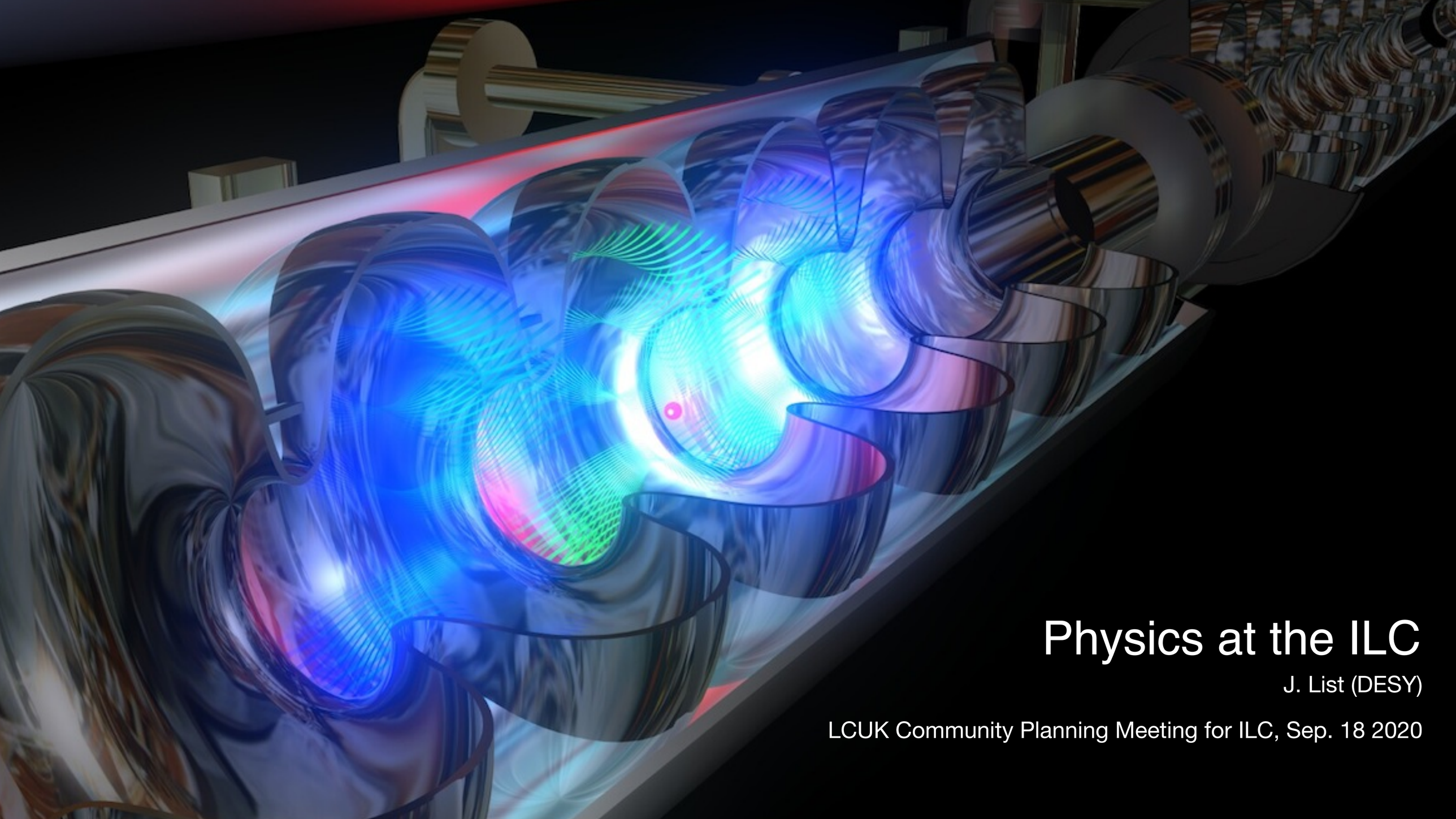
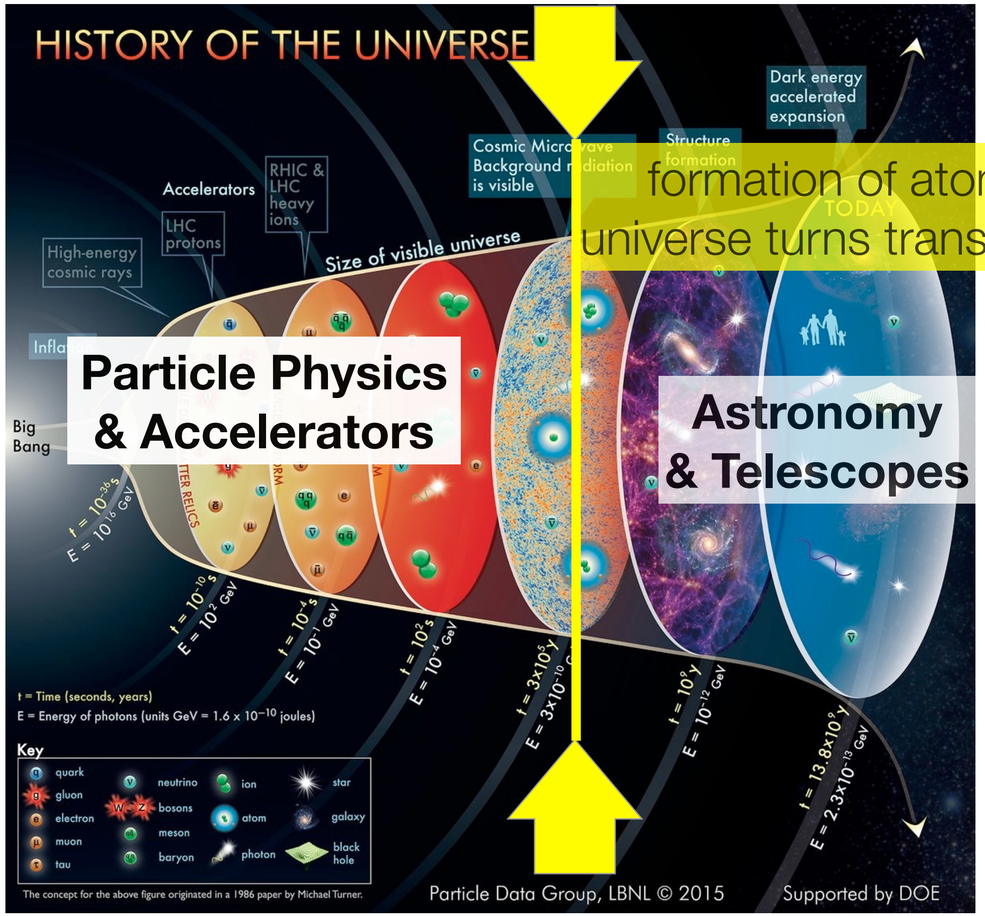


Physics at the ILC

J. List (DESY)

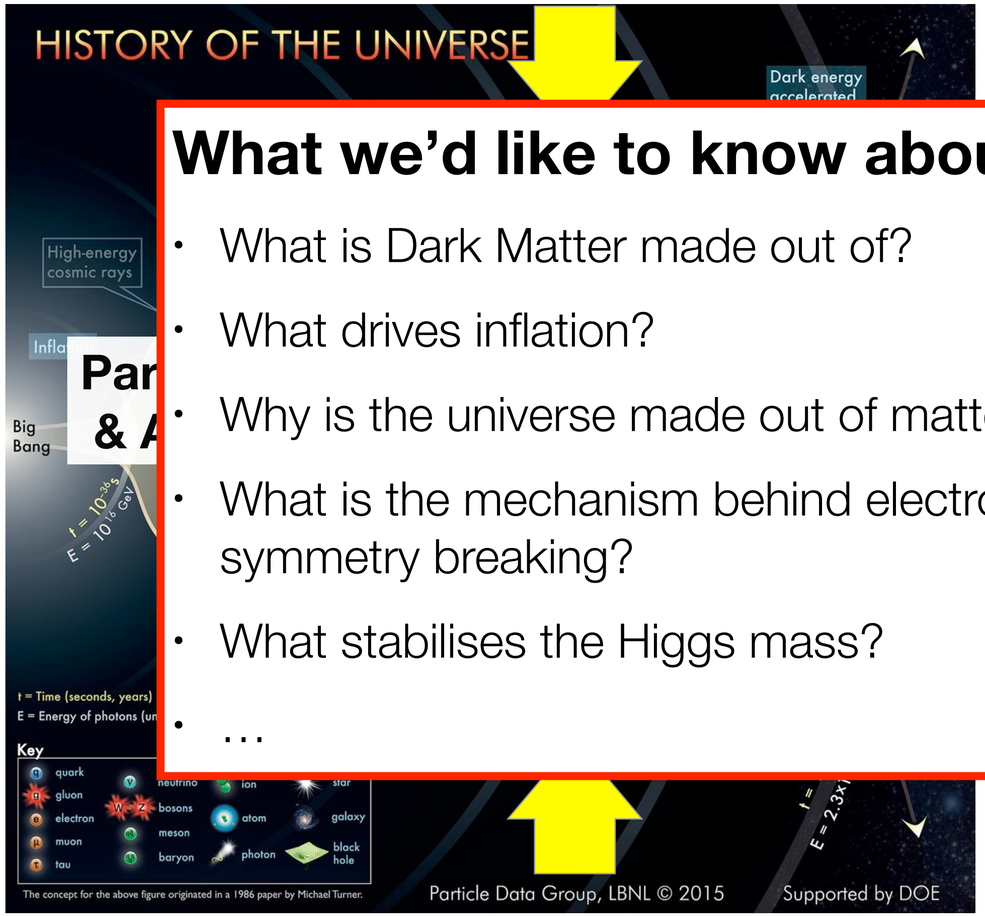
LCUK Community Planning Meeting for ILC, Sep. 18 2020

Big Questions and how to tackle them at e^+e^- colliders



formation of atoms:
universe turns transparent

Big Questions and how to tackle them at e^+e^- colliders



What we'd like to know about:

- What is Dark Matter made out of?
- What drives inflation?
- Why is the universe made out of matter?
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- What stabilises the Higgs mass?
- …

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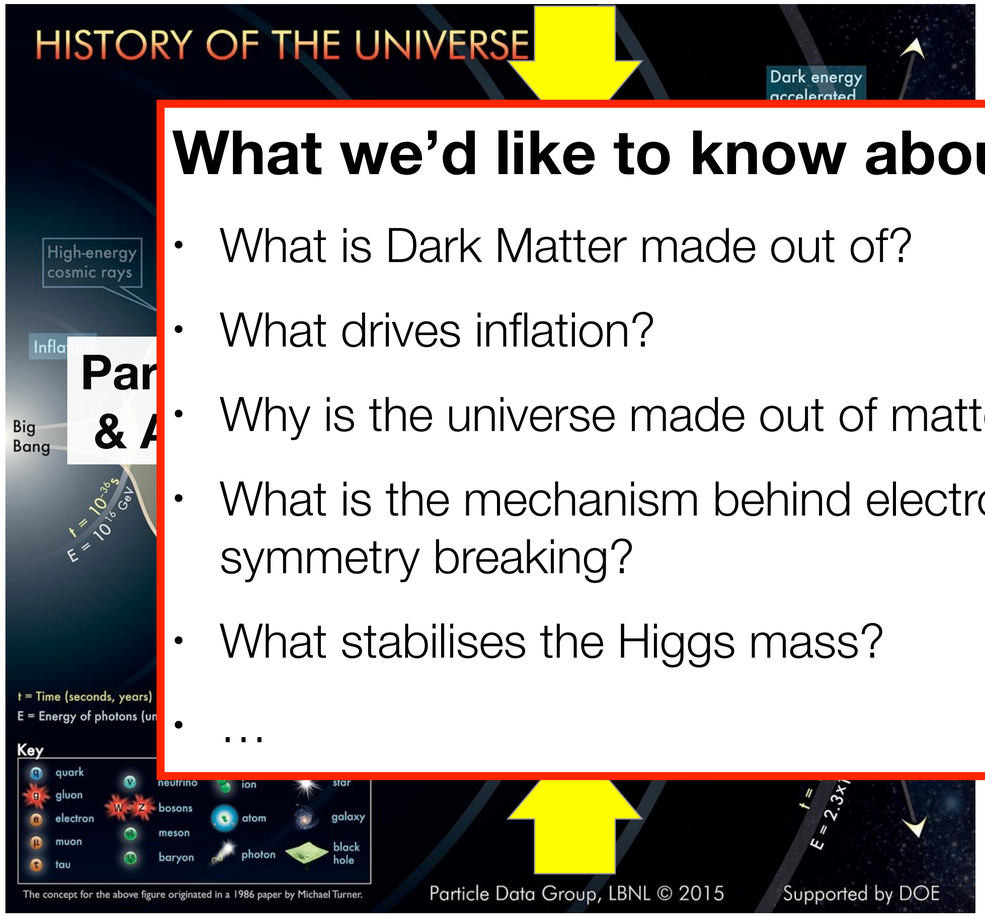

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Our tools:

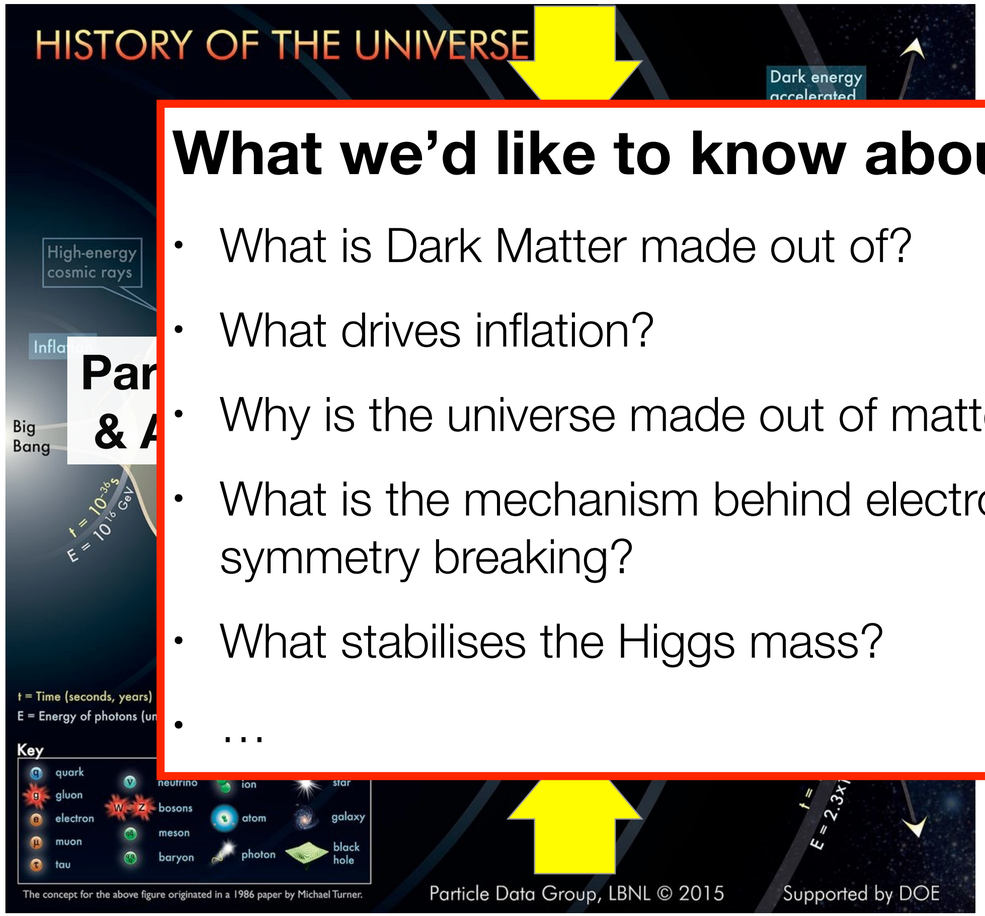
The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

Discoveries of new particles ?

Big Questions and how to tackle them at e^+e^- colliders



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these boxes have clickable links to papers etc

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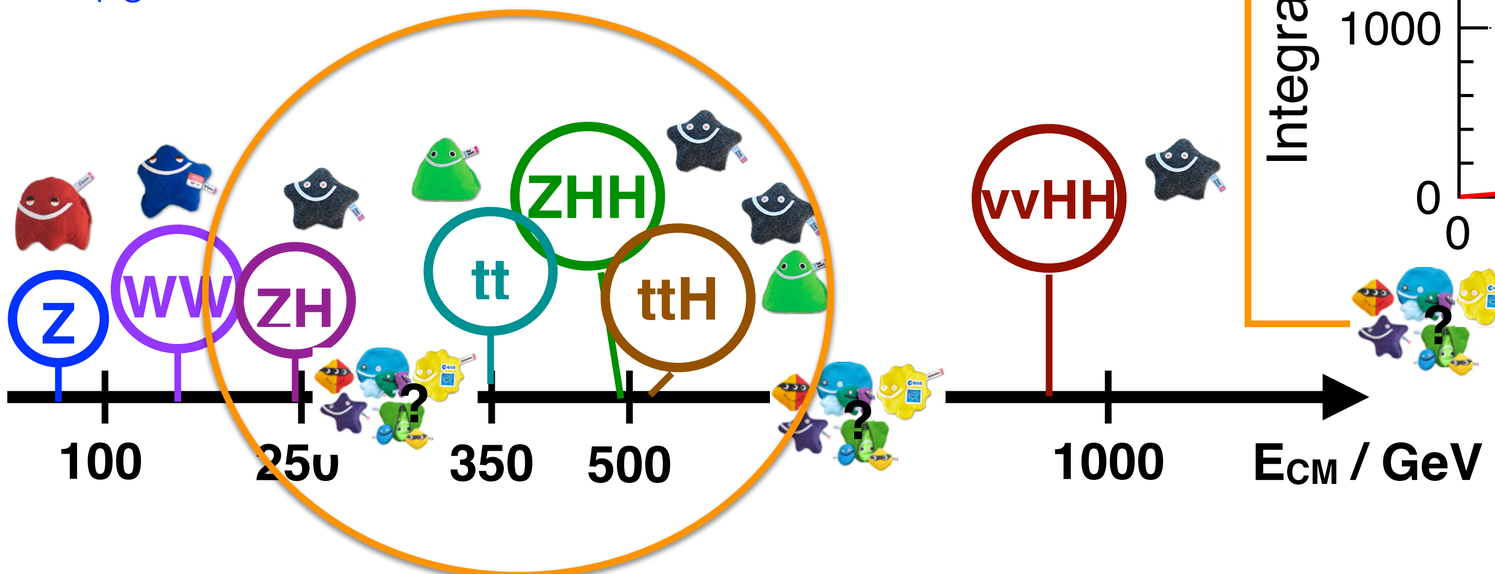
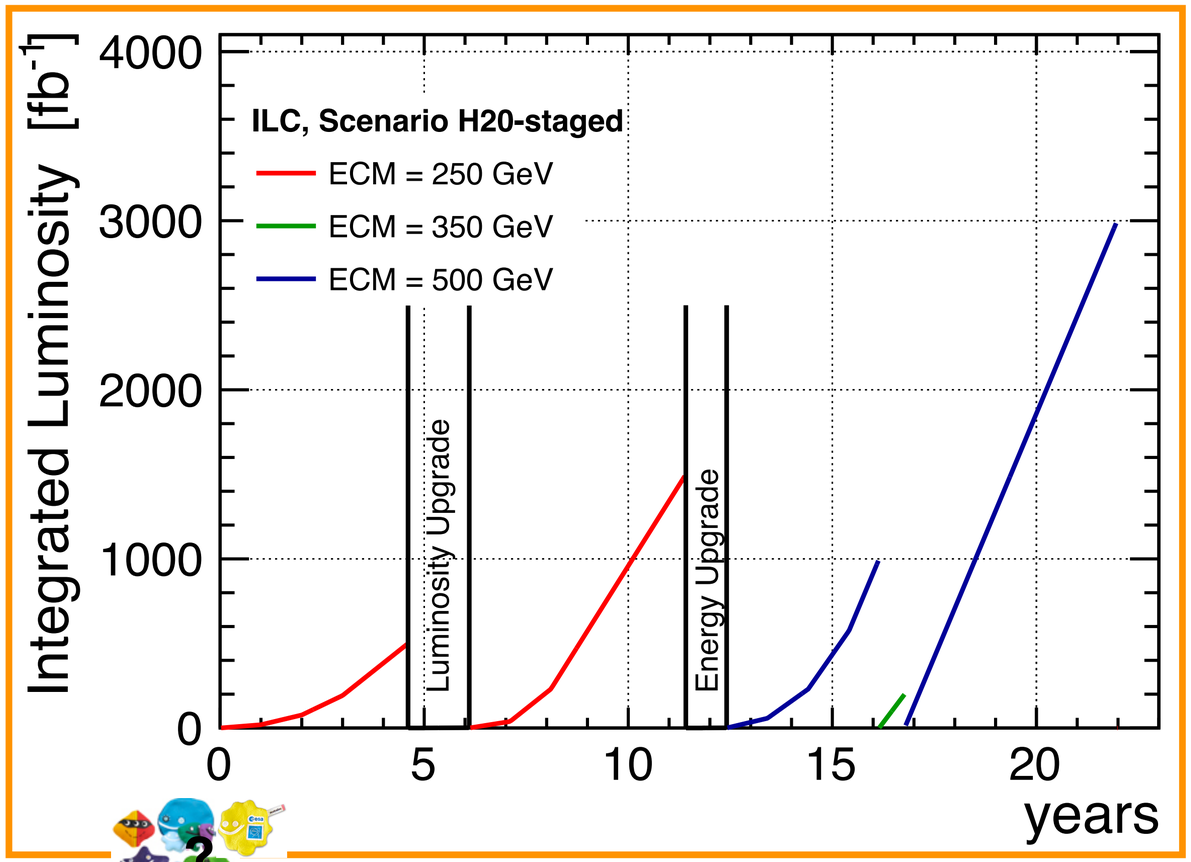
Discoveries of new particles ?

The International Linear Collider in a nutshell

all up-to-date numbers in ILC ESU Document

- e^+e^- centre-of-mass energy
  - first stage: 250 GeV
  - tunable
  - upgrades: ~~500 GeV,~~ **1 TeV, 91 /161 GeV**
- luminosity at 250 GeV:
  - 1.35 x 10^{34} /cm^2 /s
  - upgrade 2.7 x 10^{34} /cm^2 /s
- beam polarisation
  - $P(e^-) \geq 80\%$
  - $P(e^+) = 30\%$, at 500 GeV upgradable to 60%
- total length (250 GeV): 20.5 km



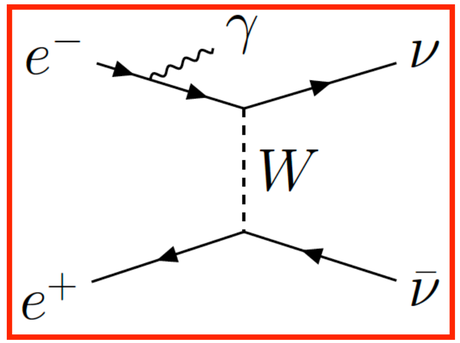


Physics benefits of polarised beams

General references on polarised e^+e^- physics:
- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

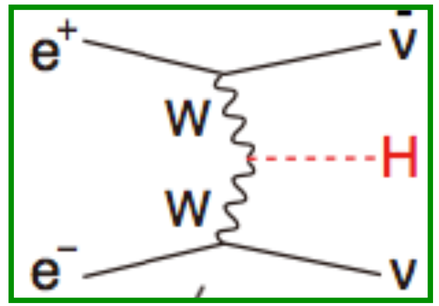
background suppression:

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



signal enhancement:

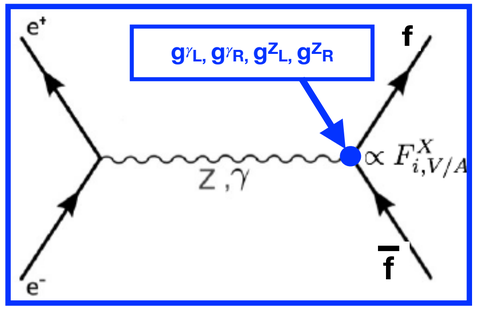
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions
- BSM:
  chiral structure unknown, needs to be determined!



redundancy & control of systematics:

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

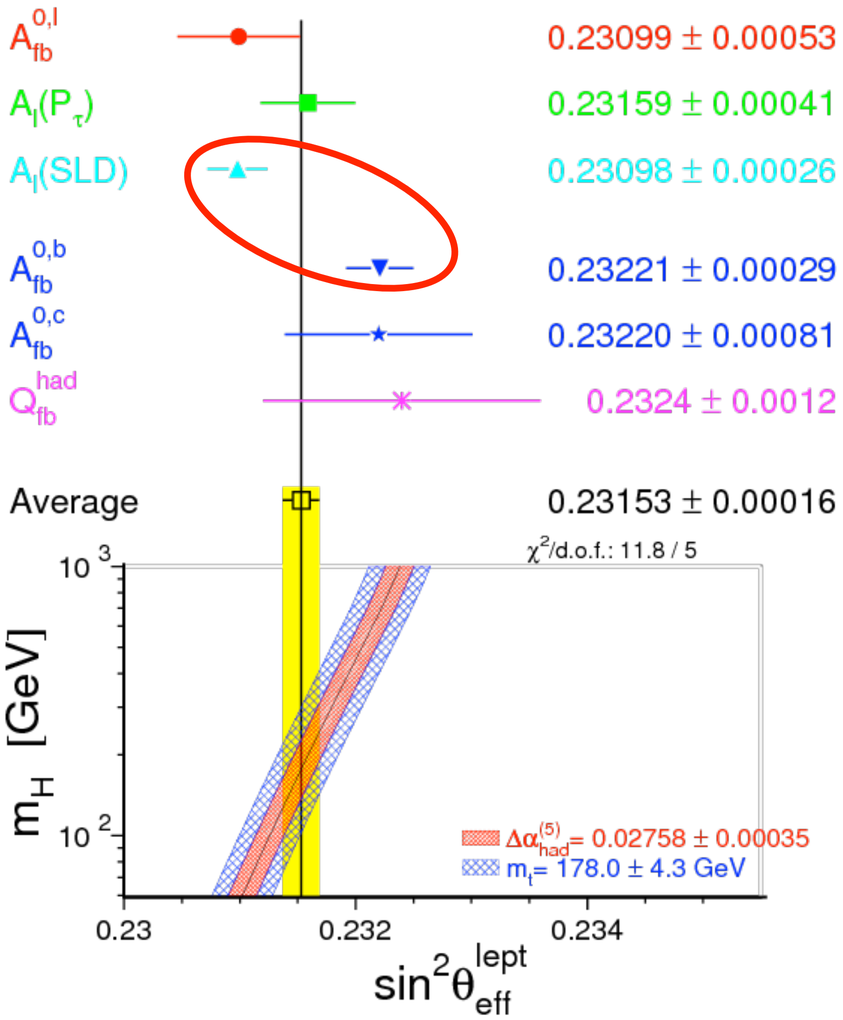
New insights from old friends…

The Top and Bottom Quark

Z & W Bosons

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

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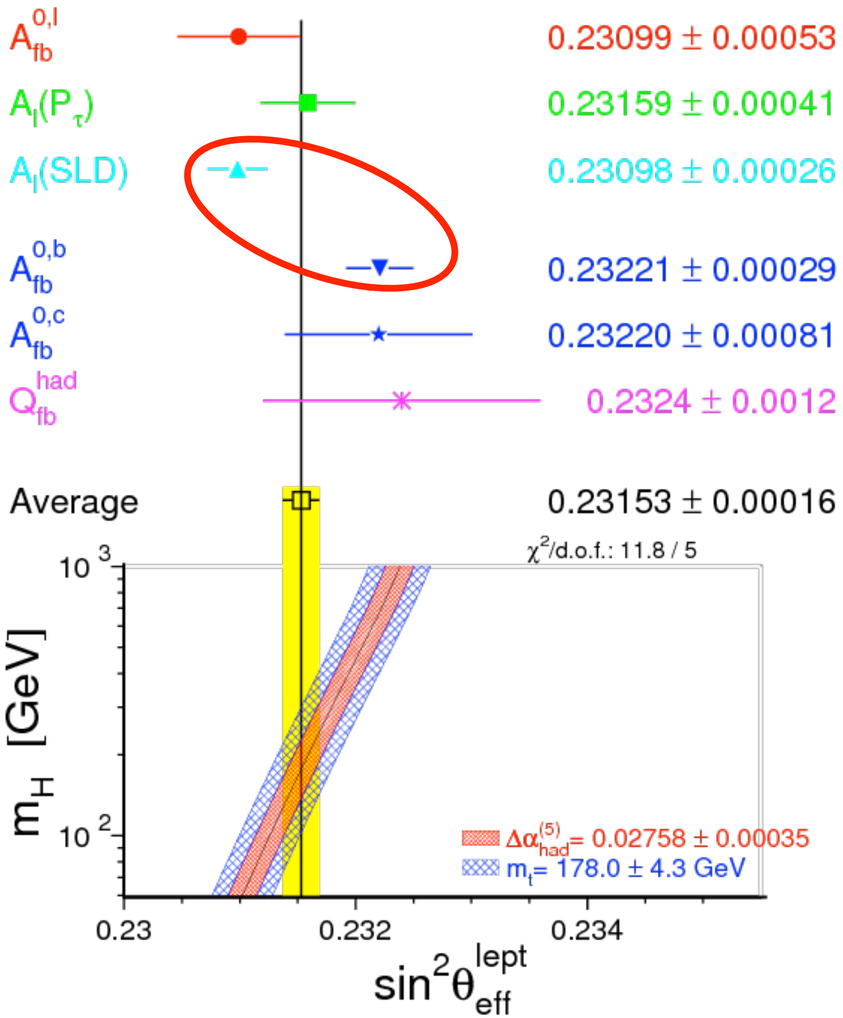

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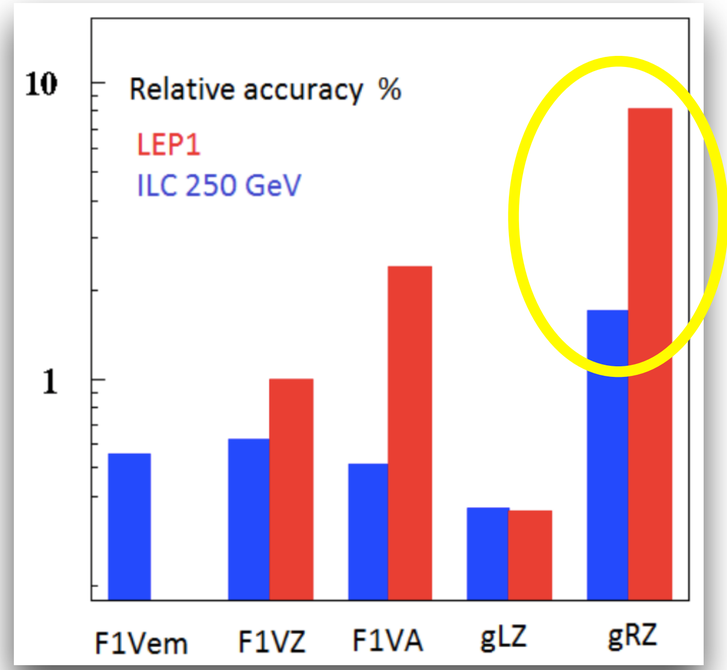

Yes, we can!

