Top physics in ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

Corfu workshop
Standard Model and Beyond
September 1, 2018

Outline

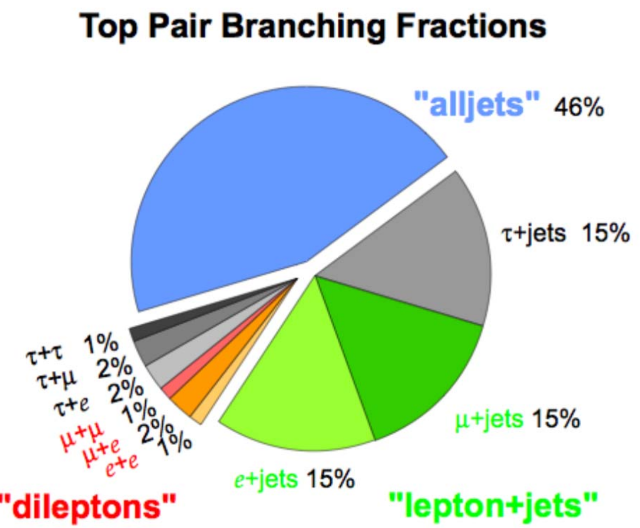
Recent results (mainly at 13 TeV) from ATLAS & CMS:

- $t\bar{t}$ cross-sections (inclusive and differential)
- $t\bar{t}$+X cross-sections
- Single top cross-sections
- FCNC top decays
- Top quark mass and width
- Signal model tuning

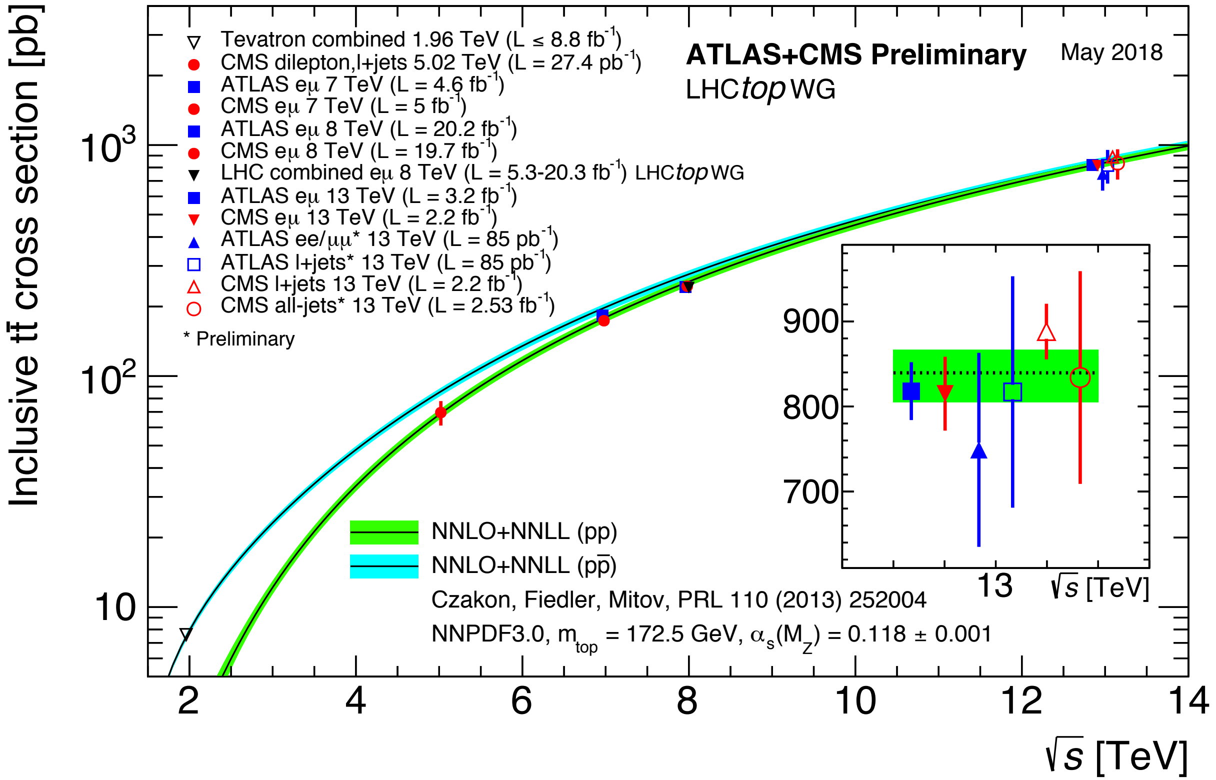
$t\bar{t}$ cross-sections (incl. and diff.)

