Overview of top quark physics at the LHC

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FOR WORKSHOP ON TOP QUARK PHYSICS AT THE LC 2016

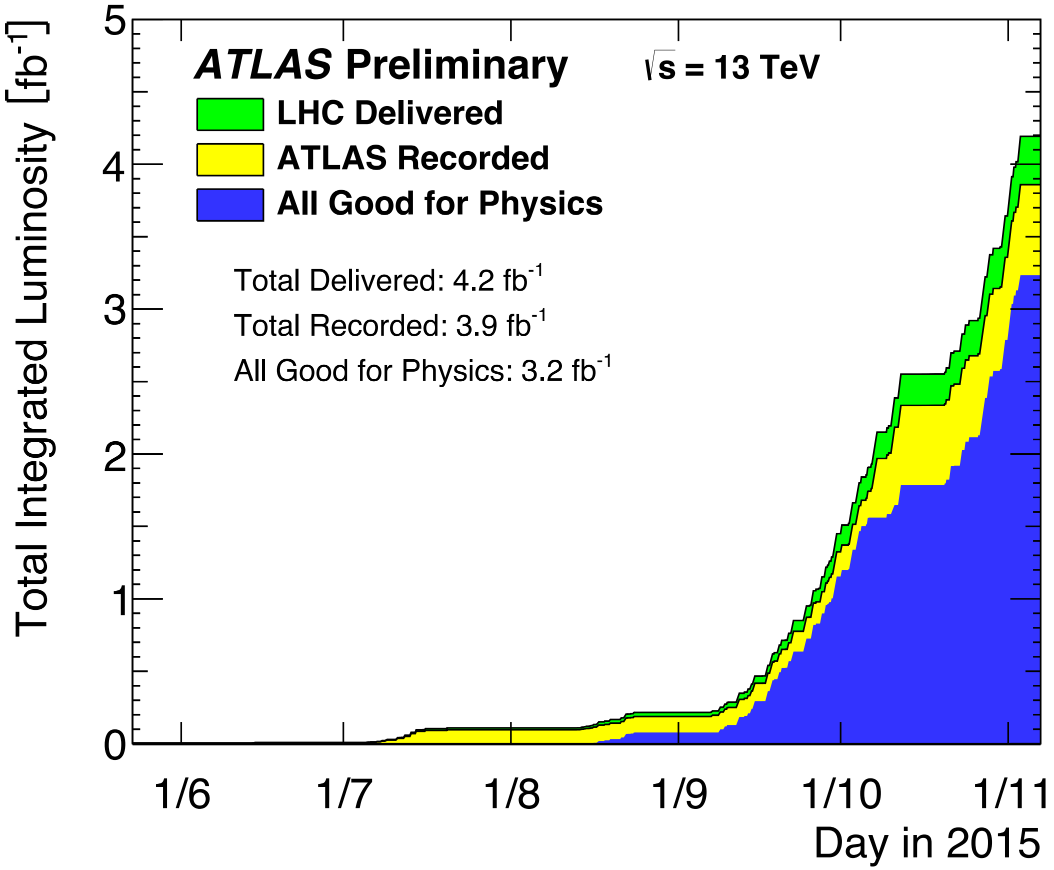
6 JULY, 2016, AT KEK, TSUKUBA

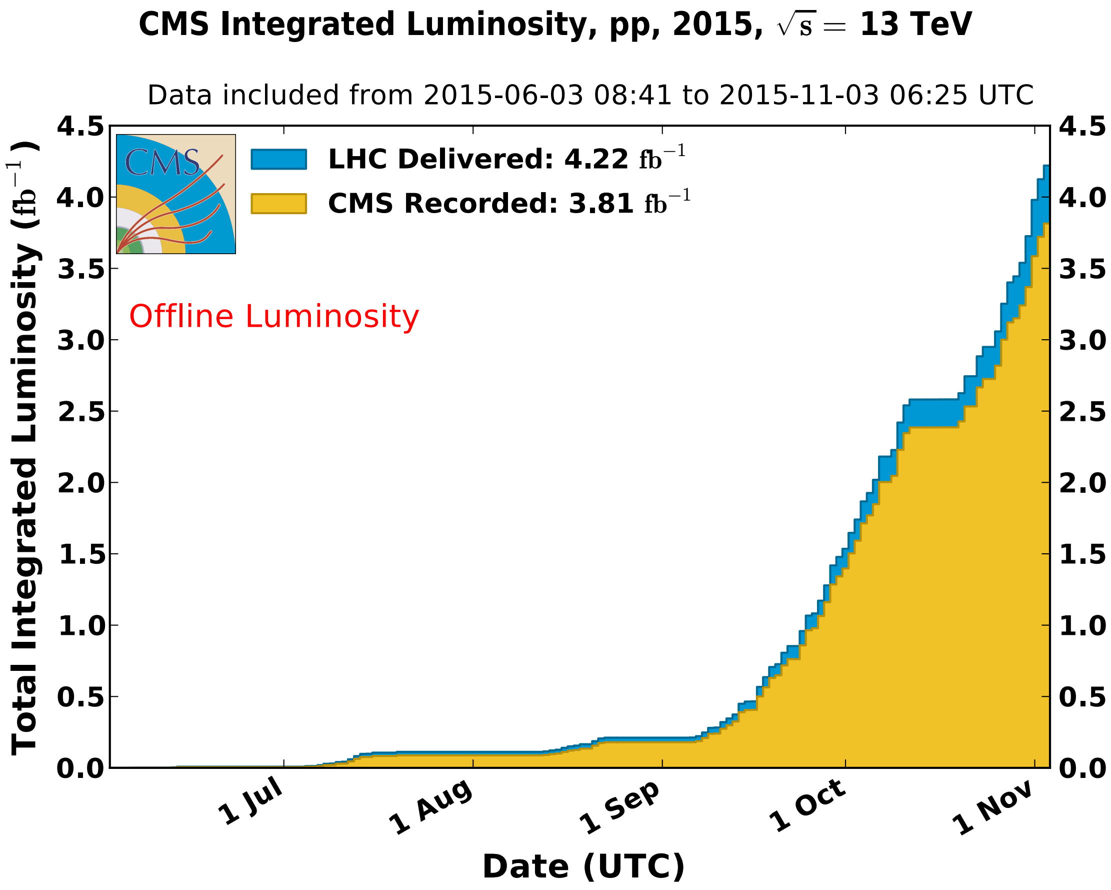
Introduction

- LHC luminosity and status
- ATLAS and CMS results (7,8 and 13 TeV)
  - Top quark cross section & mass
  - Rare processes
  - $t\bar{t}$+others (Z,W,H)
- LHCb top quark observation at 7 and 8 TeV
- Conclusion

LHC luminosity in 2015

13 TeV

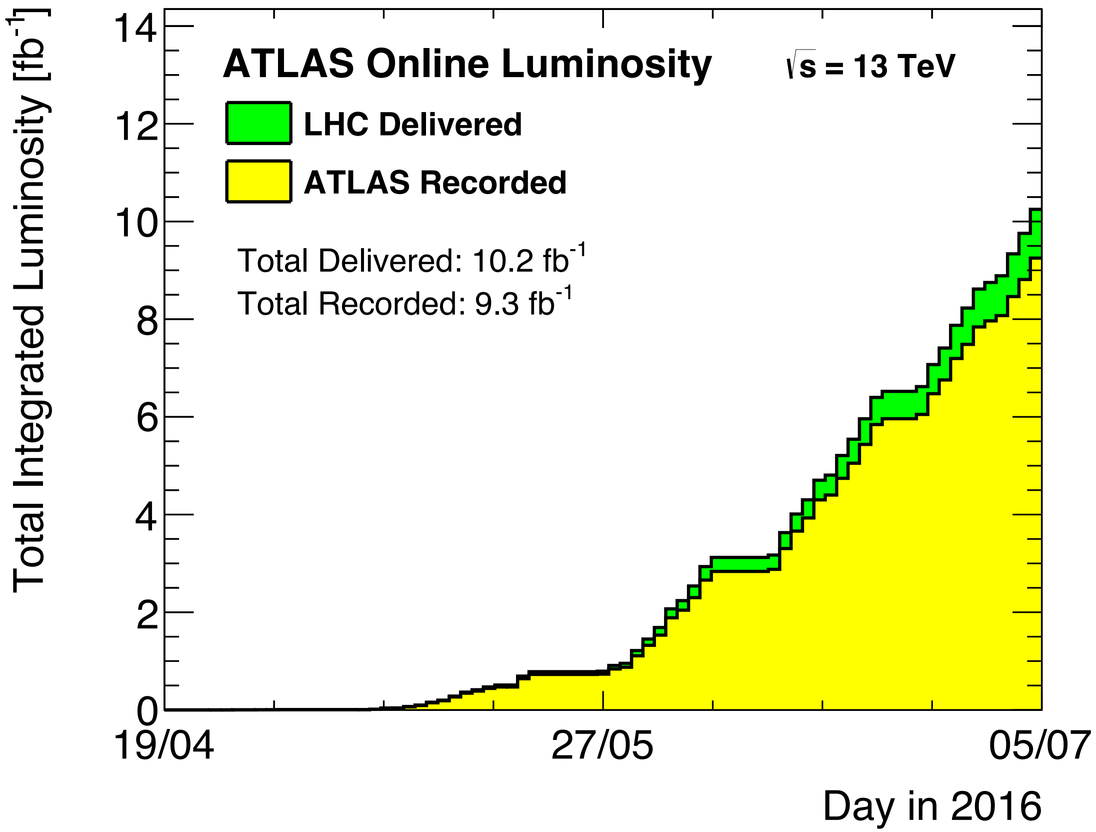


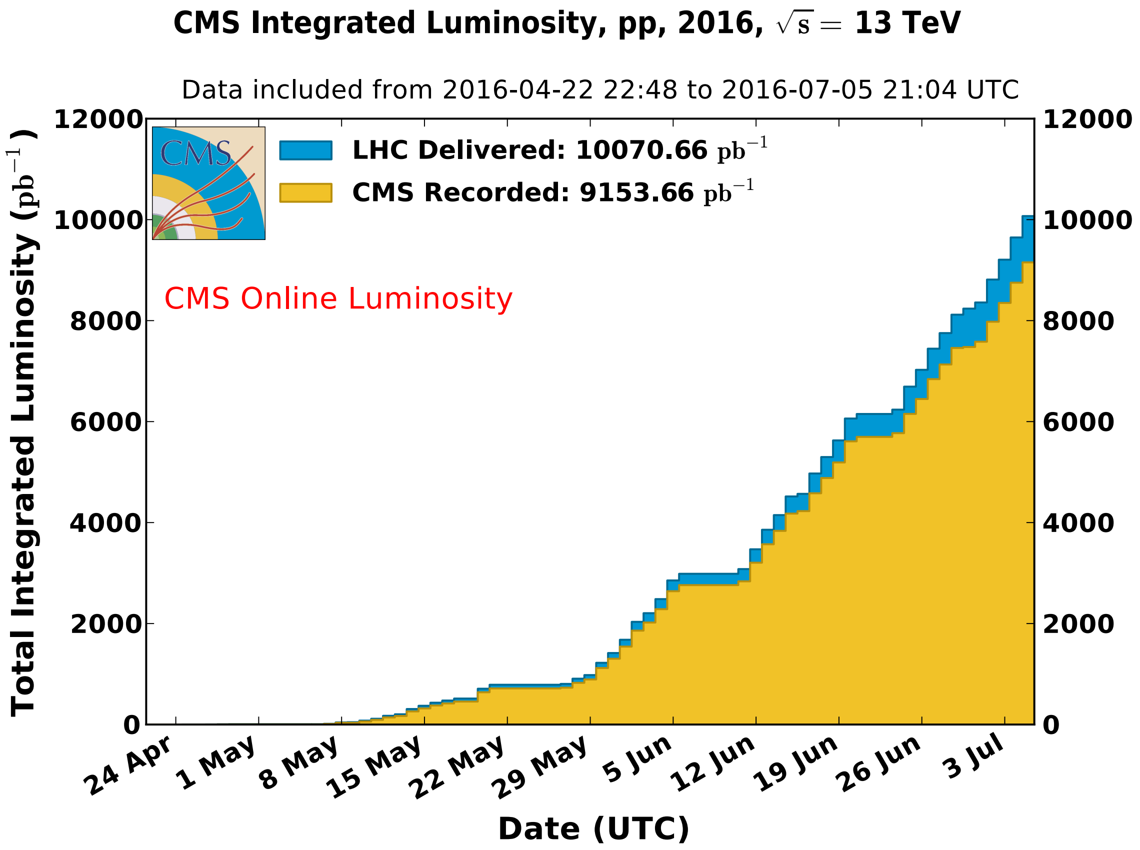


- All 13 TeV results in this talk are based on these data sets.

LHC status in 2016

13 TeV

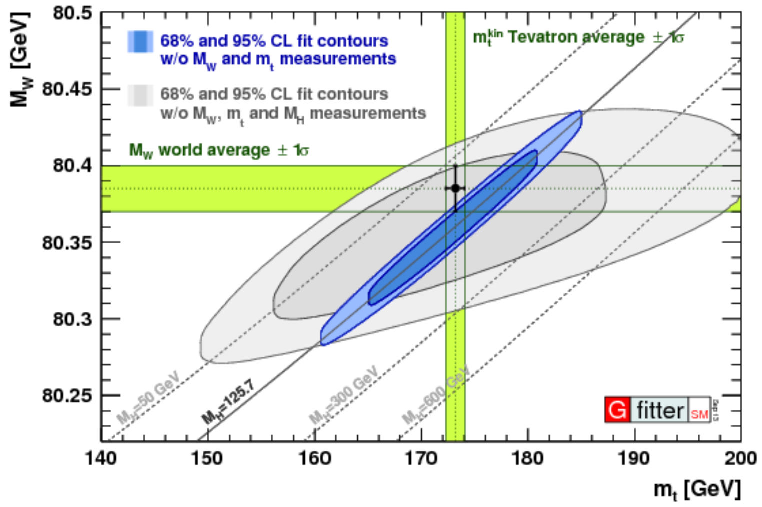


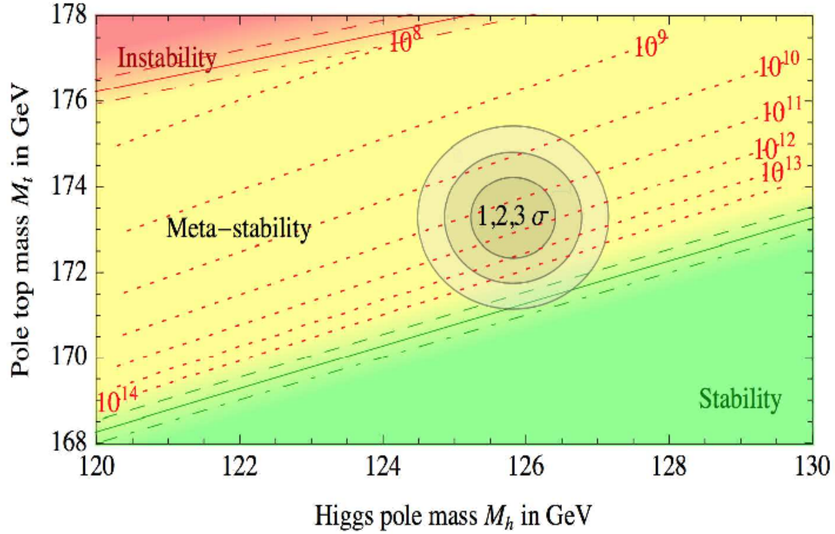


- ATLAS and CMS are in good shape!
- New results will be available soon!

Motivation

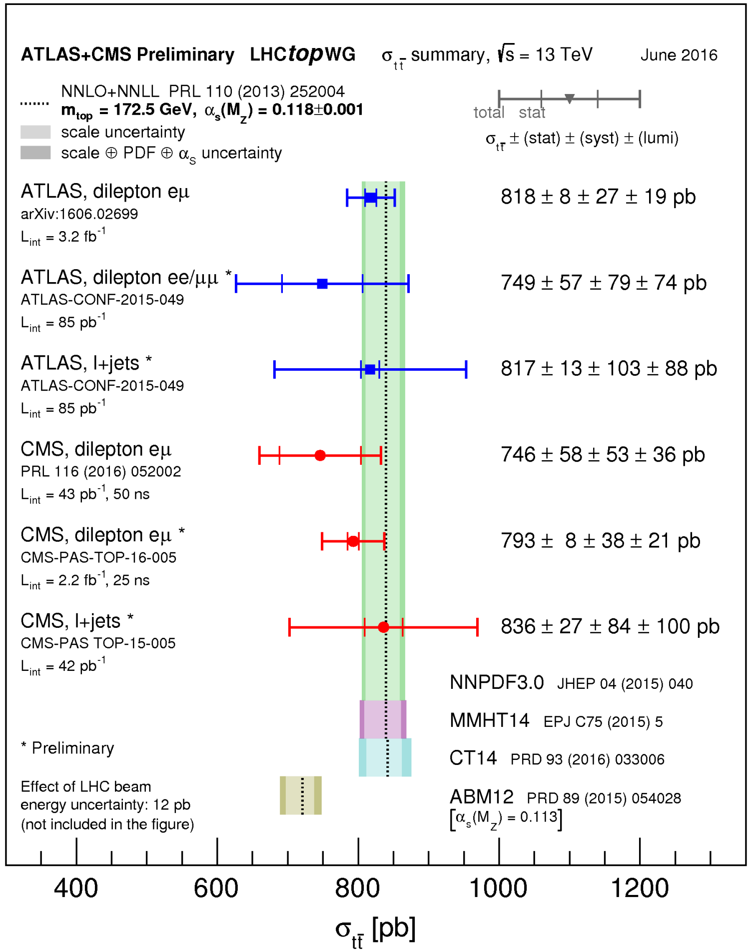
- Top quark mass is an important parameter of the standard model.
- Precise measurements of top quark mass provide critical inputs to the fits of global electroweak parameters.
- Internal consistency check with the SM.
- Affect the stability of the SM Higgs potential.
- To check the validity of perturbative QCD.
- Main background for new physics (possible deviation due to new physics)

