Top quark physics; from the LHC to a linear e^+e^- collider

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The top quark

A quark that we CAN study very well (a *nude* quark, we can easily isolate its signature from that of other quarks, we can distinguish top and anti-top quarks, we can study its polarization)

→ a couple of slides of introduction

The LHC is in the middle of a very extensive top quark physics program (measuring the top quark production and decay, its properties, and using the top quark to search for new physics)

→ a brief review (declaration of bias: I'm an ATLAS member)

A future LC holds great promise for precision top physics (the top quark is the only quark with a poorly constrained qqZ/γ vertex. Many ILC studies are at parton level: must take these to a full-fledged feasibility study.

→ the introduction to a progress report from a IFIC/LAL collaboration (see Jeremy Rouene's talk for the details

The top quark

Bibliography:

LHC:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Zhou, Whiteson, Tait, Phys.Rev. D85 (2012) 091501, arXiv:1203.5862

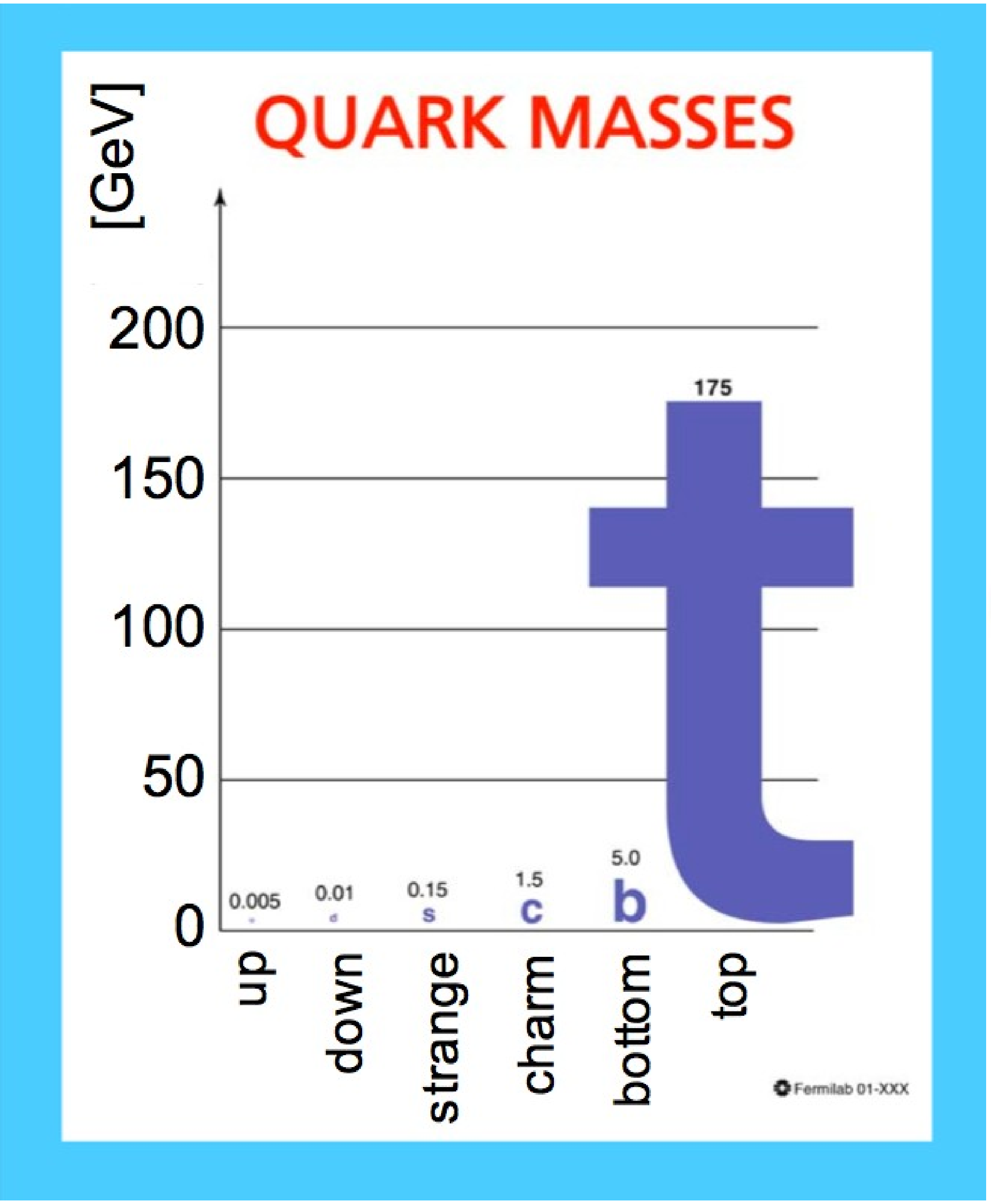
Englert et al., arXiv:1210.2570

Bernreuther, top quark physics at the LHC (2008)

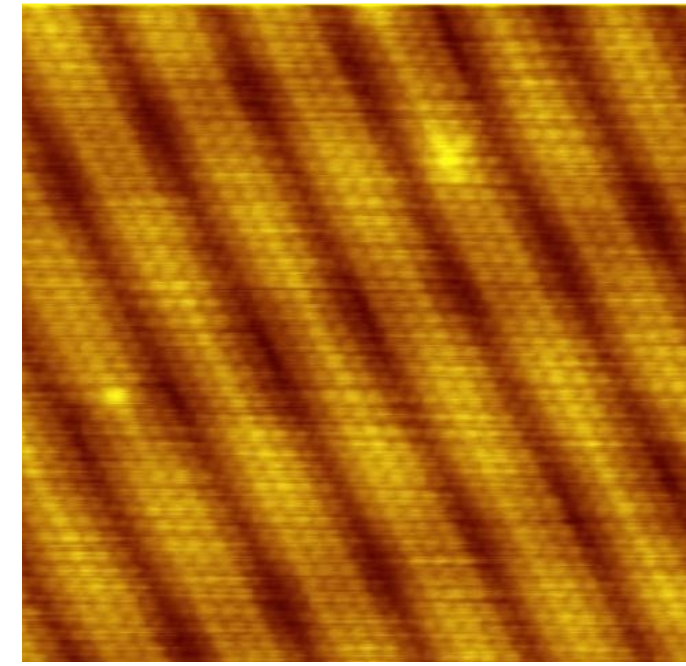
LC:

- contribution to DBD, see J. Rouene's talk in this workshop
- Tesla TDR (2001) part III on physics
- 2004 Report on the complementarity of LC and LHC
- CLIC physics report
- ILC Reference Design Report (2007): physics and detectors
- Letter Of Intent of the ILC experiments (2009) SiD and ILD
- Conceptual Design Report (2012) of the CLIC detectors

The top quark



Roughly as heavy as a Gold atom



But the top quark is elementary in the SM

Searches for contact interaction or exicted states of quarks and leptons yield limits on compositeness (from PDG2012)

observable	Compositeness scale reached [TeV]
L (eeee)	O(10) (LEP)
L (eeqq)	O(10) (LEP)
L (qqqq)	2.9 (D0) 3.4 (ATLAS) 5.6 (CMS)
$e^* \to e\,\gamma$	1 (CMS)
$q^* \to q\,g$	2.5 TeV (CMS), 1.3 TeV (ATLAS 2010)

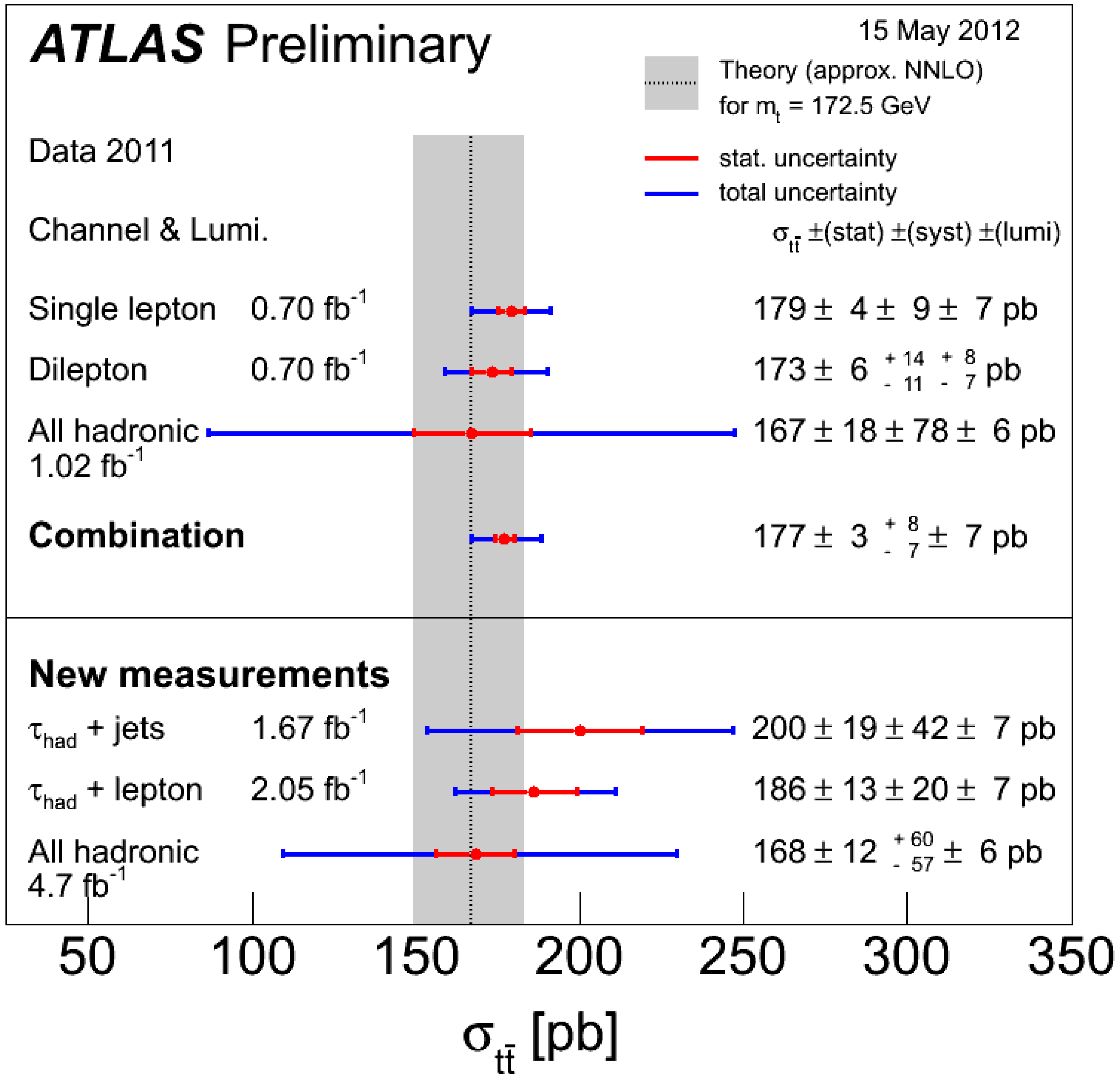
The top quark at the LHC

Top quark production at the LHC
– no obvious suprises

Cross-section combination ATLAS and CMS:

σ_{tt} = 173.3 ± 2.3 (stat.) ± 7.6 (syst.) ± 6.3 (lumi.) pb

→ 5.8 % precision (TOP-12-003-PAS)



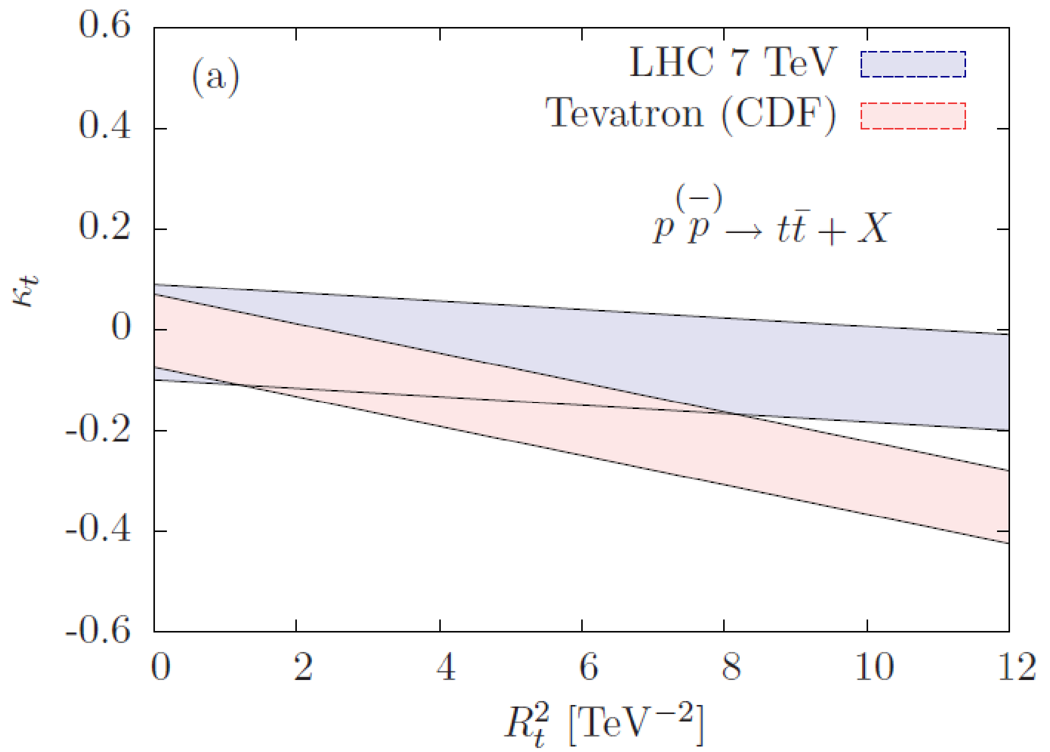
Constraints on top quark structure

C. Englert, A. Freitas, M. Spira and P. Zerwas,

arXiv:1210.2570 [hep-ph]

Constraining the top chromo-magnetic moment using gg → tt

	R_t [TeV^{-1}] / [10^{-16} cm]	$\|k_t\|$
Tevatron + LHC @ 7 TeV	2.9 / 0.57	0.17
Tevatron + LHC @ 14 TeV	2.1 / 0.41	0.07
LHC @ 14 TeV + boosted top	0.7 / 0.14	0.05



See also: Degrande, Gerard, Grojean, Maltoni, Servant, Phys.Lett. B703 (2011) 306-309

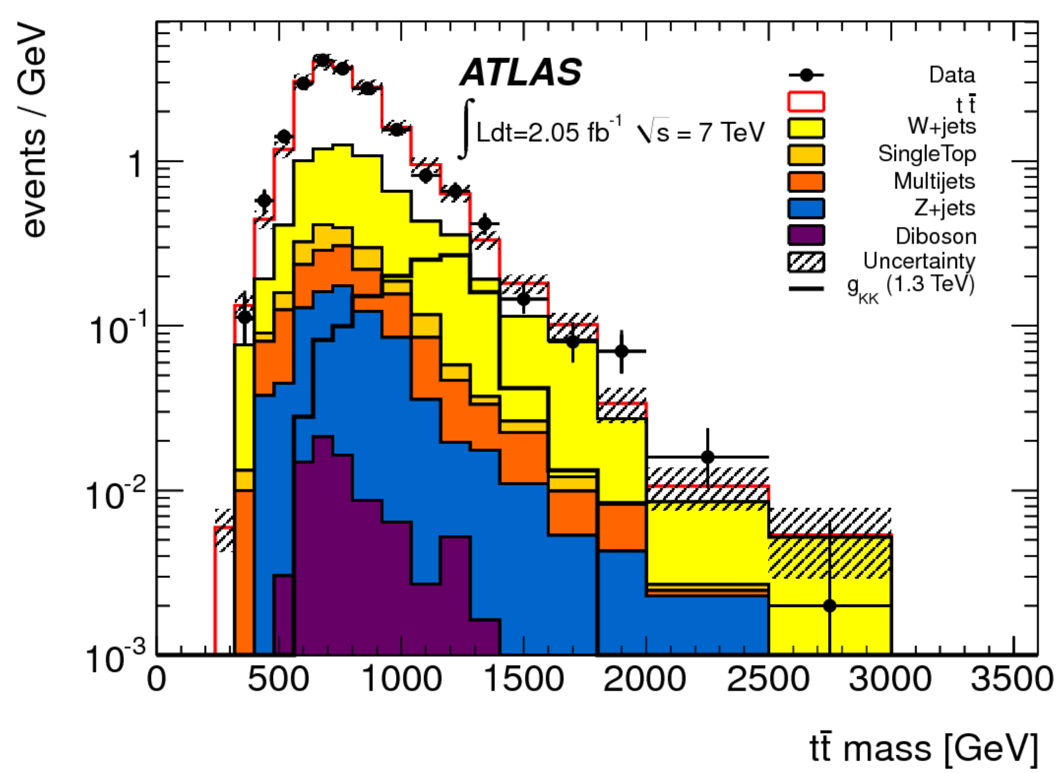
Boosted top quarks

http://cerncourier.com/cws/article/cern/50799

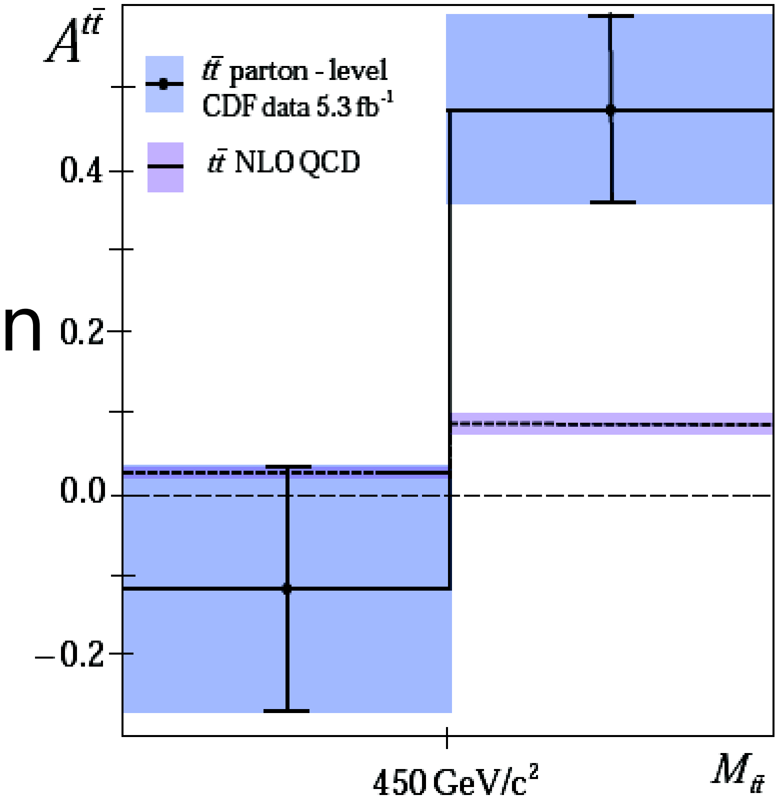
Expected number of events	Tevatron run II 10 fb^{-1} @ 1.96 TeV	LHC 2012 20 fb^{-1} @ 8 TeV	LHC design 300 fb^{-1} @ 13 TeV	High-energy LHC 300 fb^{-1} @ 33 TeV
Inclusive $t\bar{t}$ production	60,000	4,000,000	200,000,000	1,400,000,000
Boosted production $m_{t\bar{t}} > 1$ TeV	23	60,000	5,200,000	71,000,000
Highly boosted $m_{t\bar{t}} > 2$ TeV	0	480	110,000	3,900,000

tt resonance search using boosted top quarks. No new physics, but proof of principle for novel reconstruction of high pT top quarks

