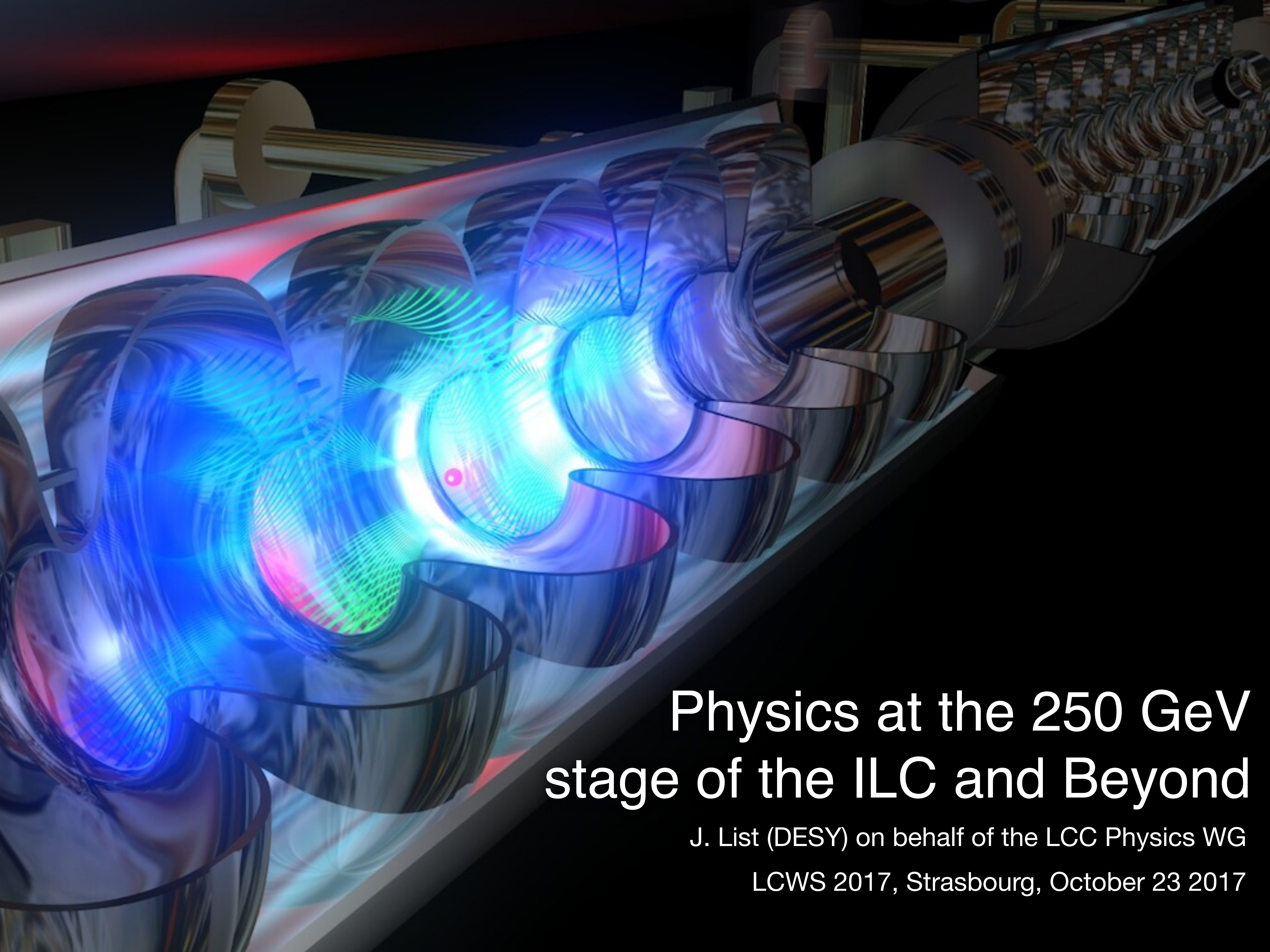


Physics at the 250 GeV stage of the ILC and Beyond

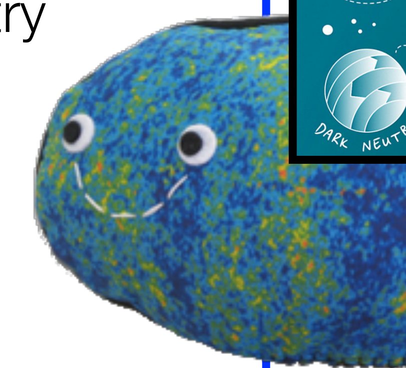
J. List (DESY) on behalf of the LCC Physics WG

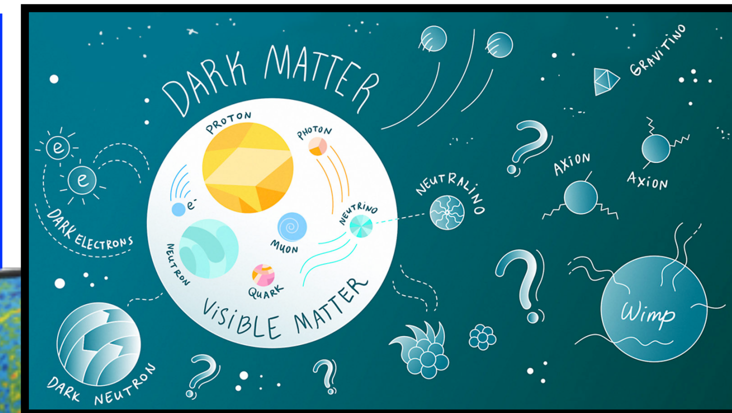
LCWS 2017, Strasbourg, October 23 2017

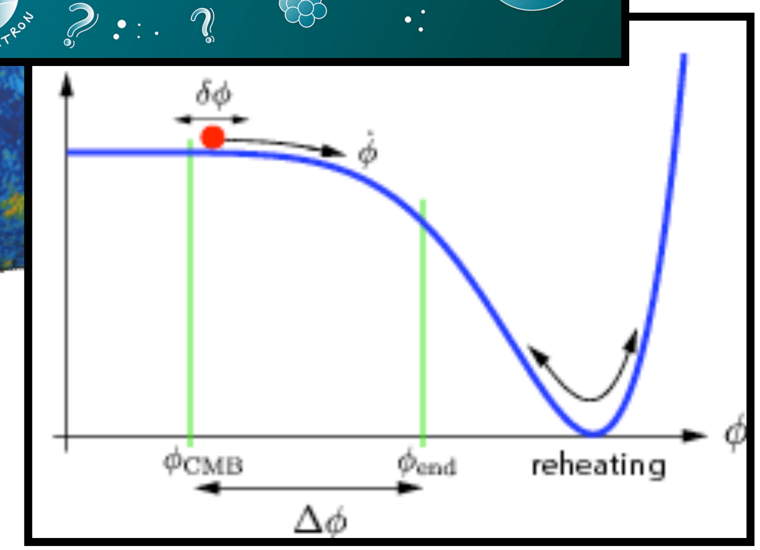
The big questions for future colliders….

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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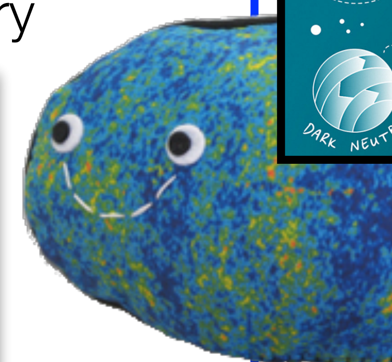

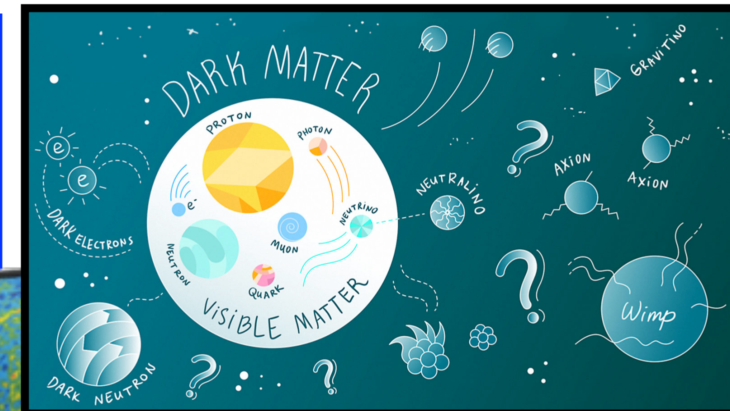

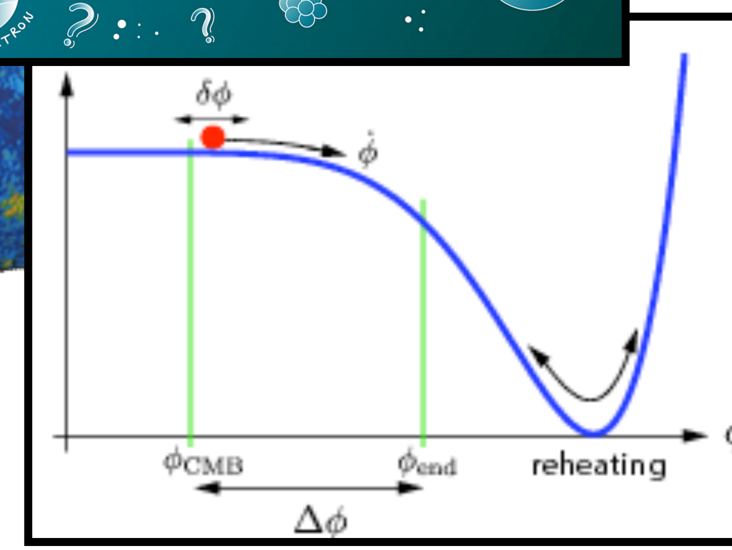

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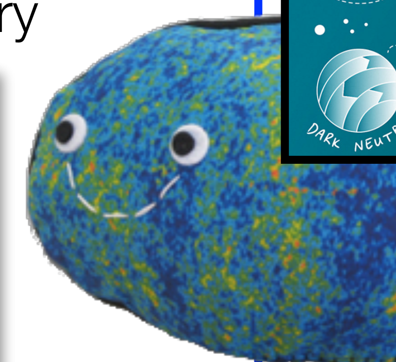

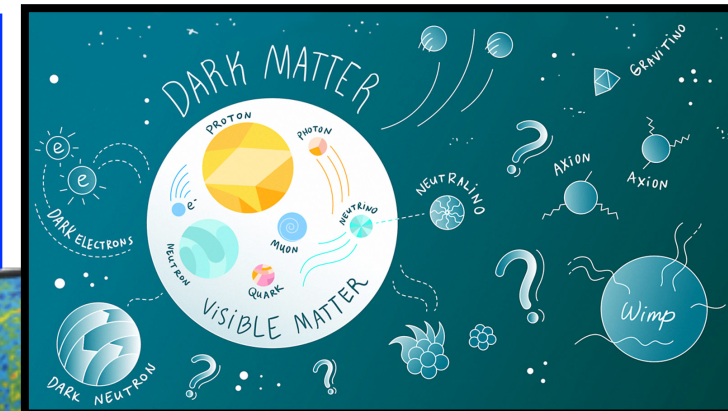

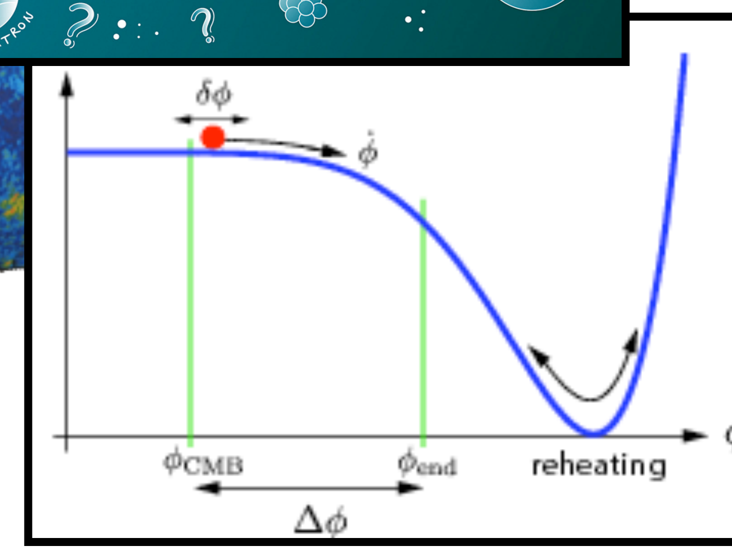

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- all hints for BSM come out of the electroweak sector, incl. Higgs

=> some new particles must be charged under electroweak interactions

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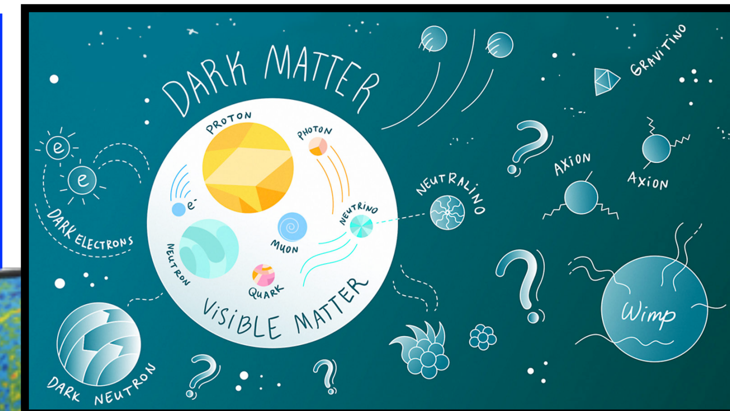

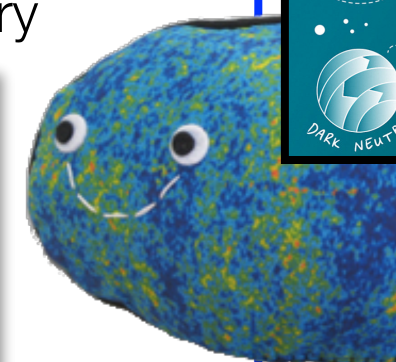

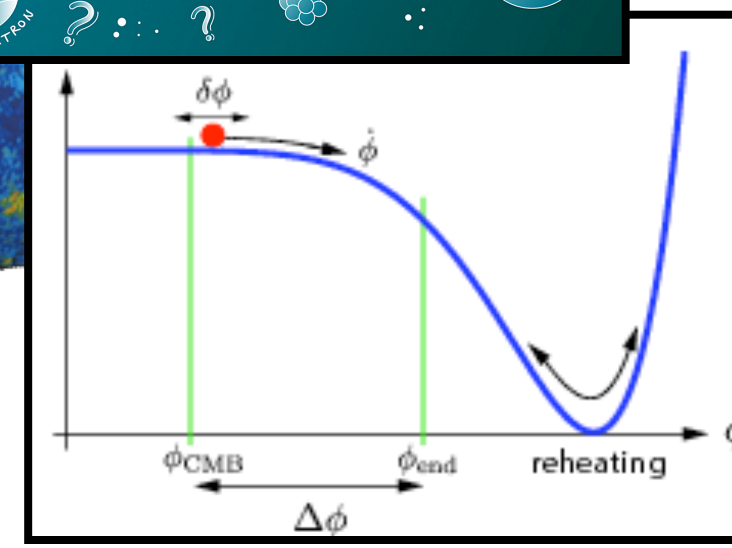

What we know:

- all 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 colliders

Our tools:

The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

Discoveries of new particles ?

… and how to tackle them at colliders

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Discoveries of new particles ?

Choosing the next collider

- technical readiness, cost etc.
- **added physics value w.r.t.**
  - **HL-LHC**
  - and all kinds of other experiments

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

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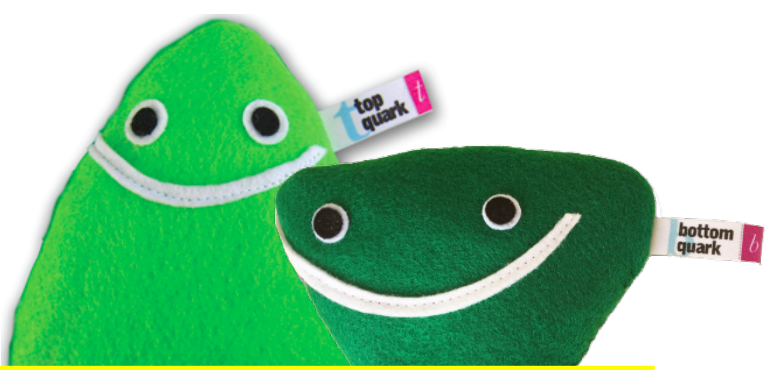
What is the added value of a 250 GeV e+e- Linear Collider ?

more c.f. arXiv:1710.07621
and many, many talks at this WS

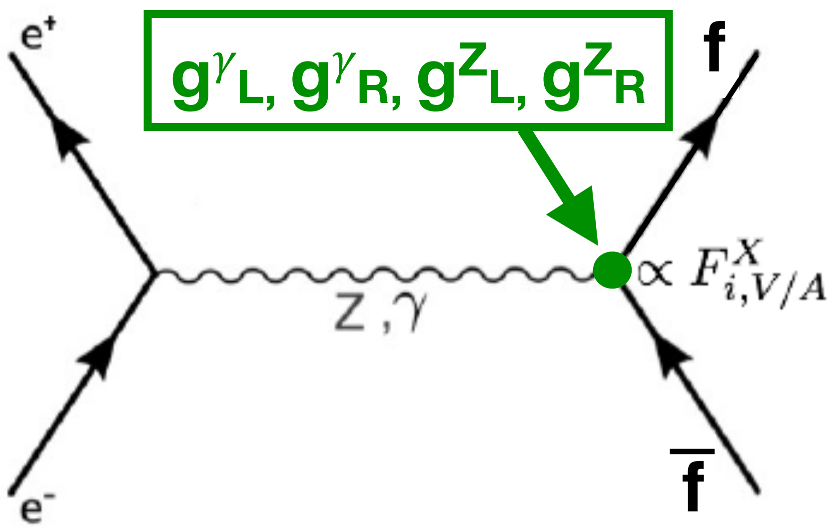
New insights from old friends…



The Top and Bottom Quark

Z & W Bosons

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

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

Polarised beams

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

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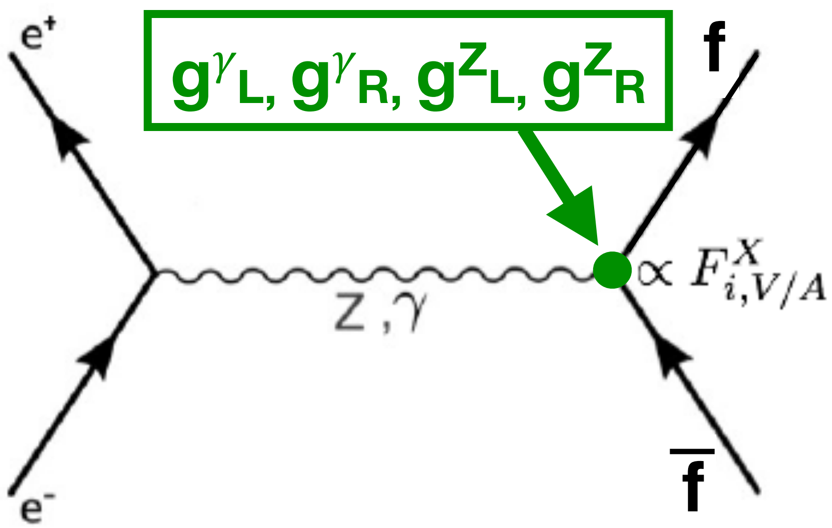

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$P(e^-) = \pm 80\%$ $\quad$ $P(e^+) = \mp 30\%$

3rd generation of quarks

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

Polarised beams

- allow to disentangle g^{γ} vs g^Z
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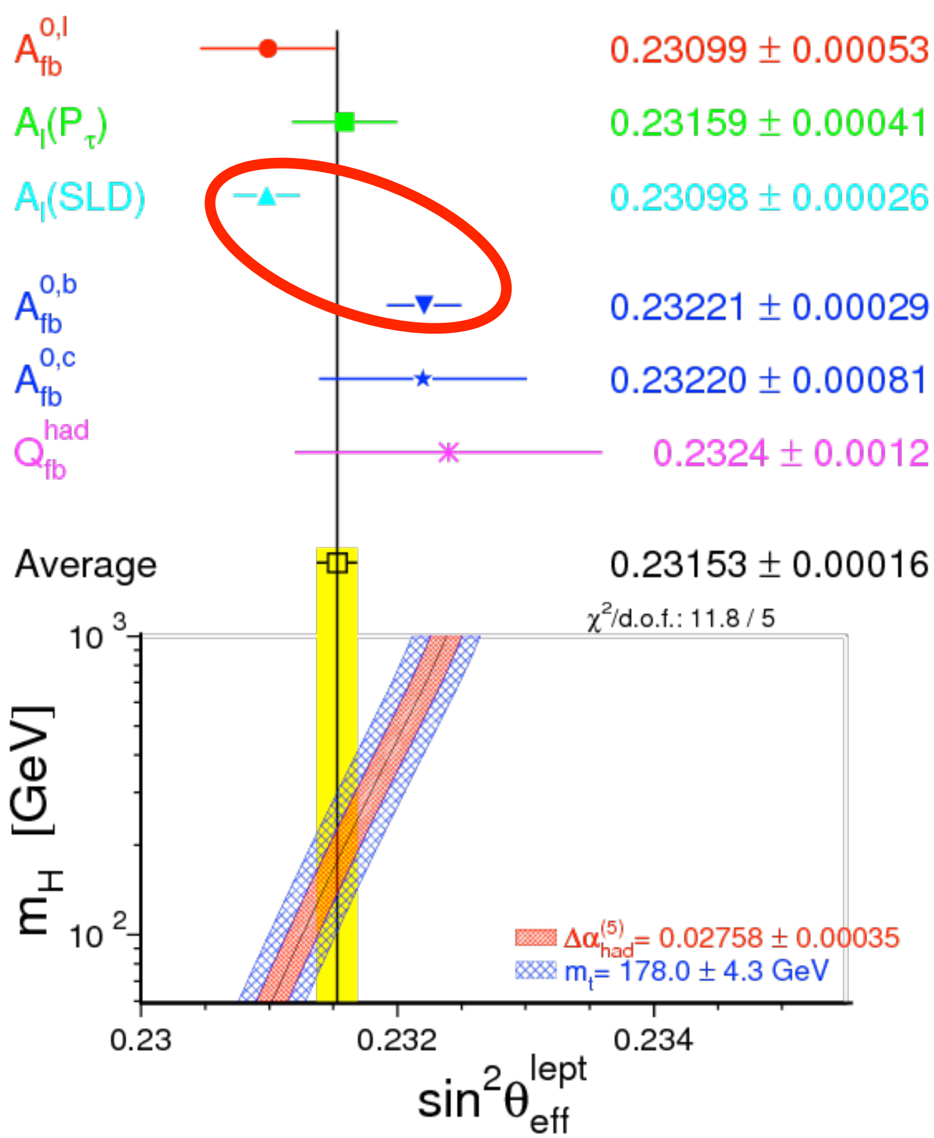
The Top and Bottom Quark

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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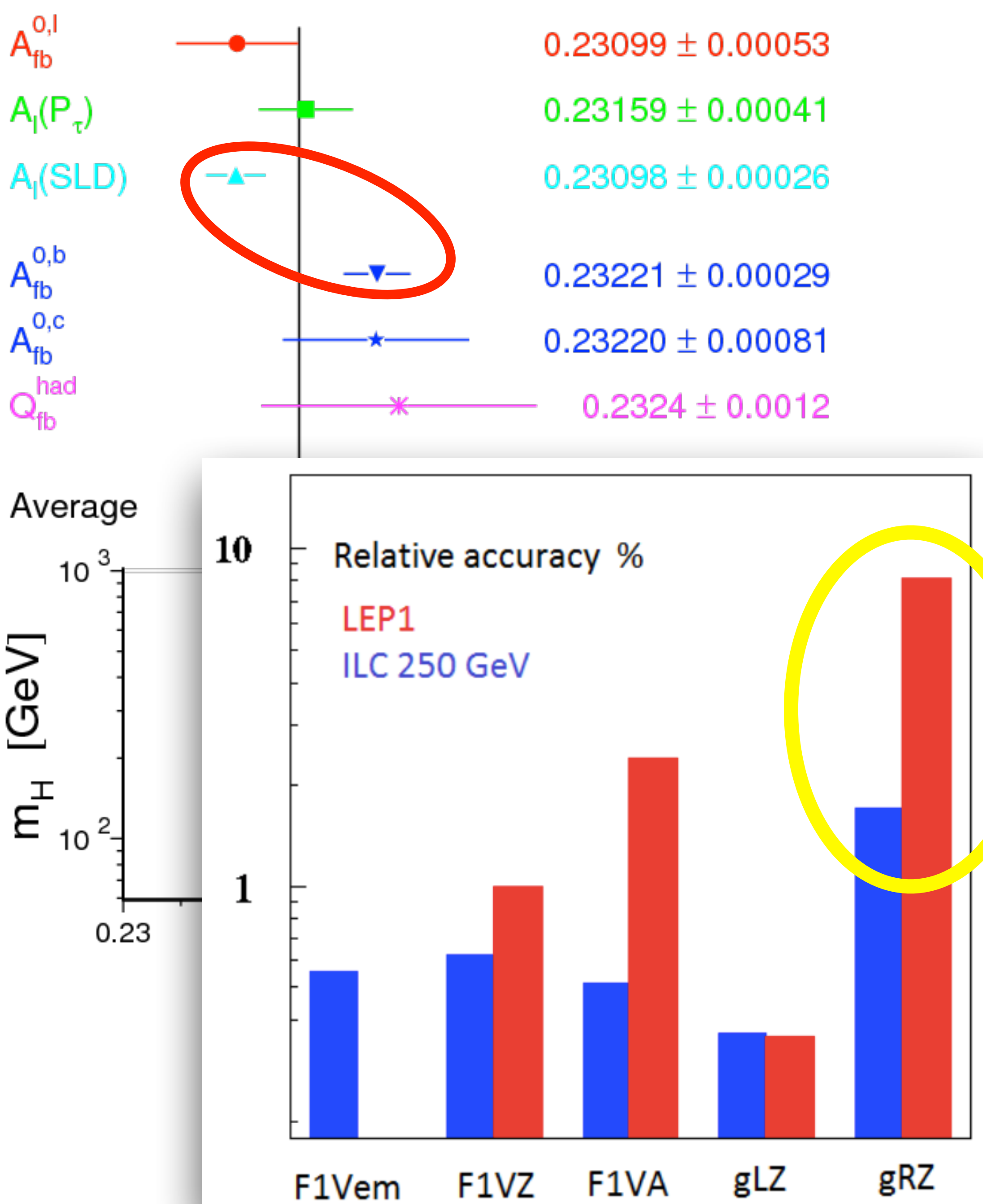
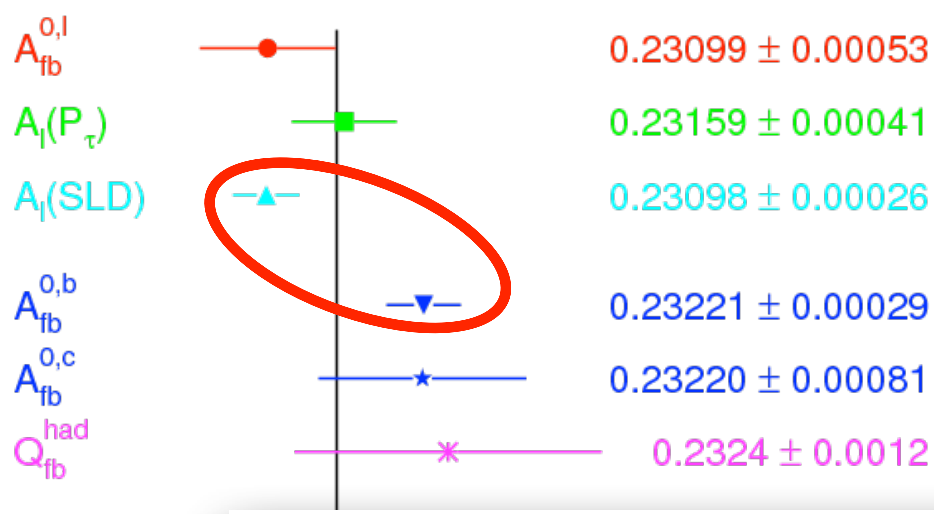


