Top quark properties

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on behalf of the ATLAS, CDF, CMS, and DØ collaborations

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Introduction

- Why study top quark properties?
  - heaviest quark in the standard model
    - large coupling to Higgs
    - probe for new theories above the electroweak scale
  - top quark decays before hadronisation
    - study properties of a "bare"quark
  - stringent test of the SM, with many possibilities for manifestation of new physics
    - tops could be produced from decay of new particles
    - tops could decay into new particles
  - important to understand top as a background for other measurements and searches

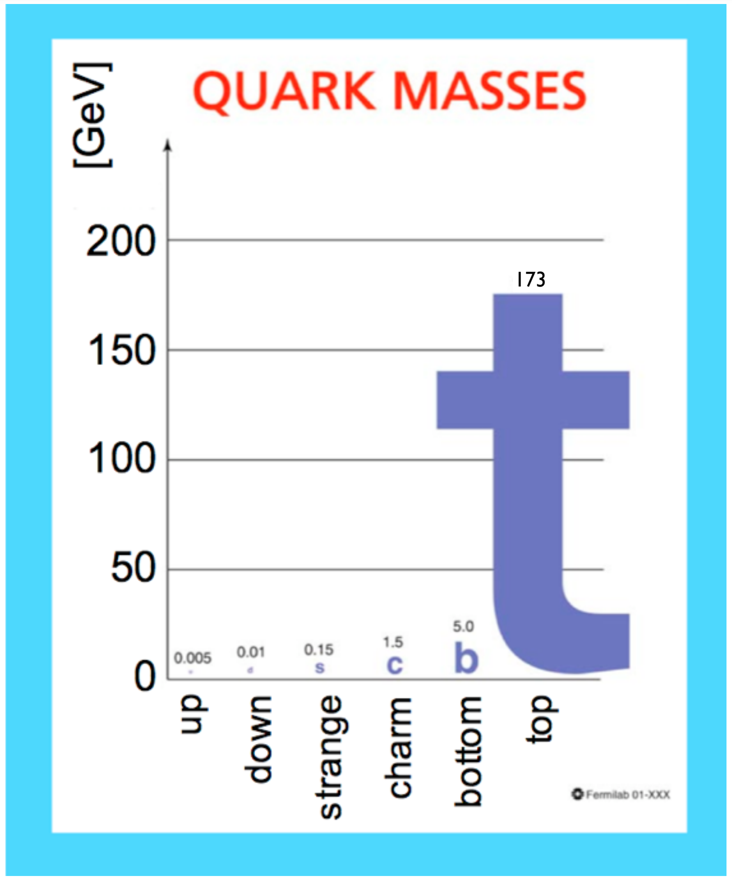
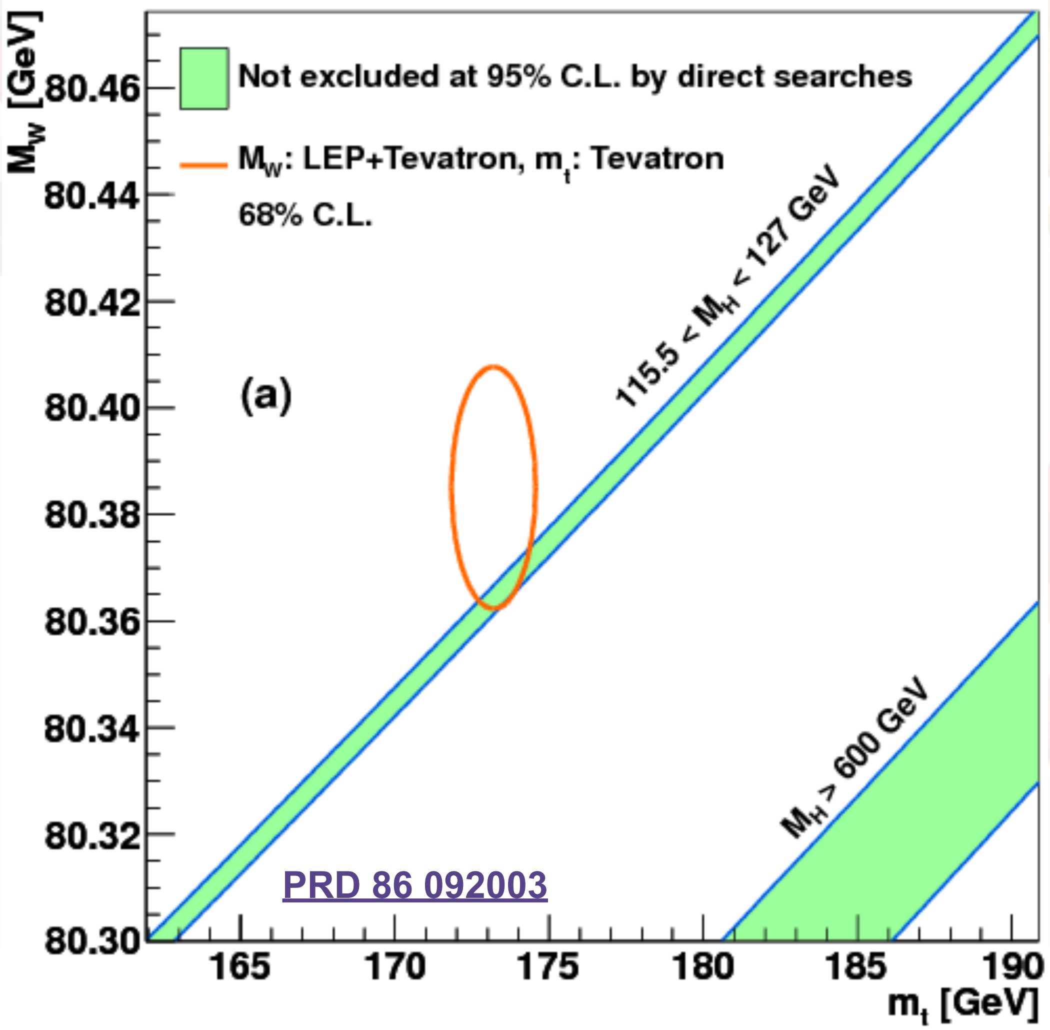


Table of contents

- I shall present results from the last year in the following categories:
  - top quark mass
  - $t\bar{t}$ cross-section
  - top charge asymmetry
  - W helicity and anomalous Wtb couplings
  - search for FCNC in $t\bar{t}$ decays

Top quark mass

- fundamental parameter of the SM
- large coupling to Higgs

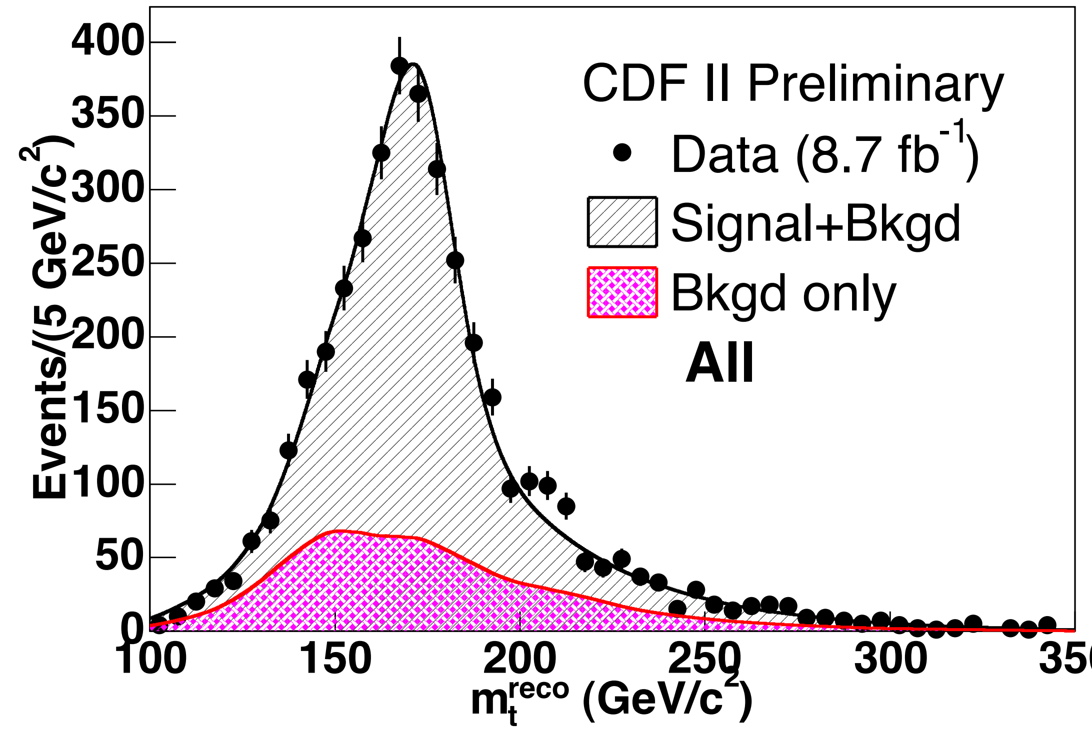


Top mass: CDF lepton+jets

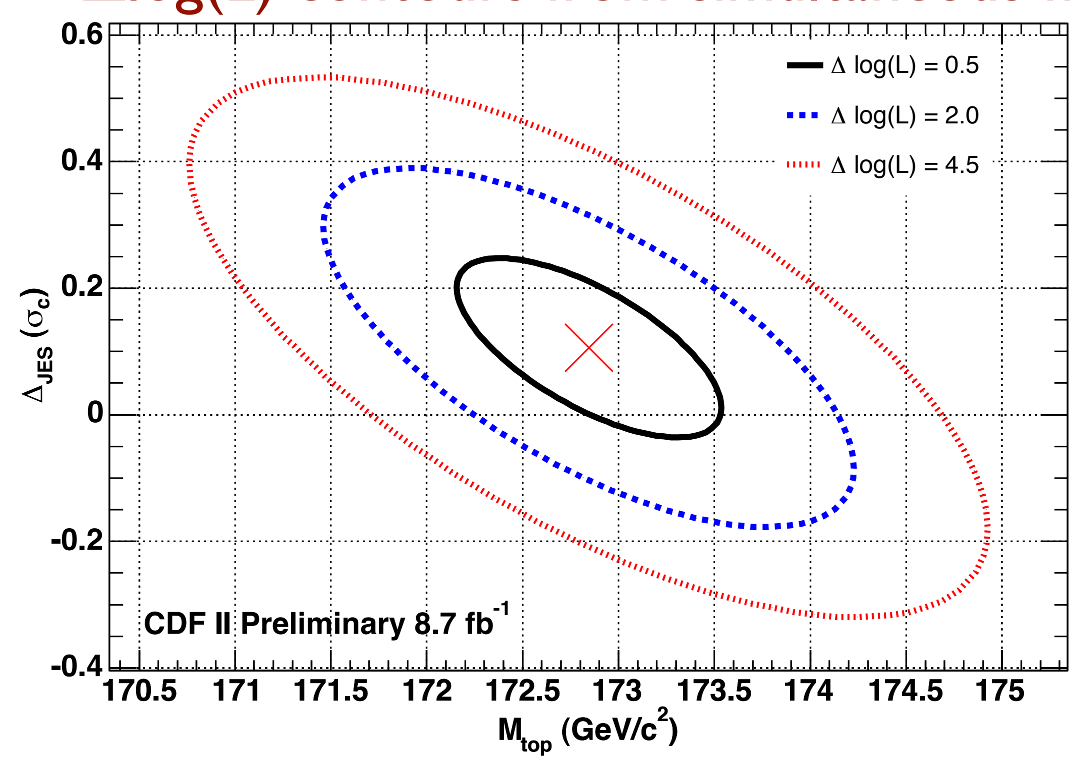
- CDF lepton+jets channel until recently most precise single measurement
  - latest result with 8.7 fb^{-1} at 1.96 TeV, e/μ + ≥4j
- Jet energy scale (JES) leading systematic
  - reduce uncertainty by measuring JES simultaneously with m_t using m_W constraint
- $t\bar{t}$ system reconstructed using χ^2 minimisation
- Per-event likelihood for true m_t and JES, based on measured m_t^{reco} and m_W^{reco}
  - from sum of signal and background probability density functions (pdfs), from MC
- Mass and JES simultaneously extracted from 2D fit to combined likelihood
- **m_t = 172.85 ± 1.10 (total) GeV**

PRL 109 152003

m_t^{reco} distribution



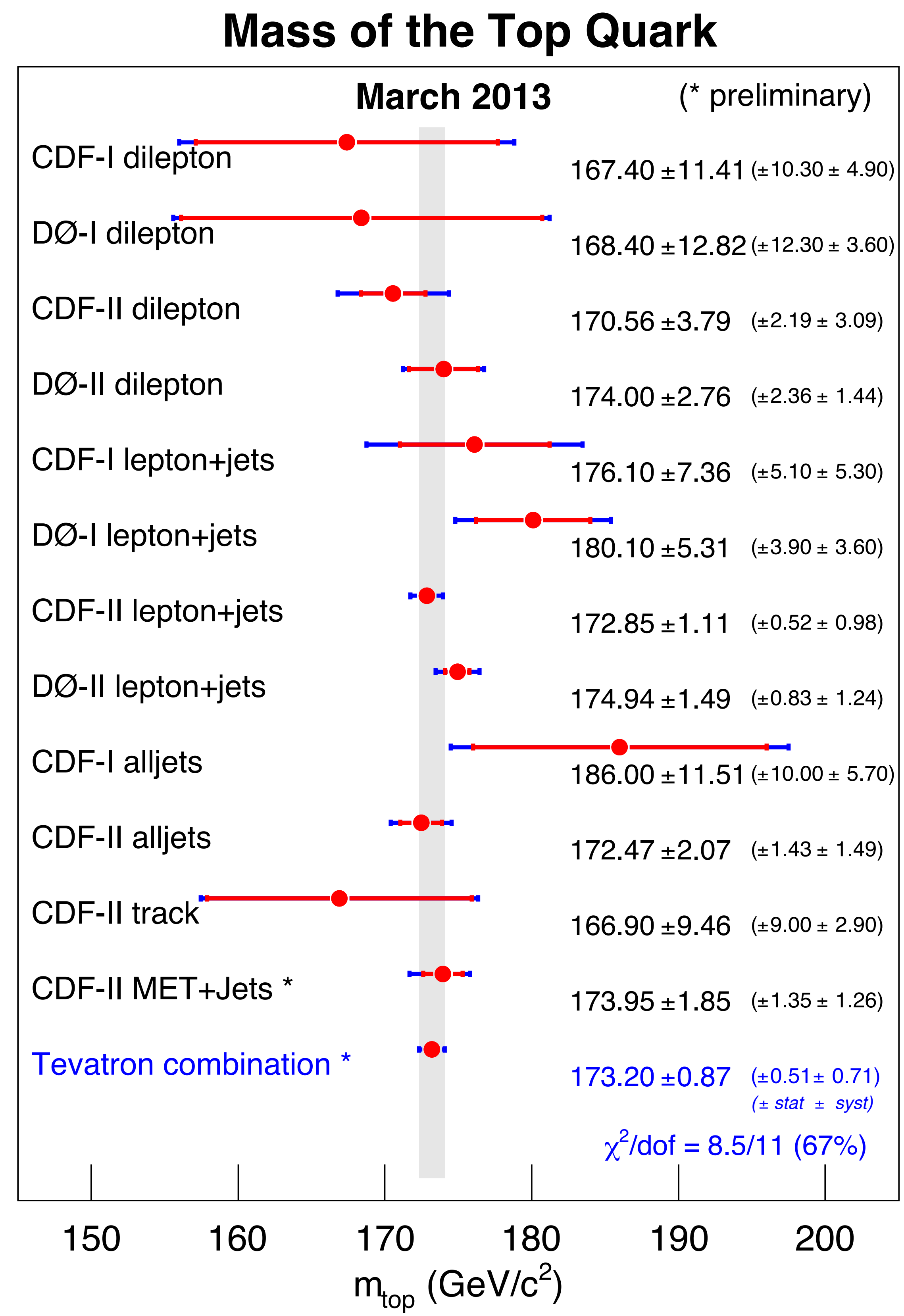
Δlog(L) contours from simultaneous fit

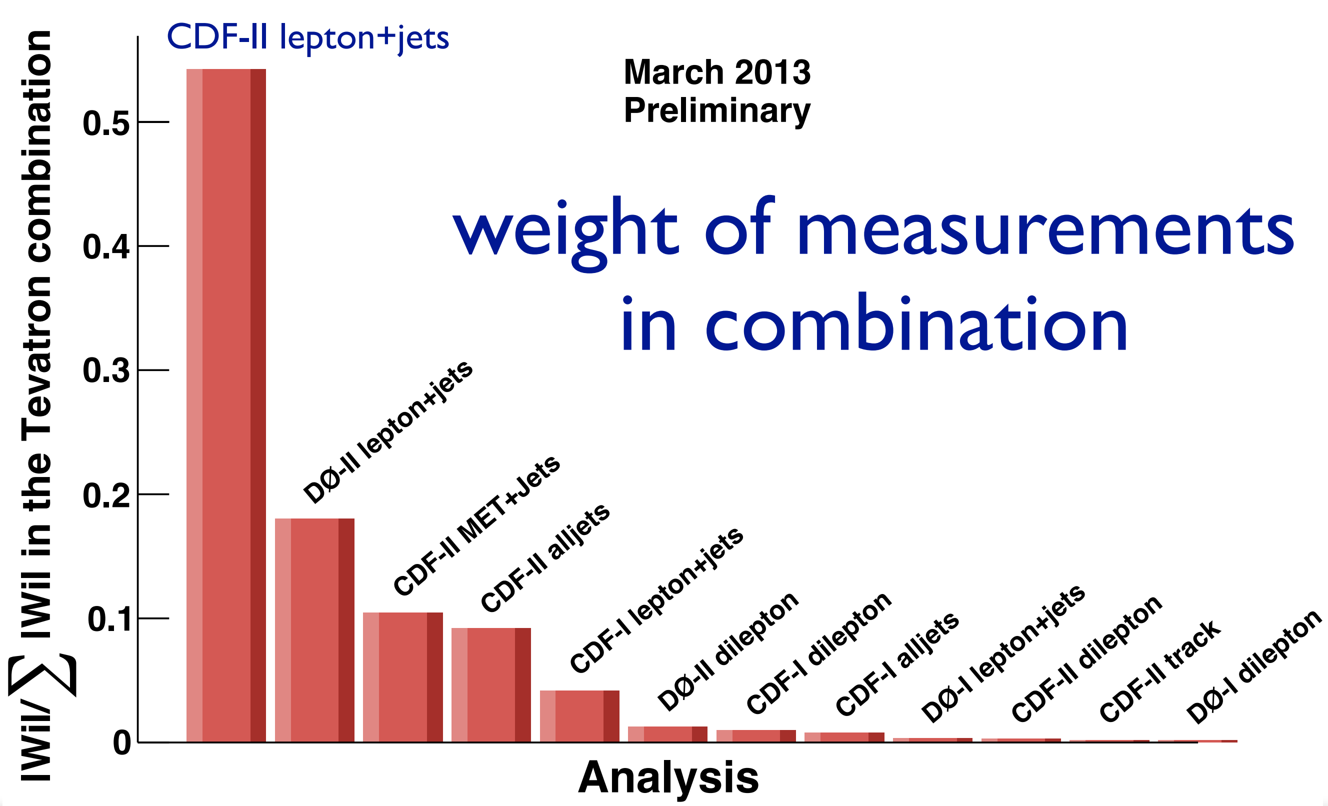


Tevatron top quark mass combination

- Tevatron measurements combined using best linear unbiased estimator (BLUE) method
- Compared to previous (2011) combination, uses updated Run II CDF lepton+jets and MET+jets measurements
  - full 8.7 fb^{-1} of data, and improved analysis technique and jet energy resolution for lepton+jets
- **m_t = 173.20 ± 0.87 (total) GeV**
  - relative uncertainty of **0.50%**

