Top quark couplings

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Top quark physics

One of (at least) two particles to escape (direct) scrutiny at lepton colliders

It is **important** to know its properties: contributions through loops

It is a quark we **can** characterize well: top-anti-top tagging, polarization

The portal to new physics? If top is part of the (hierarchy) problem is the (extended) top sector part of the solution too? Many examples of BSM setups where top is special (top partners in 5D, little Higgs, SUSY)

See M. Peskin in Monday's plenary

SM physics?

The SM precision measurement IS the search for new physics

Precise measurements of interactions between SM particles provide excellent sensitivity to new physics

Ex. constraints on $Z \rightarrow b\bar{b}$ vertex (LEP/SLC)

Ex. Measurement of branching ratio $B_s \rightarrow \mu^+\mu^-$ (Tevatron/LHC)

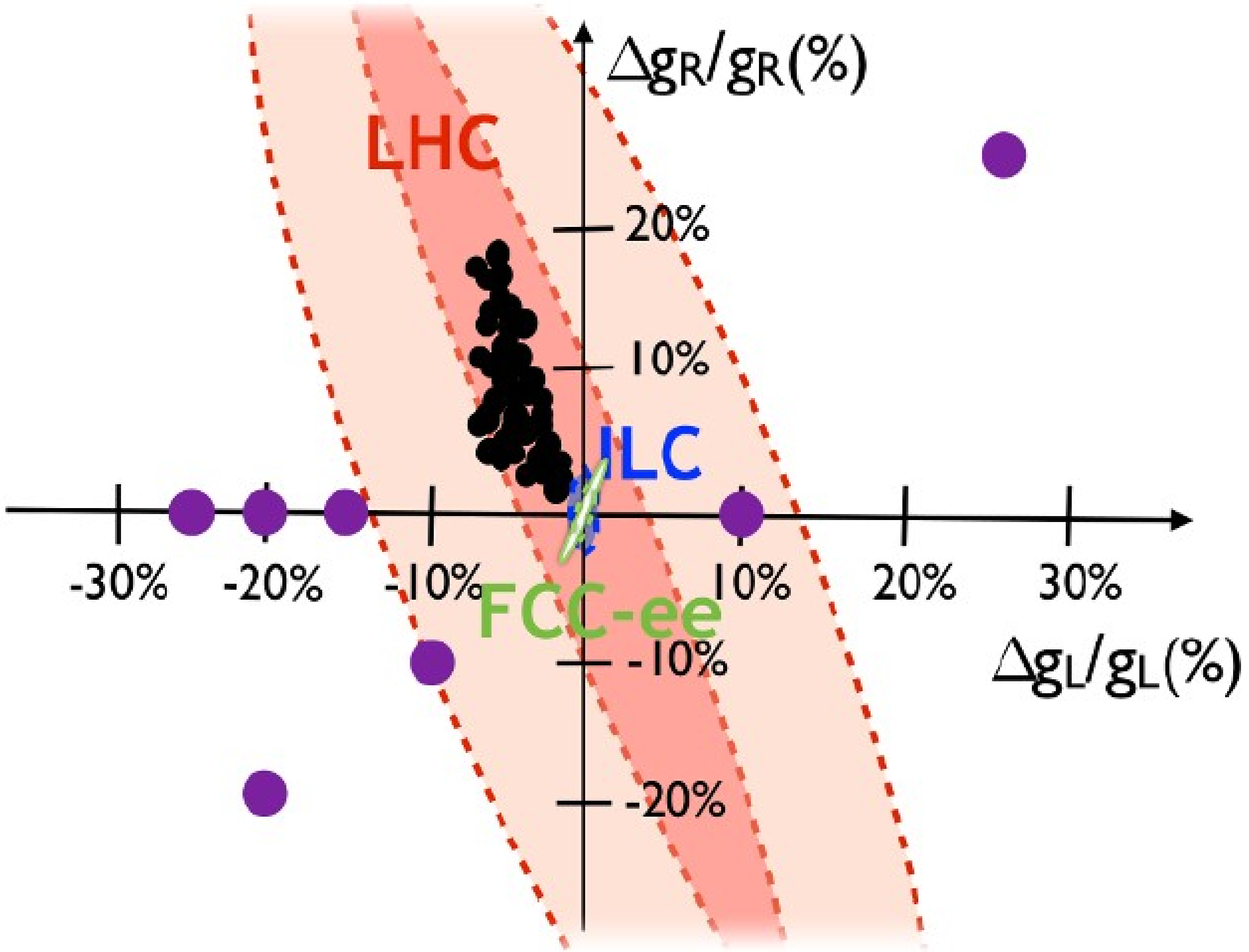
Ex. Higgs BR to invisible (LHC/LC)

Ex. Couplings of the top quark to the photon and Z-boson (LC!)

BSM physics

Certain classes of SM extensions predict sizable deviations from the SM prediction for the $t\bar{t}Z$ coupling

Extra dimension models typically yield order 10% deviations for Λ ~ 1 TeV

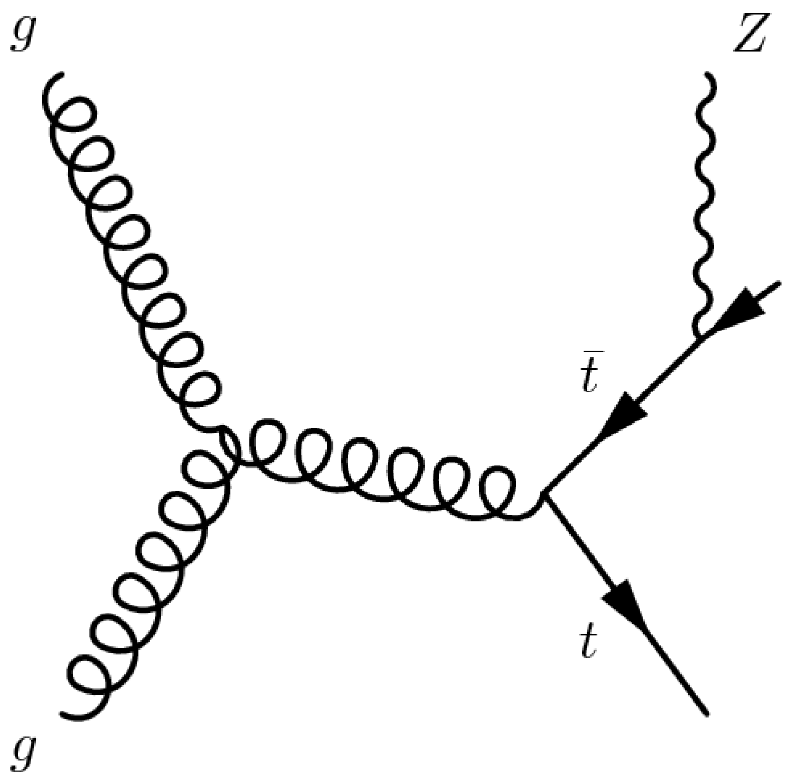


- 5D models proposed by several authors
  Richard, arXiv:1403.2893
- 4D Composite Higgs Model
  Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

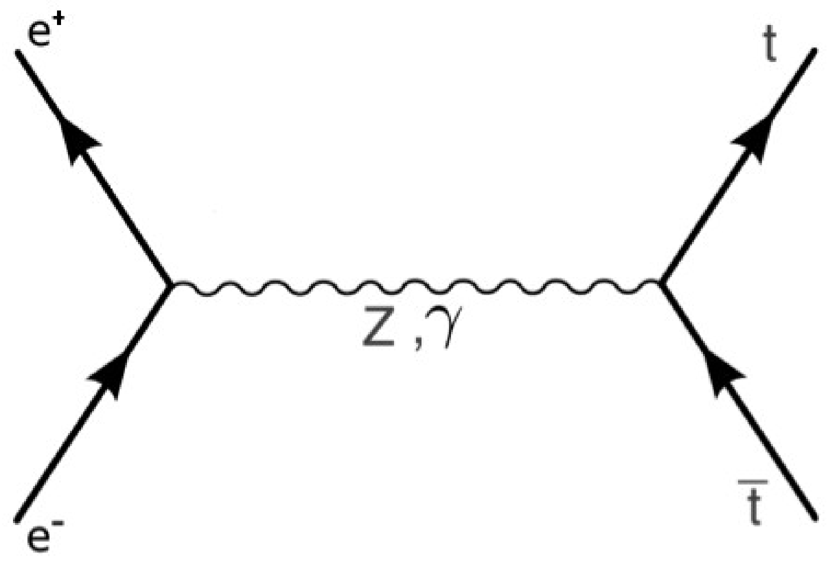
Top and Z/γ

Couplings of the top quark to neutral EW gauge bosons

At the LHC, $q\bar{q} \rightarrow Z/g \rightarrow t\bar{t}$ is inaccessible. Must use associated production



