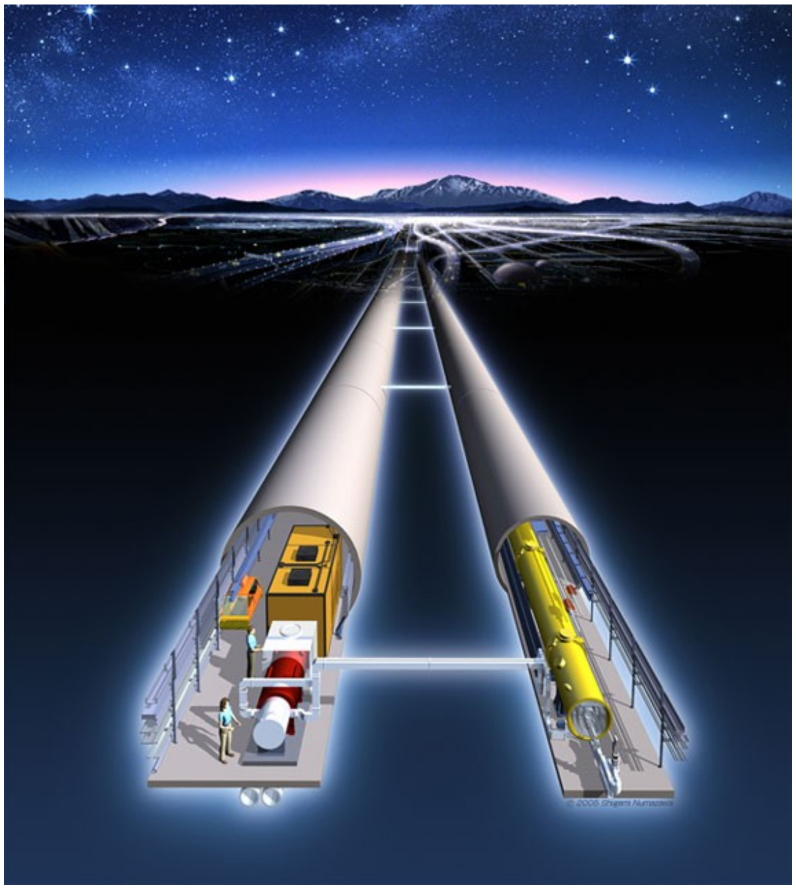
Top electroweak couplings at Linear Colliders



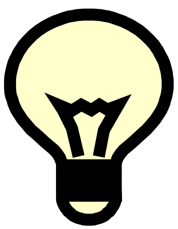
Roman Pöschl

On behalf of

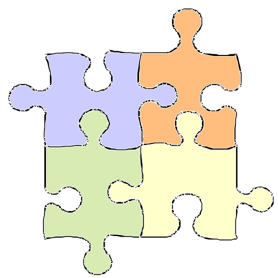
... and the ILD Detector Concept

Top@LC15 – Valencia/Spain July 2015

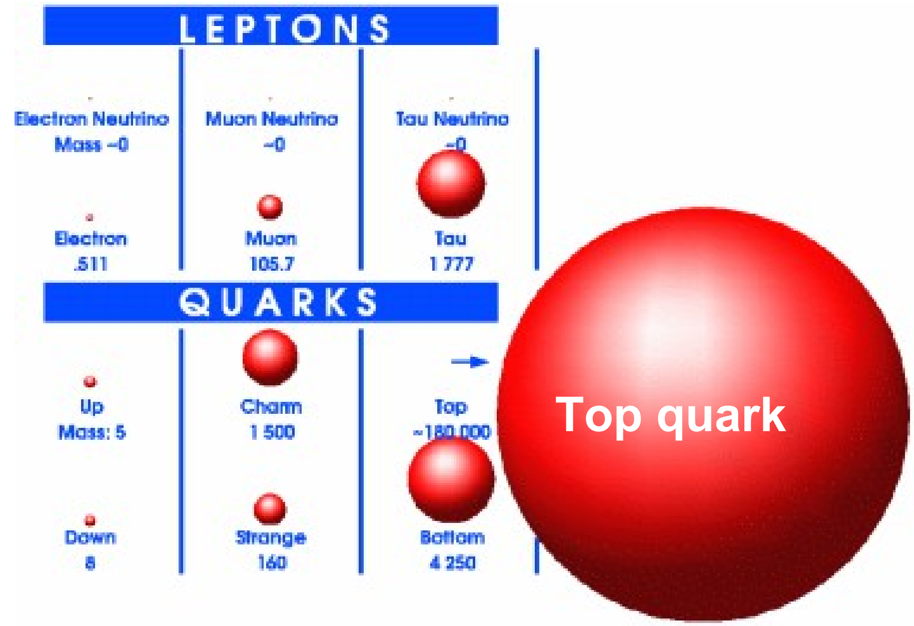
An enigmatic couple



Elementary Scalar?



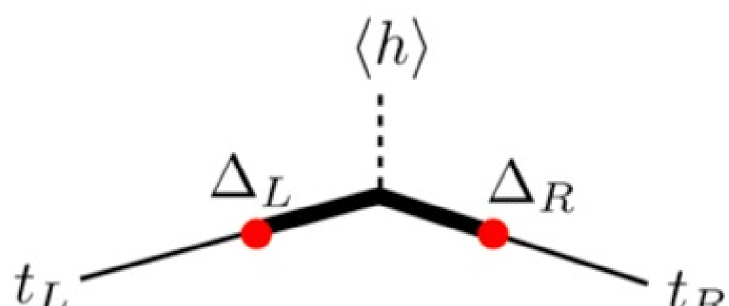
Composite object?



- 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?

- LC perfectly suited to decipher
  both particles

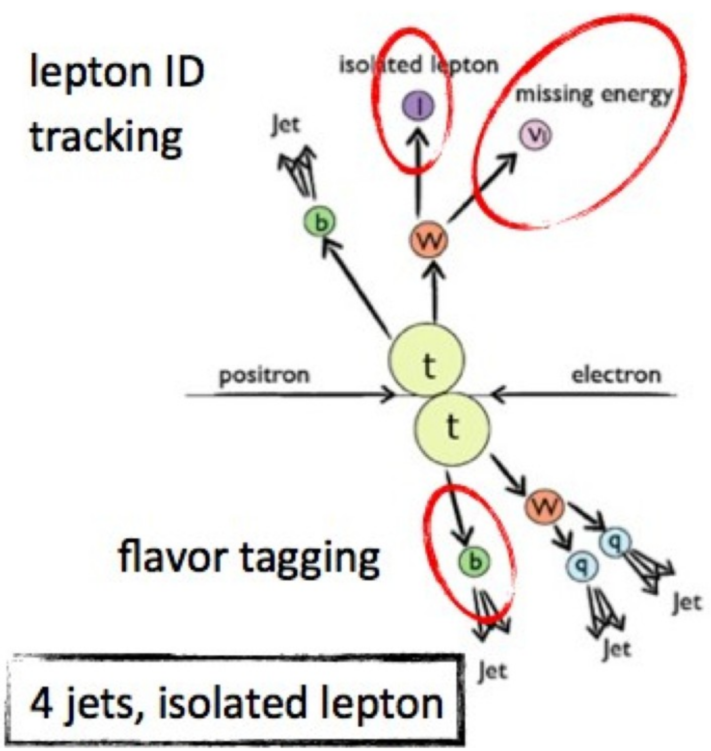


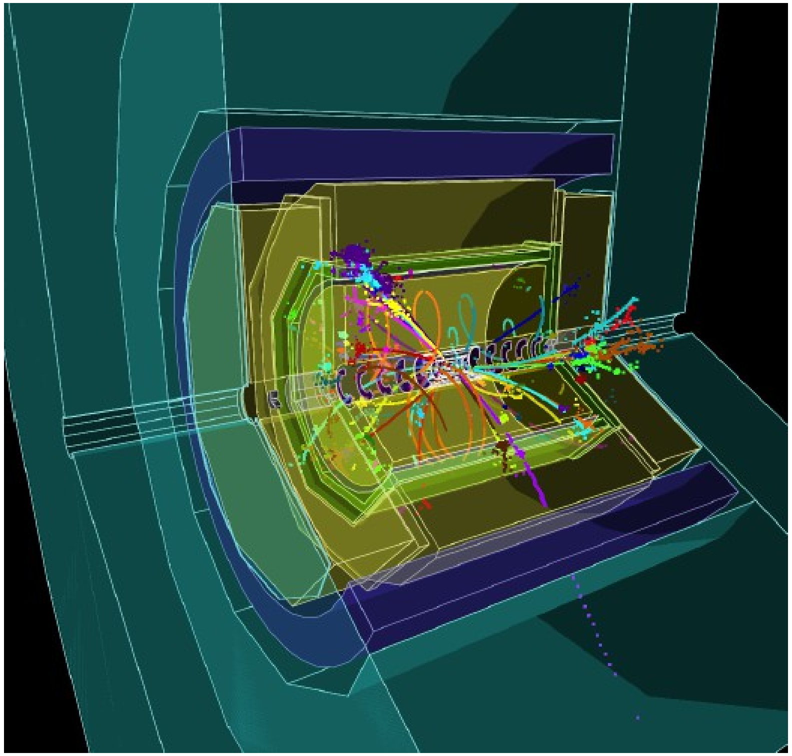
Courtesy of S. Rychkov

Elements of top quark reconstruction

Three different final states:
1) Fully hadronic (46.2%) → 6 jets
2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

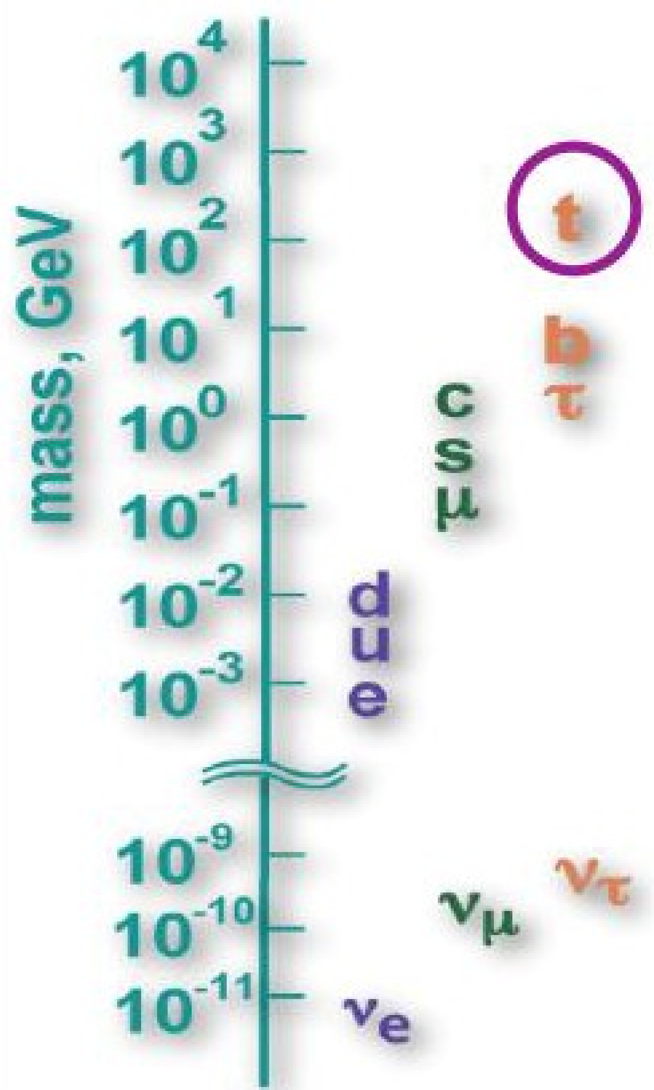
$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(b\ell\nu)$$





Final state reconstruction uses all detector aspects
Results shown in the following are based on full simulation of ILD Detector at $\sqrt{s}$ = 500 GeV

