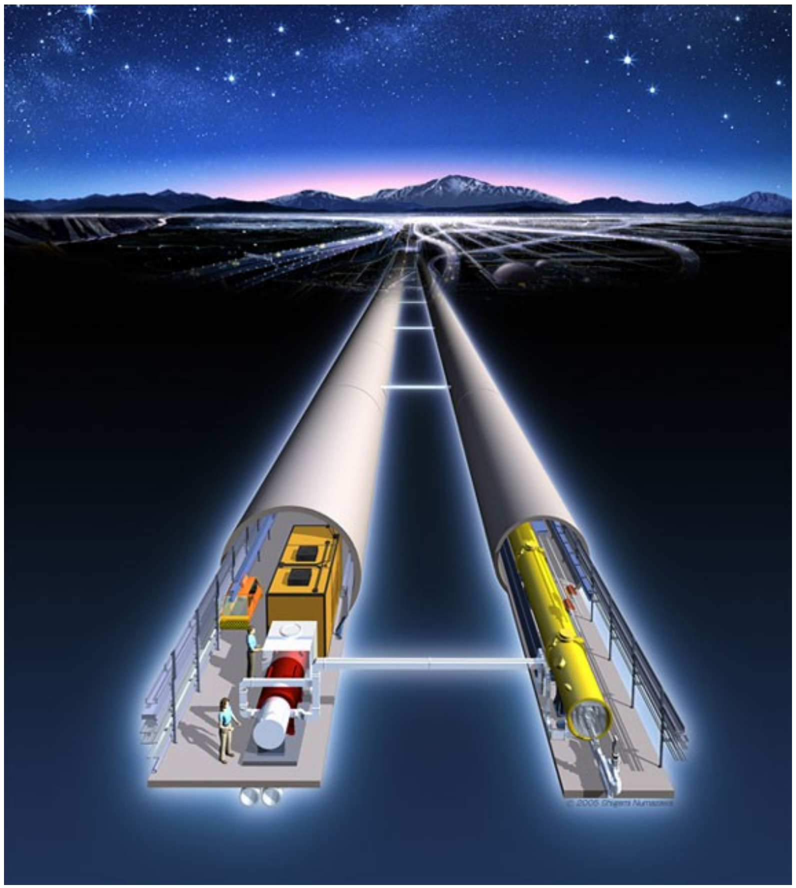
Top electroweak couplings at Linear Colliders



Roman Pöschl

CNRS IN2P3 Les deux infinis · Laboratoire de l'Accélérateur Linéaire · Université Paris Sud – Comprendre le monde, construire l'avenir® · P2IO Physique des 2 Infinis et des Origines

On behalf of

Laboratoire de l'Accélérateur Linéaire · IFIC Institut de Física Corpuscular · KEK-JAPAN · Tohoku University · 東京大学 The University of Tokyo

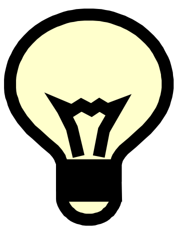
... and the ILD Detector Concept

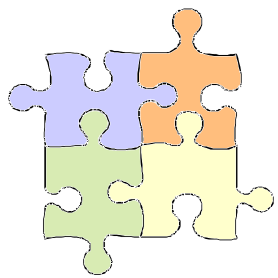
LCWS2015 Whistler/Canada – November 2015

Message


THERE ARE THINGS KNOWN AND THINGS UNKNOWN AND IN BETWEEN ARE THE DOORS.
.. is the top quark
Jim Morrison
American singer-songwriter
QuoteHD.com
(1943-1971)

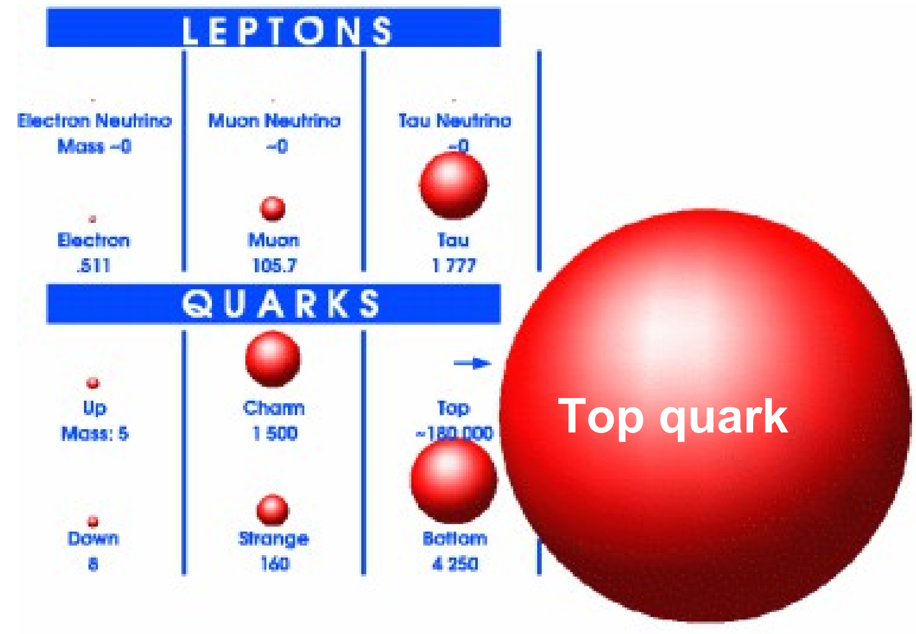
An enigmatic couple





Elementary Scalar?

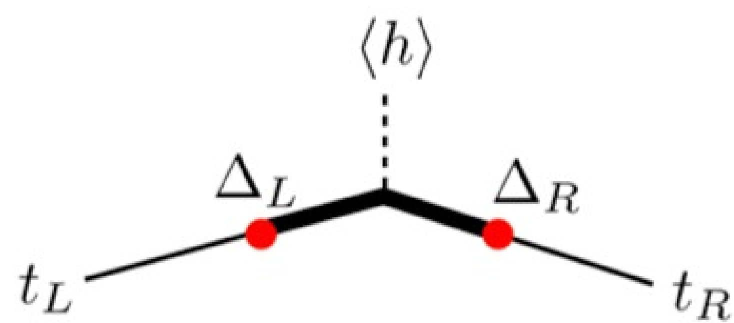
Composite object?



- 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

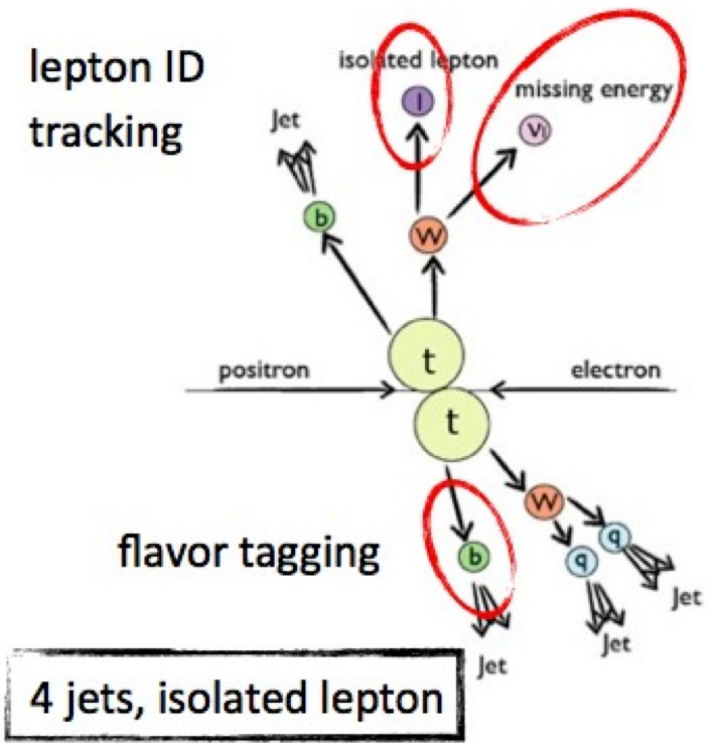
Three different final states:

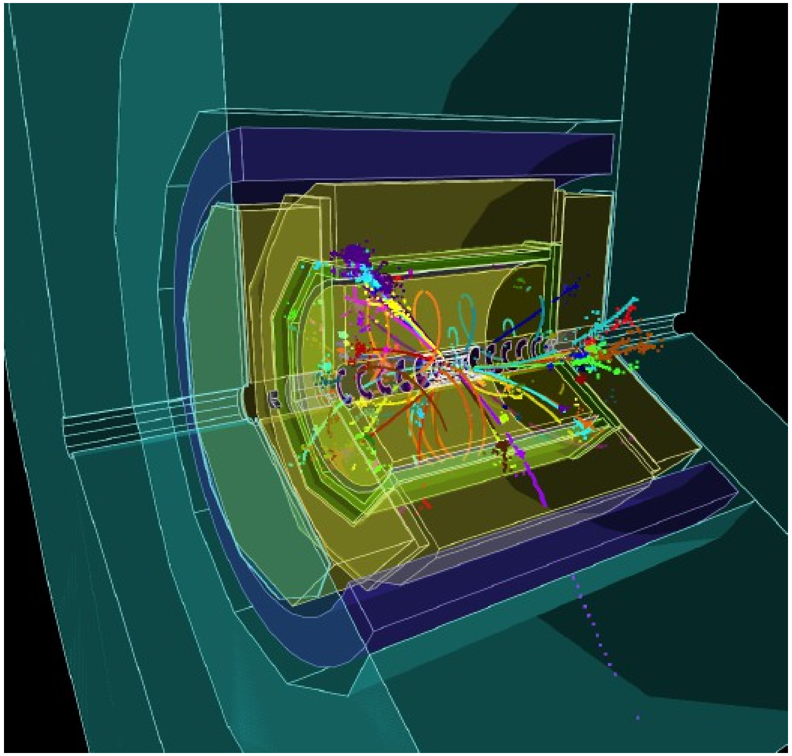
1) Fully hadronic (46.2%) → 6 jets

2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino

3) Fully leptonic (10.3%) → 2 jets + 4 leptons

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





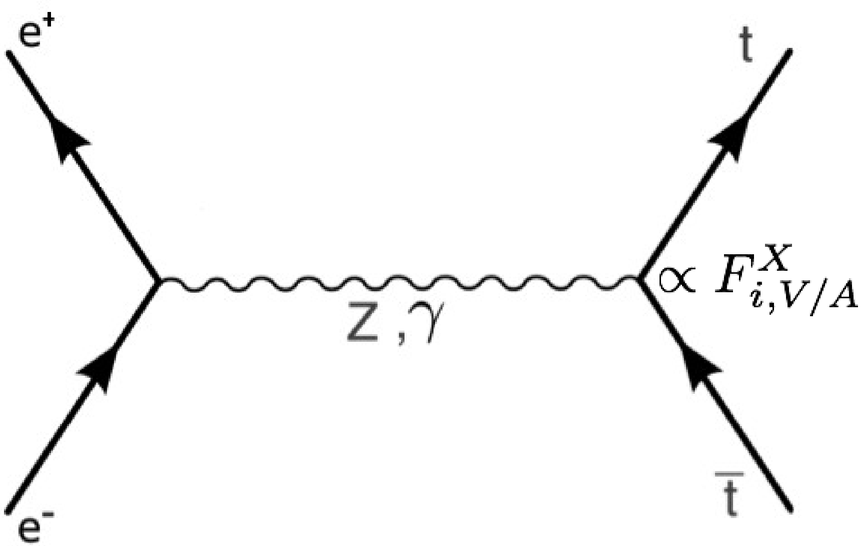
Final state reconstruction uses all detector aspects

Results shown in the following are based on full simulation of ILD Detector at $\sqrt{s}$ = 500 GeV

Testing the Chiral Structure of the Standard Model

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

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



Manifestation of New Physics:

- Modification of Ztt coupling
  Mixing between top and partners
  Mixing Z/Z'

- s-channel exchange of New Z'
  Including interference effects

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

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

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

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

⇩

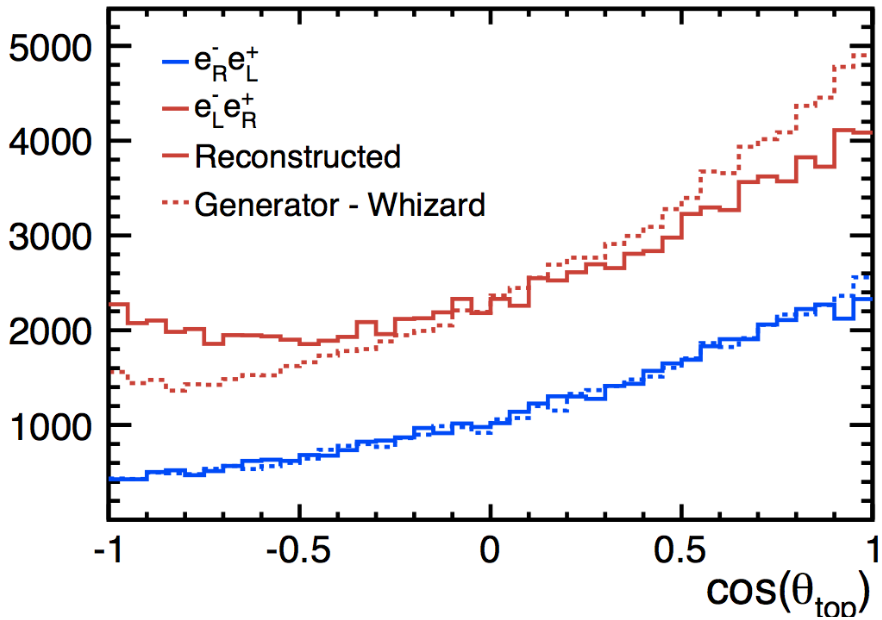
Extraction of relevant unknowns

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

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

Semi Leptonic Analysis - Reconstruction of θ_{top} at $\sqrt{s}$=500 Gev

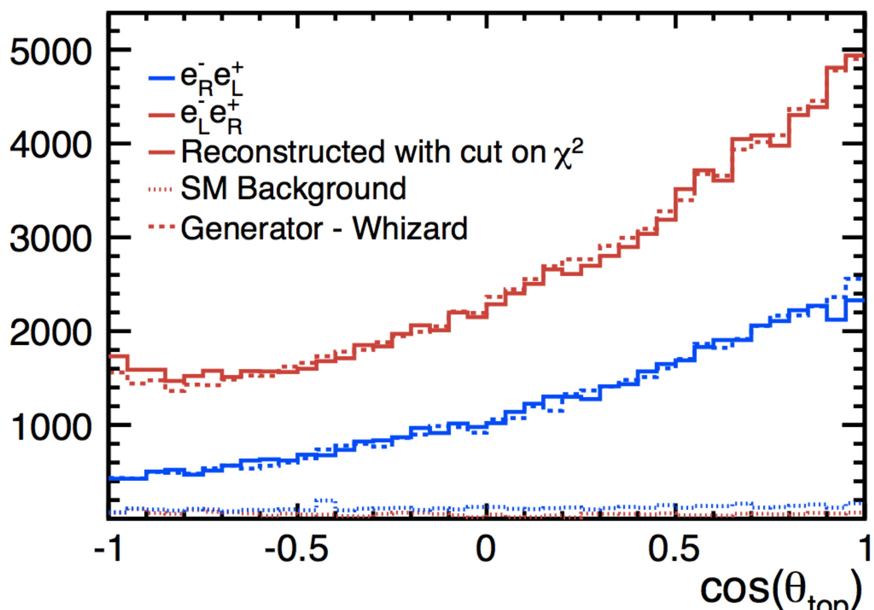
Arxiv:1505.06020
EPJC (2015) 75:512



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

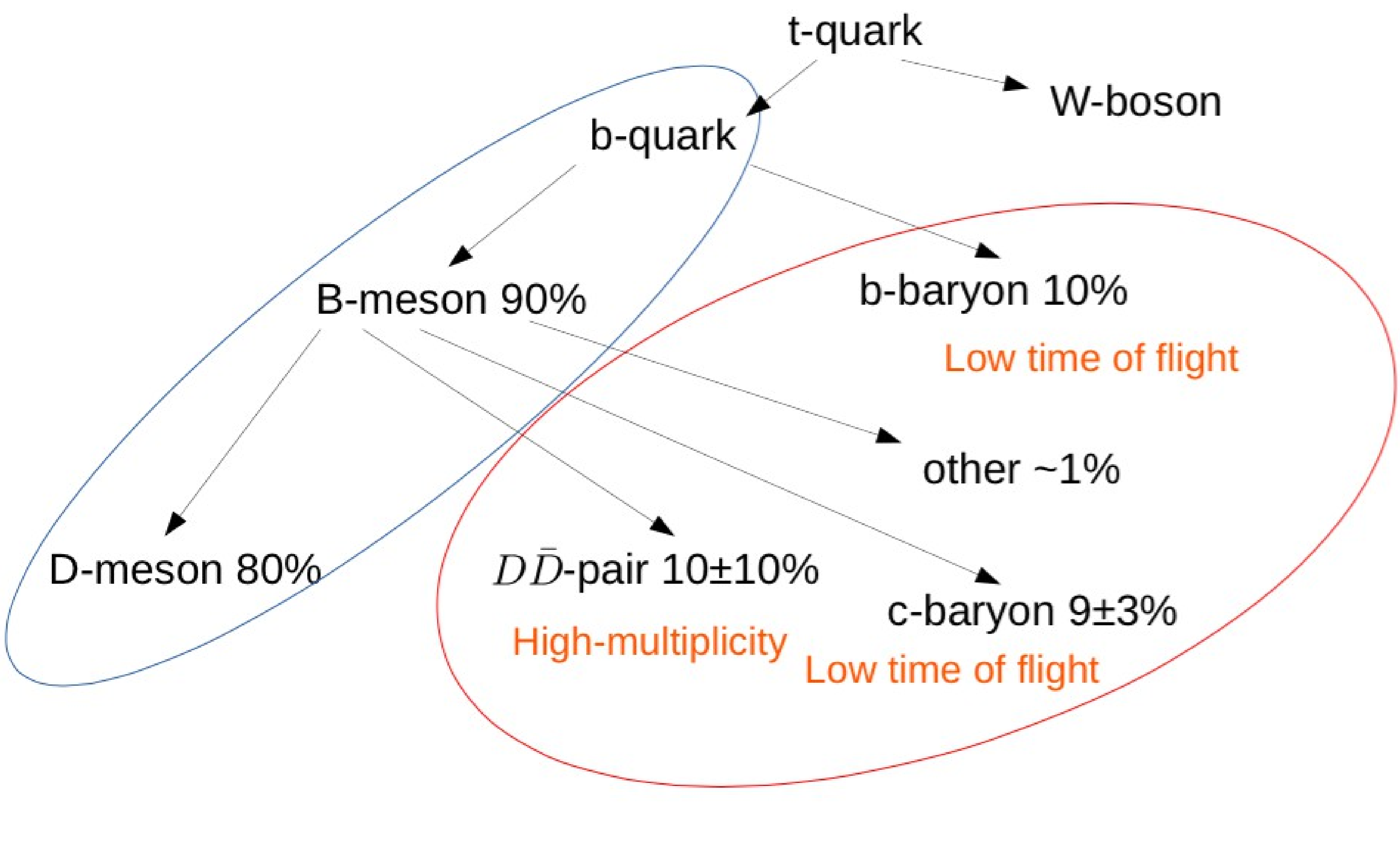
- Efficiency Penalty for e_L
- ε_{tot}: e_R ~ 50%, e_L ~ 30%

