Precision top quark physics at a future linear e^+e^- collider

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With special thanks to:
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F. Richard, R. Poeschl (LAL Orsay)
I. Garcia, M. Perello, E. Ros, P. Ruiz Femenia (IFIC Valencia)

LC top physics – canonical programme

350 GeV:

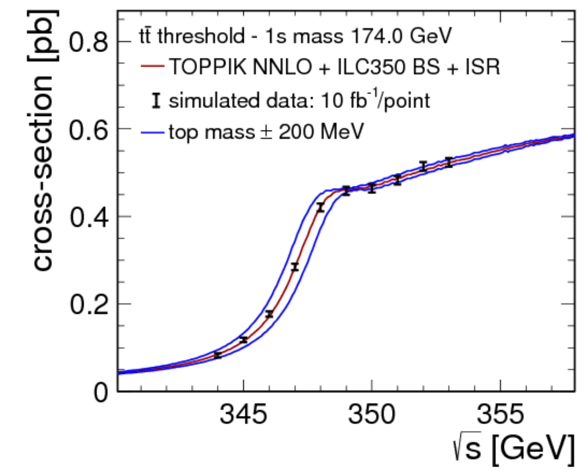
Threshold: top quark mass to < 100 MeV (+width & Yukawa)

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

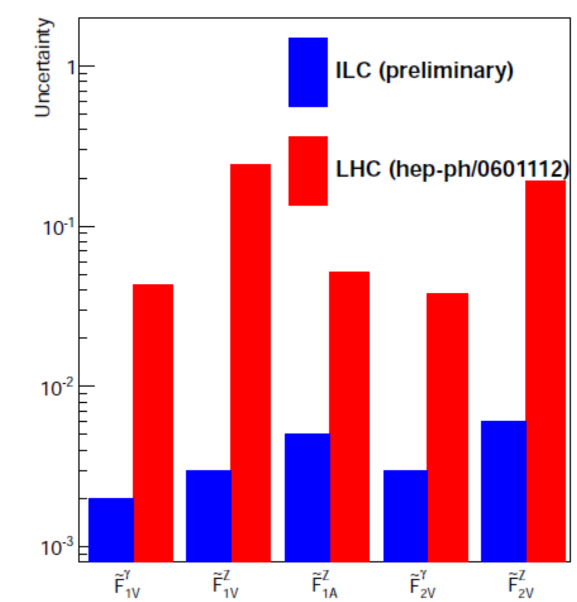


500 GeV:

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

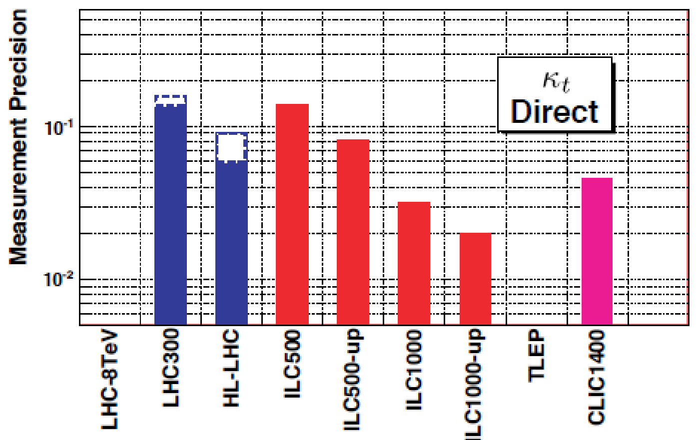
M.S. Amjad et al., arXiv:1307.8102

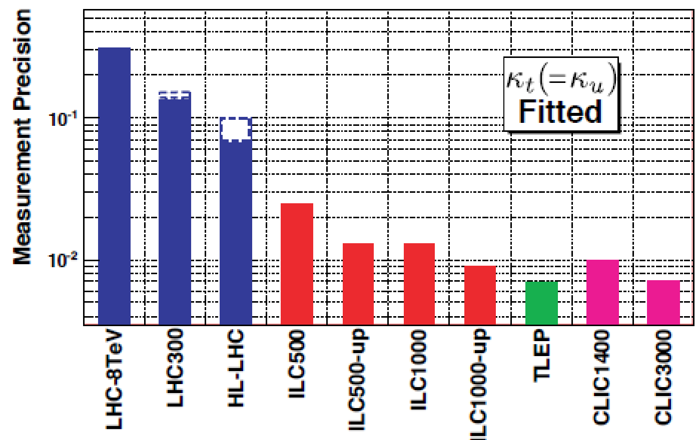
F. Richard, arXiv:1403.2893



500-1500 GeV:

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





Some analyses require limited sqrt(s) range (threshold scan, ttH)
How well can we measure A_{FB} at √s = 420 GeV?

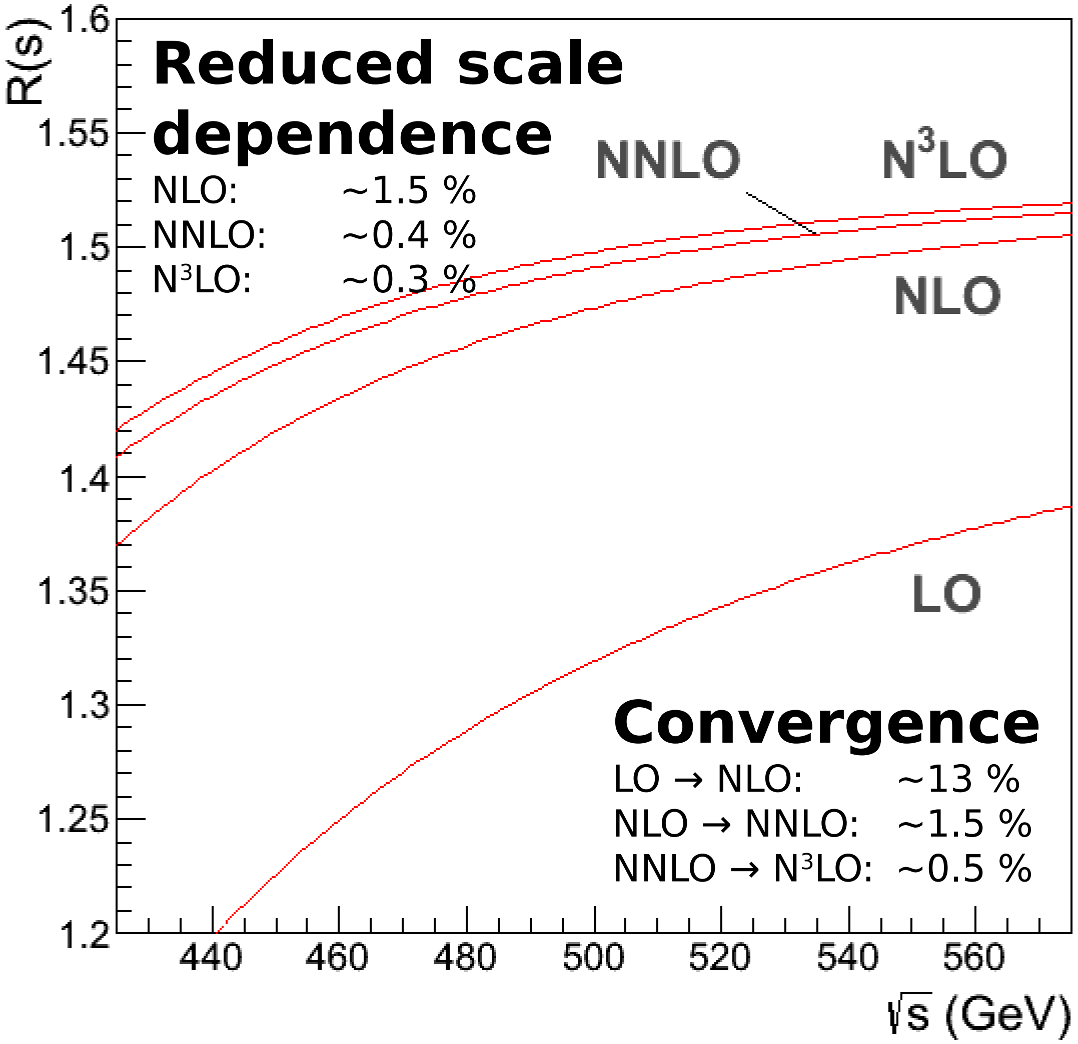
Dependence of the sensitivity to new physics of a measurement of the ttZ and ttγ vertices on √s ?