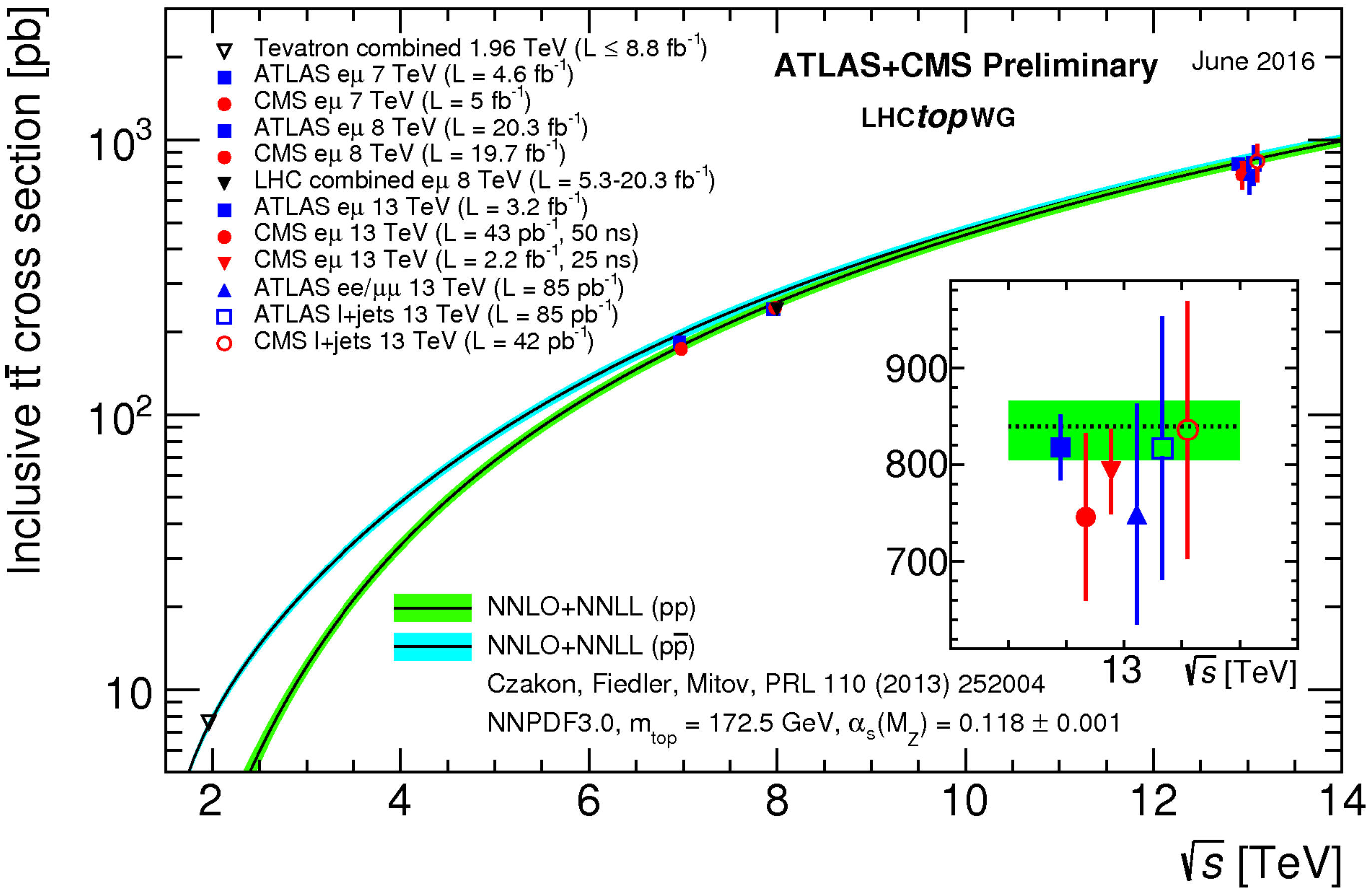




Top quark Pair production cross section

13 TeV

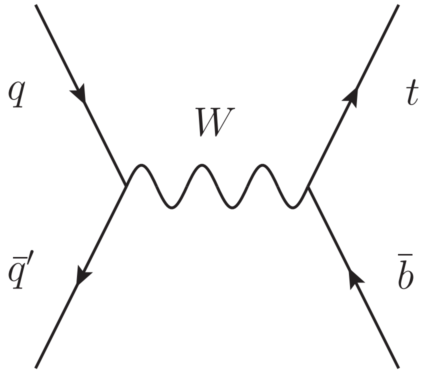


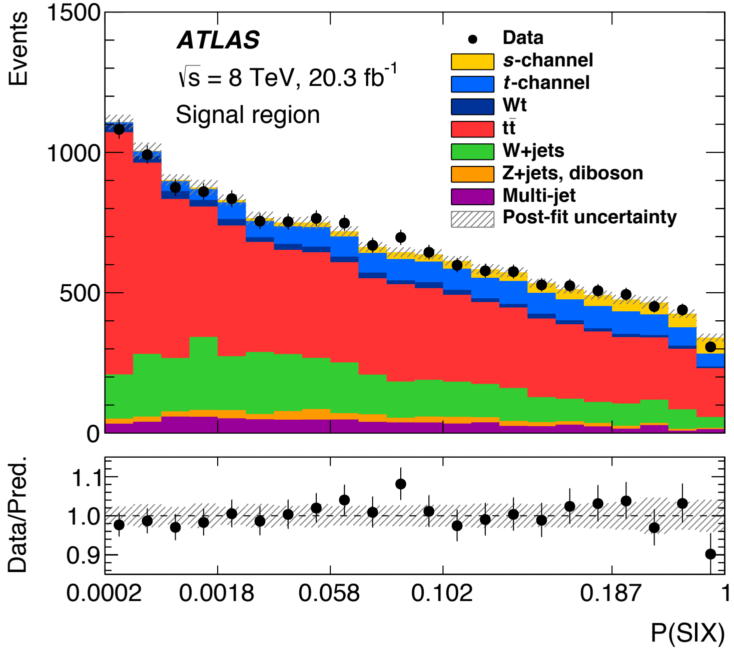


Single top production (s-channel)

8 TeV

PLB 756 (2016) 229-246



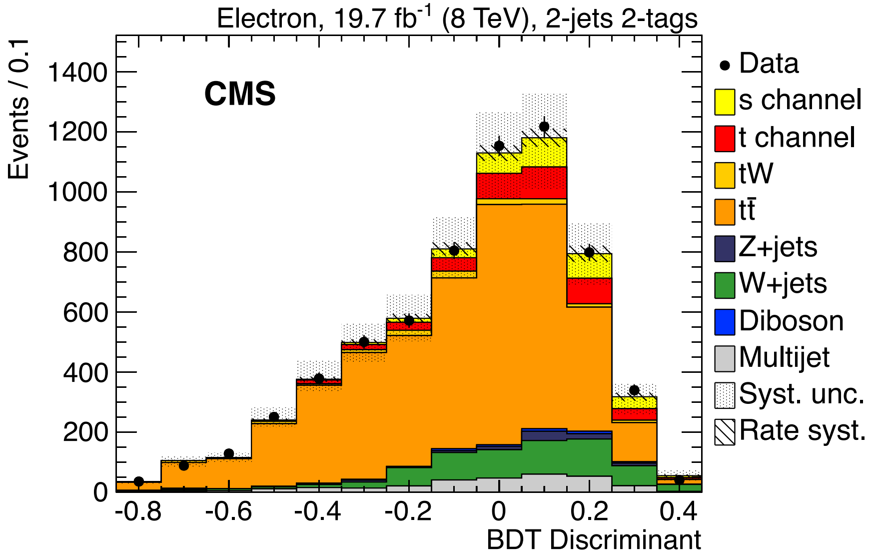


$$\sigma_s = 4.8 \pm 0.8\,(stat.)^{+1.6}_{-1.3}\,(syst.)\ \text{pb}$$

3.9 σ

arXiv:1603.02555

7+8 TeV

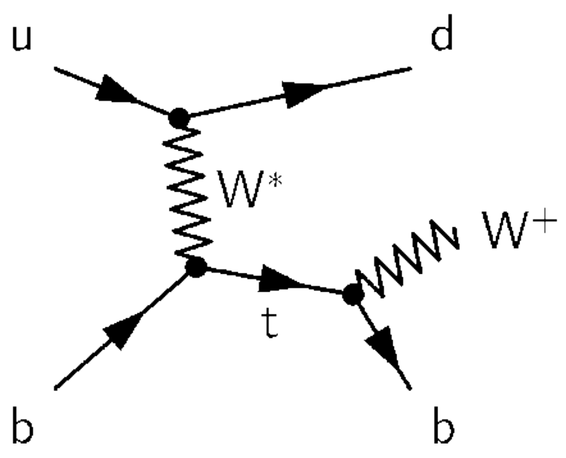


$$\sigma_s^{7\,TeV} = 7.1 \pm 8.1\ \text{pb}$$

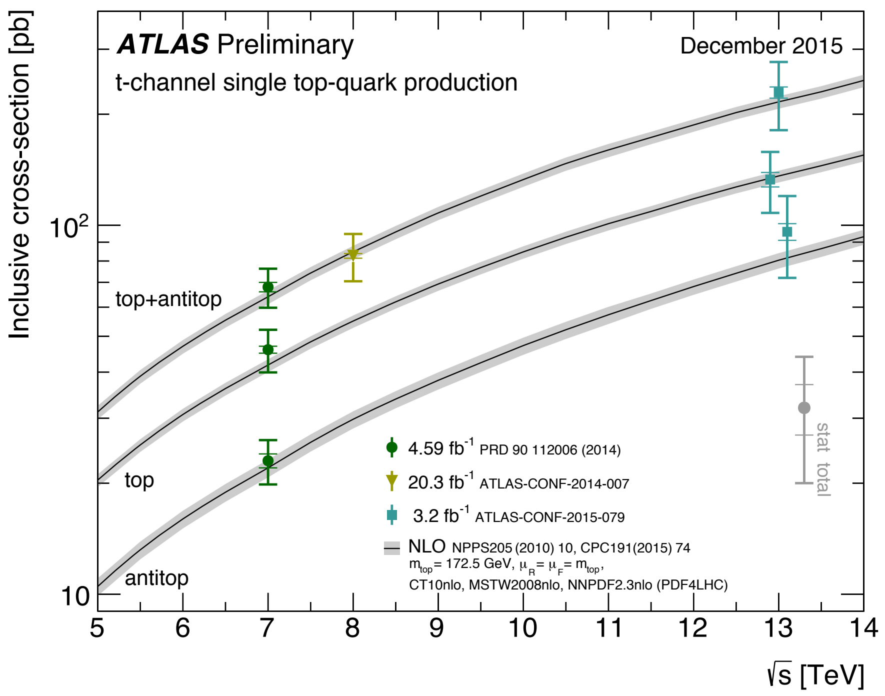
$$\sigma_s^{8\,TeV} = 13.4 \pm 7.3\ \text{pb}$$

Significance for combination = 2.5 σ

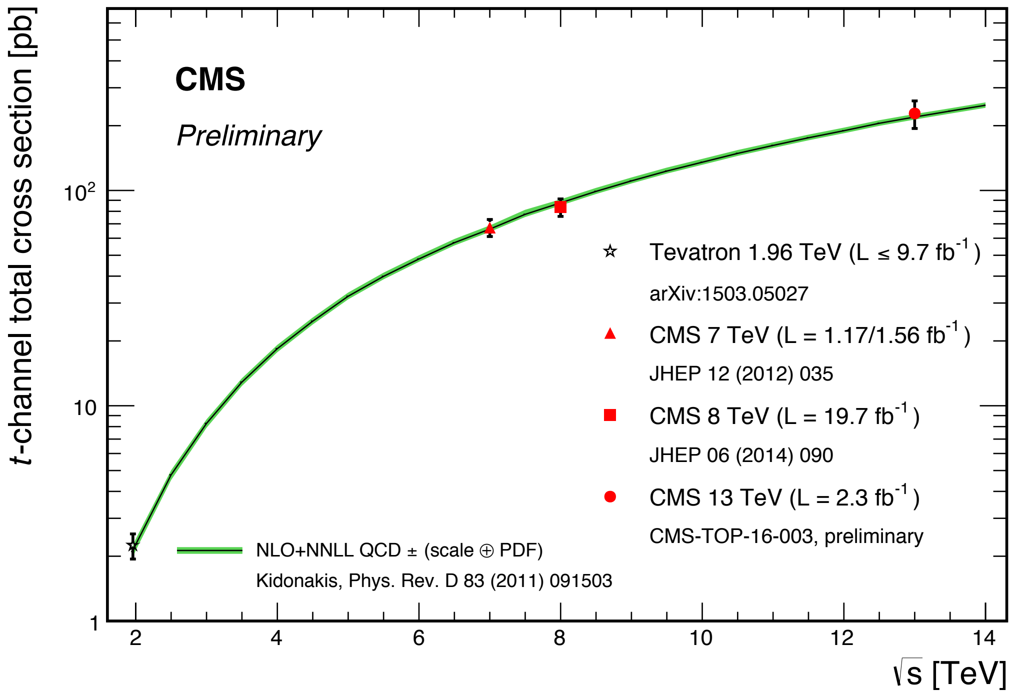
Single top production (t-channel)



ATLAS-CONF-2015-079



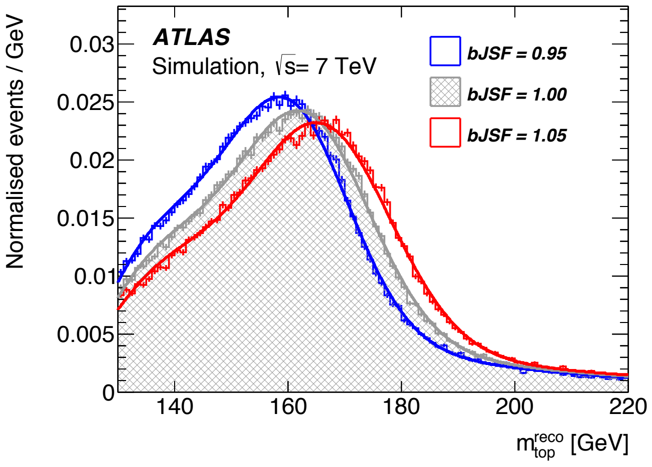
CMS-PAS-TOP-16-003

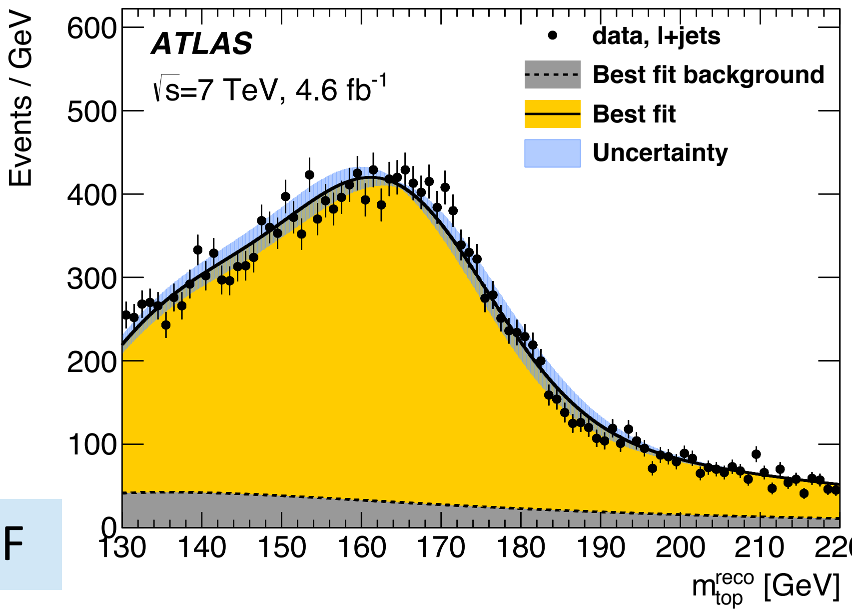


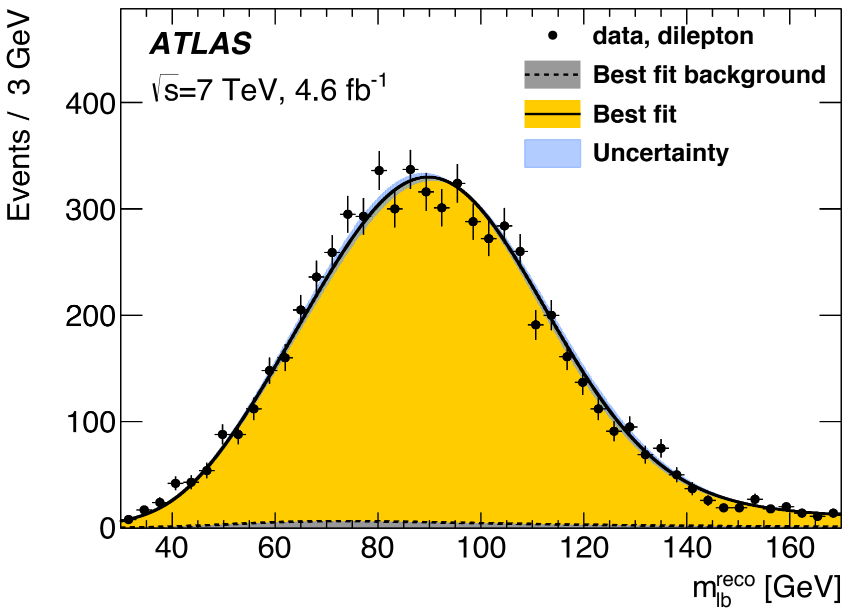
Mass measurement

7 TeV

Eur. Phys. J. C (2015) 75:330







3D fitting for m_{top}, JSF and bJSF

- m_{top}^{reco}, m_W^{reco}, R_{bq}^{reco} (ratio b jet / light jet) for the fitting in lepton+jet while m_{lb}^{reco} in dilepton.

$$m_{\text{top}}^{\ell+\text{jets}} = 172.33 \pm 0.75\ (\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.02\ (\text{syst})\ \text{GeV},$$

$$m_{\text{top}}^{\text{dil}} = 173.79 \pm 0.54\ (\text{stat}) \pm 1.30\ (\text{syst})\ \text{GeV}$$

$$m_{\text{top}}^{\text{comb}} = 172.99 \pm 0.48\ (\text{stat}) \pm 0.78\ (\text{syst})\ \text{GeV} = 172.99 \pm 0.91\ \text{GeV}.$$