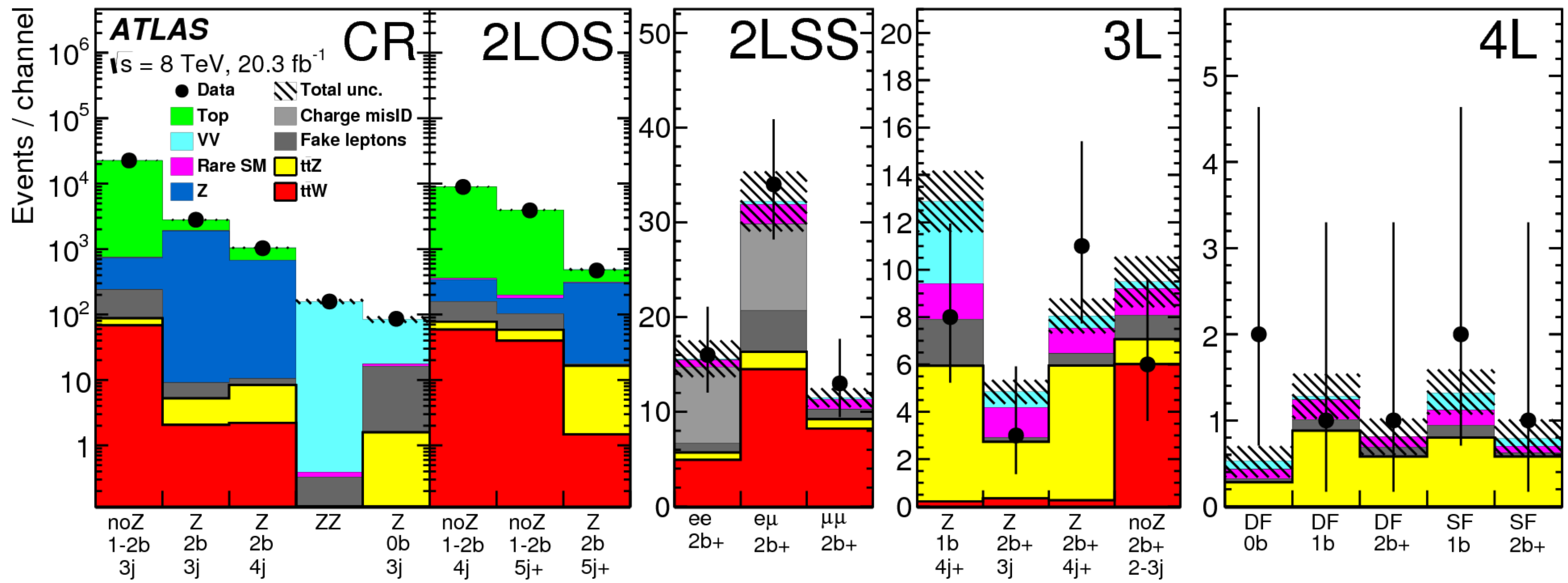
At a LC $e^+e^- \rightarrow t\bar{t}$ production is one of the most prominent 6f processes and readily isolated



Some overlap with studies of tWb vertex at LHC (single top, top decay), and indirect sensitivity of LEP precision tests and B-factories

LHC results so far

Complex, multi-channel analysis. ATLAS/CMS, initially found 3σ each for $t\bar{t}Z$ (EPJ C74 (2014) 3060, ATLAS-CONF-2014-038)



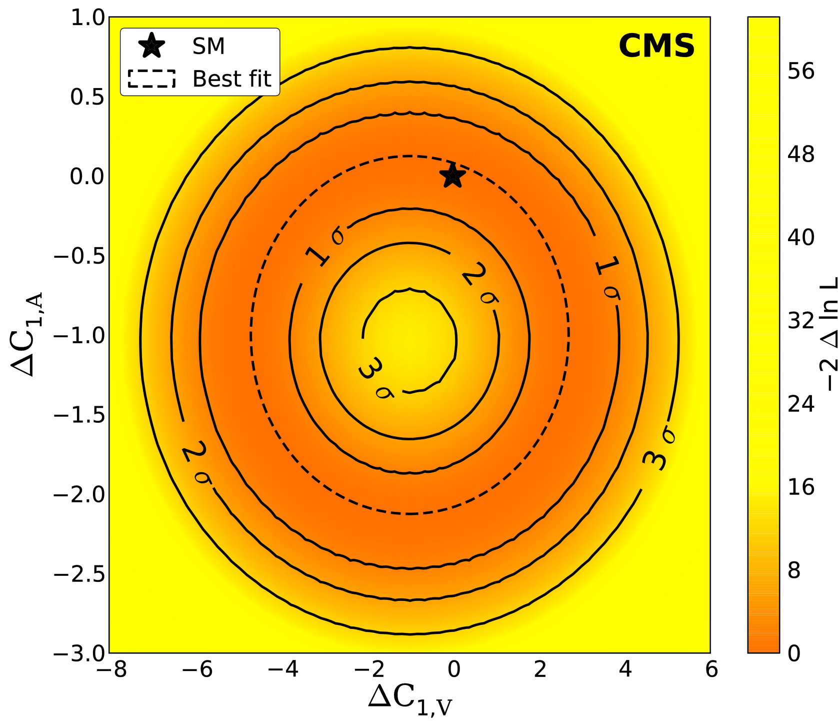
ATLAS/CMS have improved their analyses considerably

5 σ observation for all top + EW associated production channel

	ttW	ttZ	ttγ
ATLAS	5.0 σ ArXiv:1509.05276	4.2 σ ArXiv:1509.05276	5.3 σ (7 TeV) ArXiv:1502.00586
CMS	4.8 σ ArXiv:1510.01131	6.4 σ ArXiv:1510.01131	CMS-PAS-TOP-13-011

See Nadia Barone, Wednesday top session

LHC prospects



We have actually observed the ttγ and ttZ processes

We have NLO predictions for both

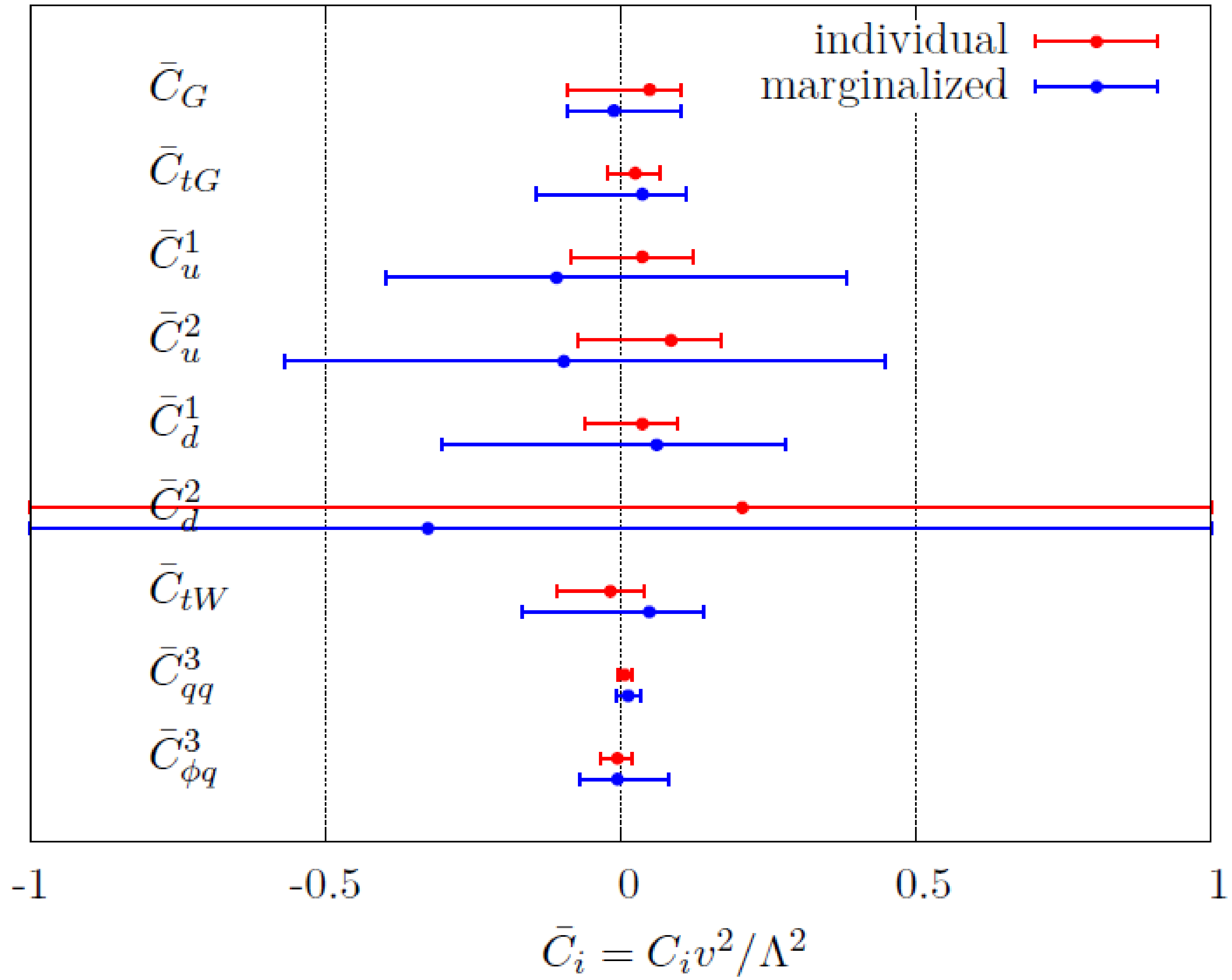
Roentsch and Schulze, arXiv:1501.05939 [hep-ph], JHEP 1407 (2014) 091

We even have first (weak) limits on t-Z vector and axial coupling

Data from Tevatron and LHC (from cross-sections to spin correlations) provide precise multi-dimensional constraint

Simultaneous fit to effective operators affecting top quark sector

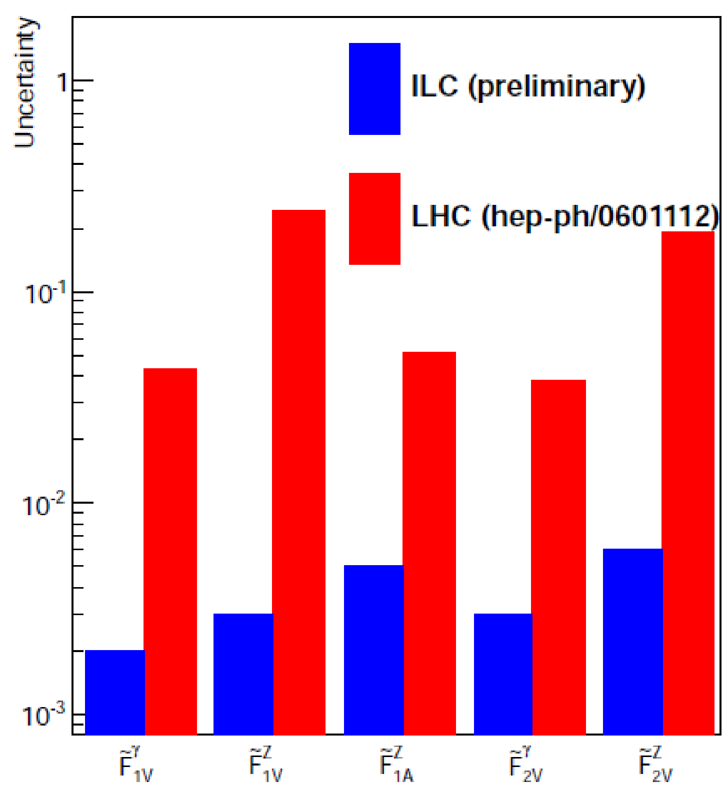
arXiv:1506.08845



LHC prospects

Shouldn't we update the LHC prospects?

