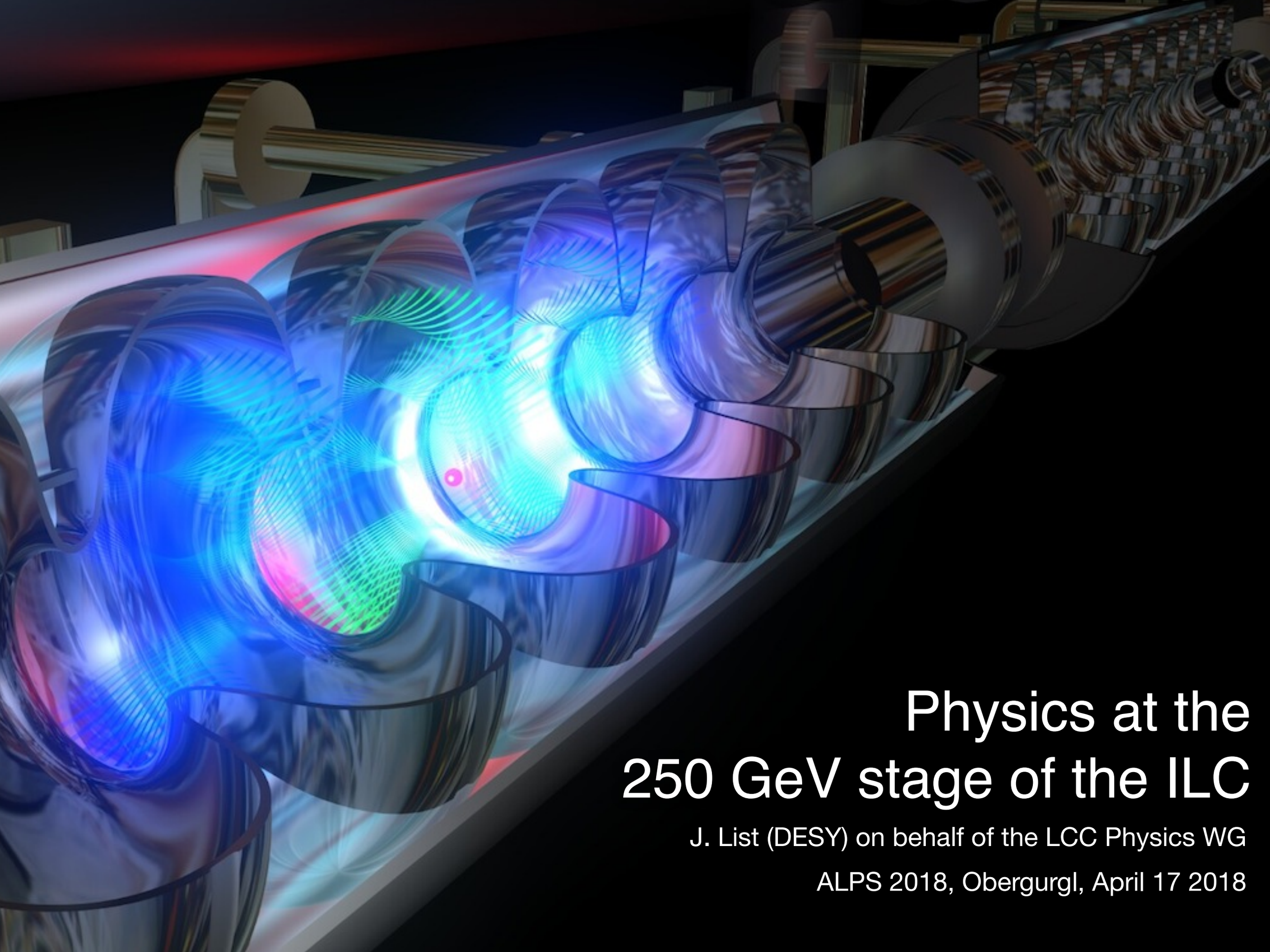


Physics at the 250 GeV stage of the ILC

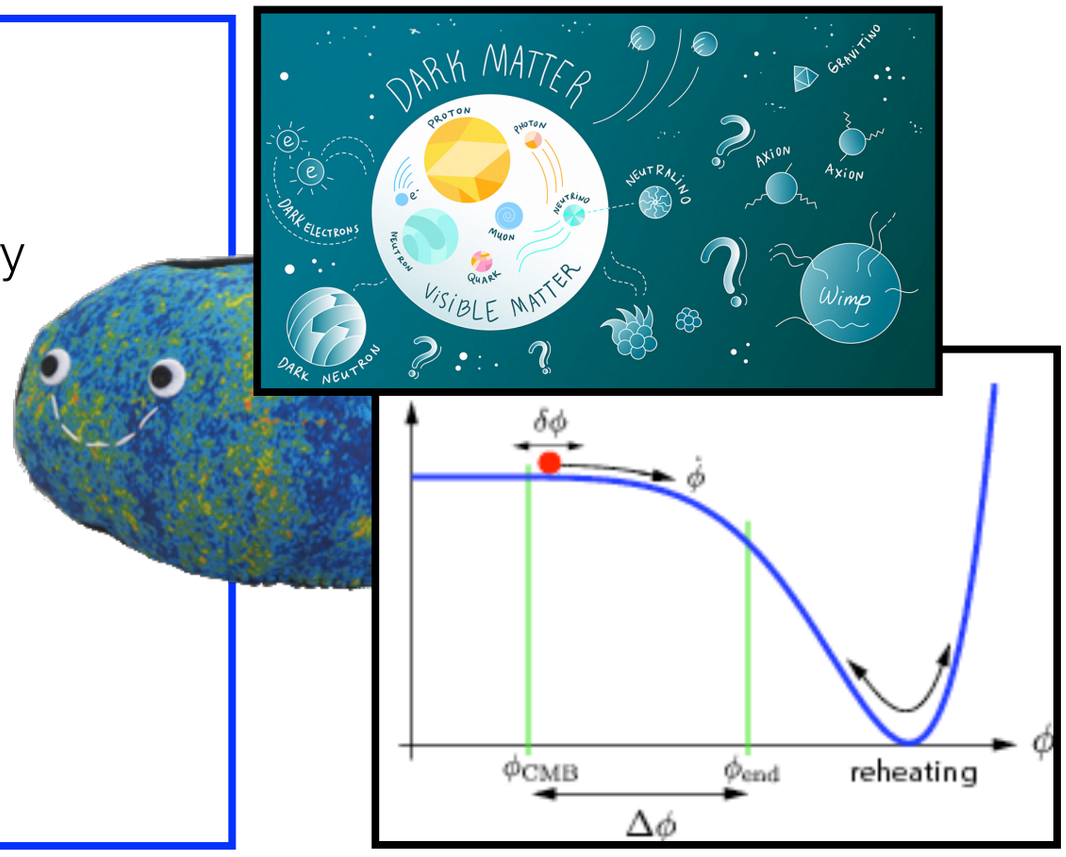
J. List (DESY) on behalf of the LCC Physics WG

ALPS 2018, Obergurgl, April 17 2018

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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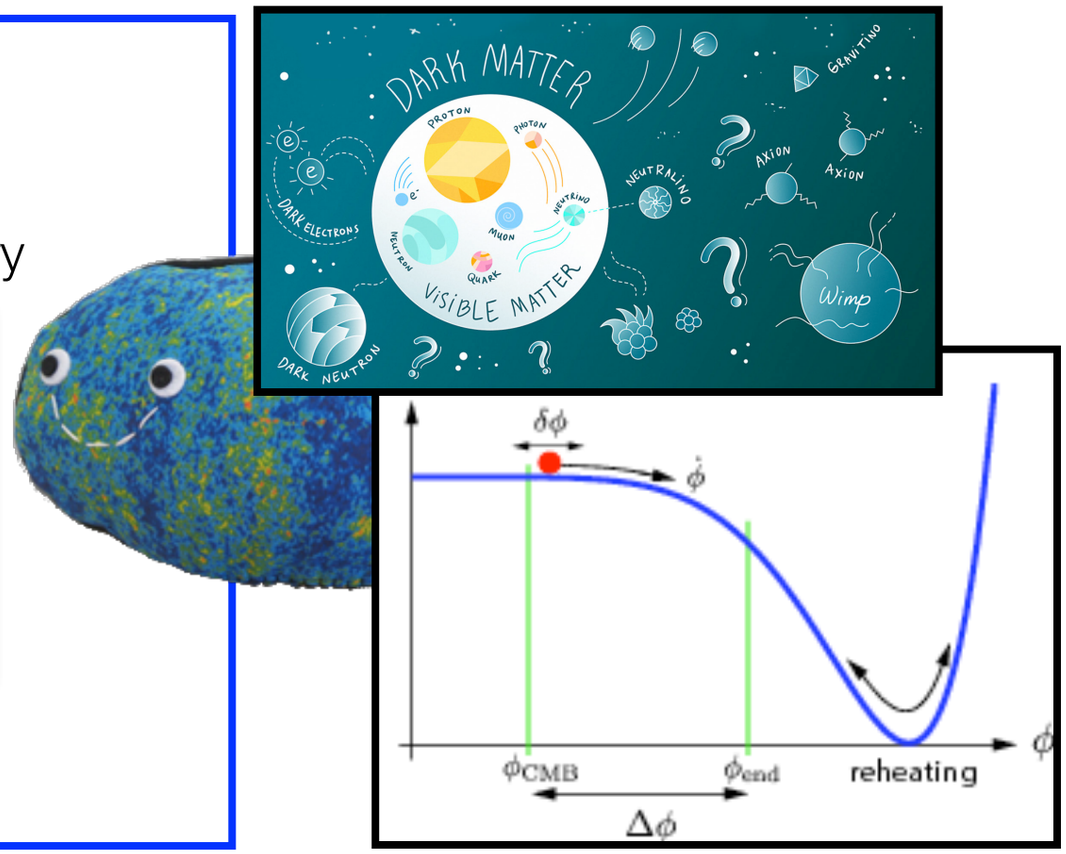

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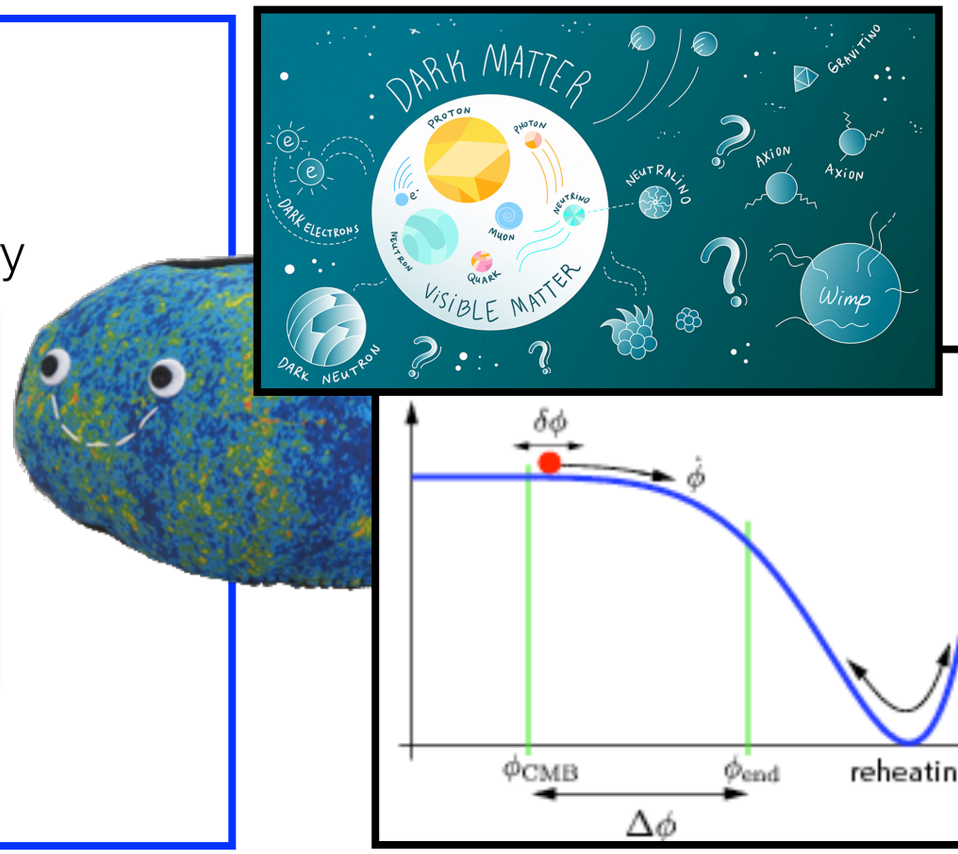

What we know:

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

  => some new particles must be charged under electroweak interactions

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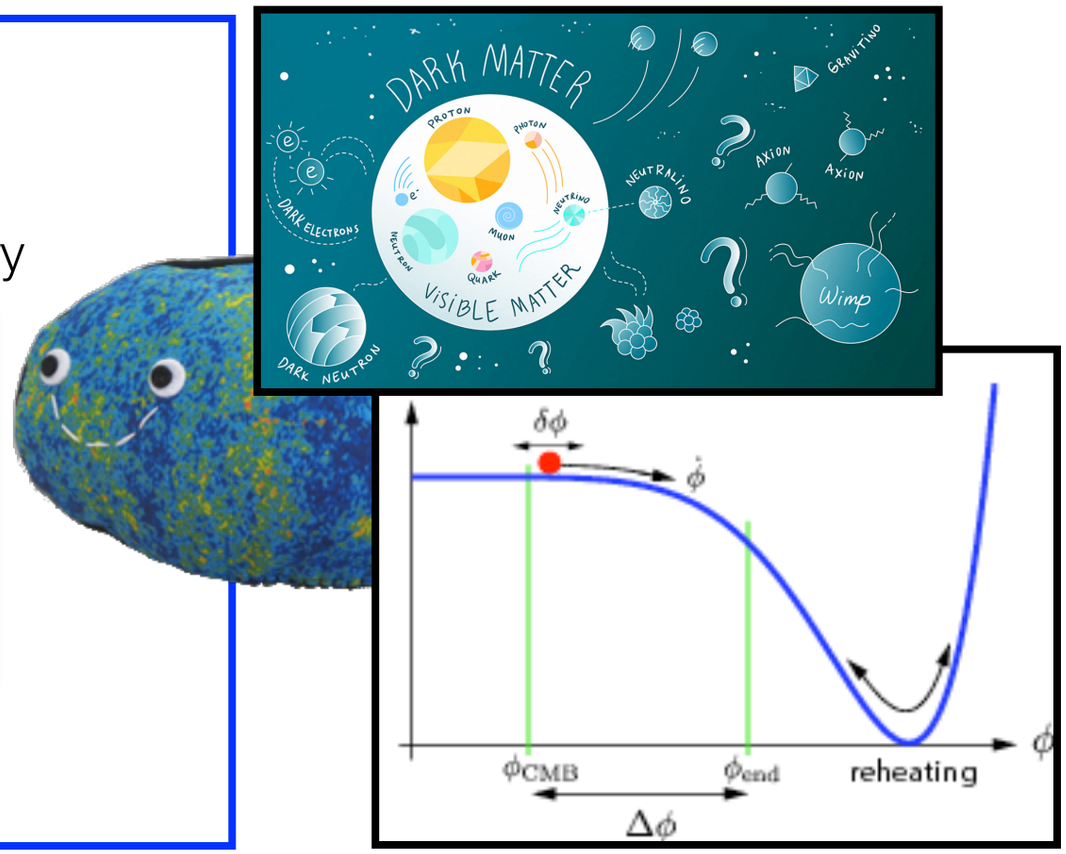

What we know:

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

  => some new particles must be charged under electroweak interactions

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 e^+e^- colliders

Our tools:

The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

Discoveries of new particles ?

… and how to tackle them at e^+e^- colliders

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Choosing the next collider

- technical readiness, cost etc.
- **added physics value w.r.t.**
  - **HL-LHC**
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What is the added value of a 250 GeV e^+e^- Linear Collider ?

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What is the added value of a 250 GeV e+e- Linear Collider ?

this talk is based on arXiv:1710.07621

New insights from old friends…

The Top and Bottom Quark

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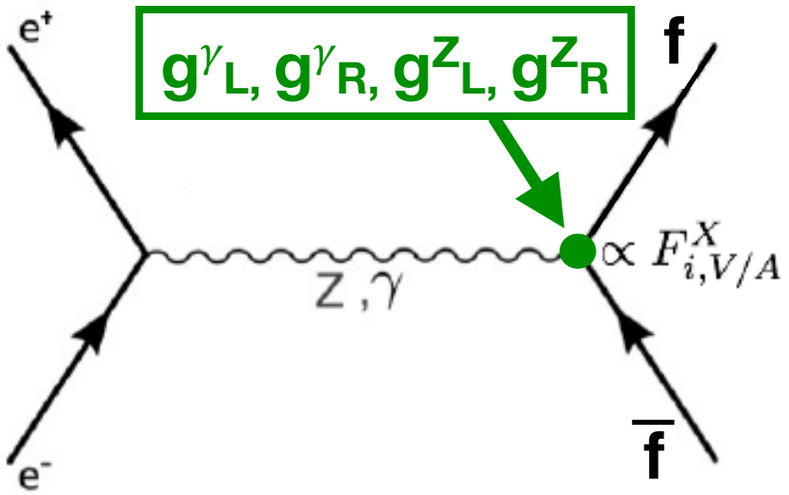
Electroweak precision in 2-fermion processes



Pure γ or pure $Z^0 : \sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference $: \sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $P(e^+) = \mp 30\%$

Polarised beams

- allow to disentangle g^{γ} vs g^{Z}
- provide robustness against systematic uncertainties
- minimise higher-order corrections

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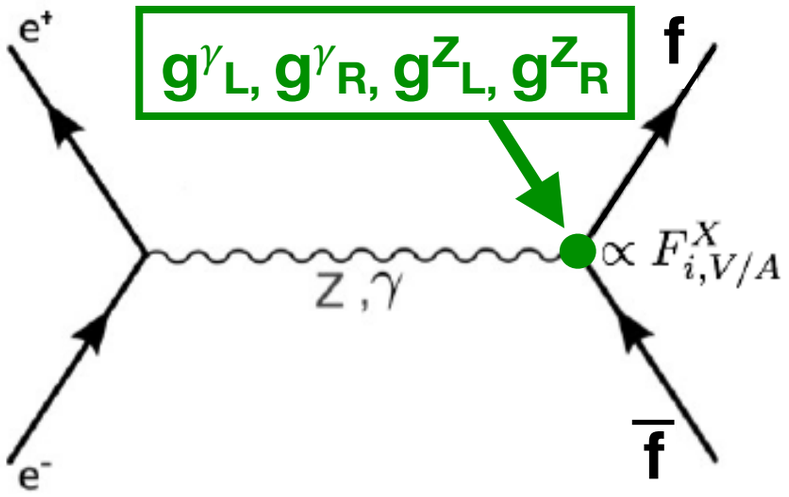

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3rd generation of quarks

- is heaviest
- closest connection to electroweak symmetry breaking
- could they be (partially) composite?

The Top and Bottom Quark

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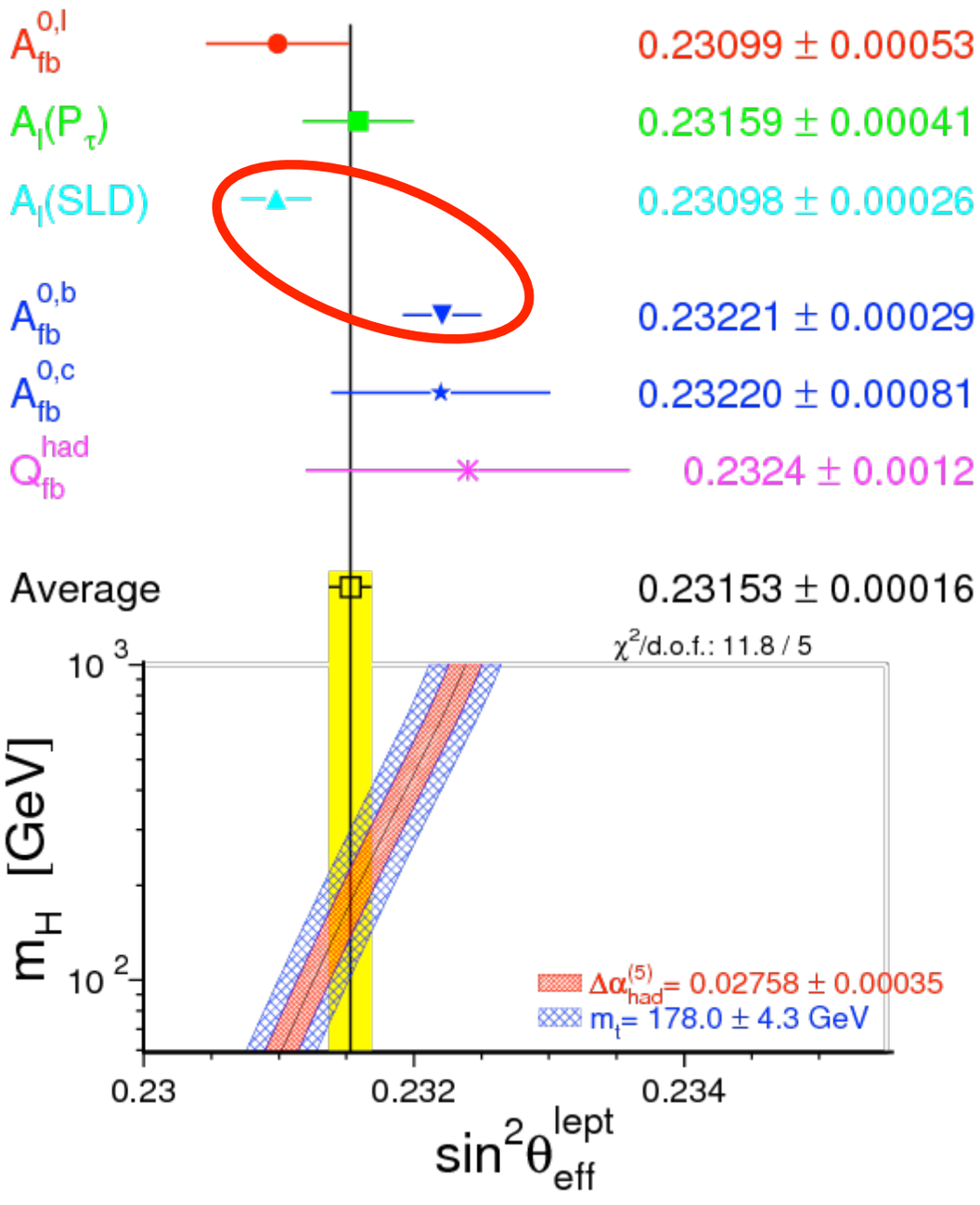
ILC 250 GeV: The Bottom Quark

The Bottom Quark



- **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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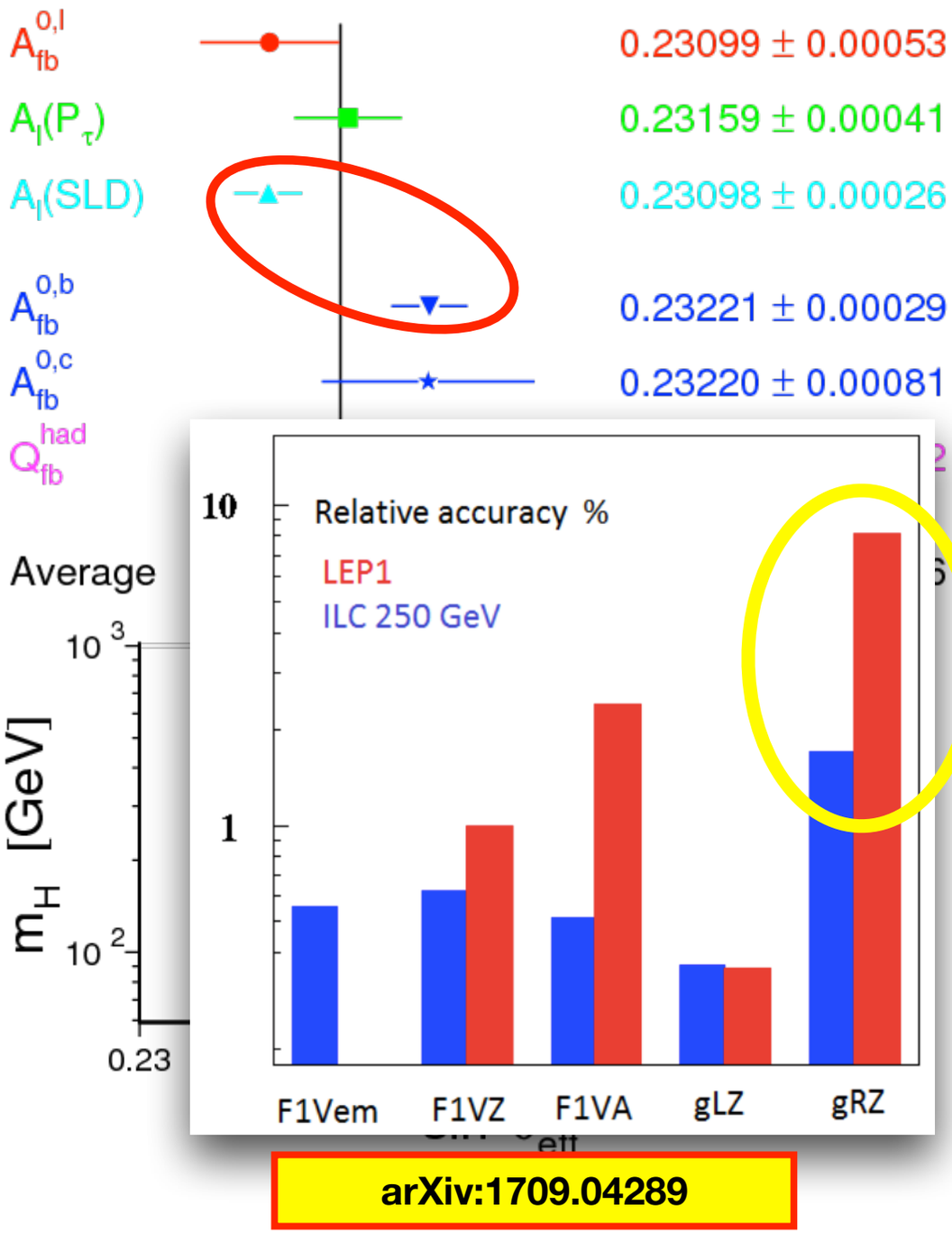

arXiv:1709.04289

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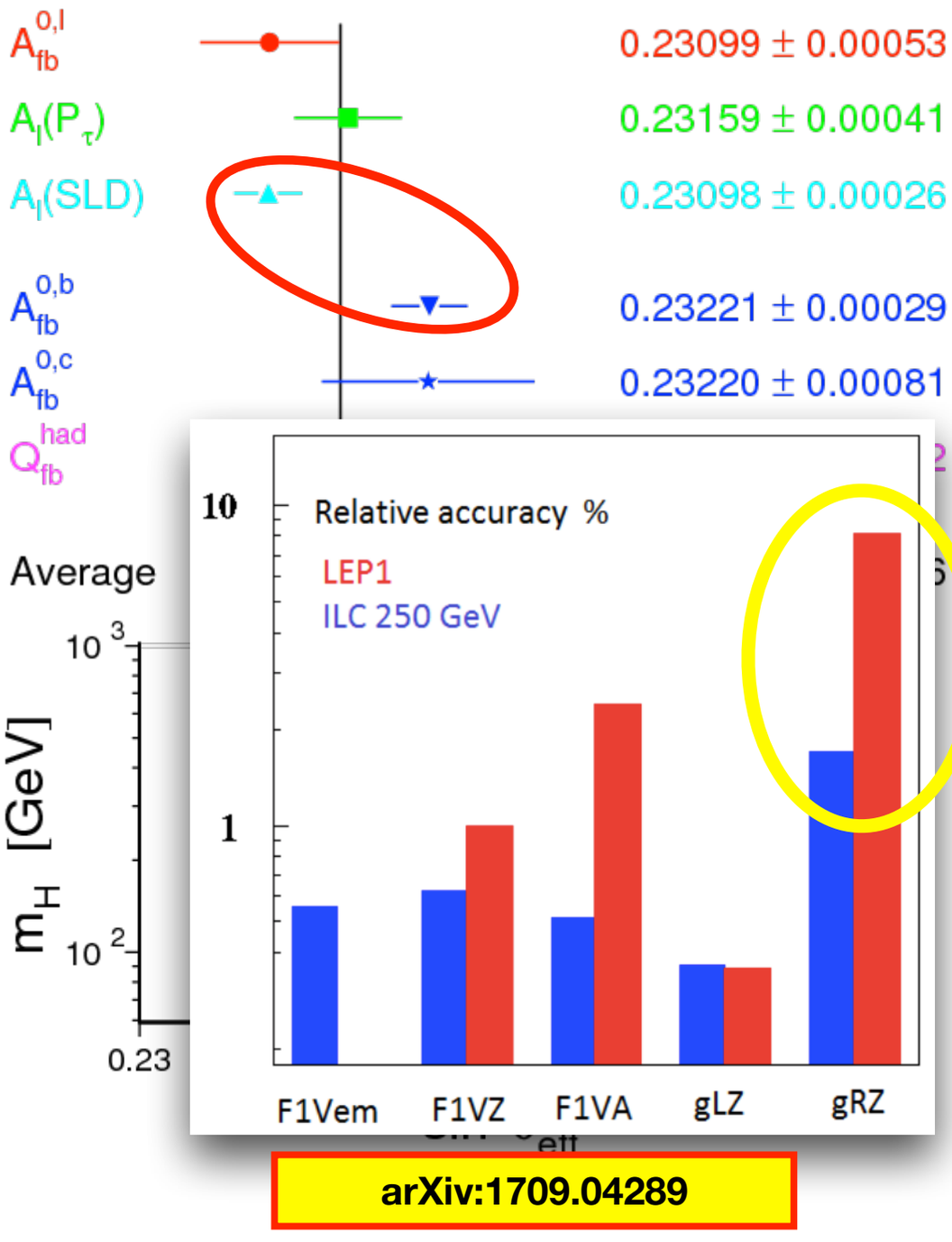

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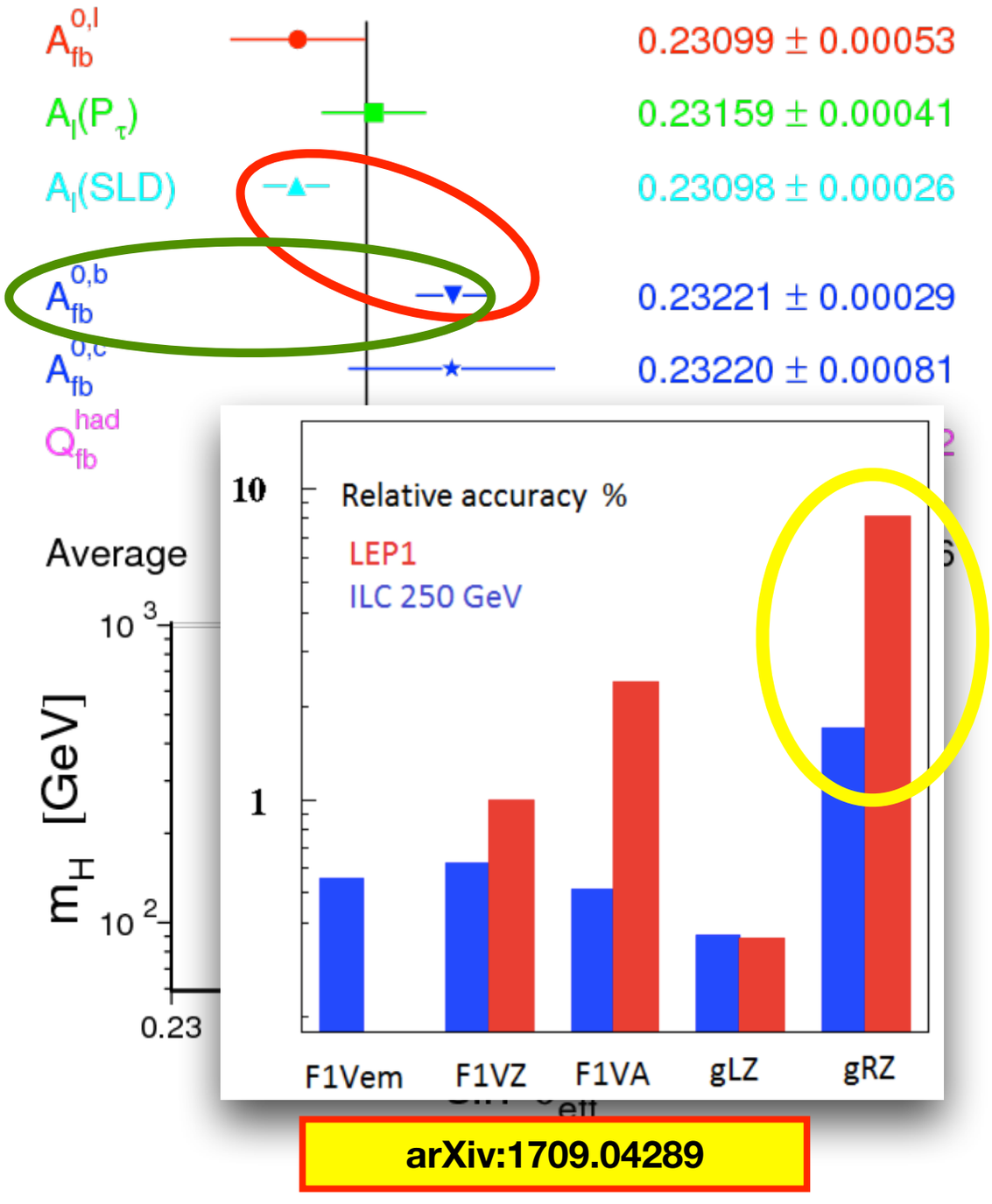

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Yes, we can!

allows to probe NP scales up to ~60 TeV

expect at least similar improvement also for **charm quarks**
=> profit from > 30 years of advances in detector technology!