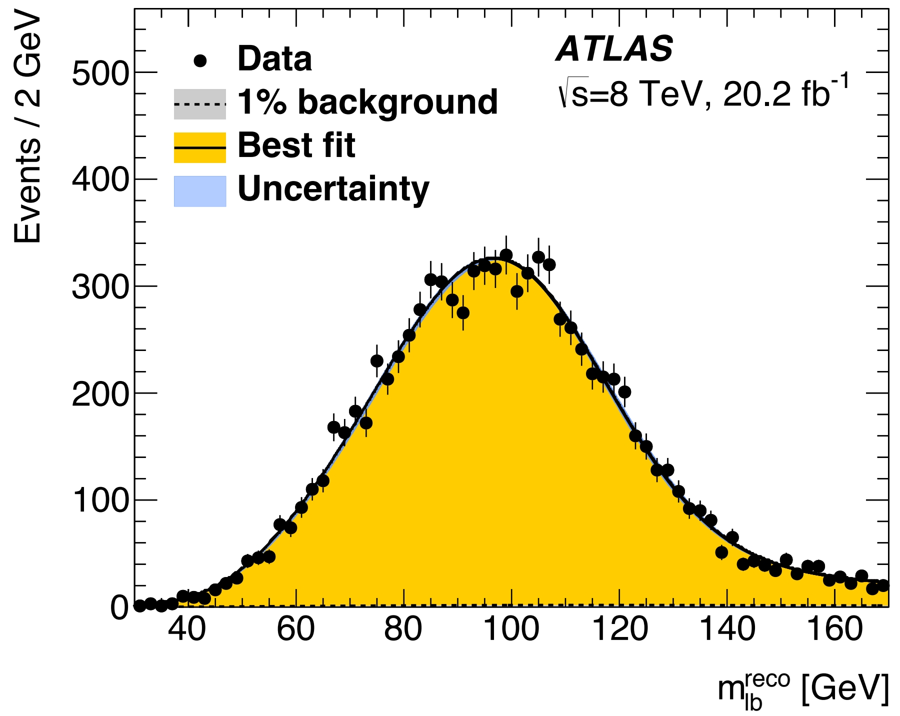
total 0.5%

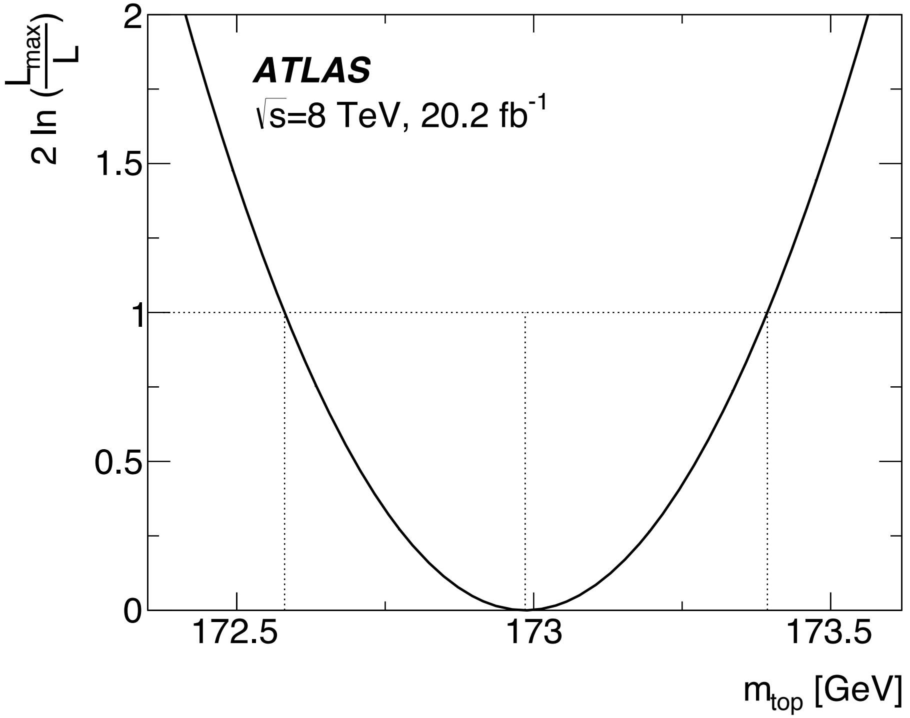
main uncertainties : hadronization, JES, bJES (not for lepton+jet due to 3D fit)

Mass measurement

7 and 8 TeV

arXiv:1606.02179





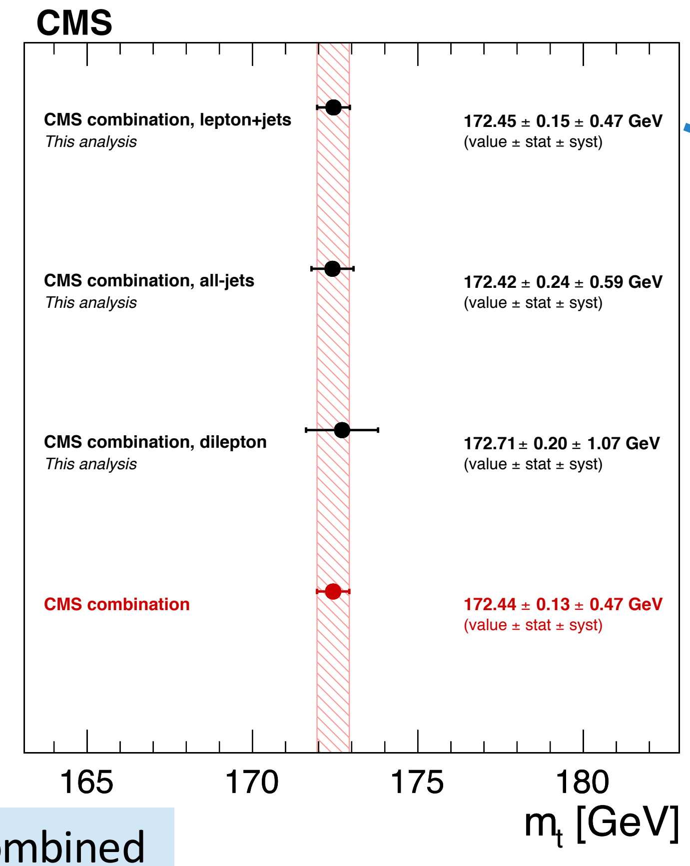
8 TeV $m_{top} = 172.99 \pm 0.41\ (\text{stat}) \pm 0.74\ (\text{syst})\ \text{GeV}$

7+8 TeV $m_{top} = 172.84 \pm 0.34\ (\text{stat}) \pm 0.61\ (\text{syst})\ \text{GeV}$ total 0.4%

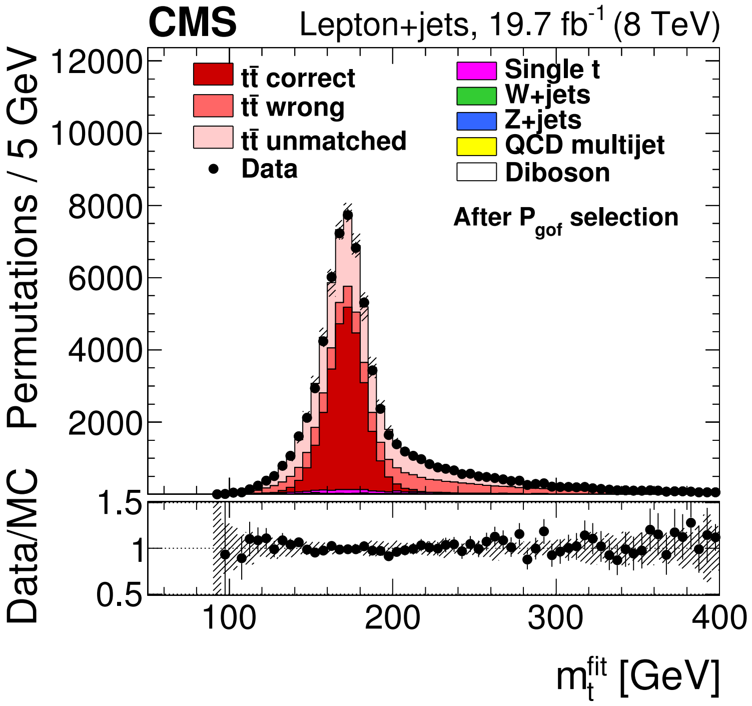
Mass measurement

7 and 8 TeV

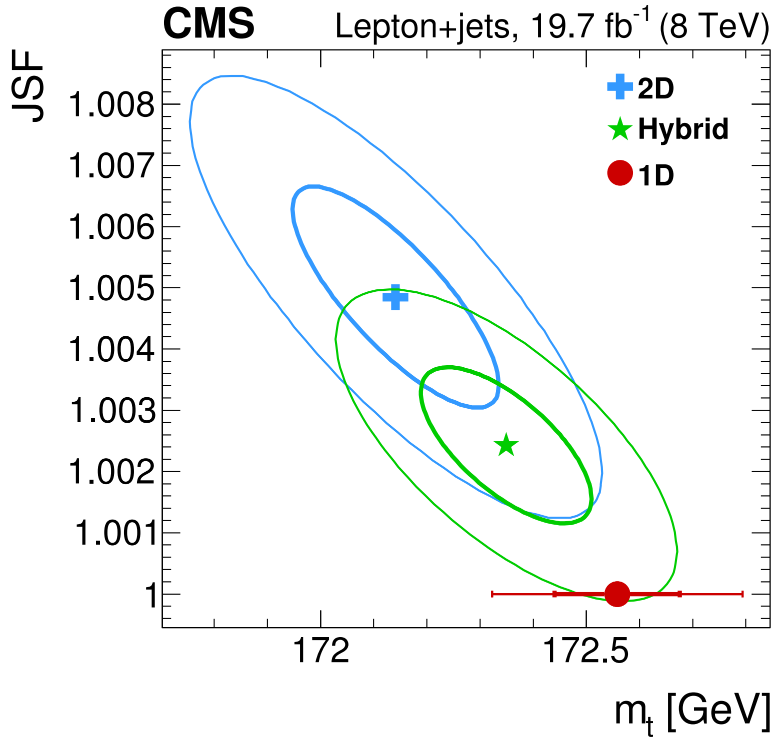
CMS-PAS-TOP-14-022



combined



The weight is mostly from lepton+jet with ideogram method



2D : simultaneous fit to both m_t and JSF (no prior knowledge of the JSF)

Hybrid : incorporates the prior knowledge about the jet energy scale by using a Gaussian constraint.

$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV}$$

total 0.3%

main uncertainties : JEC for flavor, b jet modeling

Pole mass measurement

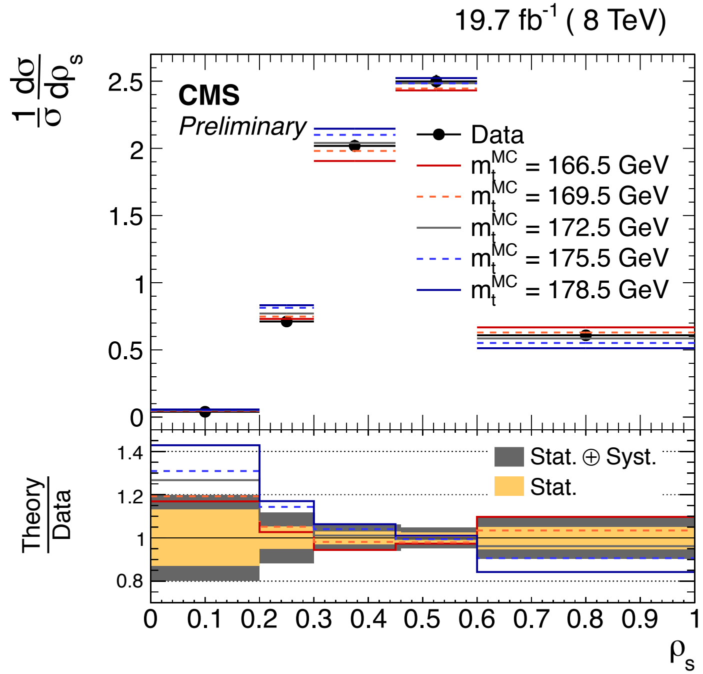
7, 8 TeV

CMS-PAS-TOP-13-006

JHEP 10 (2015) 121

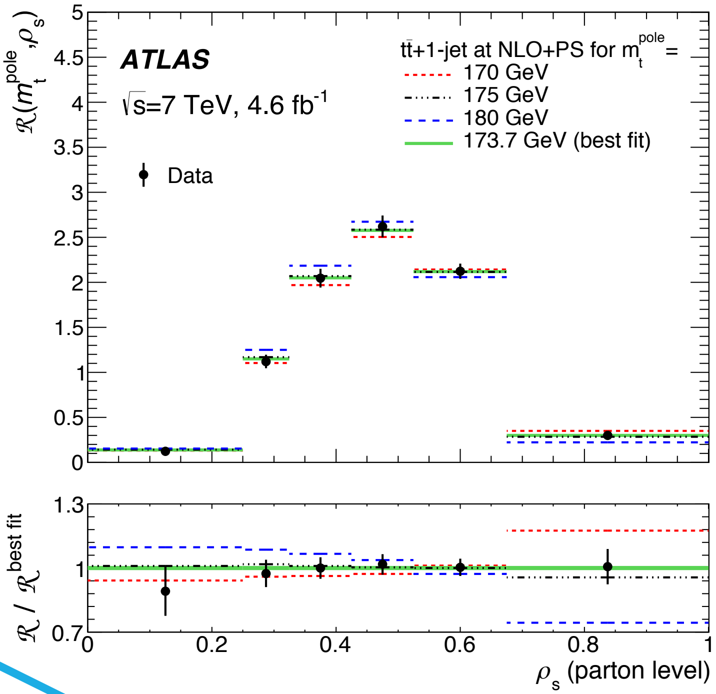
- Pole mass can be extracted from the normalized cross section with $t\bar{t} + 1$ jet at parton level.
- Performed in the semi-leptonic decay mode at ATLAS while in di-leptonic mode at CMS.

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}, \quad \frac{1}{\sigma}\frac{d\sigma^i}{d\rho_s} = \frac{1}{\sigma}\frac{\sum_j A_{ij}^{-1}(N^j_{\text{data}} - N^j_{\text{non}-t\bar{t}\,\text{bkg}}) \cdot f^{\text{signal}}}{\Delta^i_x \mathcal{L}}$$



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

Dominant uncertainty :
JES, Q2 scale



(ATLAS) $m_t^{\text{pole}} = 173.7 \pm 1.5\ (\text{stat.}) \pm 1.4\ (\text{syst.})\ ^{+1.0}_{-0.5}\ (\text{theory})$ GeV

Pole mass measurement

ATLAS : arXiv:1406.5375

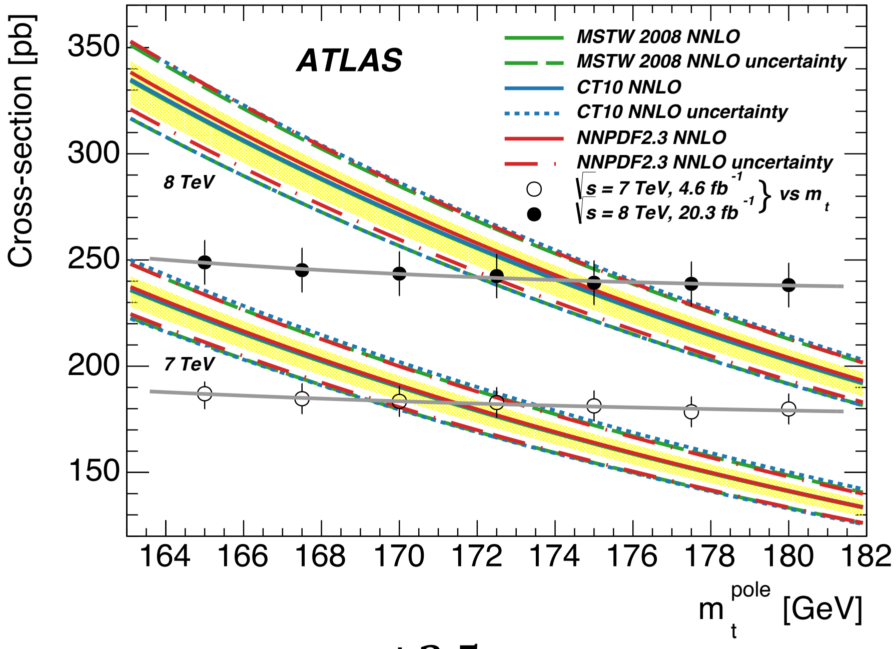
CMS: arXiv:1603.02303

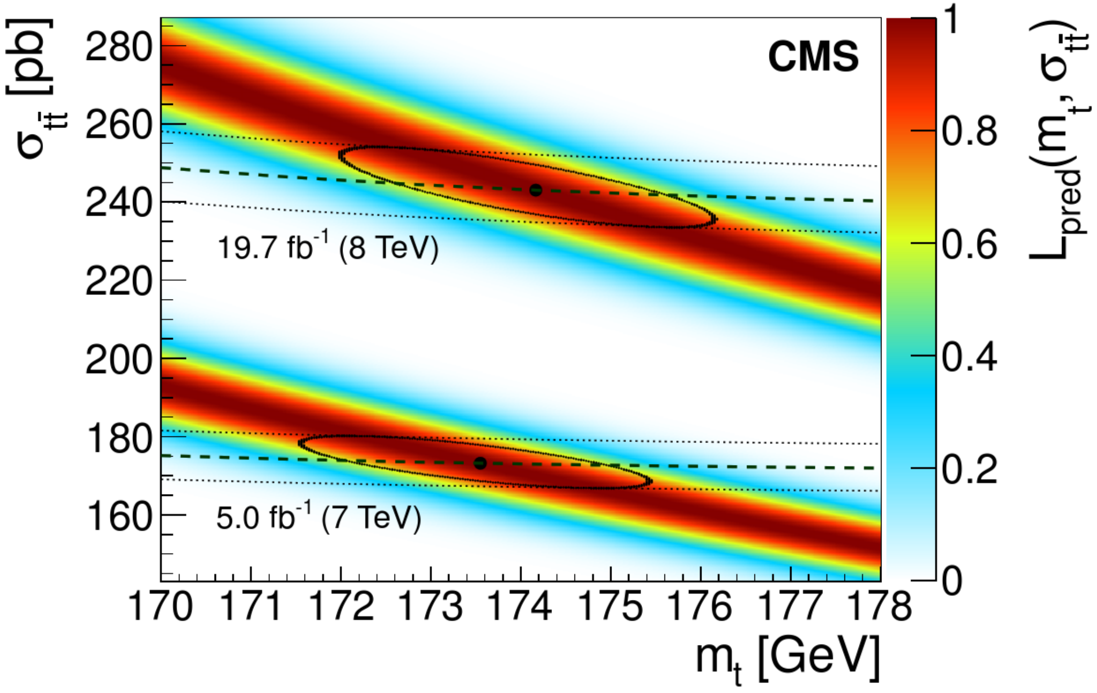
7, 8 TeV

- Pole mass is extracted from the $t\bar{t}$ pair production cross section measurement in the $e\mu$ channel only at 7 and 8 TeV.