Core delivery of the LHC. Statistics O(1000) times Tevatron:

- Unique test of QCD with massive partons
- Constraints on QCD soft scale modelling
- Background for many BSM and Higgs signals
- Indirect determination of m^{pole}
- Constraints on anomalous EFT terms



Inclusive $t\bar{t}$ cross-section

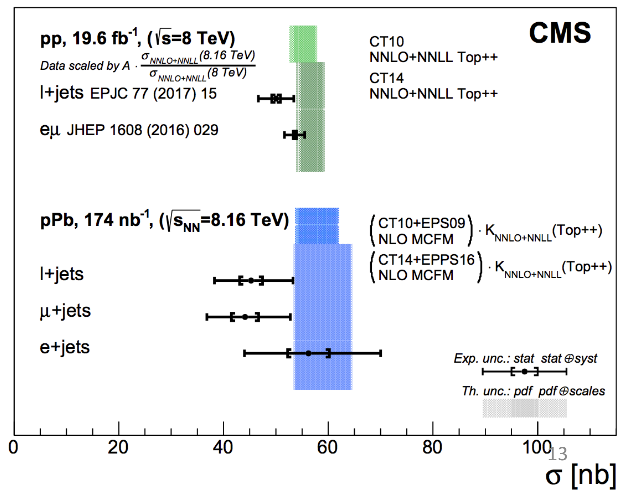


Impressive progress at the LHC!

Single measurement precision: ~3.5%

Limited mainly by luminosity and signal model uncertainty.

σ_{tt} in pPb collisions



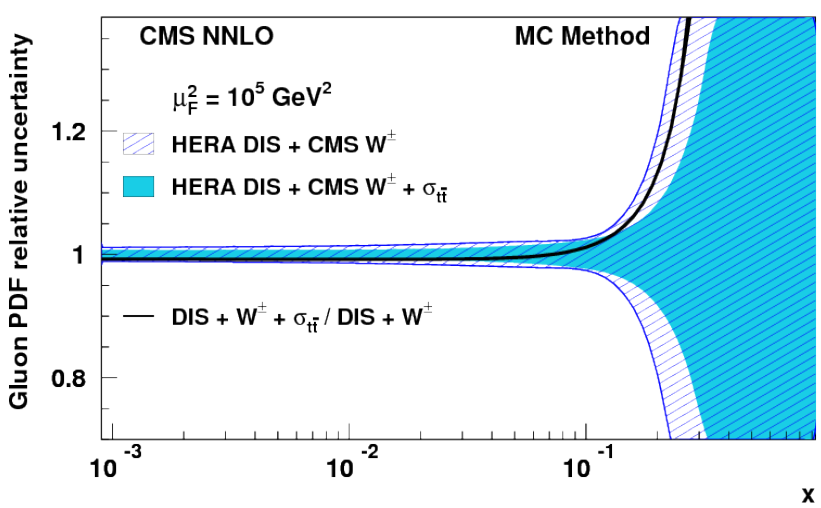
PRL 119, 242001 (2017)

Consistent with perturbative QCD within uncertainties:

Meas: σ_{tt} = 45 ± 8 nb Pred: σ_{tt} = 59 ± 6 nb

No significant nuclear modification

$t\bar{t}$ cross-sections and pdf's



JHEP 1803 (2018) 115

CMS: $\sigma_{t\bar{t}}$ @5.02 TeV. Dilepton and l+jets channels. L=27.4pb^{-1}

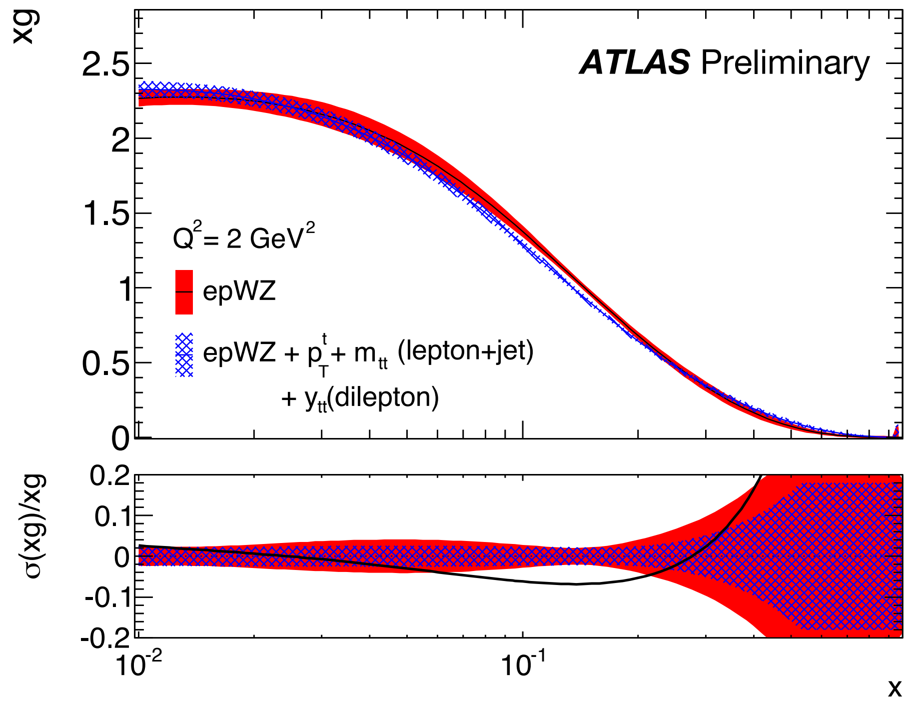
Moderate improvement in high-x gluon PDF uncertainty.

ATLAS-PUB-2018-017

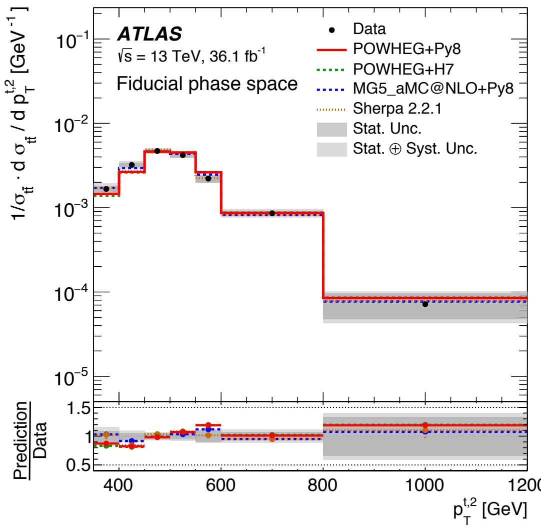
ATLAS: Global fit of the PDFs to

- The HERA DIS data set
- differential W/Z cross-sections at 7 TeV
- $d\sigma/p_T^t$ and $d\sigma/m_{tt}$ in $t\bar{t} \rightarrow l + jets$ at 8 TeV
- $d\sigma/y_{tt}$ in $t\bar{t} \rightarrow dilepton + X$ at 8 TeV

The result is a marginally harder gluon and smaller uncertainties



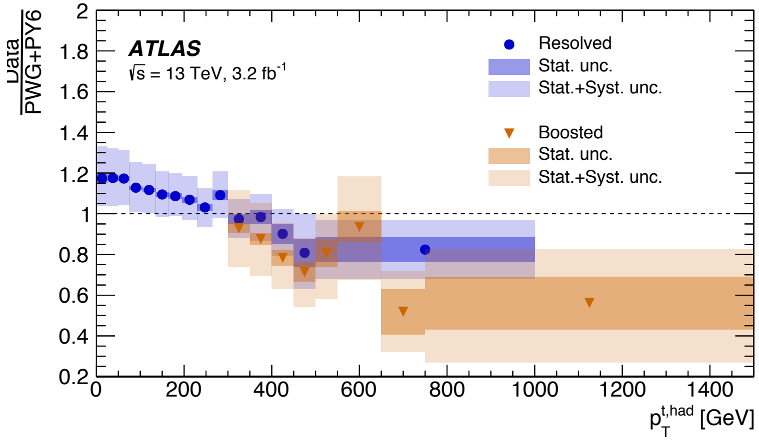
Differential $t\bar{t}$ cross-sections @ 13 TeV – top p_T



