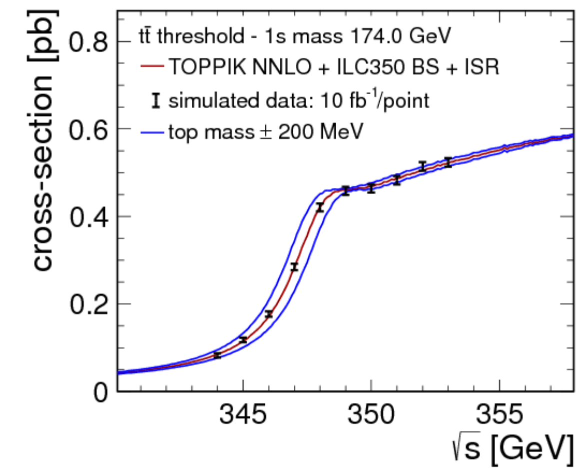
Precision top quark physics at a future linear e^+e^- collider; top EW couplings versus center-of-mass energy

Marcel Vos
IFIC (U. Valencia/CSIC), Spain

With special thanks to:
F. Bach (DESY), W. Bernreuther (RWTH Aachen), A. Hoang (U. Vienna),
P. Ruiz-Femenia (MPI), M. Stahlhofen (DESY)
F. Richard, R. Poeschl (LAL Orsay)
I. Garcia, M. Perello, E. Ros (IFIC Valencia)

LC top physics – canonical programme



350 GeV:

Threshold: top quark mass to << 100 MeV (+width & Yukawa)

Kuhn, Acta Phys.Polon. B12 (1981) 347

Martinez, Miquel, EPJ C27, 49 (2003)

Seidl, Simon, Tesar, Poss, EPJC73 (2013) 2530

A. Juste et al. ArXiv:1310.0799

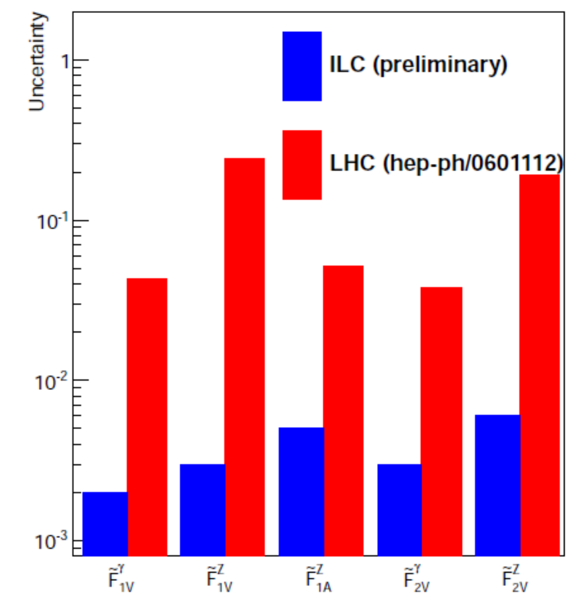
P. Marquard et al., arXiv:1502.01030

500 GeV:

New physics: precise characterization of $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices

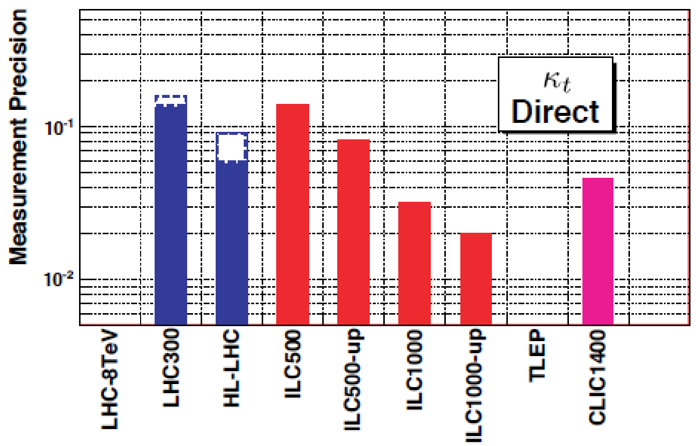
M.S. Amjad et al., arXiv:1307.8102

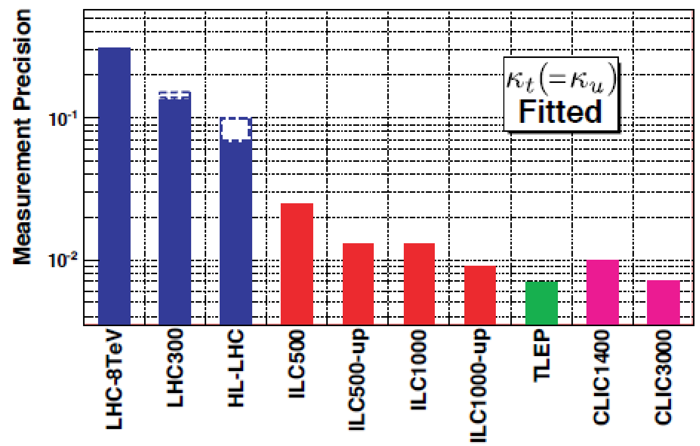
F. Richard, arXiv:1403.2893



500-1500 GeV:

$t\bar{t}H$ direct access to top Yukawa coupling





Studies at relevant thresholds (tt, ttH) and at 500 GeV
How well can we measure couplings at √s other than 500 GeV?
Which sensitivity to new physics do we gain?

Top quark couplings in a nutshell

measure

$\sigma(+)\quad A_{FB}(+)$

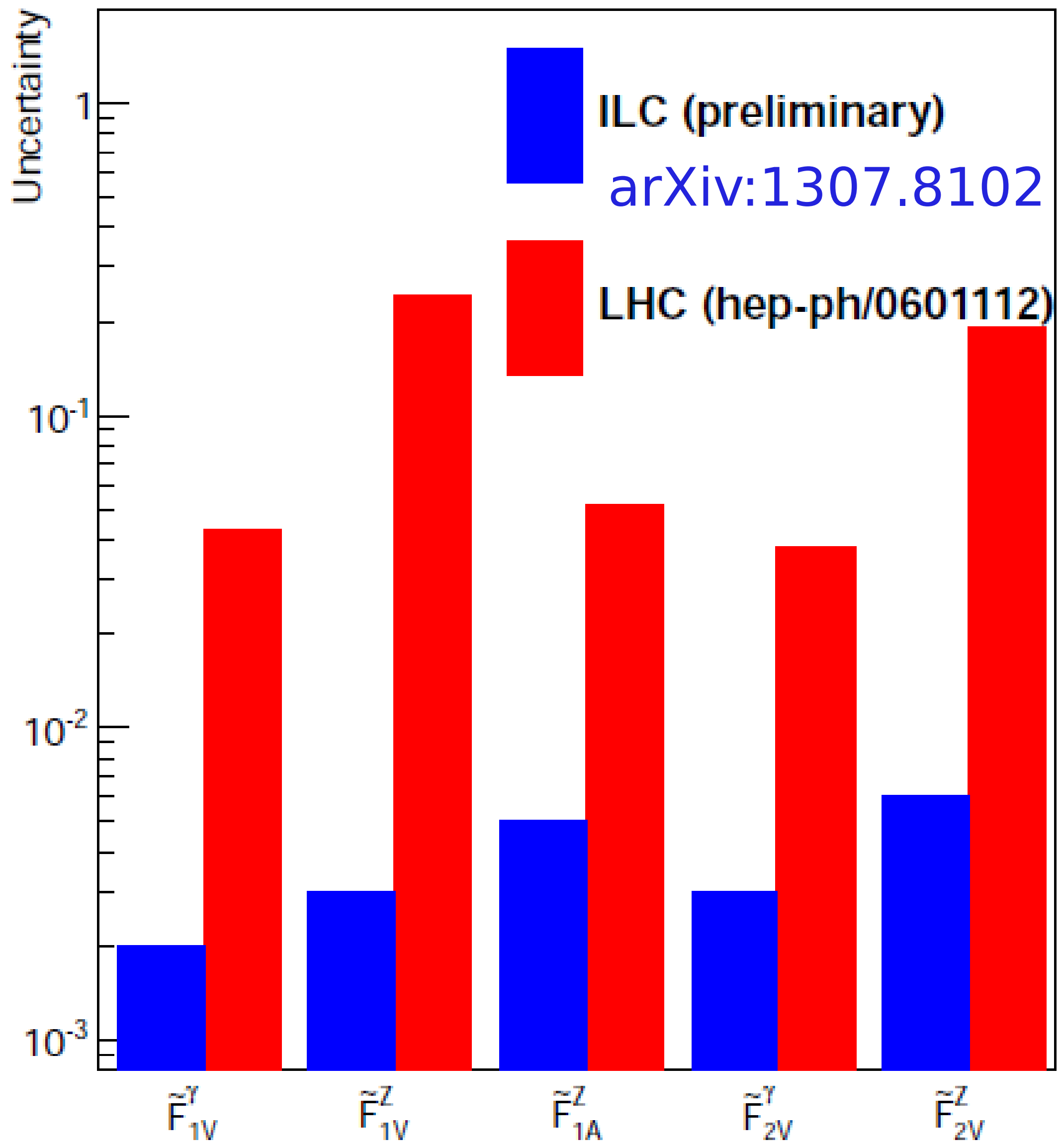
$\sigma(-)\quad A_{FB}(-)$

extract

$$\left.\begin{matrix}(+=e^-_R)\\(-=e^-_L)\end{matrix}\right\}\Rightarrow\left\{\begin{matrix}F^{\gamma}_{1V} & * & F^{\gamma}_{2V}\\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V}\end{matrix}\right\}$$

Measure 2 observables
for 2 beam polarizations:
- x-section
- FB asymmetry

Extract form factors in groups
(assuming SM for remaining groups)



Assumptions:

LHC: 14 TeV, 300/fb

LC: √s = 500 GeV, L = 500/fb

$P(e^-)$ = +/- 80%, $P(e^+)$= -/+ 30%

$\delta\sigma$ ~ 0.5% (stat. + lumi)

δA_{FB} ~ 1.8% (stat., covers systematics?)

Polarization needed to disentangle photon and Z-boson form factors!