Theory status

State-of-the-art: $O(\alpha_s^3)$ QCD corrections of $e^+e^- \rightarrow tt$ x-sec with per mil precision

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

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



QCD corrections

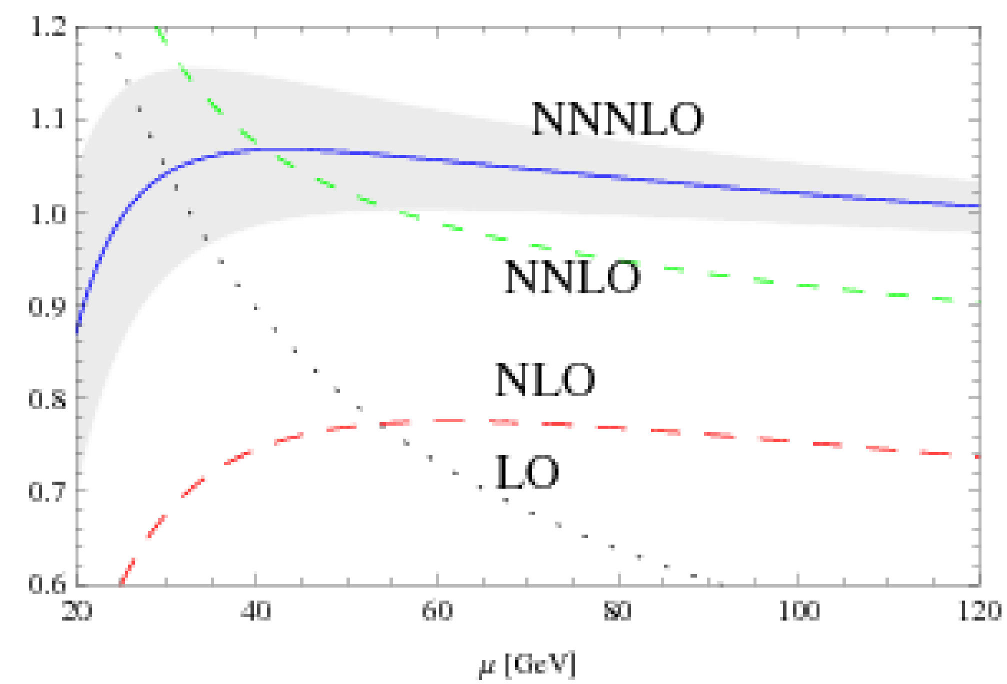
to $e^+e^- \rightarrow tt + X$

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

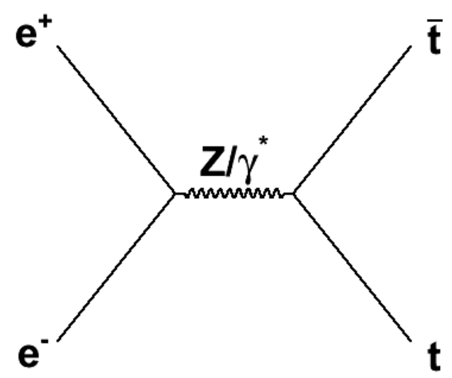
Electroweak corrections

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

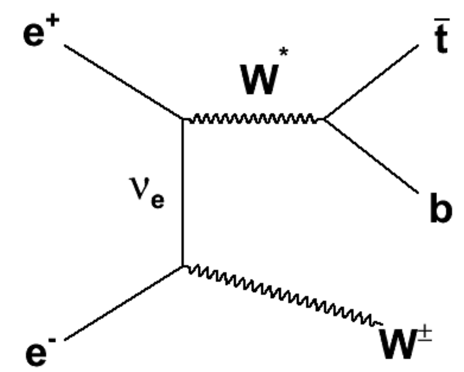


At threshold: NNNLO resummed calculations include quasi-bound-state effects

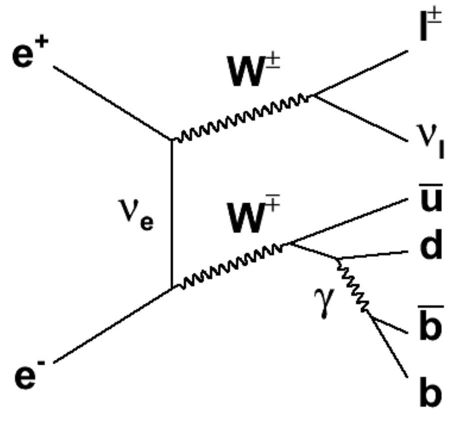
Top quark pairs vs. WbWb



Top quark pair production...



...Single top quark production...



...WWγ/Z/h...

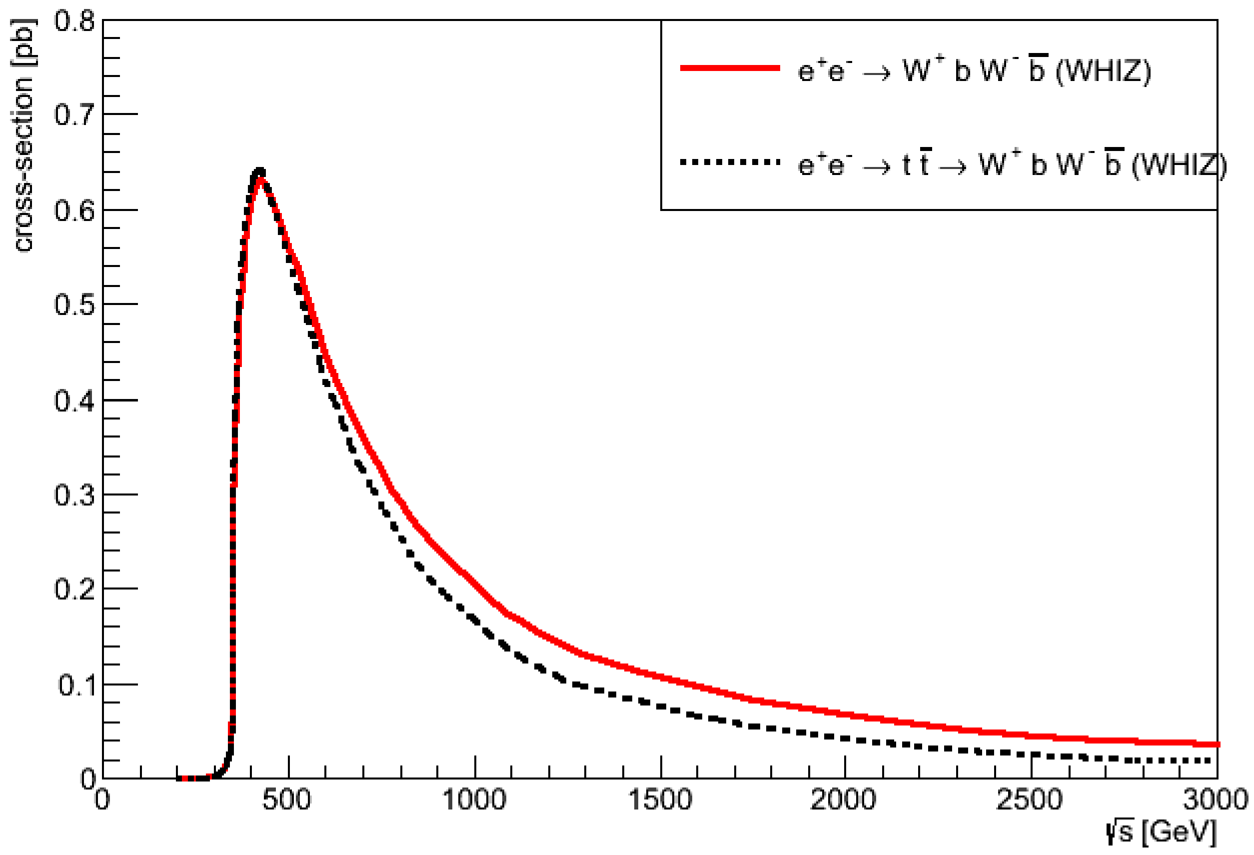
WbWb̄ → 6 fermions has several non-negligible sources

(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 tt̄ 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!

Compare: top quark mass

Threshold scan is clearly the ultimate mass measurement?

Of course, we will perform a top quark mass measurement also at $\sqrt{s}$ >> 350 GeV

Linear Collider alternatives to threshold scan:

-1- Direct measurement (Seidel et al.)

(stat. precision ~80 MeV at $\sqrt{s}$ = 500 GeV, unclear interpretation)

-2- Extract pole/$\overline{\mathrm{MS}}$ mass in continuum (Boronat, Fuster, in progress)

(precision to be evaluated)

-3- Boosted top quark jets at a 1 TeV e^+e^- collider

- Extraction from top jets (Hoang, Mantry et al., PRD77 (2008) 074010 & 114003)

  (rigorous SCET interpretation, $\sqrt{s}$ = 1 TeV, can "compete" with threshold scan)

- Experimental studies largely lacking so far

These ideas are receiving more attention...