Top Quark and Flavor Hierarchy



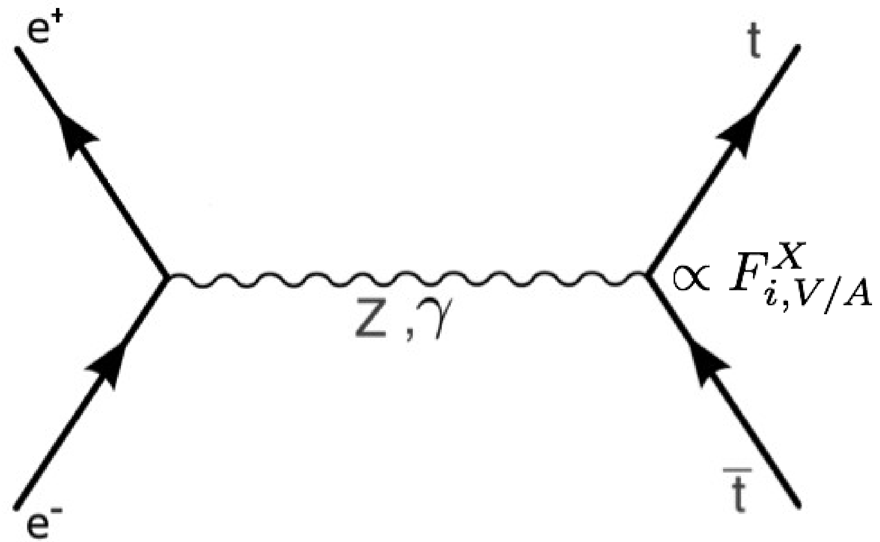
- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

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

- Expect residual effects for particles with masses closest to symmetry breaking scale
  - A_{FB} anomaly at LEP for b quark

Strong motivation to study chiral structure of top vertex in high energy e+e- collisions

Testing the Chiral Structure of the Standard Model



$$\Gamma^{ttX}_{\mu}(k^2, q, \overline{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}, \quad (2)$$

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

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

Disentangling

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

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

There exist a number of observables sensitive to chiral structure, e.g.

$$\sigma_I \qquad A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \qquad (F_R)_I = \frac{(\sigma_R)_I}{\sigma_I}$$

x-section | Forward backward asymmetry | Fraction of right handed top quarks

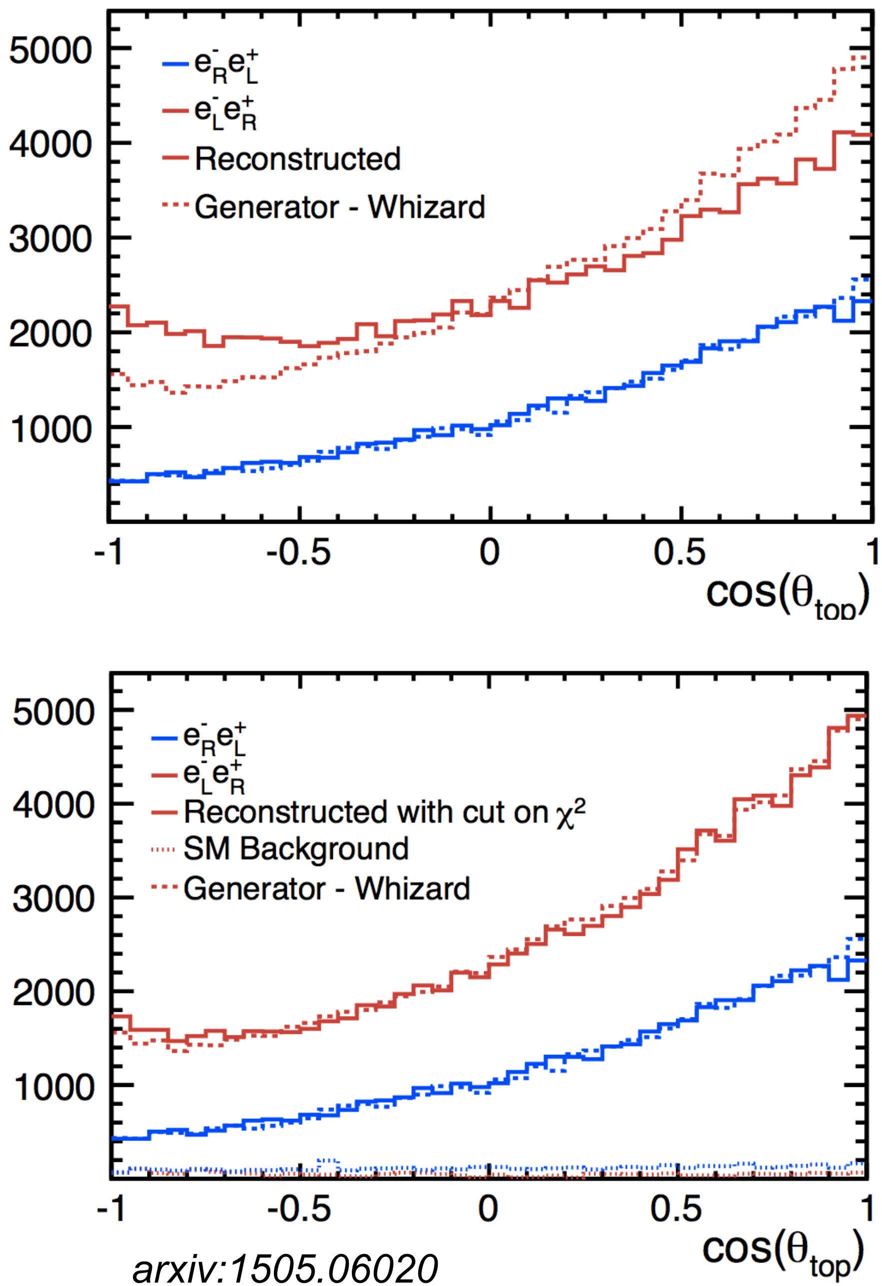
⇩

Extraction of relevant unknowns

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

or equivalently $g^{\gamma}_{L},\ g^{\gamma}_{R},\ g^{Z}_{L},\ g^{Z}_{R}$

Semi Leptonic Analysis - Reconstruction of top quark production angle



arxiv:1505.06020

Ambiguities in case of
left handed electron beams
Due to V-A structure at ttX vertex

Precise reconstruction of θ_{top}
in case of right handed electron beams

Remedy to address ambiguities:
Select cleanly reconstructed events by χ^2 analysis
or
Reconstruction of b quark charge

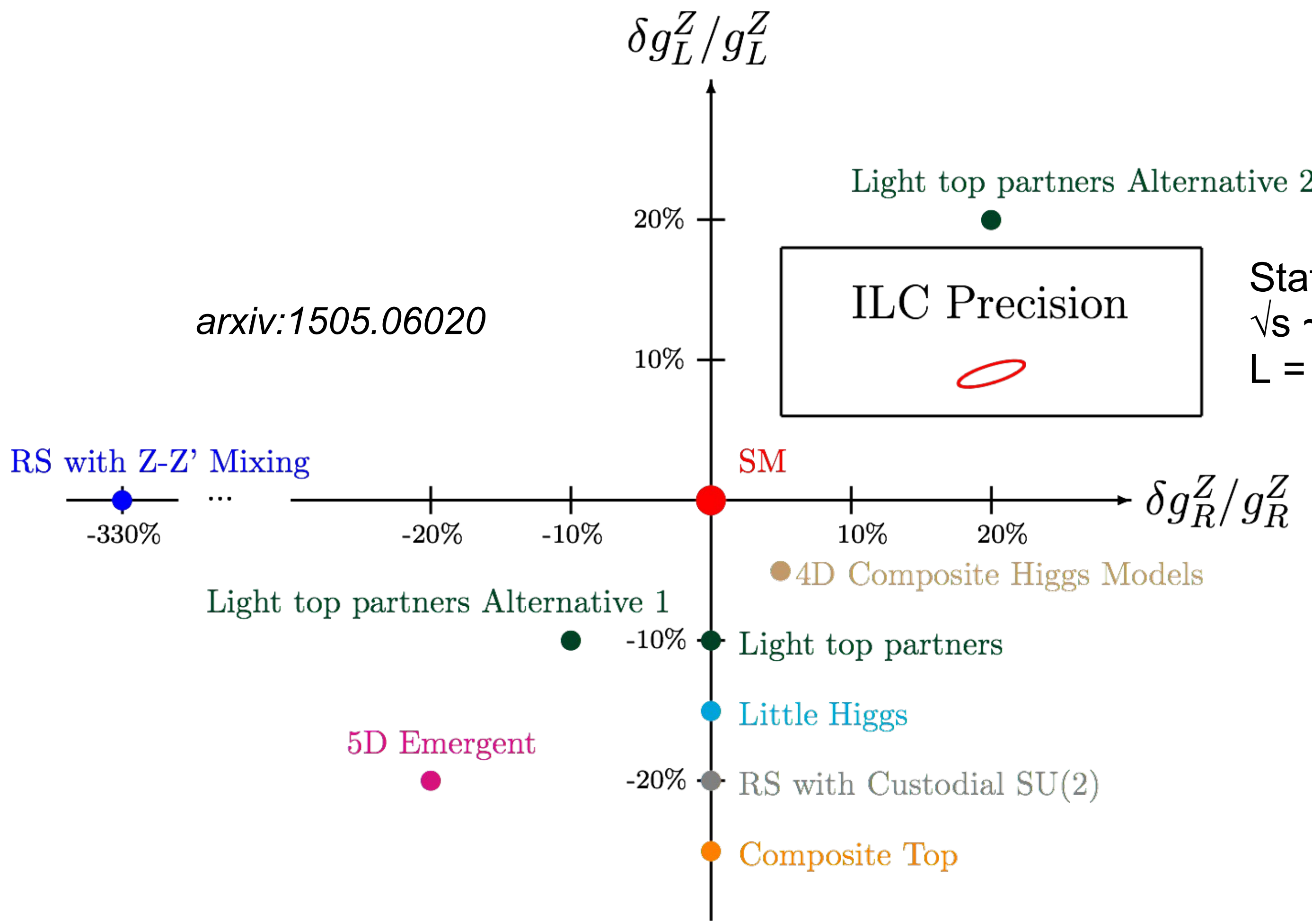
Precise reconstruction for both beam polarisations

- Efficiency Penalty for e_L
- ε_{tot}: $e_R \sim 50\%$, $e_L \sim 30\%$

Precision on $A_{FB} \sim 2\%$

Sensitivity to New Physics

Top is primary candidate to be a messenger new physics in many BSM models
Incorporating compositeness and/or extra dimensions



Statistical error:
√s ~ 500 GeV
L = 500 fb^{-1}

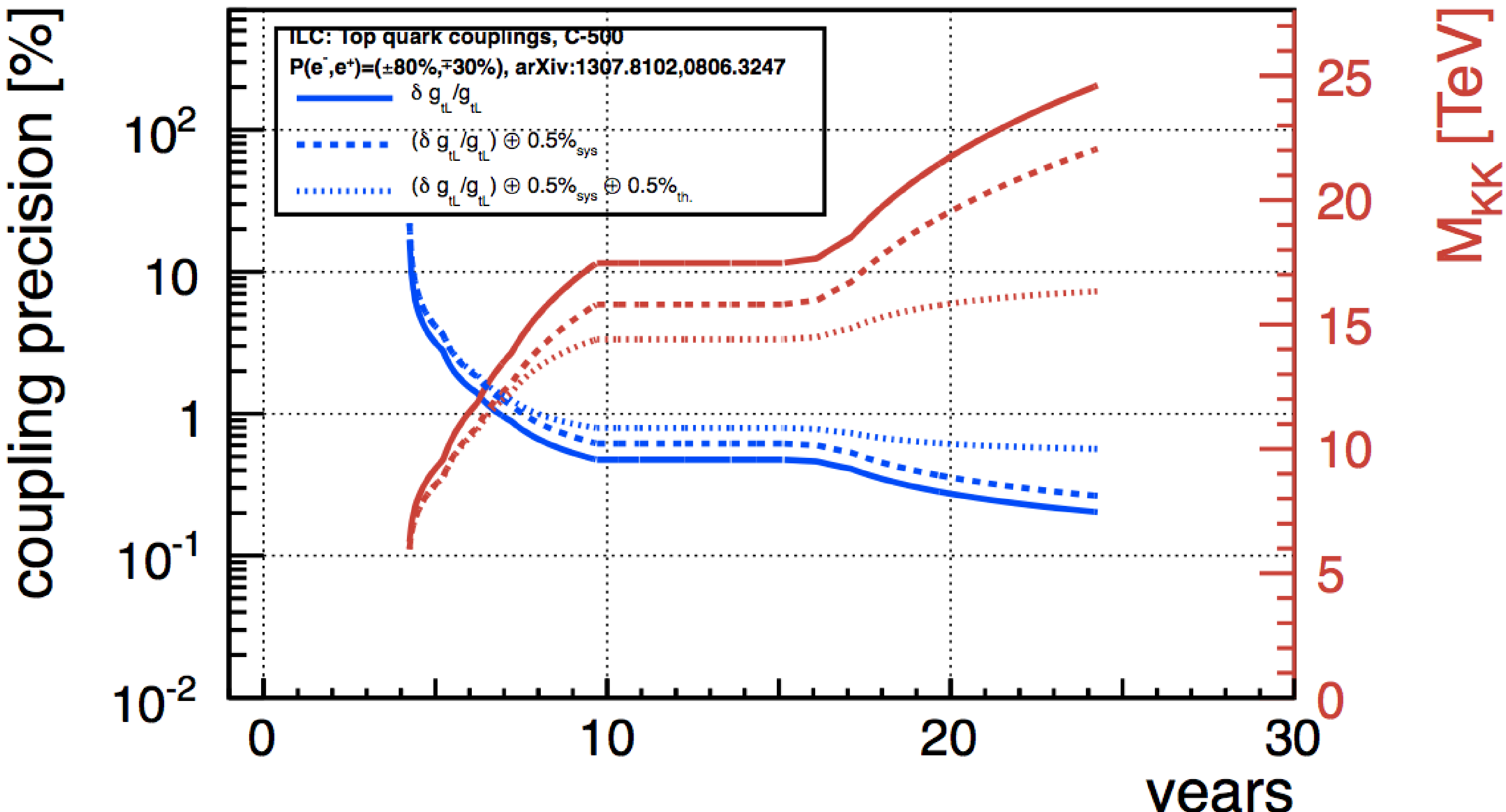
Precision expected for top quark couplings will allow to distinguish between models

