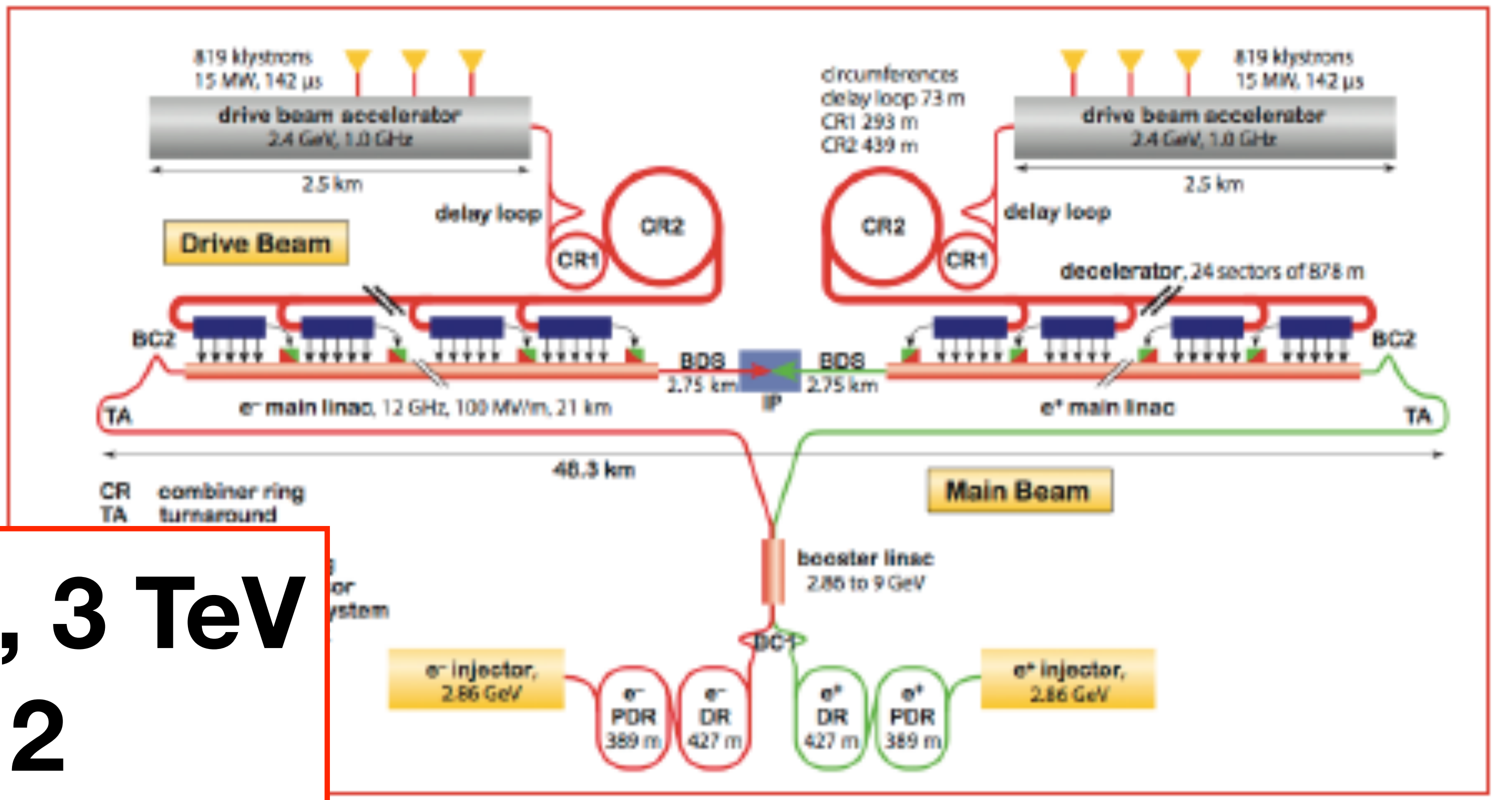

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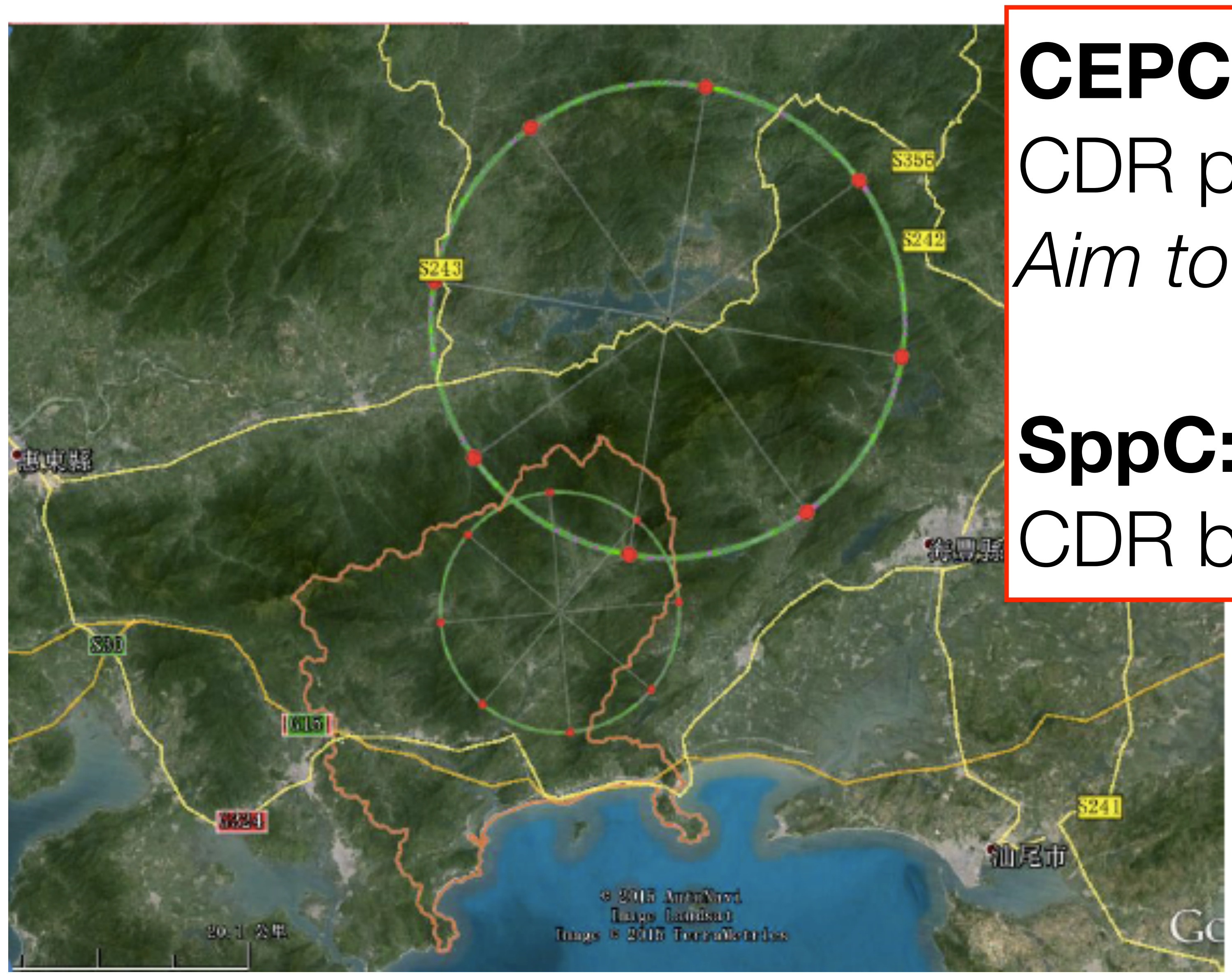

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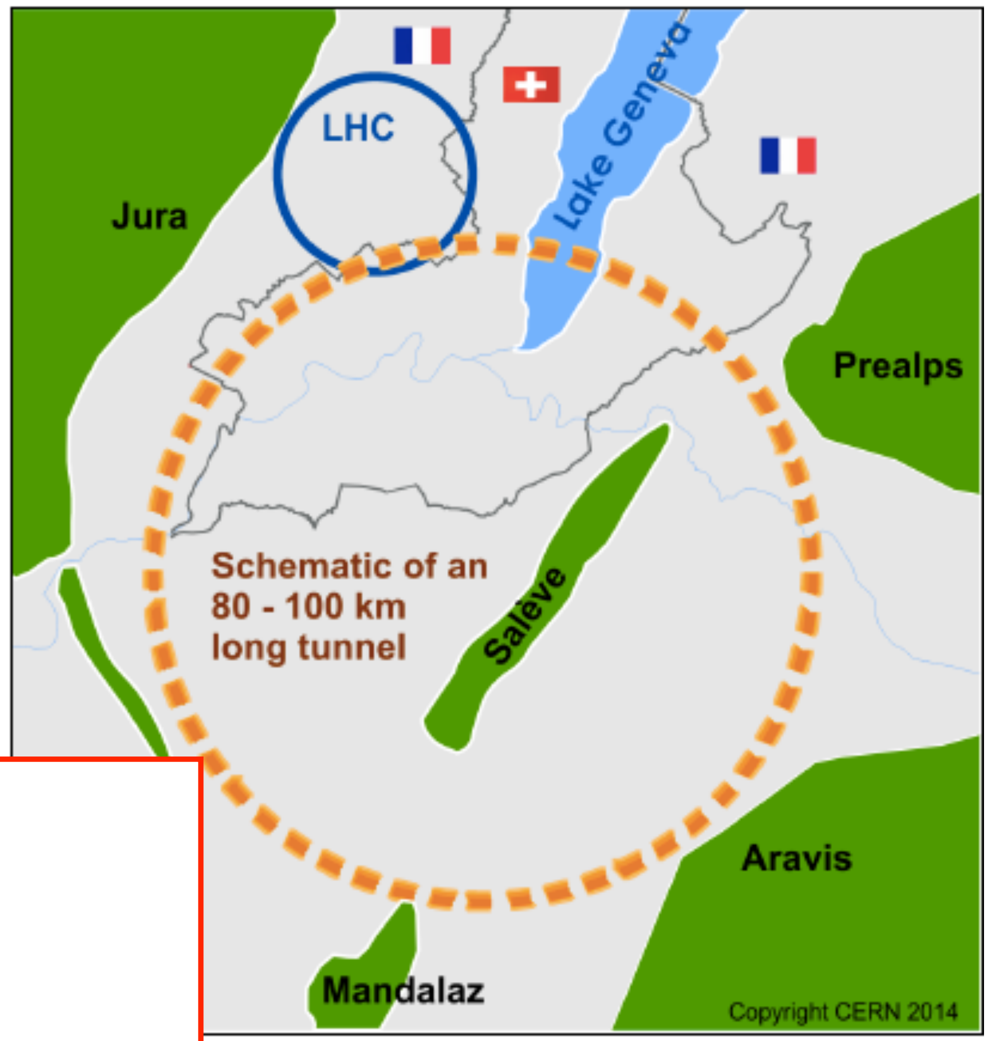

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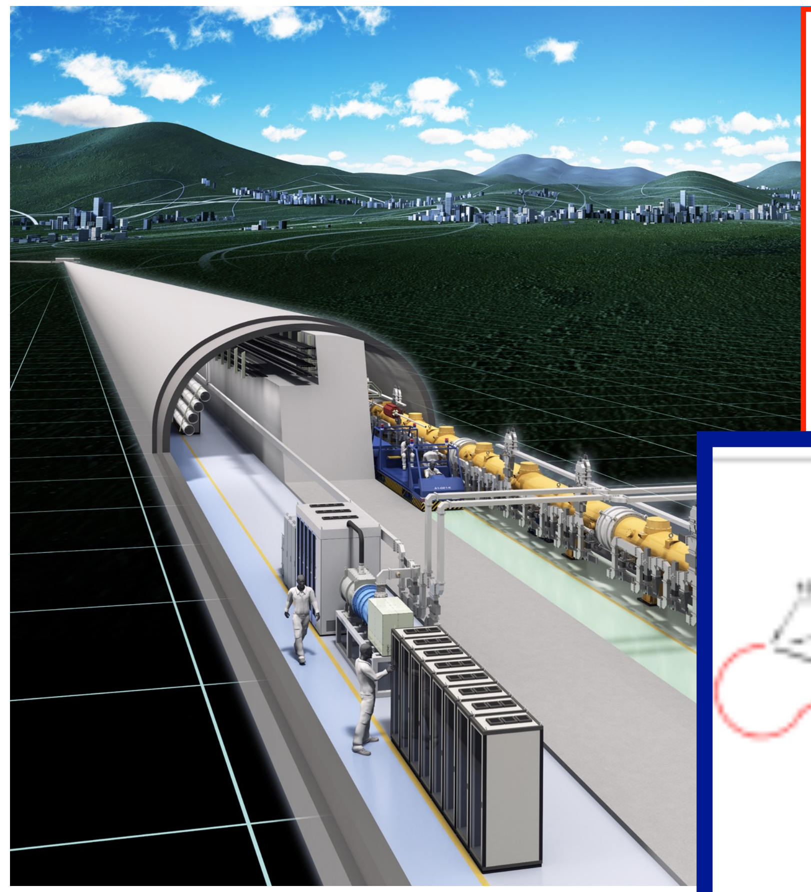

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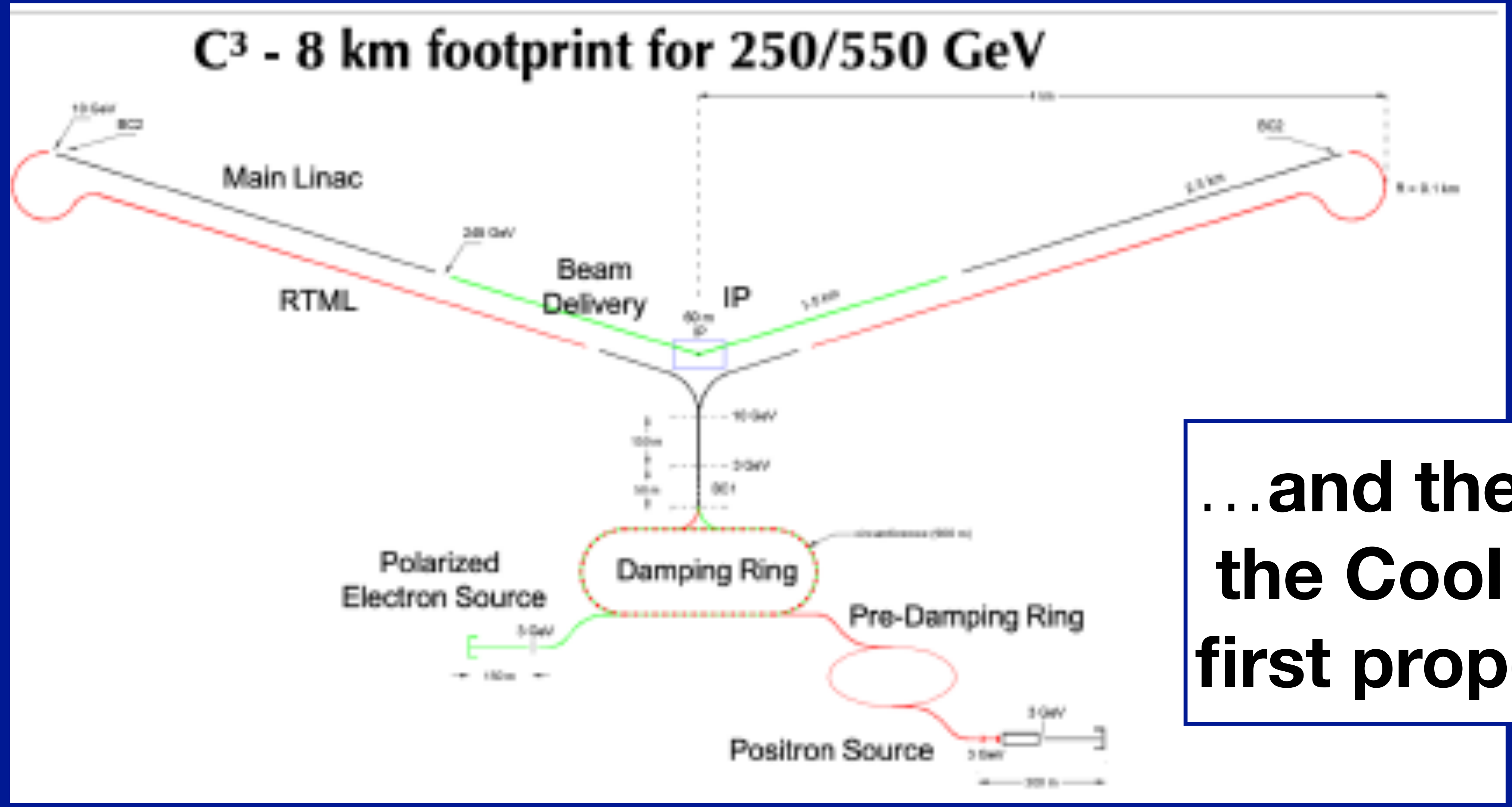

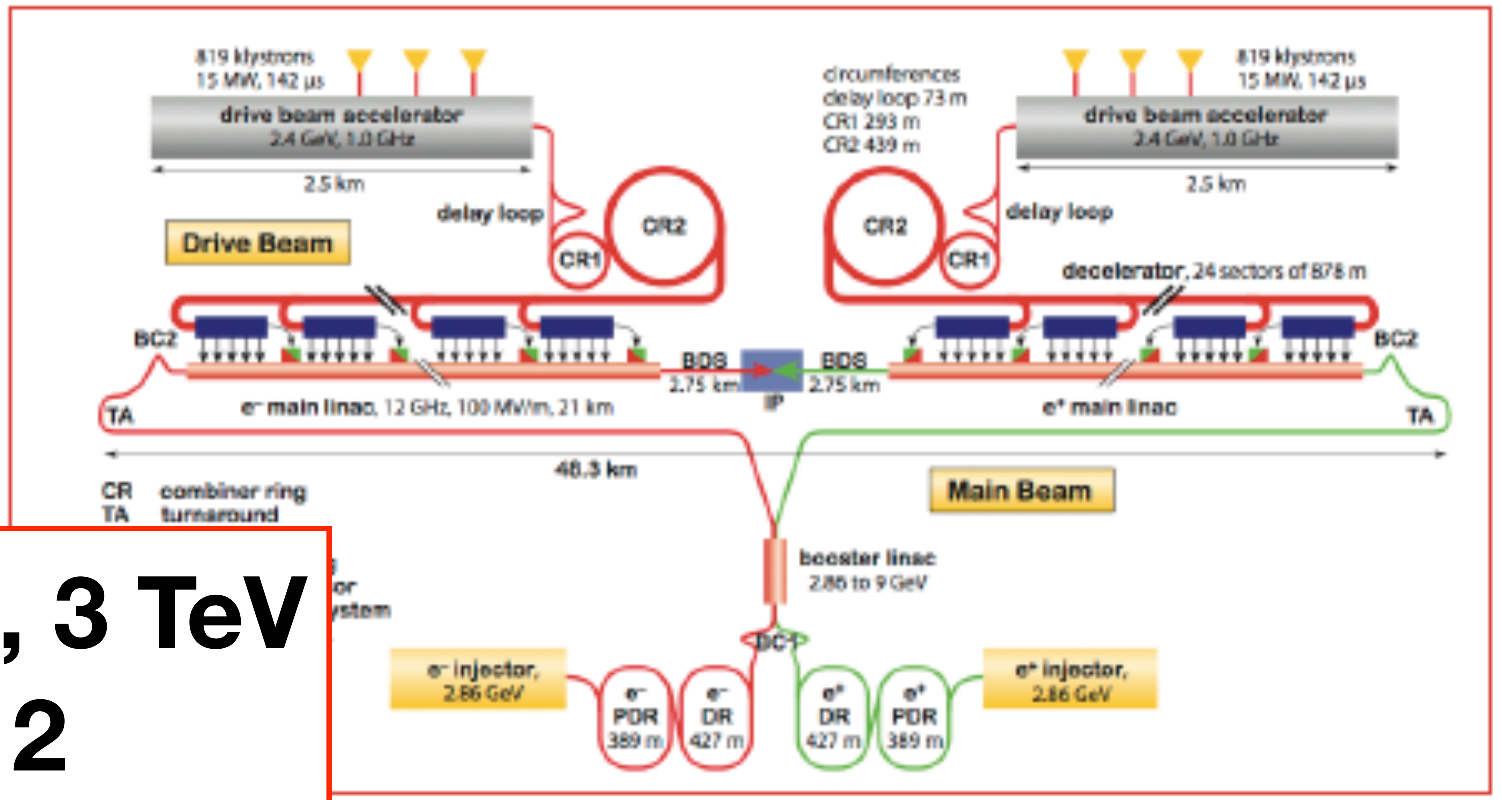

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…and the new kid on the block:
the Cool Copper Collider C³,
first proposed 2018 arXiv:1807.10195

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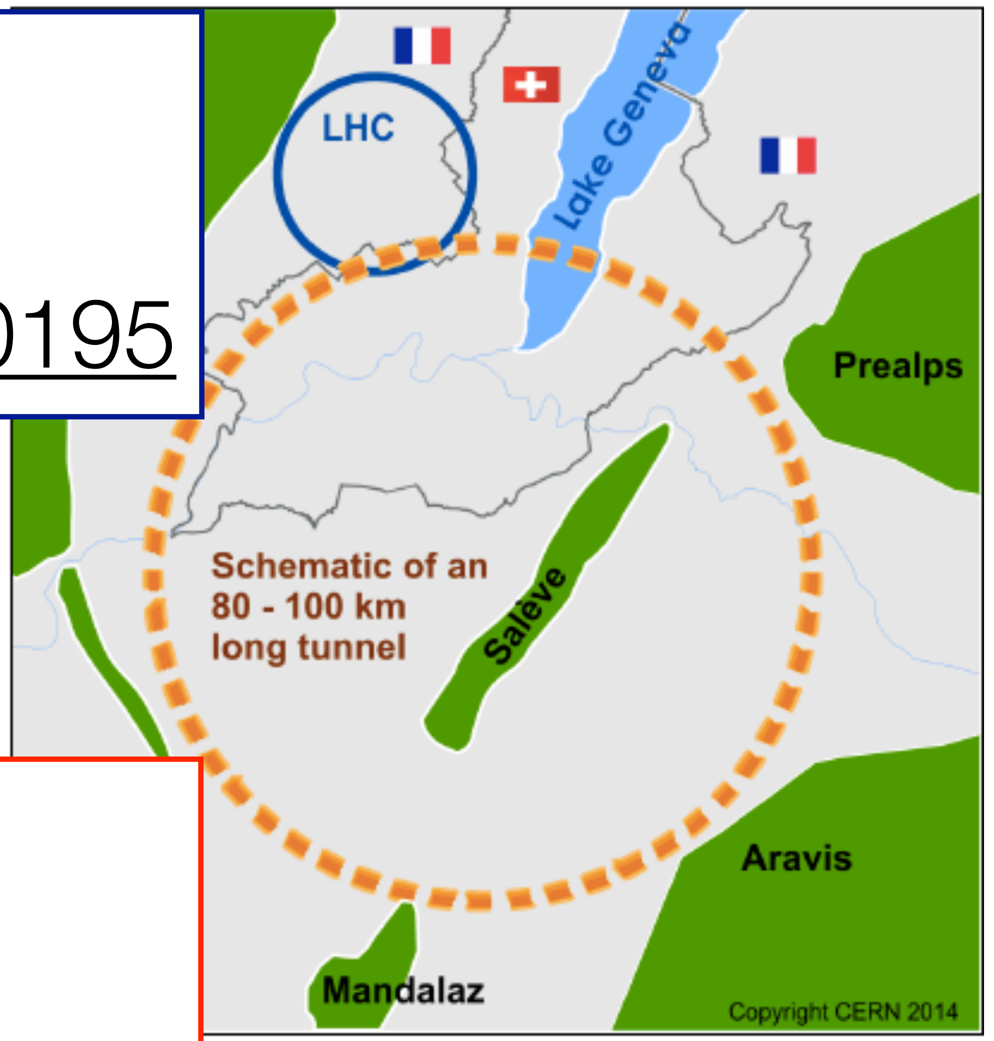