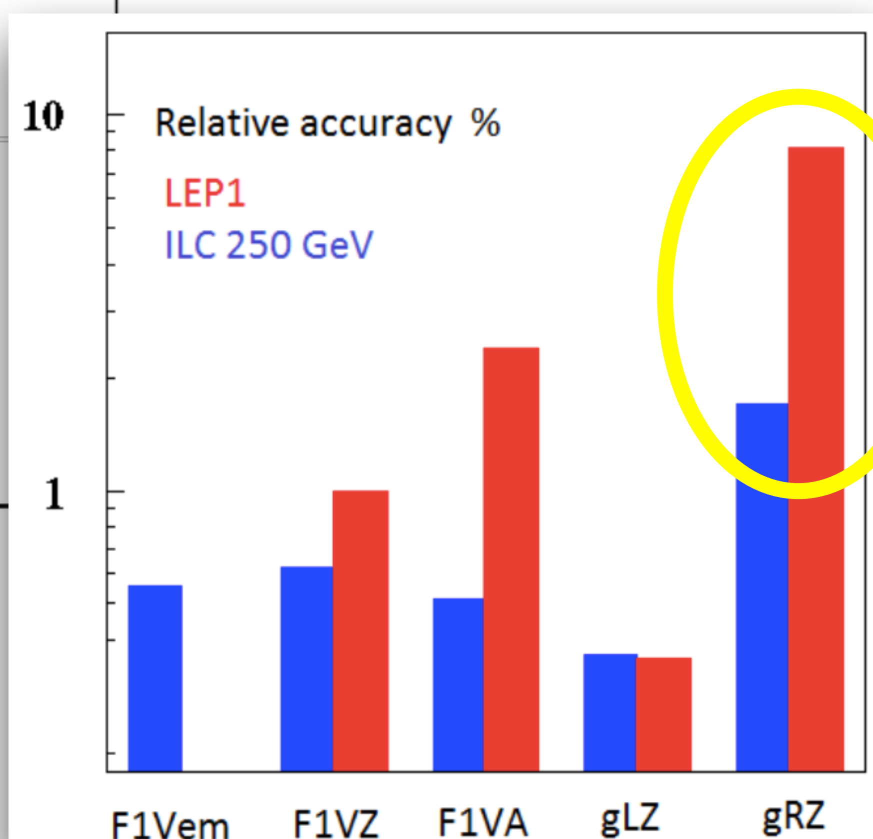
Yes, we can!

arXiv:1709.04289

ILC 250 GeV: The Bottom Quark

The Bottom Quark





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Yes, we can!

allows to probe NP scales up to ~60 TeV

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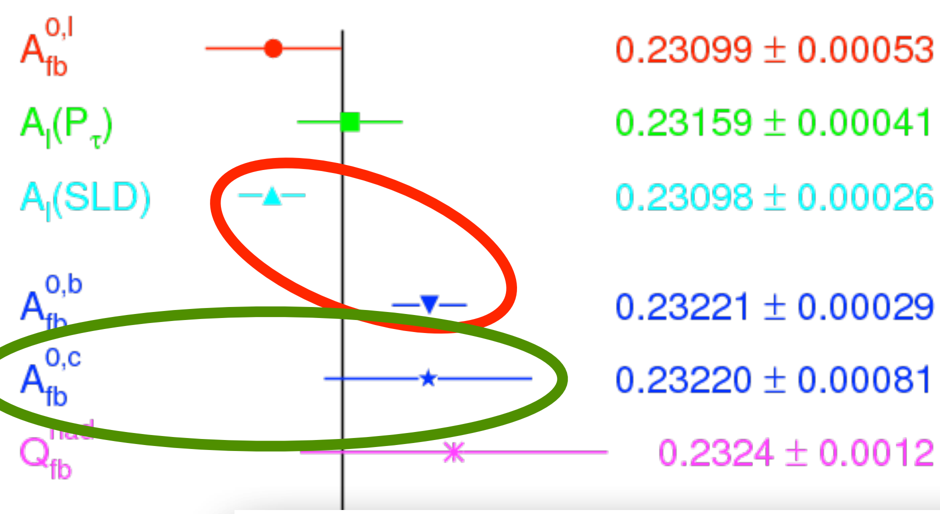

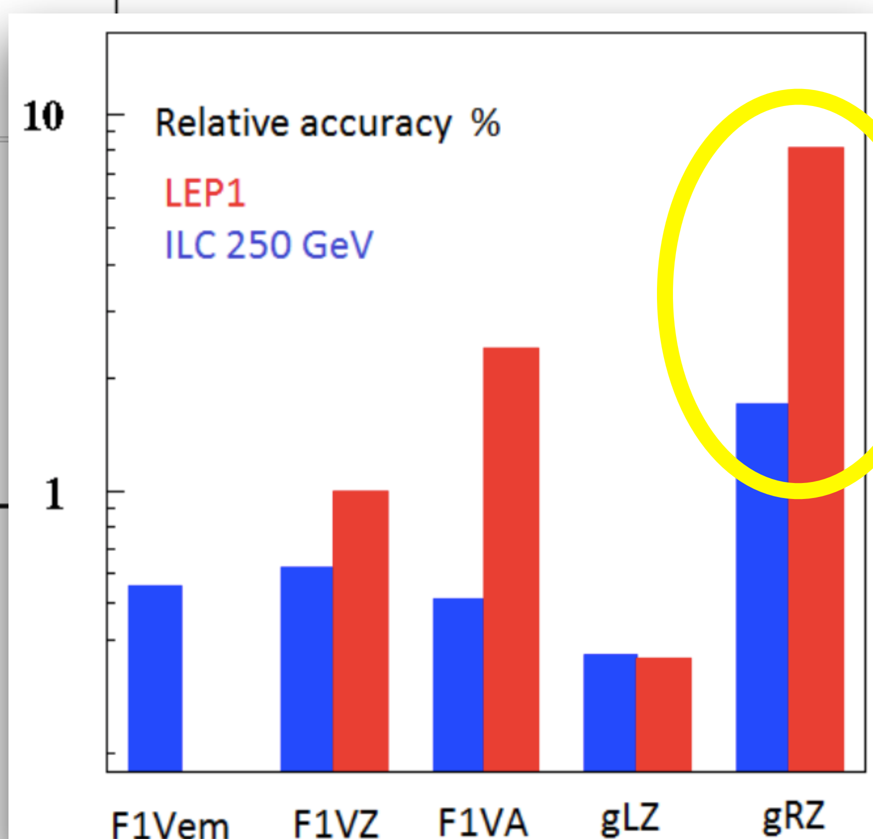

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Yes, we can!

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:

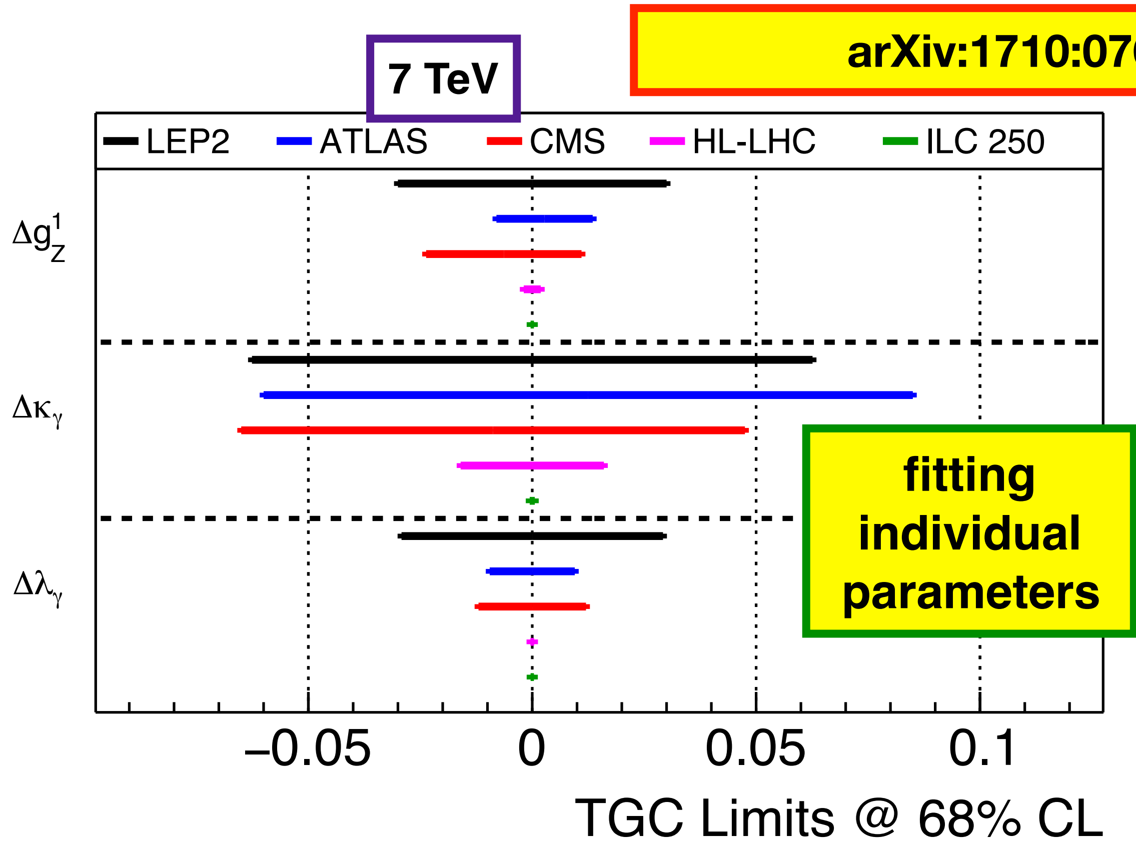
- semi-leptonic & fully hadronic channels
- all 5 angles
- individual and simultaneous fits of 3 couplings

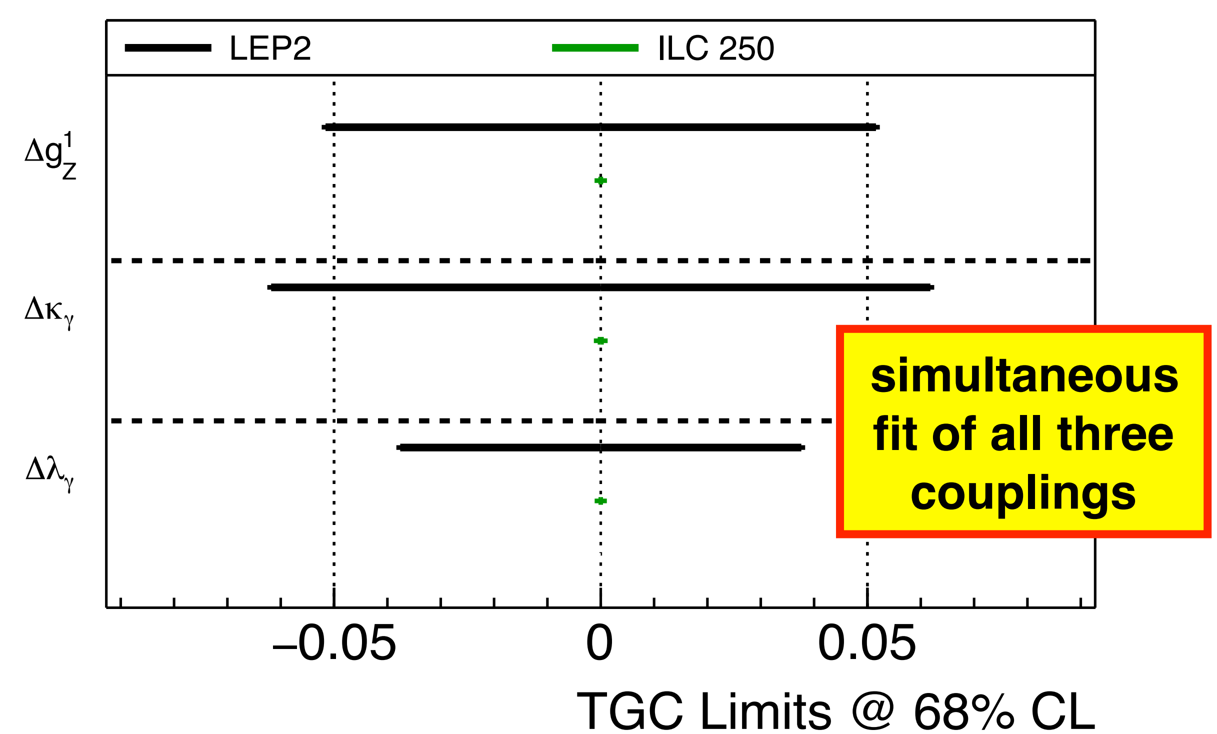
250 GeV: full ILD study is work in progress

=> 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

arXiv:1710:07621



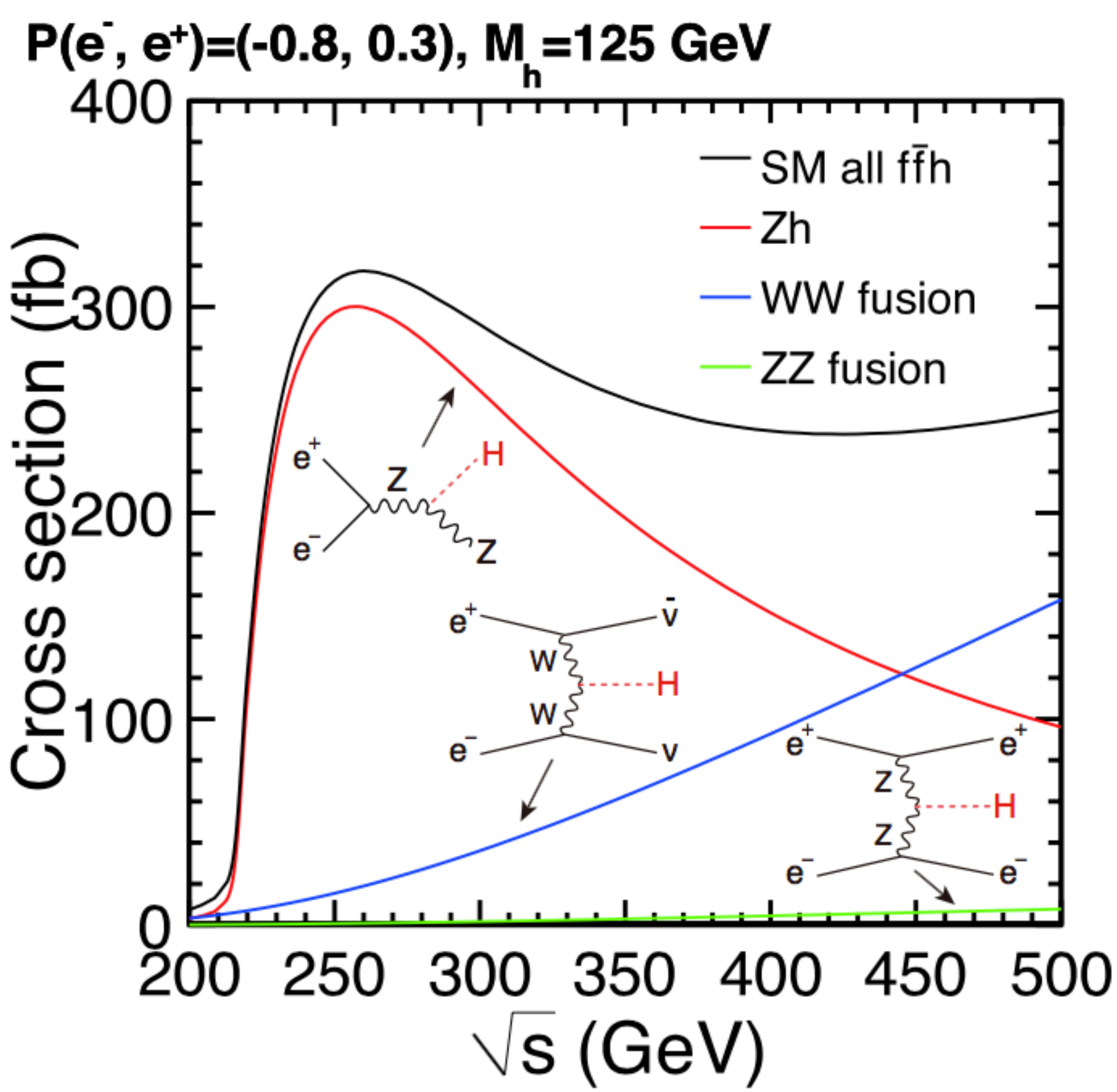


New insights from our new friend…

The Higgs Boson

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
  - CP properties of Zh coupling
  - ….

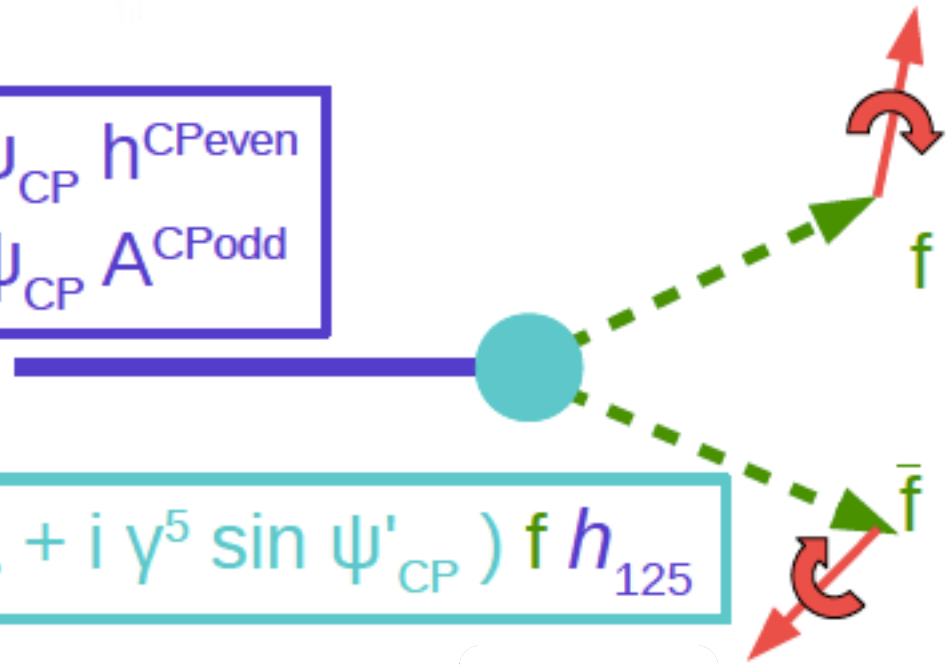
Image courtesy of Stuart Miles at FreeDigitalPhotos.net

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

The Higgs Boson

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

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

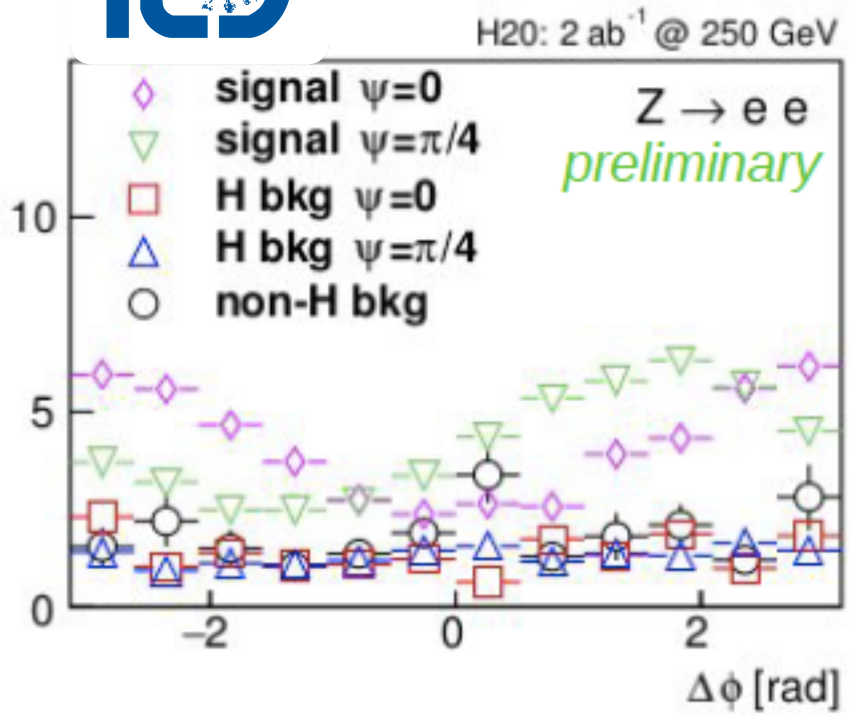


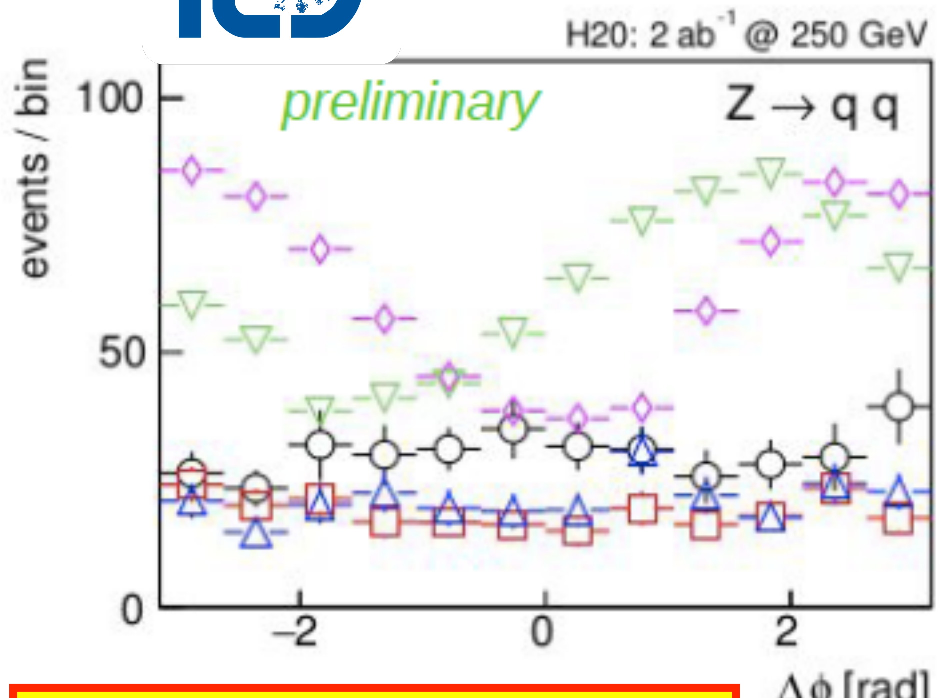
$$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$$

h is a spin 0 state:

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

[ψ = 0 CP even,
$\pi/2$ CP odd]





based on NIM A810 (2016) 51-58

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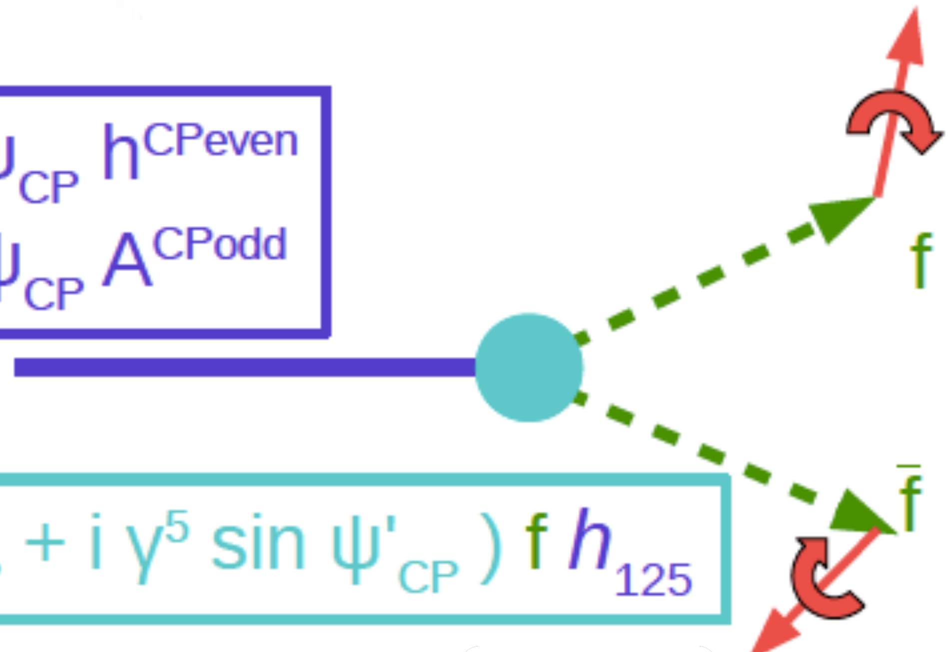