CDF Note 10976, DØ Note 6381

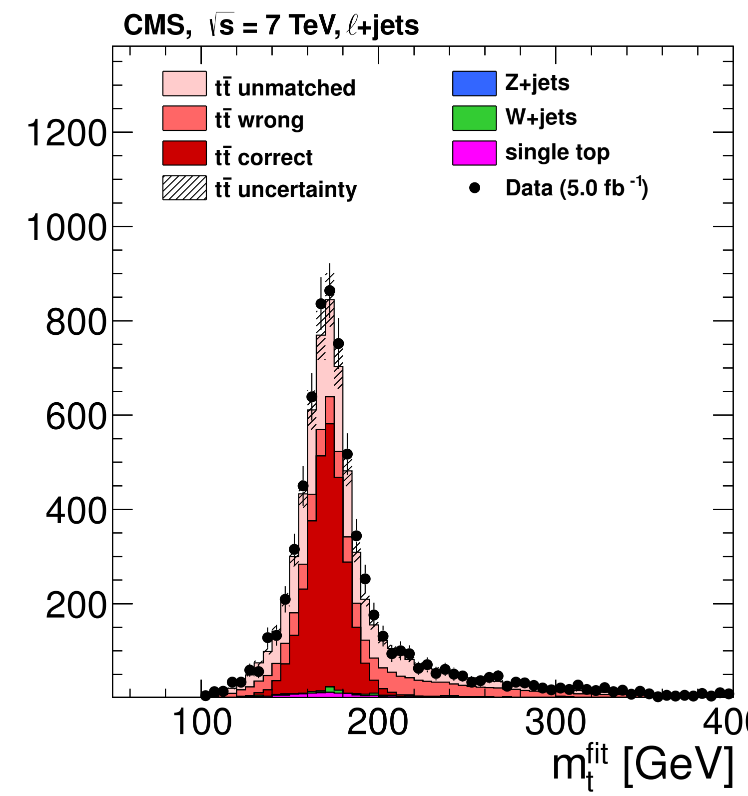




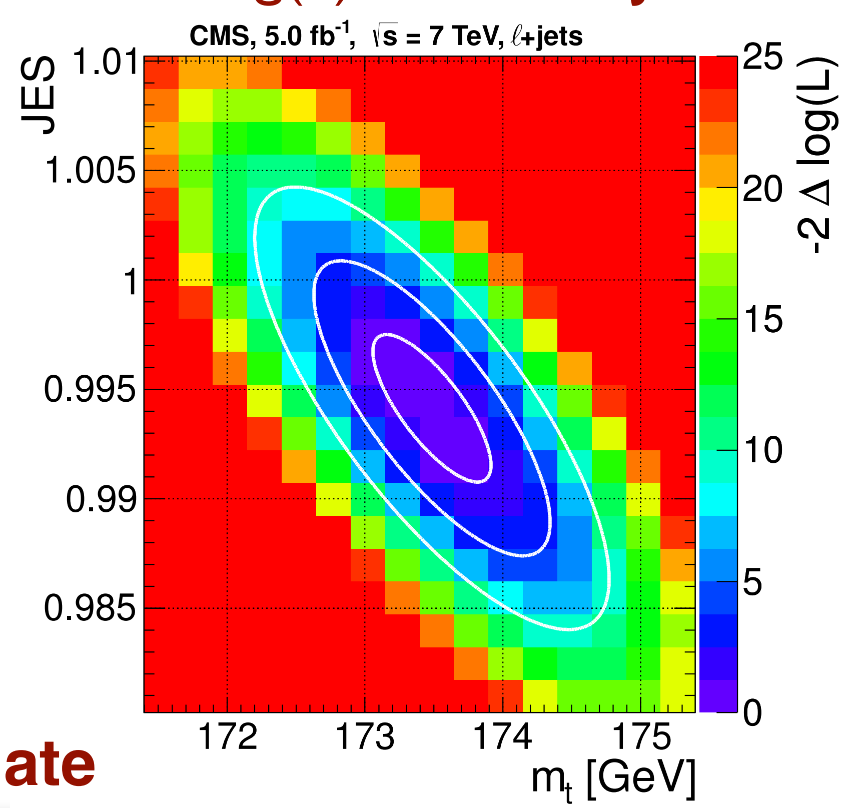
Top mass: CMS lepton+jets

- 5 fb^{-1} 7 TeV lepton+jets data (e/μ + ≥4j, ≥2 b-tags)
- Kinematic fit to reconstruct mass of top quarks in each event, m_t^{fit}
  - 2 possible parton to b-jet assignments per event, weighted based on fit χ^2 (and with high χ^2 cut to increase fraction of correct permutations and reject background)
- Per-event likelihood for m_t and JES based on m_t^{fit} and m_W^{reco} (Ideogram method)
  - includes sum of pdfs for $t\bar{t}$ with "correct" and "wrong" jet permutations, and also "unmatched" where the 4 jets do not correspond to the 4 partons
- Mass and JES simultaneously extracted from combined likelihood:
- **m_t = 173.49 ± 1.07 (total) GeV**
- JES = 0.994 ± 0.009 (total)

m_t^{fit} distribution



log(L) vs m_t and JES



JHEP 12 (2012) 105

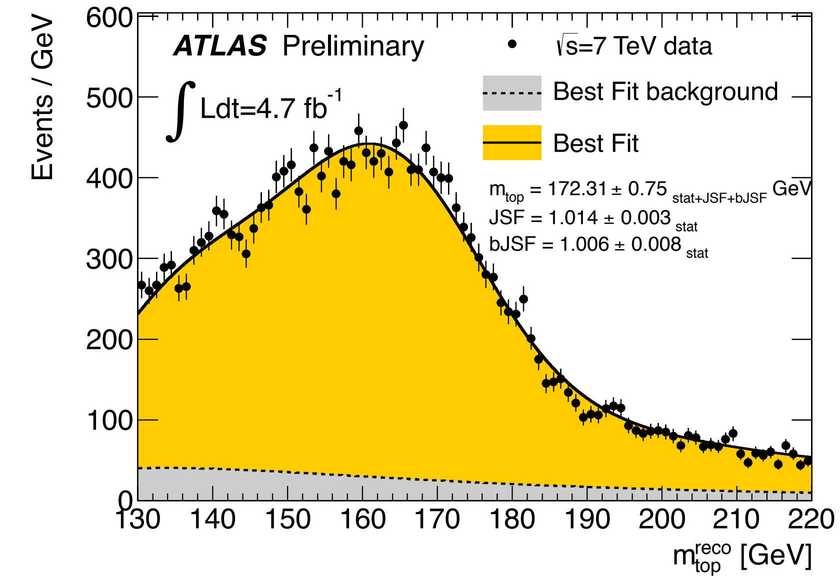
most precise single measurement to date

3D template fit top mass analysis

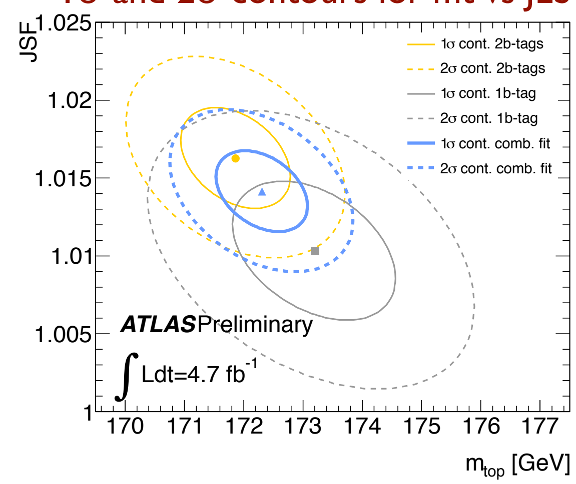
- New result from ATLAS seeks to reduce b-jet JES systematic by adding an independent correction to the b-jet JES, **bJSF**, to the simultaneous fit
- Template fit, using 3 variables from a kinematic fit of each event
  - m_t^{reco} templates as a function of input m_t, JES, and bJSF
  - m_W^{reco} templates as a function of JES
  - templates of $R_{lb}^{reco,2b} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet_1}} + p_T^{W_{jet_2}}}$ as a function of m_t and bJSF

(and a similar quantity for events with 1 b-tag)

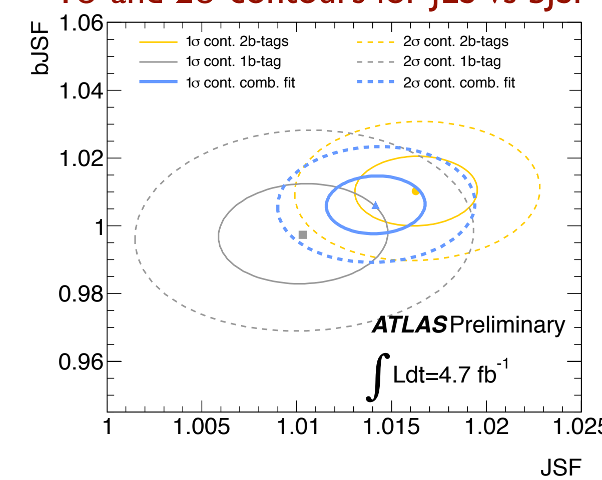
m_t^{reco} distribution



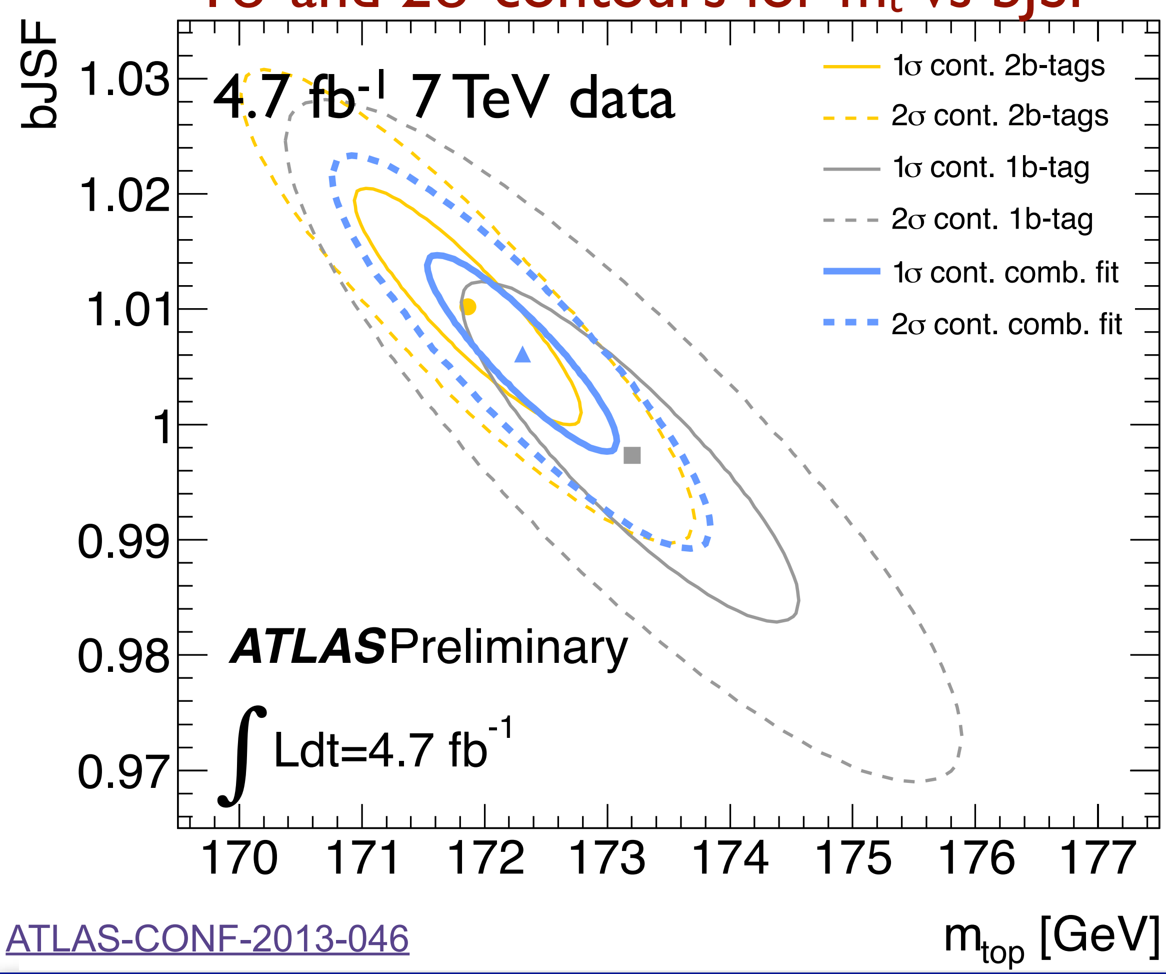
1σ and 2σ contours for mt vs JES



1σ and 2σ contours for JES vs bJSF



1σ and 2σ contours for m_t vs bJSF



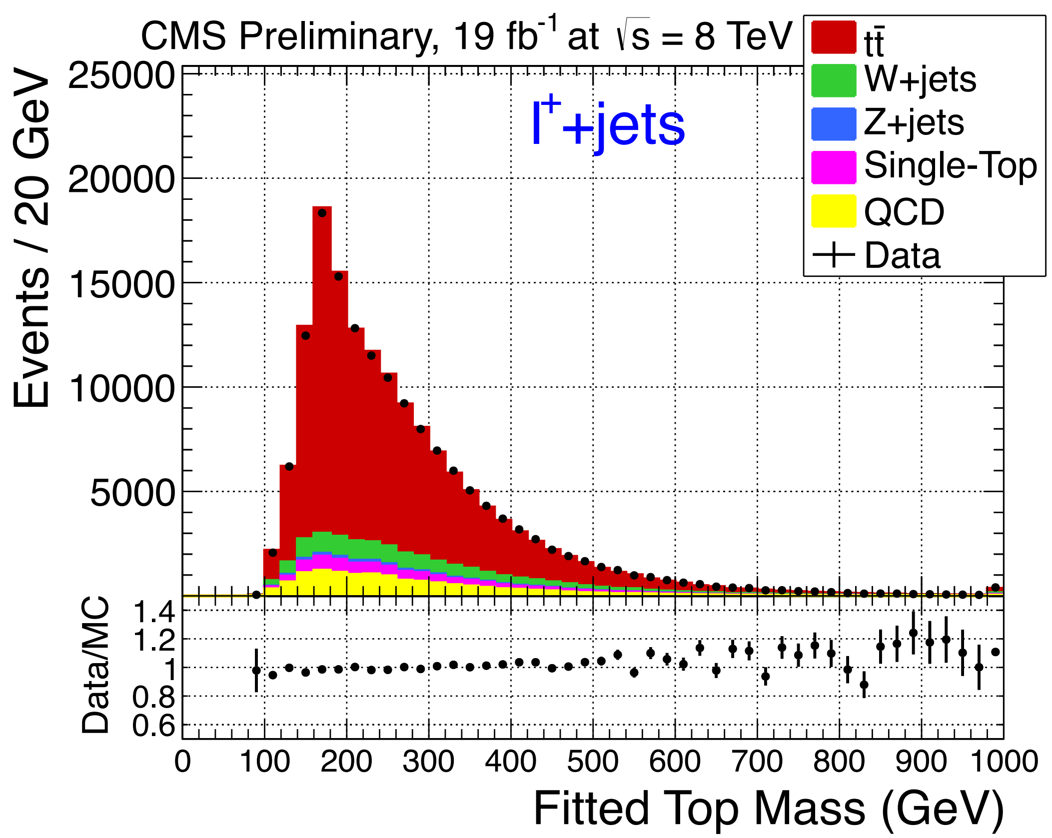
ATLAS-CONF-2013-046

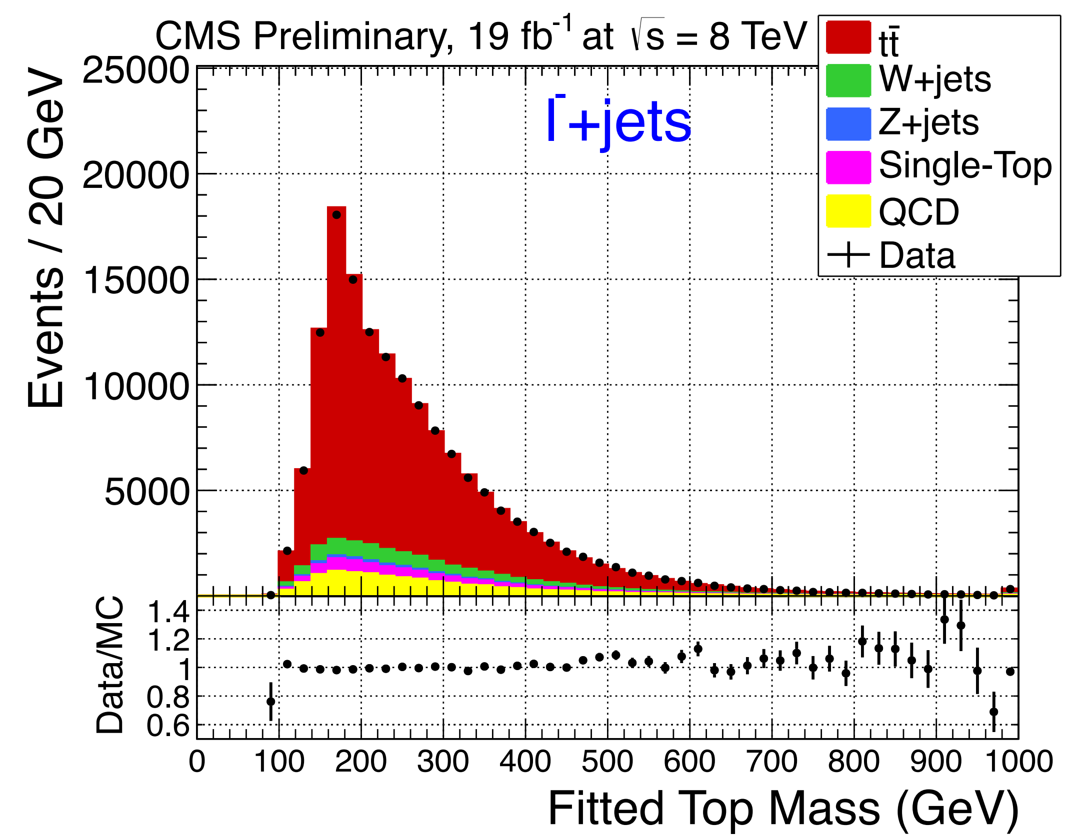
- Results from simultaneous fit to 3D likelihood function:
  - **m_t = 172.31 ± 1.55 (total) GeV**
- Uncertainty reduced compared to result using traditional 2D fit (with bJSF set = 1):
  - **m_t = 172.8 ± 2.05 (total) GeV**

top - antitop mass difference

CMS PAS TOP-12-031

- SM invariance under CPT predicts equality of particle and antiparticle masses
  - test by measuring the mass difference between top and antitop, $\Delta m_t = m_t - m_{tbar}$
  - 19 fb^{-1} 8 TeV lepton+jets data (e/μ + ≥4j, ≥1b-tag)
- Kinematic fit to reconstruct mass of hadronically decaying top in each event, using M_W constraint
- Mass extracted from combined likelihood (Ideogram method)
  - per-event likelihood terms for signal with correct and incorrect jet combinations, and for background
- Event sample split in two based on lepton charge, and m_t extracted from 1D fit to likelihood





