Precision top quark physics at a future linear e^+e^- collider; mass & top EW couplings

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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)

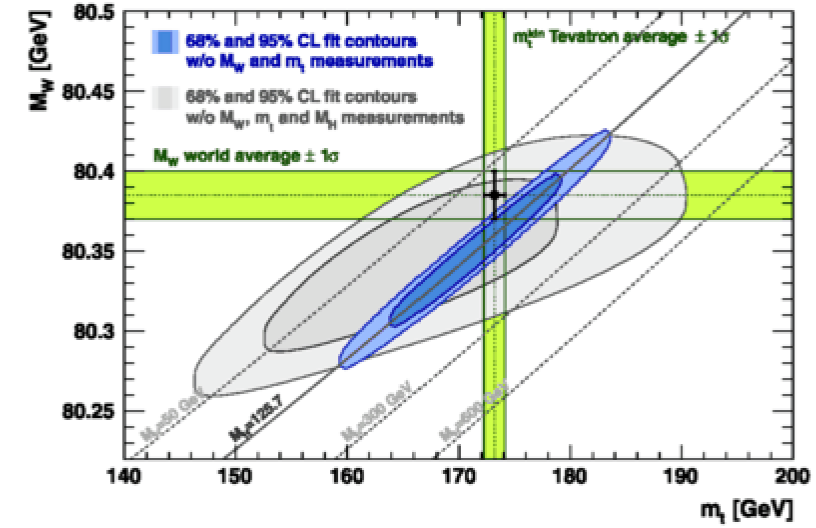
Top is turning 20 this year

Of course, parents love all their kids equally

Top's maturing, Higgs is turning 3 this year

She's so cute; it's only natural that the new-born gets a bit more attention

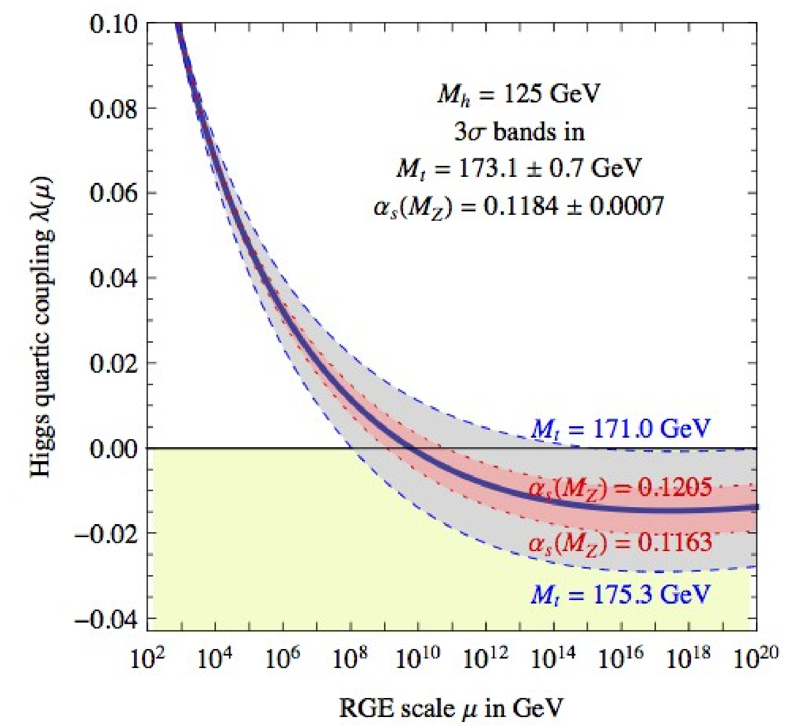
Top at lepton colliders



Only quark that escaped direct scrutiny at LEP/SLC

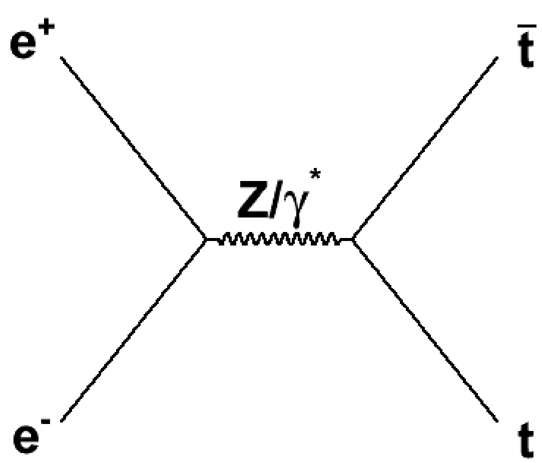
Top quark mass is an important parameter

- EW fit, Higgs loops, fate of the universe

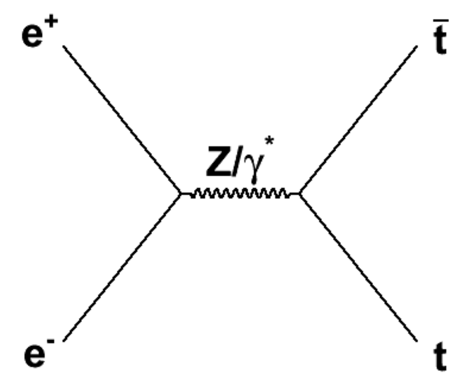


First chance to study top couplings to neutral EW bosons

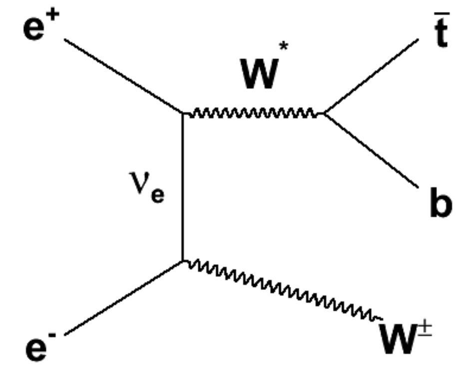
- $q\bar{q} \rightarrow \gamma/Z \rightarrow t\bar{t}$ produced at Tevatron and LHC, but swamped by QCD production
- associated production $t\bar{t}\gamma$ and $t\bar{t}Z$ are (slowly) building up strength at the LHC



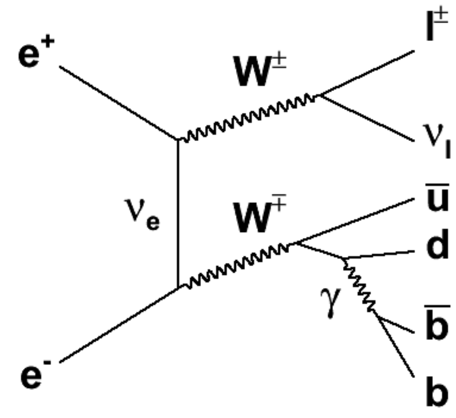
Top quark pairs



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

300.000 pairs after 4 years at 500 GeV

Drop in (s-channel) cross-section at higher sqrt(s)

partially compensated by higher luminosity

Large boosted samples from CLIC/μ–Collider

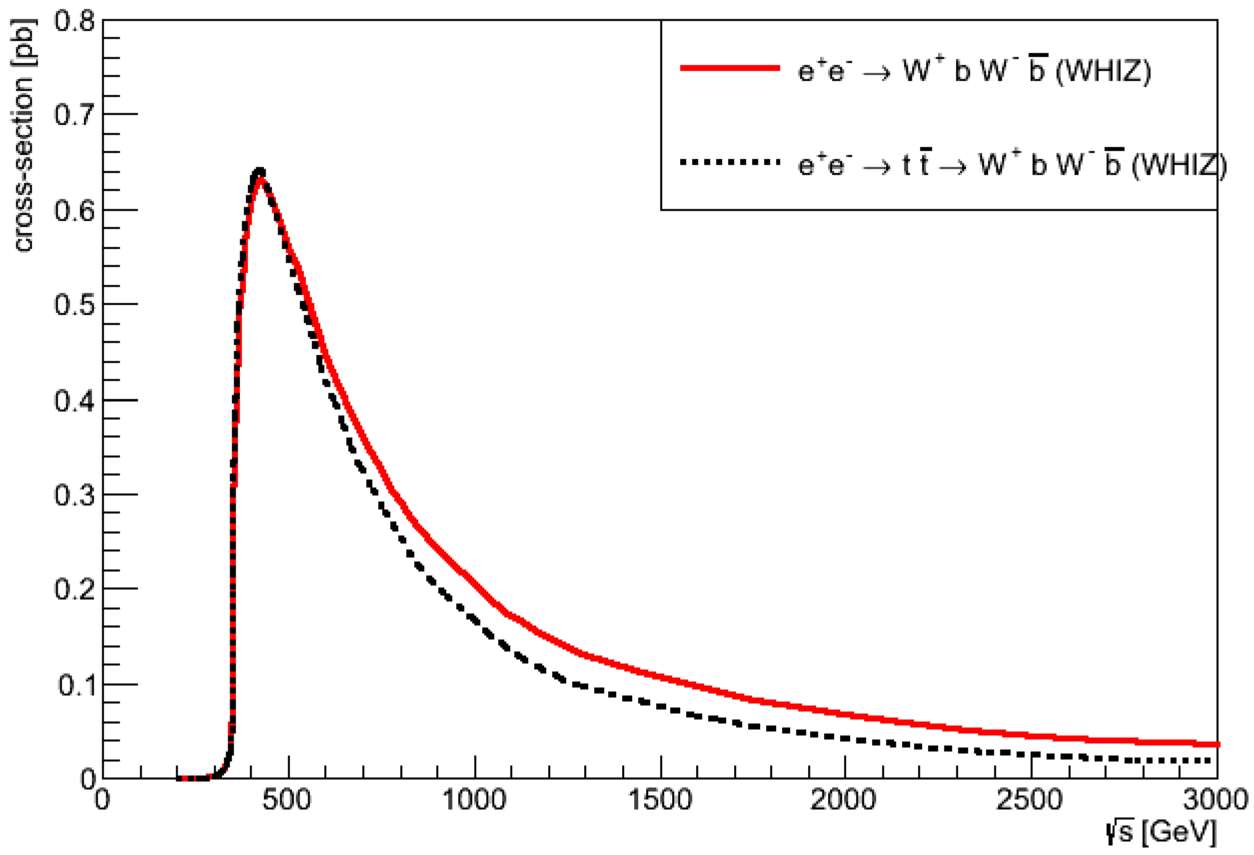
$e^+e^- \rightarrow WbW\bar{b} \rightarrow$ 6 fermions has several non-negligible sources

(at 500 GeV: tt ~ 90%, single top ~9%, WWγ/Z/h ~ 1%)

At 500 GeV single top is ~indistinguishable from pairs

The x-sec for WbWb is 5 to 50% larger than $t\bar{t}$

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



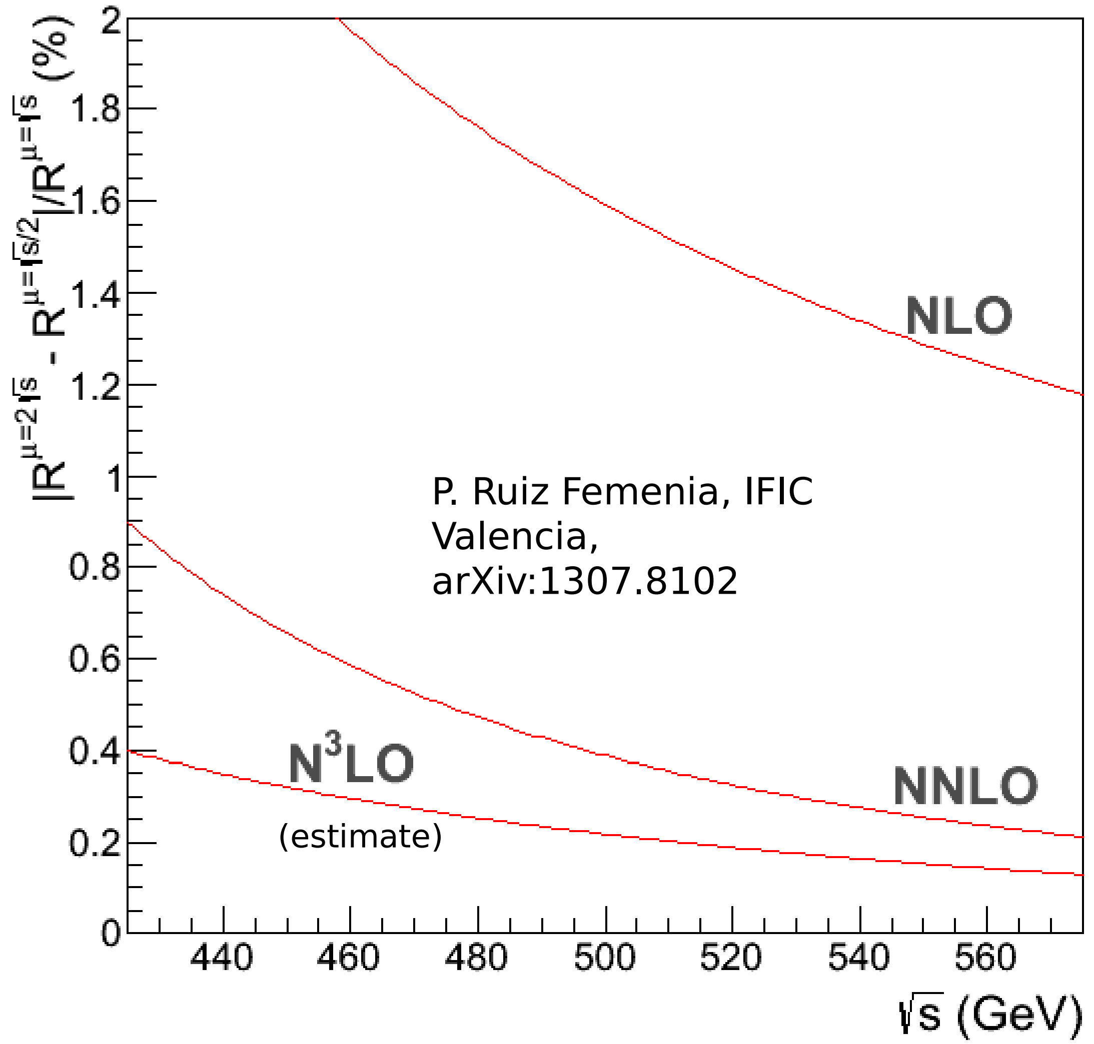
Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

top quark production at lepton colliders

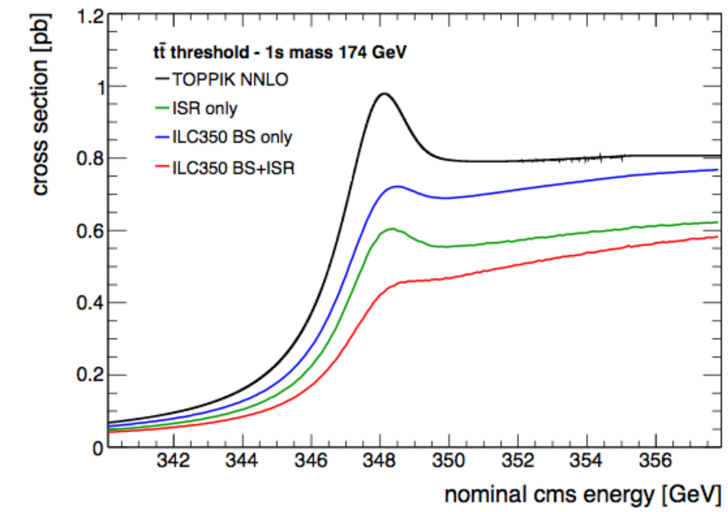
For precision there is nothing like e^+e^-

QCD corrections calculated to N^2LO
Scale variations at N^3LO estimated at ~ 0.3%.
Electroweak corrections are sizable, though.
Calibrate center-of-mass-energy to 1 in 10^4 and luminosity to 0.1%

Variation in x-section due to scale variations

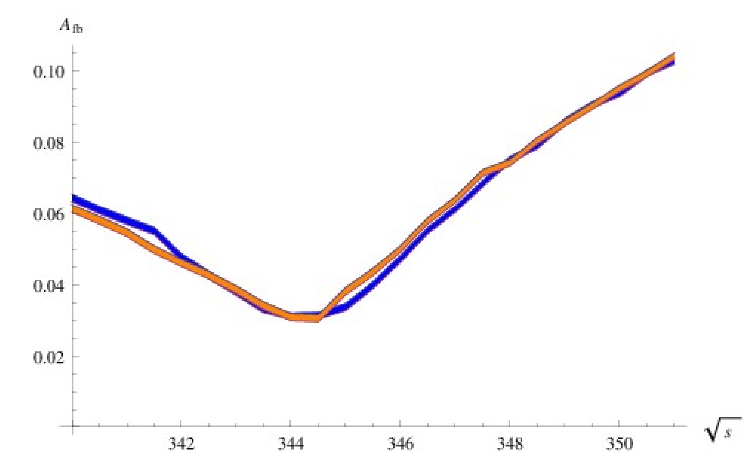


Top at threshold



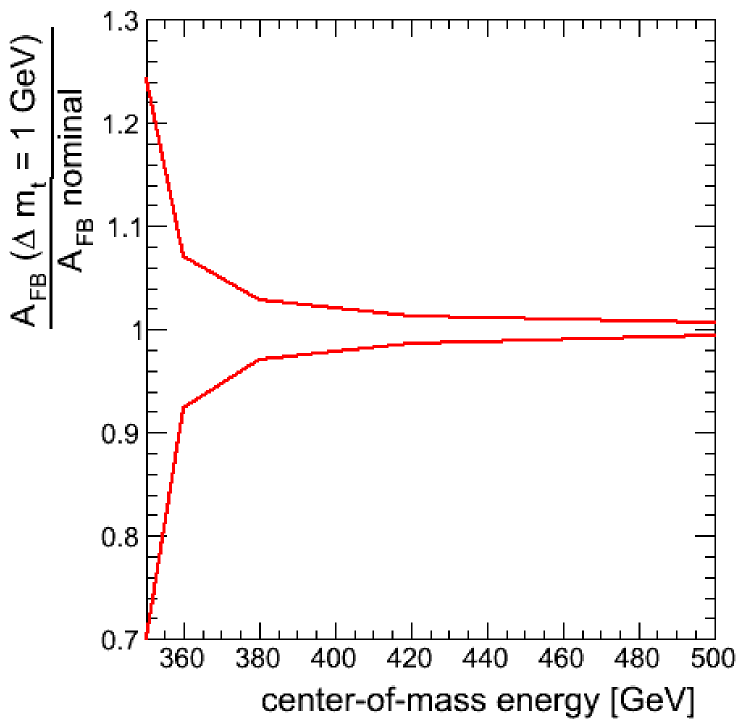
At threshold we have to include QCD bound-state corrections in calculations

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



Parametric uncertainty due to top quark mass AND width are important at threshold
(Martinez & Miquel extracted 4 parameters from fit)