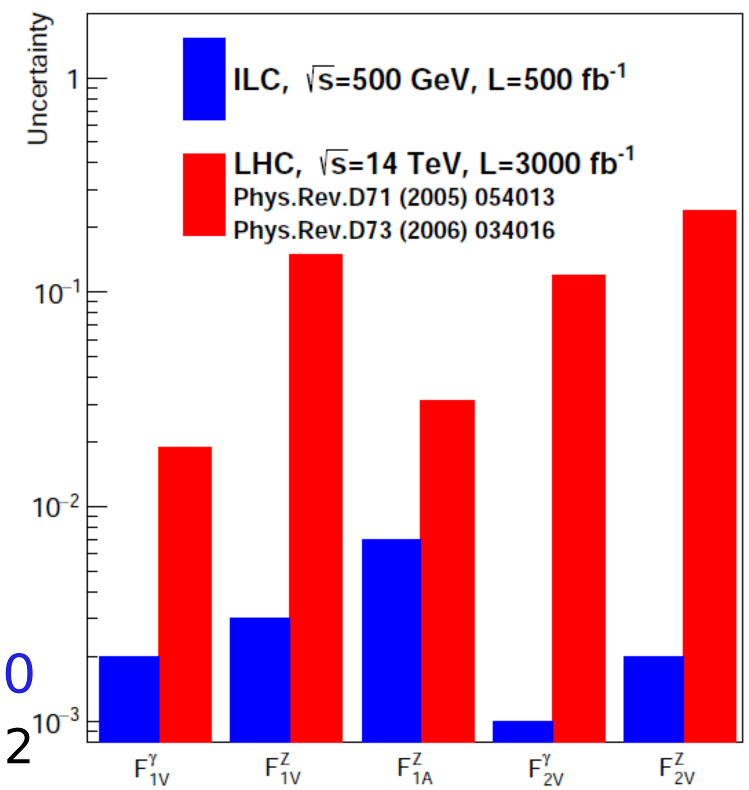
3 ab^{-1} prospects instead of 300 fb^{-1}, but still from 2006 study



arXiv:1307.8102

arXiv:1505.06020

Eur.Phys.J. C75 (2015) 10, 512



No official prospects from ATLAS/CMS. Some theory work:

Roentsch and Schulze, arXiv:1501.05939 [hep-ph], JHEP 1407 (2014) 091

LC: precise predictions

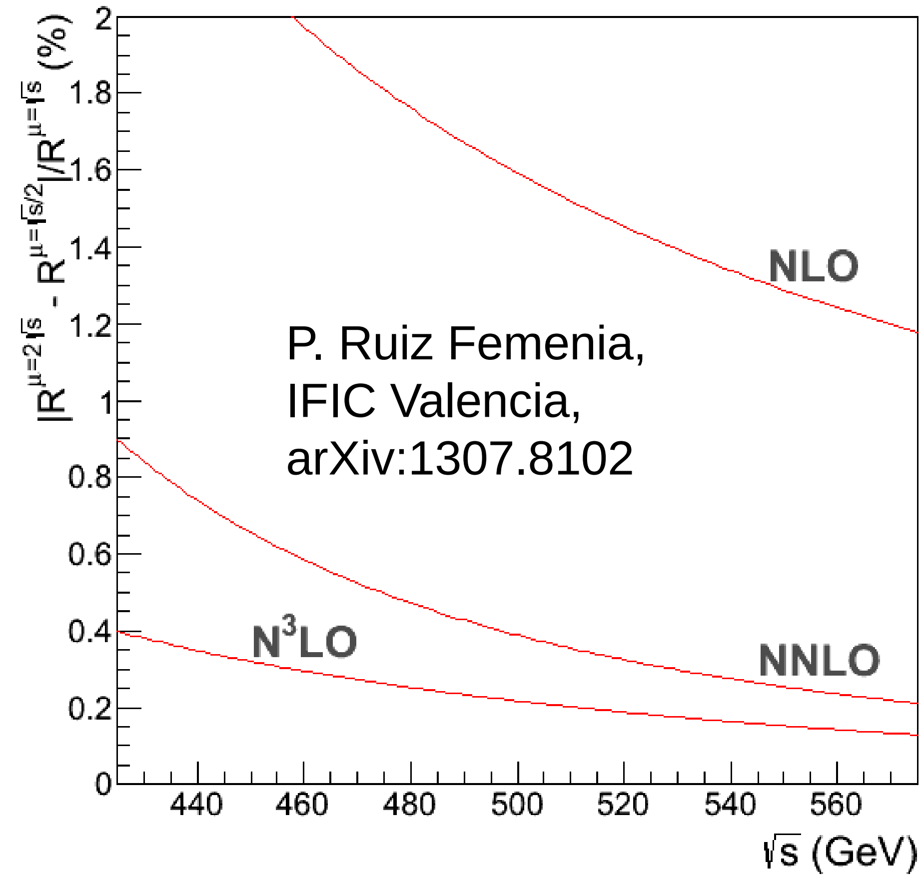
For theory precision there is nothing like e^+e^-

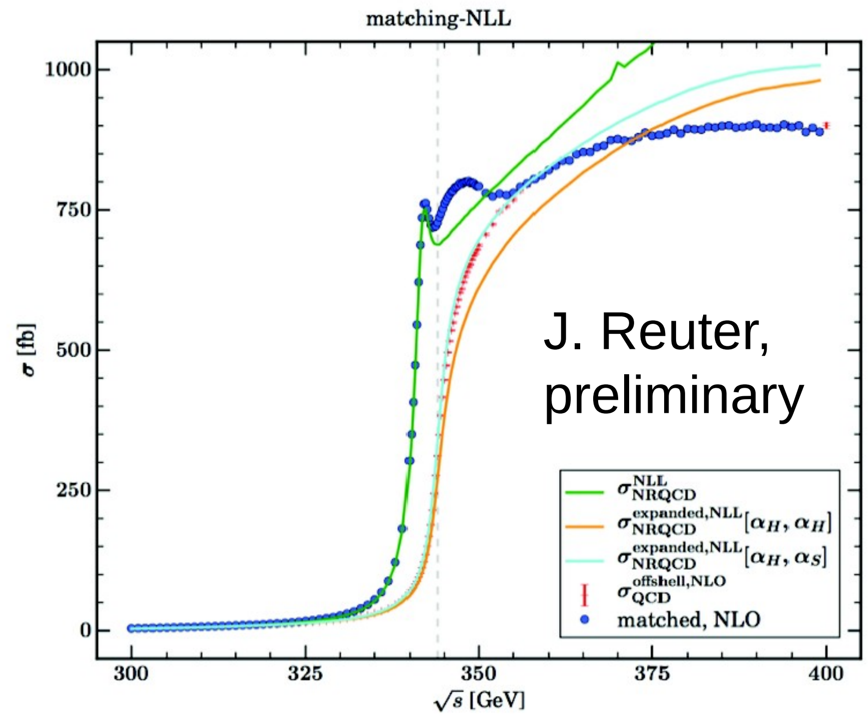
Continuum
QCD corrections calculated to N^2LO
Scale variations at N^3LO estimated at ~ 0.3%.
Electroweak corrections are sizable, though.