Results:

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{stat.}$ [%]	$(\delta A^t_{FB}/A^t_{FB})_{stat.}$ [%]
$-0.8, +0.3$	0.47	1.8
$+0.8, -0.3$	0.63	1.3

Top quark decay chain

- Hadronization and decay modes of b-quark:

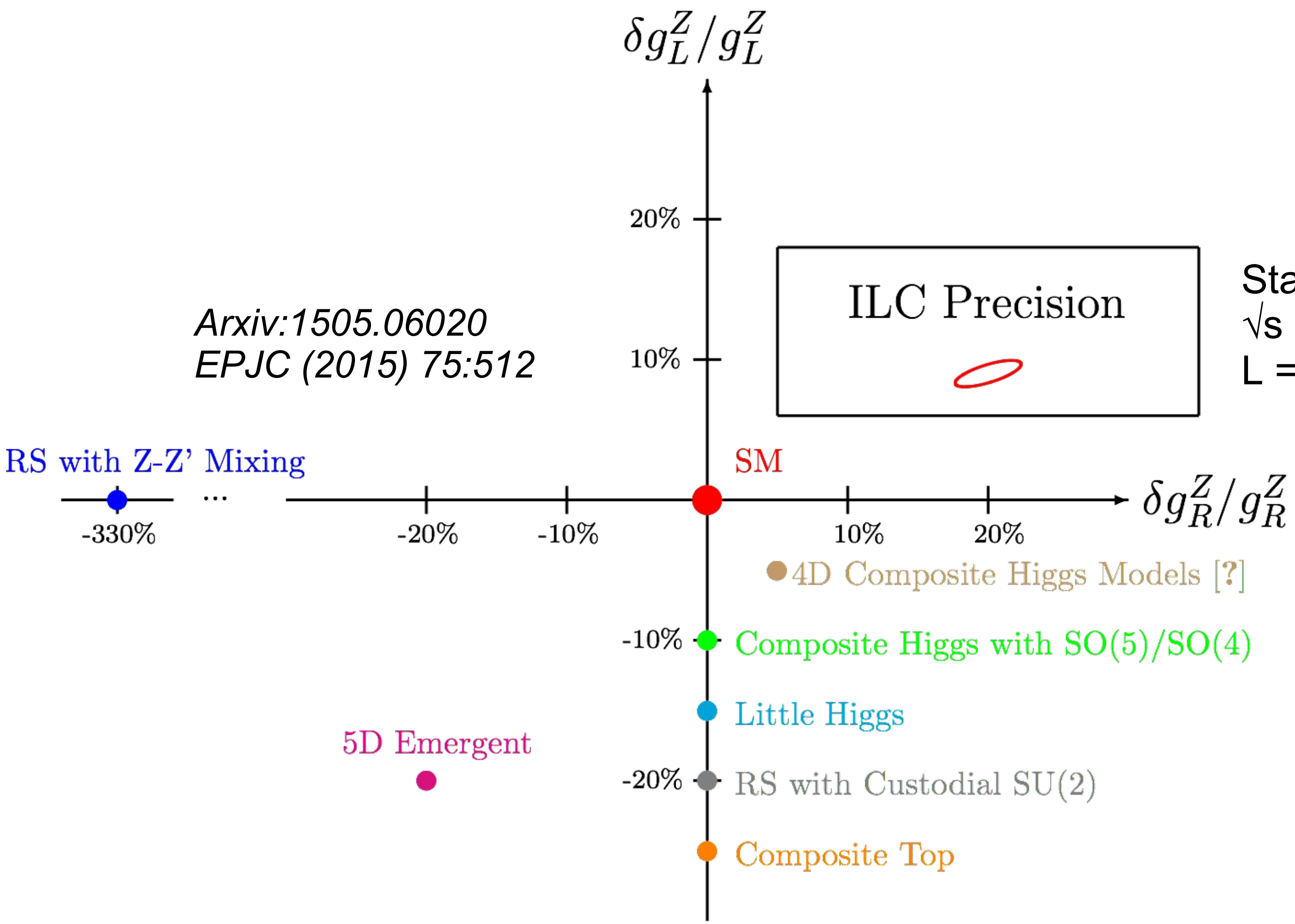


> 70% of the tops lead to “straightforward” reconstructable final states
Exploiting this observation is subject of PhD thesis at LAL (results from 2016 onward

Collaboration within French-Japanese TYL/FJPPL research programme

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

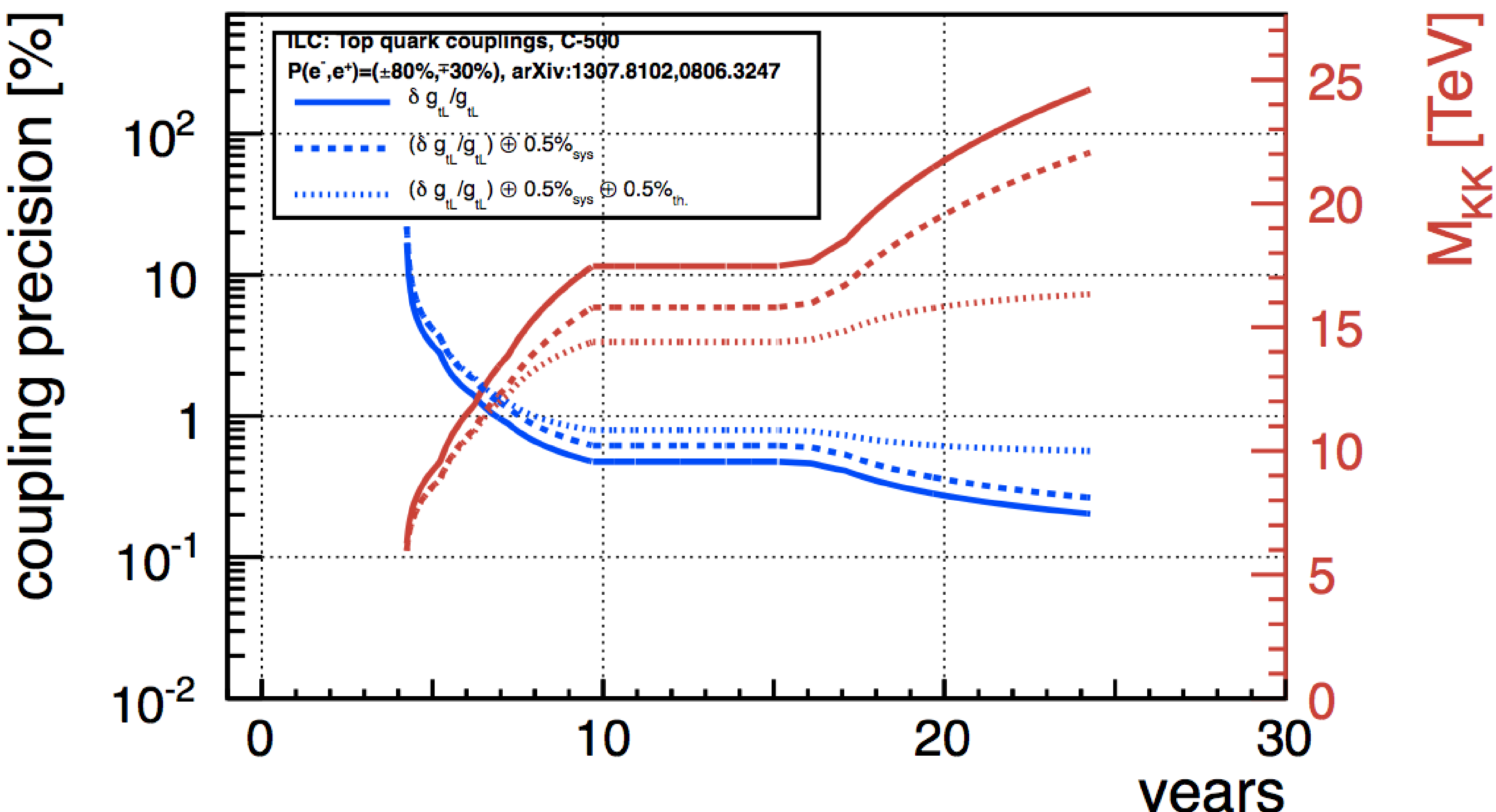
Precision expected for top quark couplings will allow to distinguish between models

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

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)