arXiv:1709.04289

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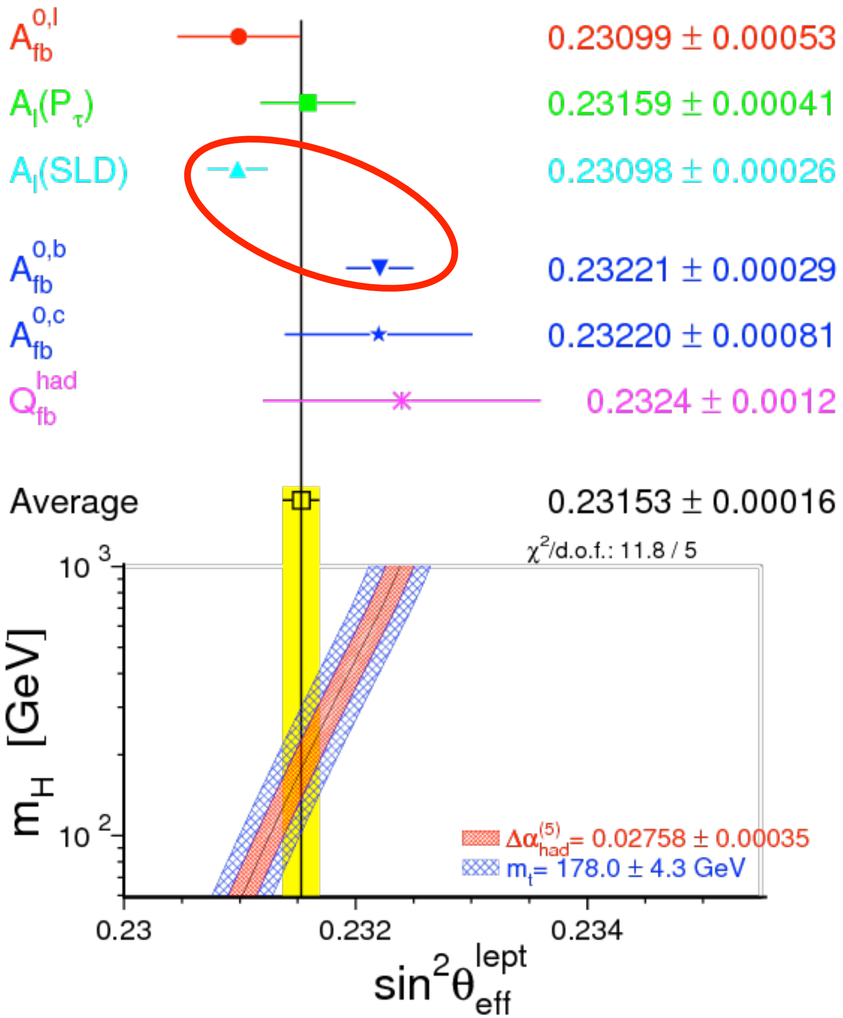

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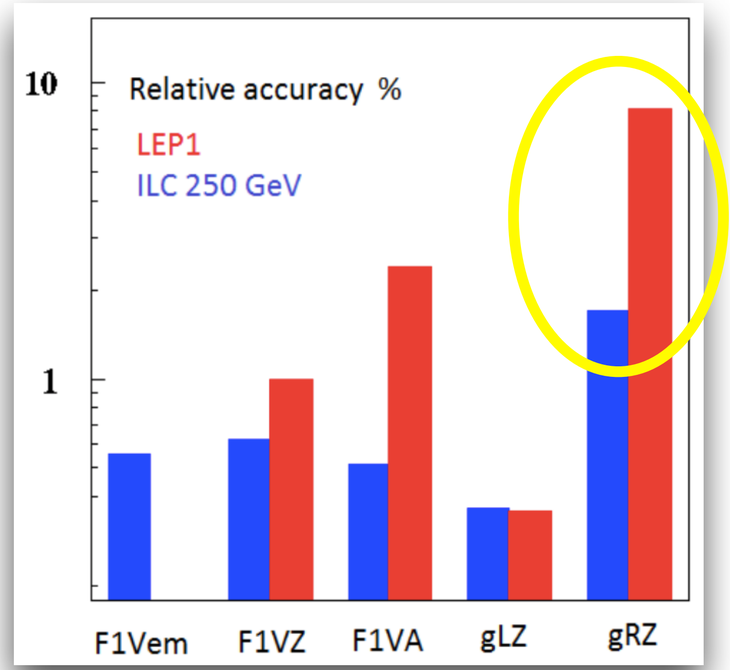

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allows to probe NP scales up to ~60 TeV

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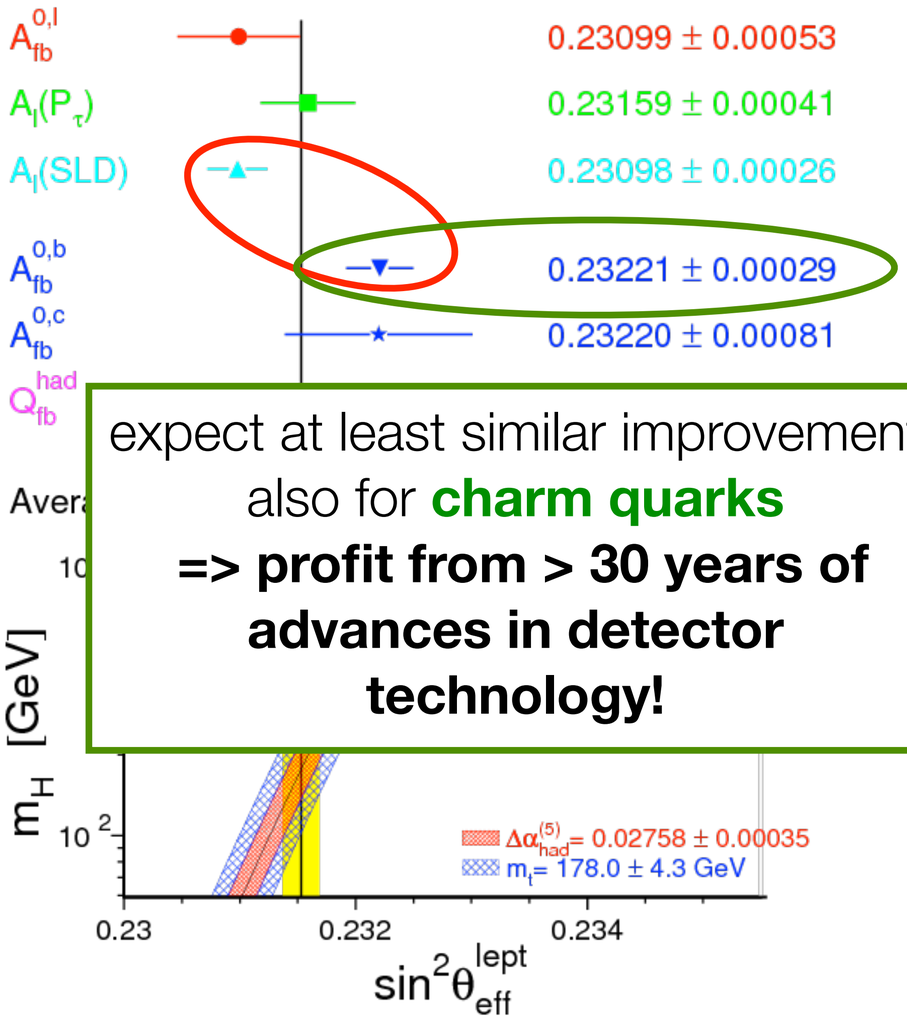

expect at least similar improvement also for **charm quarks**
=> profit from > 30 years of advances in detector technology!

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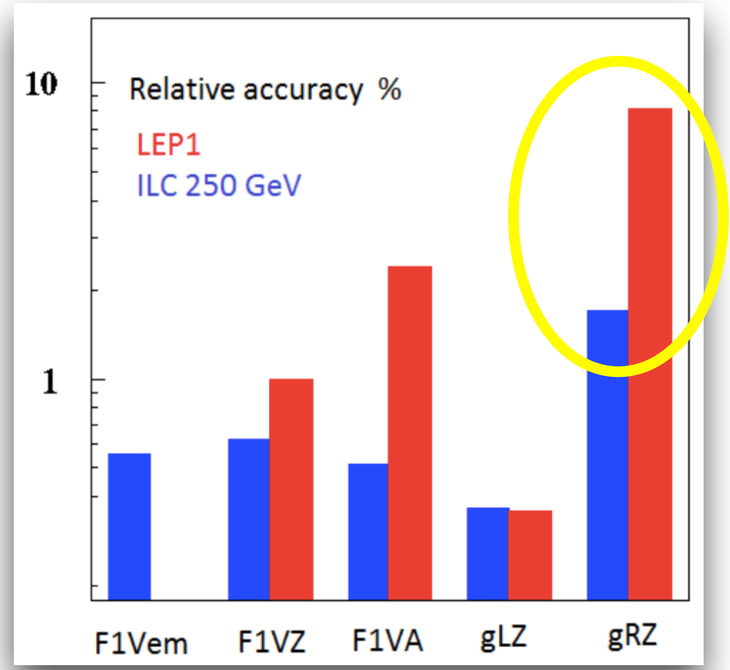

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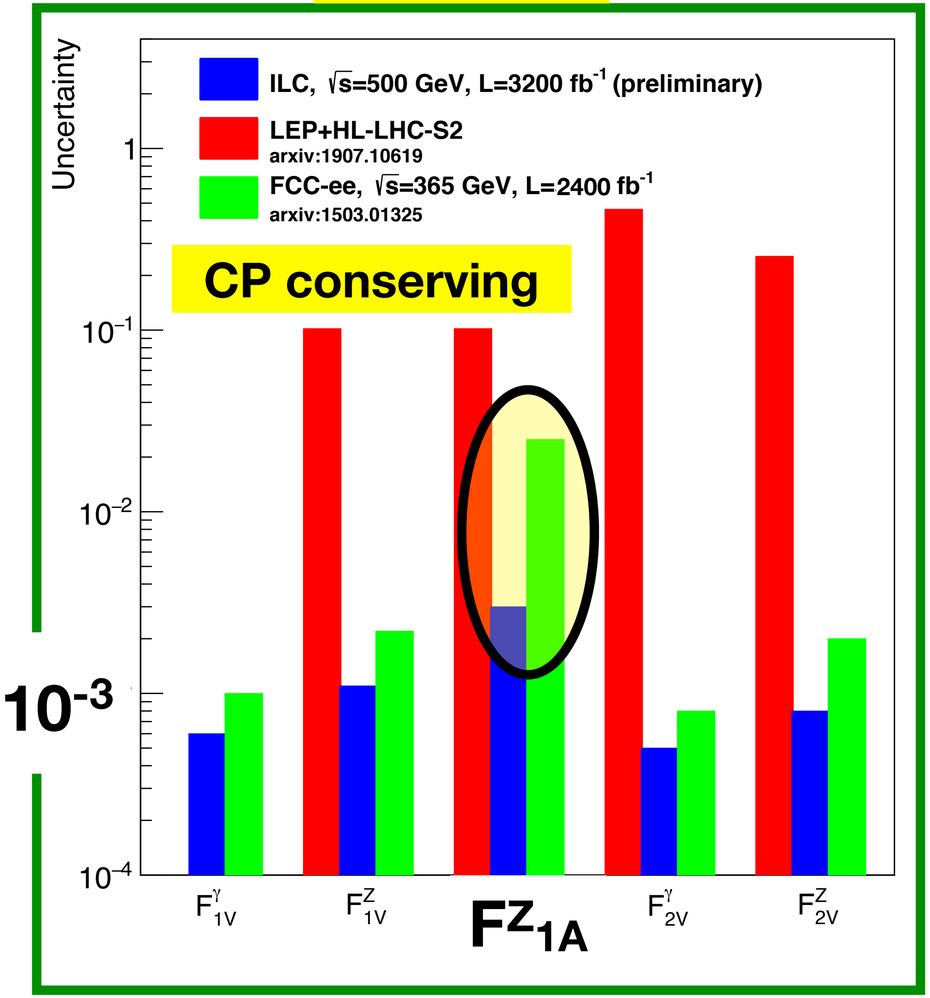
… and at higher energies

The Top Quark

- **e^+e^- -> tt: possible above ~360 GeV**
- **near threshold: no boost**
  => little sensitivity to *axial* coupling
- beam **polarisation disentangles Z and** γ exchange
- few **10^{-3} for all couplings requires ≥ 500 GeV *and* polarisation**
- probes **BSM** into the **multi-ten TeV regime**



ILD-PHYS-PUB-2019-007, arXiv:1908.11299, Eur.Phys.J. C78 (2018) no.2, 155]

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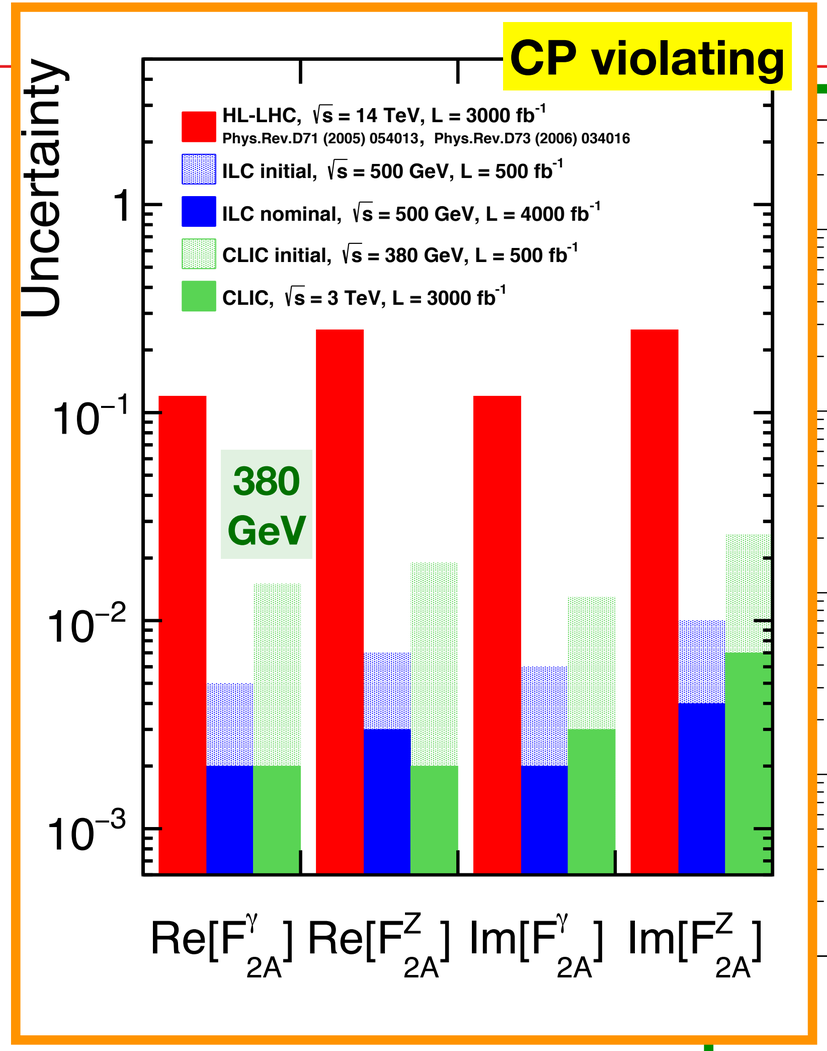

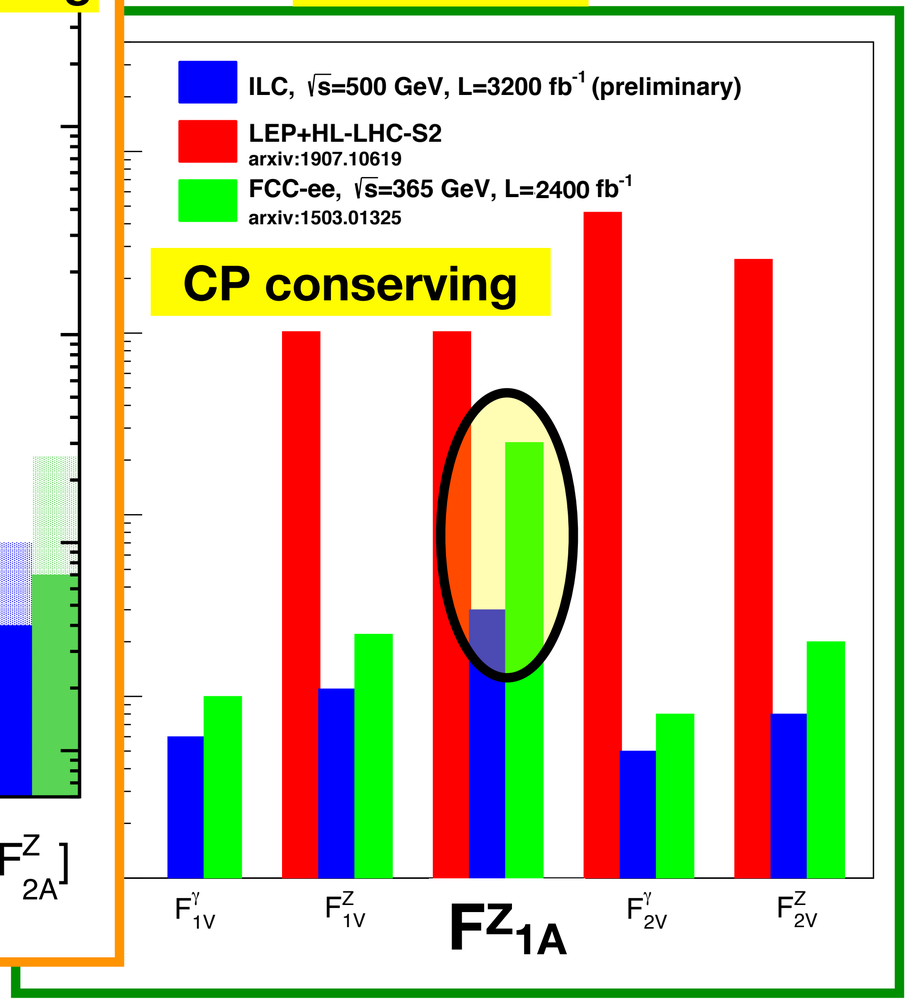

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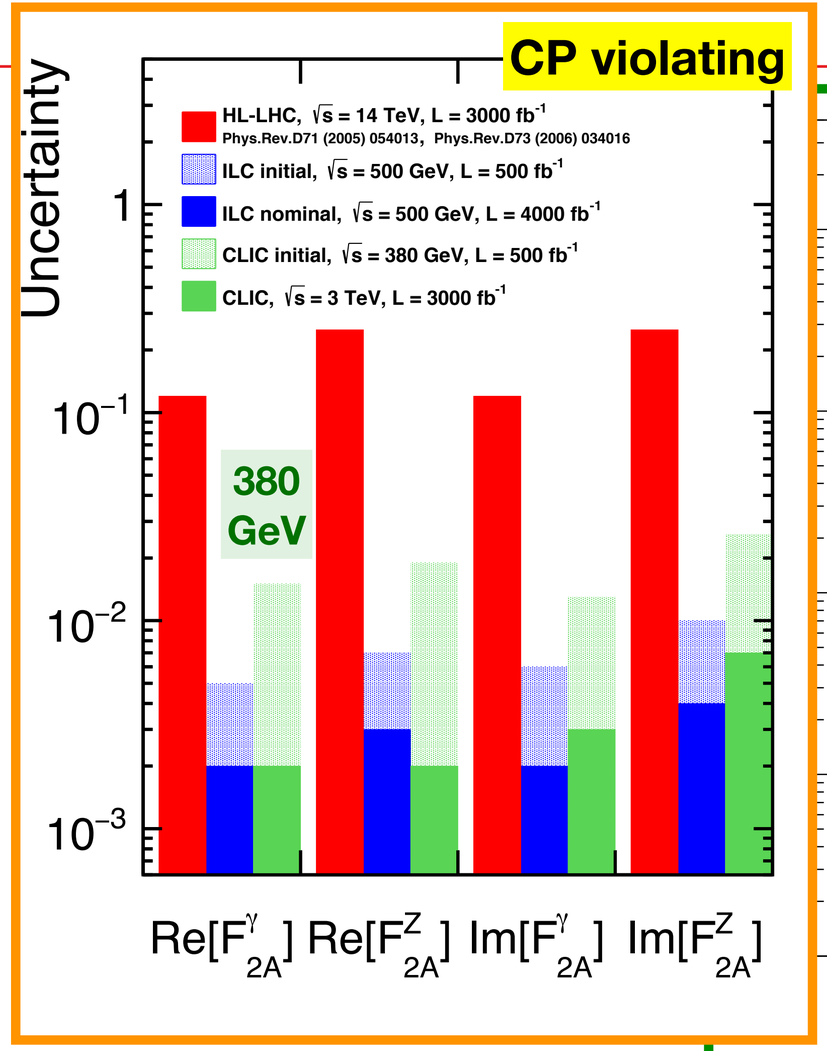
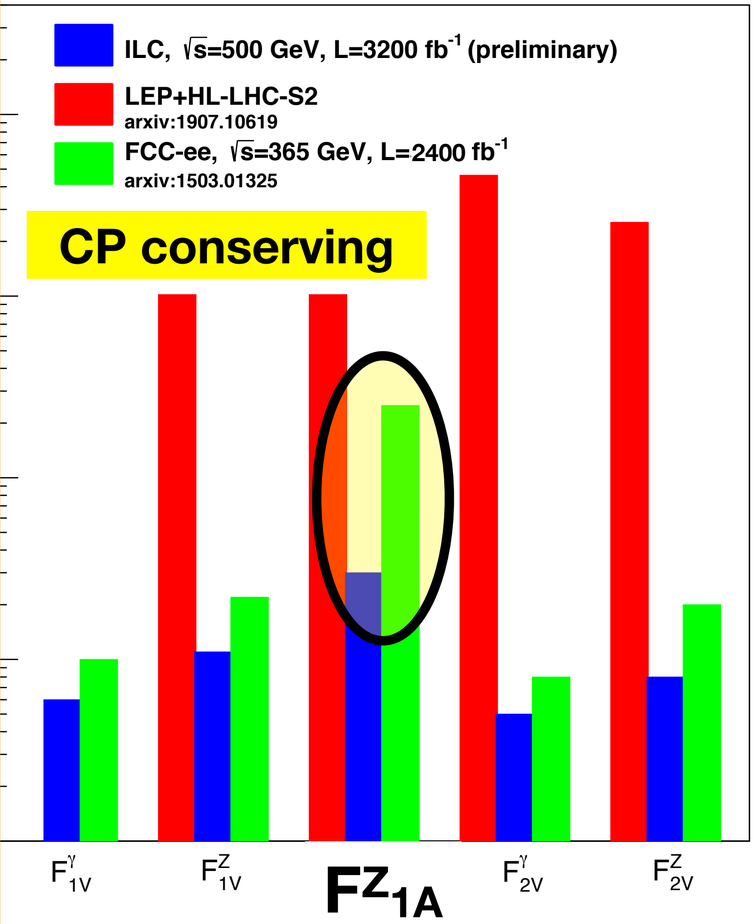
full SM-EFT:

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





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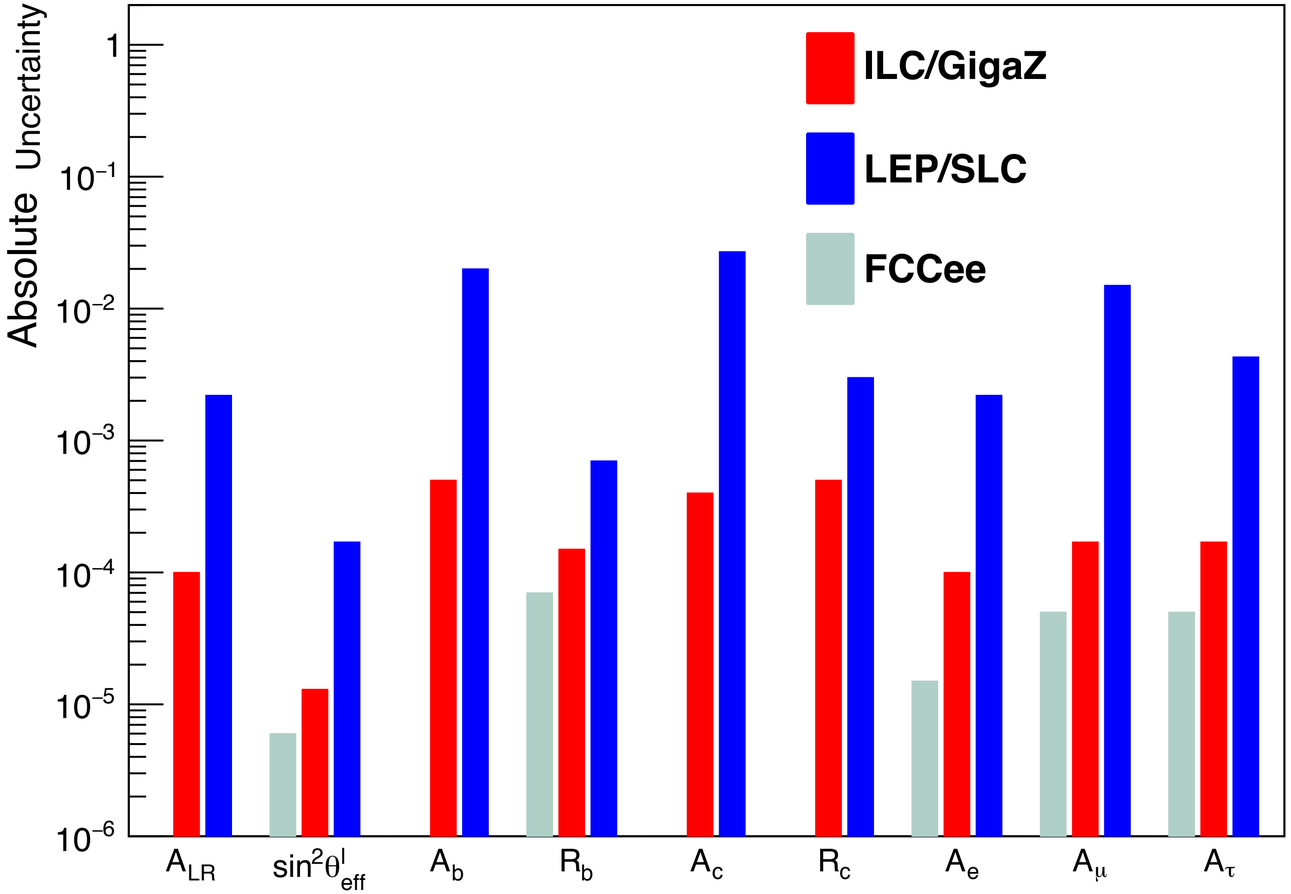
Polarisation & Electroweak Physics at the Z pole

new detailed studies by ILD:

- at least factor 10, often ~50 improvement over LEP/SLC
- note in particular:
  - **A_c nearly 100 x better** thanks to excellent charm / anti-charm tagging:
    - excellent vertex detector
    - tiny ILC beam spot
    - Kaon-ID via dE/dx in ILD's TPC

typically only factor 2-3 less precise than FCCee's unpolarised *TeraZ*
=> polarisation buys
a factor of ~100 in luminosity



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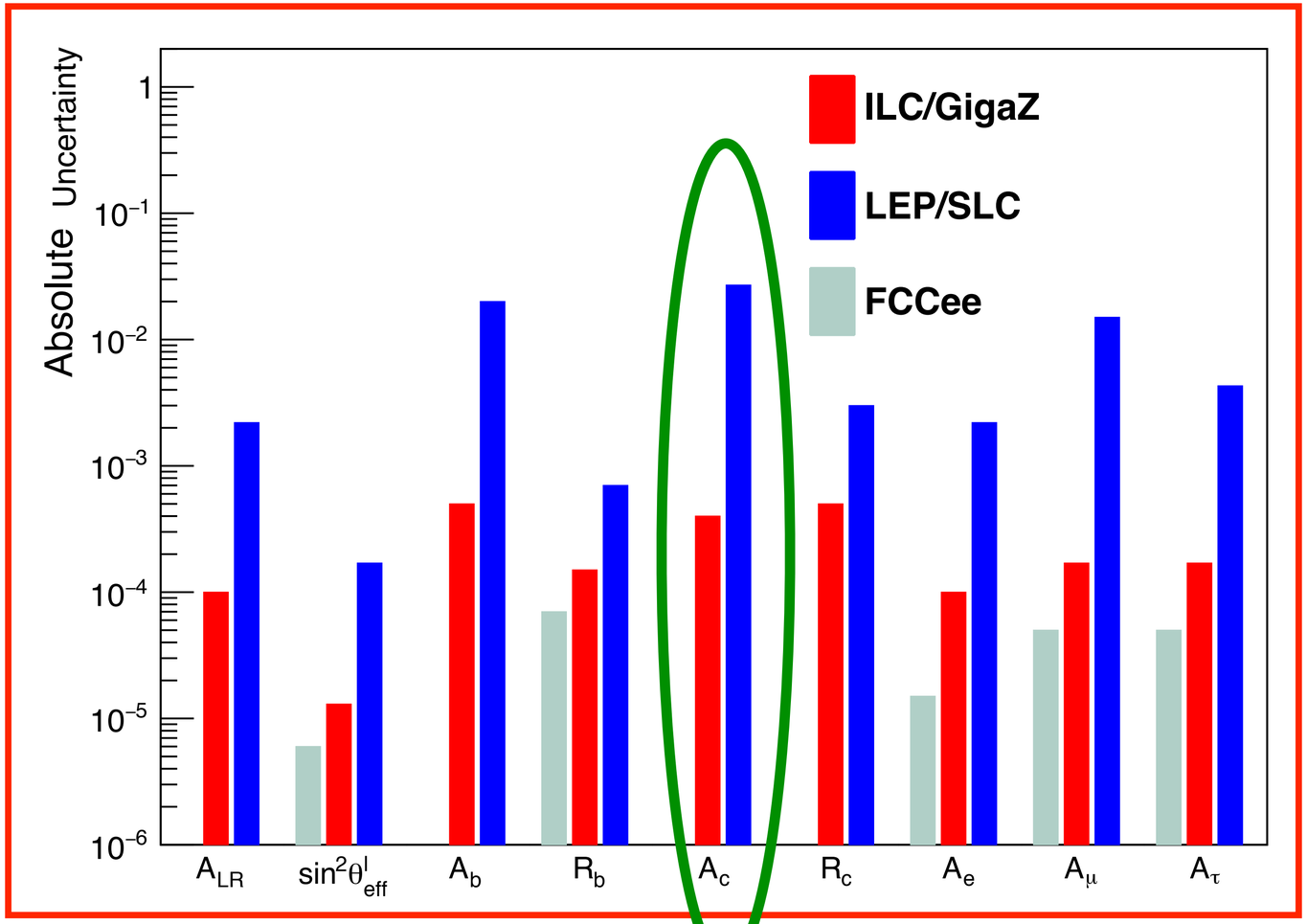

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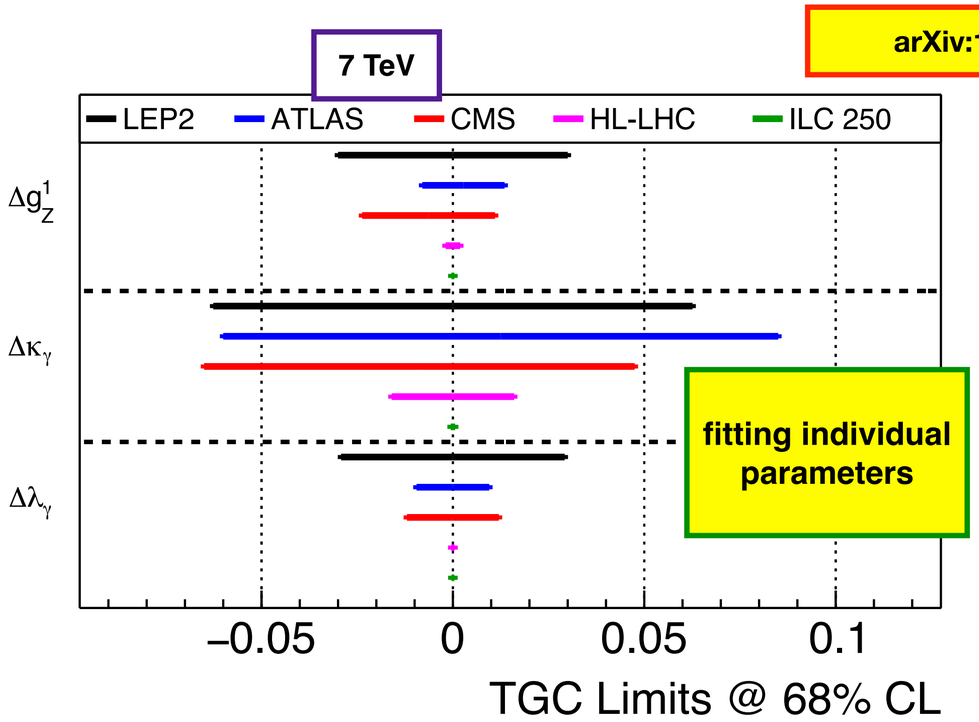
Triple Gauge Couplings

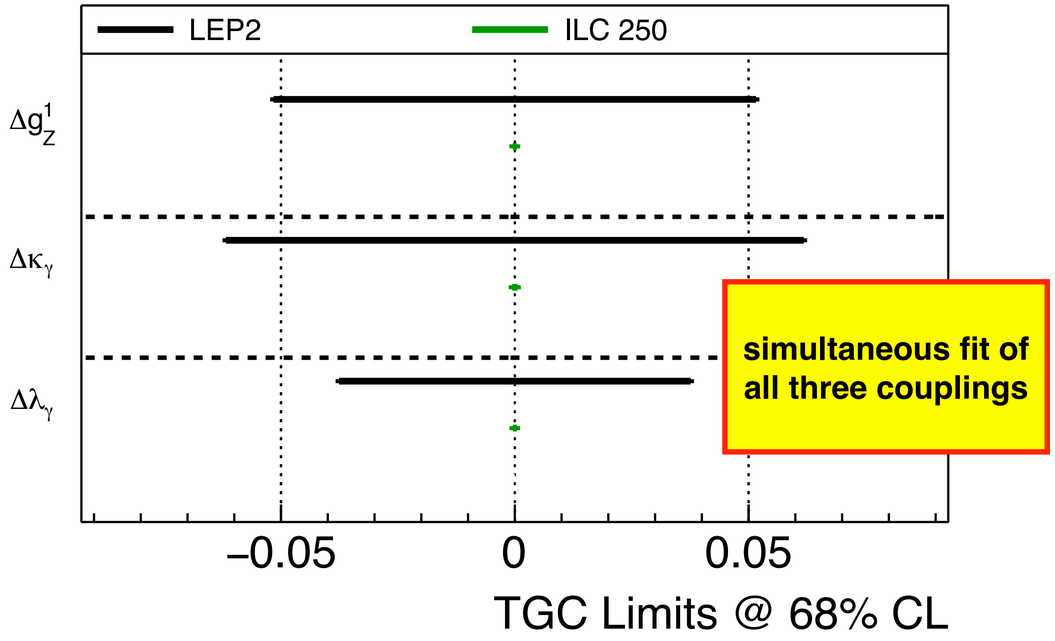
ILD full sim at 500 GeV & 1 TeV:

- 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





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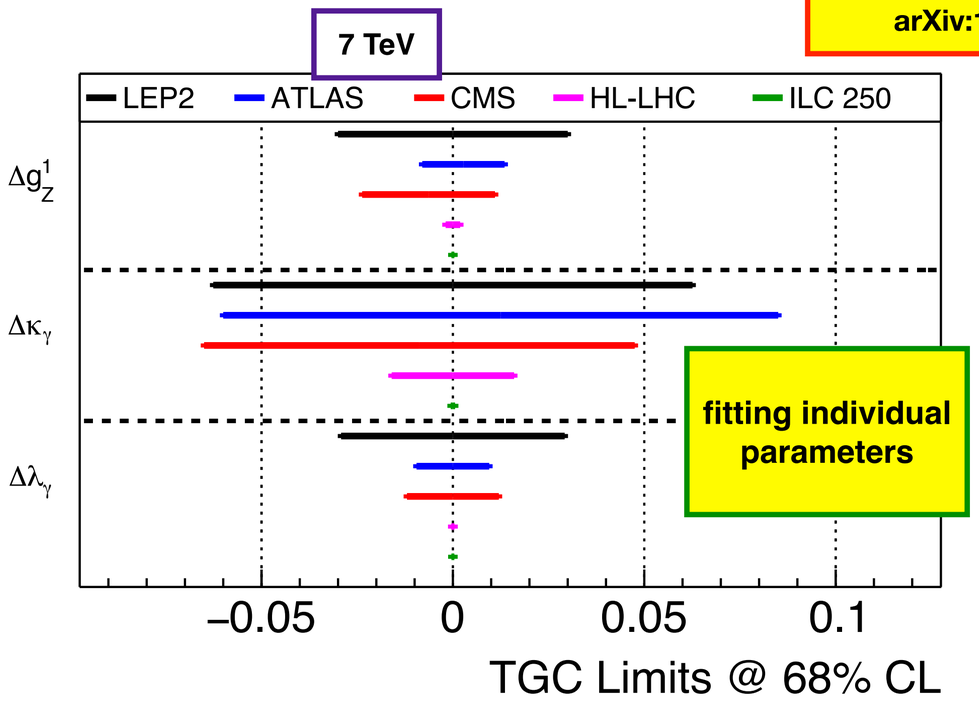
250 GeV:
full study still missing!

