Top Quark Properties

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(On behalf of ATLAS, CDF, CMS and D0)

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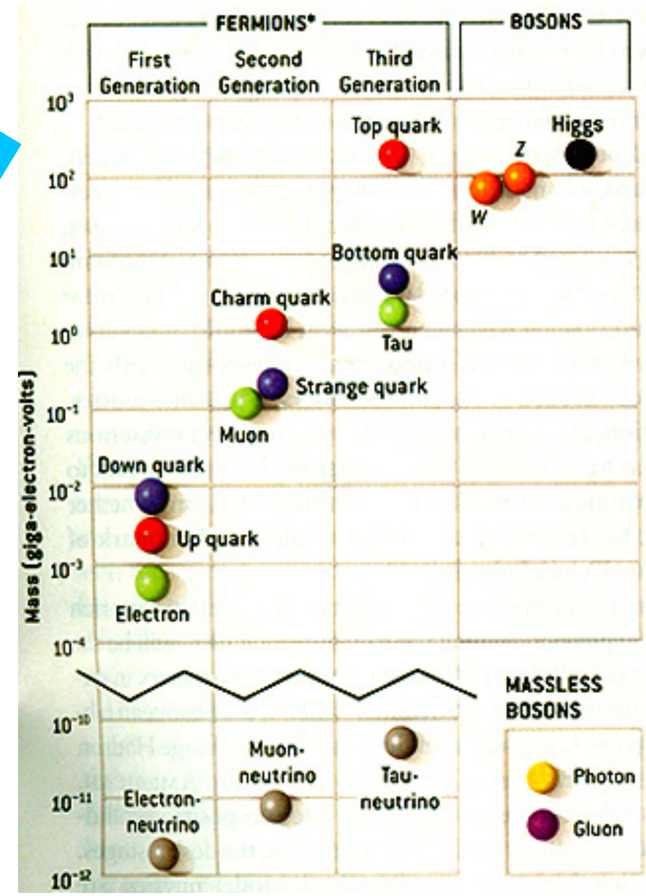
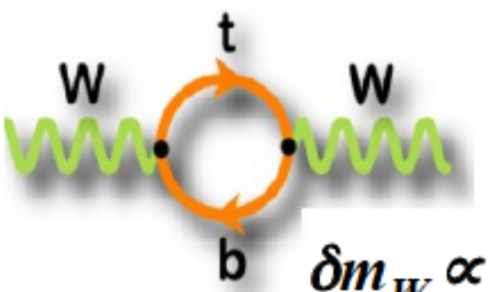
Why bother about top?

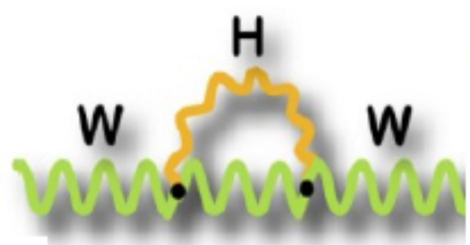


- Special in many accounts
  - Heaviest among all elementary particles
  - Couples strongly to the Higgs boson
  - Decays much before it can hadronize
  - Spin properties are transferred to decay products

- An excellent benchmark to check self-consistency of the standard model (SM)

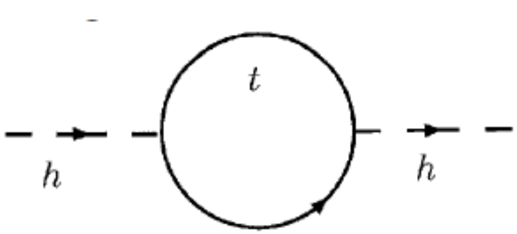


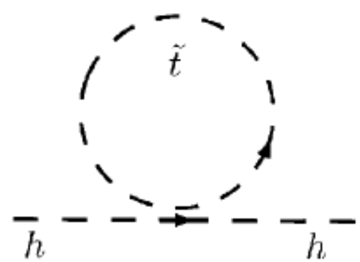
$\delta m_W \propto m_t^2$



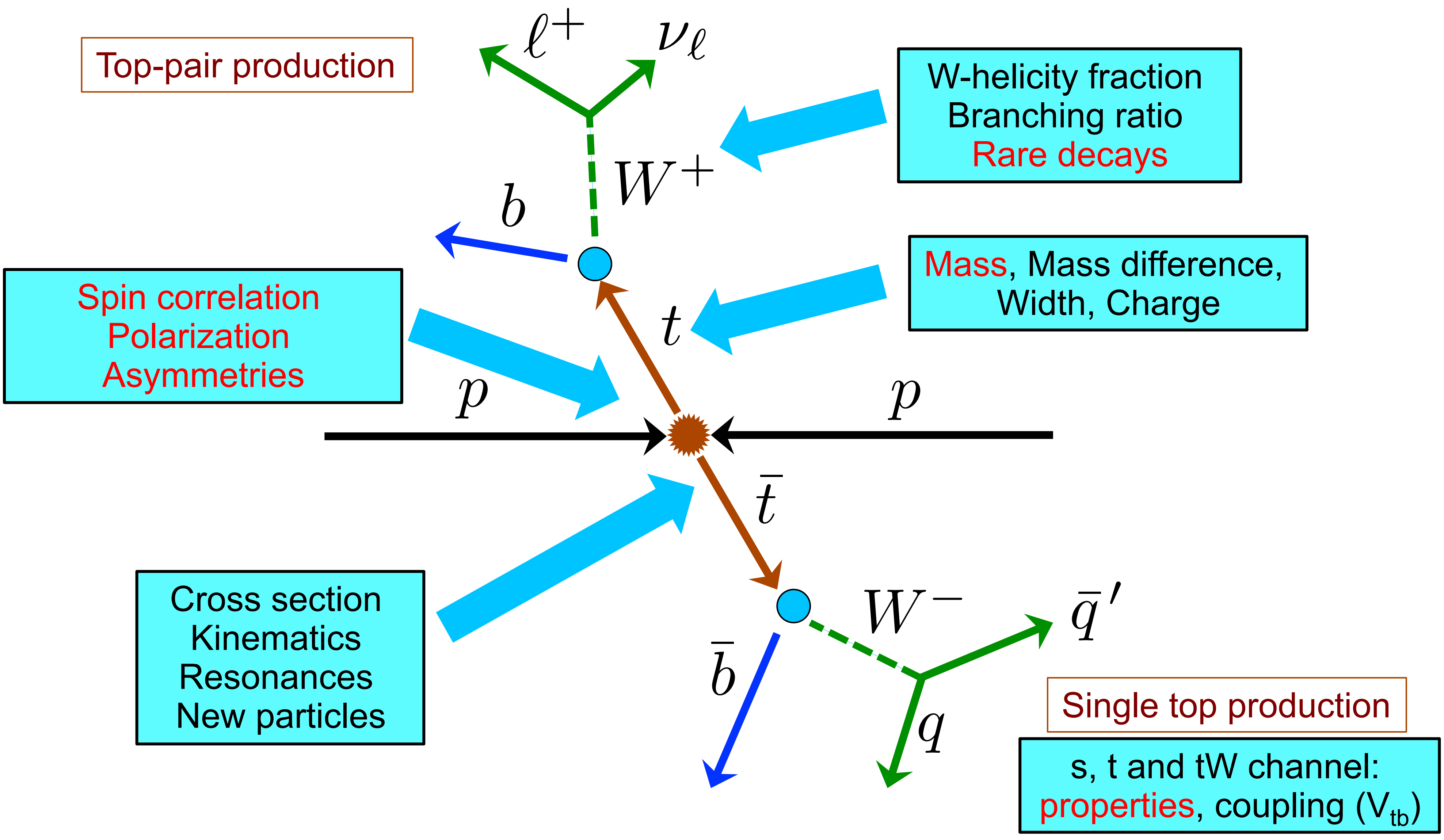
$\delta m_W \propto \ln(m_H)$

- Expect to have a good connection with new physics (NP)





Top properties: production and decay

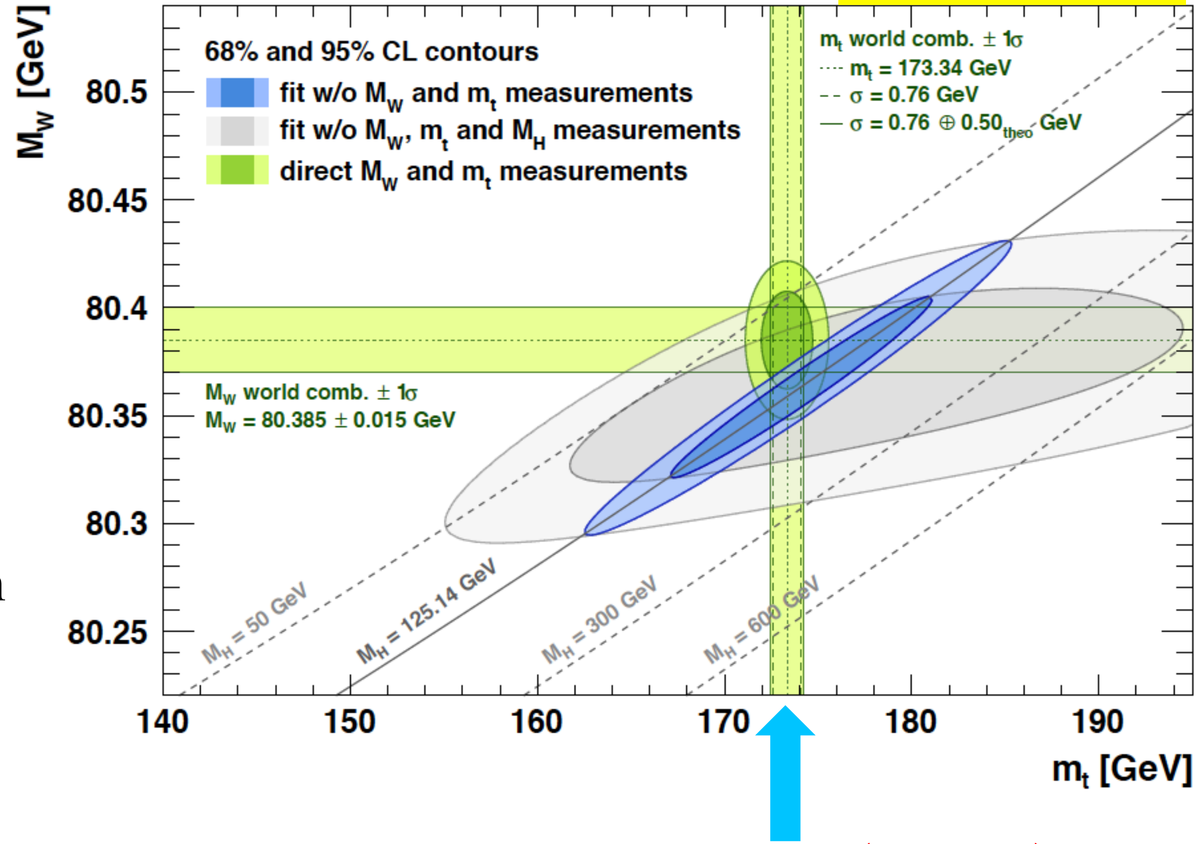


- Shall cover the recent results from LHC and Tevatron on the red coloured items

Top-quark mass

arXiv:1407.3792

- **Top-quark mass is scheme dependent**
  - ‘Pole mass’: view the top as a free particle
  - Other schemes, e.g, $\overline{\text{MS}}$ scheme yield different results



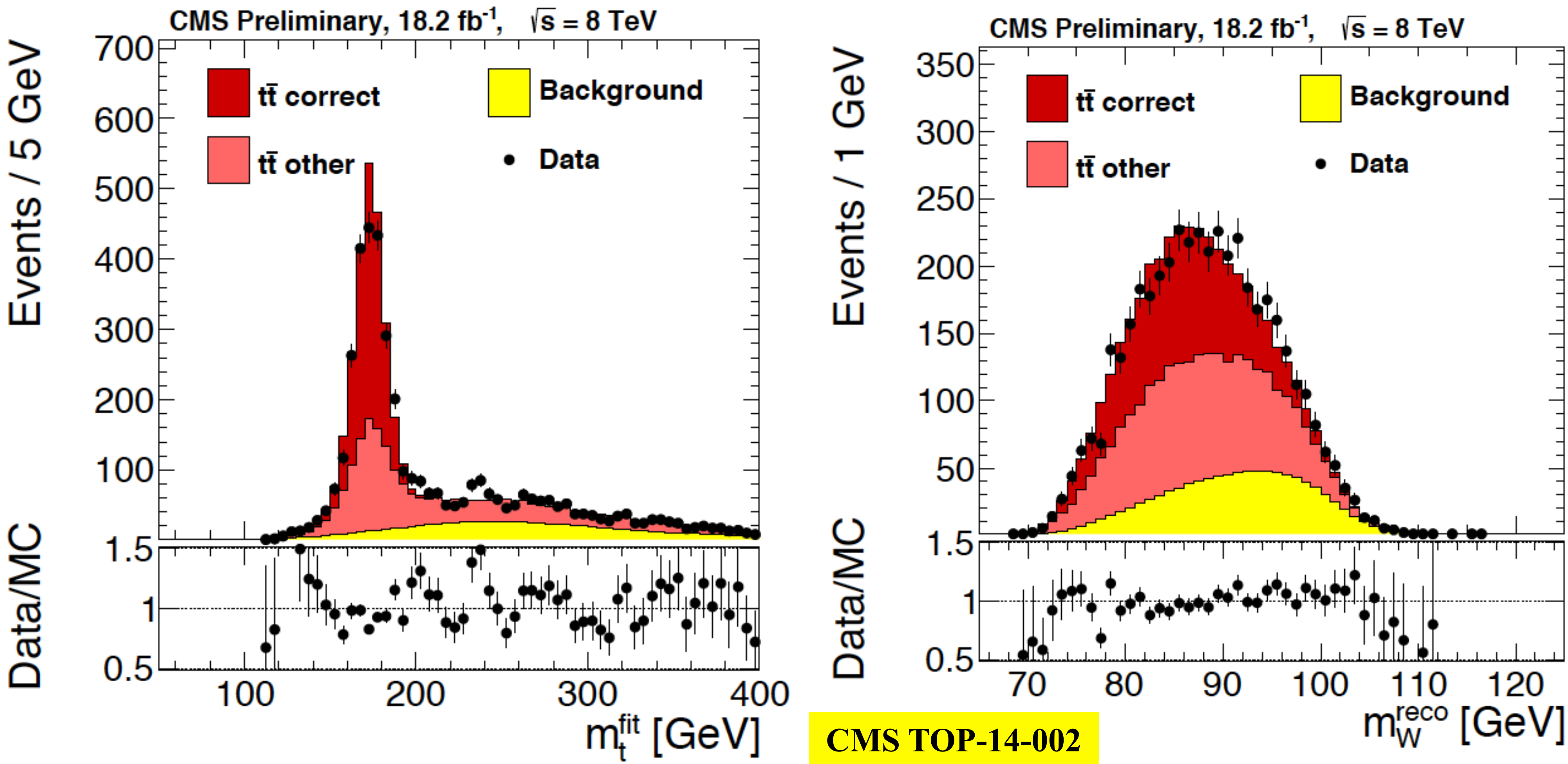
$$m_{\mathrm{WA}} \pm \mathcal{O}(1\,\mathrm{GeV})$$

- **‘Direct’ mass measurement**
  - First reconstruct m_{top}(rec) and then extract the m_{top}(true) value
  - Experimentally, most precise
  - Limitations are flavour-dependent jet energy scale (JSF) uncertainty, hadronization, fragmentations and colour reconnection

- **‘Alternative’ mass measurement**
  - Complementary experimental and theoretical uncertainties
  - Can further pin-down the global error when combined with the ‘direct’ mass results

Results from the all-jets final state

- Two-dimensional likelihood fit to extract m_{top} and light-quark jet energy scale applying the W-mass constraint **CMS TOP-14-002**
- b-jet energy scale checked using Z+b events **CMS JME-13-001**