- Same idea might work when ported to a hadron collider

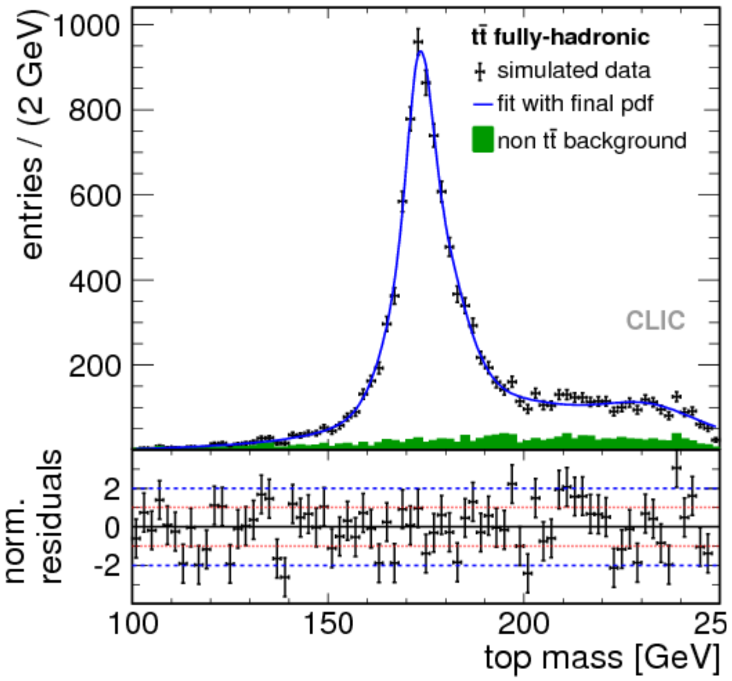
→ important experimental challenges (pile-up)

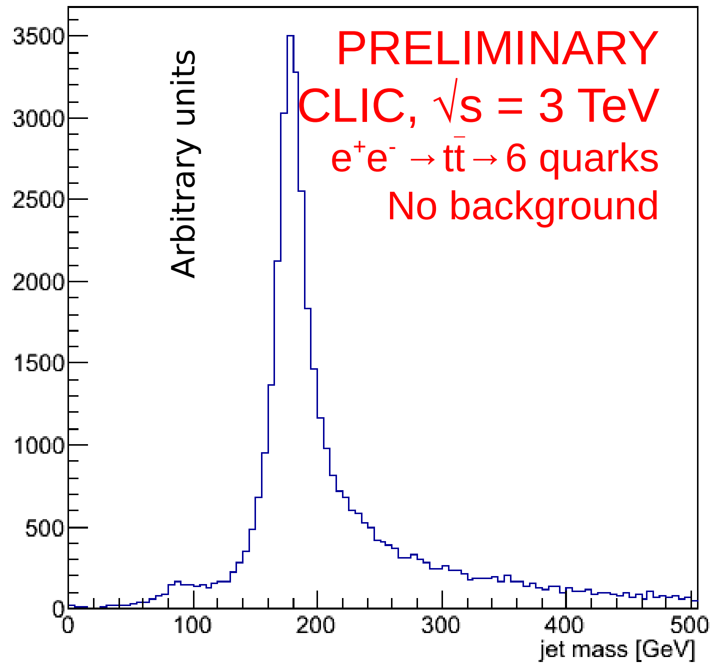
→ calculations much more complex, but tractable...

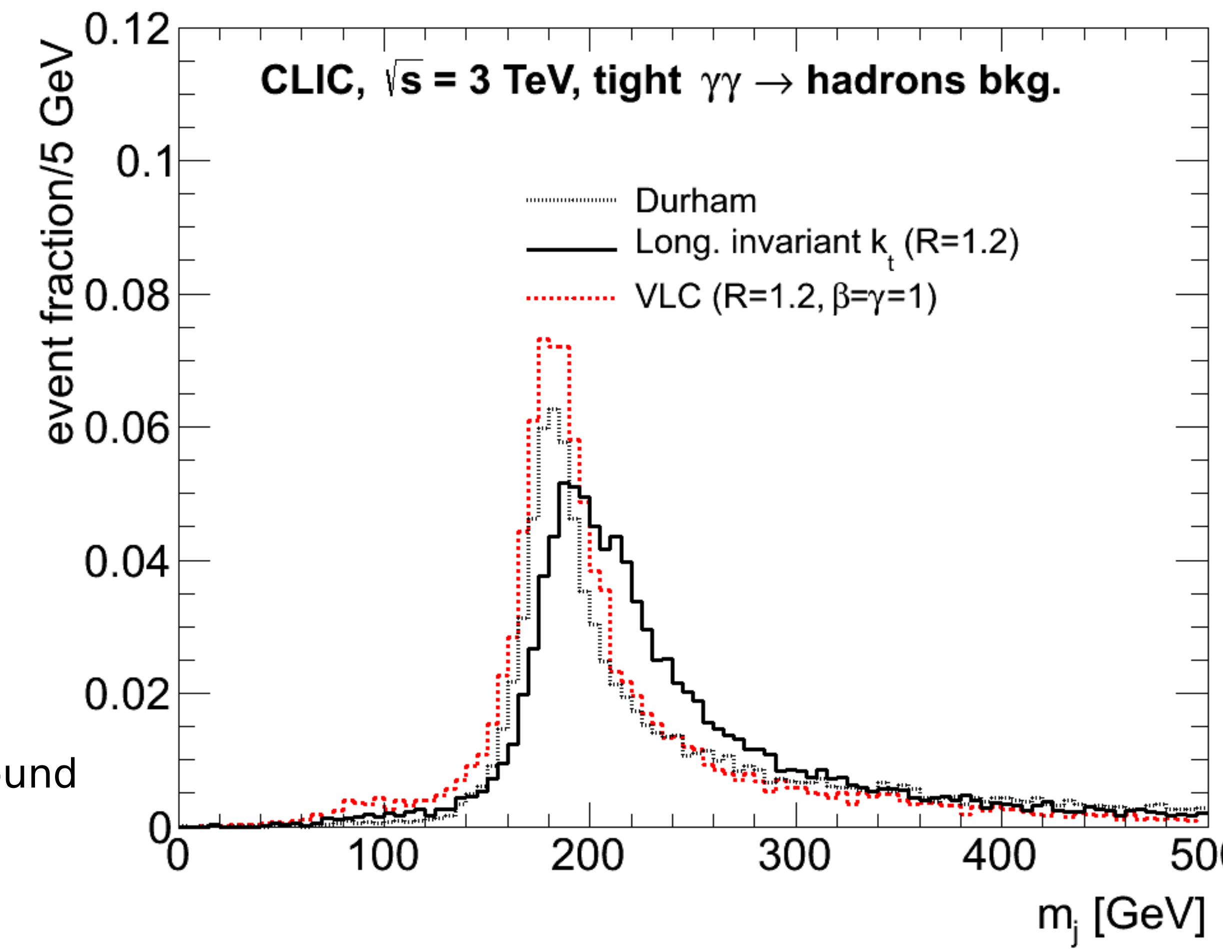
- Discover relation between pole mass and MC mass?