CMS

	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

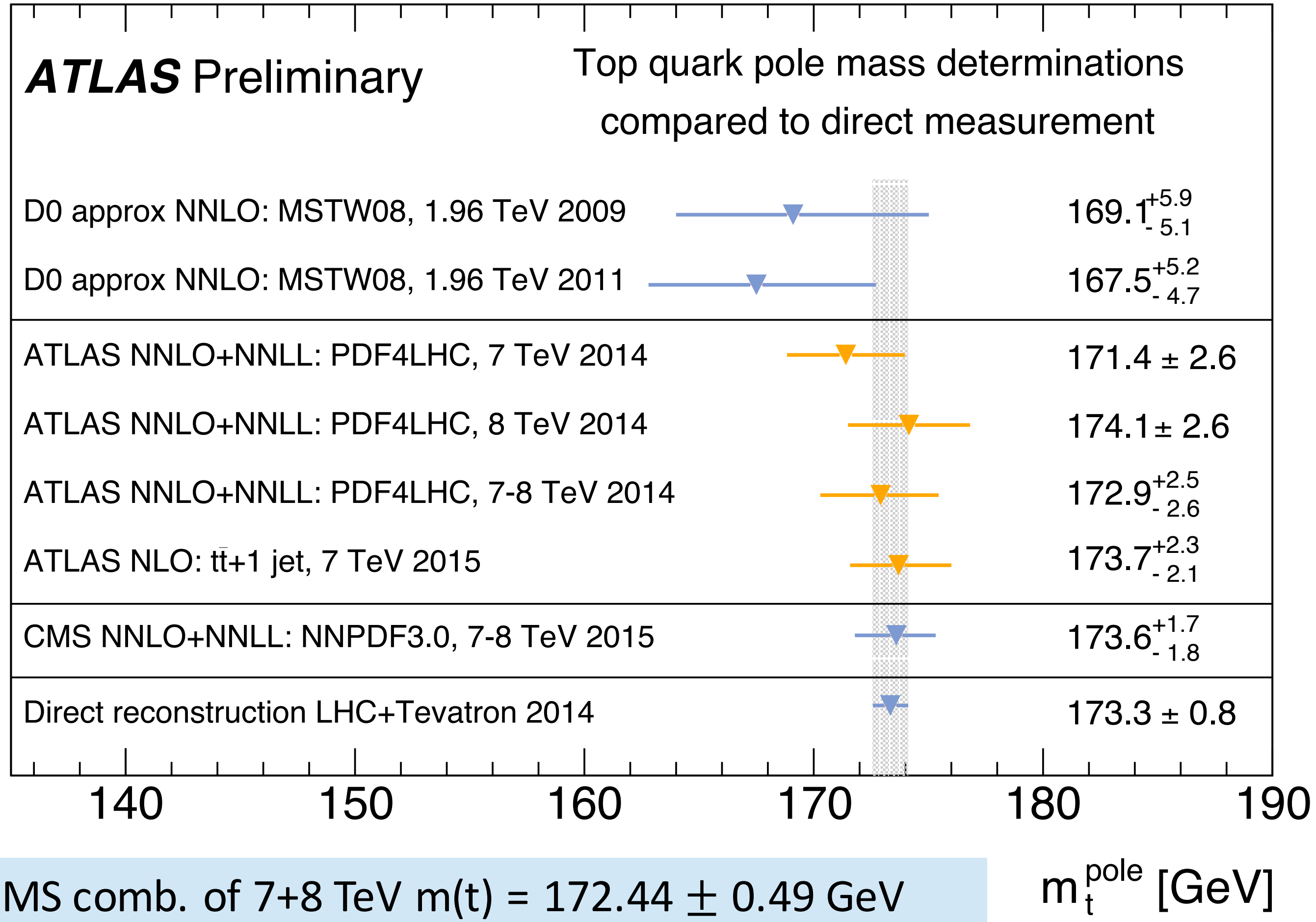


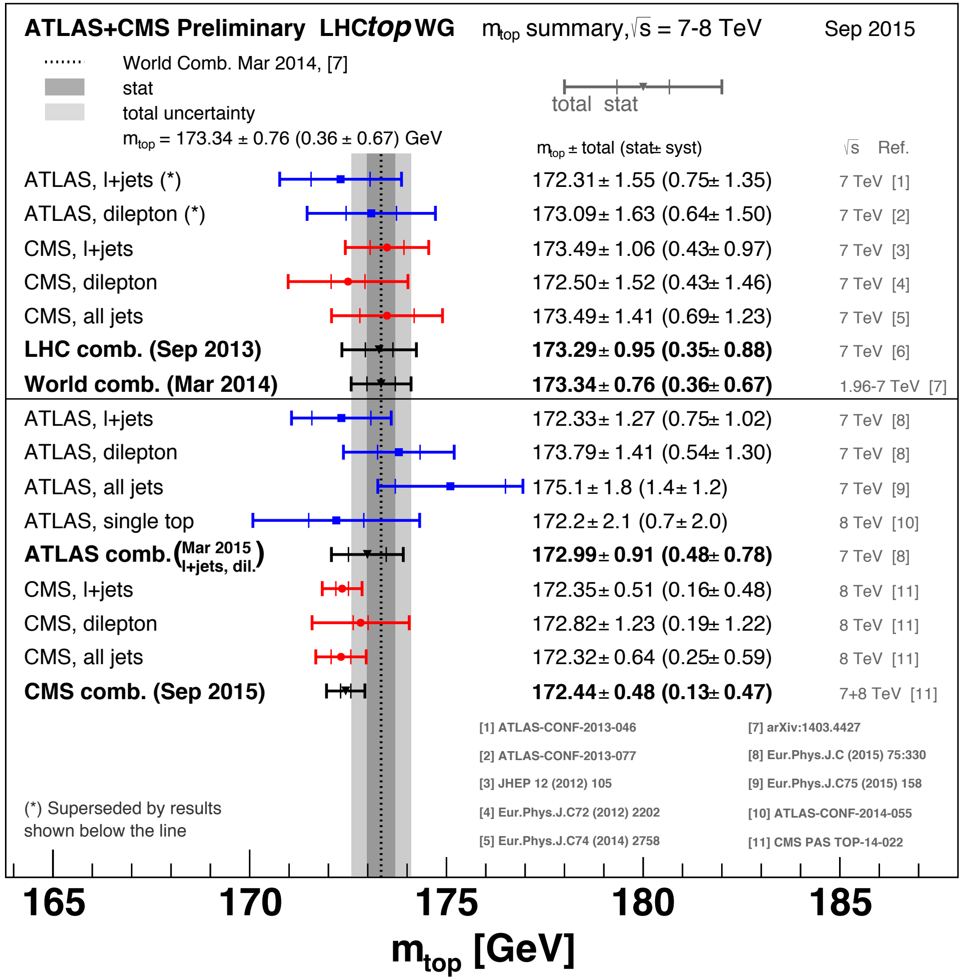


ATLAS $172.9^{+2.5}_{-2.6}$GeV (using old PDFs)

Top quark mass measurement

7-8 TeV





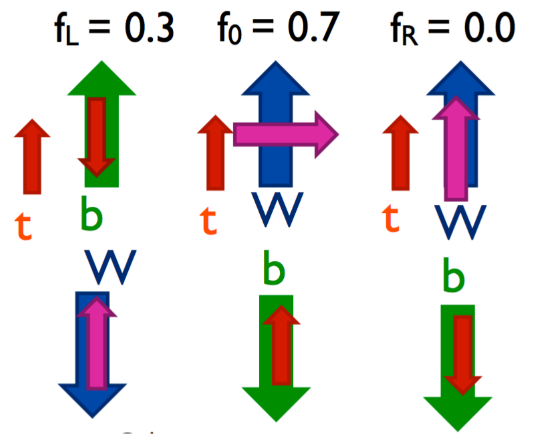
CMS comb. of 7+8 TeV m(t) = 172.44 ± 0.49 GeV
ATLAS comb. of 7+8 TeV m(t) = 172.84 ± 0.70 GeV

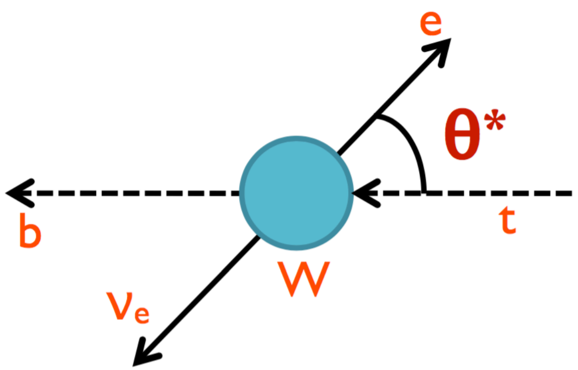
W boson helicity

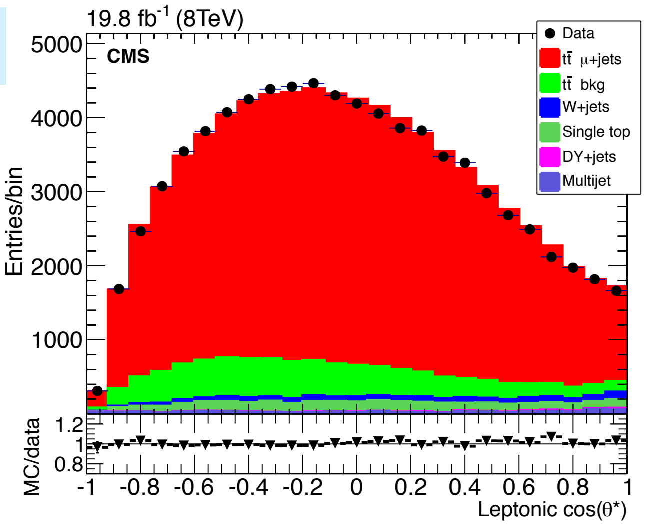
8 TeV

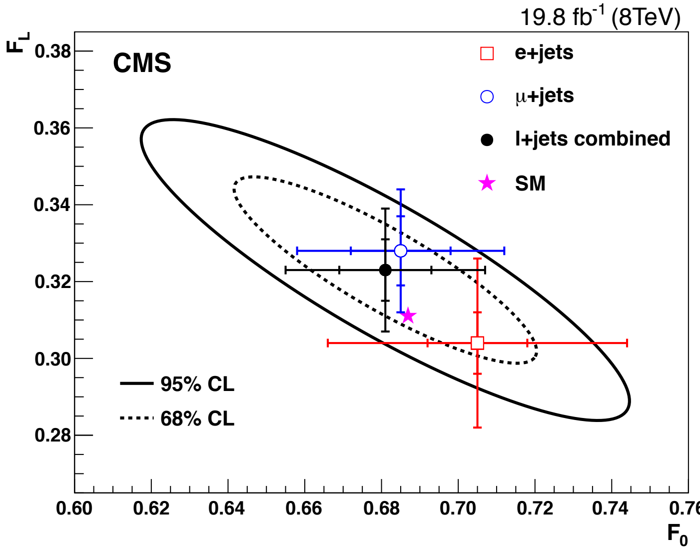
arXiv:1605.09047

In W rest frame





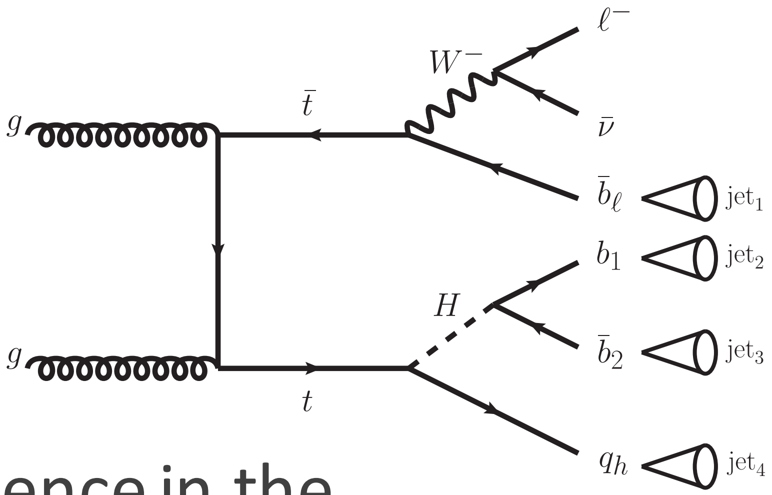




- $con\theta^*$ = angle between the direction of down type fermion from W and reversed direction of top quark
- The polarization fraction was extracted by fitting to data $con\theta^*$ distribution.

$$F_0 = 0.681 \pm 0.012\ (stat) \pm 0.023\ (syst)$$
$$F_L = 0.323 \pm 0.008\ (stat) \pm 0.014\ (syst)$$
$$F_R = -0.004 \pm 0.005\ (stat) \pm 0.014\ (syst)$$

FCNC searches



Flavor Changing Neutral Currents (FCNC)

- FCNC is suppressed by GIM mechanism.
- $Br(t \rightarrow Xq) \sim 10^{-17} - 10^{-12}, X = H, \gamma, Z, g$

A wide variety of models shows a strong dependence in the measureable FCNC quantities.

- $\boldsymbol{Br(t \rightarrow cH)}$ in 2HDM is ~ $\mathbf{10^{-4}}$.

The study of FCNC is one of the most interesting research topics in top quark physics.

$t \to qH$ at ATLAS (8 TeV)

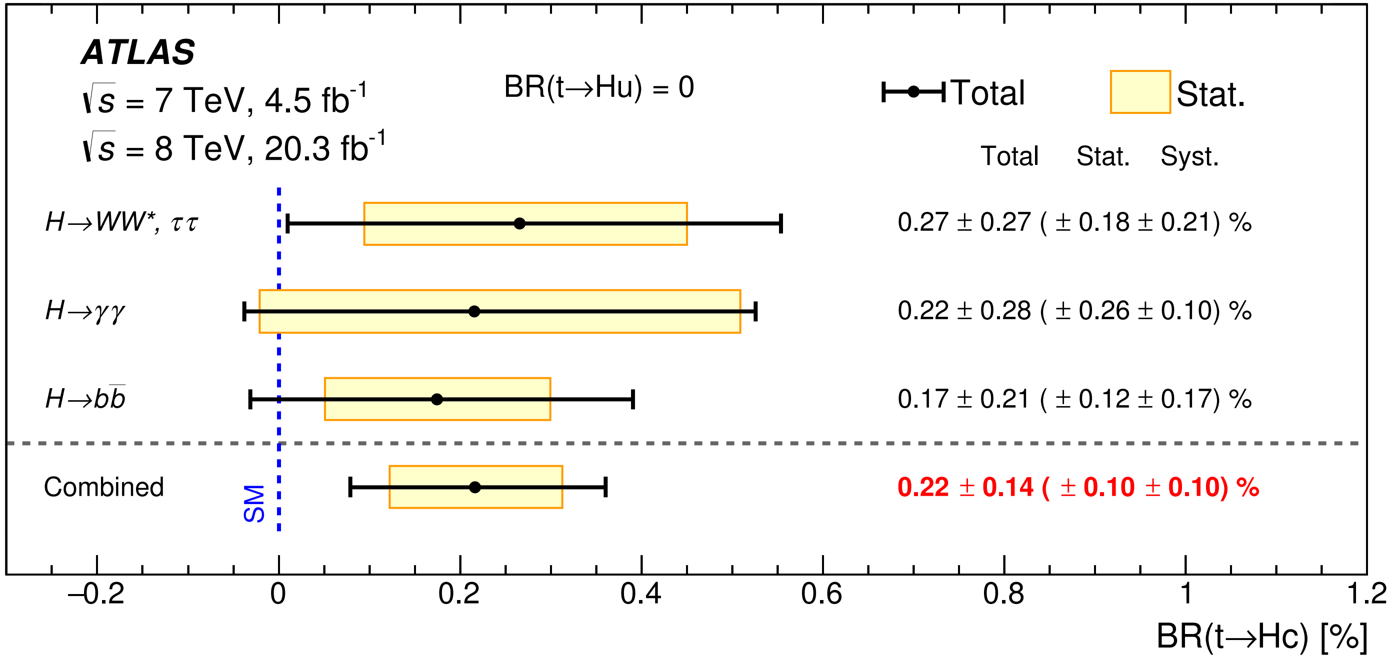
8 TeV

JHEP 12 (2015) 061

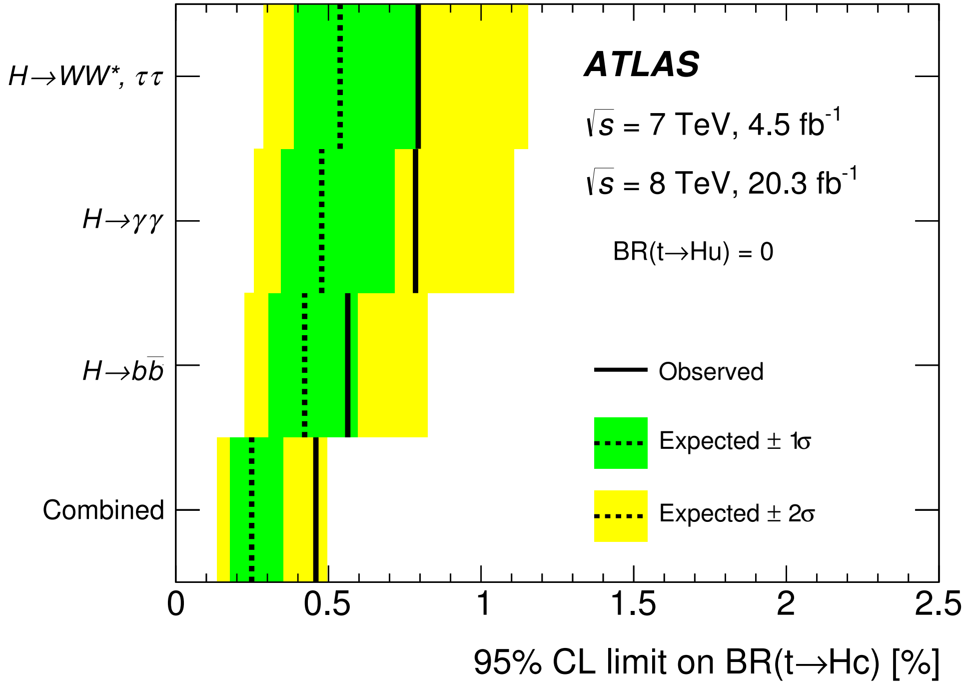
ATLAS EXPERIMENT

- Combination of $H \to b\bar{b}$ with $H \to \gamma\gamma$ and $H \to WW^*, \tau\tau$ improves the sensitivity.

