Precision electroweak capabilities of ILC

LCWS 2019

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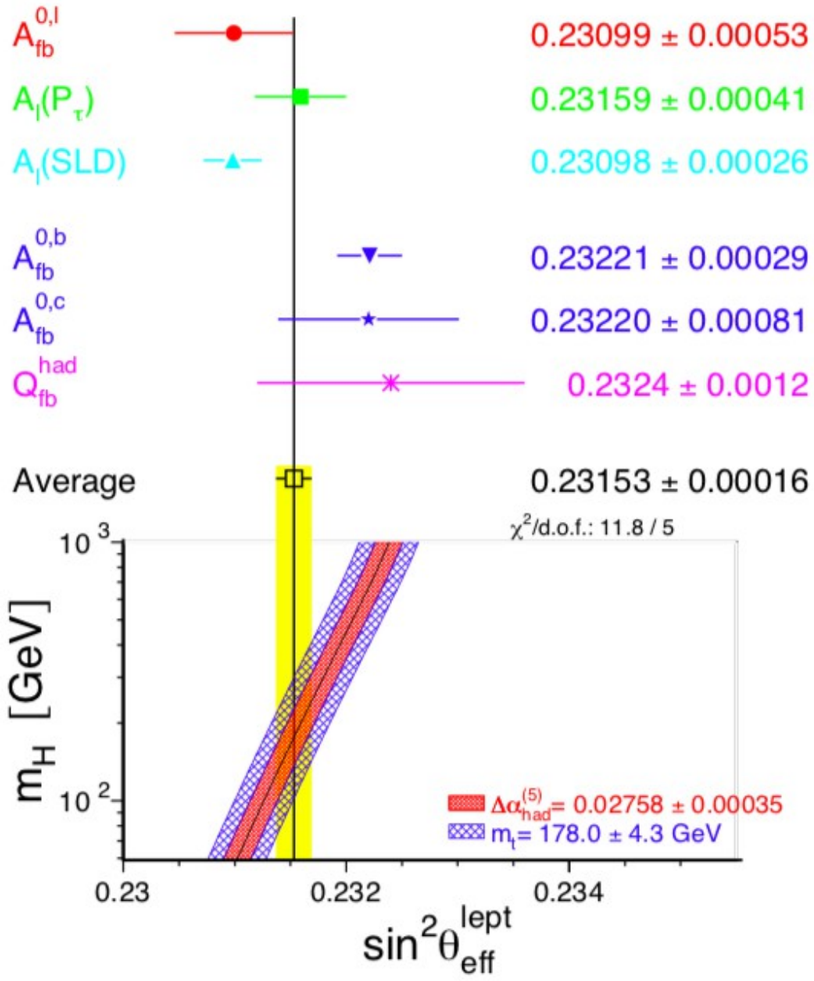
Based on material of a number of distinguished colleagues

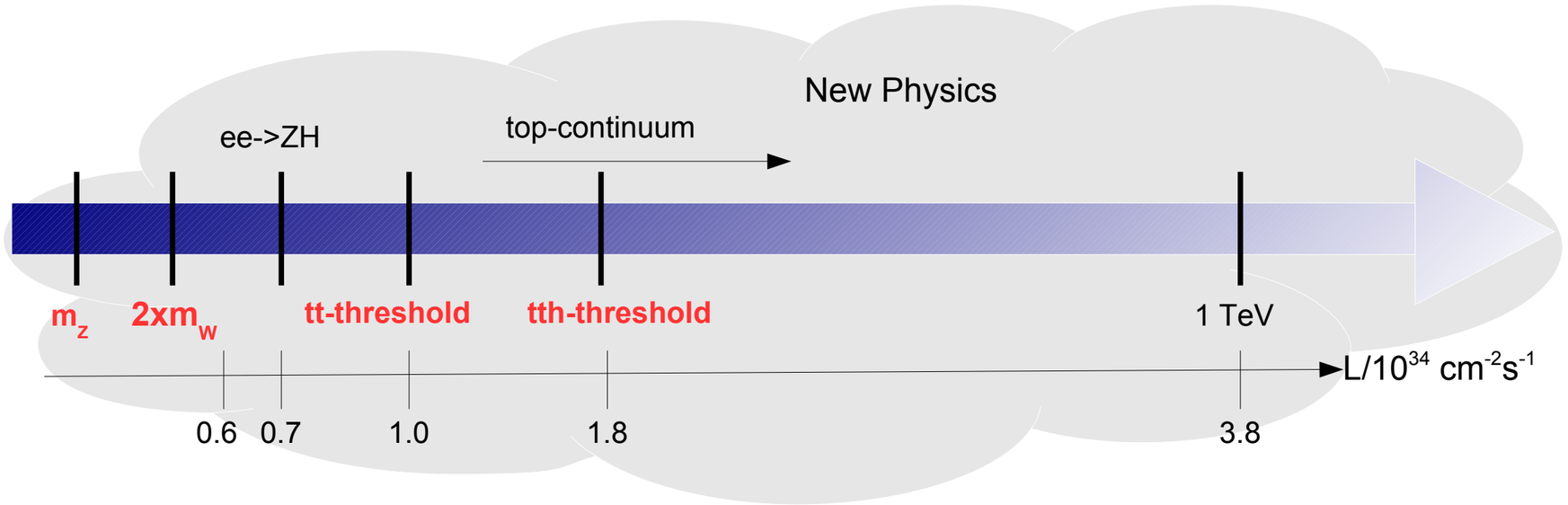
Sendai Japan – October/November 2019

Electroweak precision tests - Motivation

- ILC is more than a Higgs Factory
- Many new physics models have impact on electroweak processes e.g. 2f processes
- Z pole is “pure” Z => Therefore new physics (or not) due to Z has to be pinned down
- Many questions at Grenada to ILC capabilities on the pole
  - Some answers were at hand (arXiv: 1905.00220)



e+e- Physics program



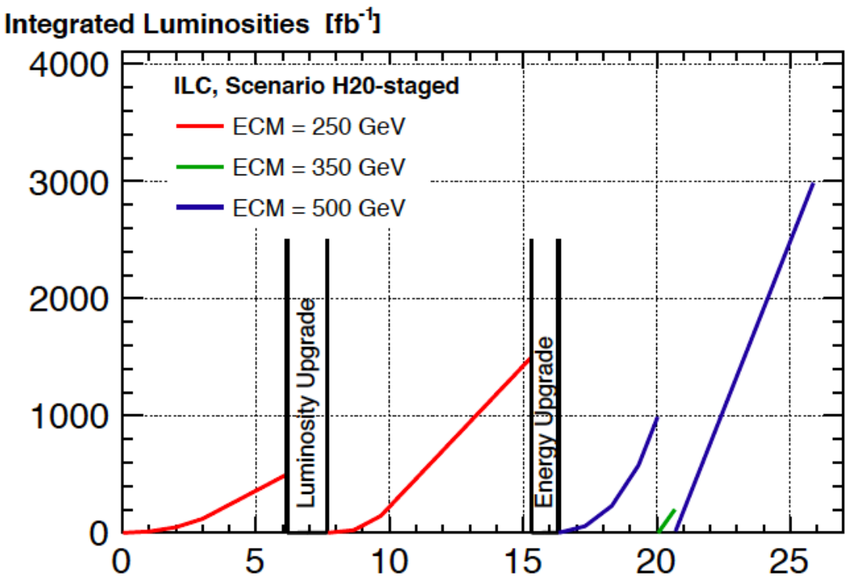
- All Standard Model particles within reach of planned e+e- colliders
- High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation (straightforward at linear colliders)

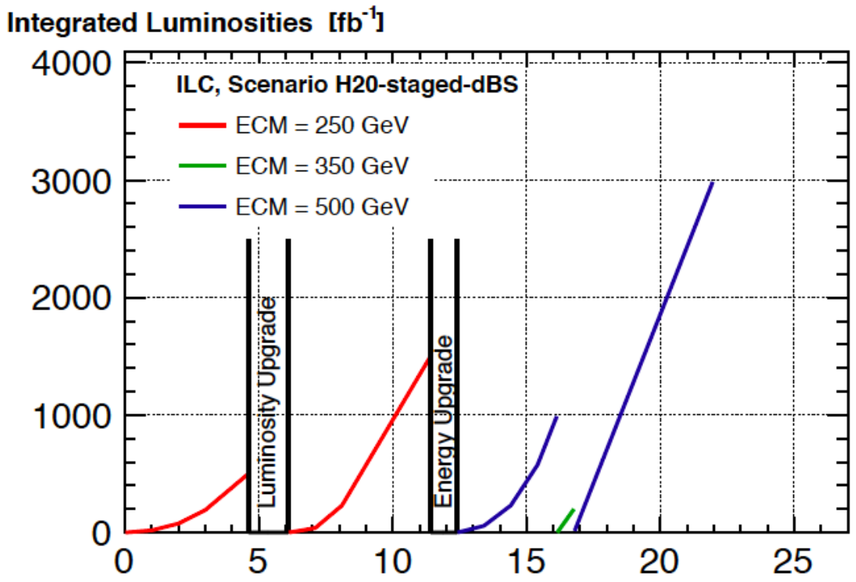
$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL}) + (P-P')(\sigma_{RL}-\sigma_{LR})\right]$$

- **Background free** searches for BSM through beam polarisation

ILC Running Scenarios

arXiv:1506.07830



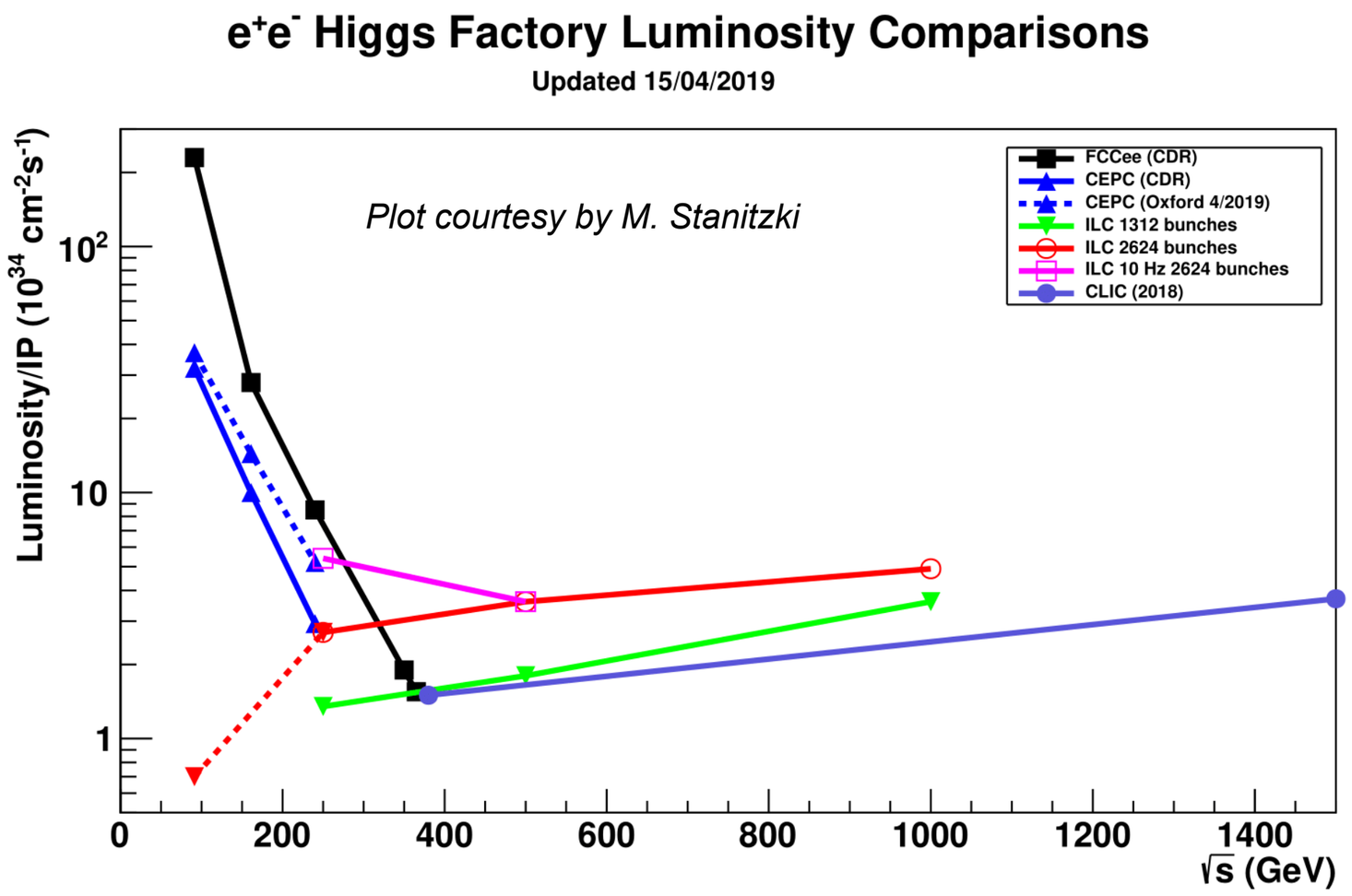


In 2019 – Revision of capabilities to run on the Z Pole - GigaZ

	sgn($P(e^-), P(e^+)$) =				
	(-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	83.5	63.7	50.0	40.6	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

- Pole running can happen before and after the luminosity upgrade
- Further details see arxiv: 1908.08212

Linear vs. circular e+e- machines – Instantaneous luminosities



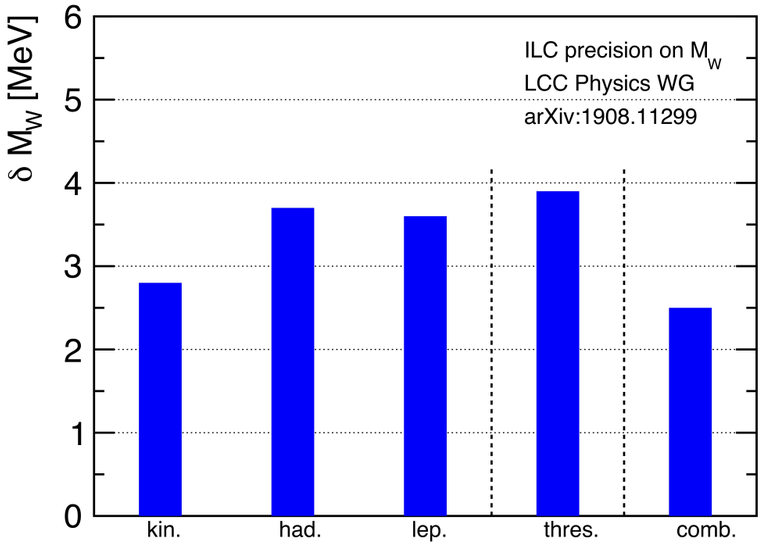
- High energies ~above tt-threshold
  Domain of linear colliders
- Low energies e.g. Z-pole
  Domain of circular machines
  - However, see later ...
- Transition region, i.e. HZ threshold
  … not so clear
  Comparable numbers for all proposals
- Linear colliders are more versatile to test chiral theory due to polarised beams
- Detailed design parameters see backup

W - Parameters

W Mass from ...:

- Constrained WW reconstruction
- Hadronic mass from hadronic W decays
- Lepton endpoints: $m_W^2 = E_l(E_b - E_l),\ E_l = E_b(1 \pm \beta_W)/2$
- Dilepton pseudo mass from constrained fit
- Polarised W scan

$$\Delta m_W(MeV) = 2.4(stat.) \oplus 3.2(syst.) \oplus 0.8(\sqrt{s}) \oplus \text{theory}$$

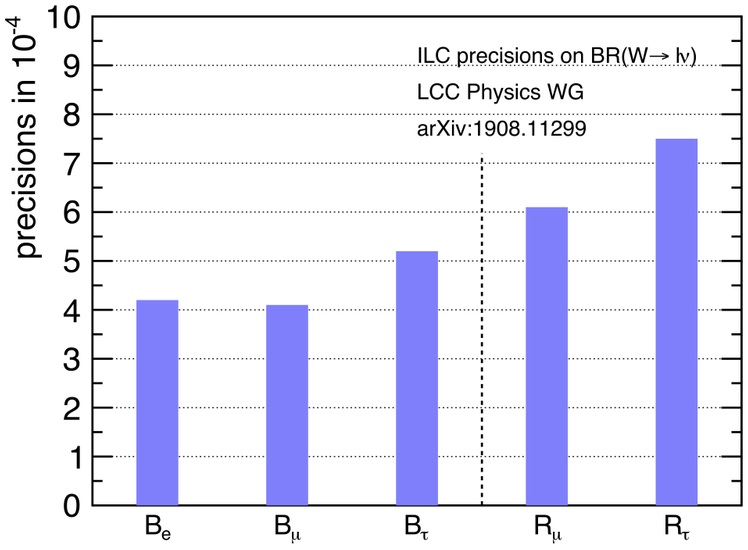


Branching ratios

From simultaneous fit to all 10 decay combinations

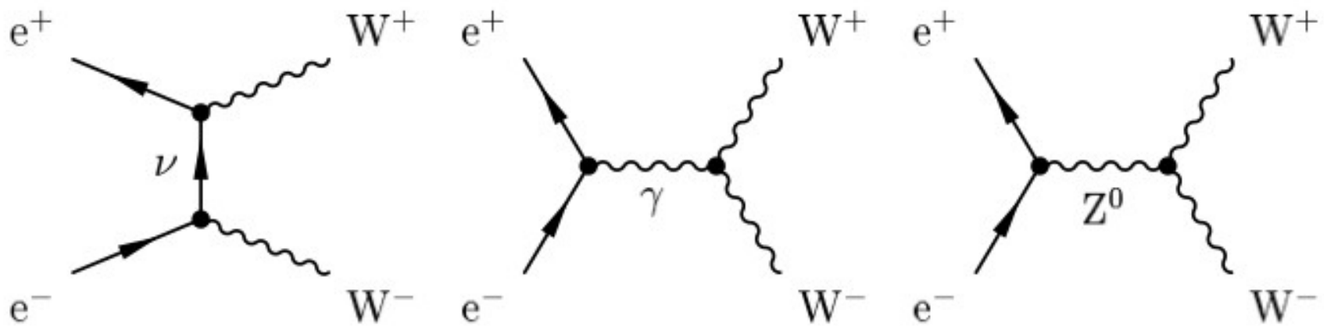
=> σ_{tot} and $B_{e,\mu,\tau}$ and $B_{had} = 1 - B_e - B_\mu - B_\tau$

W width: $\Delta\Gamma_W = 3.2$ MeV



See talks by G. Wilson and J.L. Singer-Anguiano on newest re

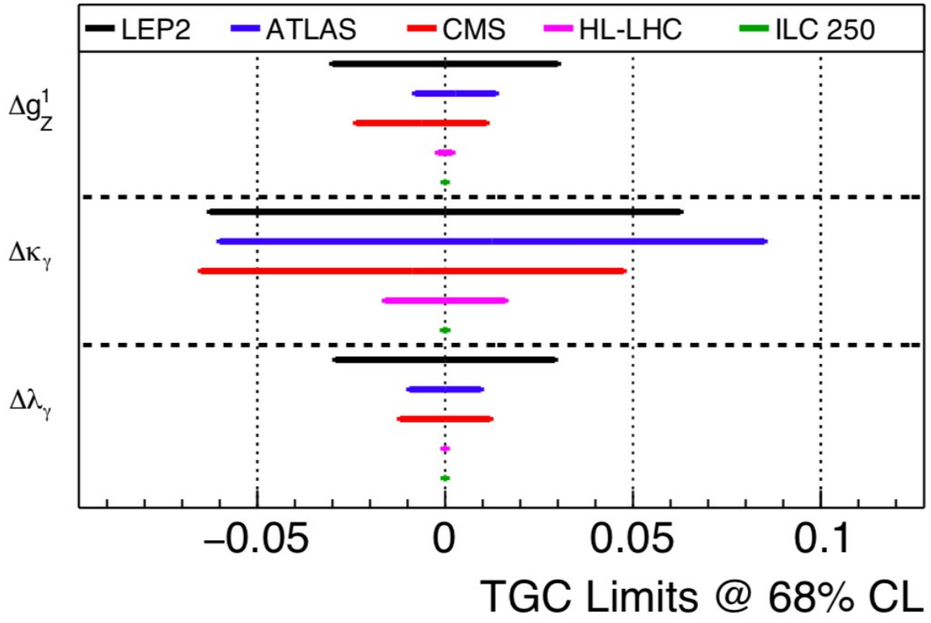
Anomalous Triple Gauge Couplings

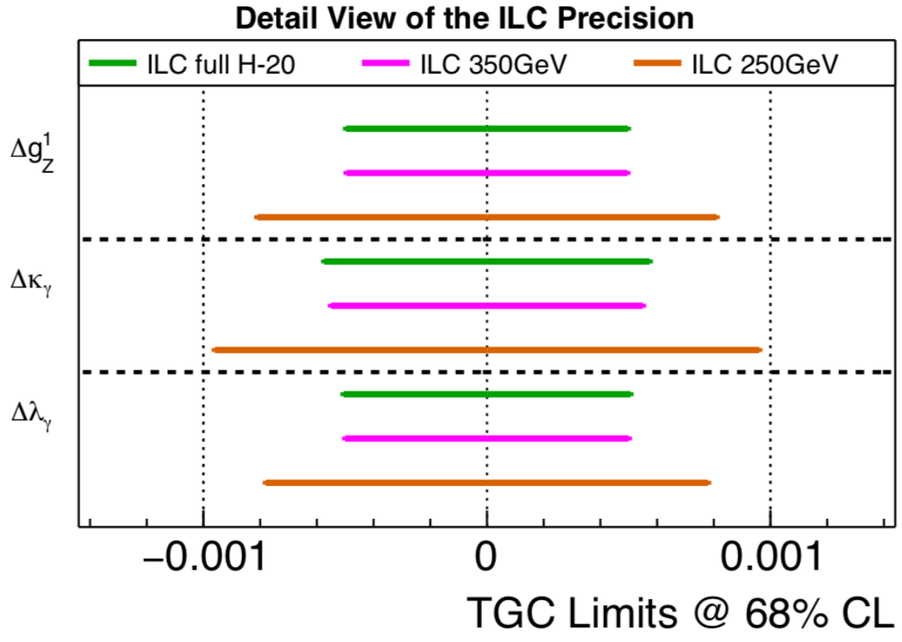


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

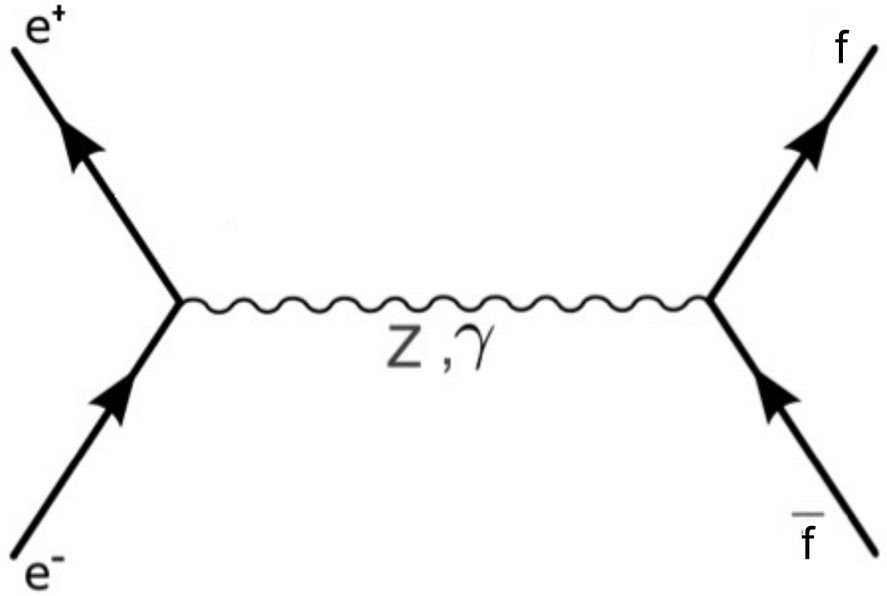
=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)
See talk by J. Beyer on newest results

