Higgs & BSM Physics at Future e^+e^- Linear Colliders

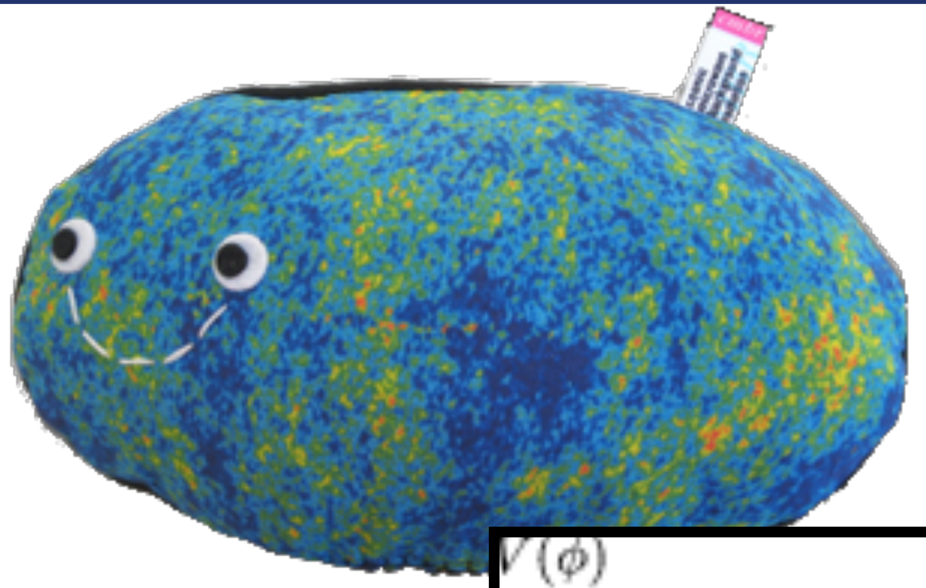
J. List (DESY)

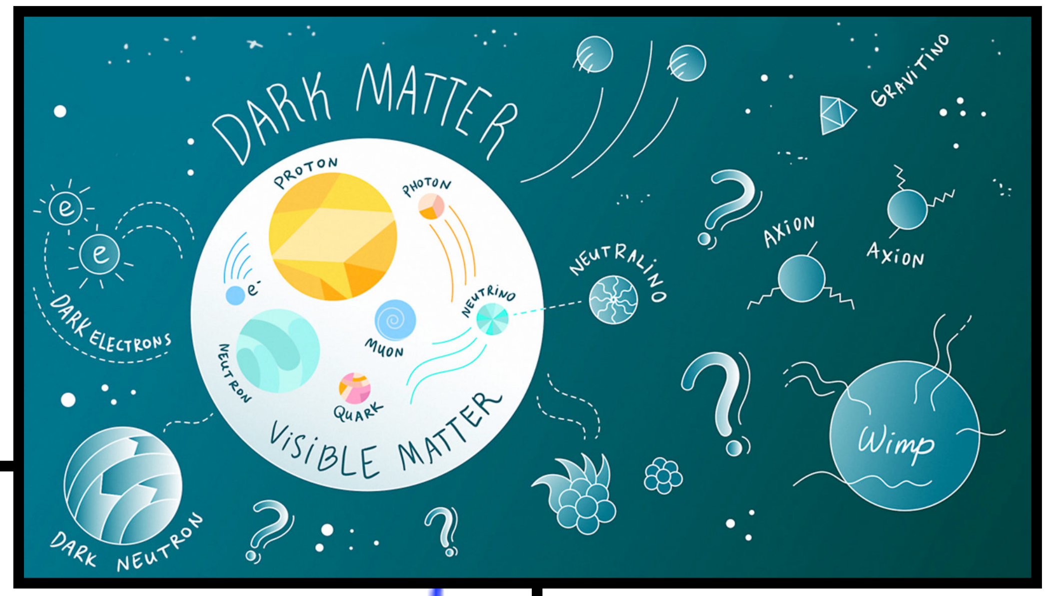
Snowmass Energy Frontier WS, Brown University & zoom, March 31 2022

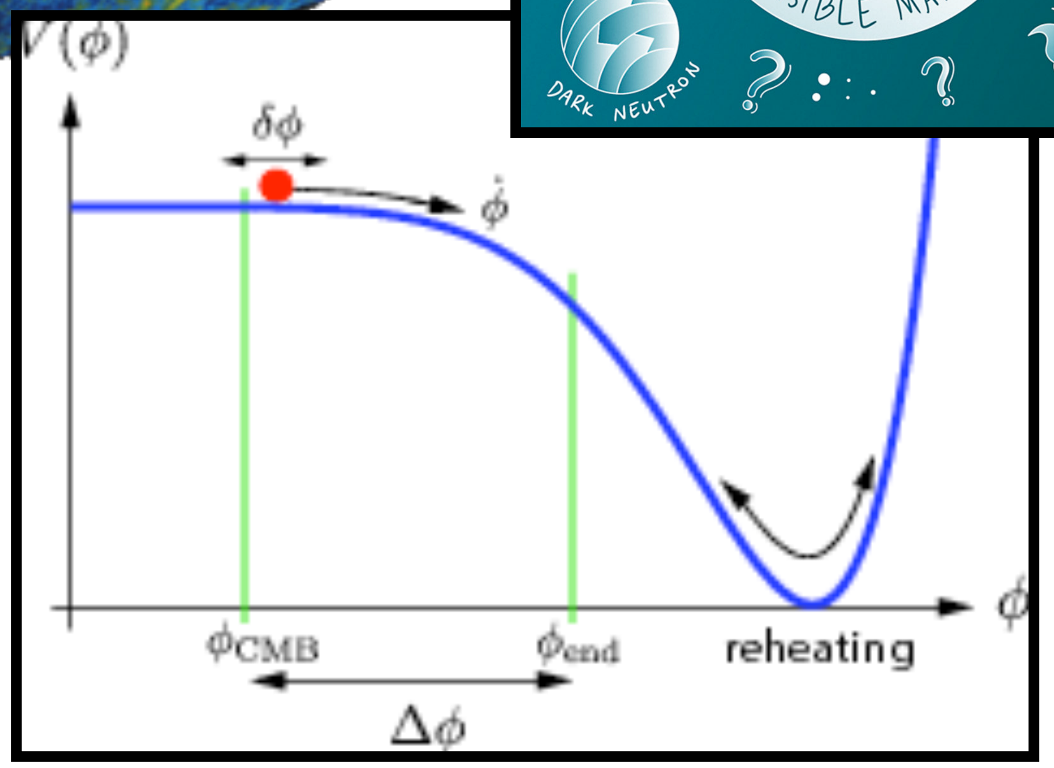
The big questions for future colliders

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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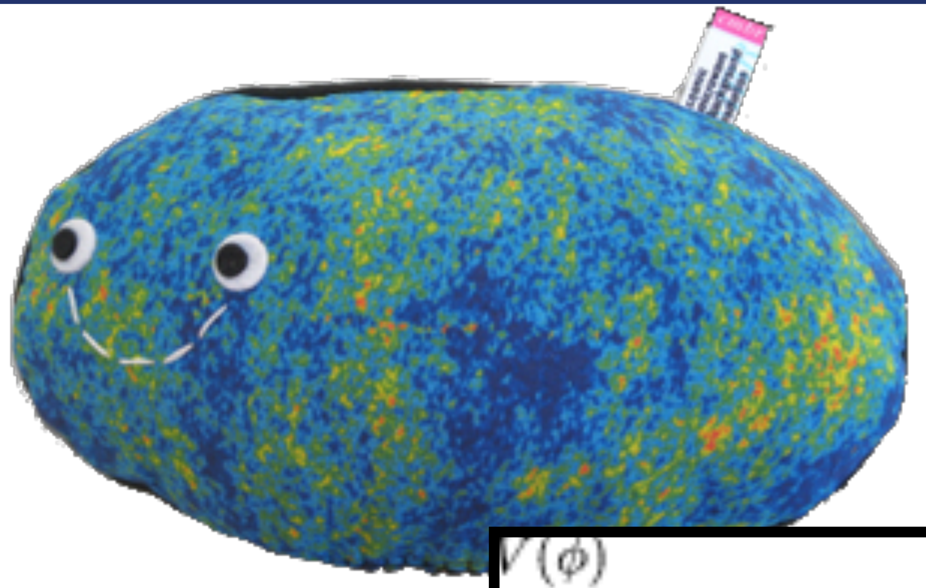

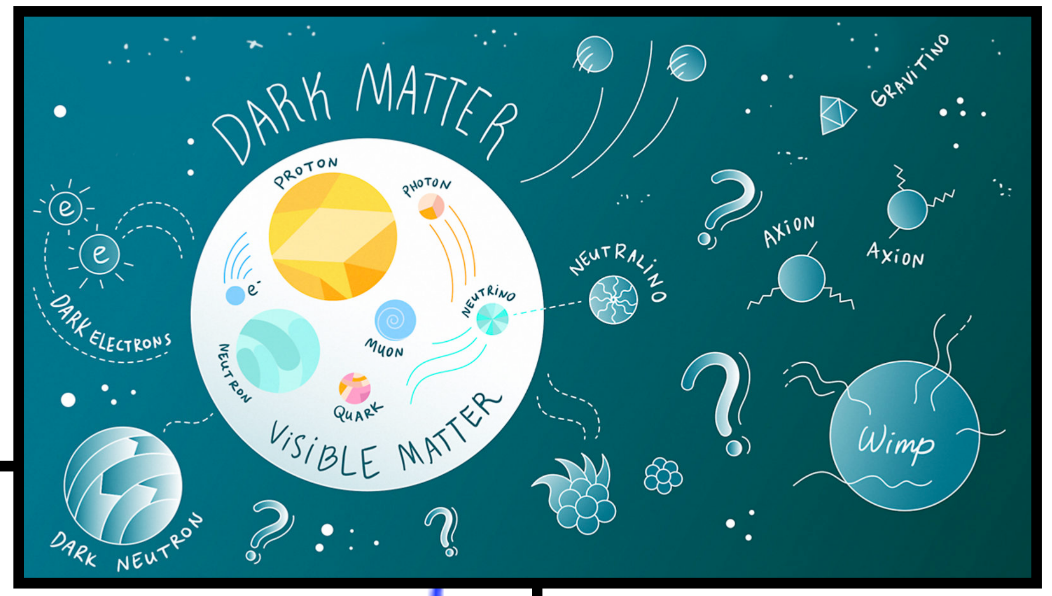

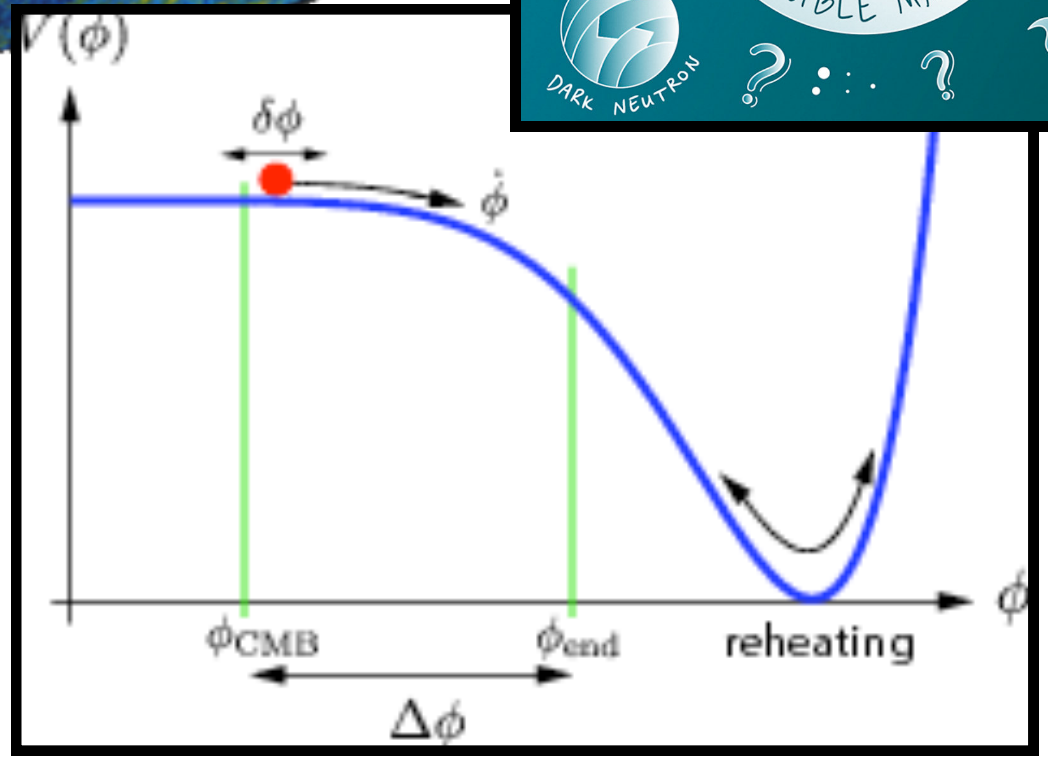

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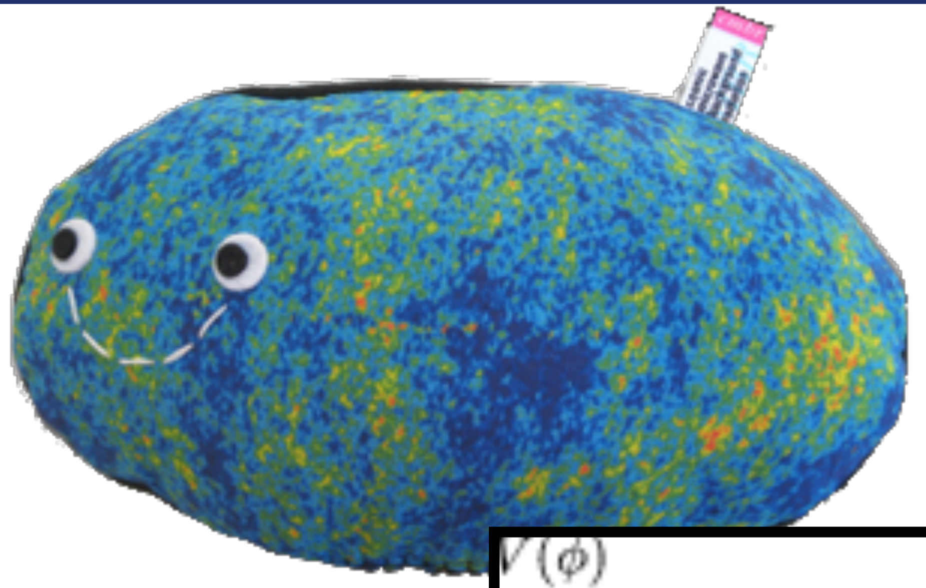

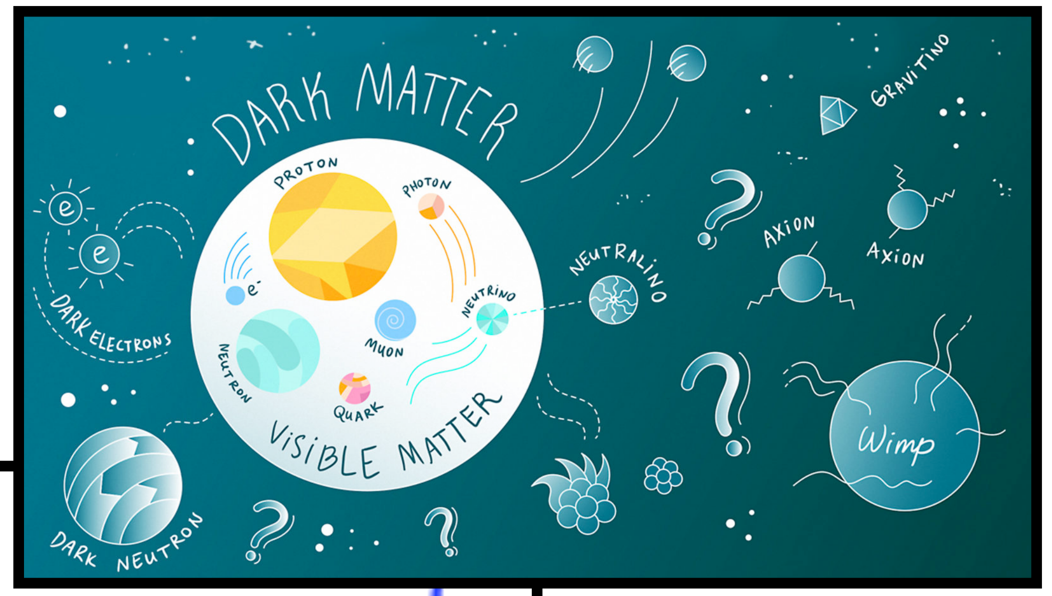

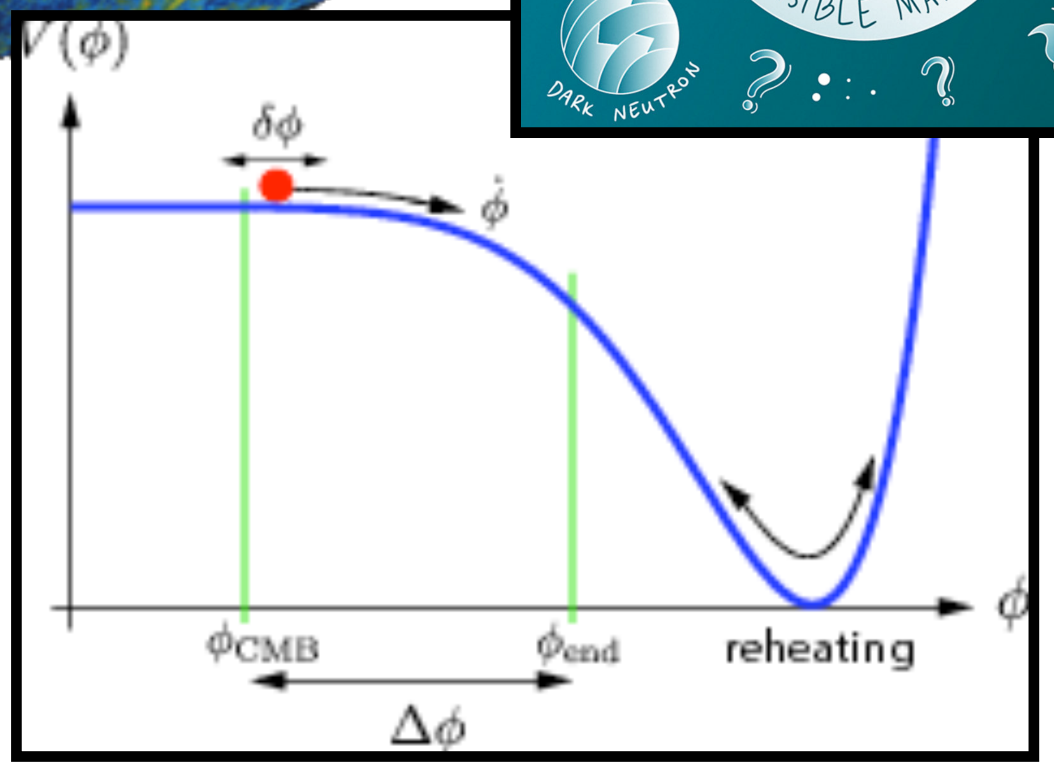

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  - **search in e+e-**
  - **study the Higgs - precisely!**

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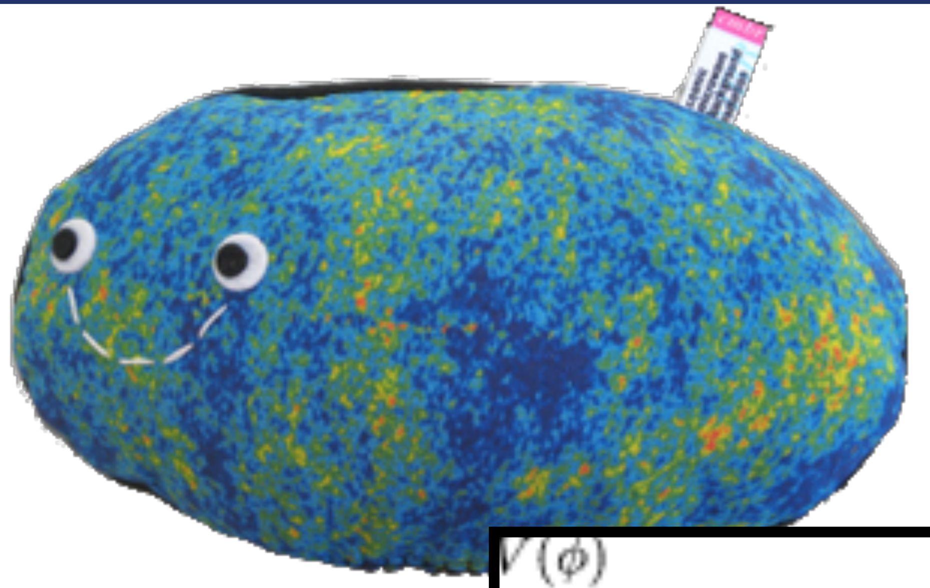

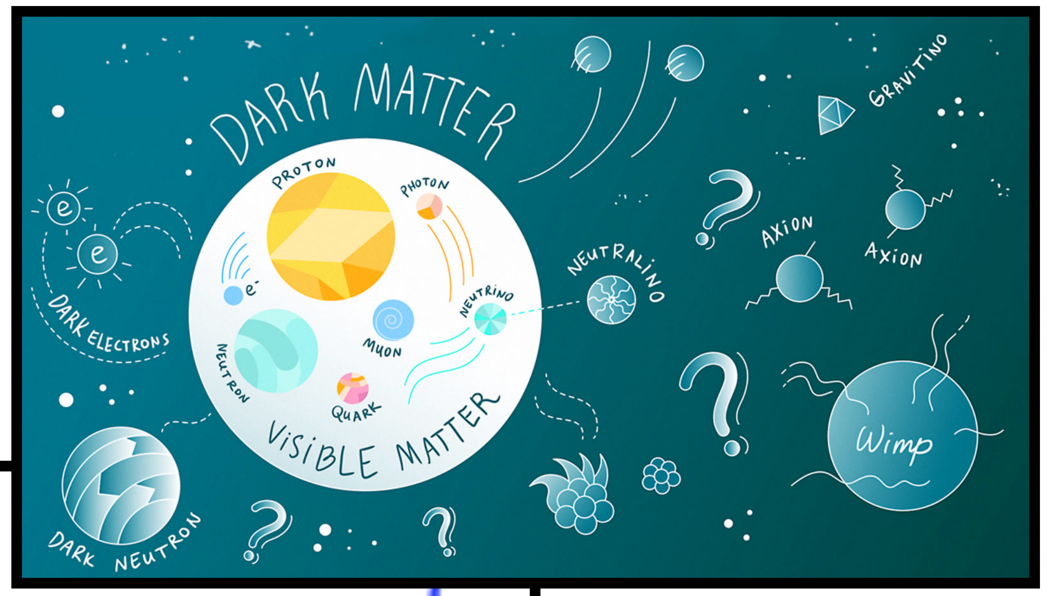

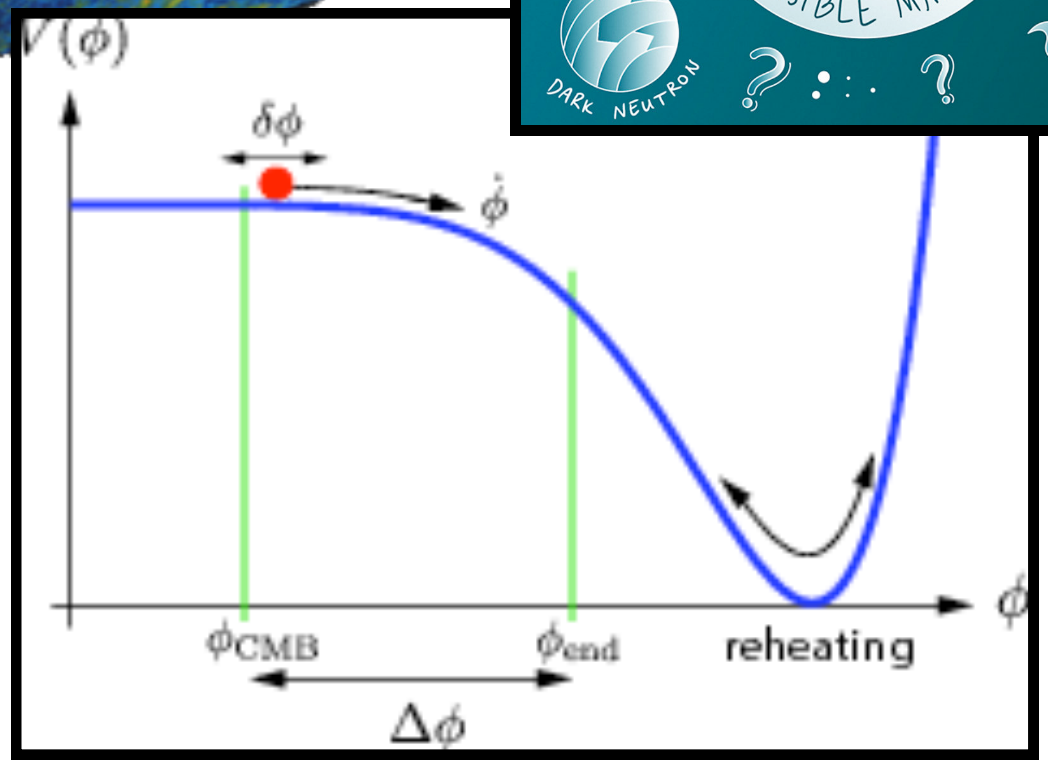

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What we don't know:

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

=> no guarantee for direct production of new particles

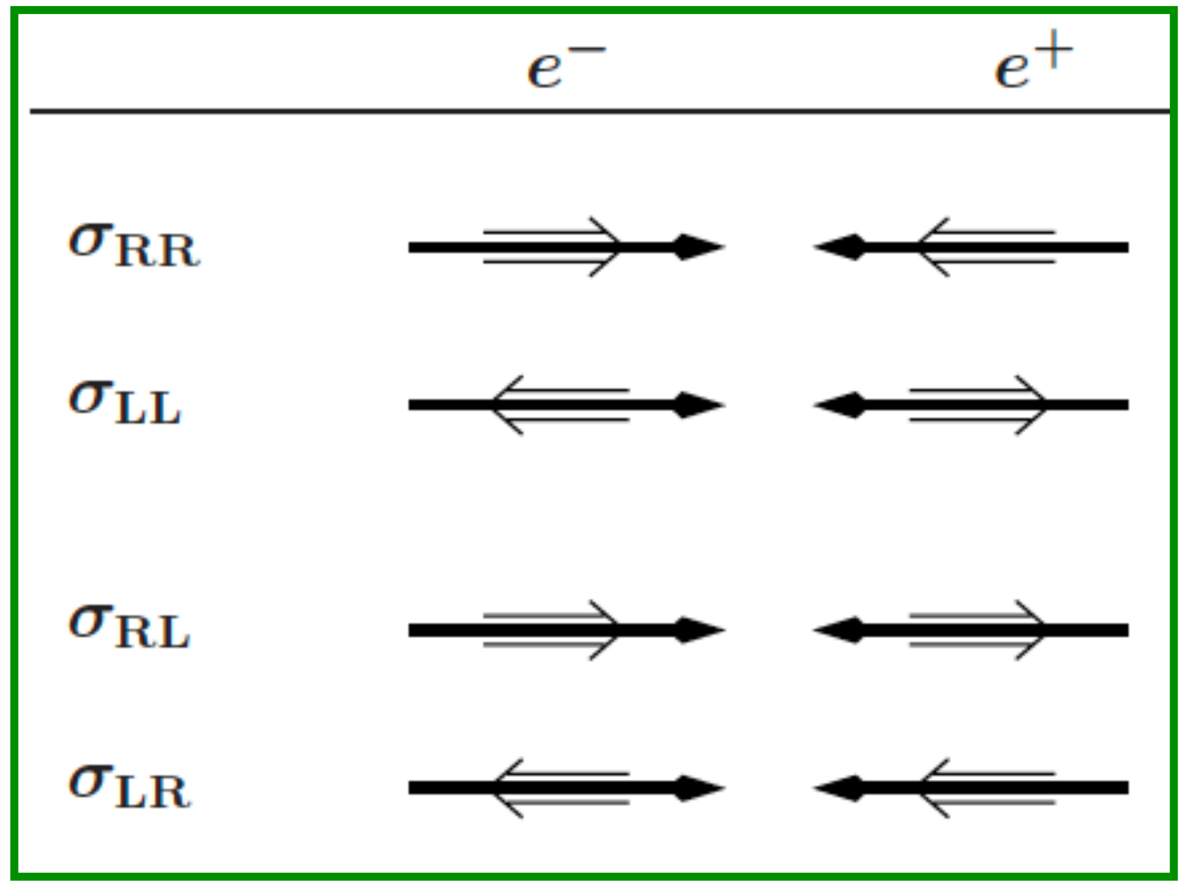
=> need to explore various complementary experimental approaches

Special features of Linear e^+e^- Colliders

- **Intrinsic upgradability in energy => make longer with same technology — or upgrade technology - or both**
- Longitudinally **polarised beams**:
  - SLC: $P(e^-) = \pm 80\%$, $P(e^+) = 0\%$
  - ILC: $P(e^-) = \pm 80\%$, $P(e^+) = \pm 30\%$ (upgrade 60%)
  - CLIC, C3: $P(e^-) = \pm 80\%$, $P(e^+) = 0\%$

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

- Electroweak interactions highly sensitive to chirality of fermions: $SU(2)_L \times U(1)$
  - every cross section depends on beam polarisations
  - **with both its beams polarised, ILC is “four colliders in one”:**



Physics benefits of polarised beams

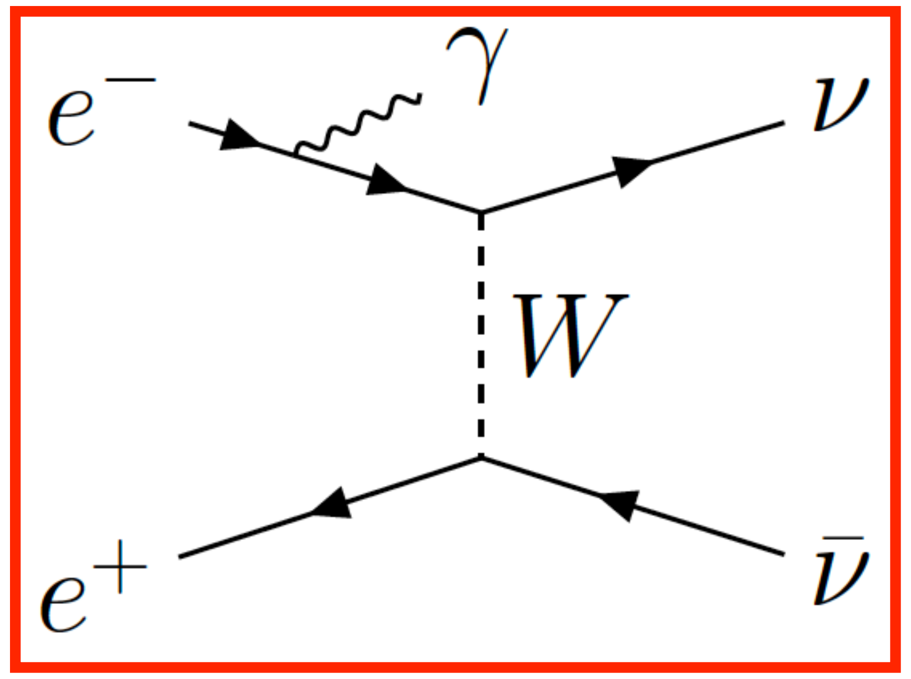
cf also talk by Michael Peskin on Monday

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

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

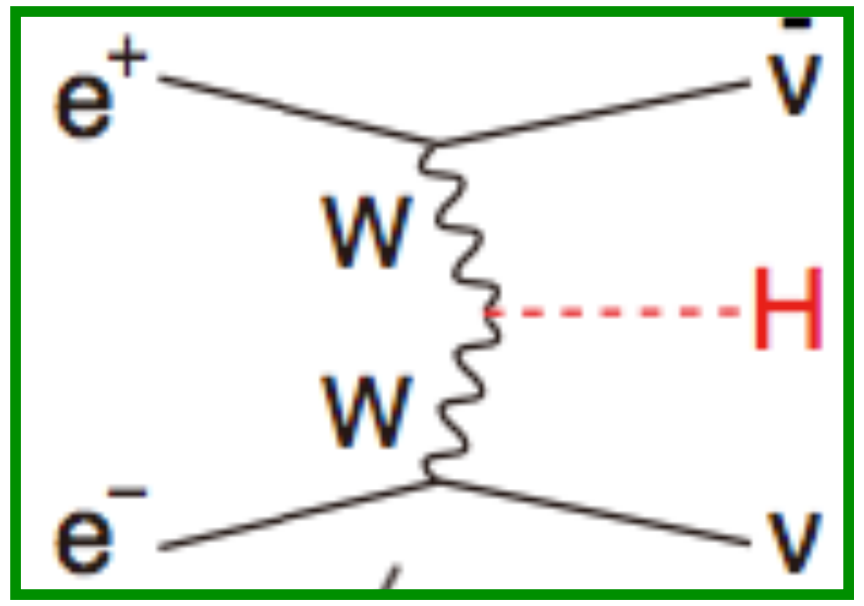
background suppression:

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



signal enhancement:

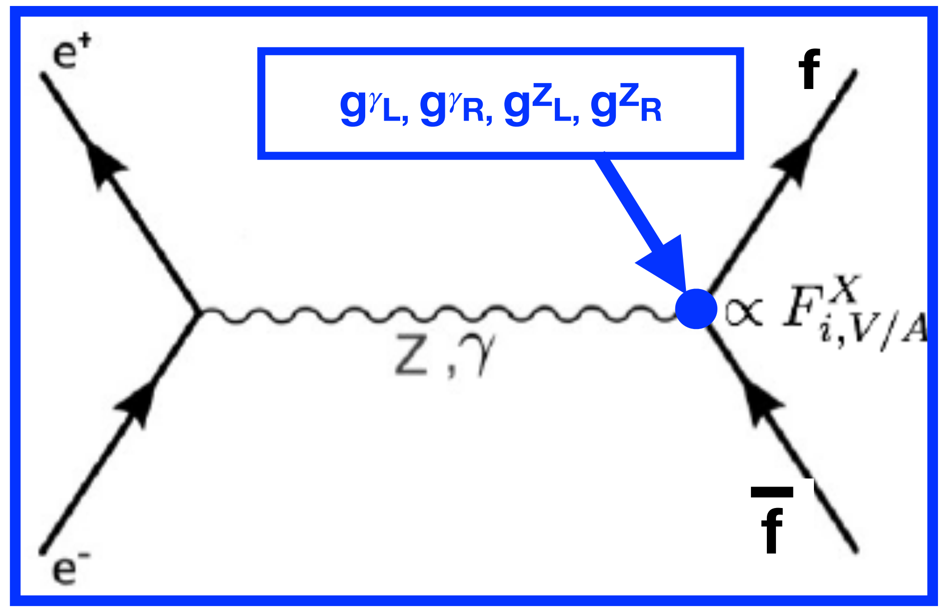
- Higgs production
  in WW fusion
- many BSM processes



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!

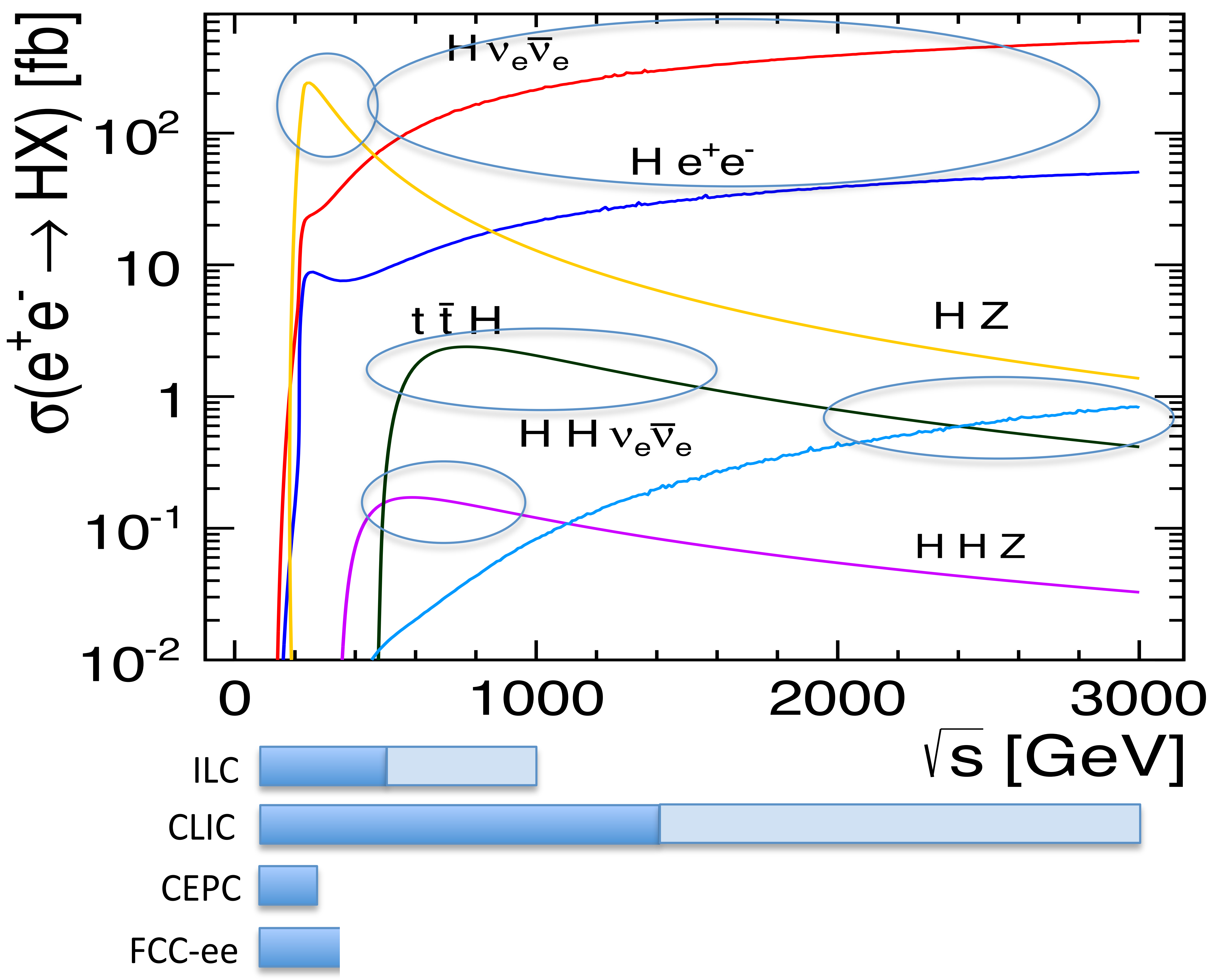
redundancy & control of systematics:

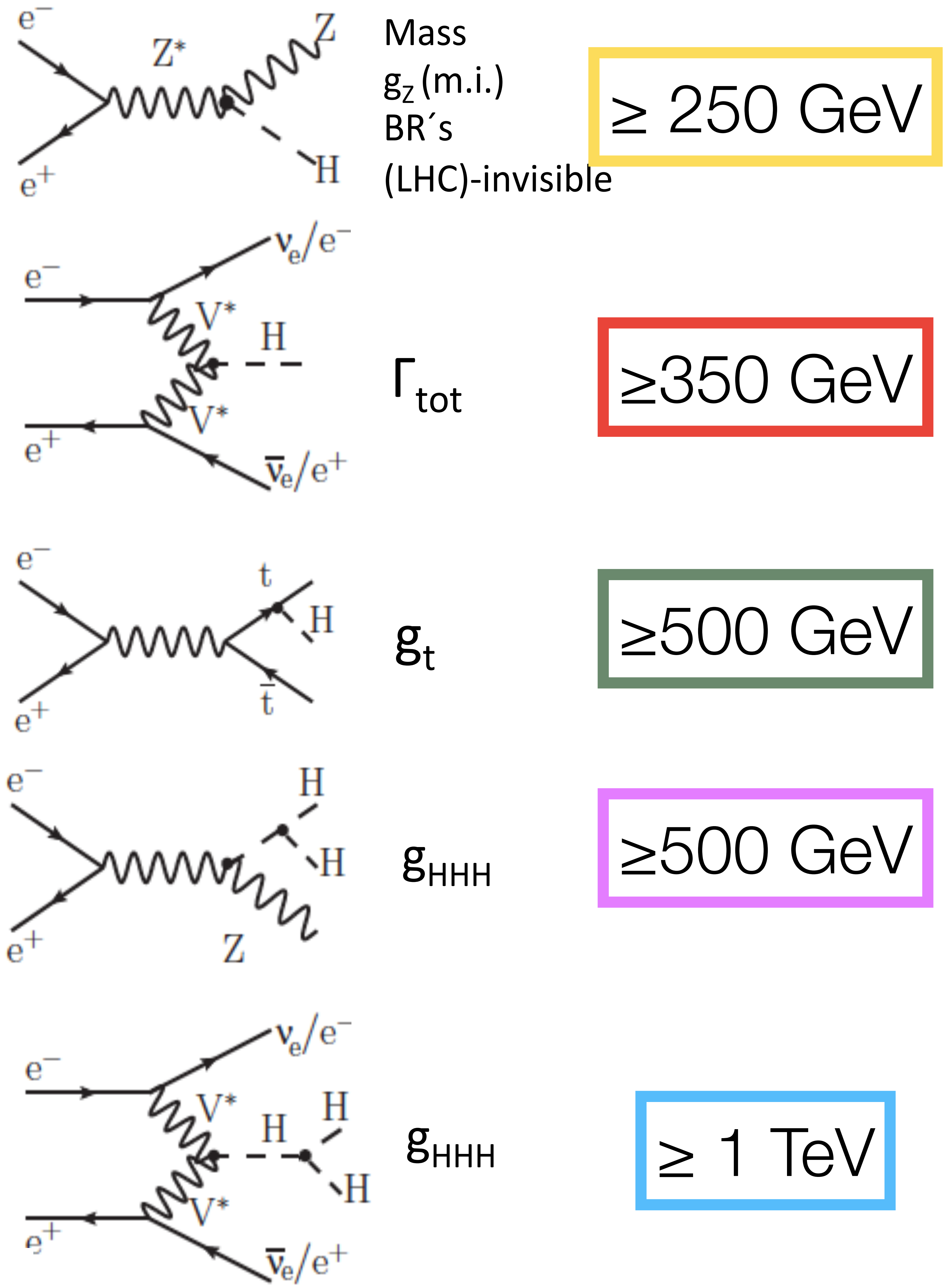
- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

New insights from our new friend

The Higgs Boson

Higgs production in e+e- collisions





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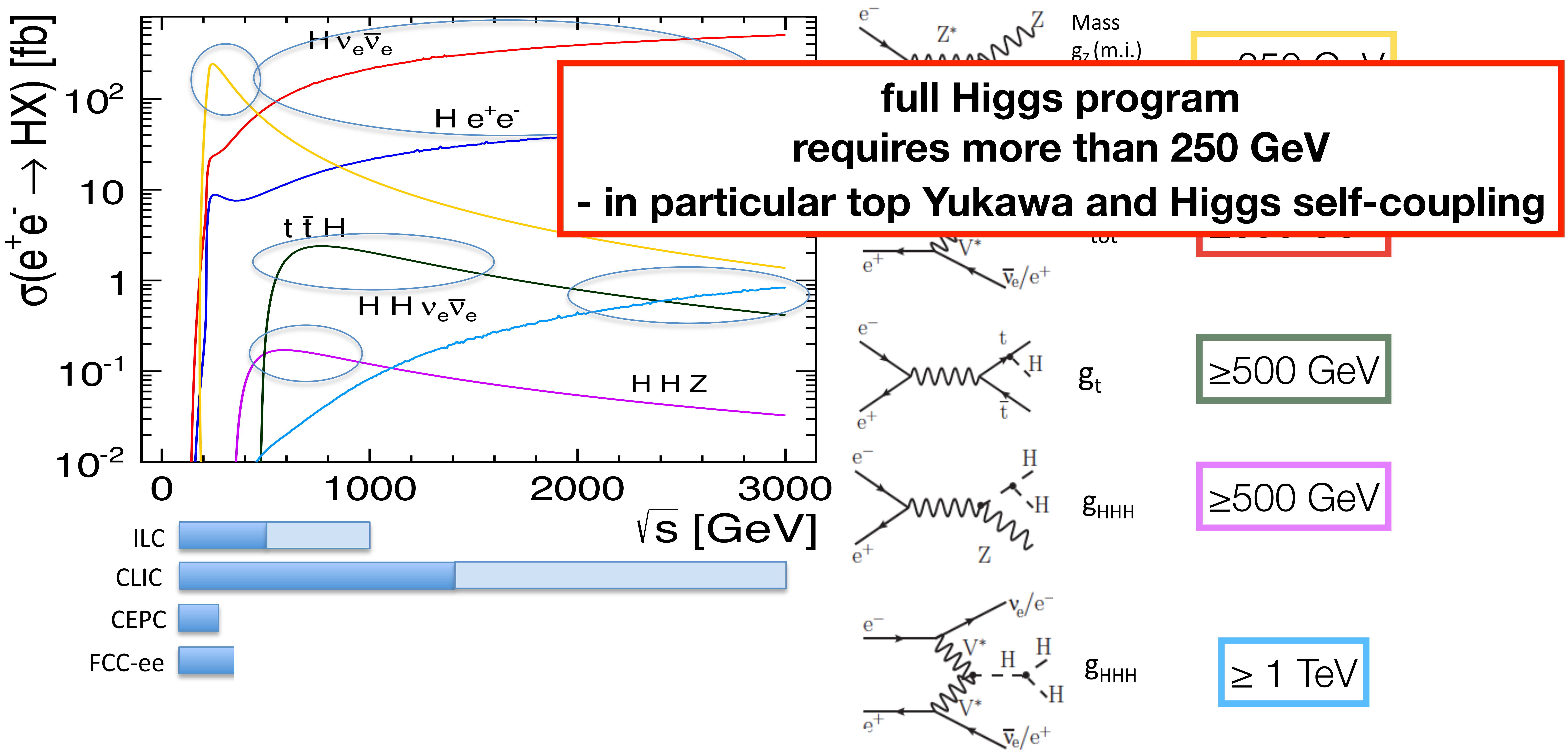
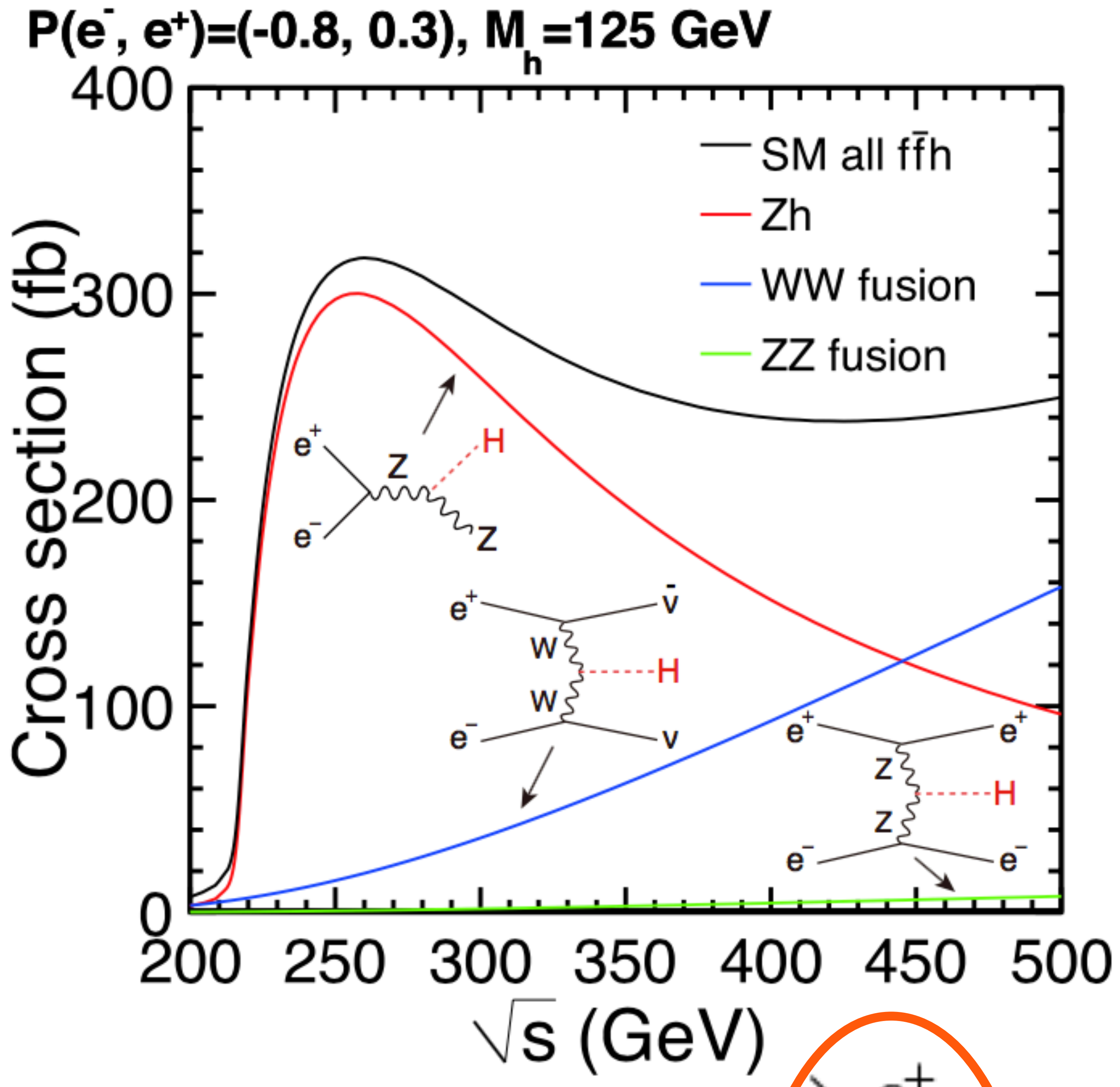
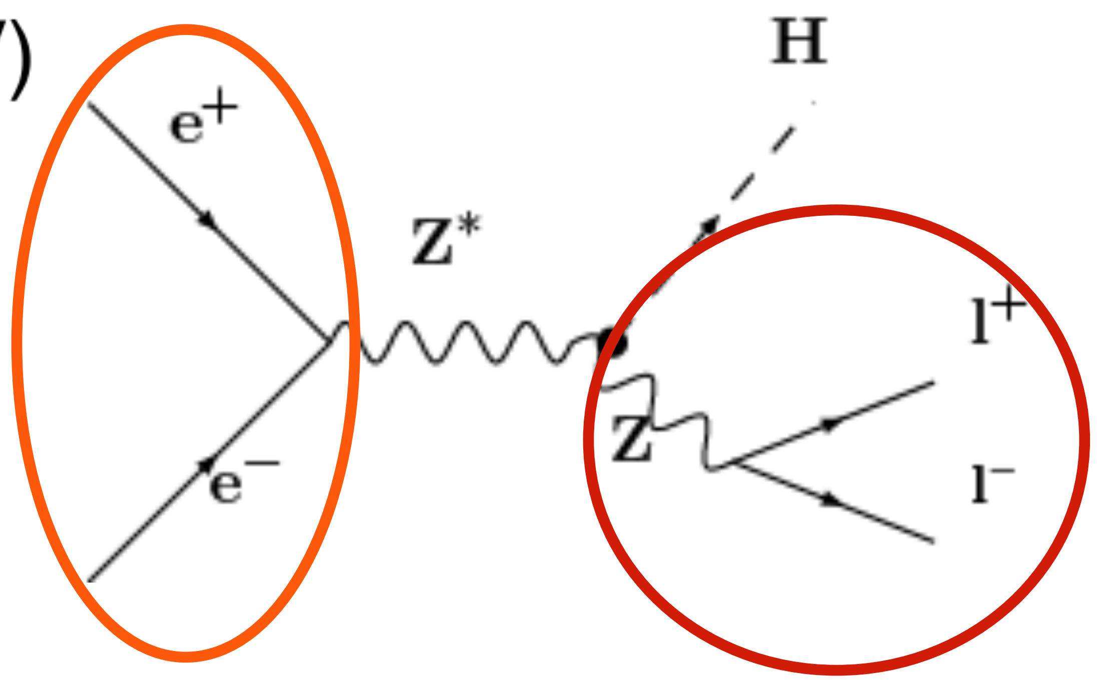


full Higgs program
requires more than 250 GeV
- in particular top Yukawa and Higgs self-coupling

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**
  - CP properties of Zh coupling
  - ….