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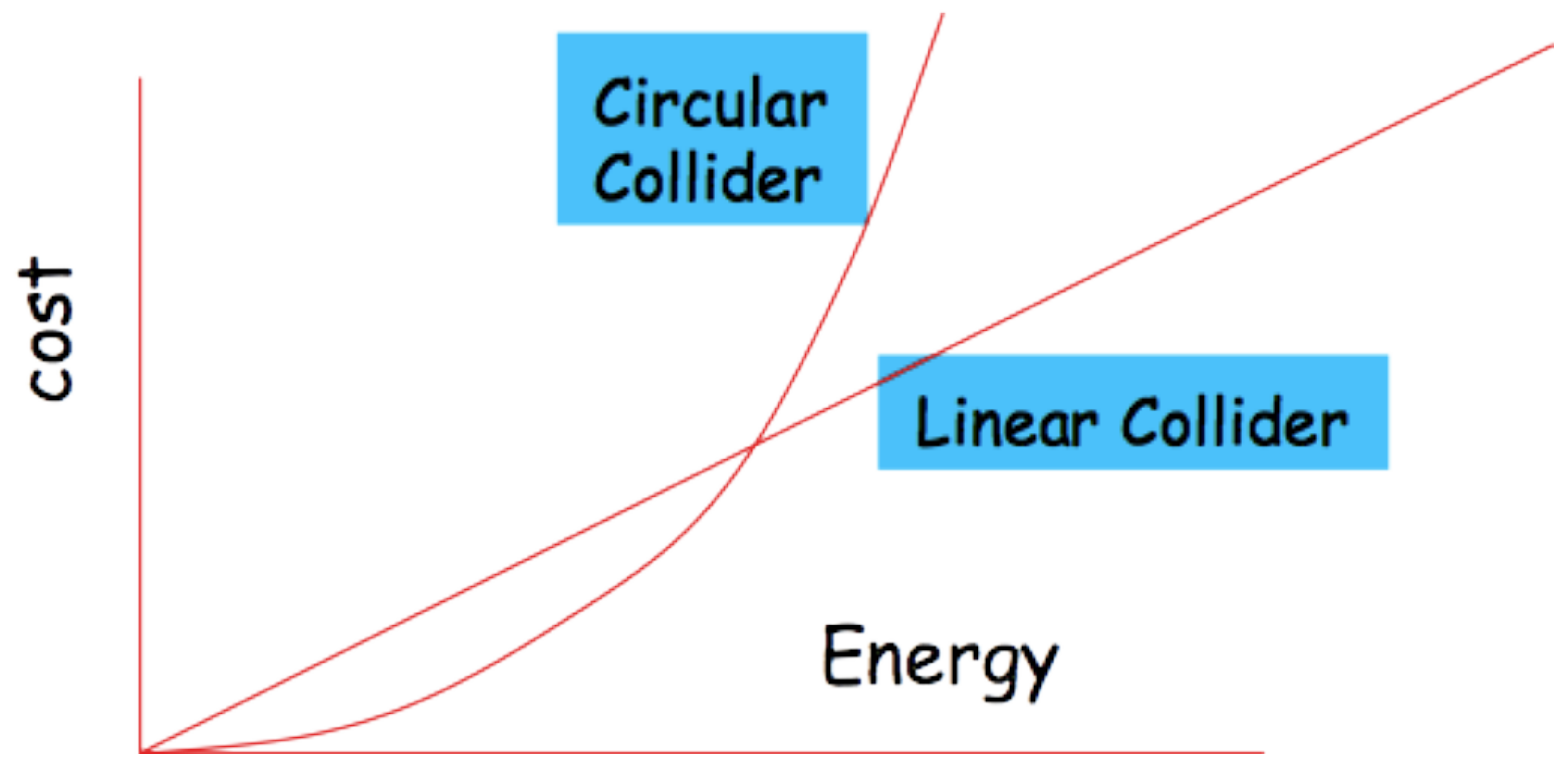
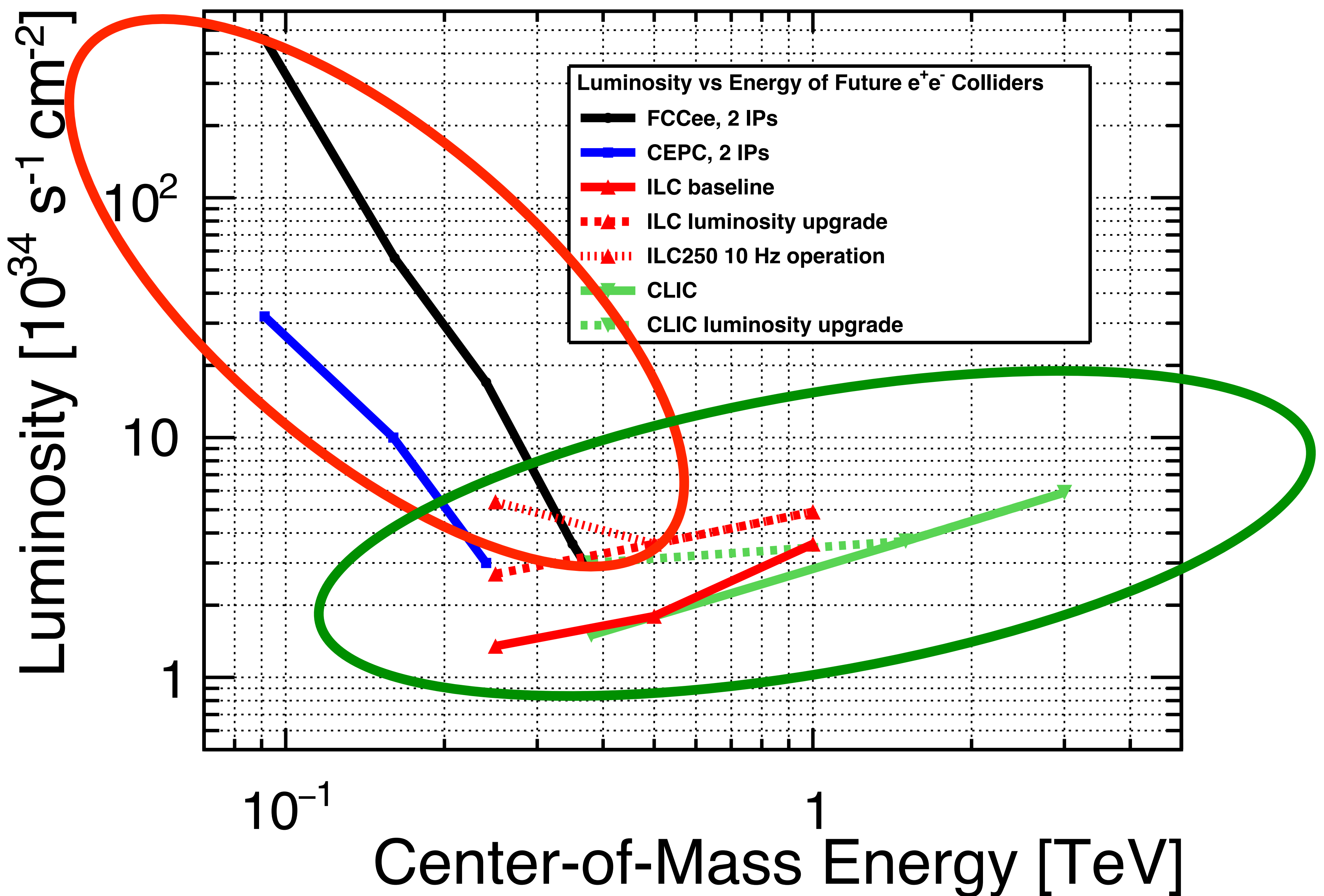
Linear or Circular ?

- **synchrotron radiation:**
  - **$\Delta E \sim (E^4 / m^4 R)$** per turn => 2 GeV at LEP2
- **cost in high-energy limit:**
  - **circular :**
    $\$\$ \sim a\,R + b\,\Delta E \sim a\,R + b\,(E^4 / m^4 R)$

    optimisation => $R \sim E^2$ => **$\$\$ \sim E^2$**
  - **linear :** $\$\$ \sim$ **Length**, with **$L \sim E$** => **$\$\$ \sim E$ => scalable**





Advantanges of Circular Colliders
- high luminosities at low energies
- multiple interaction regions
- **little beamstrahlung**

Advantanges of Linear Colliders
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- **energy extendability**
- **polarised beam(s)**

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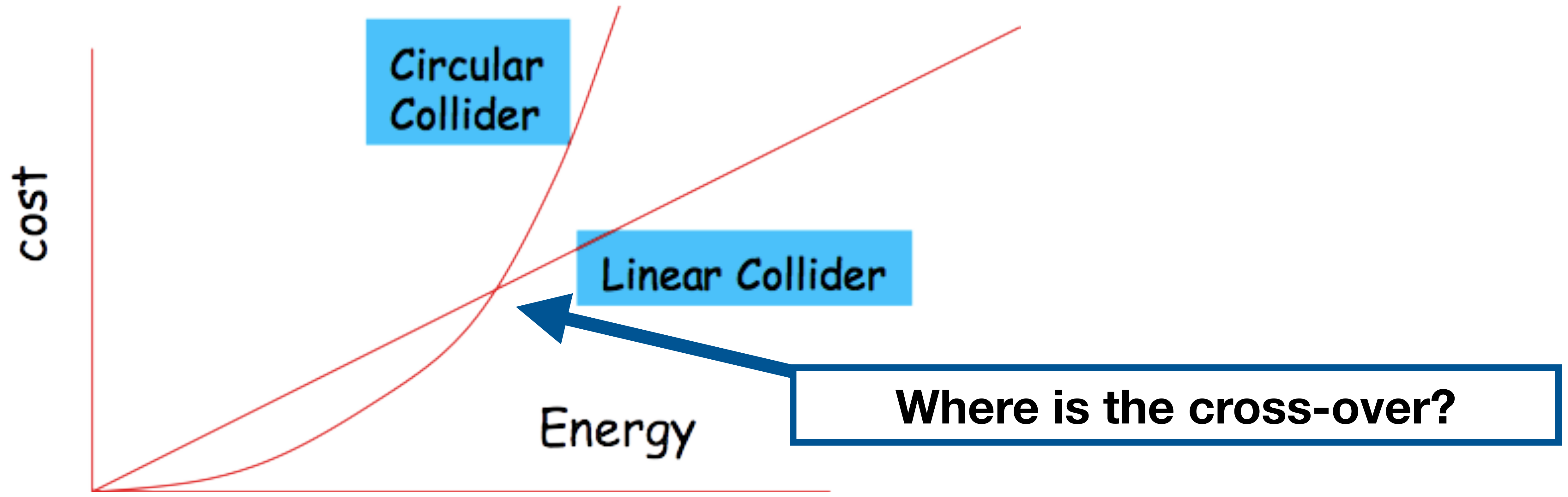

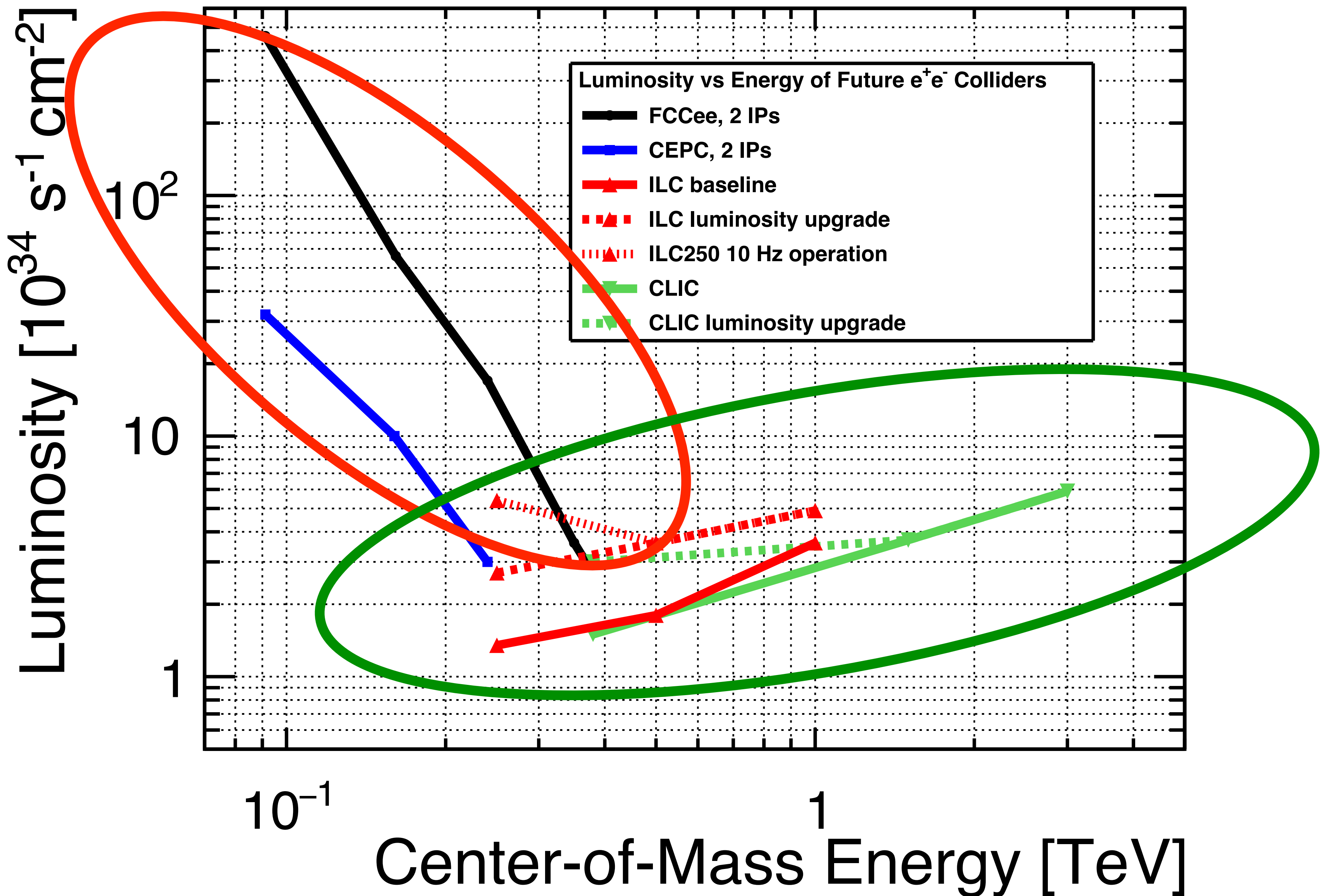

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New insights from our new friend…at 250 GeV

The Higgs Boson

How big can BSM effects be?

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

The Higgs Boson couplings

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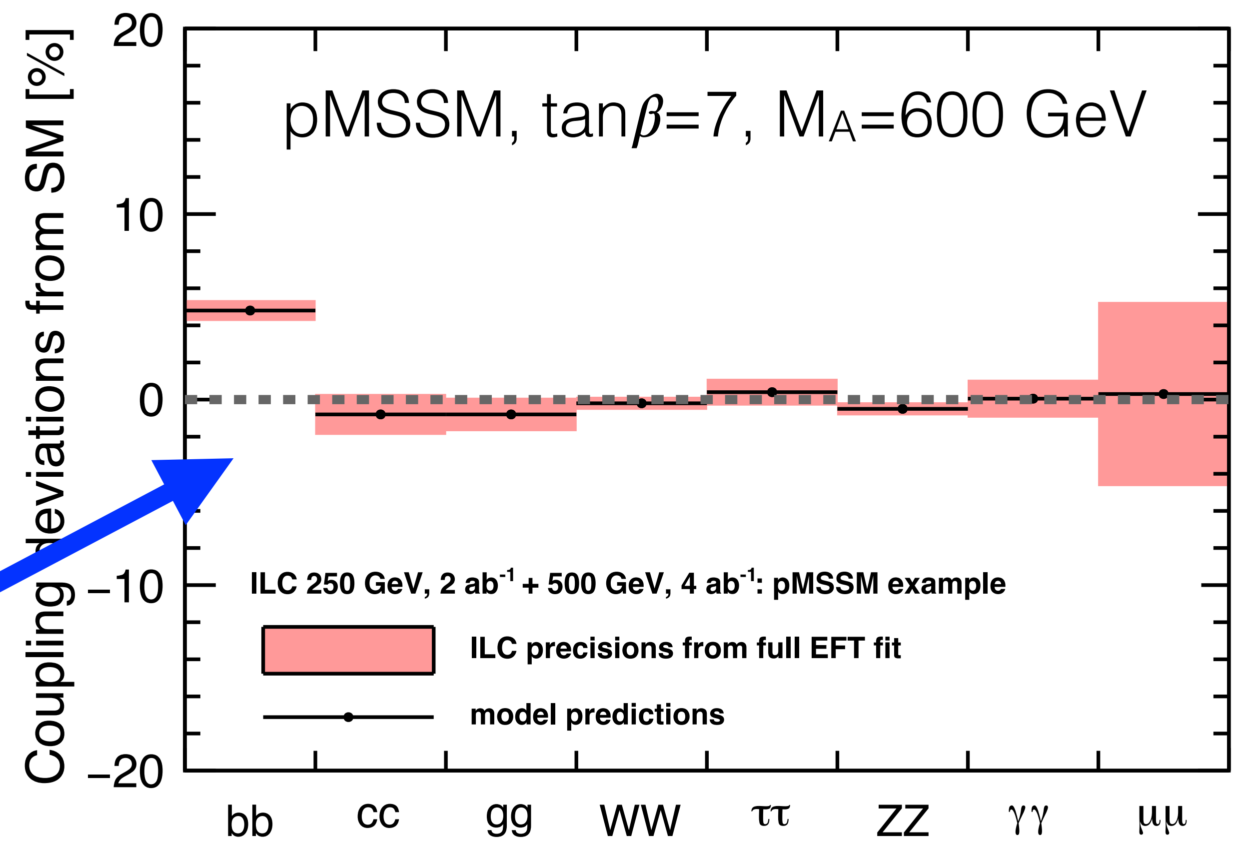

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The Higgs Boson couplings

How big can BSM effects be?

- low scale new physics
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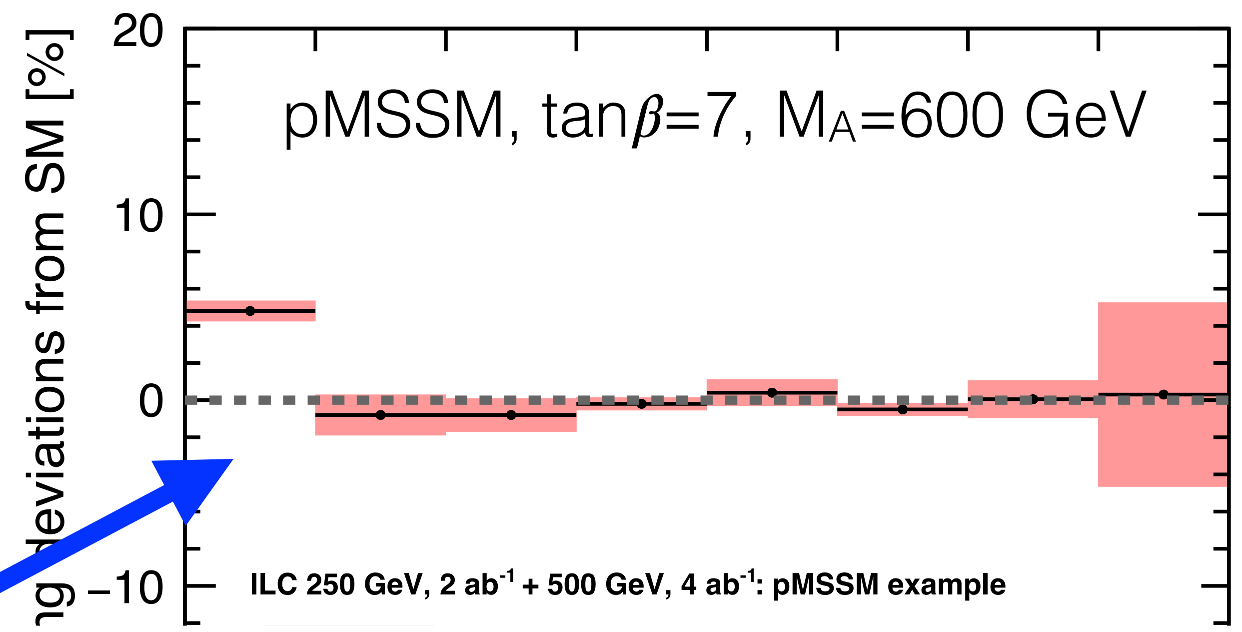

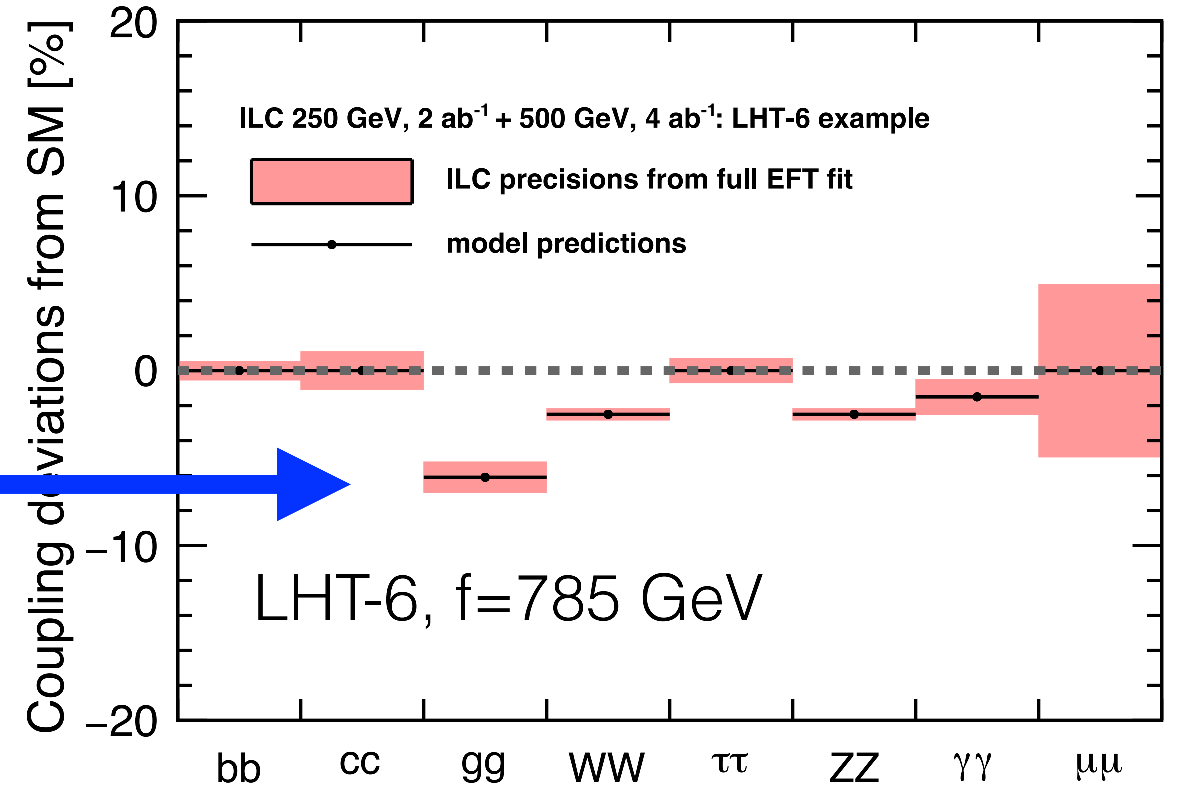

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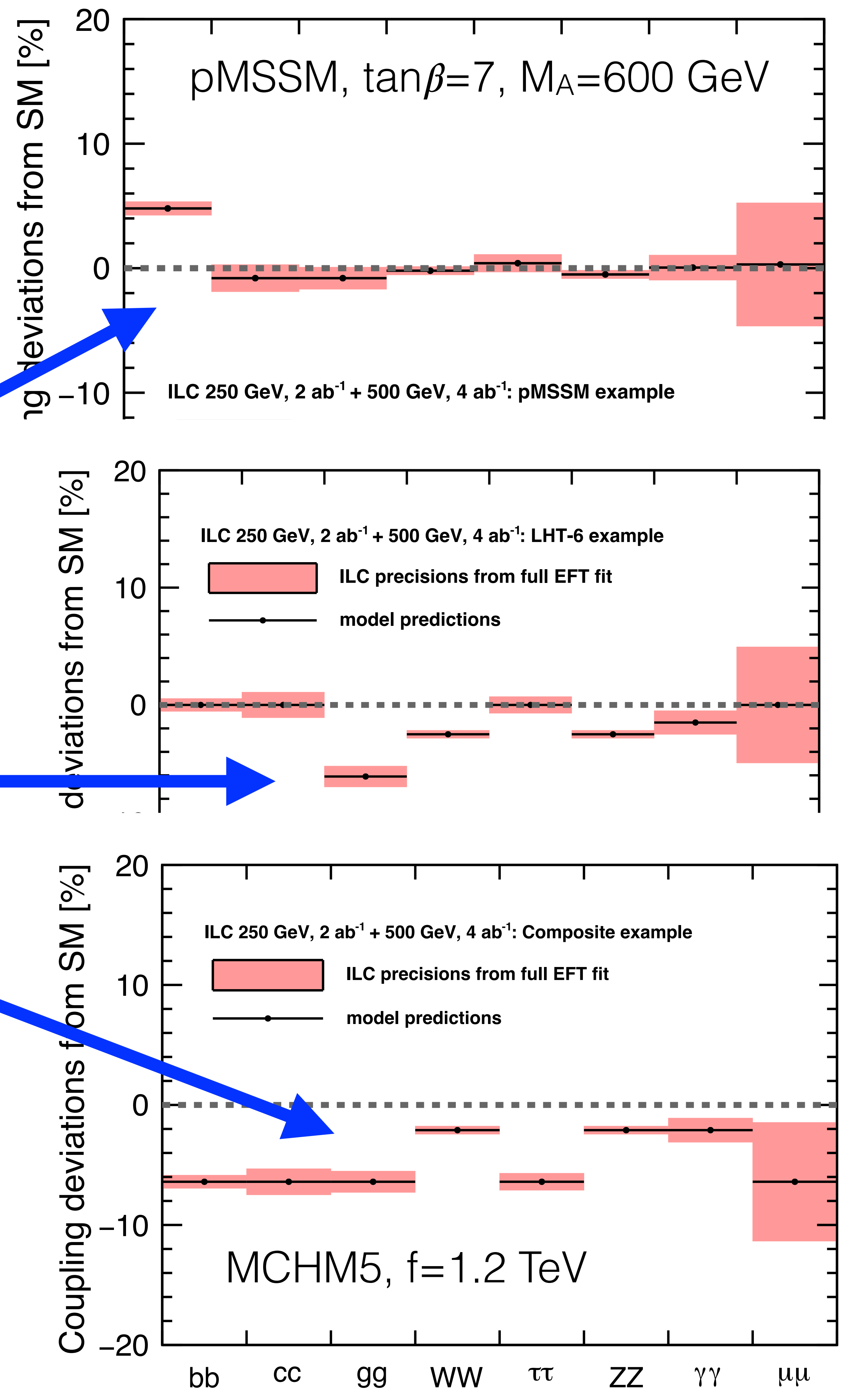