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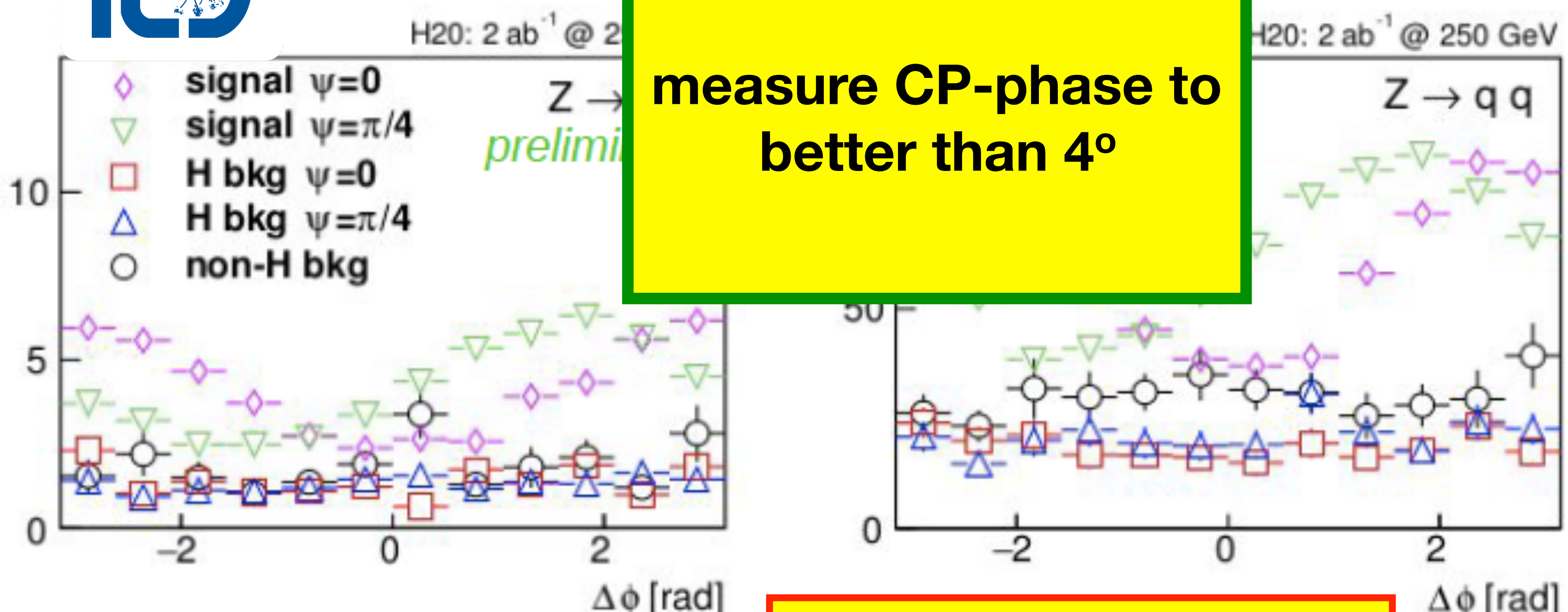

measure CP-phase to better than 4°

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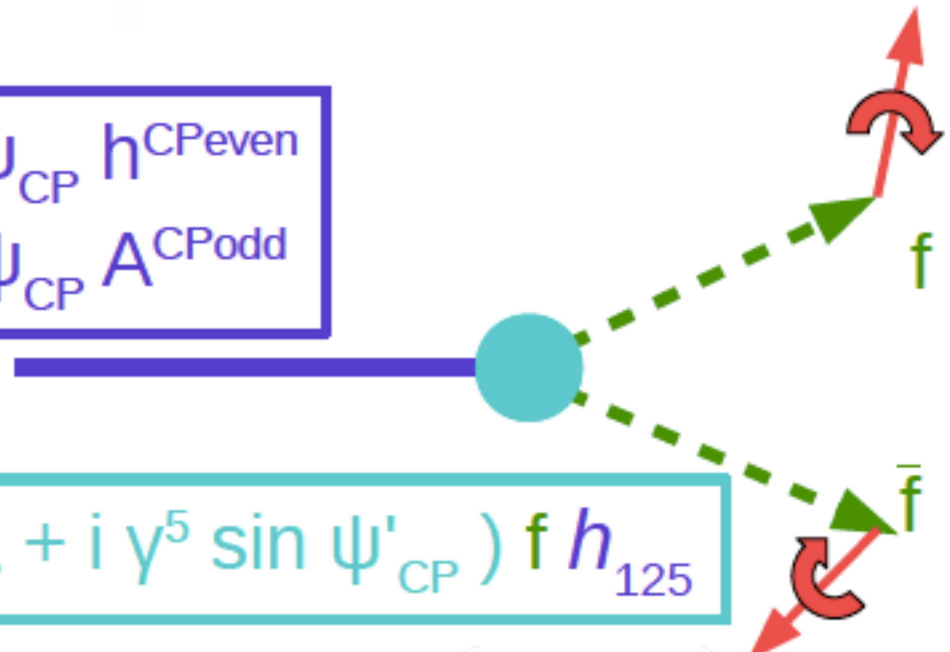

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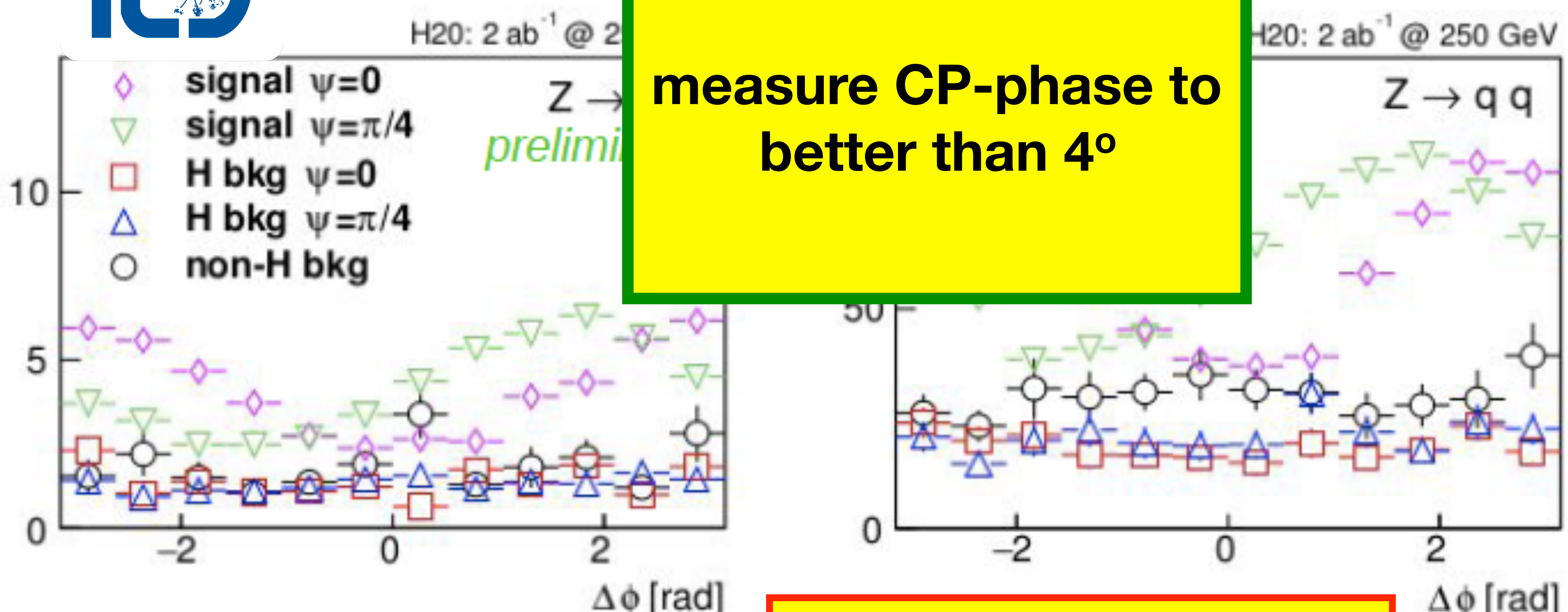


measure CP-phase to better than 4°

..and CPV in Zh coupling:

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

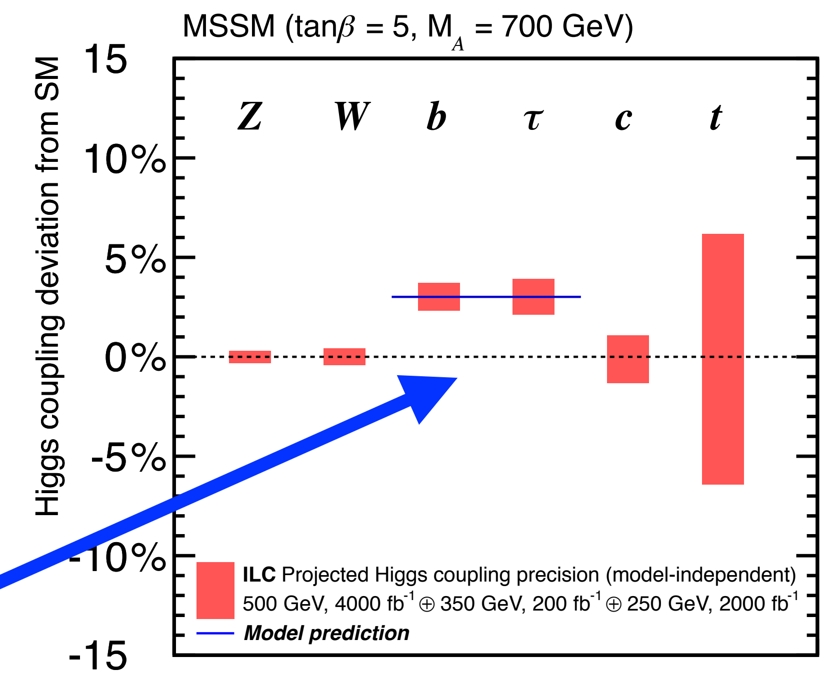
=> $\tilde{b}$ **to ±0.005**

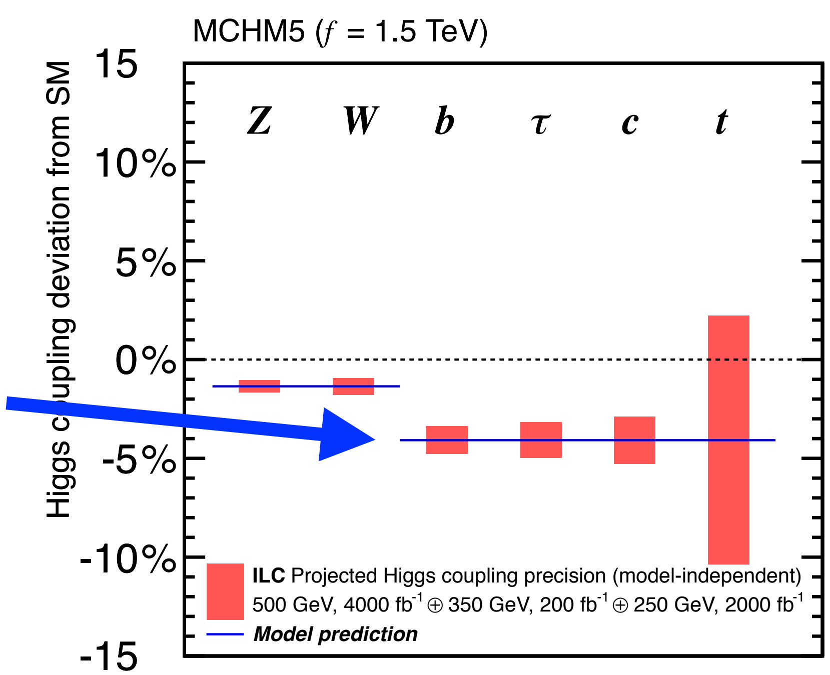
based on NIM A810 (2016) 51-58

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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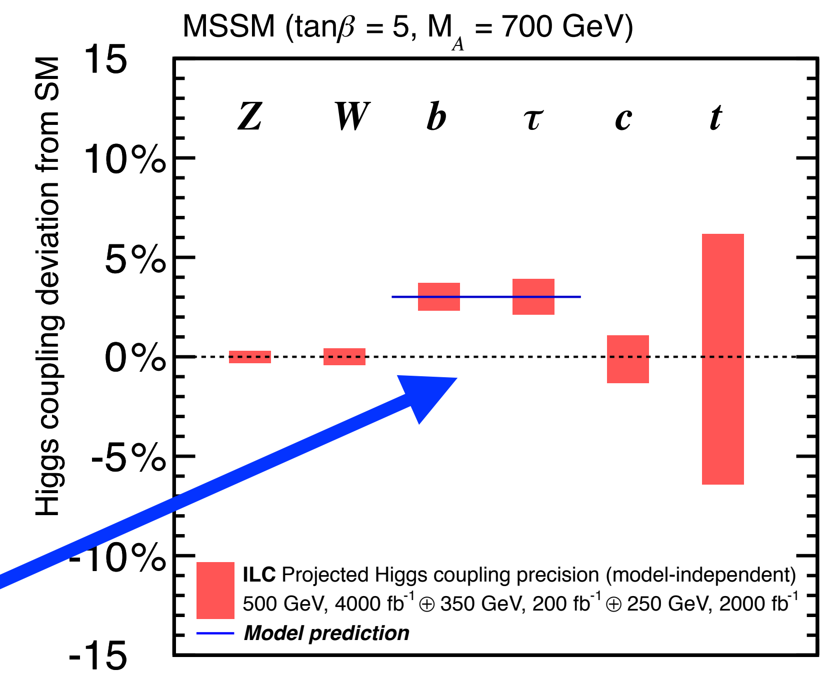

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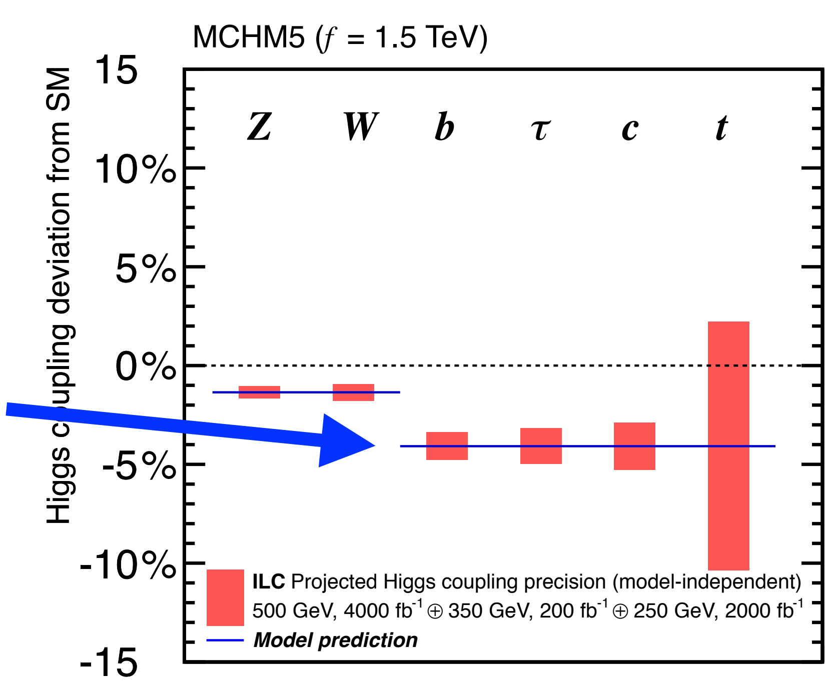


At least percent-level precision required!

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
  - even more "model-independent" since new momentum-dependent operators included, e.g.: $\delta\mathcal{L} = \frac{m_Z^2}{v}(1+\eta_Z)hZ_\mu Z^\mu + \zeta_Z \frac{1}{v} h Z_{\mu\nu} Z^{\mu\nu}$ ⇒ $\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$, $\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)$
  - general EFT fineprint: no light new particles…
    => treat H->invisible as additional degree of freedom
  - allows to include:
    - EWPO: current state assumed apart from Γ_W
    - **triple gauge couplings**

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

other approaches use up to 17 parameters

Precision Measurement of M_h

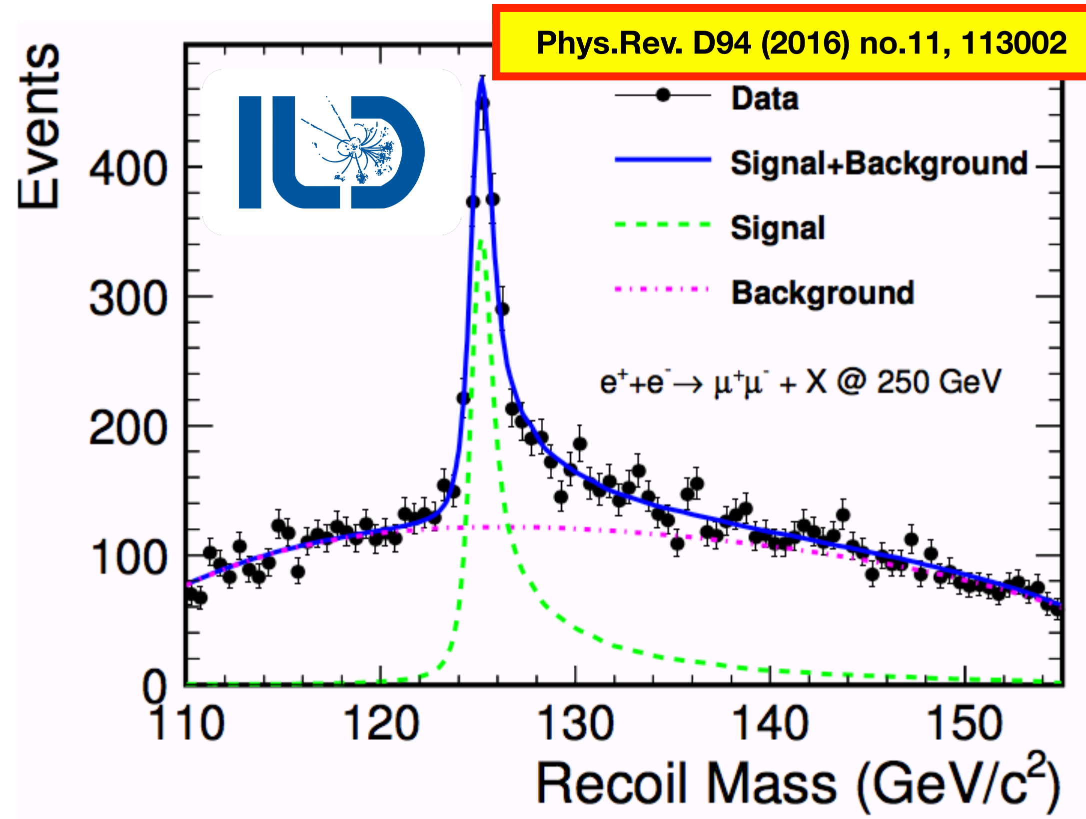
The Higgs Boson

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)



- **$\delta m_h = 0.2\%$ => $\delta_W = 1.4\%$ - not adequate for precision goal!**
- **leptonic recoil mass at ILC 250 GeV: $\delta m_h \simeq 14$ MeV => $\delta_W = 0.1\%$**
- watch impact of new beam parameters: => preliminary estimate: 20 MeV - still ok

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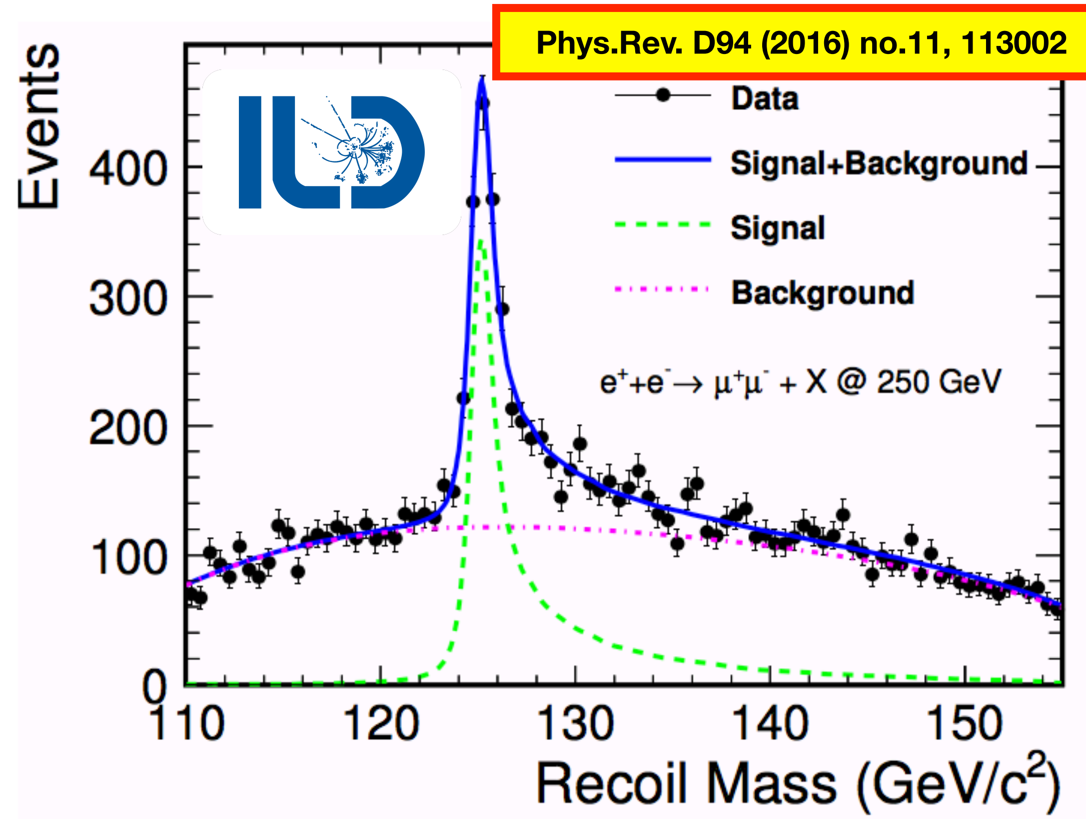
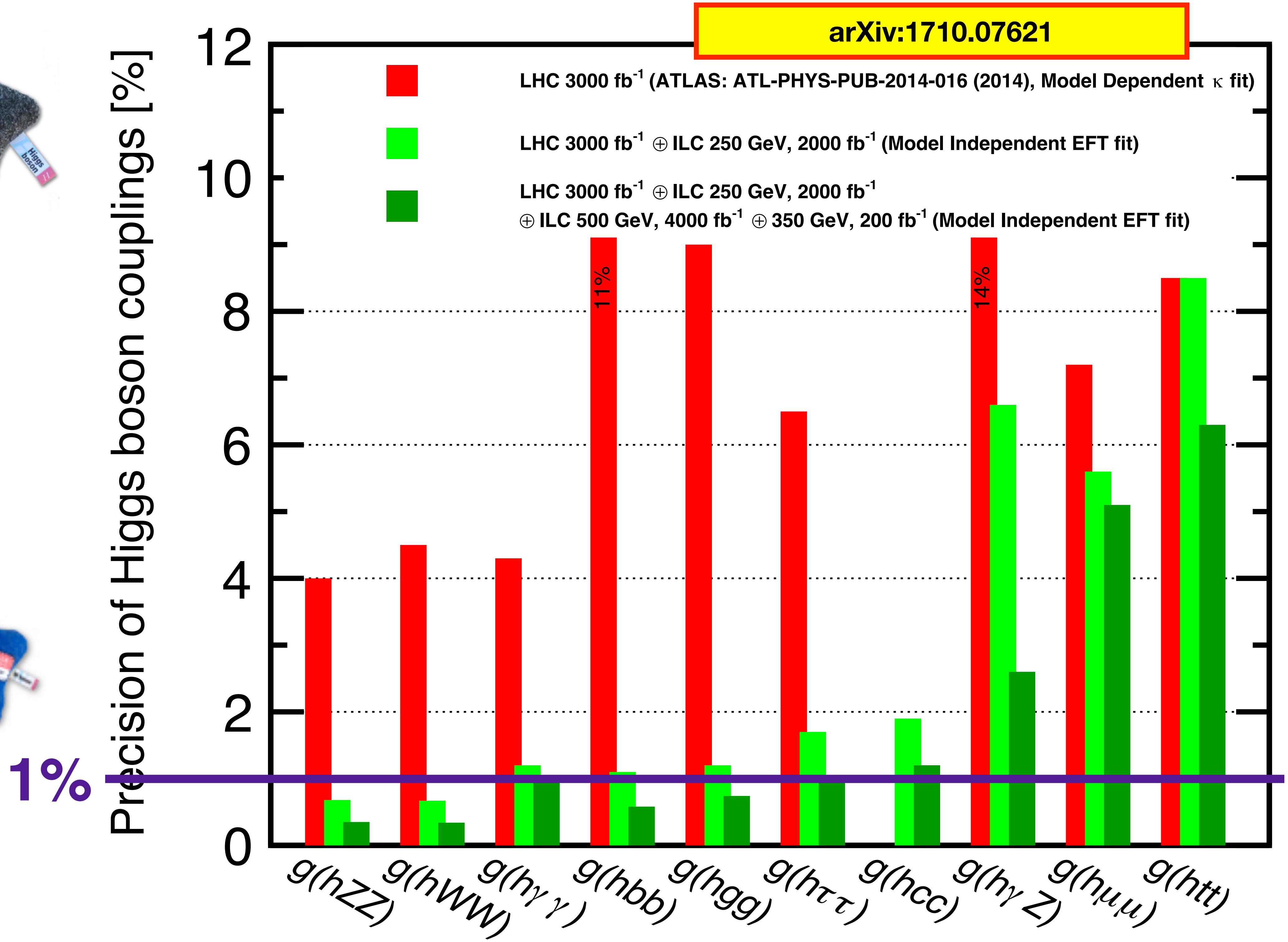


- **$\delta m_h = 0.2\%$ => $\delta_W = 1.4\%$ - not adequate for precision goal!**
- **leptonic recoil mass at ILC 250 GeV: $\delta m_h \simeq 14$ MeV => $\delta_W = 0.1\%$** ✔
- watch impact of new beam parameters: => preliminary estimate: 20 MeV - still ok