Limits on Triple Gauge Couplings@250 GeV





Two fermion processes



Differential cross sections for (relativistic) di-fermion production*:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RL}(1+\cos\theta)^2 + \Sigma_{RR}(1-\cos\theta)^2$$

*add term ~$sin^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

- Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R (or g_V, g_A)
- $\Sigma_{IJ} \neq \Sigma_{I'J}'$ => (characteristic) asymmetries for each fermion
- Forward-backward in angle, general left-right in cross section
- **All four** helicity amplitudes for all fermions **only available with polarised beams**

Helicity amplitudes and new physics

Helicity amplitudes can be analysed in several ways (not mutually exclusive):

Oblique Parameters W, Z:

$$Q_{e_i f_j} = Q_e^\gamma Q_f^\gamma + \frac{g_{e_i}^Z g_{f_j}^Z}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + \mathrm{i}\Gamma_Z M_Z} + \frac{s}{m_W^2} f_{i,j}(W,Y)$$

Contact interactions with e.g. compositeness scale Λ:

$$Q_{e_i f_j} = Q_e^\gamma Q_f^\gamma + \frac{g_{e_i}^Z g_{f_j}^Z}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + \mathrm{i}\Gamma_Z M_Z} + \frac{g_{contact}^2}{2\Lambda^2} \eta_{e_i f_j}$$

New propagators in concrete models of new physics:

$$Q_{e_i f_j} = Q_e^\gamma Q_f^\gamma + \frac{g_{e_i}^Z g_{f_j}^Z}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + \mathrm{i}\Gamma_Z M_Z} + \sum \frac{g_{e_i}^{Z'} g_{f_j}^{Z'}}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_{Z'}^2 + \mathrm{i}\Gamma_{Z'} M_{Z'}}$$

Always with I,j being the helicities of the initial state electron e and the final state fermion f

Rates and asymmetries

Partial fermion width:

$$R_f = \frac{N_f}{N_{had}} = \frac{(g_f^L)^2 + (g_f^R)^2}{\sum_{i=1}^{n_q}[(g_i^L)^2 + (g_i^R)^2]}$$

- Sensitive to sum of coupling constants
- Available at linear and circular colliders

Left-right asymmetry:

$$A_{LR} = \frac{1}{|\mathcal{P}_{eff.}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e = \frac{(g_f^L)^2 - (g_f^R)^2}{(g_i^L)^2 + (g_i^R)^2} \sim 1 - 4\sin^2\theta_{eff.}^{\ell}$$

- Direct sensitivity to Zee vertex
- Only available at linear colliders due to beam polarisation
- Circular colliders need auxiliary measurement
  - e.g. $P_\tau \sim A_e$

Forward-backward asymmetry:

$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{for } \mathcal{P}_e = 0.$$

- “Classical” observable to study P-violating effects in ee->ff
- Available at circular and linear colliders
- **Without** beam polarisation interpretation is **always model dependent**

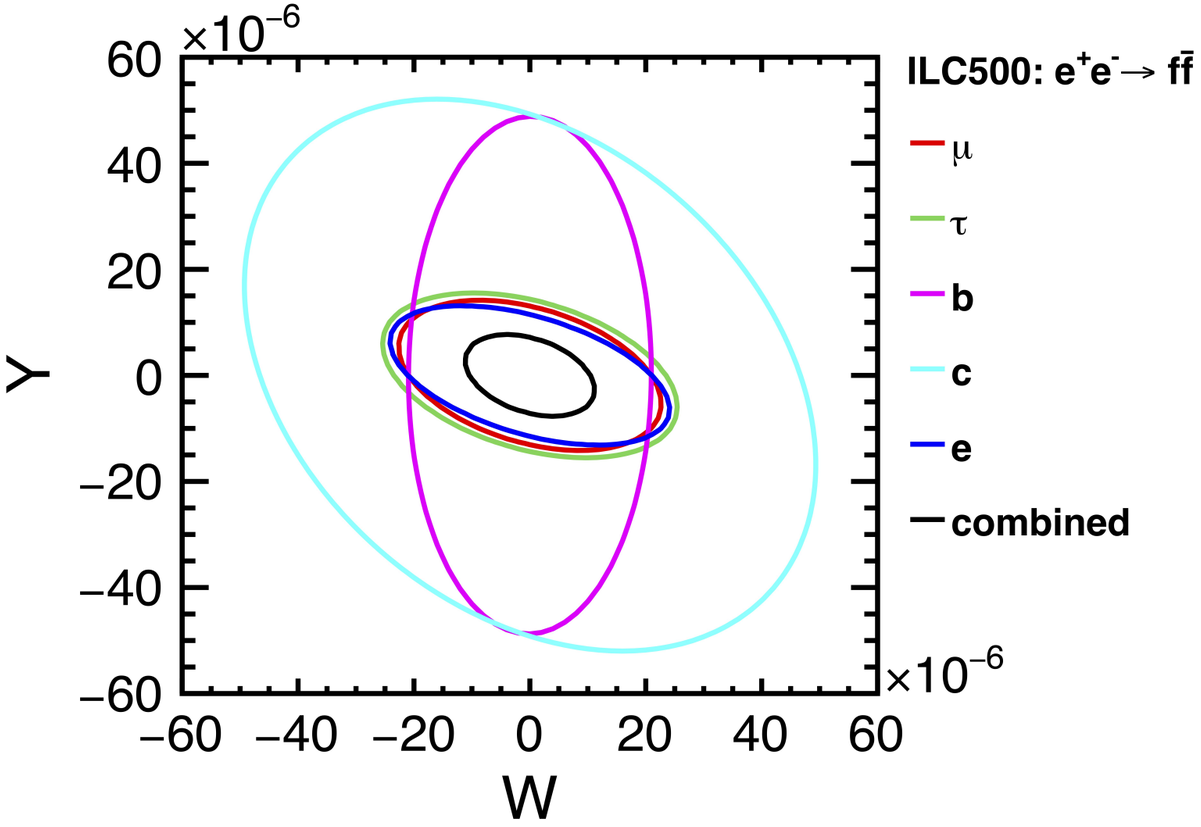
Left-right-forward-backward asymmetry:

$$A_{FB,LR}^f = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_L + \sigma_l)_R} = -\frac{3}{4}\mathcal{A}_f$$

- Combination of asymmetries above
- Only available linear colliders due to beam polarisation
- Direct and model independent measurement of A_f

Oblique parameters

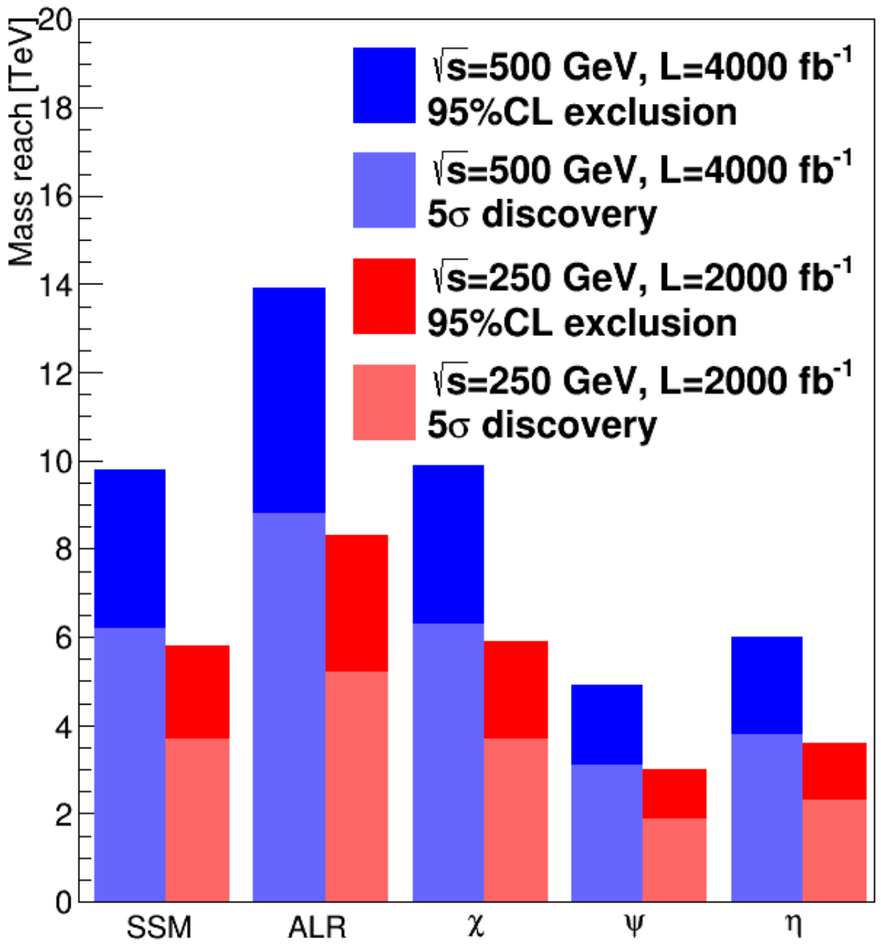
Contributions for different fermion species



$\sqrt{s}$	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

- Beam polarisation essential to disentangle effects from W and Y
- ILC250 outperforms LHC
- ILC500 and above outperforms e+e- machines w/o polarisation (at $4ab^{-1}$)

Mass reach for vector new bosons (Z') in 2-fermion production

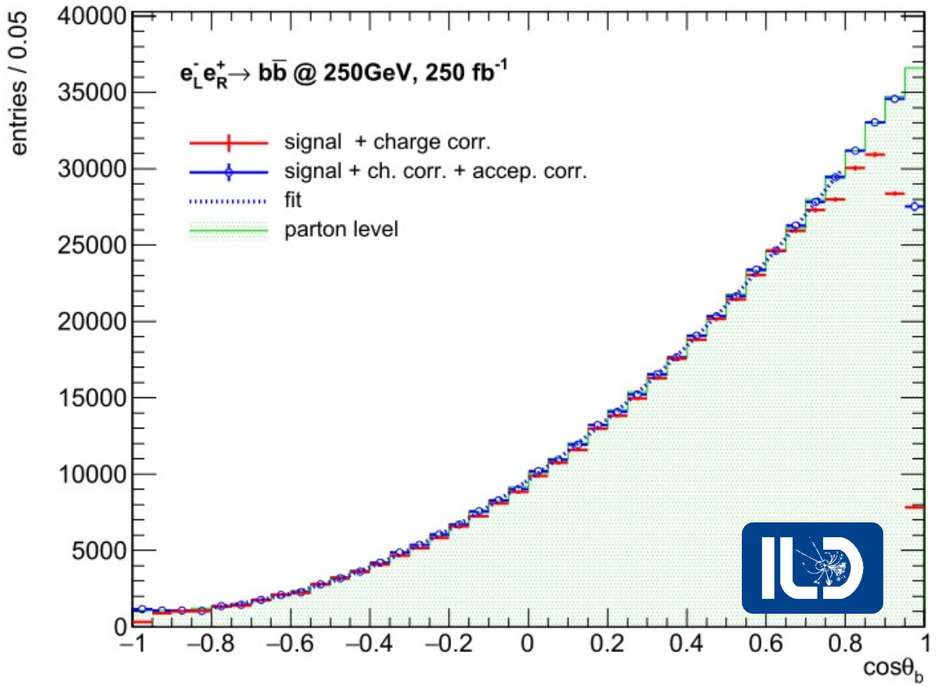


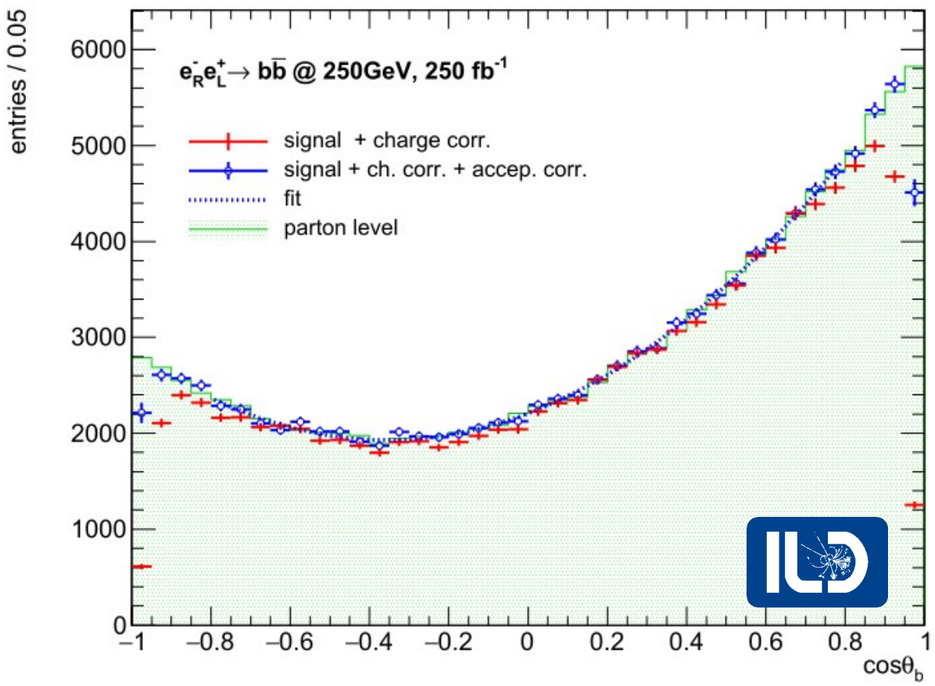
- SSM is “carbon” copy of SM Z and used as common metric in generic Z' searches
- ALR introduces an “ad hoc” $SU(2)_R$ and a Z' with orthogonal couplings to the fermions
- X, ψ, η are linear combinations of bosons appearing in Grand Unified Theories with couplings orthogonal to the SM Z

Typical mass reach 5-10 TeV

- **Reach shown for e, □ , □**
- **Adding quarks would improve limits**

Decomposing ee->bb – Differential cross section





- Full simulation study (with ILD concept), Benchmark reaction
  - Experimental challenge: Measurement of b-quark charge on event-by-event basis

- Long lever arm in cos θ_b to extract from factors or couplings

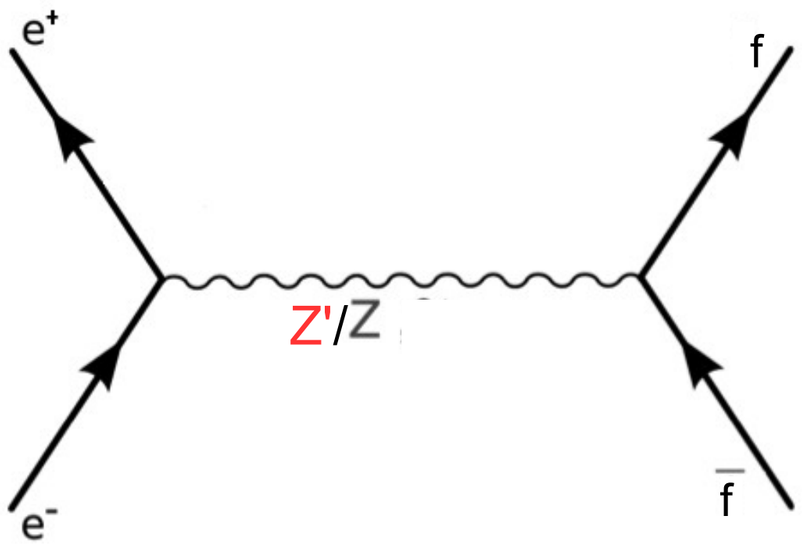
$$\frac{d\sigma^I}{d\cos\theta} = S^I(1+\cos^2\theta) + A^I\cos\theta \qquad I = L, R$$

Form factors/couplings from S and A

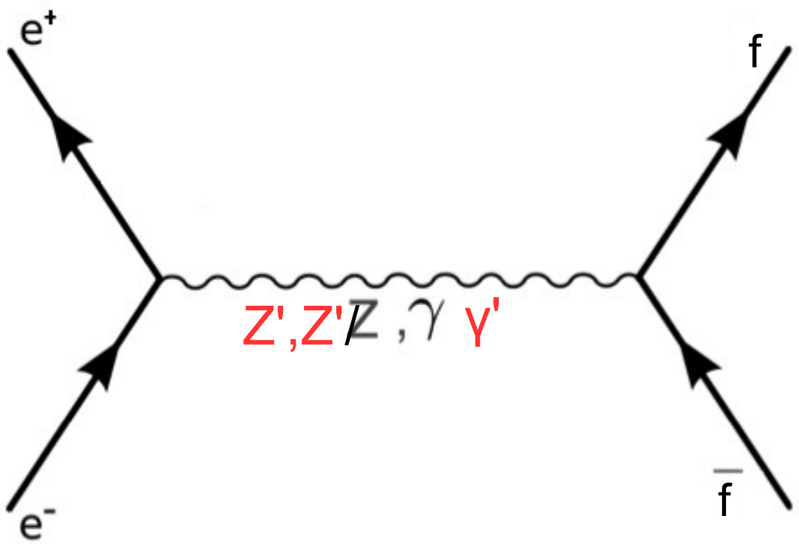
-

How can the Z-pole help?

On the Z-pole



Above the Z-pole

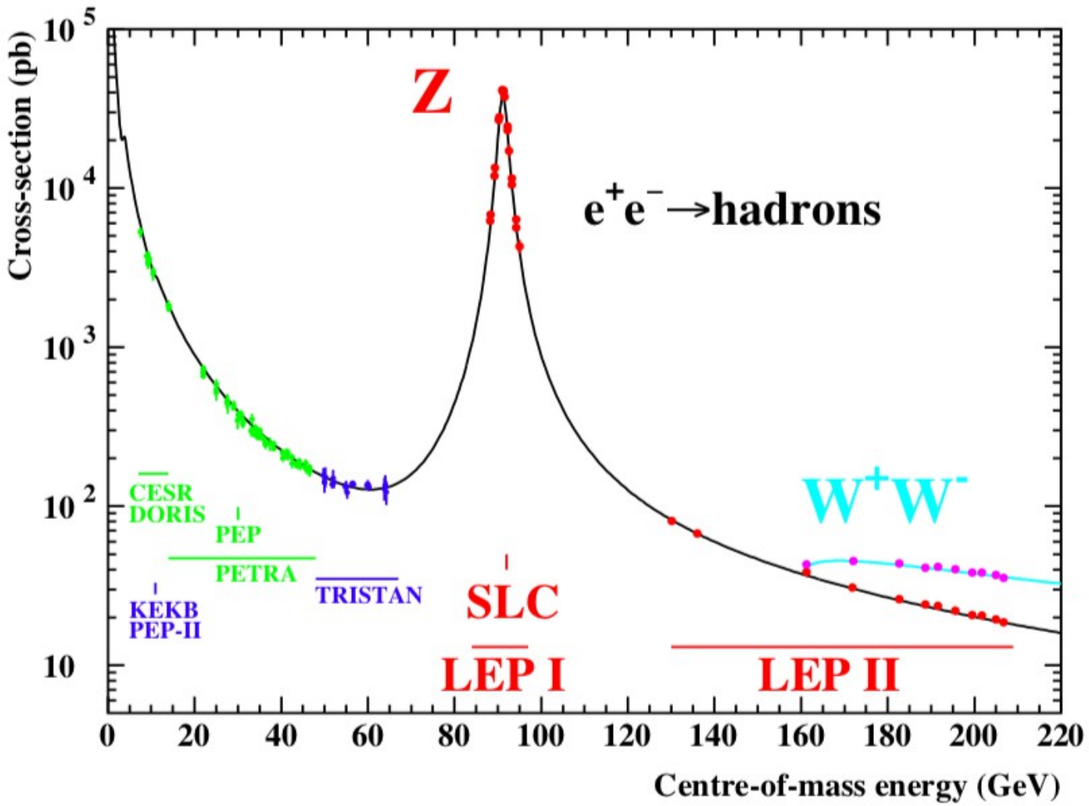


- ILC/GigaZ with ~10^9 Z
- Sensitivity to Z/Z' mixing
- Sensitivity to vector (and tensor) couplings of the Z
  - the photon does not “disturb”

- Sensitivity to interference effects of Z and photon!!
- Measured couplings of photon and Z can be influenced by new physics effects
- Interpretation of result is greatly supported by precise input from Z pole

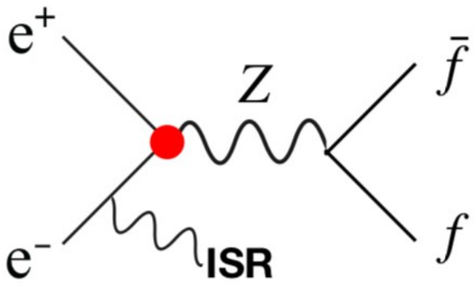
Couplings to on-shell Z Bosons

Running on Z pole "GigaZ"



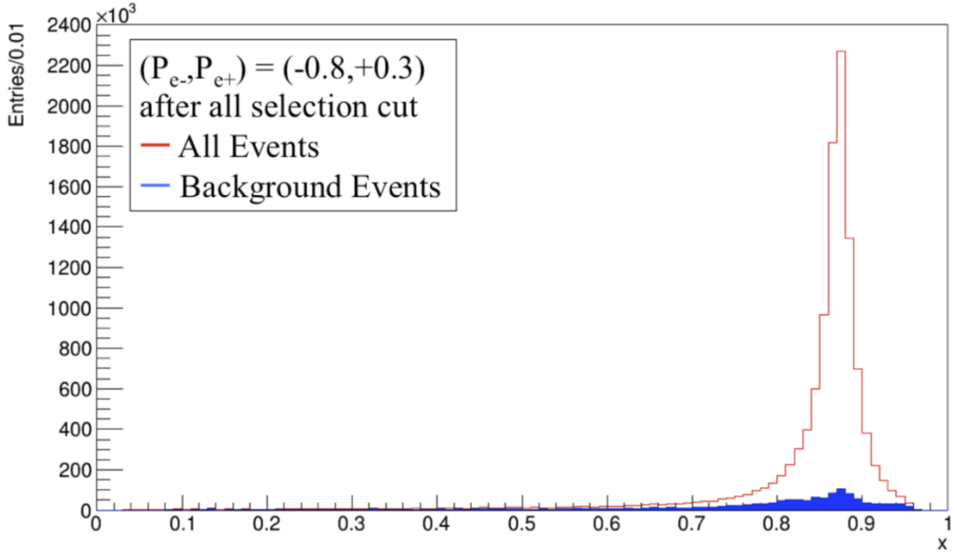
- Around 5×10^9 Z events (250xLEP)
- With beam polarisation
  ~30x250 = 7500 LEP!

Radiative return at higher energies



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

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



- ~10^8 events at 250 GeV with $2ab^{-1}$
- Beam polarisation

Precision on couplings and helicity amplitudes in ee->bb

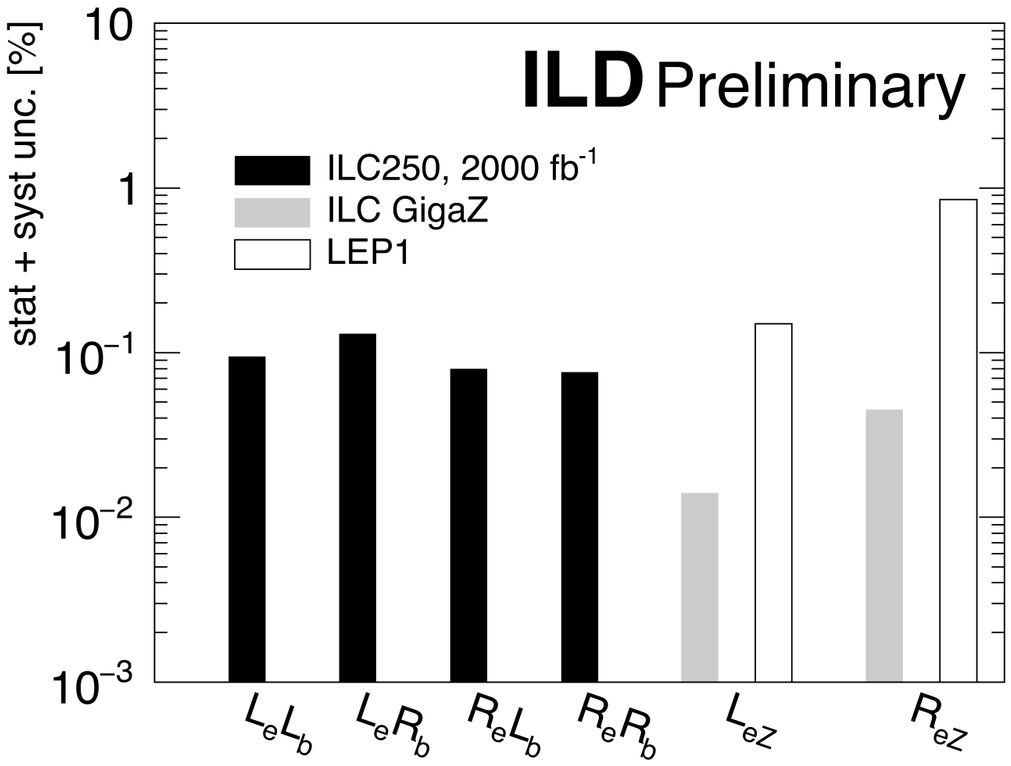


Figure: A. Irles

$$\mathrm{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'}\frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

ILC250 SM GigaZ New resonances

- Couplings are order of magnitude better than at LEP
  - In particular right handed couplings are much better constrained
- New physics can also influence the Zee vertex
  - in 'non top-philic' models
- Full disentangling of helicity structure for all fermions only possible with polarised beams!!