All-jets 36.1 fb^{-1}

PRD 98 (2018) 012003

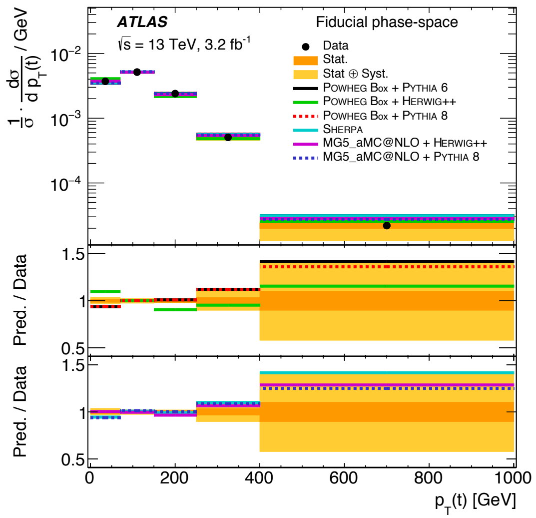
Boosted jet topologies



l+jets 3.2 fb^{-1}

JHEP 1711 (2017) 191

Both resolved and boosted jets



Particle level

eμ channel 3.2 fb^{-1}

Eur. Phys. J C77 (2017) 299

Neutrino momenta from E_T^{miss} and mass constraints

Main uncertainties: JES, b-tagging, signal and background modelling

Kinematic variables generally consistent with NLO QCD, but l+jets data have softer top p_T than predicted (also seen at 8TeV, see eg Eur. Phys. J. C76 (2016) 538)

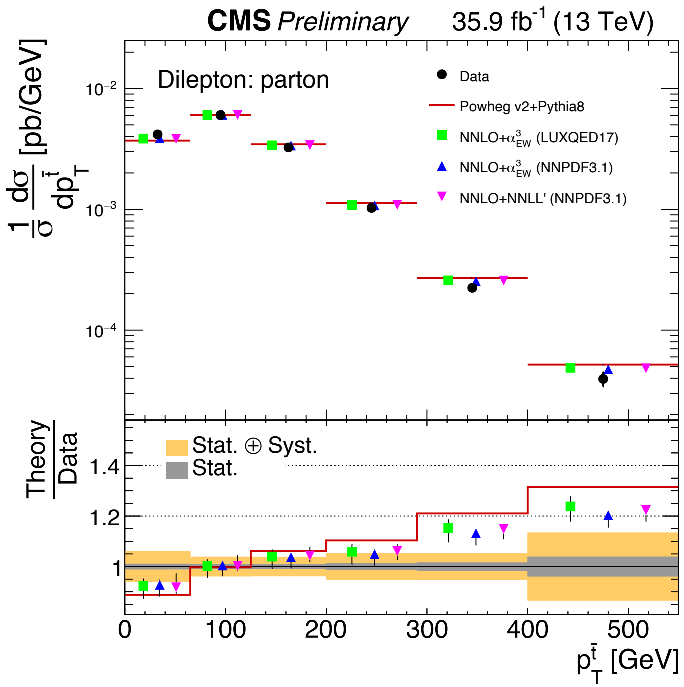
Differential $t\bar{t}$ cross-sections @ 13 TeV – top p_T