Best fit result for Br(t→cH)



CL Limit for Br(t→cH)



Obs. (Exp.) B(t→cH) < 0.46% (0.25%)

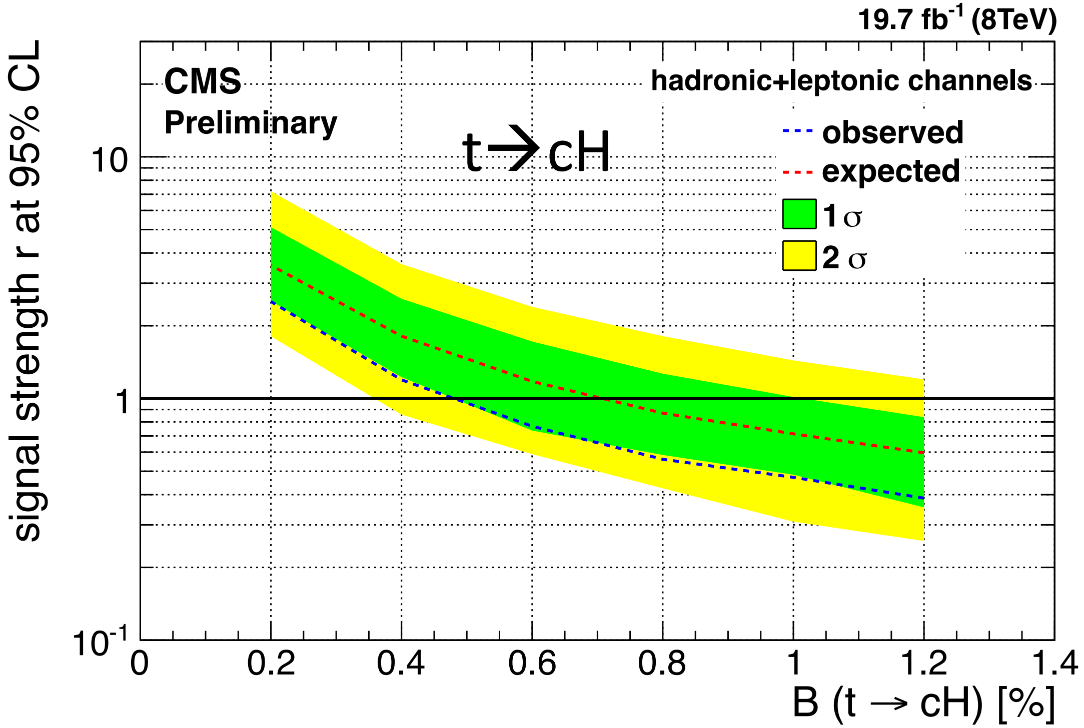
Obs. (Exp.) B(t→uH) < 0.45% (0.29%)

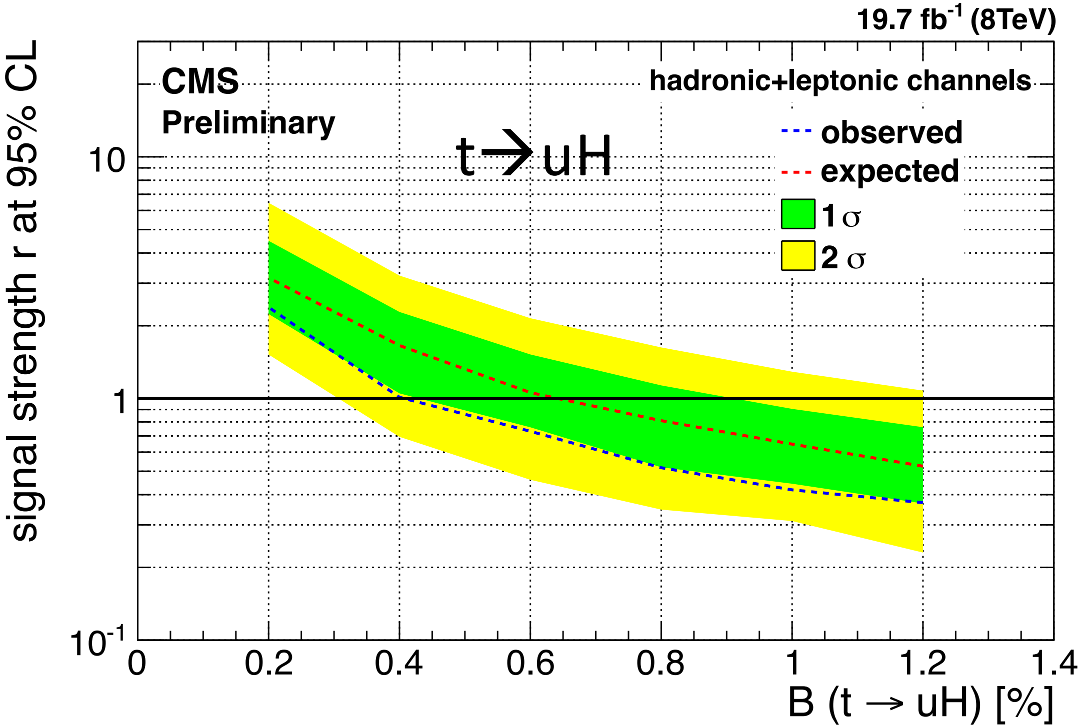
$t \to qH$ with H $\to \gamma\gamma$

8 TeV

CMS-PAS-TOP-14-019

Hadronic + Leptonic channel combined. (most of the sensitivity comes from hadronic channel)

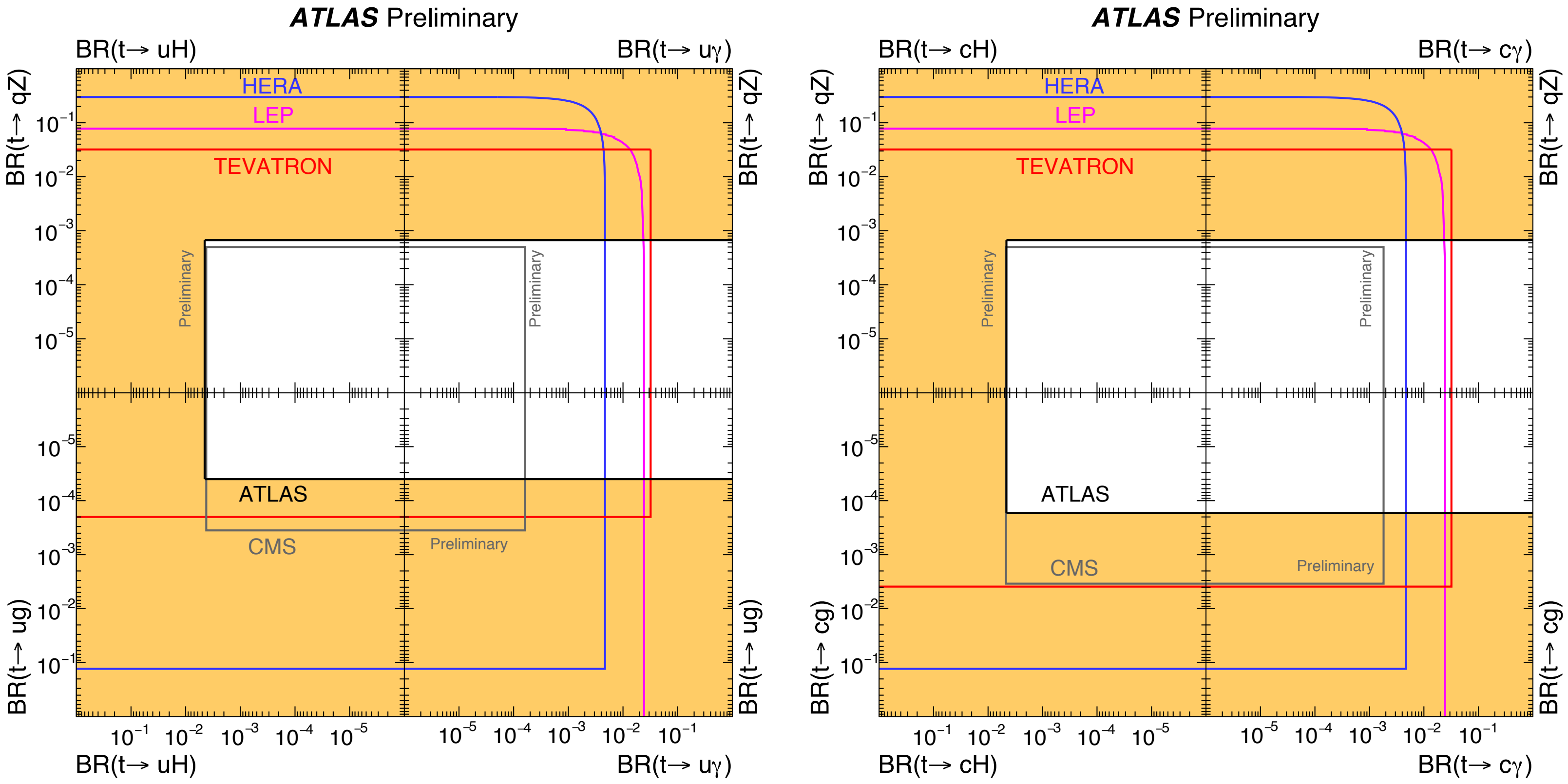


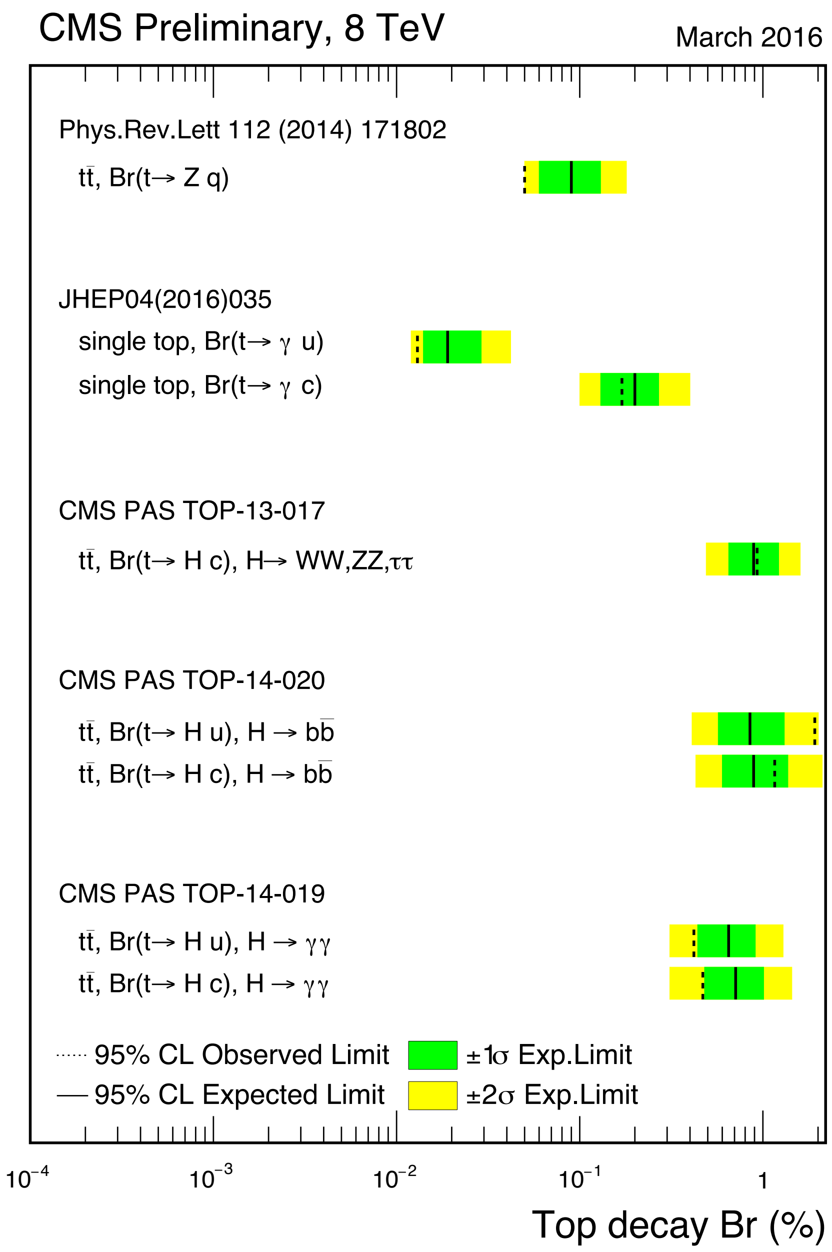


Obs. (Exp.) B(t→cH) < 0.47% (0.71%)

Obs. (Exp.) B(t→uH) < 0.42% (0.65%)

FCNC summary (+ other couplings)



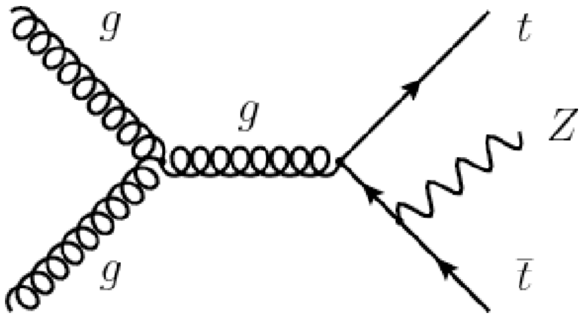


- We are very close to reach the FCNC beyond the SM!

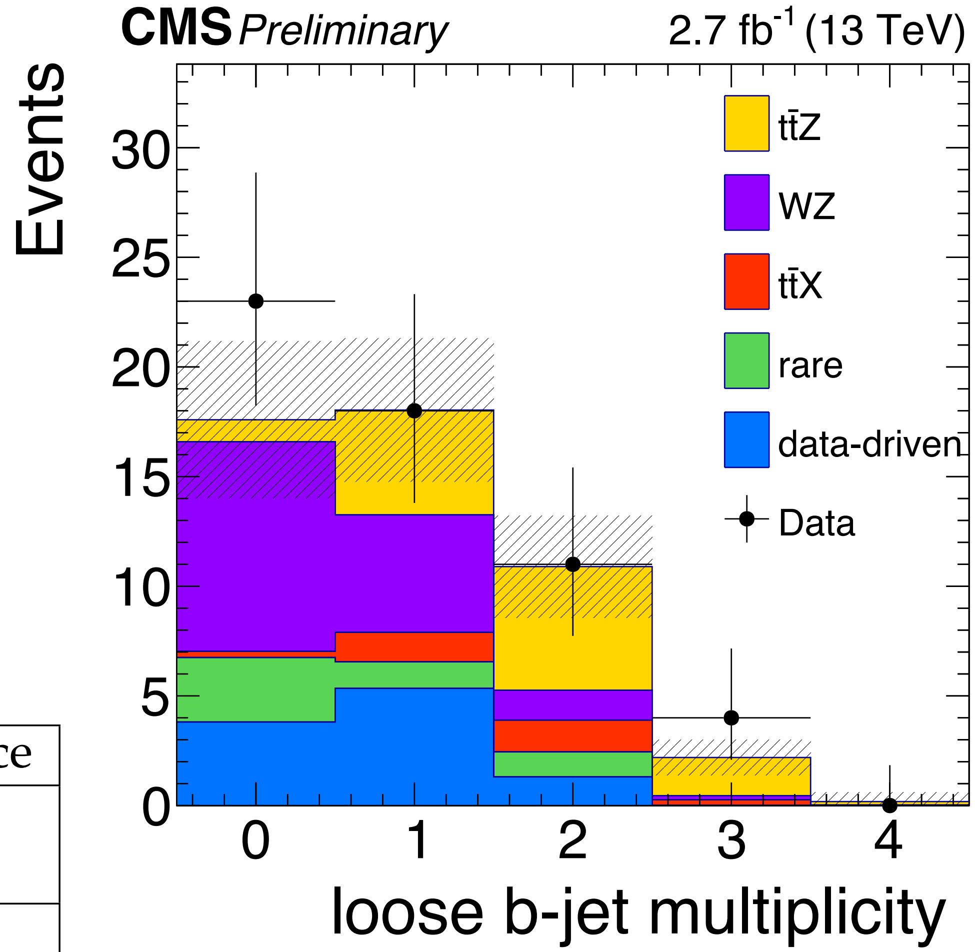
Cross section of $t\bar{t} + Z$

13 TeV

CMS-PAS-TOP-16-009



(In 8 TeV, 6.4σ sig. was achieved.)



- Z boson decays two leptons.
- Final states can be 3 or 4 lepton final states.

