TOP MASS AND PROPERTIES AT LHC AND TEVATRON

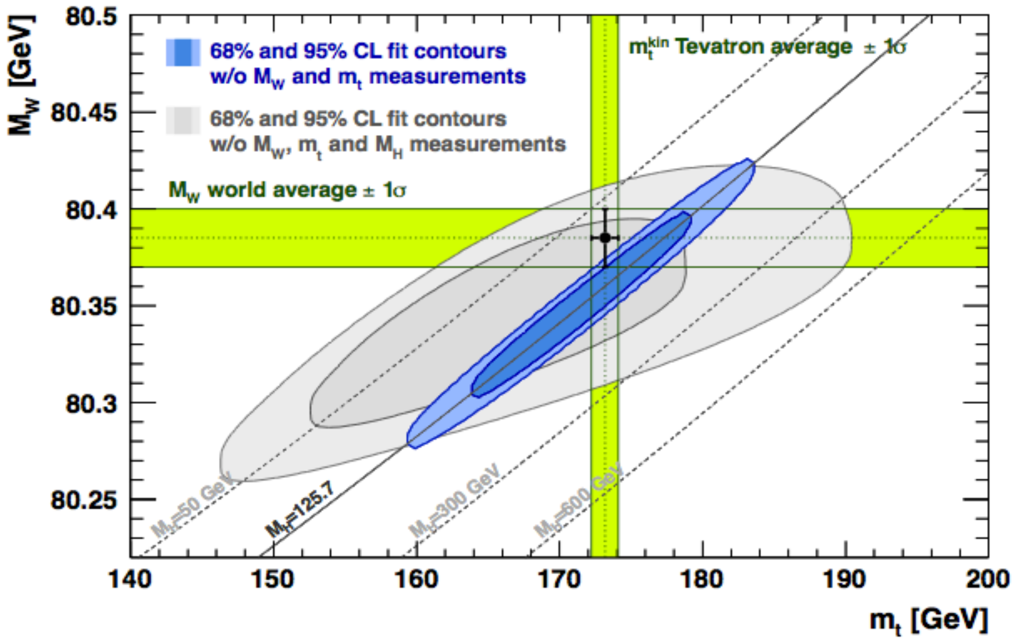
María José Costa (IFIC-Valencia)
On behalf of the CDF, D0, ATLAS and CMS Collaborations

INTRODUCTION

- The top quark is the heaviest fundamental particle leading to unique properties
  - Yukawa coupling of almost unity
  - Provides a probe for electroweak symmetry breaking
  - Sensitive to new physics in production and decay
  - Short lifetime → decays before hadronisation →

  Properties can be studied from distributions of decay products

EPJ 72 2205 (2012)
arXiv:1209.2716



Deviation of the measured top quark properties from the SM prediction would be a signal of new physics

Top mass is a free parameter of the SM, which together with m_W constrains m_H through EW quantum corrections

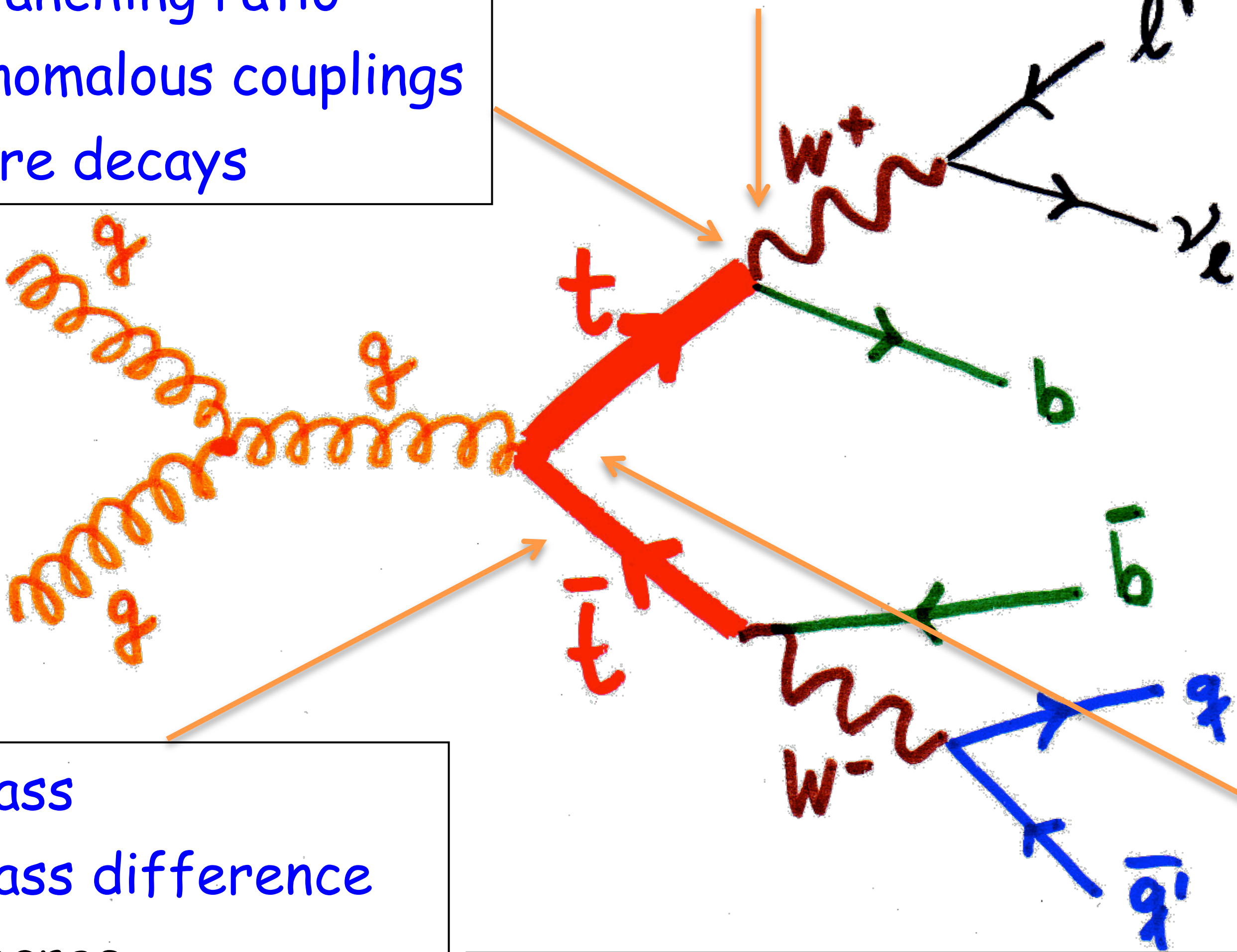
INTRODUCTION

For more information, see talks in parallel sessions:

- Tevatron combined top quark mass (P.Bartos)
- Top quark mass measurements with CMS (H.Bakhshiansohi)
- Intrinsic top quark properties: top mass, charge and polarisation at LHC in ATLAS (F.Balli)
- Top quark pair properties: spin correlations, charge asymmetry and complex final states at LHC in ATLAS (F.Rubbo)
- Measurements of the top-quark properties at CMS (A.Jafari)

W polarisation

Branching ratio
Anomalous couplings
rare decays



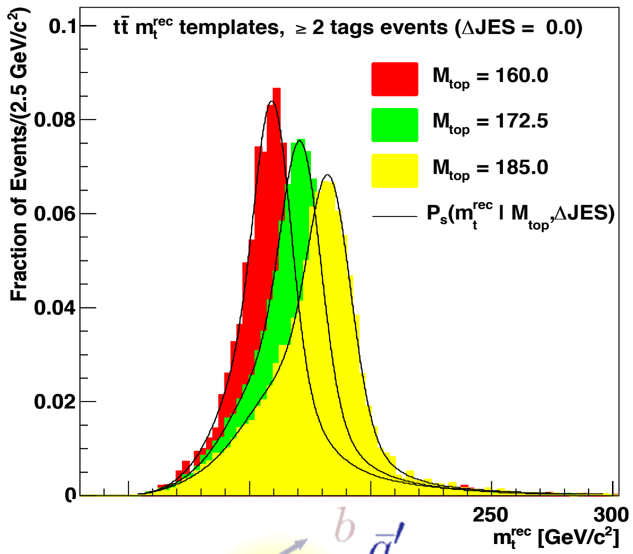
Mass
Mass difference
Charge
Width
Lifetime

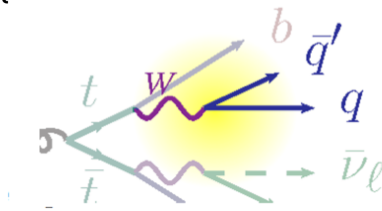
Spin correlation
Top polarisation
Charge asymmetry

Will present some of the properties measured in tt and single top events *(emphasis on latest/precise measurements)*.

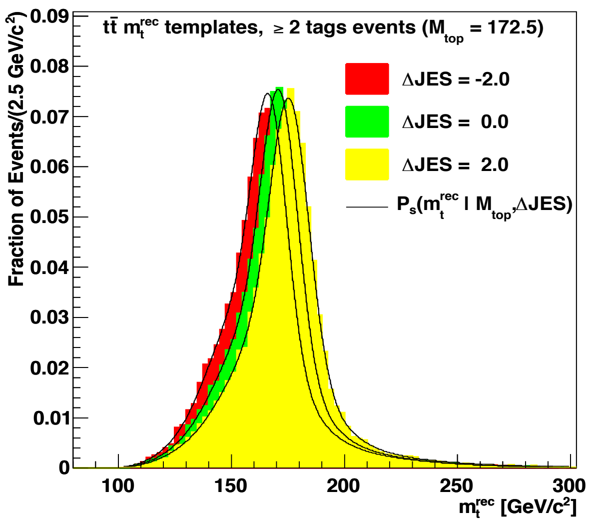
TOP MASS

- Several methods used for the most precise measurements:
  - Template method: compare data to templates from simulation with different masses
  - Ideogram method: event likelihood from Breit-Wigner (signal) convoluted with resolution
  - Matrix element method: event probability as a function of LO matrix element





In some final states W can be fully reconstructed → constrain a m_W estimator with the m_W



The analyses are generally calibrated on MC simulation → The top quark mass as defined in the MC is determined