F. Bach, preliminary
LL resummation (orange) and NLL 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

LC top physics – canonical programme

350 GeV:

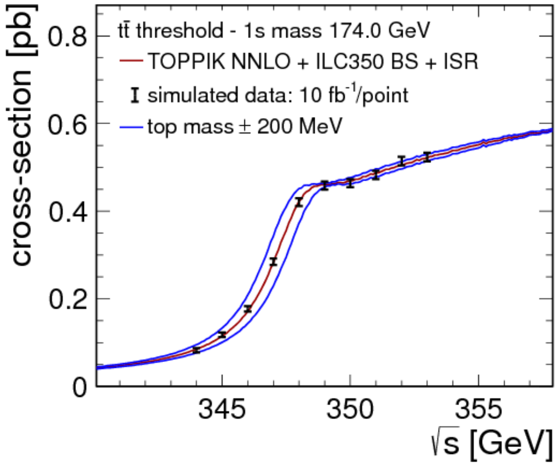
Threshold: top quark mass to < 100 MeV (+width & Yukawa)

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

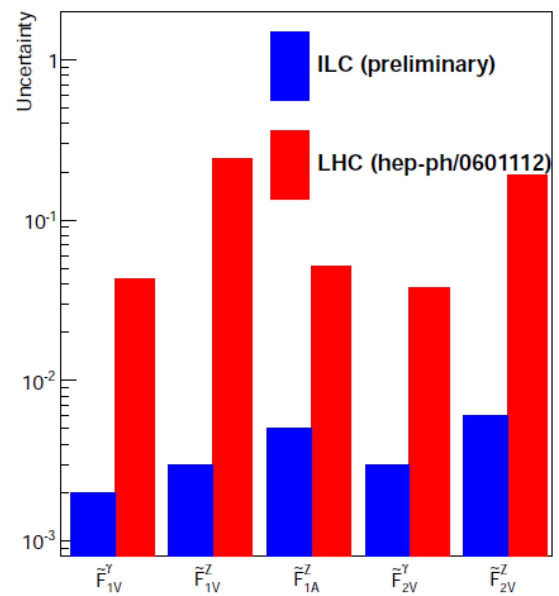


500 GeV:

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

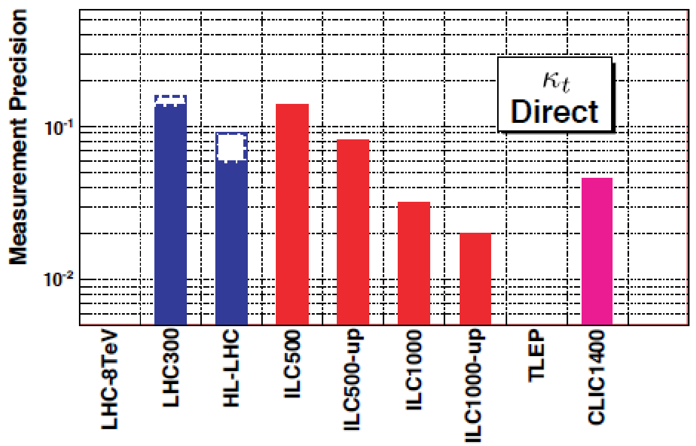
M.S. Amjad et al., arXiv:1307.8102

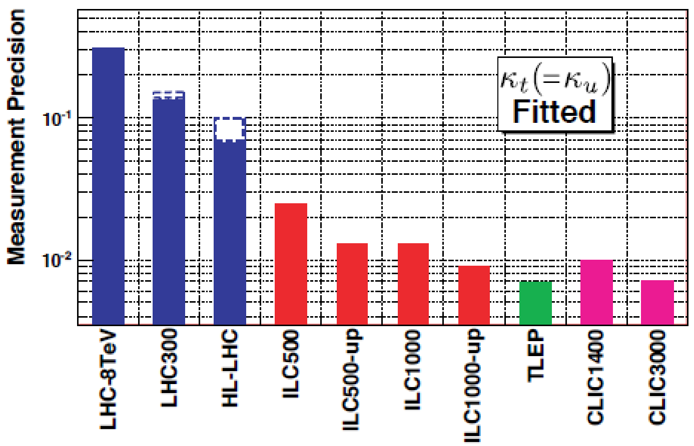
F. Richard, arXiv:1403.2893



500-1500 GeV:

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





Studies at relevant thresholds (tt, ttH) and at 500 GeV
What's the potential at other sqrt(s)?
What else can we do?

Top quark mass

Top quark masss

Historical result, first ever

LHC/Tevatron Combination

arXiv:1403.4427

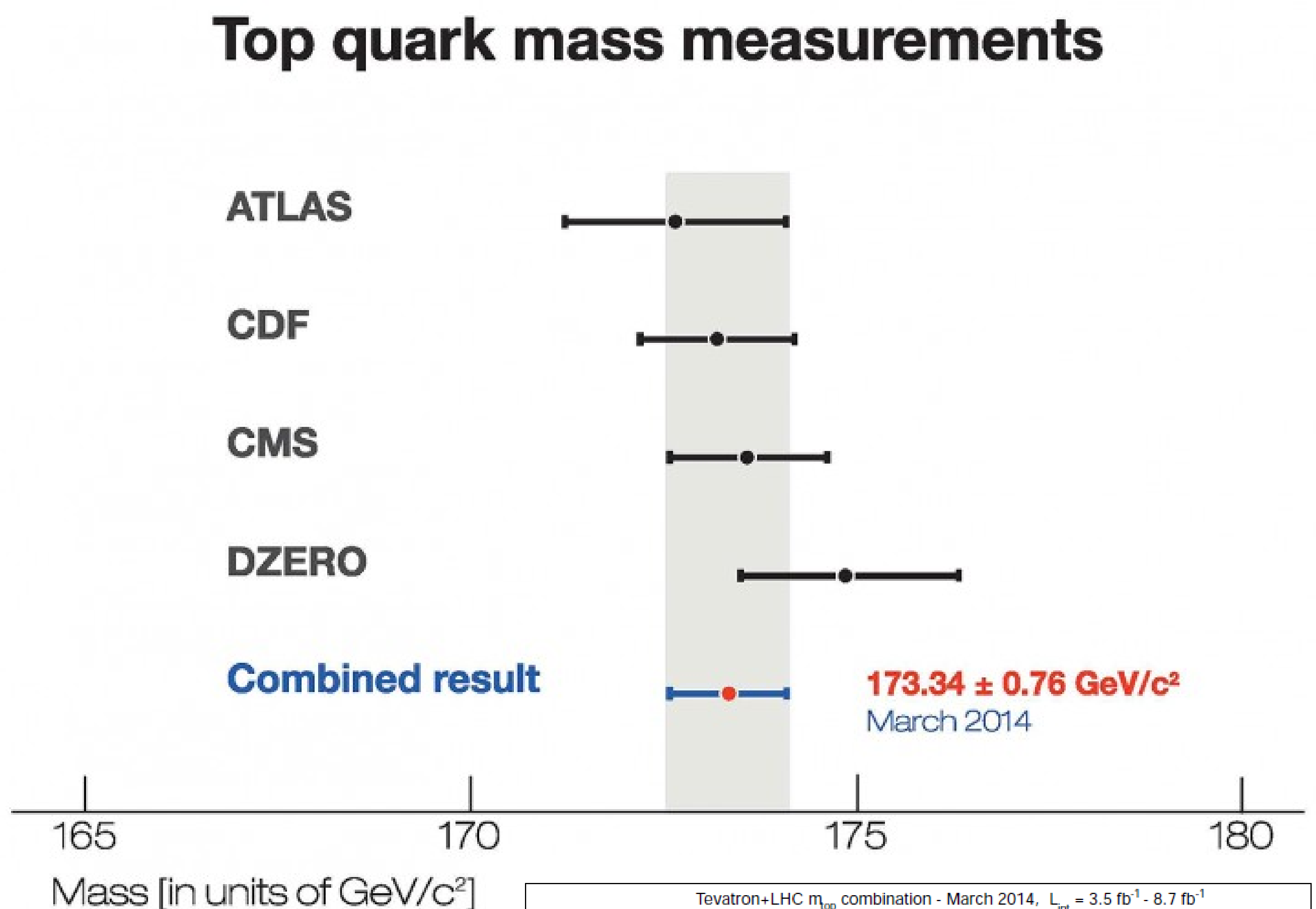
A quark mass measurement

to better than 0.5%

See, for example, Juste et al.,

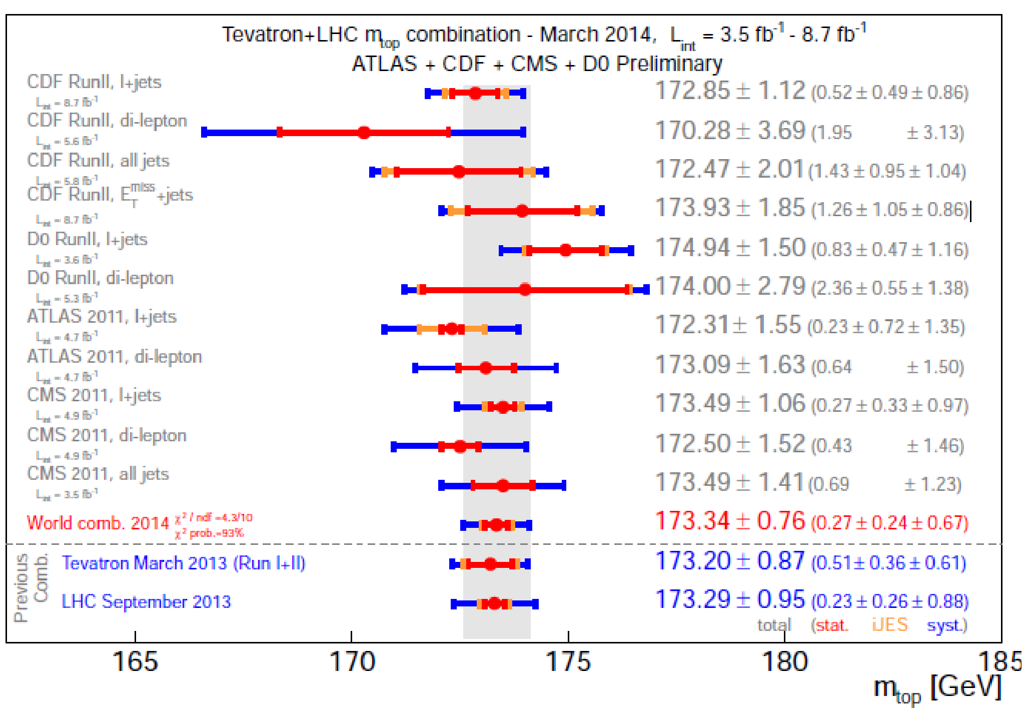
Eur.Phys.J. C74 (2014) 10, 3119

for a discussion on the interpretation

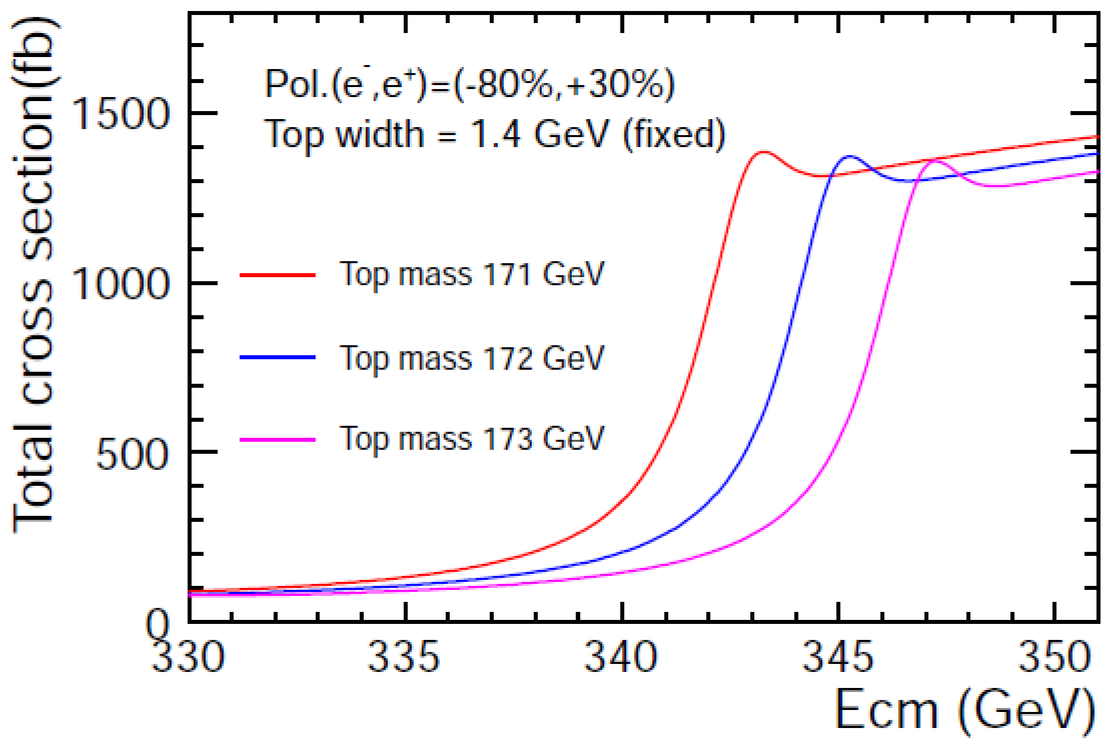


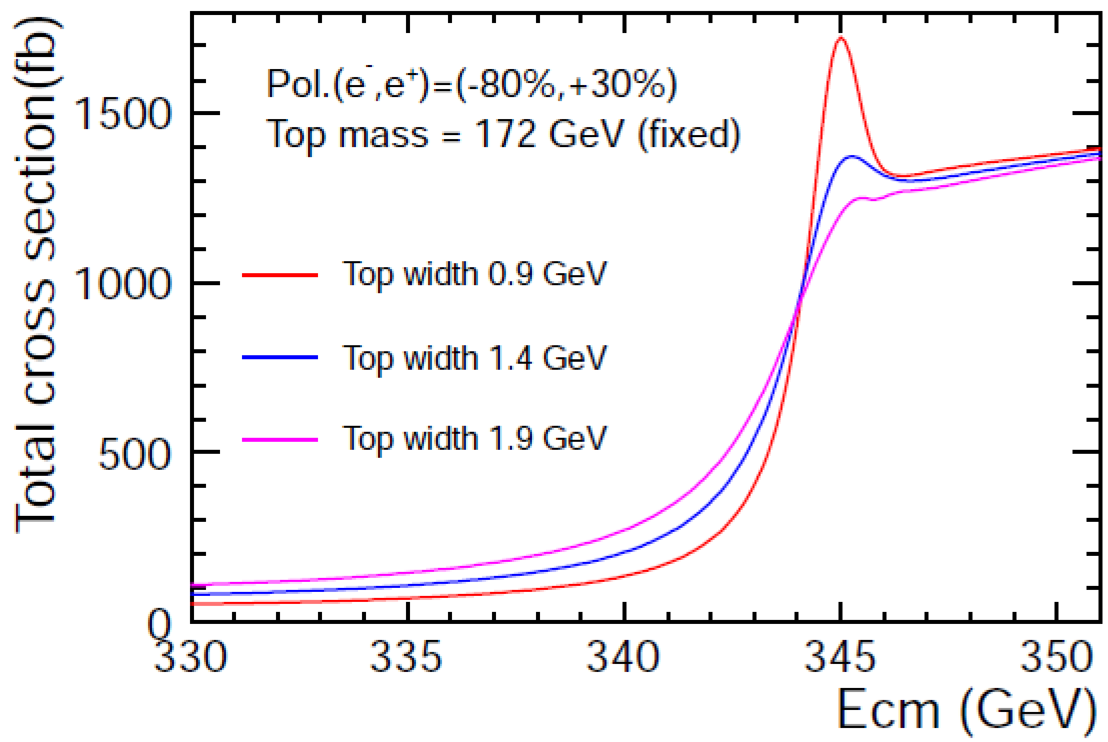
Consistent result in different experiments, continents, initial and final states and kinematic regimes

(in fact, agreement was a bit too good at this point; tension has increased a bit since)



Top quark mass at threshold



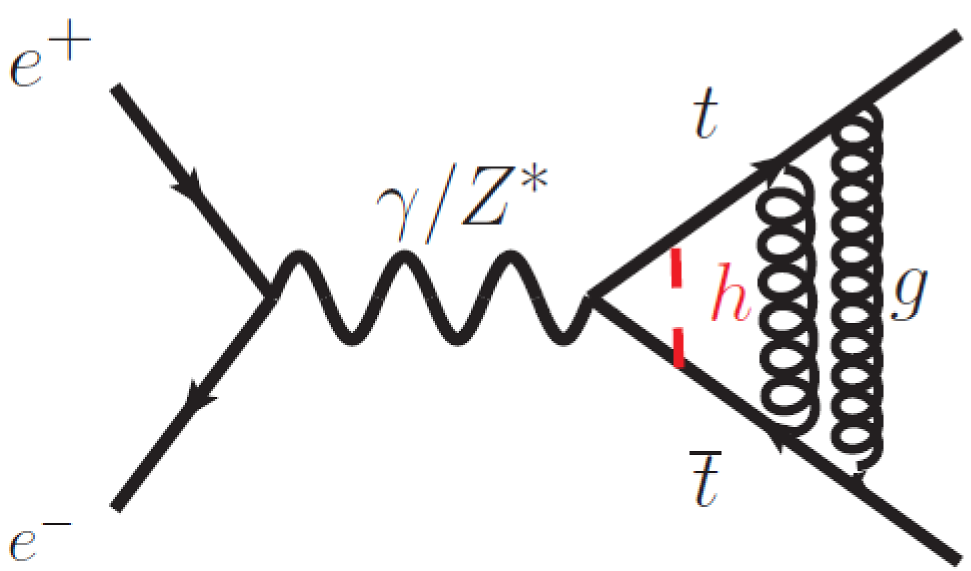


QCD bound-state effects lead to a quasi-resonant structure

Threshold shape depends on the top quark mass and top quark width, and on the strong coupling constant and top Yukawa coupling

