Selected highlights from TOP2016

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on behalf of the ATLAS and CMS Collaborations

Precision Vietnam, Qui Nhon, September 26th 2016

HELMHOLTZ ASSOCIATION

DESY

TOP2016

- 9th edition of the International Workshop on Top Quark Physics in Olomouc, Czech Republic: https://indico.cern.ch/event/486433/
- 135 participants, 60 presentations, 1 poster session and 2 Q&A sessions
- Very nice balance between theory and experiments, always fruitful discussions...

Outline

A few remarks:

- *very difficult to summarize a whole conference in 15 min, the focus here is on a few results*
- *many results from the LHC experiments were approved for this conference* 

  → most references linked to the talk
- *direct searches for new physics using tops are not shown*

> Inclusive and differential cross-section measurements

> Mass and width measurements

> Properties: spin/polarisation, CP violation

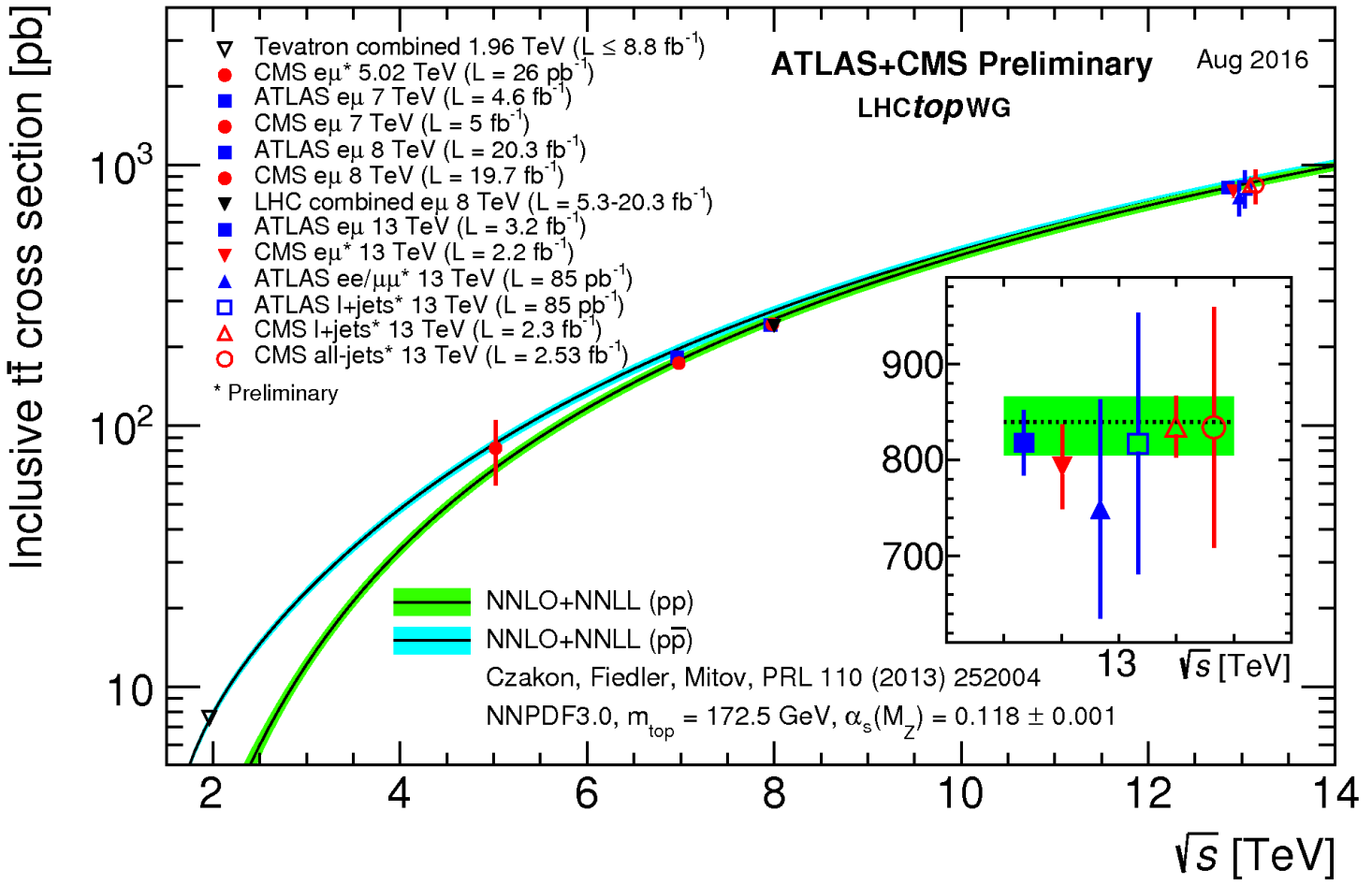
> Single top production

> Rare processes: $t\bar{t}V$, 4 tops

Cross-section measurements

> Nice complete picture of inclusive cross-sections measurements for 5 values of √s

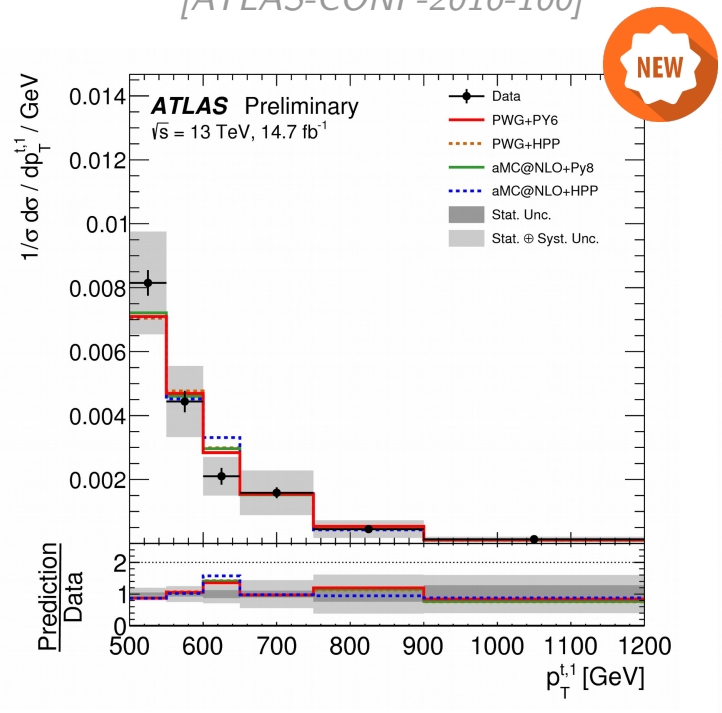
- relative precision of around 4% on the 13 TeV measurements



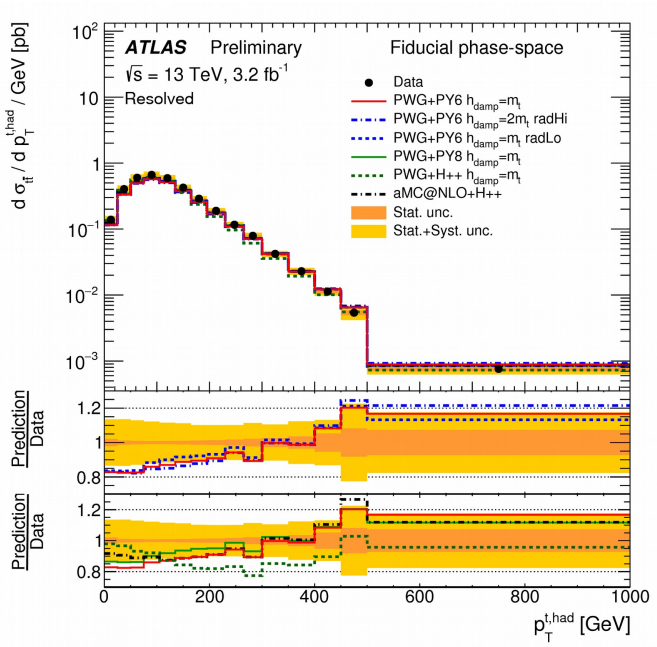
Differential cross-section measurements

- Numerous results from both experiments
- ATLAS studied the top kinematics at 13 TeV in the all-hadronic, ℓ+jets and ℓℓ channels

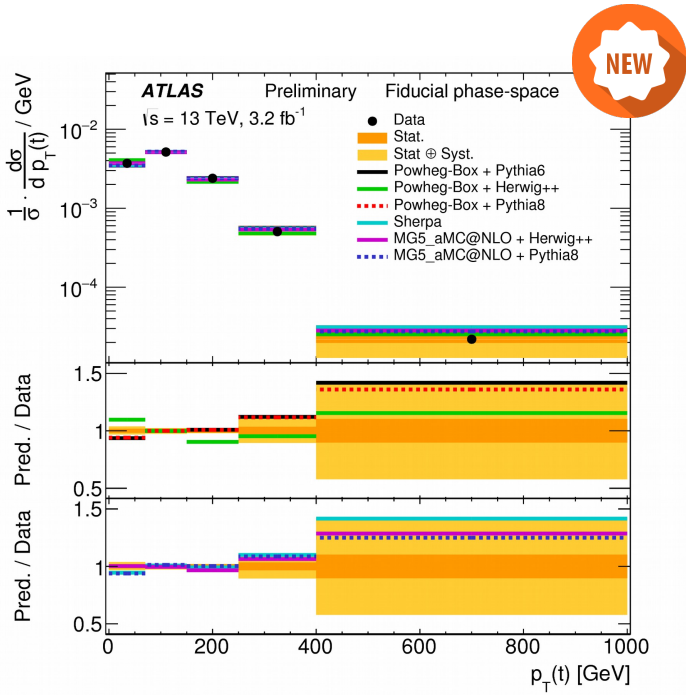
all-hadronic (2016 data)
[ATLAS-CONF-2016-100]



ℓ+jets
[ATLAS-CONF-2016-040]



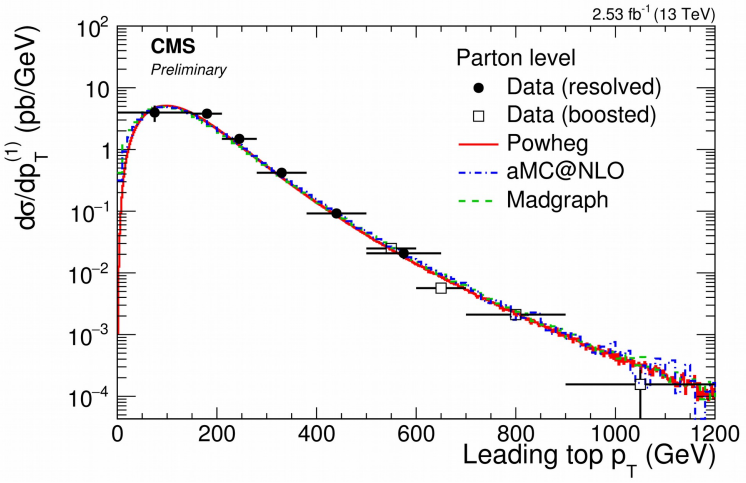
ℓℓ
[TOPQ-2016-04]



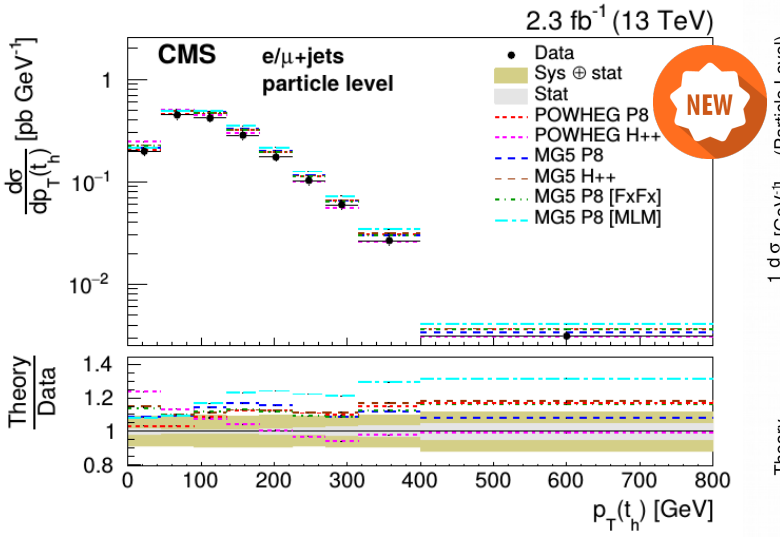
Differential cross-section measurements

> Similar measurements at CMS

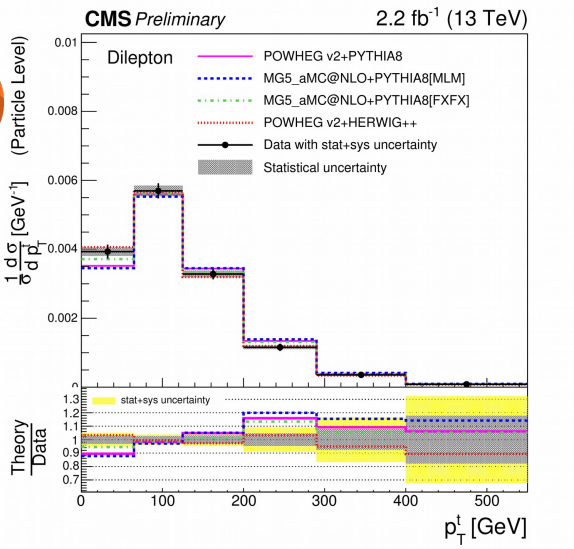
all-hadronic
[CMS-PAS-TOP-16-013]



ℓ+jets
[TOP-16-008]