TEVATRON TOP MASS MEASUREMENTS

Tevatron (CDF+D0) Combination

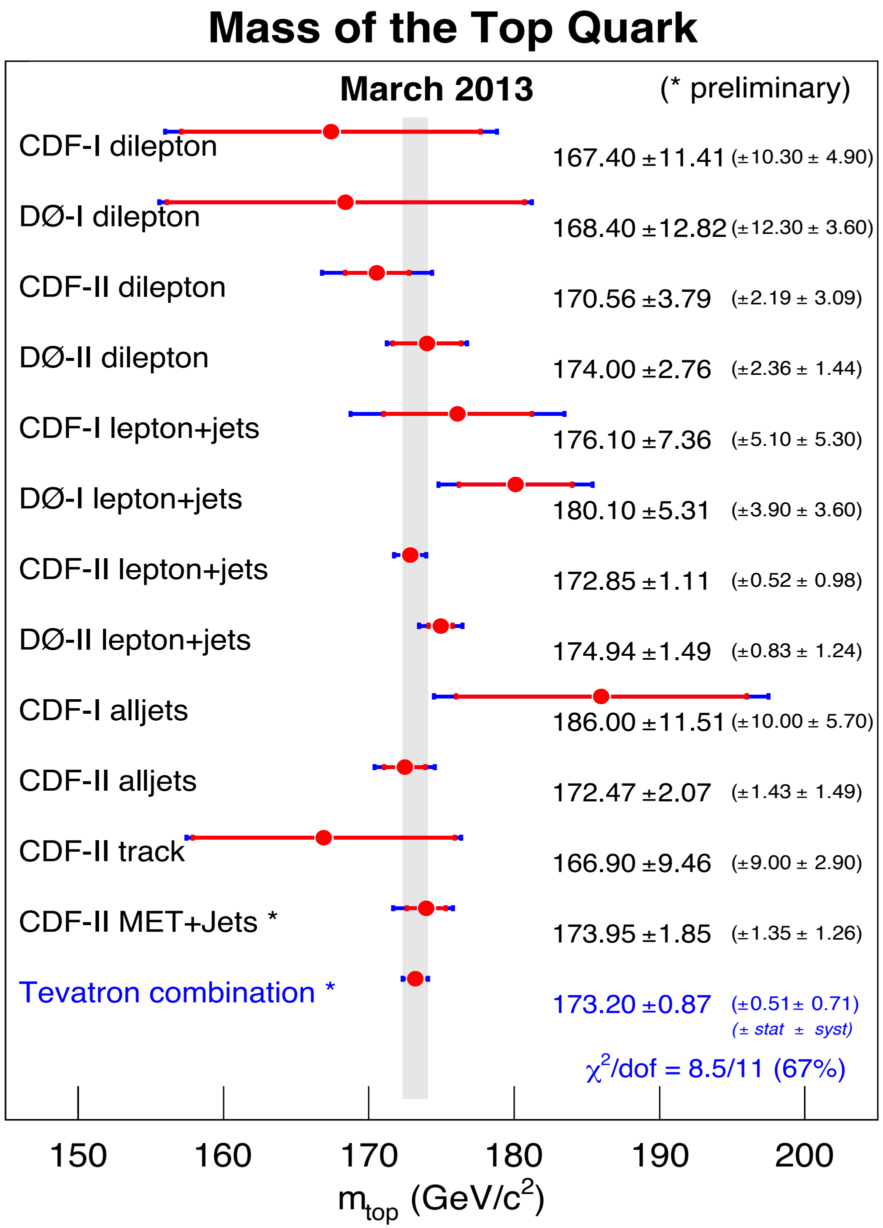
CDF Conf. note 10976, D0 Conf note 6381

- Using Best Linear Unbiased Estimator
- 12 measurements combined
- Categorisation of systematic uncertainties chosen so that they are either fully correlated or uncorrelated between experiments (see also Phys.Rev.D 86 (2012) 092003)

$$173.20 \pm 0.51\ (\mathrm{stat}) \pm 0.71\ (\mathrm{syst})\ \mathrm{GeV}$$

Dominant unc.: JES and Signal modelling

(relative precision 0.5%!)



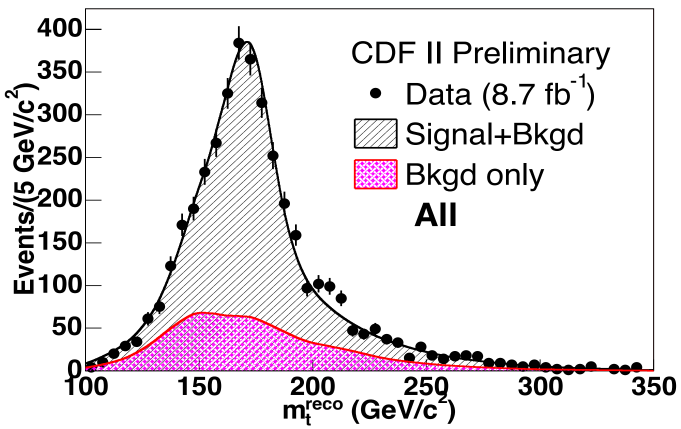
TEVATRON TOP MASS MEASUREMENTS

- The most precise measurements at Tevatron are:

PRL 109, 152003 (2012)

l+jets channel, 8.7 fb^{-1}

Templates built with 3 observables (m_t^{reco}, m_t^{reco2}, m_{jj})



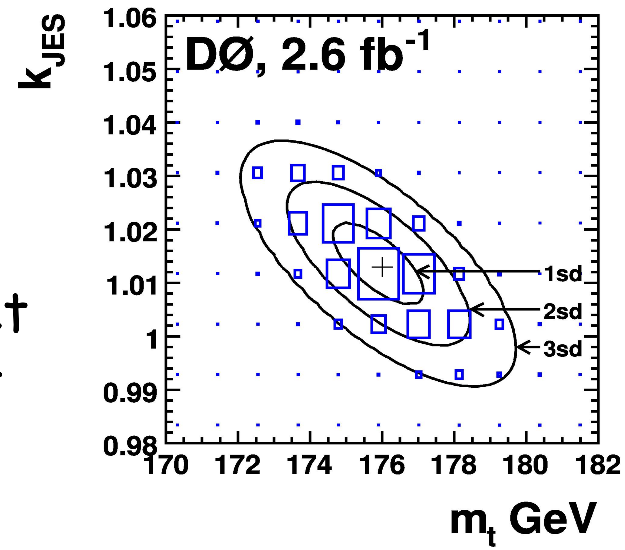
$$172.85 \pm 0.71(\text{stat}) \pm 0.85(\text{syst})\ \text{GeV}$$

(0.63%)

PRD 84 032004 (2011)

l+jets channel, 3.6 fb^{-1}

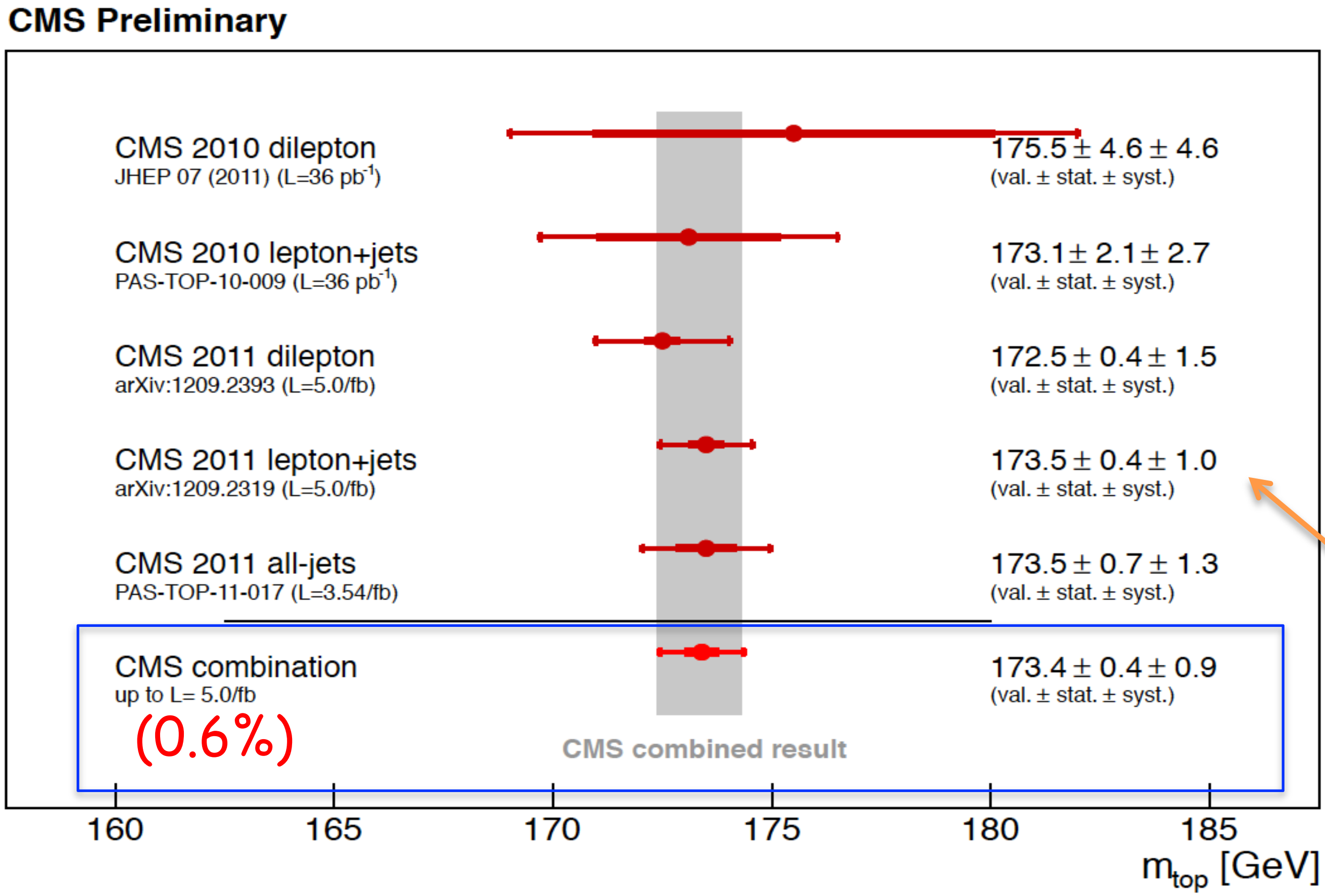
Matrix element method, Combination of 2 data set independent results



$$174.94 \pm 0.83(\text{stat}) \pm 0.78(\text{JES}) \pm 0.96(\text{syst})\ \text{GeV}$$

(0.85%)

CMS TOP MASS MEASUREMENTS



Methods:

- Lepton+jets: ideogram
- All-hadronic: ideogram
- Dilepton: analytical matrix weighting, KINb

Most precise measurement dominated by: bJES and Colour Reconnection effects

- An alternative measurement based on endpoint determinations in kinematic distributions in dilepton channel leads to compatible results (*arXiv:1304.5783*):

$$173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}$$

(dominant unc.: JES)

