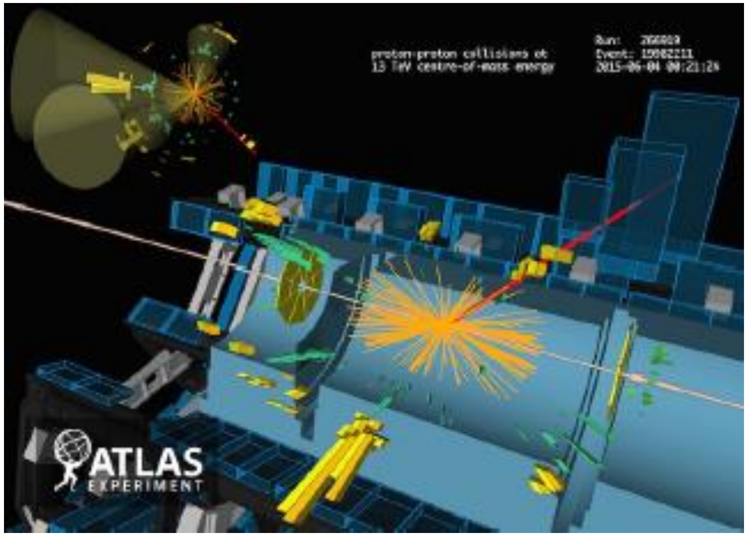


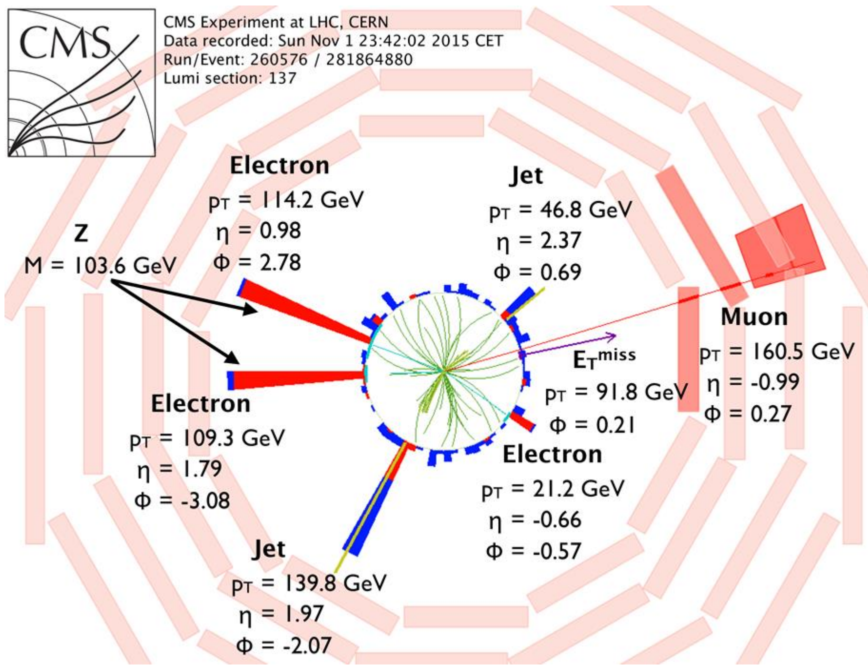
(Recent) Top Quark measurements at the LHC

Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

ATLAS EXPERIMENT

CMS

LHCb

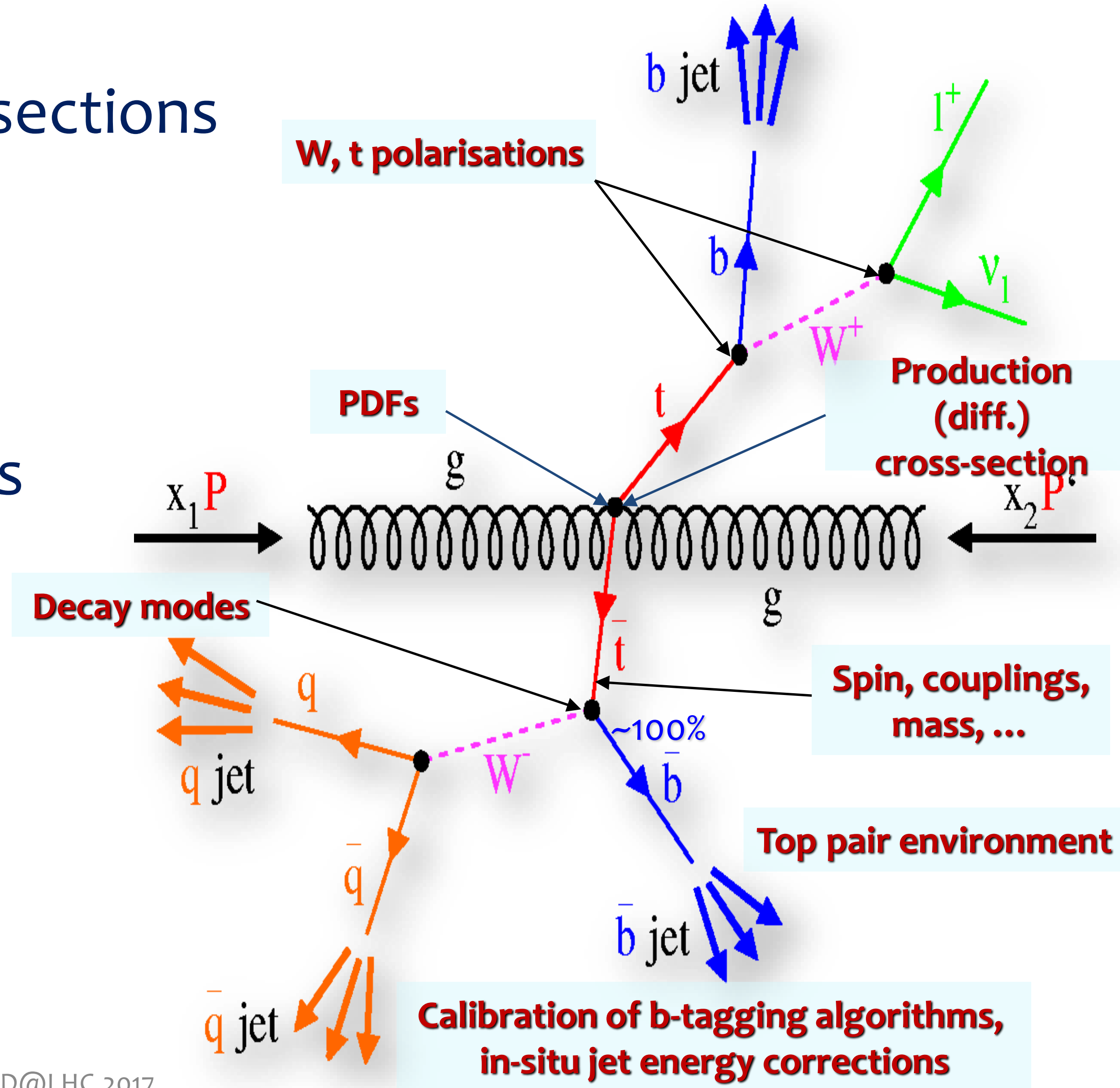


J. Cuevas
U. Oviedo (Spain)
on behalf of the **CMS, ATLAS** and **LHCb** collaborations

QCD@LHC 2017,
August 28th – Sep 1st 2017, Debrecen, Hungary

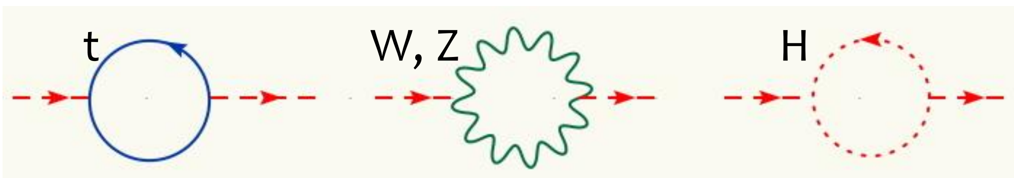
Outline

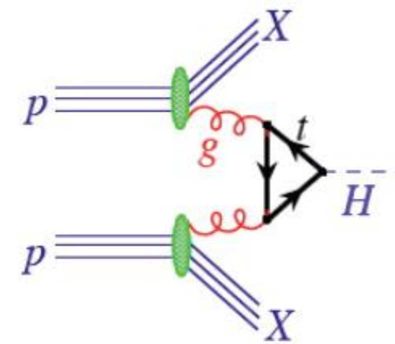
- Results on 7,8 and **13 TeV** data
- Top pair cross sections measurements
  - Inclusive
  - Differential
- Single top cross sections
- Associated production
- Top mass
- Top couplings



A particle with unique characteristics

- Special because of its enormous mass: heaviest known particle
  - Still a point-like particle in our understanding
  - The top and the Higgs are "strongly" coupled $y_t \approx 1 \quad m_t = y_t \mathrm{v}/\sqrt{2}$
  - The top mass dramatically affects the stability of the Higgs mass
    - If we consider the SM valid up to a certain scale Λ

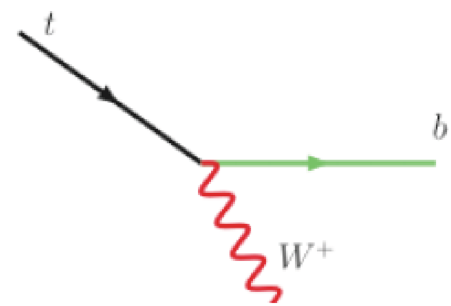




$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

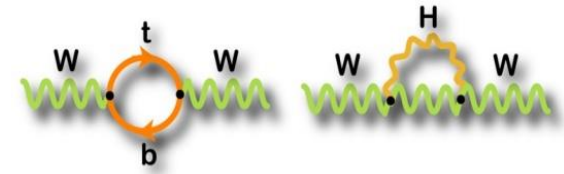
$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

- It is the only quark that does not hadronise
  - ○ $\tau(\mathrm{had}) \sim h/\Lambda_{QCD} \sim 2\ 10^{-24}$ s
  - ○ $\Gamma_{top} \approx 1.3$ GeV, $\tau(\mathrm{top}) \sim h/\Gamma_{top} \sim 5\ 10^{-25}$ s
  - ○ Compare with $\tau(b) \sim 10^{-12}$ s
  - ➢ Decays before forming a "dressed" top quarks
  - ➢ No bound tq states, its spin properties are directly passed to its decay products
  - ➢ QCD, Flavor and EWK physics at their best !



Constraining the SM

- Can use the fact that m_t, m_W, m_H are linked at loop level to constrain the SM
  - **The Higgs/symmetry breaking sector can be explored with more insights coming from top physics**

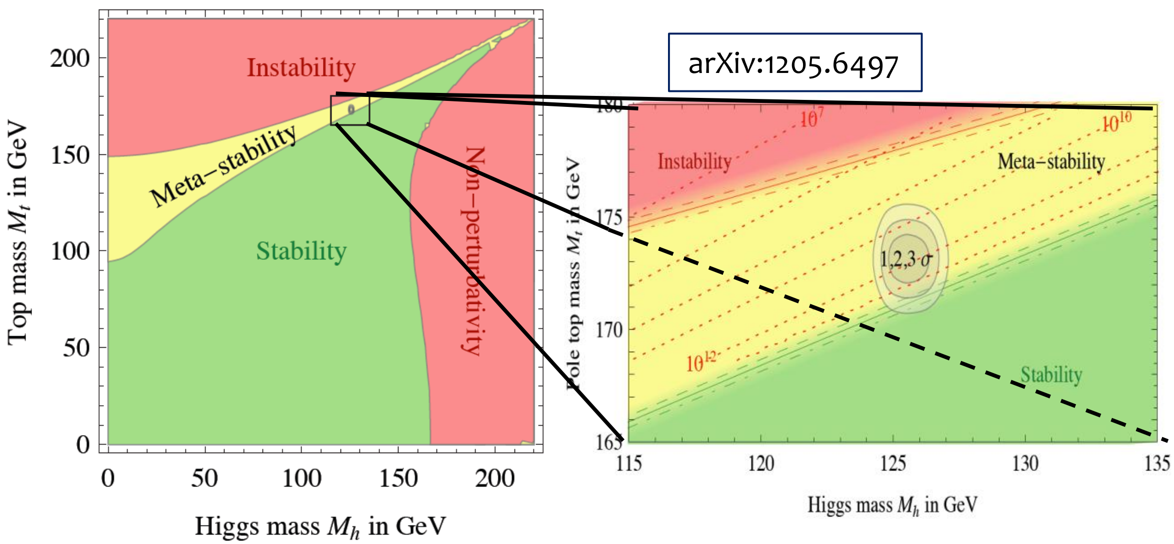


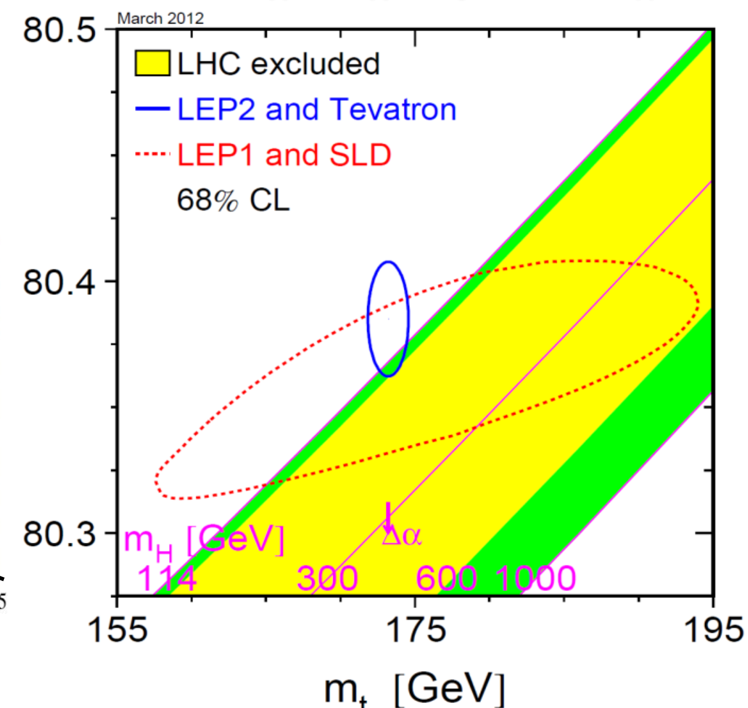
$\propto m_t^2$ $\propto ln(m_H)$

$m_W = m_W(m_t^2, \log(m_H))$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\ i} \psi_R^{\ j} \phi$$

λ now known at NNLO QCD. Vacuum meta-stability when the minimum of $V(\Phi)$ is just local



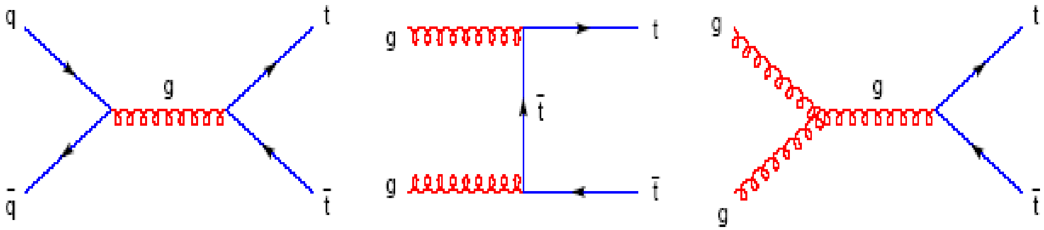


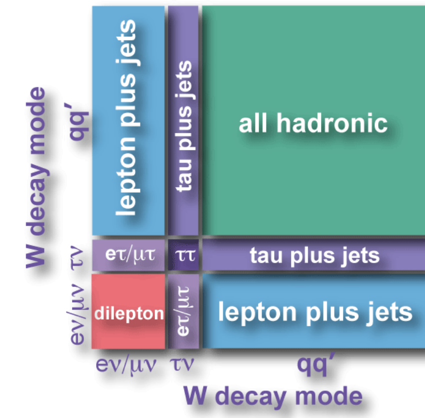
- The top quark also provide other direct constraints to the model
  - Direct access to parameters of the SM (m_t, V_{tb})
  - Other stringent tests of SM (QCD in dσ/dX, couplings, CPT invariance,…)

Top (pair) production at the LHC

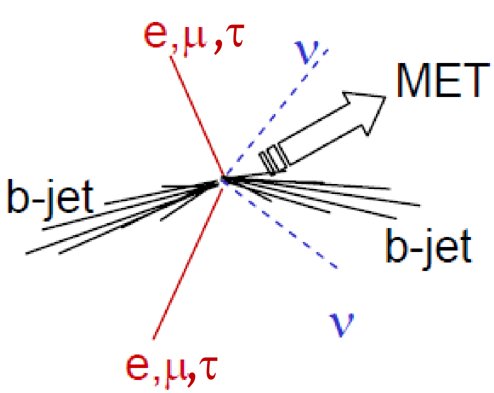
- Top pair QCD production happens mainly via gluon fusion

	σ(NNLO+NNLL) ± scales ± PDFs [pb]		
	7 TeV	8 TeV	13 TeV
Czakon, Fiedler, Mitov (PRL 110 (2013) 252004)	$172.0^{+4.4}_{-5.8}\,^{+4.7}_{-4.8}$	$245^{+6.2}_{-8.4}\,^{+6.2}_{-6.4}$	$832^{+20}_{-29} \pm 35$



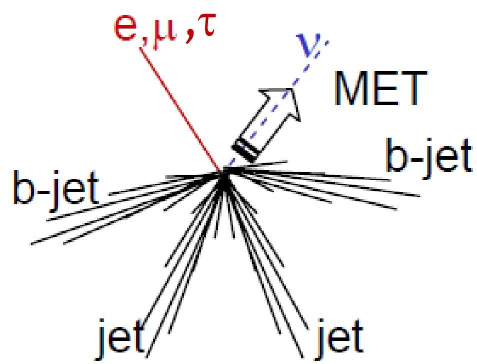


- Final states depend on the decay of the W bosons



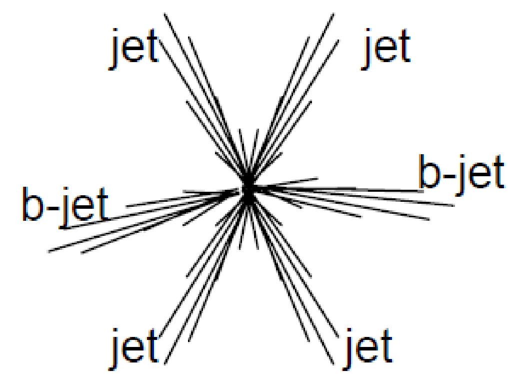
dileptons

- BR~10%



lepton + jets

- BR~44%



all hadronic

- BR~46%

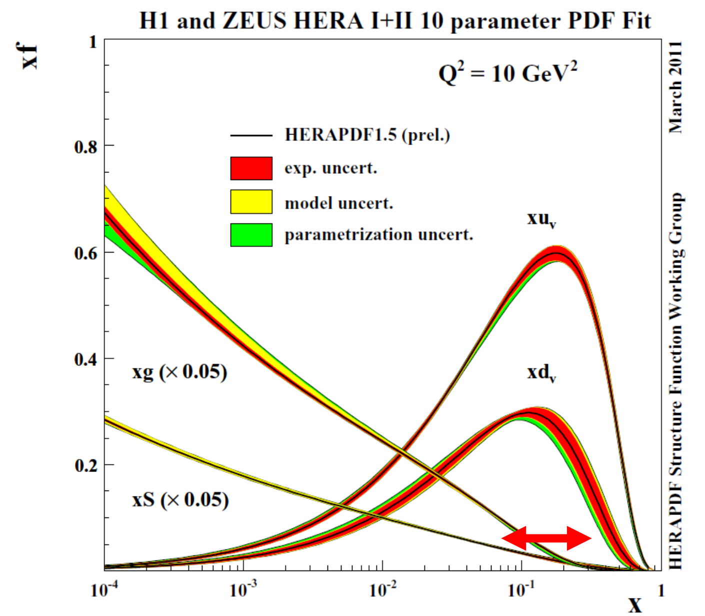
- Backgrounds coming from: W/Z+jets, single top (tW), QCD, di-boson

Total cross section measurements

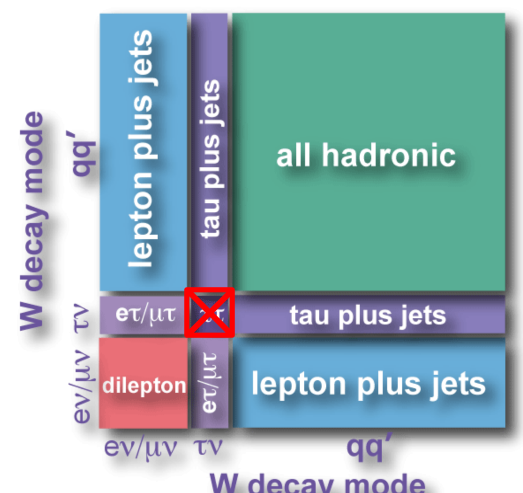
- Monitoring the total production cross section is the first fundamental step for understanding top physics at the LHC
  - Test the presence of new production mechanisms
  - In the frame of the SM, test QCD predictions and help constraining the PDFs (especially gluons)
    - Important for Higgs production

$$\sigma_{t\bar{t}}(m_t) = \sum_{i,j} \int_0^1 dx_1 dx_2 \, f_i(x_1) f_j(x_2) \, \hat{\sigma}_{ij}(m_t)$$

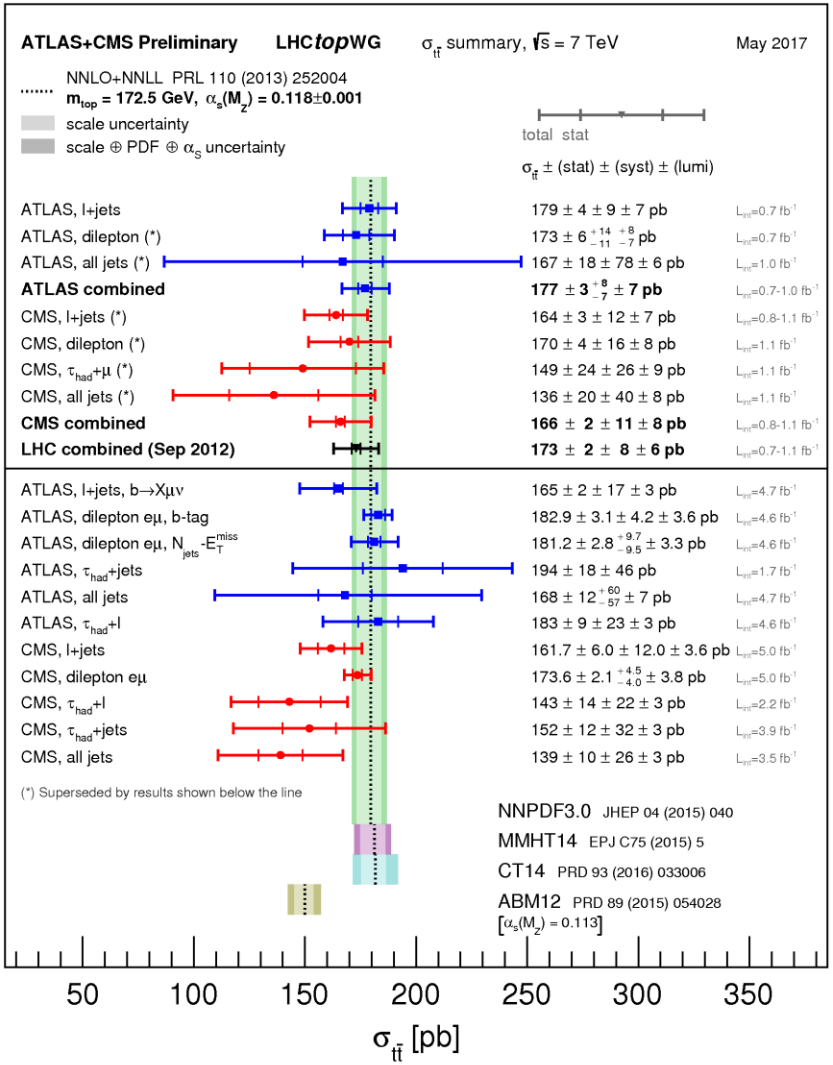
  - Indirect determination of m_t or α_S.
  - Constrain a very important background for many searches at the LHC

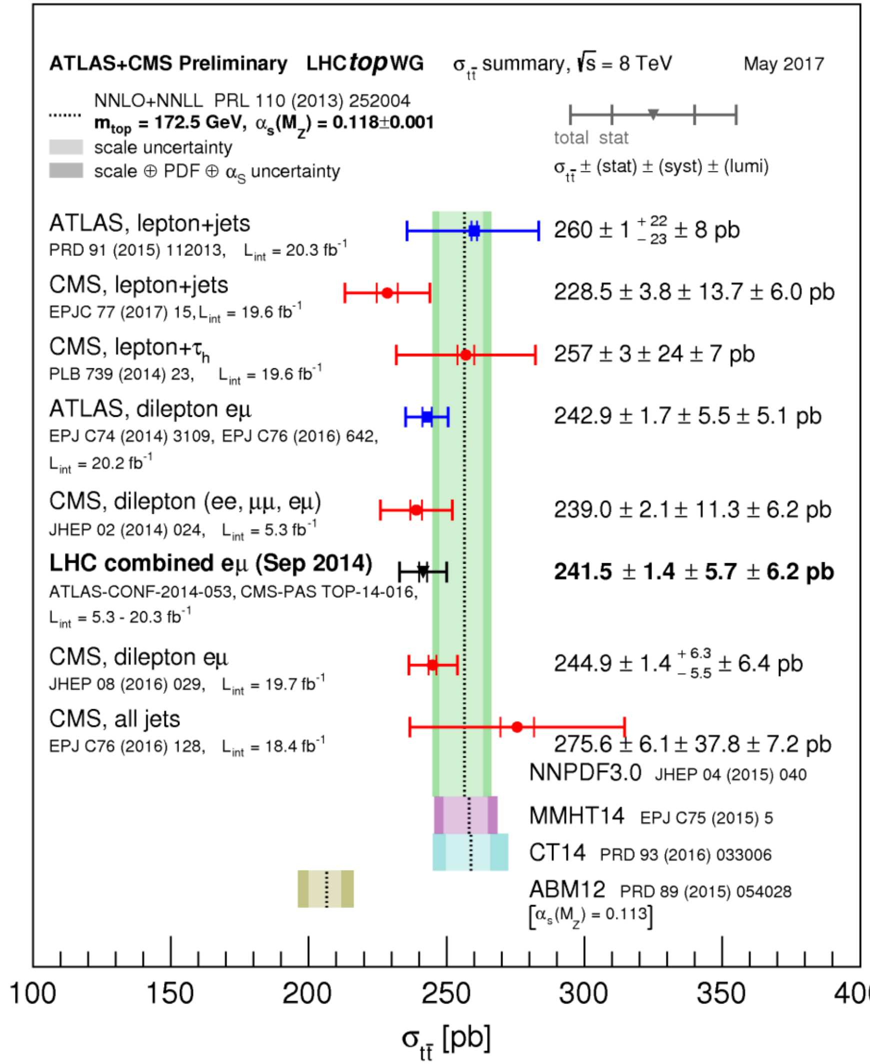


- **All decay modes are investigated at the LHC**
- The measurements are performed at different level of complexity:
  - ➢ Counting experiment in acceptance $\sigma = \dfrac{N_{data} - N_{BG}}{\epsilon_{t\bar{t}} \int \mathcal{L} dt}$
  - ➢ Fit to data in several portions of phase space with in situ constraining of various backgrounds
  - ➢ Multivariate analyses
  - ➢ Selections defined for inclusive cross sections are in general used for the rest of the measurements in that final state



CMS + ATLAS inclusive cross sections





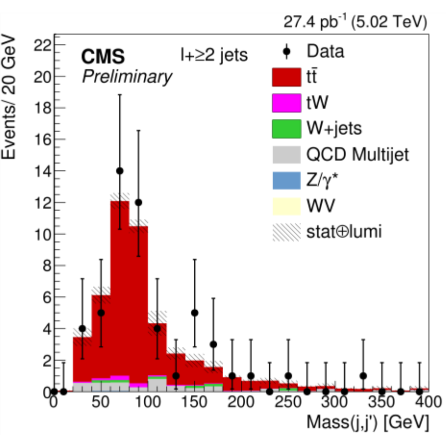
eμ channels provide the best sensitivity. Main systematic uncertainties, modelling, lepton/trigger eff., luminosity, not so easy to improve.