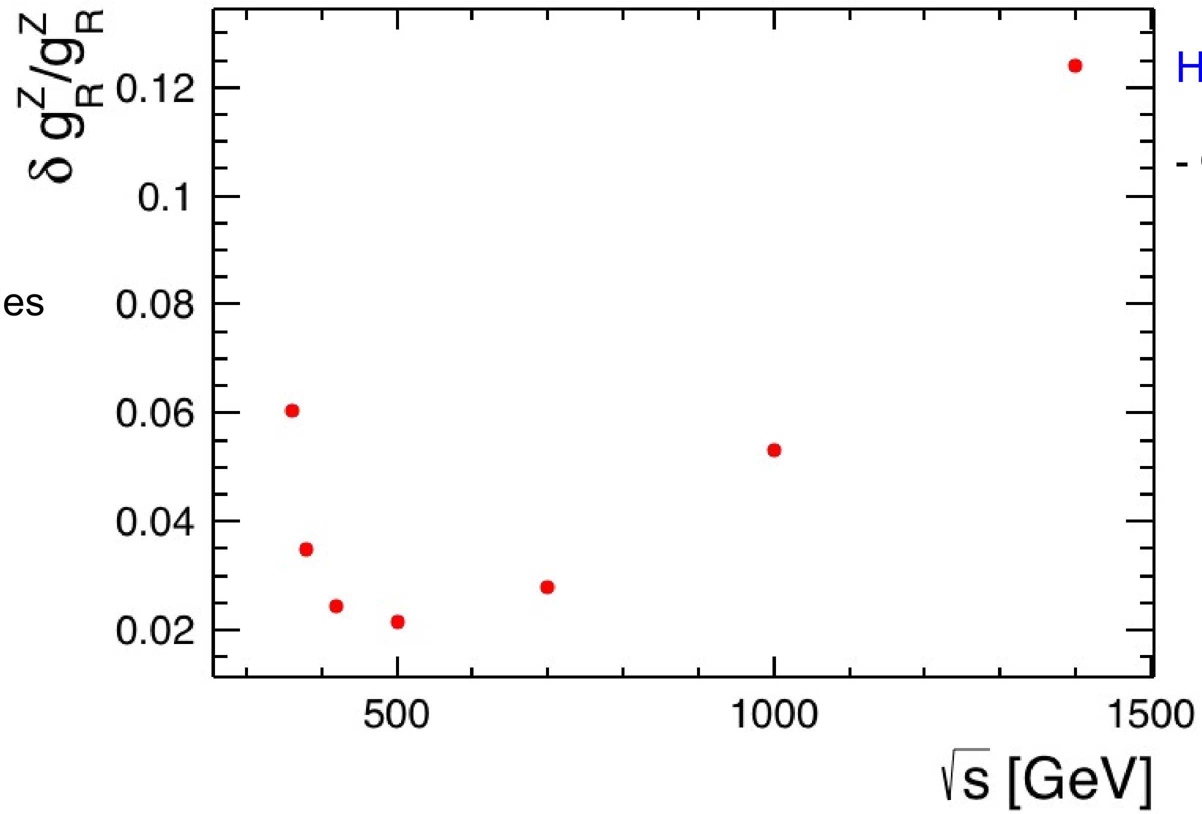
=> Important guidance for e.g. 100 TeV pp-collider

Different centre of mass energies I

... simplified discussion for gRZ

Small cms energies:

- Vanishing axial vector coupling
- On top (not shown) large QCD uncertainties (Juergen's talk)



High cms energies:

- Quickly decreasing cross section

Broad minimum between 400 and 700 GeV

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

However:

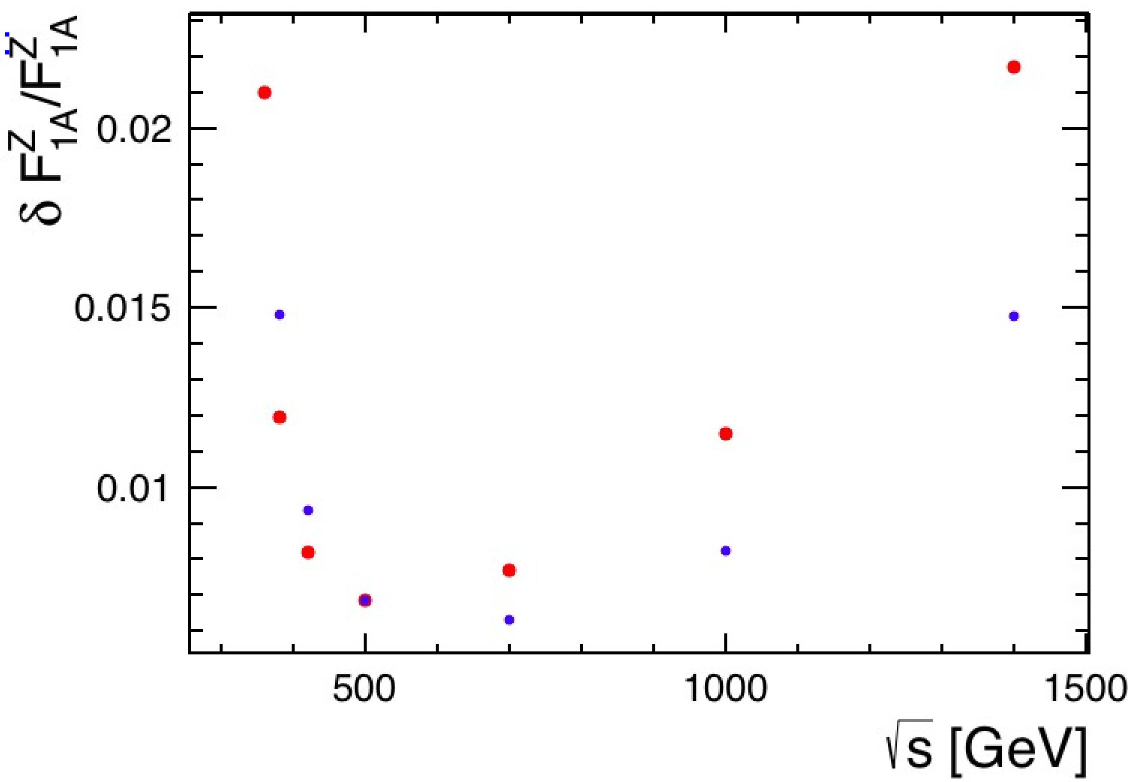
- Sensitivity to CP violating Higgs at smaller cms energies
- New physics at higher energies may increase cross section

Different centre of mass energies II

... influence of different instantaneous luminosities
(Assumption caveats, see backup)

Small cms energies:

- Vanishing axial vector coupling
  +
- Lumi decreases at linear colliders



High cms energies:

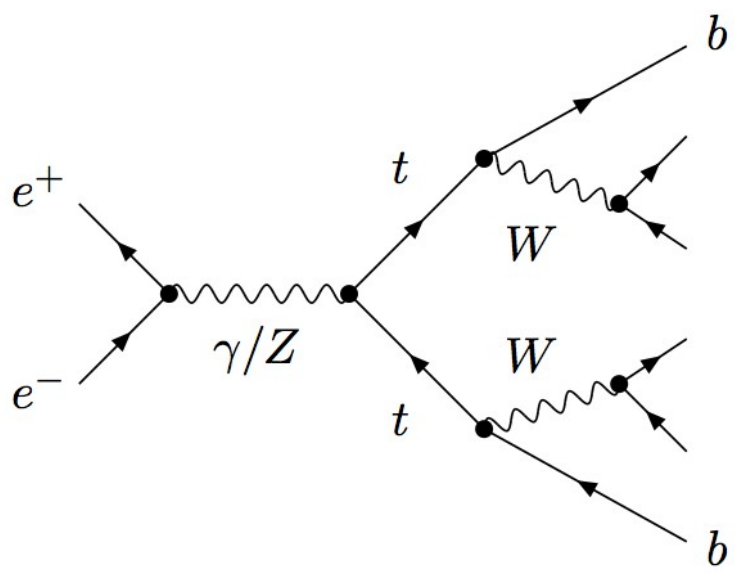
- Quickly decreasing cross section
- ... partially compensated by increasing luminosity

Broad minimum between 400 and 700 GeV

$\sqrt{s}$ ~ 500 GeV is "sweet spot" for coupling measurements
However:
- F1AZ would profit from somewhat higher energies (beta dependence)
- Remark: Full disentangling for F1VZ and F2VZ at ~1 TeV

$\sqrt{s}$ ~ 1 TeV attractive option

Trends in upcoming studies



Top pair production is effectively ee->6f process

- Role of (indistinguishable) single top production (Eur. Phys. J. C (2015) **75**: 223)
  Only relevant for e_L

- QCD and electroweak corrections for top decay chain

- Effects of finite top width and V_{tb} instead of Γ_t

- Exploitation of information of final state by matrix element method (arxiv: 1503.04247)
  Unbiased access to tensorial CP violating form factors !?

- Exotic decays as e.g. t->ch

Summary

- A LC is the right machine for **Rediscovery of the top quark** by precision physics
  Production top pairs in electroweak production!!!
  Essential pillar of LC physics program
  Experimental programme can take full advantage of flexible running (cms energy)