CMS TOP MASS KINEMATIC DEPENDENCE

CMS PAS TOP-12-029

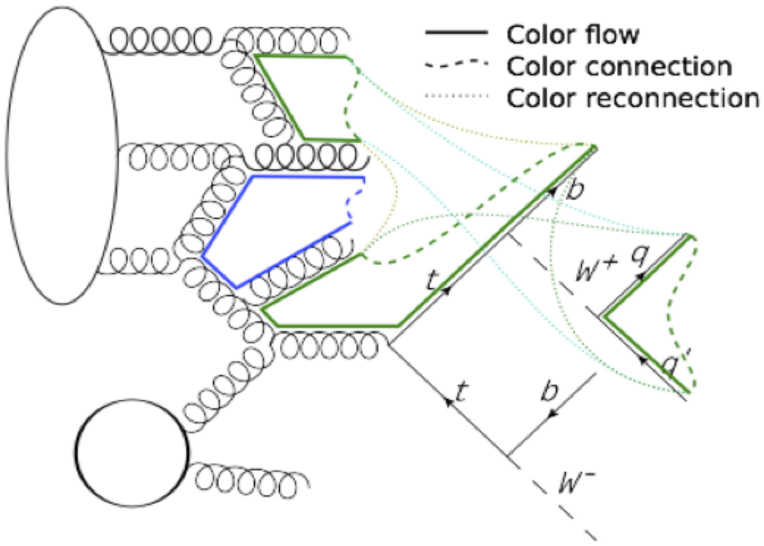
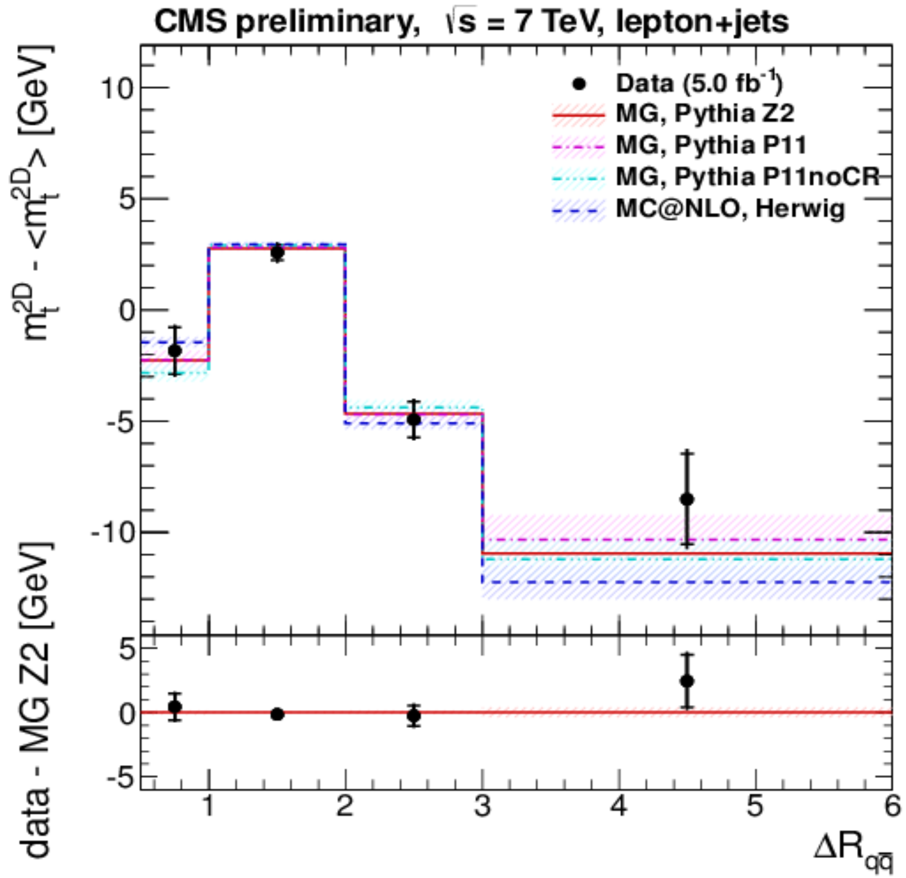
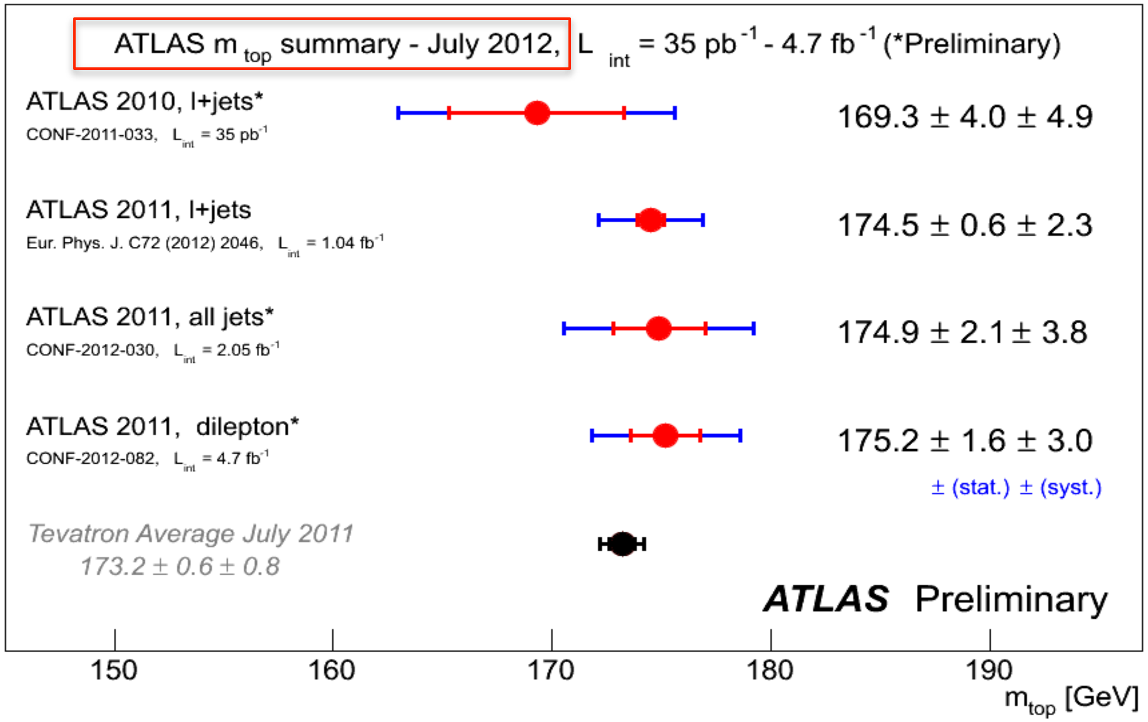


	Fig.	Observable
Colour reconnection	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b quark kinematics	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$

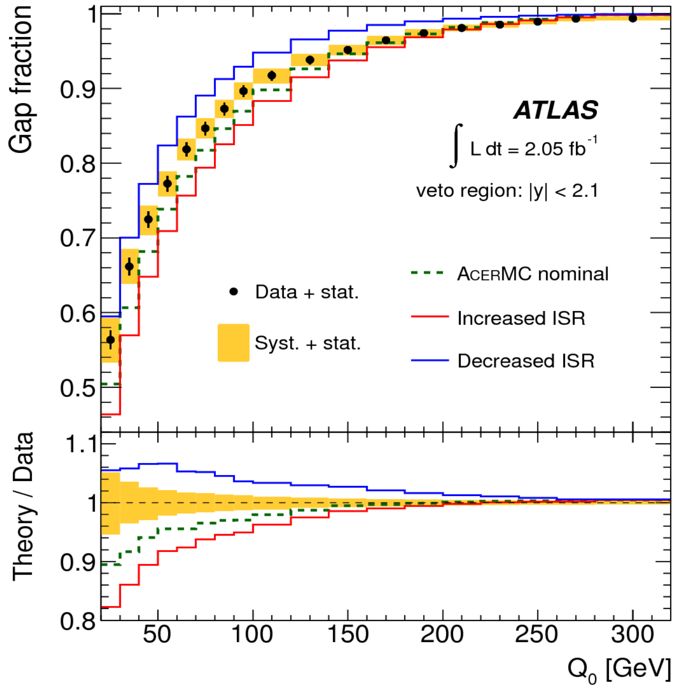


Within the current precision, no mis-modelling effect observed due to CR, ISR/FSR or b-quark kinematics

ATLAS TOP MASS MEASUREMENTS



Eur.Phys.J. C72 (2012) 2043



Most precise measurement in lepton+jets (2D template fit) dominated by:

- bJES
- ISR/FSR

Main focus in ATLAS towards a better understanding of these sources of systematics

