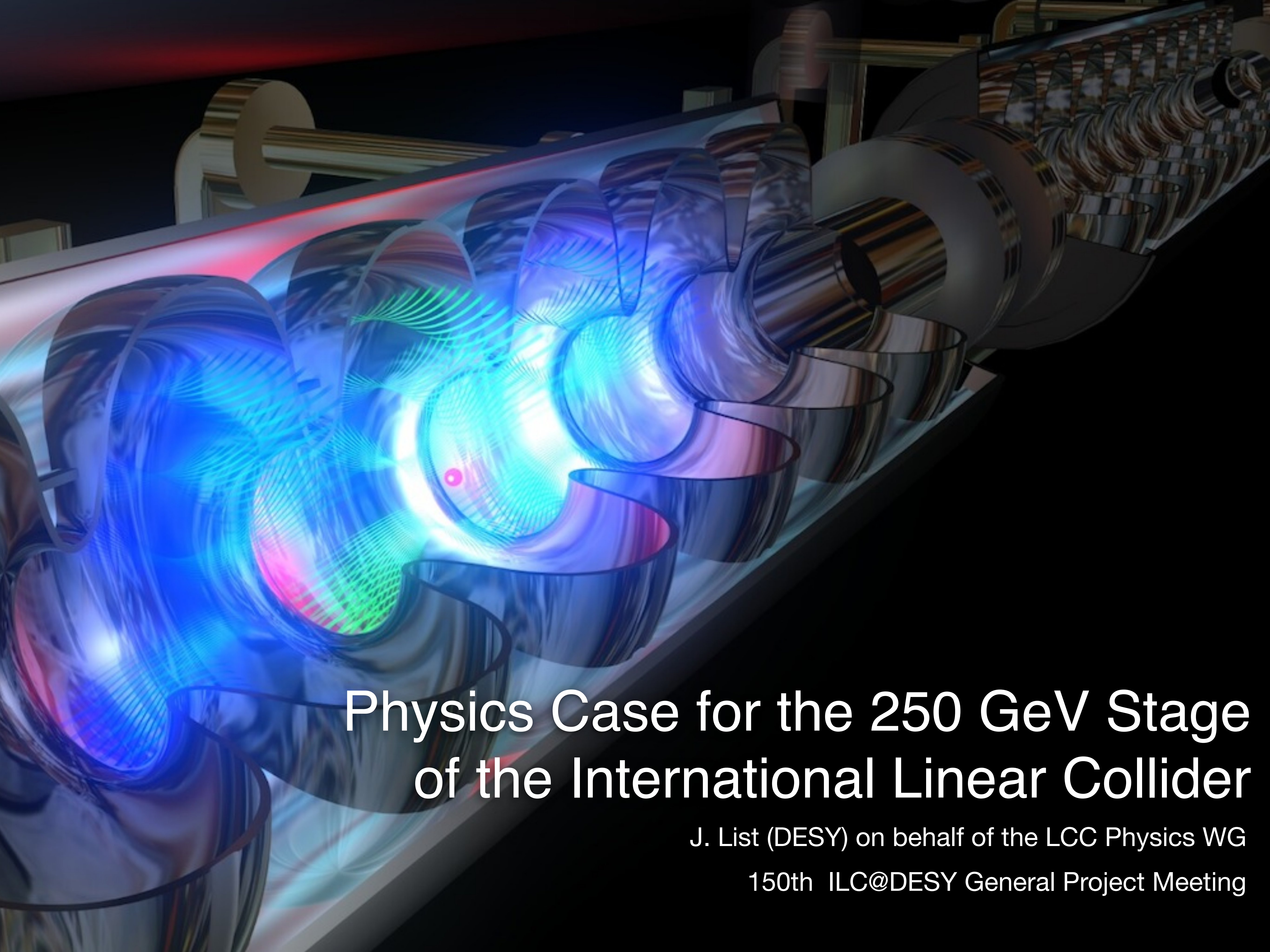


# Physics Case for the 250 GeV Stage of the International Linear Collider

J. List (DESY) on behalf of the LCC Physics WG

150th ILC@DESY General Project Meeting

# News (received via Hitoshi Yamamoto)

- Reuter Japan interview of Satoshi Fujii (one the 7 advisors to Prime Minister, one of the two on ‘Abenomics’)
- To the question of where the money gained by tax increase should be spent, he presents two examples:
- “—— What kind of fields should be specifically spent?”
- “If you take financial measures on research and development, you can expect productivity to improve over the long term, for example, the super large-scale accelerator "International Linear Collider” (ILC) is one example - for improving science and technology capabilities and human resource development In addition, the economic effect of the region can be expected. Infrastructure development of Shinkansen is also promising in that it raises public expectations.”

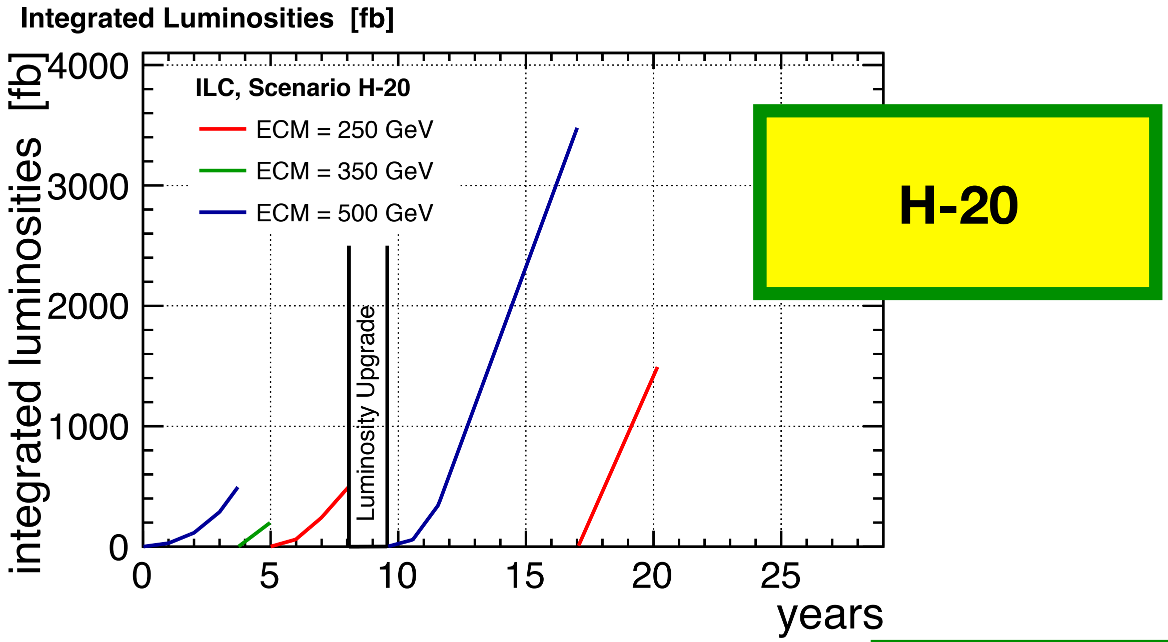
# Introduction

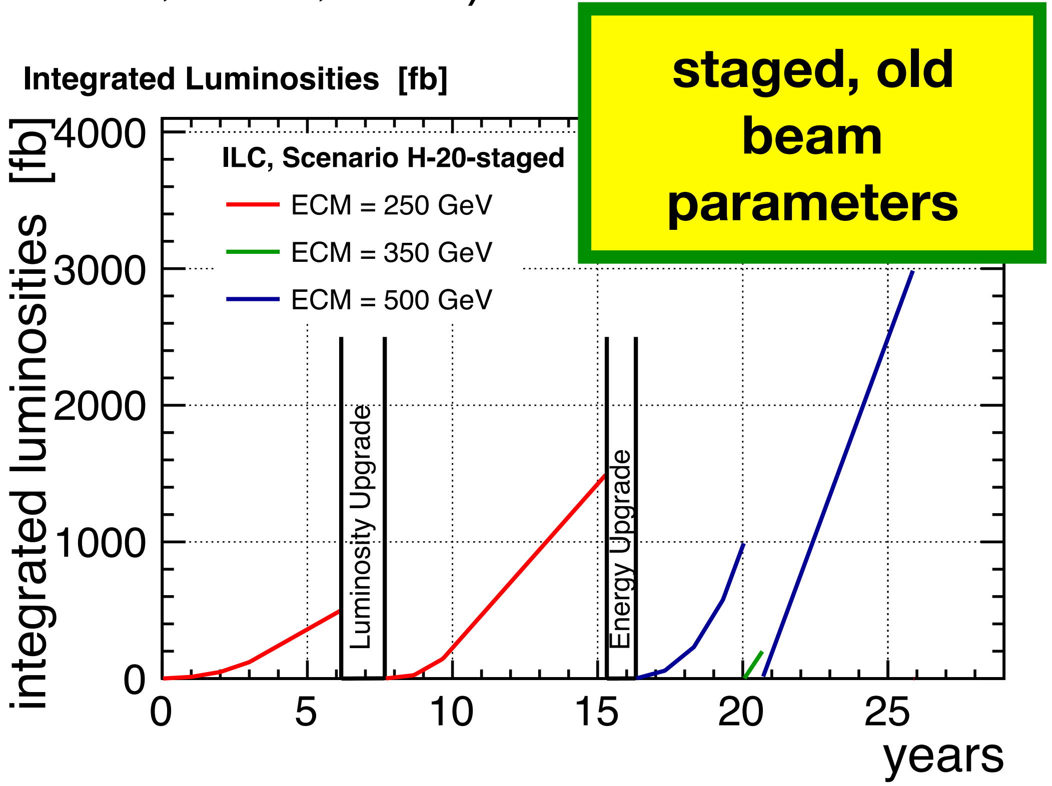
- LCC Physics WG has spend all summer on the 250 GeV physics case
- paper on EFT-based interpretation of Higgs measurements: arXiv:1708.08912, submitted to PRD, presented here in September by Tim
- NEW: complete draft of paper summarising the whole 250 GeV physics case
  - today: exclusive preview for you :)
  - plan: arxiv, LCC, LCB, ICFA **by LCWS**
  - input to discussion on staging at ICFA Seminar (Nov. 6-9 in Ottawa)

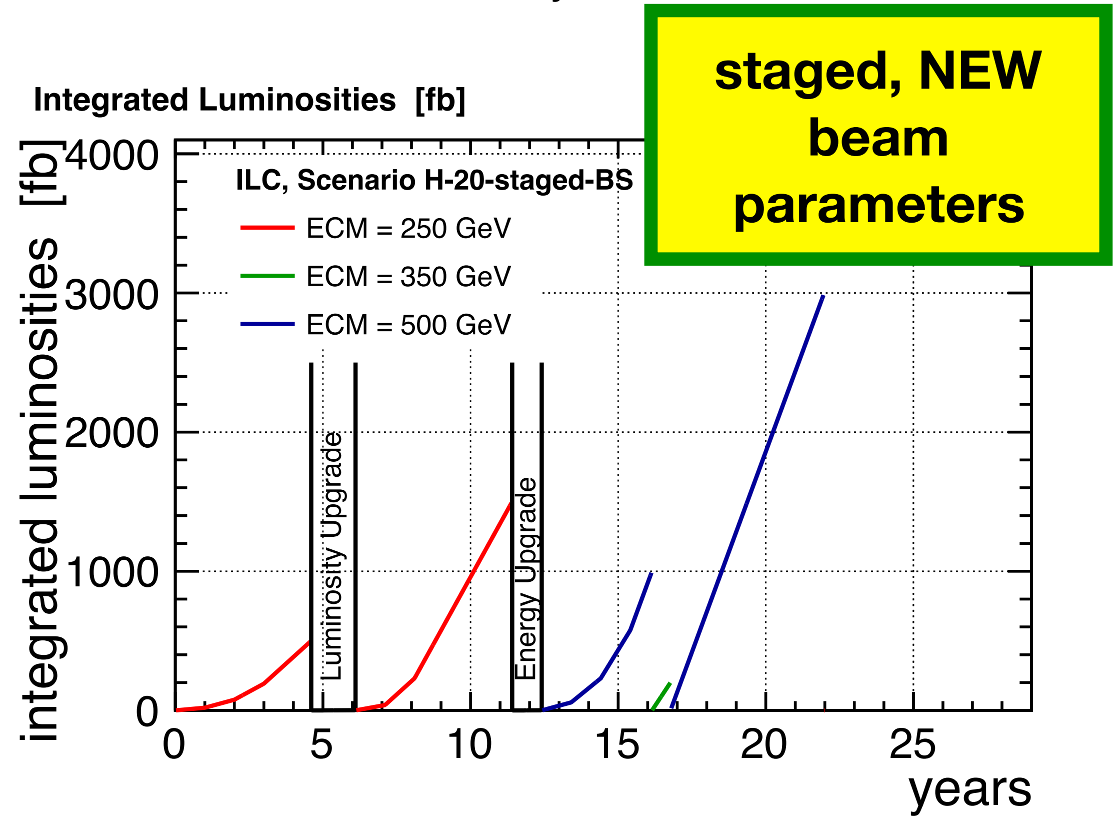
# Outline of the paper

# Run plan

- no change to total integrated luminosities / ECM
- changed helicity fractions f(-+,+-,++,—) at 250 GeV from (67.5%, 22.5%, 5%, 5%) to (45%, 45%, 5%, 5%)