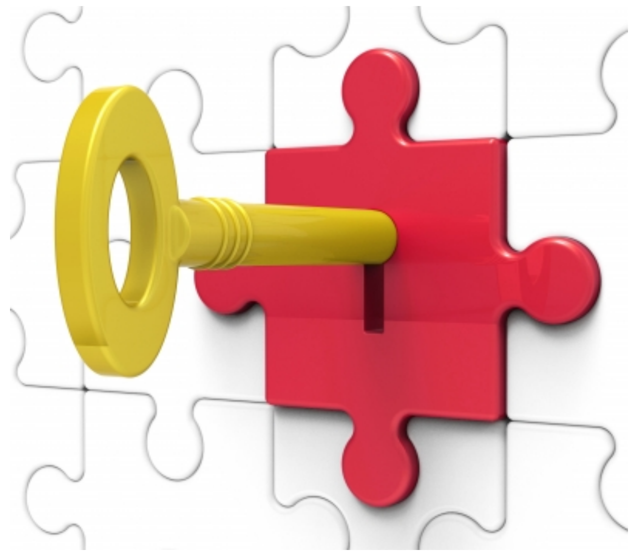


Image courtesy of Stuart Miles at FreeDigitalPhotos.net

for detailed listings of individual precisions see e.g. ILC and CLIC Whitepapers

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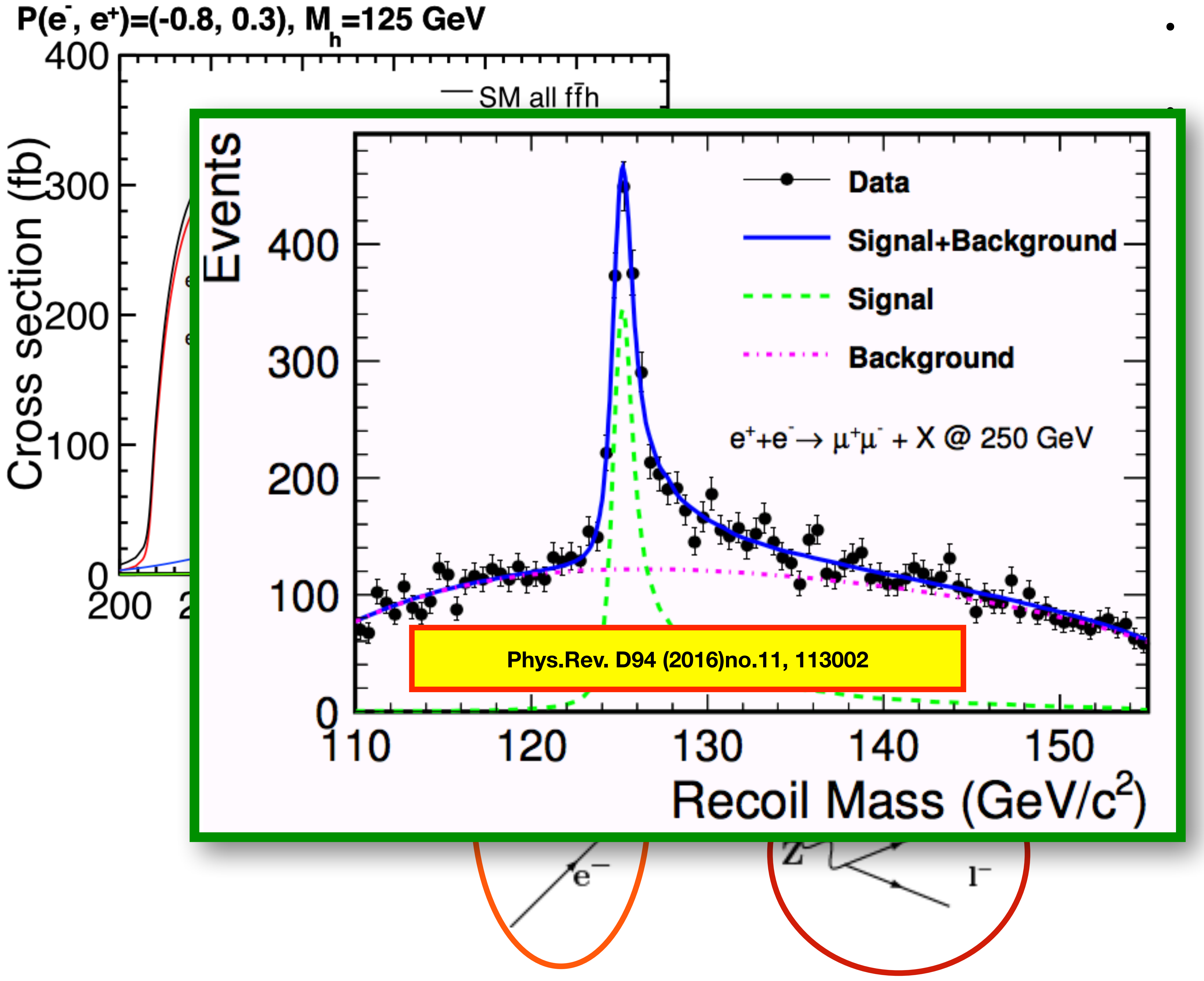

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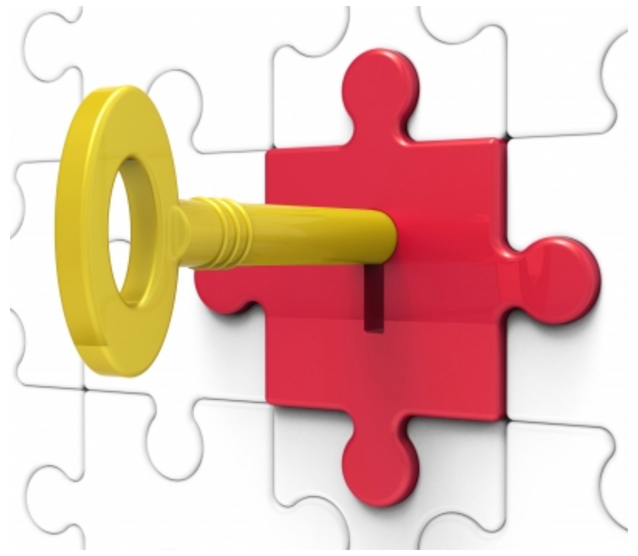

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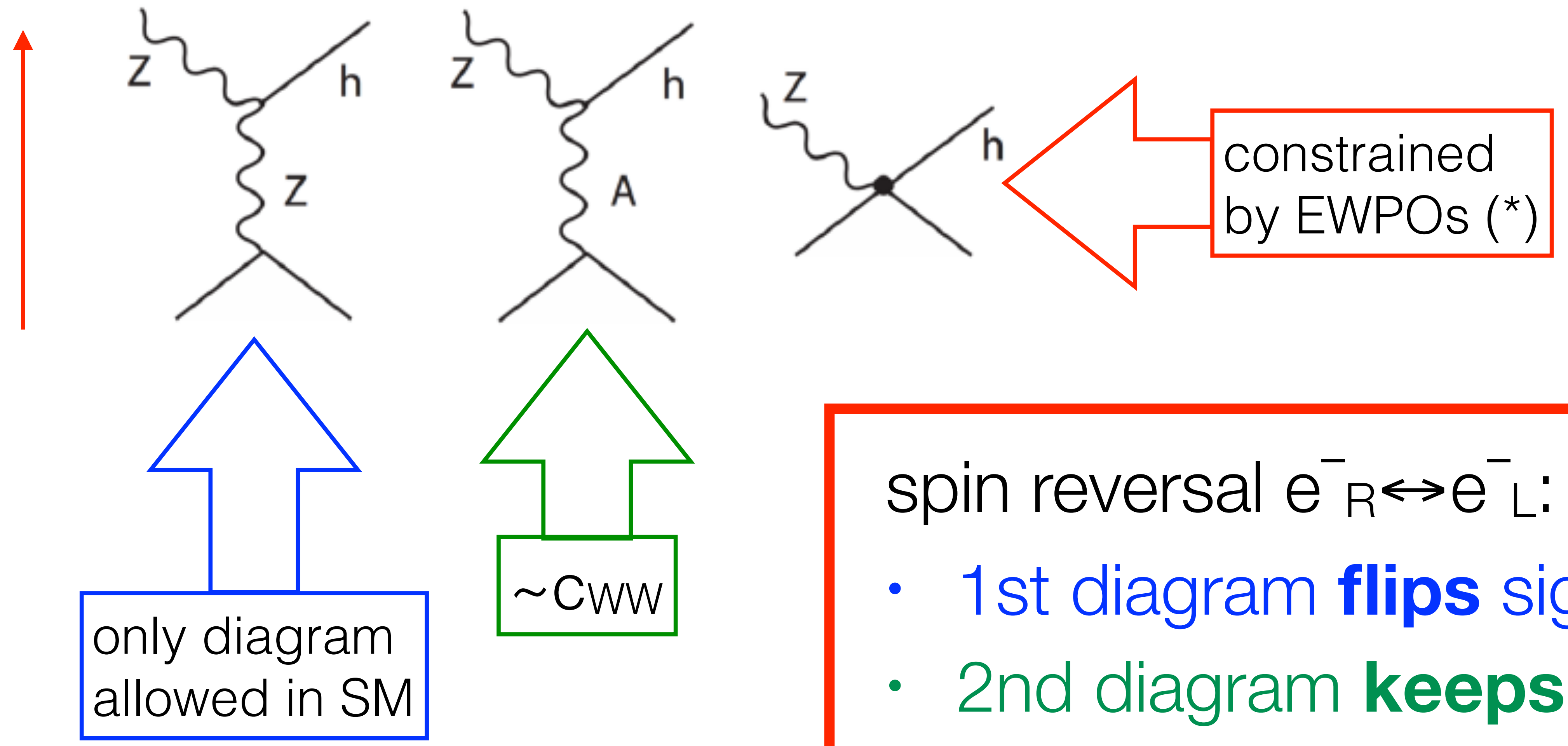
Polarisation & Higgs Couplings - Lumi vs Pol @ 250 GeV

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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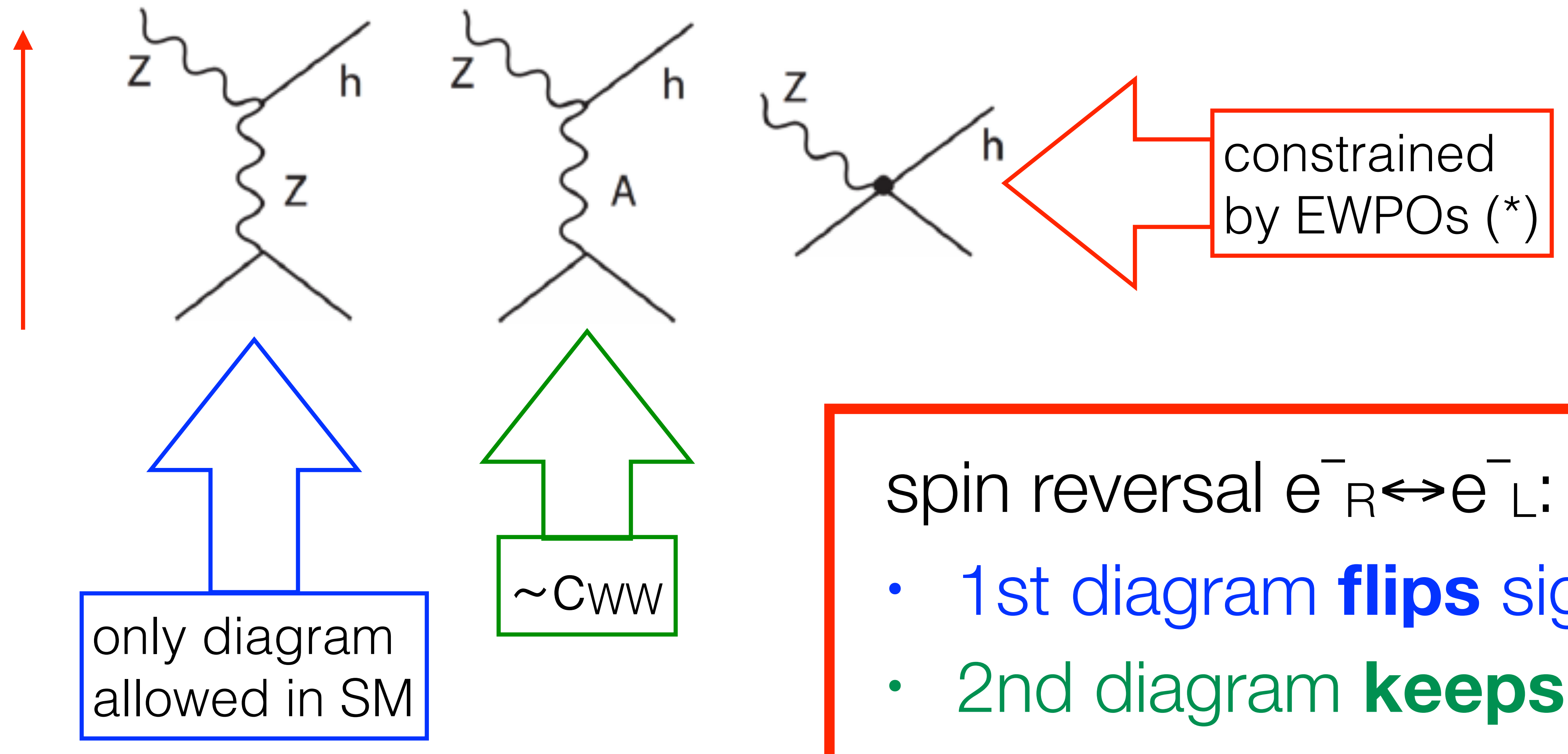

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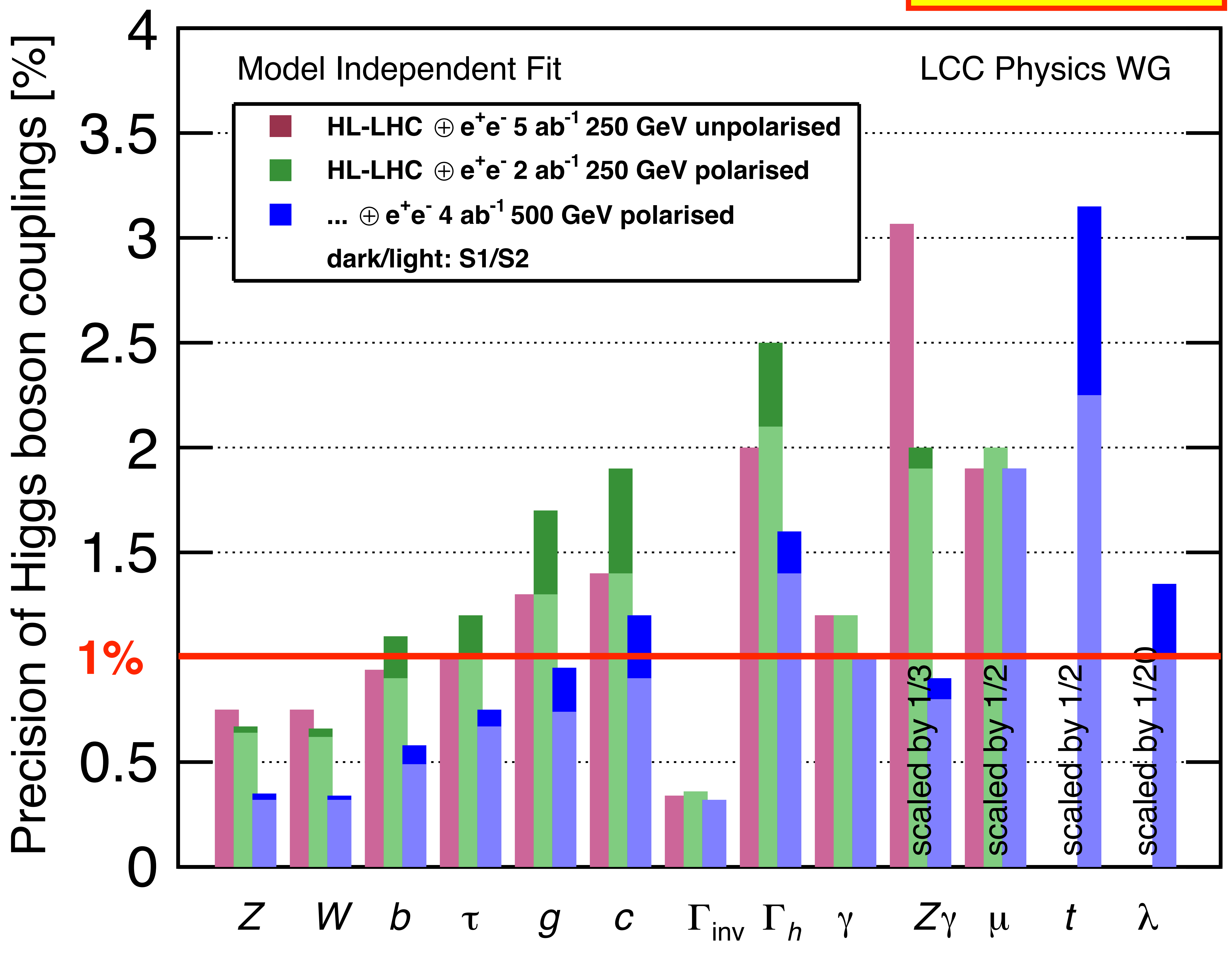

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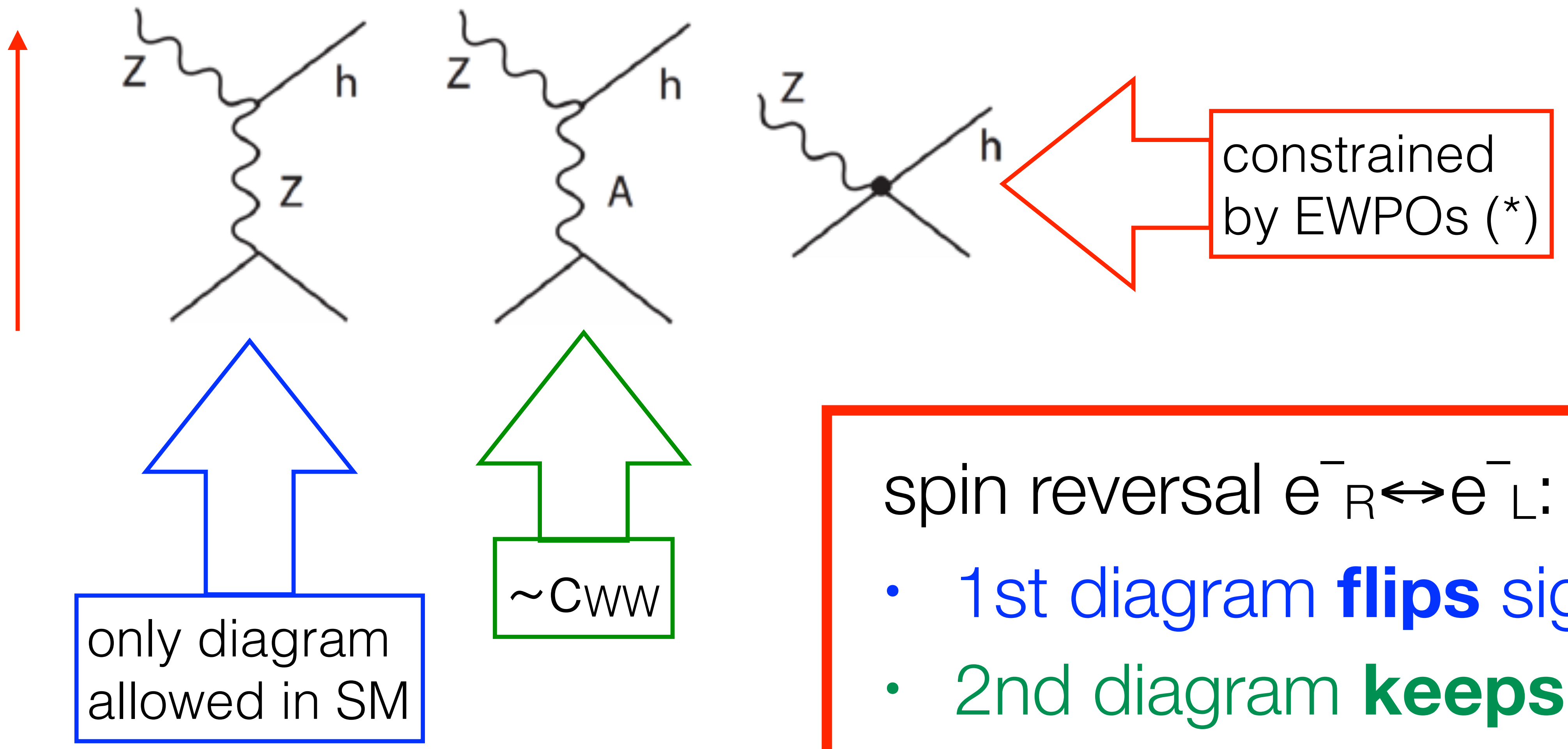

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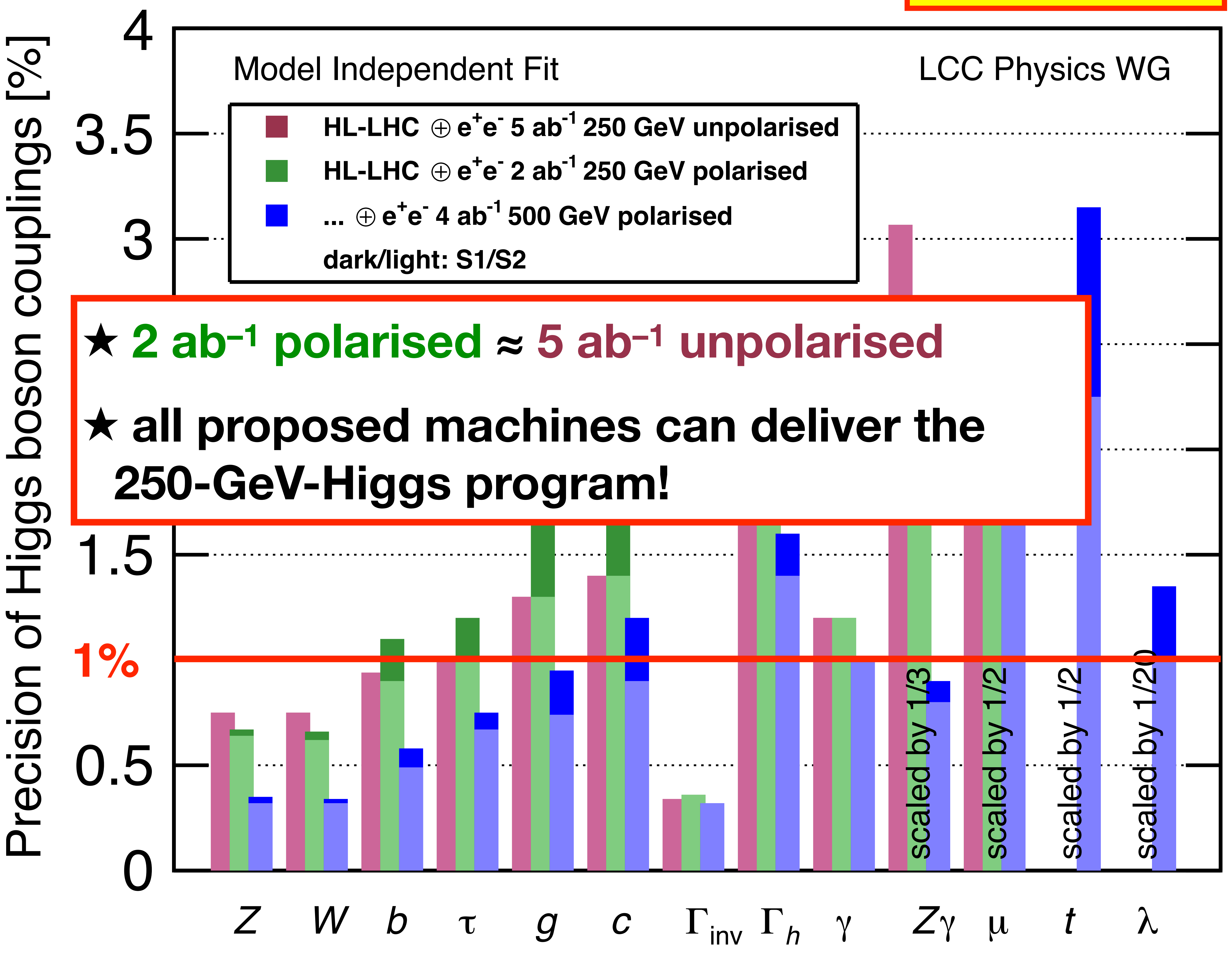
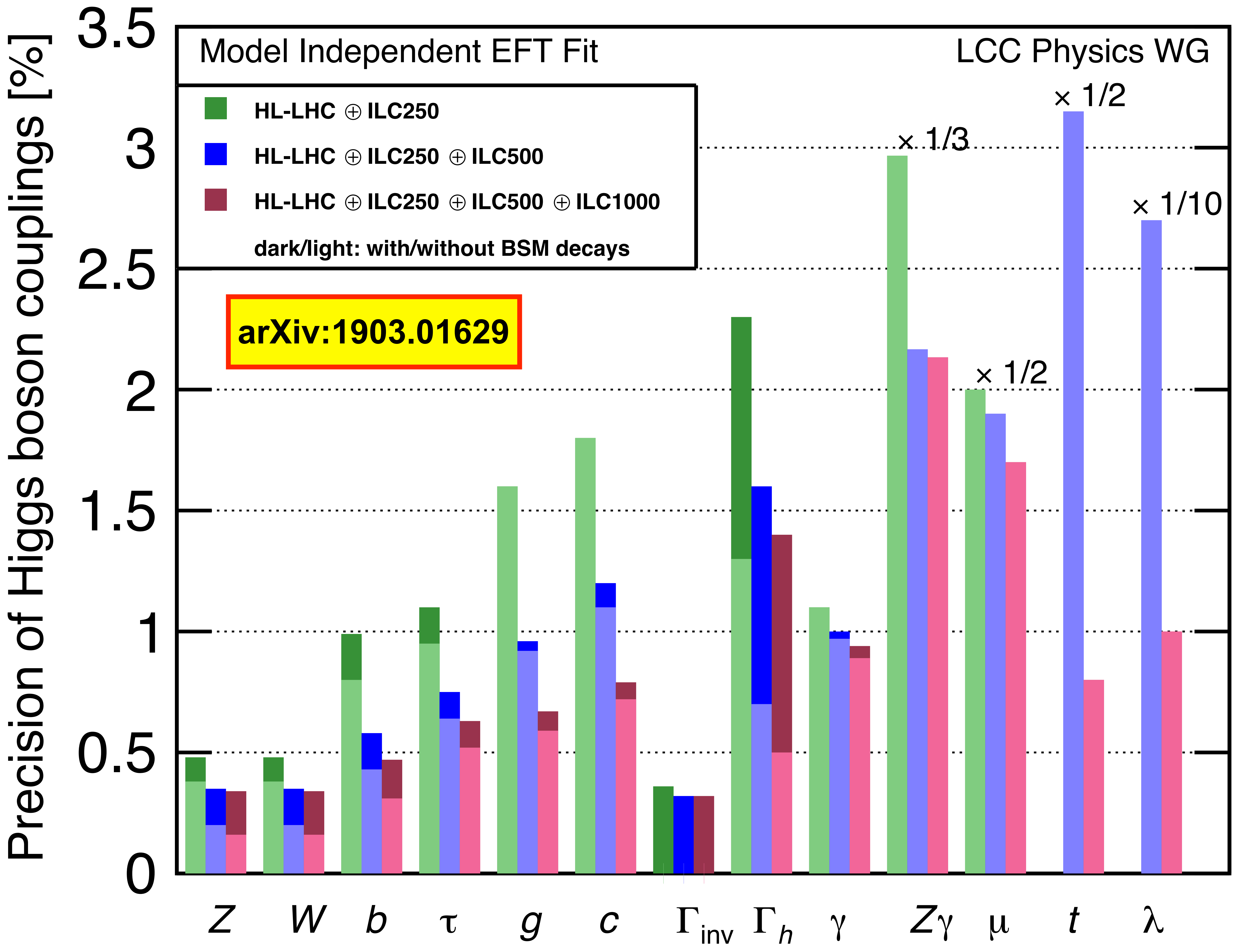


★ 2 ab⁻¹ polarised ≈ 5 ab⁻¹ unpolarised

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

Polarisation & Higgs Couplings - impact of high energies



★significant improvements in g, c, t, λ

★plot also shows that input on BSM decays is important

Higgs self-coupling

- **HL-LHC:**
  - **~3..4 σ 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:**
  - **2…4% uncertainty on λ**
  - **from fast simulation, *single-par.* fit**
  - assuming LHC detector performance despite e.g.100x higher neutron fluence
  - **plus much improved systematics, theory, pdf, …**

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These numbers apply ONLY for
$\lambda = \lambda_{SM}$
arXiv:2005.10576:
2HDM-Type-I => -0.5…1.5 x λ_{SM}

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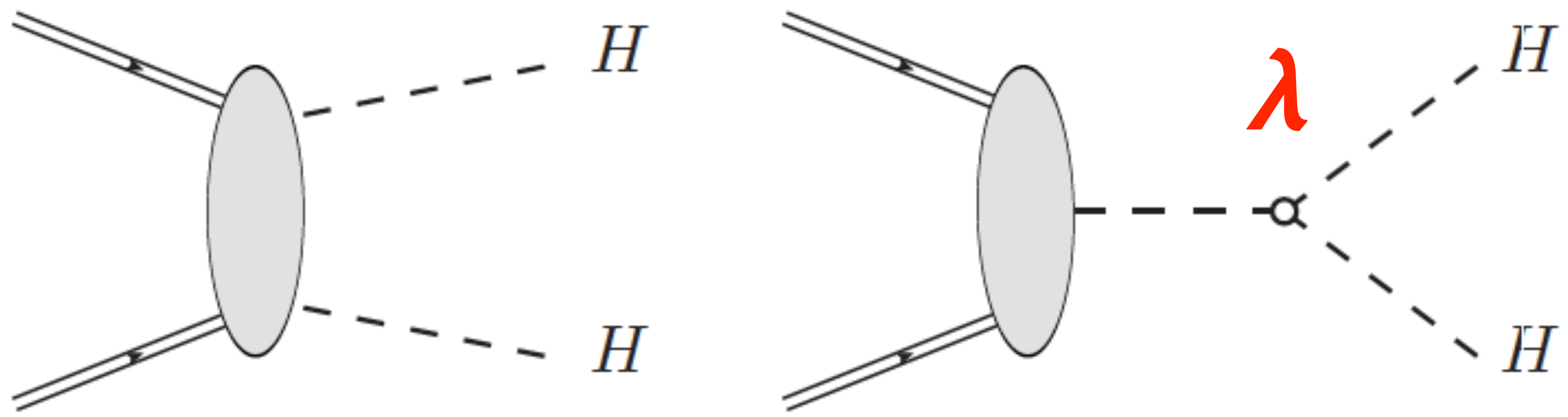

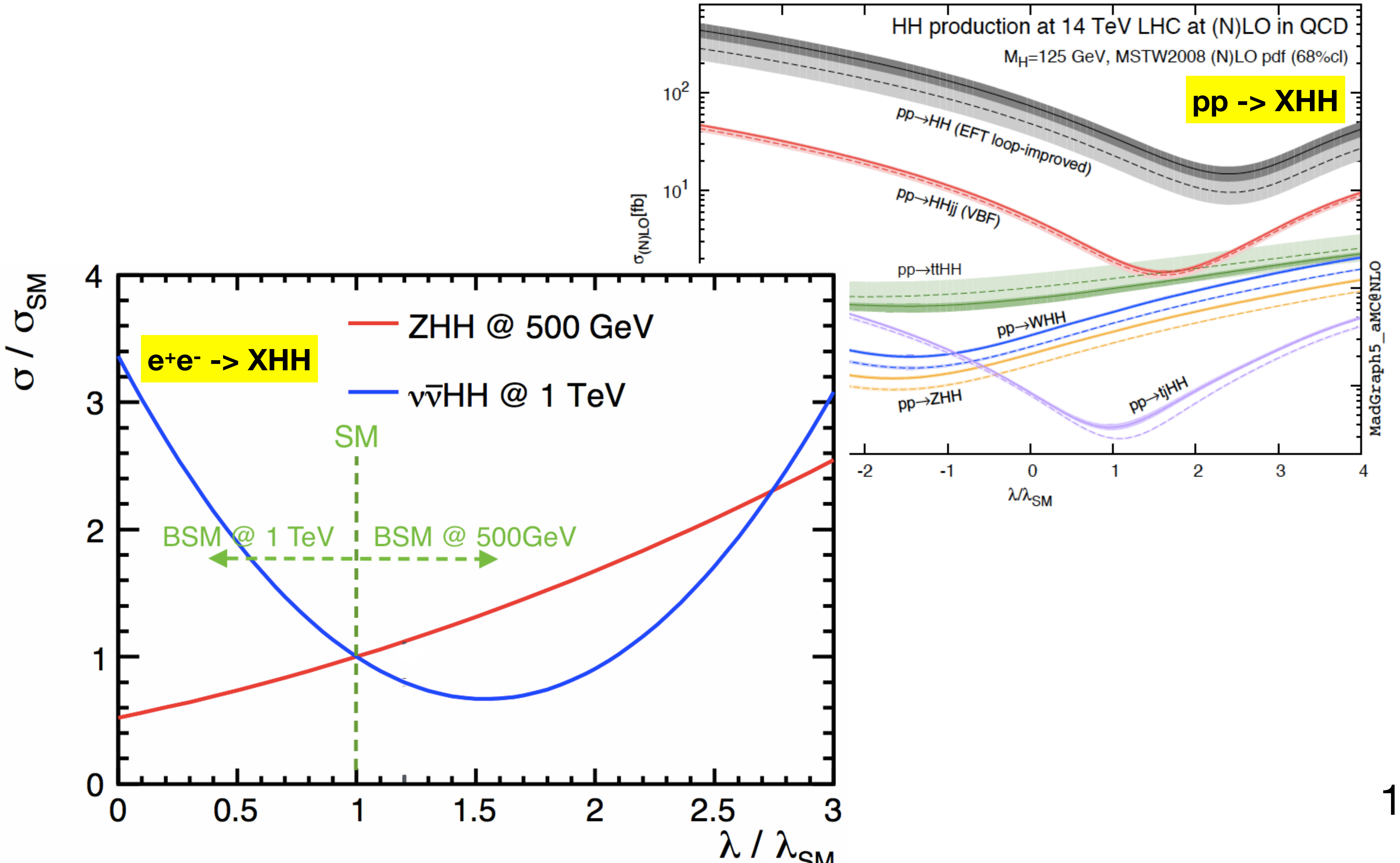

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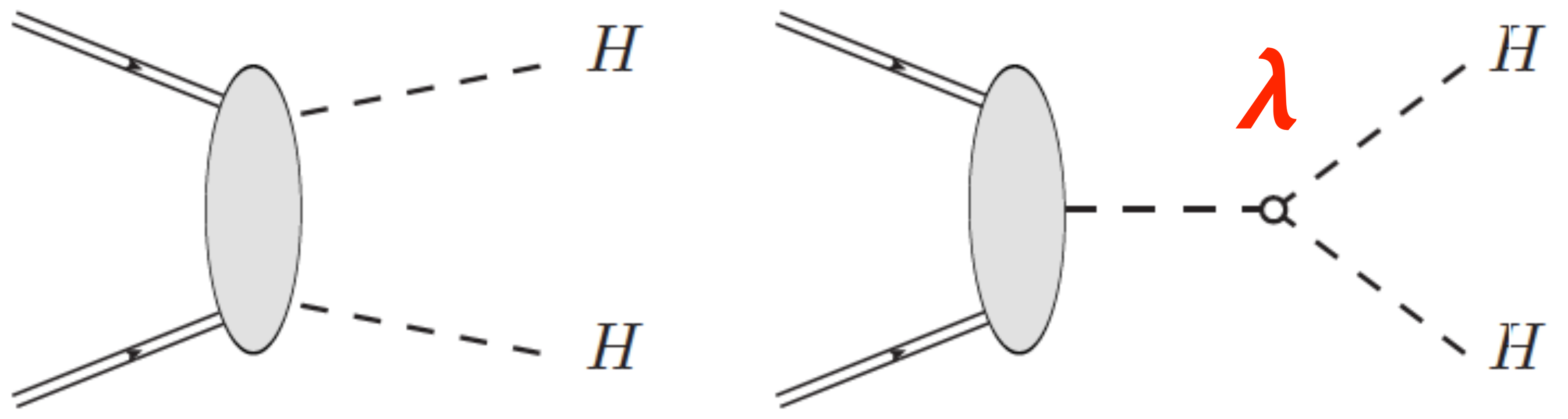
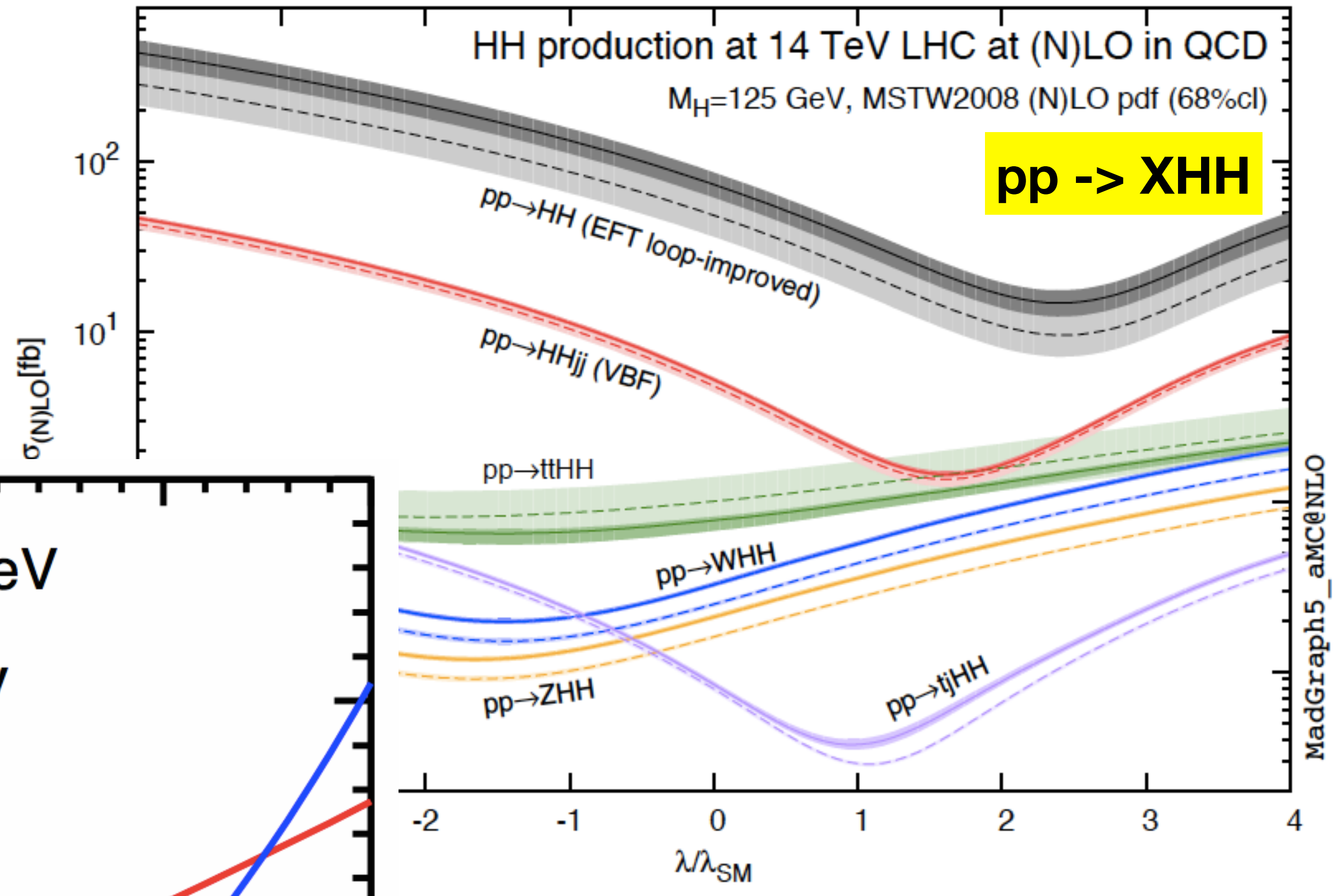
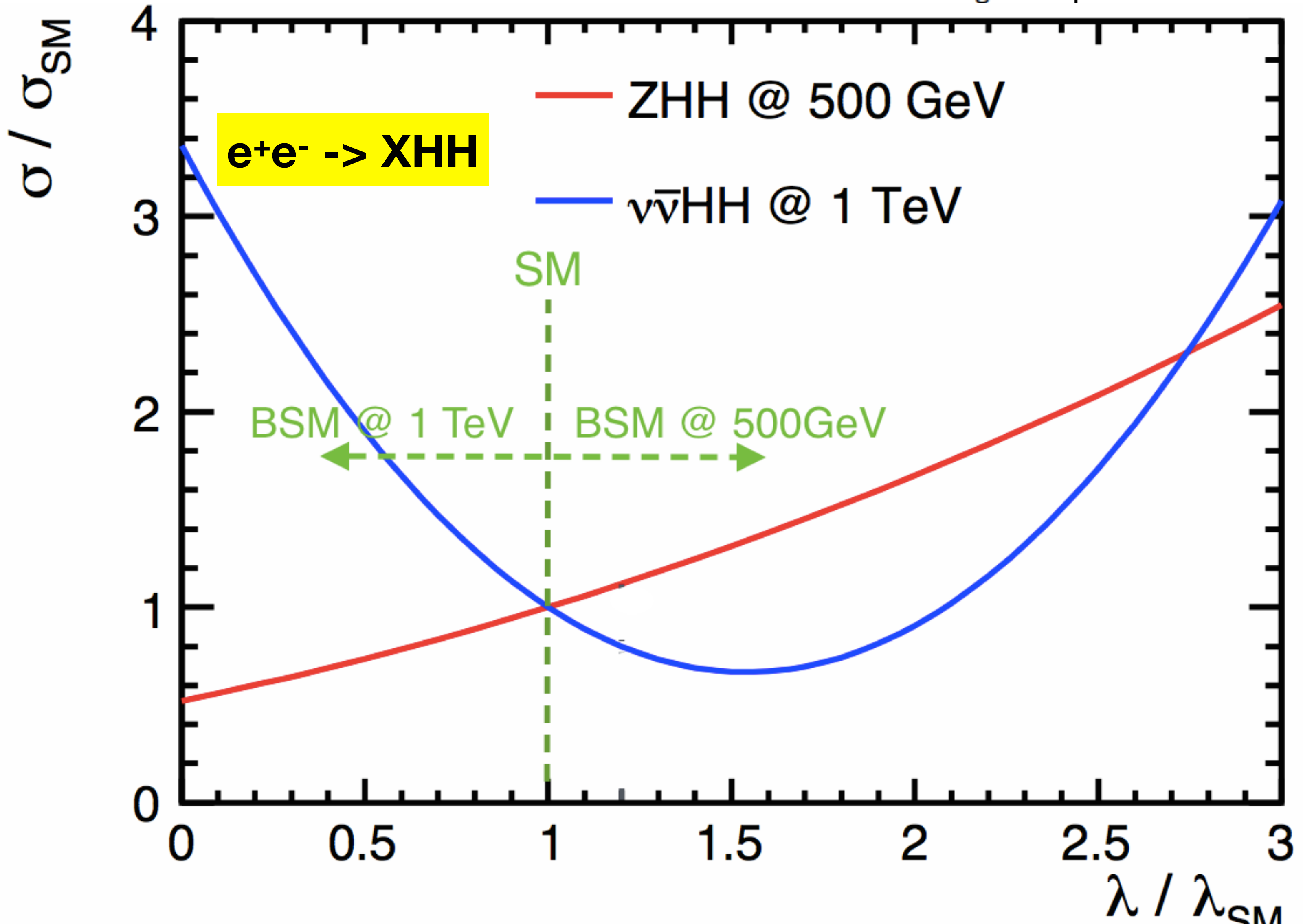
$\lambda > \lambda_{SM}$: cross section drops for fusion-type processes - in ee and in pp







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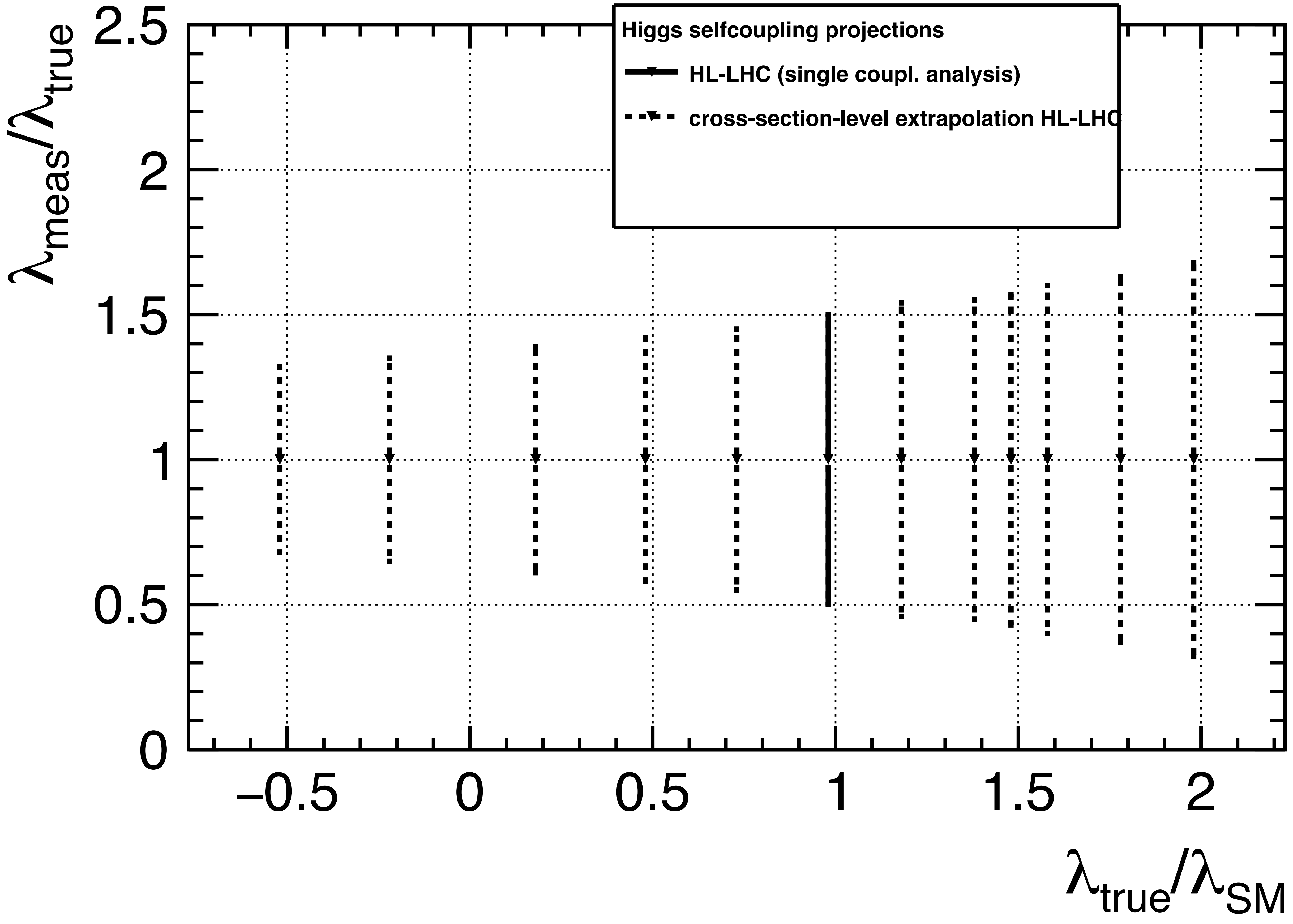
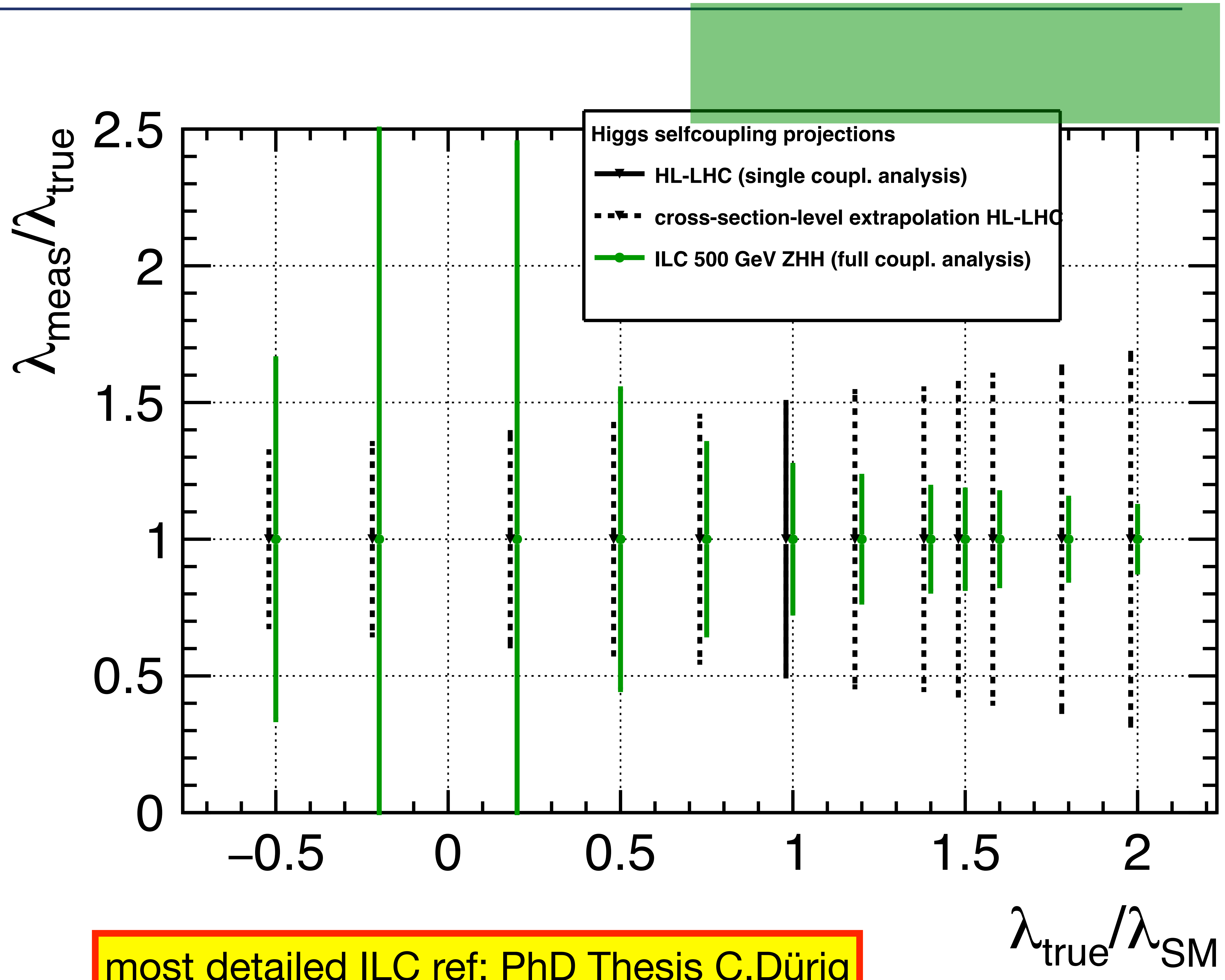


Higgs self-coupling

Region of interest for electroweak baryogenesis



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

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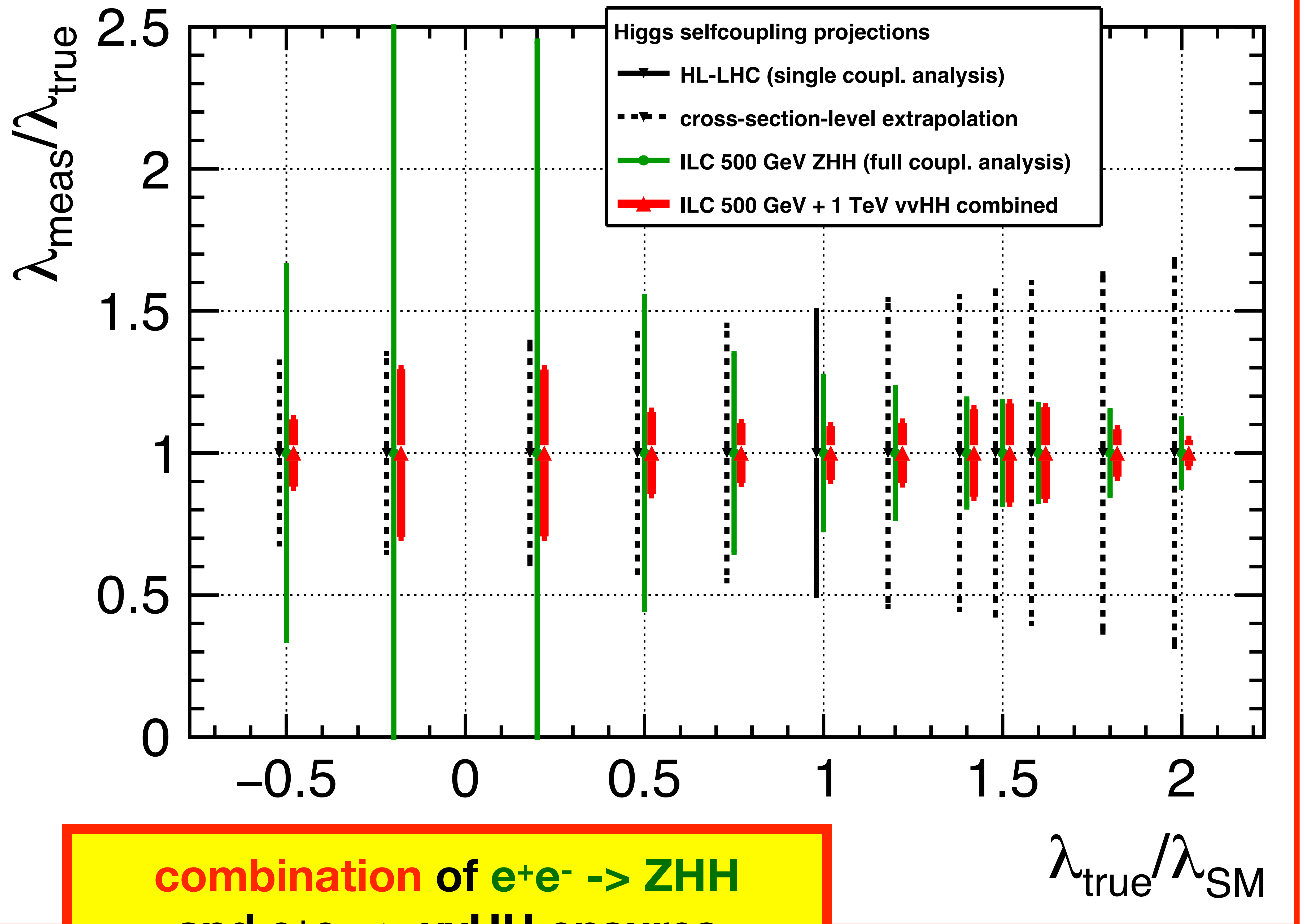
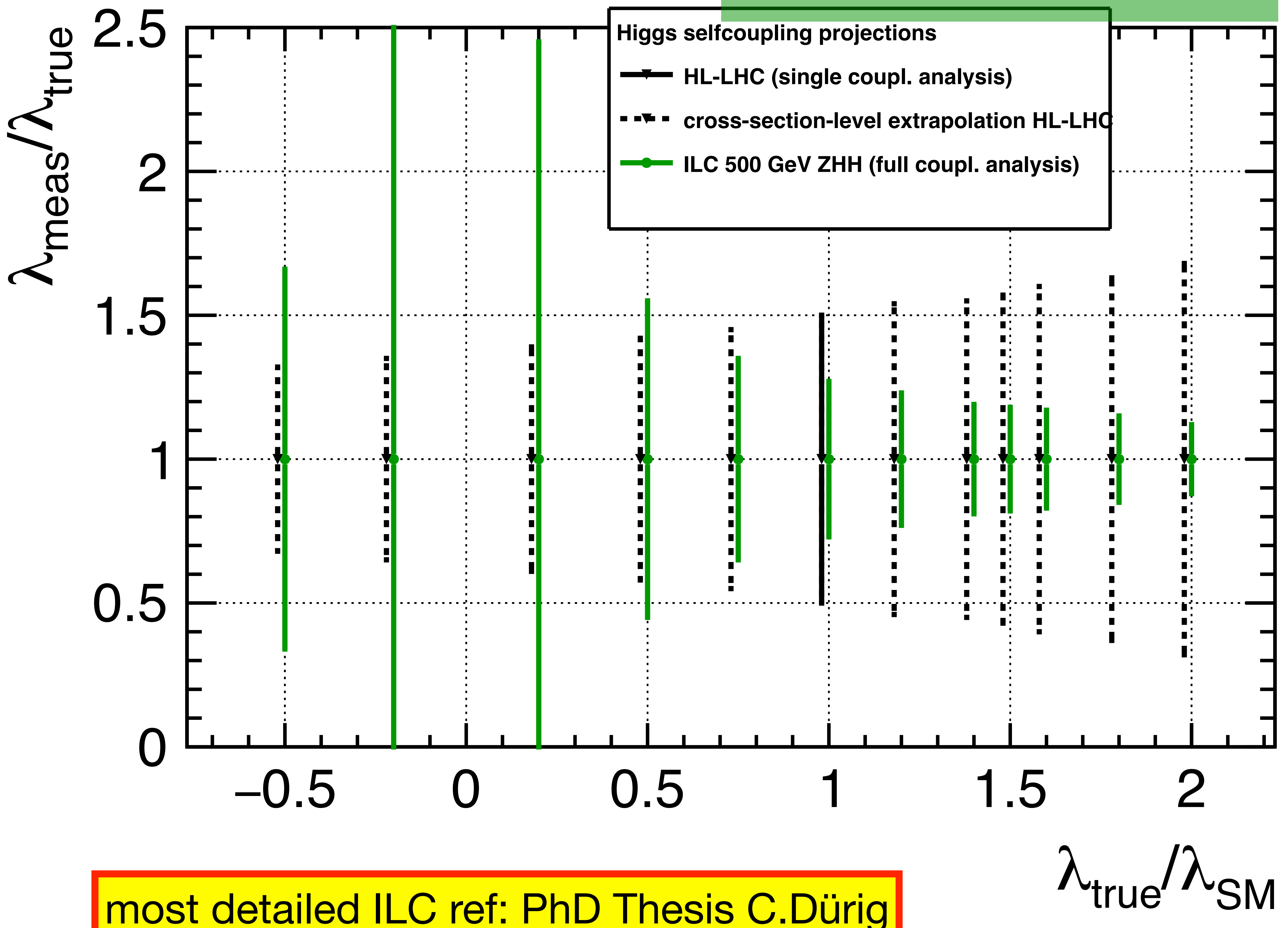


combination of e+e- -> ZHH and e+e- -> vvHH ensures at least 10-15% precision for all λ



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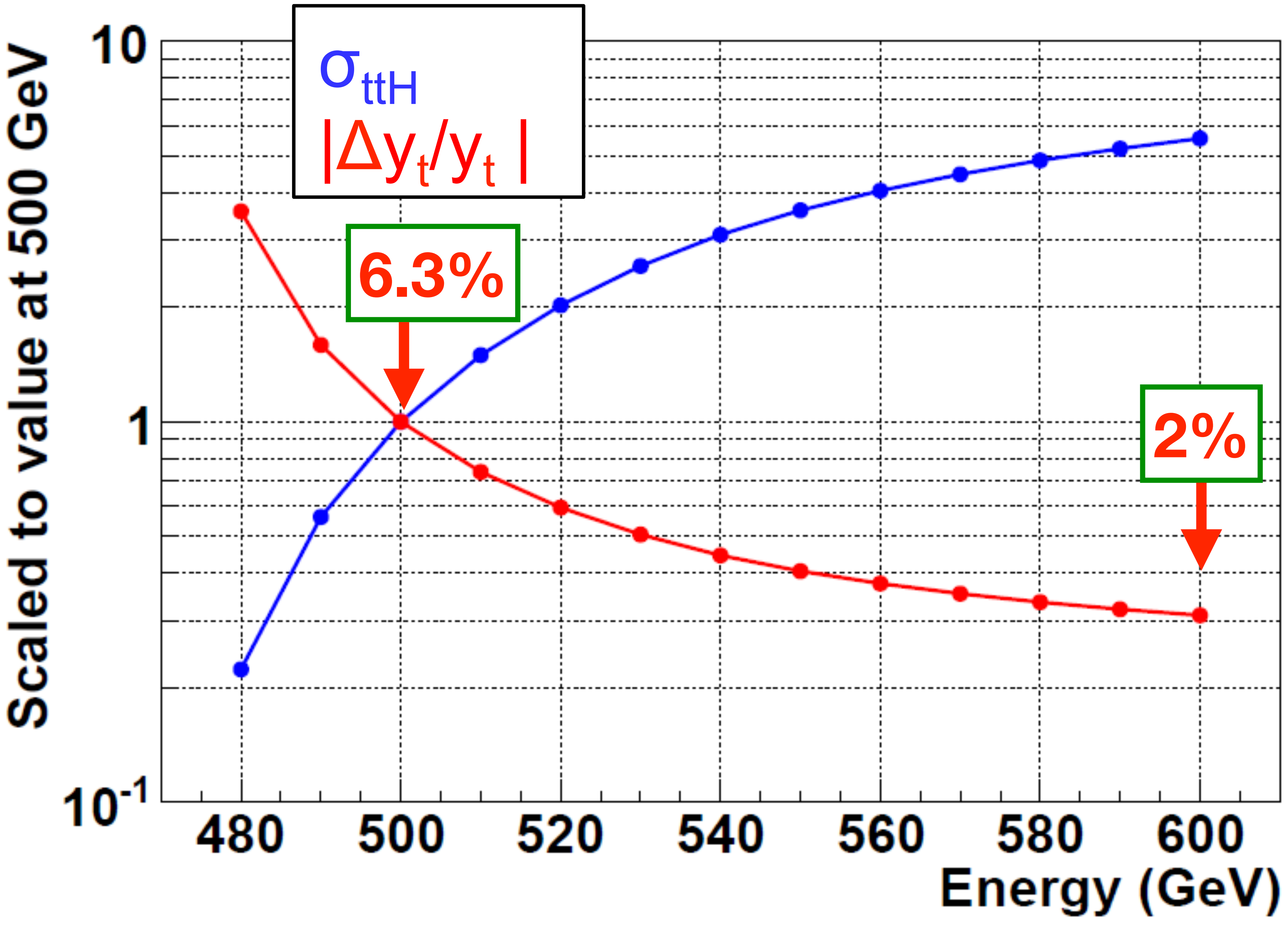
  - **HL-LHC:**
    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in $\mathrm{SMEFT_{ND}}$**
  - **ILC:**
    - current full simulation achieved **6.3% at 500 GeV**
    - ***strong dependence*** on exact choice of E_{CM}, e.g. **2% at 600 GeV**
    - *not* included:
      - experimental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

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



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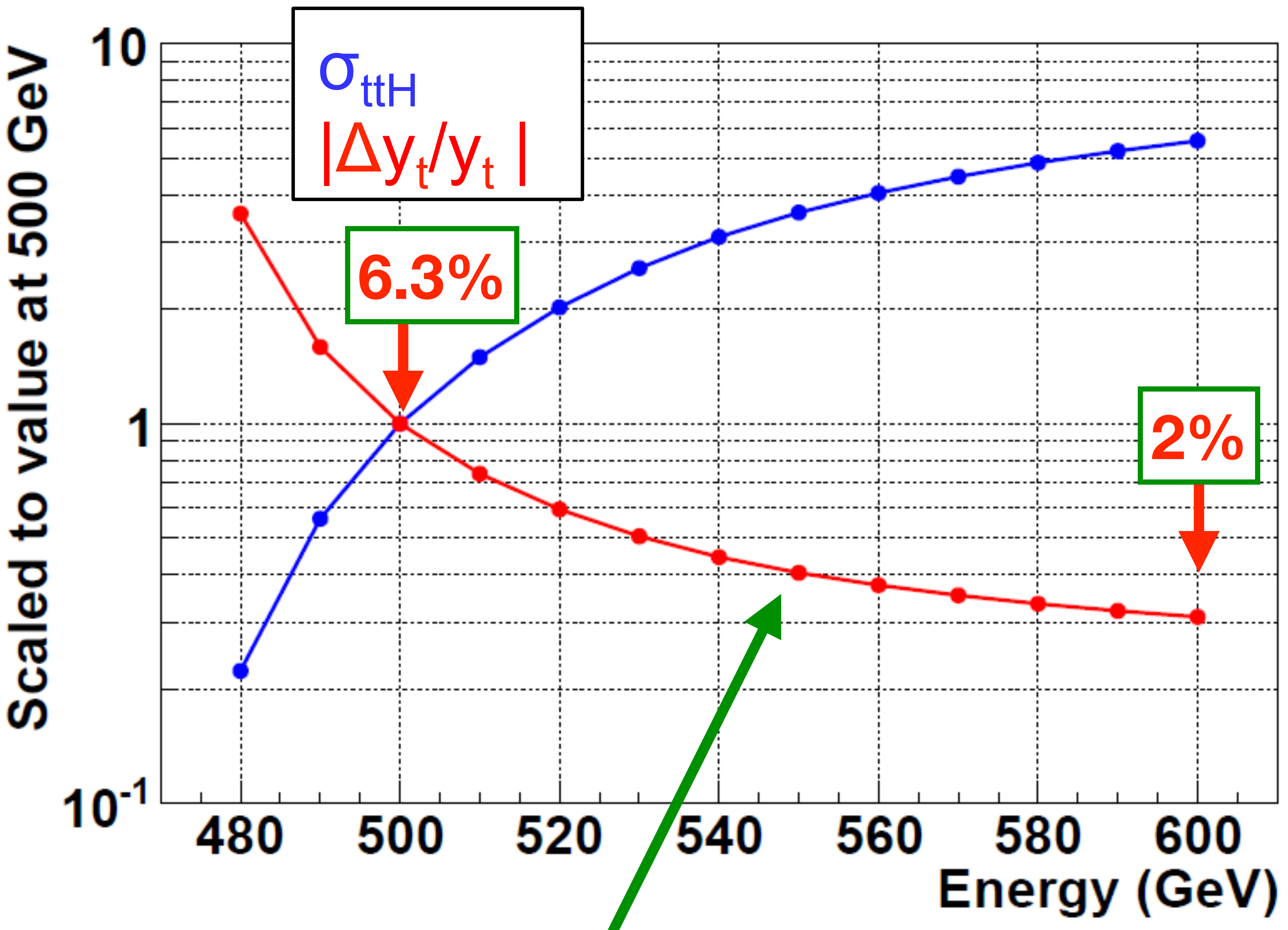

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NOTE: ILC's 500 GeV stems from before Higgs discovery
-> actual energy of 2nd stage to be determined!