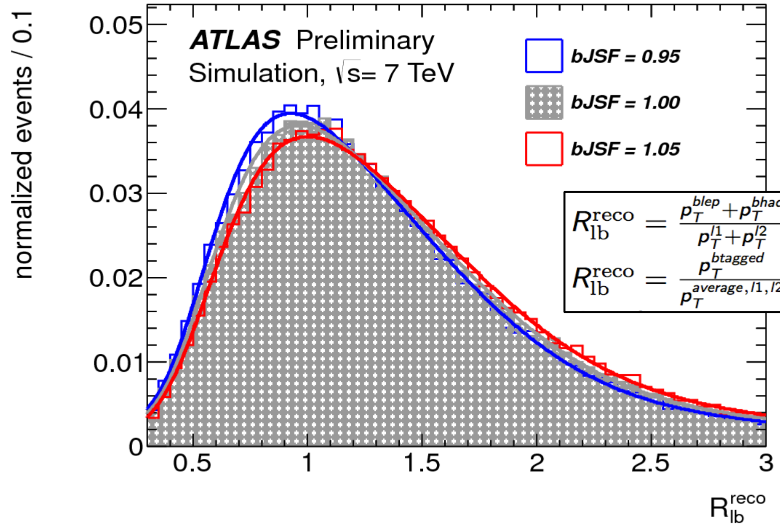
ATLAS-CONF-2013-046

NEW

ATLAS TOP MASS: 3D TEMPLATE

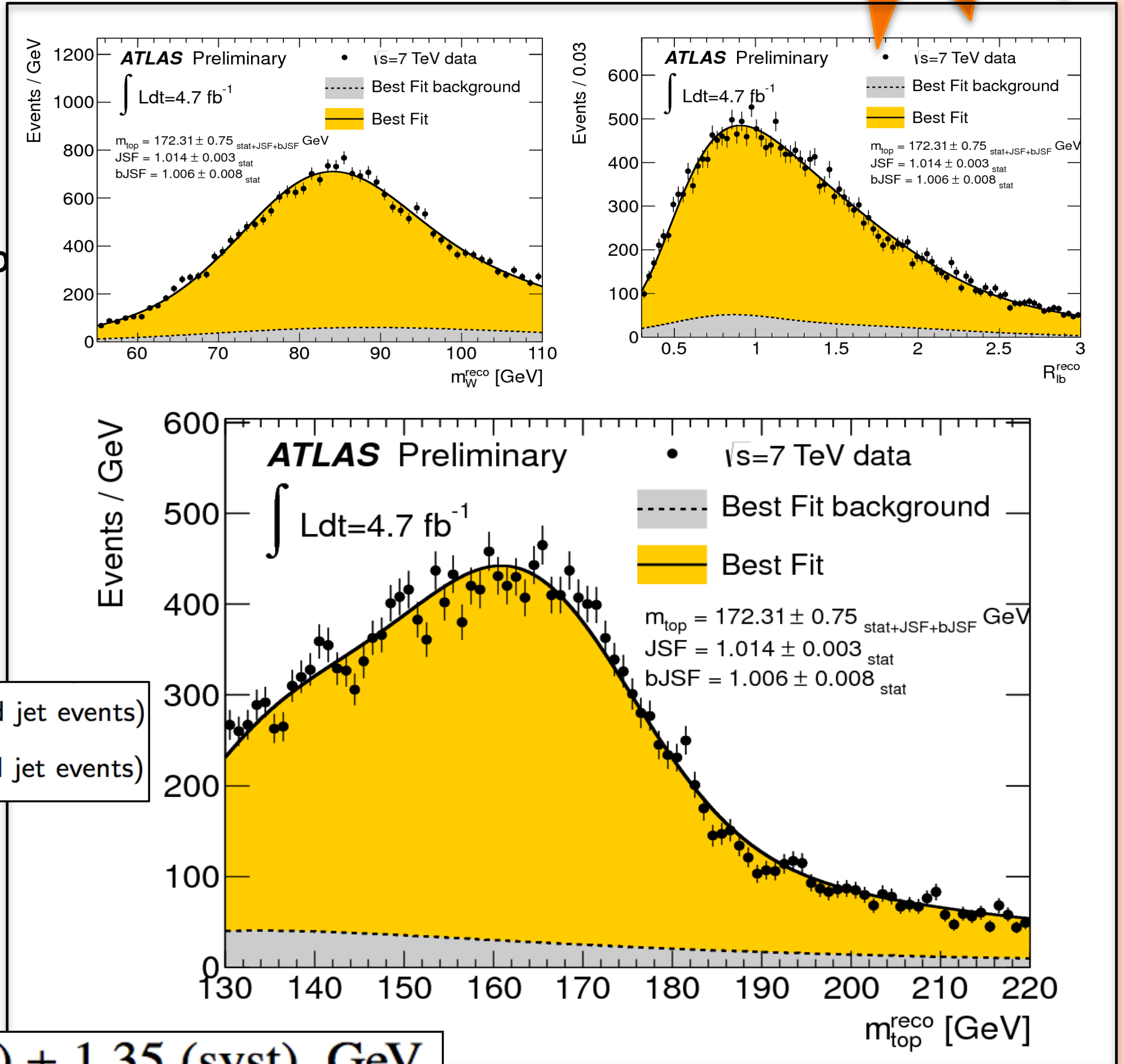
- Lepton+jets, 4.7 fb-1
- Method: 3D template fit to m_{top}^{reco}, m_W^{reco} and R_{lb}^{reco} → m_{top}, JSF, bJSF

R_{lb}^{reco} sensitive to bJES → constrain bJES from data



$$R_{lb}^{reco} = \frac{p_T^{blep} + p_T^{bhad}}{p_T^{l1} + p_T^{l2}} \quad \text{(2b-tagged jet events)}$$

$$R_{lb}^{reco} = \frac{p_T^{btagged}}{p_T^{average, l1, l2}} \quad \text{(1b-tagged jet events)}$$



$$m_{top} = 172.31 \pm 0.75\,(\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35\,(\text{syst})\ \text{GeV},$$
$$\text{JSF} = 1.014 \pm 0.003\,(\text{stat}) \pm 0.021\,(\text{syst}),$$
$$\text{bJSF} = 1.006 \pm 0.008\,(\text{stat}) \pm 0.020\,(\text{syst}).$$

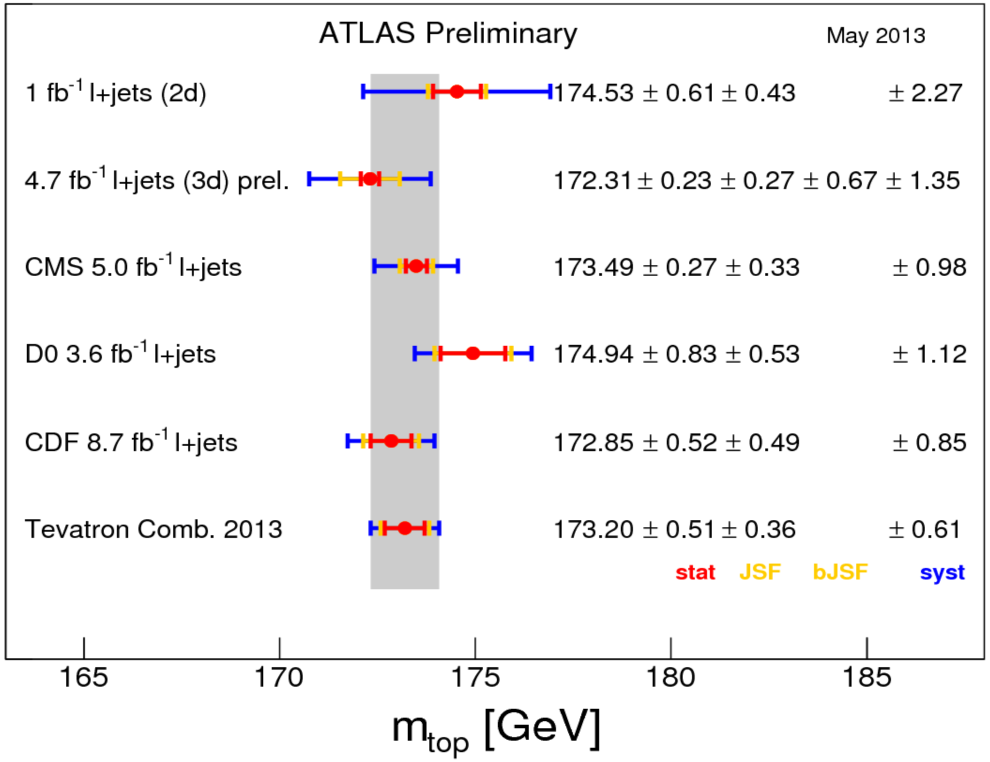
(0.89%)

ATLAS-CONF-2013-046

NEW

ATLAS TOP MASS: 3D TEMPLATE

	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



New ATLAS preliminary measurement significantly improved wrt the previous paper (dominant uncert. b-tagging)

Work towards LHC combination on going: important to achieve a common treatment of modelling uncertainties (e.g. hadronisation)

TOP ANTI-TOP MASS DIFFERENCE

- Test of CPT invariance
- Measured at both Tevatron* (CDF and D0) and LHC (CMS)
- Most recent measurement from CMS at 8 TeV using 19 fb^{-1} in the lepton+jets channel:

$$\Delta m_t = -272 \pm 196\ (\text{stat.}) \pm 122\ (\text{syst.})\,\text{MeV}.$$

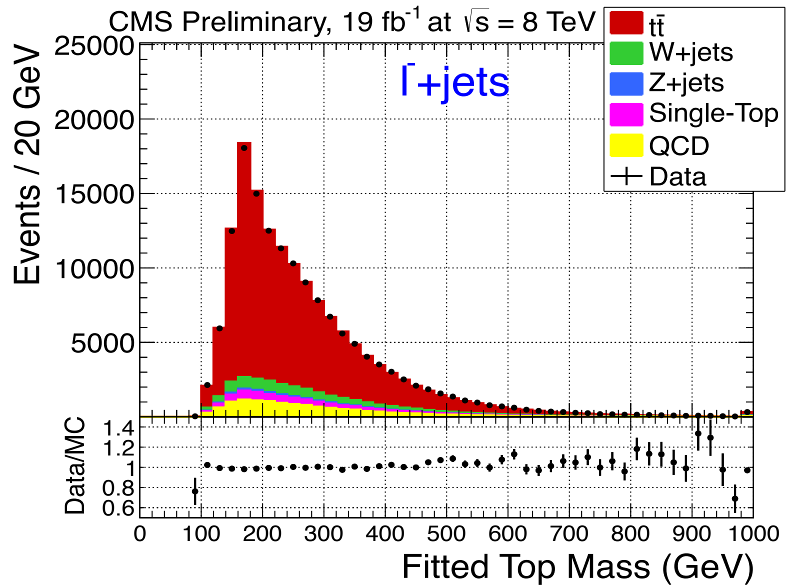
(dominant uncert. b vs $\bar{b}$ response, background composition, signal fraction, b vs b tagging efficiency)

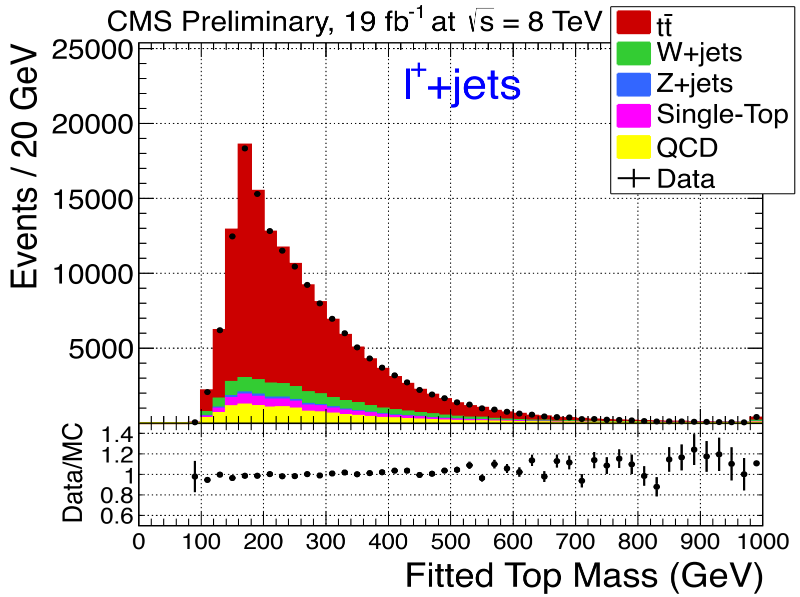
(*) Tevatron measurements:

CDF: -1.95 ± 1.11 (stat) ± 0.59 (syst) GeV *PRD 87 052013*

D0: 0.8 ± 1.8 (stat) ± 0.5 (syst) GeV *PRD 84 052005*

CMS PAS TOP-12-031

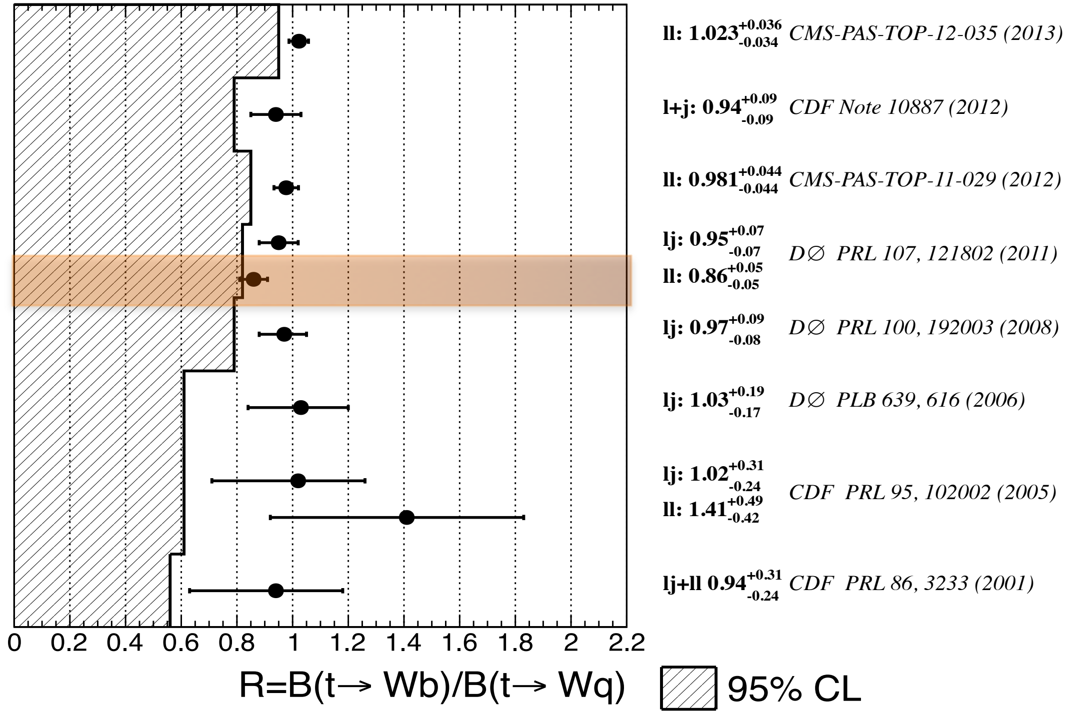


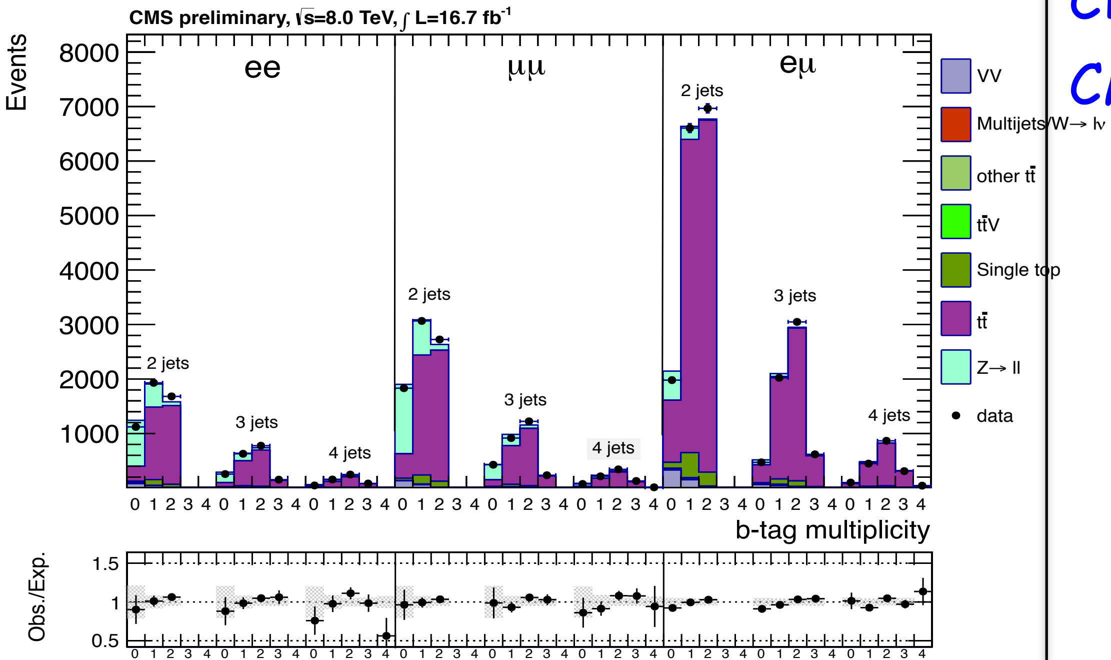


Measurements well in agreement with CPT invariance

MEASUREMENT OF THE RATIO R B(t→Wb)/B(t→Wq)

- R ≠ 1 could arise from new physics (e.g. 4th quark generation, charged Higgs)
- D0 measurement indicates a tension with SM (in particular in the dilepton)





New preliminary measurements:

CDF (l+jets): $R = 0.94 \pm 0.1(\text{stat+syst})$

CMS (dilepton): 8 TeV, 16.7 fb-1

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

$$R \leq 1 \rightarrow R > 0.945 @ 95\% CL$$

Assuming CKM unitarity $R = |V_{tb}|^2$

$$|V_{tb}| = 1.011^{+0.018}_{-0.017}(stat + syst)$$

$$R \leq 1 \rightarrow |V_{tb}| > 0.972 @ 95\% CL$$

(dominant unc.: b-tagging, signal modelling, fraction of correct assignments)

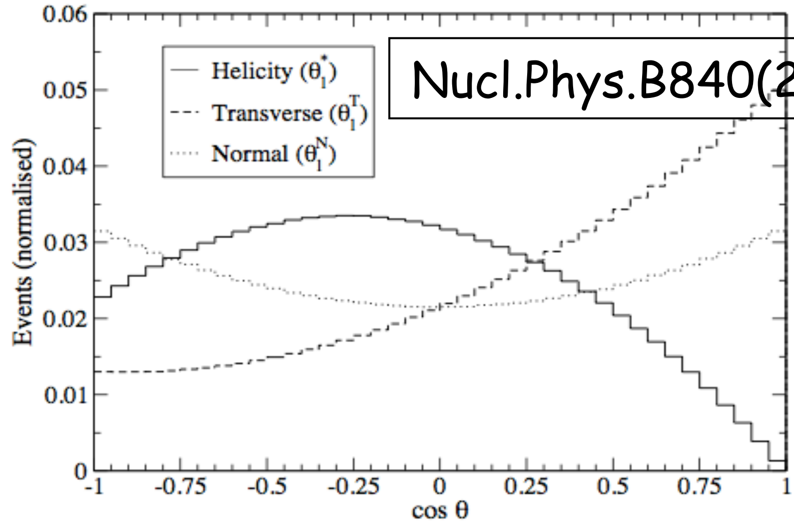
PROBING *Wtb* VERTEX

Within the effective operator framework →

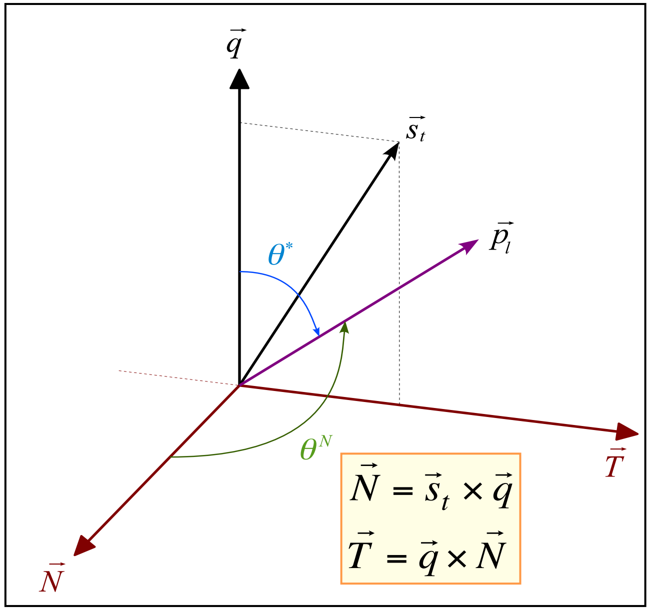
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} -\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

- For un-polarised top quark decays, the only meaningful direction in the top quark rest frame is the one of the W boson momentum (q) (e.g. $t\bar{t}$ production)
- For polarised top quark (s_t) decays further directions: N, T (e.g. t-channel top production)

SM, at tree level → $V_L = V_{tb} \simeq 1$ and $V_R = g_L = g_R = 0$



Nucl.Phys.B840(2010) 349



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^X} = \frac{3}{8}(1+\cos\theta_\ell^X)^2\,F_+^X + \frac{3}{8}(1-\cos\theta_\ell^X)^2\,F_-^X + \frac{3}{4}\sin^2\theta_\ell^X\,F_0^X$$

$F_+ + F_- + F_0 = 1$

$X = {*}, N, T$

W helicity fractions and T polarisations (or angular asymmetries) can probe the real part of the couplings while the N polarisations are sensitive to complex phases

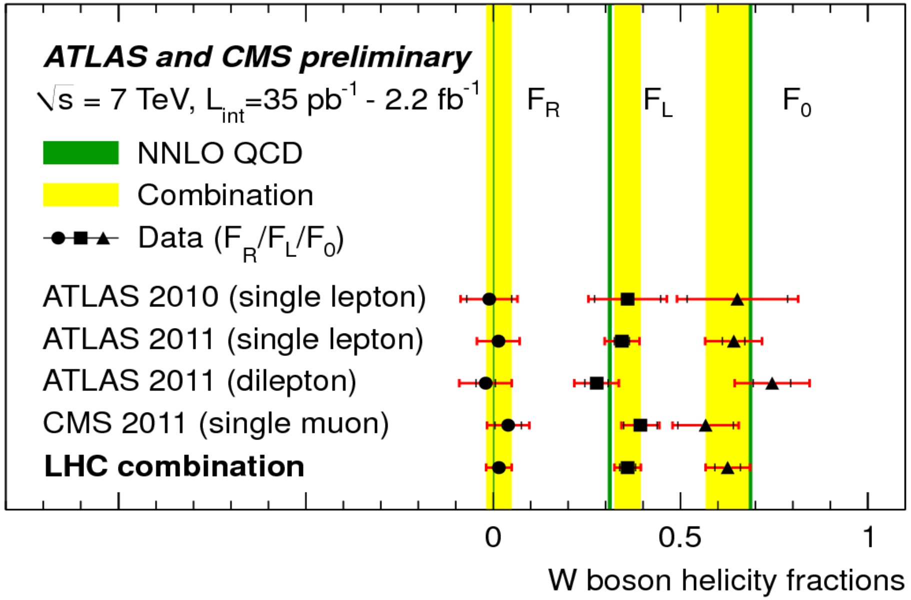
W HELICY FRACTIONS

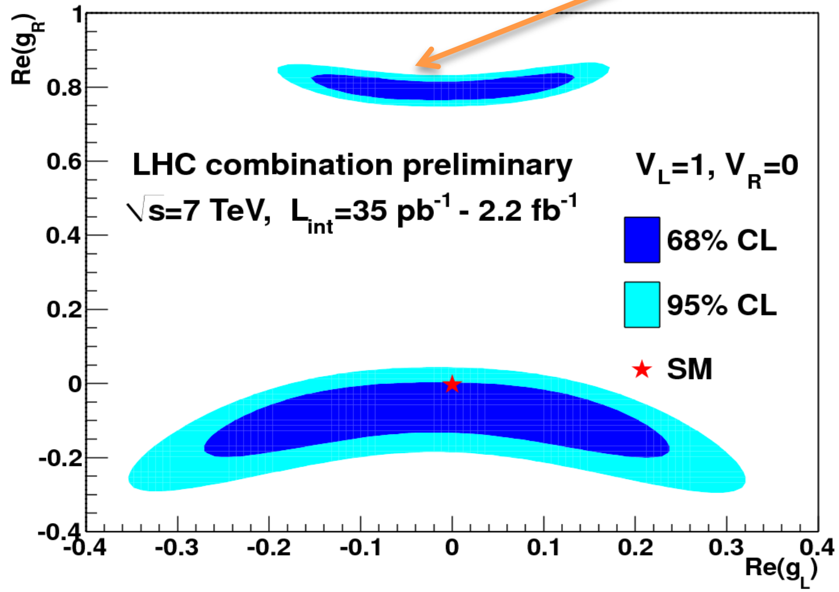
IN TOP PAIR PRODUCTION

- Measured at both Tevatron (CDF and D0) and LHC (ATLAS and CMS)
- Tevatron combination: F_0= 0.722±0.081, F_R = -0.033±0.046 *PRD 85, 091104 (2012)*
- (First) LHC combination leading to most precise measurement
  - Unitarity constrained $F_L+F_R+F_0 = 1$
  - BLUE method used (essential to understand correlations between channels/experiments)
  - Dominant unc.: radiation modelling, JES, detector modelling, m_{top}