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 and simultaneous fits of 3 couplings

250 GeV: full ILD study is work in progress

=> for now: extrapolations from 500 GeV (ILD) and ~200 GeV (LEP2)

=> uncertainties of a few 10^{-4}, also in simultaneous fit, ~2 x worse than 500 GeV

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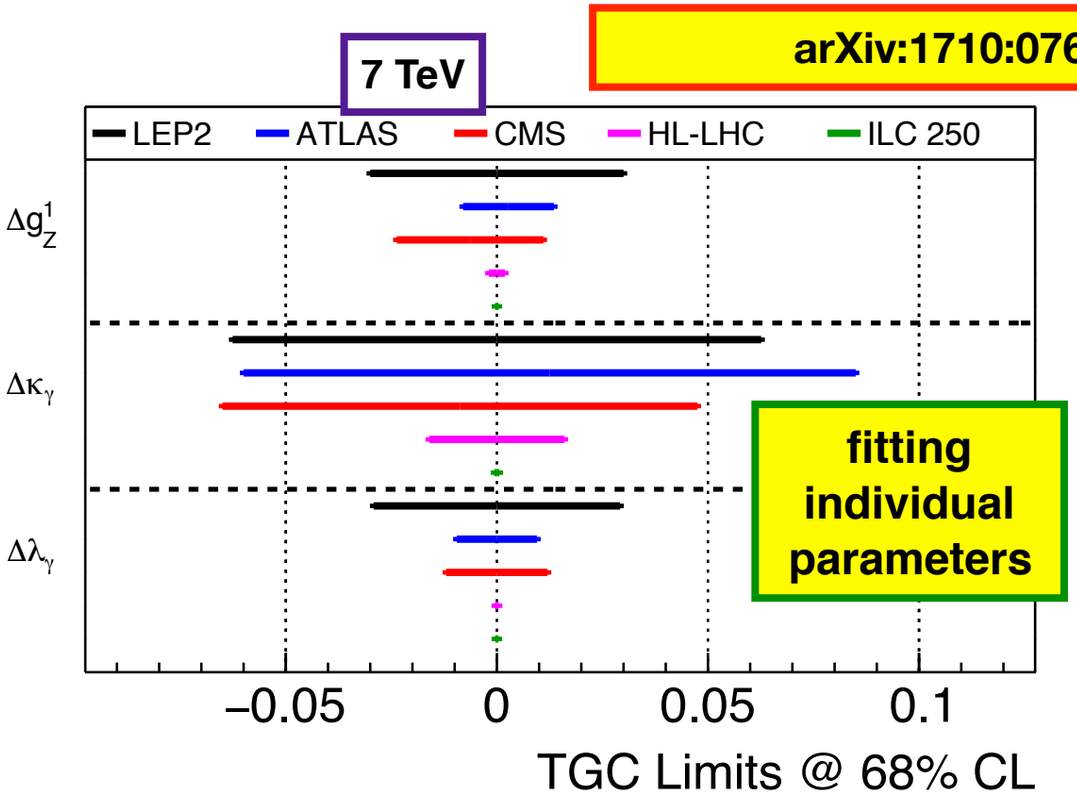

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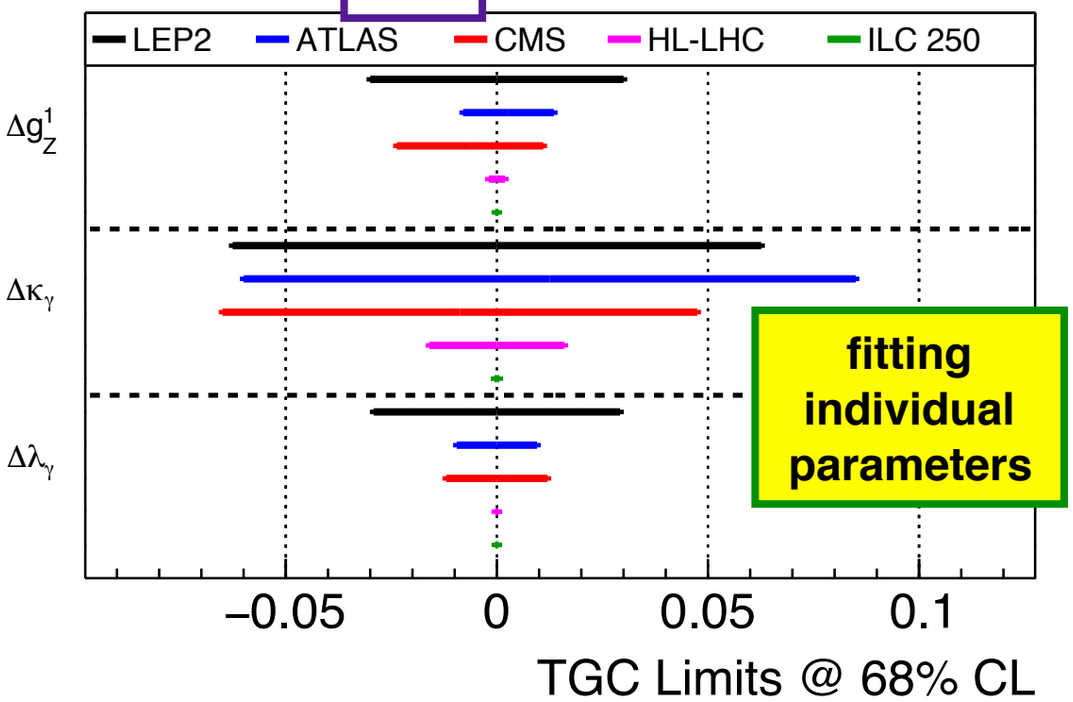
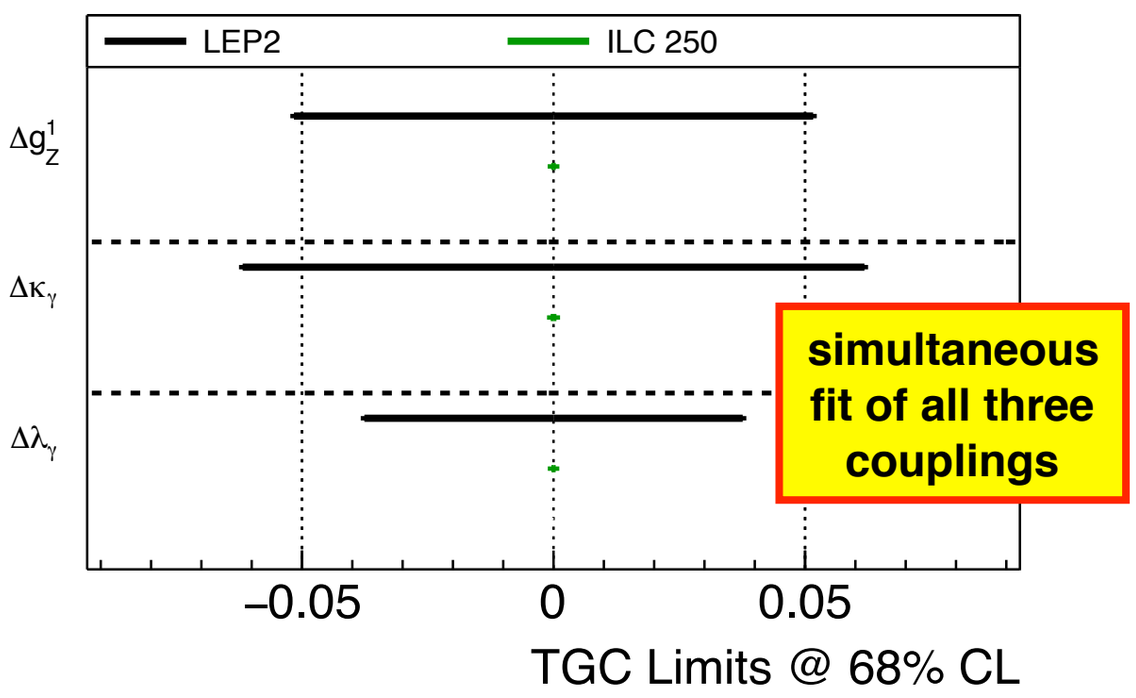
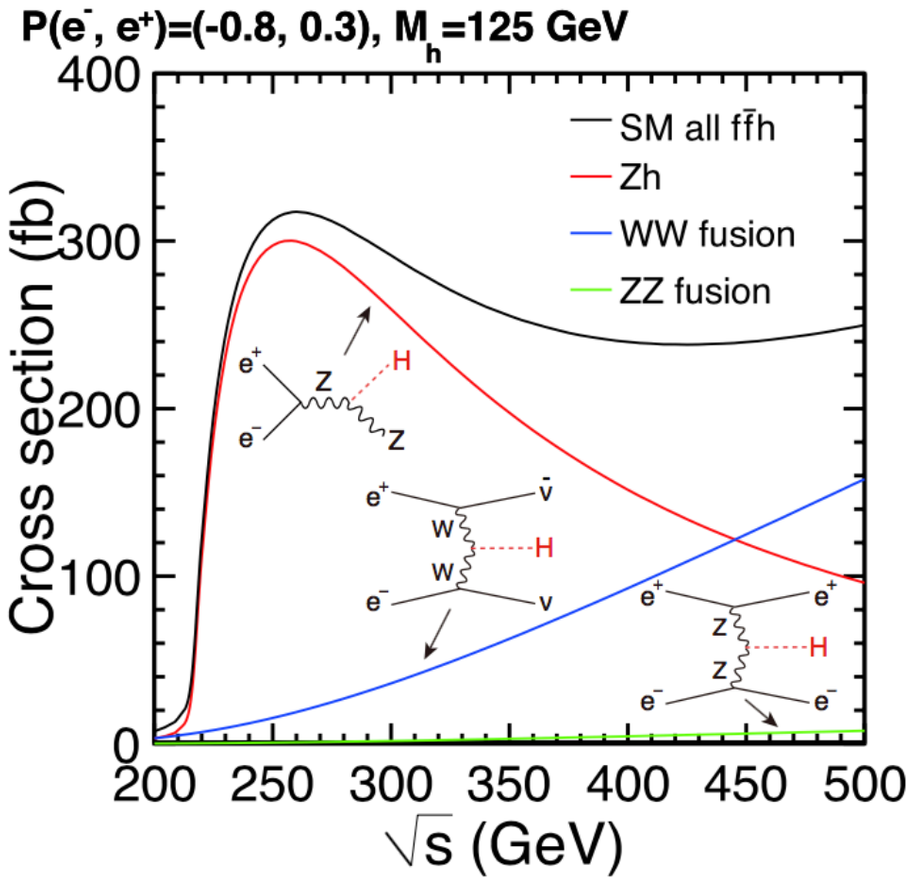




New insights from our new friend…

Precision Higgs Physics @ 250 GeV

The Higgs Boson



- 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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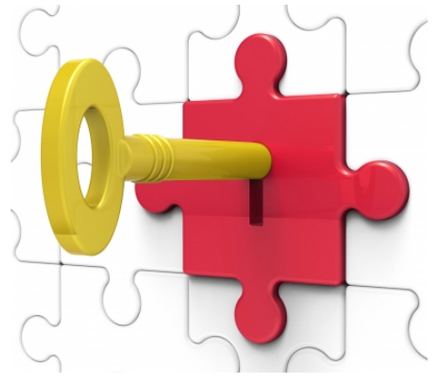

Image courtesy of Stuart Miles at FreeDigitalPhotos.net

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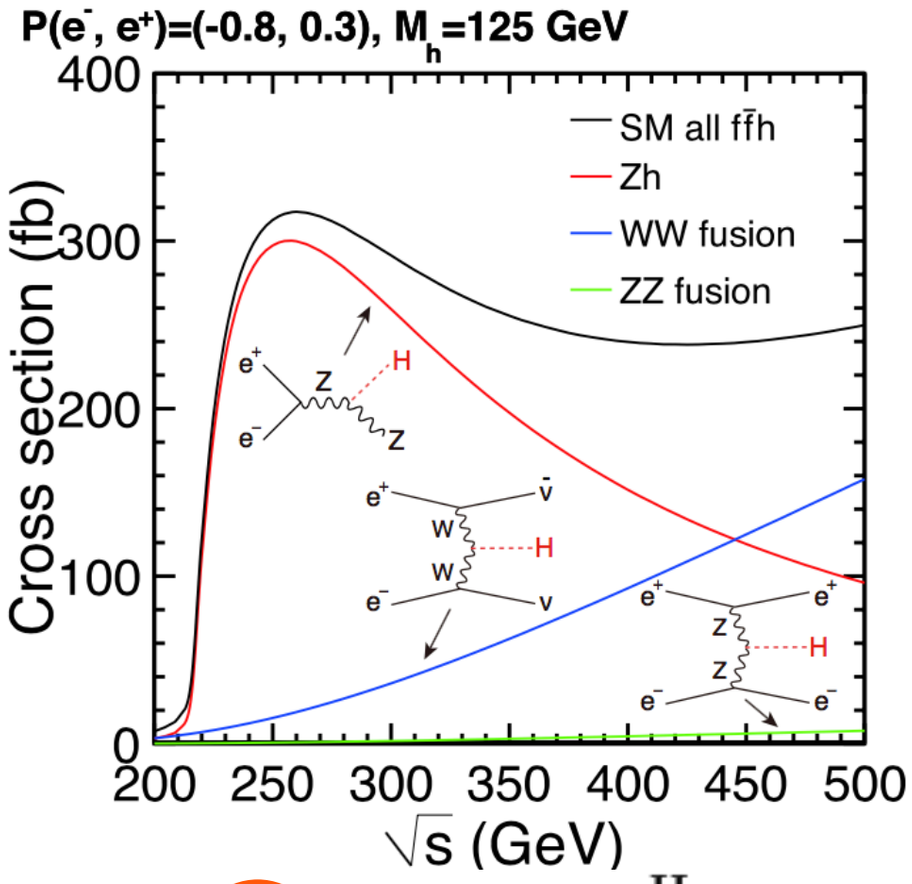

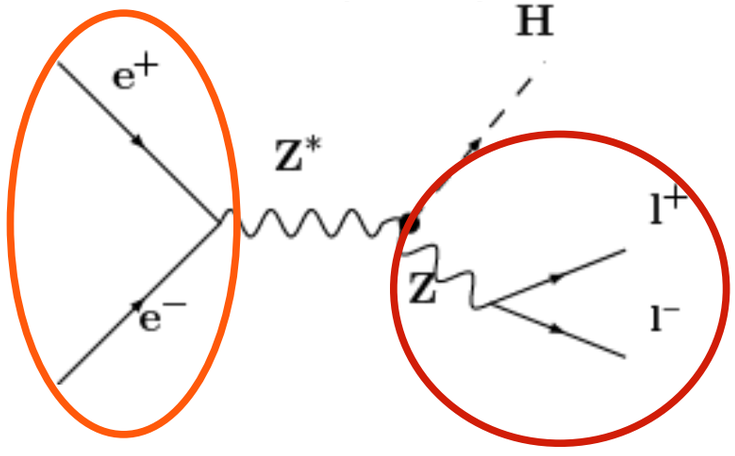

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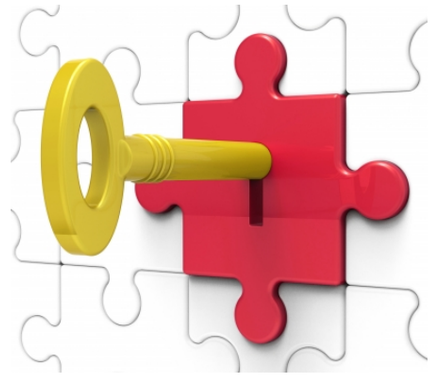

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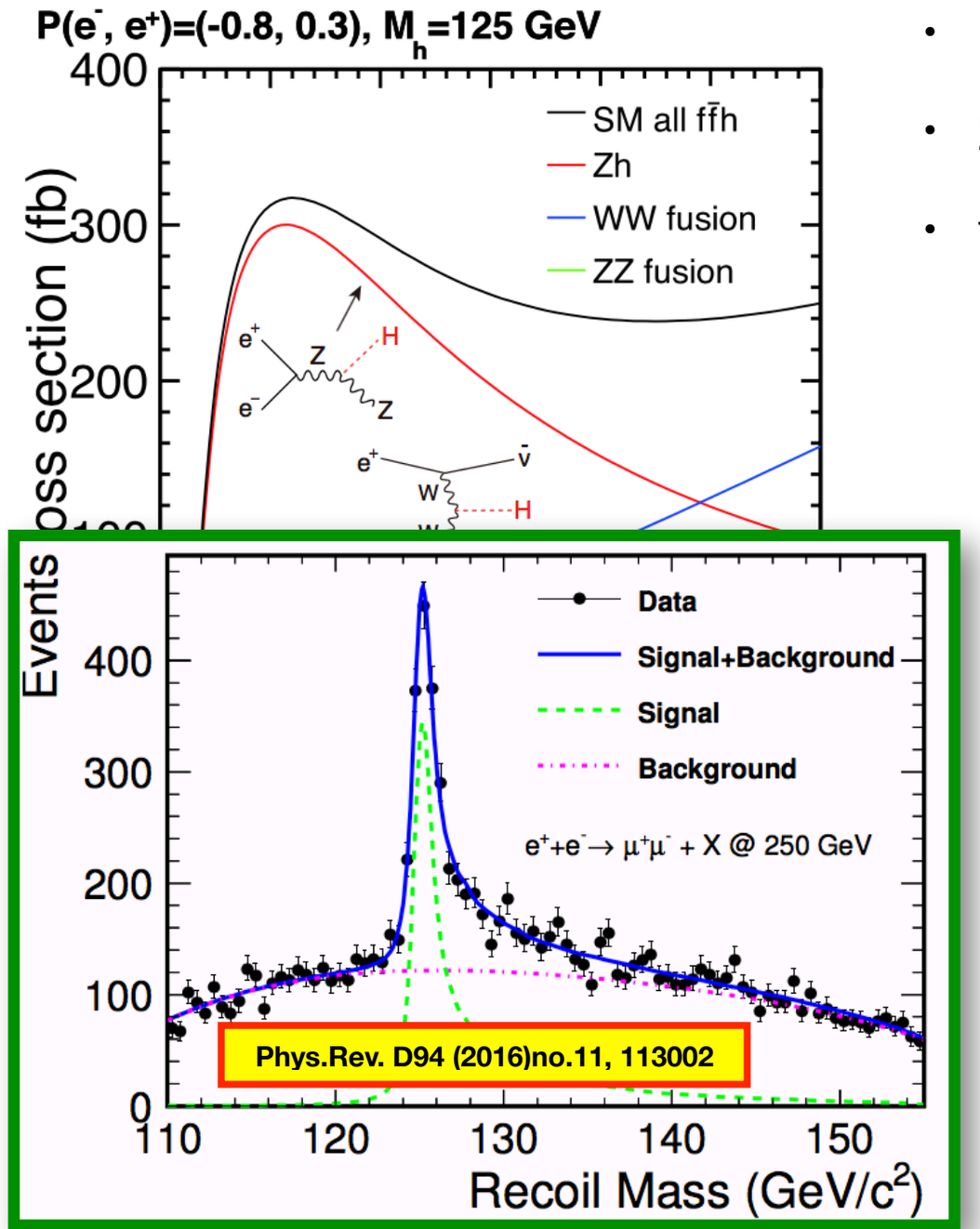

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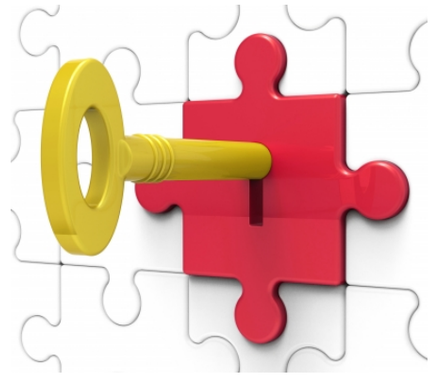

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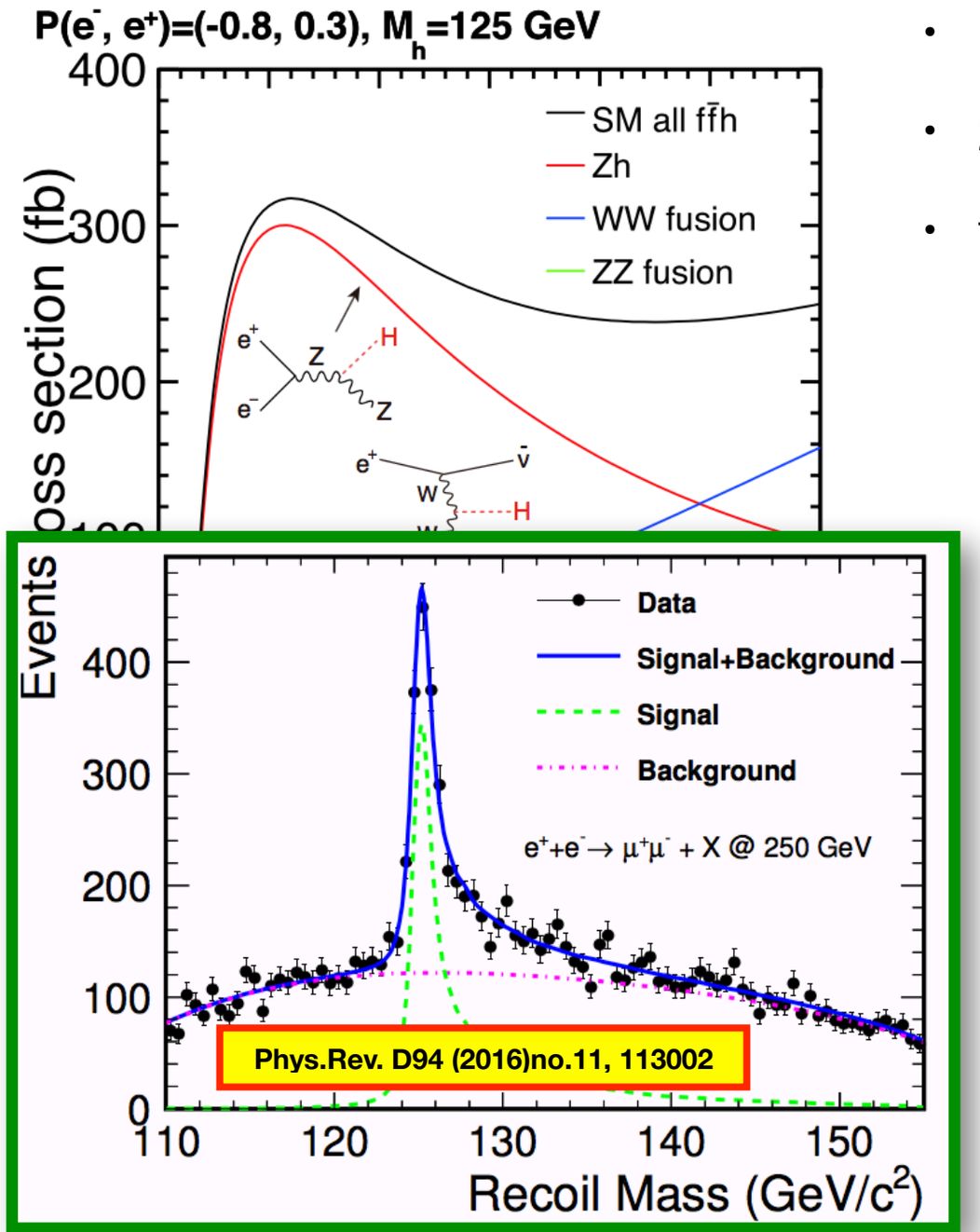

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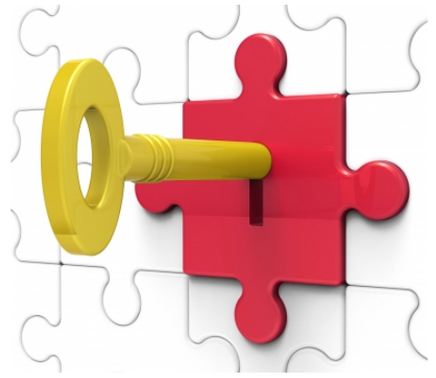

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for up-to-date listings of individual precisions c.f. arXiv:1708.08912

The Higgs Boson

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

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

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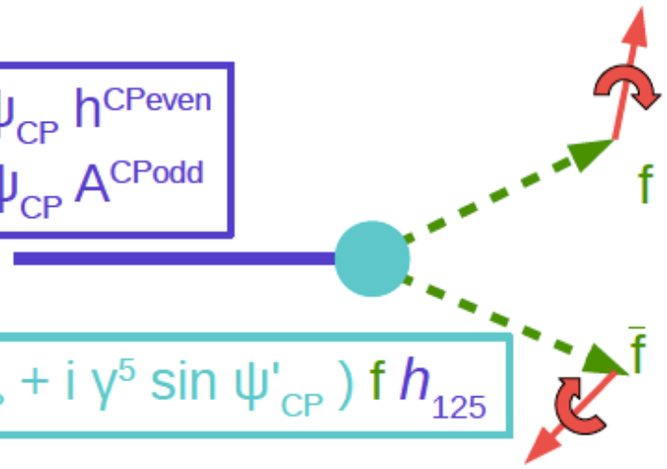

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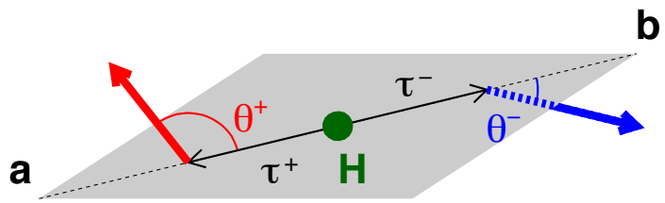

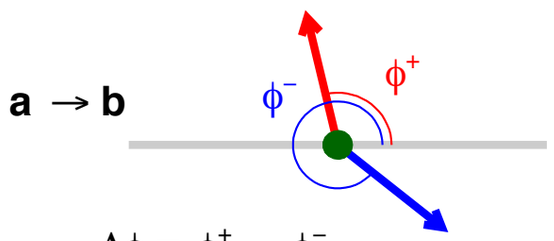

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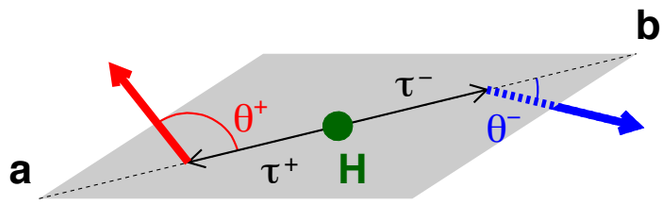

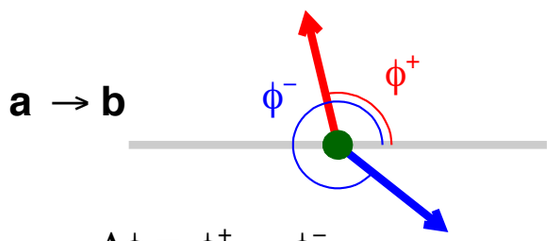

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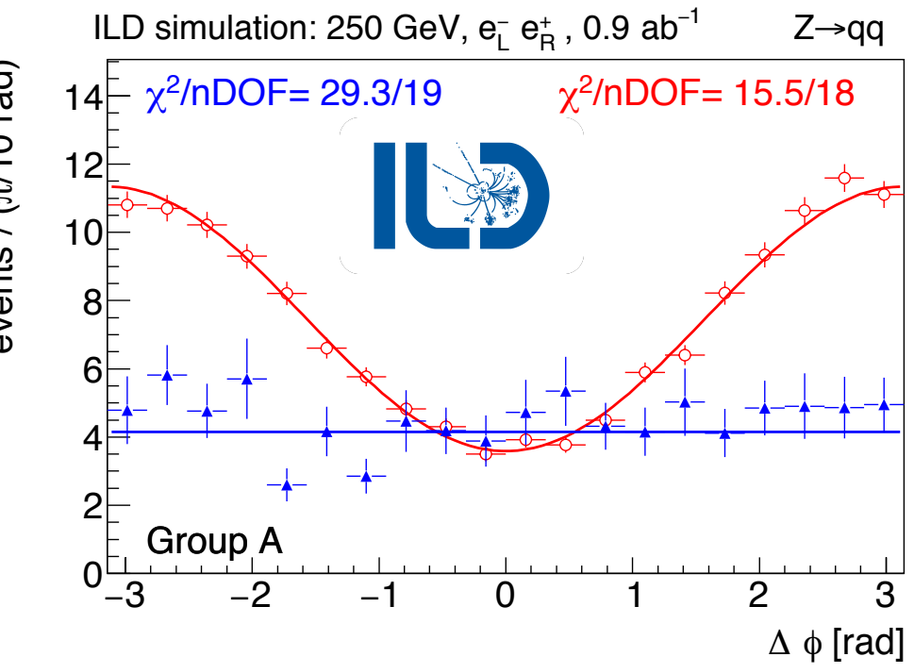