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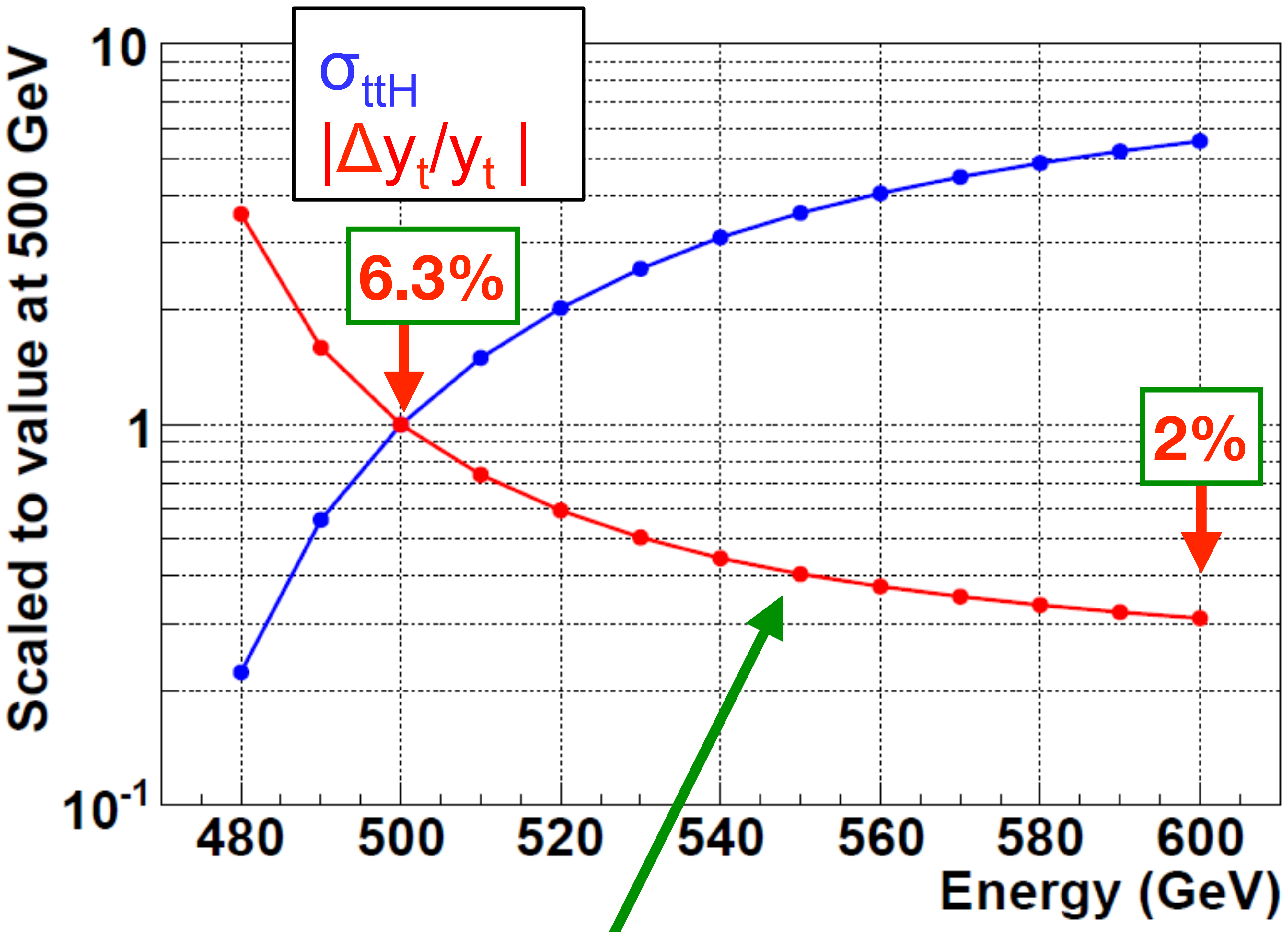

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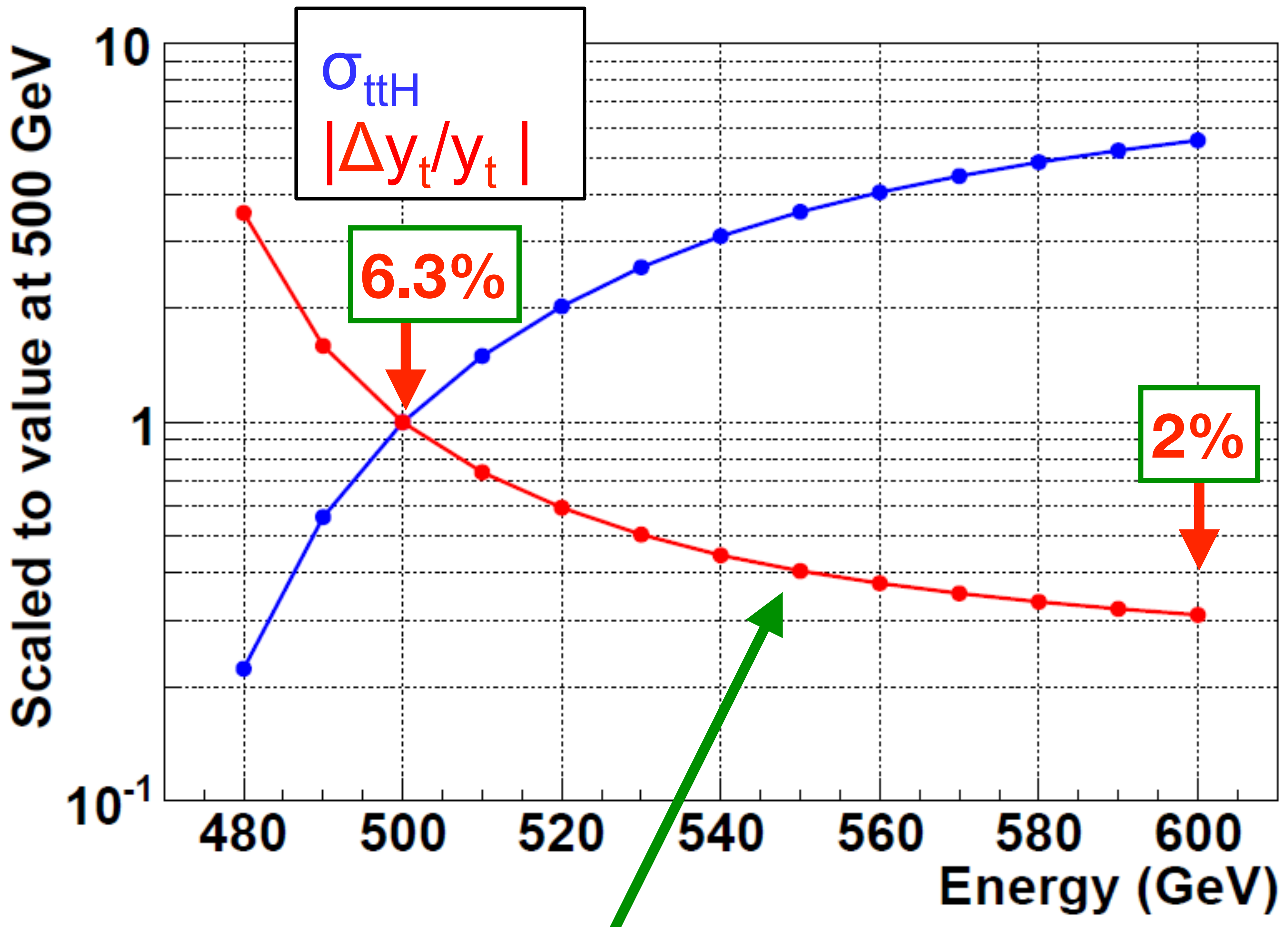
      - other channels than H->bb

- **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]



+ 1 TeV: 1.4%

C³ proposes 550 GeV

Looking for more new friends

Discoveries of new particles ?

Opportunities for direct discoveries ?

250 GeV only marginally more than 209 GeV - nothing to expect?

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- **MSSM**: most general limit (any mixing, any mass difference to LSP) on **staus** is as low as 26.3 GeV
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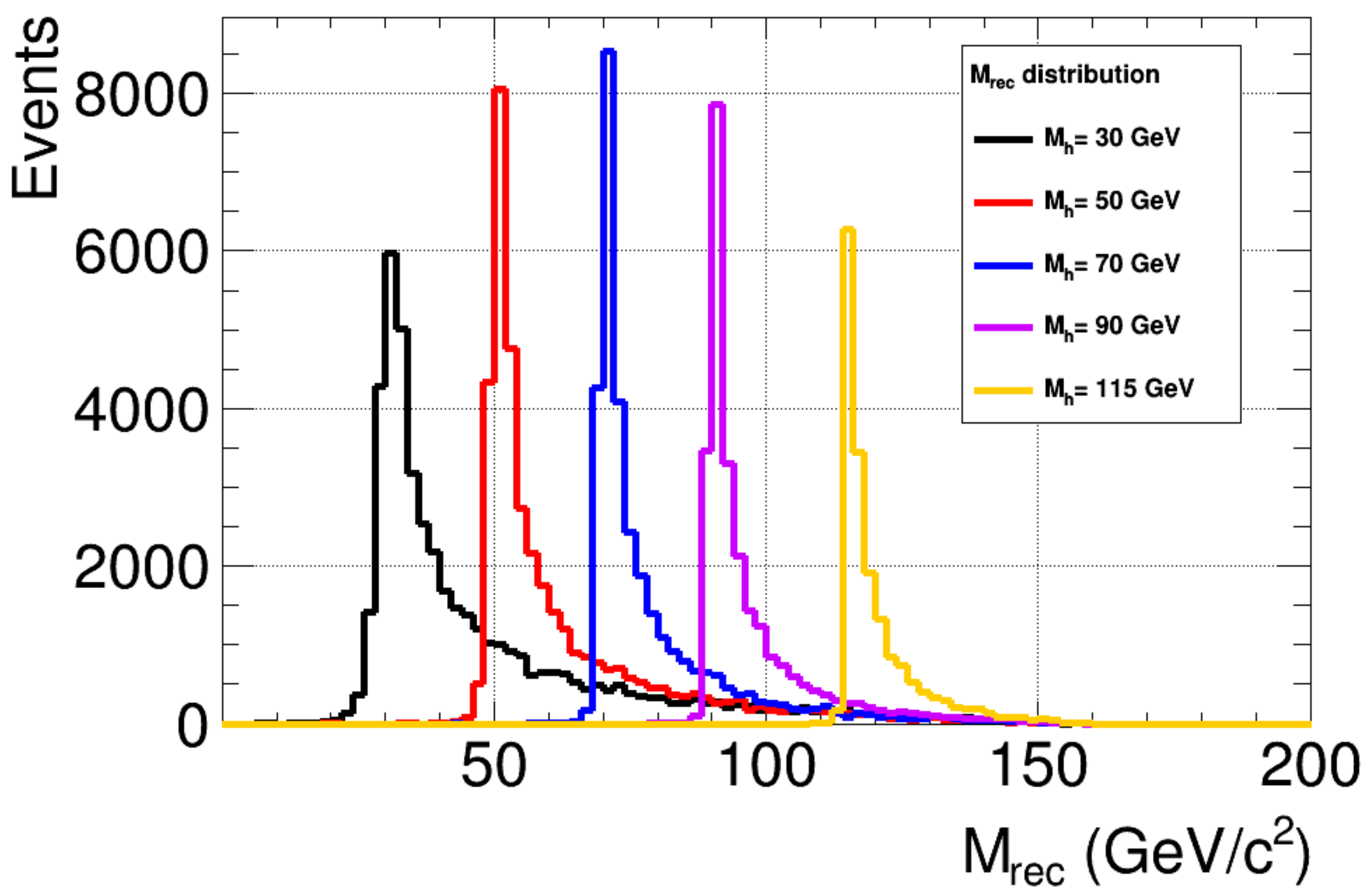
=> any search channel *limited by rate* at LEP2 will explore new territory at ILC250 !

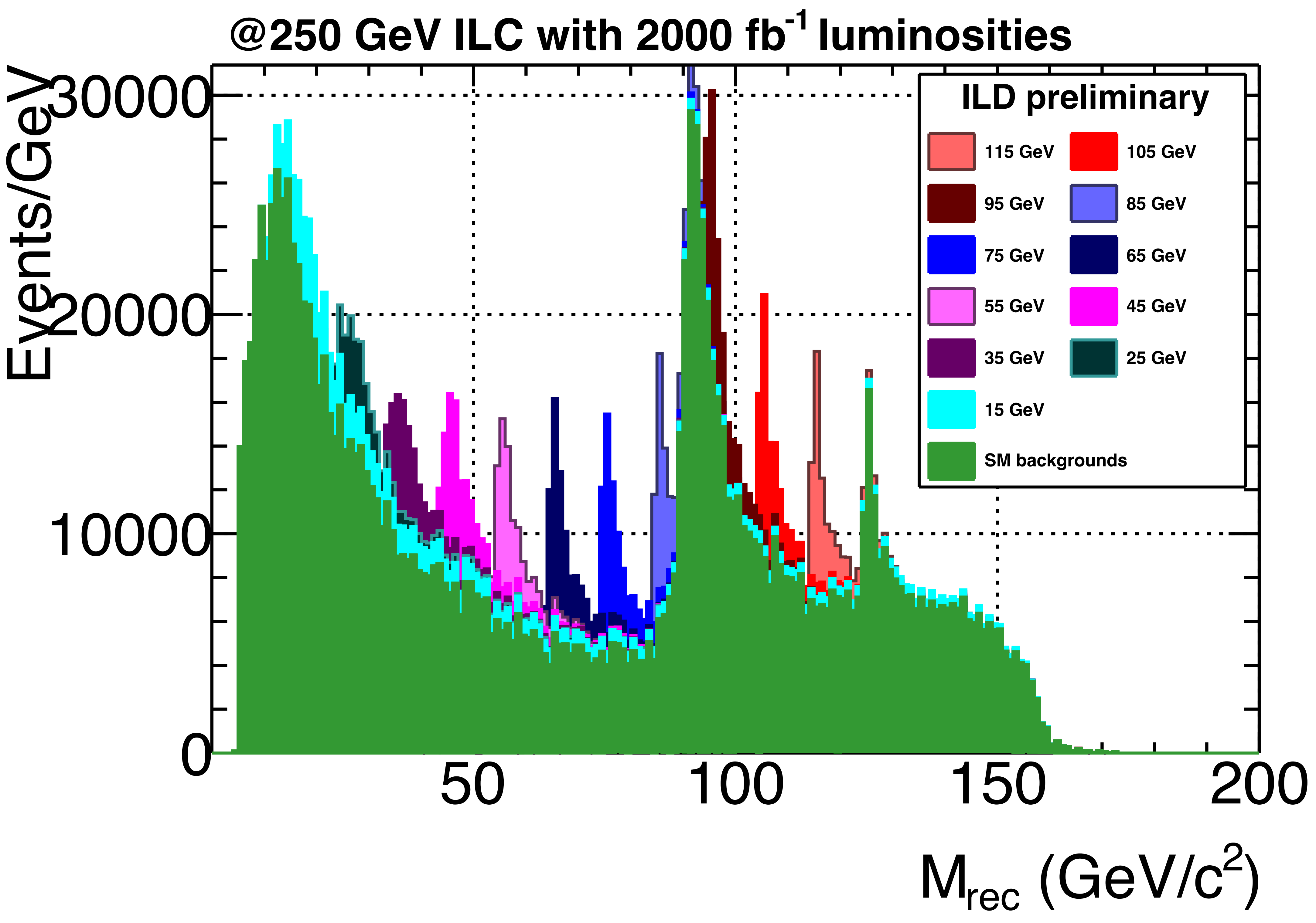
Extra Higgs Bosons

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

- 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!





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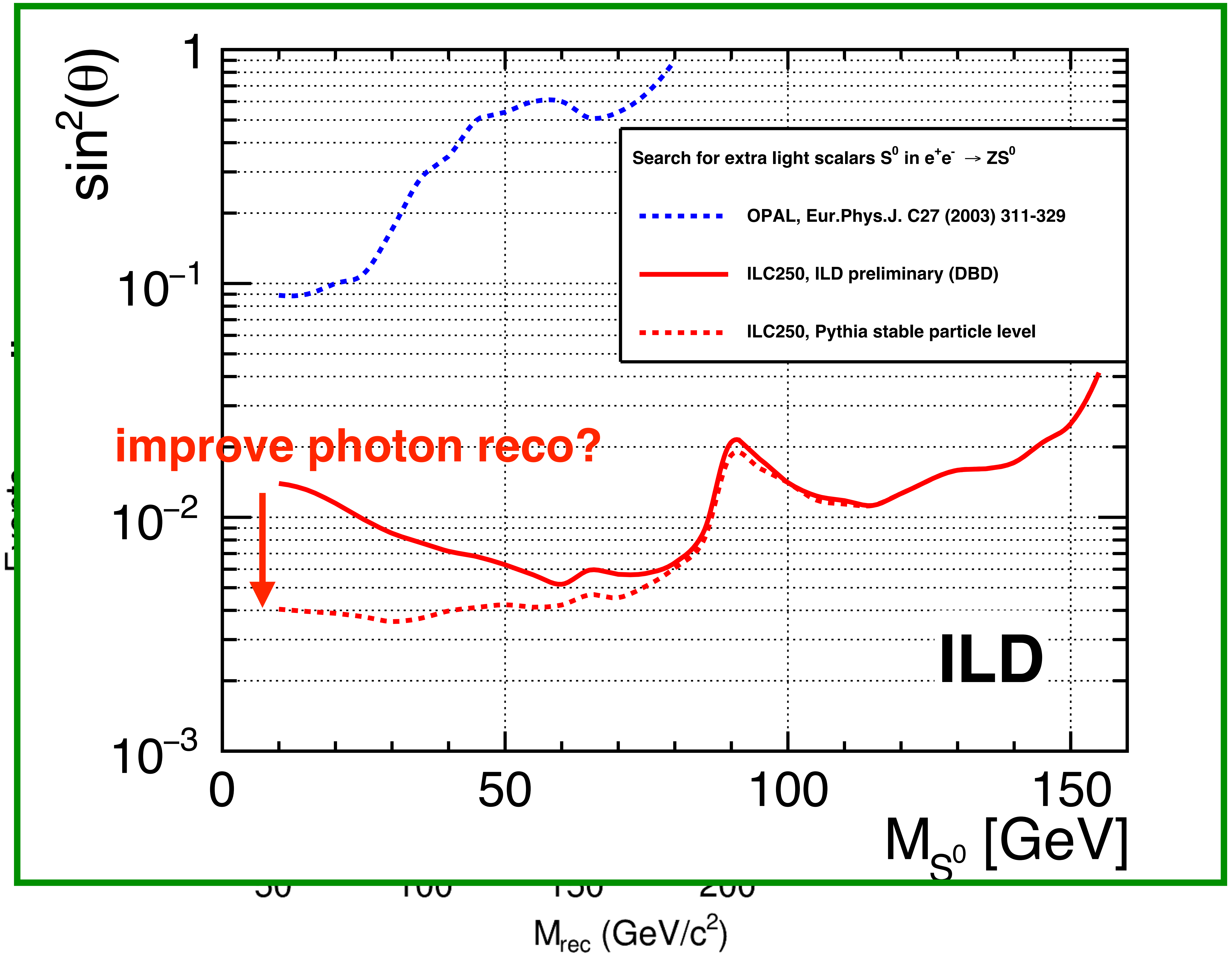

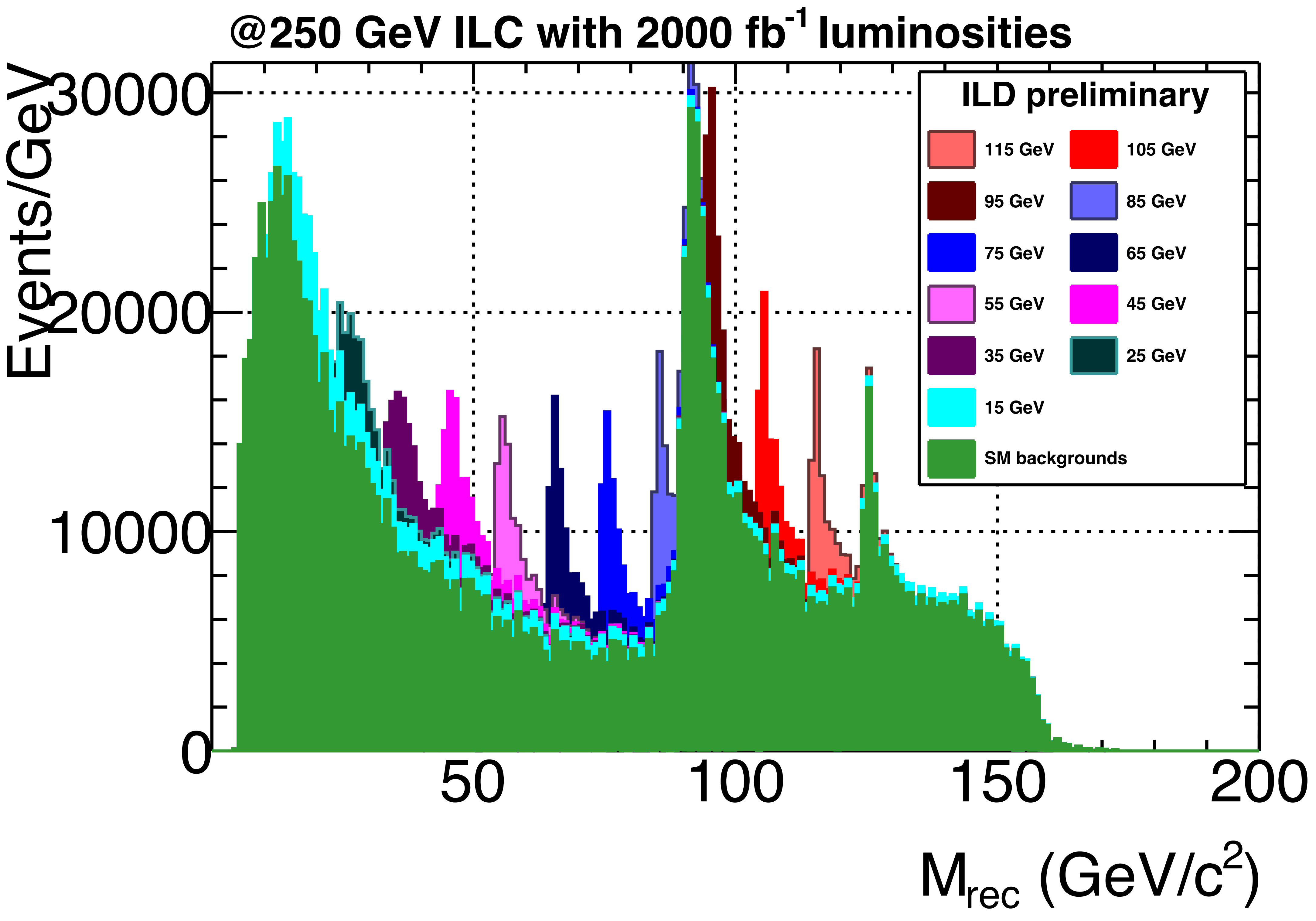

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Loop-hole free searches for BSM particles
up to **E$_{CM}$**/2 or up to **E$_{CM}$** - (M_Z / M_H / M_{LSP} / …)

- **lowish ΔM is THE region preferred by data**
  - **charginos, neutralinos, selectrons, smuons, staus**
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- **long and diverse decay chains (small BRs)**
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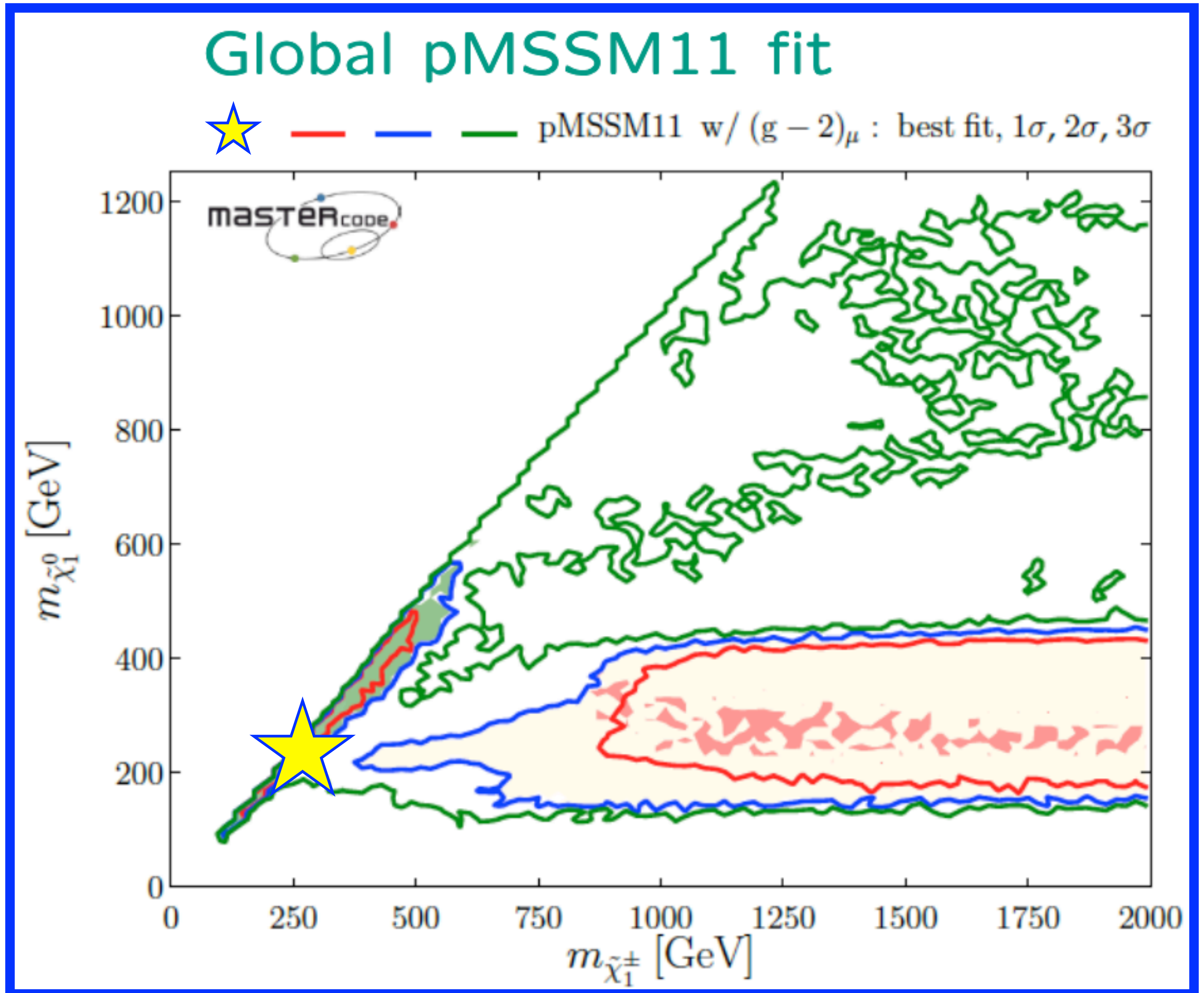

Eur.Phys.J. C78 (2018) no.3, 256

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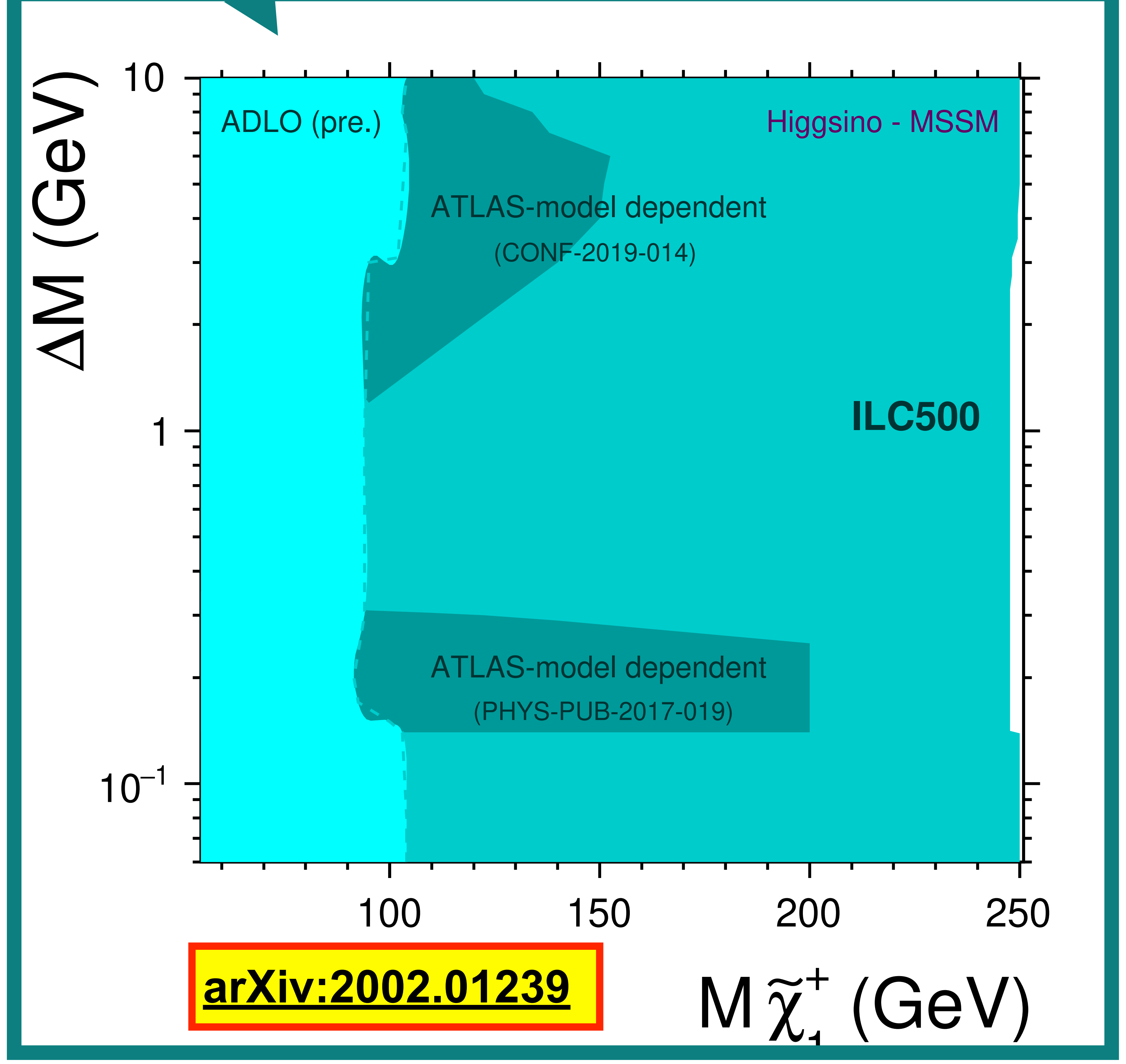
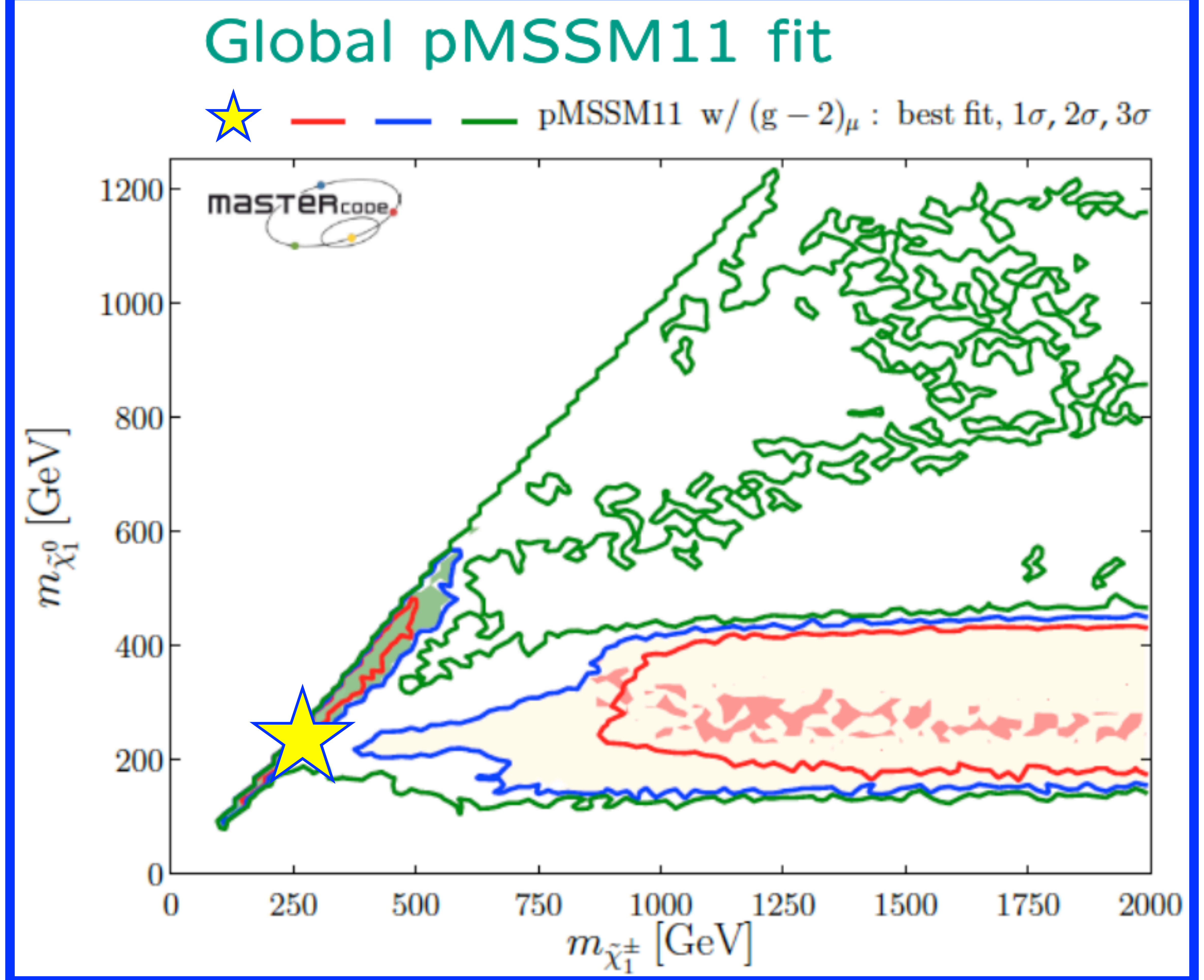


arXiv:2002.01239



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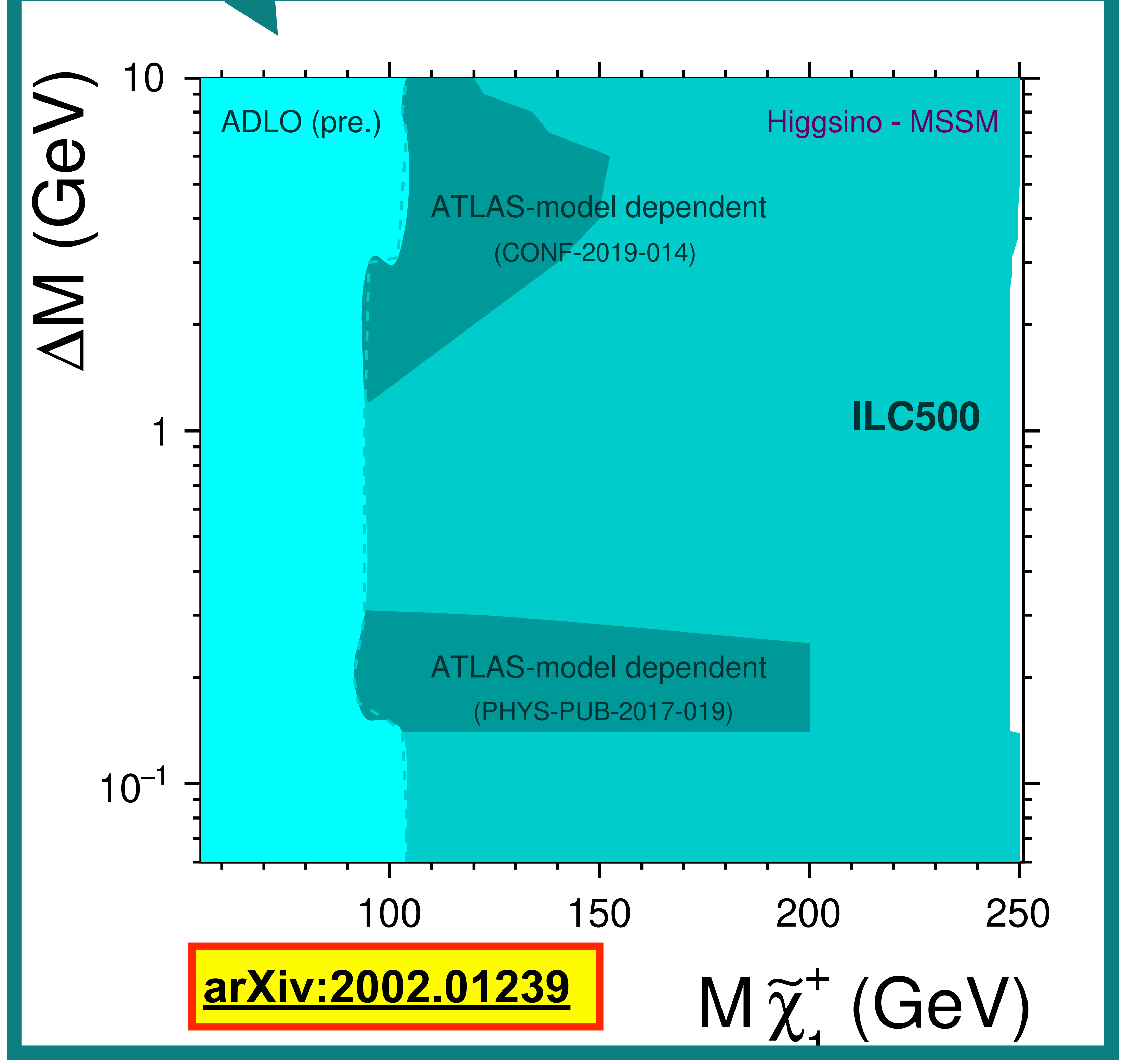

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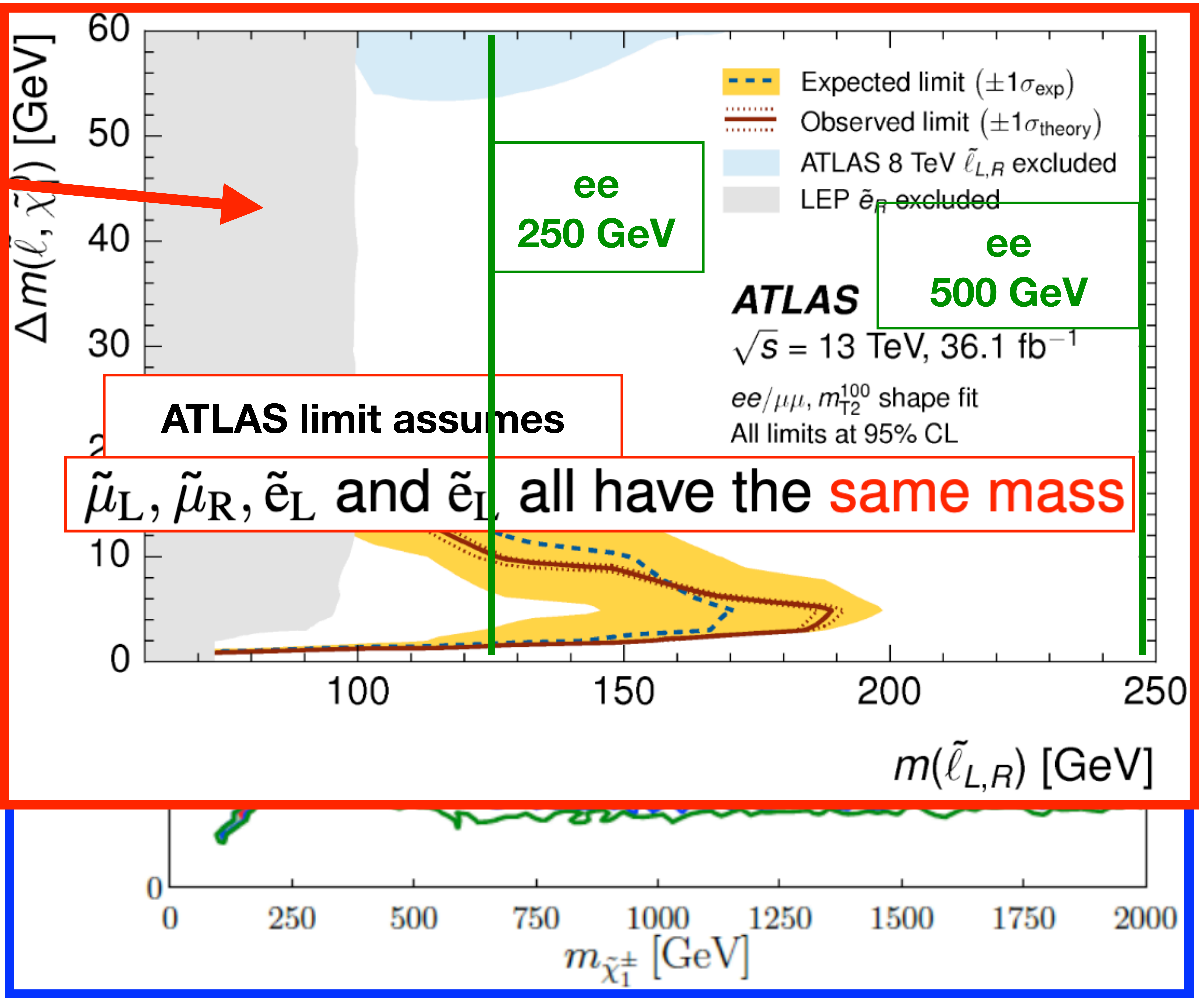

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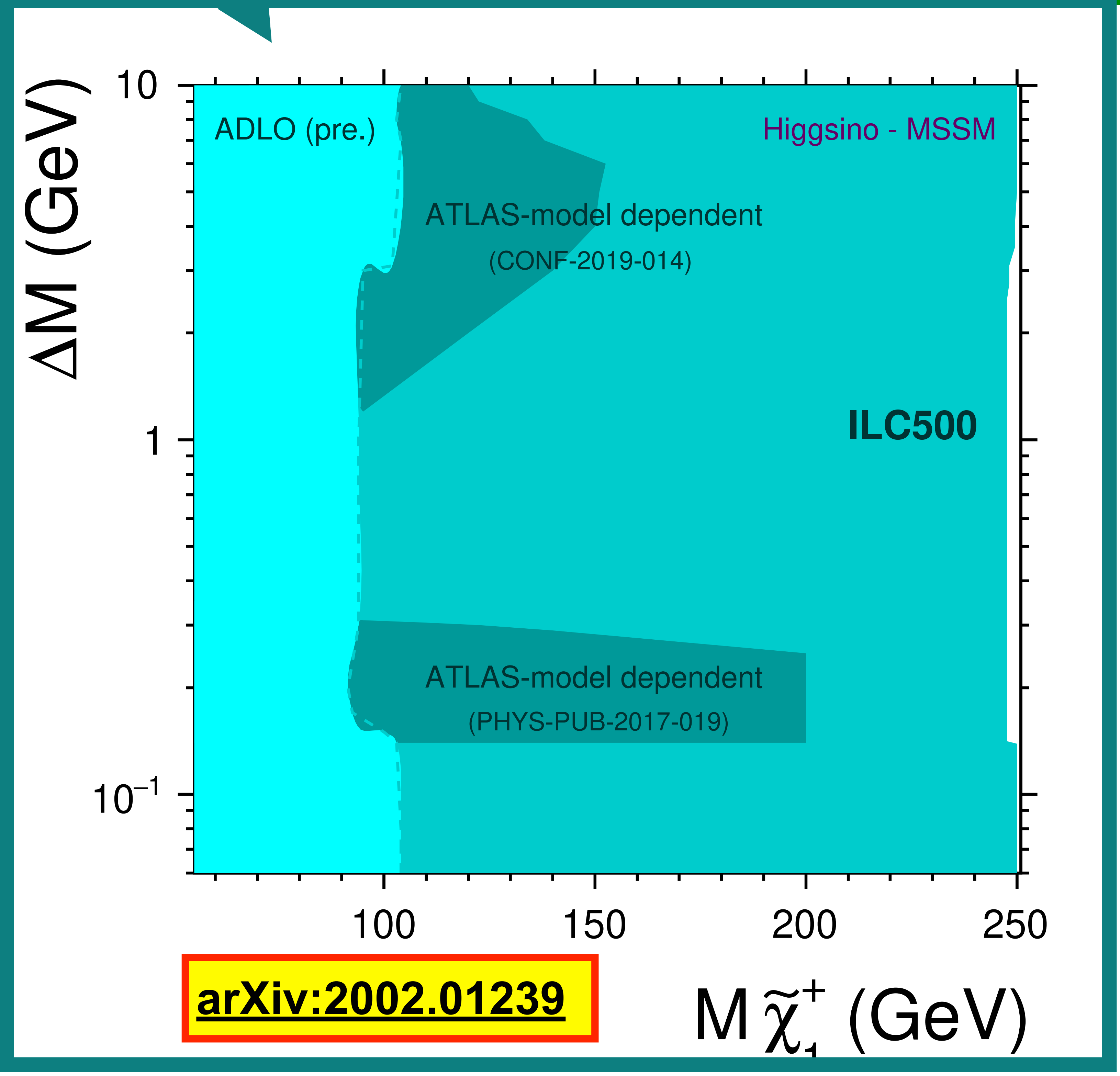

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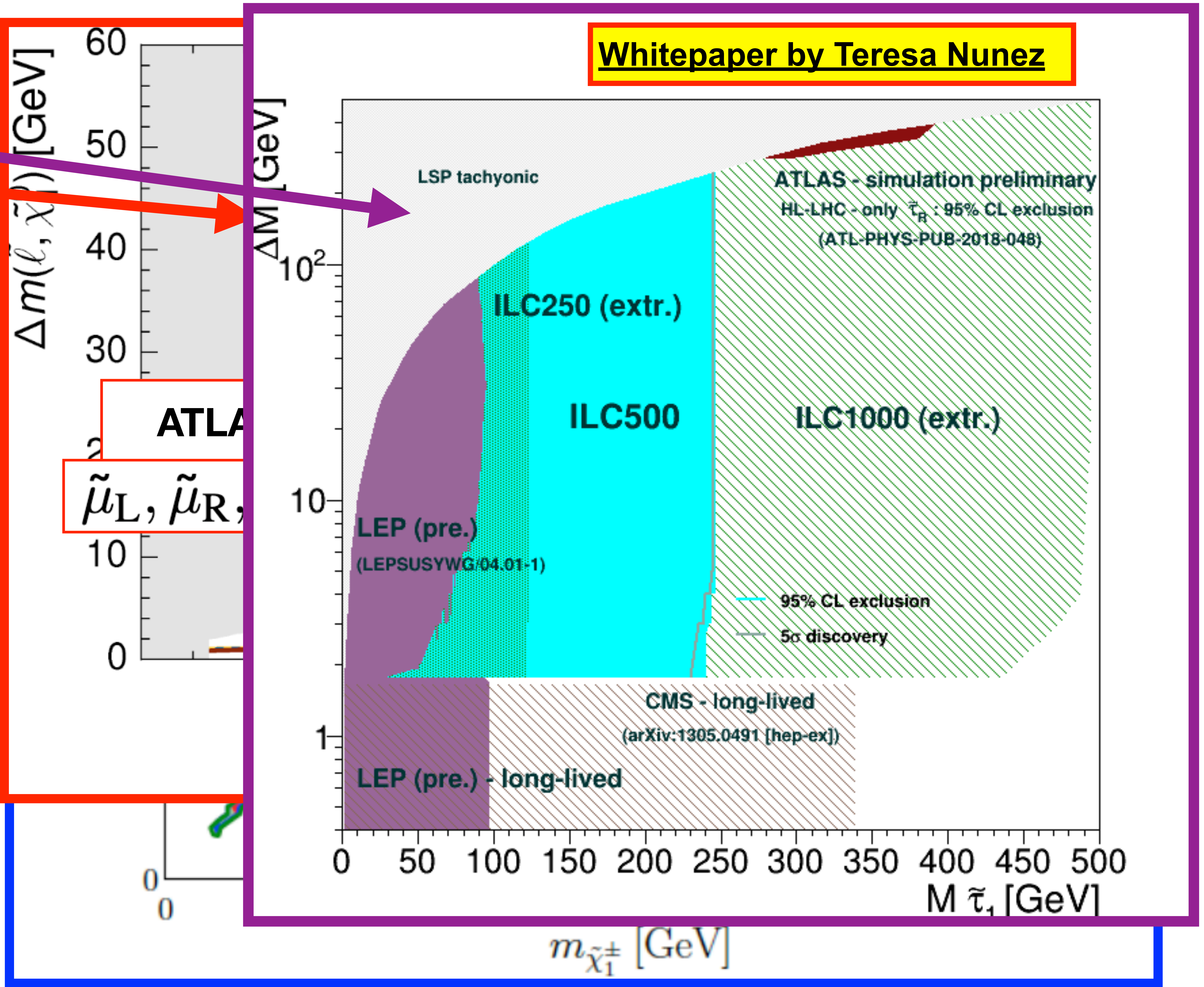