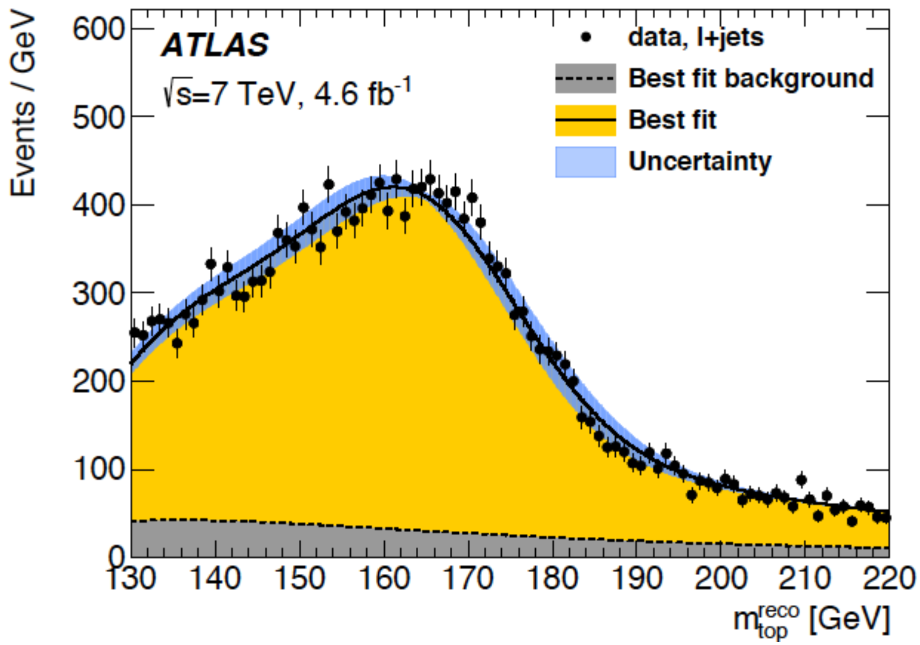


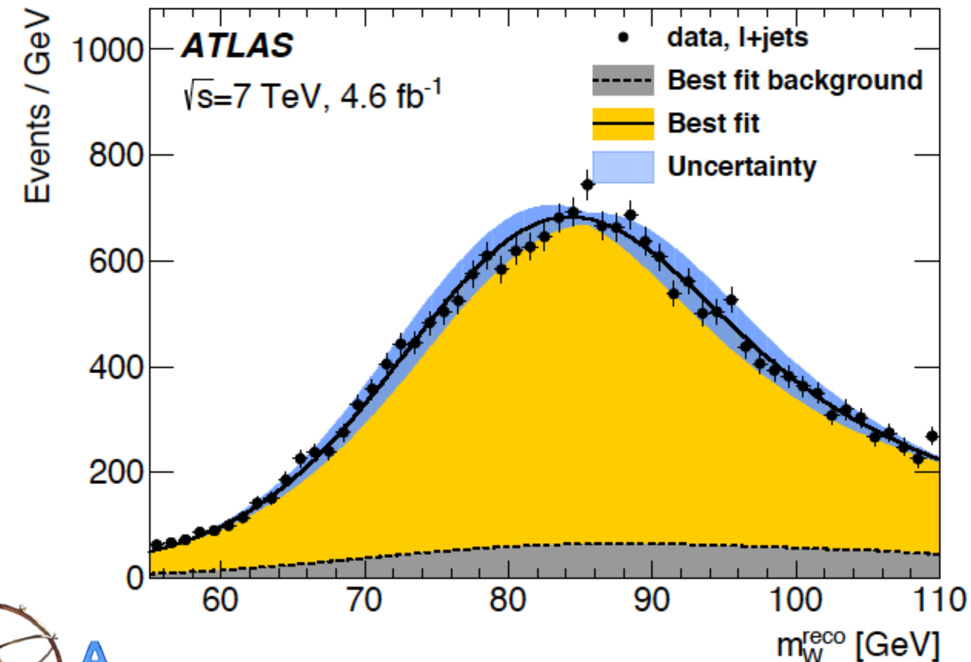
CMS TOP-14-002

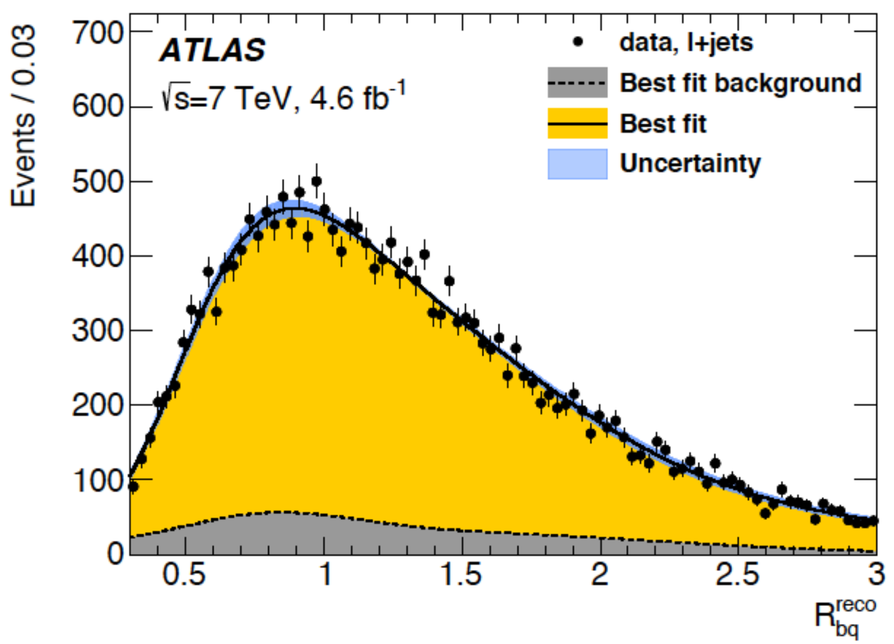
$$m_{\mathrm{top}} = 172.08 \pm 0.36(\mathrm{stat} + \mathrm{JSF}) \pm 0.83(\mathrm{syst})\ \mathrm{GeV}$$
$$\mathrm{JSF} = 1.007 \pm 003(\mathrm{stat}) \pm 0.011(\mathrm{syst})$$

Results from lepton+jets and dilepton channels

- 3D template fit to extract m_{top}, jet energy scale and b-jet energy scale







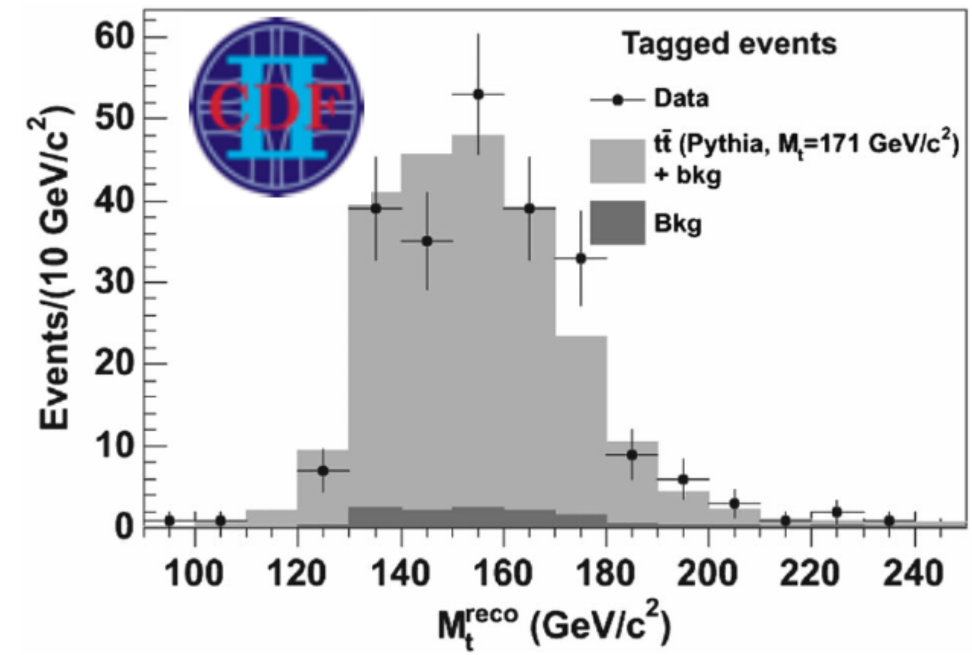
arXiv:1503.05427

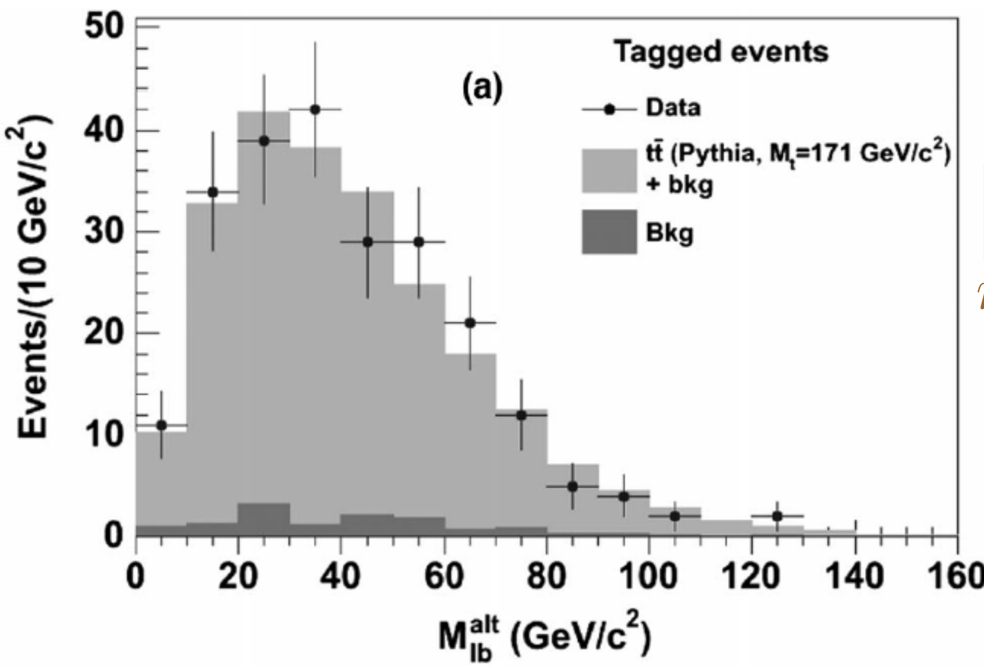
$$m_{\text{top}} = 172.99 \pm 0.48(\text{stat}) \pm 0.78(\text{syst})\ \text{GeV}$$

- Will benefit from more statistics at 8 TeV as well as Run II

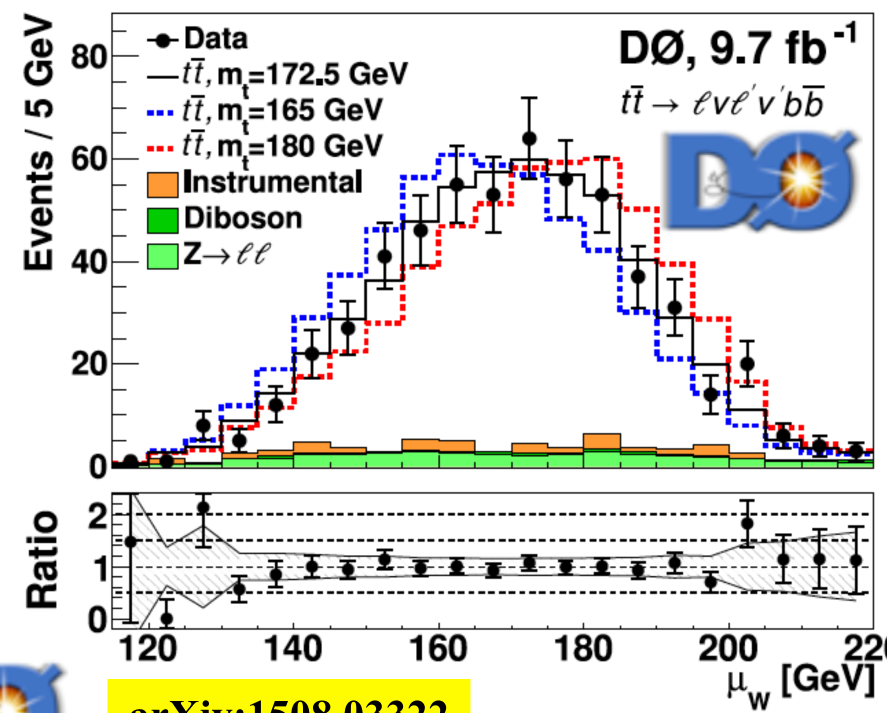
Dilepton results from Tevatron

➢ Reconstruct a) m_{top}(reco): full kinematic info & b) m_{lb}(alt): less dependence on JSF





❑ Add multiple kinematic solutions, with weights from expected neutrino spectra



arXiv:1508.03322

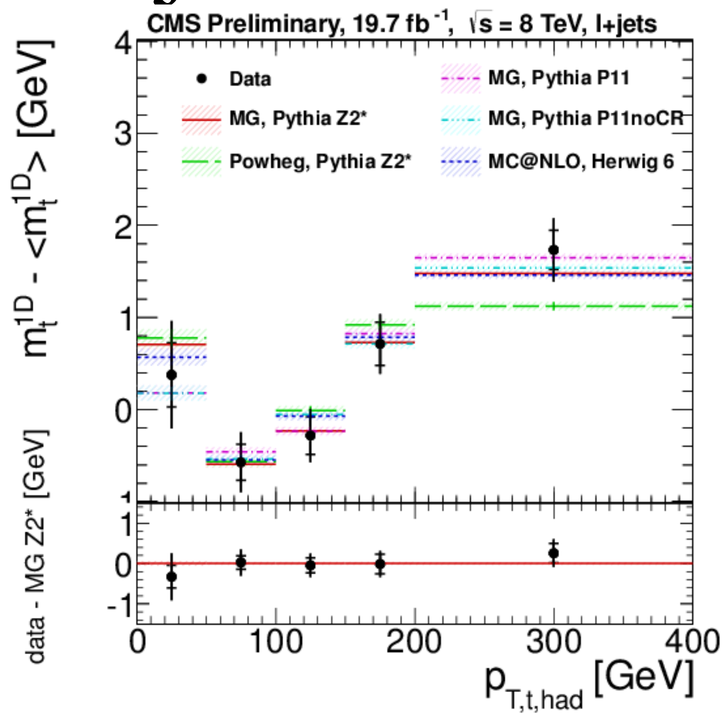
$$m_{\rm top} = 173.32 \pm 1.36({\rm stat}) \pm 0.85({\rm syst})\ {\rm GeV}$$

PRD 92, 032003 (2015)

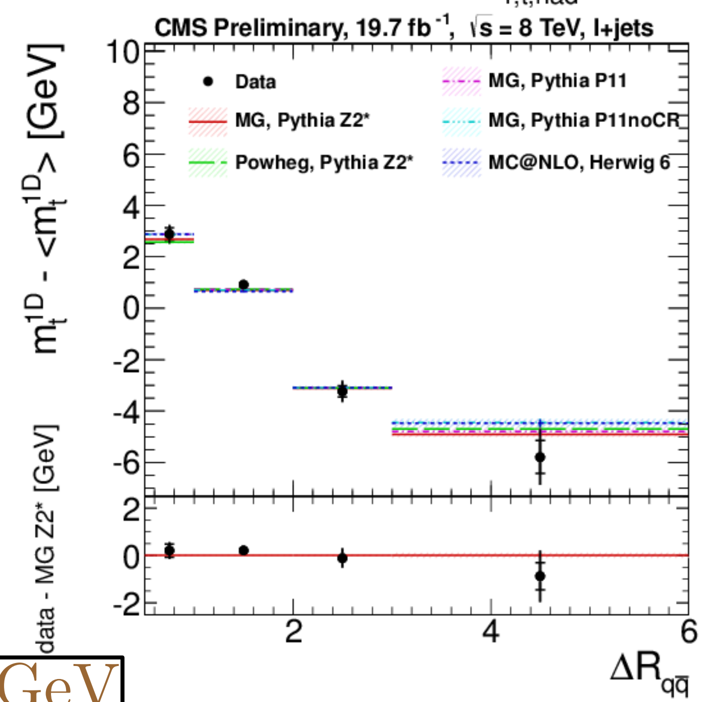
$$m_{\rm top} = 171.5 \pm 1.9({\rm stat}) \pm 2.5({\rm syst})\ {\rm GeV}$$

m_{top}(true) from CMS in lepton+jets channel

- Determine the kinematic dependence of measurement: pin down (non-)perturbative corrections that would lead to differences
- Select distributions, in total 14 of them, with sensitivity to
  - Colour reconnection
  - ISR and FSR
  - b-quark kinematics



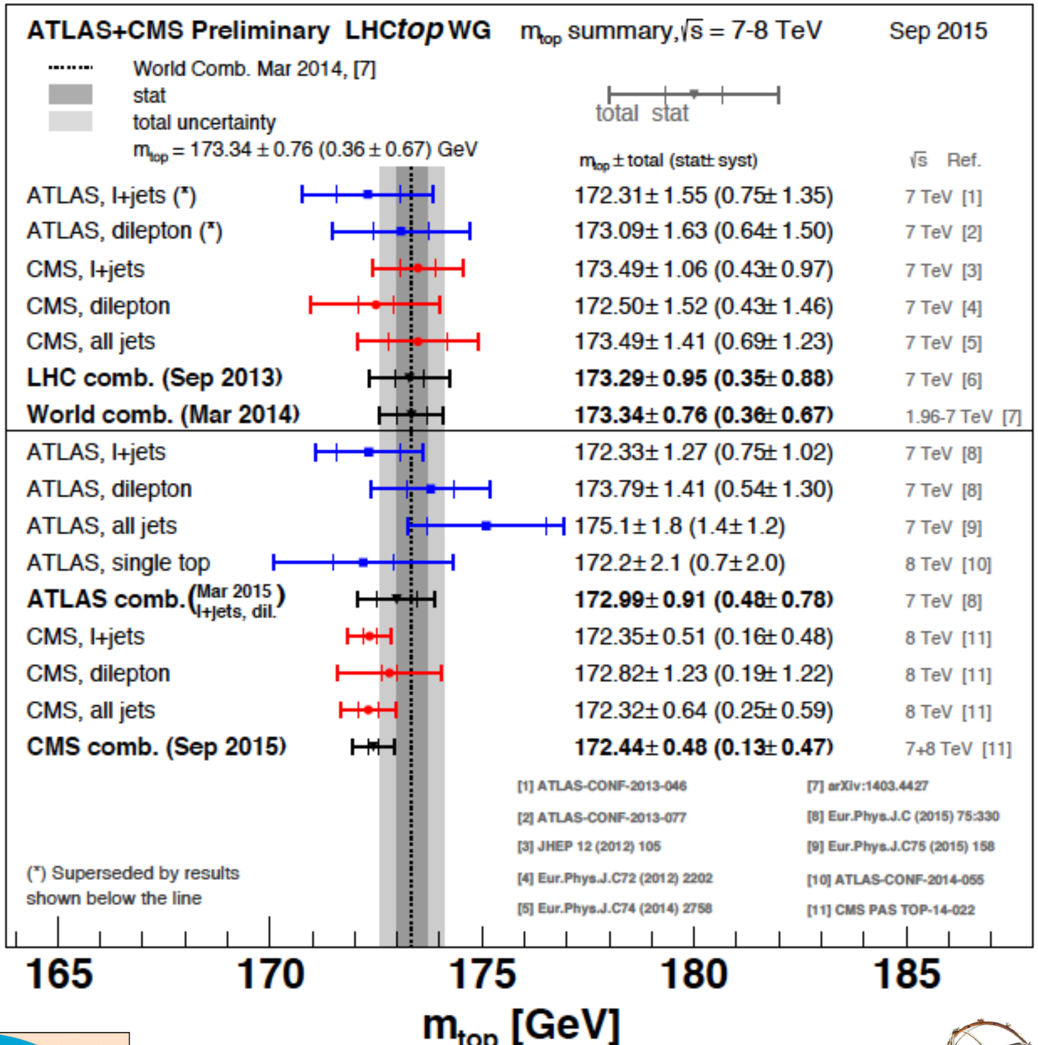
Observable	m_t^{1D} χ^2	JSF χ^2	m_t^{2D} χ^2	Ndf
$\Delta R_{q\bar{q}}$	2.87	3.66	0.83	3
$p_{T,t,had}$	0.89	12.03	5.76	4
$\|\eta_{t,had}\|$	5.56	1.22	1.14	3
H_T^4	6.19	9.18	7.54	4
$m_{t\bar{t}}$	2.16	4.69	4.22	5
$p_{T,t\bar{t}}$	1.02	1.22	1.33	4
Jet multiplicity	4.24	0.10	1.16	2
$p_{T,b,had}$	2.57	5.80	2.17	4
$\|\eta_{b,had}\|$	1.15	0.08	0.72	2
$\Delta R_{b\bar{b}}$	0.37	1.63	1.77	3
$p^1_{T,q,had}$	4.04	8.39	1.28	4
$\|\eta^1_{q,had}\|$	3.36	3.79	6.27	2
$p_{T,W,had}$	1.59	8.06	1.60	4
$\|\eta_{W,had}\|$	1.41	1.09	1.35	3
Total	37.43	60.94	37.15	47