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

Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top and or extra dimensions

Based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 TeV for extreme scenarios)

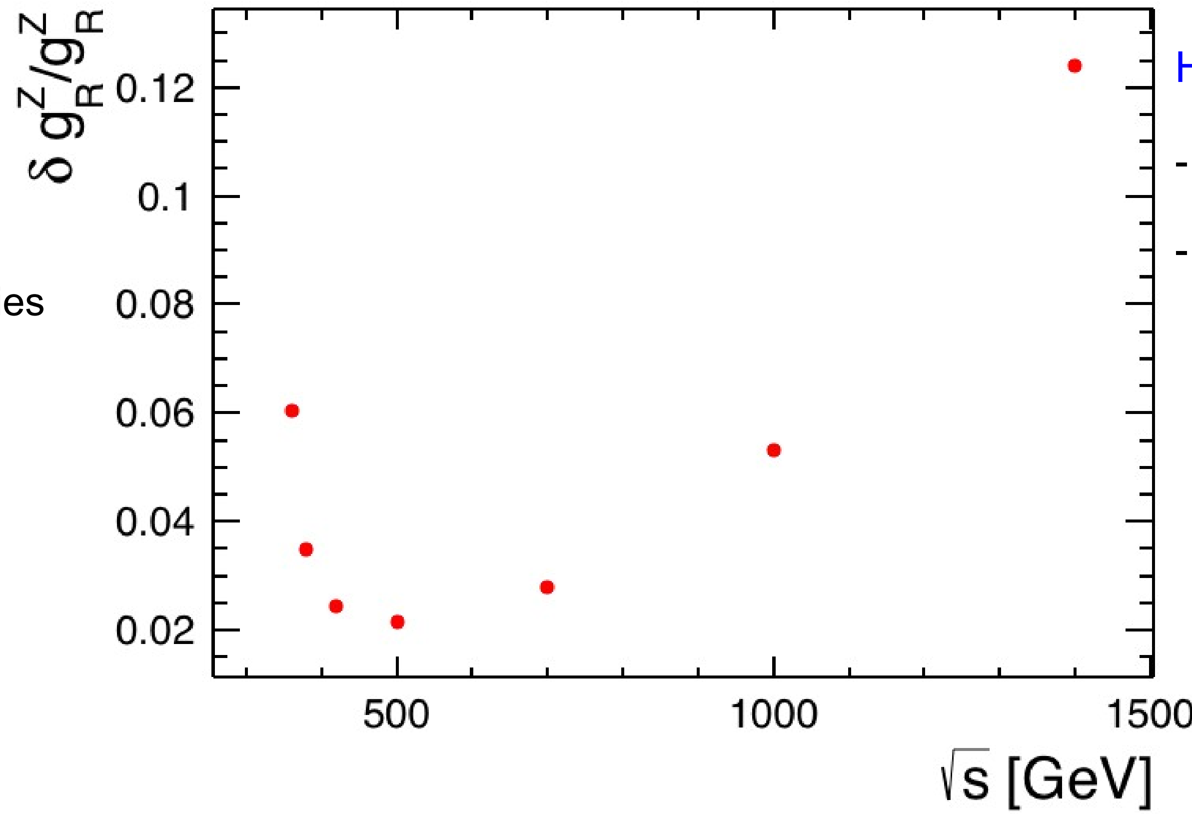
=> Important guidance for e.g. 100 TeV pp-collider

Different centre of mass energies

... simplified discussion (same lumi at each cms)

Small cms energies:

- Vanishing axial vector coupling
- On top (not shown) large QCD uncertainties ... and
- Lumi decreases at linear colliders



High cms energies:

- Quickly decreasing cross section
- ... partially compensated by increasing luminosity

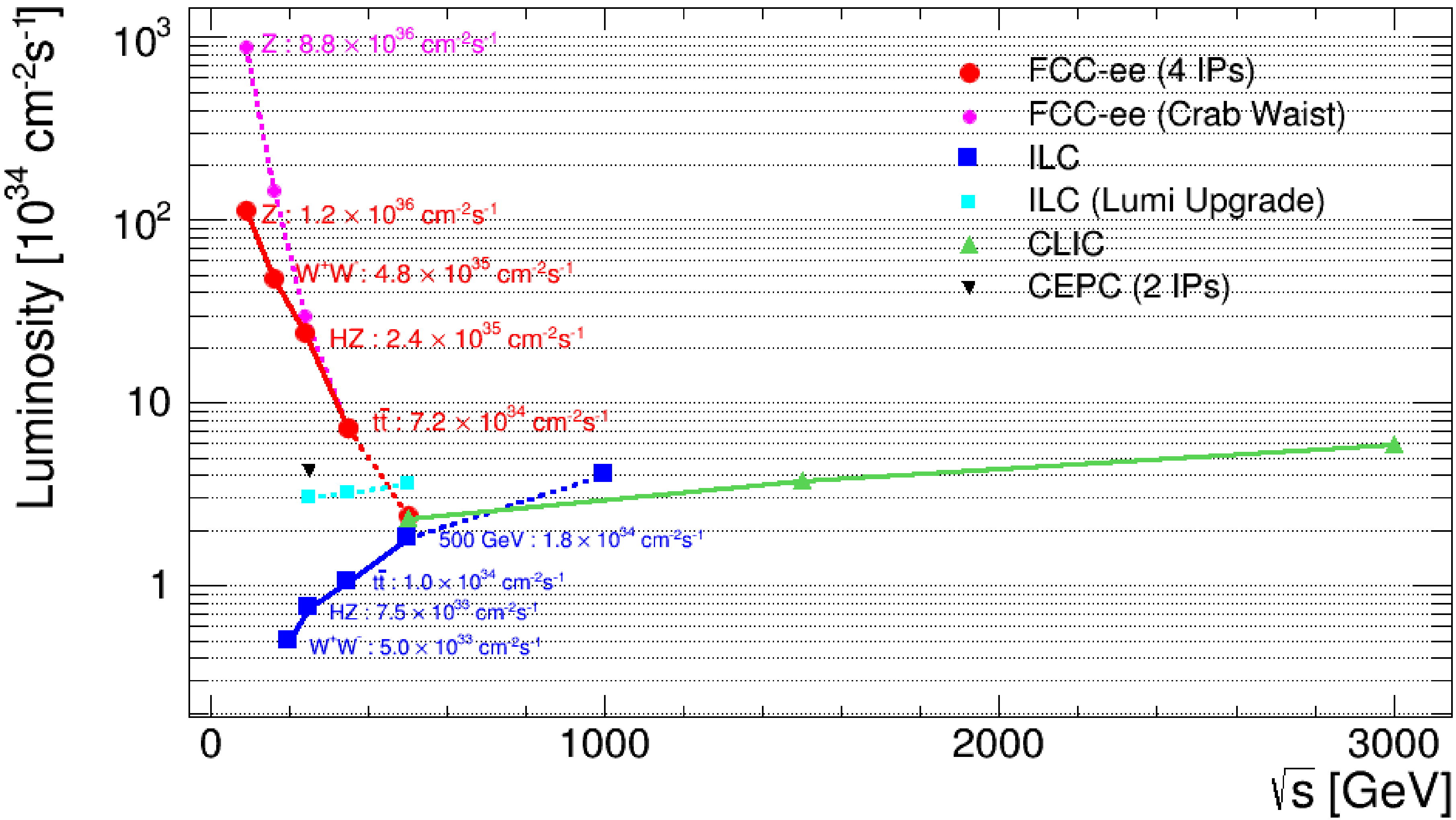
Broad minimum between 400 and 700 GeV

$\sqrt{s}$ ~ 500 GeV is "sweet spot" for coupling measurements

However:

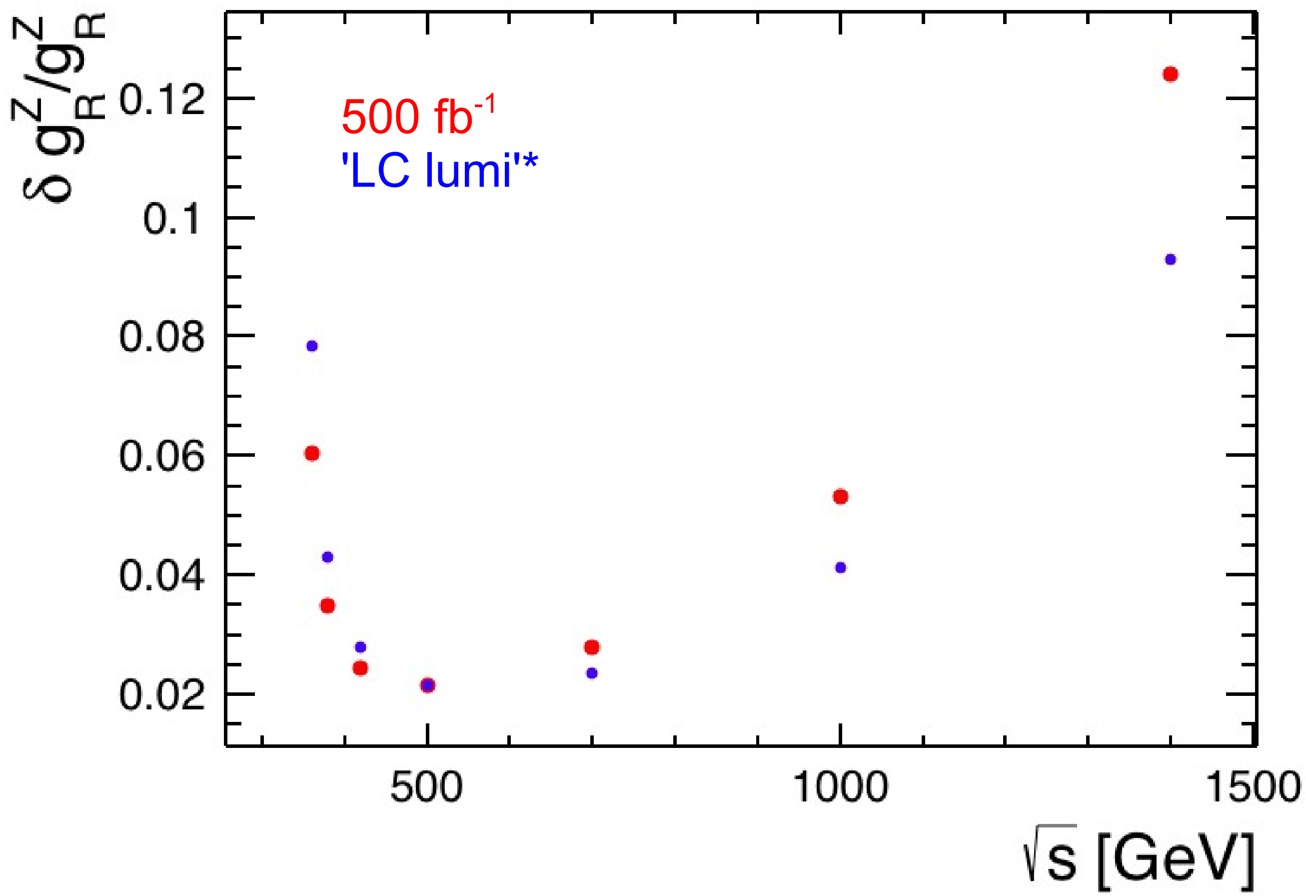
- Sensitivity to CP violating Higgs at smaller cms energies (see later)
- New physics at higher energies may increase cross section