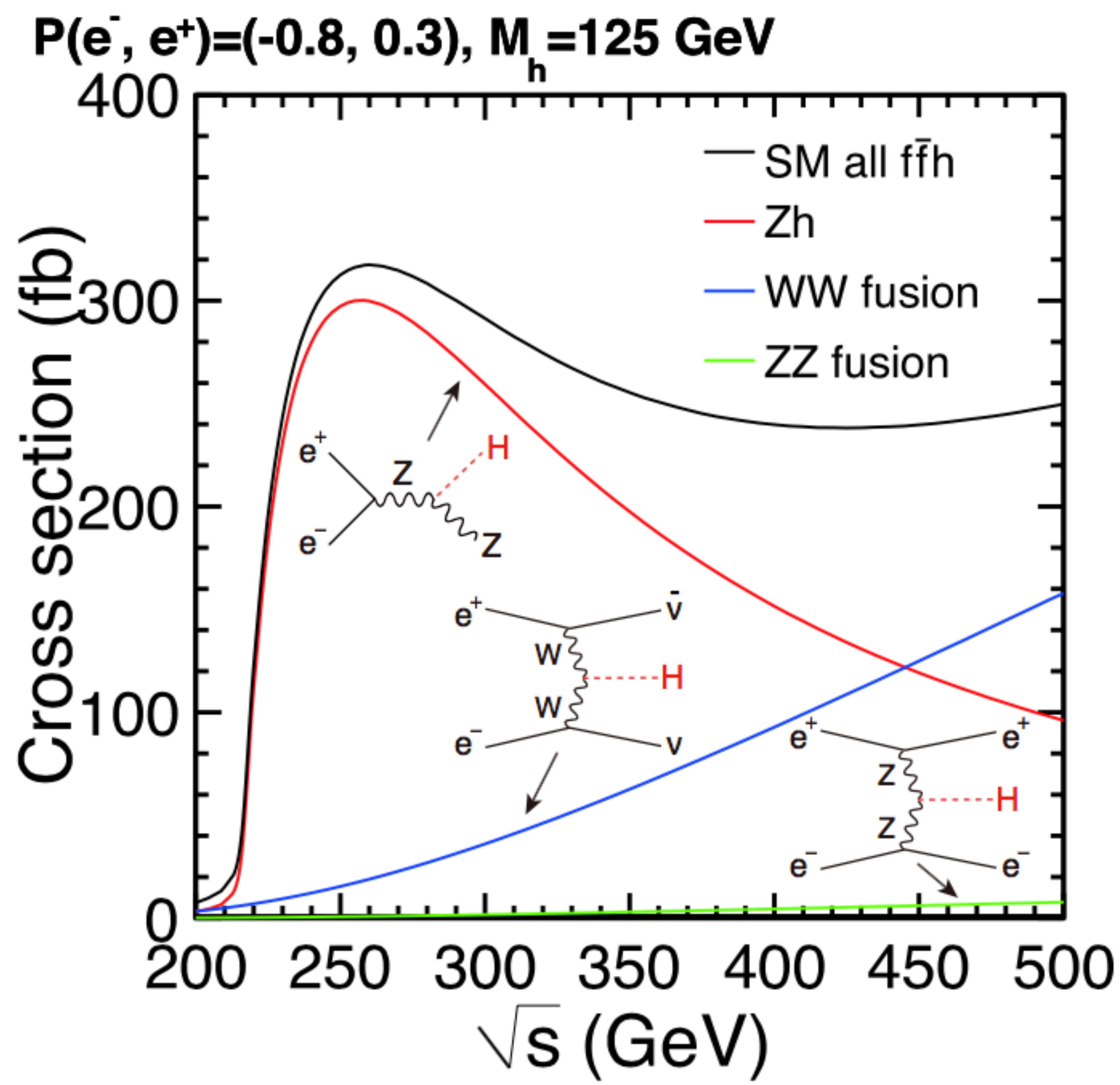



# Precision Higgs Physics @ 250 GeV

- production dominated by Zh
- 2 $ab^{-1}$ => ~600 000 Zh events
- fantastic sample for measuring:
  - (recoil) mass
  - total Zh cross section -> g(ZZh)
  - h-> invisible (Dark Matter!)
  - all kinds of branching ratios
  - CP properties of h-fermion coupling
  - CP properties of Zh coupling
- in SU(2)xU(1) gauge symmetric EFT:
  - combine with EWPO, TGCs etc

  => 1% precision also for g(WWh), $\Gamma_{tot}$

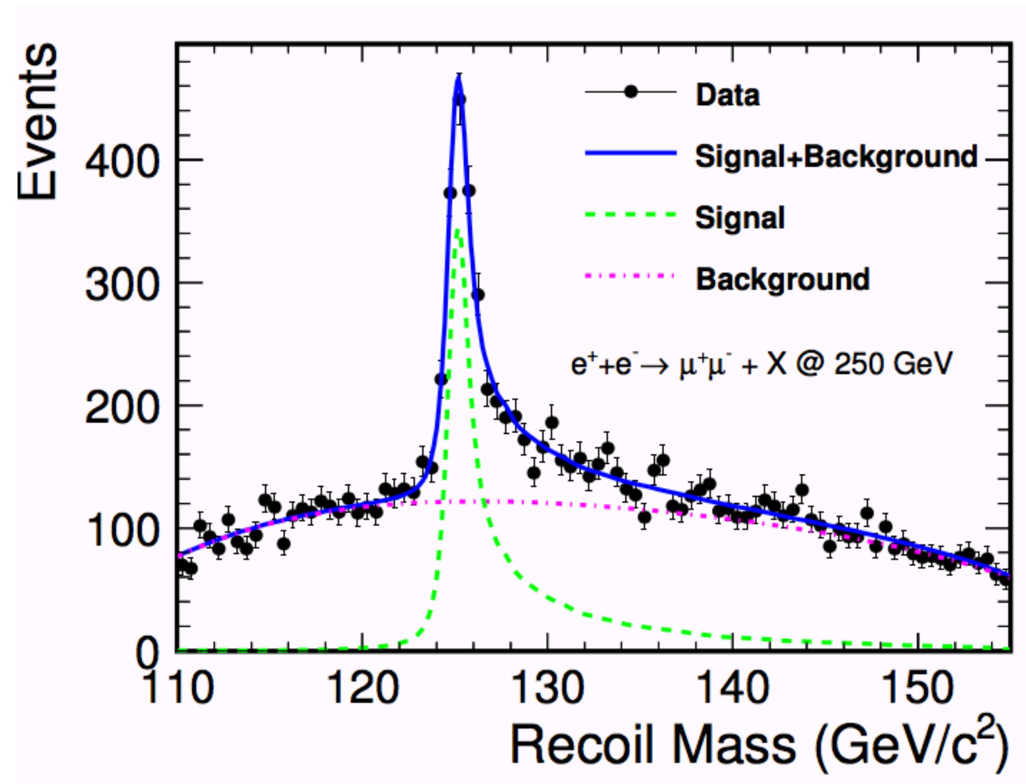


# Precision measurement of the Higgs mass

How well do we need to know the Higgs mass?

- for many applications, $\delta m_h \simeq 0.25$ GeV (or 0.2%) is ok
- notable exception: h->V V* decays very sensitive to $m_h$ due to phase space!
  => relative errors for couplings and mass relate as:

$$\delta_W = 6.9 \cdot \delta m_h, \qquad \delta_Z = 7.7 \cdot m_h,$$




- **$\delta m_h$ = 0.2% => $\delta_W$ = 1.4% not adequate for ILC precision!**
- **leptonic recoil mass at ILC 250 GeV: $\delta m_h \simeq$ 14 MeV => $\delta_W$ = 0.1%** ✔
- check impact of new beam parameters!

# Higgs coupling precisions (in %)

| | ILC250 | | +ILC500 | |
|---|---|---|---|---|
| | $\kappa$ fit | EFT fit | $\kappa$ fit | EFT fit |
| $g(hbb)$ | 1.8 | 1.1 | 0.60 | 0.58 |
| $g(hcc)$ | 2.4 | 1.9 | 1.2 | 1.2 |
| $g(hgg)$ | 2.2 | 1.7 | 0.97 | 0.95 |
| $g(hWW)$ | 1.8 | 0.67 | 0.40 | 0.34 |
| $g(h\tau\tau)$ | 1.9 | 1.2 | 0.80 | 0.74 |
| $g(hZZ)$ | 0.38 | 0.68 | 0.30 | 0.35 |
| $g(h\gamma\gamma)$ | 1.1 | 1.2 | 1.0 | 1.0 |
| $g(h\mu\mu)$ | 5.6 | 5.6 | 5.1 | 5.1 |
| $g(h\gamma Z)$ | 16 | 6.6 | 16 | 2.6 |
| $g(hbb)/g(hWW)$ | 0.88 | 0.86 | 0.47 | 0.46 |
| $g(h\tau\tau)/g(hWW)$ | 1.0 | 1.0 | 0.65 | 0.65 |
| $g(hWW)/g(hZZ)$ | 1.7 | 0.07 | 0.26 | 0.05 |
| $\Gamma_h$ | 3.9 | 2.5 | 1.7 | 1.6 |
| $BR h \to inv$ | 0.32 | 0.32 | 0.29 | 0.29 |
| $BR h \to other$ | 1.6 | 1.6 | 1.3 | 1.2 |

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**for details of EFT fit c.f. talk by Tim Barklow last project meeting!**

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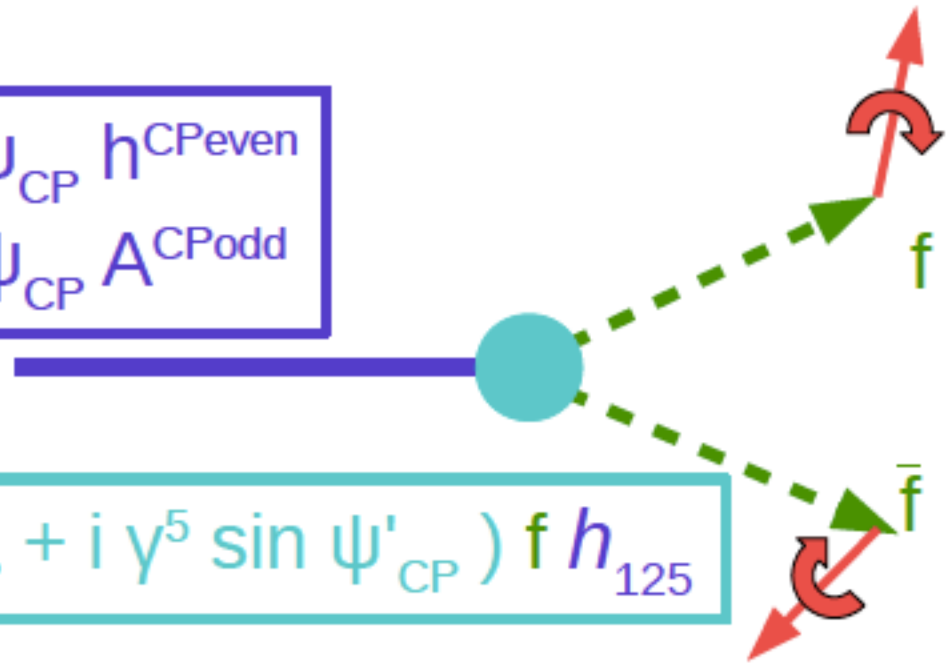
- **250 GeV does a great job**
- **+ 500 GeV improves up to a factor of ~2**

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

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

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*h* is a spin 0 state:

$$|f\,\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\,|\downarrow\uparrow\rangle$$

[ $\psi$ = 0 CP even,
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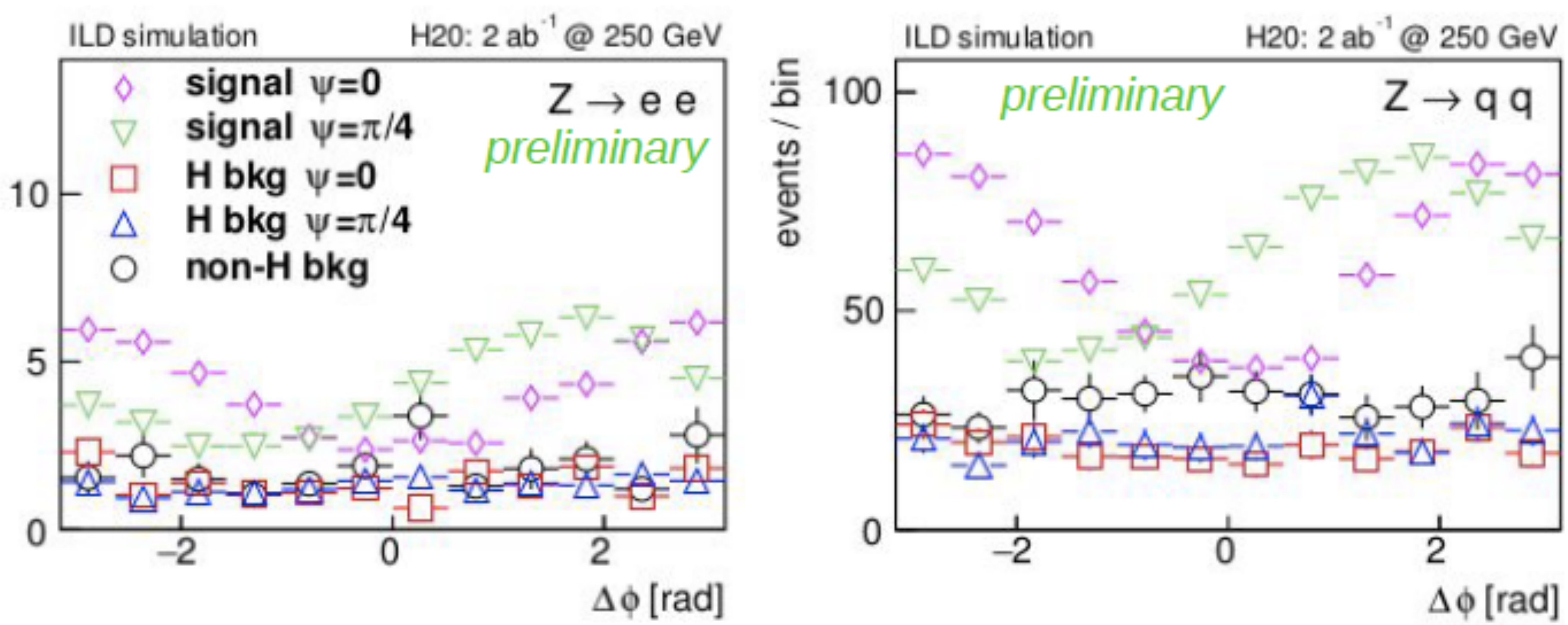