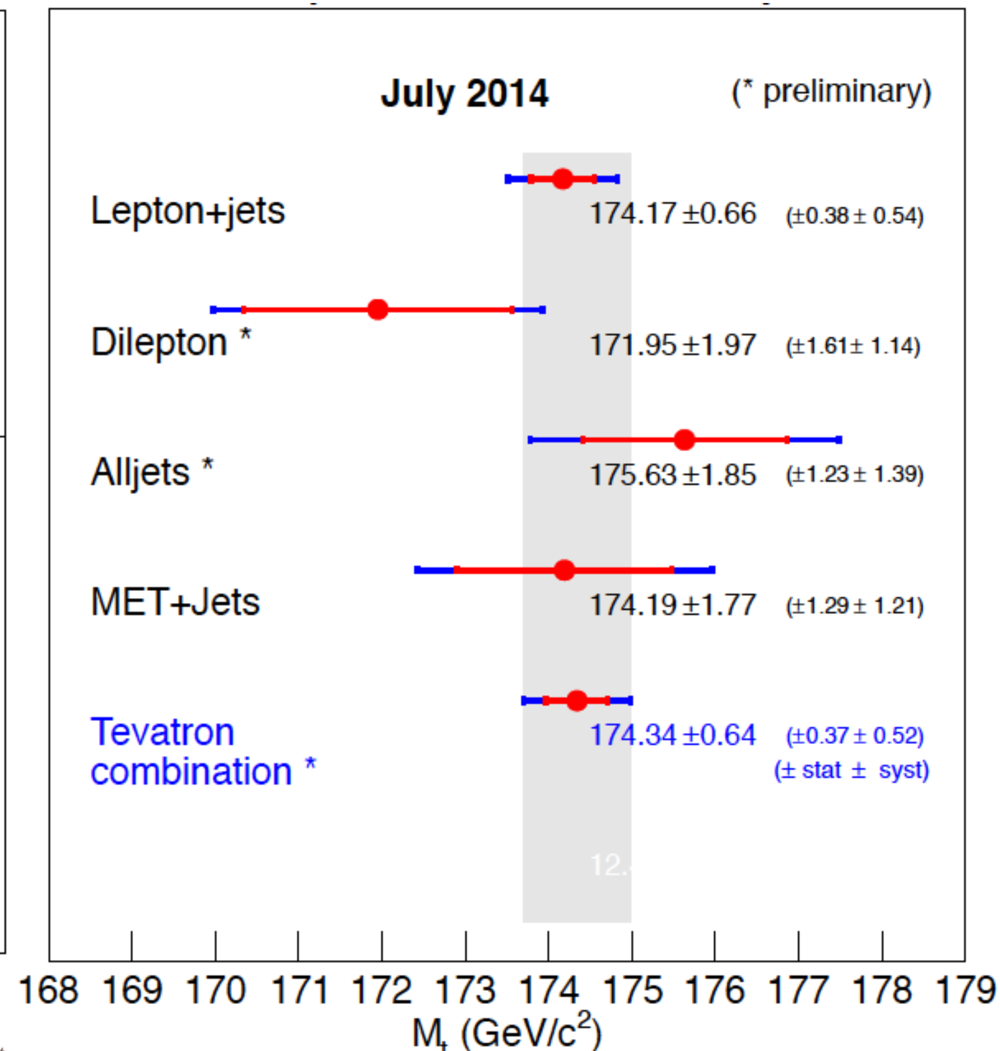


CMS PAS TOP-14-001

$$m_{top} = 172.04 \pm 0.19(\text{stat} + \text{JSF}) \pm 0.75(\text{syst})\ \text{GeV}$$

Summary from LHC and Tevatron





$$m_{\rm top} = 172.44 \pm 0.48\,{\rm GeV}$$

$$m_{\rm top} = 172.99 \pm 0.91\,{\rm GeV}$$

$$m_{\rm top} = 174.34 \pm 0.64\,{\rm GeV}$$

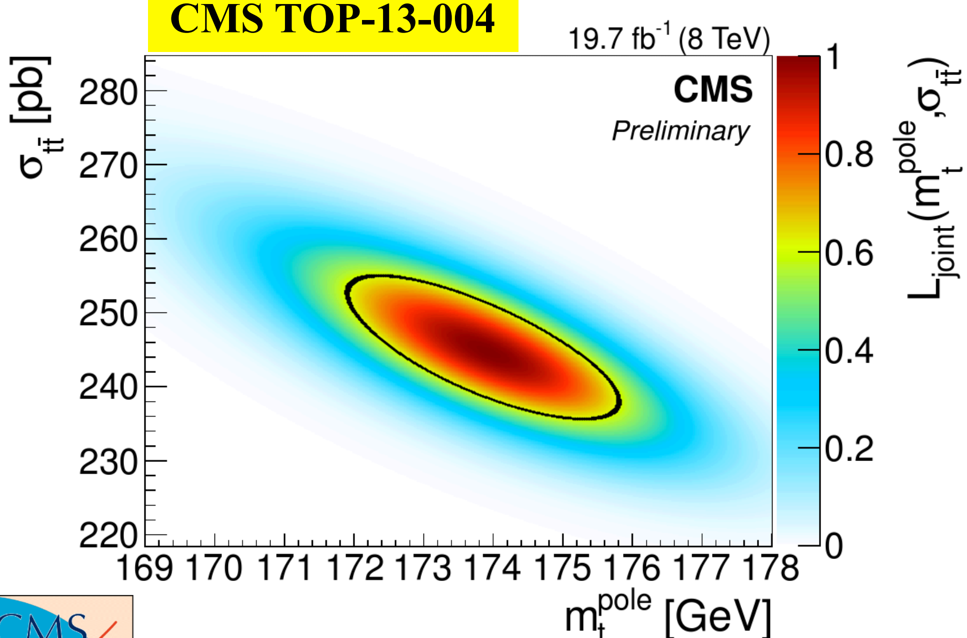
Results on m_{pole} from CMS and ATLAS

- Measure σ_{tt} (7+8 TeV) using a template fit to b-jet multiplicity, multiplicity and p_T of other jets

$$\sigma_{t\bar{t}} = 174.5 \pm 2.1(\text{stat}) \pm^{4.5}_{4.0} (\text{syst}) \pm 3.8(\text{lumi})\ \text{pb}$$
$$\sigma_{t\bar{t}} = 245.6 \pm 1.3(\text{stat}) \pm^{6.6}_{5.5} (\text{syst}) \pm 6.5(\text{lumi})\ \text{pb}$$

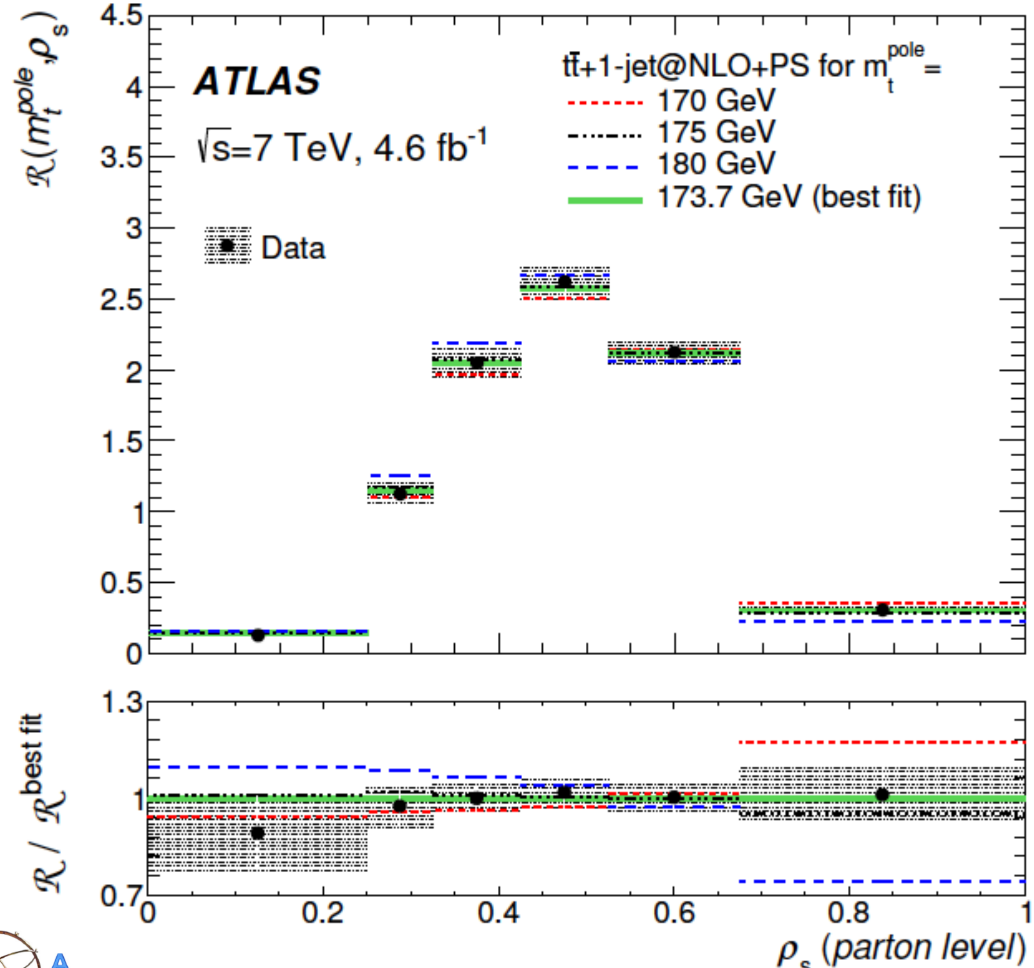
- Extract m_{pole} by comparing σ_{tt} with NNLO (+NNLL) computations

CMS TOP-13-004



$$m_{\text{pole}} = 173.6^{+1.7}_{-1.8}\ \text{GeV}$$

- tt+1-jet distribution (NLO+PS) pole mass via threshold & cone effects

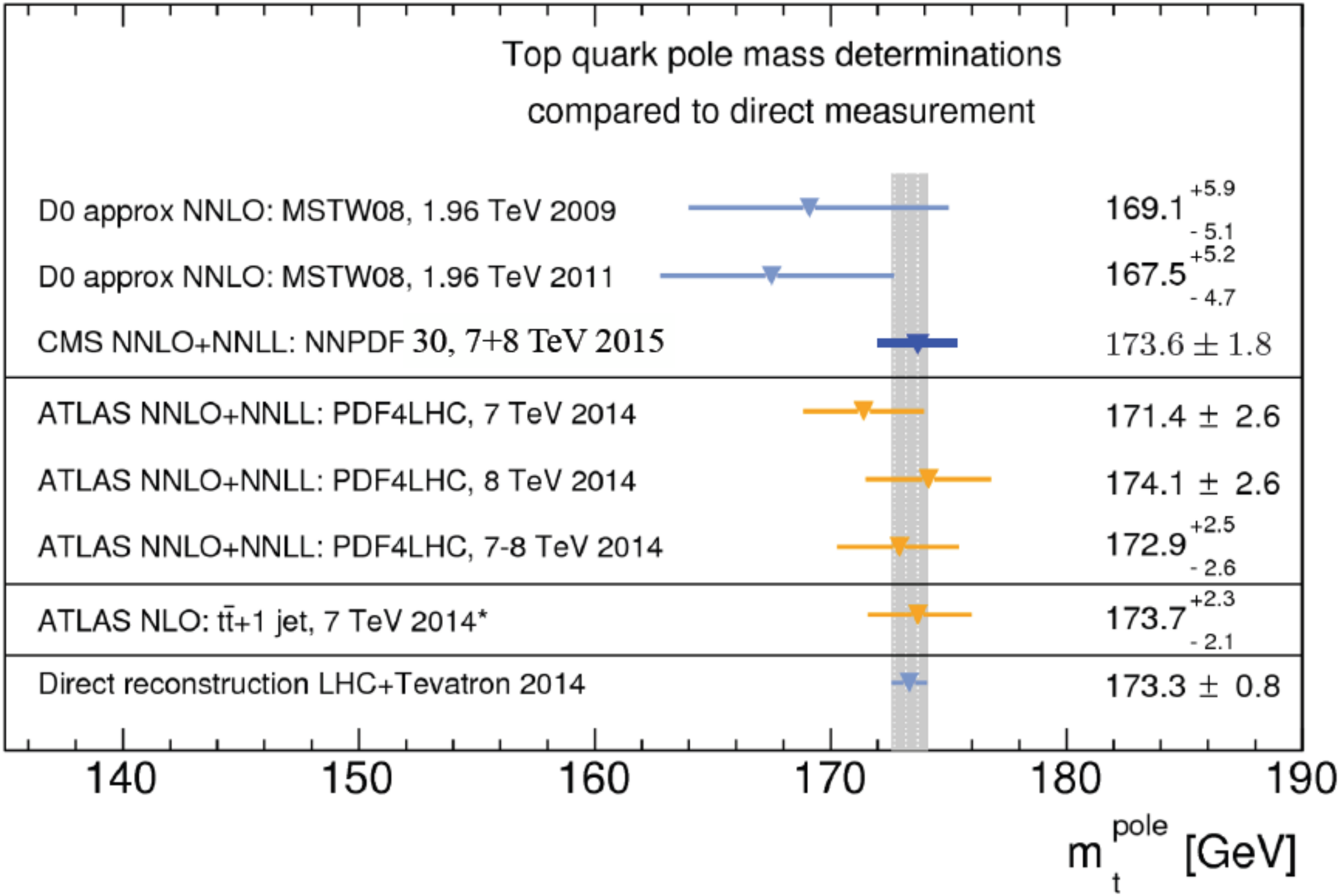


arXiv:1507.01769

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

➢ First one is the single most precise m_{pole} measurement

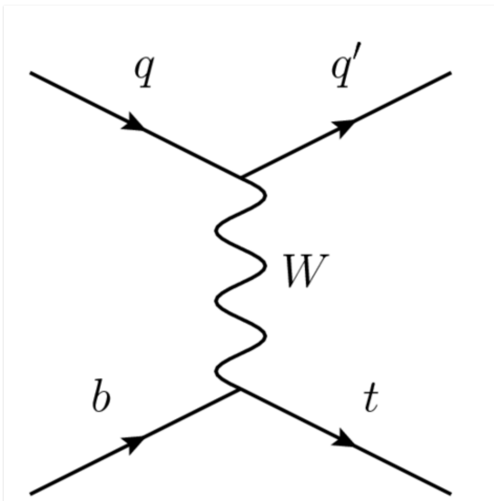
Summary from LHC and Tevatron

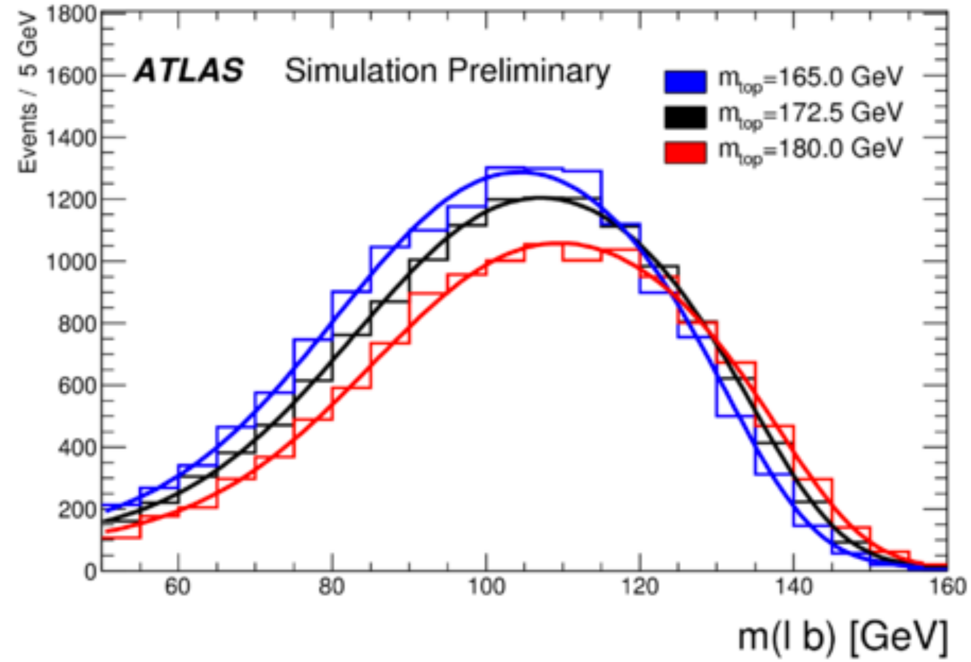


- ➢ Pole mass measurements are not yet as precise as m_{top}(true)

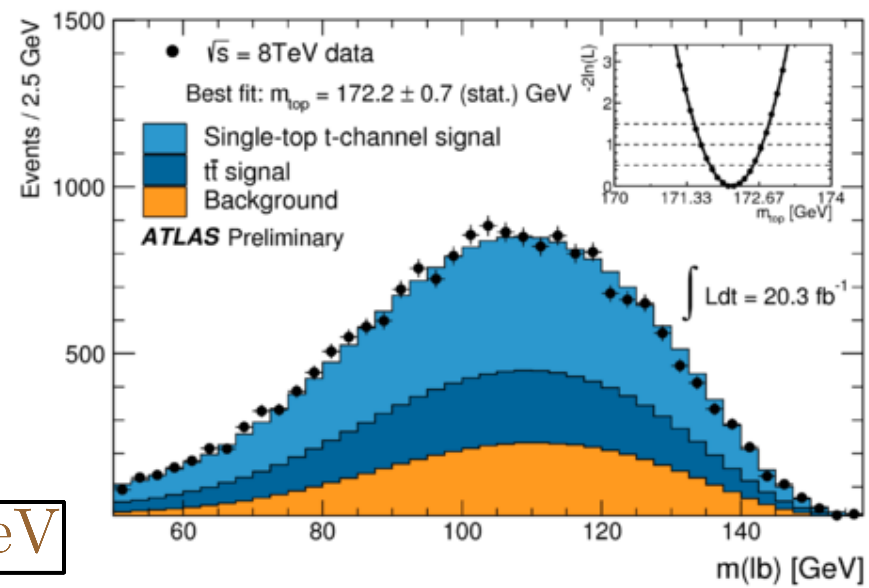
m_{top}(true) from single top events

- Use events dominated by t-channel single top quark topologies
- Employ a Neural Network to enhance the signal purity





