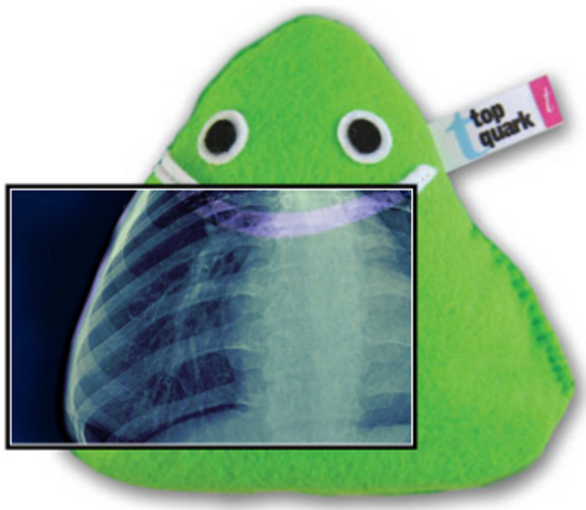
Top Quark Properties

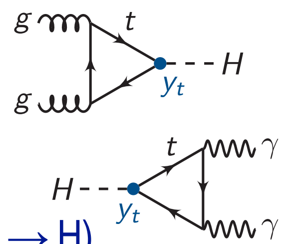
Andreas B. Meyer
on behalf of ATLAS, CDF, CMS and D0



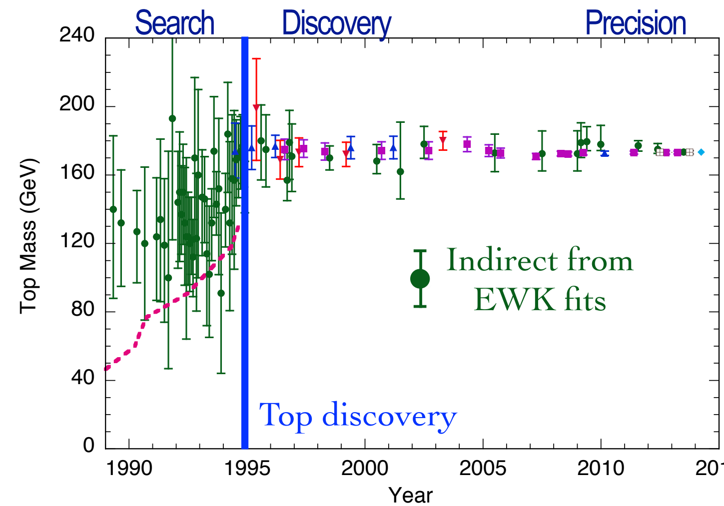
LEPTON PHOTON 2015

DESY

Top Quark Physics

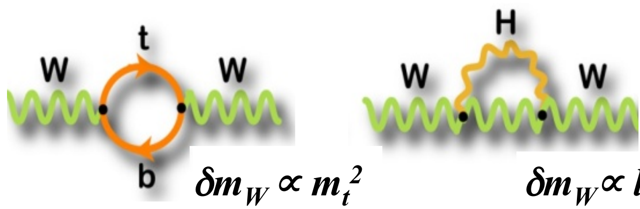


- **The top quark is special**
  - Heaviest known elementary particle
  - Strong coupling to Higgs (EWK loops, gg → H)
  - Couples via all forces
  - Production $1/m_t$ < Decay $1/\Gamma$ < Hadronization $1/\Lambda_{QCD}$ < Spin Decorrelation m_t/Λ^2 → unique features

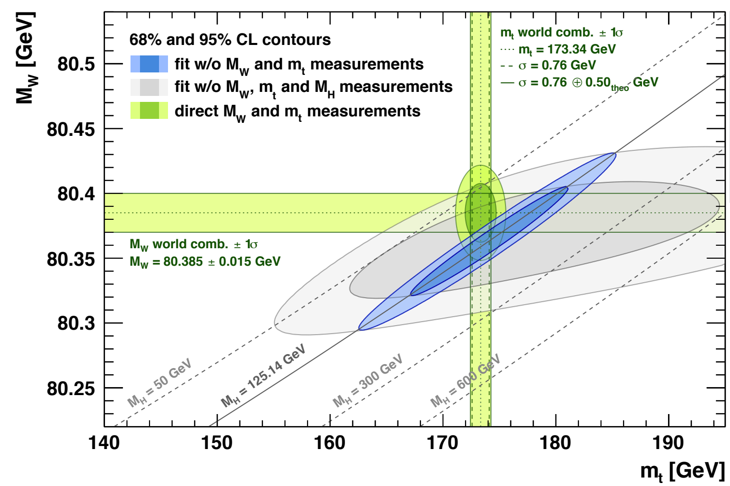


this figure taken from, N.Hadley (EPS 2015) C.Quigg

- **Precision measurement of SM parameters**
  - for use in predictions and consistency checks

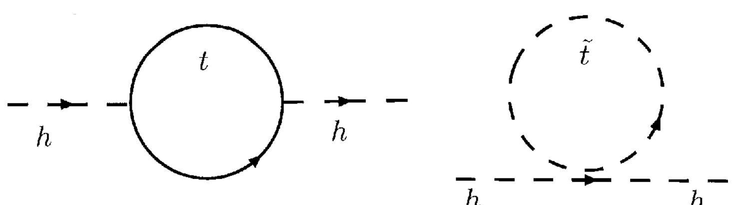


$\delta m_W \propto m_t^2$ $\delta m_W \propto \ln(m_H)$



arXiv:1407.3792

- **Top Quarks and New Physics**
  - esp. in case new physics would couple to mass
  - top is background to many searches



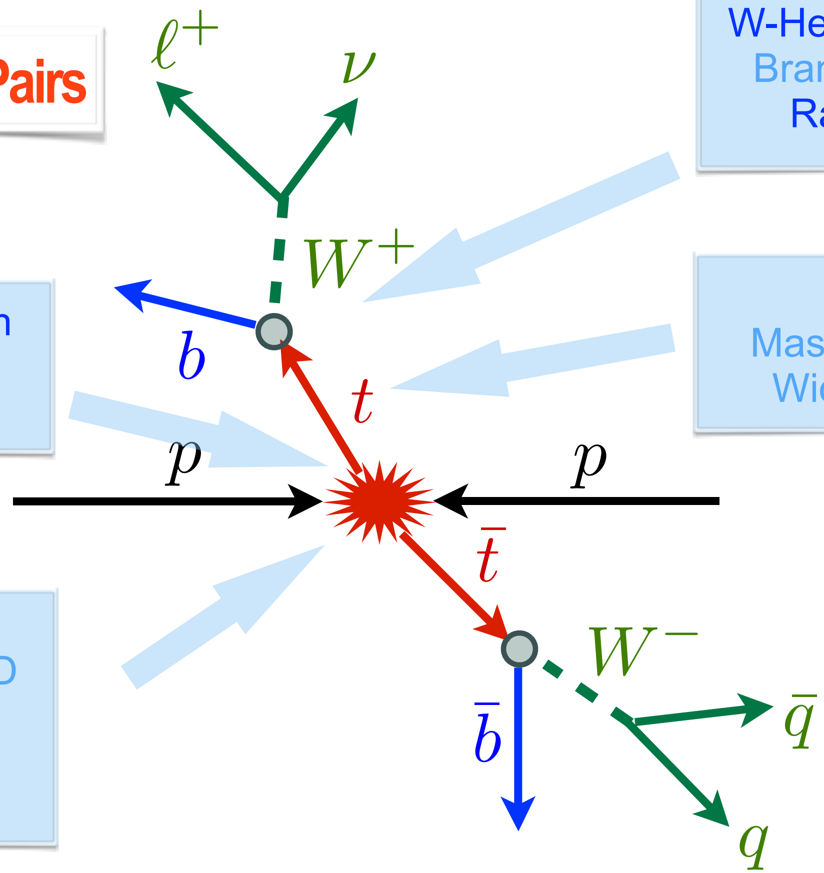
Top Quark Properties in Production and Decay

Top Quark Pairs

W-Helicity Fractions
Branching Ratios
Rare Decays

Spin Correlation
Polarisation
Asymmetries

Mass
Mass Difference,
Width, Charge



cross sections,
kinematics, QCD
parameters,
resonances,
new particles

Menu:

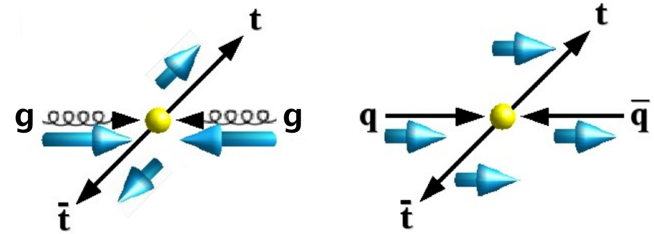
- **Angular Distributions**
- **Rare Decays**
- **Mass**

EWK Single-Top Production

s,t,tW channel production,
properties, couplings

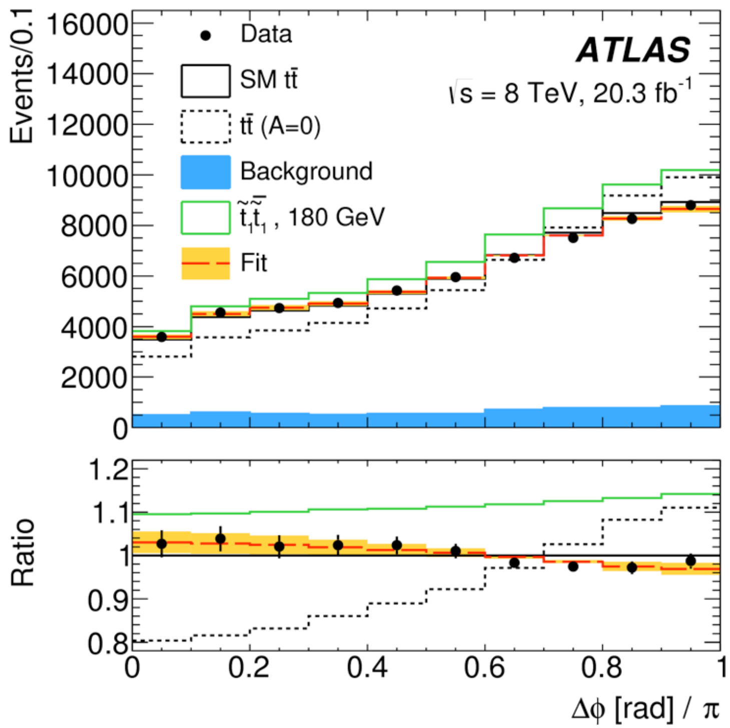
Spin Correlations

- Top quarks decay before spins de-correlate → measure
- 2ℓ channel: simple access via azimuthal angle between leptons in lab frame



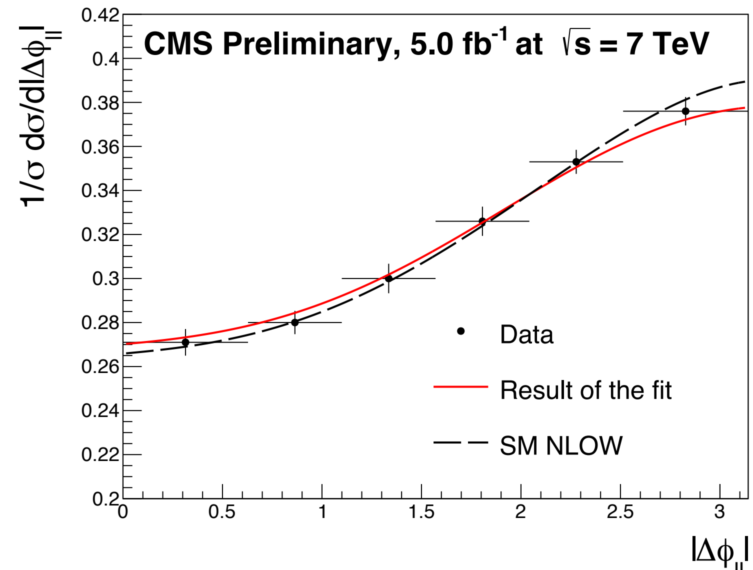
$$f_{SM} = \frac{N^{t\bar{t}}_{SM}}{N^{t\bar{t}}_{SM} + N^{t\bar{t}}_{Uncor}}$$

PRL 114, 142001 (2015)



$f_{SM} = 1.20 \pm 0.05_{stat} \pm 0.13_{syst}$

PRL 112 (2014) 182001



$f_{SM} = 1.02 \pm 0.10_{stat} \pm 0.22_{syst}$

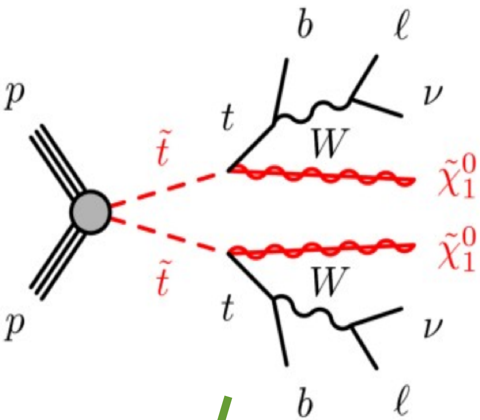
Search for chromomagnetic dipole-moments

$-0.043 < \mathrm{Re}(\mu) < 0.117$ at 95% CL

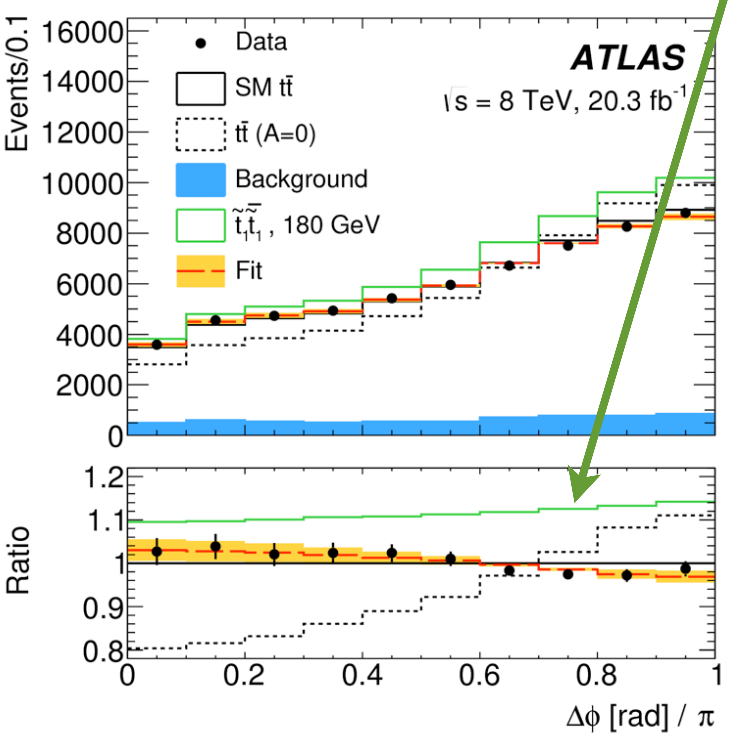
CMS TOP-14-005

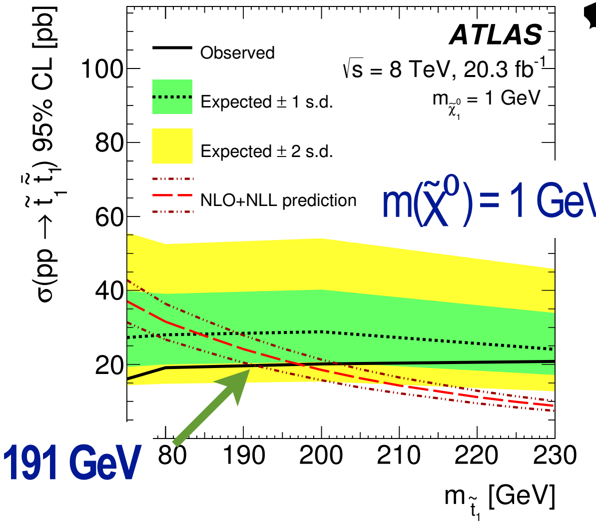
Limits on Stop

- Stop pair production: reduced spin correlation, increased tt rate



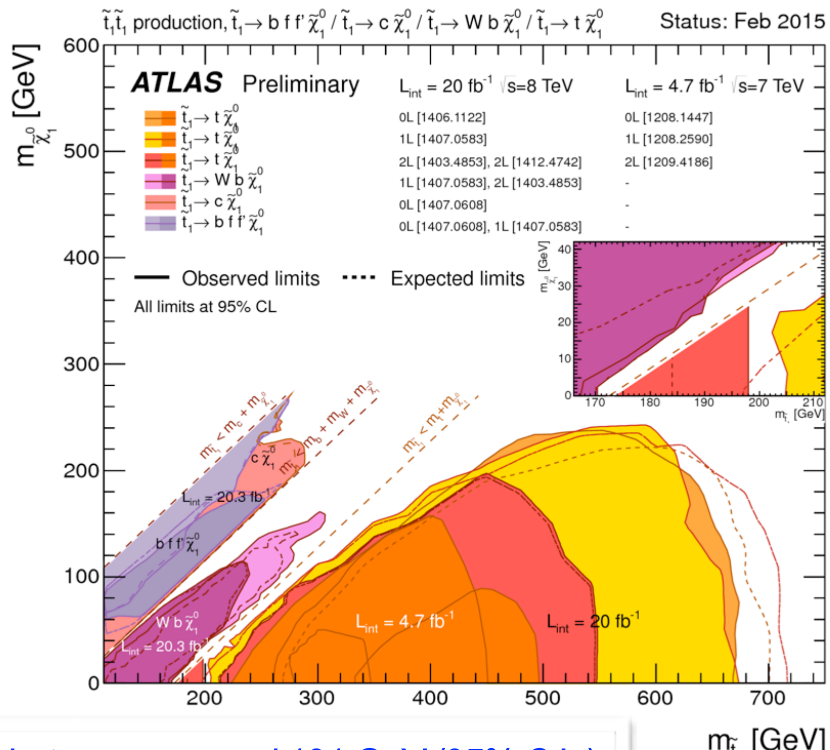
PRL 114, 142001 (2015)





$m(\tilde{\chi}^0) = 1$ GeV

191 GeV

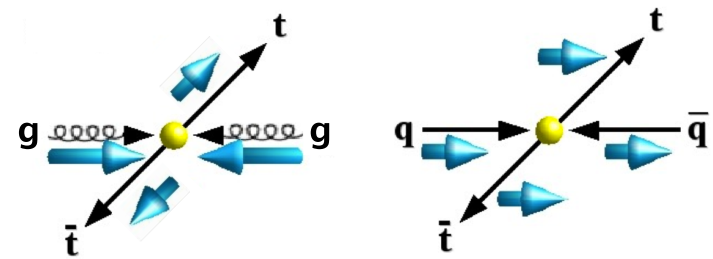


arXiv:1506.08616

For light $\tilde{\chi}^0$, top squarks excluded between m_{top} and 191 GeV (95% C.L.)