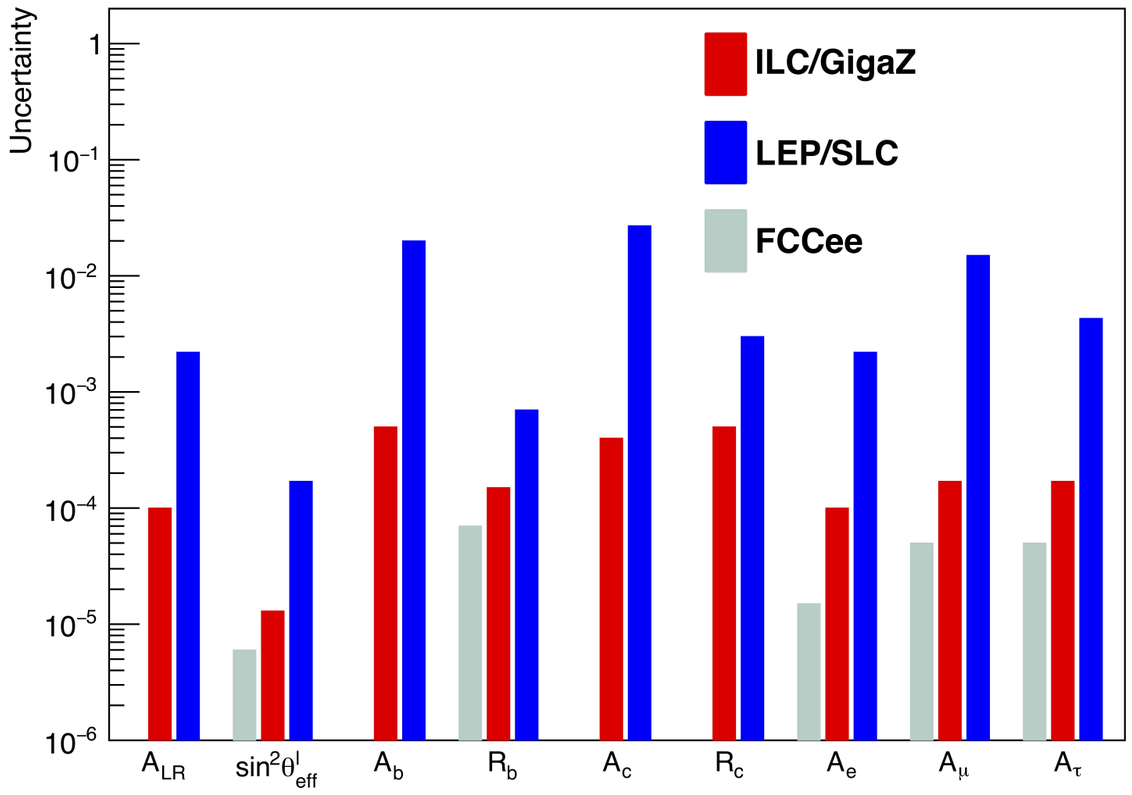
A/The central measurement A_{LR} – Some comments and results

- ALR is “simple counting” measurement
- Errors?
  - On Z-Pole
    - Energy dependency ($dA_{LR}/d\sqrt{s} \sim 2x10^{-5}/MeV$) due to γ/Z interference
      - Need excellent calibration of $\sqrt{s}$, *1 MeV seems possible*
    - Beam polarisation (Blondel scheme and polarimeters):
      - Residual uncertainty of $\Delta A_{LR} = 0.5x10^{-4}$ seems possible
    - Details see talk on Thursday in Track 1 session
    - Precision $\Delta A_{LR} = 1x10^{-4}$ is a realistic assumption for GigaZ

$$\delta \sin^2\theta^{\ell}_{\text{eff.}} \sim 1.3 \cdot 10^{-5}$$

  - Radiative return
    - Mainly limited by statistics $\Delta A_{LR} = 1.4x10^{-4}$
    - Beam polarisation $\Delta A_{LR} = 0.5x10^{-4}$ (More processes available)
    - Energy dependence 1000 x weaker than on Z-pole

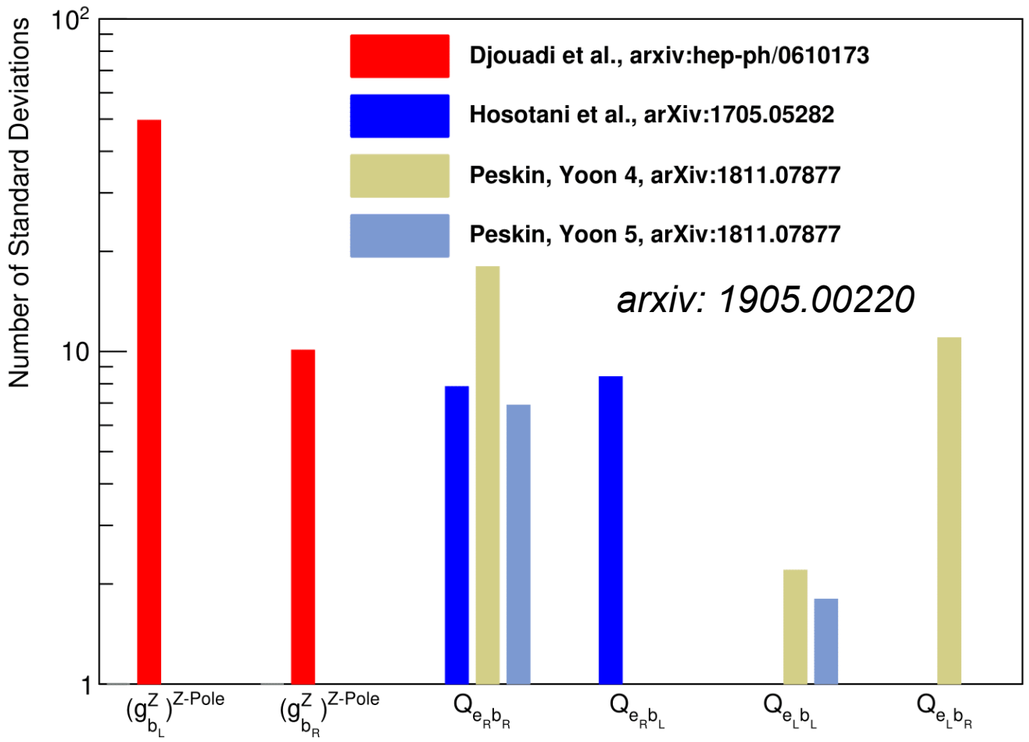
Precision on Z-pole



- Precise measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$.
  - Ten times better than LEP/SLD and competitive with FCC
  - Polarisation compensates for ~30 times luminosity
  - ... and A_{LR} at LC can benefit from hadronic Z decays
  - **No assumption on lepton universality at LC**
- Complete test of lepton universality
  - Precisions of order 0.05%
- Note excellent measurement of quark asymmetries
  - See above for ee->bb at 250 GeV
  - *More details in talks by A. Irles and R.P. in parallel sessions*

Precision on Z-pole and interplay with measurements above pole

Example: b couplings and helicity amplitudes



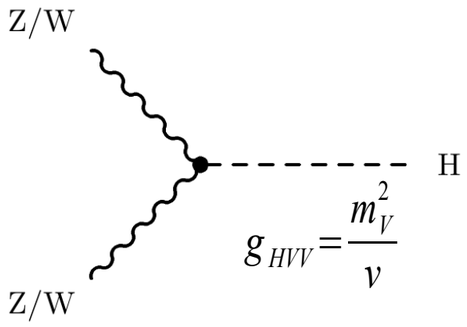
- Spectacular sensitivity to new physics in Randall Sundrum Models with warped extra dimensions
  - **Complete tests only possible at LC**
  - **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**
- Pole measurements critical input
  - Only poorly constrained by LEP
- Pole measurements will (most likely) influence also top electroweak precision program
  - (t,b) doublet

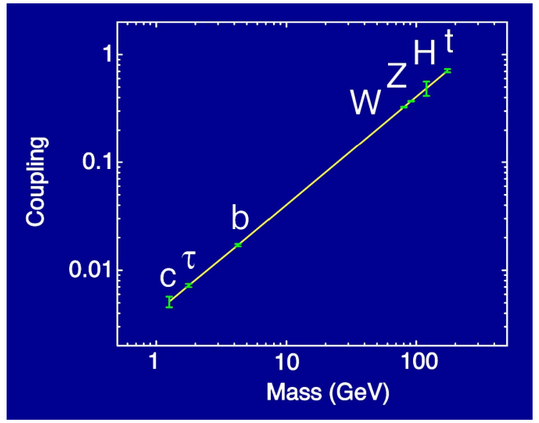
N.B.: ee->cc is new kid on the block
See talk in parallel session by A. Irles

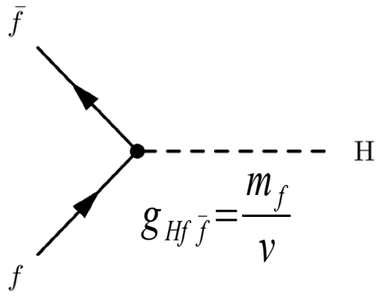
What about the Higgs?

Fitting Higgs Couplings – Kappa and EFT

Couplings to Higgs Boson in Standard Model







Analysis using Kappa-fit:

- Simple scaling of SM-couplings
- Implies that Higgs coupling to Z in production and decay are identical
- No new operators

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

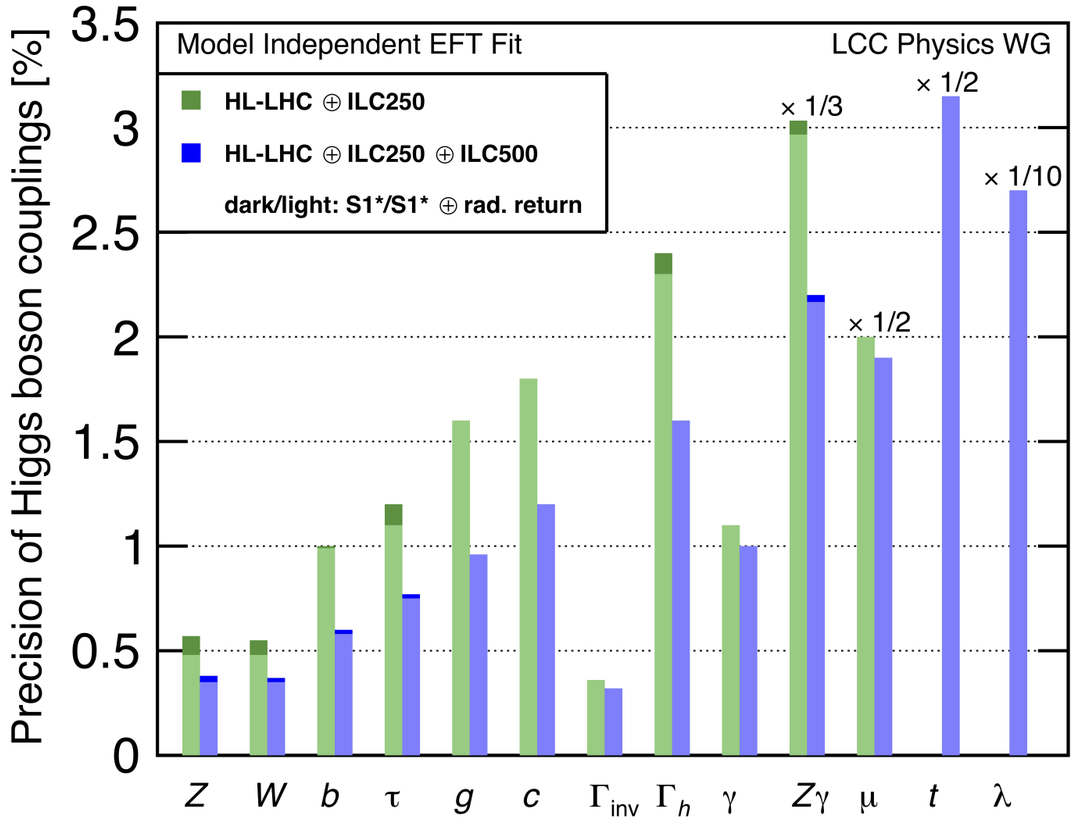
Analysis using EFT-fit:

- Introducing set of SU(2)xU(1) compatible operators
- e.g. breaks simple relation between Higgs production and decay
- Total width and Higgs to invisible as free parameters
- **Receives additional input from e.g. ee->WW and EWPO**

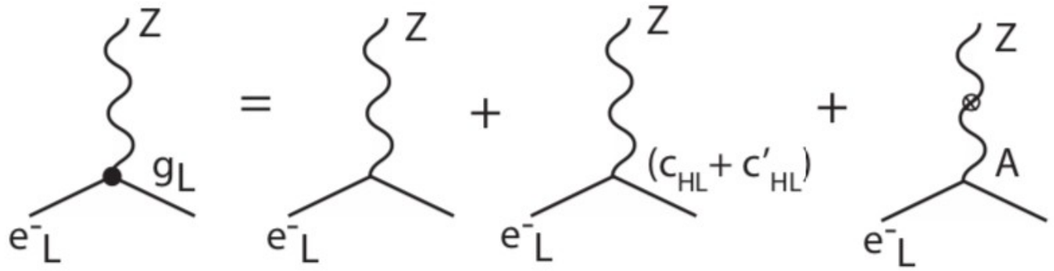
$$\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$$
$$\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)$$

EFT Framework and EWPO

Higgs couplings in EFT using A_{LR}
(Here from radiative return events

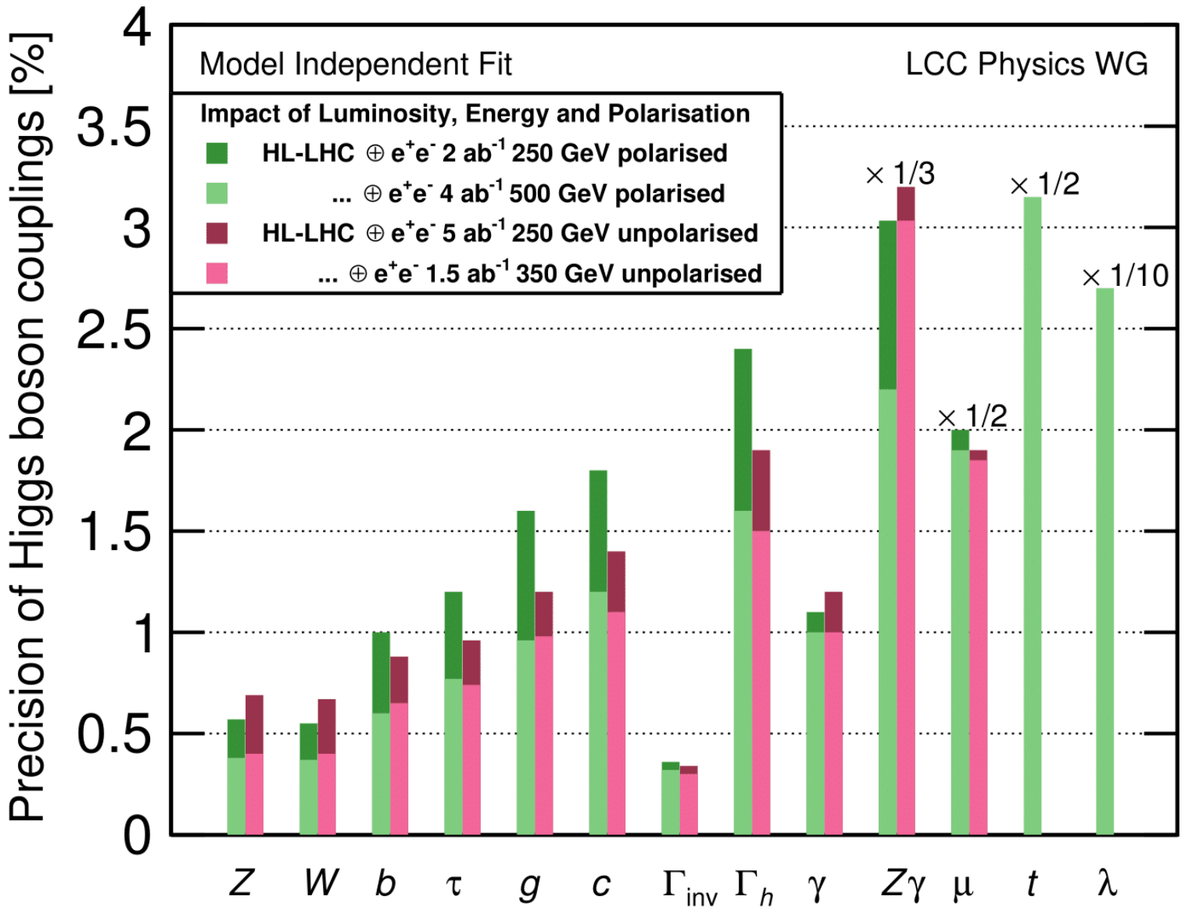


Corrections to Zee-vertex due to additional terms in EFT

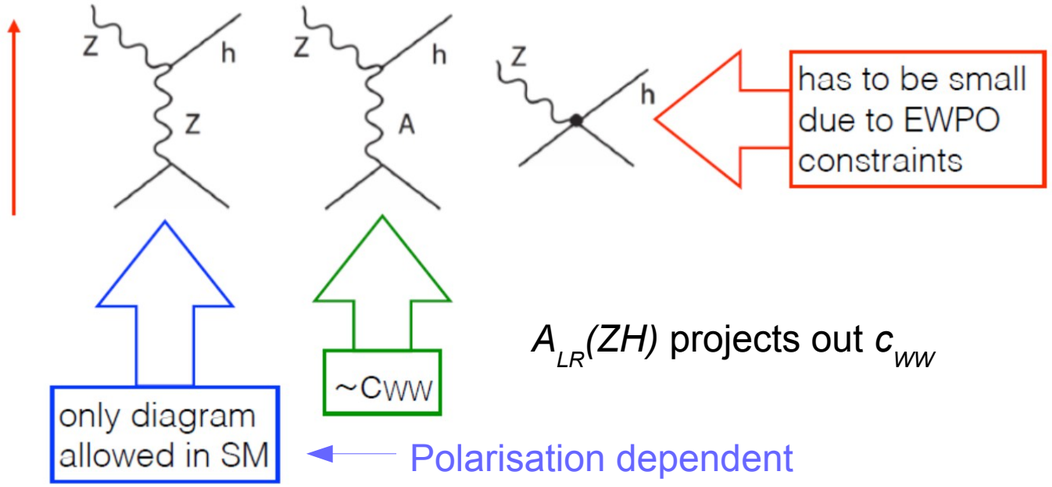


- Model independent, clean A_e from A_{LR} and Γ_e from R_e to constrain EFT fit
  - (again) No assumption of Lepton Universality
- Mild but visible improvement on some Higgs couplings at 250 GeV
  - Effect stronger in fit presented in 1905.03764 (see backup and talk by G. Durieux)

EFT Framework and beam polarisation



- EFT adds additional spin structure to ZH production cross section (see backup)



$A_{LR}(ZH)$ projects out c_{WW}

- Precision for $2ab^{-1}$ polarised = $5ab^{-1}$ unpolarised

Summary and conclusion

- ILC is electroweak precision machine
  - Most of the electroweak parameters are limited by systematics, not statistics

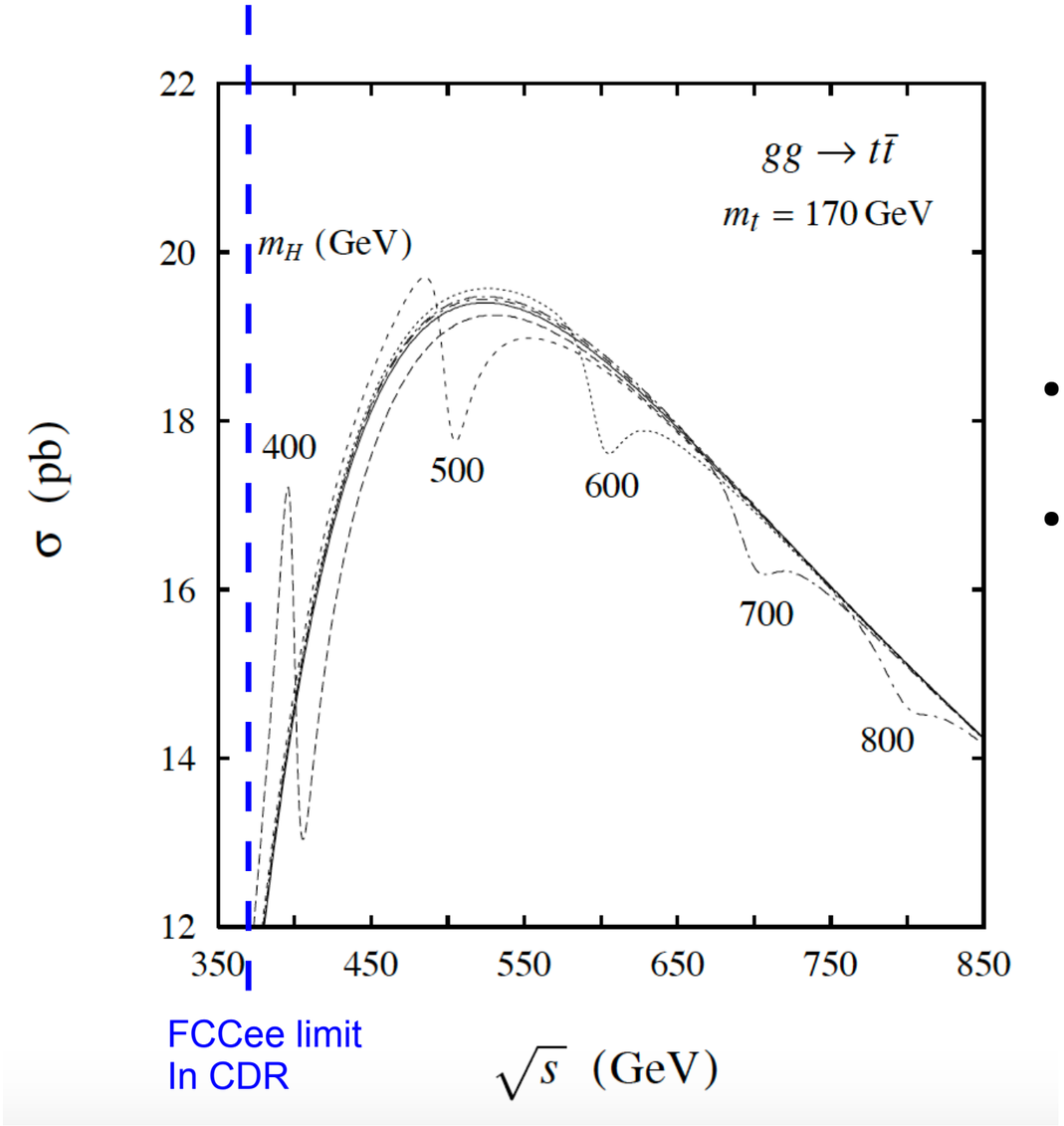
- ILC can (should) be run on the Z-pole
  - Electroweak precision observables deliver decisive input for interpretation at higher energies