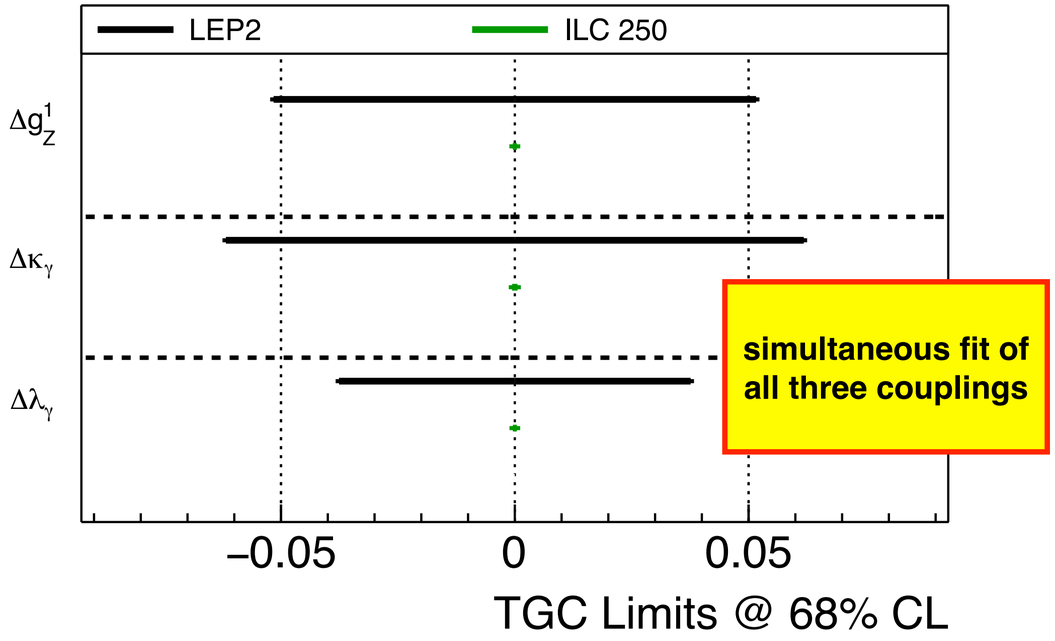
=> ILD just started a brand-new 250 GeV MC production

=> NOW is THE time to get started!

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

arXiv:1710:07621





New insights from our new friend…

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:

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

  - Littlest Higgs, eg m_T=1TeV:

$$\begin{aligned} \frac{g_{hgg}}{g_{h_{\rm SM}gg}} &= 1 - (5\% \sim 9\%) \\ \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} &= 1 - (5\% \sim 6\%). \end{aligned}$$

  - Composite Higgs, eg:

$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \text{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \text{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$$

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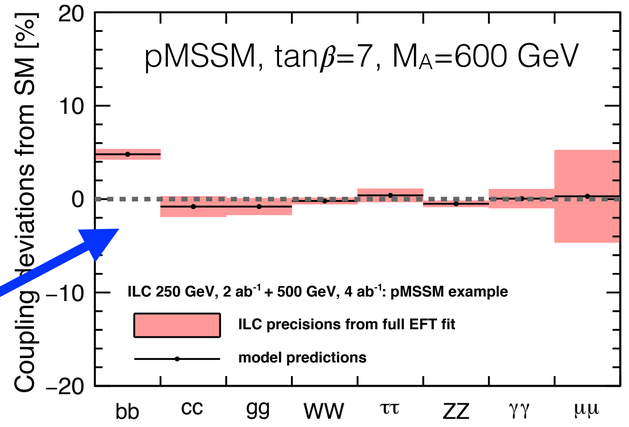

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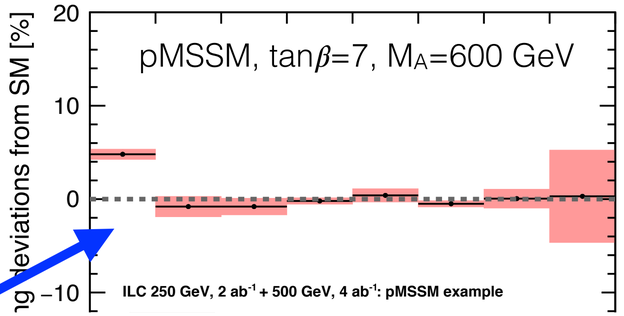

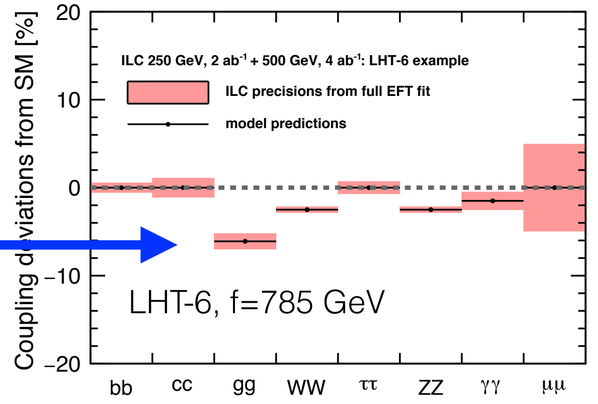

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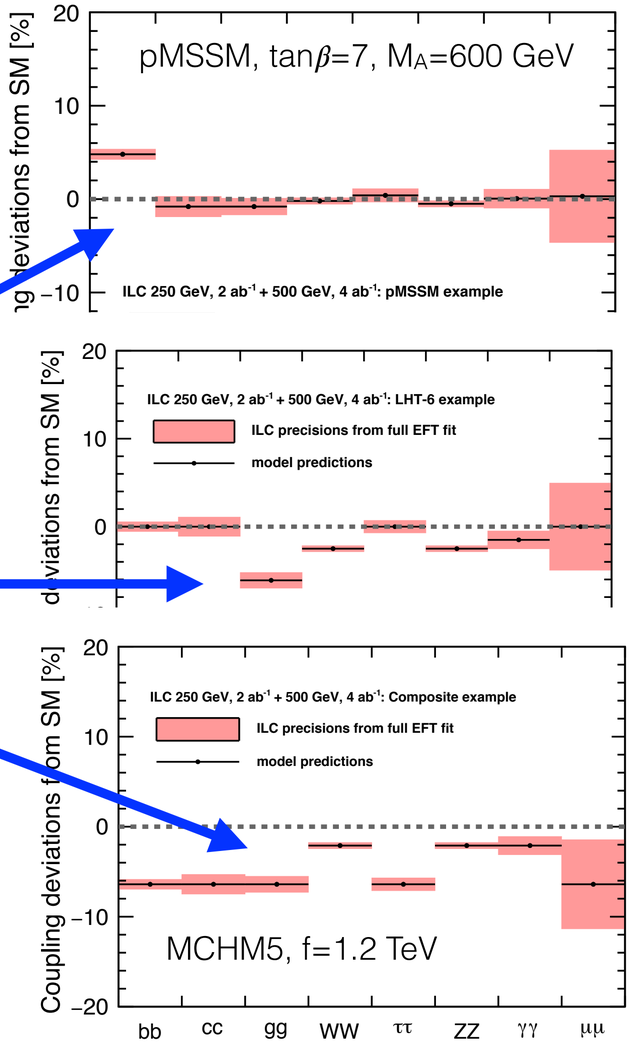

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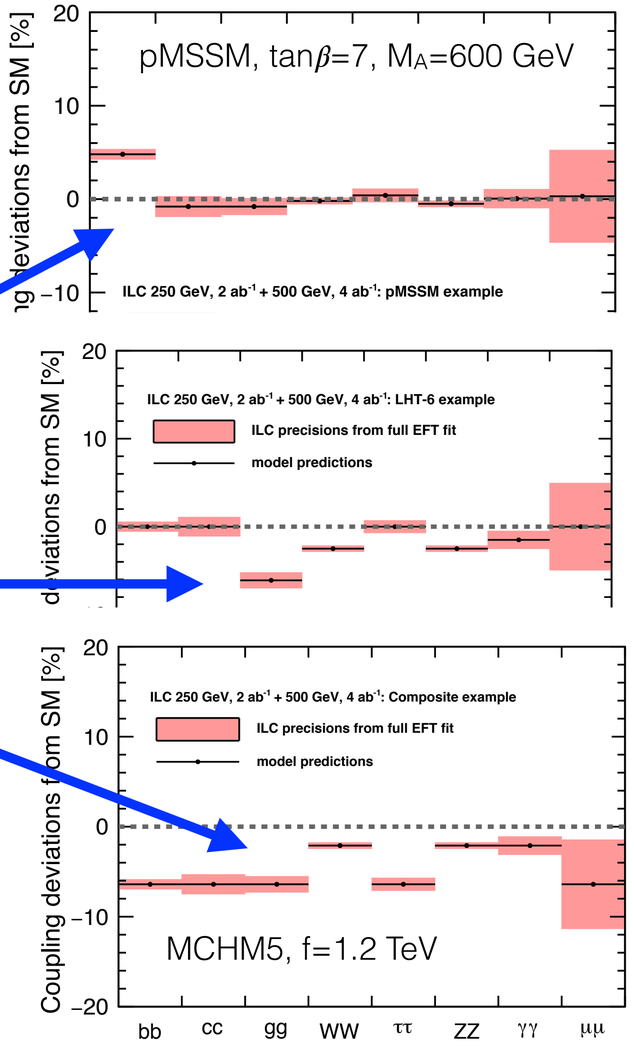
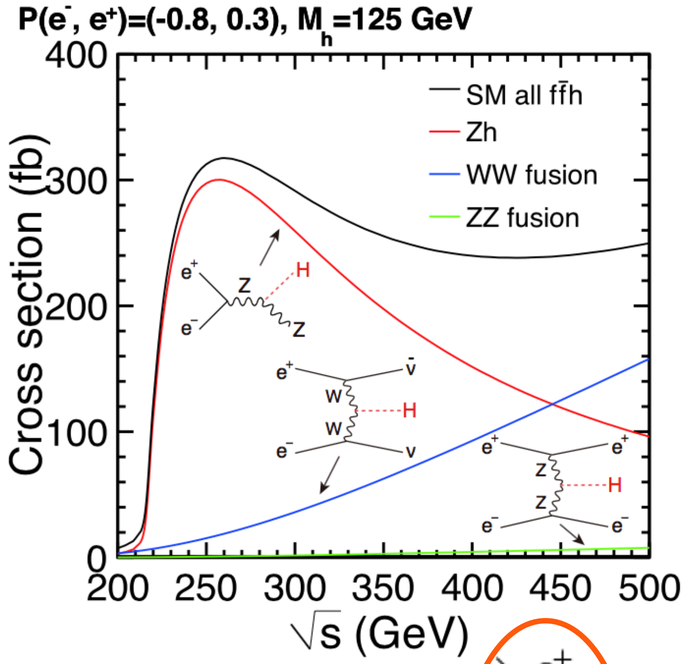
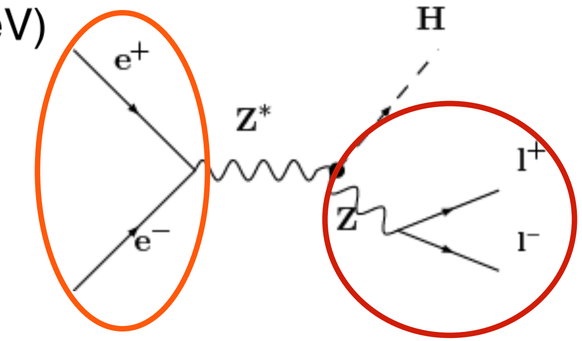


At least percent-level precision required!

Precision Higgs Physics @ 250 GeV





$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

- production dominated by Zh
- **2 ab^{-1} => ~600 000 Zh events**
- fantastic sample for measuring:
  - (recoil) mass
  - **total Zh cross section:**
    the key to model-independent determination of absolute couplings!
  - **h-> invisible (Dark Matter!):**
    expected limited < 0.3% @ 95%
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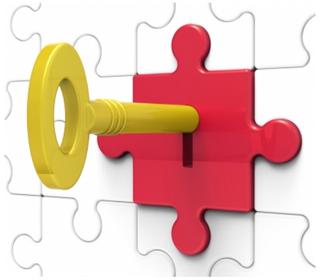
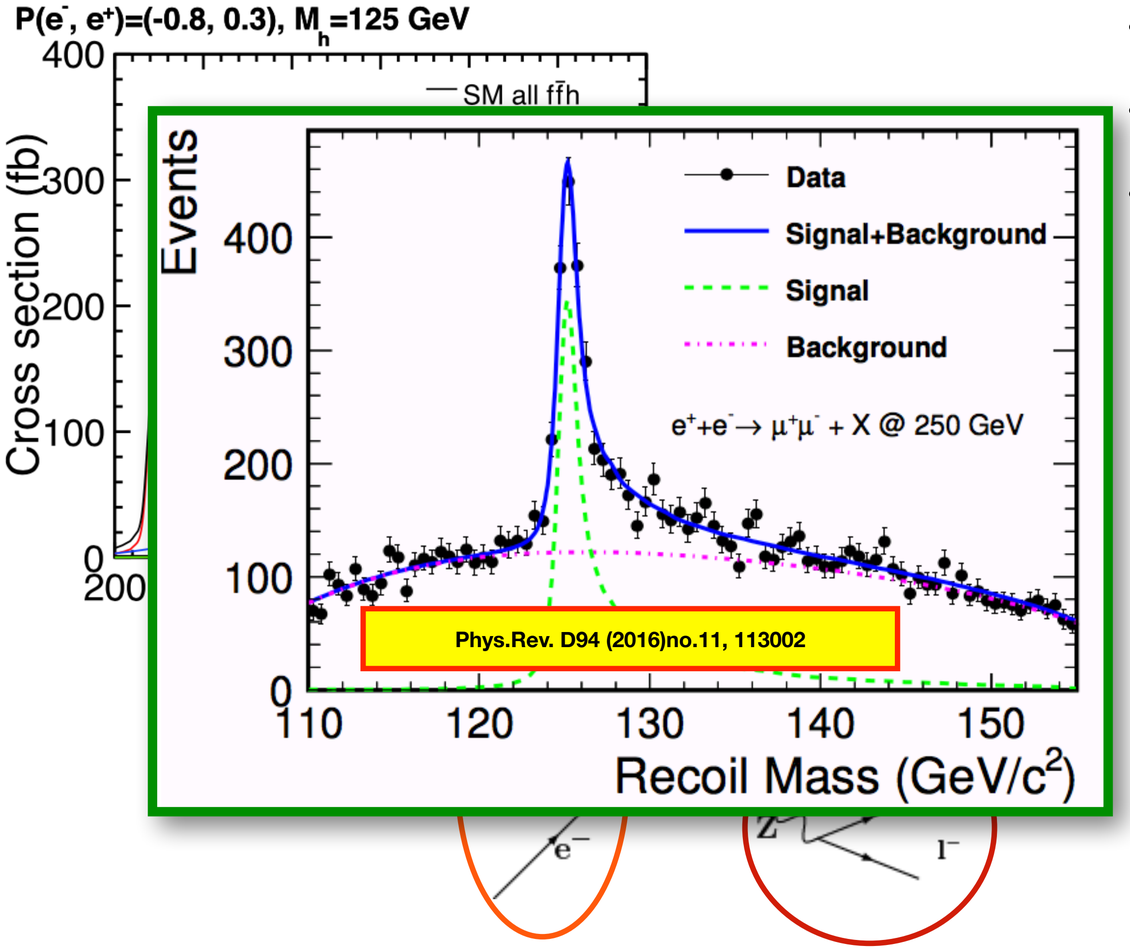


Image courtesy of Stuart Miles at FreeDigitalPhotos.net

for detailed listings of individual precisions c.f. arXiv:1708.08912

Precision Higgs Physics @ 250 GeV

The Higgs Boson



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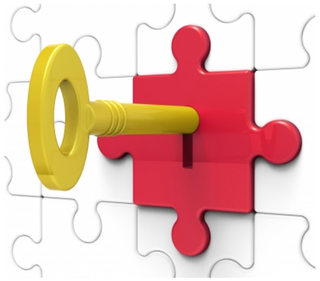

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Polarisation & Higgs Couplings

arXiv:1903.01629

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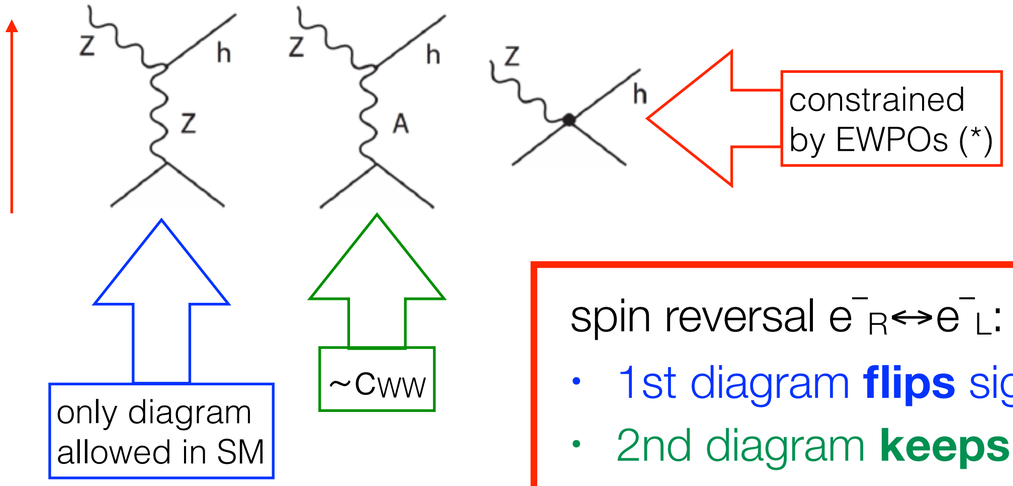
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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- 1st diagram **flips** sign
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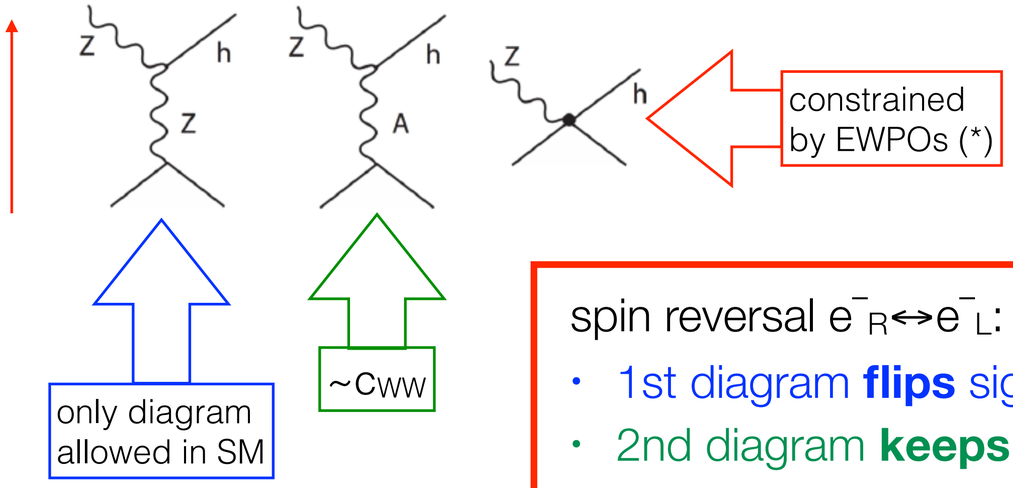

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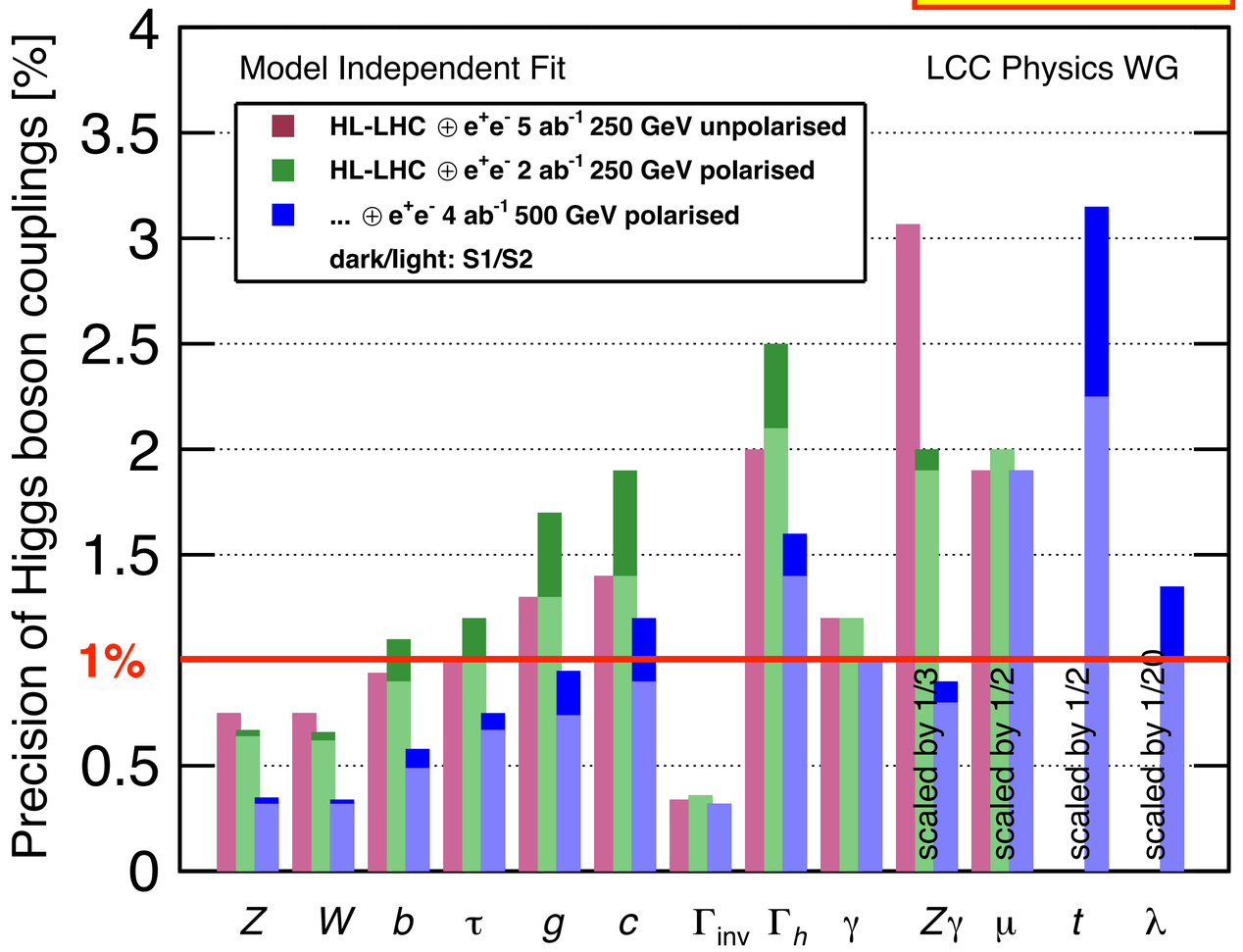

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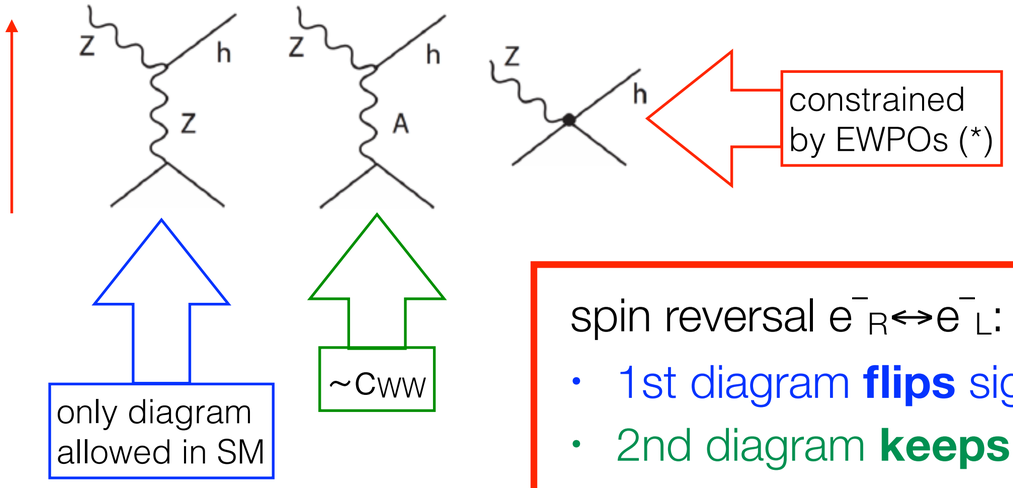

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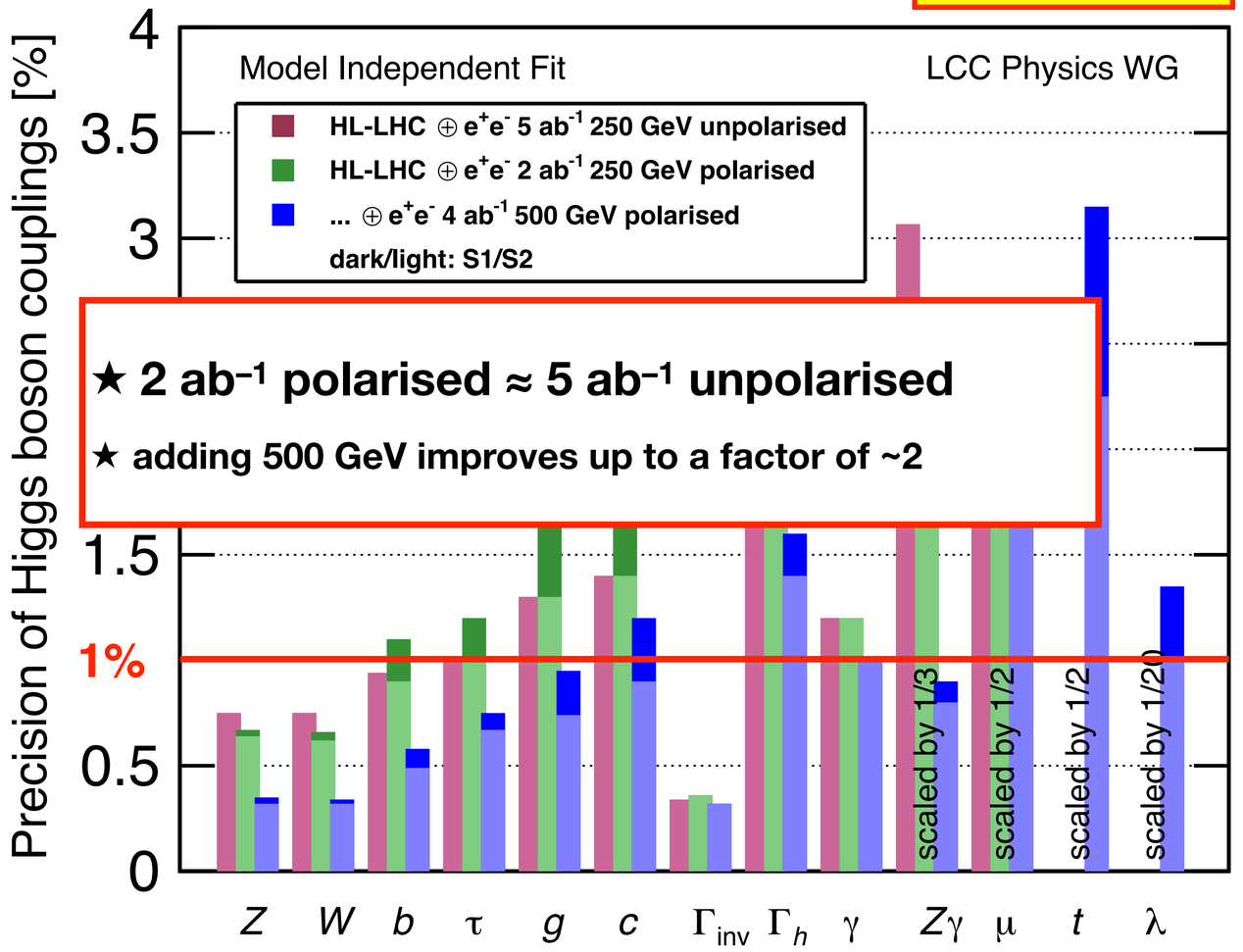