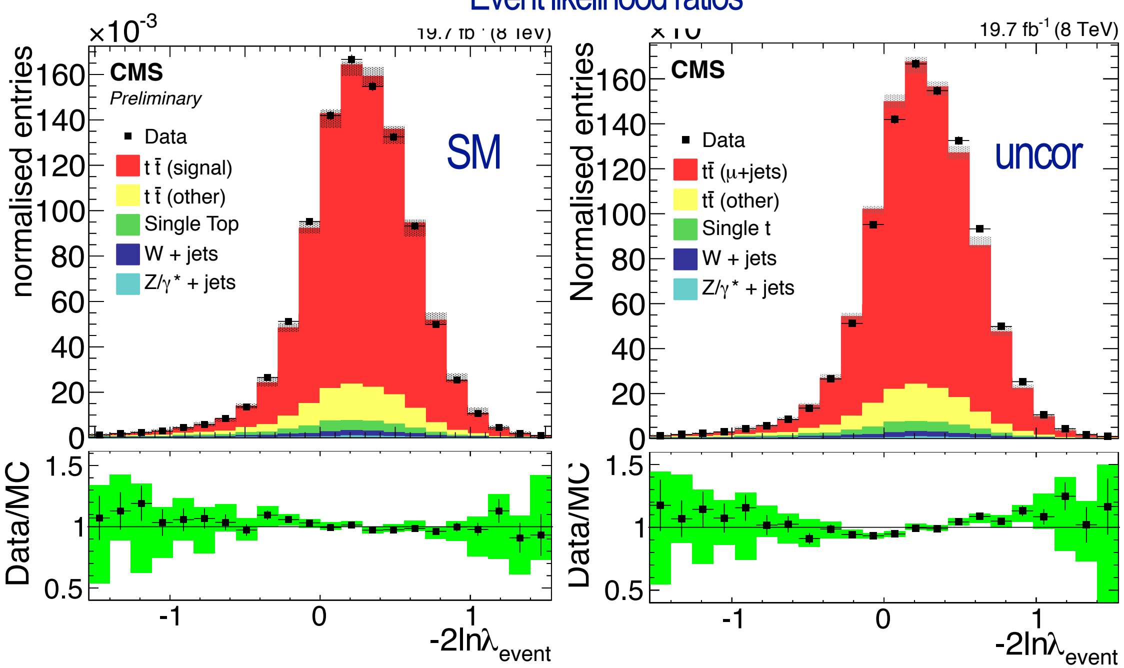
Spin Correlations

- ℓ+jets channel: require full tt event reconstruction
- CMS: Full matrix element method

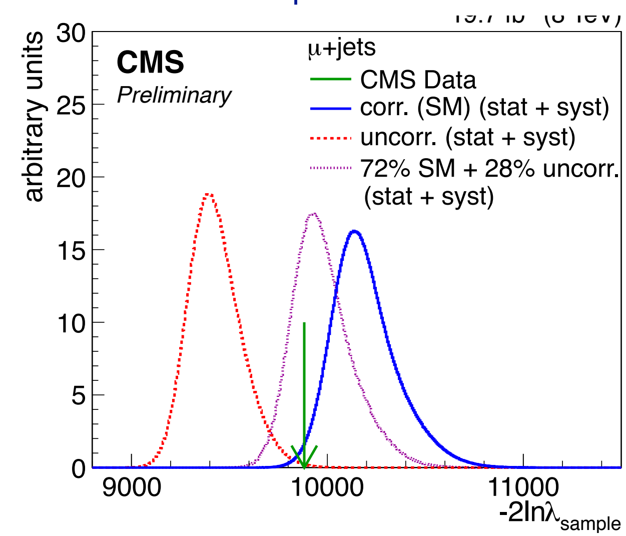


CMS TOP-13-015

Event likelihood ratios



Sample likelihoods



Template fitting

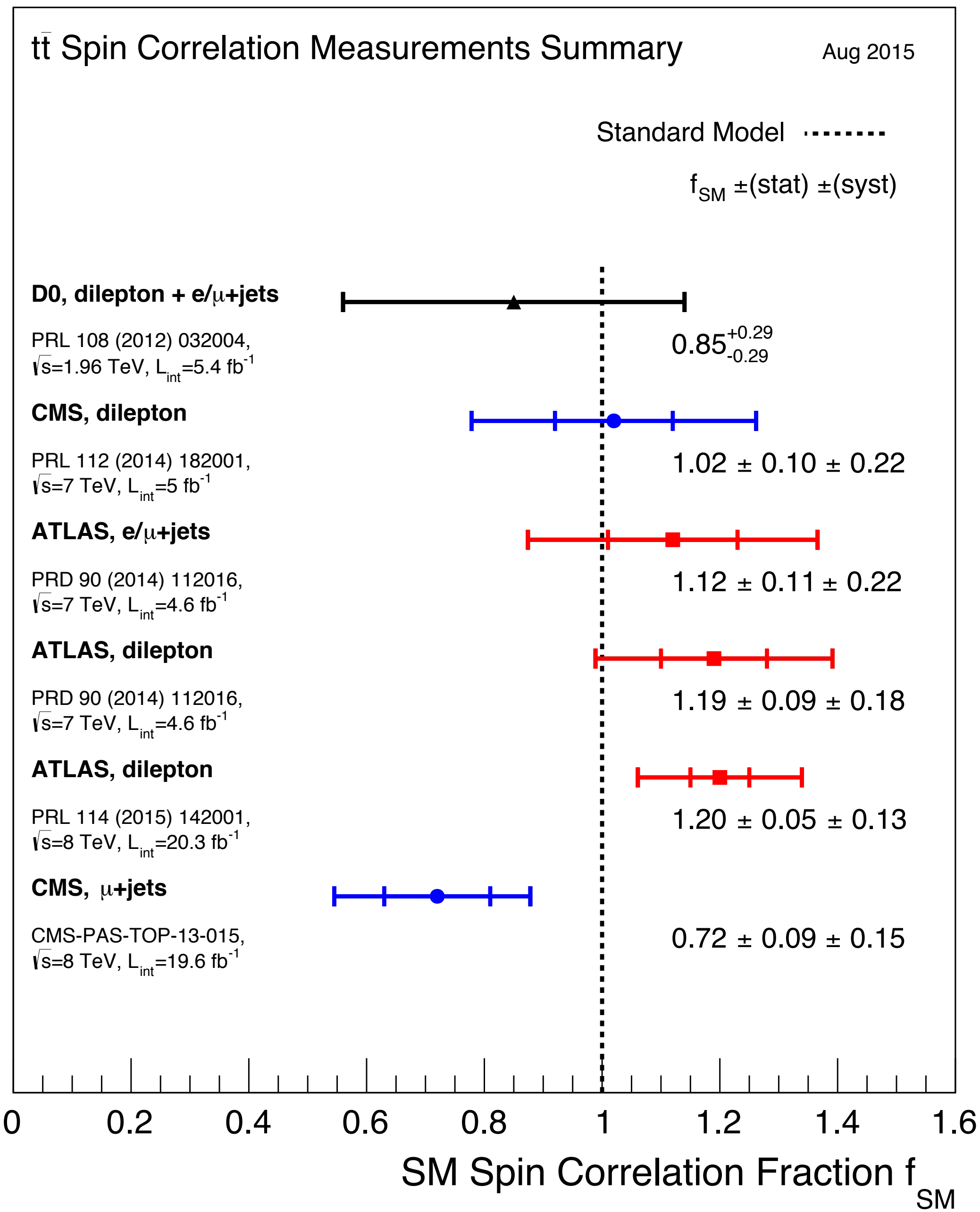
$f_{SM} = 0.72 \pm 0.08 \pm 0.13$

Hypothesis testing

CLs(SM) = 1.3%
CLs(uncor) = 0.2%

Most precise result in ℓ+jets channel to-date

Summary: Spin Correlations



$$f = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{Uncor}^{t\bar{t}}}$$

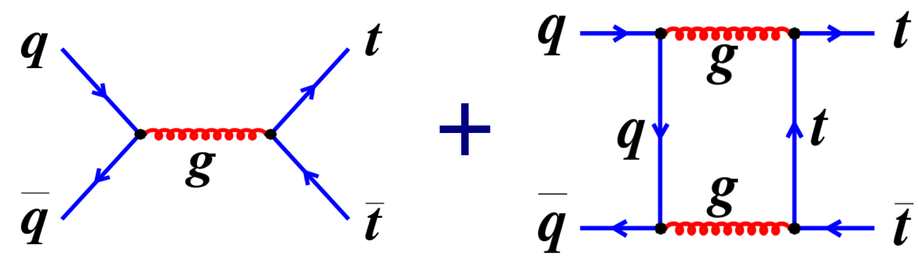
Charge/FB-Asymmetry

- LO: No asymmetry expected
- NLO: Interferences between $q\bar{q}$ diagrams
- Diluted at LHC due to large gg fraction and unknown quark direction

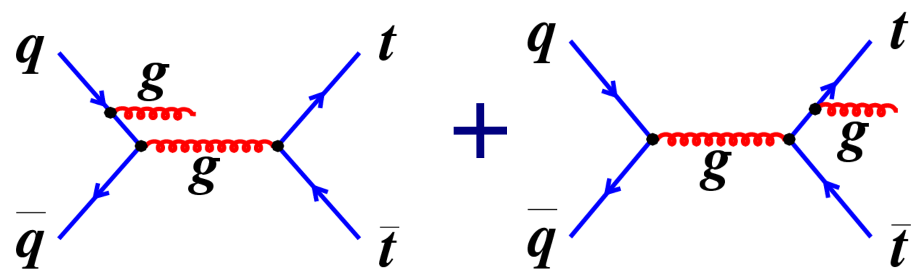
- Recent NNLO prediction for Tevatron: $A_{FB} = 0.095 \pm 0.007$

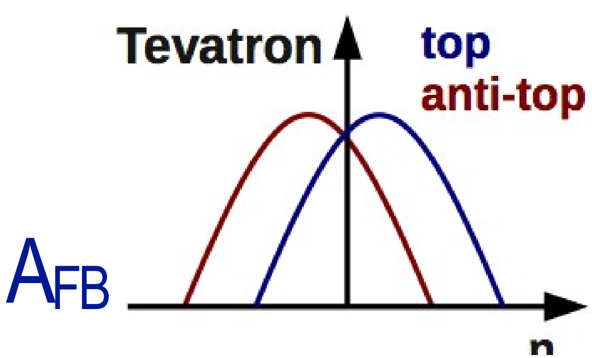
Czakon et al PRL 115, 052001 (2015)

tree-level and box diagrams: positive asymmetry



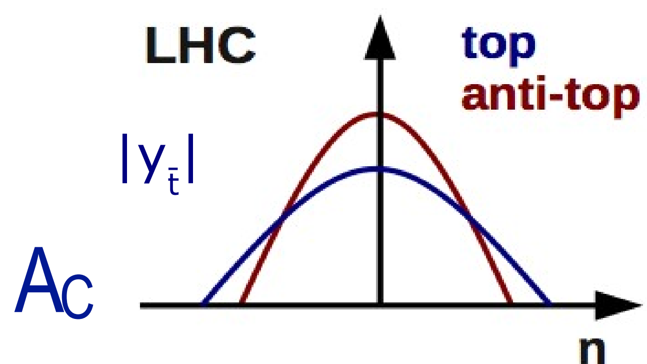
ISR/FSR: negative asymmetry





$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$



$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

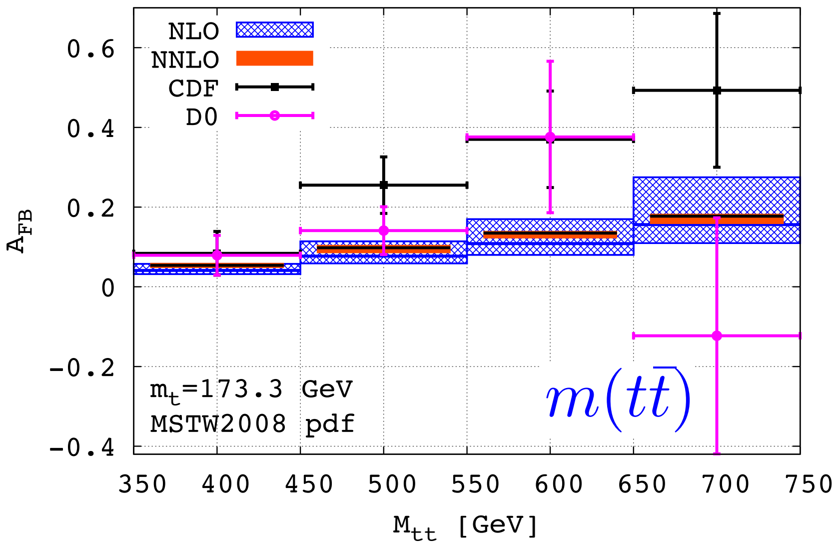
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

Charge/FB-Asymmetry

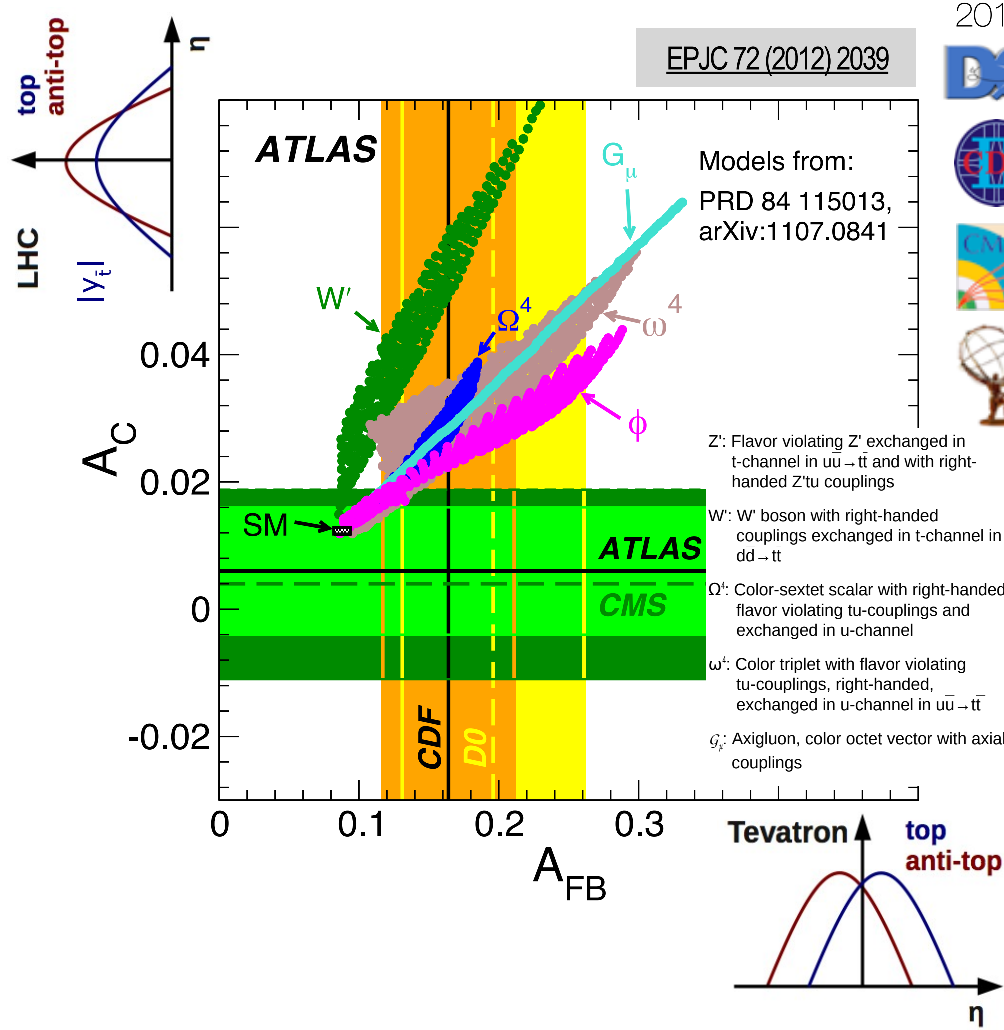
PRD 87, 092002 (2013)

PRD 90, 072011 (2014)

Czakon et al PRL 115, 052001 (2015)