SM $\sigma(\mathrm{t\bar{t}Z}) = 839.3^{+80}_{-92}(\mathrm{scale})\ ^{+25}_{-25}(\mathrm{pdf})\ ^{+25}_{-25}(\alpha_s)$

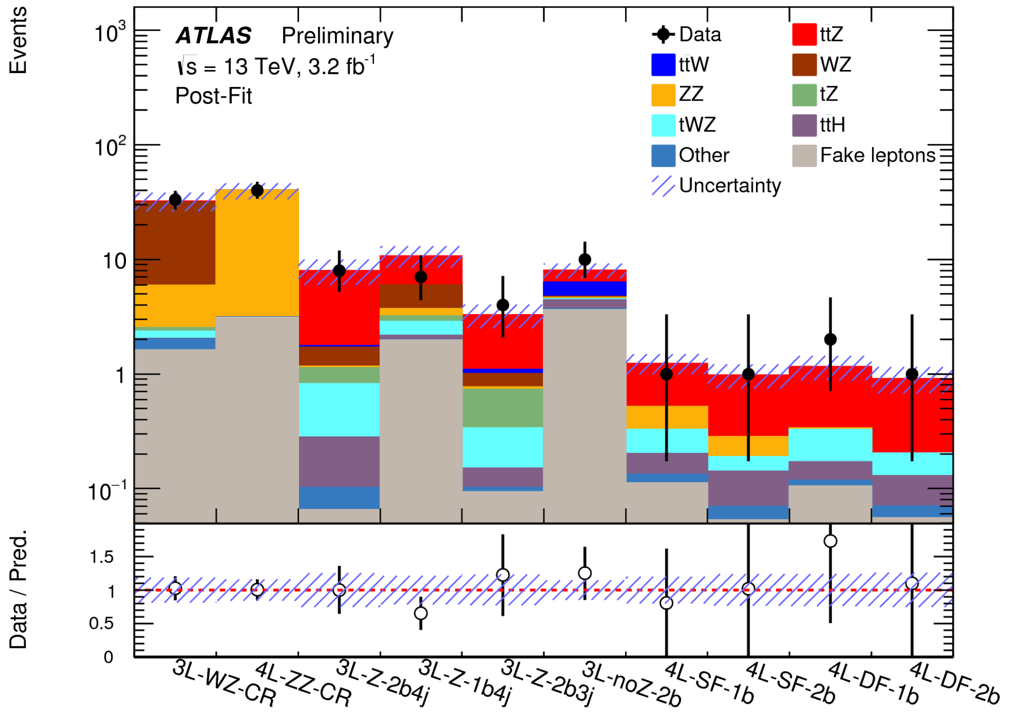
$$\sigma(\mathrm{pp} \rightarrow \mathrm{t\bar{t}Z}) = 1065\ ^{+352}_{-313}(\mathrm{stat.})\ ^{+168}_{-142}(\mathrm{sys.})\ \mathrm{fb}$$

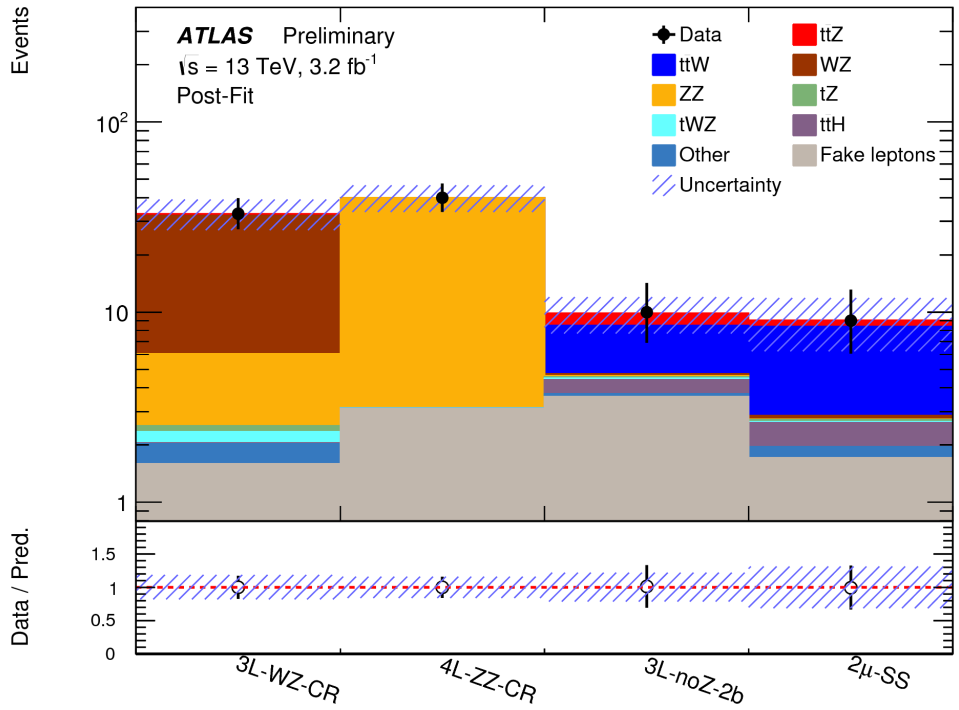
Channel	Expected significance	Observed significance
3ℓ analysis	2.9	3.5
4ℓ analysis	1.2	0.9
3ℓ and 4ℓ combined	3.1	3.6

Cross section of $t\bar{t} + Z(W)$

ATLAS-CONF-2016-003

13 TeV





Expected yields after the fit compared to data for the $t\bar{t}Z$ (left) and $t\bar{t}W$ (right).

$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.30\,(\text{stat.}) \pm 0.11\,(\text{syst.})\,\text{pb}$$

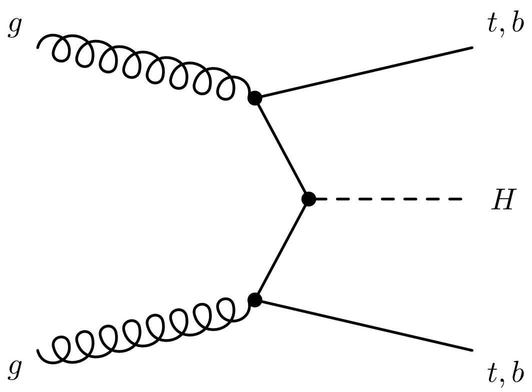
$$\sigma_{t\bar{t}W} = 1.38 \pm 0.70\,(\text{stat.}) \pm 0.33\,(\text{syst.})\,\text{pb}$$

SM $\sigma_{t\bar{t}Z} = 0.76\ pb$ $\sigma_{t\bar{t}W} = 0.57\ pb$

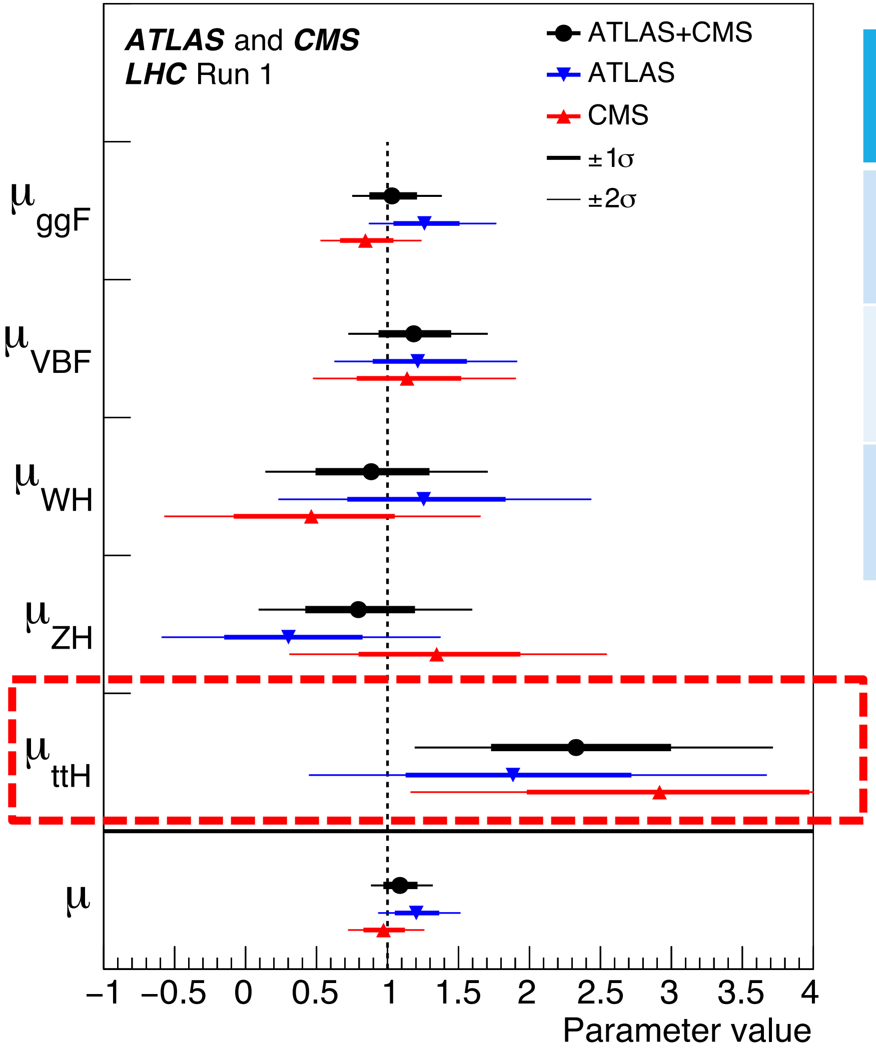
Search for $t\bar{t} + H$

8 TeV

arXiv:1606.02266



- Direct measurement of the coupling between top quark and Higgs boson.
- Cross section is directly sensitive to the top Yukawa coupling.



	$\mu_{t\bar{t}H}$
ATLAS	$1.9^{+0.8}_{-0.7}$
CMS	$2.9^{+1.0}_{-0.9}$
Combined	$2.3^{+0.7}_{-0.6}$

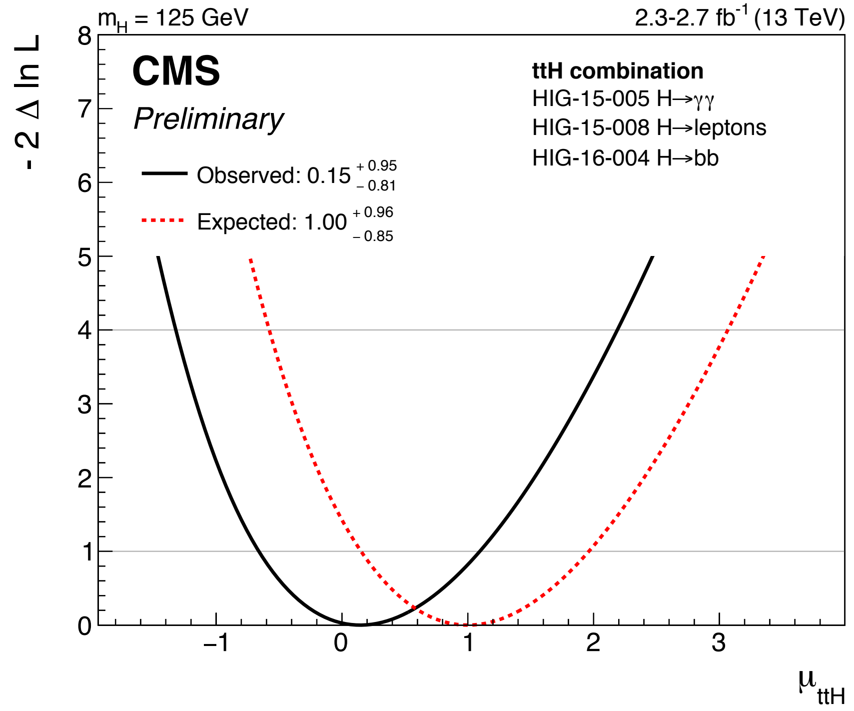
The sensitivity comes from $t\bar{t}H(\gamma\gamma)$, $t\bar{t}H$(multi-leptons), $t\bar{t}H(b\bar{b})$

Search for $t\bar{t} + H$ update

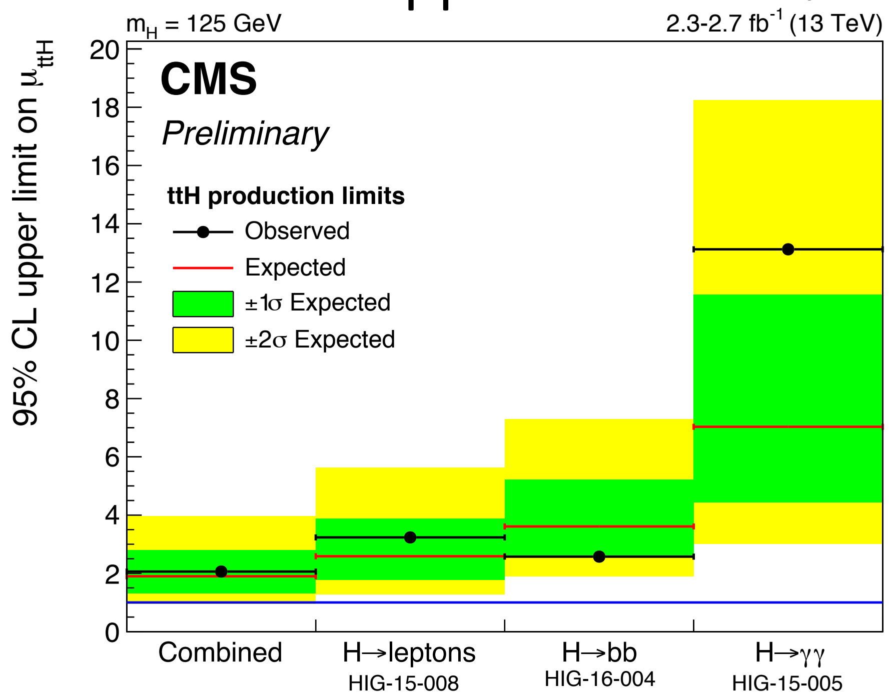
HIG-15-005 H→ $\gamma\gamma$
HIG-15-008 H→leptons
HIG-16-004 H→bb

13 TeV

Combination of three statistically independent channels :
$t\bar{t}H(\gamma\gamma)$, $t\bar{t}H$(multi-leptons), $t\bar{t}H(b\bar{b})$



Exclusion upper limit at 95% CL



SM : $\mu = 1.00^{+0.96}_{-0.85}$

Combined best fit : $\mu = 0.15^{+0.95}_{-0.81}$

- Compatible with the SM prediction
- Sensitivity is similar to 8 TeV and will be updated with full 2016 data.

Top quarks at the LHCb

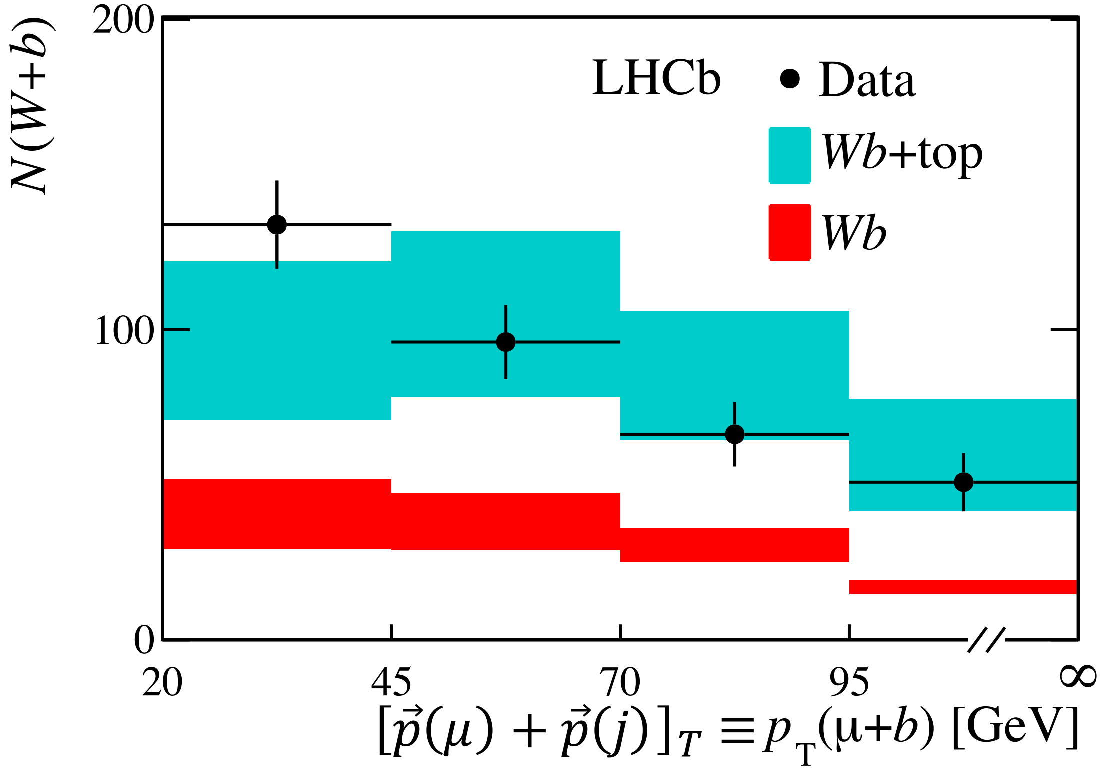
7 and 8 TeV

PRL 115 (2015) 112001

- LHCb detector is a single-arm forward spectrometer covering $2 < \eta < 5$ for the study of particles containing b or c.
- Data excess over Wb background is 5.4σ.
- Top quark observation in forward fiducial region for the cross section:

$$p_T(\mu) > 25\ GeV, 2 < \eta(\mu) < 4.5$$
$$50 < p_T(b) < 100\ GeV, 2.2 < \eta(b) < 4.2$$
$$\Delta R(\mu, b) > 0.5, p_T(\mu + b) > 20\ GeV$$

1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV



$$\sigma(\text{top})[7\ \text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\ \text{fb}$$
$$\sigma(\text{top})[8\ \text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\ \text{fb}$$

Compatible with the SM

$$180^{+51}_{-41}\,(312^{+83}_{-68})\ \text{fb at } 7(8)\ \text{TeV}$$

Conclusion

- LHC was indeed top quark factory. Millions top quark candidates were produced and analyzed to reach the best precision and search for new physics.
- Rare processes in top quark sector are now reachable.
- Run 2 top quark results with 2015 data proved that our ATLAS and CMS detectors are in a good shape at 13 TeV.
- We have many top quark physics programs not covered here or awaiting for coming more data.
- The results at 13 TeV with more data in 2016 will be coming soon!