Higgs self-coupling

- **HL-LHC:**
  - **~5σ observation of HH**
  - **~50% on λ in *single-parameter* fit**
- **e^+e^-:**
  - **500 GeV: 8σ observation of HH**
  - **27% on λ in *full coupling analysis***
  - **full, testbeam-gauged simulation**
    (note: first ILC fast sim. was ~3 times better!)
  - **1 TeV & 3 TeV: ~10%**
- **FCC-hh:**
  - **5% *statistical* uncertainty on λ**
  - **from fast simulation, *single-par.* fit**
  - assuming LHC detector performance despite e.g.100x higher neutron fluence
  - **plus systematics, theory, pdf, …**

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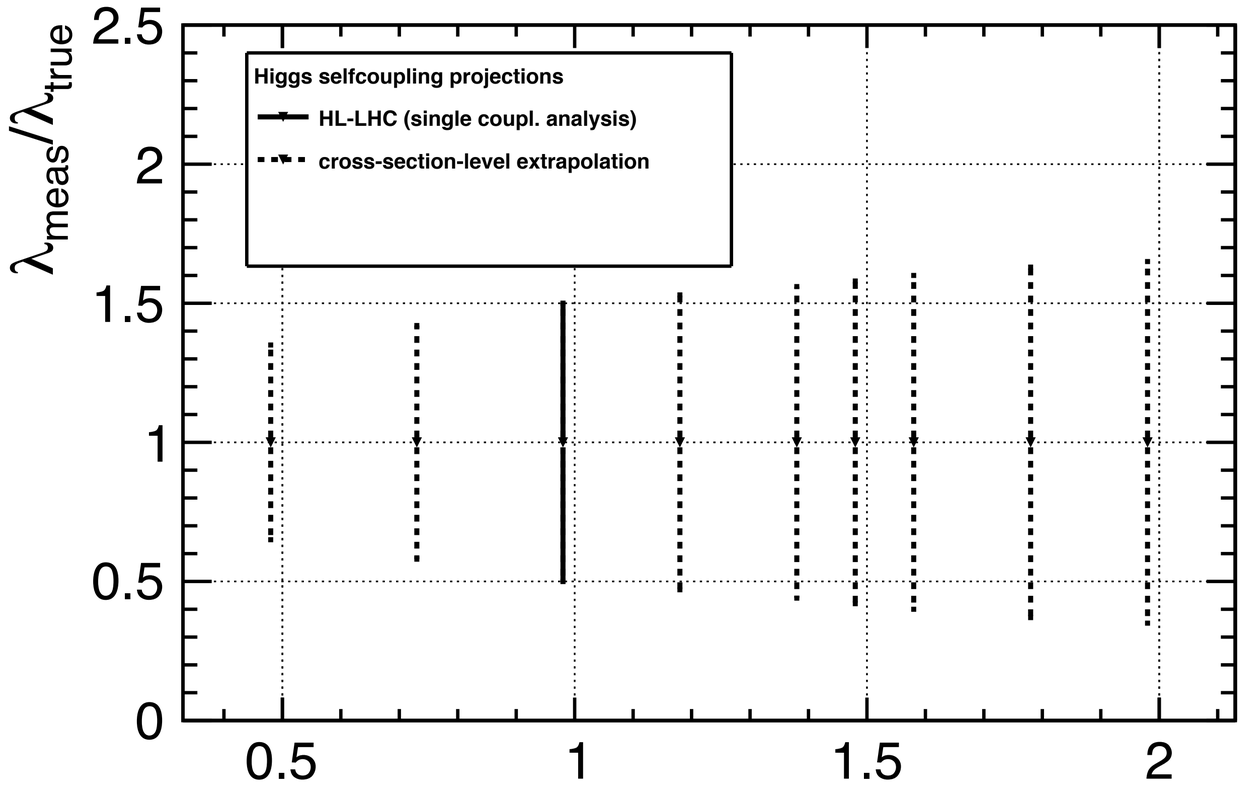

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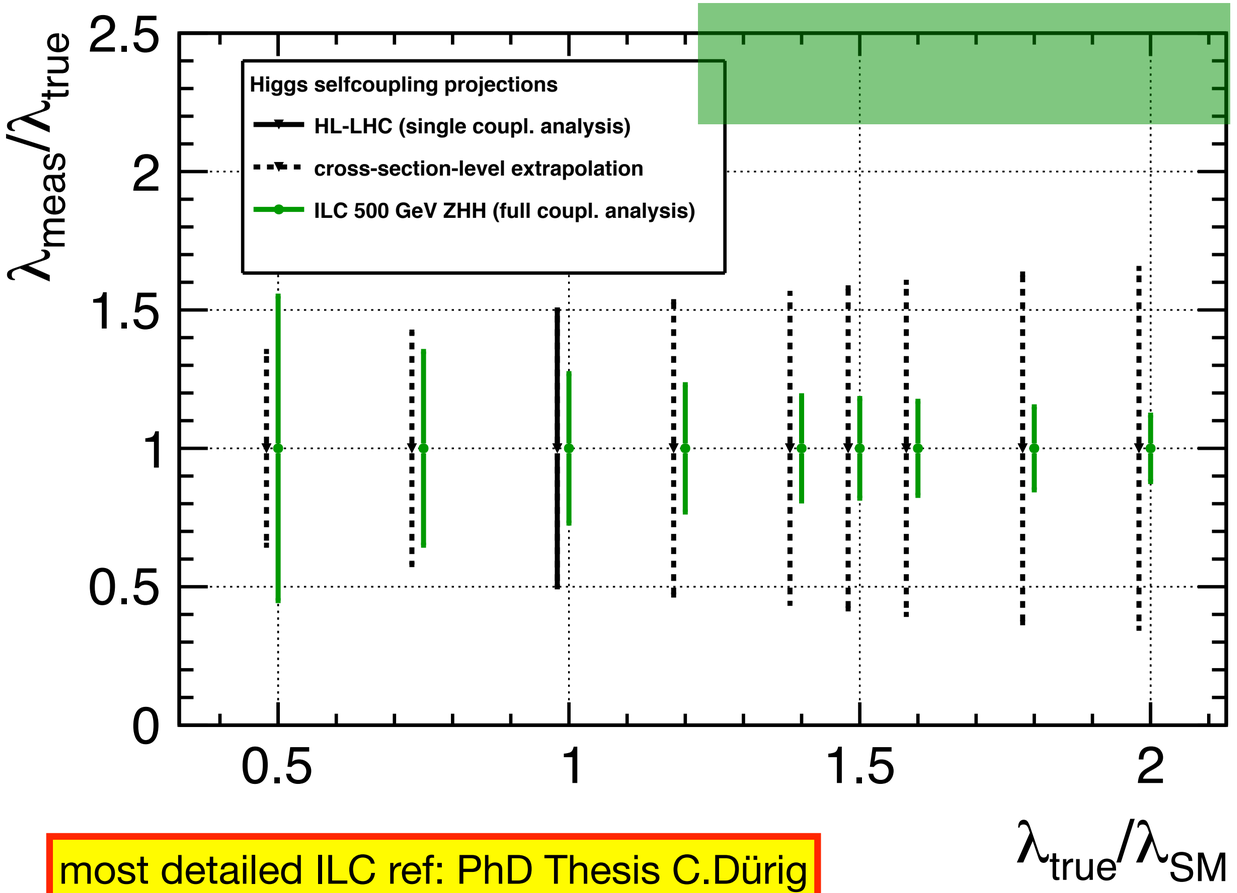

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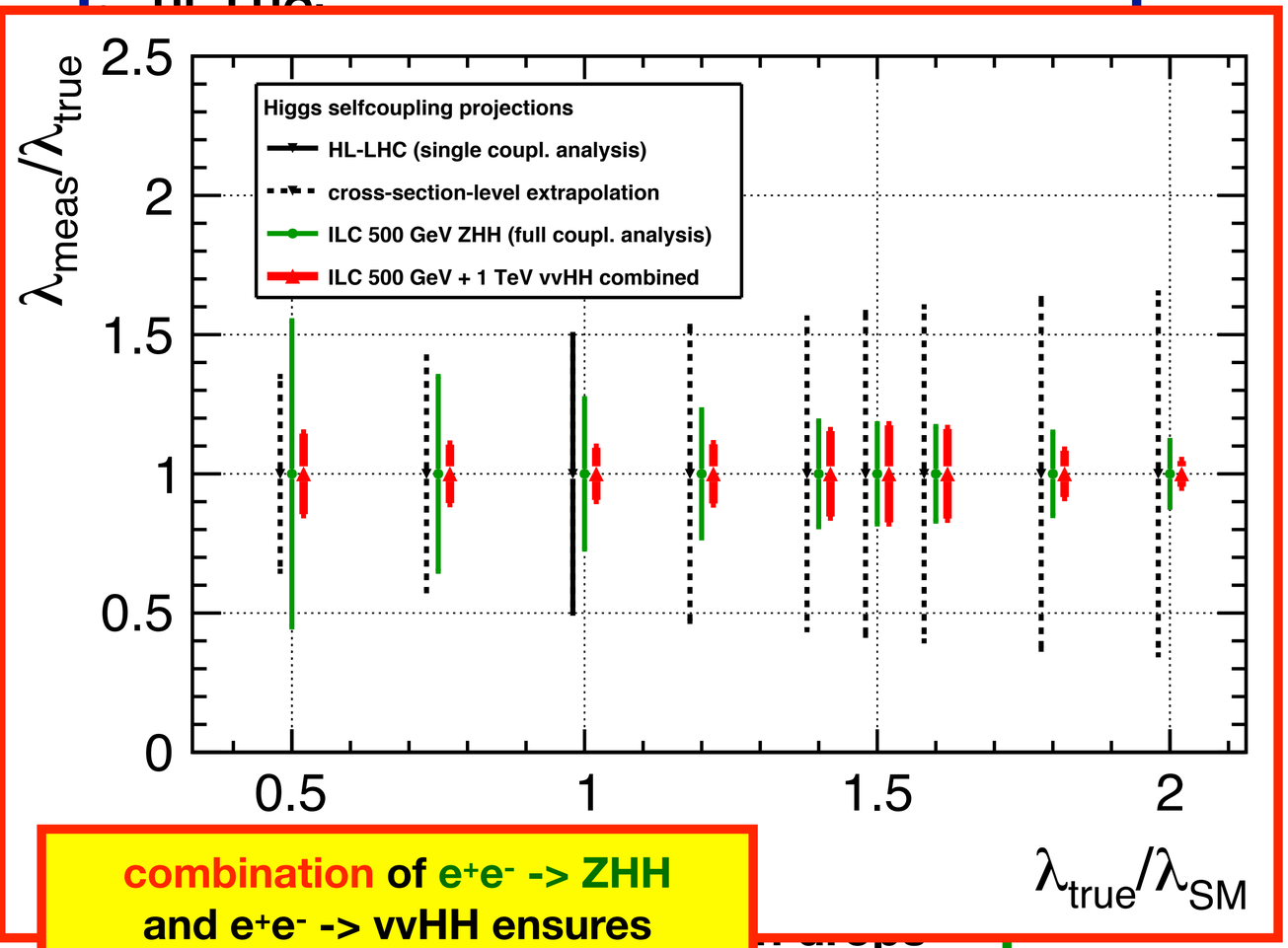
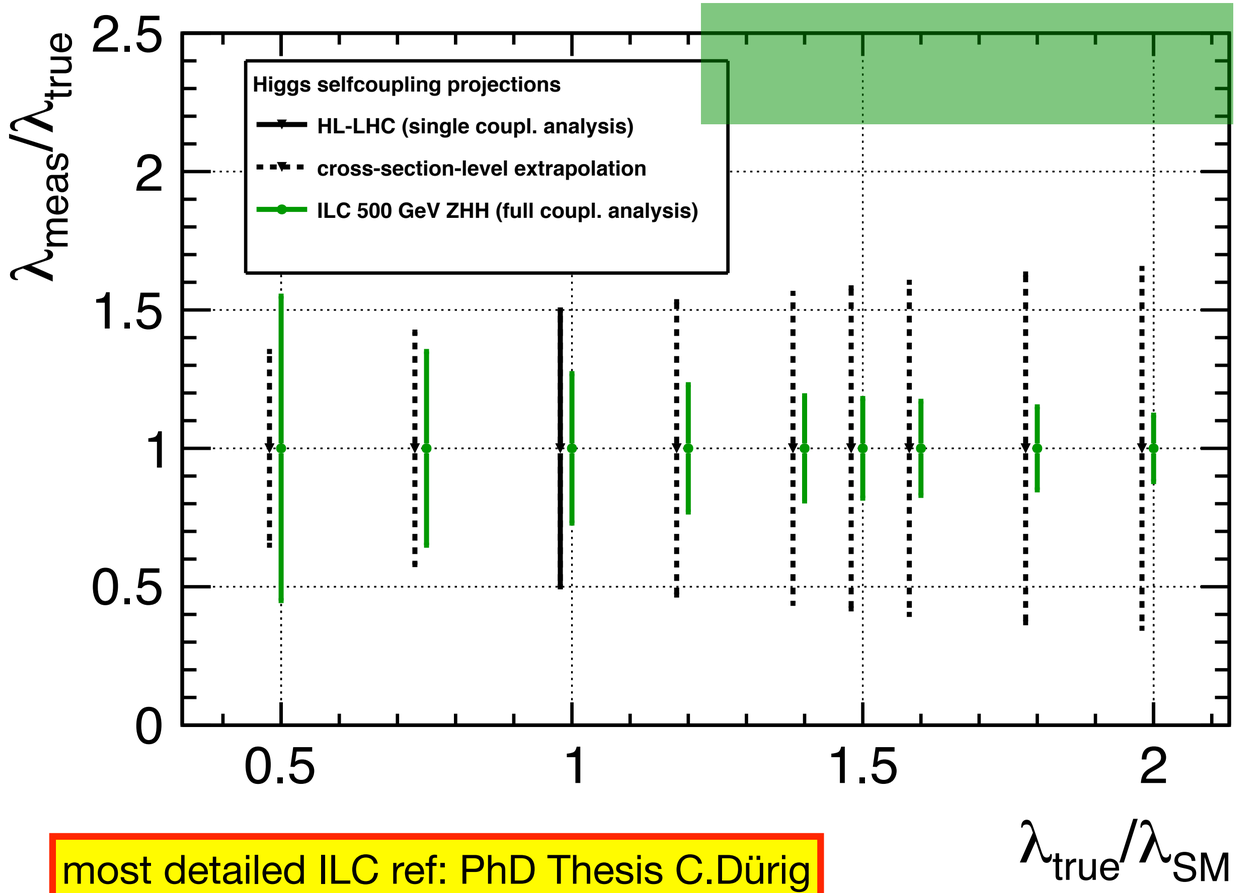


combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision for all λ



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- **absolute size of $|y_t|$:**
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    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in SMEFT$_{ND}$**
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    - ***strong dependence*** on exact choice of E_{CM}, e.g. **2% at 600 GeV**
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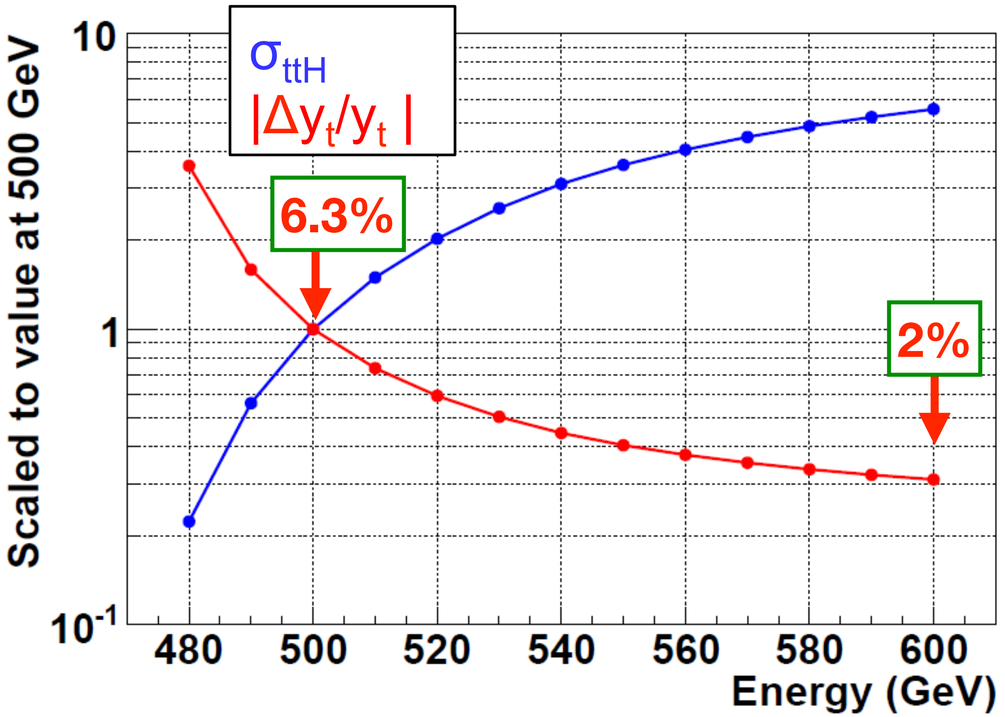
[Phys.Rev. D84 (2011) 014033 & arXiv:1506.07830]



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- **full coupling structure** of tth vertex, incl. CP:
  - **e^+e^- at E_{CM} ≥ ~600 GeV**
    => ***few percent sensitivity to CP-odd admixture***
  - **beam polarisation essential!**

[Eur.Phys.J. C71 (2011) 1681]

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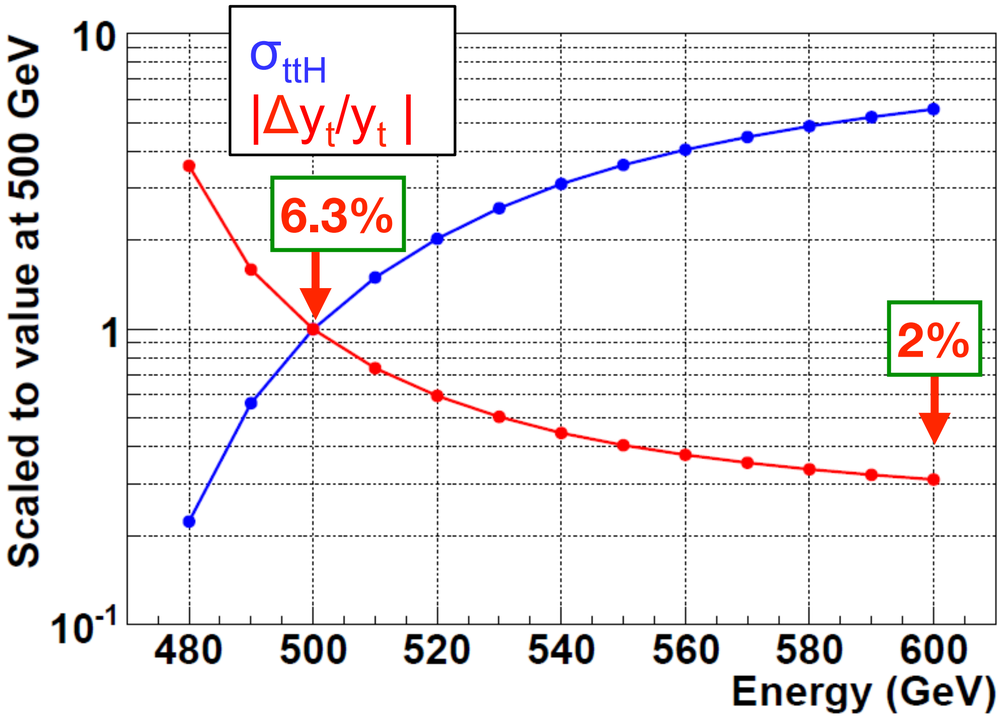

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Looking for more new friends

Discoveries of new particles ?

Opportunities for direct discoveries ?

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

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

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- **polarised beams**
  can suppress SM backgrounds
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- **tremendous advances in detector technology**,
  e.g. momentum resolution
  1-2 orders of magnitude better, vertexing,
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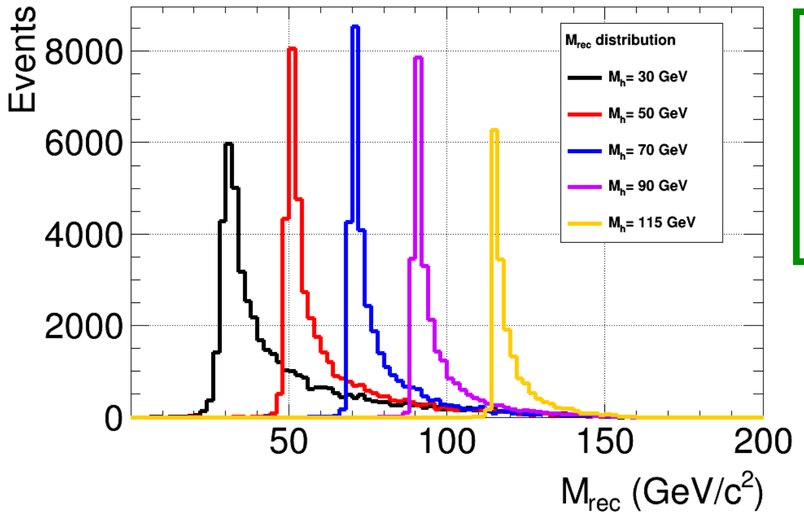
=> any search channel *limited by rate* at LEP2 will explore new territory at ILC250 !

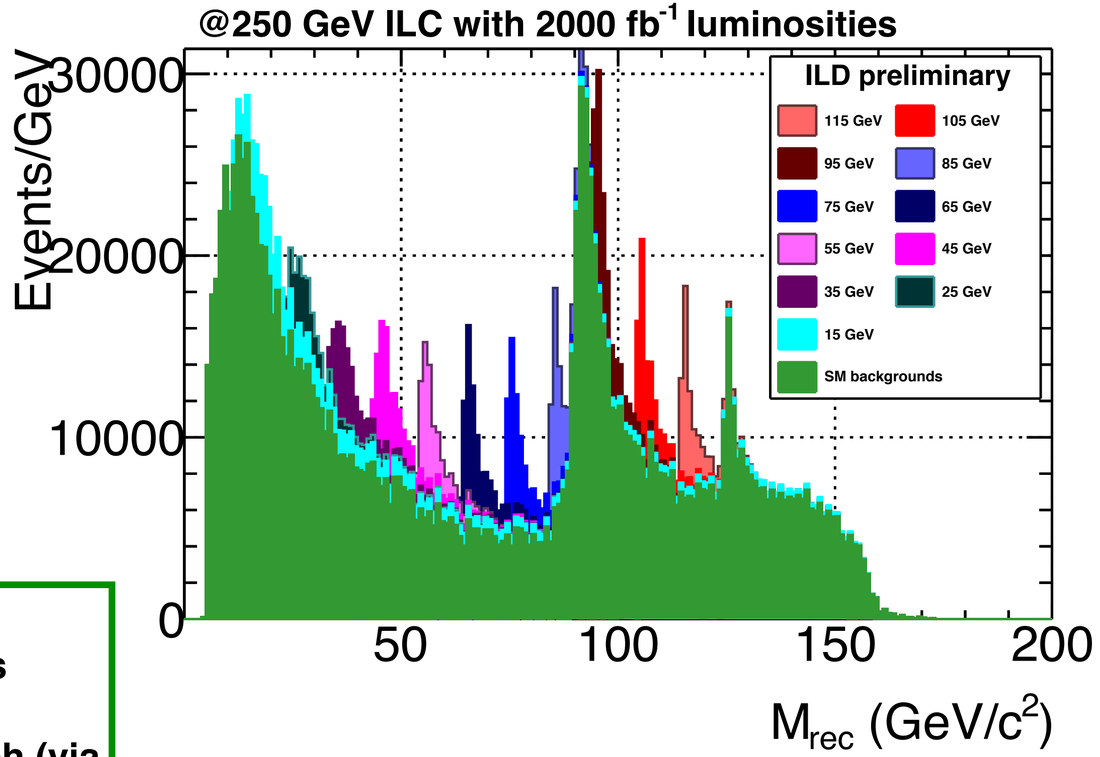
Example: Extra Higgs Bosons

- must “share” coupling to the Z with the 125-GeV guy:
  - $g_{HZZ}^2 + g_{hZZ}^2 \leq 1$
  - after ILC 250 GeV $g_{hZZ}^2 < 2.5\%\ g_{SM}^2$ excluded at 95% CL
- probe smaller couplings by ***recoil* of h against *Z***

=> decay mode independent!



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



ILD full detector simulation @ ILC 250 GeV & 500 GeV, arxiv:2005.06265

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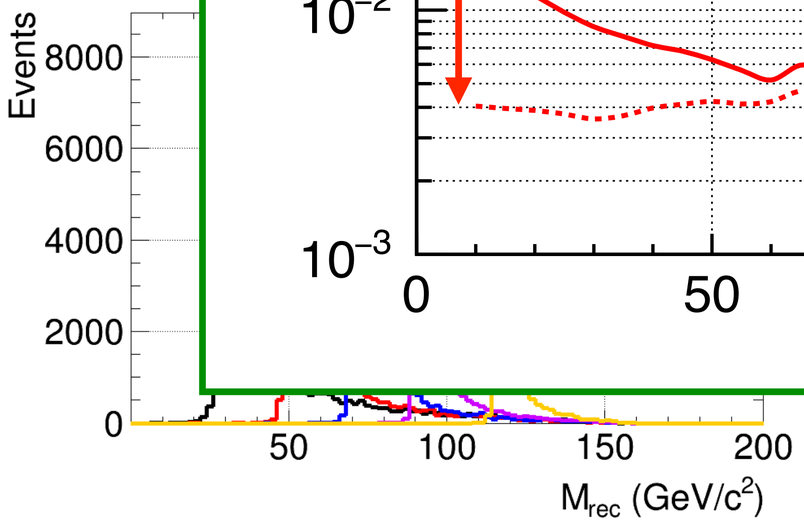
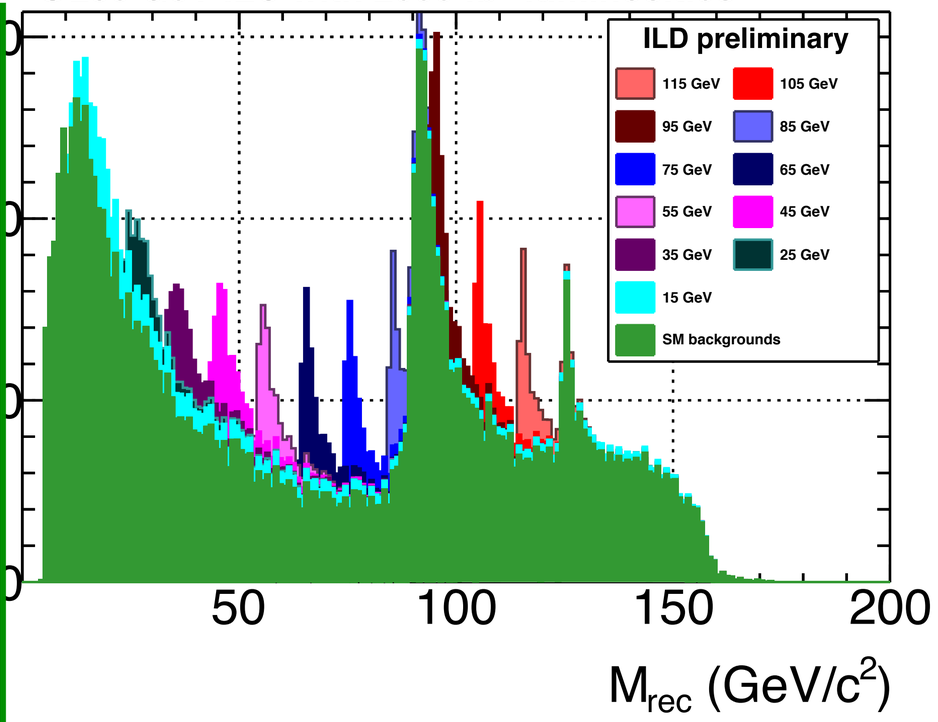
- must "s
  - g_{HZZ}^2
  - after 95%
- probe s

=> deca



@250 GeV ILC with 2000 fb^{-1} luminosities



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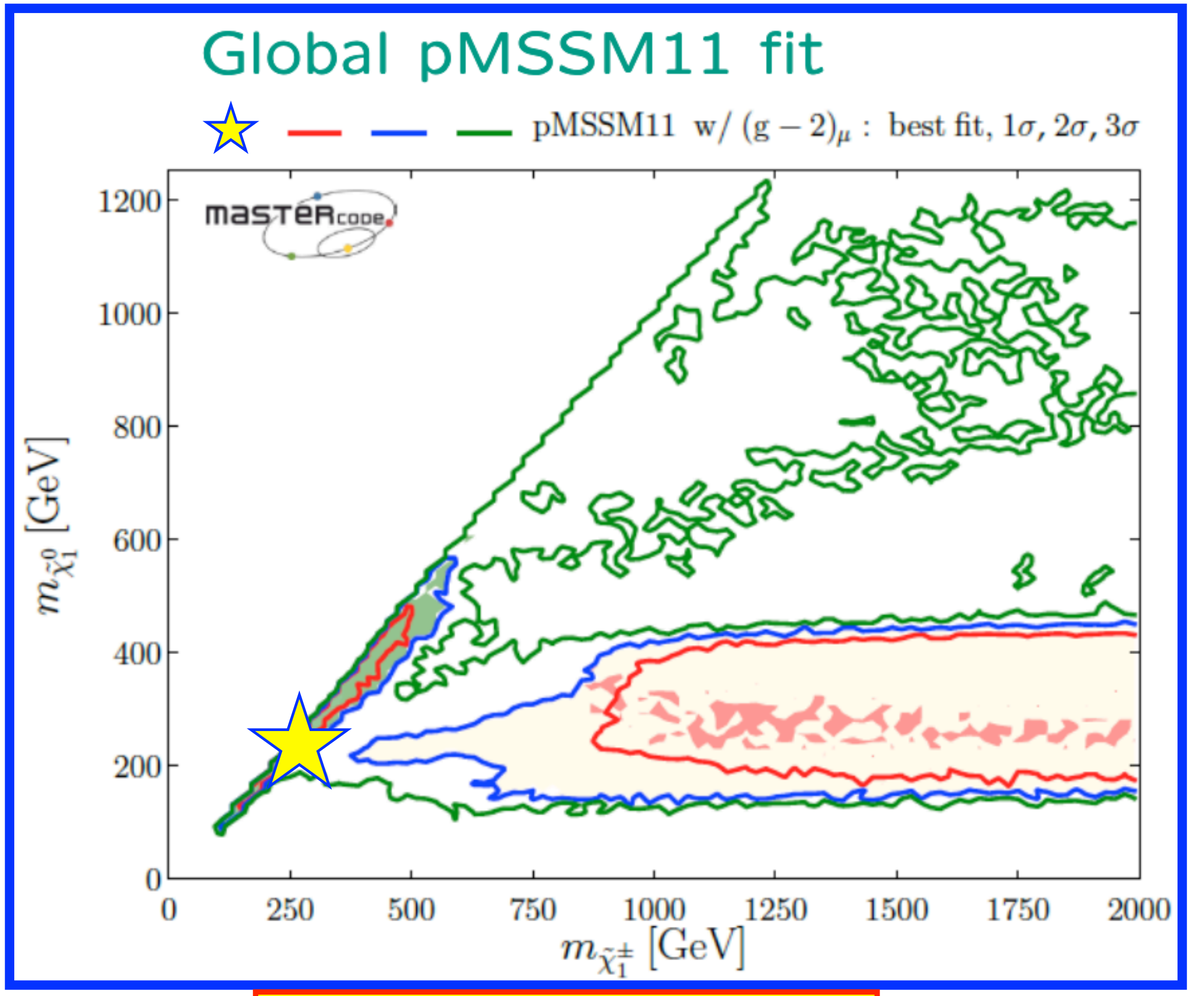
Loop-hole free searches for BSM particles
up to $E_{CM}/2$ or up to E_{CM} - (M_Z / M_H / M_{LSP} / …)