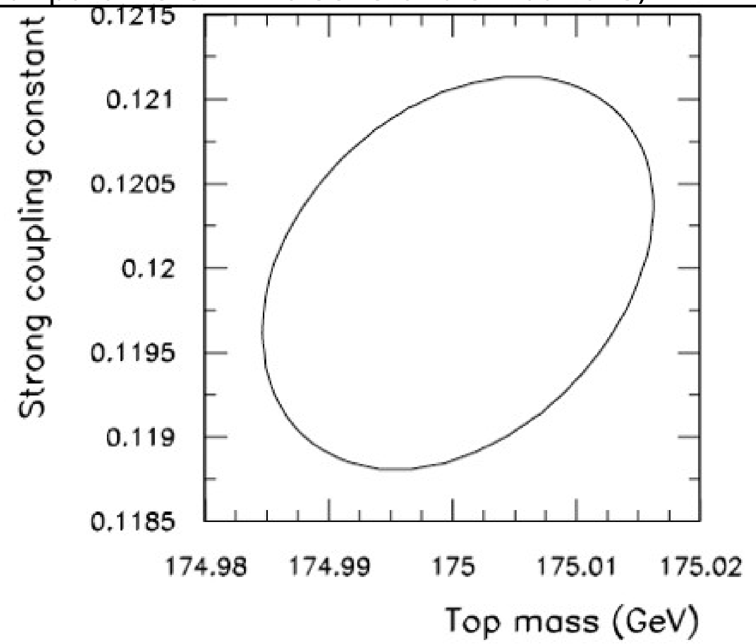
Extract top quark mass from shape

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

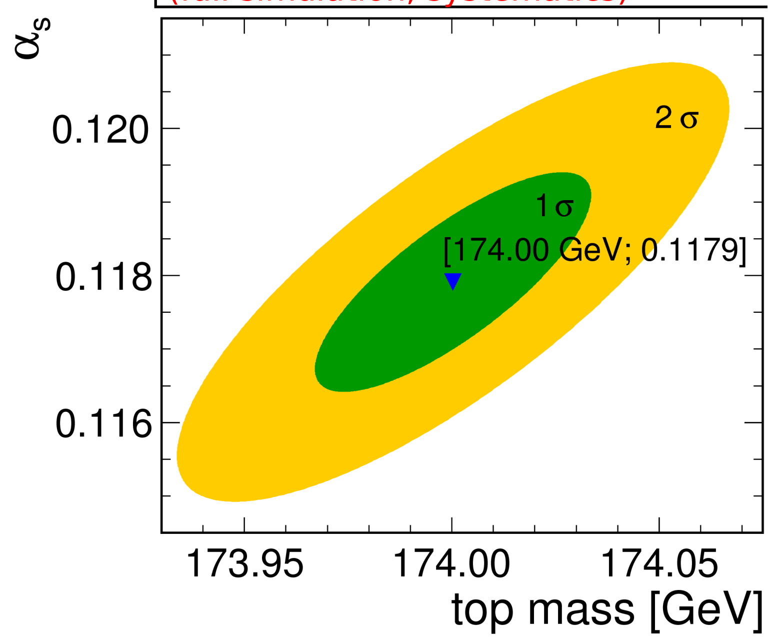


Top quark mass at an LC

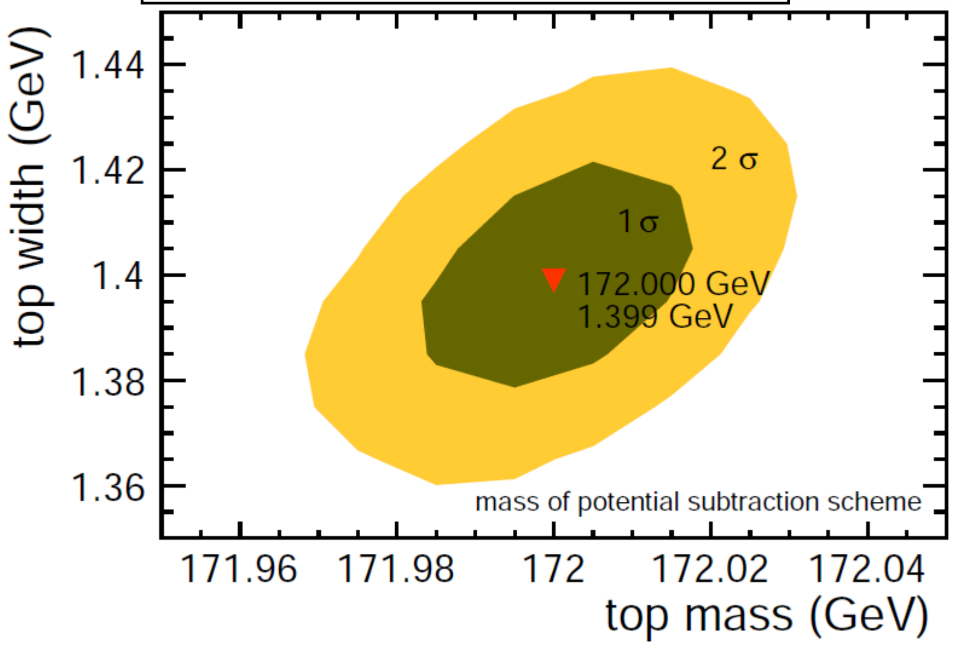
Martinez, Miquel, EPJC27, 49 (2003)
(four-parameter fit to several distributions)



Seidel, Simon, Tesar, Poss, EPJC73
(full simulation, systematics)



Horiguchi et al., arXiv:1310.0563
(include polarization, float Γ_t, fix α_s)



Uncertainties on extracted top quark mass

Stat. error ~16/34 MeV (with/without polarization)
No dependence on location of scan energy
Non tt background (5%) → 18 MeV
Precision on √s (10^{-4}) → 30 MeV
Uncertainty on lumi-spectrum → ~10 MeV
Uncertainty on theory x-sec → few MeV
Conversion 1S mass to $\overline{\text{MS}}$ → 100 MeV

1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

A very precise measurement: Δm_t < 100 MeV
+ $\Delta \alpha s$ < 0.001 (+ $\Delta \Gamma_t$ < 30 MeV) (+ $\Delta y_t/y_t$ ~ 35% *)

* could claim 4.2% (with arXiv:1310.0563) if I insert a more precise value of α_s

Top-Z and top-photon couplings and new physics

Top quark couplings in a nutshell

measure

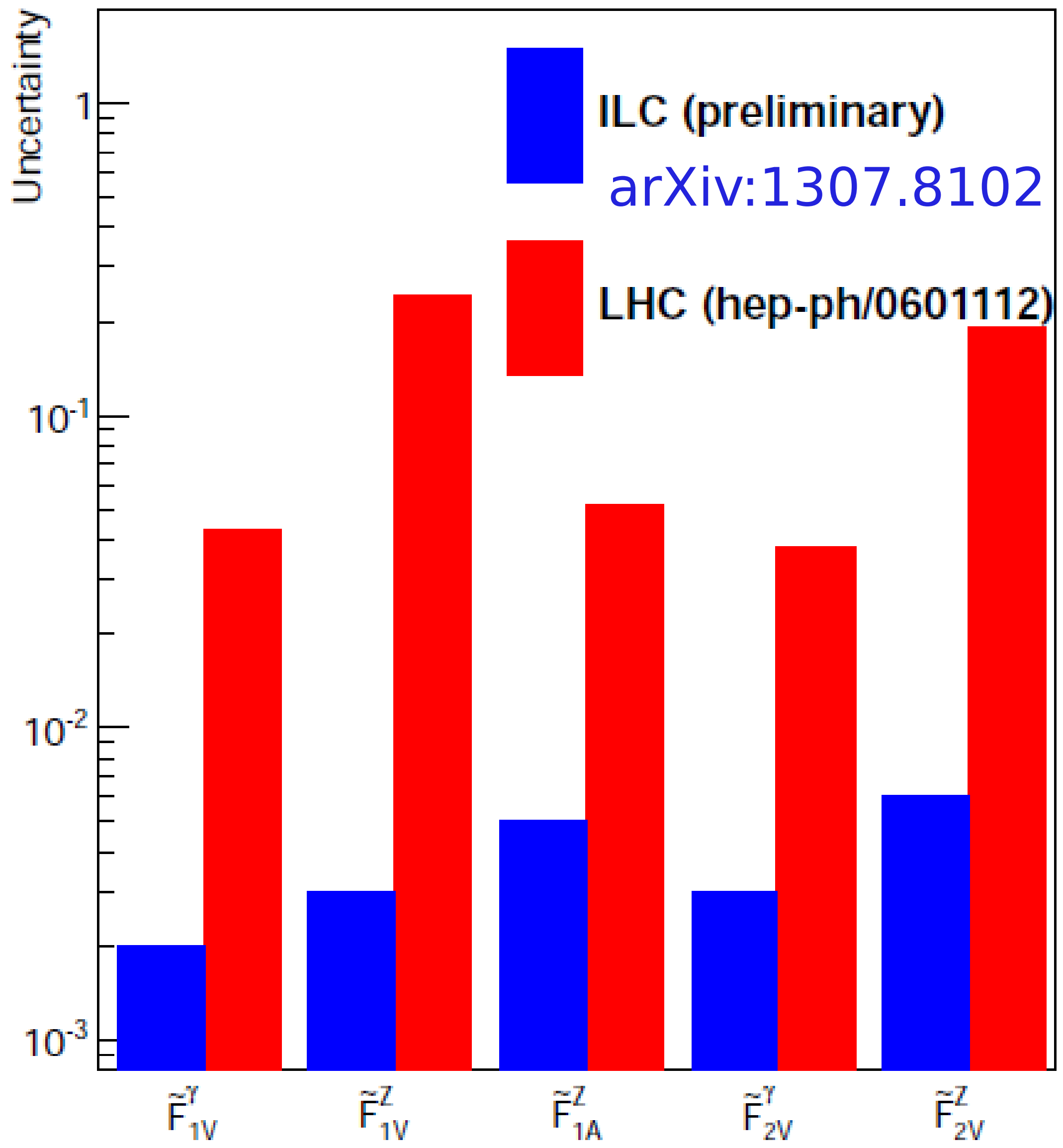
$\sigma(+)$ $A_{FB}(+)$

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

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)

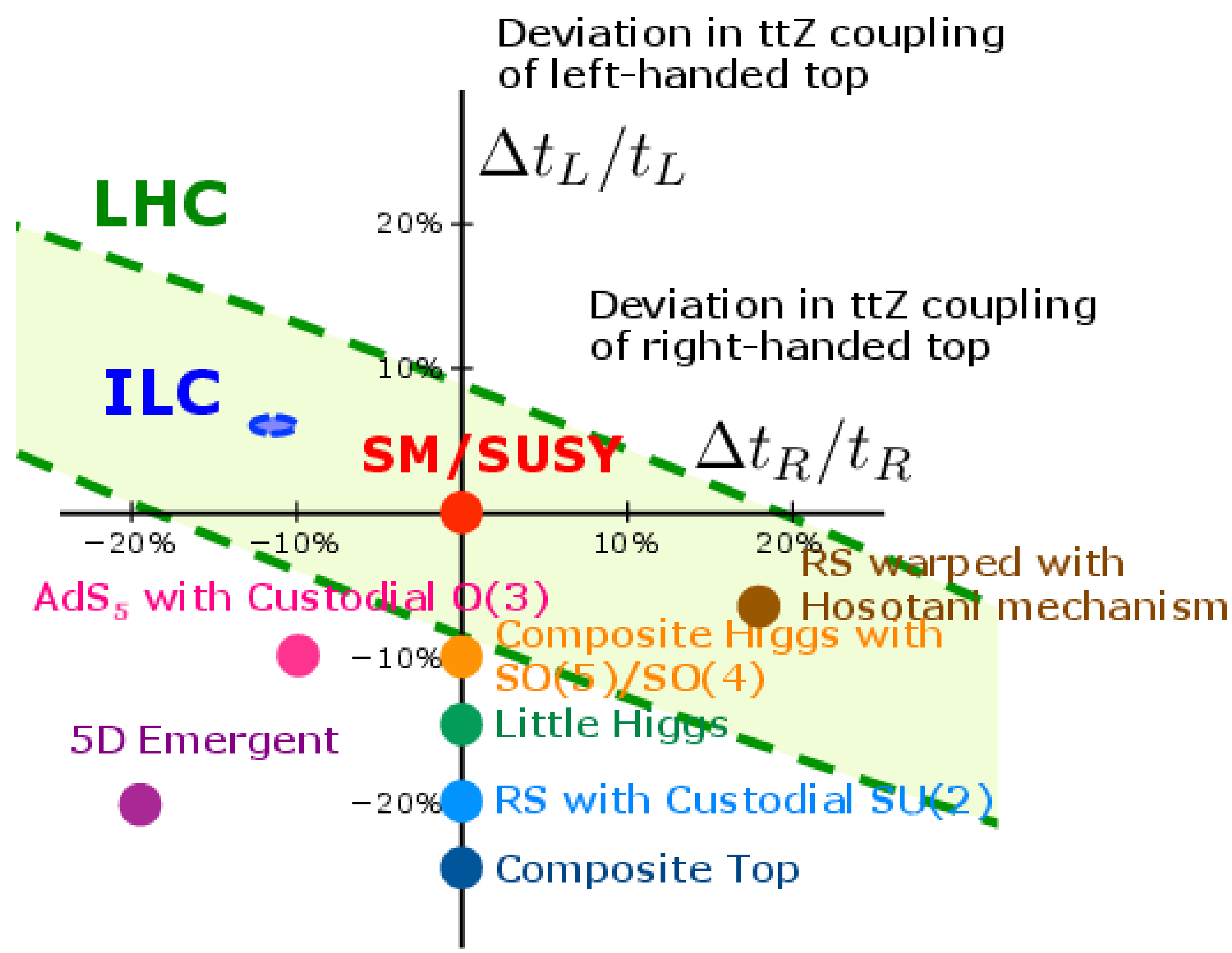
New physics sensitivity
Impact of BSM on Top Sector

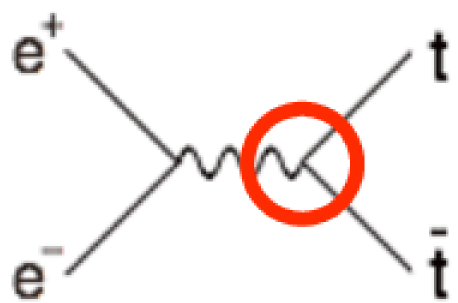
In composite Higgs models, the **top quark** is often **partially composite**.
This results in **form factors in ttZ couplings**, which can be measured at ILC.
Beam polarization is essential to distinguish **left/right-handed couplings**.

LHC, Ref. arXiv:1311.2028 →

ILC, Ref. arXiv:1307.8102 →

Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893



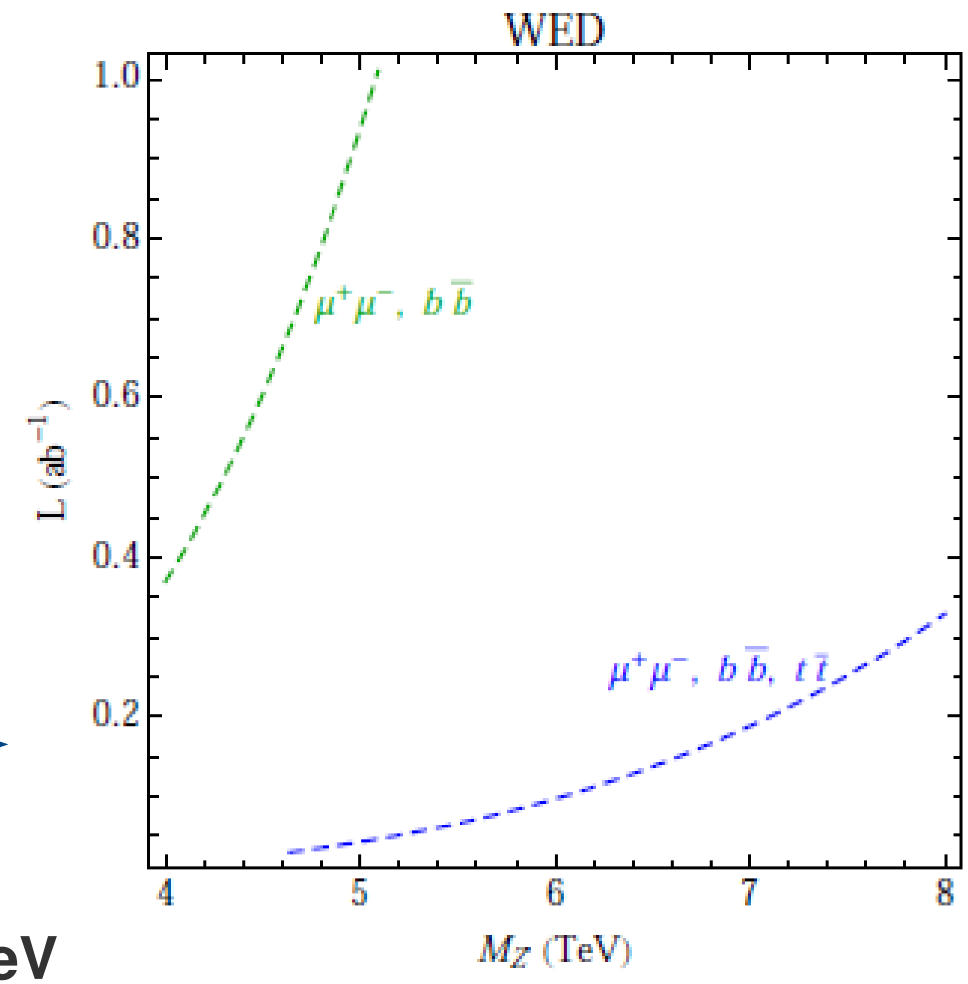


$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}.$$

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!