Especially for ttZ LC precision is better than existing (model-dependent) limits from top decay, LEP T-parameter, B-factories (full comparison in progress)

Top-Z and top-photon couplings and new physics

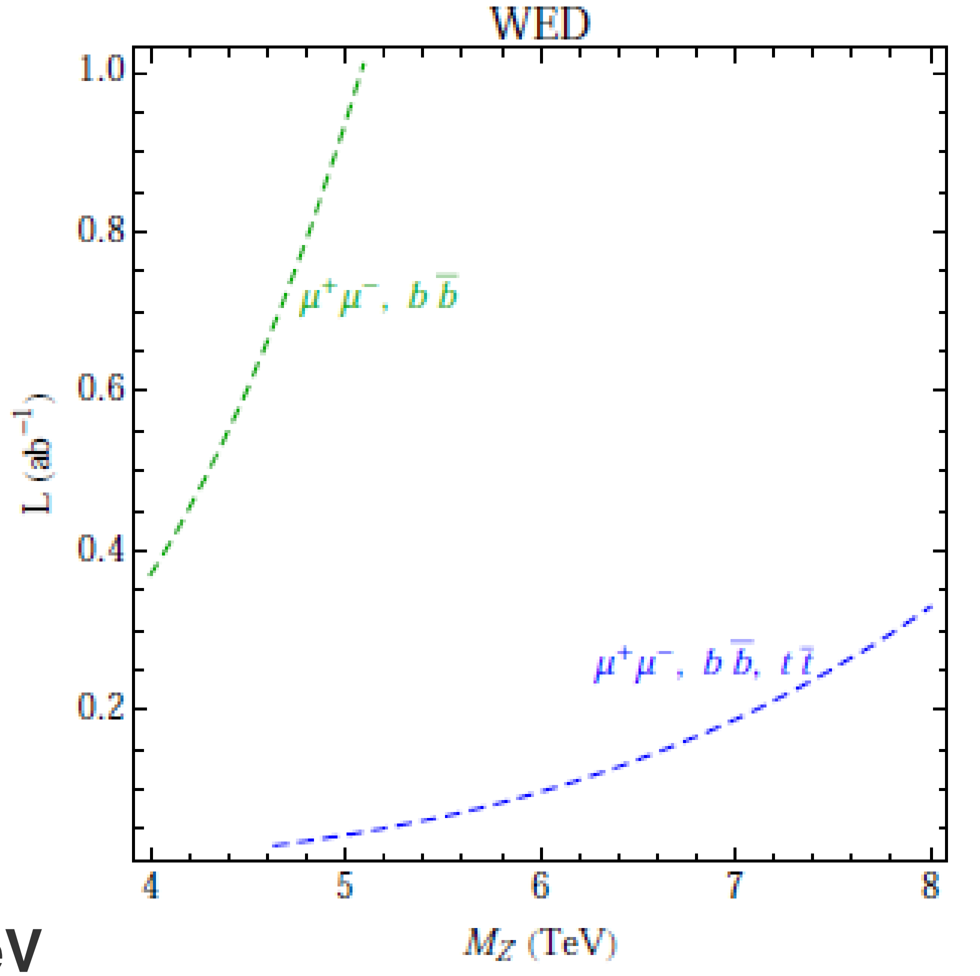
(see Roman Poeschl's talk this morning)

Marcel Vos (marcel.vos@ific.uv.es)

Sensitivity to BSM

Warped Extra Dimension (WED)
Model based on SU(2) x SU(2) x U(1) symmetry on a slice of AdS5,
features a composite top quark with preferential coupling
to the extra gauge bosons!

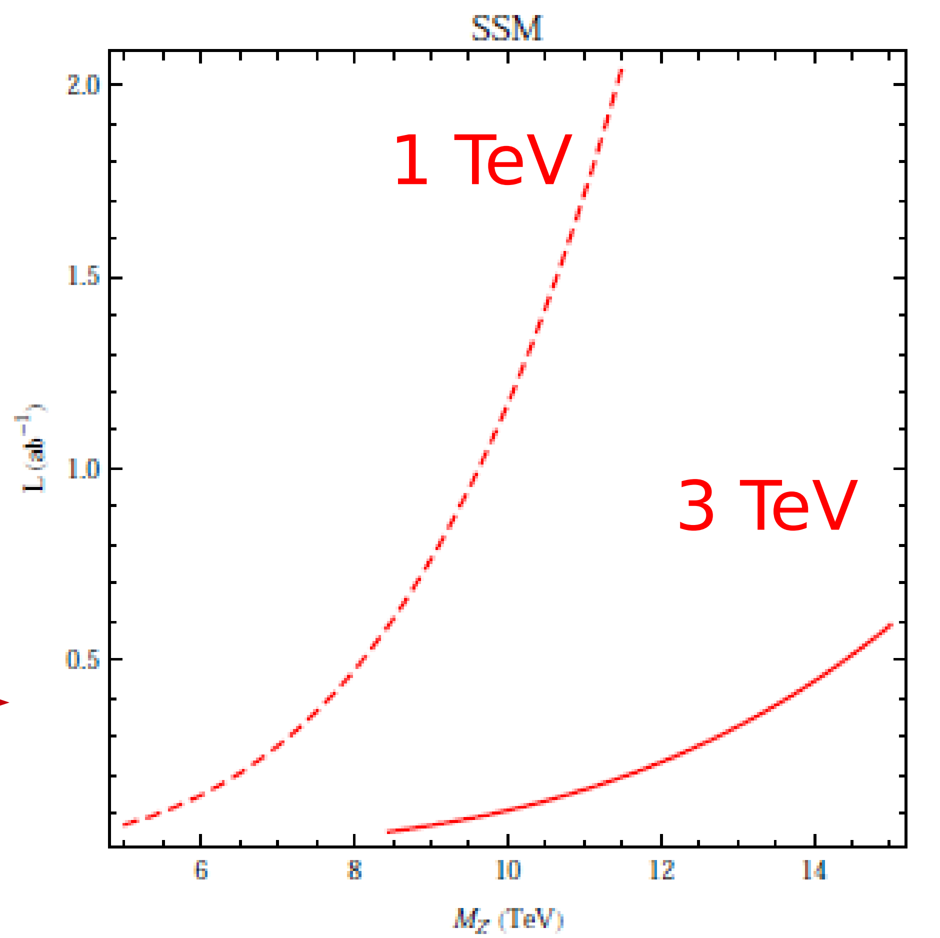
BSM reach strongly enhanced by $t\bar{t}$ FB asymmetry measurement



With the same assumptions on AFB accuracy,
a 500 GeV (1 TeV) ILC has mass reach for Z'_{SSM} > 3 (5) TeV

Naively: the closer to the new physics scale the larger the indirect effects

Dependence of Z' mass reach on center-of-mass energy
Much less luminosity required to see signal at high √s
Assumptions: $\delta\sigma/\sigma = 0.7\%$, $\delta A_{FB}/A_{FB} = 1.5\%$, $\delta A_{LR}/A_{LR} = 2\%$
F. Corradeschi, LCWS10, arXiv:1202.0660 and M. Battaglia, LCWS11



Top quark couplings

$$\Gamma^{\mu}_{t\bar{t}(\gamma,Z)} = ie\left[\gamma^{\mu}\left[\tilde{F}^{\gamma,Z}_{1V} + \tilde{F}^{\gamma,Z}_{1A}\gamma^{5}\right] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}\left[\tilde{F}^{\gamma,Z}_{2V} + \tilde{F}^{\gamma,Z}_{2A}\gamma^{5}\right]\right]$$

$$\tilde{F}^{X}_{1V} = -(F^{X}_{1V} + F^{X}_{2V}),\ F^{\gamma}_{1V} = -2/3,\ F^{Z}_{1V} = \frac{-1}{4\,sw\,cw}(1 - 8/3\,sw^{2})$$

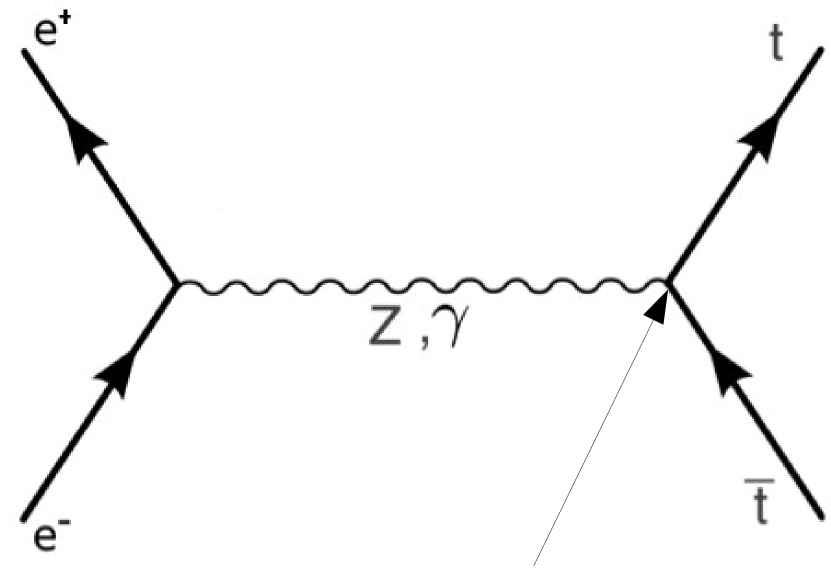
$$\tilde{F}^{X}_{1A} = -F^{X}_{1A},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A} = \frac{1}{4\,sw\,cw}$$

(fixed by gauge invariance, not considered further)

$$\tilde{F}^{X}_{2V} = F^{X}_{2V},\ F^{\gamma}_{2V} = Q_t(g-2)/2 \propto d^{X}_{V}$$

$$\tilde{F}^{X}_{2A} = -iF^{X}_{2A},\ F^{X}_{2A} \propto d^{X}_{A}$$

(Q_t = electric charge, g-2 = anom. magn. Mor
(d = dipole moment, F_{2A} violates CP)



Most general expression for this vertex...

Close to threshold observables depend on F_{1V} + F_{1A}.
Full disentangling imprecise for √s < 1 TeV.

Control over beam polarization is vital to distinguish photon and Z form factors!!

