Electroweak precision observables for the Higgs coupling determination at the ILC

J. List (DESY) on behalf of the ILD Detector Concept Group

Higgs Couplings 2019, Oxford

Introduction

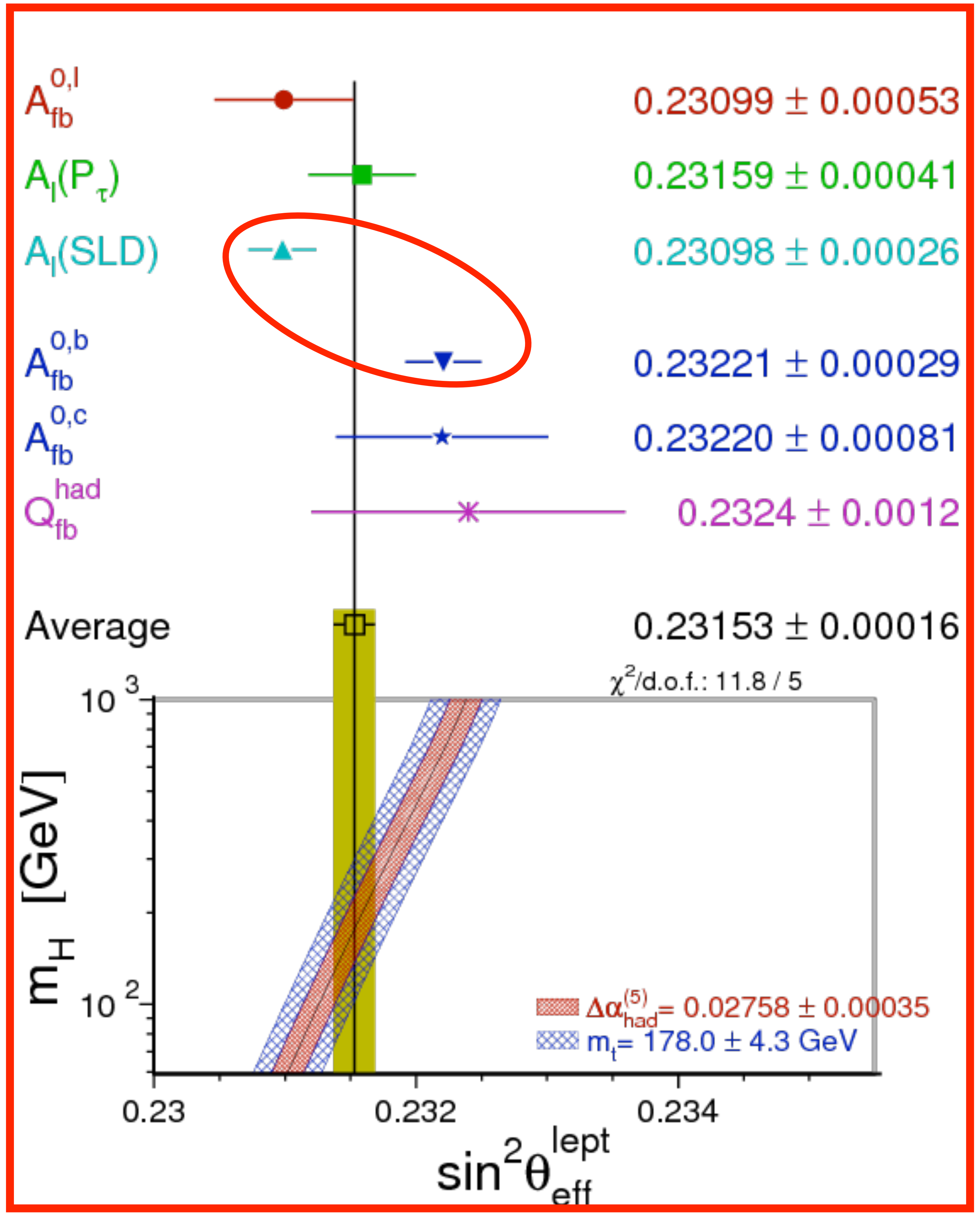
Electroweak observables provide

- **a crucial stress test of the SM**
- important input to SMEFT fit
  => Higgs property determination
- **BSM sensitivity!**

Received a lot of attention during European Strategy process, eg at Open Symposium in Granada

Required: a lot of Z's ….

Talk based on arXiv:1908.11299



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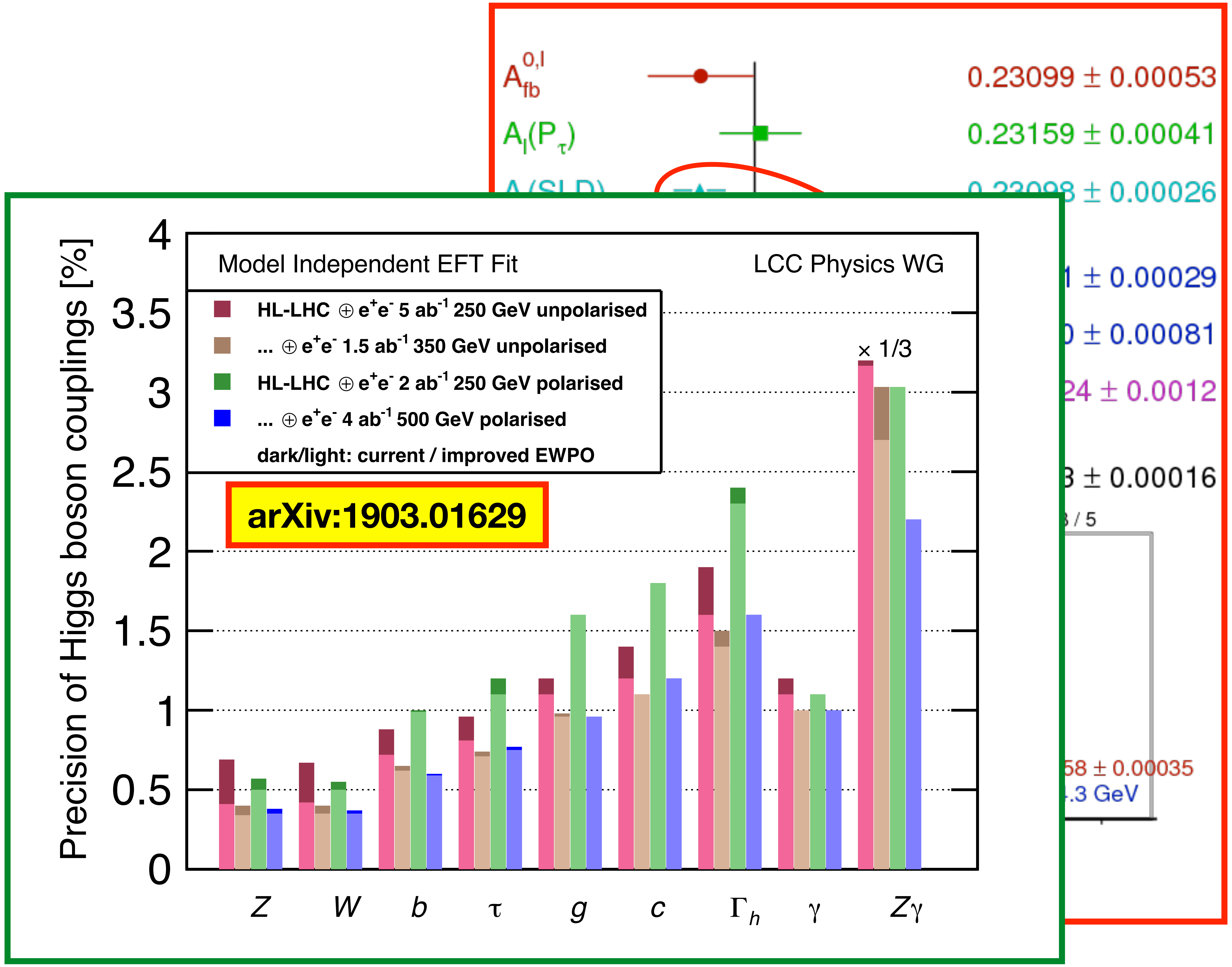


ILC running modes - and Z production

ILC e^+e^- collider

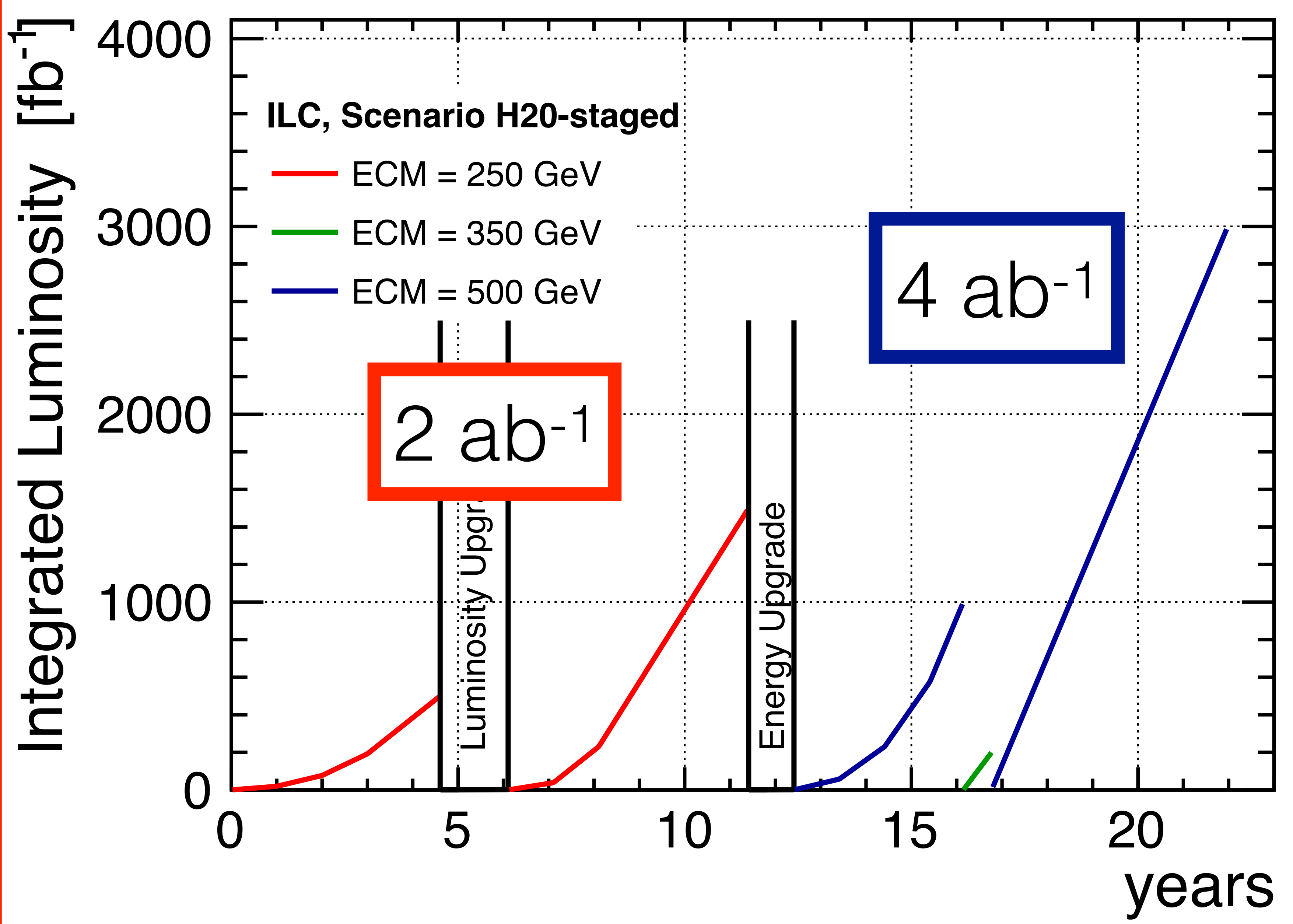
- **first stage: 250 GeV**
- **GigaZ & WW threshold possible**
- upgrades: 500 GeV, 1 TeV

polarised beams

- **$P(e^-) \geq \pm 80\%$,**
- **$P(e^+) = \pm 30\%$,**
  at 500 GeV upgradable to 60%

Since 2015 arXiv:1506.07830

$\sqrt{s}$	$\int \mathscr{L} dt$
250 GeV	2 ab^{-1}
350 GeV	0.2 ab^{-1}
500 GeV	4 ab^{-1}
1 TeV	8 ab^{-1}
91 GeV	0.1 ab^{-1}
161 GeV	0.5 ab^{-1}



(radiative) Z's in 2 ab^{-1} at **250 GeV**:

- ~77 10^6 Z->qq
- ~12 10^6 Z->ll

=> substantial increase over LEP,
….and polarised!

Z's in 0.1ab^{-1} at **91 GeV**:

- ~3.4 10^9 Z->qq
- ~0.5 10^9 Z->ll

~1-2 years of running (after lumi upgrade)

Accelerator implementation - arXiv:1908.08212

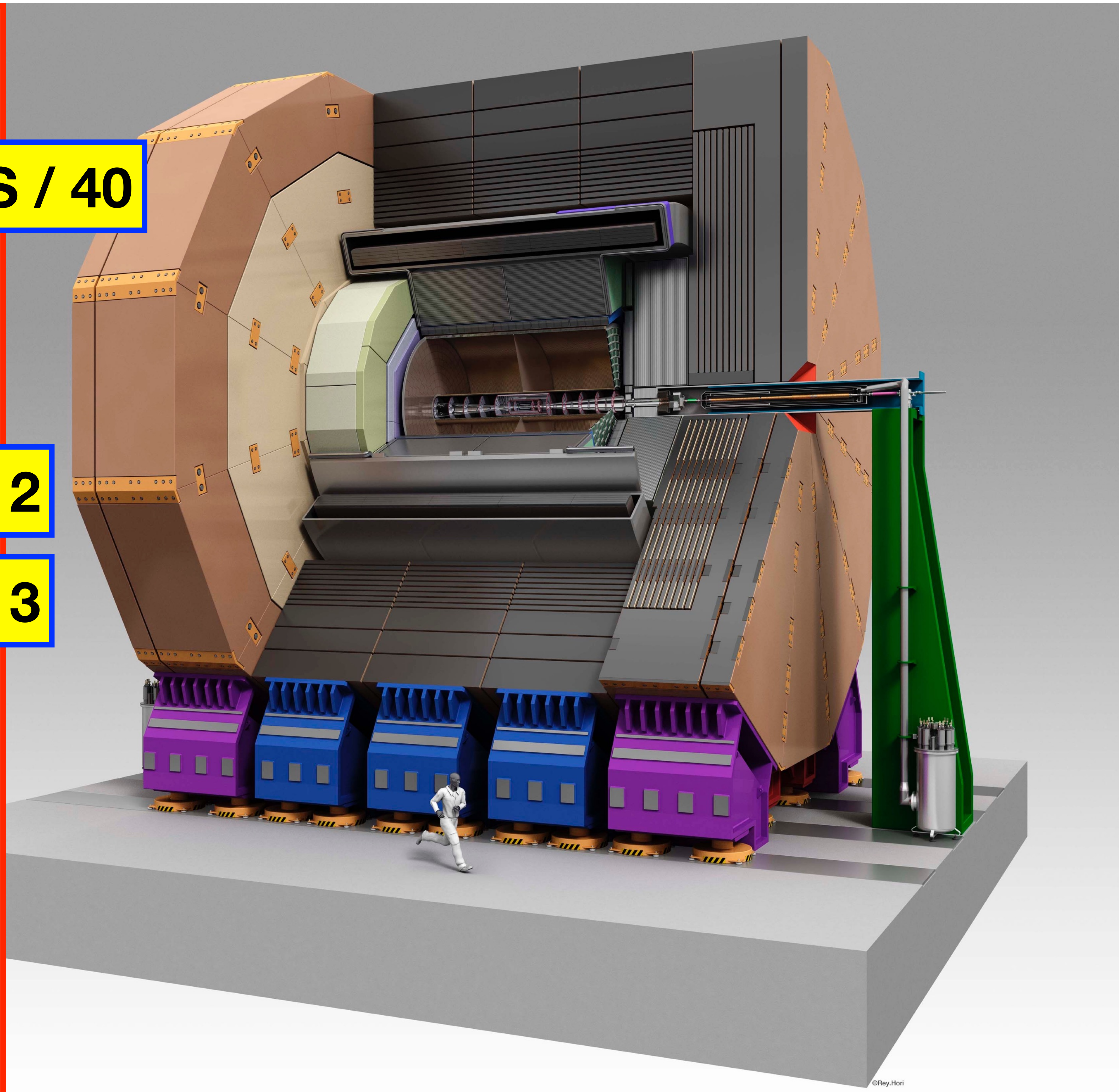
The ILD Concept

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
  ≈ CMS / 40
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
  ≈ CMS / 4
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4% **≈ ATLAS / 2**
- **hermeticity** ($H \rightarrow$ invis, BSM) $\theta_{min} = 5$ mrad **≈ ATLAS / 3**