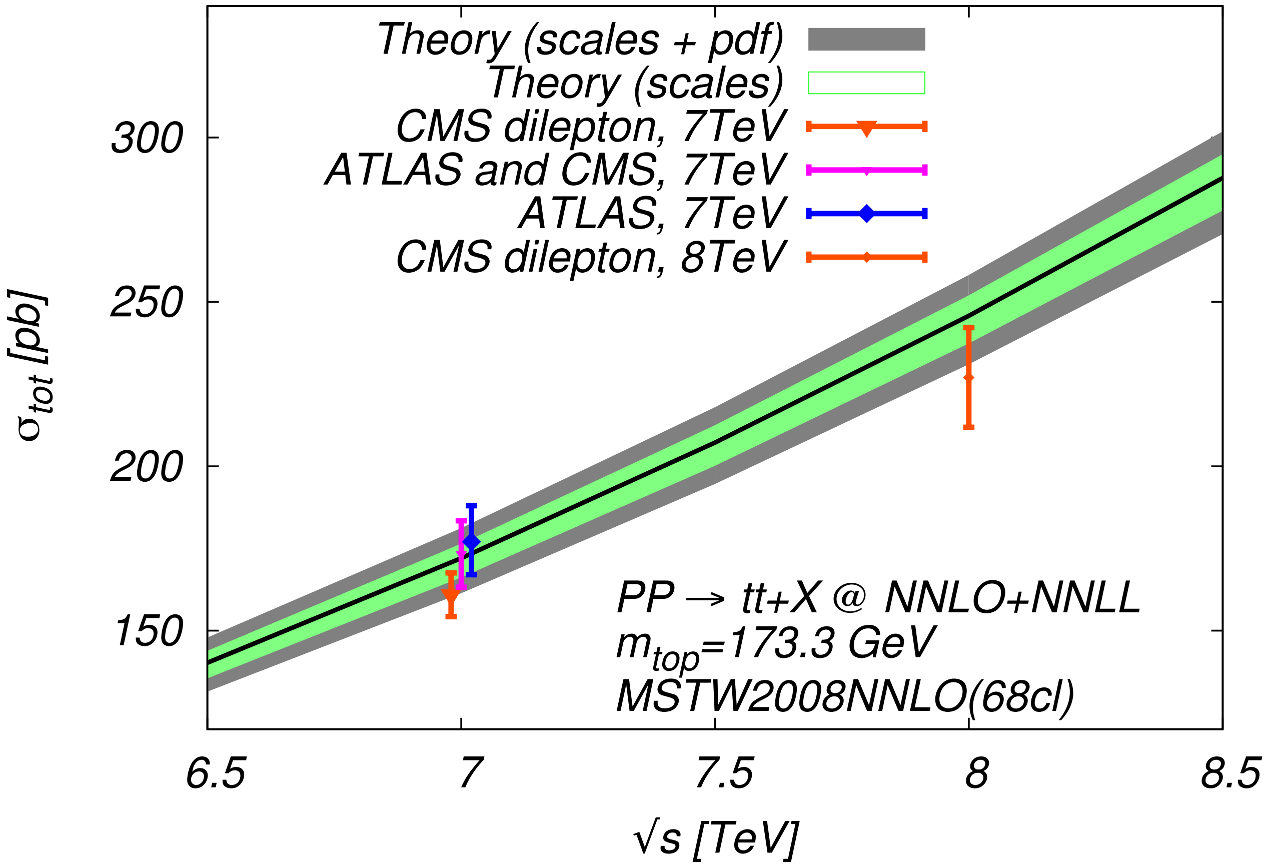
- $\Delta m_t = -272 \pm 196\ (\text{stat.}) \pm 122\ (\text{syst.})\ \text{MeV}$ (1.2σ from 0)
  - **by far the most precise measurement to date**

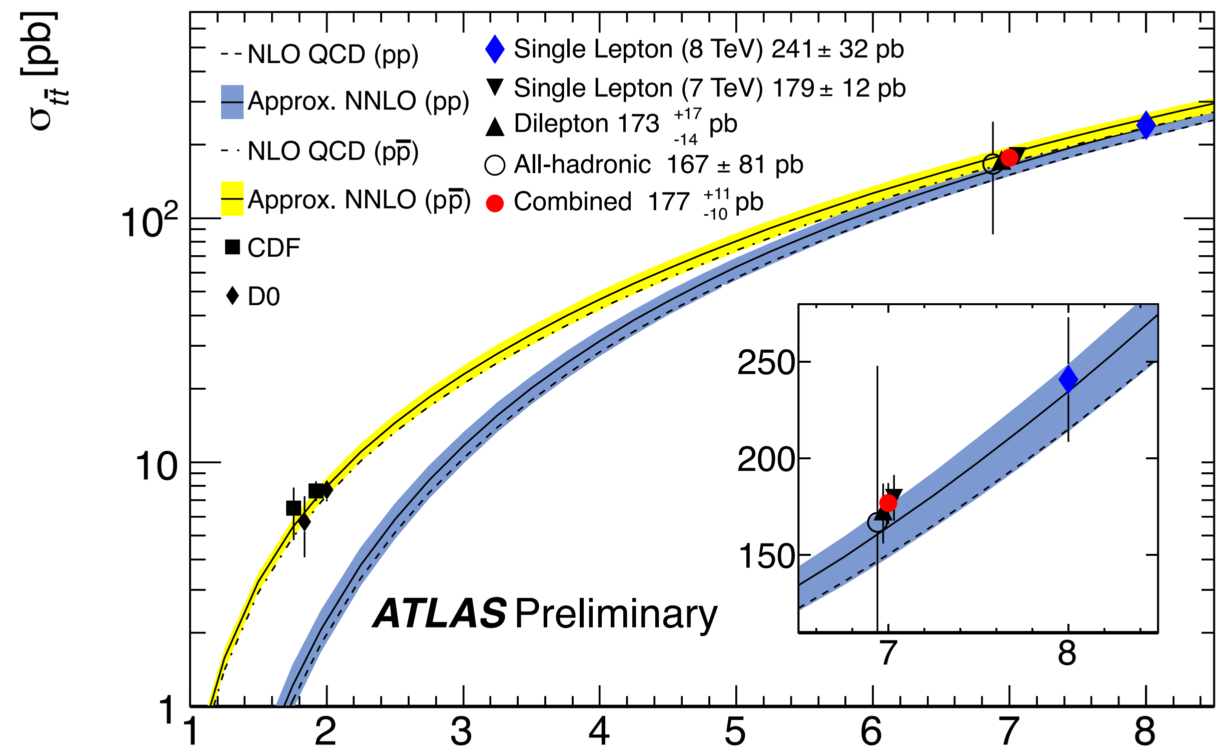
$t\bar{t}$ cross section

- good test of the SM (challenging to theory)
- sensitive to new physics

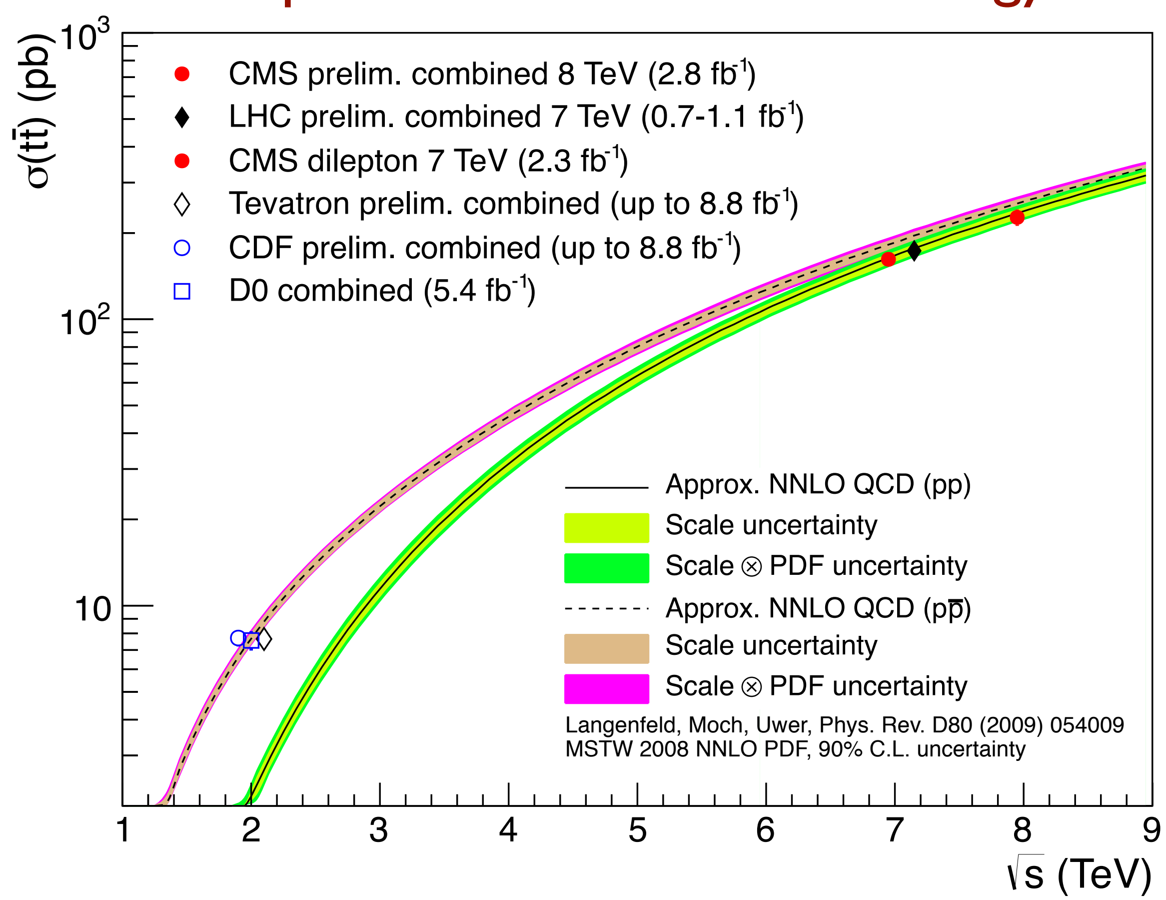
$t\bar{t}$ cross section

- Similar event selections as for mass analyses
- Measurements typically using kinematic fits to distinguish signal and background, with a likelihood fit to estimate N_{ttbar}
- Measured cross-section in good agreement with theory
  - exact NNLO calculation recently completed: arXiv:1303.6254 [hep-ph]





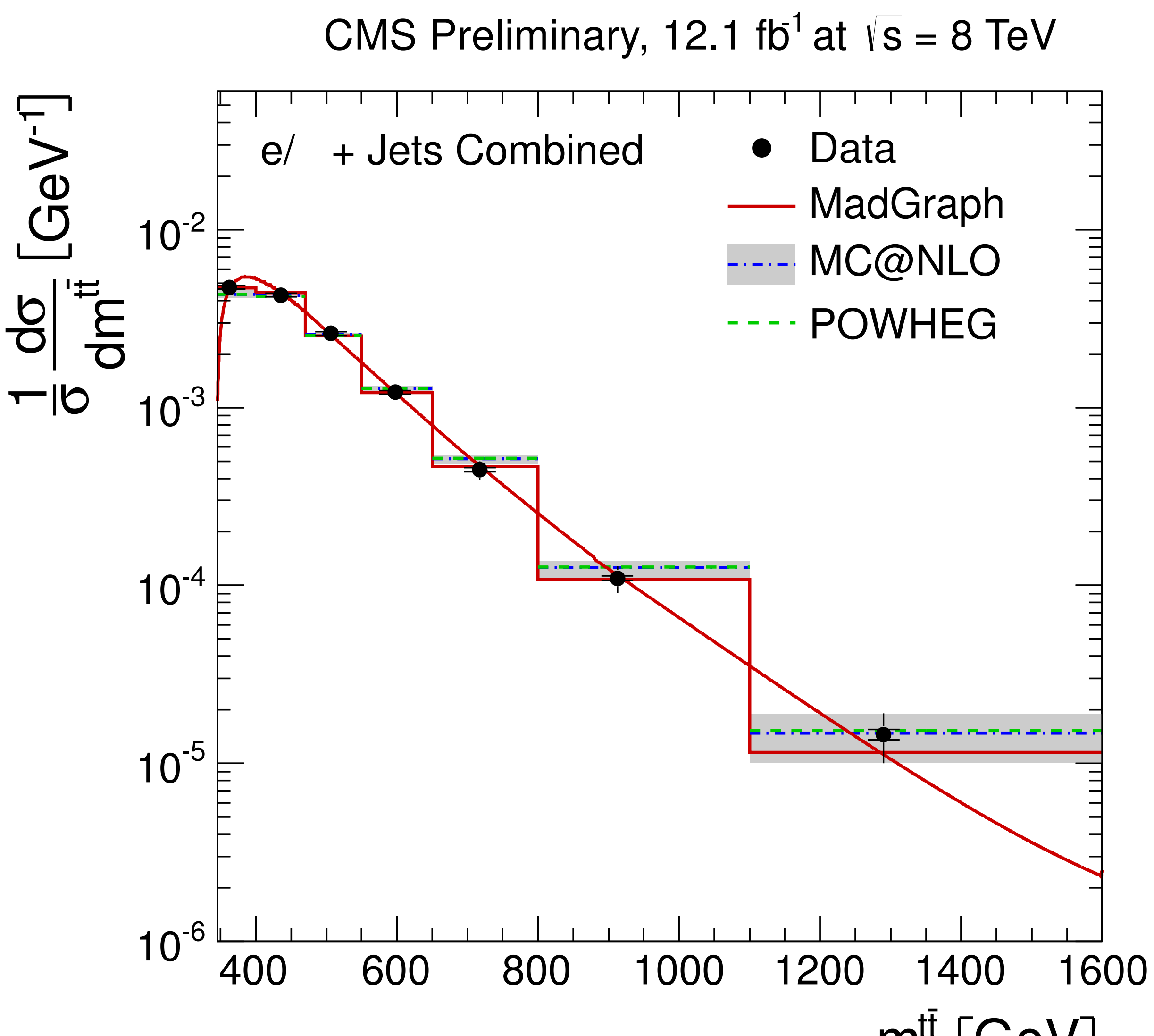
top cross-section vs CM energy



Differential cross section

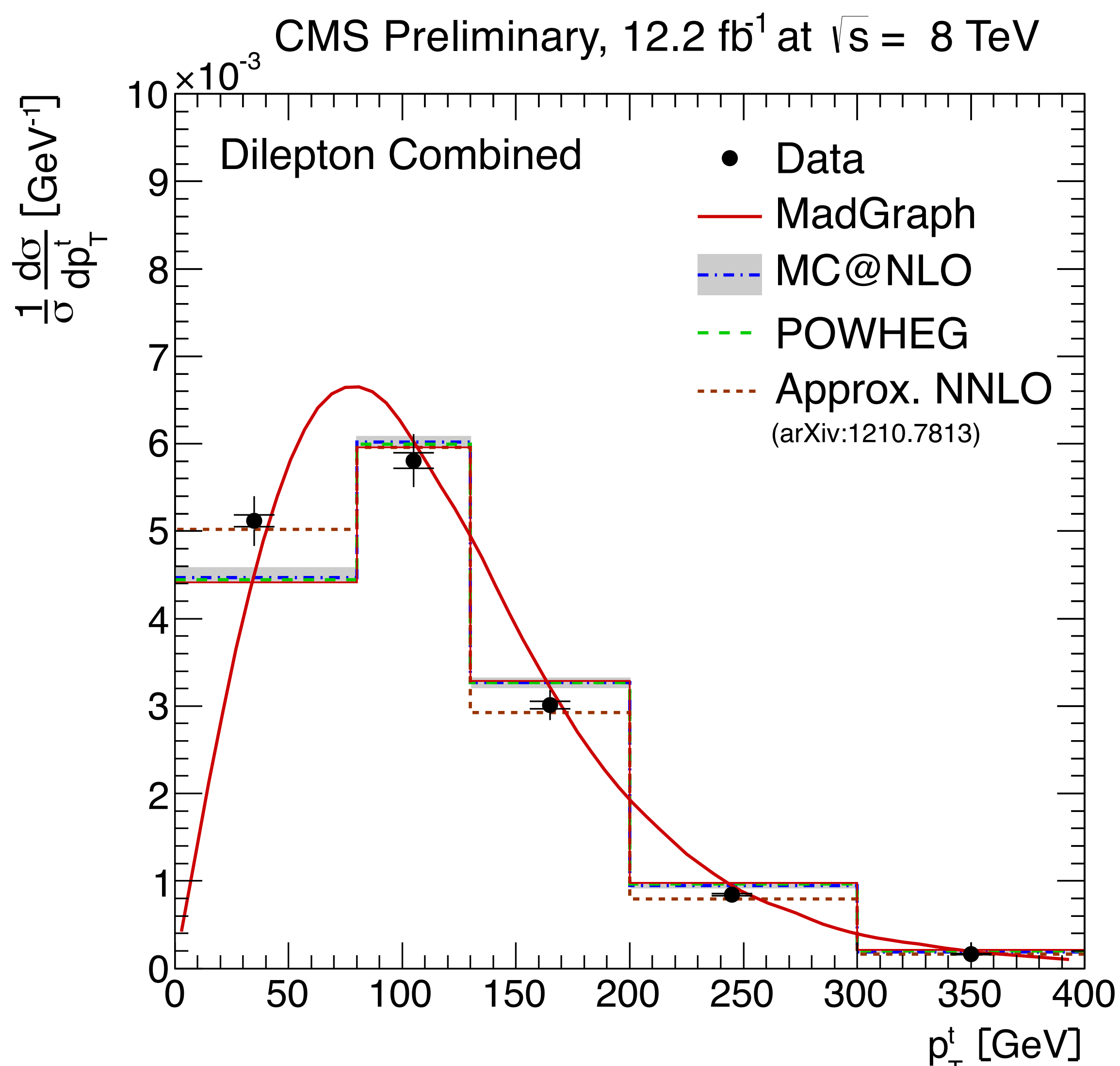
- CMS lepton+jets and dilepton channel results in 12 fb^{-1} 8 TeV data
- Measured distributions background-subtracted and unfolded to parton-level
- Resulting differential cross-section normalised to total cross-section: $\frac{1}{\sigma}\frac{d\sigma}{dX}$
- Results consistent with SM, but NNLO required to describe top p_T dependence