Higgs coupling precisions from full EFT fit



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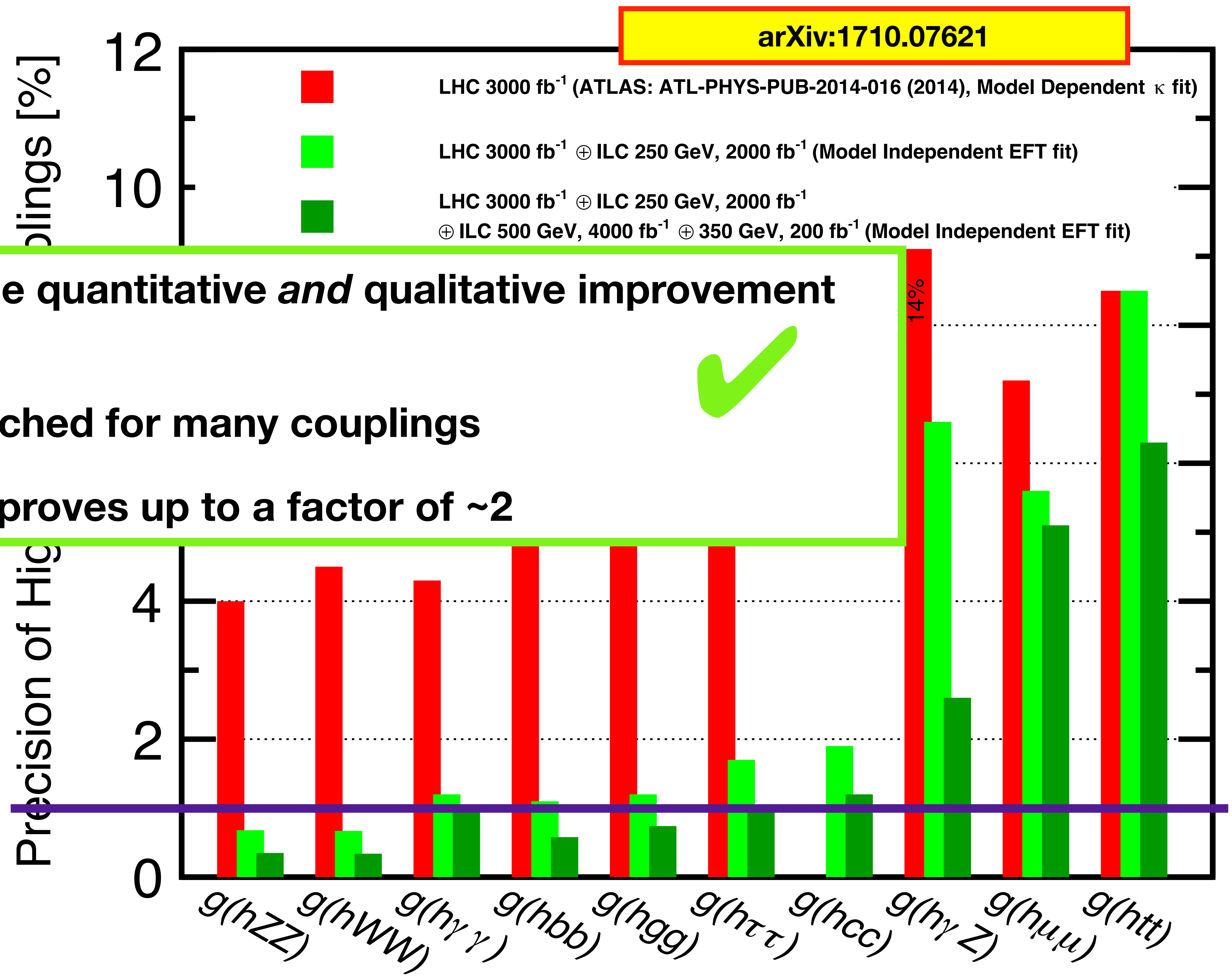
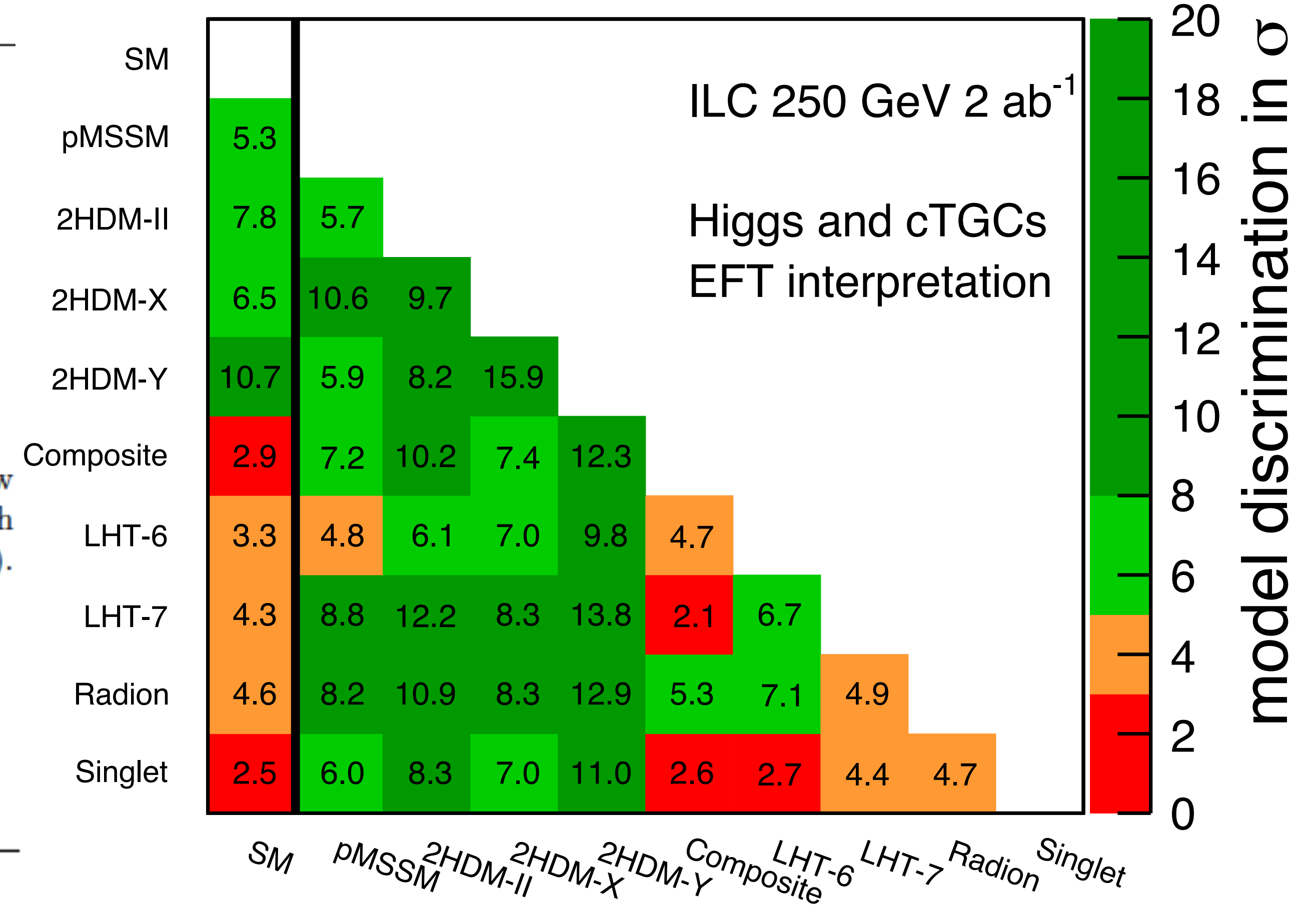


- ★ **250 GeV offers huge quantitative *and* qualitative improvement over HL-LHC** ✔
- ★ **~ 1 % or better reached for many couplings**
- ★ **adding 500 GeV improves up to a factor of ~2**

New Physics Interpretation of Higgs & EW

	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
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0
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 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].



…or more generally speaking:

arXiv:1708.08912

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

Discoveries of new particles ?

illustrates discovery and identification potential with examples of various BSM model points, all chosen to be unobservable at HL-LHC

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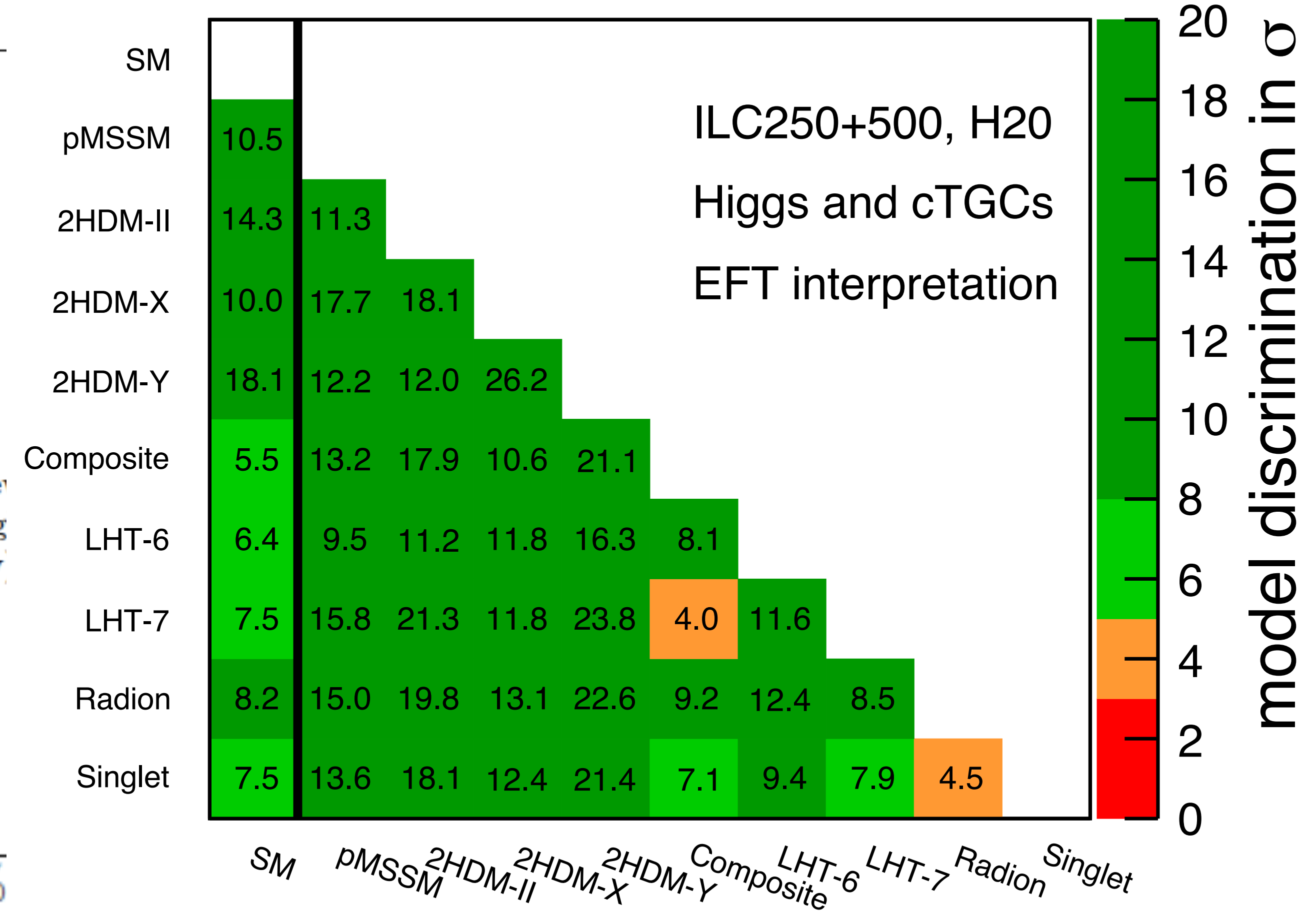

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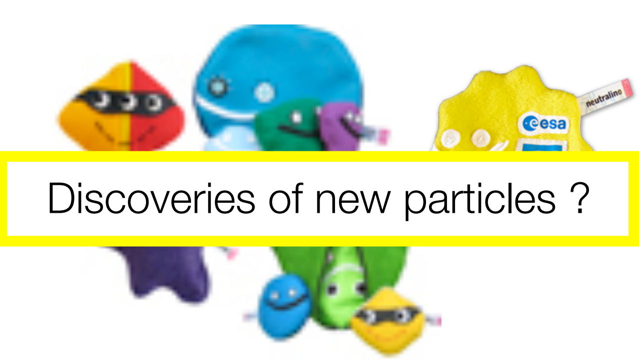

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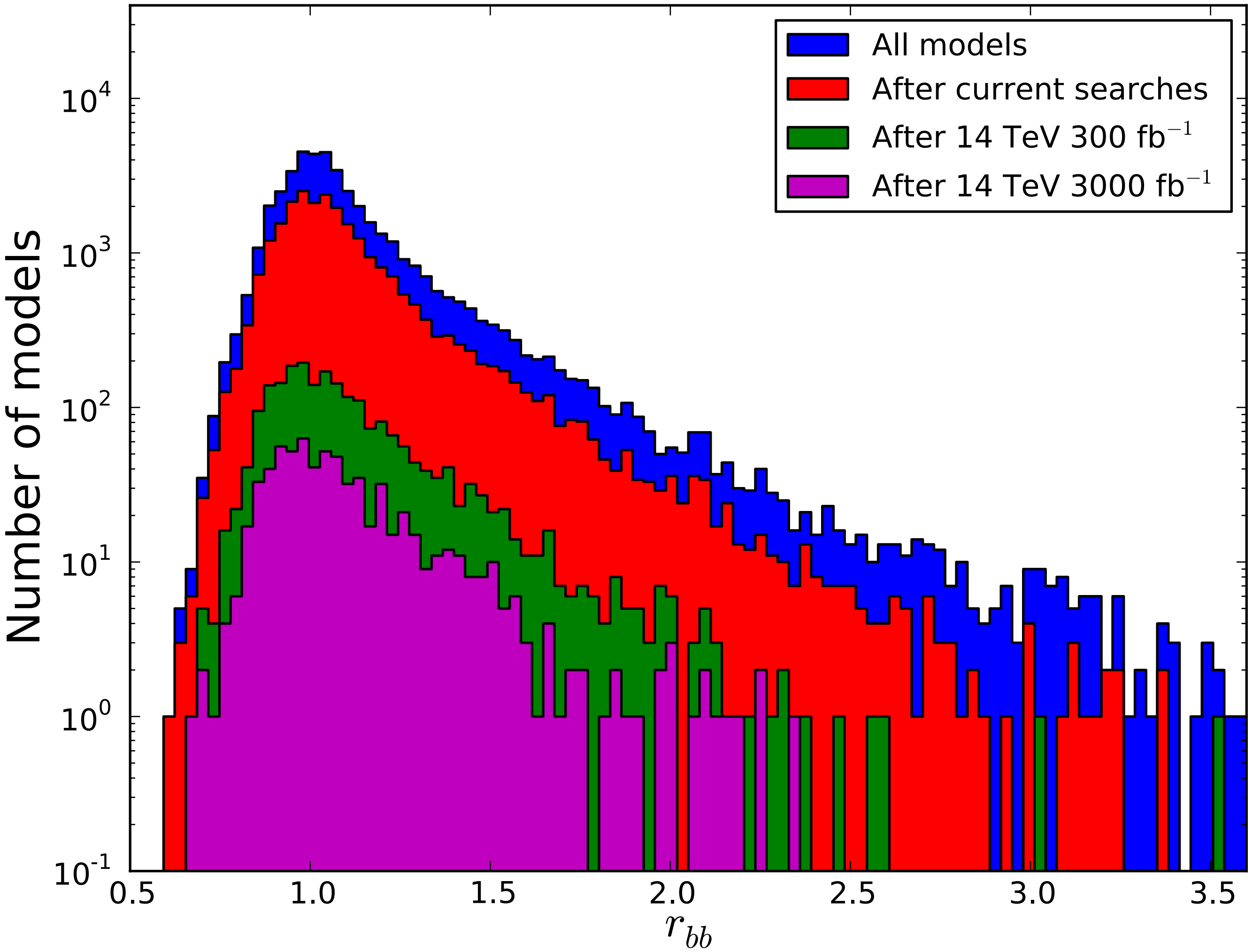
A closer look at SUSY: pMSSM scan

- 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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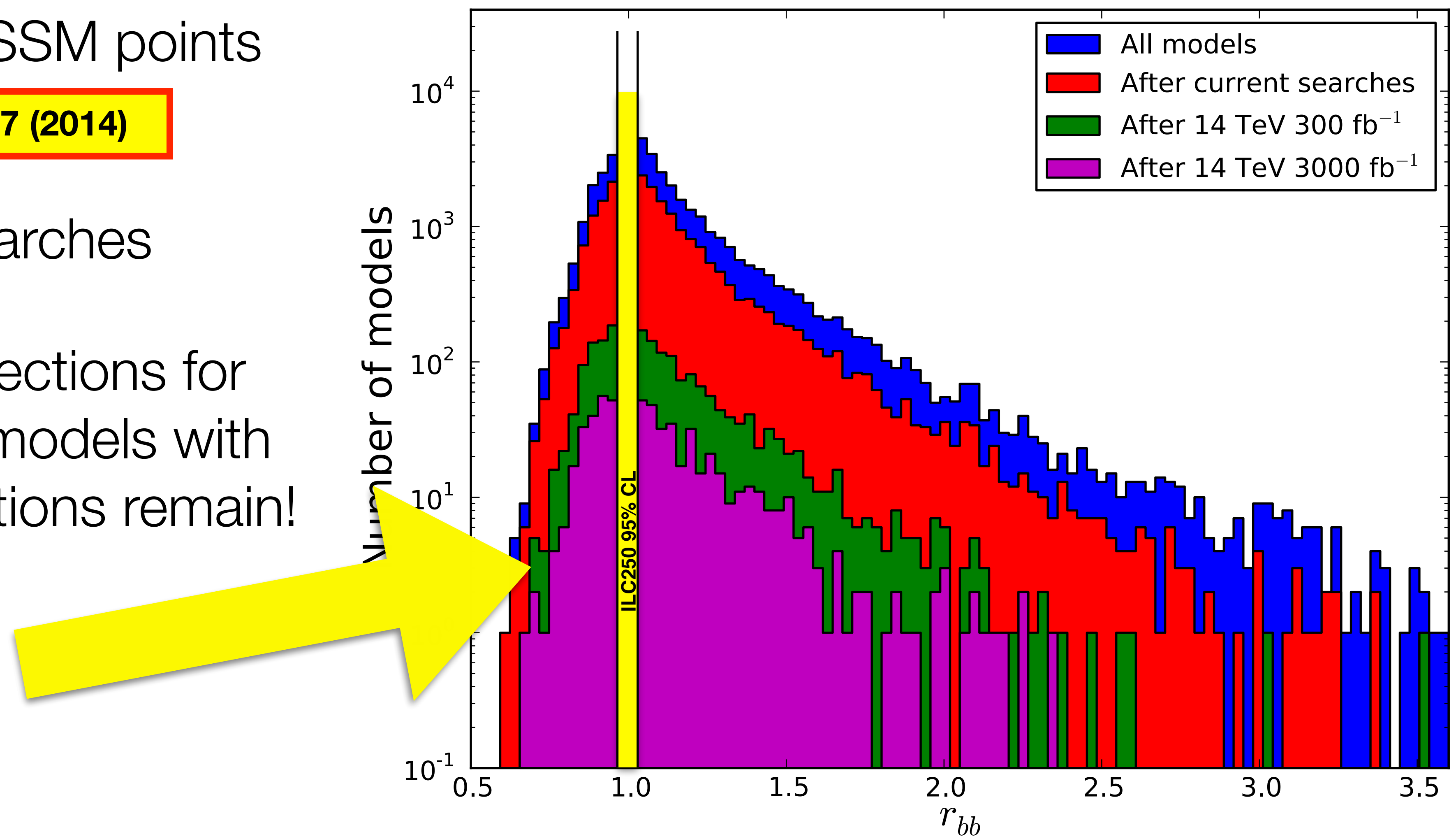

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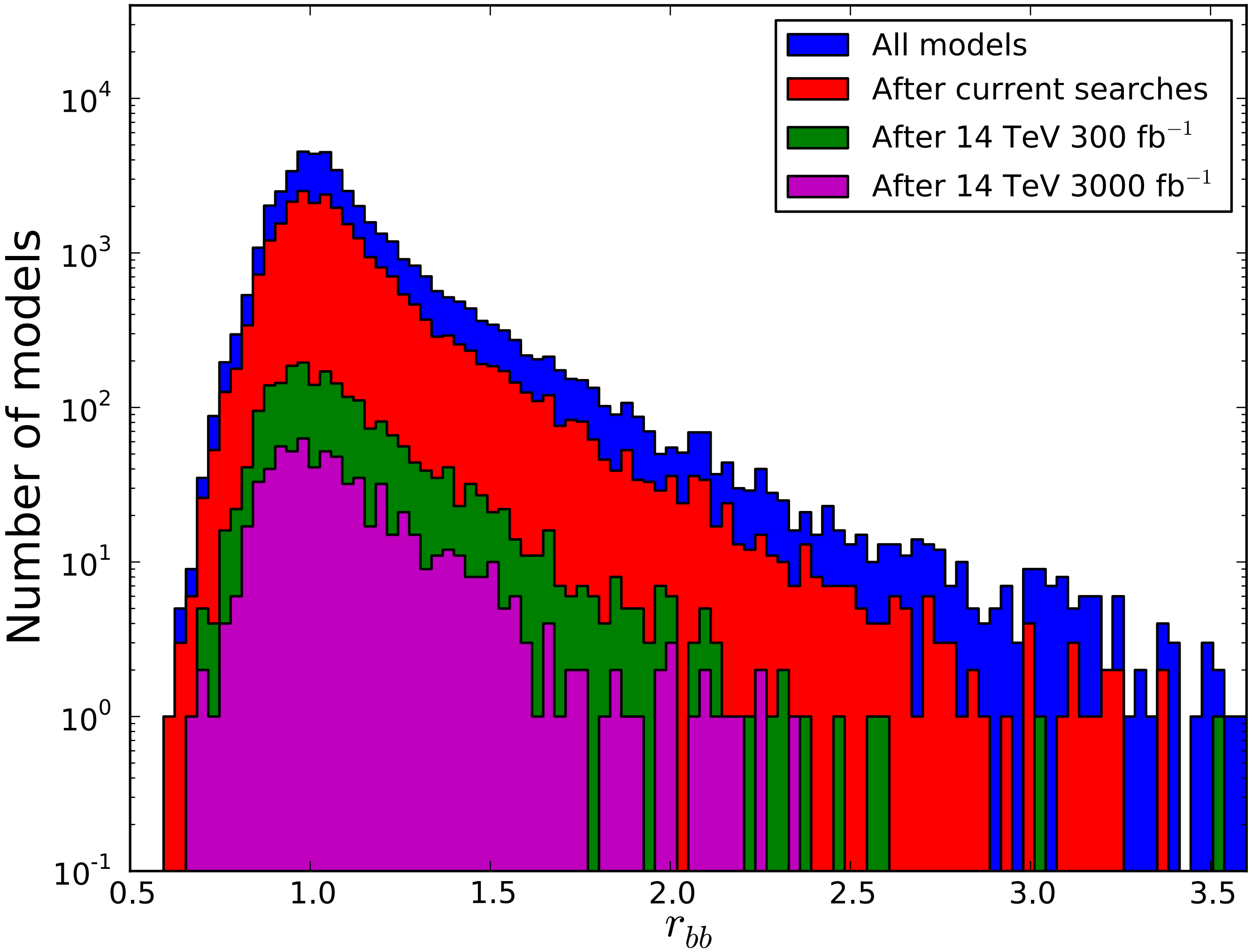

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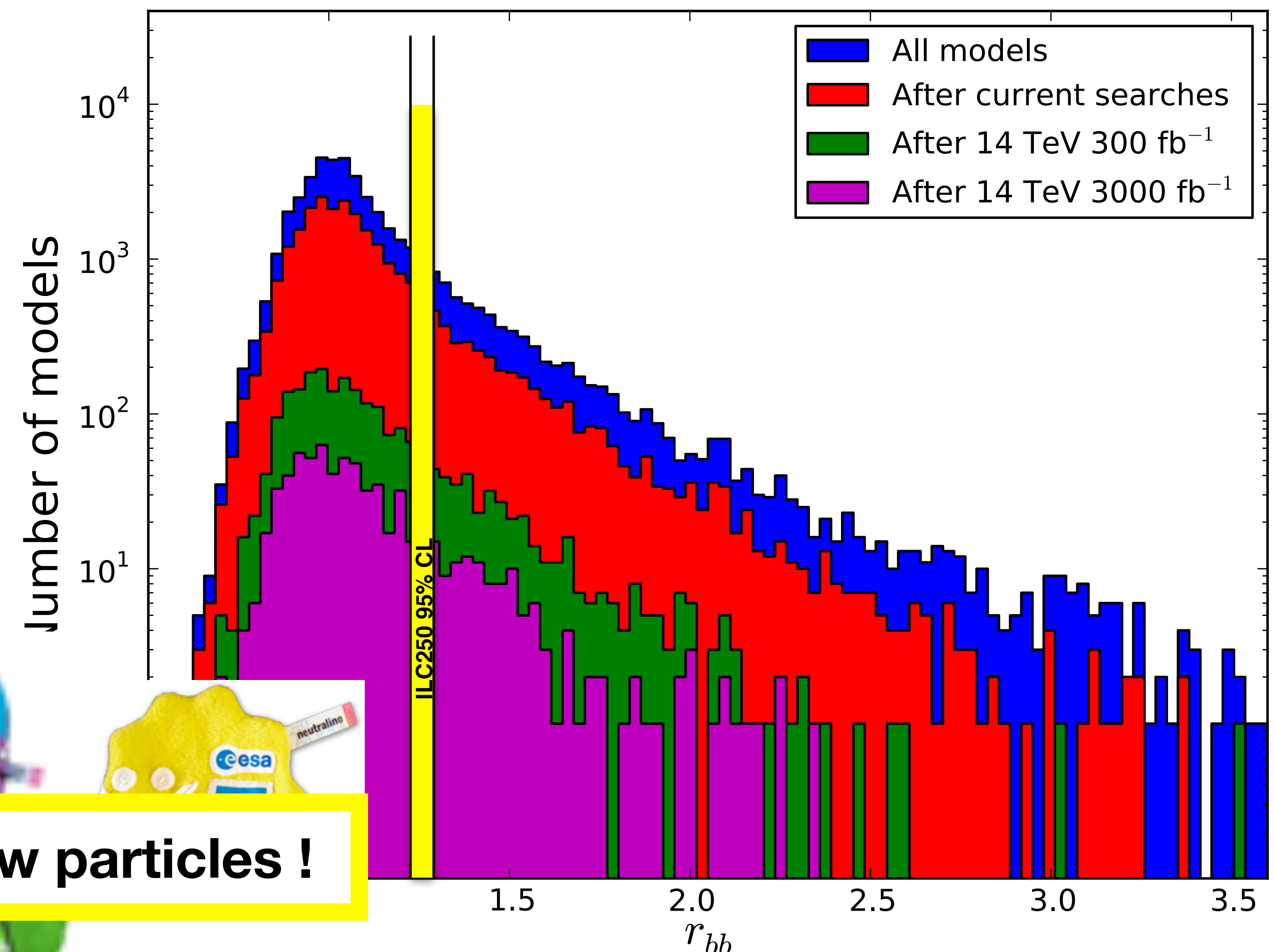

Discovery of new particles !