- **lowish ΔM is THE region preferred by data**
  - **charginos, neutralinos, selectrons, smuons, staus => no *general* limit above LEP**
- **long and diverse decay chains (small BRs)**
- **heavy Higgses**
- **Dark Matter, WIMPs**
- **the UNexpected: LCs operate trigger-less!**



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

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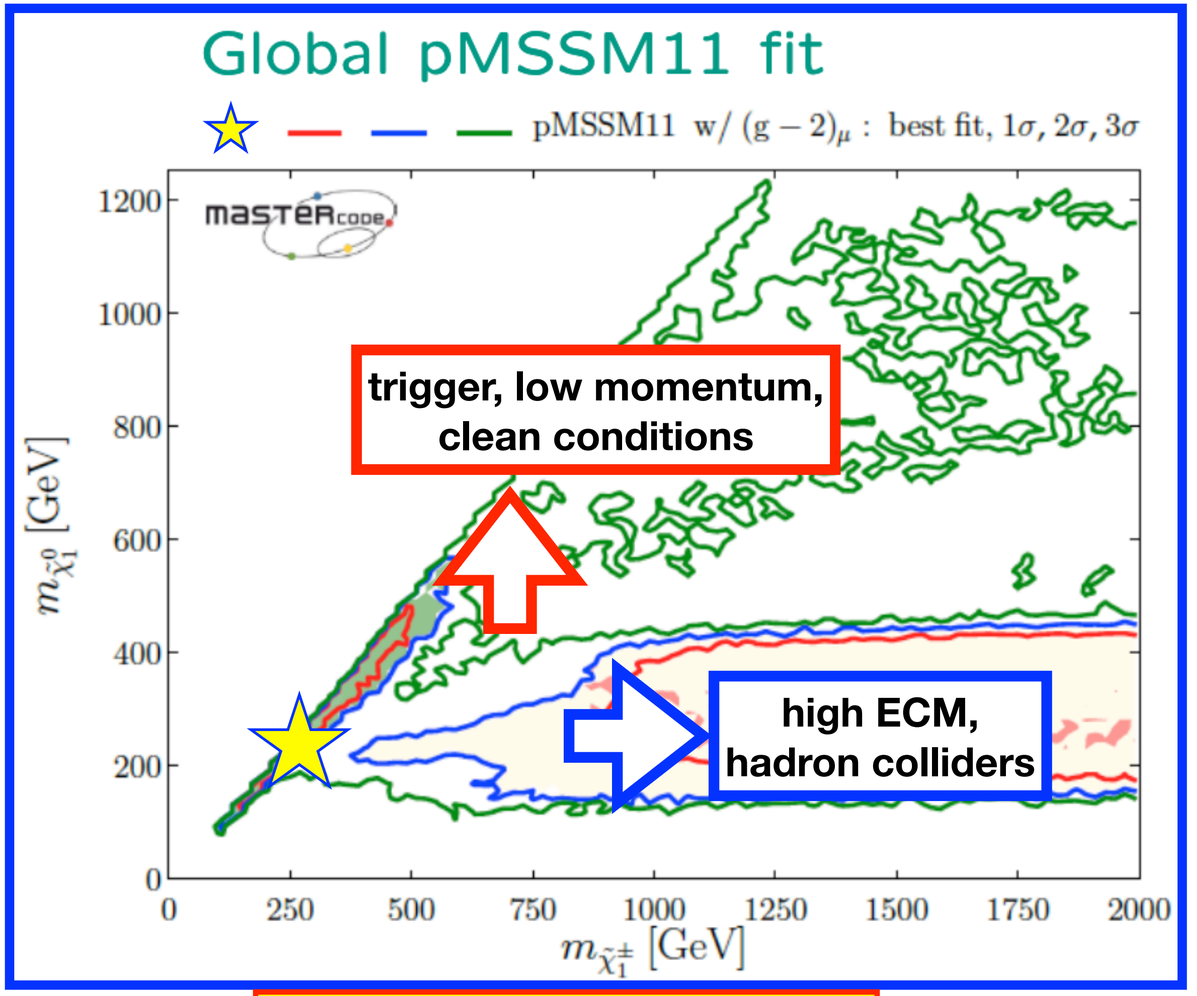

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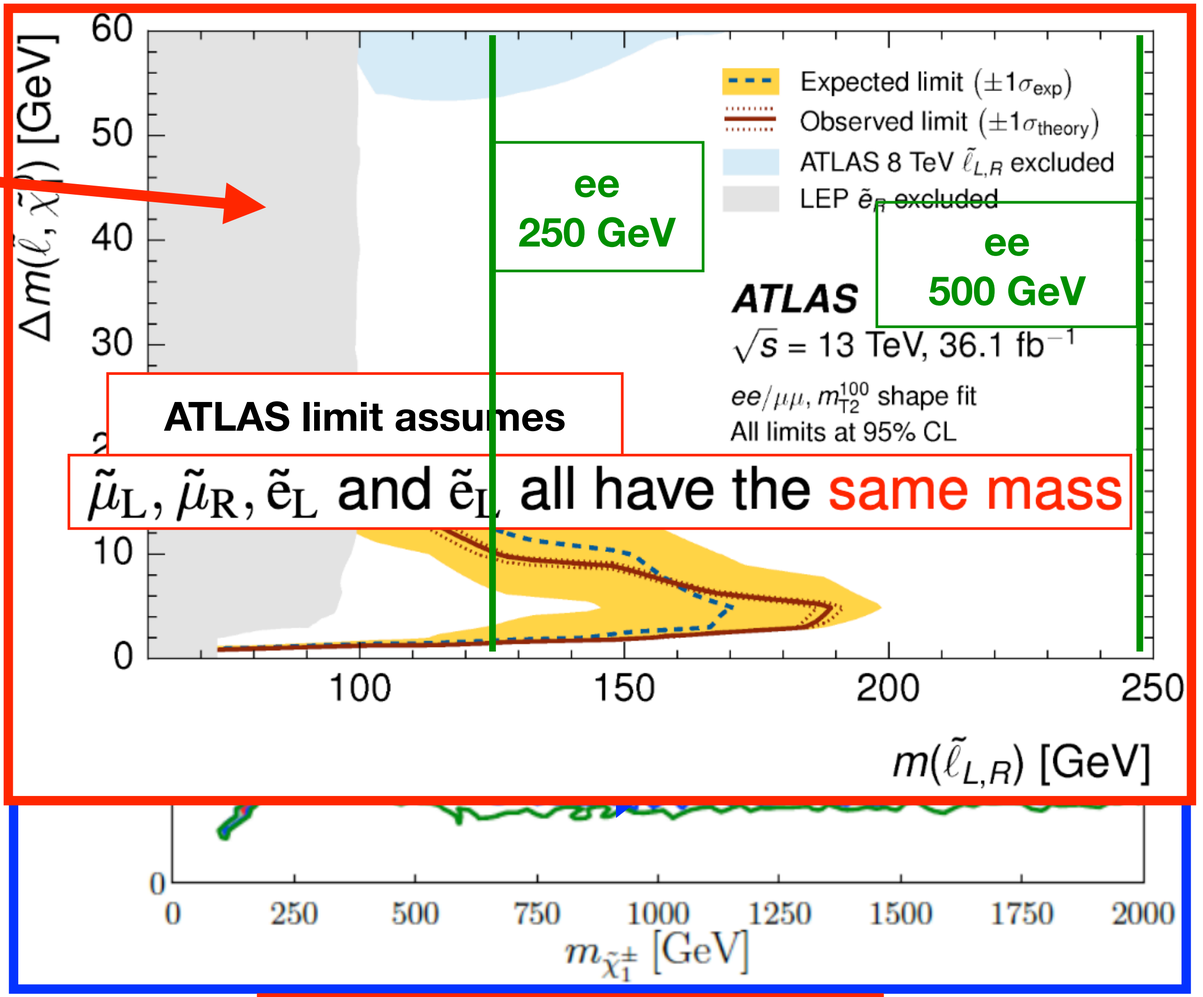

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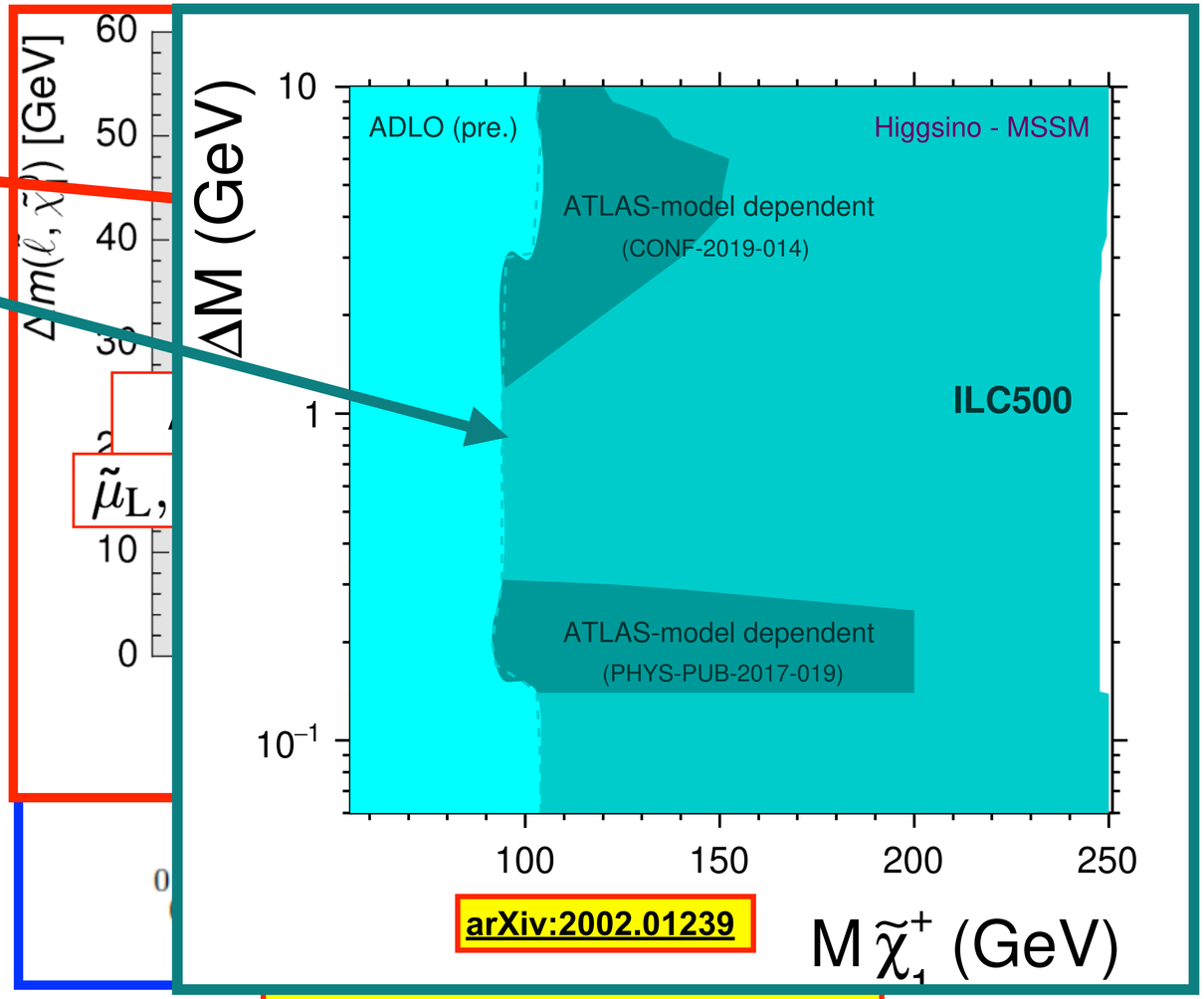

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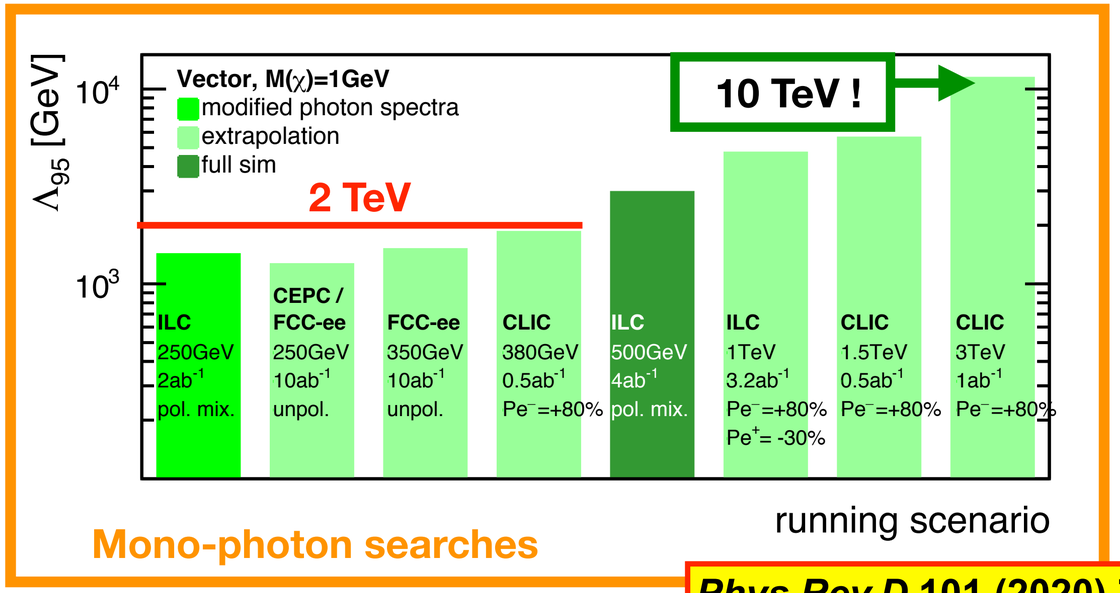
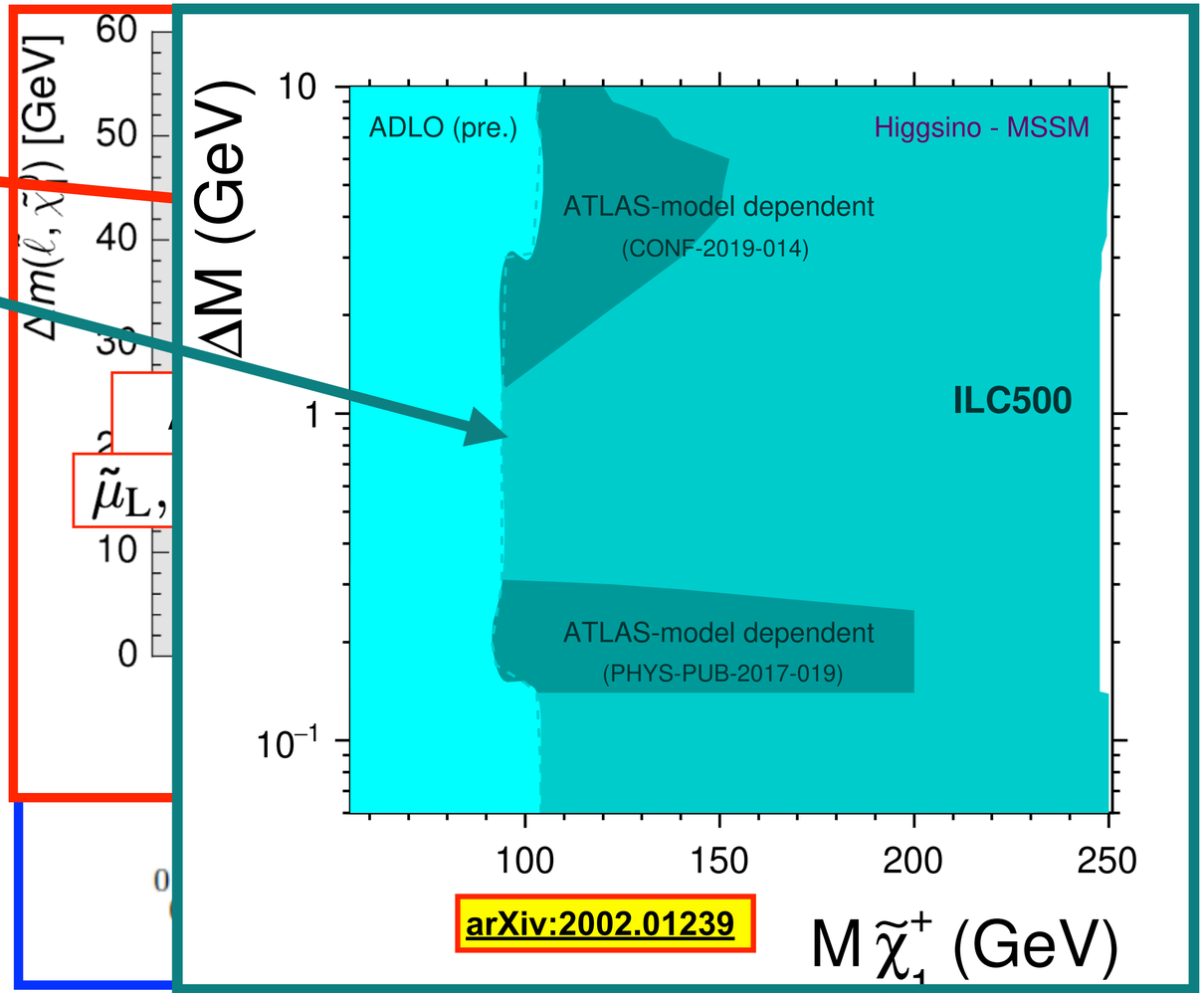


Mono-photon searches

***Phys.Rev.D* 101 (2020) 7, 075053**



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

Conclusions

- **There is a clear and significant physics case for e^+e^- collisions at E_{CM} = 250 GeV — and at ≥ 500 GeV — complementary to pp collisions!**
- **Therefore the next e^+e^- collider must be energy upgradable.**
- **CLIC and ILC both fulfill this criterion.**
- The exact physical and/or operational energy stages ***beyond*** the initial "Higgs factory" mode still can be defined, taking into account
  - **physics needs**
  - **technological innovations**
- **There is still a lot to do for the physics case, eg:**
  - **TGCs @ 250 GeV**
  - **Higgs self-coupling & ttH @ 500…600 GeV**
  - **full exploitation of detector capabilities in reconstruction**
  - **re-visit detector concepts: timing capabilities, vertex detector layout, …**
  - **want to get involved? ILD Study Questions: arXiv:2007.03650**

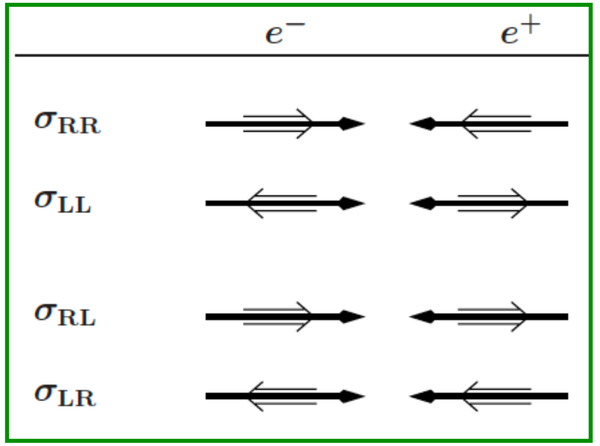
Backup

Future e^+e^- Colliders and (longitudinally) Polarised Beams

- Longitudinally **polarised beams** are a special feature of **Linear e^+e^- Colliders**:
  - SLC: P(e^-) = ± 80%, P(e^+) = 0%
  - ILC: P(e^-) = ± 80%, P(e^+) = ± 30% (upgrade 60%)
  - CLIC: P(e^-) = ± 80%, P(e^+) = 0%

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

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



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

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

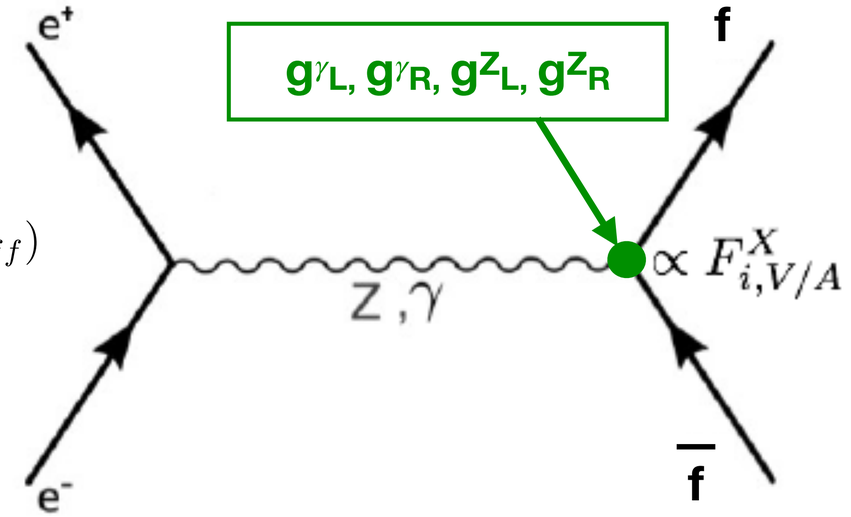
Polarisation & Electroweak Physics

- similarly, disentangle Z / γ exchange in $e^+e^- \to f\bar{f}$

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

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

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



at an ***un***polarised collider:

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

=> no direct access to A_e, only via tau polarisation

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

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

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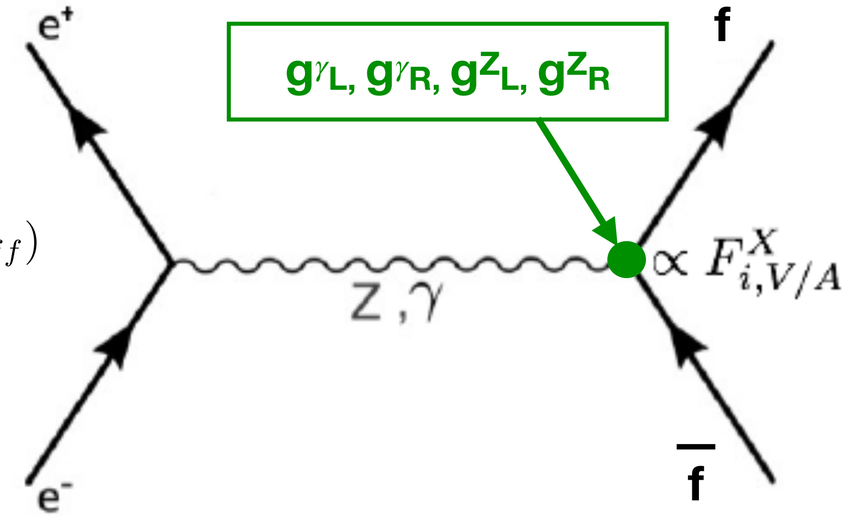

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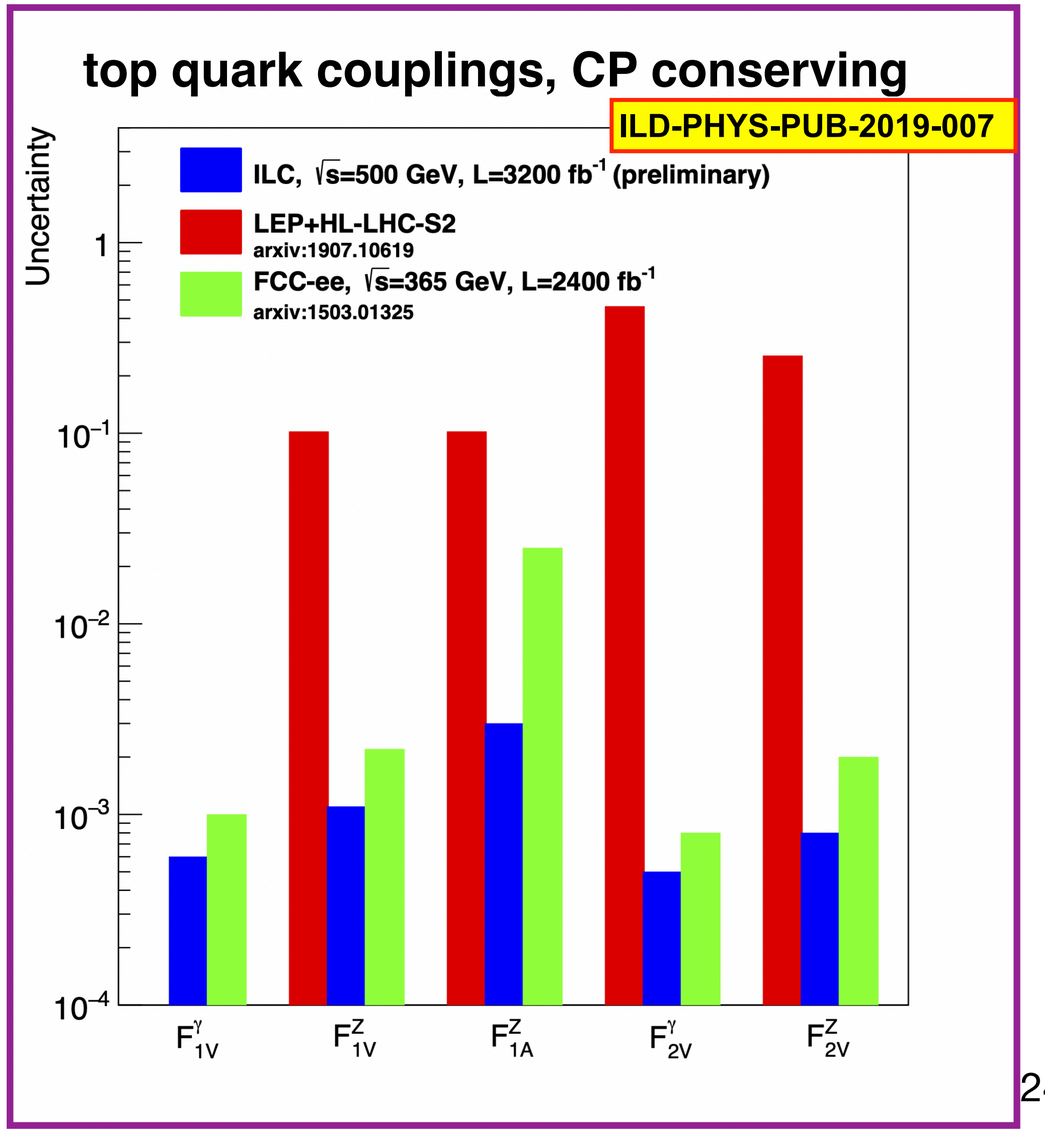
trading theory uncertainy:

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

… and at higher energies

- ex1: top quark pair production - disentangle Z / γ:
  - unpolarised case: from final-state analysis only
  - polarised case: direct access
    - final state analysis can be done in addition
    => redundancy, control of systematics
- ex2: oblique parameters for 4-fermion operators
  - beam polarisation essential to disentangle Y vs W
  - ILC 250 outperforms HL-LHC
  - ILC 500 outperforms unpolarised e^+e^- machines



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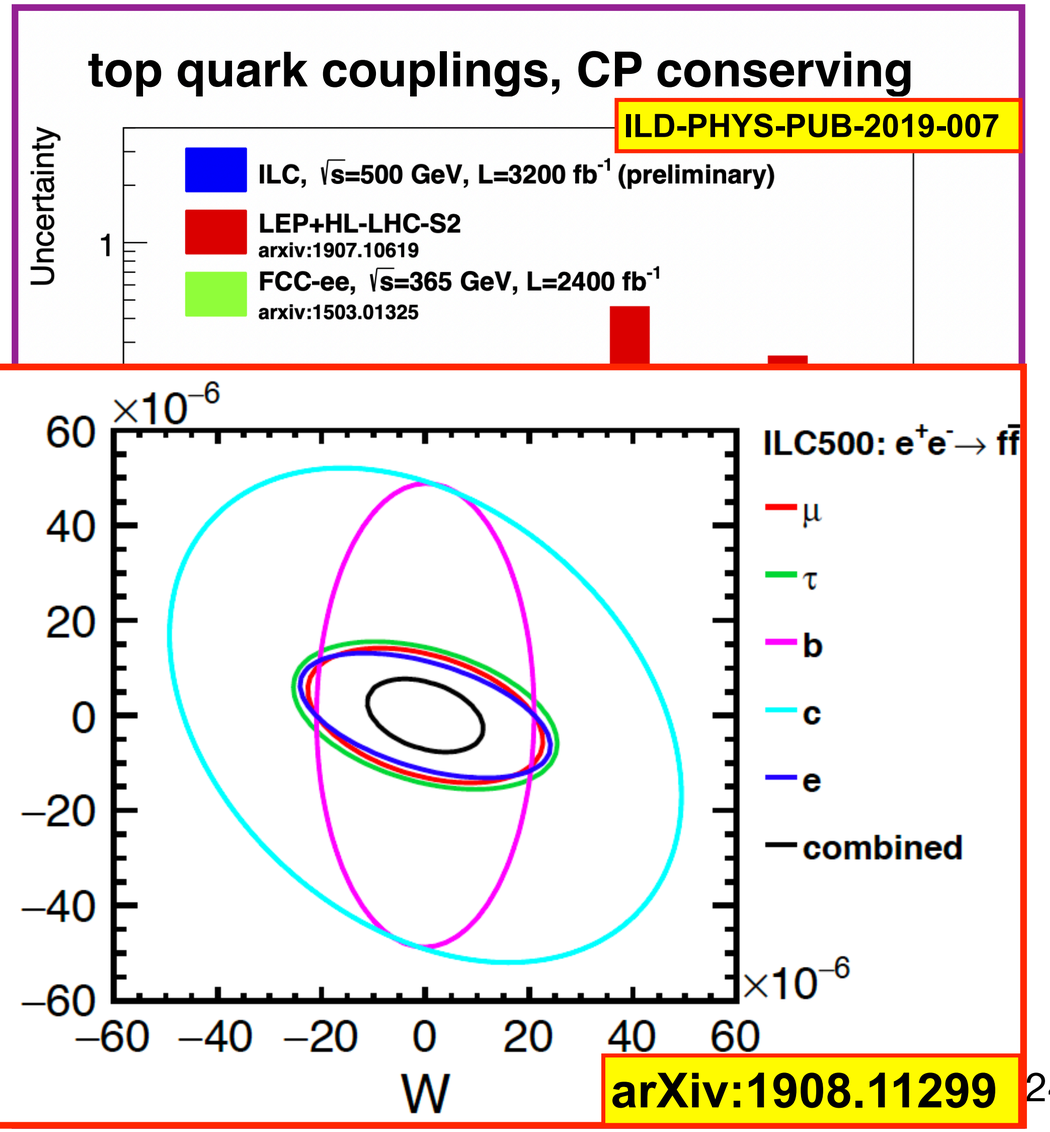
$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78



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.
  - no new operators considered
  - called “model-independent” because no assumptions on any size of coupling or total width

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

- **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.:

$$\delta\mathcal{L} = \frac{m_Z^2}{v}(1+\eta_Z)hZ_\mu Z^\mu + \zeta_Z \frac{1}{v} hZ_{\mu\nu}Z^{\mu\nu}$$

$$\begin{aligned}\Gamma(h \to ZZ^*)/SM &= (1 + 2\eta_Z - 0.50\zeta_Z) \\ \sigma(e^+e^- \to Zh)/SM &= (1 + 2\eta_Z + 5.7\zeta_Z)\end{aligned}$$

  - general EFT fineprint: no light new particles…
    => treat H->invisible as additional degree of freedom
  - also includes:
    - 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

New Physics Interpretation of Higgs & EW

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

Discoveries of new particles ?

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
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5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
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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].