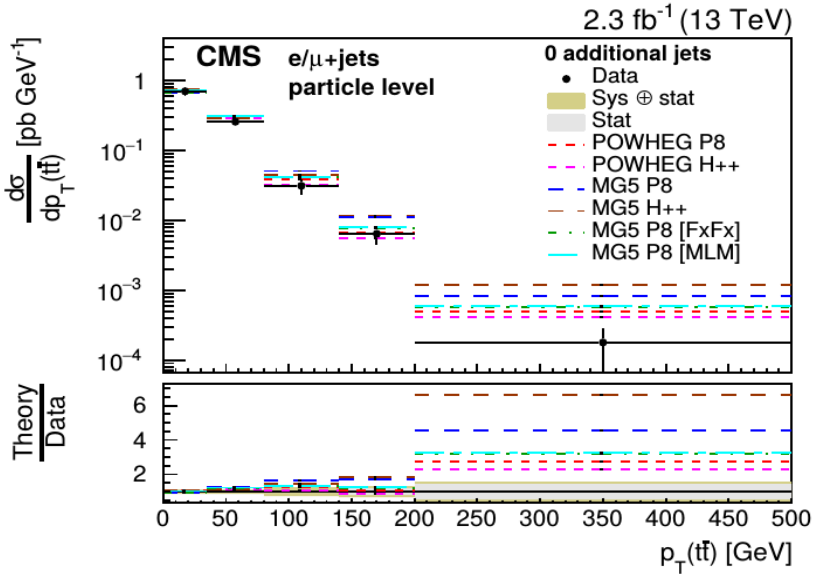


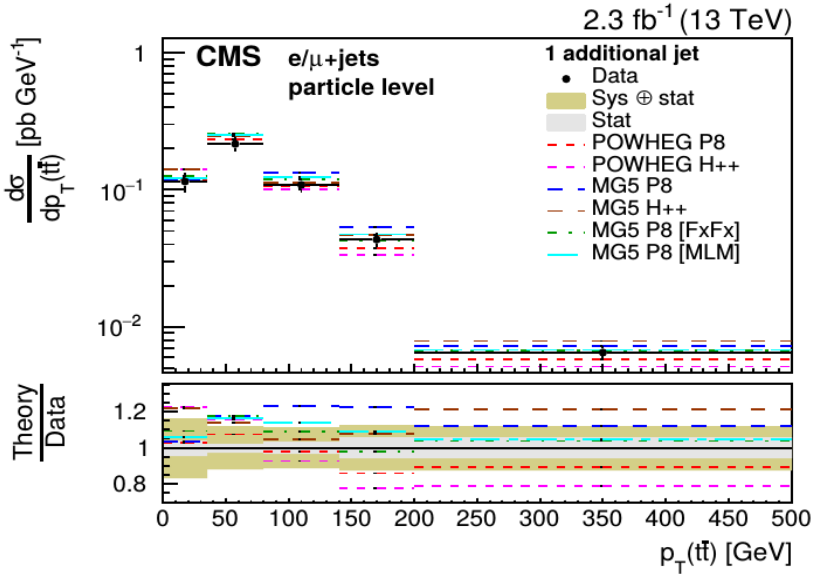
$\ell\ell$
[CMS-PAS-TOP-16-007]

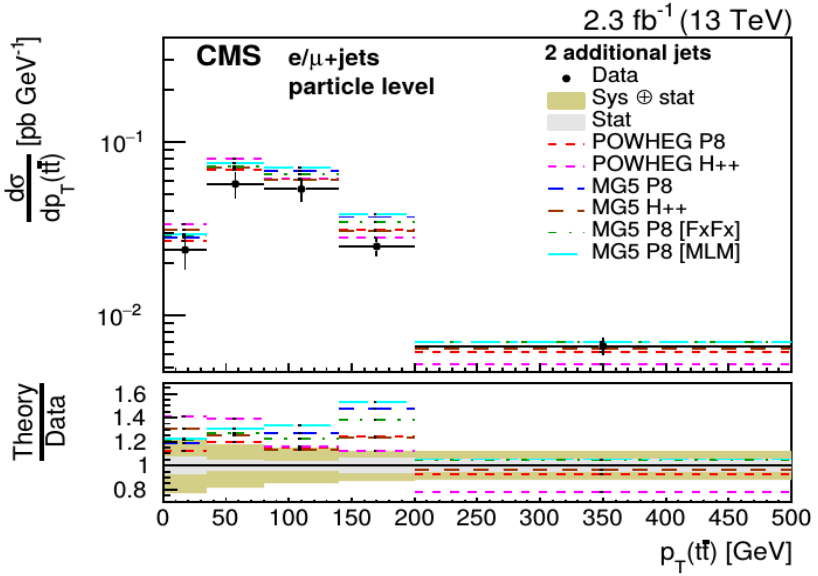


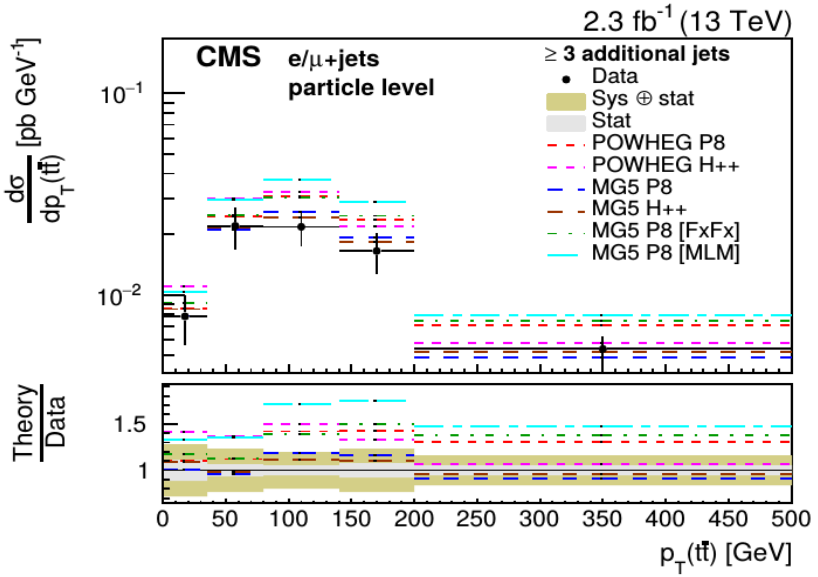
Differential cross-section measurements

> CMS also looked double differential cross sections *[TOP-16-008]* for instance $p_T^{t\bar{t}}$ as a function of the number of additional jets



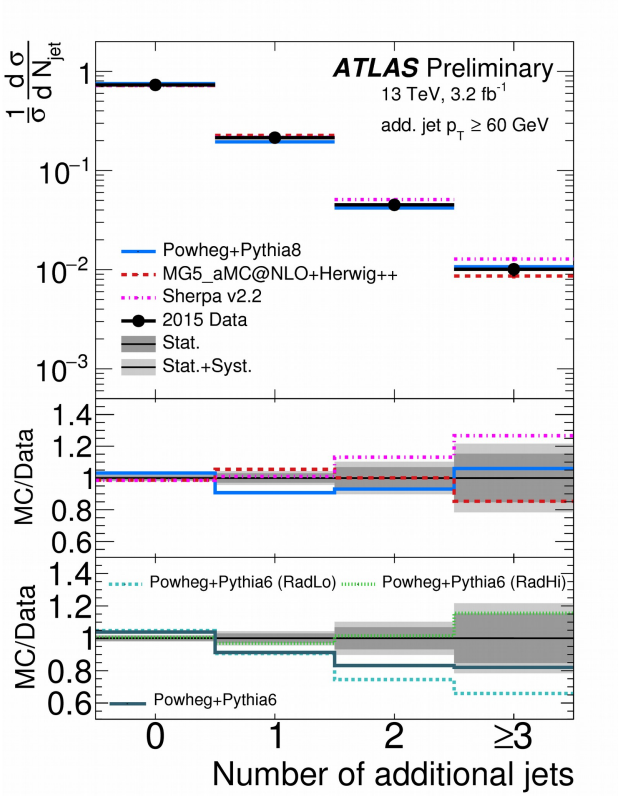


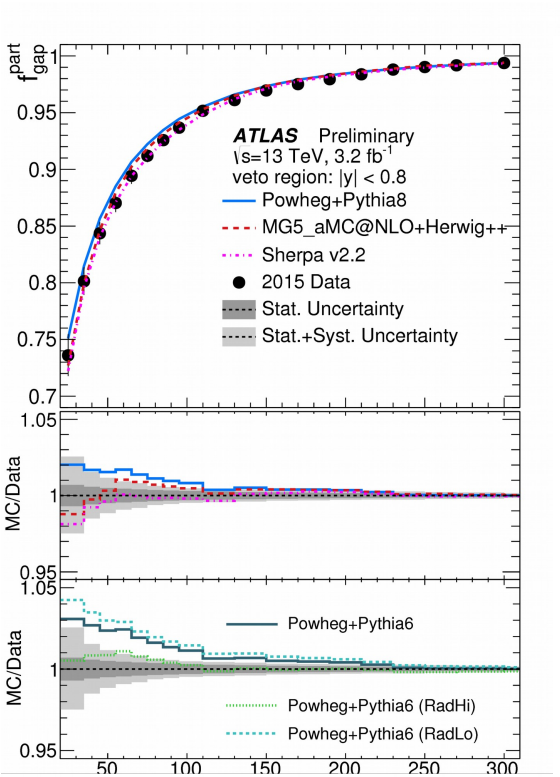


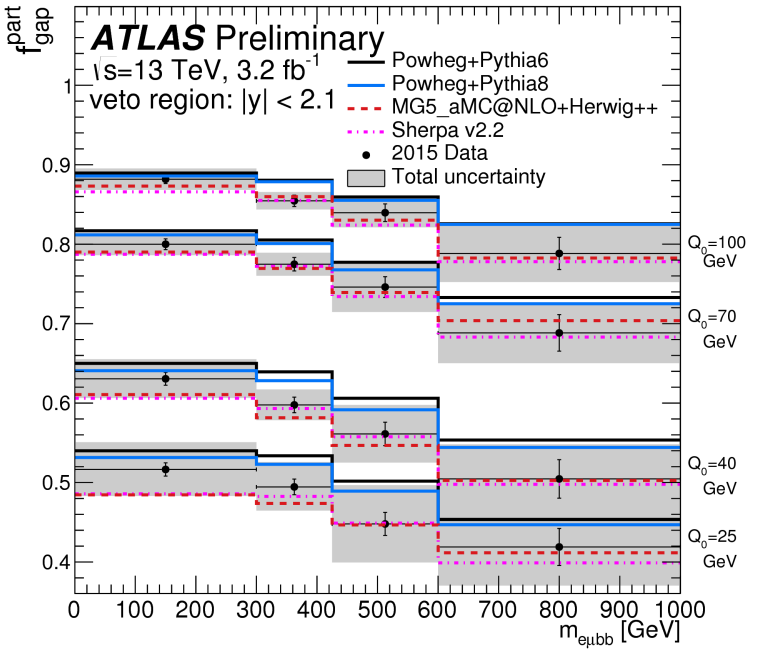


Jet activity

- Measurement of the number of additional jets and gap fraction at ATLAS *[TOPQ-2015-17]*
  - events with eμ + 2 *b*-jets
  - unfold to stable particle level in a fiducial phase-space
  - study modelling of various MC generators and parton showers

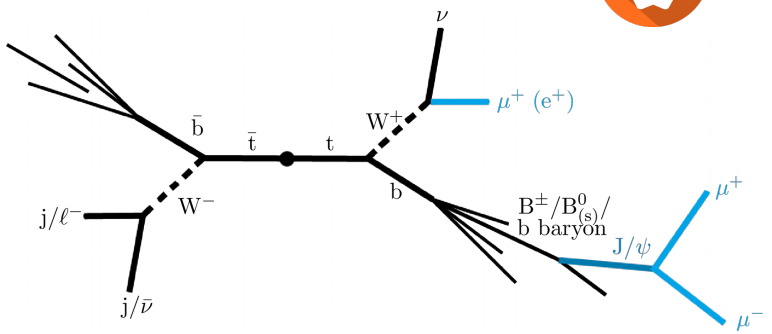


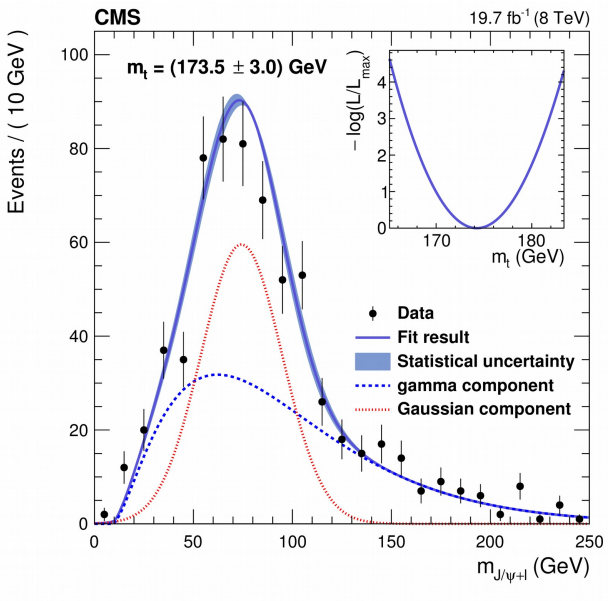




Mass and width

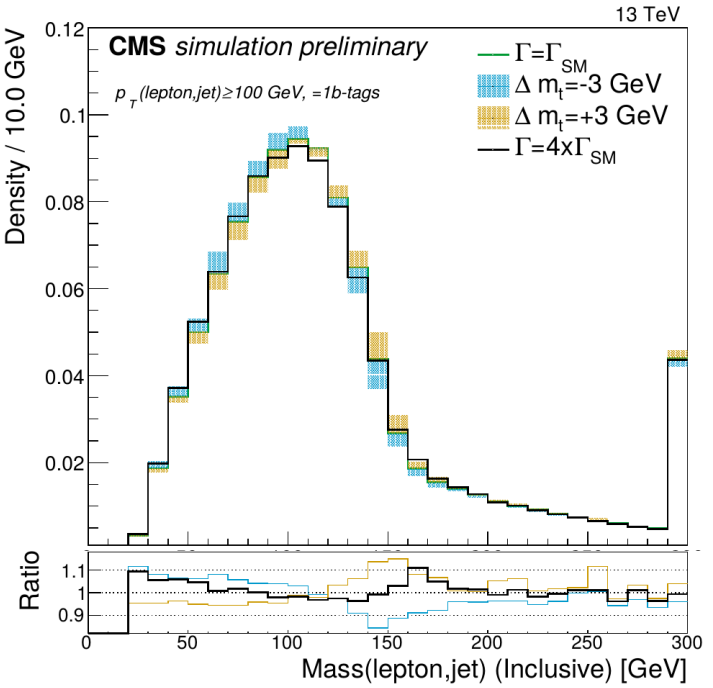
> Mass measurement using decays with a J/Ψ meson at CMS *[arXiv:1608.03560]*