EPJC 72 (2012) 2039

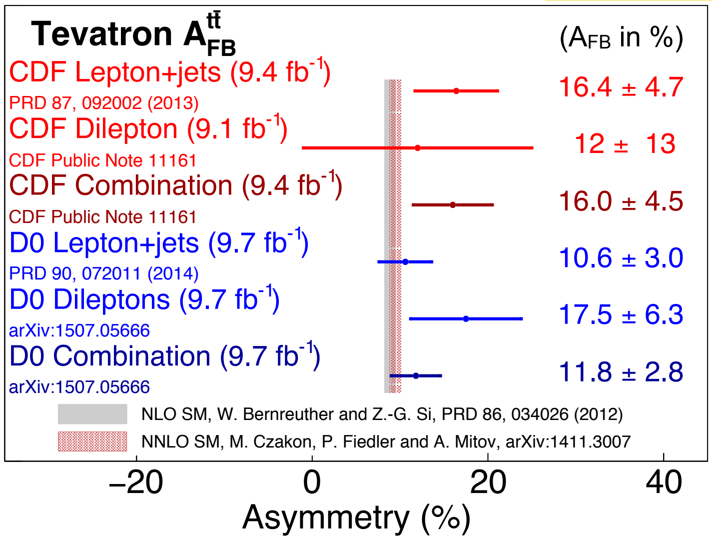


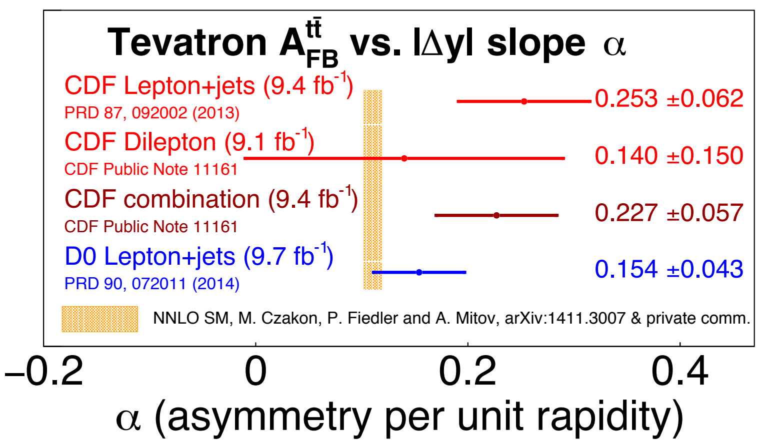
Latest Tevatron vs. new NNLO
D0: consistent, CDF: ~1.5σ

Combination of Tevatron and LHC:
Several New Physics models disfavoured

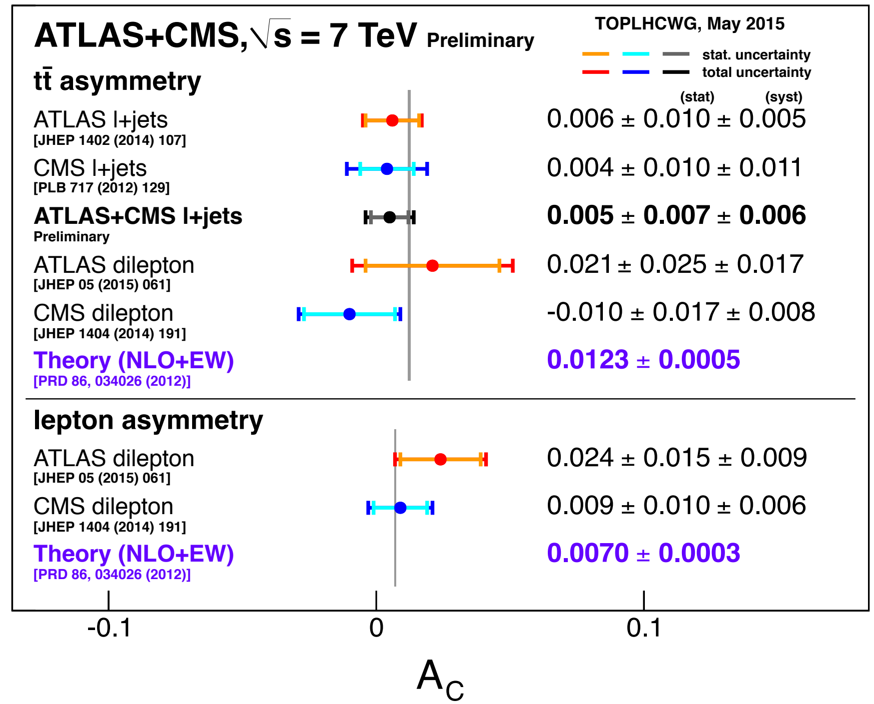
Summary: Charge/FB-Asymmetry

CDF-11161





TOPLHCWG



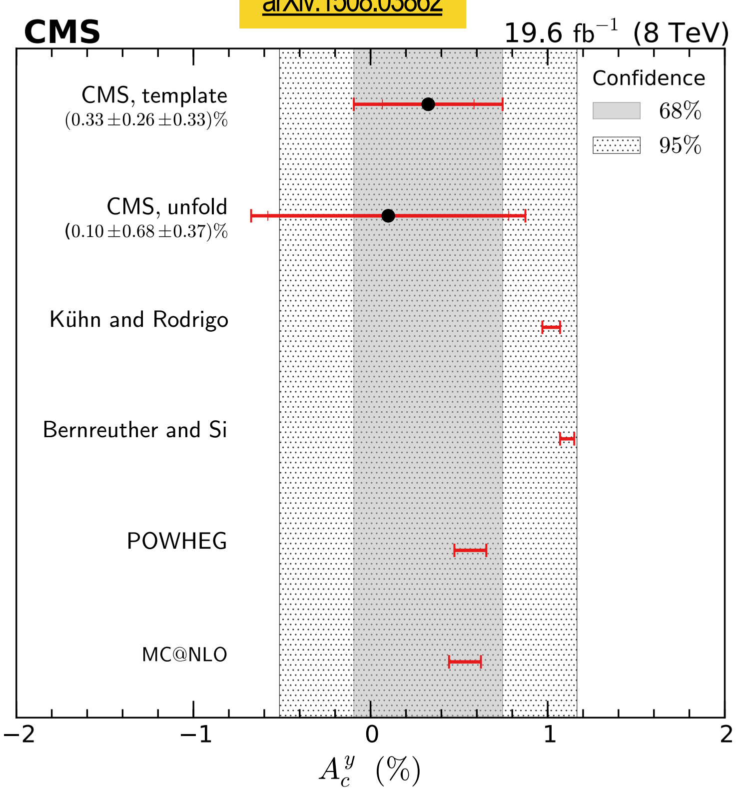
Latest Tevatron vs. new NNLO
D0: consistent, CDF: ~1.5σ

LHC: Good agreement
statistical uncertainties still large → more data

Charge-Asymmetry at 8 TeV

- Differential A_C measurements (also in fid. phase space)
- Template method also exploiting shape of Δ|y| distribution

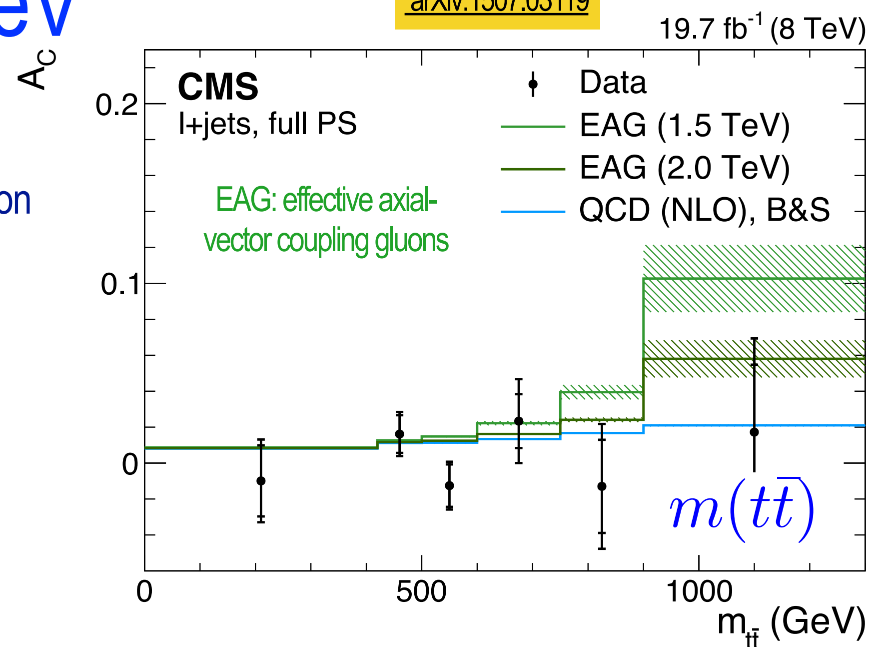
arXiv:1508.03862

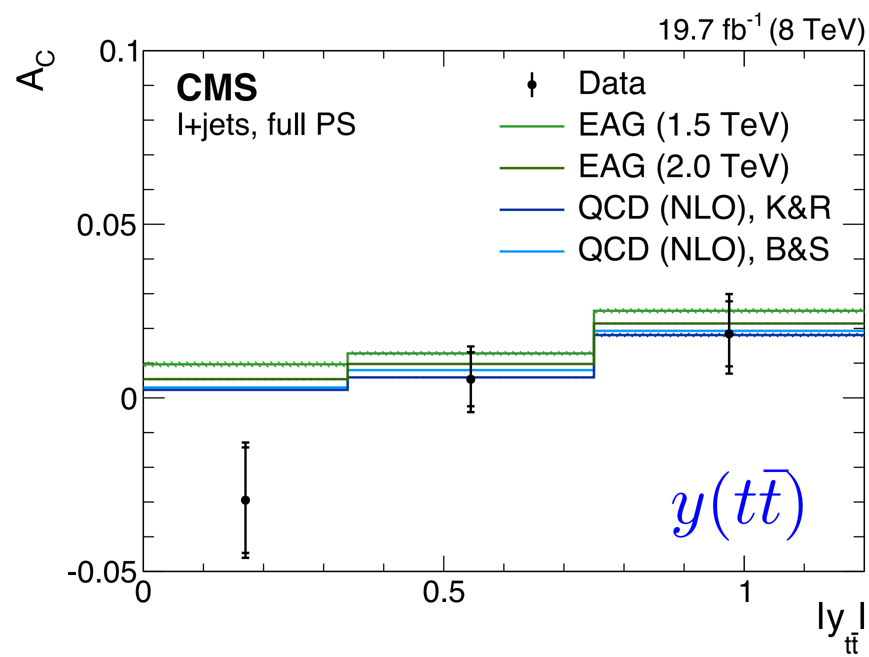


$A_C = 0.33 \pm 0.26_{stat} \pm 0.33_{syst}$

Most precise result to-date

arXiv:1507.03119





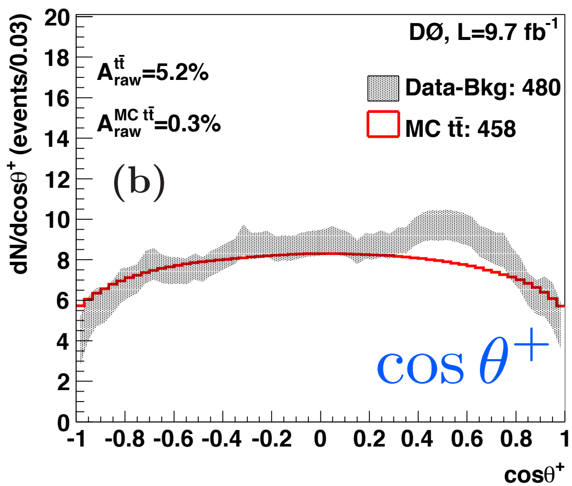
Top-Quark Polarisation

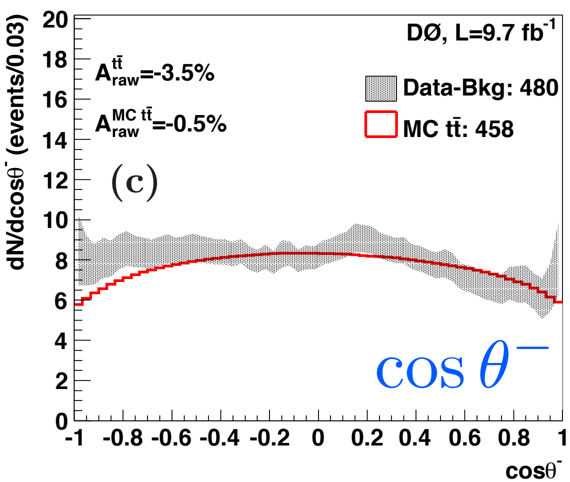
arXiv:1507.05666

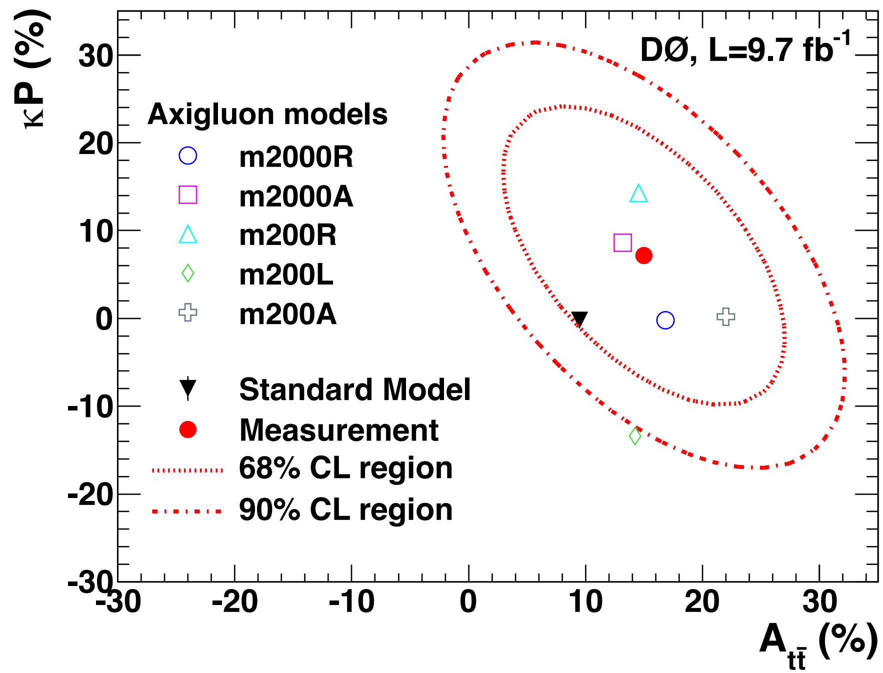
- Using lepton angular distributions relative to quantisation axis (here: beam basis)
- Matrix-Element technique for event kinematics

$$A_{\hat{n}}^{\ell^\pm} = \frac{N(\cos\theta^\pm > 0) - N(\cos\theta^\pm < 0)}{N(\cos\theta^\pm > 0) + N(\cos\theta^\pm < 0)}$$

$$\kappa P = \frac{1}{2}\left(\kappa^+ P^+ - \kappa^- P^-\right) = A^{\ell^+} - A^{\ell^-}$$



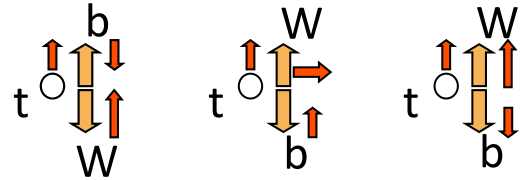




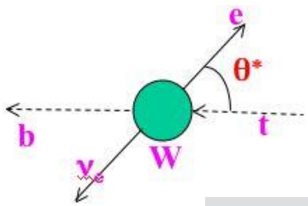
P = 11.3 ± 9.1$_{stat}$ ± 1.9$_{syst}$ % (for A$_{FB}$ = 9.5±0.5%)

First measurement of polarization at the Tevatron, simultaneously with (anti-correlated) A$_{FB}$