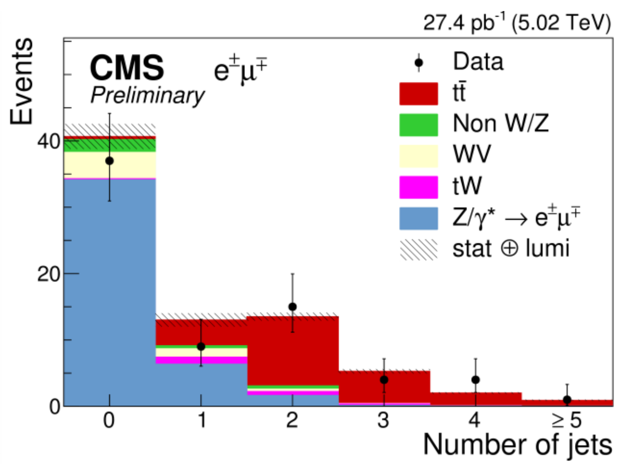
CMS and ATLAS new results on $t\bar{t}$ production at 5 and 8 TeV

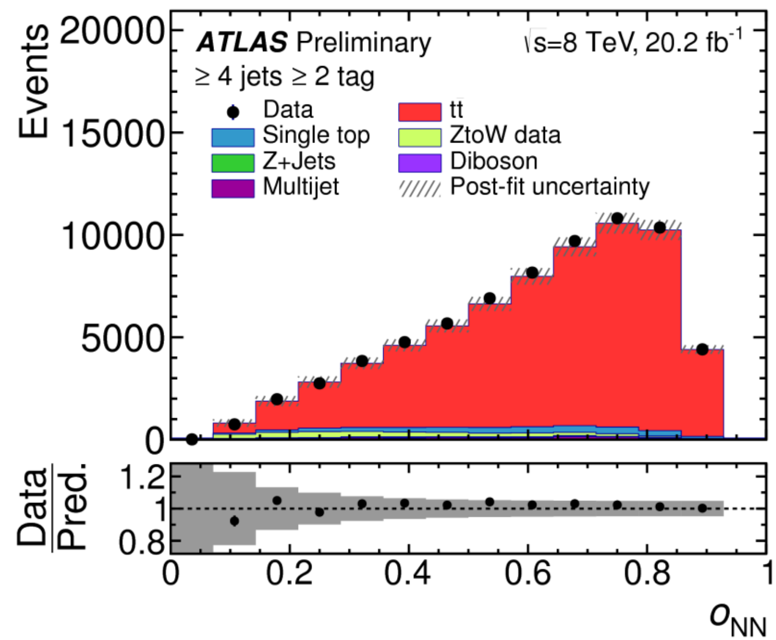
- Measurement at **5 TeV** in **$t\bar{t}\to\ell$+jets, eμ** and **μμ**. Short **5.02 TeV** pp run (HI ref.) **CMS-TOP-16-023.**
  - Dilepton (eμ, μμ) and single-lepton channels combined. Single-lepton in b-jet categories.
  - W -> jj obtained from ΔR(jj')

- New measurement in **$t\bar{t}\to\ell$+jets** at **8 TeV. ATLAS-CONF-2017-054**
  - 3 signal regions (n jets, n tags)
  - NN with kinematical variables likelihood fit
  - largest **uncertainties**: modeling, JES, lepton ID, trigger,

- **Becoming competitive with eμ.**





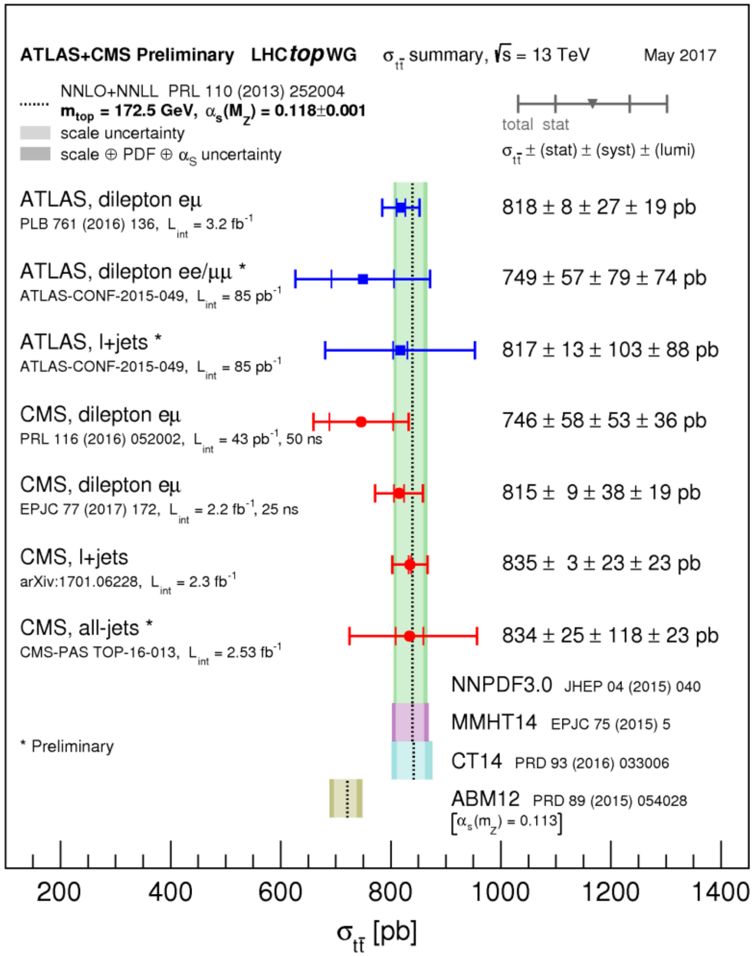


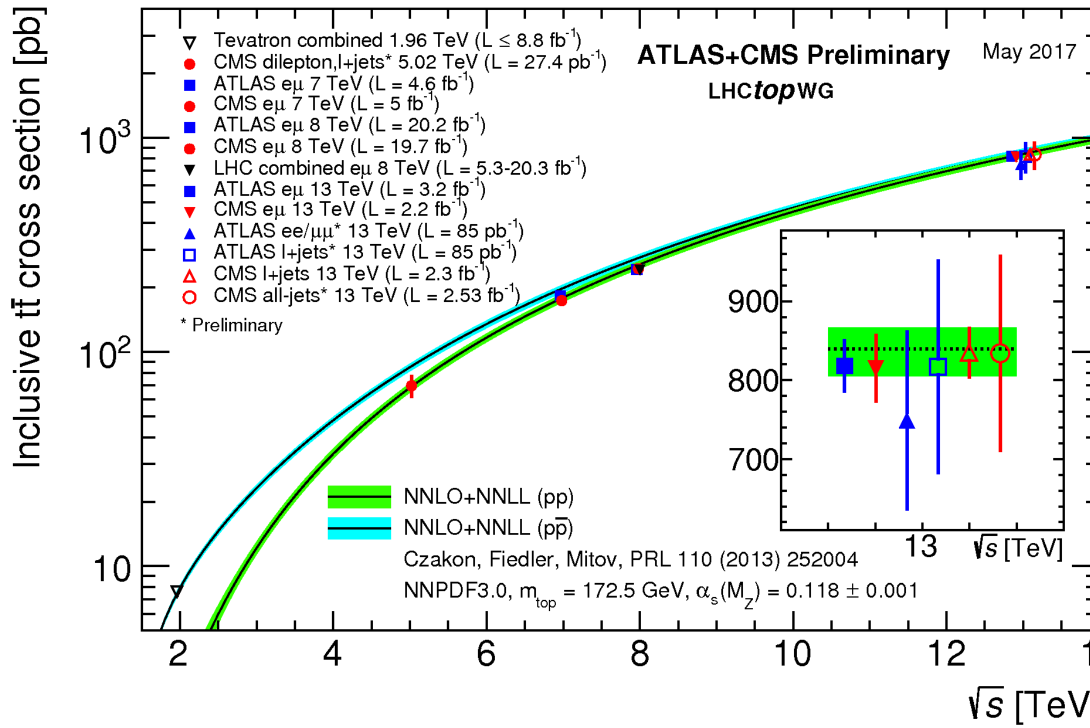
σ_{tt}=69.5±6.1(stat.)±5.6(syst.)±1.6(lumi.) pb

A moderate decrease of the uncertainty in the gluon distribution is observed at high fractions of the proton momentum carried by the gluon

σ_{tt}=248.3±0.7(stat.)±13.4(syst.)±4.7(lumi.) pb

$t\bar{t}$ inclusive cross section





All channels already considered at 13 TeV. Not all luminosity collected at this energy used. Systematics limited

Rapid rise: reflecting the gluon density

Measurements at different centre of mass energies and in many channels, provide consistent results, and good agreement with full NNLO+NNLL calculations.

Experimental sensitivity: 3.5-4%

Top pair differential cross sections

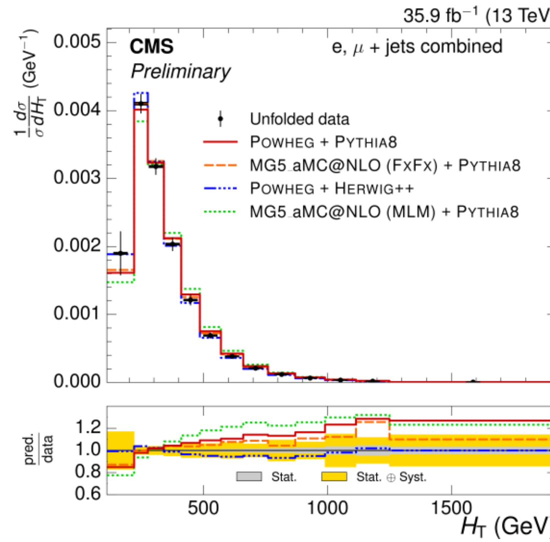
$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\text{Data}} - N^i_{\text{BG}}}{\Delta^i_{\text{X}}\epsilon^i L}$$

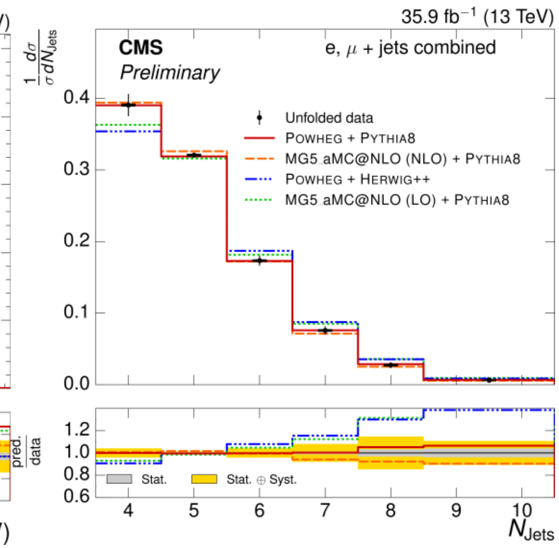
- Test top physics in different portions of the phase space
  - Test of perturbative QCD, constrain of different generators, theory uncertainties, systematic effects. Window to new physics
  - Use unfolding techniques on background-subtracted reconstructed distributions for a direct comparison to theory predictions
  - Propagation of the systematic errors (only shape errors important)
    - Most relevant coming from lepton/trigger ID, background knowledge, MC modelling
- Look at lepton, jets, and to more complex variables in top quark final states
  - Compare to reference generators and predictions on differential distribution from theory
- Defined with respect to **tt̄** signal:
  - **Parton level (full phase space)**
    - After QCD radiation and before decay.
    - Trying to mimic definition of bare quark used often in theory calculations of fixed order.
    - **Used to extract SM parameters.**
  - **Particle level (fiducial phase space)**
    - Based on stable particles after hadronization
    - Fiducial phase space defined according to detector level cuts
    - Effects from extrapolation are reduced
    - **Used to tune MC and test of BSM models**

CMS 0/1 lepton differential distributions

CMS-TOP-PAS-16-014

- Global event variables.
  - No need to reconstruct the **tt** system.
  - Particle level.
- Normalized differential σ_{tt}
  - Compared to MC predictions
- Overall good agreement data/predictions

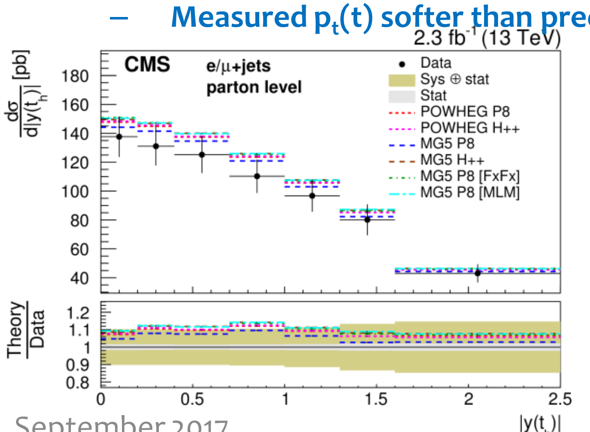


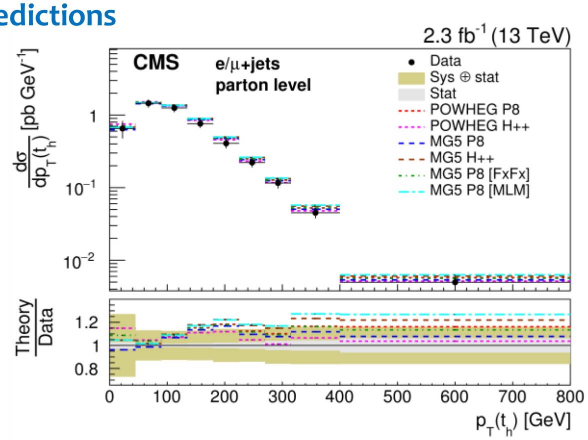


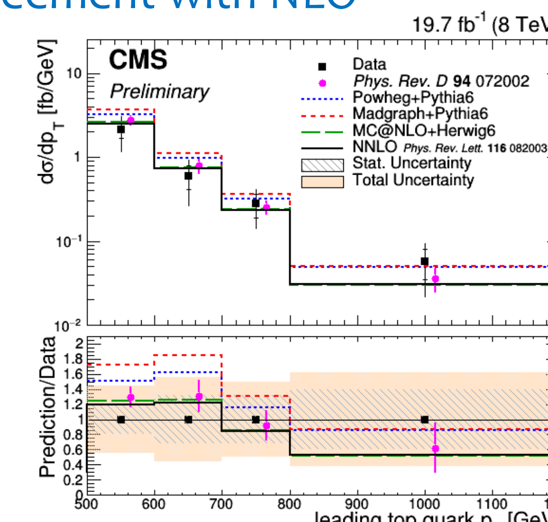
Phys. Rev. D 95, 092001 (2017)

- Dominant uncertainties
  - MC modelling and hadronization at parton level
  - JES and PS scale at particle level
- In general, compatible within uncertainties
  - **Measured $p_t(t)$ softer than predictions**

CMS-TOP-PAS-16-018, All-jets, **high-p_T regime**, **new**, 8 TeV. Corrected to parton level. Good agreement with NLO calculations.



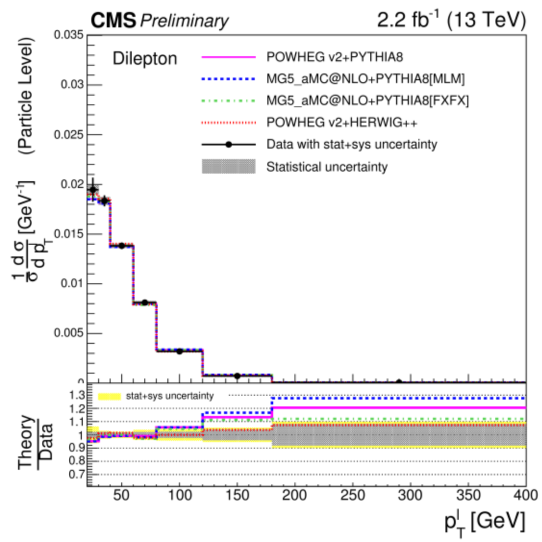


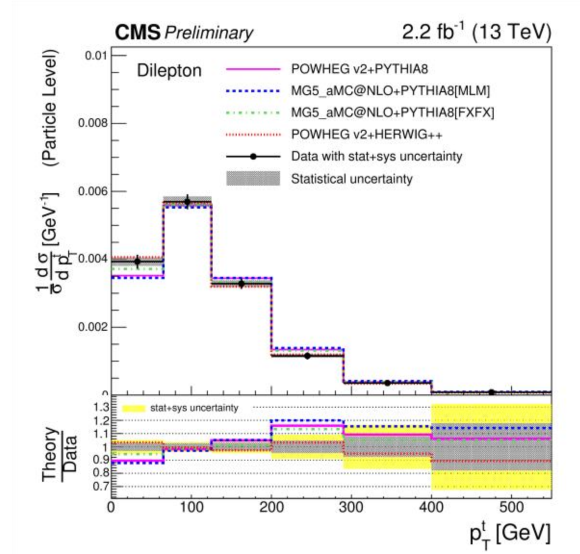


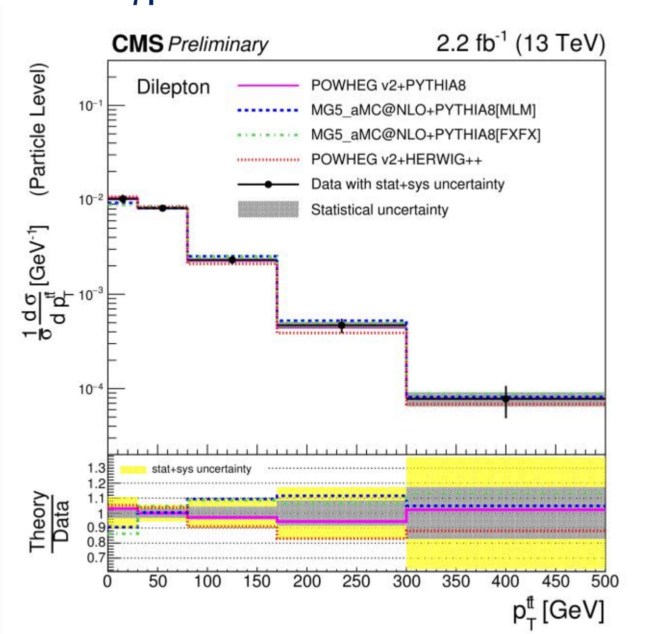
CMS dilepton differential distributions

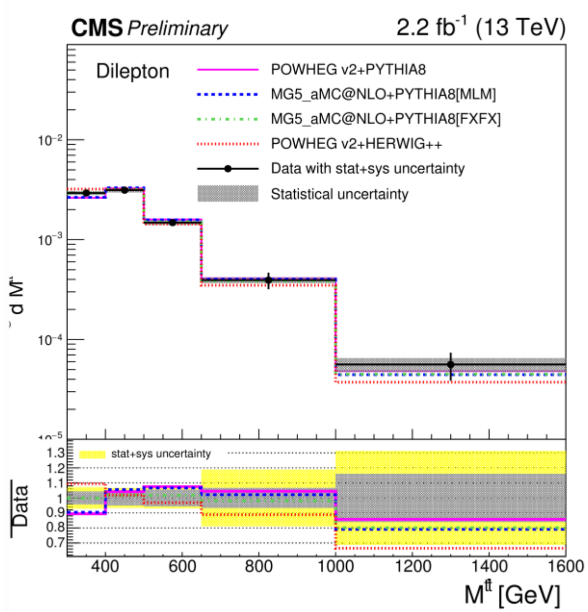
CMS-TOP-PAS-16-007
arXiv:

- Normalized differential σ_{tt}
  - as a function of the kinematic properties of the leptons, b jets, top quarks, and top quark pairs at particle level
  - Visible phase space
  - Compared to MC prediction
- Overall good agreement data/predictions.









Dominant uncertainties:

MC modelling, hadronisation and scales.

Experimental: JES, JER, b jet SF.

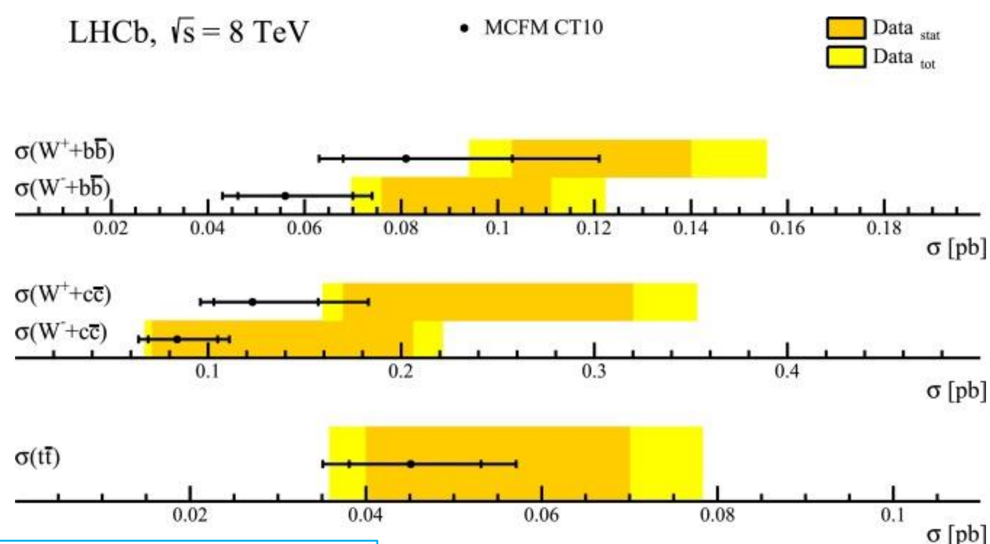
In general, results compatible within uncertainties.