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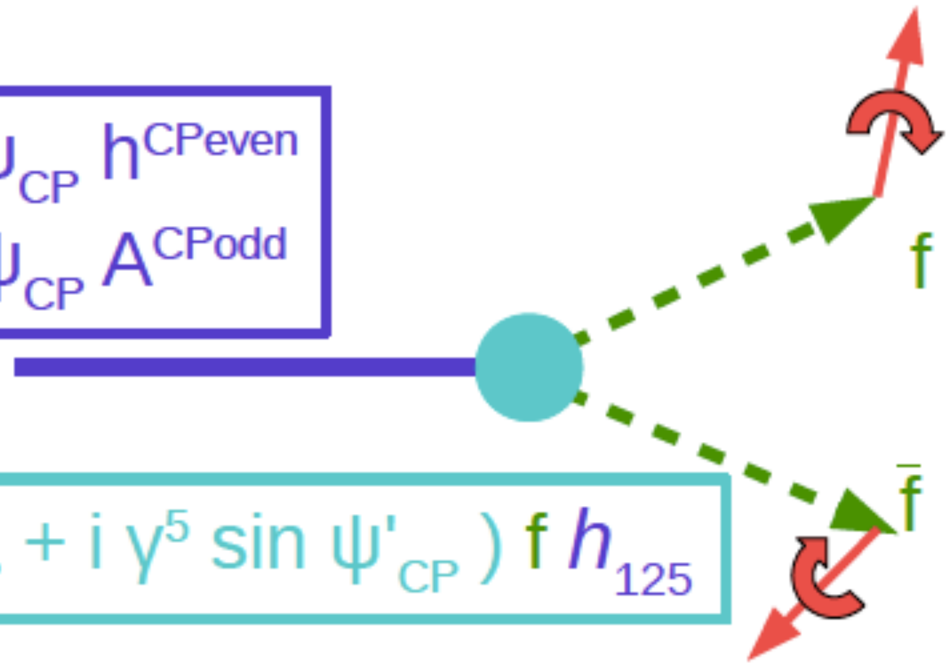


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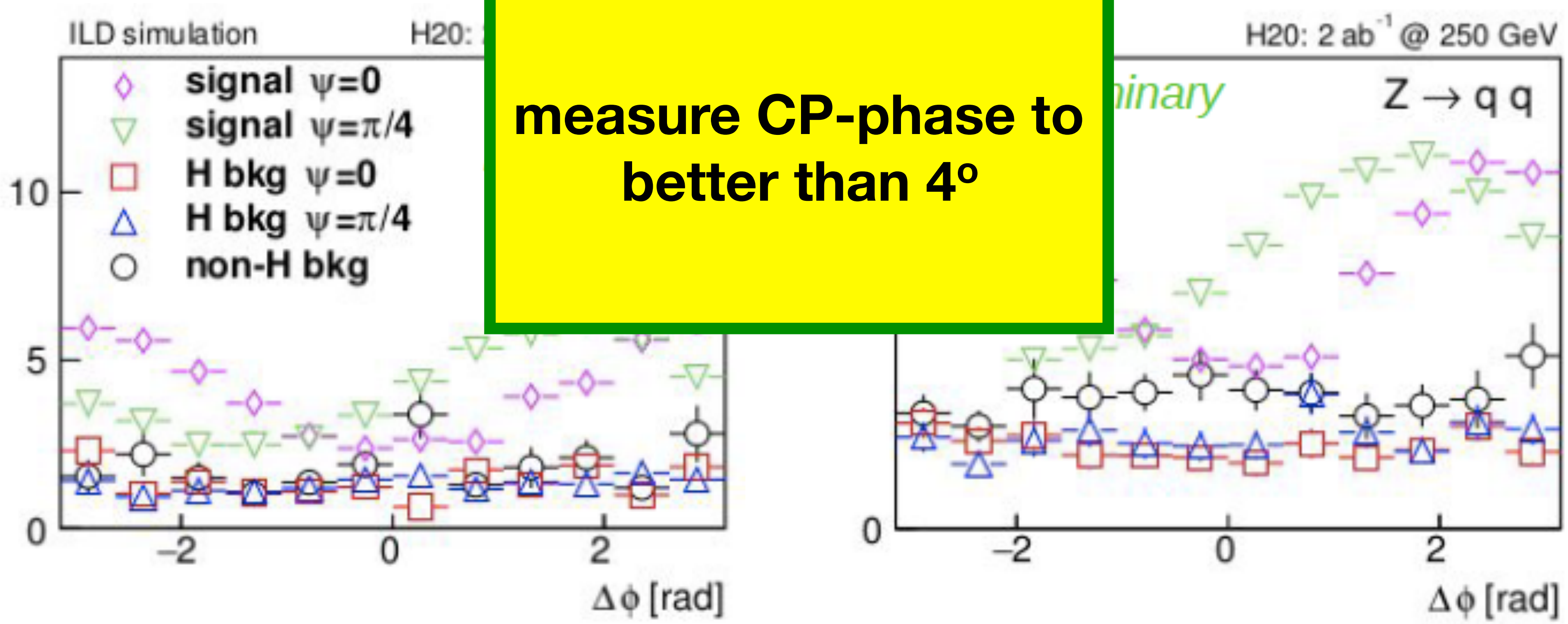


**measure CP-phase to better than 4°**

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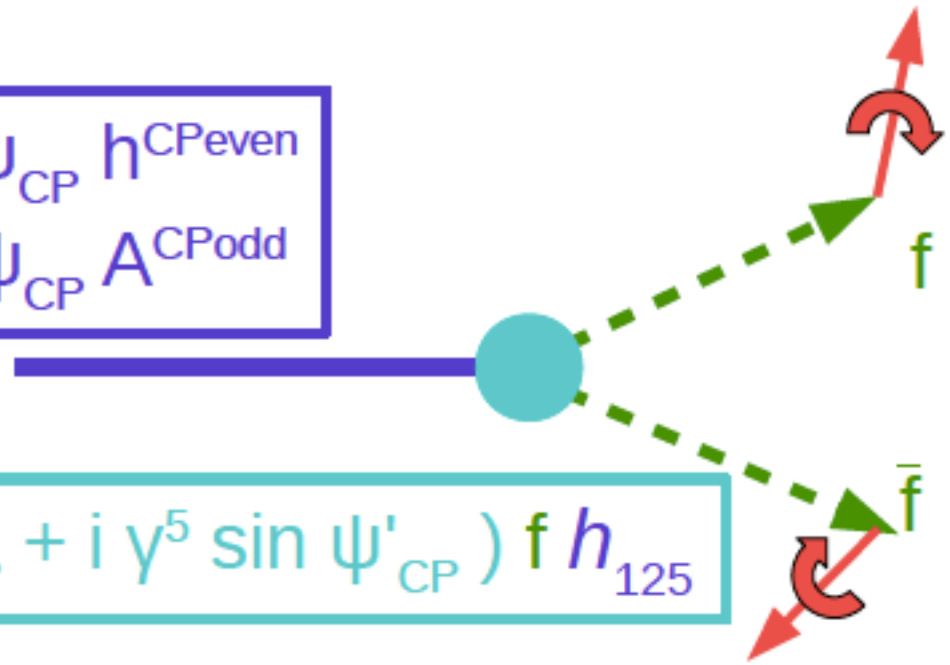


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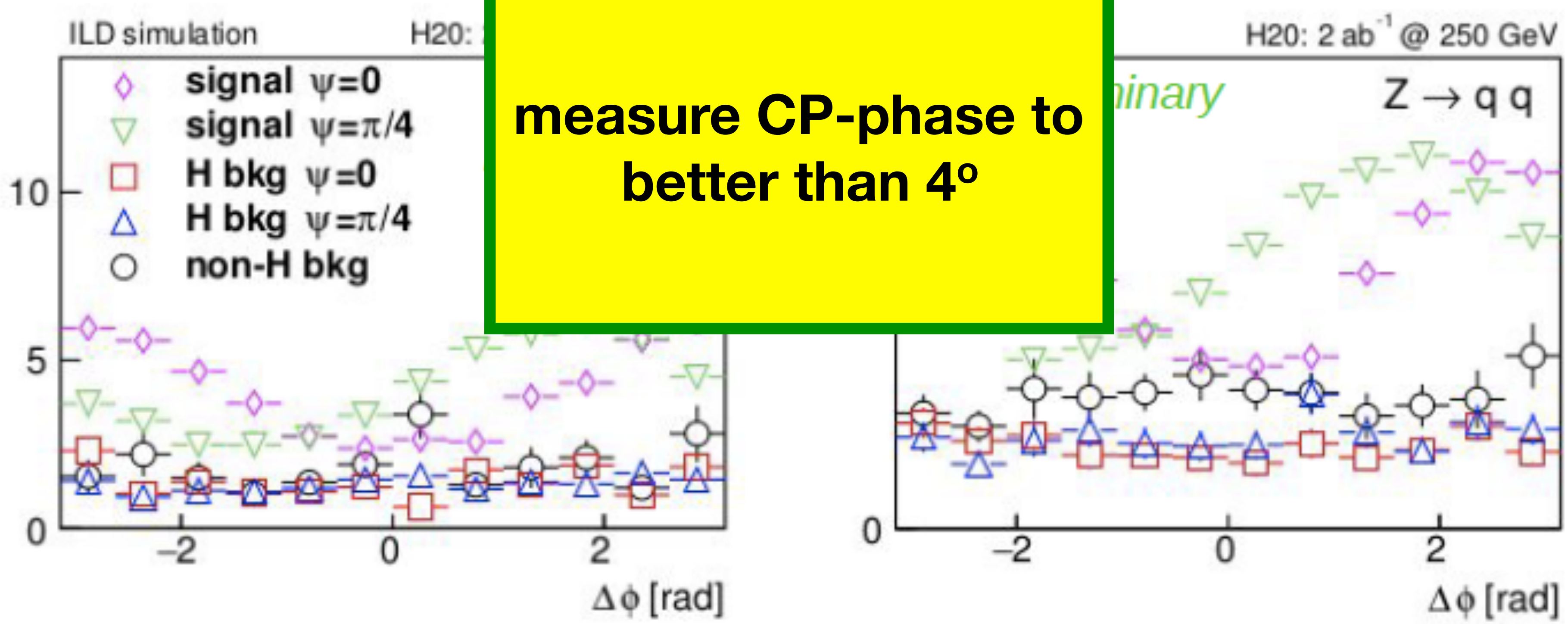



**measure CP-phase to better than 4°**

..and CPV in Zh coupling:

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

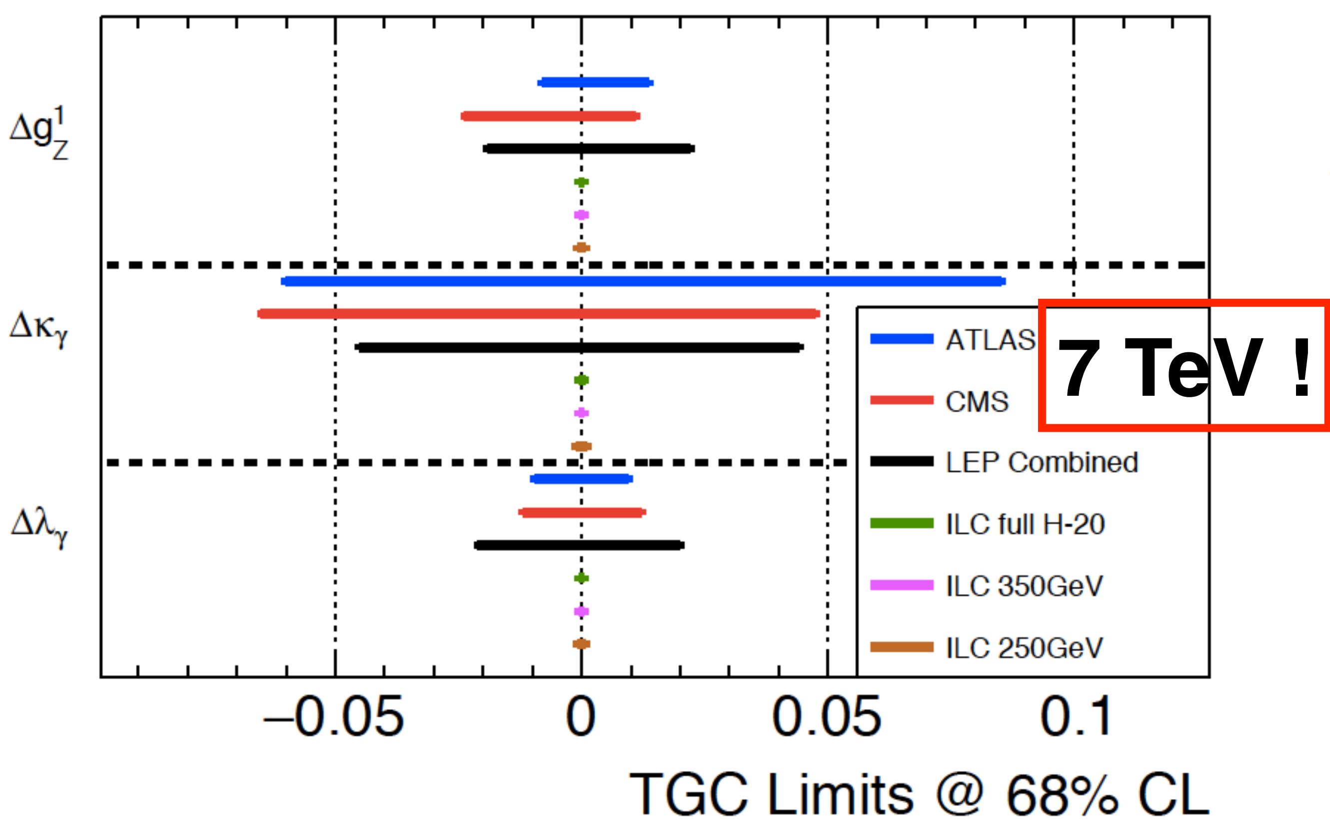
**=>** $\tilde{b}$ **to ±0.005**

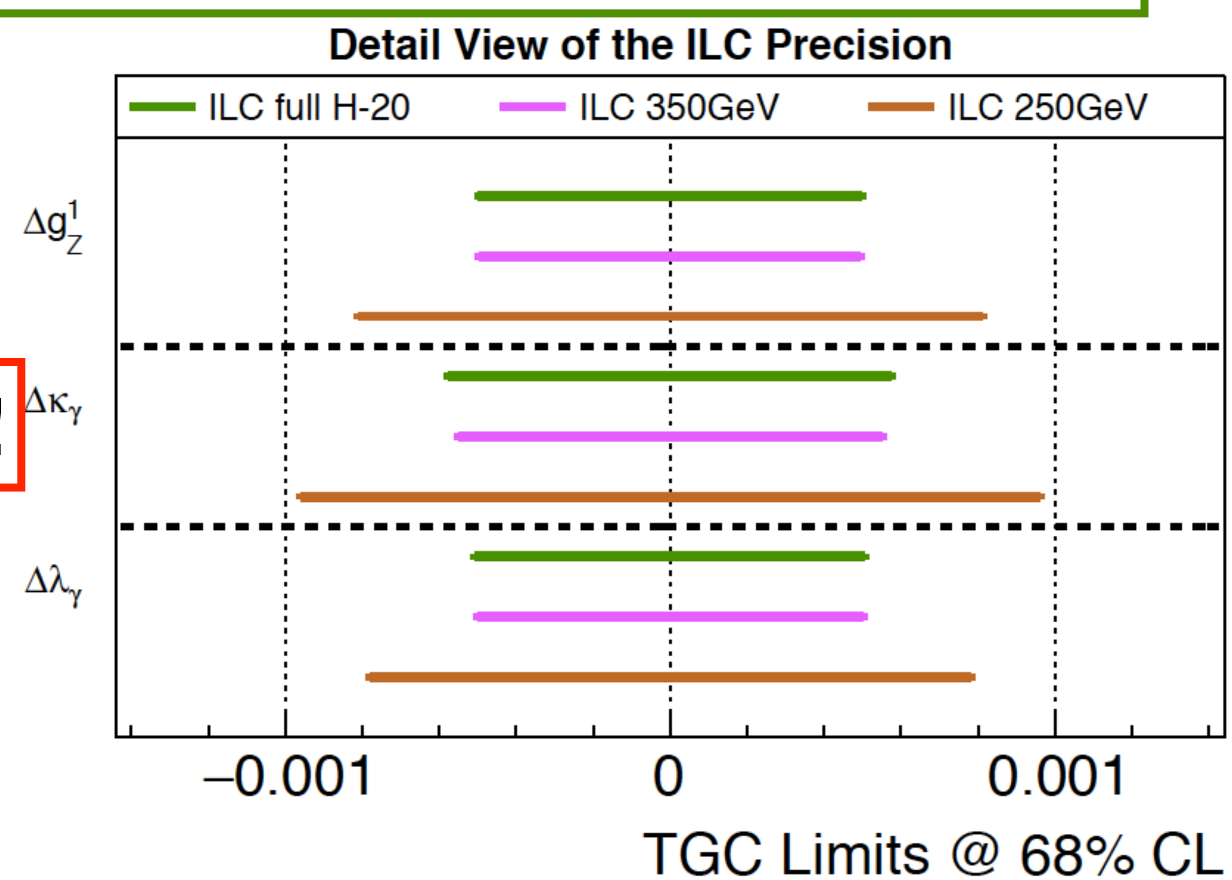
# Triple Gauge Couplings

- ILD full sim at 500 GeV & 1 TeV:
  - semi-leptonic channel only
  - using 3 angles
  - simultaneous fit of 3 couplings
- real results at ~200 GeV LEP2:
  - semi-leptonic & fully hadronic channels
  - all 5 angles
  - individual fits of 3 couplings

**250 GeV: full study still to be done**

**=> extrapolations from 500 GeV (ILD) and ~200 GeV (LEP2)**



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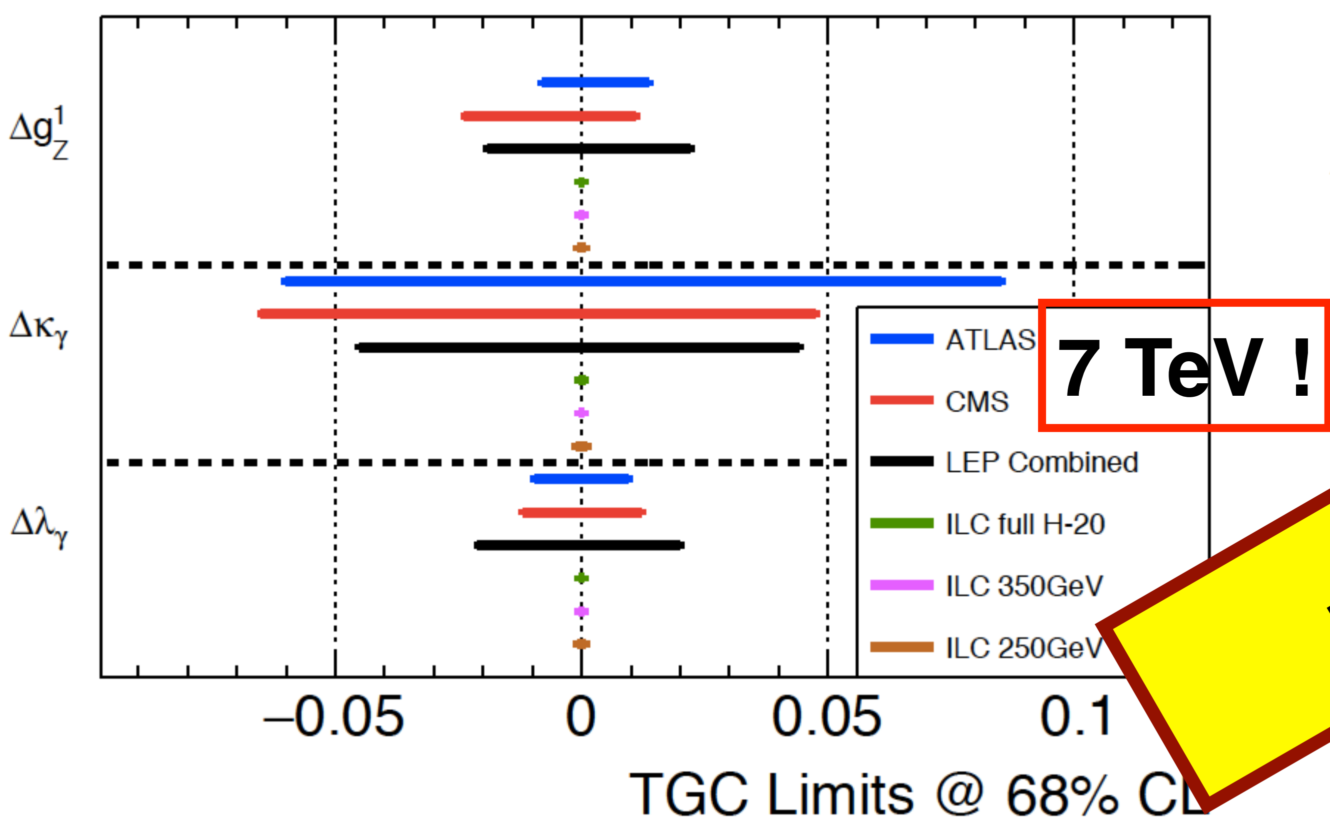


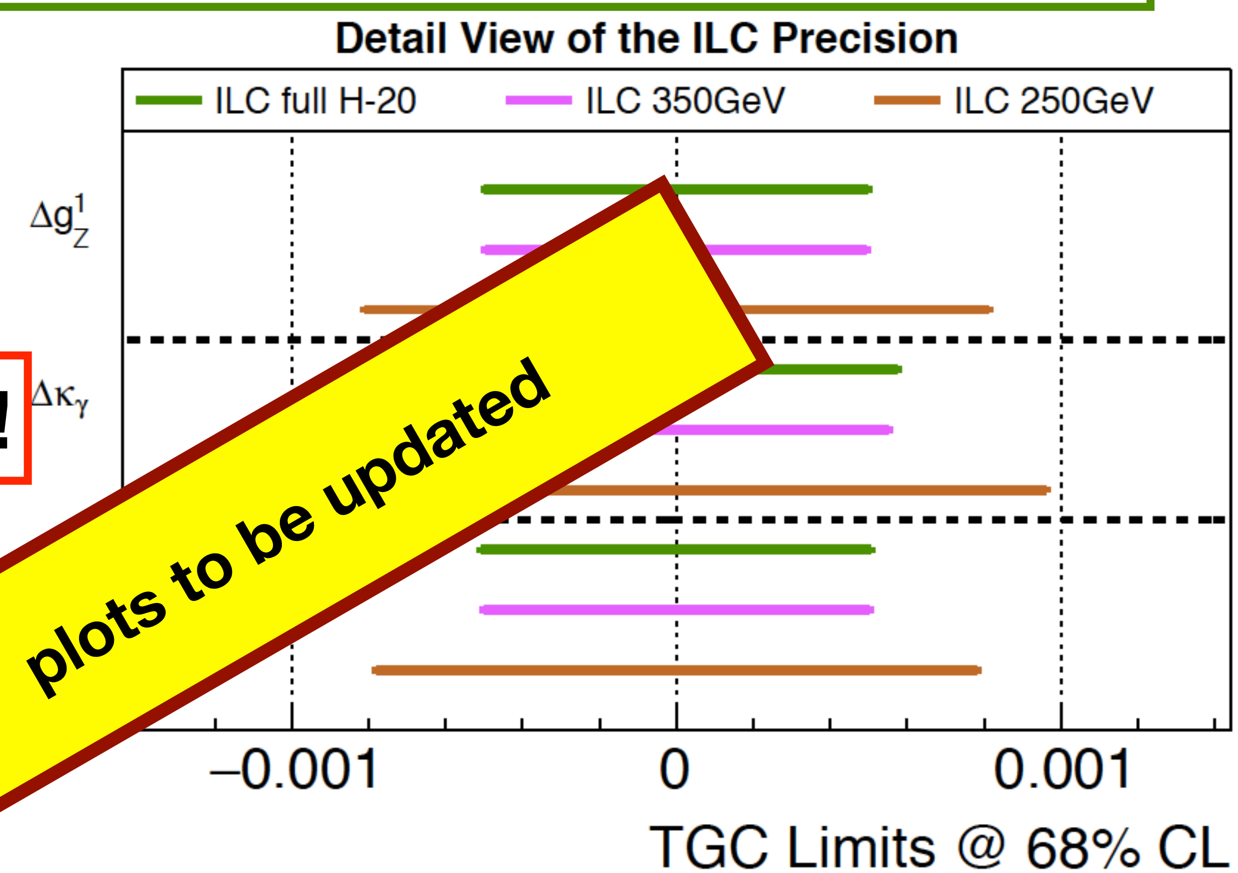

# Electroweak precision in 2-fermion processes

- 3rd generation of quarks is heaviest
  => closest connection to electroweak
  symmetry breaking
  **=> could they be (partially) composite?**

- **$b_R$ compositeness** could explain e.g. long-standing tension between two most precise determinations of **$\sin^2\vartheta_{eff}$** - one of them from $A_{FB}^b(M_Z)$

- can we remeasure couplings of $b_R$ and $A_{FB}^b(250GeV)$ and improve on LEP1?