Lumi development – e+e- colliders



Different cms folded with lumi

Linear Colliders



*from fit to combined ILC and CLIC spectrum

Potential systematic uncertainties

- Luminosity: Critical for cross section measurements
  Expected precision 0.1% @ 500 GeV

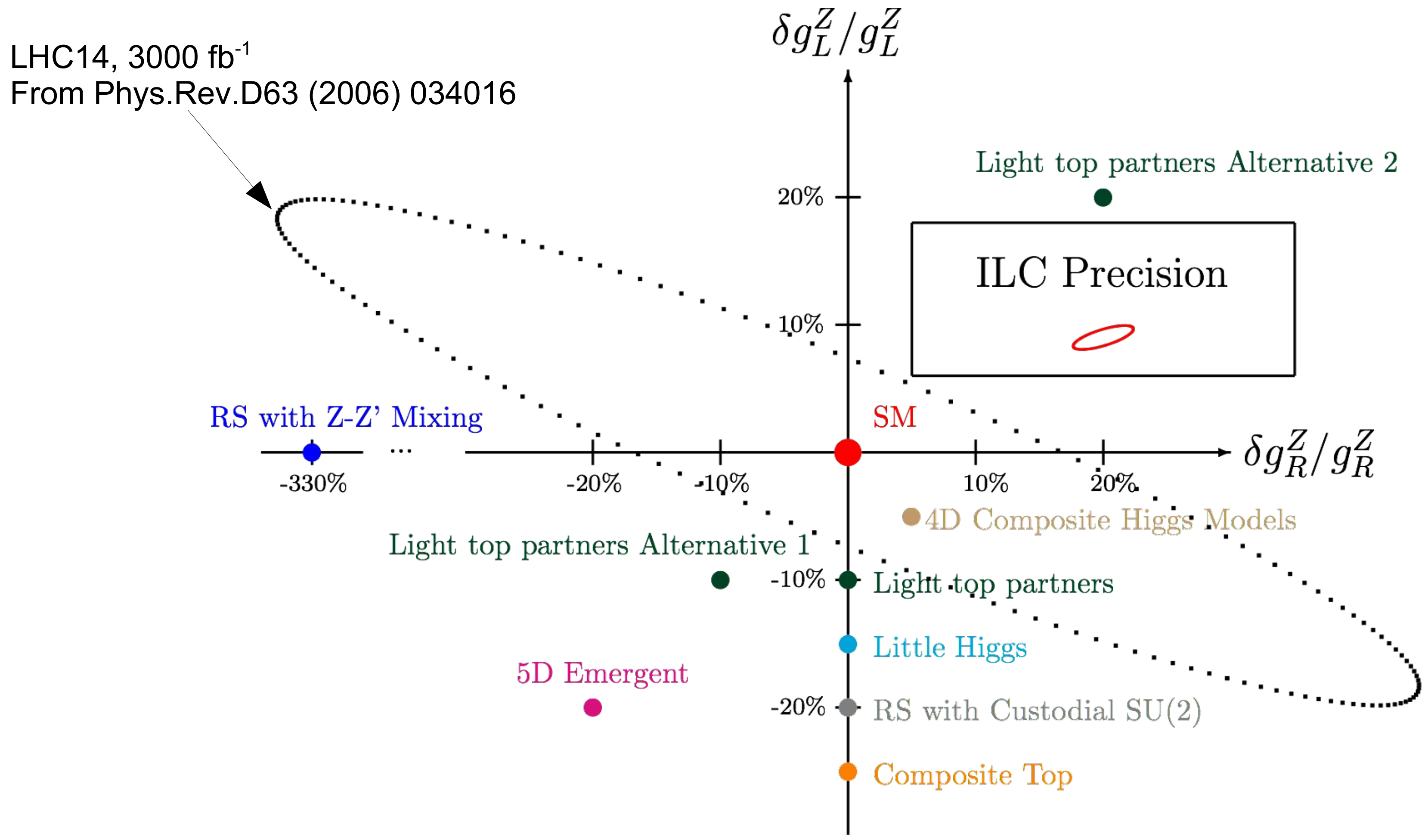
- Beam polarisation: Critical for asymmetry measurements
  Expected to be known to 0.1% for e- beam
  and 0.35% for e+ beam

- Migrations/Ambiguities: Critical for A_{FB}:
  PFLOW important for selection of 'clean events' but maybe subleading w.r.t. jet clustering
  Control of b charge is most relevant topic !!!!

- Other effects: b-tagging, passive material etc.
  LEP1 claims 0.2% error on R_b -> guiding line for LC

Under discussion with theory groups:
- Consideration full 6f final state (Interference with single top and ZWW)
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)
- Update and maintenance of event generators (WHIZARD, MADGRAPH etc.)

What about LHC perspectives?



Linear Collider will outperform LHC results

- Particular poor constraint on g_R (this holds also for flavor physics results)
- LHC LO QCD analysis, ~30% improvement through NLO QCD
- LHC may still be capable to exclude models

First LHC result ?

ttW and ttZ measurements		ttW				ttZ			
		Cross section		Significance		Cross section		Significance	
Data	Analysis	Theory*	Obs.	Exp.	Obs.	Theory*	Obs.	Exp.	Obs.
7 TeV ($5\ fb^{-1}$)	CMS[1]	147^{+14}_{-16}	-	-	-	137^{+12}_{-16}	280^{+150}_{-110}	?	3.3
7 TeV ($5\ fb^{-1}$)	ATLAS[2]		-	-	-		< 710	-	-
8 TeV ($20\ fb^{-1}$)	CMS[3]	203^{+20}_{-22}	170^{+110}_{-100}	2.0	1.6	206^{+19}_{-24}	200^{+90}_{-80}	3.1	3.1
8 TeV ($20\ fb^{-1}$)	ATLAS[4]		300^{+140}_{-110}	2.3	3.1		150^{+58}_{-54}	3.4	3.1
8 TeV ($20\ fb^{-1}$)	**CMS *Preliminary***		**382^{+117}_{-102}**	**3.5**	**4.8**		**242^{+65}_{-55}**	**5.7**	**6.4**

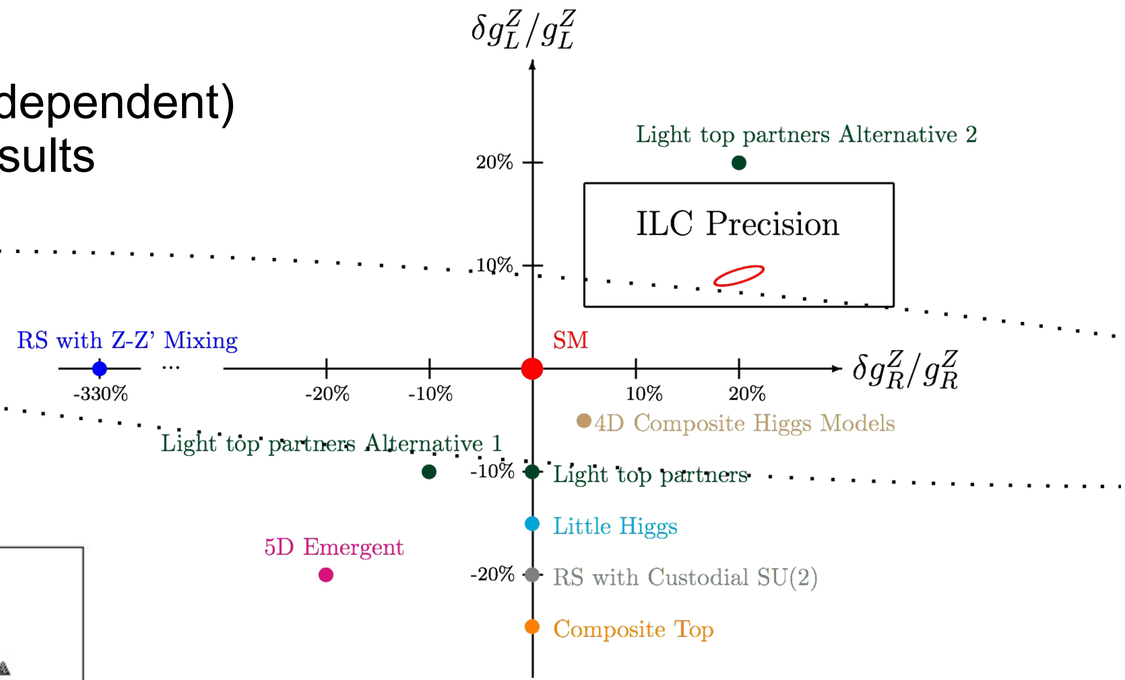
Preliminary documentation: twiki.cern.ch/twiki/bin/view/CMSPublic/**PhysicsResultsTOP14021**

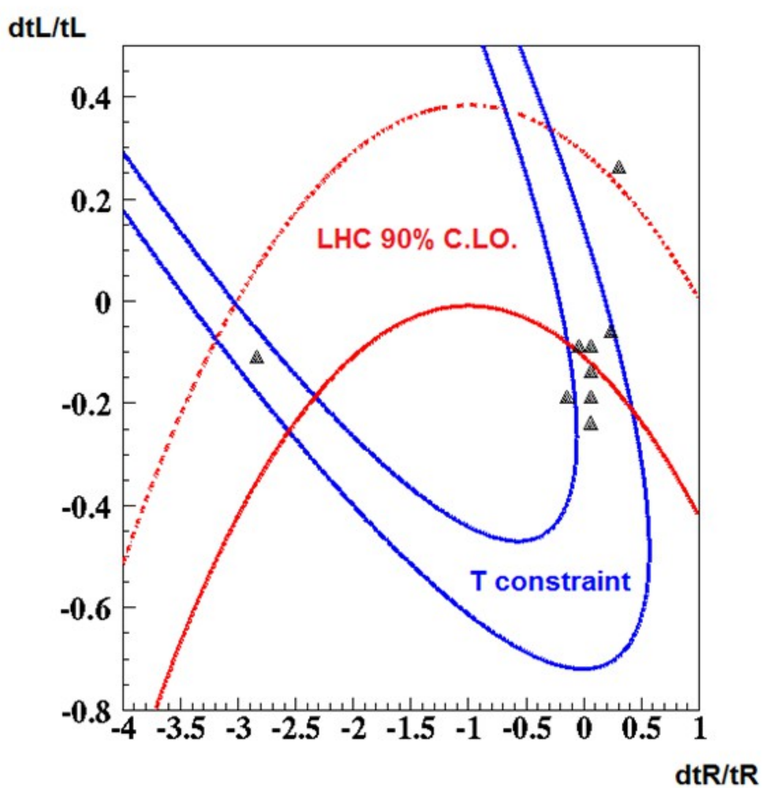
[1] CMS: *Phys. Rev. Lett.* 110 (2013) 172002
[2] ATLAS-CONF-12-126
[3] CMS: EPJ C74 (2014) 3060
[4] ATLAS-CONF-2014-038

* NLO cross sections with scale uncertainties from Garzelli et. al., JHEP 11 (2012) 056

Comparison with current LHC results

LHC input:
- Single top (Model dependent)
- Latest x-section results





- Result based on latest x-section results
- Takes into account possible sign flip of couplings

LHC (not yet) competitive but this is real data!!!

Time to compare with older simulated result about to be over!!!