W Helicity Fractions



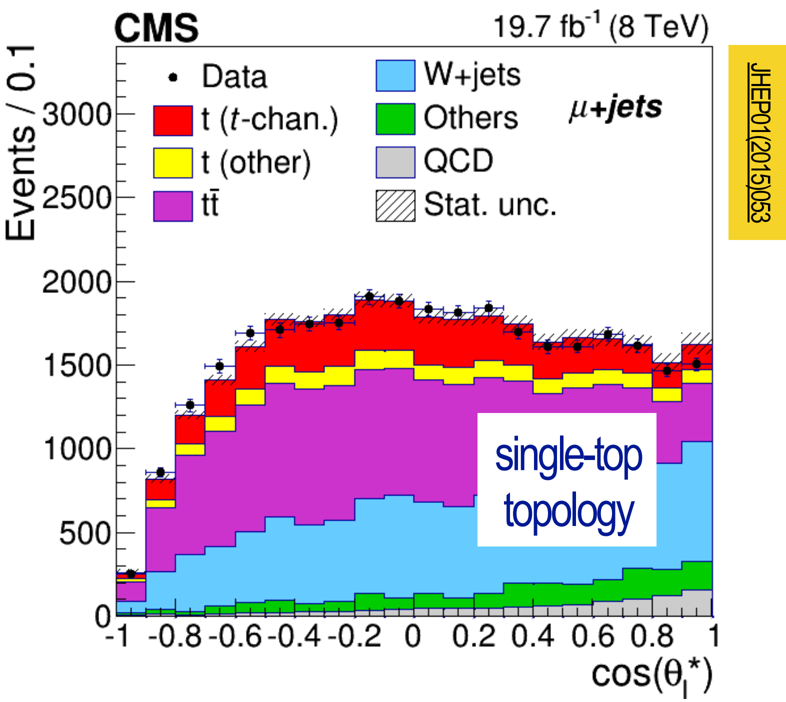
$F_L + F_R + F_0 = 1$

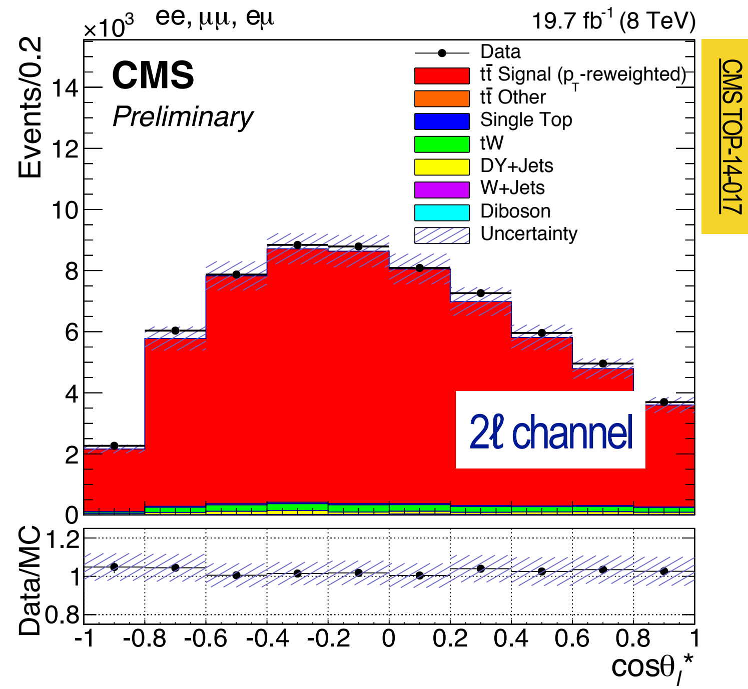


$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0$$

Czarnecki et al PRD 81 (2010) 111503

0.311 0.0017 0.687





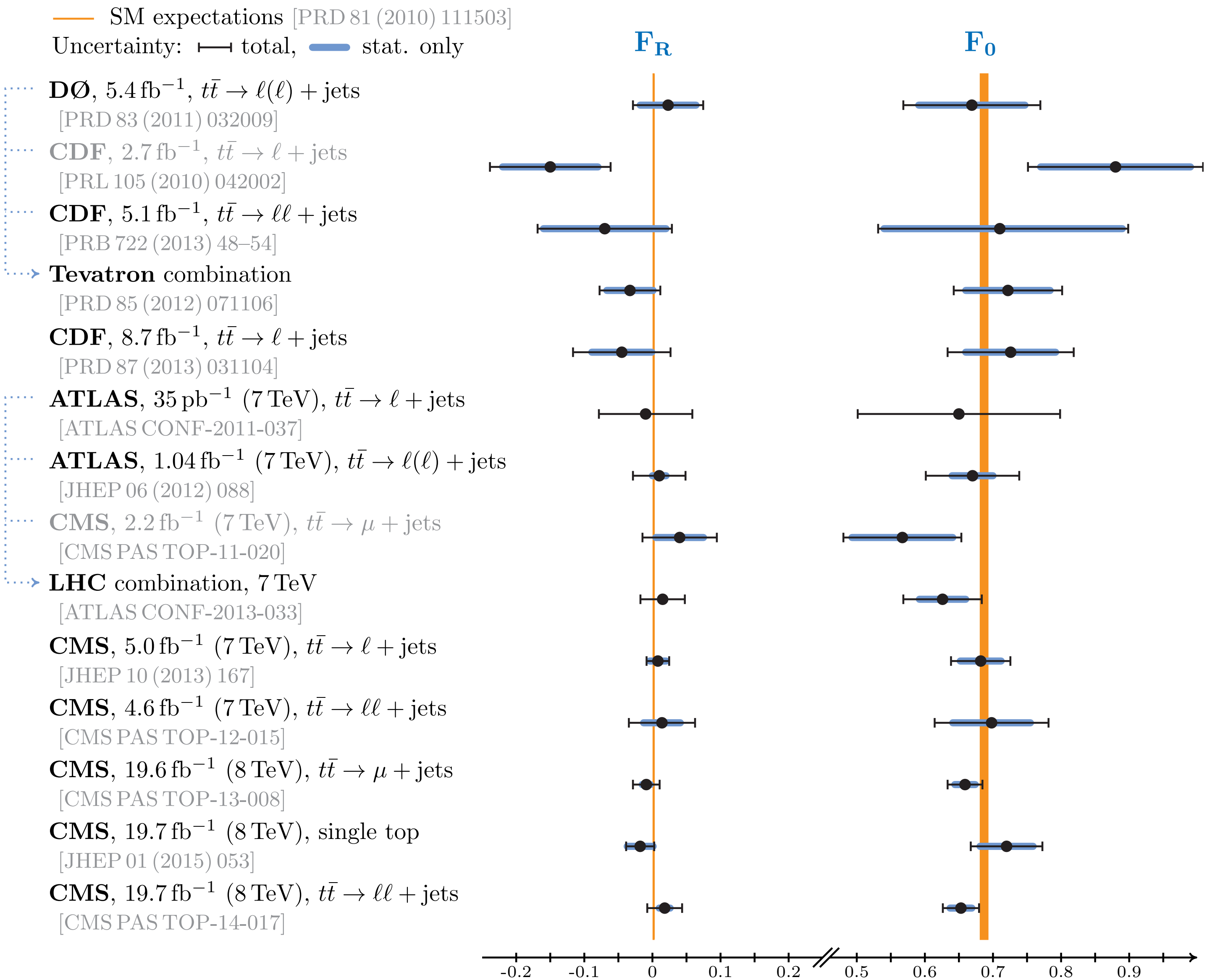
$F_R = -0.018 \pm 0.019_{stat} \pm 0.011_{syst}$

$F_0 = 0.720 \pm 0.039_{stat} \pm 0.037_{syst}$

$F_R = 0.018 \pm 0.008_{stat} \pm 0.026_{syst}$

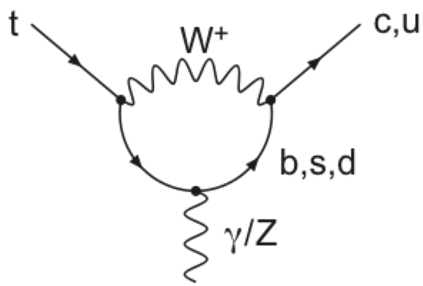
$F_0 = 0.653 \pm 0.016_{stat} \pm 0.024_{syst}$

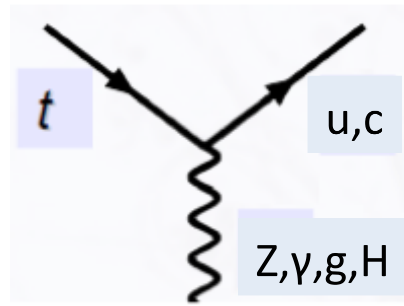
Summary: W Helicity Fractions



LHC currently finishing Run-I measurements ⟶ combine

Flavour Changing Neutral Currents





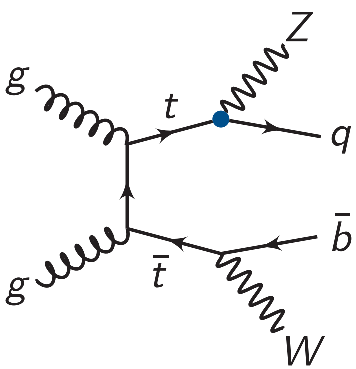
ACTA Phys. Pol. B 35 (2004)

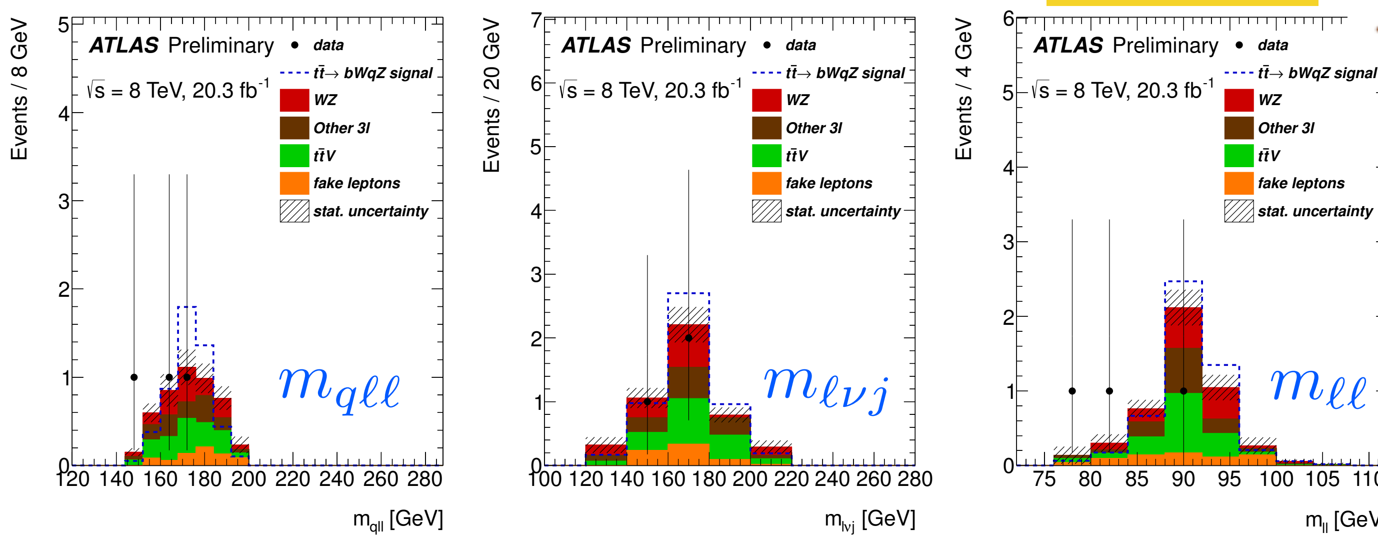
SM: BR ~ 10^{-12} ... 10^{-17}

BSM: BR ~ 10^{-5} ... 10^{-9}

New Physics could enhance FCNC couplings by many orders of magnitude

ATLAS TOPQ-2014-08

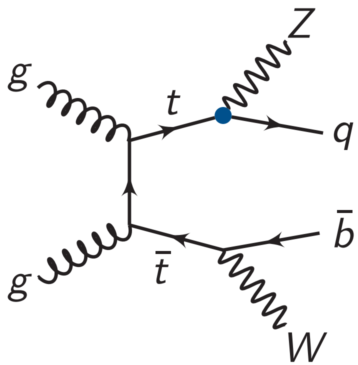


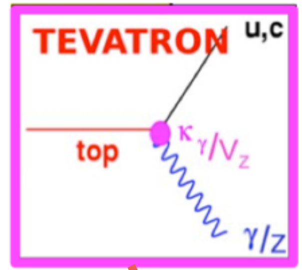


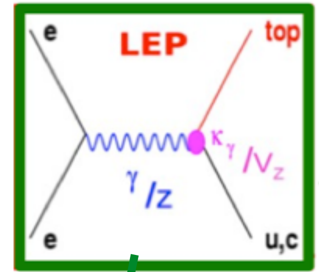
- t→ qZ (3ℓ)
- backgrounds from control regions

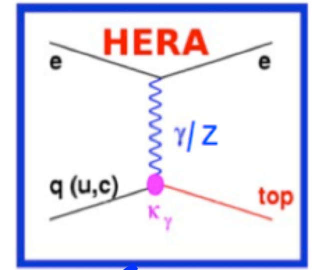
Upper limit on branching ratio: BR(t→Zq) < 0.07% (95%CL)

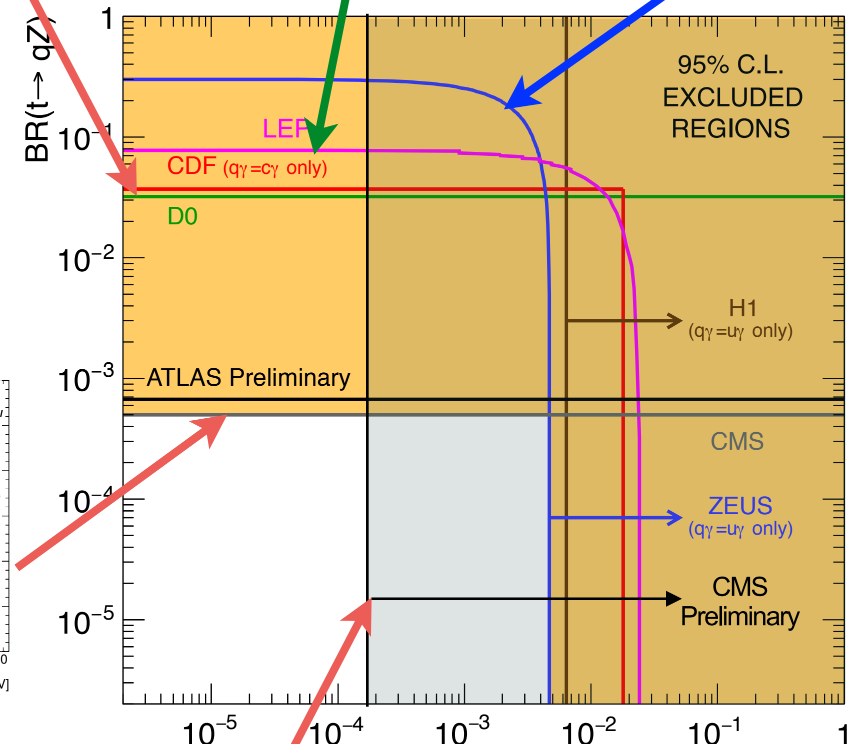
FCNC: t→(u,c)Z/γ(*)





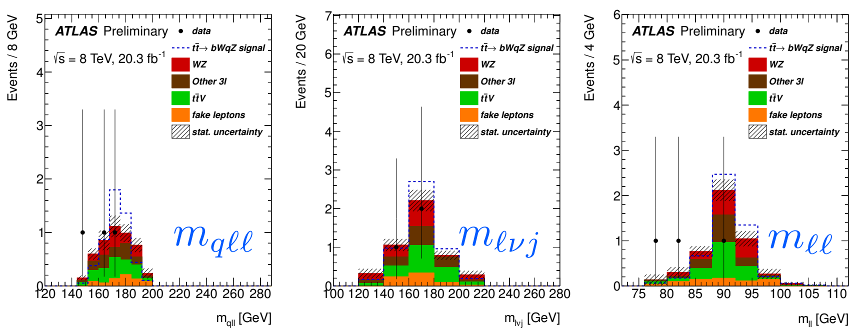




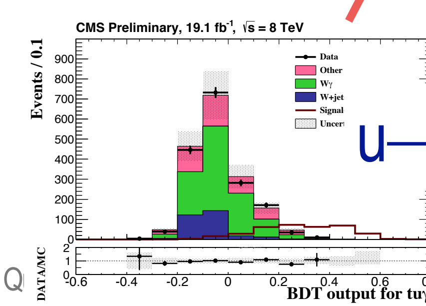


ATLAS TOPQ-2014-08

t→qZ (3ℓ)

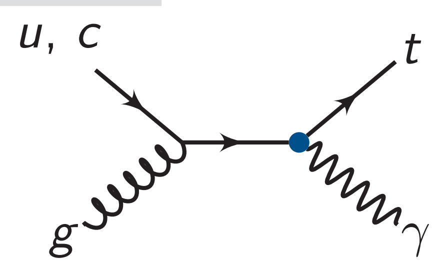


LEP, HERA, Tevatron:
complementary results
now being superseded by the LHC



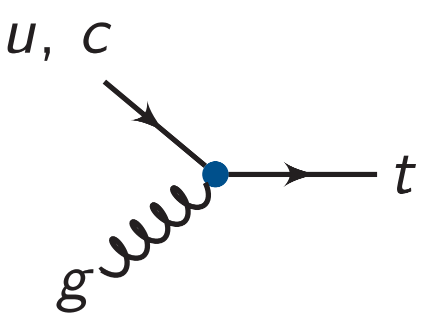
u→tγ

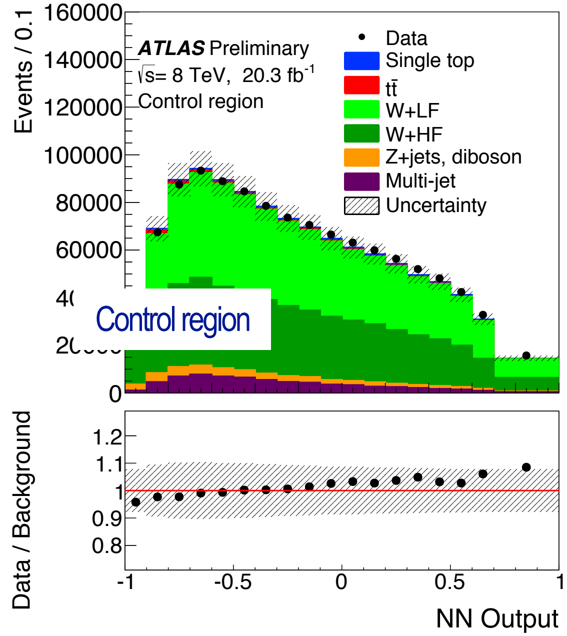
CMS TOP-14-003

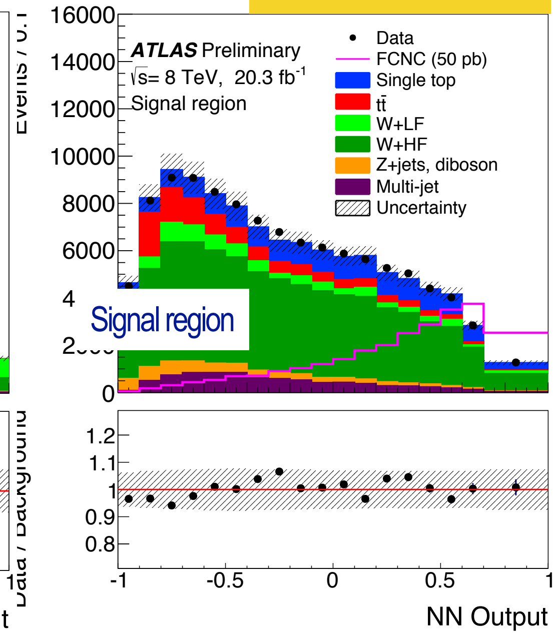


FCNC: (u,c)g⟶t

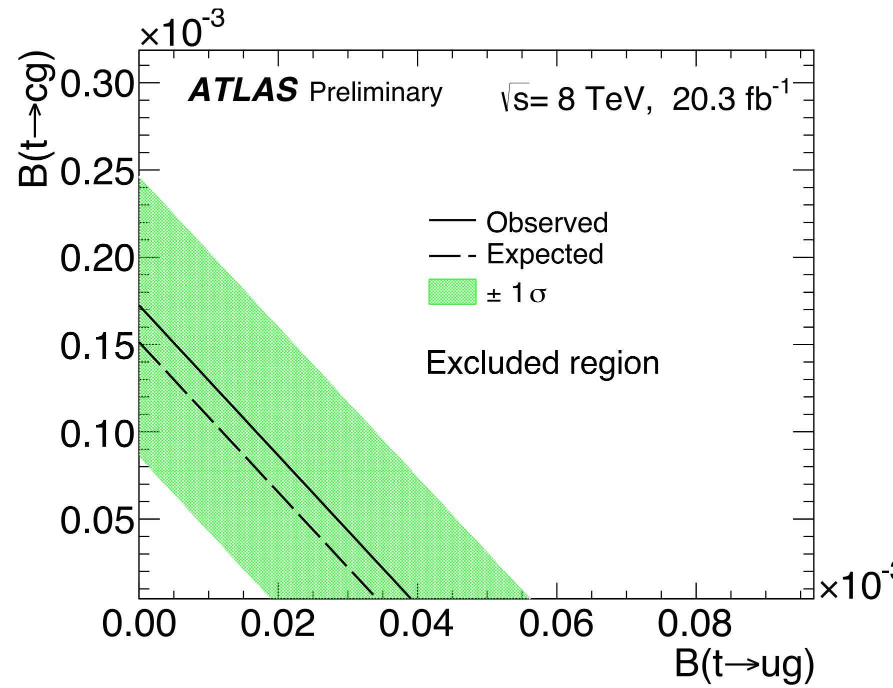
ATLAS-TOPQ-2014-13







- t-channel single top selection (1ℓ, 1b-tag, Missing ET)
- neural net trained to separate FCNC signal from SM-background