- 1D template fit to the invariant mass of the lepton and b-tagged jet
- JSF is the dominant source of systematic

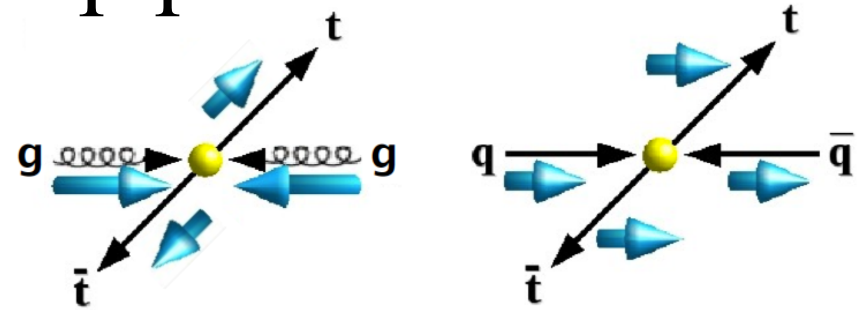


ATLAS-CON-2014-055

$$m_{\rm pole} = 172.2 \pm 0.7({\rm stat}) \pm 2.0({\rm syst})\ {\rm GeV}$$

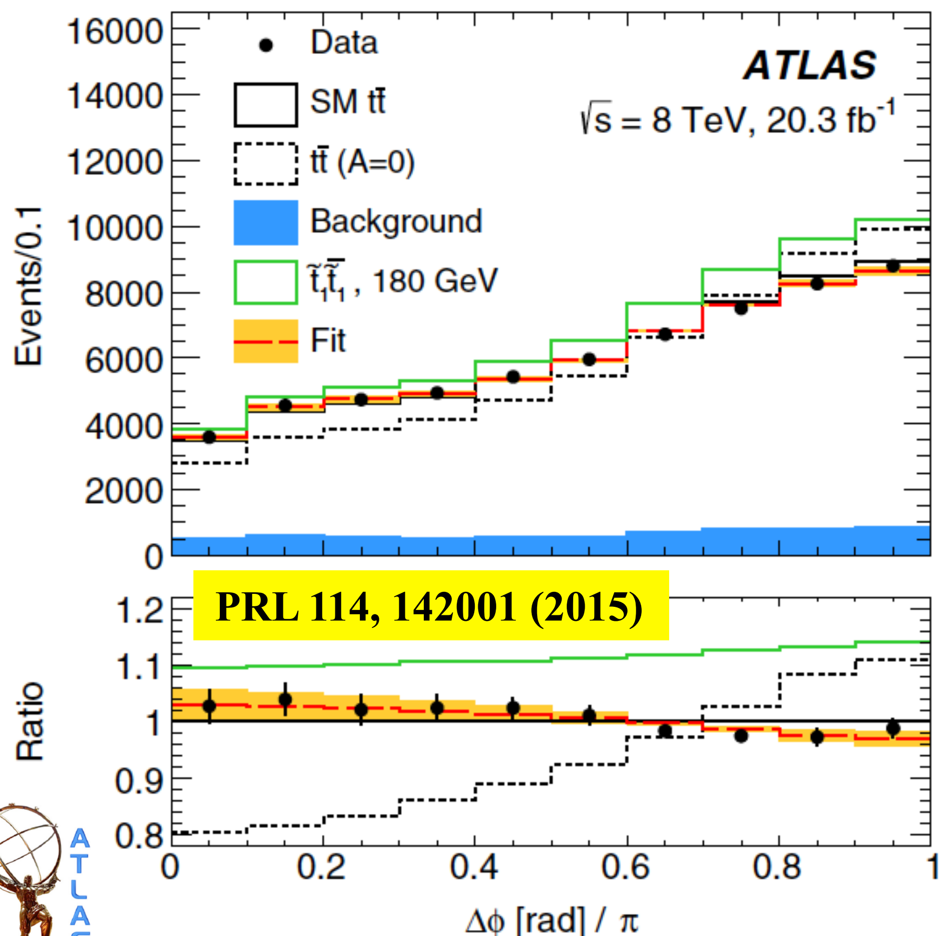
Spin correlation in top pair events

- Top quarks decay before their spins can de-correlate ➔ spin correlation
- Use dilepton channel: access the above via azimuthal angle difference of two leptons in the laboratory frame

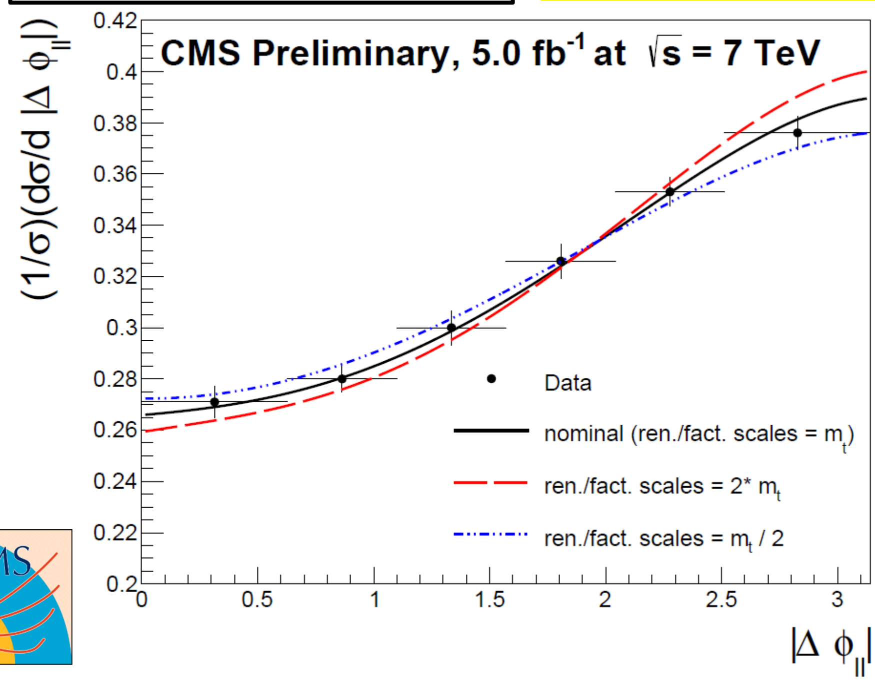


$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{Uncor}^{t\bar{t}}}$$

PRL 112, 182001 (2014)



PRL 114, 142001 (2015)



$$f_{SM} = 1.02 \pm 0.10(\text{stat}) \pm 0.22(\text{syst})$$

CMS TOP-14-005

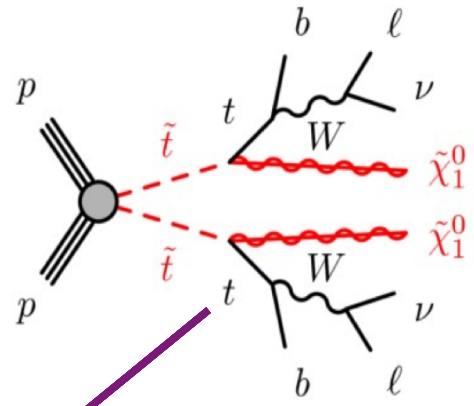
Search for chromomagnetic dipole-moments

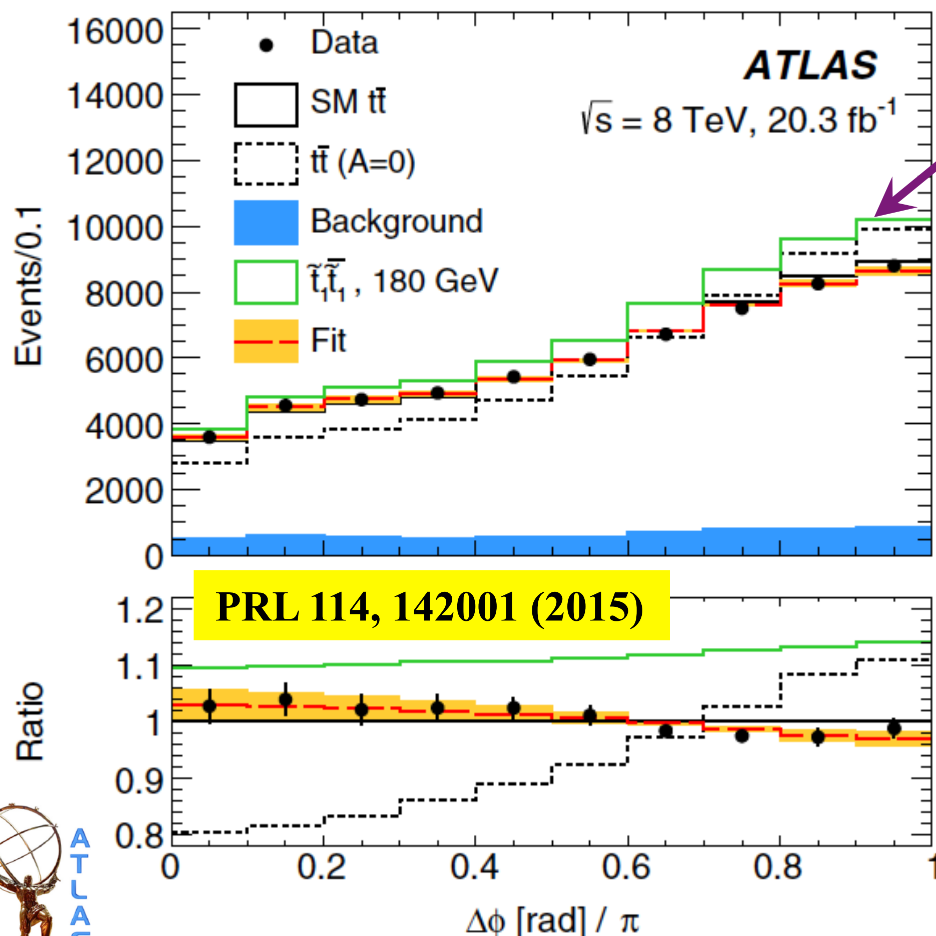
-0.043 < Re(μ) < 0.117 at 95% CL

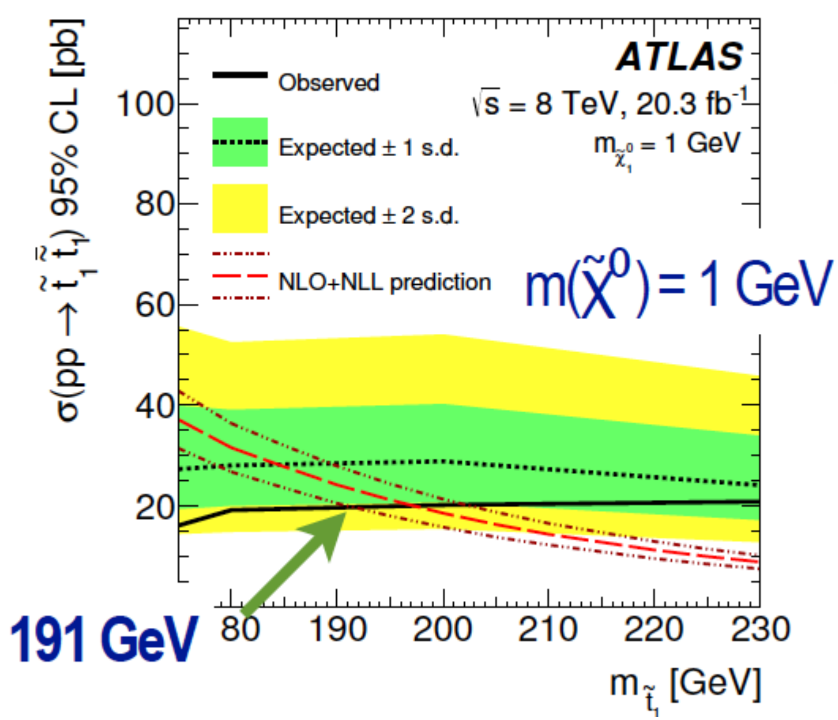
$$f_{SM} = 1.20 \pm 0.05(\text{stat}) \pm 0.13(\text{syst})$$

Spin correlation as a NP probe

- Stop pair production ➔ reduced spin correlation and increased top-pair rate





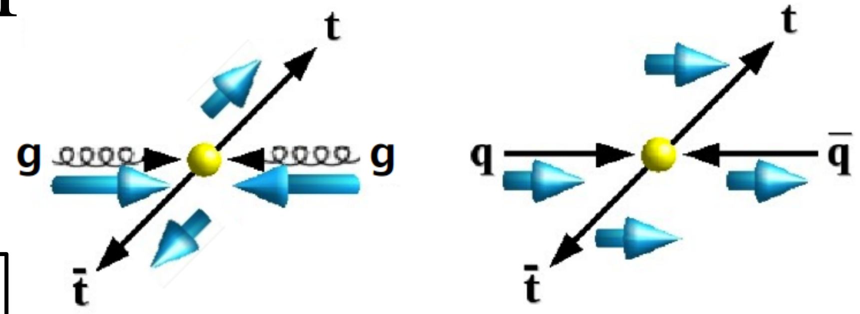


- Exclude top squark masses between m_{top} and 191 GeV at 95% CL

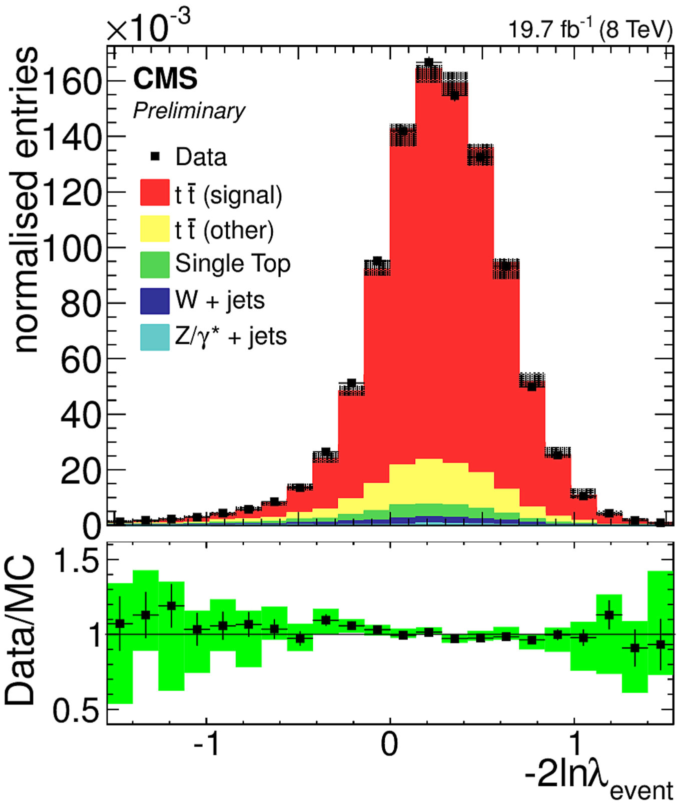
$$f_{SM} = 1.20 \pm 0.05(\text{stat}) \pm 0.13(\text{syst})$$

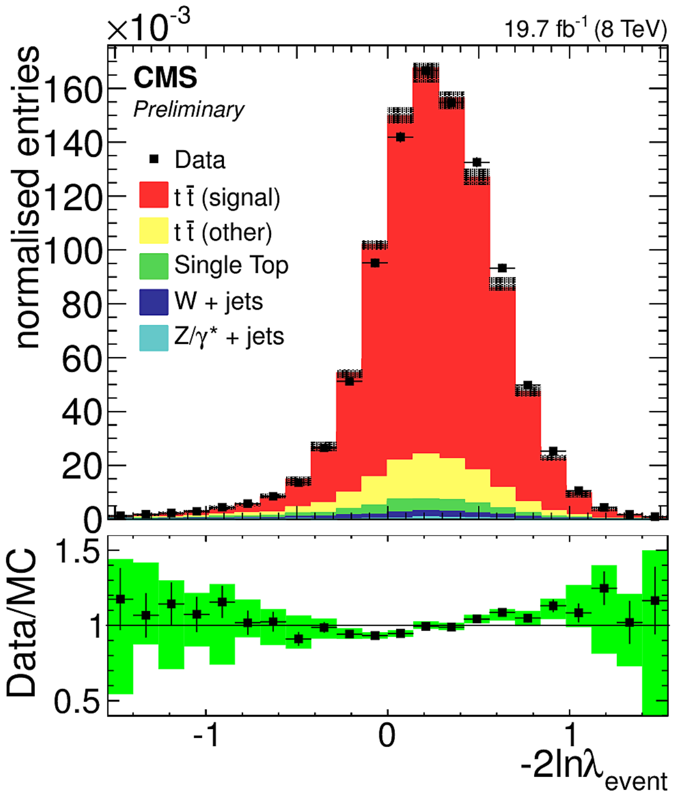
Recent results on spin correlation

- Use the lepton+jets channel ➔ require full top-pair event reconstruction
- Employ the full matrix element method