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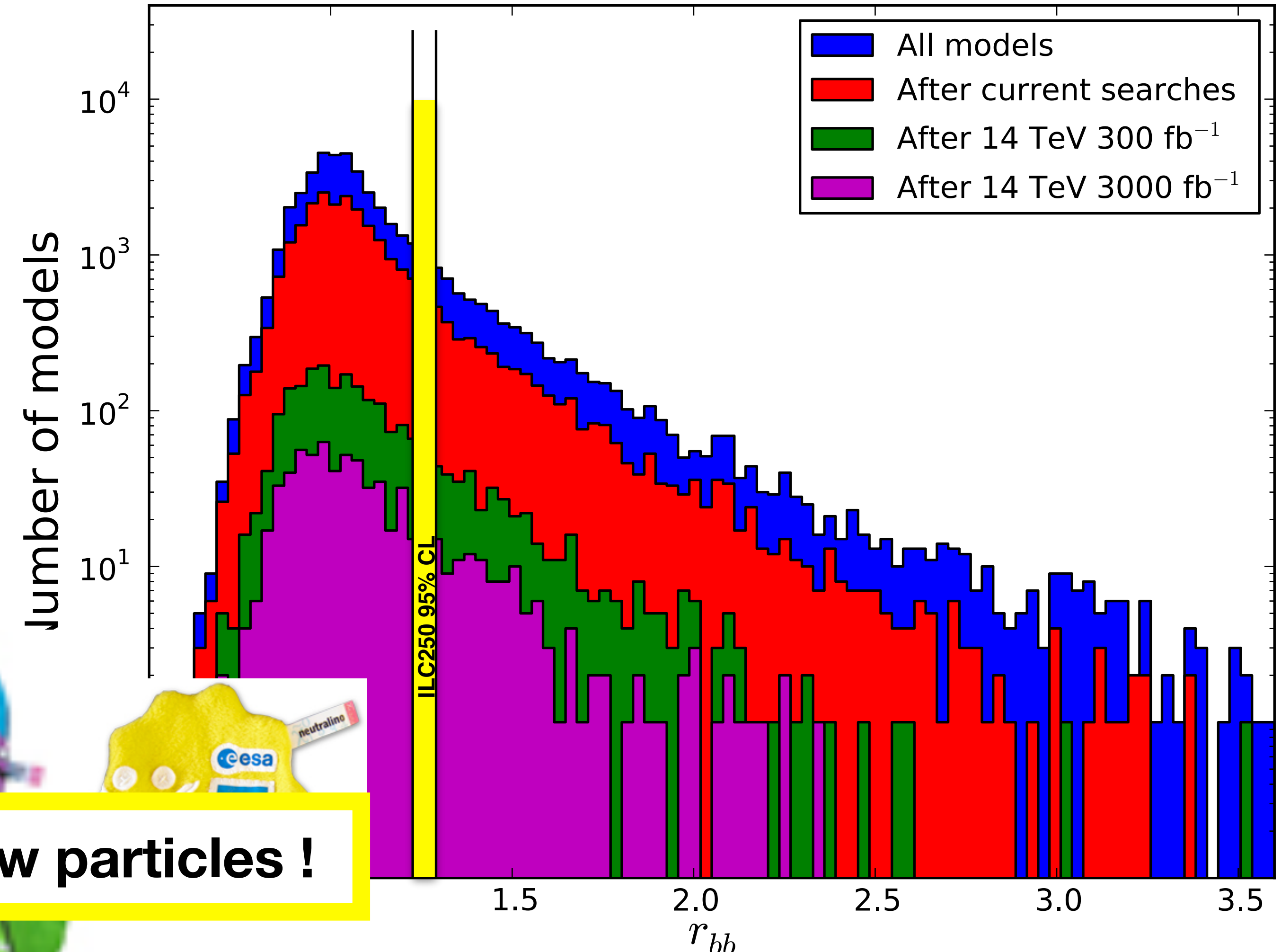

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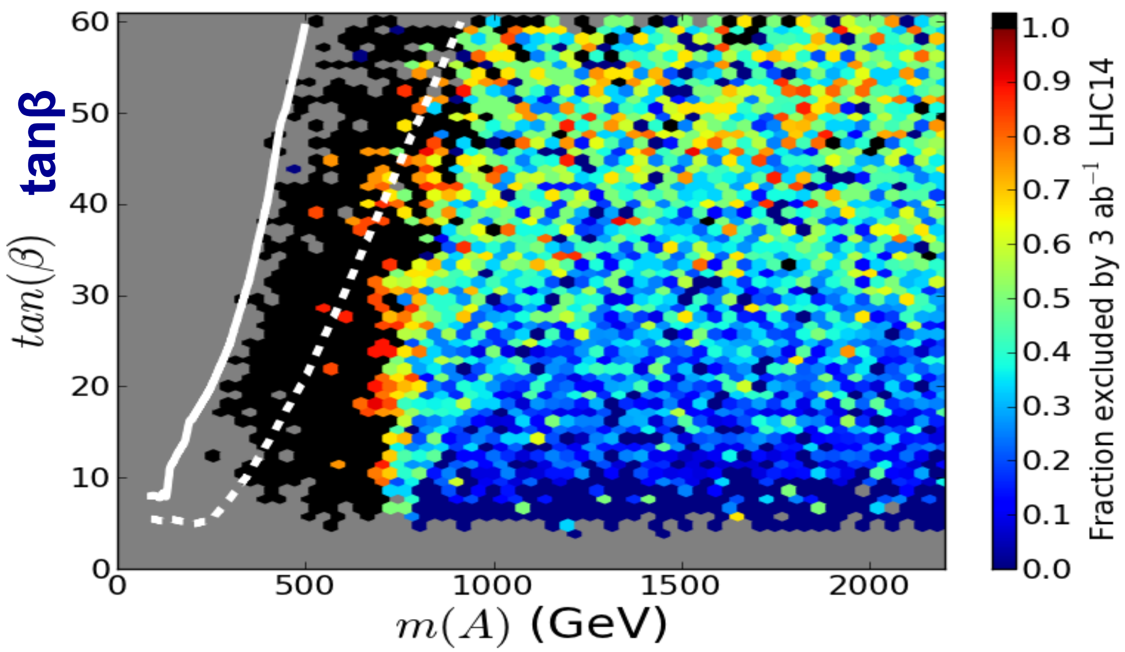
$$r_X = \frac{\Gamma(h \to X)}{SM}$$

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

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

HL-LHC 3000 fb-1

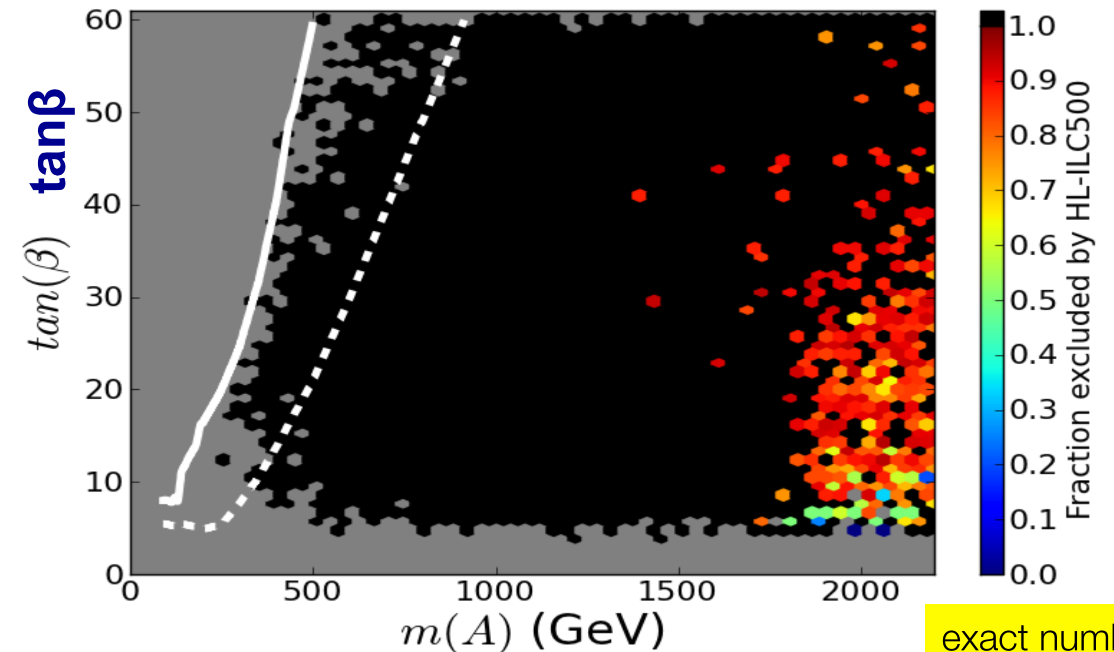
tanβ



Heavy Higgs mass

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

tanβ



Heavy Higgs mass

exact numbers outdated

Discoveries of new particles ?

Phys. Rev. D 90, 095017 (2014)

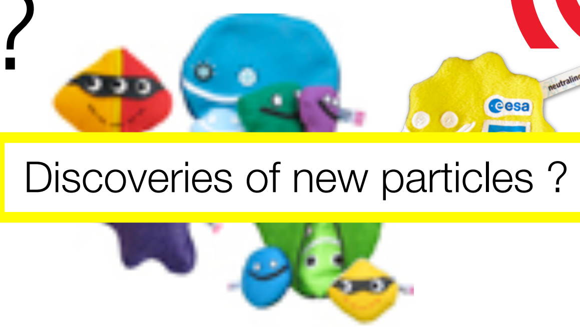
- colour scale: fraction of scan points excluded via coupling precisions
- white lines: LHC / HL-LHC direct search reach for heavy Higgses

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

Looking for more new friends

Discoveries of new particles ?

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, ….

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**!

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

Example 1: Extra Higgs Bosons

- 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
- **or recoil against Z**
    - **even if coupling strongly reduced!**
    - quantitative studies in full detector simulation ongoing

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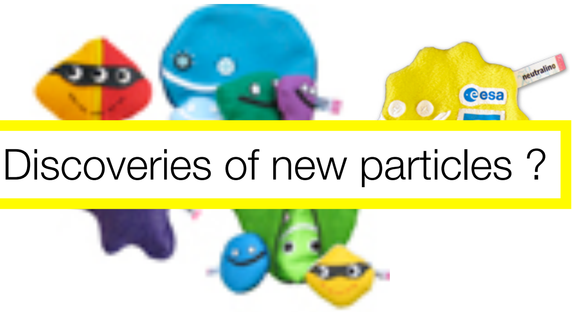

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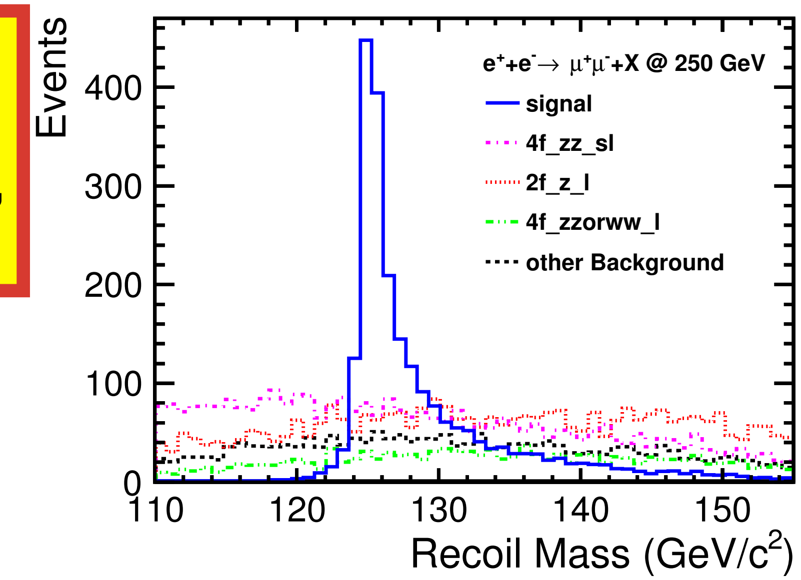
SM Higgs: ILD full simulation Phys. Rev. D 94, 113002 (2016)



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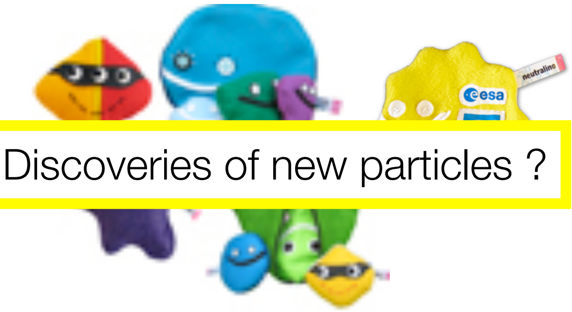

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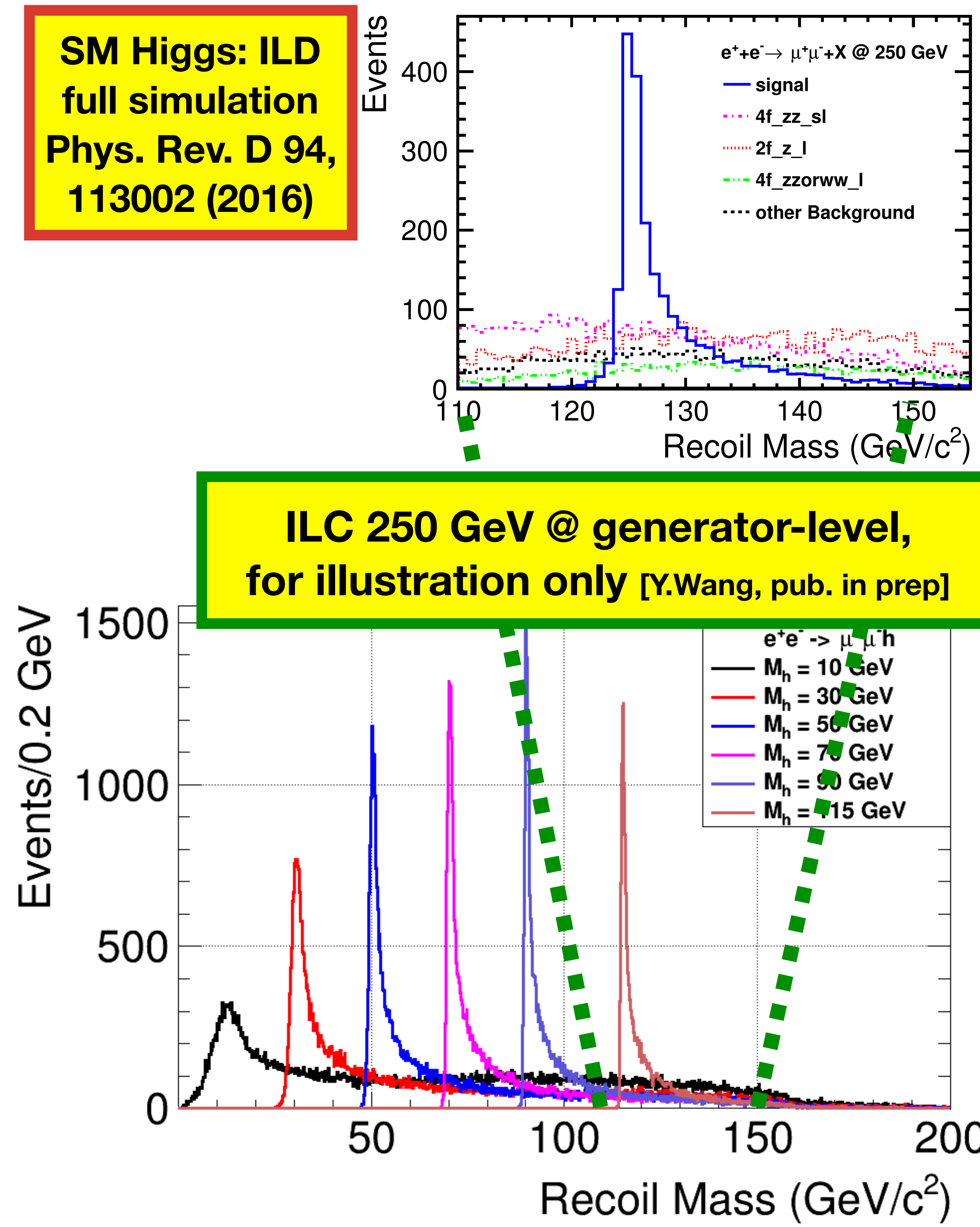

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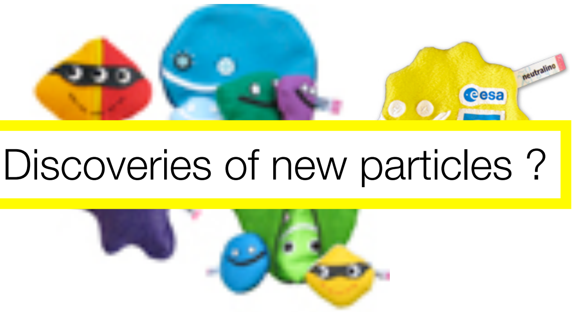

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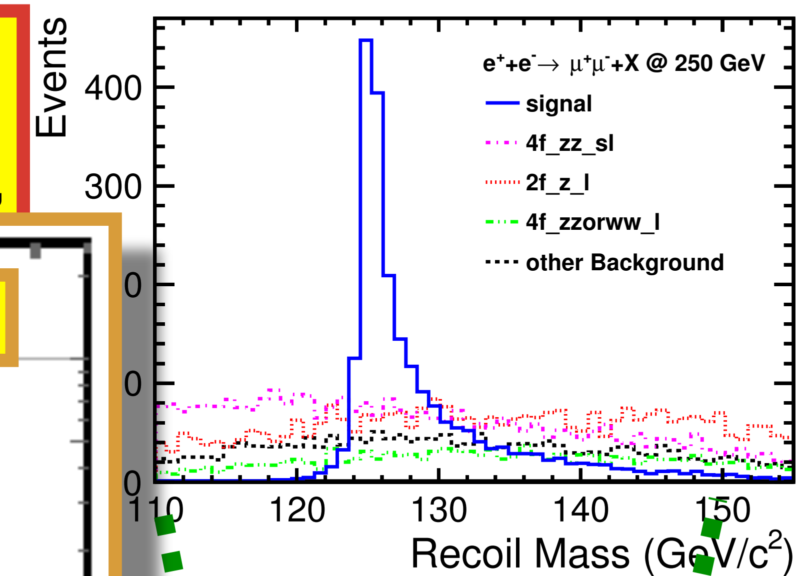
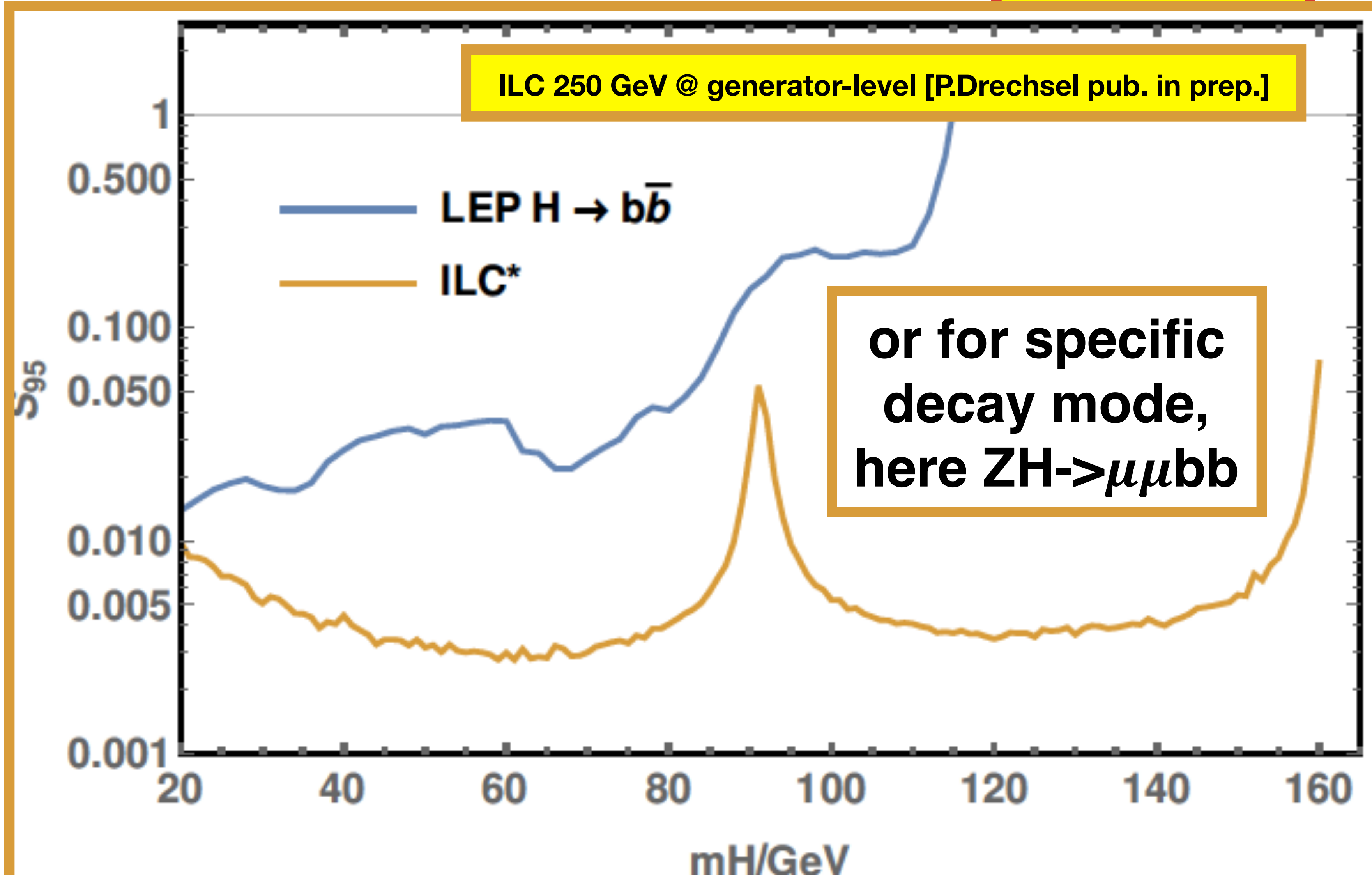
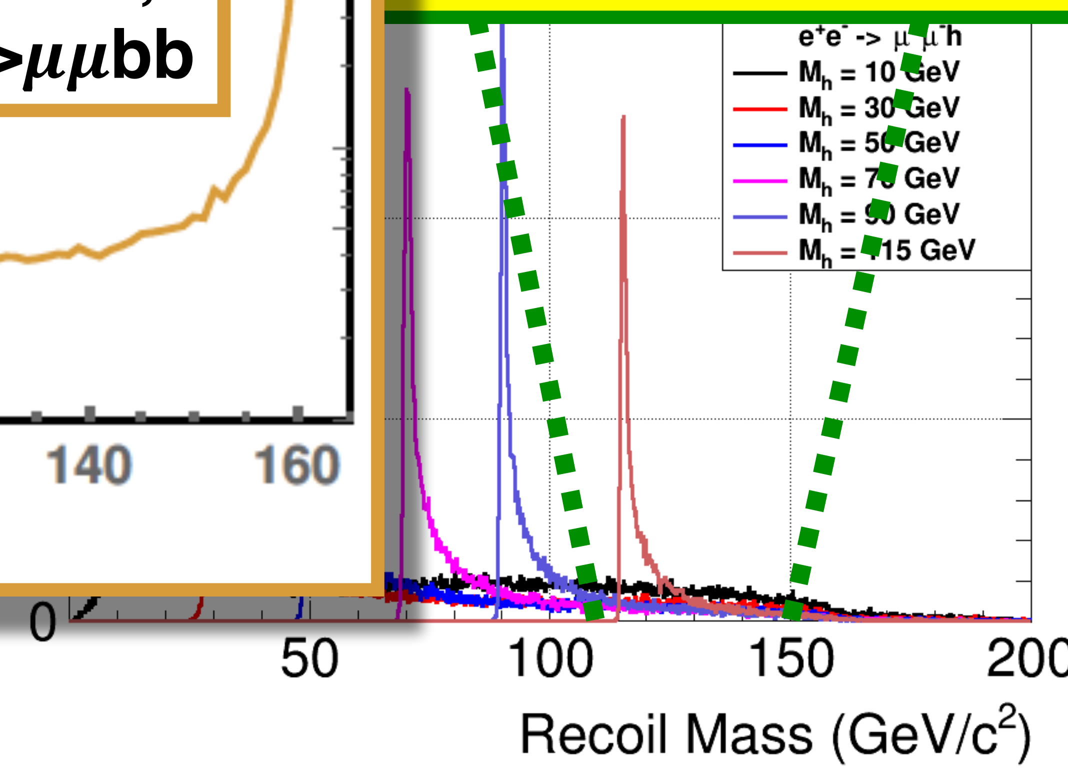


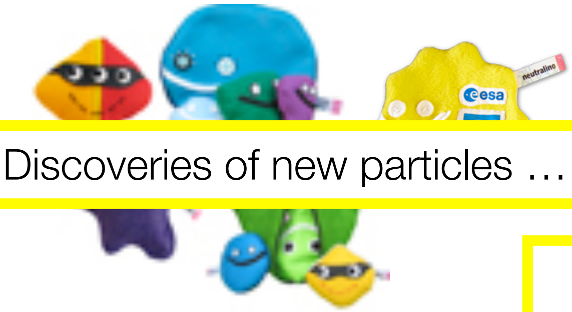


GeV @ generator-level, ation only [Y.Wang, pub. in prep]