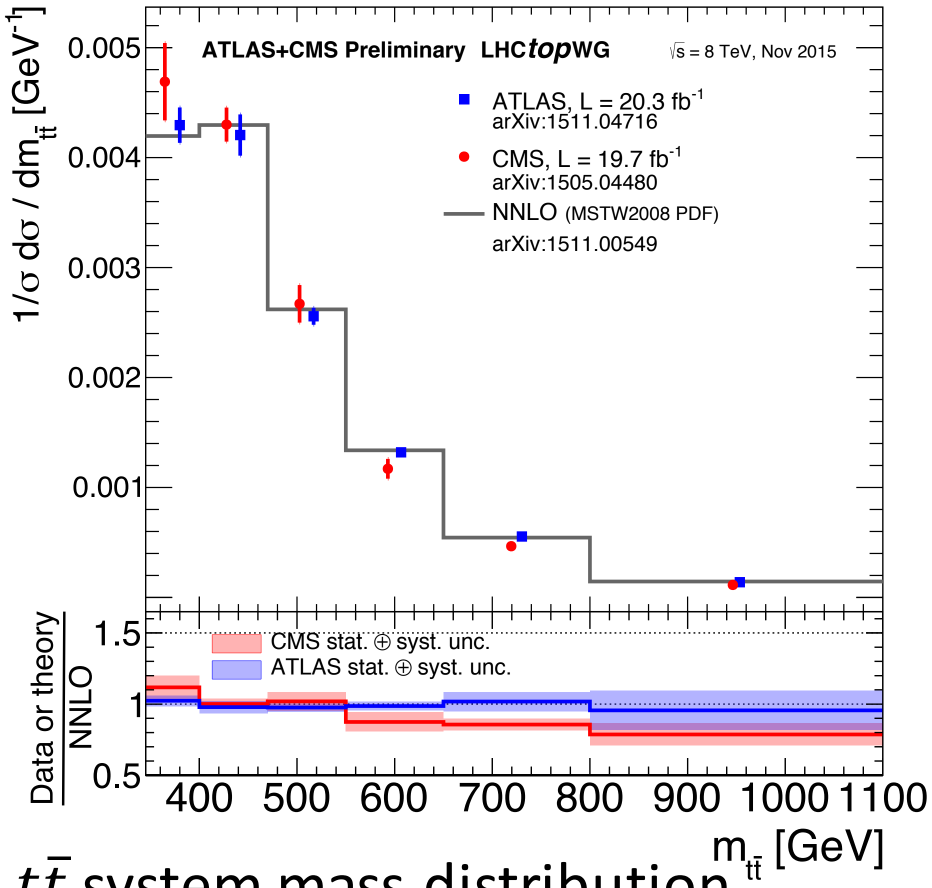
Differential cross section

8 TeV

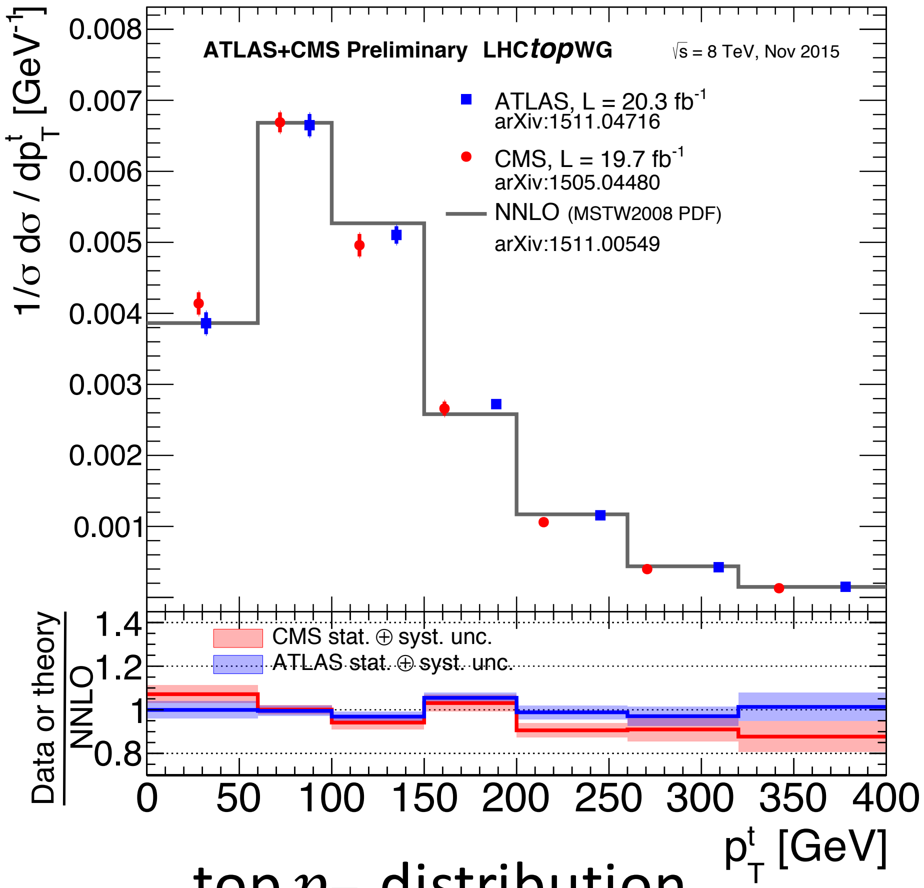
ATLAS: arXiv:1511.04716

CMS: arXiv:1505.04480

Unfolded distributions are compared with NNLO prediction.



$t\bar{t}$ system mass distribution

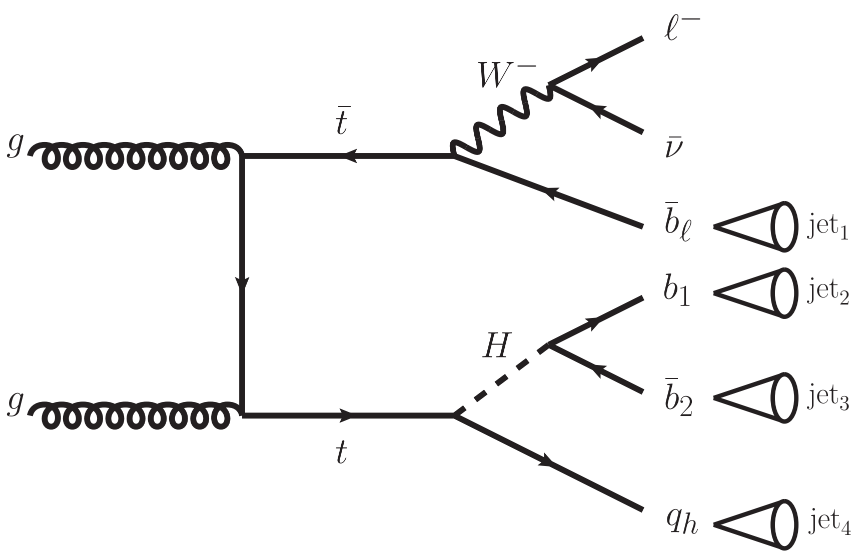


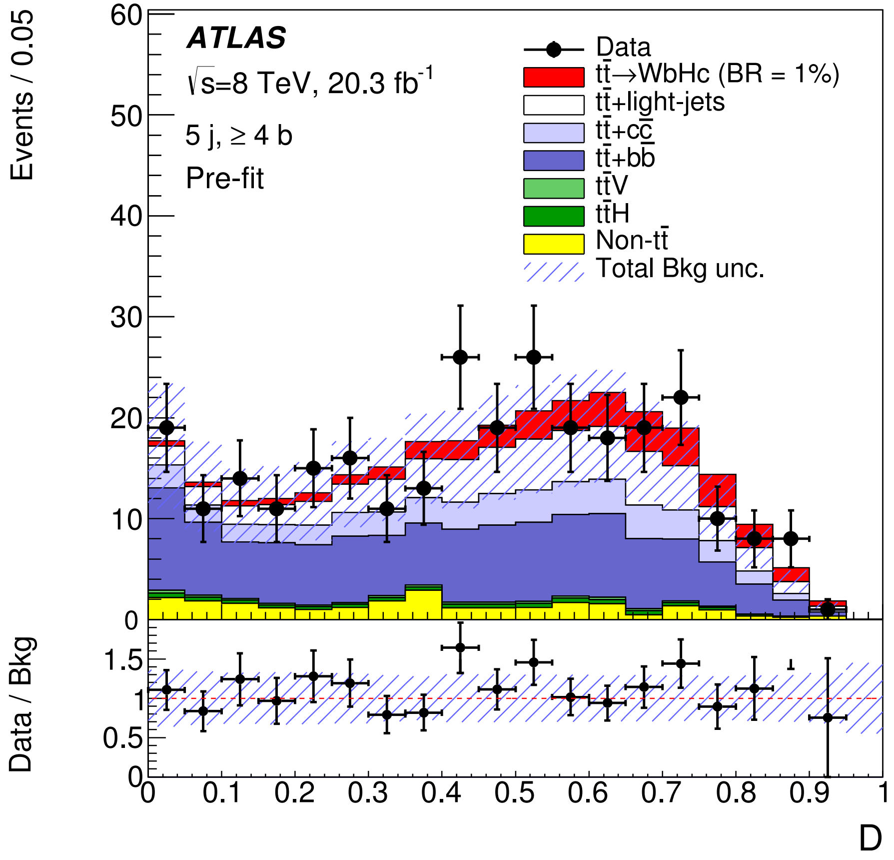
top p_T distribution

$t \to qH$ with H $\to b\bar{b}$

8 TeV

JHEP 12 (2015) 061





$$D(\mathbf{x}) = \frac{P^{\rm sig}(\mathbf{x})}{P^{\rm sig}(\mathbf{x}) + P^{\rm bkg}(\mathbf{x})}$$

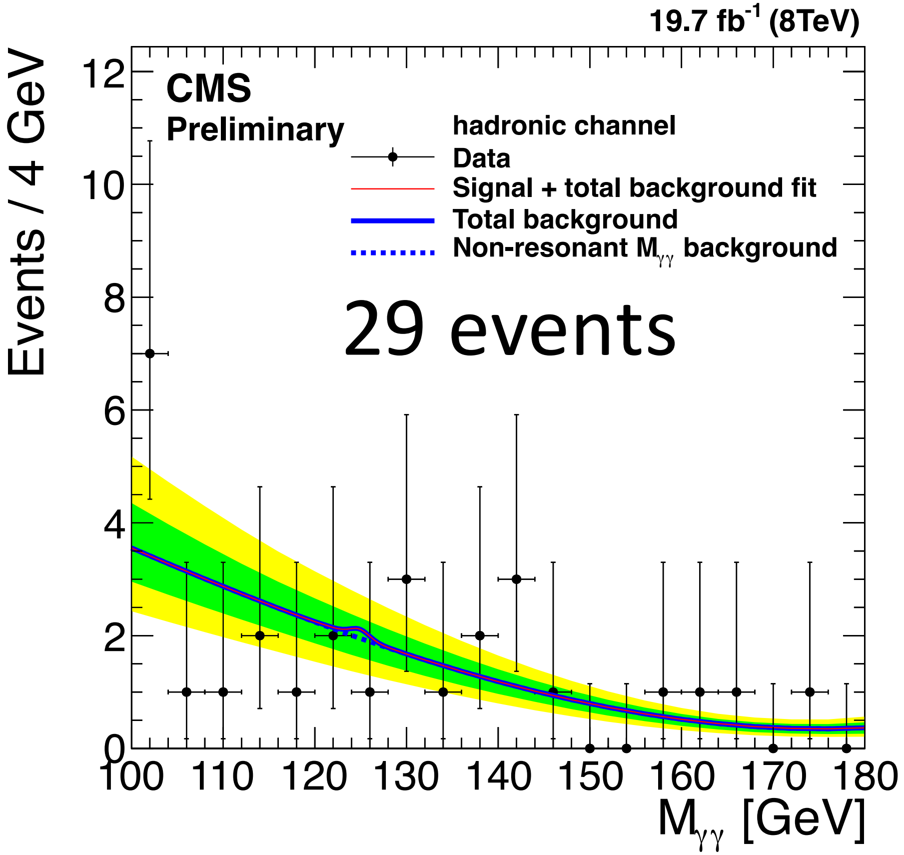
- Main background is $t\bar{t} + jets$ (Heavy flavor)
- Modeled by POWHEG-BOX+PYTHIA

$t \to qH$ with H $\to \gamma\gamma$

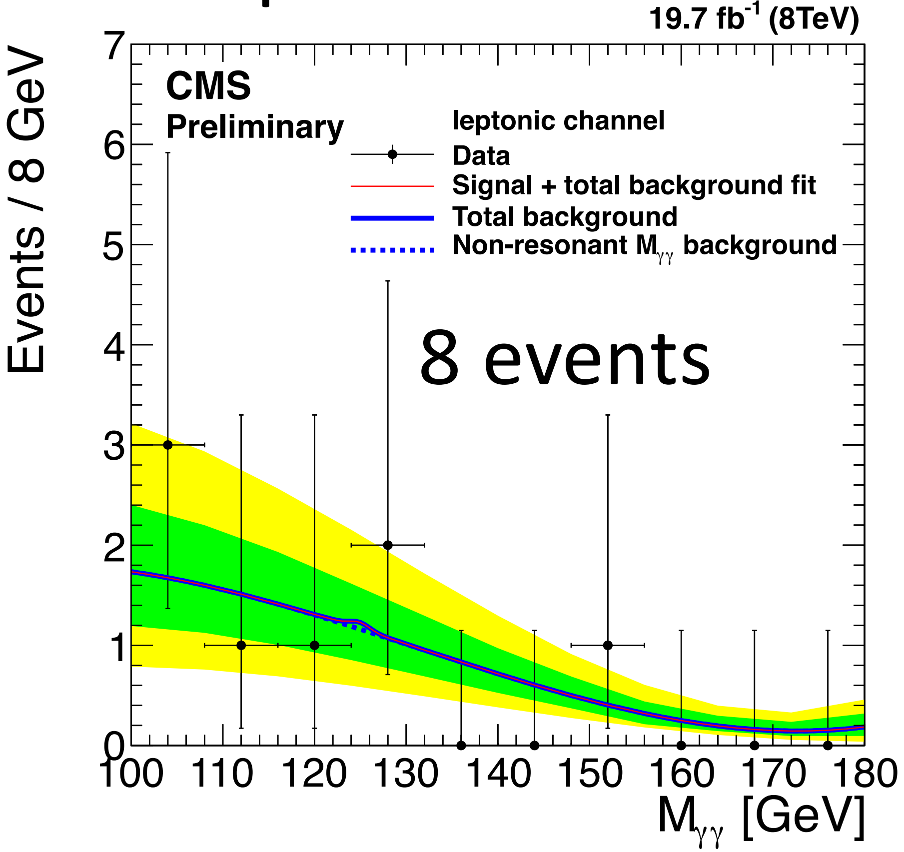
8 TeV

CMS-PAS-TOP-14-019

Hadronic channel



Leptonic channel

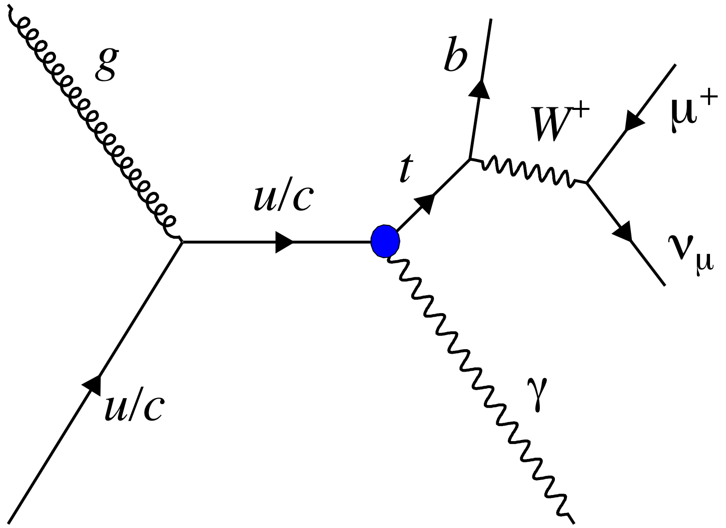


No significant excess is observed.

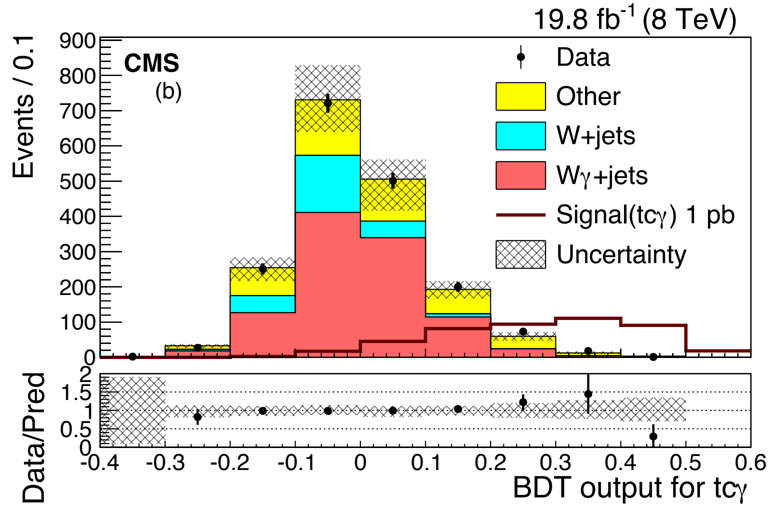
$t \to u(c)\gamma$ in single top

8 TeV

JHEP 04 (2016) 035



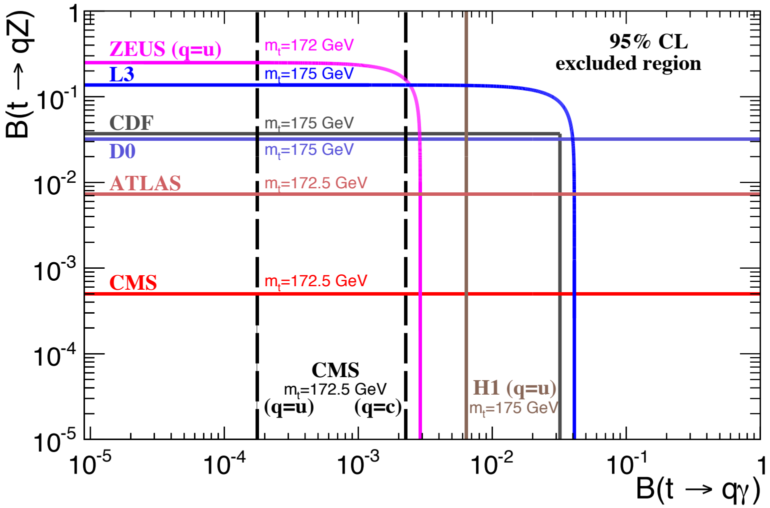
BDT : transverse momentum of μ, b jets and γ, angles with γ, b discriminant, jet multiplicity, lepton charge



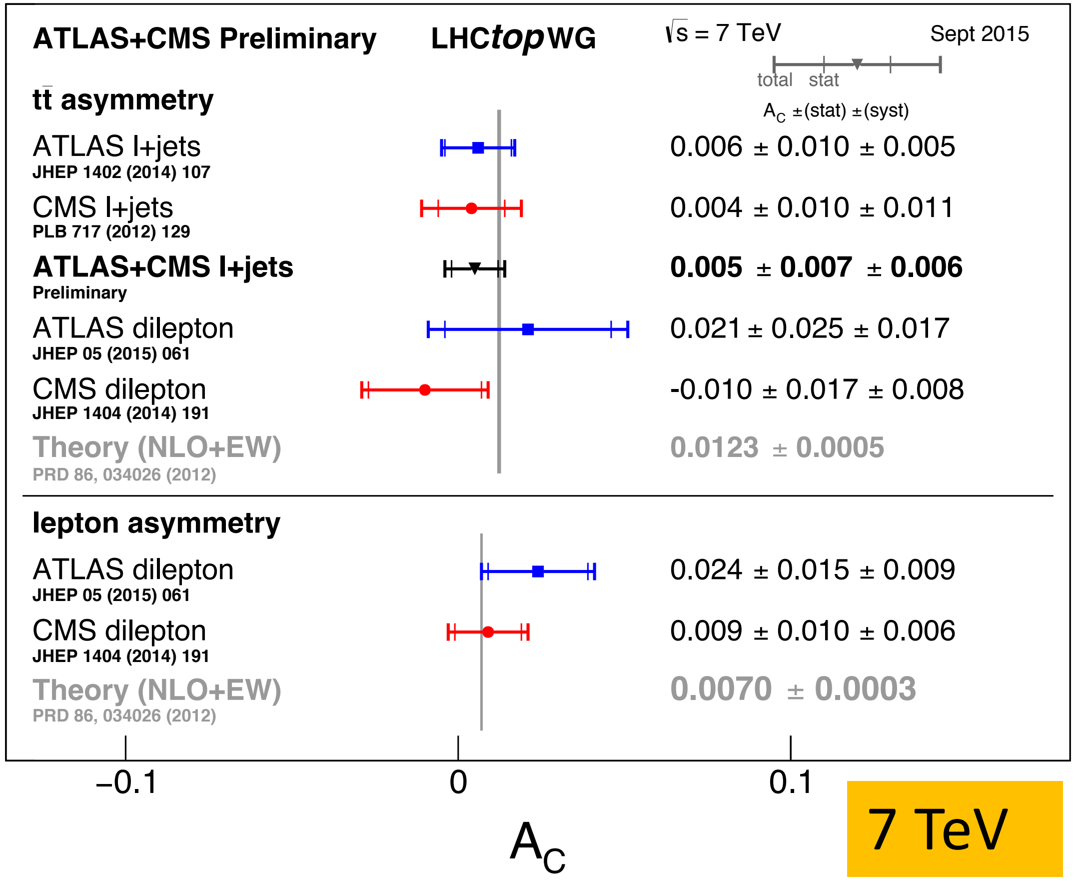
- High p_T photon with 50 GeV
- At least one lepton with 20 GeV
- Jets with 30 GeV
- Events with more than one b-tagged jets are rejected.