- 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

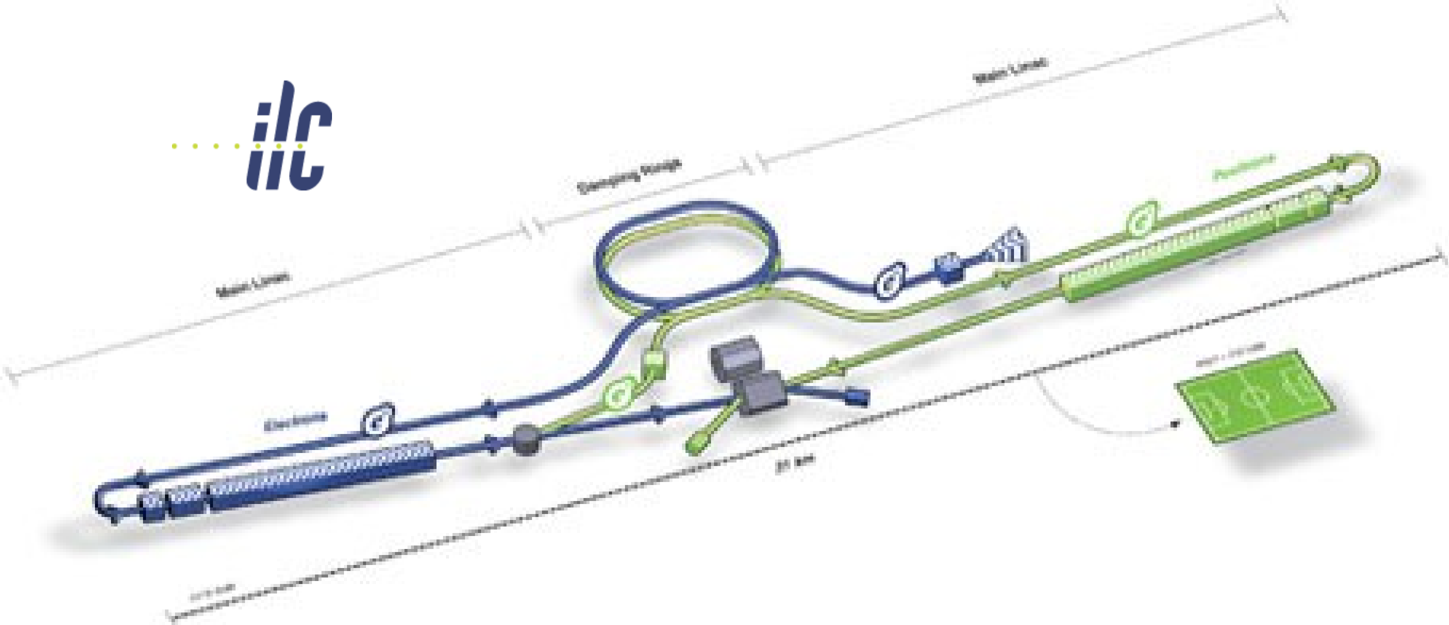
- Main experimental issues is control of migrations in A_{FB}
  … but keeping the promises is maybe biggest challenge in coming years

- Alternatives with matrix element method under study (see F. LeDiberder)

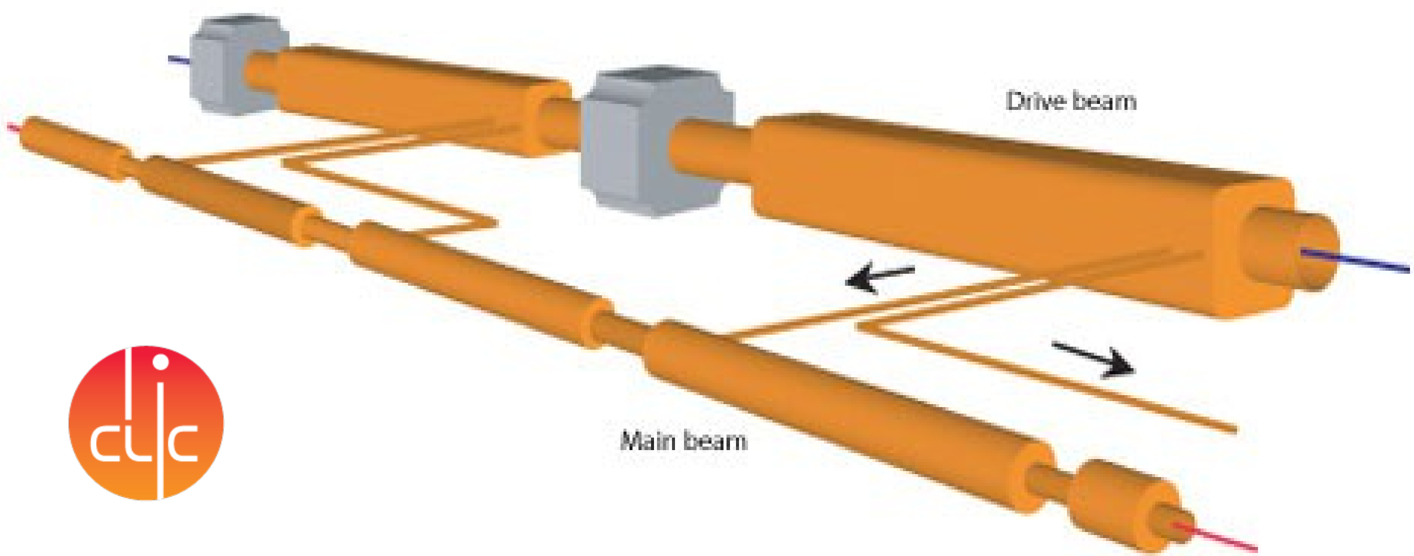
- Next step (many years project) is full experimental and theoretical understanding of six-fermion final state

Backup ....

Future Linear Electron-Positron Colliders



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



Energy: 0.5 - 3 TeV

CDR in 2012

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\text{GeV}]\sin^{3/2}\theta)]$ μm(1/3 x SLD)

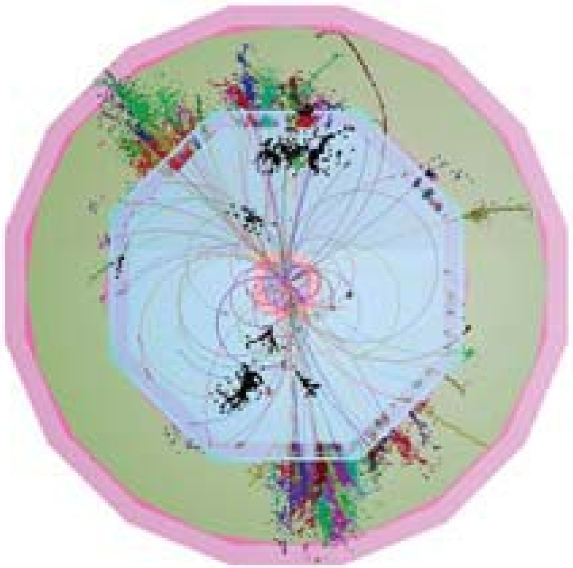
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\text{GeV}))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g. SUSY)



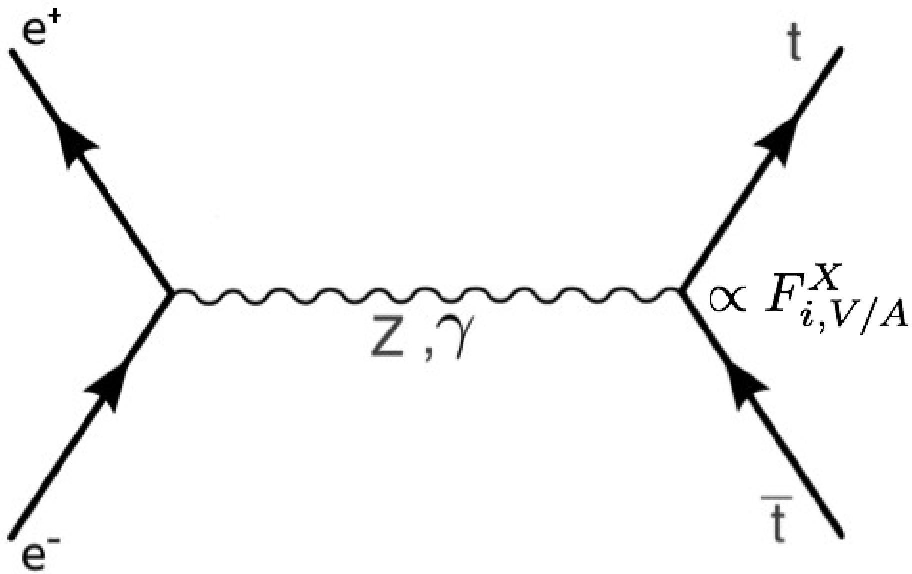
Final state will comprise events with a large number of charged tracks and jets(6+)

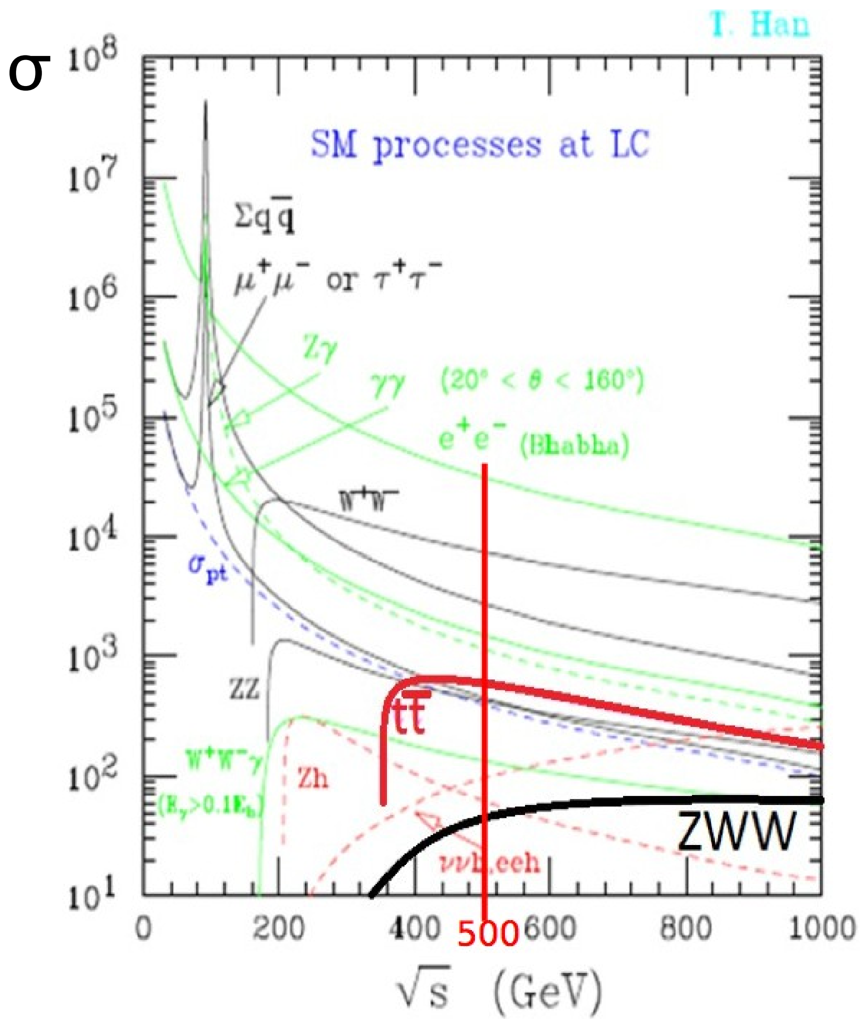
- High granularity
- Excellent momentum measurement
- High separation power for particles