Challenges → opportunities



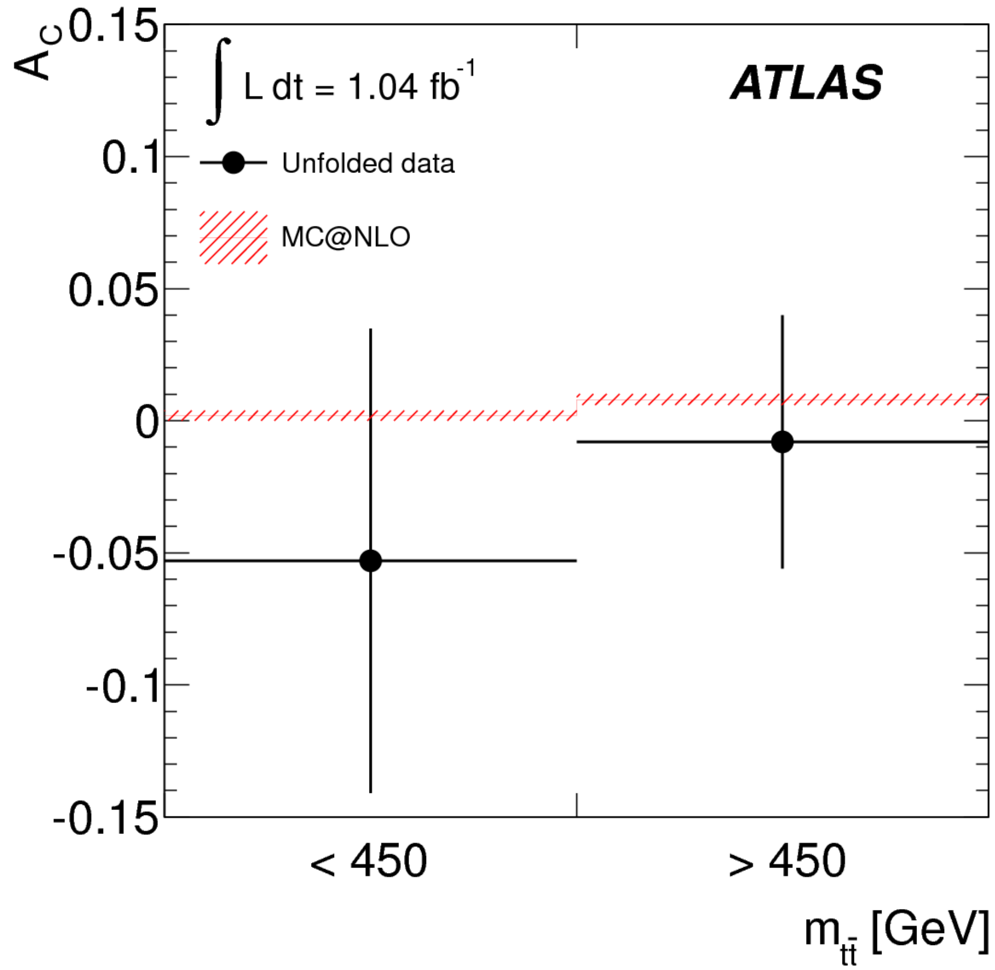
Top quark charge asymmetry



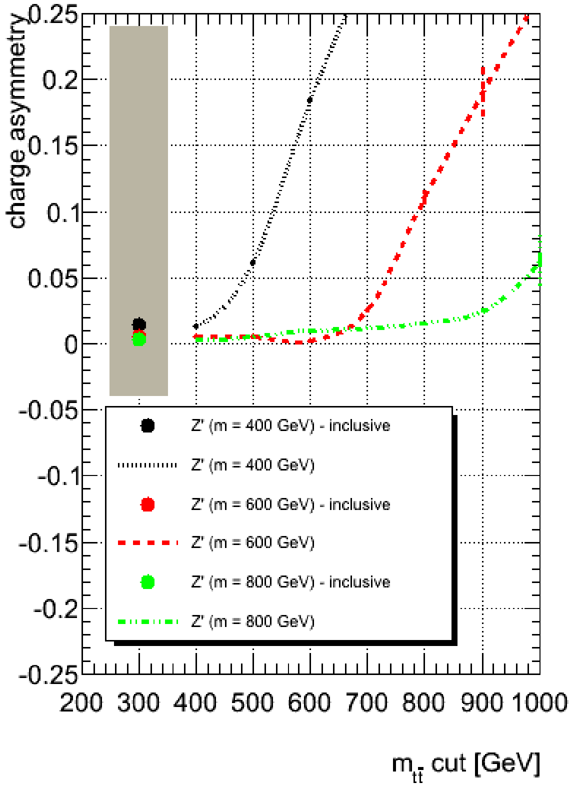
Asymmetries in the production of third generation quarks has been an interesting area for decades

The CDF collaboration, "*Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production*," Phys.Rev.D83 (2011).

Meaasurement of the charge asymmetry in top quark pair production....
arXiv:1203.4211



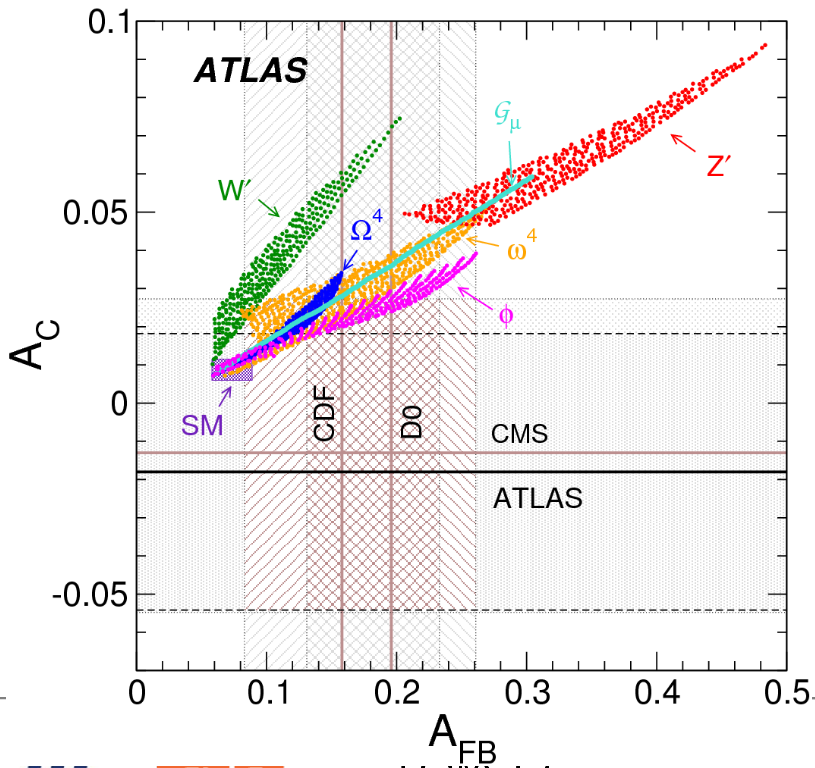
Charge asymmetry



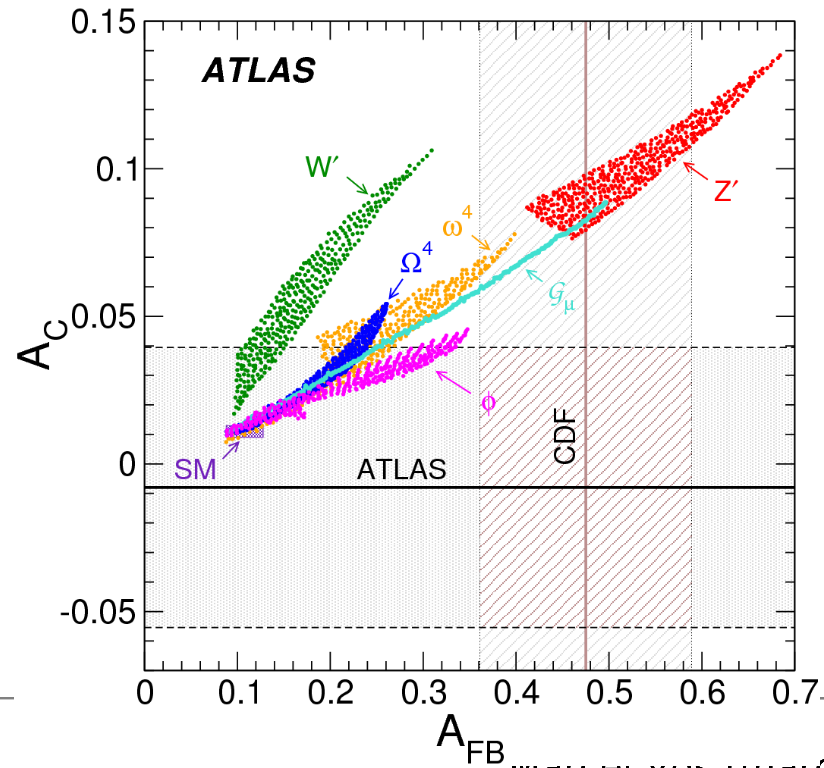
Inclusive measurement and two mass bins (<450 GeV, >450 GeV)

A_C vs. mass for Z' model (V. Sanchez, A. Hyaya)

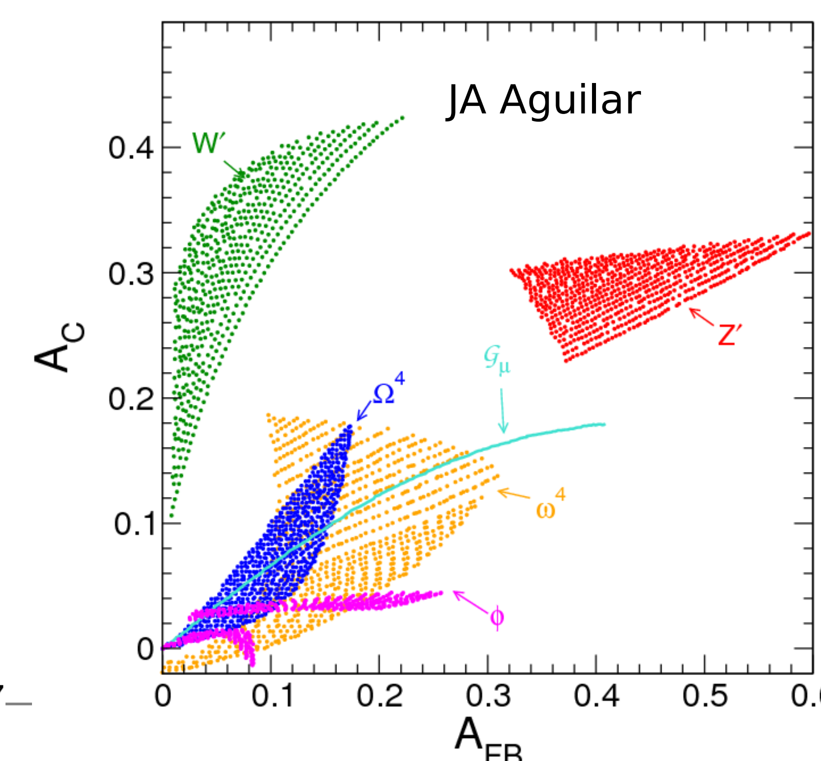
Impact on model zoo inclusive



m_{tt} > 450 GeV (Tevatron and LHC)

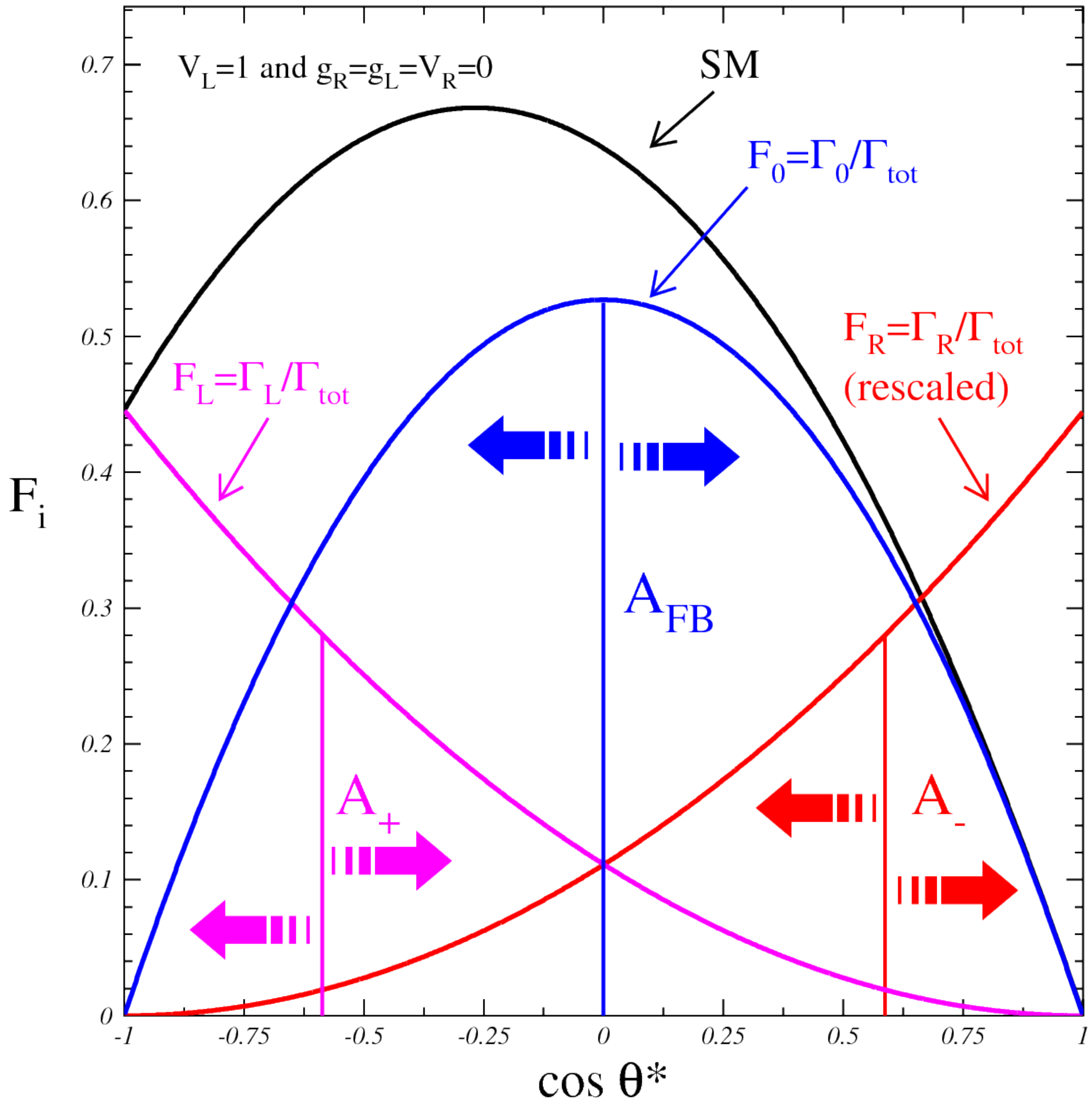


M_{tt} > 800 GeV (LHC only)

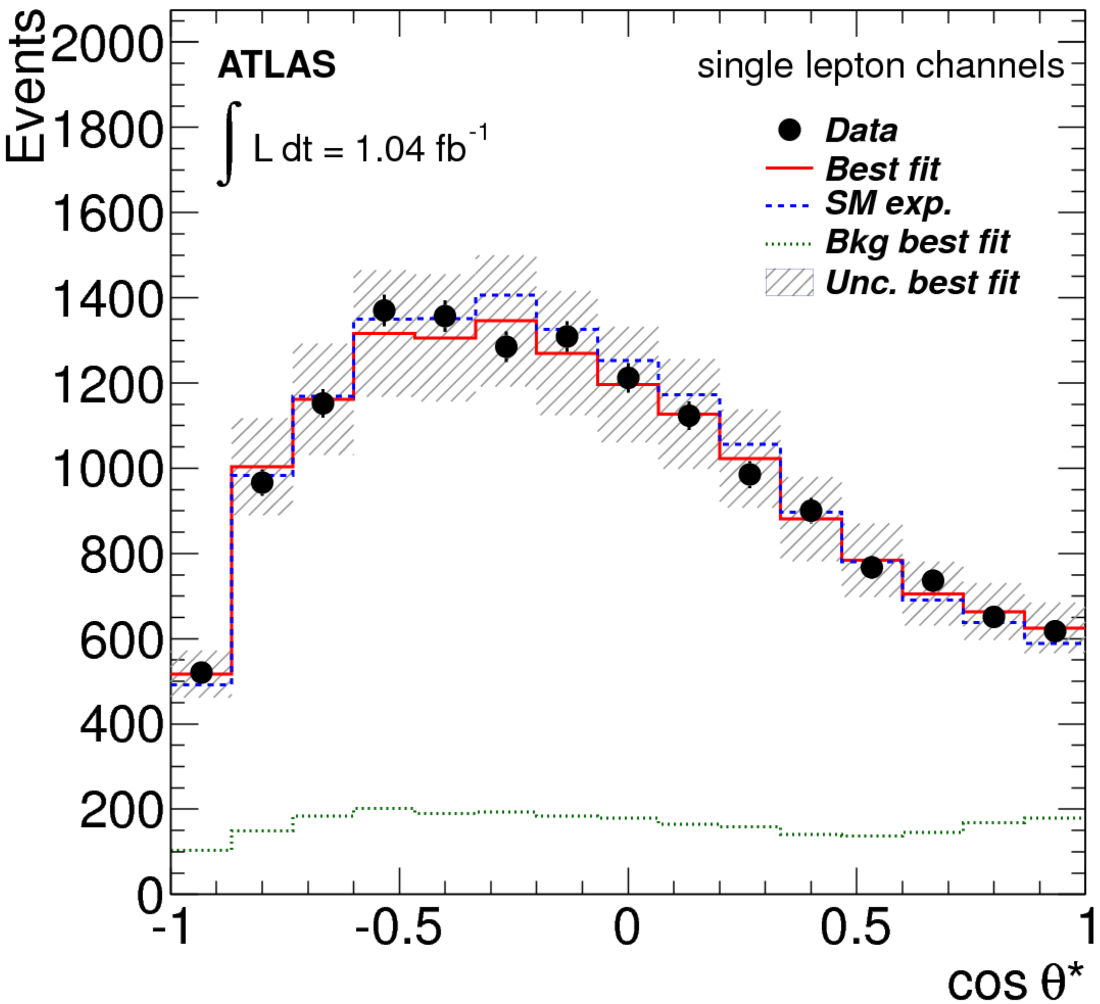


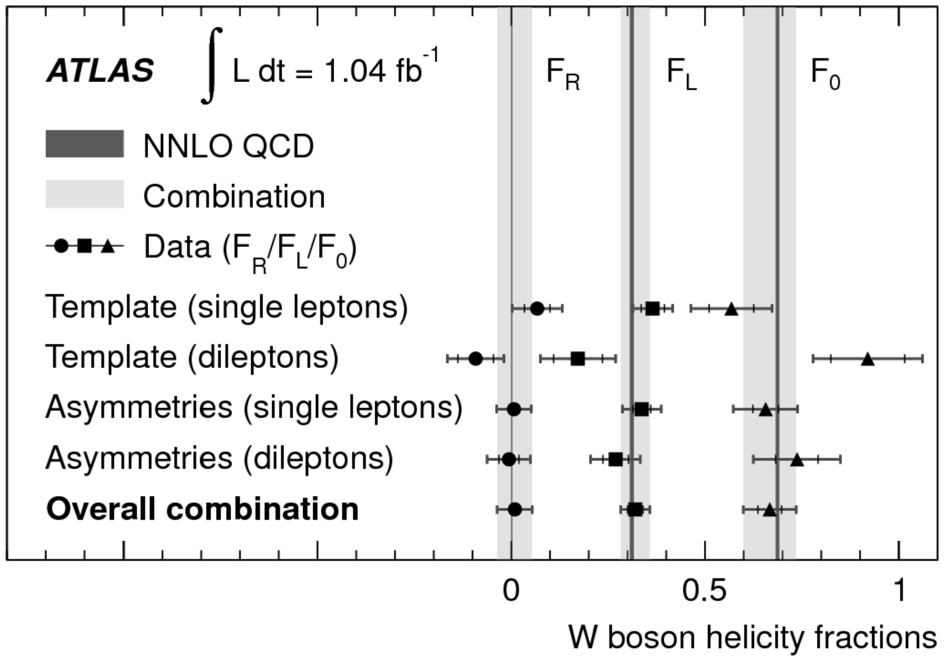
Top decays

Measure the angle between the charged lepton (from W → lν) and the reversed momentum direction of the b-quark (from t → Wb), both boosted to the W boson rest frame