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

Strongly constrained by single top XS measurements





$$F_0 = 0.626 \pm 0.034\ (\text{stat.}) \pm 0.048\ (\text{syst.})$$
$$F_L = 0.359 \pm 0.021\ (\text{stat.}) \pm 0.028\ (\text{syst.})$$

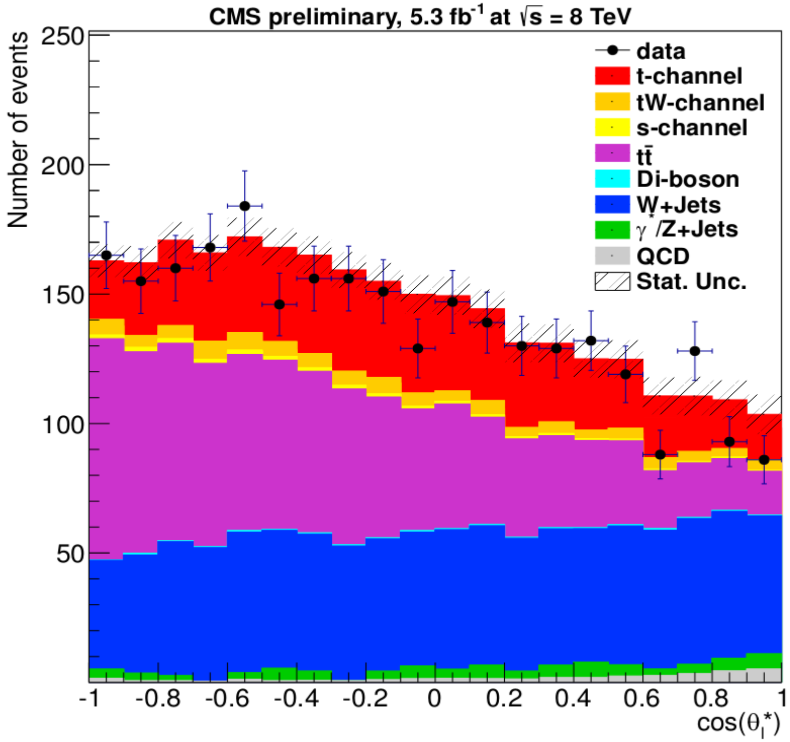
The combination does not include a new result from CMS in dilepton channel (CMS PAS TOPQ-12-05)

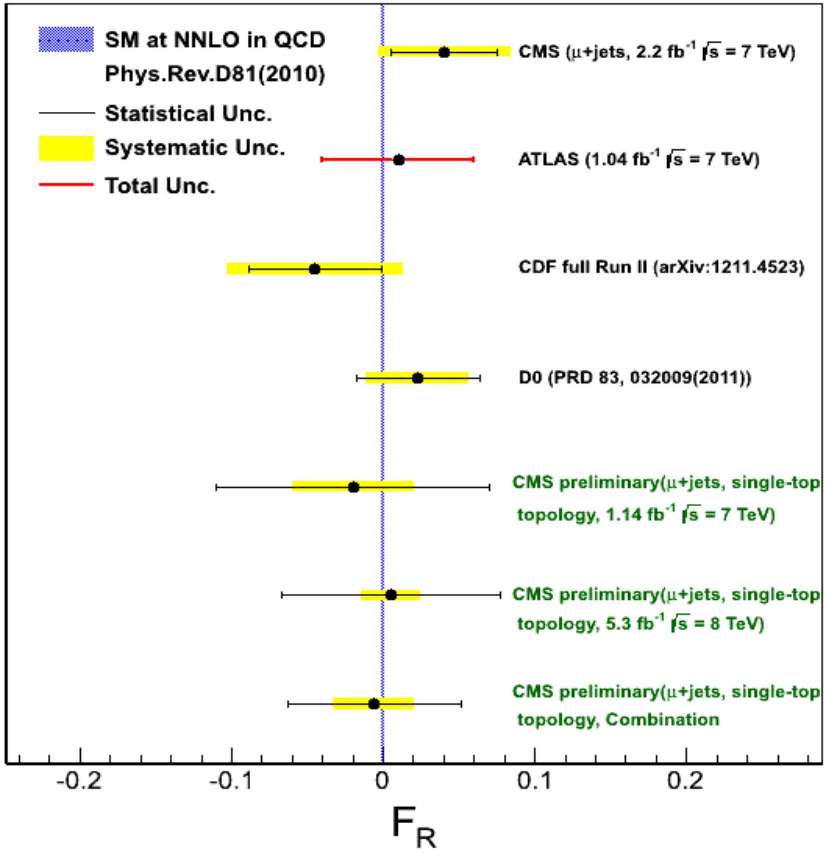
W HELICY FRACTIONS

SINGLE TOP TOPOLOGY

CMS PAS TOPQ-12-020

- First measurement of W helicity in single top topology
- 7 and 8 TeV, muon+jets channel





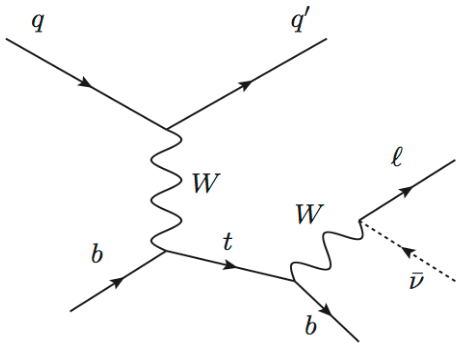
Results consistent with the SM and with measurements in top pair events

(dominant unc.: MET, signal modelling, W+jets shape)

A_{FB}^{N} MEASUREMENT IN SINGLE TOP t-CHANNEL: CP VIOLATION SEARCH IN TOP DECAYS

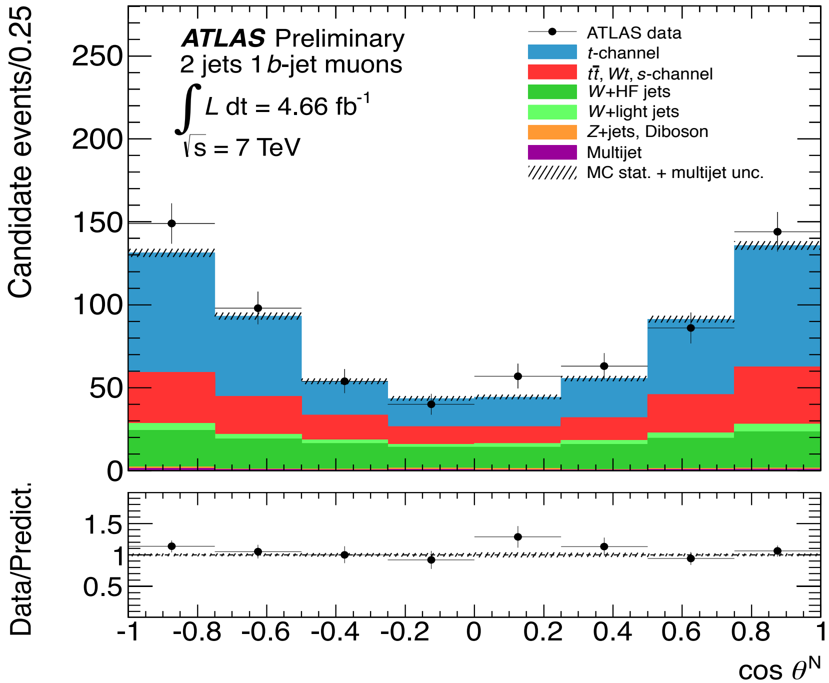
ATLAS-CONF-2013-032

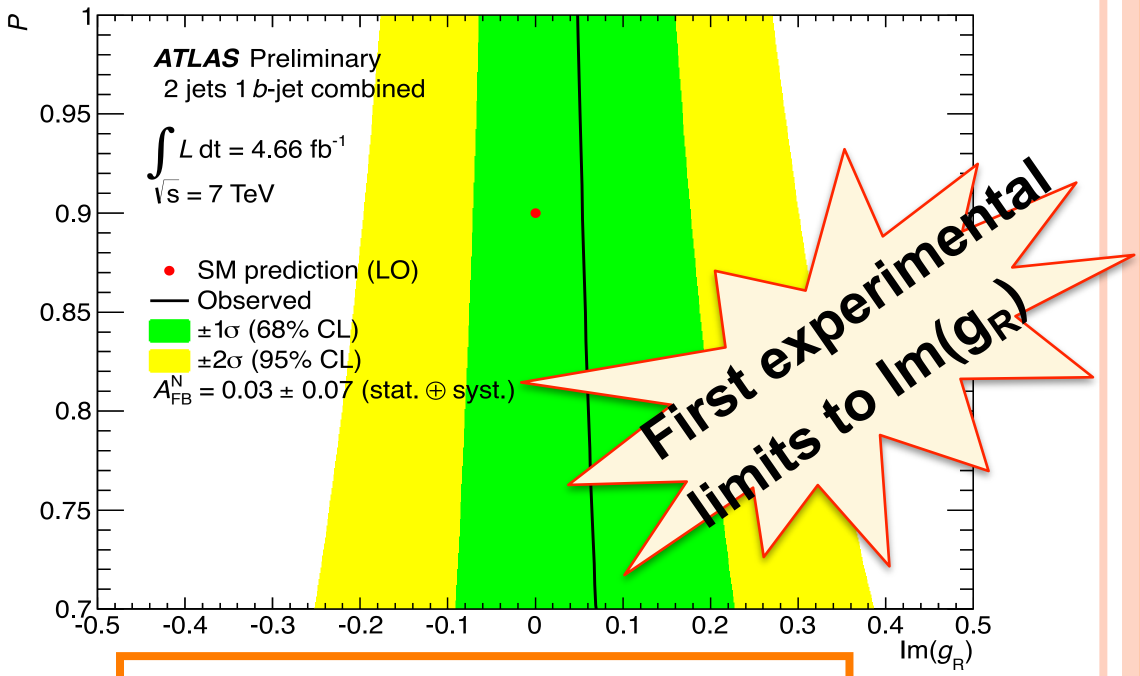
$$A_{FB}^{N} = \frac{N(\cos\theta_N > 0) - N(\cos\theta_N < 0)}{N(\cos\theta_N > 0) + N(\cos\theta_N < 0)}$$



$$A_{FB}^{N} \approx 0.64 \cdot P \cdot Im(g_R)$$

→$A_{FB}^{N} \neq 0$ implies CP violation in top quark decays!!