Photon-Z interference brings sensitivity to sign of form factors

CP violating form factors F2A are best measured with special CP observables (TESLA TDR)

For a translation to effective operators language, see J.A. Aguilar Saavedra, Nucl. Phys. B812 (2009), arXiv:1308:

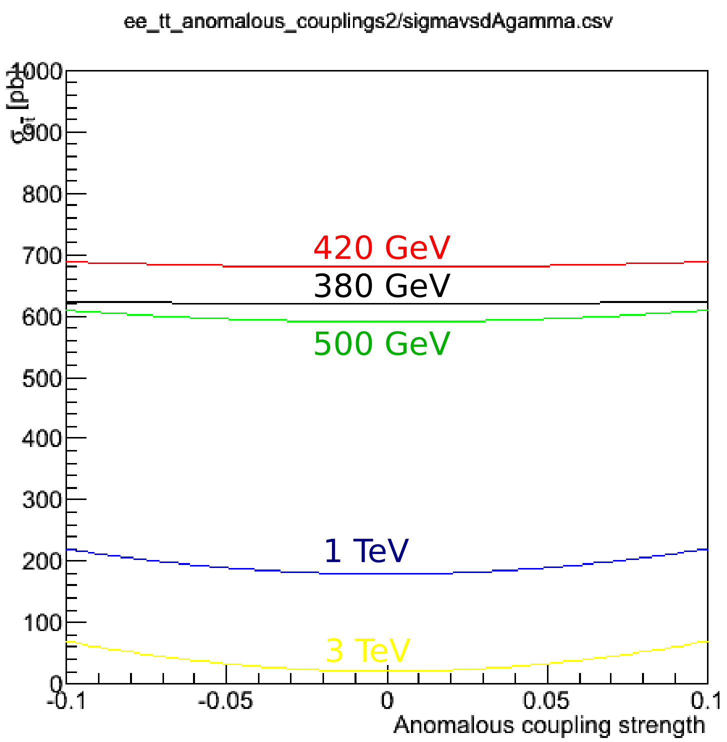
$$L_{eff} = \Sigma \frac{C_x}{\Lambda^2} O_x$$

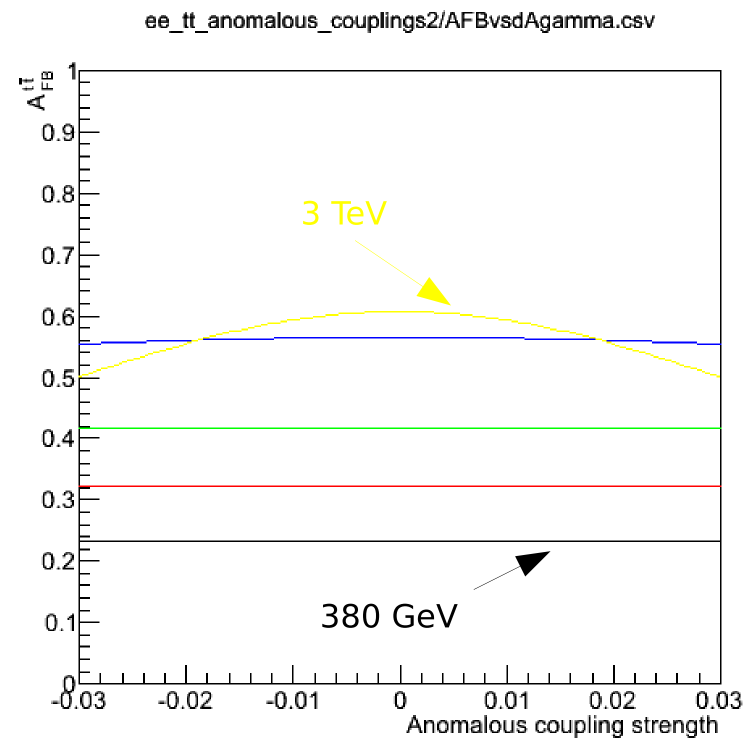
$$X^{R}_{tt} \propto F^{Z}_{1V} + F^{Z}_{1A} + c$$

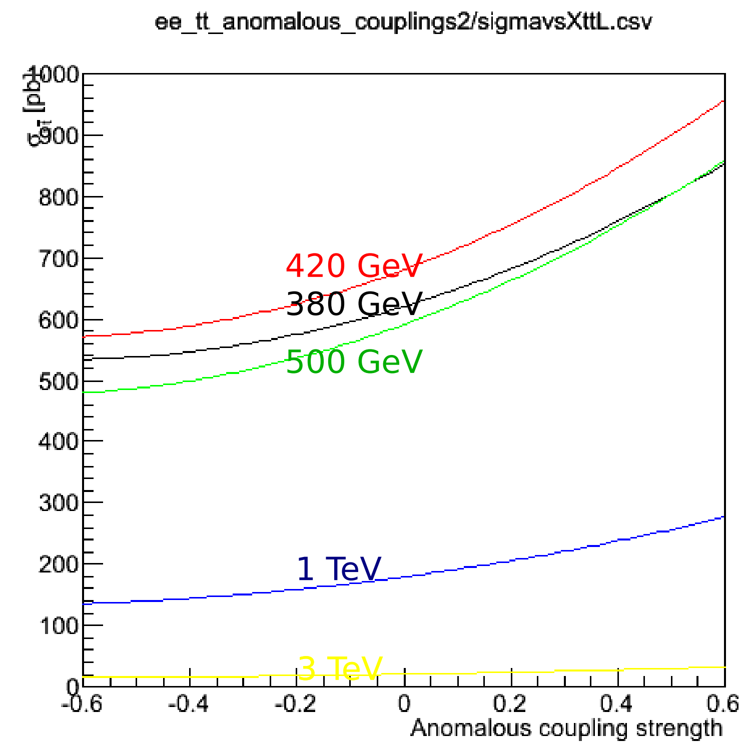
$$\delta X^{R}_{tt} = -\Re(C^{33}_{\varphi u})\frac{v^2}{\Lambda^2}$$

relations with W-t-b and gluon-t-t vertices
explicit dependence on new physics scale
Roentsch/Schulze (arXiv:1501.05939)
Fiolhais/Aguilar-Saavedra (JHEP 1207, 180)
Implemented in WHIZARD (F. Bach)

Impact of new physics







Vary anomalous couplings in narrow range around 0 and register changes in cross-section and A_{FB}

Repeat at different center-of-mass energies:

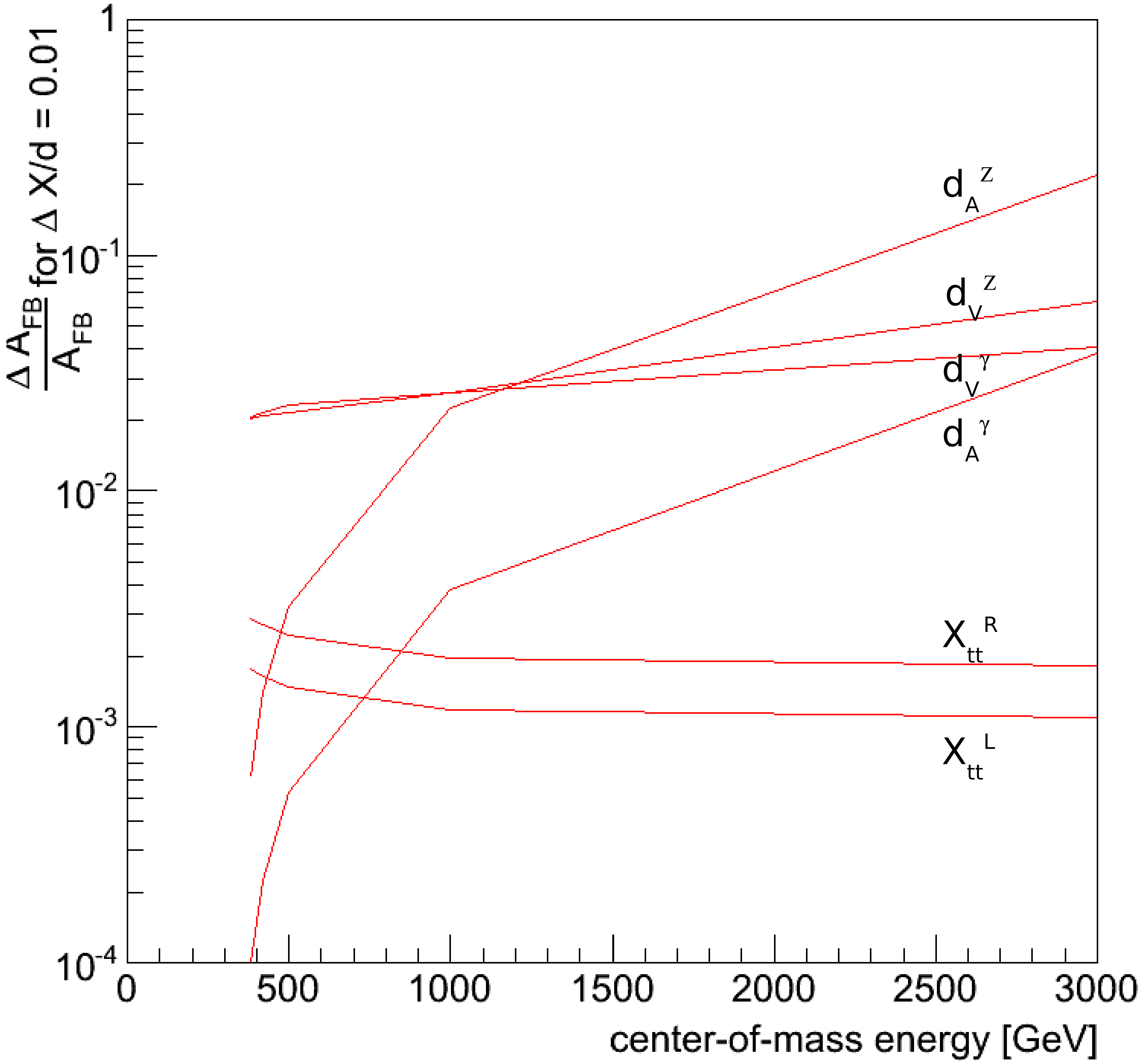
380 (black), 420 (red), 500 (green), 1000 (blue) and 3000 GeV (yellow)

Confirm naïve picture for some operator-observable pairs (larger impact at 3 TeV), but not universal...