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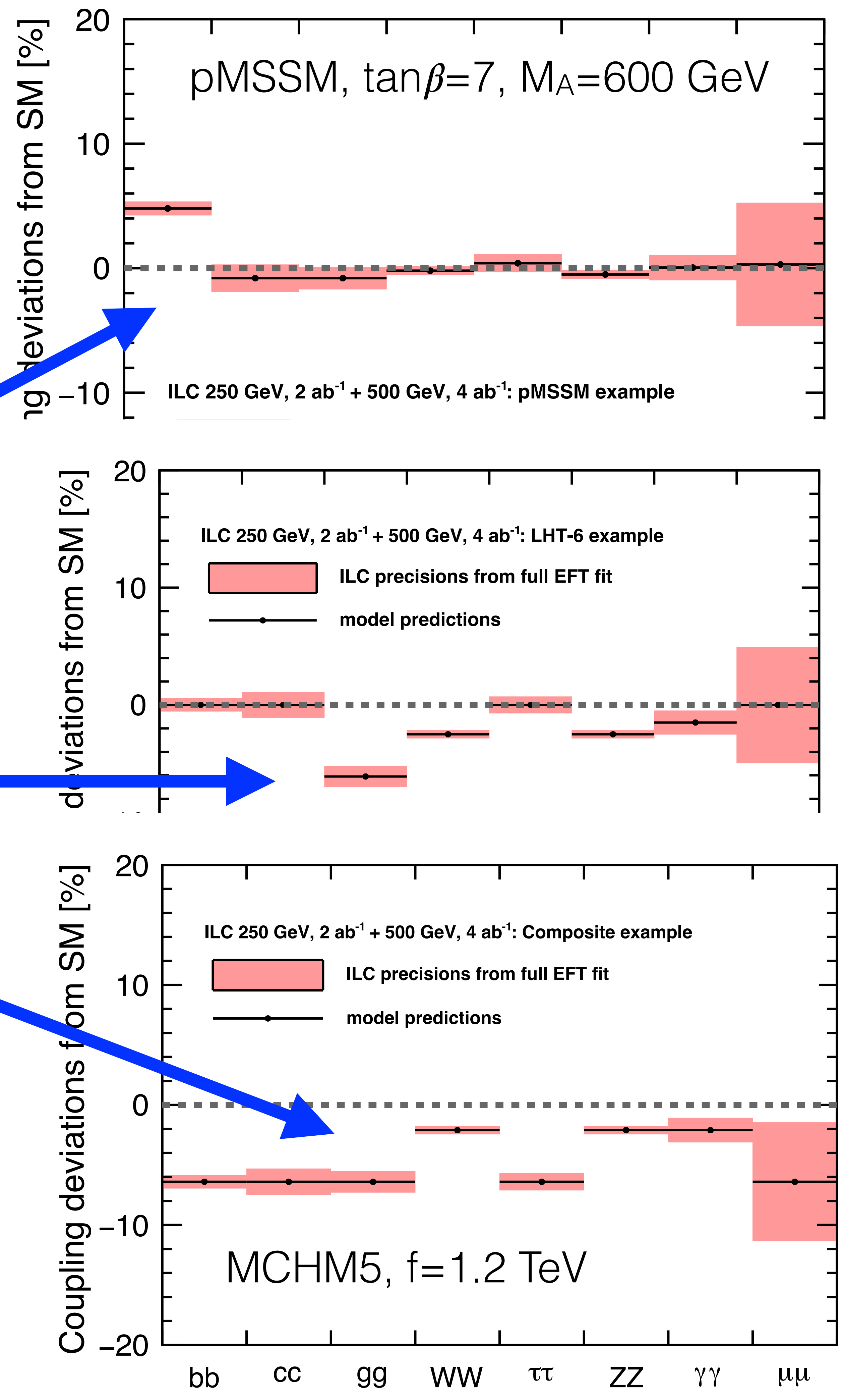
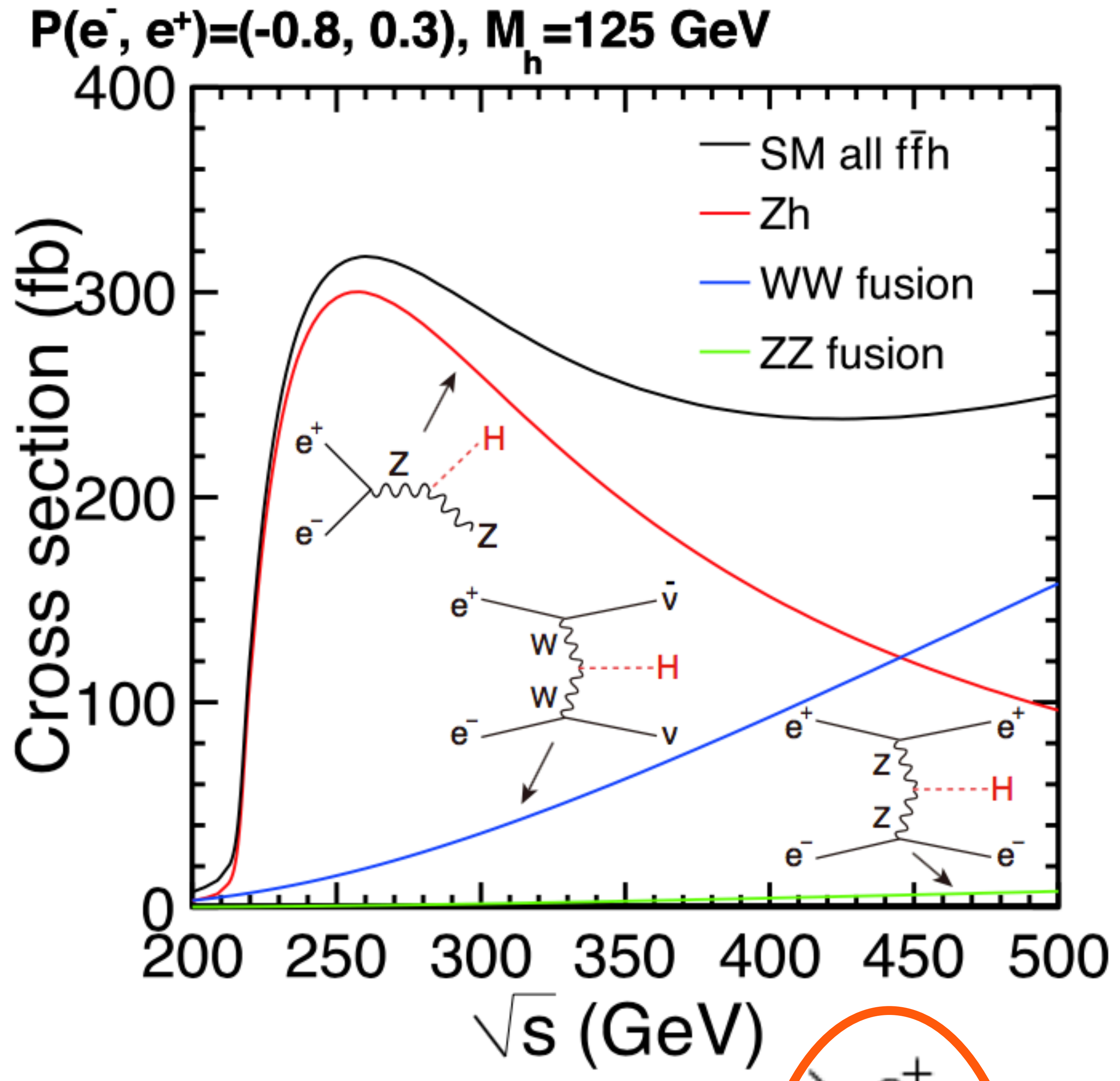
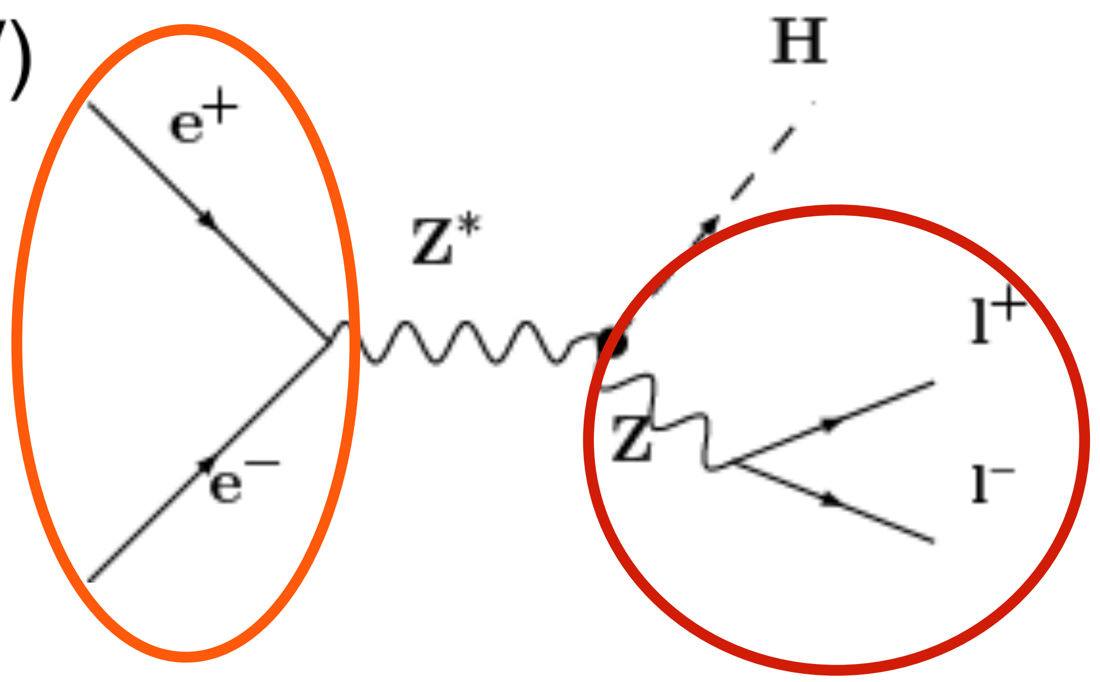
At least percent-level precision required!



Precision Higgs Physics @ 250 GeV





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

- production dominated by Zh
- **2 ab^{-1} => ~600 000 Zh events**
- fantastic sample for measuring:
  - (recoil) mass
  - **total Zh cross section:**
    the key to model-independent determination of absolute couplings!
  - **h-> invisible (Dark Matter!): expected limited < 0.3% @ 95%**
  - all kinds of branching ratios
  - **CP properties of h-fermion coupling**
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  - ….

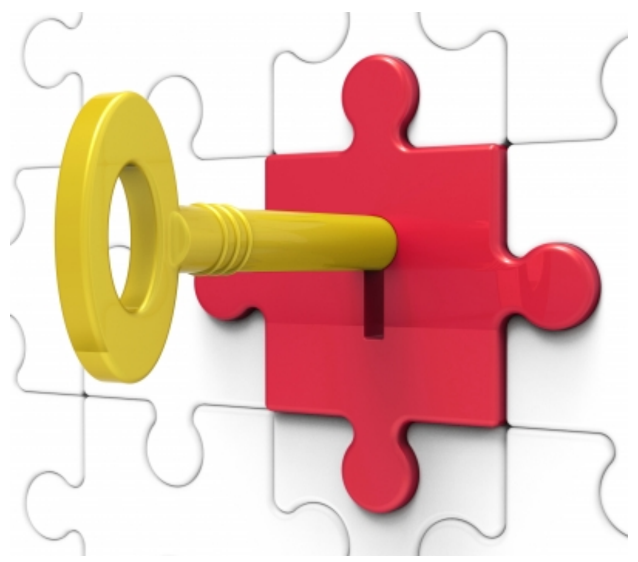

Image courtesy of Stuart Miles at FreeDigitalPhotos.net

for detailed listings of individual precisions c.f. arXiv:1708.08912

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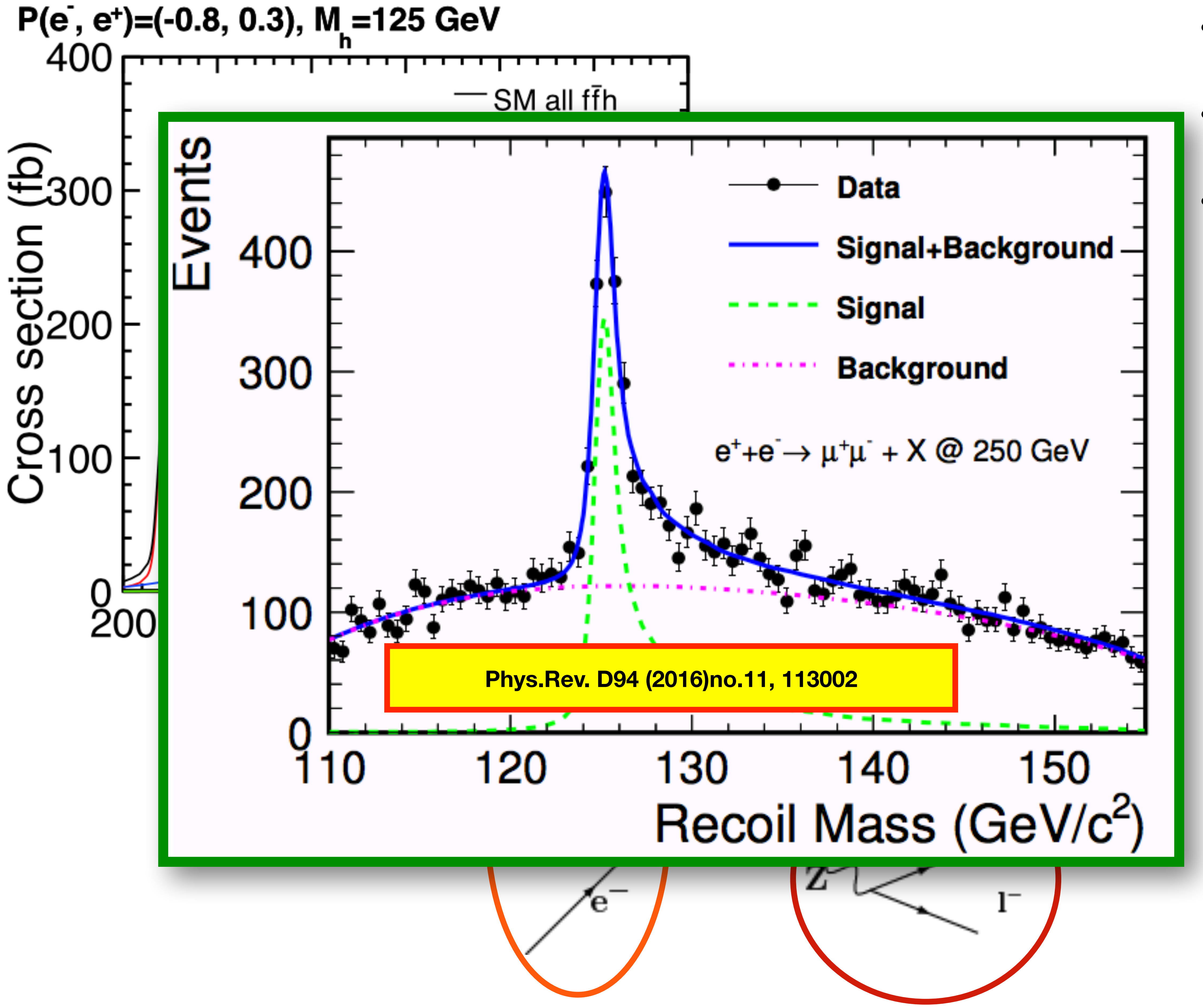

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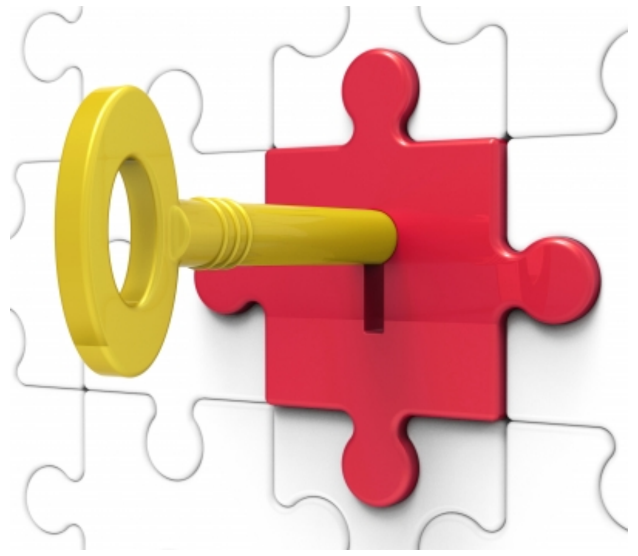

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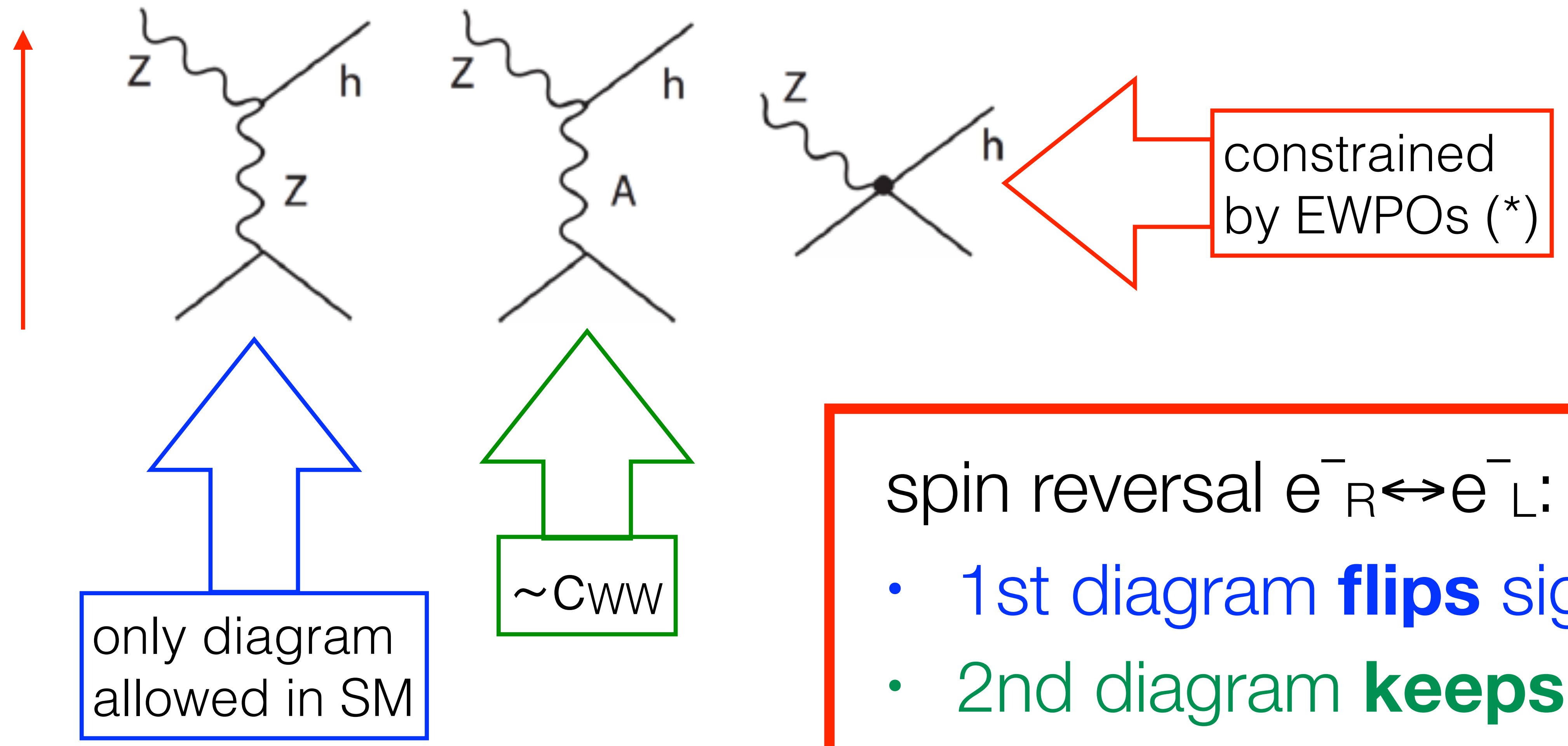
Polarisation & Higgs Couplings

arXiv:1903.01629

- **THE key process** at a Higgs factory: **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
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⇒ A_{LR} lifts degeneracy between operators!

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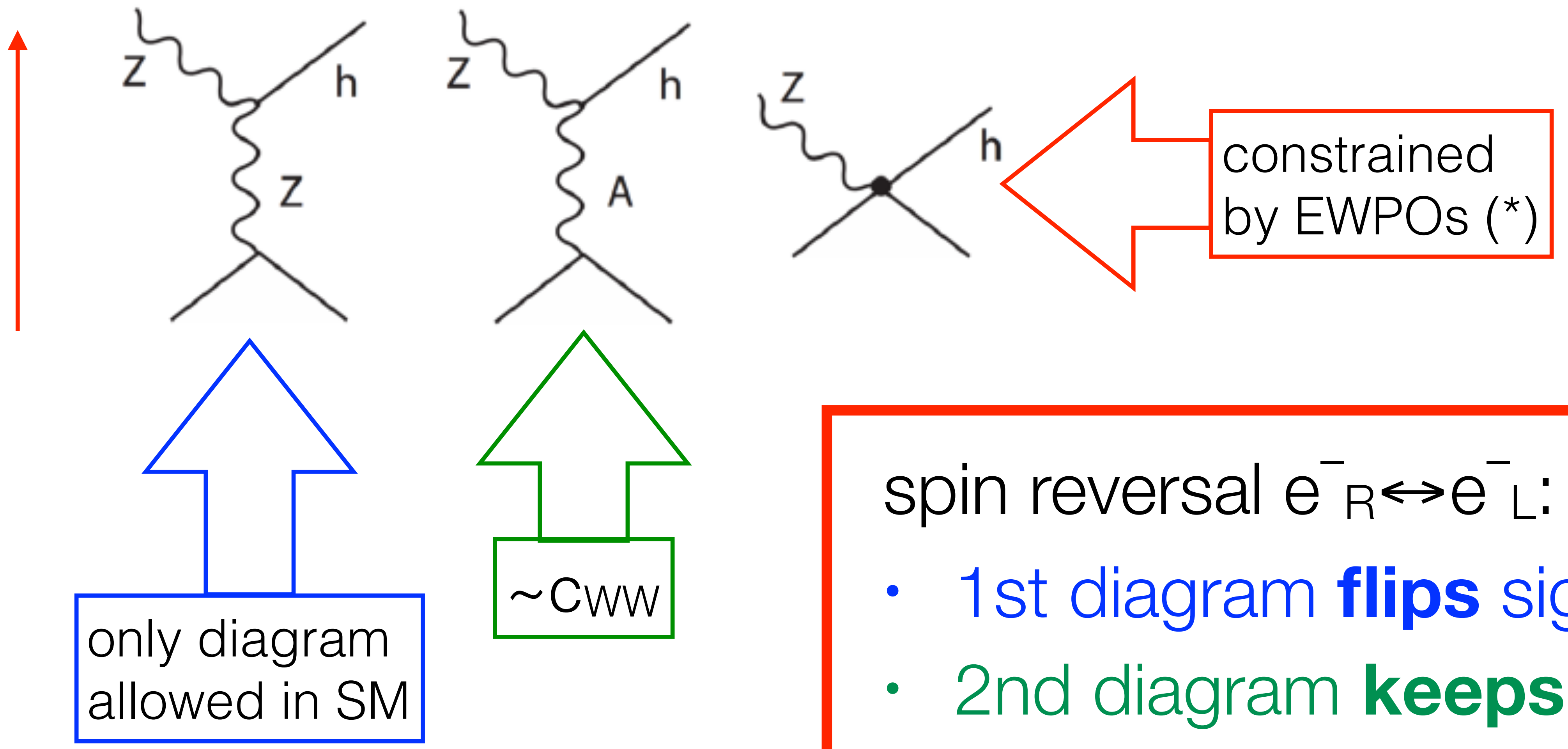

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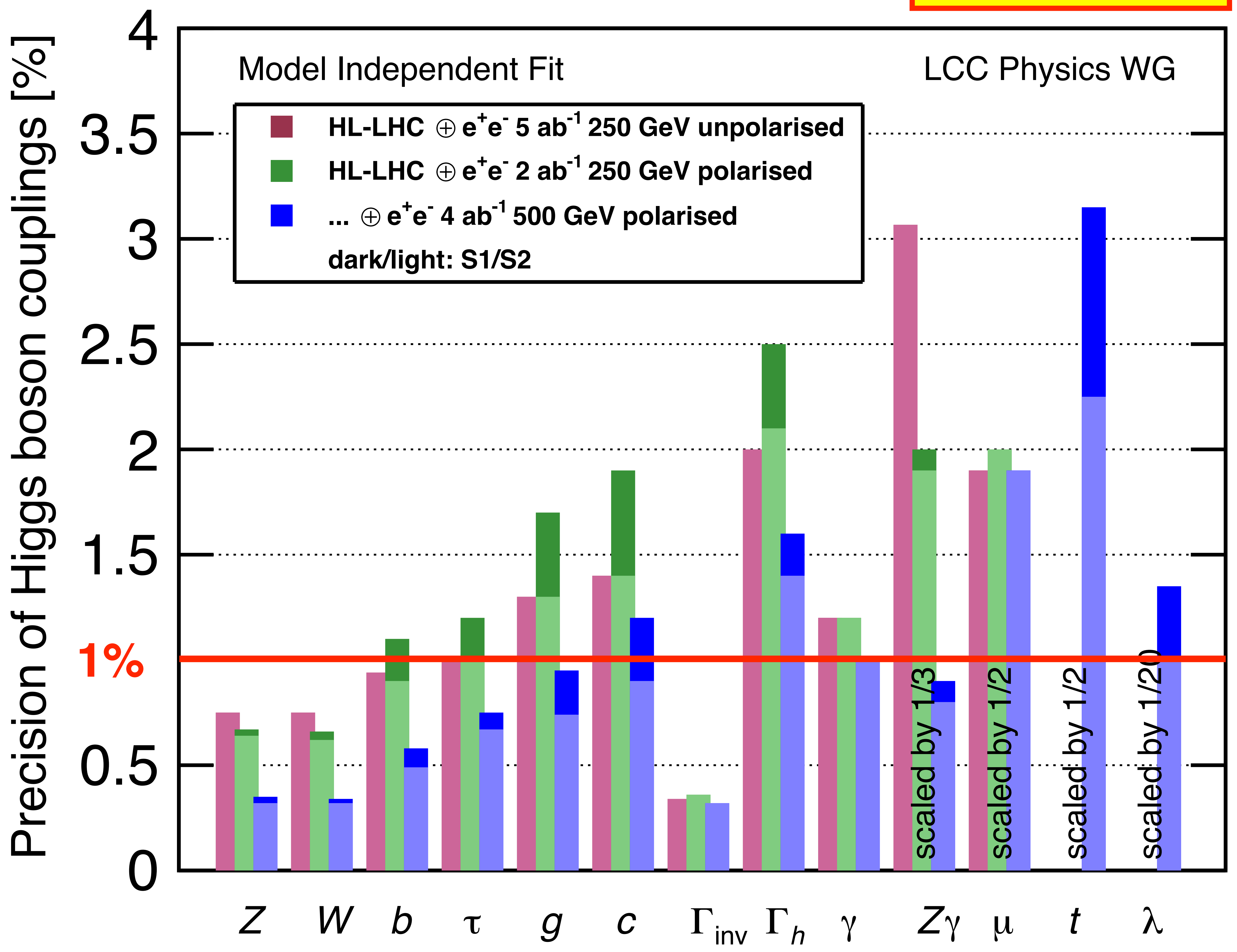

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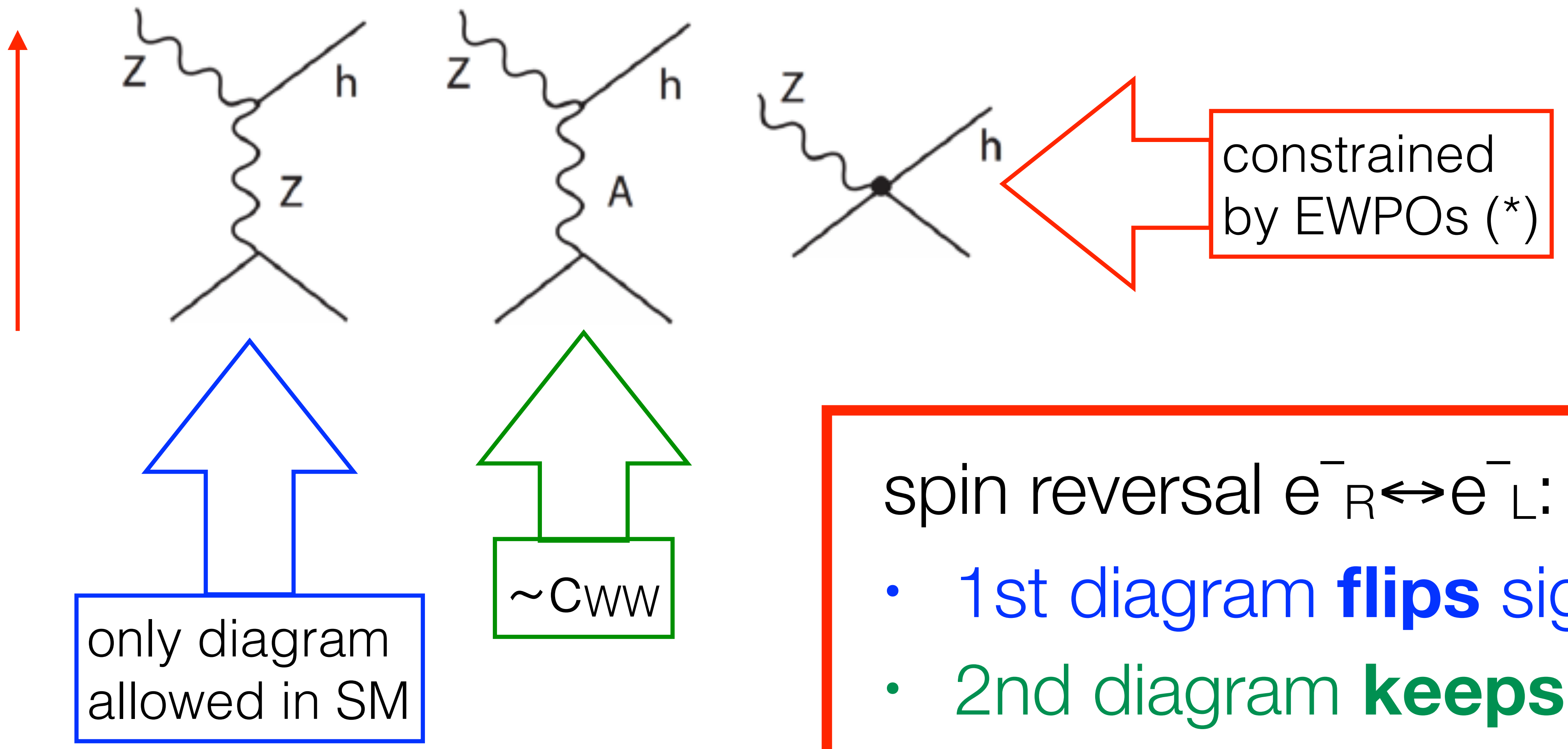