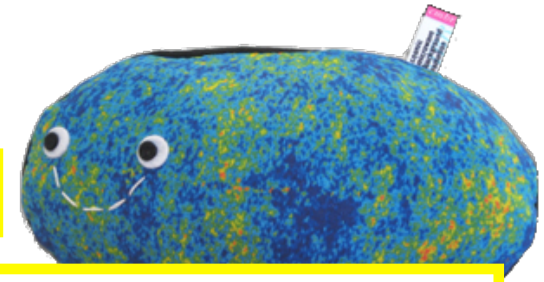


detector simulation ongoing

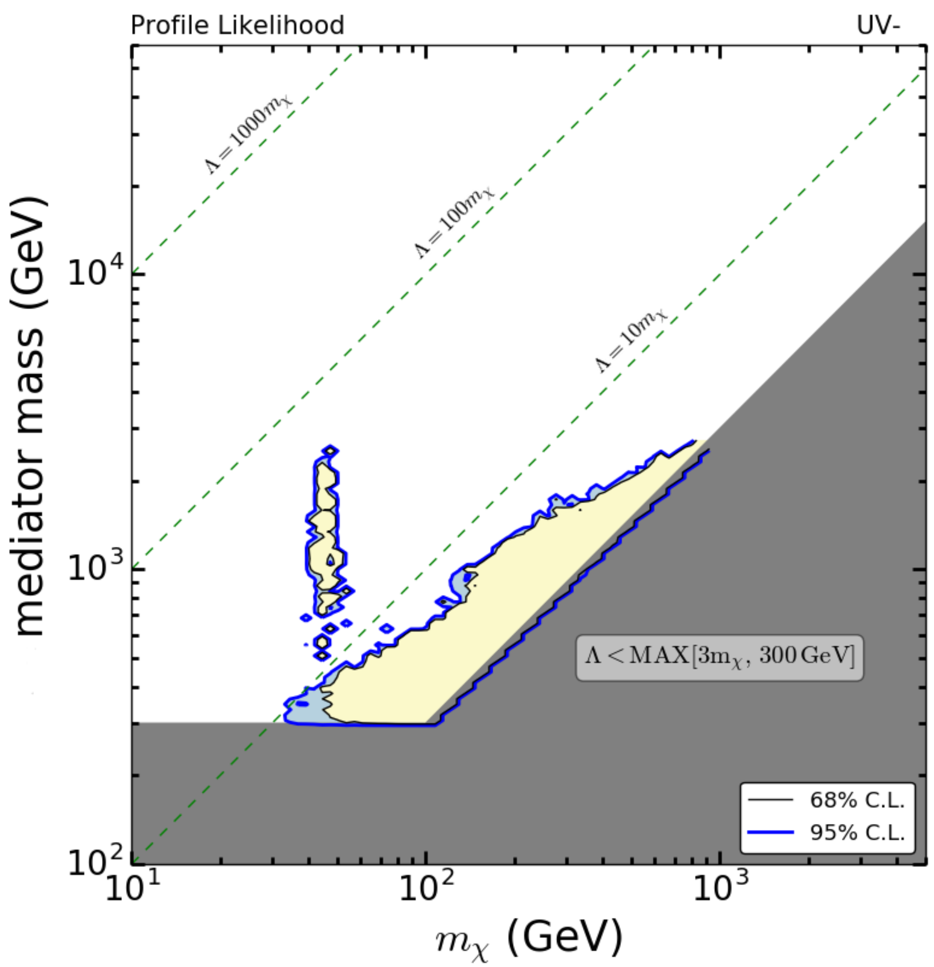
Example 2: WIMPs



Discoveries of new particles …



…and the universe

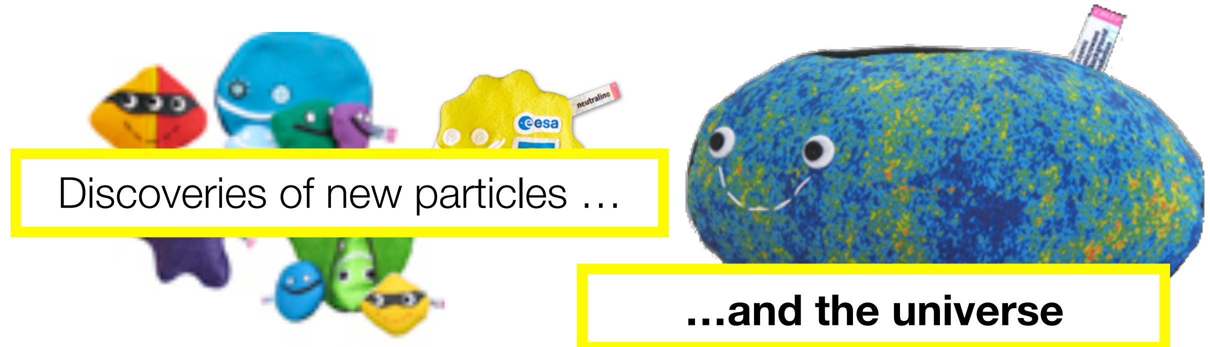


- likelihood scan over WIMP parameter space including existing and future direct, indirect and collider experiments (apart from ILC)
- e.g. here: singlet like fermion WIMP

=> 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
  - **up to ~1.9 TeV @ 250 GeV**
  - up to ~3 TeV @ 500 GeV



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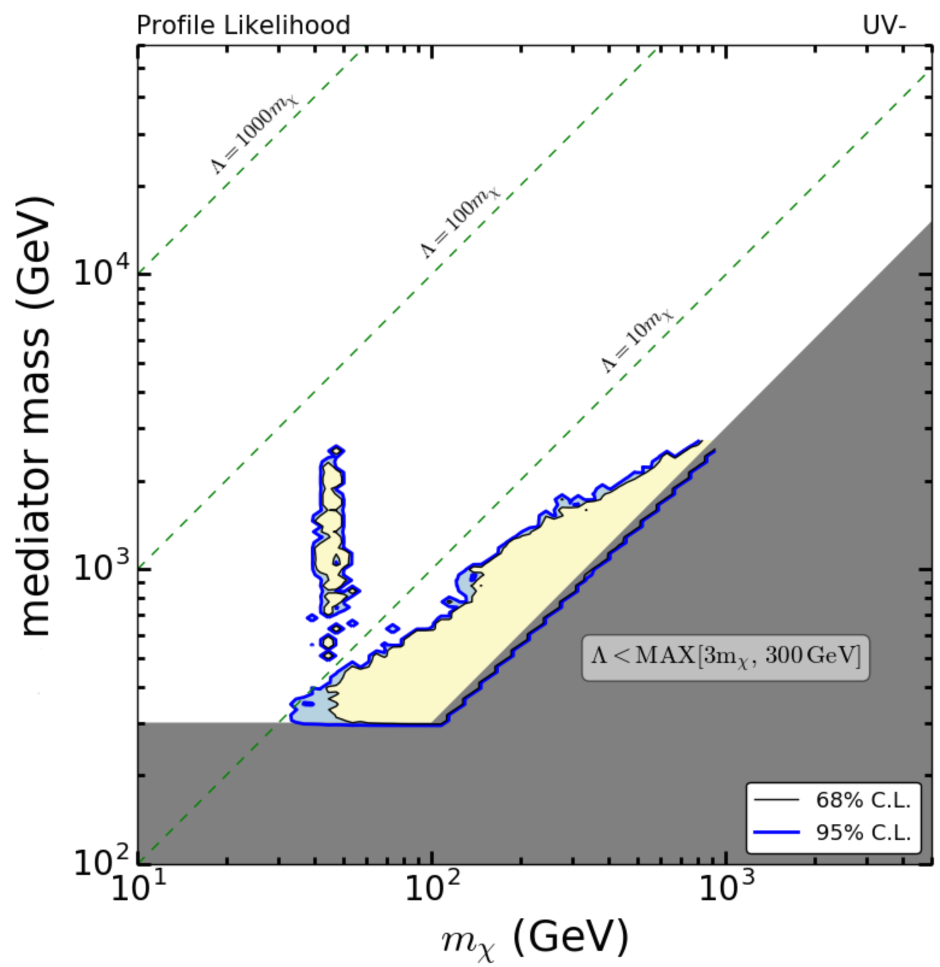

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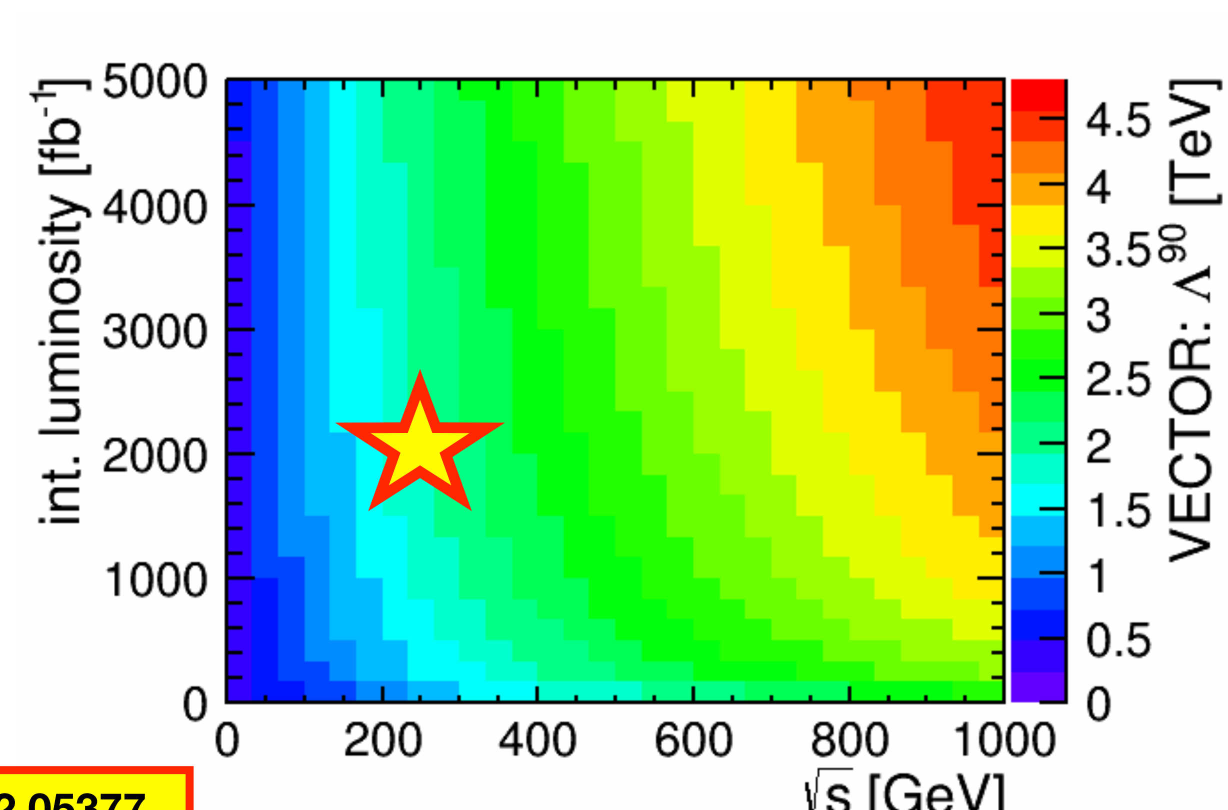
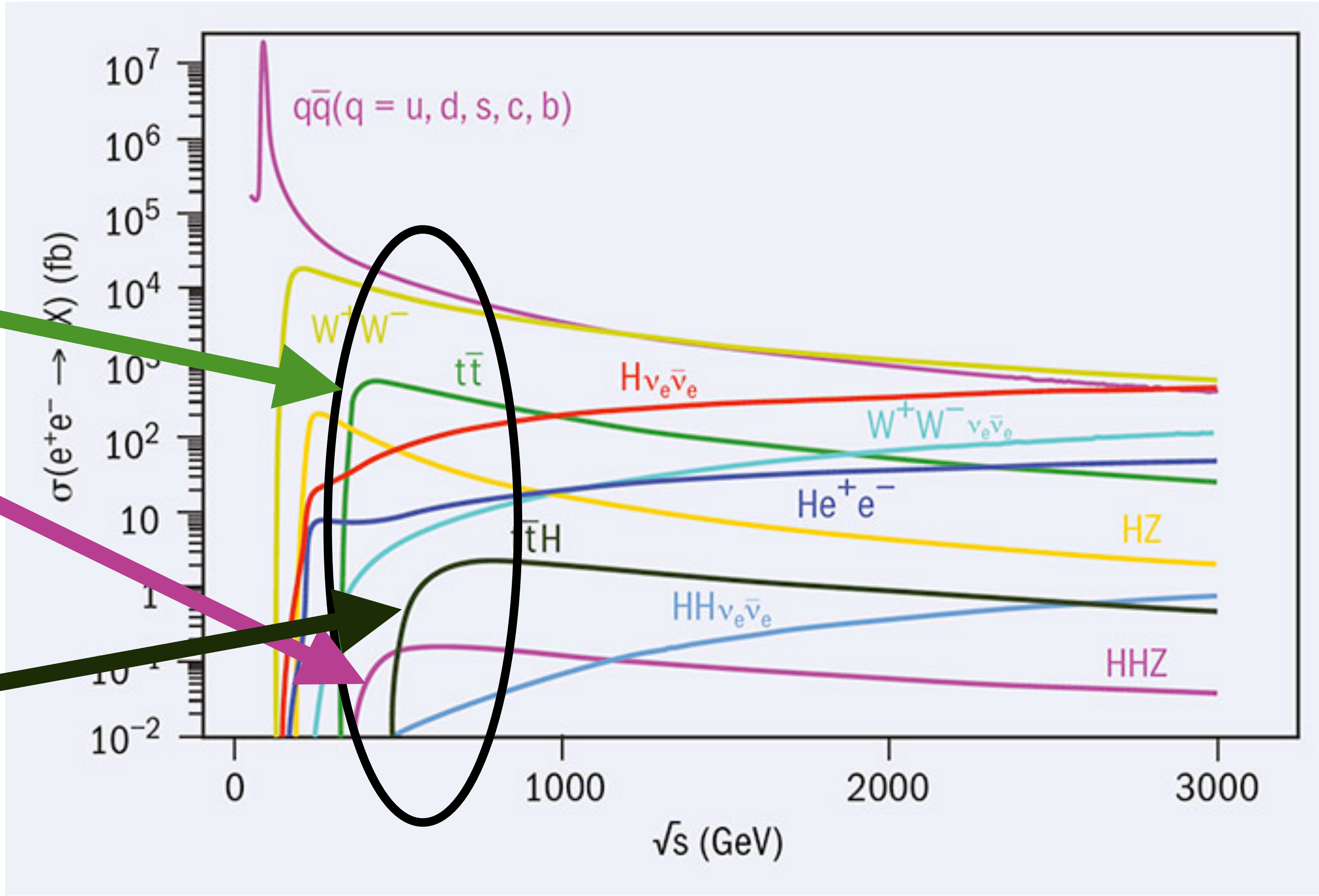


arXiv:1702.05377

Why 250 GeV cannot be the end…

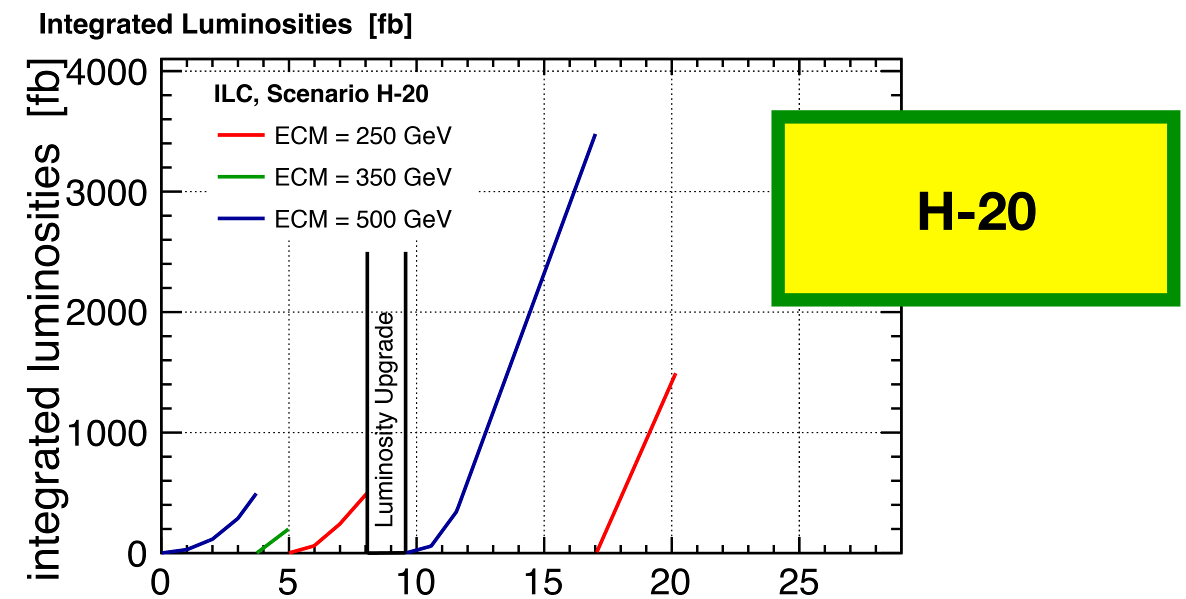
- **tt : ≳ 350 GeV**
- **ZHH : ≳ 450 GeV**
- **ttH : ≳ 500 GeV**

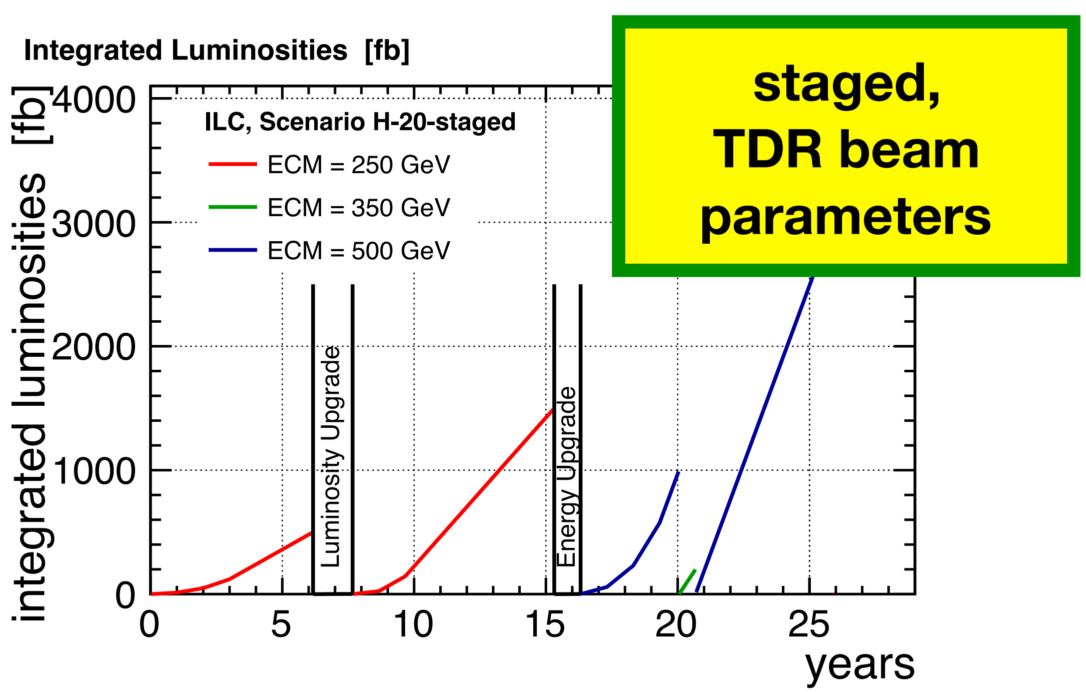


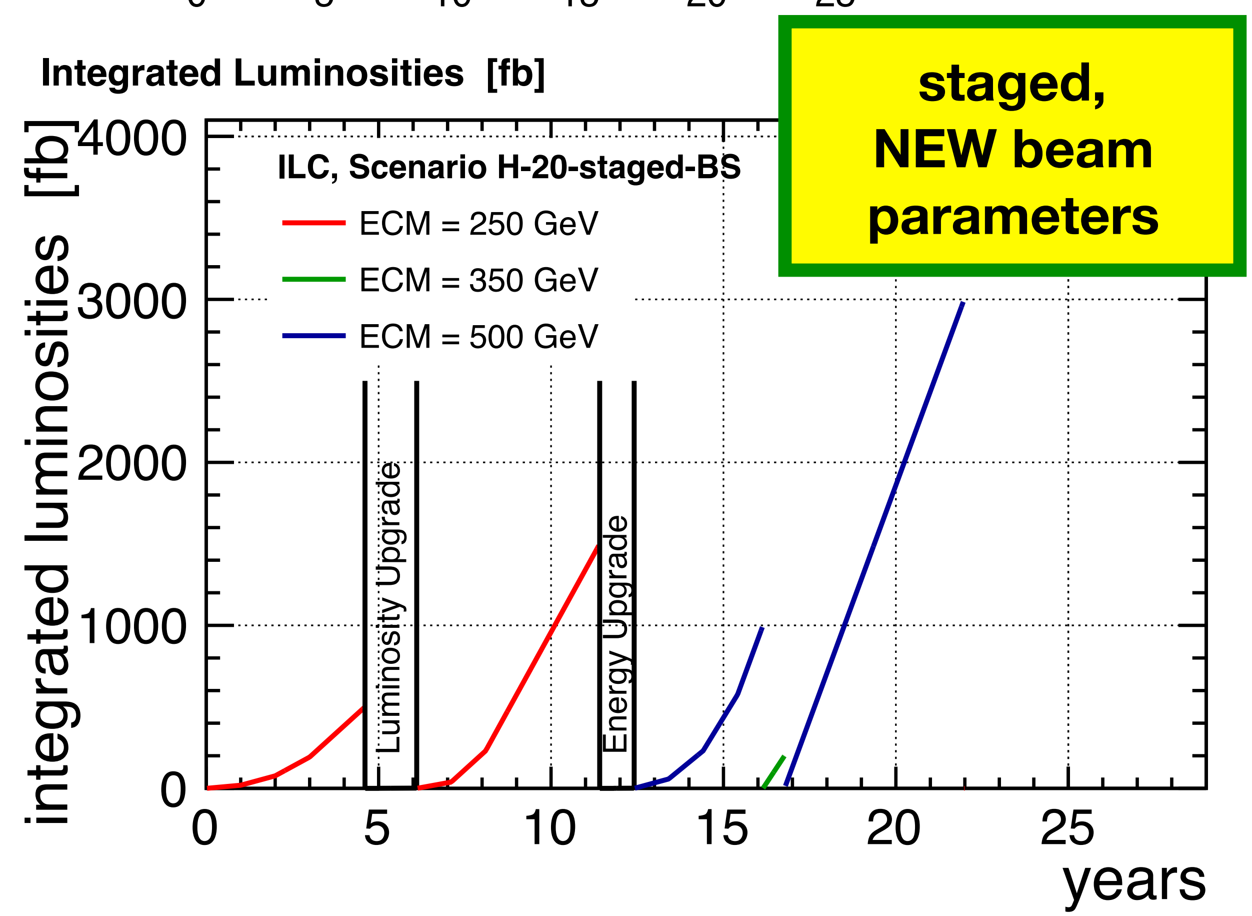
Looking beyond 250 GeV

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

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



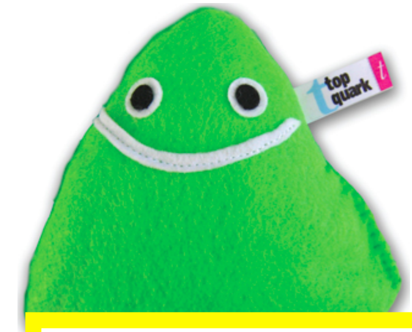




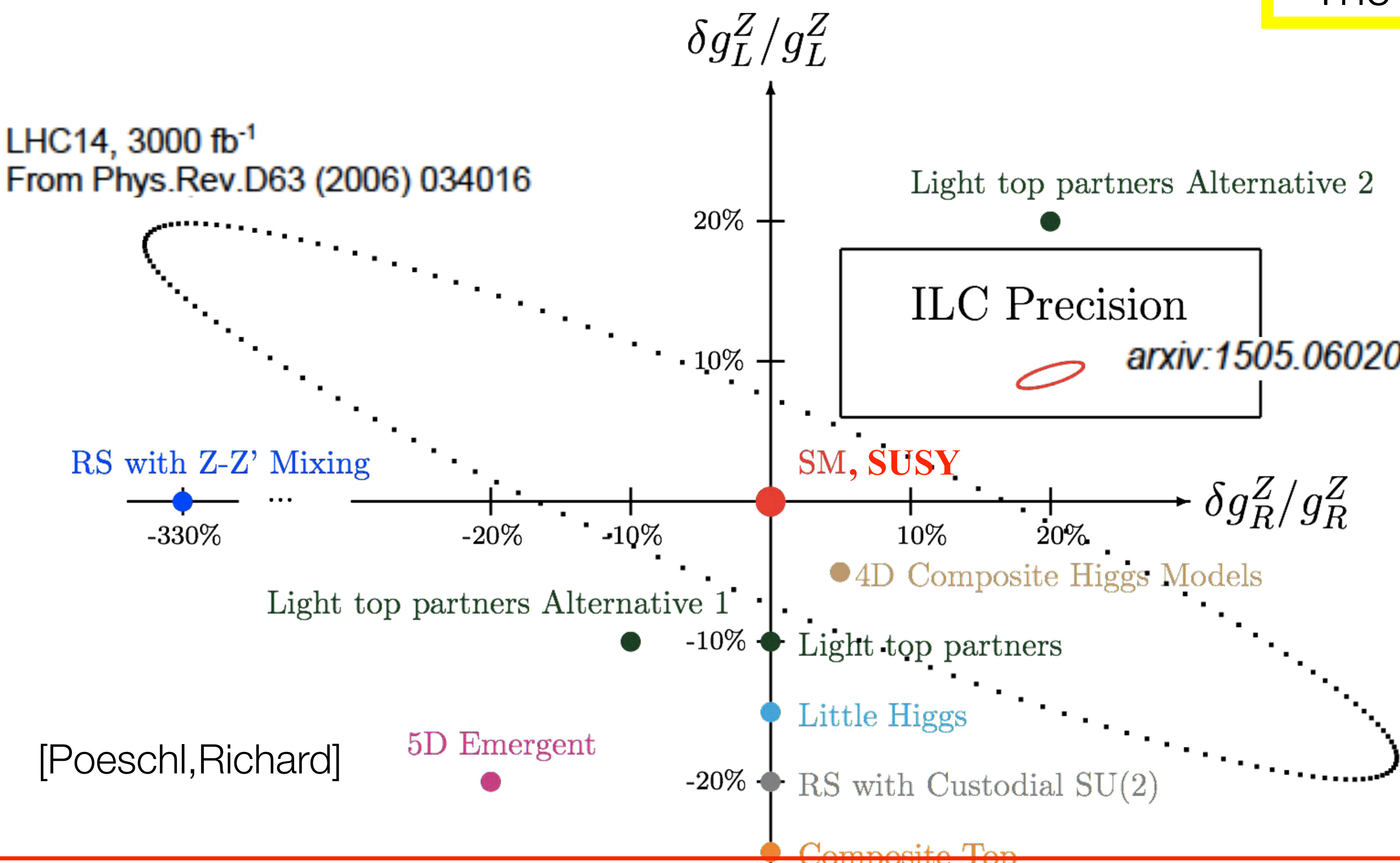
350/380 GeV: top pair production threshold

Will be covered by Igor in the next talk!