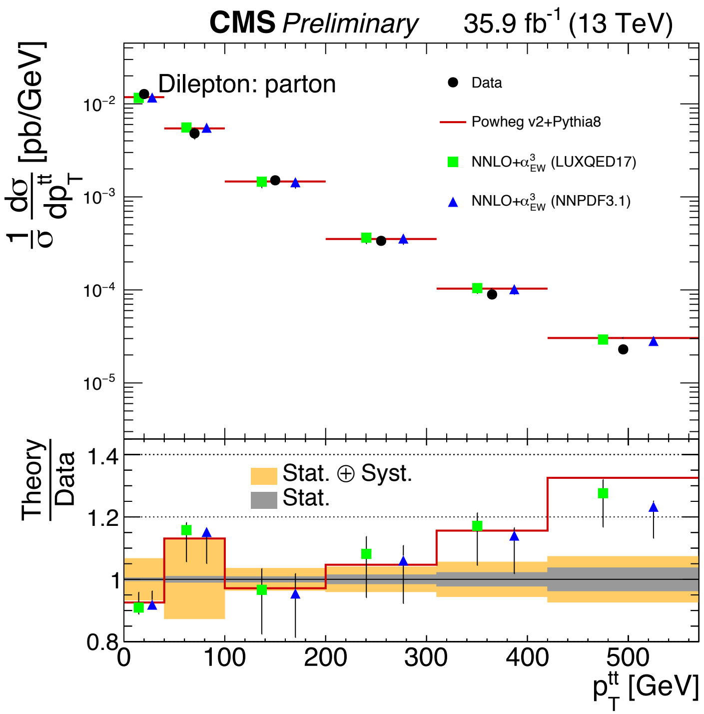
Parton level

Dilepton channel

Full phase space

CMS-PAS-TOP-17-014

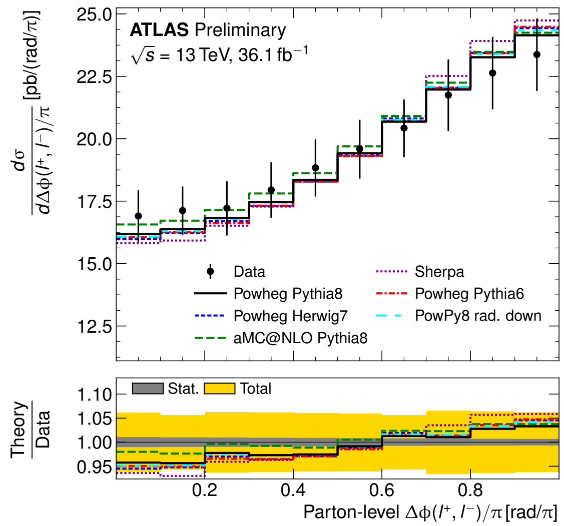




CMS new dilepton results clearly show a softer top p_T than predicted.
Higher order QCD and EW corrections help, but not enough.
Other variables related to top p_T (p_T^{tt}, m_{tt} and N_{jets}) are also in tension.
Other kinematic variables (y_t, y_{tt}, $\Delta\phi_{tt}$) are consistent with PWHG+PY8.

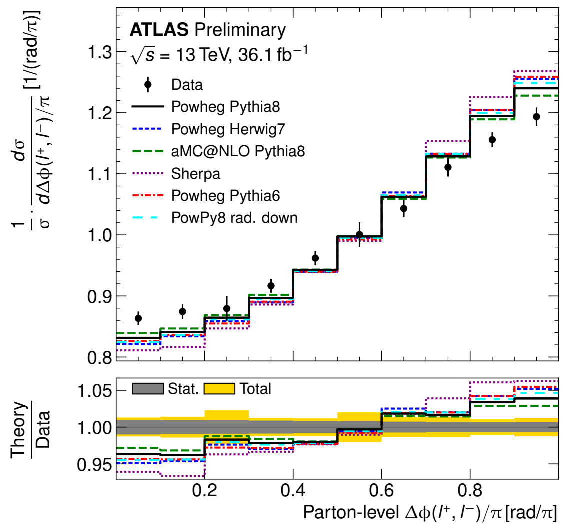
dσ/dΔφ_{ll} and spin correlations

absolute



(a)

normalized



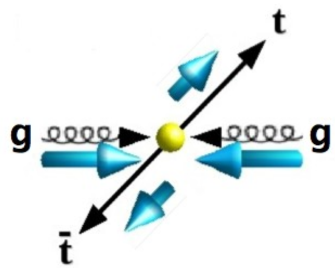
(b)

