FCC-ee Phenomenology

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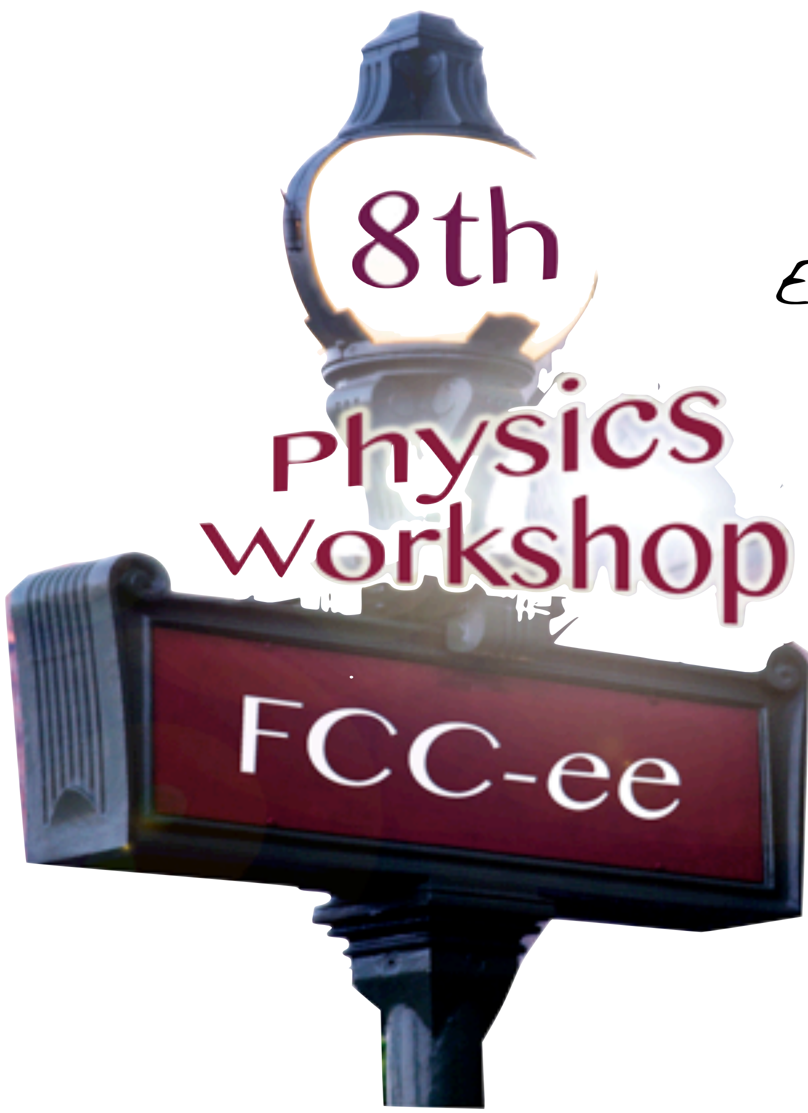