differential cross-section wrt top-antitop mass



CMS PAS TOP-12-027

differential cross-section wrt top p_T



CMS PAS TOP-12-028

top charge asymmetry

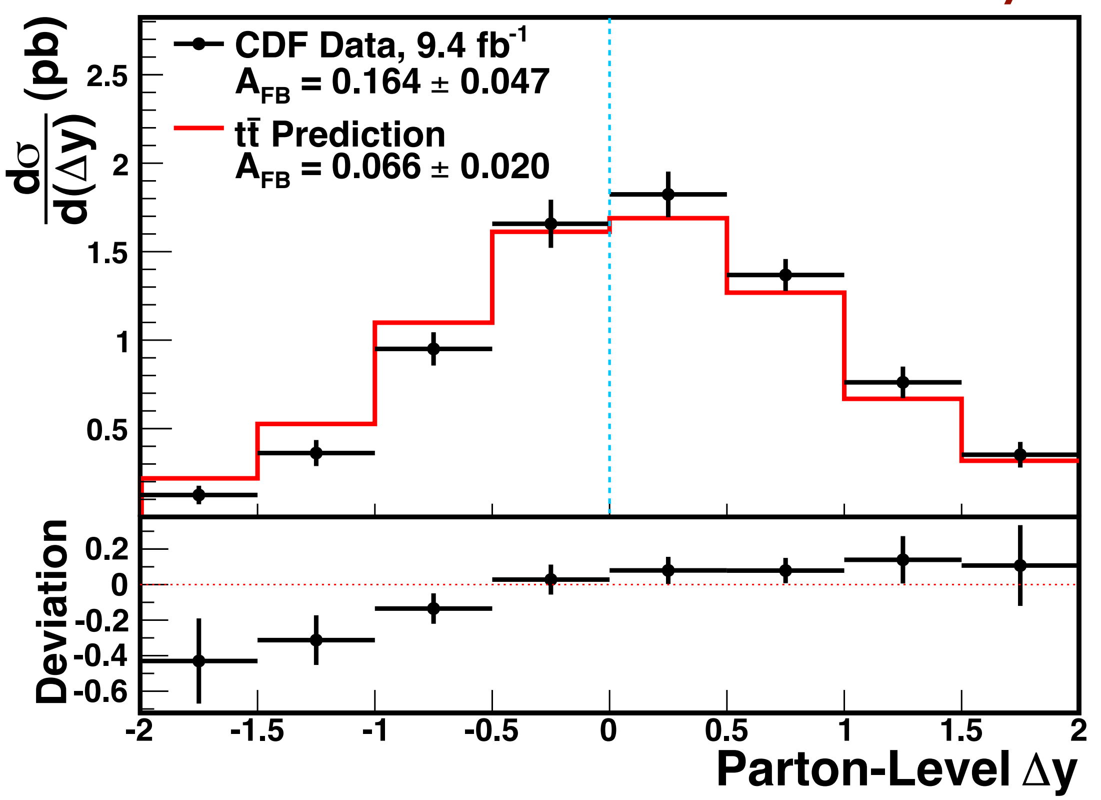
- focus on charge asymmetry of differential cross-section
- sensitive to new physics

Top charge asymmetry

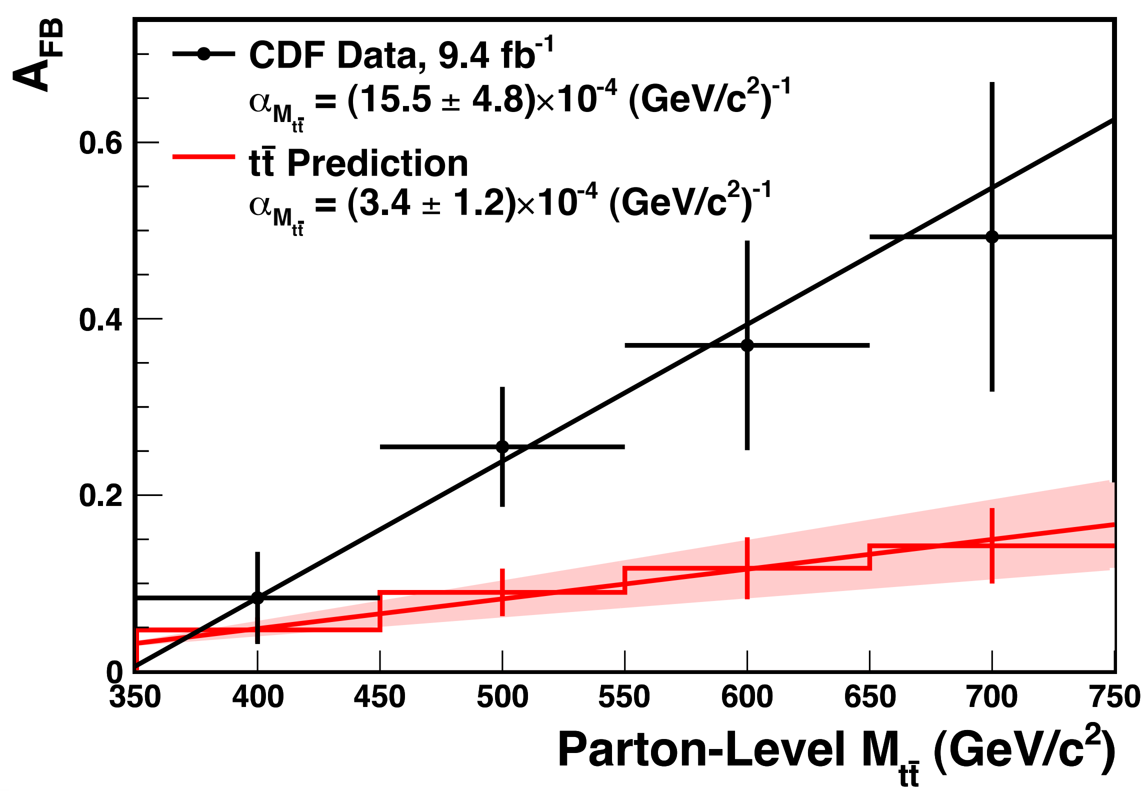
PRD: arXiv:1211.1003

- Great interest in the tension between the Tevatron measurements and the SM prediction for charge asymmetry
  - $$A_{\mathrm{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$
  - $\Delta y = y_t - y_{tbar}$
- The SM calculation has been improved
  - electroweak processes that contribute to the asymmetry
  - progress on NNLO calculation
  - studies of the choice of renormalisation scale
  - small increase in the expected asymmetry, but not enough to resolve the tension with observation.
- Plots show latest CDF lepton+jets result with 8.7 fb^{-1} at 1.96 TeV (parton-level)

differential cross-section wrt Δy

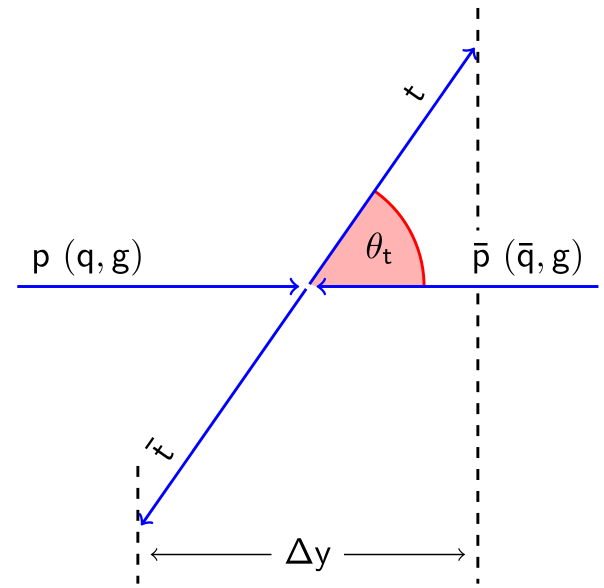


AFB vs Mtt

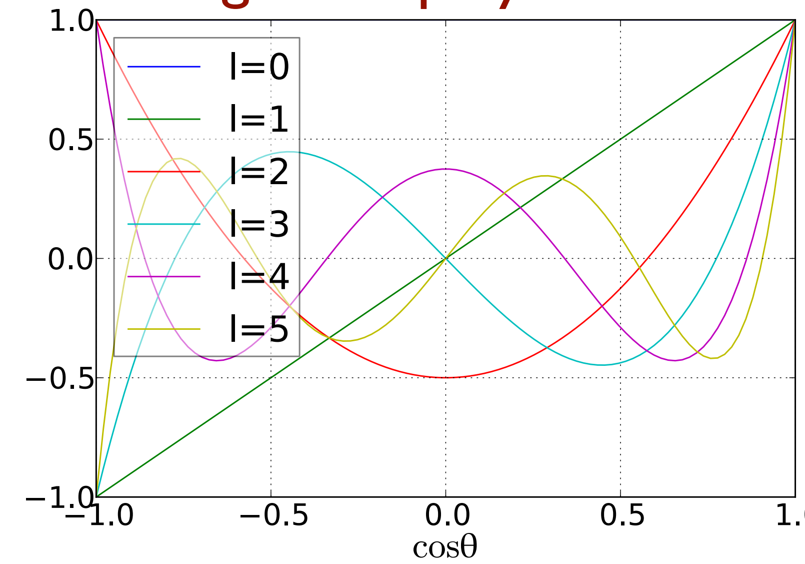


Characterisation of $d\sigma/d\cos\theta_t$

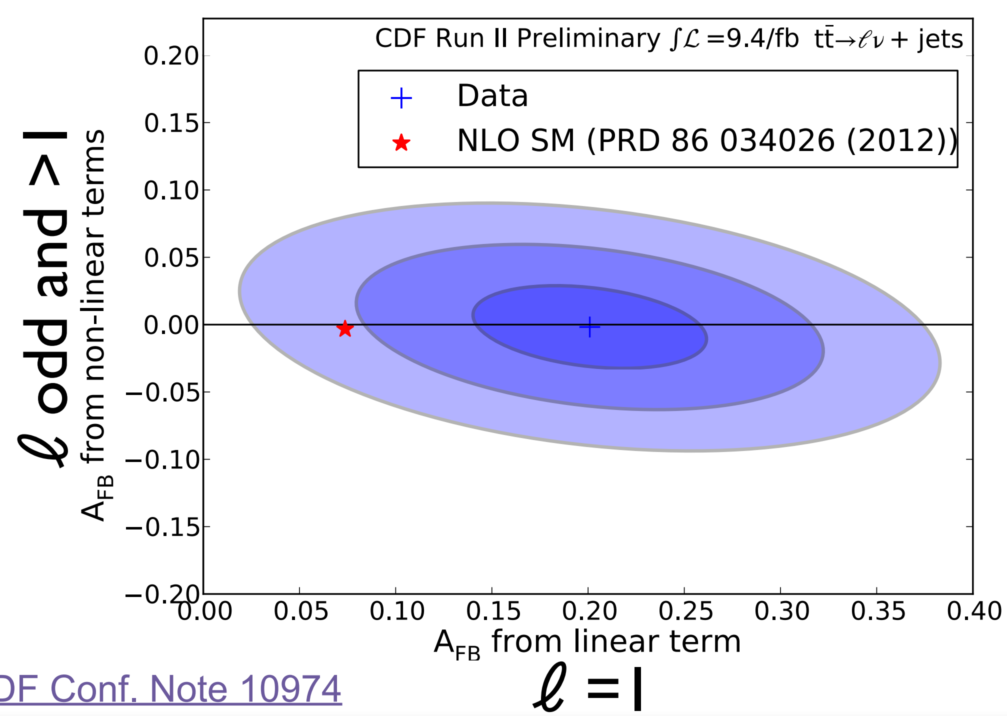
- $A_{FB}(\Delta y) \simeq A_{FB}(\cos\theta_t)$ (equal when $p_T(t\bar{t})=0$)
- Angular dependence of $q\bar{q} \rightarrow t\bar{t}$ scattering completely characterised by sum of Legendre polynomials (in CM frame)
  - contributing polynomials determined by angular momentum J of intermediate states
- LO SM: contributions only from ℓ =0,2
- Non-zero A_{FB} from odd moments
- Results from fit to $\cos\theta_t$ in data, background subtracted and corrected to parton level
- Observed A_{FB} all comes from ℓ =1 term



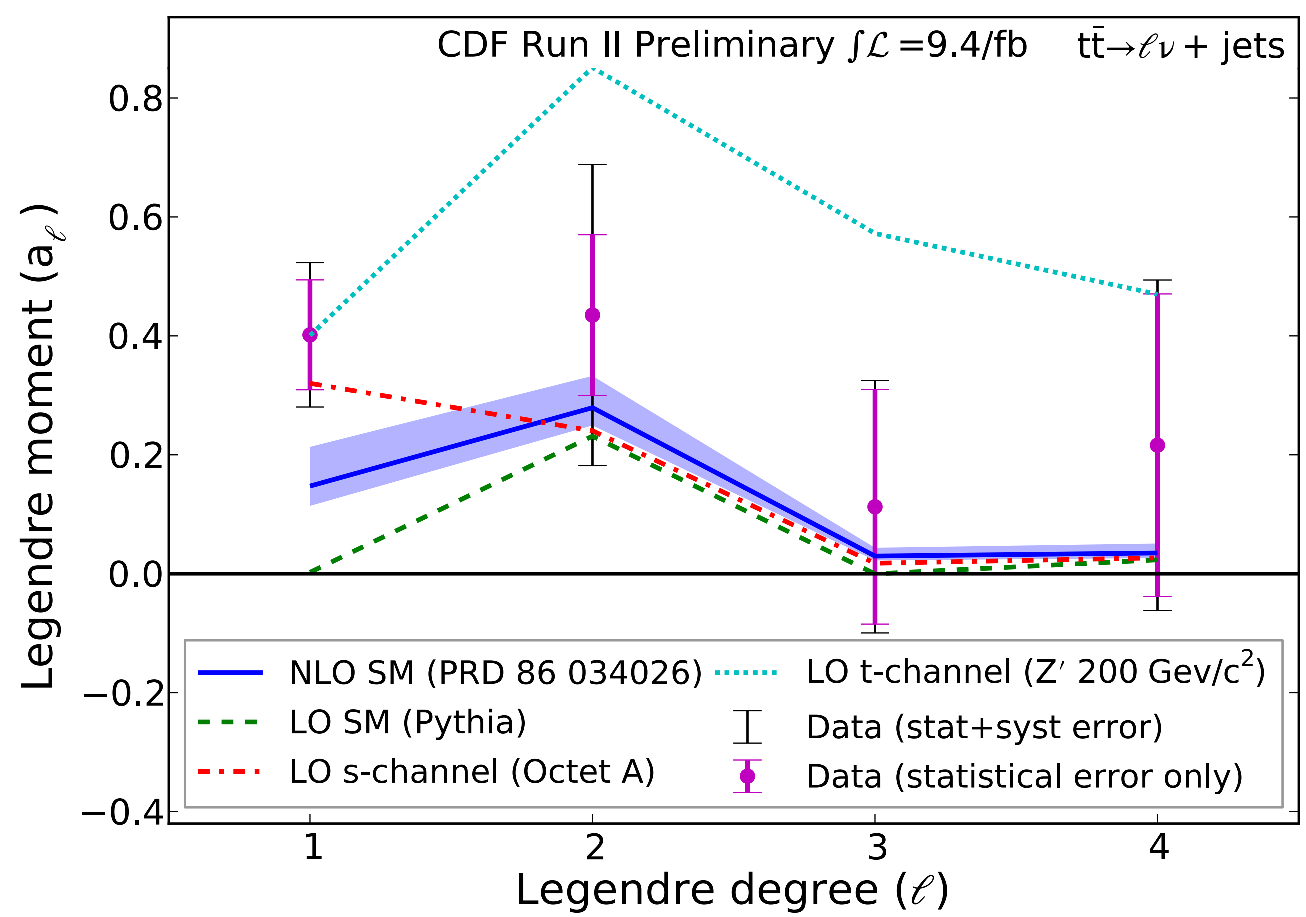
Legendre polynomials



contribution to A_{FB} from first vs other moments



Measured Legendre moments ℓ (parton level)