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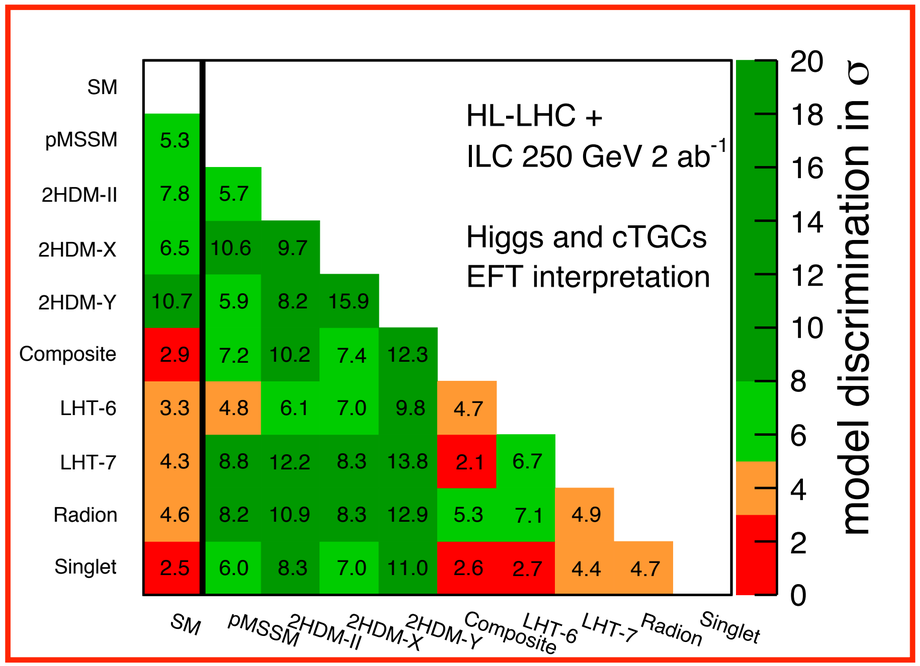

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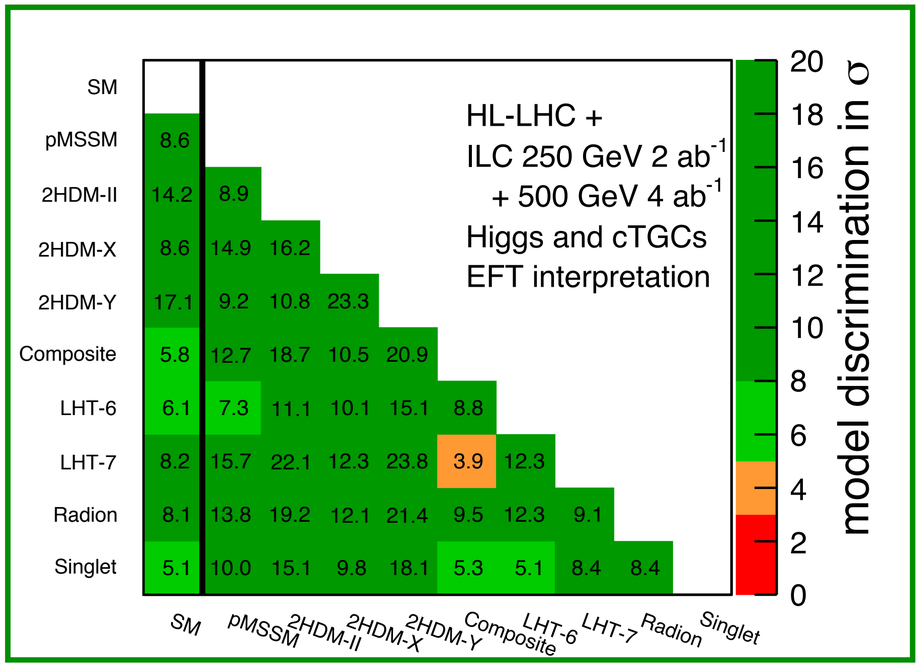

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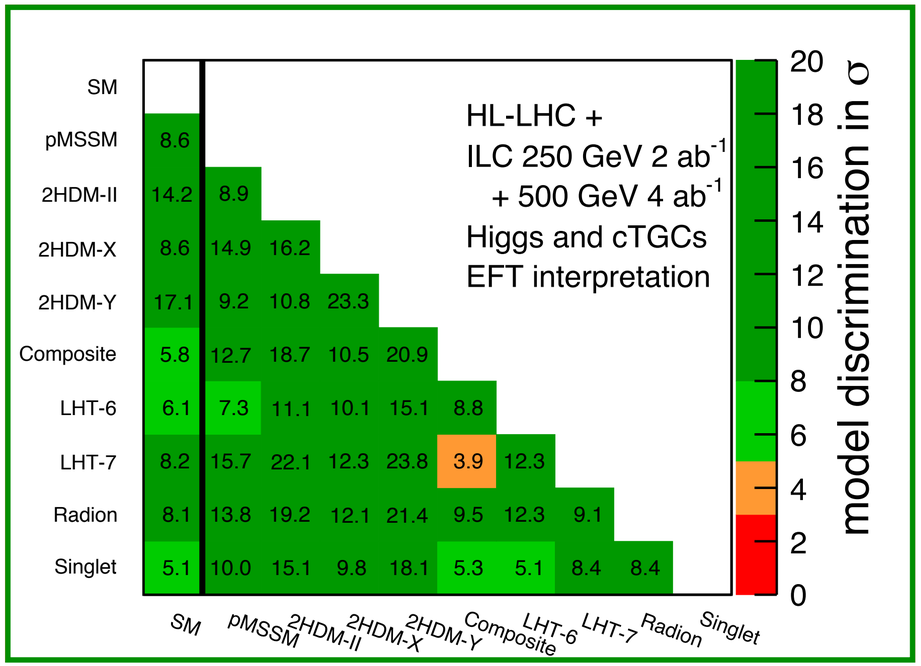

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illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

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

The Higgs Boson

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

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

h is a spin 0 state:

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

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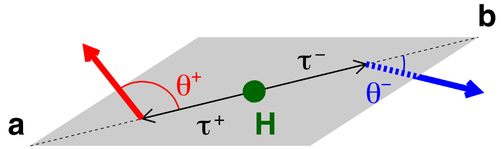

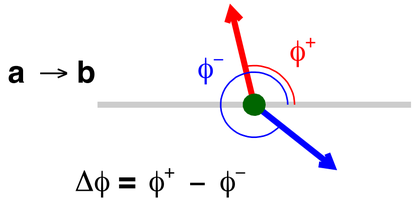

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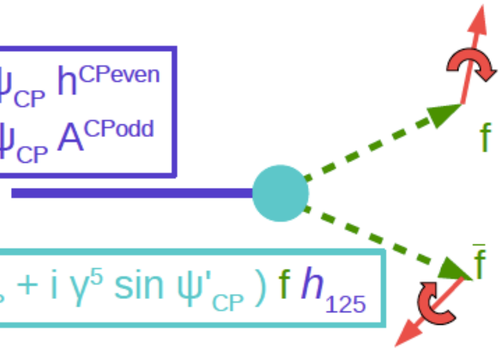

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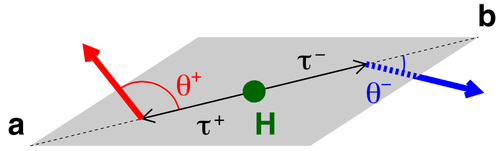

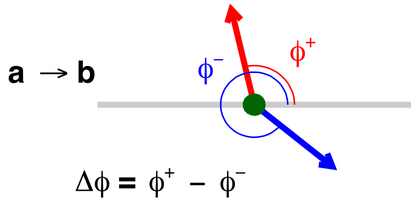

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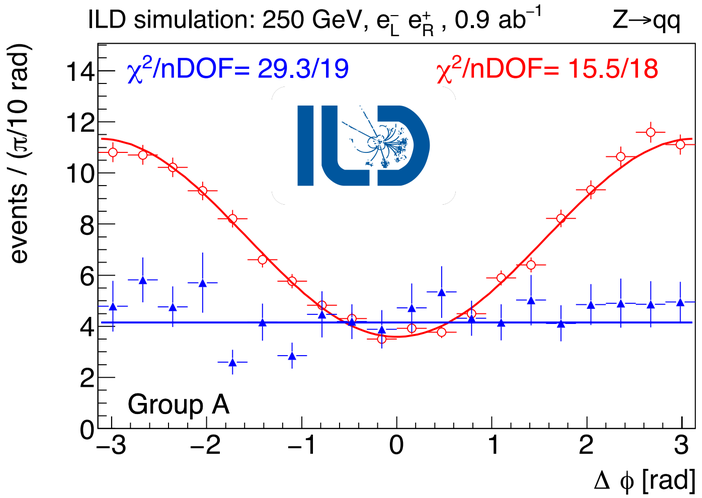

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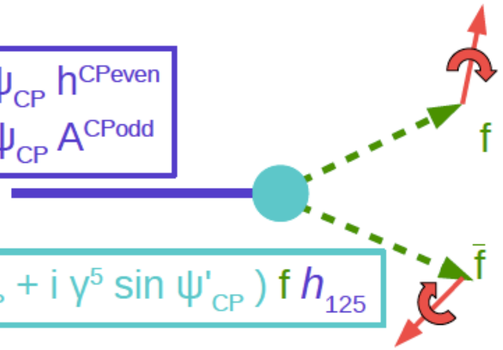

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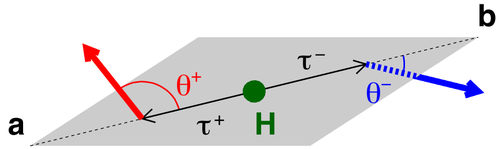

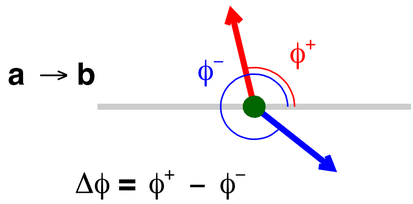

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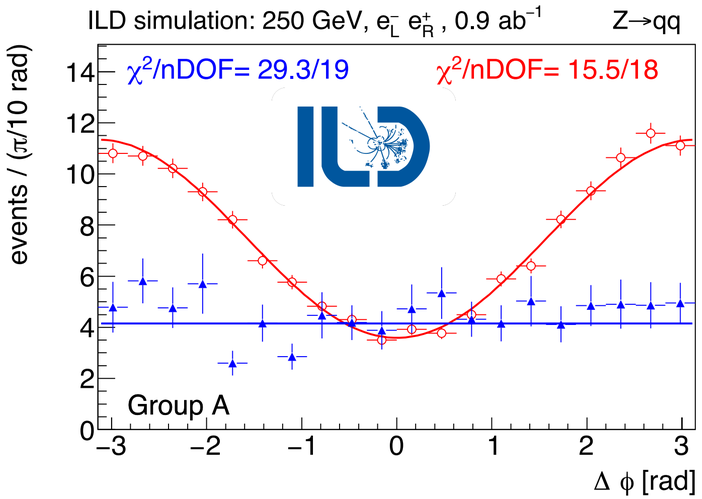

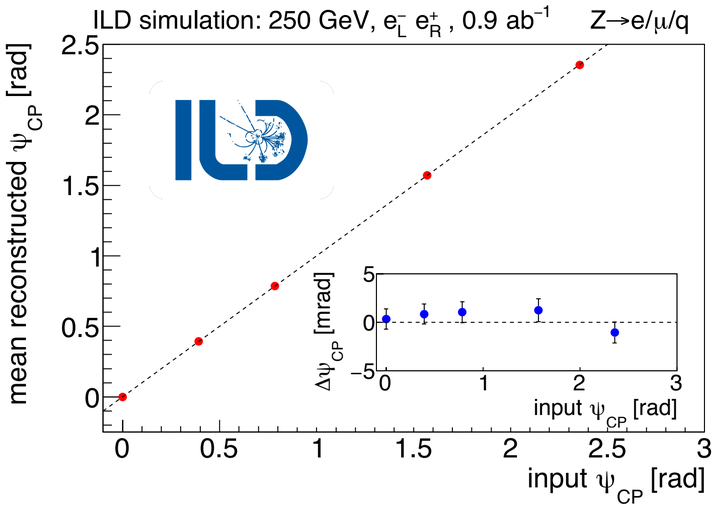

arxiv:1804.01241

based on NIM A810 (2016) 51-58

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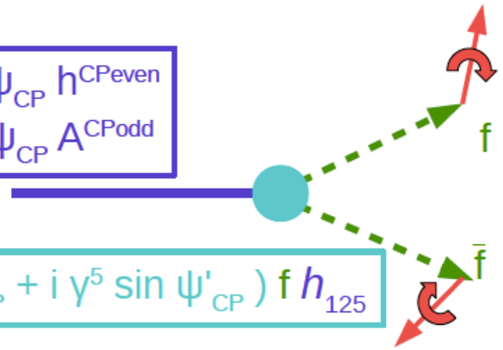

$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\,f\,h_{125}$

h is a spin 0 state:

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

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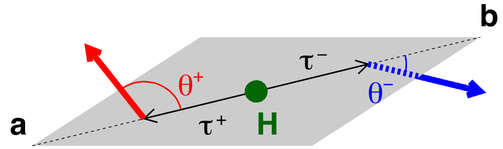
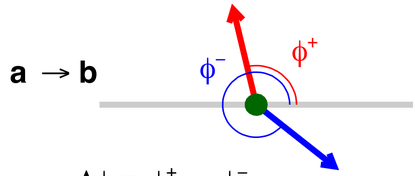
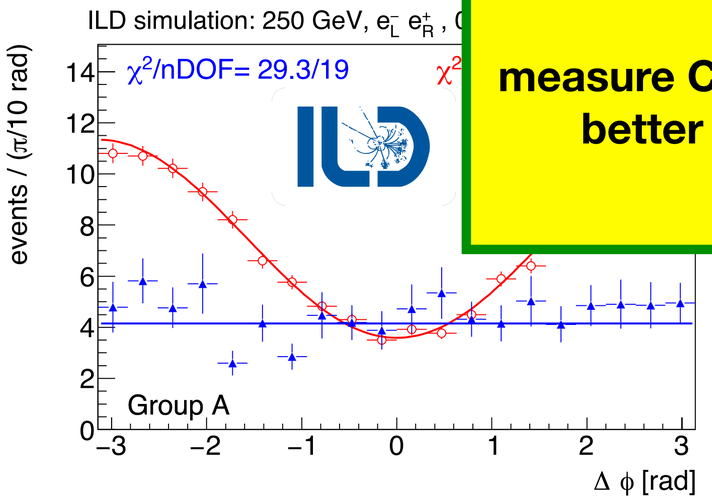
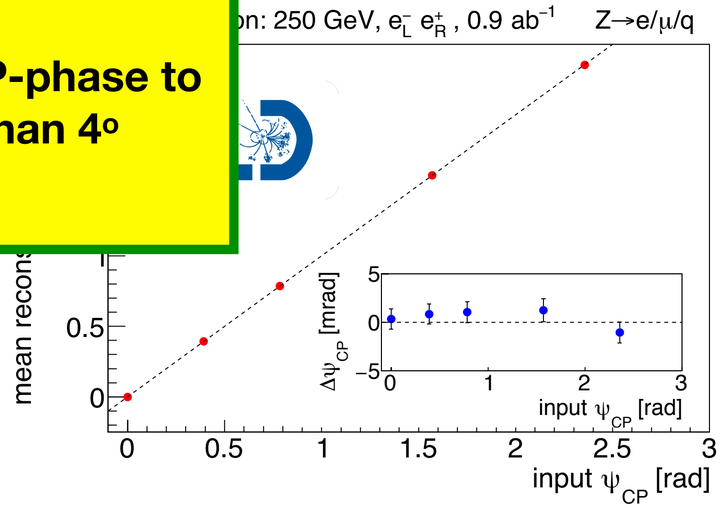




$\Delta\phi = \phi^+ - \phi^-$

measure CP-phase to better than 4°





arxiv:1804.01241

based on NIM A810 (2016) 51-58

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

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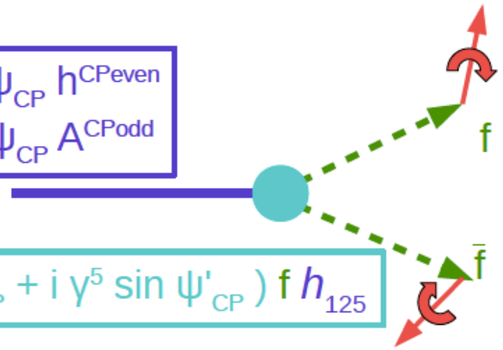

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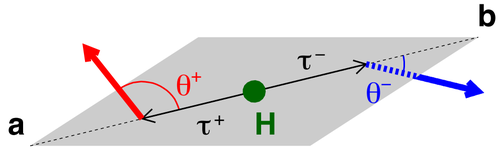

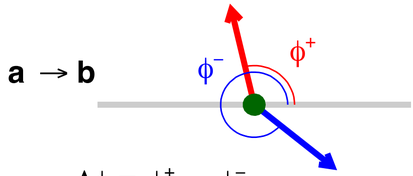

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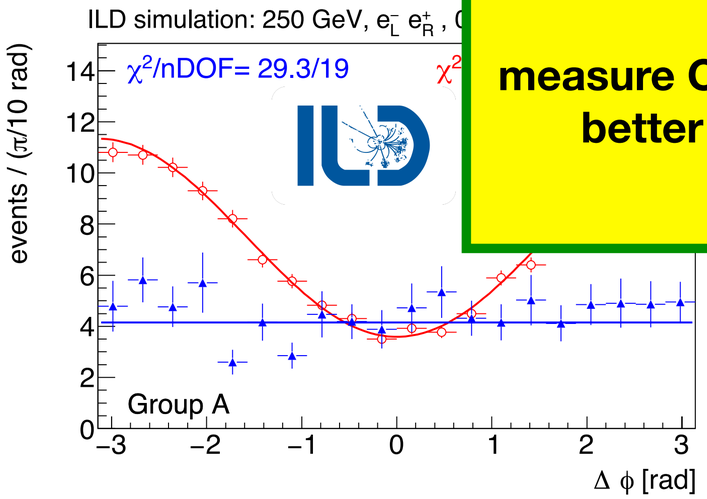

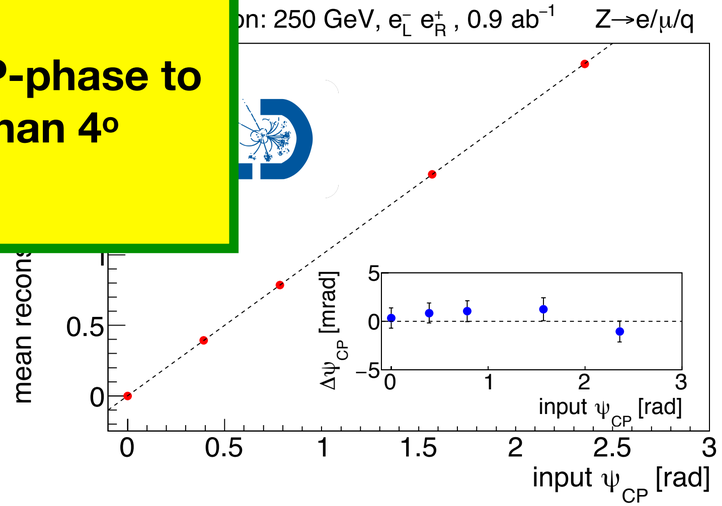

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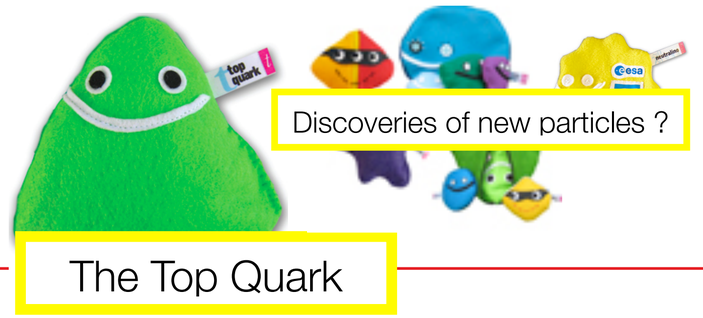
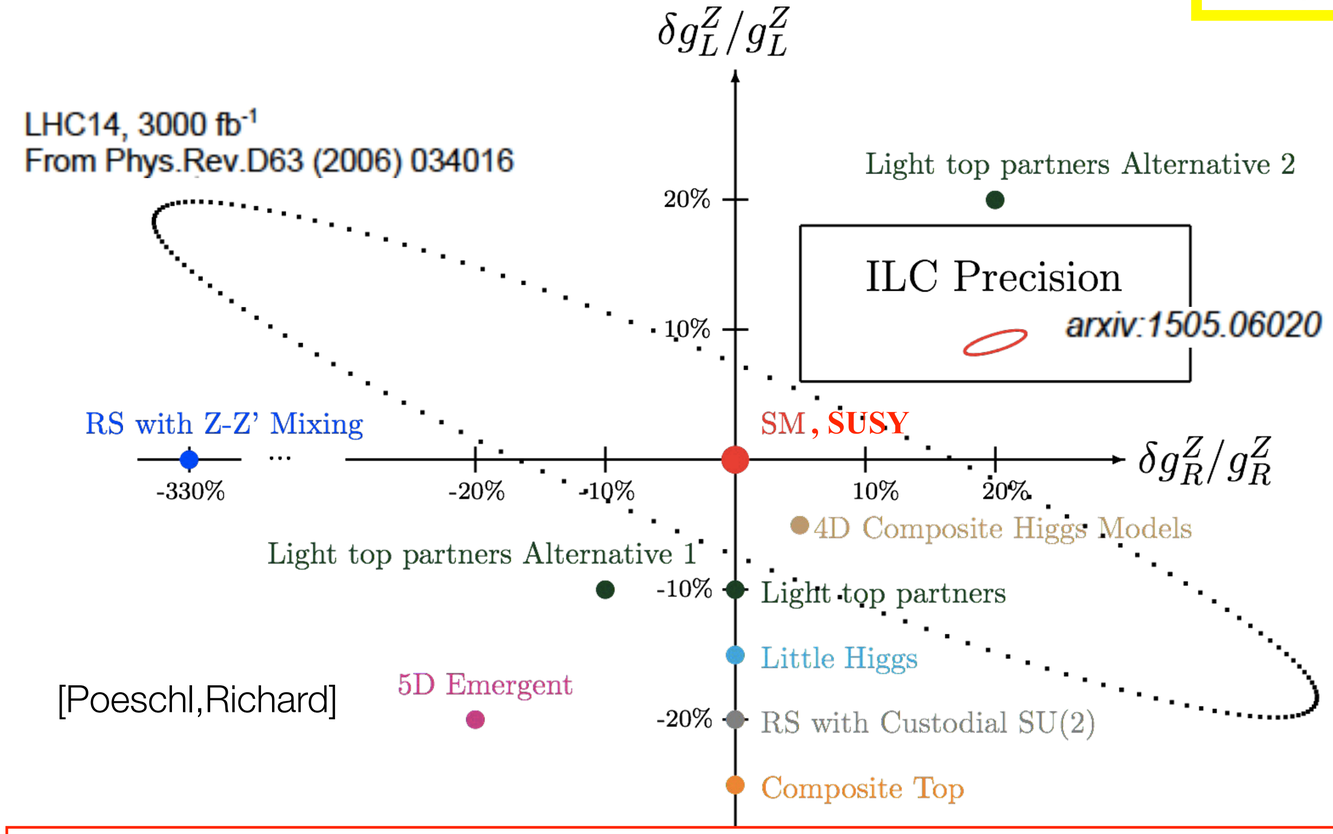
..and CPV in Zh coupling:

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

=> $\tilde{b}$ to ±0.005

Top EW Couplings at 500 GeV





[Poeschl,Richard]

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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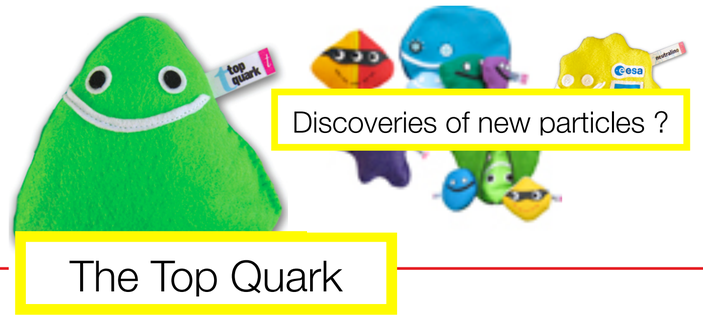

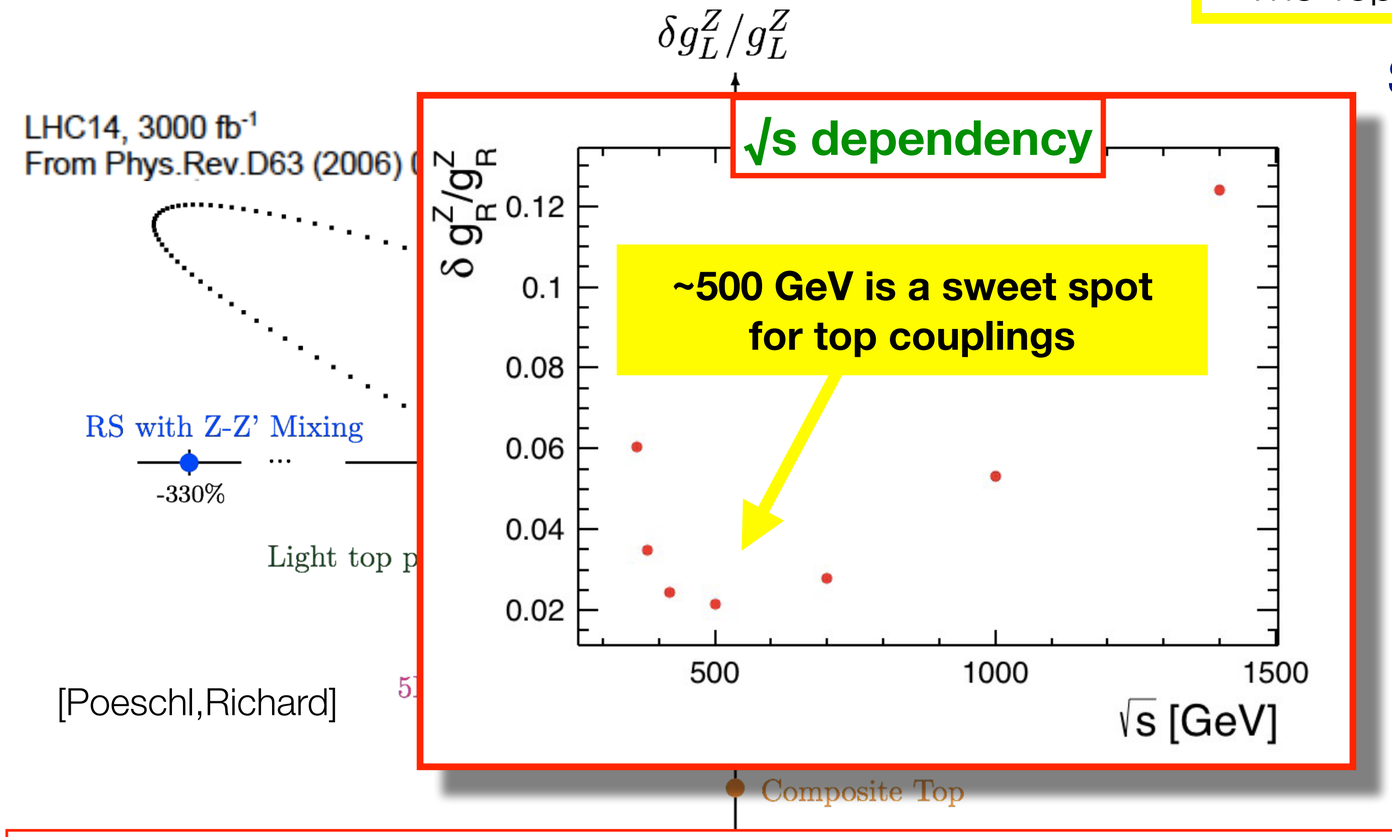

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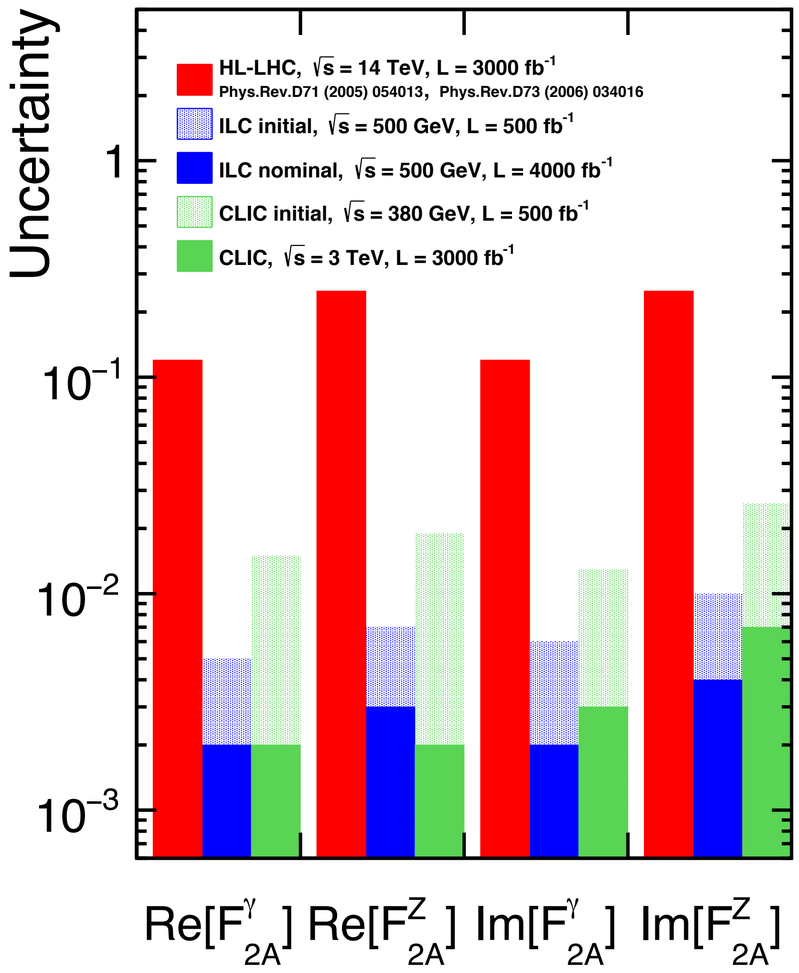
More CP violation?