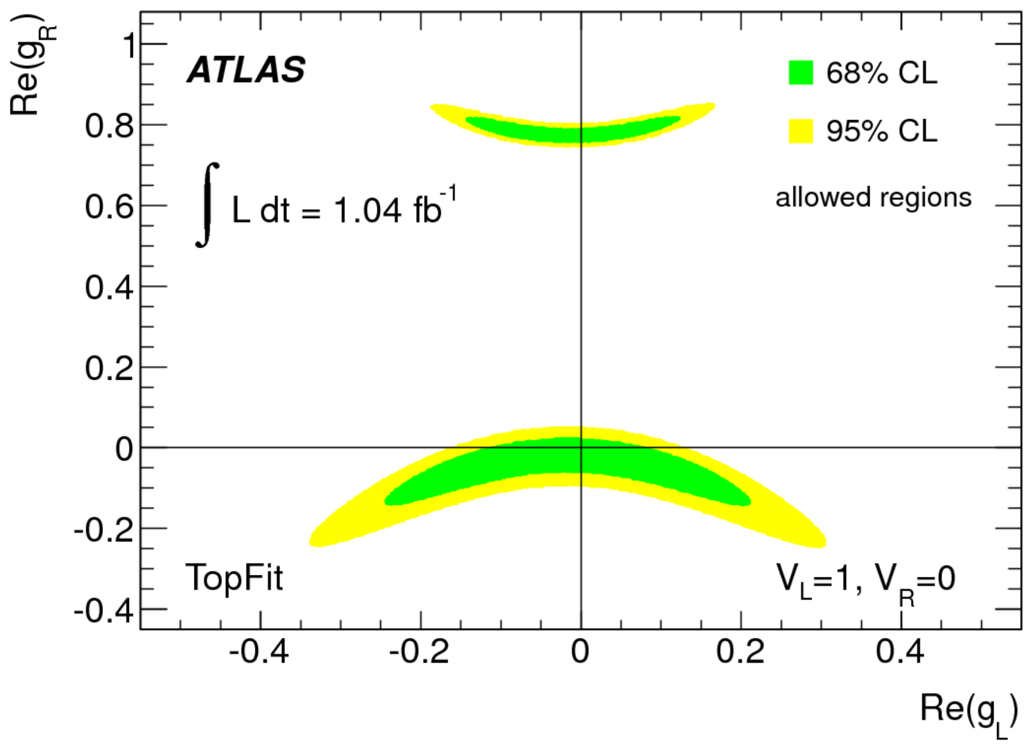
Top decays





$F_0 = 0.67 \pm 0.07$, $F_L = 0.32 \pm 0.04$, $F_R = 0.01 \pm 0.05$,
in agreement with the Standard Model predictions.

Ideas exist on how to proceed beyond helicity fractions
J.A. Aguilar, J. Bernabeu



$t\bar{t}\gamma$, $t\bar{t}Z$

LHC measurements of the rate of top pairs production in association with photons or Z-bosons:

$t t\gamma$

$\sigma = 2.0 \pm 0.5$ (stat.) ± 0.7 (syst.) ± 0.08 (lumi.) pb

(1/fb, ATLAS-CONF-2011-153)

ttZ

$\sigma < 0.71$ pb (95% C.L.)

(4.7/fb, ATLAS-CONF-2012-126)

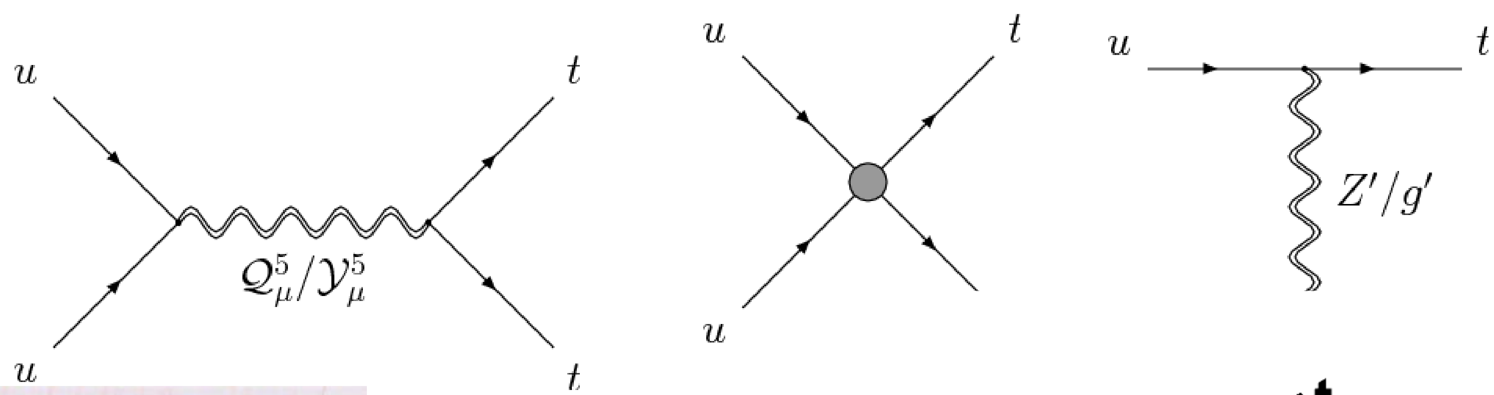
$s = 0.3\ ^{+0.14}_{-0.11}$ (stat.) $^{+0.04}_{-0.02}$ (syst.) $\rightarrow 3.66\ \sigma$ significance

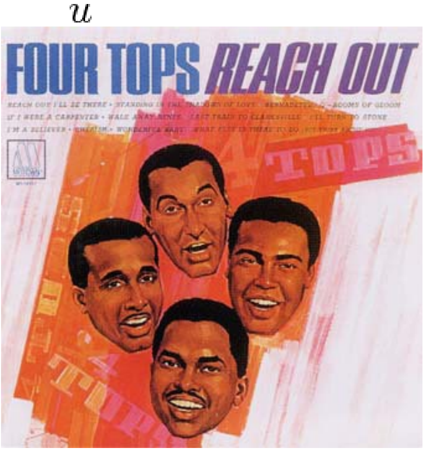
(5.0/fb, TOP-12-014-PAS)

Same sign top/4 top production

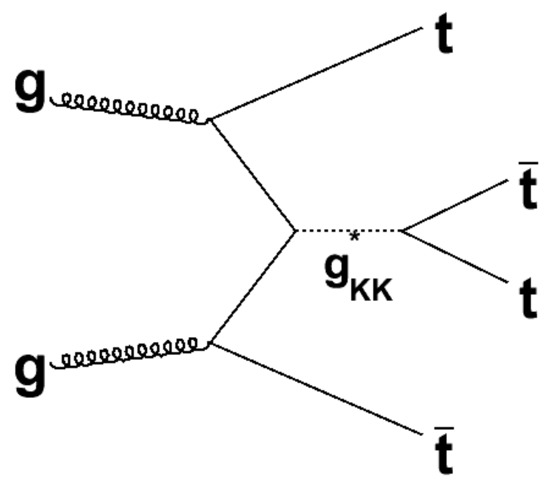
Same-sign top production (tt, tt)

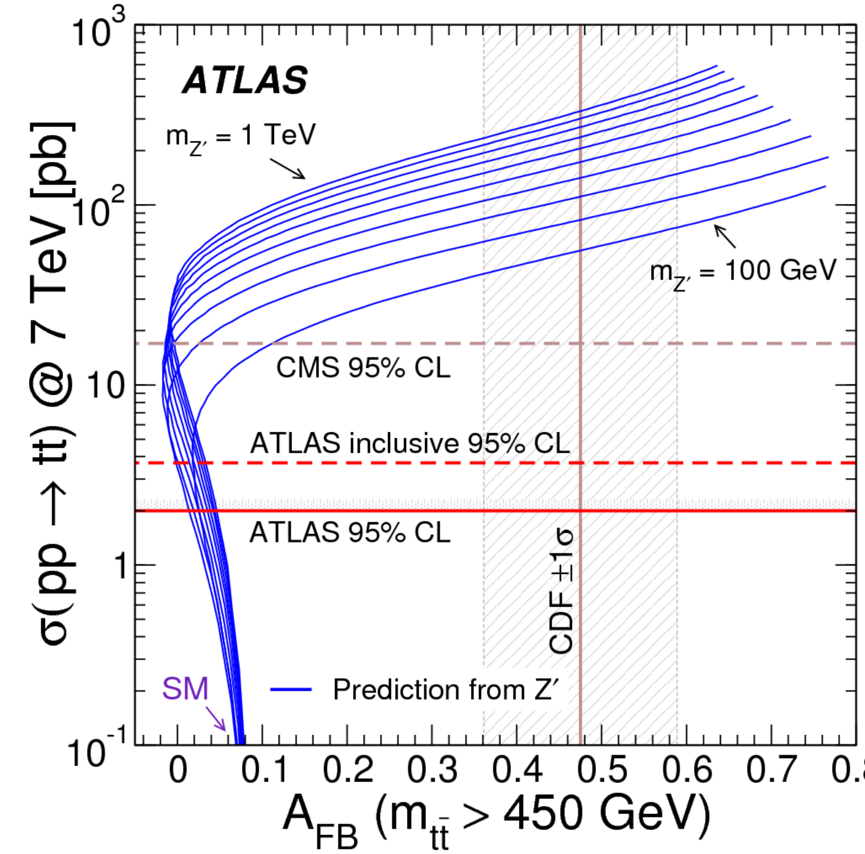
E. Berger et al, arXiv:1005.2622 [hep-ph]





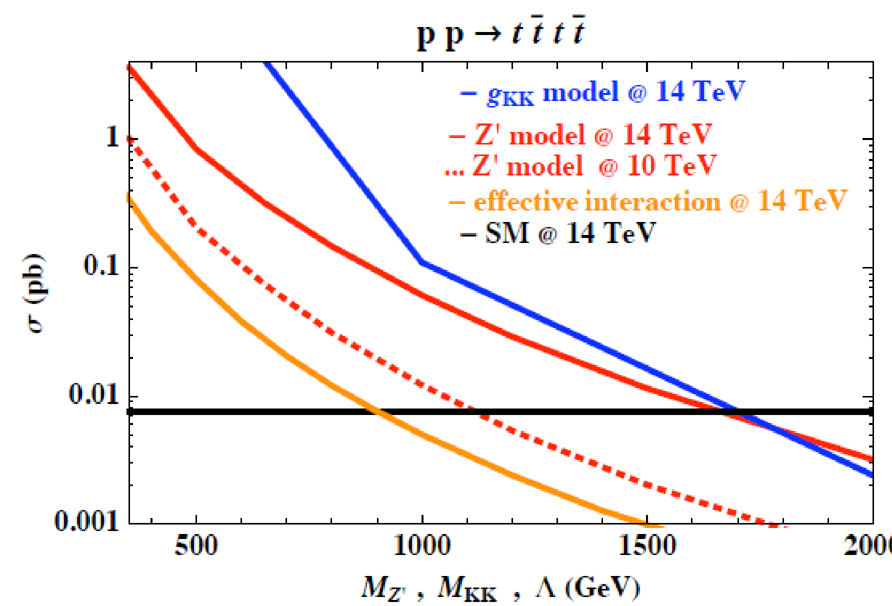
Four-top production





(fb-level in SM, possibly enhanced by tt → tt contact interactions, or top-philic resonances)

Pomarol/Serra, G. Servant, M.V., arXiv:1005.1229 [hep-ph]

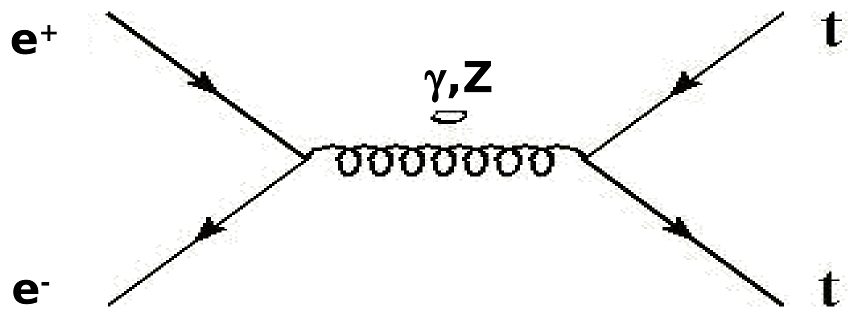


Limit derived from negative result of same-sign top search: s (tttt) < 1 pb.

>> SM rate, but strong enough to constrain BSM enhancement

Zhou, Whiteson, Tait, Phys.Rev. D85 (2012) 091501

Top quark structure at a future LC

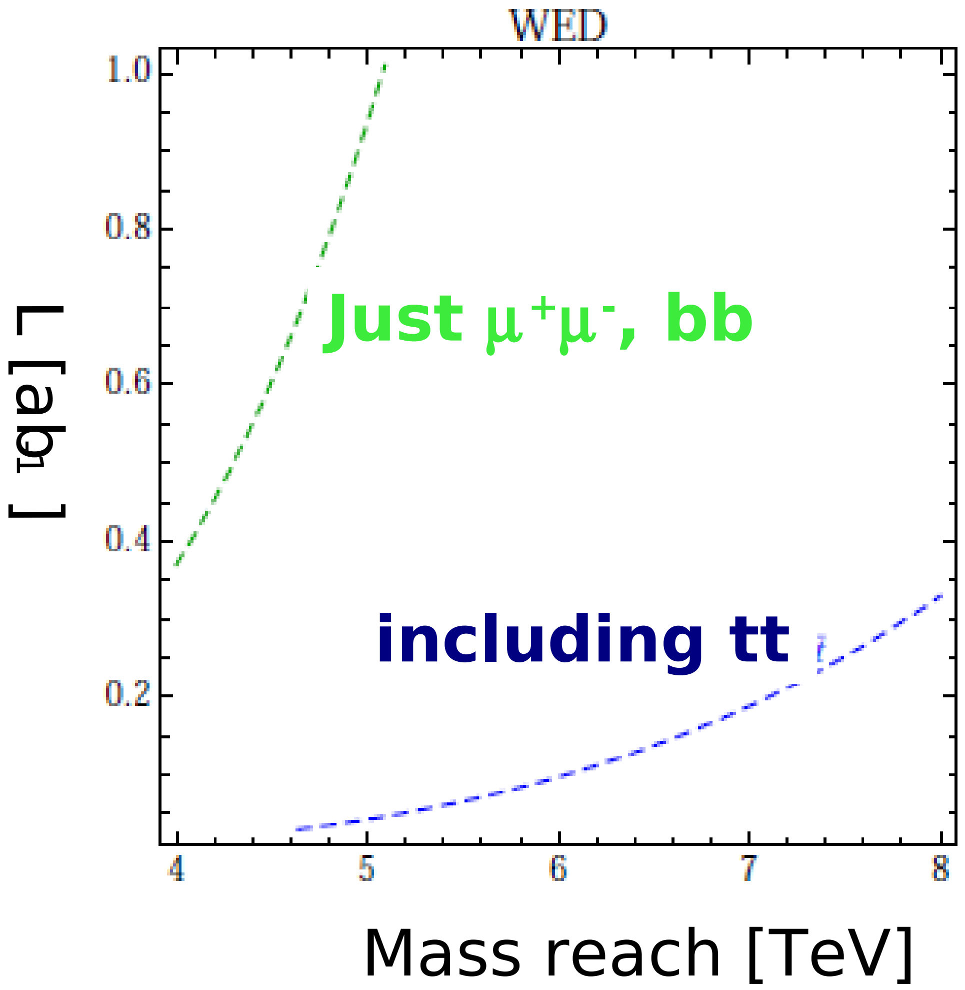


$t\bar{t}$ production at a LC:
σ~0.6 pb
at √s = 500 GeV
~0.2 pb
at √s = 1 TeV

Detailed study of tt production at LC may greatly enhance the sensitivity to BSM physics

Example: Warped Extra Dimensions at LC 3 TeV

F. Corradeschi, LCWS10, arXiv:1202.0660
M. Battaglia, LCWS11



Top quark couplings

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

Parton-level studies show how measurements on tt production at LC (σ, A_{FB}, A_{LR}, ...) constrains the form factors F

Form factor	SM value	LC prospects $\sqrt{s}$ = 500 GeV
F_{1V}^{Z}	1	1.9%
F_{1A}^{Z}	1	1.6%
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}_{t}$	0	1.1%
Re F_{2A}^{γ}	0	0.7%
Re d_t^{γ}	0	4%
Re F_{2A}^{Z}	0	0.8%
Re d_t^{Z}	0	5%
Im F_{2A}^{γ}	0	0.8%
Im F_{2A}^{Z}	0	1.0%

TESLA TDR

to be explored in complete studies with detailed simulation

The program

Find enough observables to constrain the most general $t\bar{t}$ γ/Z vertex

- using the control over the polarization that an LC can offer
- using different center-of-mass energy
- ...

Many ideas have been around for a long time. For polarization studies, for example, see Godbole et al.