Eigth FCC-ee Physics Workshop

Paris, October 27-29, 2014

Rich physics perspectives for e^+e^- machines

TLEP (physics case) '13

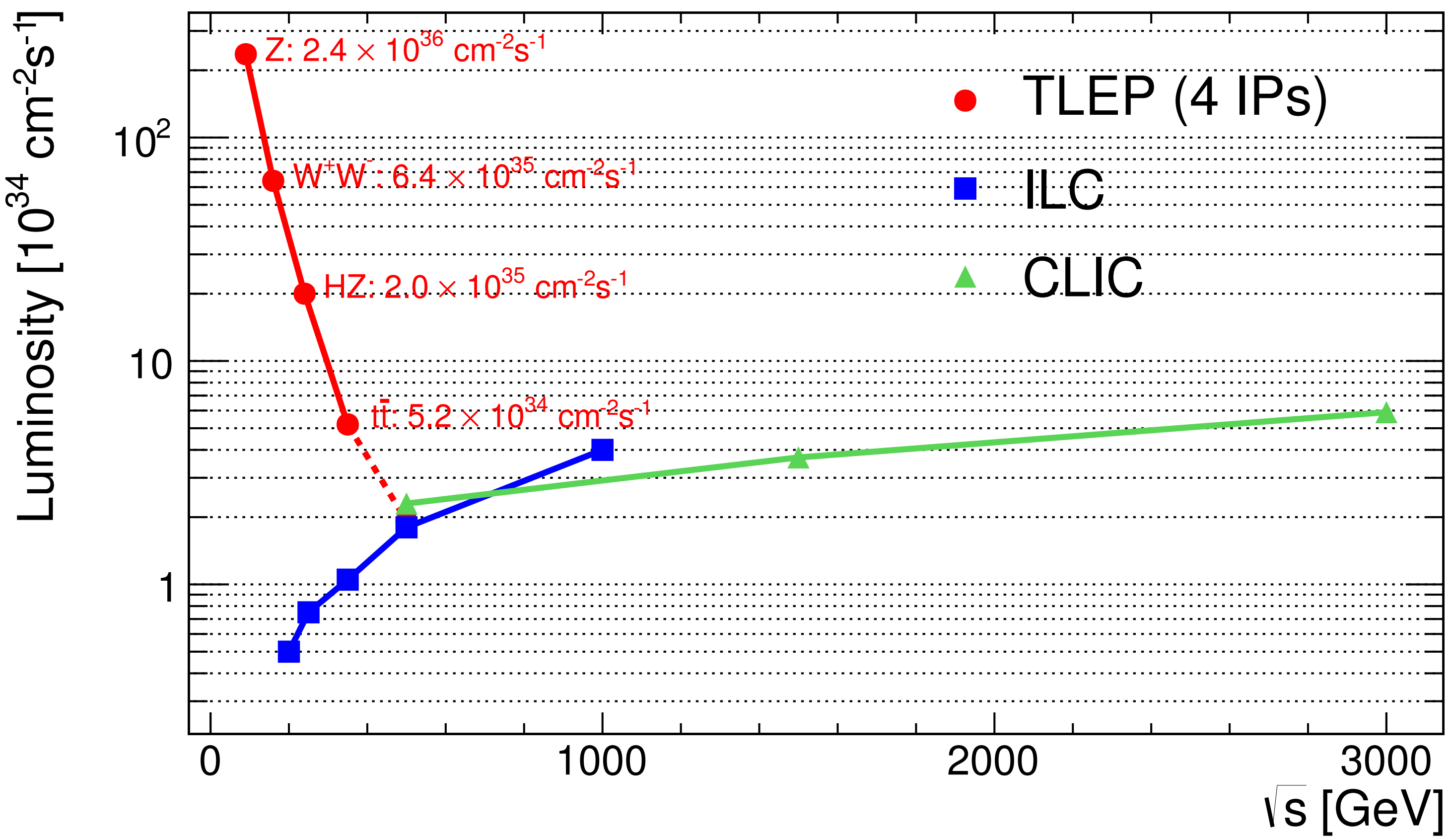

Figure 3. Instantaneous luminosity, in units of 10^{34} cm^{-2}s^{-1}, expected at TLEP (full red line), in a configuration with four interaction points operating simultaneously, as a function of the centre-of-mass energy. For illustration, the luminosities expected at linear colliders, ILC (blue line) and CLIC (green line), are indicated in the same graph. As explained in the text, the TLEP luminosity at each interaction point would increase significantly if fewer interaction points were considered. The possible TLEP energy upgrade up to 500 GeV, represented by a dashed line, is briefly discussed in section 5.

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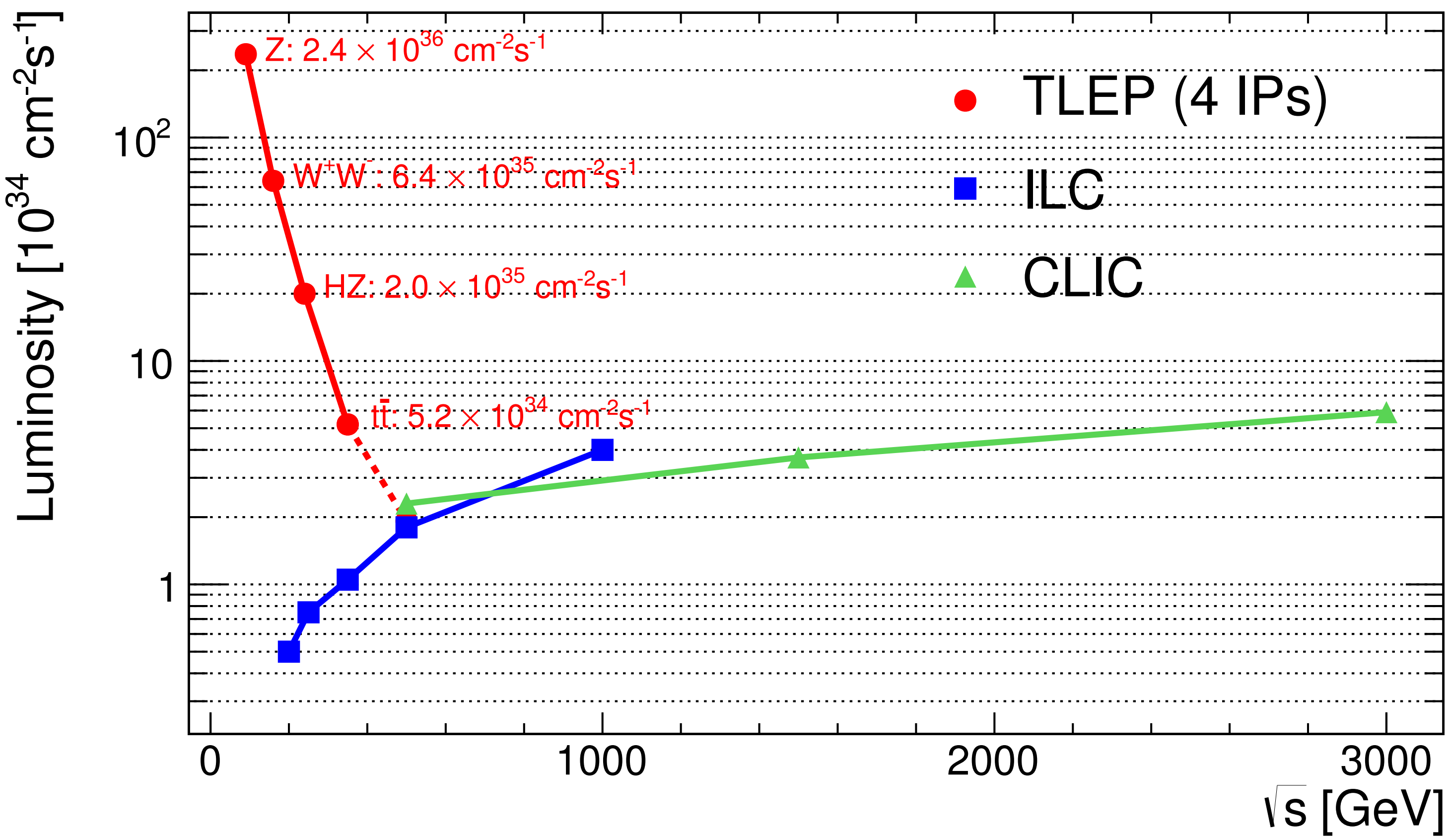

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What are the luminosity/energy good for?