ATLAS-CONF-2018-027

Parton level

$t\bar{t} \rightarrow e\mu + X$
selection

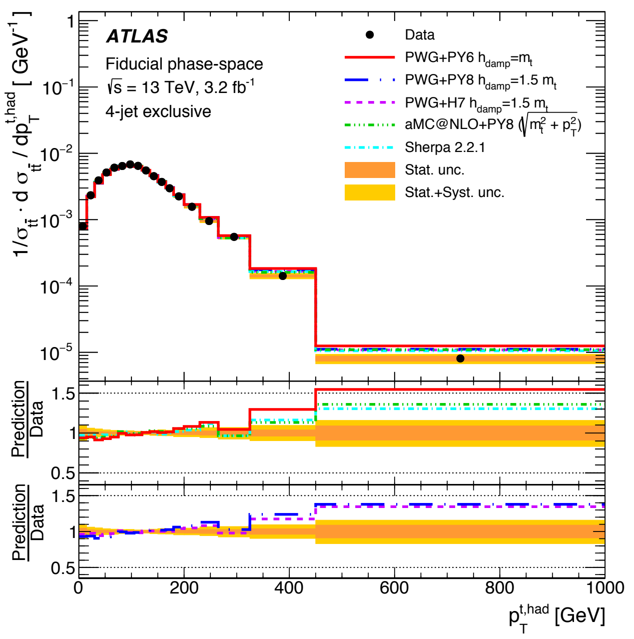
Full phase space



The *normalized* distribution (1/σ)dσ/dΔϕ_{ll} is sensitive to spin correlations between the t and $\bar{t}$.
ATLAS finds these correlations to be 3.2σ larger than NLO generator predictions. This discrepancy tends to grow with m_{tt}.

CMS uses Δϕ(l^+l^-) to constrain a chromomagnetic dipole EFT operator O_{tG} (see 1503.08841) which modifies the top-gluon interaction. A coefficient ~1σ above zero is found. CMS-PAS-TOP-17-014

$\bar{t}t + jets$

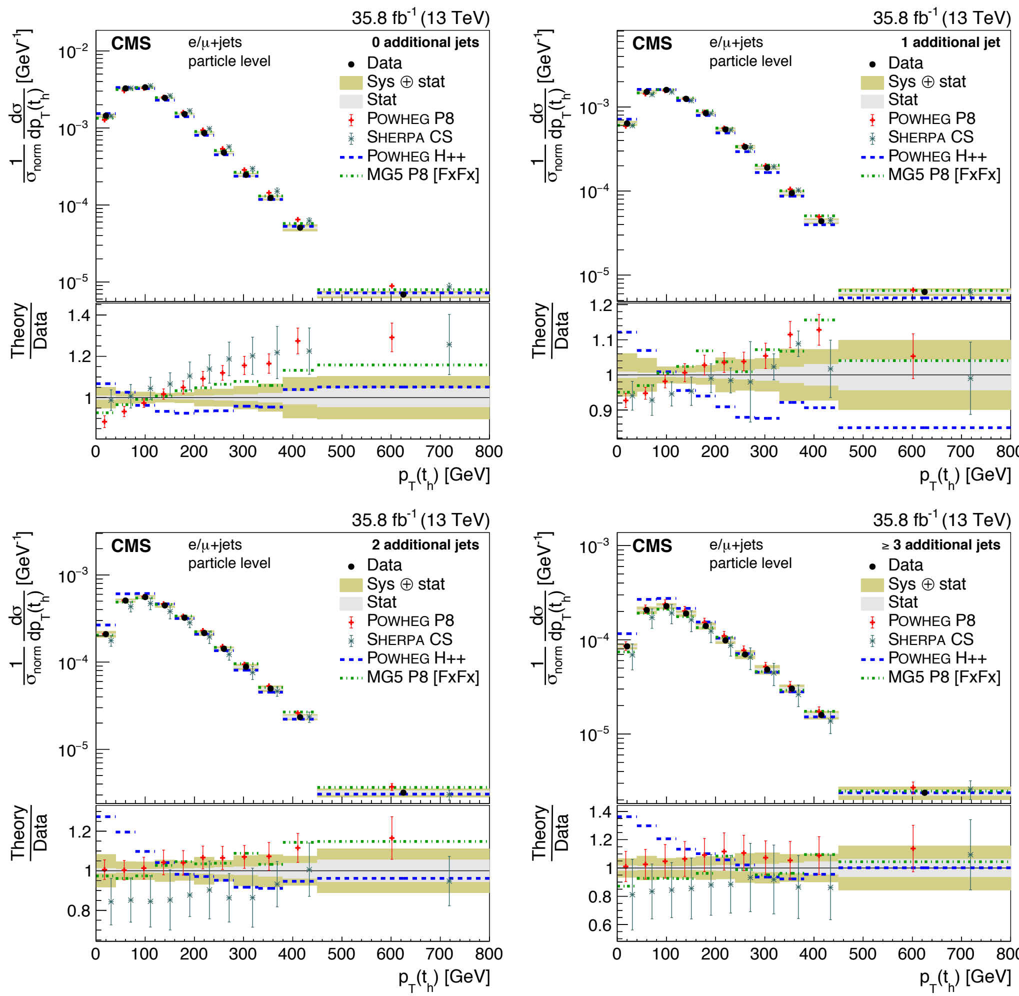


ATLAS l + N jets, 13 TeV 3.2 fb^{-1}

arXiv:1802.06572

p_T problem most pronounced in the exclusive 4-jet configuration (no additional jet).