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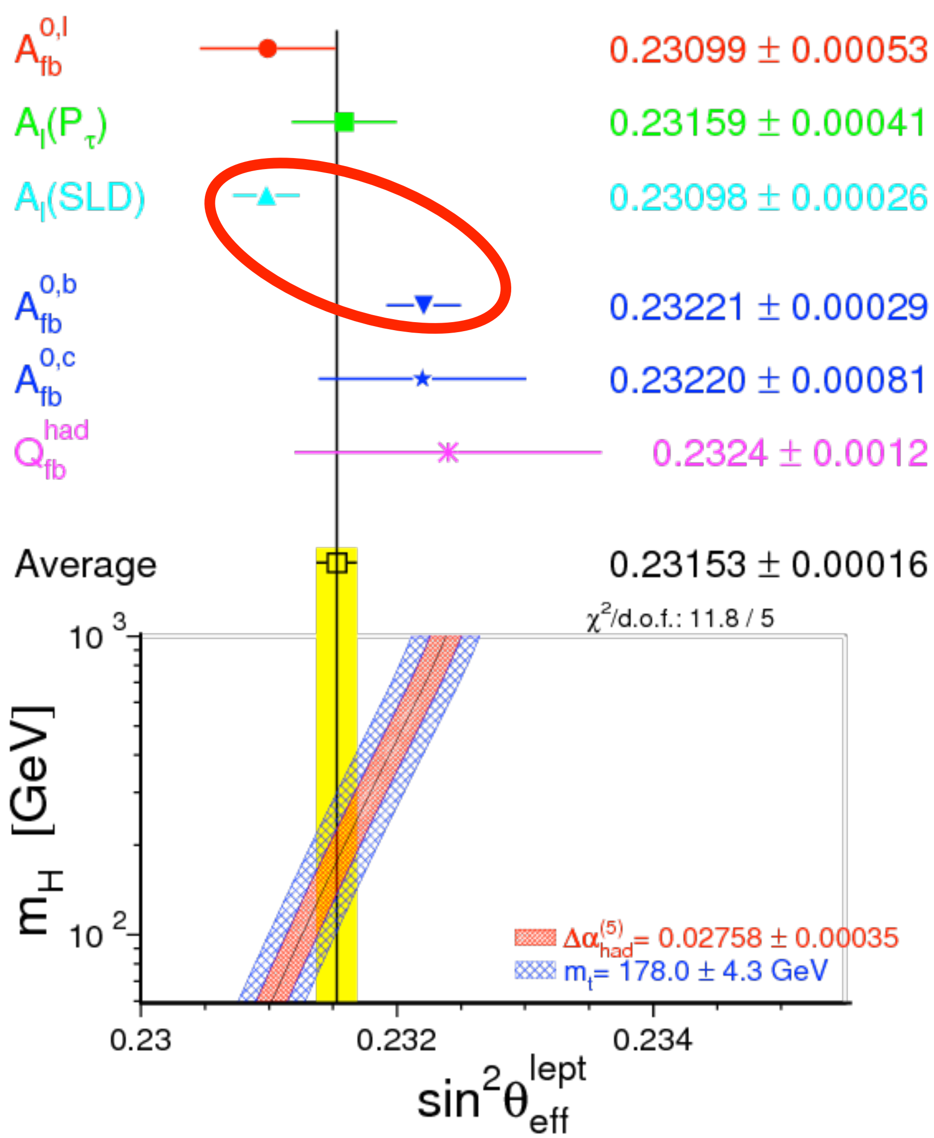


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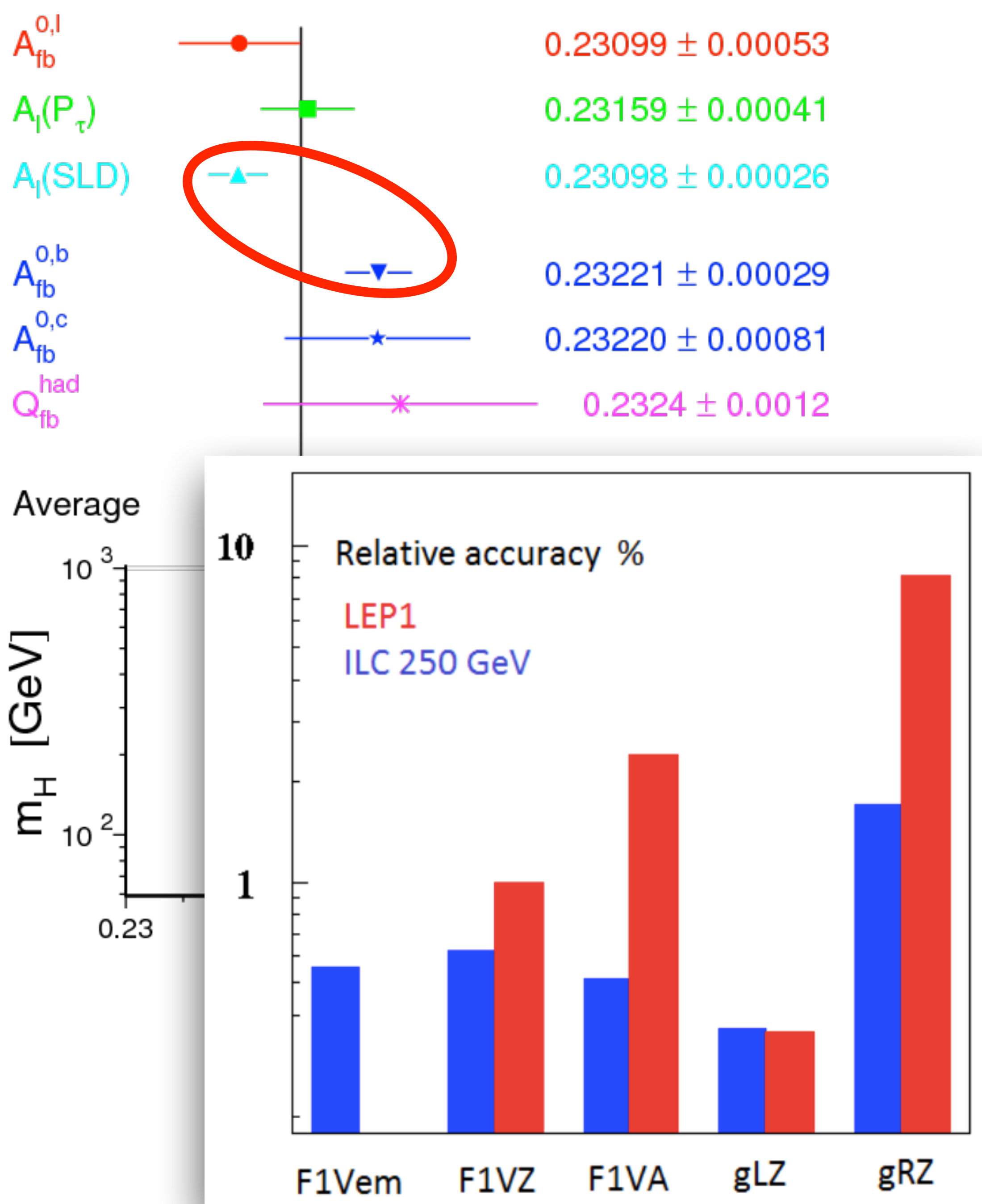


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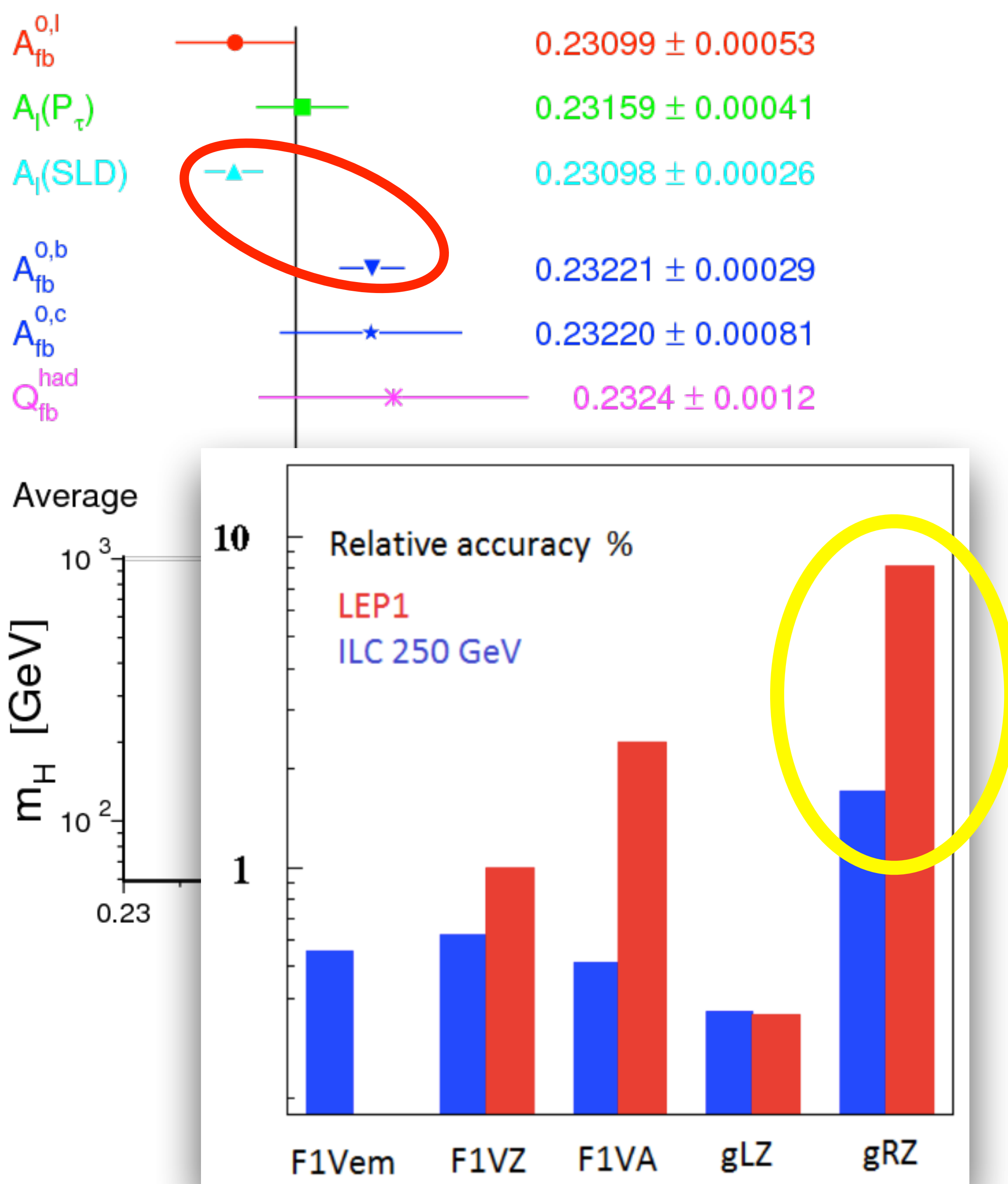