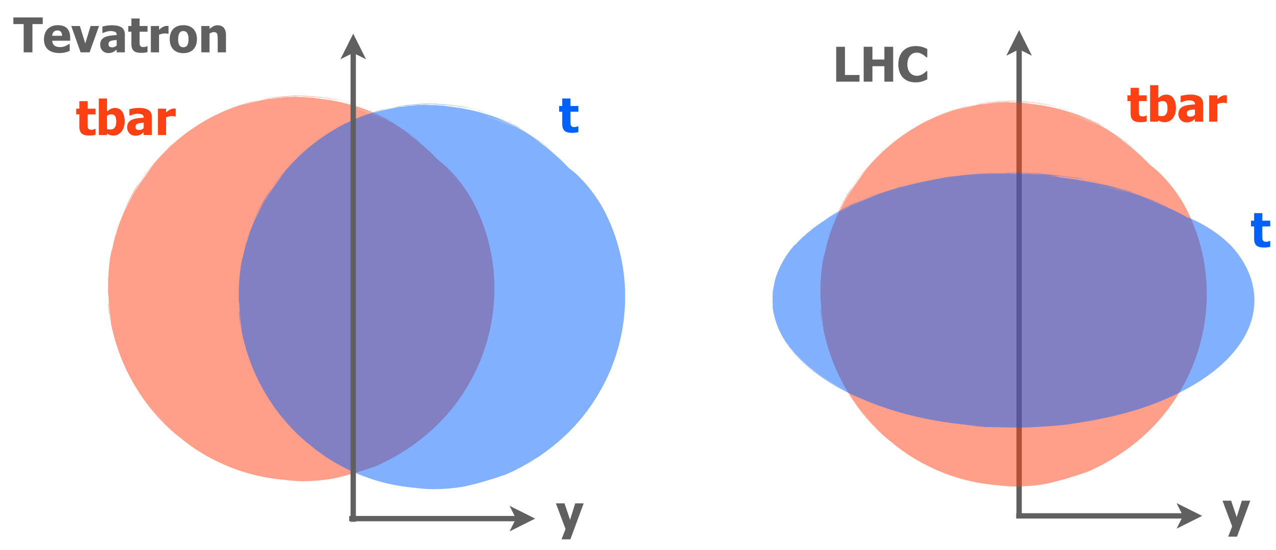


CDF Conf. Note 10974

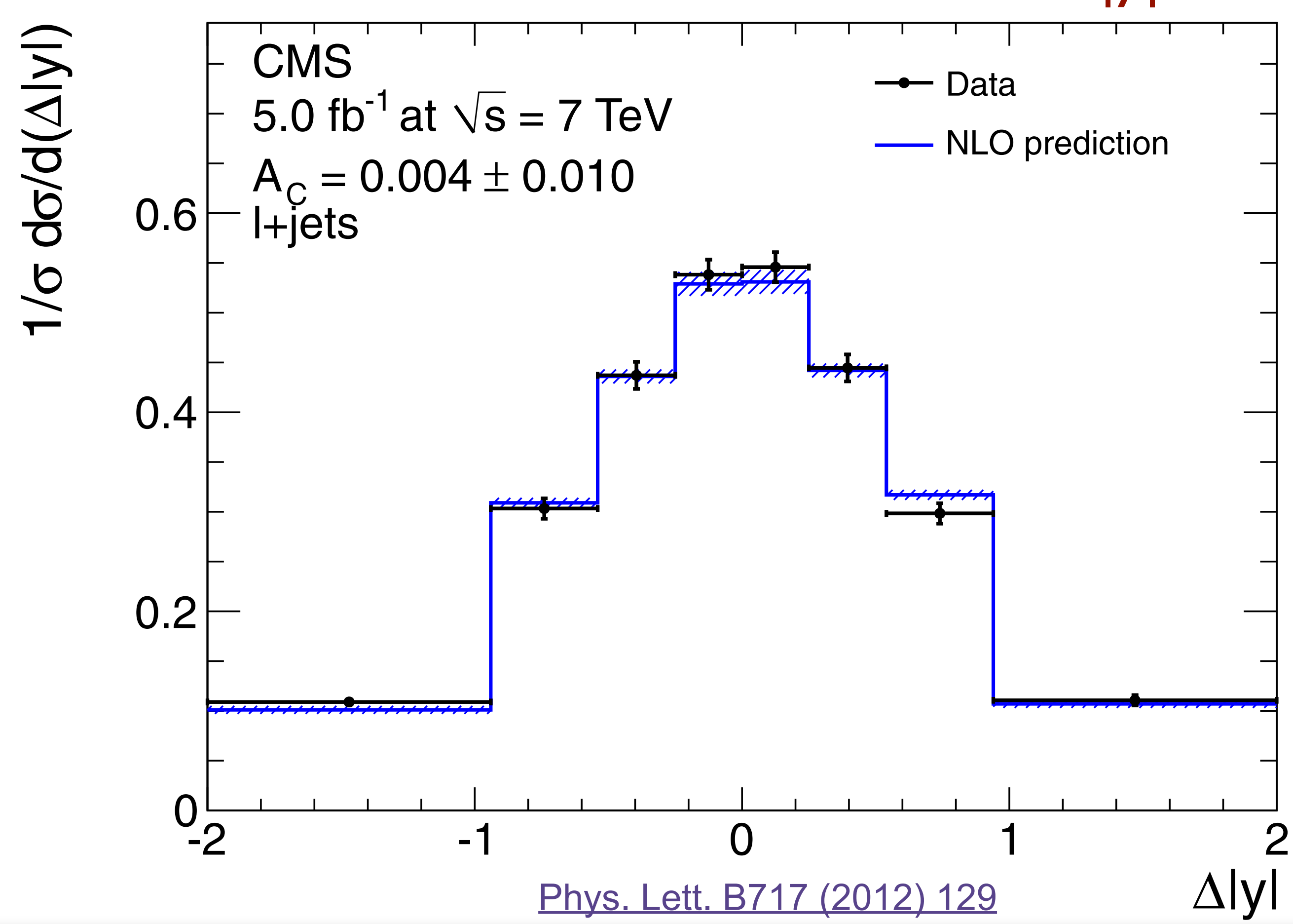
Charge asymmetry at the LHC (I)

- A_{FB} variable not useful at LHC because initial state is forward-backward symmetric (pp)
- If top quark preferentially emitted along the direction of q, expect tops to be more forward than antitops, i.e. $|y_t|>|y_{tbar}|$
  - because q have higher average momentum fraction than q̄ since there are no "valance" antiquarks
- $$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$
- LHC measurements consistent with SM ($A_C \simeq 0.006$):
  - $A_C = 0.004 \pm 0.015$ (CMS l+jets)
  - $A_C = 0.029 \pm 0.023$ (ATLAS, l+j and dilepton combined) ATLAS-CONF-2012-057

Comparison of expected rapidity distributions



differential cross-section wrt Δ|y|

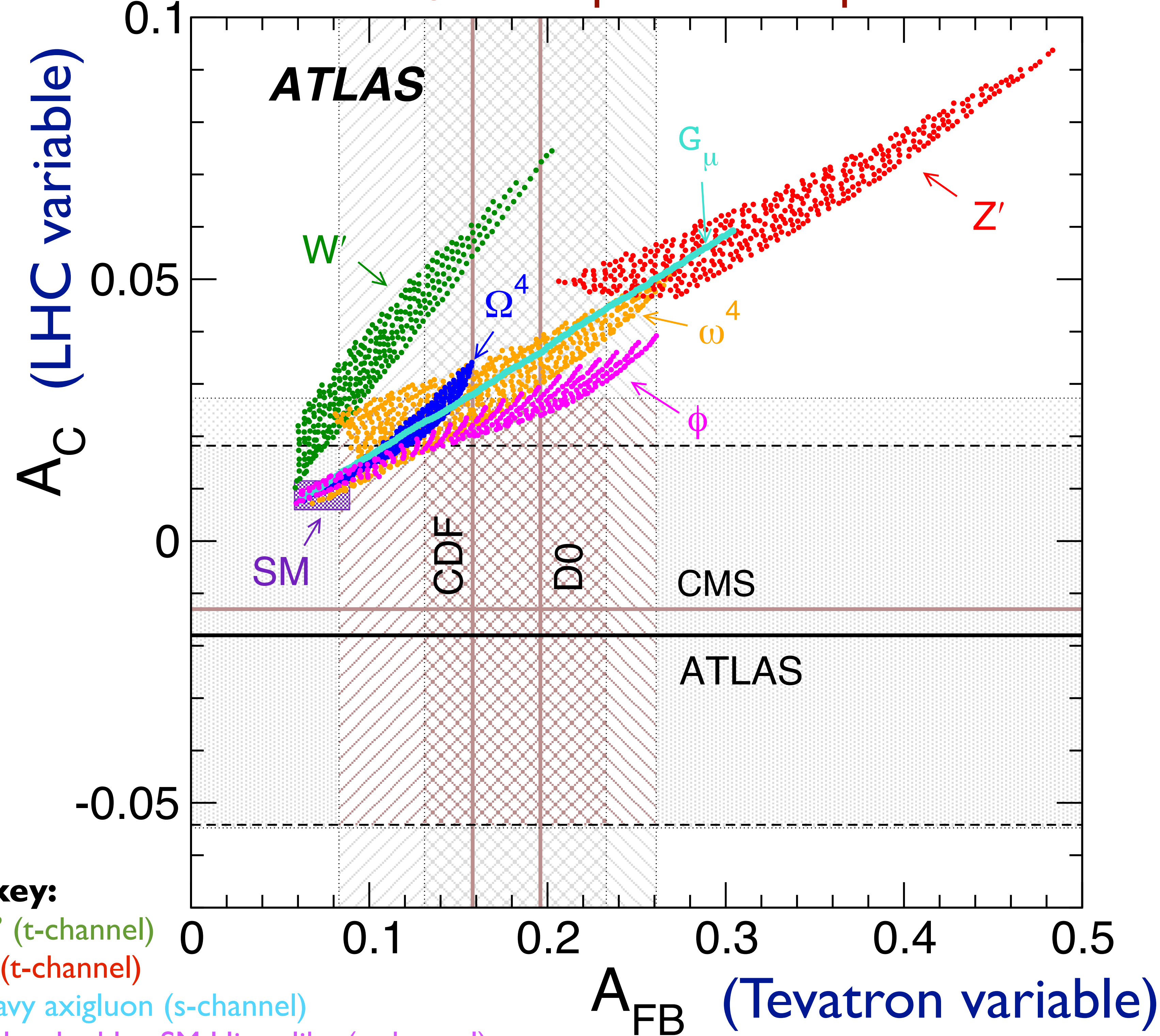


Phys. Lett. B717 (2012) 129

Charge asymmetry at the LHC (II)

- Certain NP models allow smaller discrepancy in LHC variable than in Tevatron variable
- Plot shows A_C vs A_{FB} parameter space
  - areas favoured by experiment are shaded
  - allowed areas in different theories marked by dots
- Newer LHC measurements (previous slide) favour higher A_C than the older results in the plot

A_C vs A_{FB} parameter space



key:
W' (t-channel)
Z' (t-channel)
heavy axigluon (s-channel)
scalar doublet, SM Higgs-like (t-channel)
charge 4/3, scalar, colour triplet (u-channel)
charge 4/3, scalar, colour sextet (u-channel)

Eur.Phys.J. C72 (2012) 2039

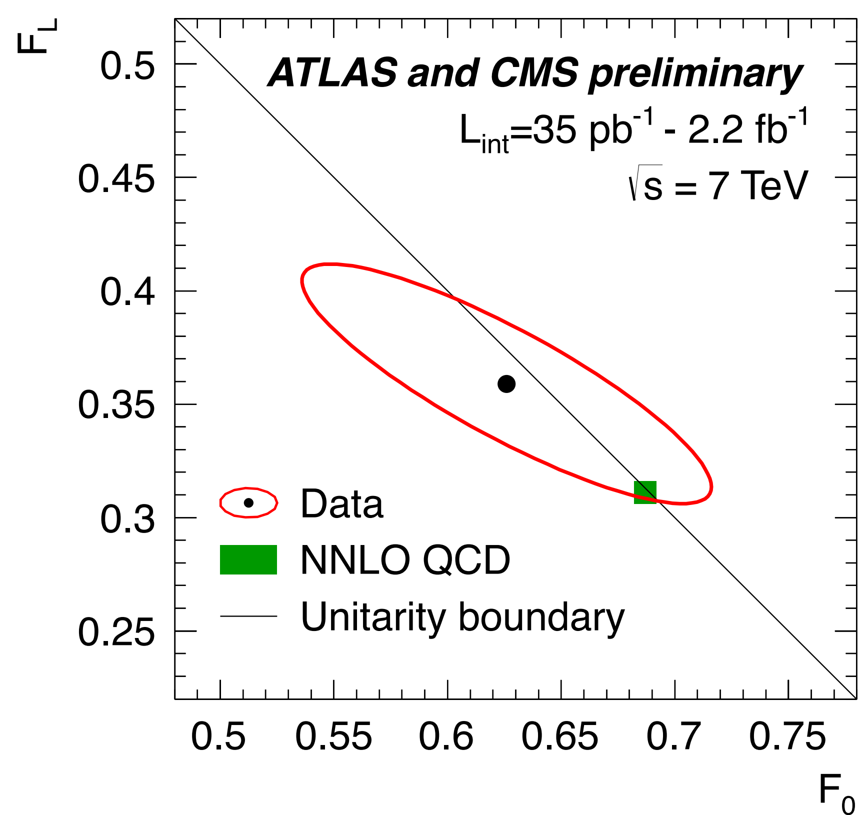
W helicity and anomalous Wtb couplings

- good test of the SM
- sensitive to new physics

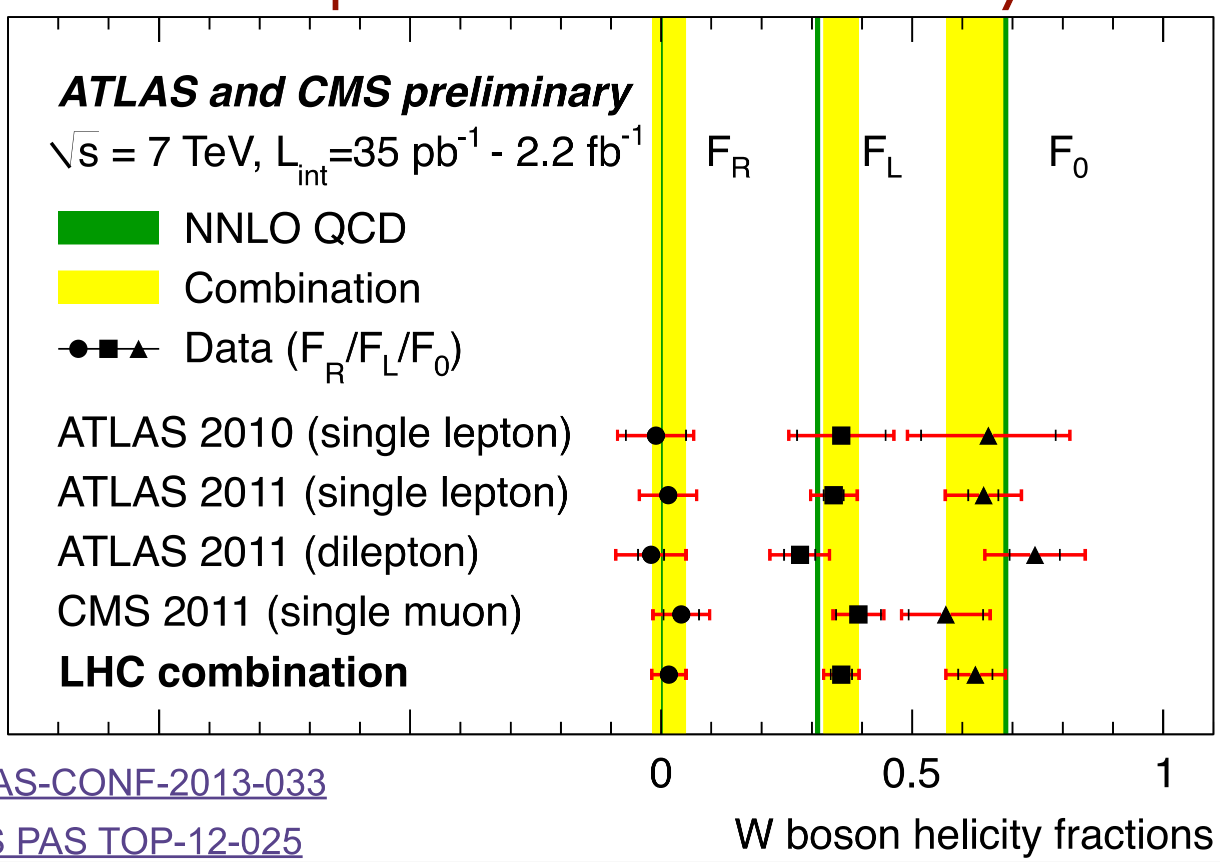
W helicity fractions in top decays (LHC combination)

- Measure W helicity fractions (F_R, F_L, and F_0) using θ* distribution in $t\bar{t}$ events
  - $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1+\cos\theta^*)^2\ F_R + \frac{3}{8}(1-\cos\theta^*)^2\ F_L + \frac{3}{4}\left(1-\cos^2\theta^*\right)\ F_0$$
  - θ* : angle of lepton in W rest frame, measured wrt the W momentum in top rest frame
- ATLAS measurements using template fitting method, and also acceptance-corrected angular asymmetries
- CMS result based on reweighting MC in likelihood technique to find fractions F_i preferred in data
- CMS and ATLAS results combined using BLUE

1σ confidence interval for F_L and F_0



Measured and predicted W boson helicity fractions



ATLAS-CONF-2013-033

CMS PAS TOP-12-025

F_0 = 0.626 ± 0.034 (stat.) ± 0.048 (syst.)

F_L = 0.359 ± 0.021 (stat.) ± 0.028 (syst.)