POWHEG-HERWIG++ prediction describes the data slightly better than the PYTHIA 8 interface, with the exception of the M_{tt} distribution.

$t\bar{t}$ cross section at large η/p_T

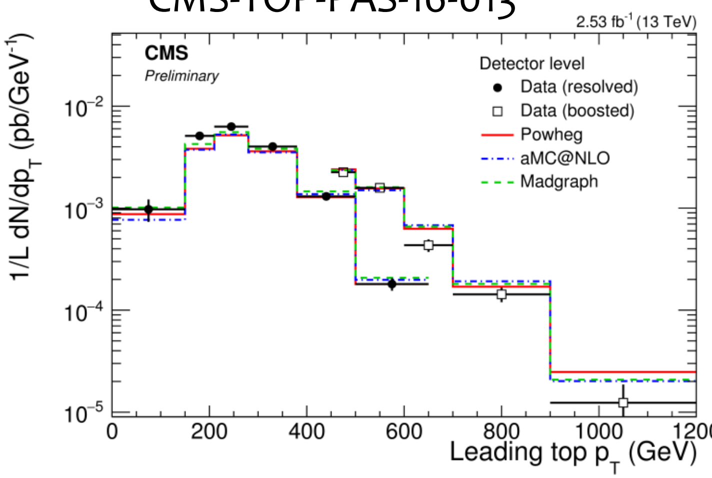
- **Unique** measurement from **LHCb** in the forward region **$2.2 < \eta < 4.2$** Performed with 2.0 fb^{-1} at 8 TeV: **PLB 767, 110 (2017)**
- **ℓ+ 2 heavy flavor jets**
  - 4-dimensional fit to mjj to:
    - $t\bar{t}$, W+$c\bar{c}$, W+$b\bar{b}$ and bkg. distributions.
  - both e/mu+ $b\bar{b}$ used.
- First observation of W+$c\bar{c}$
- **This continues the LHCb programme from the first measurement (that had signal over 5 sigma): PHYS. REV. LETT. 115, 112001 (2015)**

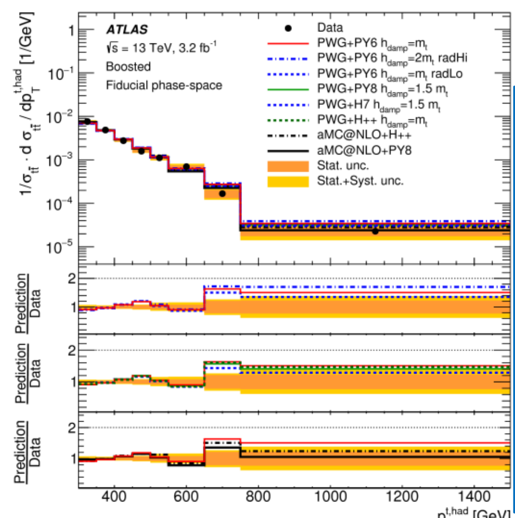
$t\bar{t}$ signal observed with 4.9 σ, 40% precision



Large Transverse Momentum

CMS-TOP-PAS-16-013



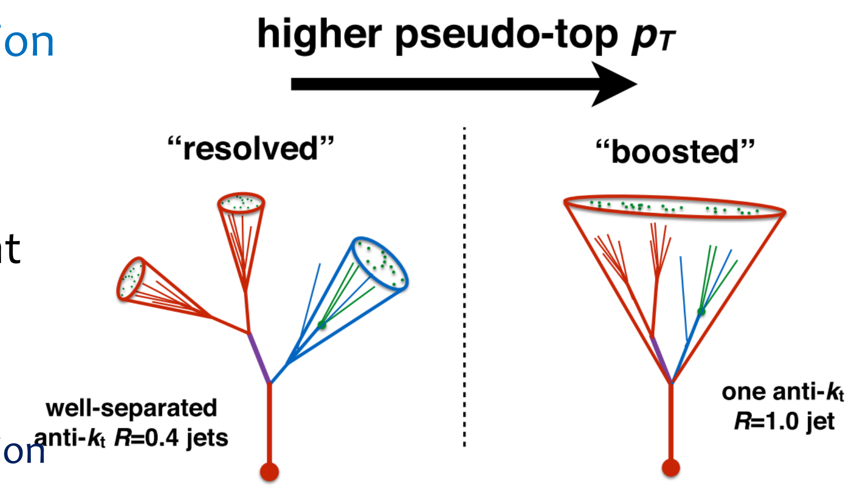


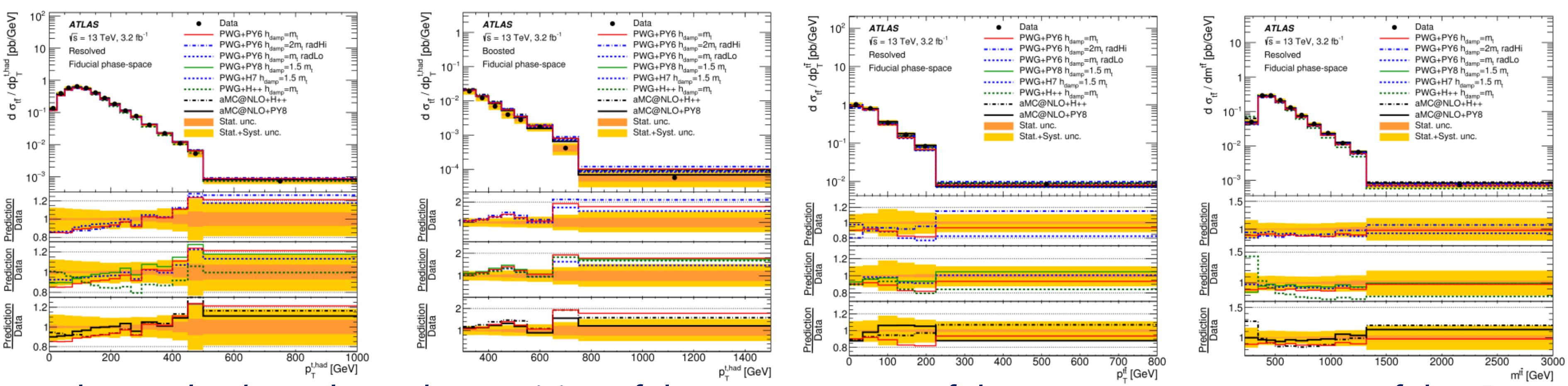
ATLAS: *arXiv:1708.00727*

p_T of the top quarks tend to be softer than NLO MC generator predictions, while NNLO calculations improve the agreement.
Some differences between ATLAS and CMS measurements.

ATLAS $t\bar{t}$ differential distributions in lepton+jets at 13 TeV *arXiv:1708.00727*

- Differential cross-sections of top-quark pair production in fiducial phase-spaces as a function of top-quark and $t\bar{t}$ system kinematic observables.
- Resolved and boosted top reconstruction
- Large-R jet JES uncertainty becomes dominant at high-p_T
- In general, the Monte Carlo predictions agree with data in a wide kinematic region
  - The shape of the transverse momentum distribution of hadronically decaying top quarks is poorly modelled by all NLO + PS predictions, where the disagreement is largest at high transverse momentum.





In the resolved topology, the precision of the measurement of the transverse momentum of the $t\bar{t}$ system makes it possible to distinguish between different settings in the NLO+PS calculations.

ATLAS lepton differential distributions

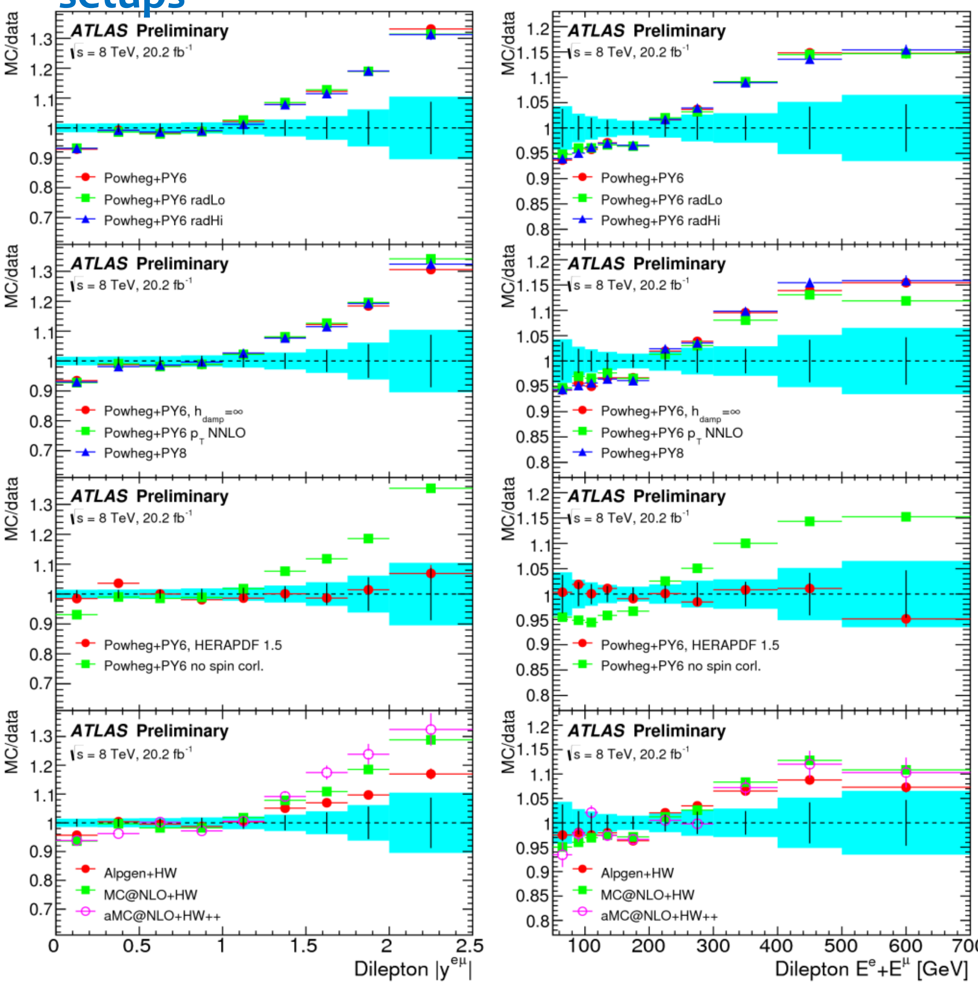
ATLAS-CONF-2017-044

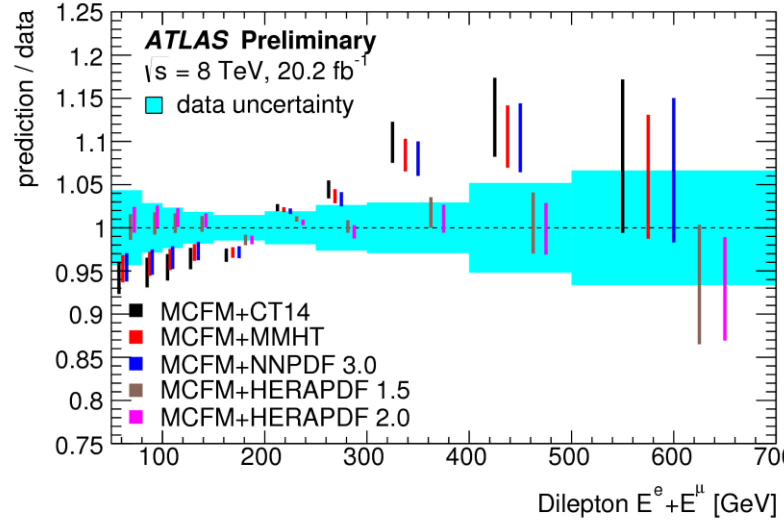
Use eμ events for background rejection

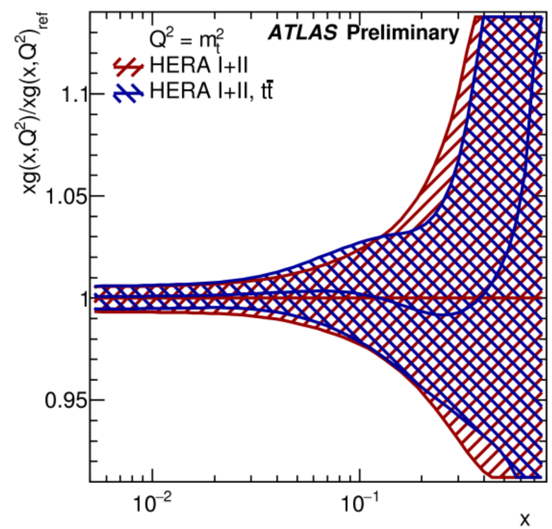
90% purity, tW main bkg.

Largest uncertainties from MC modelling, lepton ID, trigger.

Discrepancies with data from some generator setups





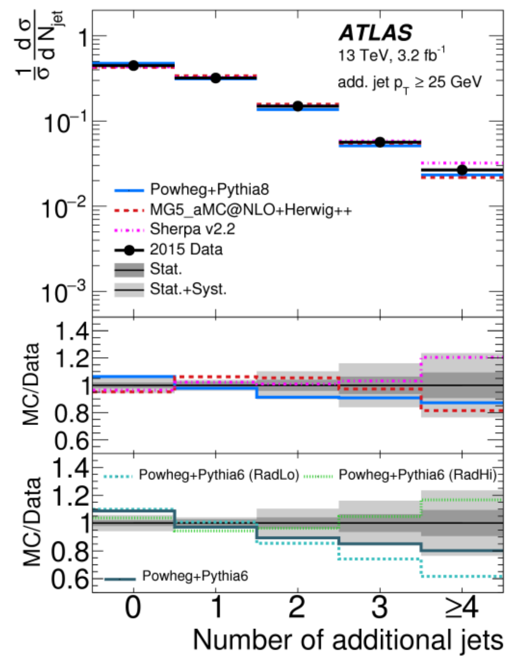


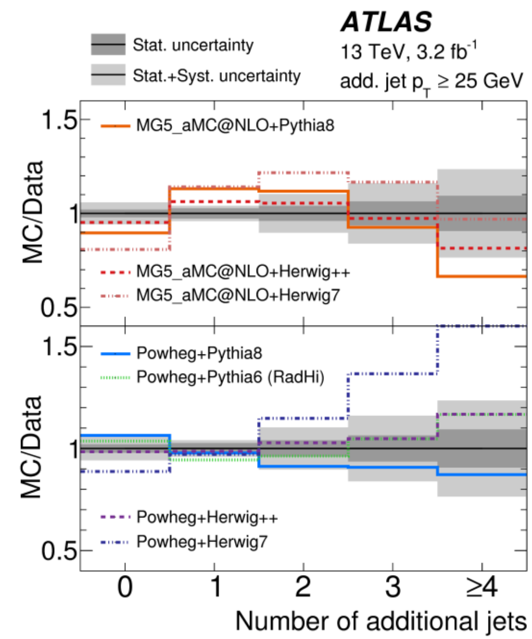
Different observables have sensitivity to the choice of the PDFs

ATLAS: $t\bar{t}$+jets in eμ at 13 TeV

ATLAS: EPJ C 77 (2017) 20

- Measurement of QCD radiation produced with top quark pair crucial to tune MC parameters
  - Improve modelling of parton shower and hadronization and overall top kinematics description
  - Additional jets (those produced in addition to the 2 highest p_T b-jets) are identified as jets above p_T thresholds of 25, 40, 60 and 80 GeV
- **Good agreement with MC predictions. Sensitive to PS models and QCD radiation scale**



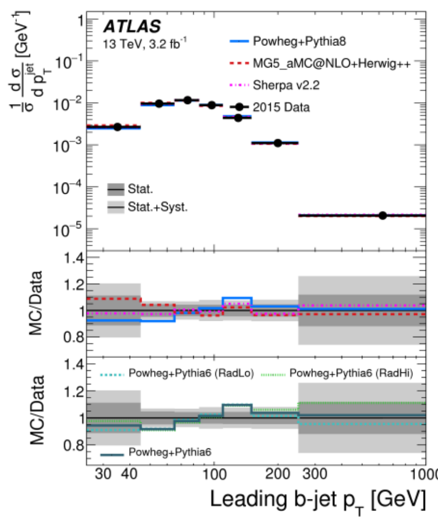


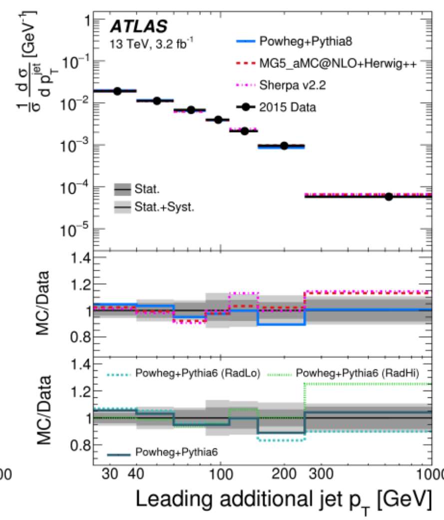
Particle-level normalized differential cross-sections vs **b-jets and additional jet p_T**

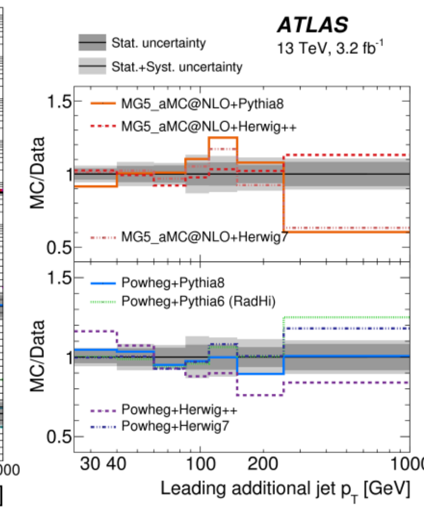
Significant systematic sources JES/JER, NLO generator and PS hadronization modeling

Comparison with various PS models

Generally in good agreement



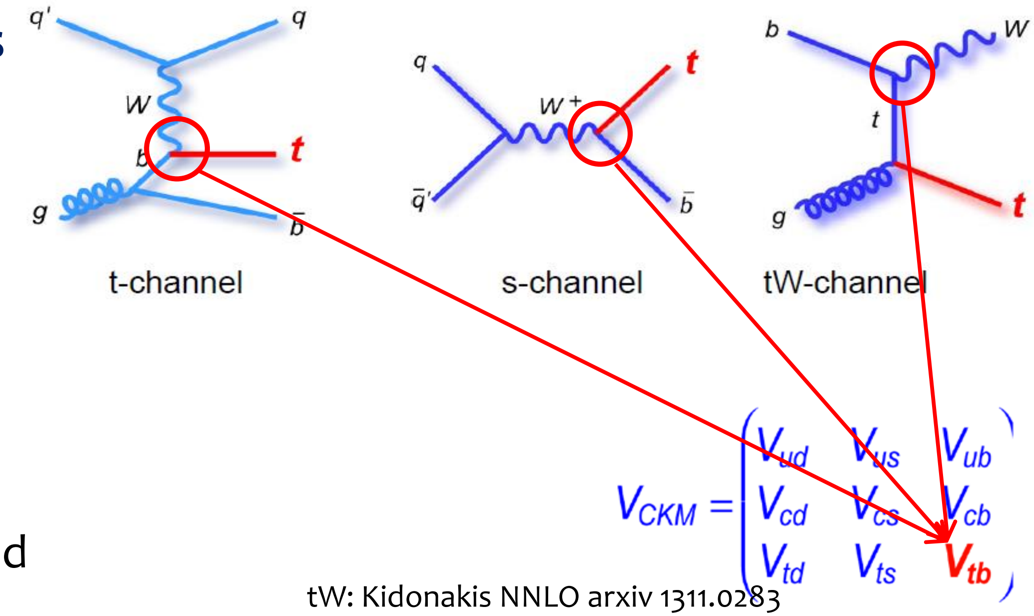




Single top quark production

Top quarks produced singly via electroweak interaction

- **The production cross section gives direct access to the CKM matrix element $|V|_{tb}$**
  - May also test the presence of a possible 4th generation quark, charged W', H^+
  - Check for presence of FCNC
  - Important background for, among others, Higgs searches in associated production W/ZH→qqbb



tW: Kidonakis NNLO arxiv 1311.0283

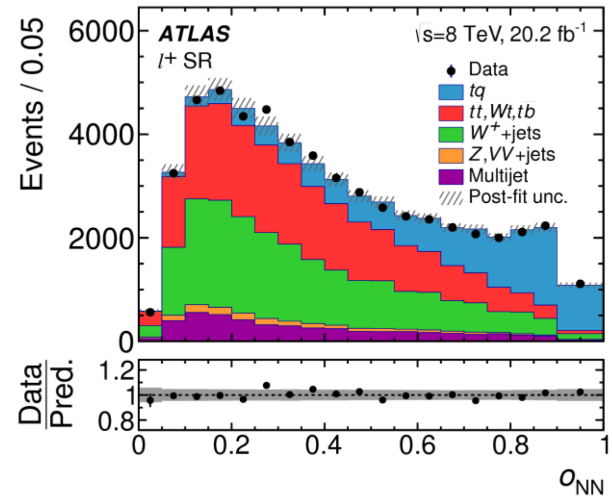
	8TeV	13 TeV	order
t-chan.	84^{+3}_{-3} pb	217^{+9}_{-8} pb ($213.7^{1.6}_{0.8}$pb)	NLO (NNLO)
tW-chan.	22^{+4}_{-4} pb	71^{+4}_{-4} pb	aNNLO
s-chan.	$5.2^{+0.22}_{-0.20}$ pb	10^{+4}_{-4} pb	NLO

- **Investigate t-channel and tW production**
  - ➢ s-channel still out of range for an observation
  - ➢ **t-channel:** 1 isolated e or μ, one b-tagged jet, one forward jet, missing E_T
  - ➢ **tW channel:** 2 isolated charged leptons (e, μ), one b-tagged jet, missing E_T
- **Main backgrounds** from top-pair production (both semileptonic and di-leptonic topologies), Z(ll)/W(lν)+jets, Multijet QCD (reduced to extreme kinematic regions by selection cuts)
  - ➢ Use data whenever possible to constrain the backgrounds

ATLAS Single top t-channel at 8 TeV

arXiv:1702.02859v2, Eur. Phys. J. C 77 (2017) 531

- **Fiducial cross section**, and extrapolation to full phase space. Neural network to enhance S/B
  - Separate cross section determined for l+ and l- events
  - Binned maximum likelihood fit to extract cross section
- Uncertainties: systematically dominated: jet energy scale, NLO matching choice and lepton reconstruction



$$|f_{LV}.V_{tb}|^2 = \frac{\sigma(tq+\bar{t}q)_{\text{meas.}}}{\sigma(tq+\bar{t}q)_{\text{pred.}}} = 1.09 \pm 0.048$$

$$\sigma_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}}{L_{\text{int}}}$$

Measured number of signal events

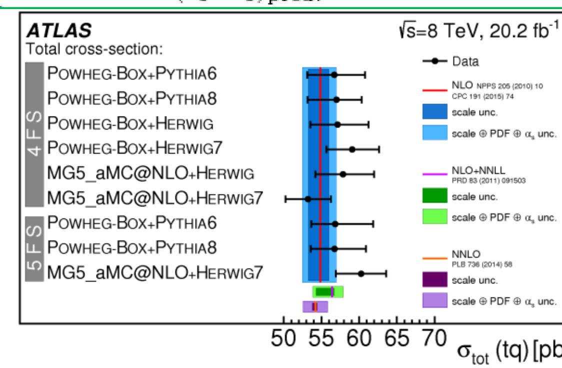
$$\sigma_{\text{fid.}}(tq) = 9.78 \pm 0.57 \text{ pb}$$

$$\sigma_{\text{fid.}}(\bar{t}q) = 5.77 \pm 0.45 \text{ pb}$$

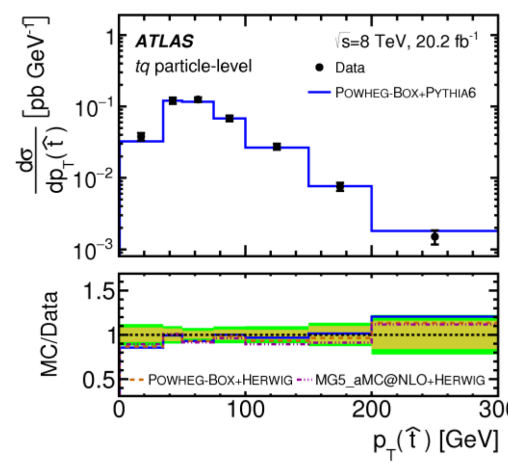
$$\sigma_{\text{tot}} = \frac{N_{\text{tot}}}{N_{\text{fid}}} . \sigma_{\text{fid}}$$

$$\sigma_{tq}^{\text{tot}} = 56.7^{+4.3}_{-3.8} \text{ pb}$$

$$\sigma_{\bar{t}q}^{\text{tot}} = 32.9^{+3.0}_{-2.7} \text{ pb}$$



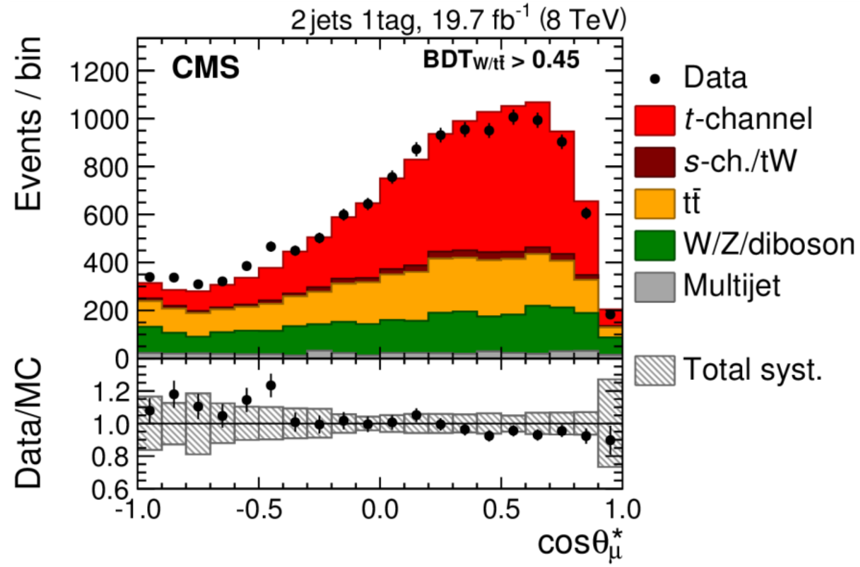
- **Differential measurements**, $O_{NN}>0.8$ to enhance signal purity.
- Unfolded distributions:
  - $P_T(t)$ and $y(t)$ for top and anti-top at parton level
  - $P_T(t)$, $|y(t)|$, $P_T(j)$, $|y(j)|$ for top and anti-top at particle level
- **Good agreement with NLO predictions.**



CMS top polarization in t-channel at 8 TeV

JHEP 04 (2016) 073

- Measurement of the differential cross section as a function of $cos\theta*$ (lepton in top rest frame and recoiling jet).
- Sensitive to the top-quark polarisation.