Also, PWHG+PY has difficulties simultanously reproducing *both* Njets and $p_T(t\bar{t})$.

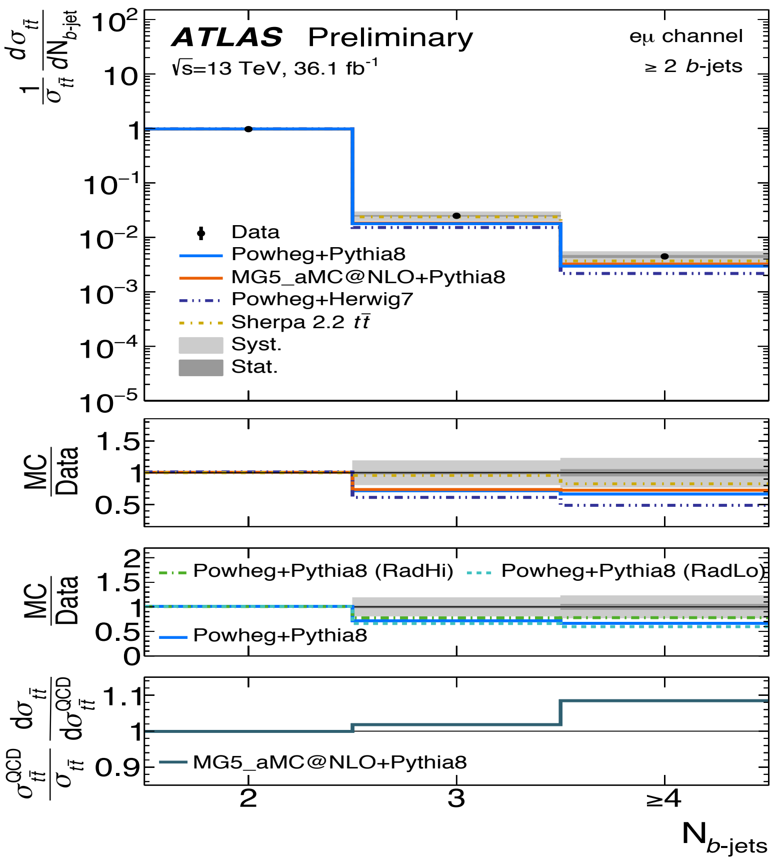


CMS l + N jets, 13 TeV, 35.8 fb^{-1}

PRD 97 (2018)) 112003

Very similar conclusions

$t\bar{t}$ + bjets – important for the $t\bar{t}$H signal



CMS PLB 776 (2018) 355

13 TeV, 2.3 fb^{-1}, ll + b-jets

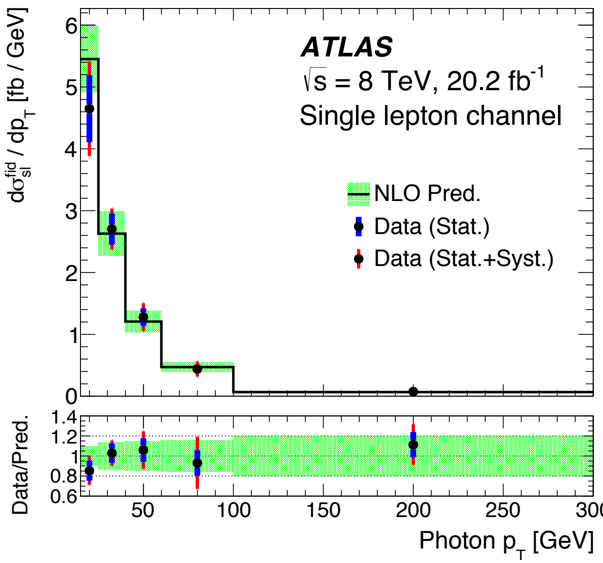
New: ATLAS-CONF-2018-029

13 TeV, 36.1 fb^{-1}, e and/or μ + b-jets

Pythia8 and Herwig7 predictions of extra b-jets are too low - but compatible within 2σ.