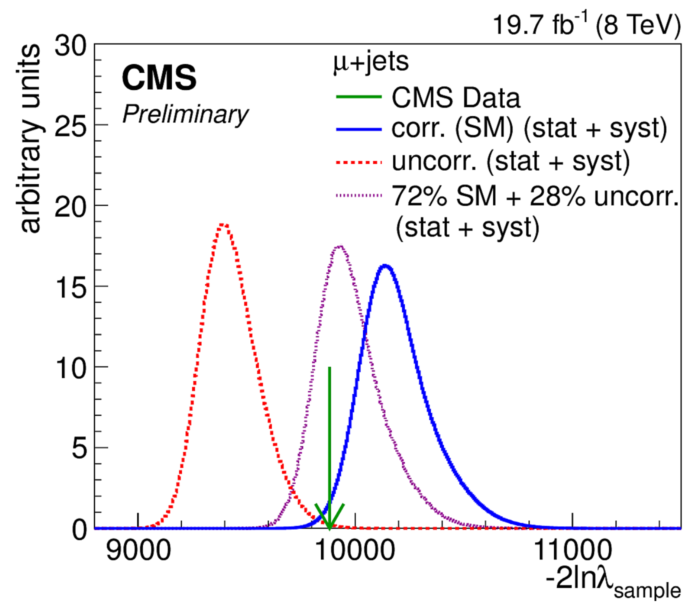


$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{Uncor}^{t\bar{t}}}$$





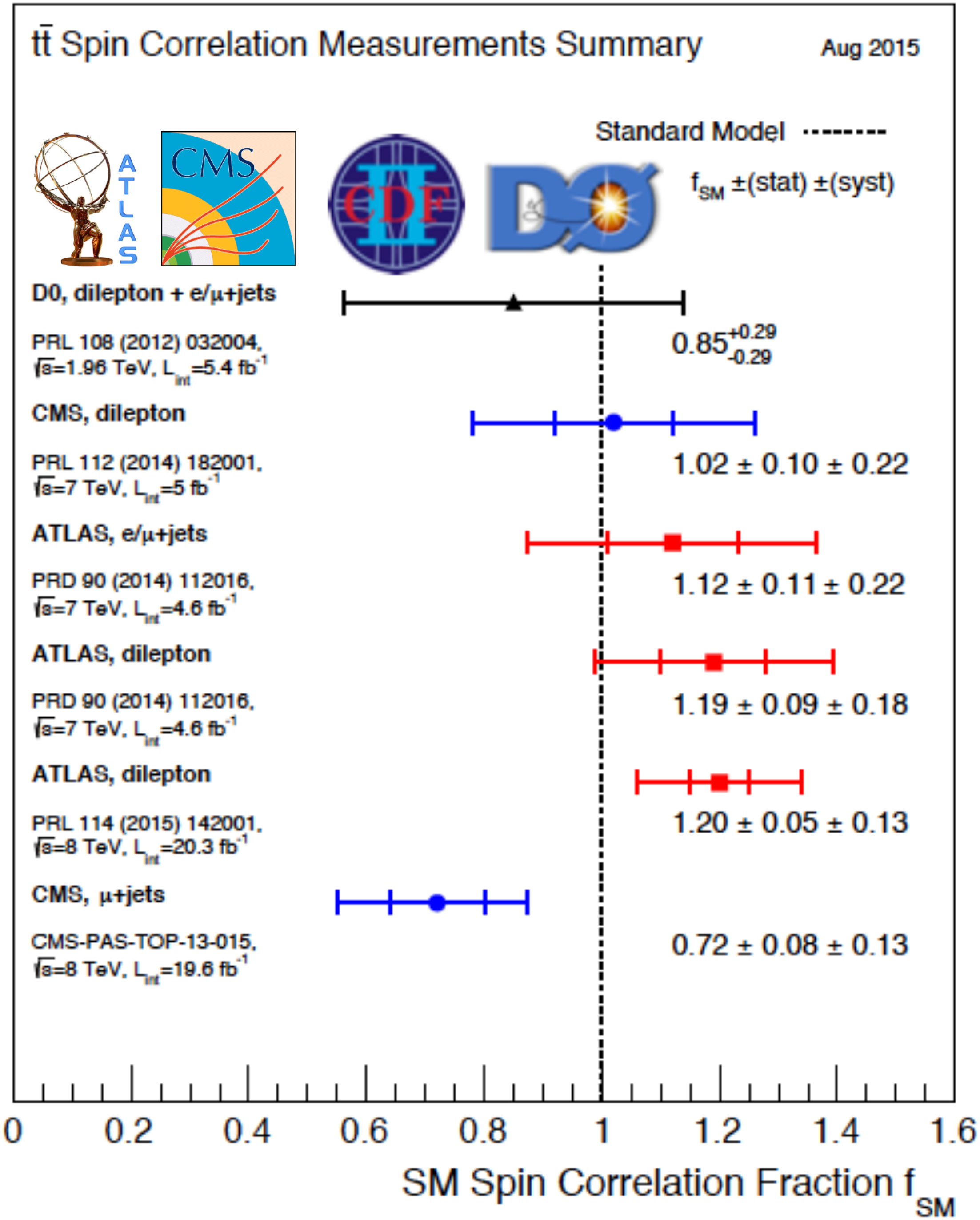
CMS TOP-13-015



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

- ➢ CL_s(SM) =1.3%
- ➢ CL_s(uncorr) = 0.2%

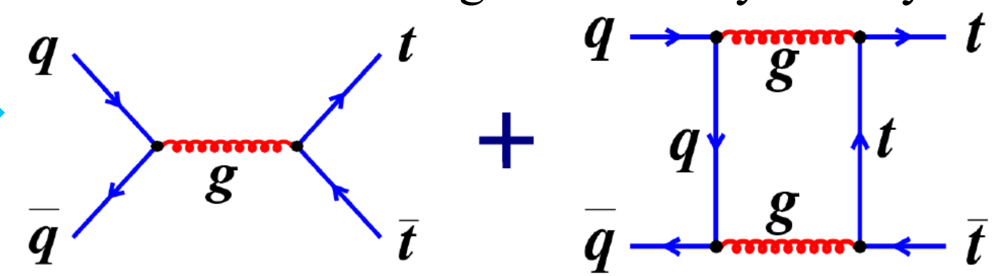
Summary from LHC and Tevatron



Forward-backward and charge asymmetries

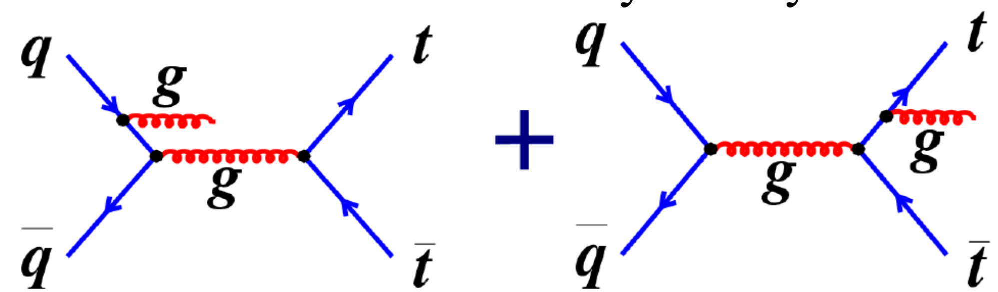
- LO: we don't expect any asymmetry
- NLO: arises due to interference between the qq diagram
- Diluted at LHC owing to large gg fraction coupled with unknown quark direction

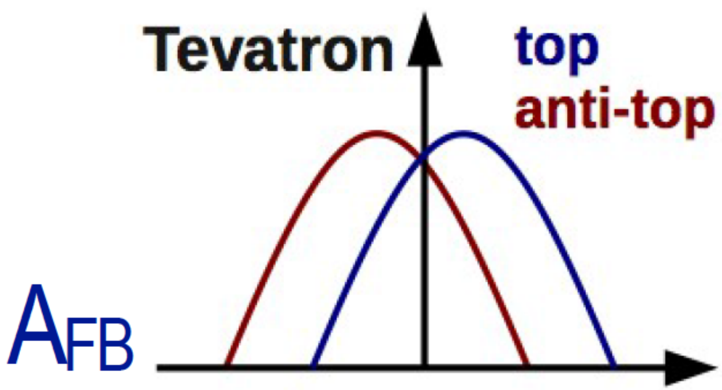
tree-level and box diagram: +ve asymmetry

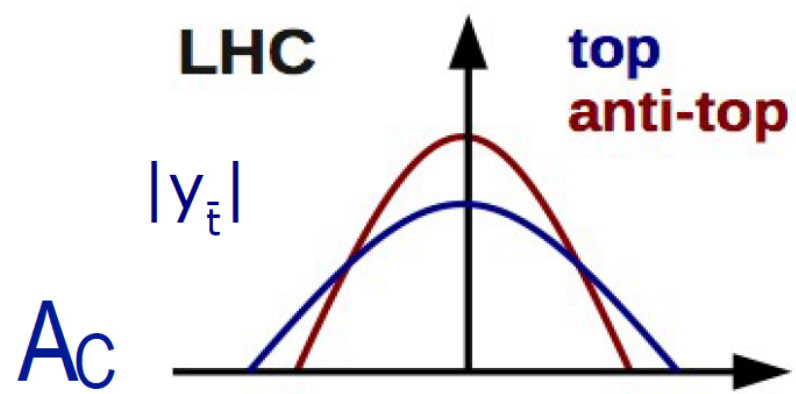


- Recent NNLO prediction for Tevatron: $A_{FB} = 0.095 \pm 0.007$ **PRL 115, 052001 (2015)**
  - Agrees with latest D0 measurement and just 1.5σ below the CDF value

ISR and FSR: −ve asymmetry







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

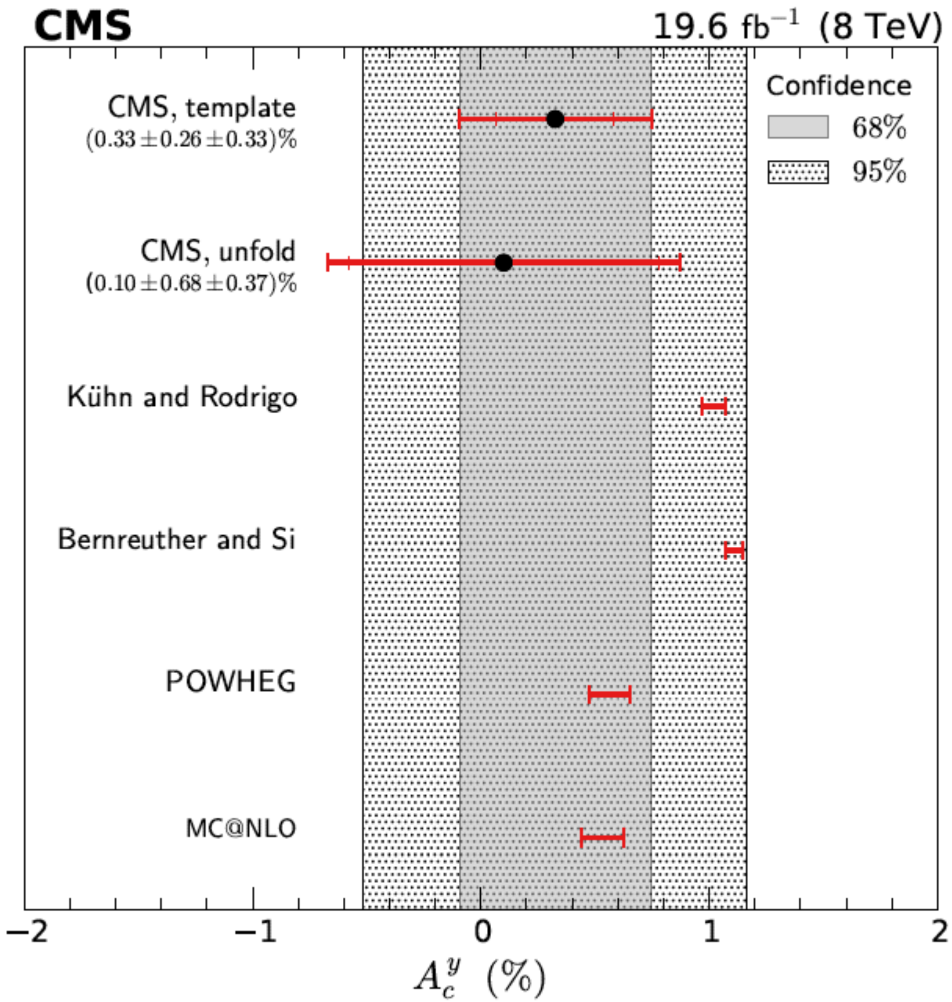
$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

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

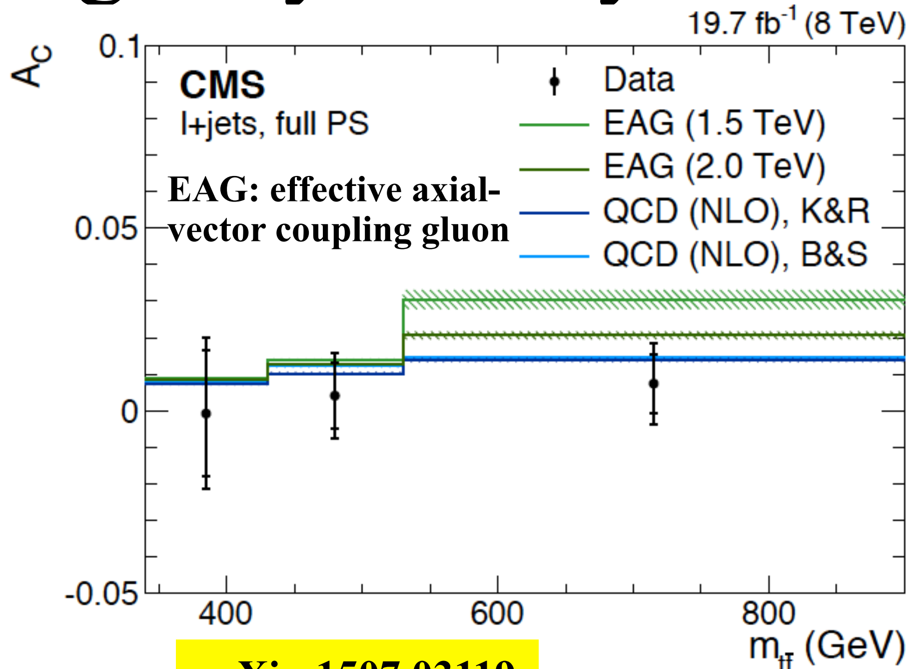
$$\Delta |y| = |y_t| - |y_{\bar{t}}|$$

Recent results on charge asymmetry

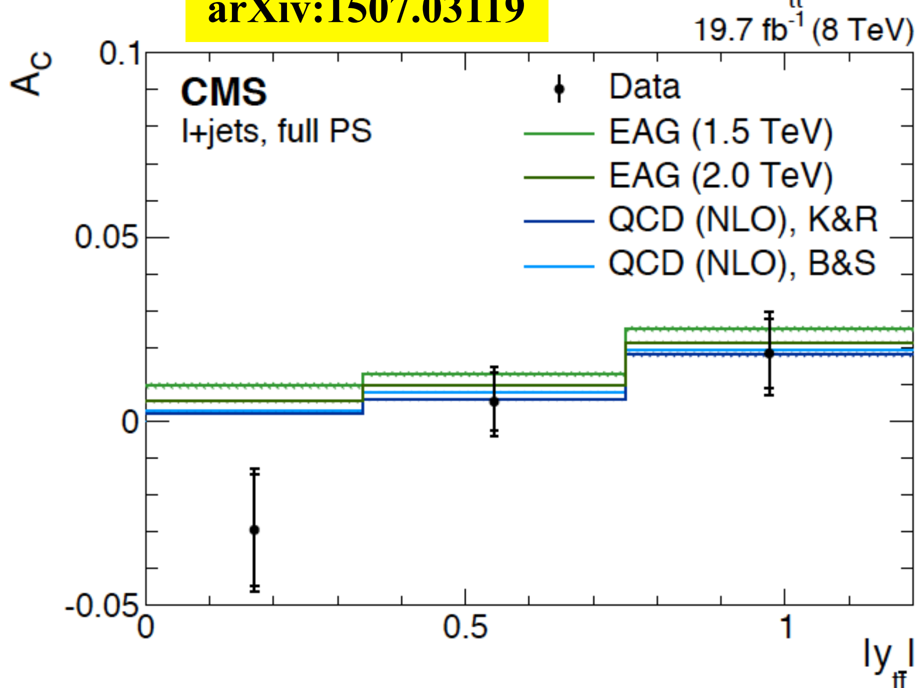
- Differential AC measurement (also in fiducial phase space)
- Template method exploits the shape of $\Delta|\eta|$ distribution as well