To key features of the detector:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



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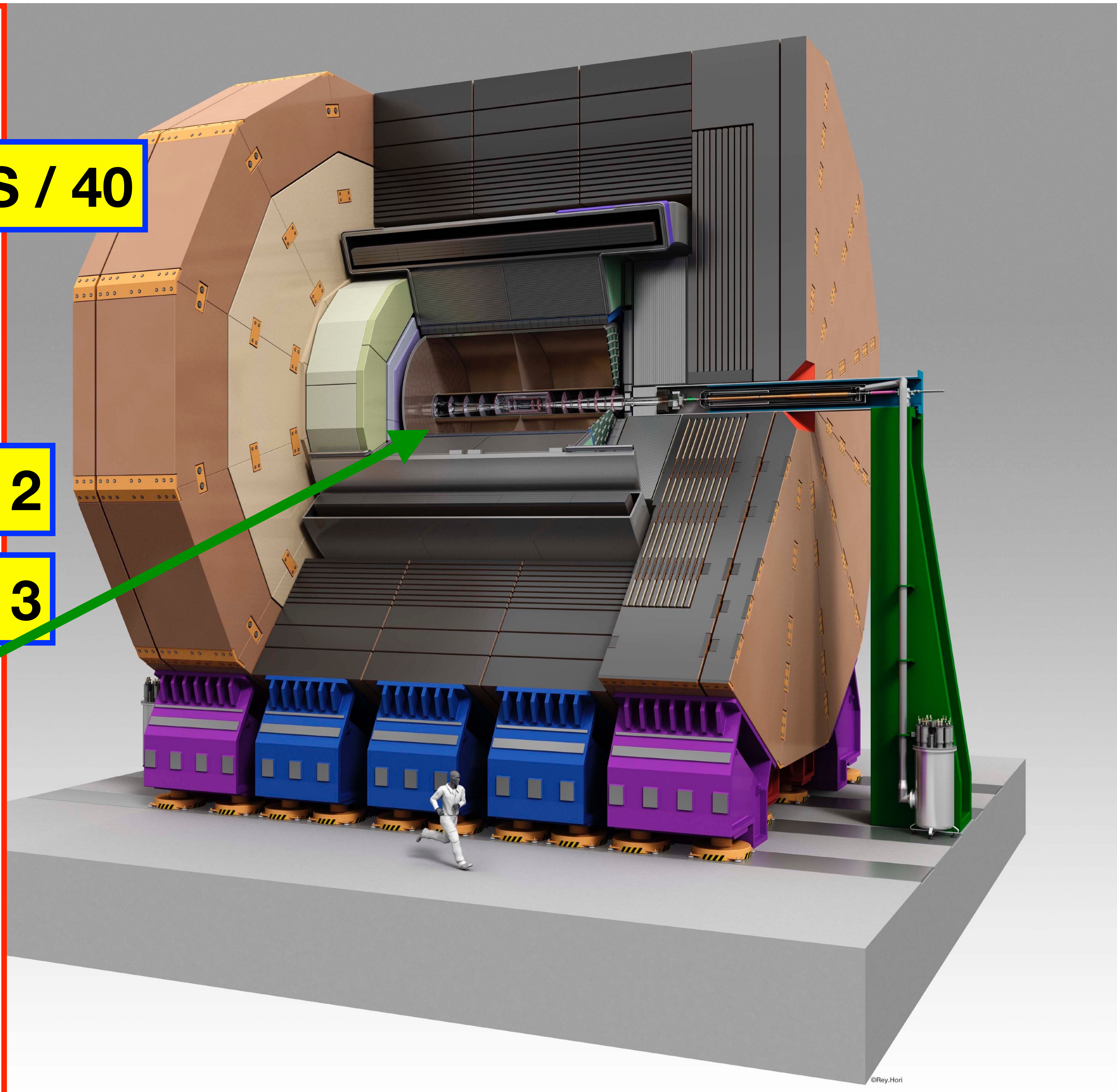

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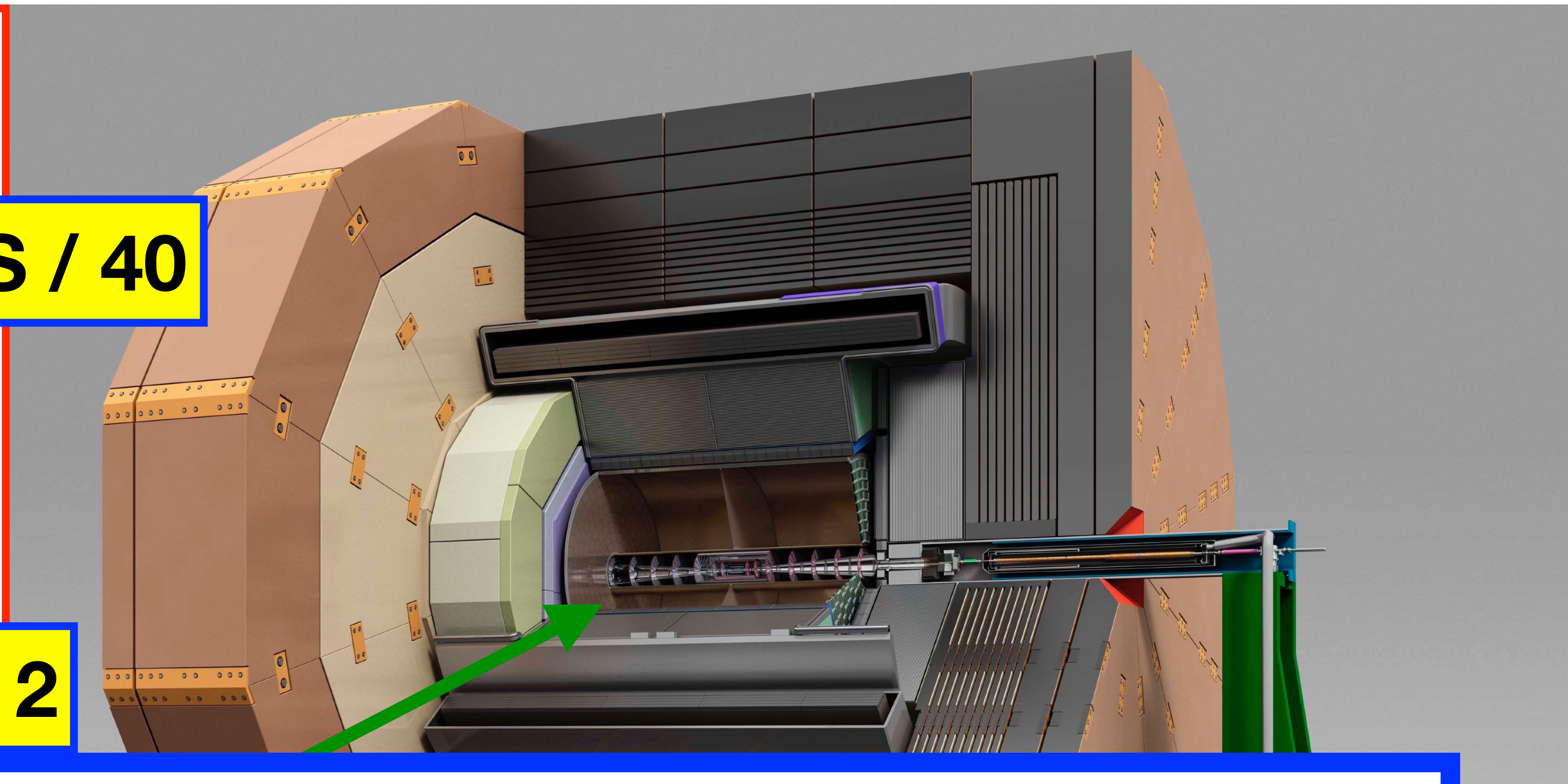


Possible since experimental environment at ILC very different from LHC:

- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**

enable

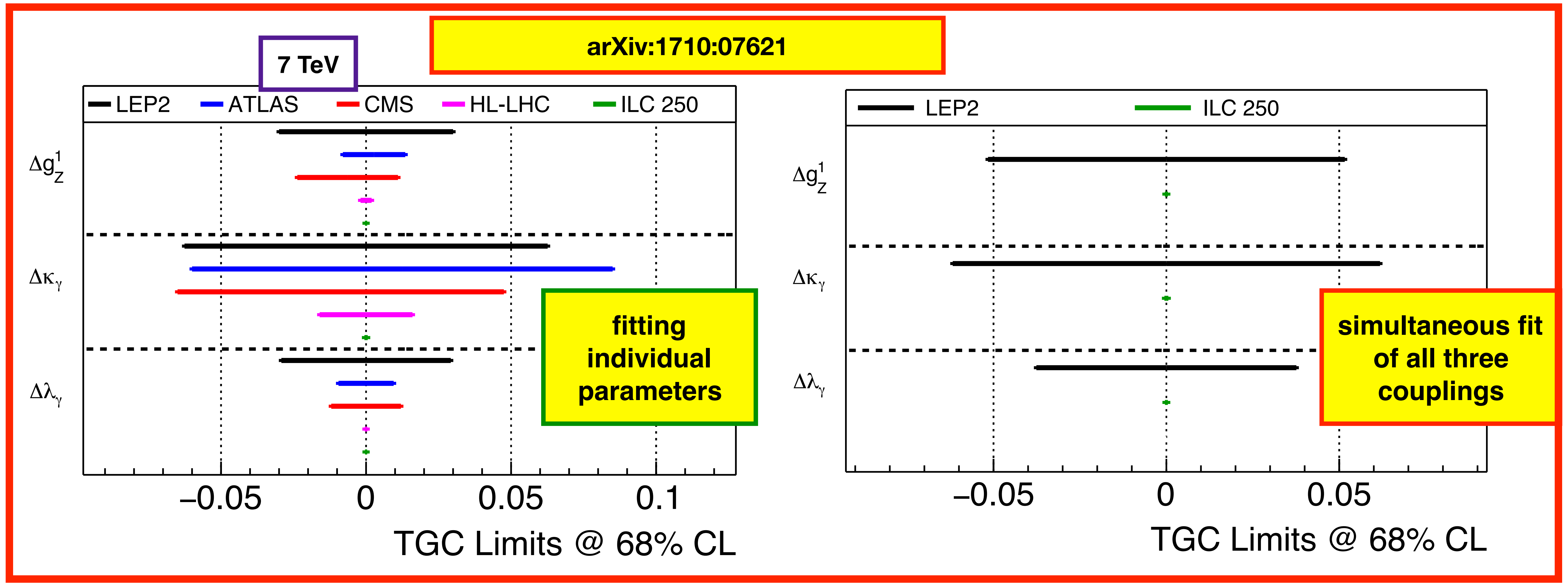
- **power pulsing => low material budget!**
- **triggerless operation**