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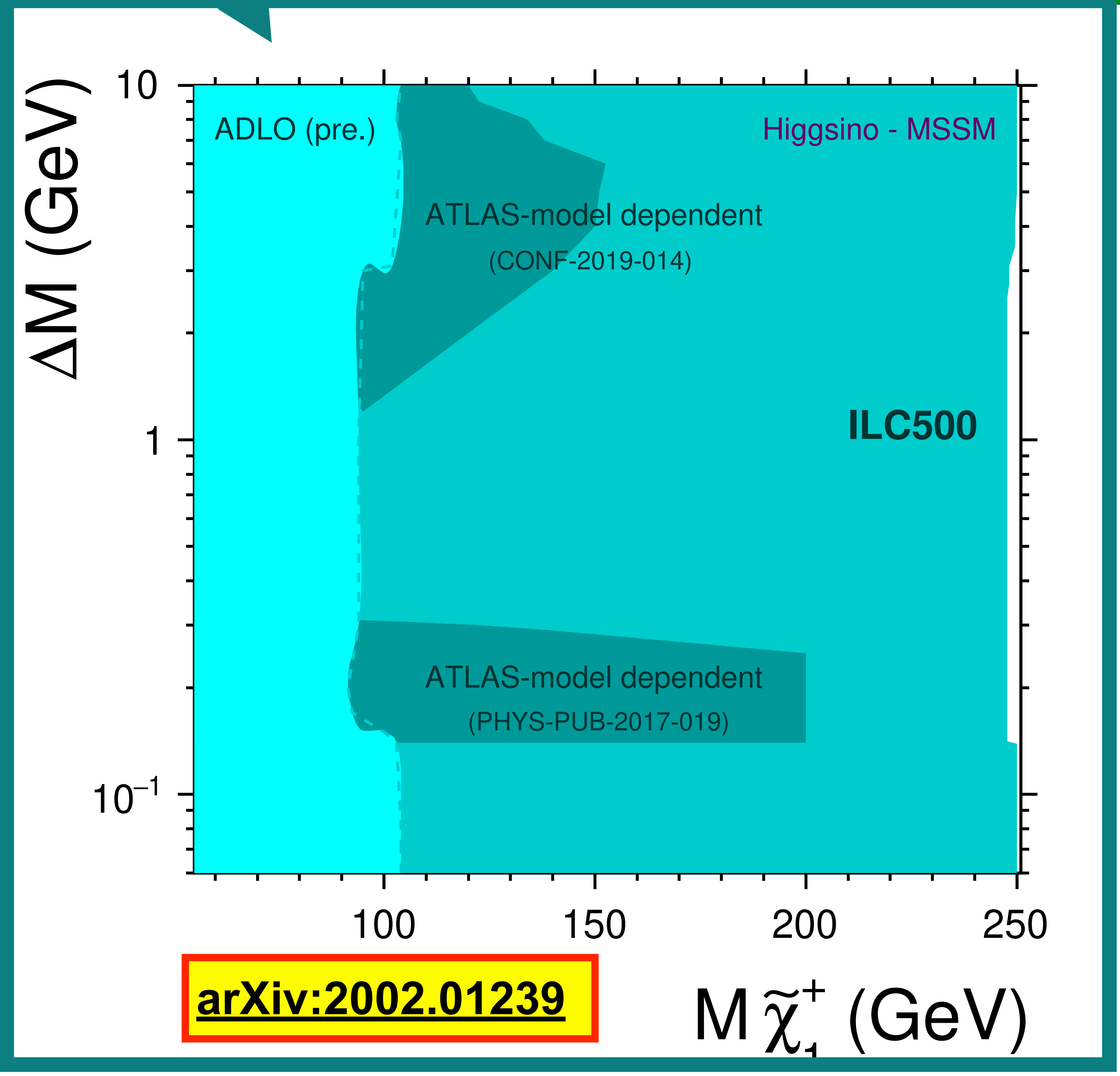

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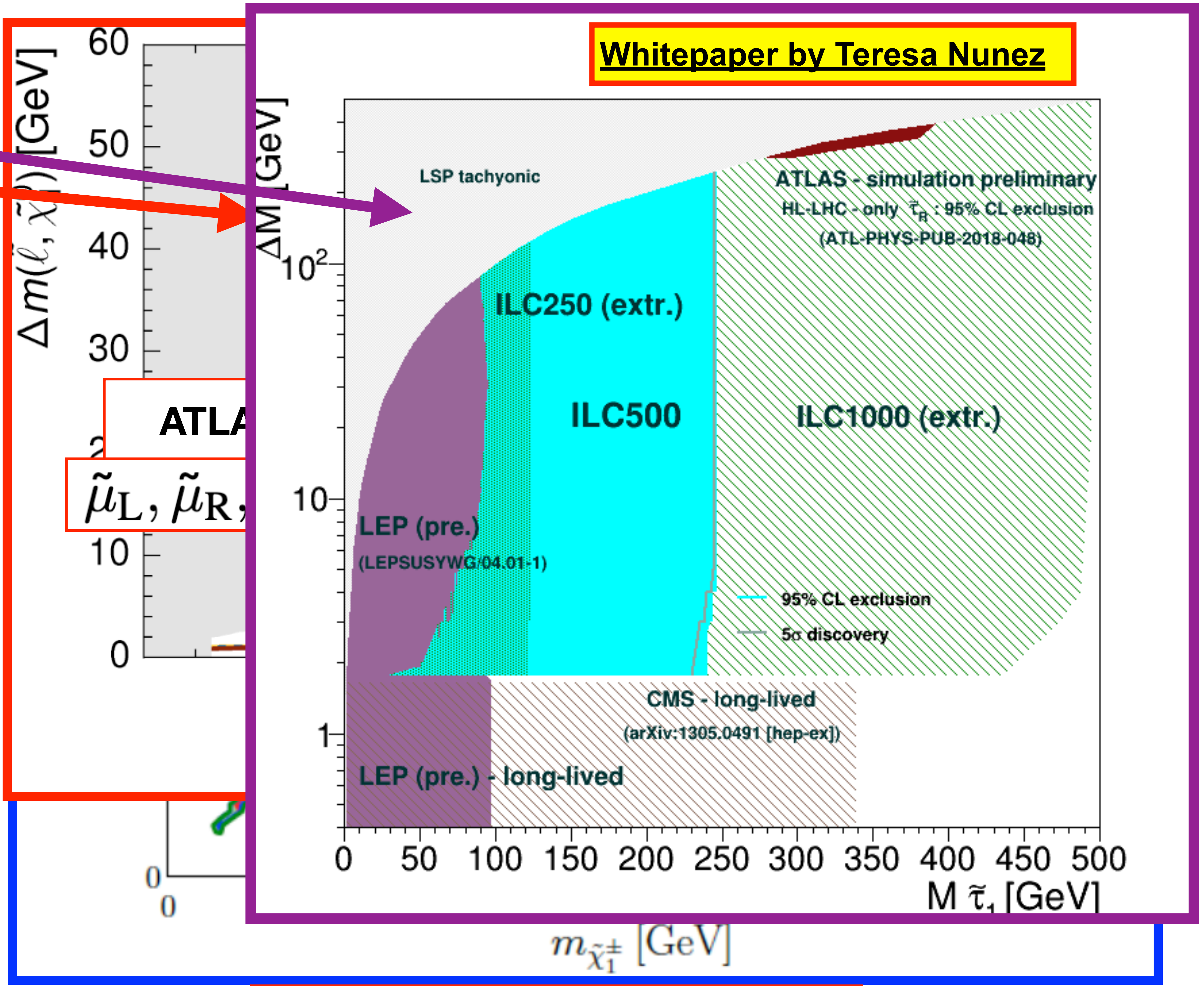

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cf also talk by Michael Peskin on Monday

Polarisation & Beyond the SM: Dark Matter

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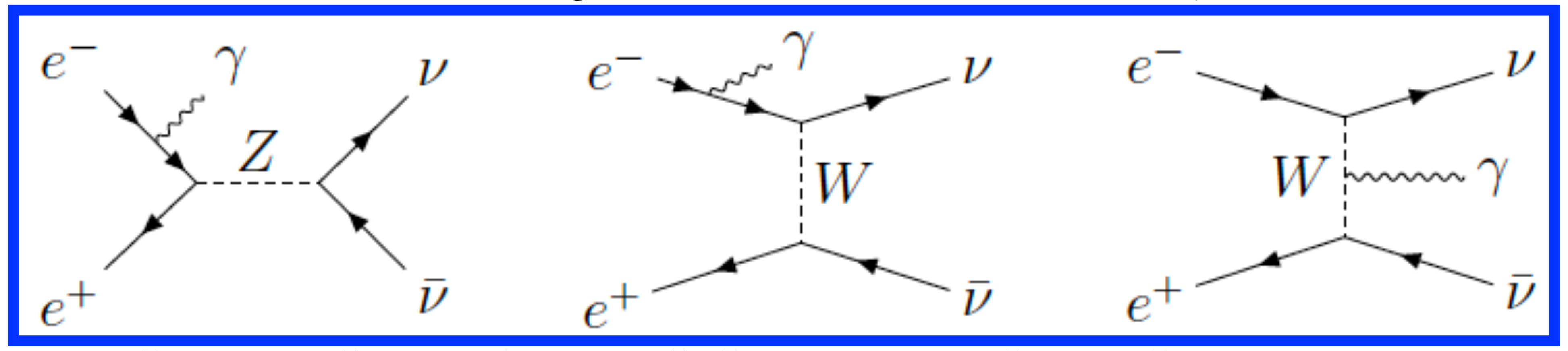
- main SM background: $e^+e^- \to \nu\nu\gamma$



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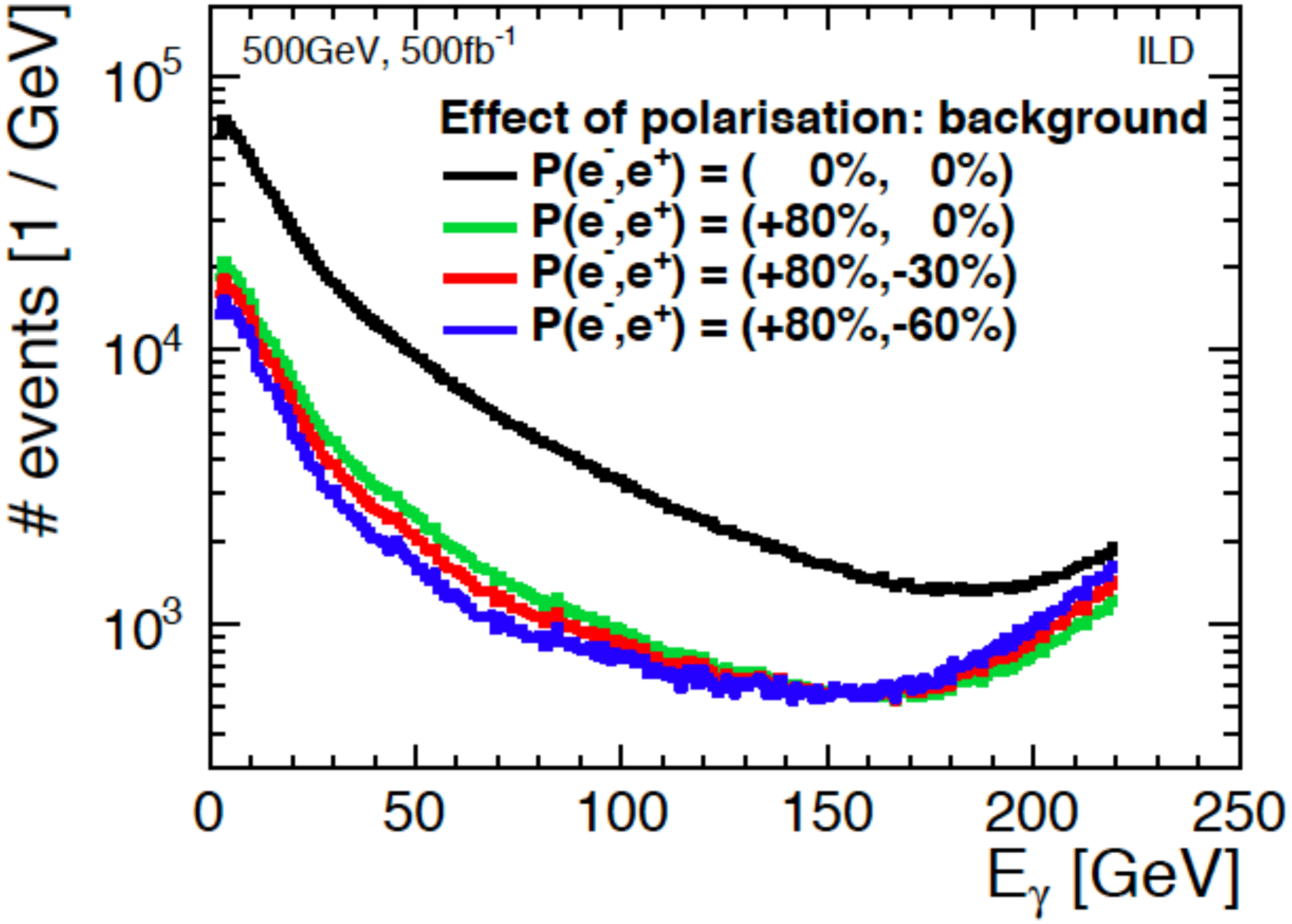
- **200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised**



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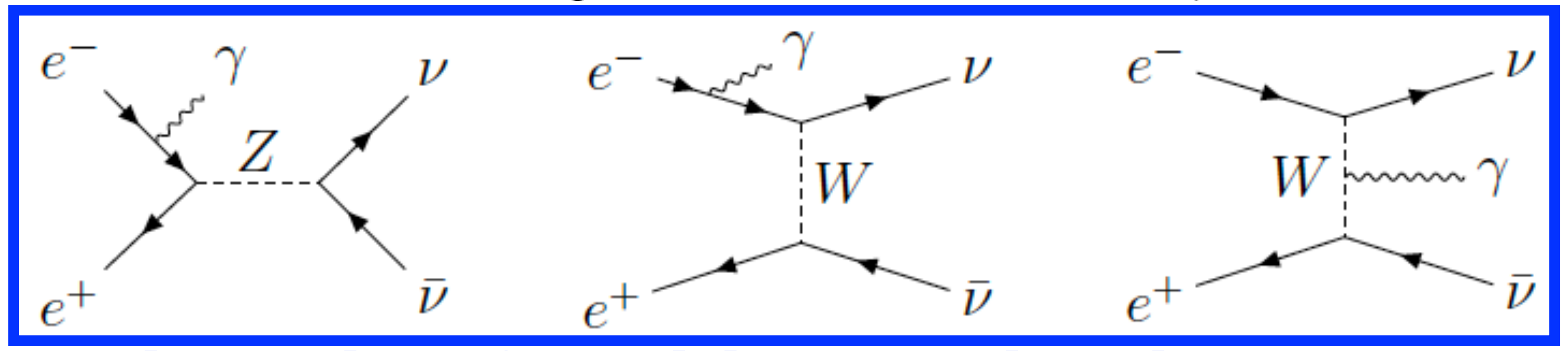

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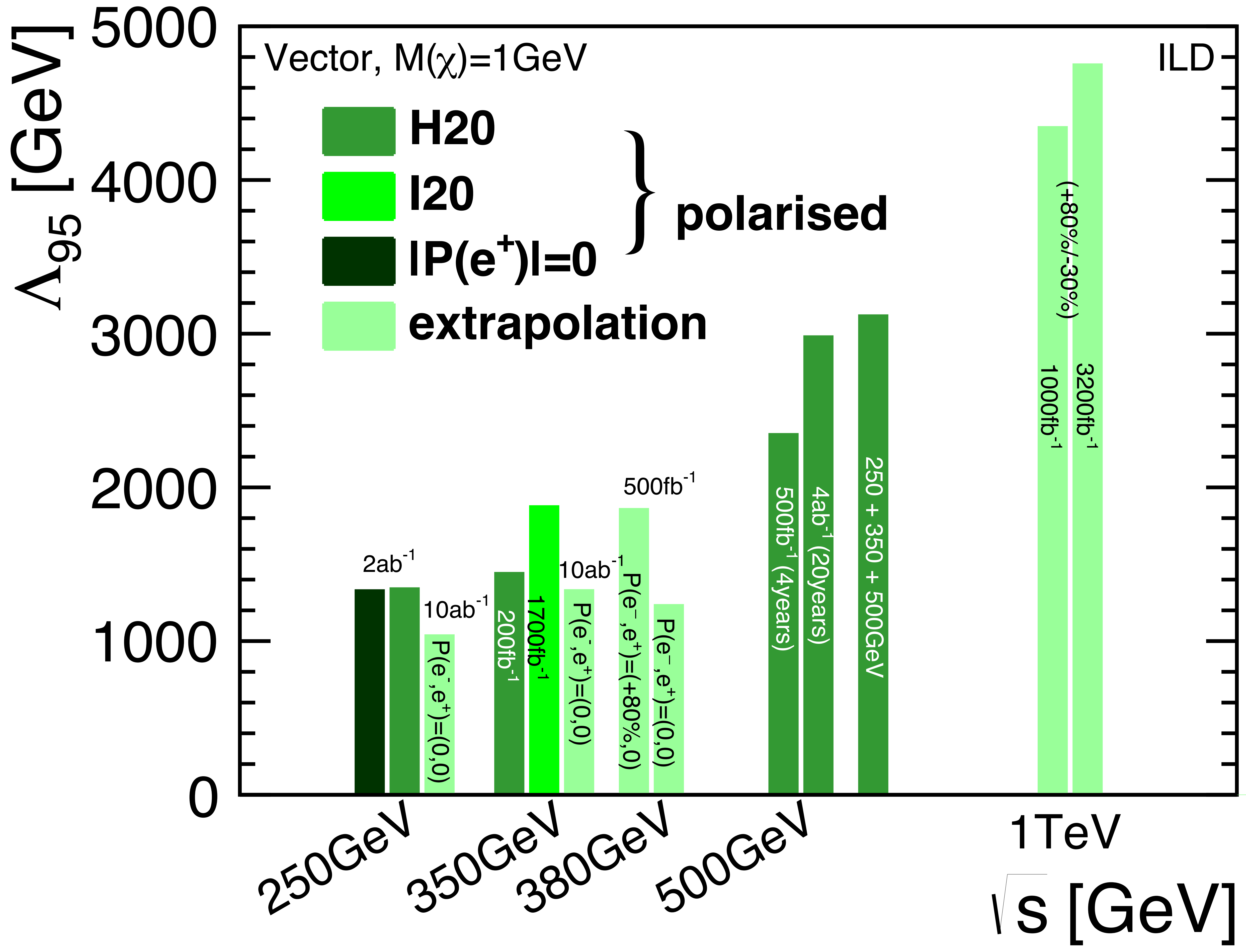
Phys. Rev. D 101 (2020) 7



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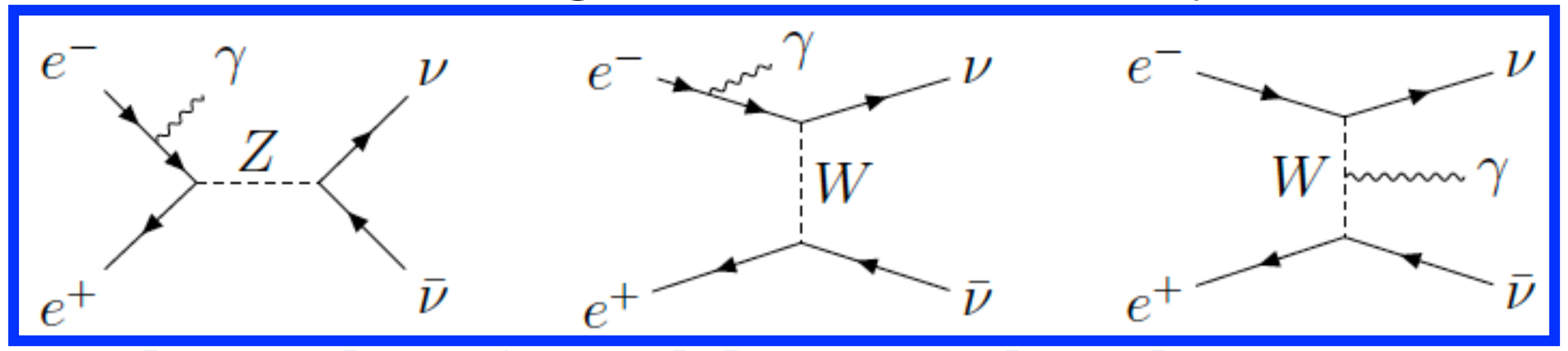

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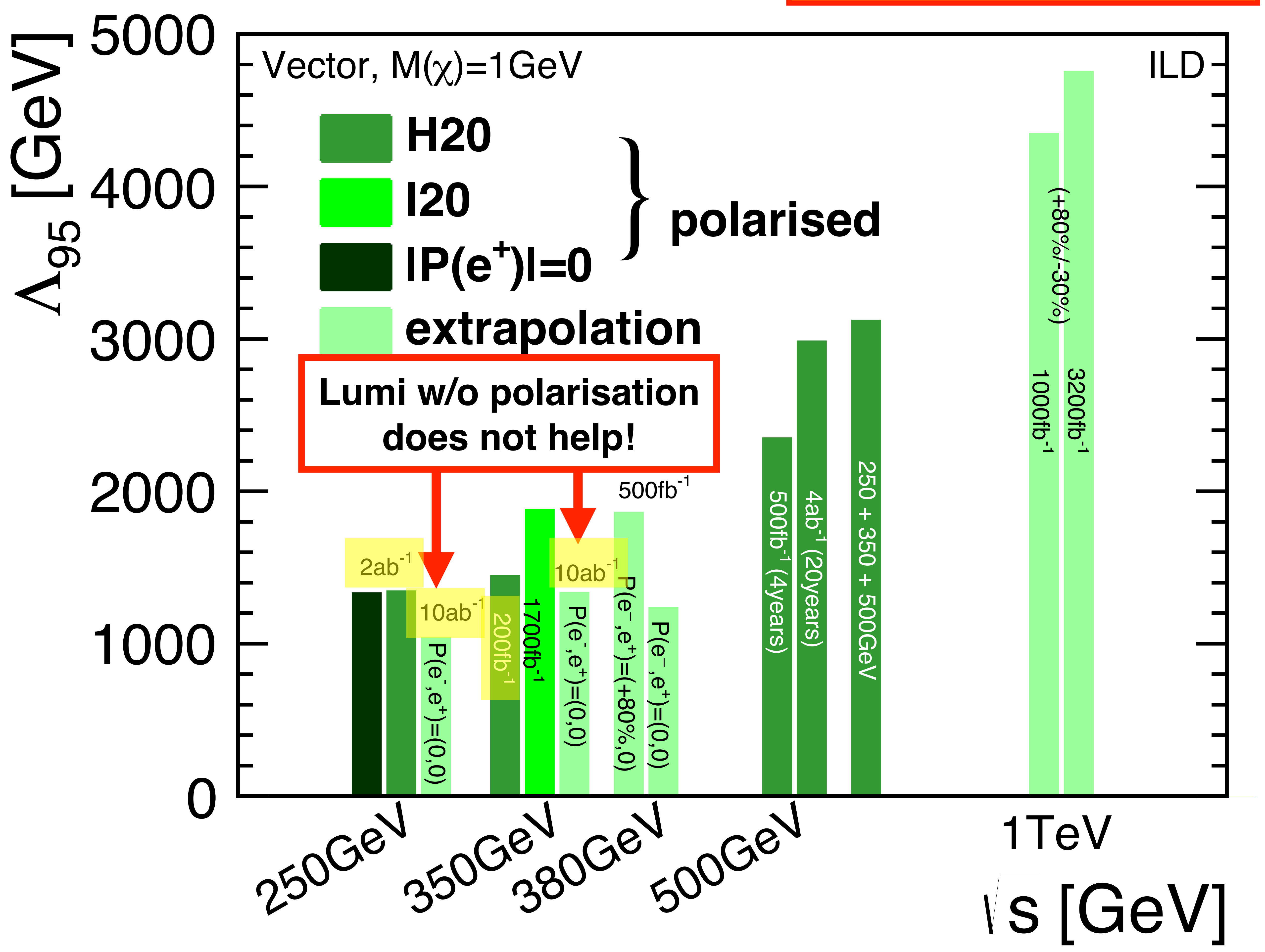

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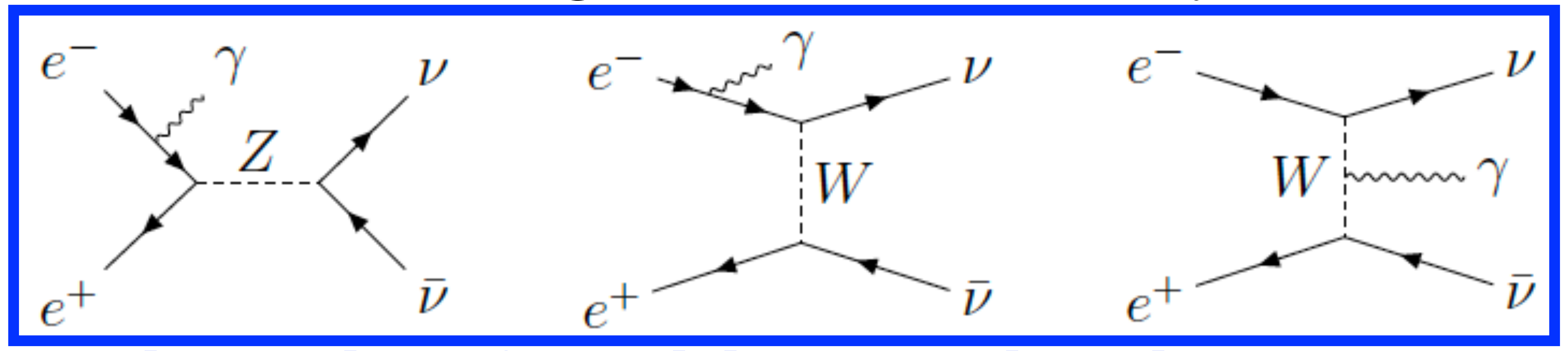

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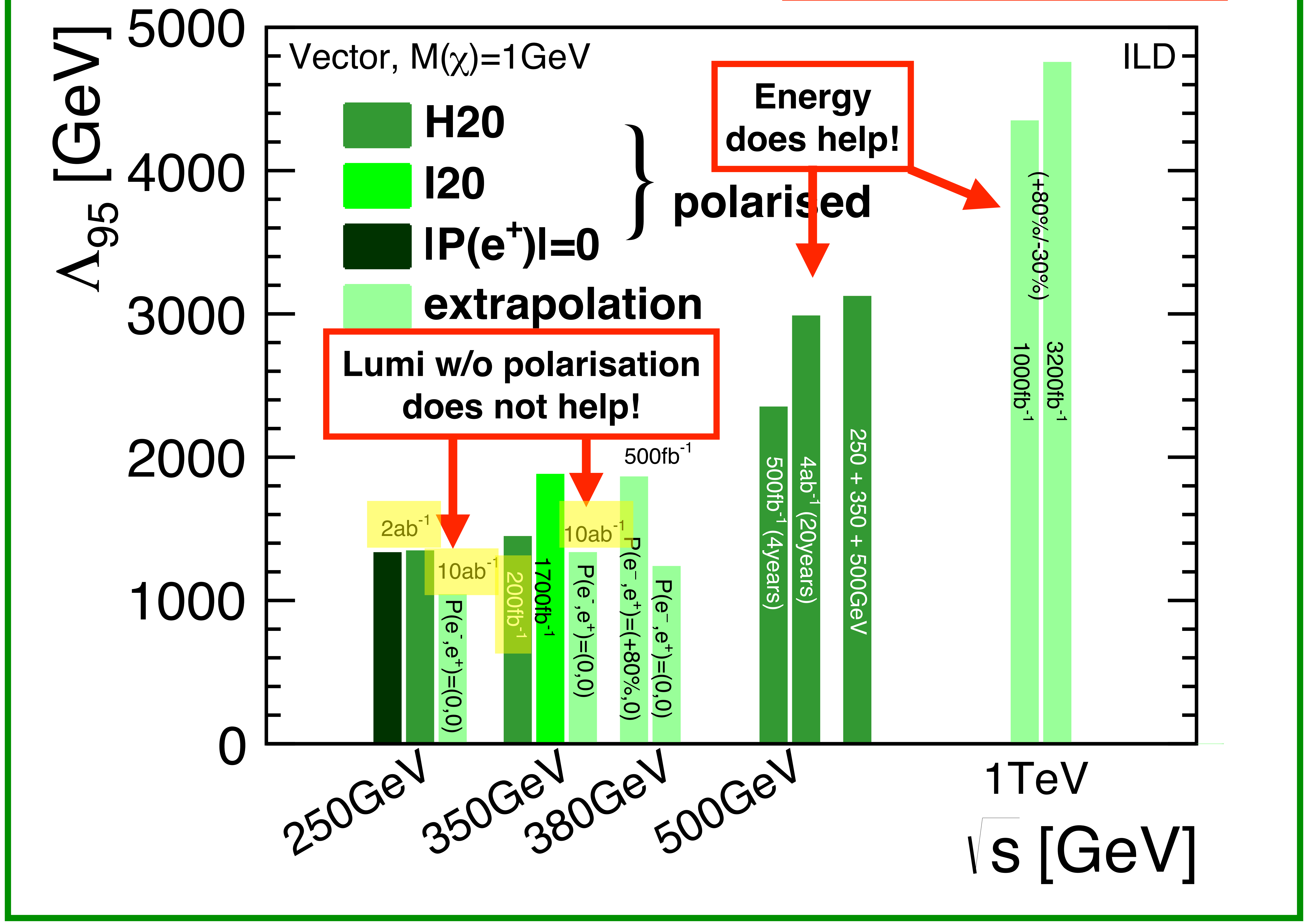

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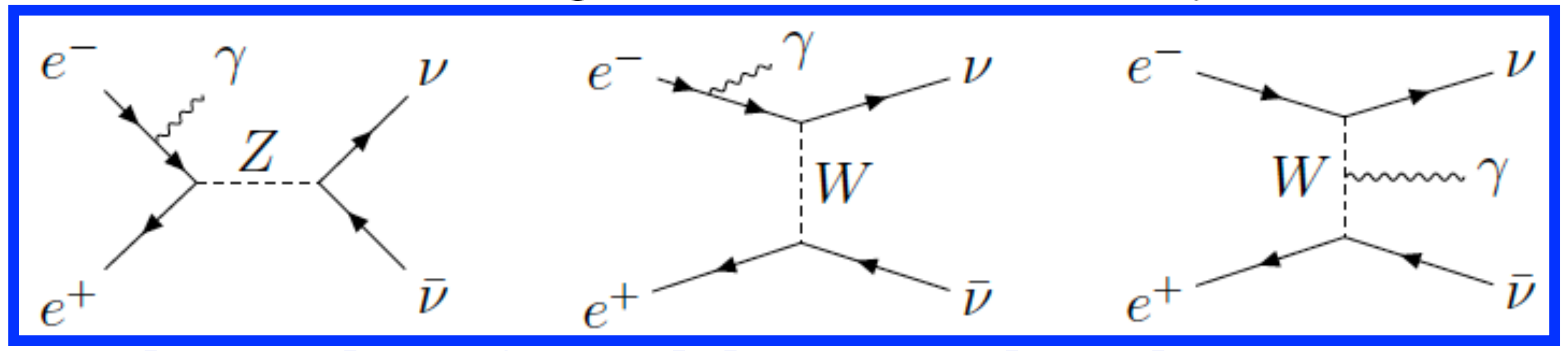

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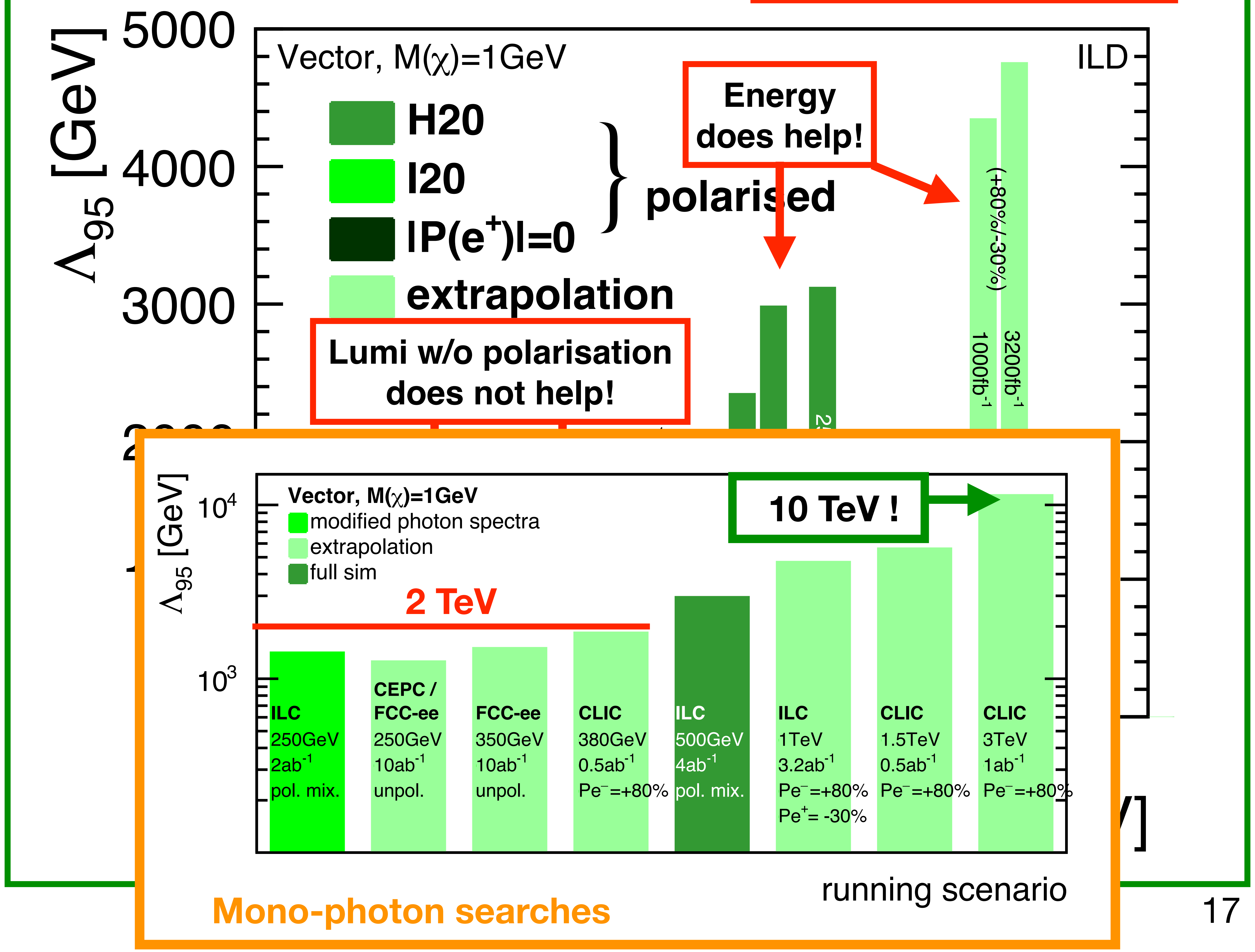

Conclusions

- **There is a clear and significant physics case for e^+e^- collisions at E_{CM} = 250 GeV — and at ≥ 500 GeV — complementary to pp collisions.**

- **Therefore the next e^+e^- collider must be energy upgradable.**

- **Linear Colliders (CLIC, ILC, C3, …) fulfill this criterion.**

- The exact physical and/or operational energy stages ***beyond*** the initial “Higgs factory” mode still can be defined, taking into account
  - **physics needs**
  - **technological innovations**

Invitation for after Snowmass….

- The European Strategy for Particle Physics identified an e+e- Higgs factory as the highest-priority next collider
- 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
  - will give input to next round of ESU
  - if you don't won't to commit to a specific collider project / detector concept (yet) => this is your way to contribute => get in touch!

Backup

How big can BSM effects be?

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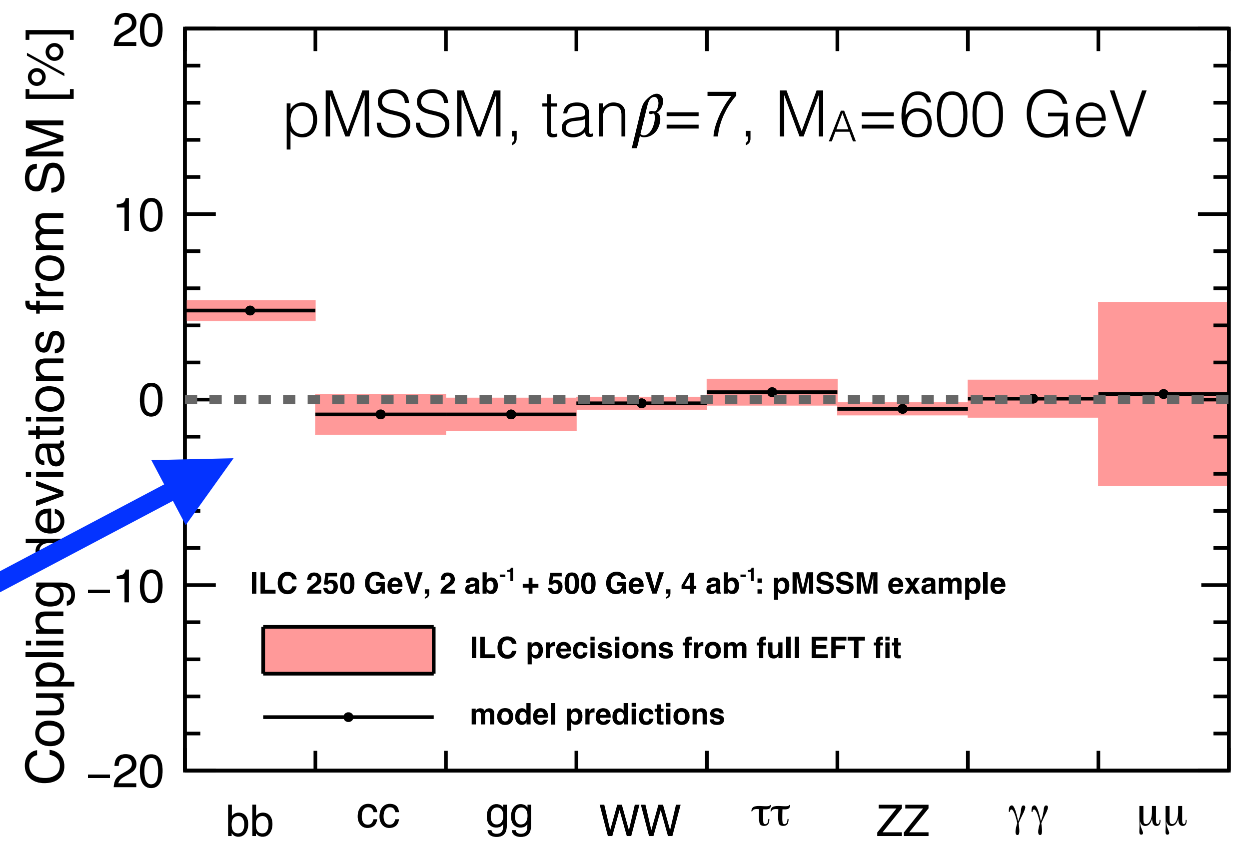

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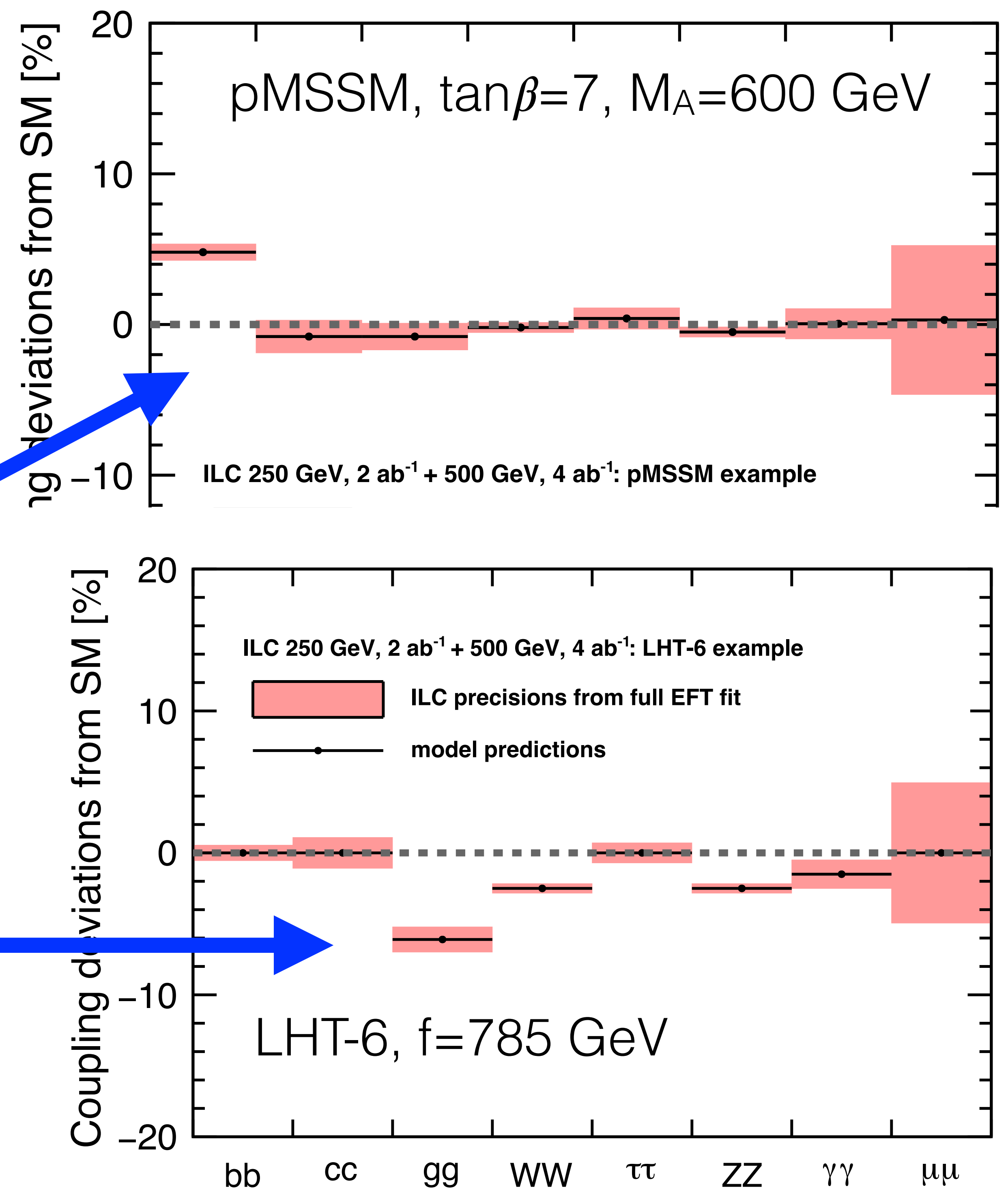

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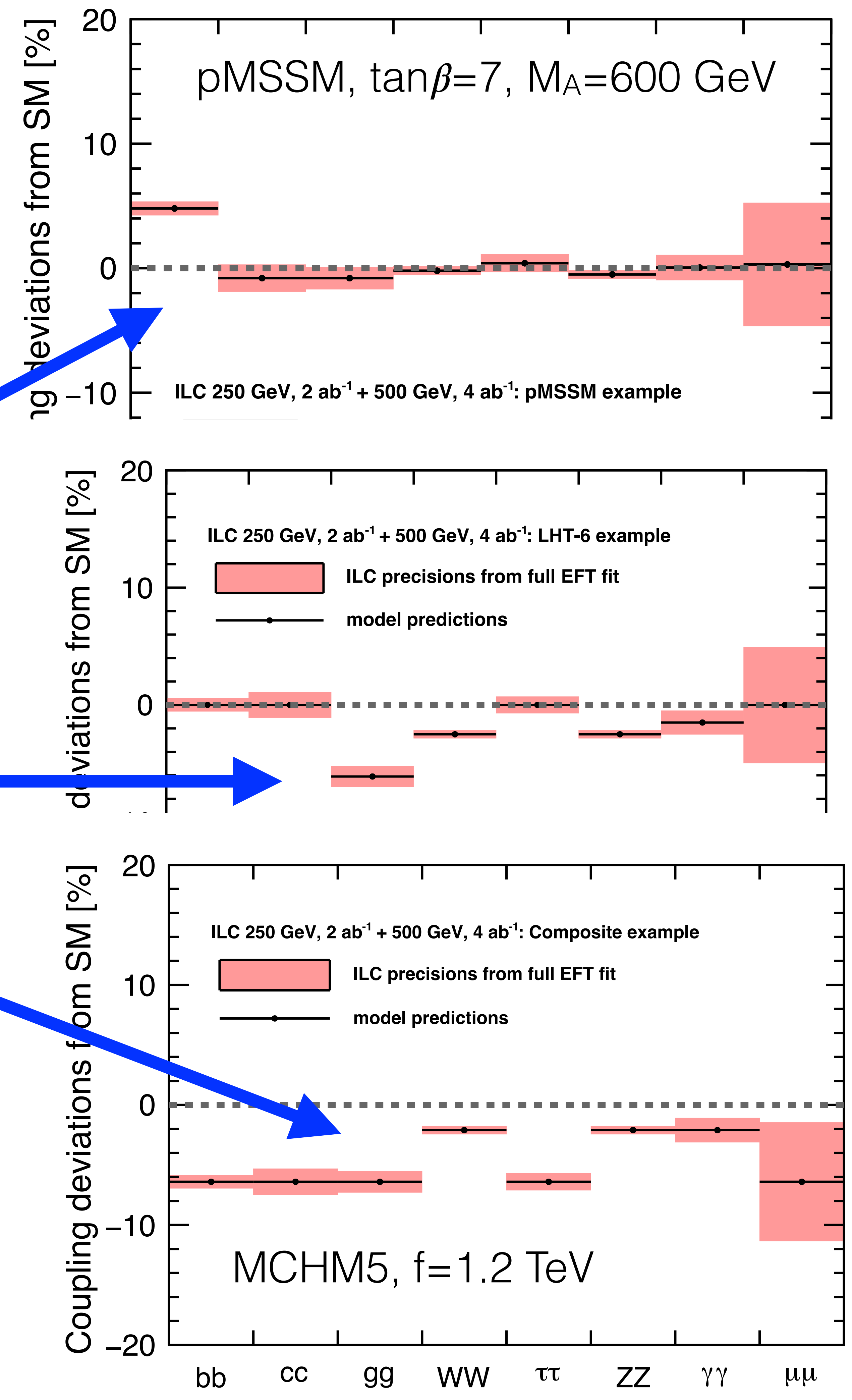

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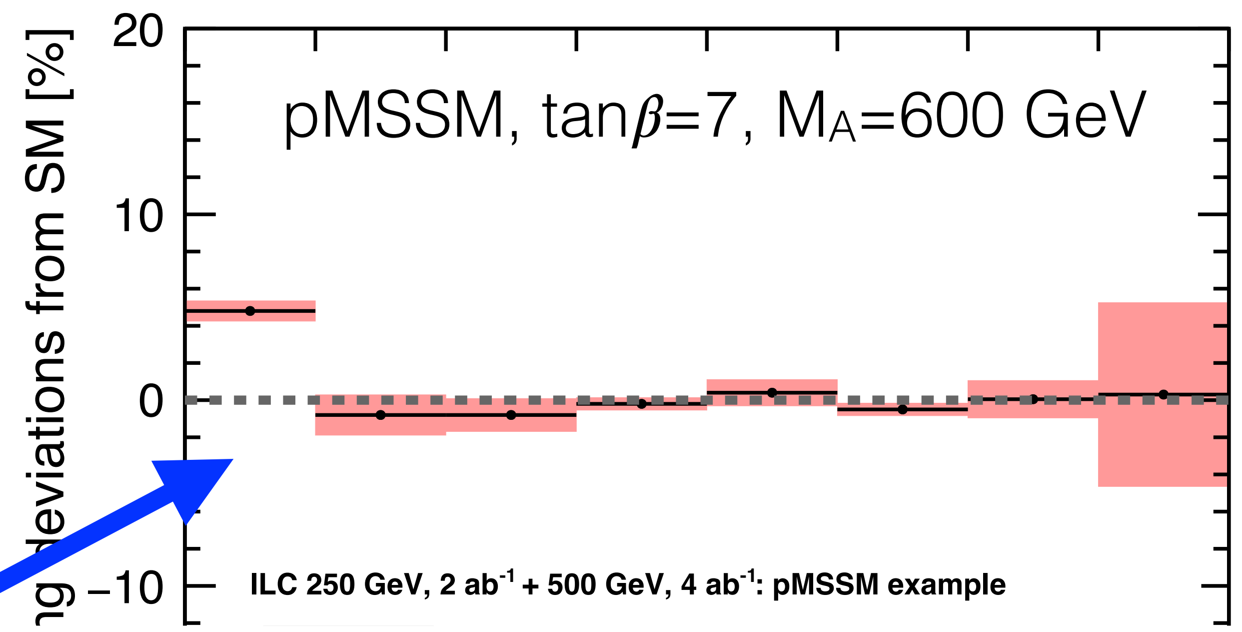
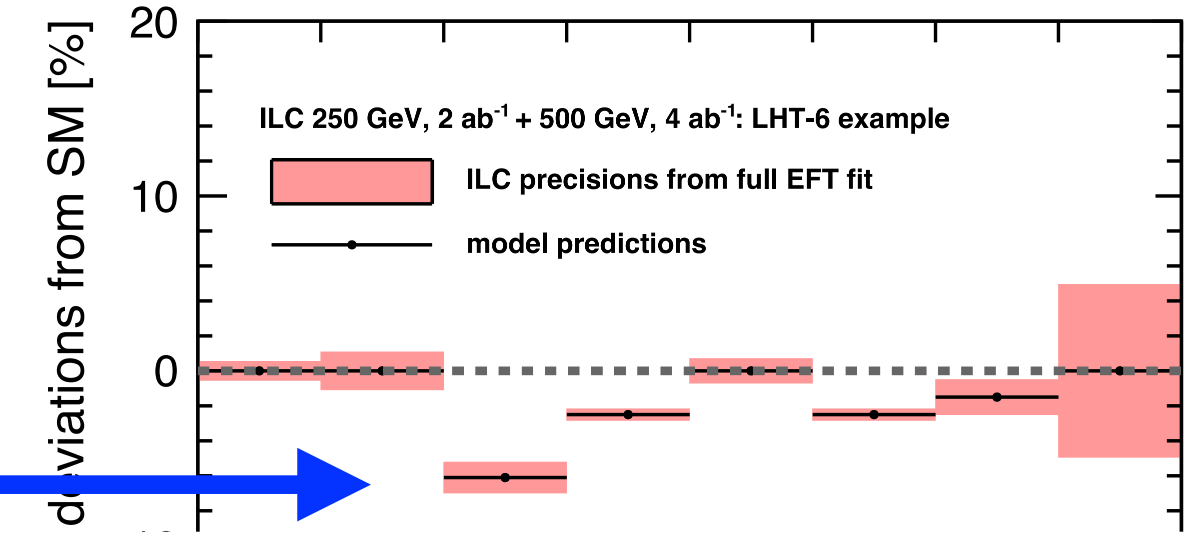
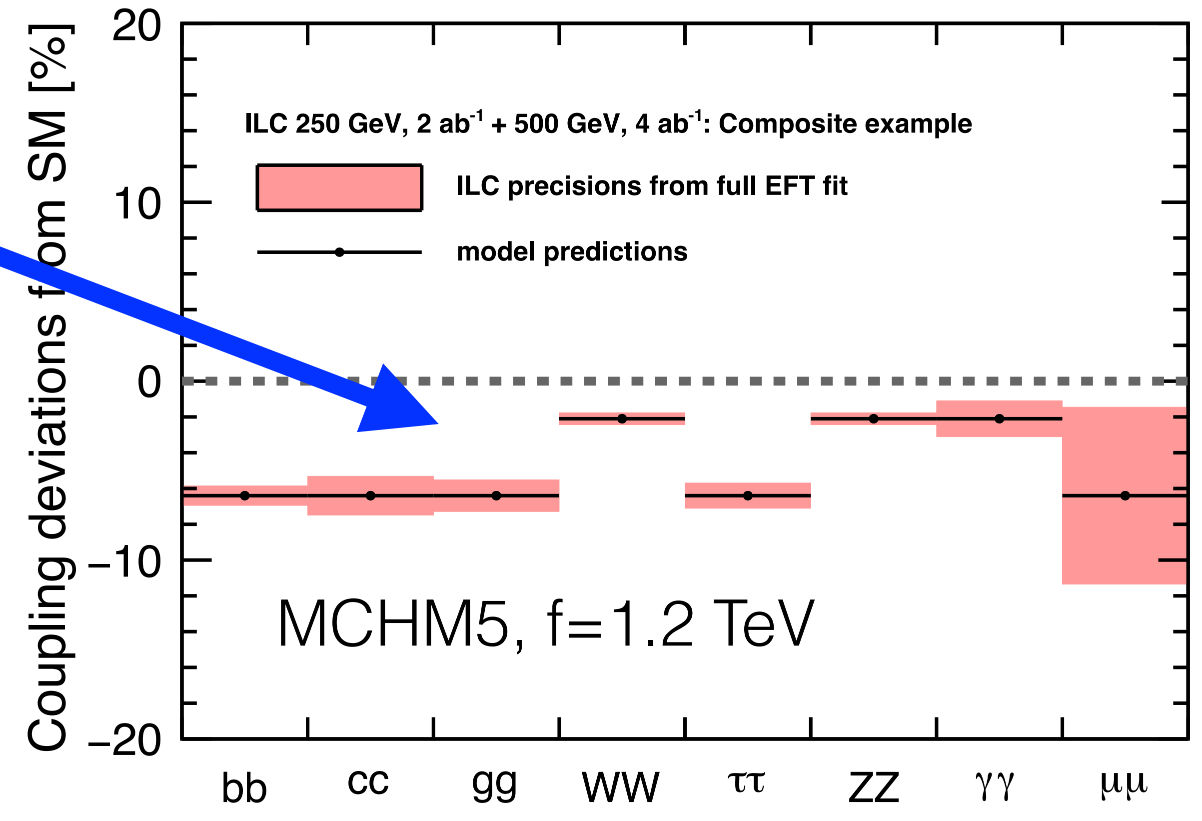
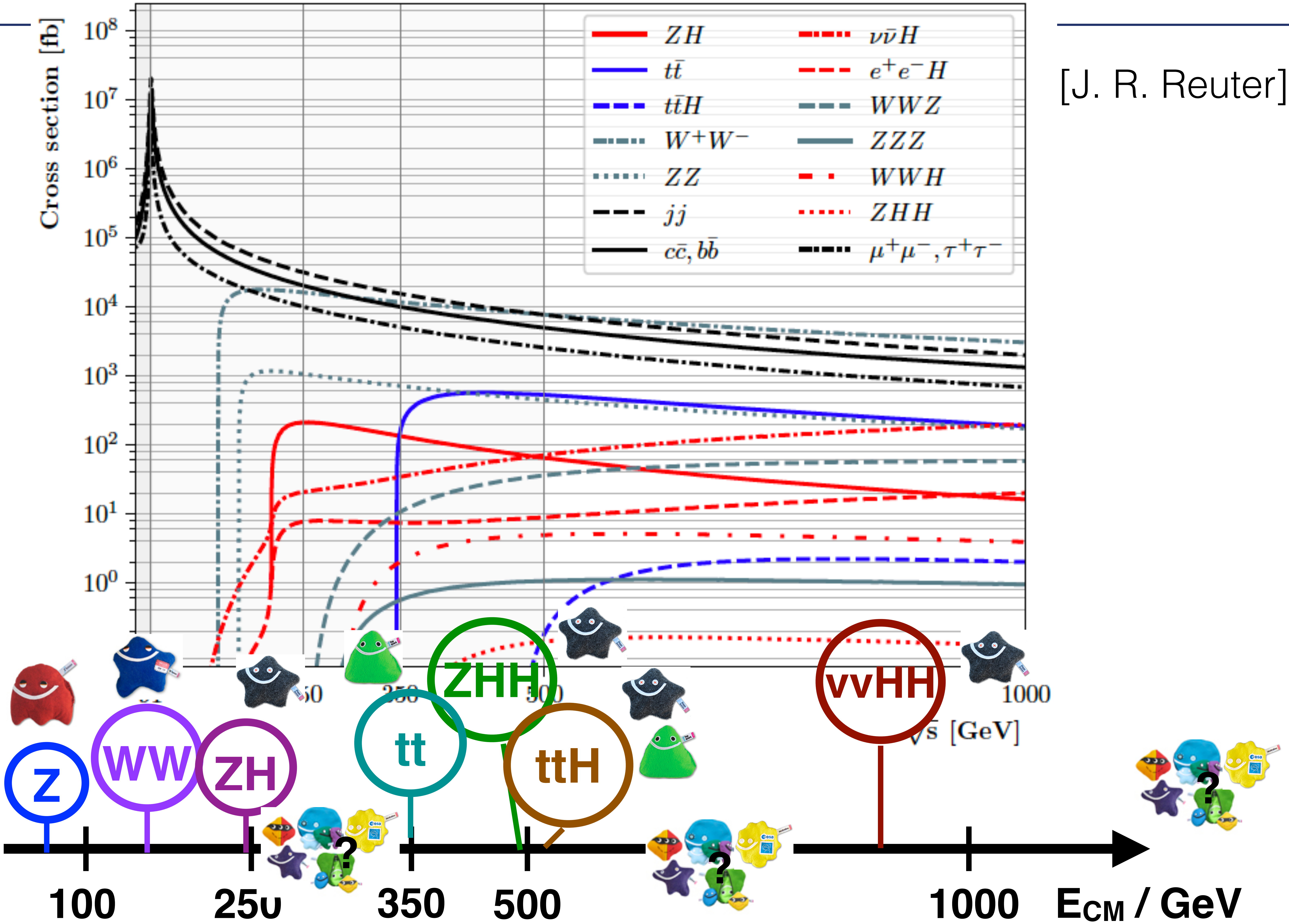
At least percent-level precision required!