Needed: best, consensuated estimate of theory uncertainty versus $\sqrt{s}$

QCD threshold effects
Match threshold & continuum calculations and supply them in a generator (WHIZARD)
F. Bach (DESY), A. Hoang (Vienna), M. Stahlhofen (DESY)

Parametric uncertainty:
Uncertainty on top mass/width propagates to x-sec:
→ 0.2% at 380 GeV
→ 0.1% at 420 GeV





Top quark couplings: TDR times

measure

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

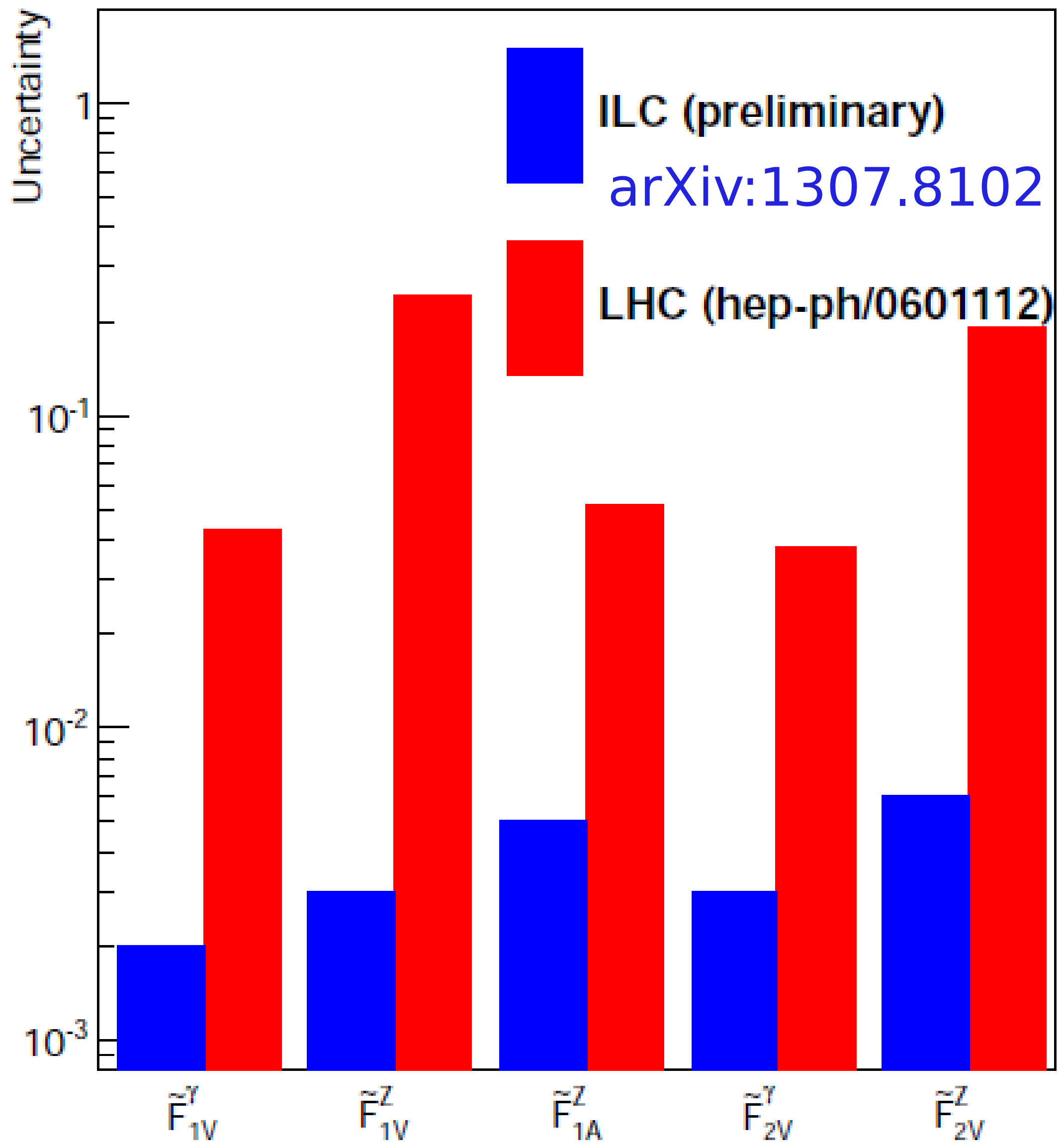
$\sigma(-) \quad A_{FB}(-)$

extract

$$\left.\begin{matrix}(+=e_R^-)\\(-=e_L^-)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix}F_{1V}^{\gamma} & * & F_{2V}^{\gamma}\\ F_{1V}^{Z} & F_{1A}^{Z} & F_{2V}^{Z}\end{matrix}\right\}$$

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)

BSM sensitivity vs. √s

Impact of new physics on cross-section and asymmetries depends on **√s**

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

BSM impact on cross-section and A_{FB} increases strongly with √s for axial dipole moments and four-fermion operators;

→ factor 10 and more between 0.5 and 3 TeV

Much less pronounced increase for vector dipole moments, none for $F^{\gamma,Z}_{1V/A}$

For details, see talk in CLIC workshop, CERN, January 2015:
https://indico.cern.ch/event/336335/session/1/contribution/174

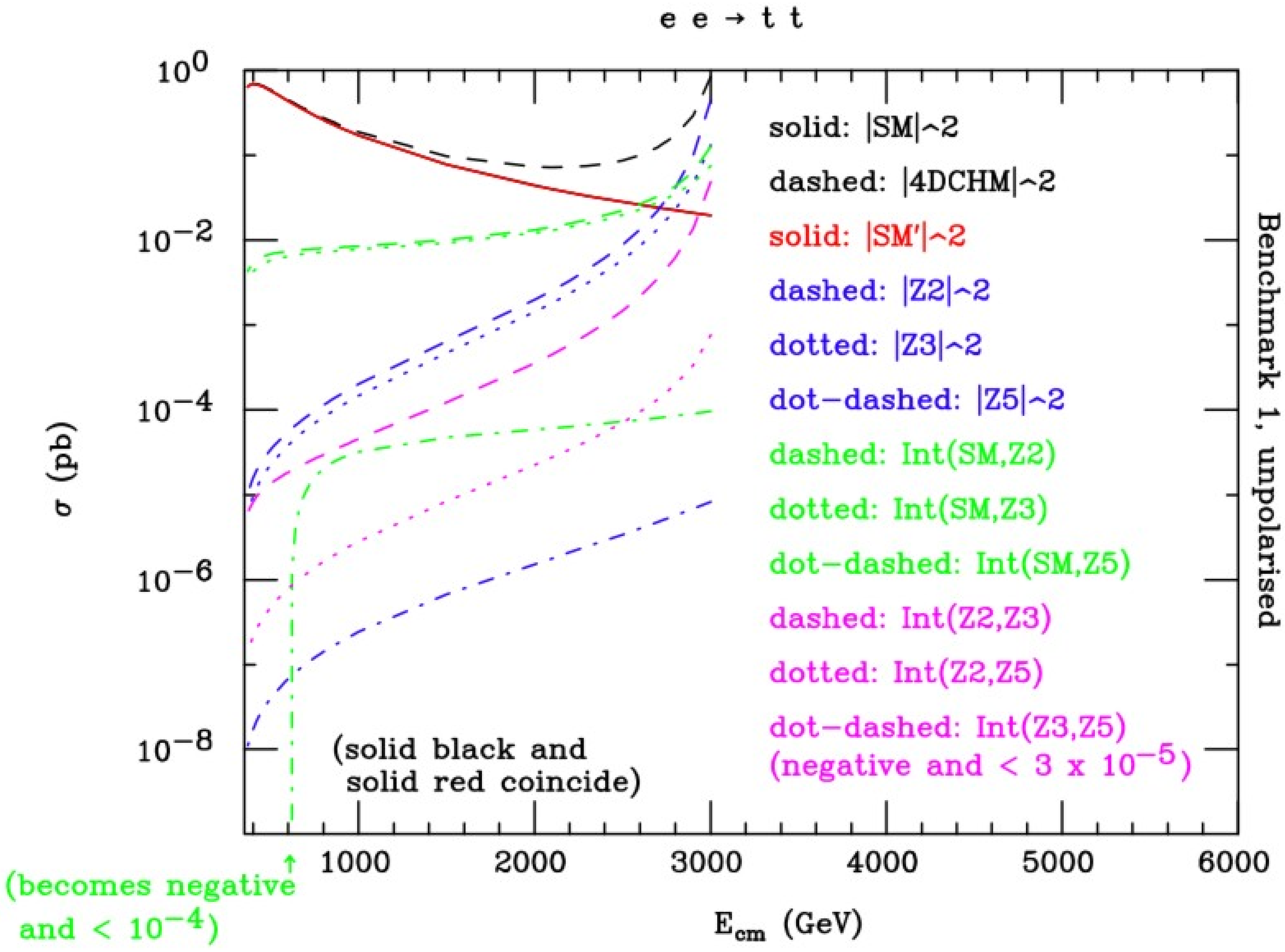
BSM physics: concrete model

A concrete example: the 4D Composite Higgs Model predicts for a benchmark point with mZ' ~ 3.1-4.3 TeV

$\Delta\sigma$ = 4% @380 GeV

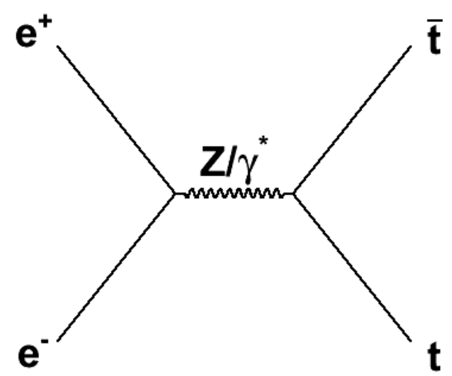
= 9% @500 GeV

= 53% @1 TeV

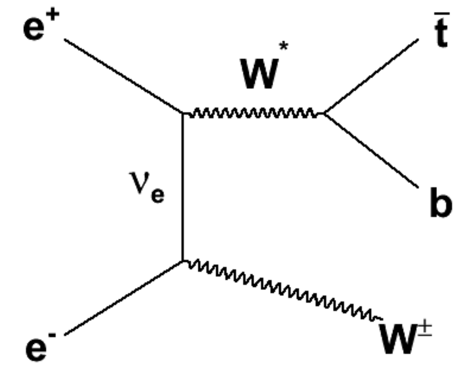


4D Composite Higgs Model
Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

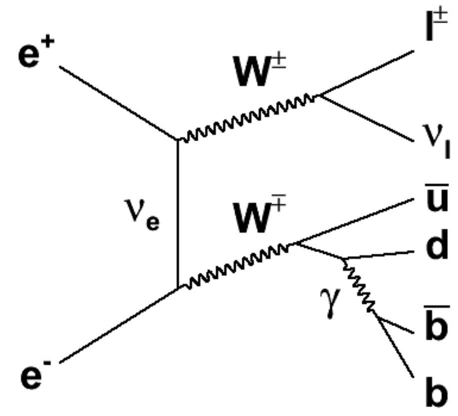
Challenge: selection



Top quark pair production...