- Higgs boson physics
- indirect search for new physics
- top quark physics

Rich physics perspectives for FCC machines

-- **Higgs physics:**
- precision studies
- higher-dimensional operators, composite Higgs
- rare and exotic decays
- multiple Higgs production
- extra Higgs bosons

-- **Interface with cosmology:**
- dark matter
- baryogenesis
- right-handed/(almost) sterile neutrinos

-- **New physics related to EWSB:**
- WW scattering
- supersymmetry
- extra dimensions
- composite models

-- **Rare flavour-changing processes:**
- Rare H decays
- Rare Z decays
- Rare top decays
- lepton-flavour violation

-- **Extensions of the SM:**
- extra vector-like fermions
- $SU(2)_R$ models
- leptoquarks

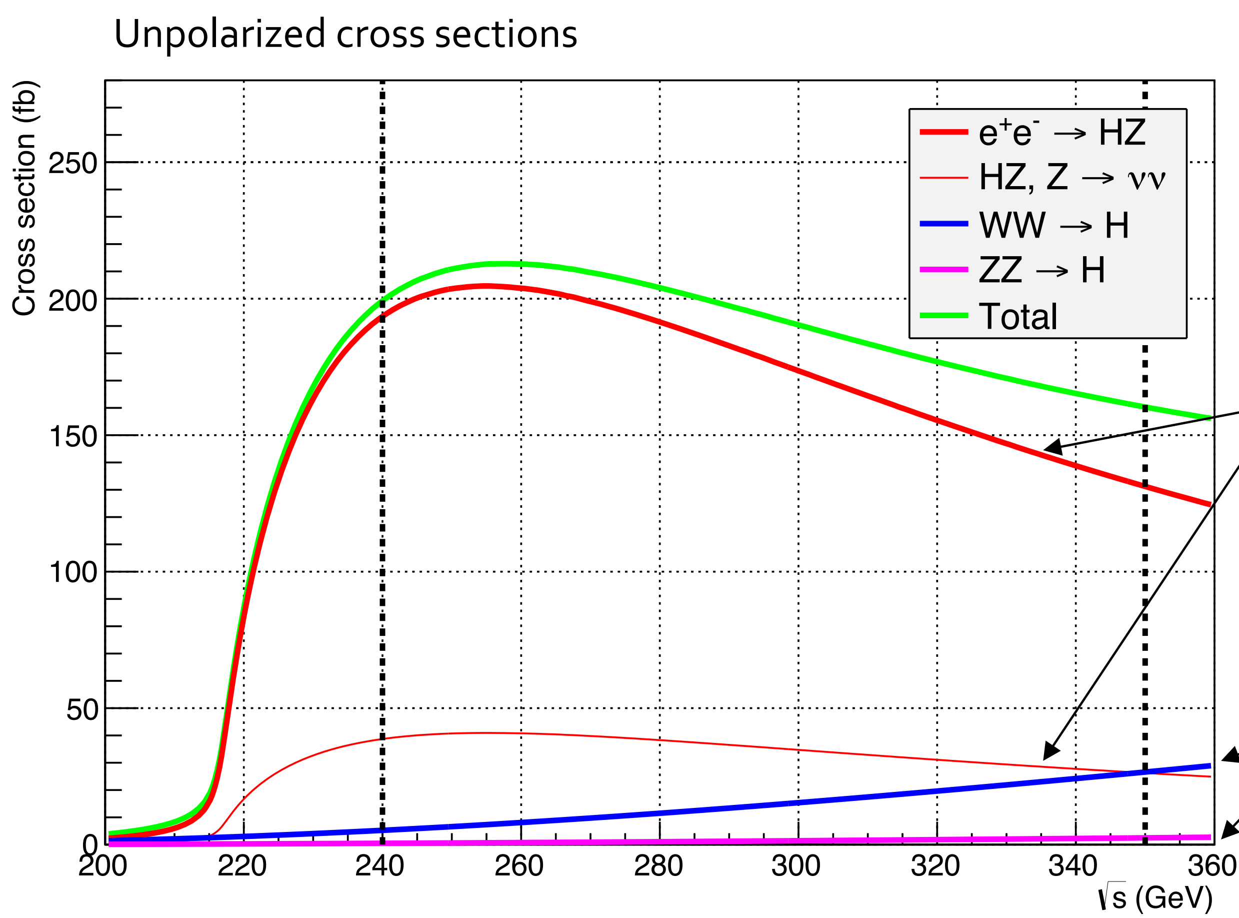
-- **QCD:**
- Perturbation theory
- Modelling final states

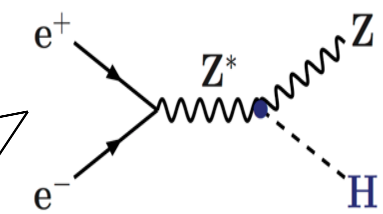
-- **EW/SM precision issues**
- parameter measurements (m_{top}, m_W)
- higher-order EW corrections
- triple and quadruple gauge boson (anomalous) couplings
- top (anomalous) couplings
- charm/bottom flavor studies