> Width measurement using M_{lb} at CMS *[TOP-16-019]*

- SM prediction $\Gamma = 1.35$ GeV at NLO
- obtained bounds: $0.6 < \Gamma < 2.5$ GeV at 95% CL
- 1st direct measurement at the LHC

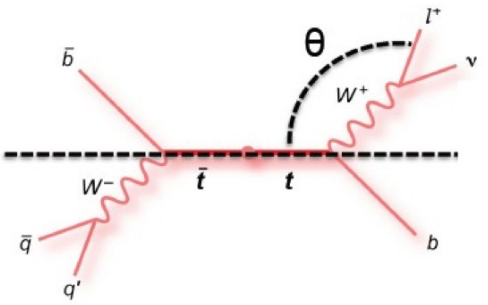


→ precision to be compared with "traditional" measurements: latest ATLAS result quotes an uncertainty of 0.70 GeV

> **More results in the backup**

Spin and polarization

- Goal is to get a **full picture of the production spin density matrix**
- Common observables used:
  - $\Delta\Phi$: difference of azimuthal angle between the two leptons
  - $\cos\theta$ and $\cos\theta_1\cos\theta_2$ with θ the angle between the lepton and a spin quantization axis
- CMS measurement at 8 TeV *[PRD 93 (2016) 052007]*
  - asymmetries of $\Delta\Phi$, $\cos\Phi$, $\cos\theta$ and $\cos\theta_1\cos\theta_2$ distributions
  - differential as a function of $M_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p^{T}_{t\bar{t}}$

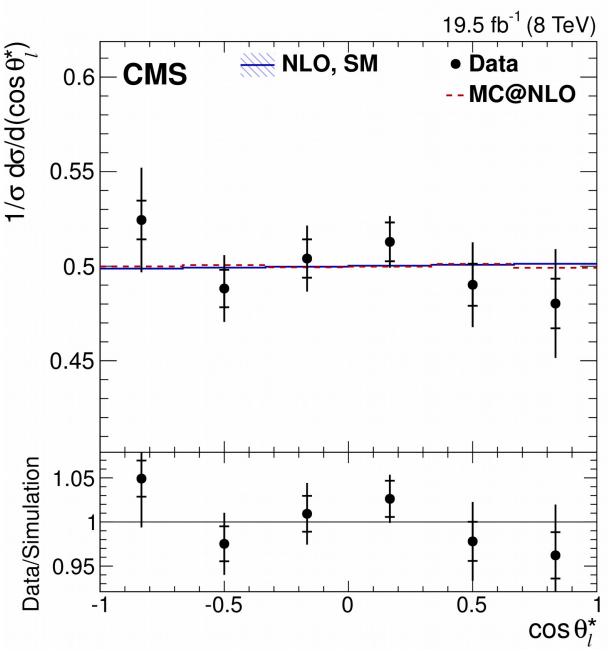


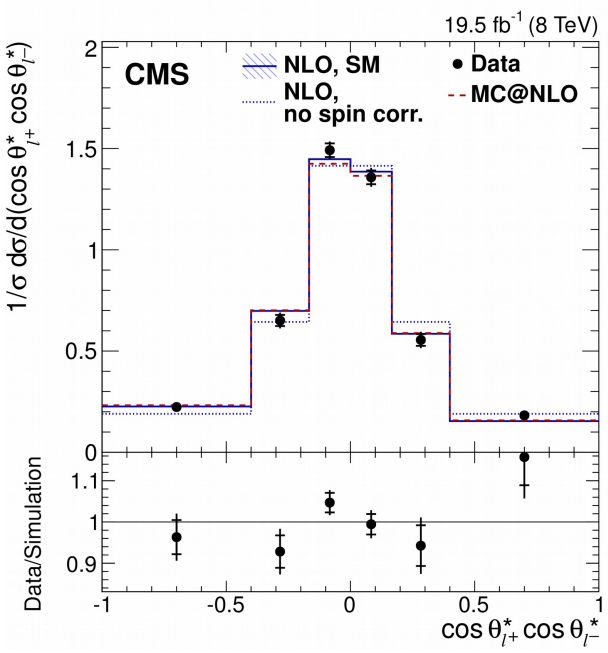
Possible quantization axes:

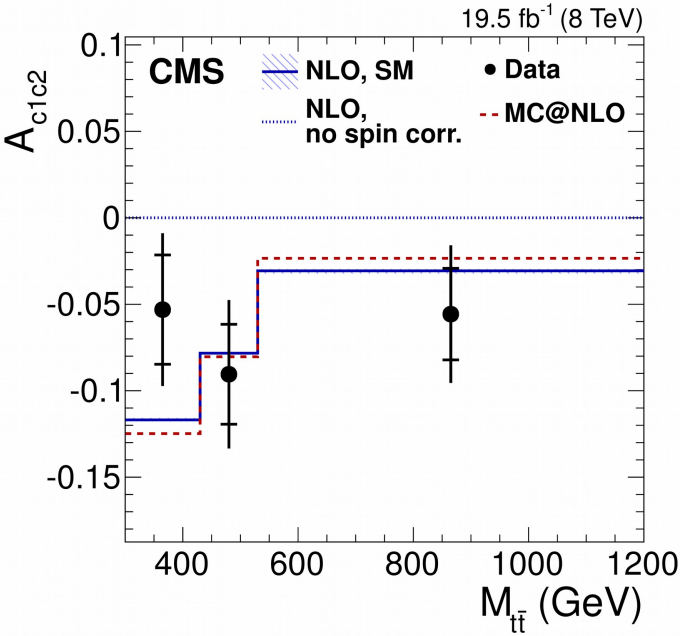
→ helicity axis *k*: top direction in $t\bar{t}$ rest frame

→ transverse axis *t*: axis transverse to beam axis and top direction

→ axis *r*: axis orthogonal to the two previous ones



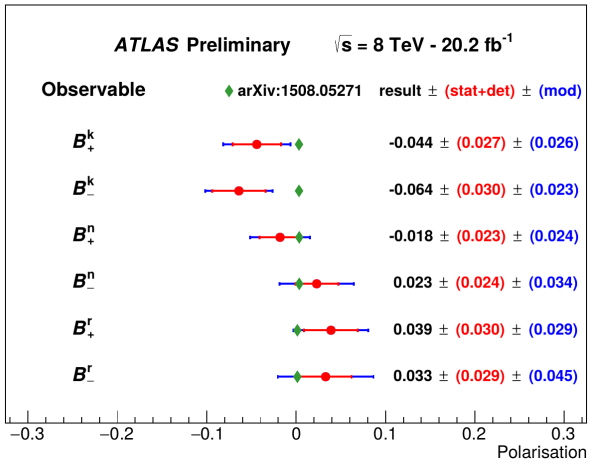


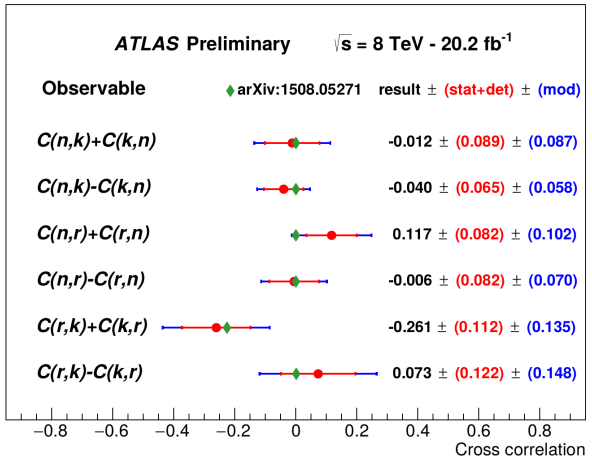


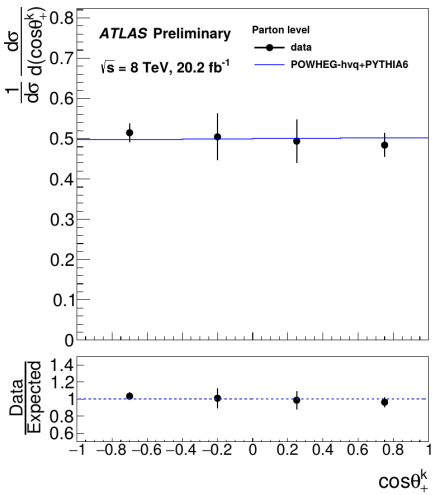
Spin and polarization

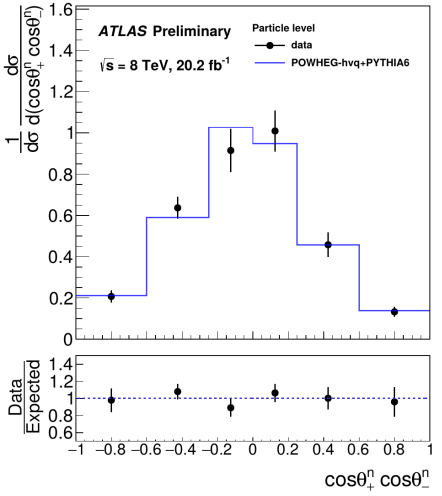
> New ATLAS measurement at 8 TeV with $t\bar{t}$ events *[ATLAS-CONF-2016-099]*

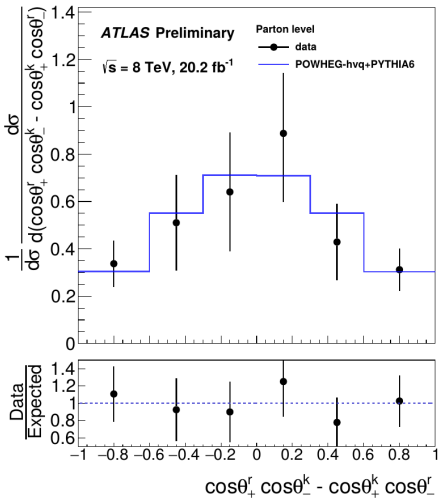
- 15 observables defined along 3 spin quantization axes
- 10 observables measured for the first time, spin correlation along the transverse axis ≠0 at 5.1σ









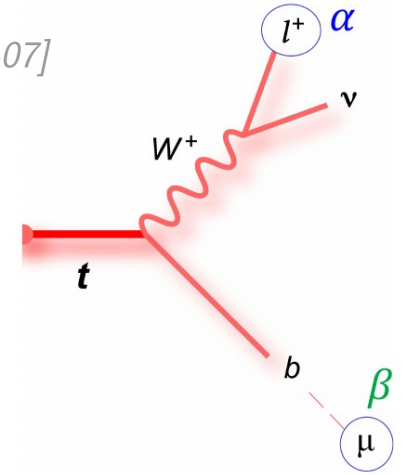


> Very new and complete measurement in the single top t-channel: see backup

CP violation

> Search for CP violation in b-decays using $t\bar{t}$ events in ATLAS *[TOPQ-2016-07]*

- two sources of CPV: Direct:: $P(b \to l^+X) \neq P(\bar{b} \to l^-X)$
  Mixing:: $P(b \to \bar{b} \to l^+X) \neq P(\bar{b} \to b \to l^-X)$



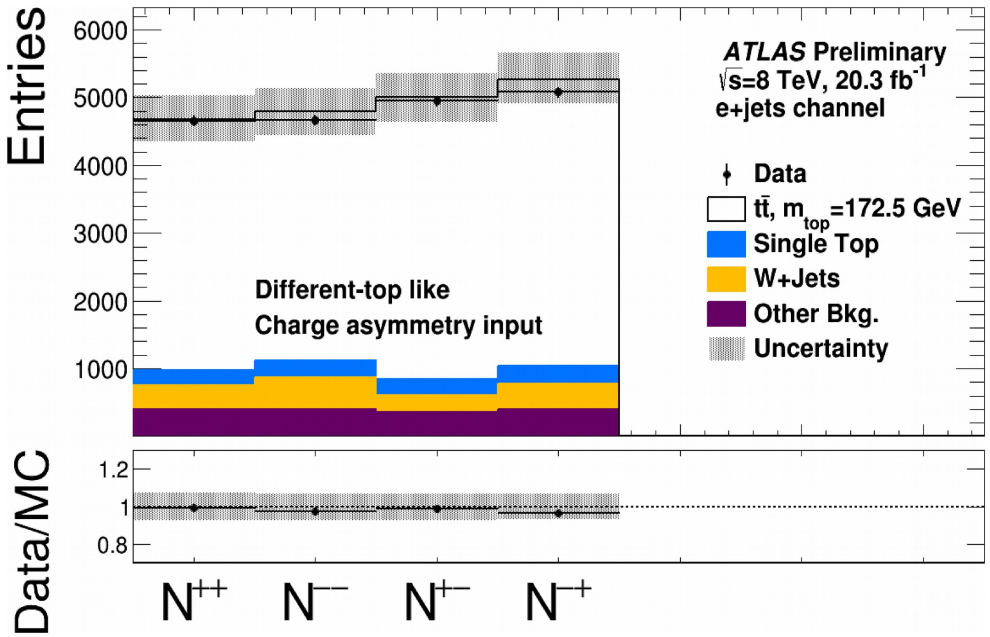
- tag sign of b at production with the isolated lepton, and at decay with the tagged muon
- use asymmetries of same-sign or opposite sign lepton pairs
  $\rightarrow$ in agreement with SM expectations of $< 10^{-4}$

$$A^{ss} = \frac{\left(\frac{N^{++}}{N^+} - \frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+} + \frac{N^{--}}{N^-}\right)}$$

$$= -0.007 \pm 0.006 \text{ (stat.)} \,^{+0.002}_{-0.002} \text{ (expt.)} \pm 0.005 \text{ (model)}$$

$$A^{os} = \frac{\left(\frac{N^{+-}}{N^+} - \frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+} + \frac{N^{-+}}{N^-}\right)}$$

$$= 0.0041 \pm 0.0035 \text{ (stat.)} \,^{+0.0013}_{-0.0011} \text{ (expt.)} \pm 0.0027 \text{ (model)}$$