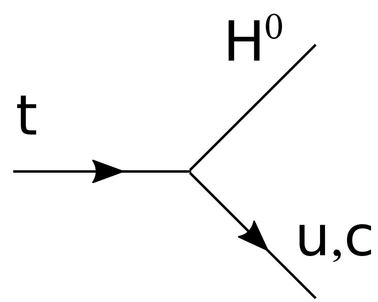


Upper limit on branching ratios:

$BR(t\to ug) < 4\cdot 10^{-5}$ @ 95% CL

$BR(t\to cg) < 17\cdot 10^{-5}$ @ 95% CL

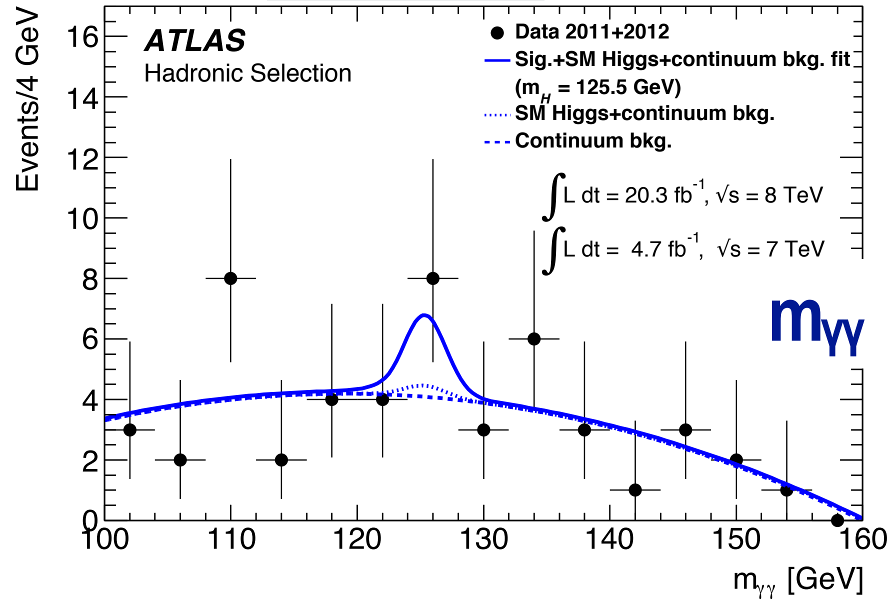
FCNC: $t \rightarrow (u,c)H$



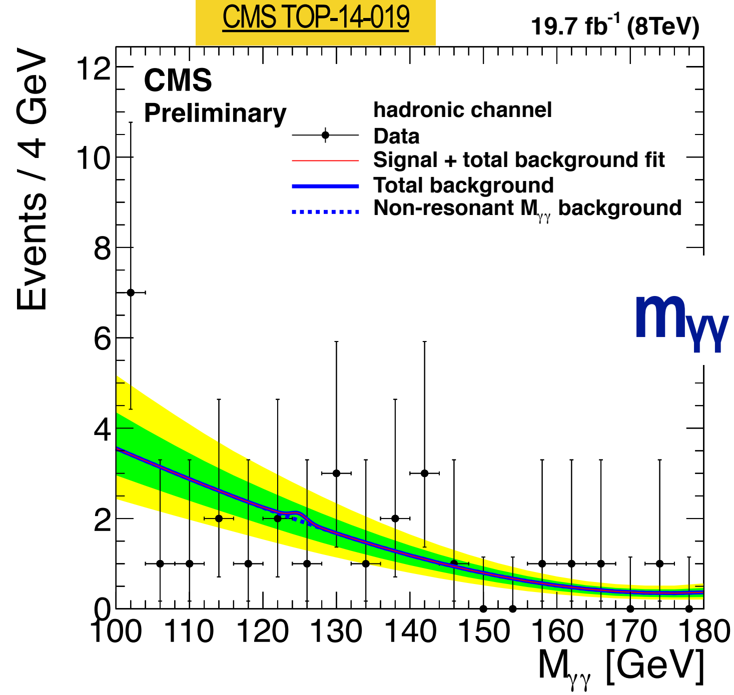
ATLAS upper limits:
BR($t \rightarrow qH$) < 0.79% obs (0.51% exp)

CMS upper limits:
BR($t \rightarrow cH$) < 0.47% obs (0.71% exp)
BR($t \rightarrow uH$) < 0.42% obs (0.65% exp)

JHEP06 (2014) 008



CMS TOP-14-019



Summary: FCNC

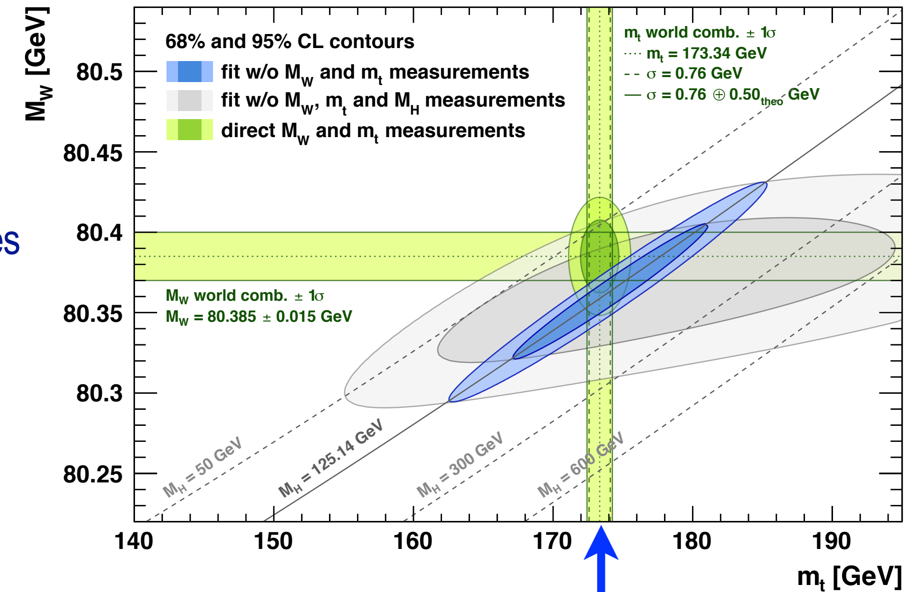
Exp.	$\sqrt{s}$	$\mathcal{B}(t \to u\gamma)$	$\mathcal{B}(t \to c\gamma)$	Reference
CDF	1.96 TeV	$3.2 \cdot 10^{-2}$		PRL 80 (1998) 2525
CMS	8 TeV	$1.6 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	CMS TOP-14-003
		$\mathcal{B}(t \to uZ)$	$\mathcal{B}(t \to cZ)$	
CDF	1.96 TeV	$3.7 \cdot 10^{-2}$		PRL 101 (2008) 192002
DØ	1.96 TeV	$3.2 \cdot 10^{-2}$		PLB 701 (2011) 313
ATLAS	7 TeV	$7.3 \cdot 10^{-3}$		JHEP 09 (2012) 139
CMS	7 TeV	$5.1 \cdot 10^{-3}$	$1.1 \cdot 10^{-1}$	CMS TOP-12-021
CMS	7+8 TeV	$5 \cdot 10^{-4}$		PRL 112 (2014) 171802
ATLAS	8 TeV	$7 \cdot 10^{-4}$		ATLAS TOPQ-2014-08
		$\mathcal{B}(t \to ug)$	$\mathcal{B}(t \to cg)$	
CDF	1.96 TeV	$3.9 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$	PRL 102 (2009) 151801
DØ	1.96 TeV	$2.0 \cdot 10^{-4}$	$3.9 \cdot 10^{-3}$	PLB 693 (2010) 81
ATLAS	7 TeV	$5.7 \cdot 10^{-5}$	$2.7 \cdot 10^{-4}$	PLB 712 (2012) 351
ATLAS	8 TeV	$3.1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	ATLAS CONF-2013-063
CMS	7 TeV	$3.6 \cdot 10^{-4}$	$3.4 \cdot 10^{-3}$	CMS TOP-14-007
ATLAS	8 TeV	$4 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$	ATLAS TOPQ-2014-13
		$\mathcal{B}(t \to uH)$	$\mathcal{B}(t \to cH)$	
ATLAS	7+8 TeV	$7.9 \cdot 10^{-3}$		JHEP 06 (2014) 008
CMS	8 TeV	—	$5.6 \cdot 10^{-3}$	PRD 90 (2014) 112013
CMS	8 TeV	—	$9.3 \cdot 10^{-3}$	CMS TOP-13-017
CMS	8 TeV	$4.2 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$	CMS TOP-14-019

Getting close to BSM scenarios

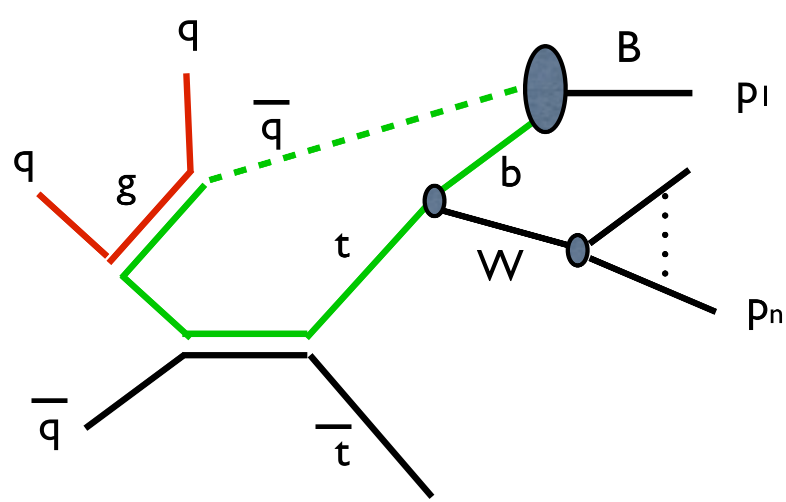
Top-Quark Mass

arXiv:1407.3792

- Quark mass is scheme-dependent
  - Pole-mass: viewing top quark as a free parton
  - Other schemes, e.g. $\overline{\text{MS}}$ scheme give different values
- Difference between 'direct' MC mass and pole mass estimated to be O(1) GeV
- 'Direct' mass measurements
  - Reconstruct m_{top}(rec) and extract m_{top}(MC)
  - Experimentally most precise, limited by
    - (Flavour-dependent) jet energy scale uncertainties
    - Final state modeling: hadronization, fragmentation, colour reconnection
- 'Alternative' mass measurements
  - Complementary (experimental or theoretical) uncertainties
  - Comparison/combination with 'direct' mass measurements can reduce uncertainties further



$m_{WA} \pm \mathcal{O}(1\ \text{GeV})$

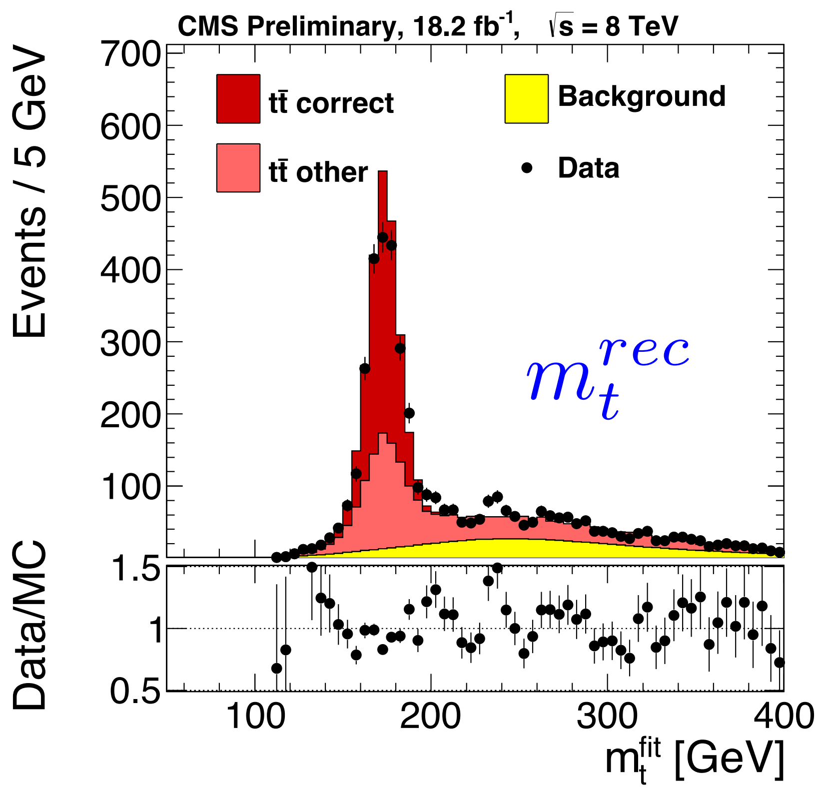


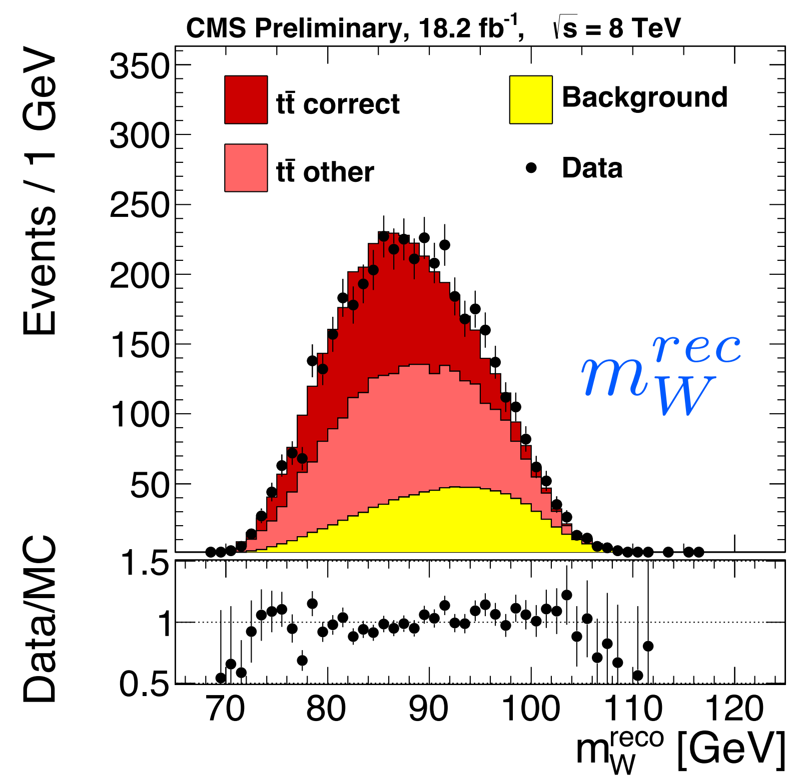
m_{top}(MC): CMS

all jets

CMS TOP-14-002

- '2D' likelihood fit to extract m_{top} and light-quark jet energy scale from W-mass constraint