- Particle Flow Detectors

Detector concepts ILD and SiD

Top Quark Physics at Electron-Positron Colliders

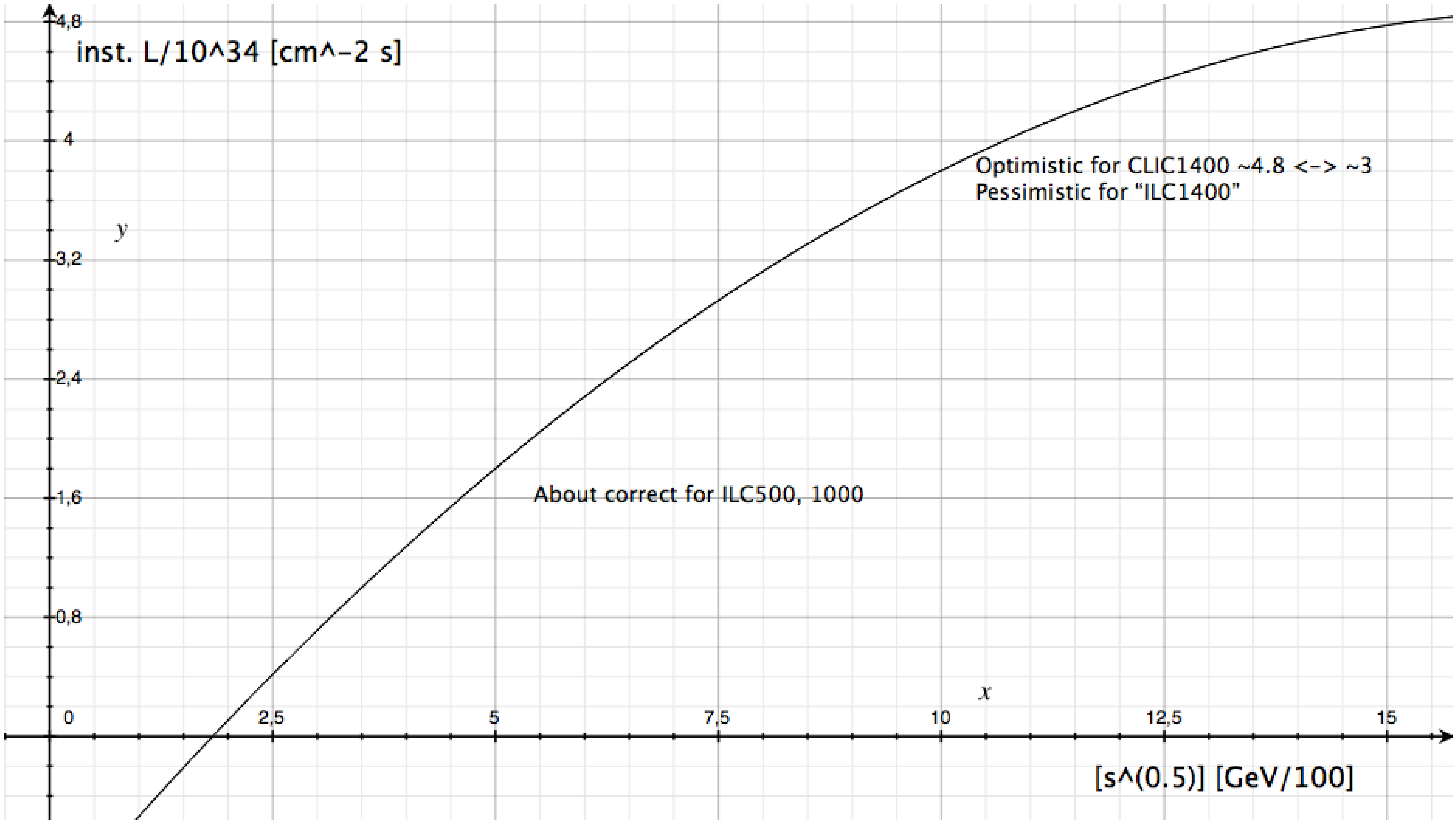




- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

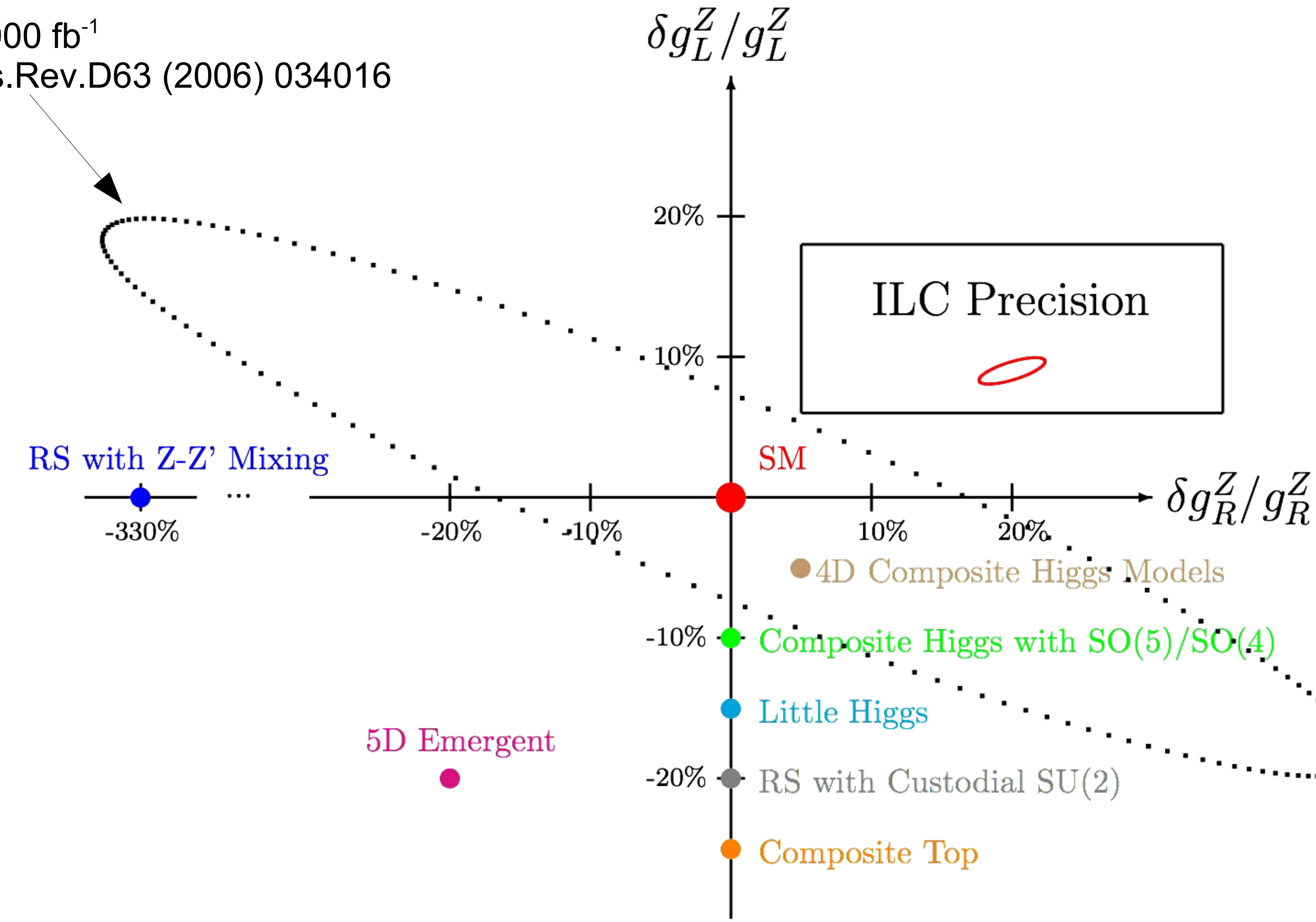
- High precision measurements
  - Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F and couplings g

Assumptions for Lumi scaling



What about LHC perspectives?