→ see Hoang, LCWS14

Top quark selection/reconstruction







ILC / CLIC top jet mass resolution, including realistic background
→particle flow response is excellent
→background mitigated by jet algorithm (arXiv:1404.4294)

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

Low energy: challenging combinatorics

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

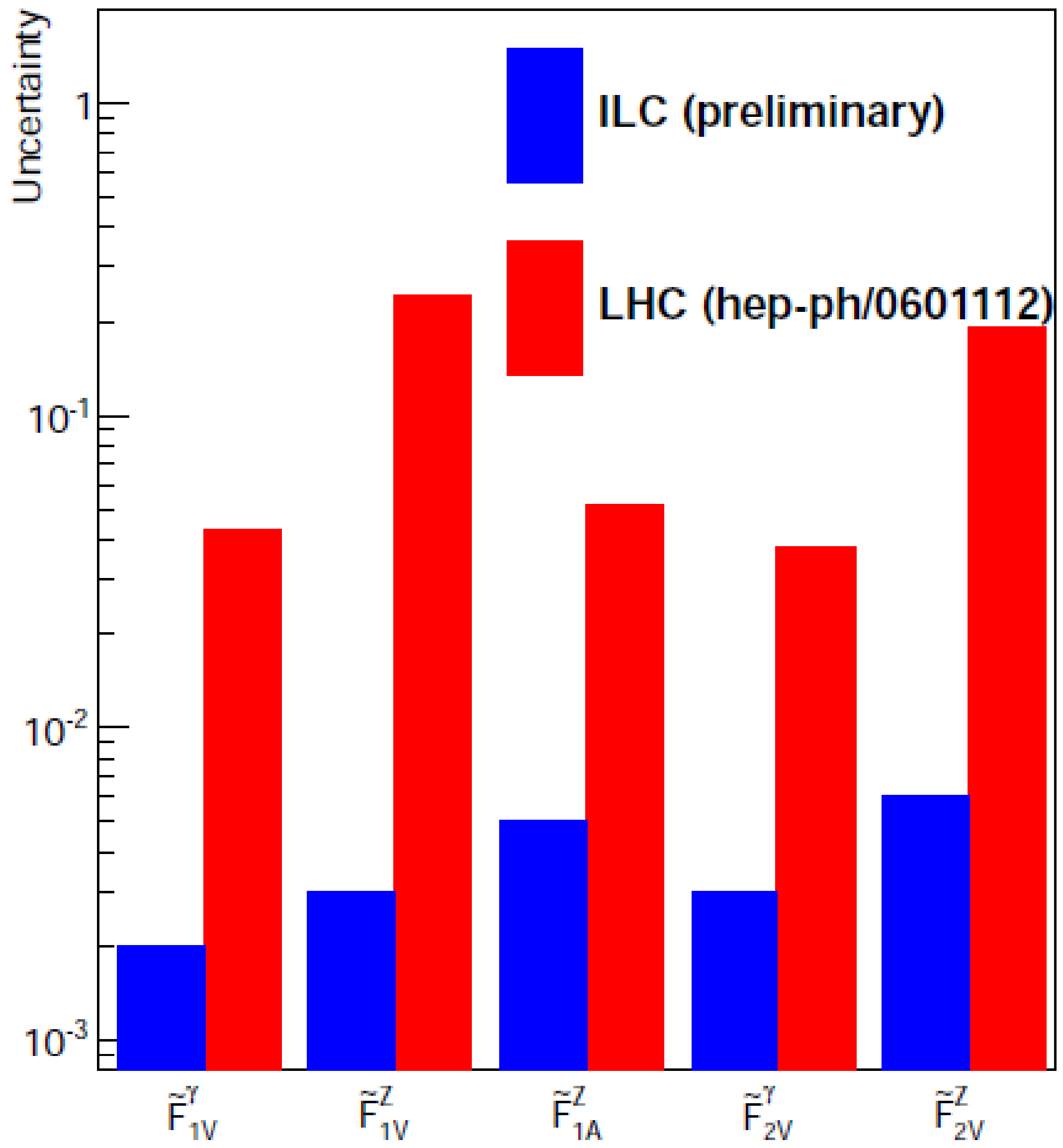
Provided we can deal with the γγ → hadrons background in fat jets, top reconstruction at high energy may well be more precise than at low energy!

Top quark couplings

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

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

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



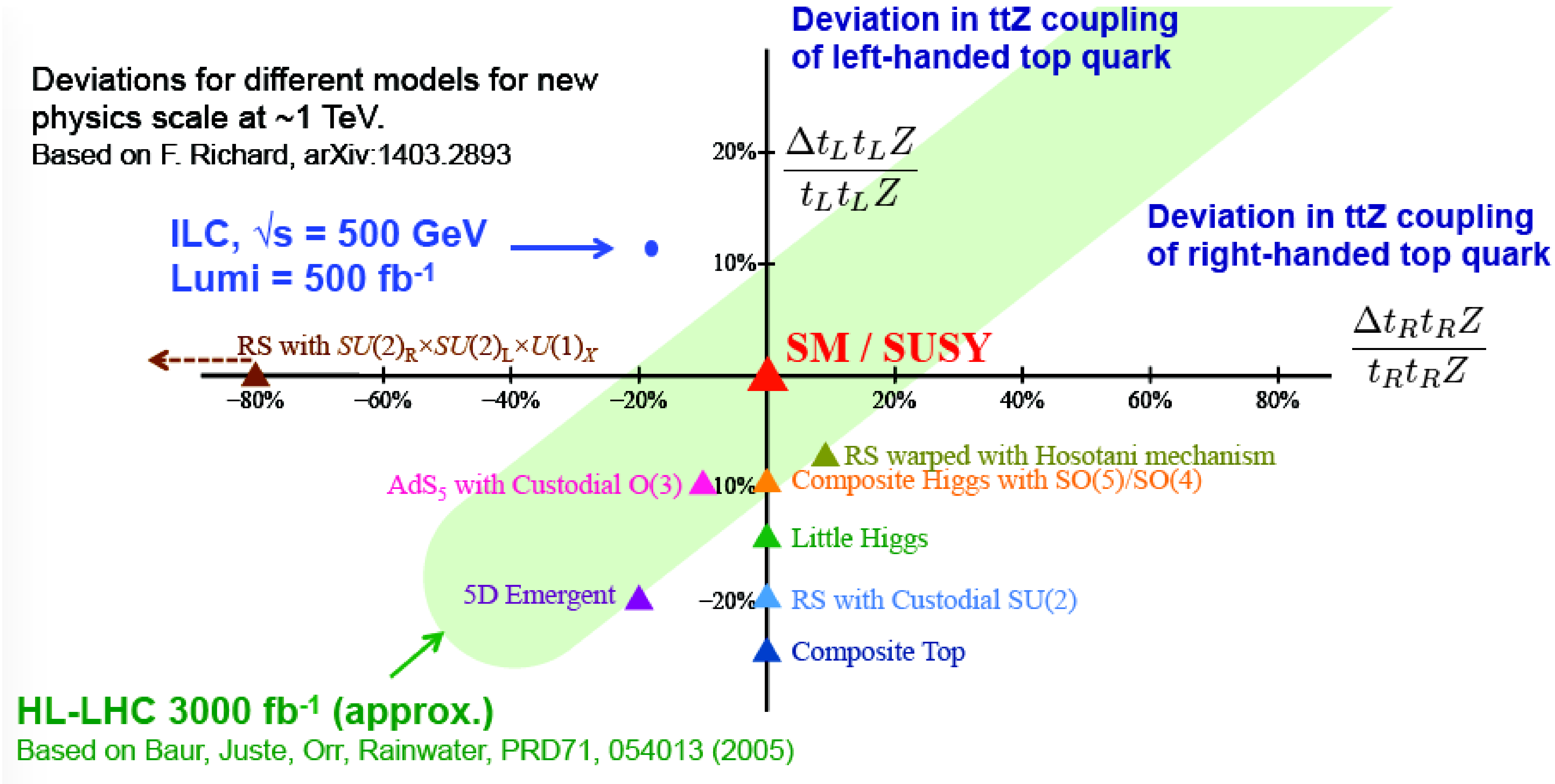
Assumptions:

LHC: 14 TeV, 300/fb
LC: $\sqrt{s}$ = 500 GeV, L = 500/fb
$P(e^-)$ = +/- 80%, $P(e^+)$= -/+ 30%
$\delta\sigma$ ~ 0.5% (stat. + lumi)
δA_{FB} ~ 2% (stat. + syst.)