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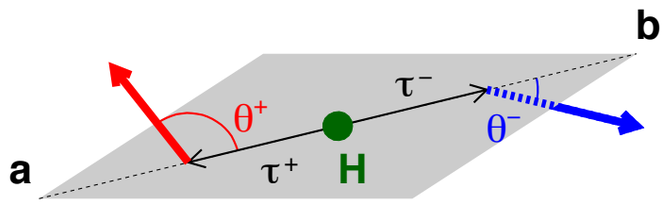

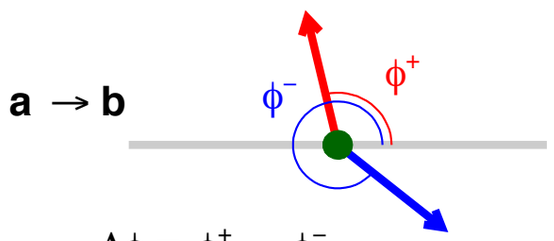

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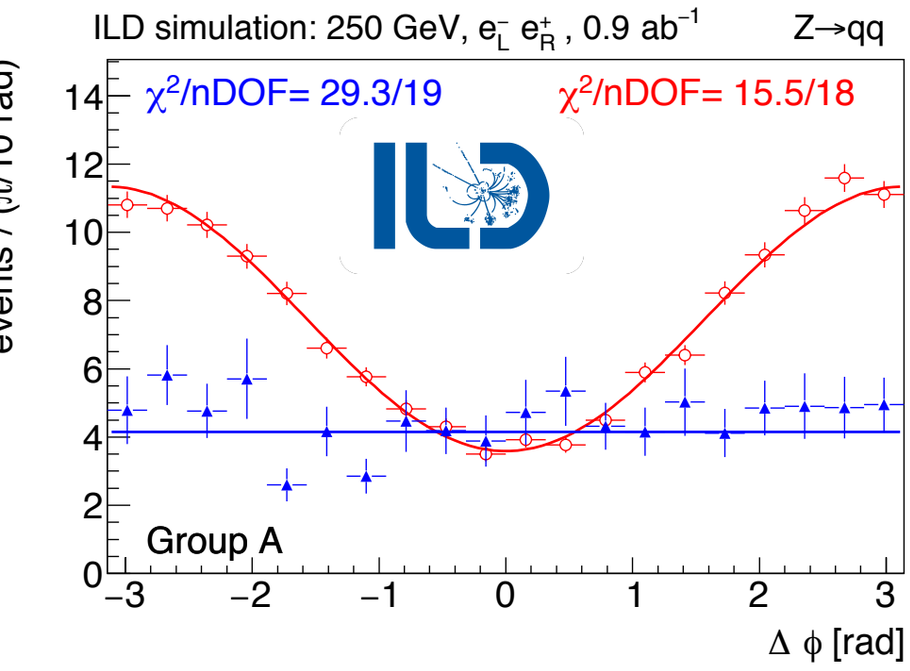
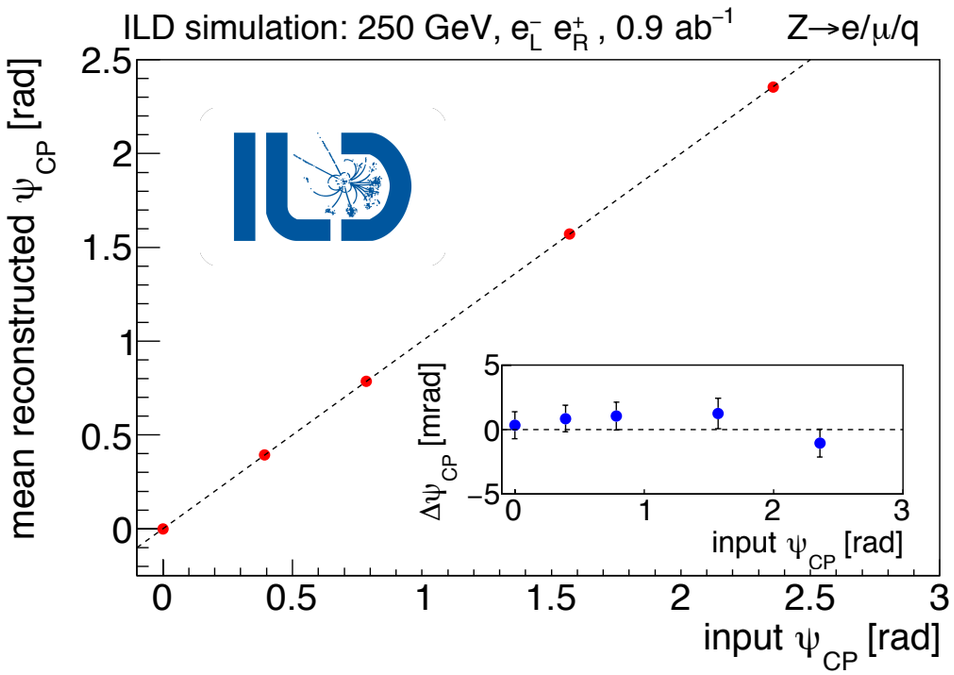




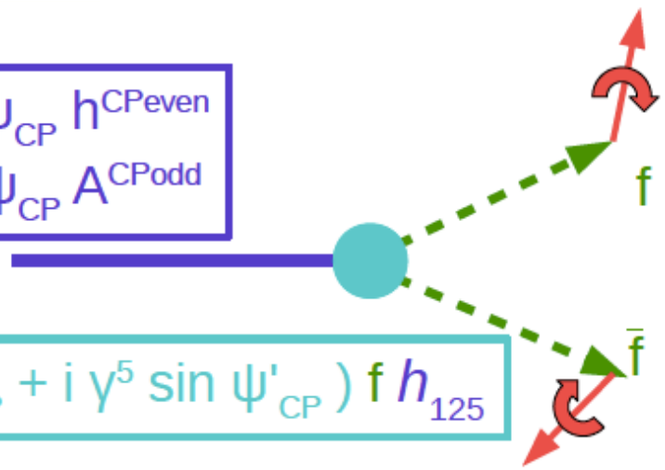
arxiv:1804.01241

based on NIM A810 (2016) 51-58

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

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

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



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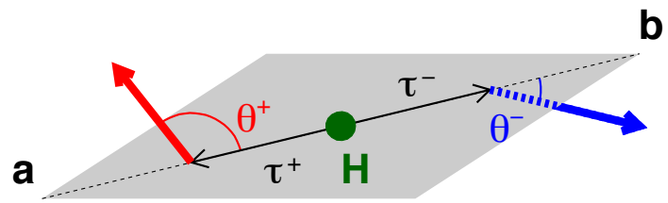

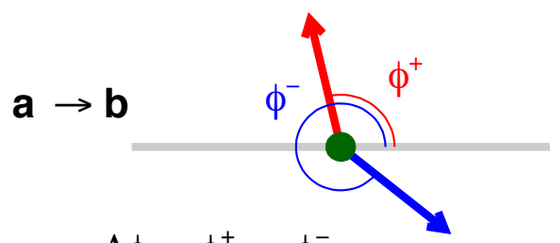

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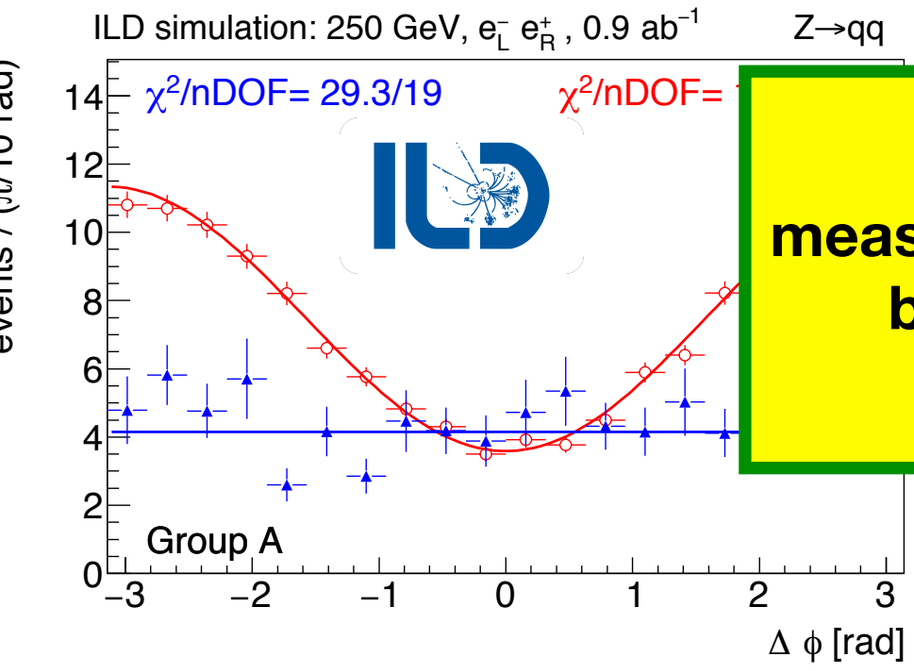

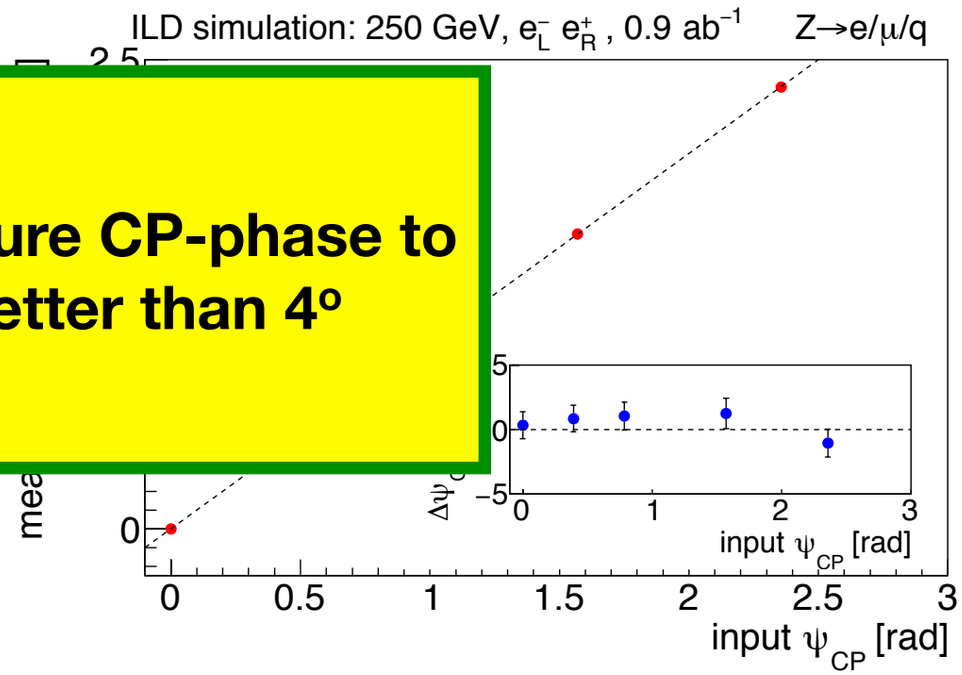

measure CP-phase to better than 4º

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The Higgs Boson

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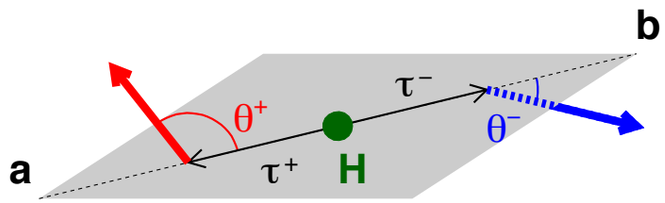

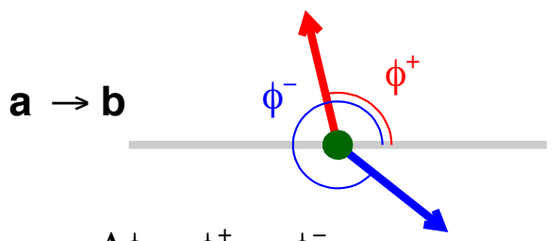

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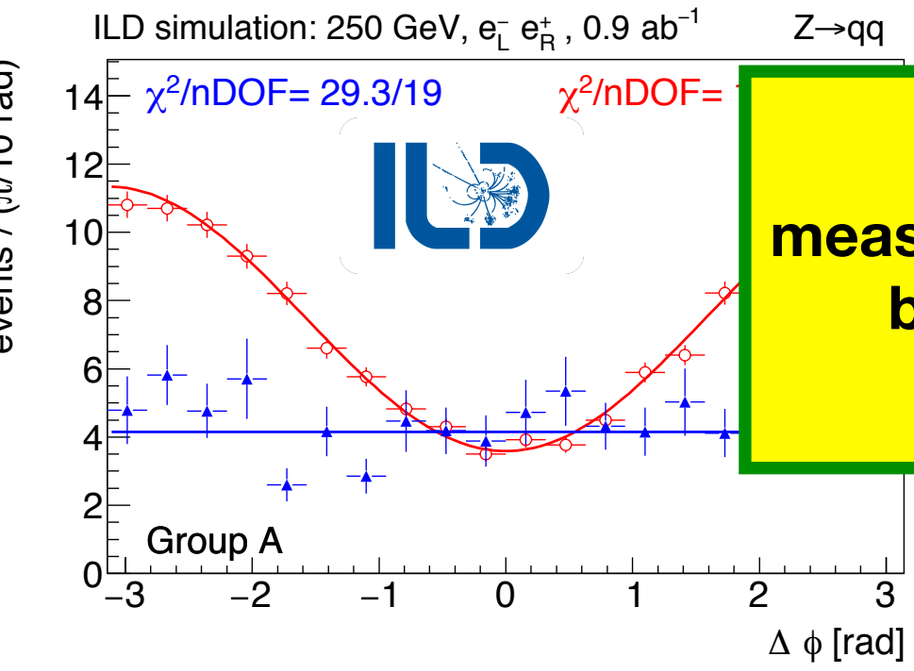
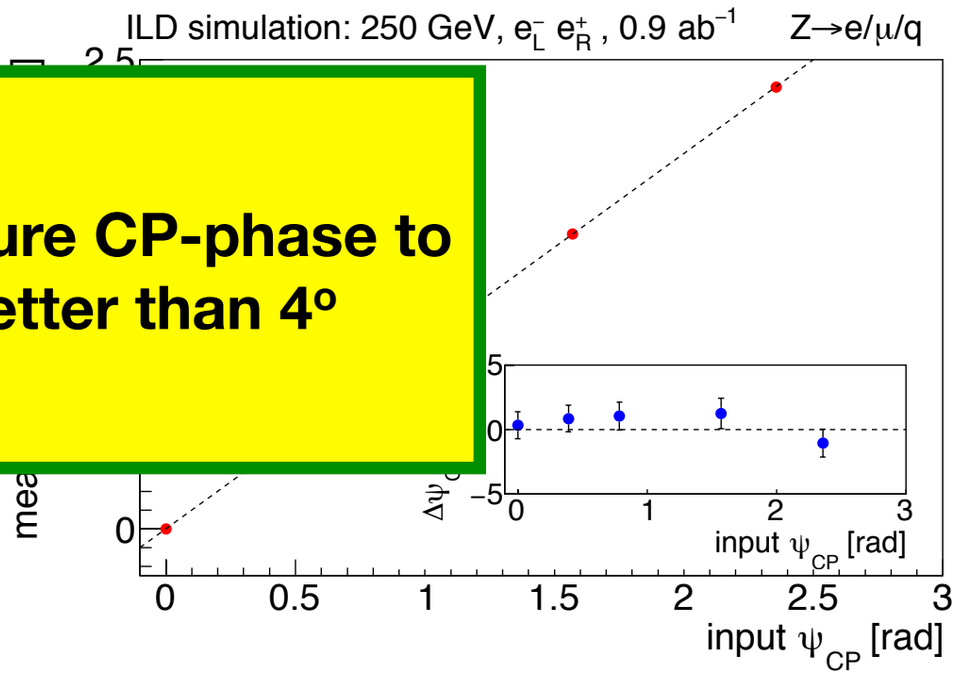




measure CP-phase to better than 4º

..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

arxiv:1804.01241

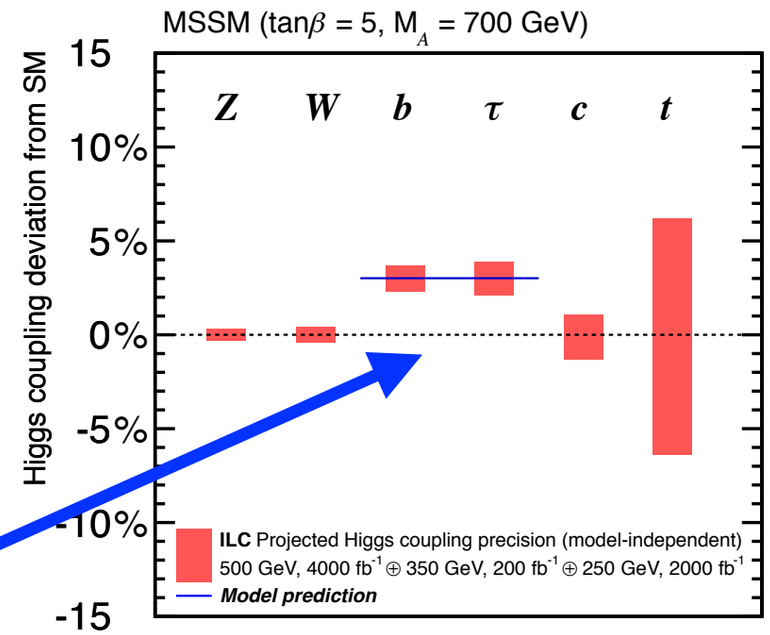
based on NIM A810 (2016) 51-58

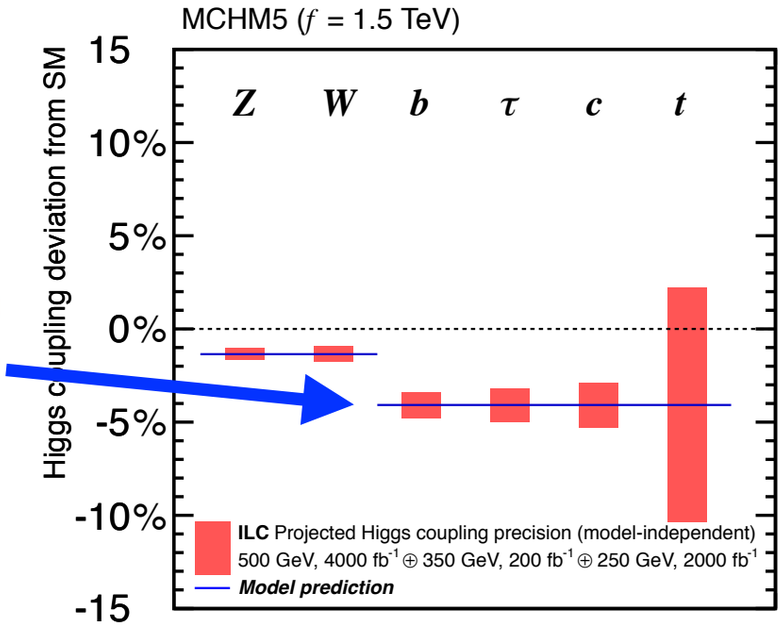
The Higgs Boson couplings

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: $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$
- Littlest Higgs, eg m_T=1TeV: $\frac{g_{hgg}}{g_{h_{SM}gg}} = 1 - (5\% \sim 9\%)$, $\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} = 1 - (5\% \sim 6\%)$.
- Composite Higgs, eg: $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \text{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \text{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$





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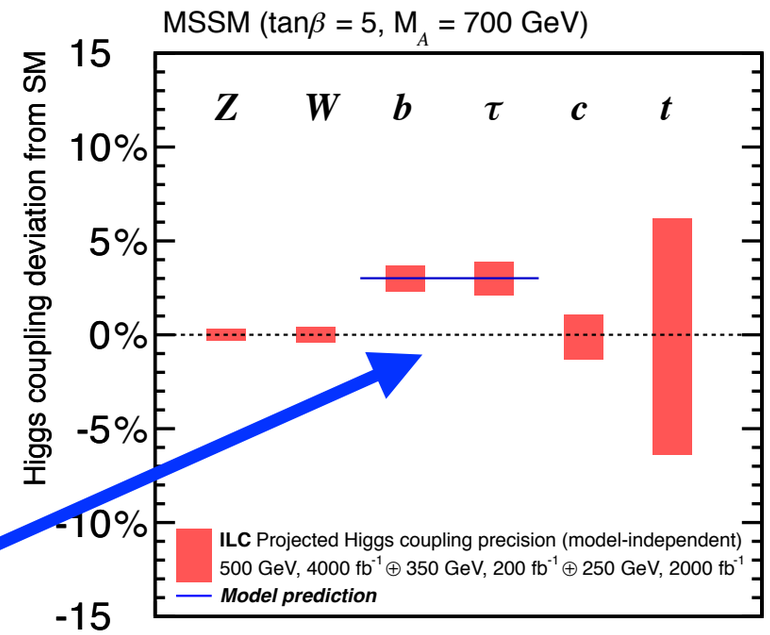
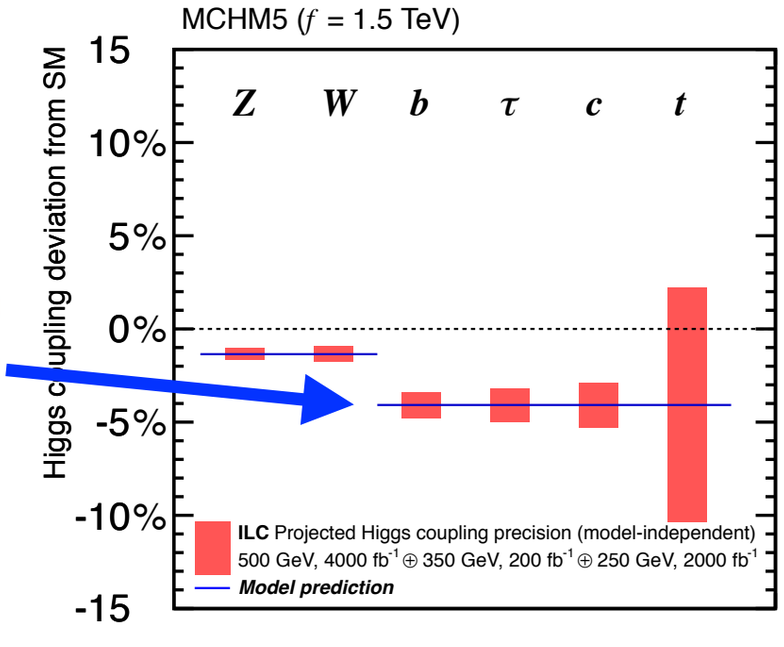
At least percent-level precision required!





A new way to determine the Higgs couplings

- **until recently: so-called κ-framework**
  - simple scaling of couplings which exist in the SM, e.g.

$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \,, \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

  - no new operators considered
  - called “model-independent” because no assumptions on any size of coupling or total width
- **NEW: EFT-based framework**
  - consistent set of SU(2)xU(1) allowed dim-6 operators (assumes custodial symmetry!)
  - even more “model-independent” since new momentum-dependent operators included, e.g.:
  - general $\delta\mathcal{L} = \frac{m_Z^2}{v}(1+\eta_Z)hZ_\mu Z^\mu + \zeta_Z \frac{1}{v} hZ_{\mu\nu}Z^{\mu\nu}$.

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    => treat H->invisible as additional degree of freedom
  - allows to include:
    - EWPO: current state assumed apart from Γ_W
    - **triple gauge couplings**
- **still included in ILC fits as before: systematics** (b-tag, L, P, Theo)

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the following based on 10-parameter fit in arXiv:1708.08912

other approaches use up to 17 parameters

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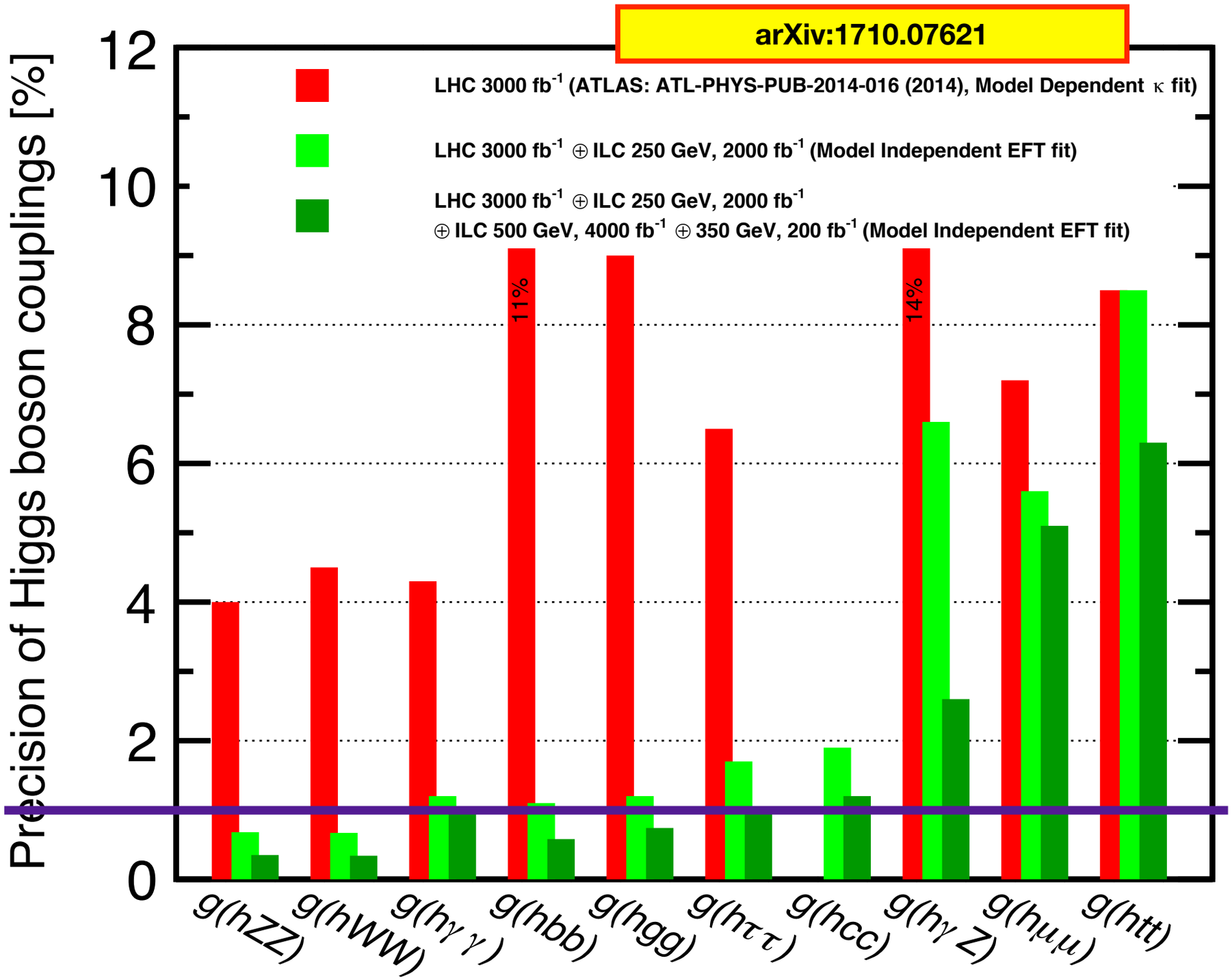
Higgs coupling precisions from full EFT fit

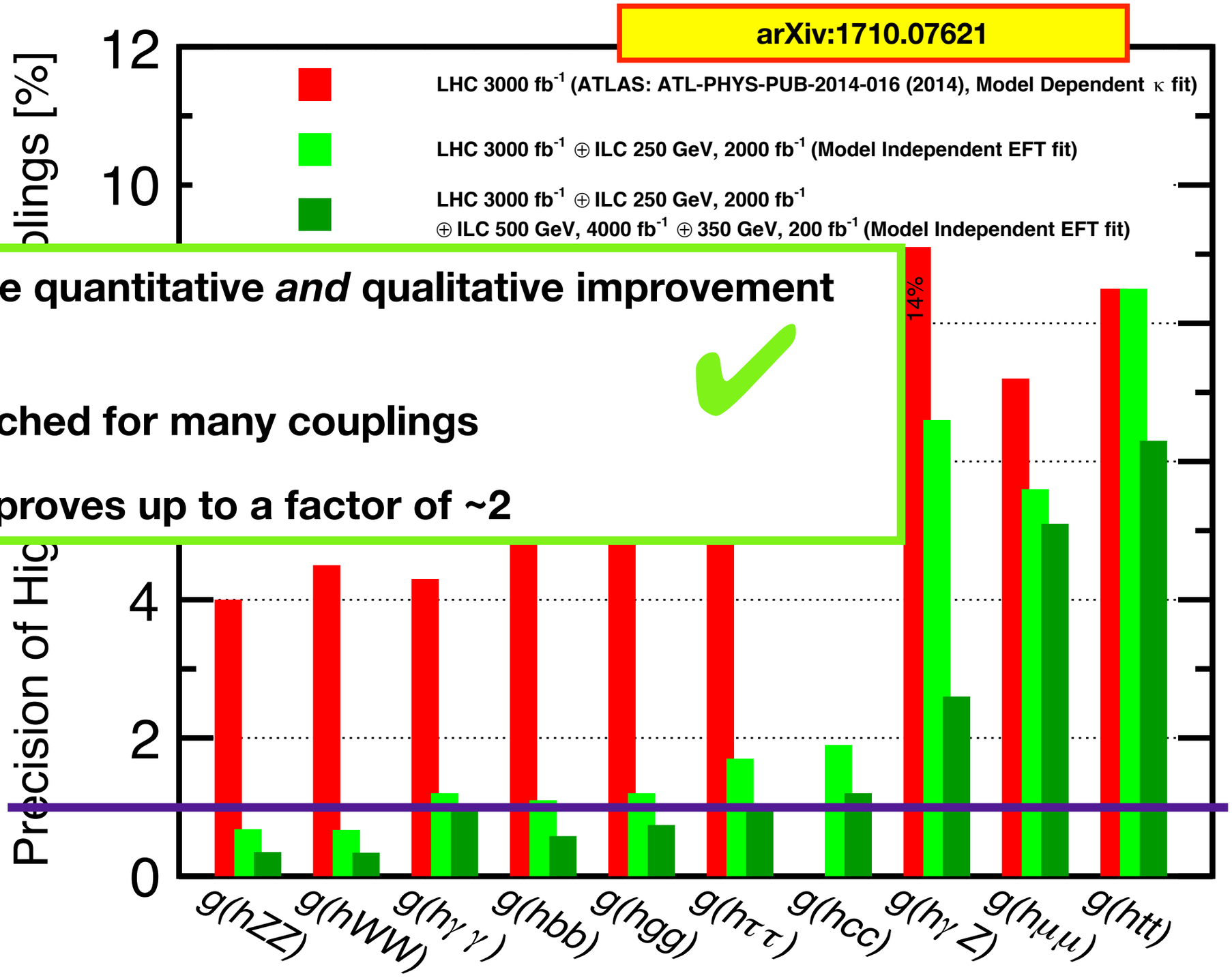


Higgs coupling precisions from full EFT fit

★ 250 GeV offers huge quantitative *and* qualitative improvement over HL-LHC

★ ~ 1 % or better reached for many couplings

★ adding 500 GeV improves up to a factor of ~2



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
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5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
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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 ($3\,\text{ab}^{-1}$ of integrated luminosity). From [15].