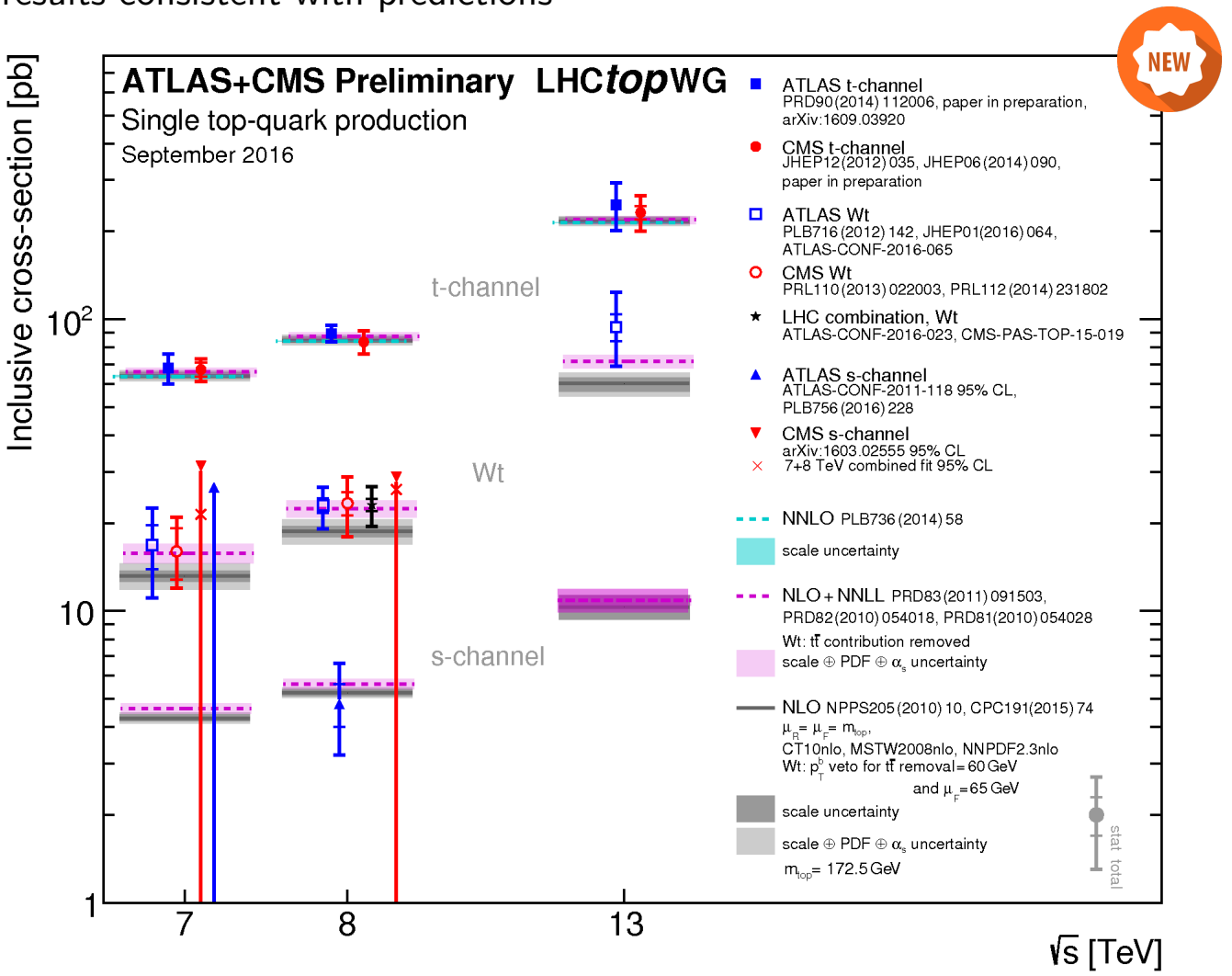


$\rightarrow$ See also CMS result *[TOP-16-001]*

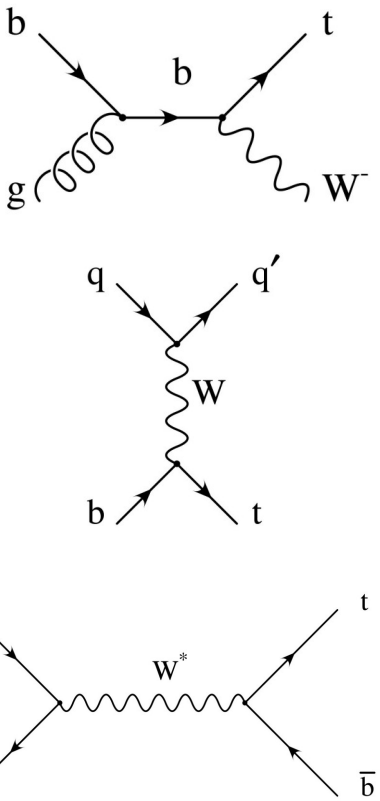
Single top

> The 3 channels are scrutinized:

- t-channel and Wt cross-sections measured at 7, 8 and 13 TeV (Wt combination: talk by Y. Peters)
- s-channel evidence at 8 TeV
- all results consistent with predictions

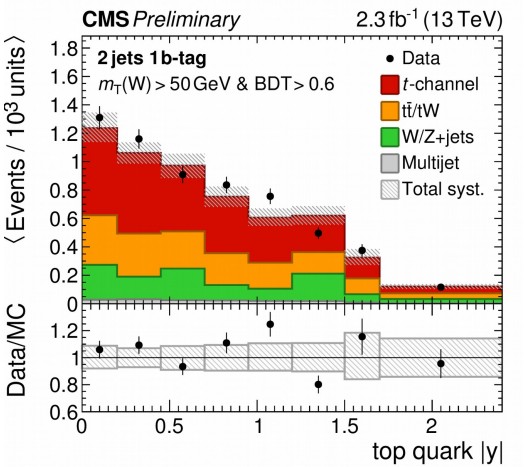


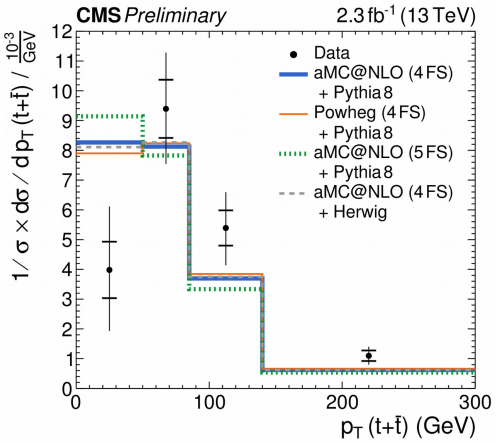
NEW

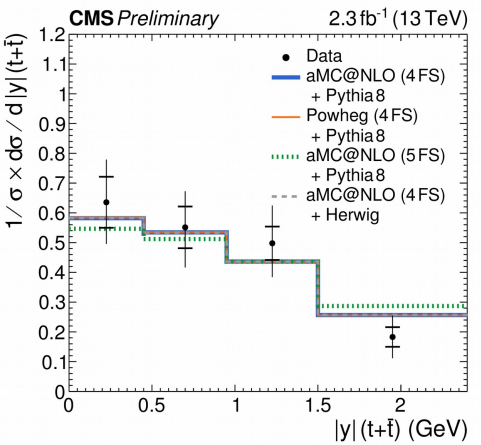


Single top

- At 13 TeV: t-channel
  - ATLAS: inclusive + ratio of tq and $\bar{t}q$ *[arxiv:1609.03920]*
  - CMS: inclusive and differential cross-section *[CMS-PAS-TOP-16-004] [CMS-PAS-TOP-16-003]*

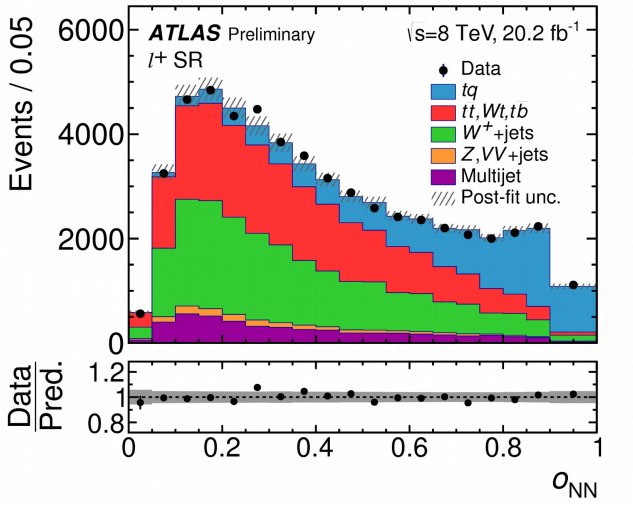


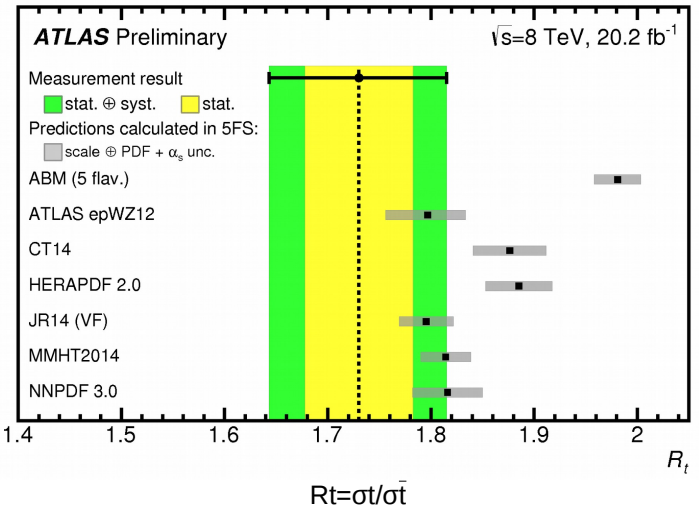


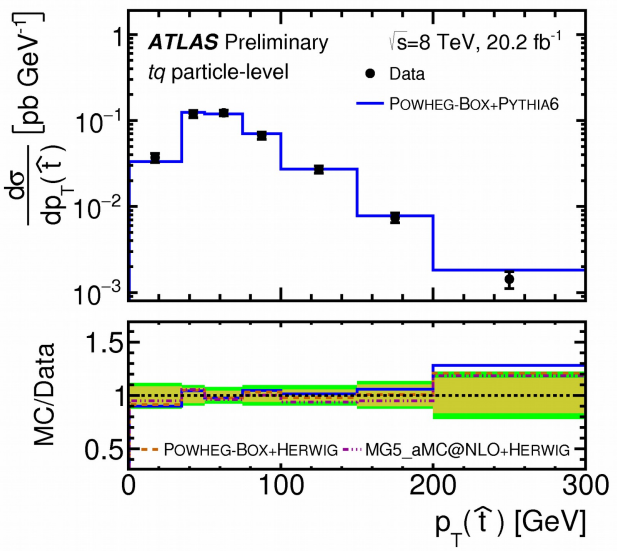


- ATLAS 8 TeV t-channel legacy paper: fiducial, total and differential cross-sections

NEW



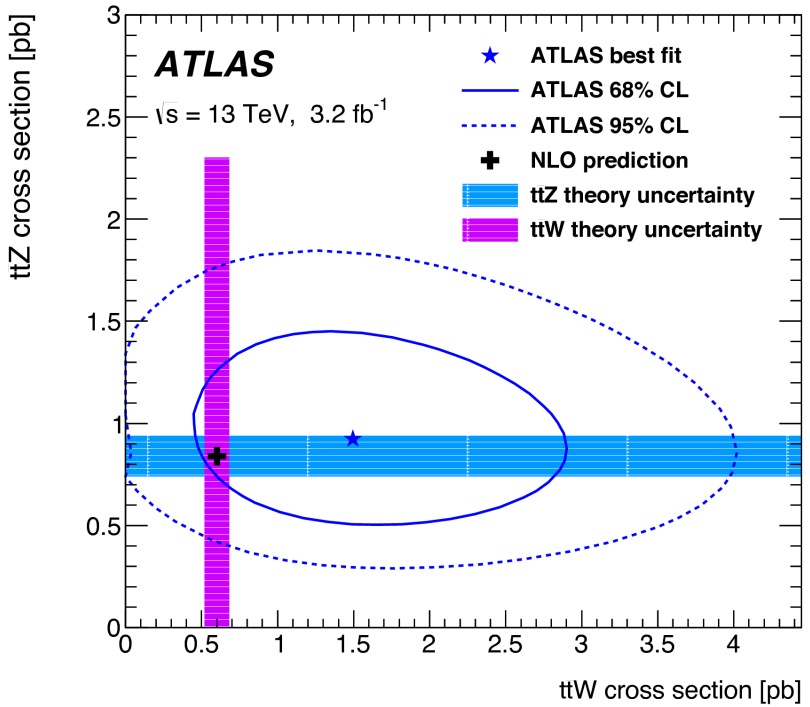


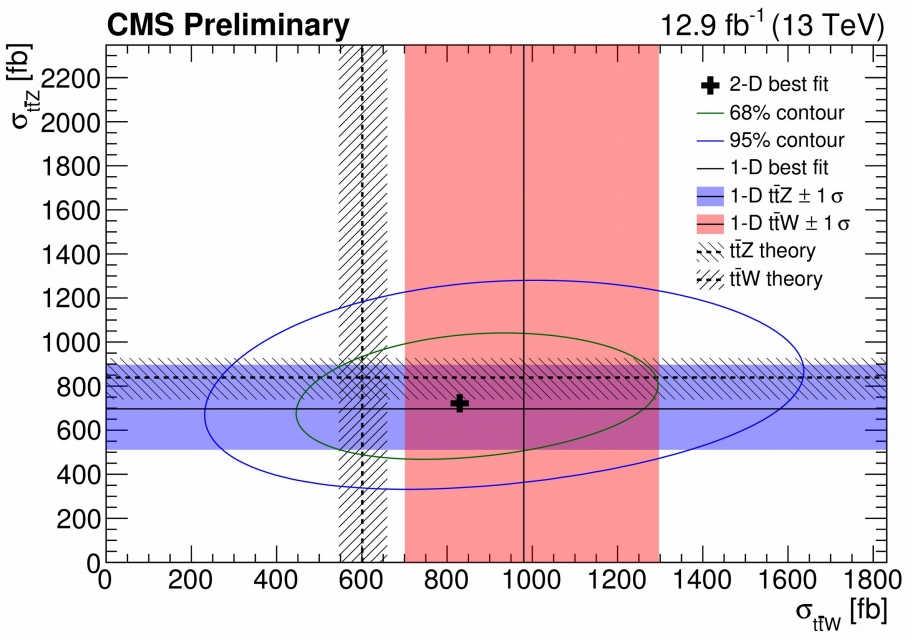


[TOPQ-2015-05]