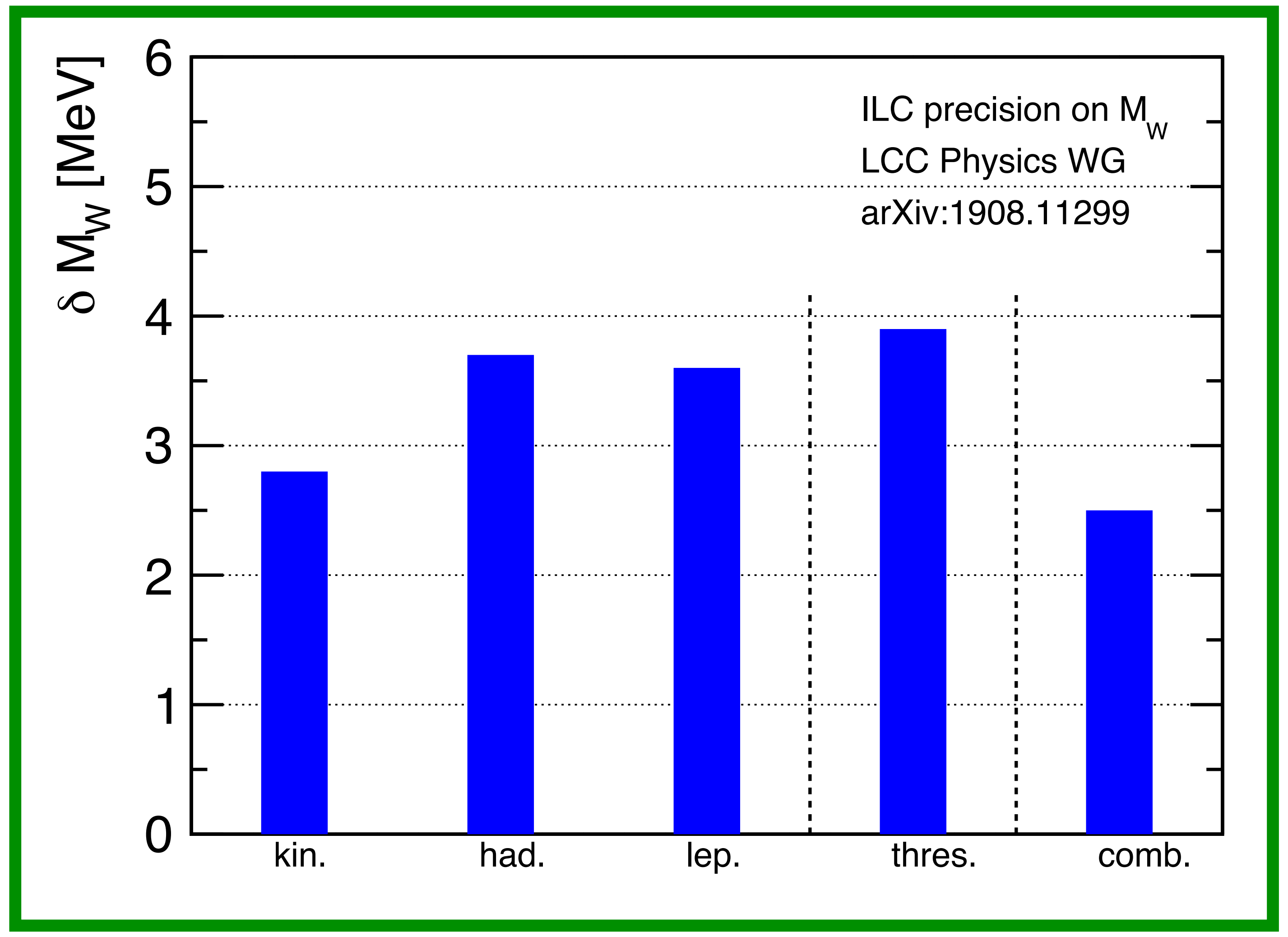
Interludium: Precision W measurements

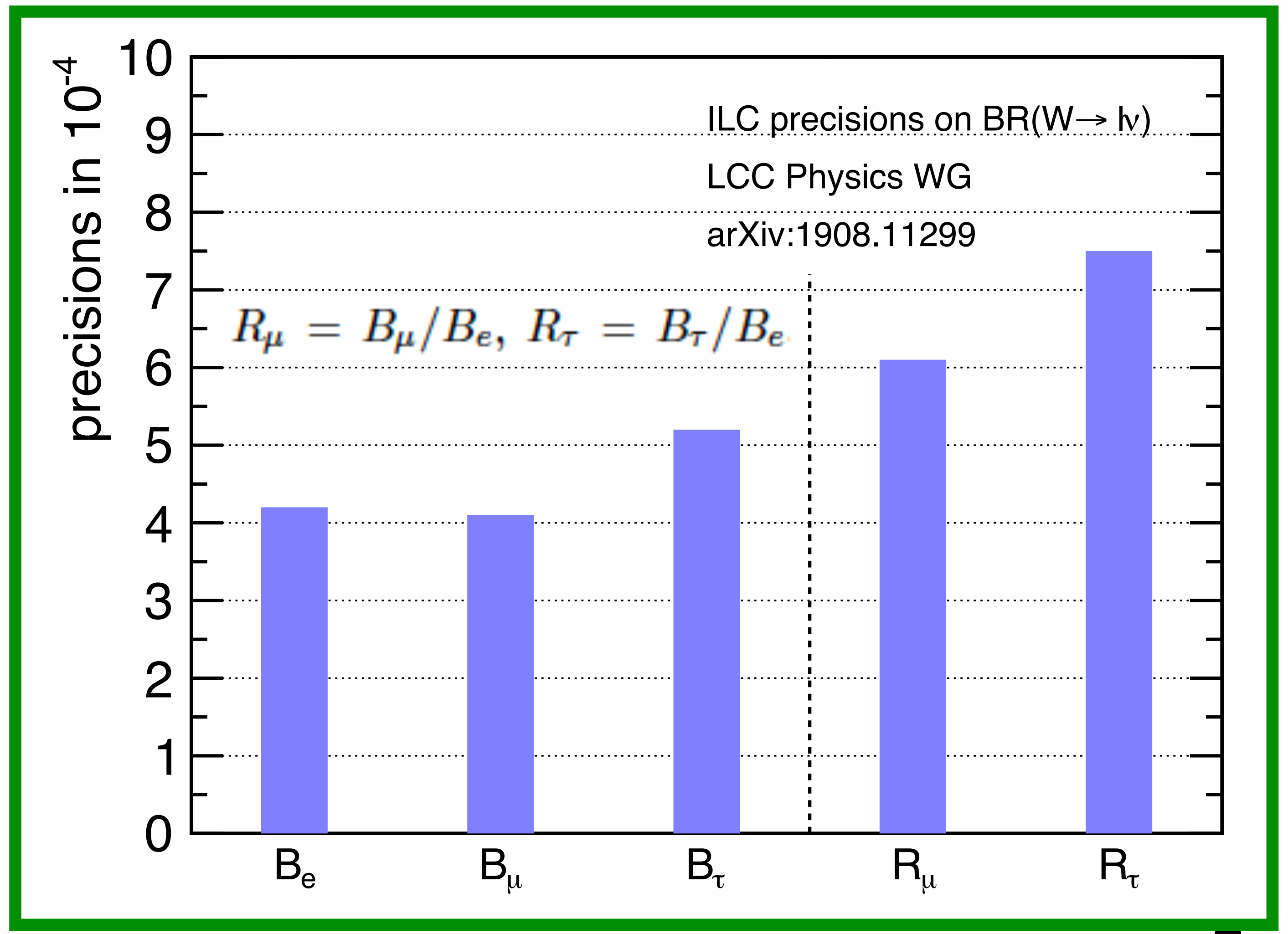
- Triple Gauge Couplings: few 10^{-4}, 1-2 orders of magnitude improvement over HL-LHC => input to SMEFT fit!
- W mass at 250 GeV - several methods *with very different systematic limitations*
- W mass from threshold scan - with ~1 year dedicated running:

$$\Delta m_W\,(\mathrm{MeV}) = 2.4\,(\mathrm{stat}) \oplus 3.1\,(\mathrm{syst}) \oplus 0.8\,(\sqrt{s}) \oplus \mathrm{theory}$$

- W branching ratios: simultaneous fit to all 10 σ_{tot} x BR for σ_{tot} and BR's (4 parameters)
- W width: $\Delta\Gamma_W$ = 3.2 MeV





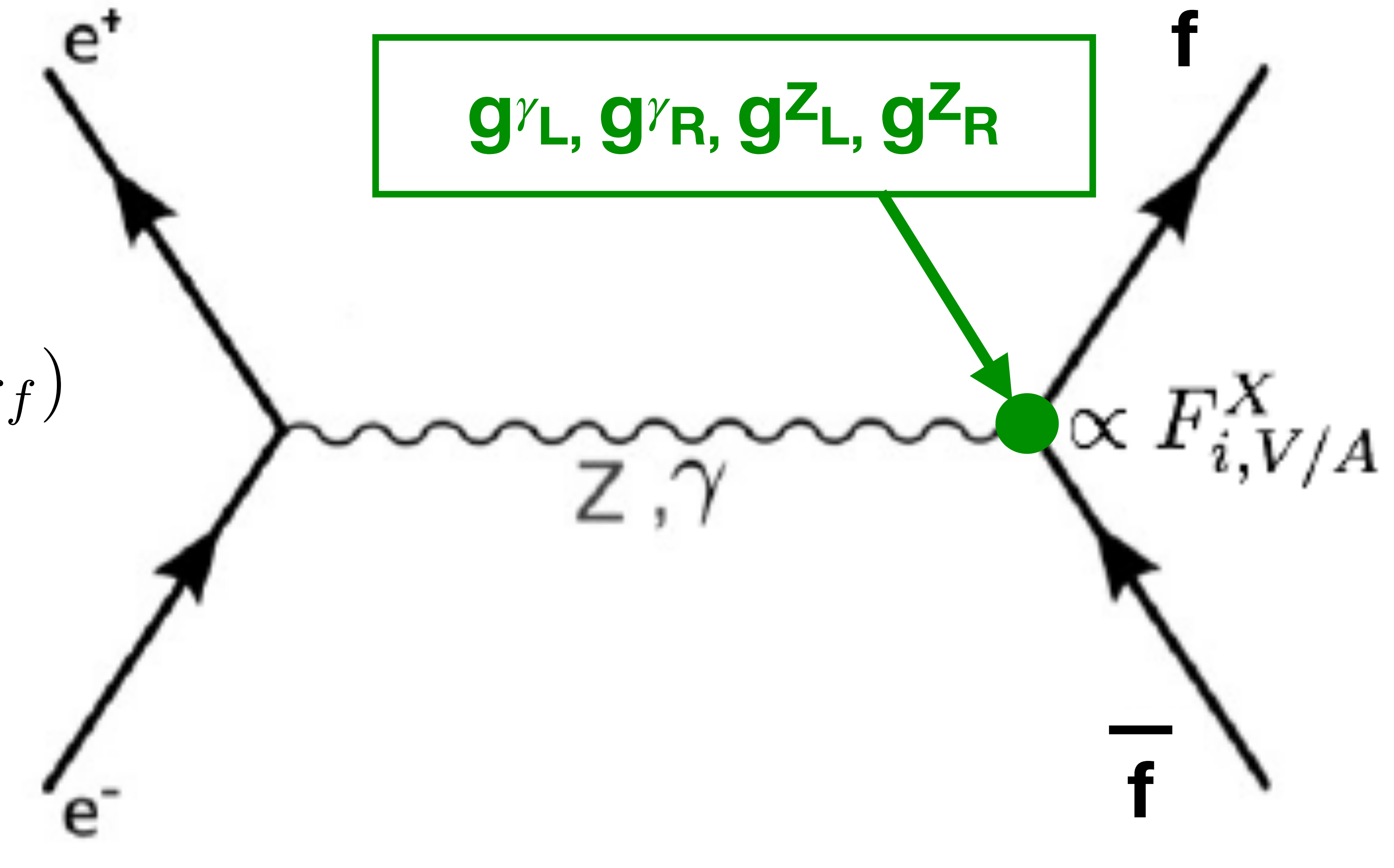


Electroweak precision observables

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions

=> $$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

specifically for the electron: $$A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$$



at an *unpolarised* collider:

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

=> no direct access A_e,
only via tau polarisation

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

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

Furthermore R_q and R_l:

$$R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \text{hadrons})} \ , \quad 1/R_\ell = \frac{\Gamma(Z \to \ell^+\ell^-)}{\Gamma(Z \to \text{hadrons})}$$ => $$R_q \ , \ 1/R_\ell \propto (g_{Lf}^2 + g_{Rf}^2)$$

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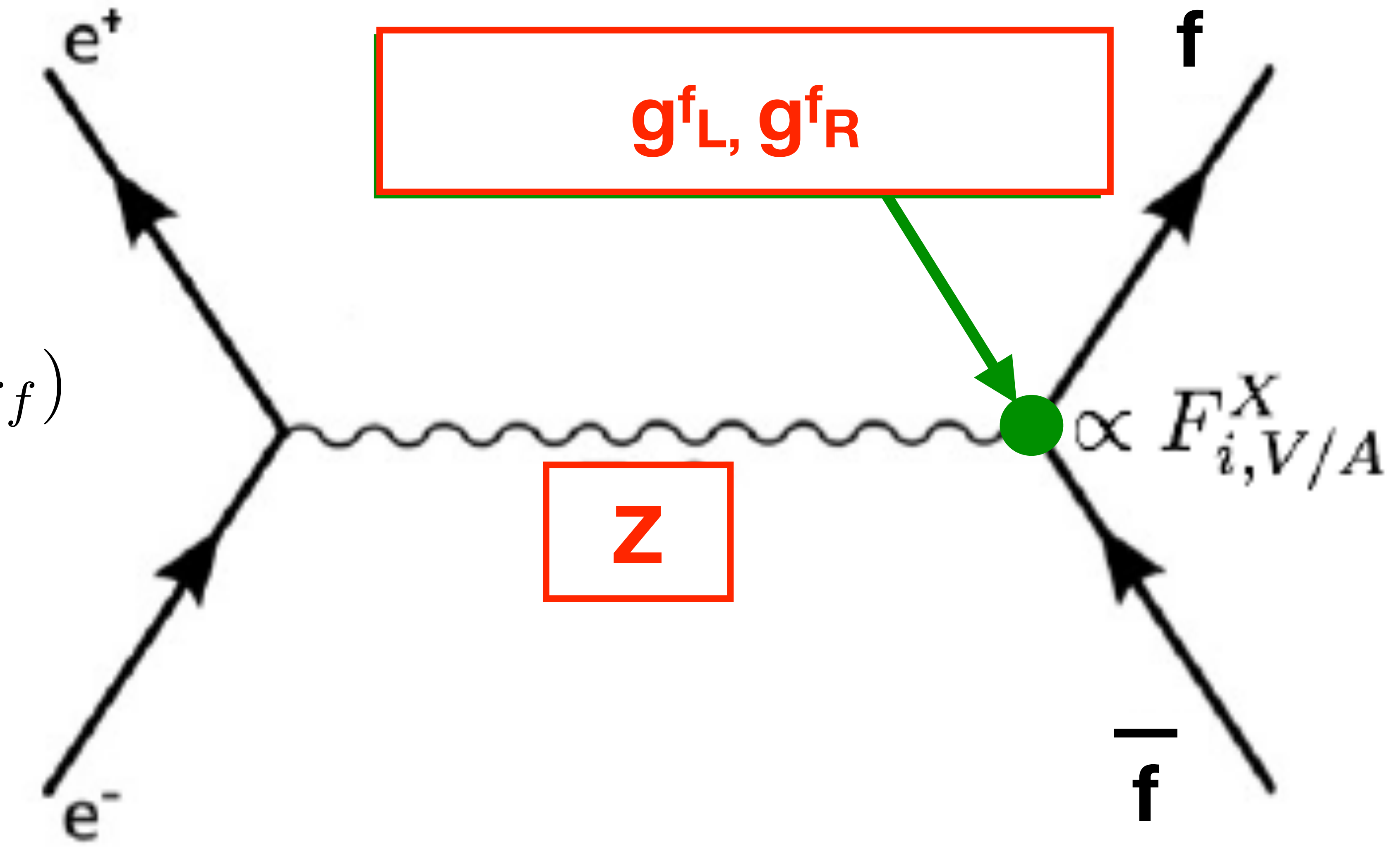

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Precision EW at 250 GeV from radiative return

- e^+e^- -> Z γ : Z boosted by $\beta \approx 0.76$

$$|\beta| = \frac{|E_1 \cos\theta_1 + E_2 \cos\theta_2|}{E_1 + E_2} = \frac{|\sin(\theta_1 + \theta_2)|}{\sin\theta_1 + \sin\theta_2}$$

$$m_{12}^2 = \frac{1 - |\beta|}{1 + |\beta|} \cdot s$$

=> reconstruct from angles only!