arXiv:1708.08912

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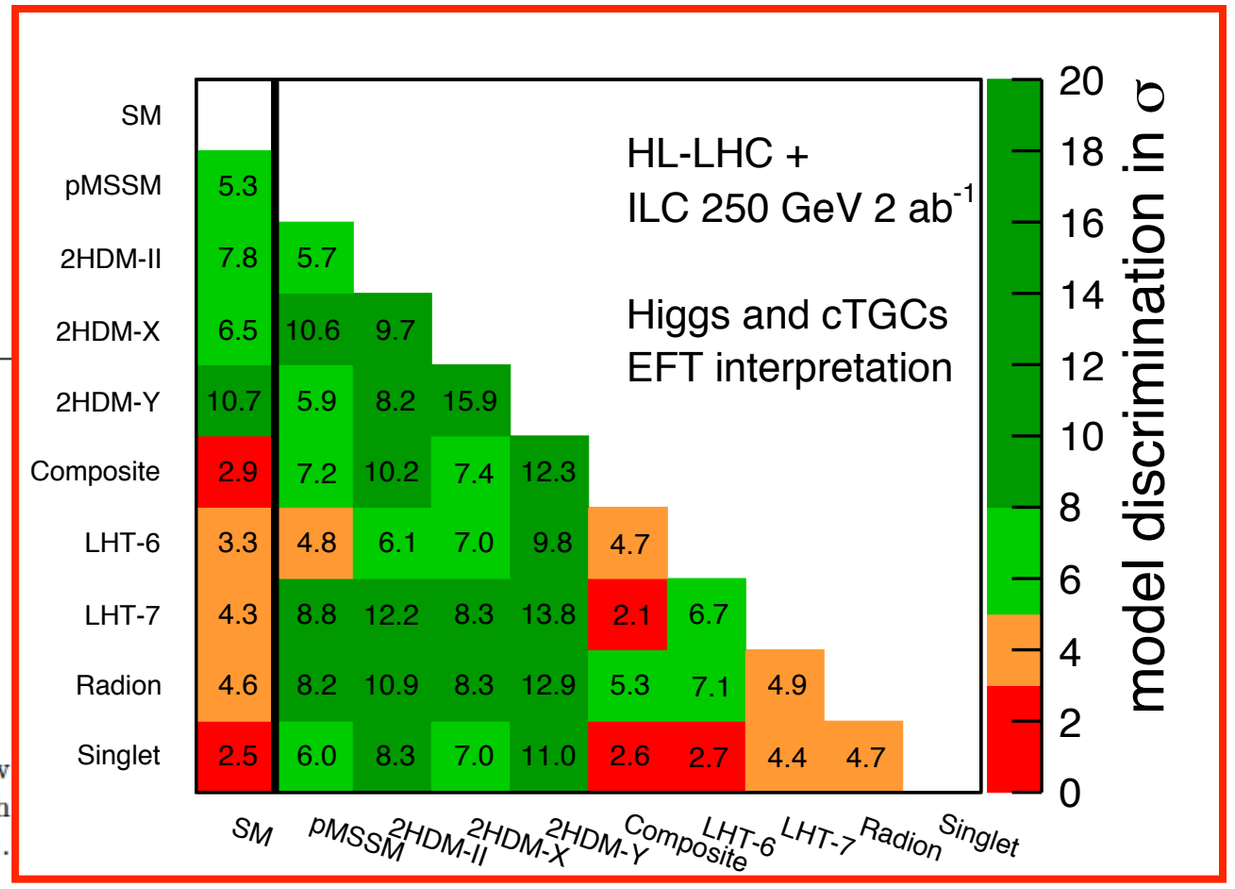

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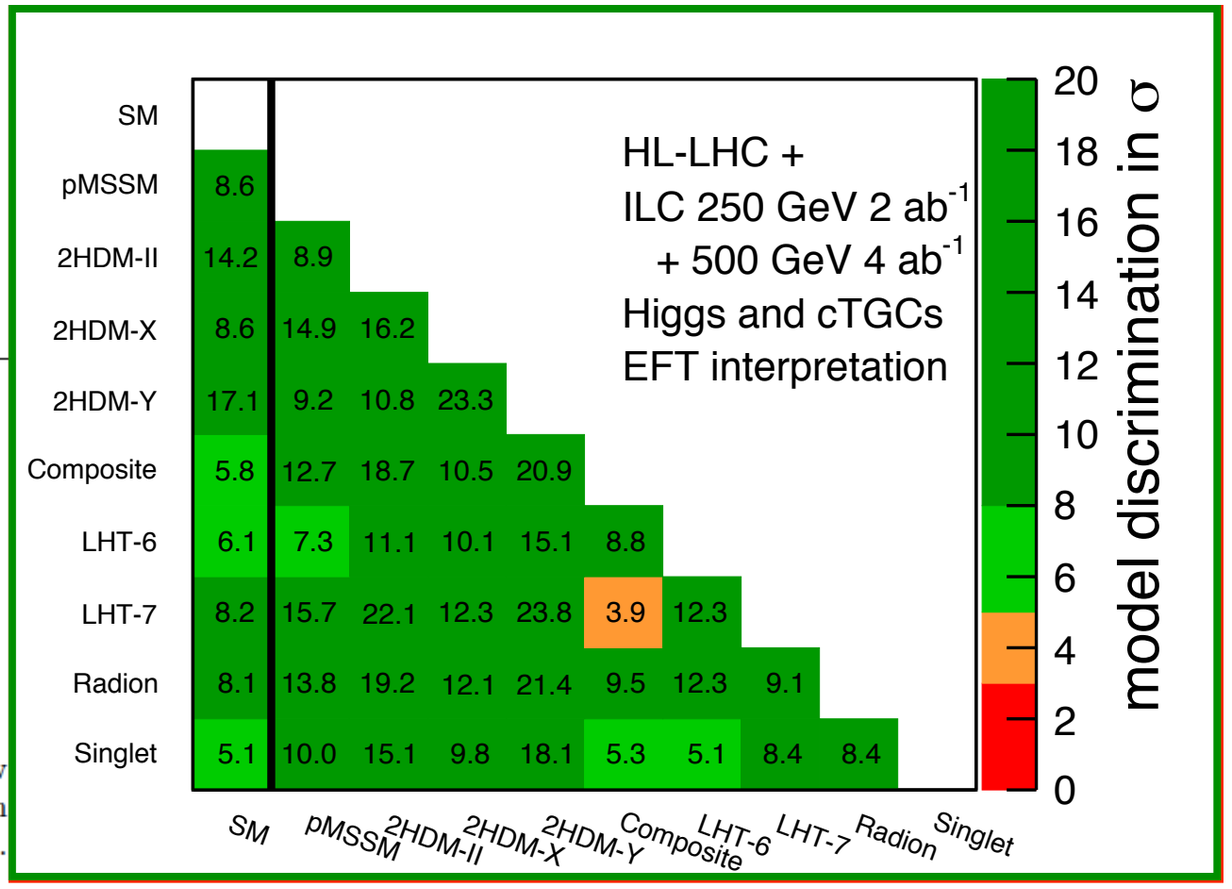

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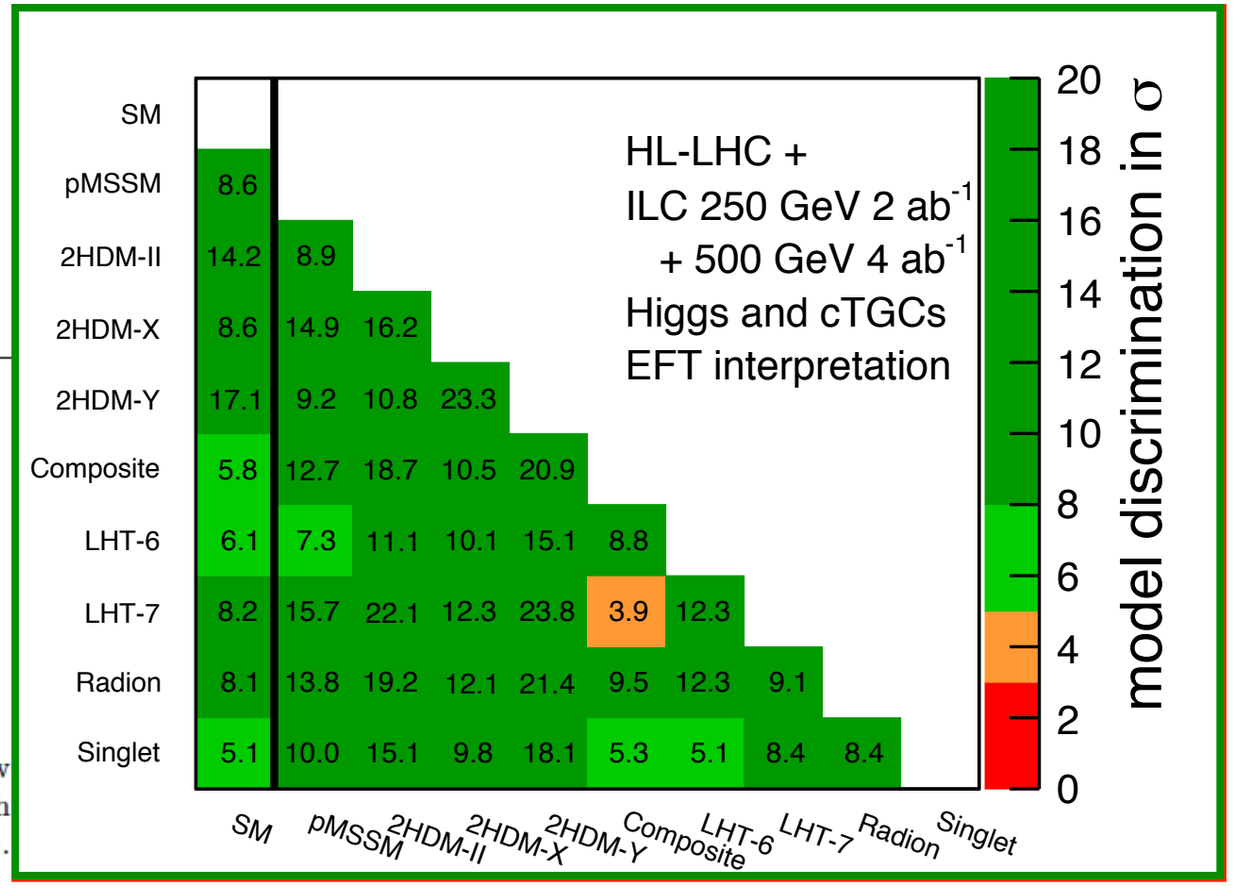

arXiv:1708.08912

Discoveries of new particles ?

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

Looking for more new friends

Opportunities for direct discoveries ?

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

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Closer look at **ILC250** vs **LEP2**:

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- **polarised beams**
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- **tremendous advances in detector technology**,
  e.g. momentum resolution
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=> any search channel *limited by rate* at LEP2 will explore new territory at ILC250 !

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- e.g. 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 tanβ
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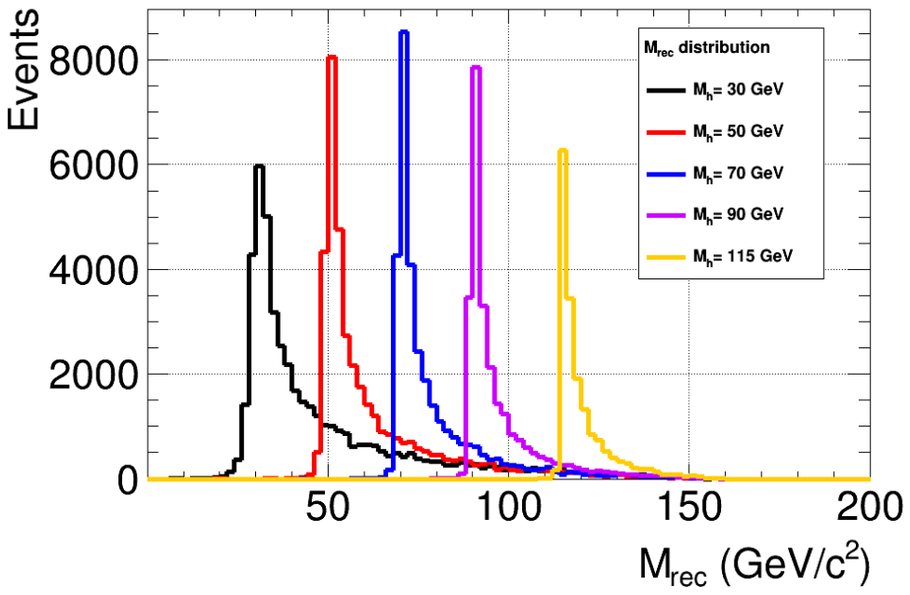

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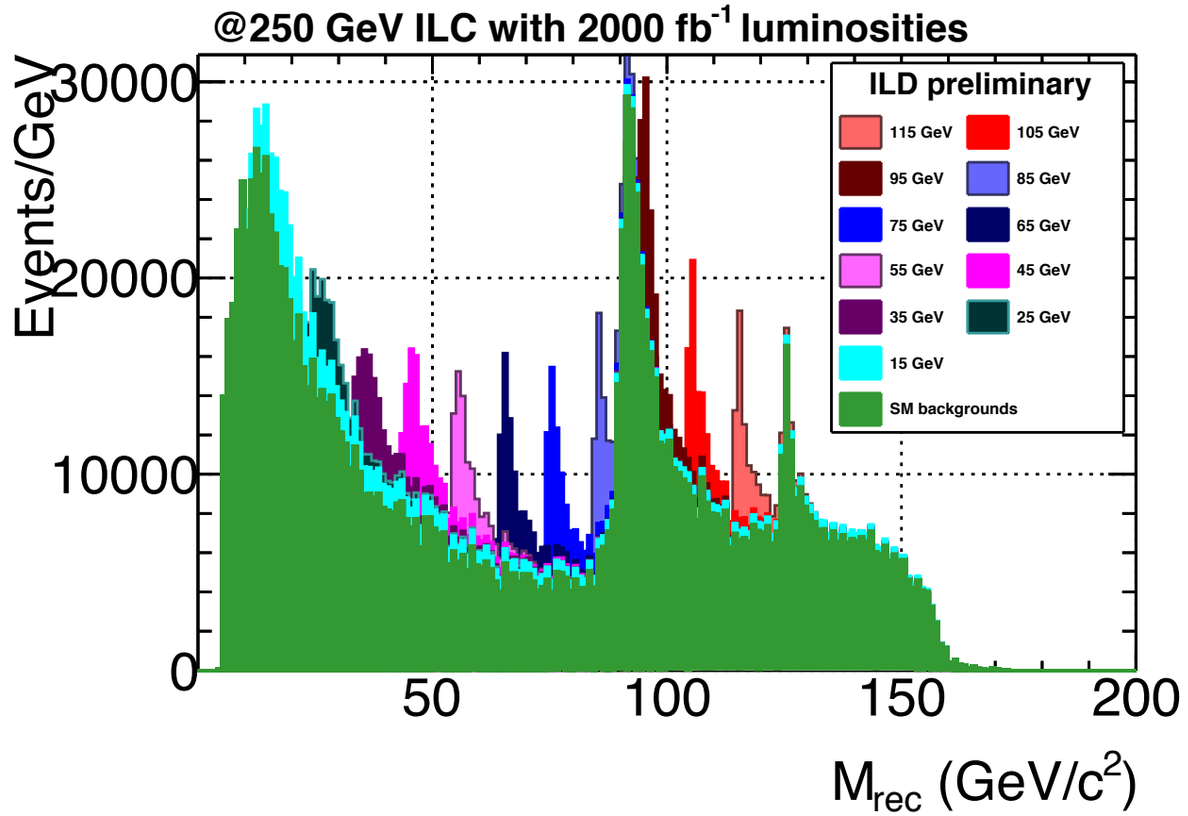

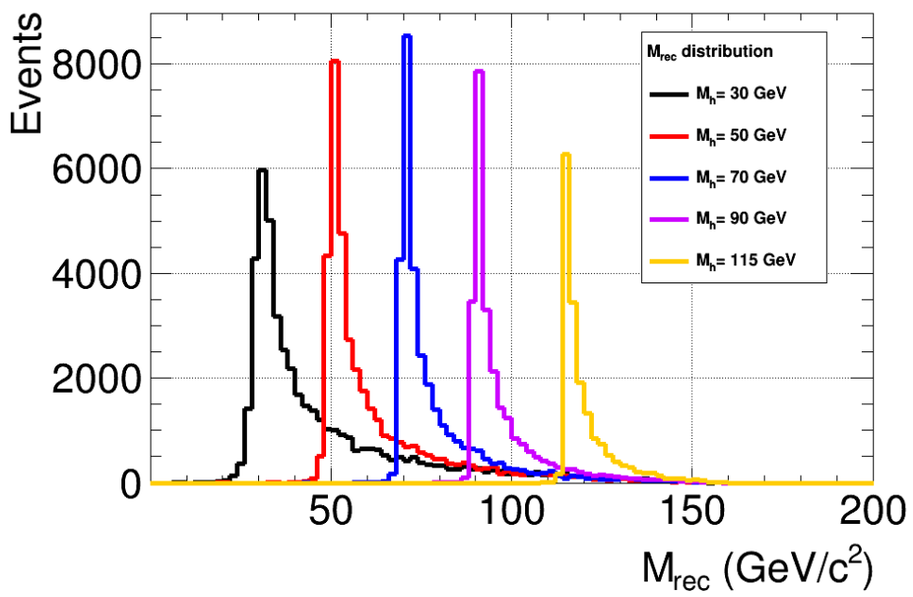

ILD full detector simulation @ ILC 250 GeV, update of arxiv:1801.08164

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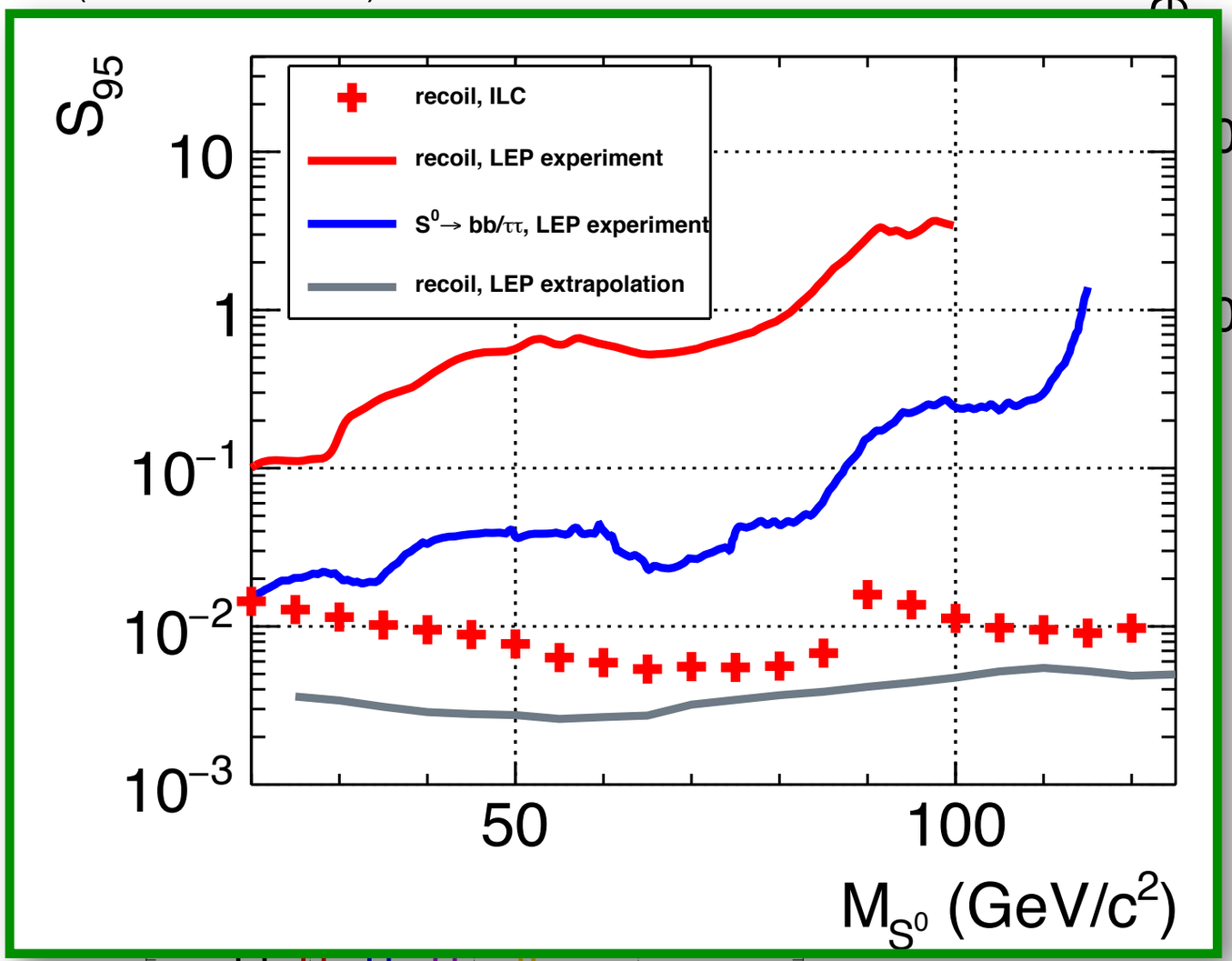
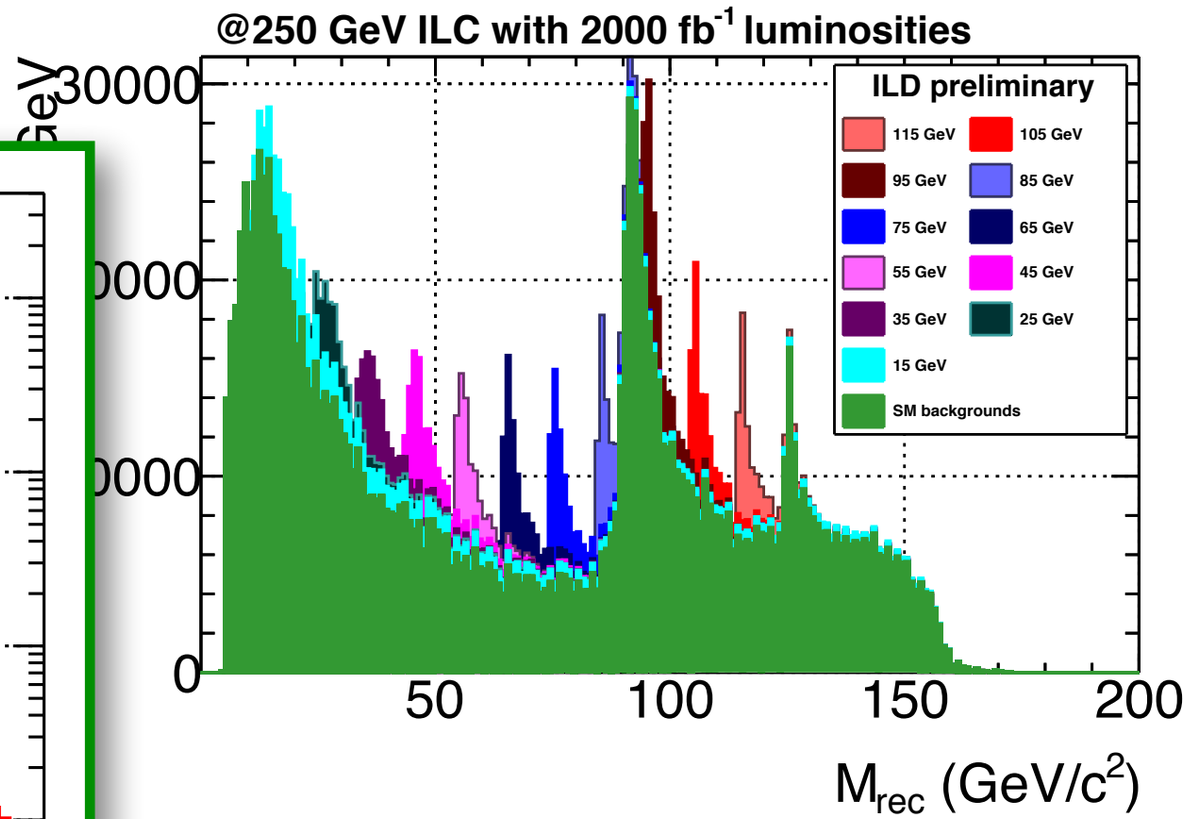
- e.g. from 2HDMs or additional singlets (as in NMSSM)





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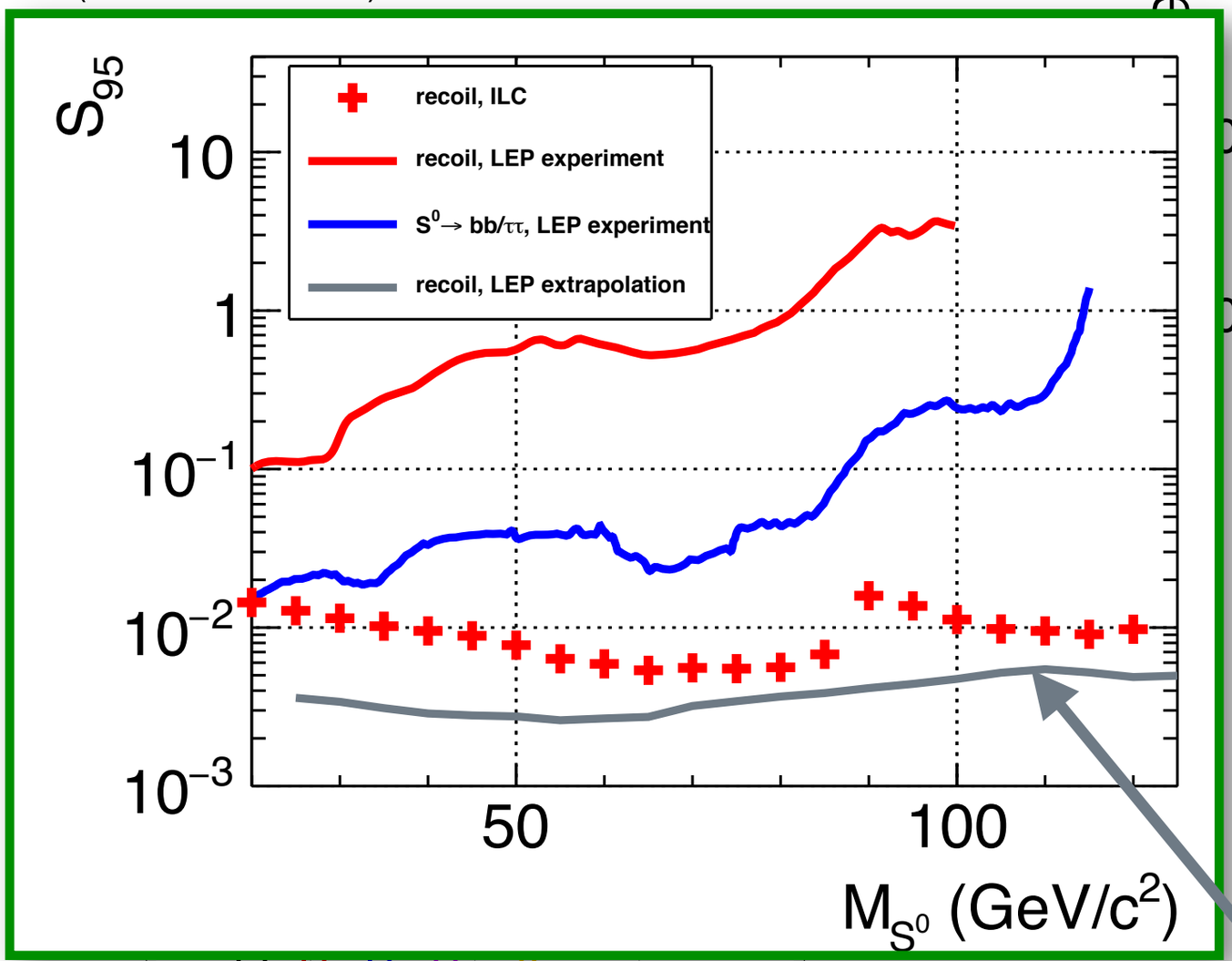