F_R = 0.015 ± 0.034 (assuming unitarity)

Limits on anomalous couplings

- The combined helicity fractions are in agreement with NNLO QCD predictions and can be used to set limits on new physics contributing to the Wtb vertex.
- Start with most general Wtb vertex:

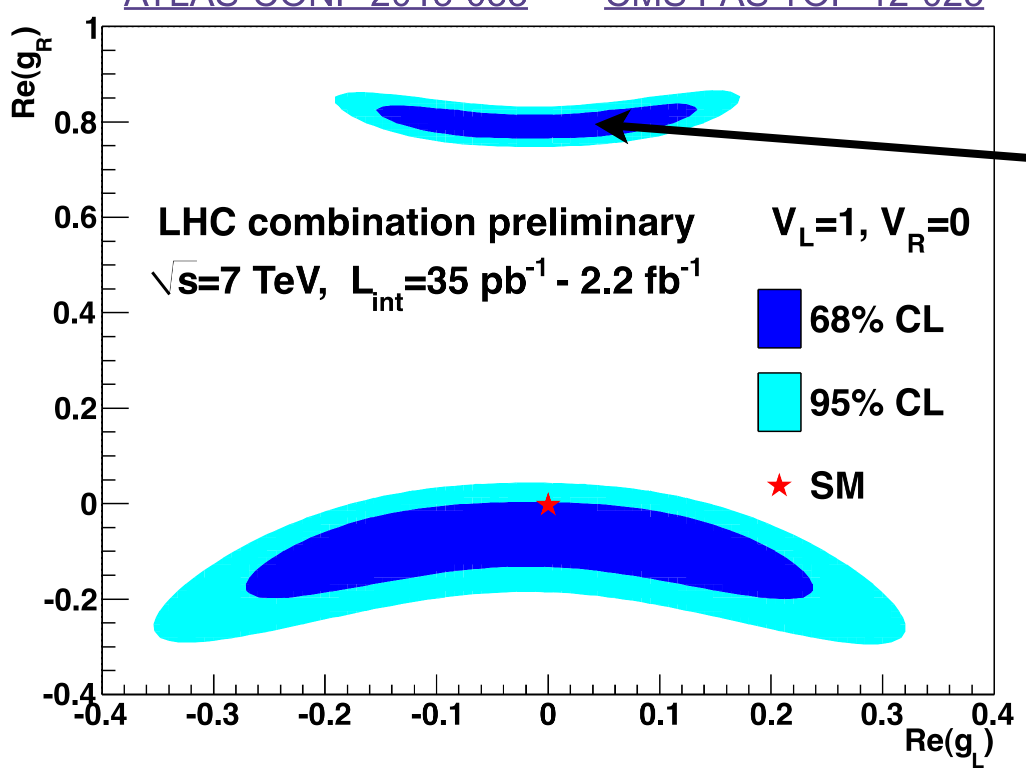
left and right handed vector couplings — left and right handed tensor couplings

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)\,tW_{\mu}^{-} + \text{h.c.}$$

SM part, $V_L = V_{tb}$ — anomalous couplings (zero in SM)

- Assuming V_L=1 and V_R = 0, set limits on real parts of g_L and g_R

ATLAS-CONF-2013-033 CMS PAS TOP-12-025



region highly disfavoured by single top cross-section measurements

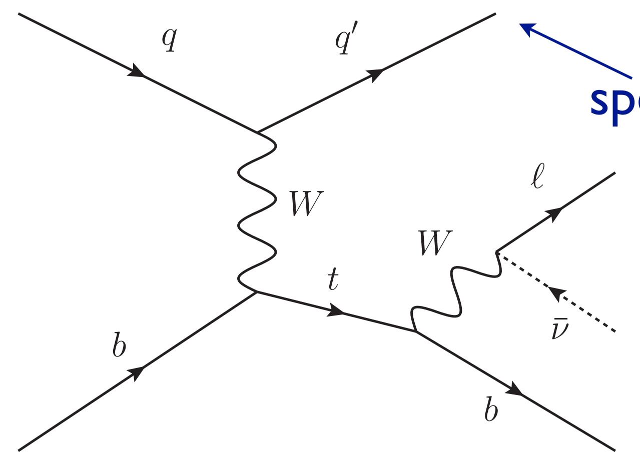
- Also assuming g_L=0:

$$\text{Re}(g_R) = -0.10 \pm 0.06\ (\text{stat.})\ ^{+0.07}_{-0.08}\ (\text{syst.})$$

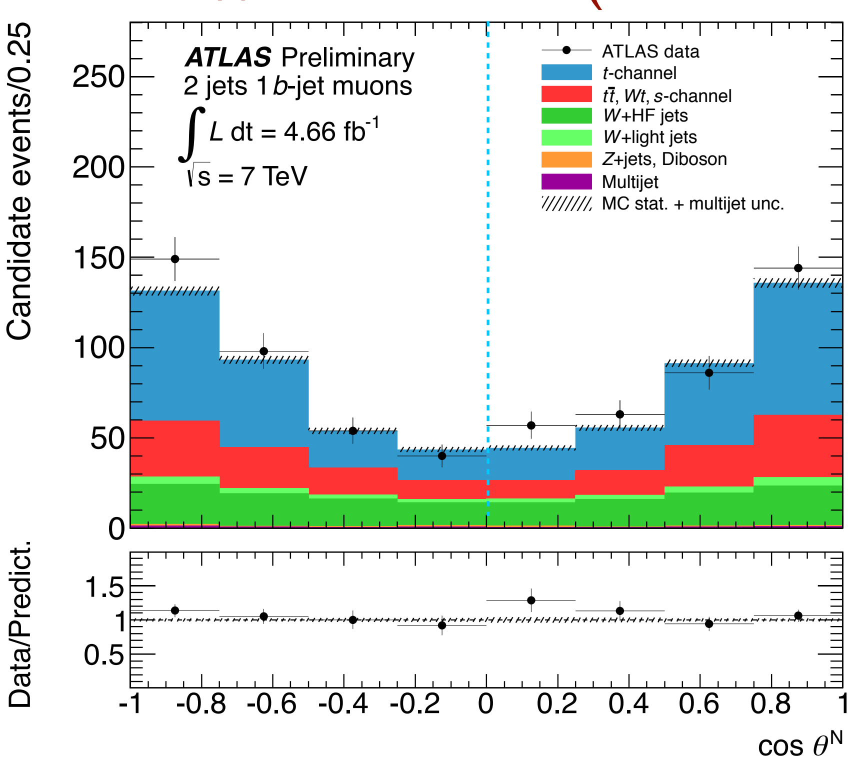
Search for CP violation in single top quark events

ATLAS-CONF-2013-032

- Helicity fractions measured using θ* not sensitive to all anomalous couplings
  - limits apply to real parts of couplings, not complex phases that would imply a CP-violating component
- Single-top quarks produced in the t channel predicted to be highly polarised (P~0.9) in direction of spectator quark
  - allows measurement of θ_N: similar to θ*, but angle measured wrt normal to W direction and top spin direction
- forward-backward asymmetry in the normal direction, A^N_{FB}, sensitive to imaginary part of g_R:
  - $A^{\mathrm{N}}_{\mathrm{FB}} \simeq 0.64\, P\, \mathbb{I}(g_{\mathrm{R}})$
- $\cos\theta_N$ distribution bkg-subtracted and unfolded to parton level for comparison with theory



$\cos\theta_N$ distribution (reco level)

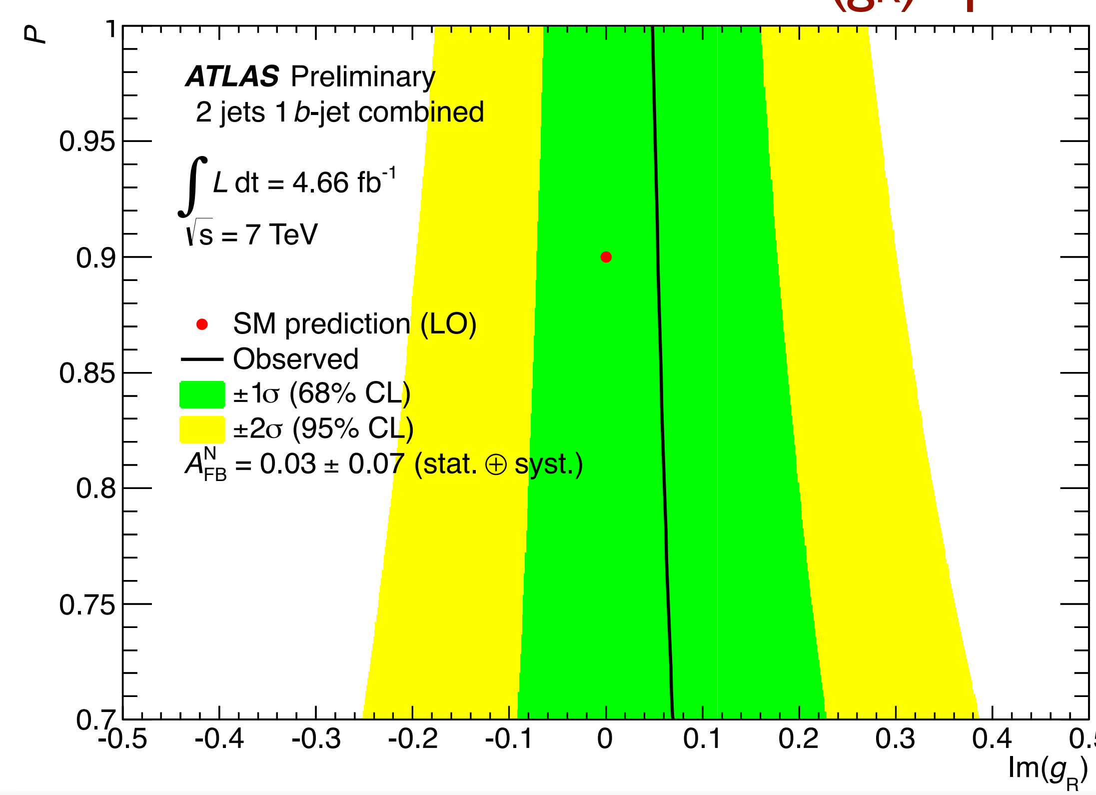


A^N_{FB} = 0.03 ± 0.07

$Im(g_R) \in$ [-0.20, 0.30] at 95 % CL (P=0.9)

first experimental limits on $Im(g_R)$

constraints in P vs $Im(g_R)$ space

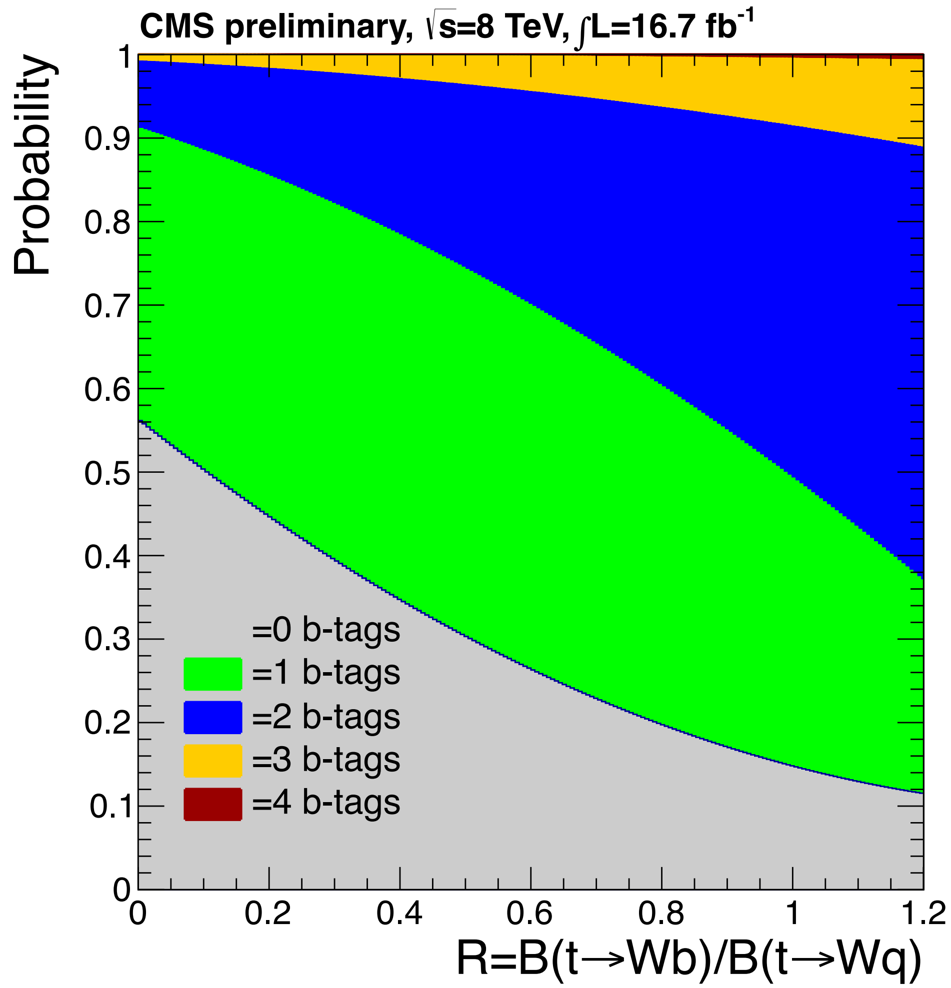


Ratio B(t → Wb)/B(t → Wq)

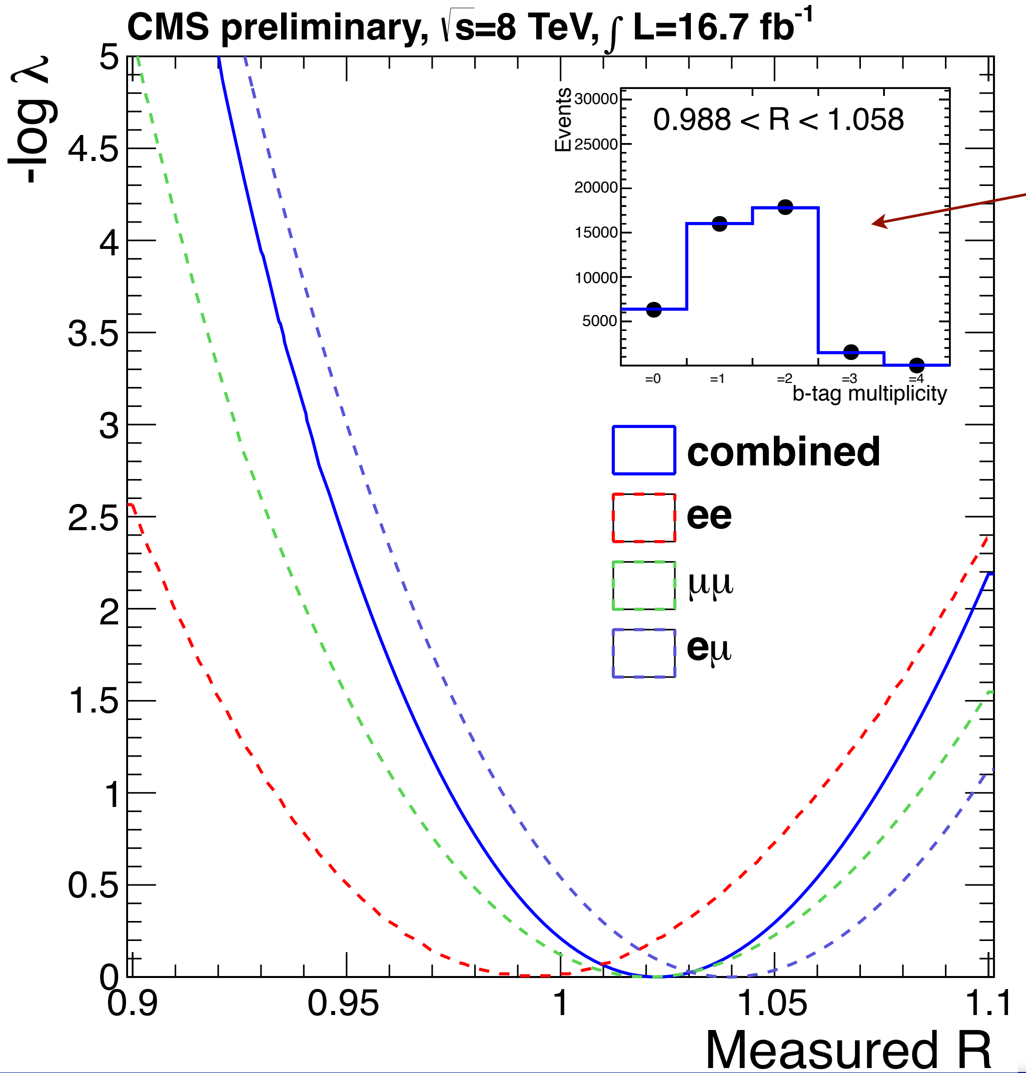
CMS PAS TOP-12-035

- Measurement in dilepton final state with 16.7 fb^{-1} 8 TeV data
- Construct probability model for expected b-tag multiplicities vs R where $\mathcal{R} = B(t \to Wb)/B(t \to Wq)$
  - done separately for different event categories based on channel (ee, eμ, μμ) and jet multiplicity
- Likelihood fit for R using observed b-tag multiplicity distribution

Probability model as a function of R



log likelihood for the 3 channels



b-tag multiplicity distribution (inclusive)

$$\mathcal{R} = 1.023^{+0.036}_{-0.034} \text{ (stat+syst)}$$

$$\mathcal{R} > 0.945 \text{ at 95\% CL}$$

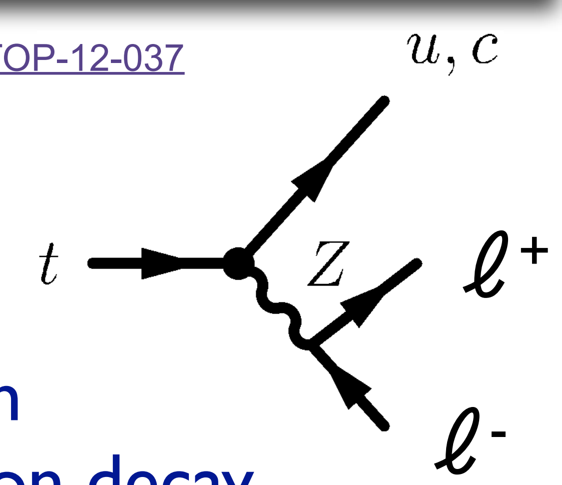
$$|V_{tb}| > 0.972 \text{ at 95\% CL} \quad (\text{using } \mathcal{R} = |V_{tb}|^2)$$

most precise measurement to date

Search for FCNC in top decays

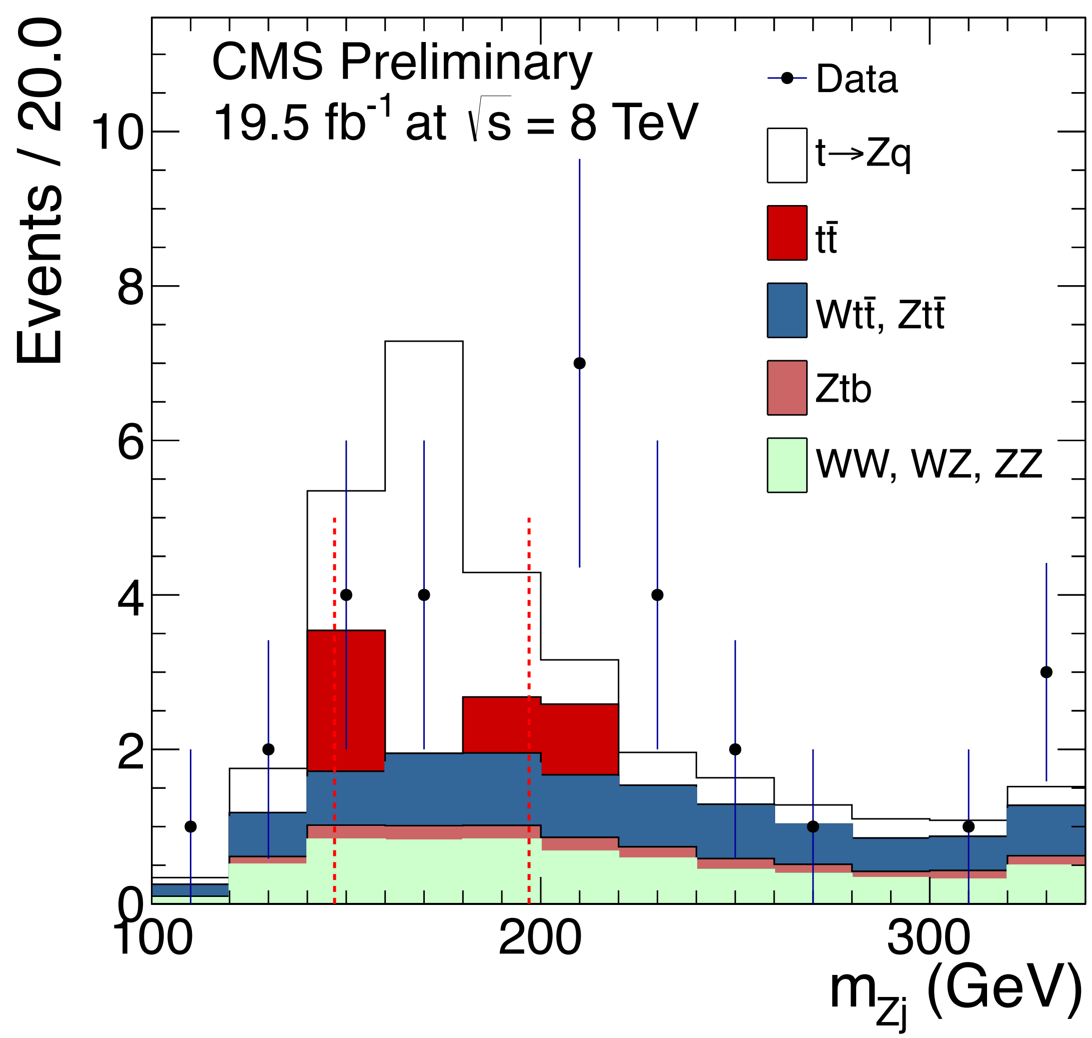
- Flavour changing neutral currents highly suppressed in SM