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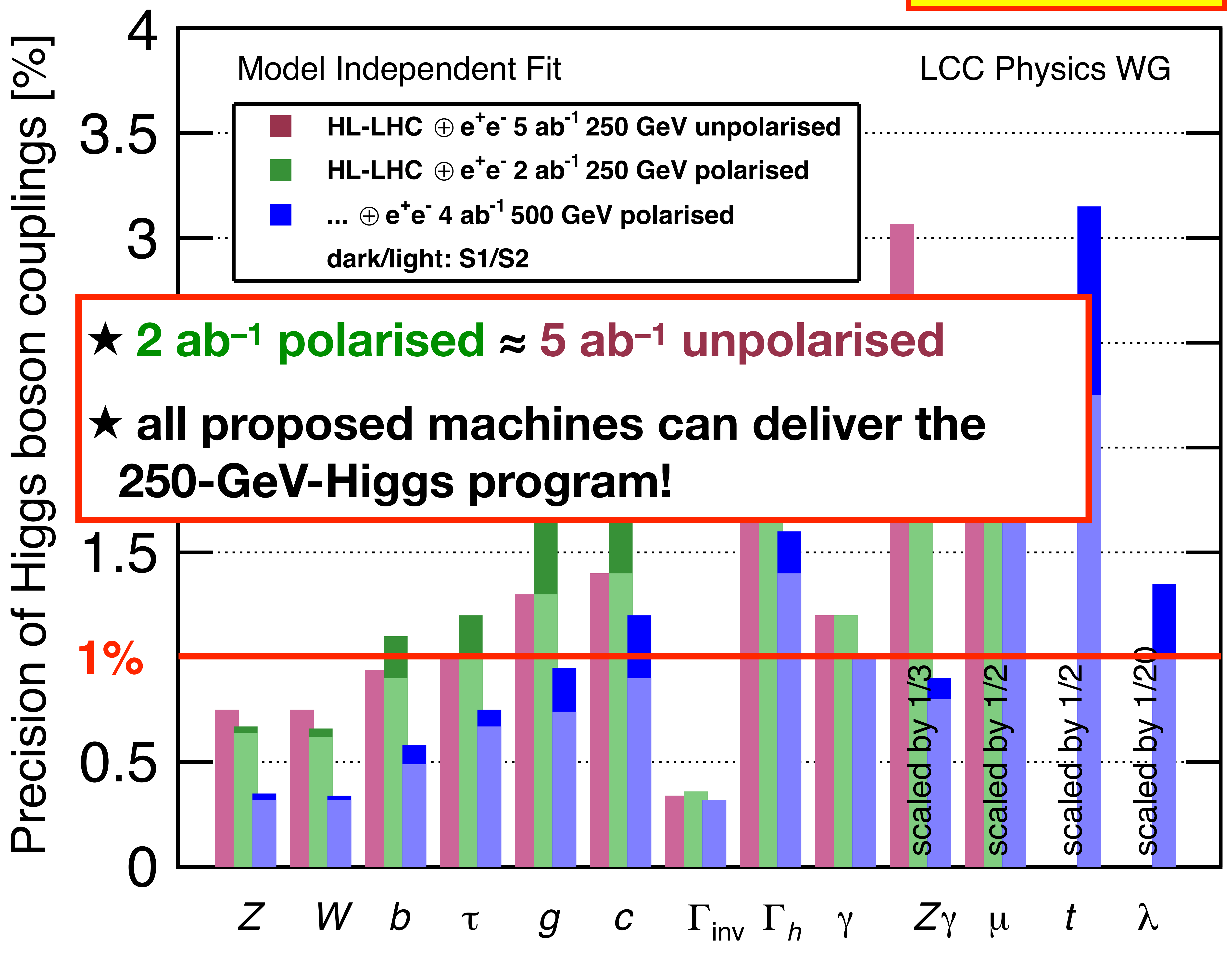


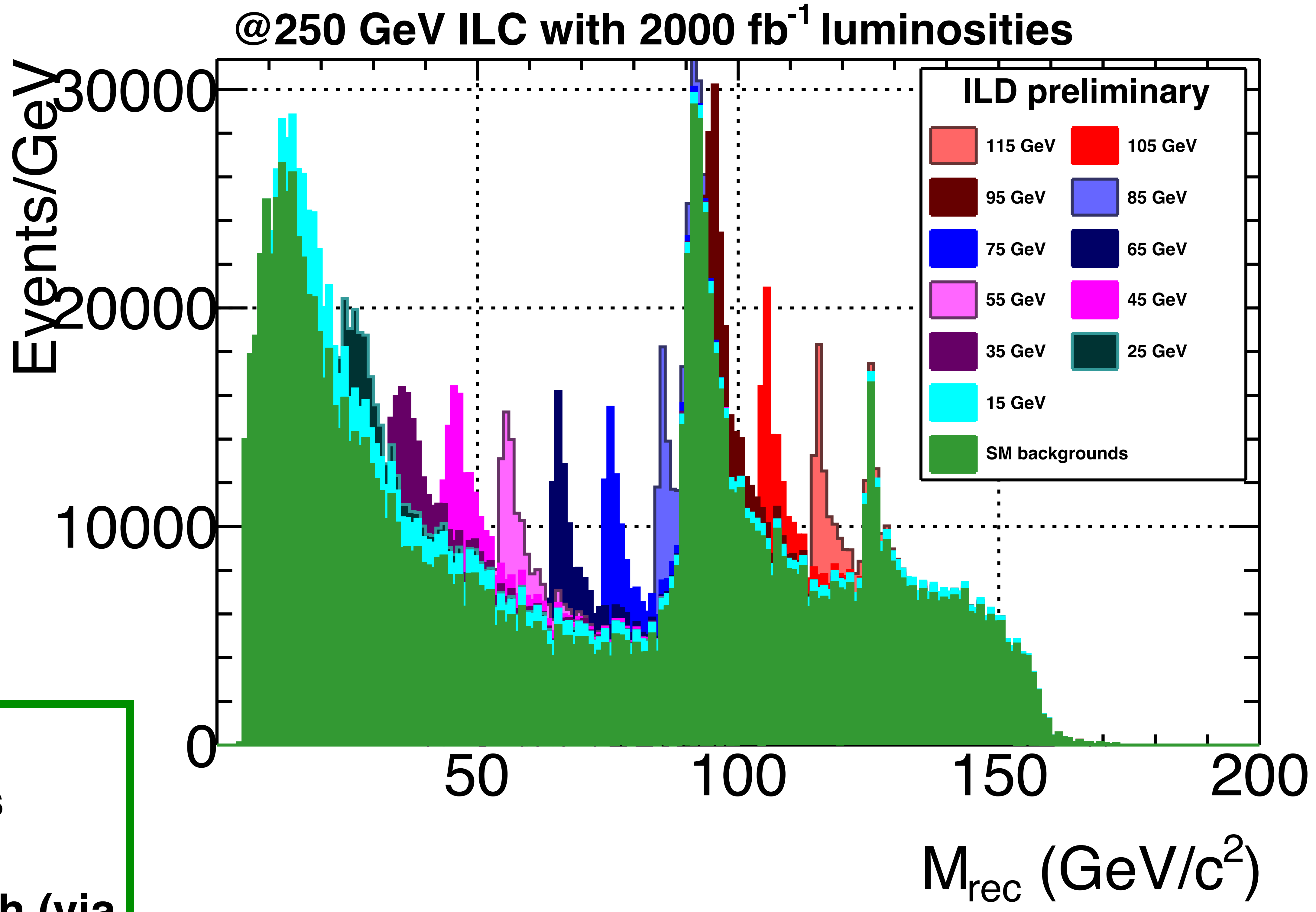
★ **2 ab^{-1} polarised ≈ 5 ab^{-1} unpolarised**

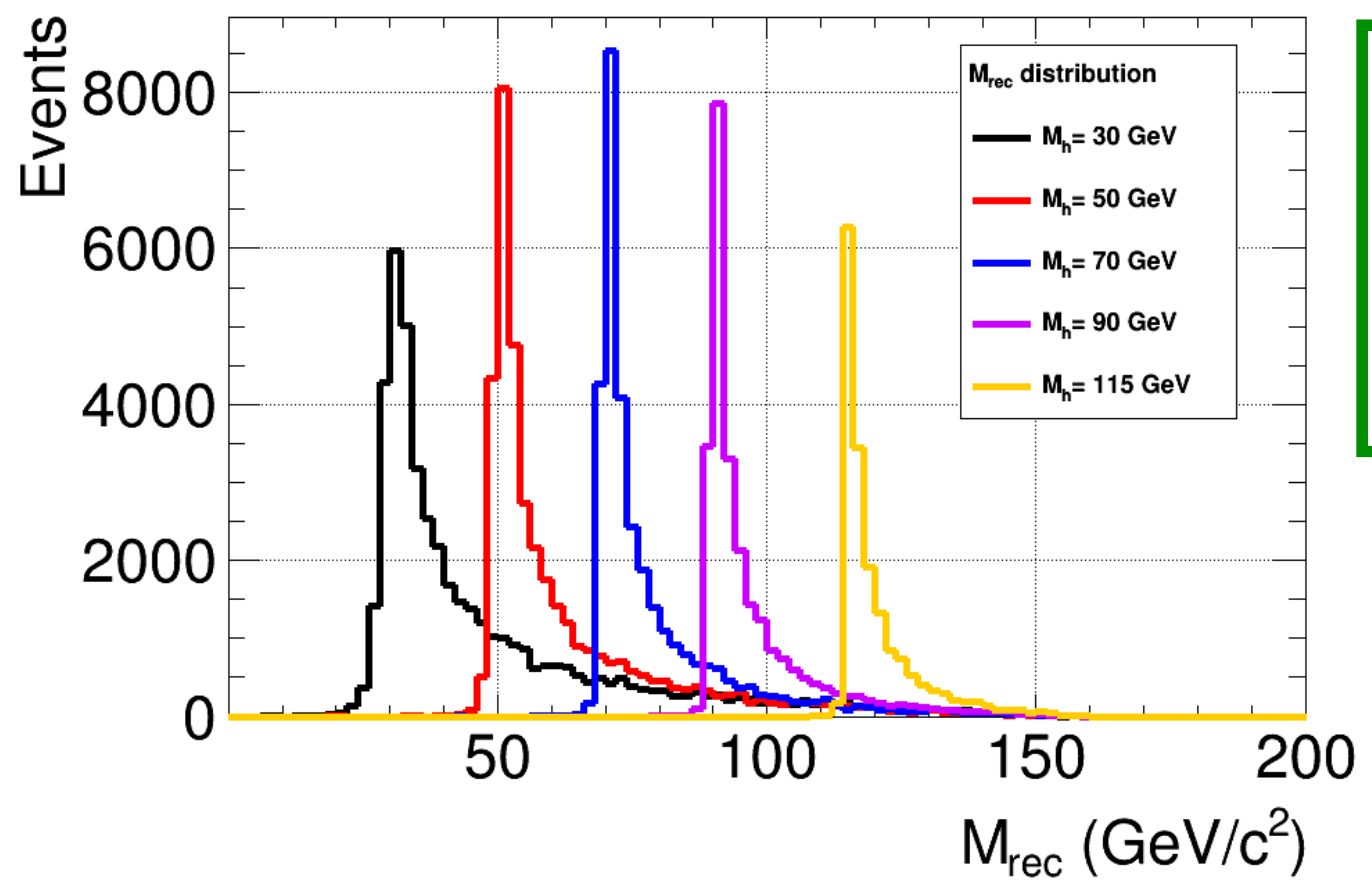
★ **all proposed machines can deliver the 250-GeV-Higgs program!**

Extra Higgs Bosons ?

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

=> decay mode independent!





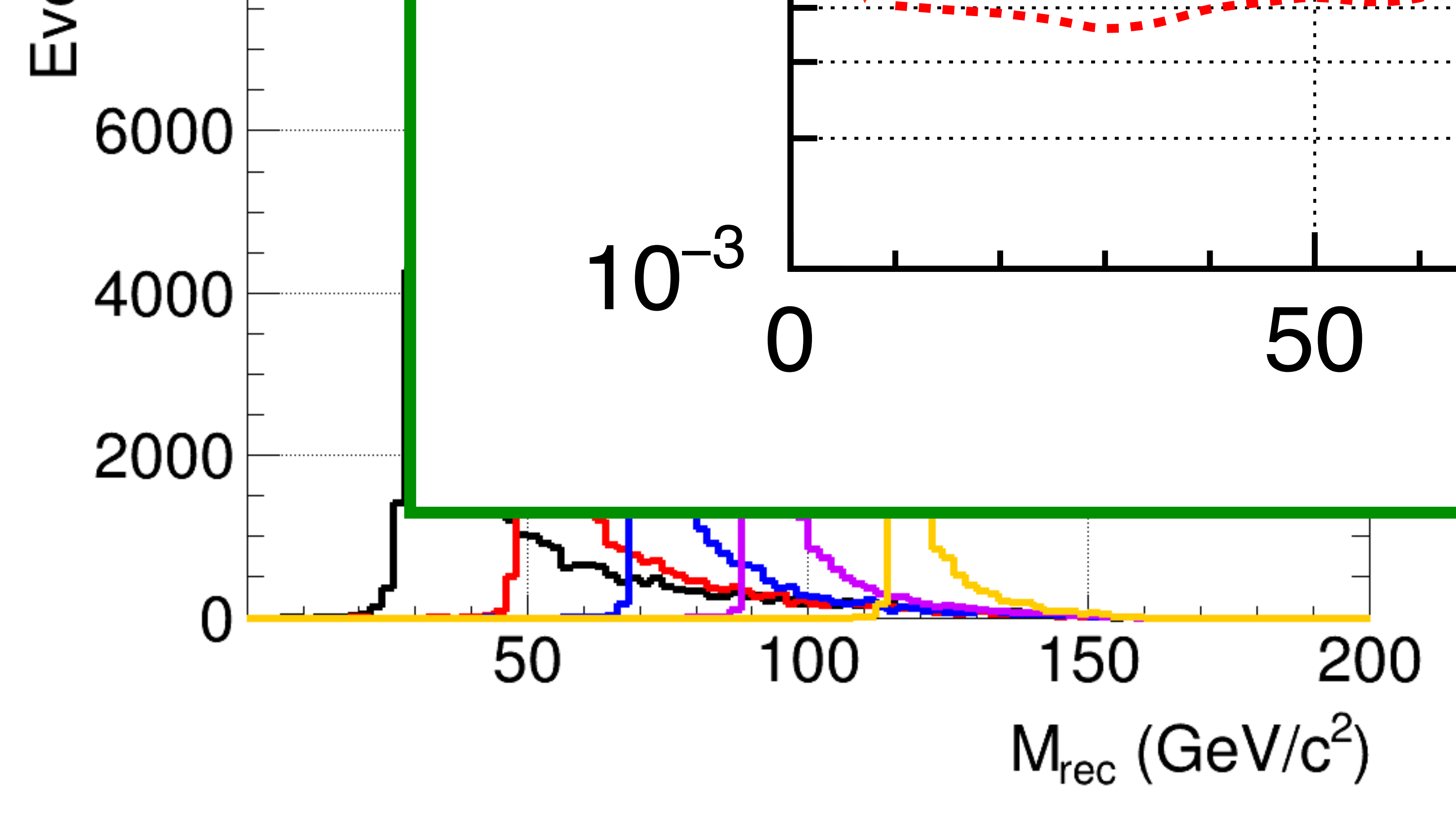
- **fully complementary to measurement of ZH cross section**
- **other possibility: ee -> bbh (via Yukawa coupling)**

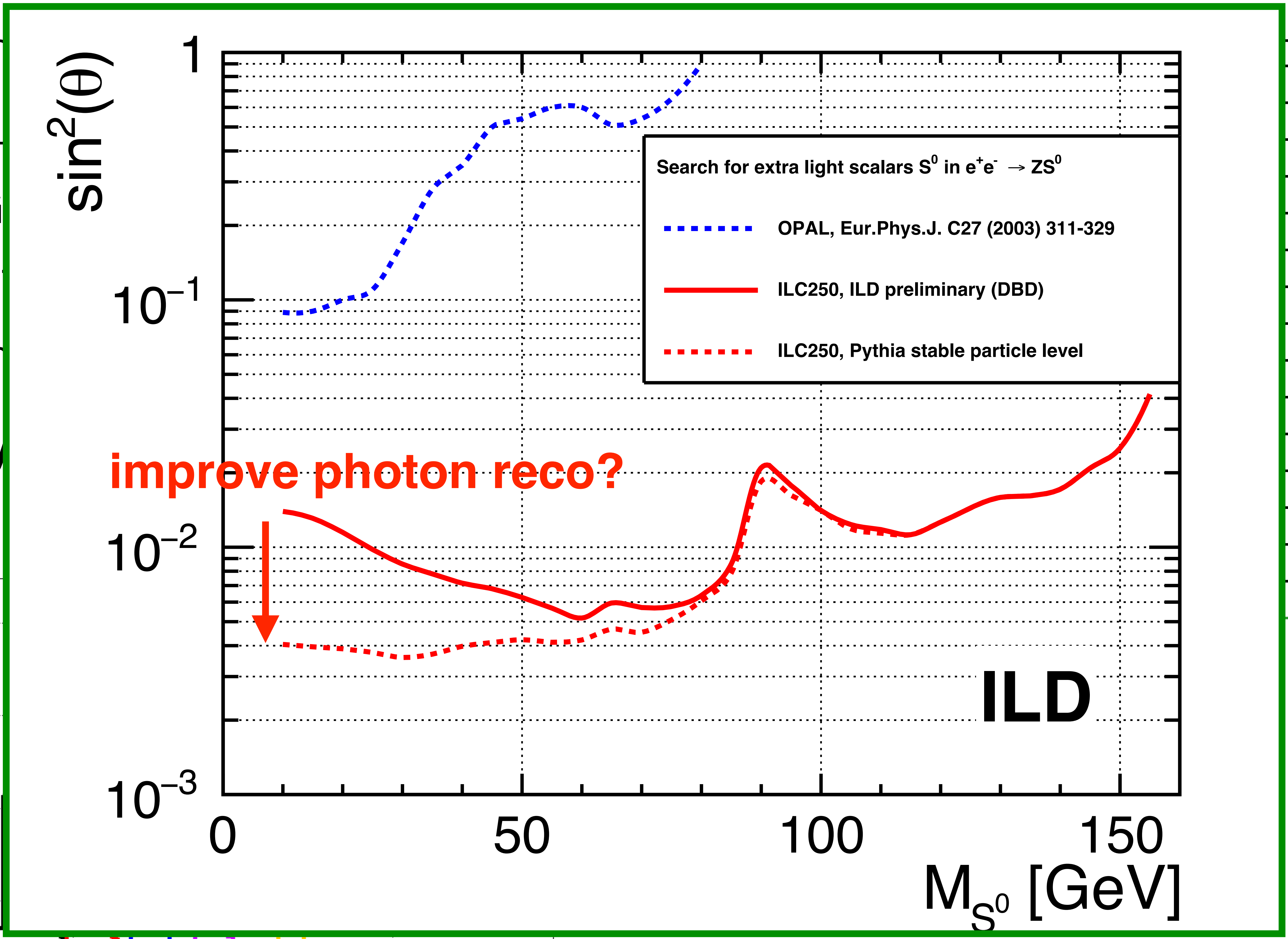
ILD full detector simulation @ ILC 250 GeV & 500 GeV, arxiv:2005.06265

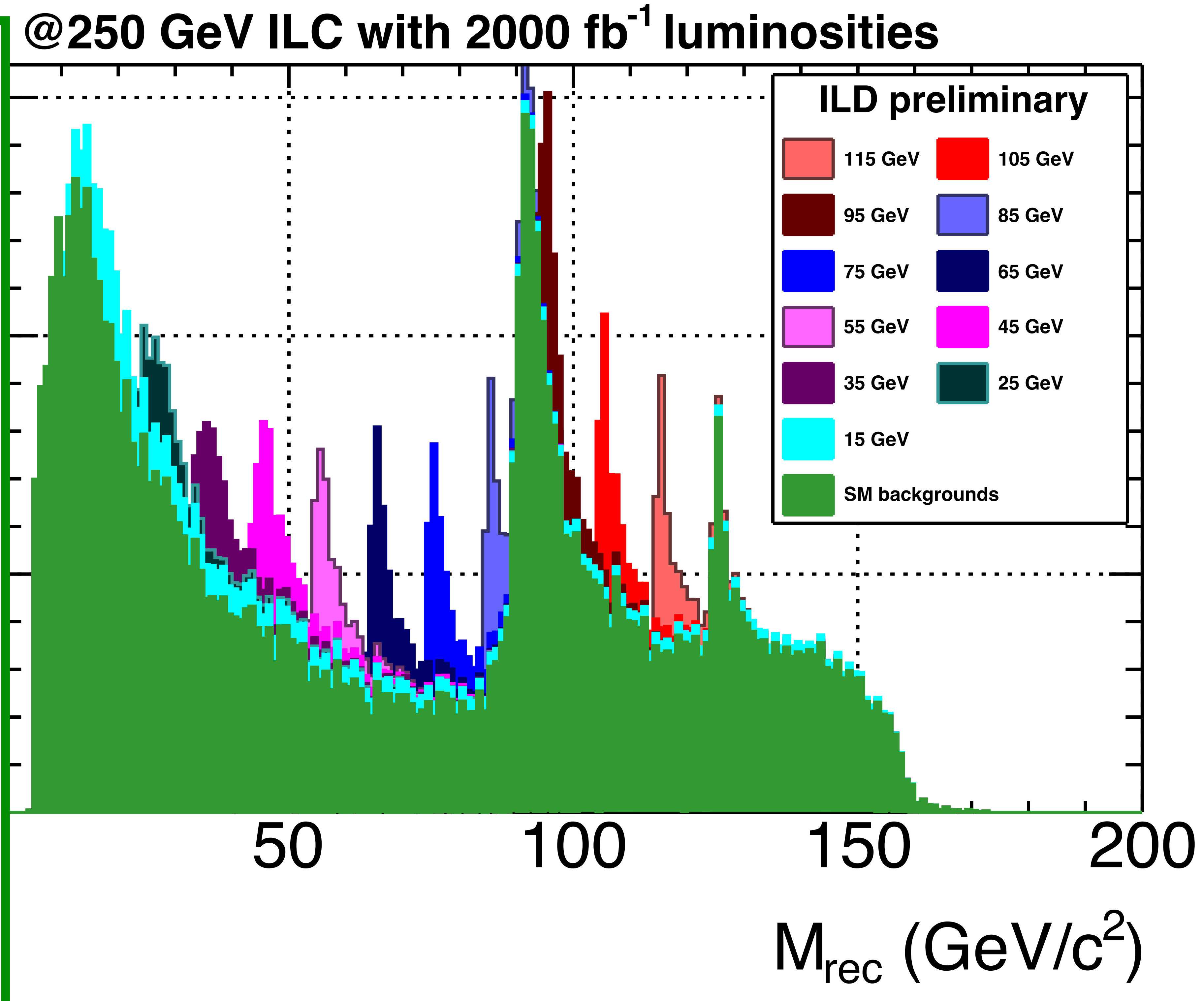
Extra Higgs Bosons ?