Impact of new physics on asymmetry

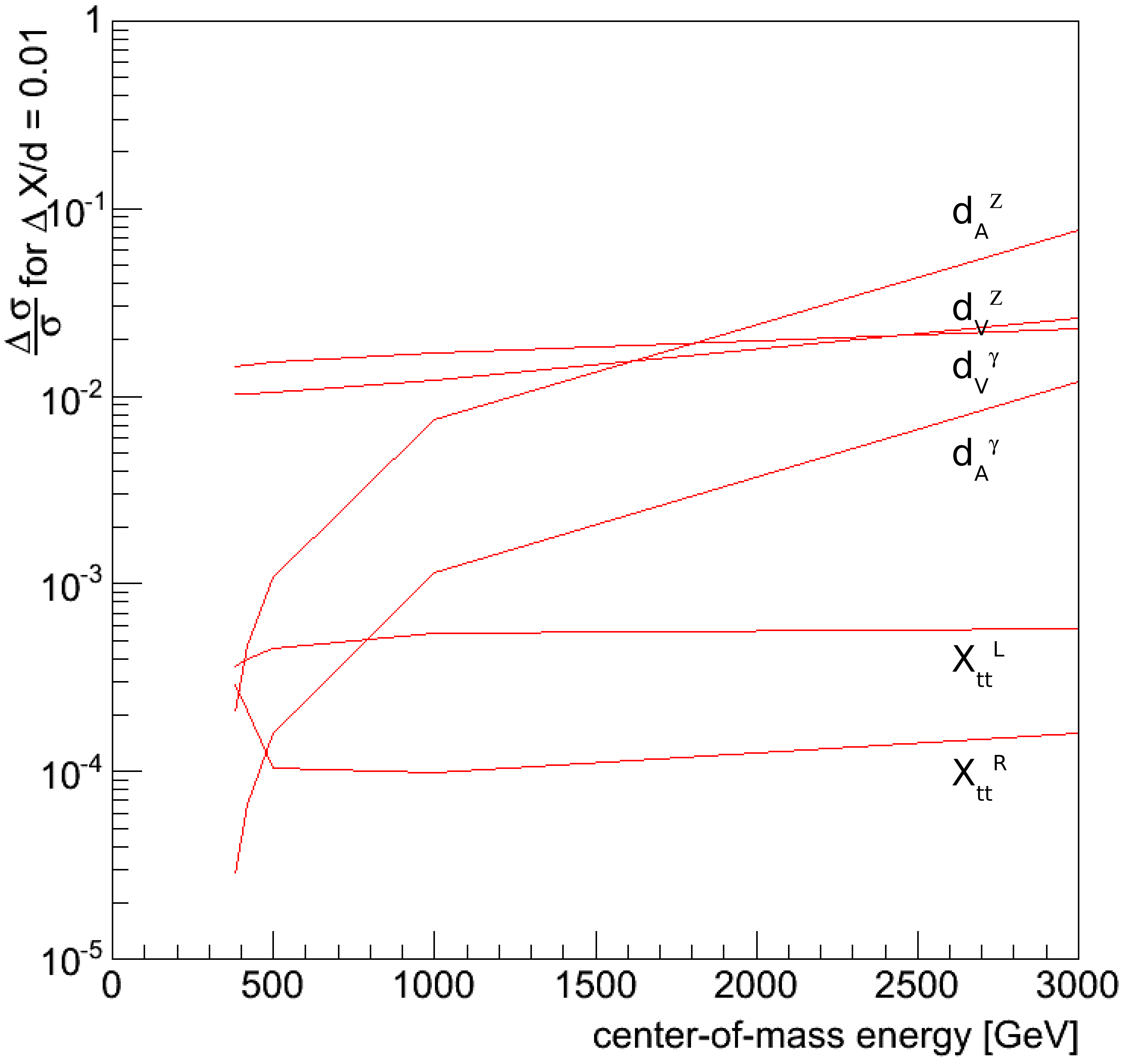
The impact of F2A form factors grows
- very strongly - with $\sqrt{s}$

The relative impact of X_{tt}^{L} and X_{tt}^{R} operators (F_{1V} and F_{1A} of the Z boson) is ~ flat



Impact of new physics on x-section

A similar picture in A_{FB}
Extend to further observables



ttZ and ttγ coupling extraction: status of theory

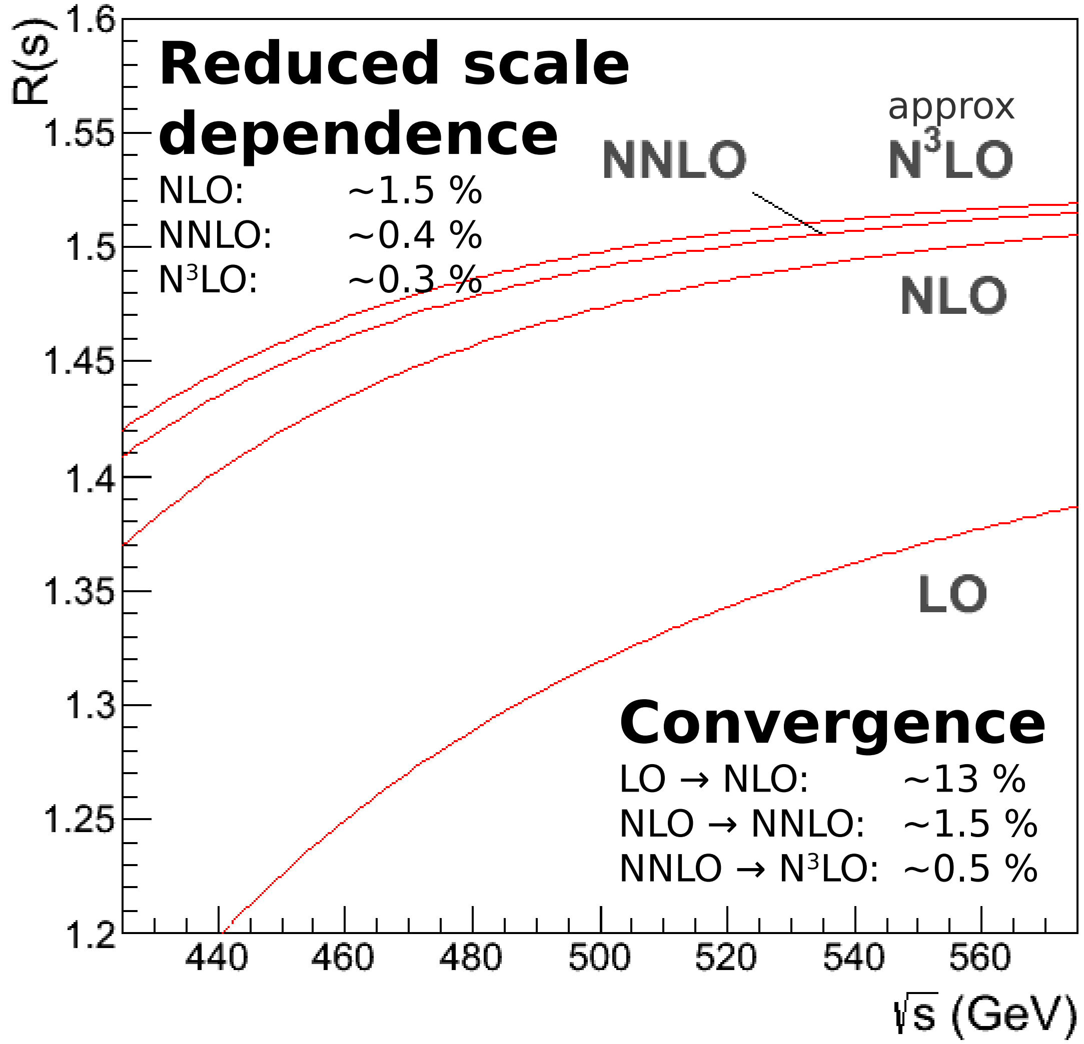
Theory status

State-of-the-art: approx. $O(\alpha_s^3)$ QCD corrections of $e^+e^- \rightarrow t\bar{t}$ x-sec → per mil precision

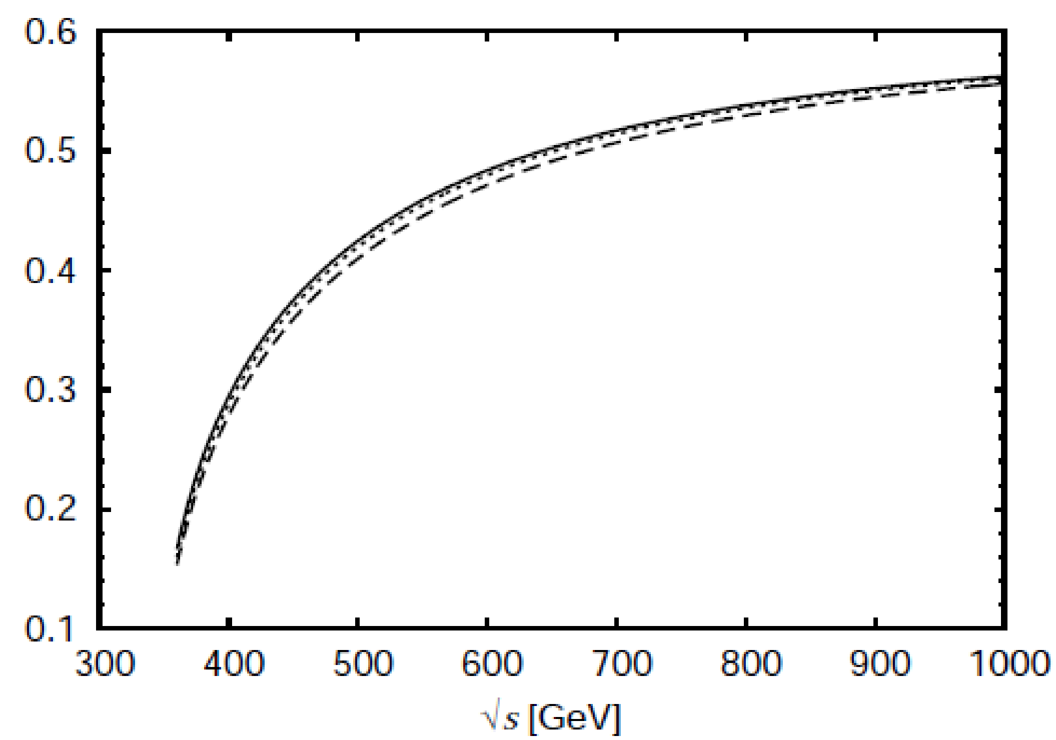
One-loop EW corrections have a large effect: 3% on σ, next order likely small

Differential calculations have fewer loops and larger errors → Roentsch/Schulze, arXiv:1501.05939

R(s) = cross-section normalized to x-sec for massless fermion



Electroweak corrections
Glover et al. hep/ph04010110
Fleischer et al. hep/ph0302259
Khiem et al., arXiv:1403.6556/6557



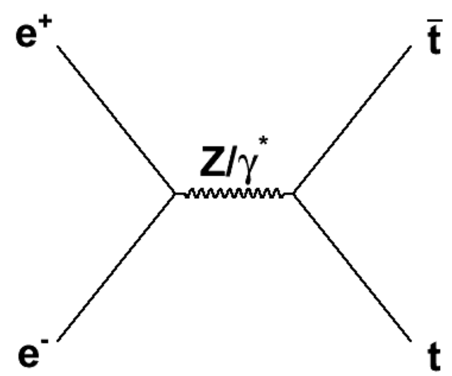
QCD corrections
to $e^+e^- \rightarrow t\bar{t} + X$
Kiyo, Maier, Maierhöfer, P. Marquard, arXiv:0907.2120
Hoang, Mateu, Zebarjad, Nucl. Phys. B 813 (2009) 349-369

Bernreuther, Bonciani et al., hep-ph/0604031

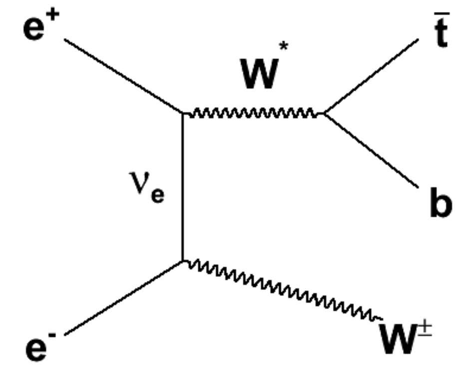
AFB: Scale variation <1% @ NNLO

One-loop EW: 20% effect on A_{FB} at 500 GeV.
Two-loop contribution seems small

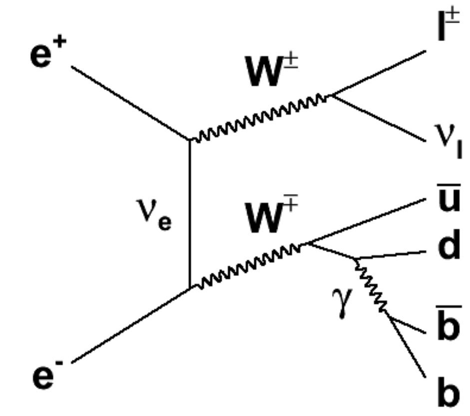
Top quark pairs vs. WbWb



Top quark pair production...