$A_C = 0.33 \pm 0.26 \pm 0.33$



arXiv:1507.03119

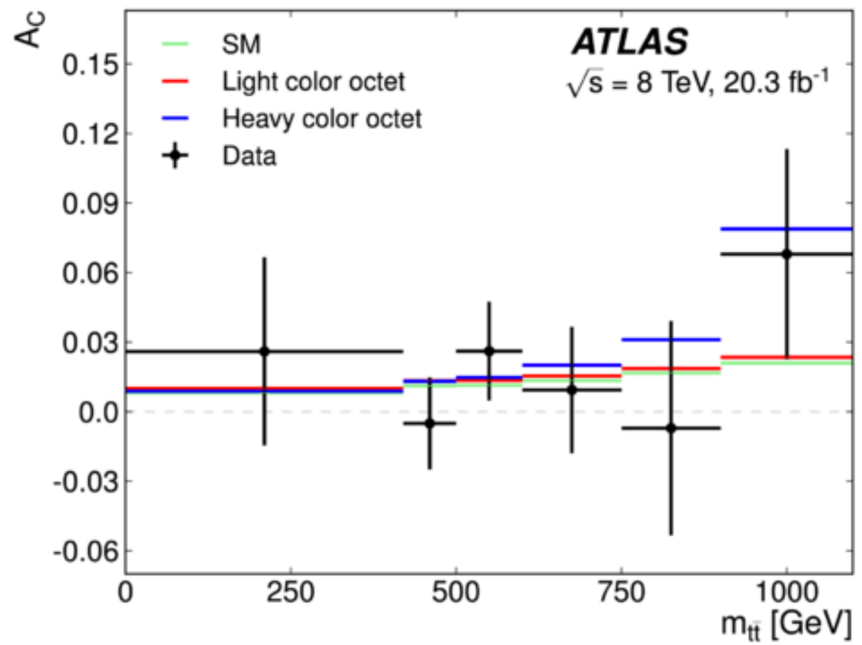


➢ Consistent with SM predictions

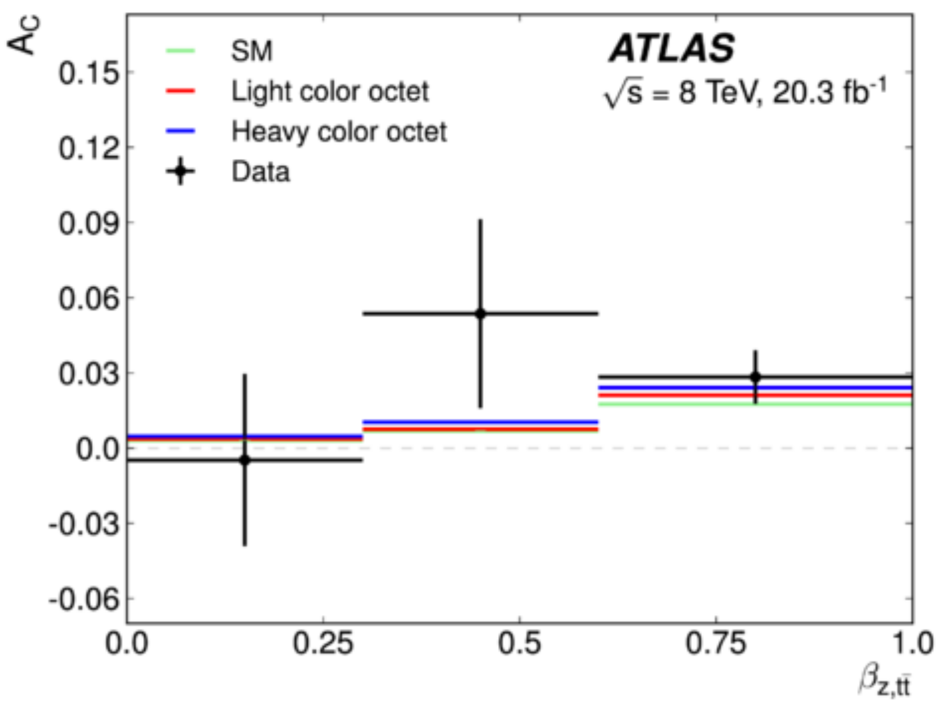
Recent results on charge asymmetry

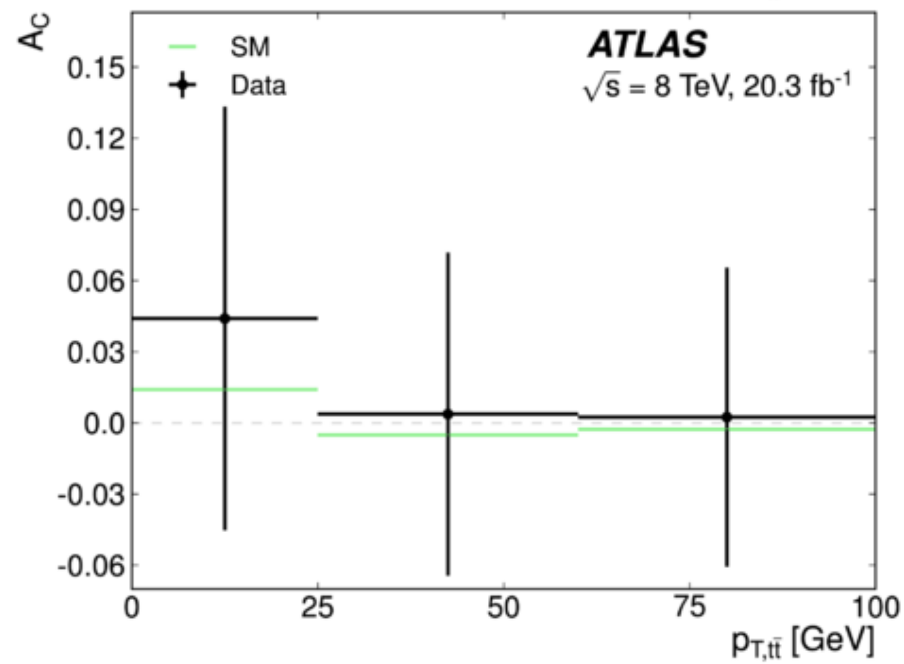
TOPQ-2014-16

- Inclusive as well as differential measurement in m_{tt}, $p_{T,tt}$ and $|\beta_{tt}|$ ➔ enhance NP sensitivity
- Reconstruct of top and anti-top four momenta based on a likelihood fit
- Correction for resolution/acceptance using full Bayesian unfolding



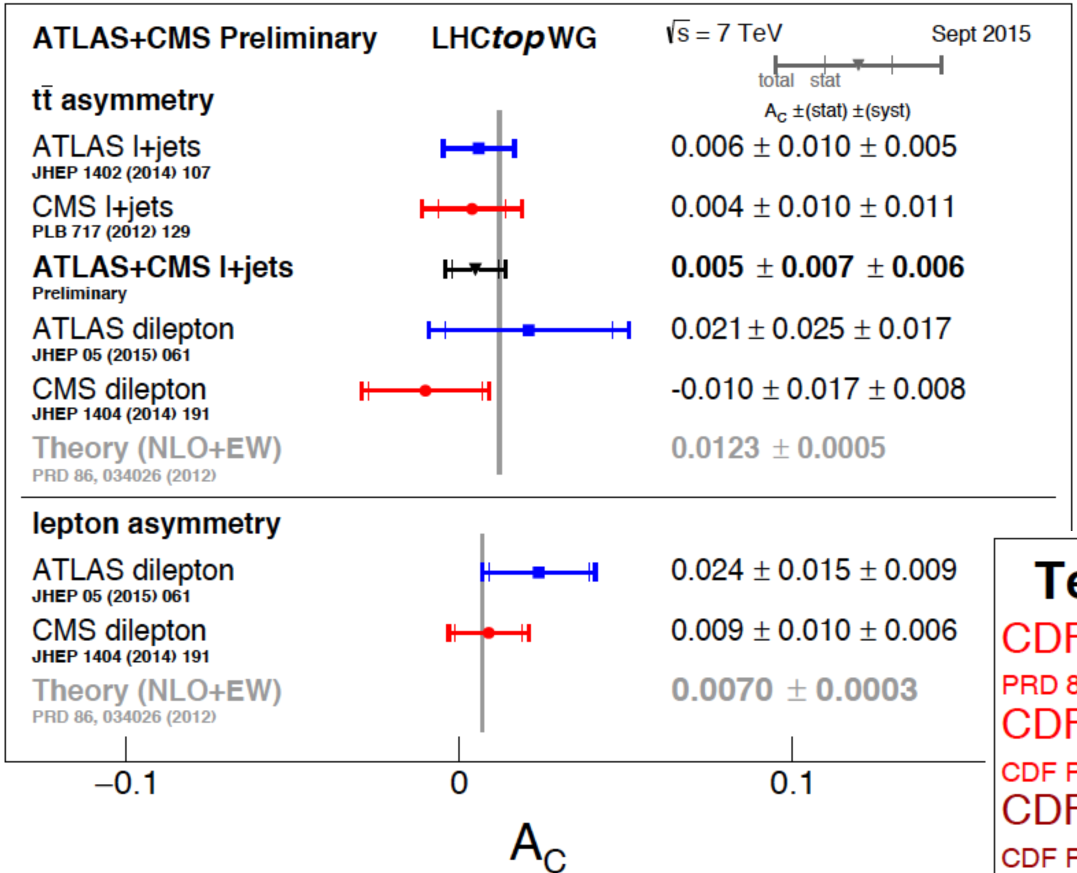
$$A_C = 0.009 \pm 0.005\ (\text{stat.+syst.})$$

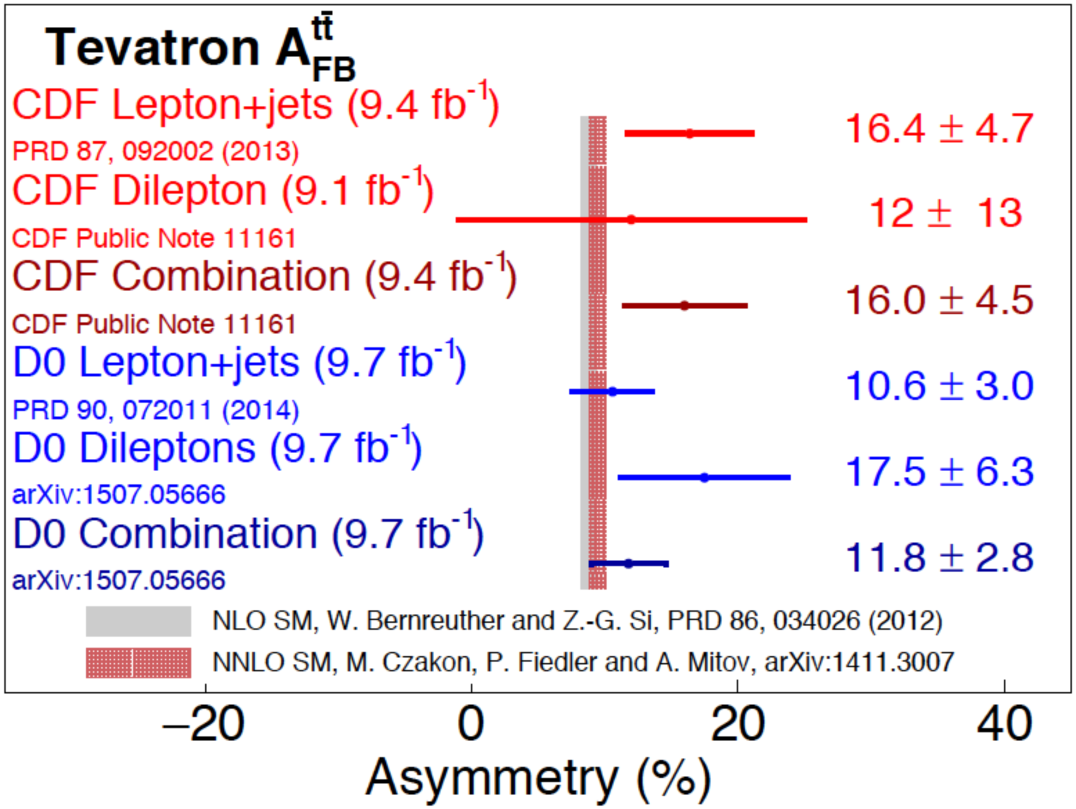




➢ In agreement with SM (~1.1%)

Summary from LHC and Tevatron





Complementarity between LHC and Tevatron

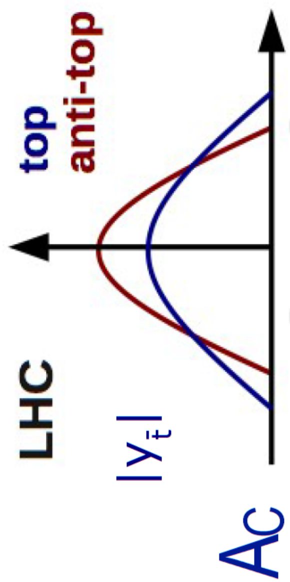
Z': Flavor violating Z' exchanged in t-channel in $u\bar{u} \to t\bar{t}$ and with right-handed Z'tu couplings

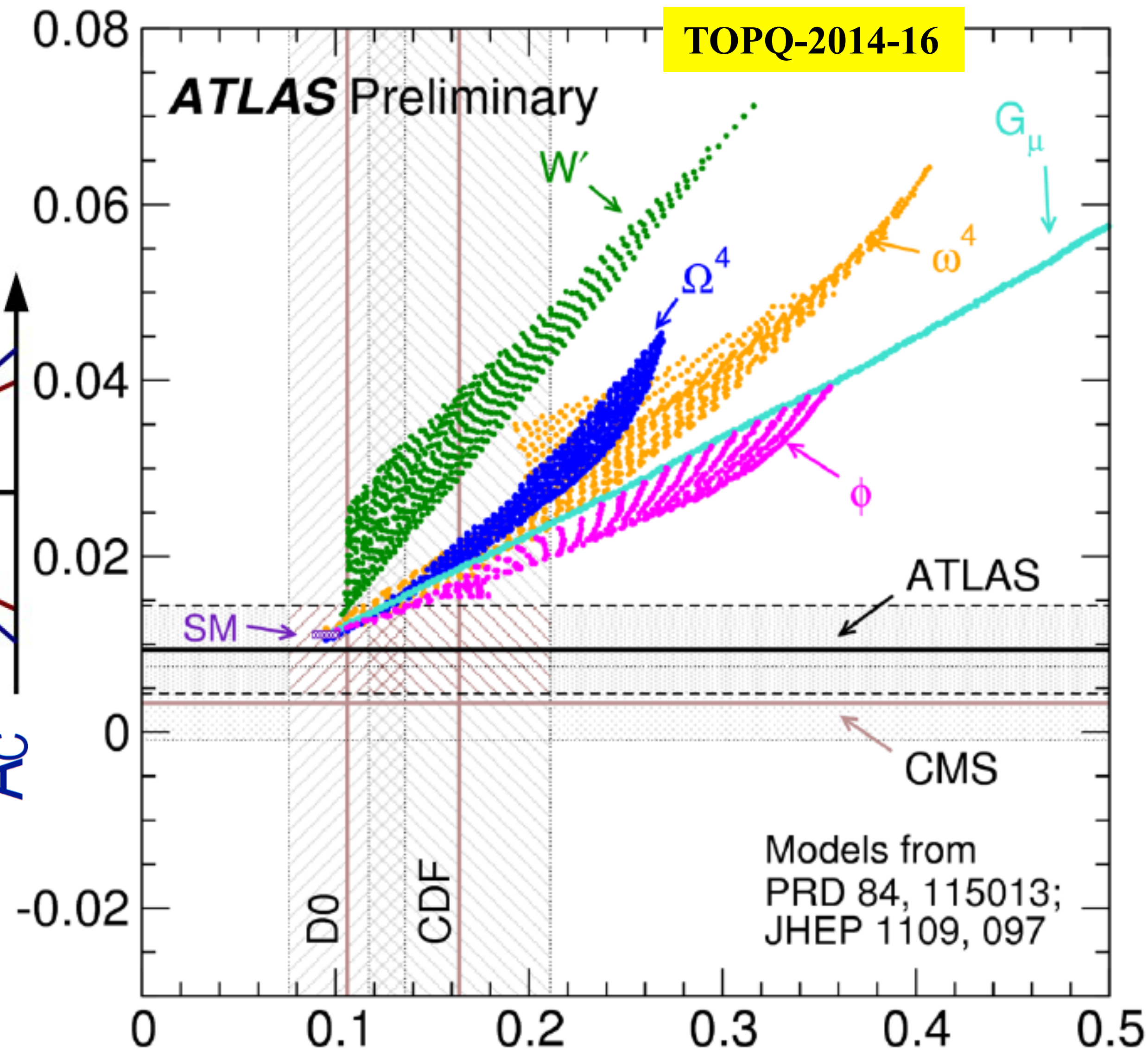
W': W' boson with right-handed couplings exchanged in t-channel in $d\bar{d} \to t\bar{t}$

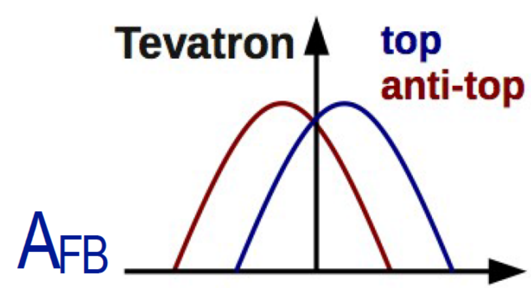
Ω^4: Color-sextet scalar with right-handed flavor violating tu-couplings and exchanged in u-channel

ω^4: Color triplet with flavor violating tu-couplings, right-handed, exchanged in u-channel in $u\bar{u} \to t\bar{t}$

$\mathcal{G}_\mu$: Axigluon, color octet vector with axial couplings







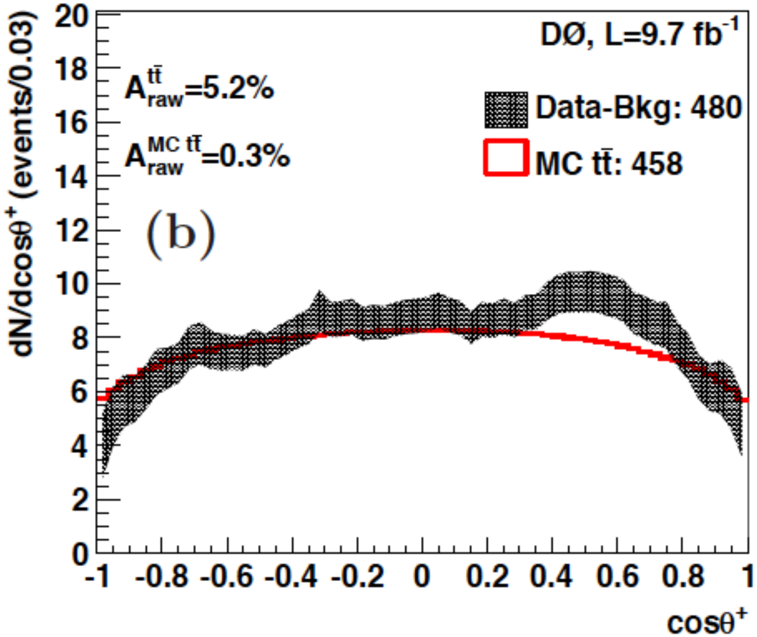
- Combined results from Tevatron and LHC put constraints on varieties of NP models

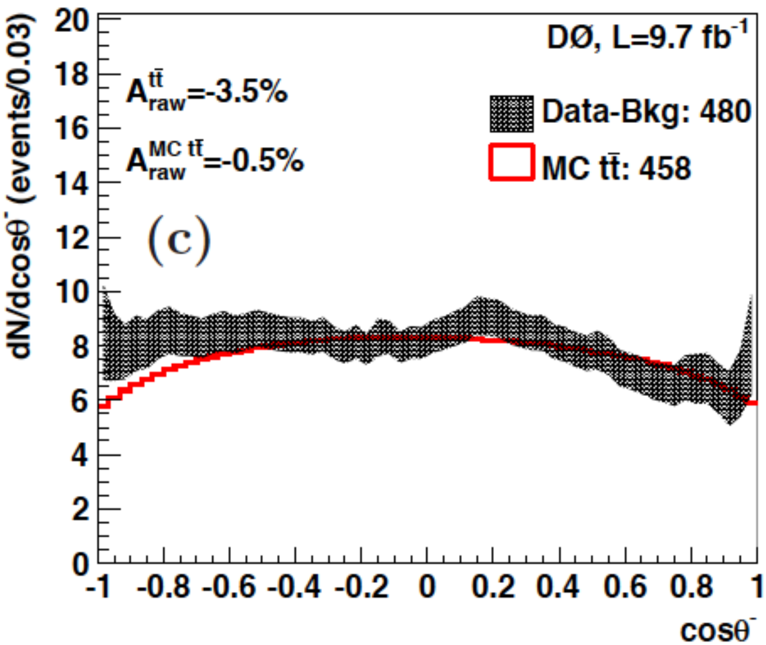
First measurement of polarization @ Tevatron

- Use lepton angular distributions w.r.t. the quantization axis (here, beam axis)
- Matrix-element techniques for event kinematics