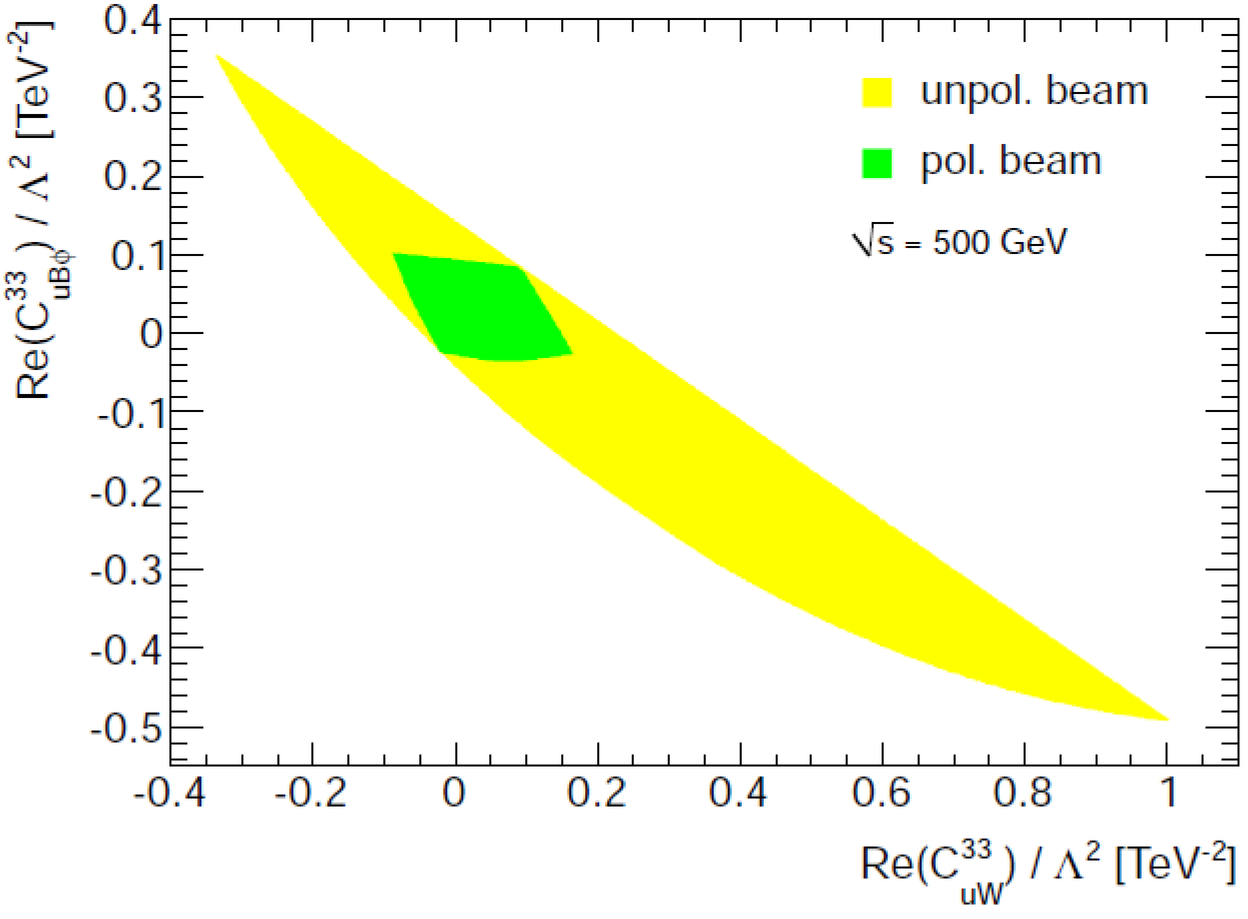
Check with theorists that they can be reliably predicted

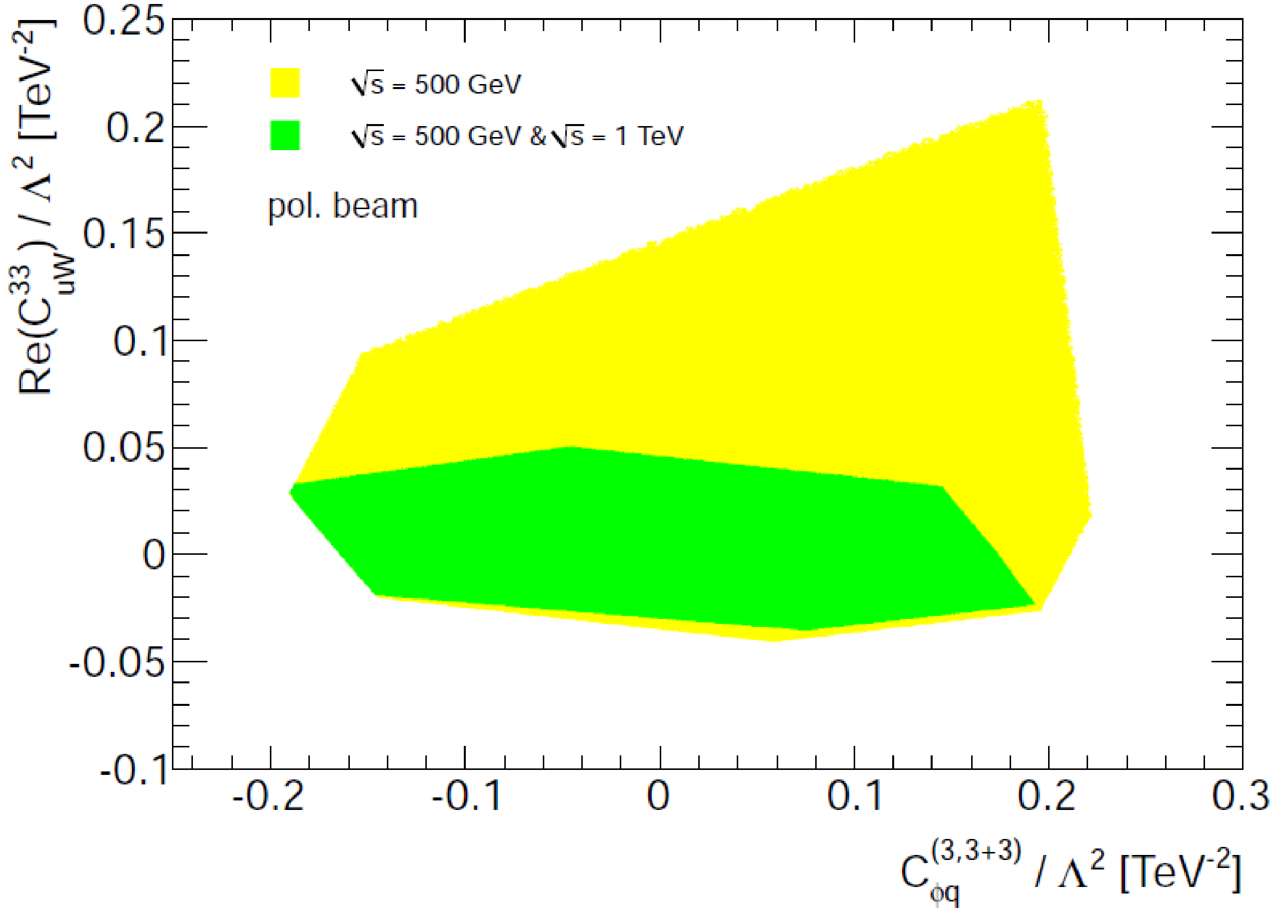
....

Ensure that they are experimentally well under control

- $t\bar{t}$ events are a bit more complex than $\mu^+\mu^-$ or $b\bar{b}$ events
- we don't want to just count them; we need to be very sure that we can reliably reconstruct angular distributions
- let's not take for granted that the statistical error dominates

Disentangling γ and Z





Constrain and disentangle all operators (anomalous couplings) using:
- polarization to distinguish photon and Z contributions
- center-of-mass energy to distinguish vector (γ^μ) and tensor ($\sigma^{\mu\nu}$) terms

CAVEATs:

Simplified setup, only two operator strengths varied at any one time

Experimental uncertainties based on preliminary estimates

From: J.A. Aguilar et al., arXiv:1206.1033

Full simulation

Fully hadronic tt events are a benchmark channel in SiD and ILD LOI

Basic selection:

- visible energy
- number of (charged) particles
- y_{min} (6 jets)
- W-boson mass
- b-tagging

Efficiency: 51%

Purity: 69 %

Kinematic fit:

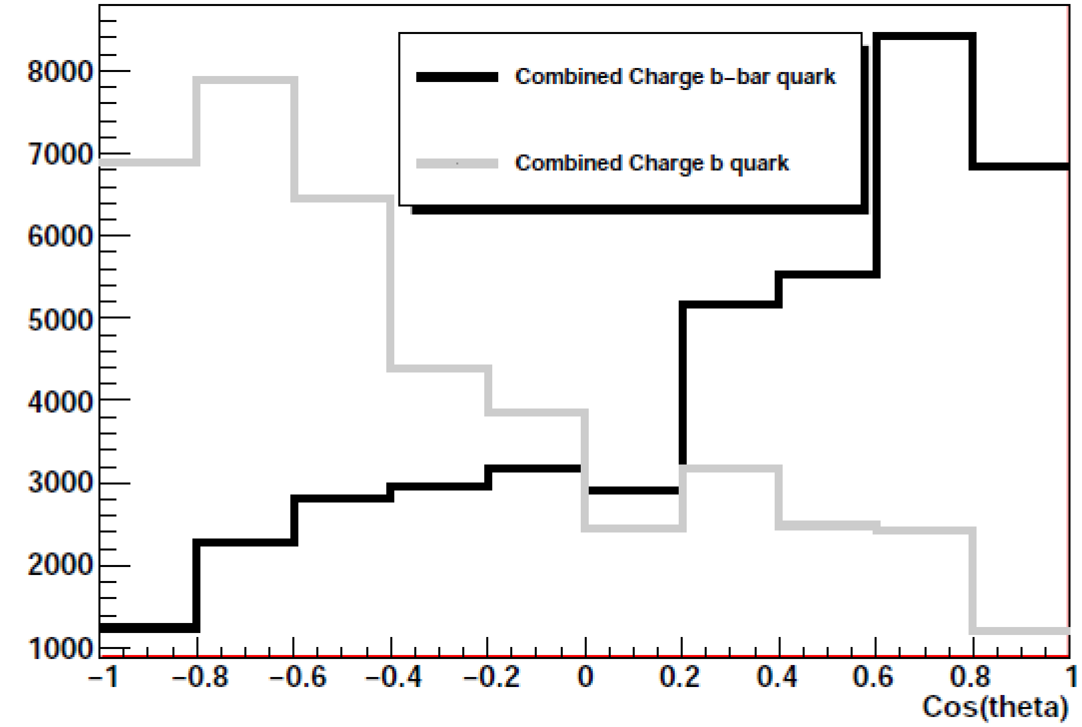
- $m_t = m_t$
- $m_W = 80.4$ GeV
- $E_{vis} = 500$ GeV
- $P_x = P_y = P_z = 0$

Efficiency: 31%

Purity: 86%

Excellent flavour tagging, vertex charge and jet charge determination allow to reconstruct the A_{FB}^{tt} (and that of b-quarks in tt events) to ~5%

Lepton + jets final state offers better distinction of t and $\bar{t}$ directions

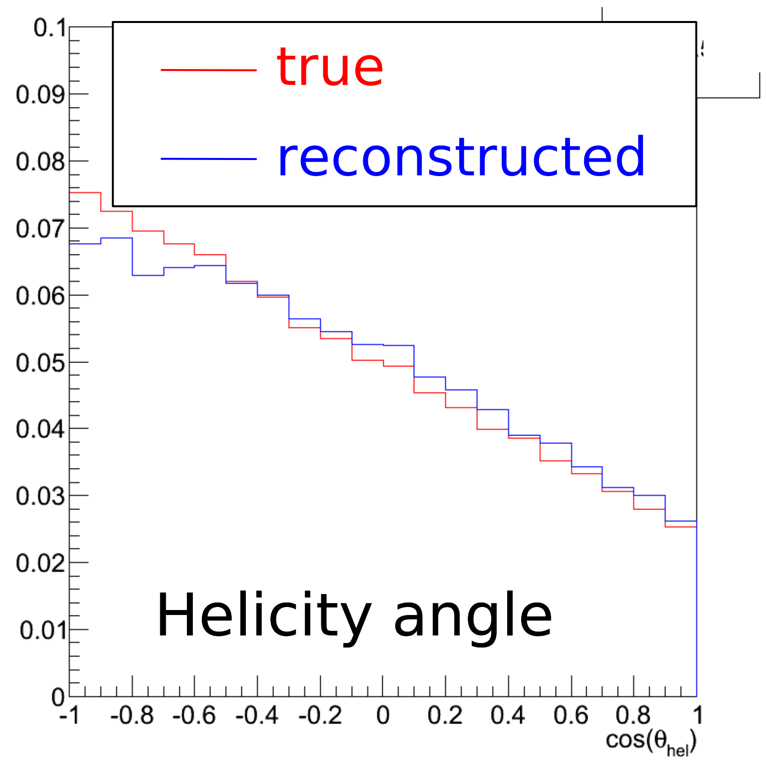


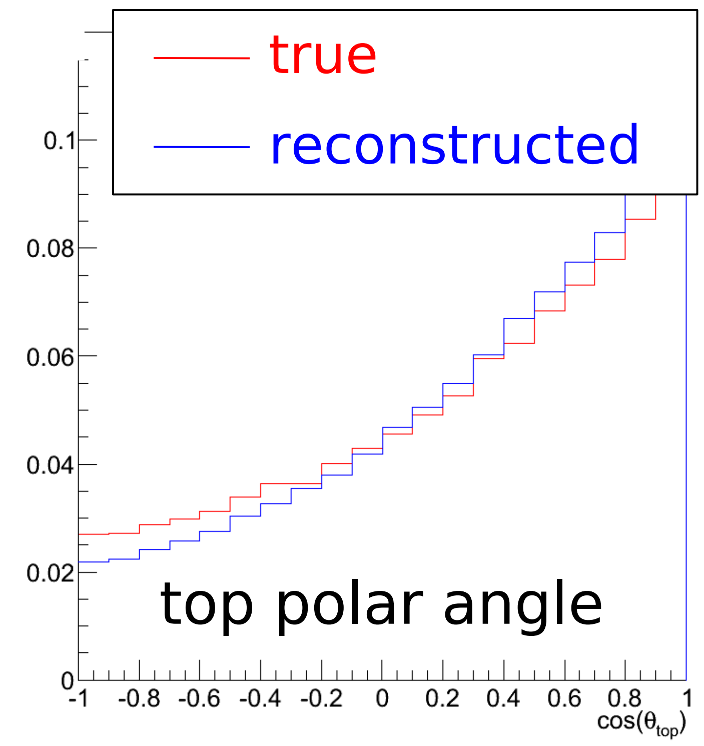
Work in progress

Revisiting the parton-level study for the Detailed Baseline Design

LAL/IFIC preliminary results
The impact of experimental errors
See talk by Jeremy Rouene in this session

Cross-section and helicity angle distiributions for two beam polarizations are sufficient to constrain 4 form factors

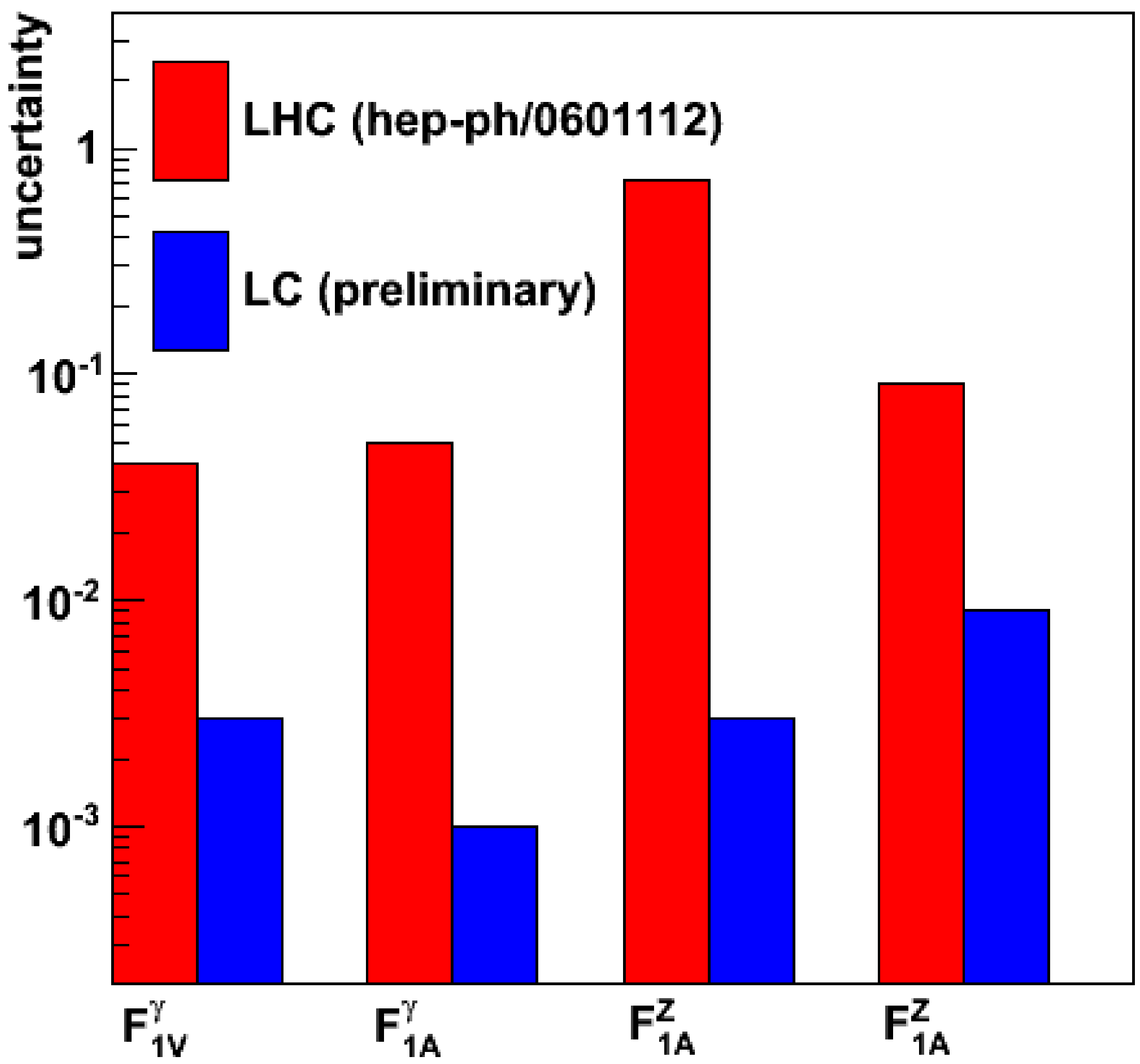




Full simulation in ILD concept to understand experimental challenges and estimate systematic errors. Preliminary: migrations due to ambiguities in tt reconstruction can be controlled at an LC

Work in progress

Revisiting the parton-level study for the Detailed Baseline Design



Assumptions:

LC: $\sqrt{s}$ = 500 GeV, L = 500/fb

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

LHC: 14 TeV, 300/fb

LAL/IFIC preliminary results

Extension to other parameters under way

top polar angle

Summary

The LHC is rapidly improving its characterization of top quark production and decay

IFIC and LAL are taking old TESLA and Snowmass studies to full simulation level

Discovering significant experimental challenges AND finding ways to deal with them

Confirmed so far:

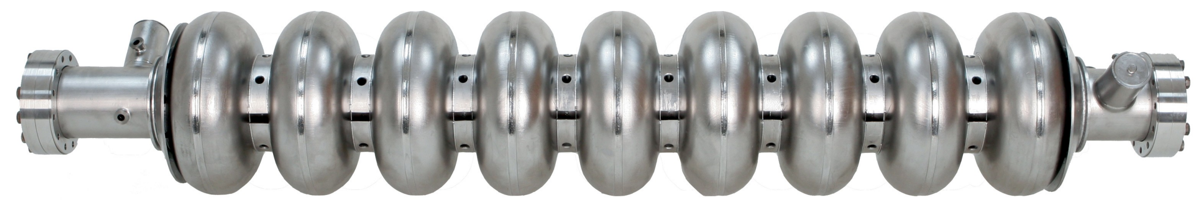
- that polarization allows to disentangle γ and Z
- that excellent precision can be achieved

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

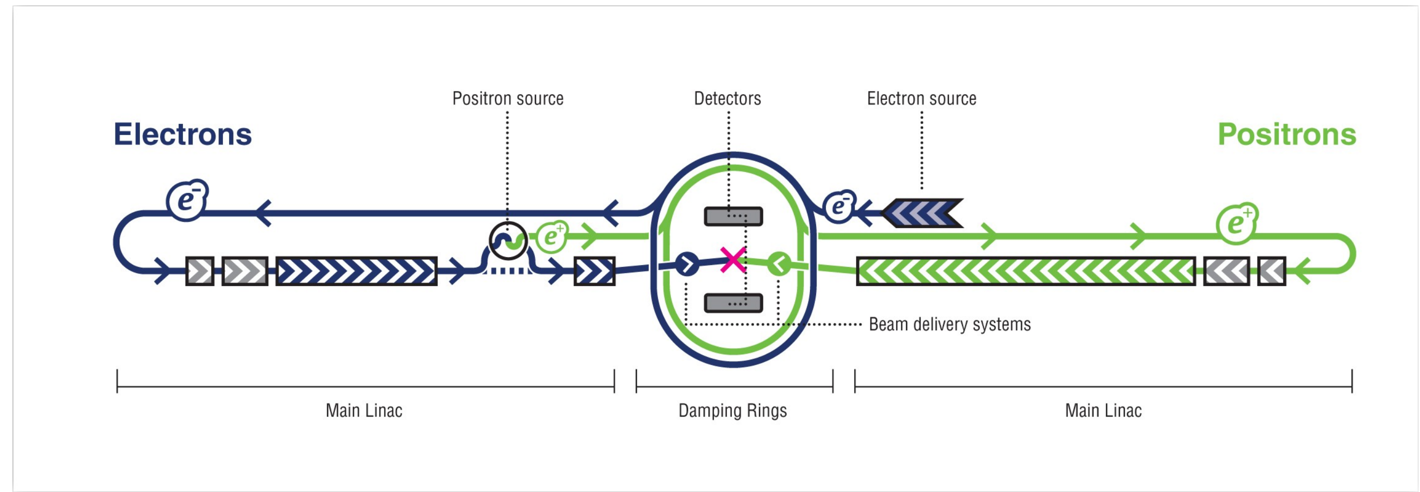
LHC and ILC are complementary (with some overlap). The ILC precision for the tt g/Z vertex is unrivaled.