...Single top quark production...



...WWγ/Z/h...

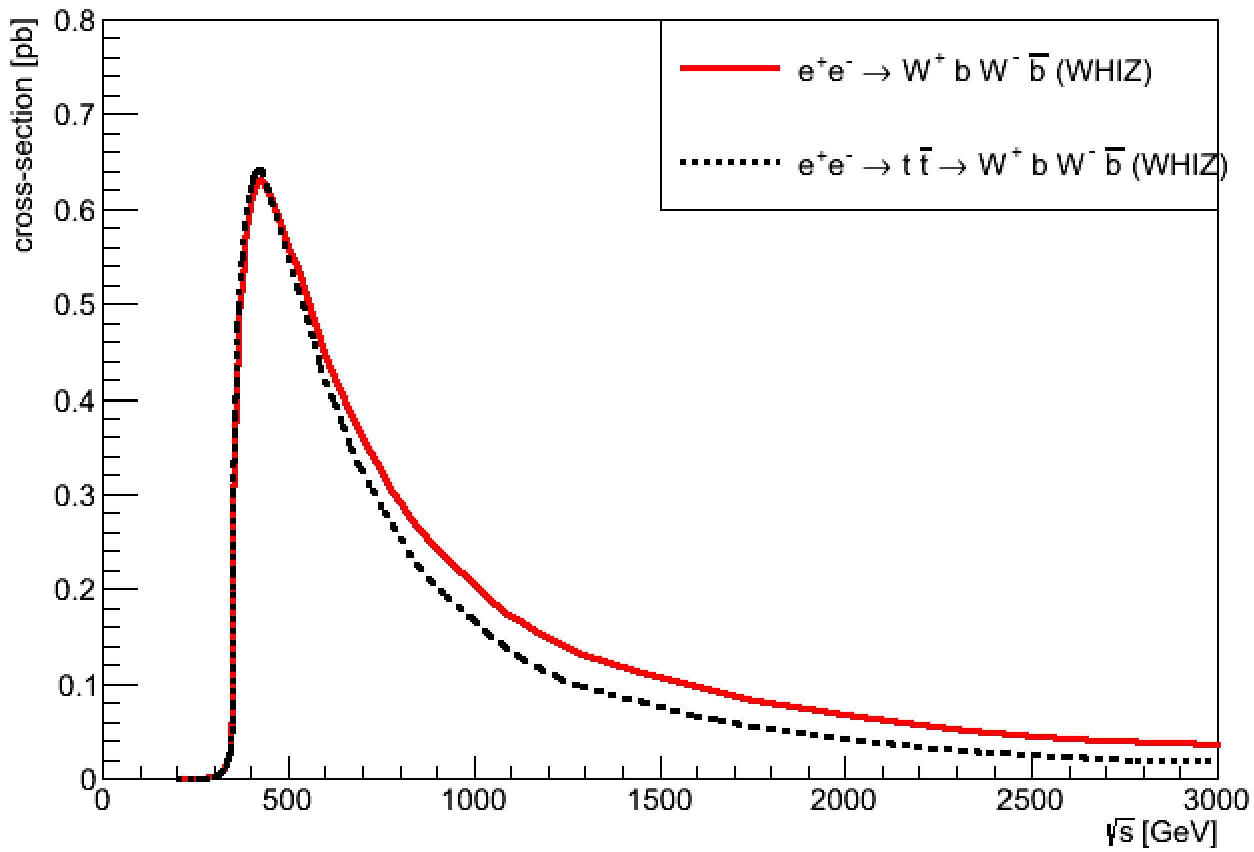
WbW$\bar{b}$ → 6 fermions has several non-negligible sources

(tt ~ 90%, single top ~9%, WWγ/Z/h ~ 1%)

At 500 GeV single top is practically indistinguishable from pairs

The WbWb cross section is 5 to 50% larger than the t$\bar{t}$ cross-section

See: *Garcia, Perello, Ros, Vos, Study of single top production at high energy electron-positron colliders, arXiv:1411.2355*



Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

Close to threshold

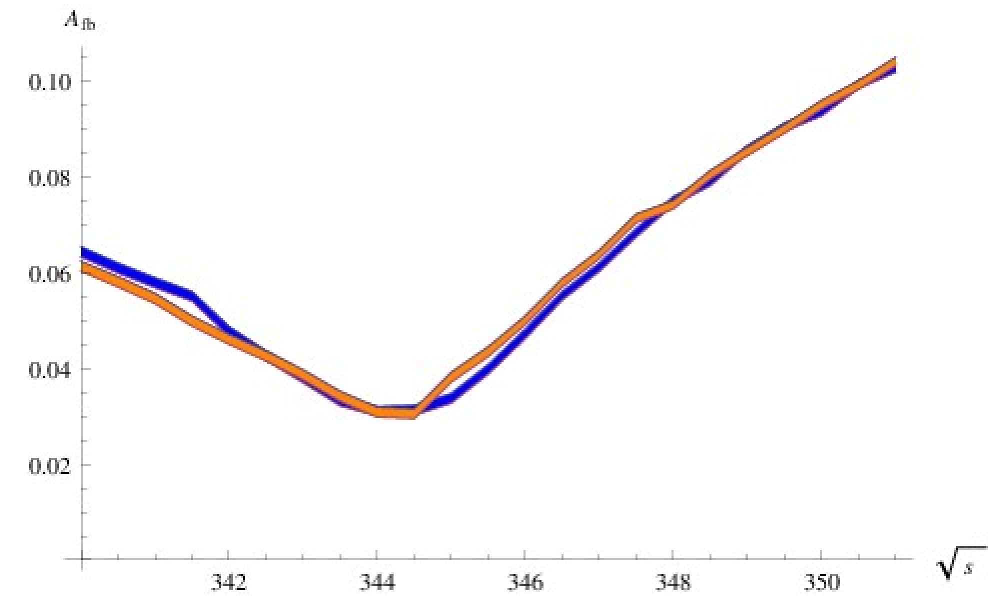
To extract form factors at threshold we have to include QCD bound-state corrections in calculations

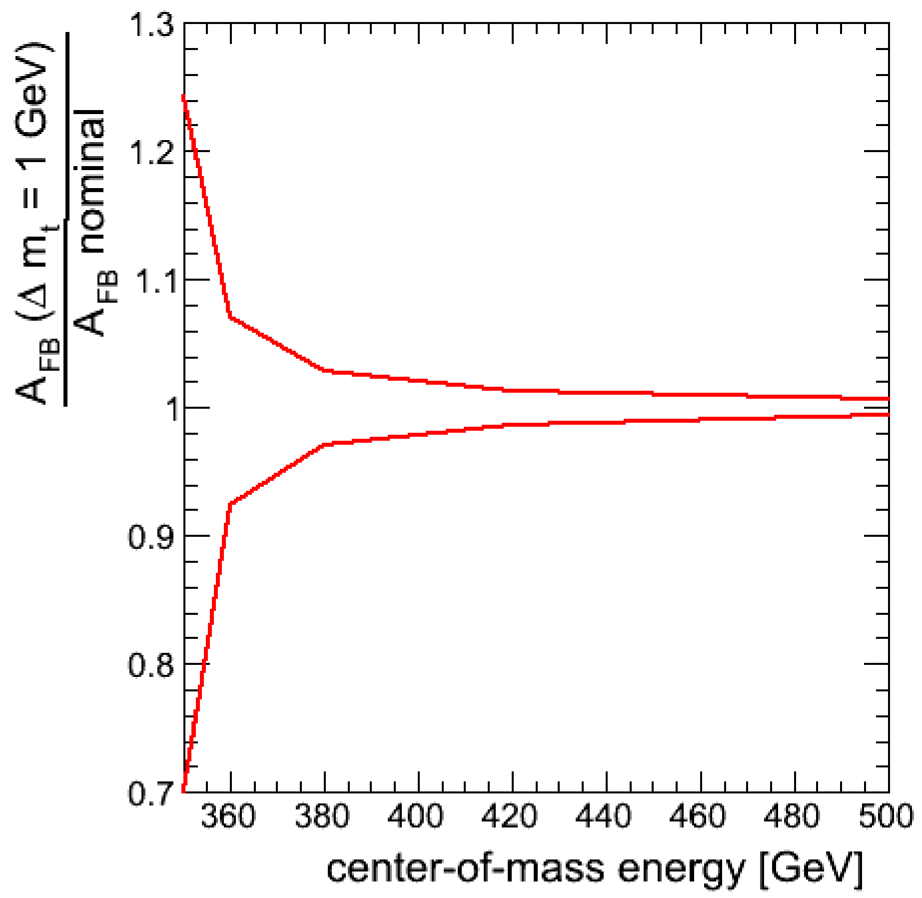
Match threshold & continuum calculations
F. Bach (DESY), A. Hoang (Vienna), M. Stahlhofen (DESY)
See Jürgen Reuter's presentation in this workshop

Theory calculation seems quite well behaved

Parametric uncertainty due to top quark mass AND width are now important
(Martinez & Miquel included A_{FB} in the fit)

F. Bach, preliminary
Leading Log resummation (orange) and Next-to-Leading Log resummation (blue) for FB asymmetry versus center-of-mass energy, m(1S) = 172 GeV, WHIZARD 2.2.3_beta_2