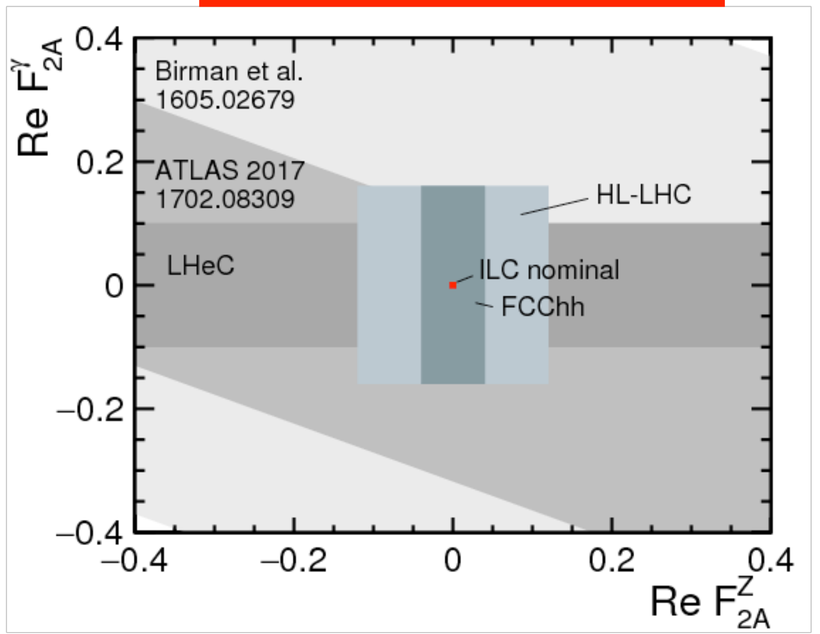


e^+e^- -> tt at $\sqrt{s} \geq 380$ GeV:

Probe for CP violation in coupling of the top quark to Z boson and photon

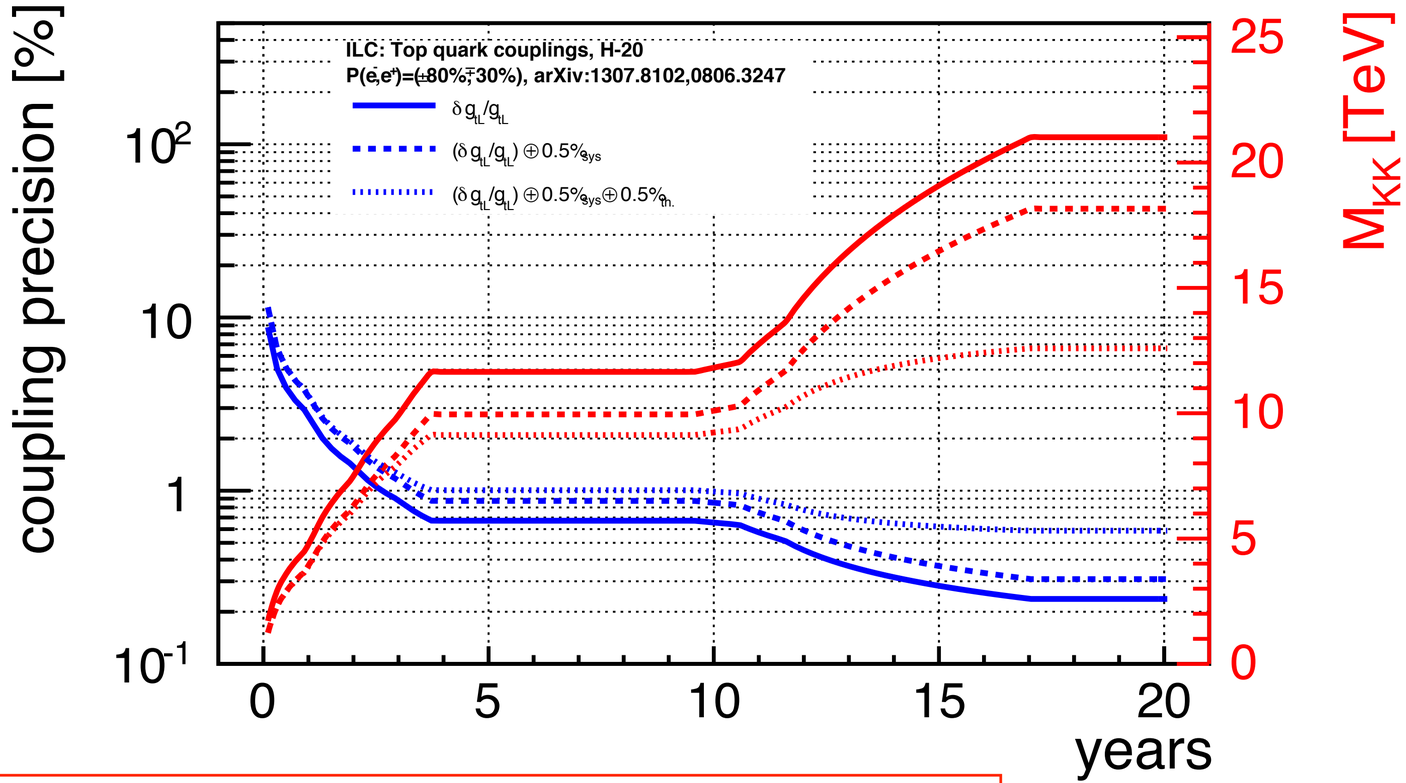
H2DM, SUSY: form factors up to 0.01

Eur.Phys.J. C78 (2018) no.2, 155



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



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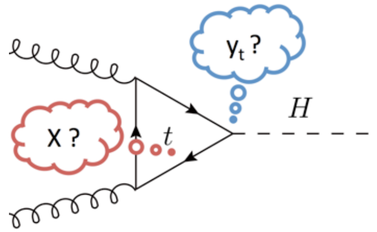
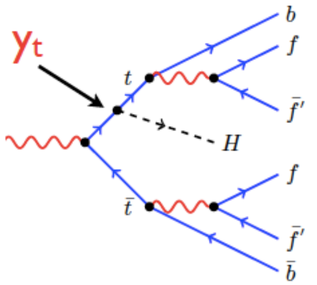
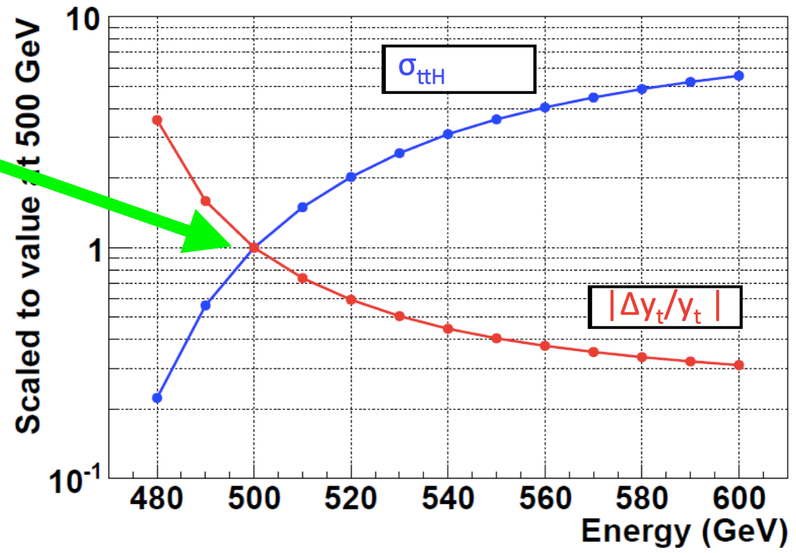
Direct Determination of the Top Yukawa Coupling

- **(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
- **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)





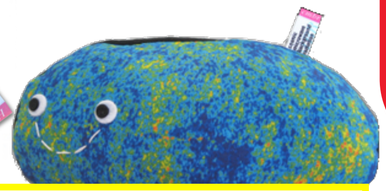
arXiv:1310.8361



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

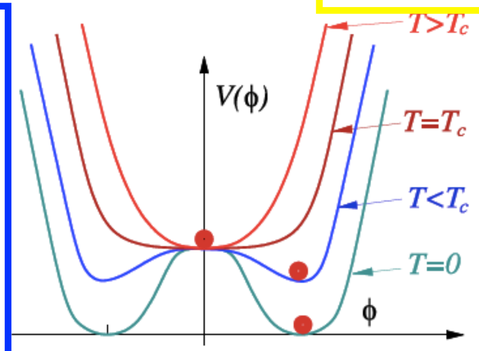
The Higgs self-coupling

The Higgs Boson …

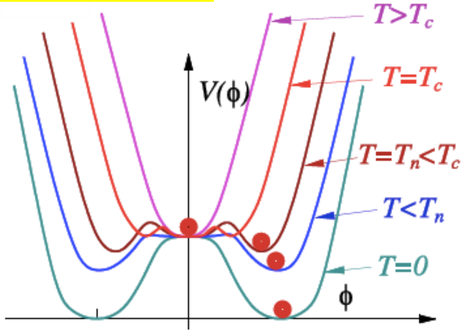


…and the universe

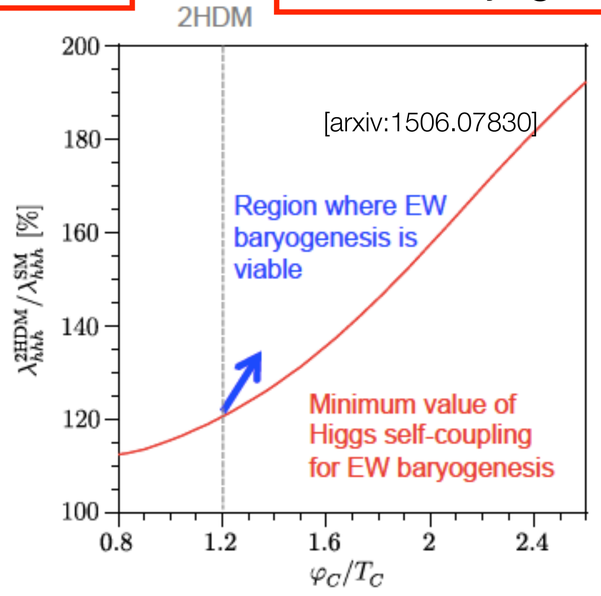
- determines shape and evolution of Higgs potential => cosmology!
- many BSM models influence λ, deviations from SM value can be **large**! E.g.:
  - up to O(100%) in general 2HDMs, even if other couplings are SM-like
    [c.f. e.g. Phys.Lett. B558 (2003) 157-164]
  - **electroweak baryogenesis: $\lambda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



2nd order, SM with M_H = 125 GeV



1st order, required for EW baryogenesis



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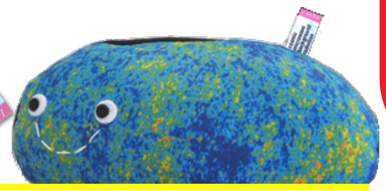

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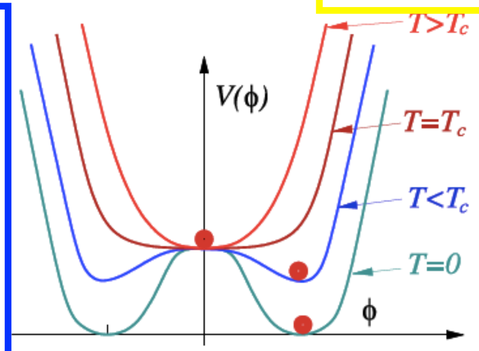

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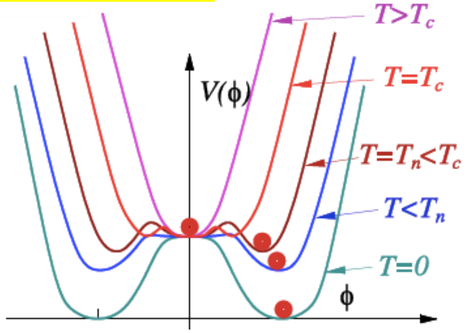

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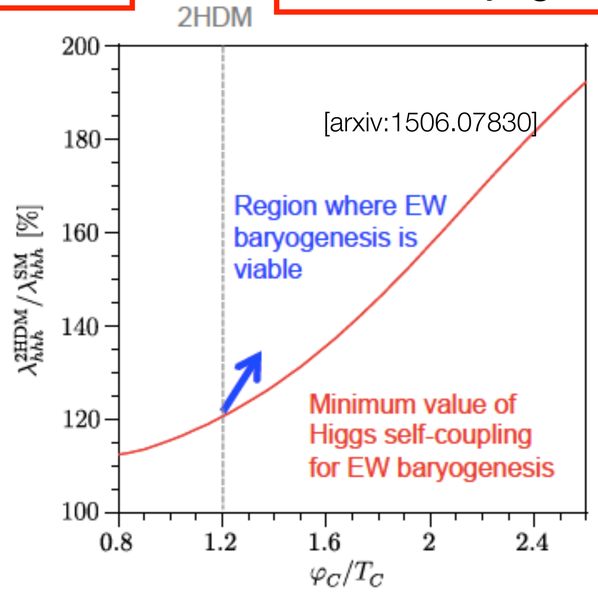

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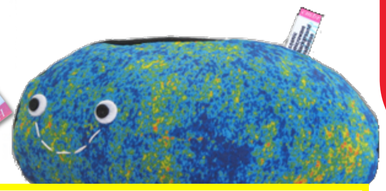

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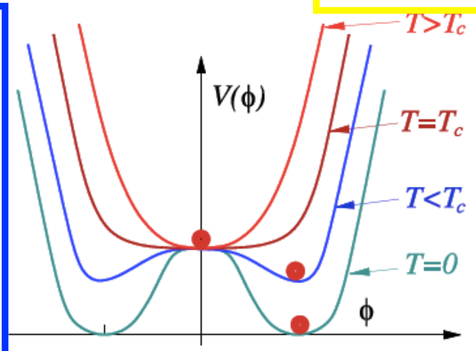

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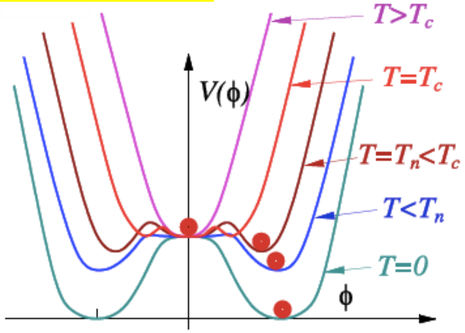

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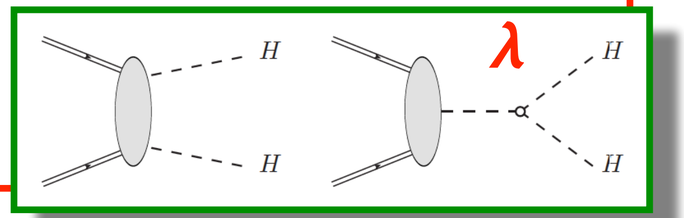

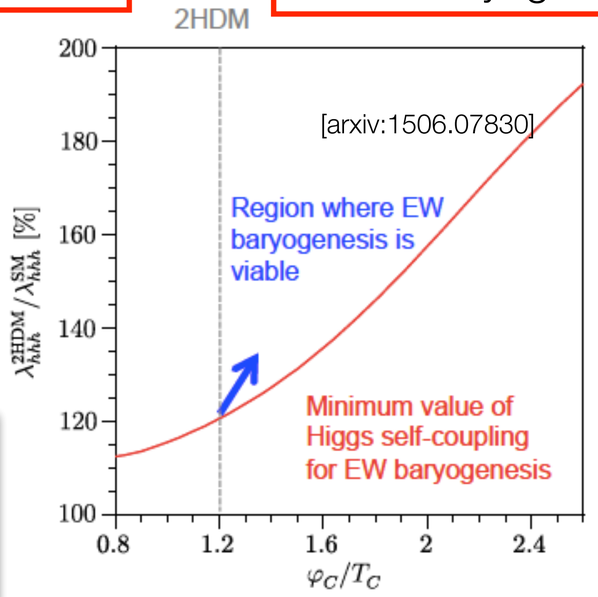

Measurement Prospects

The Higgs Boson …

…and the universe

recent update: ATL-PHYS-PUB-2018-053

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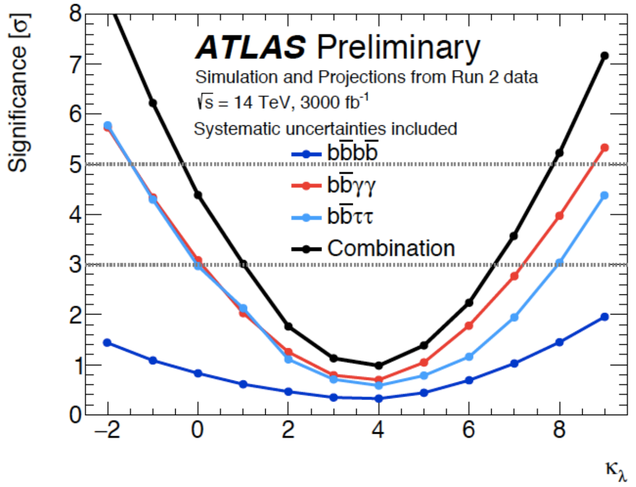

Dissertation C.Dürig, Uni Hamburg, 2016

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arXiv:1708.09079

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  - + 3 TeV, 3ab-1: $\delta\lambda/\lambda\,|_{SM}$ = 16%
  - exploit differential distributions at 3 TeV: ~ 10%

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

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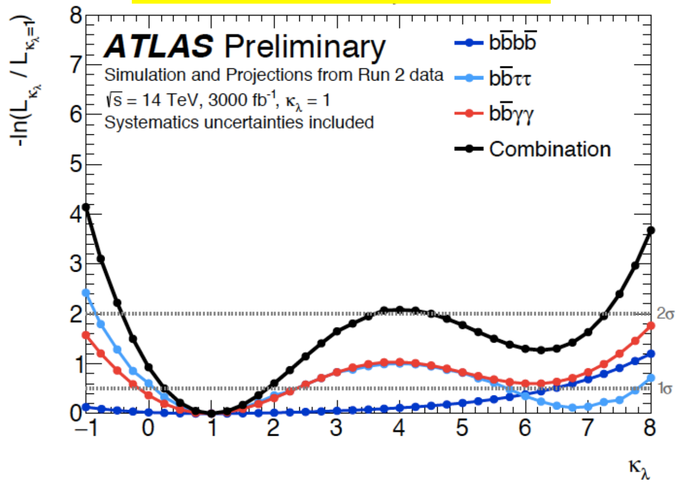

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Measurement Prospects

The Higgs Boson …

…and the universe

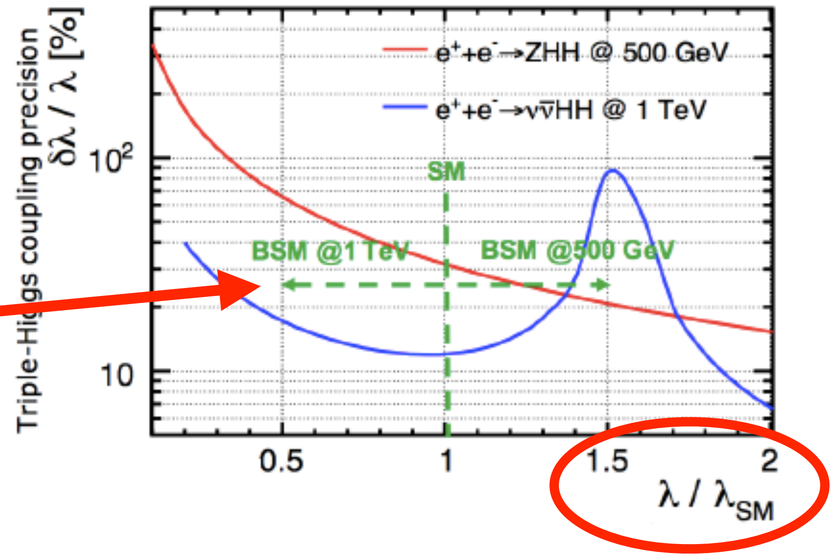
In any case: e^+e^- offers significant added value w.r.t. HL-LHC

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

=> BSM can change the picture

=> need combination of ZHH and vvHH

=> running near 500 GeV required!



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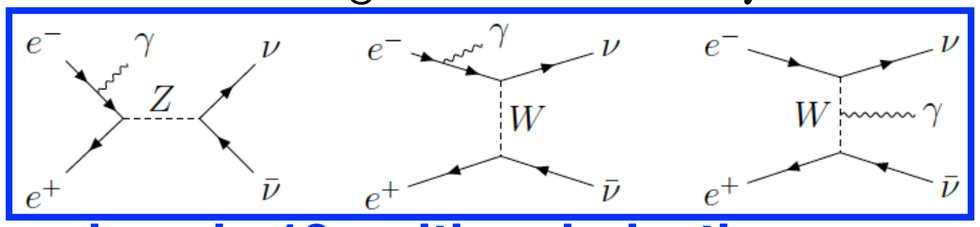
Eur.Phys.J. C77 (2017) nc

Polarisation & Beyond the SM: Dark Matter

mono-photon search $e^+e^- \to \chi\chi\gamma$

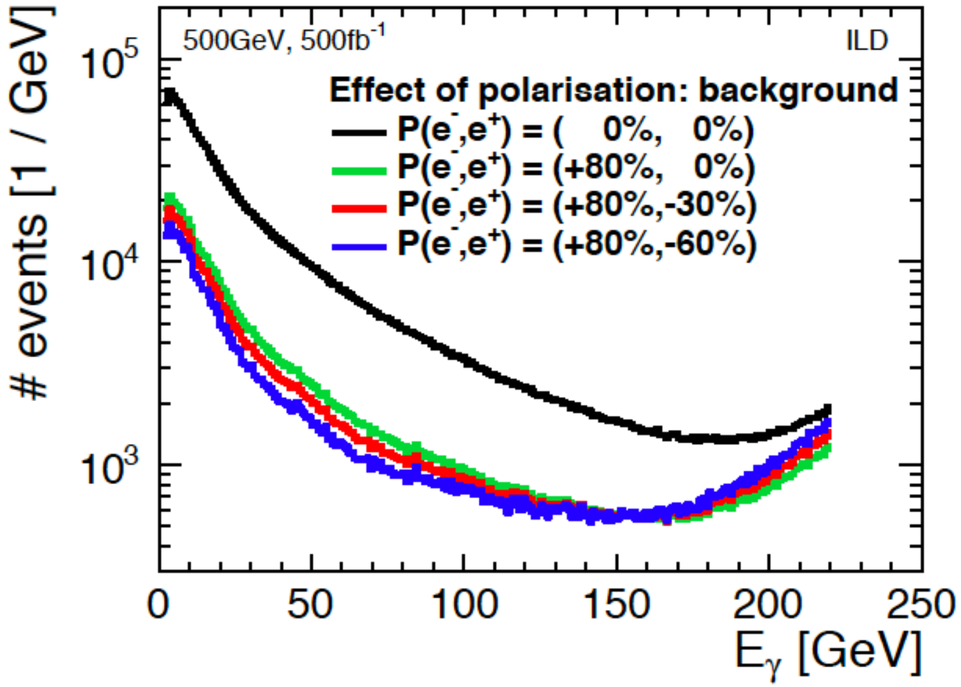
- main SM background: $e^+e^- \to \nu\nu\gamma$



reduced ~10x with polarisation

- shape of observable distributions changes with **polarisation** sign
  => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
  beats down the effect of **systematic uncertainties**

- **200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised**



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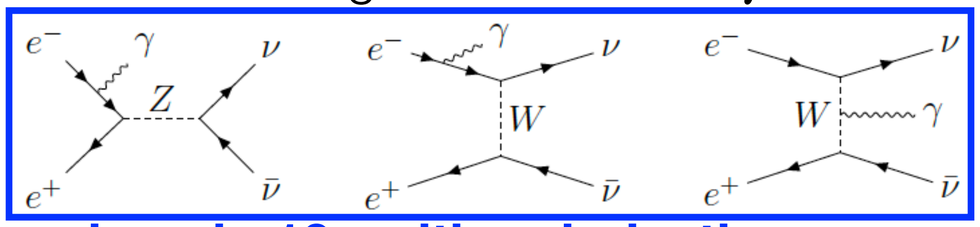

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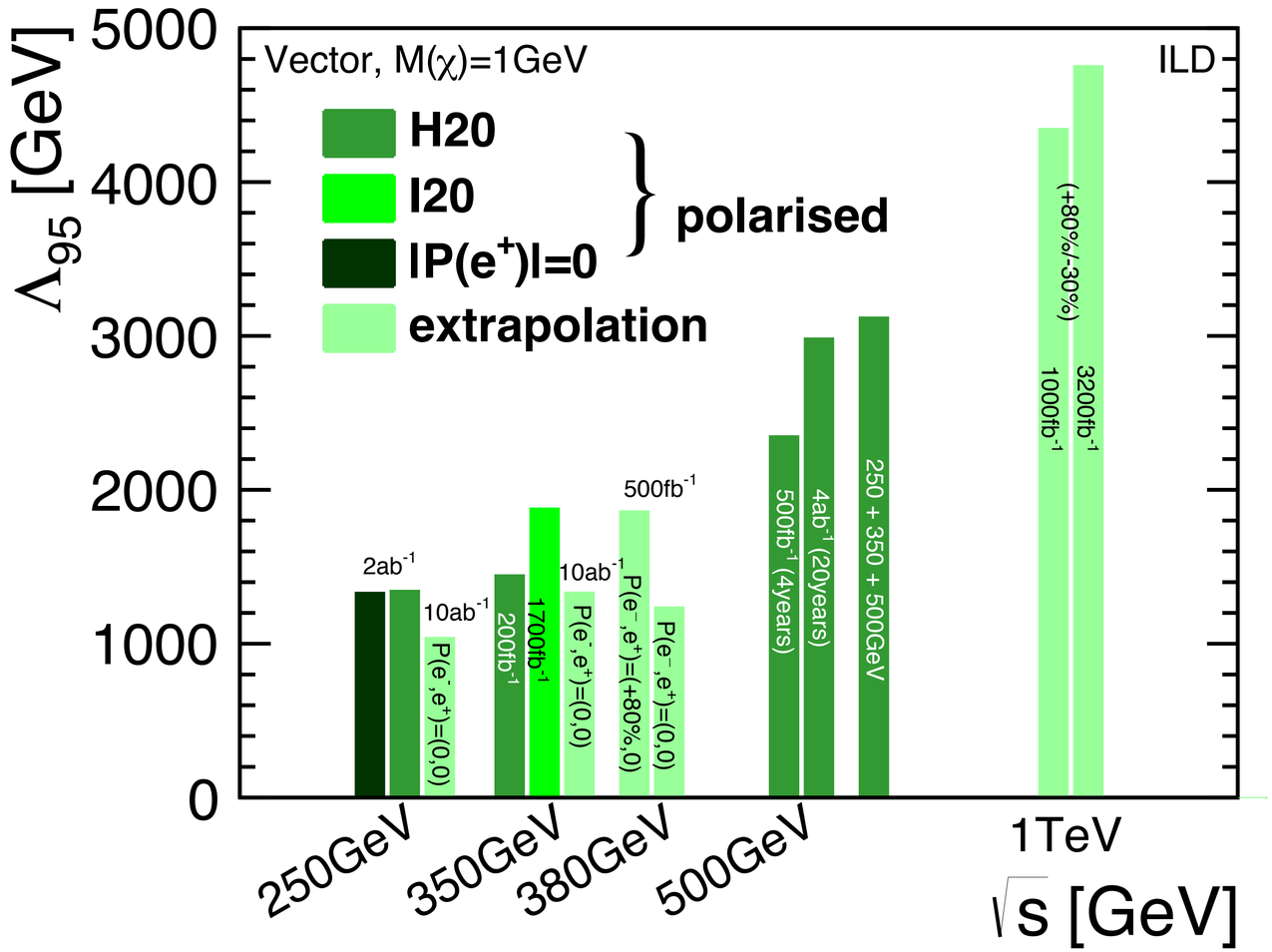
Phys. Rev. D 101 (2020) 7



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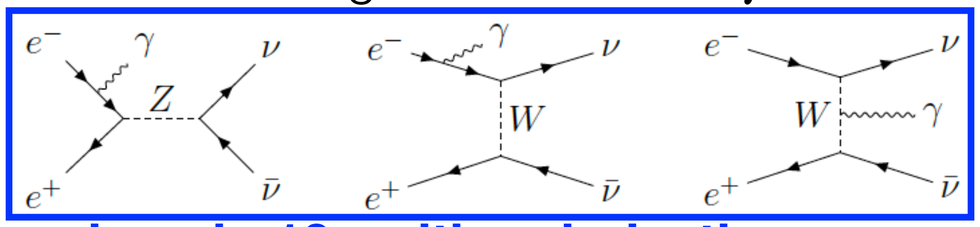

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- shape of observable distributions changes with **polarisation** sign => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–) **beats down** the effect of **systematic uncertainties**

- **200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised**

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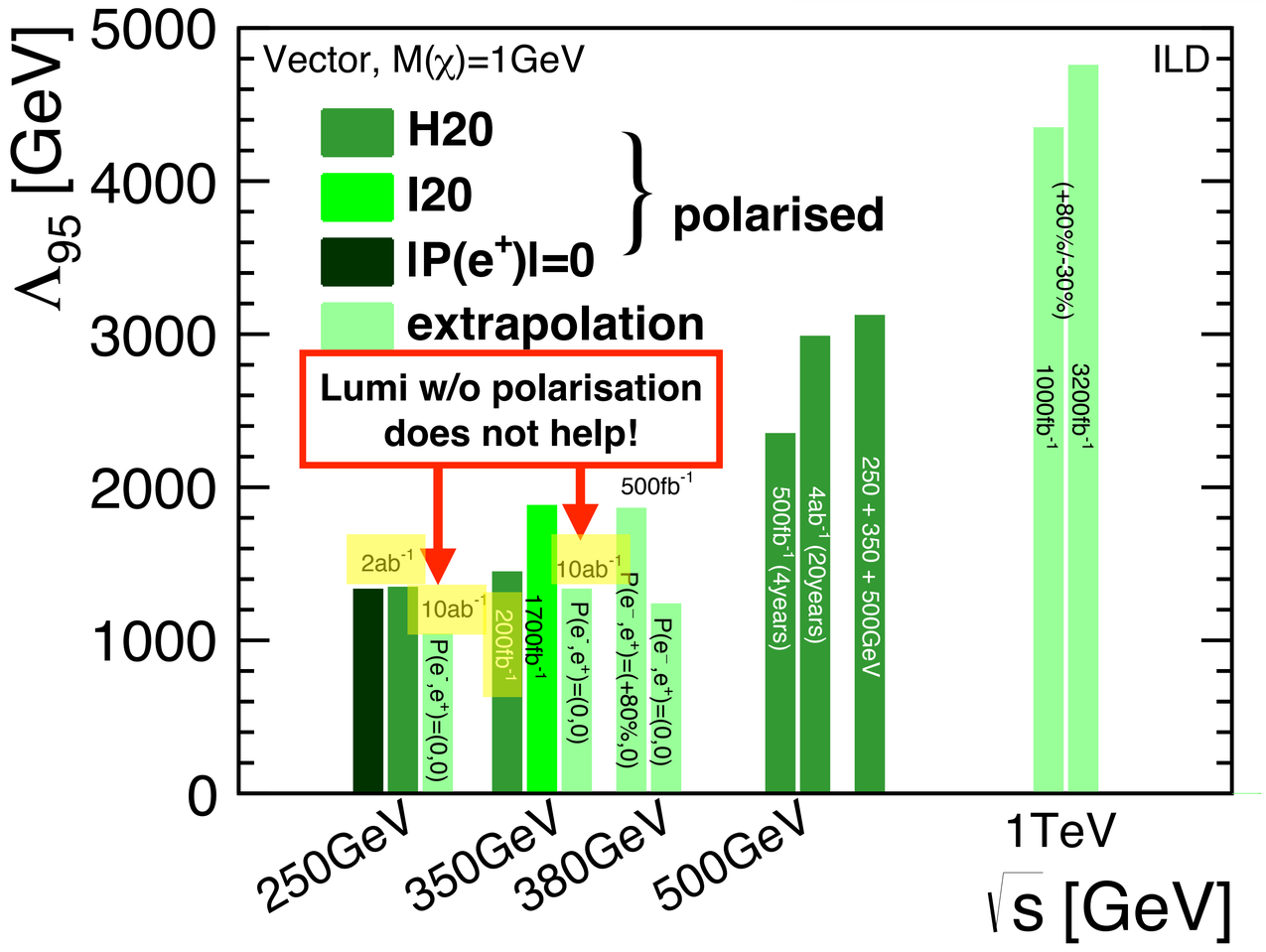
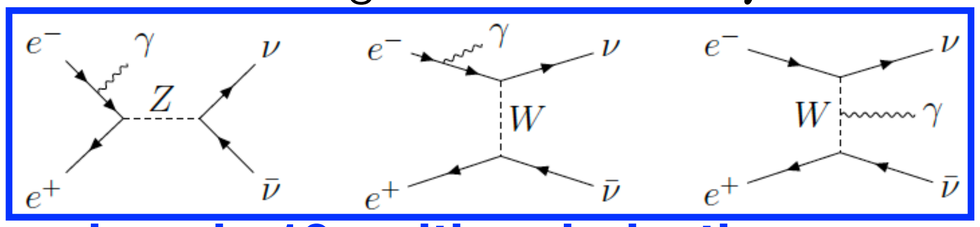