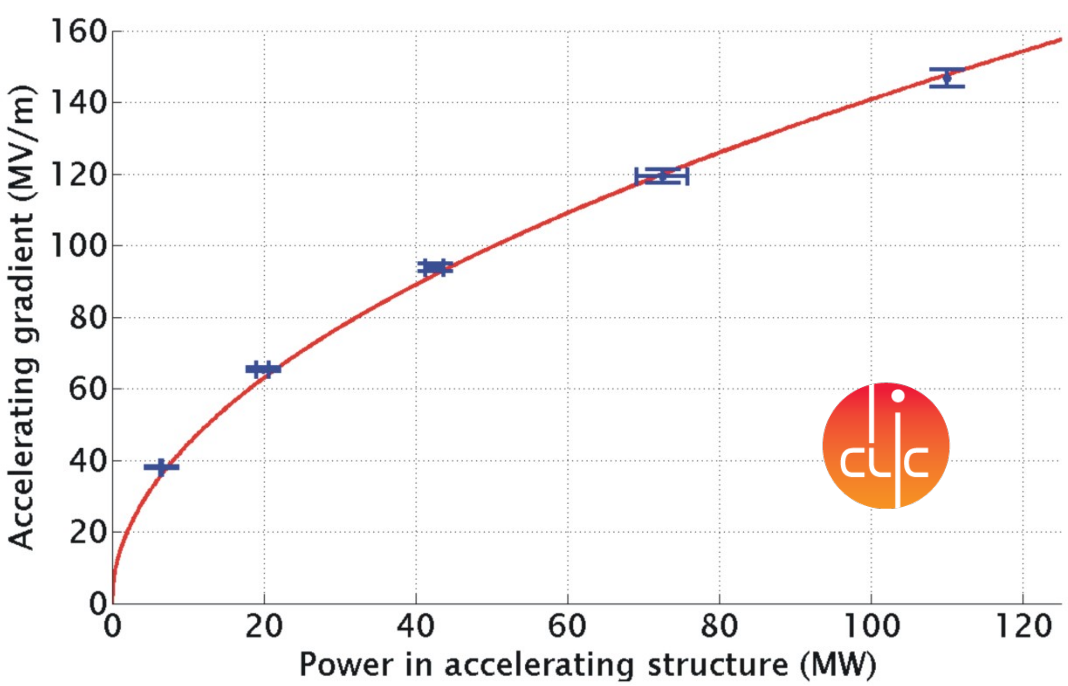
More results in Jeremy Rouene's talk in a minute!

Future e^+e^- colliders



- Superconducting RF cavities are in the industrialization phase and routinely reach gradients well over 30 MV/m. ILC is shovel-ready.
- Still higher gradient (~100 MV/m) can be achieved using drive beam concept. CLIC can open up the multi-TeV regime.





R&D around the globe
Non-exhaustive list of test facilities:
ATF@KEK, nm size, low emittance beams
CESR/IT@Cornell (electron cloud)
CTF3@CERN, drive beam
XFEL@DESY, cavities

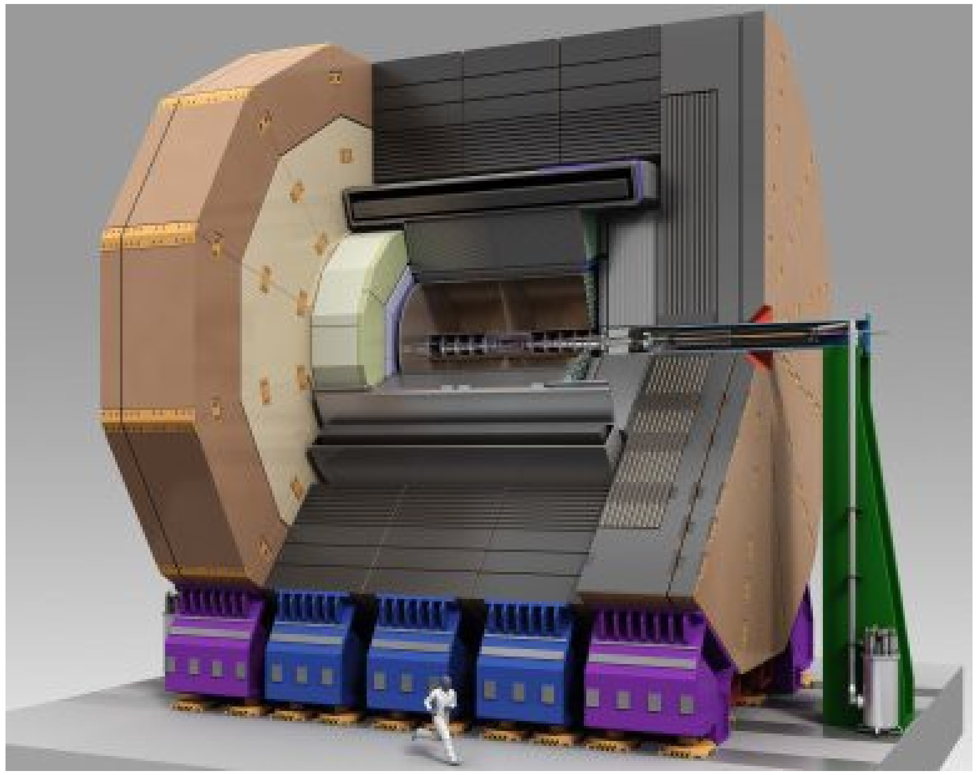
LC technology exists for a low-energy machine (√s ~ 250-500 GeV)
R&D is ongoing for √s ~ 1-3 TeV

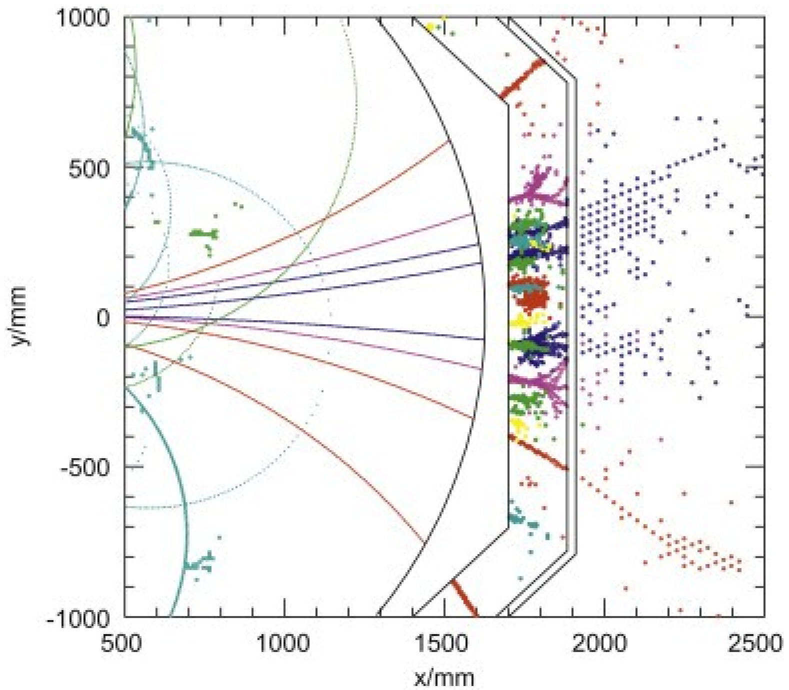
Contributions on 07/07 in TR14:
Steinar Stapnes, the CLIC project
Phil Burrows, beam feedback
Jenny List , polarimetry
Tony Hartin, spin tracking

LC detectors

LC environment and detector R&D allow for a big leap in performance

- Signal and bkg x-sections of similar magnitude
- Well-defined initial state (CM energy, polarization)
- Triggerless read-out
- Background confined to innermost detectors





Particle Flow: highly granular calorimetry inside a large 3.5-5 Tesla solenoid allows to follow every single visible particle produced in the collisions from the cradle to the grave → best possible estimate of the jet energy: $\Delta E/E \sim 3\text{-}5\%$

Transparent and precise tracking/vertexing:

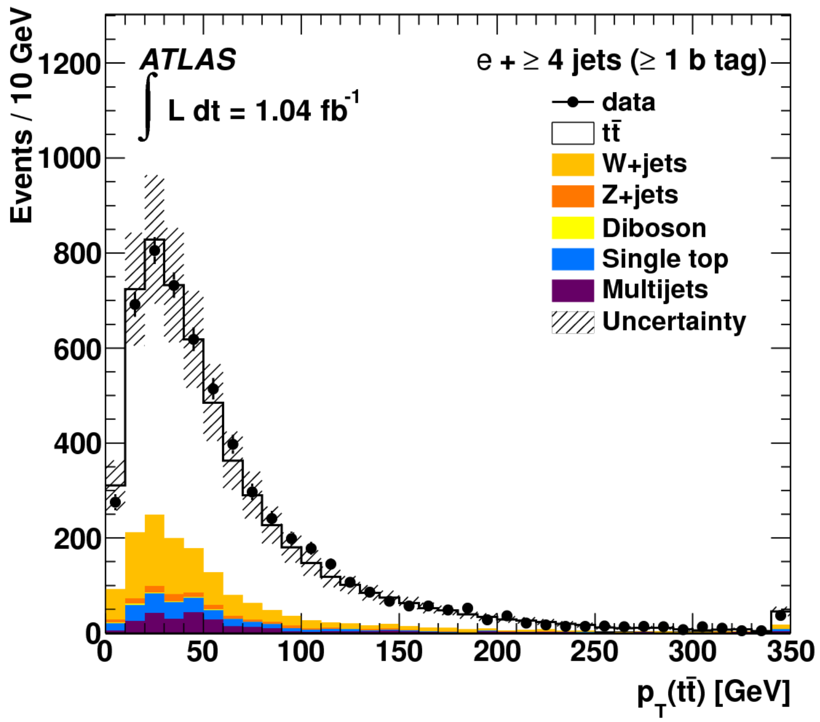
$\Delta(1/p_T) \sim 10^{-5}\ \text{GeV}^{-1}$

$\Delta(d_0) \sim 5 \oplus 10\text{-}20 / (p \sin^{3/2} \theta)$

Detailed Geant4 model and sophisticated reconstruction software allow realistic estimates of performance

Contributions on 07/07 in TR13:
Tomohiko Tanabe on ILD
Andy White on SiD
Frank Simon on CLIC detectors

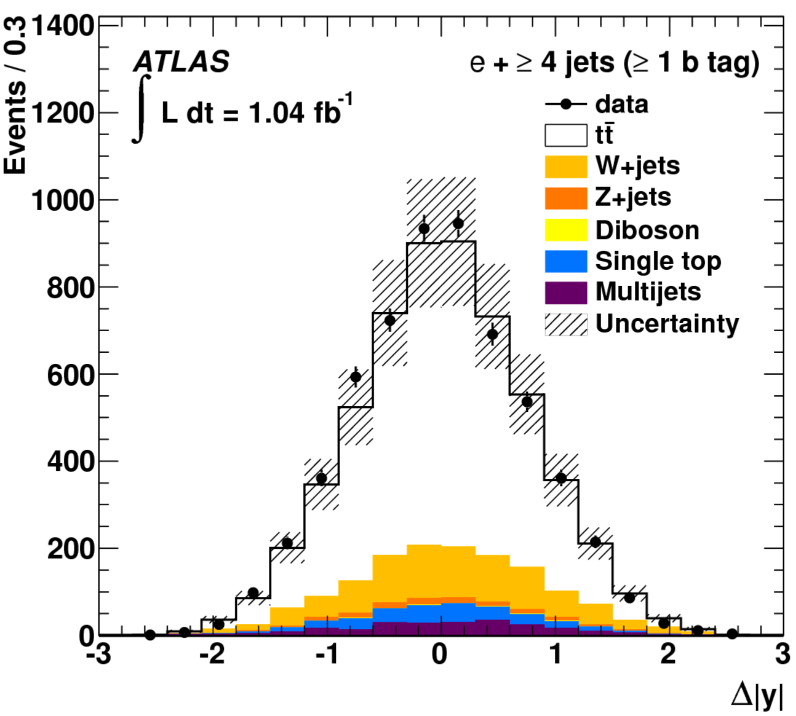
Charge asymmetry

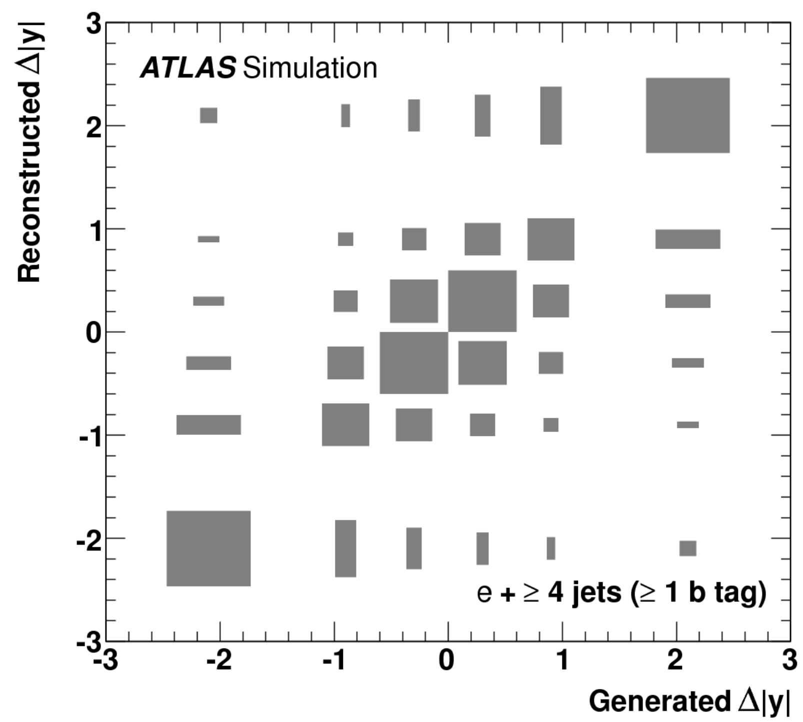


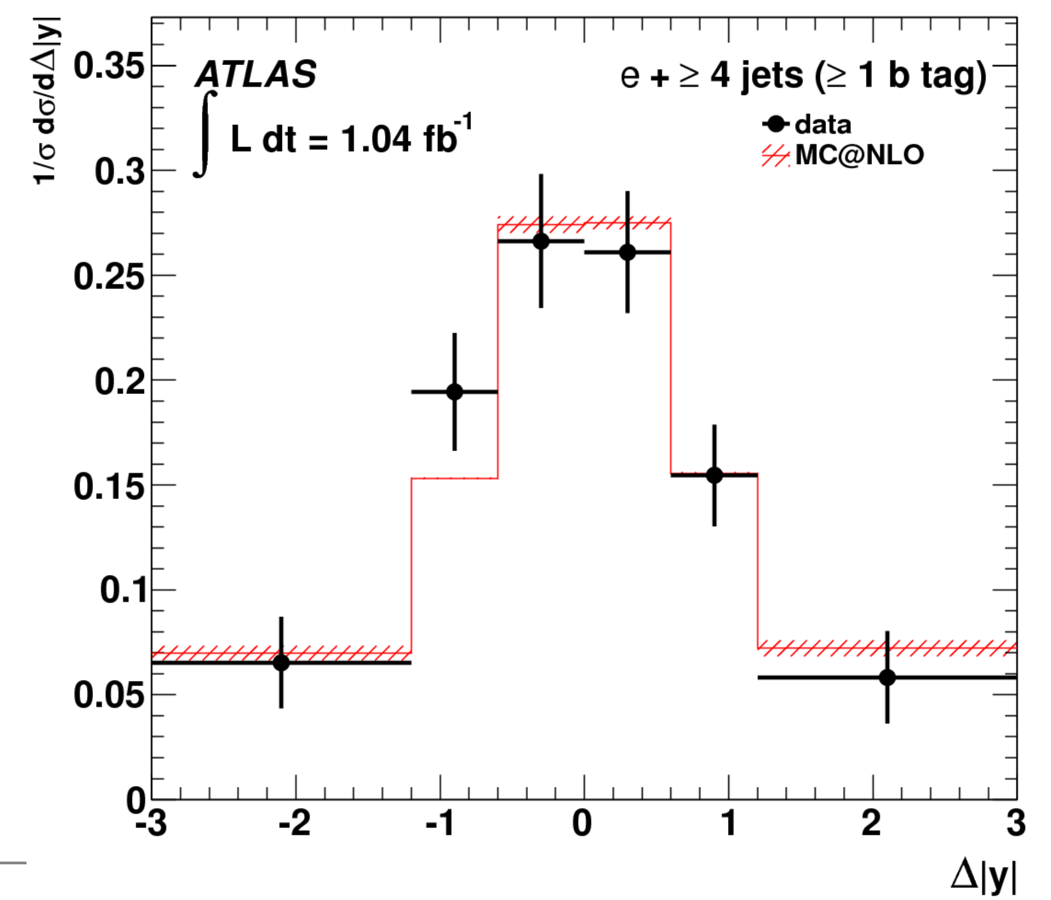
Clean tt selection, mostly close to threshold