Polarization needed to disentangle photon and Z-boson form factors! arXiv:1307.8102
But, no need for effective polarization >90%
Dropping positron polarization does not change results dramatically

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

New physics sensitivity



New physics reach of a precise top couplings measurement

Sensitivity to BSM physics

Assuming 1.5 % deviations on A_{FB} measurement can be observed (J. Trenado, M.V.):

ILC500 GeV: sensitive for Z'_{SSM} mass up to ~3 TeV

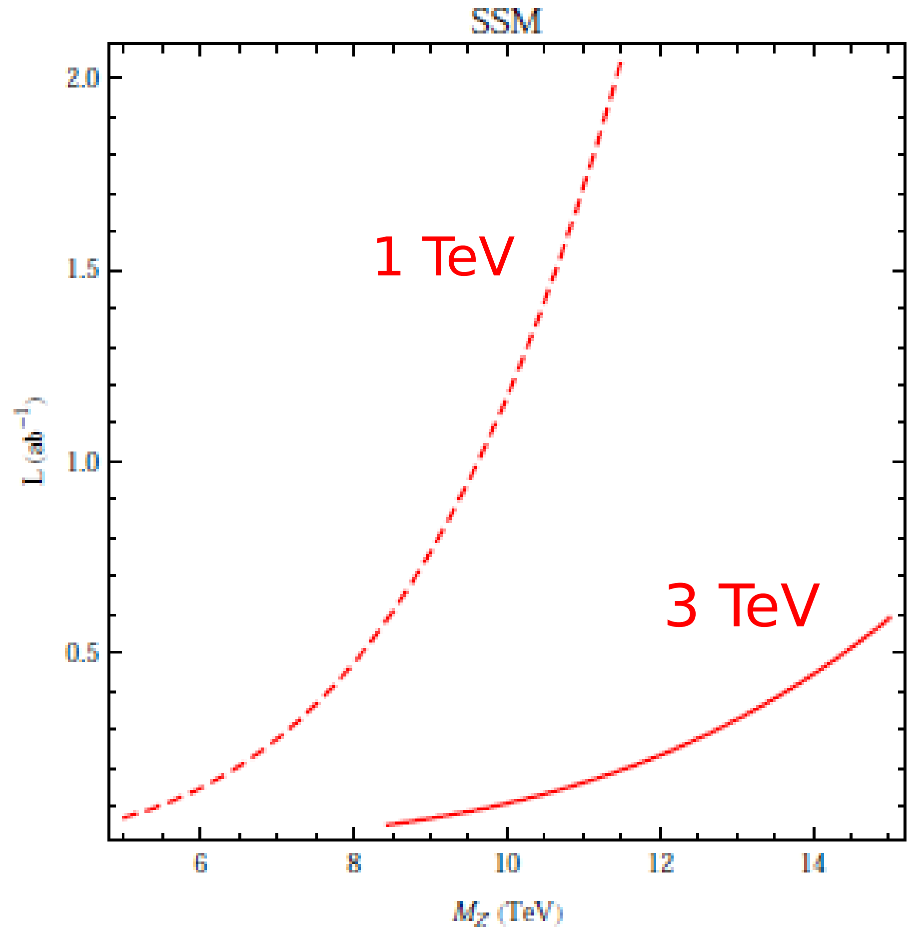
Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
A_{FB}^{tt}	0.41 ± 0.01	0.289	0.382	0.397	0.401	0.407

ILC1 TeV : mass reach for Z'_{SSM} > 5 TeV

Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
A_{FB}^{tt}	0.554	0.289	0.434	0.513	0.532	0.537

Luminosity required to see signals of massive Z' *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



The closer we get [to the new physics scale], the more we feel [its indirect effects]

Made explicit in effective operator analysis → constant form factors replaced by c/Λ^2, where Λ is new physics scale

J.A. Aguilar argues for measurements at several energies, arXiv:1206.1033

Generators

Continuum

WHIZARD can produce LO $e^+e^- \rightarrow$ 6 fermions (samples used for ILC TDR) that includes top quark pair production and single top (most results in this talk)

aMC@NLO, merger of MadEvent and MC@NLO, provides an automated way to generate a full NLO description (not extensively validated for this particular process)

Close to the production threshold, bound state effects enhance the x-section

- fully differential result not available so far
- Fabian Bach (DESY) nearly ready to provide WHIZARD ttbar_threshold (expected v2.2.3)
- Nacho Garcia and Martin Perello tested beta version predictions for x-sec, A_{FB}, etc.
  (some plots in this talk from this study)
- Good agreement with literature (cf. Martinez & Miquel)
- matching to NLO continuum calculation is in progress (A. Hoang, F. Bach)

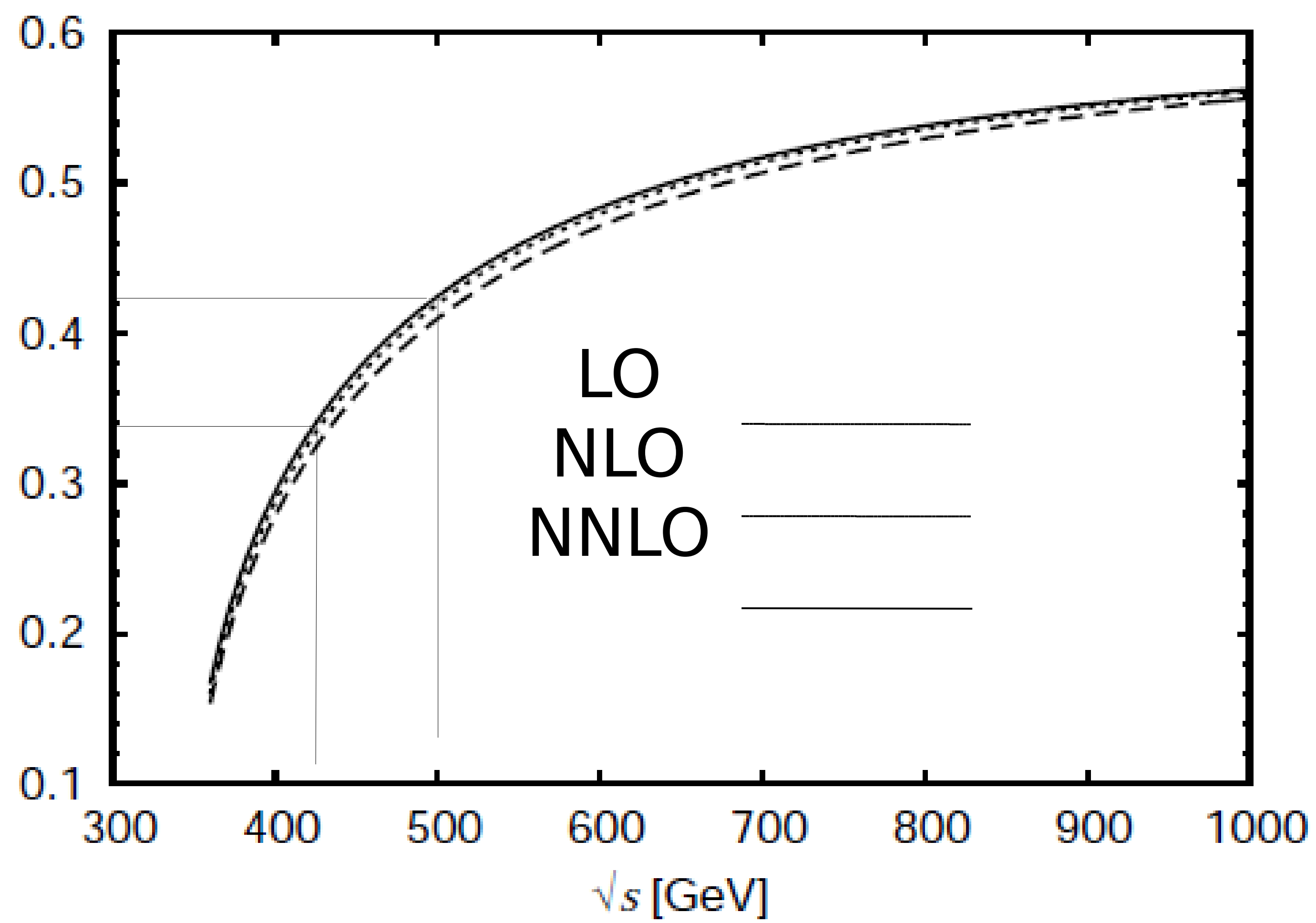
A_{FB} versus √s

A_{FB} vs. sqrt(s)

Order α_s^2 results in

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

"… we conclude that the 2-parton QCD corrections to the lowest order asymmetry are moderate to small for √s > 400 GeV"



Scale variations yield <1% error @ NNLO

One-loop EW corrections have a large effect: 20% on A_{FB}, at 500 GeV.