Here Rontsch and Schulze

- Some dimension six operators would specifically affect the vector and axial components of top-Z coupling

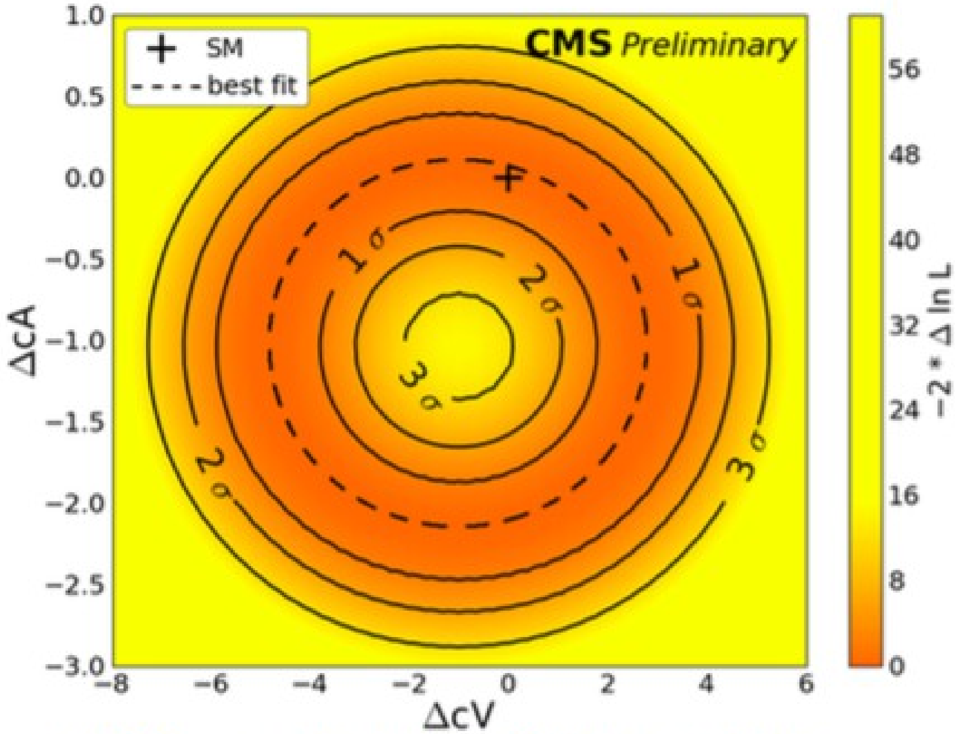
- Interpret ttZ cross section measurement in terms of best fit to, and limits on $C_{1,V}$ and $C_{1,A}$

PRELIMINARY

$$C_{1,V} = C_{1,V}^{SM} + \left(\frac{v^2}{\Lambda^2}\right) \mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right]$$

$$C_{1,A} = C_{1,A}^{SM} + \left(\frac{v^2}{\Lambda^2}\right) \mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33}\right]$$

*From http://arxiv.org/abs/1404.1005



Difference between SM C_V and $C_{1,V}$

UNIVERSITY OF

Alternative – Matrix element method

For details see arxiv: 1503.04247

Basic idea: Final state top polarisation cointains information about factors

$$
\begin{aligned}
\mathcal{M}(e_L\bar{e}_R \to t_L\bar{t}_R)^{\gamma/Z} &= c_L^{\gamma/Z}[F_{1V}^{\gamma/Z} - \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1+\cos\theta)e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_R\bar{t}_L)^{\gamma/Z} &= c_L^{\gamma/Z}[F_{1V}^{\gamma/Z} + \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1-\cos\theta)e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_L\bar{t}_L)^{\gamma/Z} &= c_L^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} + \beta F_{2A}^{\gamma/Z})]\sin\theta e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_R\bar{t}_R)^{\gamma/Z} &= c_L^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} - \beta F_{2A}^{\gamma/Z})]\sin\theta e^{-i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_L\bar{t}_R)^{\gamma/Z} &= -c_R^{\gamma/Z}[F_{1V}^{\gamma/Z} - \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1-\cos\theta)e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_R\bar{t}_L)^{\gamma/Z} &= -c_R^{\gamma/Z}[F_{1V}^{\gamma/Z} + \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1+\cos\theta)e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_L\bar{t}_L)^{\gamma/Z} &= c_R^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} + \beta F_{2A}^{\gamma/Z})]\sin\theta e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_R\bar{t}_R)^{\gamma/Z} &= c_R^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} - \beta F_{2A}^{\gamma/Z})]\sin\theta e^{i\phi}
\end{aligned}
$$

=> different sensitivities in different individual matrix elements:

$$\omega_i = \frac{\partial \mid \mathcal{M} \mid^2 (\alpha)}{\partial \alpha_i}_{|\alpha^0} \frac{1}{\mid \mathcal{M} \mid^2 (\alpha^0)}$$

For each alpha (=ff) there is one (measurable) wi

Using full matrix element information -> Full event reconstruction

$$\mathrm{dLips} \propto \mathrm{d}\cos\theta_t\ \mathrm{d}\cos\theta_b\ \mathrm{d}\phi_b\ \mathrm{d}\cos\theta_{\bar{b}}\ \mathrm{d}\phi_{\bar{b}}\ \mathrm{d}\cos\theta_{l^+}\ \mathrm{d}\phi_{l^+}\ \mathrm{d}\cos\theta_{l^-}\ \mathrm{d}\phi_{l^-}\ \mathrm{d}q_t^2\ \mathrm{d}q_{\bar{t}}^2\ \mathrm{d}q_W^2$$

Alternative – Matrix element method

Parton level analysis with GRACE using fully leptonic final state

Simultaneous extraction of 10 FF including CP violation Ffs and disentangling of F1V F2V

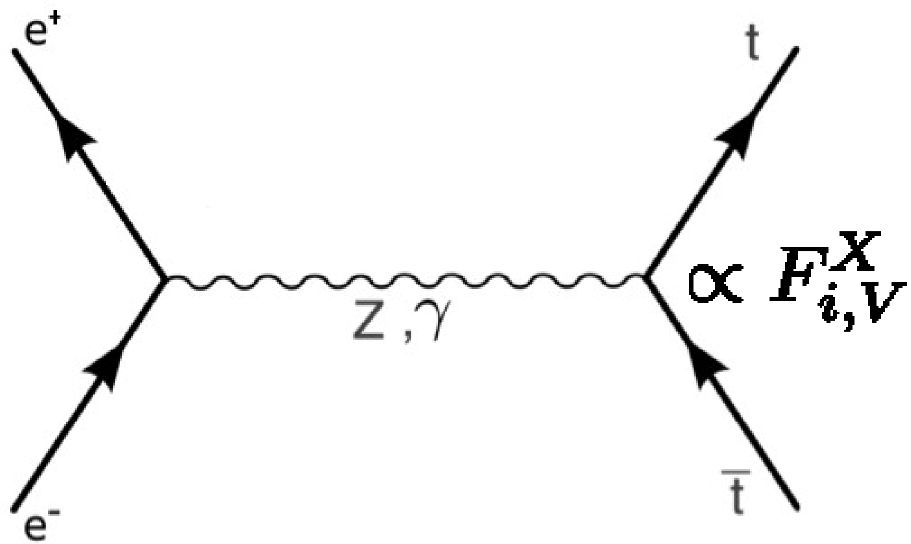
$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{1V}$	$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{1A}$	$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2V}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{2V}$	$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{2A}$	$\mathcal{I}m\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{I}m\ \delta\tilde{F}^{Z}_{2A}$
0.0037	−0.18	−0.09	+0.14	+0.62	−0.15	0	0	0	0
	0.0063	+.14	−0.06	−0.13	+0.61	0	0	0	0
		0.0053	−0.15	−0.05	+0.09	0	0	0	0
			0.0083	+0.06	−0.04	0	0	0	0
				0.0105	−0.19	0	0	0	0
					0.0169	0	0	0	0
						0.0068	−0.15	0	0
							0.0118	0	0
								0.0069	−0.17
									0.0100

No particular improvement through beam polarisation

- No background, no smearing

- Needs experimental study

CP Violation – What's been done?



$$\Gamma^{ttX}_{\mu}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu \left(iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}, \quad (2)$$

CP Violation through electric and weak dipole moment

$$d^X = (e/2m_t)F^X_{2A}, X = \gamma, Z$$

F2A is a complex number

$$F_{2A} = \lambda_{Re} Re(F_{2A}) + \lambda_{Im} Im(F_{2A})$$

CP Violation – What's been done?

ILC 'provides' two beam polarisations

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

$$t\ \bar{t} \quad \rightarrow \quad \ell^+(\mathbf{q}_+) + \nu_\ell + b + \overline{X}_{\rm had}(\mathbf{q}_{\bar{X}}),$$

$$t\ \bar{t} \quad \rightarrow \quad X_{\rm had}(\mathbf{q}_X) + \ell^-(\mathbf{q}_-) + \bar{\nu}_\ell + \bar{b}\ \ ,$$

'Optimal' observables to measure F2A

$$O_+^{Re} = (\hat{k}_{\bar{t}} \times \hat{q}_+)\hat{e}_+ \qquad O_-^{Re} = (\hat{k}_t \times \hat{q}_-)\hat{e}_+$$

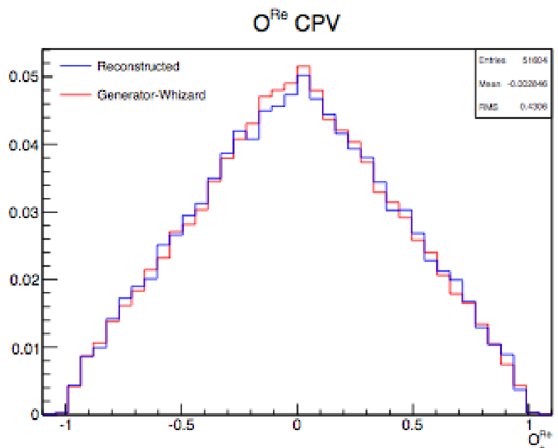
$$O_+^{Im} = -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{q}_{\bar{X}} \times \hat{e}_+)^2]\hat{q}_+^* \cdot \hat{q}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{q}_{\bar{X}} \cdot \hat{e}_+ \hat{q}_+^* \cdot \hat{e}_+$$

Extraction of four unknowns due to beam polarisation P

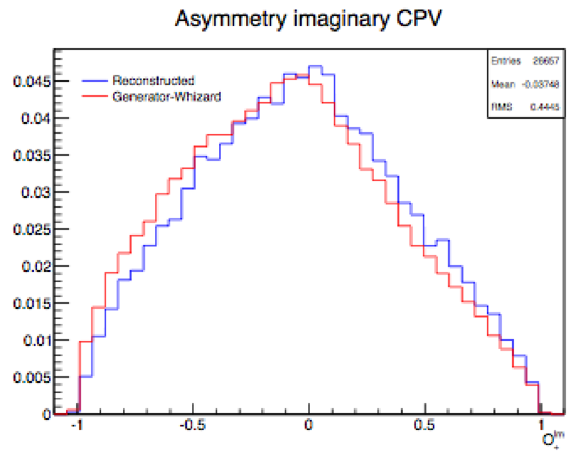
$$A_{\gamma,Z}^{Re} = \langle O_+^{Re} \rangle - \langle O_-^{Re} \rangle = c_\gamma [P Re(F_{2A}^\gamma) + KZ Re(F_{2A}^Z)]$$

$$A_{\gamma,Z}^{Im} = \langle O_+^{Im} \rangle - \langle O_-^{Im} \rangle = d_\gamma [Im(F_{2A}^\gamma) + PKZ Im(F_{2A}^Z)]$$

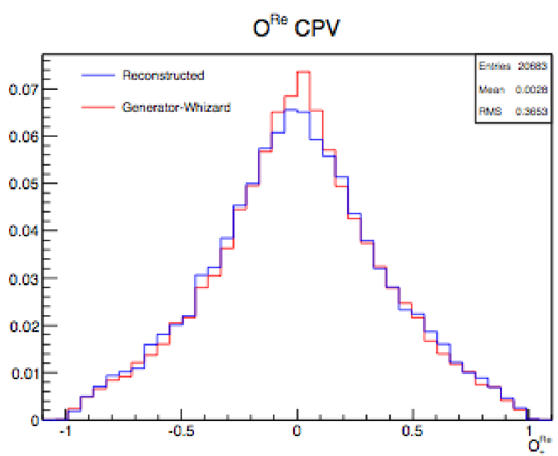
CP Violation – What's been done?



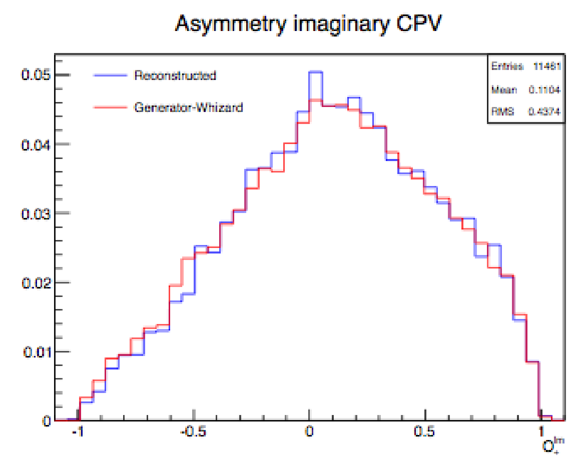
(a) O_+^{Re} P=-1



(b) O_+^{Im} P=-1



(c) O_+^{Re} P=1



(d) O_+^{Im} P=1

CPV obs	Generated	Reconstructed
$\langle O_+^{Re} \rangle$	-0.00285	-0.00206
$\langle O_-^{Re} \rangle$	0.00296	0.00116
$\langle O_+^{Im} \rangle$	-0.08922	-0.0375
$\langle O_-^{Im} \rangle$	-0.08654	-0.0341
$\bar{RMS}$	0.43	0.44
δ_{stat}	0.0014	0.002

	Generated	Reconstructed
$A_{\gamma,Z}^{Re}$	-0.0058 ± 0.002	-0.0032 ± 0.003
$A_{\gamma,Z}^{Im}$	-0.0027 ± 0.002	-0.0034 ± 0.003

CP Violation – Role of Higgs exchange?