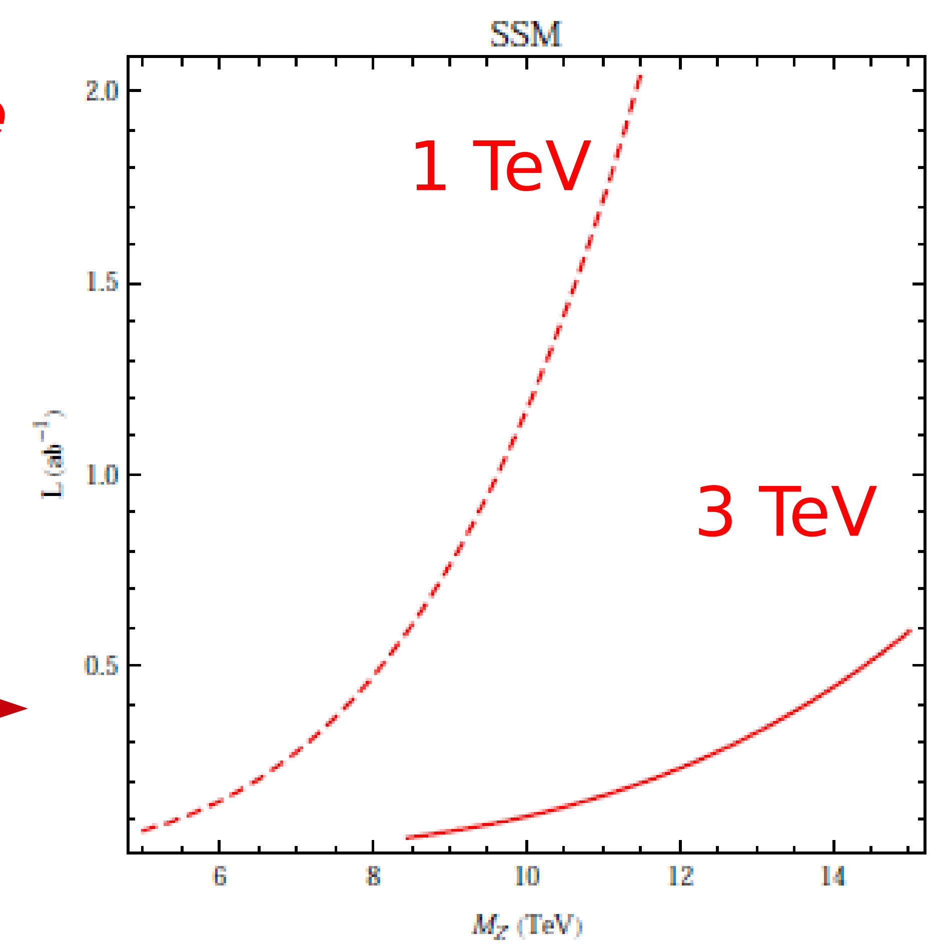
BSM reach strongly enhanced by $t\bar{t}$ FB asymmetry measurement



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

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

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

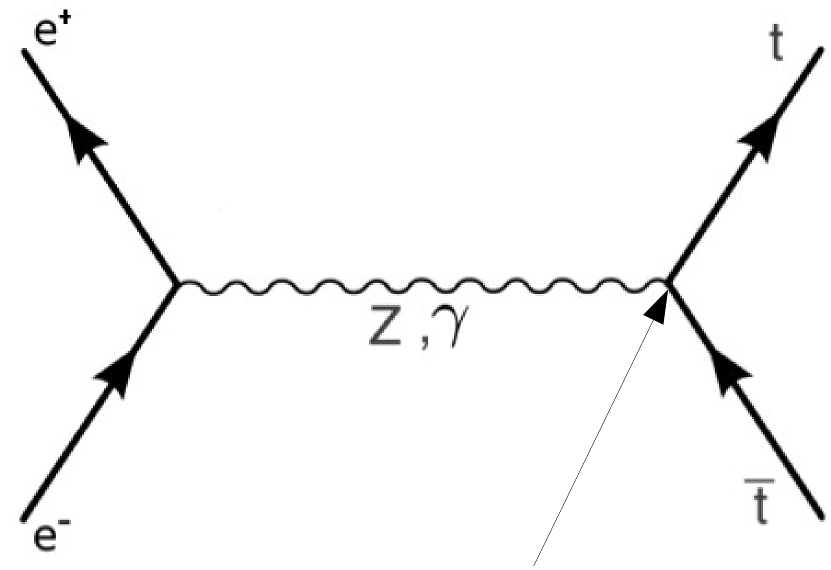
$$\widetilde{F}^{X}_{1A}=-F^{X}_{1A}, F^{\gamma}_{1A}=0, F^{Z}_{1A}=\frac{1}{4\,sw\,cw}$$

(fixed by gauge invariance,
not considered further)

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

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

(Q_t = electric charge, g-2 = anom. magn. Mom
(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:

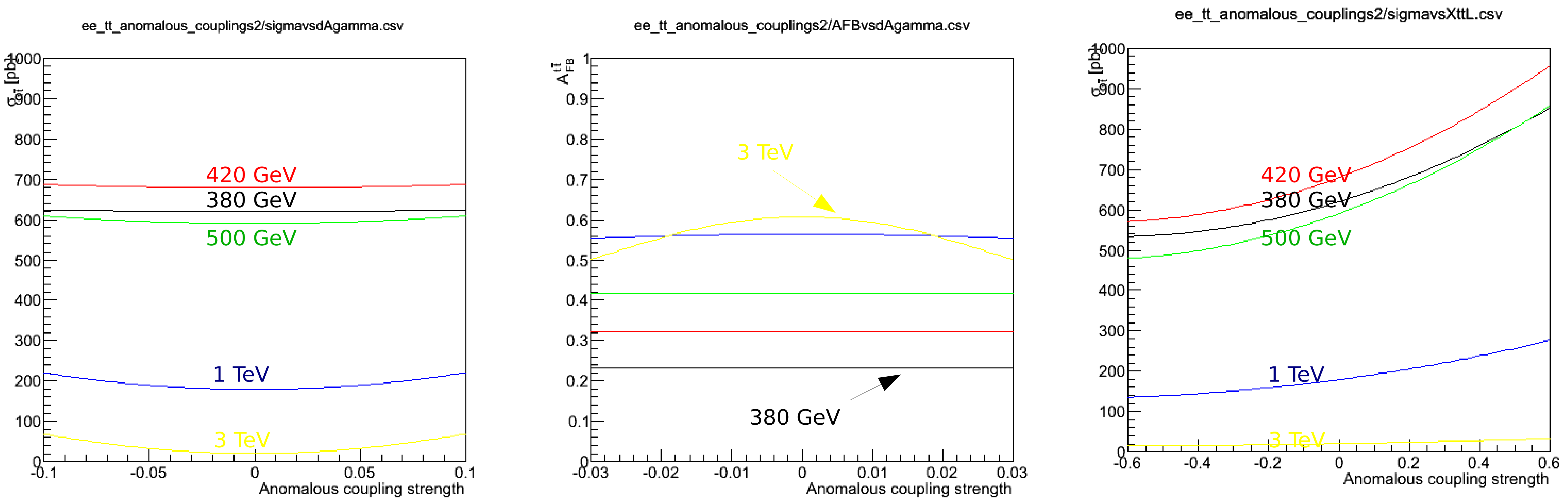
$$L_{eff}=\Sigma\frac{C_x}{\Lambda^2}O_x$$

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

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

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:

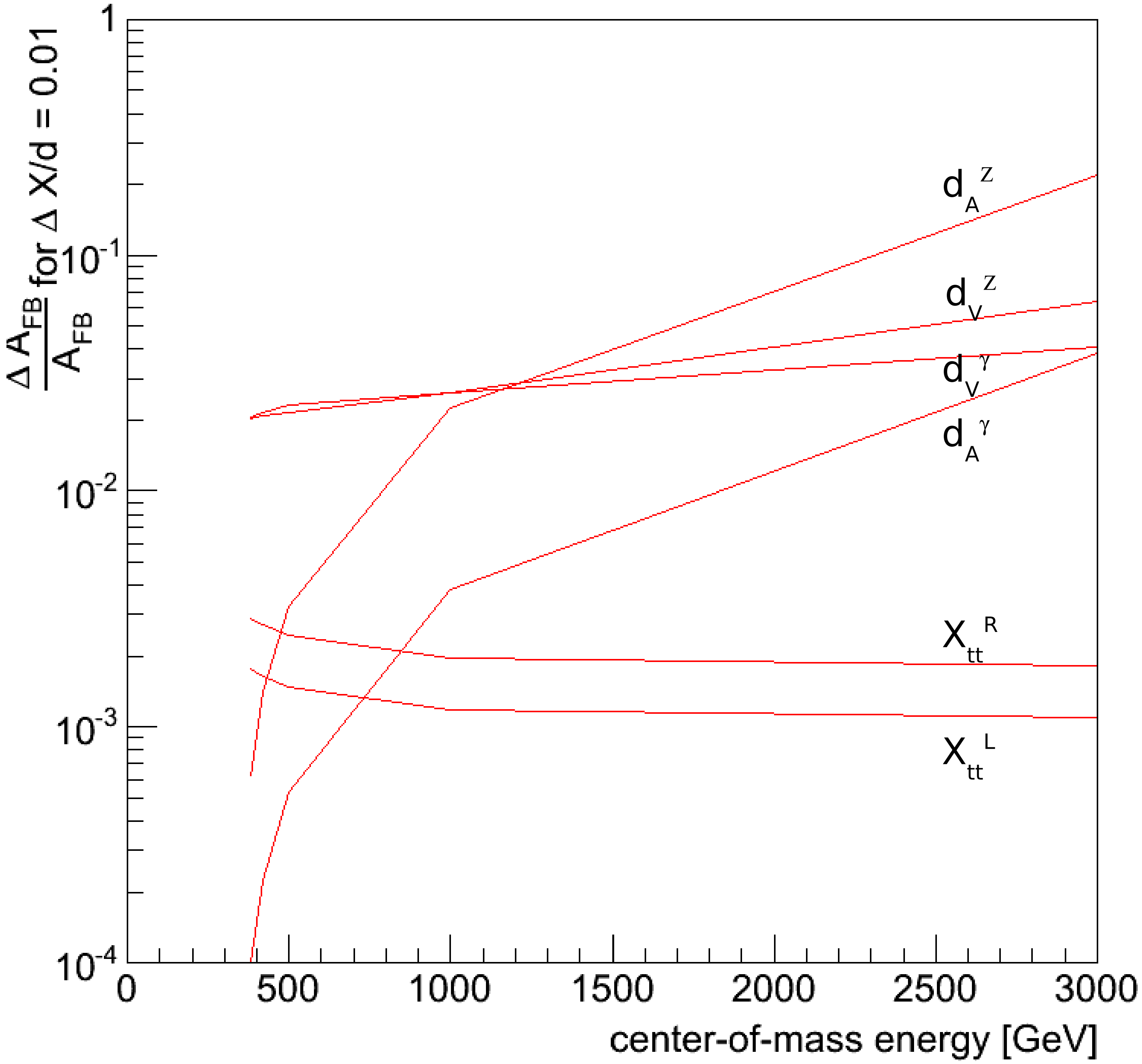
380 (black), 420 (red), 500 (green), 1000 (blue) and 3000 GeV (yellow)

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

Impact of new physics on asymmetry

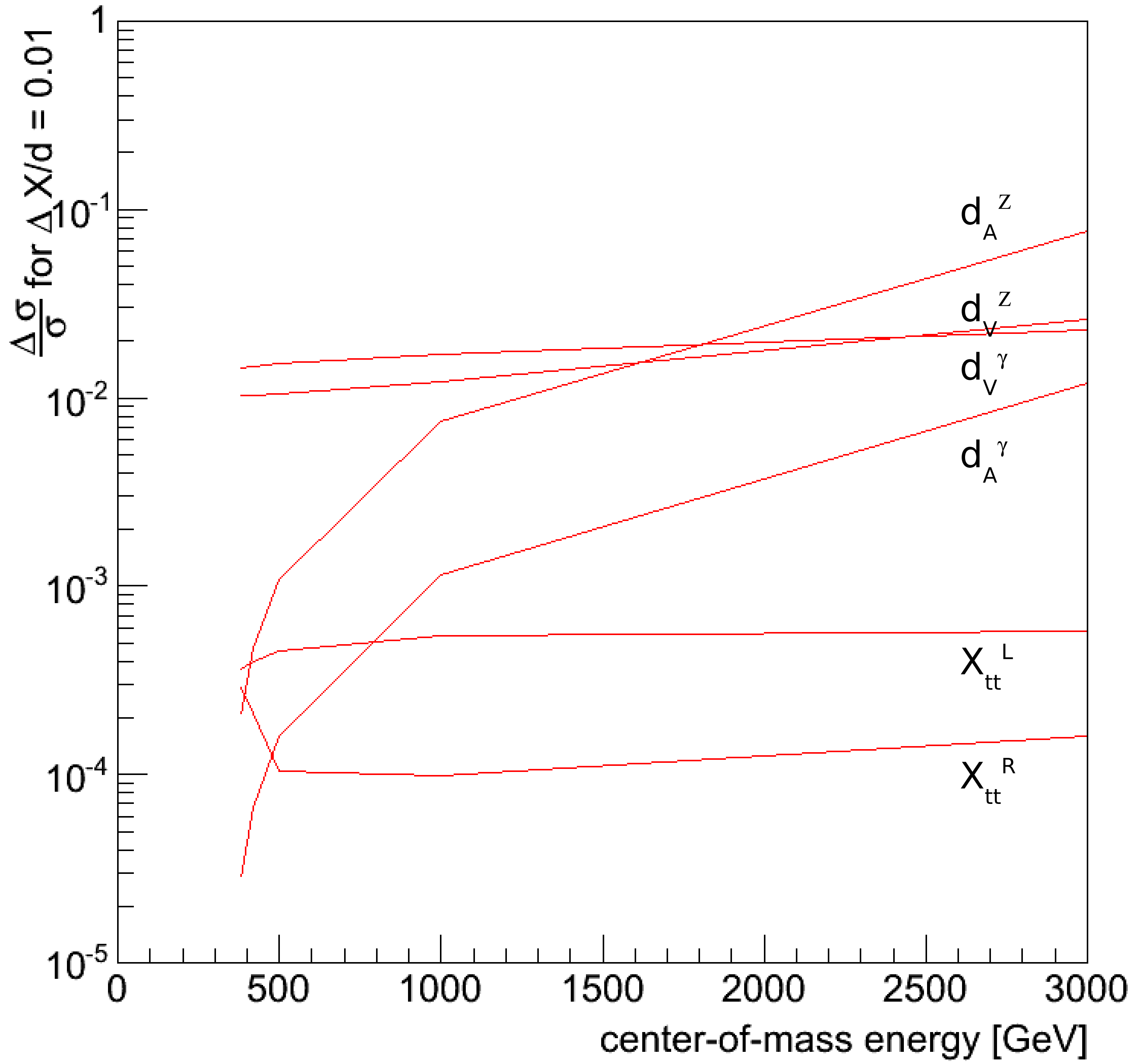
The impact of F2A form factors grows
- very strongly - with √s

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



Top quark reconstruction vs. center-of-mass energy

Top quark reconstruction

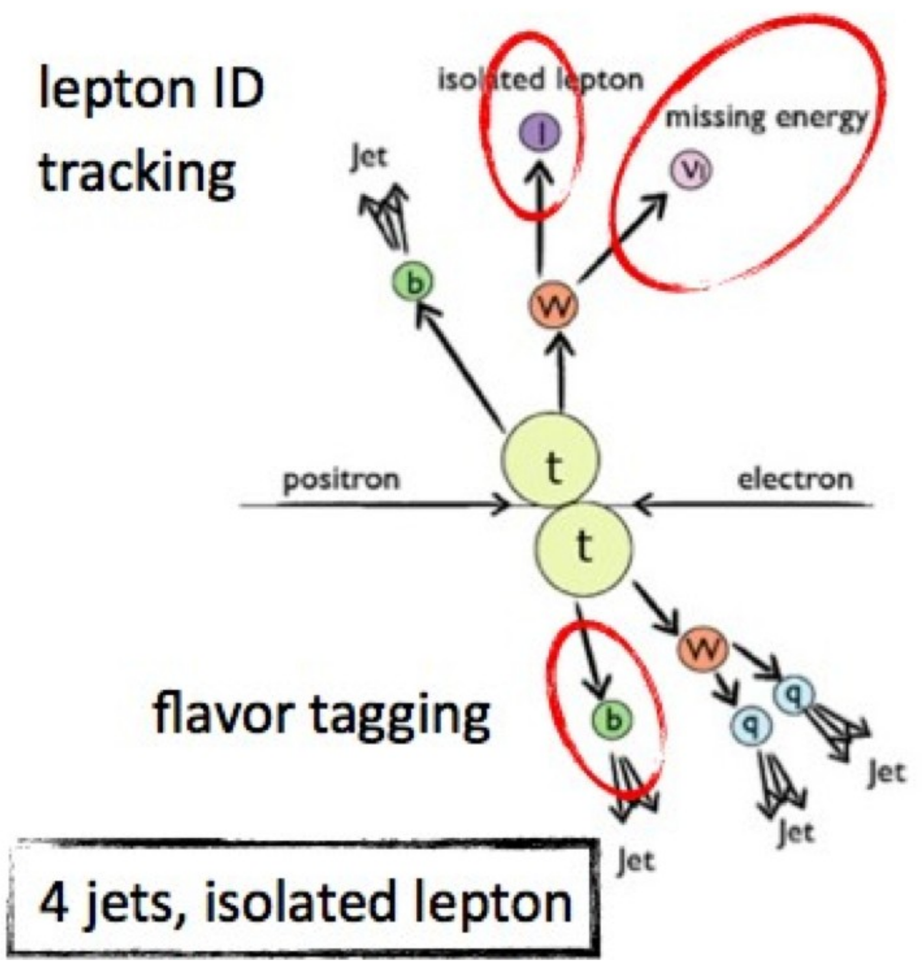
Three different final states:

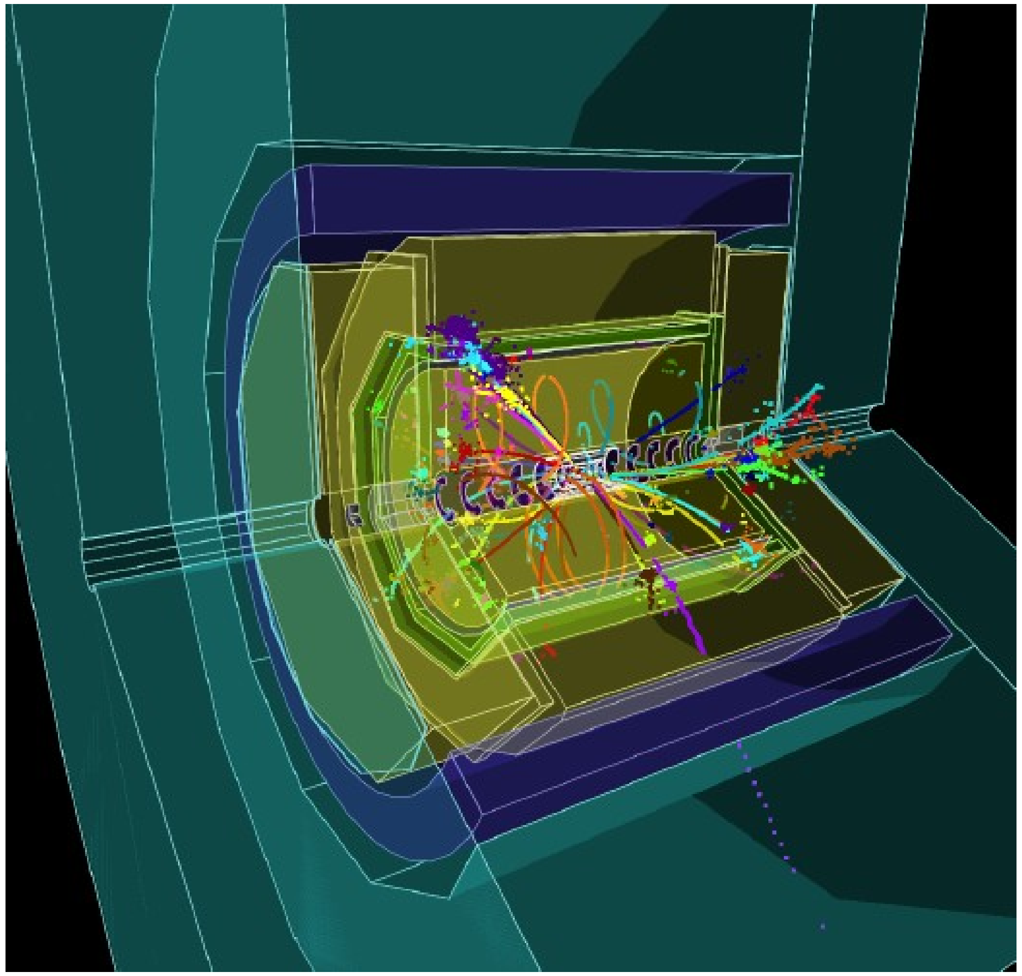
1) Fully hadronic (46.2%) → 6 jets

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

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

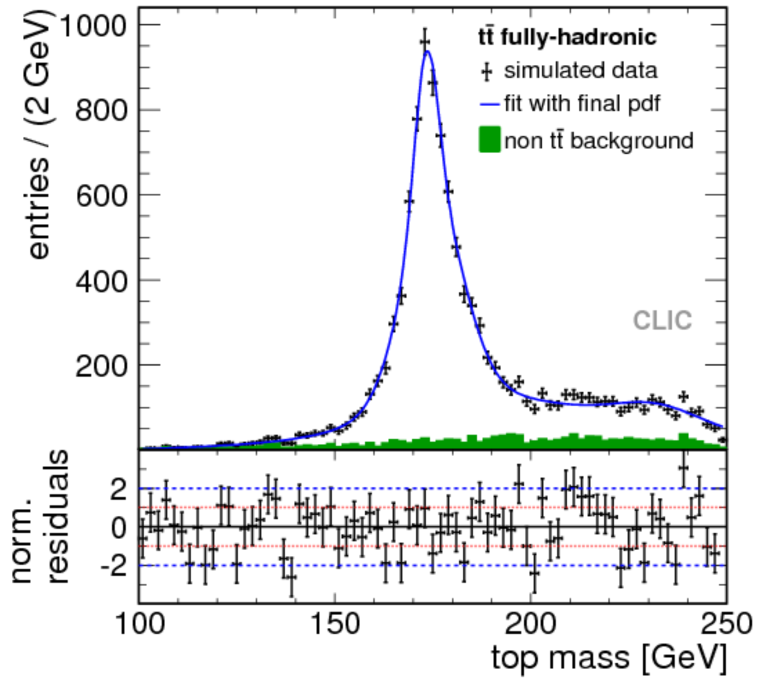
$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(b\ell\nu)$$