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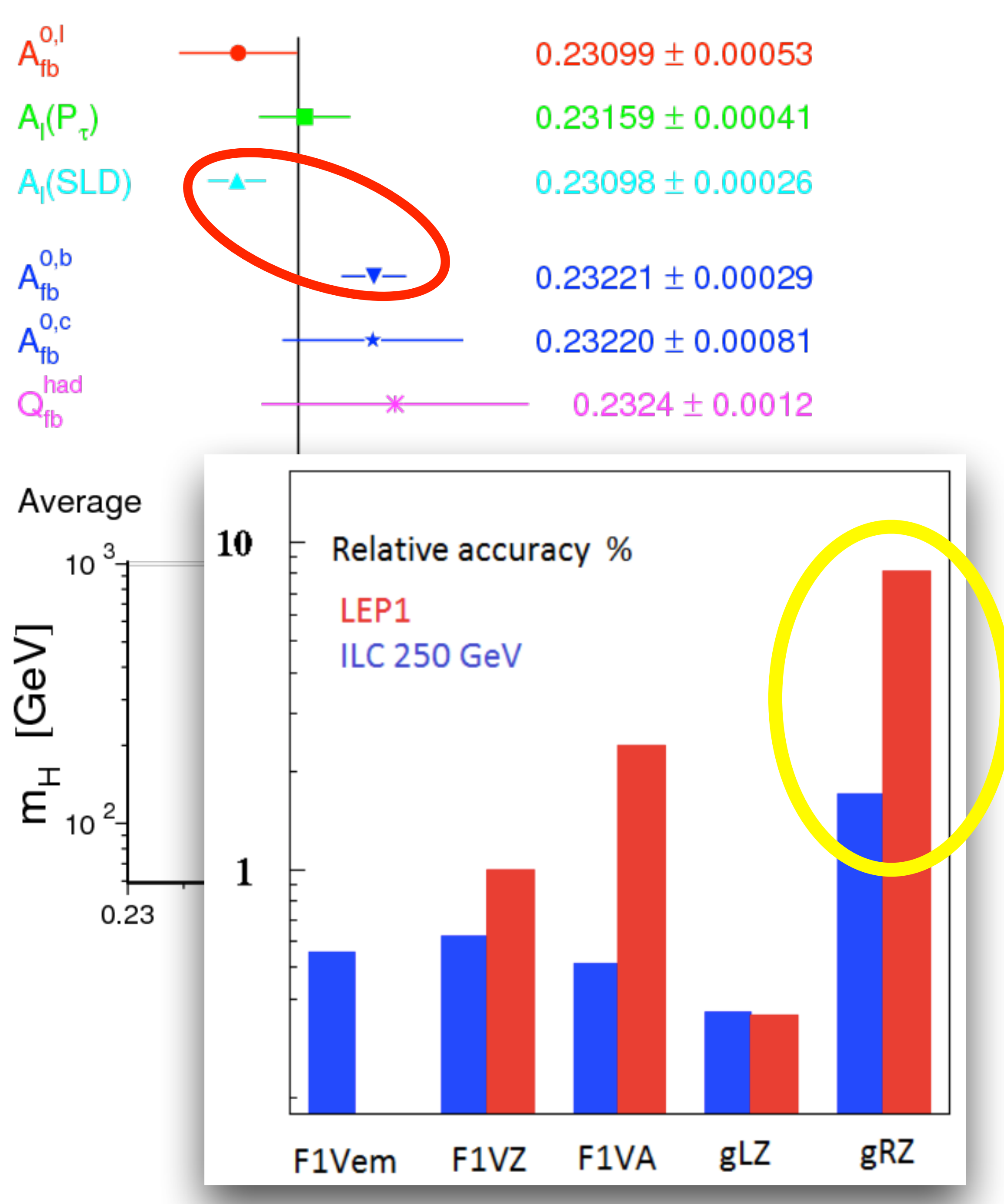


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- allows to probe NP scales up to ~60 TeV
- expect at least similar improvement also for charm quarks => vertexing very important!

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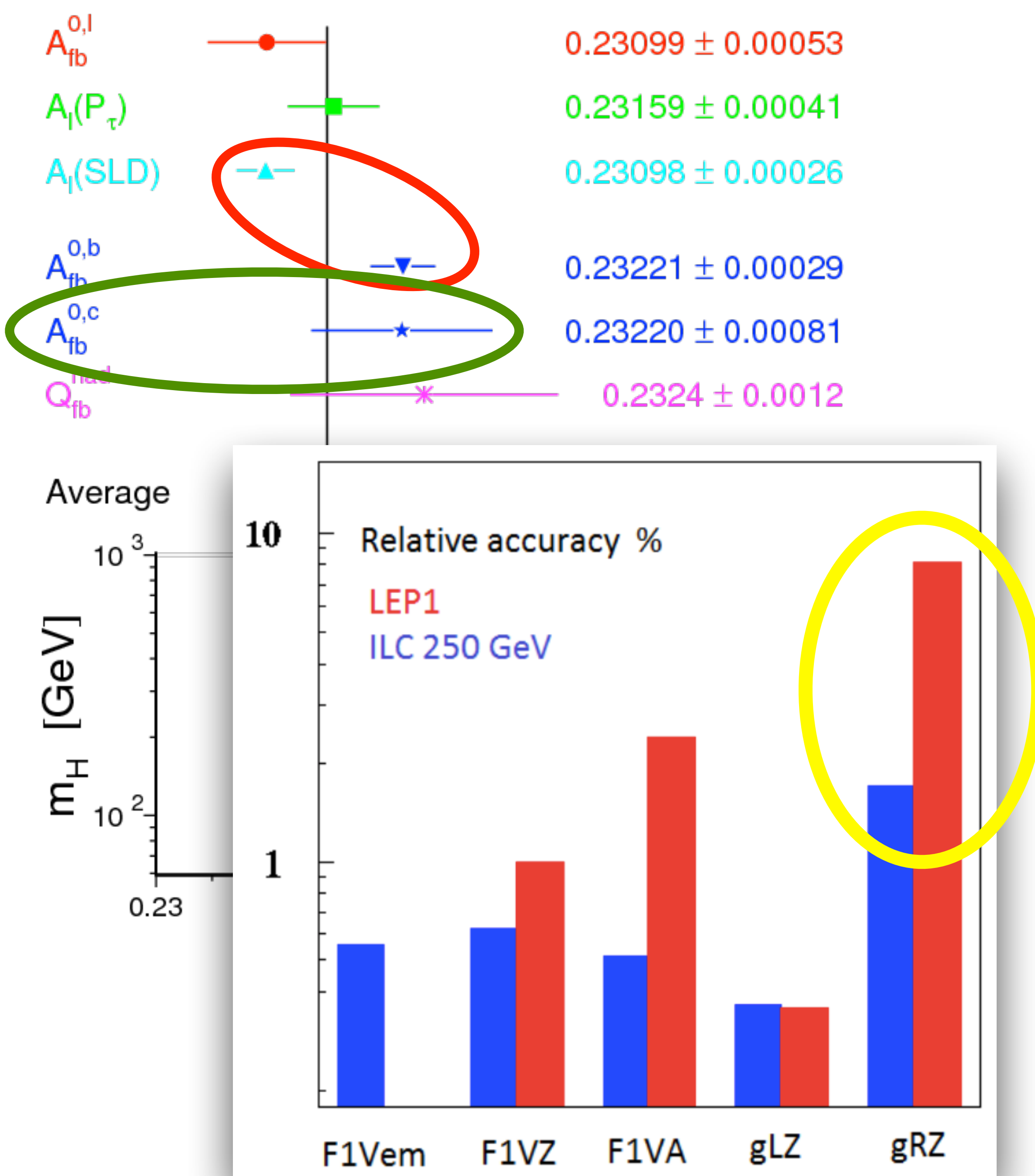


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# New Physics Interpretation of Higgs & EW

| | Model | $b\bar{b}$ | $c\bar{c}$ | $gg$ | $WW$ | $\tau\tau$ | $ZZ$ | $\gamma\gamma$ |
|---|---|---|---|---|---|---|---|---|
| 1 | MSSM [36] | +4.8 | -0.8 | - 0.8 | -0.2 | +0.4 | -0.5 | +0.1 |
| 2 | Type II 2HD [35] | +10.1 | -0.2 | -0.2 | 0.0 | +9.8 | 0.0 | +0.1 |
| 3 | Type X 2HD [35] | -0.2 | -0.2 | -0.2 | 0.0 | +7.8 | 0.0 | 0.0 |
| 4 | Type Y 2HD [35] | +10.1 | -0.2 | -0.2 | 0.0 | -0.2 | 0.0 | 0.1 |
| 5 | Composite Higgs [37] | -6.4 | -6.4 | -6.4 | -2.1 | -6.4 | -2.1 | -2.1 |
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| 8 | Higgs-Radion [40] | -1.5 | - 1.5 | +10. | -1.5 | -1.5 | -1.5 | -1.0 |
| 9 | Higgs Singlet [41] | -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 nev physics models. These model points are unlikely to be discoverable at 14 TeV LHC througl new particle searches even after the high luminosity era (3 ab$^{-1}$ of integrated luminosity) From [15].

**…or more generally speaking:**

| | $\Delta g(hVV)$ | $\Delta g(ht\bar{t})$ | $\Delta g(hb\bar{b})$ |
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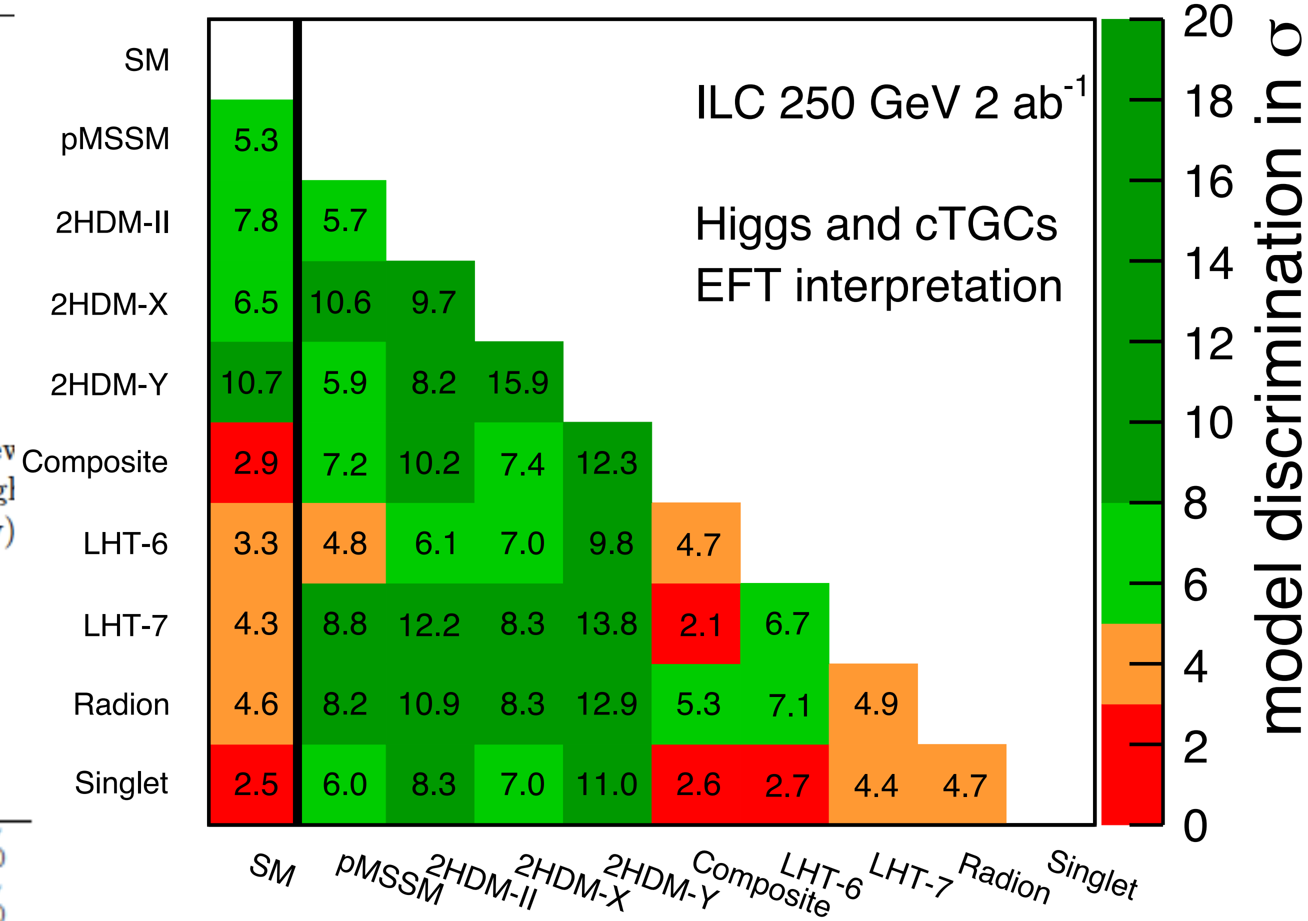
| Composite Higgs | 10% | tens of % | tens of % |
| Minimal Supersymmetry | < 1% | 3% | tens of % |
| Mixed-in Singlet | 6% | 6% | 6% |