Energy thresholds in e+e- collisions



[J. R. Reuter]

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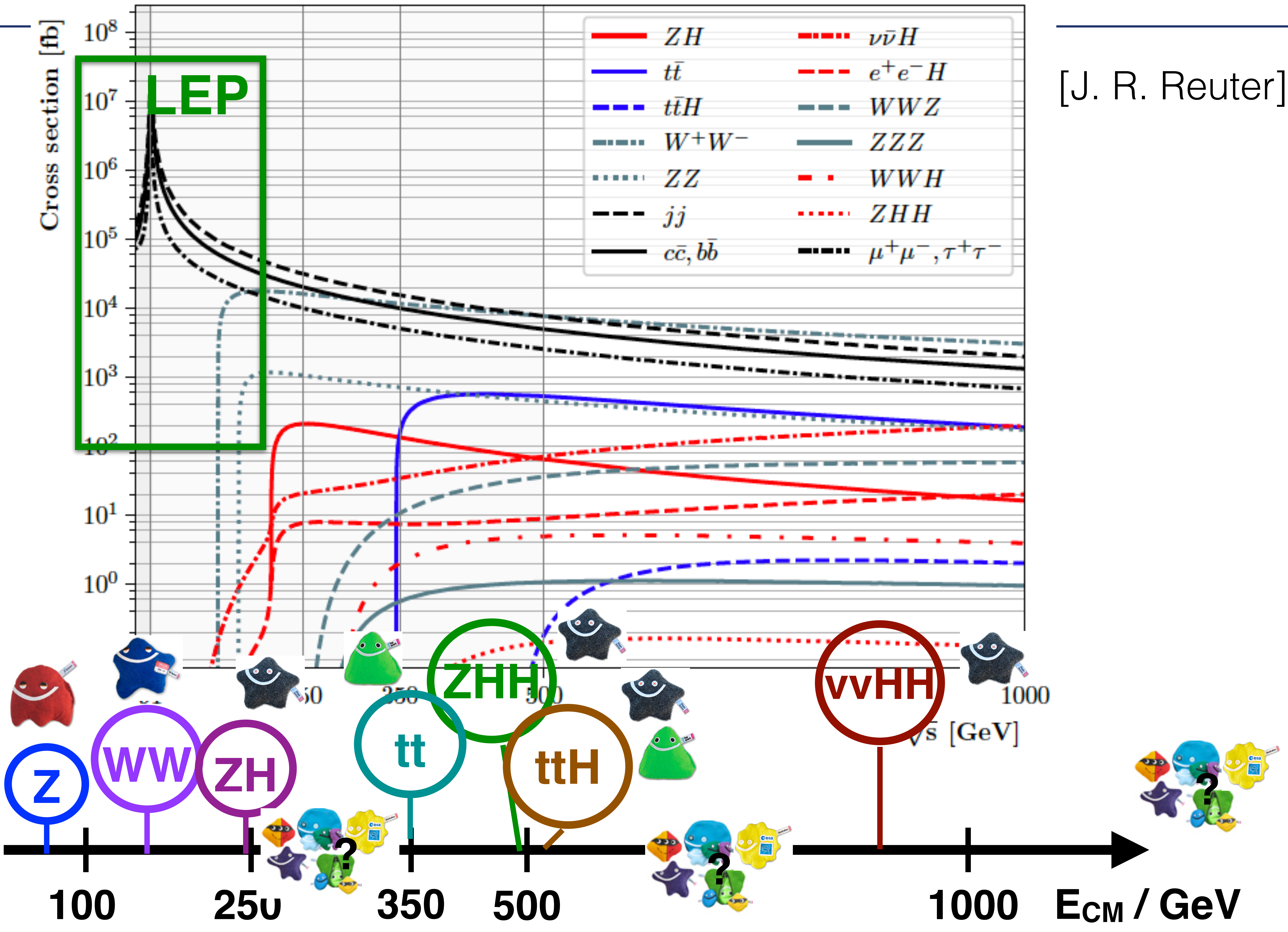
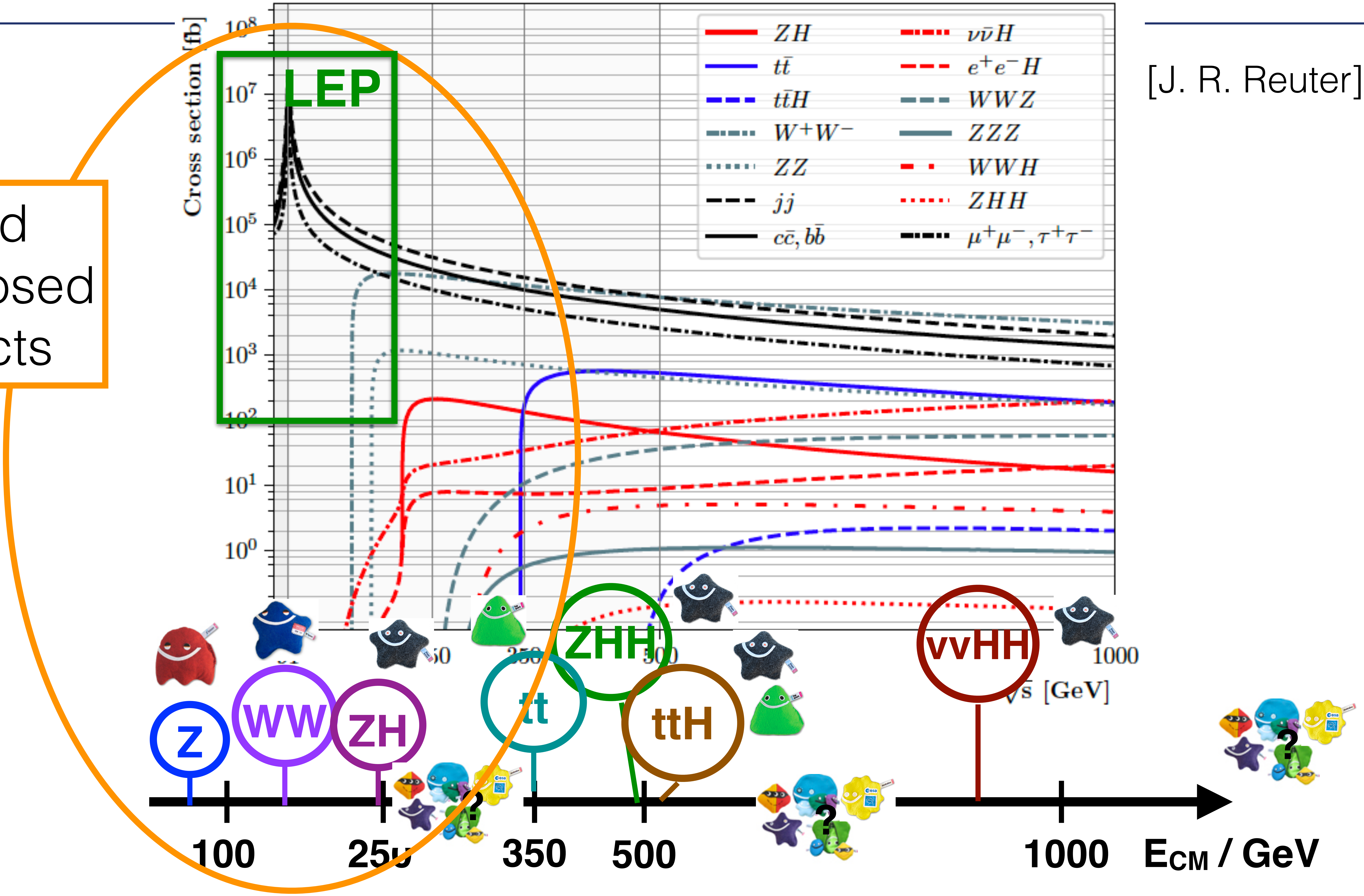


[J. R. Reuter]

Energy thresholds in e+e- collisions

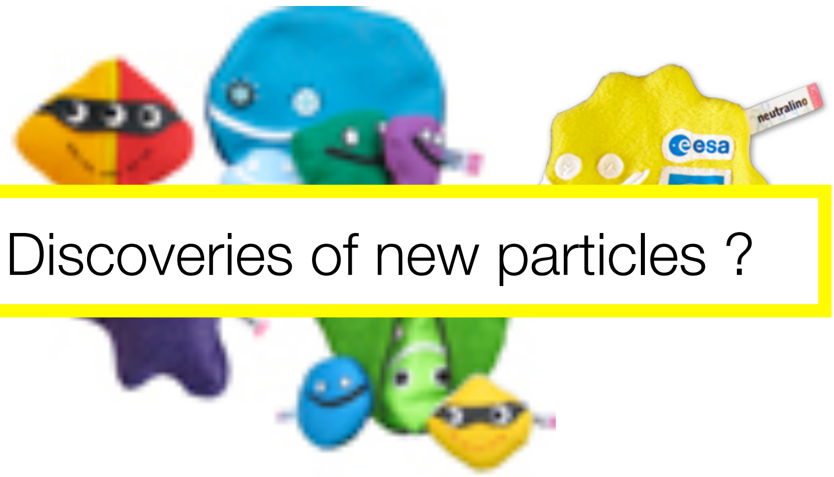
considered
by ~all proposed
e+e- projects



[J. R. Reuter]

New Physics Interpretation of Higgs & EW

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



	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era (3 ab^{-1} of integrated luminosity). From [15].

arXiv:1708.08912

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  triple Higgs coupling
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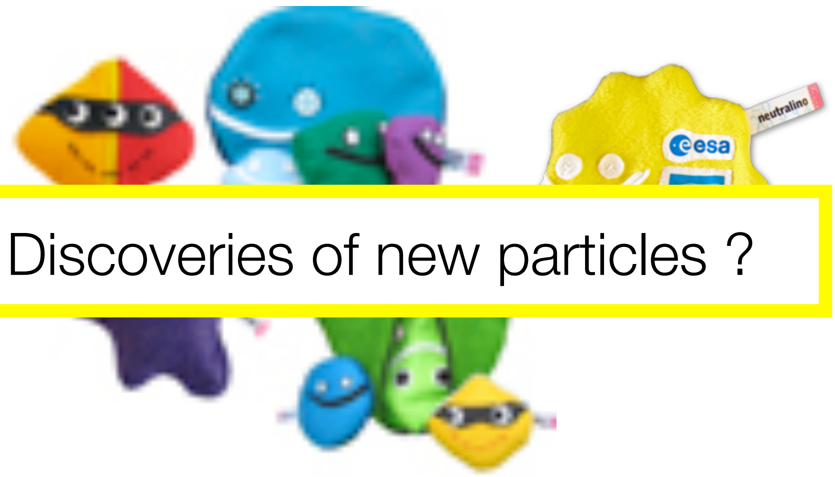
New Physics Interpretation of Higgs & EW

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



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3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
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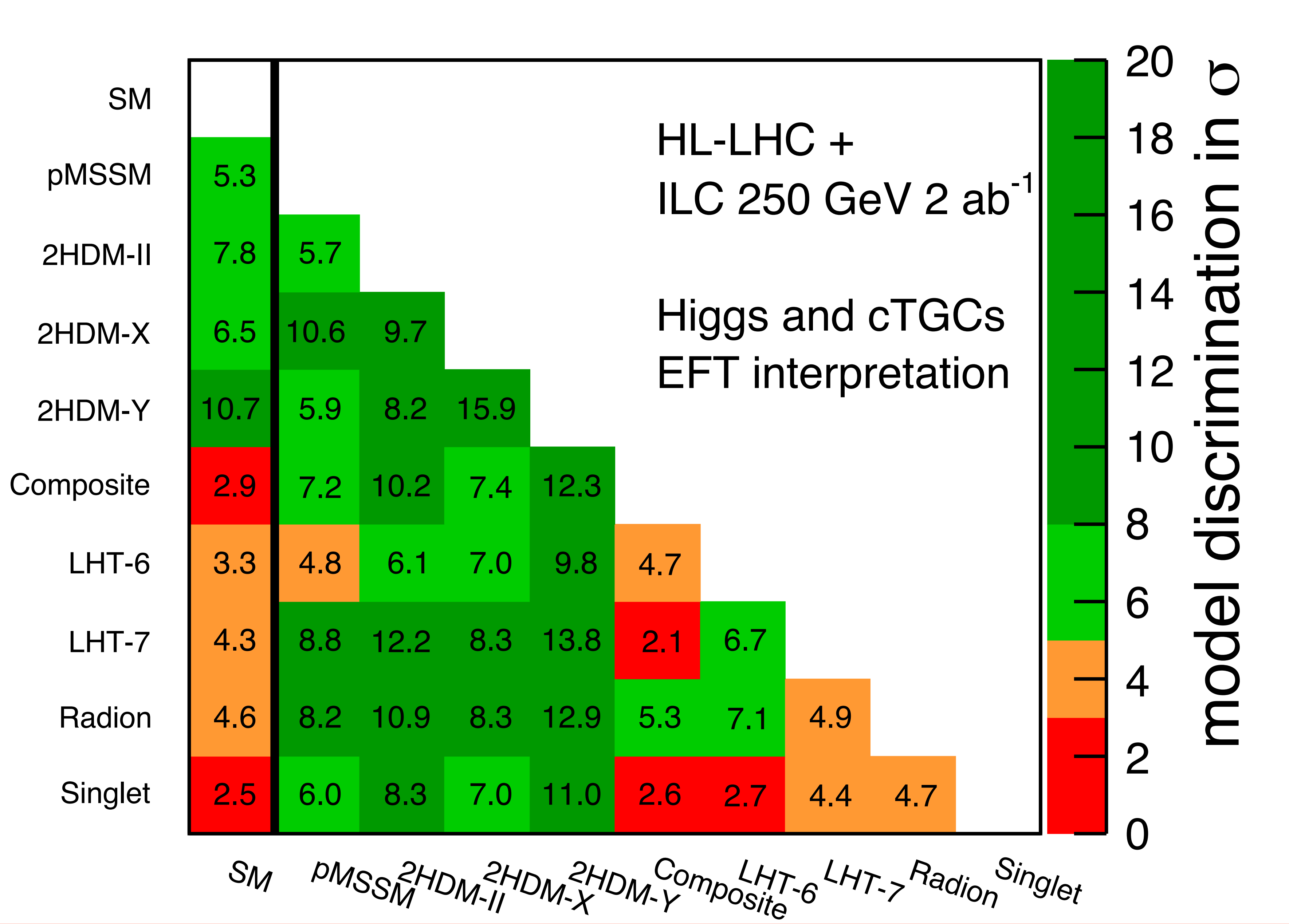

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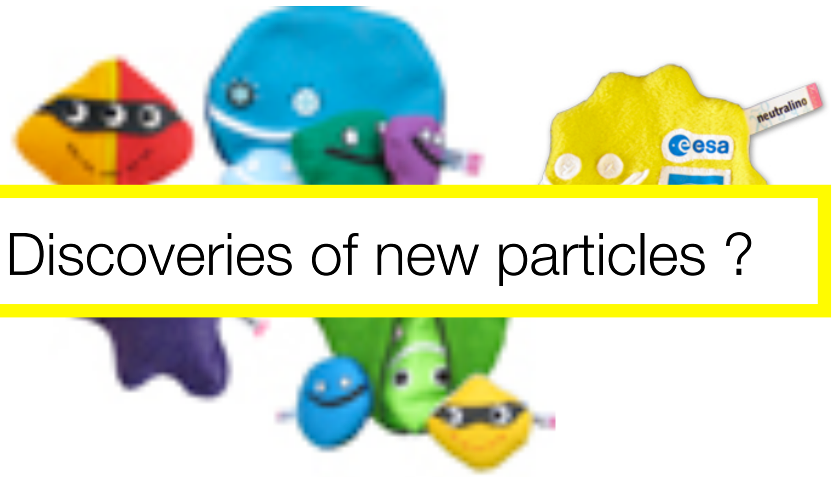

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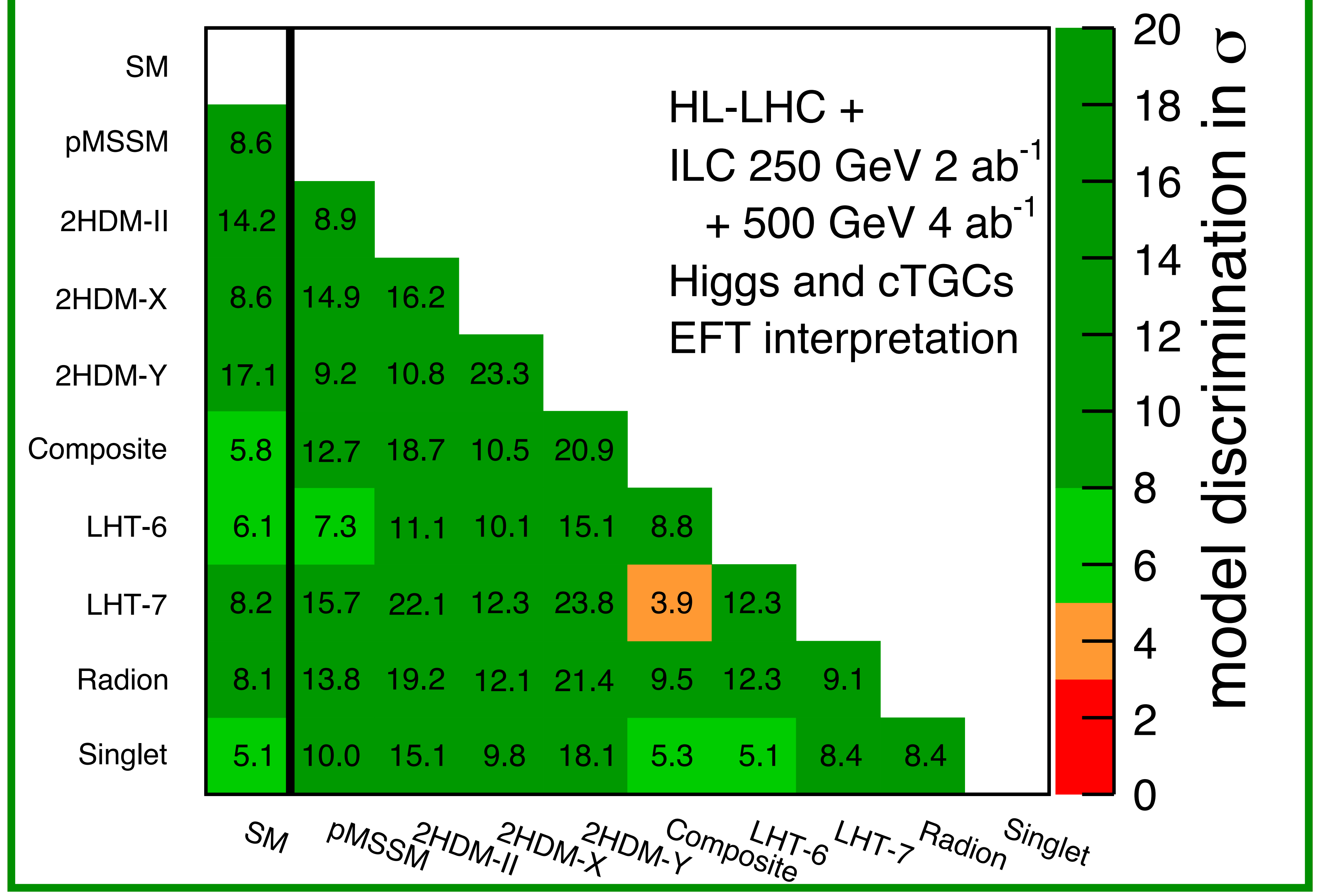

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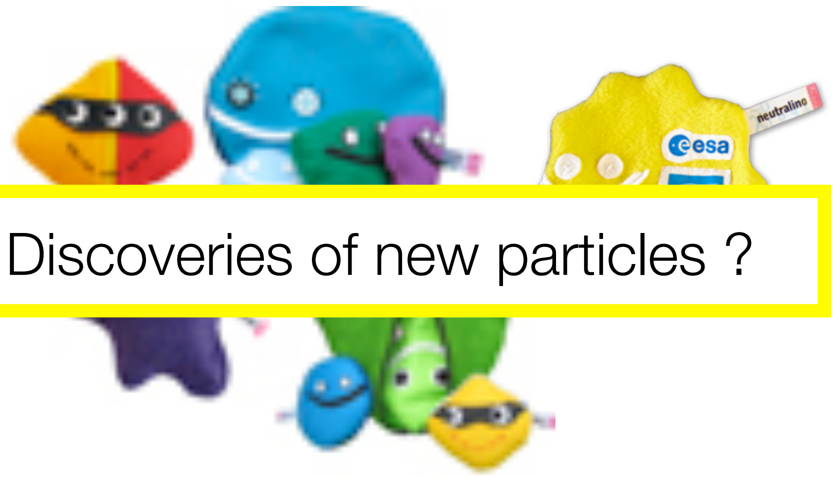

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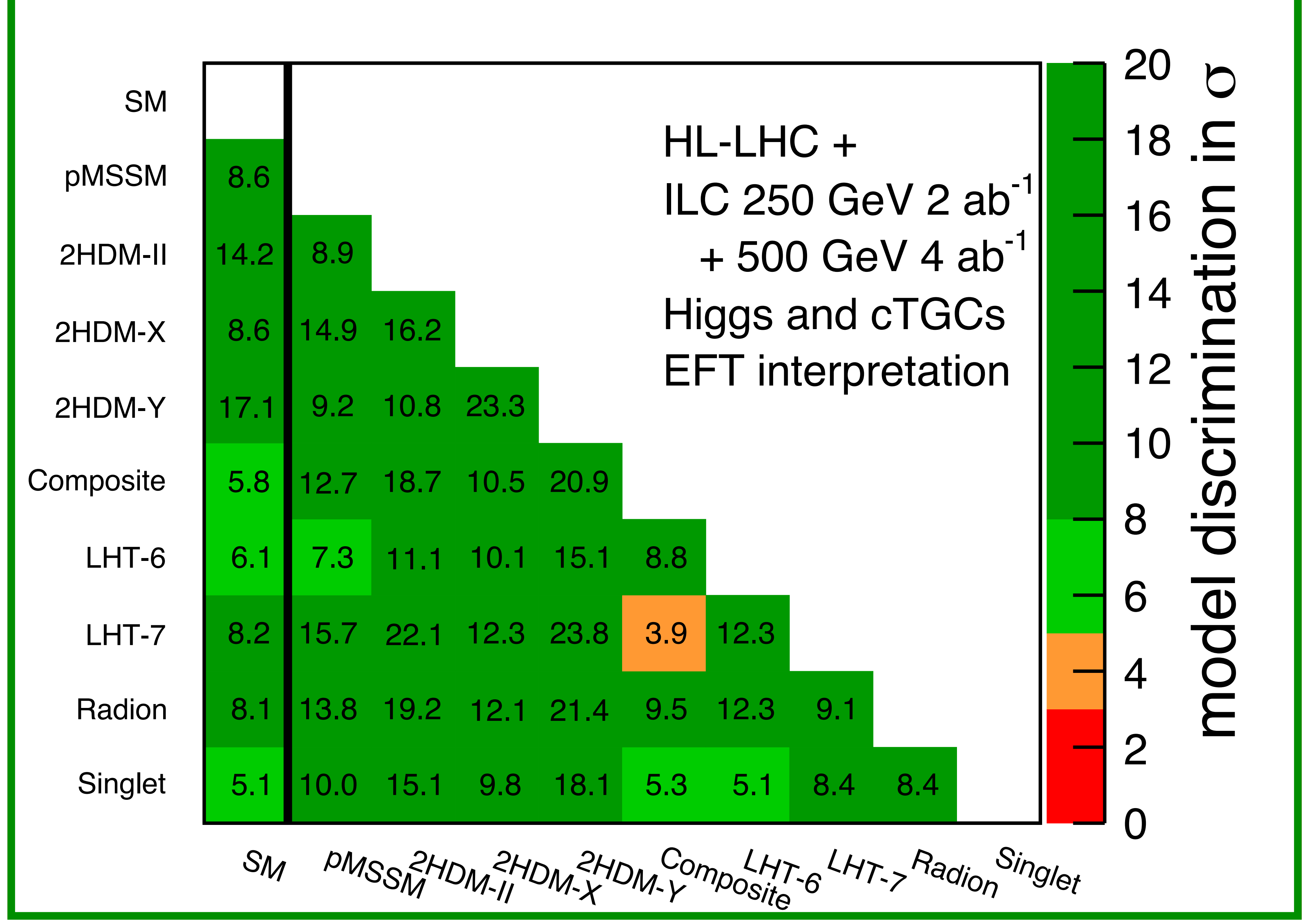

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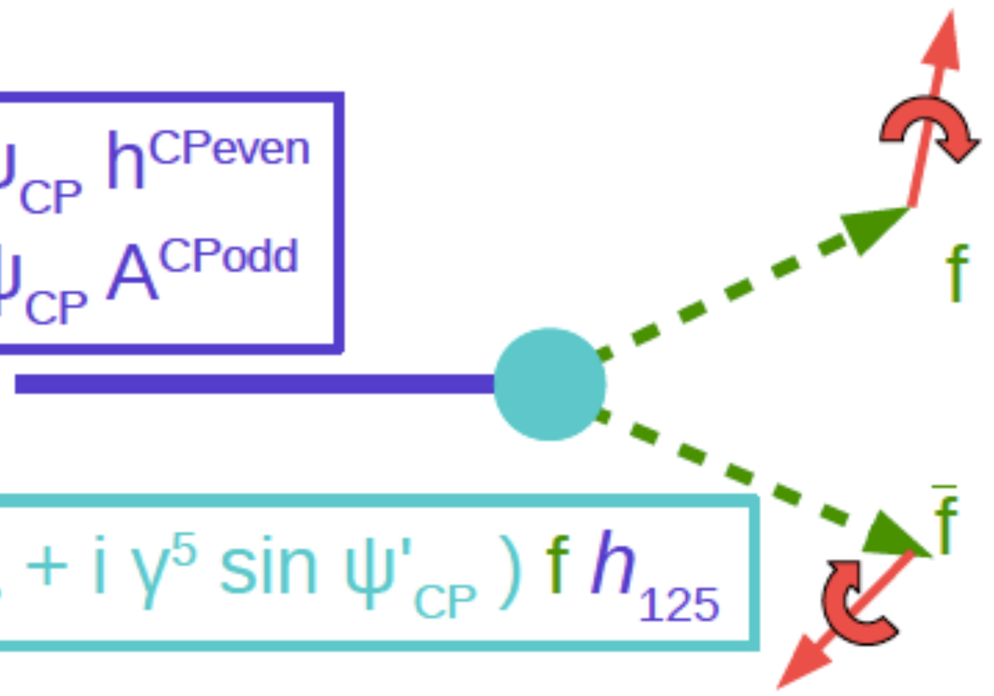
illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

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

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



$$g\, \bar{f}\, (\cos\psi'_{CP} + i\, \gamma^5 \sin\psi'_{CP})\, f\, h_{125}$$

h is a spin 0 state:

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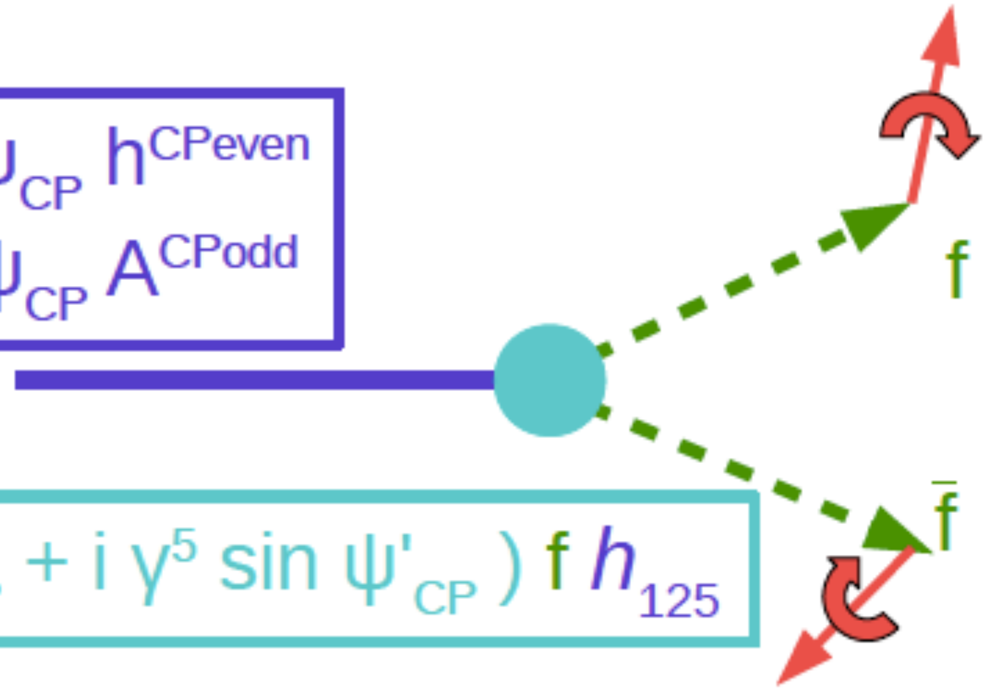

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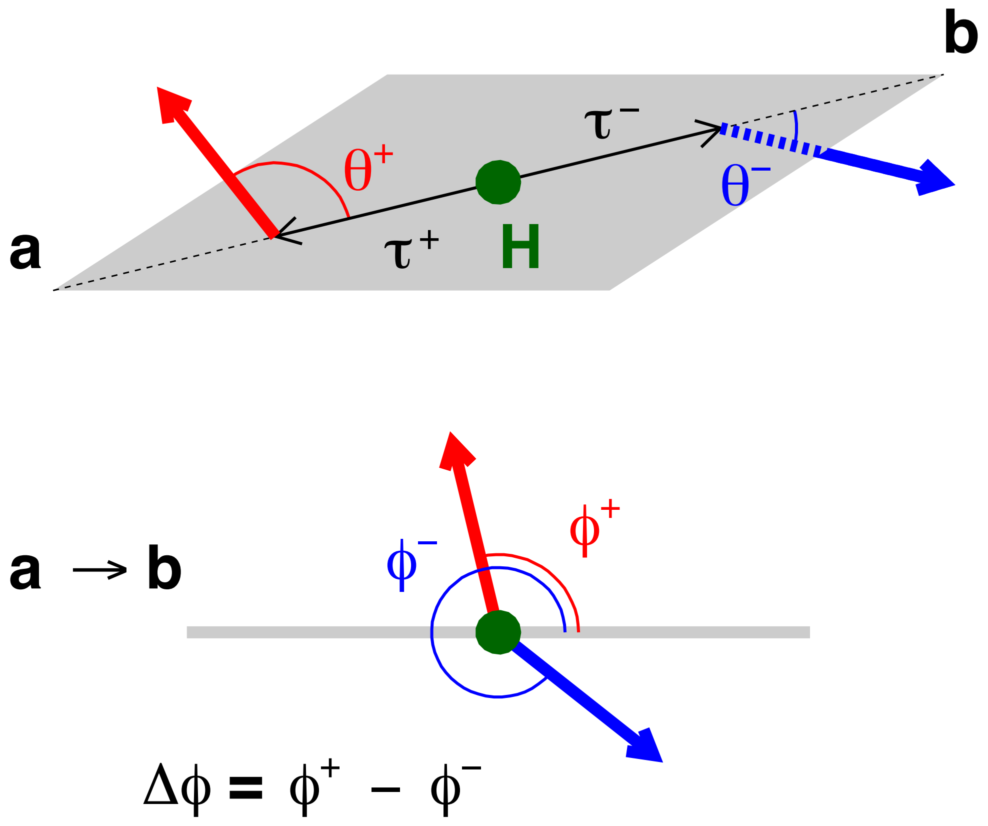

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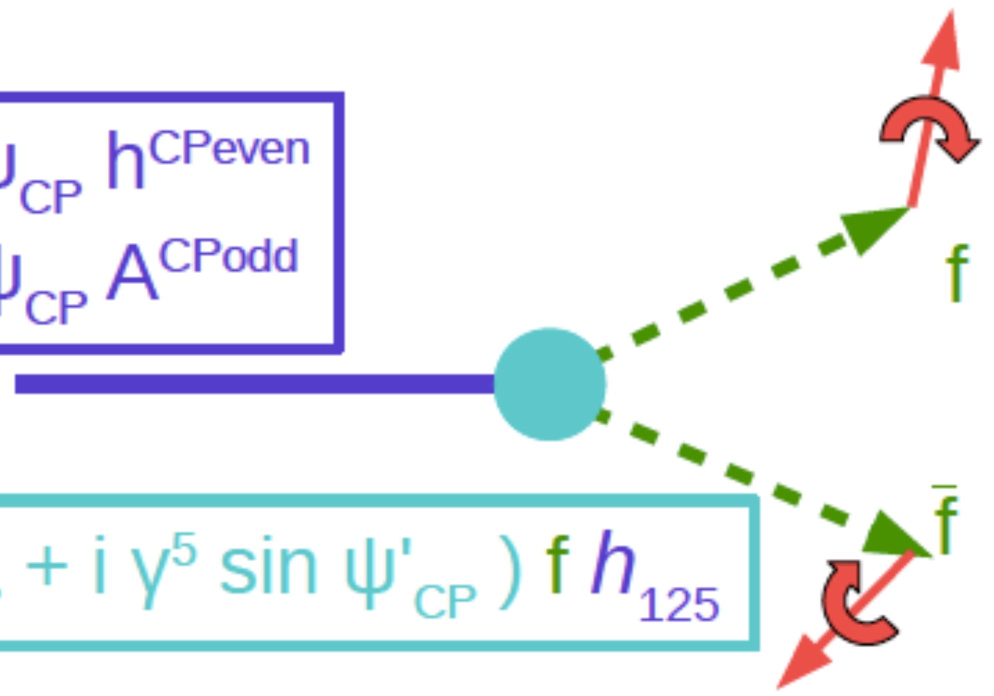

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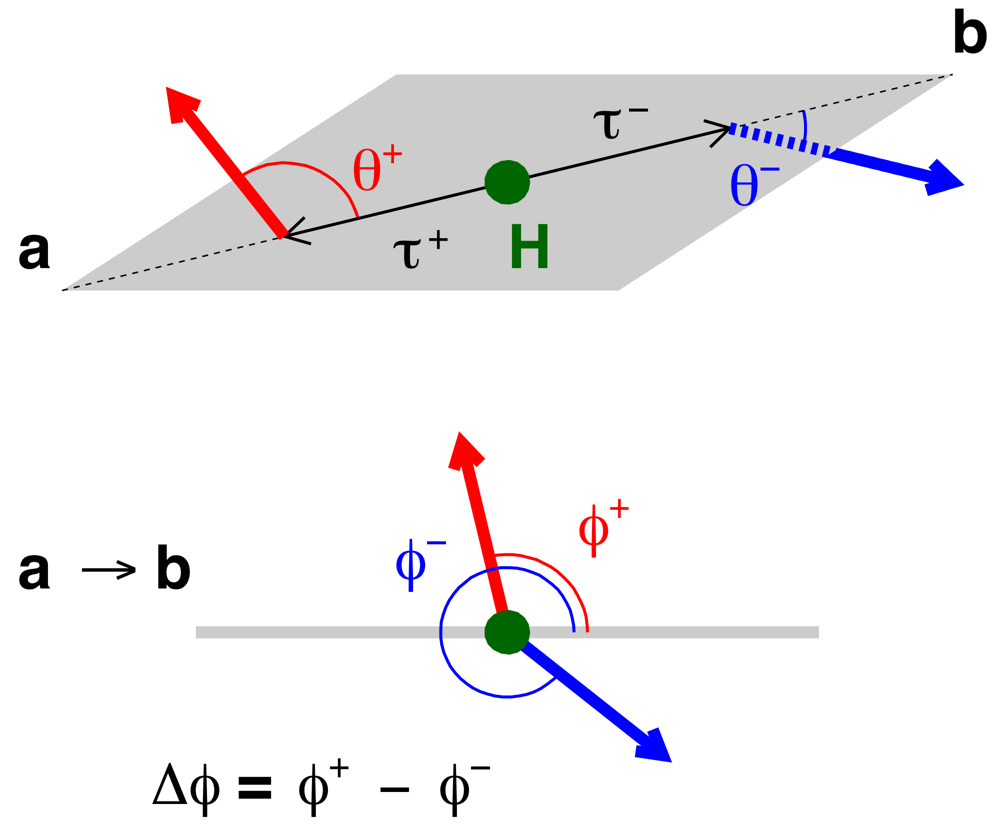

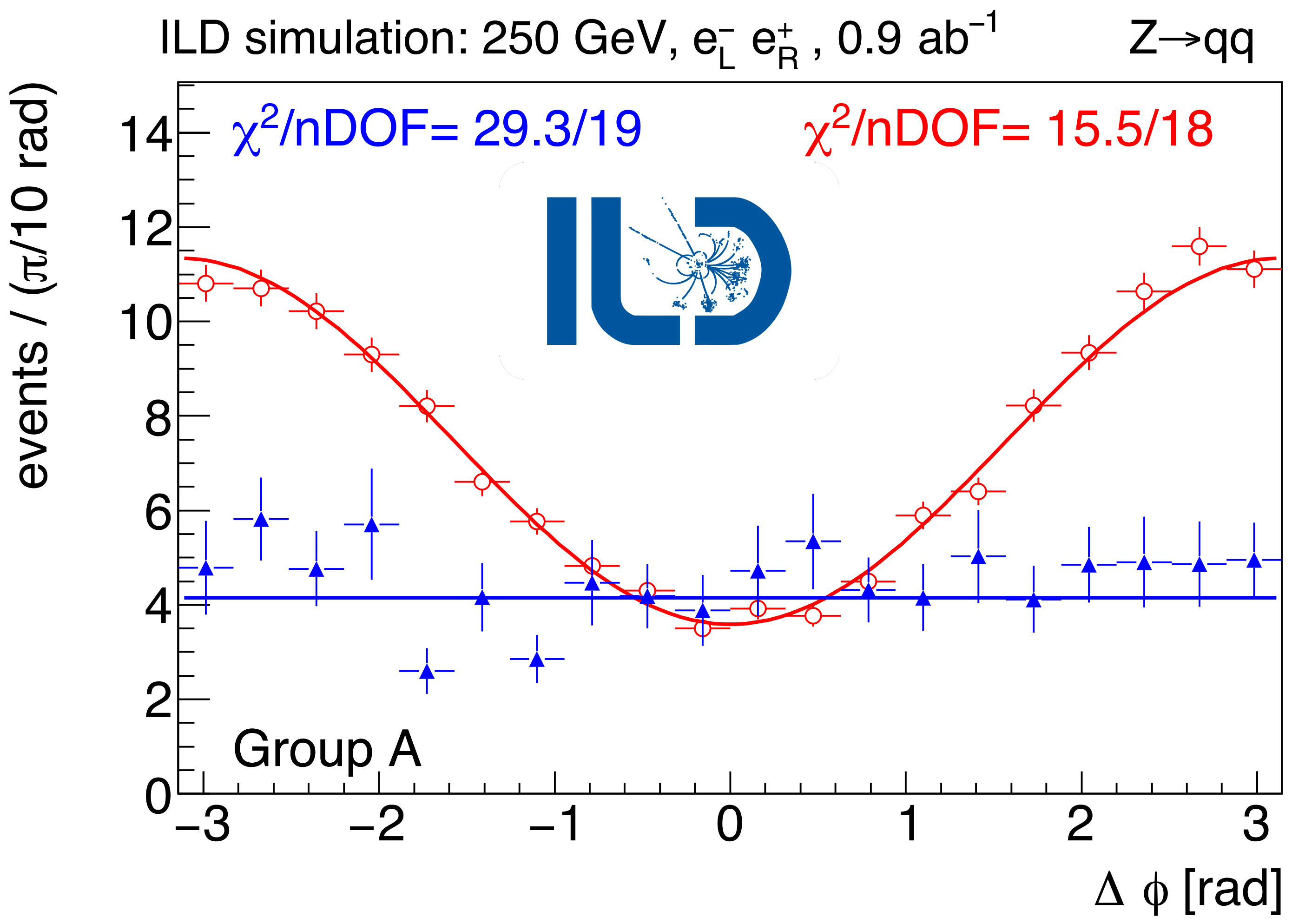

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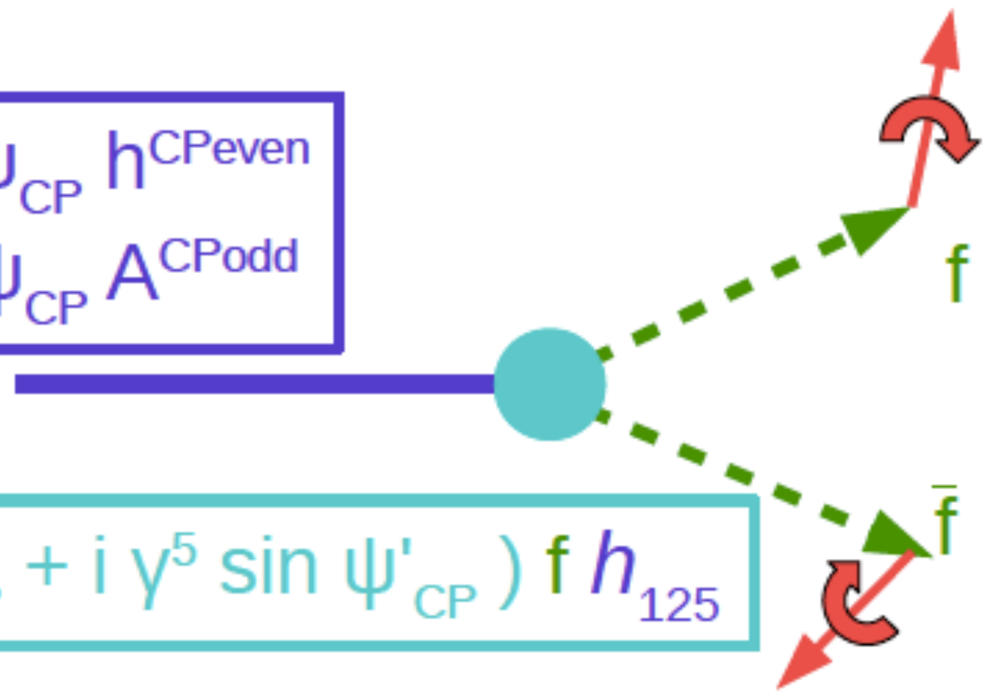

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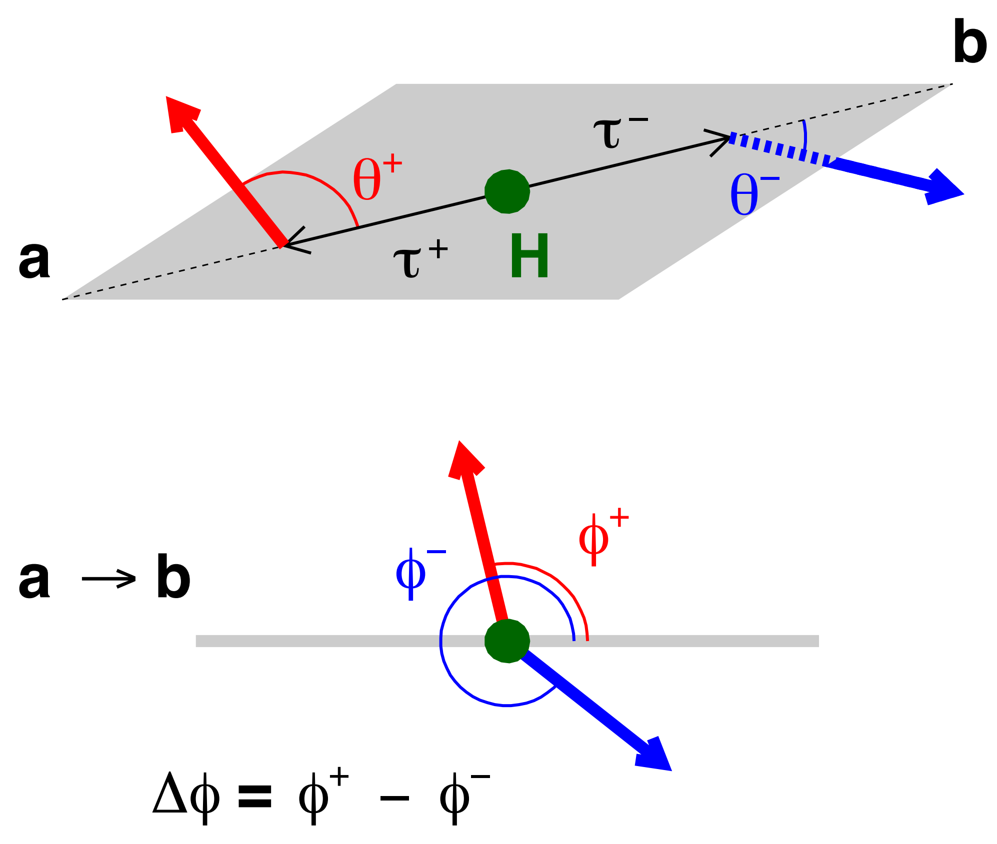

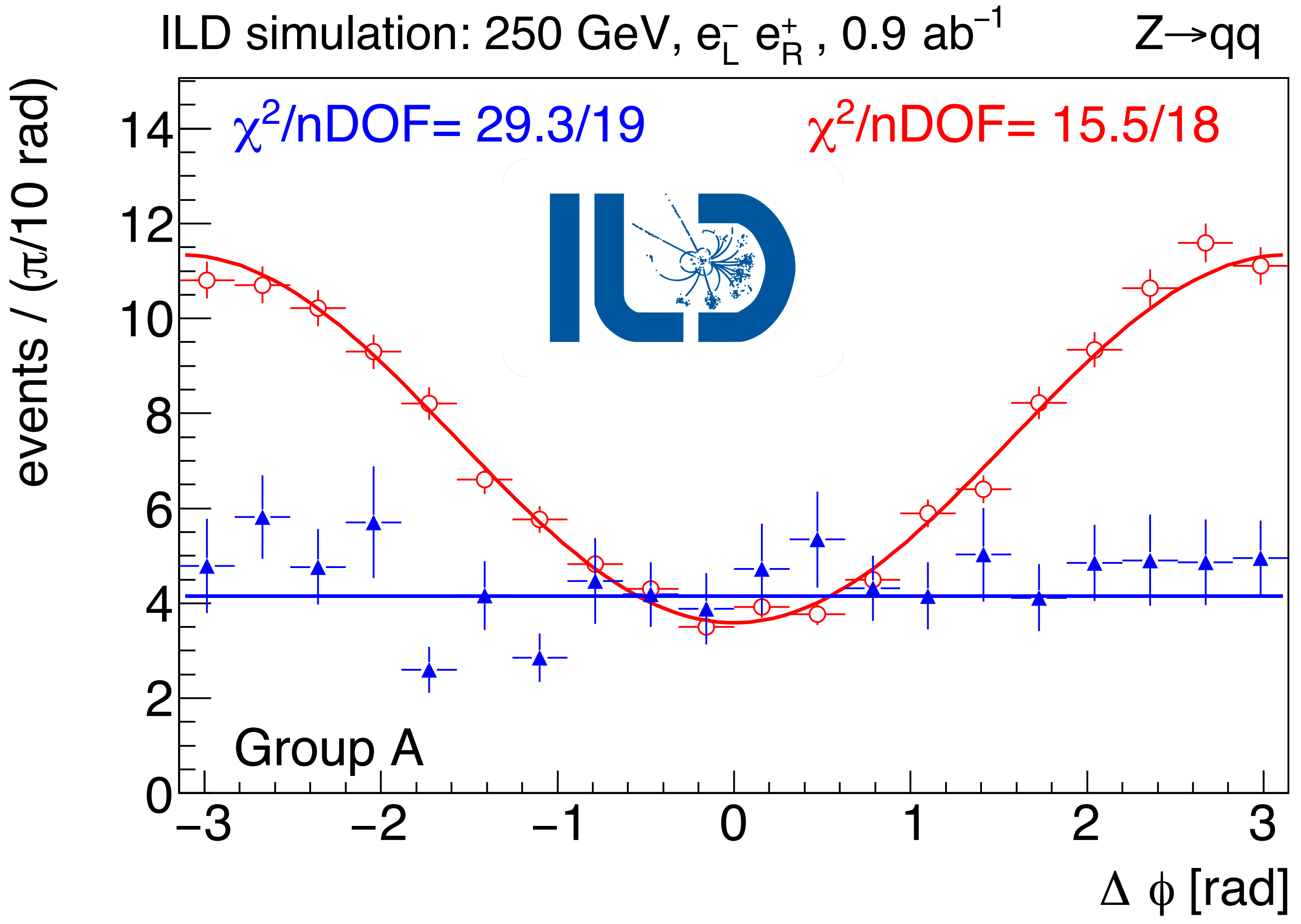

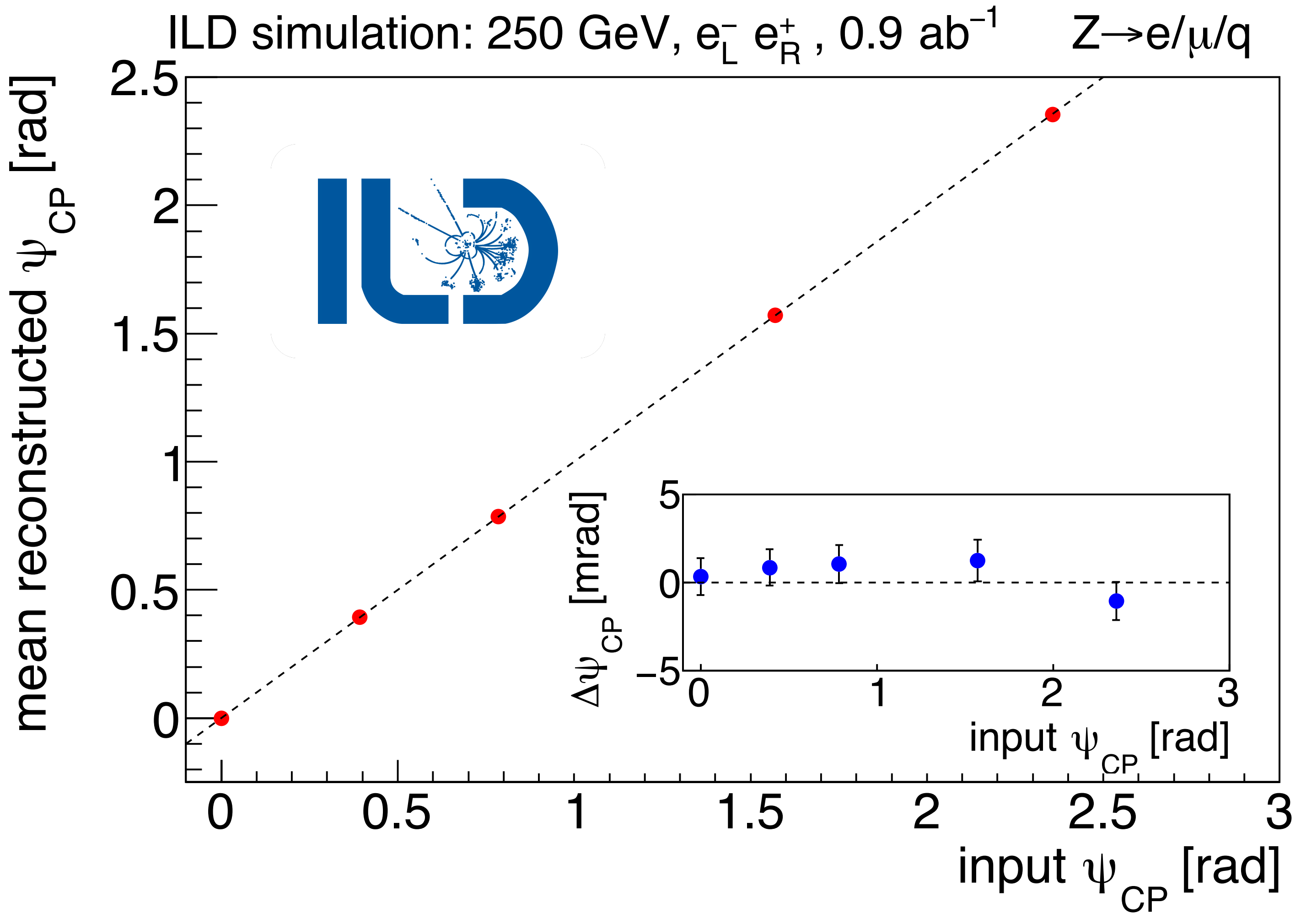

arxiv:1804.01241

based on NIM A810 (2016) 51-58

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

The Higgs Boson

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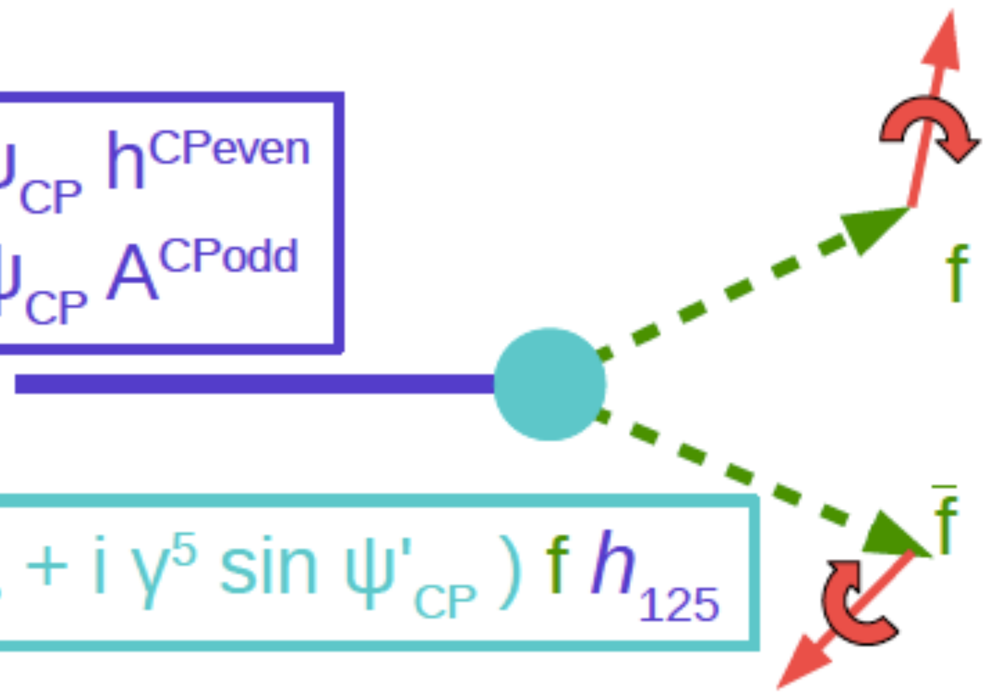