Study by Francois Richard

Higgs sector

- It should be noted that for what concerns the Higgs sector (non-minimal) contribution there could be a much larger enhancement for the 3d generation **df~m³f** at one-loop
- Higgs exchange is larger near threshold and the sensitivity for Re(F2A) drops to 0 at 500 GeV

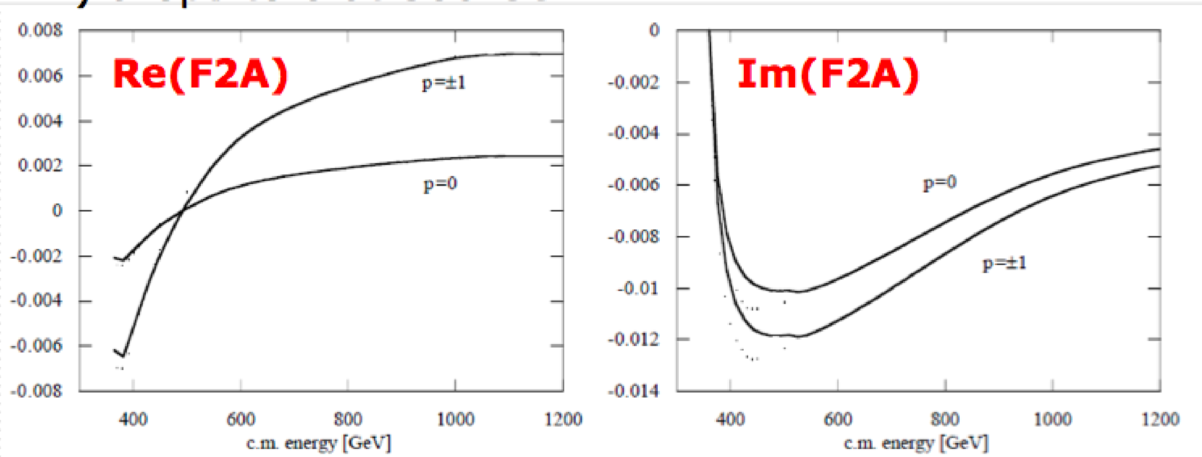


Fig 1: Ratios r_1 (left figure) and r_2 (right figure) for the optimized dispersive and absorptive observables $\mathcal{O}_{\pm}(i)$, $i = 1, 2$ defined in [6] for $m_t = 180$ GeV, $m_{\varphi_1} = 100$ GeV, and $\gamma_{CP} = 1$.

8

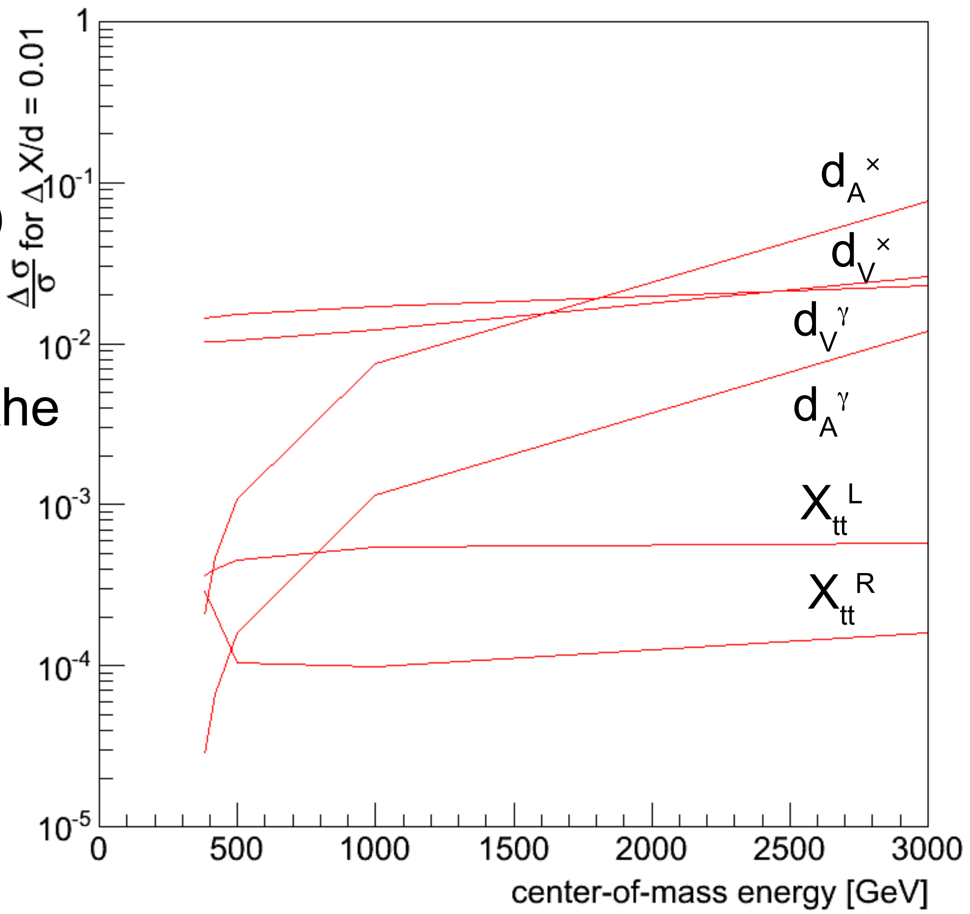
Exchange of CP Violating Higgs is most probable source of CP violation
In tt production (dixit Werner Bernreuther)

Impact of x-section on New Physics

Dimension 6 effective operators
(~equivalent role to anomalous form factors)
have been implemented in WHIZARD...

Allow to map the dependence on √s of the impact of new physics on given observable

May help to explore the sensitivity of new/additional observables



Summary

- First iteration of study on anomalous form factor finished

  Demonstration of outstanding potential of high-precision measurements
  Outperforming of LHC precisions (incoming results will be observed with great interest
  Essential pillar of LC physics program

- Precision on form factors and couplings of the order of 1%

  No sign ambiguity
  Sensitivity to new physics up to several 10 TeV

- Beam polarisation is major asset for control of theoretical and experimental ambiguities

- Still, a lot has to be done

  - b-charge measurement (=> FF grom tt -> hadrons, Afb as function of fermion mass)
  - Step tt -> WbWb
  – understanding of large elw. NLO corrections to AFB and x-section
  – Matrix element method <-> 'robust' experimental quantities (understanding of drawbacks and advantages
  – Experimental study of ME Method needed
  – How to address CP violation (Experimental observables or ME Method?)
  - EFT approaches w.r.t. Complete models

- tt analysis enters new phase

Backup ....

ILC Basic Parameters and Comments

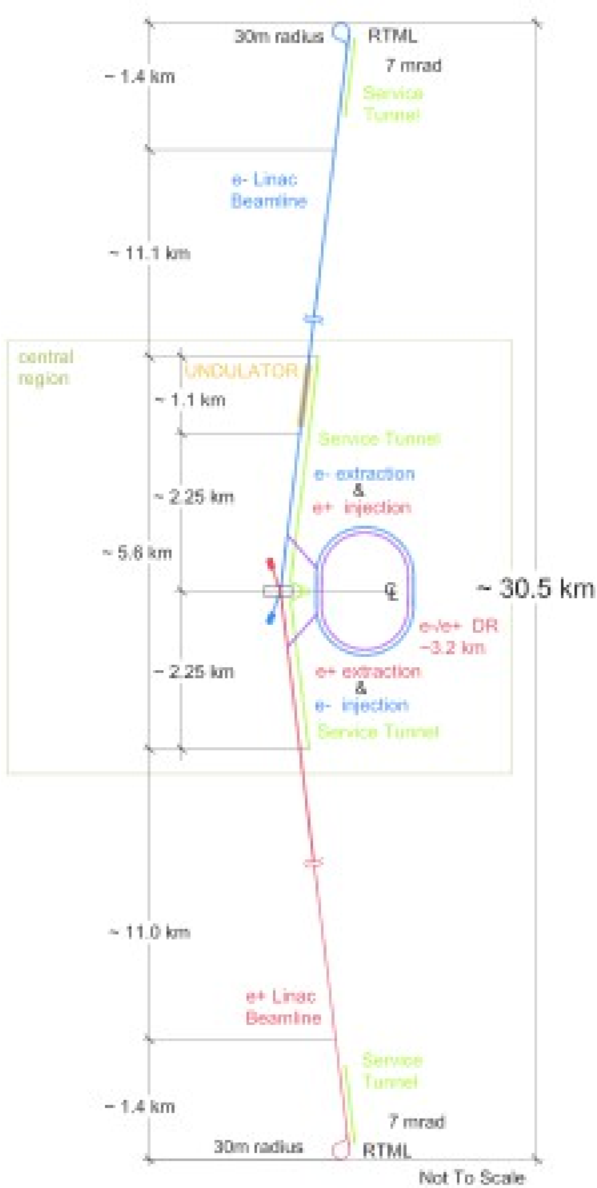
ILC design parameters		Comment
$\sqrt{s}$	91-500 GeV	500 GeV is baseline Option to upgrade to 1 TeV
$\mathcal{L}$	$2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	~Factor 4 technically possible
P_{e^-}	>80%	Proven by SLC
P_{e^+}	upto 30%	~Conservative estimate
Length	~31 km	Current site allows for 50km

- Discussion on possible running scenarios has started

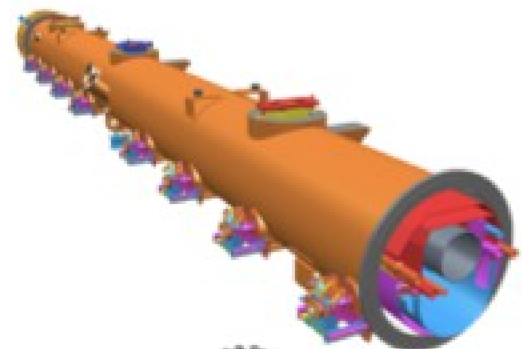
- Luminosity and running time to achieve at a ~25 years research programme
  That includes running at 250 GeV, 350 GeV, 500 GeV and 1 TeV

- No official statement yet but integrated luminosities indicated in following
  transparencies are realistic

ILC in a Nutshell



N. Walker, ILC School 2013



- **SCRF Technology**
  - 1.3GHz SCRF with 31.5 MV/m
  - 17,000 cavities
  - 1,700 cryomodules
  - 2×11 km linacs

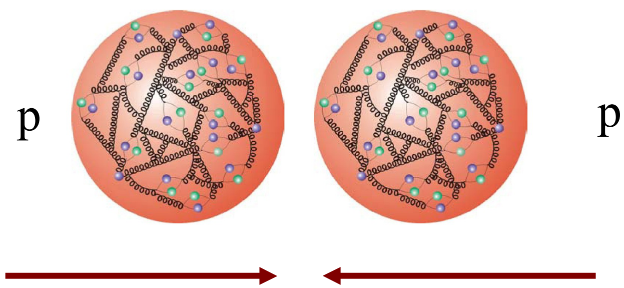
Luminosity

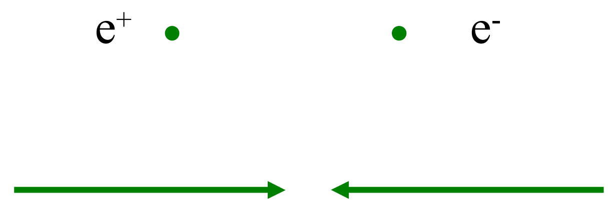
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D$$

η_{RF} ~ 40% for SCRF technology

-> efficient technology

Why e+e- collisions?