CMS TOP-14-015

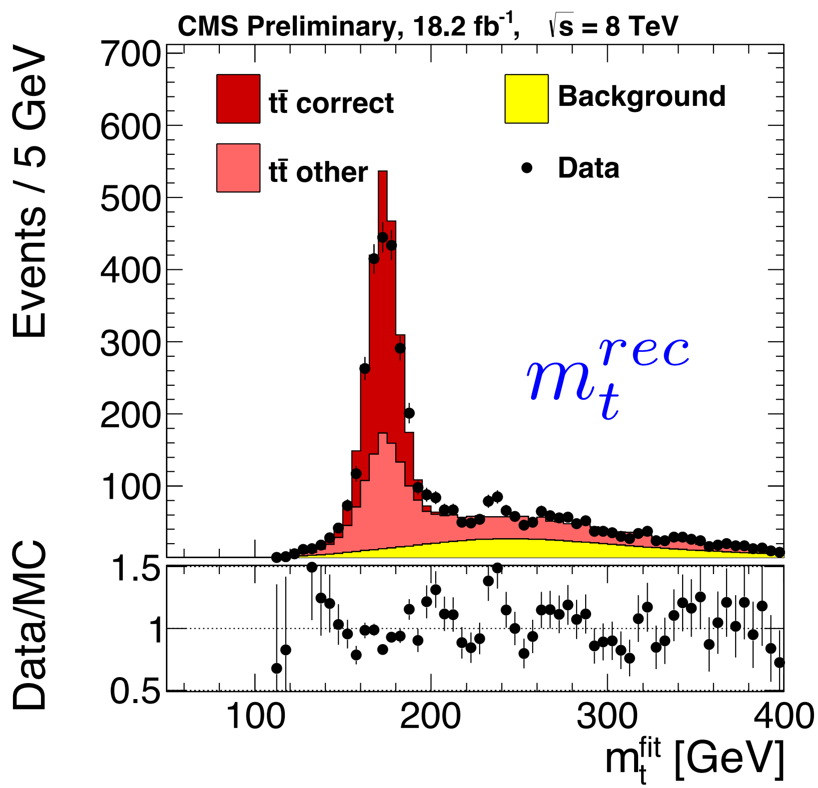
CMS Run-I combination:

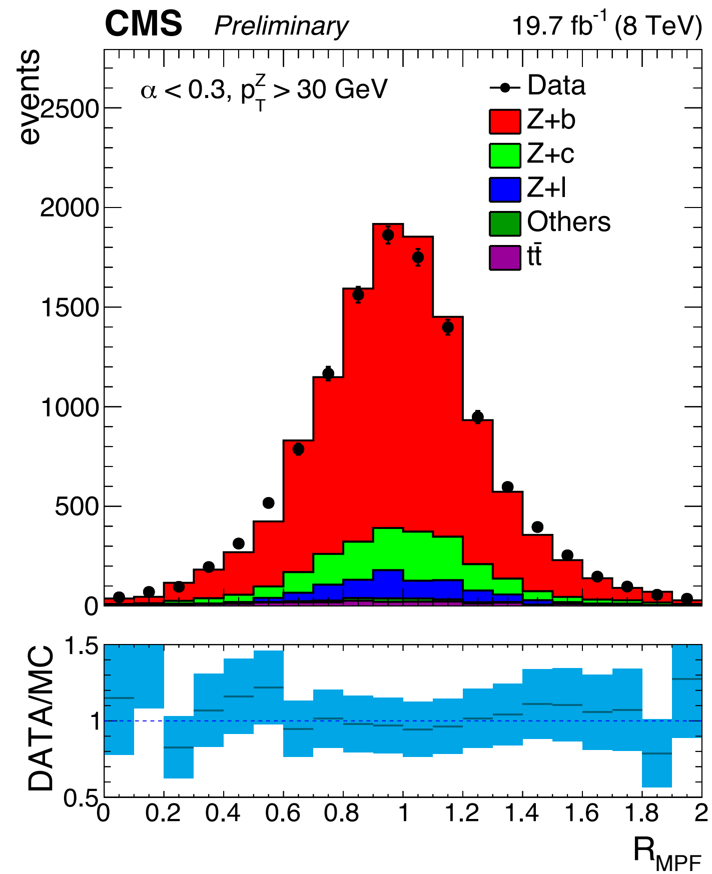
$m_{top} = 172.38 \pm 0.10_{stat} \pm 0.65_{syst}$ GeV

m_{top}(MC): CMS all jets

CMS TOP-14-002

- ‘2D’ likelihood fit to extract m_{top} and light-quark jet energy scale from W-mass constraint
- b-jet energy scale cross checked using Z+b





CMS JME-13-001

CMS TOP-14-015

CMS Run-I combination:

m_{top} = 172.38 ± 0.10$_{stat}$ ± 0.65$_{syst}$ GeV

b-jet energy scale correction

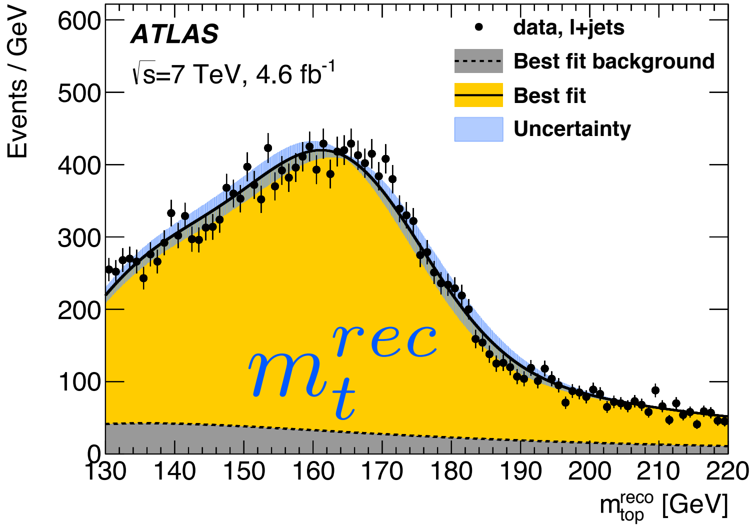
C_{corr} = 0.998 ± 0.004 $_{stat}$ ± 0.004 $_{sys}$

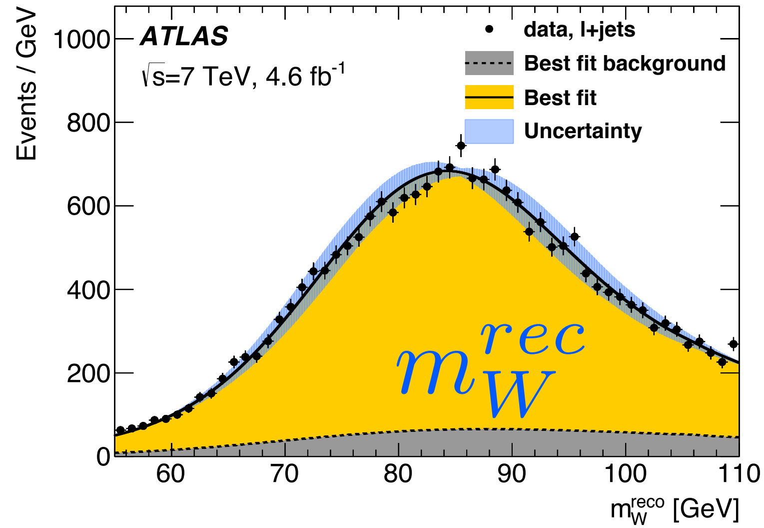
m_{top}(MC): ATLAS

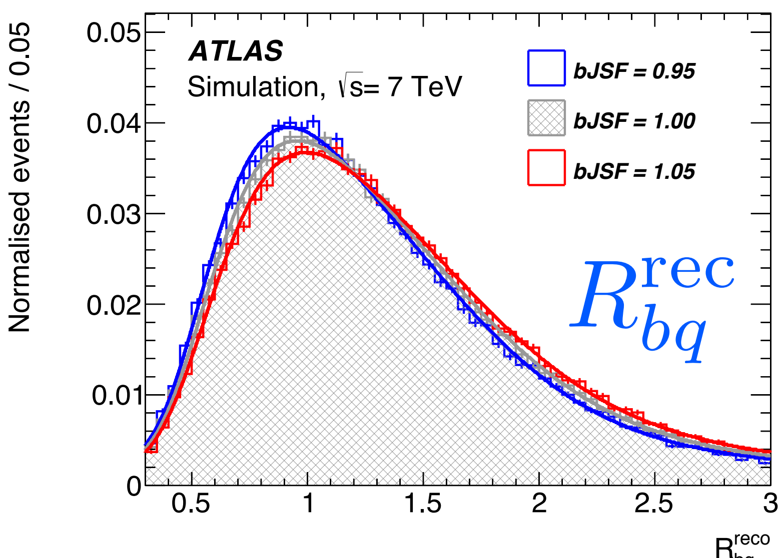
ℓ+jets

arXiv: 1503.05427

- 3D template fit to mtop, jet energy scale and b-jet energy scale







$$R_{bq}^{rec} = \frac{p_T^{b_h} + p_T^{b_\ell}}{p_T^{j_1^W} + p_T^{j_2^W}}$$

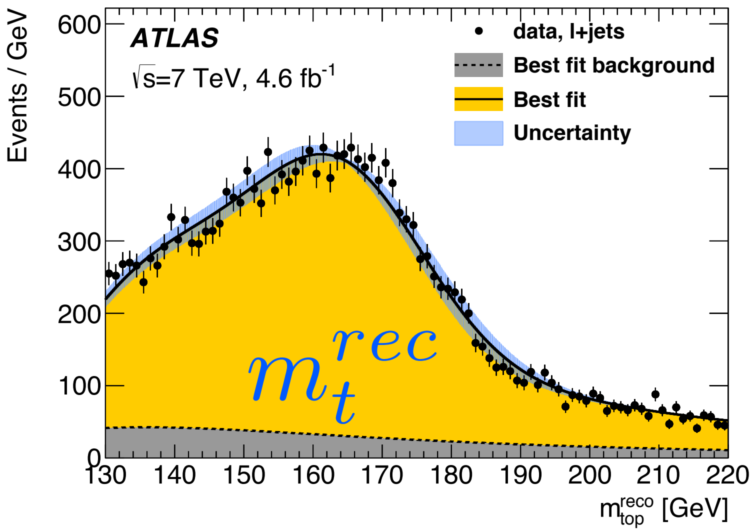
- R_{bq}^{rec}: sensitive to b-jet energy scale
- insensitive to light-quark jet energy scale and m_{top}

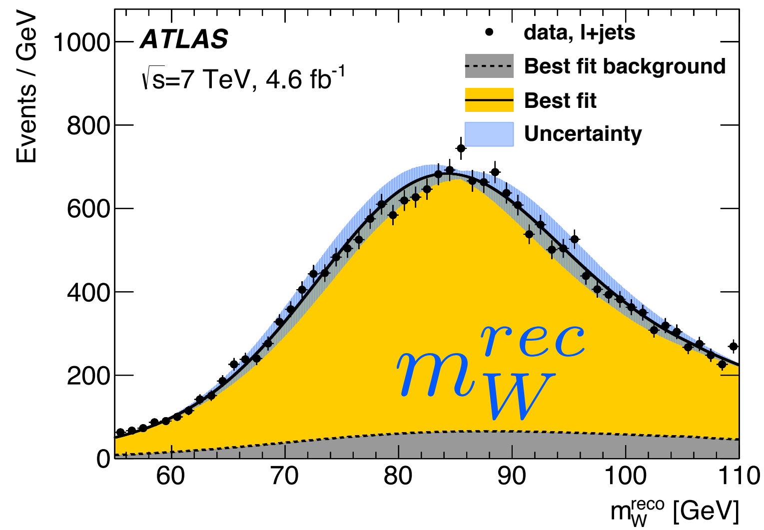
m_{top}(MC): ATLAS

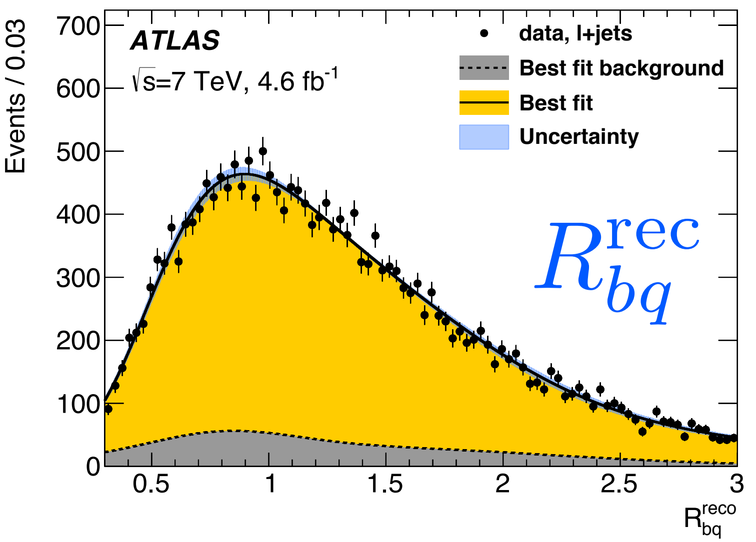
ℓ+jets

arXiv: 1503.05427

- 3D template fit to mtop, jet energy scale and b-jet energy scale







ATLAS Combination

$m_{top} = 172.99 \pm 0.48_{stat} \pm 0.78_{syst}$ GeV

Will benefit from more statistics at 8 TeV and Run-II

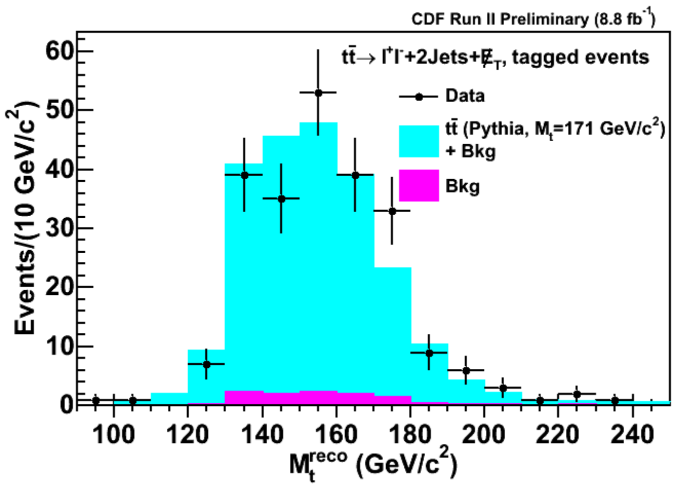
m_{top}(MC): CDF and D0

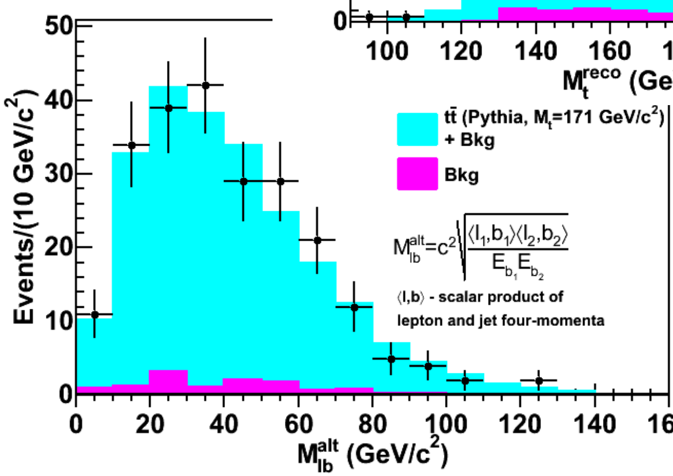
2ℓ channel

- Reconstruct two observables
  - m_{top}(reco): from full kinematic reconstruction
  - m_{lb}(alt): dampen dependence on jet-energy scale

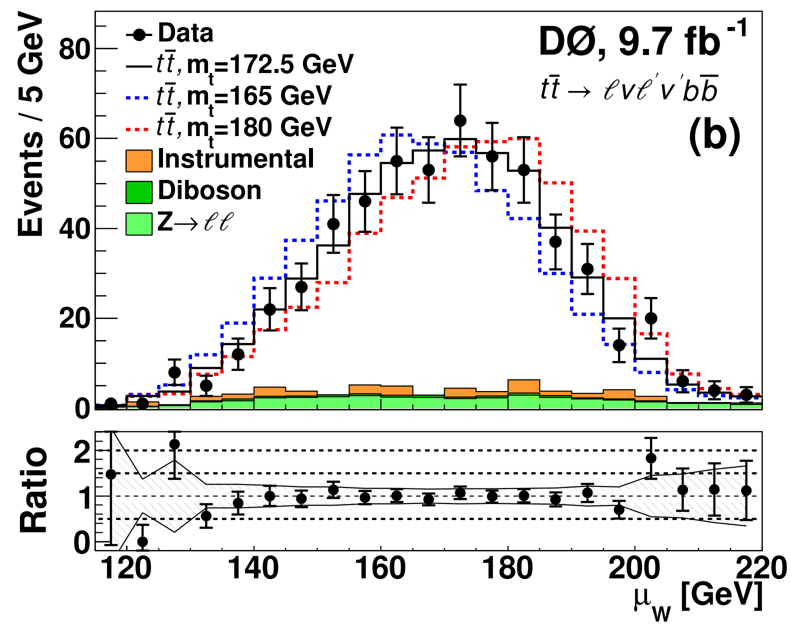
- Include multiple kinematic solutions, using weights from expected neutrino spectra.