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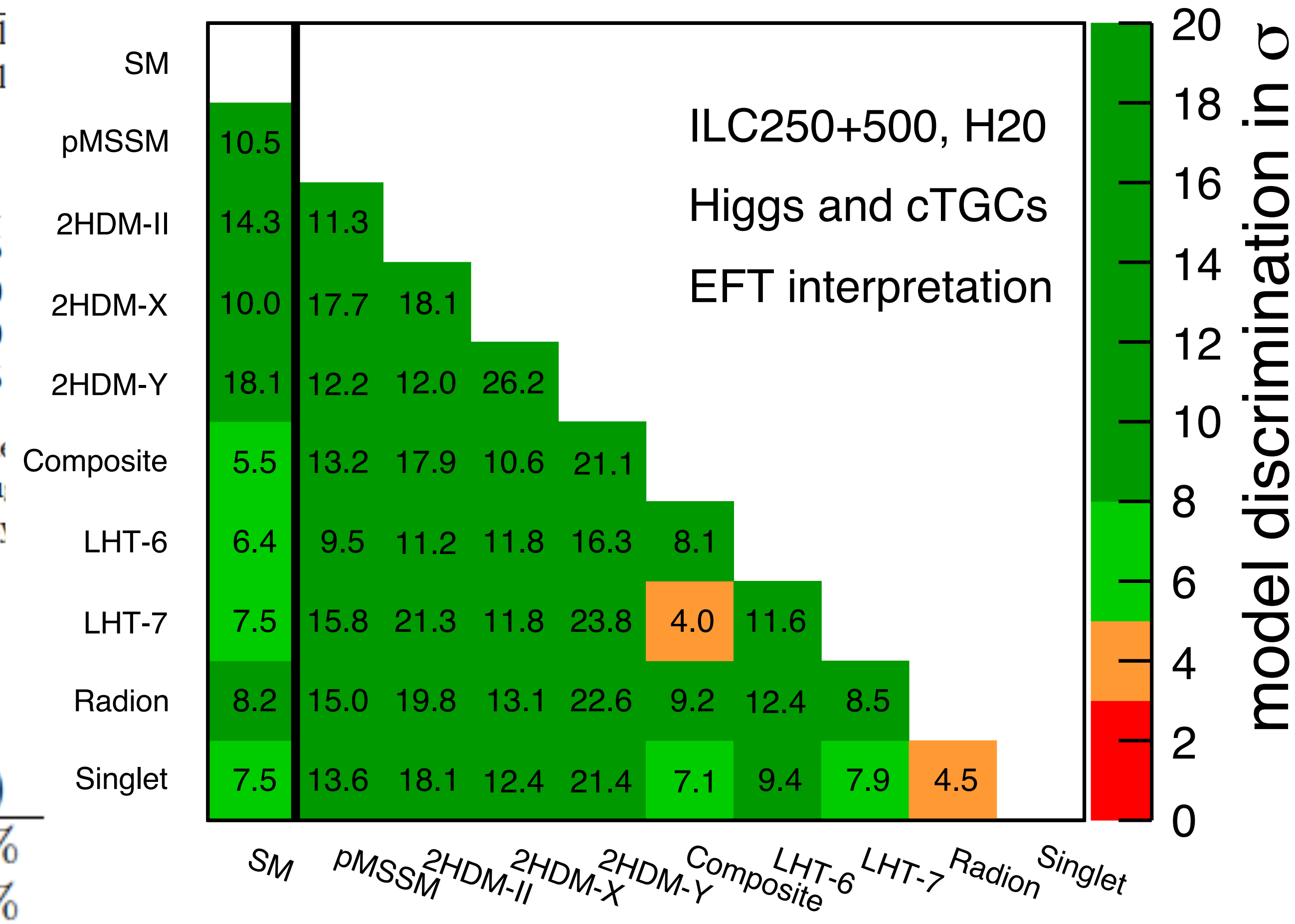


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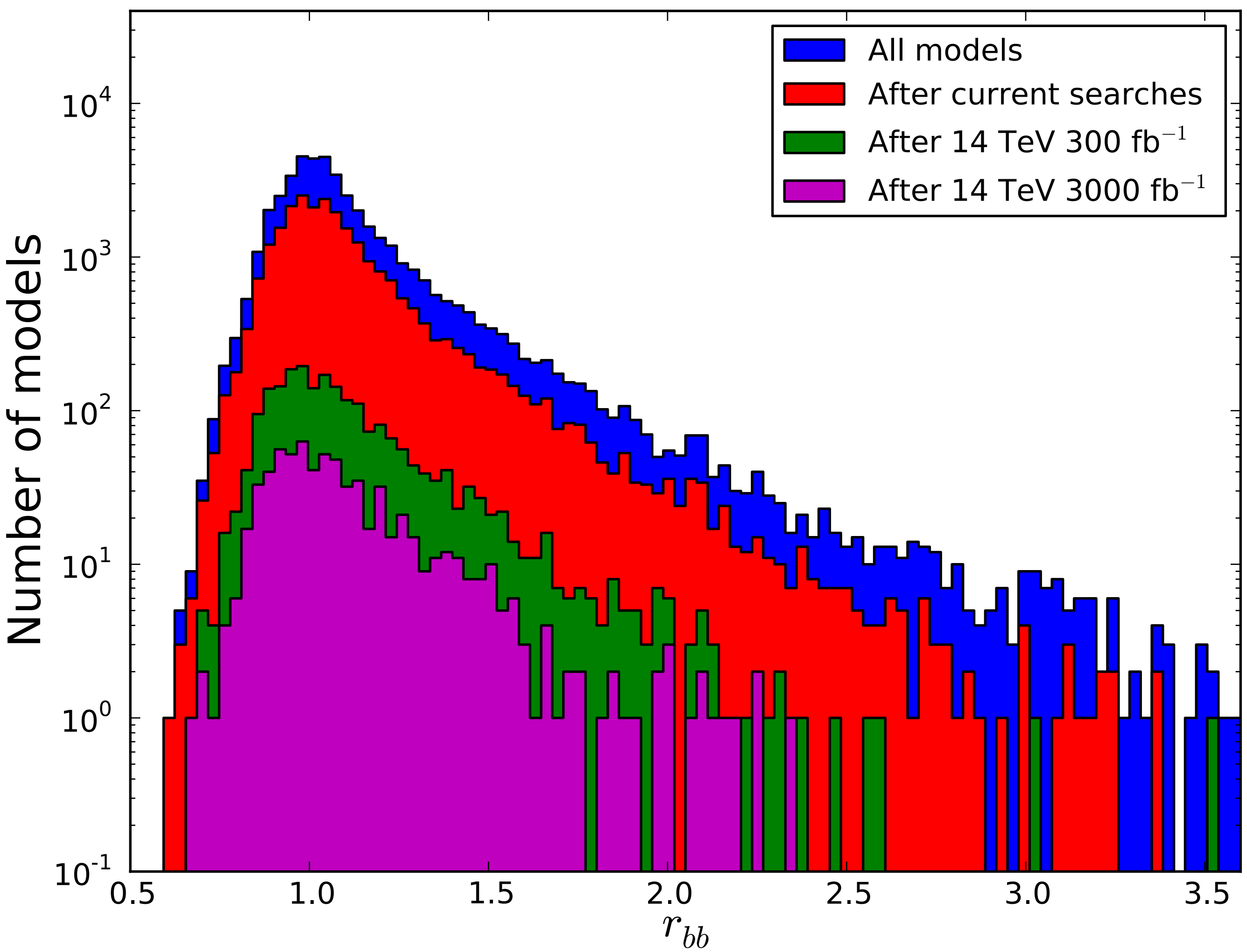
# A closer look at SUSY: pMSSM scan

- scan over 250 000 pMSSM points (Rizzo et al)
- check against direct searches
- even after HL-LHC projections for direct searches, many models with sizeable coupling deviations remain!
- **EFT fit ILC 250 GeV: δg(hbb) = 1.7%**
- EFT fit ILC H20: δg(hbb) = 0.95%




$$r_X = \frac{\Gamma(h \to X)}{SM}$$

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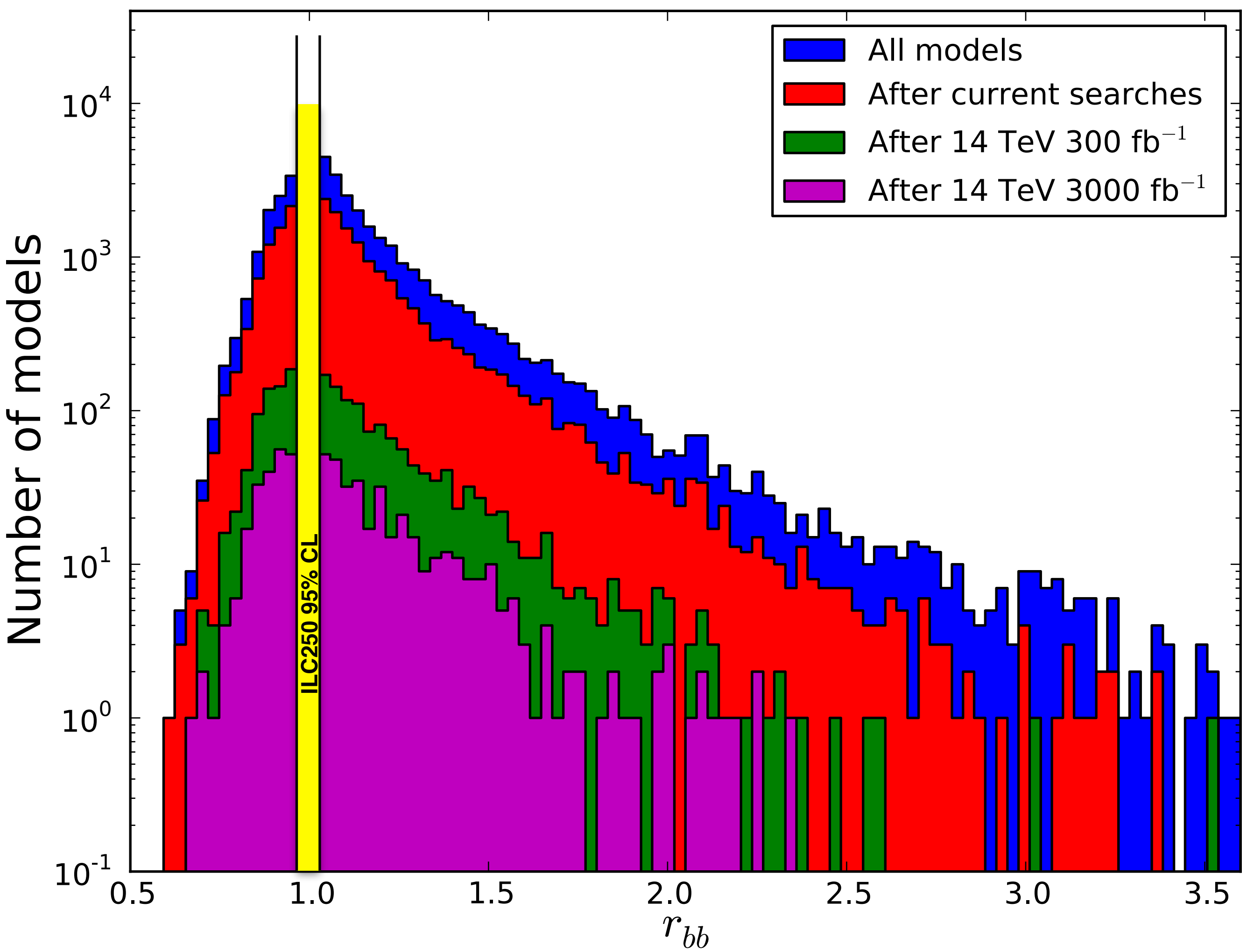


$$r_X = \frac{\Gamma(h \to X)}{SM}$$

# A closer look at SUSY: pMSSM scan

- scan over 250 000 pMSSM points (Rizzo et al)
- check against direct searches
- even after HL-LHC projections for direct searches, many models with sizeable coupling deviations remain!
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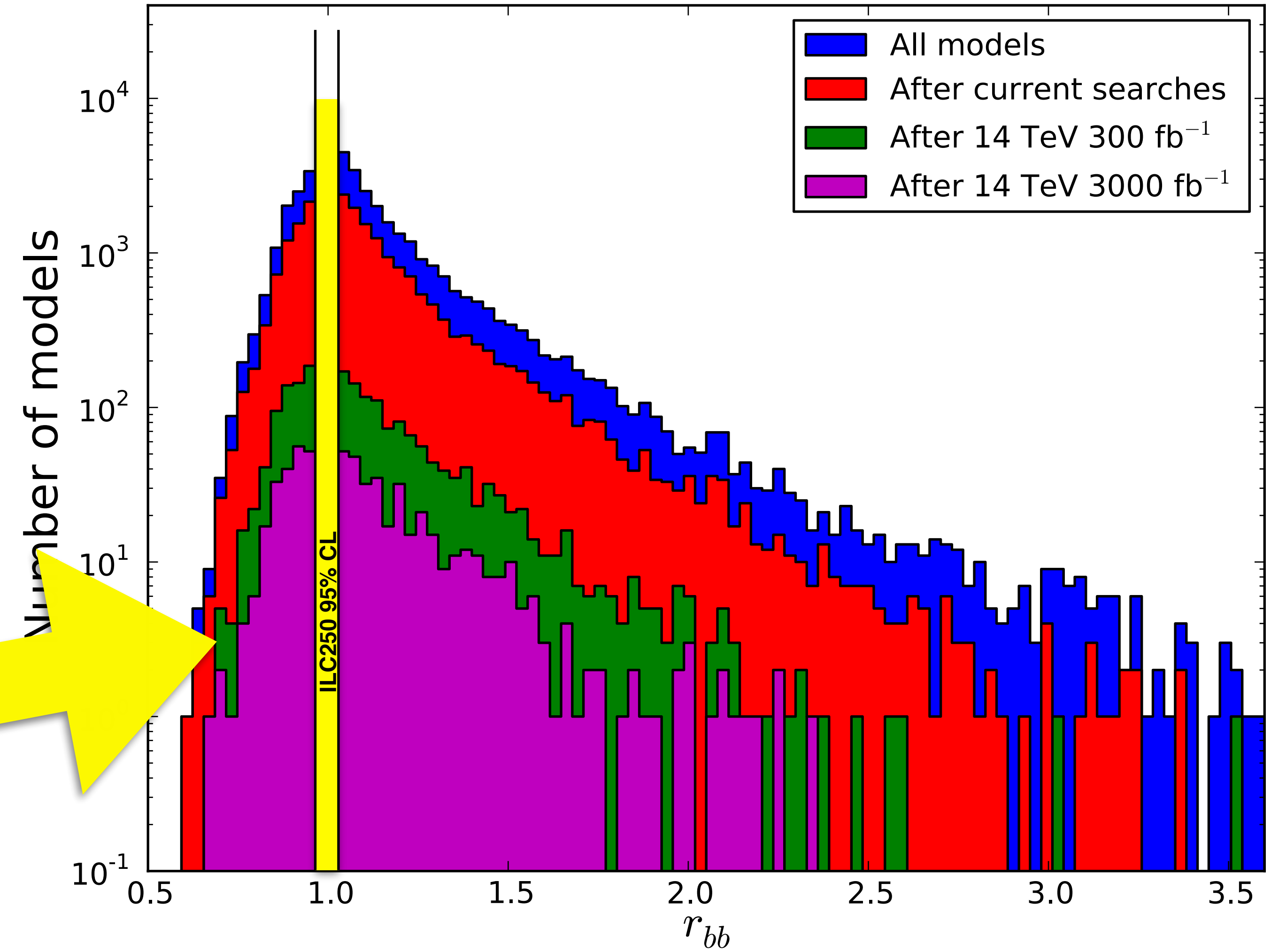


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# Opportunities for direct discoveries ?