=> clean sample with high efficiency

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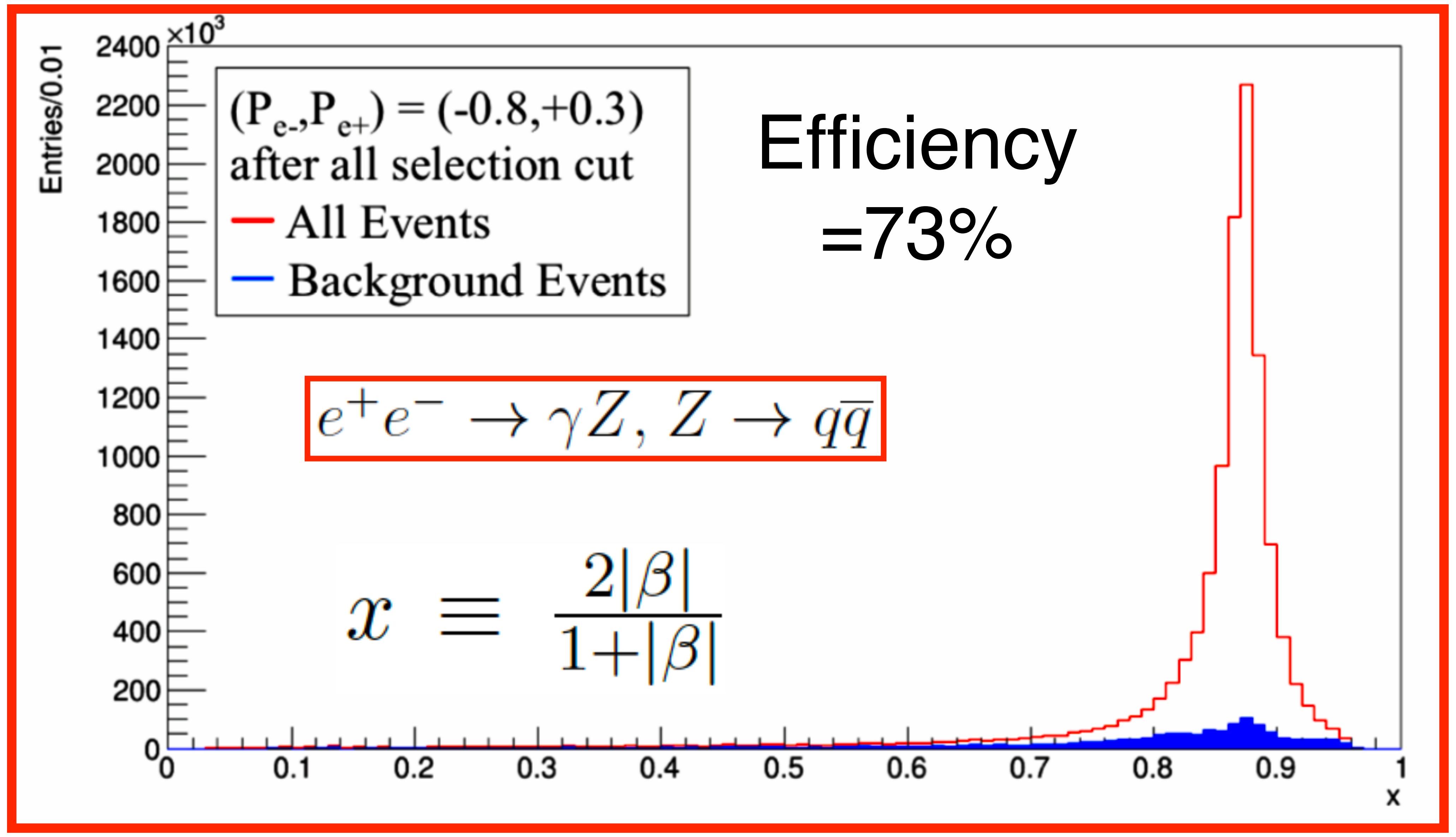
=> rel. stat.: $\delta A_e = 9.5 \times 10^{-4}$

lead. syst. from polarisation: 3×10^{-4}

- factor 10 improvement over current value "for free"! => ~12% improvement on g_{HZZ}



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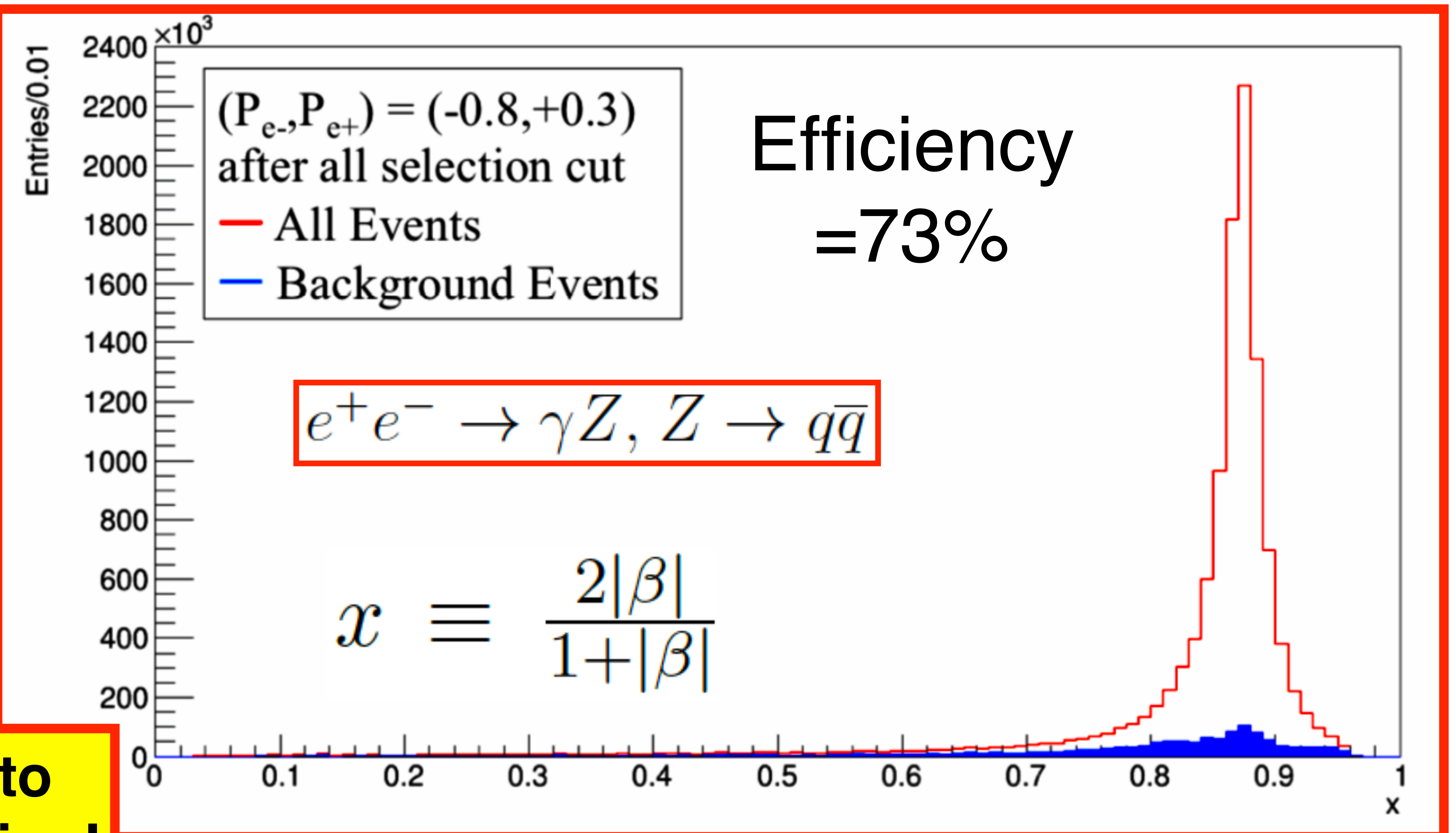

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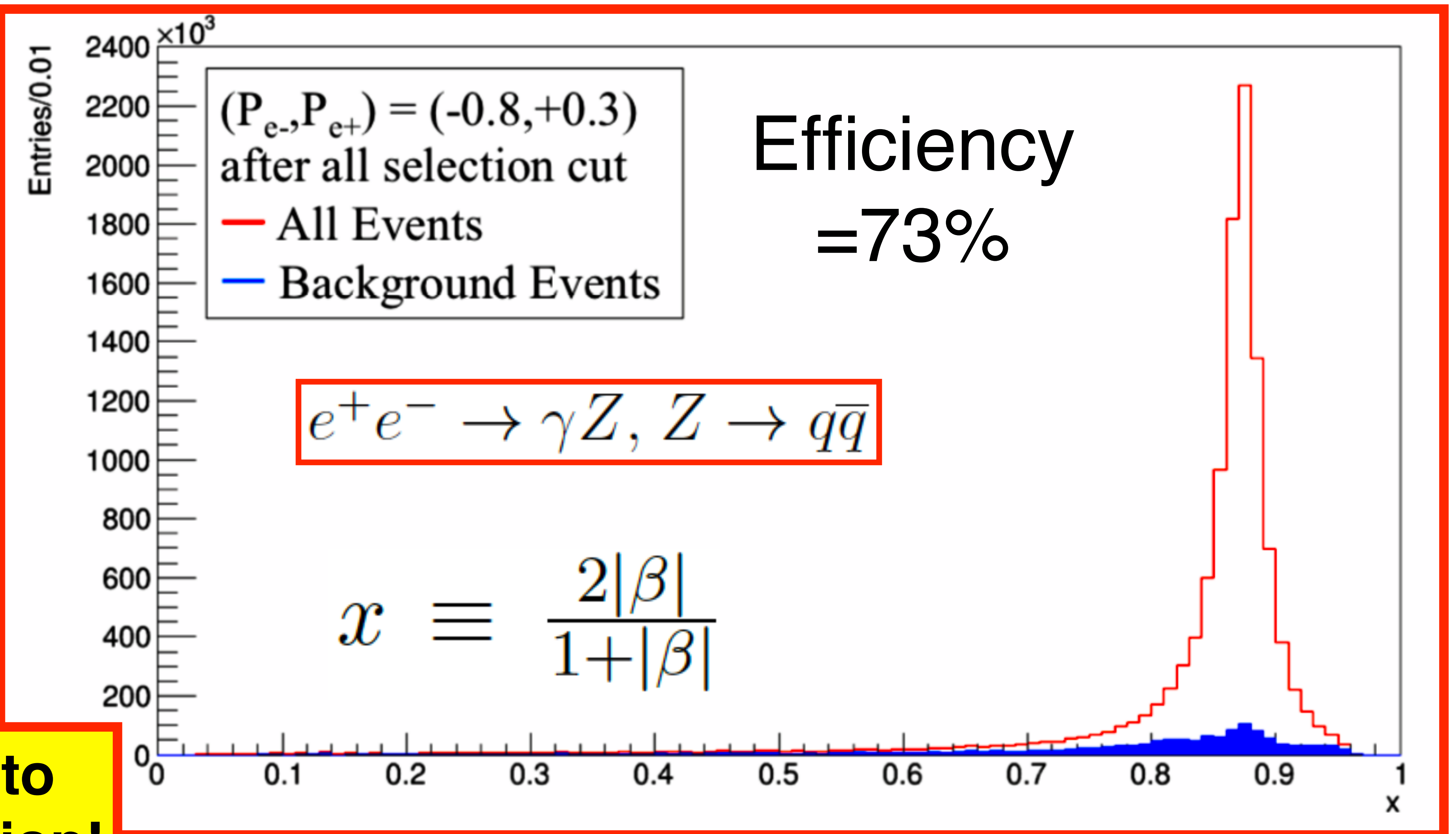

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Important:

- **Near √s =M$_Z$,** $A_{obs} = A_e + \Delta A$ has strong dependence on √s due to Z-γ interference
  => requires excellent knowledge of √s!
- **At √s =250 GeV**, this dependence is at least 1000 x weaker => not an issue…

Precision EW at the GigaZ

- ~250 x LEP, with beam polarisation => expect at least factor 10 improvement
- Measure A_e via A_{LR} as before - **now crucial:** knowledge of $\sqrt{s}$!
  - Exploit excellent momentum measurement of ILD (or SiD)
  - calibrate with $J/\psi \to \mu^+\mu^-$
    => **obtain $\sqrt{s}$** from $\mu^+\mu^-\gamma$ events **to 1 MeV precision => $\delta A_e(\sqrt{s})$=2 x 10^{-5}**, comparable to stat. error.
    => final number dominated by polarisation uncertainty
- Fermion asymmetries for μ / τ /c /b: **new, detailed ILD studies in 2019 -** profit from
  - **tiny ILC beam spot (@91.2 GeV): 1.12 μm x 14.6 nm x 410 μm** **Accelerator - arXiv:1908.08212**
  - large statistics & excellent detector => **use double-tagged events only for q /anti-q separation!**

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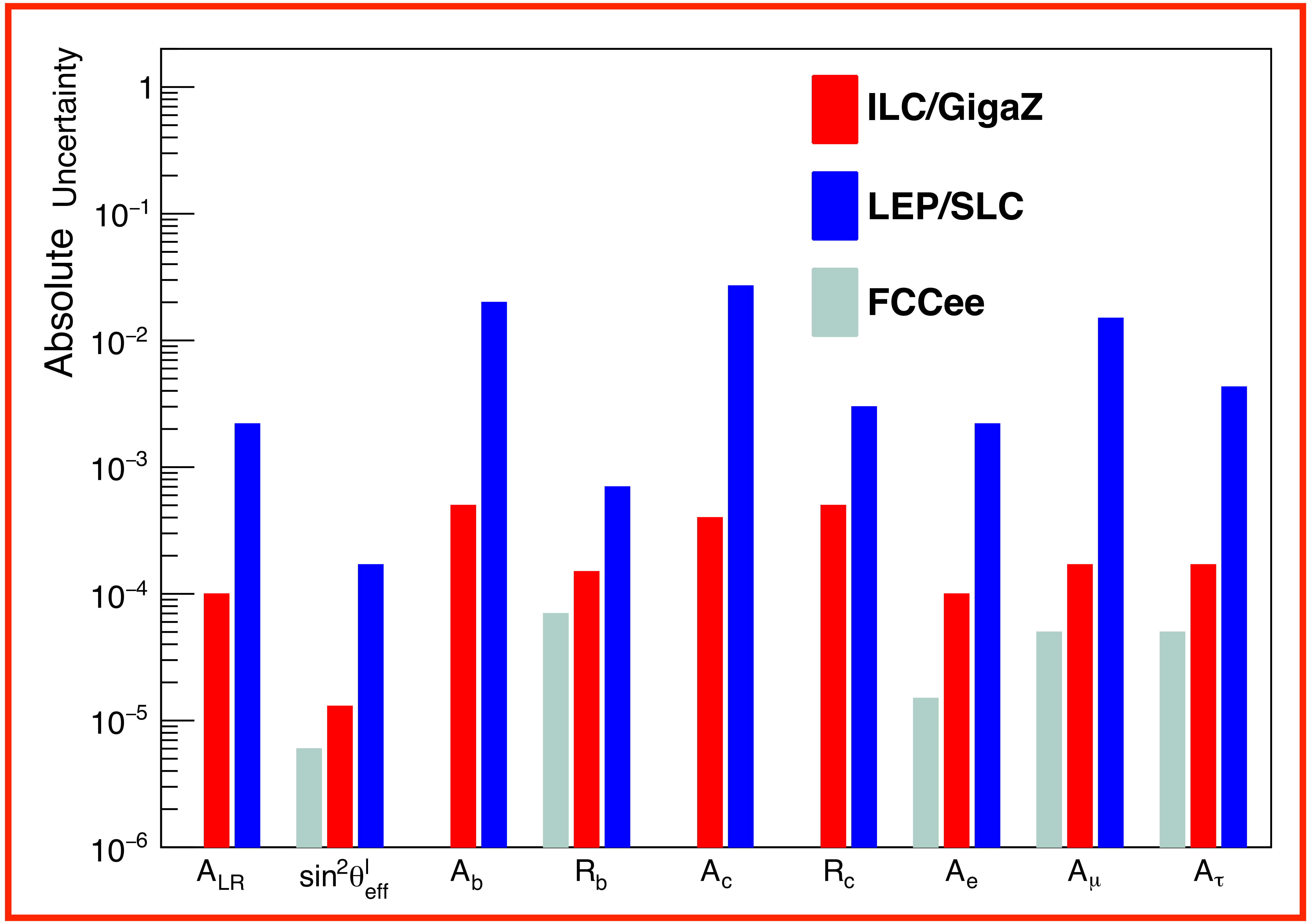
Also: the polarised $A^f_{FB,LR}$ receives **7 x smaller radiative corrections** than the unpolarised A^f_{FB} !