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

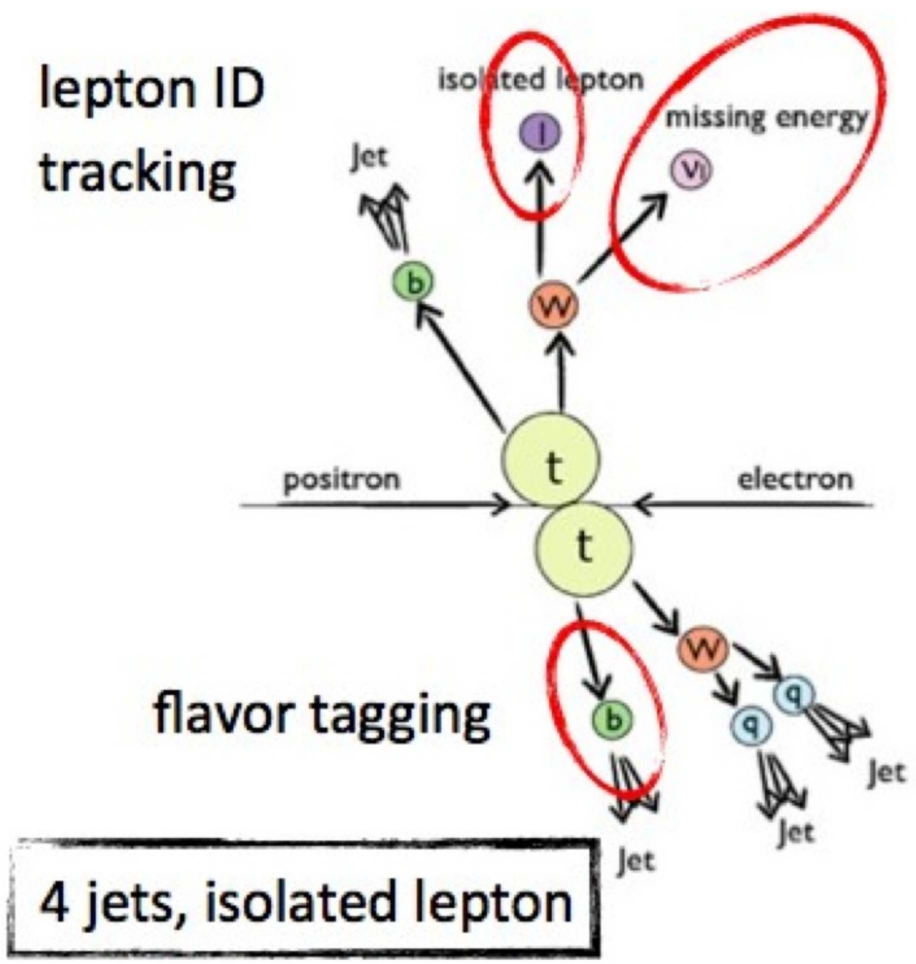
With the assumption of a 100 MeV pole mass measurement at threshold, the remaining uncertainty is one per mil or less above 420 GeV

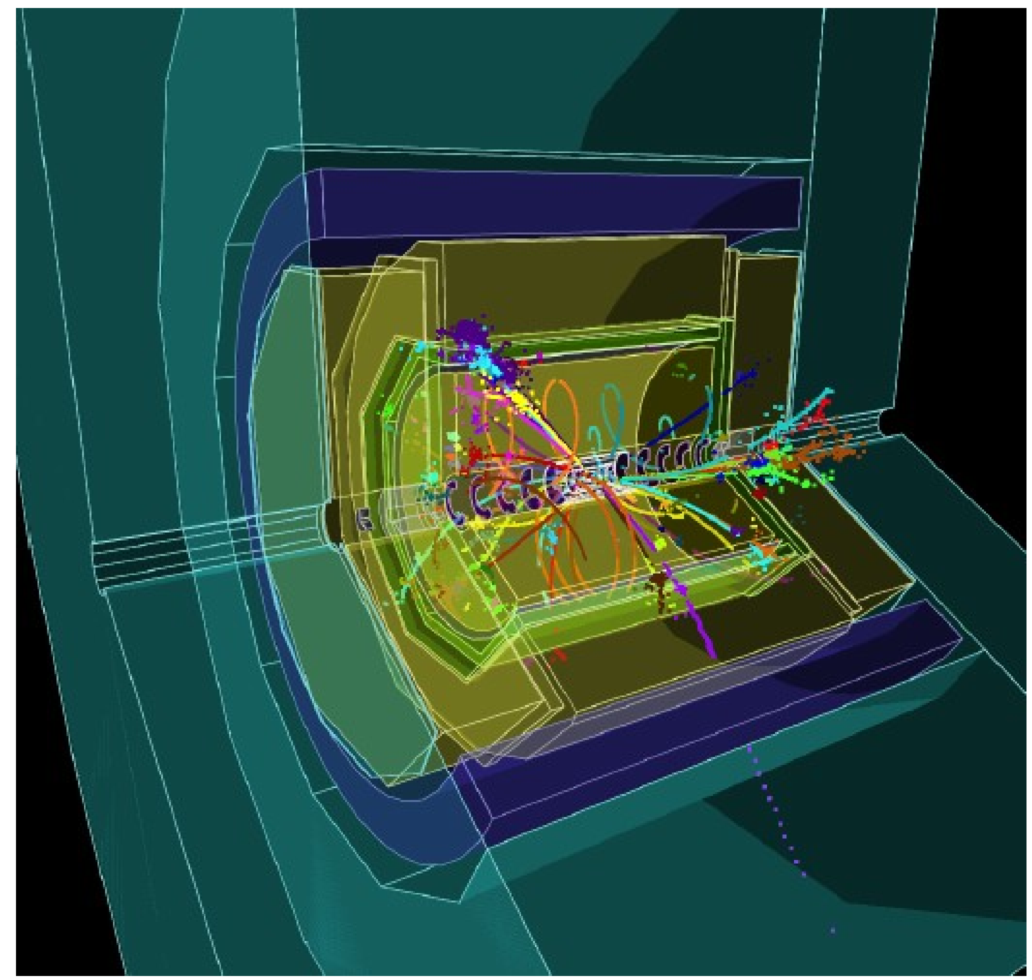
Top quark reconstruction vs. center-of-mass energy

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

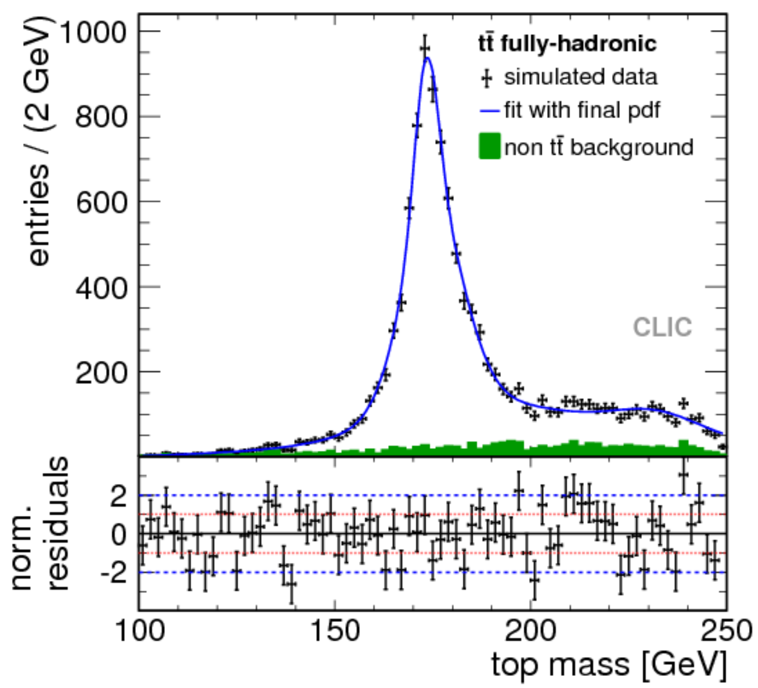
$$t\bar{t} \to (bW)(bW) \to (bqq')(b\ell\nu)$$