Proton:

Composed particle (hadron)
Unknown energy of collision partners
Parasitic reactions
Strong interaction
=> Considerable physics background
Advantage: Scan of energy
Range within one experiment

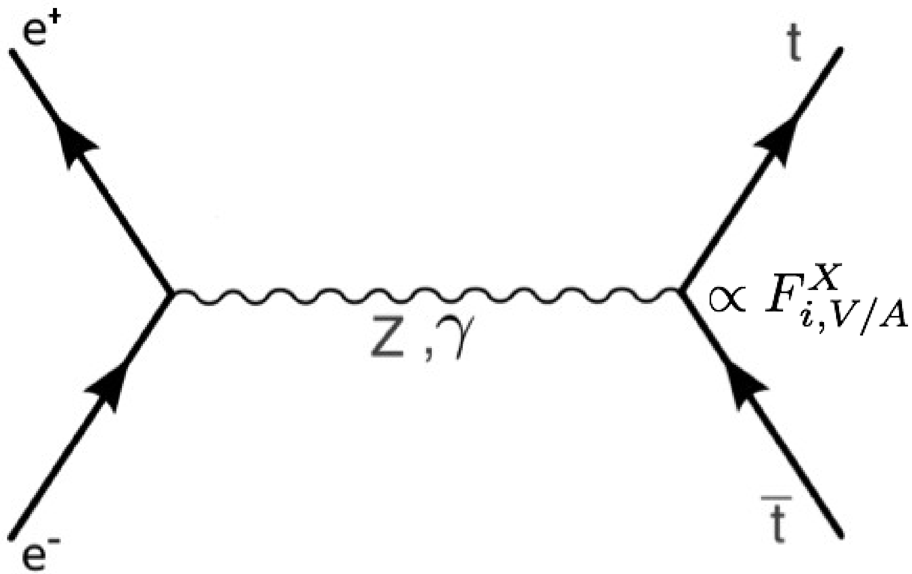
Electron:

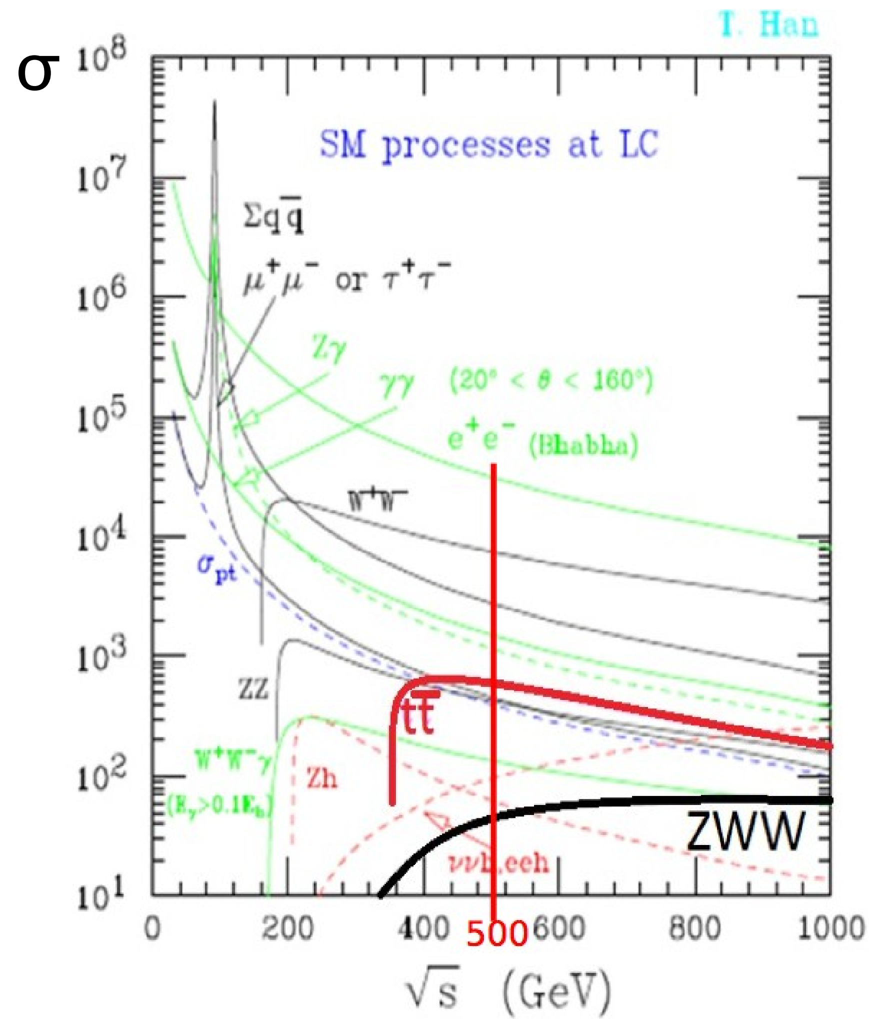
Elementary particle
Well known and adjustable energy of collision partners

Each energy point needs a
New set of machine parameters

High precision measurements

Top Quark Physics at Electron-Positron Colliders



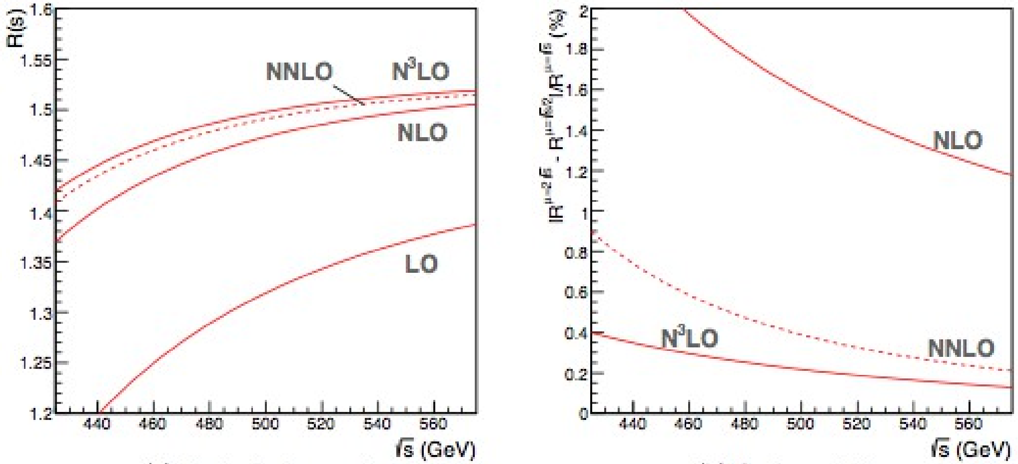


- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

- High precision measurements
  - Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F and couplings g

Theoretical uncertainties

✶QCD corrections are known up to N³LO

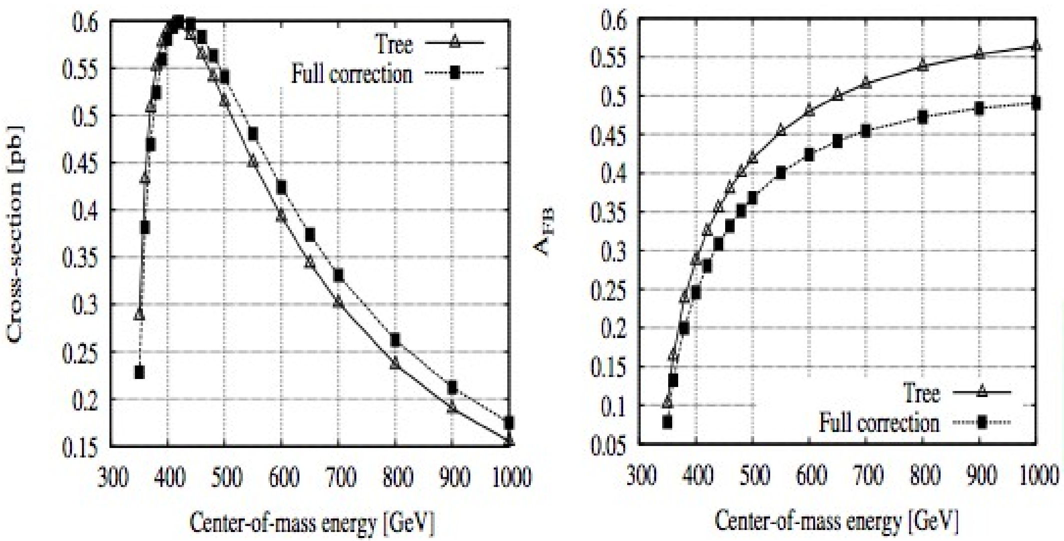


(a) Perturbation series (b) Scale variations

QCD correction (N³LO) is at the per mil level

Kiyo, Maier, Maierhofer, Marquard, NCP B823 ('09)
Bernreuther, Bonciani, Gehrmann, Heinesch, Leineweber. NPB750 ('06)
Hoang, Mateu, Zebarjad, NPB813 ('09)

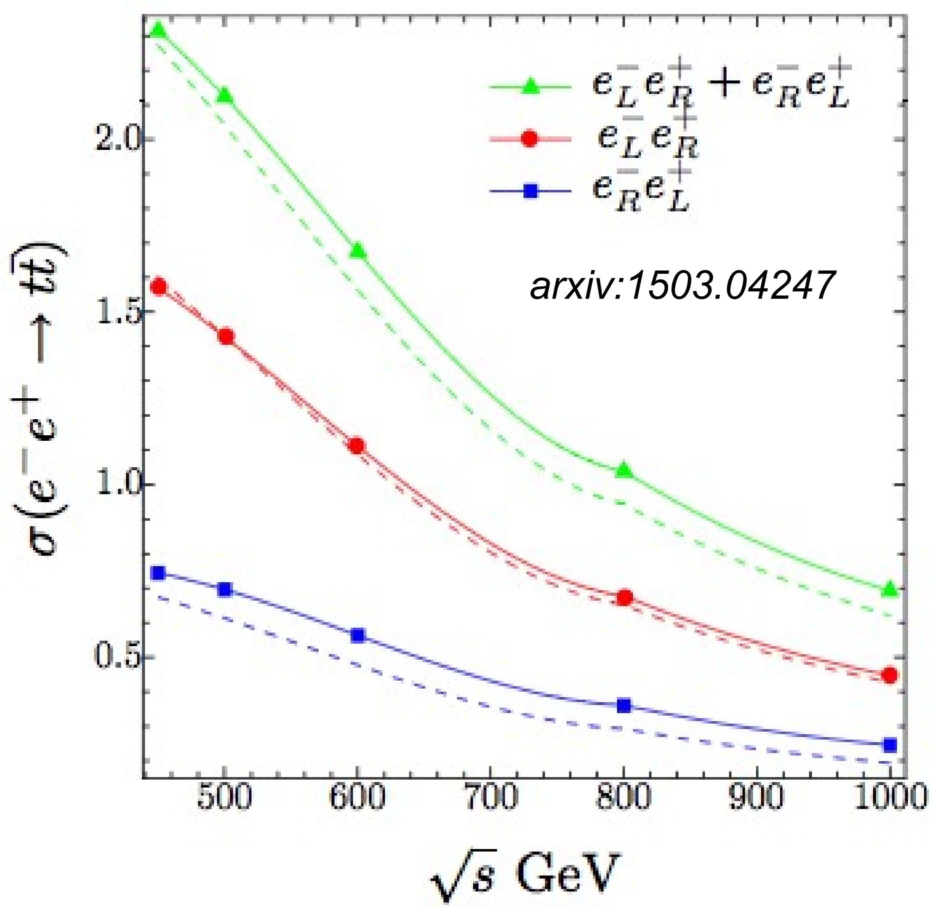
✶Electroweak corrections are known at one-loop level

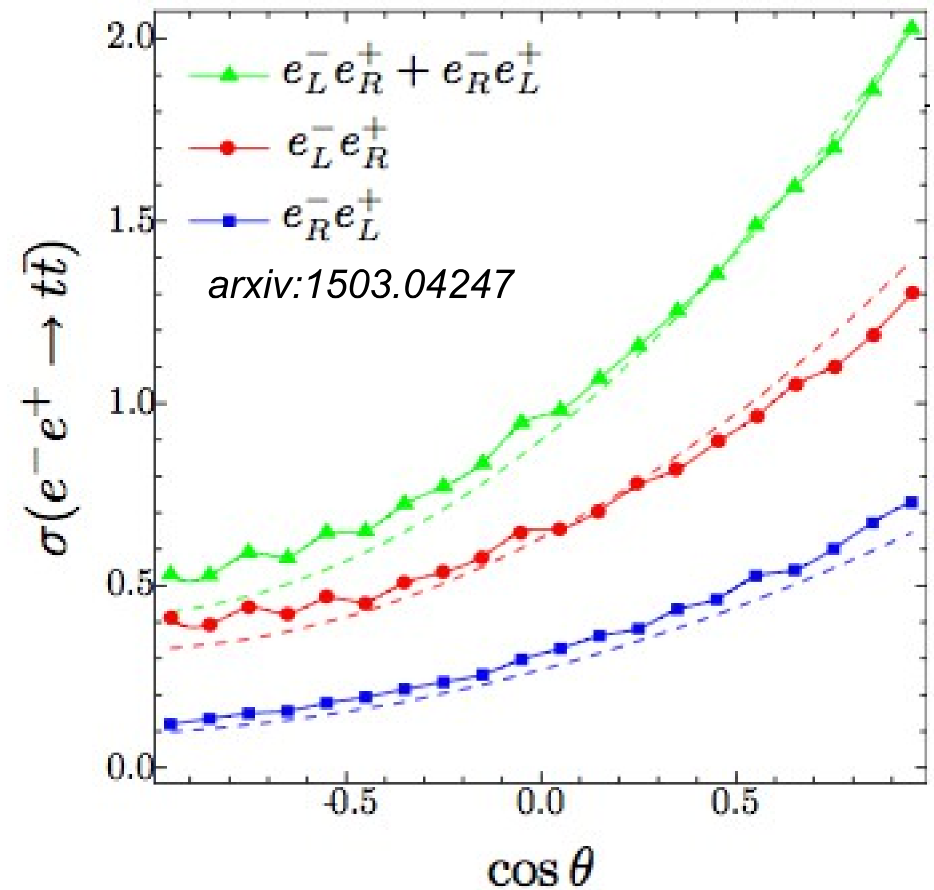


EW correction at one-loop is ~5% for cross section ~10% for A_{FB}

Fleischer, Leike, Riemann, Werthenbach, EJPC31 ('03)
Kheim, Fujimoto, Ishikawa, Kaneko, Kato, arXive:1211.1112