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_X} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X \cos\theta^*_X) = \left(\frac{1}{2} + A_X \cos\theta^*_X\right)$$

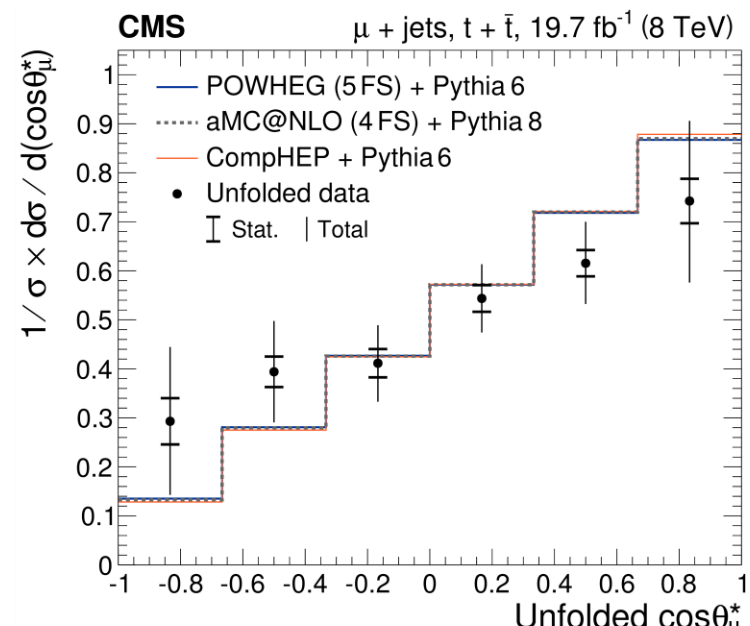
$$A_X \equiv \frac{1}{2} P_t \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

$$\boldsymbol{A_\mu(SM) = 0.44}$$

- Event selection and signal extraction: similar to the t-channel inclusive cross section measurement.
- Differential cross section unfolded at parton level. Top quark spin asymmetries :

$$A_\mu(t) = 0.29 \pm 0.03\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.29 \pm 0.11,$$
$$A_\mu(\bar{t}) = 0.21 \pm 0.05\,(\text{stat}) \pm 0.13\,(\text{syst}) = 0.21 \pm 0.14,$$
$$A_\mu(t+\bar{t}) = 0.26 \pm 0.03\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.26 \pm 0.11,$$

2σ deviation w.r.t. SM

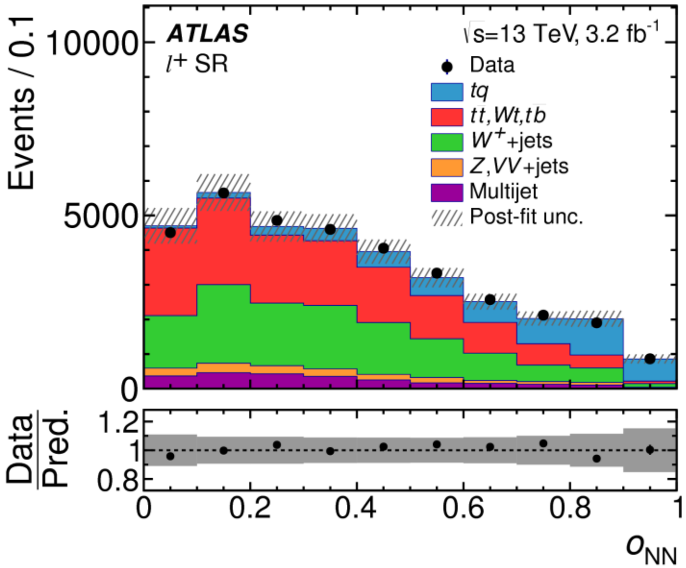


Single top t-channel at 13 TeV

ATLAS: arXiv:1609.03920 JHEP04(2017)086 , CMS: arXiv:1610.00678, acc. PLB

Similar strategy wrt 8 TeV analysis.

Total uncertainty 18%(l^+) ,20%(l^-) Leading systematics: PS (14%) b-tagging efficiency (7%)

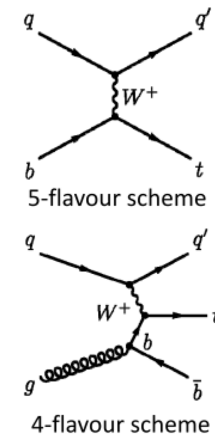


$$\sigma_{tq} = 156 \pm 5(\text{stat.}) \pm 27(\text{syst}) \pm 3(\text{lumi})\ \text{pb}$$

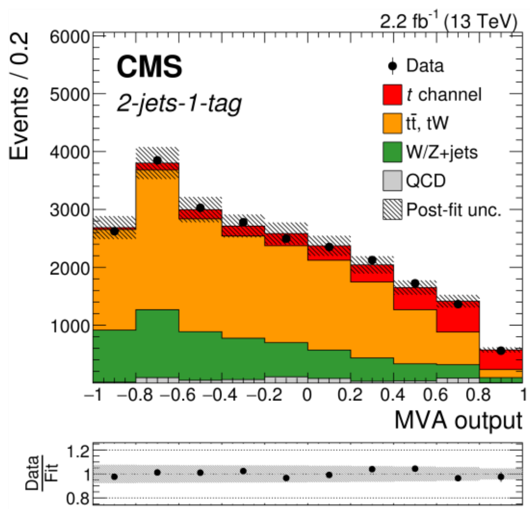
$$\sigma_{\bar{t}q} = 91 \pm 4(\text{stat.}) \pm 18(\text{syst}) \pm 2(\text{lumi})\ \text{pb}$$

$$R_t = 1.72 \pm 0.09(\text{stat.}) \pm 0.18(\text{syst})$$

$$f_{LV} \cdot |V_{tb}| = 1.07 \pm 0.09$$



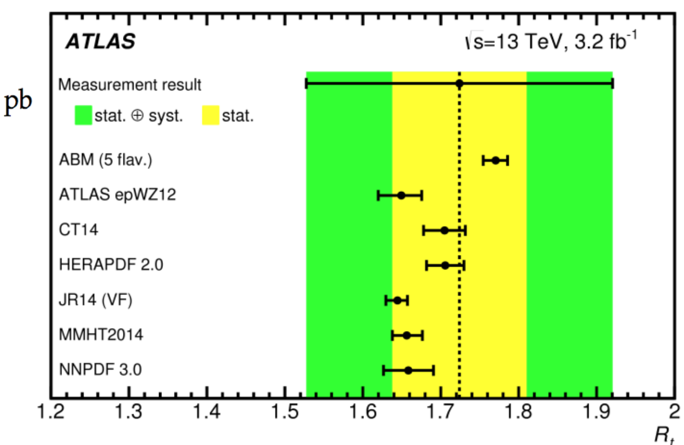
b-quark in the proton (5-Flavour Scheme, 5FS)?
Or should be produced dynamically from gluons (4FS)?
Need to factorise the two diagrams properly



$$\sigma^{\text{th}}_{t\text{-ch.},t+\bar{t}} = 238 \pm 13\,(\text{stat}) \pm 12\,(\text{exp}) \pm 26\,(\text{theo}) \pm 5\,(\text{lumi})\ \text{pb} = 238 \pm 32\ \text{pb}.$$

$$|f_{LV} V_{tb}| = 1.05 \pm 0.07\,(\text{exp}) \pm 0.02\,(\text{theo})$$

$$R_{t\text{-ch.}} = 1.81 \pm 0.18\,(\text{stat}) \pm 0.15\,(\text{syst}).$$

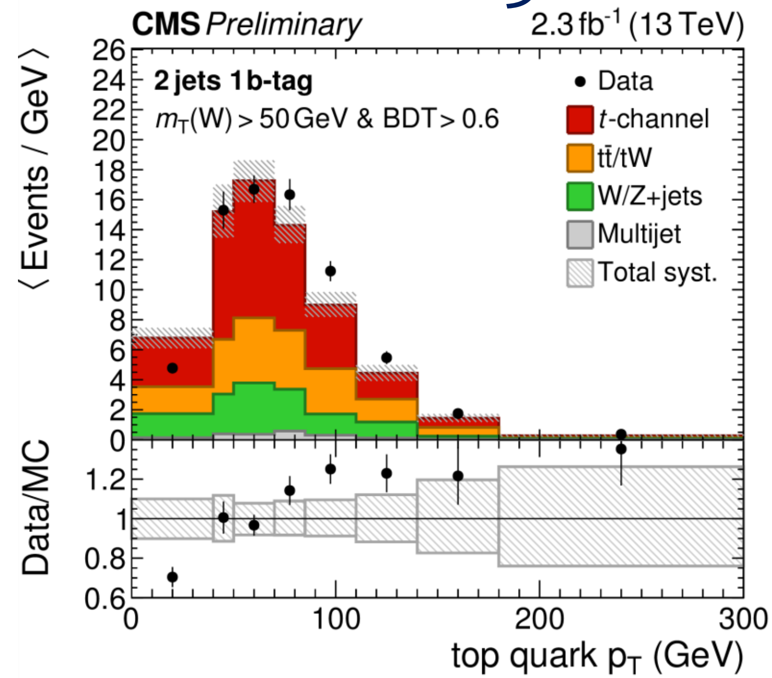


R_t agrees with PDFs

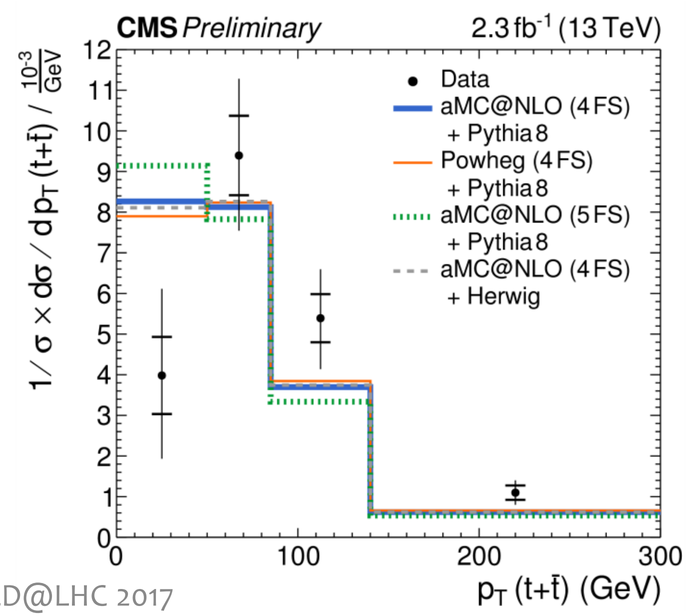
Single top t-channel, differential cross-section at 13 TeV

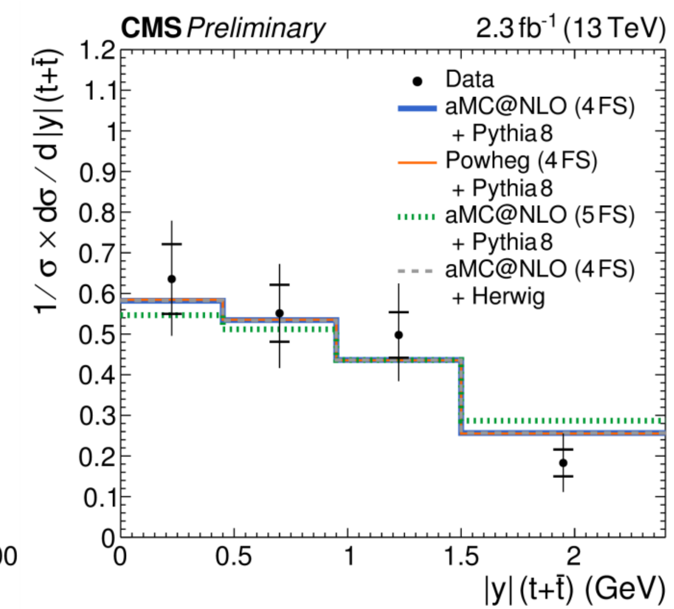
CMS: TOP-16-004

- Event Selection : similar to inclusive cross-section measurement (*arXiv:1610.00678*)
- Top quark reconstructed from the muon, the b-jet and the MET + W mass constrain.
- Signal extraction also similar to inclusive cross-section measurement
  - Choice of BDT variables : avoid bias in the measurement,
  - in the 2J1T, fit of a BDT for $m_T(W)$>50 GeV, use $m_T(W)$ distribution otherwise.

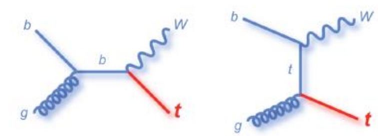


Differential measurements, unfolded to parton level after background subtraction.





Single top tW channel

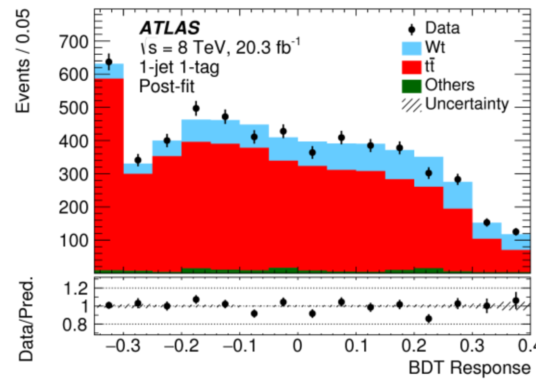


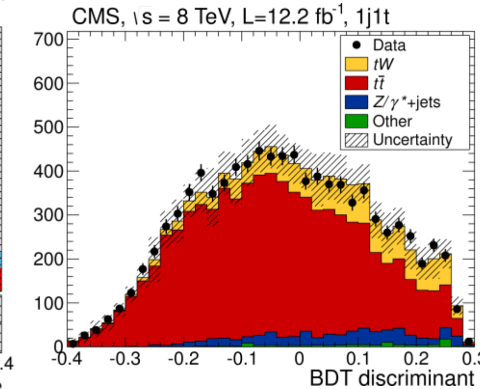
8 TeV: CMS: PRL 112, 231802 (2014), ATLAS: JHEP01(2016)064, **13 TeV**: ATLAS: arXiv:1612.07231

$\sigma_{tW(th)}$ = 22.2 ± 0.6(scale) ±1.4(PDF) pb

tW production observed at LHC

– Only leptonic (e, μ) decays of W considered
– In the dilepton topology: two isolated leptons, MET and one b-jet, main backgrounds: Top pairs and Z+jets
– Signal and control regions defined according to the number of jets and number of b-jets.





BDT used to enhance S/B

– Main syst. uncertainties: tt normalization, Jet Energy Scale (JES), ISR/FSR

$$\sigma_{tW} = 20.0 \pm 1.3(\text{stat.})^{+3.2}_{-3.5}(\text{syst.}) \pm 1.1(\text{lumi.})\text{pb}$$
$$|V_{tb}| = 1.01 \pm 0.10$$

Observed (expected) significance 7.7σ (6.9σ)

Observed/Expected significance **6.1 σ/5.4σ.**
Cross-section: $\boldsymbol{\sigma_{tW} = 23.4 \pm 5.4}$ **pb**

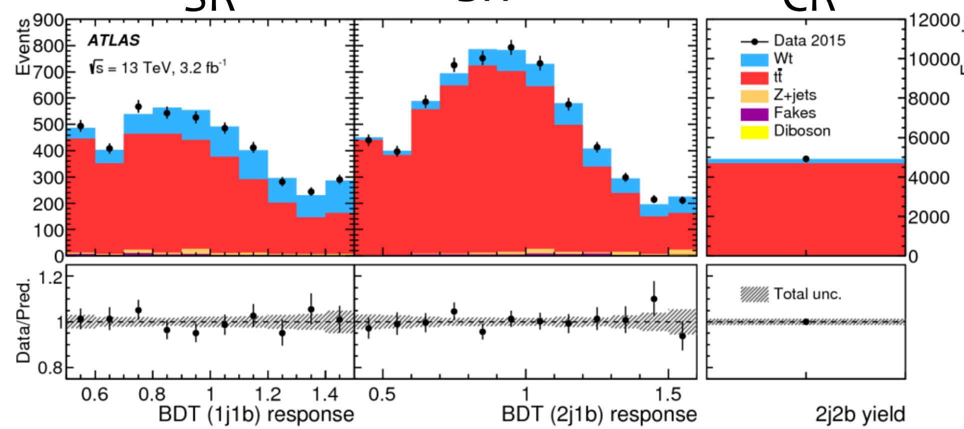
ATLAS 13 TeV similar to the 8 TeV analysis
2 separate BDTs trained in two signal regions (1j1b and 2j1b)

Profile binned likelihood fit used to extract the cross section

Main systematic uncertainties:

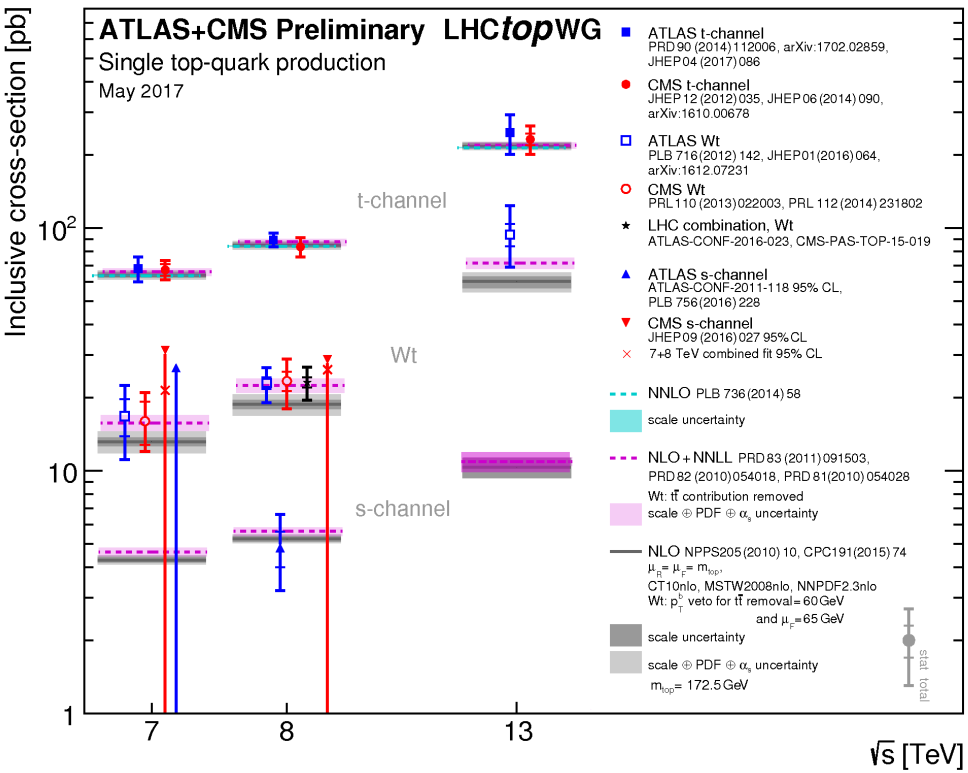
– JES
– NLO matrix element

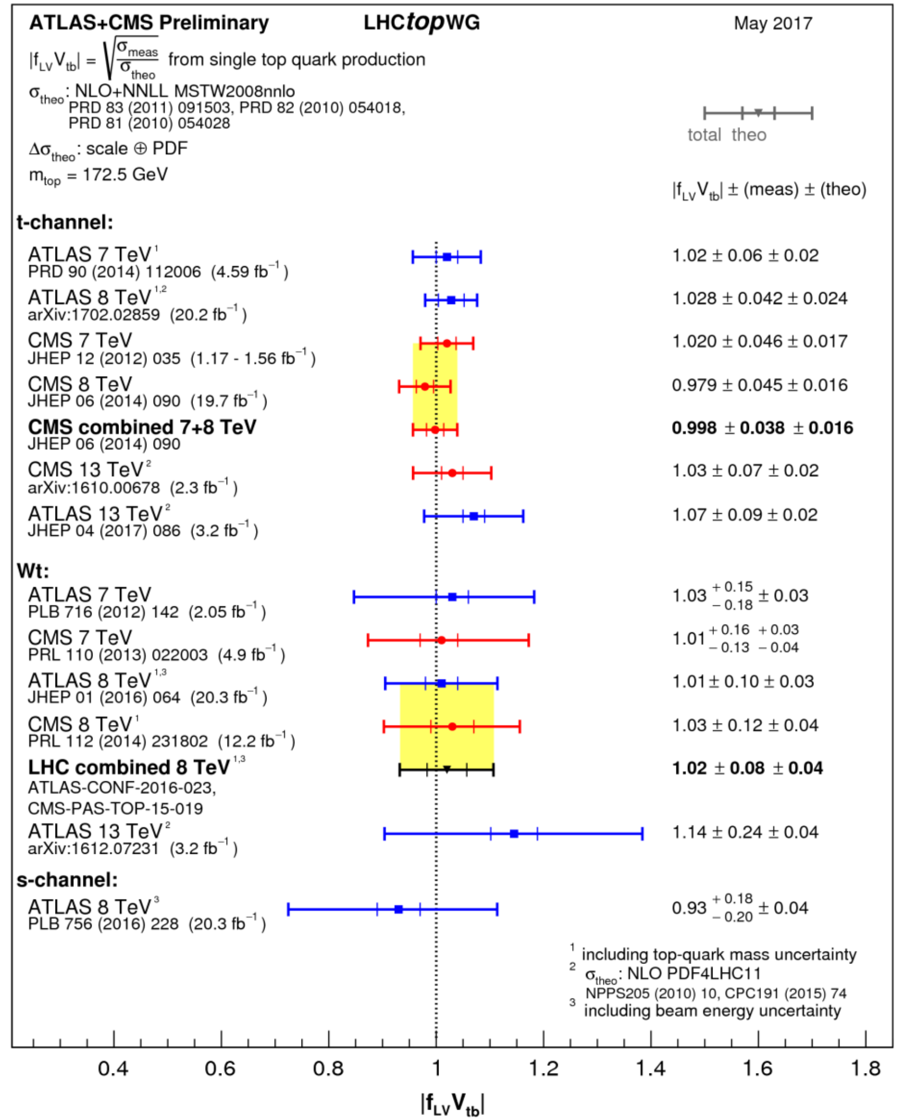
SR SR CR



$$\sigma_{tW} = 94 \pm 10(\text{stat.})^{+28}_{-22}(\text{syst.}) \pm 2(\text{lumi.})\text{pb}$$
$$\text{significance} = 4.5(3.9)\sigma,\ \text{observed (expected)}$$