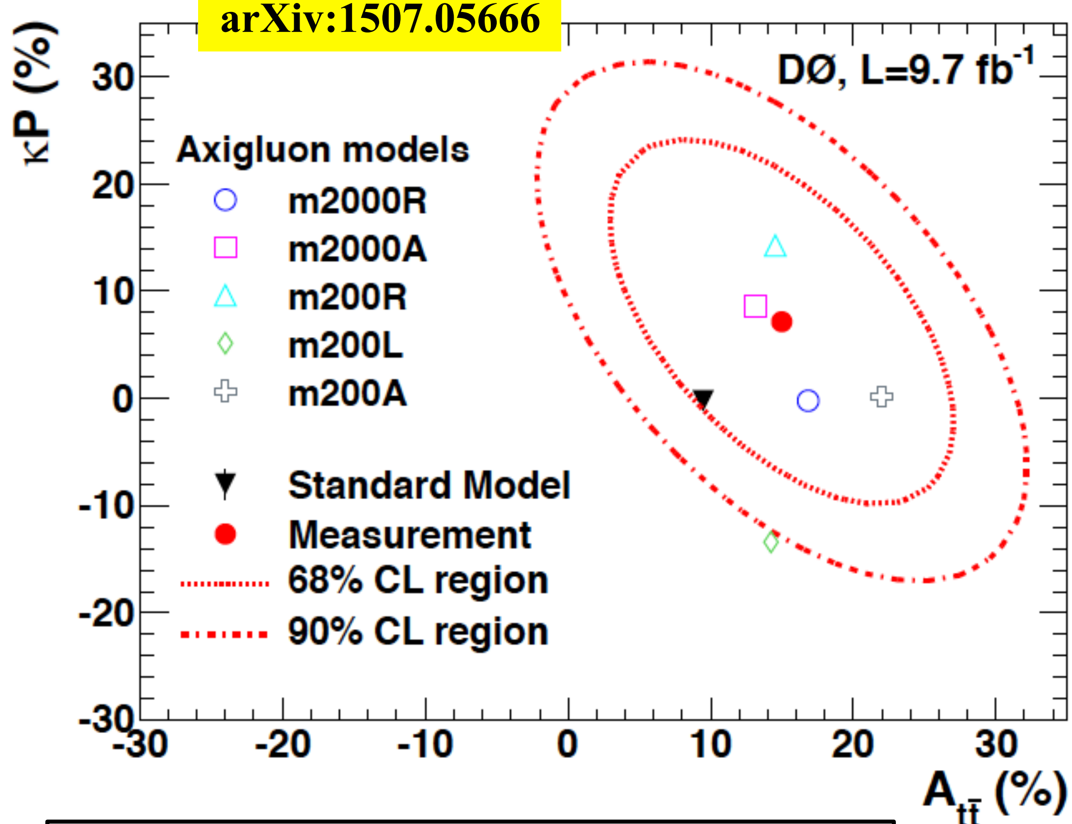
$$A_{\hat{n}}^{\ell^\pm} = \frac{N(\cos\theta^\pm > 0) - N(\cos\theta^\pm < 0)}{N(\cos\theta^\pm > 0) + N(\cos\theta^\pm < 0)}$$

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



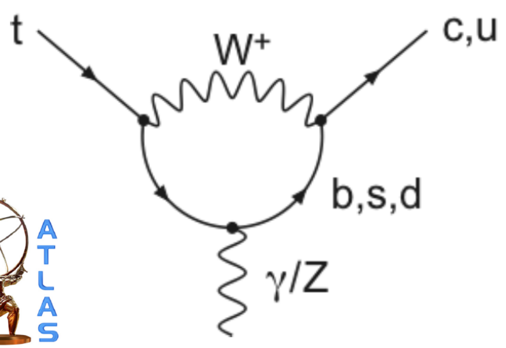


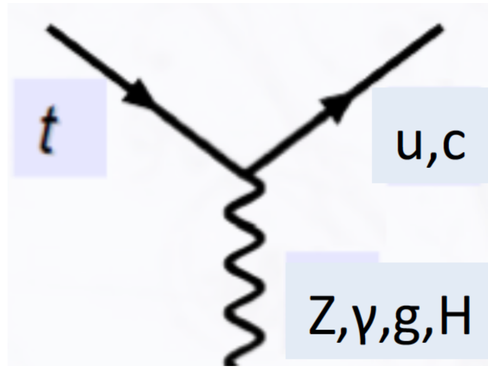
arXiv:1507.05666



$$P = 11.3 \pm 9.1_{\rm stat} \pm 1.9_{\rm syst}\%$$
$$\text{for } A_{\rm FB} = 9.5 \pm 0.5\%$$

Flavour changing neutral currents





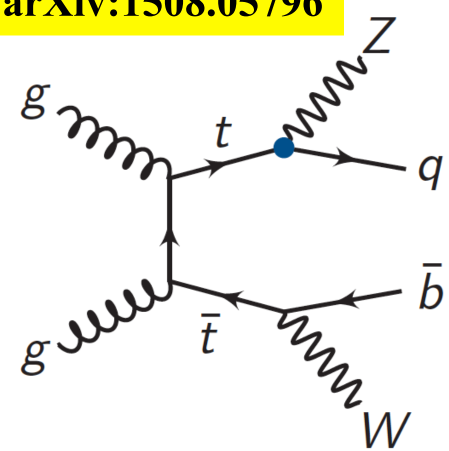
- NP could enhance FCNC couplings by many orders of magnitude

ACTA Phys. Pol. B 35 (2004) 2695

SM: BR $\sim 10^{-12} \ldots 10^{-17}$

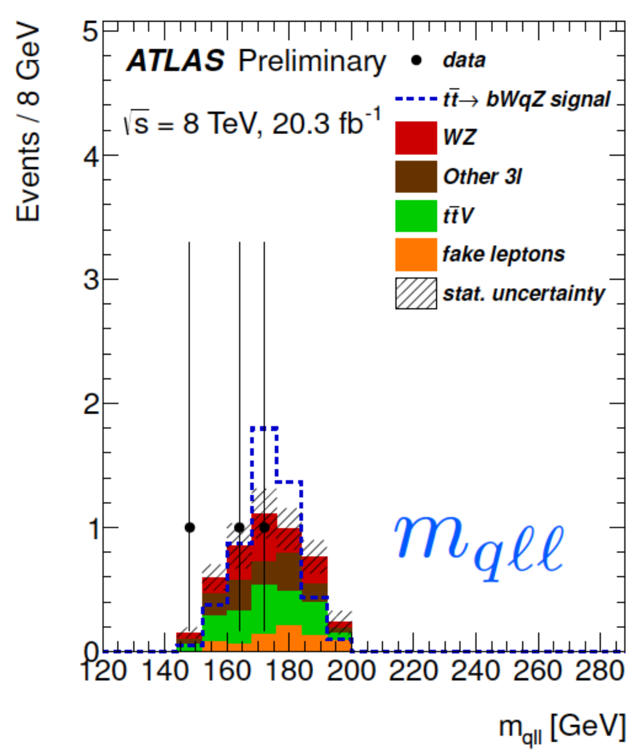
NP: BR $\sim 10^{-5} \ldots 10^{-9}$

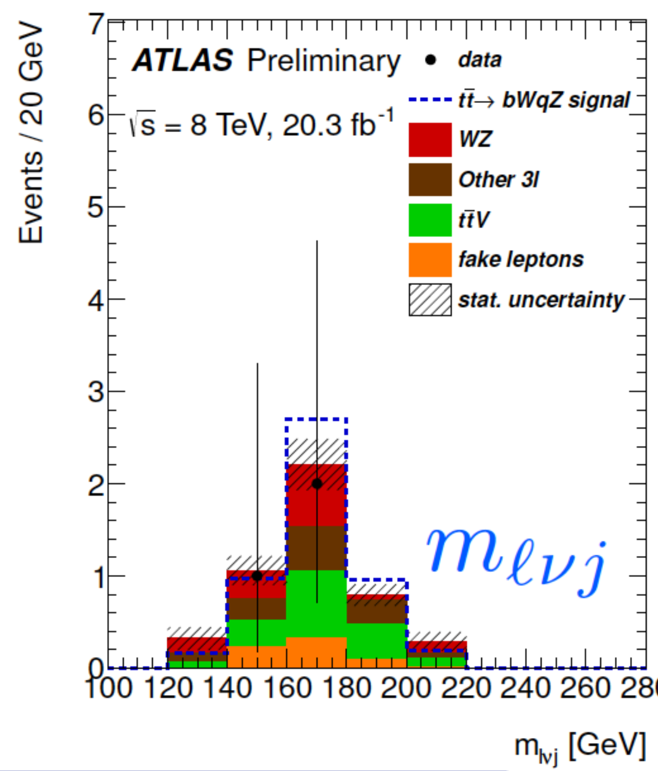
arXiv:1508.05796



- Signal:

  $t \to qZ(\to \ell\ell)$
- Backgrounds from the control regions

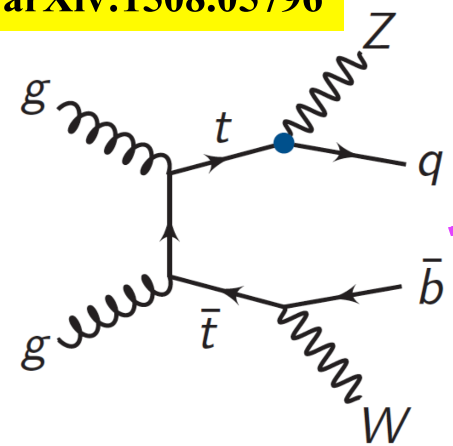


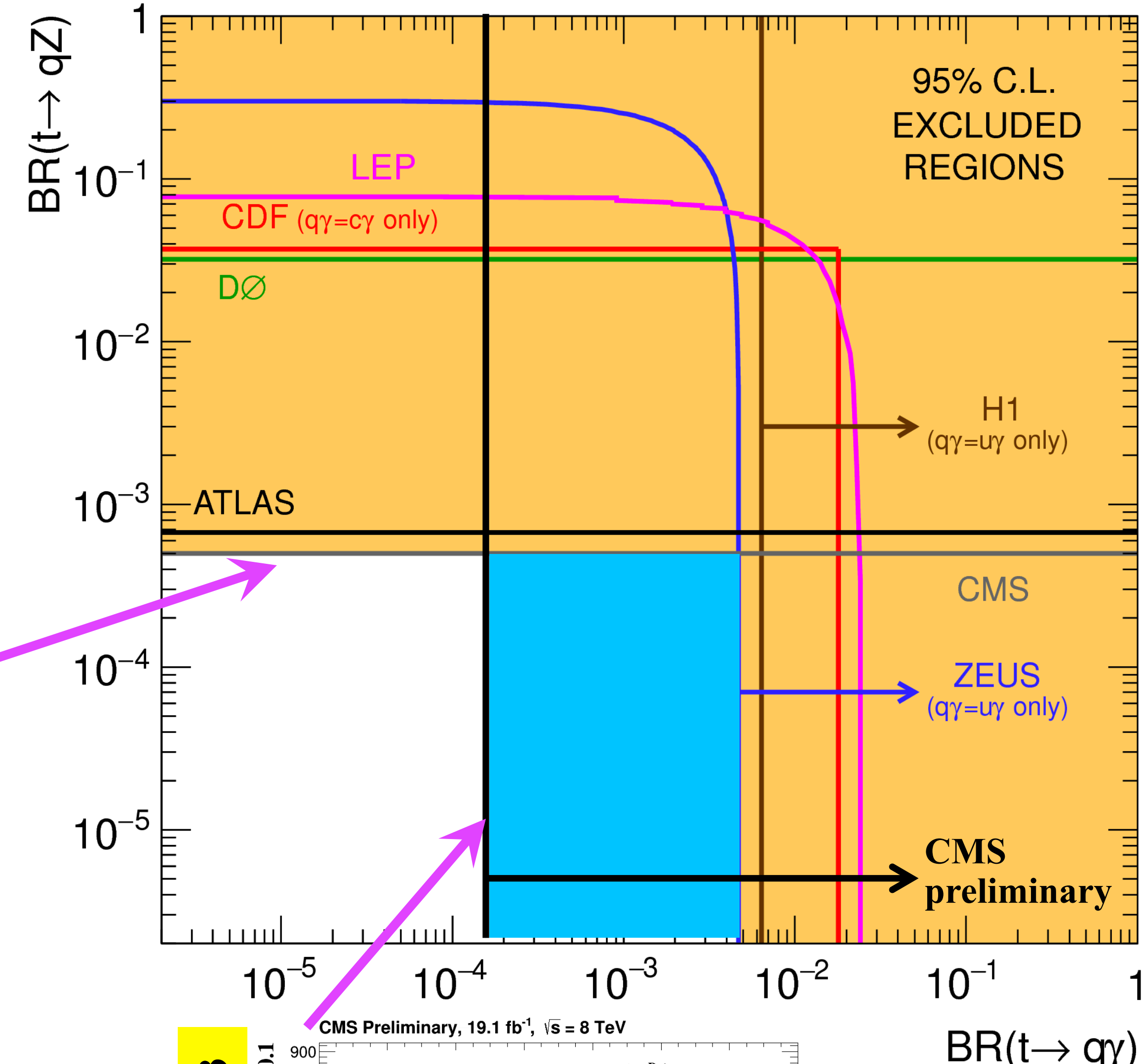


Upper limit on branching ratio: BR($t\to Zq$) < 0.07% (95%CL)

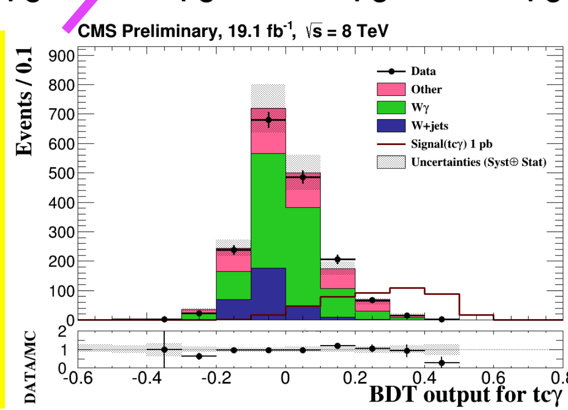
Flavour changing neutral currents – II

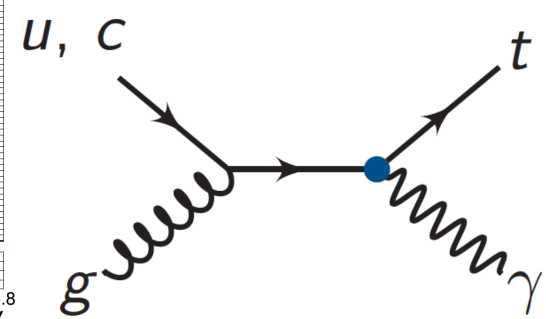
arXiv:1508.05796





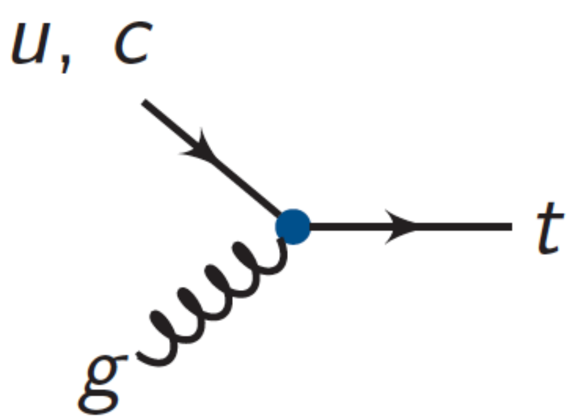
CMS TOP-14-003

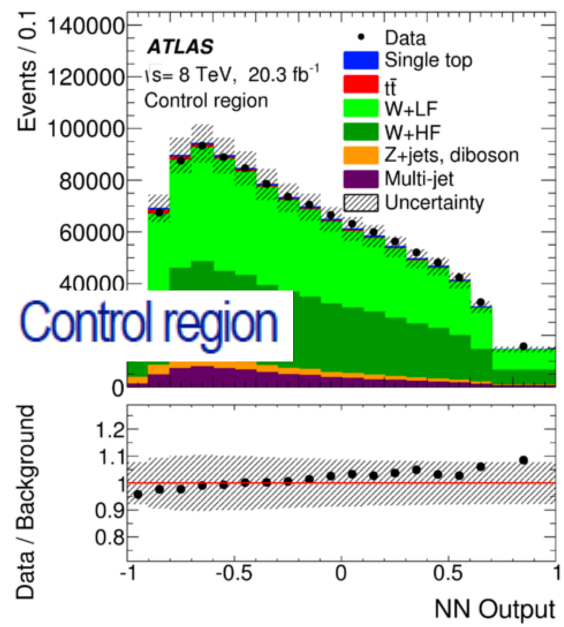


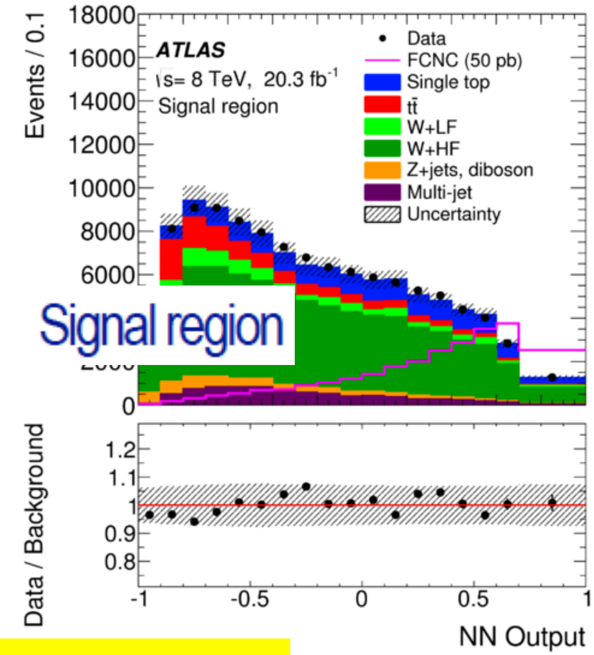


- Complementary results from LEP, HERA, Tevatron are now being superseded by the LHC