CMS PAS TOP-12-037

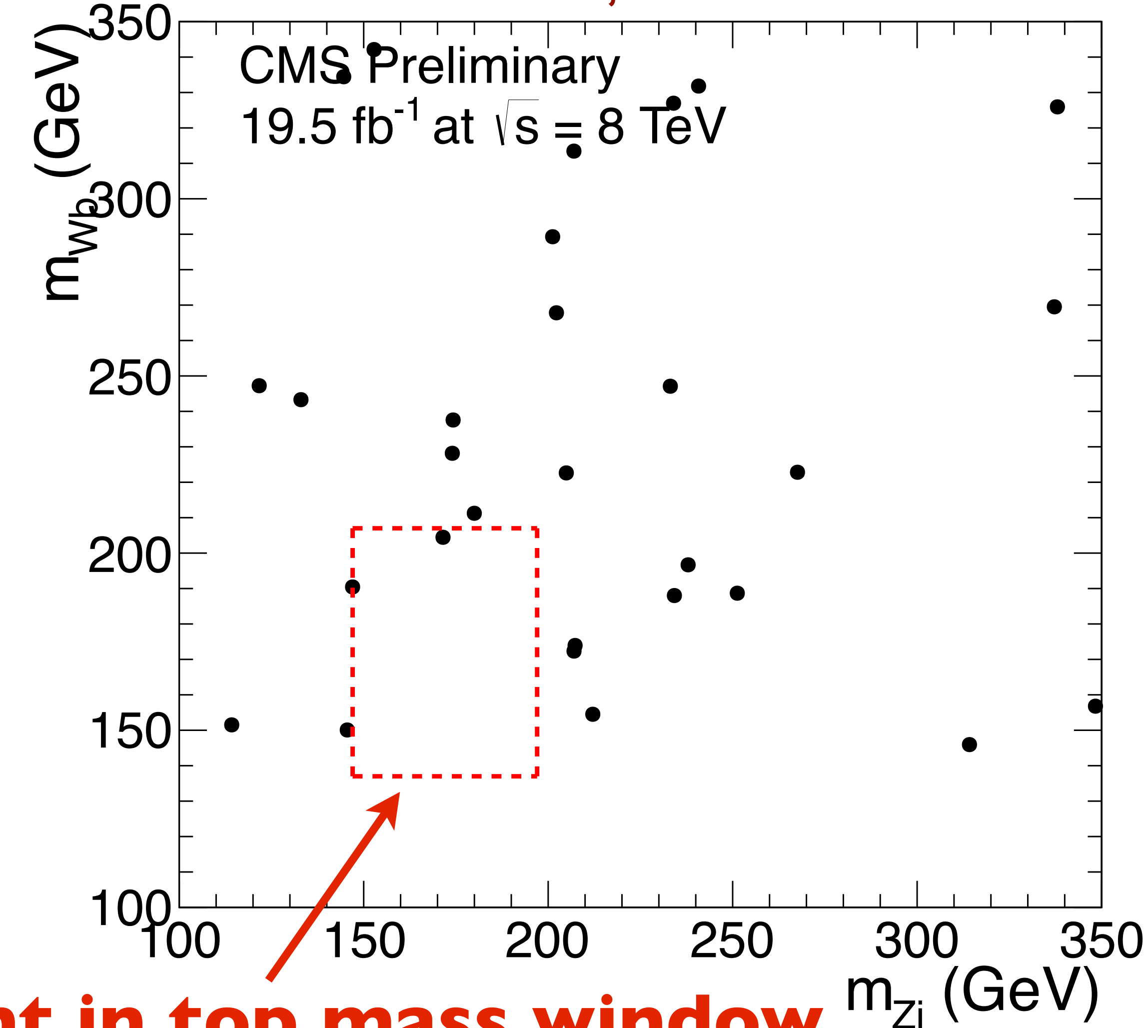


- Search for $t\bar{t}$ events with a FCNC decay, $t \rightarrow Zq$
  - $tt \rightarrow Wb + Zq \rightarrow \ell\nu b + \ell\ell q$
- Require two opposite-sign, isolated leptons (e or μ) consistent with Z-boson decay and an extra charged lepton consistent with W-boson decay
- Perform counting experiment in signal region: $\mathcal{B}(t \rightarrow Zq) < 0.07\%$ (95% CL)

m_{Zj} distribution (before m_{Wj} requirement)



m_{Wb} vs m_{Zj} distribution



1 event in top mass window

Conclusions and prospects for 13 TeV

- LHC top mass measurements matching precision of Tevatron
  - Tevatron was built as a top factory, but LHC now has far more statistics

- Abundance of tops at LHC allows for more detailed studies of top quark properties compared to Tevatron
  - differential cross-section compared to theory at NNLO
  - top, antitop mass difference and limits on V_{tb} and FCNC far exceed Tevatron precision

- Tevatron A_{FB} result still the only hint at new physics (good agreement with SM elsewhere)

- Many exciting results for full 2012 LHC dataset (~20 fb^{-1} at 8 TeV) still to come!

- $t\bar{t}$ cross section increases by factor of ~3 from 8 TeV to 13 TeV
  - statistical precision of 7 and 8 TeV datasets will be quickly eclipsed
  - higher precision test of the SM, with increased chance of observing new physics!

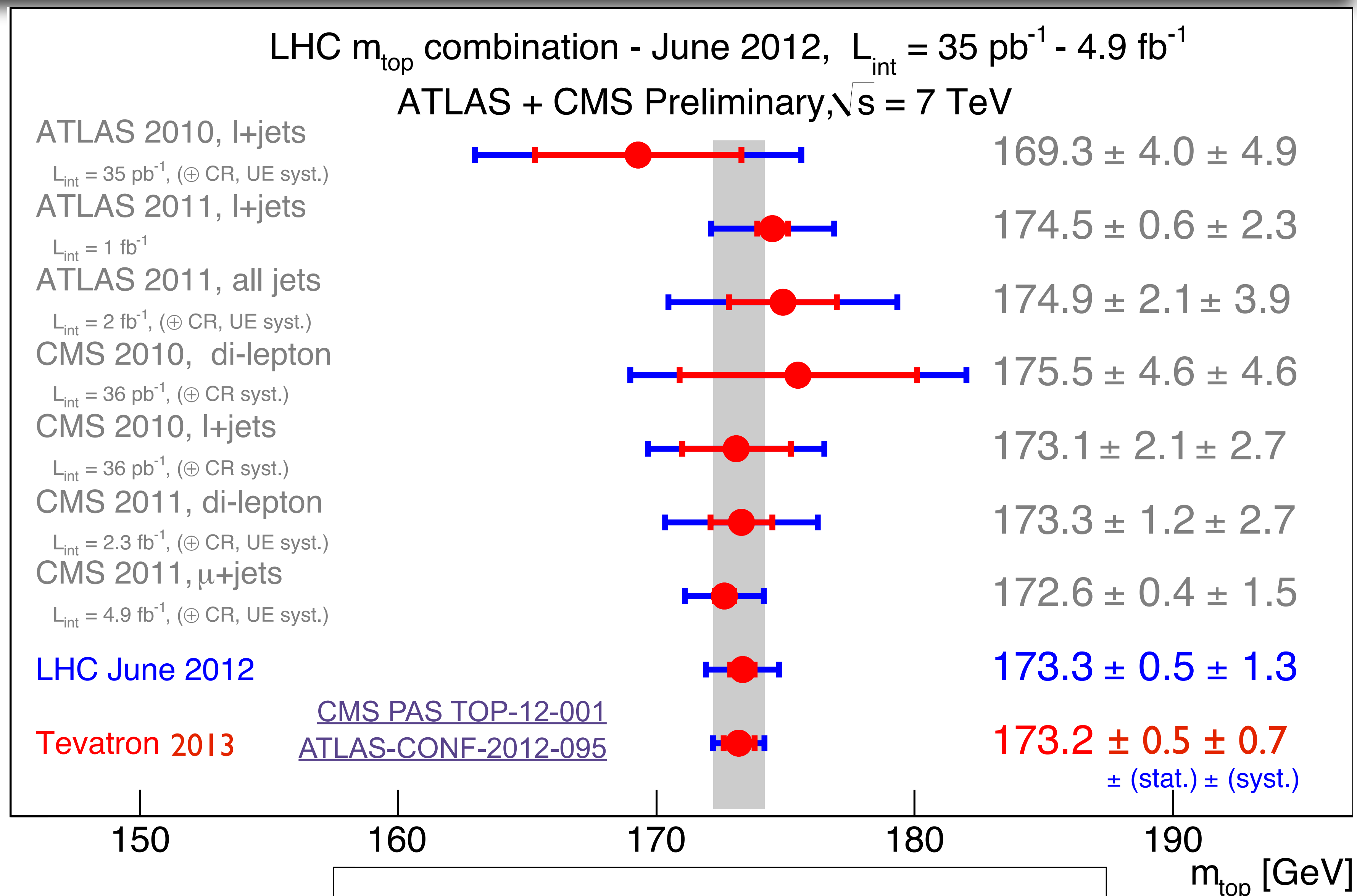
Backup

Public results

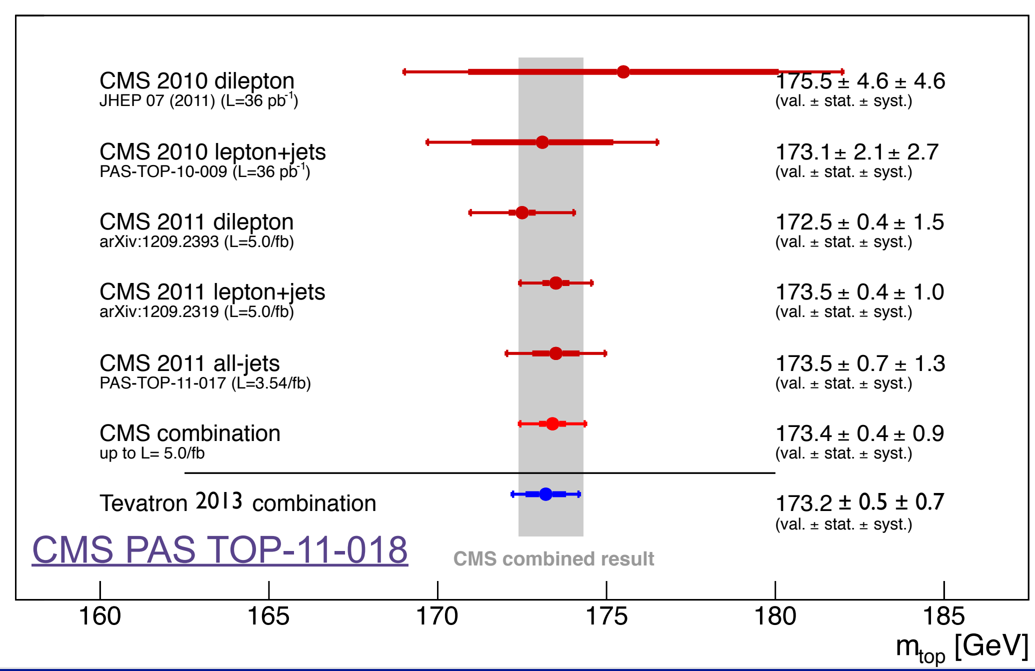
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- http://www-cdf.fnal.gov/physics/new/top/top.html
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- http://www-d0.fnal.gov/Run2Physics/top/

Mass combination at the LHC

- June 2012 combination, using BLUE
- Lepton+jets channel best sensitivity
  - smallest syst. unc.



- CMS results updated since combination
- CMS combination:
  - m_t = 173.4±0.4±0.9 GeV
- Consistent with Tevatron



CMS lepton+jets (slide 7)

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	μ+jets		e+jets		ℓ+jets	
	$\delta^{\mu}_{m_t}$ (GeV)	$\delta^{\mu}_{\mathrm{JES}}$	$\delta^{e}_{m_t}$ (GeV)	$\delta^{e}_{\mathrm{JES}}$	$\delta^{\ell}_{m_t}$ (GeV)	$\delta^{\ell}_{\mathrm{JES}}$
Fit calibration	0.08	0.001	0.09	0.001	0.06	0.001
b-JES	0.60	0.000	0.62	0.000	0.61	0.000
p_T- and η-dependent JES	0.30	0.001	0.28	0.001	0.28	0.001
Lepton energy scale	0.03	0.000	0.04	0.000	0.02	0.000
Missing transverse momentum	0.05	0.000	0.07	0.000	0.06	0.000
Jet energy resolution	0.22	0.004	0.24	0.004	0.23	0.004
b tagging	0.11	0.001	0.15	0.001	0.12	0.001
Pileup	0.07	0.002	0.08	0.001	0.07	0.001
Non-$t\bar{t}$ background	0.10	0.001	0.16	0.000	0.13	0.001
Parton distribution functions	0.07	0.001	0.07	0.001	0.07	0.001
Renormalization and factorization scales	0.23	0.004	0.41	0.005	0.24	0.004
ME-PS matching threshold	0.17	0.000	0.15	0.001	0.18	0.001
Underlying event	0.26	0.002	0.24	0.001	0.15	0.002
Color reconnection effects	0.66	0.004	0.39	0.003	0.54	0.004
Total	1.06	0.008	1.00	0.007	0.98	0.008

Table 1: List of systematic uncertainties for the muon+jets and electron+jets final states, and for the combined fit to the entire data set.

ATLAS lepton+jets (slide 8)

ATLAS-CONF-2013-046

	2d-analysis		3d-analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	0.008	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

Table 2: The measured values of m_{top} and the contributions of various sources to the uncertainty of the 2d-analysis and 3d-analysis.The corresponding uncertainties on the measured values of the JSF and for the 3d-analysis also the bJSF are also shown. The *Signal MC generator* systematic uncertainty is obtained from pairs of independent Monte Carlo samples. The statistical precision on m_{top} of all Monte Carlo samples in the 3d-analysis (2d-analysis) is about 0.15 GeV (0.07 GeV). The corresponding values for the JSF and bJSF are 0.0017 and 0.0006, respectively. Consequently, for the uncertainty source *Signal MC generator* the statistical uncertainty of the evaluation of the systematic uncertainty on m_{top} is 0.21 GeV for the 3d-analysis and 0.10 GeV for the 2d-analysis. For the sources *Hadronisation*, *Underlying event*, *Colour reconnection*, *ISR and FSR* the same hard scattering events before hadronisation are used, albeit with respective different further processing for the source under study. For these sources the samples are not independent, and the statistical uncertainty of the evaluation of the systematic uncertainty is correspondingly smaller.