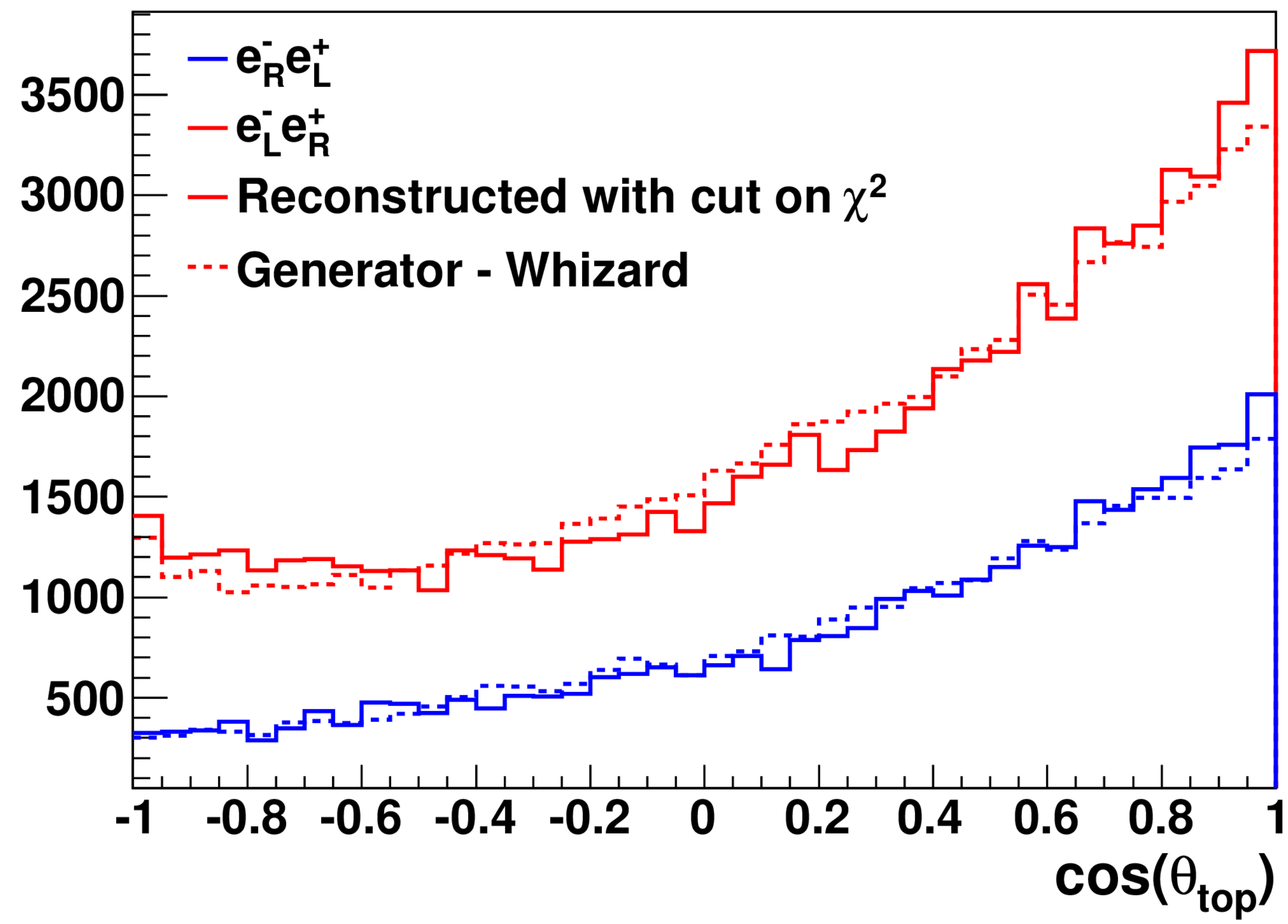




Final state reconstruction uses all detector aspects

Top quark selection/reconstruction





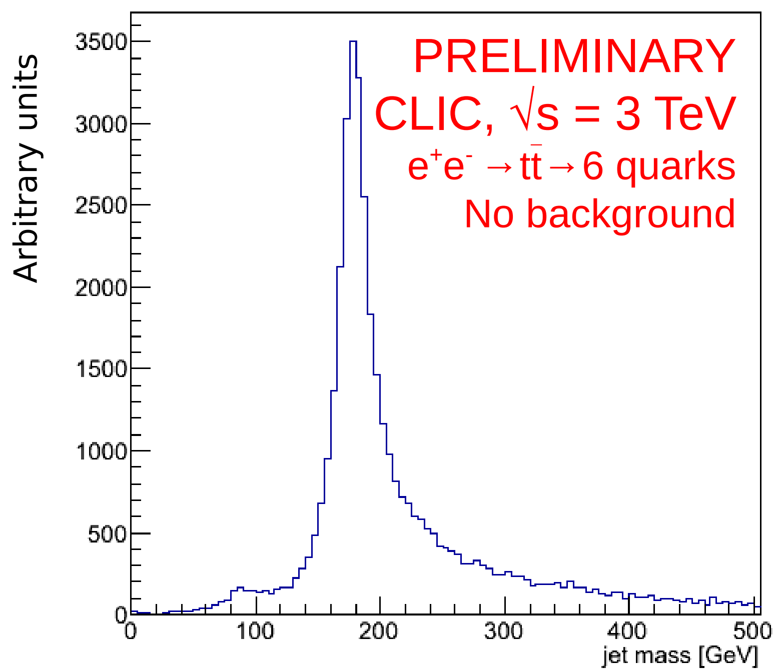
Top reconstruction is non-trivial at any center-of-mass energy

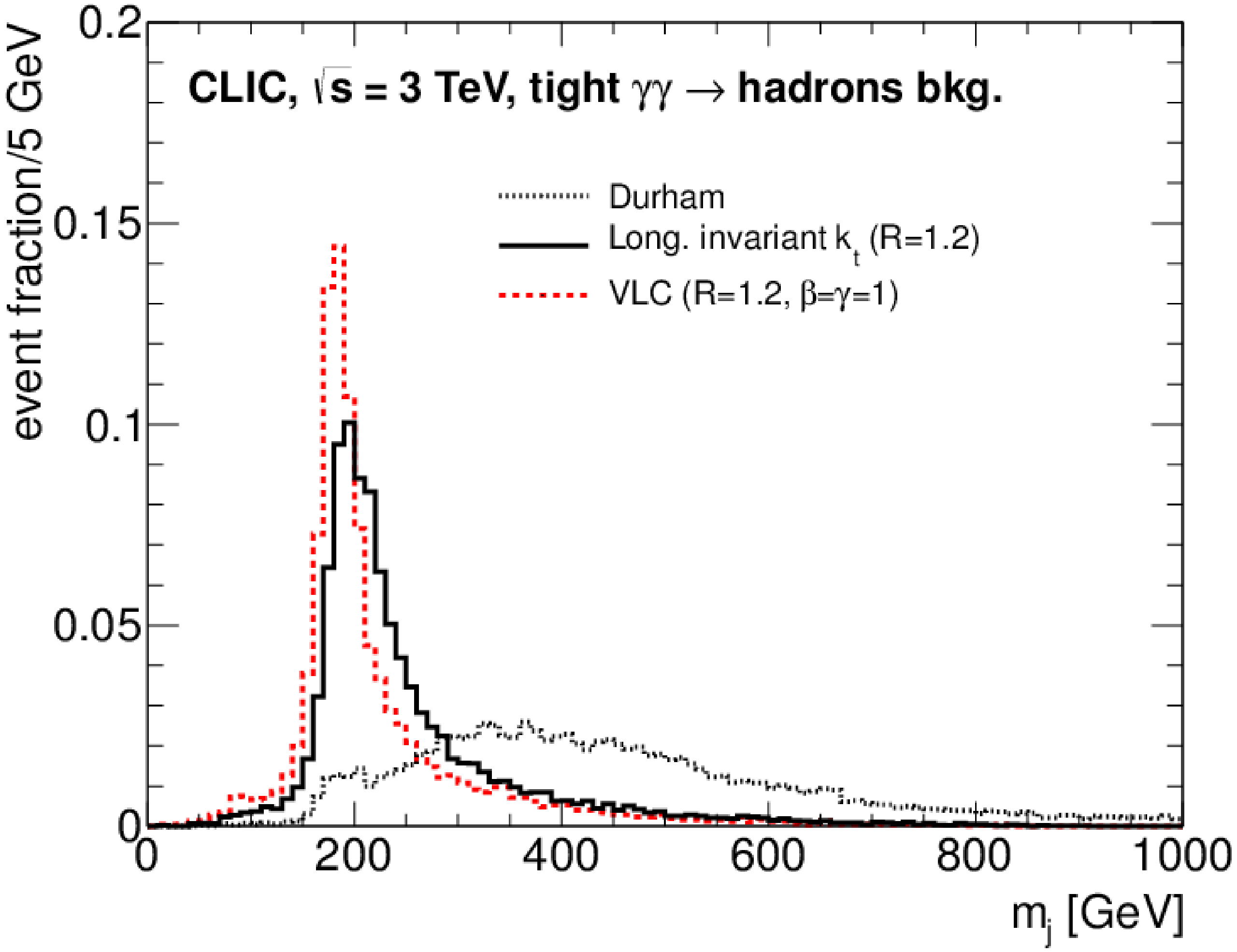
Low energy (~500 GeV):

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!

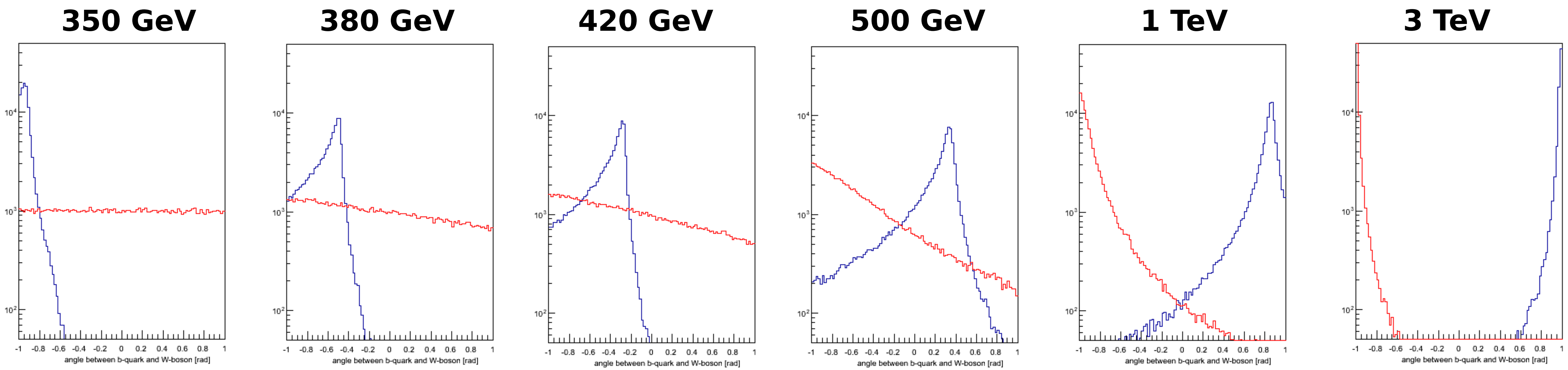
Provided we can deal with the γγ → hadrons background in fat jets, top reconstruction at high energy may well be more precise than at low energy!

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

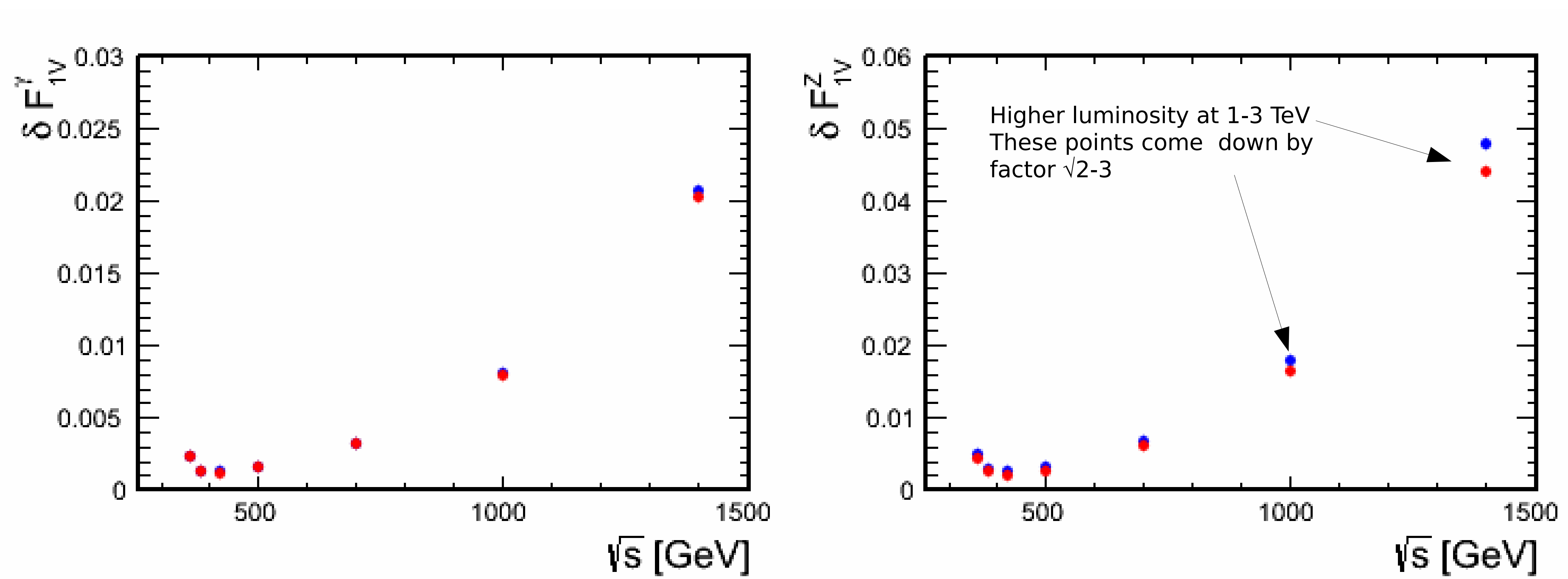
First extraction of couplings at $\sqrt{s} \neq 500$ GeV

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

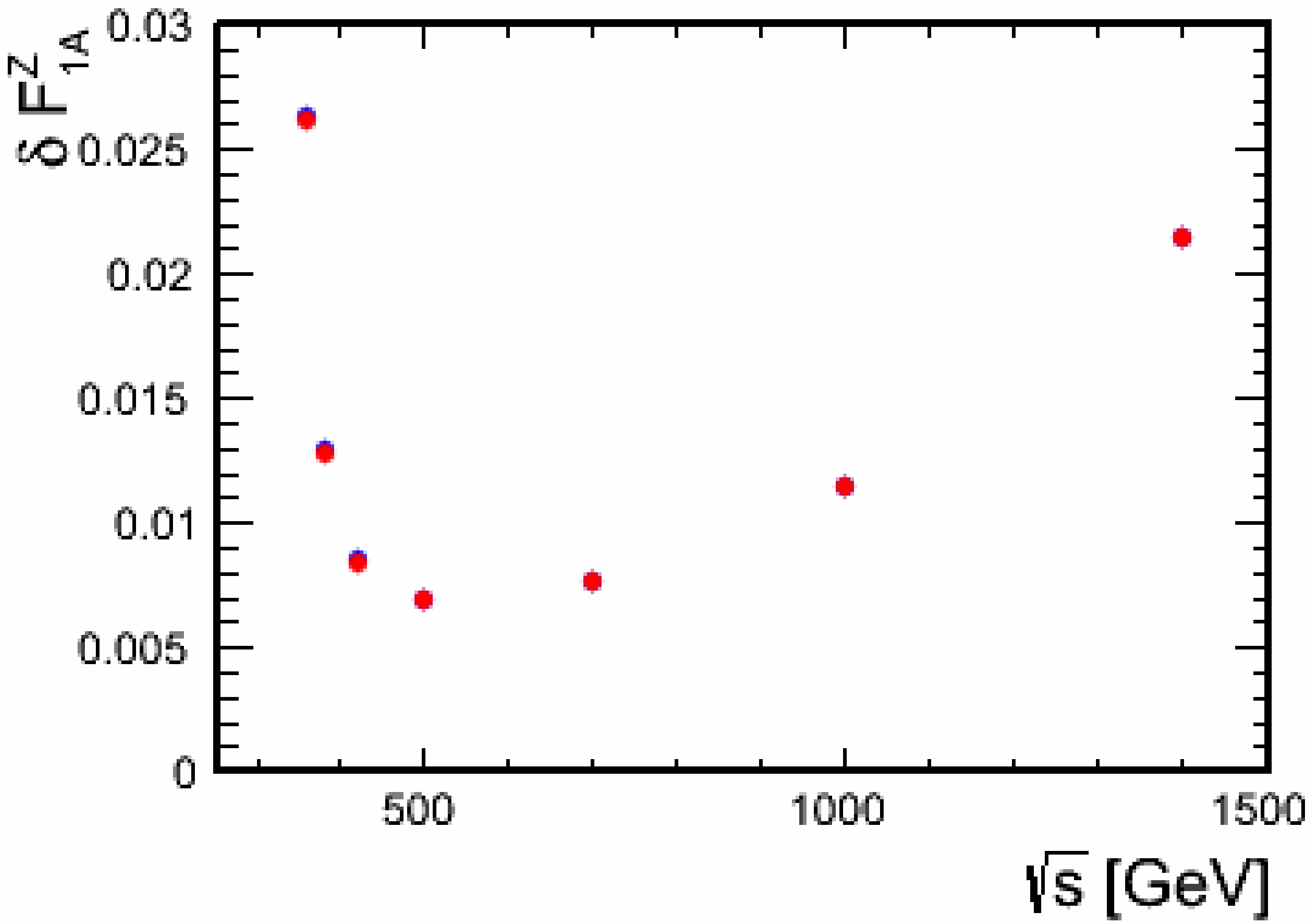
Very different behaviour for F1A;
extraction relies strongly on AFB