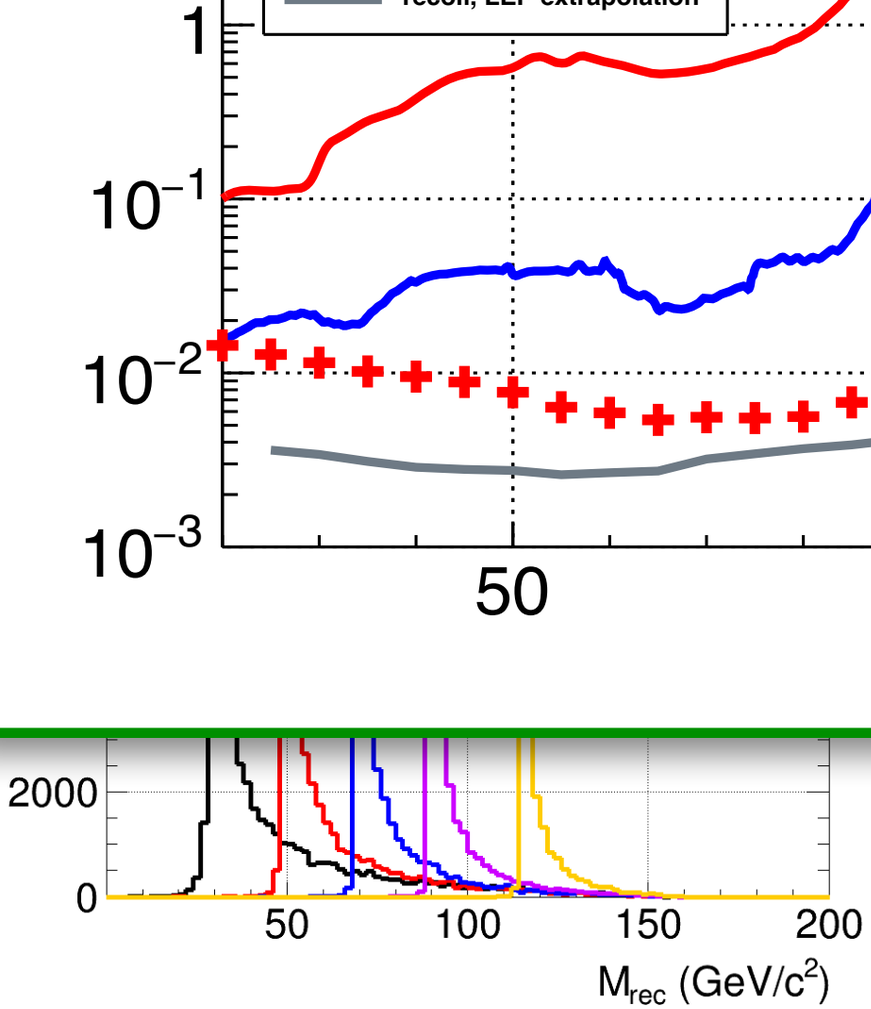

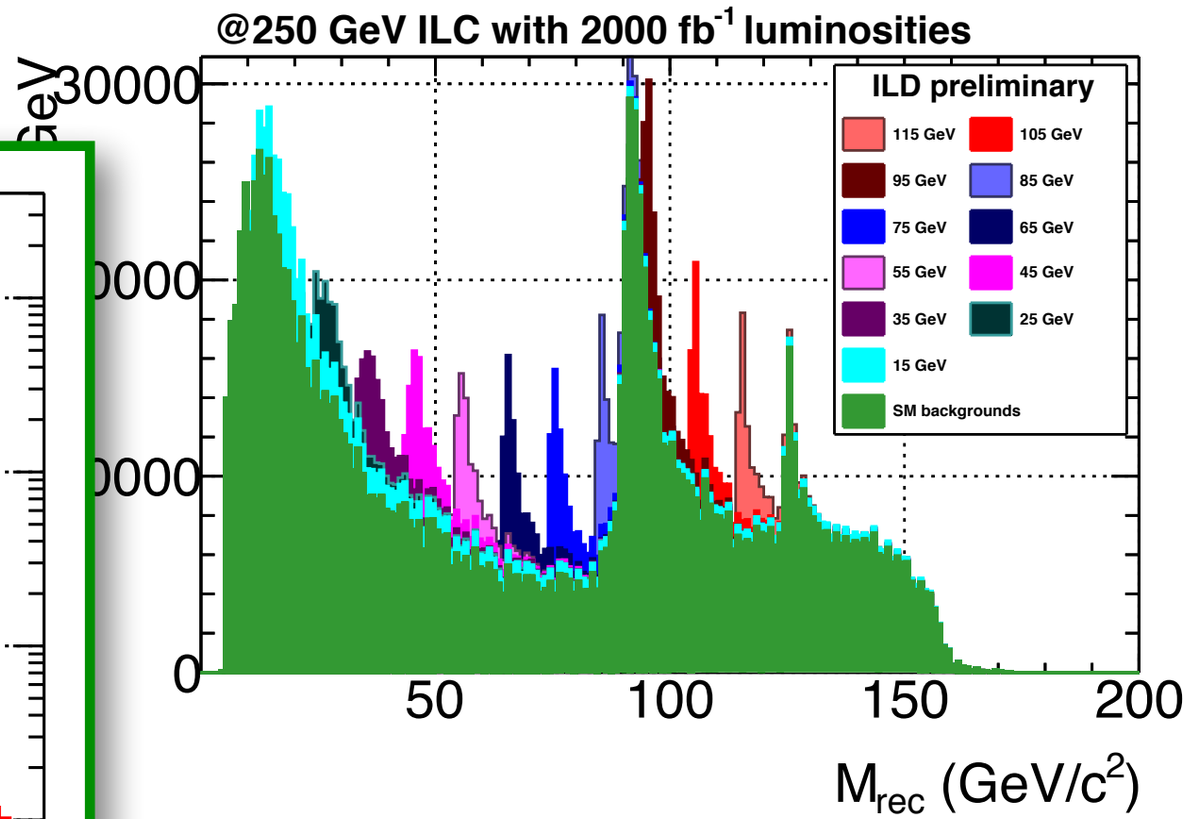

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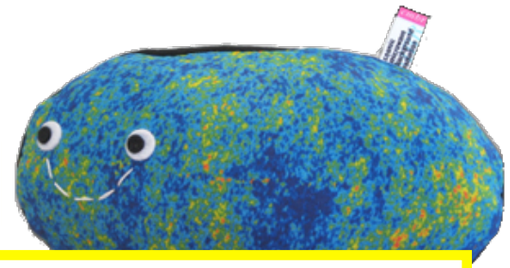
grey line by cross-section scaling from LEP by P.Drechsel et al, arxiv:1801:09662

Example 2: WIMPs

Discoveries of new particles …



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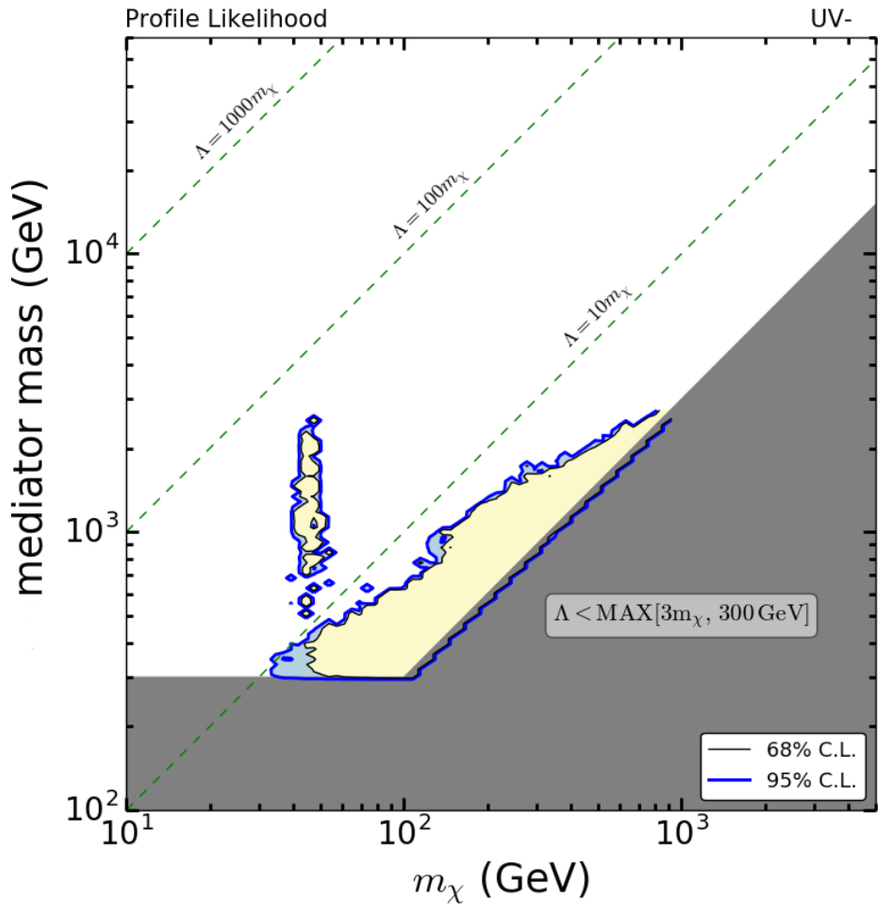

- likelihood scan over WIMP parameter space including existing and future direct, indirect and collider experiments (apart from ILC)
- e.g. here: singlet like fermion WIMP

=> significant unexplored regions below M=120 GeV !!!

arXiv:1702.05377

- $e^+e^- \to \chi\chi\gamma$ "mono-photons"
- **Effective operator interpretation**
  [nota bene: valid in e^+e^- collider sensitivity range]
- for M_χ < 100 GeV ILC probes Λ (95% CL)
  - **up to ~2 TeV @ 250 GeV**
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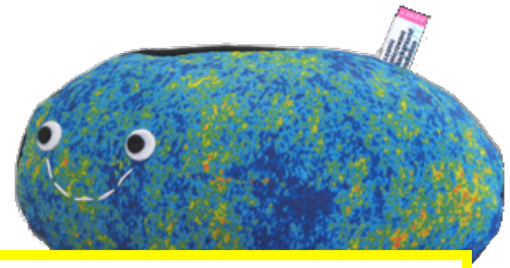

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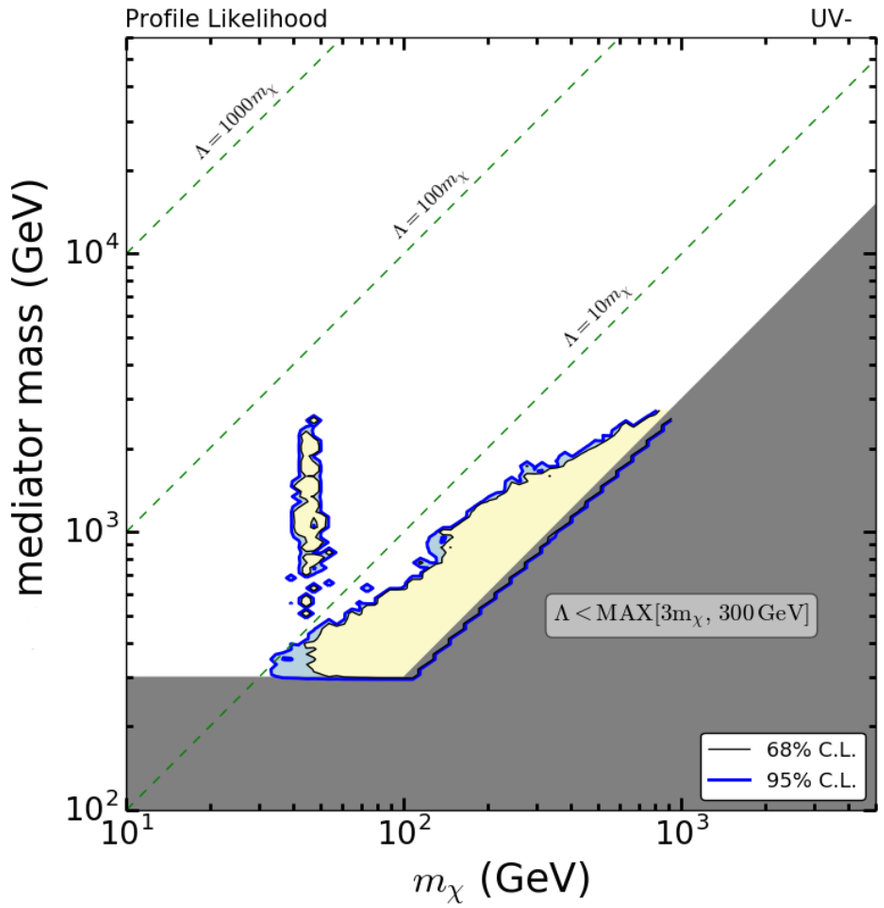

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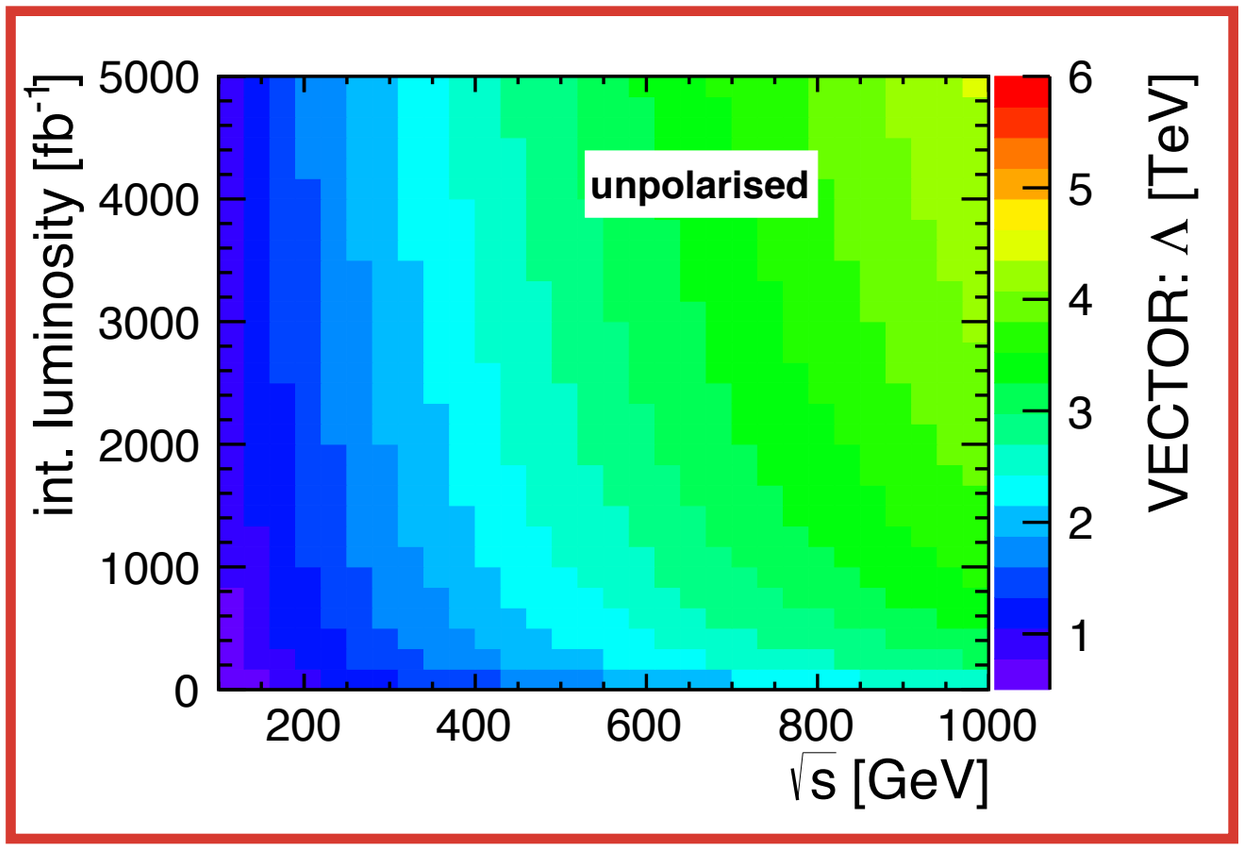

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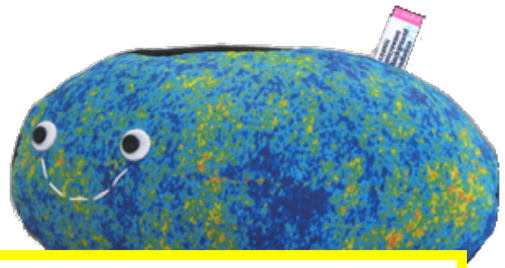

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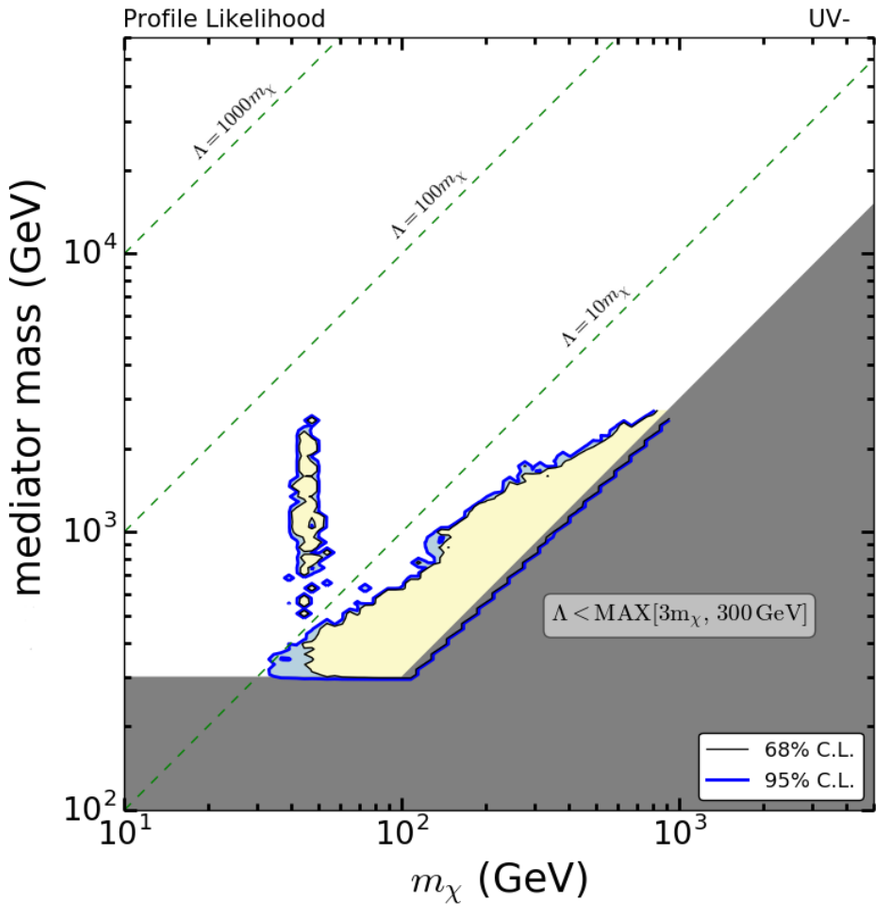

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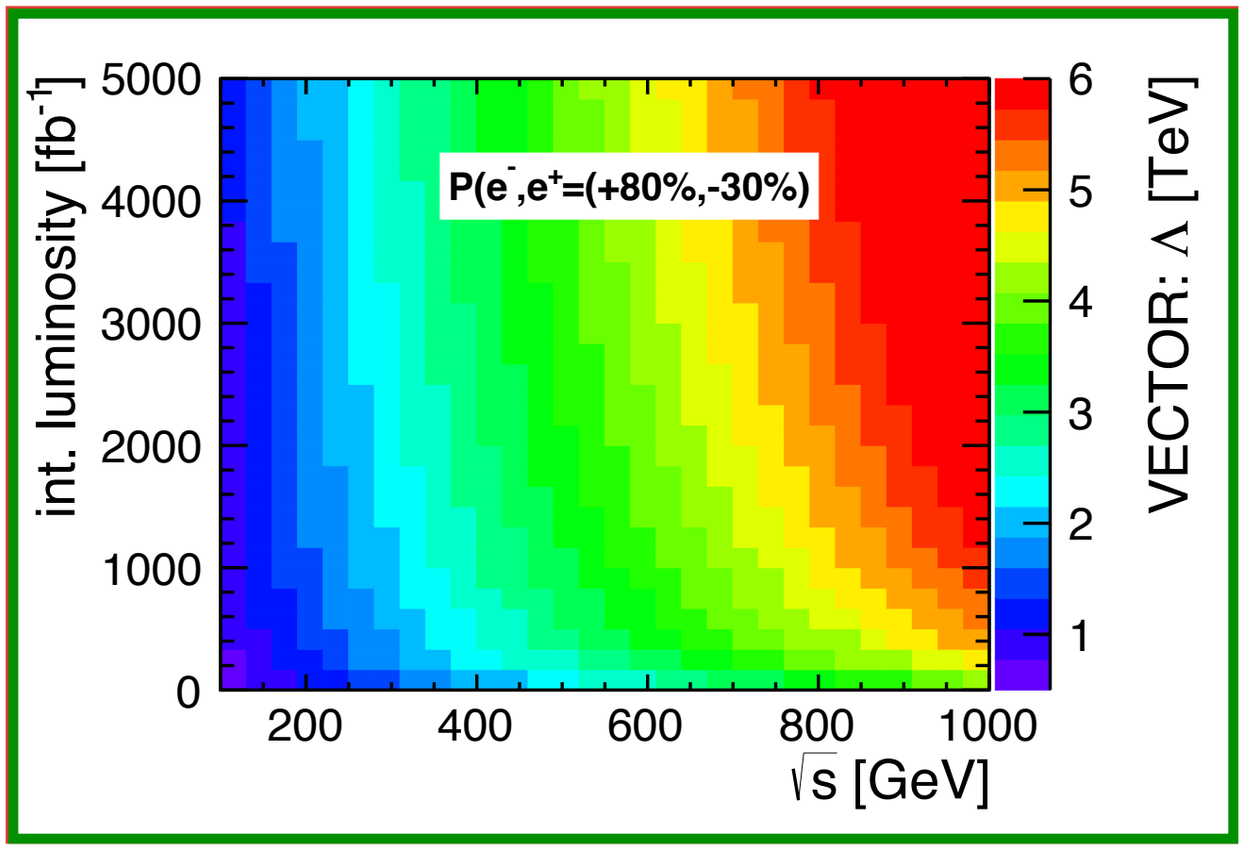

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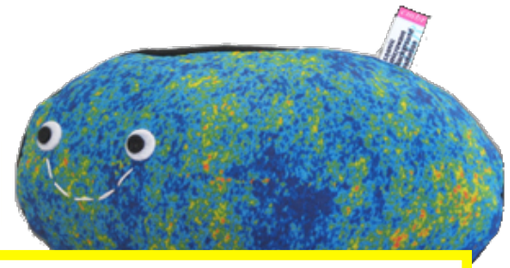

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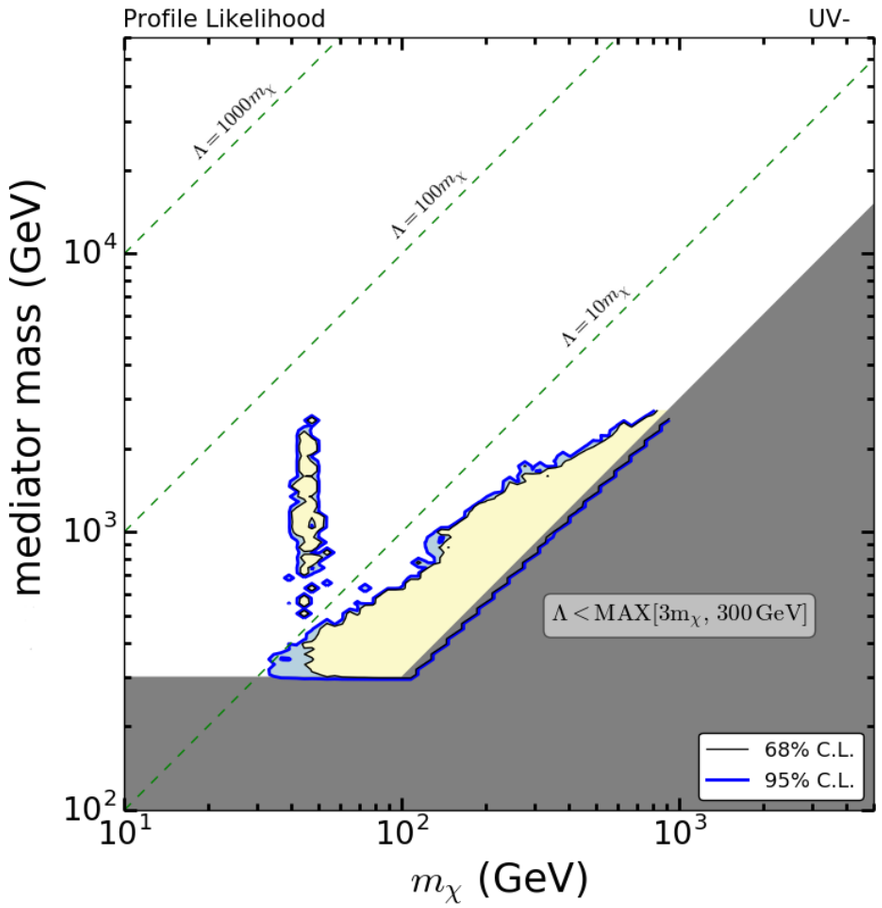

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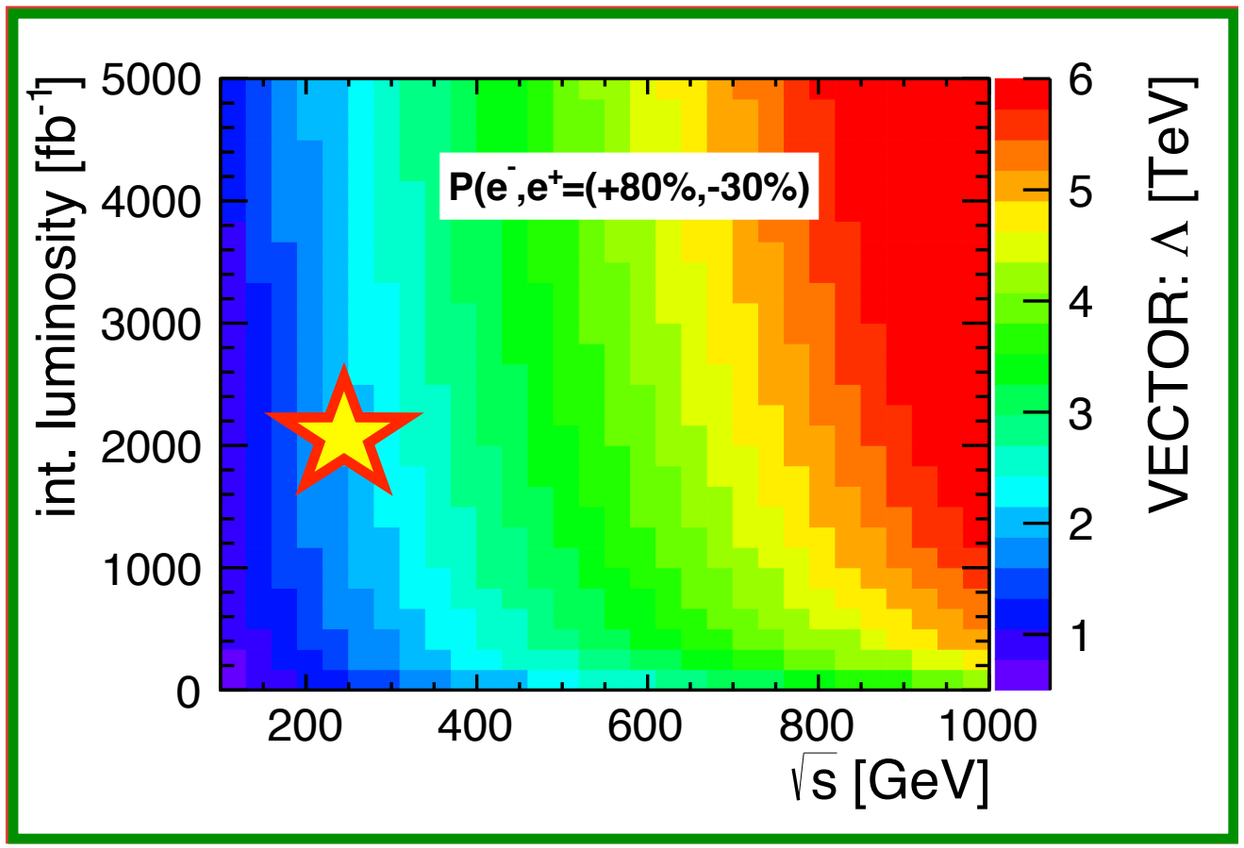

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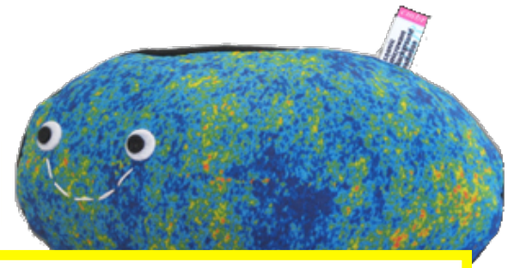

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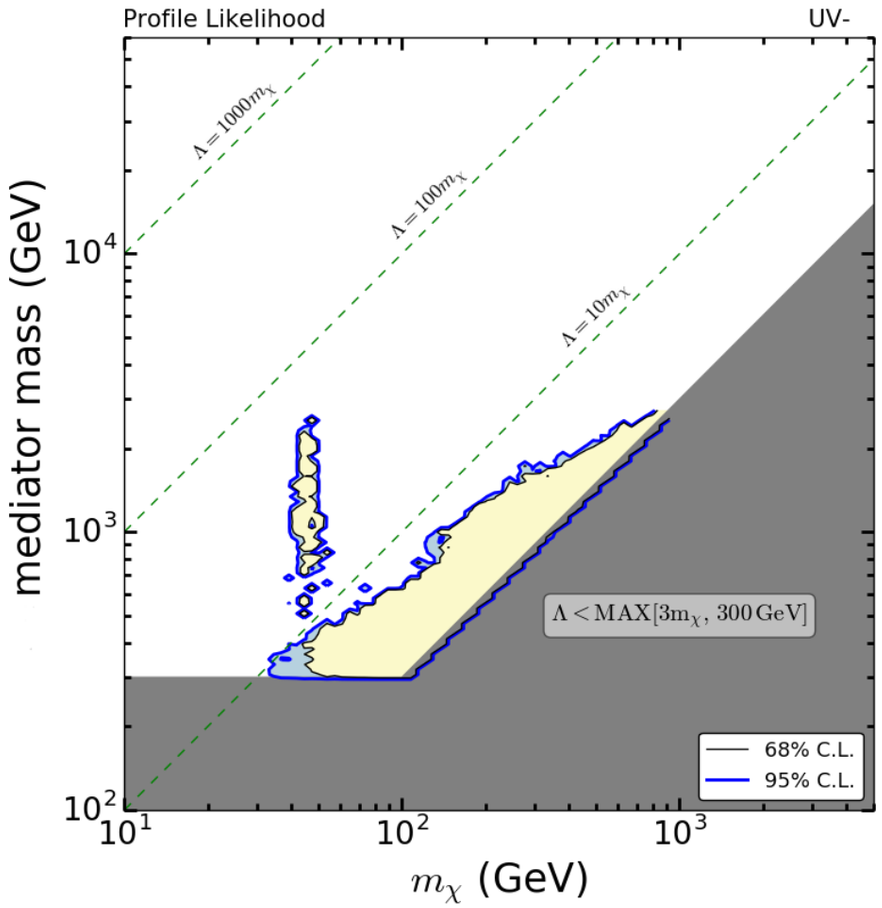