Rare processes - $t\bar{t}V$

> New results at 13 TeV for ATLAS and CMS *[arxiv:1609.01599] [CMS-PAS-TOP-16-017]*

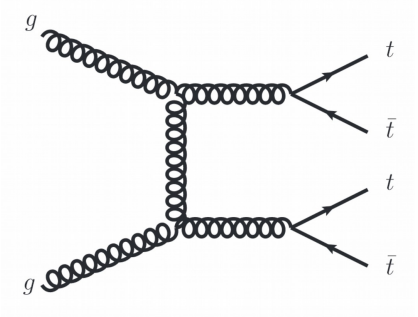




- 2015 data
- channels:
  - 2 same-charge muons
  - 3 and 4 leptons
- significances of 3.9σ for $t\bar{t}Z$ and 2.2 for $t\bar{t}W$

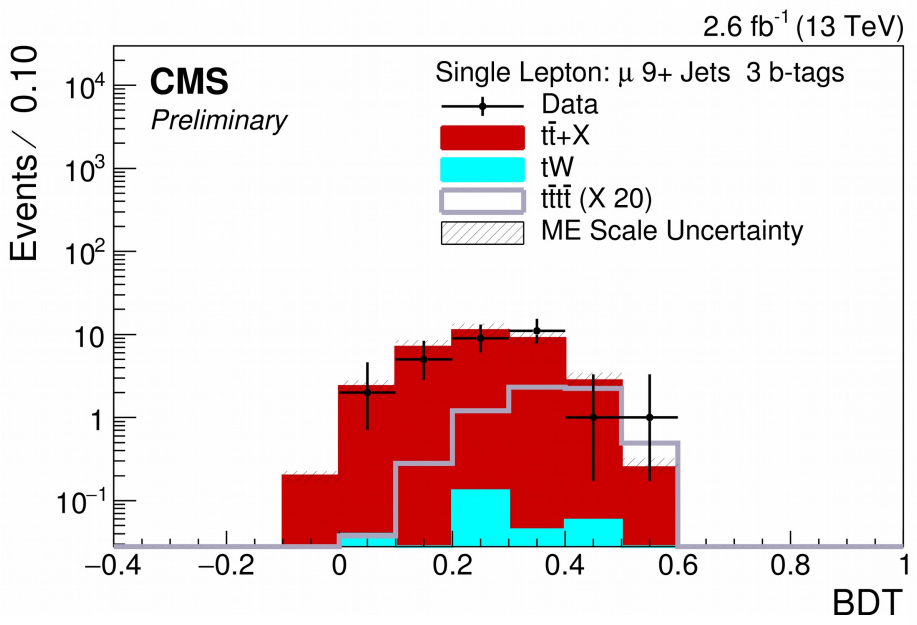
- 2016 data
- channels:
  - 2 same-charge leptons
  - 3 and 4 leptons
- significances of 4.6σ for $t\bar{t}Z$ and 3.9 for $t\bar{t}W$
- see also new $t\bar{t}\gamma$ result *[TOP-14-008]*

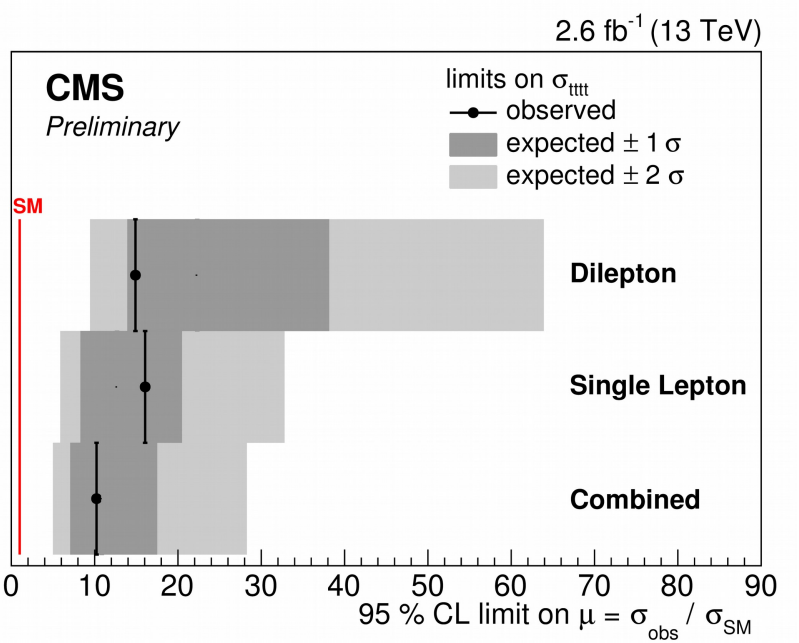
Rare processes – four tops



- Four top production is a very rare SM process:
  - at 8 TeV: $\sigma^{SM}_{tttt} \approx 1.3$ fb
  - at 13 TeV: $\sigma^{SM}_{tttt} \approx 9$ fb

- Most stringent limits from new CMS results dedicated to the search at 13 TeV *[CMS-PAS-TOP-16-016]*
  → limit at ~10xσ^{SM}_{tttt}



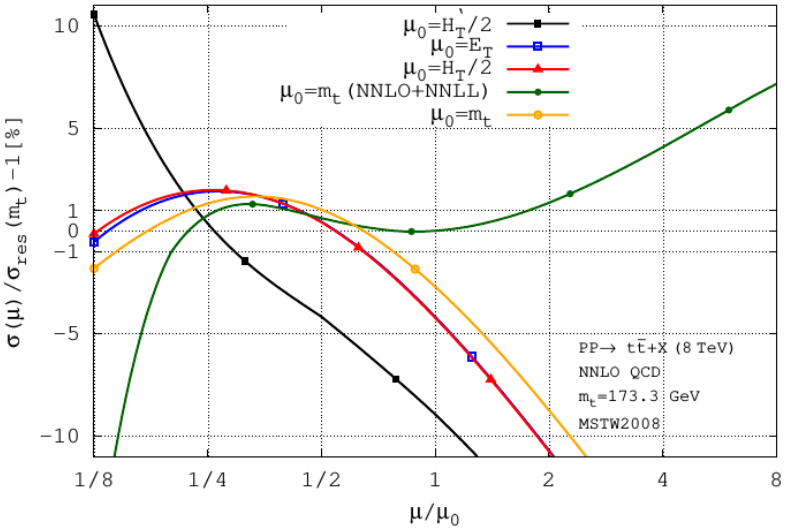


Theory

> New theory calculations:

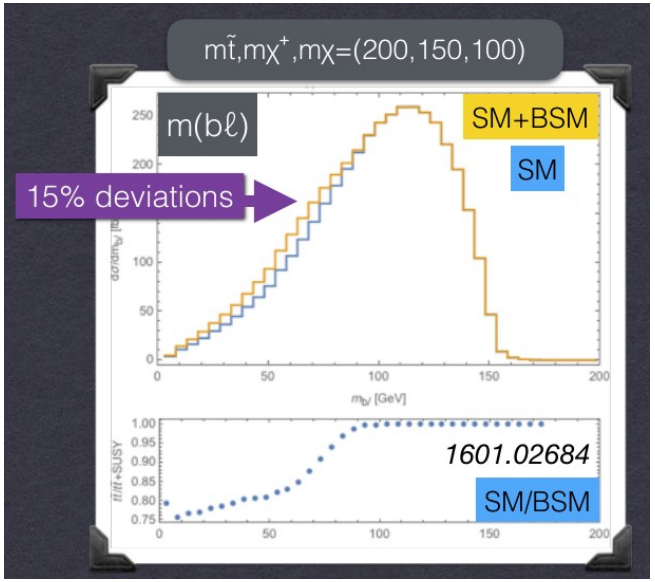
- NNLO calculations with dynamical scales *[arxiv:1606.03350]*
- estimation of off-shell effects:

  → at NLO in QCD for $t\bar{t}$ + jets *[arxiv:1609.01659]*
  → at NLO in EW for $t\bar{t}$ production *[arxiv:1607.05571]*
- single-top at NNLO in QCD with NWA *[arxiv:1606.08463]*



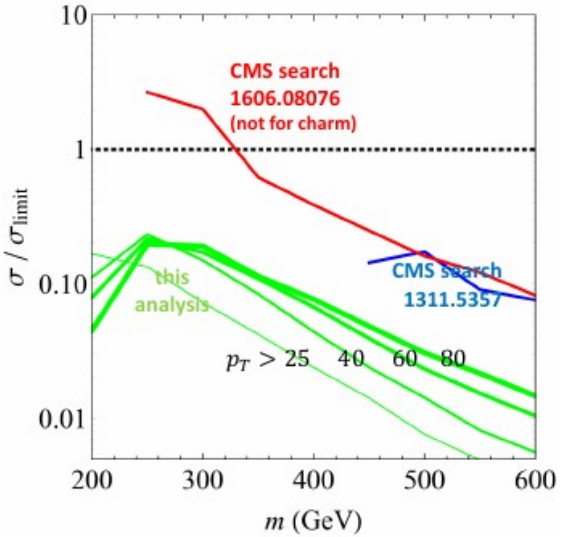
> Suggestions and requests to interpret properties measurement as exclusion