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)

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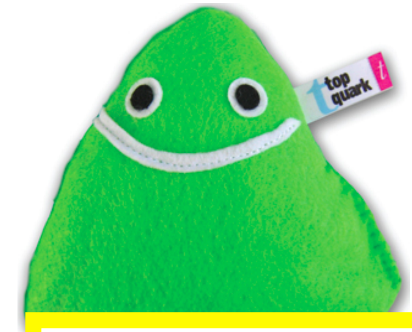

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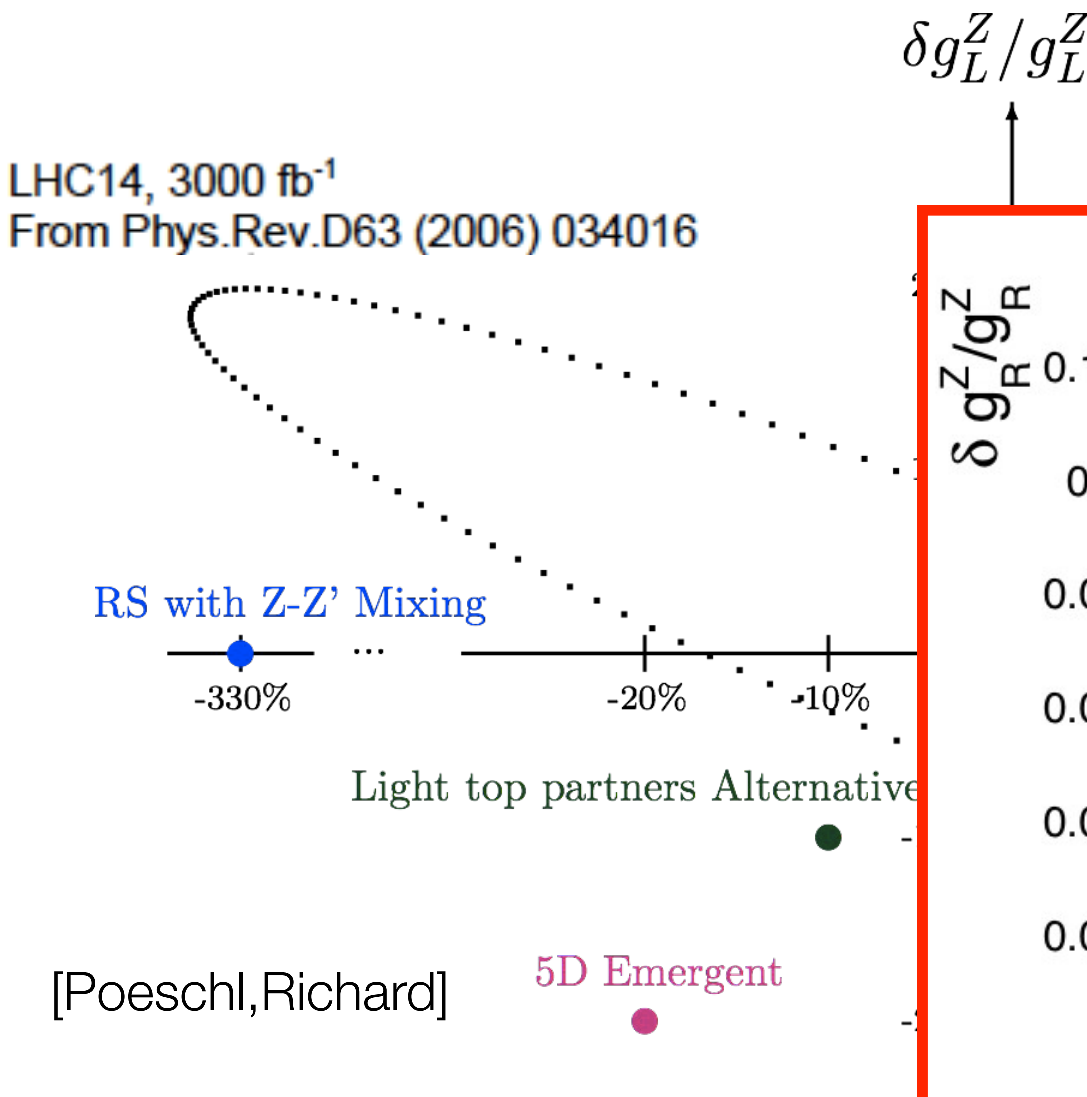

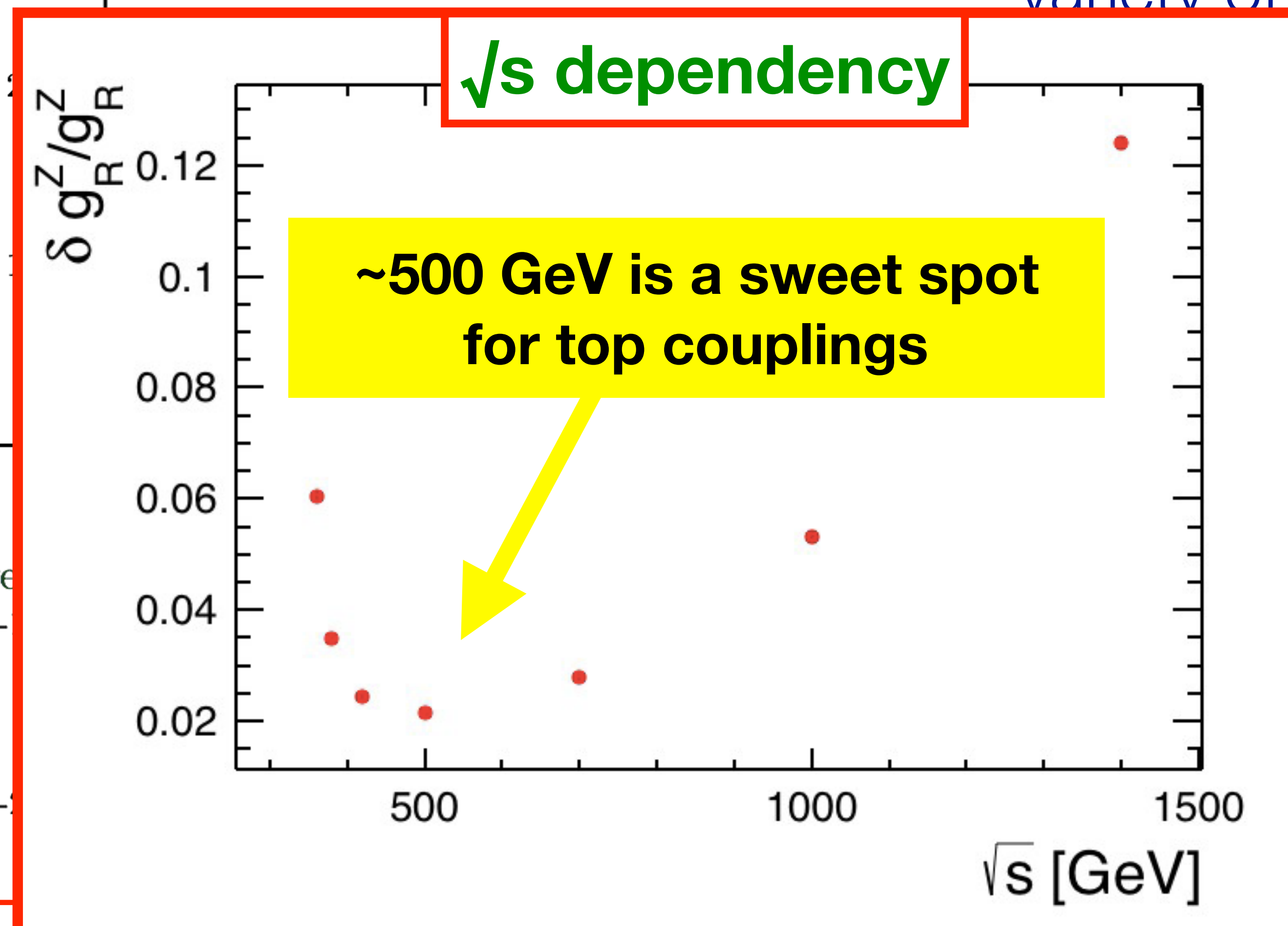

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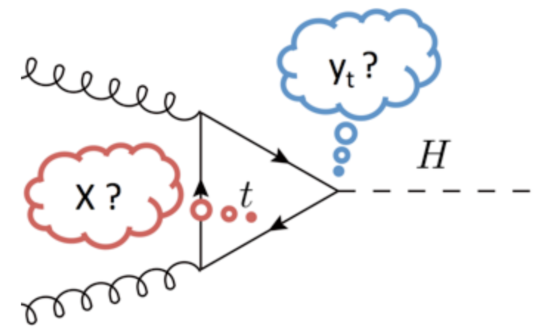
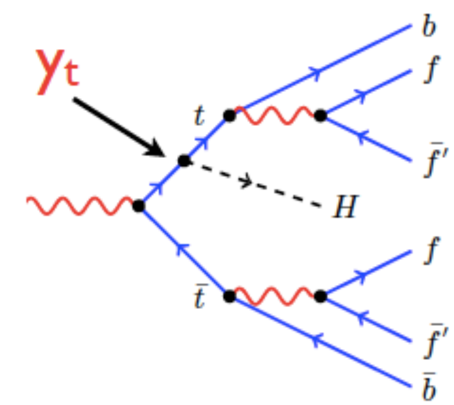
The Higgs and the Top

Direct Determination of the Top Yukawa Coupling

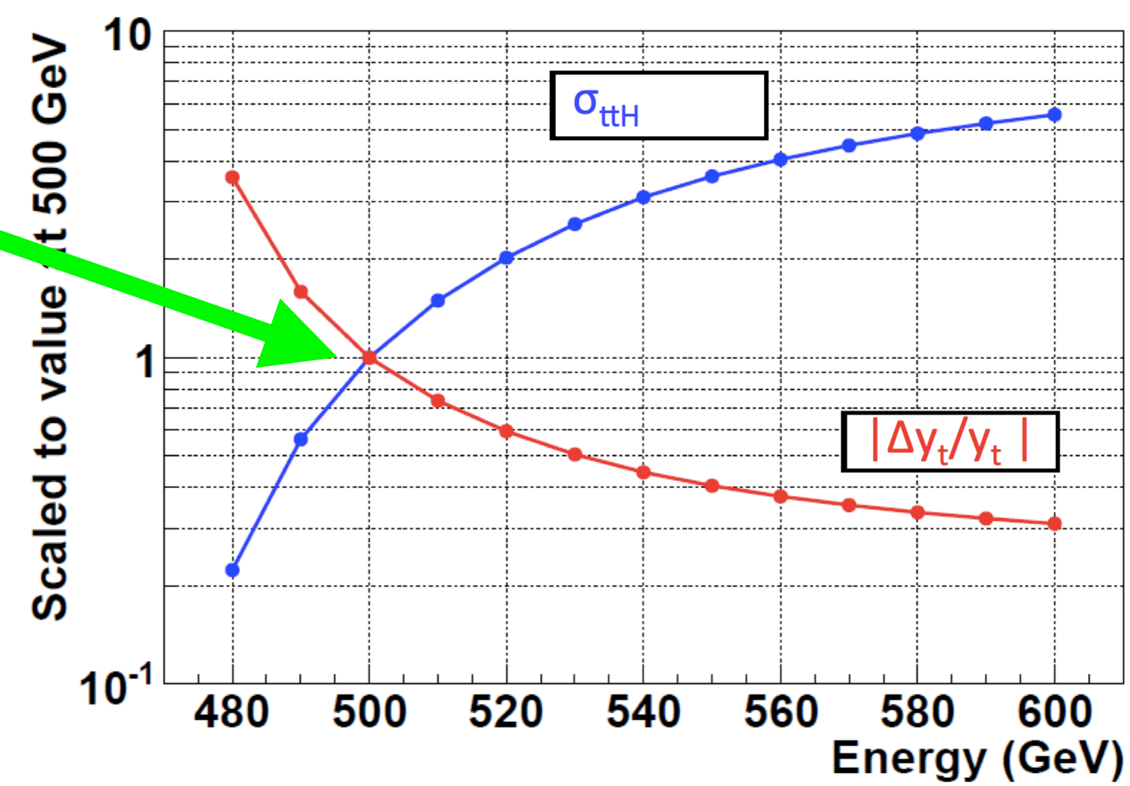
- **(HL-)LHC 14 TeV:**
  - SM σ(ttH) = 0.6 pb
  - "theory" studies indicate δ**y$_t$ ~15% (~10%)** with 300fb^{-1} (3ab^{-1}) might be possible

arXiv:1310.8361





- **e$^+$e$^-$:**
  - **threshold at √s = 475 GeV**
  - SM σ(ttH) = 0.45fb @ 500 GeV
    => ILC full running scenario:
    δy$_t$ = 6.3%
  - could be **2.5% if √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]
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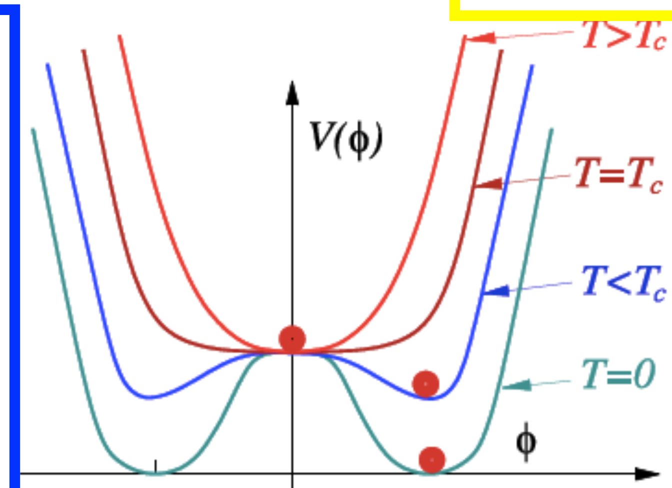
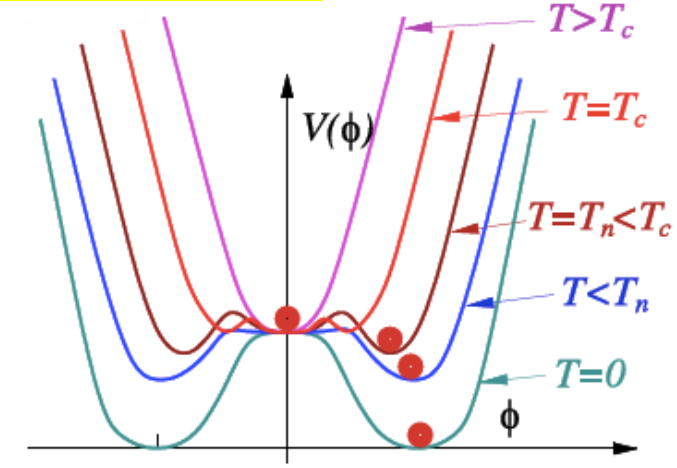
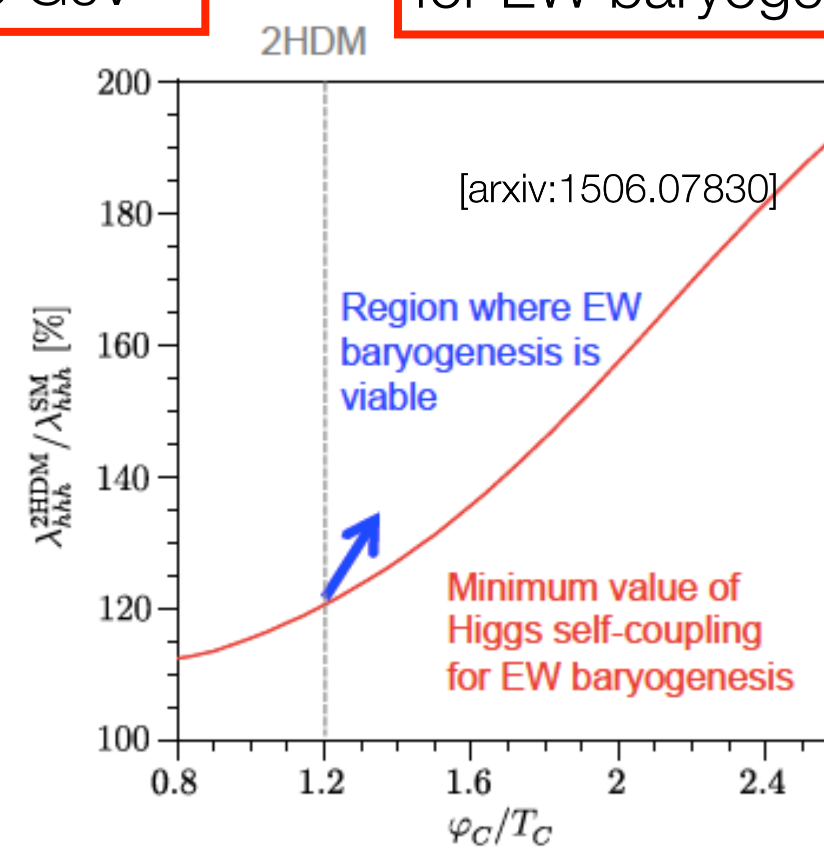


2nd order, SM with M_H = 125 GeV



1st order, required for EW baryogenesis



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.:
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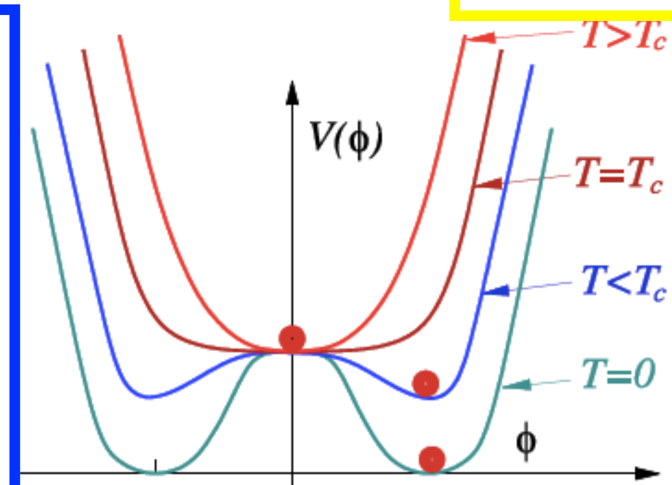

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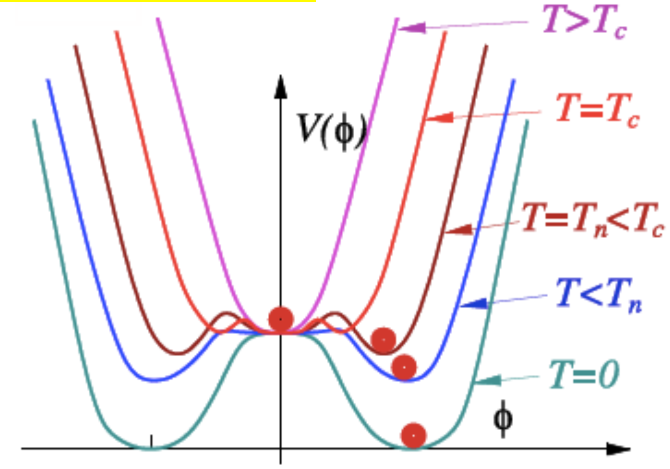
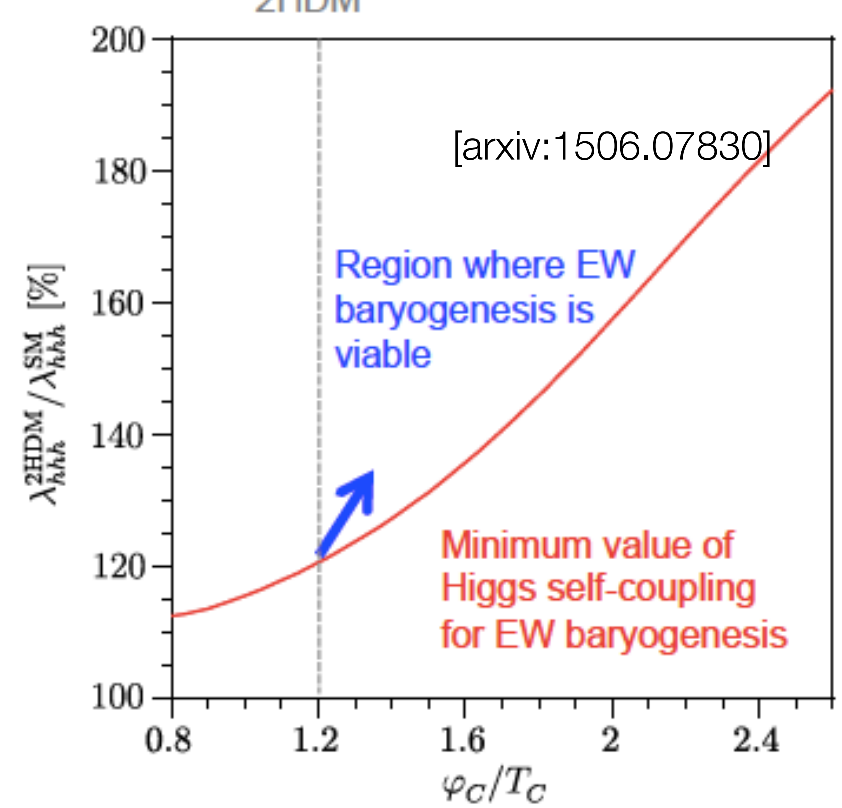


1st order, required for EW baryogenesis

- 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

2HDM



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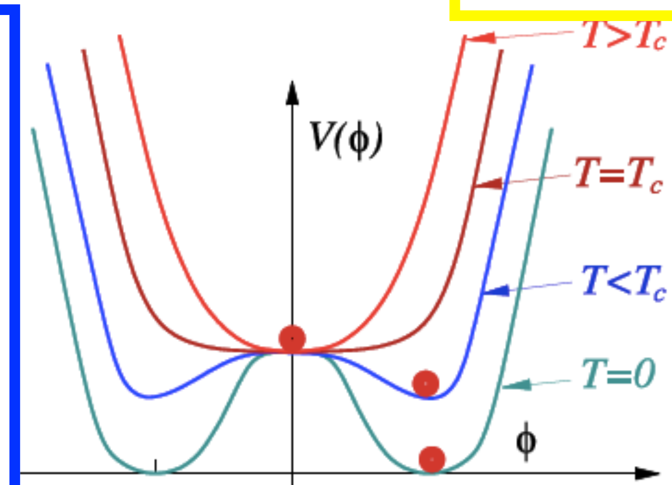

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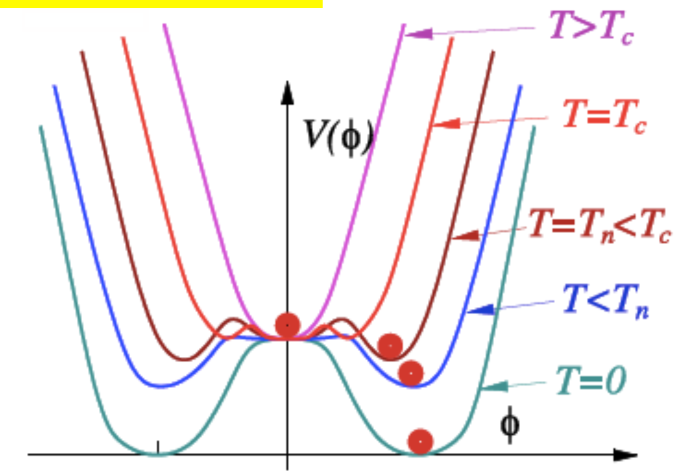

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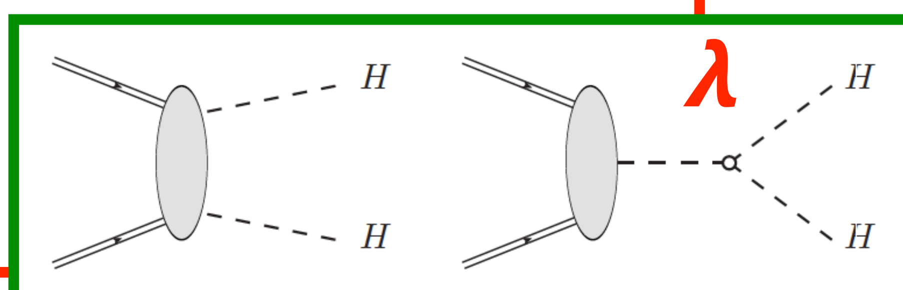
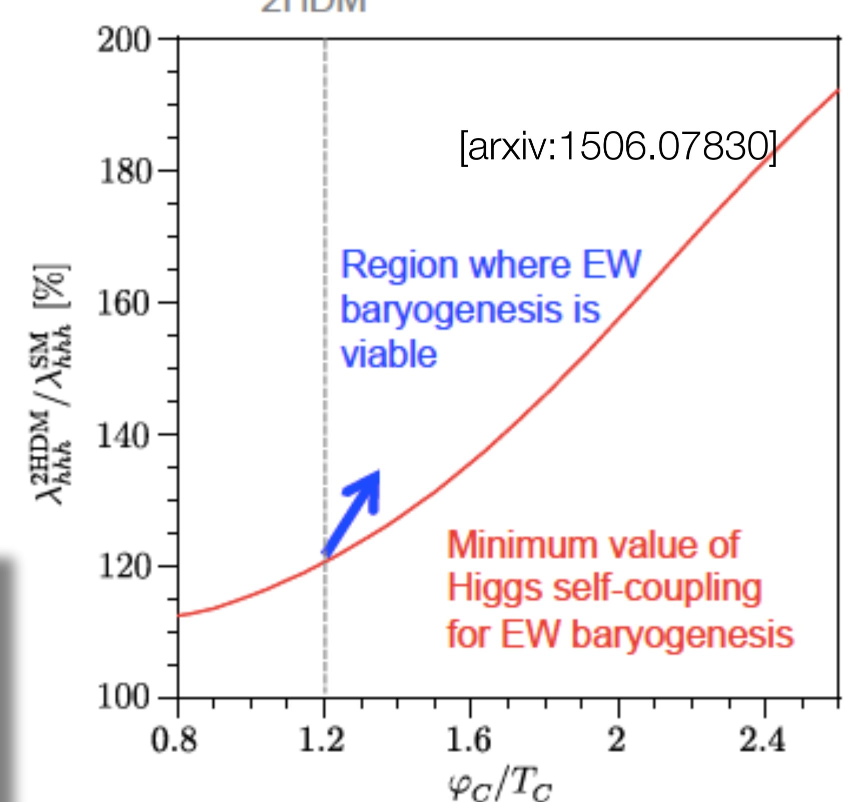
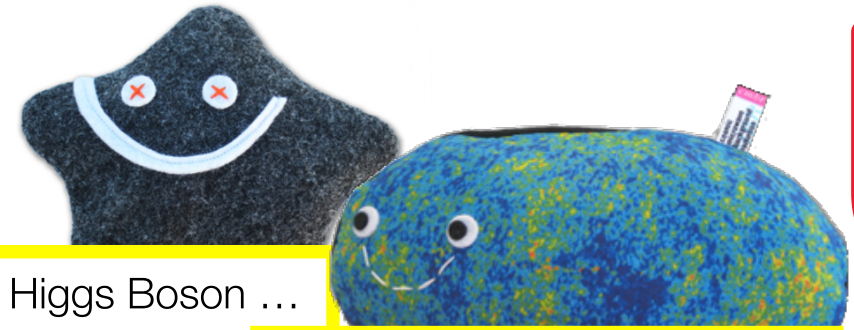