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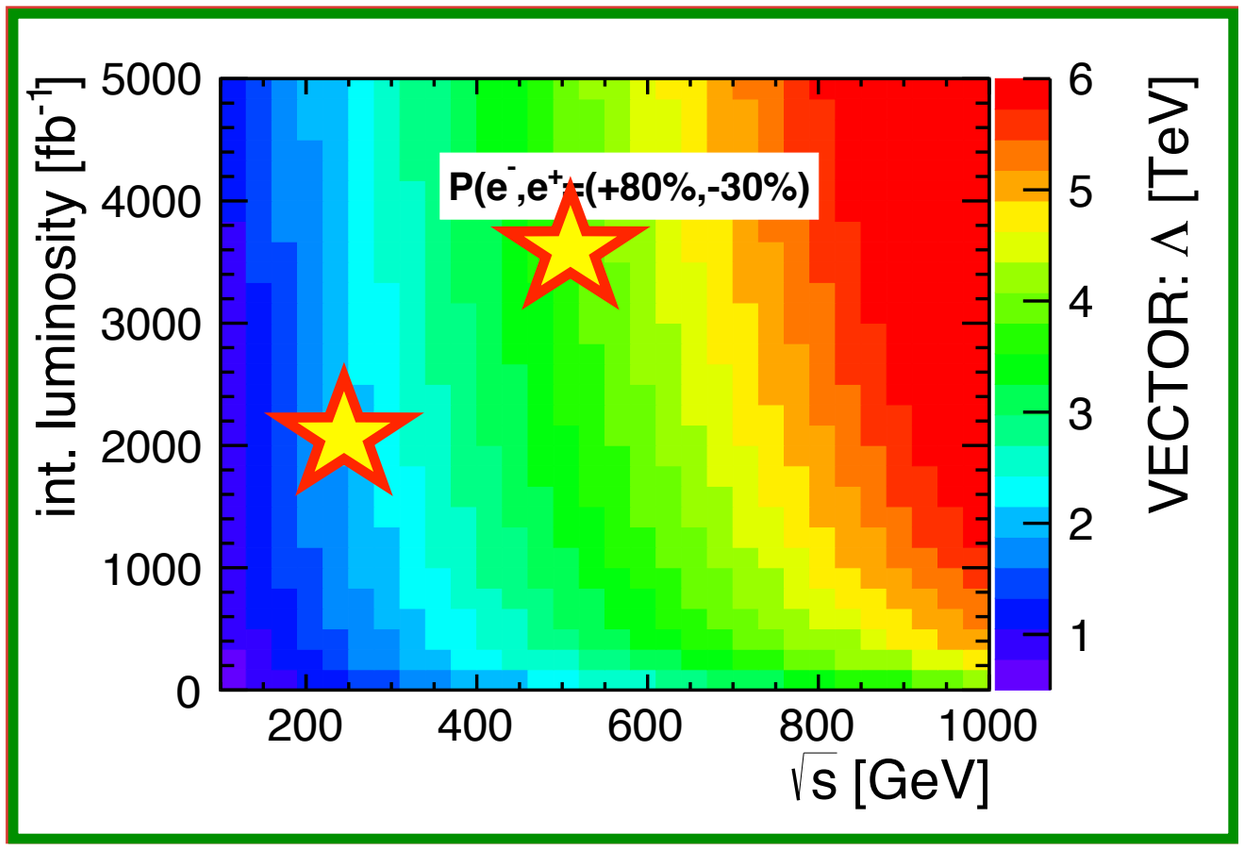
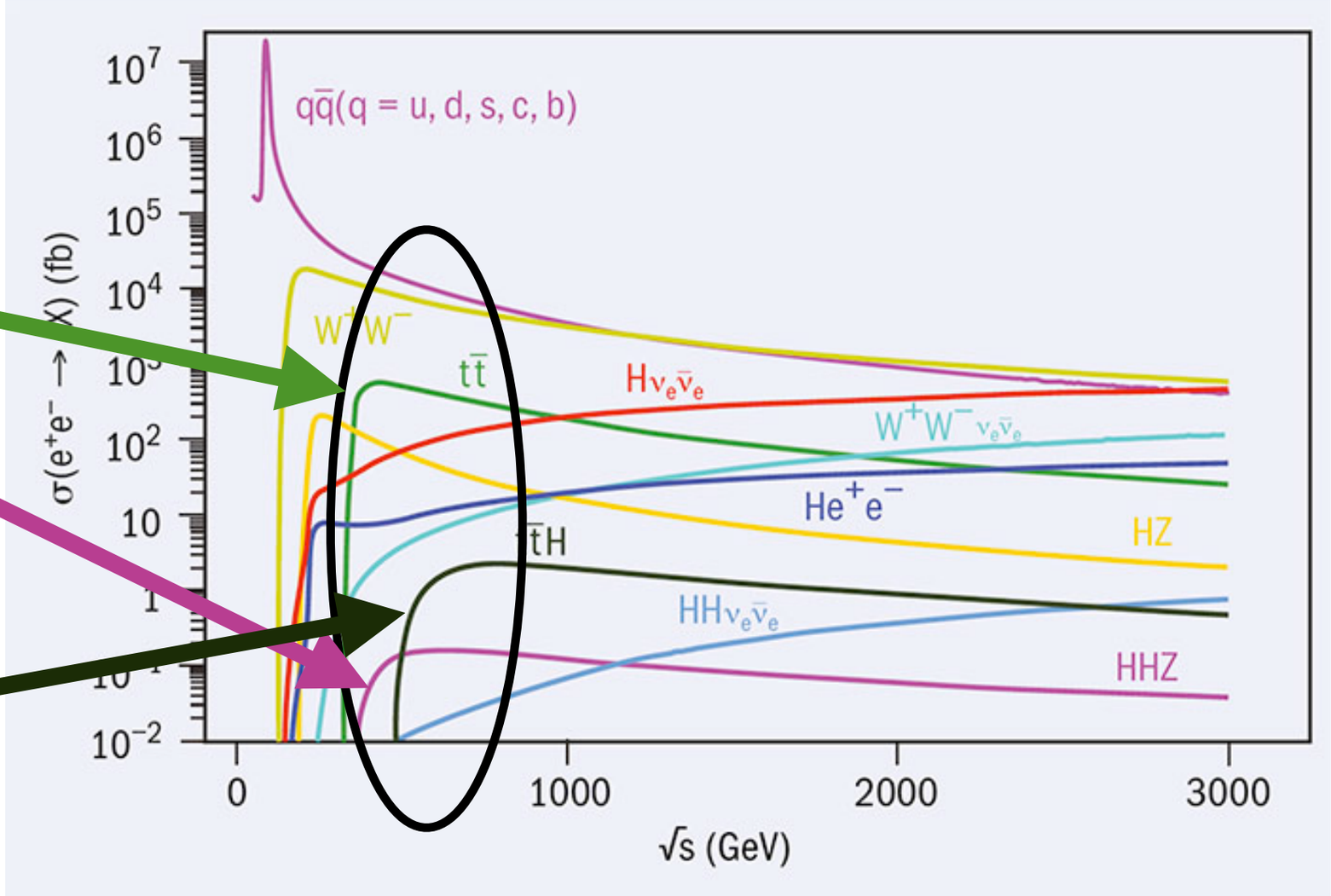


Why 250 GeV cannot be the end…

- **tt : ≳ 350 GeV**
- **ZHH : ≳ 450 GeV**
- **ttH : ≳ 500 GeV**



Conclusions

- The next generation of collider must address the big open questions of particle physics and expand our understanding of the universe
- **An e^+e^- Linear Collider at 250 GeV with polarised beams offers a formidable and physics program, reaching beyond the capabilities of HL-LHC:**
  - ★ via precision measurements of fermions, gauge bosons and the Higgs boson
  - ★ via direct searches complementary to hadron collider reach
- **There is currently a unique window of opportunity with the Japanese government evaluating the possibility to host the ILC**

=> The world-wide particle physics community should make it a priority to fund and construct it as quickly as possible

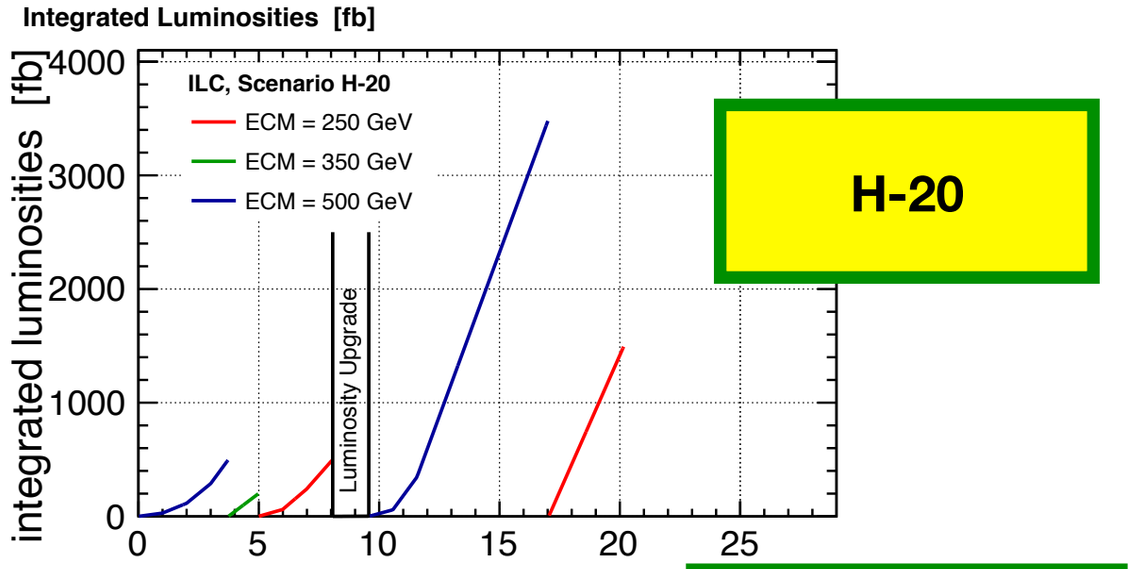
- … and 250 GeV cannot be the end:
  - ★ three additional important thresholds up to ~500 GeV known today
  - ★ **Linear Colliders are intrinsically energy upgradable!**

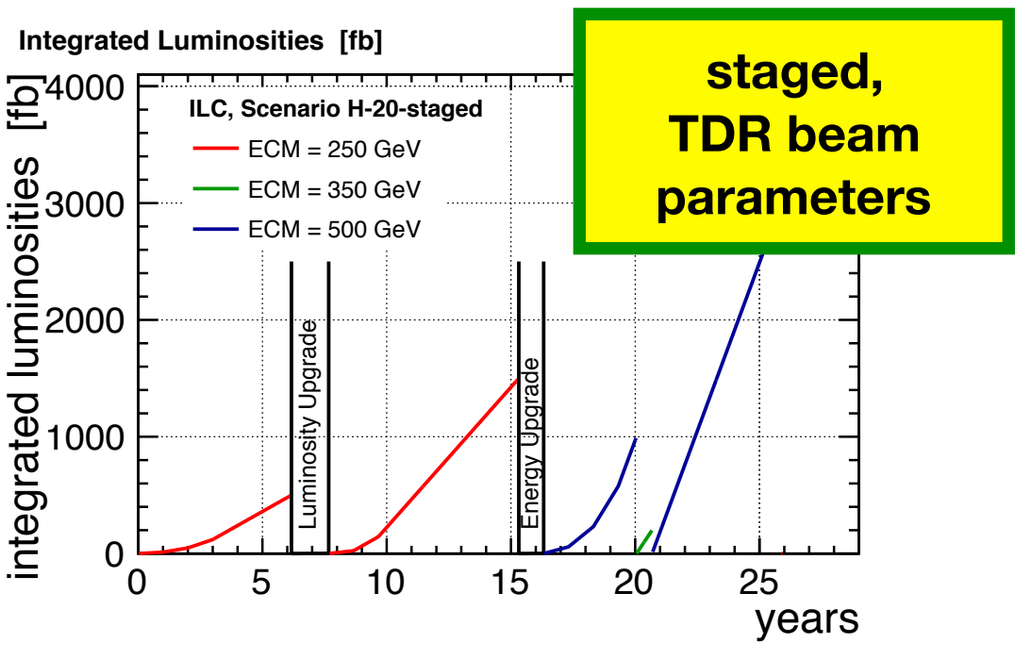
Backup

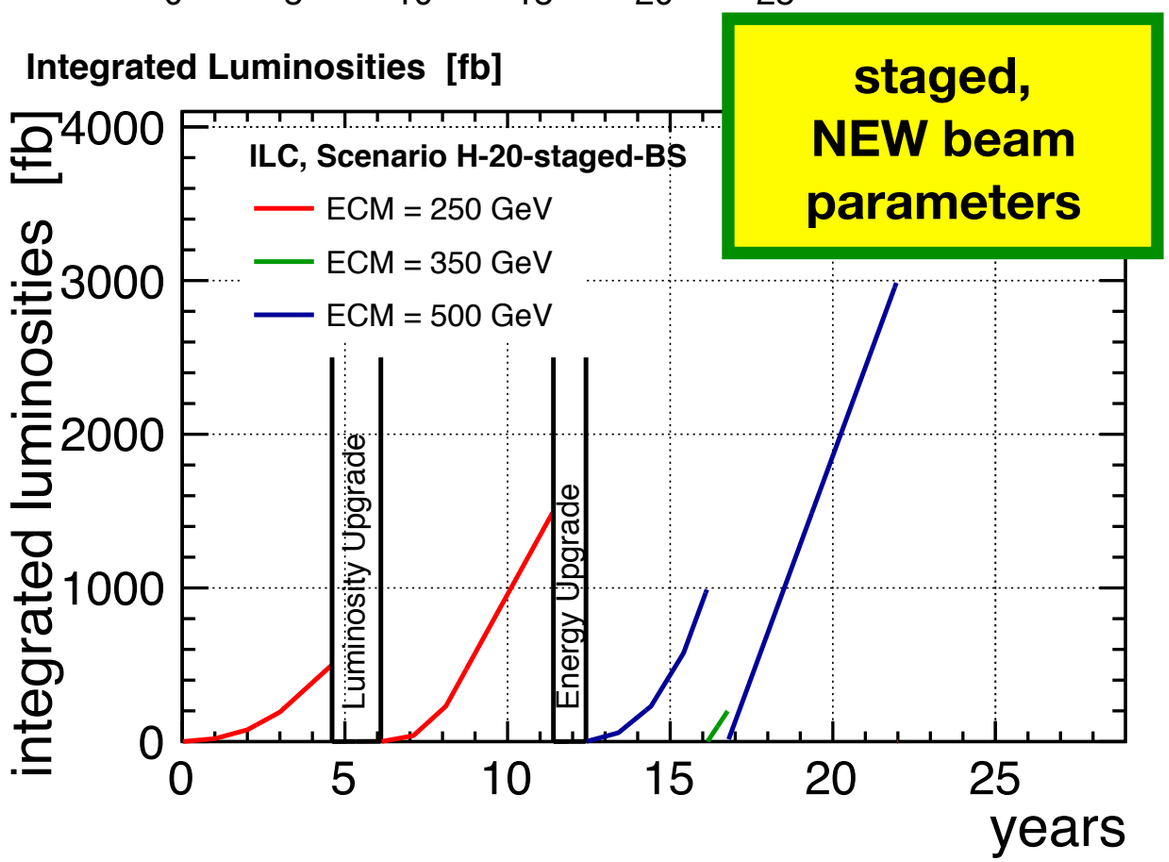
Looking beyond 250 GeV

A Linear Collider is *extendable* in length = energy !

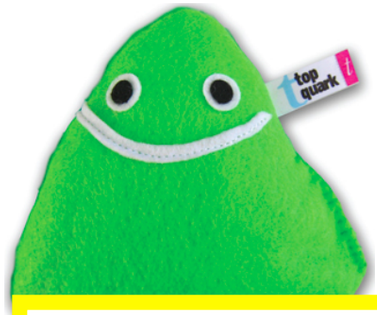
The *total* ILC run plan is still the full H-20 scenario



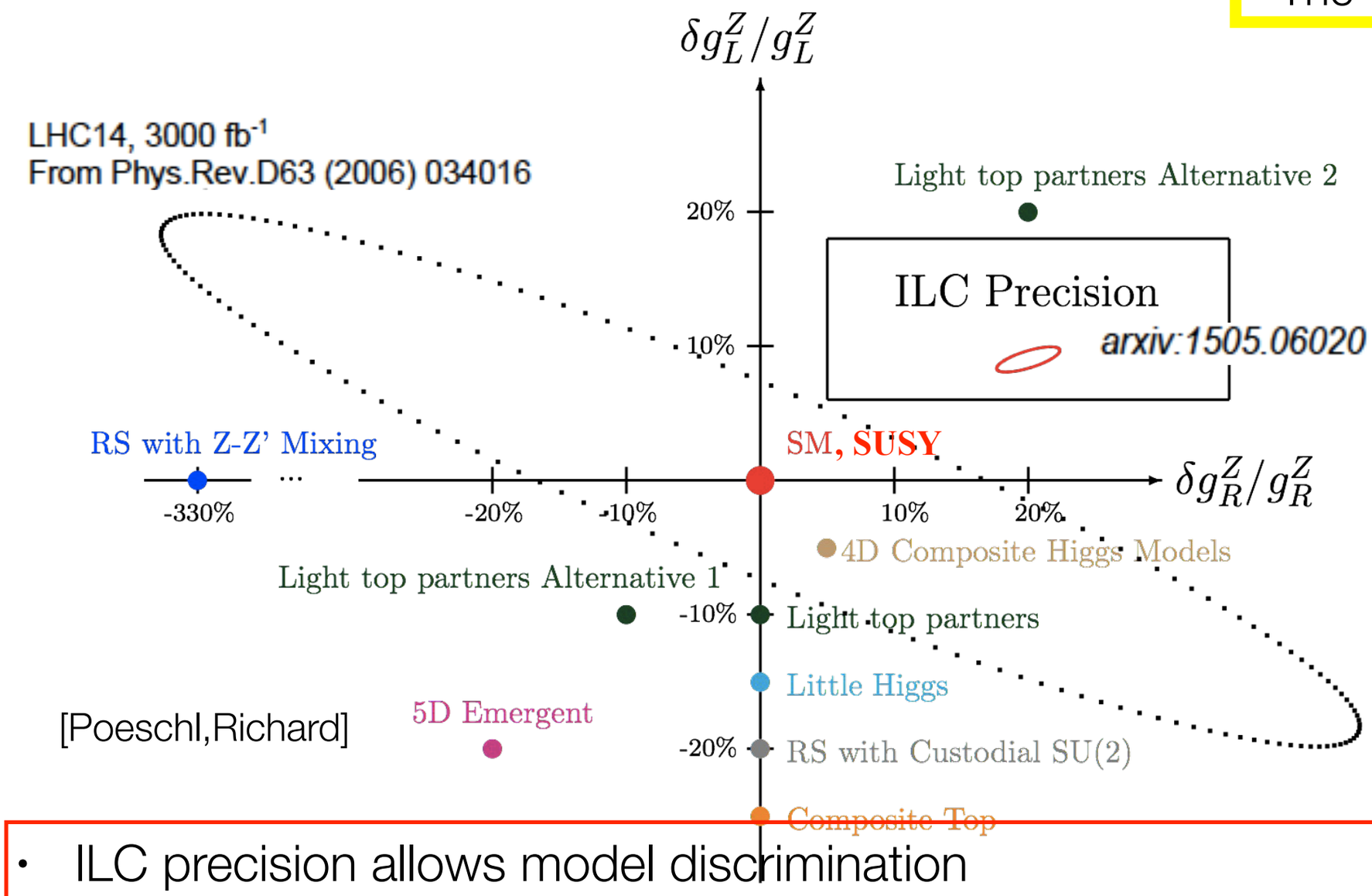




Top EW Couplings at 500 GeV



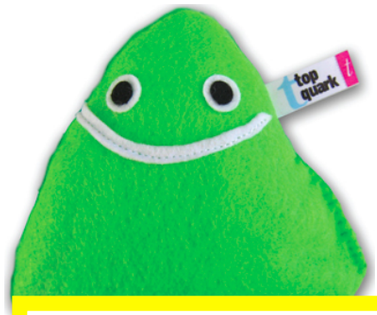
The Top Quark



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

- ILC precision allows model discrimination
- sensitivity in g^Z_L, g^Z_R plane complementary to LHC
- **Can probe new physics scales of ~20 TeV in typical scenarios** (… and up to 80 TeV for extreme scenarios)

Top EW Couplings at 500 GeV



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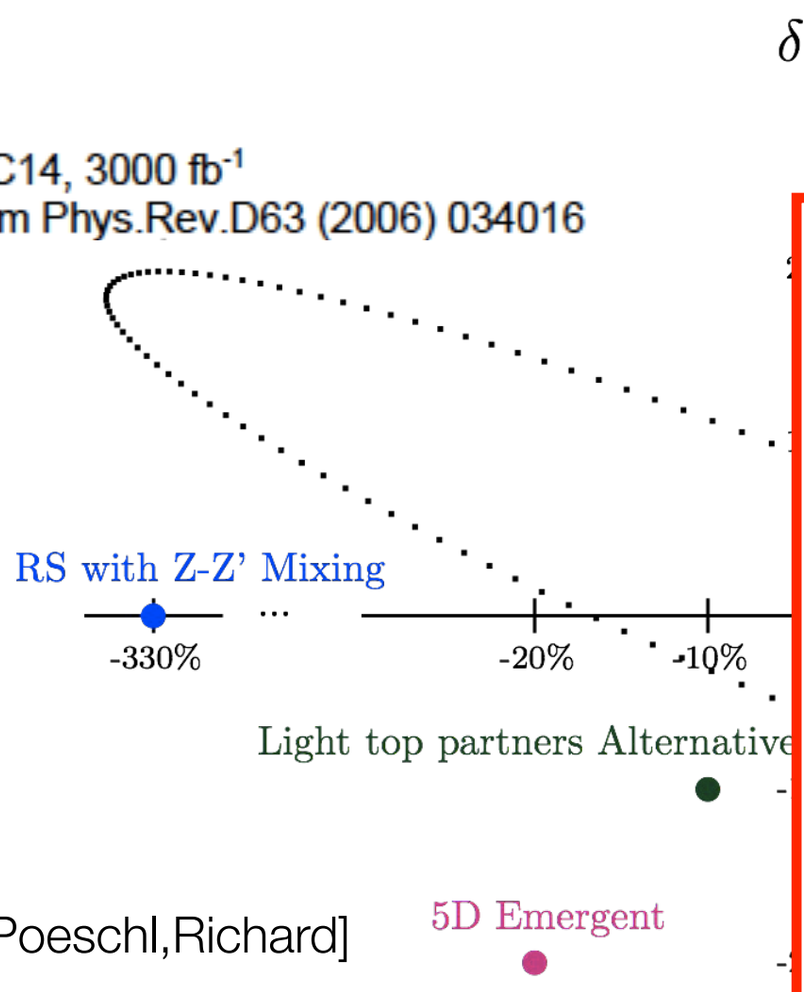
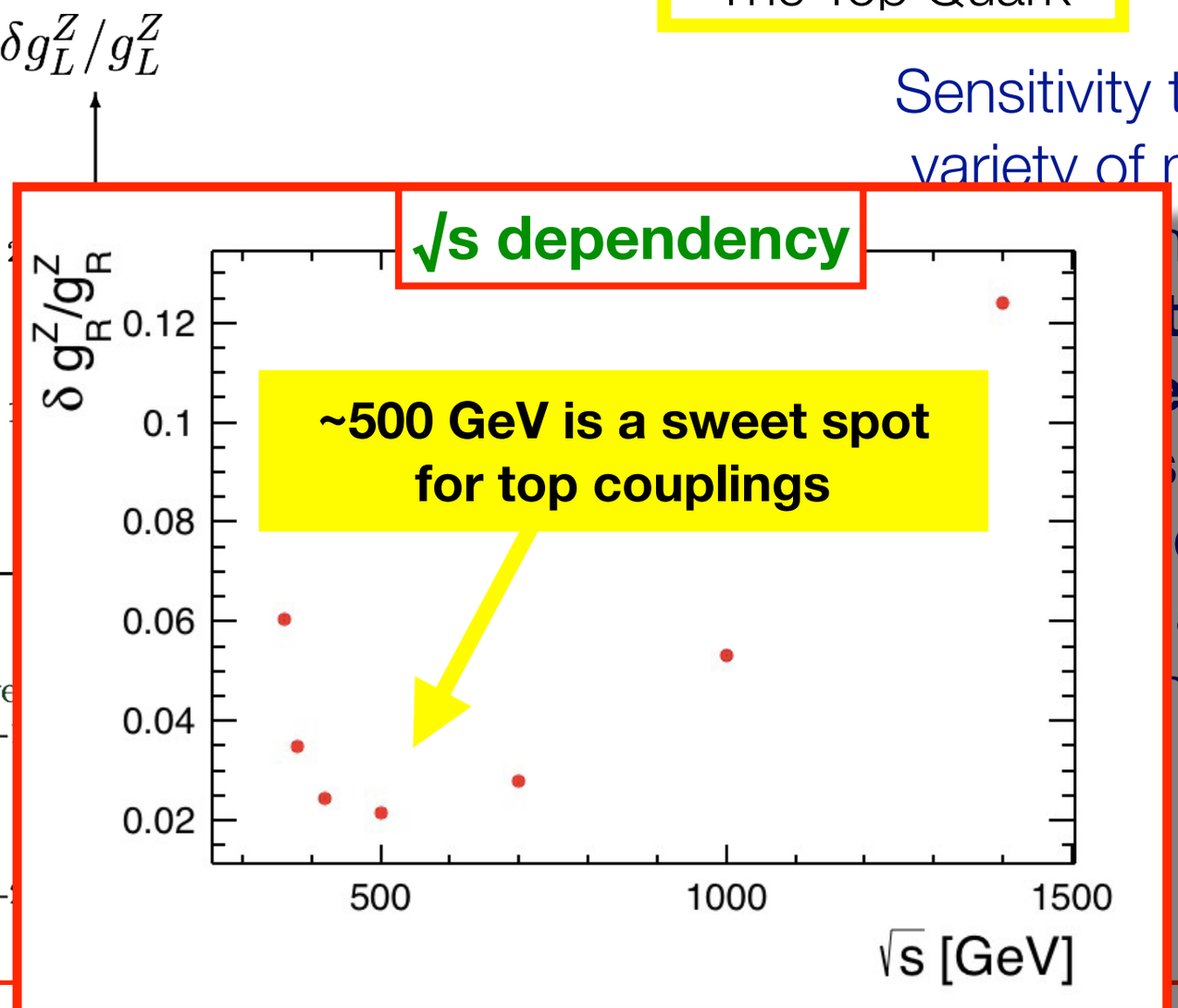
LHC14, 3000 fb^{-1}
From Phys.Rev.D63 (2006) 034016



[Poeschl,Richard]



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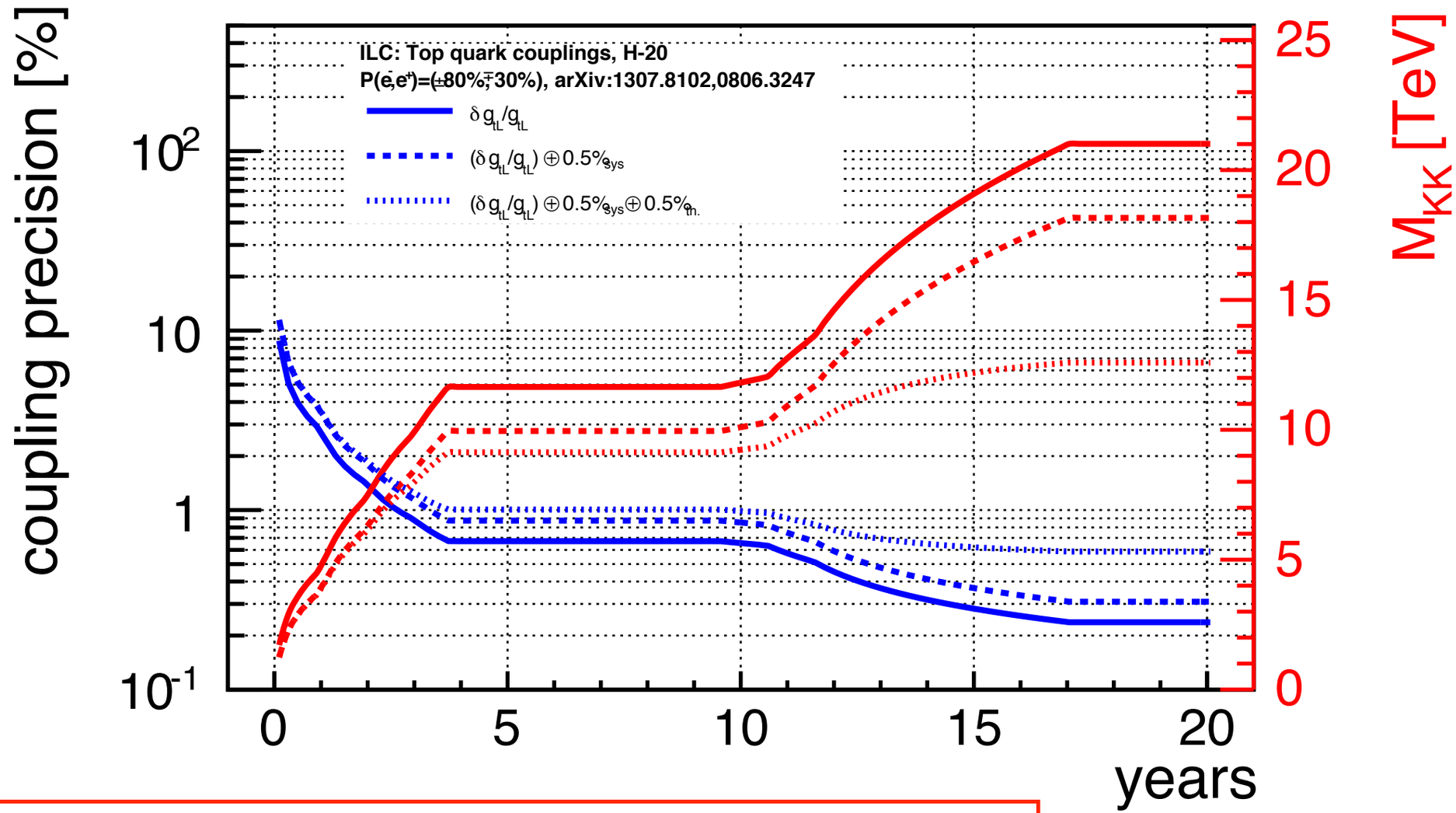
New Physics Reach of full ILC500 Program

….for typical BSM scenarios with **composite Higgs/Top and/or extra dimensions**
based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~20 TeV in typical scenarios
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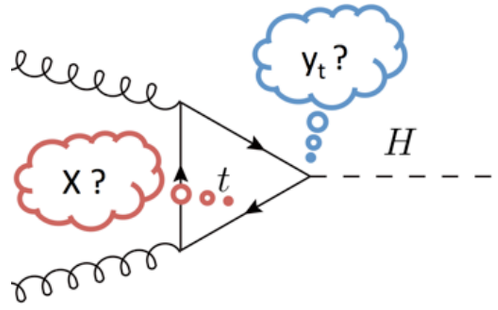
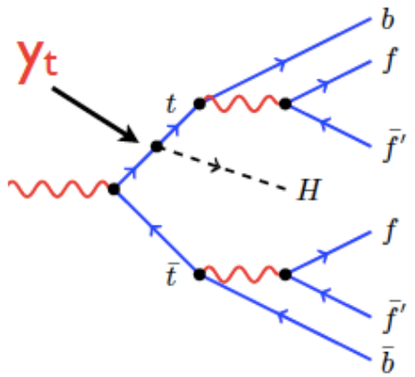
Direct Determination of the Top Yukawa Coupling

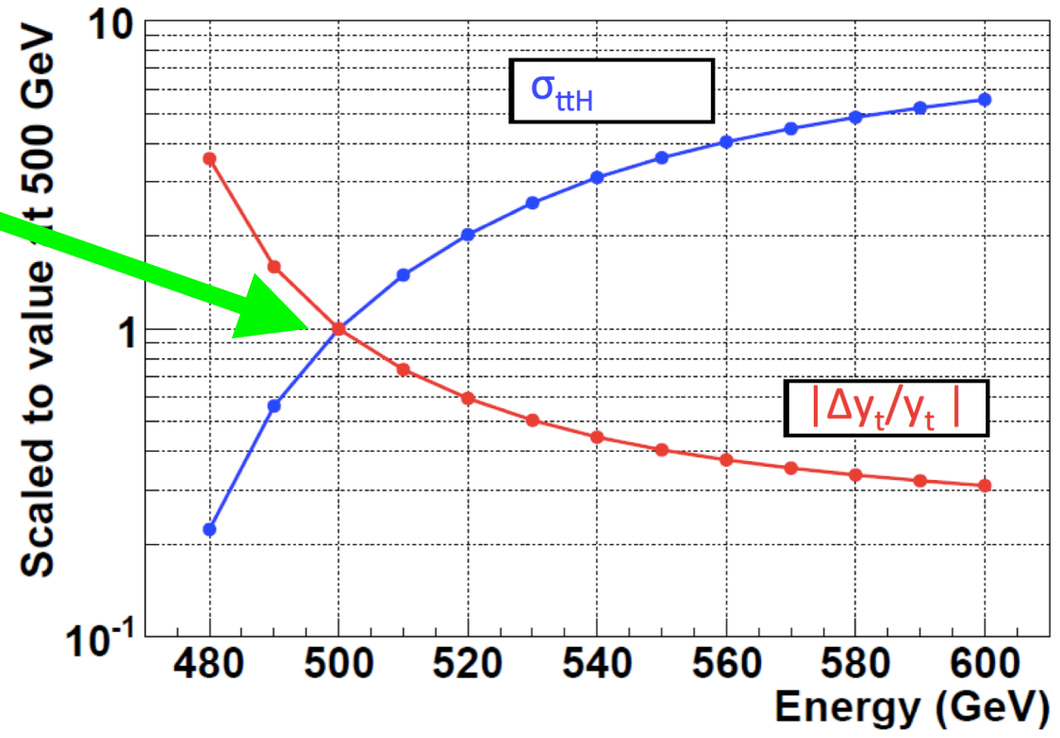
- **(HL-)LHC 14 TeV:**
  - SM σ(ttH) = 0.6 pb
  - "theory" studies indicate δy_t **~15% (~10%)** with 300fb^{-1} (3ab^{-1}) might be possible



arXiv:1310.8361



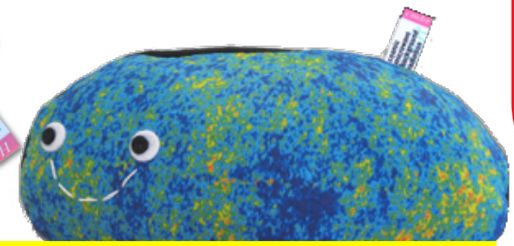
- **e^+e^-:**
  - **threshold at $\sqrt{s}$ = 475 GeV**
  - SM σ(ttH) = 0.45fb @ 500 GeV
    => ILC full running scenario:
    δy_t = 6.3%
  - could be **2.5% if $\sqrt{s}$ = 550 GeV**
  - **1 TeV, 4ab^{-1}: δy_t = 2%**
  - **CLIC 1.4 TeV, 1.5 ab^{-1}: δy_t = 4.2%**
    - no improvement at 3 TeV (σ drops)