LHC14, 3000 fb^{-1}
From Phys.Rev.D63 (2006) 034016

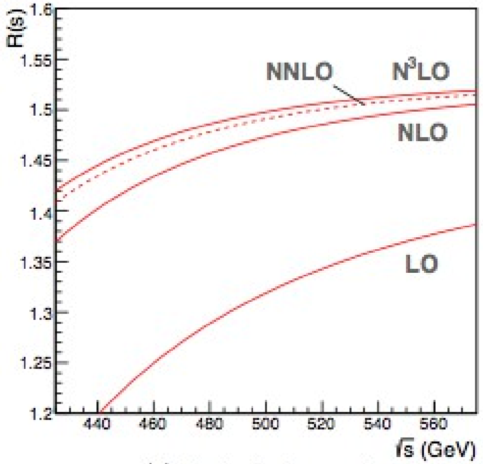


Linear Collider will outperform LHC results

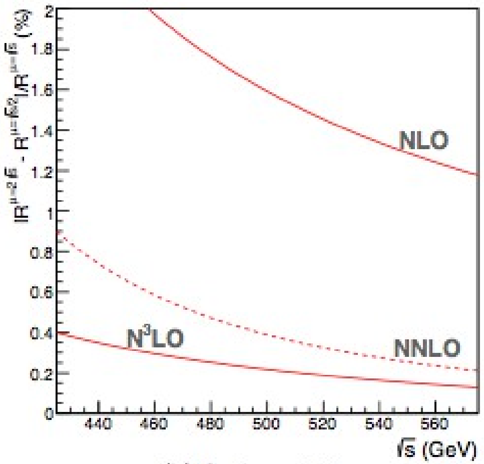
- Particular poor constraint on g_R (this holds also for flavor physics results)
- LHC LO QCD analysis, ~30% improvement through NLO QCD
- LHC may still be capable to exclude models