...Single top quark production...



...WWγ/Z/h...

Maximum x-section for pair production ~0.6 pb

peak well above threshold ~ 420 GeV

Drop in (s-channel) cross-section at higher $\sqrt{s}$

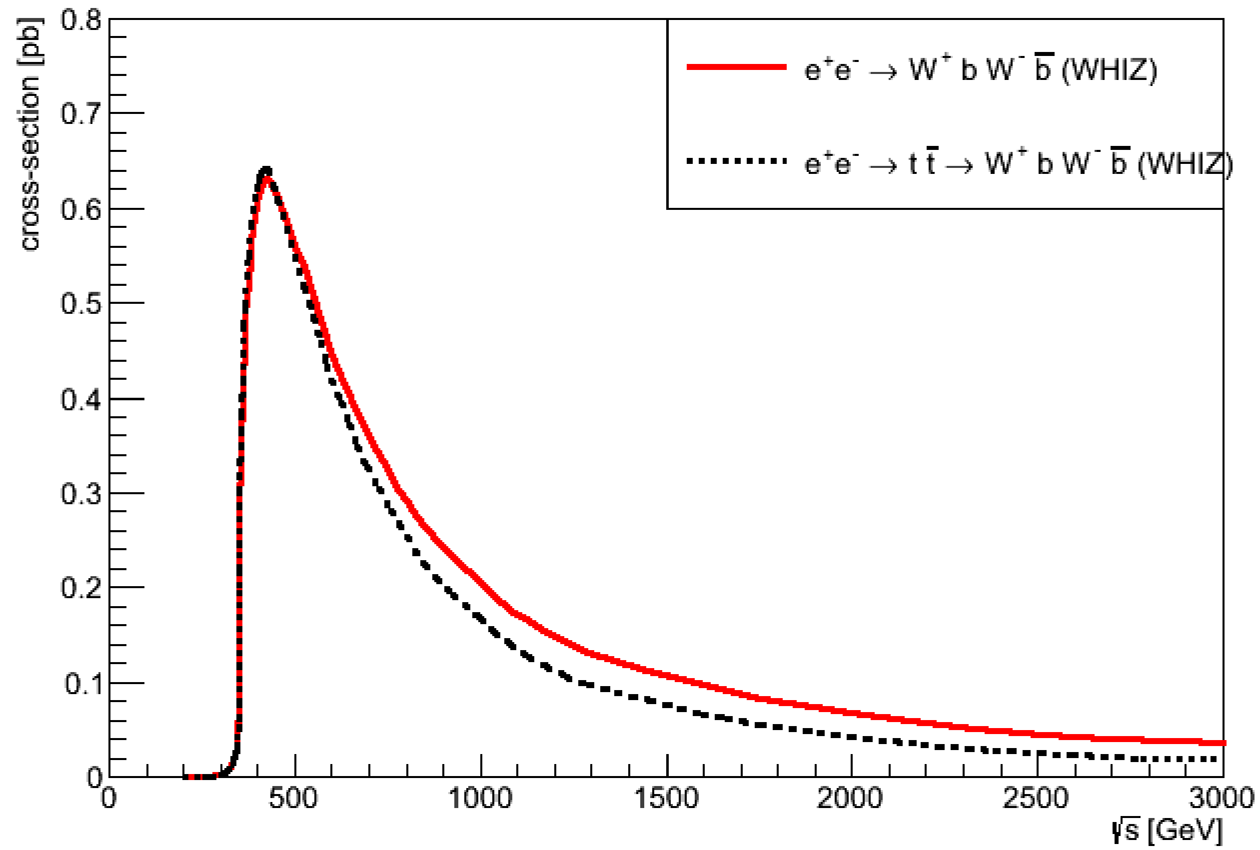
partially compensated by higher luminosity

$e^+e^- \rightarrow WbW\bar{b} \rightarrow$ 6 fermions is "contaminated" by single top production:

380 GeV: ~5%
500 GeV: ~9%
3 TeV: ~50%

As far as we can (at 500 GeV) single top is ~indistinguishable from pair production

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



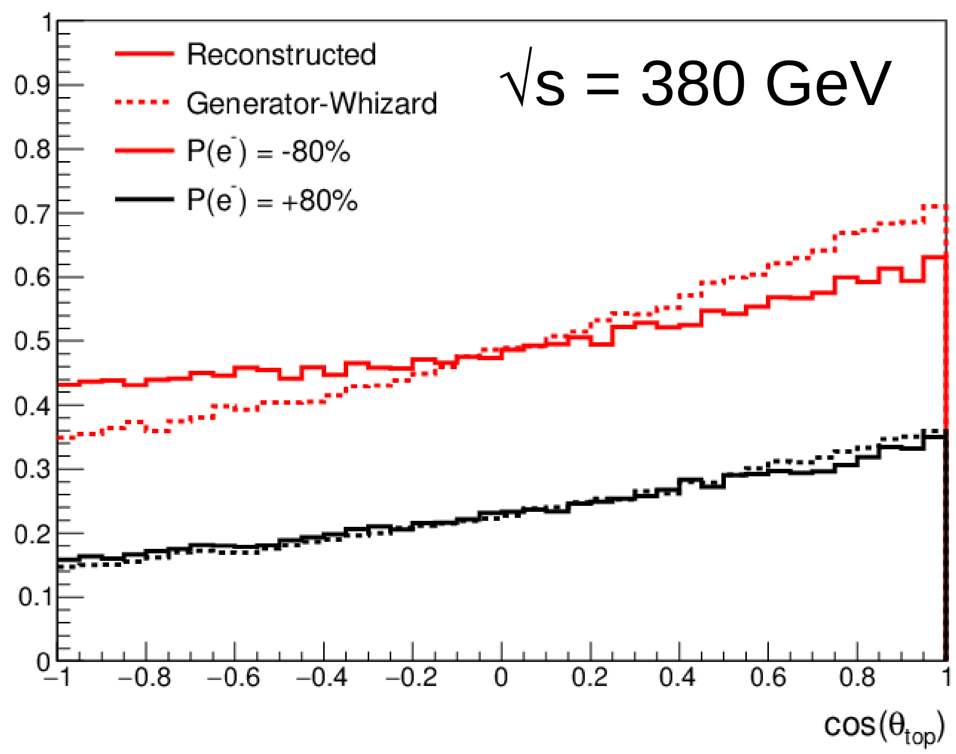
Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

Challenge: reconstruction

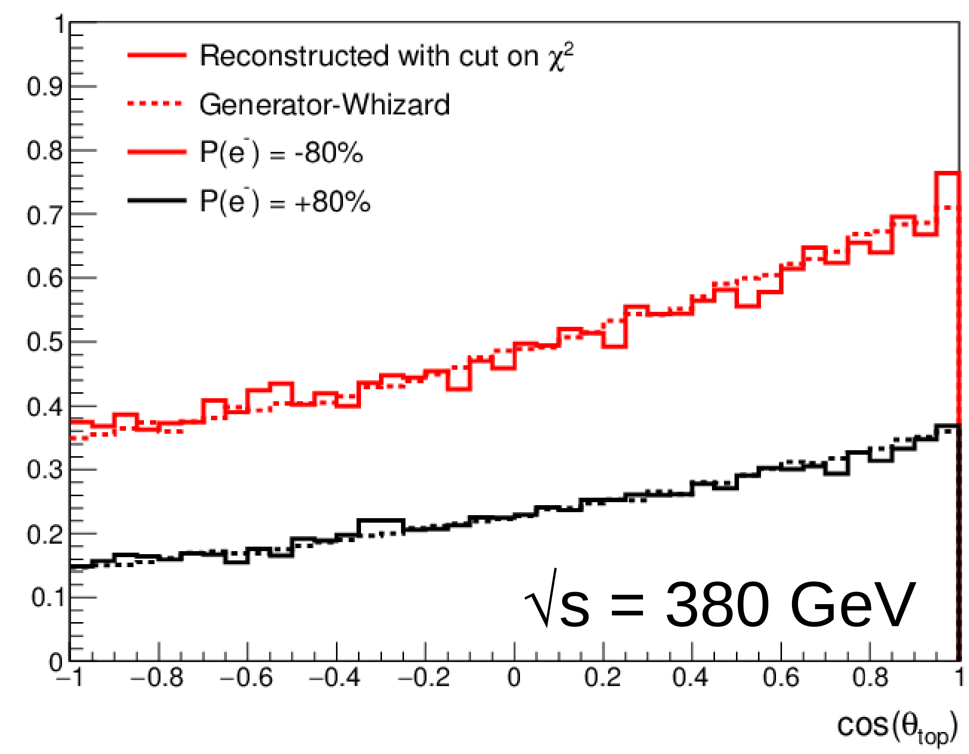
$t\bar{t}$ pairs at rest form a quite different final state than in at 500 GeV

- Full simulation results for CLIC@380 appearing (CERN + IFIC)
- A_{FB} much smaller and migrations due to ambiguity in b-W pairing more severe at 380 GeV than at 500 GeV (esp. for -80%, +30% polarization)
- Turning the crank on the usual machinery – a very tight cut on reconstruction quality – works at a rather high prize in statistics (and quite possibly modelling systematics)