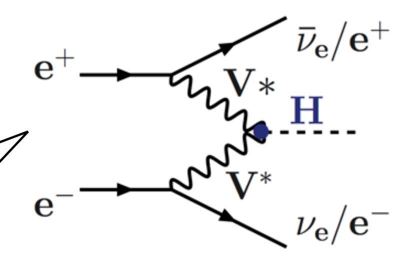
A good share
between
FCC-ee & FCC-hh

Higgs @ TLEP

TLEP (physics case) '13







	TLEP 240	ILC 250
Total Integrated Luminosity (ab^{-1})	**10**	0.25
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**	70,000
Number of Higgs bosons from boson fusion	**50,000**	3,000

	TLEP 240	ILC 250
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**	100%

TLEP = the ultimate Higgs factory

Higgs couplings measurement projections

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

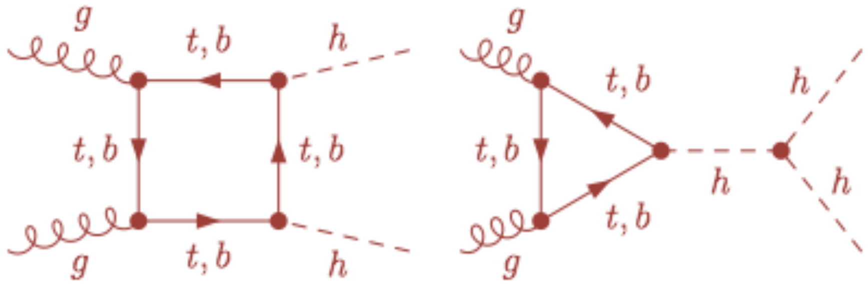
Rich experimental program of (sub)percent precision

TLEP has a unique subpermil precision in hZZ

(can be used to probe models of EW baryogenesis with a quantum induced first order phase transition!)

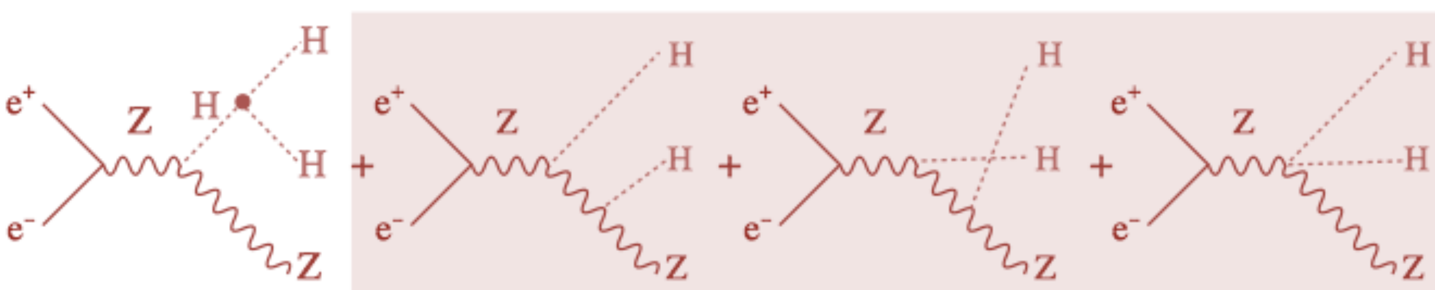
H^3 @ TLEP

- At LHC (Requires $E_{CM} > 2\, m_h$):



Dolan, Englert, Spannowsky

- At ILC (Requires $E_{CM} > 2\, m_h + m_Z$):



J. Tian, K. Fujii

Slides from M. McCullough, TLEP vidyo '14

H^3 @ TLEP

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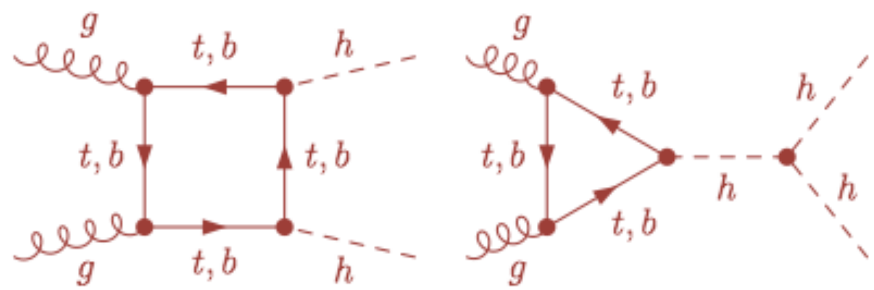