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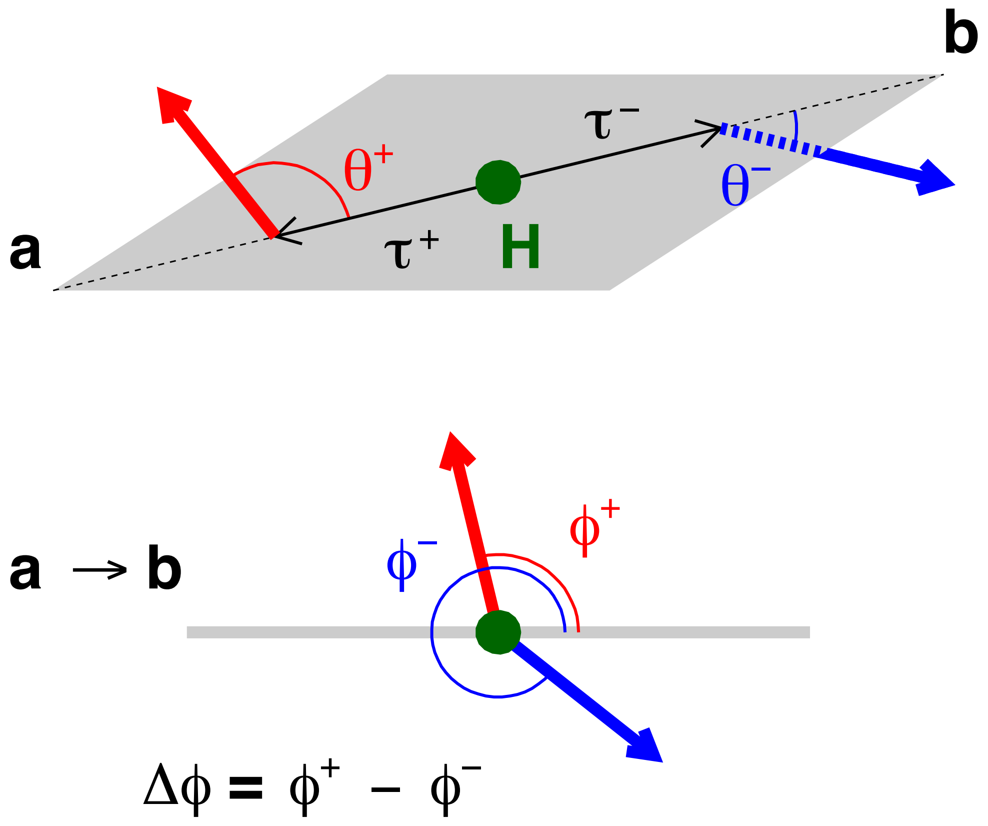

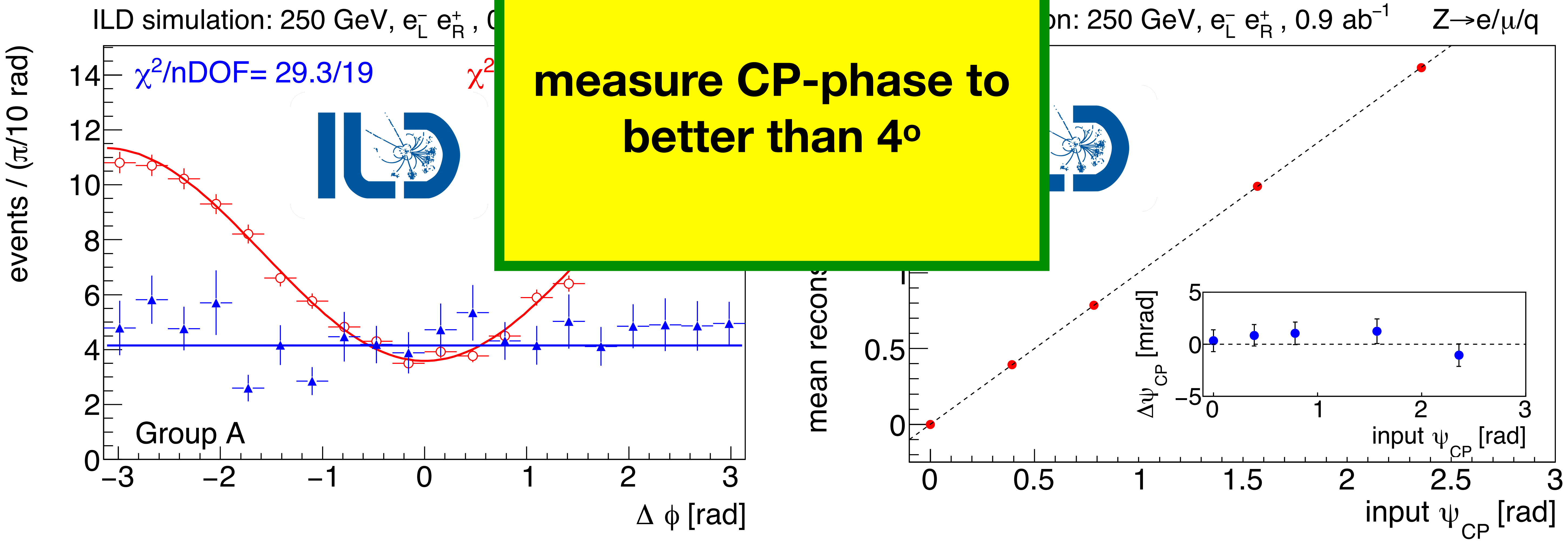

measure CP-phase to better than 4°

arxiv:1804.01241

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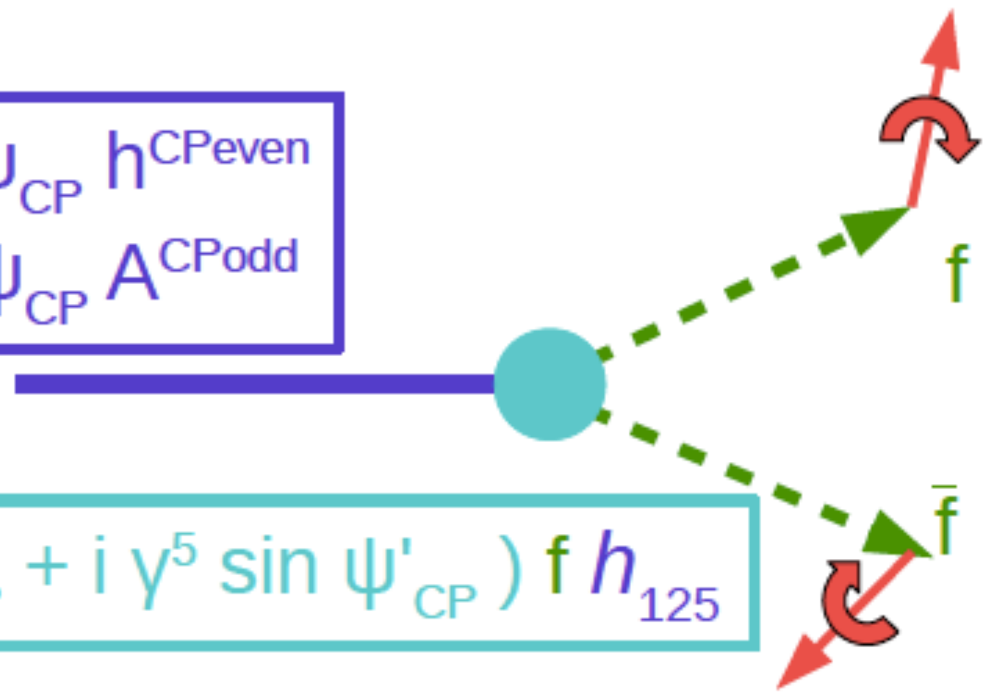

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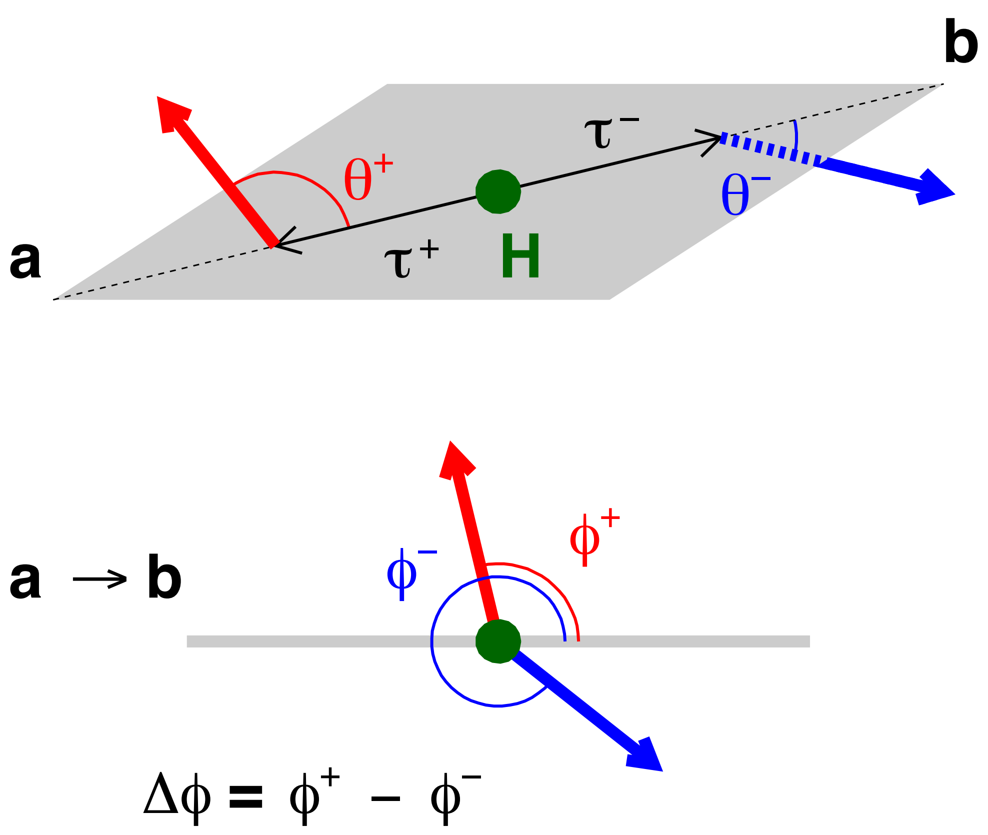

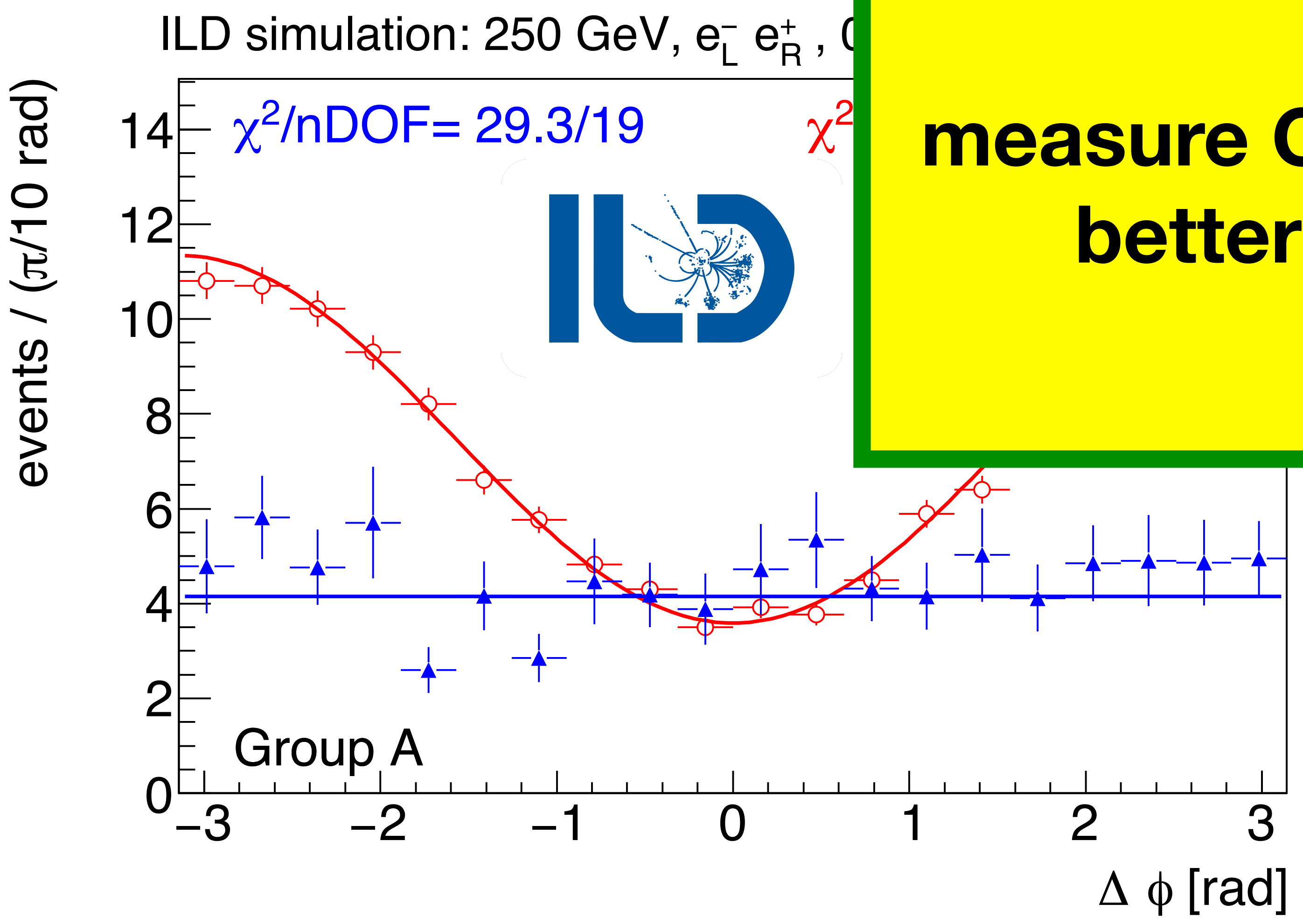

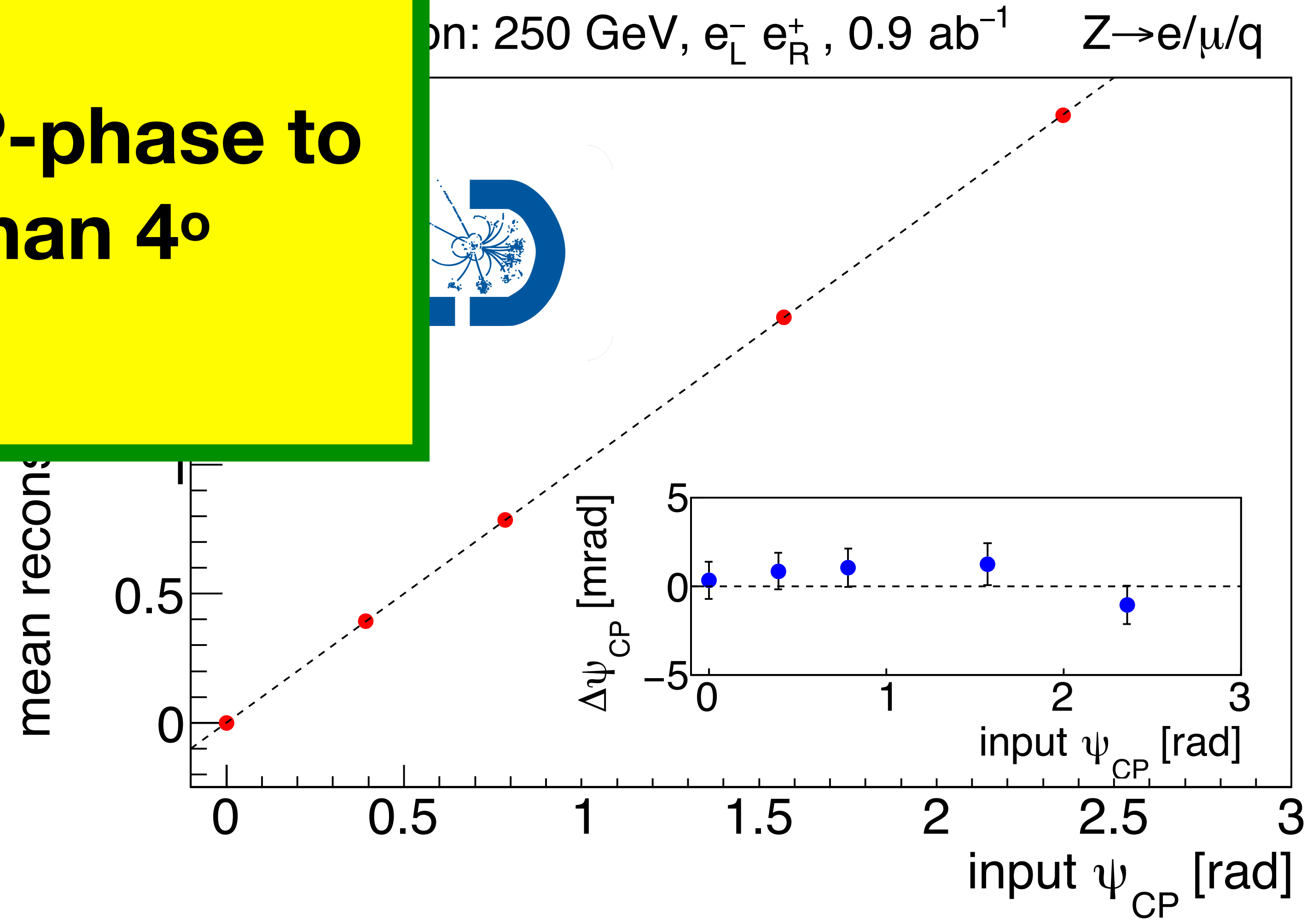

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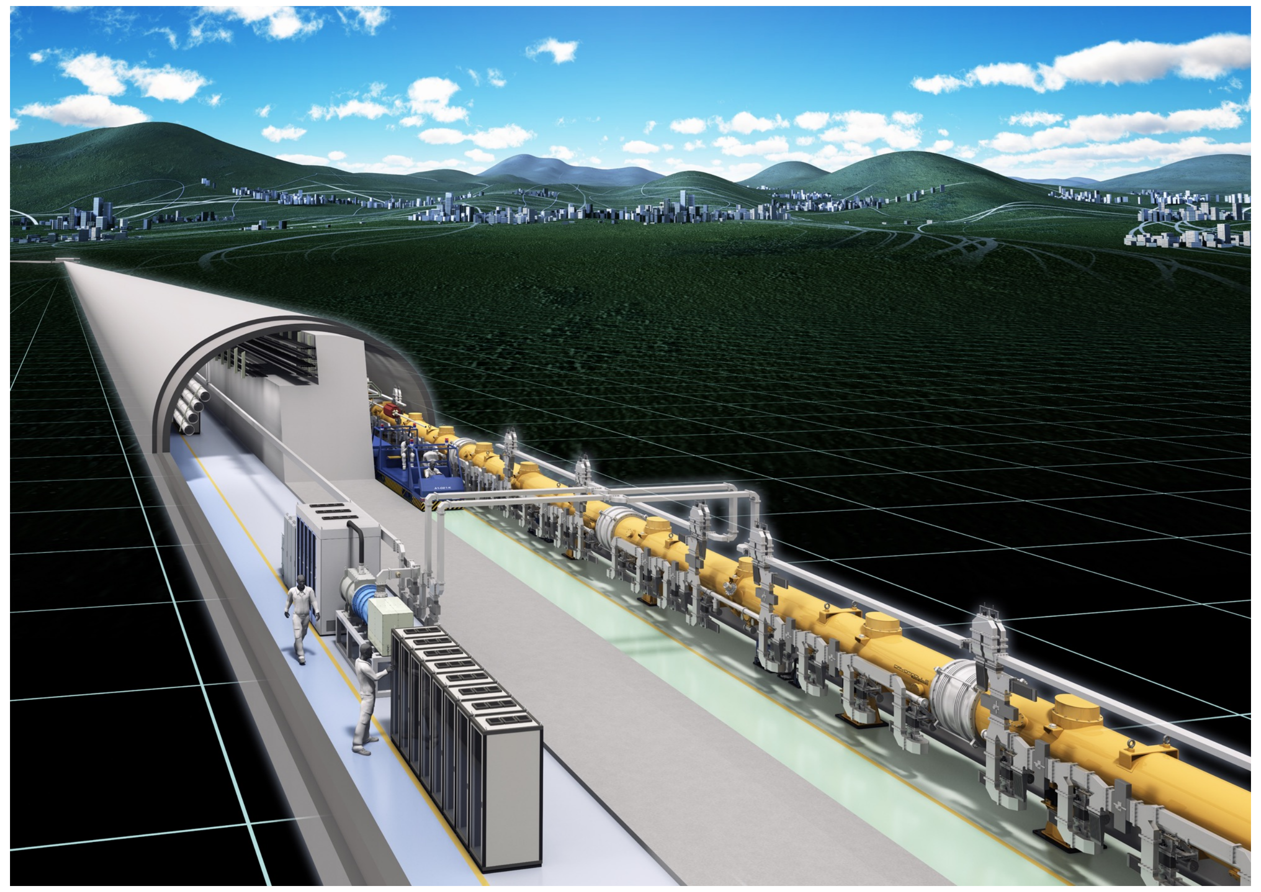
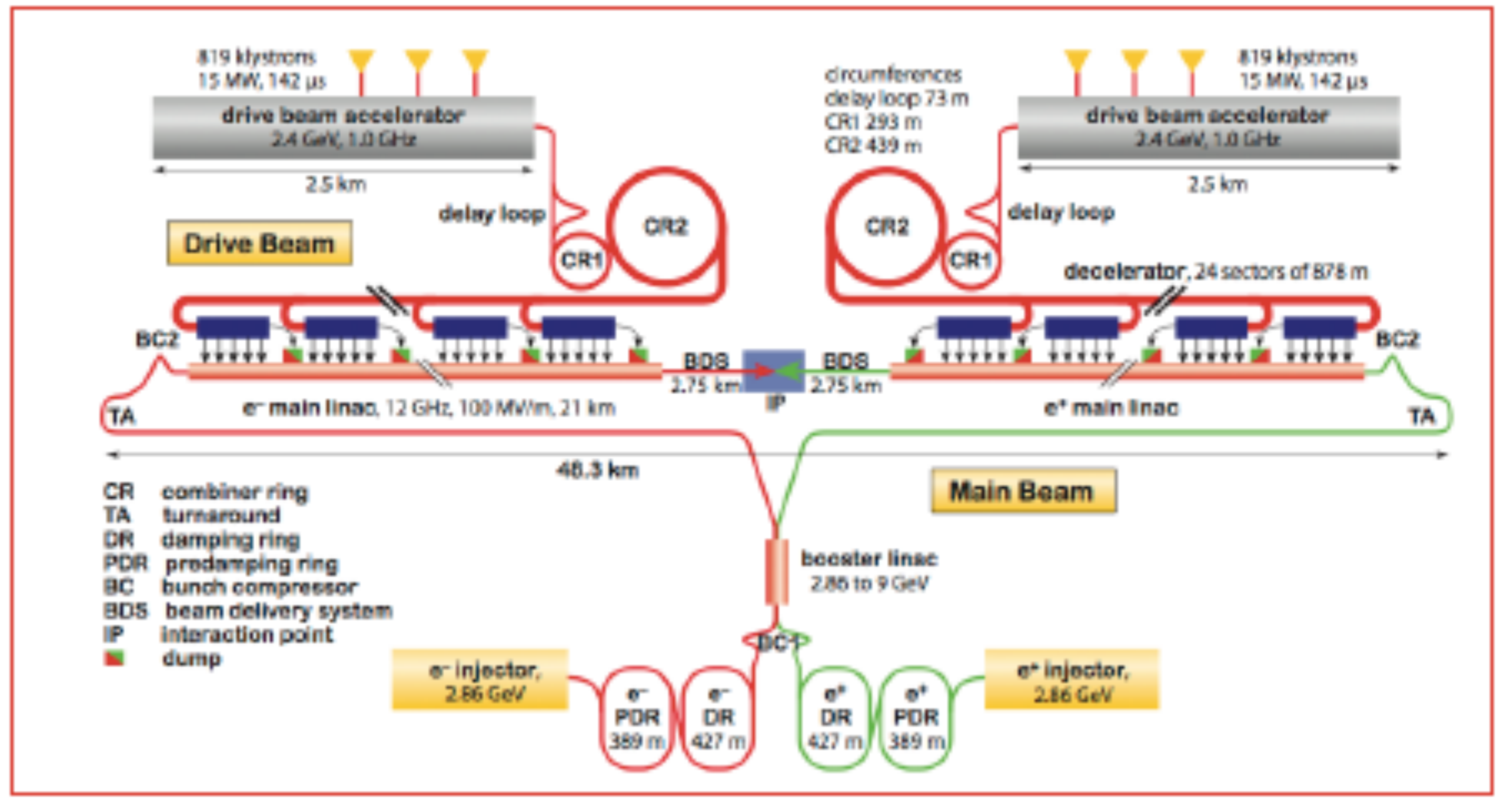
..and CPV in Zh coupling:

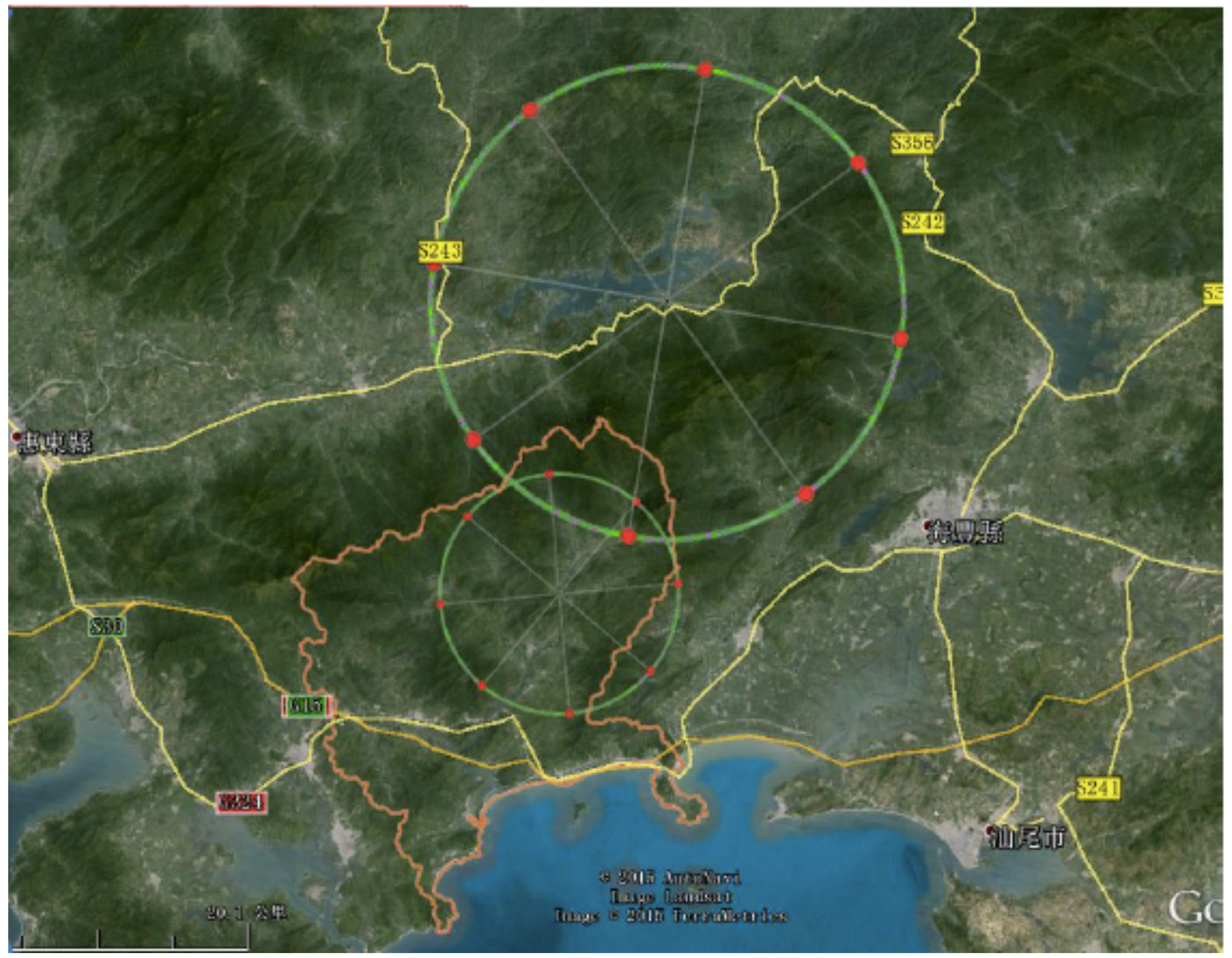
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

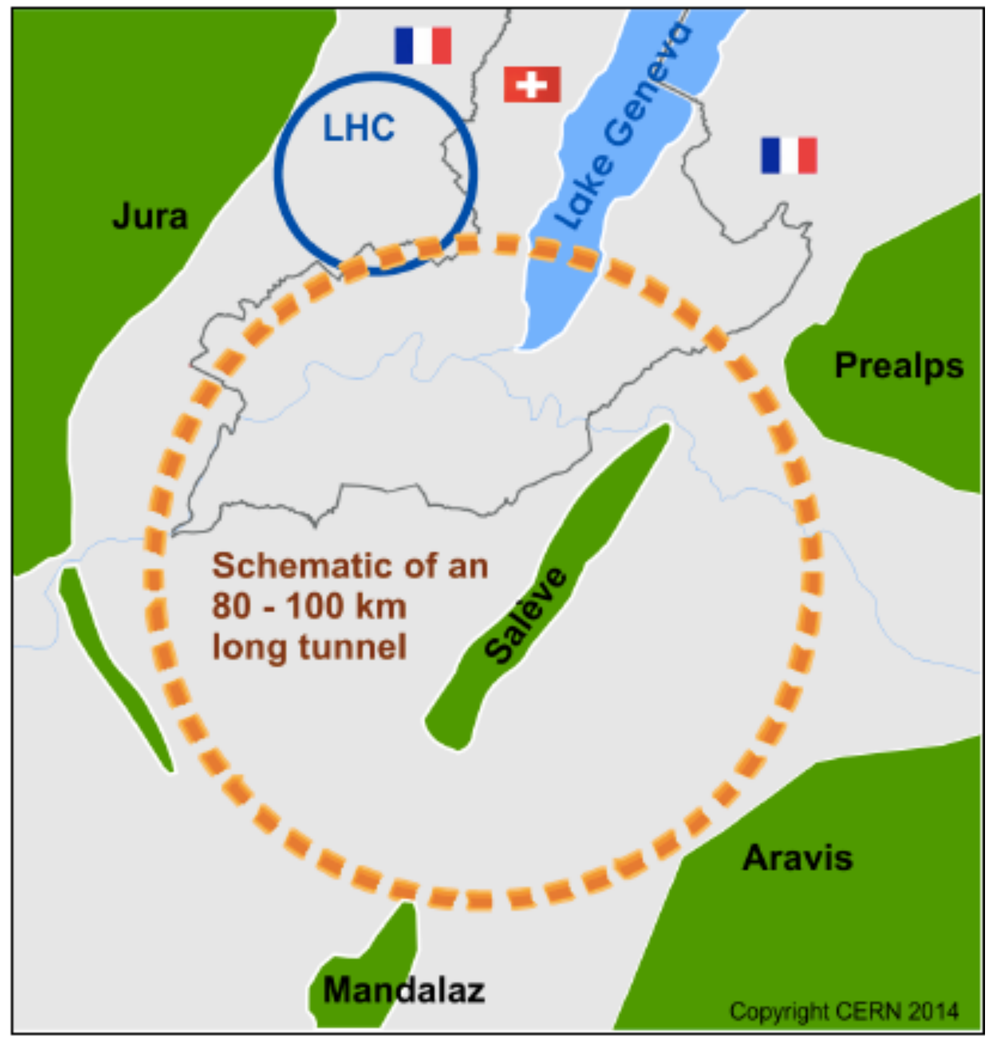
=> $\tilde{b}$ **to ±0.005**

The Key Contenders









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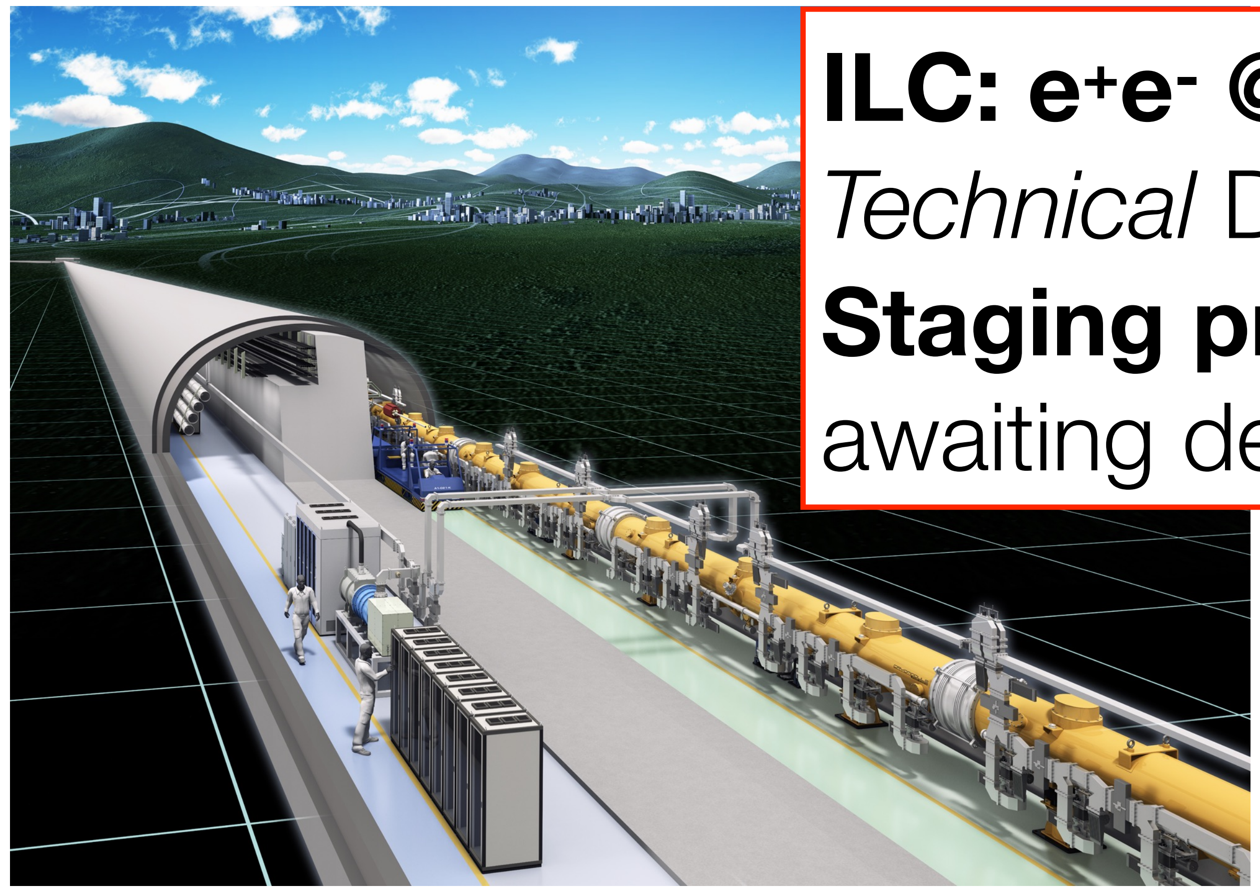
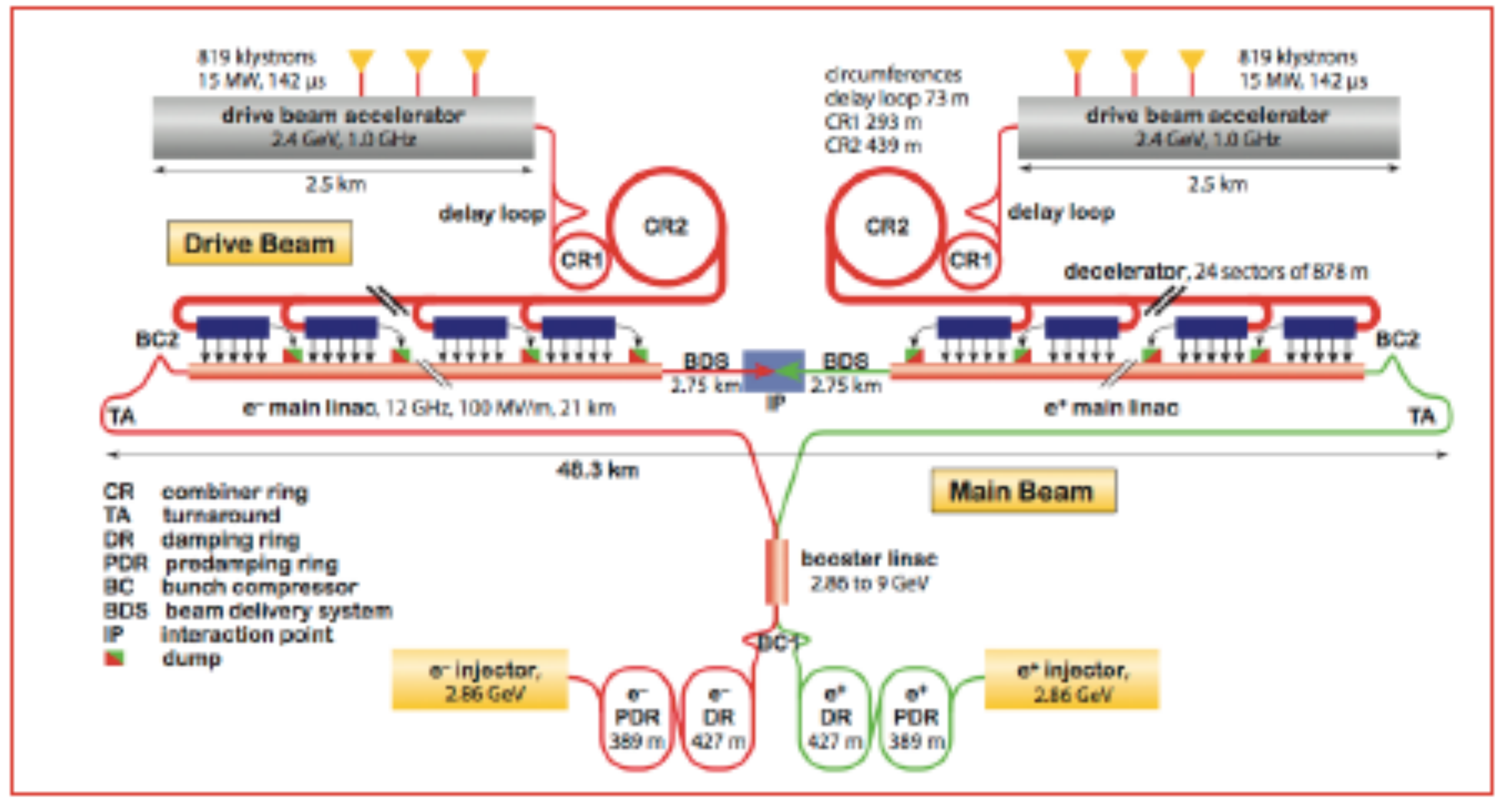
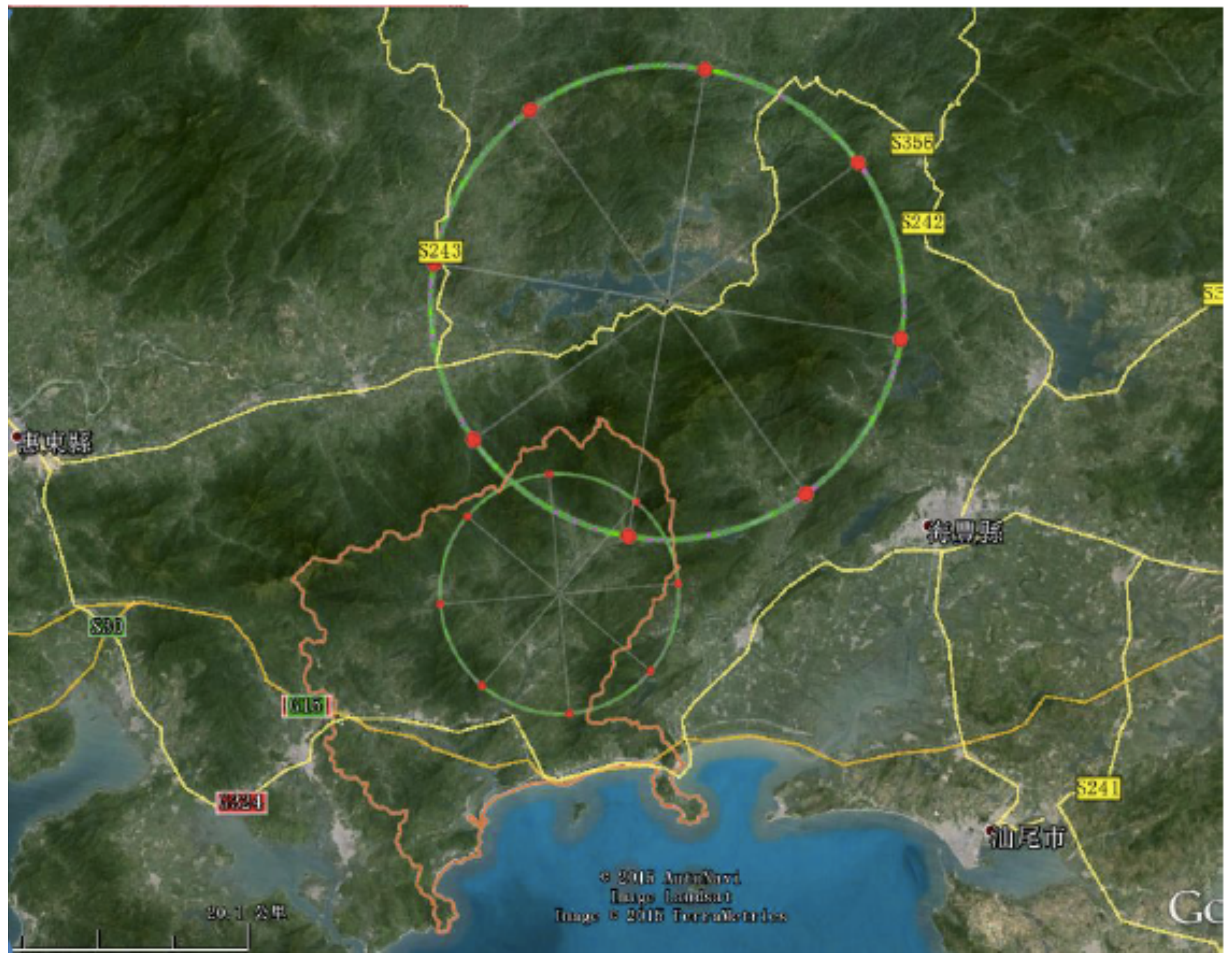
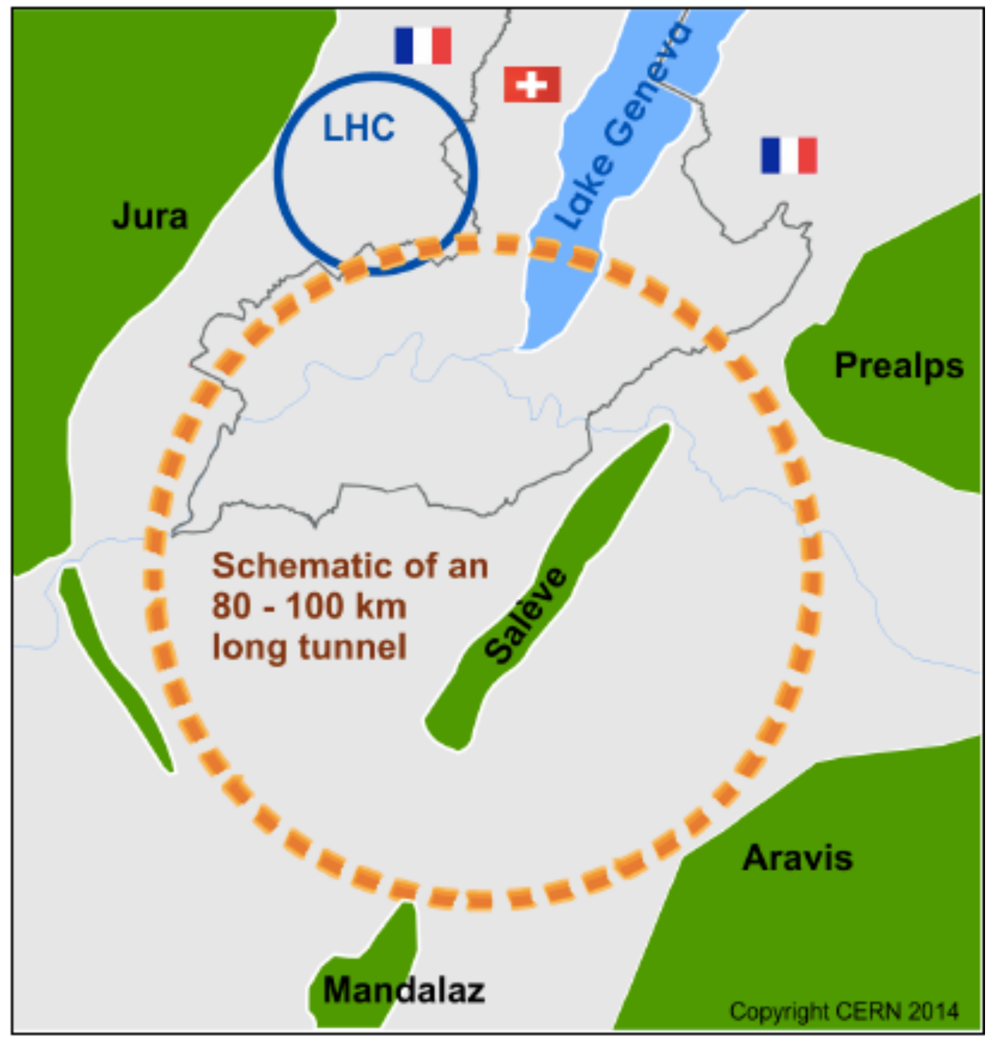


ILC: e+e- @ 200-500 GeV (91 GeV-1TeV)
Technical Design Rep. in **2012**
Staging proposal 2017: start at 250 GeV
awaiting decision by Japanese Government







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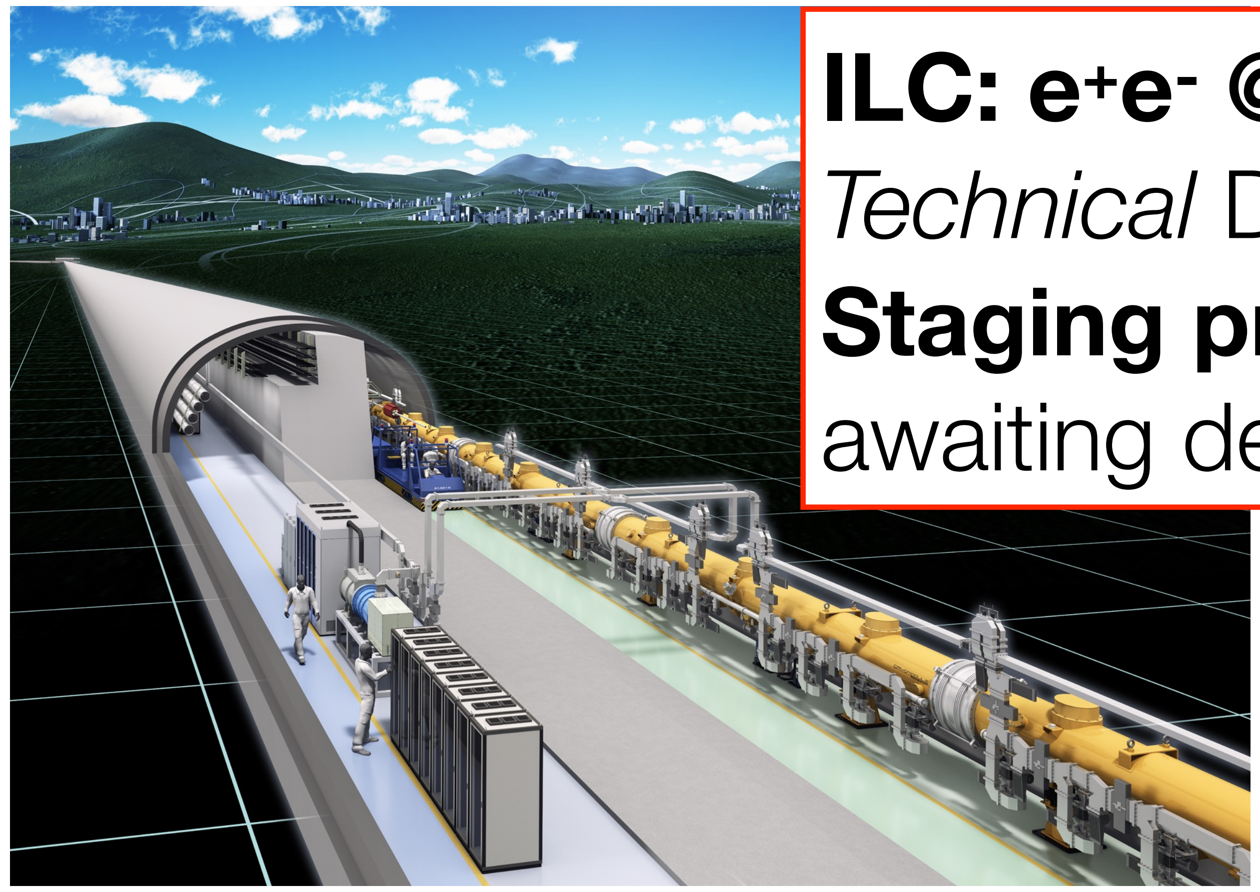

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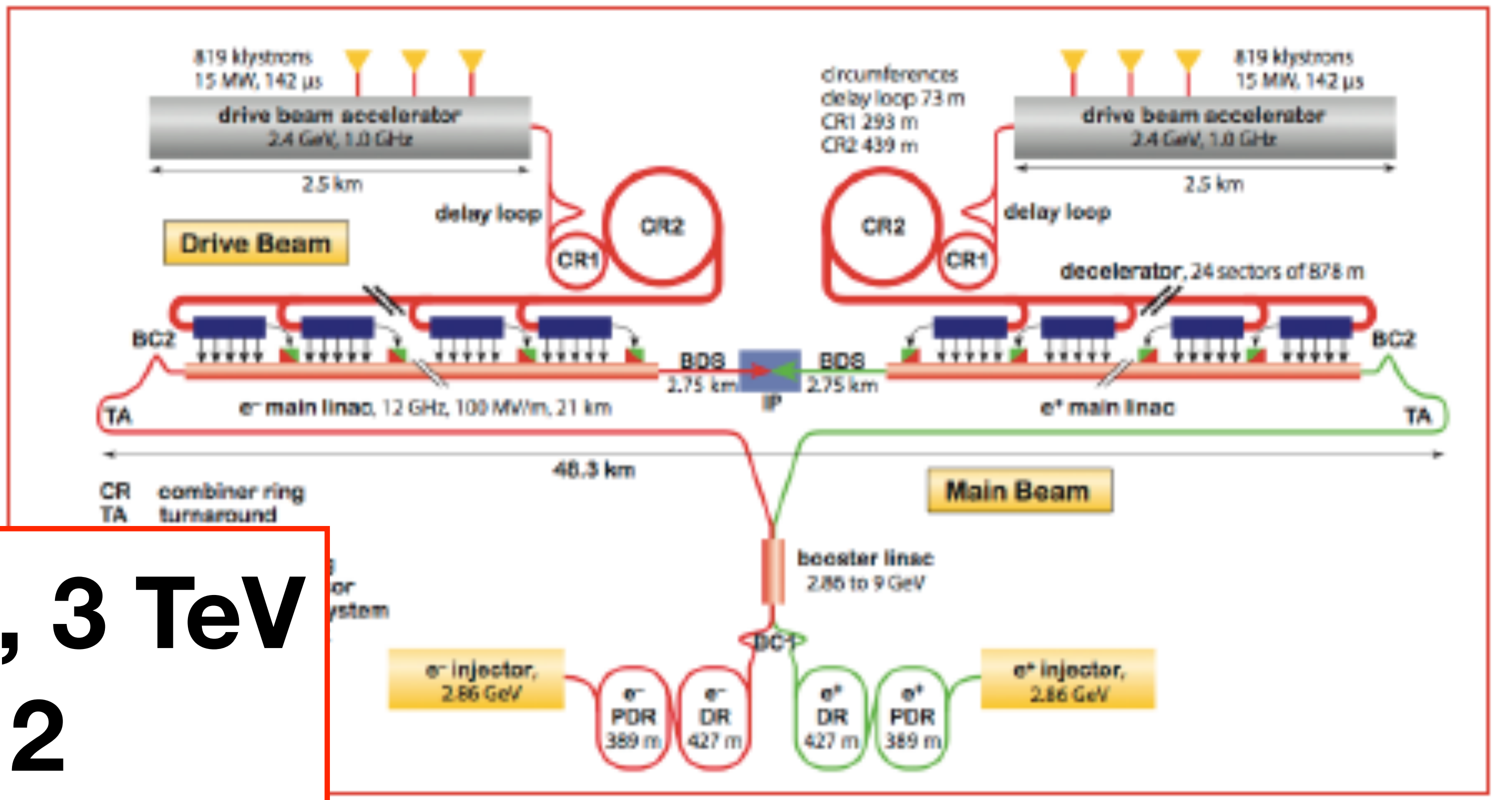
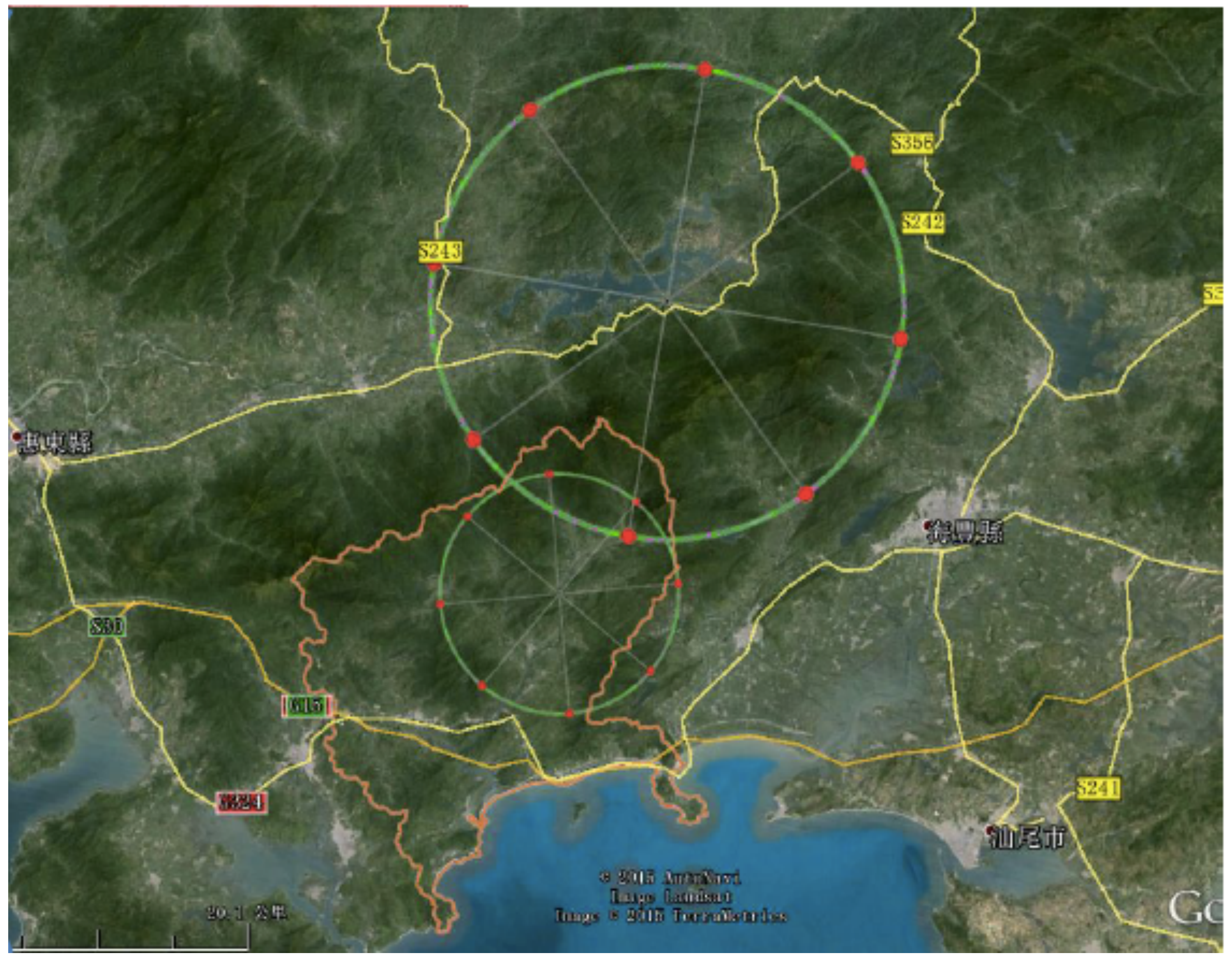
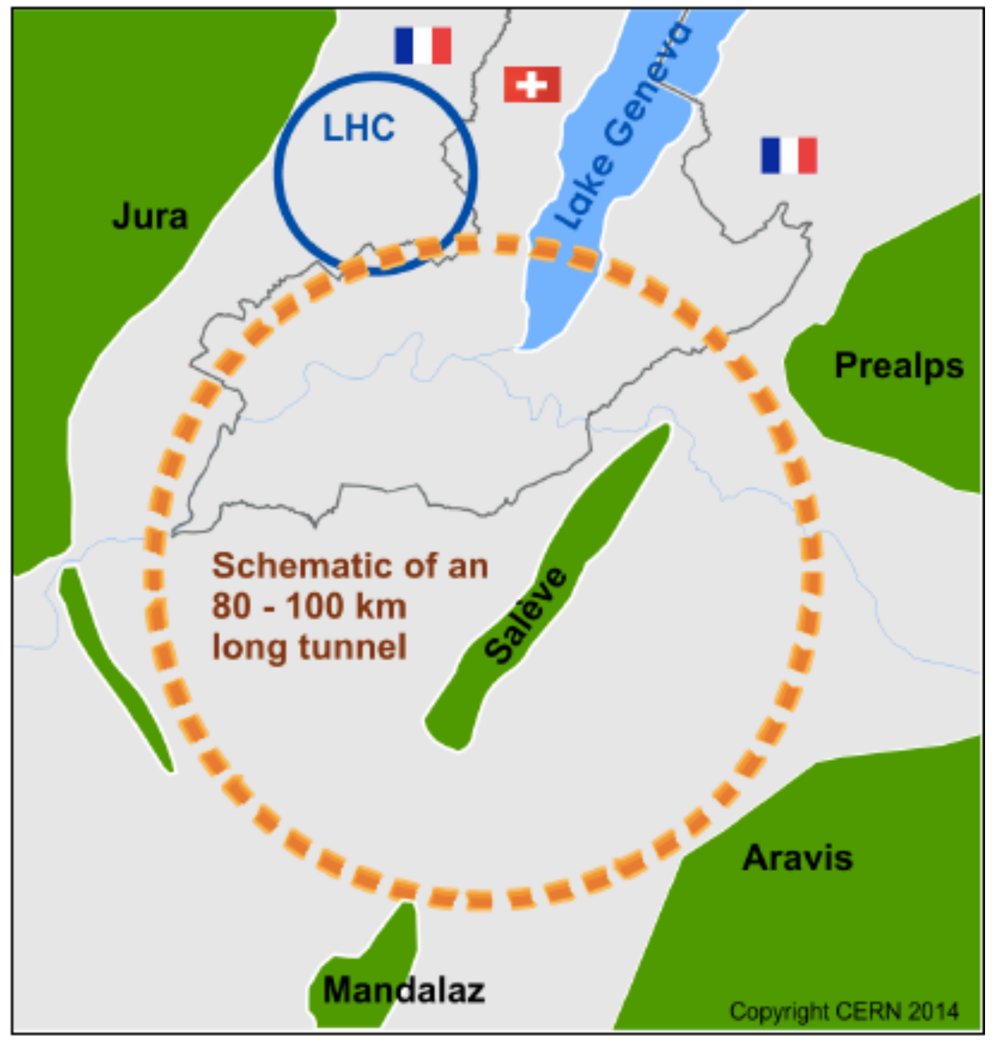