2HDM



Measurement Prospects

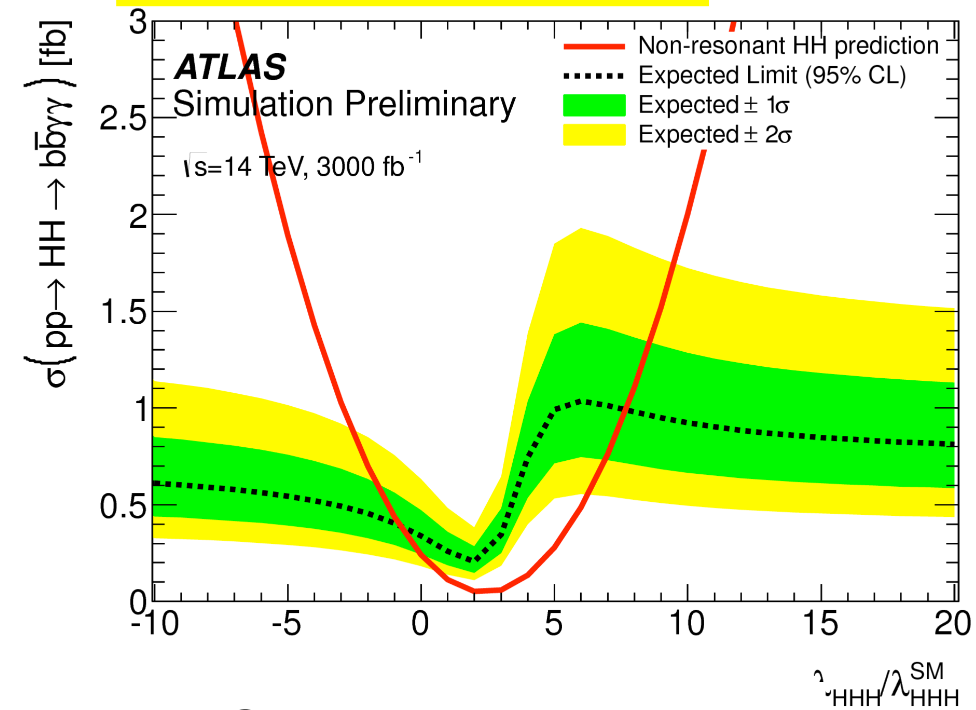


The Higgs Boson …

…and the universe

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

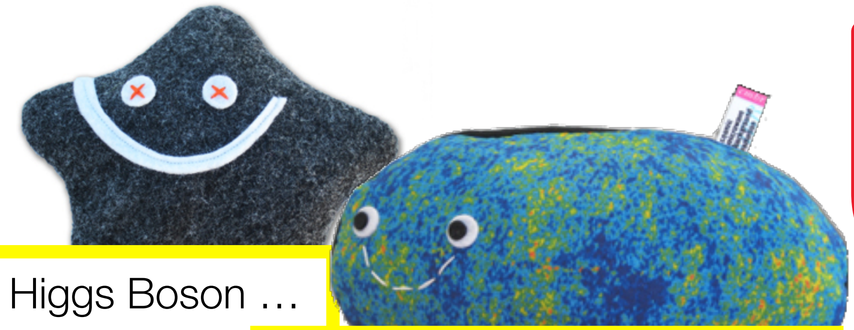
- **e^+e^- at 500 GeV, ZHH, full simulation:**
  1. Observation of HH with ~8σ ✔
  2. extract $\lambda|_{SM}$ with 27% uncertainty
  3. recent demonstration that parametric uncertainties from other couplings well under control with full ILC Higgs program

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

Measurement Prospects



The Higgs Boson …

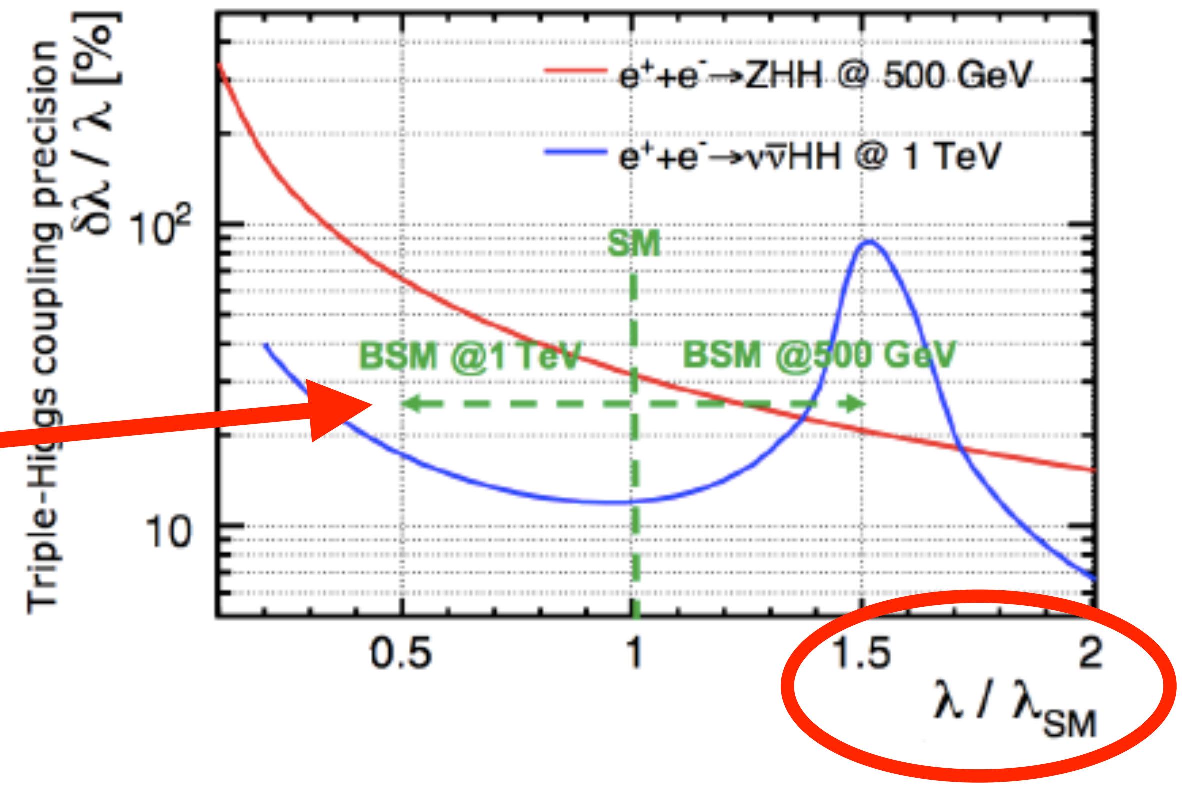
…and the universe

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!



Dissertation C.Dürig, Uni

3. recent demonstration that parametric uncertainties from other couplings well under control with full ILC Higgs program

arXiv:1708.09079

- 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)

Conclusions

- The next generation of collider must address the big open questions of particle physics and expand our understanding of the universe
- **A 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

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

- … and beyond a first step at 250 GeV:
  - ★ explore three additional important thresholds up to ~500 GeV
  - ★ **Linear Colliders are intrinsically energy upgradable!**

Backup

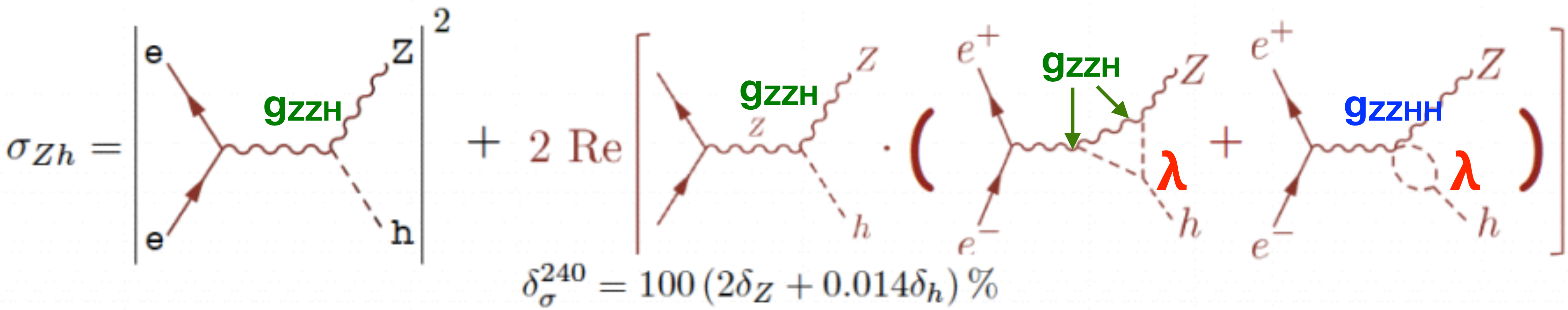
Higgs coupling precisions (in %)

	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
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
[illegible]	[illegible]	[illegible]	[illegible]	5.1
[illegible]	[illegible]	[illegible]	[illegible]	2.6
[illegible]	[illegible]	[illegible]	[illegible]	0.46
[illegible]	[illegible]	[illegible]	[illegible]	0.65
$g(hWW)/g(hZZ)$	[illegible]	[illegible]	[illegible]	0.05
Γ_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

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

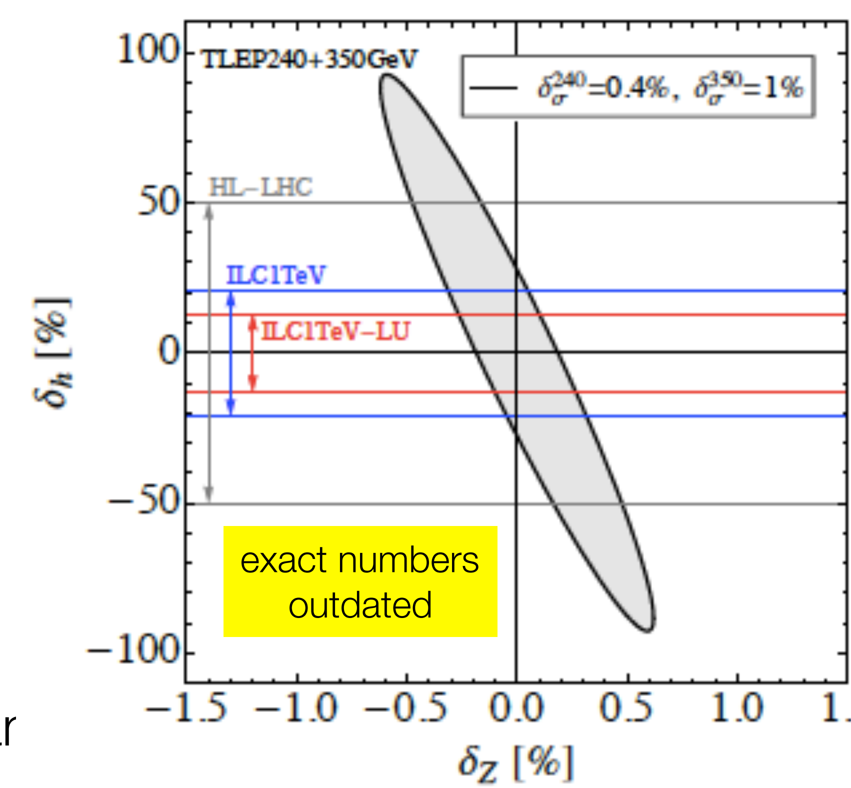
✔

Higgs self-coupling from loop corrections?



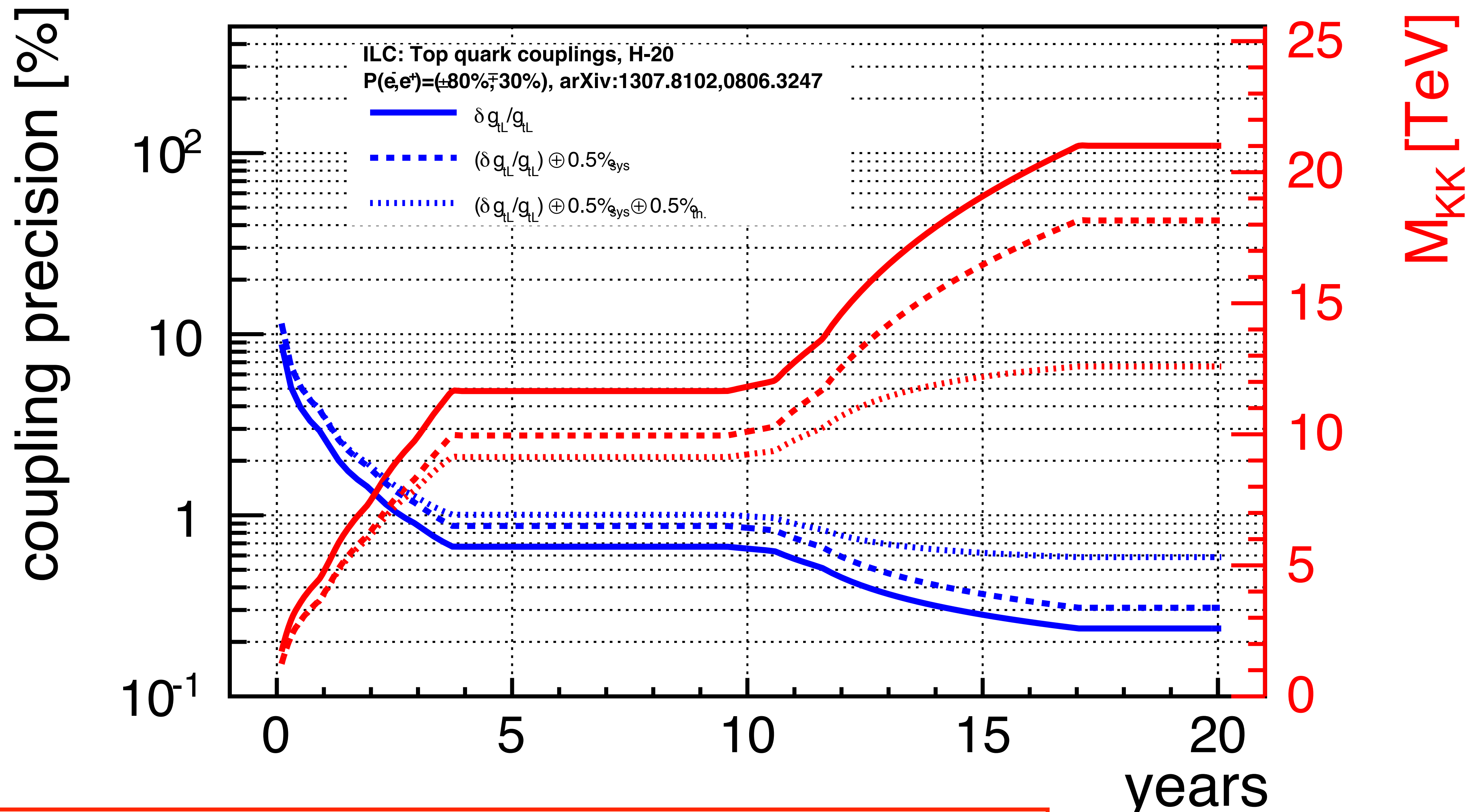
- sub-% precision on σ_{ZH} possible at all proposed e+e- colliders
- however: indirect and model-dependent method
- interesting consistency check, *not* an independent measurement
- n.b.: what about other loop contributions?
  - top -> y_t ? W -> g_{WWH} ?
  - or even BSM ?
- **better look at plot the 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]



New Physics Reach of full ILC500 Program

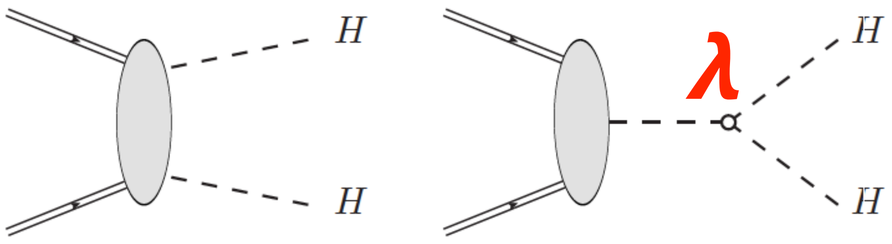
….for typical BSM scenarios with **composite Higgs/Top and/or extra dimensions**
based on phenomenology described in Pomerol et al. arXiv:0806.3247



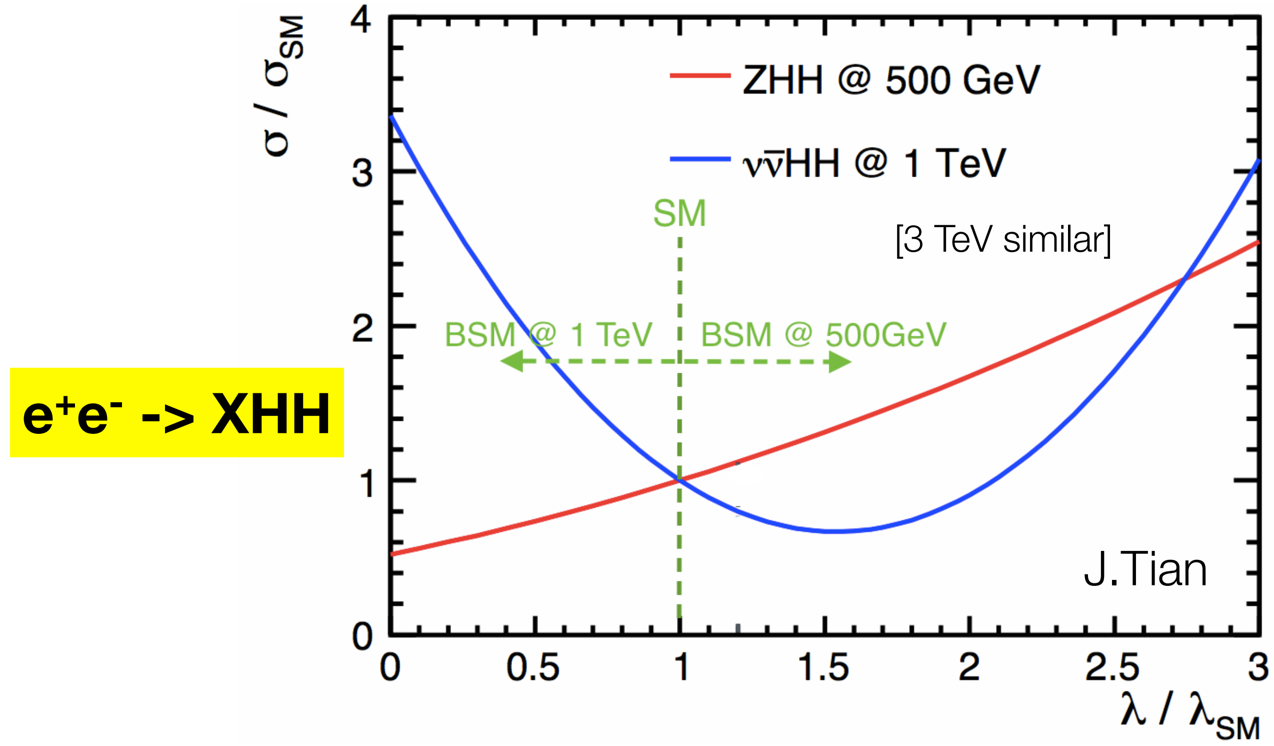
Can probe scales of ~20 TeV in typical scenarios
(… and up to 80 TeV for extreme scenarios)

Double Higgs Production

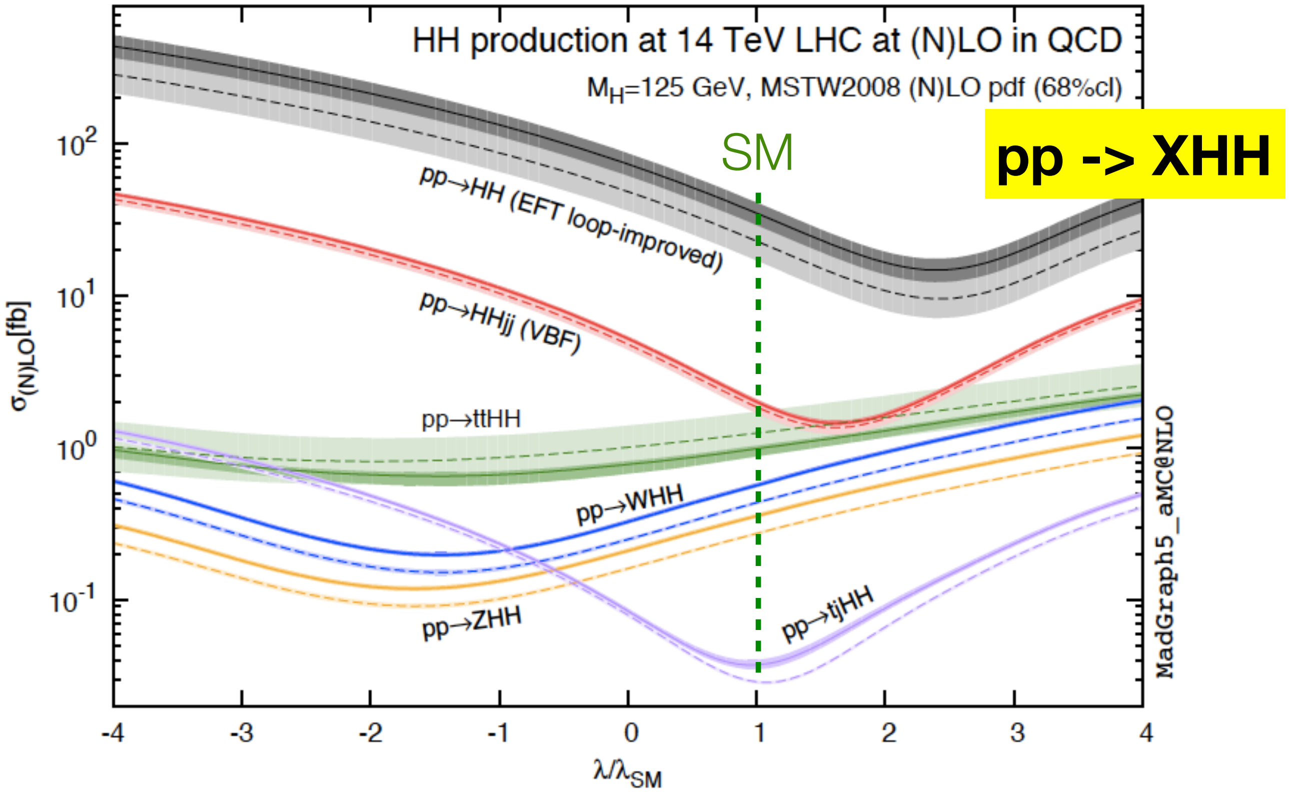
- always multiple diagrams contributing - with and without Higgs self-coupling λ
- interference induces *non-trivial relations* between cross sections and λ



- 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**



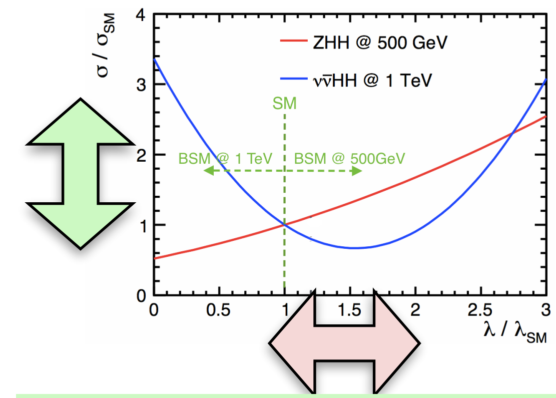
[arxiv:1401.7340]



From cross section to self-coupling in e^+e^-

- $\delta\lambda/\lambda = k\ \delta\sigma/\sigma$; n.b.: k = "$(\partial\sigma/\partial\lambda)^{-1}$" | $_{\lambda=\lambda obs}$

	500 GeV ZHH	1 TeV vvHH	1.4 TeV vvHH, pol	3 TeV vvHH,pol
∫Ldt	4 ab^{-1}	2.5 ab^{-1}	1.5 ab^{-1}	3 ab^{-1}
$\delta\sigma/\sigma$	**16 %**	**13 %**	**33 %**	**11 %**
k_{SM}	1.64	0.76	1.22	1.47
$\delta\lambda/\lambda\ \|_{SM}$	27 %	10 %	40 %	26 %



HL-LHC 2 exp: 38%

HL-LHC, 95%CL:
$-1.3 < \lambda/\lambda_{SM} < 8.7$

- **$\delta\sigma/\sigma \leq$ 20% => $\geq 5\sigma$ discovery of Higgs pair production**
- for **SM** case, 1 TeV is a "sweet spot" with k < 1
(sensitivity to λ largest close to threshold! - could analogous effect reduce the benefit of the factor 40 in σ from 14 TeV to 100 TeV?)
- **BSM** can change the picture: consider e.g. $\lambda = 1.5\ \lambda_{SM}$
=> 500GeV: $\delta\lambda/\lambda$ = 20%, 1TeV: $\delta\lambda/\lambda \rightarrow \infty$
- **with combination of 500 GeV and 1 TeV we're always on the safe side!**

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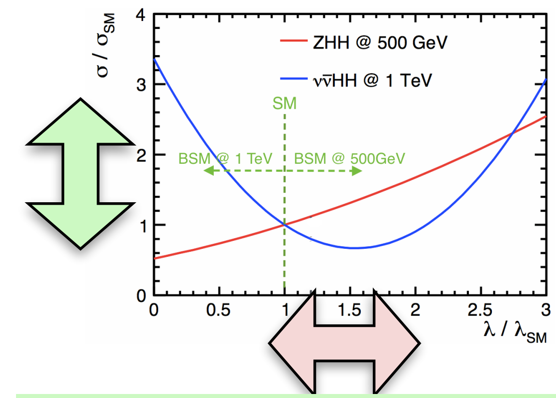

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Quantitative studies needed!

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