→ *suffers at low energy*

→ *less degraded at high energy*

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

Electron polarization only



Extraction of dipole moments F2V

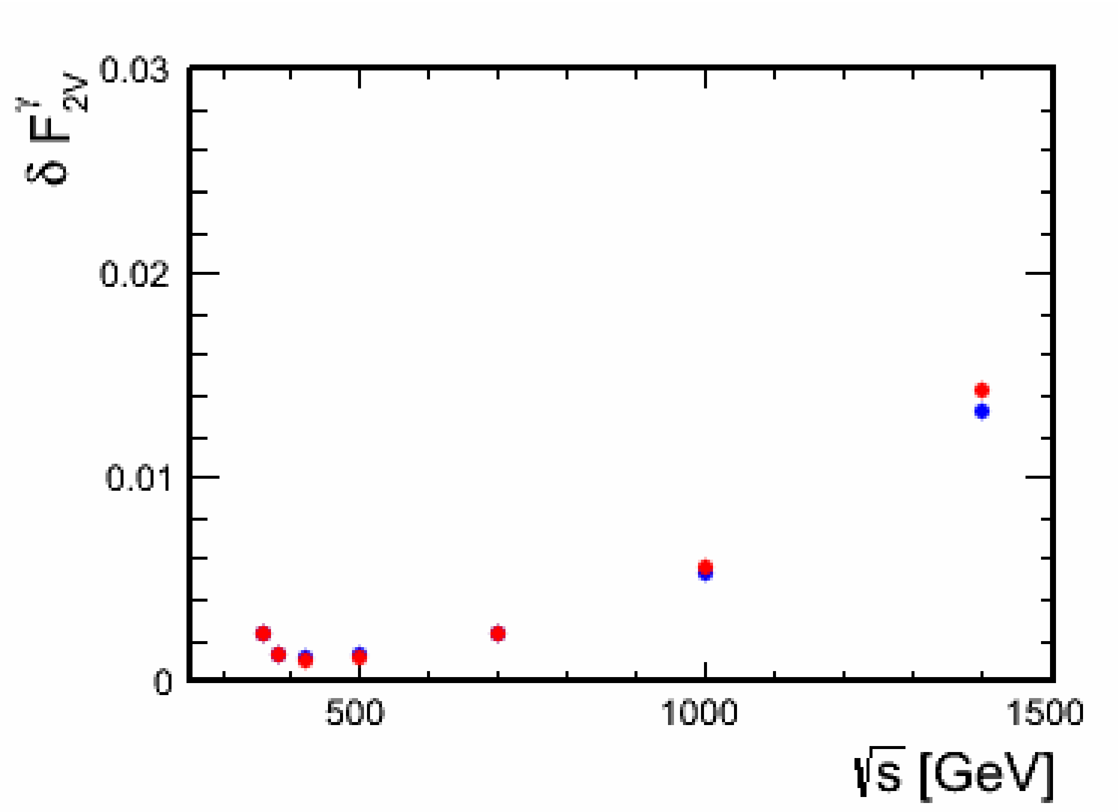
F2V; a factor 7-10 from most (500 GeV) to least sensitive (1.4 TeV)

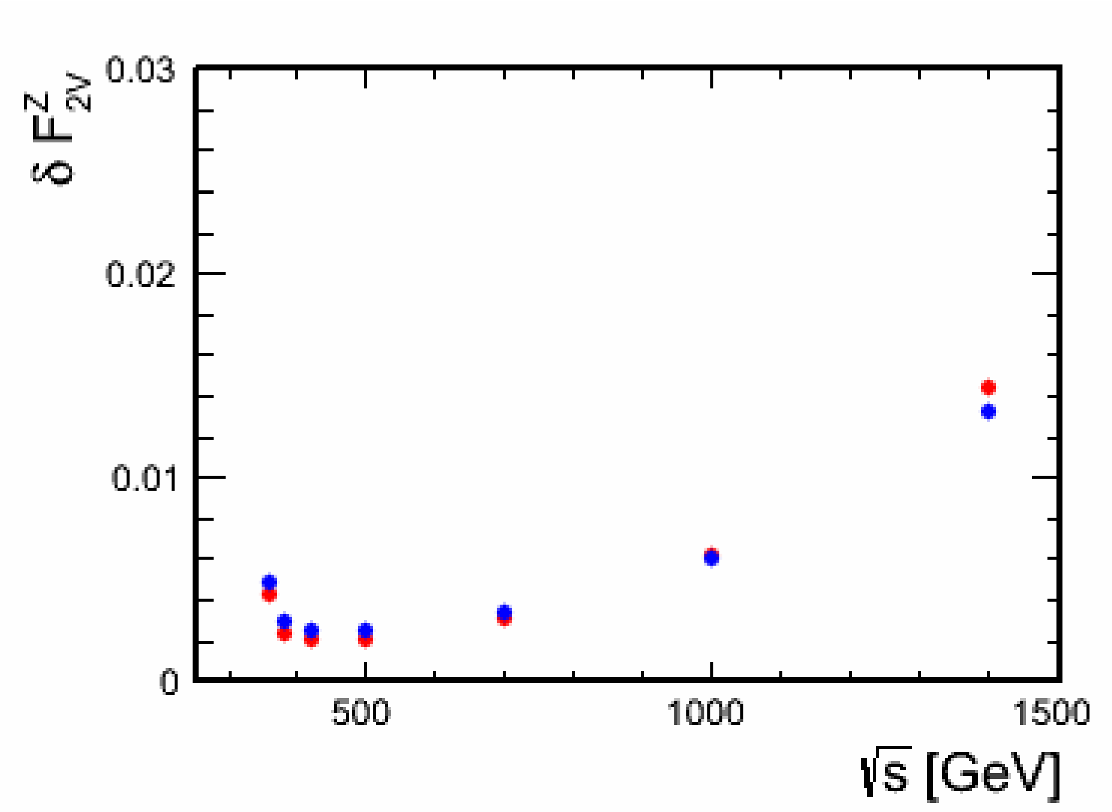
→ 4-6 taking into account increased luminosity

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

Lepton colliders can get a very precise top quark mass

→ stat. error ~ few tens of MeV

→ exp. syst. error ~ few tens of MeV

→ theory error ~ 10 MeV

→ 1S → $\overline{\text{MS}}$ conversion ~ 100 MeV

Carefully distinguish targets from prospects

$t\bar{t}Z$ and $t\bar{t}\gamma$ couplings measurement to < 1% are unique opportunity at a lepton collider

Every sqrt(s) regime brings additional potential;

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

where A_{FB} and cross-section are large and precise calculations are "easy"

→ Dipole moments and 4-fermion contact interactions might show high-scale NP in TeV regime

→ Polarization is needed to disentangle photon and Z couplings,

Much more to explore:

top physics potential below threshold

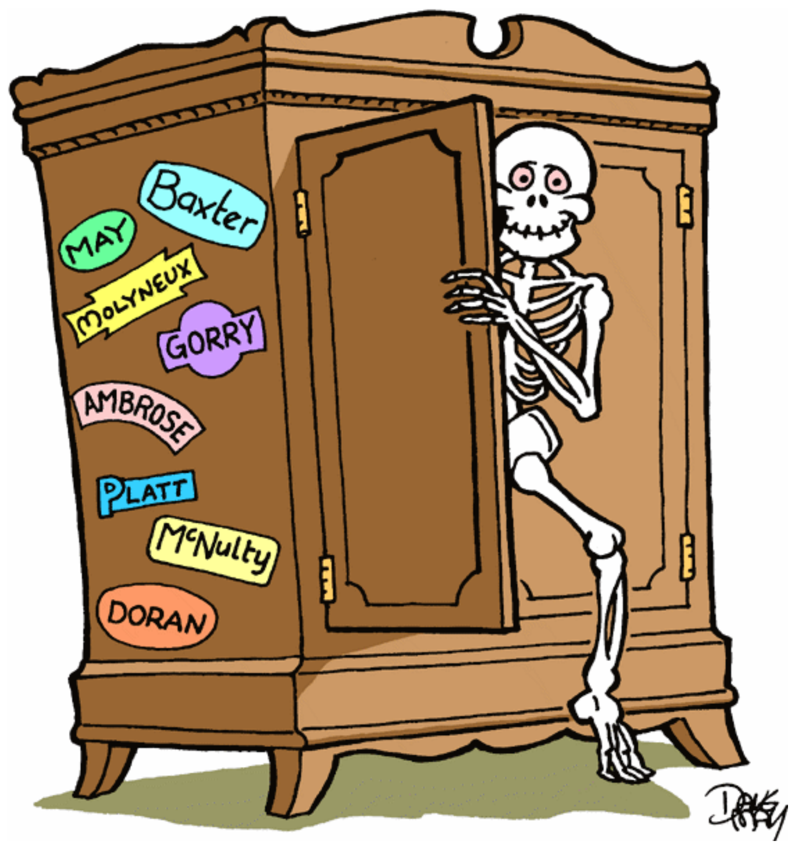
The top quark mass combination, small print

all measurements considered in the present combination, the analyses are calibrated to the Monte Carlo (MC) top-quark mass definition. It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV (see Refs. [19, 20] and references therein).

to jet calibration and modelling of the $t\bar{t}$ events. Given the current experimental uncertainty on m_{top}, clarifying the relation between the top quark mass implemented in the MC and the formal top quark pole mass demands further theoretical investigations. The dependence of the result on the correlation assumptions between mea-

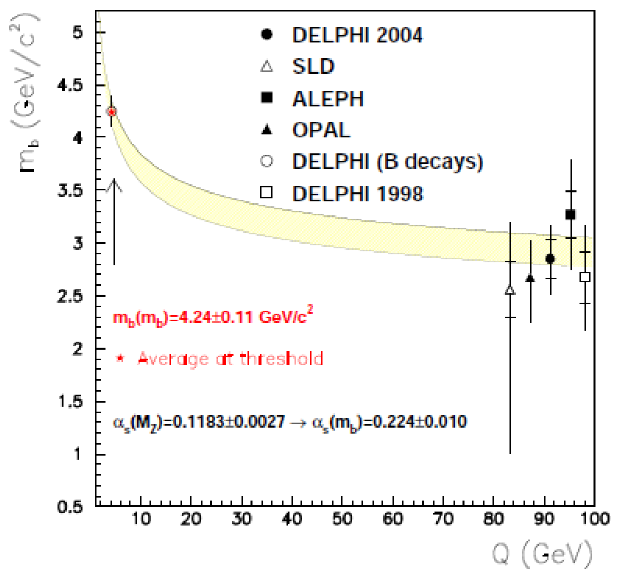
[19] General-purpose generators for particle physics

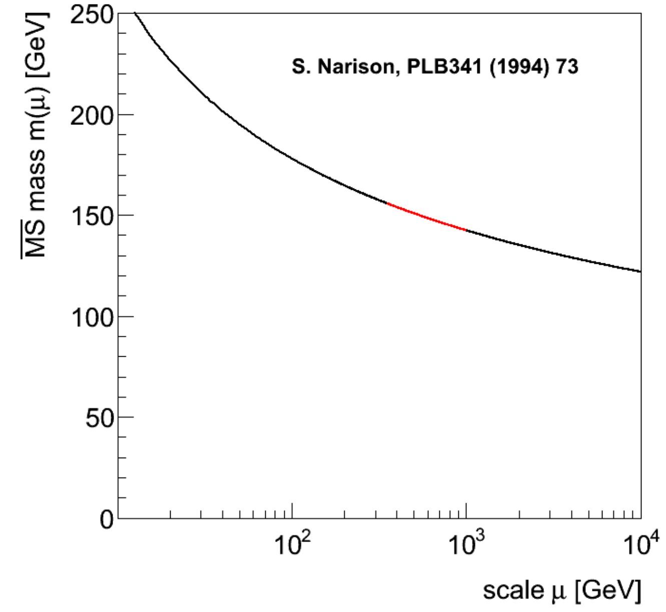
Note: it's likely that the GeV is at least partially accounted for in current modelling uncertainty



Scheme dependence – an old debate

Even if it decays (rather than hadronizes) the top is a quark, a coloured object. Mass is not an observable, but must be inferred from measurements.



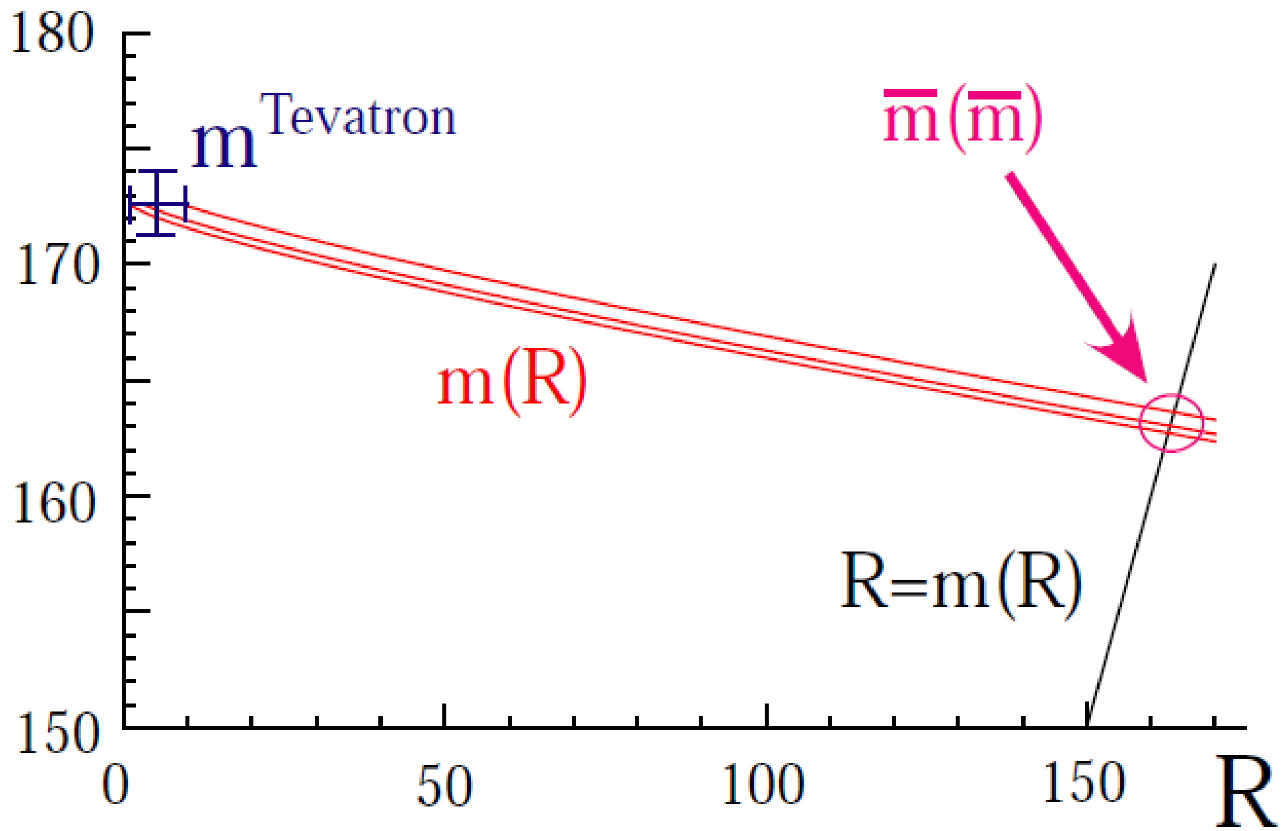


The scheme makes a difference:
For a top pole mass of 173 GeV,
the $\overline{\text{MS}}$ mass at the top mass ~167 GeV

Quantify the difference between pole and any other mass scheme
Hoang & Stewart, Nucl.Phys.Proc.Suppl. 185 (2008) 220-226

$$m_t^{pole} = m_t(R,\mu) + R\,\Sigma_k \Sigma_n a_{nk} \left[\frac{\alpha_s(\mu)}{4\pi}\right]^n \ln^k\left(\frac{\mu}{R}\right)$$

R is the scale chosen the scheme
(dial m for MS, 0 for pole mass)



Top quark mass: interpretation

Which top quark mass did we implement in our MC?

Matrix Element: ~ pole mass (for NLO)

Parton Shower: ~ pole mass

Hadronization: ?