Two-loop contribution seems small (P. Ruiz Femenia)

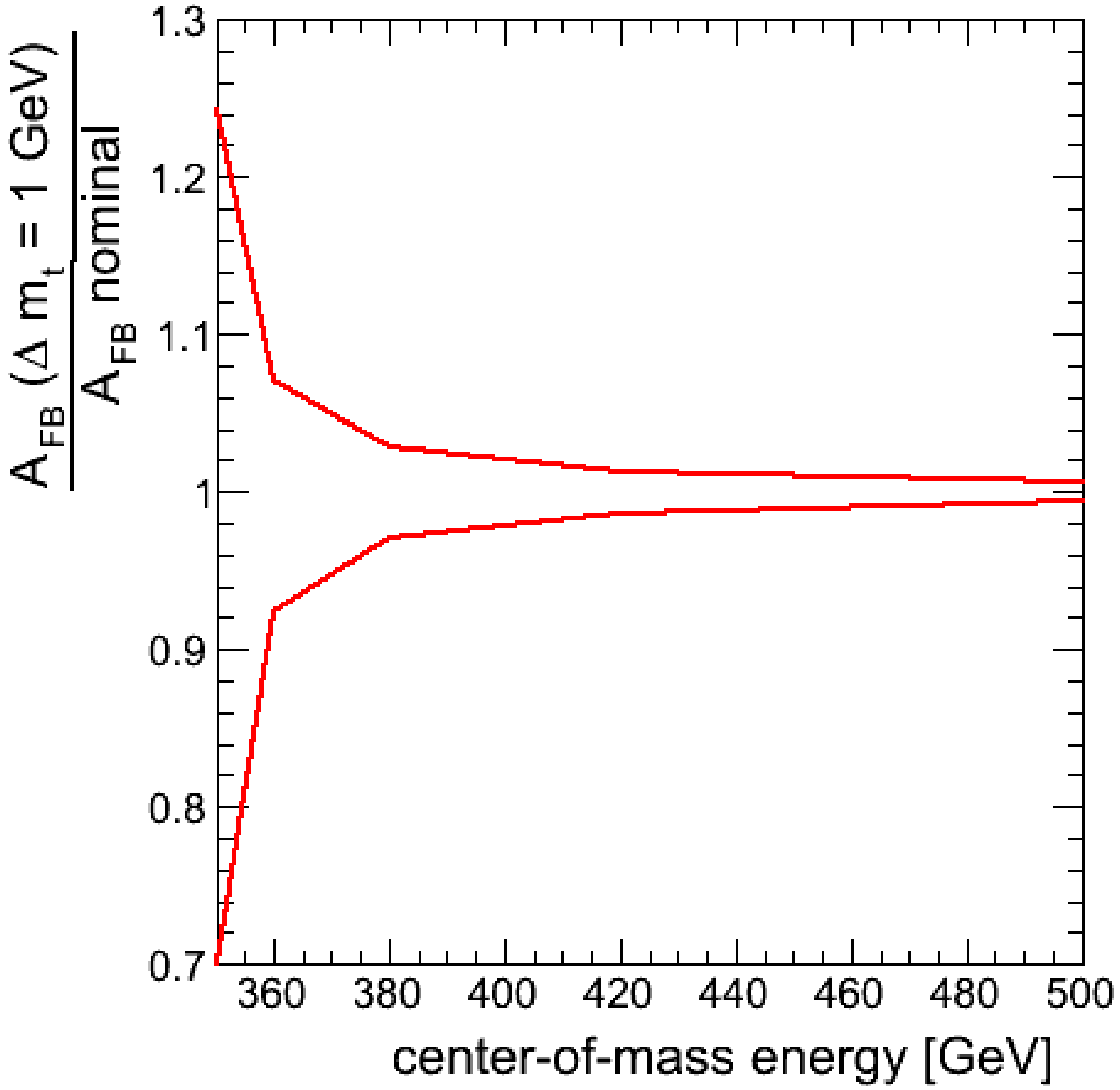
A 500 GeV LC has a 50% higher asymmetry than at 420 GeV.
Statistical uncertainty is similar (lumi makes up for x-sec)

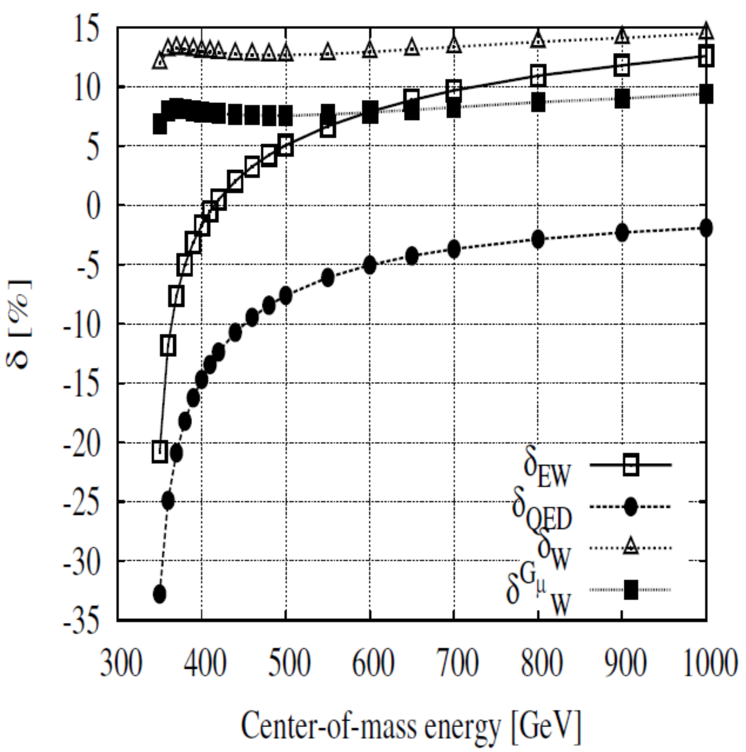
Parametric uncertainty

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

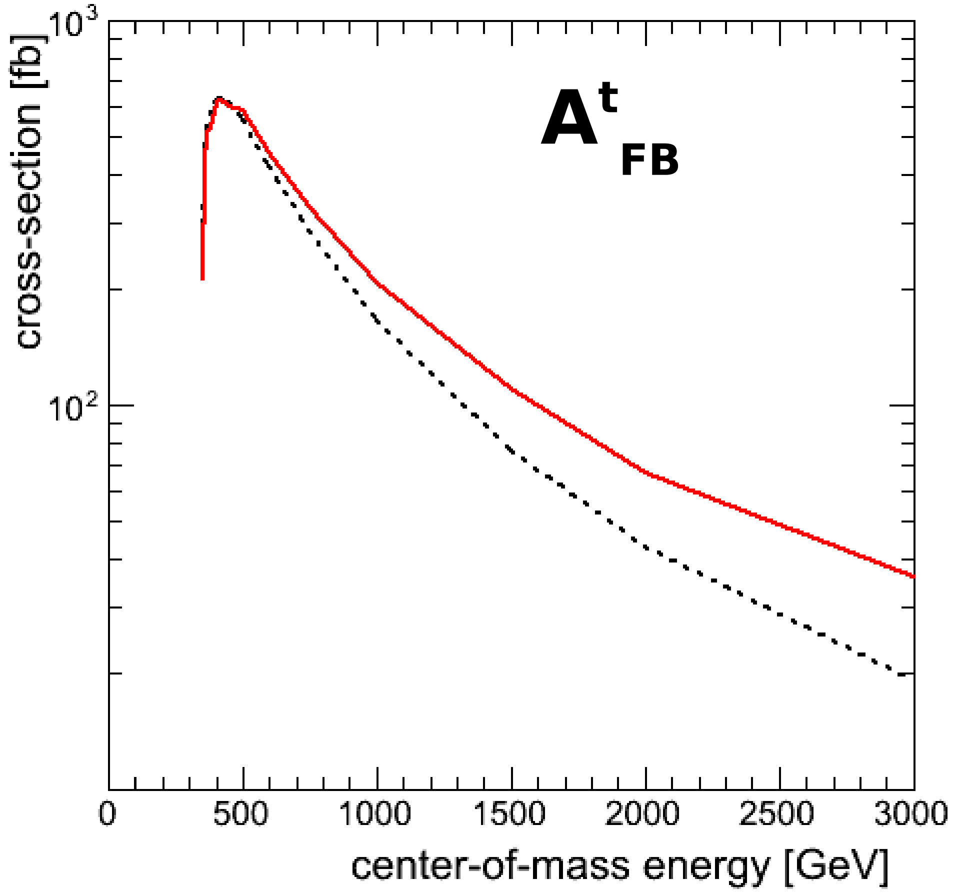
With the assumption of a 100 MeV pole mass measurement at threshold, the remaining uncertainty is one per mil or less above 420 GeV