GigaZ: results of new detailed ILD studies

- as expected, 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 ILC beam spot
    - Kaon-ID via dE/dx in ILD's TPC
- typically only factor 2-3 less precise than FCCee's unpolarised *TeraZ*



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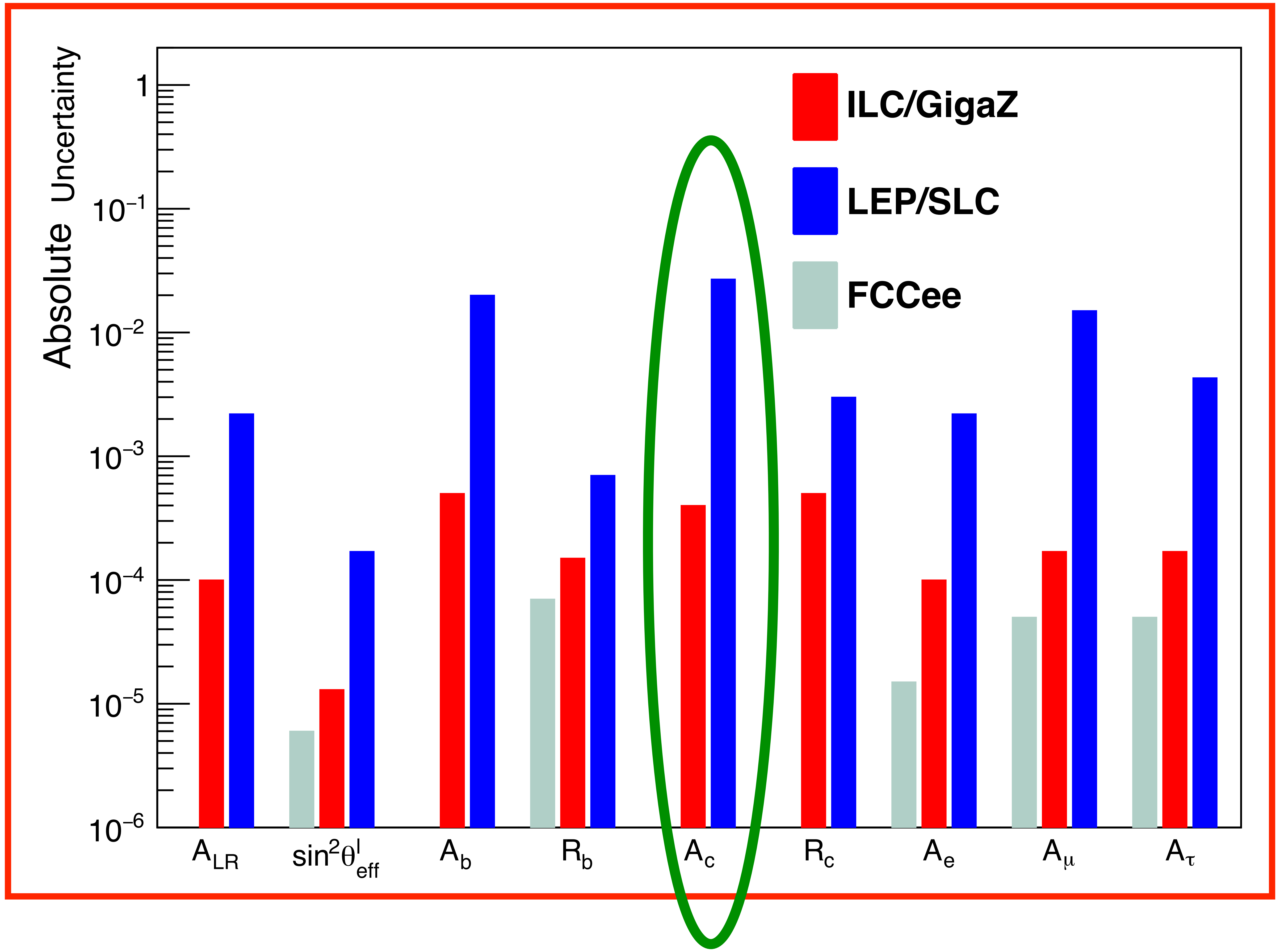


Conclusions

- **Electroweak observables are an important part of the physics case of future e^+e^- colliders**
- ILC offers significant progress over LEP already at 250 GeV
- Even more improvement from dedicated Z pole running
- Beam polarisation boosts "return on invested ab^{-1}"
- ILC GigaZ program has been scrutinized, again, in summer 2019 following discussions in Granada => results are now included in SMEFT fits by the ECFA WG on HiggsCouplings@ Future Colliders for the Briefing Book of the European Strategy Update!
- Tiny ILC beam spot leverages excellent 2ndary vertex resolution
- Kaon identification via dE/dx in ILD TPC enhances b- and c-charge separation
- **ILC offers a very attractive and competitive electroweak precision program!**

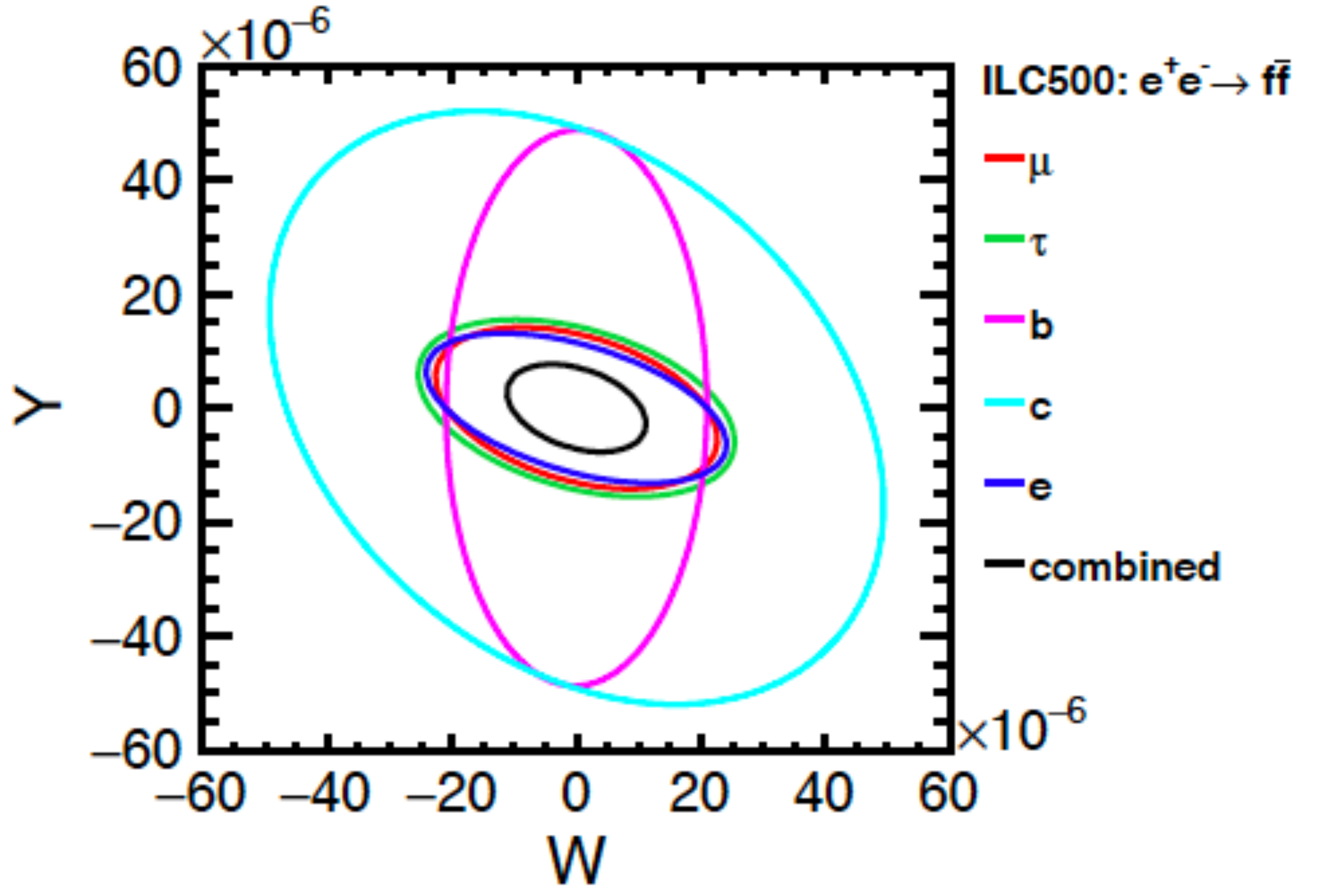
Backup

4-Fermion Processes

$\sqrt{s}$	Λ_{LL}	Λ_{RR}	Λ_{VV}	Λ_{AA}
universal Λ's				
ILC250	108	106	161	139
ILC500	189	185	280	240
ILC1000	323	314	478	403
$e^+e^- \to e^+e^-$				
ILC250	71	70	118	71
ILC500	114	132	214	135
ILC1000	236	232	376	231
$e^+e^- \to \mu^+\mu^-$				
ILC250	80	79	117	104
ILC500	134	133	198	177
ILC1000	224	222	332	296
$e^+e^- \to \tau^+\tau^-$				
ILC250	72	72	109	97
ILC500	127	126	190	168
ILC1000	215	214	321	286
$e^+e^- \to b\bar{b}$				
ILC250	78	73	103	106
ILC500	134	124	175	178
ILC1000	226	205	292	296
$e^+e^- \to c\bar{c}$				
ILC250	51	52	75	68
ILC500	90	90	130	117
ILC1000	153	151	220	199

	250 GeV,	2 ab^{-1}	500 GeV,	4 ab^{-1}	1 TeV,	8 ab^{-1}
Model	excl.	disc.	excl.	disc.	excl.	disc.
SSM	7.8	4.9	13	8.4	22	14
ALR	9.5	6.0	17	11	25	18
χ	7.0	4.5	12	7.8	21	13
ψ	3.7	2.4	6.4	4.1	11	6.8
η	4.2	2.7	7.3	4.6	12	7.9

$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

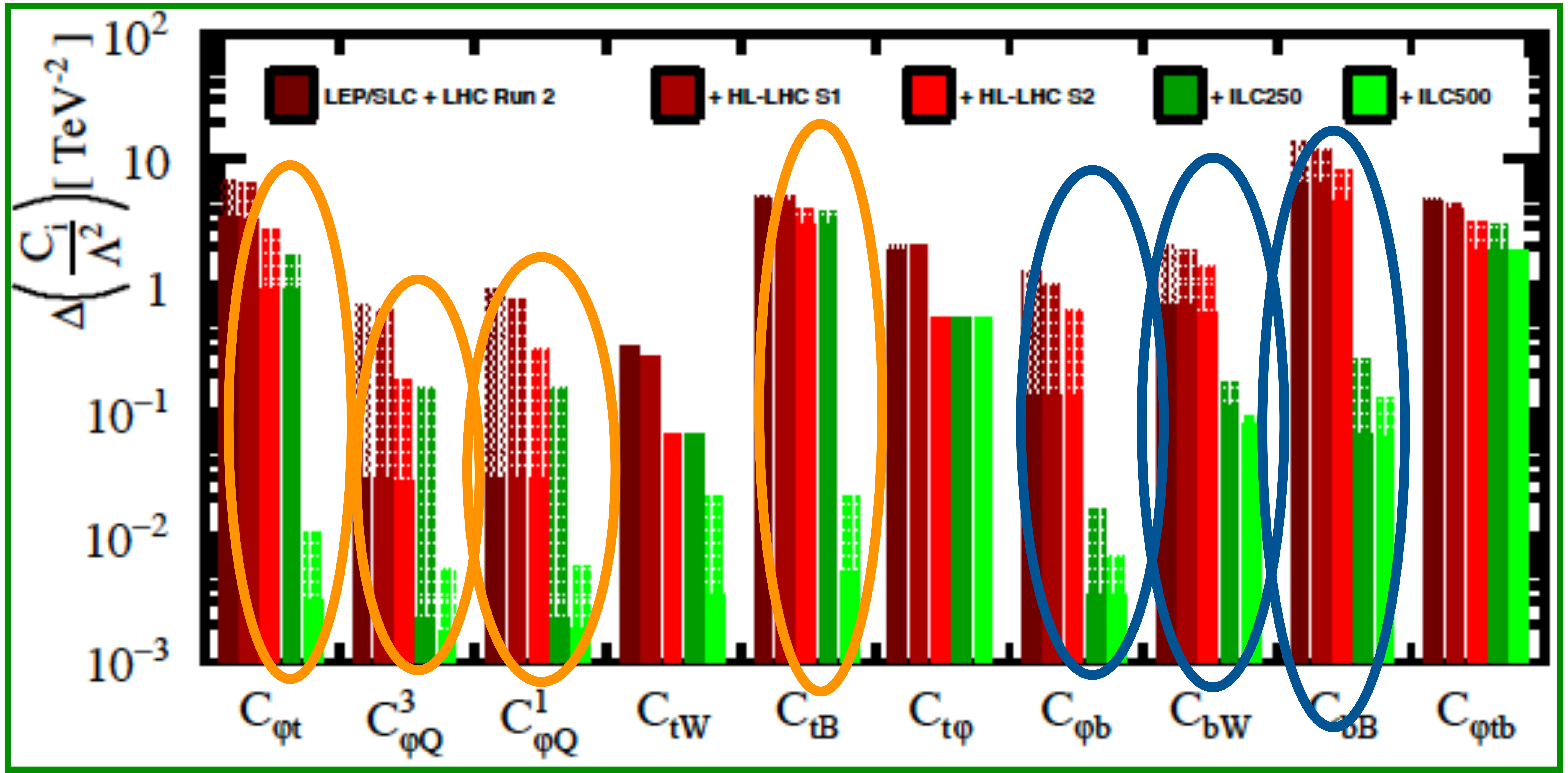


Outlook to higher energies: top / bottom EFT

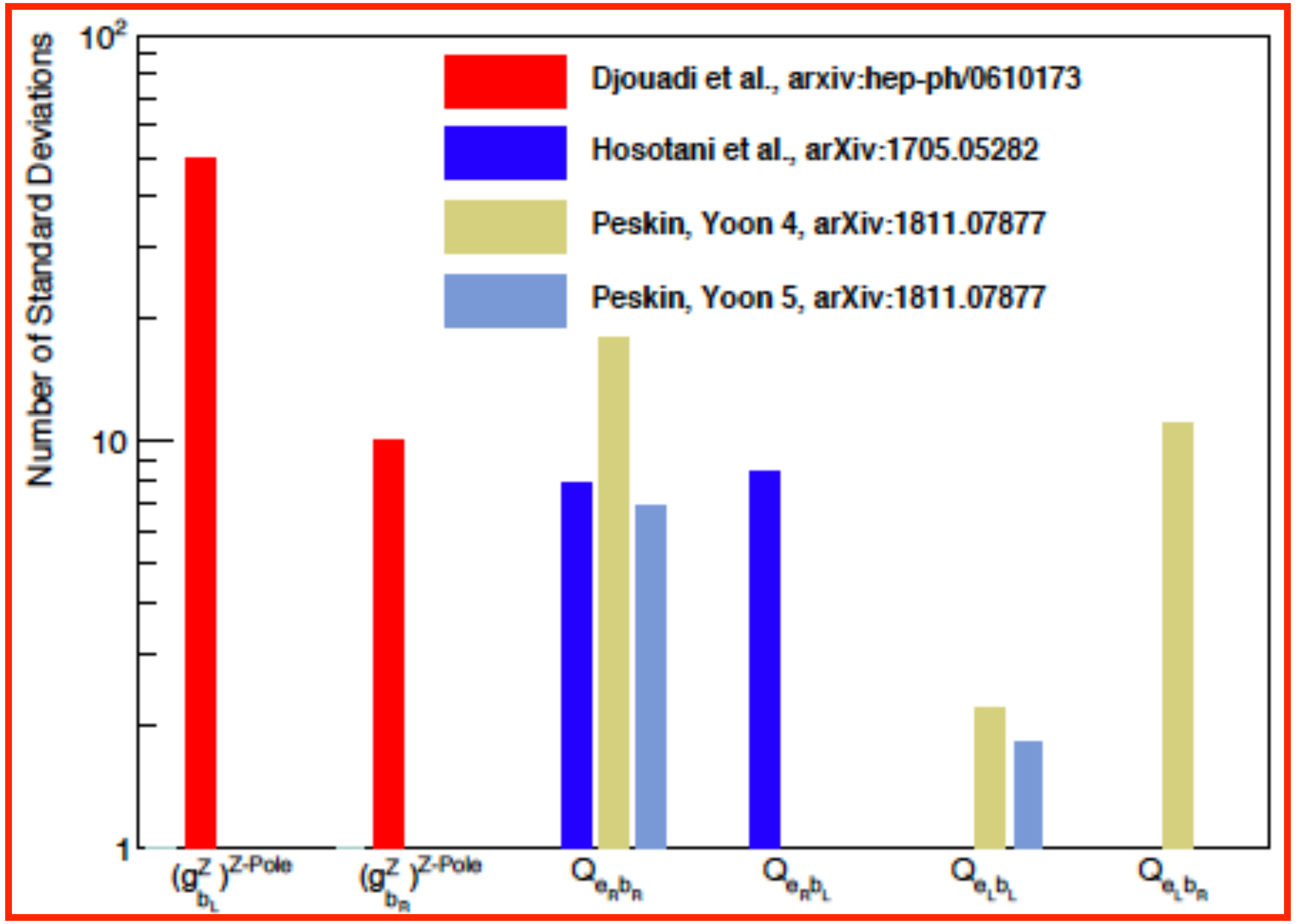
- Fit of 10 Wilson coefficients of SMEFT that modify top and bottom production

arXiv:1907.10619

- Already e^+e^- -> bb at ILC250 helps a lot
- ILC500 with e^+e^- -> tt even more so!