CLIC: e^+e^- @ 0.38, 1.4, 3 TeV
Conceptual Design **2012**
Updated Baseline in **2017**





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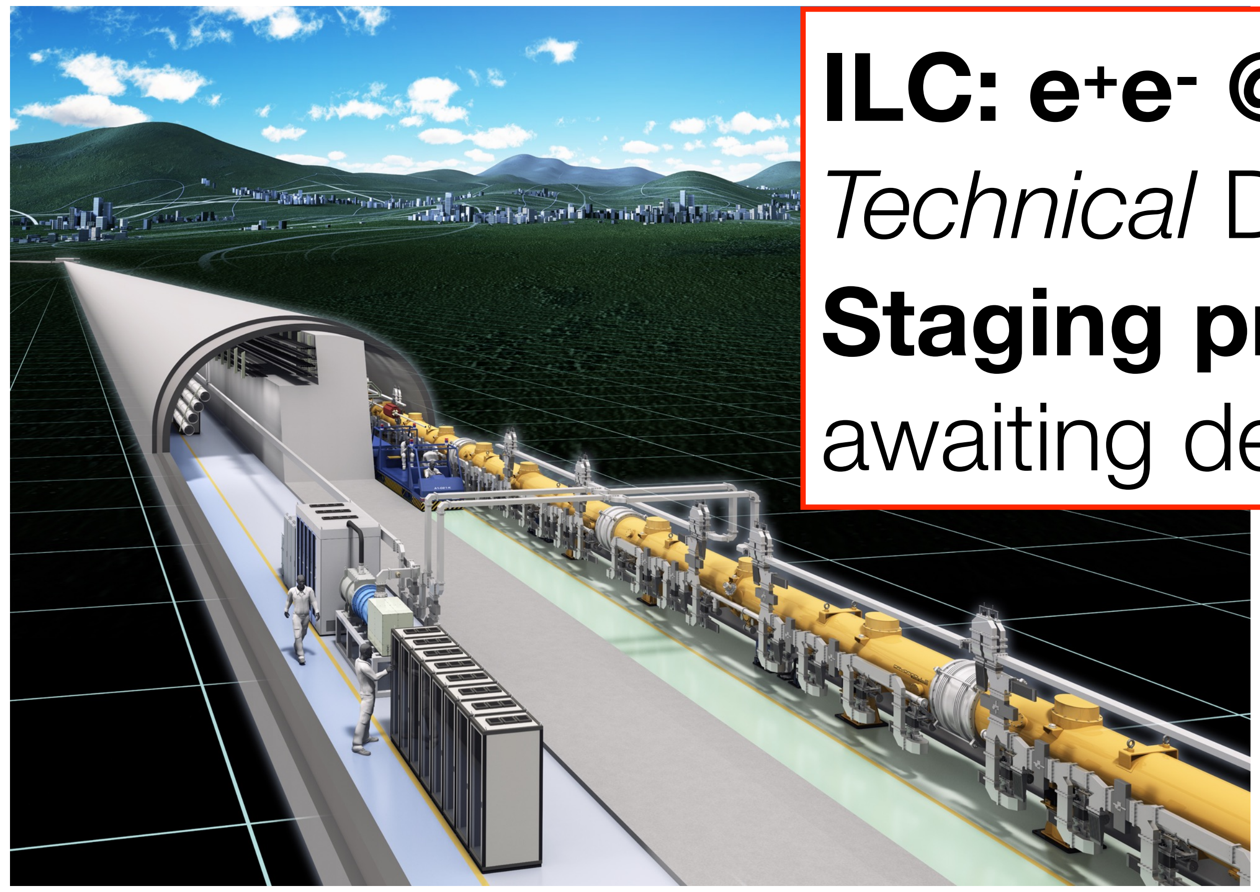

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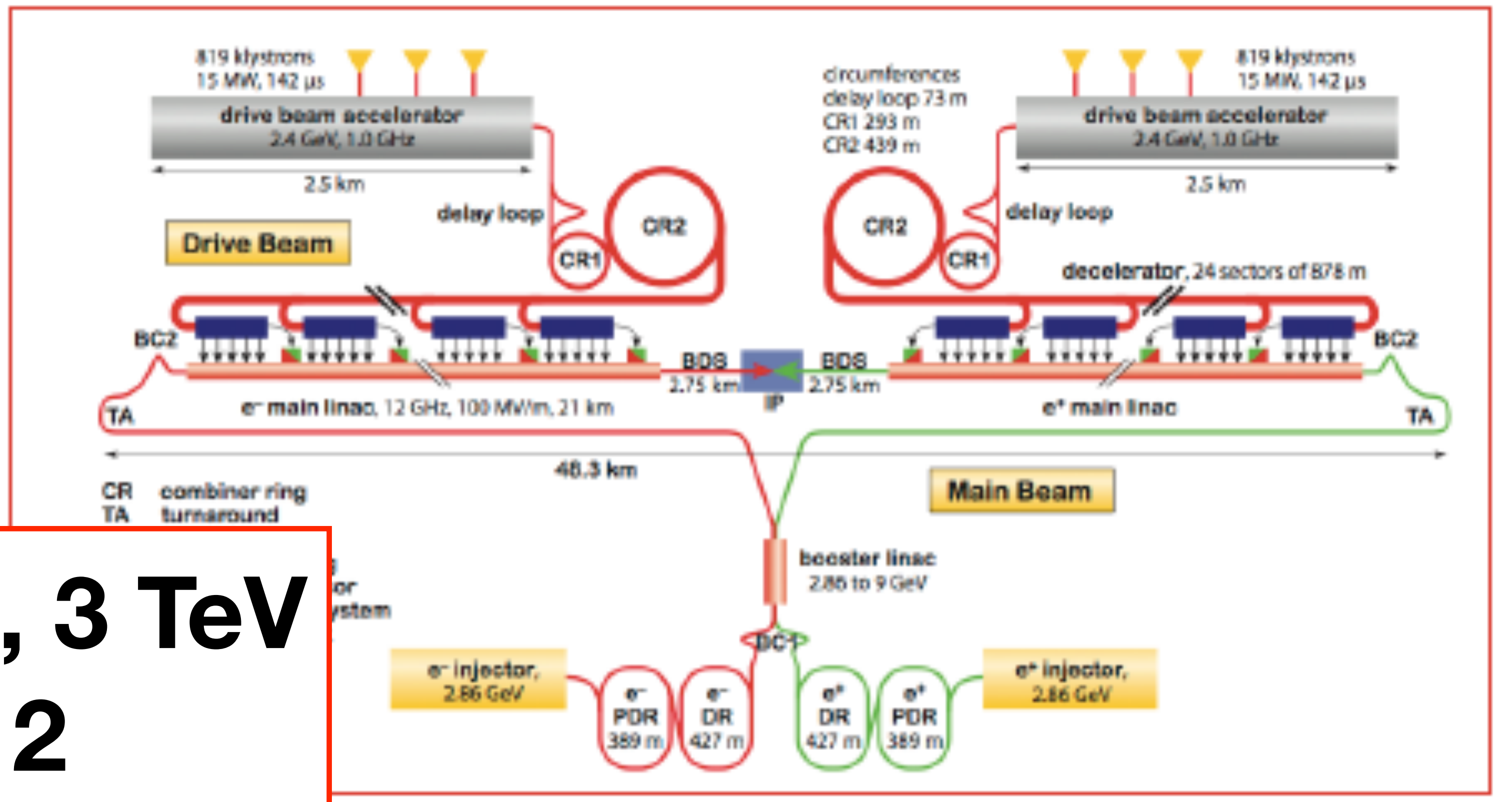

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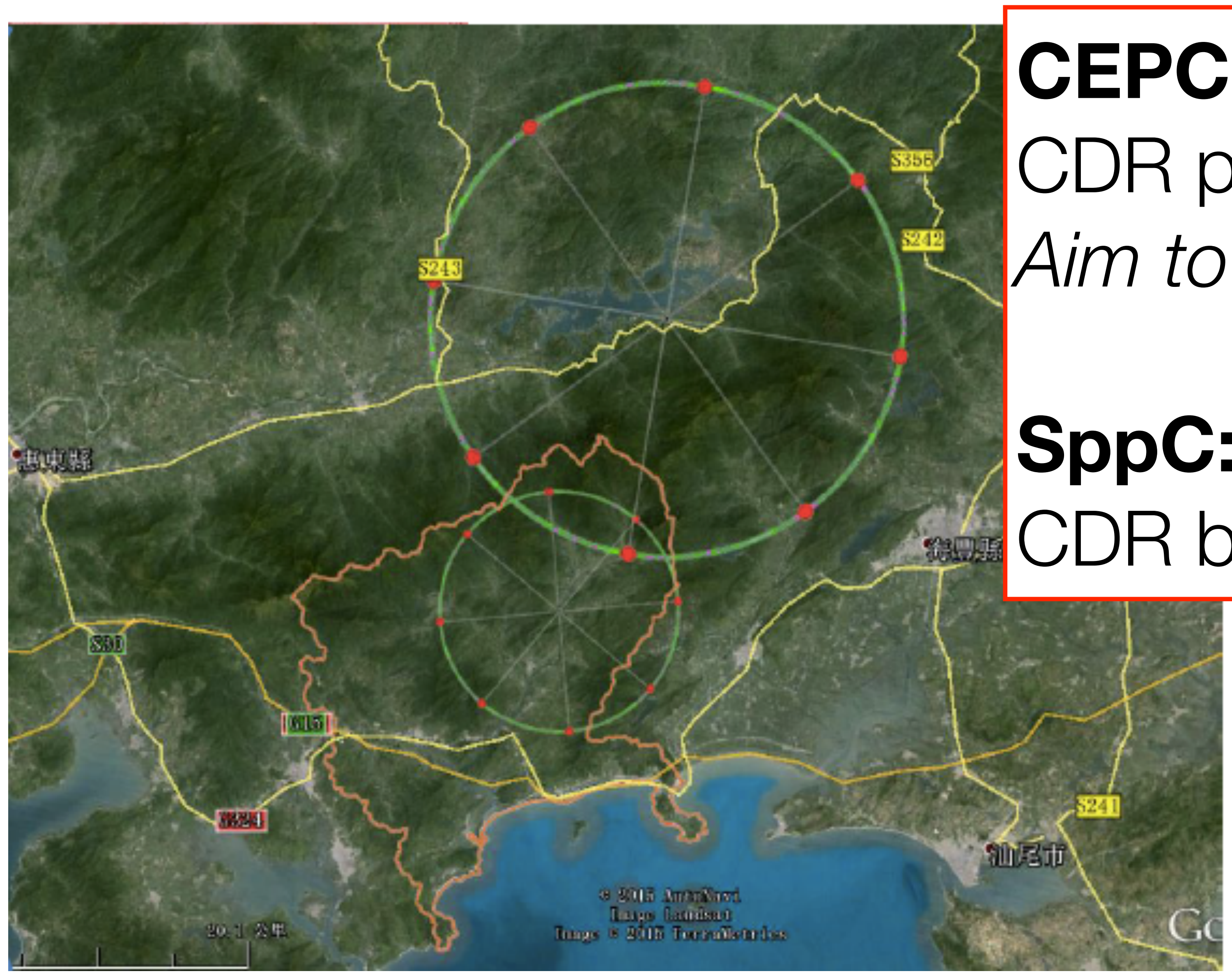
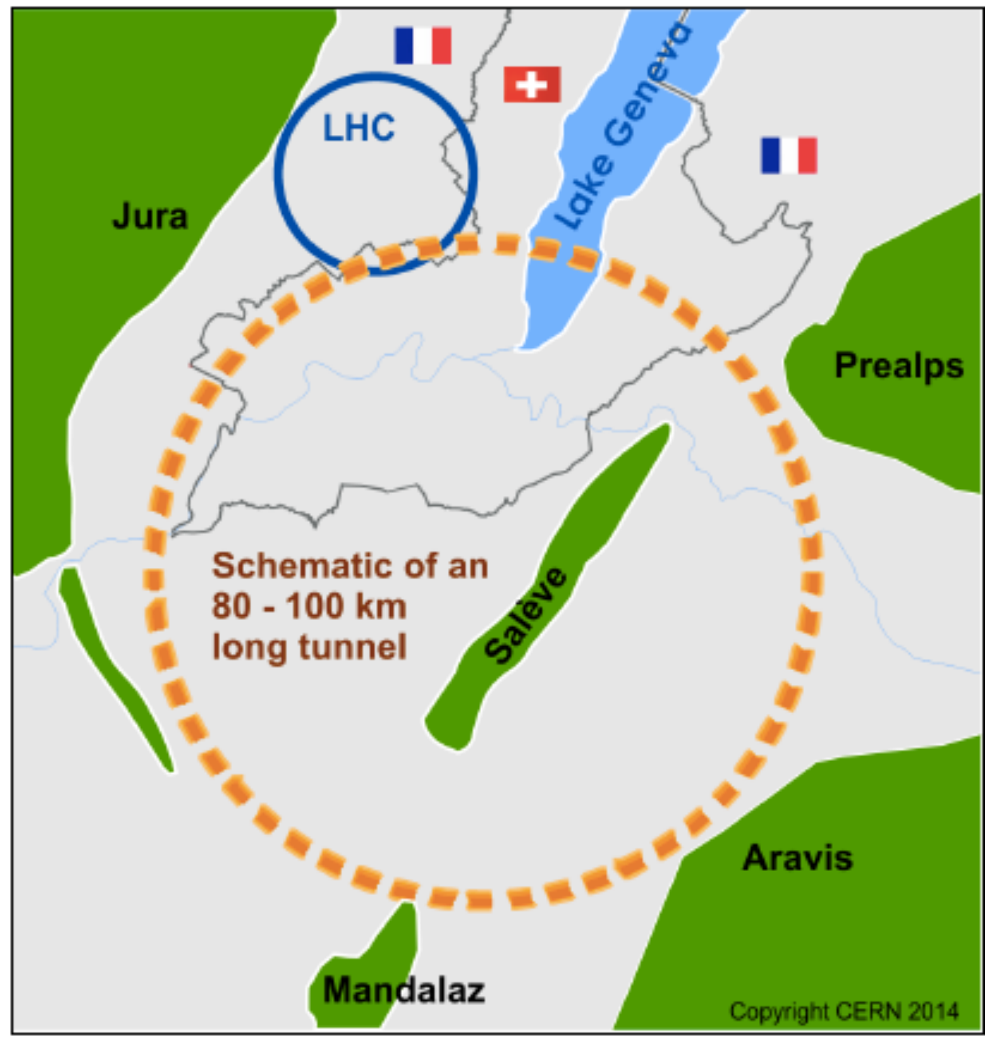
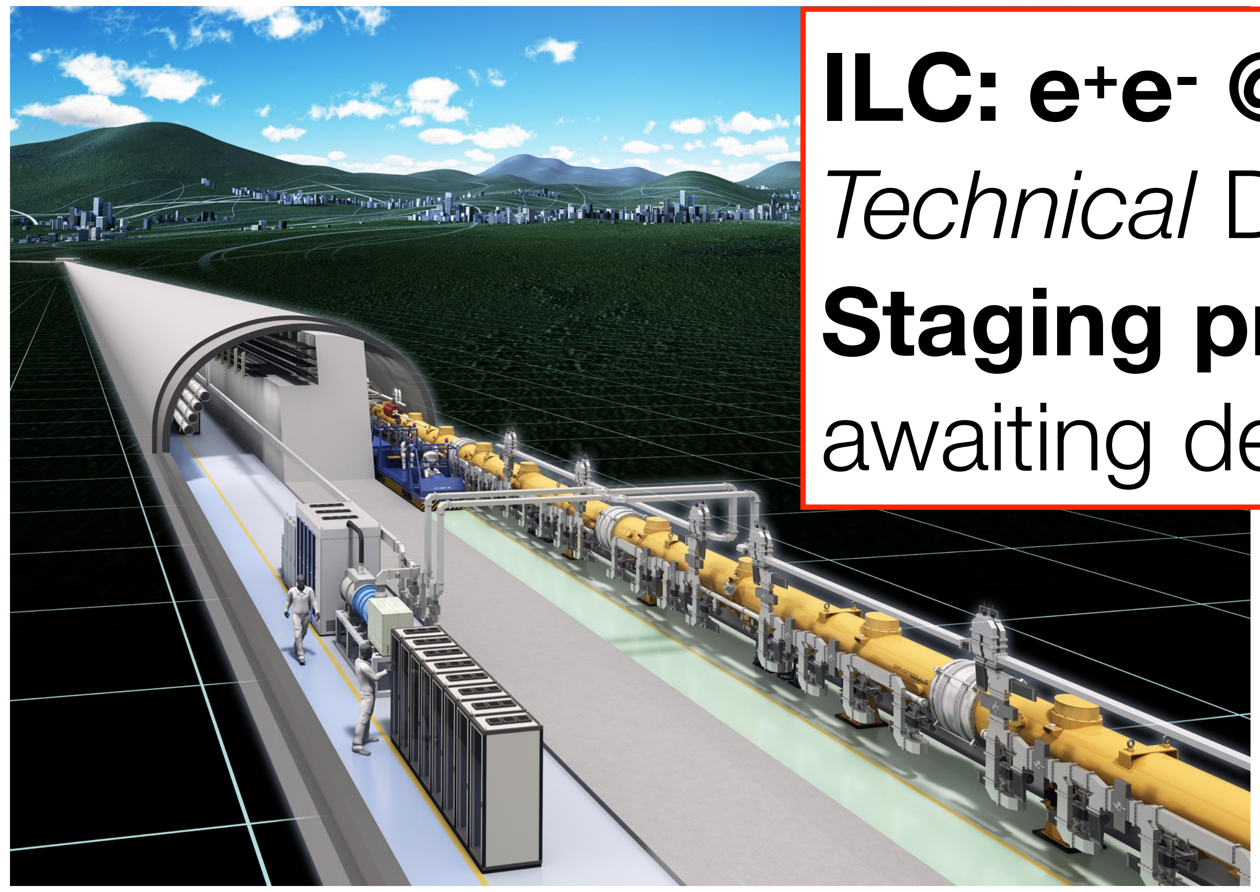


CEPC: e+e- @ 240 GeV
CDR published in **2018**
Aim to start construction in **2023**

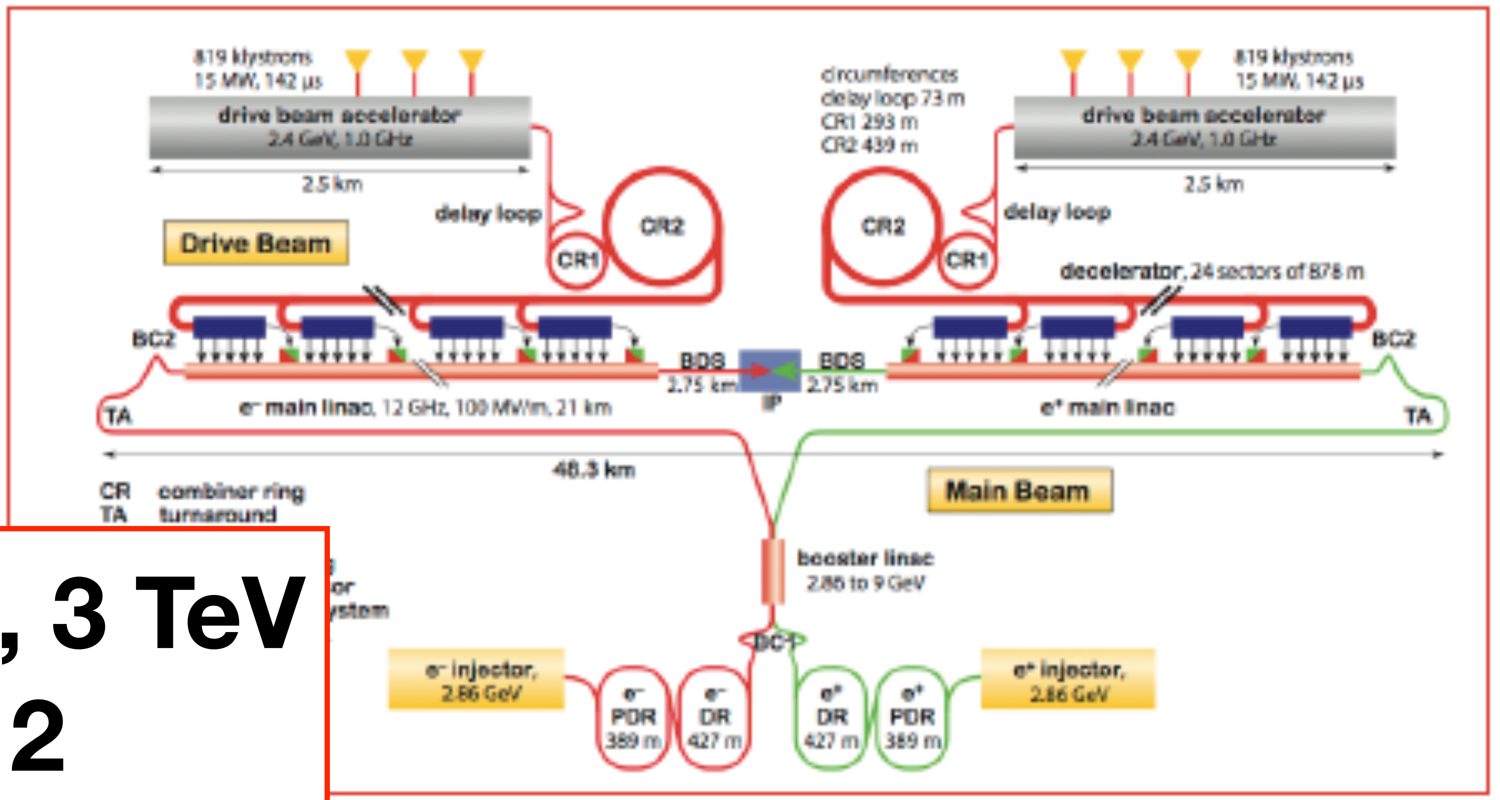
SppC: pp @ 50-70 TeV
CDR by **2035**



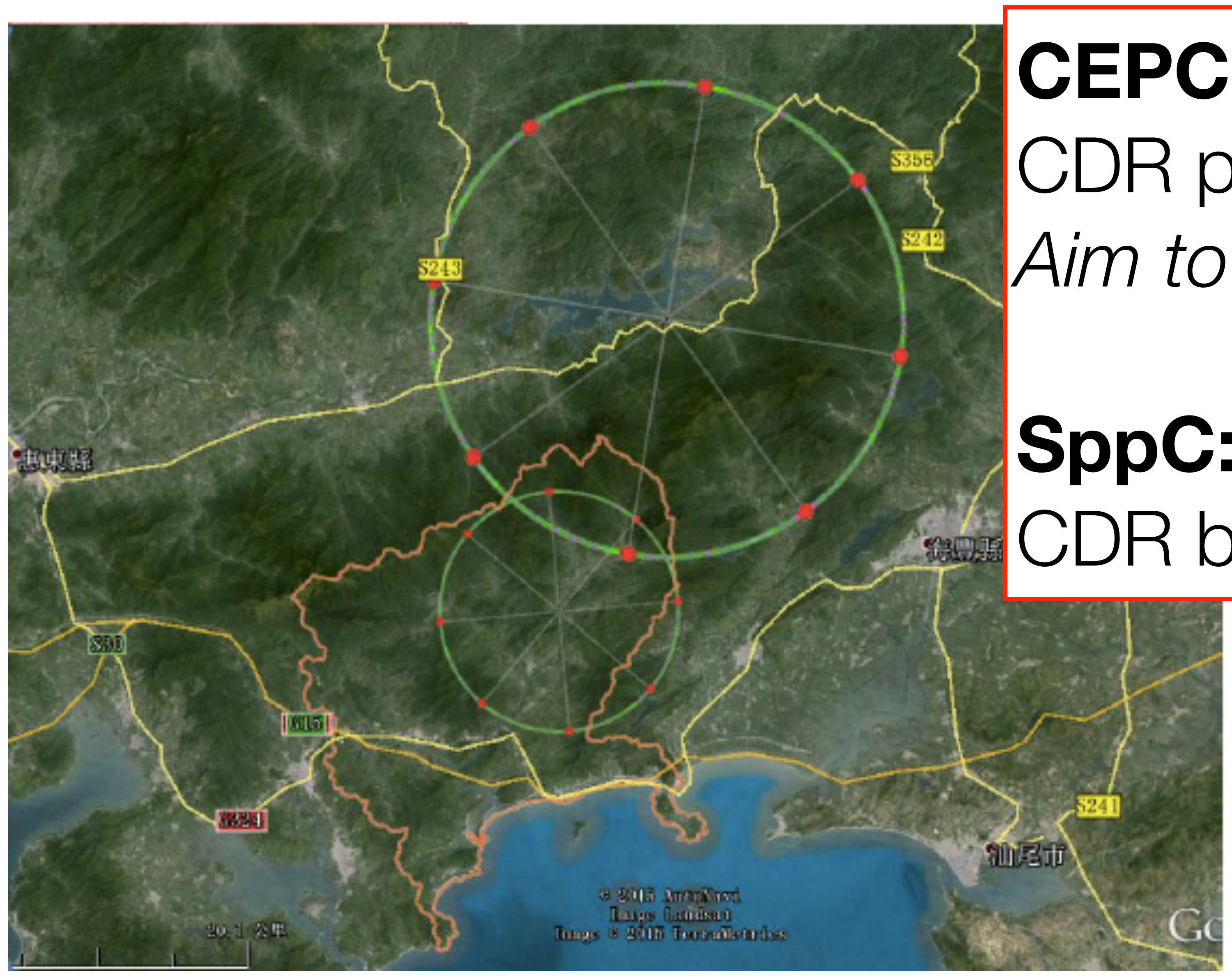
The Key Contenders



ILC: e+e- @ 200-500 GeV (91 GeV-1TeV)
Technical Design Rep. in **2012**
Staging proposal 2017: start at 250 GeV
awaiting decision by Japanese Government

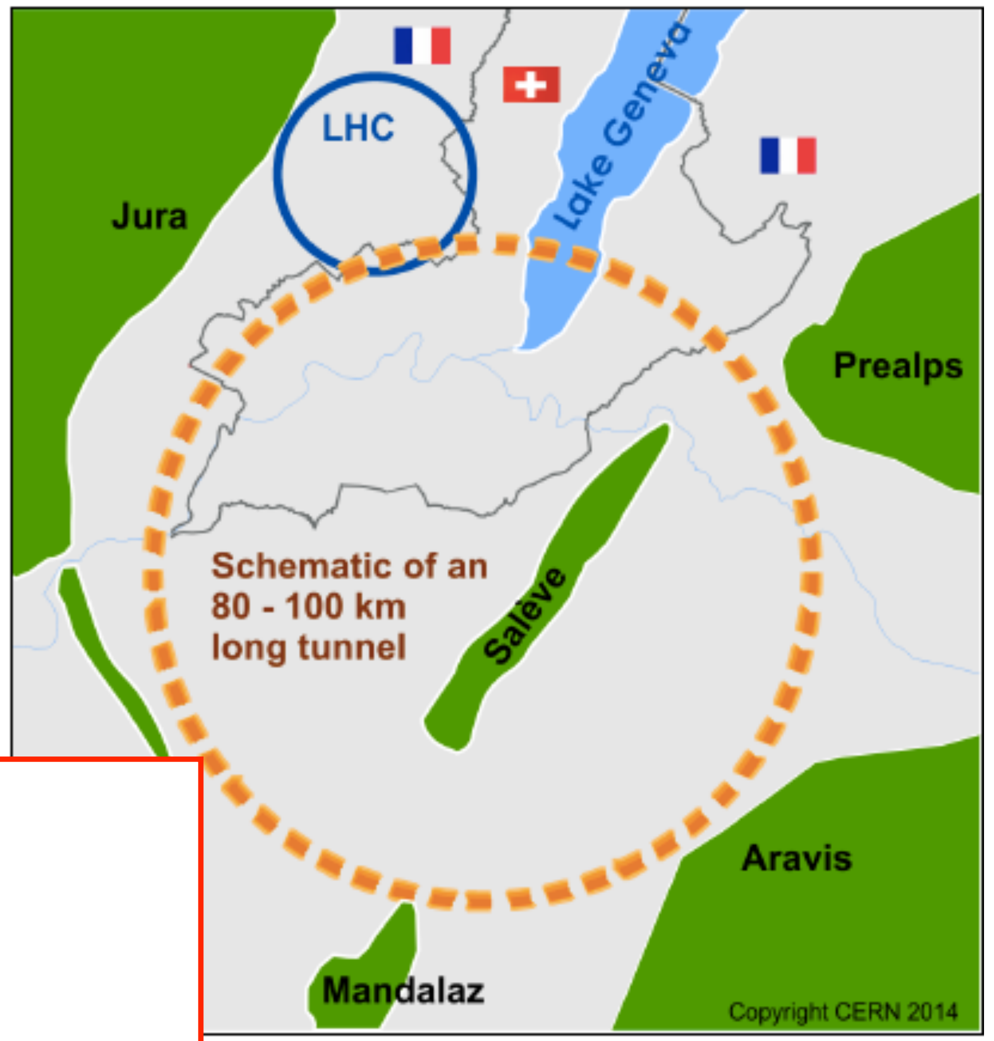


CLIC: e+e- @ 0.38, 1.4, 3 TeV
Conceptual Design **2012**
Updated Baseline in **2017**



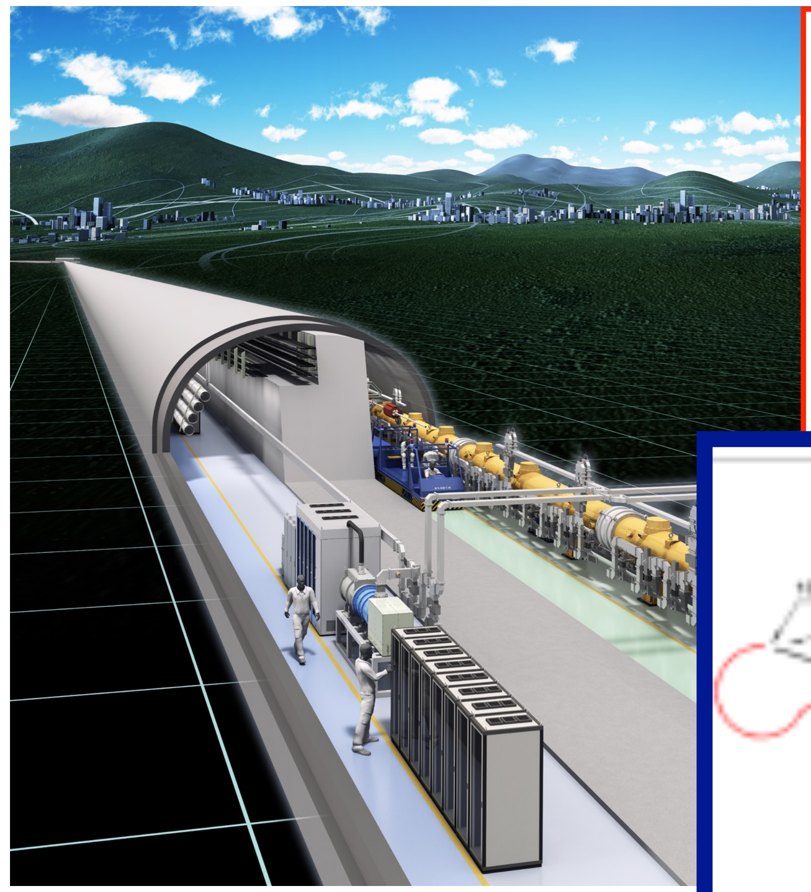
CEPC: e+e- @ 240 GeV
CDR published in **2018**
Aim to start construction in **2023**

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



FCC: pp @ 100 TeV
& precursor **e+e- @ 90-350 GeV**
Feasibility Study ongoing

The Key Contenders



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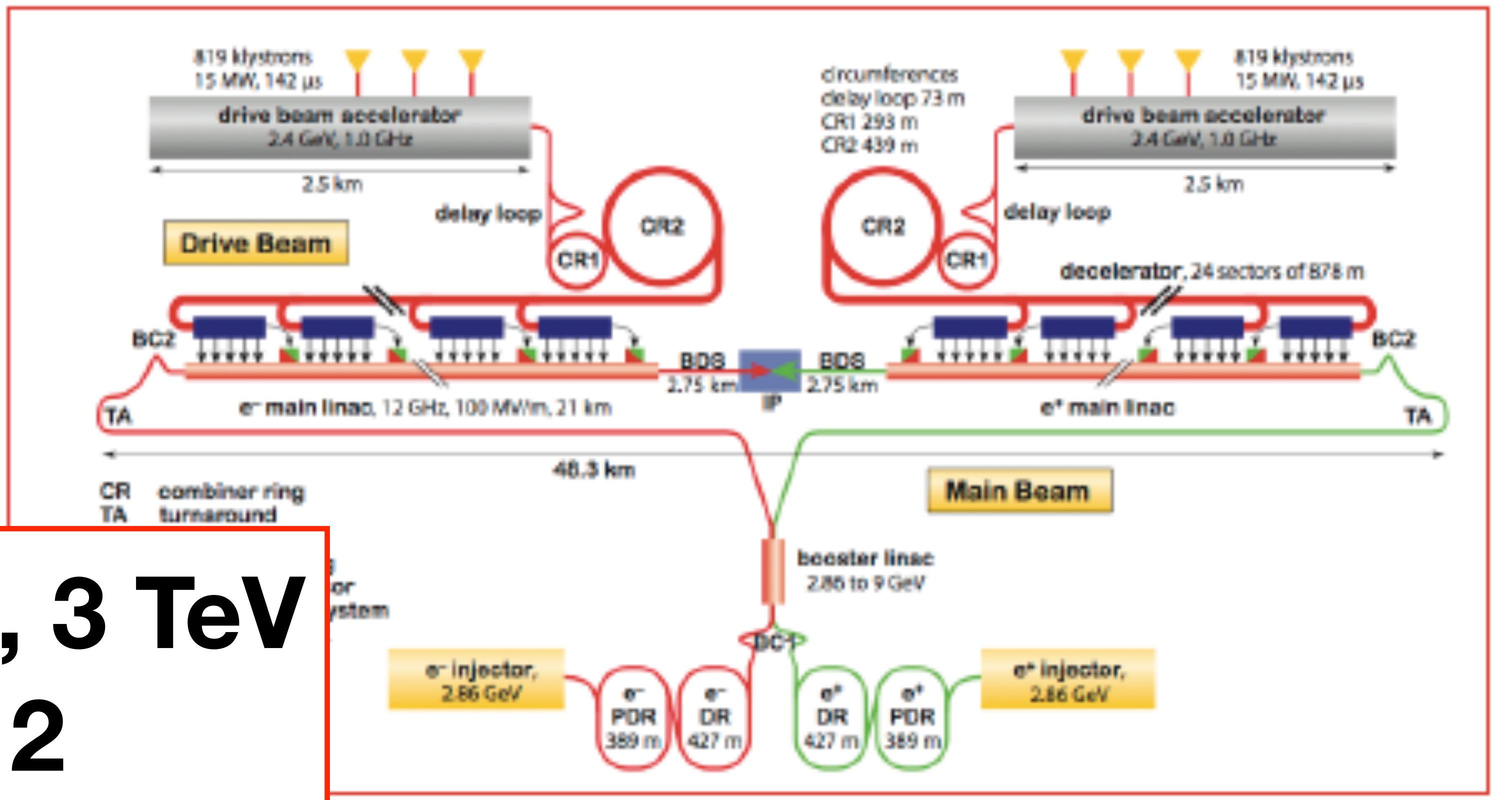

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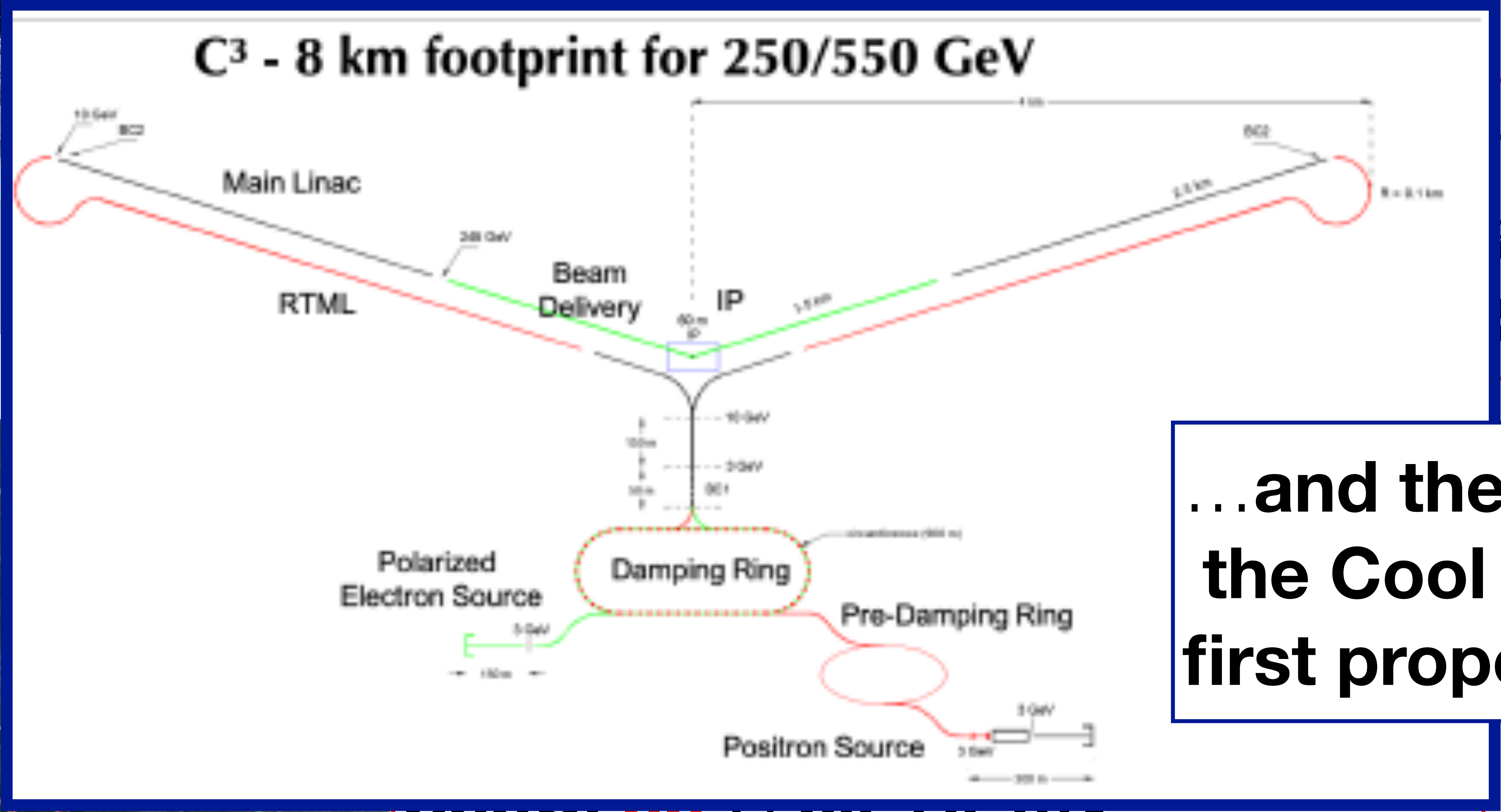
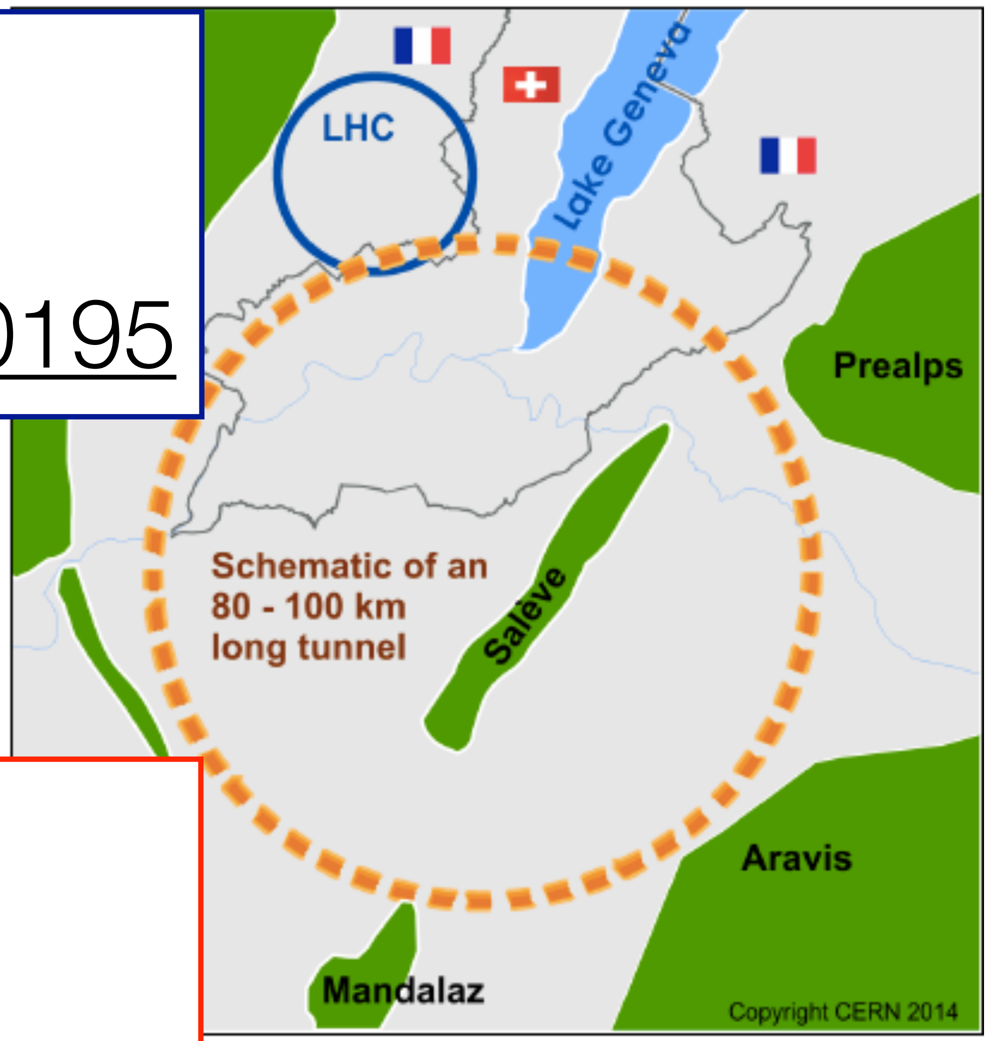


pp
CDR by **2035**

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



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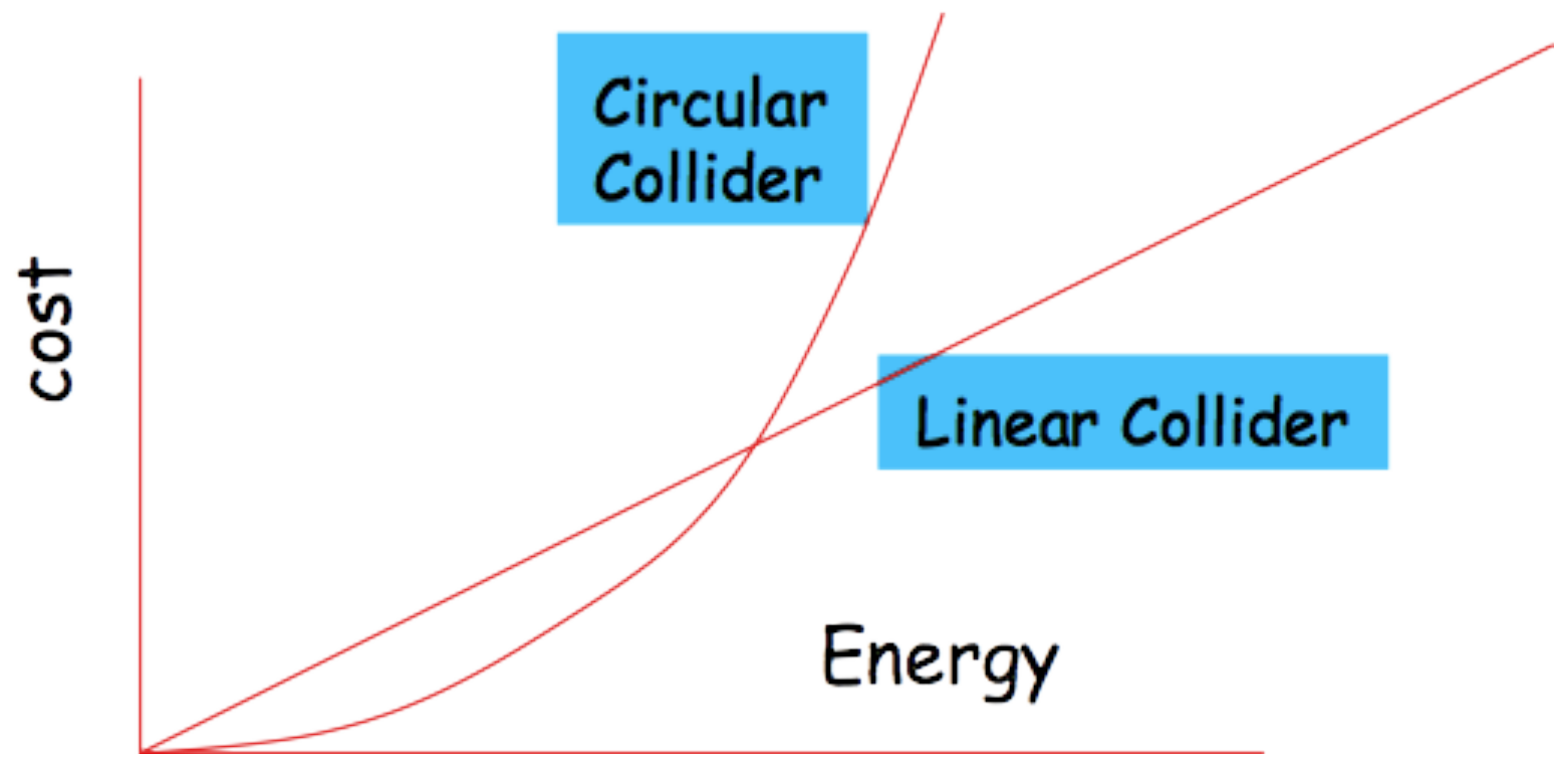
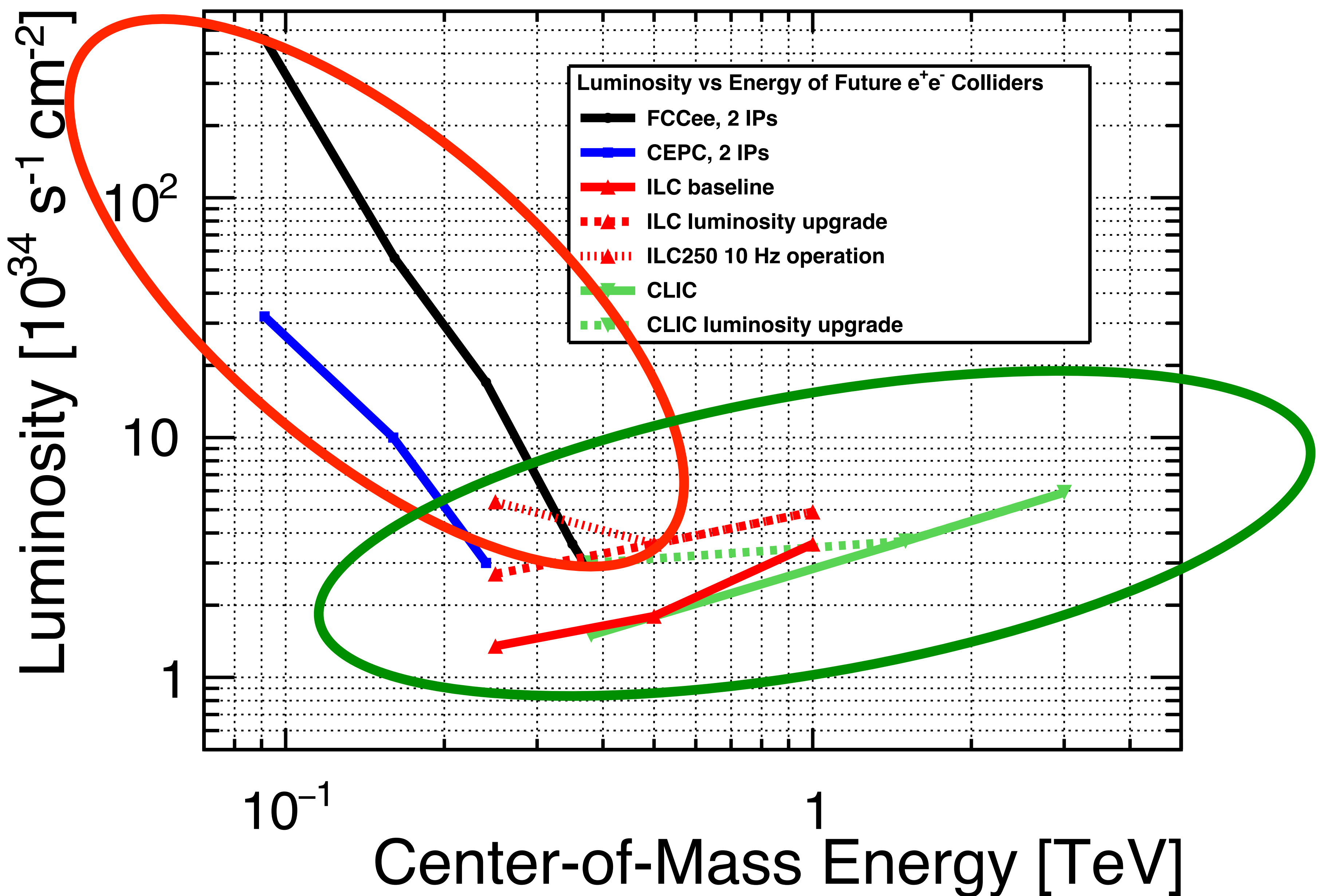
Linear or Circular ?