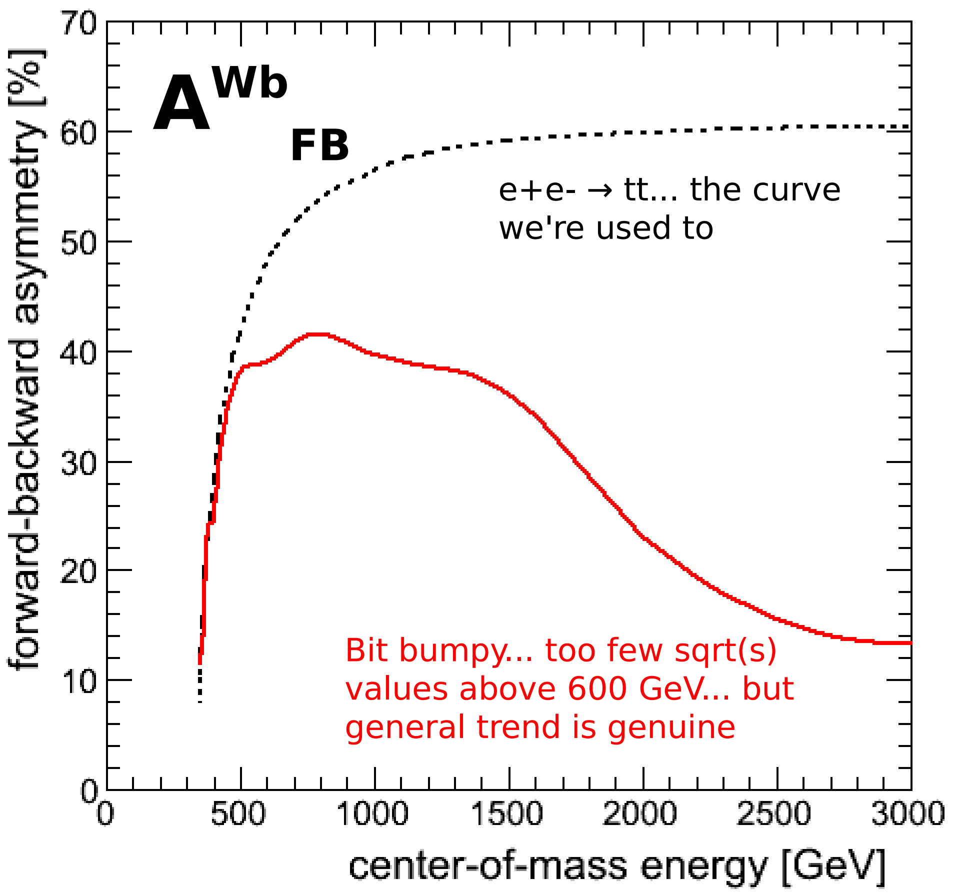




Expect also larger contribution from other sources when approaching the threshold?
EW corrections, Khiem et al., arXiv:1211.1112

Impact of single-top





Single top known to become important at large center-of-mass energy
Particularly important for $\sqrt{s}$ > 500 GeV

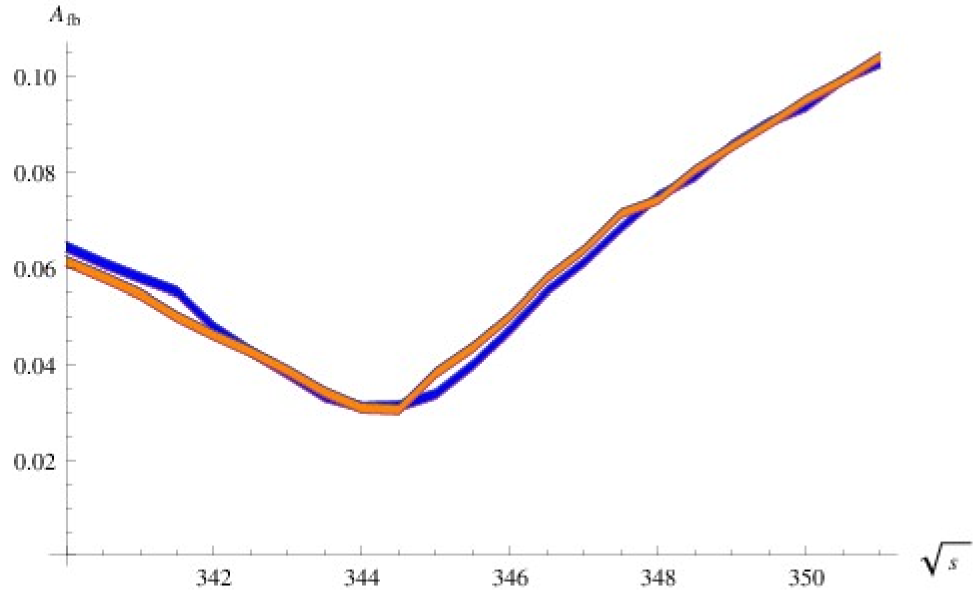
At threshold

Can we measure the asymmetry very close to the threshold?