Dolan, Englert, Spannowsky

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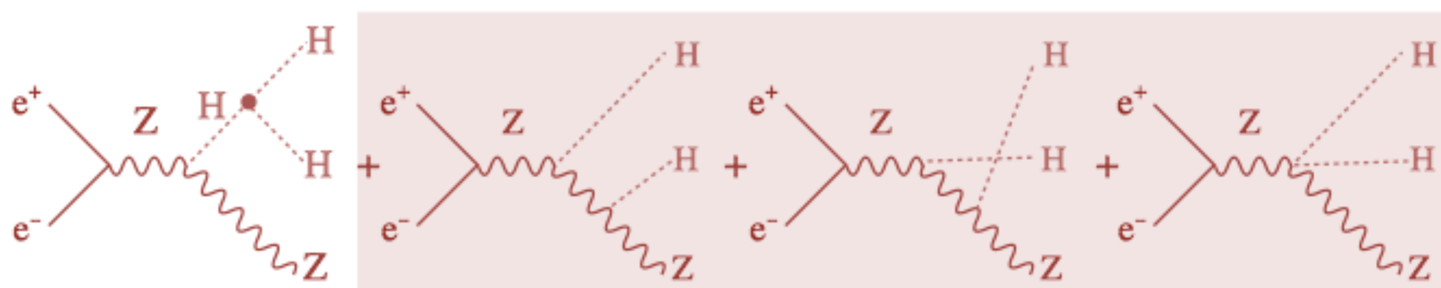

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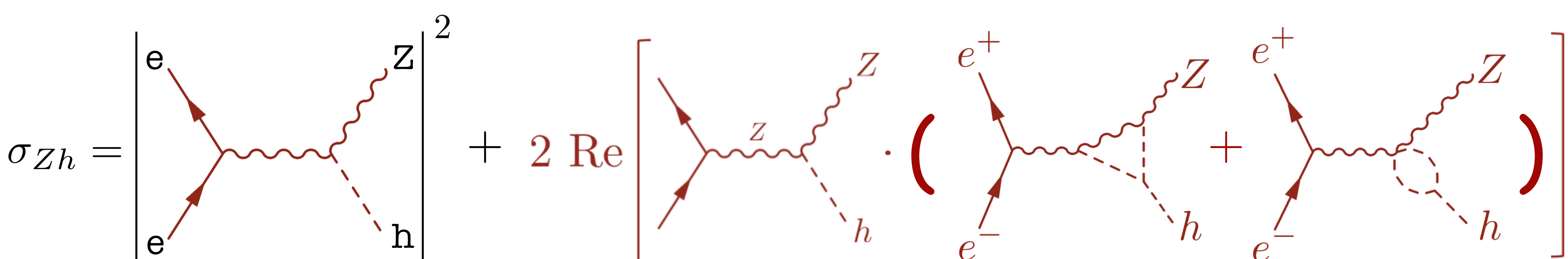
- At TLEP 240 GeV: M. McCullough '14



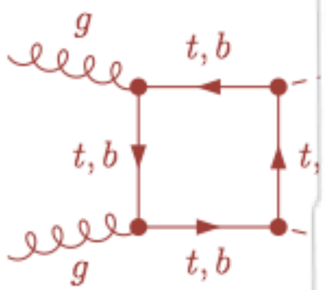
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh (0.05%)

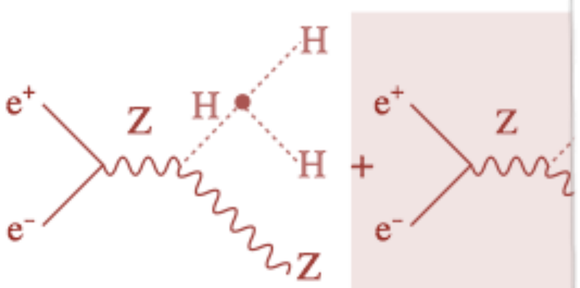
H^3 @ TLEP

Slides from M. McCullough, TLEP vidyo '14

- At LHC (Requi



- At ILC (Requir



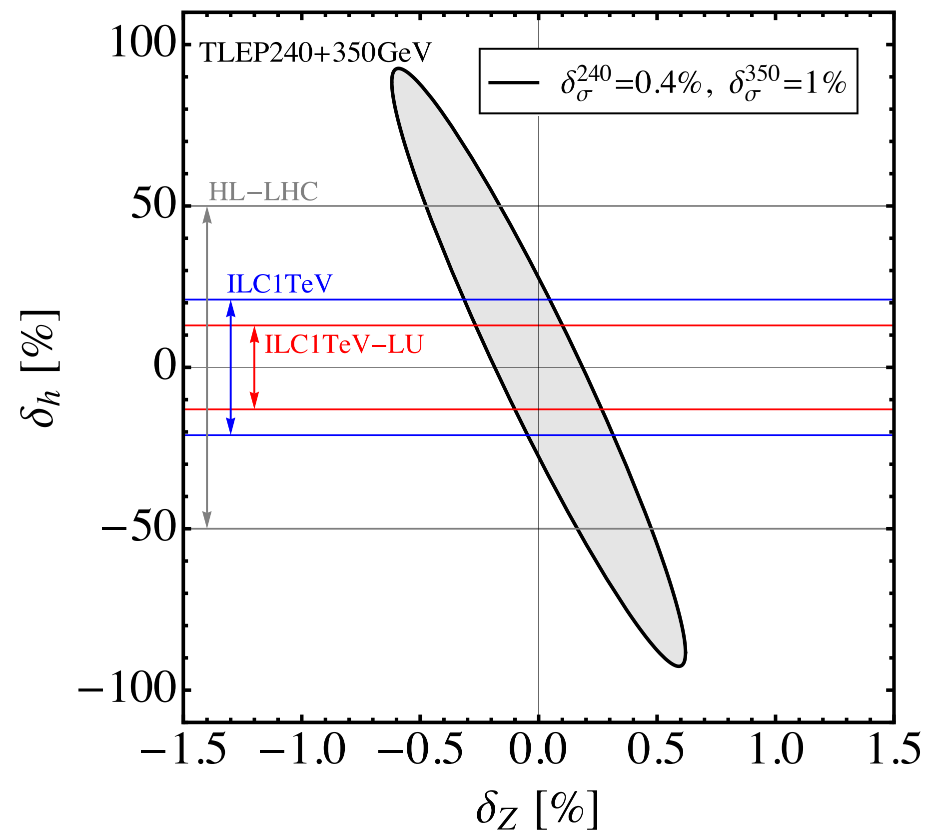
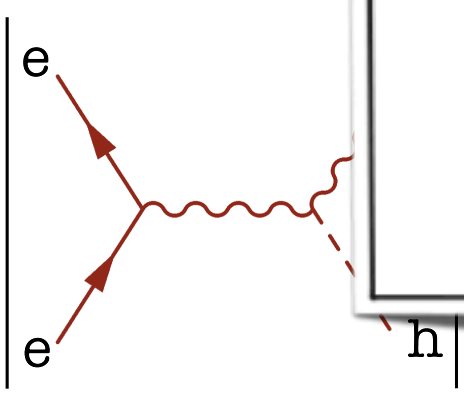
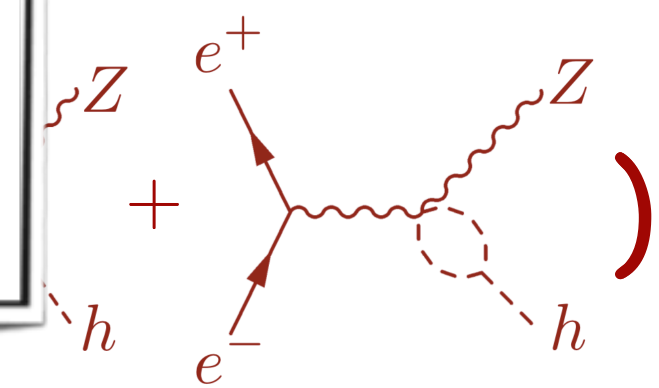