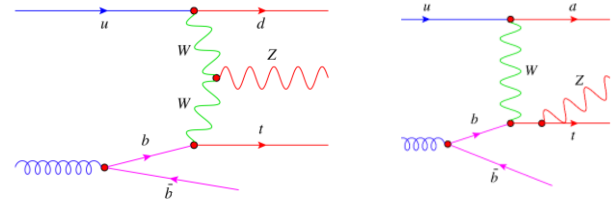
Summary of **single top quark** production inclusive cross-sections, and extractions of the **CKM matrix element V_{tb}** at LHC



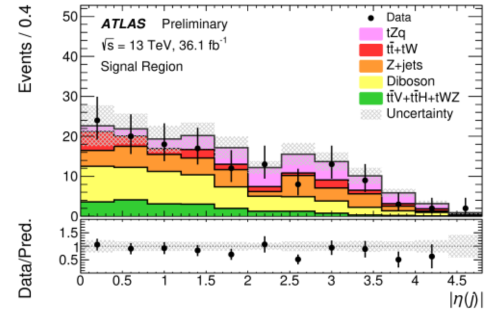


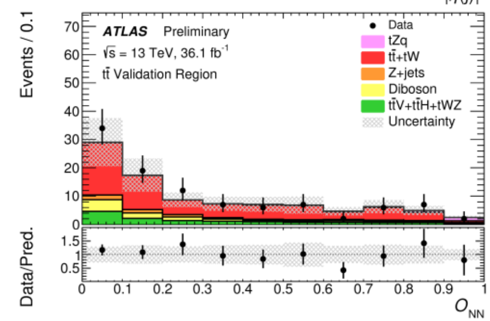
- No longer statistically limited for **inclusive** cross-section measurements.
- t-channel can be measured without MVA and tW probably as well

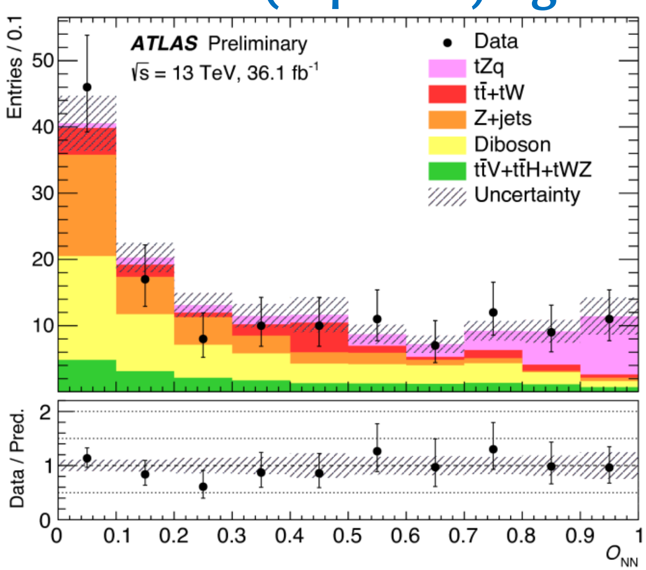
top quark in association with a Z boson: tZq



- **ATLAS 13 TeV, ATLAS-CONF-2017-052**
- **Electroweak process not yet observed**, 0.8 pb at 13 TeV. Sensitive to tZ and WWZ coupling, and first step on the way to tH measurement.
- Trilepton channel is most promising for first observation despite small BR (2.2%)
- Main backgrounds: tt+tW, Z+jets, Diboson and tt+V/H.
- Neural network used to enhance S/B
  - 10 variables used as input: η(j), P_T(j), m(t), P_T (l^W) (well modelled in the signal and validation regions)
- Full NN distribution is used in the fit
- **The observed (expected) significance is 4.2σ (5.4σ)**







σ_{tZq} = 620 ± 170(stat.) ± 160(syst.)fb, 800 fb expected

FCNC upper limit tZ final state

Br(t → Zu) < 0.022%,

Br(t→ Zc) < 0.049% 95% CL

CMS performed a search at 8 TeV arXiv:1702.01404, acc. by JHEP

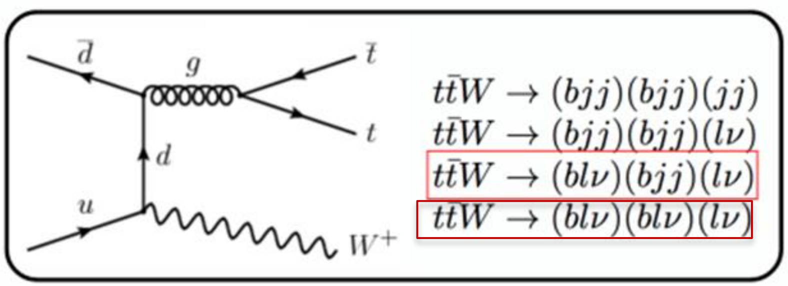
Signal extracted using a BDT (2J1T), non-prompt leptons constrained.

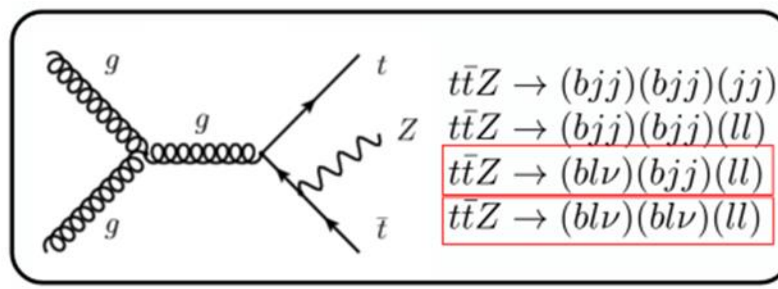
Observed significance = 2.4 (1.8 exp.)

Associated production of top and W/Z at 13 TeV

CMS-PAS-TOP-17-005, ATLAS: EPJ C77 (2017) 40

- Measure couplings to bosons (top and Z)
- **Important background for tt+H** and for BSM searches (SUSY, VLQ)
- Results start to be interpreted in the framework of Effective field theories (EFT).
  - They provide a framework to interpret results in a model independent way if there is new physics at high energy.
  - Top quark pair production with an additional vector gauge boson is sensitive to most of the leading EFT operators that preserve charge-parity and flavor in neutral-currents.
- Analyses are performed in bins of the number of selected leptons (2,3,4) with same (SS) or opposie charge (OS), and split in categories depending on jet multiplicity, number of b-tagged jets and ETmiss, optimised individually to increase sensitivity. **C&C and BDTs used**.





JHEP 06, 184 (2015), JHEP 07, 079 (2014)

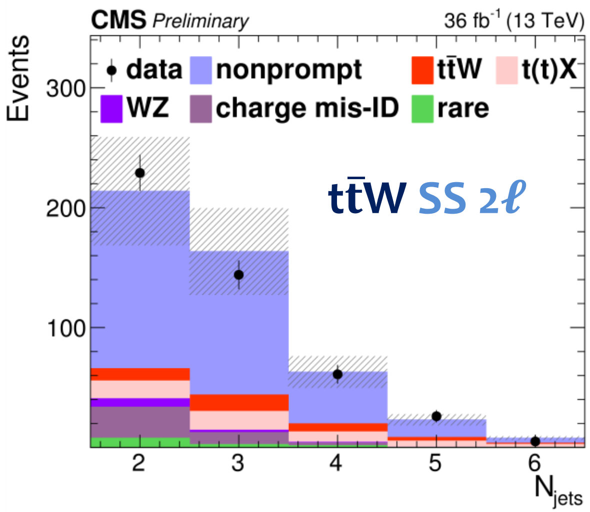
- Main backgrounds, from data and MC:
  - **Non-prompt leptons for SS and 3 lepton categories. Lots of studies, instrumental, b-hadron fakes.**
  - WZ diboson for 3 leptons (CR with 3 leptons and no b-jets)
  - ZZ diboson for 4 leptons.

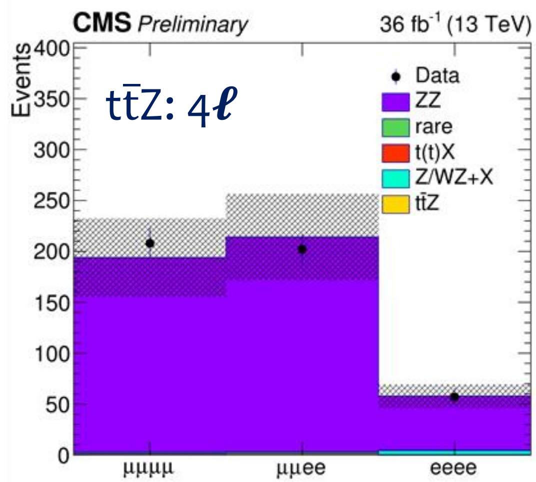
NLO QCD cross section predictions:

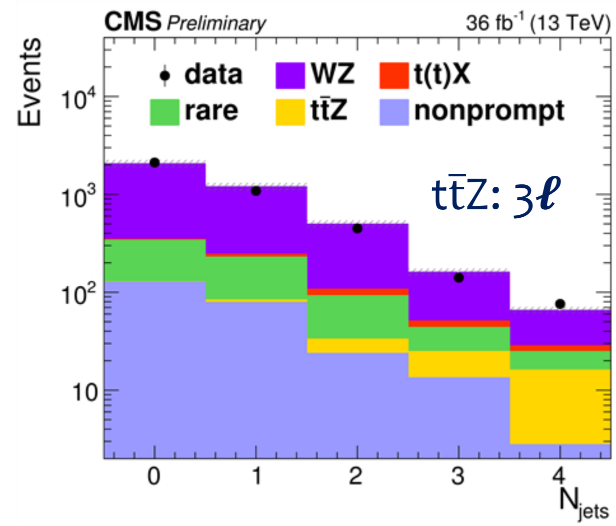
ttW: $601^{+56}_{-51}(scale)^{+25}_{-25}\,(pdf)^{+25}_{-25}(\alpha_s)$ **fb**

ttZ(γ*): $839^{+80}_{-92}(scale)^{+9}_{-9}\,(pdf)^{+11}_{-11}(\alpha_s)$ **fb**

$t\bar{t}$ W/Z: background estimate and systematic uncertainties



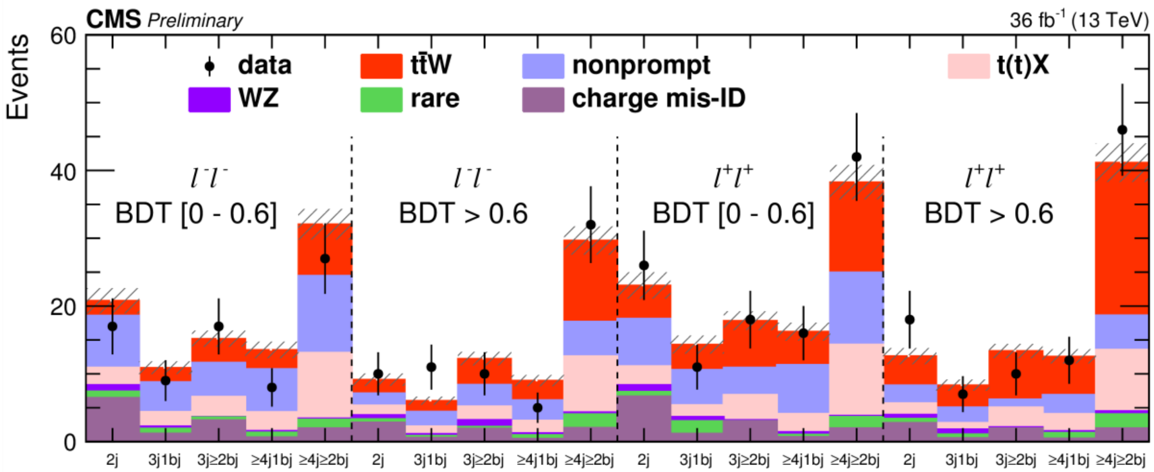


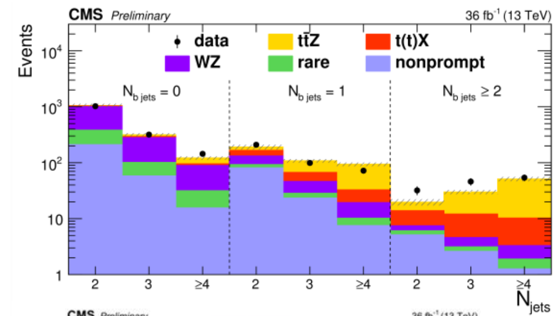


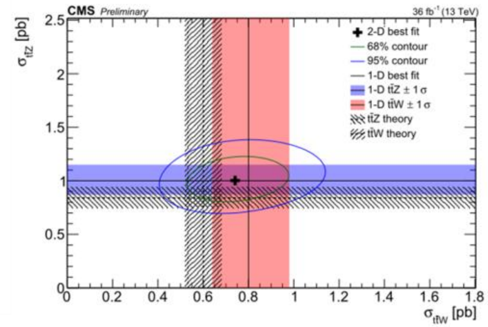
Source	Uncertainty range	Impact on ttW cross-section	Impact on ttZ cross-section
Luminosity	2.5%	4%	3%
Jet Energy Scale/Resolution	2-5%	3%	3%
Trigger	2-4%	4-5%	5%
B tagging	1-5%	2-5%	4-5%
PU modeling	1%	1%	1%
Lepton ID, efficiency	2-7%	3%	6-7%
μ_R/μ_F scale choice	1%	<1%	1%
PDF choice	1%	<1%	1%
Nonprompt background	30%	4%	< 2%
WZ cross section	10-20%	<1%	2%
ZZ cross section	20%	-	1%
Charge misidentification	20%	3%	-
Rare SM background	50%	2%	2%
ttX background	10-15%	4%	3%
Stat. unc. for nonprompt	5-50%	4%	2%
Stat. unc. rare SM processes	20-100%	1%	< 1%
Total systematic	-	14%	12%

- Lepton, b tagging and trigger efficiency have the largest effect on the $t\bar{t}$W and $t\bar{t}$Z
- The uncertainty on non-prompt background gives a significant contribution to the systematic uncertainty of the $t\bar{t}$W cross section measurement.

$t\bar{t}$ W/Z : results





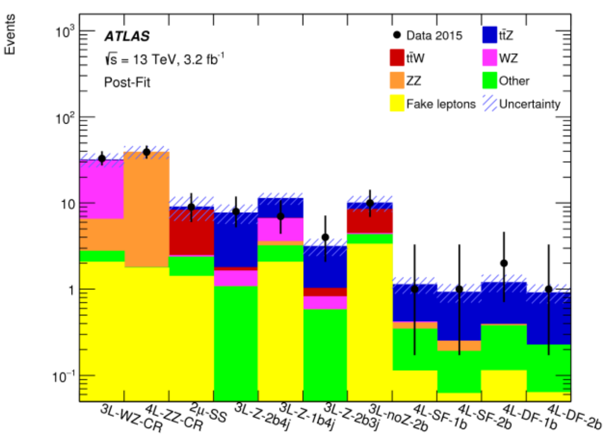


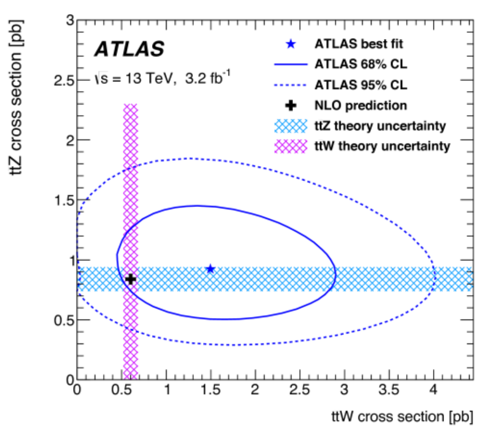
Channel	Expected significance	Observed significance
$2\ell ss$ analysis $t\bar{t}W^-$	2.4	2.3
$2\ell ss$ analysis $t\bar{t}W^+$	4.3	5.9
$2\ell ss$ analysis ($t\bar{t}W$)	4.6	5.5
3ℓ analysis ($t\bar{t}Z$)	8.4	8.7
4ℓ analysis ($t\bar{t}Z$)	4.8	4.6
3ℓ and 4ℓ combined ($t\bar{t}Z$)	9.5	9.9

> 5σ for both processes simultaneously at 13 TeV

$$\sigma\,(t\bar{t}W) = 0.80^{+0.12}_{-0.11}\,(\text{stat.})^{+0.13}_{-0.12}\,(\text{syst.})\text{ pb}$$

$$\sigma\,(t\bar{t}Z) = 1.00^{+0.09}_{-0.08}\,(\text{stat.})^{+0.12}_{-0.10}\,(\text{syst.})\text{ pb}$$





$$\sigma\,(t\bar{t}W) = 0.9 \pm 0.3\text{ pb}$$

$$\sigma\,(t\bar{t}Z) = 1.5 \pm 0.8\text{ pb}$$

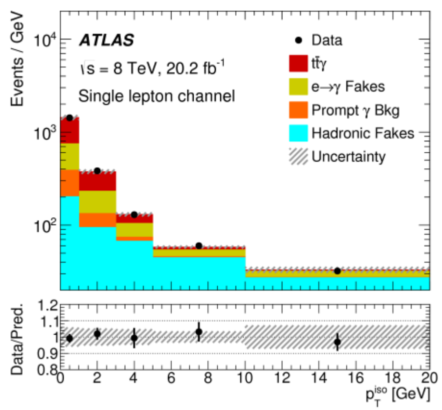
ATLAS results based on 2015 dataset.
Analysis ongoing with 2015+2016 data ($36 fb^{-1}$)

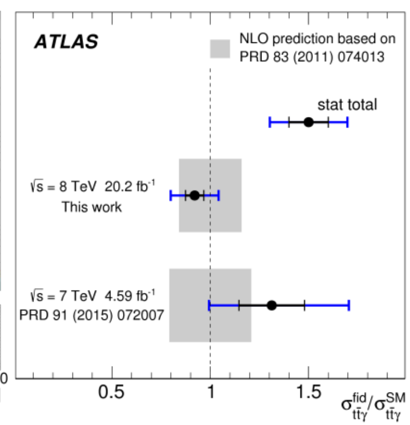
$t\bar{t}\gamma$ cross section at 8 TeV

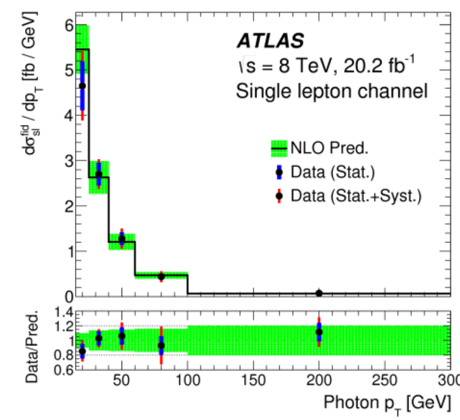
ATLAS: 1706.03046, sub. to JHEP
CMS: 1706.08128, sub. to JHEP

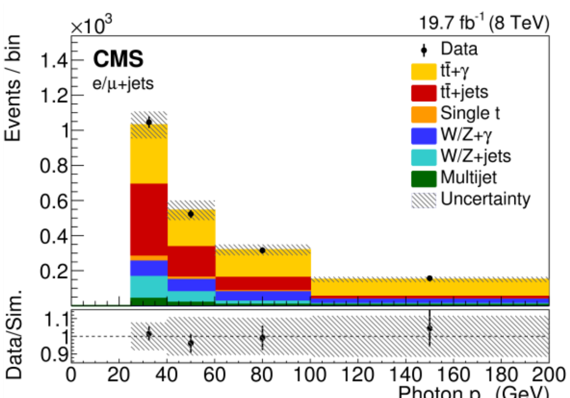
- Strength of the electromagnetic coupling of top quark and γ can be probed.
- Deviations from SM expectation could indicate new physics, anomalous top quark dipole moment.
- Measurement performed in the 1 lepton +jets final state
- Combined fit to signal and background templates to extract the number of $t\bar{t}\gamma$ events. Good agreement with NLO prediction.

Particle level differential cross-sections wrt photon p_T and |η| also measured by ATLAS.







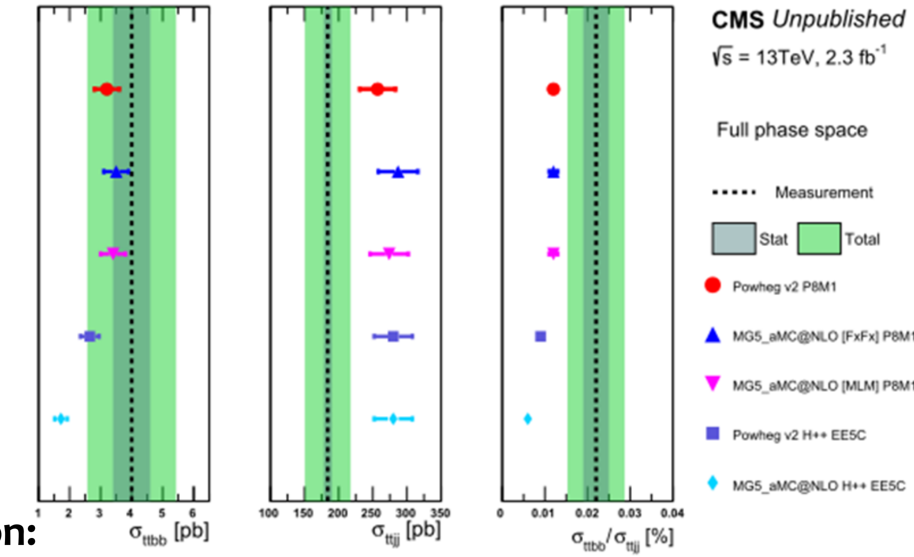


Category	R	$\sigma^{\mathrm{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales) ± 30 (PDFs)

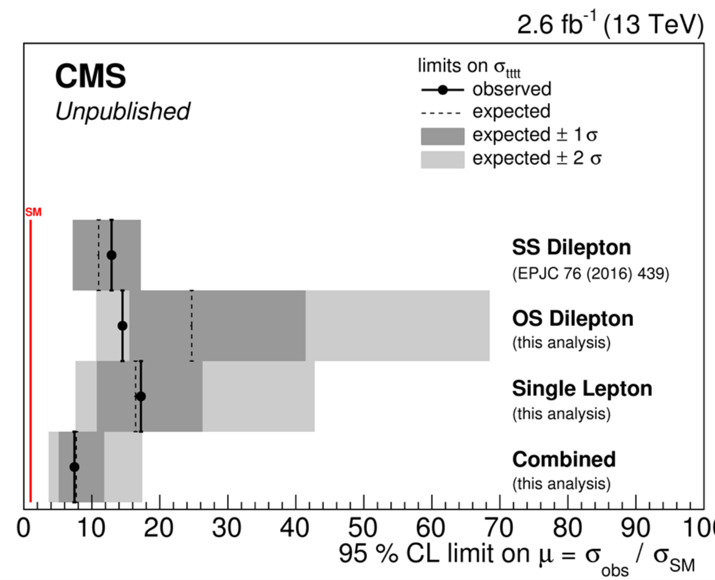
$t\bar{t}bb$, $t\bar{t}jj$, and search for $t\bar{t}t\bar{t}$ at 13 TeV

CMS: 1705.10141 sub. to PLB
1702.06164, sub. to PLB
1704.07323, sub. to EPJC

- Essential to understand the $t\bar{t}$ bb and $t\bar{t}$ jj processes for the study of the $t\bar{t}H(b\bar{b})$ production mode of the Higgs.
  - $t\bar{t}\,b\bar{b}$ is the main irreducible background for $t\bar{t}H$ searches in the H-> $b\bar{b}$ mode, $t\bar{t}$ jj is the reducible background faking b-jets.
- Event selection: exactly 2 OS leptons, at least 4 jets (at least 2 b jet)
- Main uncertainties: JES & JER, b tagging, the choice of MC generator and scale in parton shower.