Full simulation, "standard" reconstruction



Same + cut on reconstruction quality χ^2

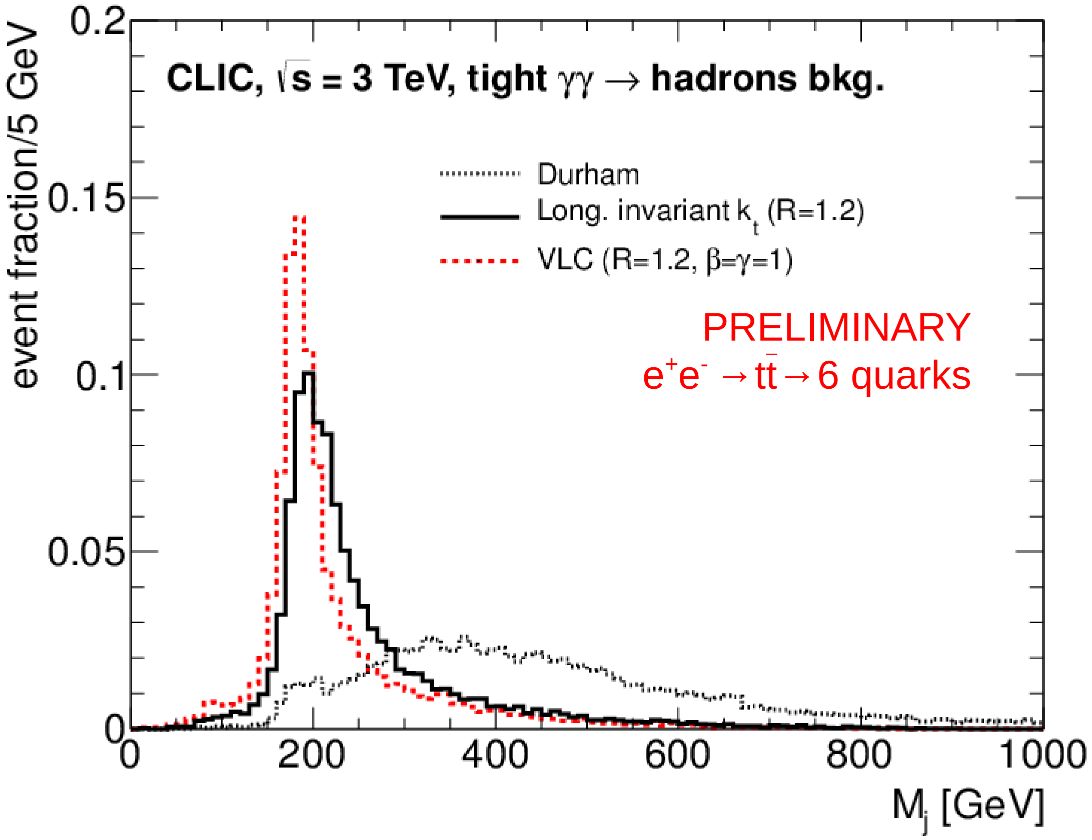


Top quark couplings at a (multi-) TeV collider

TeV top quarks in CLIC high energy phase are "an entirely different beast"

- available statistics
  - s-channel process: drop in x-section not compensated by increase in luminosity
- selection
  - What to do with the low-energy tail due to ISR and beam energy spread tail?
  - Top-tagging: very striking signal, small backgrounds → high efficiency?
  - Fat jet substructure to replace fermion counting? ($t\bar{t}$ – WW – $q\bar{q}$ separation)
- reconstruction
  - no ambiguity for highly boosted tops

systematic comparison just starting

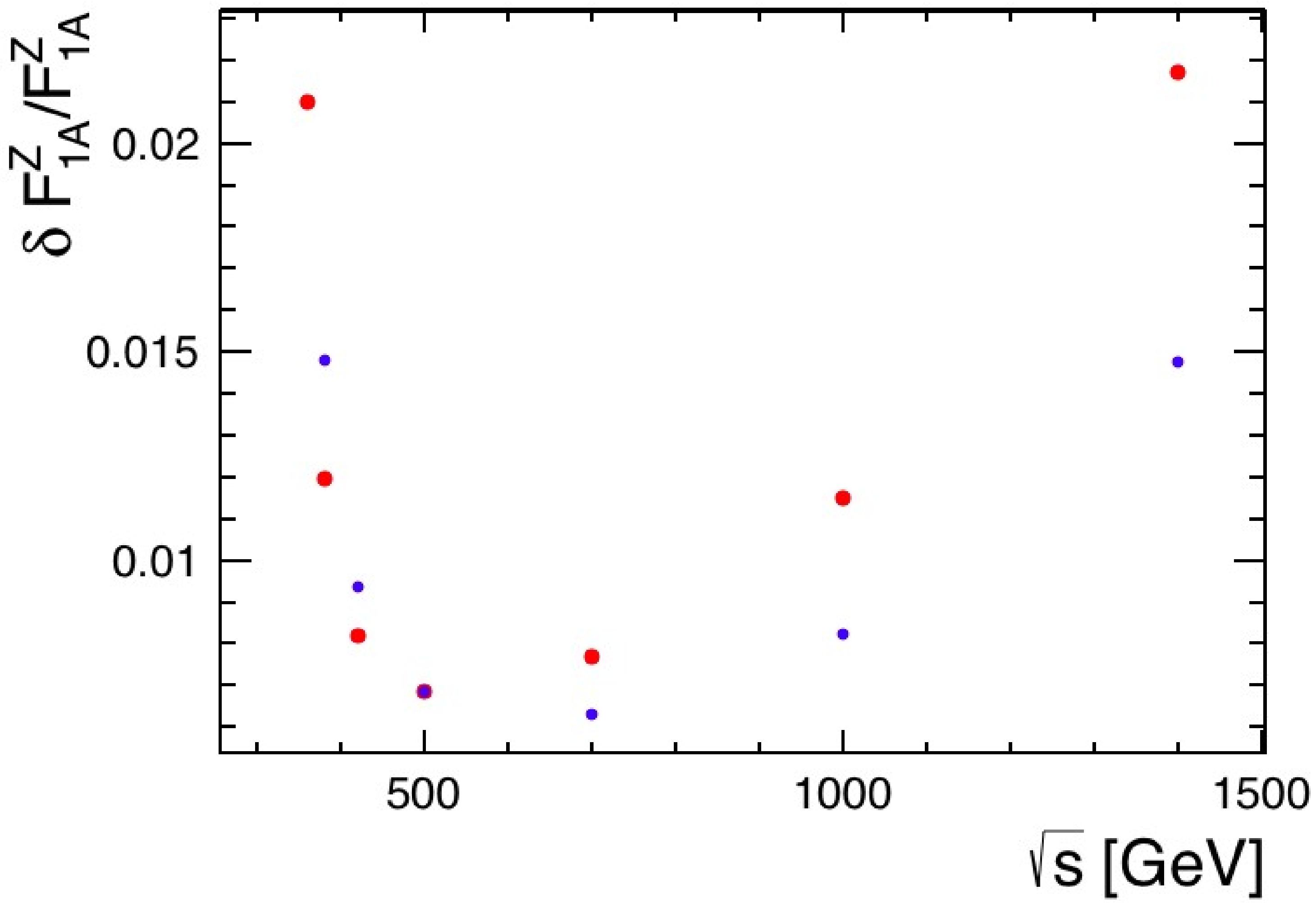


Top quark couplings: sensitivity vs. sqrt(s)

Luminosity proportional to $\sqrt{s}$ — Flat Luminosity: 500/fb

Small cms energies:

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



High cms energies:

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

From Roman Poeschl, Wednesday top session

- F1AZ profits from somewhat higher energies (beta dependence)
- Remark: Full disentangling for F1VZ and F2VZ at ~1 TeV

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

Top quark couplings: sensitivity vs. sqrt(s)

Simple evaluation of statistical uncertainty. A thorough full-simulation CLIC study started.

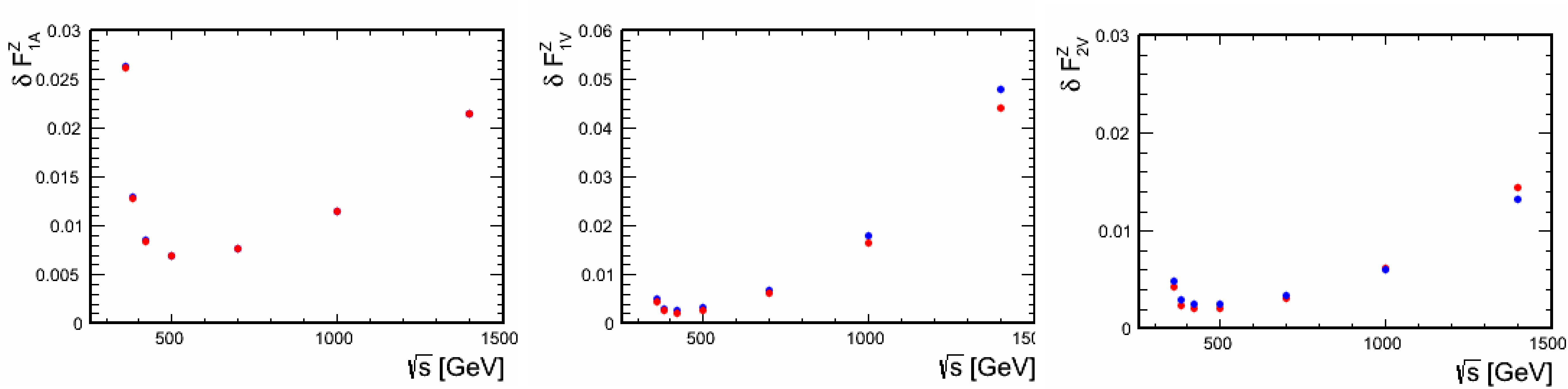
stat. dominated uncertainty:

$\delta\sigma/\sigma \sim 1/\sqrt{N}$ $\delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$