FIG. 3: Indirect 1σ constraints possible in $\delta_Z - \delta_h$ parameter space by combining associated production cross section measurements of 0.4% (1%-estimated) precision at $\sqrt{s} = 240$ GeV, (350 GeV) in solid black. It should be kept in mind that for large values of $|\delta_h|$ this ellipse can only be considered qualitatively as the calculation is only valid to lowest order in δ_h. The different axes scales should also be noted. Direct constraints possible at the high luminosity LHC and 1 TeV ILC (with LU denoting luminosity upgrade) are also shown for comparison. Lines are drawn to emphasize that direct constraints do not suffer from uncertainty in the hZZ coupling.

- At TLEP 240 (

$\sigma_{Zh} =$





$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh (0.05%)

Open issues for Higgs @ TLEP

- Access to light quark couplings via rare decays, e.g. $h \rightarrow J/\Psi+\gamma$ or $h \rightarrow \Phi+\gamma$?
  See Y. Soreq's talk
- Access to electron coupling? See D. d'Enterria's talk
- Complementarity with EW precision data and Anomalous gauge couplings?
  See A. Falkowski's talk
- Probing CP-odd couplings?
- Probing invisible Higgs decay, e.g. for Dark Matter Higgs portals?
- Estimating the sensitivity on flavor-violating Higgs decay, e.g. $h \rightarrow \tau+\mu$?

Physics with Large statistics

- 10^{12} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^{8} W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks $\Rightarrow$ >20'000 $B_s \rightarrow \tau^+\tau^-$
- TLEP@340/500: 10^{6} top pairs (pole mass, probe FCNC decays, top Yukawa)

The benefit of being precise

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's

TLEP (physics case) '13

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Ratio TLEP/LEP
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6)	< 100	20
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10)	< 100	20
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	25
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004	
N_ν	... and sterile ν's	2.92 ± 0.05	Zγ, 161 GeV	0.0010 (12)	< 0.001	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	10
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	100
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)	< 0.5	3
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12)	< 10	100

Table 9. Selected set of precision measurements at TLEP. The statistical errors have been determined with *(i)* a one-year scan of the Z resonance with 50% data at the peak, leading to 7×10^{11} Z visible decays, with resonant depolarization of single bunches for energy calibration at O(20min) intervals; *(ii)* one year at the Z peak with 40% longitudinally-polarized beams and a luminosity reduced to 20% of the nominal luminosity; *(iii)* a one-year scan of the WW threshold (around 161 GeV), with resonant depolarization of single bunches for energy calibration at O(20min) intervals; and *(iv)* a five-years scan of the $t\bar{t}$ threshold (around 346 GeV). The statistical errors expected with two detectors instead of four are indicated between brackets. The systematic uncertainties indicated below are only a "first look" estimate and will be revisited in the course of the design study.

Measurements of EW observables improved by ~20÷30 @TLEP/now

➠ oblique parameters (S,T,W,Y) uncertainty better by same amount (ILC/now≈2÷3)

Would be important to present a prospective full EW fit!