Search for FCNC single top production

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- Classify events with leptonic single top-quark signature into signal and background using a neural network
- No signal observed, so set 95 % CL upper limits on $\sigma(qg \to t) \times B(t \to Wb)$
- $\sigma(qg \to t) \times B(t \to Wb) < 3.9$ pb
  - $K_{ugt}/\Lambda < 6.9 \times 10^{-3}$ TeV^{-1} (95 % CL)
  - $K_{cgt}/\Lambda < 1.6 \times 10^{-2}$ TeV^{-1} (95 % CL)
  - $B(t \to ug) < 5.7 \times 10^{-5}$ (95 % CL)
  - $B(t \to cg) < 2.7 \times 10^{-4}$ (95 % CL)
- Also search in ttbar decays (2.1 fb^{-1} 7 TeV data):
  - $\mathcal{B}(t \to Zq) < 0.73\%$ (95% CL)

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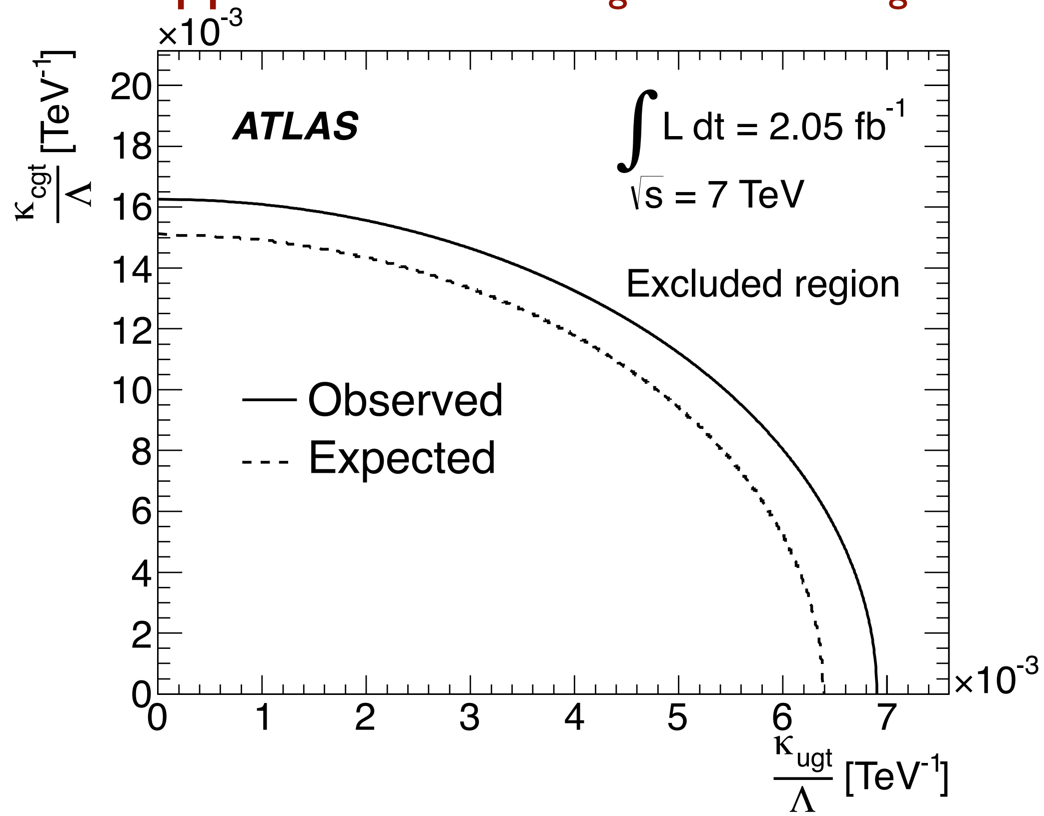
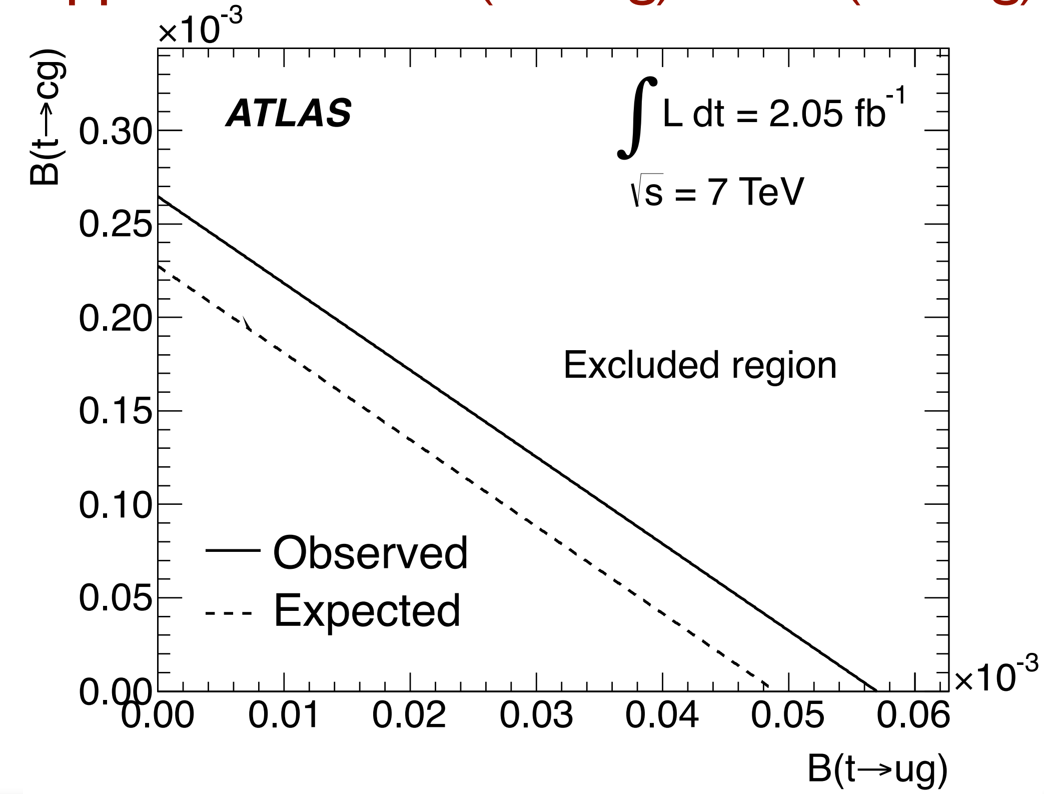
upper limit on K_{ugt}/Λ and K_{cgt}/Λ



upper limit on B(t→ ug) and B(t→ cg)

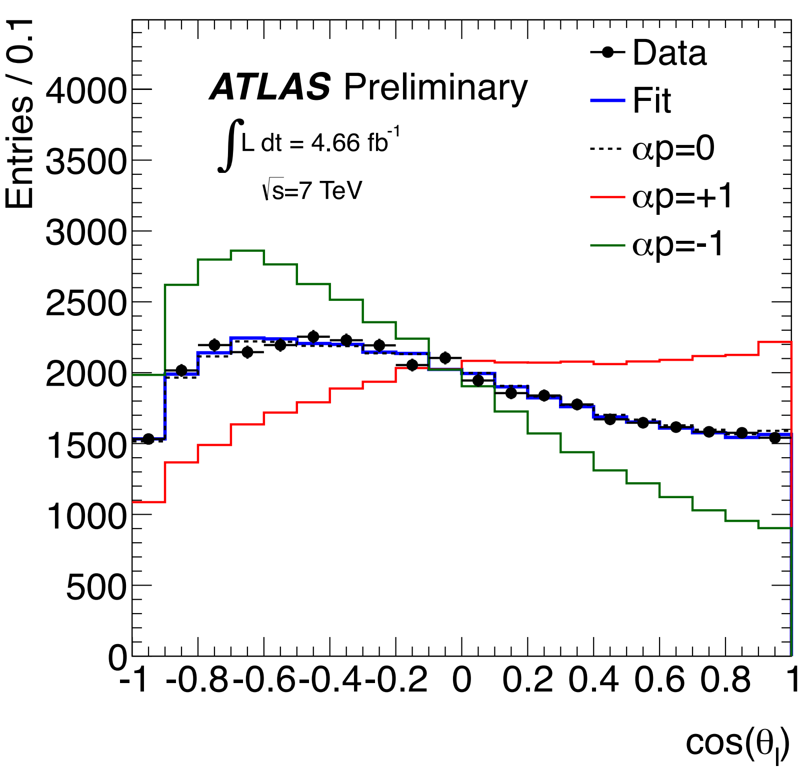


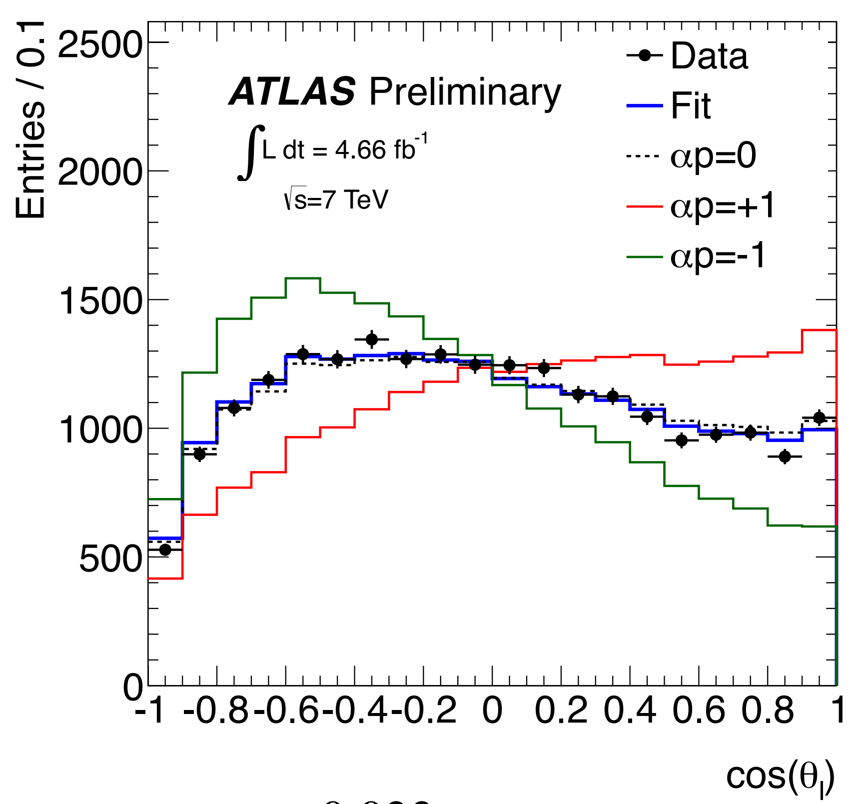
Top polarisation

[ATLAS-CONF-2012-133](#) [CMS PAS TOP-12-016](#)

- Atlas: lepton+jets, template fit
- CMS: dilepton, unfolded to parton level
- Distribution of angle of lepton in top CM (helicity basis) $\propto 1 + \alpha_i p \cos\theta_i$
- alpha=1 in SM at LO
- fraction of + polarised tops: $$f = \frac{1}{2} + \frac{N(\cos\theta_l > 0) - N(\cos\theta_l < 0)}{N(\cos\theta_l > 0) + N(\cos\theta_l < 0)}$$

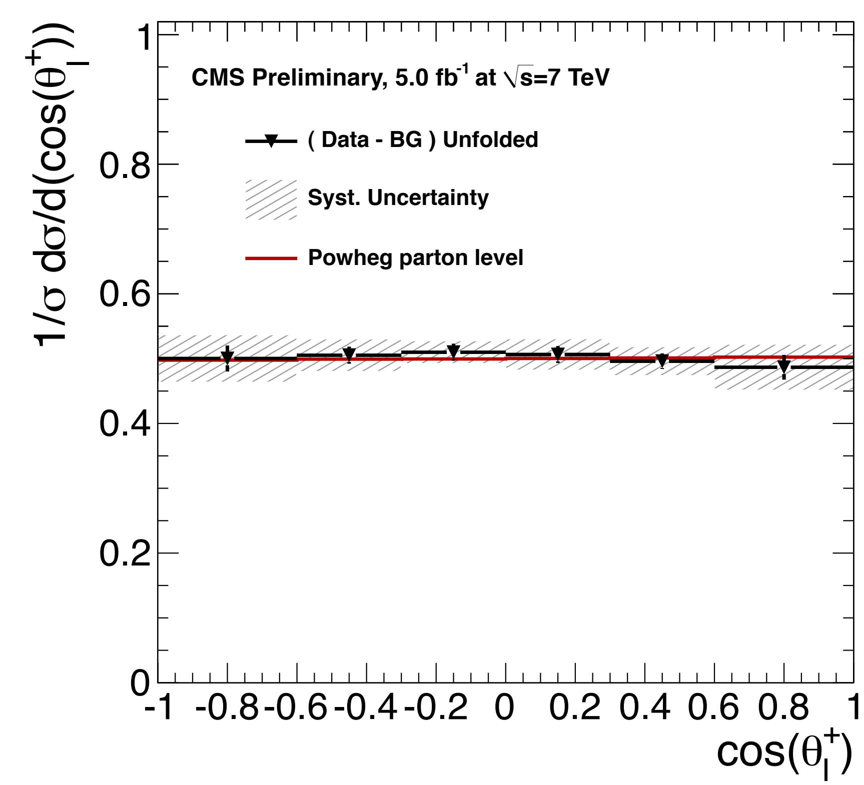
Reco level





$$f = 0.470 \pm 0.009(\text{stat})^{+0.023}_{-0.032}(\text{syst})$$

Parton level

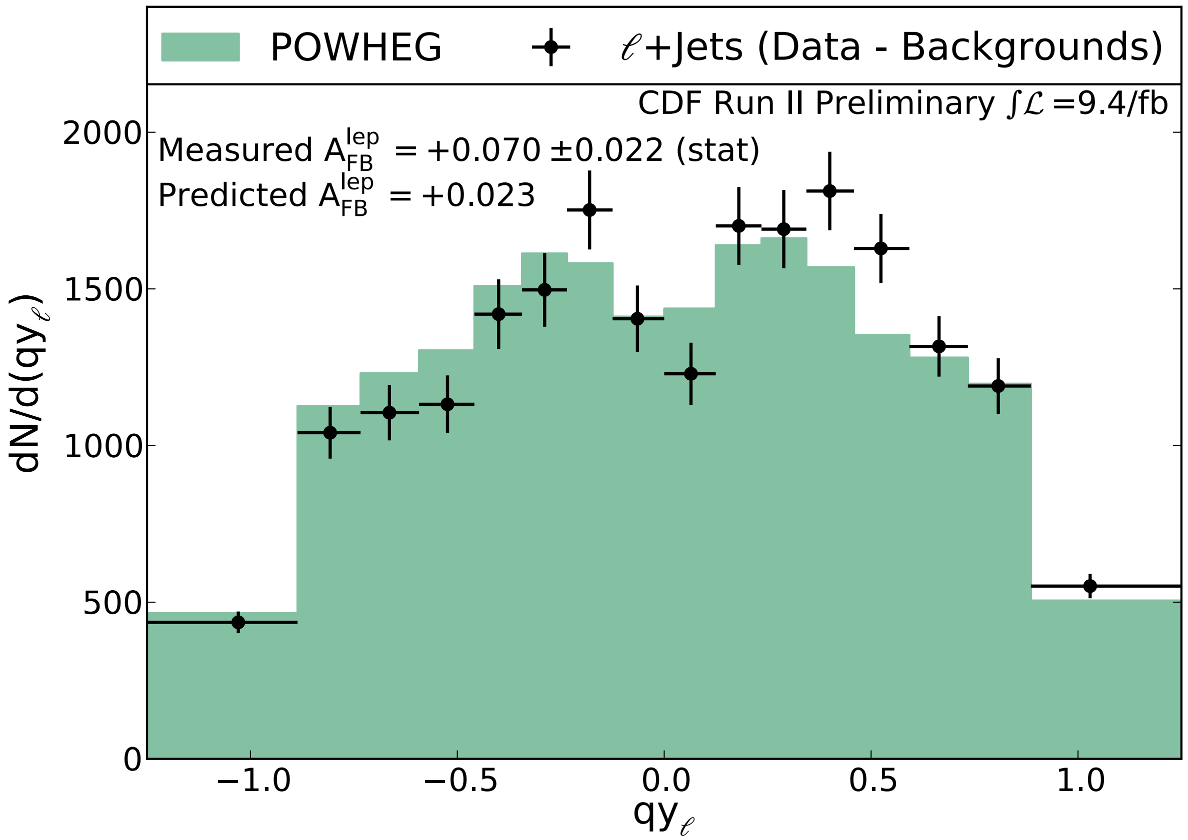


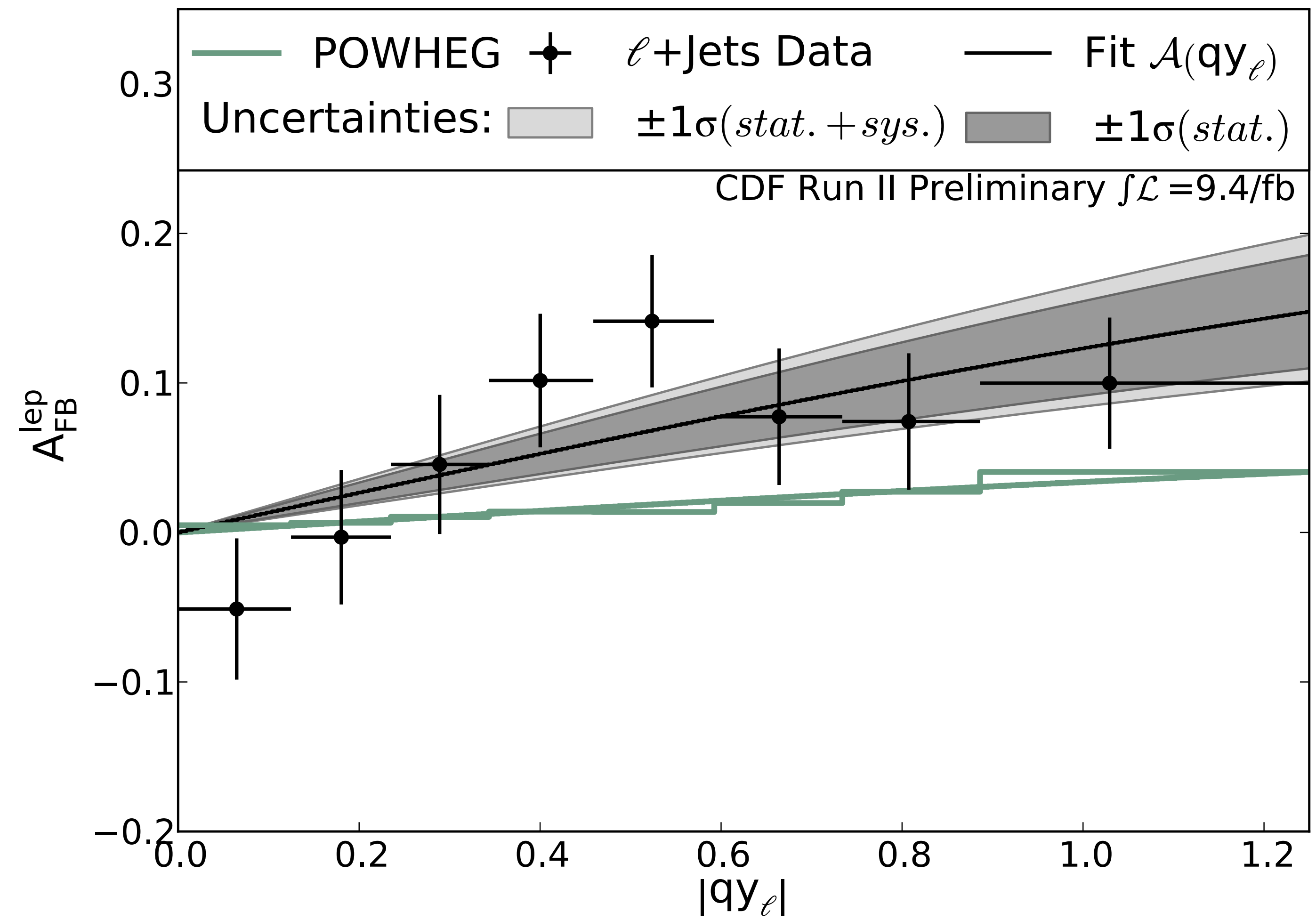
f = 0.491±0.029±0.041

Lepton charge asymmetry

[CDF Conf. Note 10975]

- lepton inherits some of the asymmetry of its parent top
- also sensitive to the polarization of the ttbar





CDF Run II Preliminary $\int \mathcal{L} = 9.4/fb$

Correction Level	CDF Data	POWHEG
Data Only	0.067±0.016	0.032
Backgrounds Subtracted	0.070±0.019 ± 0.011	0.023
Fully Extrapolated	$0.094 \pm 0.024^{+0.022}_{-0.017}$	0.027