Integrated luminosity: 2 x 250/fb

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

Electron polarization only



F_{1V}; shallow minimum → *optimal around 400 GeV*

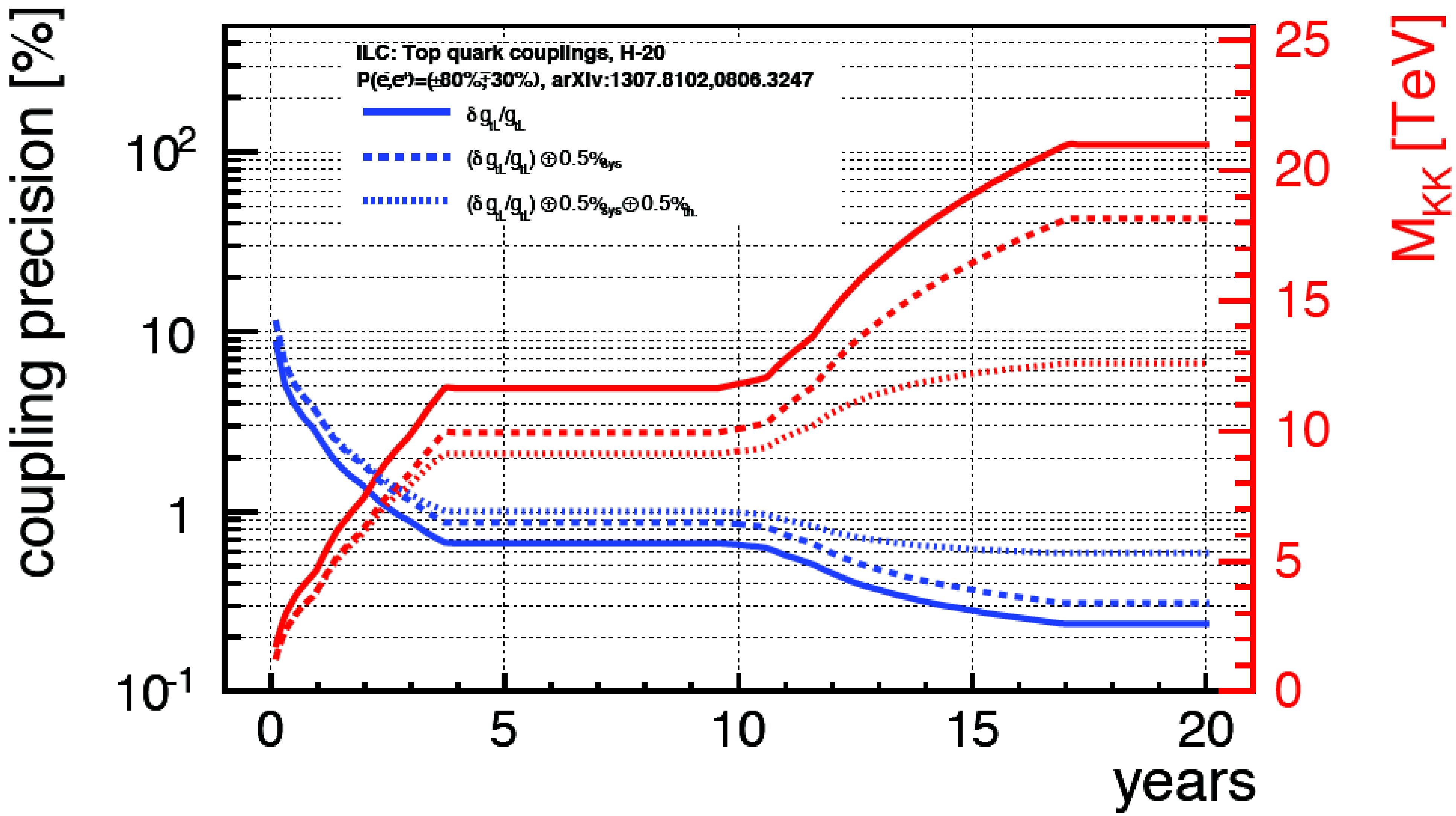
F_{1A}; A_{FB} degraded strongly close to threshold → *500 GeV*

F_{2V}; impact of new physics grows strongly with energy → 1-3 TeV

Truly optimal: comprehensive program at several energies

Complete 20-year ILC programme

H20: 500/fb @ 500 GeV, 200/fb @ 350 GeV, 500/fb @ 250 GeV, 3500/fb @ 500 GeV, 1500/fb @ 250 GeV



Sensitivity to new physics well beyond the direct kinematic reach

CP violating couplings

The “baseline” study was limited to CP-conserving form factors, but e^+e^- is known to do well also for CP-violationg F2A at least since TESLA times

Reconstructing Bernreuther's optimal CP observables that measure differences in polarization orthogonal to production plane and in top quark flight direction.
In the lepton + jets final state:

$$O_+^{Re} = (\hat{q}_+^* \times \hat{q}_{\bar{X}}) \cdot \hat{e}_+ \qquad O_-^{Re} = (\hat{q}_-^* \times \hat{q}_X) \cdot \hat{e}_+$$

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

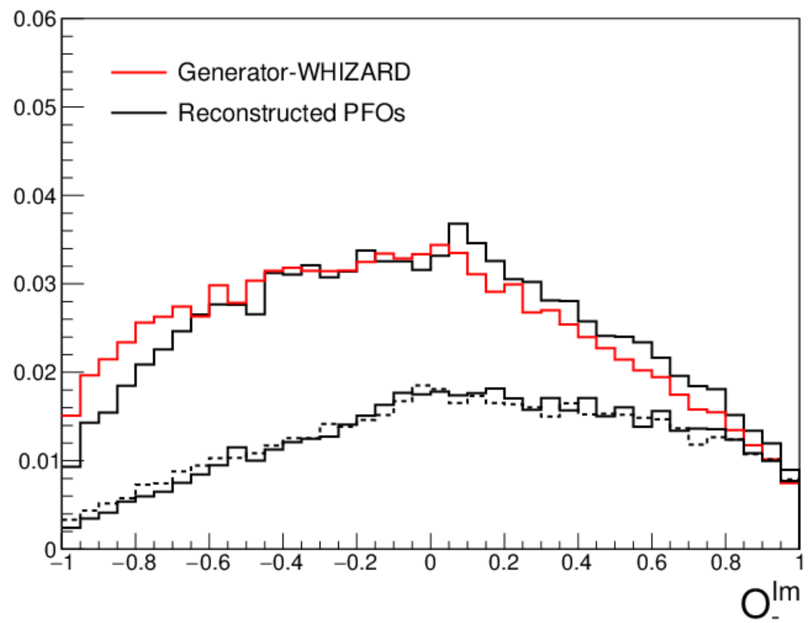
Where q= charged lepton momentum, X = hadronic top system, e = positron momentum

These observables have simple relations to the four F2A form factors:

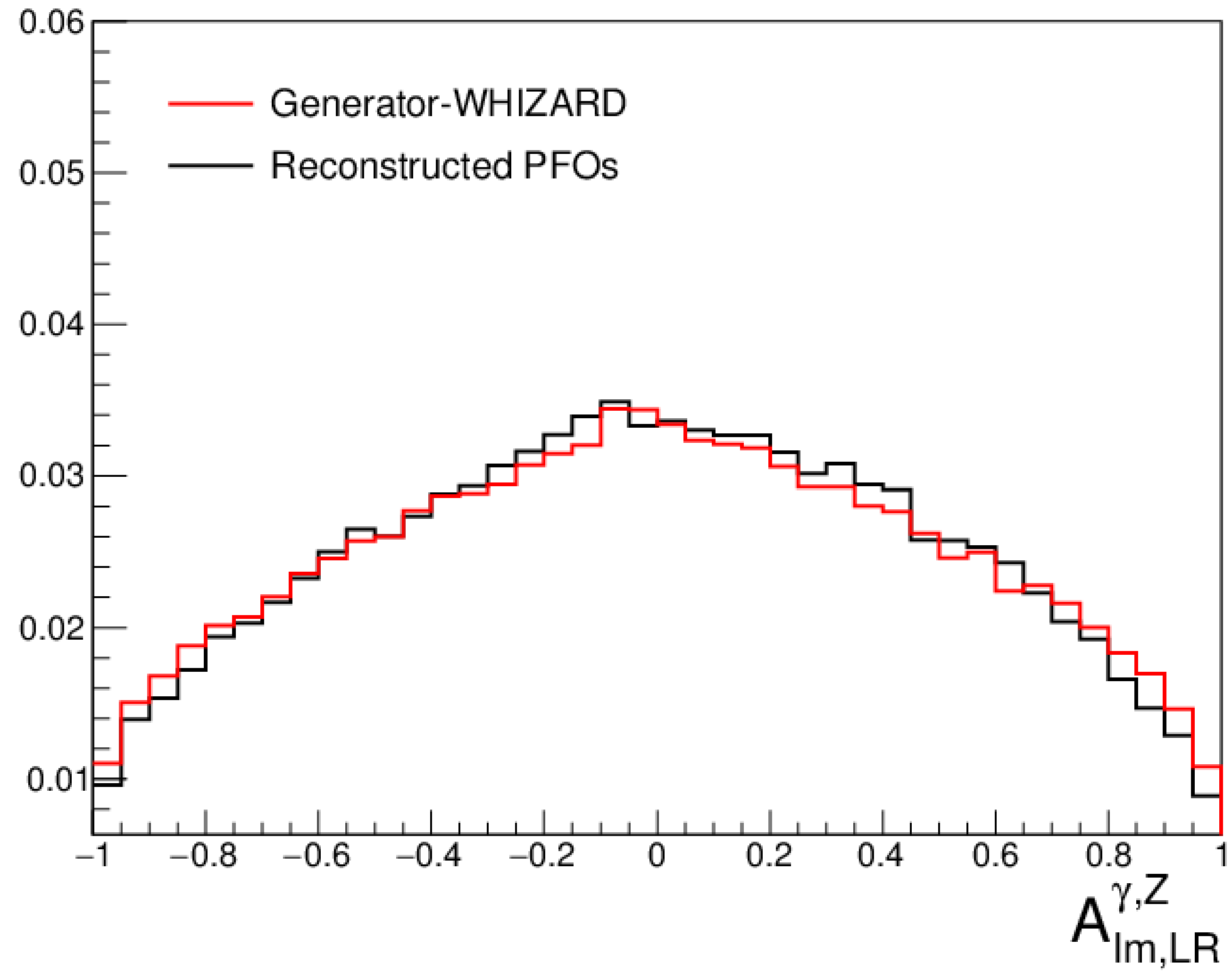
$$A_{\gamma,Z}^{Re} = \langle O_+^{Re} \rangle - \langle O_-^{Re} \rangle = c_\gamma [P Re(F_{2A}^\gamma) + KZ Re(F_{2A}^Z)]$$

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

F2A form factors



Significant migrations in the Oim distributions, largely cancel in asymmetry



Full simulation results exist for 500 GeV and 380 GeV.