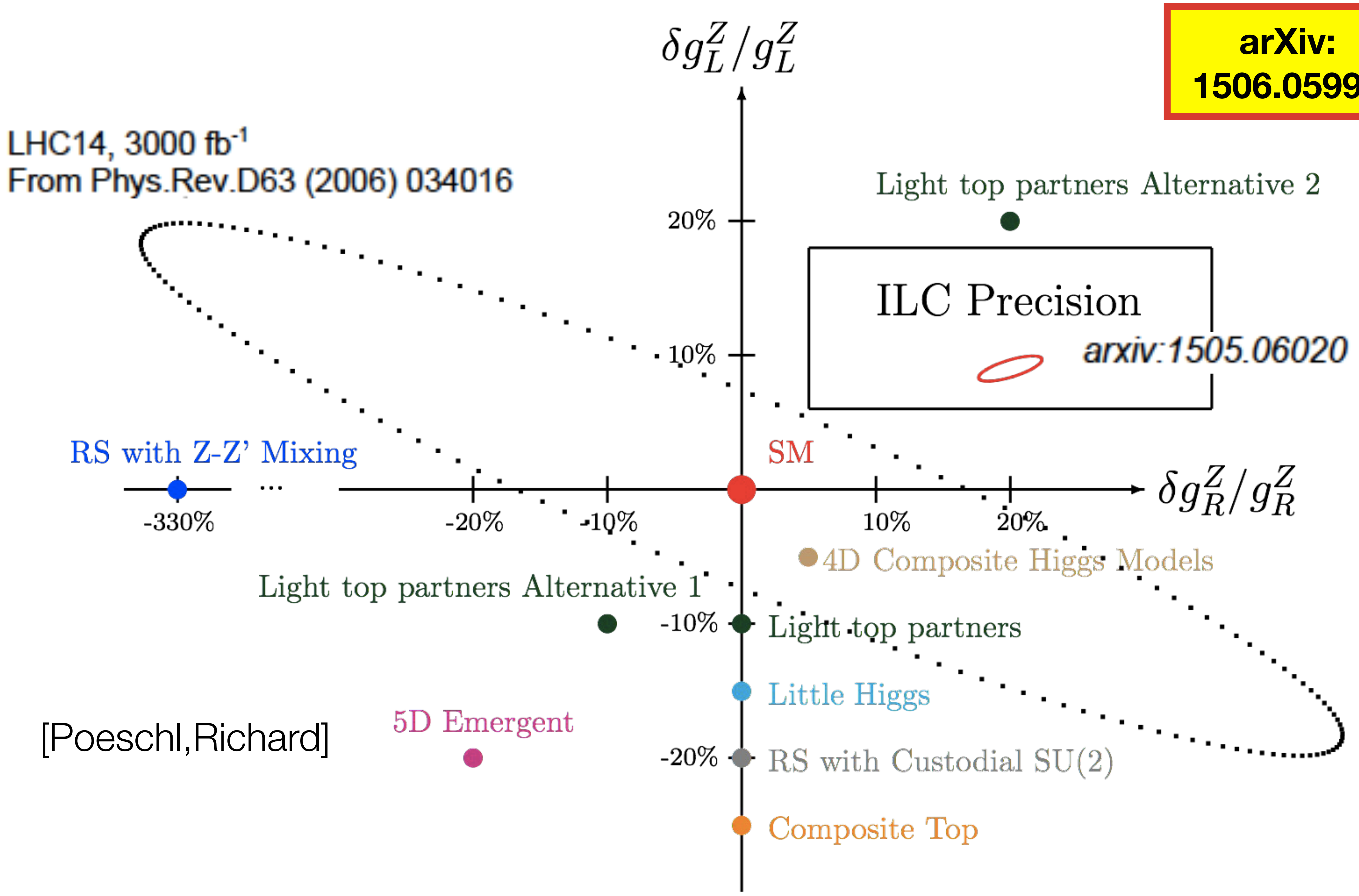


BSM significances



New Properties of the Top Quark

arXiv: 1506.05992



- **ILC precision allows model discrimination**
- **sensitivity in g^Z_L, g^Z_R plane complementary to LHC**

Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

Also from other e^+e^- -> ff:

- probe Z' up to ~10 TeV 500fb^{-1} @ 500 GeV (initial run)
- up to ~17 TeV for 1ab^{-1} at 1 TeV
- polarised beams gain ~ 2TeV in reach

Lumi/IP vs energy

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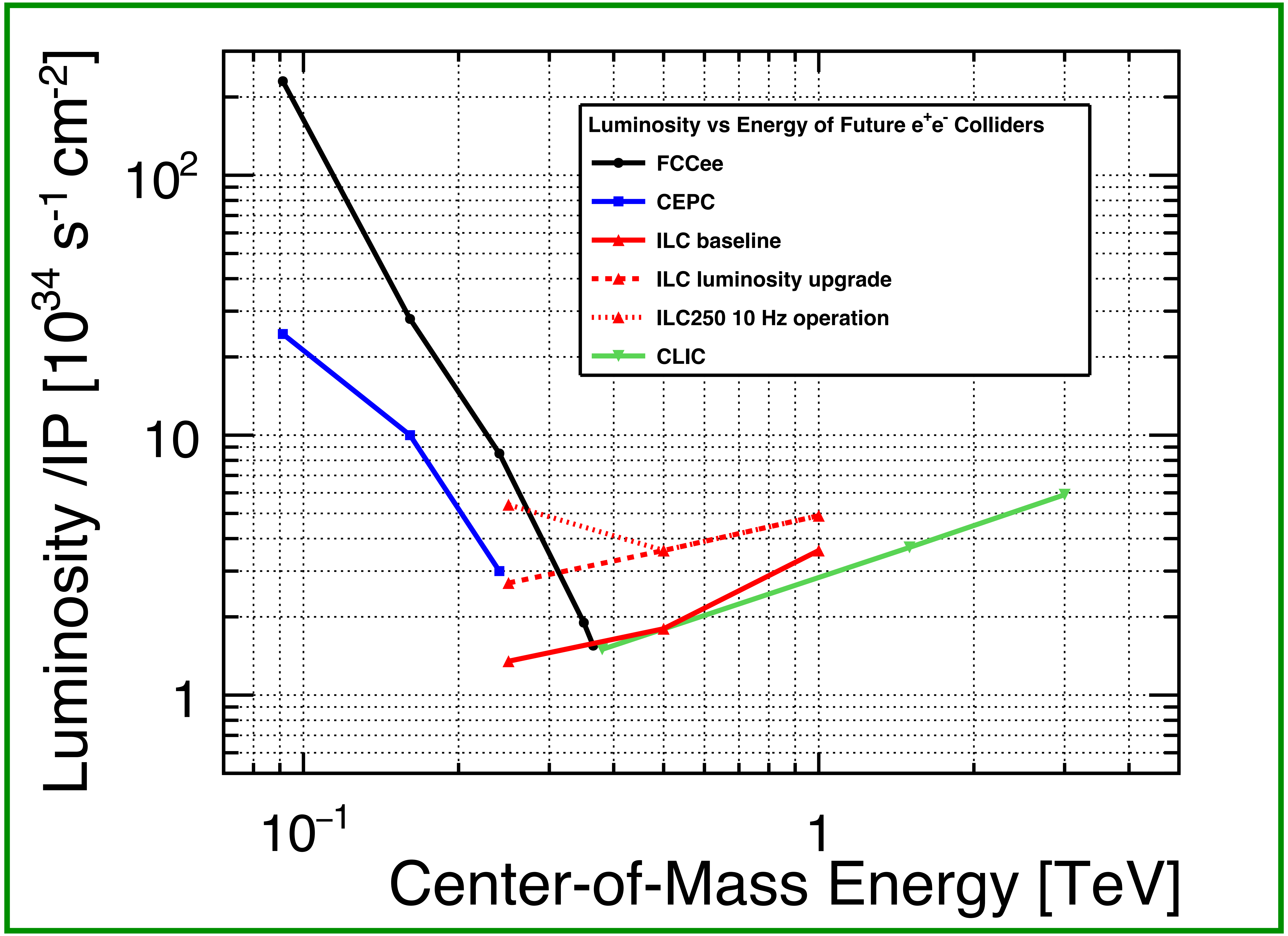
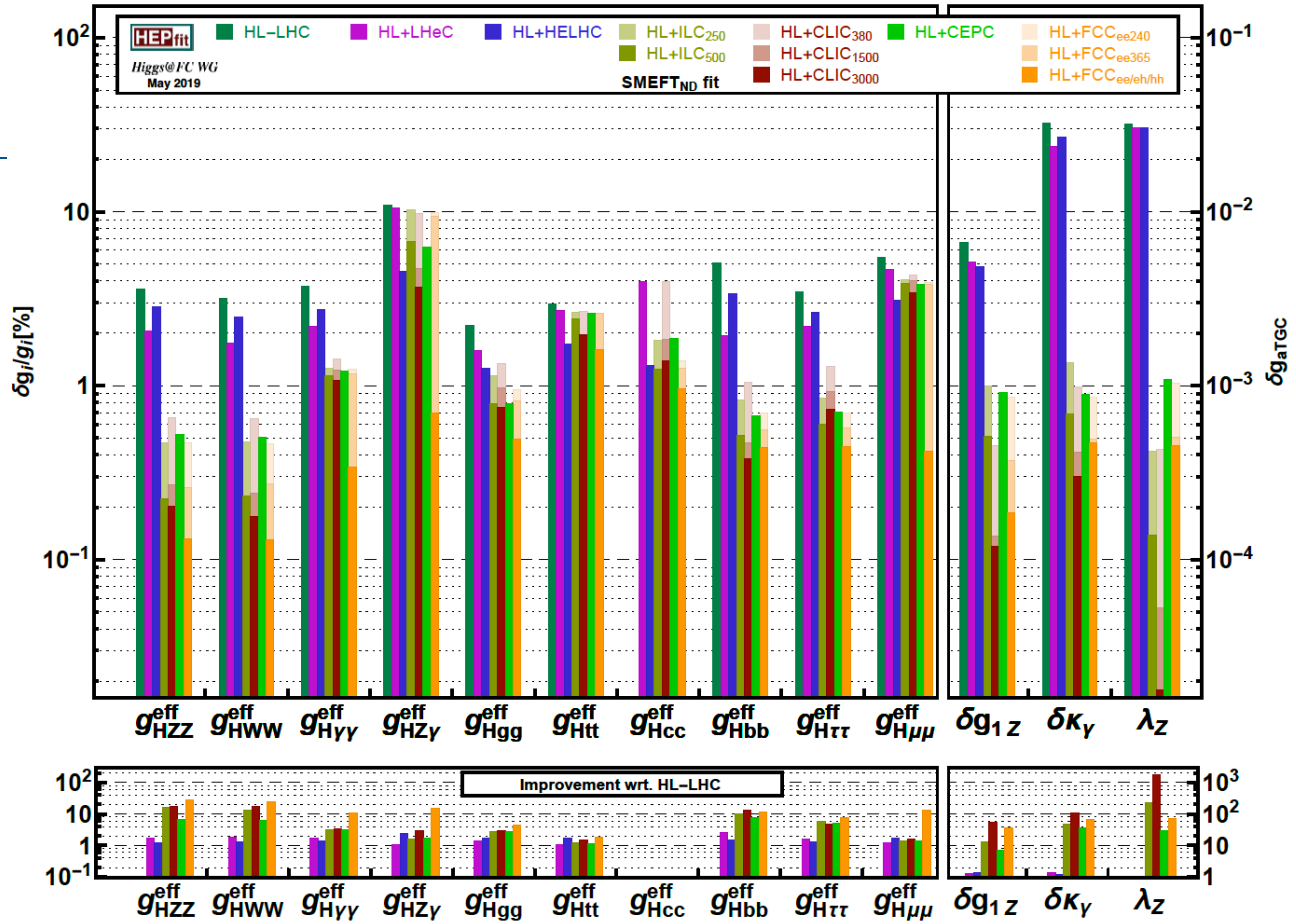