- must “sh
  - g_{HZZ}^2 -
  - 250 G
    g_{hZZ}^2
- probe sm

=> decay







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New insights from old friends… at the Z pole and up to 250 GeV

The Top and Bottom Quark

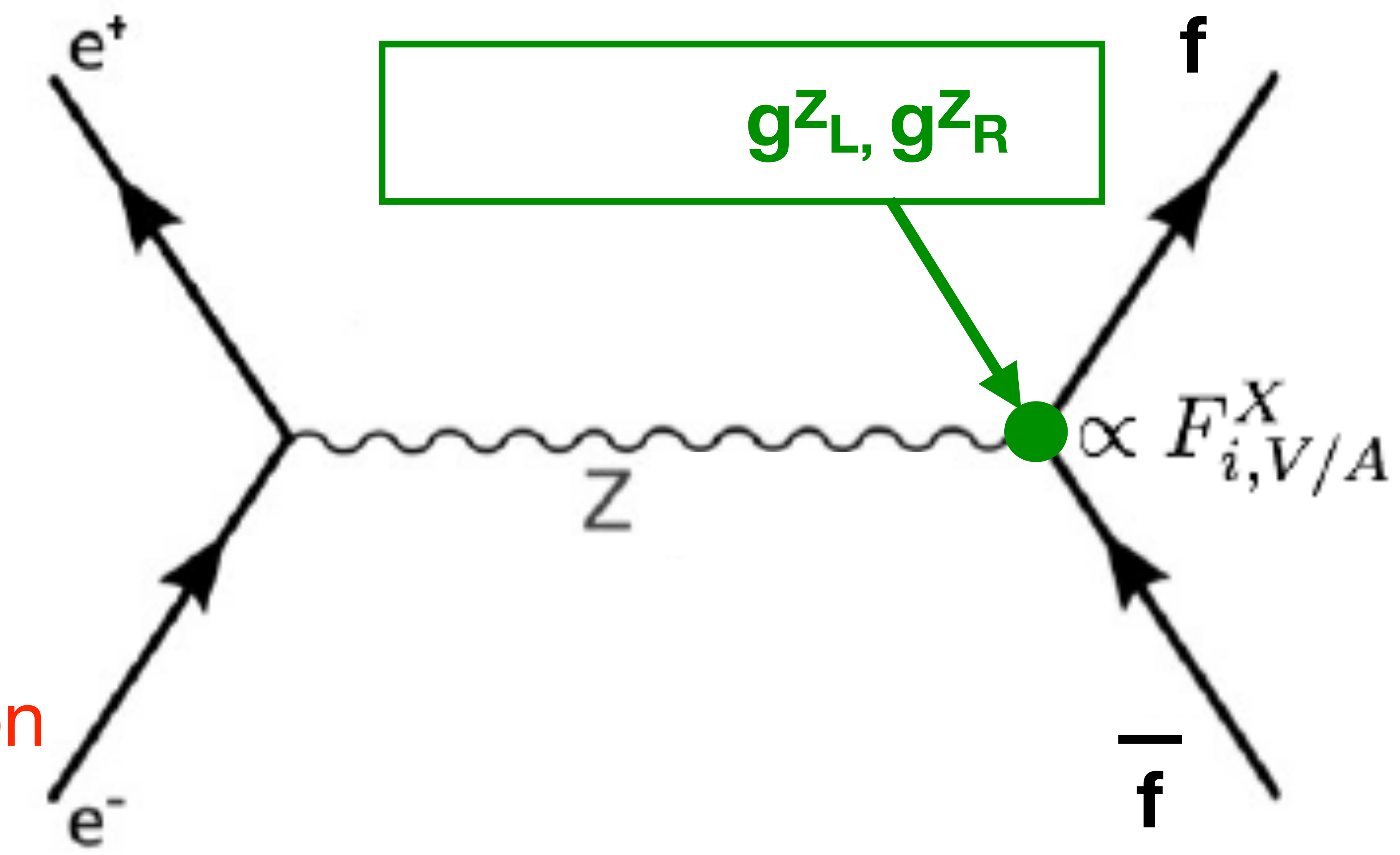
Z & W Bosons

Polarisation & Electroweak Physics

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:

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

=> A_e O(0.1) reduces sensitivity to A_f,
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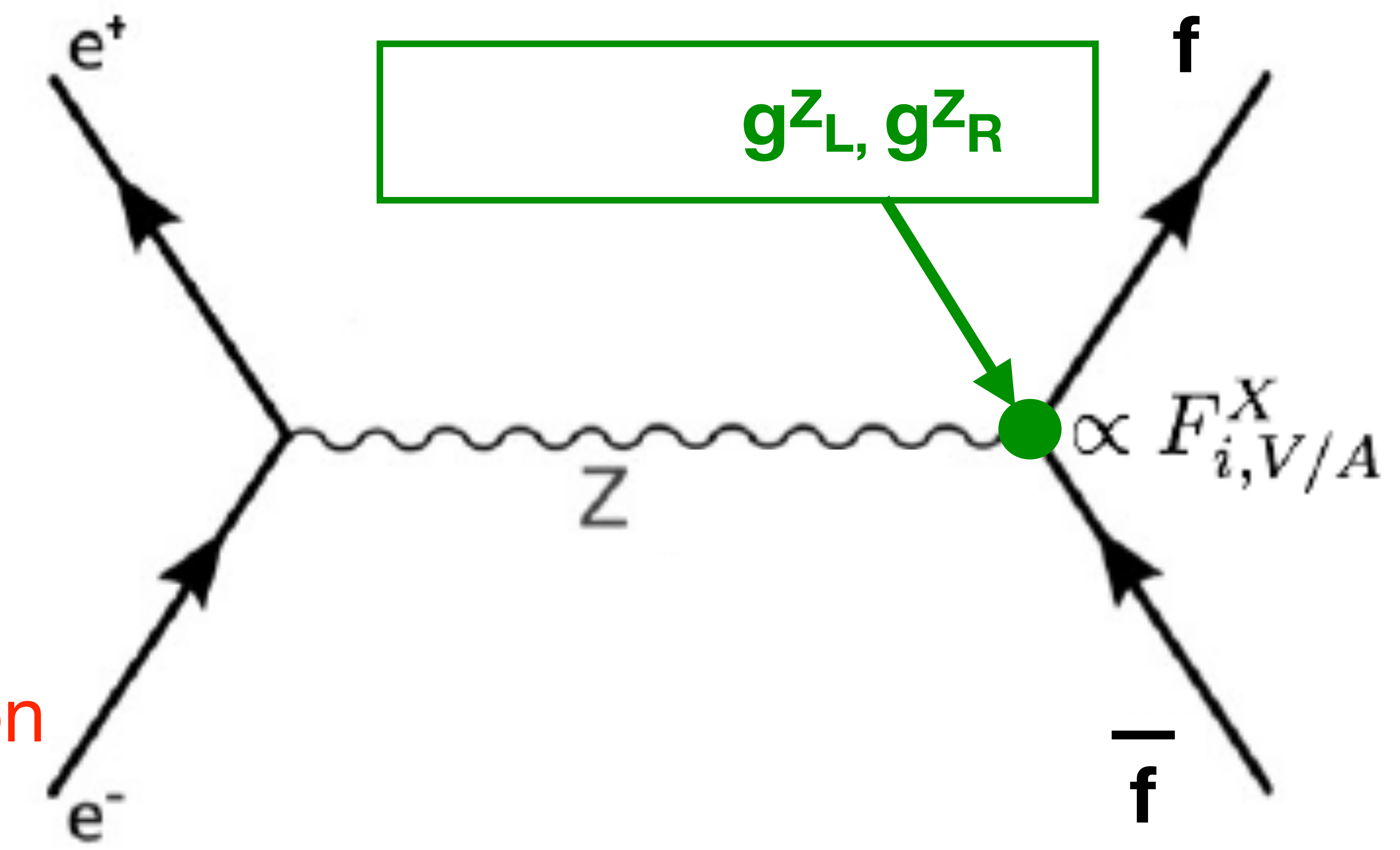

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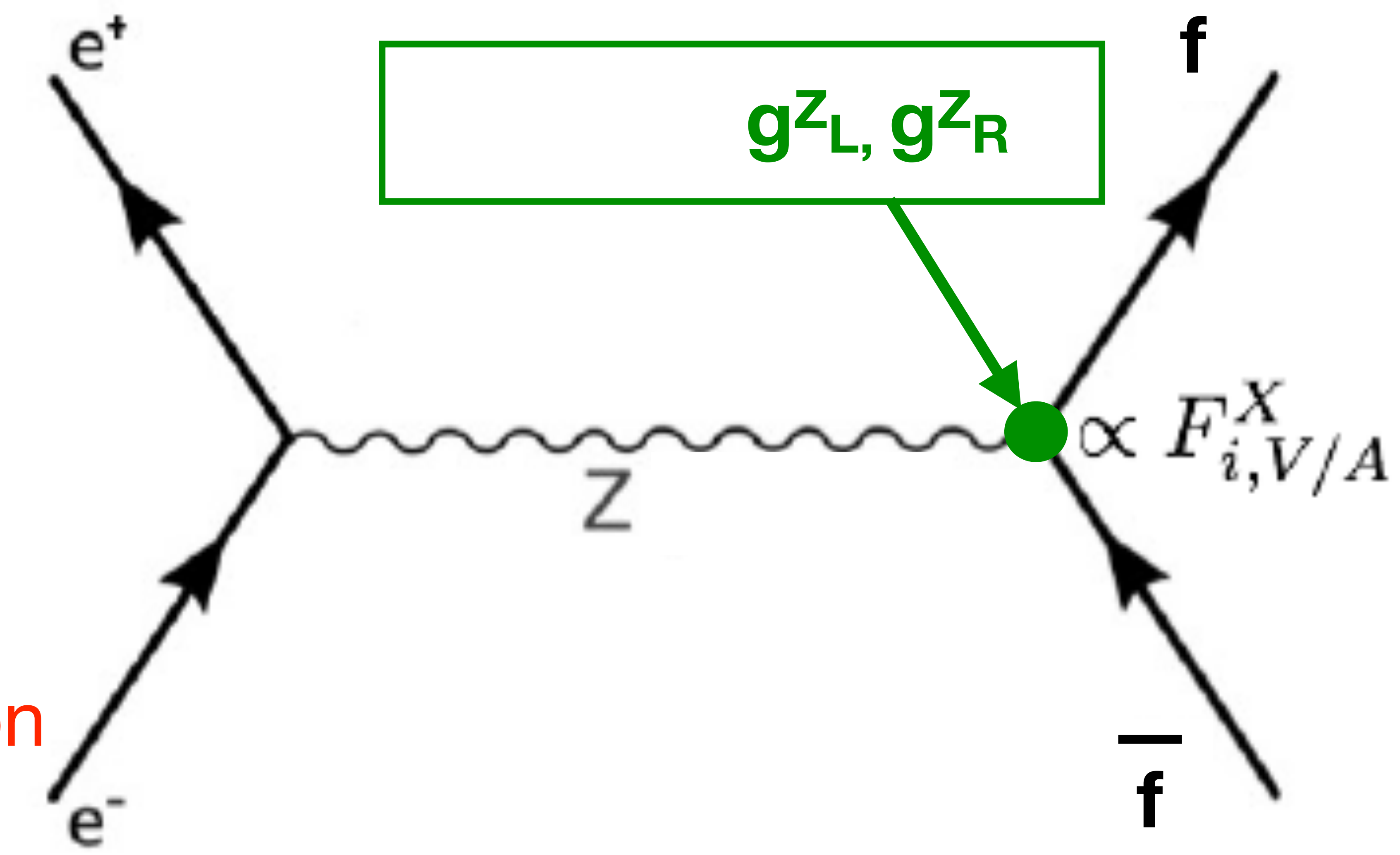

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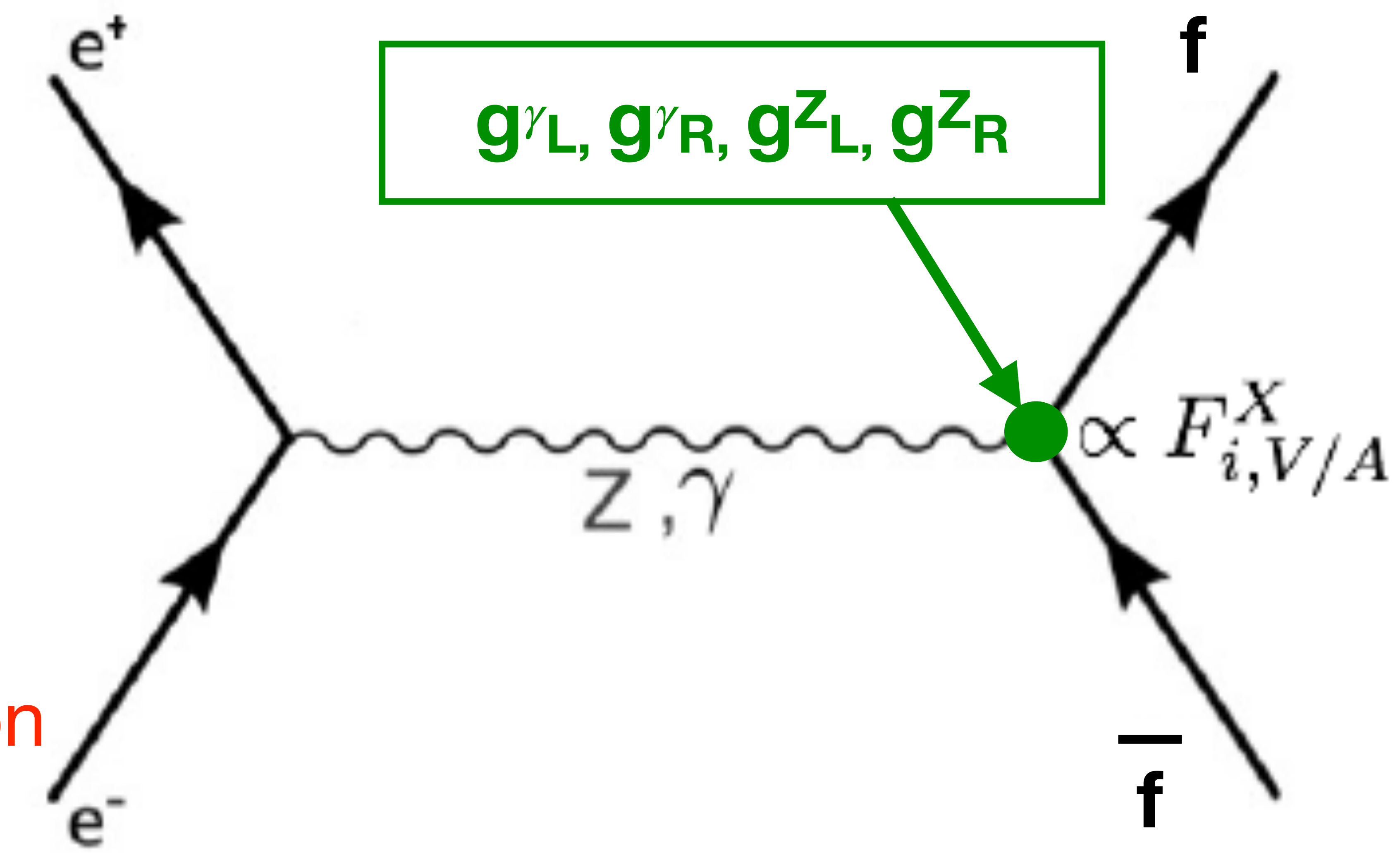

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Polarisation & Electroweak Physics at the Z pole

new detailed studies by ILD@ILC:

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

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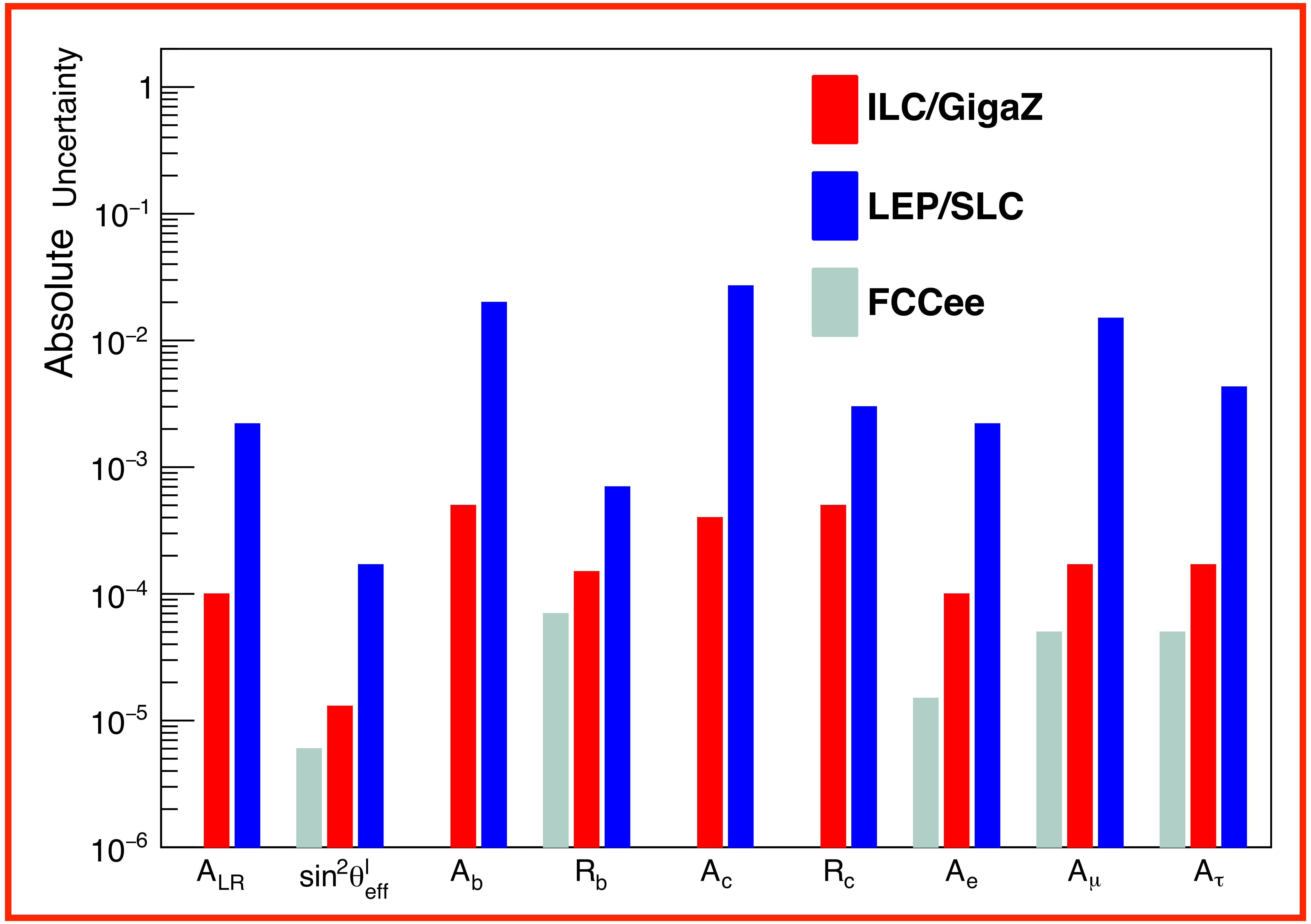
a factor of ~100 in luminosity

Note: not true for pure decay quantities!



arXiv:1908.11299

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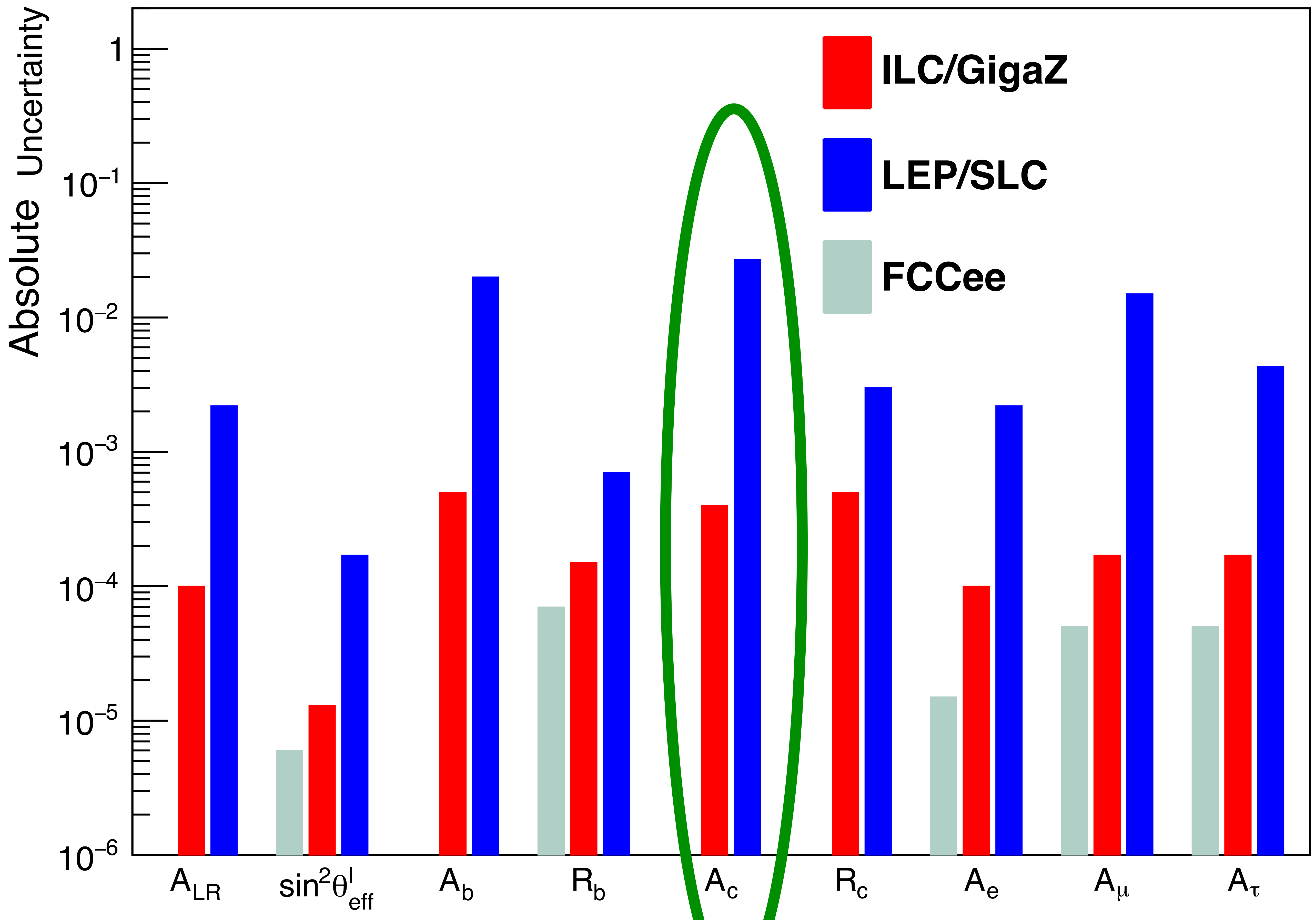

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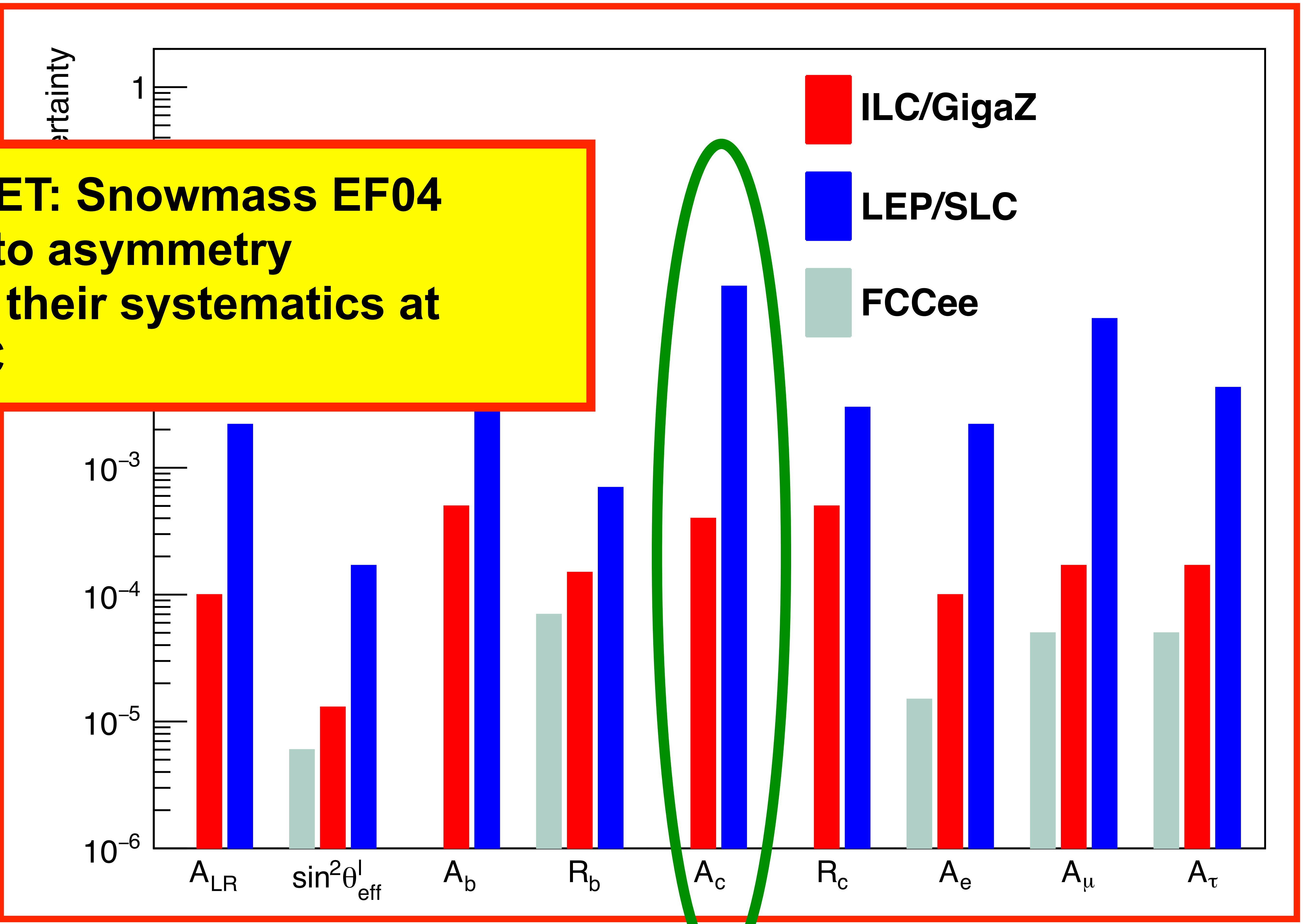
Thu Jan 20, 4 pm CET: Snowmass EF04 meeting dedicated to asymmetry measurements and their systematics at FCCee, CEPC & ILC



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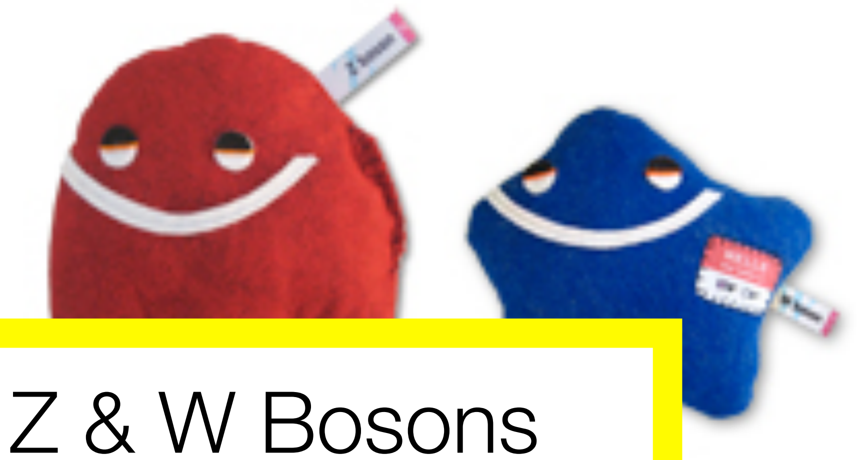
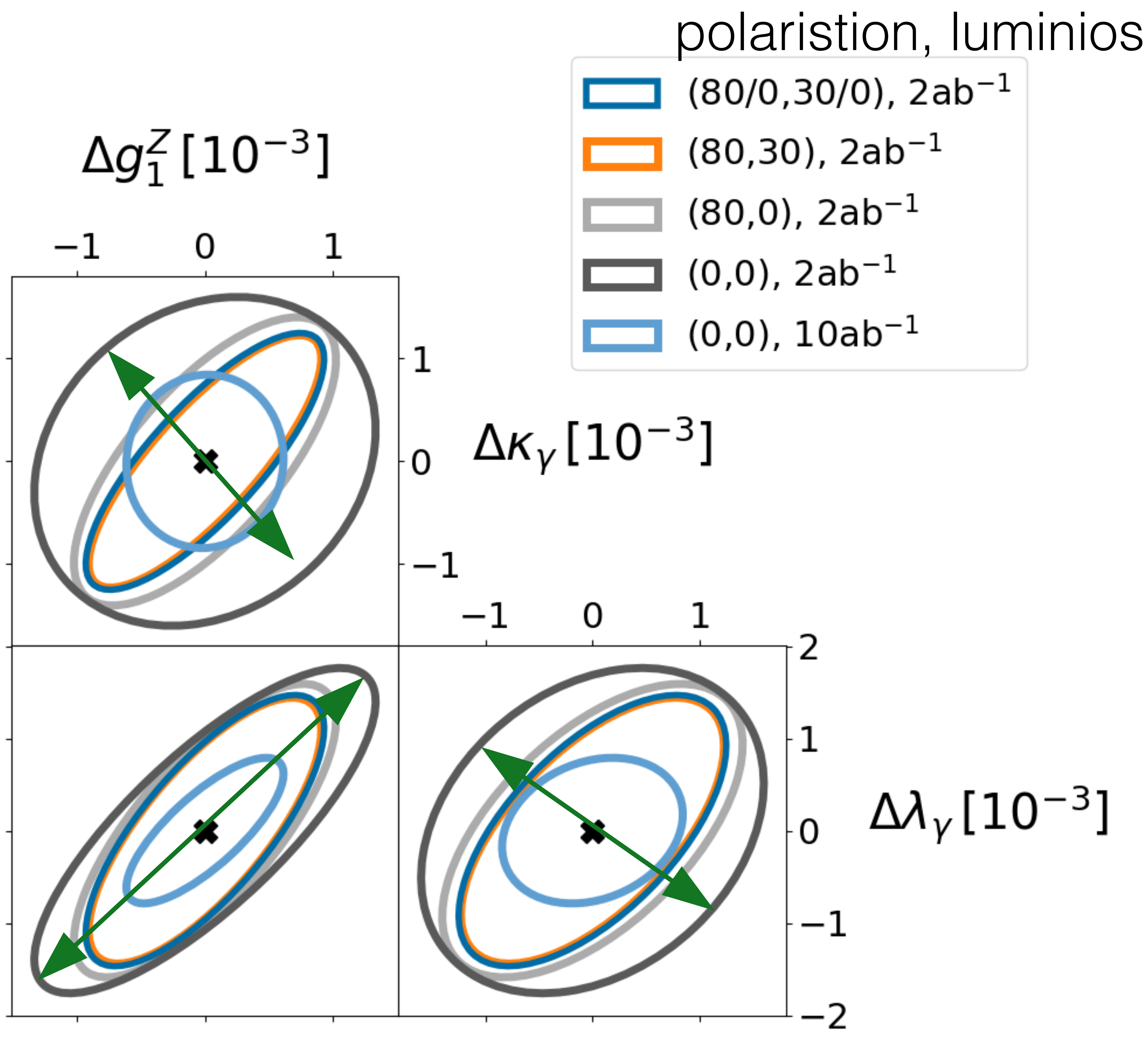


Z & W Bosons

Triple Gauge Couplings at 250 GeV

- previously studied in full detector simulation at 500 GeV & 1 TeV for ILC => few 10^{-4} level at 500 GeV
- NEW: generator-level study of ee→$\mu\nu$qq @ 250 GeV focusing on polarisation impact [J.Beyer, PhD thesis in preparation]
- W production and decay angles (triple-differential cross section fit)
- polarisation => ability to measure A_{LR} (ee→$\mu\nu$qq) adds important information



Arrow'ed direction: LR shape ~ constant → constraint only from A_{LR}

The Higgs Boson

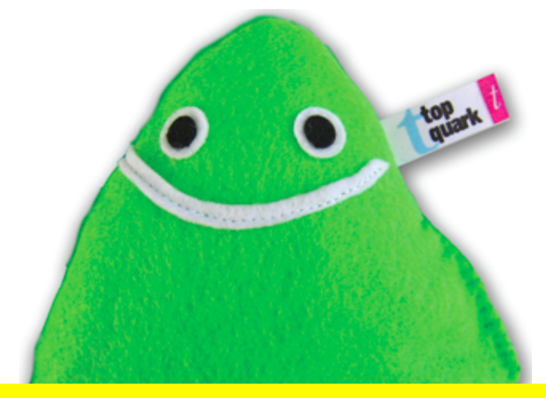
Discoveries of new particles ?