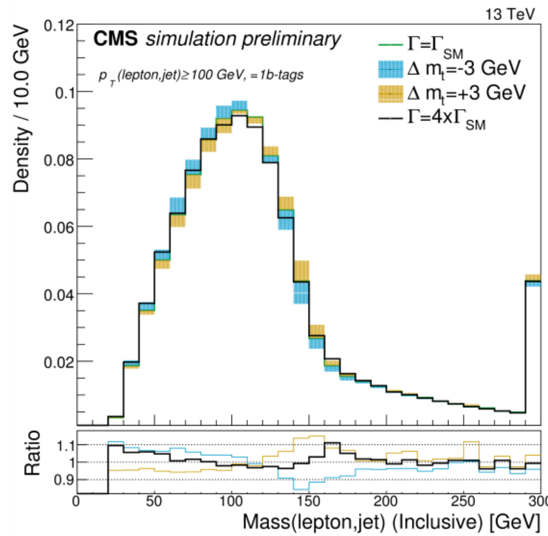
- $t\bar{t}t\bar{t}$ Measure the cross-section, **SM expectation: $9.2^{+2.9}_{-2.4}$ fb**
- BSM models leads to enhanced four top production cross-section
  - Selection: 1 or 2 isolated leptons, large jet and b-jet multiplicity and hadronic energy. Use a BDT to rank reconstructed tops built from tri-jet candidates
  - Main background, $t\bar{t}$ +jets
  - Largest systematic uncertainty: variation of QCD scale choice at ME
  - No deviation from background-only is expected and observed the limits on cross-section are set

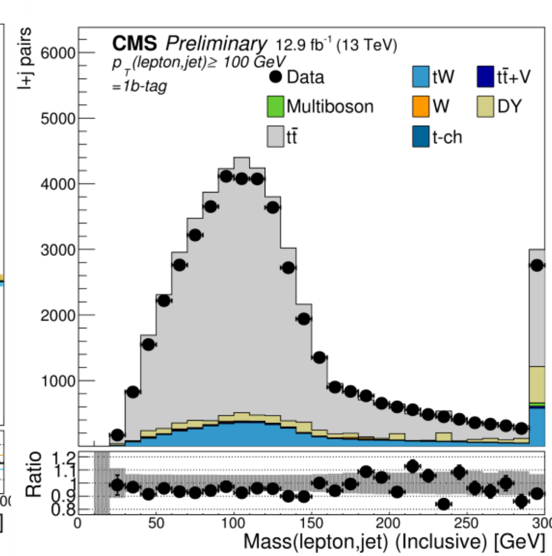


top width (decay to unknows?)

ATLAS-CONF-2017-056, CMS-PAS-TOP-16-019

- **Less tested of the top quark properties,**
- **SM prediction: 1.322 GeV for 172.5 GeV top mass.**
- **CMS: Dilepton channel**
  - Reconstructed mass of the decay products (l and b) used to probe variations in Γ_{top}.
  - Observable compared to the simulated expectations for different Γ_{top} scenarios
- MC modelling main systematic

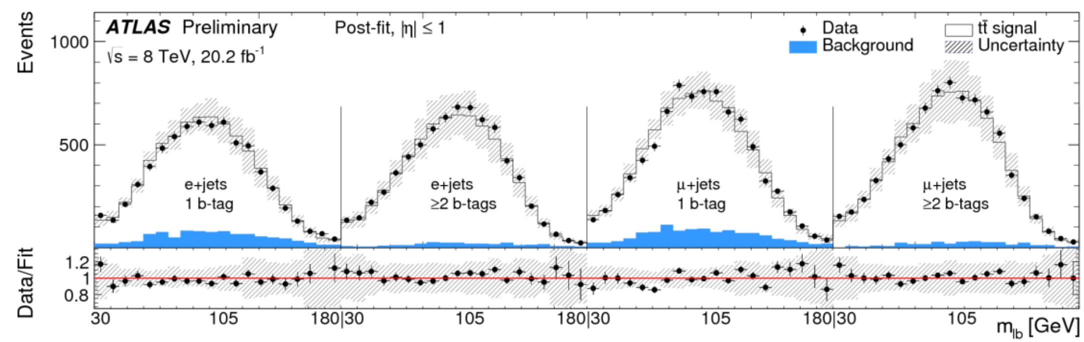




Observed limit: 0.6 ≤ Γ_{top} ≤ 2.5 GeV,

Expected limit: 0.6 ≤ Γ_{top} ≤ 2.4 GeV at 95% CL

- **ATLAS: lepton+jets**
  - measured using a template fit to distributions of kinematic observables associated with the hadronically and semileptonically decaying top quarks

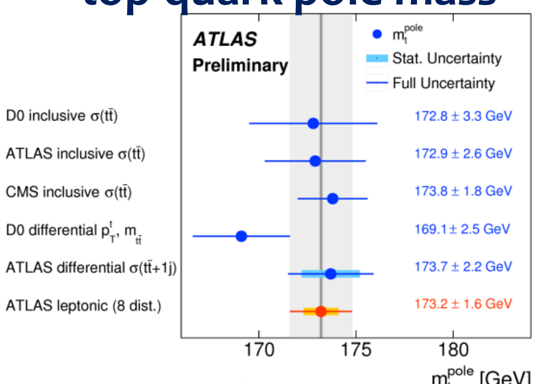


$$\Gamma_{top} = 1.76 \pm 0.33(\text{stat.})^{+0.79}_{-0.68}(\text{syst.})\ \text{GeV}$$

compatible with SM prediction

SM completion with the **top mass**

- **The top mass, the W mass and the Higgs mass depend on each other**
- **Direct mass measurement at Tevatron**
  - m(top) = 174.3 ± 0.65 GeV
- **Not an observable, i.e. scheme-dependent**
  - **Pole-mass: viewing top quark as a free parton**
    - **inclusive/differential cross section (NNLO) dependent on top-quark pole mass**



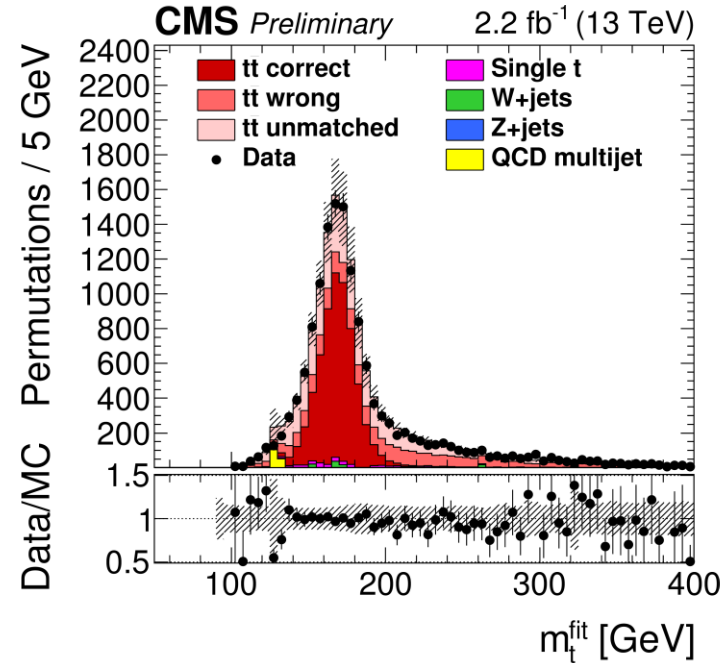
  - MS scheme (“running mass”):
    - “MC mass”: (N)LO+PS yet different from pole or MS mass

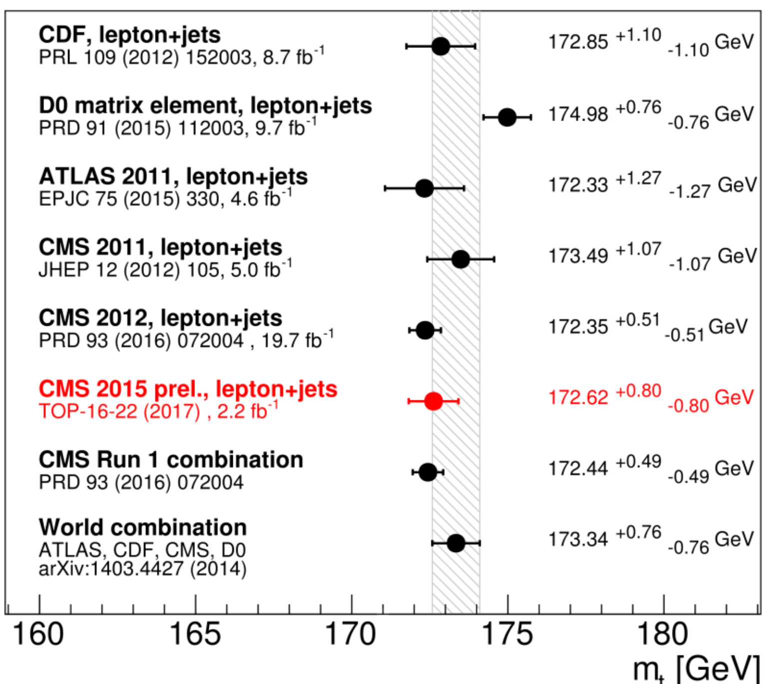
- **Direct reconstruction methods**
  - ➢ Full reconstruction by resolving the pairing ambiguities (all channels studied)
  - ➢ Use kinematic constrained fitting to improve the mass resolution
    - o Constrain the light jet energy scale in situ by using the W mass constraint
  - ➢ Fit the mass with MC template fits or event by event likelihood fits
    - o Methods very sensitive to the description of radiation and JES uncertainties
- **Indirect methods**
  - Use the dependence on the top mass on other variables
    - o Top pair cross section
    - o Lepton p_T and end-point methods
    - o Invariant mass of the system J/Ψ+lepton from W
    - o Decay length of the b hadron
  - ➢ Main issue: need of a lot of statistics

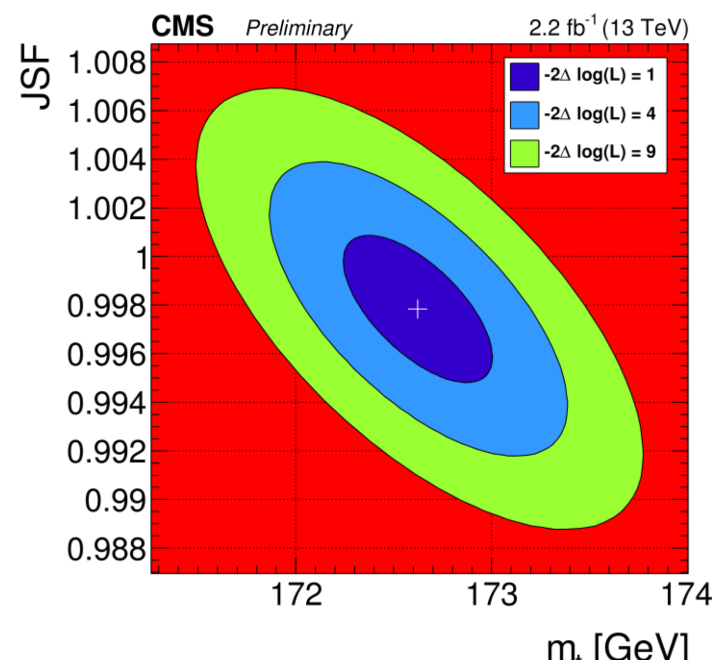
CMS top mass with lepton+jets events at 13TeV

CMS-TOP-16-022

- Follows the 8 TeV measurement using μ+jet events
  - Not yet as precise as Run I measurement
  - New generators used in Run II still being tuned.
- **In very good agreement with other measurements**

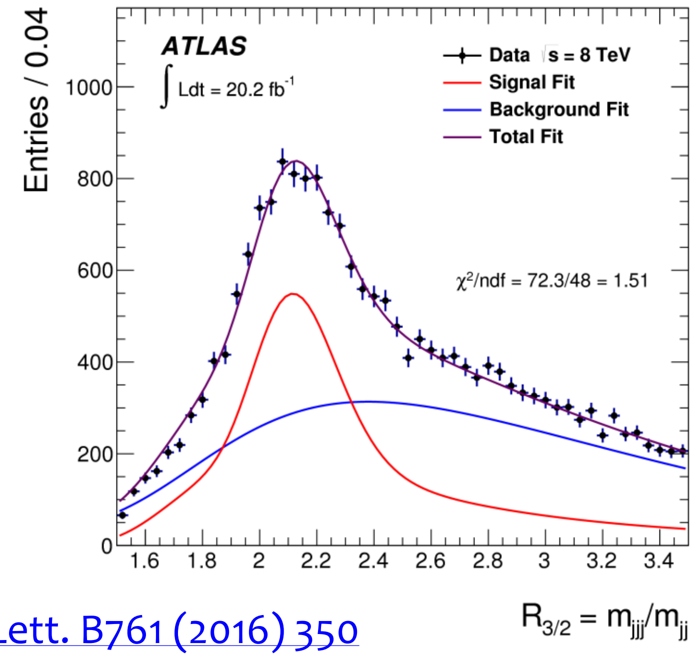






ATLAS top mass

- **All-jets channel from 8 TeV data** arXiv:1702.07546
  - The number of b-tagged jets amongst the six leading jets and <ΔΦ(b, W)> in the signal and three control regions are used to determine the shape of the background distributions from data.
  - Choosing the R_{32} distribution stabilises m_{top} against a global JES uncertainty.
- m_{top} = 173.72 ± 0.55 (stat.) ± 1.01 (syst.) GeV
  - Most important systematic uncertainties: JES (0.60 GeV) bJES (0.34 GeV) and hadronisation (0.64 GeV).
  - 40% improvement compared to the 7 TeV analysis.



Phys. Lett. B761 (2016) 350

dilepton channel at 8 GeV

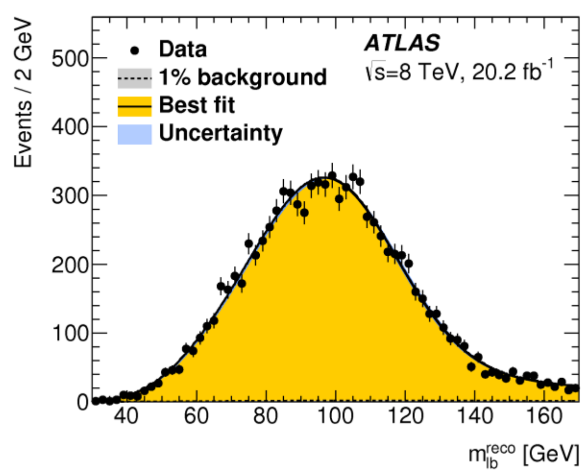
m_{top} = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV

Largest exp. unc. from JES, modelling unc. from hadronisation, ISR/FSR.

- **Three-dimensional lepton + jets analysis from 7 TeV data.** Template-based approach with observabes: m_{top}^{reco}, m_W^{reco} and R_{bq} (ratio of $p_T^{b\ had}$ and $p_T^{b\ lep}$ over $p_T^{Wjet1+2}$)
  - In-situ calibration of JES (m_W^{reco}) and bJES (Rbq), relative to udsg.

$$m_t = 172.33 \pm 0.75\ (\text{stat+JSF+bJSF}) \pm 1.02\ (\text{syst})\ \text{GeV}$$
$$\text{JSF} = 1.019 \pm 0.003\ (\text{stat}) \pm 0.027\ (\text{syst})$$
$$\text{bJSF} = 1.003 \pm 0.008\ (\text{stat}) \pm 0.023\ (\text{syst})$$

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

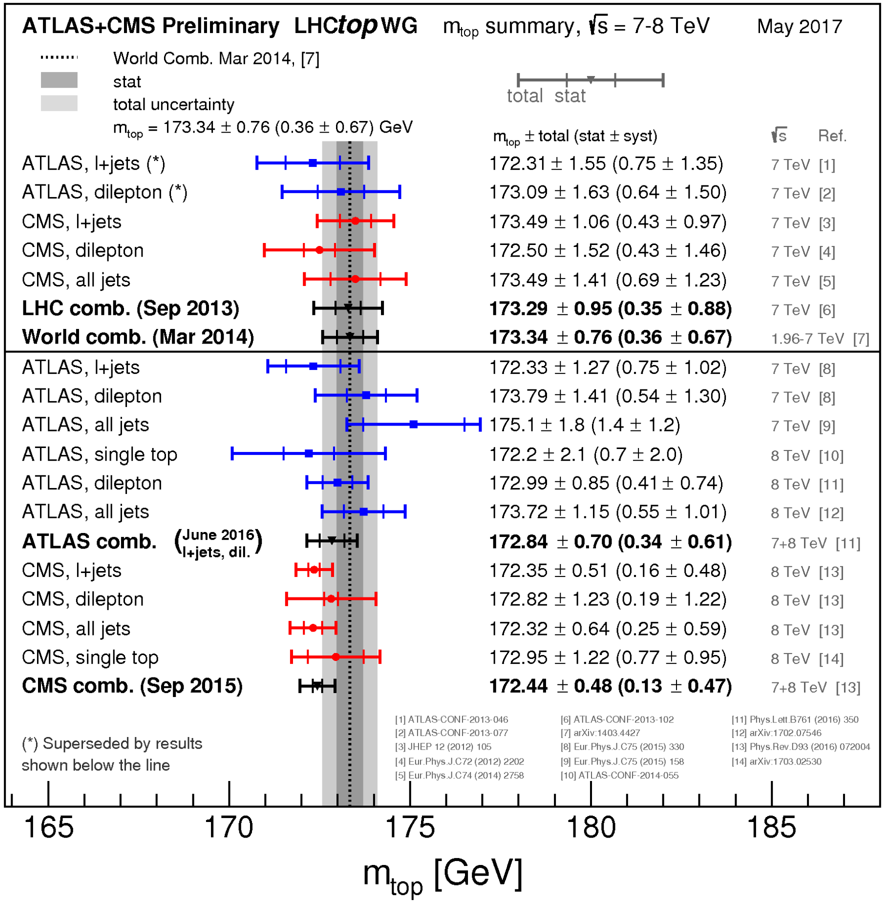


0.84 GeV unc. in total

Most precise ATLAS measurement

CMS + ATLAS m_{top} (MC)

LHCTOPWG



- **Analysis reaching a precision close to 0.5 GeV (<0.3%)**

- Precision limited by understanding modeling of hadronization
- Different ways to improve
  - Use cleaner observables
  - Avoid jets
  - Use theoretically calculable observables sensitive to the mass σ(tt), m(lb)

CMS combination m_{top} = 172.44 ± 0.48 GeV

ATLAS combination m_{top} = 172.84 ± 0.70 GeV

Tevatron combination m_{top} = 174.30 ± 0.65 GeV

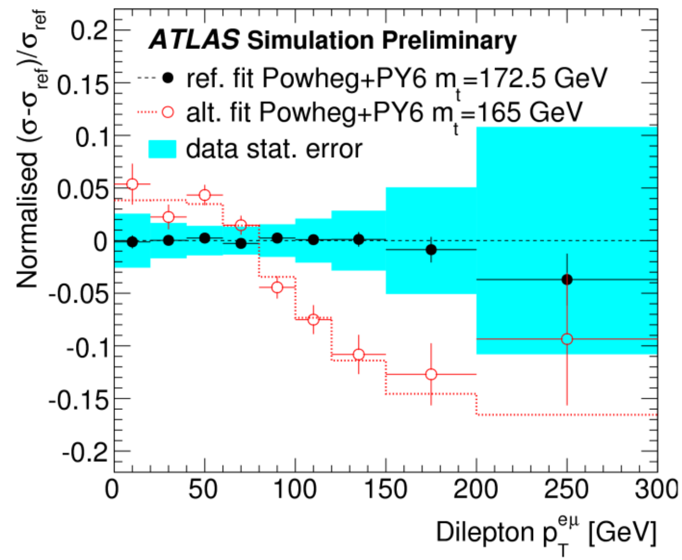
ATLAS and **CMS** in good agreement, Some tension with **Tevatron** average

Best measurements from 8 TeV (mature data), being published (2016-2017)

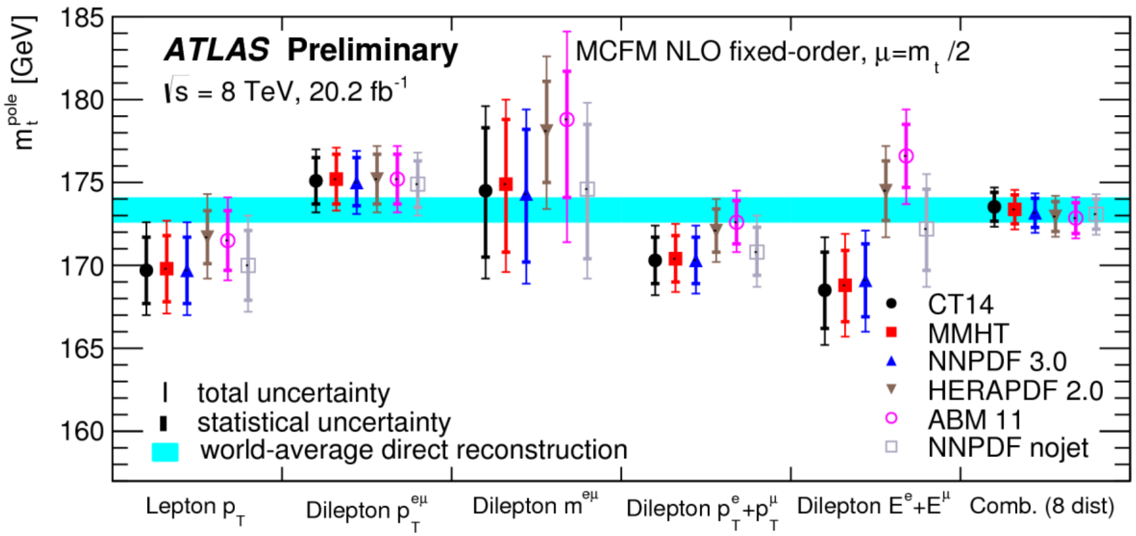
m_{top} from lepton diff. cross section

ATLAS-CONF-2017-044
CMS-PAS-TOP-16-002

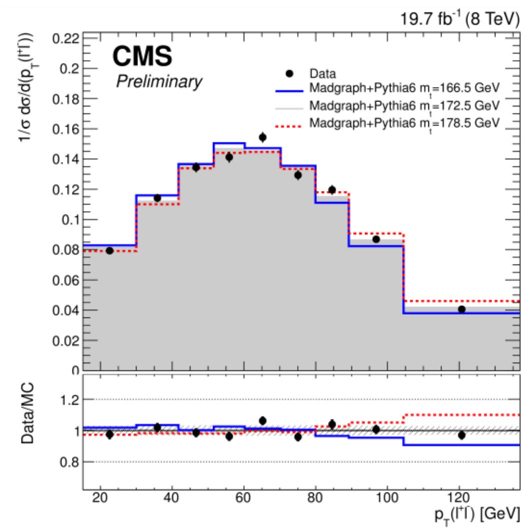
- Measure a number of lepton differential distributions in tt → eμ + X events, correct to particle level, subtract background and convert into normalised diff. cross-sections
- Sensitivity to m_{top} for: p_T^ℓ, $p_T^{e\mu}$, $m^{e\mu}$, $p_T^e+p_T^\mu$, E^e+E^μ
- The lepton differential cross-sections can be used to determine m_{top} or m_{top}^{pole}



$m_t = 171.7 \pm 1.1\,(\text{stat.}) \pm 0.5\,(\text{exp.})\ ^{+2.5}_{-3.1}\,(\text{th.})\ ^{+0.8}_{-0.0}\,(p_T\,(t))$ GeV



$m_{top}^{pole} = 173.2 \pm 0.9\,(\text{stat.}) \pm 0.8\,(\text{syst.}) \pm 1.2\,(\text{theo.})\ \text{GeV} = 173.2 \pm 1.6\ \text{GeV}$

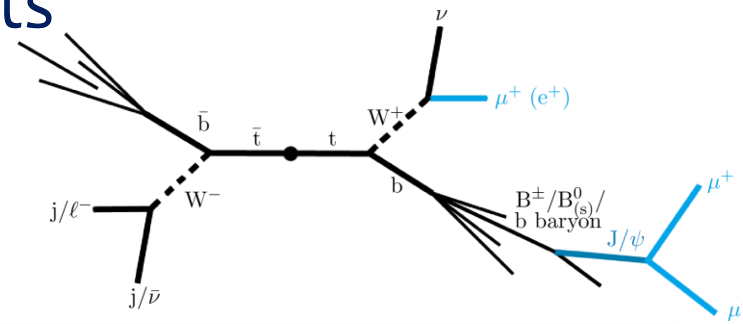


Based on LO Madgraph (Run I MC)
Expected to improve using NLO+PS

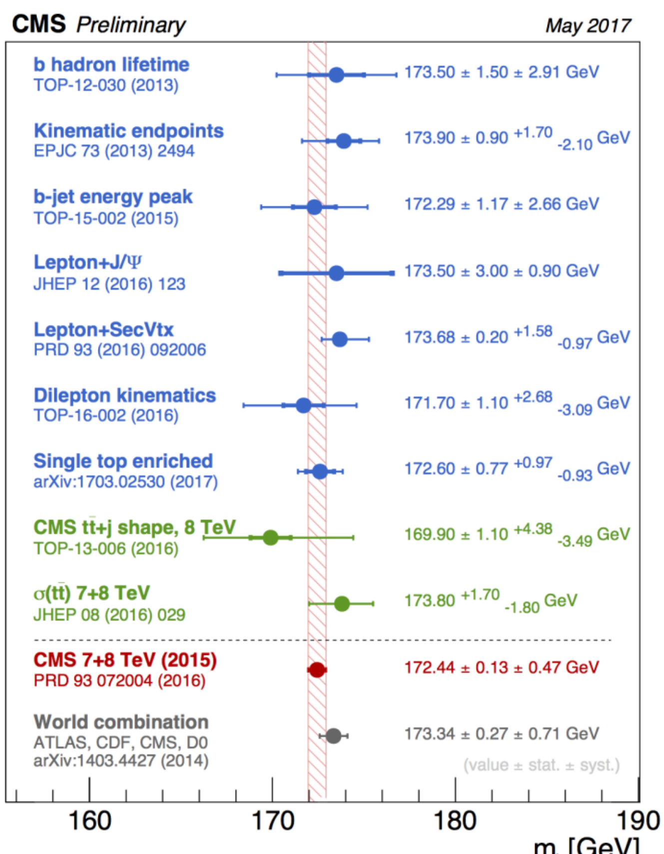
- The th. uncertaintites are 0.3 GeV from PDFs and 1.1 GeV from scale variations (dominant source of unc.)