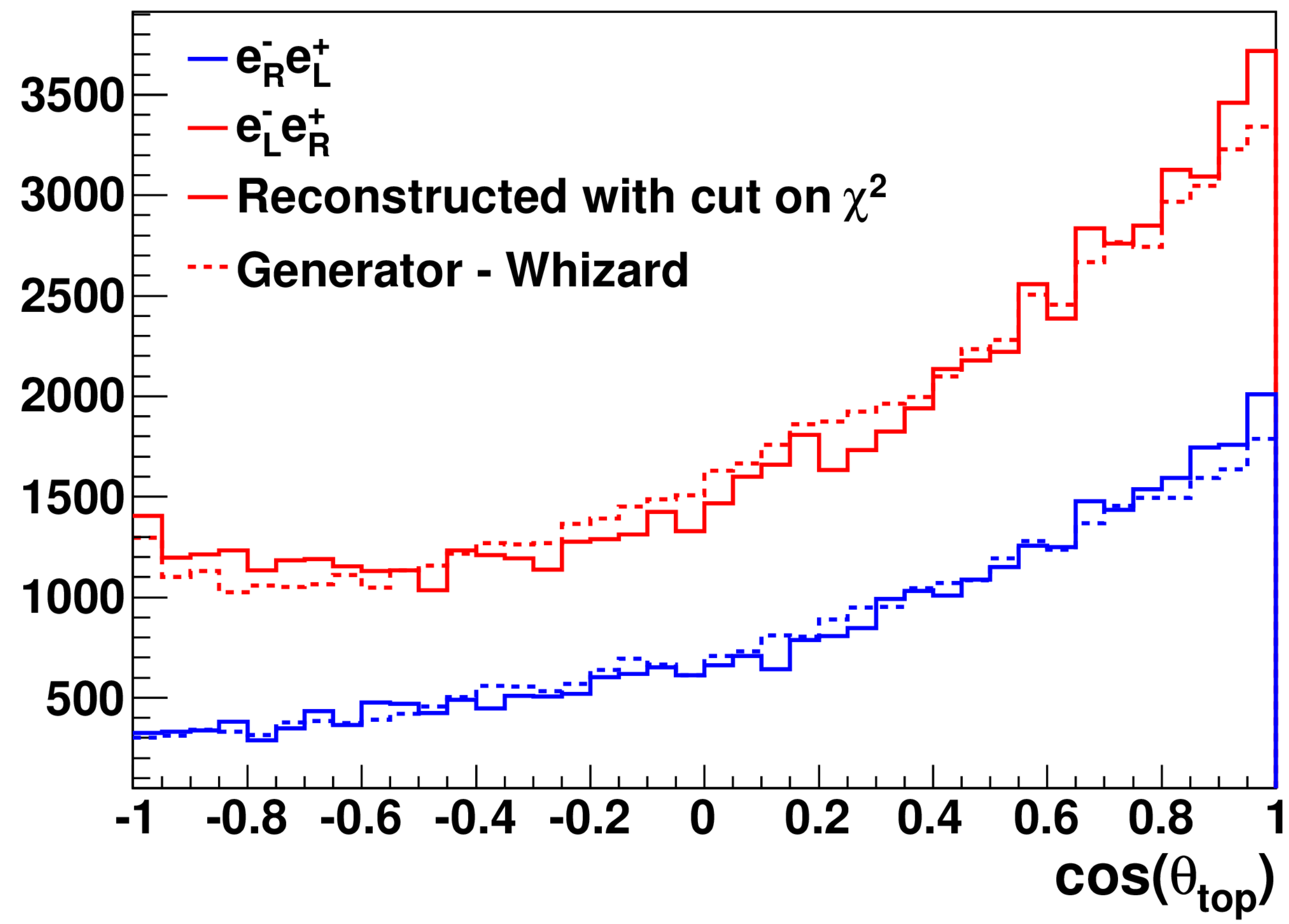




Final state reconstruction uses all detector aspects

Top quark selection/reconstruction

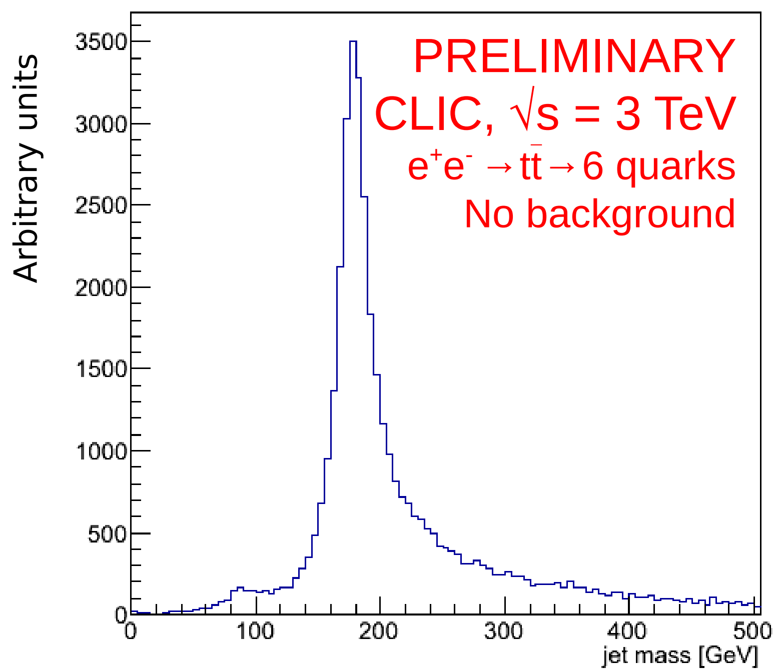


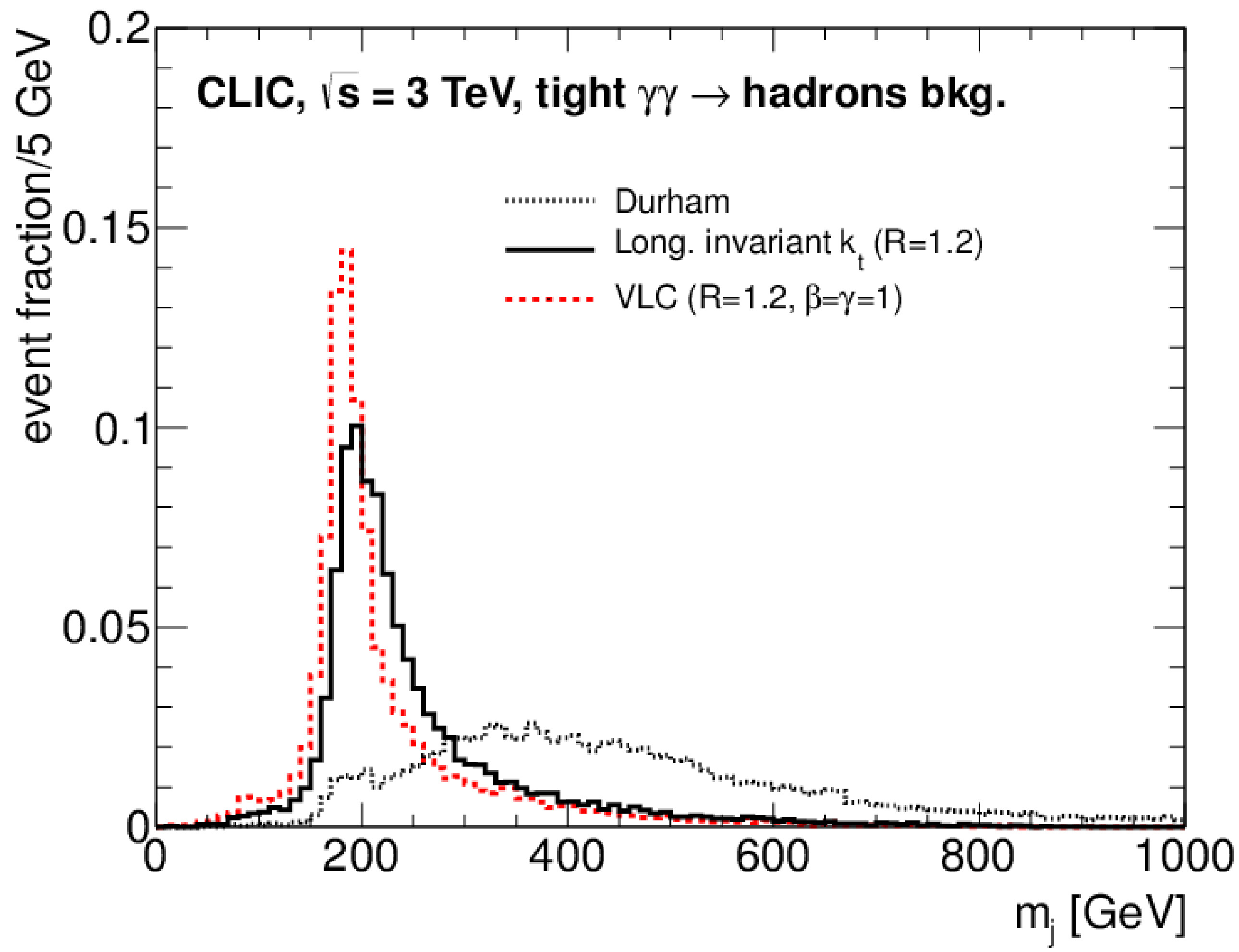


Top reconstruction is non-trivial at any center-of-mass energy

Low energy (~500 GeV):
Challenging combinatorics: migrations due to combining wrong W^+/W^- and $b/\bar{b}$ dilute measurements that rely on top quark reconstruction
Distinguishing top from anti-top with lepton in "lepton+jets" and jet charge in "fully hadronic" final state.

Top quark selection/reconstruction





ILC / CLIC top jet mass resolution, includin
→particle flow response is excellent
→background mitigated by jet algorithm (ar

Top reconstruction is non-trivial at any center-of-mass energy

High energy: top jets → no combinatorics for 1 TeV and up!

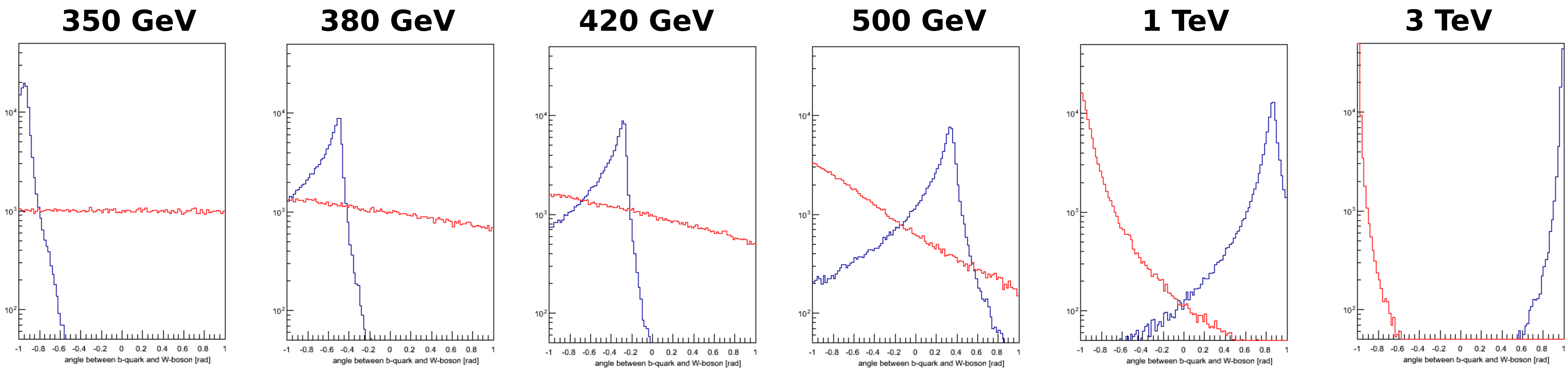
Provided we can deal with the γγ → hadrons background in fat jets, top reconstruction at high energy may well be more precise than at low energy!

Reconstruction vs. √s

Angle between W-boson and b-quark that are to form the top candidate

$t\bar{t}$ production in MG5_aMC@NLO, no ISR, no luminosity spectrum, no polarization,