Old and new friends… above 250 GeV

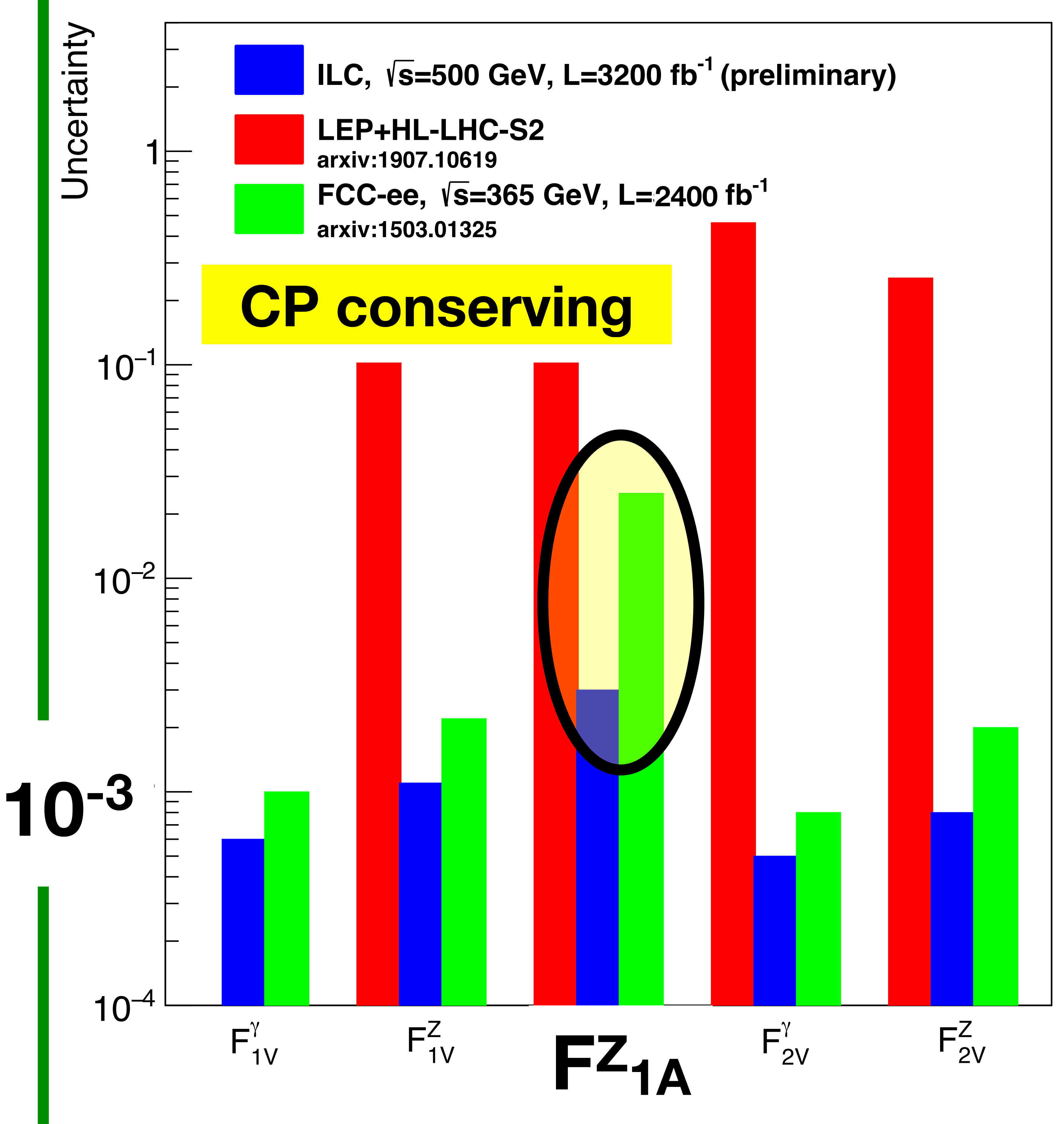
The Top and Bottom Quark

Z & W Bosons

Top quark couplings



- e^+e^- -> tt: possible above ~360 GeV
- **near threshold: no boost**
  => little sensitivity to *axial* coupling
- beam **polarisation disentangles Z and γ** exchange
- few **10^{-3} for all couplings requires ≥ 500 GeV *and* polarisation**
- probes **BSM** into the **multi-ten TeV regime**



ILD-PHYS-PUB-2019-007, arXiv:1908.11299, Eur.Phys.J. C78 (2018) no.2, 155]

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- **near threshold: no boost**
  => little sensitivity to *axial* couplin
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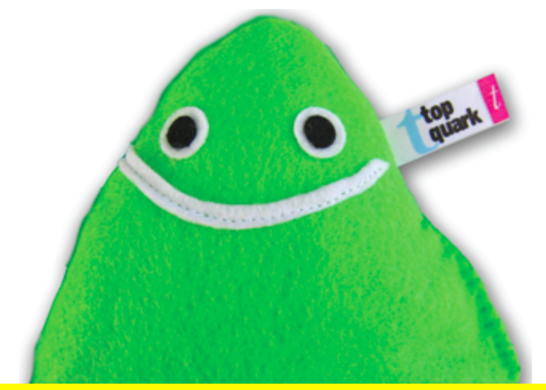
  γ exchange
- few **10^{-3} for all couplings requires**
  ≥ 500 GeV *and* polarisation
- probes **BSM** into the **multi-ten TeV regime**



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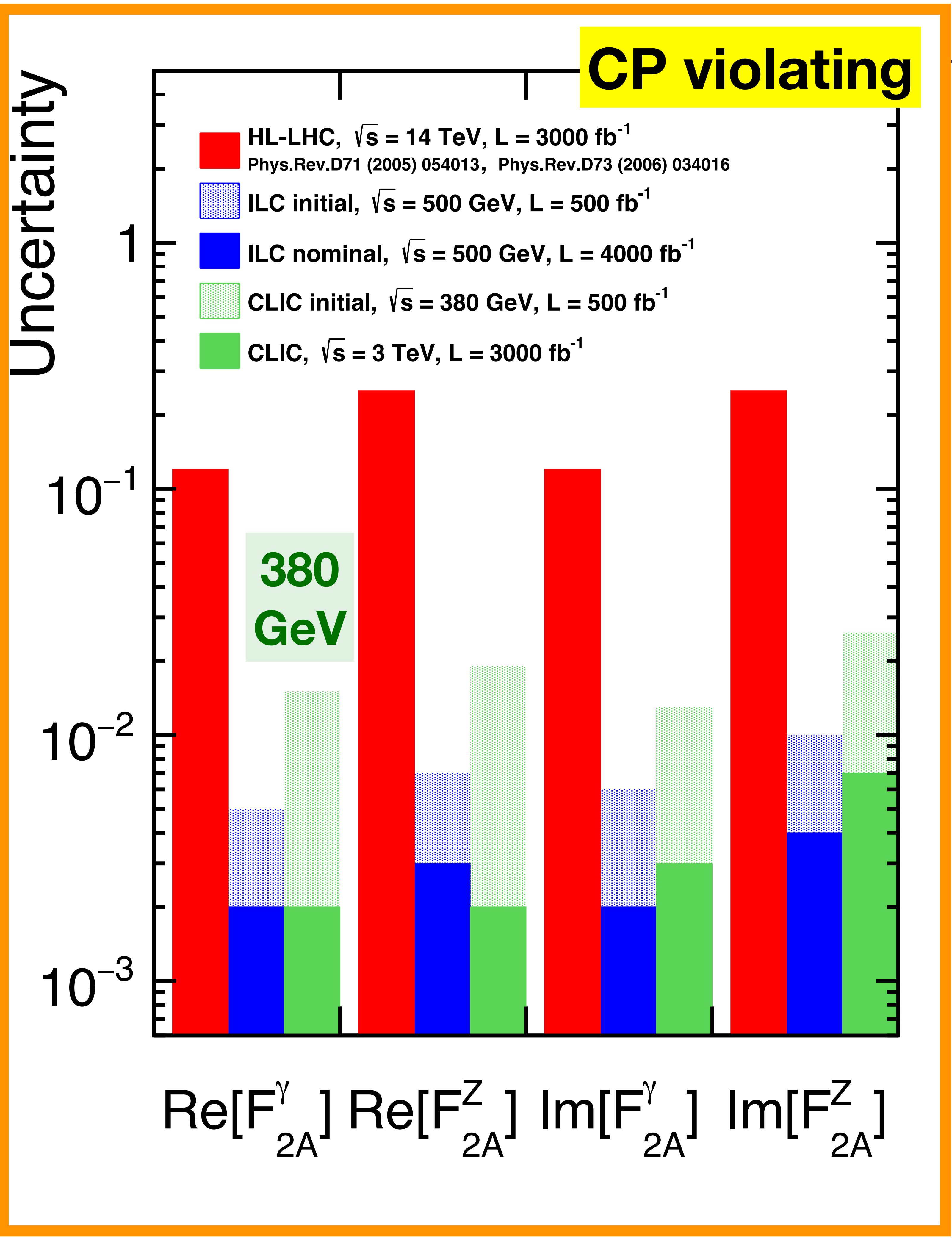

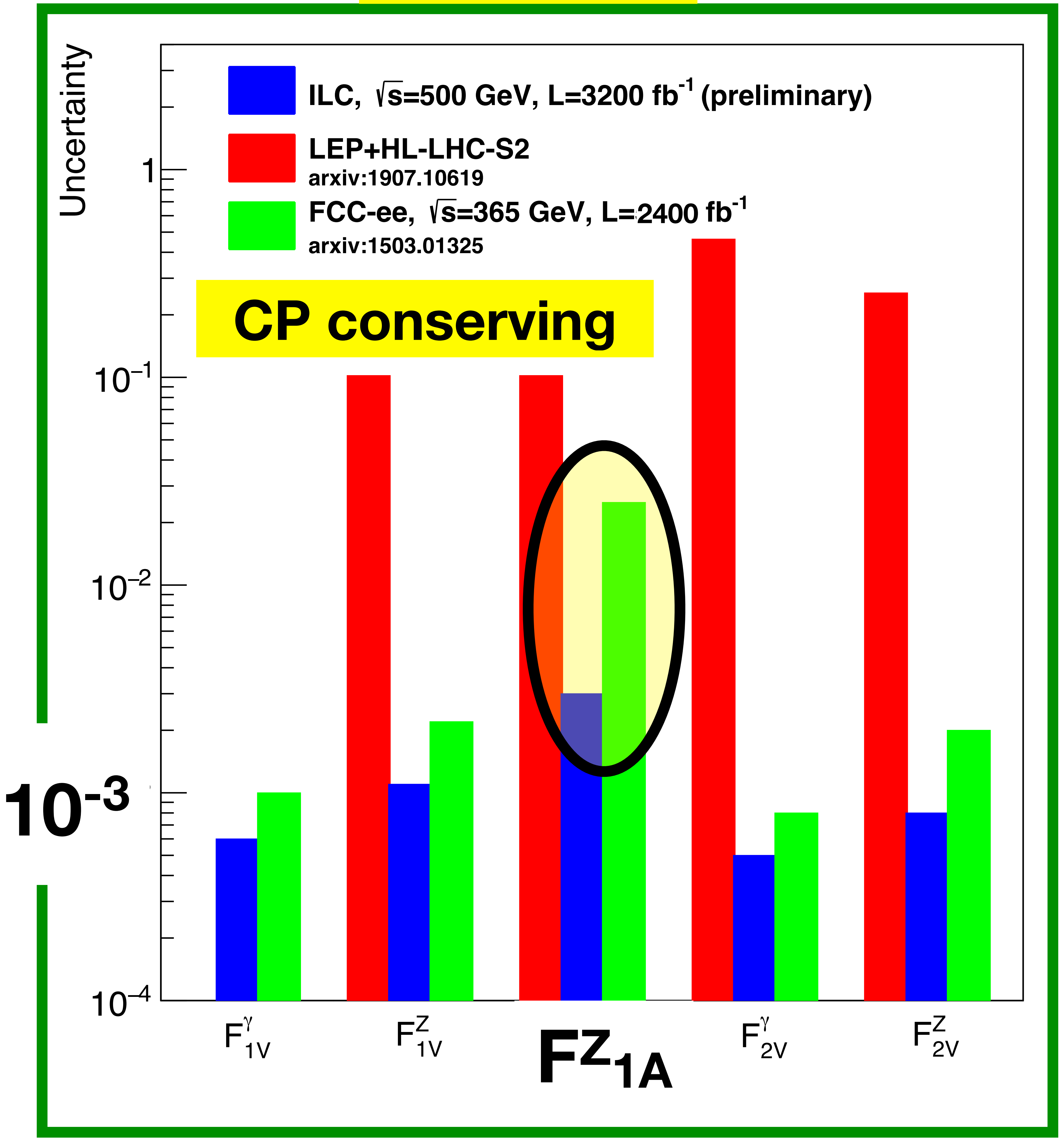

ILD-PHYS-PUB-2019-007, arXiv:1908.11299, Eur.Phys.J. C78 (2018) no.2, 155]

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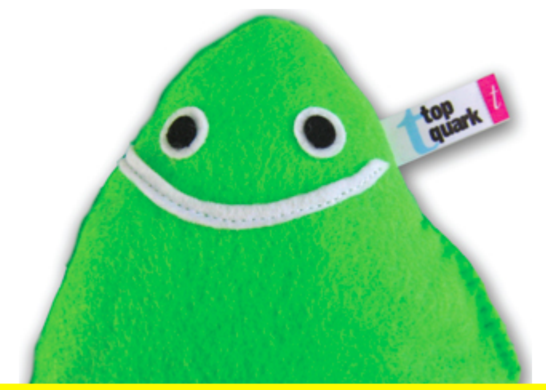

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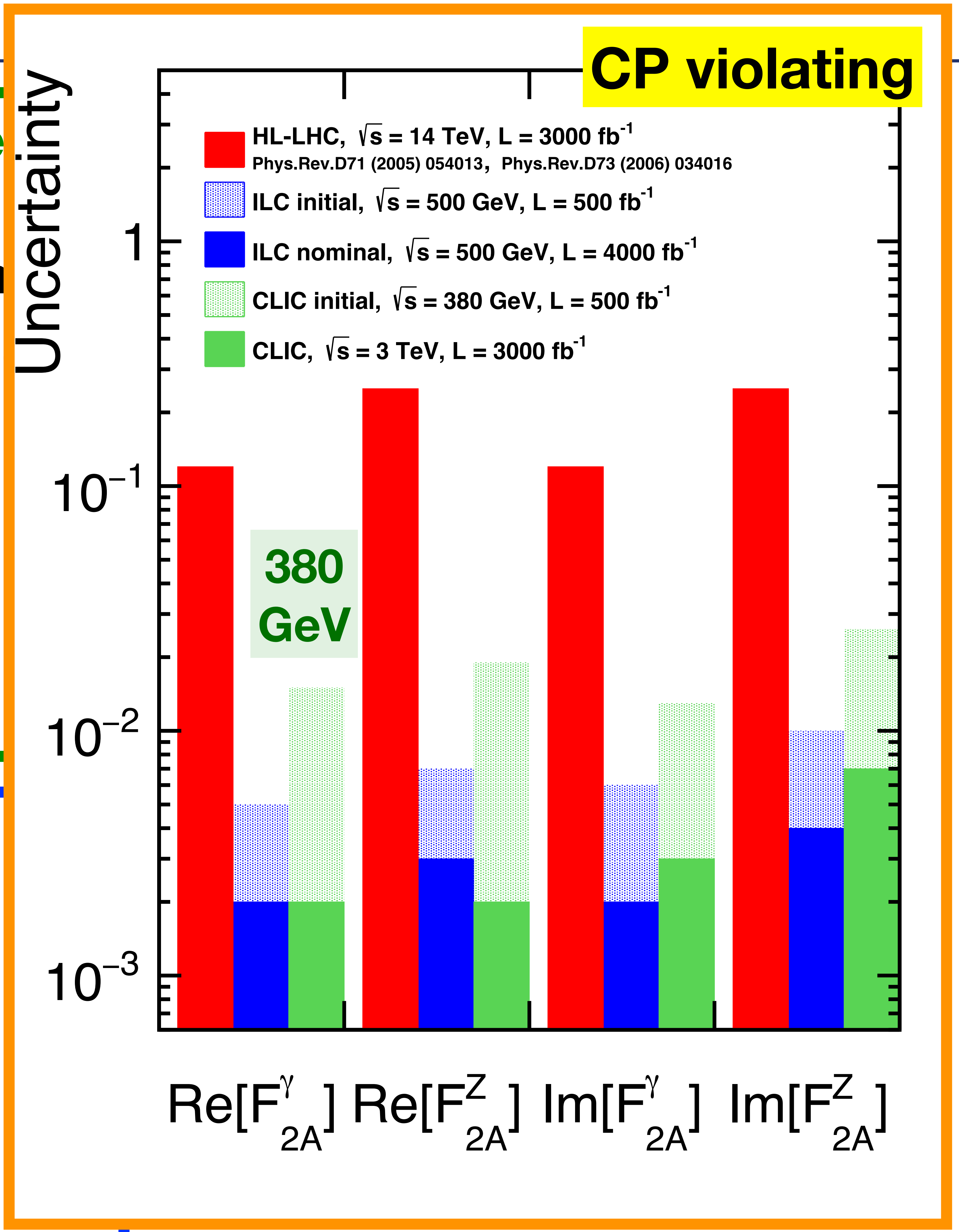

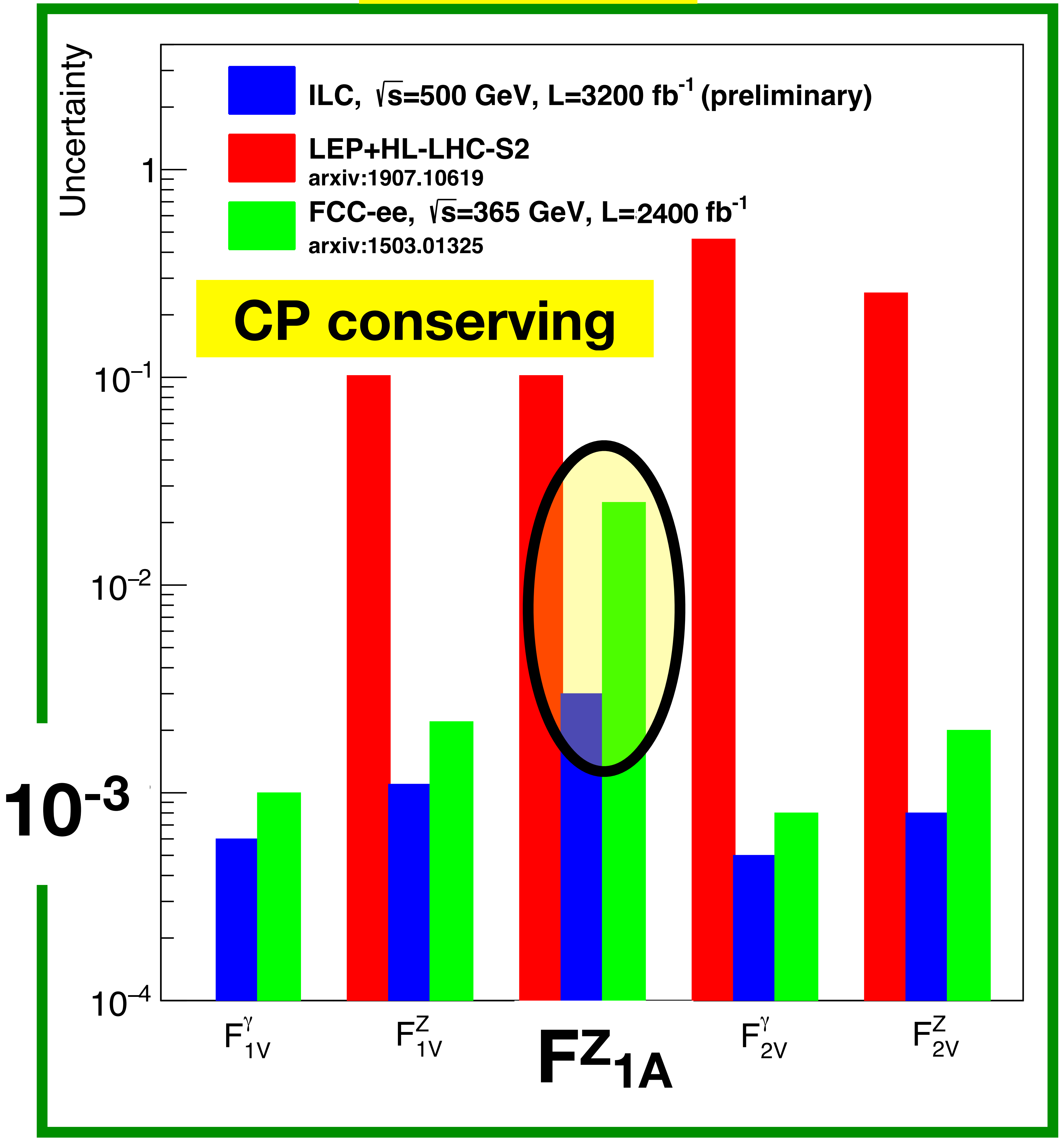

full SM-EFT:

- **500 GeV improves** various coefficients **by 2 orders of magnitude**
- **4-fermion operators profit quadratically from higher energies**

[ILD-PHYS-PUB-2019-007, arXiv:1908.11299, Eur.Phys.J. C78 (2018) no.2, 155]

Higgs self-coupling

- **HL-LHC:**
  - **~5σ observation of HH**
  - **~50% on λ in *single-parameter* fit**
- **e⁺e⁻:**
  - **500 GeV: 8σ observation of HH**
  - **27% on λ in *full coupling analysis***
  - **full, testbeam-gauged simulation**
    (note: first ILC fast sim. was ~3 times better!)
  - **1 TeV & 3 TeV: ~10%**
- **FCC-hh:**
  - **5% *statistical* uncertainty on λ**
  - **from fast simulation, *single-par.* fit**
  - assuming LHC detector performance despite e.g.100x higher neutron fluence
  - **plus systematics, theory, pdf, …**

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

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

arXiv:2005.10576:

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

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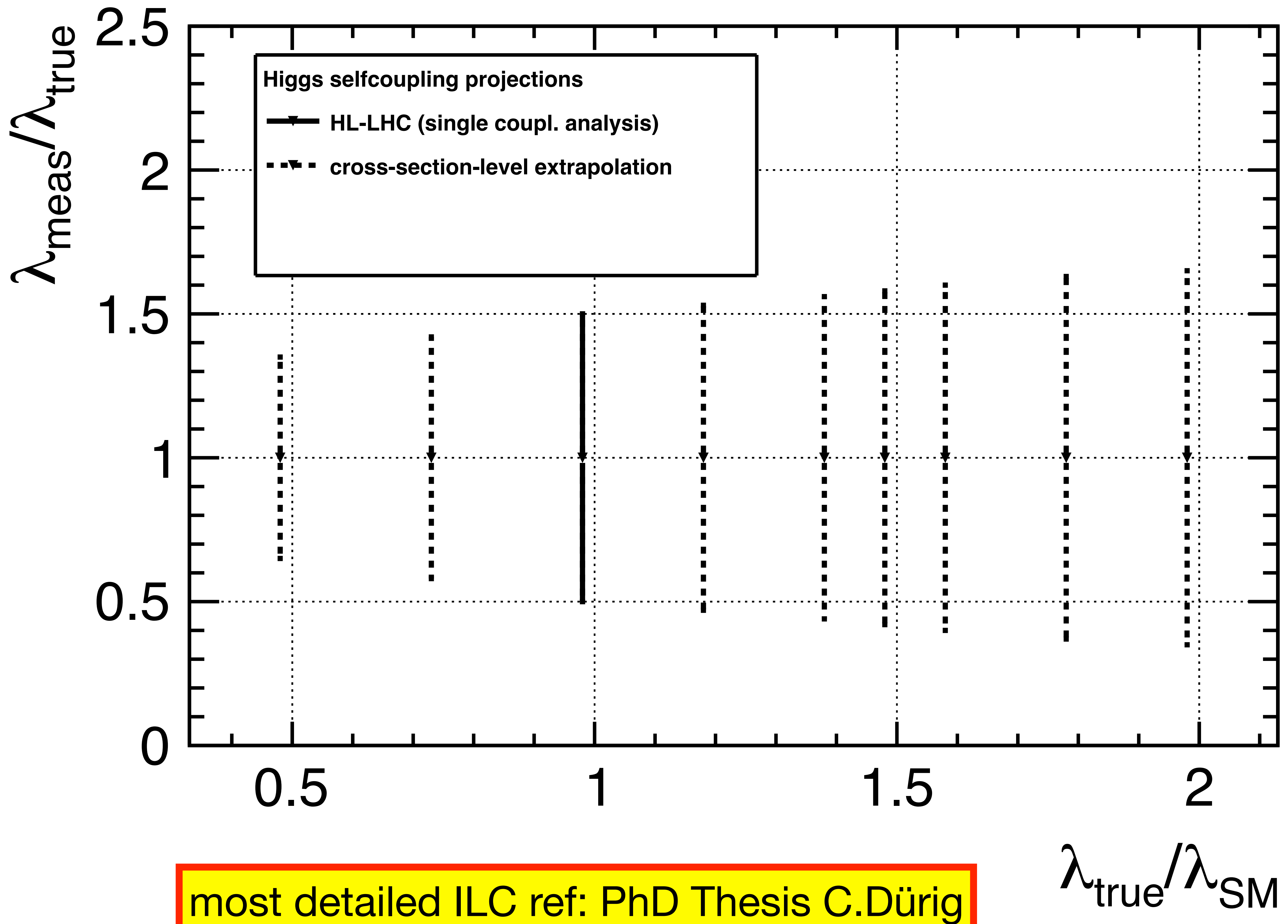

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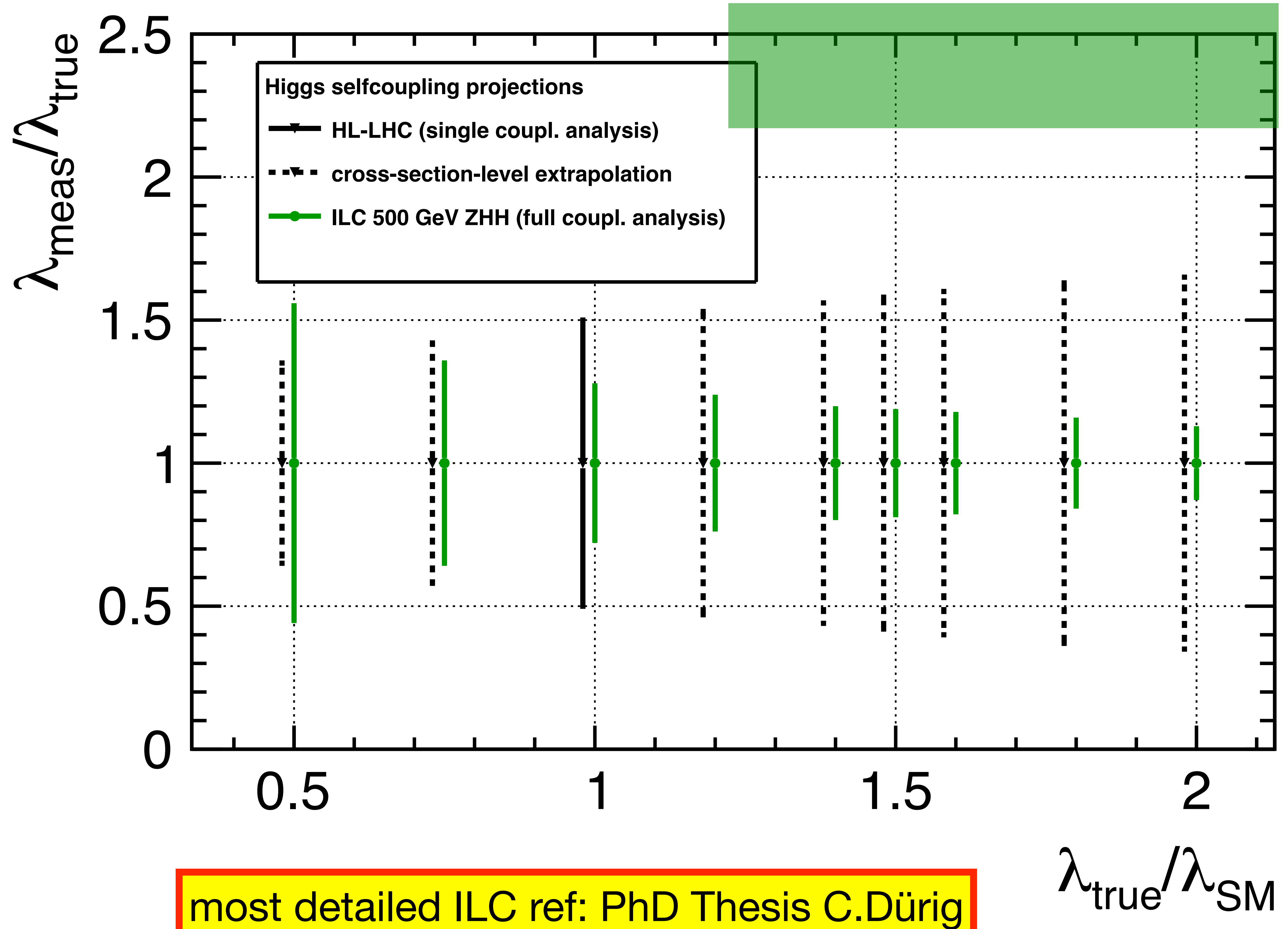

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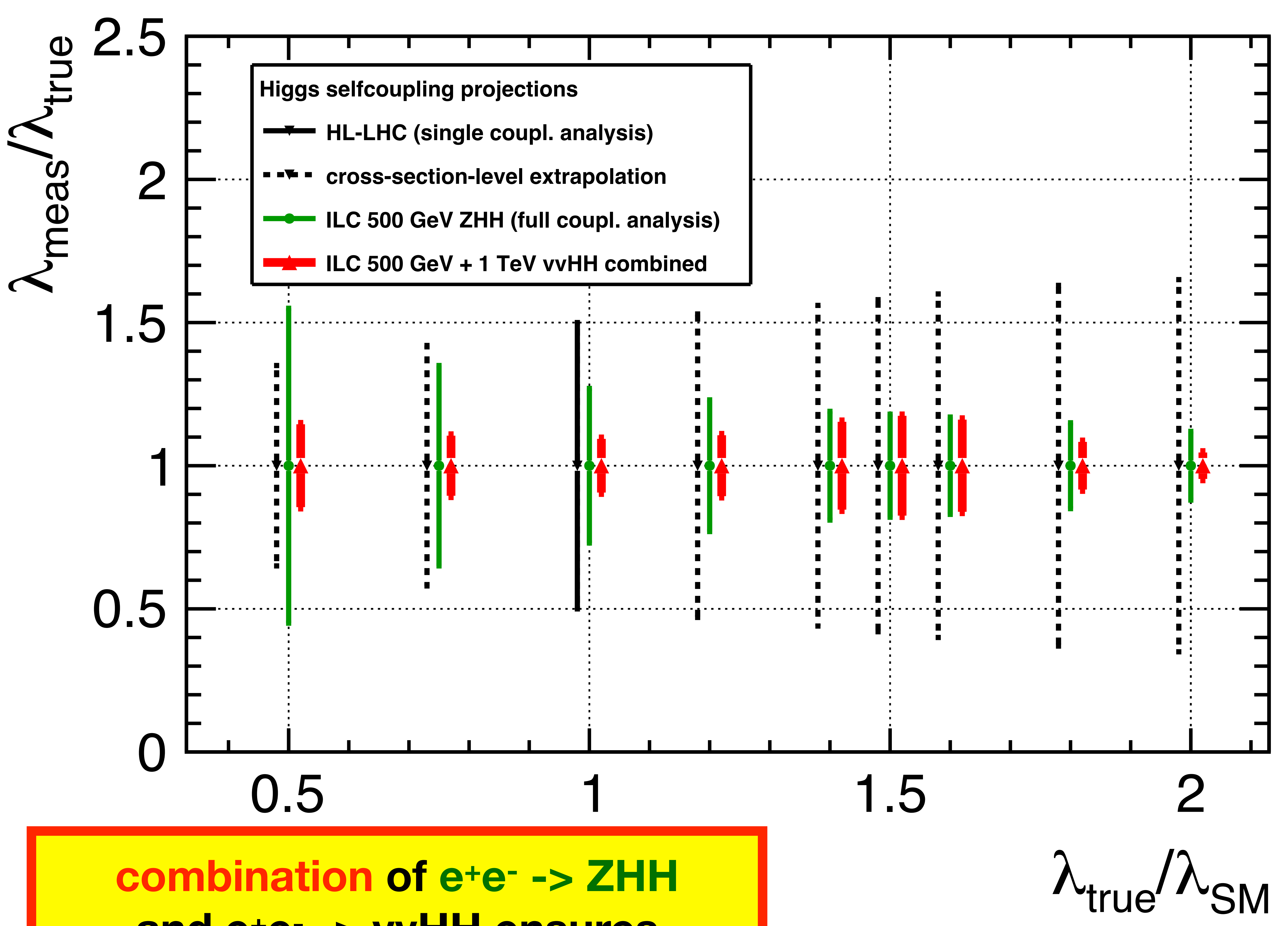

combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision for all λ

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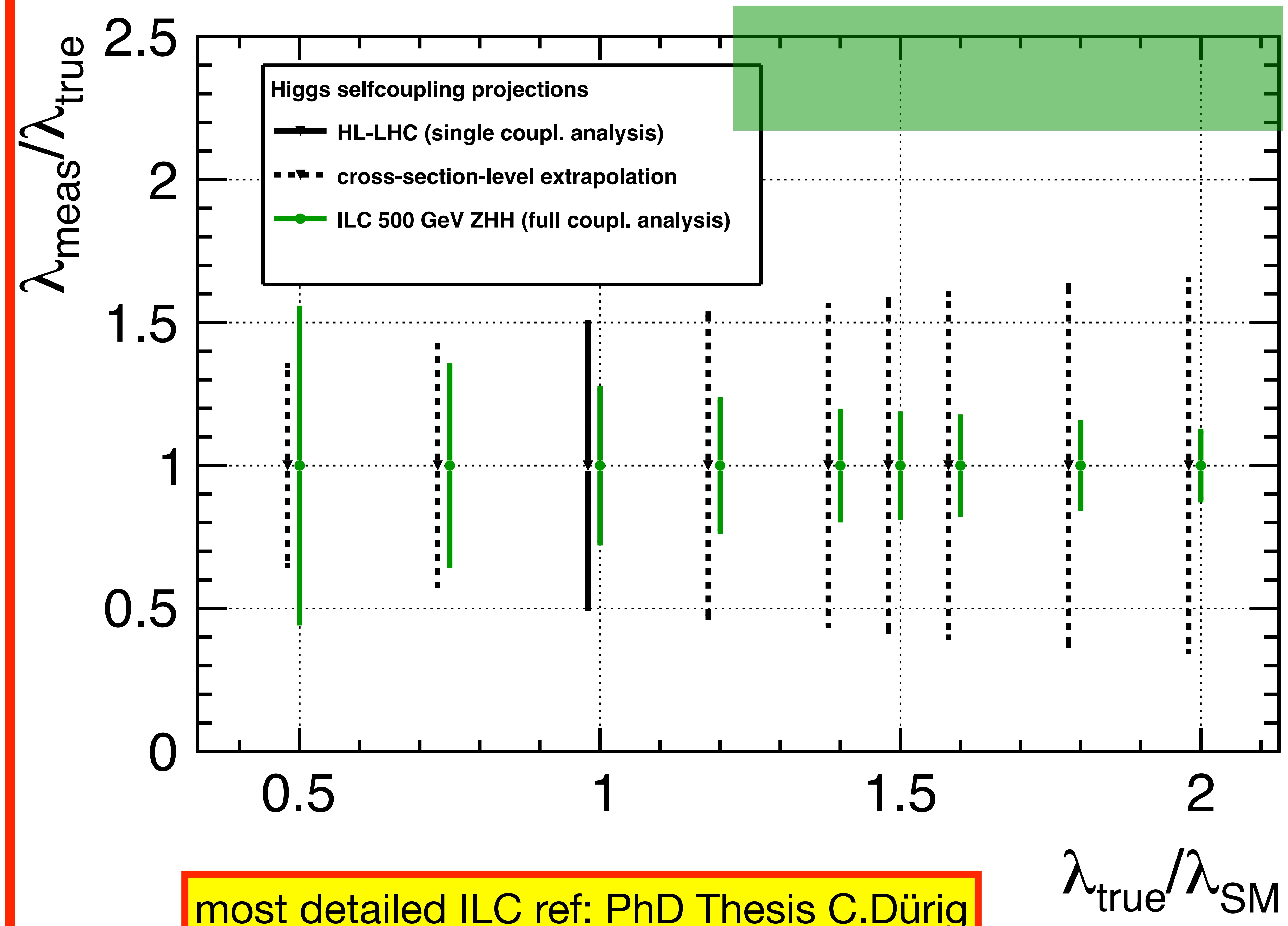

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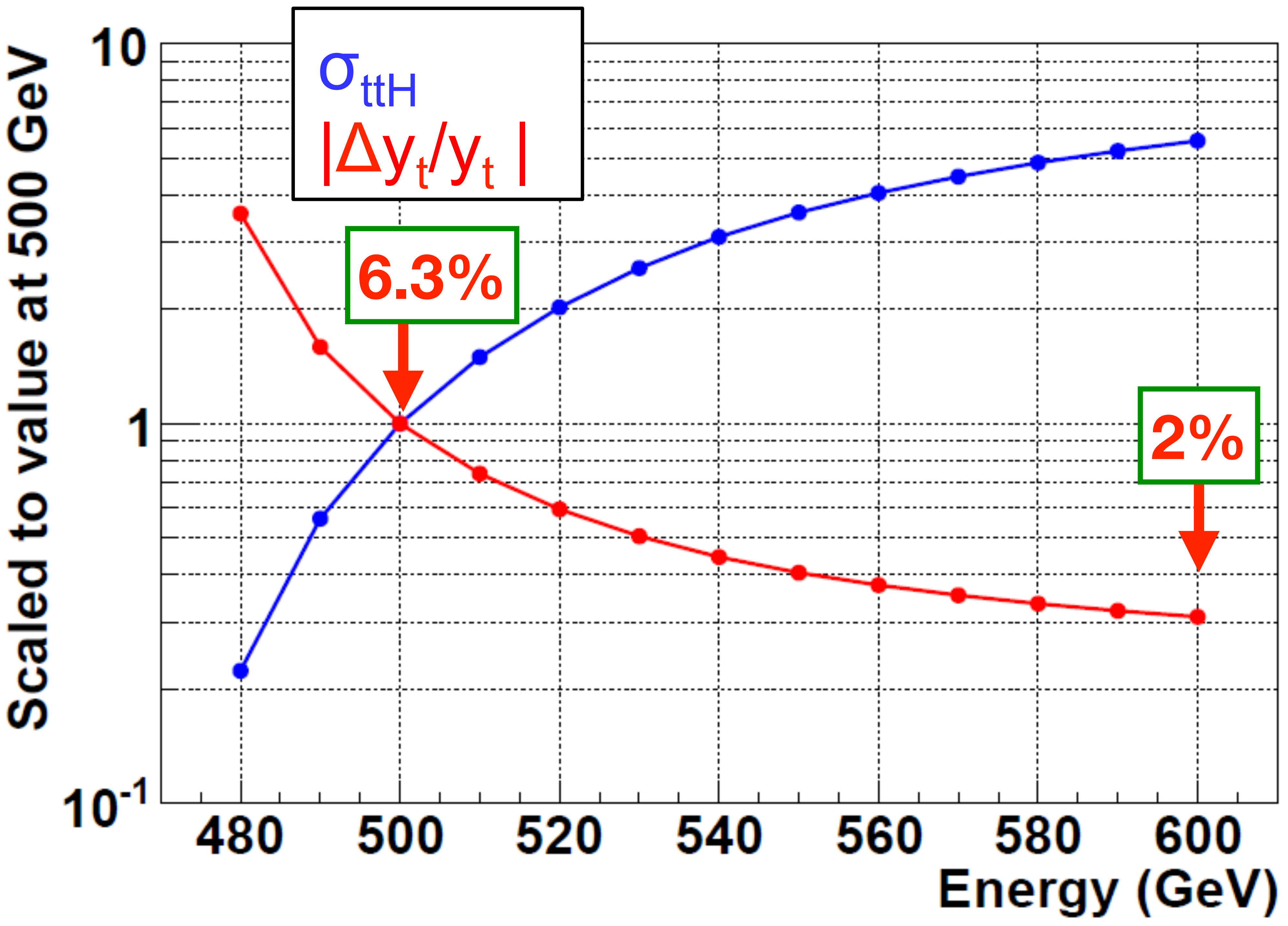
Top Yukawa coupling

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

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



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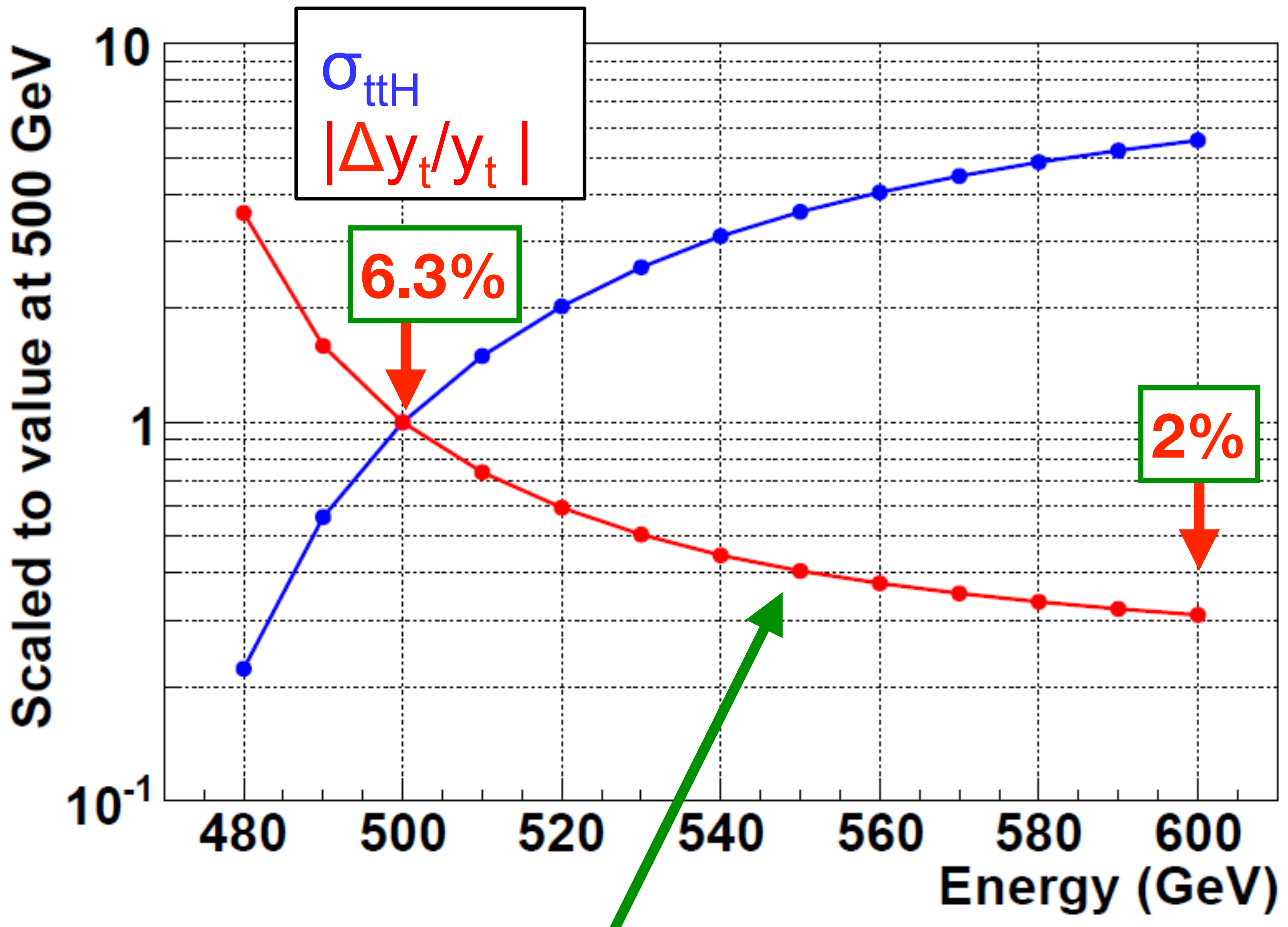

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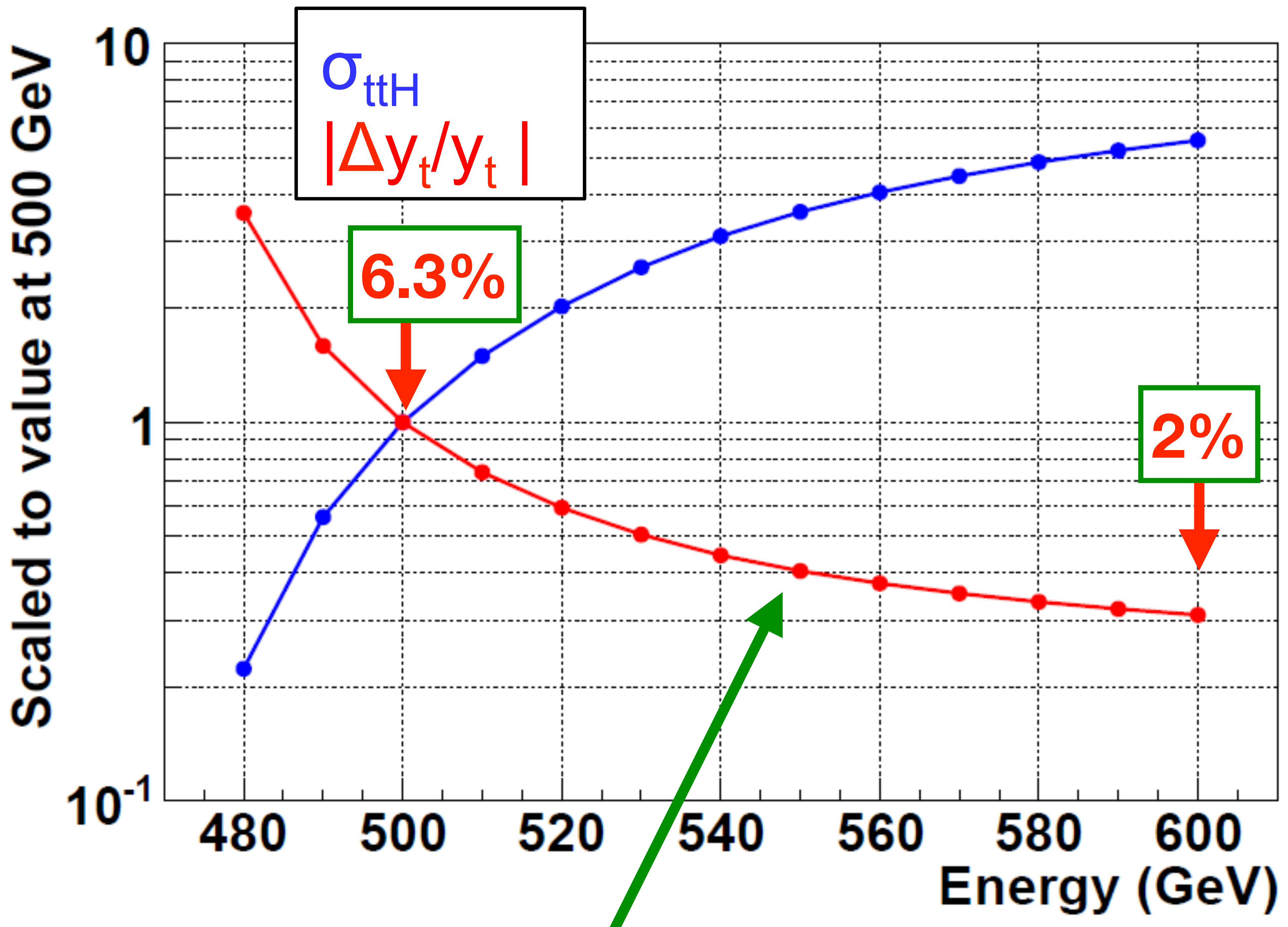
- **full coupling structure** of tth vertex, incl. CP:
  - **e^+e^- at E_{CM} ≥ ~600 GeV**
    => ***few percent sensitivity to CP-odd admixture***
  - **beam polarisation essential!**