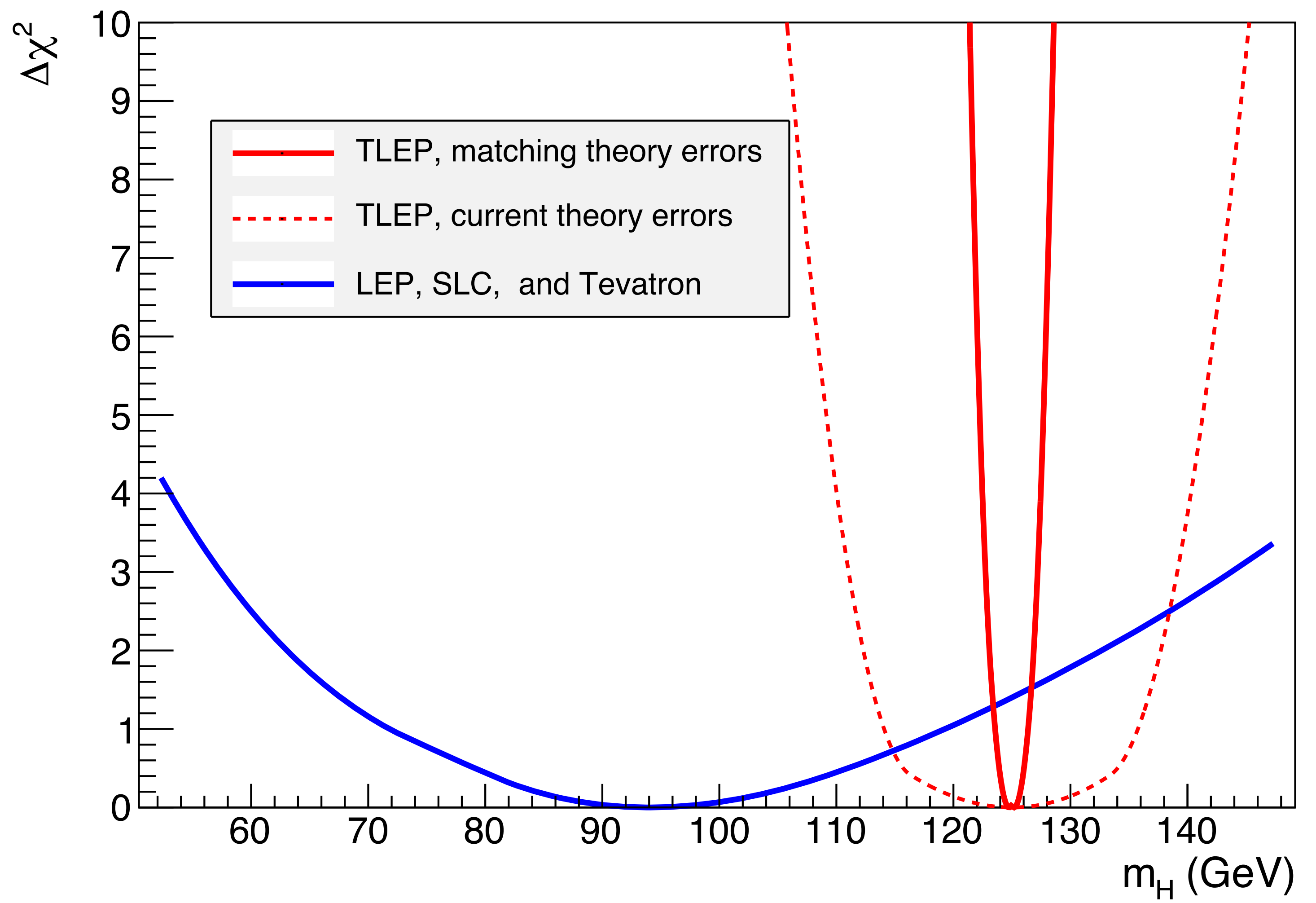
Can we improve the systematics uncertainties?

The benefit of being precise

The measurements of today give the input parameters of tomorrow

e.g. a precise Higgs mass measurement needed for the Higgs couplings measurements

Δm_H = 200 MeV shifts prediction for BR($H \to VV$) by 2%



TLEP (physics case) '13

W mass and New Physics

See S. Heinemeyer's talk

In the SM, W mass is "predicted"
in terms of Z mass, G_F, α_{em}...

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

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Any deviation (if the TH uncertainty can be kept under control) tests NP