----- = correct Wb combination ----- = incorrect combination



Top at rest → W and b back-to-back

Broad distribution vs. tilted background

Migrations known to disappear for boosted top quarks

Too naïve to expect relative syst. uncertainty to be constant vs. √s

Precision on couplings vs. center-of-mass energy

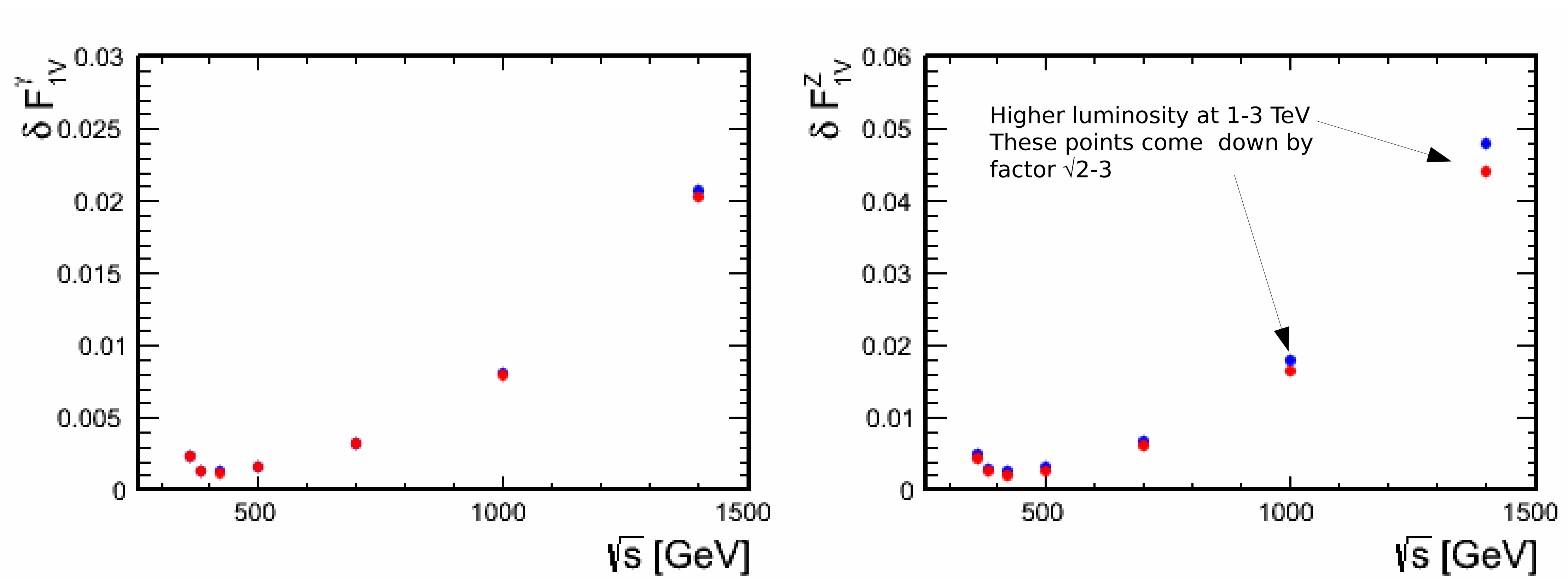
First extraction of couplings at $\sqrt{s}$ = 380 GeV

Rerun the extraction of the couplings from measurement of σ, A_{FB} ***(Roman Poeschl, LAL)***

- *set fixed integrated luminosity: 2 x 250/fb, with P = (+80,-30) and P = (-80,+30), at any center-of-mass energy*
- *cross-section initially ~constant: σ = 550 pb at 380 GeV, 530 pb at 500 GeV, then rapid drop-off*
- *the value of A_{FB} drops rapidly as sqrt(s) → 2 m_t*
- *assuming stat. dominated uncertainty: $\delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$*

Nominal beam polarization (e^- 80%, e^+ 30%)

Electron polarization only



For the F1V couplings we find excellent results also at 420 GeV
Drop in x-section at center-of-mass energy ≥ 1 TeV only partially recovered by greater instantaneous luminosity → sensitivity for F1V degraded by factor 5-10

Extraction of axial coupling

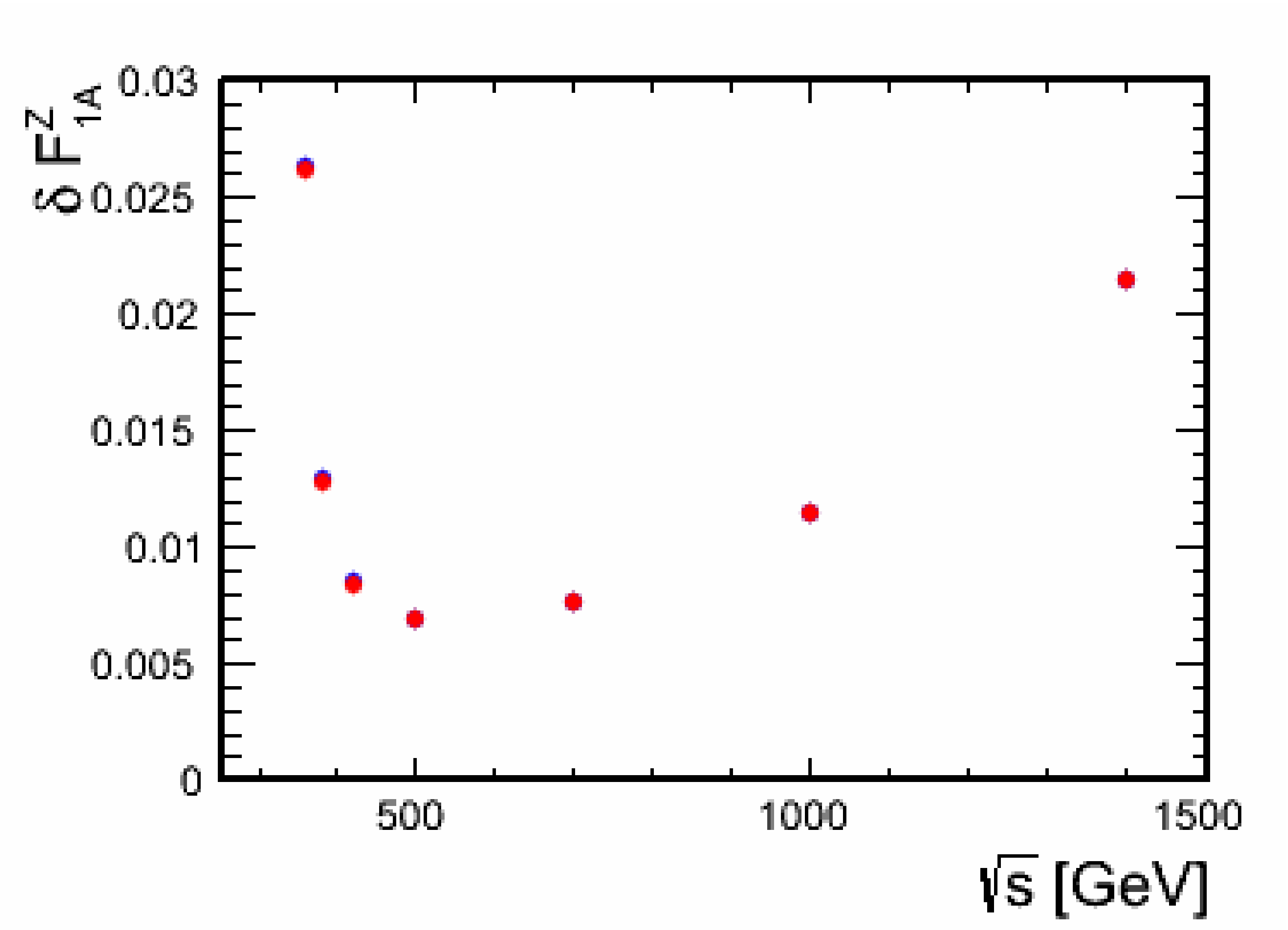
Very different behaviour for F1A;
extraction relies strongly on AFB

→ *suffers at low energy*

→ *less degraded at high energy*

Nominal beam polarization (e^- 80%, e^+ 30%)

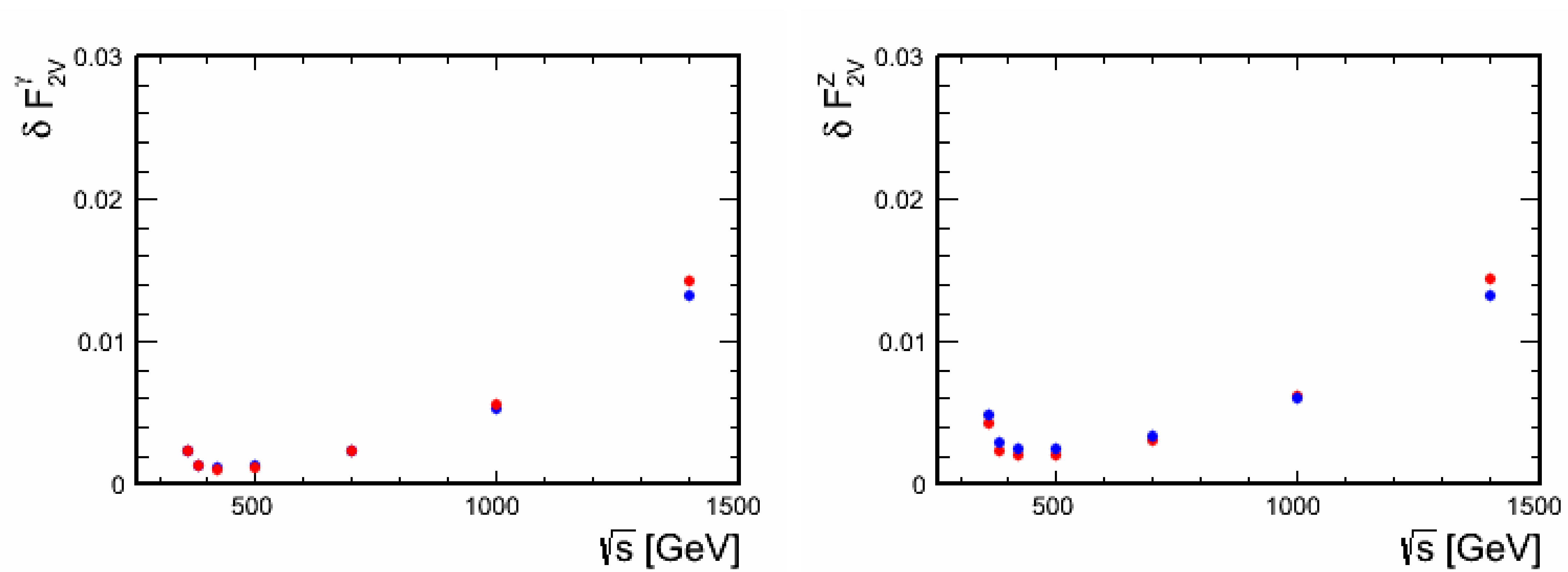
Electron polarization only



Extraction of dipole moments F2V

F2V; a factor 7-10 from most (500 GeV) to least sensitive (1.4 TeV)
→ 4-6 taking into account increased luminosity
Remember: same effective operator strength yields factor 5 larger impact at 1.4 TeV

Nominal beam polarization (e^- 80%, e^+ 30%)
Electron polarization only



Summary

$$\delta F_{1V}^{\gamma,Z}, \delta F_{1A}^{\gamma,Z} < 1\,\%$$

$t\bar{t}Z$ and $t\bar{t}\gamma$ couplings measurement are unique opportunity at the LC

Full LC programme offers great potential;

→ Threshold region is great for mass and Higgs loops

→ Dipole moments might show high-scale NP in TeV regime (CLIC)

→ Polarization is needed to disentangle photon and Z couplings,

but dropping only positron polarization has small effect

Coupling measurement (in particular F1AZ) has sweet spot around 420-700 GeV

where AFB and cross-section are large

degradation at high energy more tractable (lumi, reco) than at low energy

Caveats:

Reconstruction efficiency and systematic uncertainties are likely **NOT** constant against sqrt(s)!

to be taken into account more consistently across all energies:

theory uncertainties, single top strategy, fully hadronic final state