GigaZ events

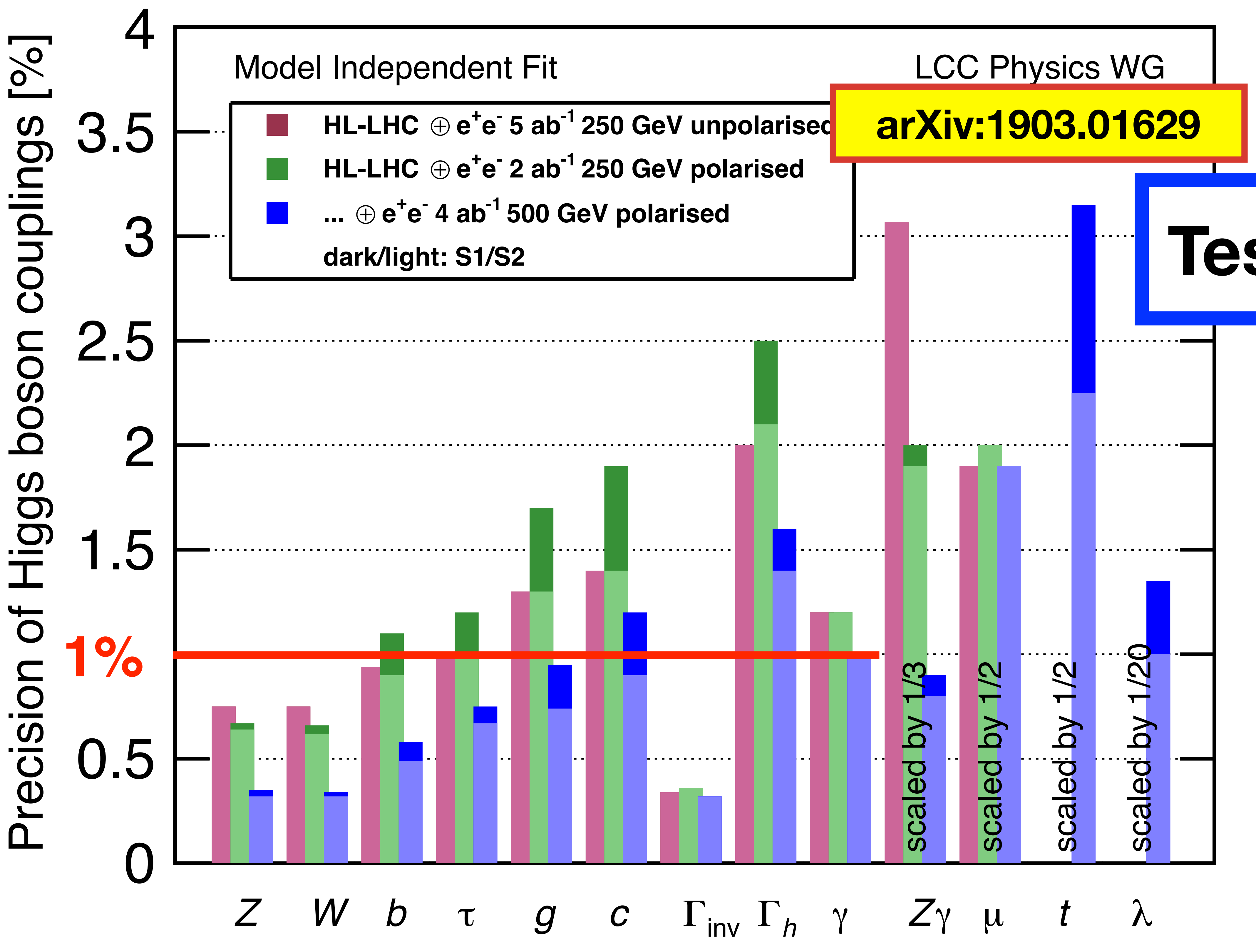
	sign$(P(e^-), P(e^+))$ =				
	$(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	60.4	46.1	35.9	29.4	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

TGCs

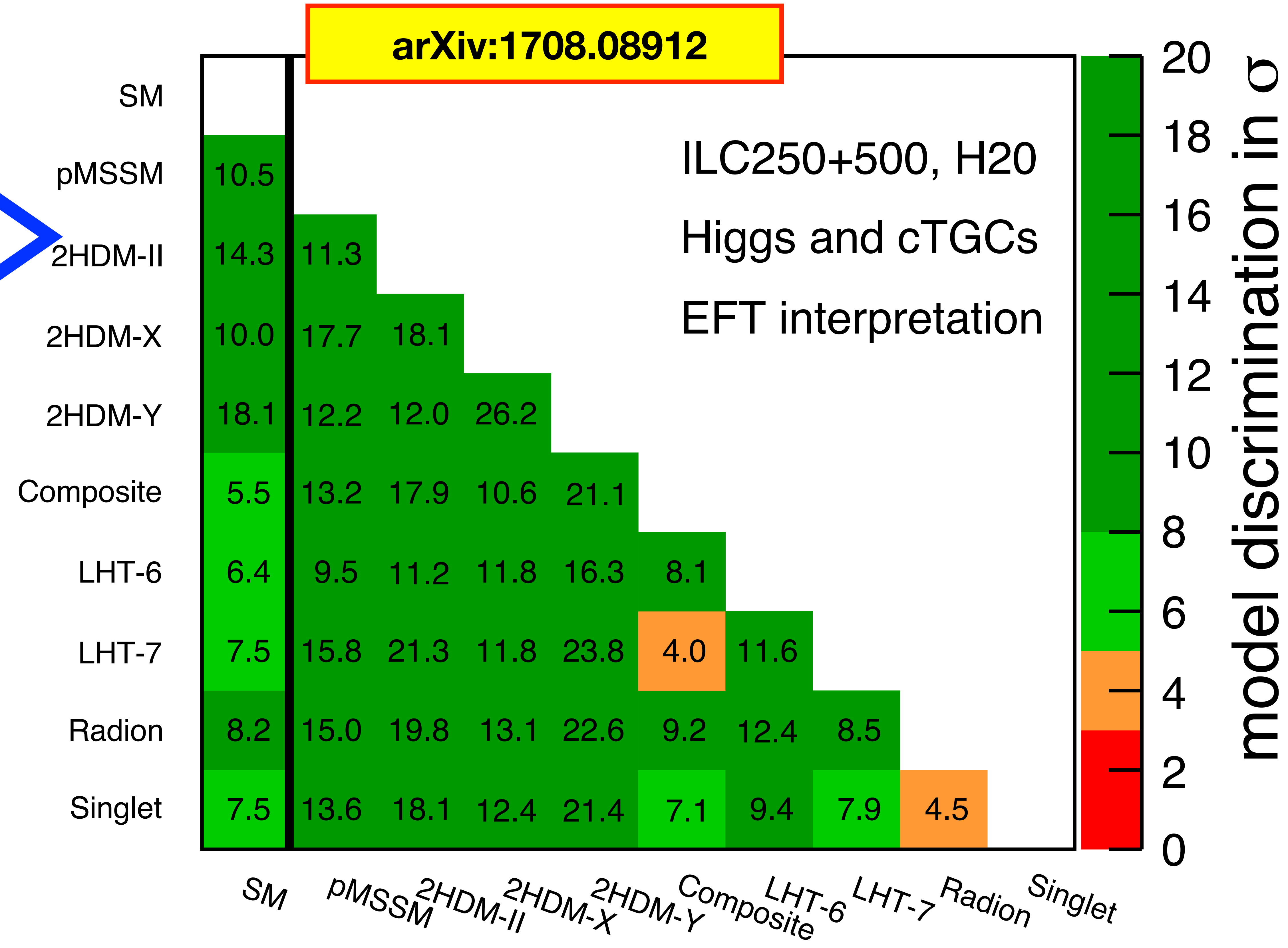


HEPfit
Higgs@FC WG
May 2019
HL−LHC
HL+LHeC
HL+HELHC
HL+ILC250
HL+ILC500
HL+CLIC380
HL+CLIC1500
HL+CLIC3000
HL+CEPC
HL+FCCee240
HL+FCCee365
HL+FCCee/eh/hh
SMEFTND fit
δgi/gi[%]
δgaTGC
Improvement wrt. HL−LHC

New Properties of the Higgs Boson



Test BSM



discovery and identification of various BSM benchmark models (not observable at LHC)

Additional Scalar(Higgs) Bosons

- e.g. from 2HDMs or additional singlets (as in NMSSM)
- Can be searched for with various techniques

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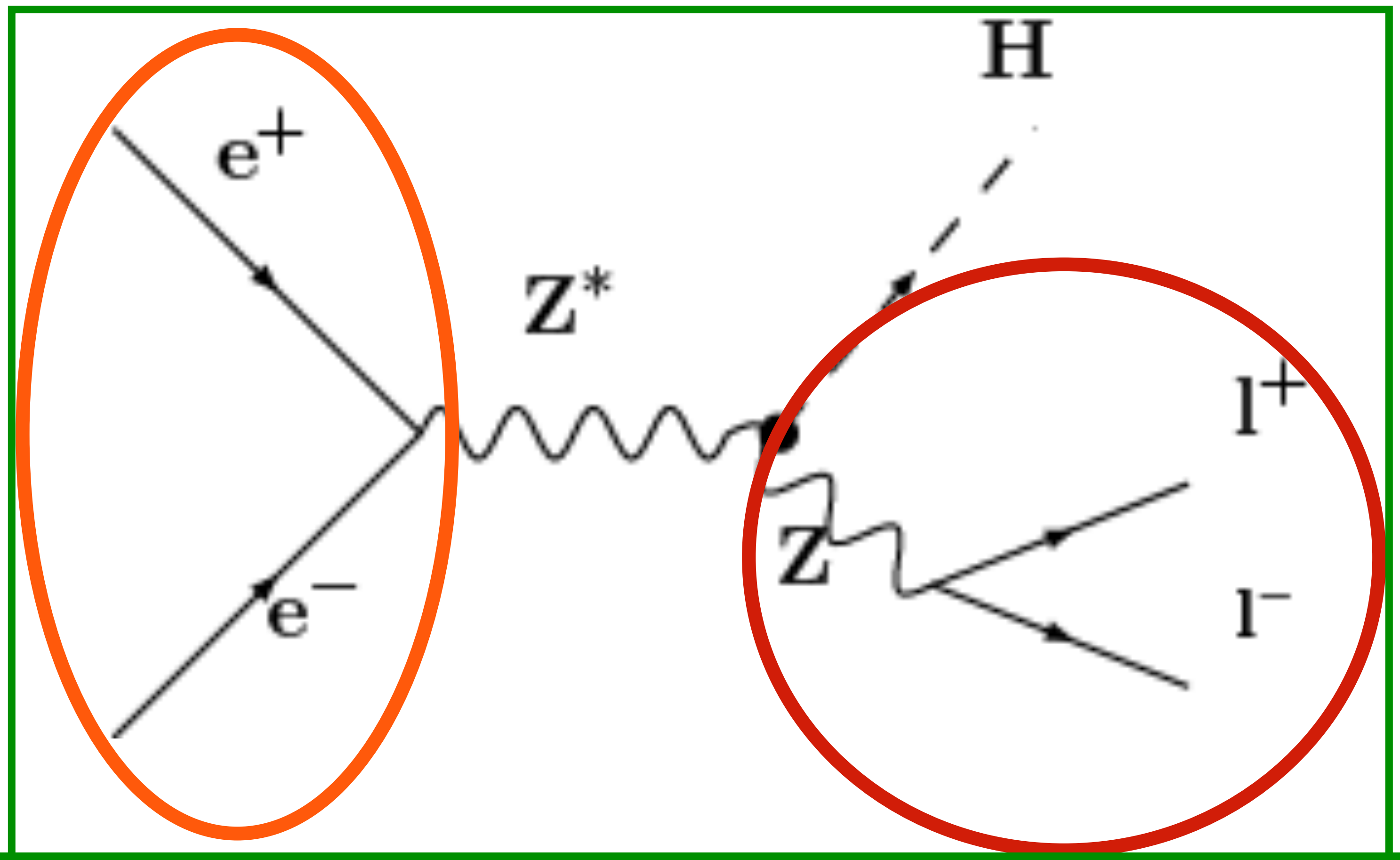

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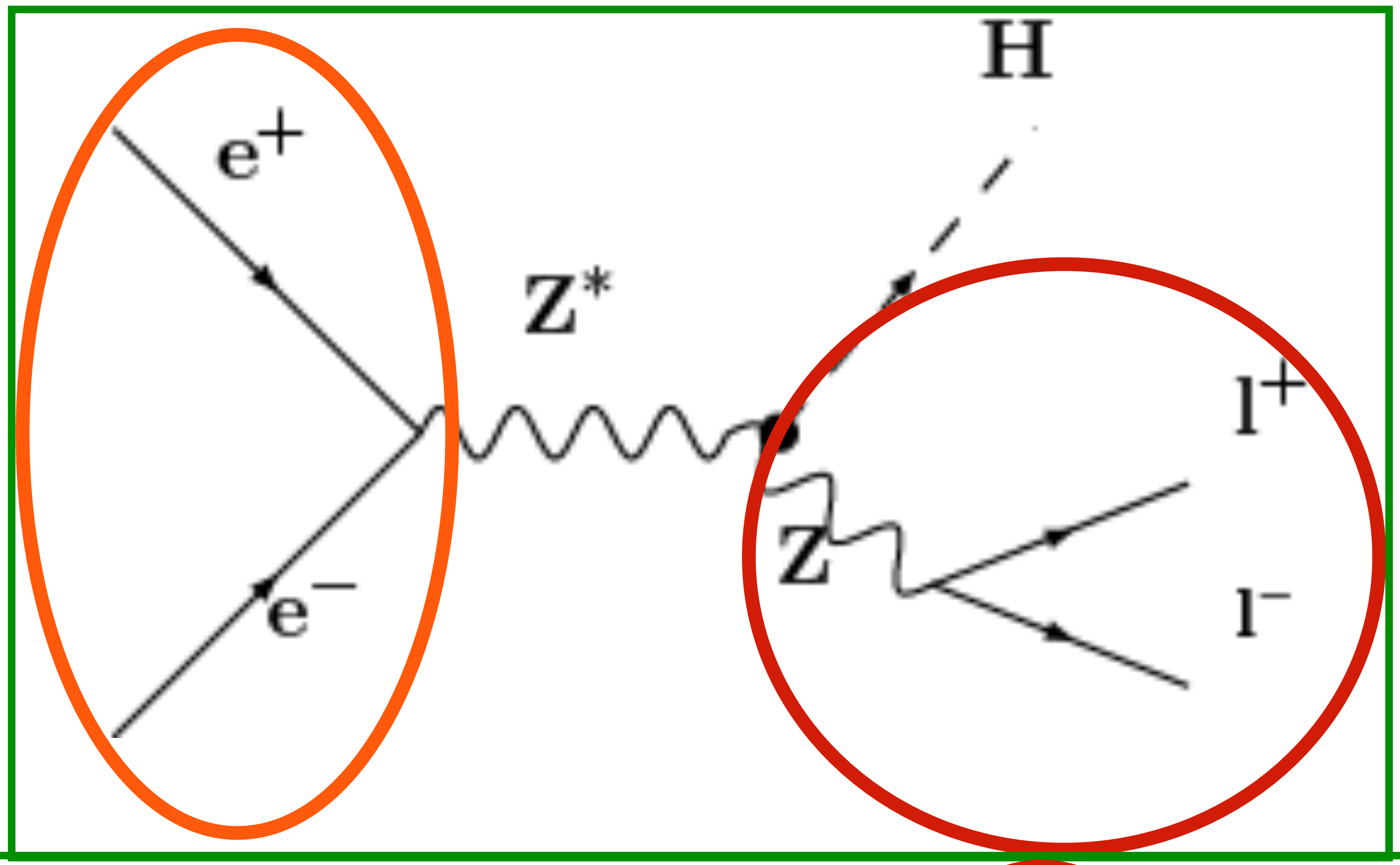