Flavour changing neutral currents – III

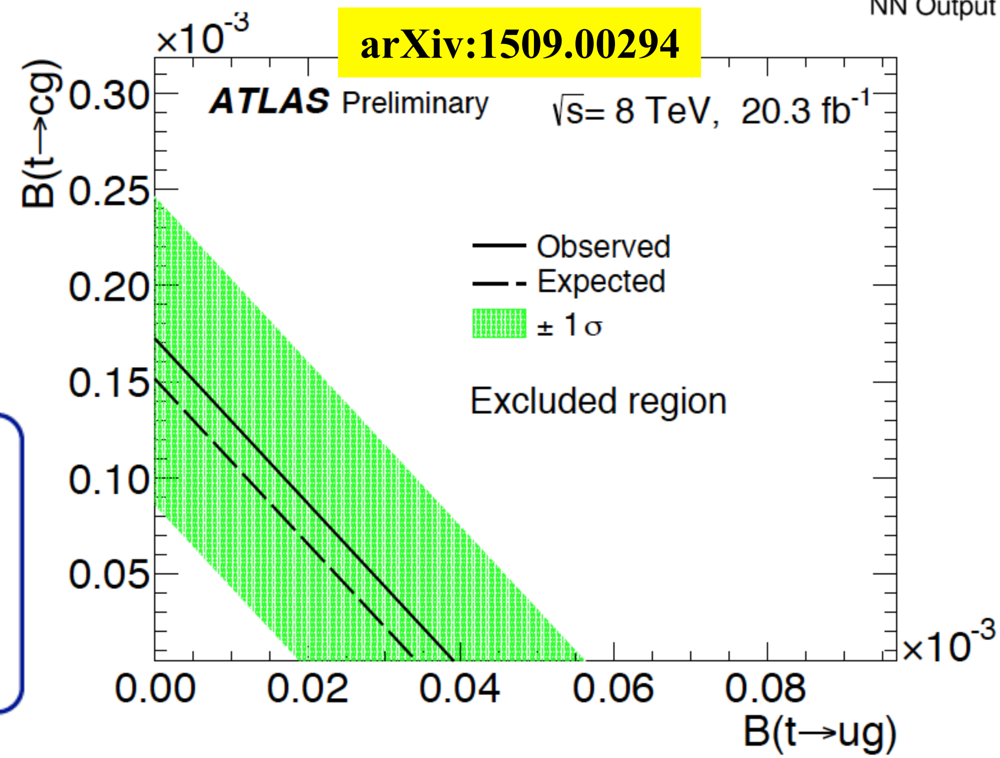






- t-channel single top selection: 1 lepton, 1 b-tagged jet and missing E_T
- Neural network to separate signal from SM backgrounds

arXiv:1509.00294

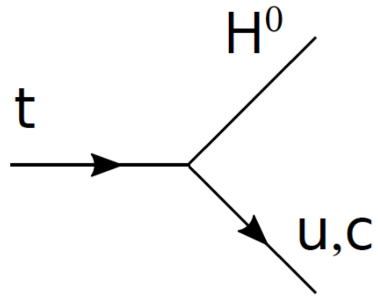


Upper limit on branching ratios:

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

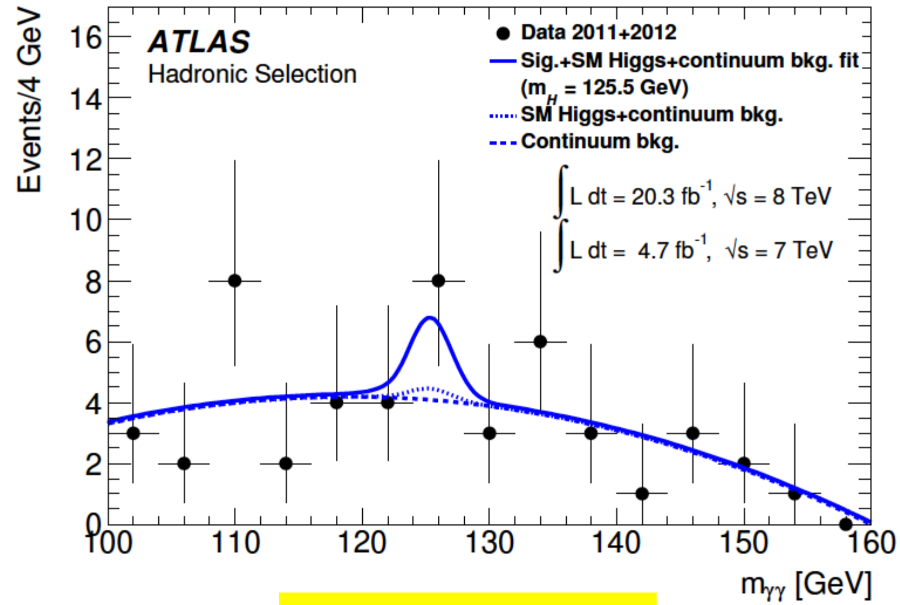
$BR(t \to cg) < 17 \cdot 10^{-5}$ @ 95% CL

Flavour changing neutral currents – IV



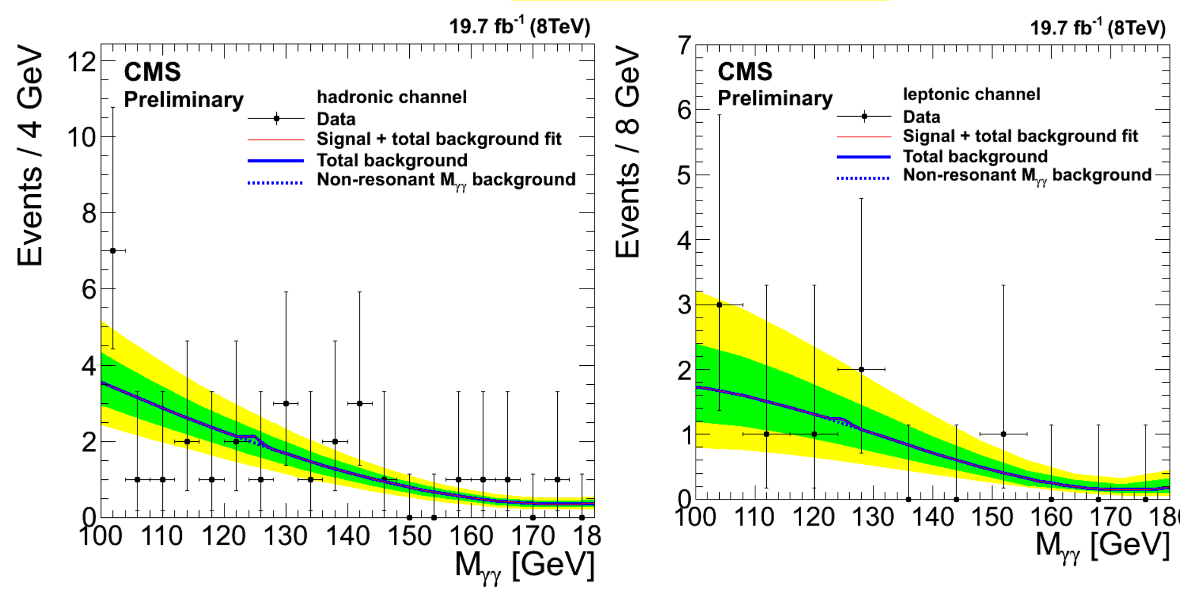
- Look for events with one top decaying bW (hadronic & leptonic) and other top to Hq (q = u,c), where H decays to two photons

JHEP06 (2014) 008



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

CMS TOP-14-019



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

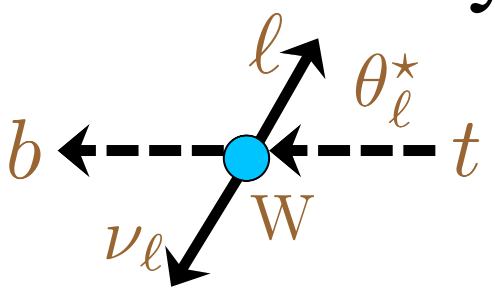
Summary and Outlook

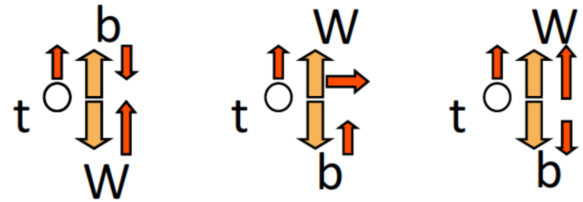
- Top physics is indeed 'top physics': it is everywhere (QCD, electroweak and NP)
  - ✓ Tevatron and LHC data provide complementary information
  - ✓ A detailed picture of the beast(!) has been established
  - ✓ Experiments are finishing up legacy publication (Tevatron & LHC Run1)
- What do we expect at Run II? 100 fb^{-1} per experiment by 2018
  - ✓ 80×10^6 top-pair and 20×10^6 single top events (>10 Hz at 10^{34} $cm^{-2}s^{-1}$)
  - ✓ 80,000 tt+Z and t+Z events, each
- Statistics ➔ systematics and reach
  - ✓ Beat down systematics using statistics and combining different methods
  - ✓ Ultimate precision also would call for advances in theory (e.g, top mass)
- Top as a NP probe
  - ✓ Direct and indirect searches
  - ✓ Couplings, FCNC, asymmetries, angular distributions

➢ Run II: expect substantial progress in experiment and theory, and stay positive for (un)known unknowns

Bonus Materials

W helicity fraction

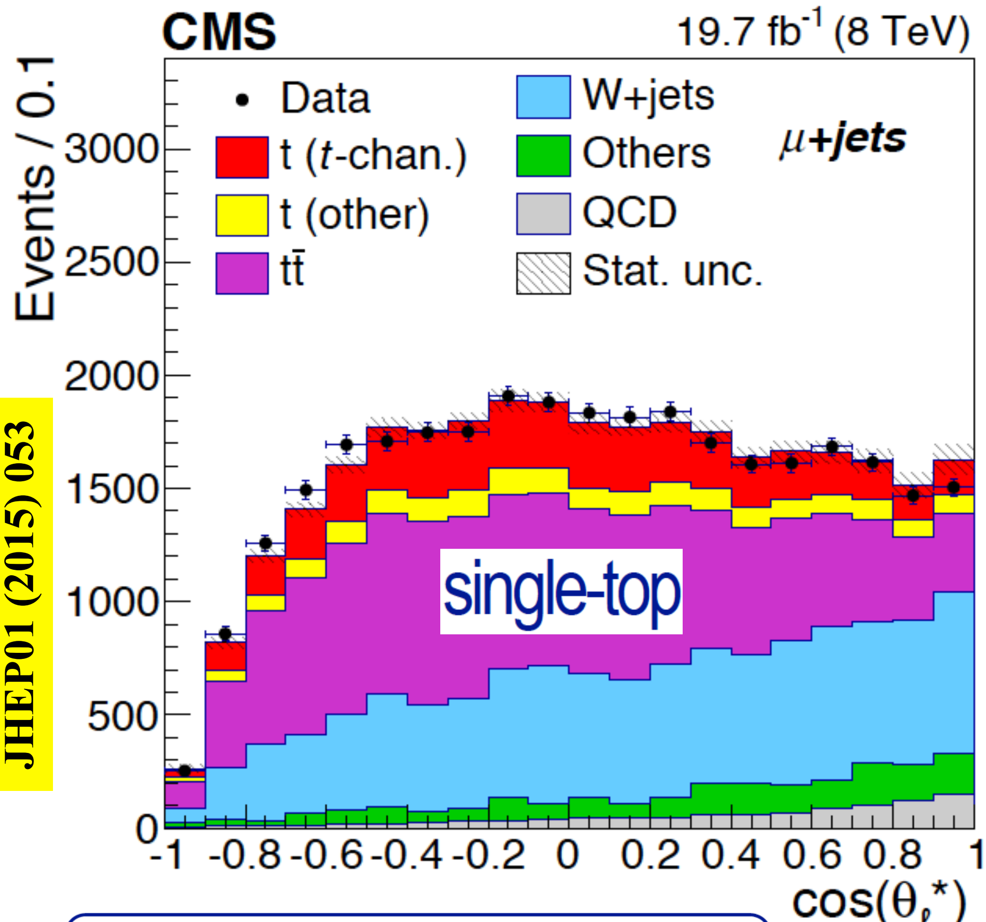




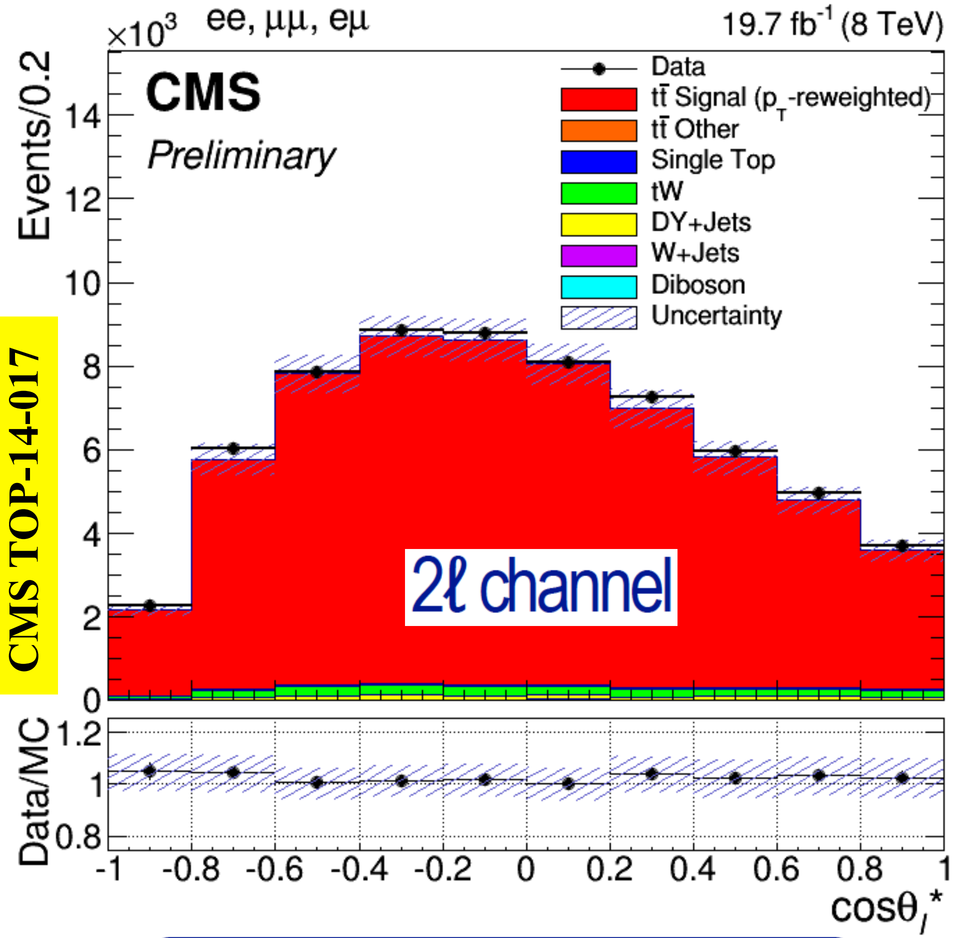
$F_L + F_R + F_0 = 1$

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

JHEP01 (2015) 053



CMS TOP-14-017



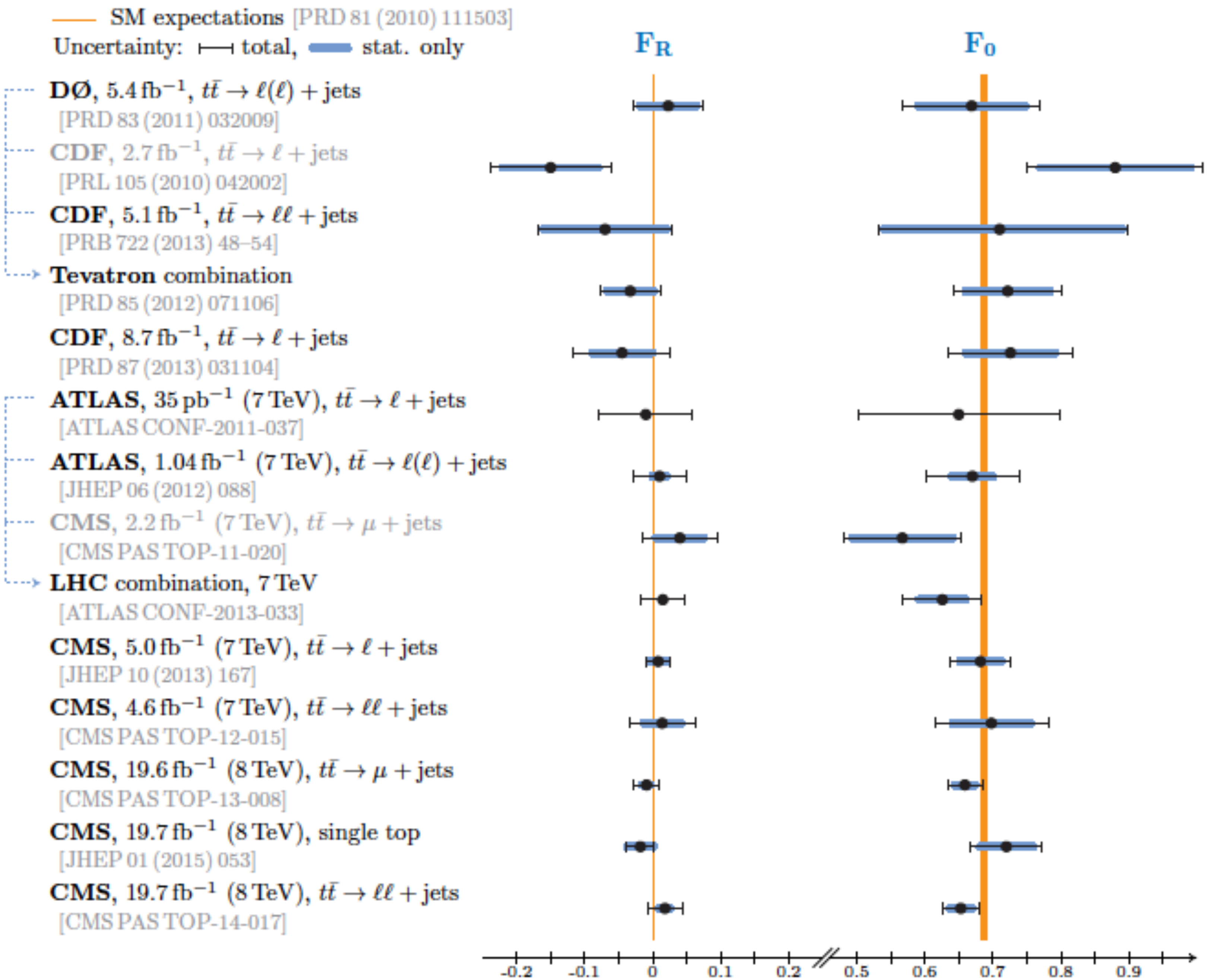
$F_R = -0.018 \pm 0.019_{stat} \pm 0.011_{syst}$

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

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

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

Summary: W helicity fraction



- Combination is on the way

Summary: FCNC top decays

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

- Sensitivity getting closer NP scenarios

Theory predictions for FCNC in top sector

ACTA Phys. Pol. B 35 (2004) 2695

	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

Table 1: Branching ratios for top FCN decays in the SM, models with $Q = 2/3$ quark singlets (QS), a general 2HDM, a flavour-conserving (FC) 2HDM, in the MSSM and with R parity violating SUSY.