- Full exploitation of physics potential by large energy coverage and polarised beams

  - Clean model independent measurements due to beam polarisation
    - => Superior to circular colliders due to larger set of observables
    - Tests of lepton universality
  - Measurement of patterns for indirect discovery of new physics
    - Spectacular mass reach for new physics already art 250 GeV demonstrated
    - Flexbility of beam energy allows for systematic tracing of the the onset of new physics

- Energy expandability opens access to
  - Top quark precision studies including tth (see talk by M. Perello)
  - Access to HHH coupling (see talk by G. Durieux)
  - Flexible response to produce directly new particles (to not get stucked just before the “new” Higgs)

Heavy Higgs decays at LHC

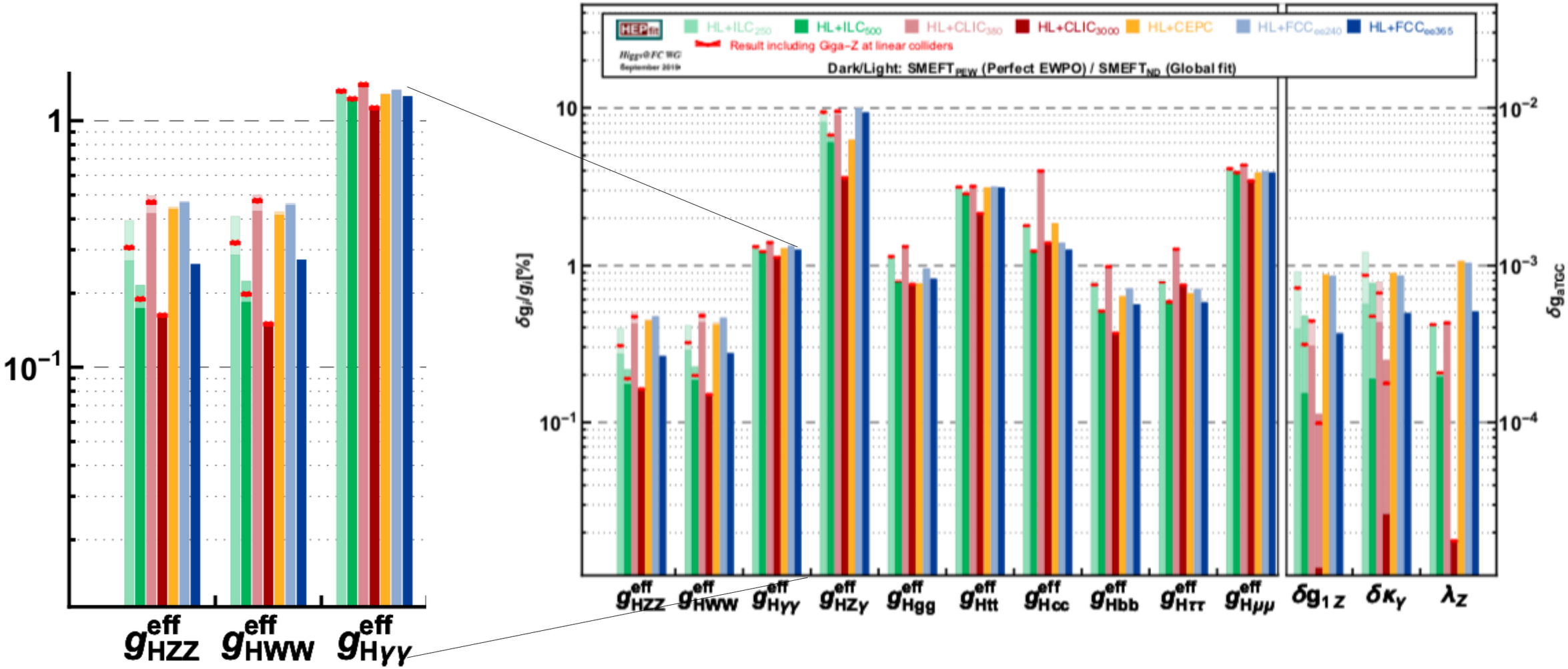


Plot by F. Maltoni, Seminar at LAL, Comment by R.P.

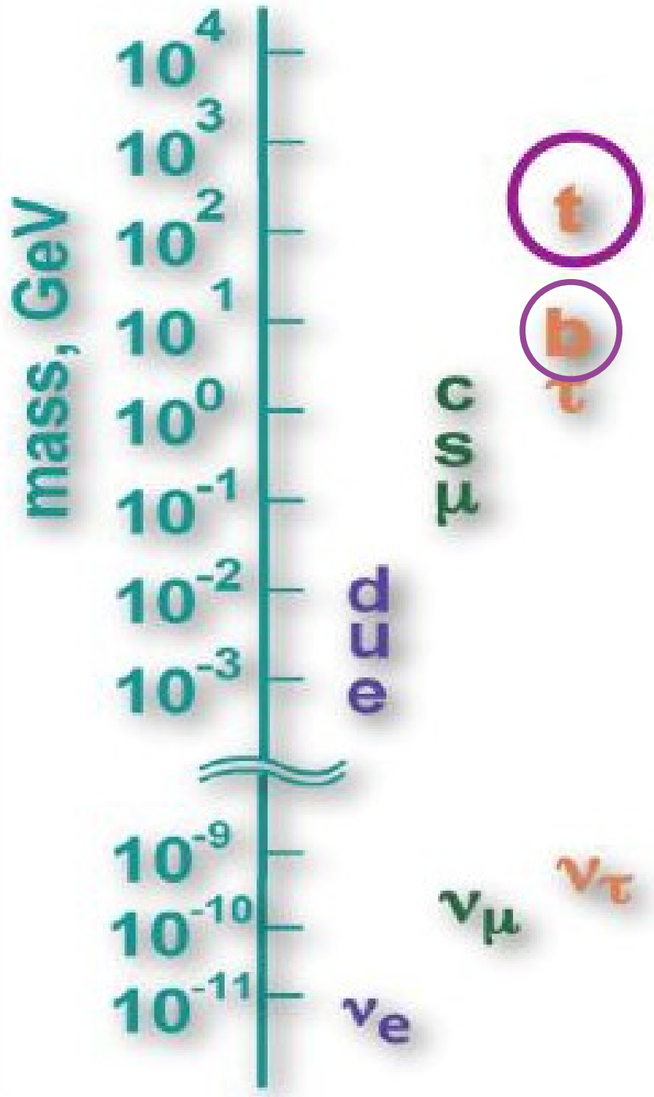
- LHC only sensitive if M_H = *400 GeV*
- LC with 500 GeV should be able to see resonances
  - ~$\sin^2\theta$ compared with 1+/-$\cos^2\theta$ for ee->tt

Backup

Higgs couplings and EWPO in ESU-Fit – 1905.03764



Electroweak couplings of heavy quarks



- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- Fermion mass generation closely related to the origin electroweak symmetry breaking

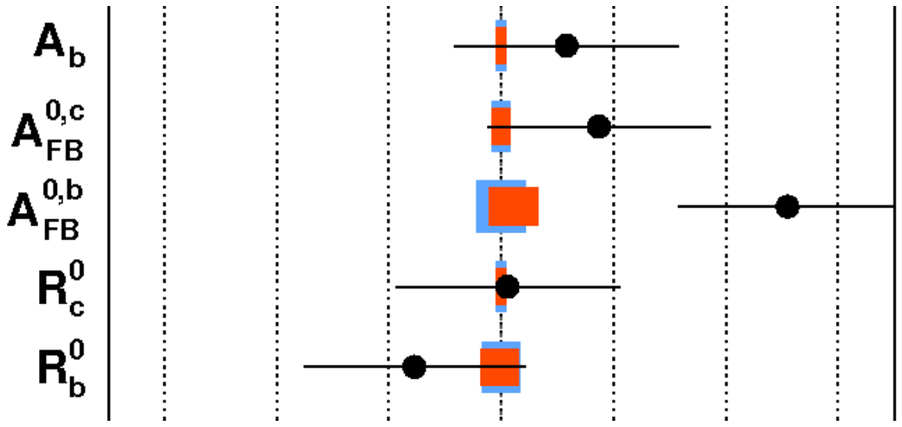
- Expect residual effects for particles with masses closest to symmetry breaking scale

$$\begin{pmatrix} t \\ b \end{pmatrix}_L$$

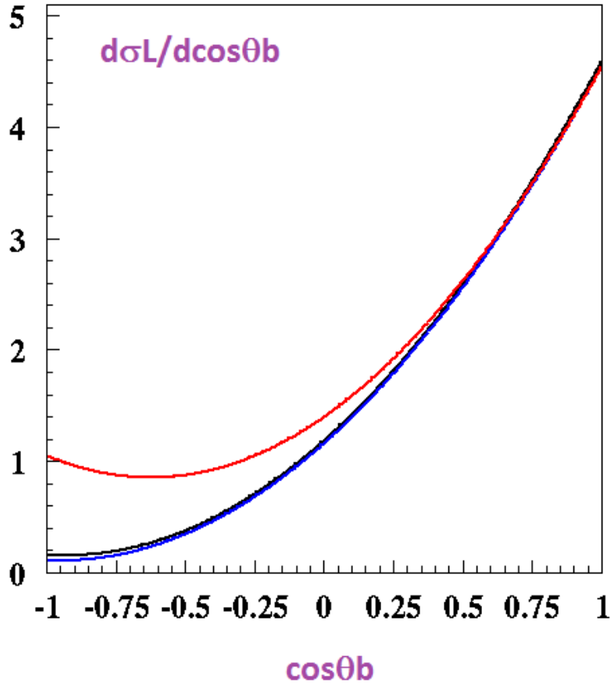
Strong motivation to study chiral structure of heavy quark vertices in high energy e+e- collisions

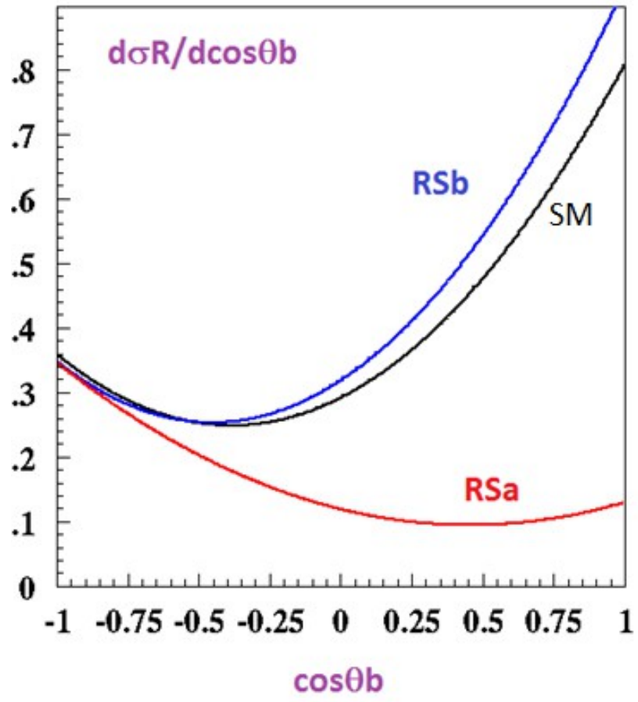
New physics below tt threshold? - Example b quark couplings

~3σ in heavy quark observable A^b_{FB}



ee->bb@250 GeV





Randall Sundrum Models Djouadi/Richard '06

- Is tension due to underestimation of errors or due to new physics?
- High precision e+e- collider will give final word on anomaly
- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings
- Randall Sundrum Models generate basically automatically a symmetry group of type $SU(2)_R$

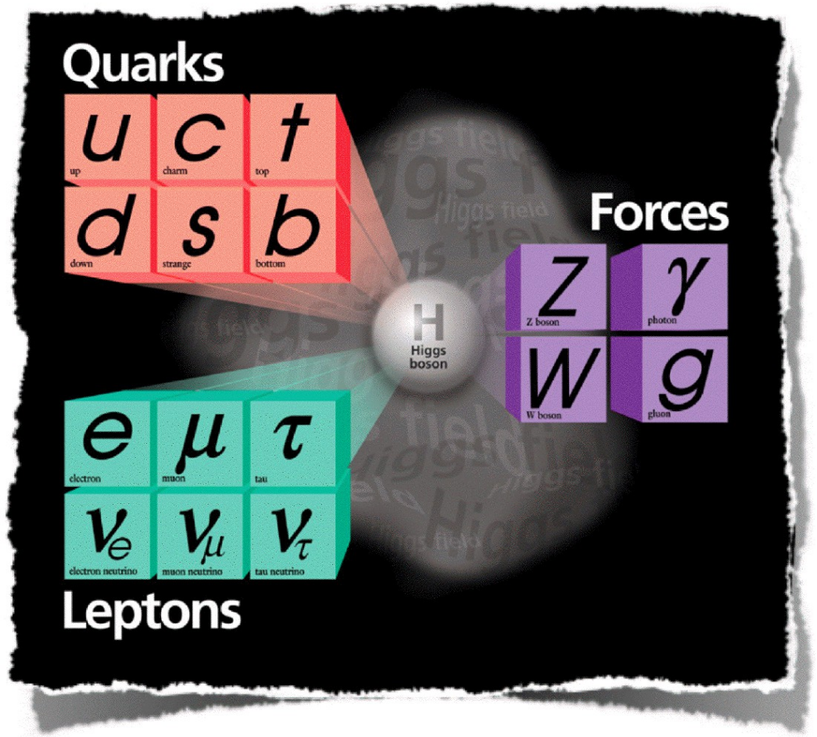
Energy Frontier Electron-Positron Collider Projects

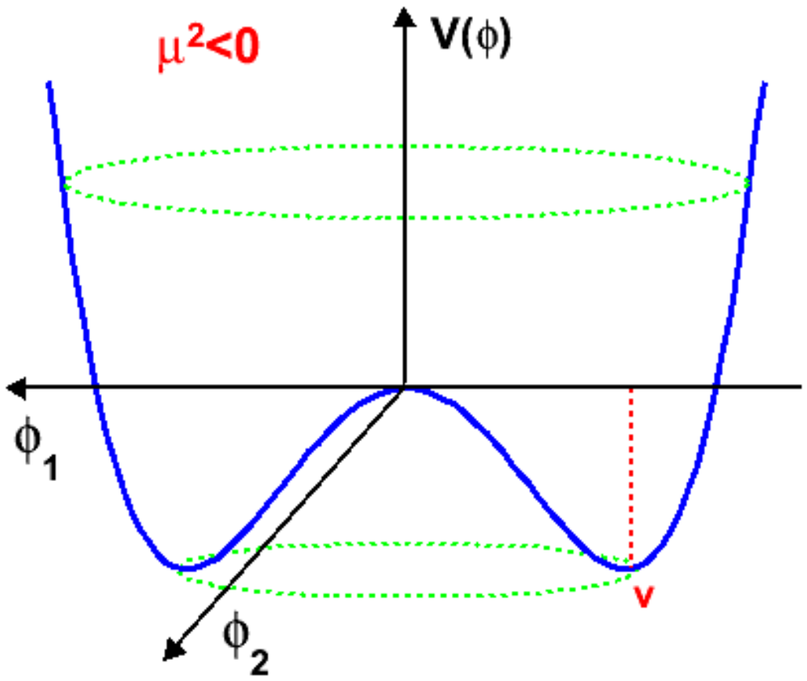
	√s	beam polarisation	∫Ldt for Higgs	R&D phase	
ILC	0.1 - 1 TeV	e-: 80% e+: 30%	2000 fb-1 @ 250 GeV 200 fb-1 @ 350 GeV 4000 fb-1 @ 500 GeV	TDR completed in 2013	Details see talk by Y. Okada
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1000 fb-1 @ 380 GeV 2500 fb-1 @ 1.5 TeV 5000 fb-1 @ 3 TeV	CDR completed in 2012	
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb-1 @ 240 GeV	CDR completed in 2018	Details see talk by M. Ruan
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	5000 fb-1 @ 250 GeV 1700 fb-1 @ 350 GeV	CDR completed in Jan 2019	

Table courtesy of J. Brau

Open questions

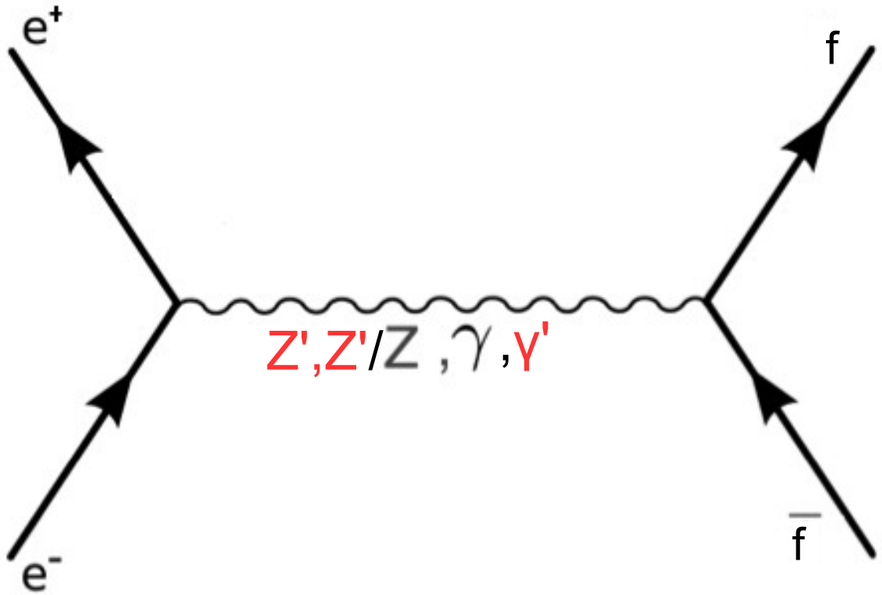
The Standard Model is complete





- We know that there exists at least one fundamental scalar with a non-vanishing expectation value
- We don't know what shapes the potential and whether the potential is the footprint of a larger mass scale

Two fermion production and asymmetries



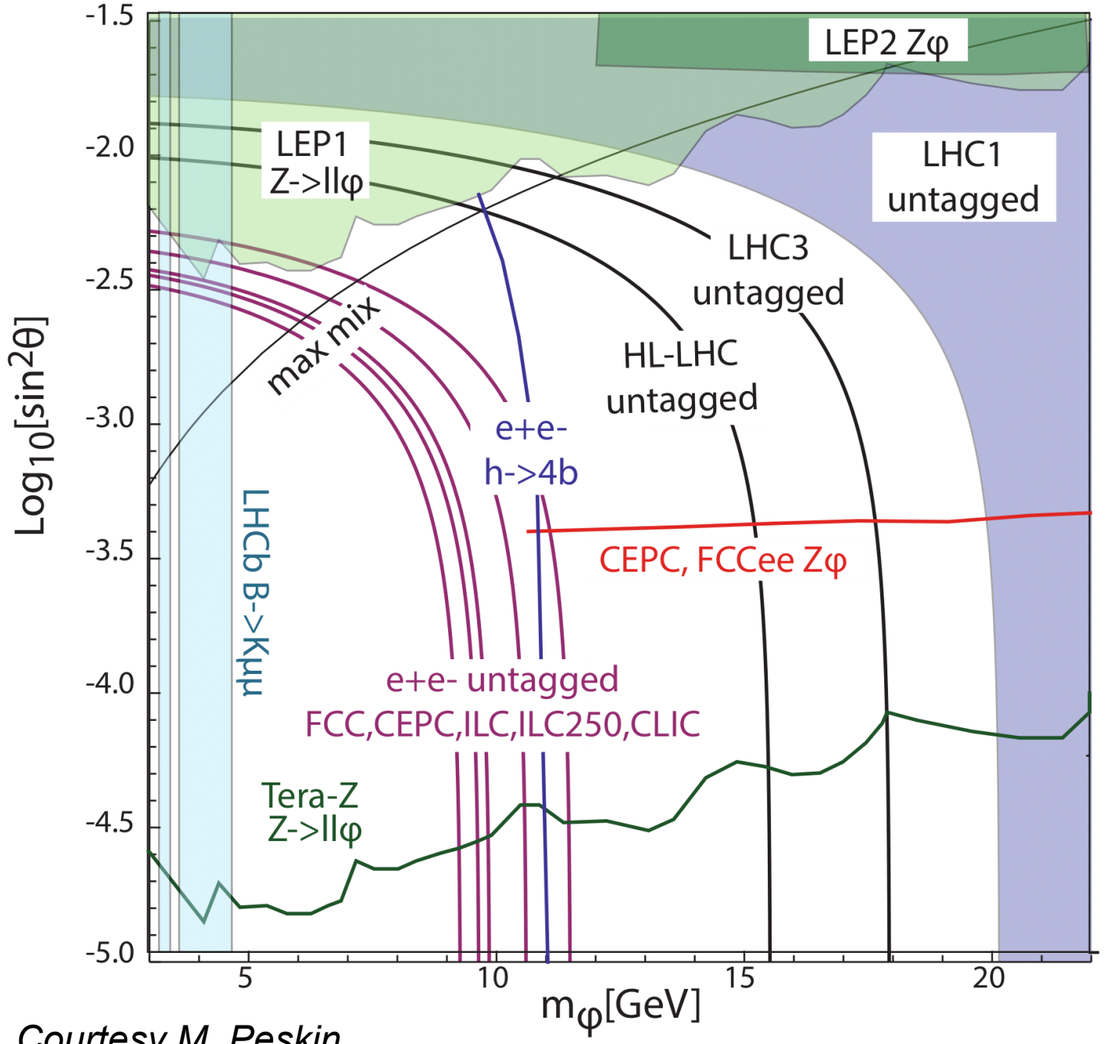
Differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left[A_0(1+\cos^2\theta) + A_1\cos\theta\right]\begin{cases} \sim (1+\cos^2\theta) & \text{'Usual' Vector current, symmetric in } \cos\theta \\ \backsim \cos\theta & \text{Axial Vector current, asymmetric in } \cos\theta \end{cases}$$

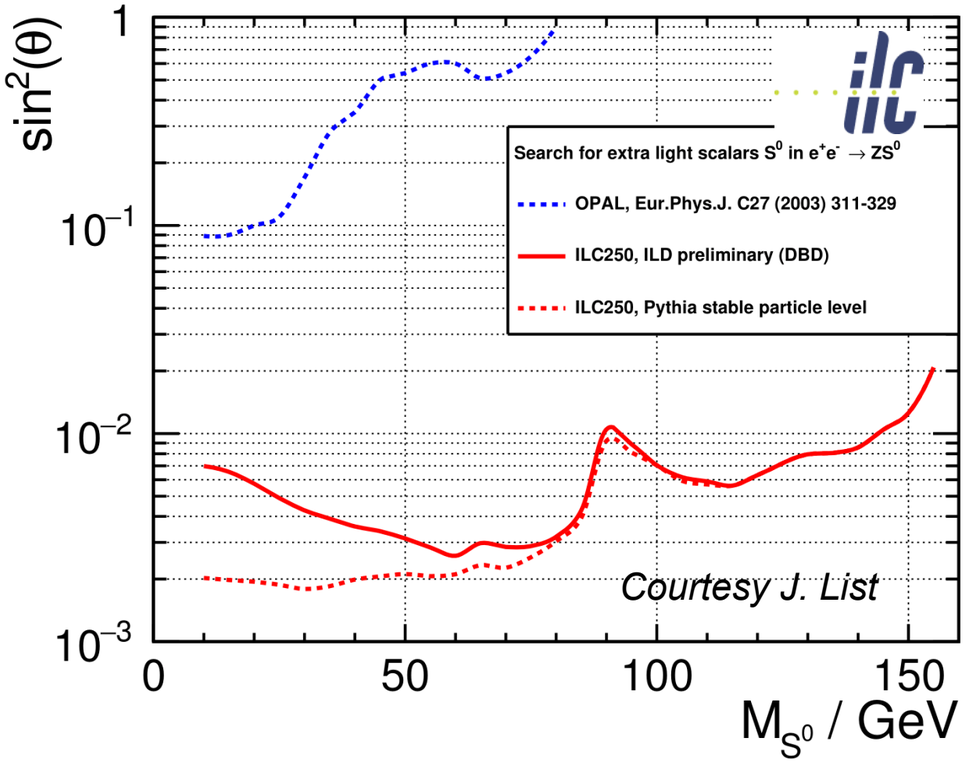
- $SU(2)_L x U(1)_Y$ symmetry of Standard Model introduces forward backward asymmetry and Left-Right asymmetry, i.e. $A_{i,L} \neq A_{i,R}$ => Observables highly dependent on beam polarisation
- New physics implying **new vector bosons** will modify coefficients and asymmetries
- Discovery potential in e+e- is supported best by **polarised beams**