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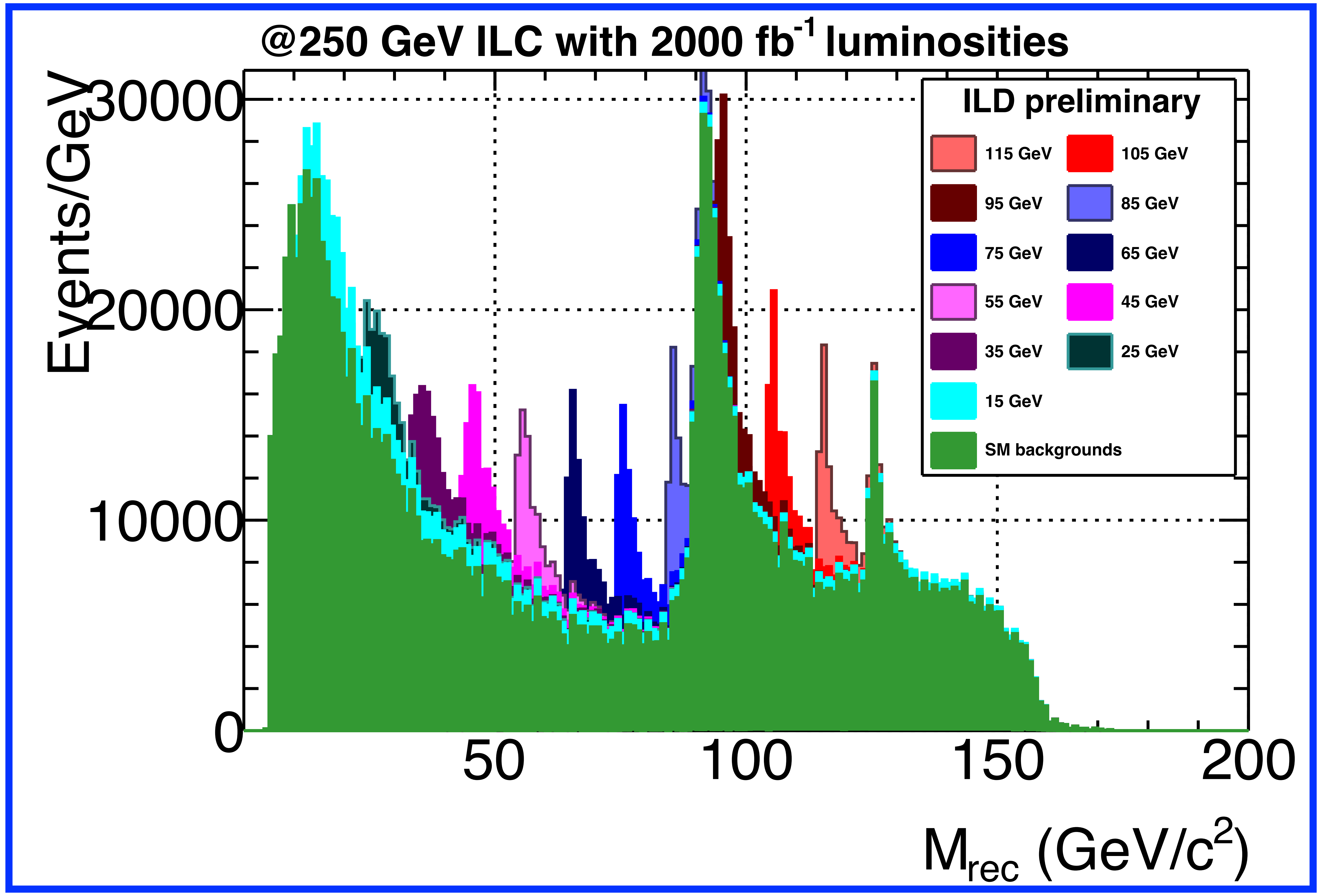

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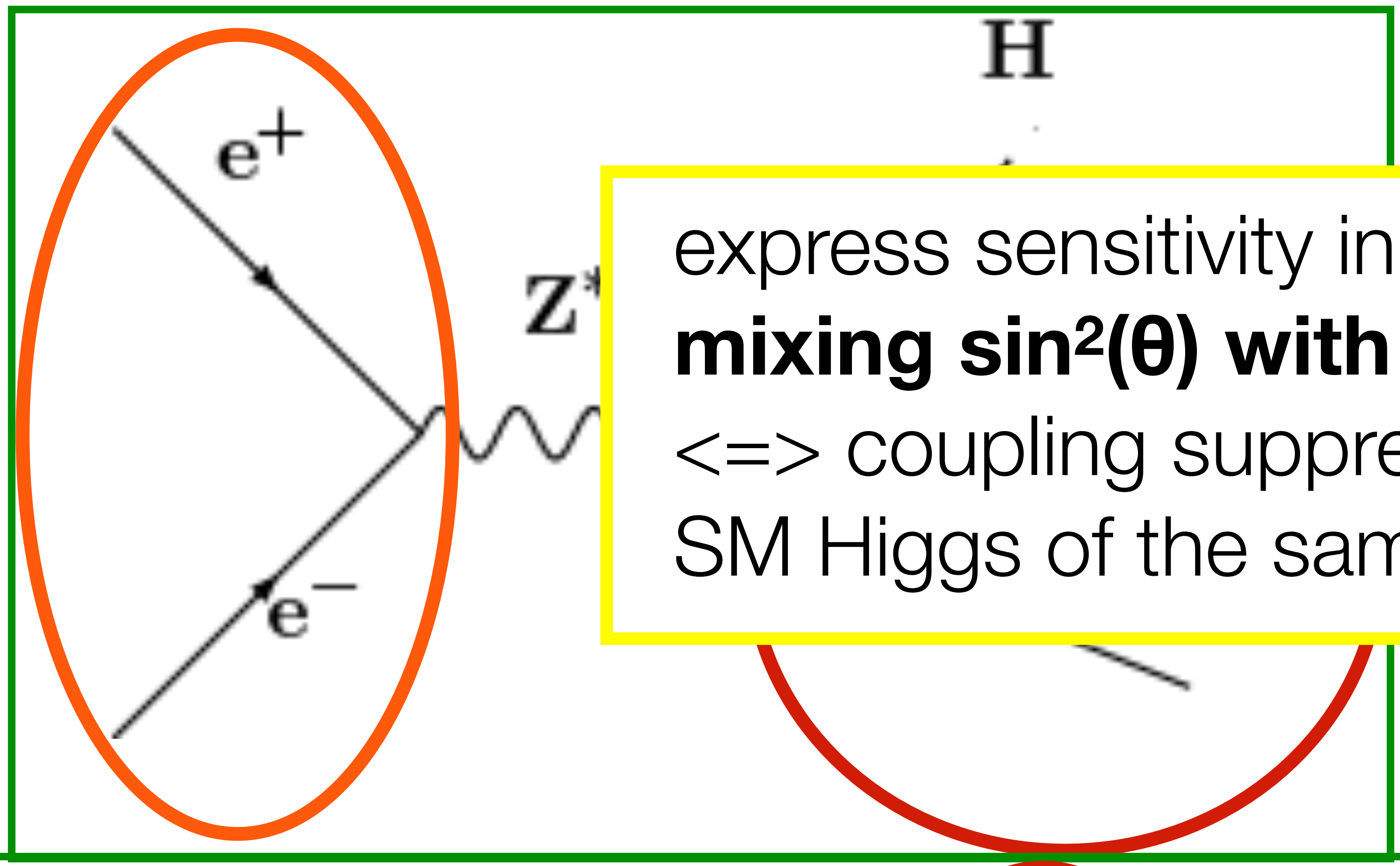

express sensitivity in terms of **mixing sin²(θ) with SM Higgs** <=> coupling suppression wrt SM Higgs of the same mass

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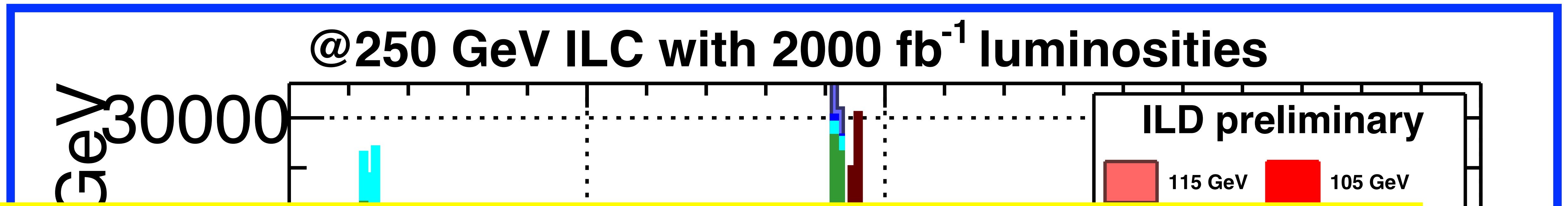

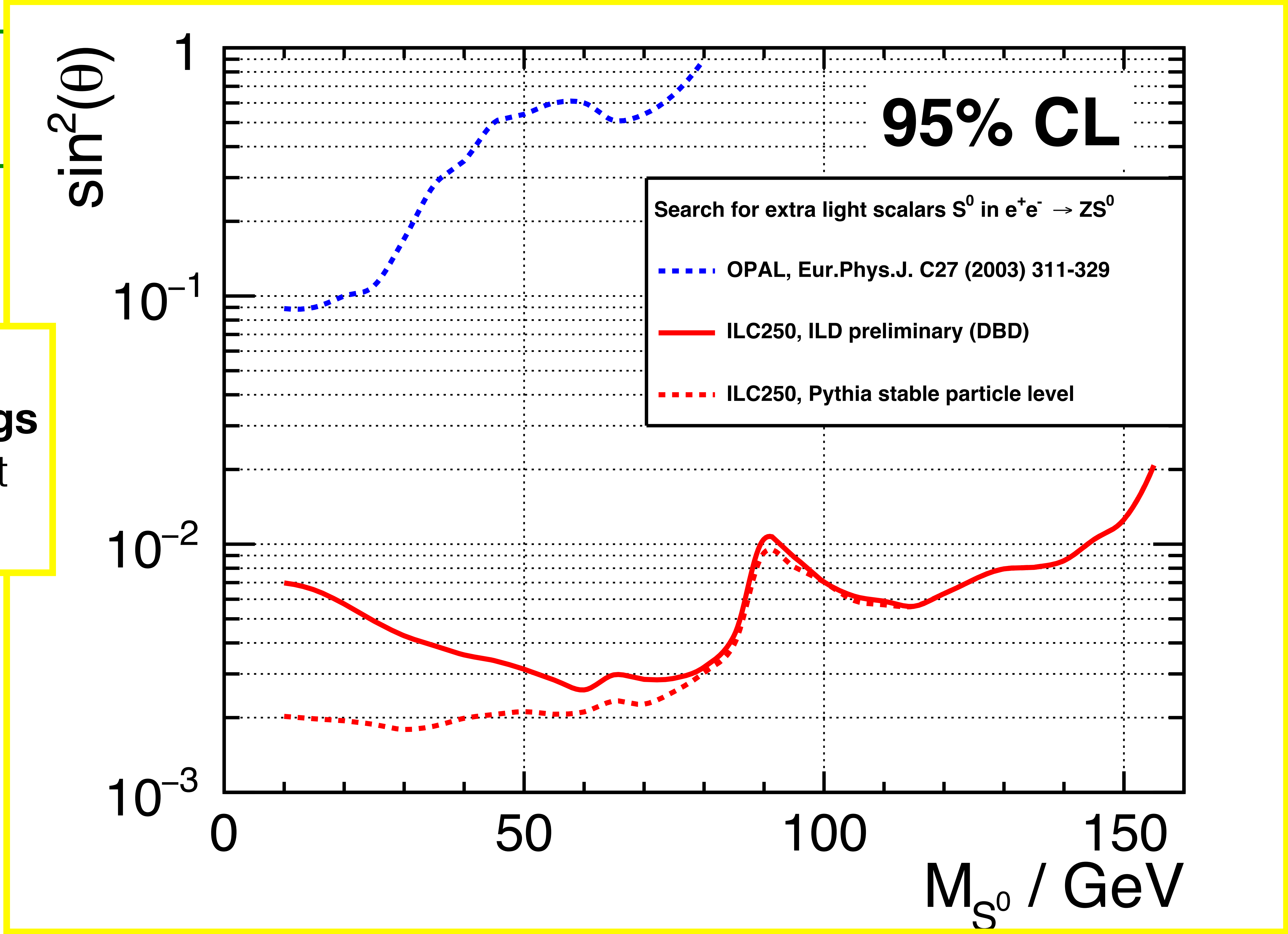

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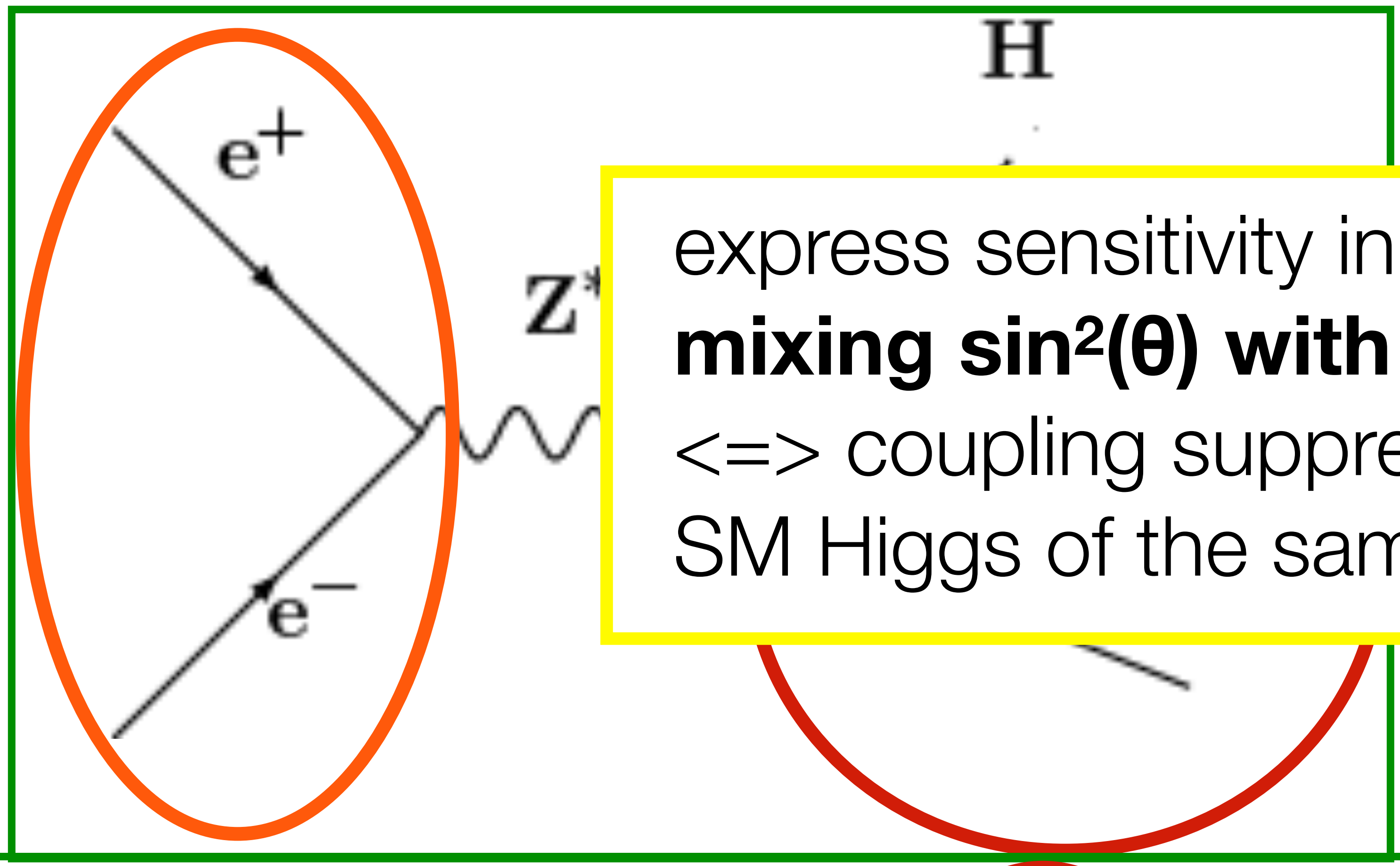

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express sensitivity in terms of **mixing sin²(θ) with SM**
<=> coupling suppress...
SM Higgs of the same

detector & reconstruction => room for improvement!