No attempt to enrich qq initiated production beyond binning in m_{tt}

Unfolding

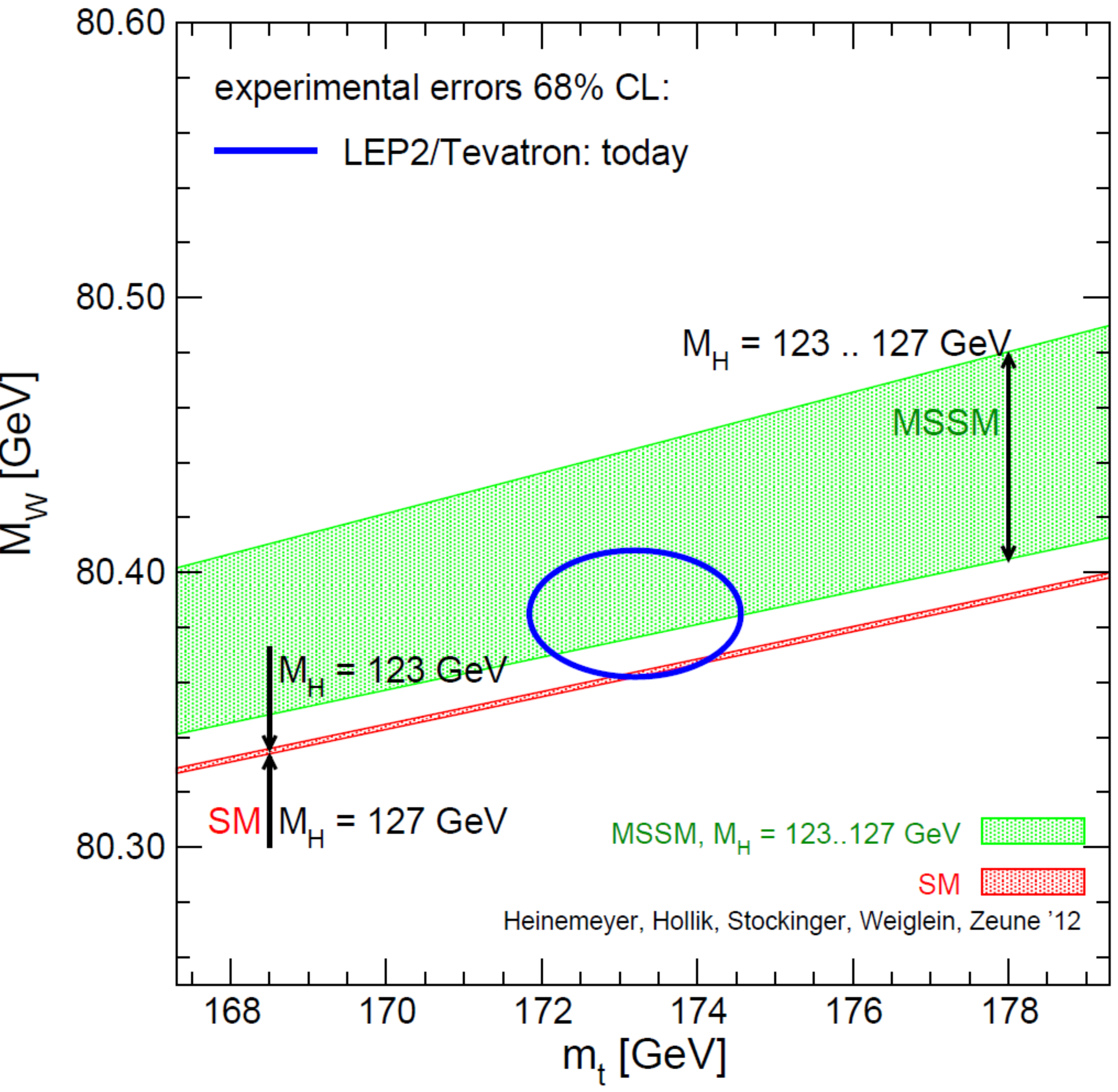


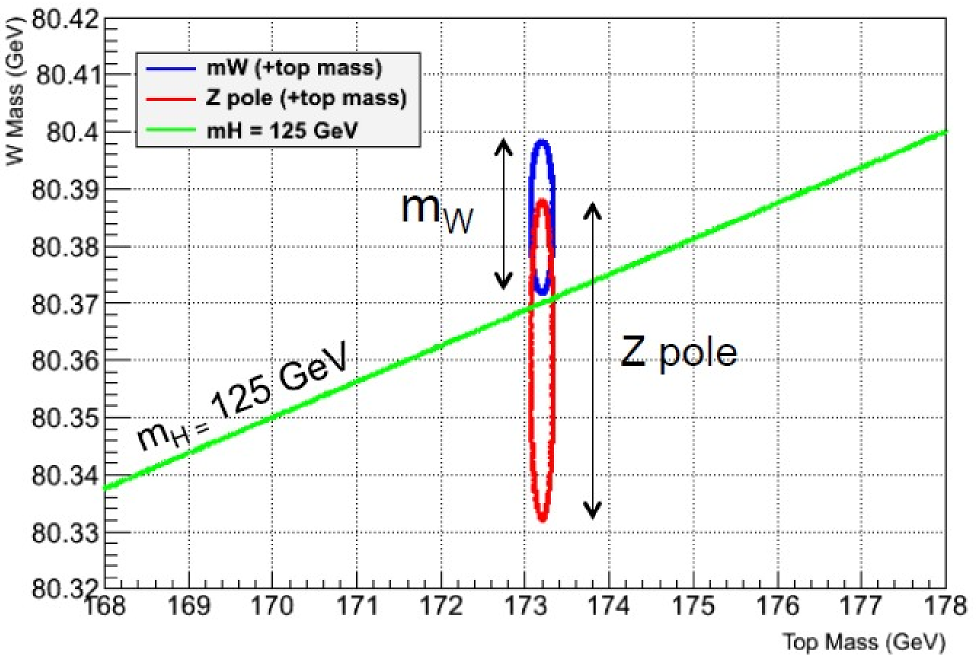


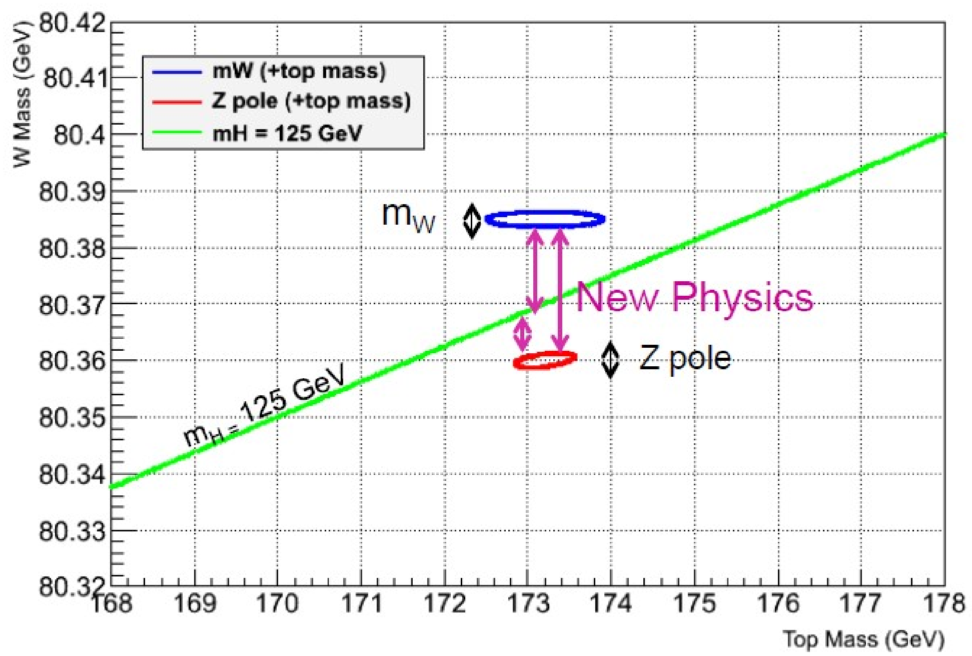


How important is the top mass measurement?

[Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '12]



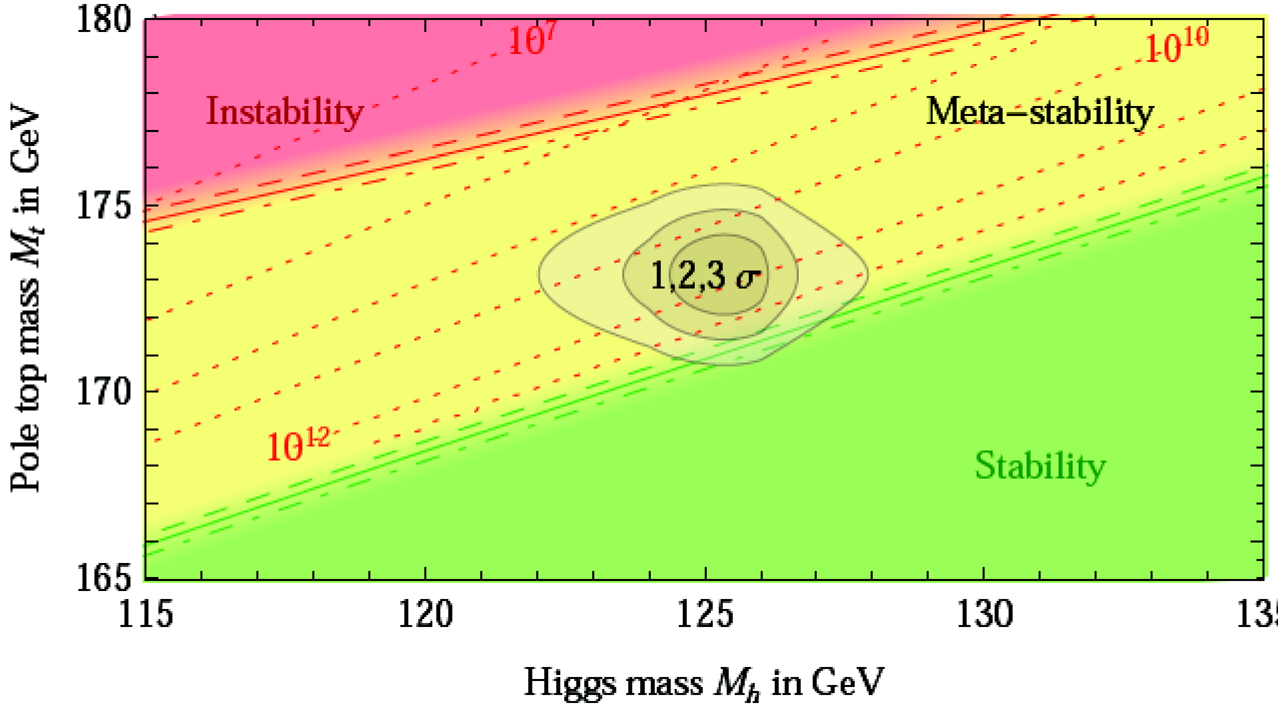


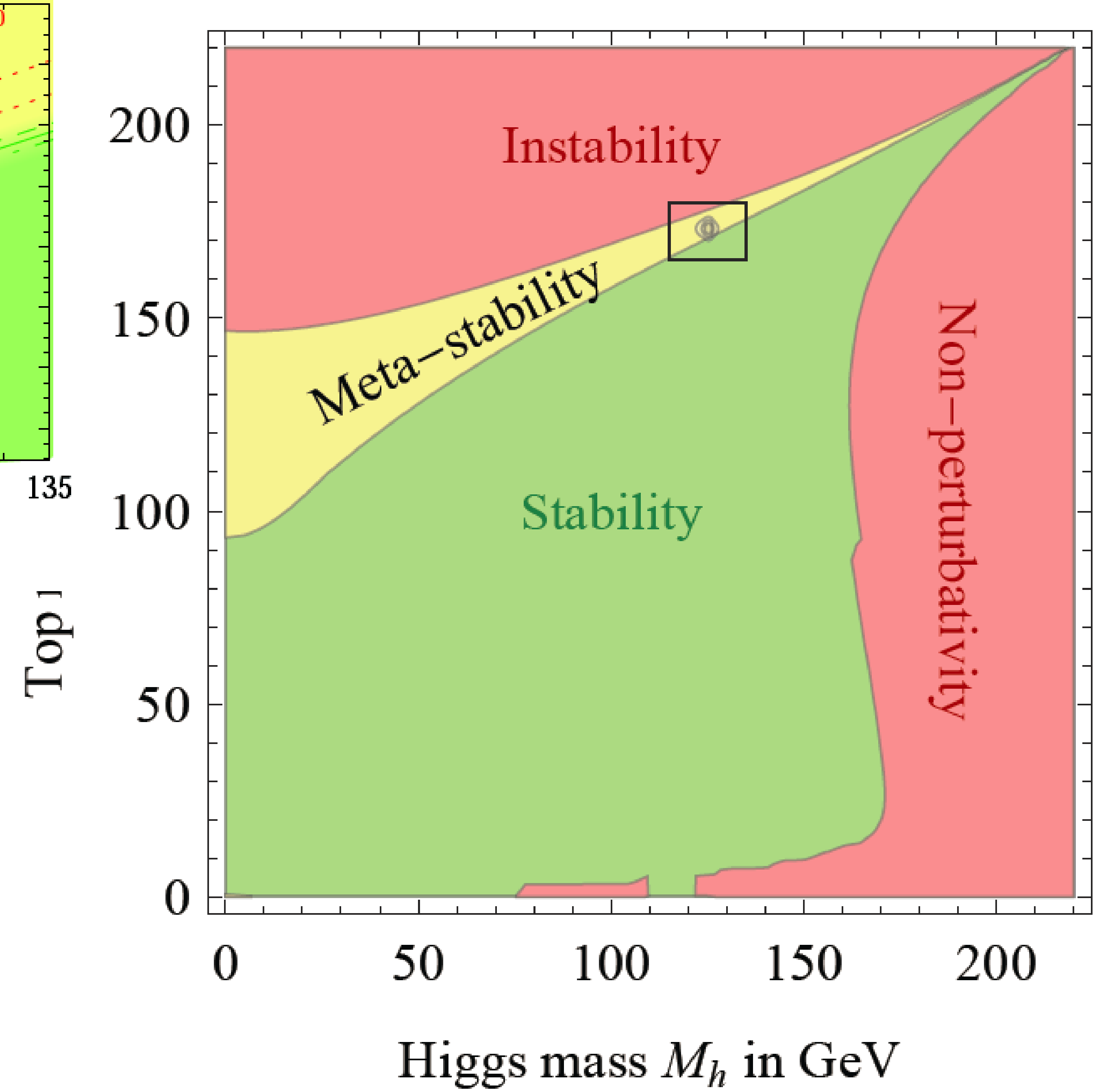


CMS-NOTE-2012/003; must be accompanied by better m_W measurement

How important is the top mass measurement?

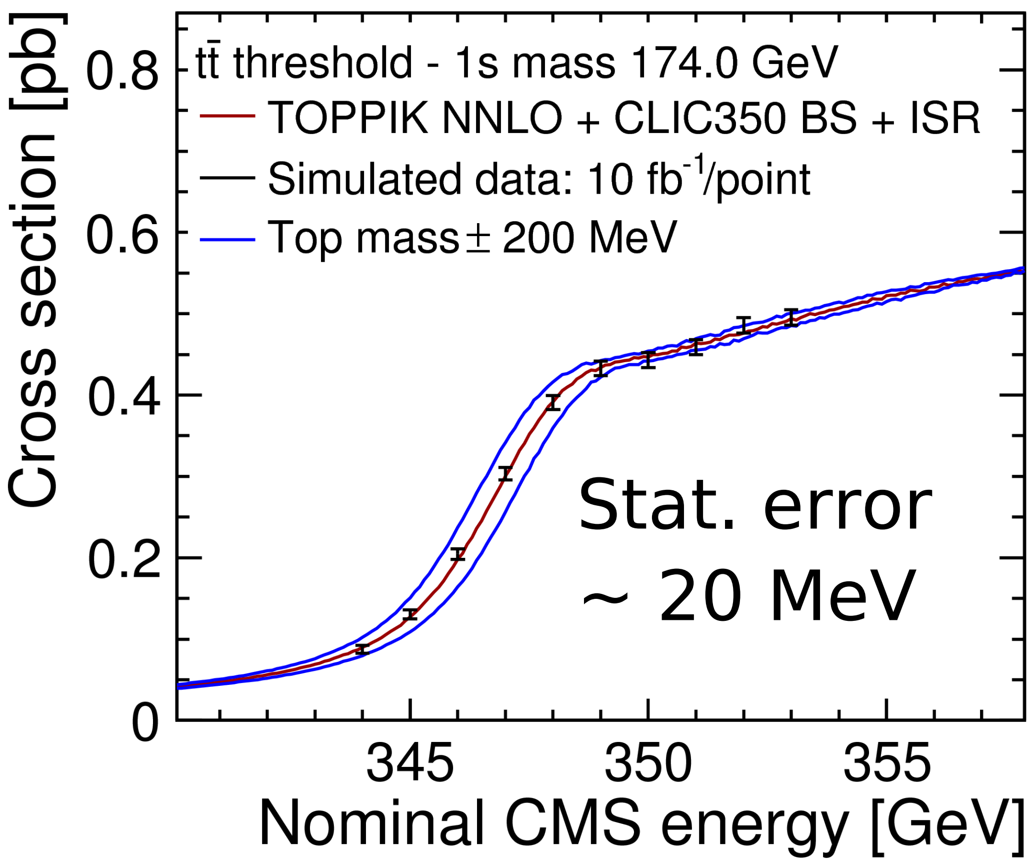
[Degrassi, Di Vita, Elias-Miro,Spinosa,Giudici ’12,
Alekhin, Djouadi, Moch ’12]

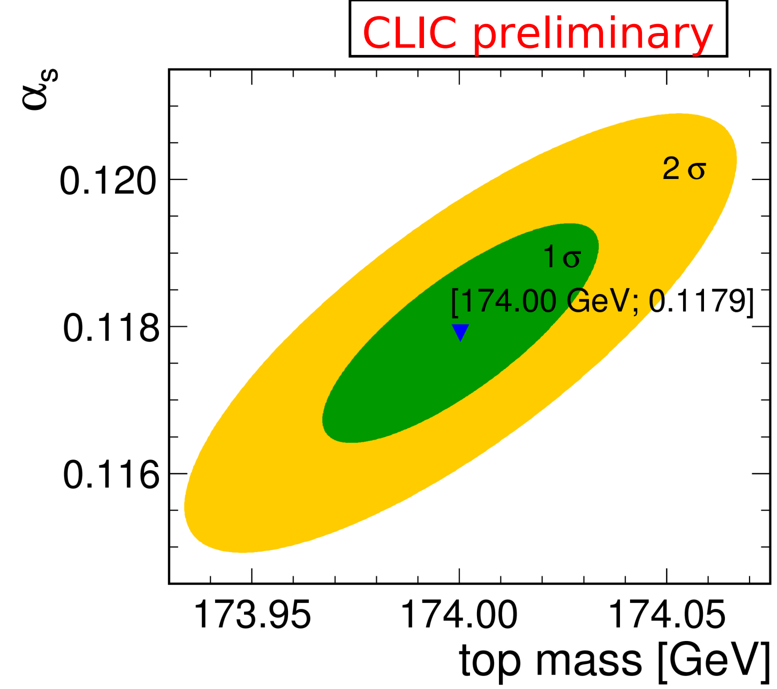


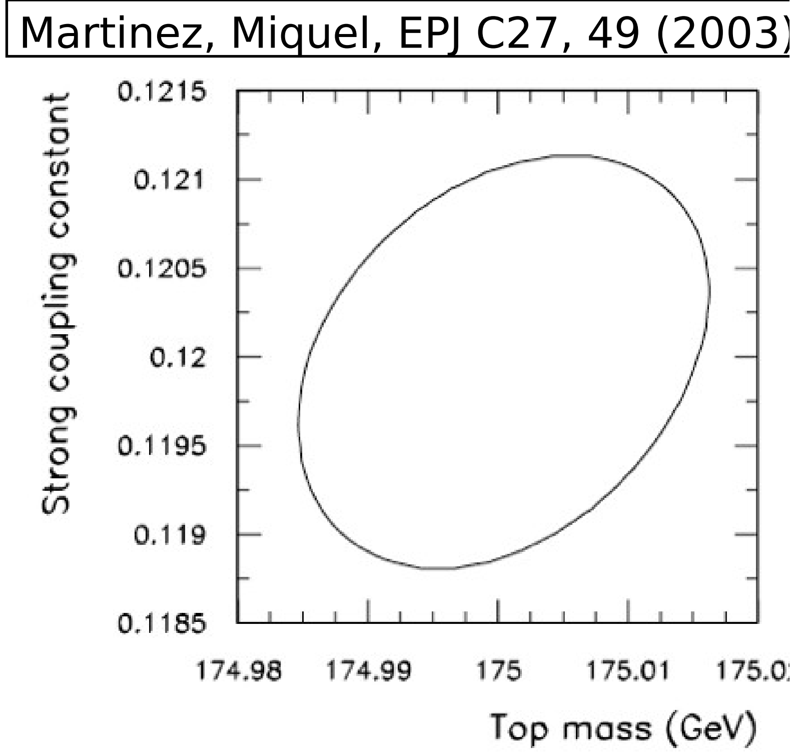


The dominant uncertainty is experimental […] mostly from the measurement of m_t.
[…] will remain the largest source of uncertainty [at the LHC]. If no new physics other than the Higgs boson is discovered at the LHC [this] provides a valid motivation for improved top quark mass measurements, possibly at a linear collider.