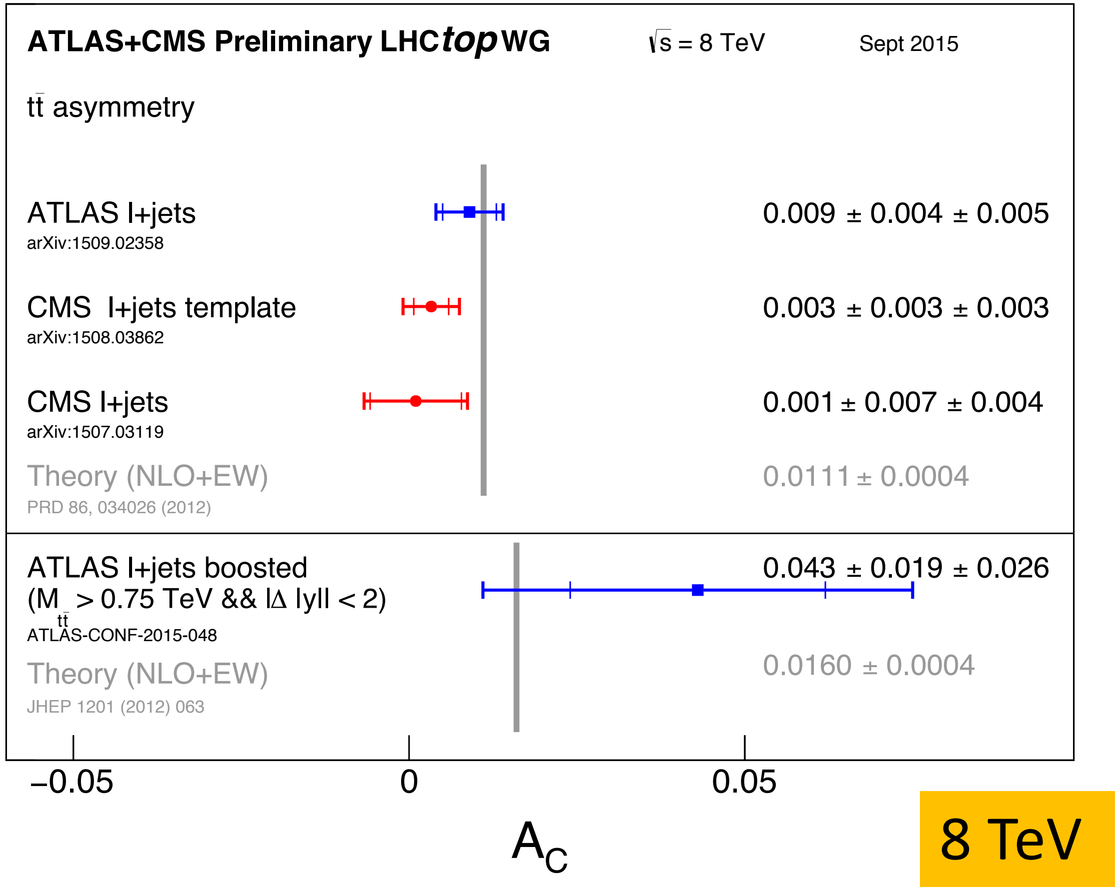
$$\mathcal{B}(t \to u\gamma) < 1.3 \times 10^{-4}$$

$$\mathcal{B}(t \to c\gamma) < 1.7 \times 10^{-3},$$



Charge Asymmetry



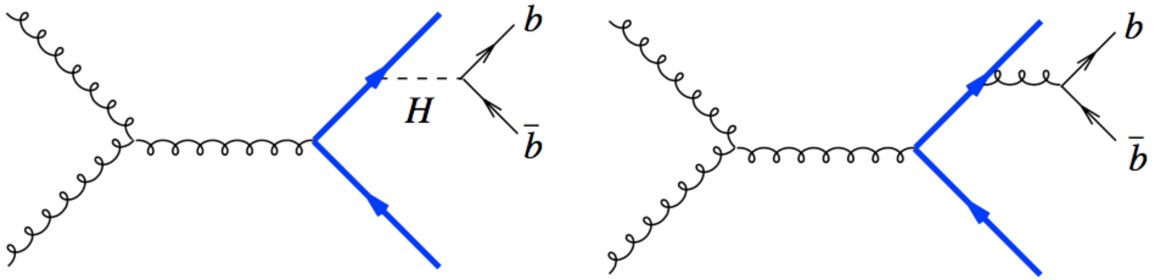


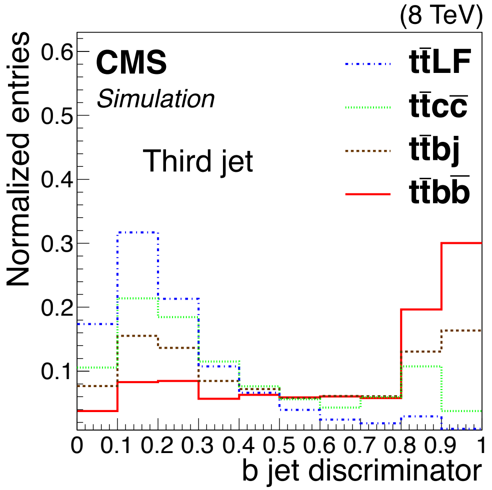
- The charge asymmetry result is consistent with the theory (NLO+EW).

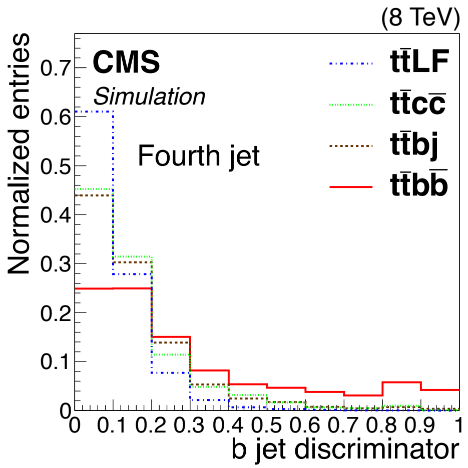
Cross section of $t\bar{t} + b\bar{b}$

8 TeV

PLB 746 (2015) 132







Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20$ GeV/c	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20$ GeV/c	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40$ GeV/c	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40$ GeV/c	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003

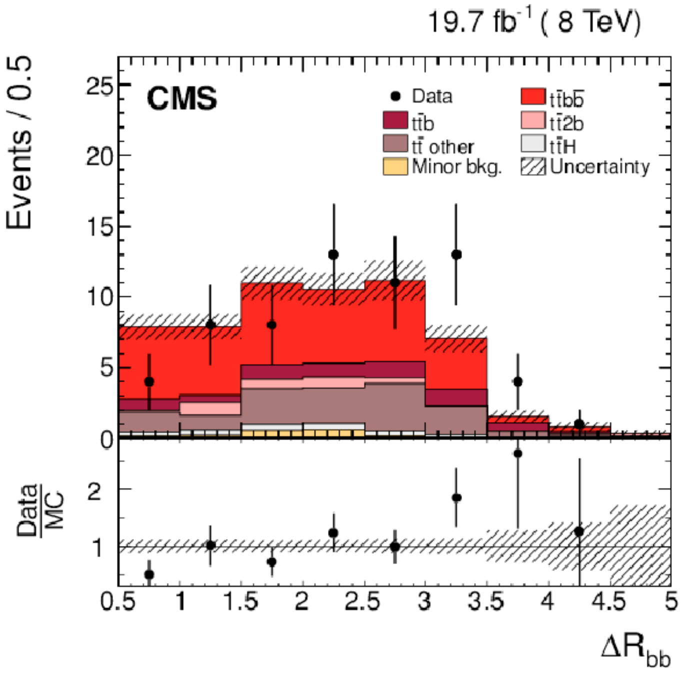
Cross section of $t\bar{t} + b\bar{b}$

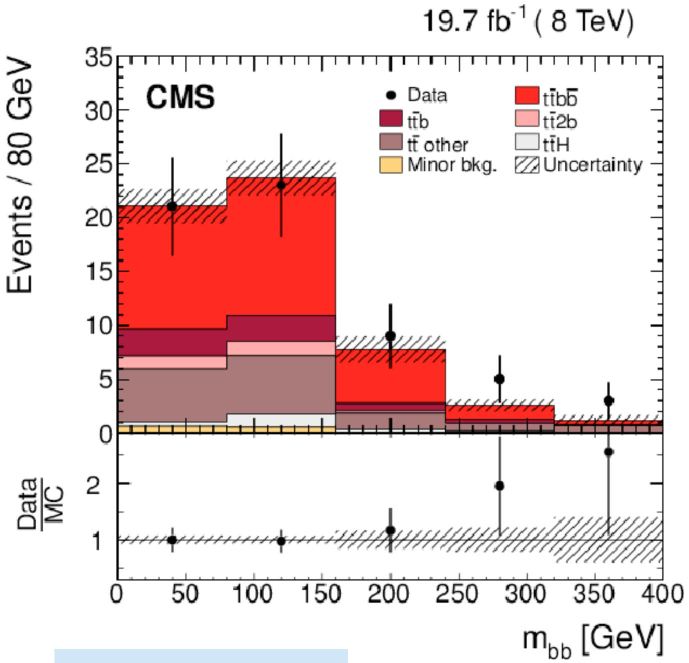
8 TeV

- In lepton+jets at 8 TeV, the result shows more direct comparison with NLO calculation → measured the cross section in ME.
- Differential measurements of the additional two b jets was performed.

	$\sigma(t\bar{t}b\bar{b})$	$\sigma(t\bar{t}jj)$	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
hardB:			
this analysis	271 fb ± 40%	23.1 pb ± 16%	0.012 ± 34%
theory NLO (*arXiv*:1403.2046)	229 fb $^{+18\%}_{-24\%}$	21.0 pb $^{+15\%}_{-13\%}$	0.011 $^{+39\%}_{-13\%}$
MadGraph+pythia	174 fb ± 28%	24.3 pb ± 20%	0.007 ± 10%
hadronB:			
this analysis	348 fb ± 38%	23.1 pb ± 16%	0.015 ± 32%
CMS dilepton (*arXiv*:1411.5621)	360 fb ± 36%	16.1 pb ± 14%	0.022 ± 29%
MadGraph+pythia	216 fb ± 35%	24.3 pb ± 20%	0.009 ± 14%

TOP-13-016



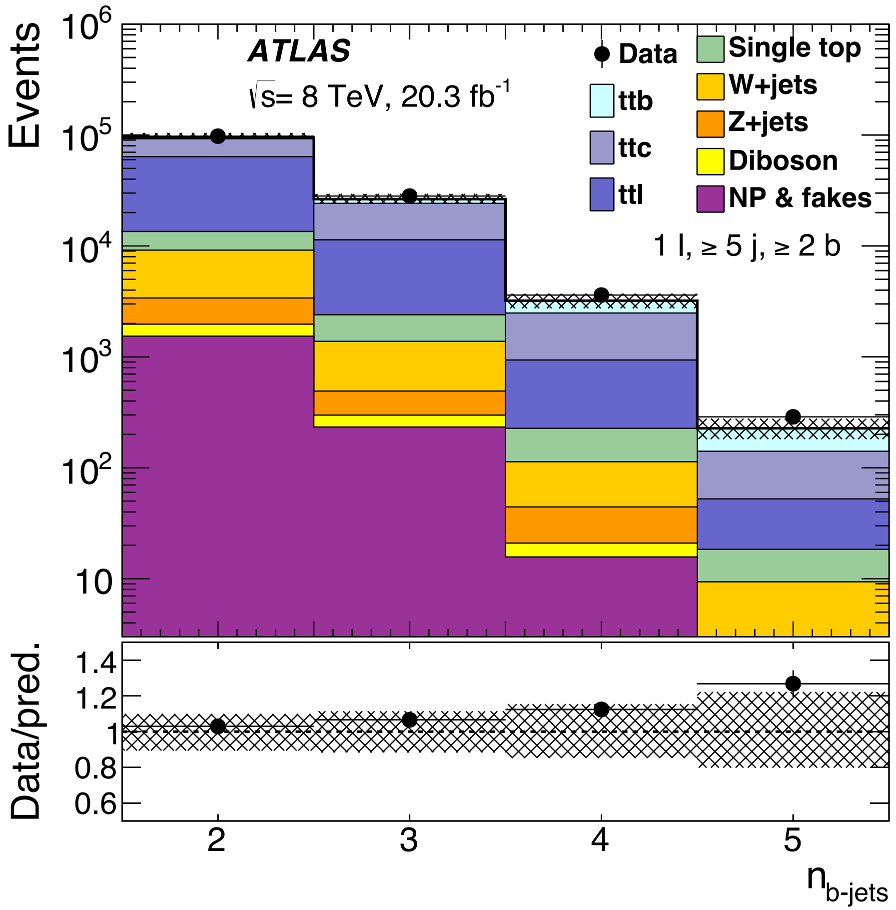


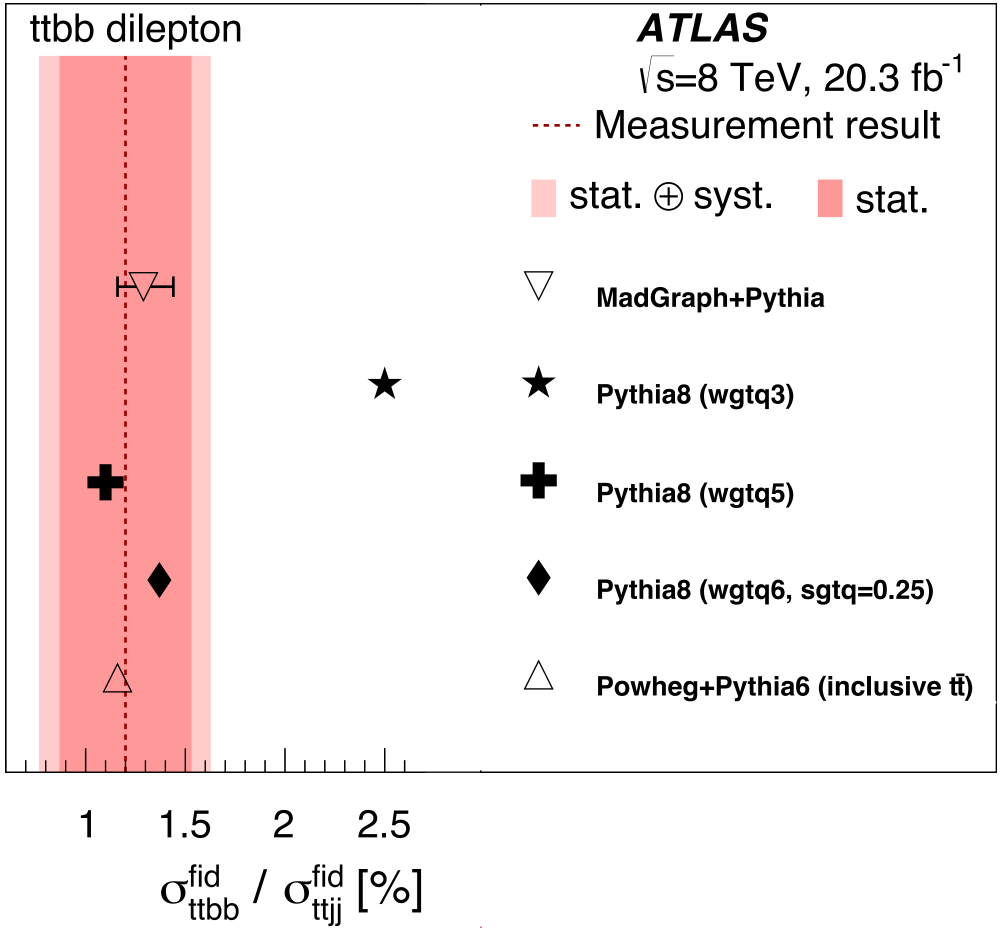
TOP-12-041

Cross section of $t\bar{t} + b\bar{b}$

8 TeV

Eur. Phys. J. C (2016) 76:11





- The ratio of $t\bar{t}b\bar{b}/t\bar{t}jj$ is 1.4% which is consistent with MC within the uncertainty.