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

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





Advantanges of Circular Colliders

- high luminosities at low energies
- multiple interaction regions
- **little beamstrahlung**

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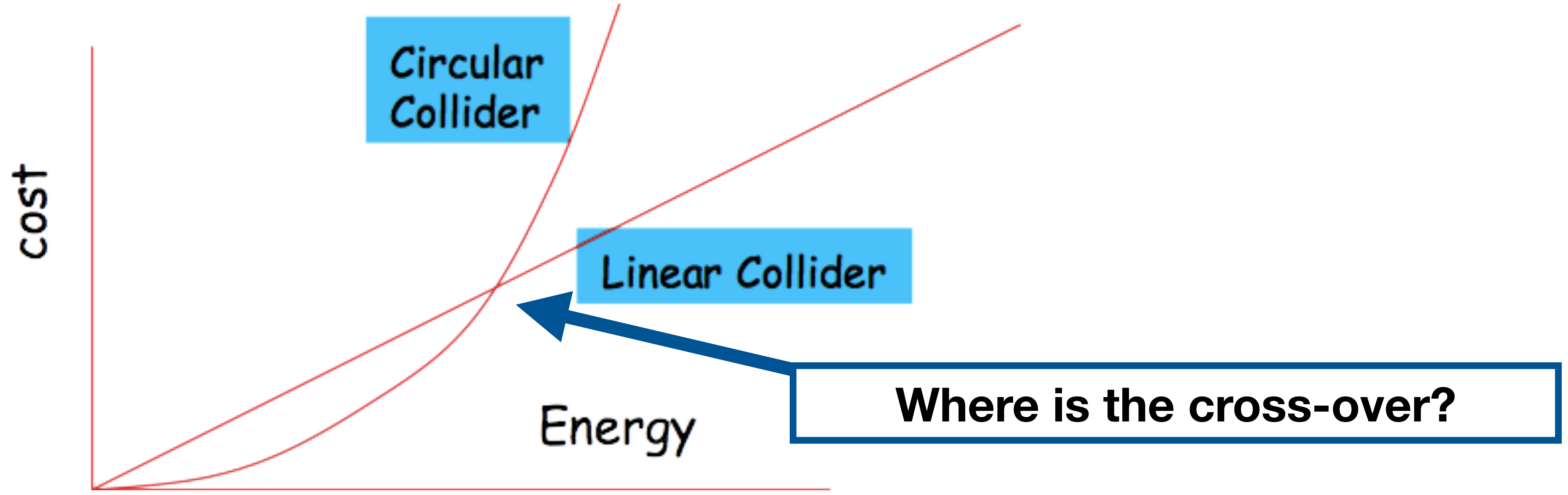

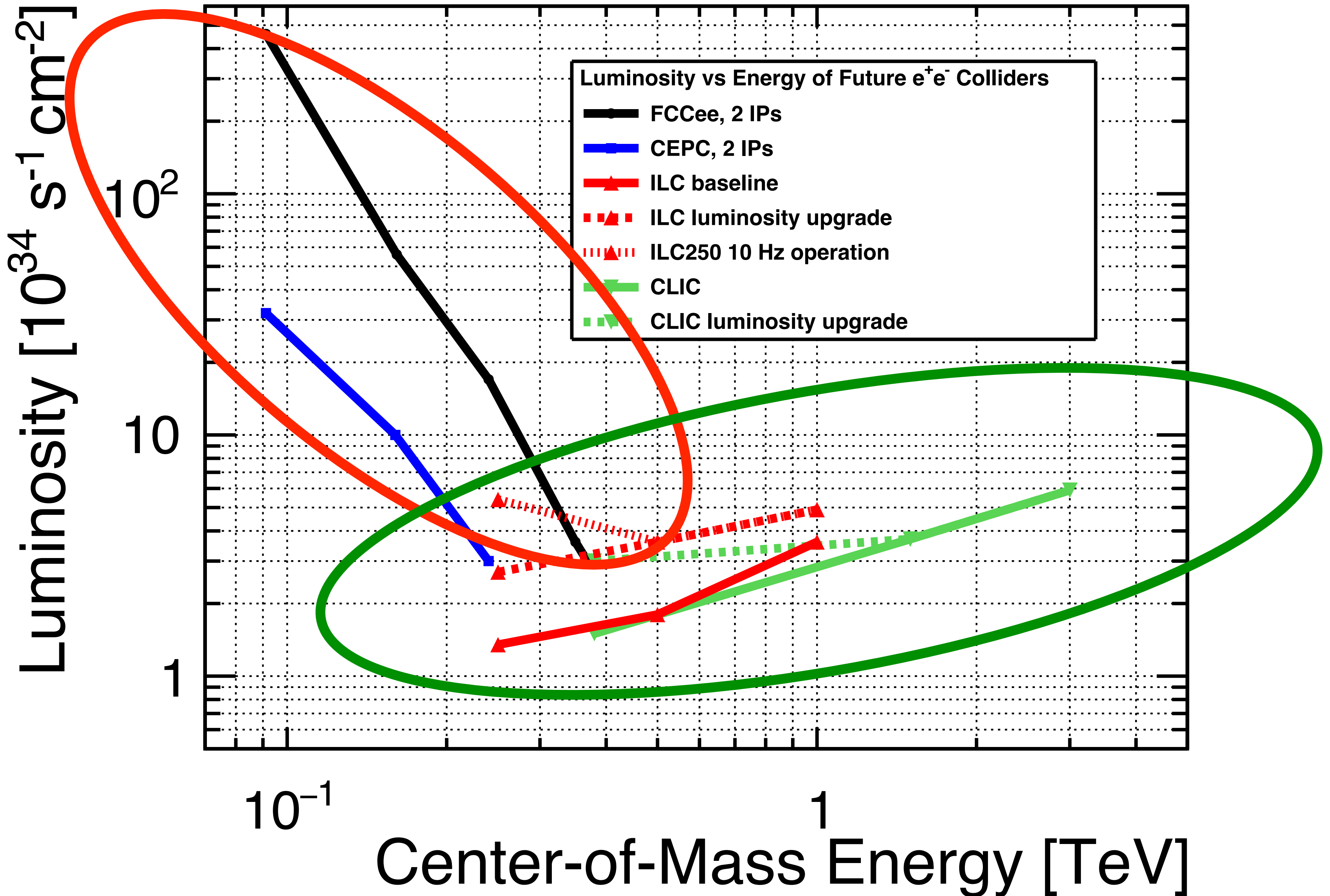

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New insights from old friends… at the Z pole and up to 250 GeV

The Top and Bottom Quark

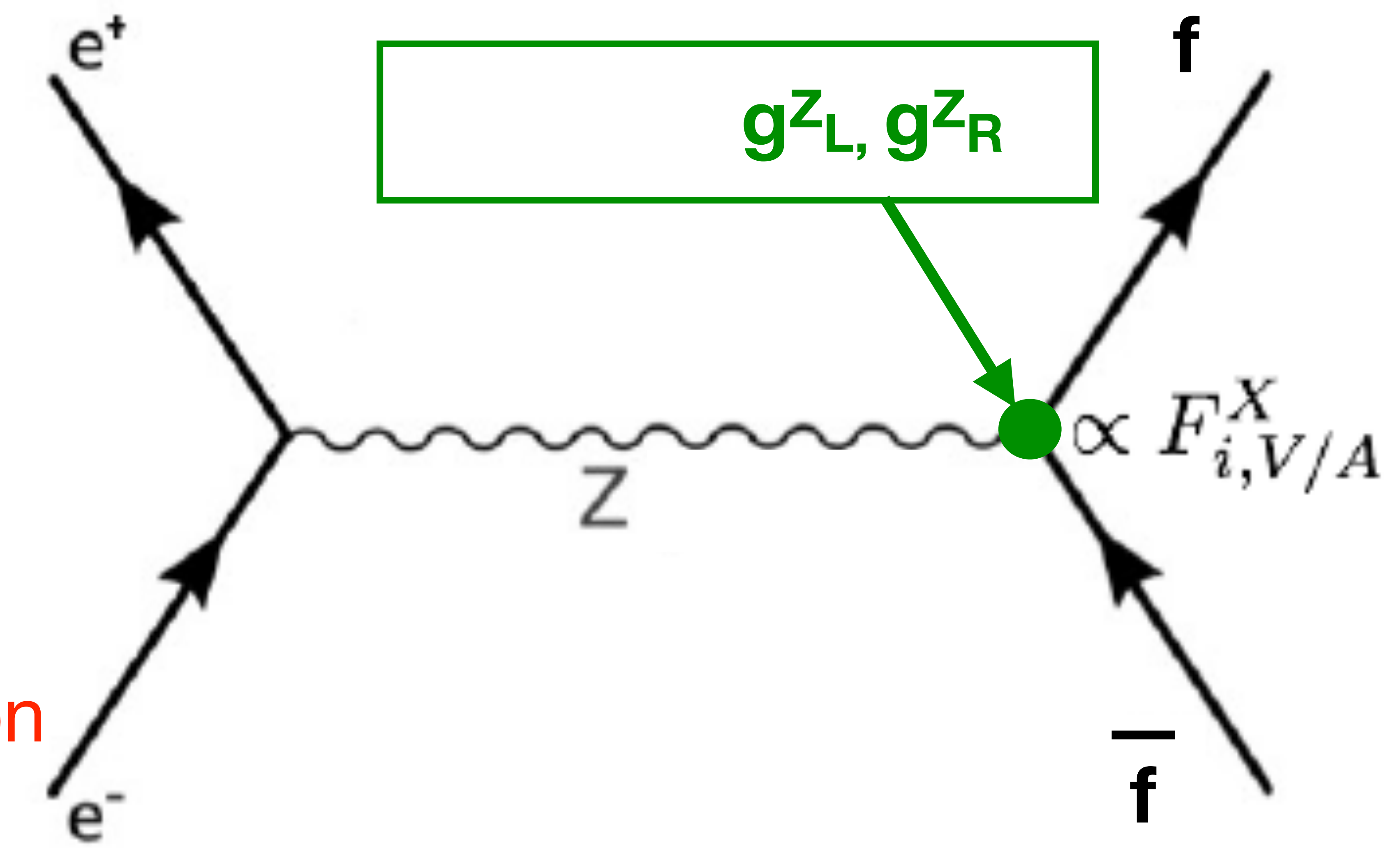
Z & W Bosons

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:

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

=> A_e O(0.1) reduces sensitivity to A_f,
and must be accessed via τ polarisation

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

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

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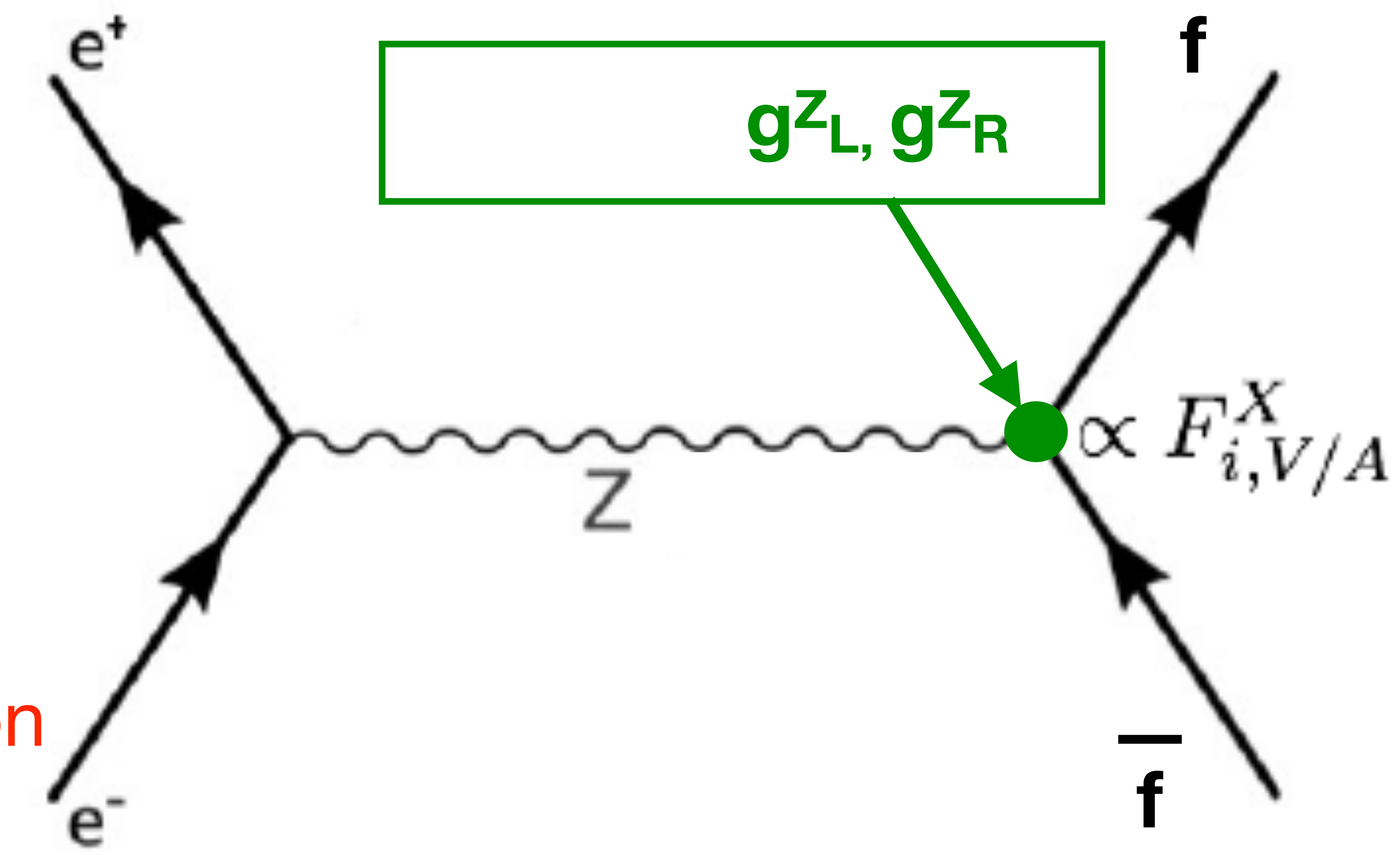

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trading theory uncertainy:

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

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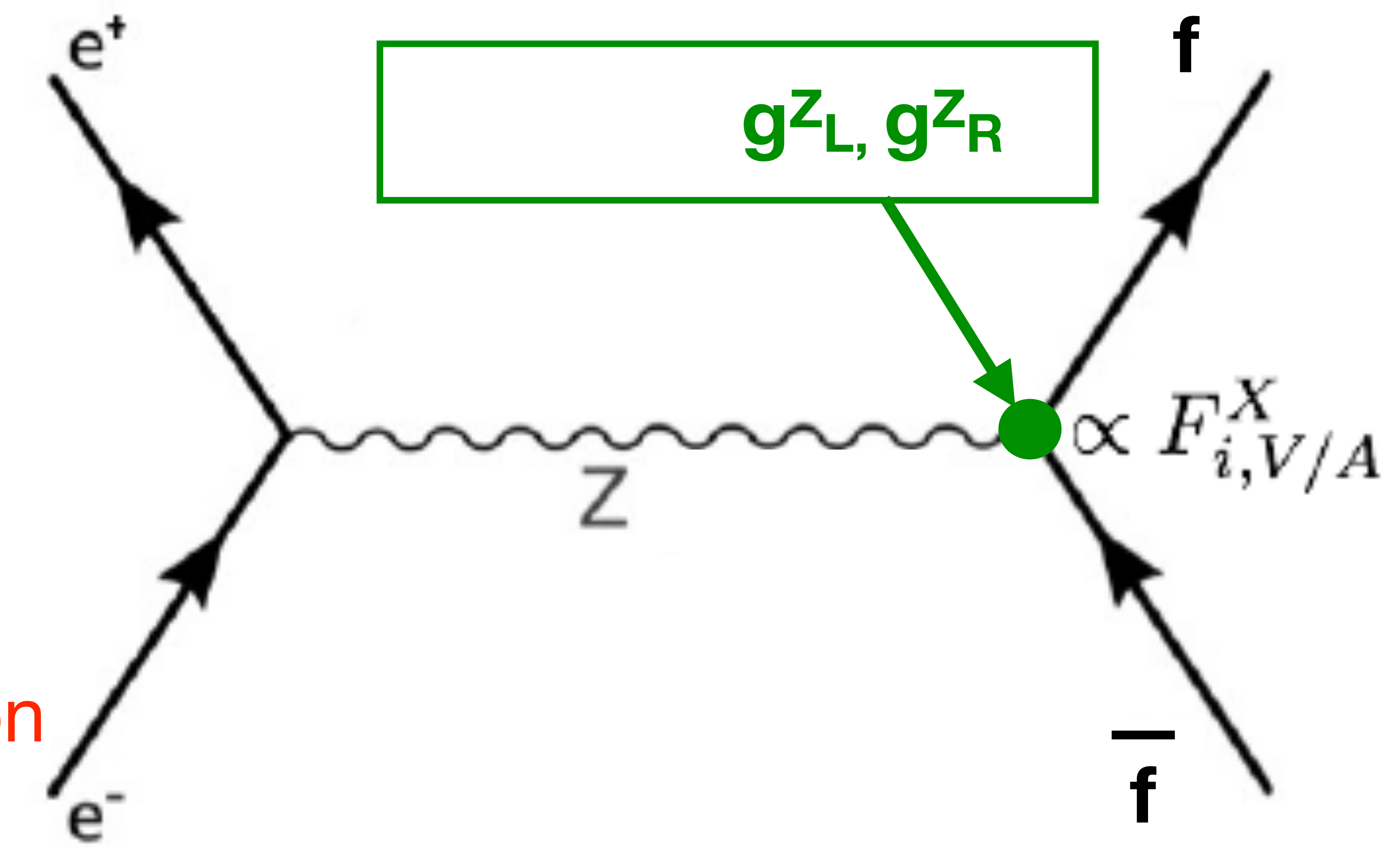

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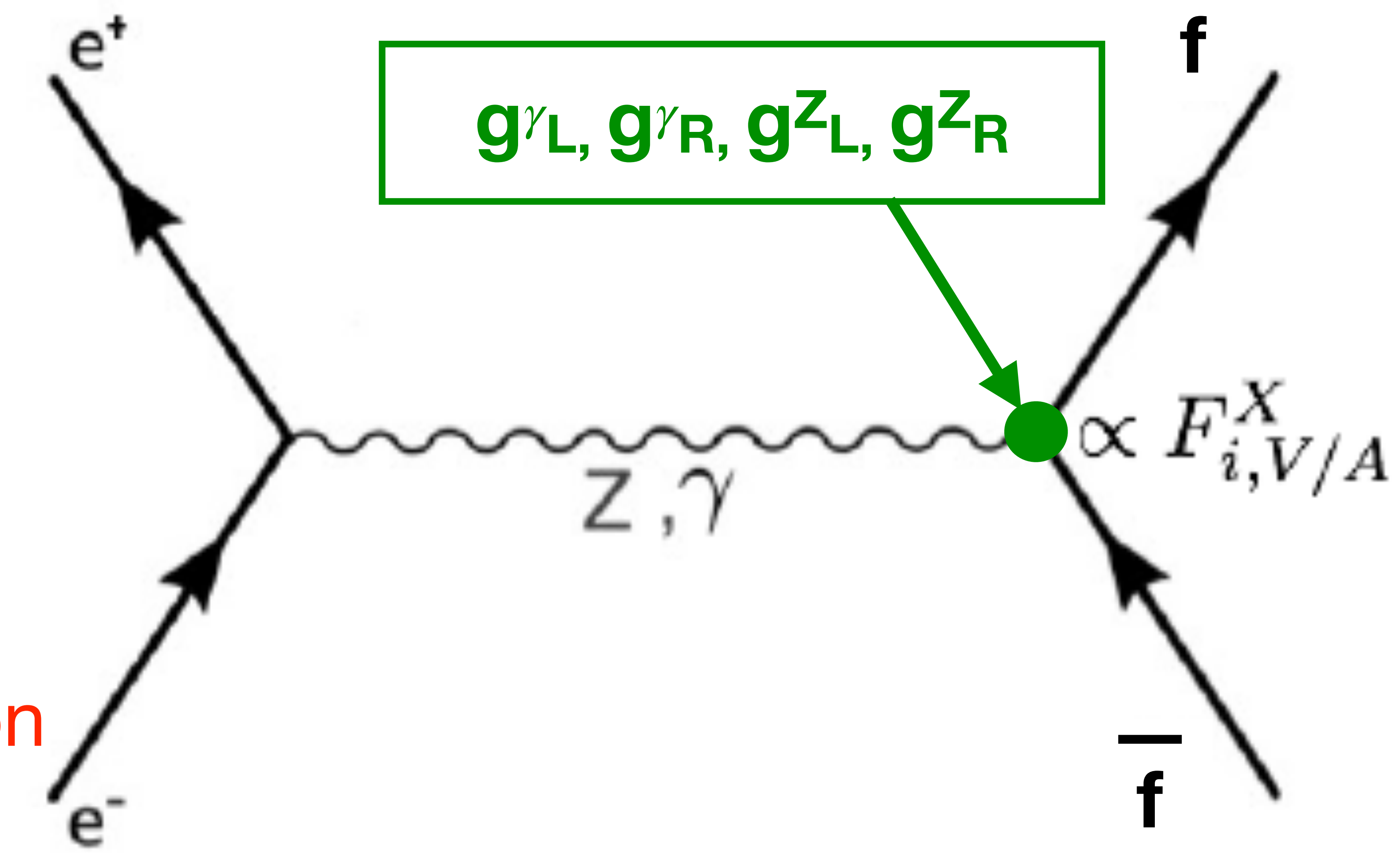

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Polarisation & Electroweak Physics at the Z pole

Z Boson

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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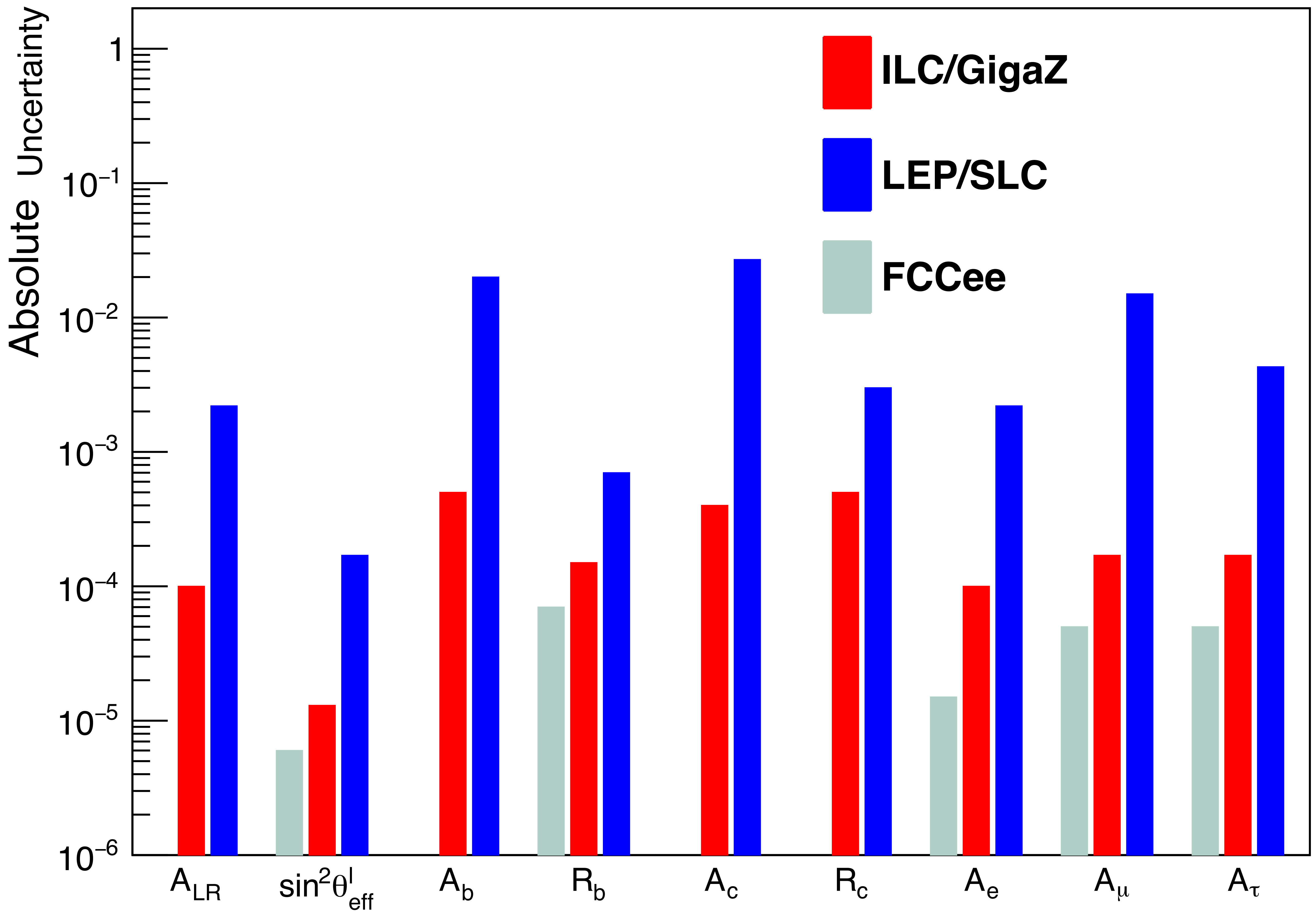
=> polarisation buys
a factor of ~100 in luminosity

Note: not true for pure decay quantities!



arXiv:1908.11299

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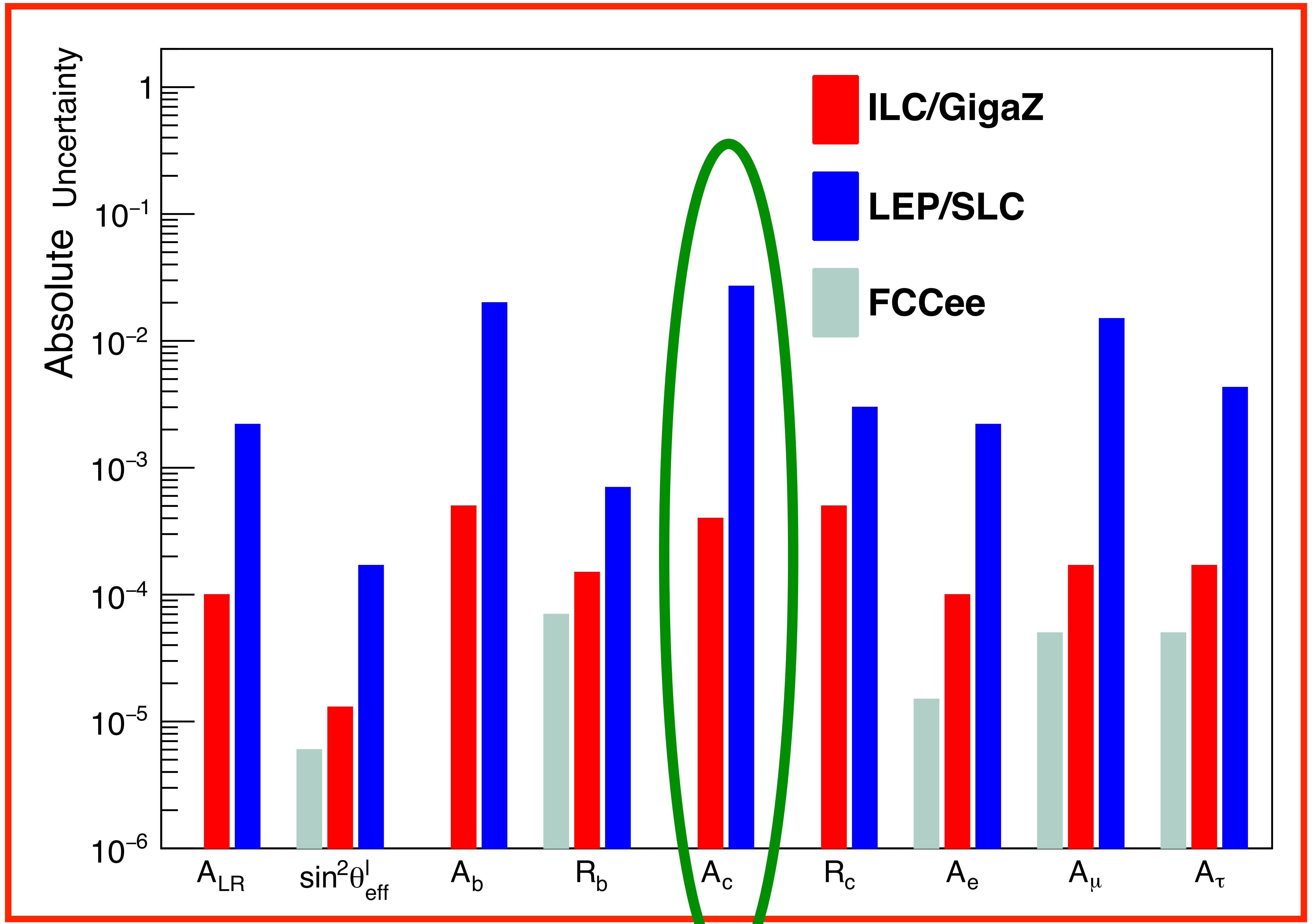

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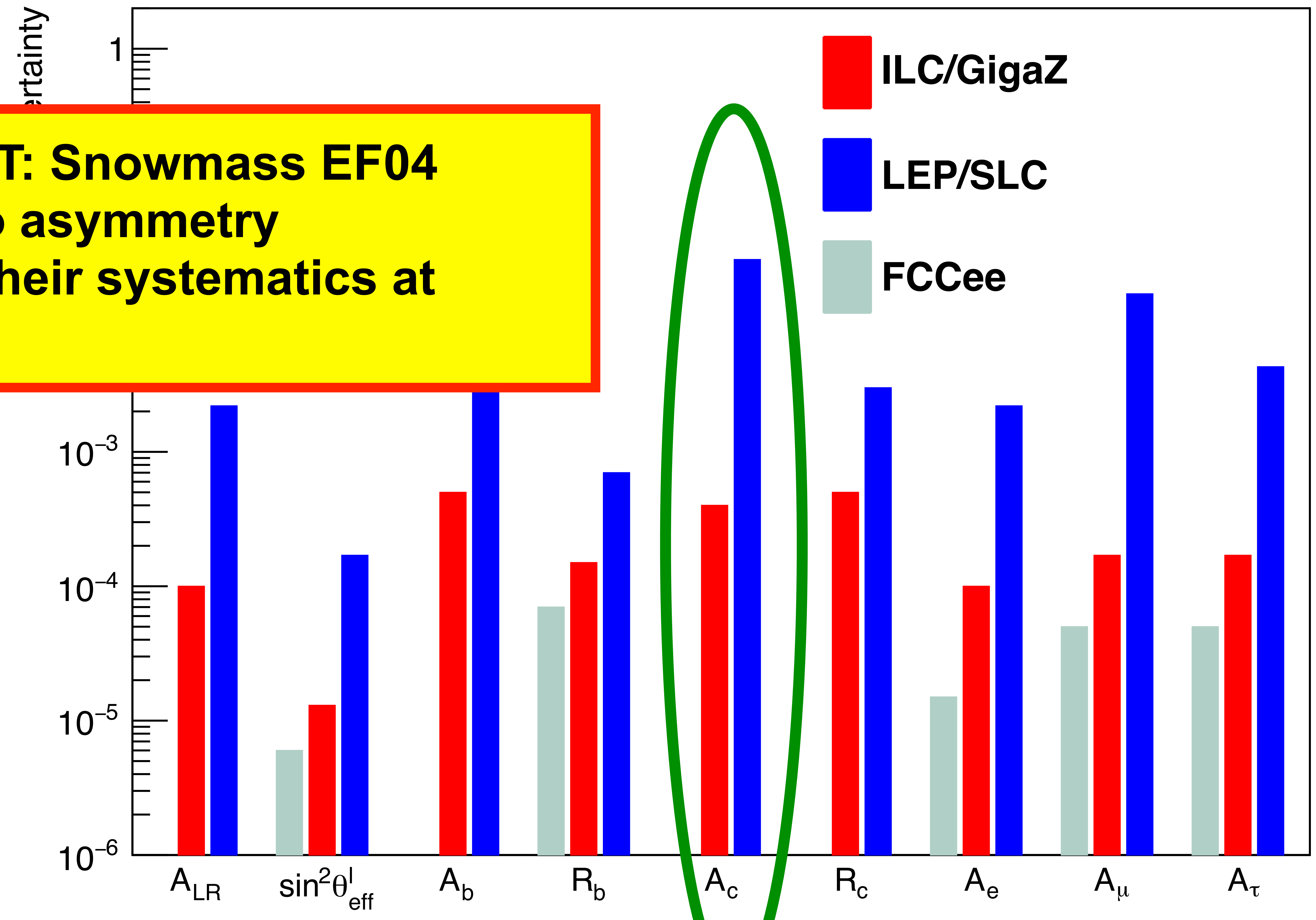
Thu Jan 20, 4 pm CET: Snowmass EF04 meeting dedicated to asymmetry measurements and their systematics at FCCee, CEPC & ILC



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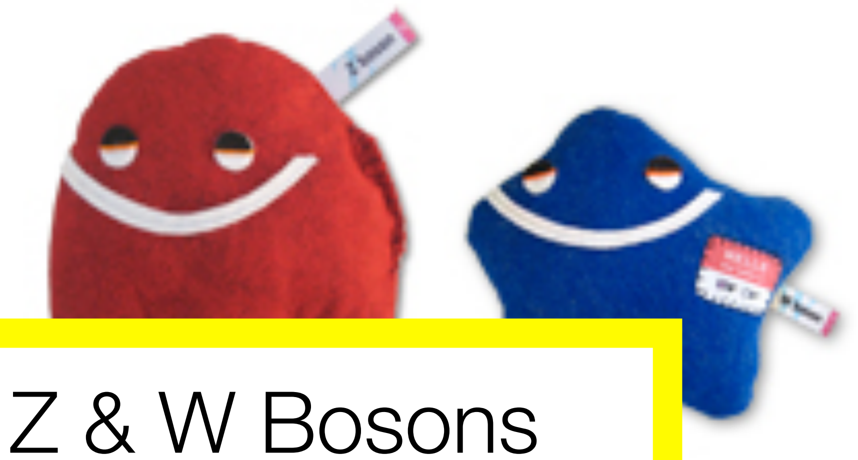
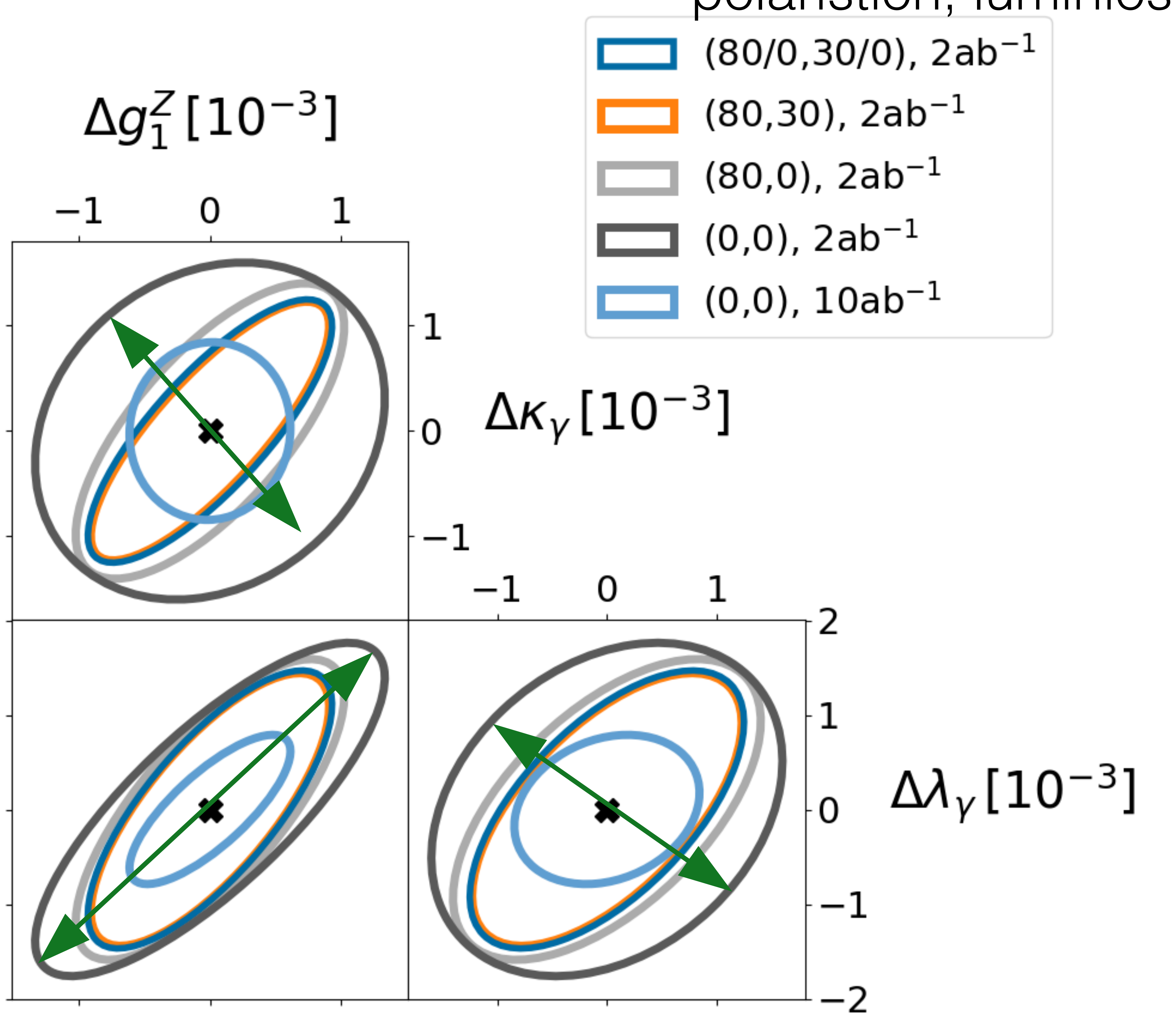
Triple Gauge Couplings at 250 GeV



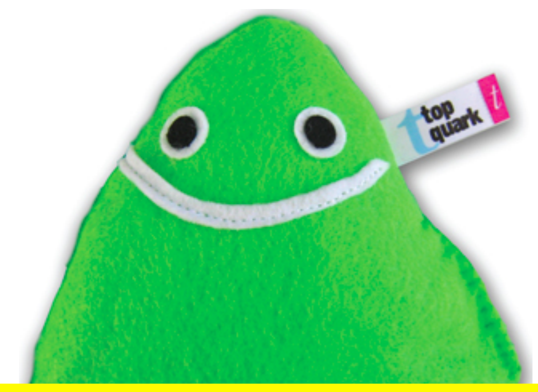
Z & W Bosons

- 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



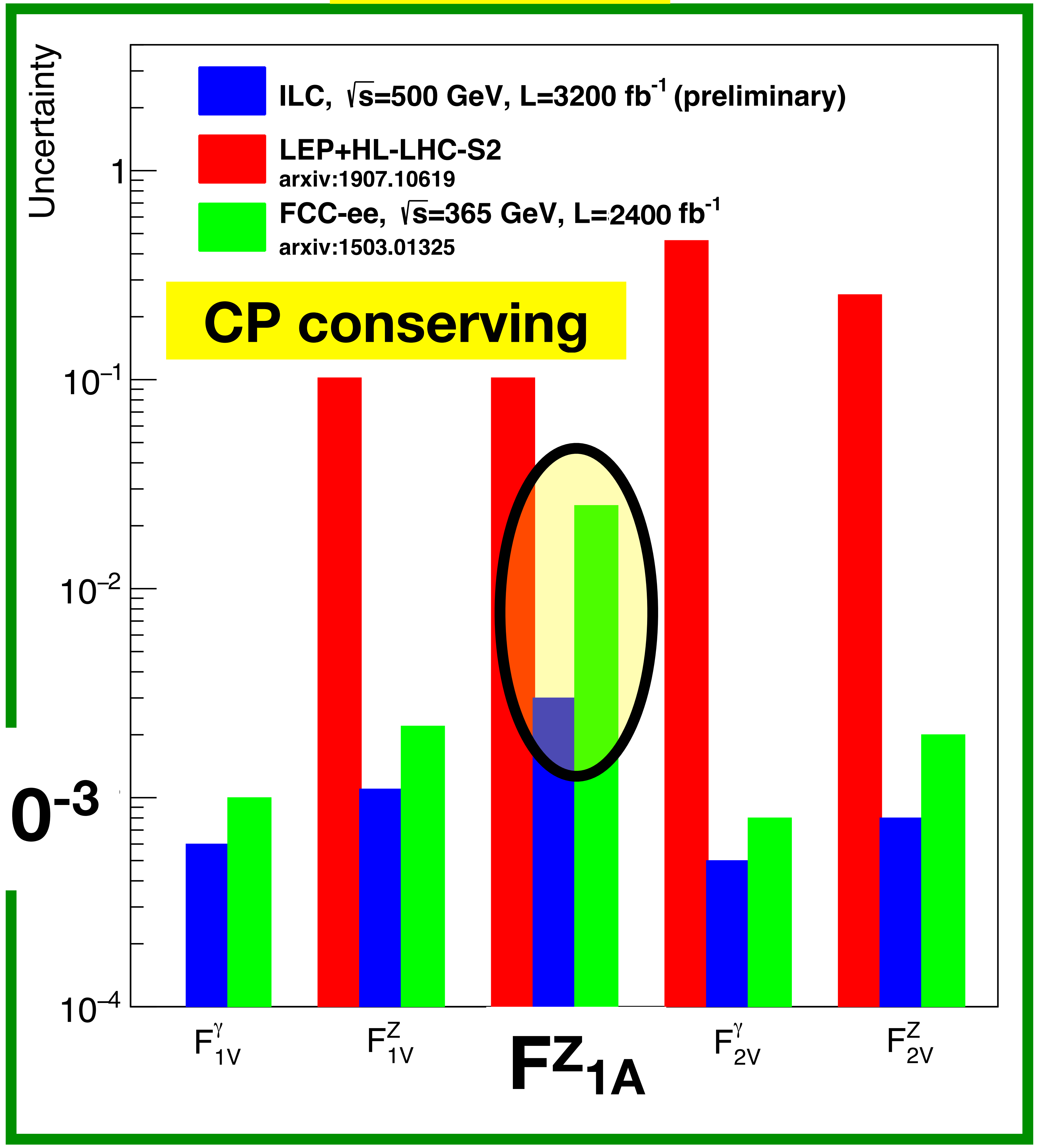
Arrow'ed direction: LR shape ~ constant
→ constraint only from A_{LR}

Top quark couplings



The Top Quark

- 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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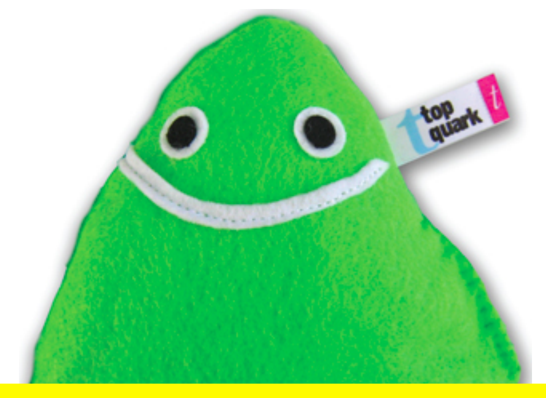

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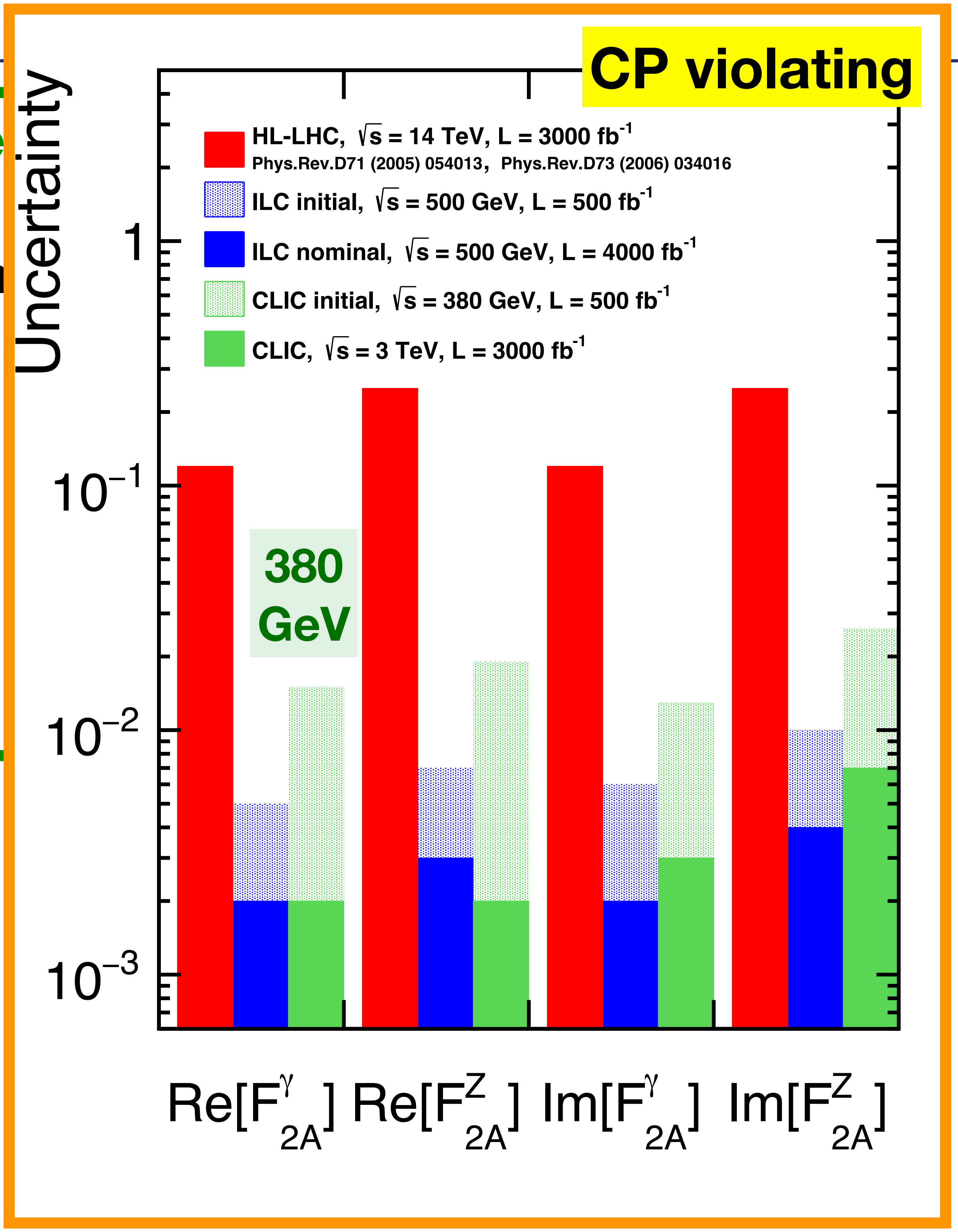

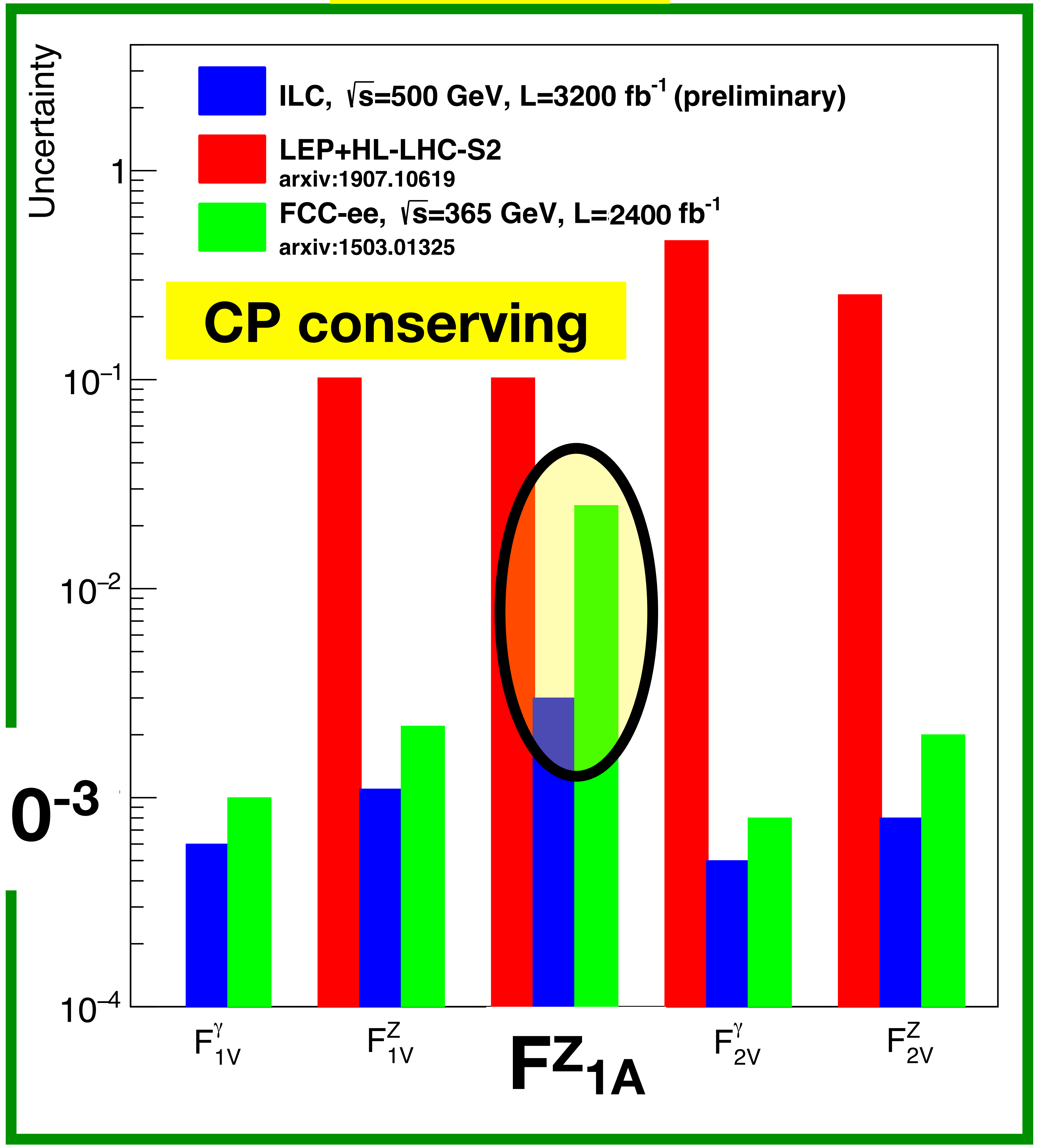

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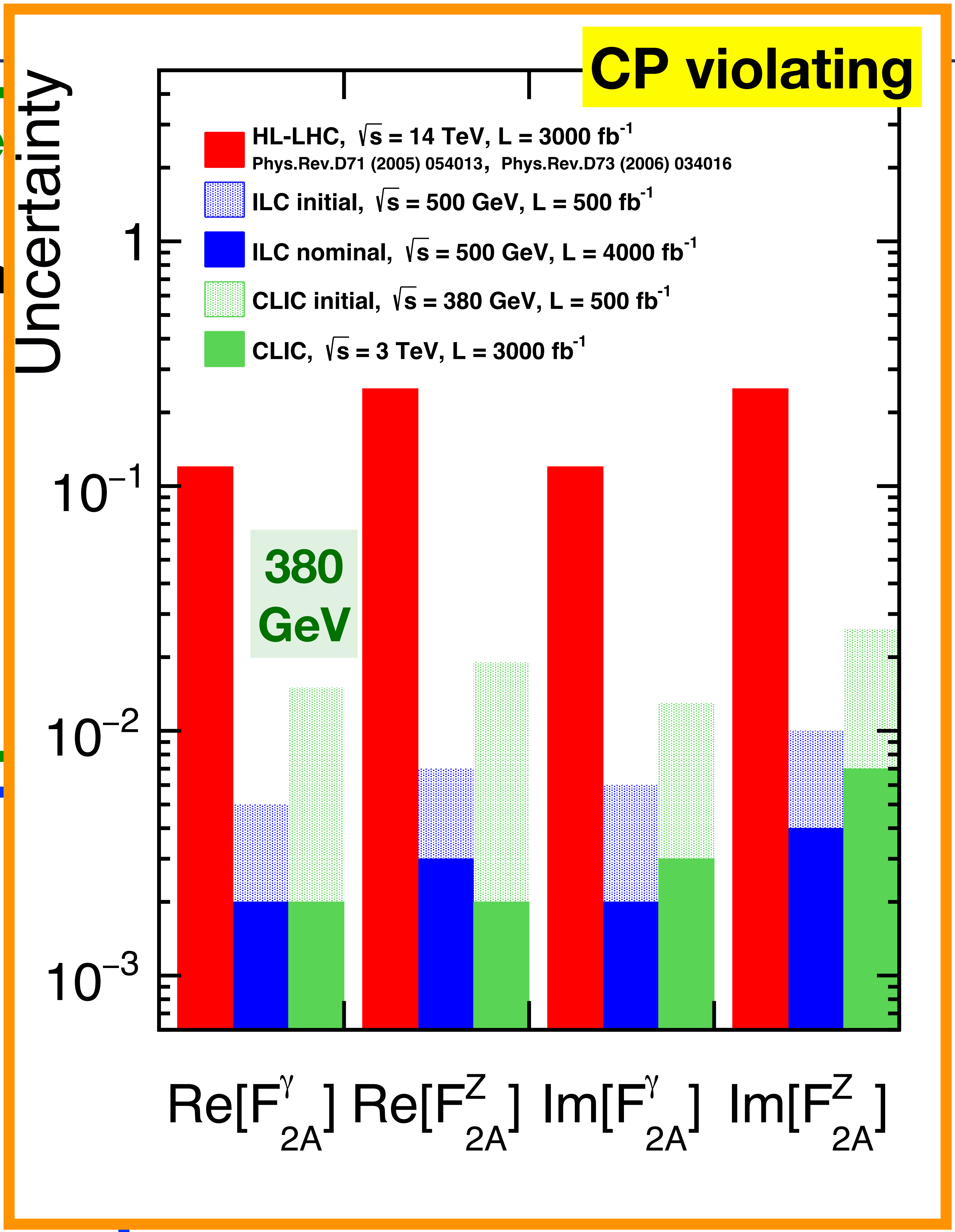
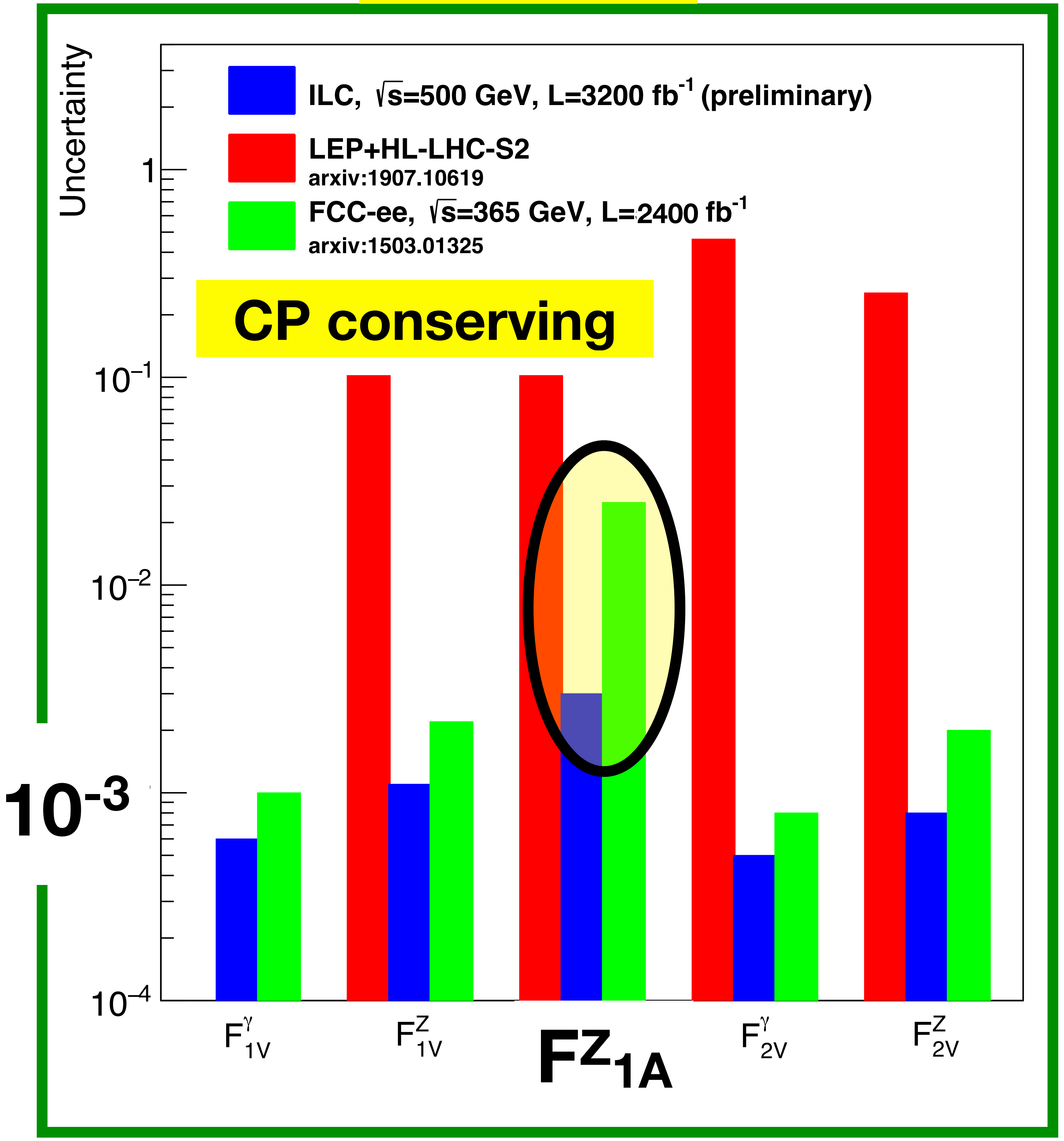
full SM-EFT:

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





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