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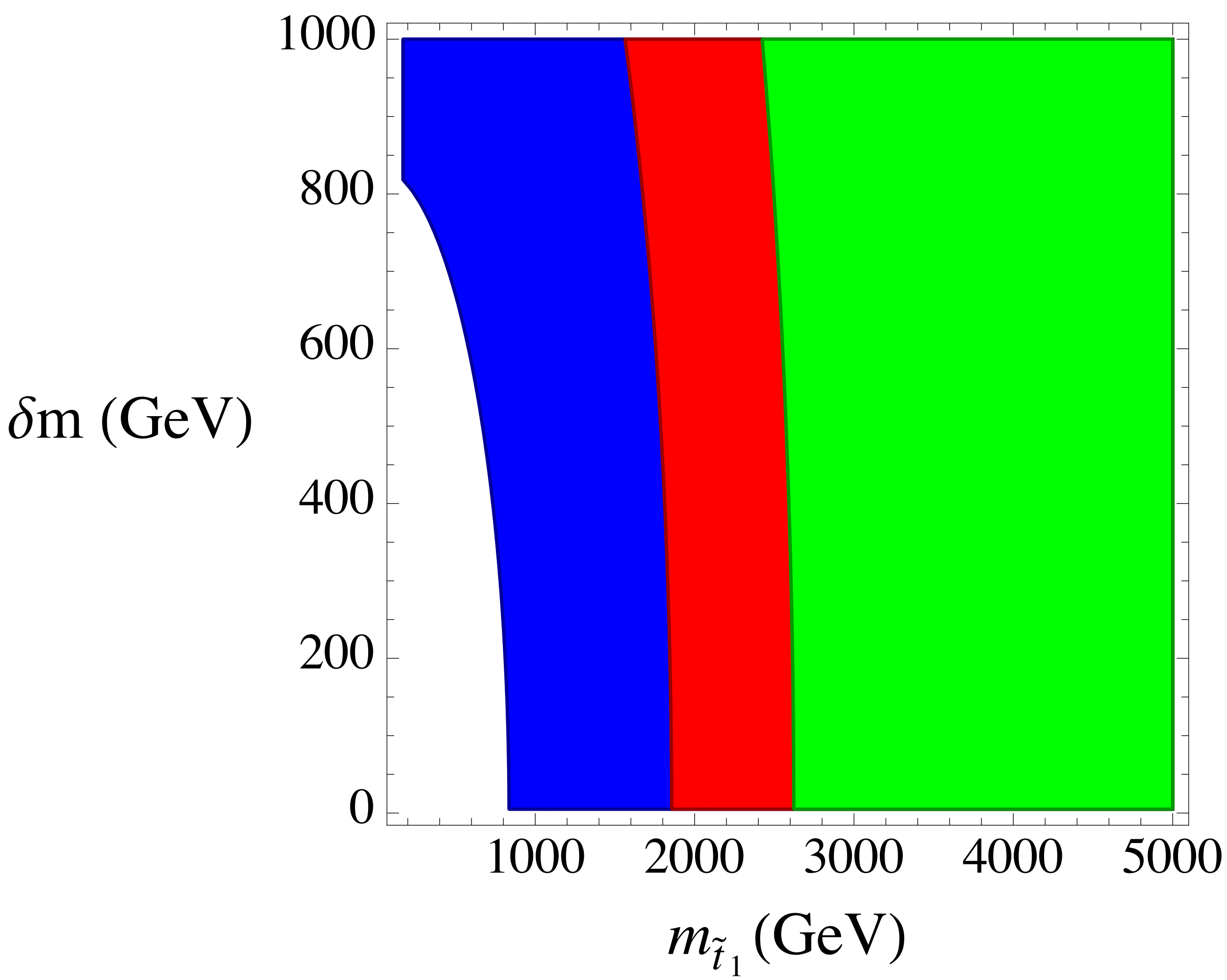

Probing MSSM stops

$\delta m_W < 5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 850\,\mathrm{GeV}$

$\delta m_W < 1\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 1.9\,\mathrm{TeV}$

$\delta m_W < 0.5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 2.6\,\mathrm{TeV}$

TLEP (physics case) '13

Top couplings as a NP discriminator

ILC physics WG '14

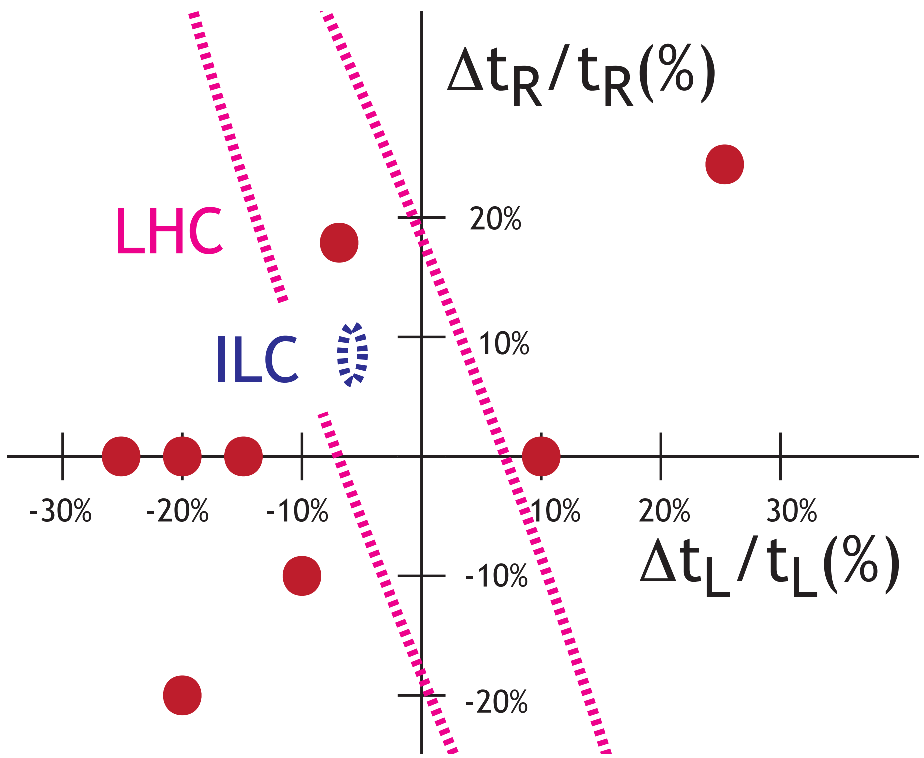

Figure 9: The heavy dots display the shifts in the left- and right-handed top quark couplings to the Z boson predicted in a variety of models with composite Higgs bosons, from Ref. [31]. The ellipses show the 68% confidence regions for these couplings expected from the LHC [26] and the ILC [30].

Need to estimate the sensitivity in the ttZ couplings
@ 350GeV and 500GeV

The polarization of the initial beams is a big asset!