Franceschini

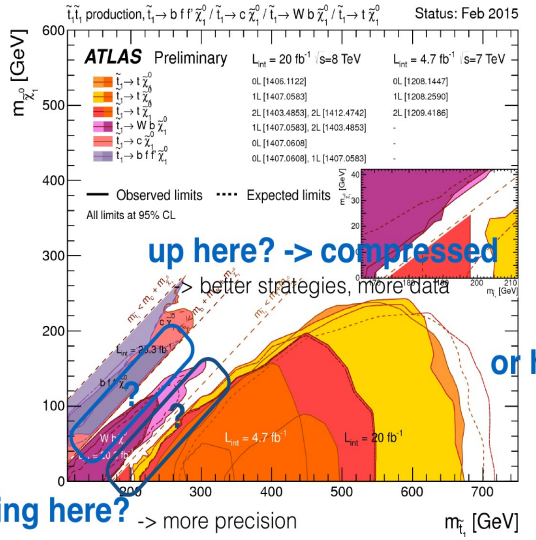


Kats

using $t\bar{t}$ cross section measurements



Weiler

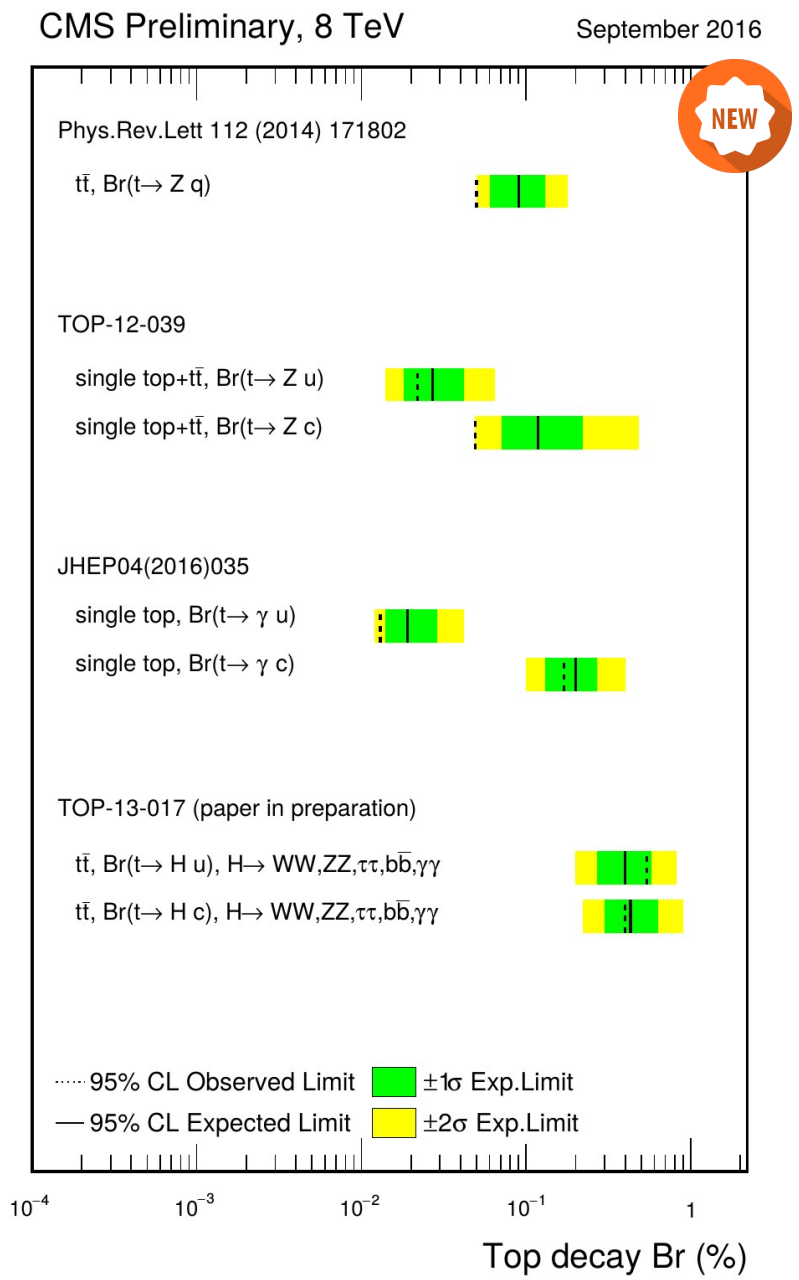


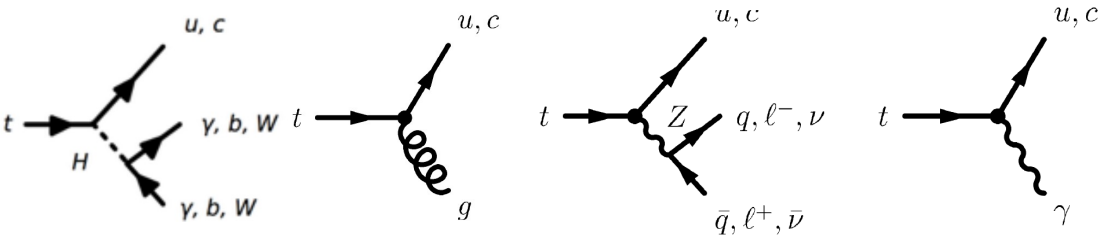
Conclusion

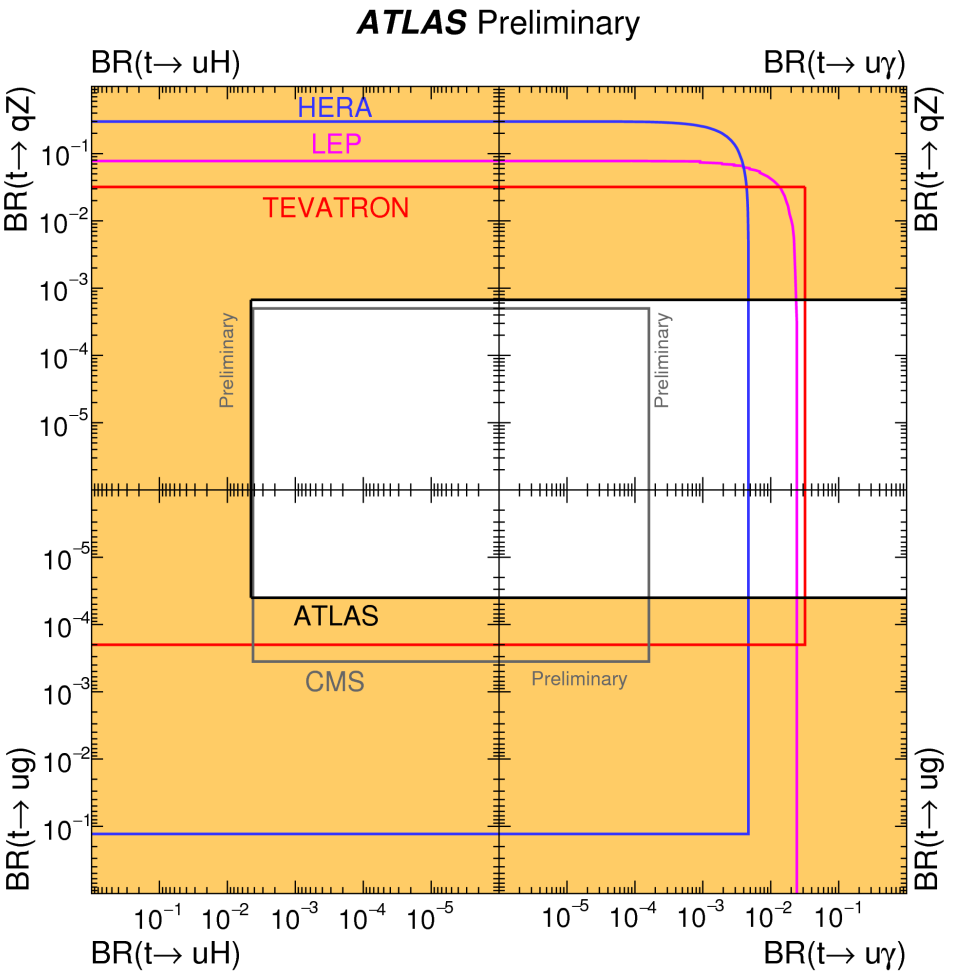
- Very successful conference with **plenty of new results** on top physics
- Great interaction between theorists and experimentalists
- With increased statistics, look into:
  - finer differential or double differential cross sections
  - more complex observables: spin density matrix, Wtb structure (backup), CP violation
  - rare processes: $t\bar{t}V$, four tops, FCNC, tZ (backup)...
  - and more!

Backup

Searches for FCNC



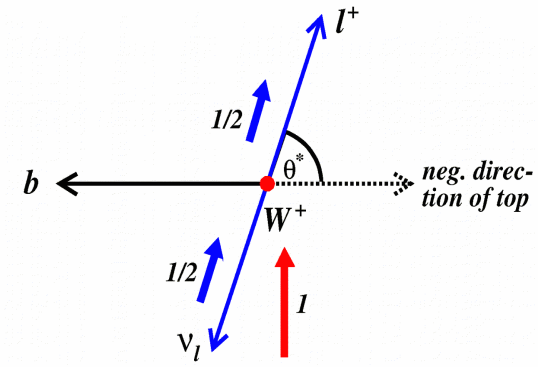


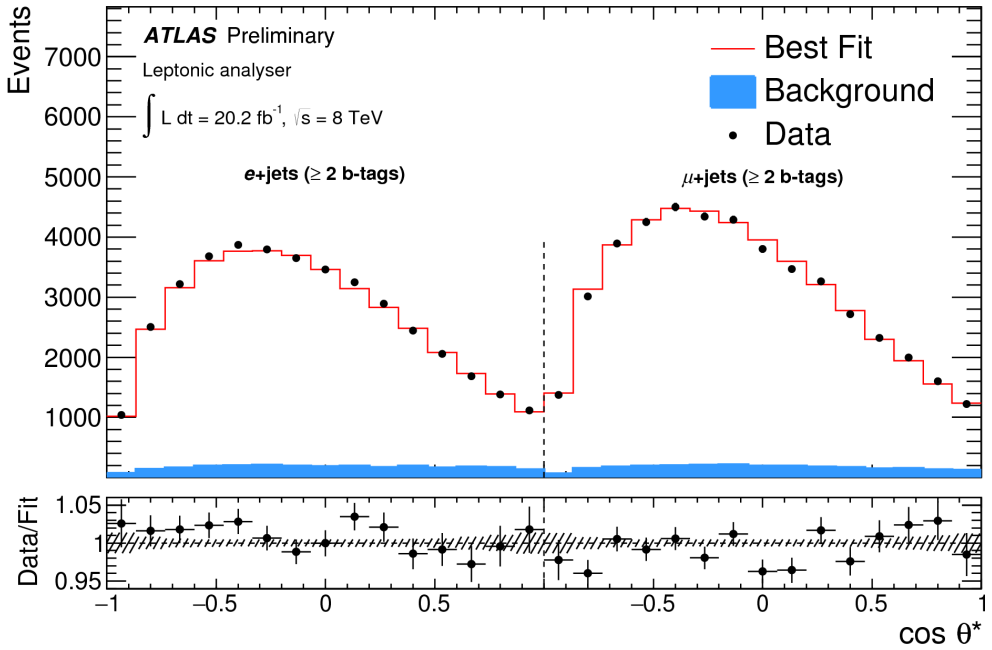


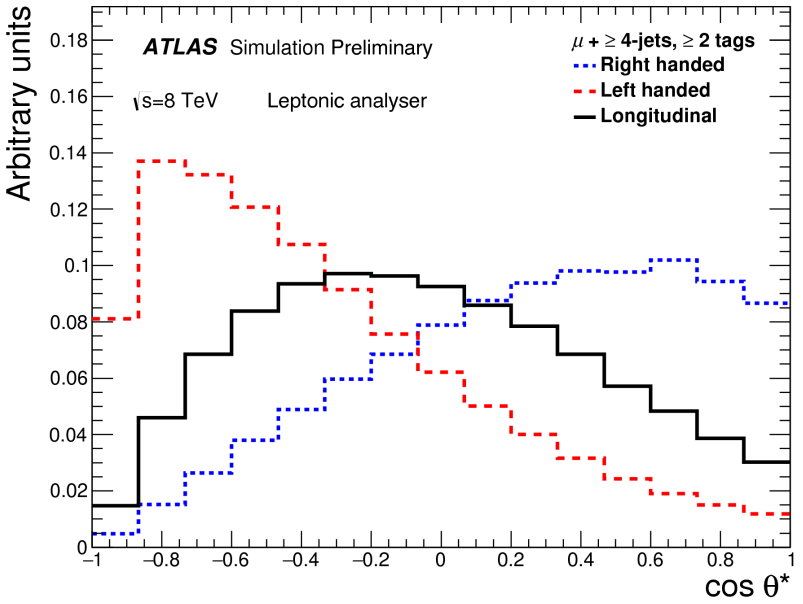
W helicity

NEW

> Extract the fraction of left-, right-handed and longitudinal *W* bosons from the cosθ distribution of leptons and down-type quarks





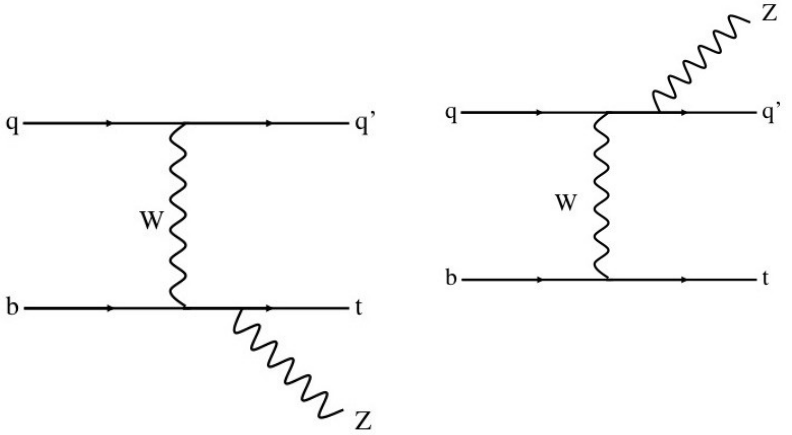


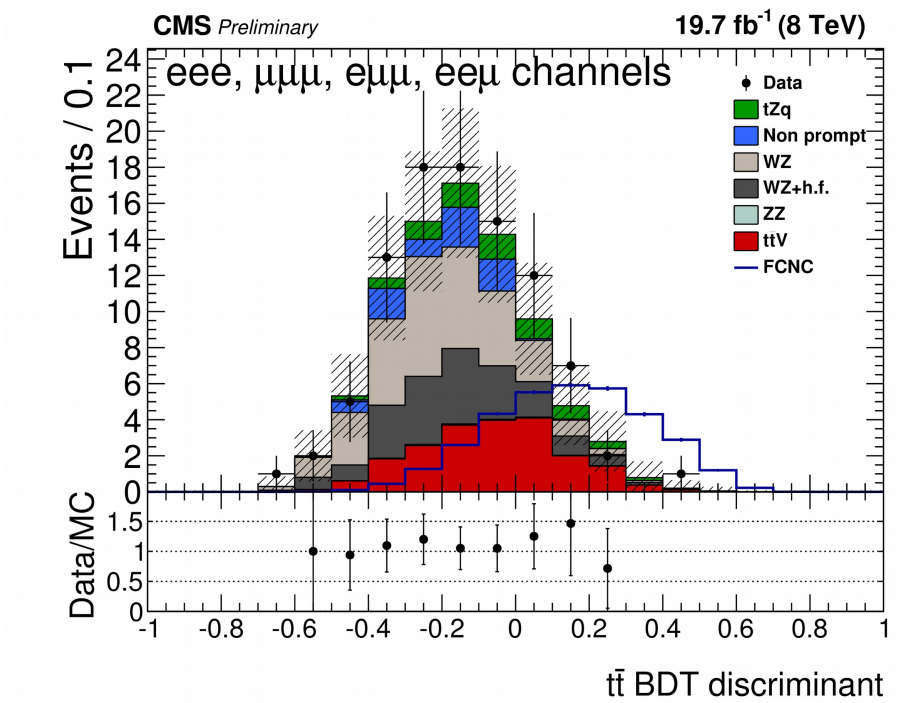
	Results (stat.+bkg. norm.)(syst.)	QCD (NNLO) predictions
F_L	0.299 ± 0.008 ± 0.013	0.311 ± 0.005
F_0	0.709 ± 0.012 ± 0.015	0.687 ± 0.005
F_R	-0.008 ± 0.006 ± 0.012	0.0017 ± 0.0001