$$A_{FB}^{N} = 0.031 \pm 0.065\,(\text{stat.})\,^{+0.029}_{-0.031}\,(\text{syst.})$$

Assuming P~0.9 (SM):

68% C.L.: $-0.07 < Im(g_R) < 0.18$

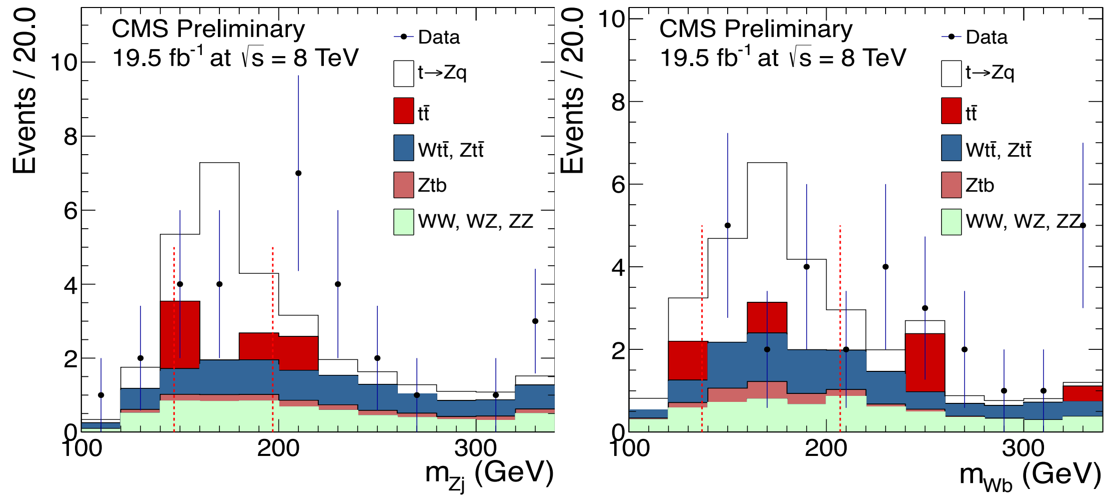
95% C.L.: $-0.20 < Im(g_R) < 0.30$

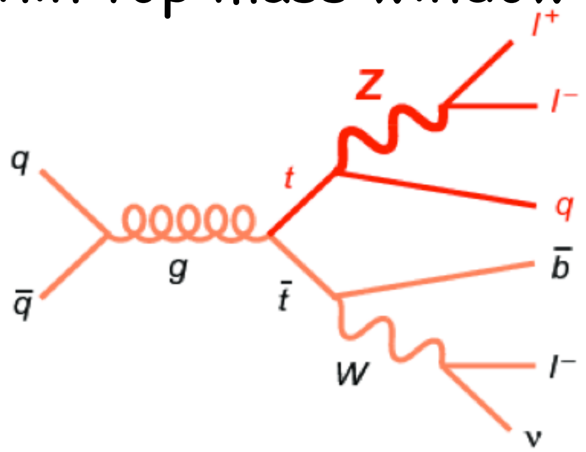
SEARCH FOR FCNC IN TOP DECAYS

NEW

CMS PAS TOPQ-12-037

- In the SM, t→ Zq (q=u,c) decays highly suppressed $O(10^{-14})$
- Enhancement predicted by some BSM models $O(10^{-4})$
- Event selection requires 3 leptons (2 consistent with Z decay), E_T^{miss} > 30 GeV, ≥2jets, 1 b-tagged jet, m_{Wb} and m_{Zj} within top mass window





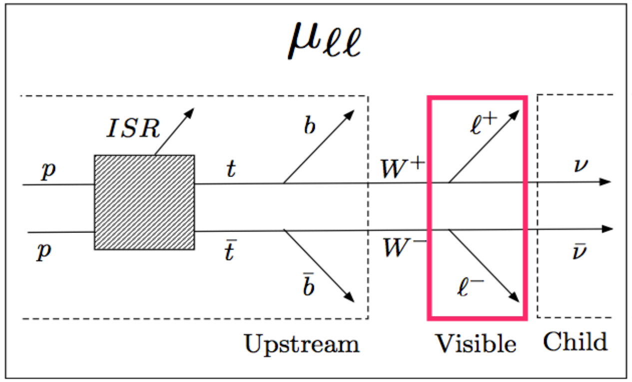
Selection	data-driven estimation
$t \to Zq$ ($\mathcal{B} = 0.1\%$)	—
WZ ZZ Drell-Yan	$1.54 \pm 0.12 \pm 0.74$
$t\bar{t}$ $Zt\bar{t}$ $Wt\bar{t}$ tbZ	$1.60 \pm 4.96 \pm 0.44$
Total background	$3.14 \pm 4.97 \pm 1.17$
Observed events	1
Expected limit	$\mathcal{B}(t \to Zq) < 0.10\%$
Observed limit	$\mathcal{B}(t \to Zq) < 0.07\%$

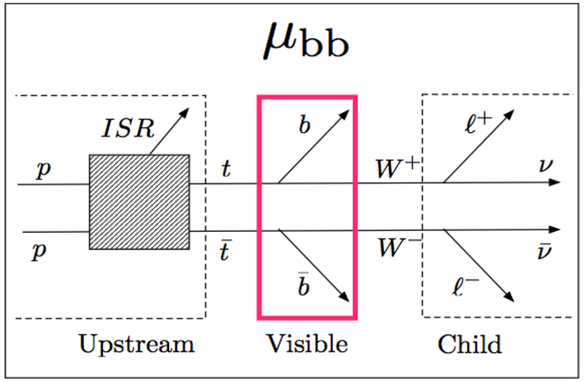
CONCLUSIONS

- Top quark properties measurements entering precision realm
- Most measurements dominated by systematic uncertainties (e.g. JES, b-tagging, signal modelling)
- Essential to achieve a good understanding of detector and keep performing measurements to constrain models
- Tevatron analyses exploiting now the full data collected
- LHC measurements provided with both 7 and 8 TeV data sets using both top pair and single top produced events.
- All measurements in agreement with the SM prediction, so far.
- Only shown some highlights of all results obtained:
  - CDF: http://www-cdf.fnal.gov/physics/new/top/top.html
  - D0: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

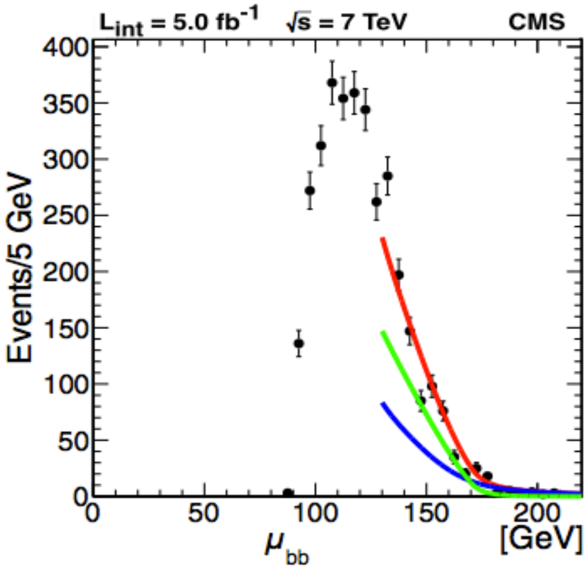
BACK UP

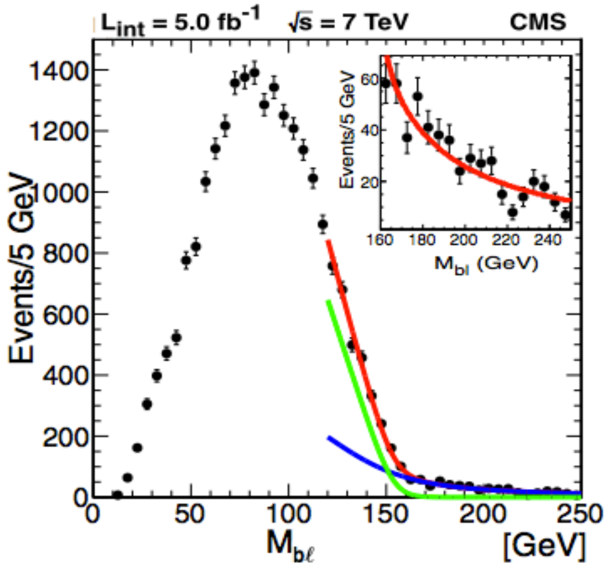
CMS TOP MASS DILEPTON KINEMATIC ENDPOINTS





arXiv:1304.5783





- μ_{bb} lower bound on m_t for known m_W
- Fit both μ_{bb} and M_{bl} endpoints, for known M_W and m_ν

Novel approach.

Dominant uncertainty: JES

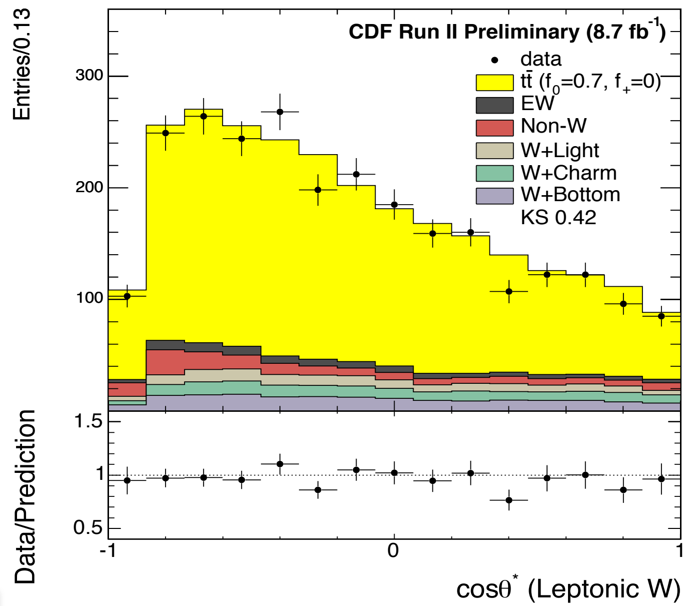
$$173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}.$$

W HELICY FRACTIONS @ TEVATRON

IN TOP PAIR PRODUCTION

- CDF, *PRD 87 031104*
- Lepton+jets, 8.7 fb-1
- Matrix element technique
- Simultaneous determination results:

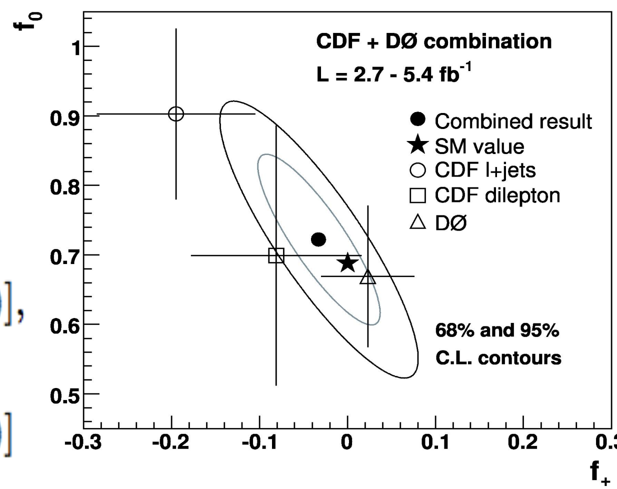
$$f_0 = 0.726 \pm 0.066(\text{stat}) \pm 0.067(\text{syst})$$
$$f_+ = -0.045 \pm 0.043(\text{stat}) \pm 0.058(\text{syst})$$