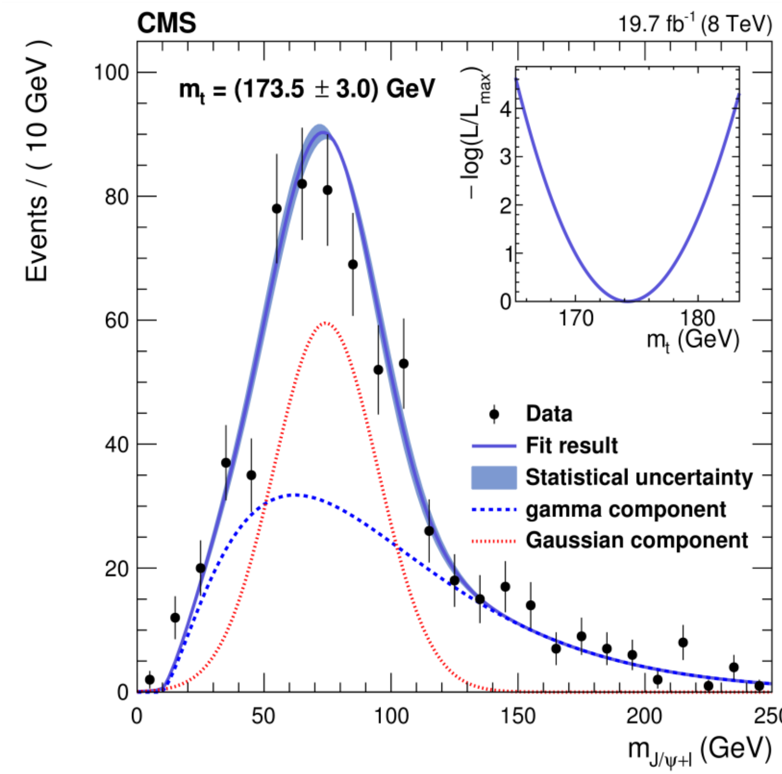
CMS top mass with lepton+J/ψ events

JHEP12(2016)123



- Well-defined leptonic observable
- Momentun of the J/ψ is used to represent the b-jet
- syst. unc. 0.9 GeV
  - top p_T modelling (0.64 GeV)
  - b-fragmentation (0.37 GeV)

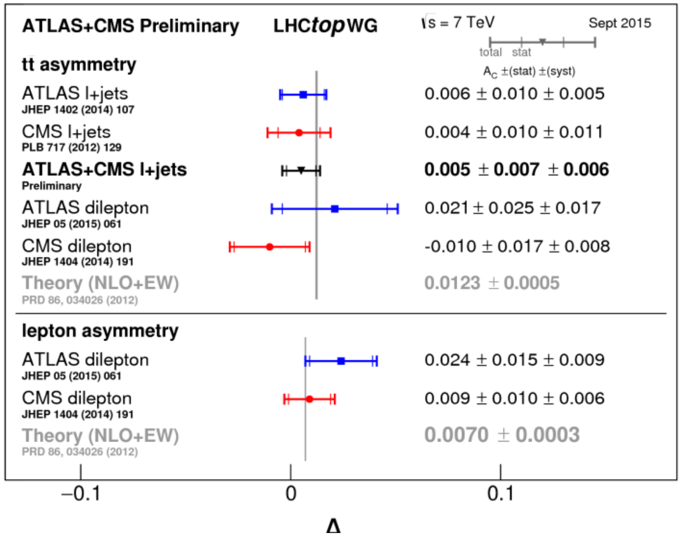


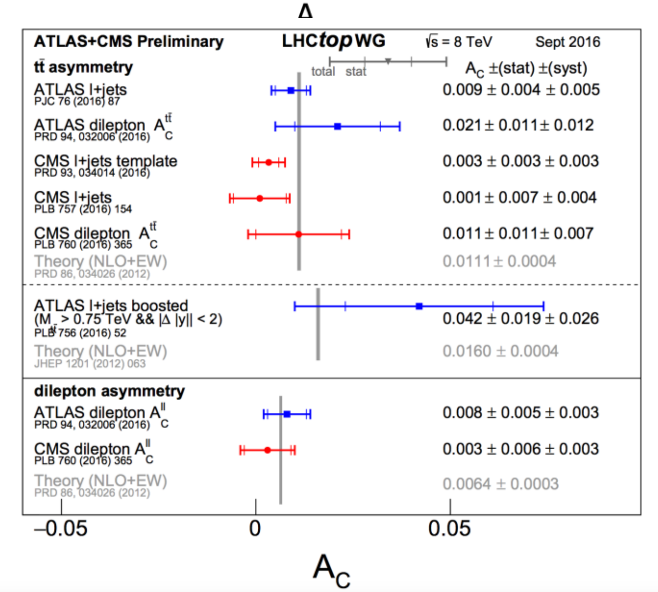


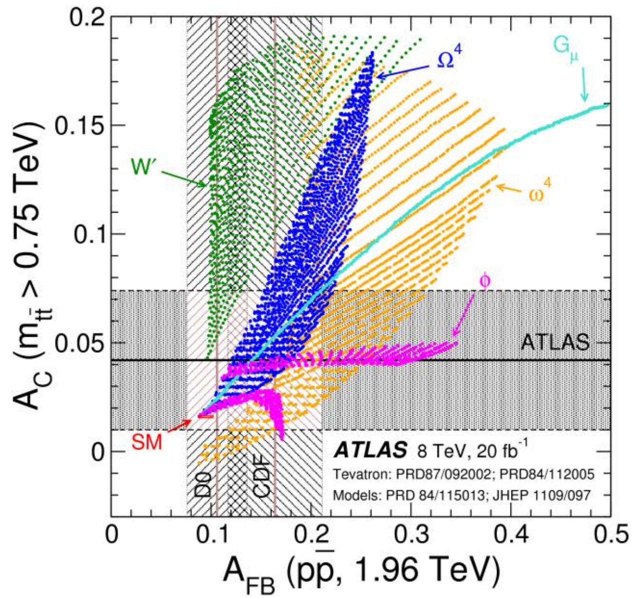
- **Direct mass measurements cross-checked by alternative methods**
  - **Consistent within large errors**

Charge asymmetry: LHC summary

LHCTOPWG







G_μ : A new color-octet neutral vector boson exchanged in the s channel

W′: A charged color-singlet vector boson Z exchanged in the t channel in dd→ tt

φ : A color-singlet scalar doublet with hypercharge −1/2 exchanged in t channel

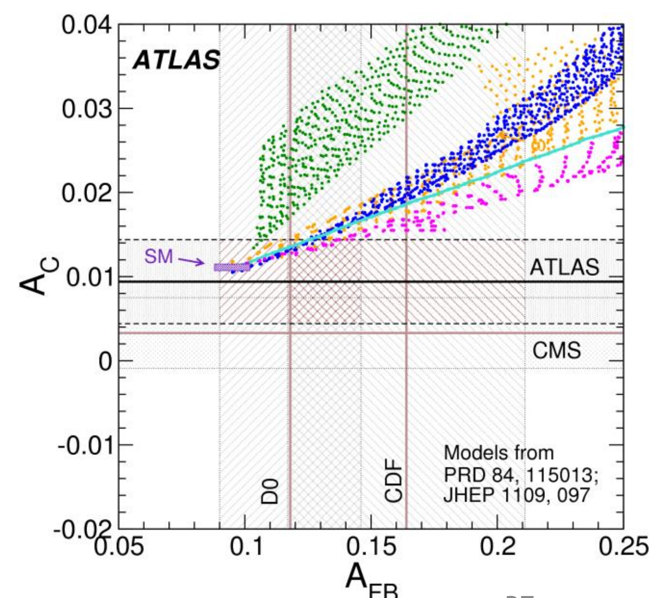
Ω_4 : A charge 4/3 scalar color sextet exchanged in the u channel

ω_4 : A charge 4/3 scalar color triplet exchanged in the u channel

Good agreement between theory and experiment

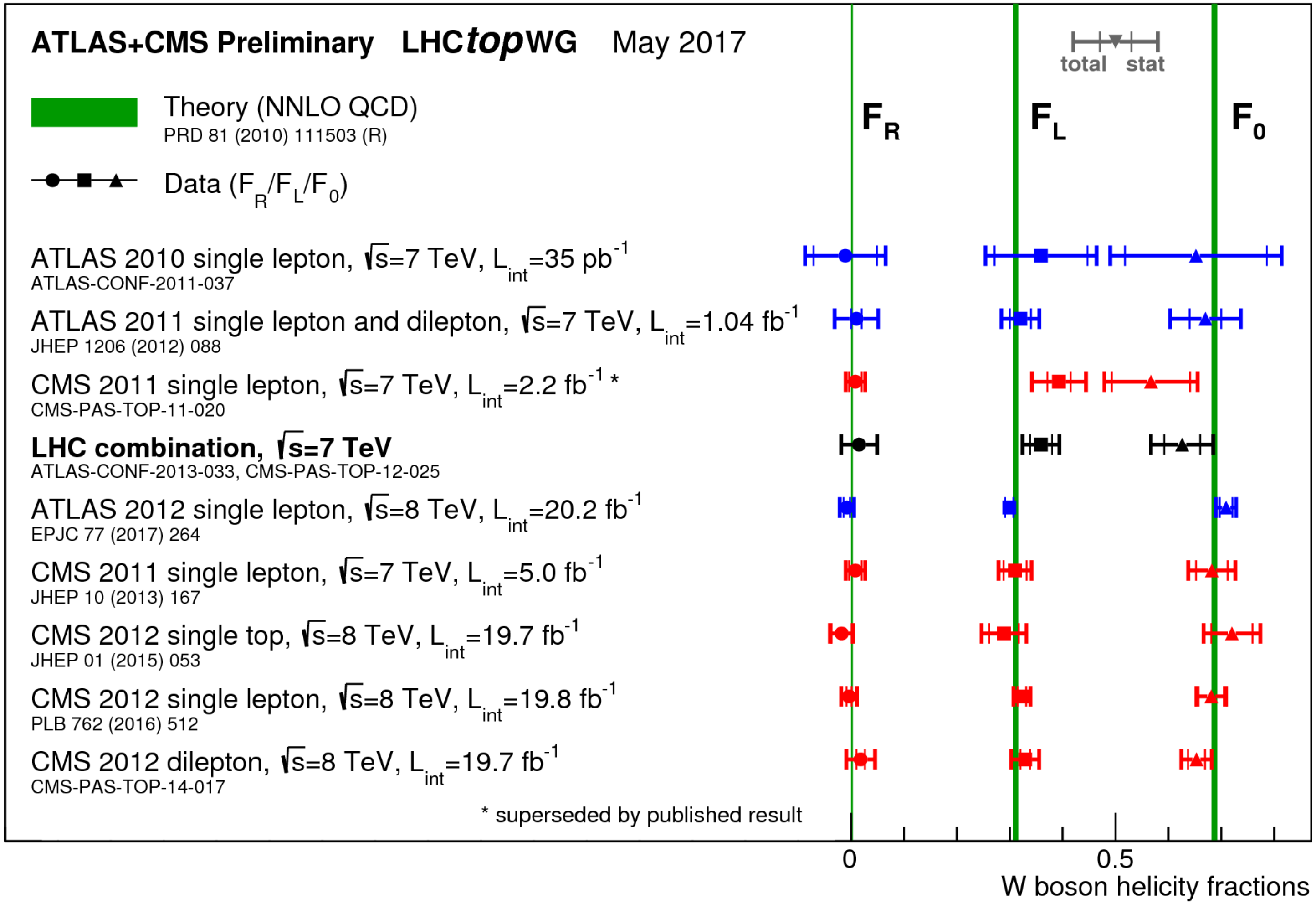
Statistical and systematic uncertainties are comparable in size

Several differential distributions available + results in high m(tt) region where asymmetry is enhanced



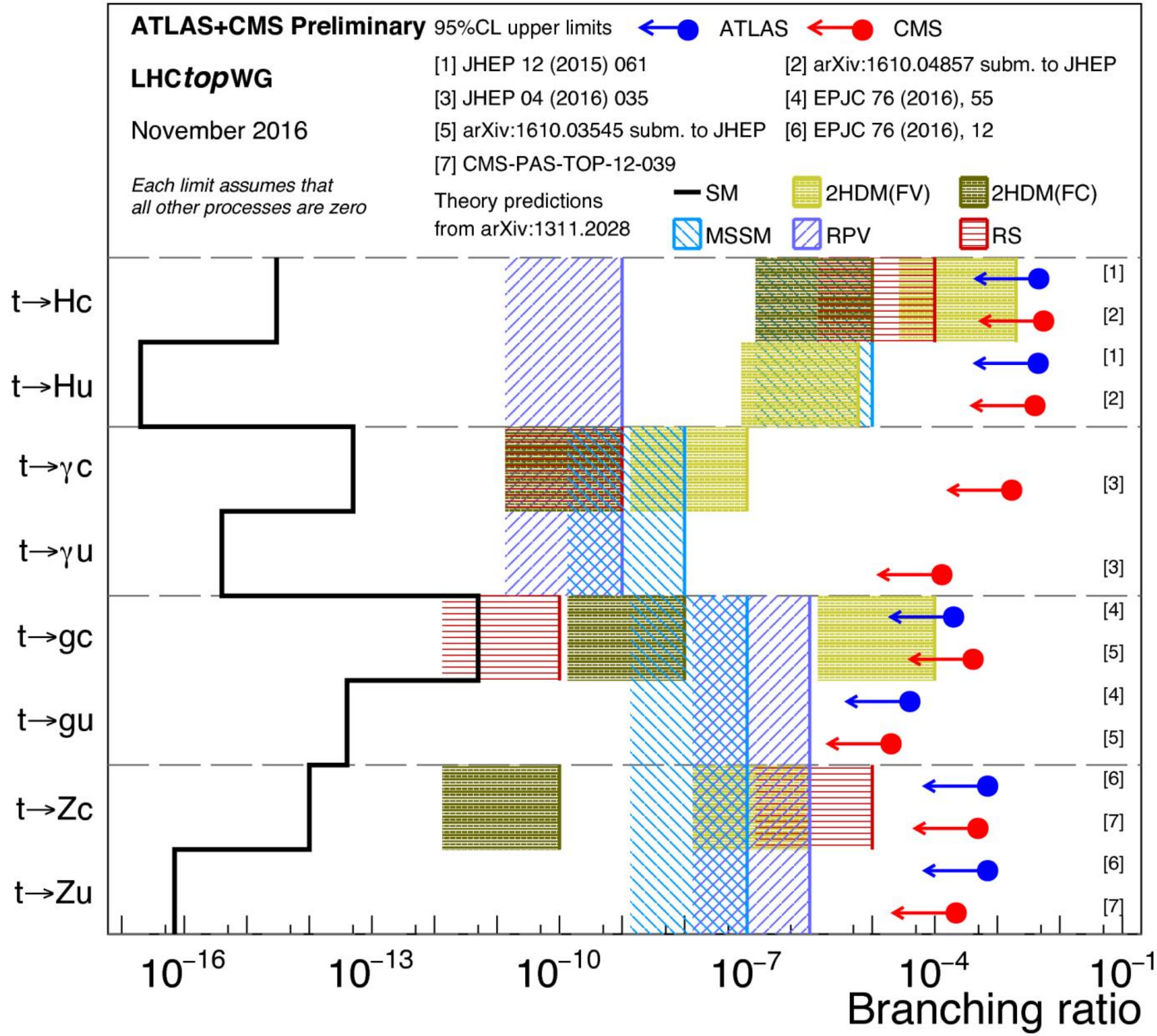
Wtb vertex structure in top decay

W-boson couplings consistent with “V-A”



Flavor-changing decays

No signs of flavor physics associate with top!

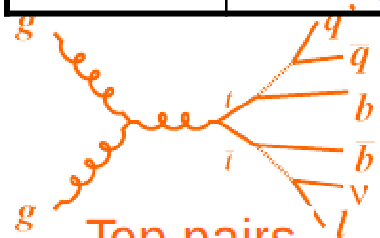


Summary

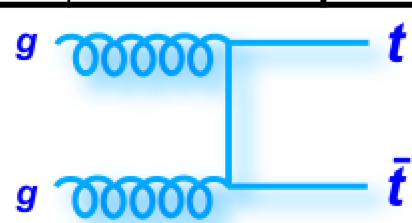
- **Top quark physics is a pillar of the current research program in HEP and provide stringent tests of pQCD . Both the CMS and ATLAS collaborations cover a wide range of top-related topics. Results in agreement with SM predictions**
- Key to QCD, electro-weak and New Physics
  - Ideal probe for constraining (directly + indirectly) the symmetry breaking of the SM
    - The top is way heavy → the Higgs scalar mostly couples to tops
  - Ideal probe for looking for new physics beyond the model itself
    - Via precision measurements
    - Via direct searches for new signals
- $t\bar{t}$ production: **Precision regime: σ_{tt} < 4%, m(top) ≤ 0.5 GeV.**
  - Already many measurements at 13 TeV
- Single top production:
  - t-channel large enough to investigate properties
  - tW channel observed at LHC. s-channel lower cross-section
  - Associated production, observation of tt+γ , tt+W/Z, important to study top-Higgs couplings.
- 3x larger dataset by the end of 2018
  - **new processes** (ttZ, tZq…) for **EW** and **BSM couplings**
  - **higher** p_T for **new physics**

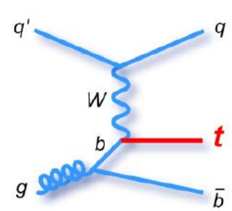
Top quark production at LHC

process	Events/s 8 TeV, peak lumi	Events/y 8 TeV, 25/fb	
bb	~10^6	~3 10^{12}	
$W \to \ell\nu$	~70	~2.5 10^8	
$Z \to \ell\ell$	~6	~25 10^6	
tt	~1.5	~6 10^6	

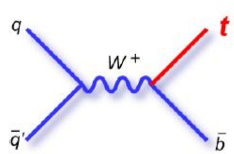


Top pairs

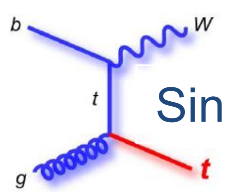




t-channel

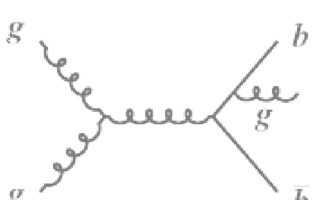


s-channel

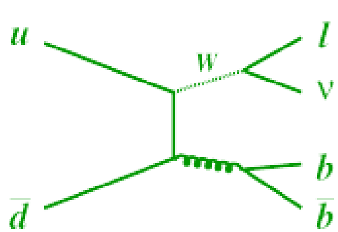


tW-channel

Single top

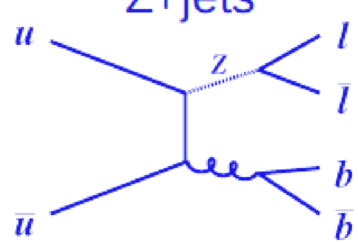


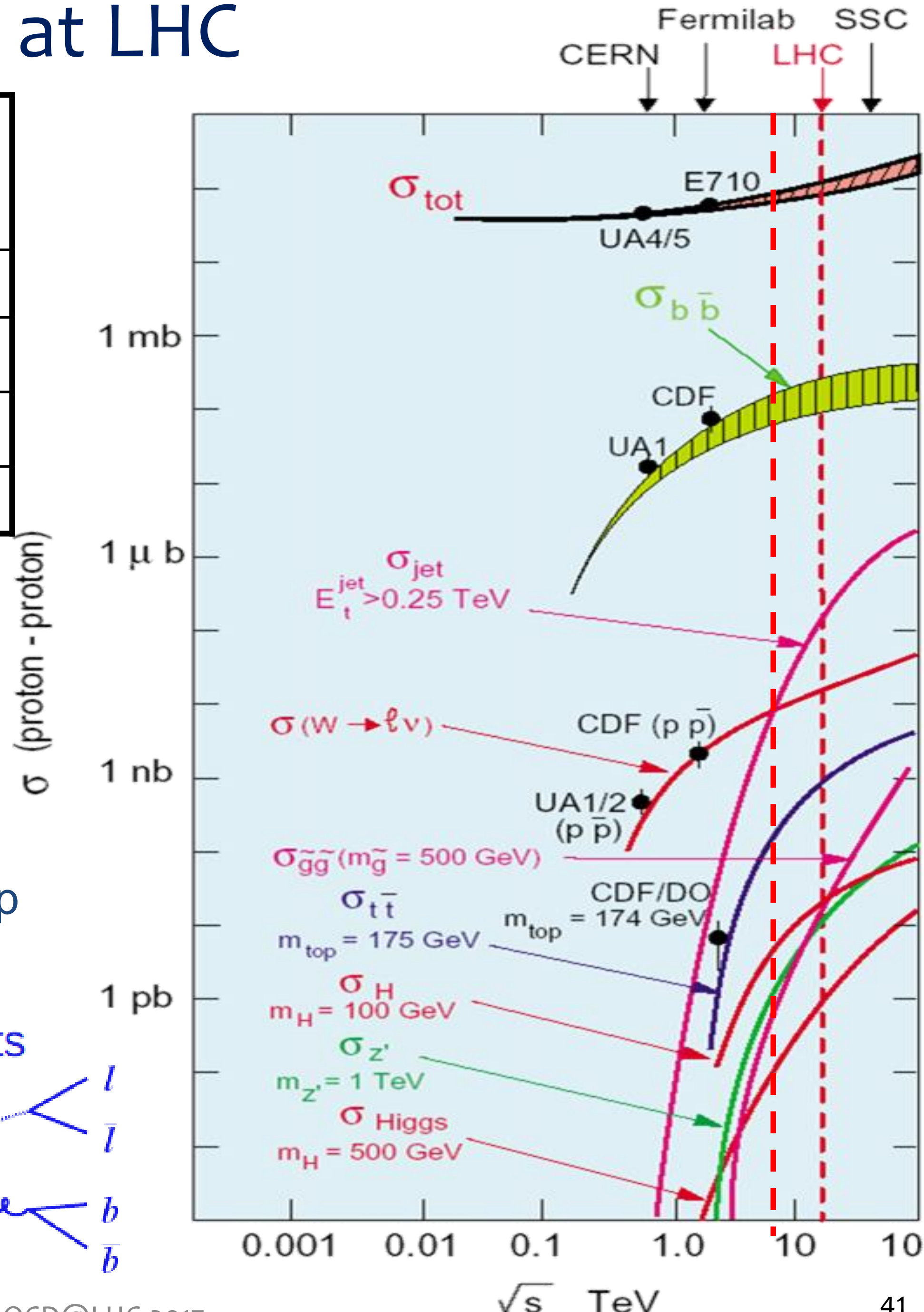
QCD



W+jets

Z+jets

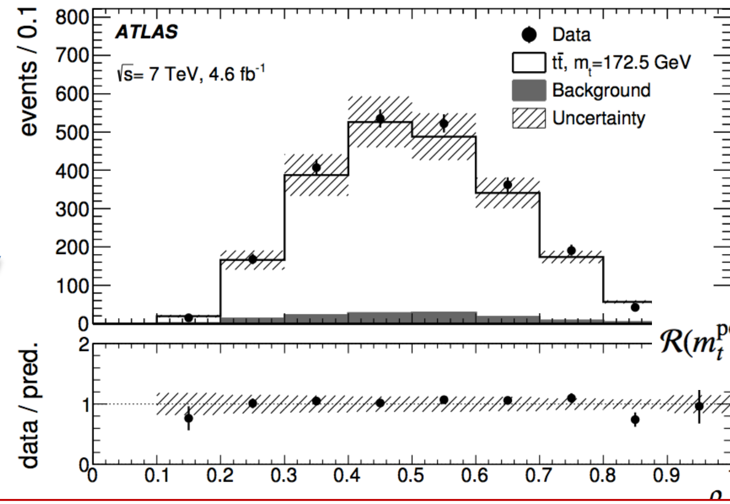




top mass: Indirect Measurements

Access to top quark pole mass directly

- difference between MC & pole mass *O(1 GeV)* (A. Hoang: arXiv:1412.3649v1)
- **Pole Mass from tt+1 - jet events** @ 7 TeV (**ATLAS**) **JHEP 10 (2015) 121**
- **m_{top} from Production Cross-Section**
  - Can take advantage of low backgrounds of eμ channel
  - Sensitivity not as strong as in direct measurements
  - Systematic uncertainties typically larger
  - **CMS: arXiv:1603.02303**
  - **ATLAS: Eur.Phys.J. C74 (2014) 3109**
- **Measurement of σ_{tt} together with NNLO theoretical prediction allows for extraction of the pole mass (m_{top})**