In practice, the impact on the measurement depends on how sensitive a given observable is to soft physics. Unfortunately, the three-jet invariant mass used to measure the most precise top quark mass is quite sensitive

R~Γ_t~ PS cut-off and:

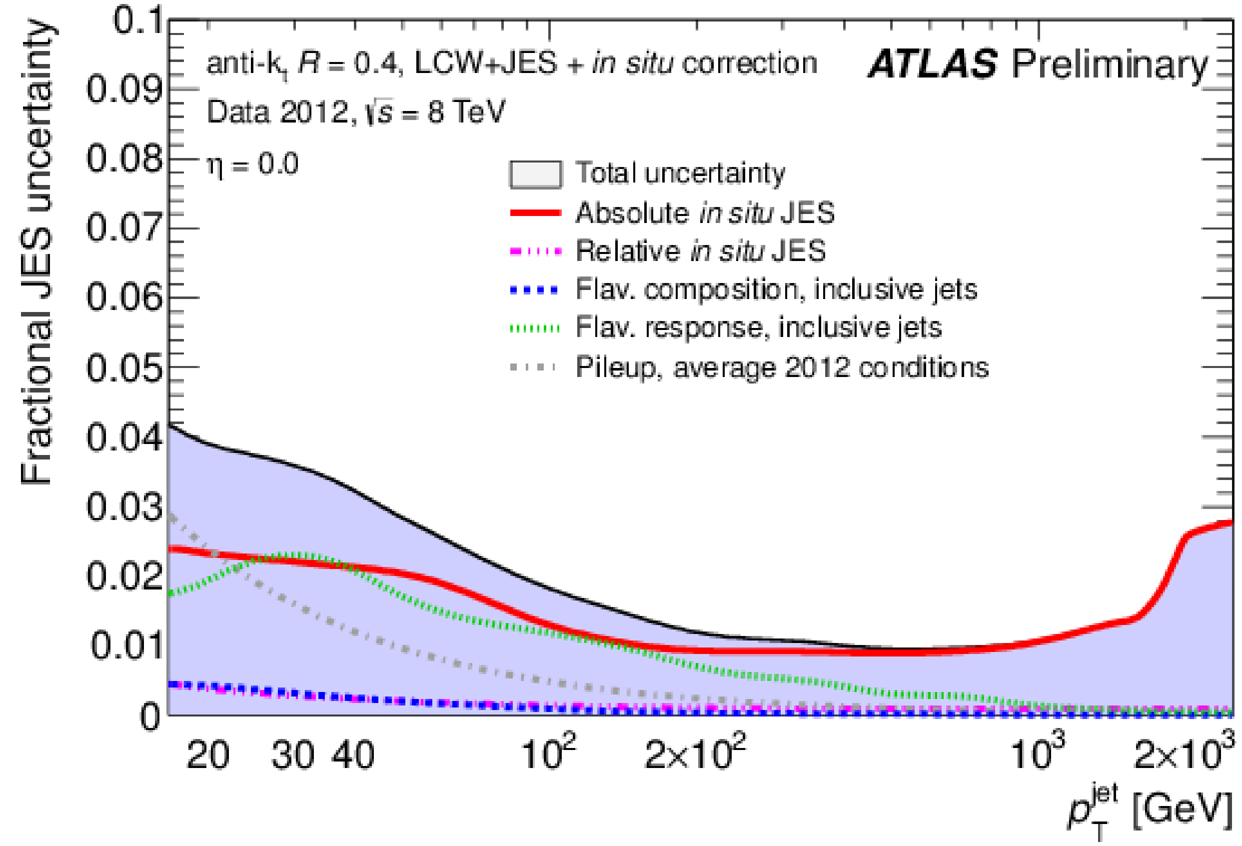
$$m_t^{pole} = m_t^{MC}(R) + R\,\alpha_s \frac{(\mu)}{4\pi}$$

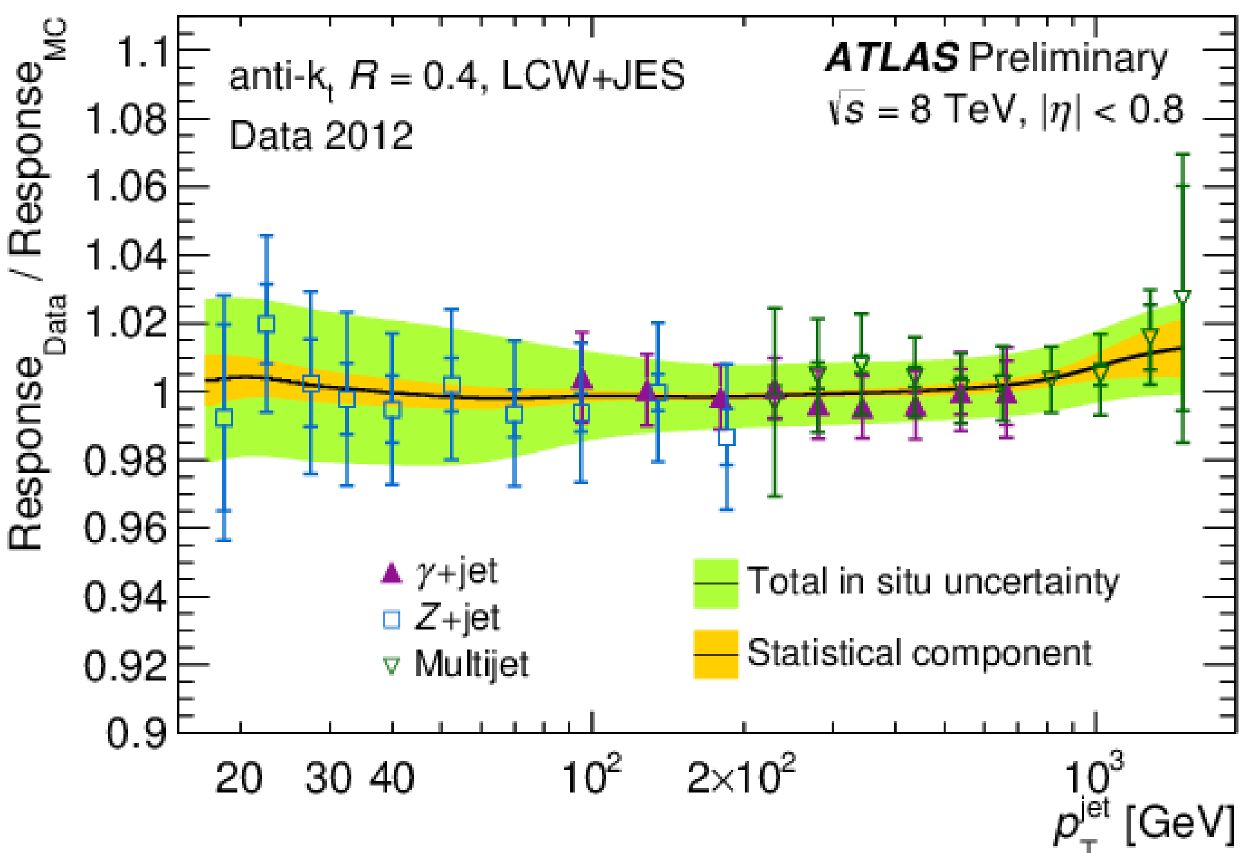
Is there a clear and universal relation between the two masses?
Can we “discover” this relation?

CMS-FTR-13-017-PAS: The relation between the pole mass and the MC top-quark mass as “not an experimental problem, but a theoretical (or phenomenological) issue.”

Theorists may actually manage to do this:
see for a serious attempt for bottom: A. Hoang, LCWS14

Perspective for improvement – systematics on combination





Break-down of uncertainties on March '14 world average:

Jet energy scale:
in situ JES (240 MeV),
standardJES (200 MeV),
flavourJES (120 MeV)
and b-JES (250 MeV)

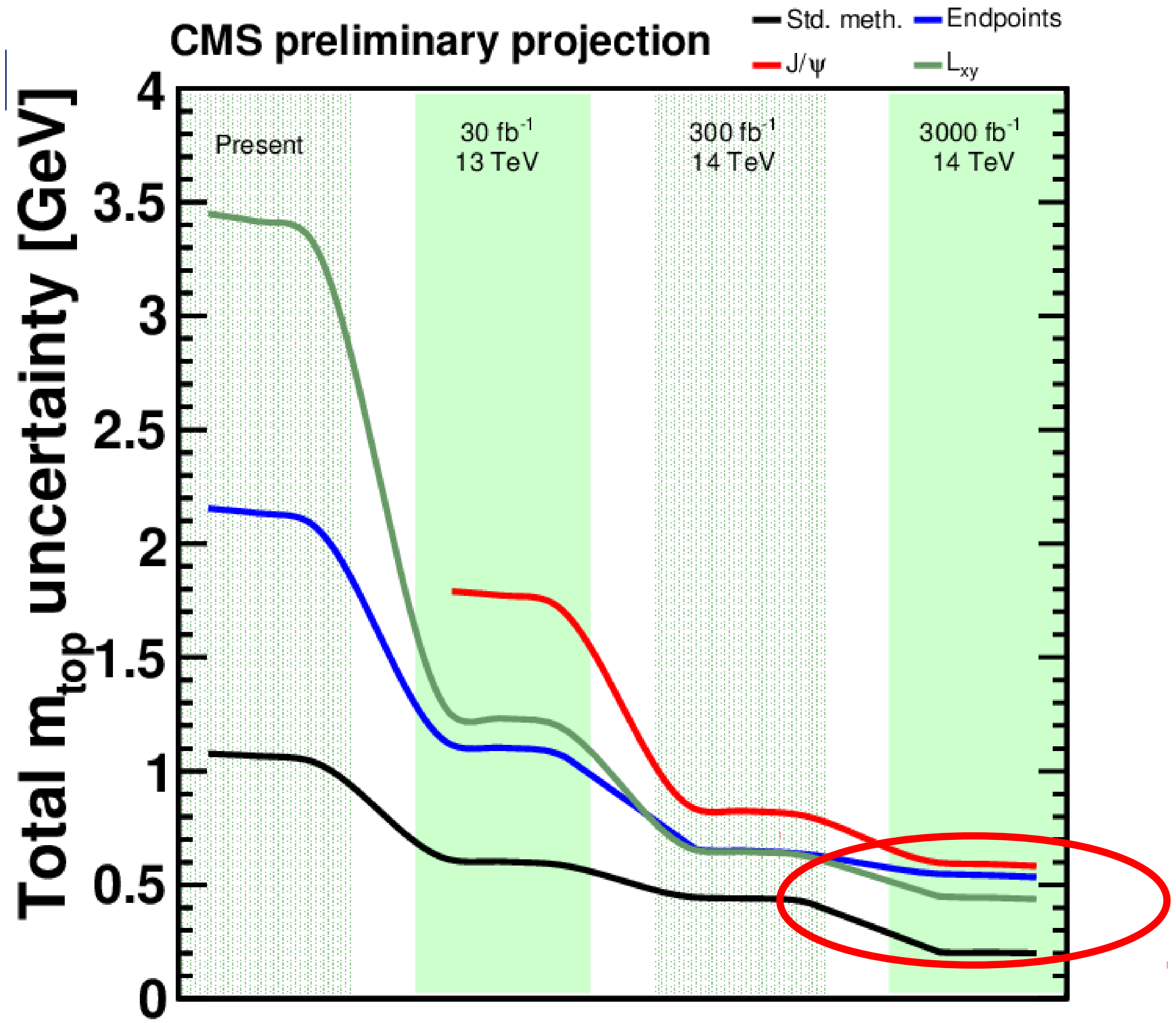
Statistics:
already < 300 MeV

Modelling:
(strongly correlated even between experiments):
Monte Carlo (380 MeV)
radiation (210 MeV)
colour reconnection (310 MeV)

Prospects for p

For a long time we claimed an LHC precision of 1 GeV

Prospect studies for top quark mass precision at Snowmass reported in arXiv:1310.0799, that I sign, concluded: *"We estimate that […] might lead to a top mass extraction with uncertainty as low as 500-600 MeV"*



CMS-FTR-13-017-PAS claims the ultimate reach of the "conventional method is 200 MeV, based on "assumptions [that] are optimistic but not unrealistic."

Clearly, the 200 MeV require a lot of work on JES and generators. Time will tell...

Top quark mass - alternatives

Endpoint measurement

CMS, arXiv:1304.5783, currently 2 GeV uncertainty)

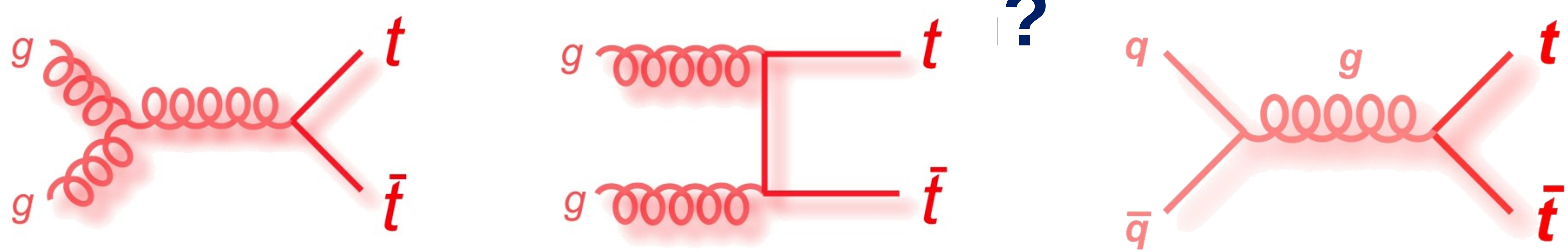
CMS estimate 600 MeV precision after the complete LHC programme

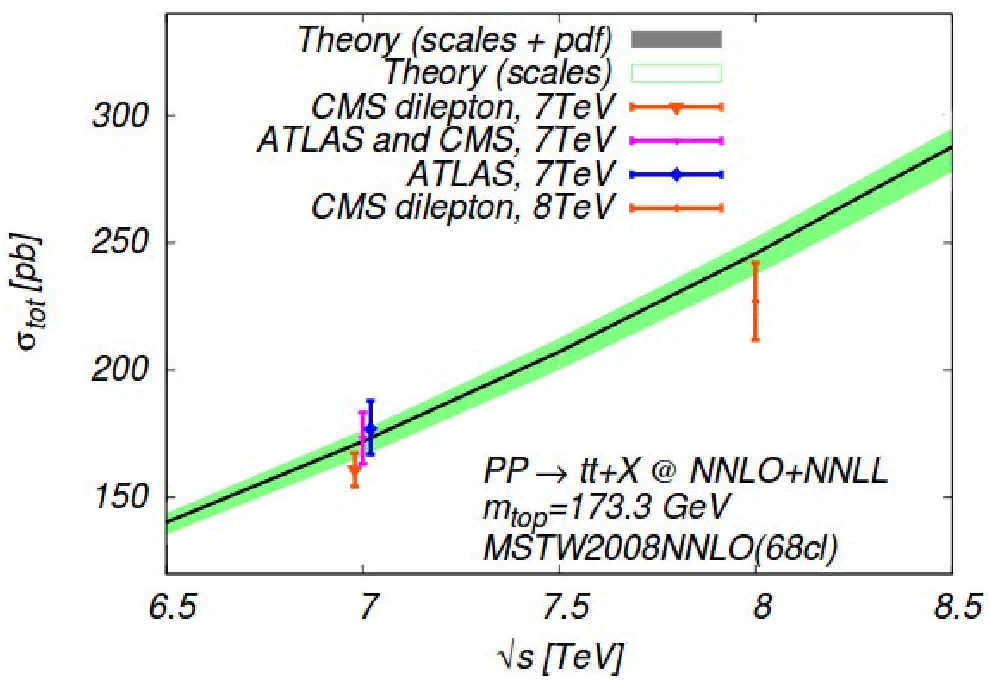
Move away from jets

(reduced dependence on shower modelling and JES)

- Extraction from m_{bl}
- Extraction from J/psi spectra t $\rightarrow$ Wb $\rightarrow$ lνb$\rightarrow$ lνJ/φ $\rightarrow$lνll

How well can we predict top quark ?





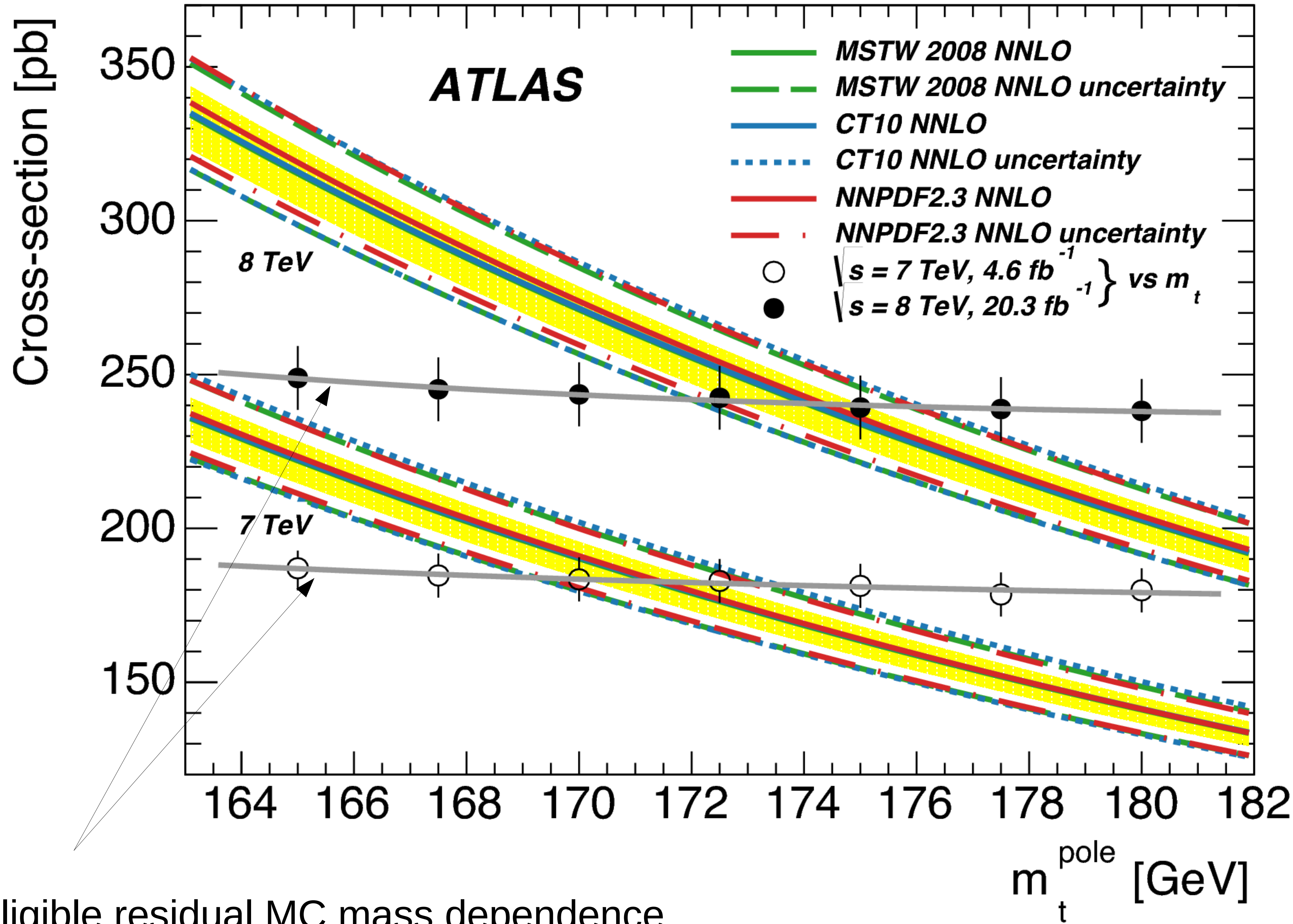
Theory milestone:
full NNLO and NNLL result for top quark pair production at hadron colliders

K-factor (NLO → NNLO) ~ 10%
Scale stability ~ 5 %
Series seems to converge...