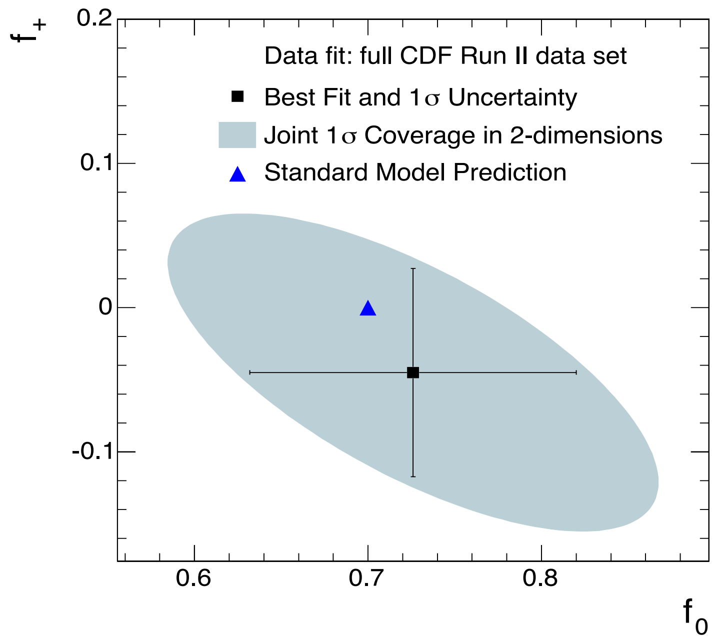


Tevatron combination up to 5.4 fb^{-1}

PRD 85, 091104 (2012)

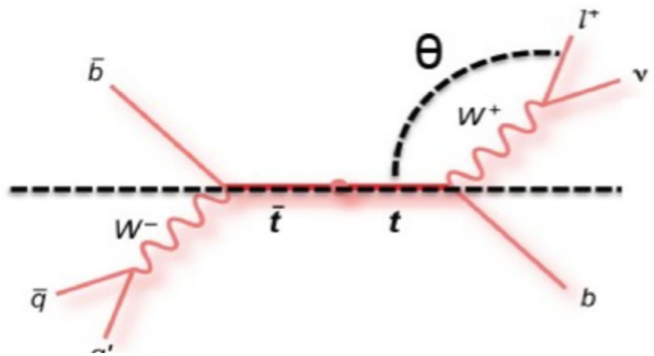
$$f_0 = 0.722 \pm 0.081$$
$$[\pm\, 0.062\ (\text{stat.}) \pm 0.052\ (\text{syst.})],$$
$$f_+ = -0.033 \pm 0.046$$
$$[\pm\, 0.034\ (\text{stat.}) \pm 0.031\ (\text{syst.})]$$





TOP POLARISATION IN TTBAR EVENTS

- P conservation in QCD and unpolarised initial state → Top quarks are produced unpolarised in SM (p~0)
- Net polarisation of top would change the angular distributions of their decay products
- First measurements performed at the LHC:
    - CMS (dilepton channel) *CMS PAS-TOP-12-016*
    - ATLAS (lepton+jets channel) *ATLAS 2012 133*

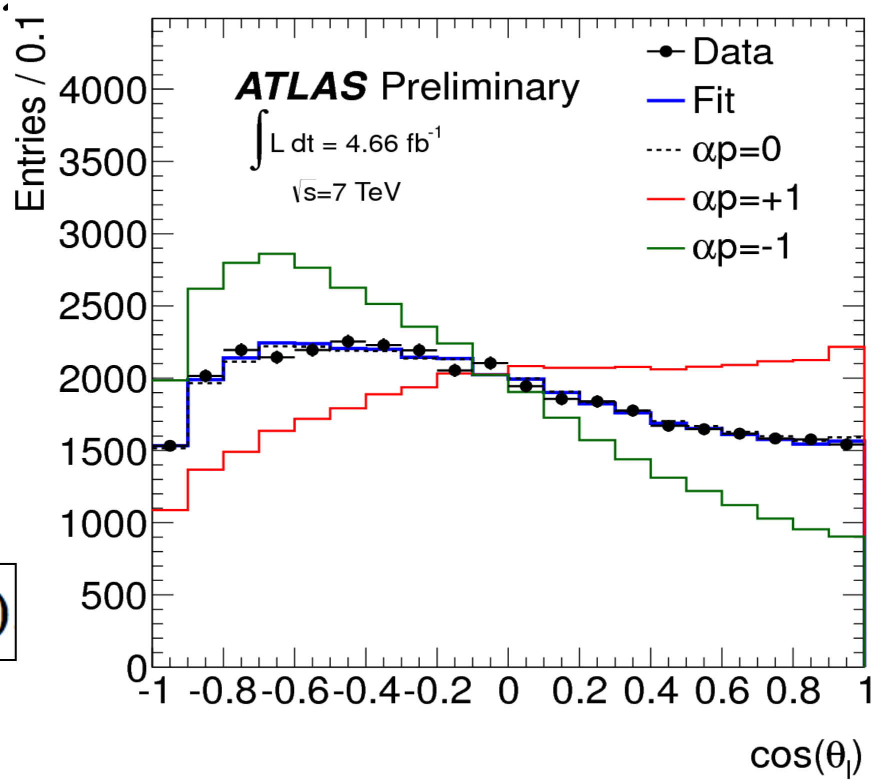


$$W(\cos\theta_i) \propto 1 + \alpha_i p \cos\theta_i$$

ATLAS result:

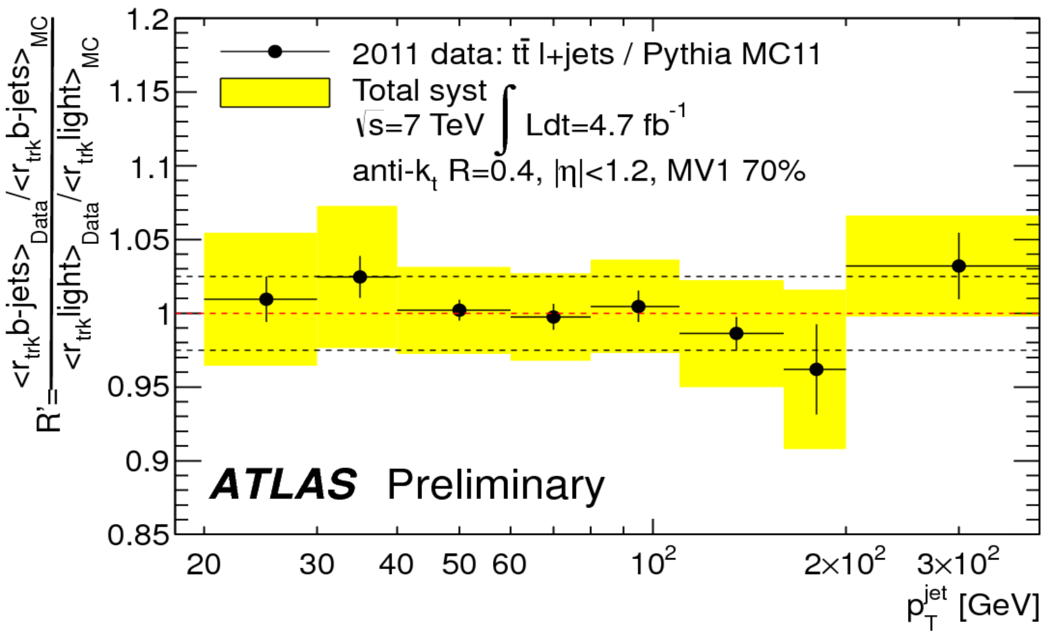
$$\alpha_\ell p = -0.060 \pm 0.018(\text{stat})^{+0.046}_{-0.064}(\text{syst})$$

(dominant unc. JES, signal modelling)

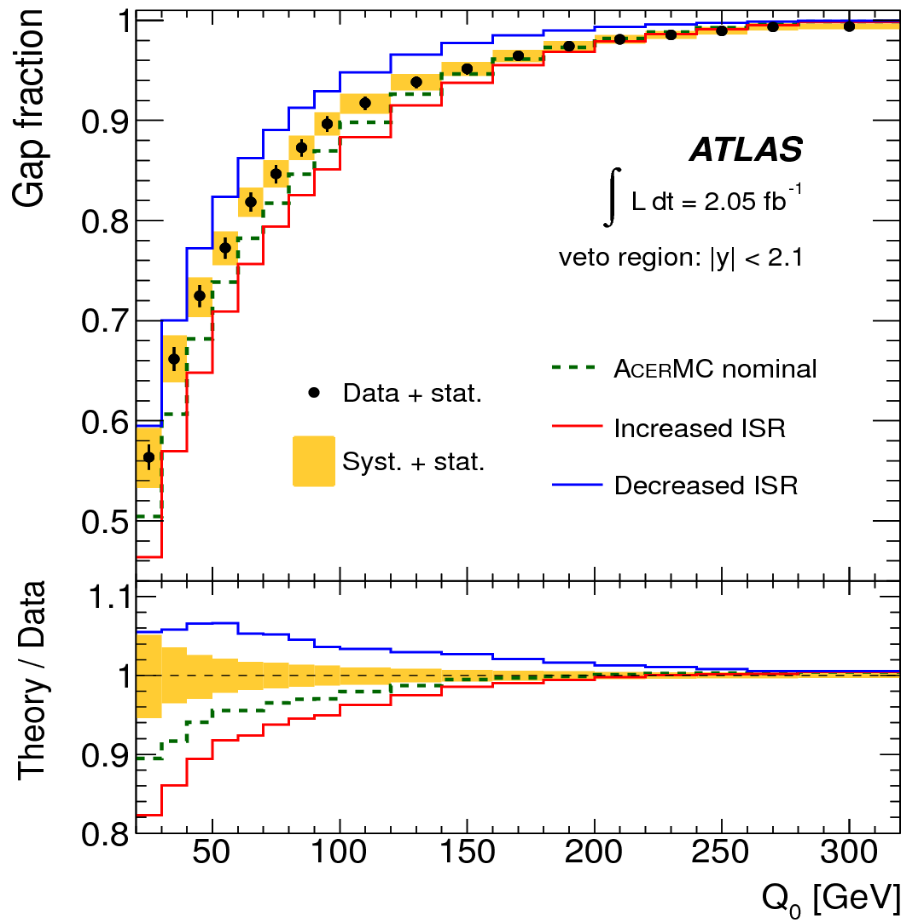


ATLAS TOP MASS MEASUREMENTS

ATLAS-CONF-2013-002



Eur.Phys.J. C72 (2012) 2043



- A better understanding of the detector led to a reduced bJES uncertainty by about 40%
- Based on jet multiplicity distributions in ttbar events, ISR/FSR was significantly constrained.