Polarisation & Beyond the SM: Dark Matter

mono-photon search $e^+e^- \to \chi\chi\gamma$

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



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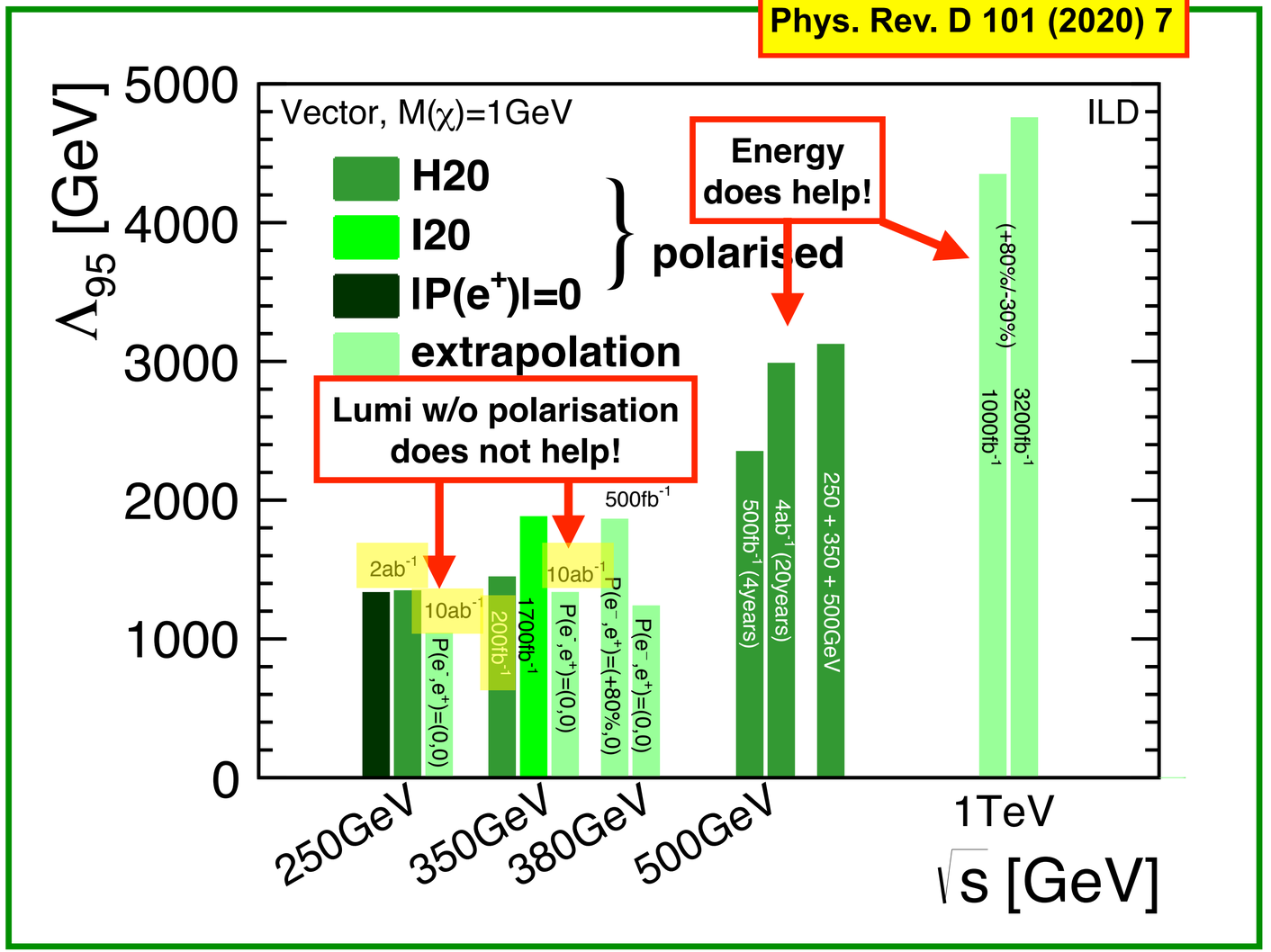


Conclusions

- 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 for the Japanese government to express their interest to host the ILC250**

  => 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

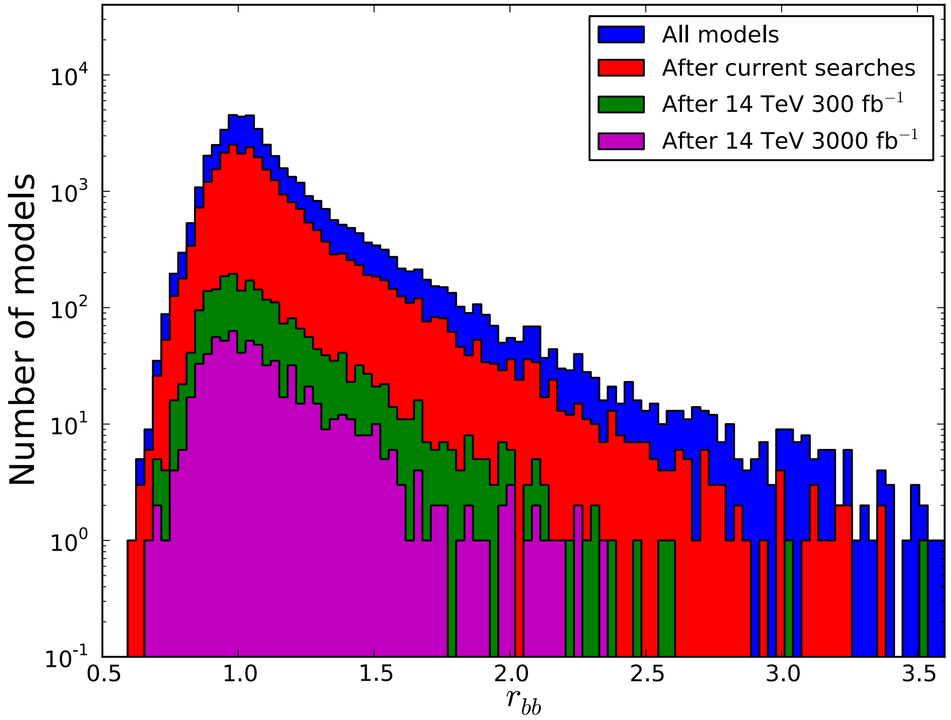
  ★ **Linear Colliders are intrinsically energy upgradable!**

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%



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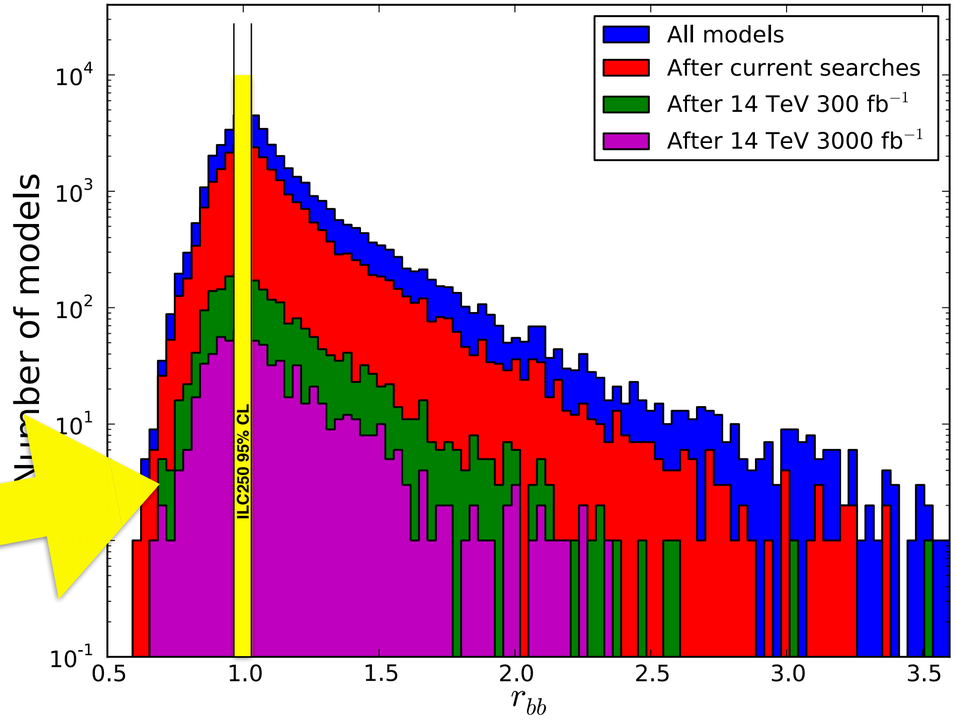

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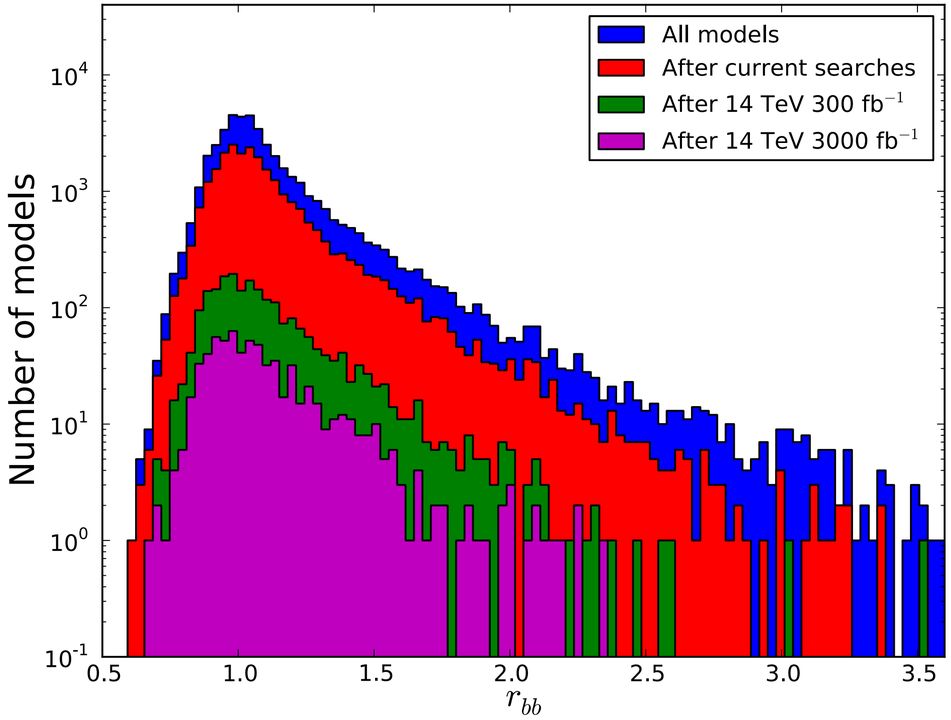

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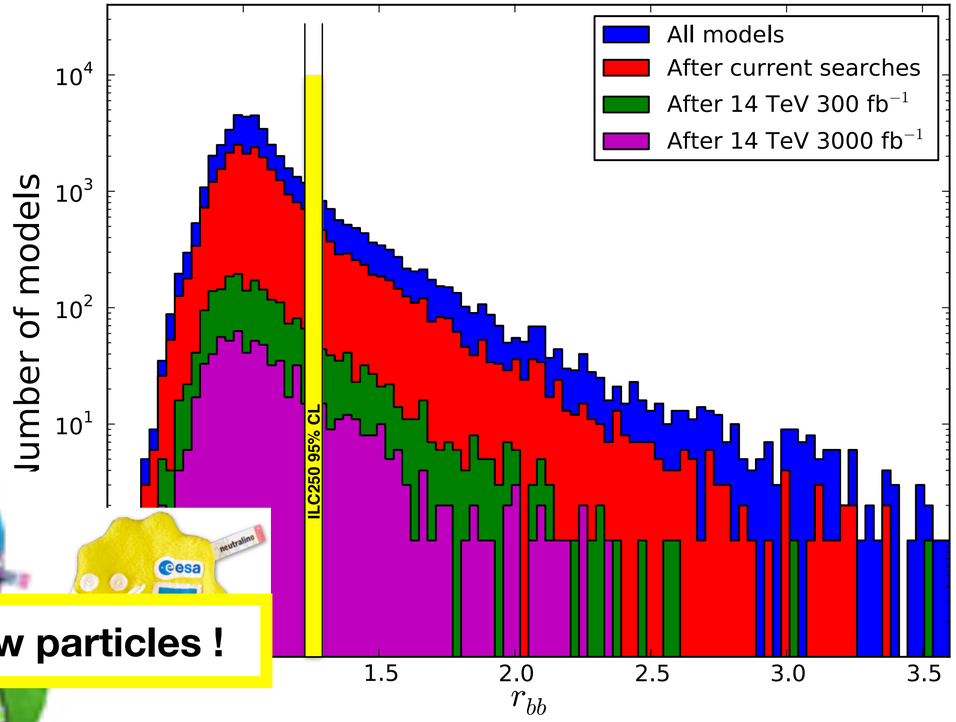

Discovery of new particles !

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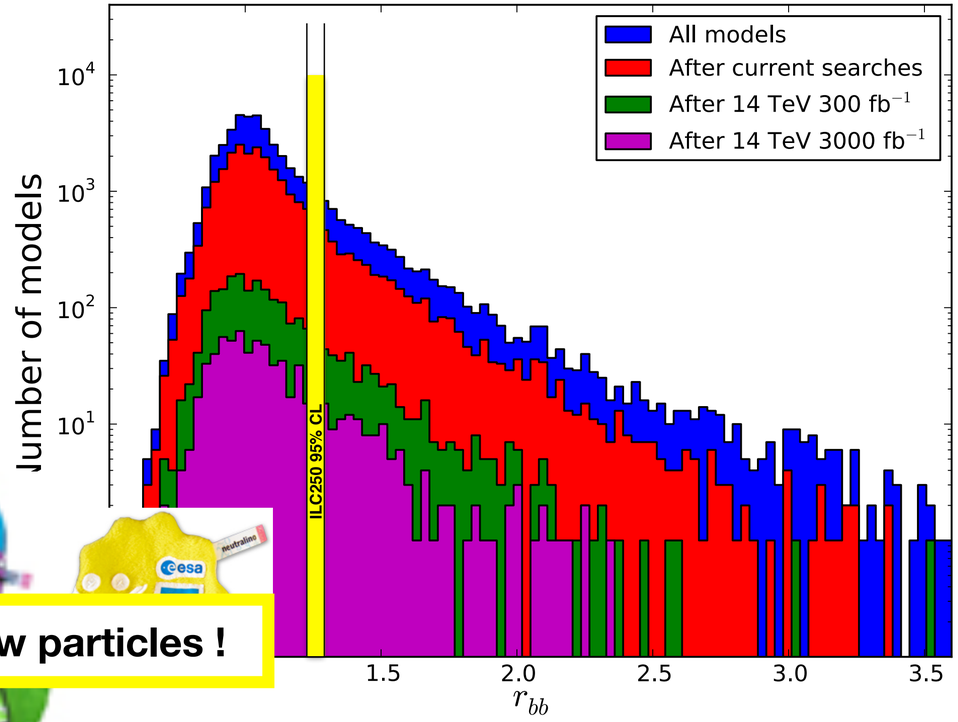


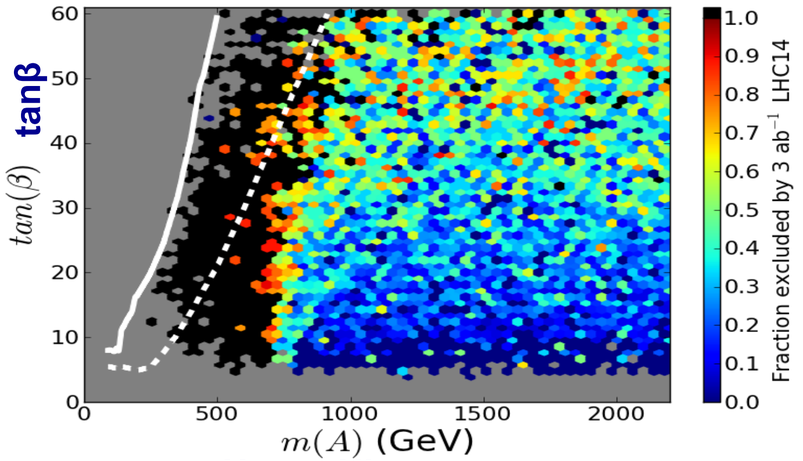
Discovery of new particles !

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

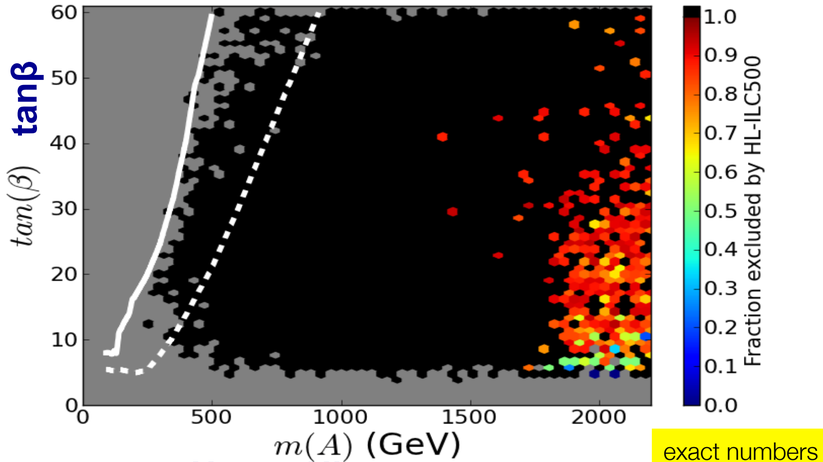
$$r_X = \frac{\Gamma(h \to X)}{SM}$$

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

HL-LHC 3000 fb-1



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



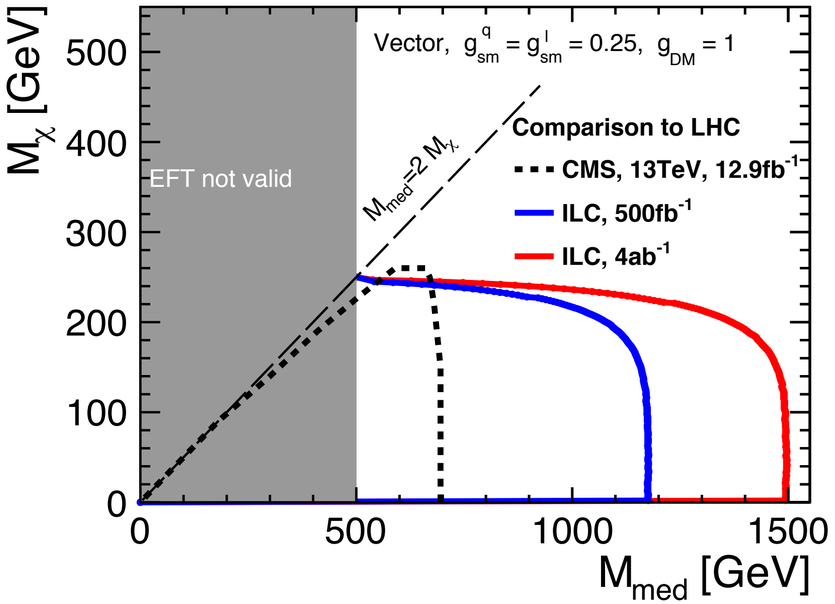
exact numbers outdated

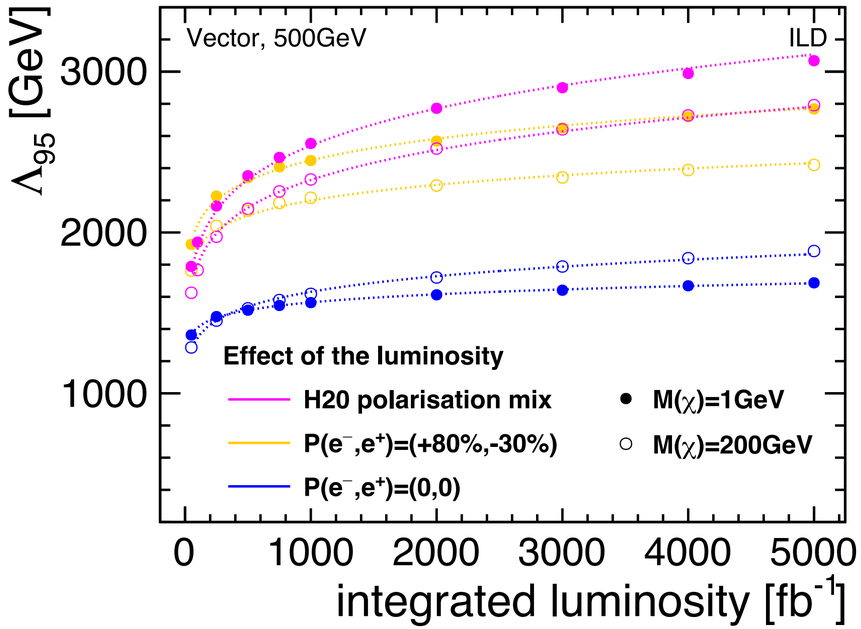
Phys. Rev. D 90, 095017 (2014)

- 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)

More on WIMPs





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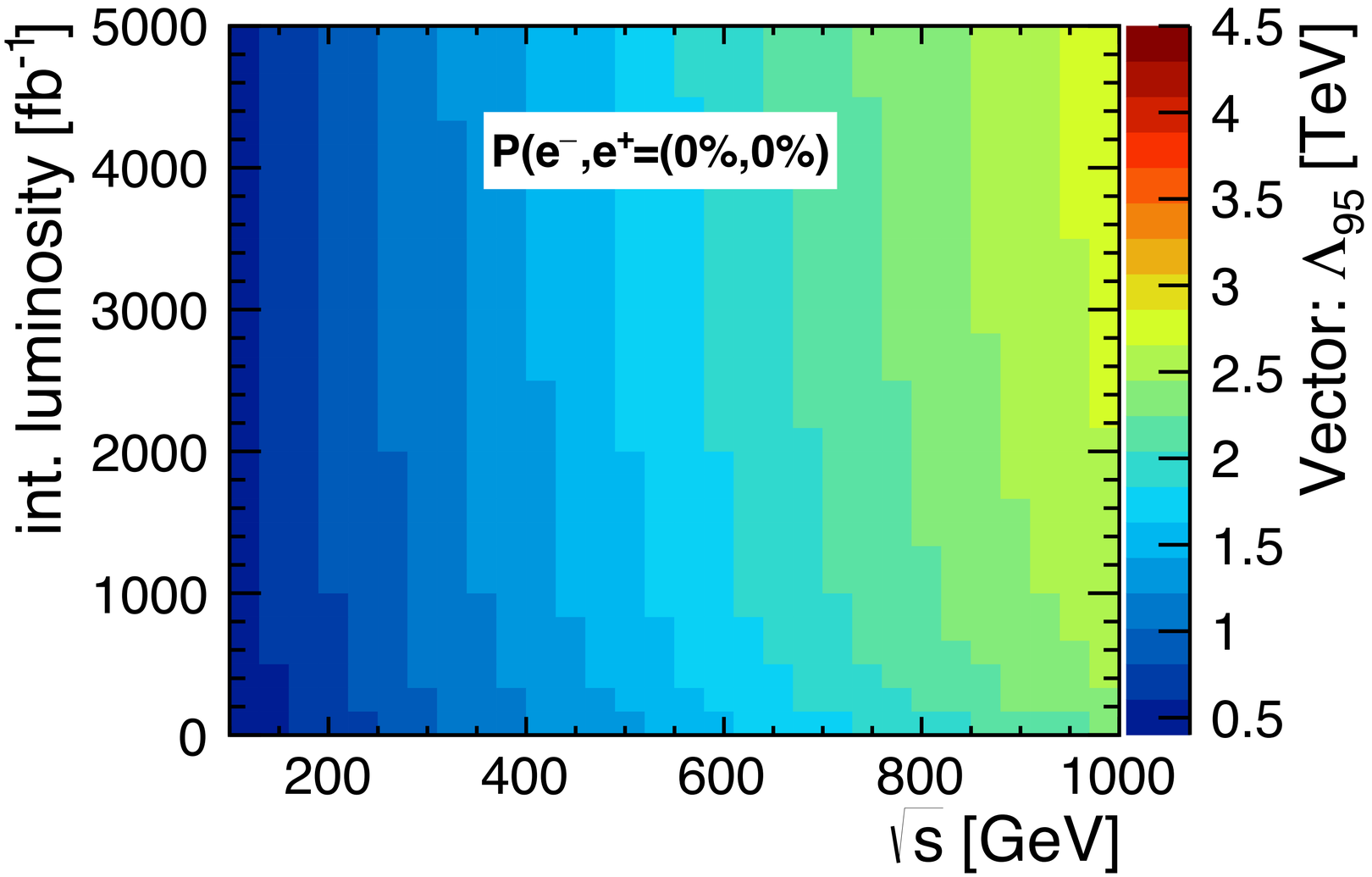

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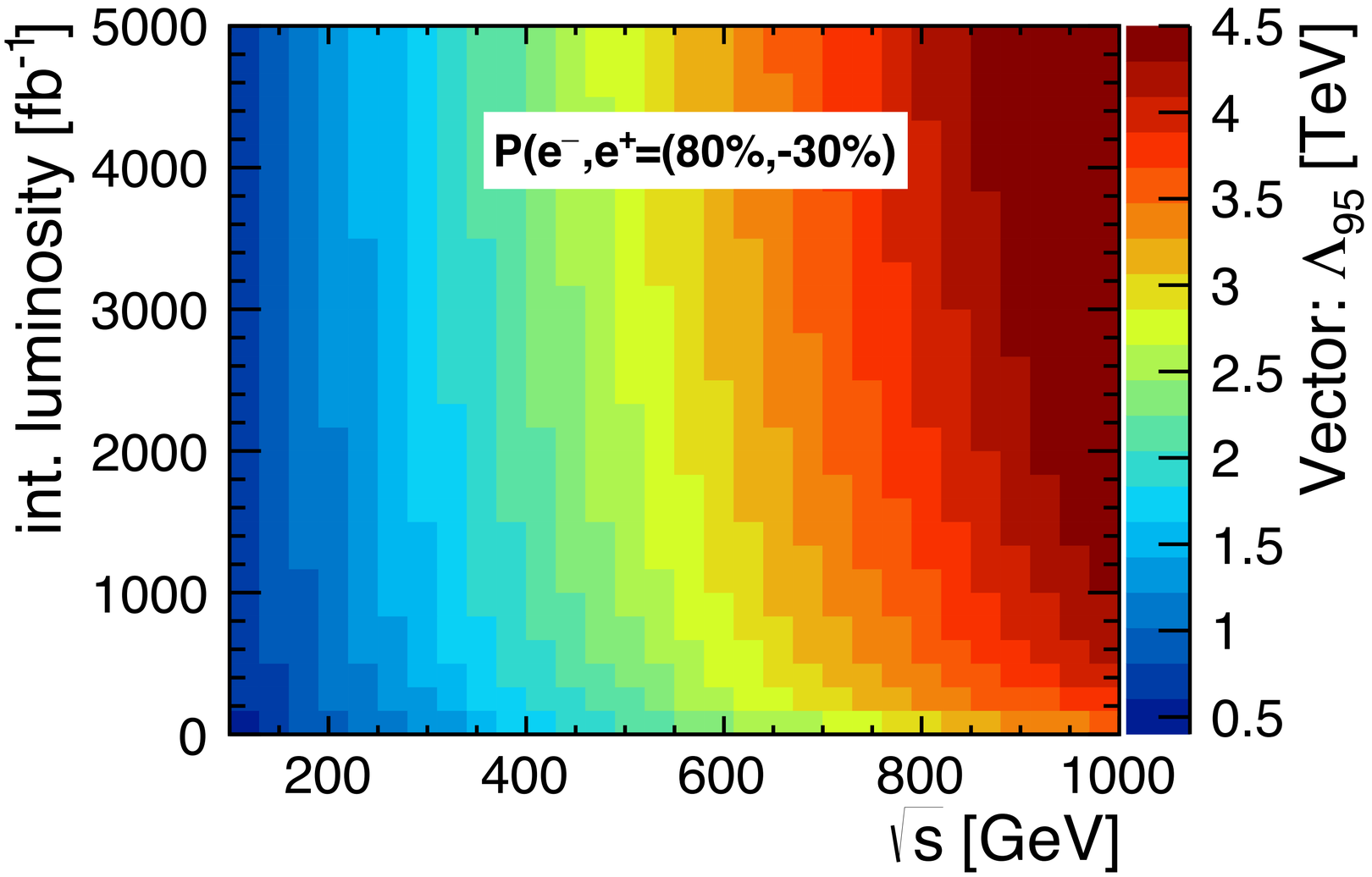


Precision Measurement of M_h

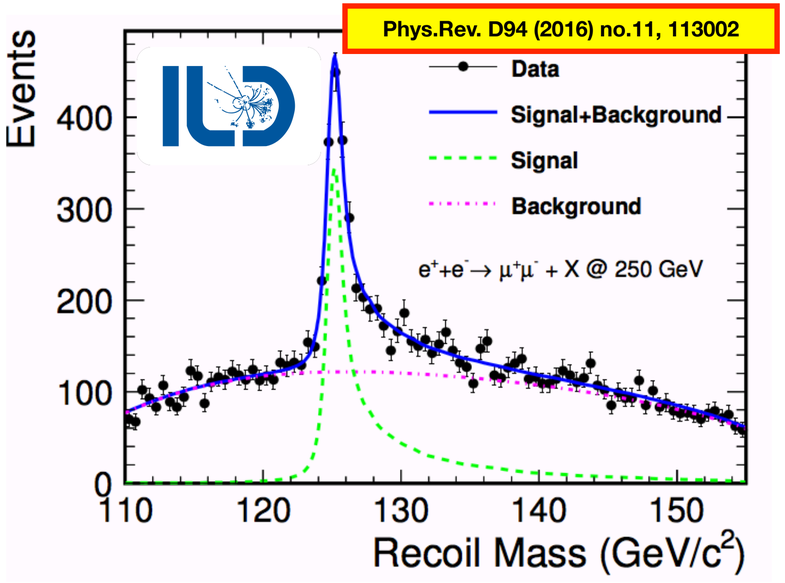
The Higgs Boson

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)



- **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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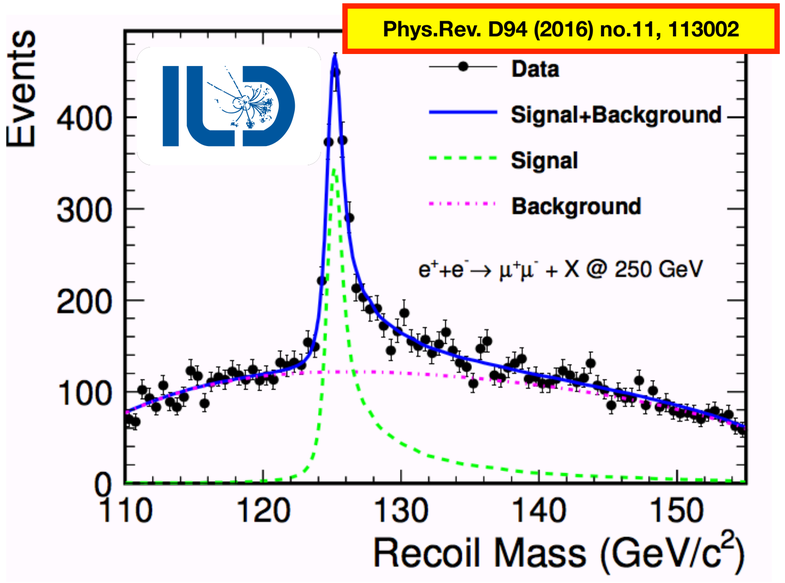

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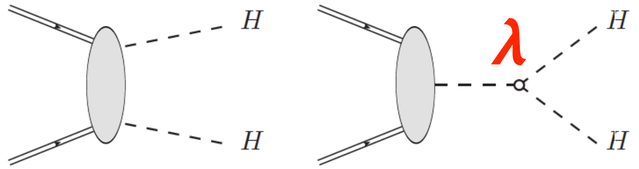
Higgs coupling precisions (in %)

	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
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
				5.1
				2.6
				0.46
				0.65
$g(hWW)/g(hZZ)$	1.7	0.67	0.28	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**

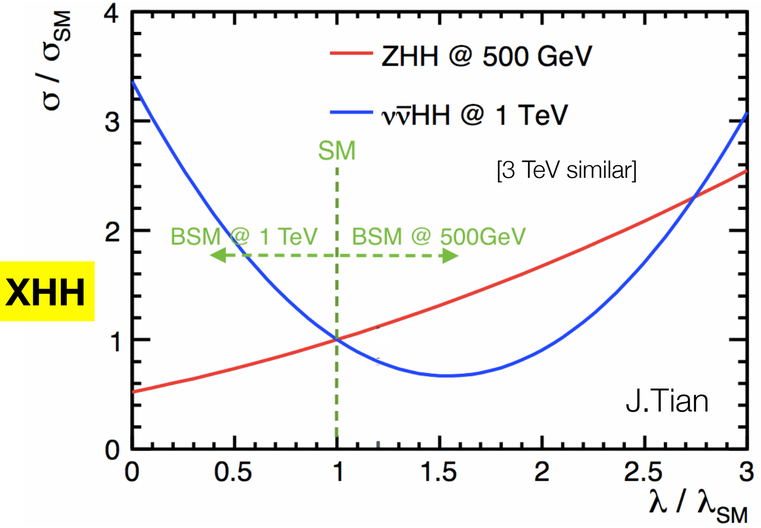
Double Higgs Production

- 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