Theoretical uncertainties

✳QCD corrections are known up to N³LO



(a) Perturbation series

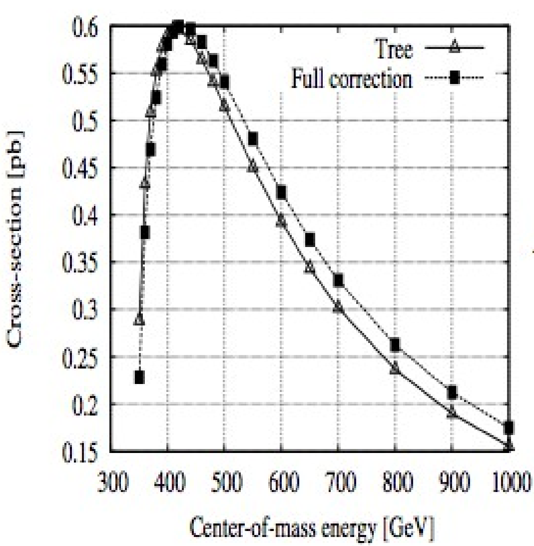


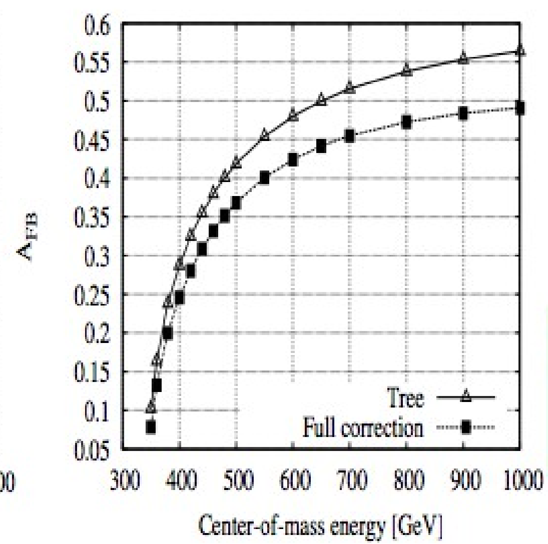
(b) Scale variations

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

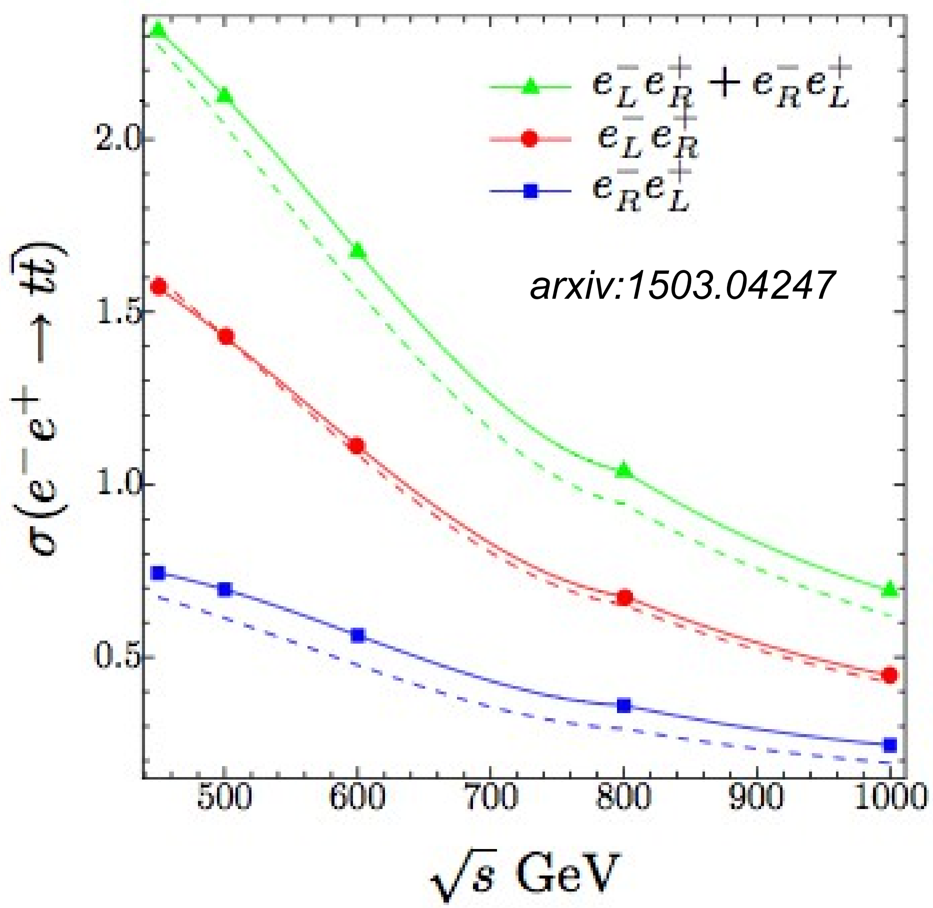


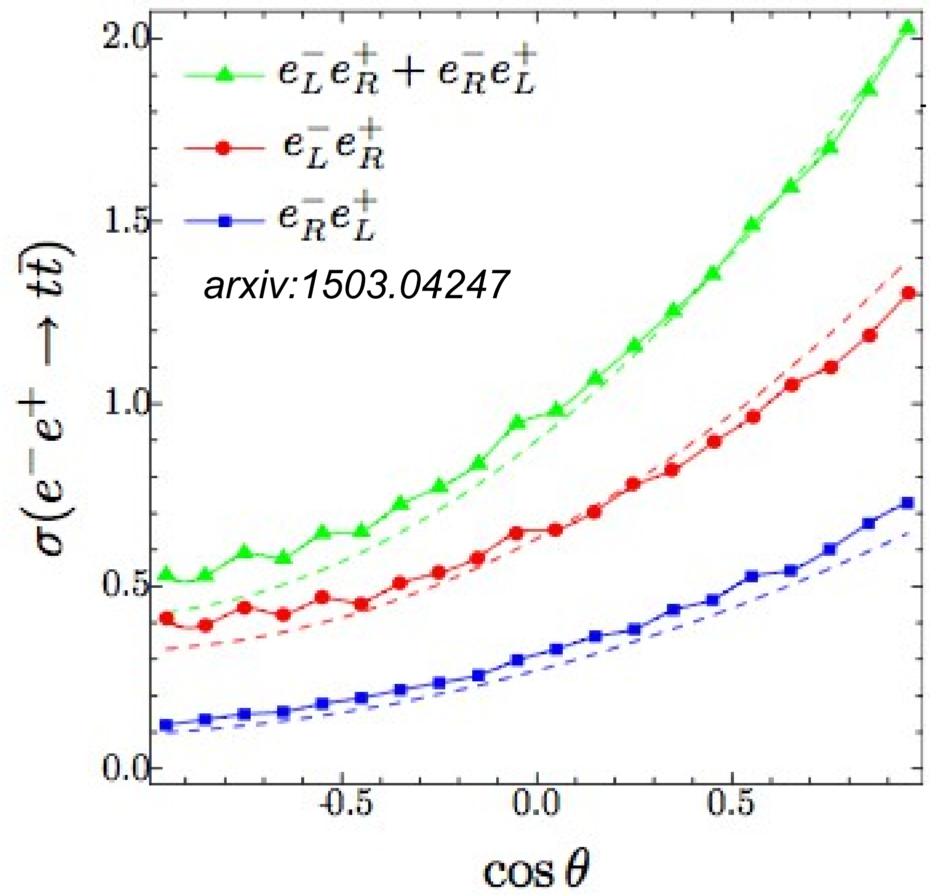


EW correction at one-loop is ~5% for cross section ~10% for A_{FB}

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

Detailed look at higher order elw. corrections - GRACE

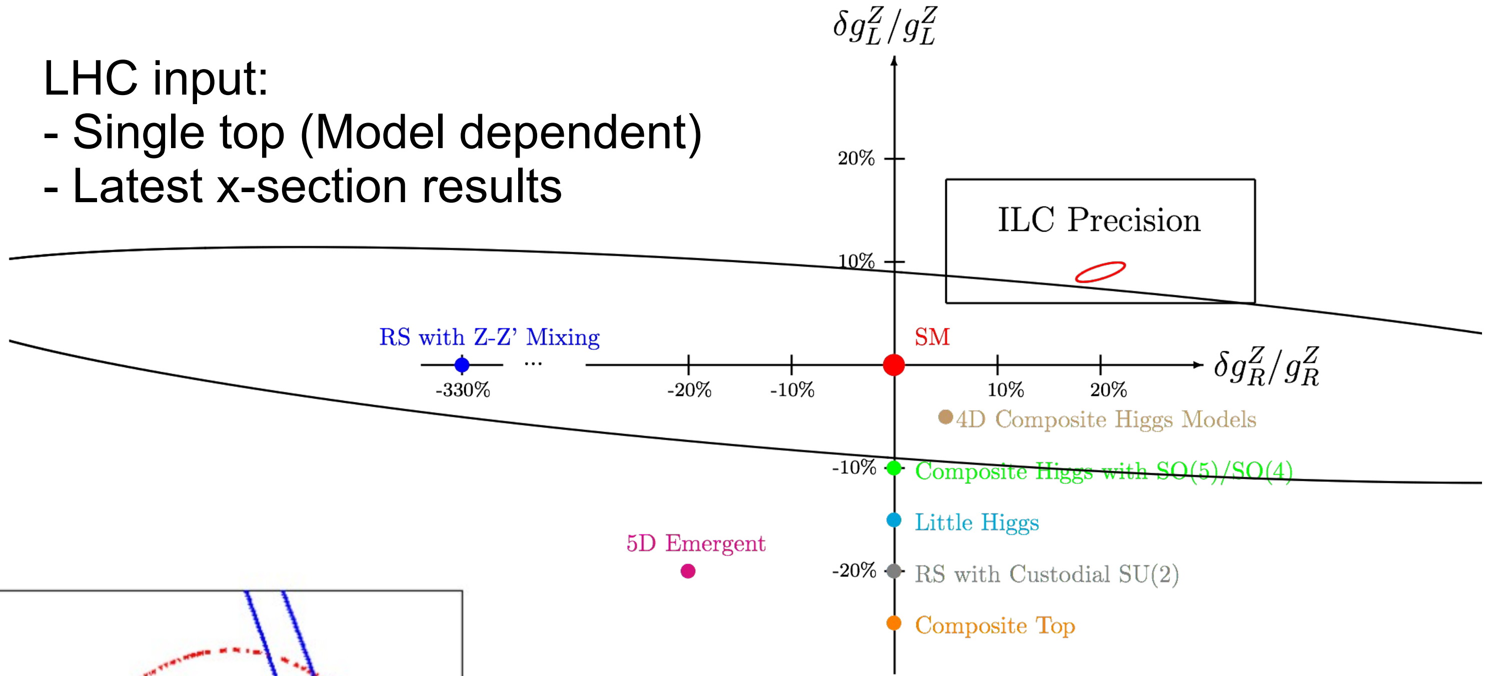


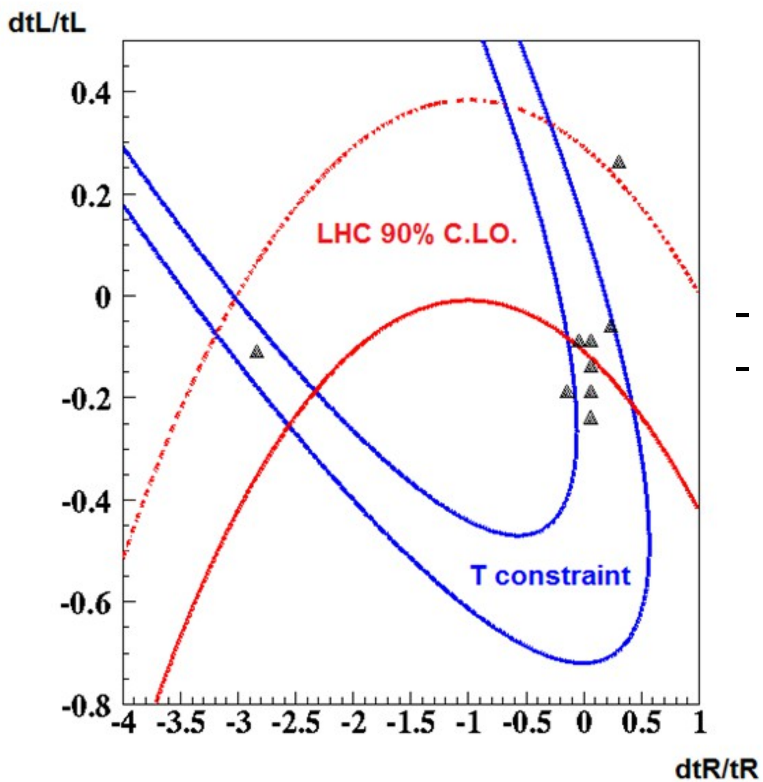


- Electroweak corrections manifest themselves differently for different beam polarisations
- Beam polarisation important asset to disentangle SM and effects of new physics
Configuration $e_R^- e_L^+$ seems to lead to "simpler" corrections

Comparison with current LHC results

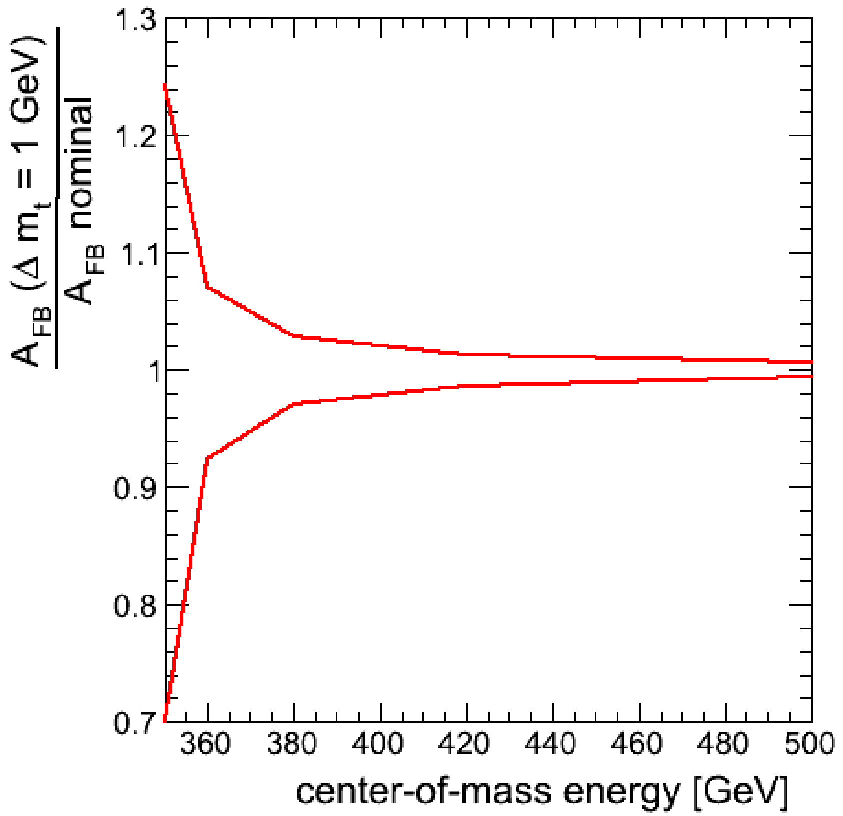
LHC input:
- Single top (Model dependent)
- Latest x-section results





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

From threshold to continuum



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

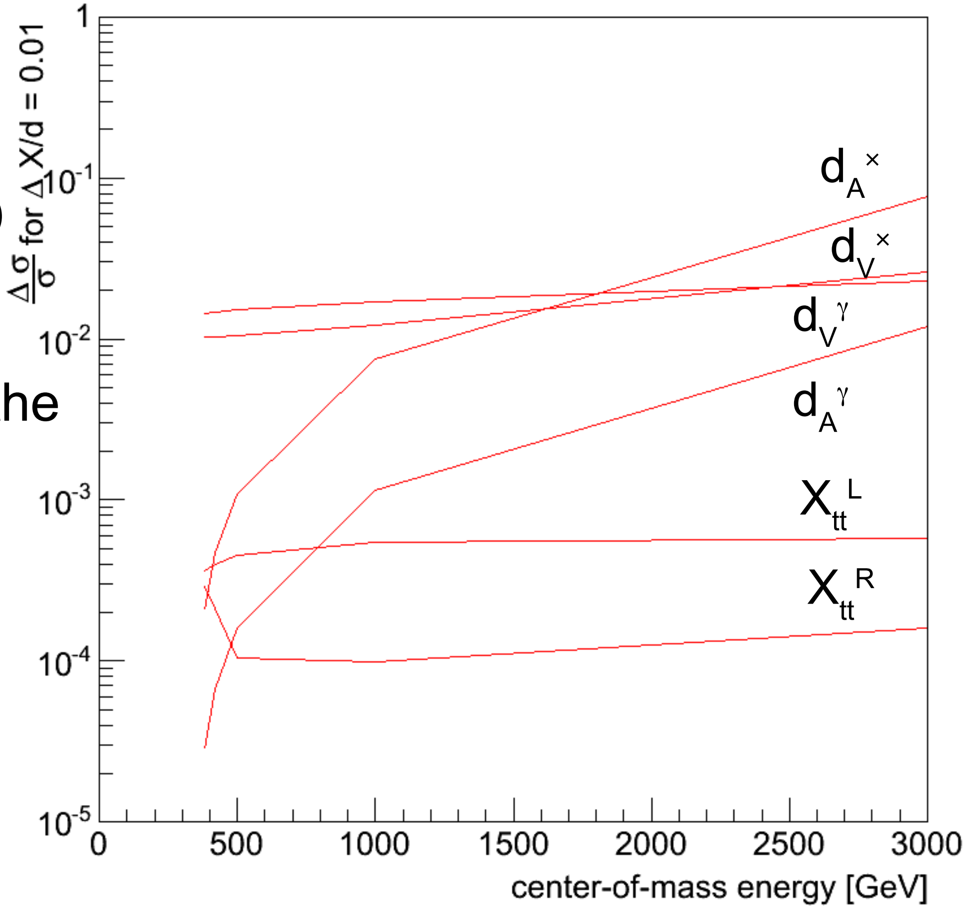
- very pronounced below √s = 360 GeV
- 2.9%/GeV at √s = 380 GeV
- 1.3%/GeV at √s = 420 GeV
- 0.6%/GeV at √s = 500 GeV

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

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



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.)