Feebly interacting particles – A summary

Light scalar may be missing piece to trigger first order 1st phase transition and/or being the radion in extra dimension theories

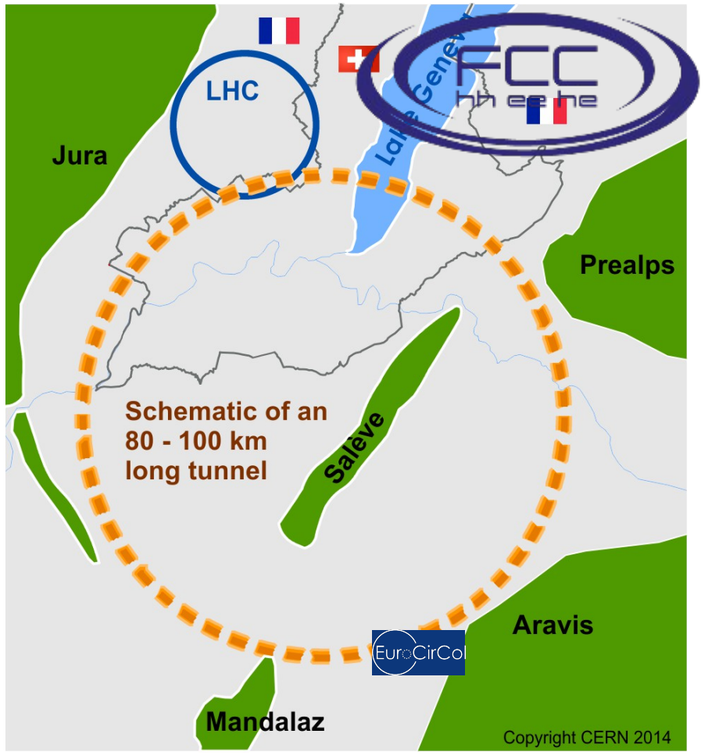


Courtesy M. Peskin



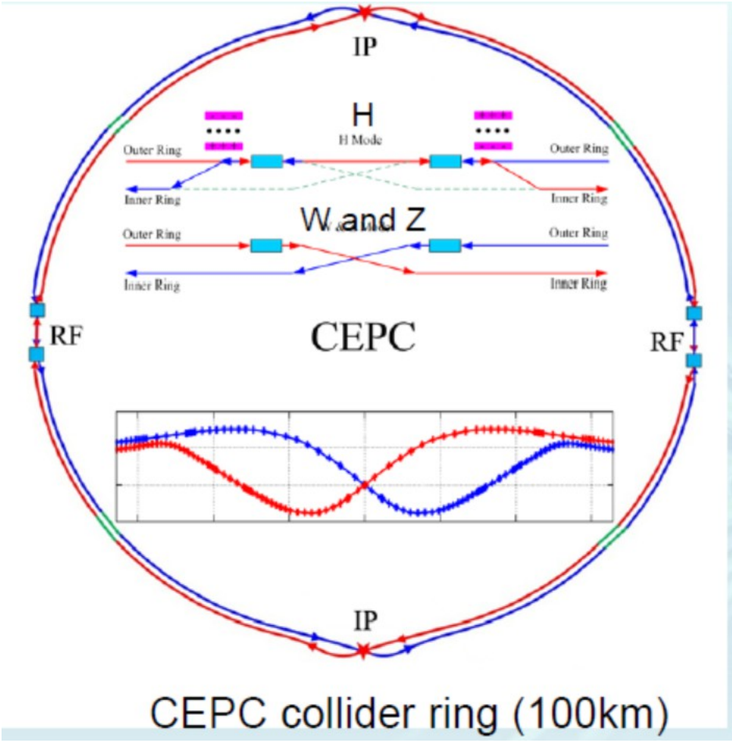
- e+e- colliders extend limits considerably w.r.t. LHC
  - Statistics helps at lowest masses
- CEPC, FCCee (>Z pole) limits order of magnitude better than ILC
  - Backgrounds taken correctly into account?
  - Similar at stable particle level

Circular Electron-Positron Colliders



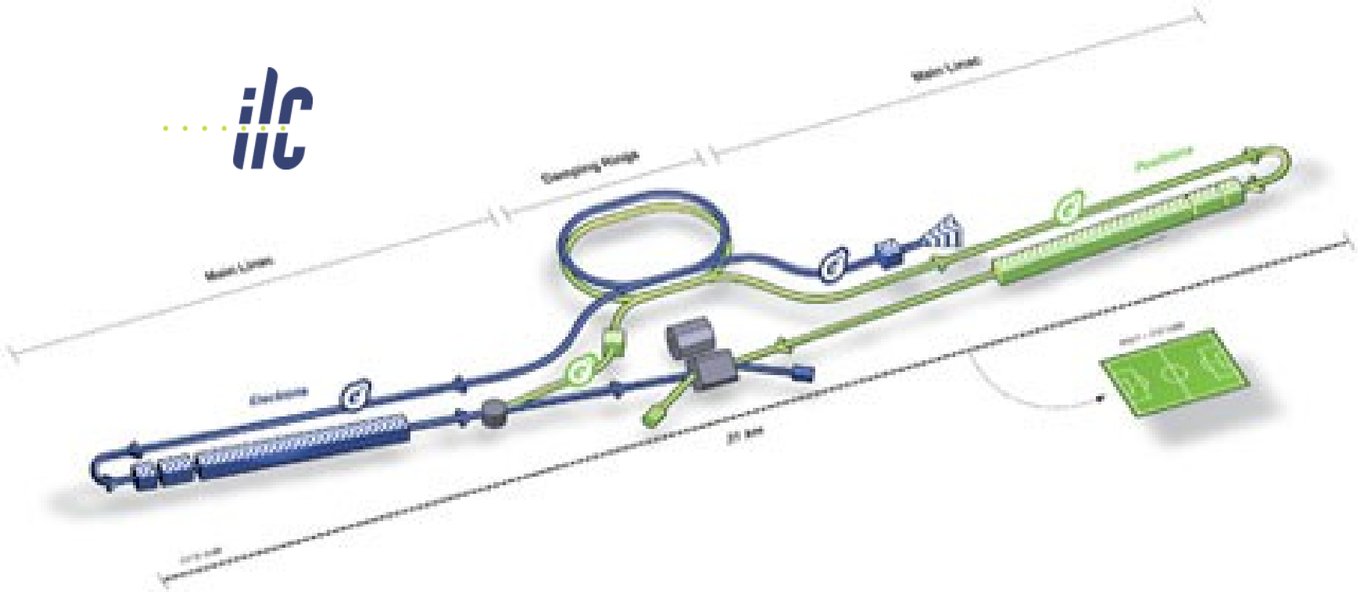
- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 350 GeV cms energy
- No long. beam polarisation
- CDR completed January 2019
  http://fcc-cdr.web.cern.ch

CEPC



- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 240 GeV cms energy
- No long. beam polarisation
- CDR completed September 2018
- Arxiv:1809.00285

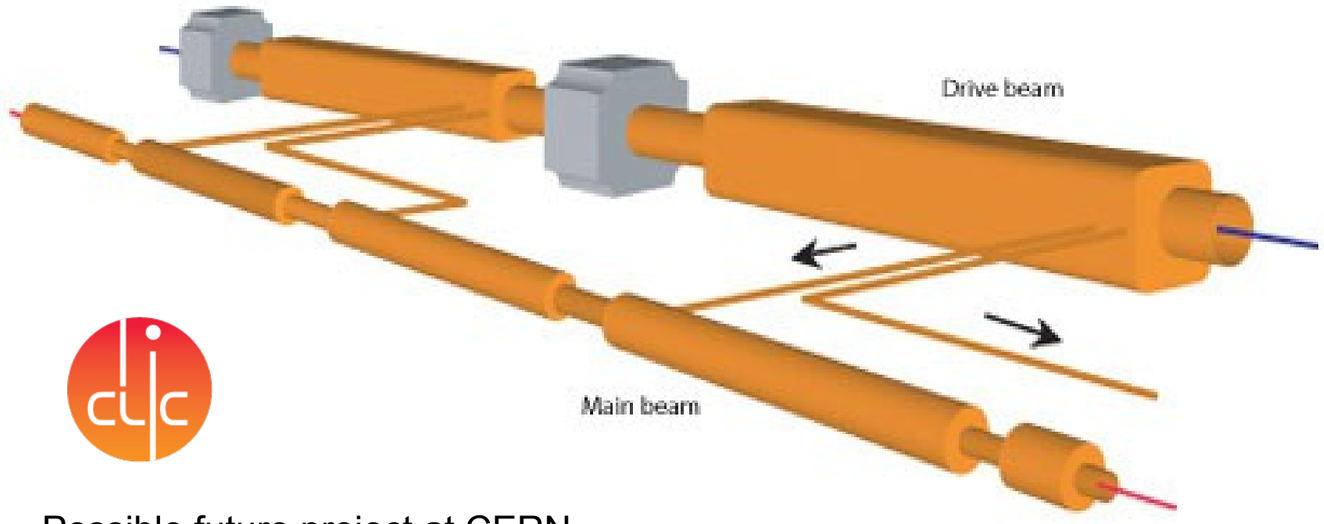
Linear Electron-Positron Colliders



Japanese Gouvernment expressed its interest in project in March 2019

Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km



Possible future project at CERN

Energy: 0.4 - 3 TeV

CDR in 2012

Footprint 48km

Initial Energy 380 GeV

New physics?

EFT: Two distinct observations

Observables at fixed mass m
(e.g. Z pole of Higgs decays)

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the measurement precision

$c_6 \sim (g^*)^2$

Typical experimental precision 0.1-1%

High energy tails of distributions
(e.g. Drell-Yan Productions

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the energy scale of measurement precision

Typical experimental precision 10%

A. Falkowski, Journée Grands Accél., LAL

New physics?

- Polarized beams play a crucial role in disentangling the two spin structures

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

The a and b coefficients depend on beam polarization:

$e_L^- e_R^+$

$$Q_{ZL} = (\frac{1}{2} - s_w^2)\ , \qquad a_L = -c_H$$

$$b_L = c_w^2(1 + \frac{s_w^2}{1/2 - s_w^2}\frac{s - m_Z^2}{s})(8c_{WW})$$

$e_R^- e_L^+$

$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

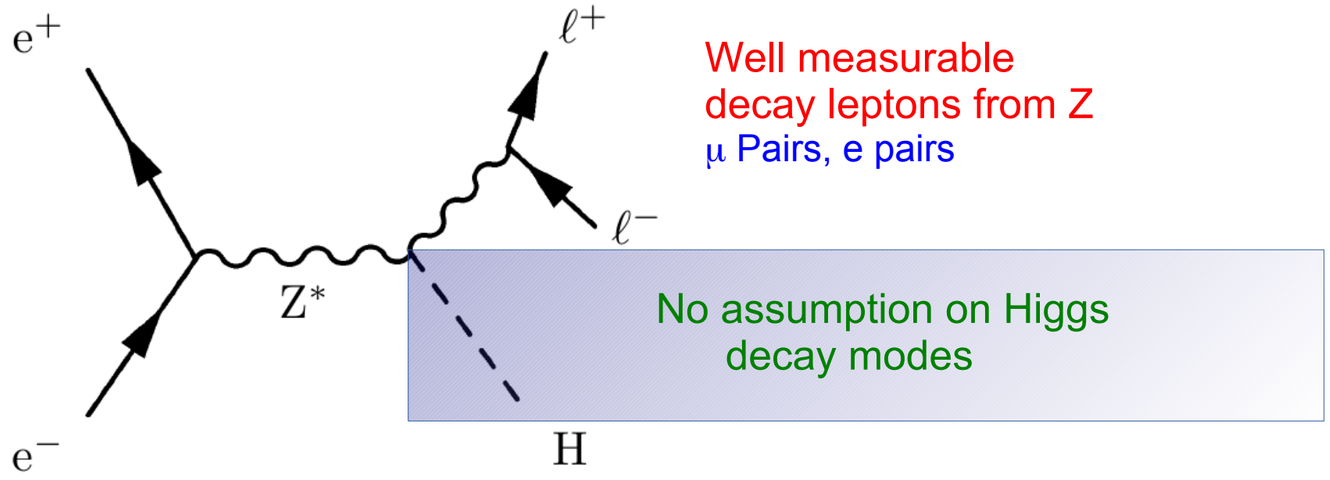
$$b_R = c_w^2(1 - \frac{s - m_Z^2}{s})(8c_{WW})$$

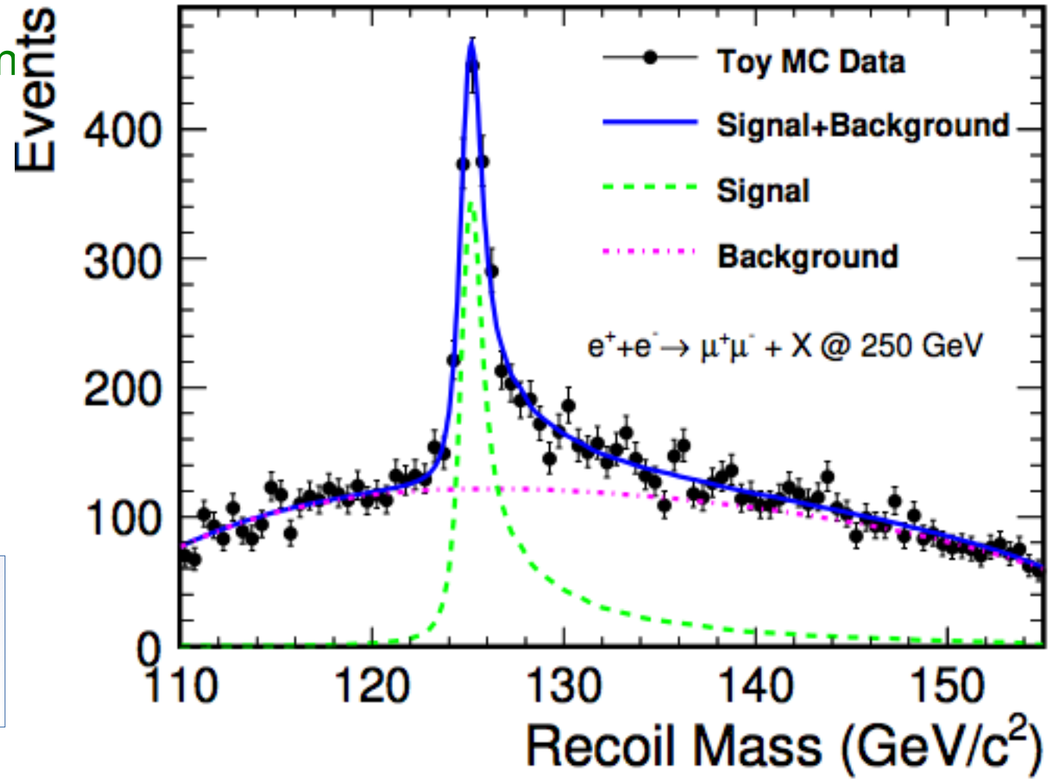
- Angular distributions in $e^+e^- \to hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

M. Perelstein: AWLC2017

Higgs-strahlung at lepton colliders

- Powerful channel for unbiased tagging of Higgs Even
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays

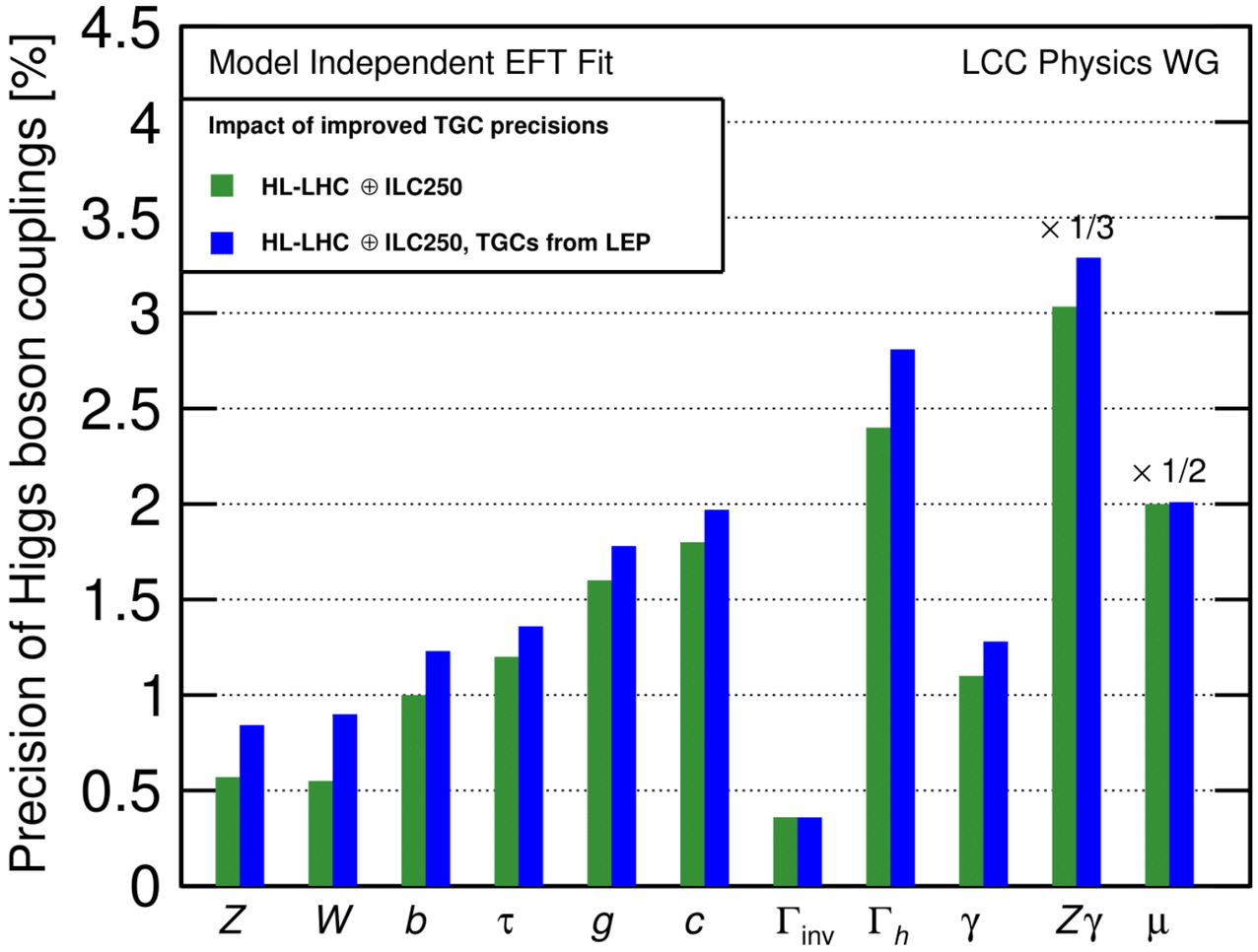




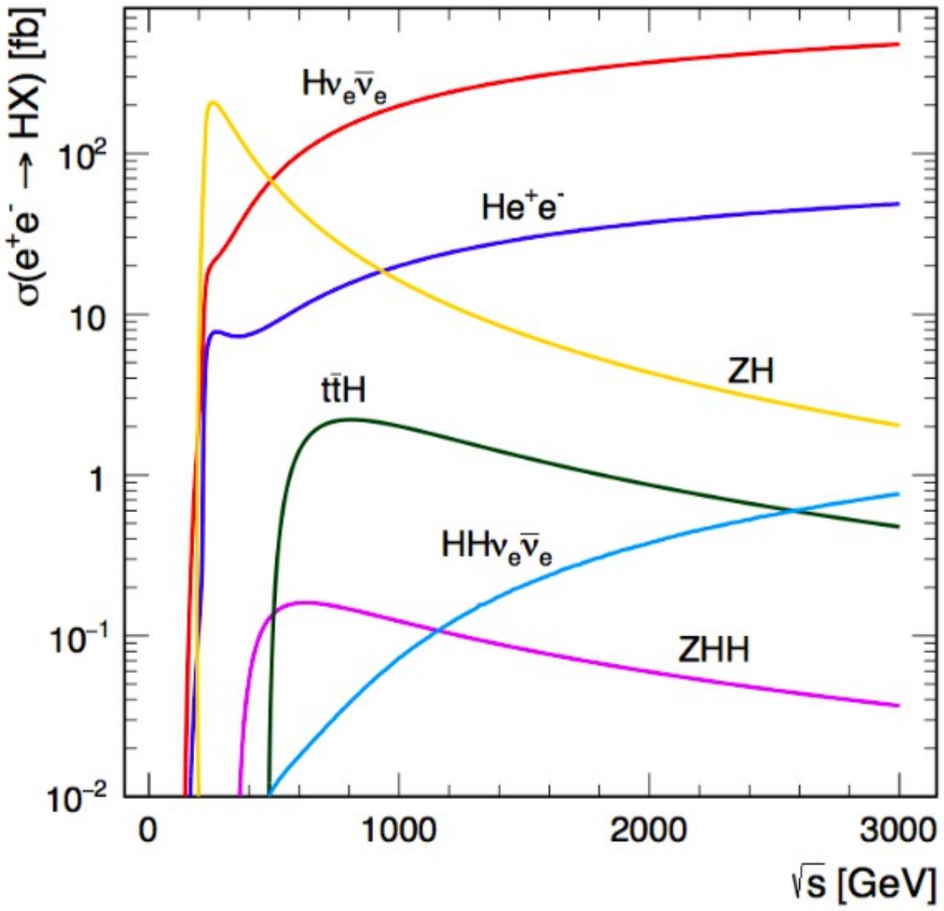
Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2 E_Z \sqrt{s}$

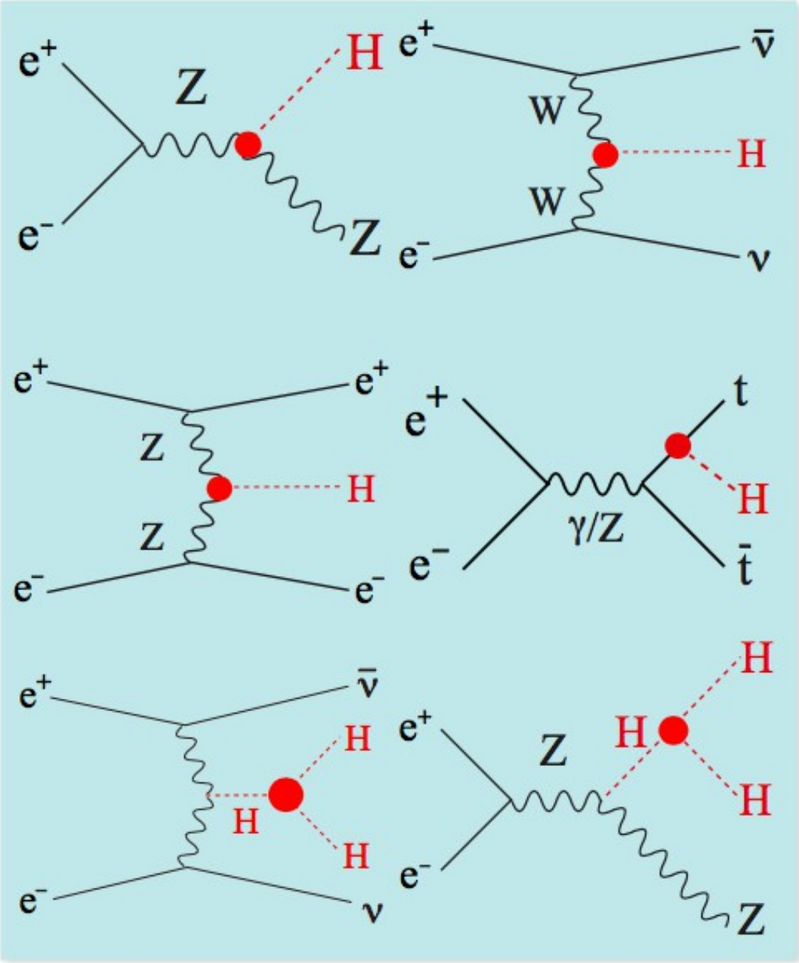
- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