MadGraph setup exists to introduce non-zero F2A in full simulation, but manpower is limited

Paper with updated numbers for LC potential in preparation

Matrix element on di-lepton final state

Khiem, Kou, Kurihara, le Diberder, Probing new phyiscs using top quark polarization in the e+e- → tt process at future Linear Colliders, arXiv:1503.04247 [hep-ph]

GRACE six-fermion process without narrow-width approximation
(no ISR, no single top, no hadronization, no detector)

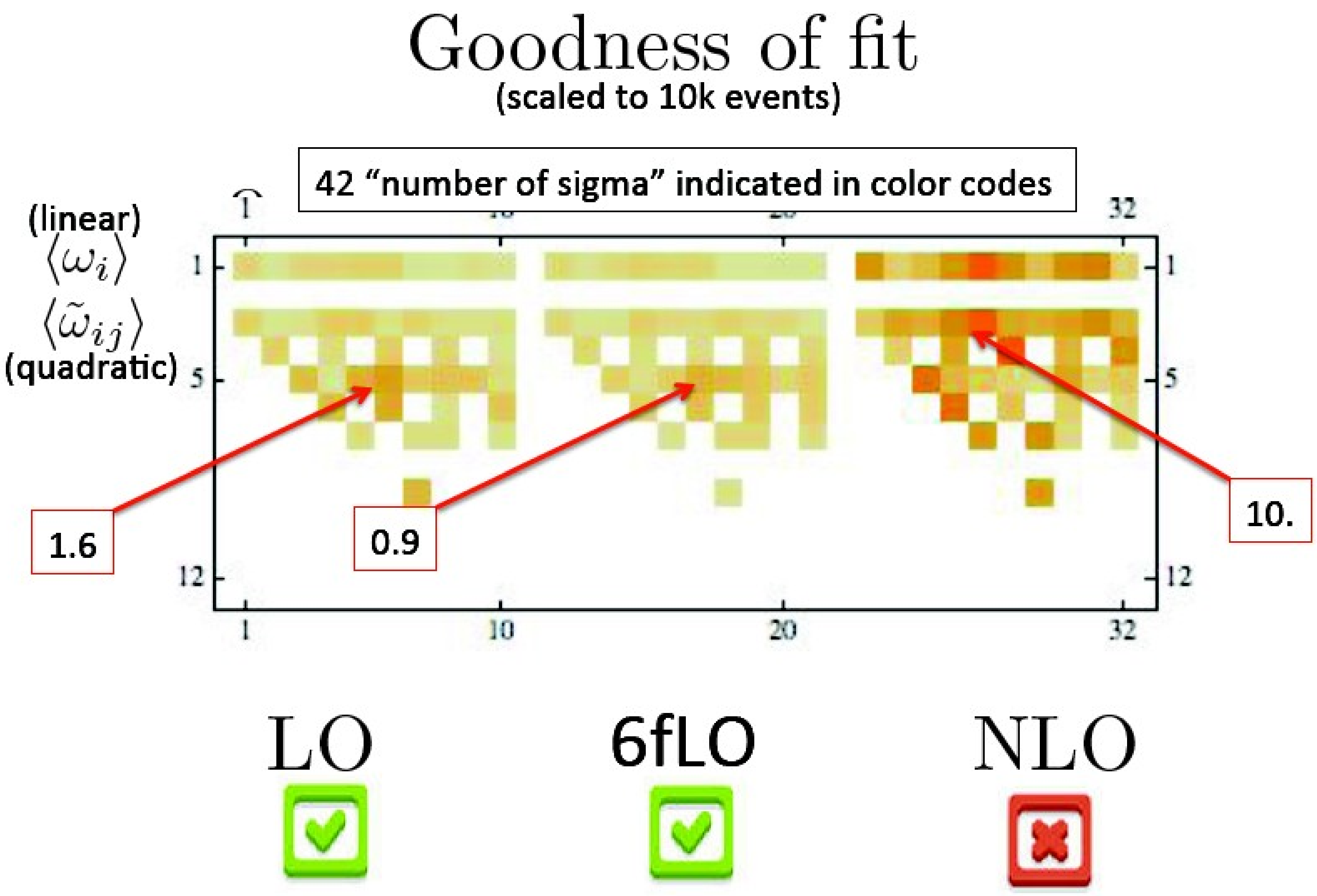
Show feasibility of kinematic reconstruction of the di-lepton final state: $e^+e^- \to t\bar{t} \to l^+\nu l^-\bar{\nu} b\bar{b}$

Optimal analysis extracts all ten form factors – simultaneously – from angular distribution using the (LO) matrix element

$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{1V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{1V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{1A}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{1A}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2A}$	$\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{Z}_{2A}$
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

Sub-% precision. Note 0 correlation F2A with CP-conserving form factors
Lepton+jets final state, with same optimal ME extraction, yields factor two better precision

LO Matrix Element

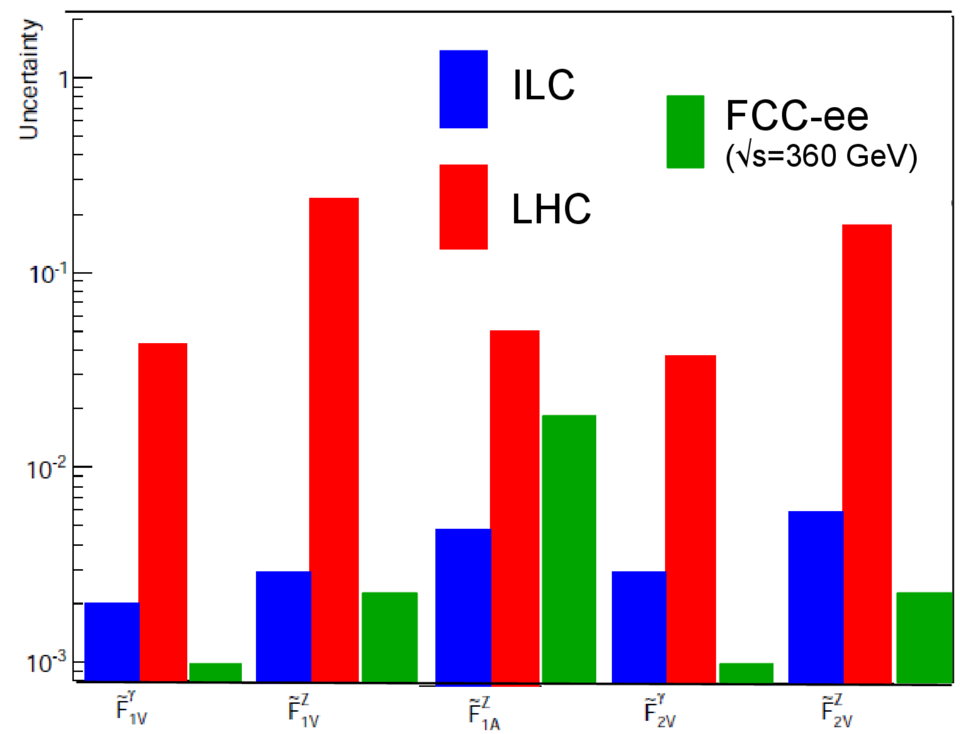


Fitting a LO template to (all-order) data expected to lead to tension in the fit and bias of the parameters
Check fitting LO template to NLO-EW Monte Carlo → large χ^2 indeed reveals a problem
Work ongoing to extend analysis to NLO

Comparison to FCC-ee

Recent publication assesses potential of FCC-ee
P. Janot, arXiv:1503.01325, arXiv:1510.09056
- run right above threshold; study assumes 2.4 ab^{-1} at $\sqrt{s}$ = 365 GeV
  (theory systematics close to threshold to be evaluated)
- no beam polarization, use final-state polarization instead
  (ILC beam polarization expected to be known to 10^{-3}, can one understand final state polarization to that level?)

Fast simulation analysis based on lepton energy and angle yields:
- similar precision to ILC for Z couplings, except F1AZ
- significantly better than ILC for photon couplings



Good to see interest in this measurement
Full study needed to understand systematics

Top quark couplings: summary

Linear Collider top quark physics programme has exquisite sensitivity to new physics through a precise characterization of $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices, with sub-% to per mil level precision on all anomalous form factors/operators, an order of magnitude better than LHC prospects from associated production

Evaluation of √s dependence of "baseline" analysis

→ **best precision** between 400 GeV and 700 GeV

→ **best sensitivity** for some form factors/operators at very high energy

Full LC programme can explore new physics up to well over 10 TeV

Adding CP violating form factors

→ confirm sensitivity of TESLA TDR study

Comparison of simple "fit" with sophisticated ME extraction of form factors

→ optimal use of information helps; simultaneous extraction of 10 form factors demonstrated

→ systematics to be propagated in a meaningful way