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

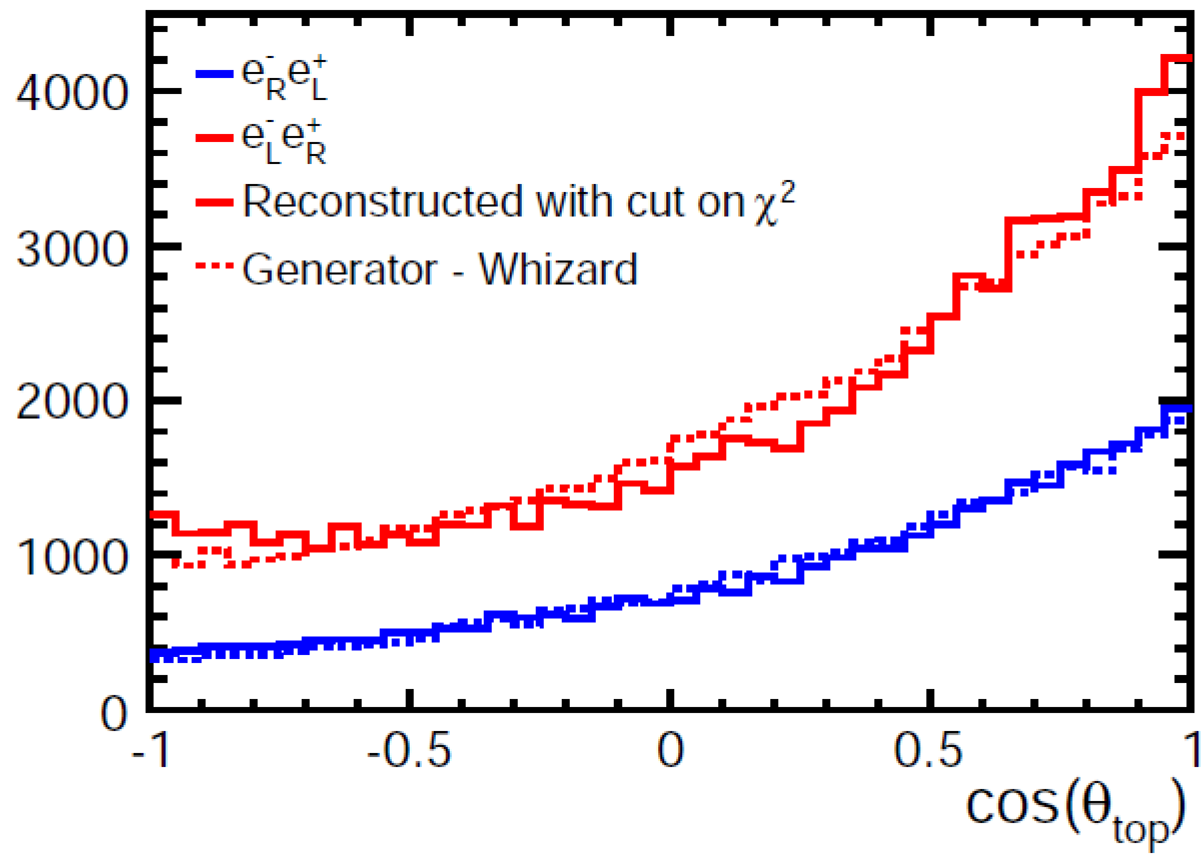


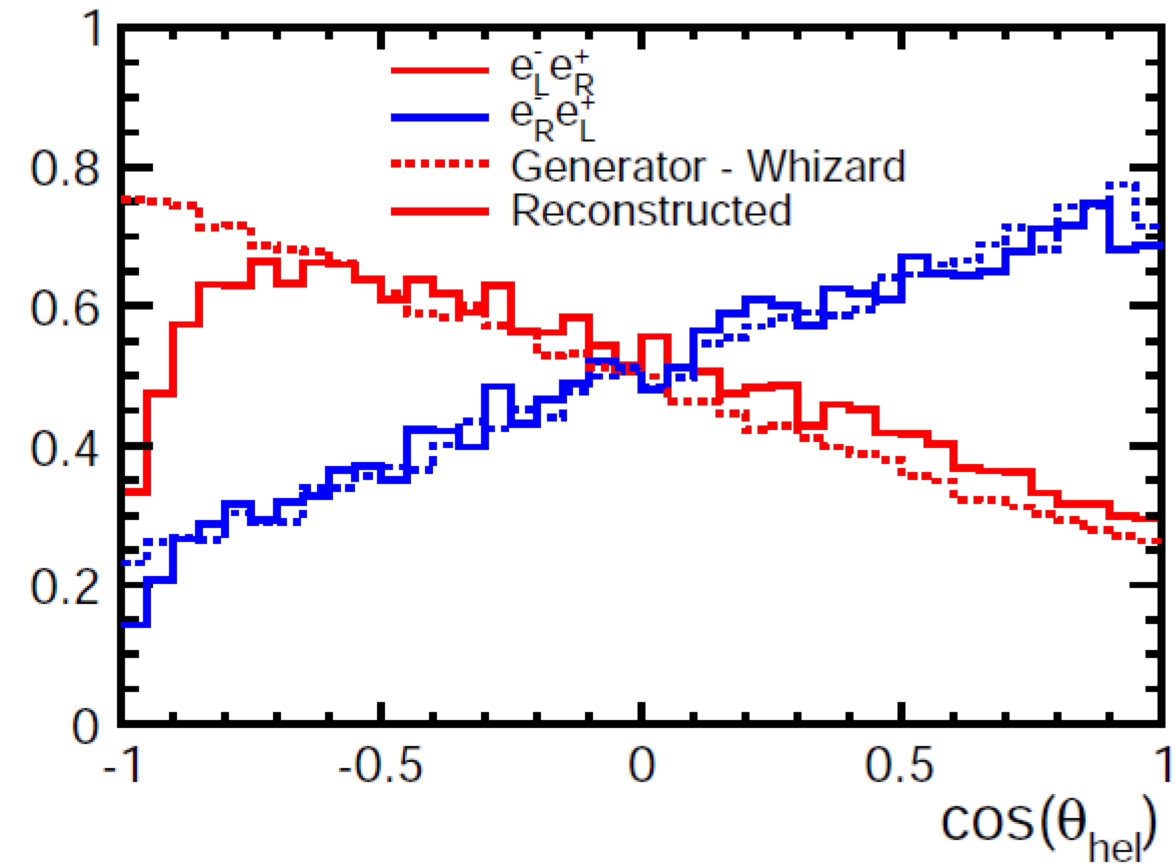
Experimental aspects

$t\bar{t}$ is not the simplest final state. Even at an LC, with fixed center-of-mass energy, top reconstruction is not straightforward.

At 500 GeV the most important systematic is dilution due to migrations

Mitigated by applying a c2 cut based on top candidate E and m, angle b and W etc.





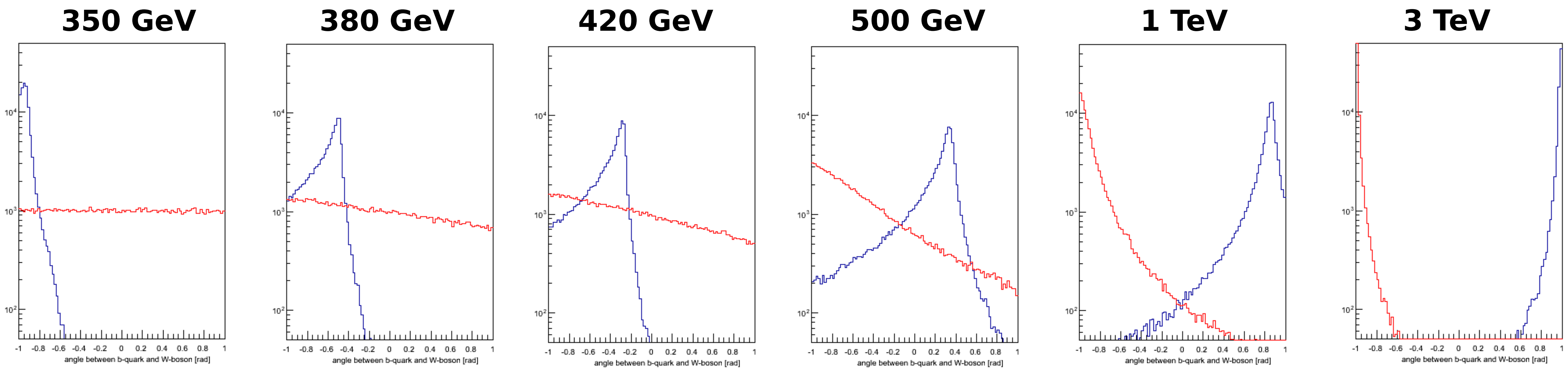
Vertex of jet charge measurement known to work (even for a fully hadronic A_{FB} measurement)

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

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

Rerun the fit that extracts the couplings from measurement of σ, A_{FB}

(Roman Poeschl, very preliminary)

- *cross-check that we retrieve 500 GeV result, repeat the exercise at 380 GeV*
- *(LO, unpolarized, no ISR or LS) cross-section nearly constant: σ = 550 pb at 380 GeV, 530 pb at 500 GeV*
- *assuming constant relative errors*
  (OK for stat. and some syst., but see previous slides)
- *only important change in inputs is the value of A_{FB}, that has come down substantially*
- *remember: deviations from SM due to massive new states tend to be larger at higher energy*

$\sqrt{s}$ = 500 GeV full polarisation

$\Delta F_{1V}(\gamma)$ = 0.0016
$\Delta F_{1V}(Z)$ = 0.0024
$\Delta F_{1A}(Z)$ = 0.0074

$\Delta F_{2V}(\gamma)$ = 0.0012
$\Delta F_{2V}(Z)$ = 0.0020

$\sqrt{s}$ = 380 GeV full polarisation

$\Delta F_{1V}(\gamma)$ = 0.0013
$\Delta F_{1V}(Z)$ = 0.0022
$\Delta F_{1A}(Z)$ = 0.0066

$\Delta F_{2V}(\gamma)$ = 0.0012
$\Delta F_{2V}(Z)$ = 0.0021

Preliminary fit result confirms that:
provided the dominant error(s) remains constant ($\Delta A_{FB}/A_{FB}$ = c),
the form factors can be determined to the same precision

Summary

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

$t\bar{t}Z$ and $t\bar{t}\gamma$ couplings measurement are pillars of the LC top physics programme

Coupling measurement can (and will) be performed anywhere in the continuum and at threshold; achieves best new physics reach at highest energy

Polarization is needed

→ effective polarization governs precision, dropping positron polarization has small effect

Some boost is needed for A_{FB}

→ asymmetry is sizeable already 10 GeV above threshold

Good reasons to assume systematics are **NOT** constant!

First fit results confirm that 380/420 yields similar precision

To be taken into account more consistently across all energies:

theory uncertainties, single top strategy

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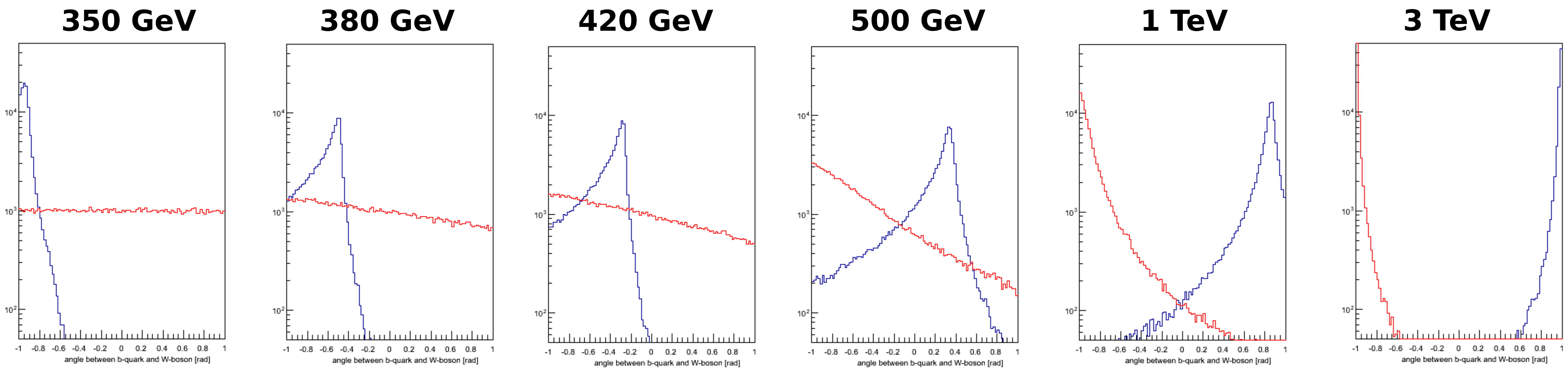

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