PRD 92 032003





arXiv:1508.03322

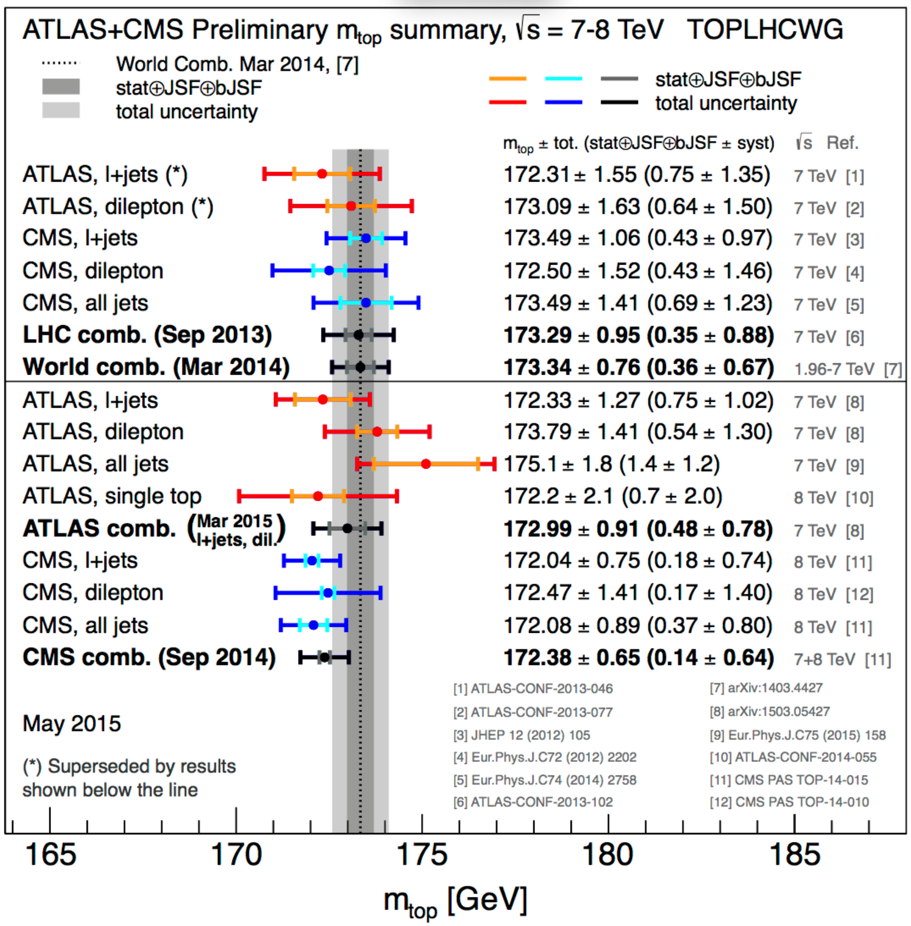


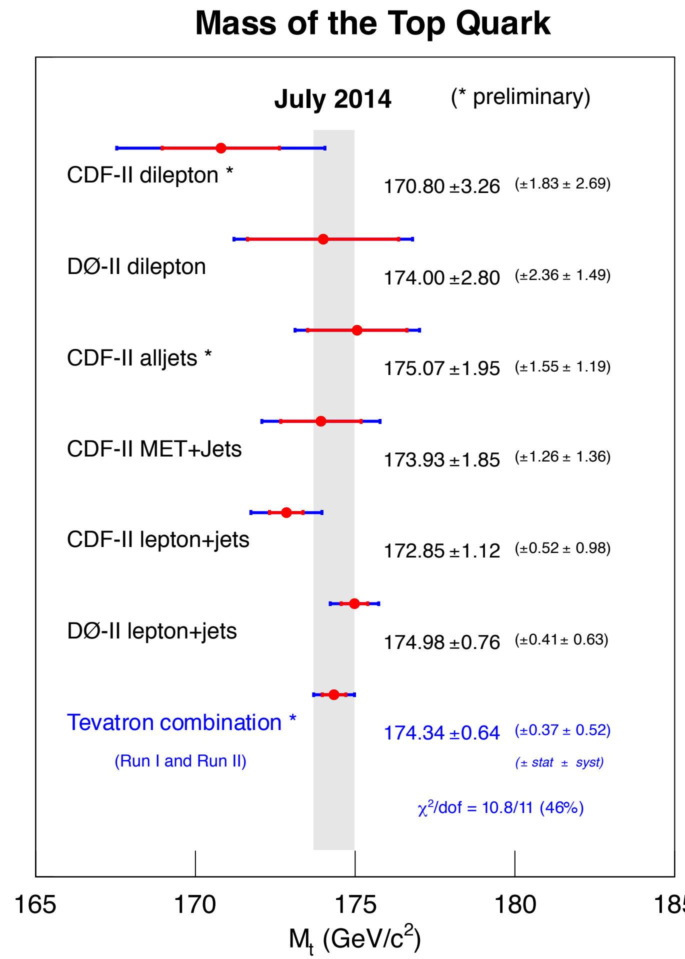
m_{top} = 171.5 ± 1.9_{stat} ± 2.5_{syst} GeV

m_{top} = 173.32 ± 1.36_{stat} ± 0.85_{syst} GeV

Summary: m_{top}(MC)

TOPLHCWG





arXiv:1407.2682

CMS Combination

$m_{top} = 172.38 \pm 0.65_{syst}$ GeV

ATLAS Combination

$m_{top} = 172.99 \pm 0.91_{syst}$ GeV

Tevatron Combination

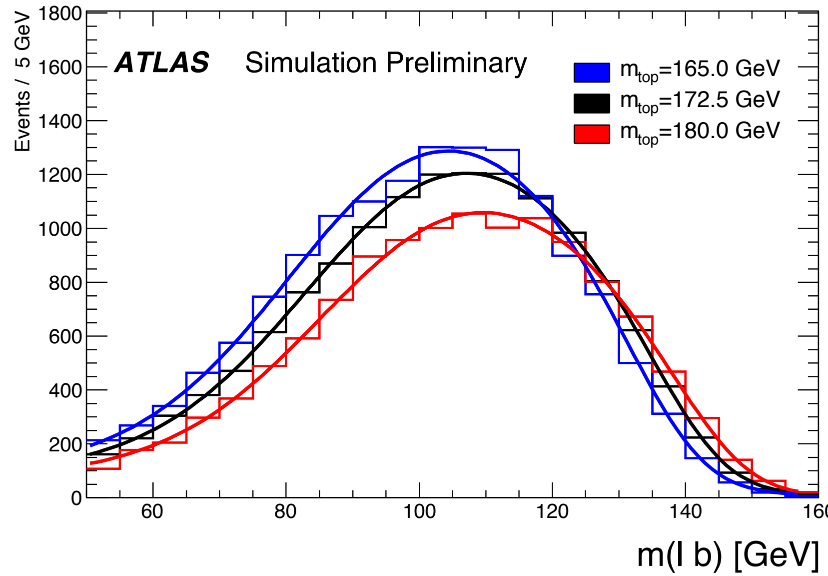
$m_{top} = 174.34 \pm 0.64_{syst}$ GeV

Work towards next world combination has started

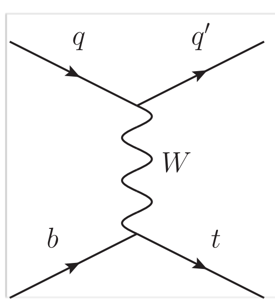
Mass from Single Top

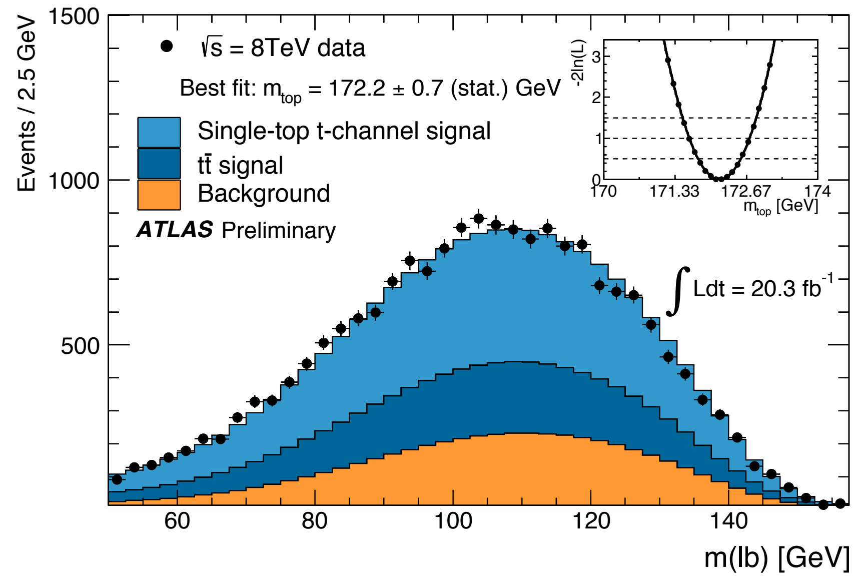
ATLAS-CONF-2014-055

- ‘Alternative’ mass measurements: different (experimental or theoretical) uncertainties
- Comparison/combination with ‘direct’ mass measurements can reduce uncertainties further



Different color reconnection process and different scale uncertainties



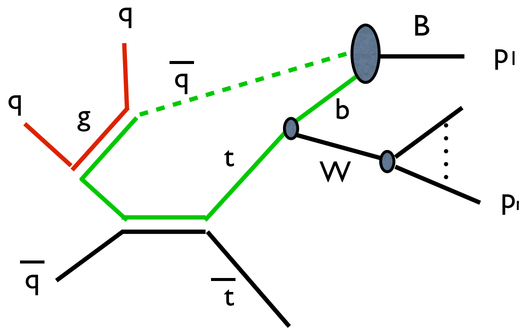


m_{top} = 172.2 ± 0.7 $_{stat}$ ± 2.0 $_{syst}$ GeV

m_{top}(MC): CMS

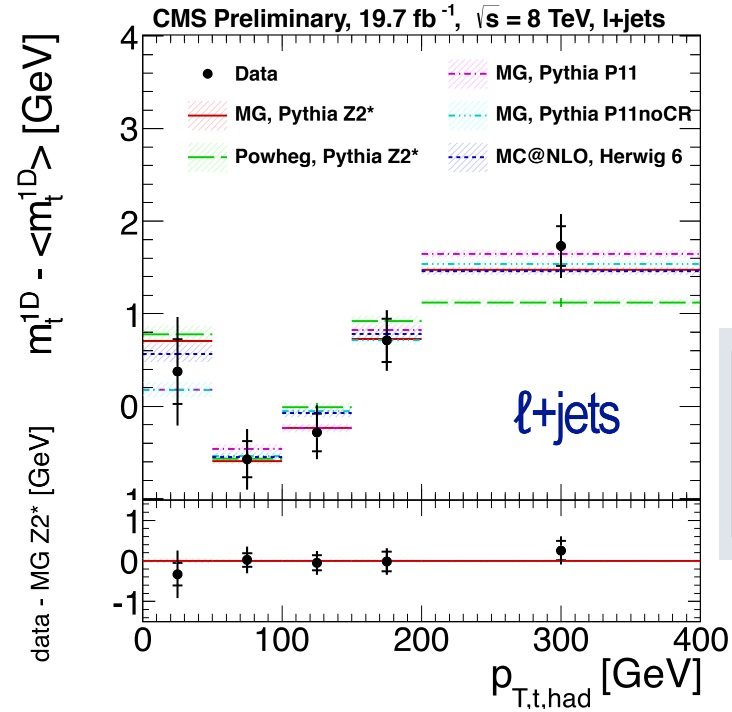
ℓ+jets

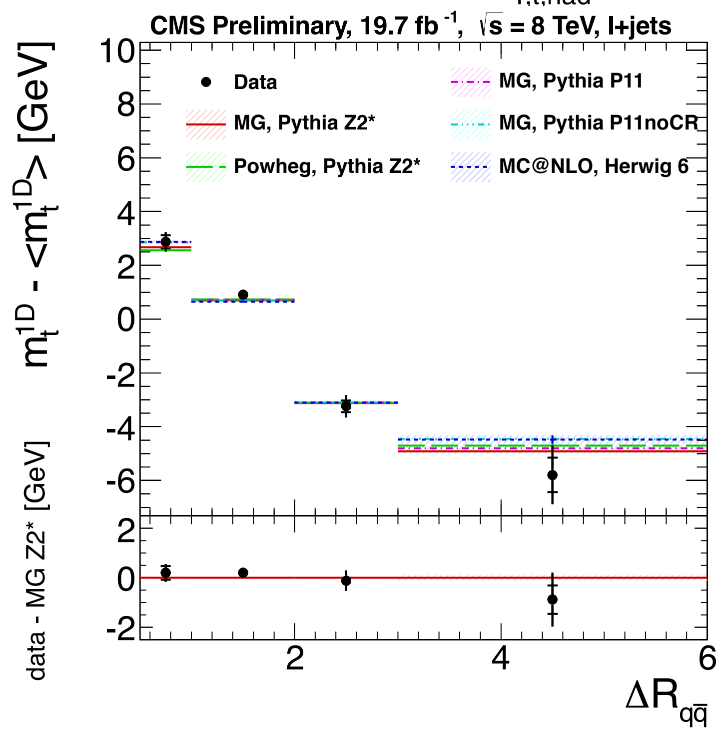
- Determine kinematic dependence of measurement: pin down those (non-)perturbative corrections that would lead to differences
- Select distributions with sensitivity to
  - Color reconnection
  - ISR/FSR
  - b-quark kinematics



Observable	m_t^{1D} χ^2			
$\Delta R_{q\bar{q}}$	2.87			
$p_{T,t,had}$	0.89	12.03	5.76	4
$\lvert\eta_{t,had}\rvert$	5.56	1.22	1.14	3
H_T^4	6.19	9.18	7.54	4
$m_{t\bar{t}}$	2.16	4.69	4.22	5
$p_{T,t\bar{t}}$	1.02	1.22	1.33	4
Jet multiplicity	4.24	0.10	1.16	2
$p_{T,b,had}$	2.57			
$\lvert\eta_{b,had}\rvert$	1.15			
$\Delta R_{b\bar{b}}$	0.37			
$p^1_{T,q,had}$	4.04			
$\lvert\eta^1_{q,had}\rvert$	3.36			
$p_{T,W,had}$	1.59			
$\lvert\eta_{W,had}\rvert$	1.41	1.09	1.35	3
Total	37.43	60.94	37.15	47

Altogether 14 different distributions have been measured to ensure that models describe behaviour of data throughout phase space





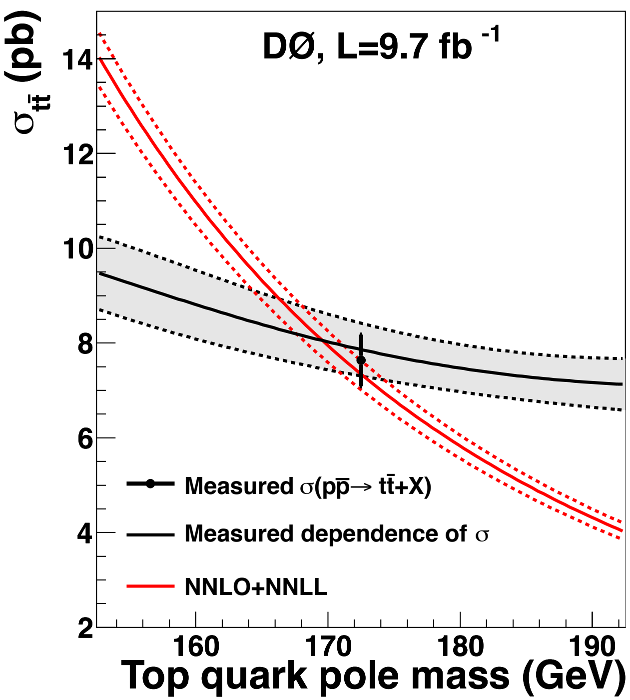
CMS TOP-14-001

Pole Mass

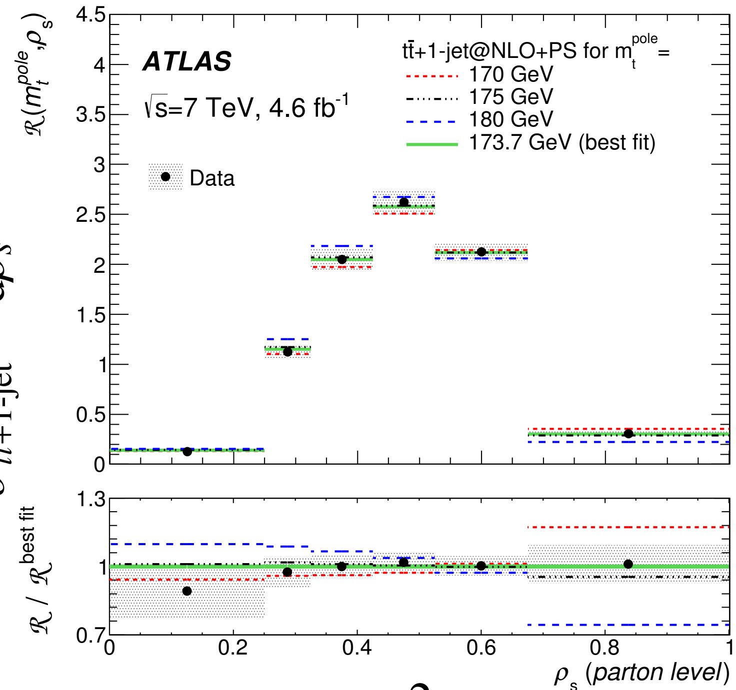
S. Alioli et al EPJC 73 (2013) 2438

- inclusive cross section (NNLO)
  dependent on top-quark pole mass

- tt+1jets distribution (NLO+PS)
  pole mass through threshold and cone effects



D0 conf 6453 (2015)



arXiv:1507.01769

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s)$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