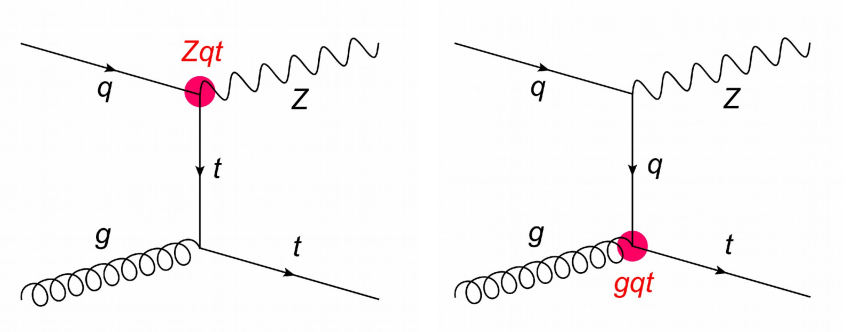
[TOPQ-2016-02]

Rare processes - *tZ*

- Single-top produced in association with a Z
  - rare process sensitive to WWZ coupling
  - important test of the SM
- New result from CMS *[CMS-PAS-TOP-12-039]*
  - final states with 3 leptons + 1 jet considered
  - result: $\sigma(tZq \rightarrow \ell\nu b\ell^{+}\ell^{-}q) = 10^{+8}_{-7}$ fb (2.4σ)
  - exclusion limits derived on FCNC





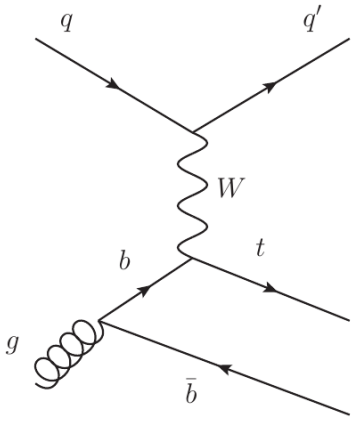


Branching ratio	Expected	1σ range	2 σ range	Observed
$\mathcal{BR}$(t→ Zu) (%)	0.027	0.018-0.042	0.014-0.065	0.022
$\mathcal{BR}$(t→ Zc) (%)	0.118	0.071-0.222	0.049-0.484	0.049

Single top – Wtb vertex

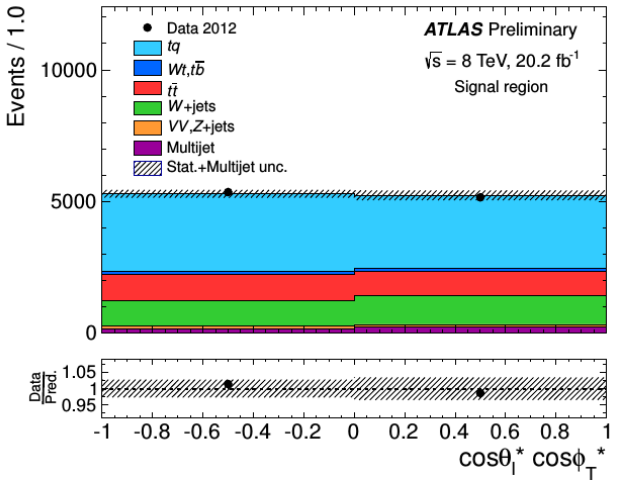
> Probe Wtb structure at 8 TeV using the single top t-channel *[ATLAS-CONF-2016-097]*

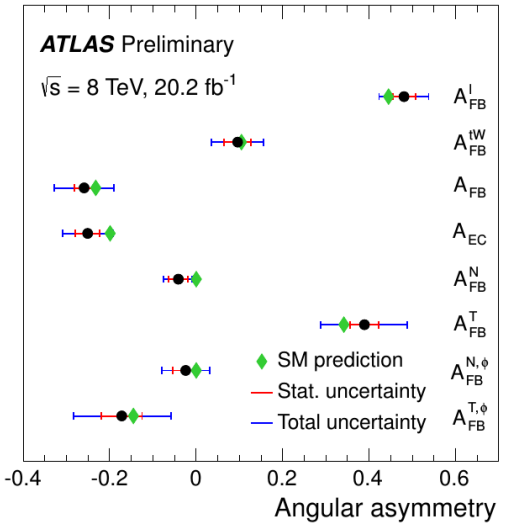
- spins of tops produced in the t-channel are expected to be very correlated with the one of the spectator quark (~0.9)
- define many angular observables, unfold their distributions and compute asymmetries



$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_X)} = \frac{1}{2}(1+\alpha_X P\cos\theta_X)$$

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W\cos\theta_\ell^*$	$\frac{3}{8}P\,(F_{\mathrm{R}}+F_{\mathrm{L}})$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}\,(F_{\mathrm{R}}-F_{\mathrm{L}})$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}\,(1-3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{\mathrm{FB}}^{T,\phi}$	$\cos\theta_\ell^*\cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{\mathrm{FB}}^{N,\phi}$	$\cos\theta_\ell^*\cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0





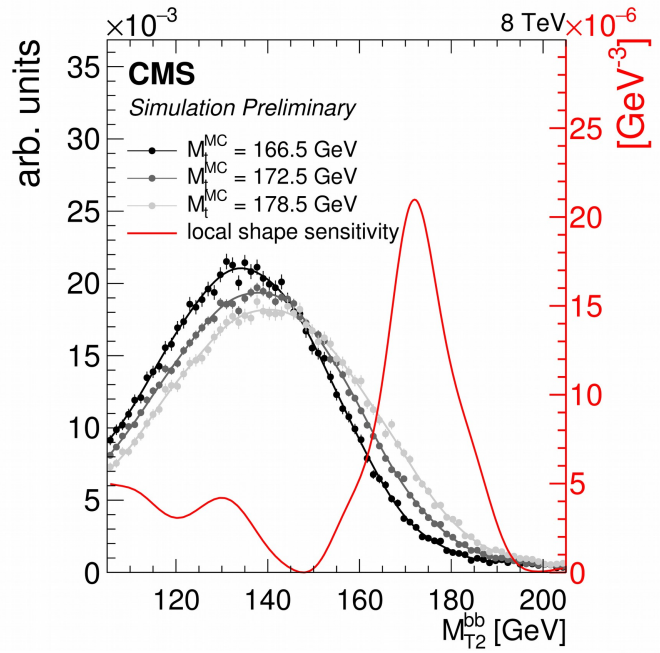
Spin/polarisation

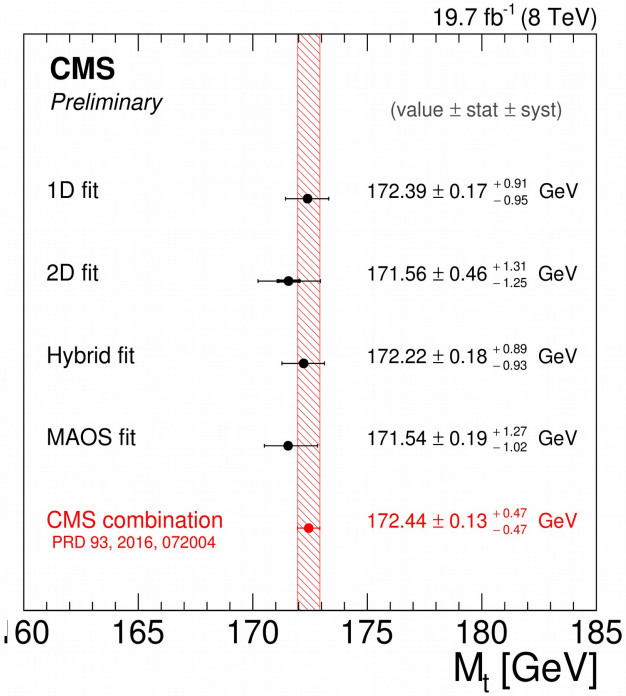
> Summary of existing measurements of top pair produced polarisation and spin correlations

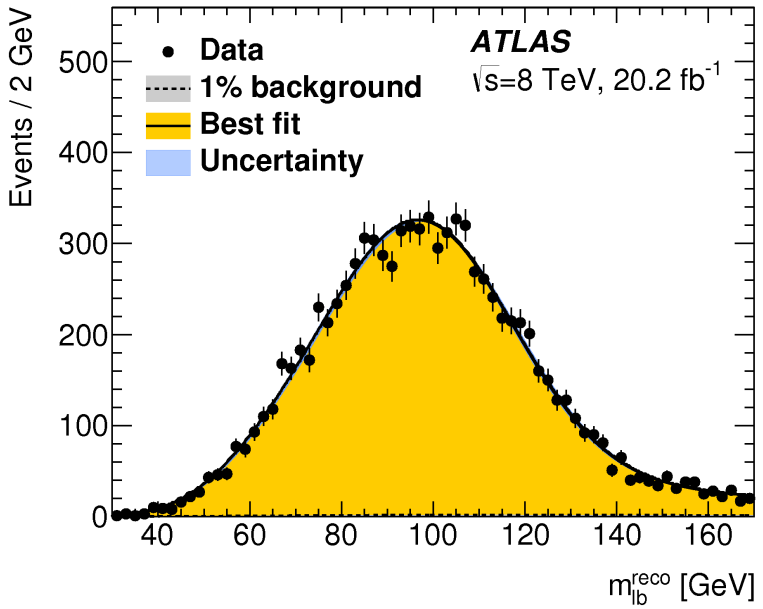
Experiment	$\sqrt{s}$	Method	B_+^k	B_-^k	$C(k,k)$	B_+^n	B_-^n
ATLAS	8 TeV	Unfolding	-0.044 ± 0.038	-0.064 ± 0.040	0.296 ± 0.093	-0.018 ± 0.034	0.023 ± 0.042
CMS [17]	8 TeV	Unfolding	-0.022 ± 0.058		0.278 ± 0.084	-	-
ATLAS [12]	7 TeV	Template fit	-0.035 ± 0.040		-	-	-
ATLAS [11]	7 TeV	Template fit	-	-	0.23 ± 0.092	-	-
ATLAS [13]	7 TeV	Unfolding	-	-	0.315 ± 0.078	-	-
D0 [18]	1.96 TeV	Template fit	-0.102 ± 0.061		-	0.040± 0.034	

Mass measurements

- Using the $M_{b\ell}$, M_{T2} and $M_{b\ell\nu}$ observables at CMS
  [CMS-PAS-TOP-15-008]





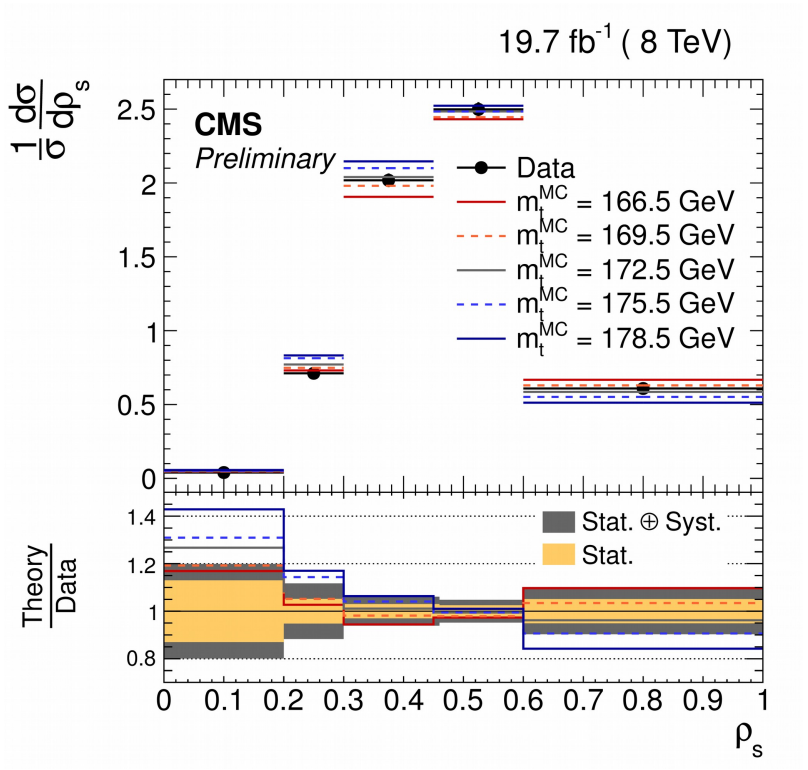


- in the $\ell\ell$ channel in ATLAS
  [PLB 761 (2016) 350]

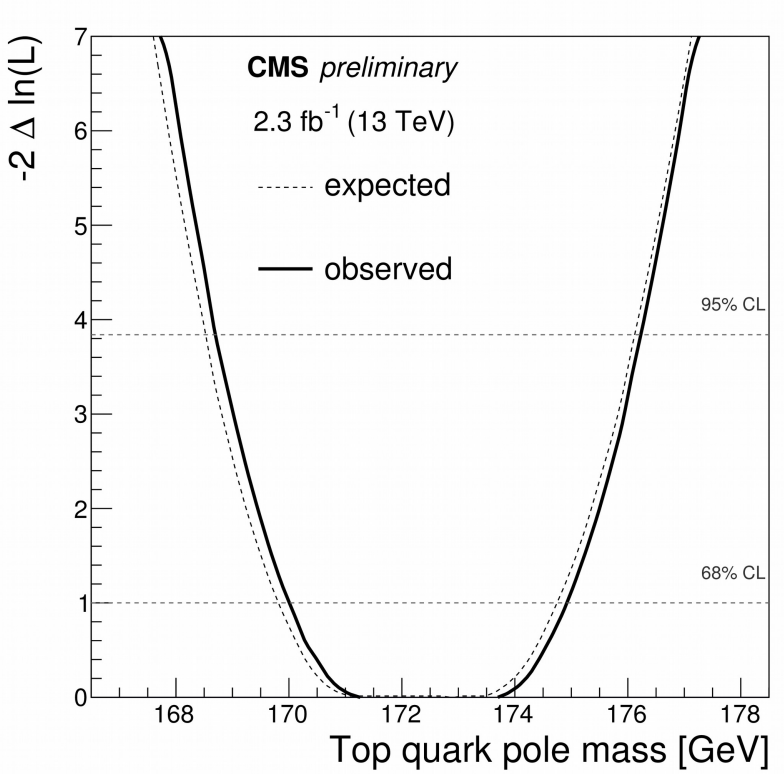
→ combination with 7 TeV $\ell\ell$ and ℓjets measurements:
$m_t = 172.84 \pm 0.34$ (stat) ± 0.61 (syst) GeV