Eur.Phys.J. C77 (2017) no.7, 475

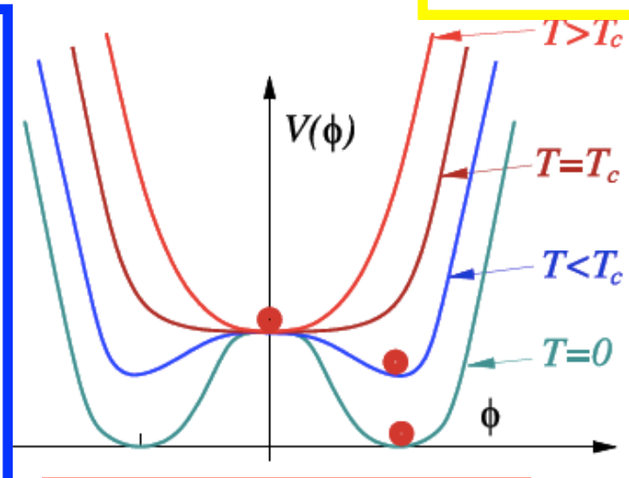
The Higgs self-coupling

The Higgs Boson …

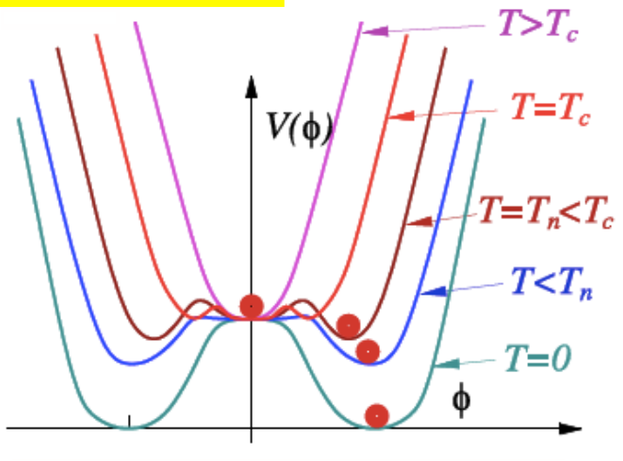


…and the universe

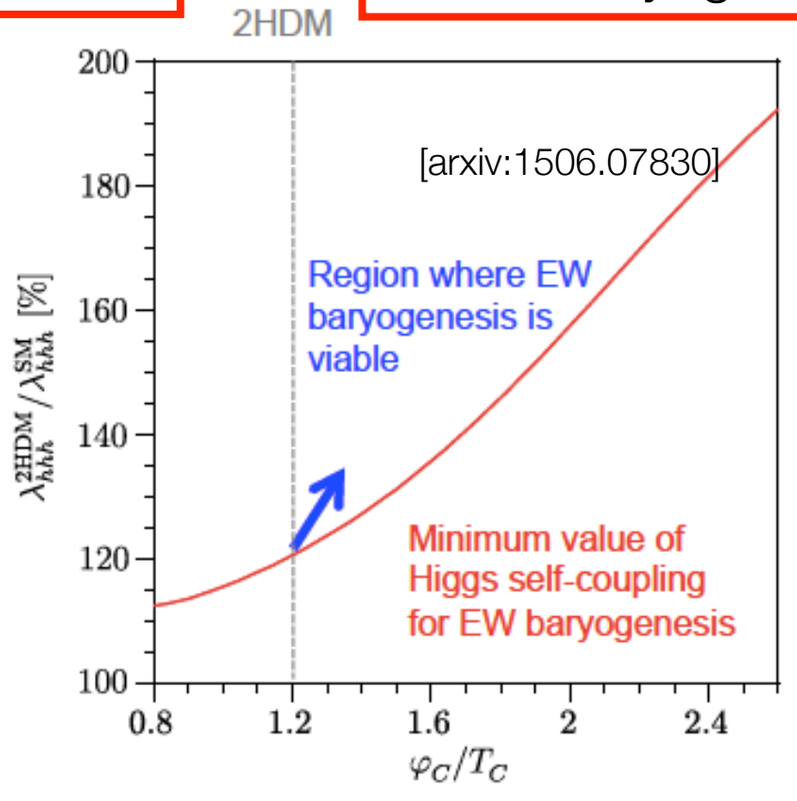
- determines shape and evolution of Higgs potential => cosmology!
- many BSM models influence λ, deviations from SM value can be **large**! E.g.:
  - up to O(100%) in general 2HDMs, even if other couplings are SM-like
    [c.f. e.g. Phys.Lett. B558 (2003) 157-164]
- electroweak baryogenesis requires $\lambda > 1.2\ \lambda_{SM}$



2nd order, SM with M_H = 125 GeV



1st order, required for EW baryogenesis



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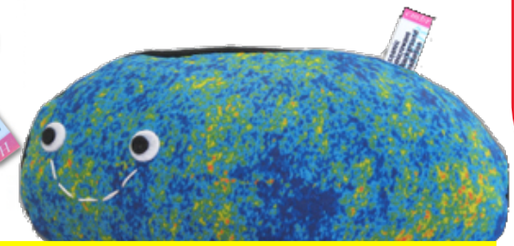

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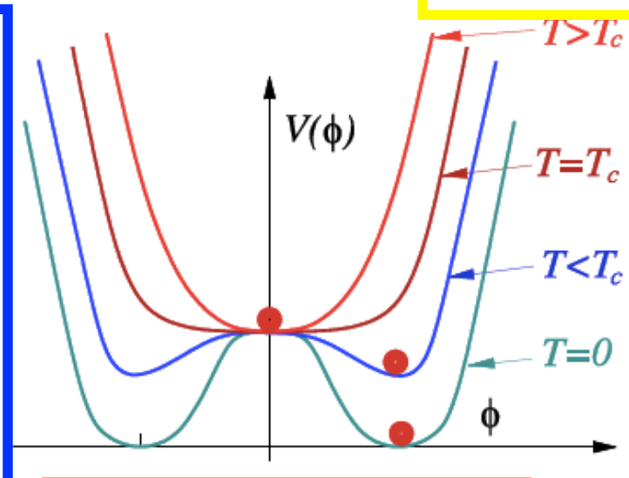
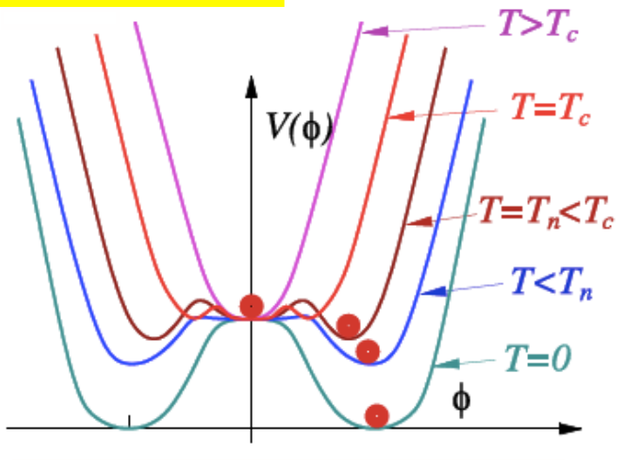
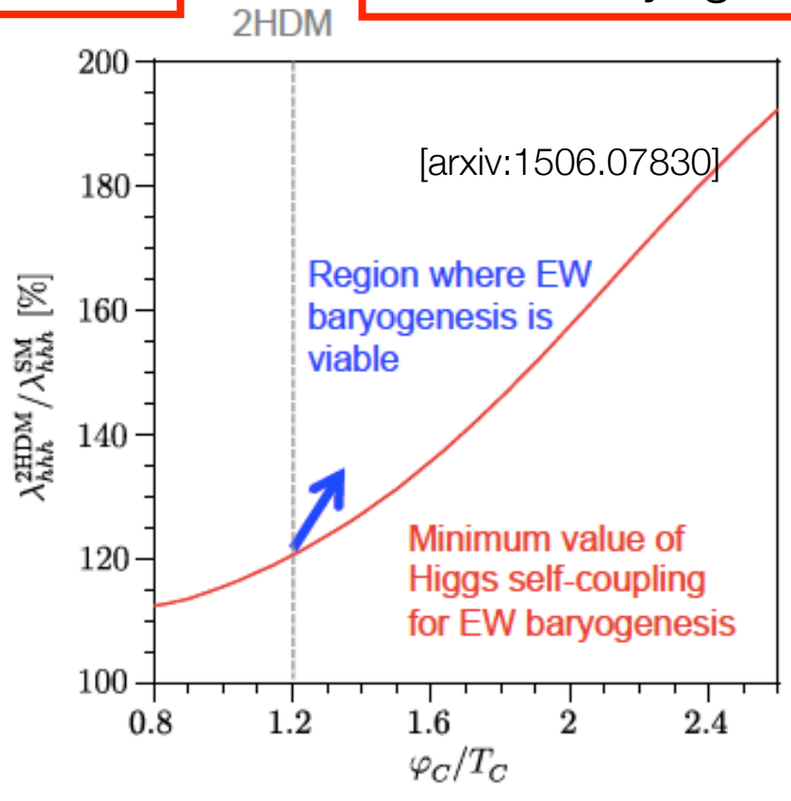


2nd order, SM with M_H = 125 GeV



1st order, required for EW baryogenesis

- the experimental key: **Higgs pair production**!
  1. establish Higgs pair production at >5σ level
  2. extract λ from cross section
- challenging at *any* collider!
- always deal with interfering diagrams with and without λ



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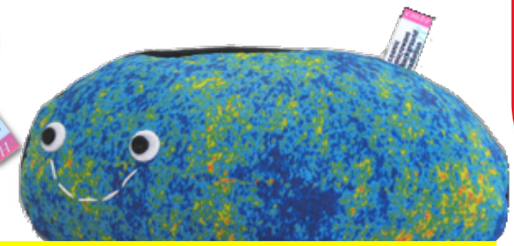

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    [c.f. e.g. Phys.Lett. B558 (2003) 157-164]
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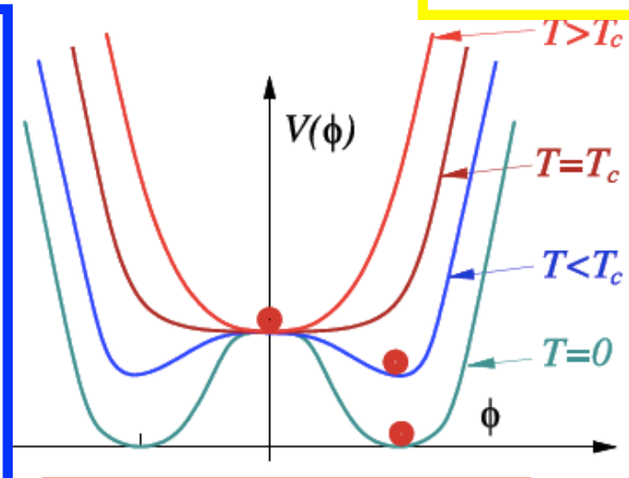
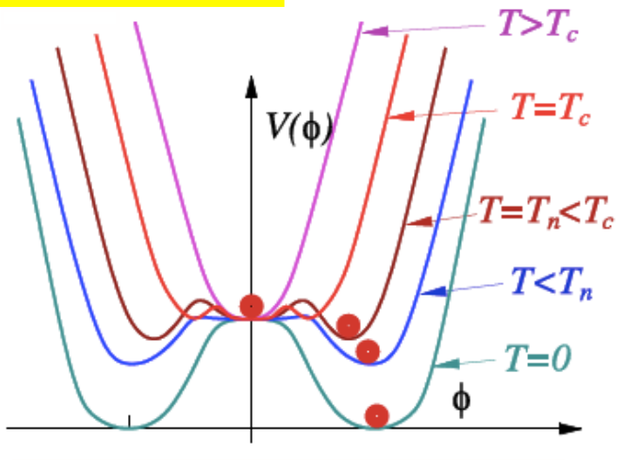
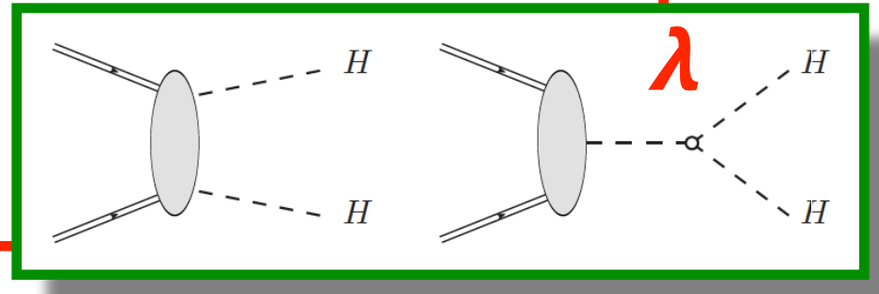


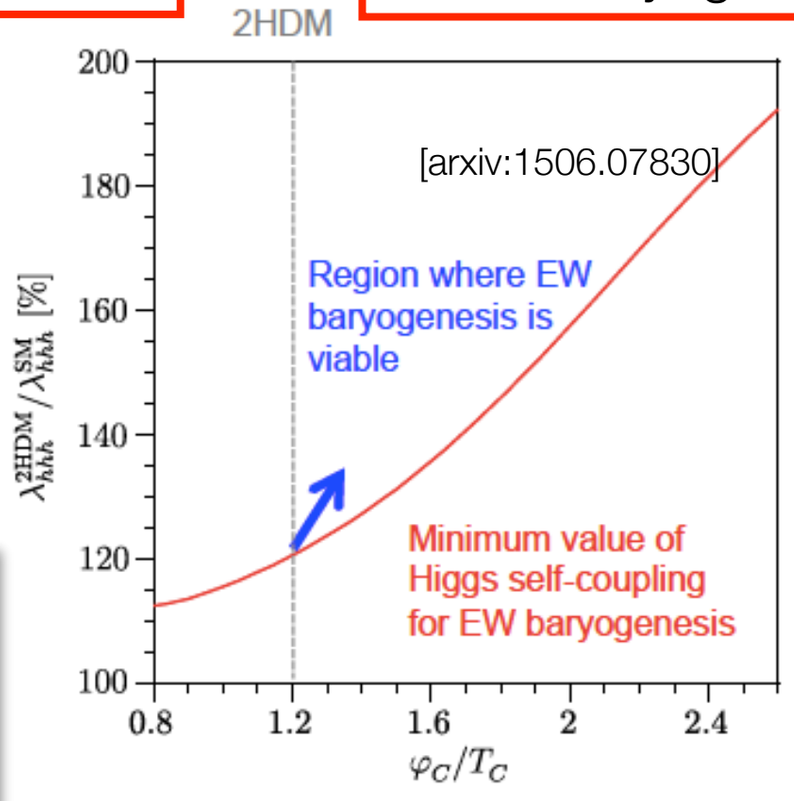
2nd order, SM with M_H = 125 GeV



1st order, required for EW baryogenesis

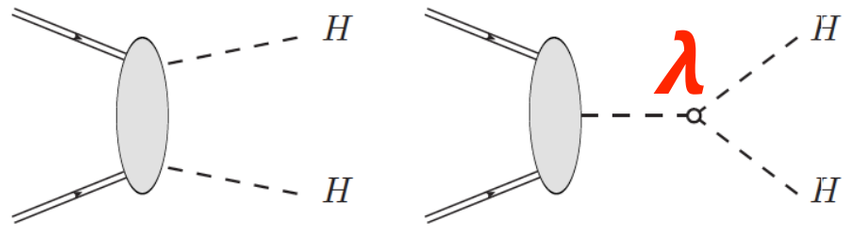
- the experimental key: **Higgs pair production**!
  1. establish Higgs pair production at >5σ level
  2. extract λ from cross section
- challenging at *any* collider!
- always deal with interfering diagrams with and without λ





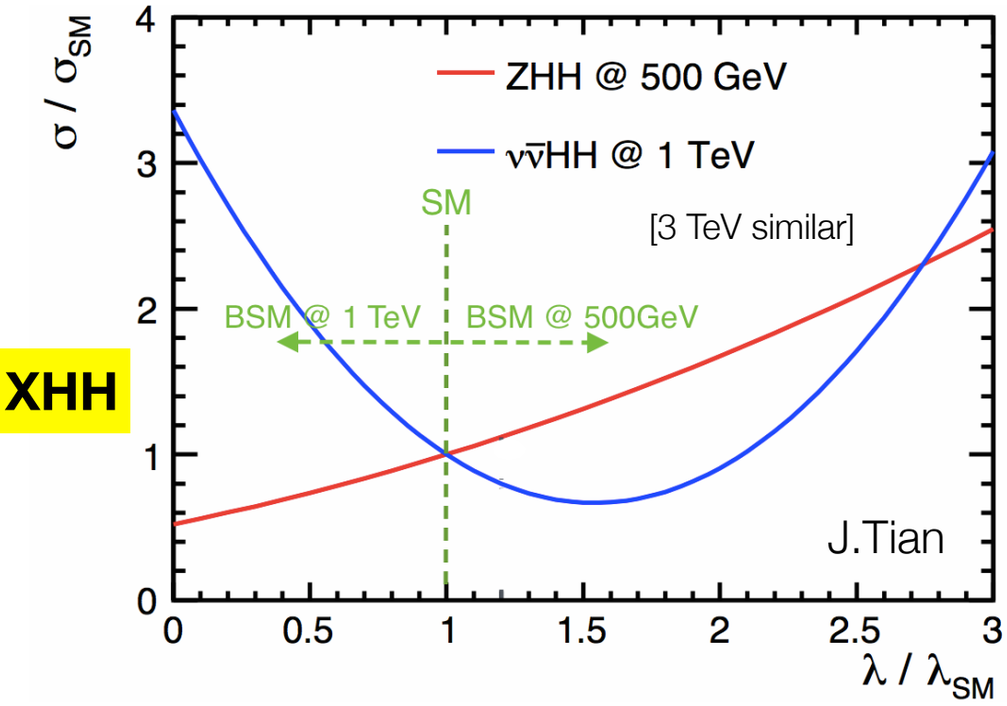
Double Higgs Production

- always multiple diagrams contributing - with and without Higgs self-coupling λ
- interference induces *non-trivial relations* between cross sections and λ



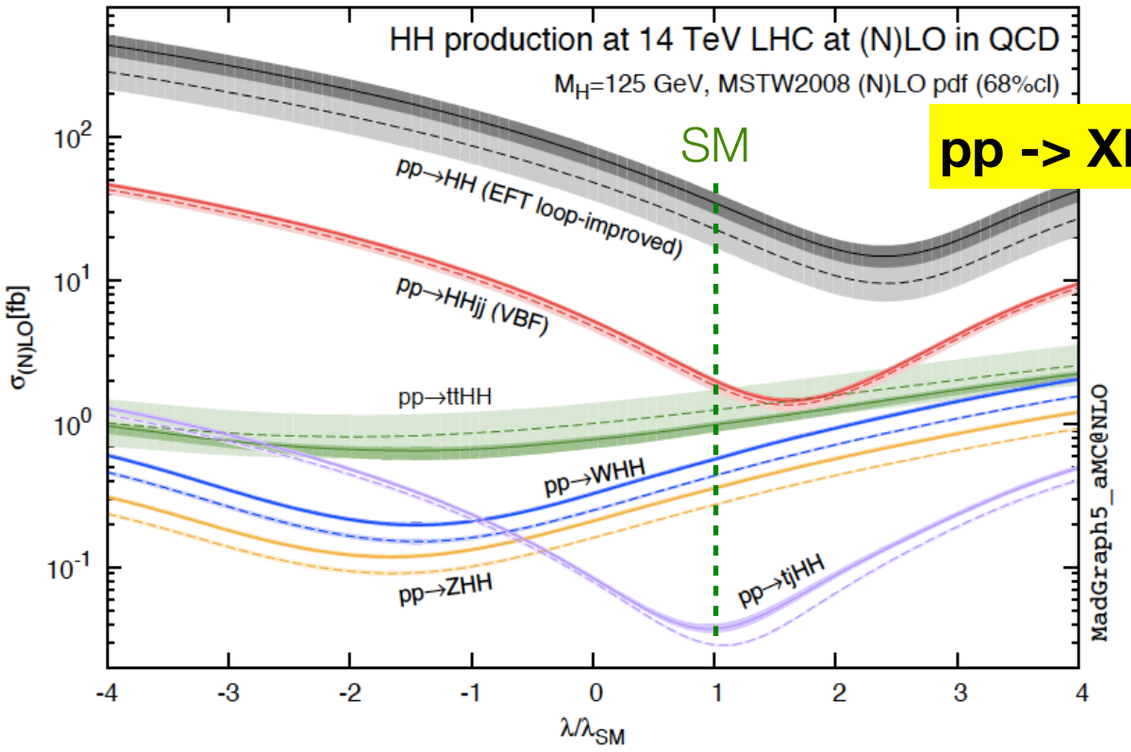
- VHH has opposite behaviour to VBF /ggF=> important independent information!
- largest sensitivity to λ near threshold => restriction to high energy / high mass does not help
- **unique for e^+e^- @ 500 GeV: access to VHH**

e^+e^- -> XHH



[arxiv:1401.7340]

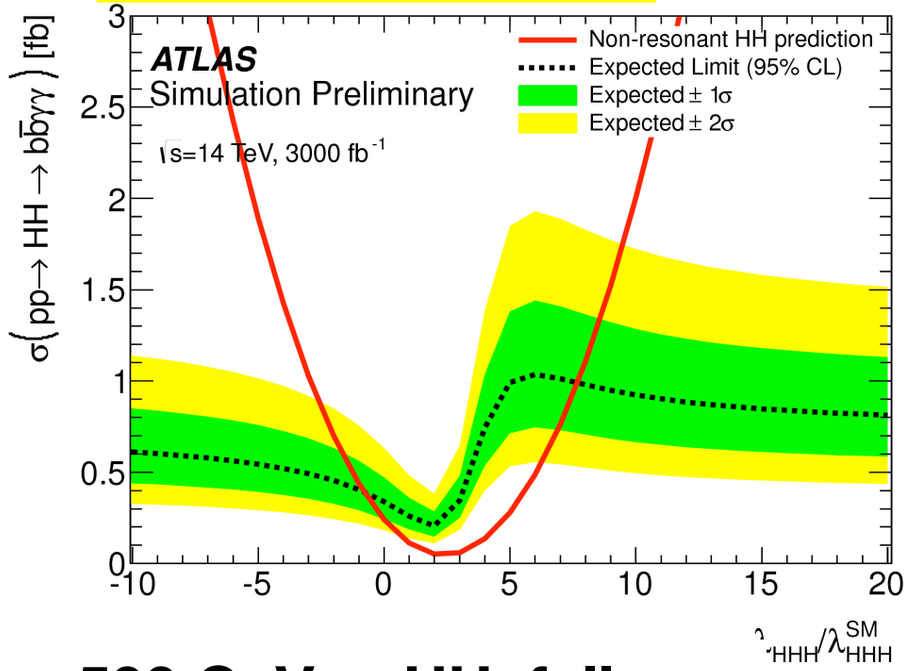
pp -> XHH



Measurement Prospects

recent update: ATL-PHYS-PUB-2017-001

- **HL-LHC, generator-level + smearing:**
  1. Observation of HH < 3σ :(
  2. exclude extreme values of λ/λ_{SM} ≲0 and ≳ 8 assuming that all other couplings = SM



Dissertation C.Dürig, Uni Hamburg, 2016

- **e^+e^- at 500 GeV, ZHH, full simulation:**
  1. Observation of HH with ~8σ ✔
  2. extract $\lambda|_{SM}$ with 27% uncertainty
  3. recent demonstration that parametric uncertainties from other couplings well under control with full ILC Higgs program

arXiv:1708.09079

- **e^+e^- at > 500 GeV, vvHH, full simulation:**
  - 1 TeV, 4ab^{-1}: $\delta\lambda/\lambda\,|_{SM}$ = 10%
  - 1.4 TeV, 1.5ab^{-1}: $\delta\lambda/\lambda\,|_{SM}$ = 40%
  - + 3 TeV, 3ab^{-1}: $\delta\lambda/\lambda\,|_{SM}$ = 16%
  - upcoming improvement: exploit differential distributions at 3 TeV: expect ~ 10%

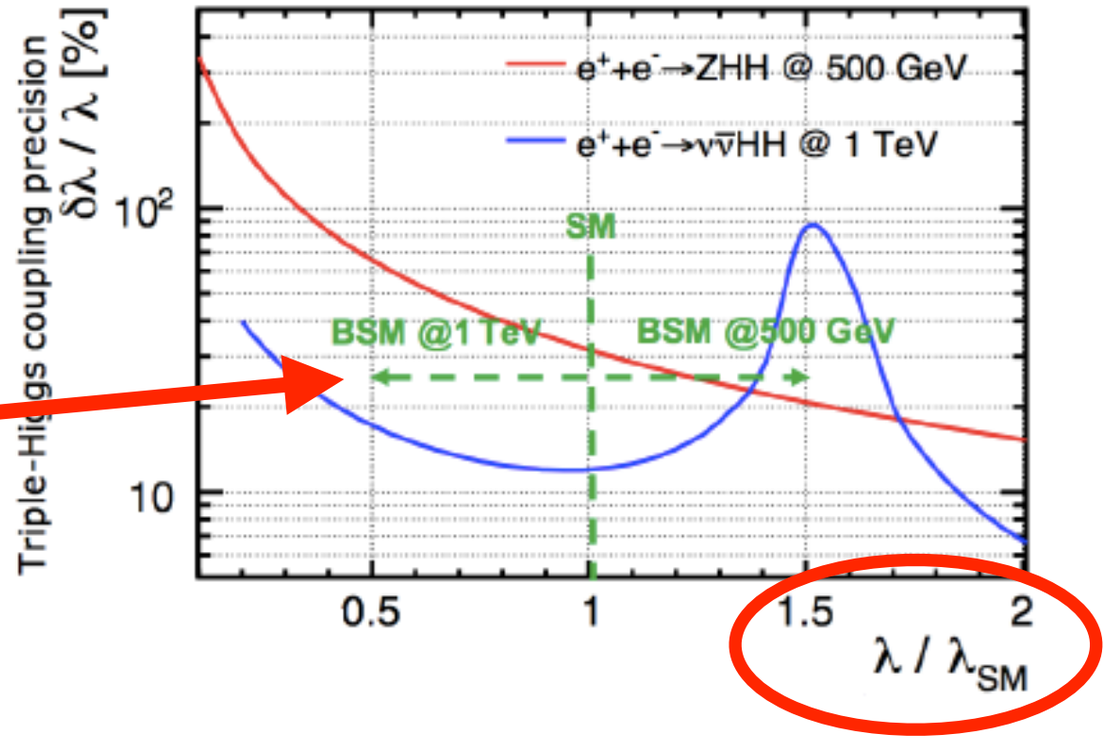
Eur.Phys.J. C77 (2017) no.7, 475

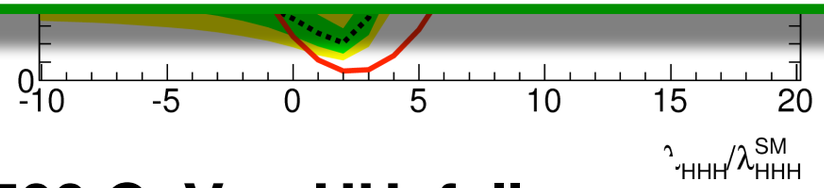
In any case: e^+e^- offers significant added value w.r.t. HL-LHC

Important: achievable precision depends strongly on actual value of λ!

=> BSM can change the picture

=> with combination of ZHH and vvHH we're always on the safe side!