Higgs couplings – Impact of TGC



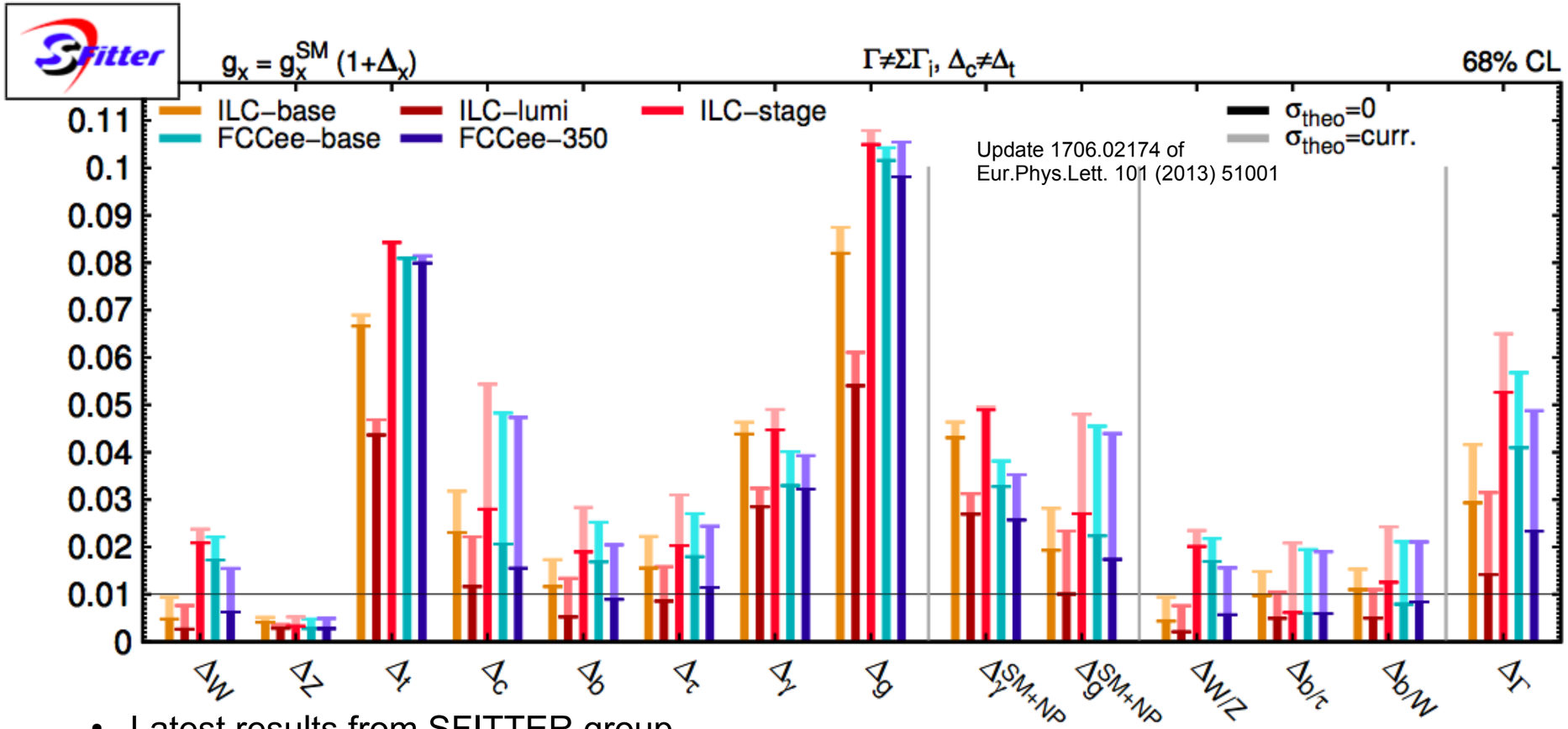
Higgs production at e+e- colliders





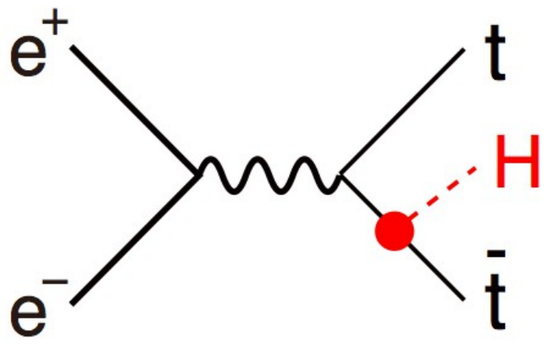
two important thresholds:
√s ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH

Precision on Higgs Physics – Kappa framework



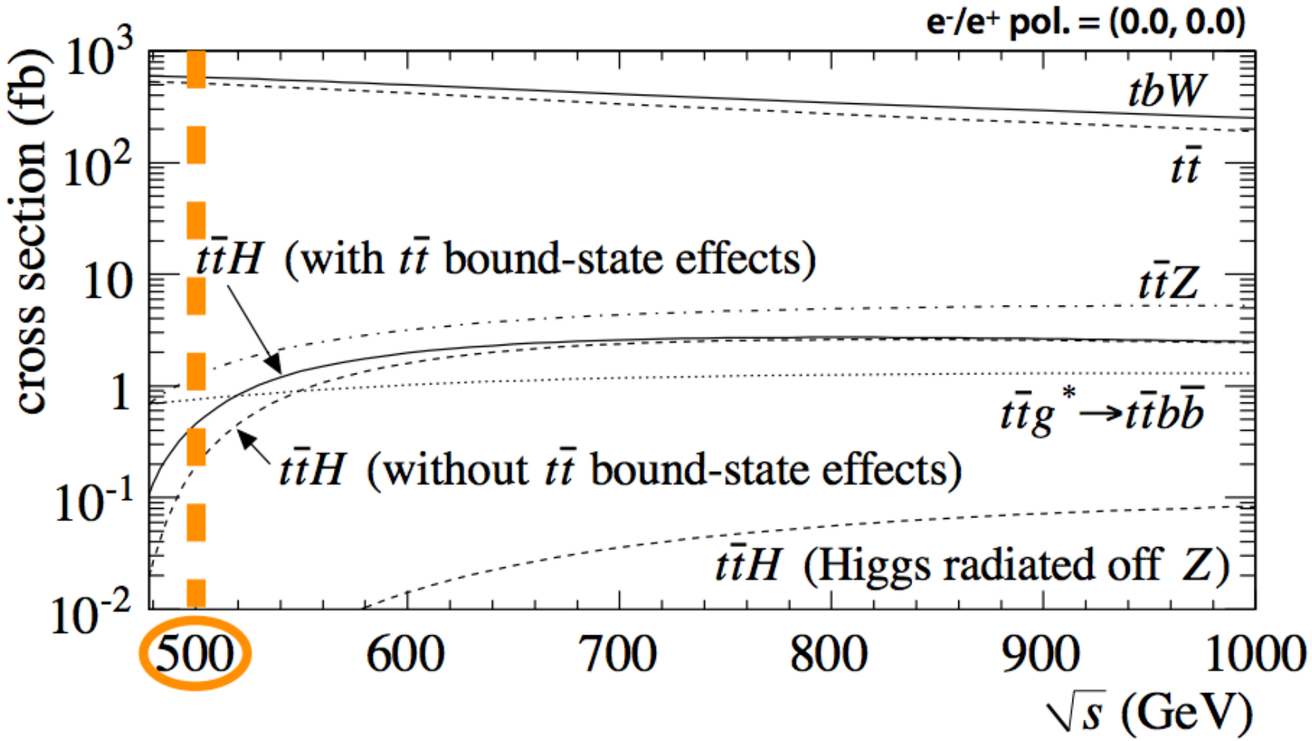
- Latest results from SFITTER group
  Assumption: HL-LHC basically completed before e+e- machine starts
- ILC250 already powerful program (needs however e.g. top-Yukawa as input)
- Higher energies beneficial for total width
  and top-Yukawa couplings (fit constraints and H->γγ)

Top Yukawa Coupling



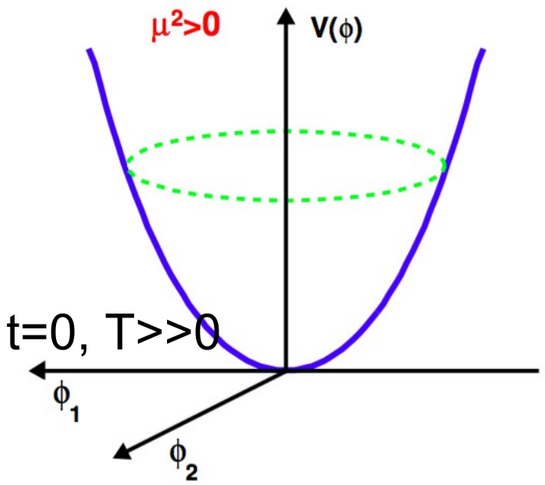
- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets

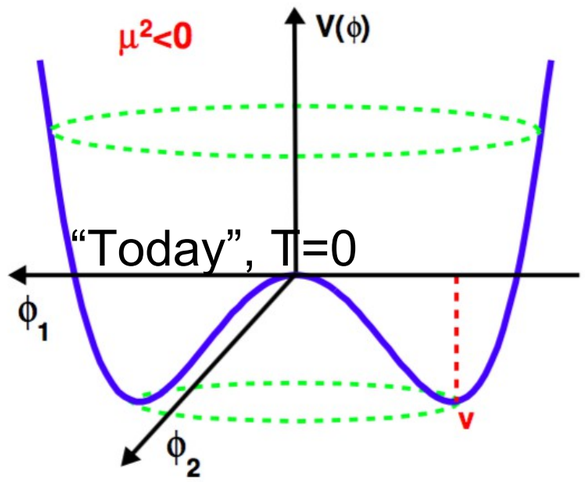


√s[GeV]	550	1000	1400
L[ab-1]	4	8	2
δyt/yt[%]	2.8	2.0	2.7

The Higgs Potential



Perfect (electroweak) symmetry and massless particles

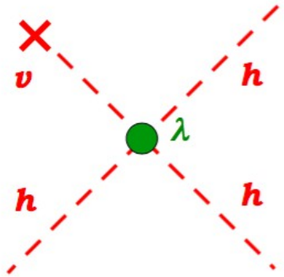


Broken (electroweak) symmetry and massive particles

Two questions:

- Shape of "today's" Higgs Potential?

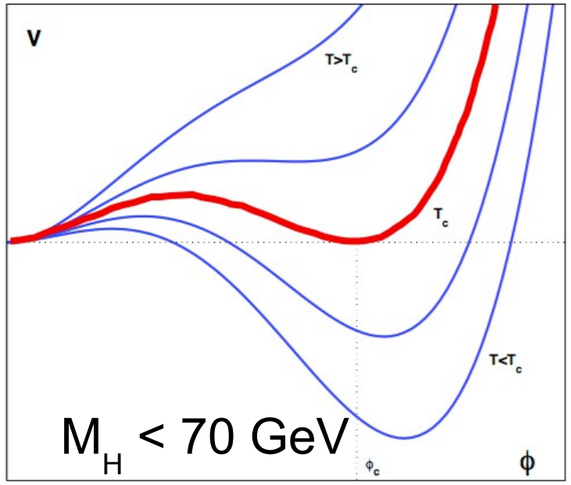
$$V(\eta) = \frac{1}{2}m^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4$$ => Triple Higgs-self coupling

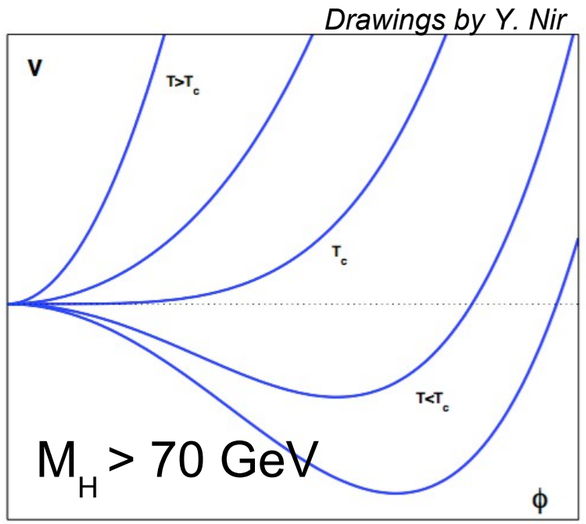


- Transition from symmetric, unbroken to broken phase?

Phase Transition in Standard Model

Electroweak Baryogenesis requires 1st Order PT





- Coexistence Two minima at **0 and v_c at T_c**

=> 1st order phase transition
and development into “today's” shape at T=0

- No coexistence of two minima at **0 and v_c**

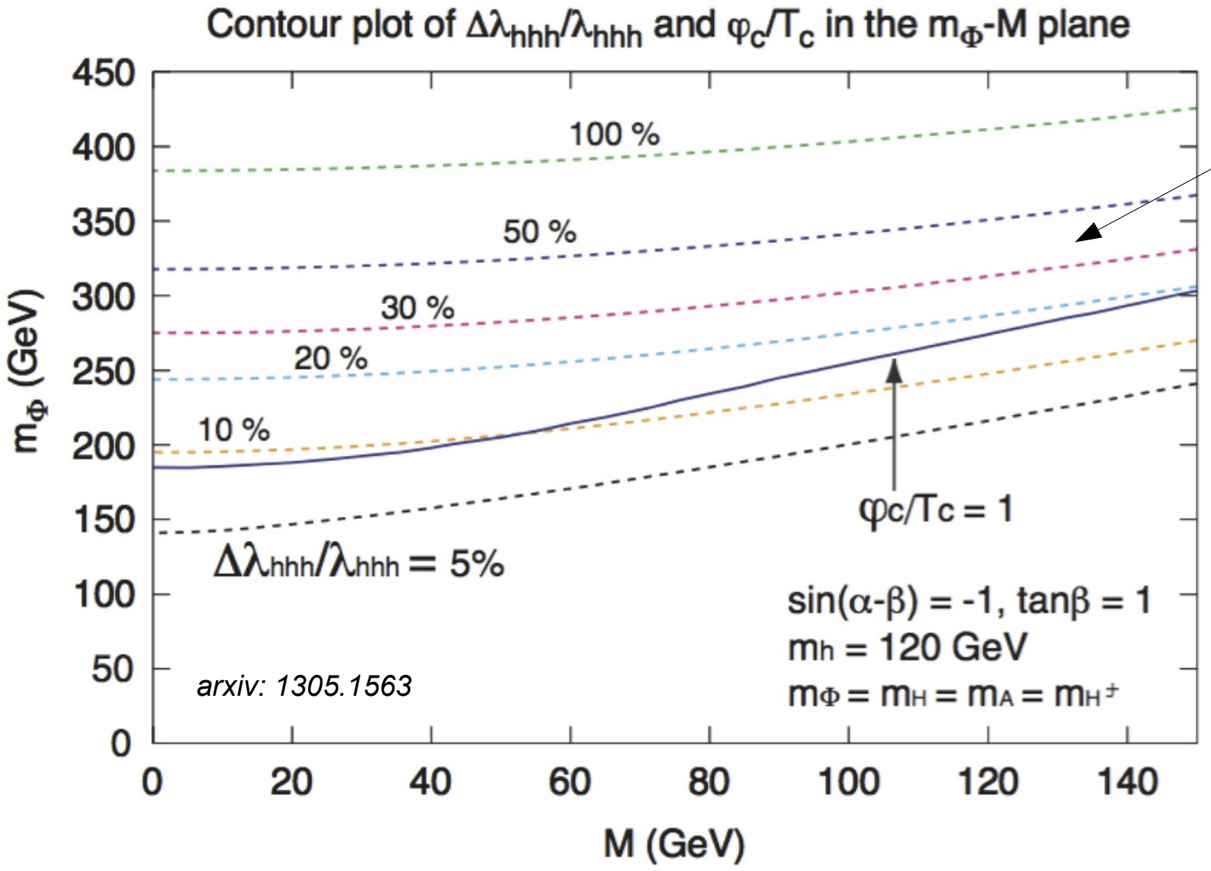
=> Cross over into “today's” shape at T=0

The discovered Higgs is too heavy to provoke a 1st order phase transition

=> New physics needed

New particles – Extended Higgs Sector

Heavy Higgs Mass

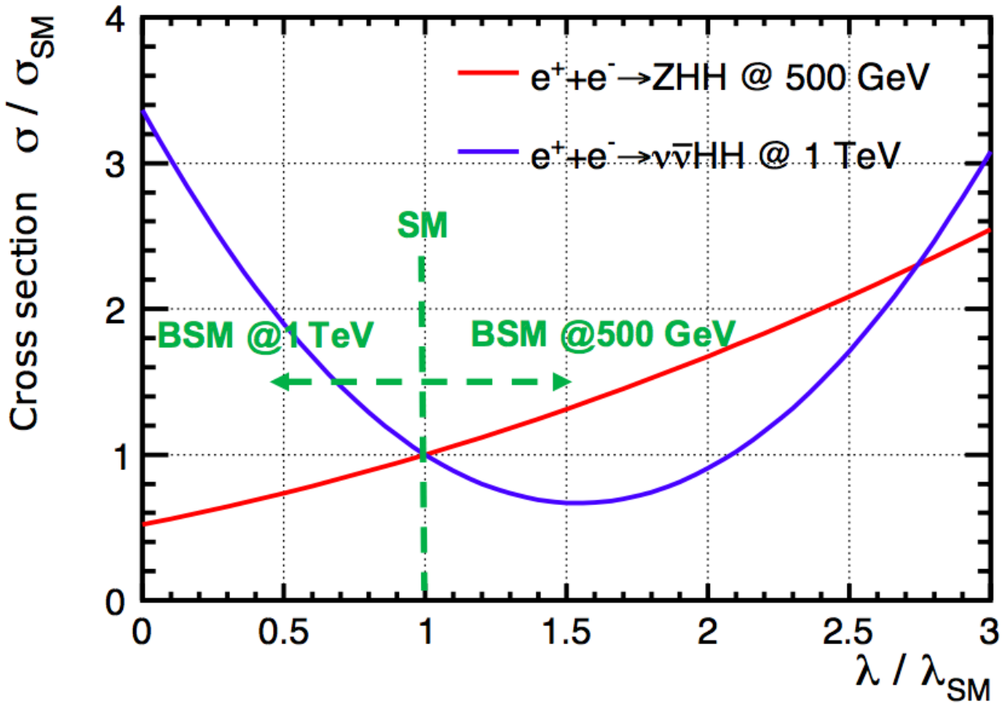


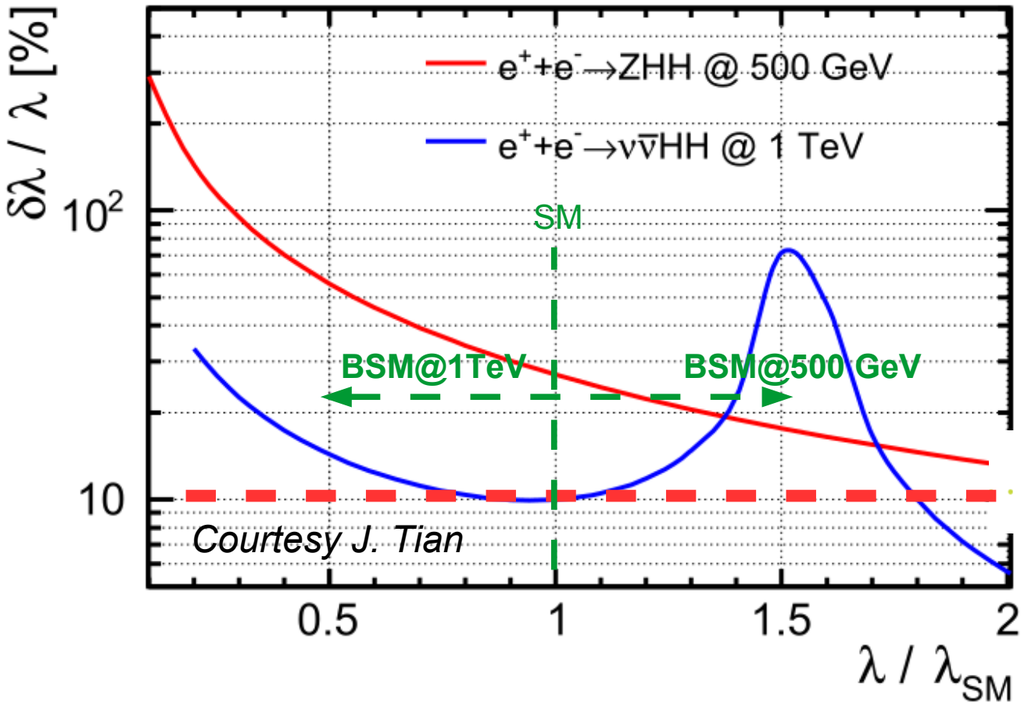
Deviations of λ from SM Value

- New (bosonic) particle may modify λ and enable 1st order phase transition
- Impact on measurements and achievable precisions of λ ?

Higgs self-coupling and new physics

Manifestation of new physics in observables and extracted results?



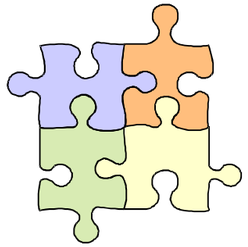


- Remarkable sensitivity of 500 GeV machine in case of large upward deviation
- 1 TeV machine superior for large upward and downward deviations

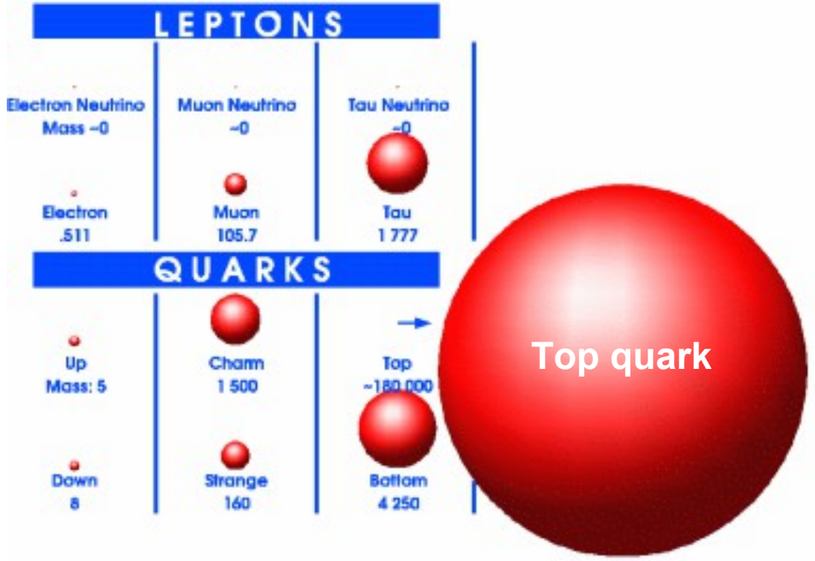
T. Tanabe, Higgs Coupling 2016

Science drivers

Elementary Scalar?

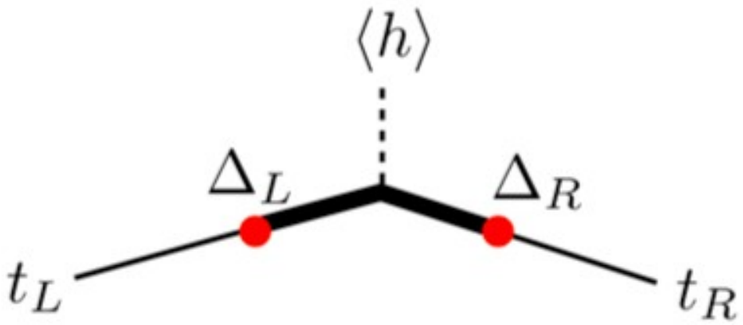


Composite object?



- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter

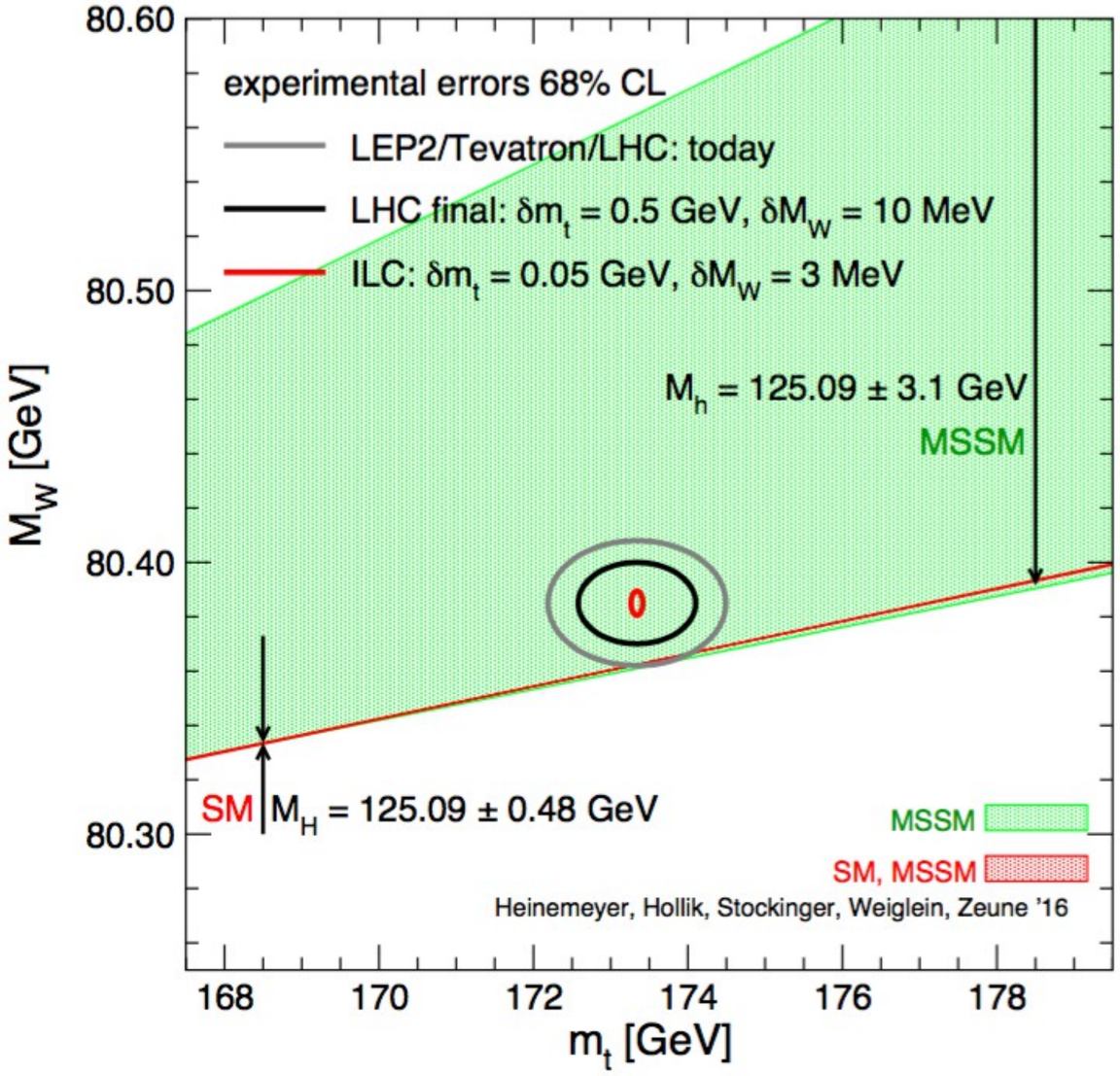
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?



Courtesy of S. Rychkov

- e+e- collider perfectly suited to decipher both particles

Top mass Higgs mass and BSM

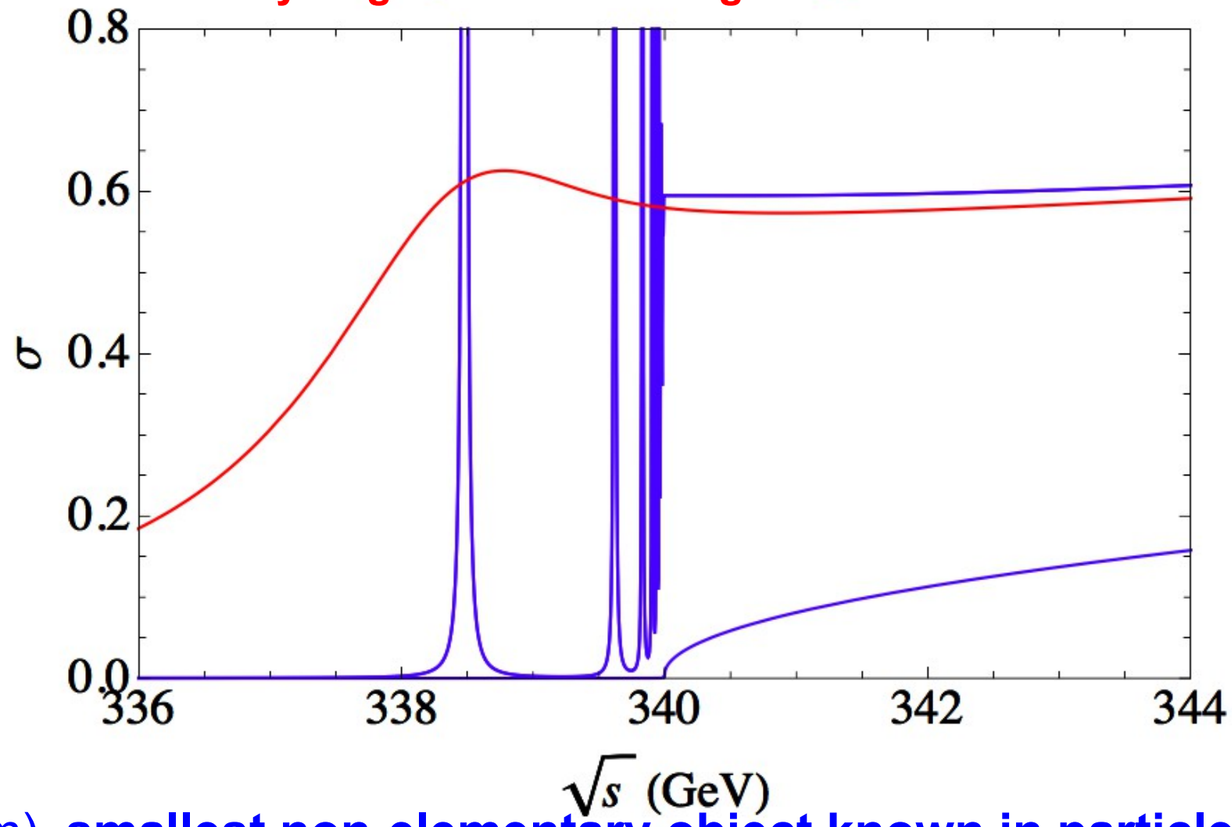


- Precise Top (and W) mass crucial to test compatibility of measured Higgs mass
- SM might not be sufficient to explain Higgs mass
- LHC may not reach sufficient discriminative power
- A lepton collider will for sure

Top pair production at threshold

"Bound states" at tt threshold

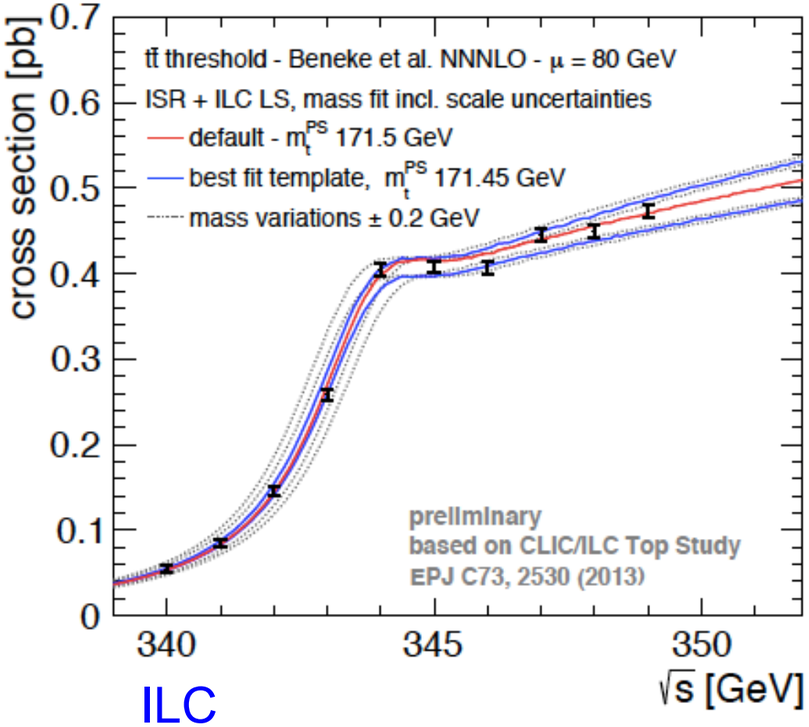
Hydrogen atom of strong interaction



- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

- Decay of top quark smears out resonances in a well defined way

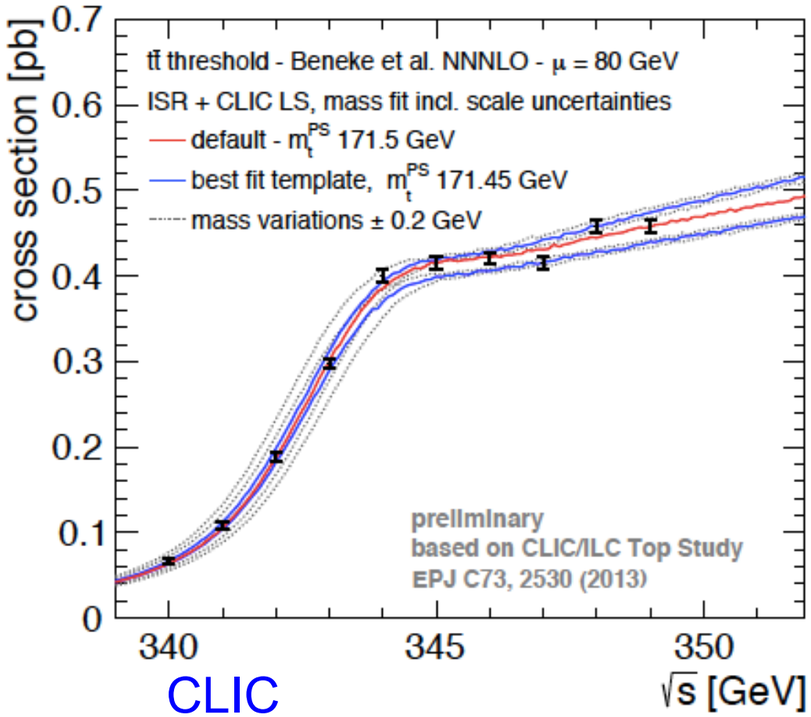
Top threshold scans at different e+e- colliders



ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)

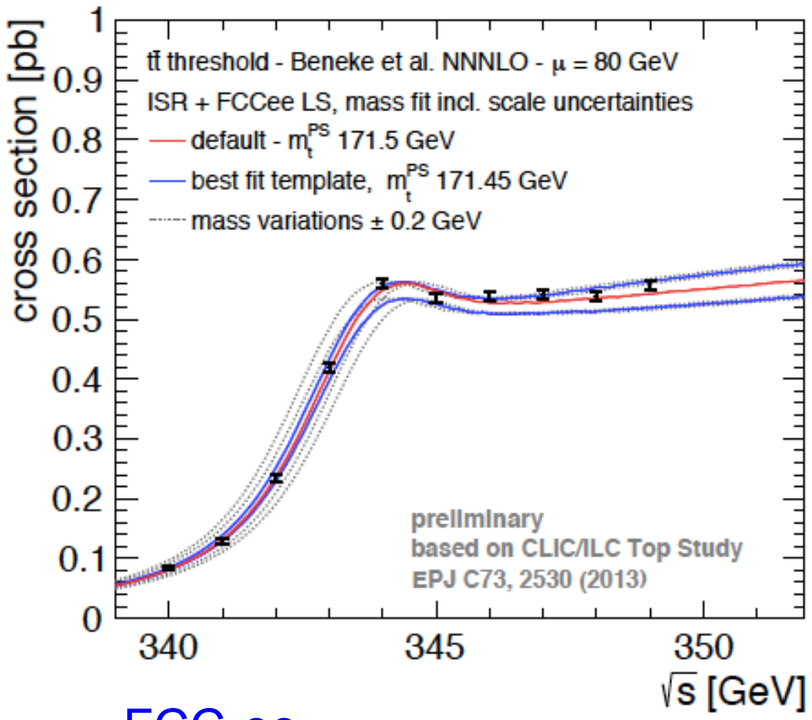
Scale uncertainty:
40 MeV



CLIC

Fit uncertainty:
31 MeV (21 MeV stat)

Scale uncertainty:
42 MeV



FCC-ee

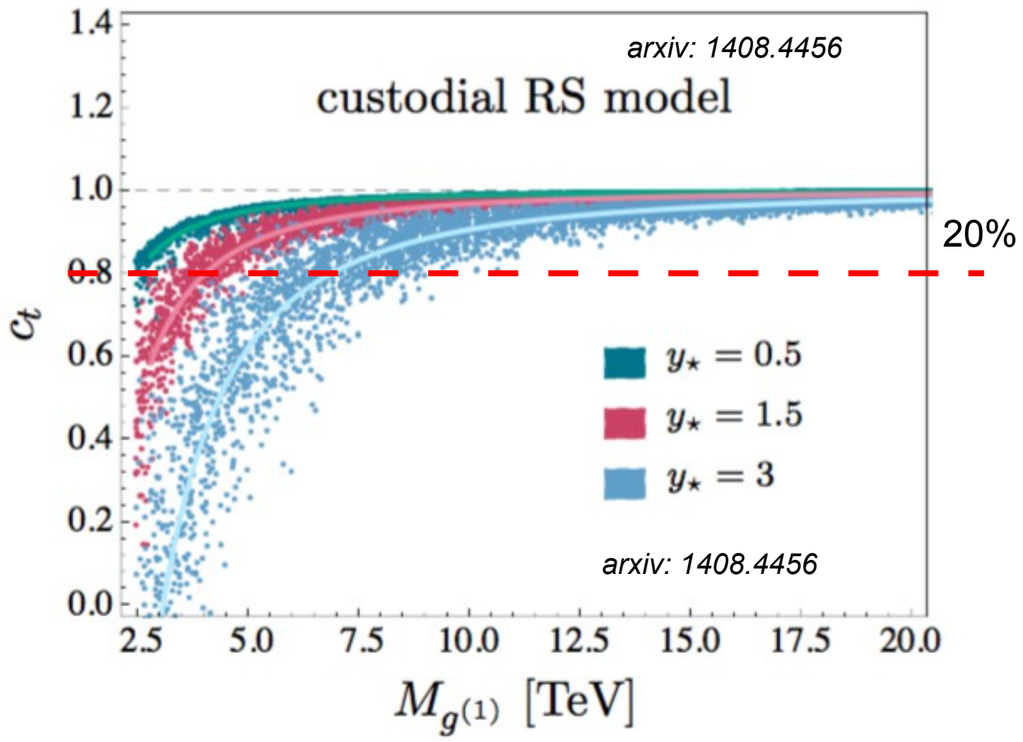
Fit uncertainty:
27 MeV (15 MeV stat)

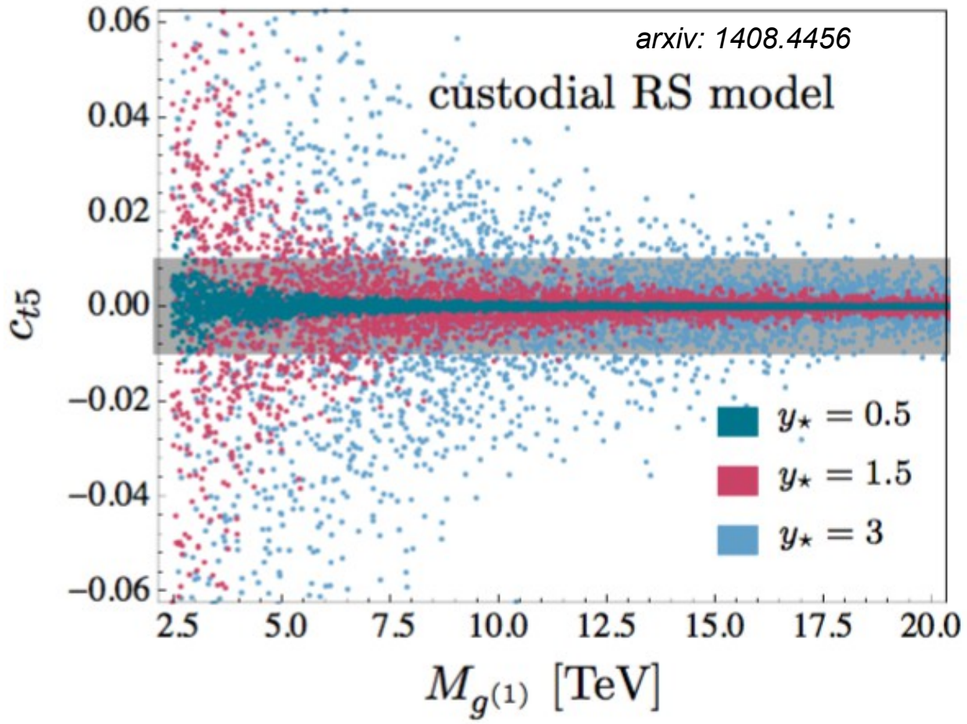
Scale uncertainty:
40 MeV

F. Simon Top@LC16

Top Yukawa Coupling and New Physics

Top-Higgs couplings in “presence” of heavy particles

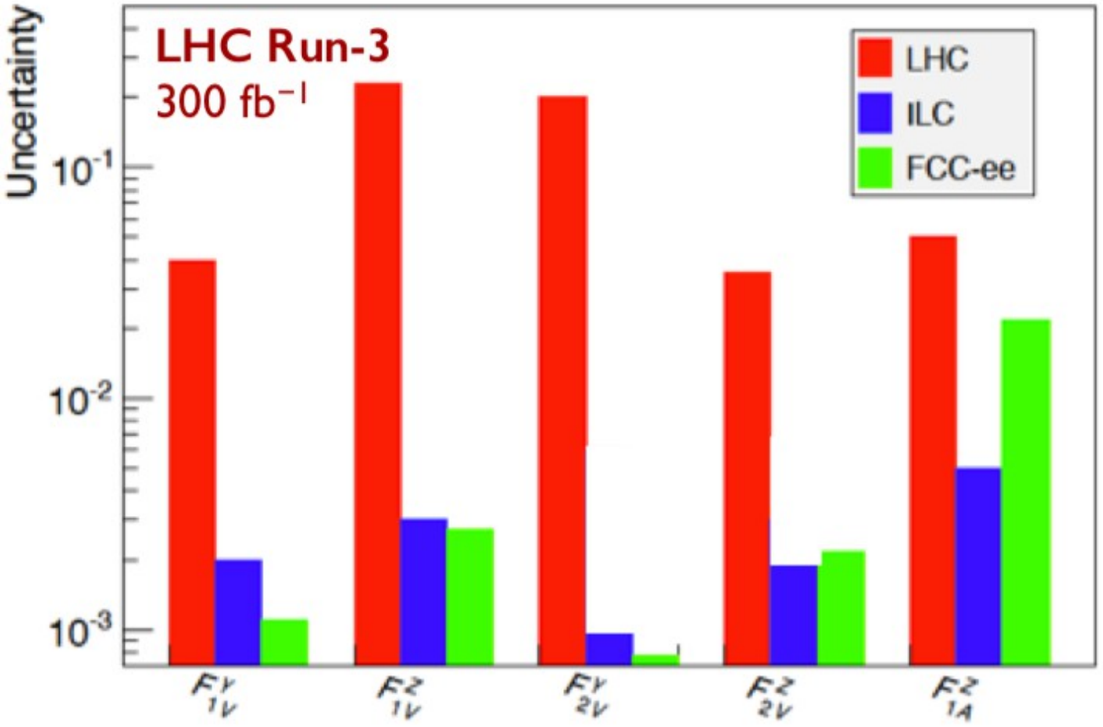




- Heavy particles, e.g. (Kaluza Klein) “duplicas” of SM particles provoke sizable effects
- Sensitivity to CP Violation !?