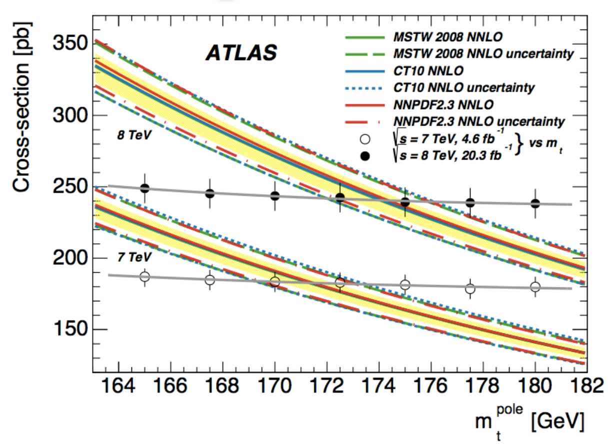


Extract top quark pole mass directly using differential tt+1-jet cross-section

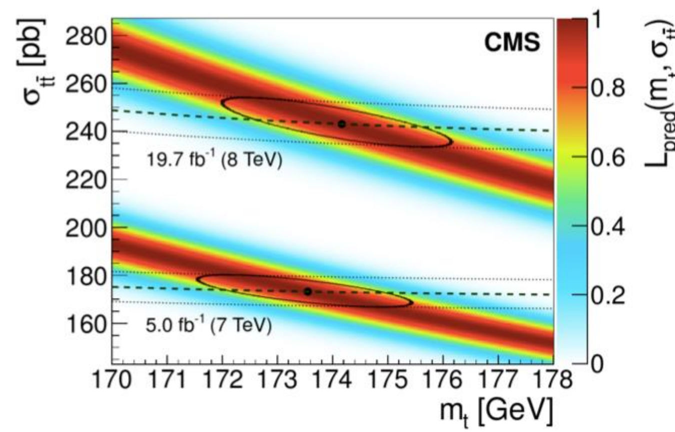
$$\mathcal{R}(m_t^{pole},\rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}}\frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{pole},\rho_s)$$

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

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



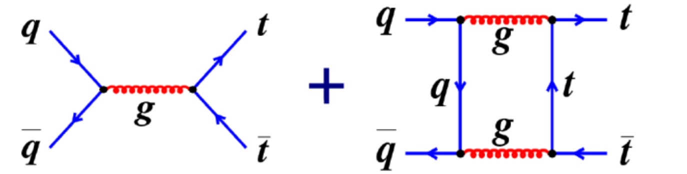
$$m_t^{pole} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$



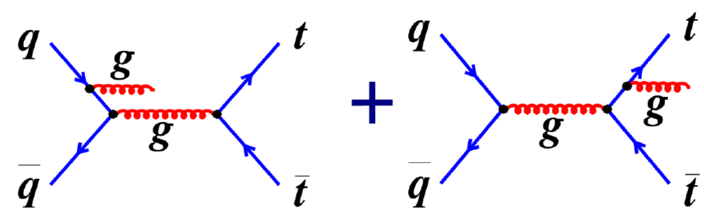
$$m_t^{pole} = 173.8^{+1.7}_{-1.8}\ \text{GeV}$$

Charge/FB asymmetry

tree-level and box diagram: asymmetry (+)

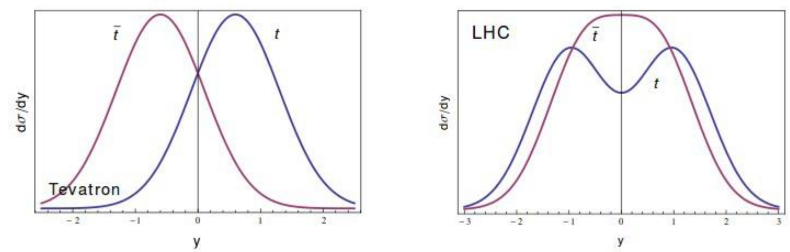


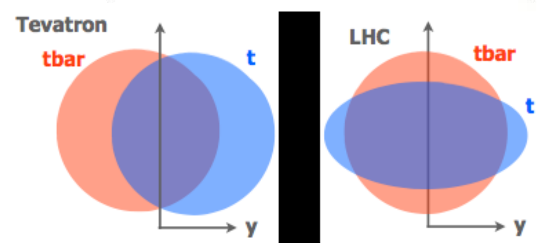
ISR and FSR: asymmetry (-)



- top quarks pair production at NLO give non zero charge asymmetry from interferences between q--qbar initiated diagrams, gg interaction symmetric

- Measurement of A_{FB} at Tevatron and A_C at LHC are complementary to evaluate new physics models
  - Could be enhanced if new physics present like with W', G, ω, φ, Ω.
- LHC has symmetric initial state (pp):
  - Quarks are mostly valence and anti---quarks are sea quarks
  - PDF's are not symmetric, quarks carry more momentum than anti-quarks
  - Rapidity distribution of tops is broader





- Evaluate asymmetry based on fully reconstructed top quarks or leptons in dilepton channel

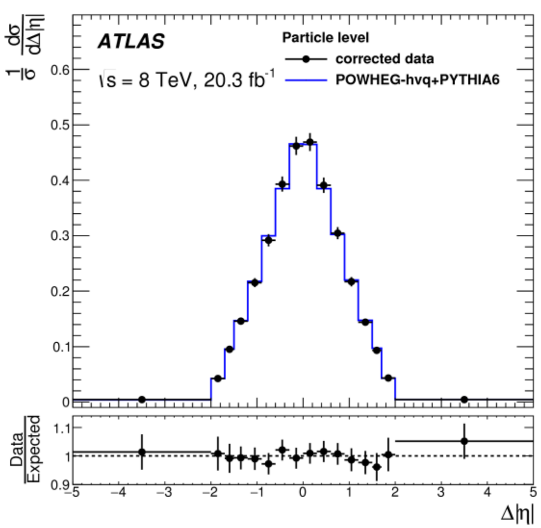
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

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

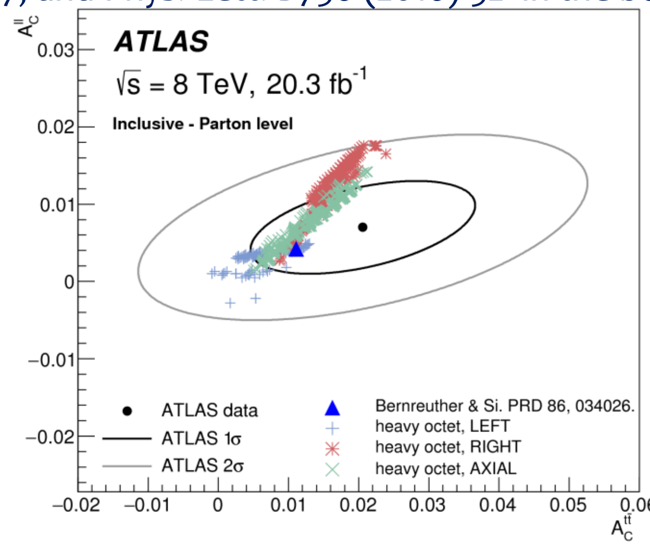
- **Differential distributions (m_{tt}, y_{tt}, $p^T{}_{tt}$) sensitive to BSM physics**

ATLAS: Charge asymmetry in dilepton and l+jets channels

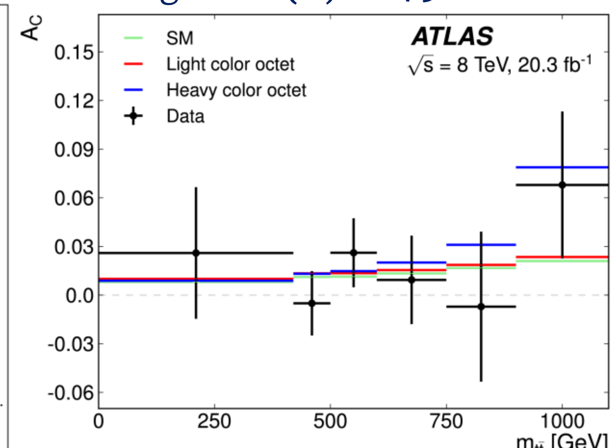
- **Dileptons**: Asymmetry defined with decay leptons and reconstructed tops
- Kinematic reconstruction of the top anti-top quark four momenta.
  - Inclusive measurements corrected to parton level in the full phase space and fiducial regions.
  - Differential measurement in m(tt), |y(tt)|, pT(tt)
- **Lepton+jets**: **Inclusive** and **differential** measurements unfolded at parton level, using a selection based on: 1 high p_T tight ℓ, large E_t^{miss} and m_T^W.
  - Eur.Phys.J. C76 (2016) no.2, 87, and Phys. Lett. B756 (2016) 52 in the boosted regime: m(tt) > 0.75 TeV

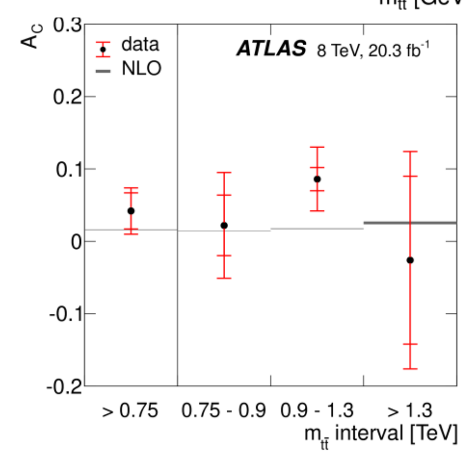


A_C = [0.021 ± 0.016 (stat+syst)]
SM pred: (0.0111 ± 0.0004)
A_{ll}^C = [0.008 ± 0.006 (stat+syst)]
SM pred: (0.0064 ± 0.0003)



A_C = [0.9 ± 0.5 (stat+syst)] %
SM pred: (1.11 ± 0.04)%
A_C = [4.2 ± 3.2 (stat+syst)] %
SM pred: (1.6 ± 0.04)%, for m(tt) > 0.75 TeV

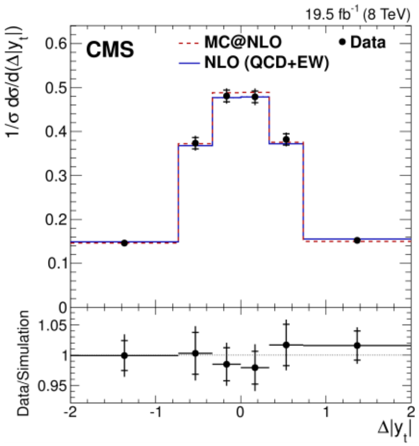


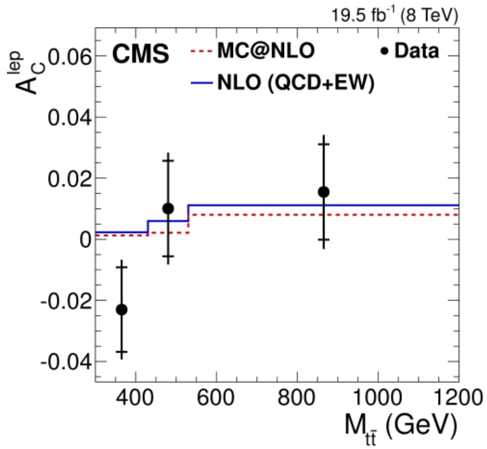


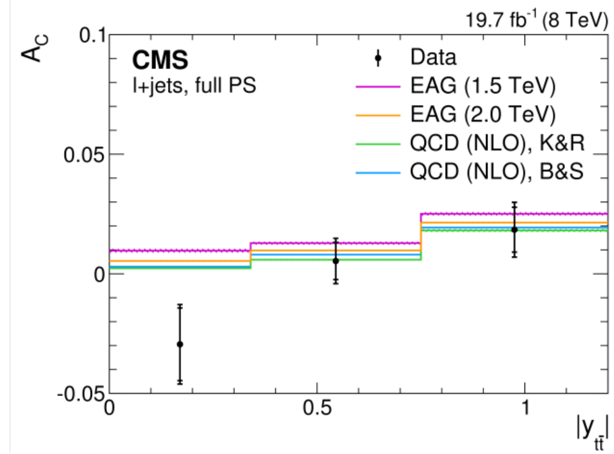
CMS: Charge asymmetry in dilepton and l+jets channels

PLB 757 (2016) 154, PLB 760 (2016) 365, PRD 93, 034014 (2016)

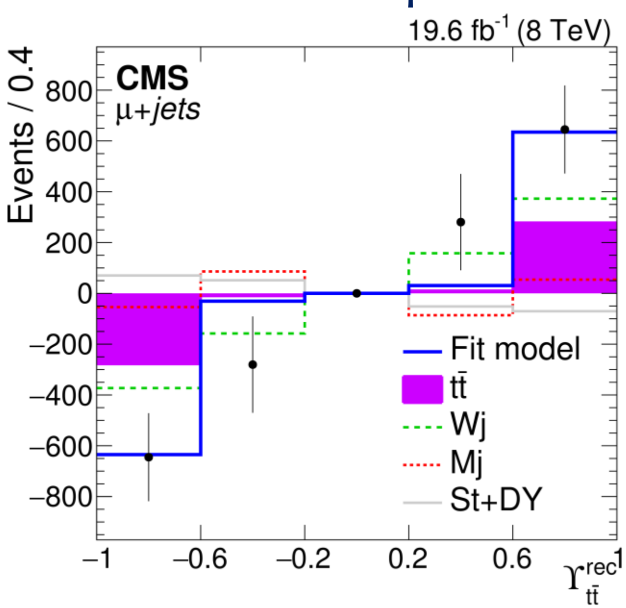
- **Inclusive** and **differential** measurements unfolded at parton level.





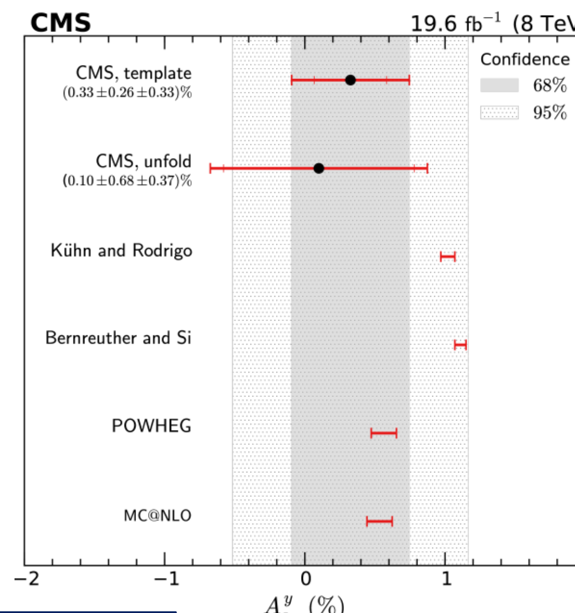


- Alternative template method using shape of Δ|η| distribution



$$\Upsilon_{t\bar{t}} = \tanh \Delta|y|_{t\bar{t}},$$

Observable needs to be bounded.
Use symmetric and asymmetric versión of MC template to fit:
$\rho^{\pm}(X)=(\rho(X) \pm \rho(-X))/2$
which has a smaller statistical uncertainty than unfolding, larger model dependence.



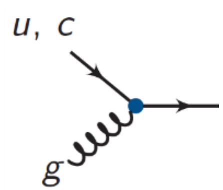
Results in agreement with SM

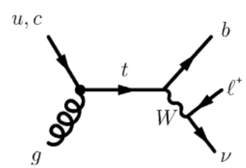
Flavor-changing neutral current

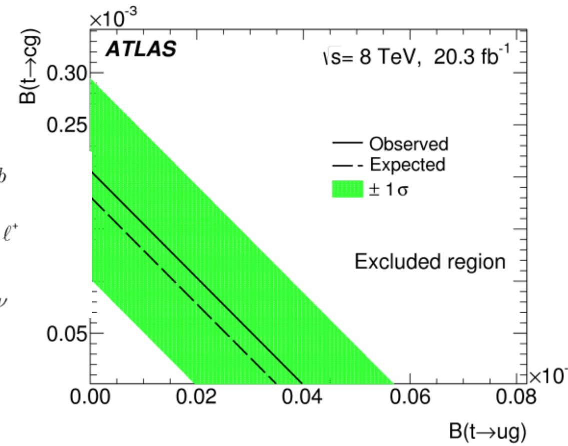
- **SM**: no FCNC at tree level (GIM suppression), BR ~ O(10^{-12} – 10^{-17})
- $t \rightarrow u/c + X$, X = g, γ, Z and H
- **BSM**: 2HDM, MSSM, and others, enhanced couplings, BR as high as 10^{-5}
- FCNC: t→qg at 8TeV, Not possible in tt because of multijet bkg.

K. Agashe et al., arXiv:1311.2028

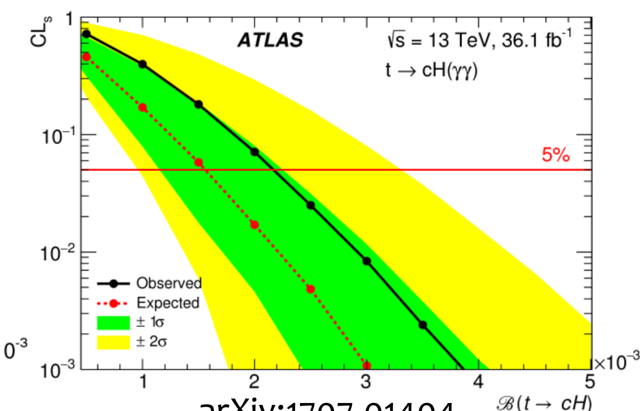
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\le 10^{-6}$	$\le 10^{-10}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\le 10^{-4}$	$\le 10^{-8}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\le 10^{-8}$	$\le 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\le 10^{-7}$	$\le 10^{-9}$	$\le 10^{-8}$	$\le 10^{-9}$	$\le 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\le 10^{-5}$	$\le 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\le 10^{-5}$	$\le 10^{-5}$	$\le 10^{-9}$	$\le 10^{-4}$







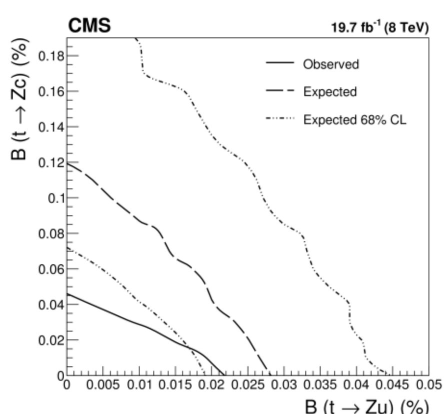
t→qH, H→γγ, √s= 13 TeV



arXiv:1707.01404

JHEP07(2017)003

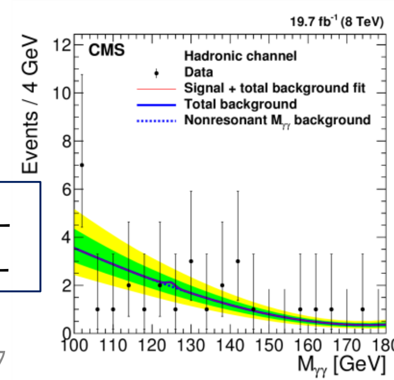
gg → tt→tZq

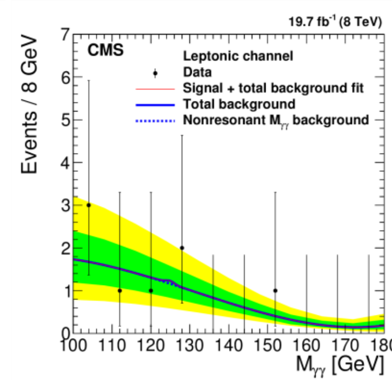


JHEP02(2017)079

tt→Wb Hq, H→γγ, ff

> B(t → Hc) < 0.40 % 95% CL
> B(t → Hu) < 0.55 % 95% CL





Wtb vertex structure in top decay

ATLAS:JHEP04(2017)124, arXiv:1707.05393,
CMS: JHEP02(2017)028

- W-helicity fractions:
  - $F_{L,R,0} = \Gamma_{L,R,0} / \Gamma_{total}$ for left-handed, right-handed and longitudinal W polarization

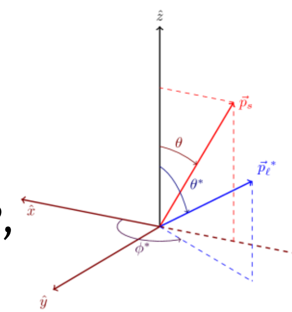
Most general CP-conserving lagrangian:

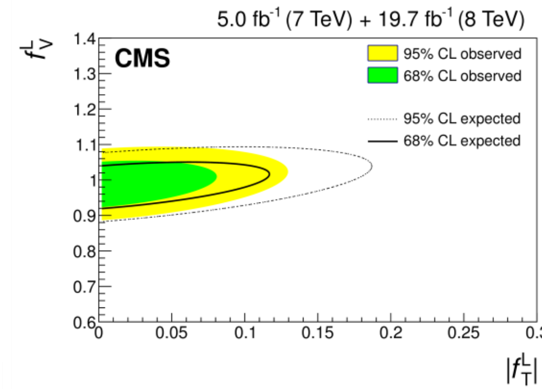
$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + h.c.$$

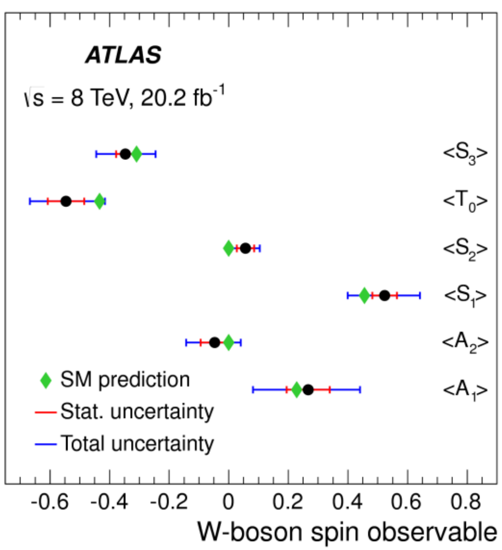
$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(f_L^V P_L + f_R^V P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(f_T^L P_L + f_T^R P_R)tW_{\mu}^{-} + h.c.$$

In the SM: $f_V^L = V_{tb}, f_V^R = f_T^L = f_T^R = 0.$

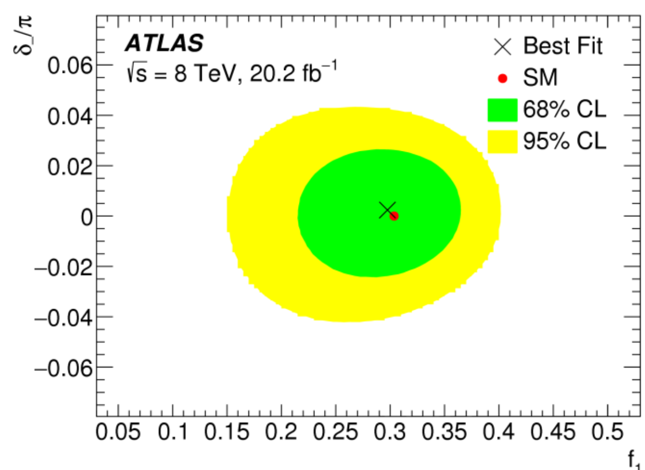
JHEP04(2017)124
Spin-density matrix for W-boson helicity components from polarised top-quark decay:
6 independent spin observables:
$\langle S_{1,2,3}\rangle\langle T_0\rangle\langle A_{1,2}\rangle$, $\langle S_{1,2}\rangle\langle A_{1,2}\rangle$ proportional to P,
$\langle S_3\rangle\langle T_0\rangle$ independent of P, related to: $F_{L,R,0}$

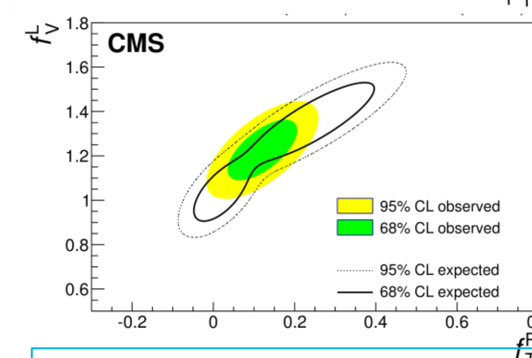






Triple-differential angular decay rates. arXiv:1707.05393





similar precision in tt and t-channel based analyses