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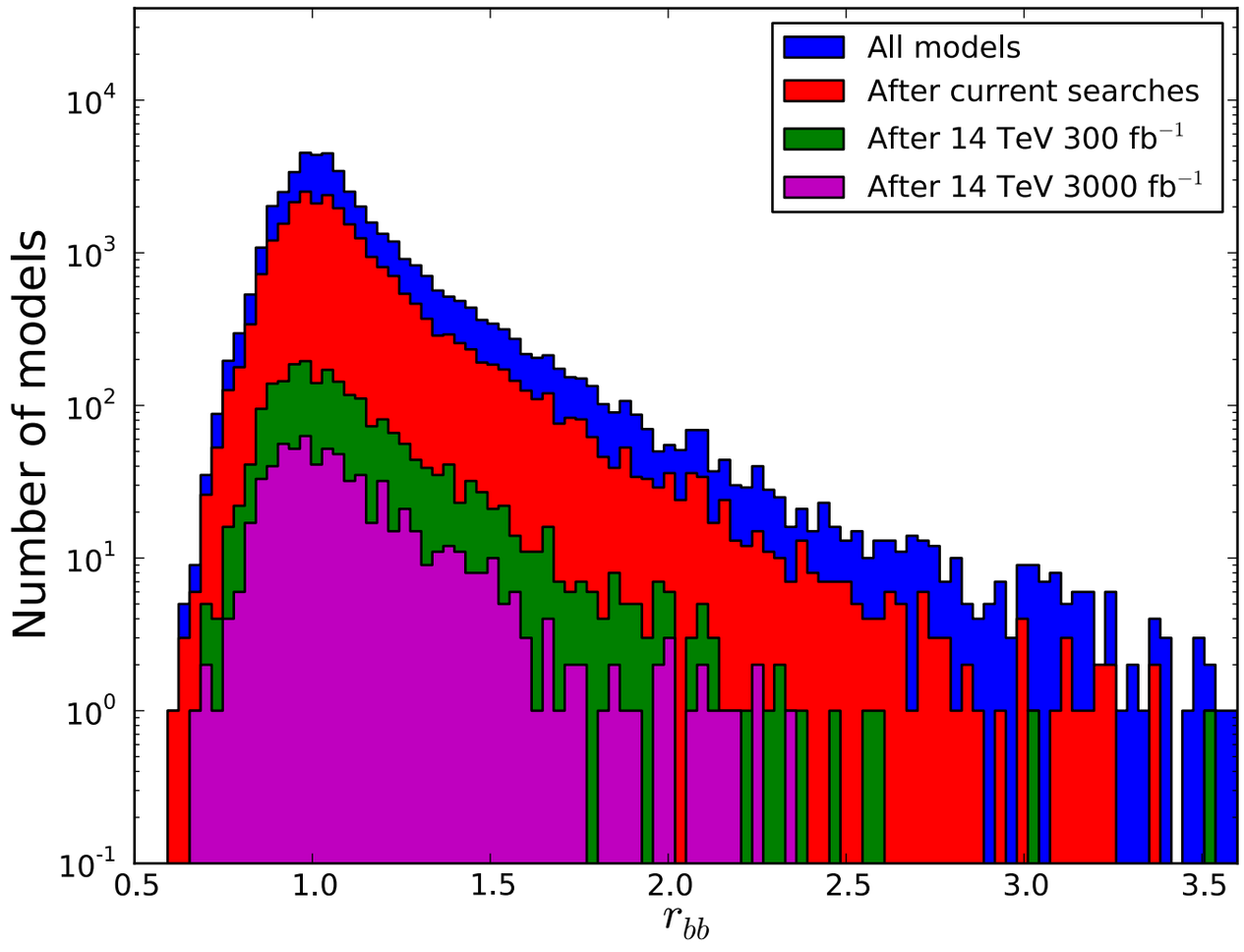
A closer look at SUSY: pMSSM scan

- scan over 250 000 pMSSM points

Phys. Rev. D 90, 095017 (2014)

- 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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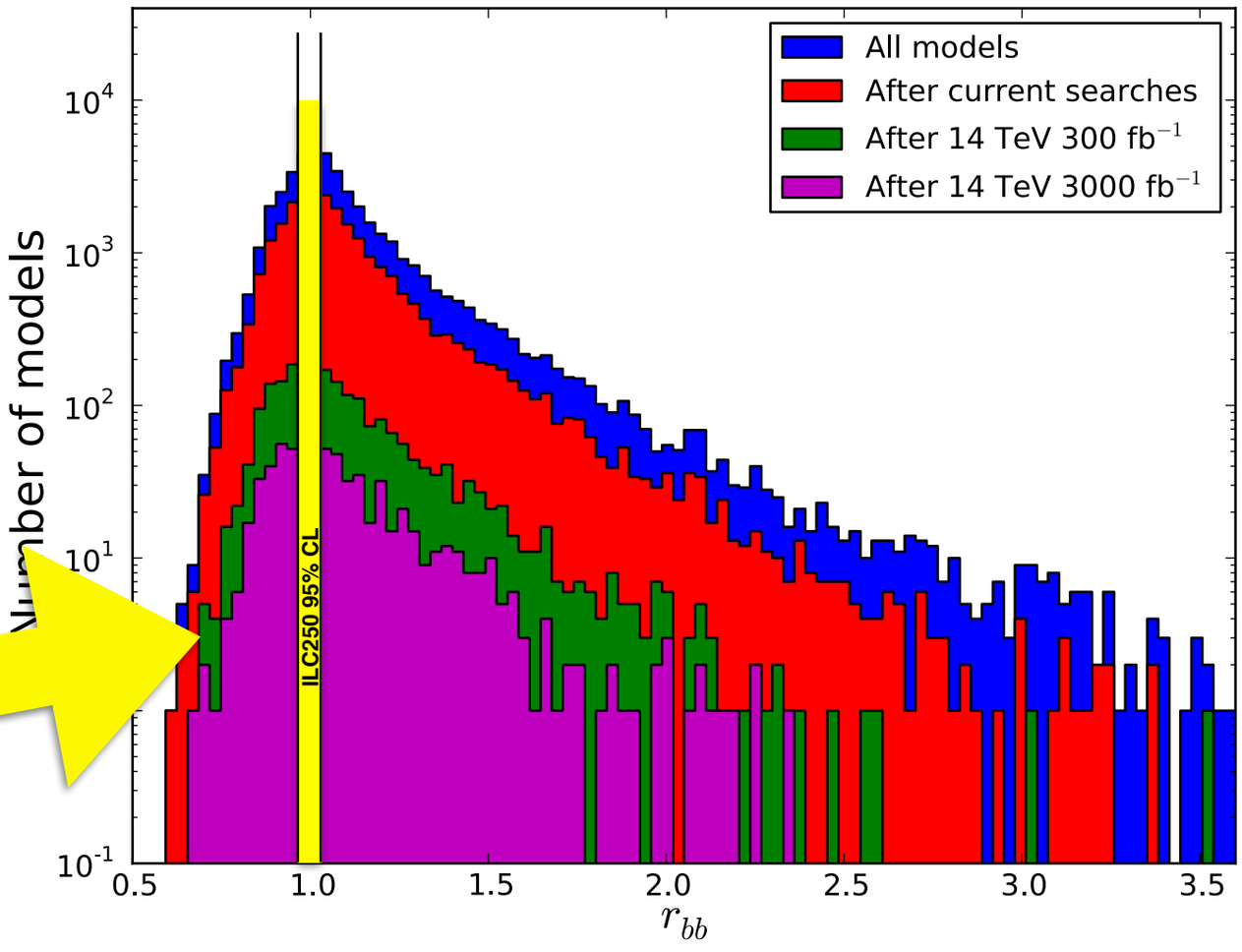

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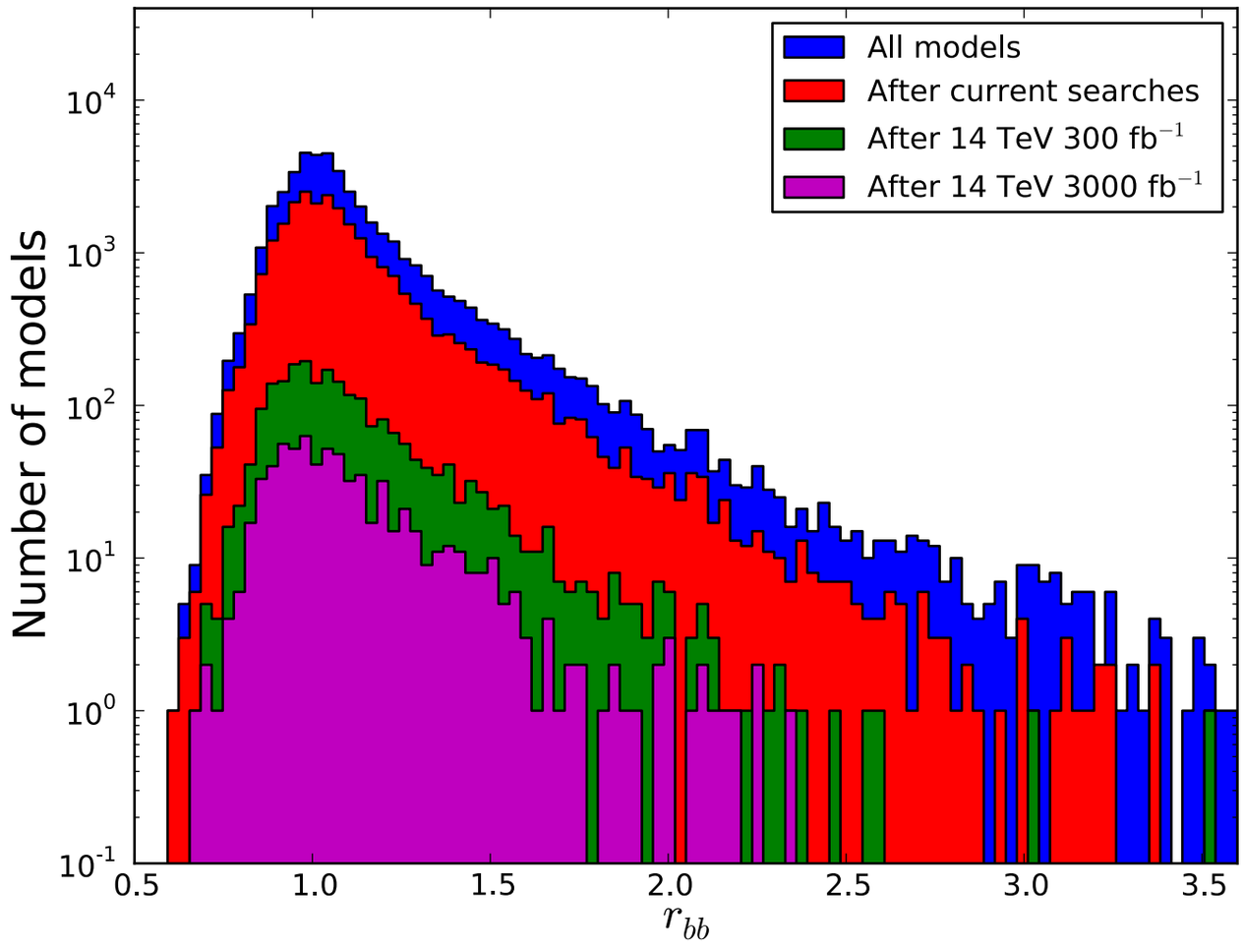

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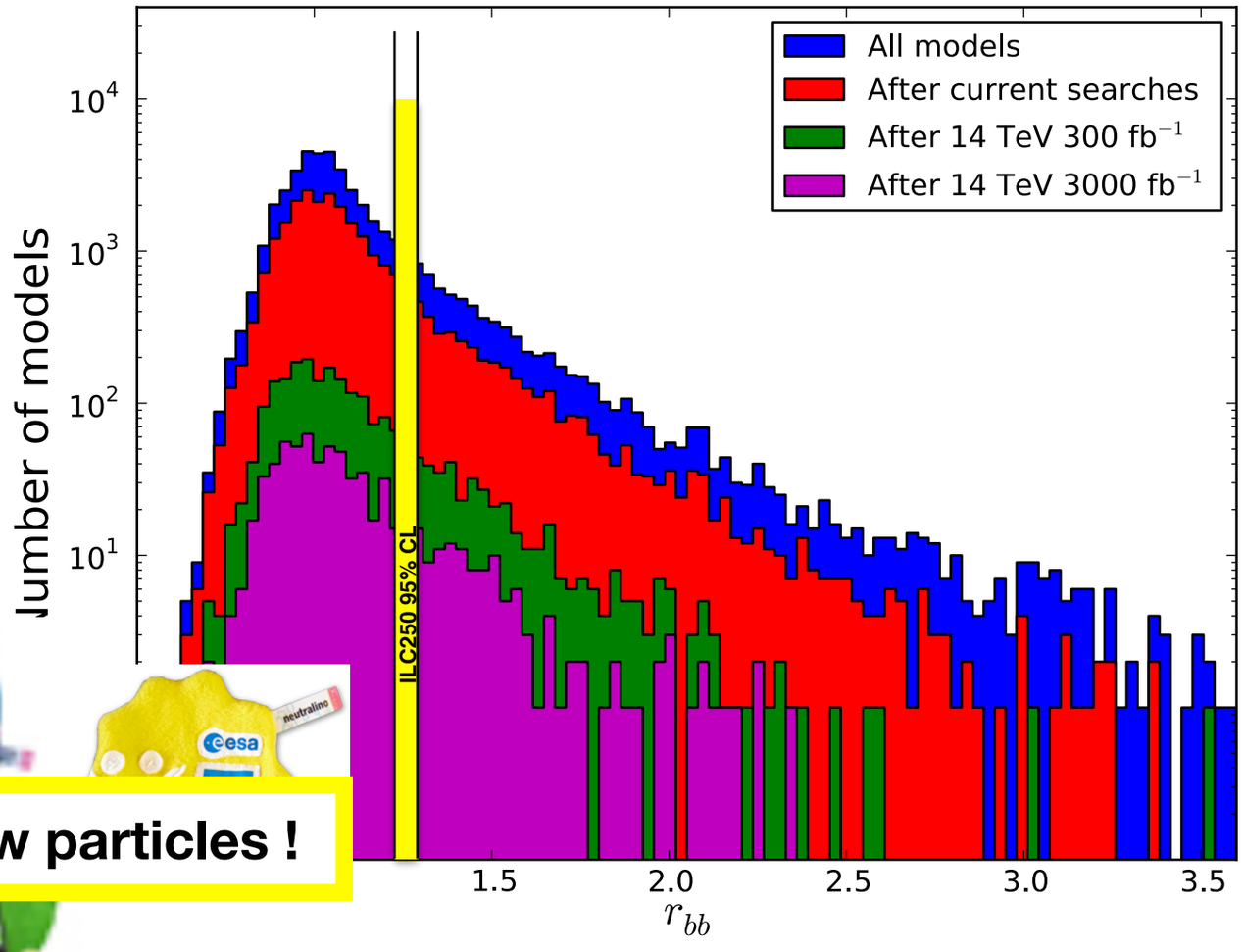

Discovery of new particles !

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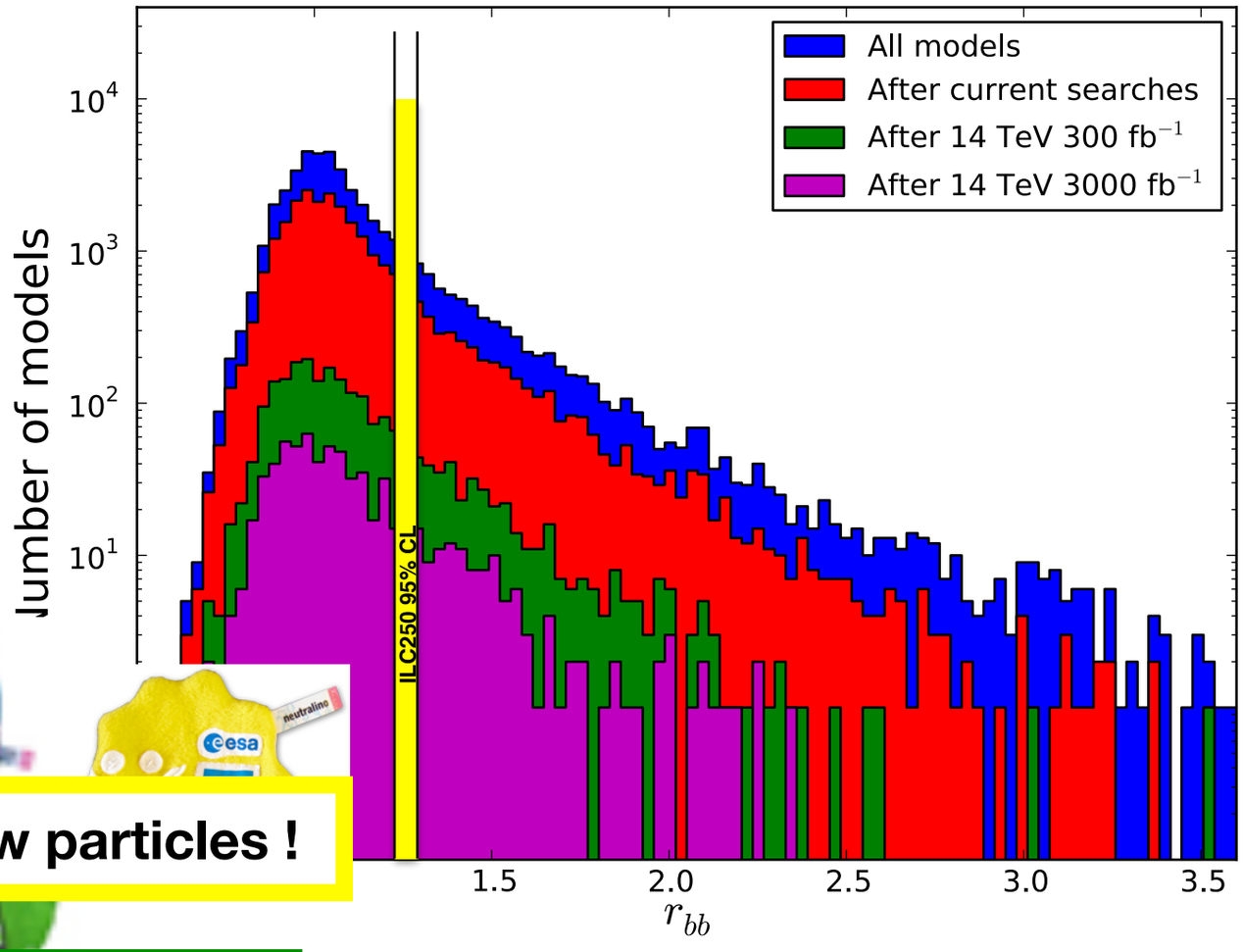


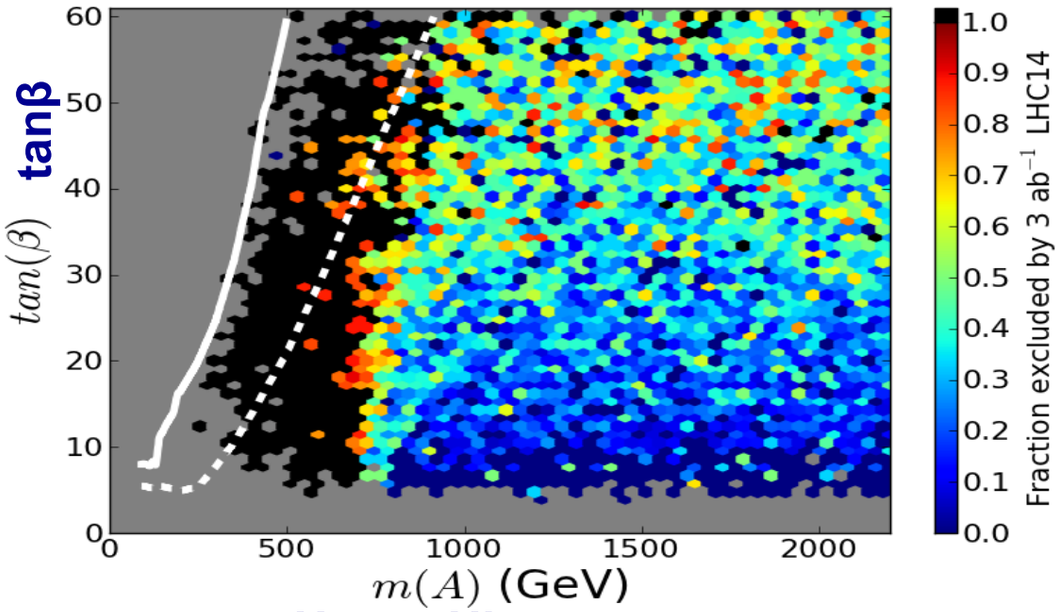
Discovery of new particles !

again clear added value and complementarity w.r.t. HL-LHC

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

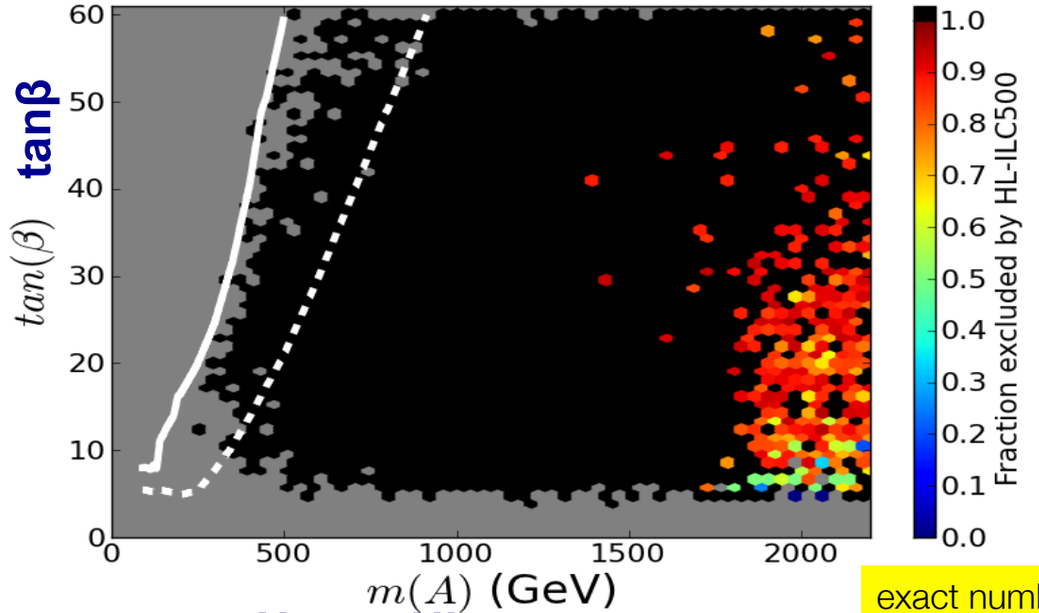
… or scanning the pMSSM with hγγ, hττ, hbb:

HL-LHC 3000 fb-1



Heavy Higgs mass

ILC (1150 fb^{-1}@250 GeV & 1600 fb^{-1}@500 GeV)



Heavy Higgs mass

exact numbers outdated

Discoveries of new particles ?

Phys. Rev. D 90, 095017 (2014)

- colour scale: fraction of scan points excluded via coupling precisions
- white lines: LHC / HL-LHC direct search reach for heavy Higgses

precisions achievable with e^+e^- machine provide powerful probe for heavy Higgs bosons up to ~2 TeV - for any tan(β)

Precision Measurement of M_h

The Higgs Boson

How well do we need to know the Higgs mass?

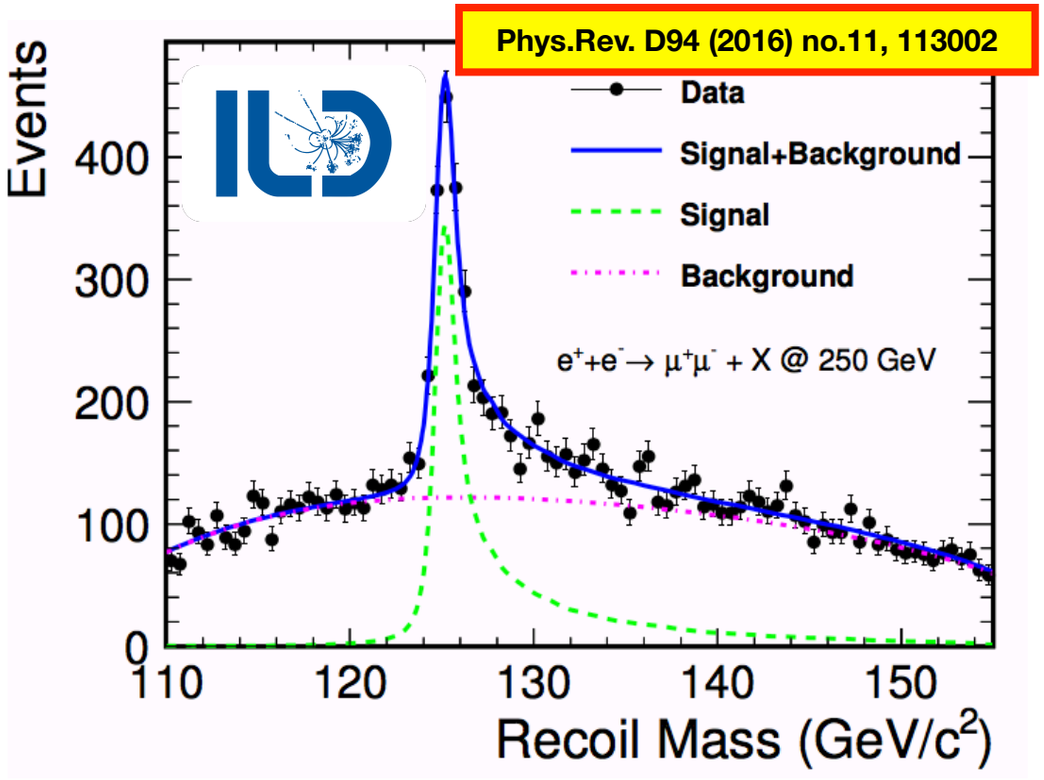
- for many applications, $\delta m_h \simeq 0.25$ GeV (or 0.2%) is ok

- notable exception: h->V V* partial widths very sensitive to m_h due to phase space!
  => relative errors for *effective couplings* $\sim\sqrt{\Gamma_V}$ and mass, assuming NWA for Higgs, relate as:

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

for in depth discussion of parametric uncertainties c.f. Phys. Rev. D 89, 033006 (2014)

Phys.Rev. D94 (2016) no.11, 113002



- **δm_h = 0.2% => δ_W = 1.4% - not adequate for precision goal!**

- **leptonic recoil mass at ILC 250 GeV: $\delta m_h \simeq$ 14 MeV => δ_W = 0.1%**

- watch impact of new beam parameters: => preliminary estimate: 20 MeV - still ok

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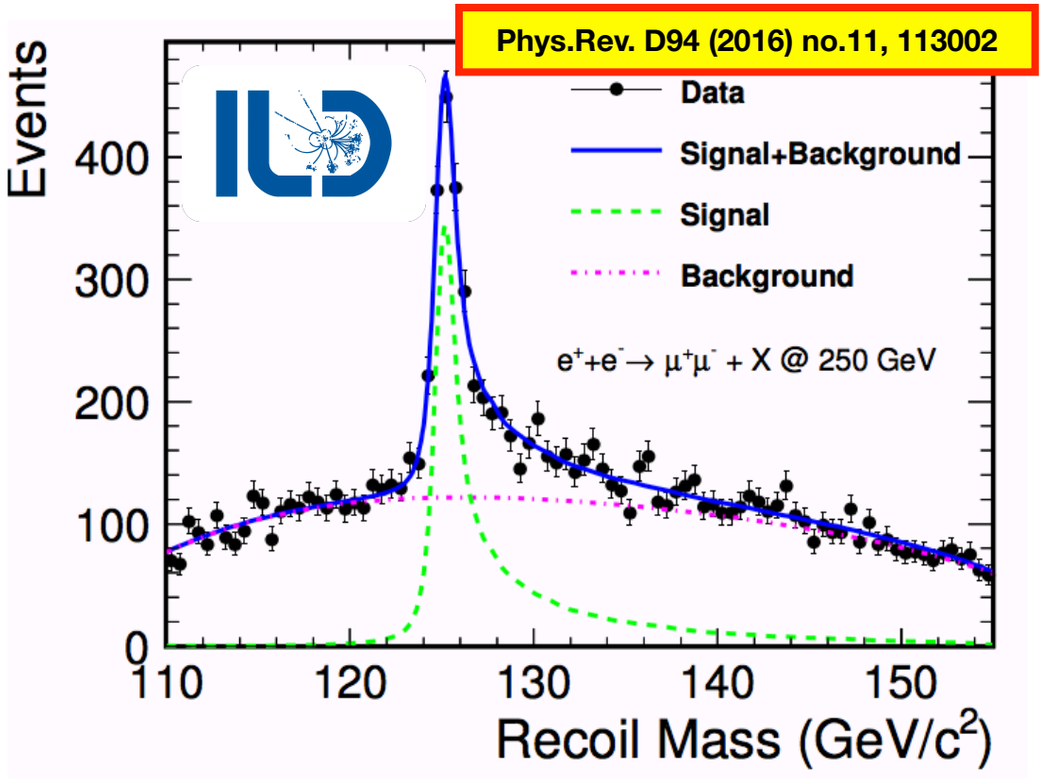

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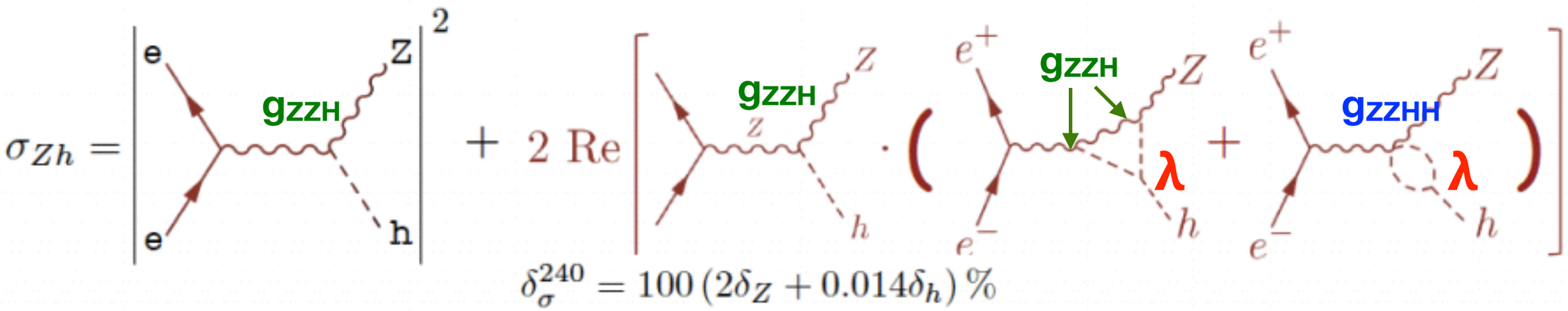
Higgs coupling precisions (in %)

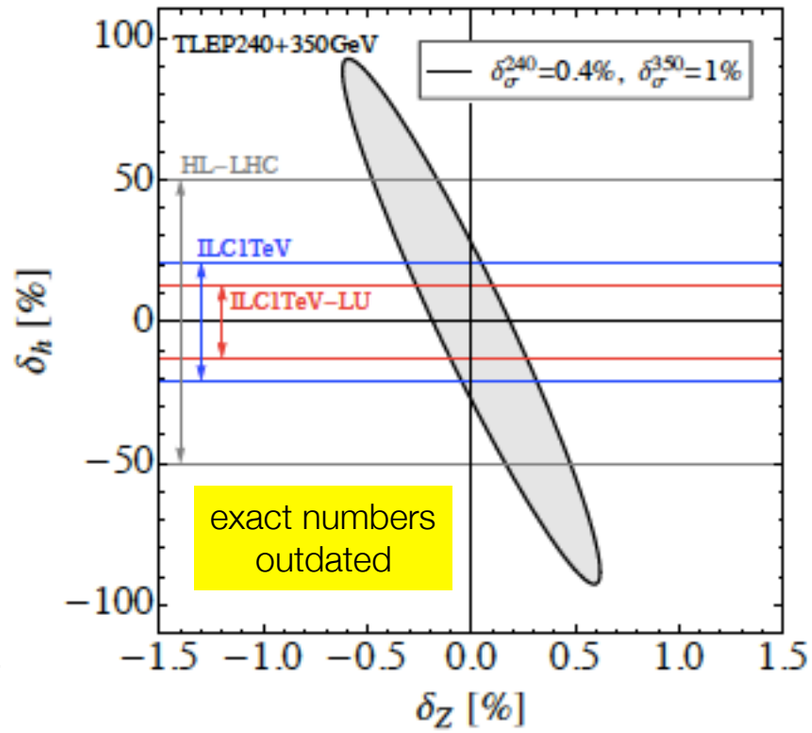
	ILC250		+ILC500	
	κ fit	EFT fit	κ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
				1.0
				5.1
				2.6
				0.46
				0.65
				0.05
Γ_h	3.9	2.5	1.7	1.6
$BRh \to inv$	0.32	0.32	0.29	0.29
$BRh \to other$	1.6	1.6	1.3	1.2

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

✔

Higgs self-coupling from loop corrections?



- sub-% precision on σ_{ZH} possible at all proposed e+e- colliders
- however: indirect and model-dependent method
- interesting consistency check, *not* an independent measurement
- n.b.: what about other loop contributions?
  - top -> y_t ? W -> g_{WWH} ?
  - or even BSM ?
- **better look at plot the other way round: will we need at some point O(10%) direct measurement of λ in order to achieve permille-level extraction of g_{ZZH} from σ_{ZH} !?**
- n.b.: at 500 GeV, NLO effects from λ on σ_{ZH} are ~7 times smaller thar at 250 GeV…..

[arXiv:1312.3322]