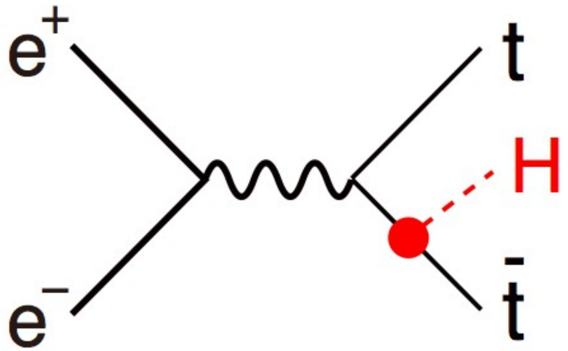
Detailed look at higher order elw. corrections - GRACE





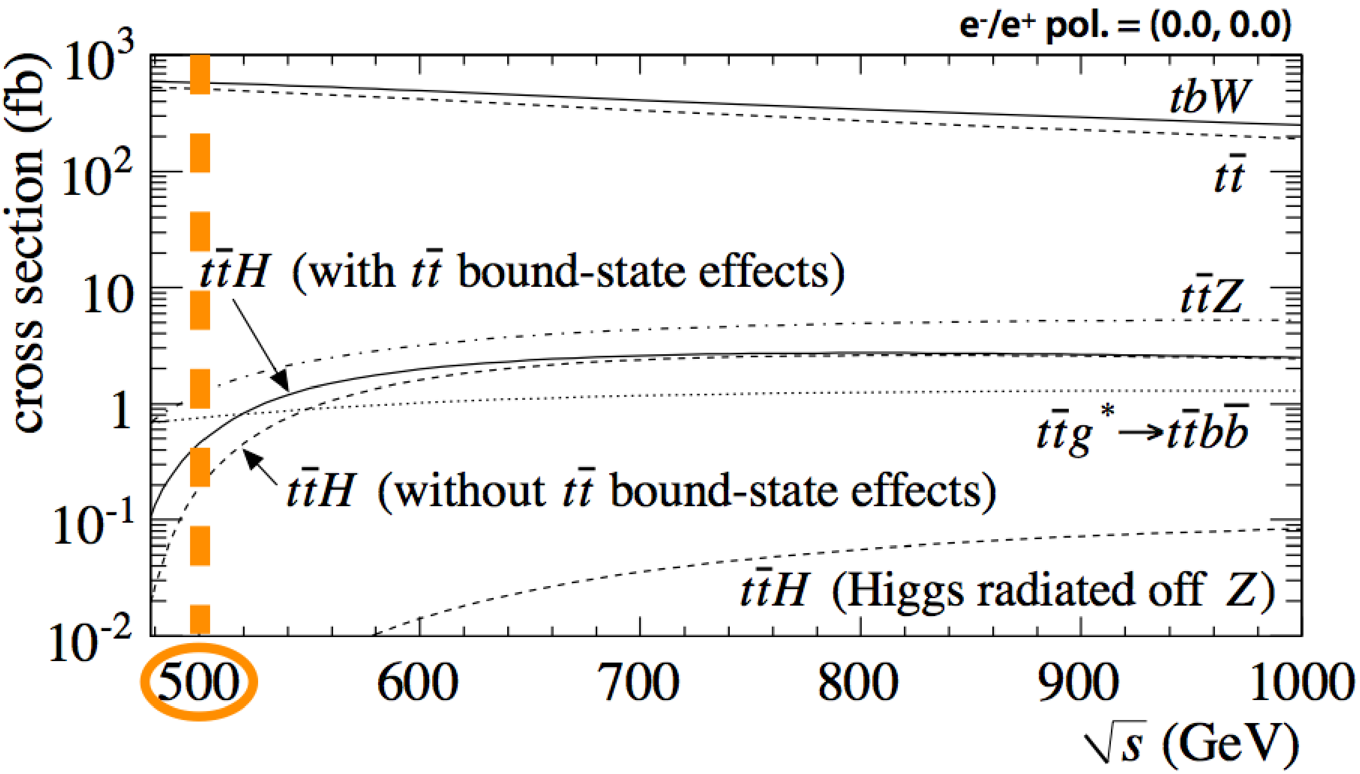
- Electroweak corrections manifest themselves differently for different beam polarisations
-
Beam polarisation important asset to disentangle SM and effects of new physics
Configuration $e_R^- e_L^+$ seems to lead to “simpler” corrections

Top Yukawa Coupling



- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets



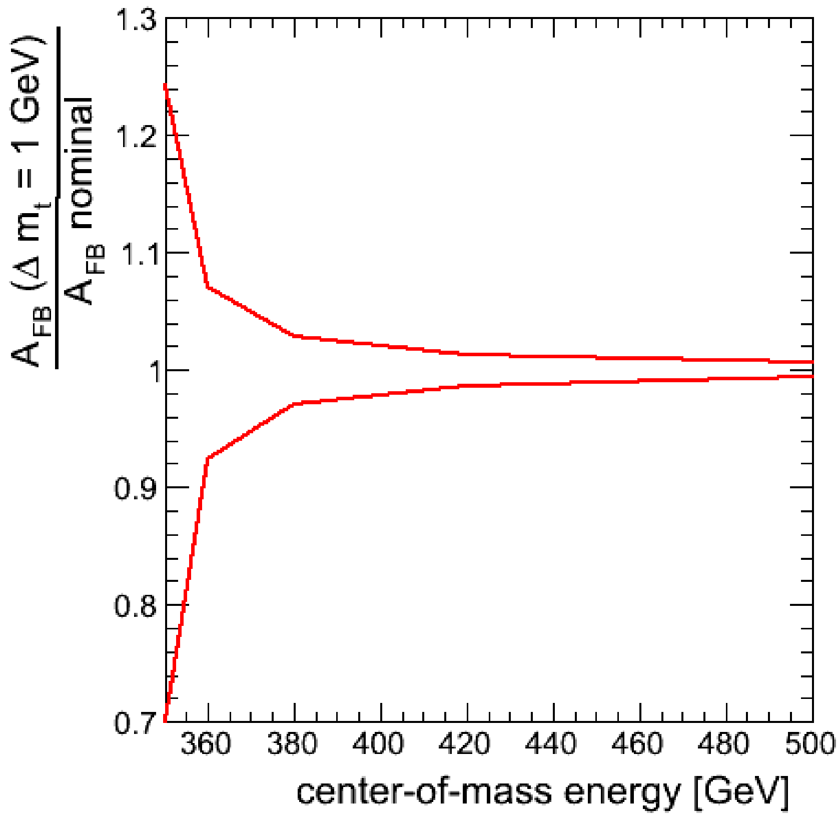
$\Delta g_{ttH} / g_{ttH}$	500 GeV	500 GeV + 1 TeV
Canonical	14%	3.2%
LumiUP	7.8%	2.0%

← ILC TDR

← Technically possible

R. Horiguchi et al.
T. Tanabe, T. Price

From threshold to continuum

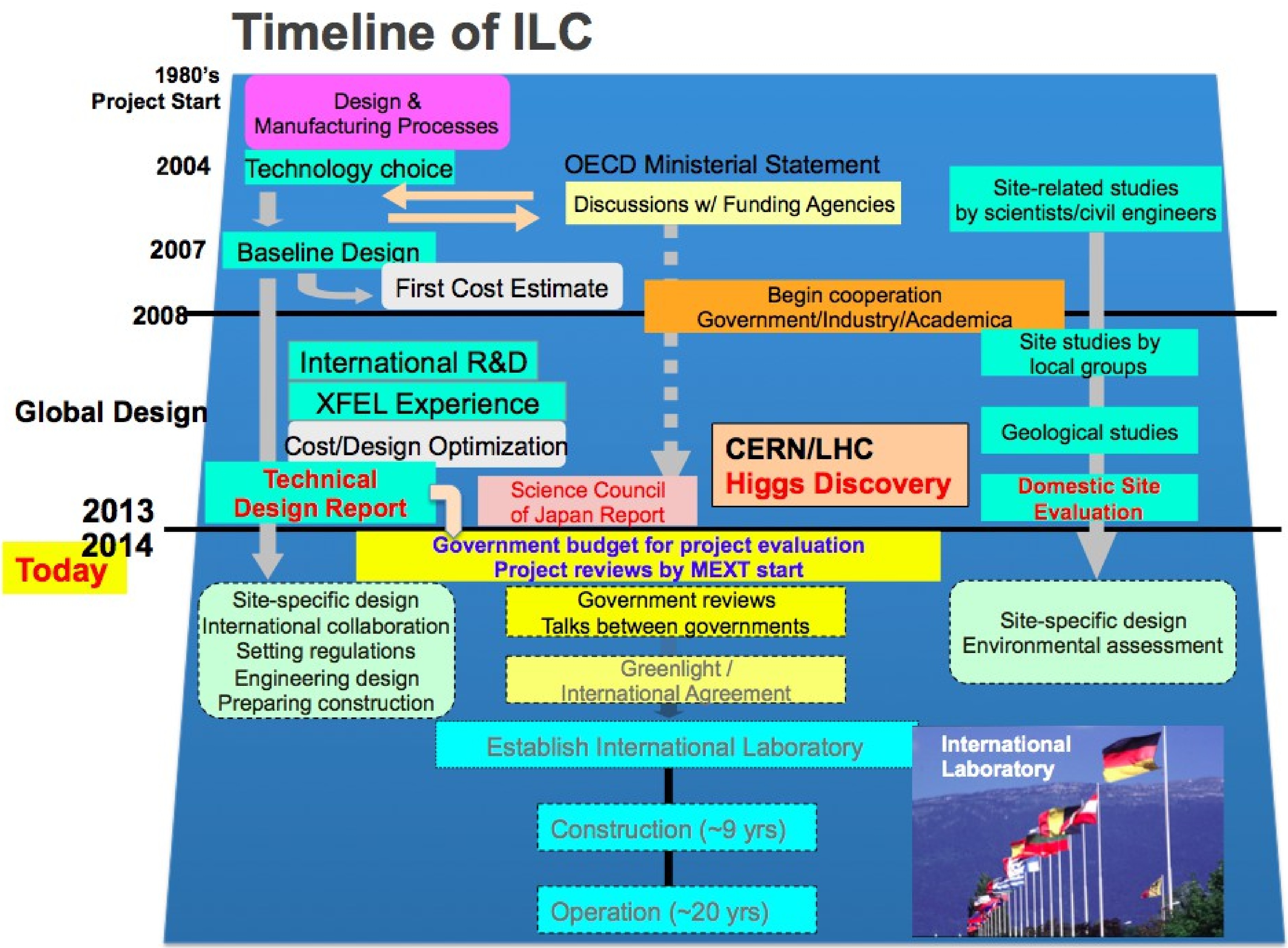


Influence of the top quark mass on x-sec and A_{FB}

- very pronounced below $\sqrt{s}$ = 360 GeV
- 2.9%/GeV at $\sqrt{s}$ = 380 GeV
- 1.3%/GeV at $\sqrt{s}$ = 420 GeV
- 0.6%/GeV at $\sqrt{s}$ = 500 GeV

With the assumption of a 100 MeV pole mass measurement at threshold, the remaining uncertainty is one per mil or less above 420 GeV

ILC Roadmap



Remark R.P.: MEXT report in March 2016