Mass measurements

- using the normalised invariant mass distribution of $t\bar{t}$+jet *[CMS-PAS-TOP-13-006]*



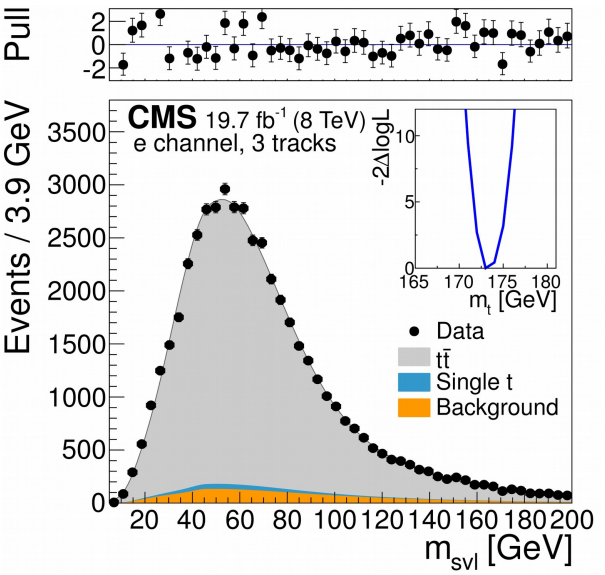
> Result:
> $m_t = 169.9 \pm 1.1\ (\text{stat})\ ^{+2.5}_{-3.1}\ (\text{syst})\ ^{+3.6}_{-1.6}\ (\text{theo})$ GeV

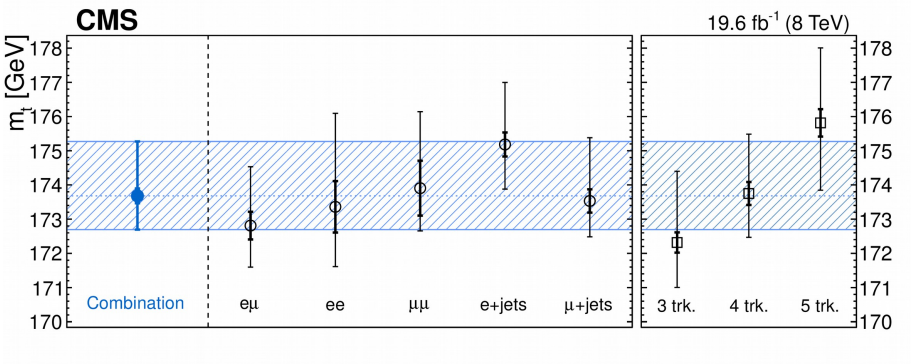


- from the inclusive cross section in the ljets channel at CMS *[CMS-PAS-TOP-16-006]*

Mass measurements

- using charged particles *[PRD 93 (2016) 092006]*



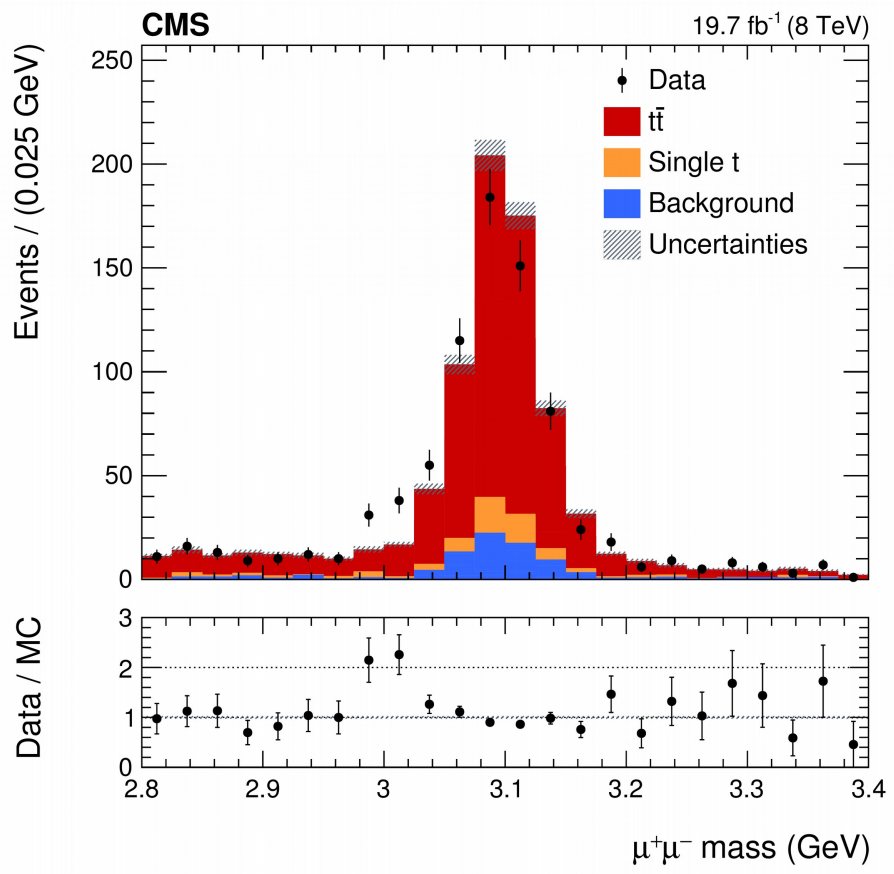


Mass from decays with J/Ψ mesons - CMS

> Selection:

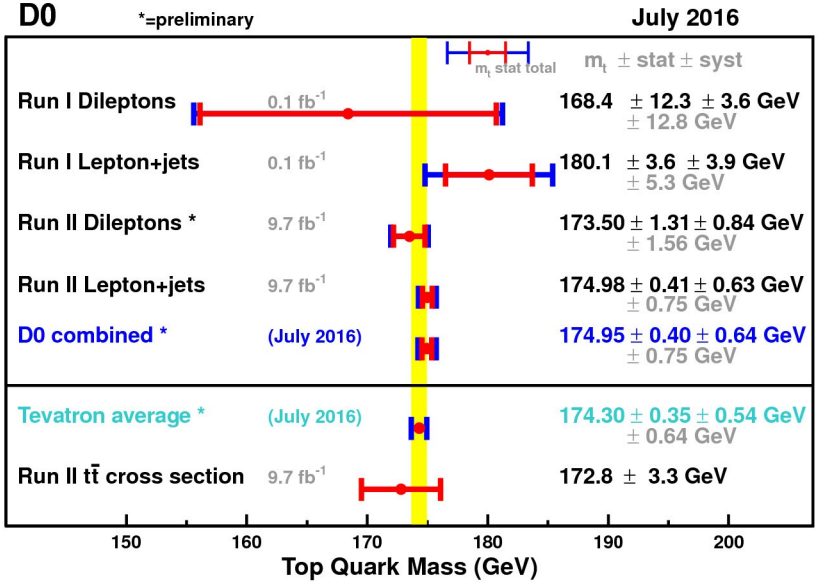
- ljets or dilepton events, Z-veto, mll $>$ 20 GeV, at least two jets
- ==1 J/Ψ candidate with 2 muons of opposite sign, pT>4 GeV, 3.0 $<$ mll $<$ 3.2 GeV

Process	Number of events	
	Leading μ	Leading e
$t\bar{t} \to b\ell^-\bar{\nu}\bar{b}q\bar{q}'$	228.1 ± 4.0	195.6 ± 3.7
$t\bar{t} \to b\ell^-\bar{\nu}\bar{b}\ell^+\nu$	66.3 ± 1.7	56.9 ± 1.6
$t\bar{t} \to b\bar{q}q'\bar{b}q\bar{q}'$	negligible	negligible
Single top quark	39.4 ± 3.8	30.6 ± 3.3
$PW \to \ell\nu +$ jets	18.3 ± 3.2	12.1 ± 2.7
$Z/\gamma^* \to \ell^+\ell^- +$ jets	4.5 ± 0.9	6.3 ± 1.0
WW, WZ, ZZ	1.1 ± 0.3	1.2 ± 0.3
Predicted yield	357.7 ± 6.6	302.7 ± 5.9
Data	355	311



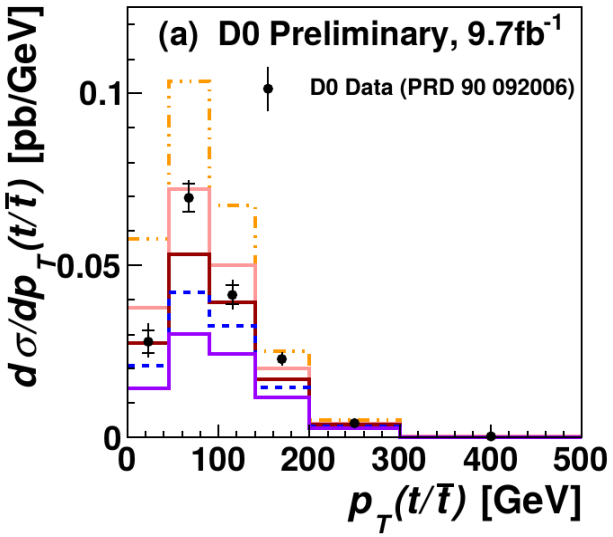
Mass measurements at the Tevatron

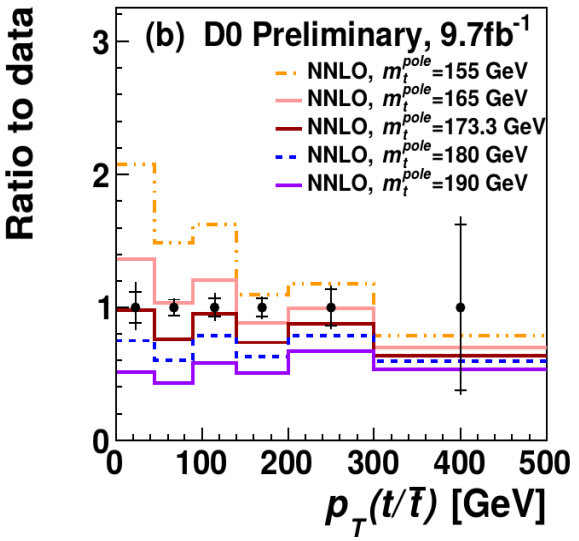
- Direct measurements from D0:
  - matrix element method in the dilepton channel *[PRD 94, 032004 (2016)]*
  - combination *[D0 note 6485]*

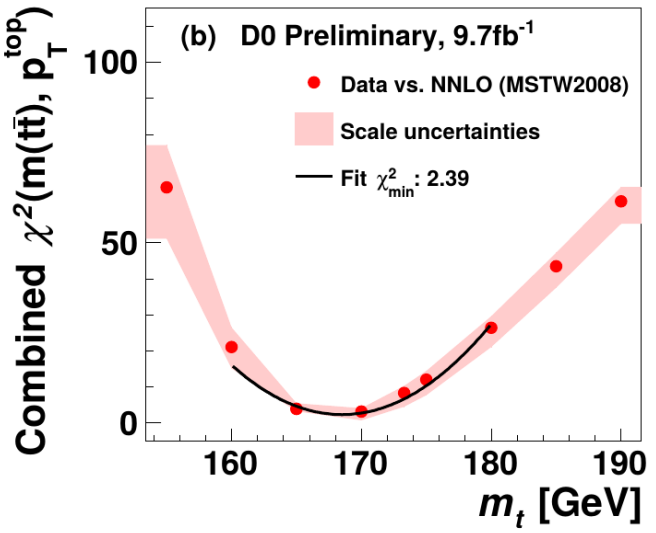


- Pole mass extraction from the inclusive cross-section *[arXiv:1605.06168]*
- Extraction from differential cross section measurements *[D0 note 6473]*
  - novel technique using NLO and NNLO calculations
  - result: $m_t = 169.1 \pm 2.5$ (tot.) $[\pm 2.2$ (exp.) ± 0.8 (scale) ± 1.2 (PDF)$]$ GeV

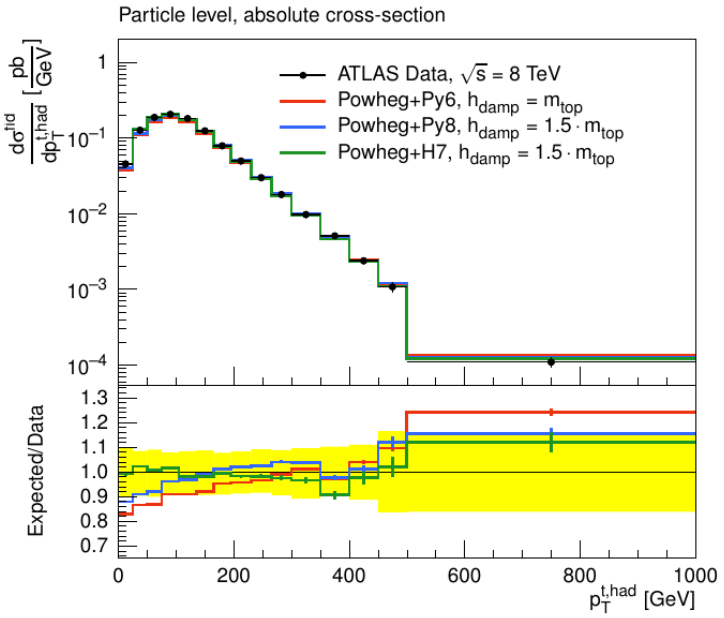
1st NEW







MC modelling



> Public note on top MC modelling *[ATL-PHYS-PUB-2016-020]*

- extensive study of generator and parton shower setups
  $\rightarrow$ improve Powheg+Pythia8 or Herwig7 modelling
- new method to deal with interferences in Wt production