Electroweak top couplings

Accuracy on CP conserving couplings



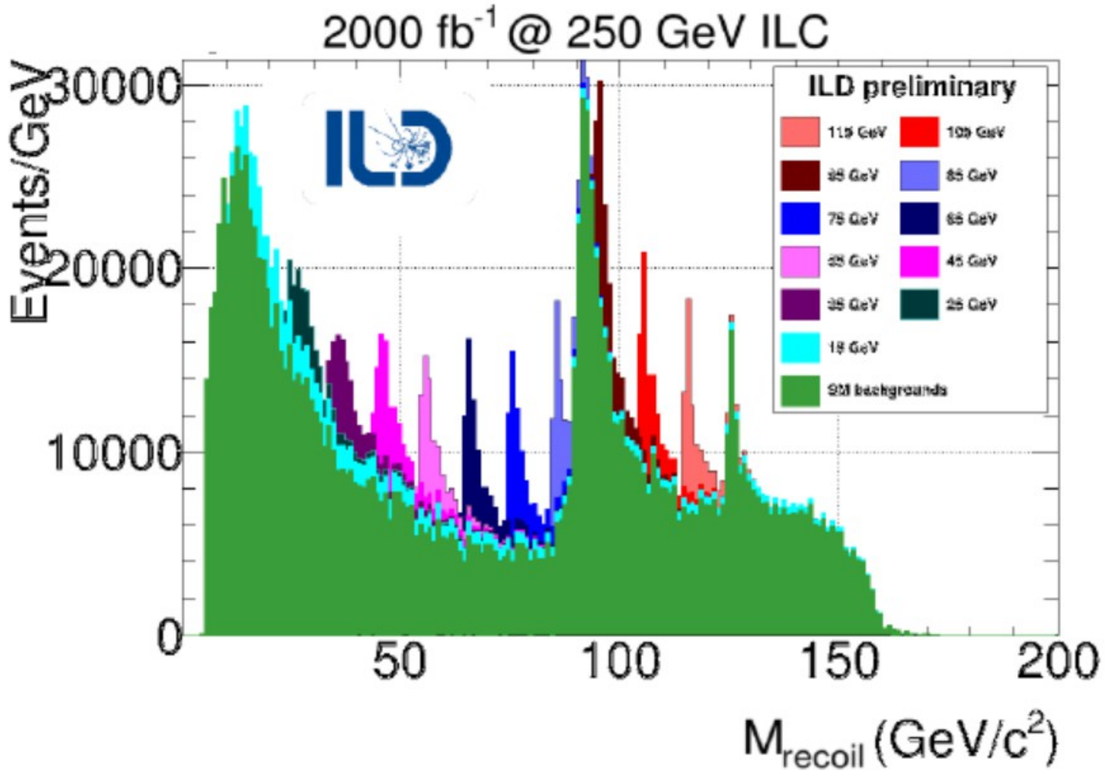
Arxiv:1503.01325
corrected for ILC values published in 1505.06020

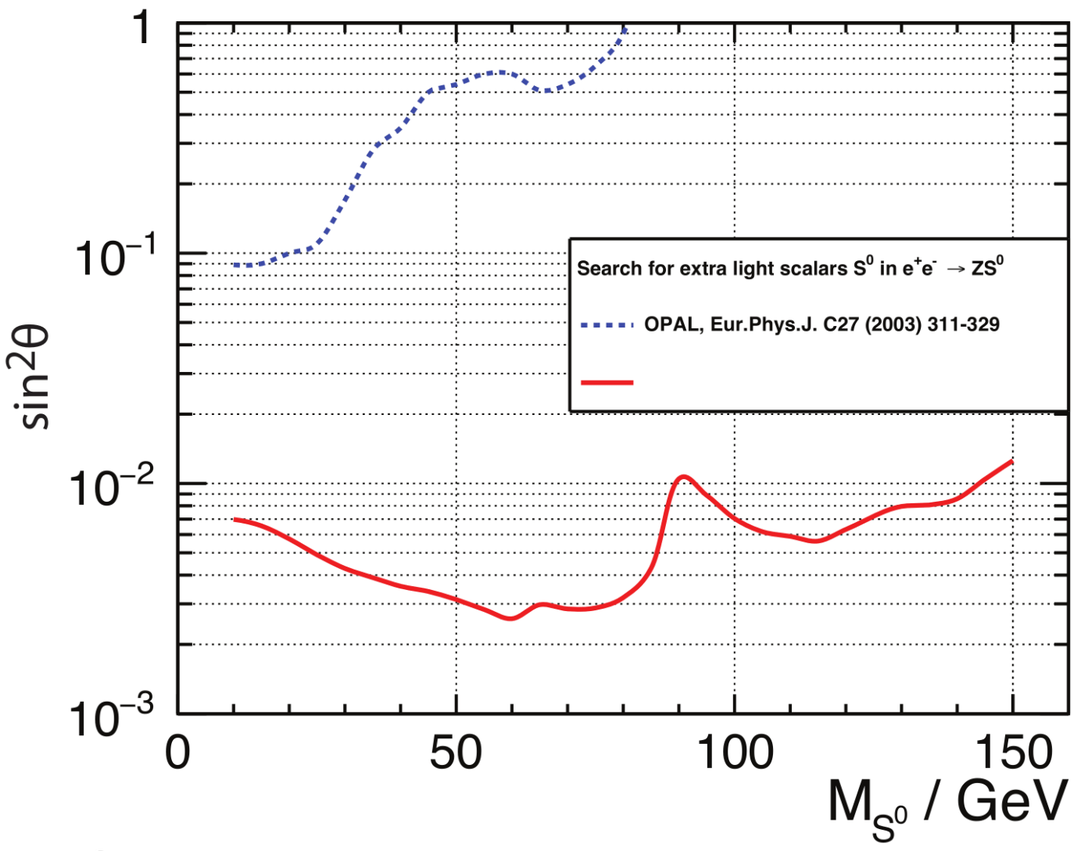
- e+e- collider might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV)
- Large disentangling of couplings for ILC thanks to polarised beams
- Final state analysis at FCCee
  - Also possible at LC => Redundancy
- Note
  - Maximal Lumi scenario for FCCee
  - Minimal Lumi scenario for ILC (~factor 4 possible with increased lumi and improved selection)

LC promises to be high precision machine for electroweak top couplings
EFT Analysis for CLIC predicts mass reaches well above 10 TeV

Light scalar study in ILD

Light scalar may be missing piece to trigger first order 1st transition and/or the being the radion in extra dimension theories

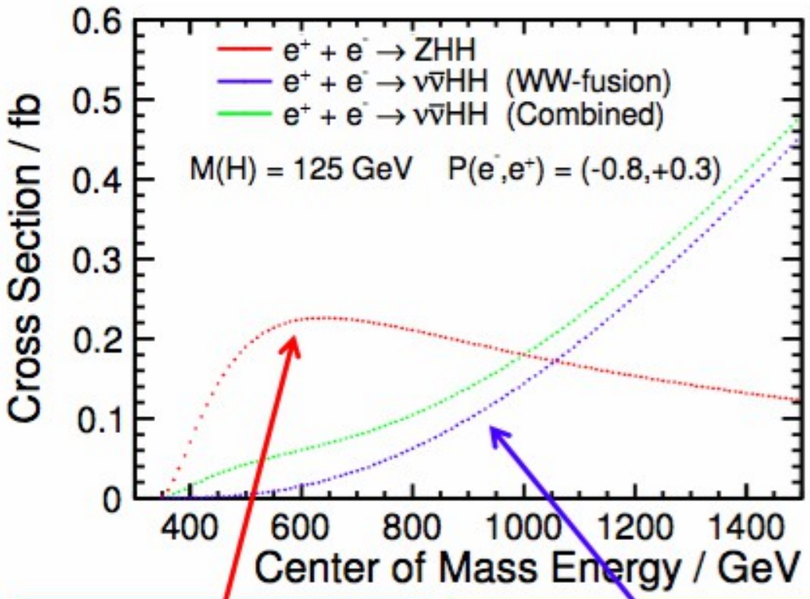


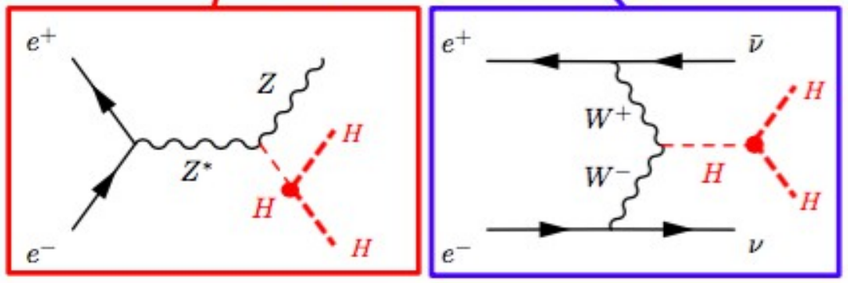


- New resonances cleanly dinstiguishable for large range of masses
- Sensitivity to mixing angle θh down to 10^{-2} (taking all relevant backgrounds into account)
- ⌊new scalar would count as “Feebly interacting Particle” (FIPS)

Higgs self-coupling – Precisions at LC

Cross section vs CM energy (e+e-)





Diagrams with triple-Higgs coupling

Expected precision based on **full detector simulation** studies:

ILC	ILC
500 GeV, 4 ab-1	500 GeV, 4 ab-1
δλ = 27%	& 1 TeV, 8 ab-1
	δλ = 10%

References:
J. Tian, LC-REP-2013-003
M. Kurata, LC-REP-2014-025
C. Duerig, Ph.D. thesis at DESY, 2016
HH→bbbb, bbWW* combination

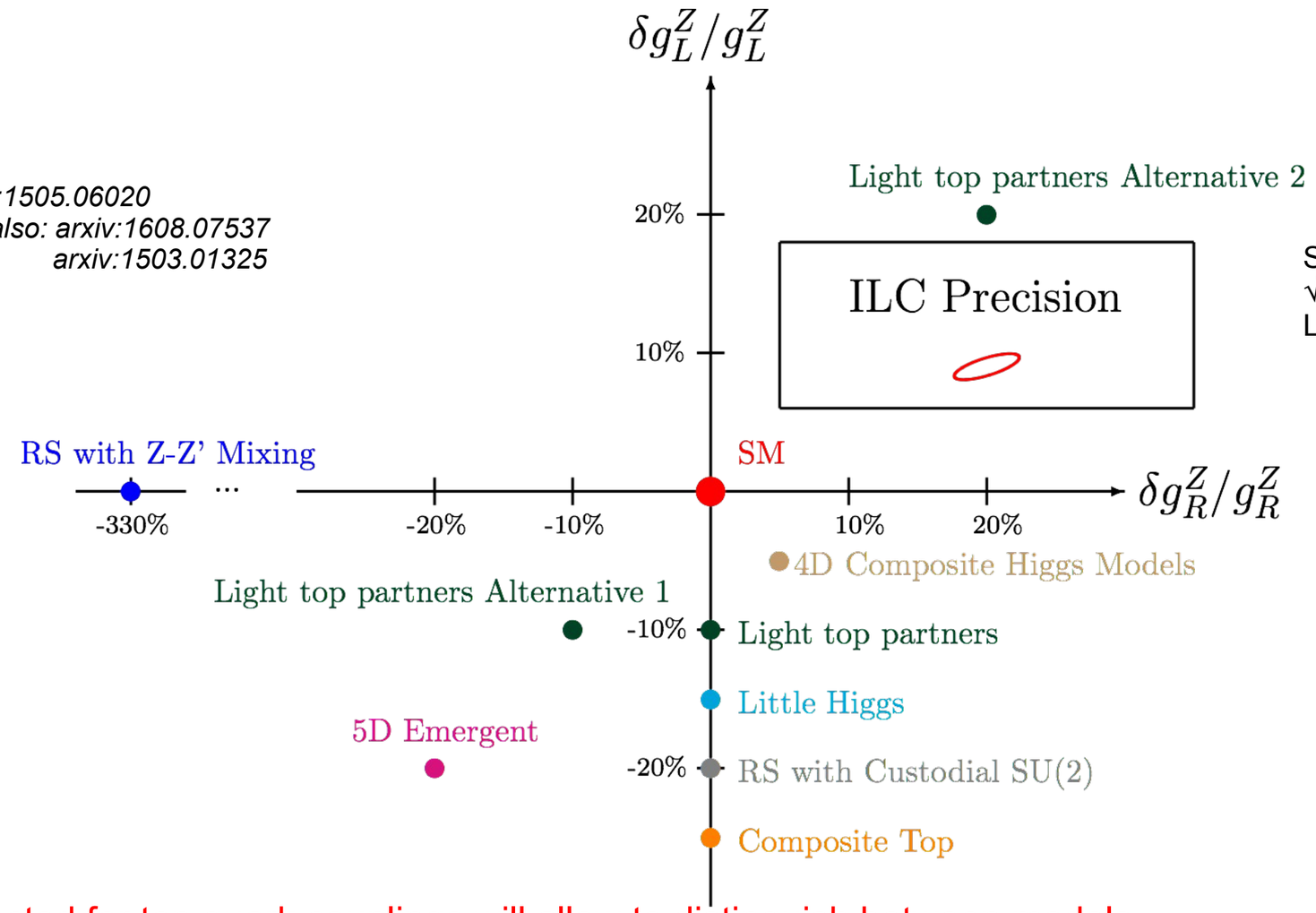
CLIC	CLIC
1.4 TeV, 1.5 ab-1	1.4 TeV, 1.5 ab-1
δλ = 21%	& 3 TeV, 2 ab-1
	δλ = 10%

References:
arXiv: 1307.5288
HH→bbbb only, upgrade in progress including bbWW*

Electroweak top couplings

Top is primary candidate to be a messenger new physics in many BSM models

arxiv:1505.06020
see also: arxiv:1608.07537
arxiv:1503.01325



Statistical error:
$\sqrt{s}$ ~ 500 GeV
L = 500 fb^{-1}

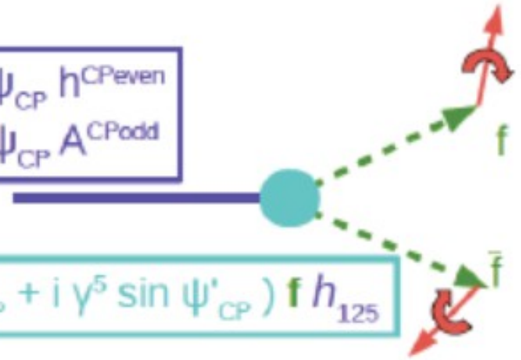
Precision expected for top quark couplings will allow to distinguish between models

Remark: All presented models are compatible with LEP elw. precision data

htautau

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

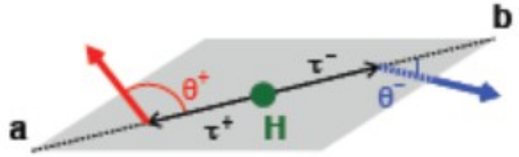
$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$

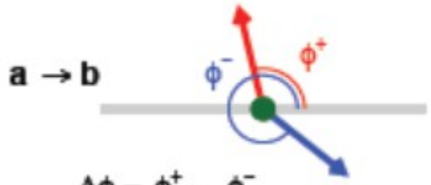


h is a spin 0 state:

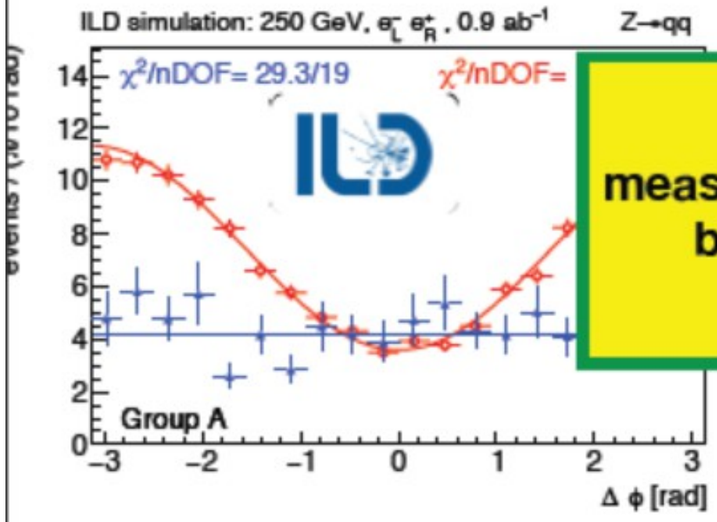
$|f\,\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\,|\downarrow\uparrow\rangle$

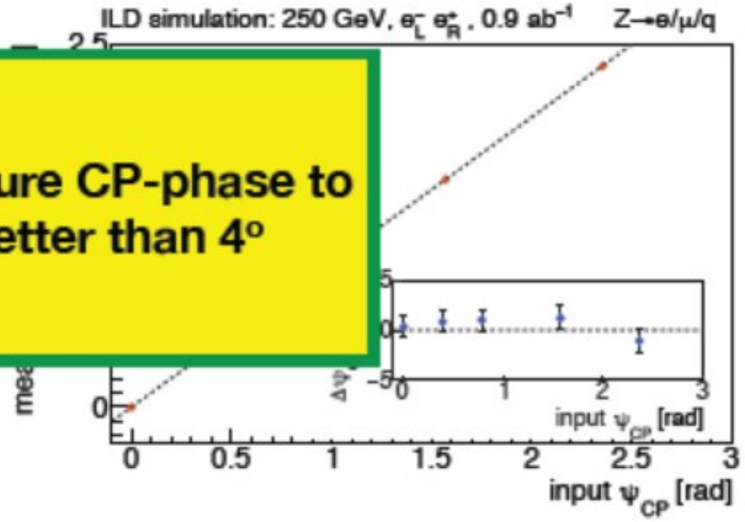
[ψ = 0 CP even, $\pi/2$ CP odd]





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





measure CP-phase to better than 4°

..and CPV in Zh coupling:

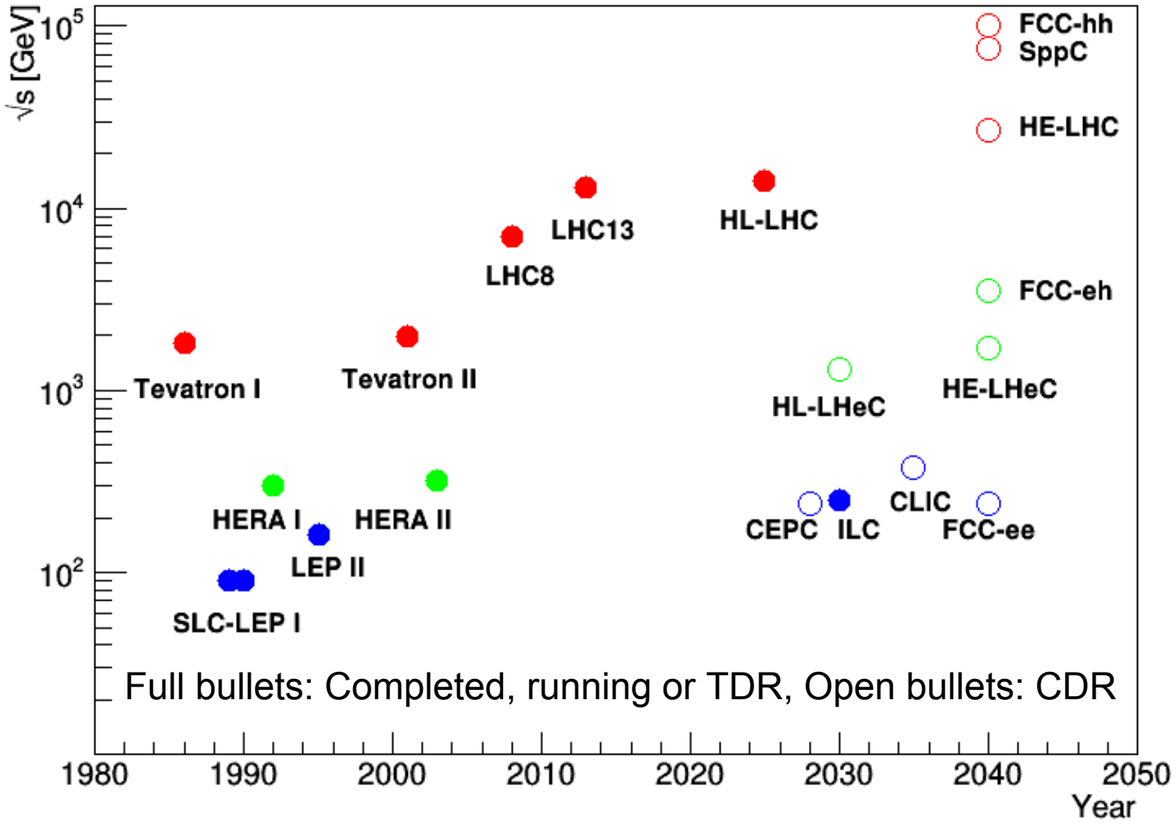
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

=> $\tilde{b}$ to ±0.005

arxiv:1804.01241

based on NIM A810 (2016) 51-58

e+e- machines (and others) - Readiness



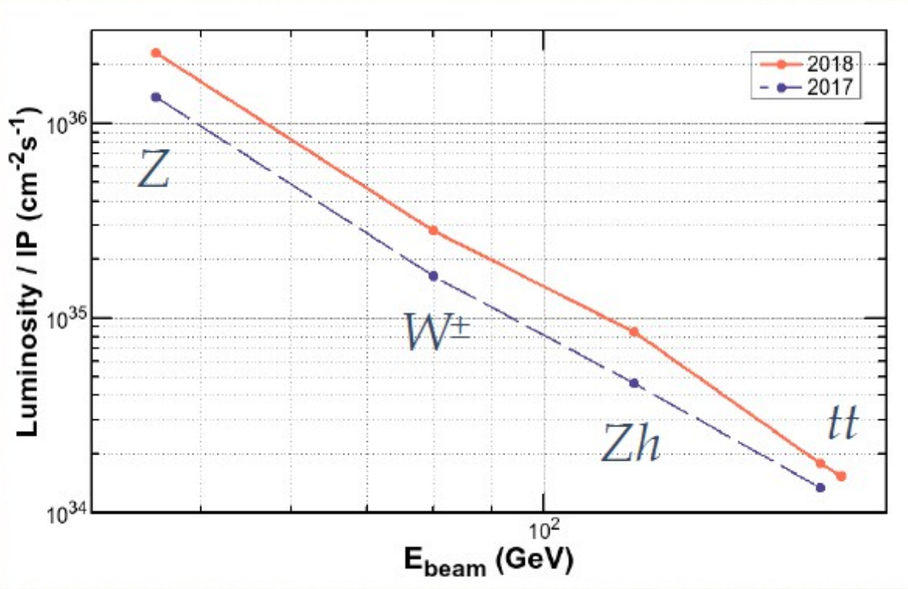
- ILC is the only machine that can be built now
  - European XFEL gives credbility for construction

ILC Parameters

			TDR		New
Center-of-mass energy	E_{CM}	GeV	250	500	250
Bunch population	N	e10	2	2	2
Bunch separation		ns	554	554	554
Beam current		mA	5.78	5.78	5.78
Number of bunches per pulse	Nb		1312	1312	1312
Collision frequency		Hz	5	5	5
Electron linac rep rate		Hz	10	5	5
Beam power (2 beams)	P_B	MW	5.26	10.5	5.26
r.m.s. bunch length at IP	σ_z	mm	0.3	0.3	0.3
relative energy spread at IP (e−)	σ_E/E	%	0.188	0.124	0.188
relative energy spread at IP (e+)	σ_E/E	%	0.15	0.07	0.15
Normalized horizontal emittance at IP	ε_{nx}	µm	10	10	5
Normalized vertical emittance at IP	ε_{ny}	nm	35	35	35
Beam polarization (e−)		%	80	80	80
Beam polarization (e+)		%	30	30	30
Beta function at IP (x)	β_x	mm	13	11	13
Beta function at IP (y)	β_y	mm	0.41	0.48	0.41
r.m.s. beam size at IP (x)	σ_x	nm	729	474	516
r.m.s. beam size at IP (y)	σ_y	nm	7.66	5.86	7.66
r.m.s. beam angle spread at IP (x)	θ_x	µr	56.1	43.1	39.7
r.m.s. beam angle spread at IP (y)	θ_y	µr	18.7	12.2	18.7
Disruption parameter (x)	Dx		0.26	0.26	0.51
Disruption parameter (y)	Dy		24.5	24.6	34.5
Upsilon (average)	Y		0.020	0.062	0.028
Number of beamstrahlung photons	n_γ		1.21	1.82	1.91
Energy loss by beamstrahlung	δ_{BS}	%	0.97	4.50	2.62
Geometric luminosity	Lgeo	e34/cm^{2}s	0.374	0.751	0.529
Luminosity	L	e34/cm^{2}s	0.82	1.79	1.35

FCC-ee Parameters

		Z	$W^{\pm}$	Zh	$t\bar{t}$	
Circumference	[km]	97.756				
Bending radius	[km]	10.760				
Free length to IP ℓ^*	[m]	2.2				
Solenoid field at IP	[T]	2.0				
Full crossing angle at IP	[mrad]	30				
SR power / beam	[MW]	50				
Beam energy	[GeV]	45.6	80	120	175	182.5
Beam current	[mA]	1390	147	29	6.4	5.4
Bunches / beam		16640	2000	328	59	48
Average bunch spacing	[ns]	19.6	163	994	2763[1]	3396[??]
Bunch population	[10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x	[nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y	[pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances	[deg]	60/60	60/60	90/90		
Momentum compaction	[10^{-6}]	14.8	14.8	7.3		
Arc sextupole families		208		292		
Horizontal β_x^*	[m]	0.15	0.2	0.3	1.0	
Vertical β_y^*	[mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ_x^*	[μm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ_y^*	[nm]	28	41	36	66	68
Energy spread (SR/BS)	[%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.196	0.150/0.192
Bunch length (SR/BS)	[mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.75/3.82	1.97/2.54
Crab sextupole ratio	[%]	97	87	80	50	50
Energy loss / turn	[GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency	[MHz]	400			400 / 800	
RF voltage	[GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Long. damping time	[turns]	1273	236	70.3	23.1	20.4
RF acceptance	[%]	1.9	2.3	2.3	3.5	3.36
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.4	
Synchrotron tune Q_z		-0.0250	-0.0506	-0.0358	-0.0818	-0.0872
Luminosity / IP	[10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55
Horizontal tune Q_x		269.139	269.124	389.129	389.104	
Vertical tune Q_y		269.219	269.199	389.199	389.175	
Beam-beam ξ_x/ξ_y		0.004/0.133	0.010/0.115	0.016/0.118	0.088/0.148	0.099/0.126
Lifetime by rad. Bhabha	[min]	68	59	38	37	40
Actual lifetime by BS	[min]	> 200	> 200	18	24	18



E. Levichev, FCC Week 2018

CEPC Parameters

	Higgs	*W*	*Z（3T）*	*Z（2T）*
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
Betatron tune ν_x/ν_y	363.10 / 365.22			
Synchrotron tune ν_s	0.065	0.0395	0.028	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	2.93	10.1	16.6	32.1

E. Levichev, Y. Wang
FCC Week 2018