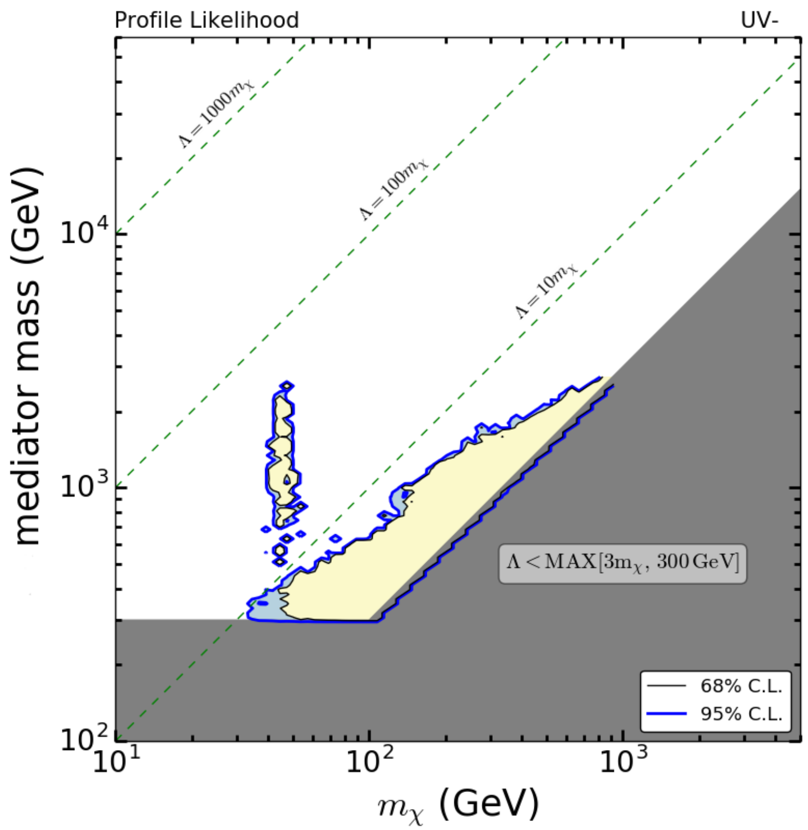
- 250 GeV only marginally more than 209 GeV - nothing to expect?
- Closer look at ILC250 vs LEP2:
  - **~1000x more integrated luminosity**
  - **polarised beams** can suppress SM backgrounds by 1-2 orders of magnitude
  - **tremendous advances in detector technology**, eg momentum resolution 1-2 orders of magnitude better, vertexing, highly granular calorimeter for tau ID, ….

**=> any search channel limited by rate will explore new territory even at ILC250 !**

Examples:

- searches for additional **light (Higgs) bosons** with reduced couplings to the Z
- **MSSM**: most general limit (any mixing, any mass difference to LSP) on **staus** is as low as 26.3 GeV
- **sterile neutrinos** with m>45 GeV from WW cross section: expect 1-2 orders of magnitude improvement on mixing parameter
- … and **WIMPs**!

# Example: WIMPs




- $e^+e^- \rightarrow \chi\chi\gamma$ "mono-photons"
- **Effective operator interpretation** [nota bene: valid at $e^+e^-$ colliders]
- for $M_\chi$ < 100 GeV ILC probes $\Lambda$
  - **up to ~1.9 TeV @ 250 GeV**

- likelihood scan over WIMP parameter space including existing and future direct, indirect and collider experiments (apart from ILC)
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**=> significant unexplored regions below M=120 GeV !!!**

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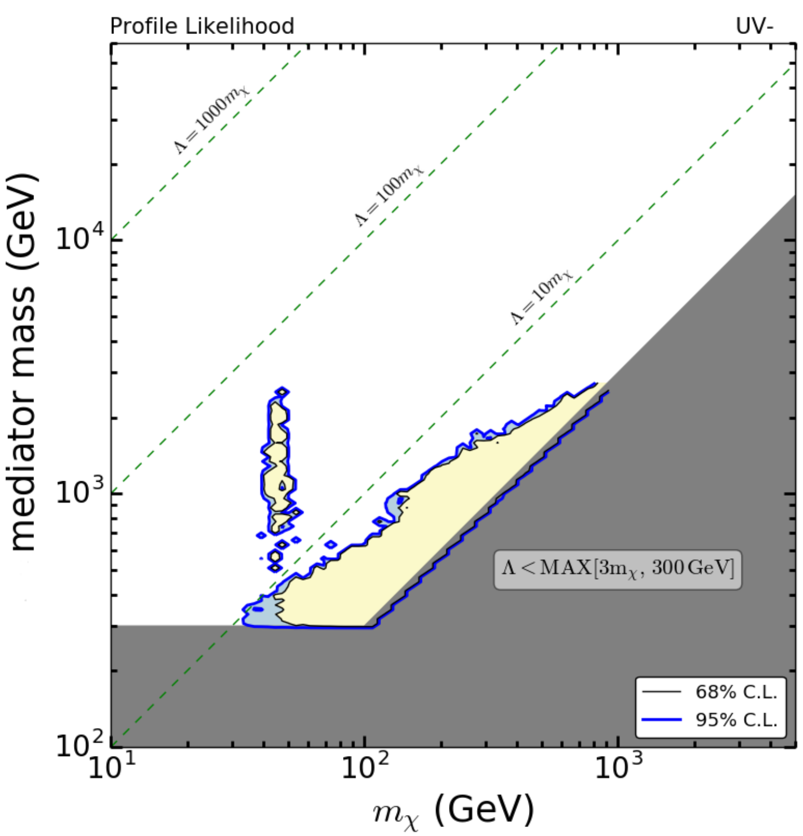


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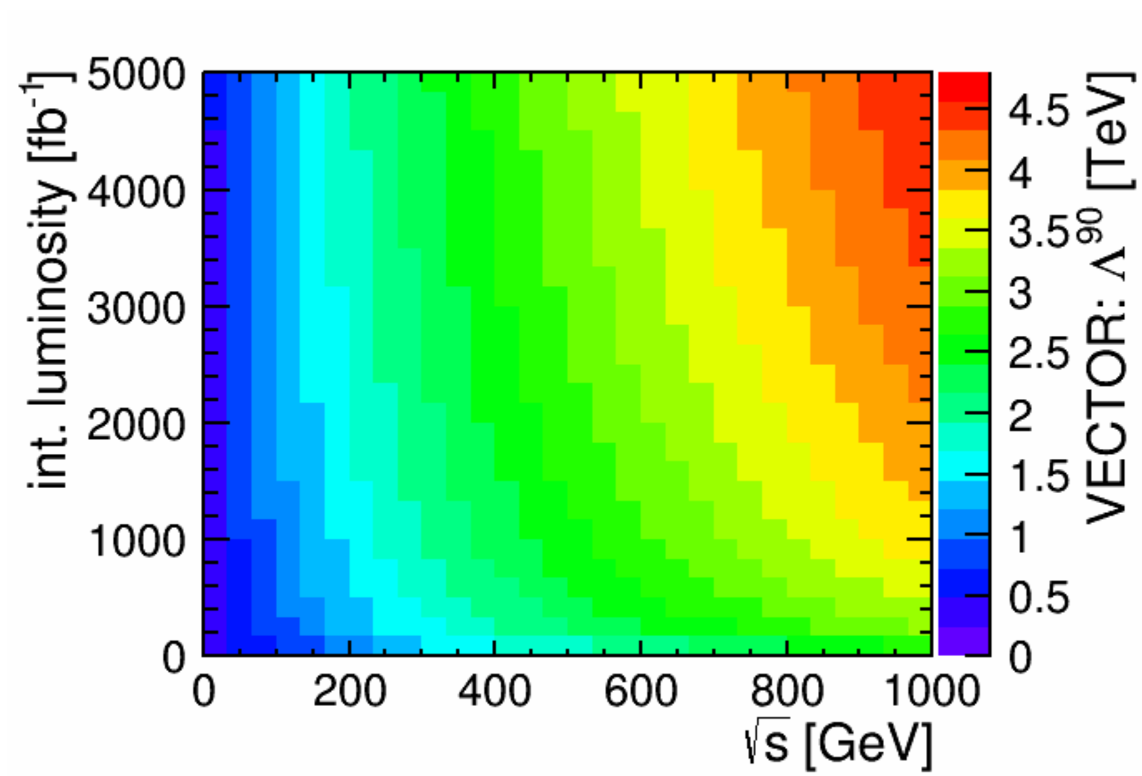

# Conclusions

All approaches explained here will profit further from later upgrades to higher energy, which will especially give access to top quark physics, the top Yukawa coupling and the Higgs self-coupling.

It is urgent today in particle physics to uncover physics beyond the Standard Model by any route. The experiments discussed in this report give a number of strategies for searches for new physics that are distinct from those currently being pursued at the LHC and elsewhere. These strategies have great potential. But to exploit them, we must construct the next $e^+e^-$ collider. The particle physics community should make it a priority to fund and construct this machine as quickly as possible.

# Conclusions

**The physics capabilities of the ILC at 250 GeV are formidable.**

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# Backup

# Additional Higgs Bosons

- eg from 2HDMs or additional singlets
(as in NMSSM)
- pair production:
  - loophole-free search for additional Higgs bosons up to masses of ~$\sqrt{s}/2$
  - regardless of tan$\beta$
- **or recoil against Z**
  - **even if coupling strongly reduced!**
  - quantitative studies in full detector simulation ongoing

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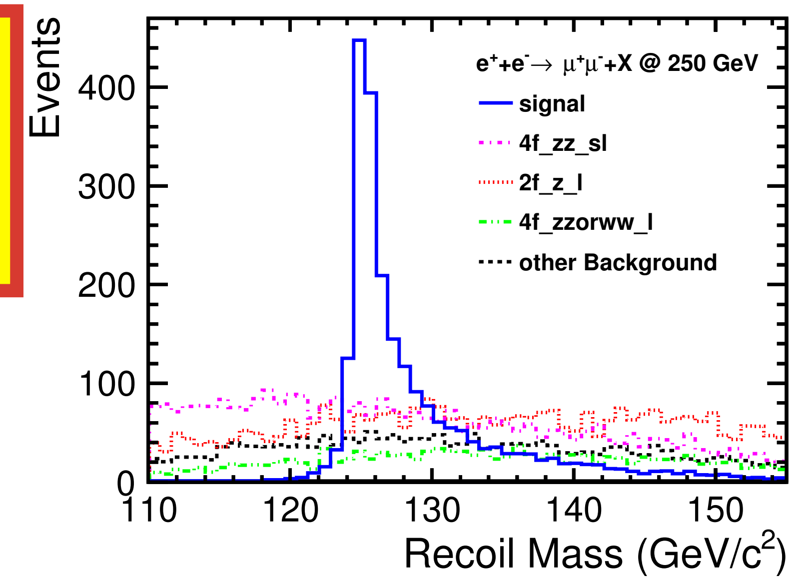
**SM Higgs: ILD full simulation Phys. Rev. D 94, 113002 (2016)**



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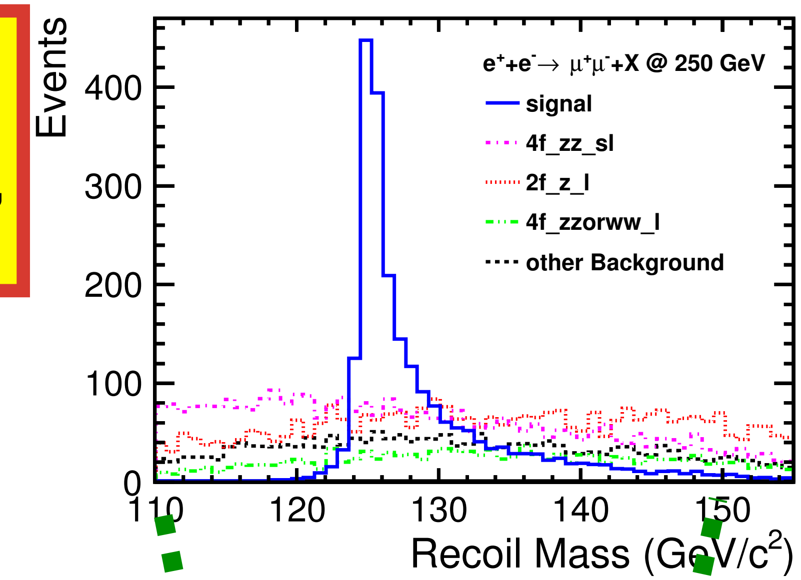


**ILC 250 GeV @ generator-level, for illustration only**