Top quark mass







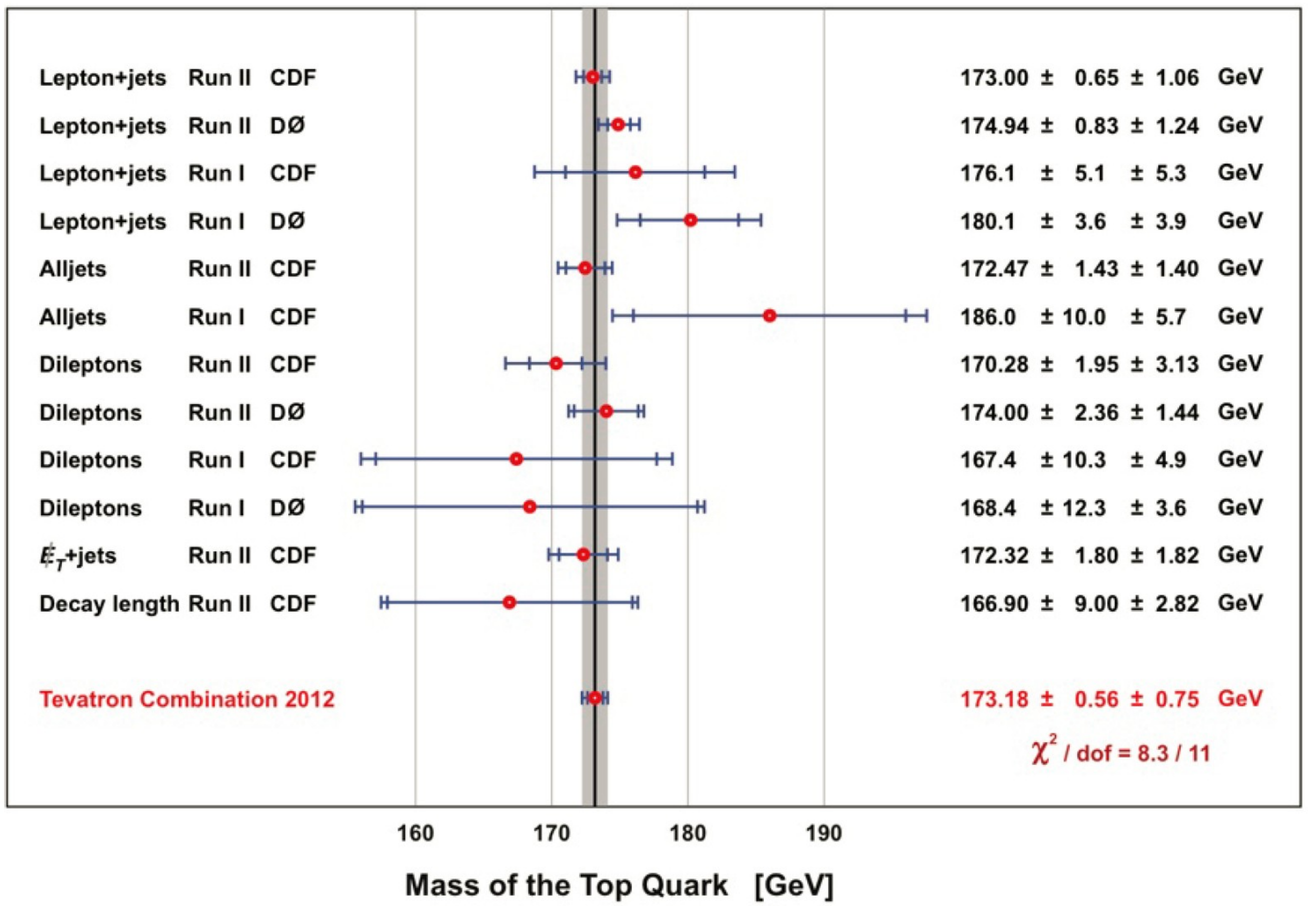
New results corroborate old studies and extend these findings to a machine with a very different technology

Measurement in the continuum ($\sqrt{s}$ = 500 GeV) is possible with a statistical error ~ 50-100 MeV (ILD/SiD, CLIC CDR). This measurement is affected by the same type of systematic uncertainties as Tevatron/LHC

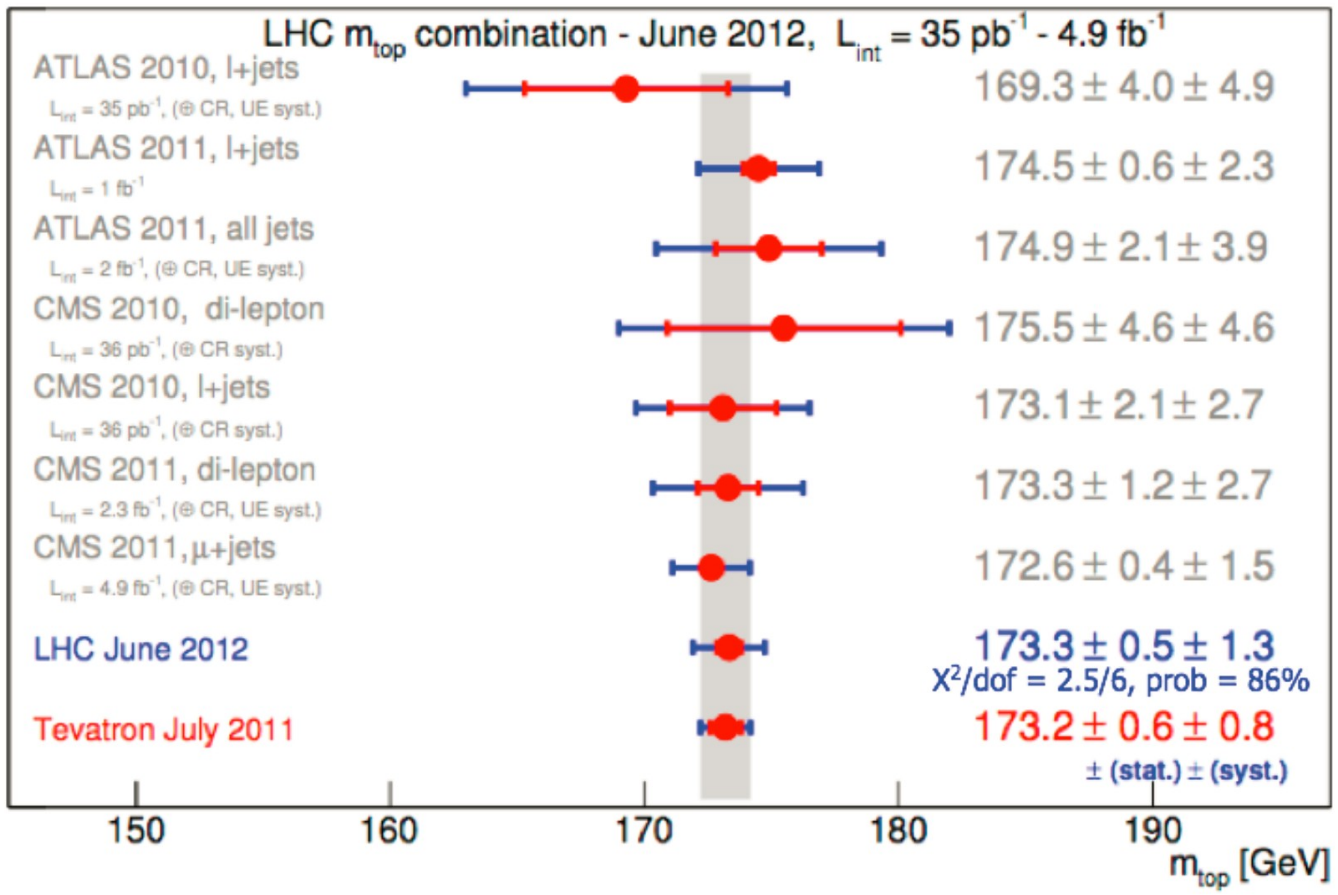
A precise measurement O(100 MeV) with a rigorous interpretation is achievable at a low energy linear collider

Experimental status – Top-quark mass

Tevatron



LHC



Top-quark mass measured to high accuracy

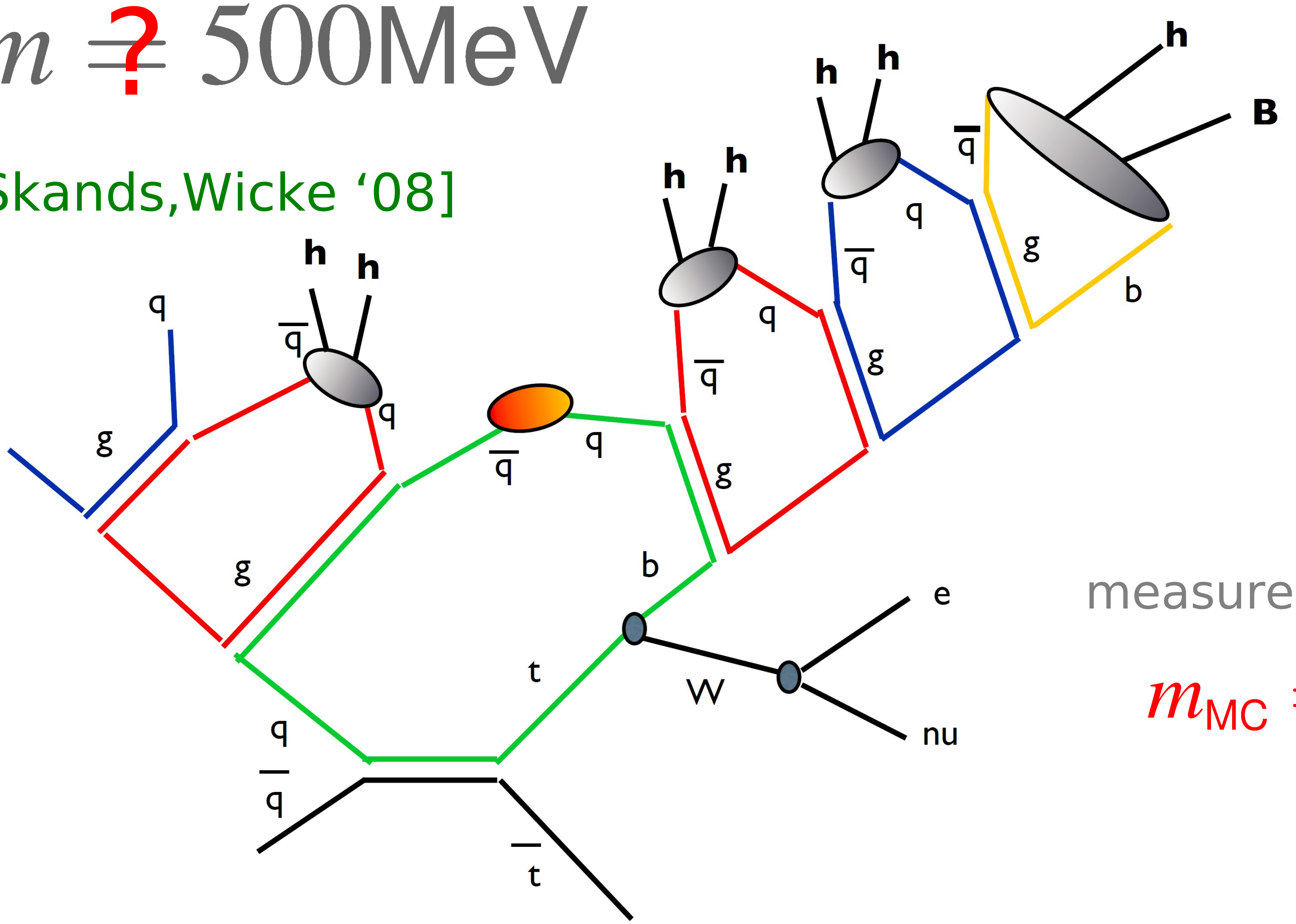
How well do we know the top-quark mass ?

Color reconnection:

$\Delta m \overset{?}{=} 500\text{MeV}$

[Skands,Wicke '08]

[Mangano, Top workshop, July 2012, CERN]



measured mass ←→ pole mass:

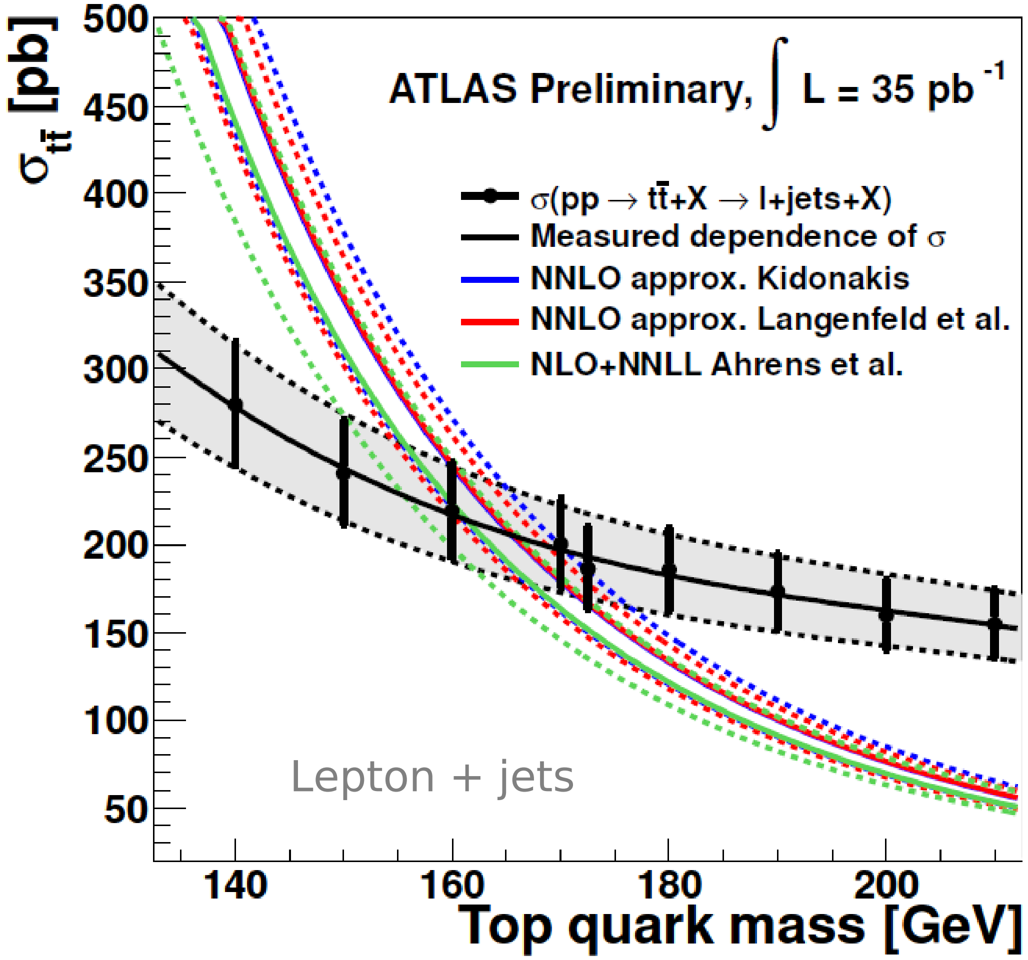
$$m_{\text{MC}} = m_{\text{Pole}}\,(1 \pm \Delta)$$

$$\Delta = \begin{cases} \frac{\Lambda}{m} \approx 0.13\% \\ \frac{\Gamma}{m} \approx 0.8\% \\ \frac{\alpha_s}{\pi} \approx 3.7\% \end{cases}$$

- Renormalization scheme not fixed (only LO theory)
- Pole mass intrinsically uncertain → Λ-QCD
- Color reconnection