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

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



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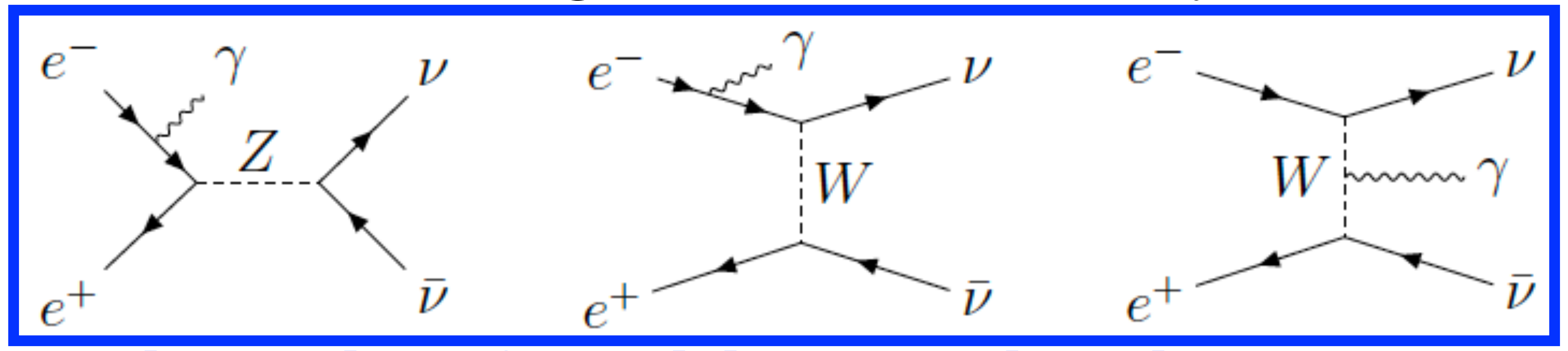
Polarisation & Beyond the SM: Dark Matter

mono-photon search $e^+e^- \rightarrow \chi\chi\gamma$

- main SM background: $e^+e^- \rightarrow \nu\nu\gamma$



  reduced ~10x with polarisation

- shape of observable distributions changes with **polarisation** sign
  => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
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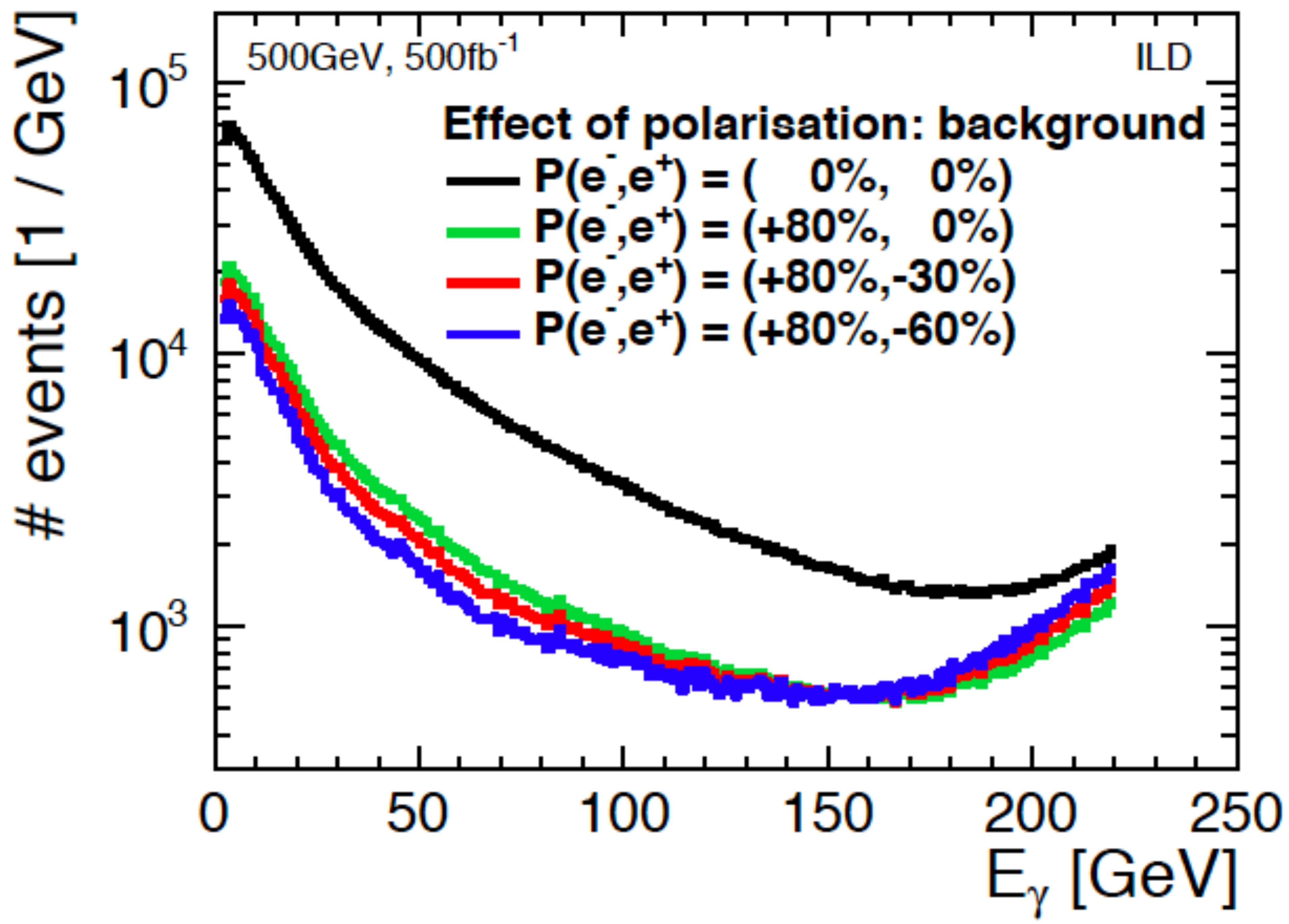
- **200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised**



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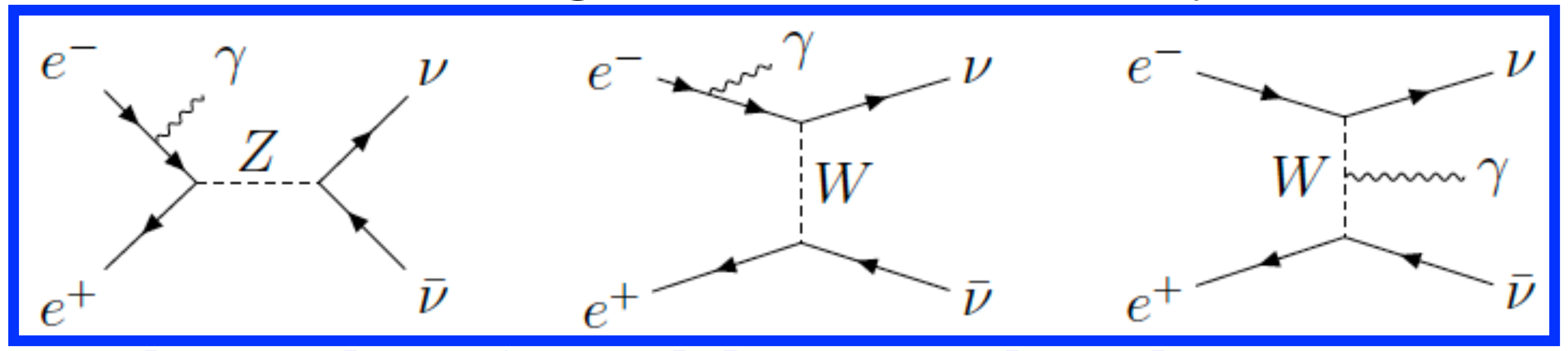

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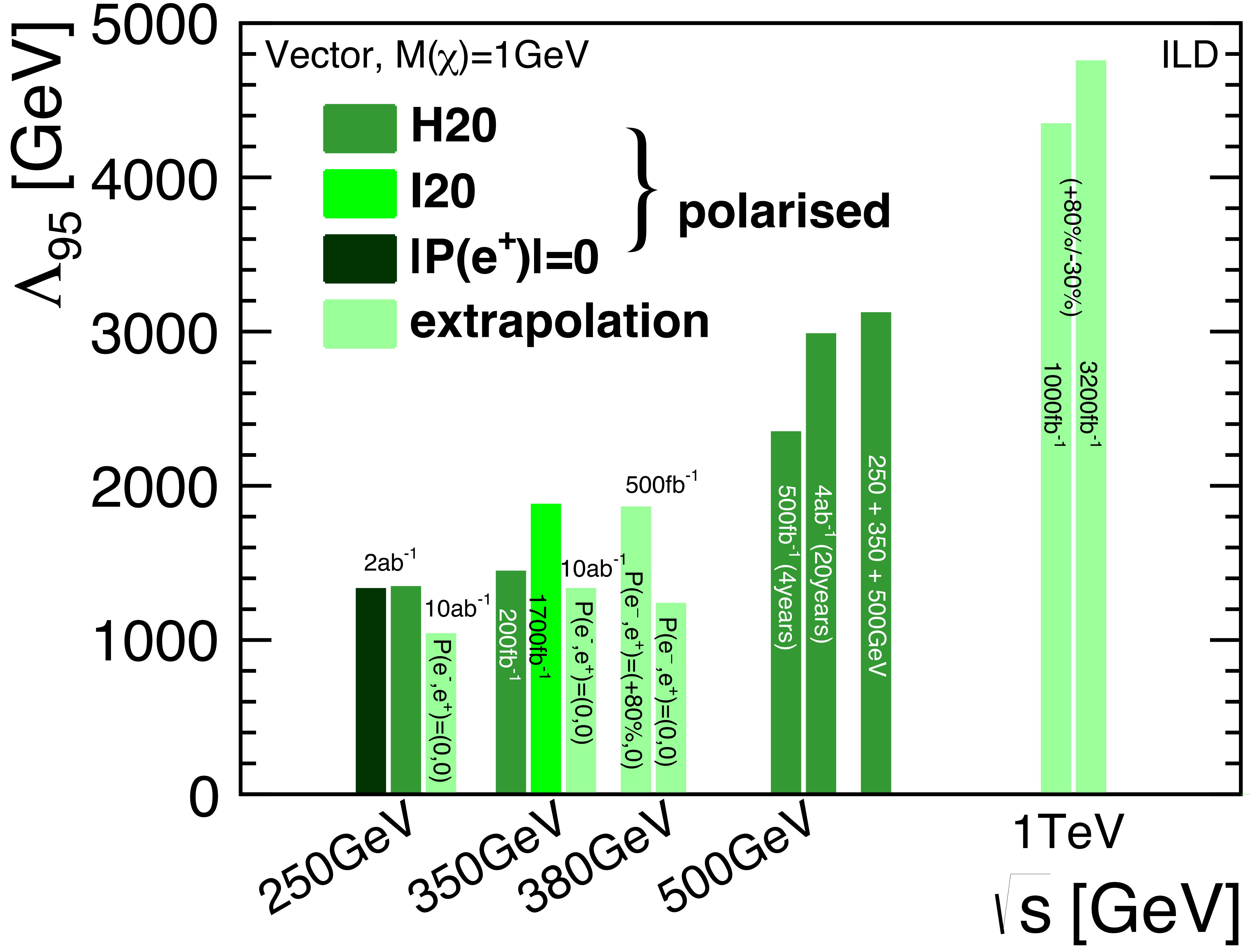
Phys. Rev. D 101 (2020) 7



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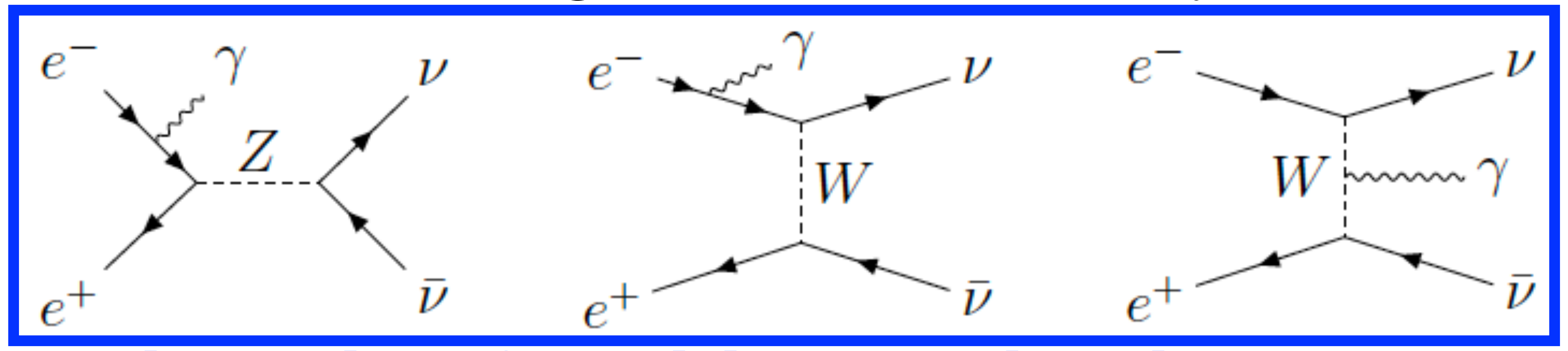

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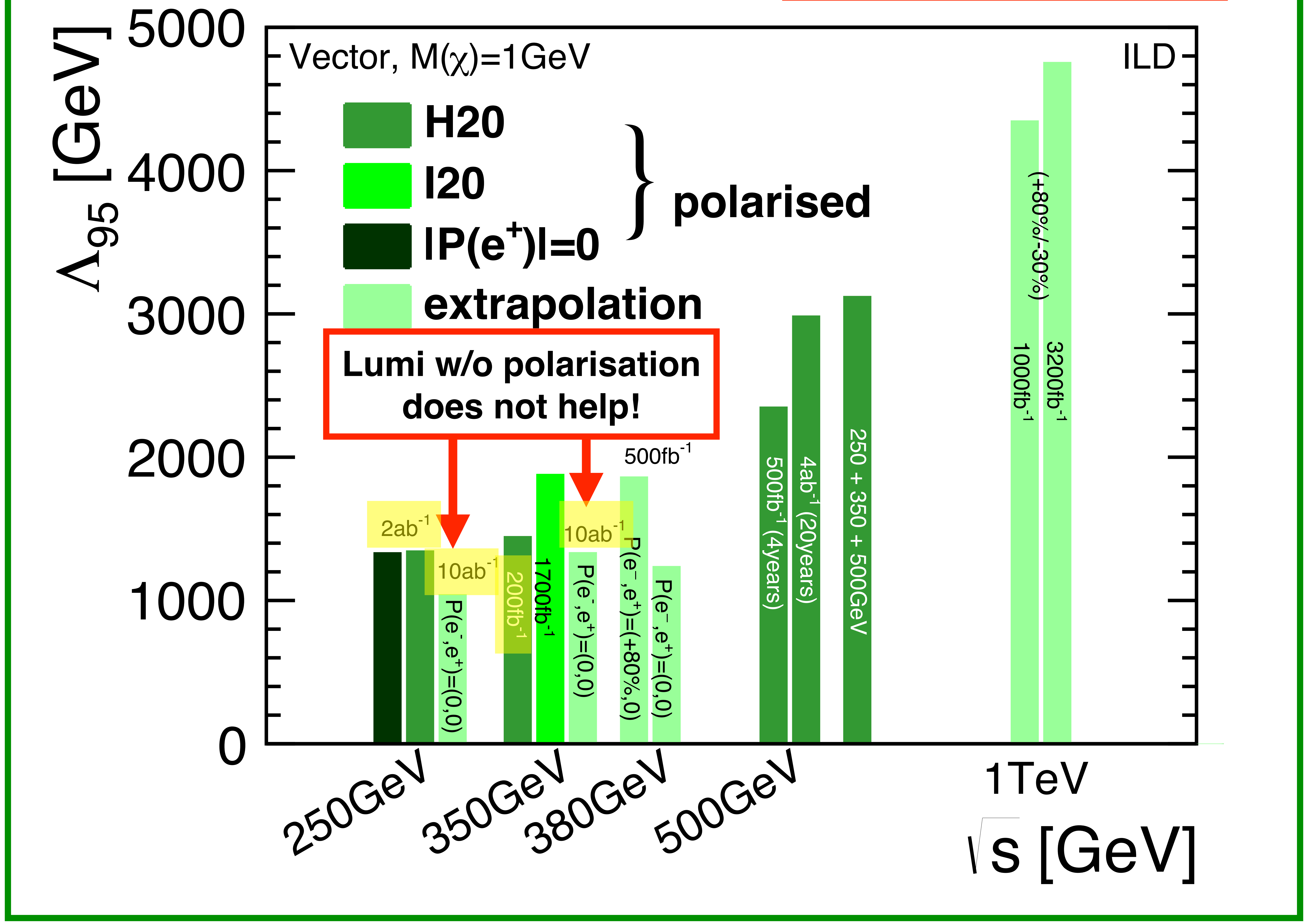

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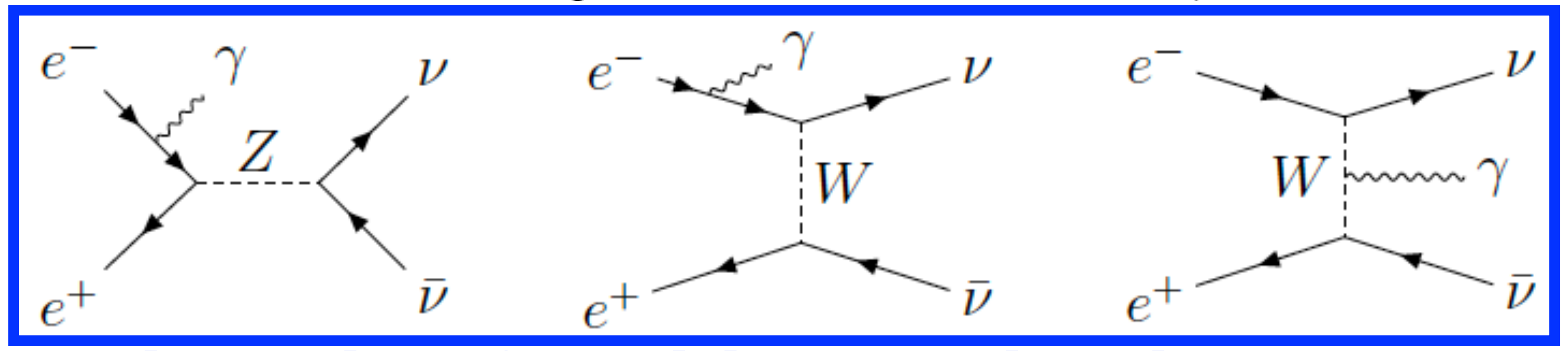

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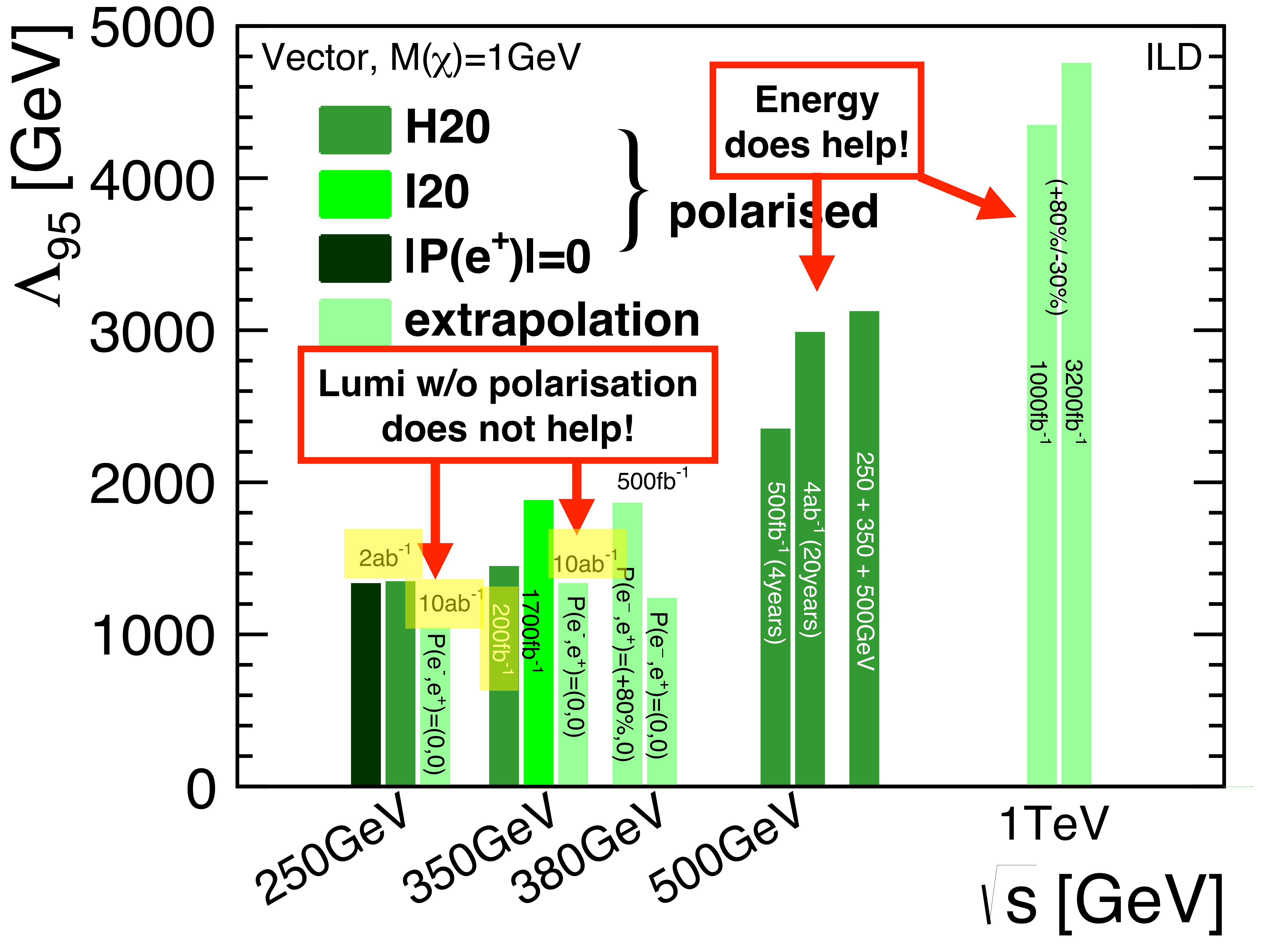

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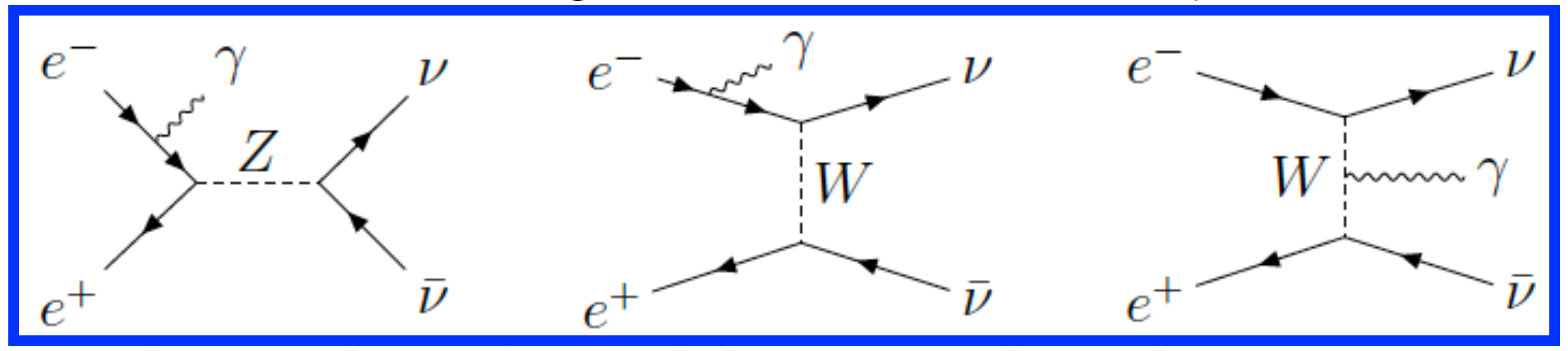

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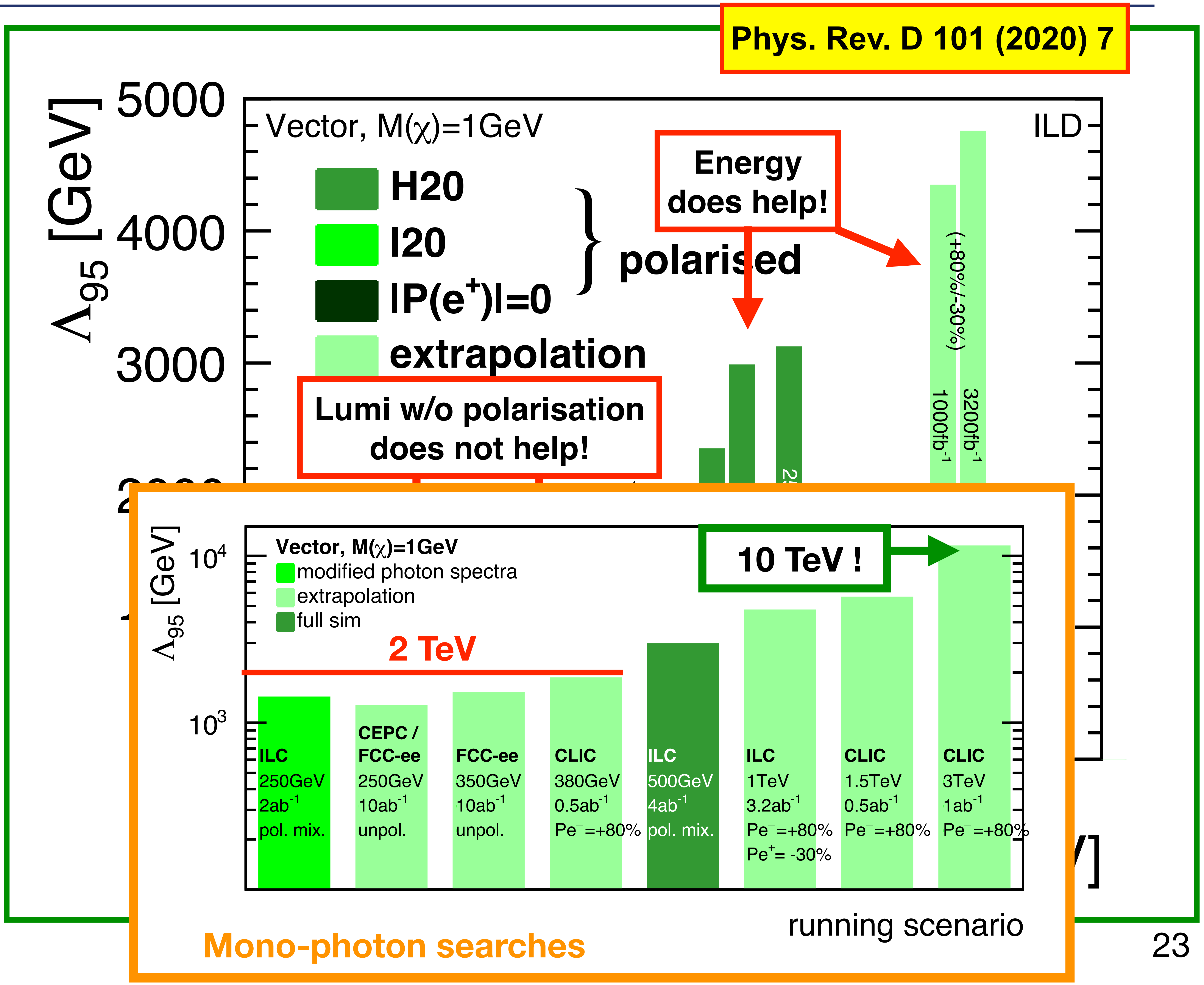

Conclusions

- **The European Strategy for Particle Physics identified an e+e- Higgs factory as the highest-priority next collider**
- **Various projects are proposed - if we want to see *any* of them realized, *anywhere* in the world, there needs to be a much larger active community behind it!**
- **ECFA set up a workshop series on Physics, Experiments and Detectors at a Higgs, Top and Electroweak factory cf https://indico.cern.ch/event/1044297/**
    - **WG1 - Physics Potential, WG2 - Physics Analysis Methods, WG3 - Detectors (tba)**
    - **main focus: topics in common between all e+e- colliders**
        - **theory prediction**
        - **assessment of systematic uncertainties**
        - **software tools**
        - **…**
    - **topical workshops, seminar series, tutorials, mailing lists -> starting up**
    - **will give input to next round of ESU**
    - **if you don't won't to commit to a specific collider project / detector concept => this is your way to contribute => get in touch!**