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259(3.7%) −0.374(5.3%)	+0.169(2.4%) −0.121(1.7%)
LHC 7 TeV	167.0	+6.7(4.0%) −10.7(6.4%)	+4.6(2.8%) −4.7(2.8%)
LHC 8 TeV	239.1	+9.2(3.9%) −14.8(6.2%)	+6.1(2.5%) −6.2(2.6%)
LHC 14 TeV	933.0	+31.8(3.4%) −51.0(5.5%)	+16.1(1.7%) −17.6(1.9%)

Alternative: top mass from cross-section

$\Delta m_t^{pole} = 2.5$ GeV



Nearly flat, negligible residual MC mass dependence

Top quark mass

Extraction from cross section - revisited

Well-defined mass scheme (pole mass, $\overline{\mathrm{MS}}$ mass)

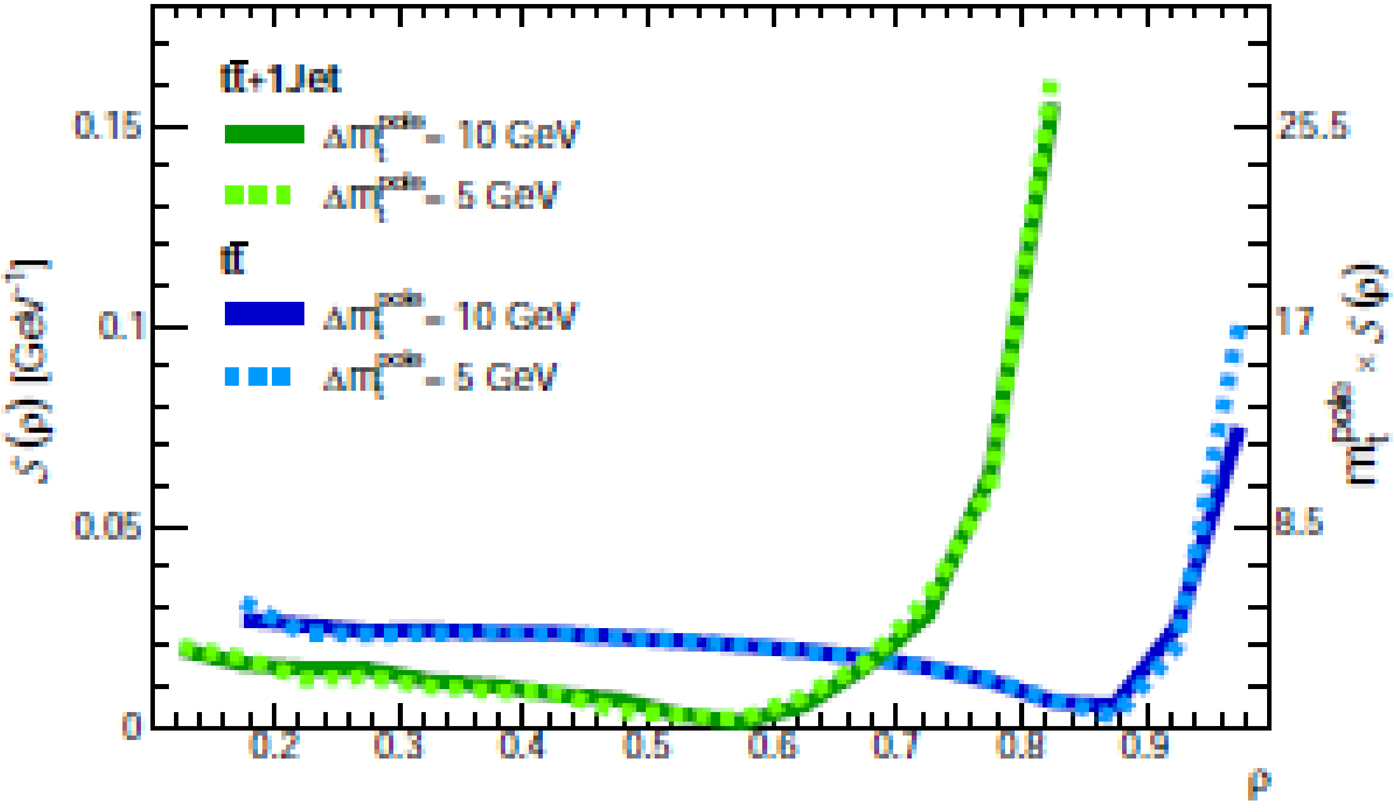
Limited by poor sensitivity: $\Delta m/m \sim 0.2\ \Delta\sigma/\sigma$

$t\bar{t}$ threshold has better sensitivity, but requires theory progress (bound states)

currently ~4 GeV uncertainty, PLB728 (2014) 496-517

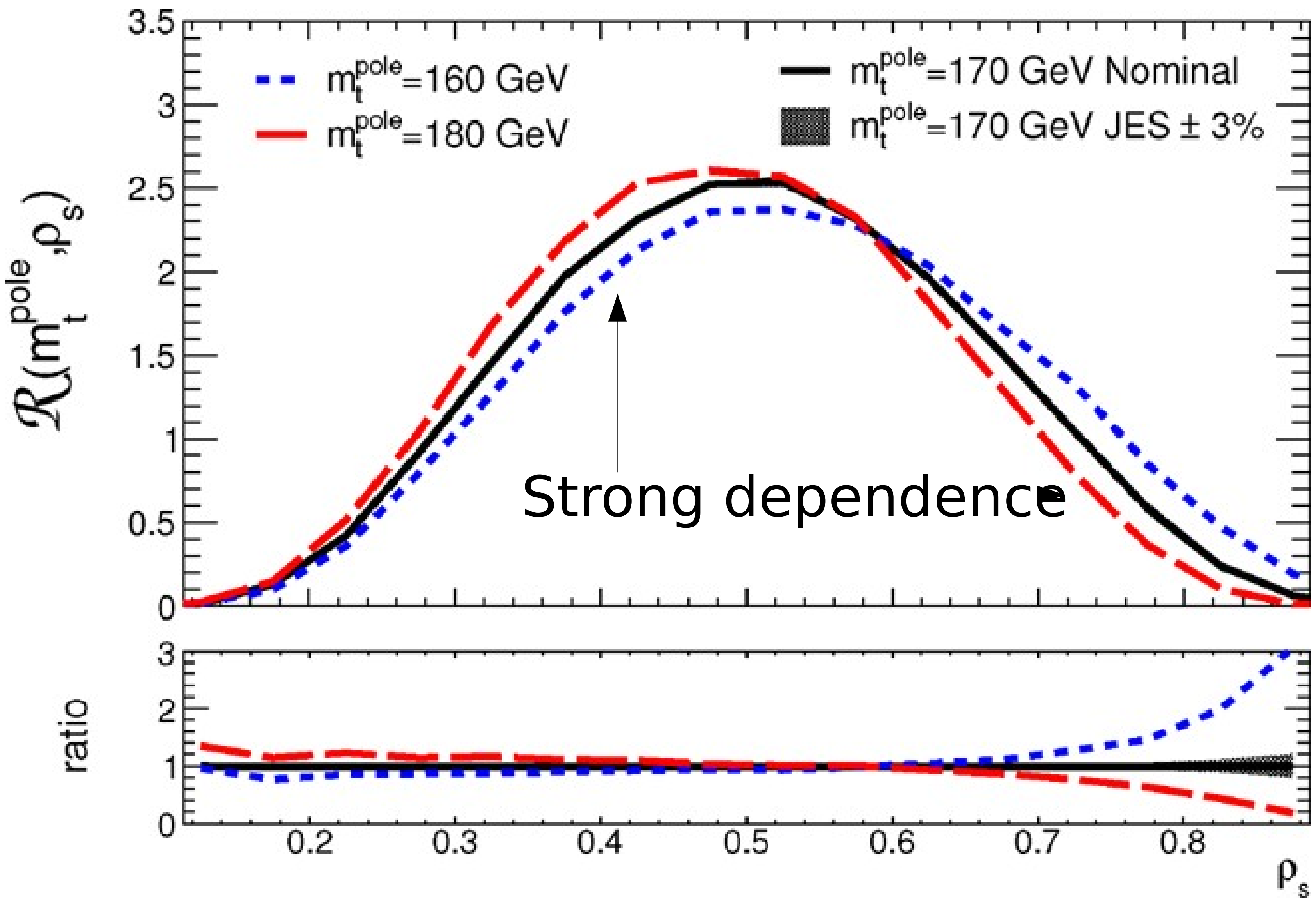
Now consider the $t\bar{t}g$ cross-section

Alioli, Moch, Uwer, Fuster, Irles, Vos, EPJC73 (2013) 2438, arXiv:1303.6415



Top quark mass

- Measure the normalized differential tt+1jet production cross-section vs. Invariant mass of the tt+1jet system.
- Extract the mass in any (well-defined) scheme. Currently: pole mass
- Theory uncertainty (due to scale and PDF) < 1 GeV
- Experimental uncertainties can be controlled to same level

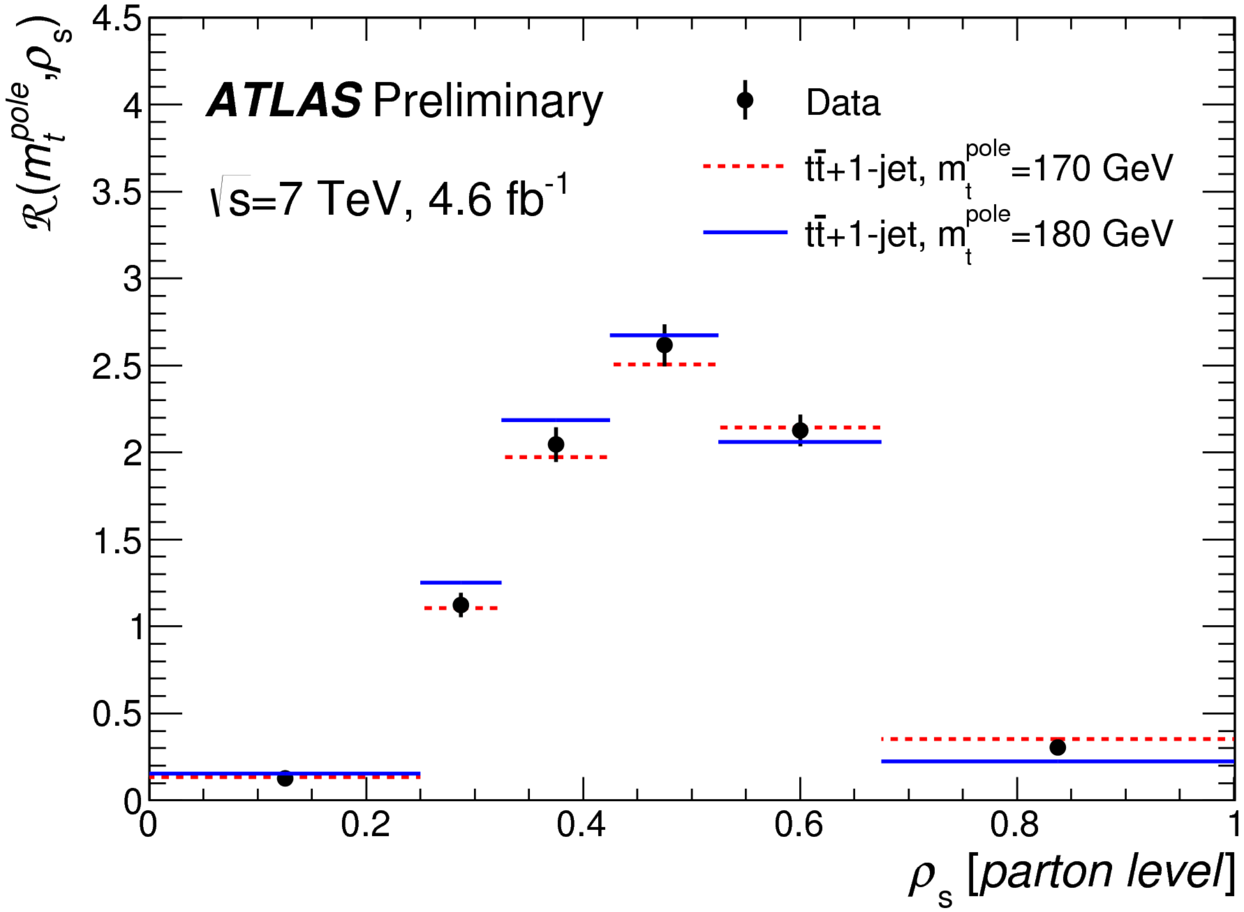


ρ_s µ $1/m(t\bar{t}j)$

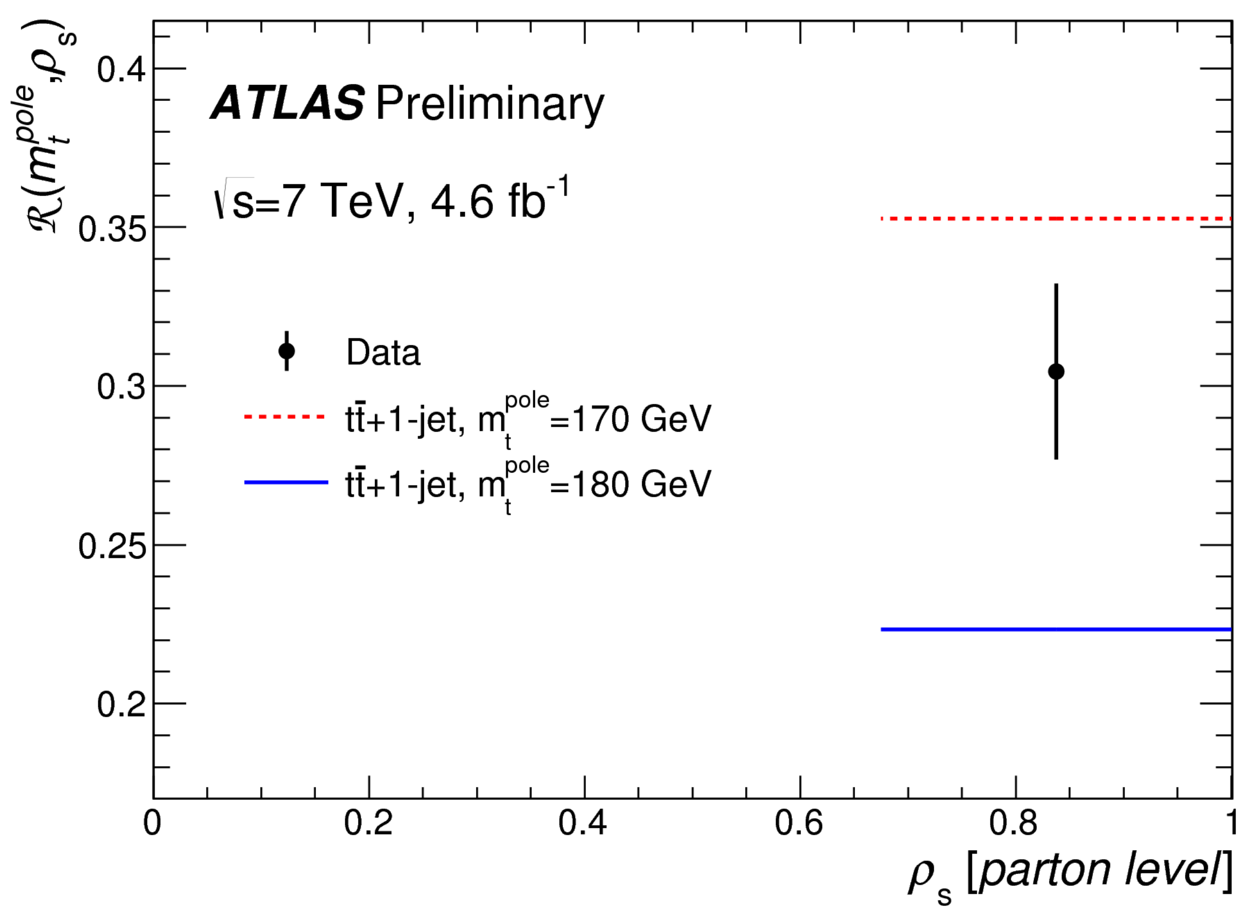
→ *1 at threshold*

→ *0 for boosted production*

Top quark mass from tt + 1 jet events



ATLAS-CONF-2014-053



Correct normalized differential cross-section to parton-level

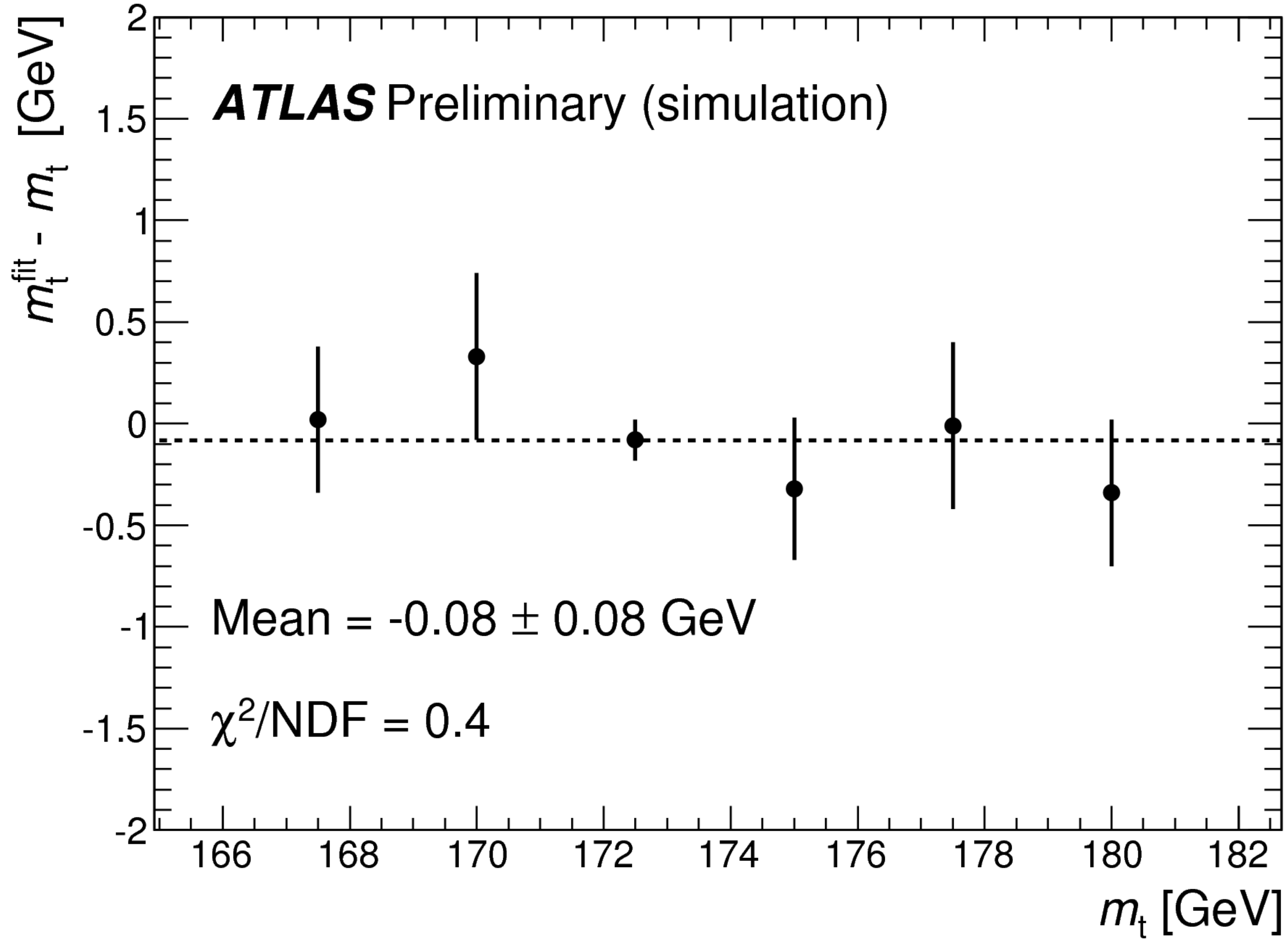
Fit with tt+jet NLO+PS theory

Is this the pole mass? Yes!
Scheme fixed in NLO calculation
(difference NLO vs. NLO+PS ~ 300 MeV)

Top quark mass

Don't you run into a MC mass dependence in the correction of the normalized differential cross-section?

No, compatible results are obtained for a large range of MC mass values.



Top quark pole mass

M_t^{pole}=173.7 +2.3 -2.1 GeV

→ *currently the most precise top quark pole mass*

1.5 (stat.), 1.4 (syst.), +1.0/-0.5 (theo.)

→ *room for improvement, even with 2012 data set (ongoing)*

→