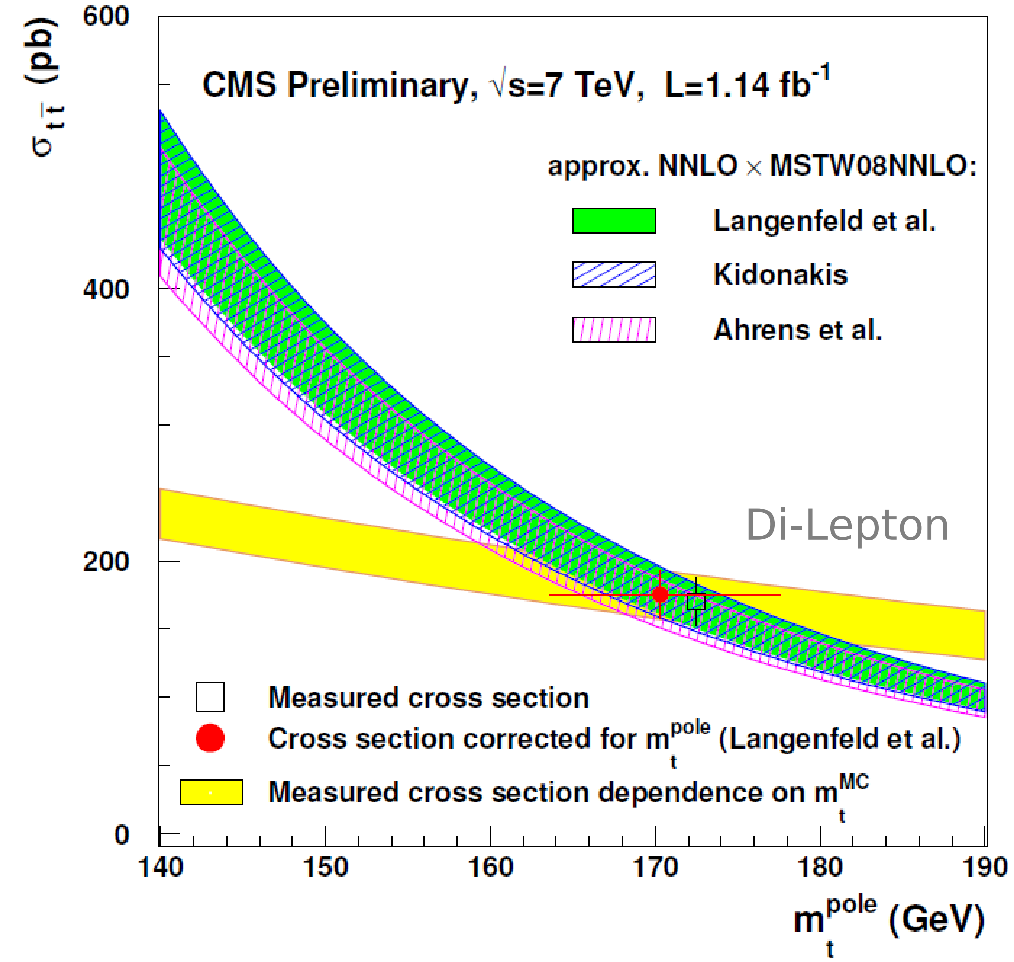
Recent measurements

ATLAS-CONF-2011-054, 35 1/pb



Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV
Langenfeld et al.	$166.4^{+7.8}_{-7.3}$
Kidonakis	$166.2^{+7.8}_{-7.4}$

CMS-PAS-TOP-11-008, 1.1 1/fb



Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al.	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis	$170.0^{+7.6}_{-7.1}$	–

Pair production cross-section measurement at the LHC yields a top quark mass determination

Rigorous interpretation possible, but the precision of this procedure seems to be limited:

$$\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \approx 5\,\frac{\Delta m_t}{m_t}$$

Alternatives at the LHC

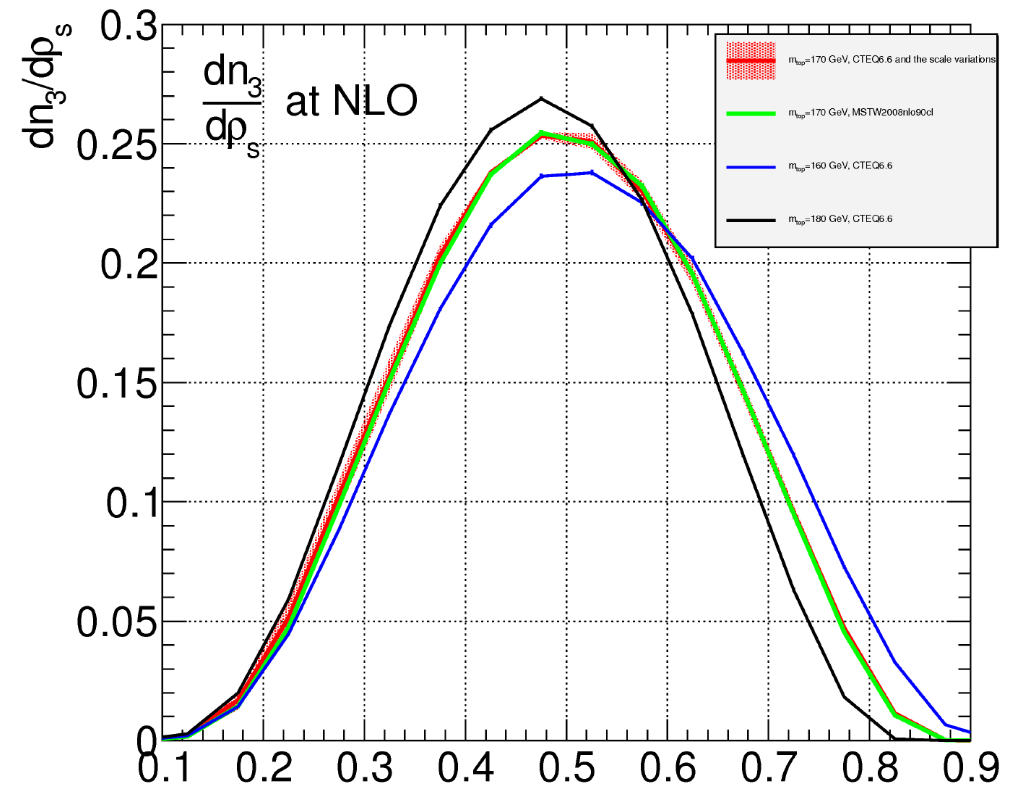
[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

To enhance mass sensitivity study:

$$\frac{dn_3}{d\rho_s}(m_{\text{Pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{Jet}}} \frac{d\sigma_{t\bar{t}+1\text{Jet}}}{d\rho_s}(m_{\text{Pole}})$$

with $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{Jet}}}}, \; m_0 = O(m)$

"1 - Distance from threshold"



	Source of uncertainty	Impact on the top quark mass
Theoretical uncertainties	μ variations	~ 0.4 GeV
	PDF choice	~ 0.2 GeV
Experimental uncertainties	MC comparison	~ 0.4 ± 0.3 GeV
	JES	~ 0.8 GeV
	Statistics (5 fb-1)	~ 1.2 GeV

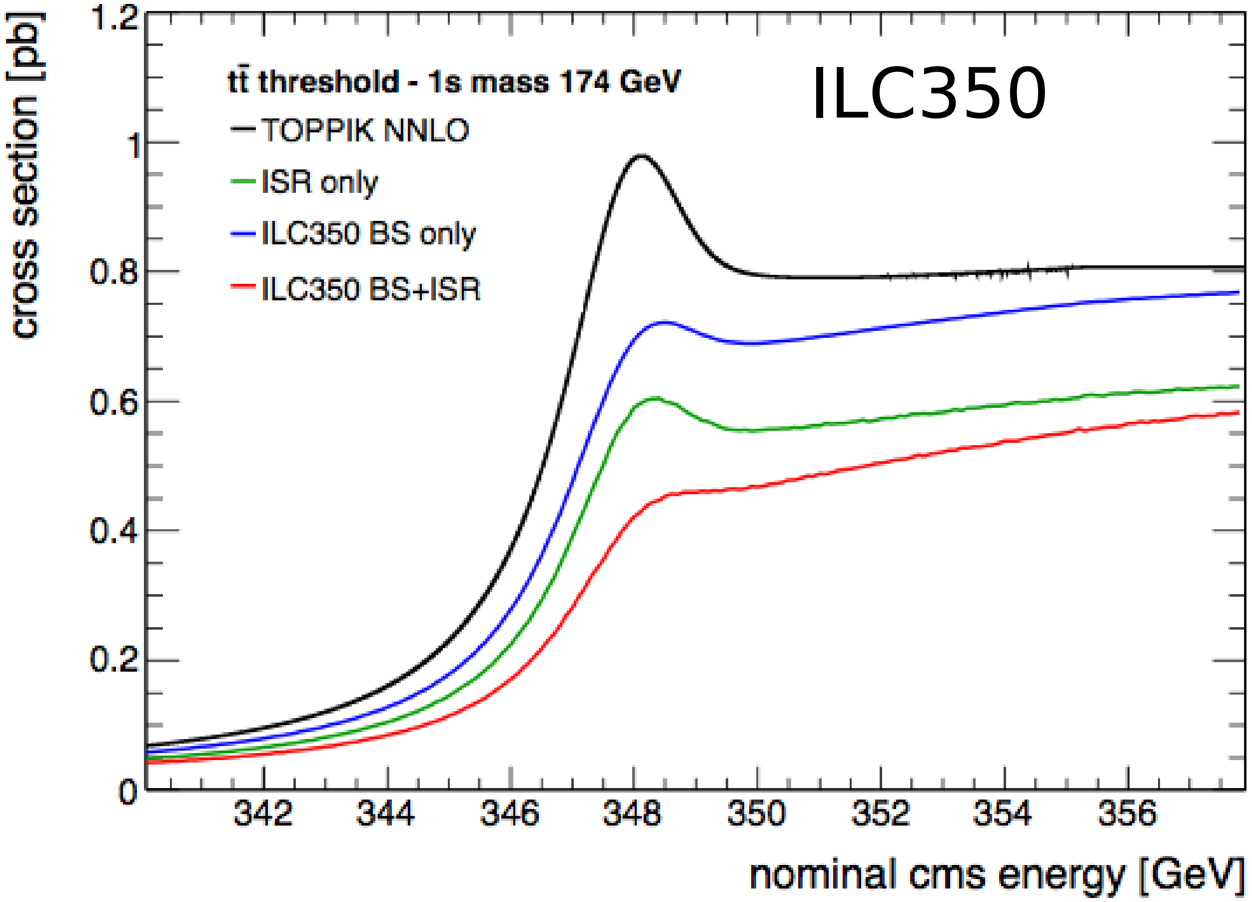
1 GeV??

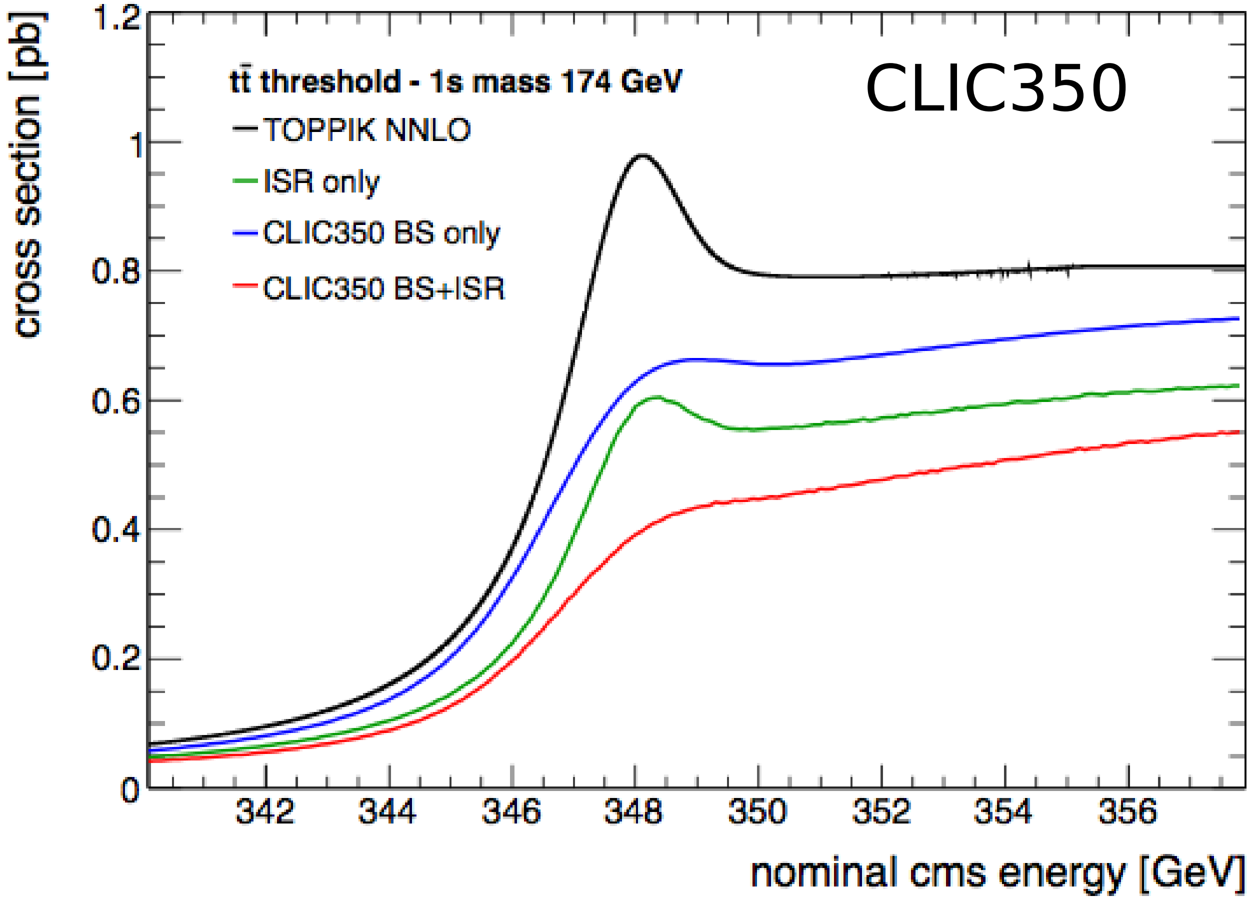
→ Interesting alternative

Top quark mass - Threshold Scan at LC

The shape of the top quark pair production cross section around threshold offers sensitivity to top quark mass, top quark width and the strong coupling constant α_s

Threshold shape is partially washed out by ISR and beam energy spread.
Larger beam energy spread at CLIC has ~15% effect on precison of the fit





ILC

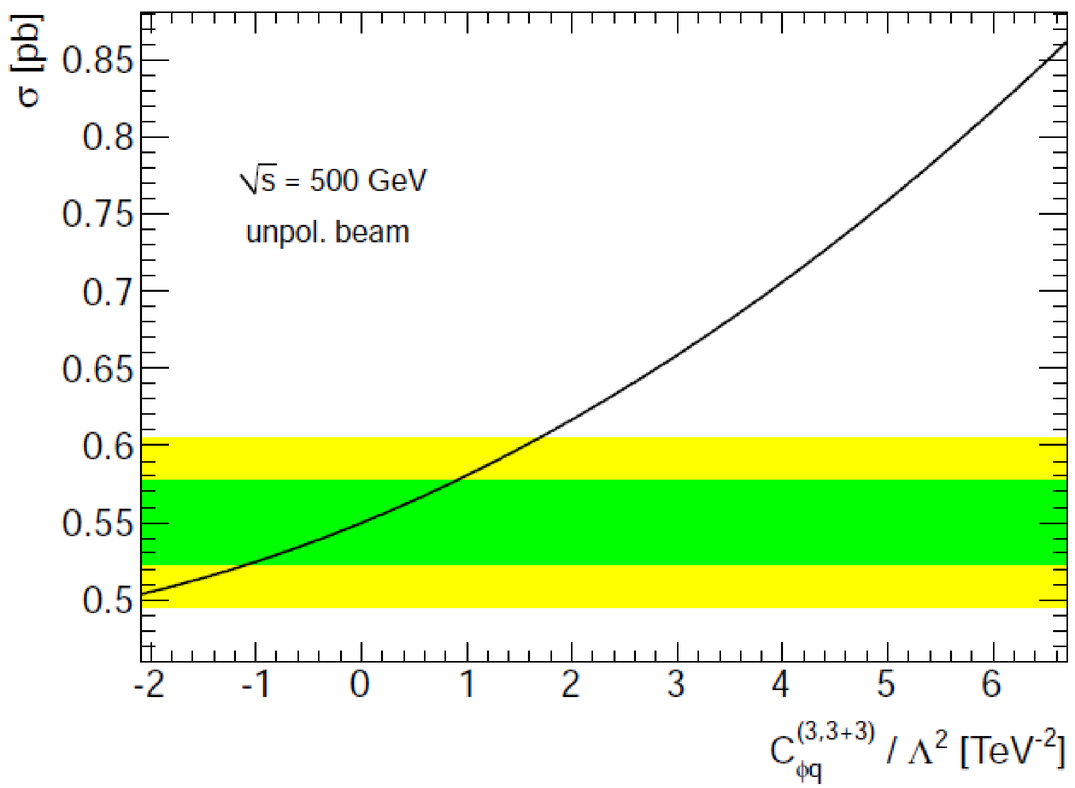
J.A. Aguilar et al., Top effective operators at the ILC, arXiv:1206.1033 (see talk by M. Fiolhais this afternoon)

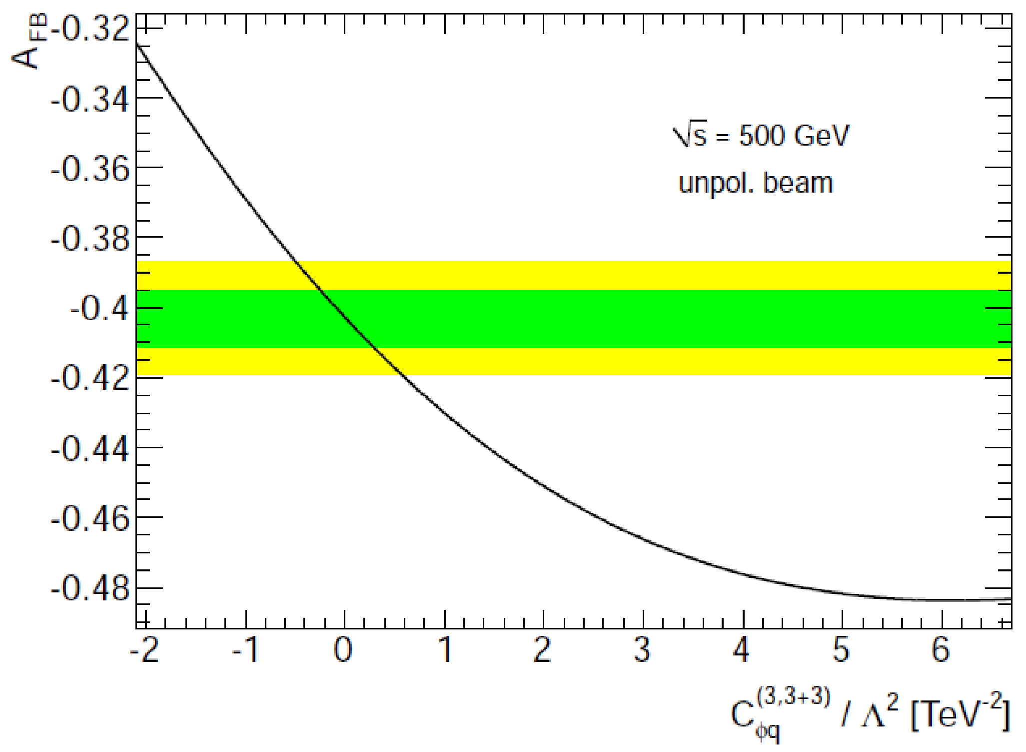
Ztt and Wtb vertices share two effective operators:

O^{33}_{uW} (which contributes to the magnetic dipole moment)

$O^{3,3+3}_{\phi Q}$

X-axis range: ATLAS limits from t-channel single-top x-section measurement (assuming no other BSM contribution to single top production at the LHC)





ILC

J.A. Aguilar, M. Fiolhais, A. Onofre, Top effective operators at the ILC, arXiv:1206.1033

Ztt and Wtb vertices share two effective operators:

O^{33}_{uW} (which contributes to the magnetic dipole moment)

$O^{3,3+3}_{\phi Q}$

X-axis range: limits derived from the ATLAS measurement of the W helicity fractions