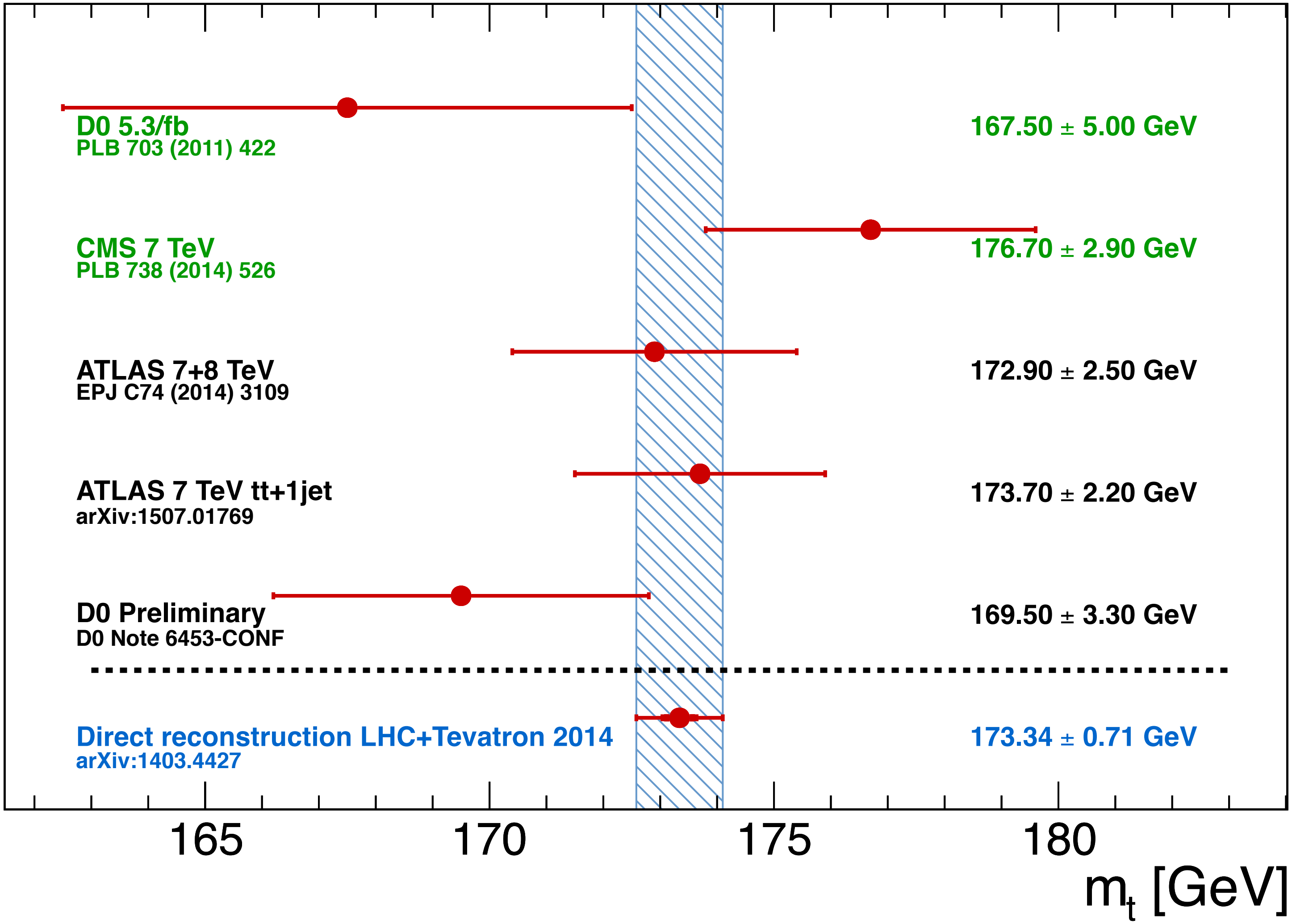
$m_{top} = 169.5\ {}^{+3.3}_{-3.4}\ {}_{tot}$ GeV

$m_{pole} = 173.7 \pm 1.5_{stat} \pm 1.4_{syst}\ {}^{+1.0}_{-0.5}\ {}_{theory}$ GeV

Precision limited in part by theoretical uncertainties

Precision limited more by statistical uncertainties

Summary: Pole Mass



Pole mass measurements, experimentally not (yet?) as precise as MC mass

Summary

- **Top quark physics: Key to QCD, electro-weak and New Physics**
  - Tevatron and LHC data provide complementary information
  - A detailed picture of top quark properties has been established
  - Experiments finishing Legacy publications (Tevatron and LHC Run-1)

- **Run-II: 100 fb^{-1} expect per experiment by 2018**
  - 80 million tt events and 20 million single top events (>10 Hz at 10^{34})
  - 80,000 tt+Z and t+Z events each

- **Statistics → systematics and reach**
  - Beat down systematics using statistics and combination of methods
  - Ultimate precision esp. for top mass (also through theory advances)

- **Top as probe of New Physics**
  - Direct and indirect searches
  - Couplings, FCNC, angular distributions

- **Run-II: expect further substantial progress in experiment and theory, and - hopefully - surprises**

Backup

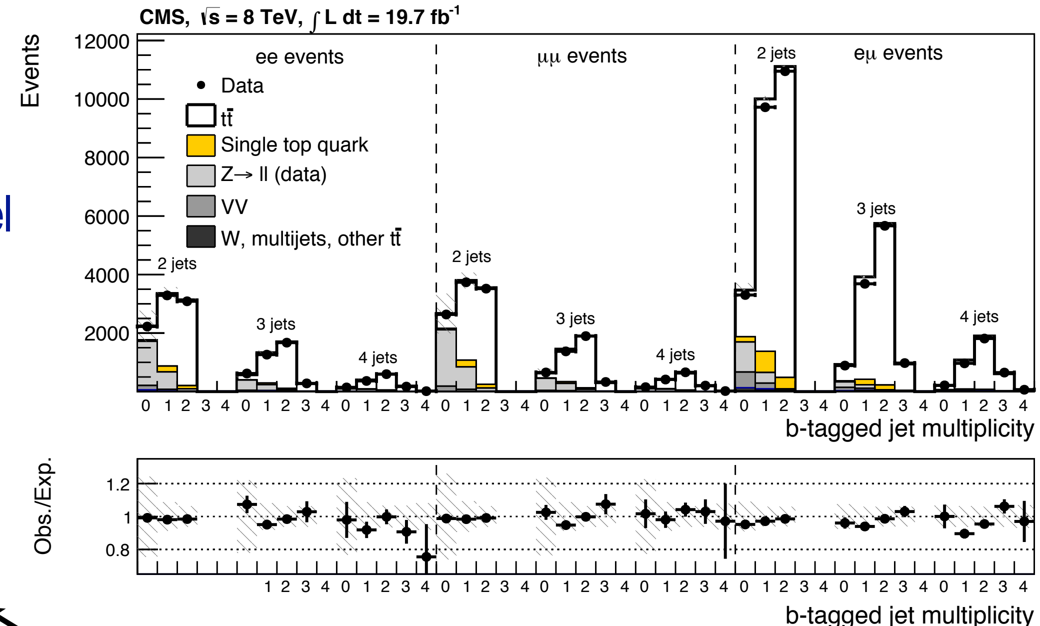
Links

- **ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults**
- **CDF: http://www-cdf.fnal.gov/physics/new/top/top.html**
- **CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html**
- **D0: http://www-d0.fnal.gov/Run2Physics/top/index.html**
- **LHCb: https://twiki.cern.ch/twiki/bin/view/LHCb/Top**

R_B = BR (tWb) / BR (tWq), Width and V_{tb}

PLB 736 (2014) 33

- $|V_{tb}|$ from R_B assuming unitary CKM
- Total width Γ_{top} from R_B and t-channel single top cross section



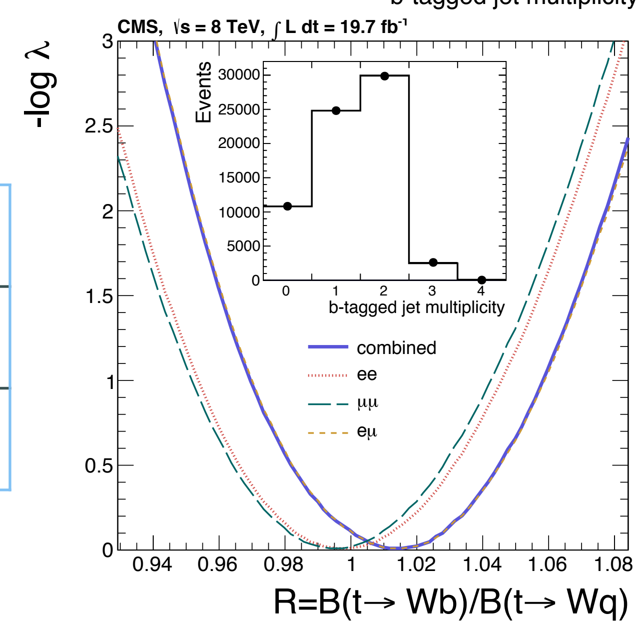
measured t-channel (7 TeV)

$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

measured R

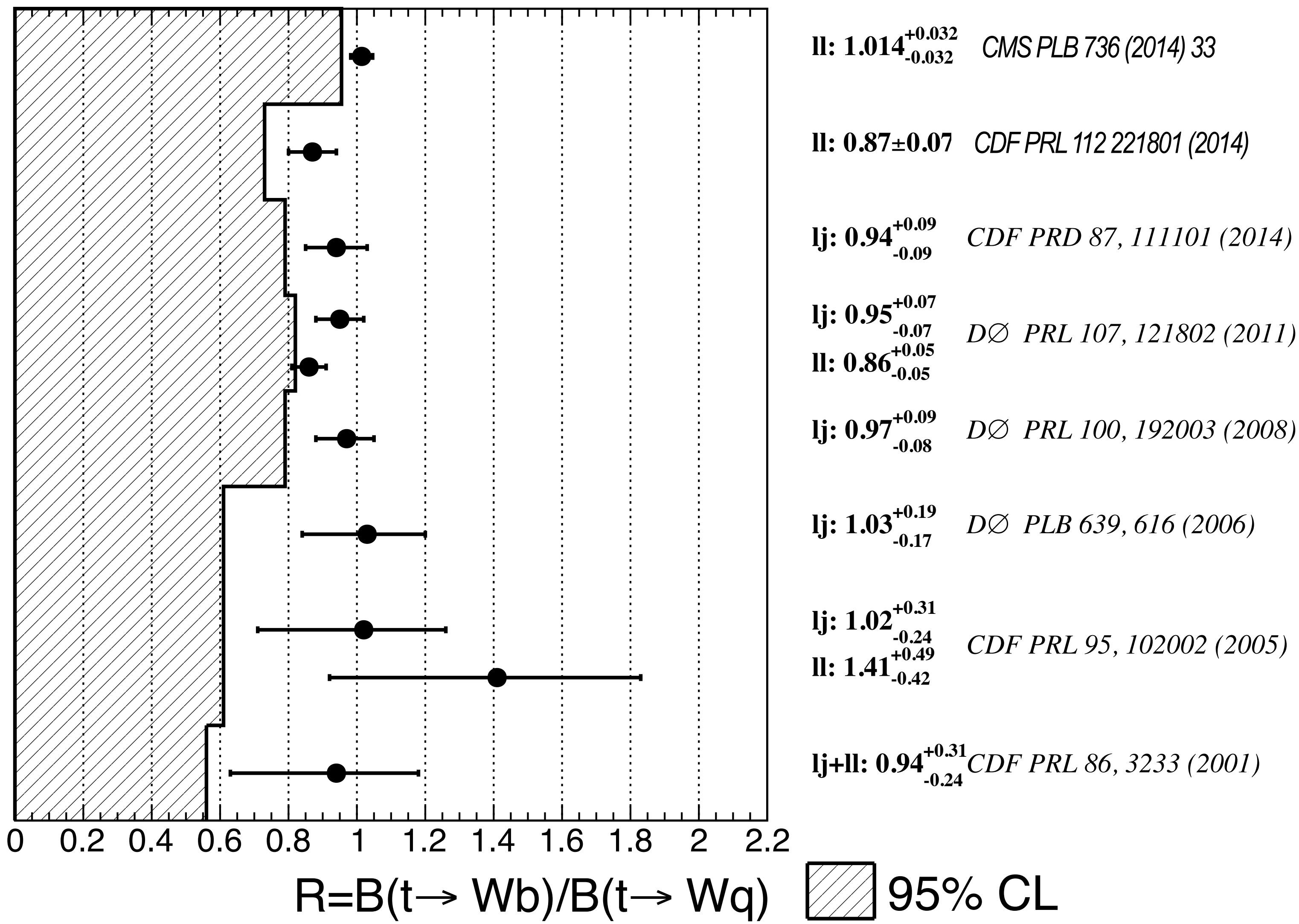
theory

R	unconstrained	1.014 ± 0.003 ± 0.032
$\|V_{tb}\|$	constrained < 1 @ 95% CL	> 0.972
Γ_{top}		$1.36 \pm 0.02_{stat} + 0.14_{syst} - 0.11_{syst}$ GeV



Most precise direct measurement of $|V_{tb}|$

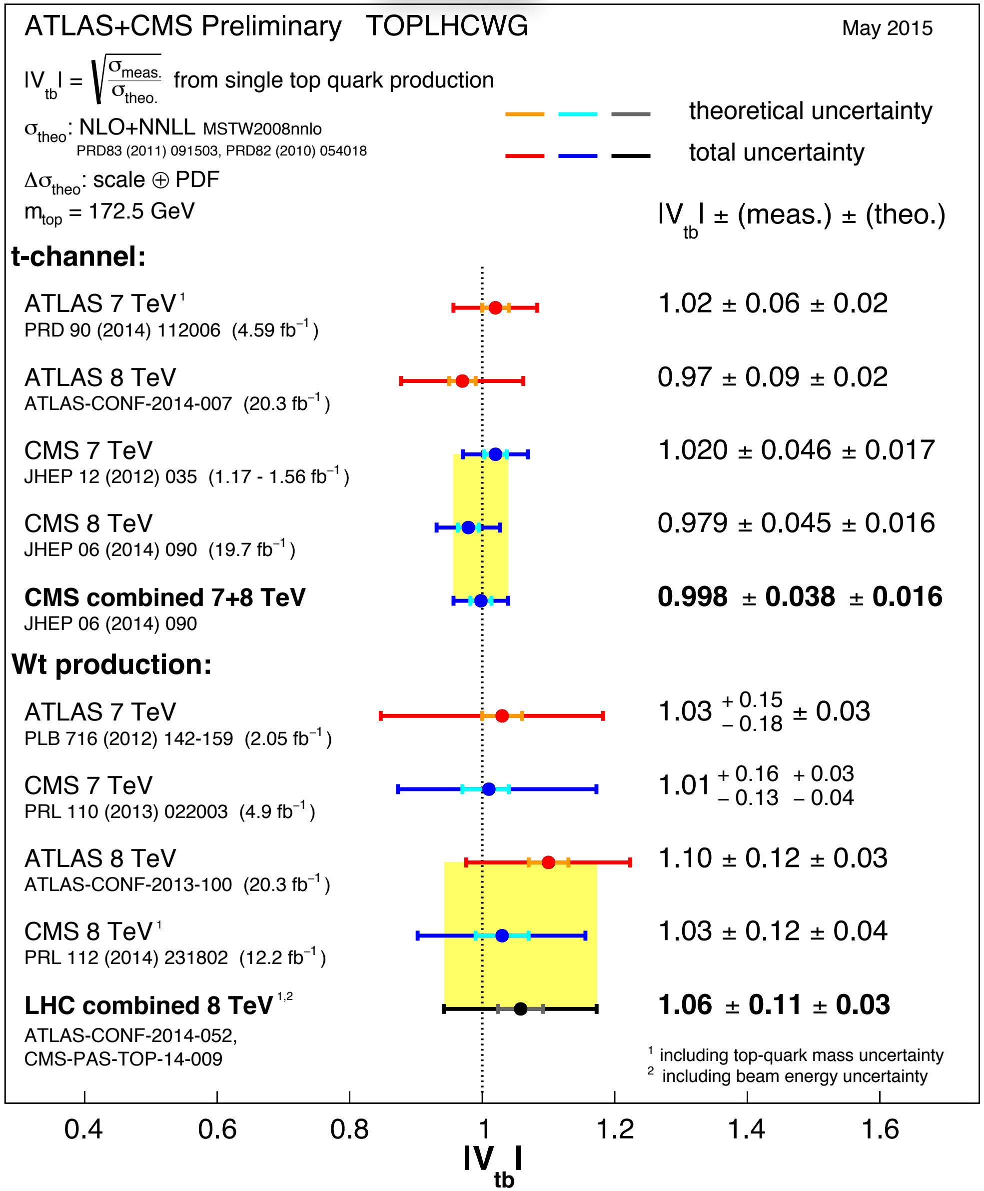
RB Summary



ll: 1.014 +0.032 -0.032 CMS PLB 736 (2014) 33
ll: 0.87±0.07 CDF PRL 112 221801 (2014)
lj: 0.94 +0.09 -0.09 CDF PRD 87, 111101 (2014)
lj: 0.95 +0.07 -0.07
ll: 0.86 +0.05 -0.05 D∅ PRL 107, 121802 (2011)
lj: 0.97 +0.09 -0.08 D∅ PRL 100, 192003 (2008)
lj: 1.03 +0.19 -0.17 D∅ PLB 639, 616 (2006)
lj: 1.02 +0.31 -0.24
ll: 1.41 +0.49 -0.42 CDF PRL 95, 102002 (2005)
lj+ll: 0.94 +0.31 -0.24 CDF PRL 86, 3233 (2001)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2
R=B(t→ Wb)/B(t→ Wq)
95% CL

$|V_{tb}|$ Summary: LHC

TOPLHCWG



Vacuum Stability

Degrassi et al, JHEP08 (2012) 098

- Evolution of quartic coupling and Higgs potential depend on top mass through radiative corrections.
- Finding: for experimental values of Top and Higgs mass there is no immediate requirement for new physics.