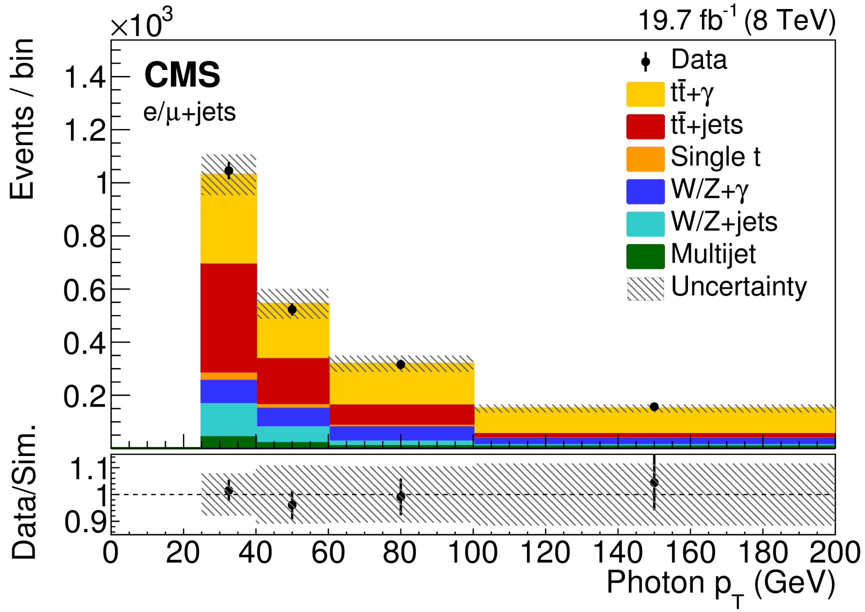
SHERPA 2.2 $t\bar{t}$ is in agreement with data.

$t\bar{t}\gamma$ @ 8 TeV



ATLAS l+jets+γ JHEP 11 (2017) 086

$\sigma_{tt\gamma}$=139 ± 18pb

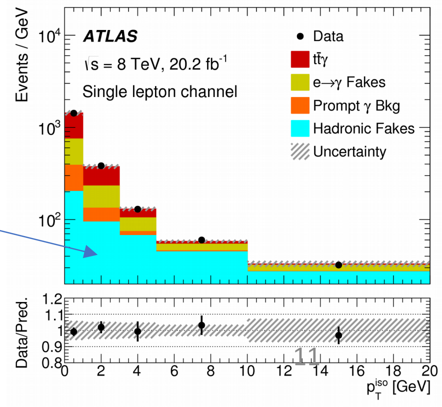


CMS l+jets+γ JHEP 10 (2017) 006

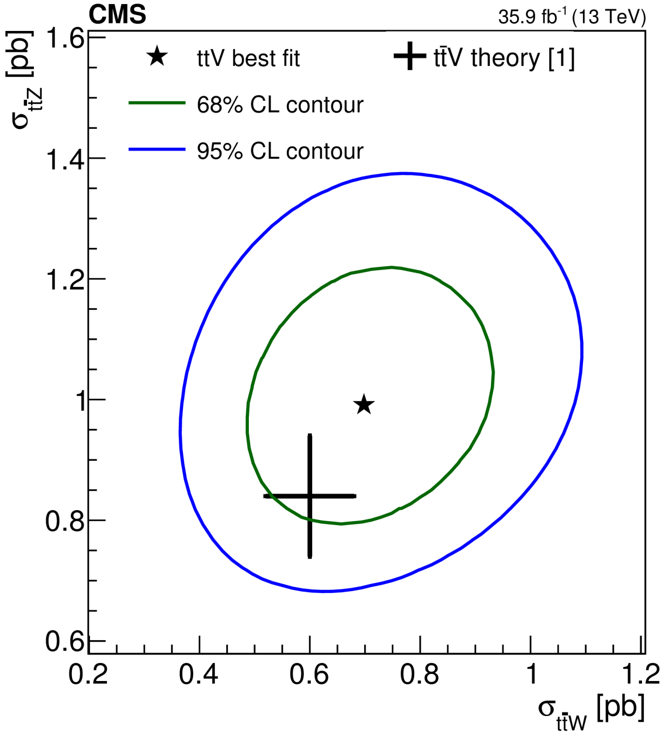
$\sigma_{tt\gamma}$=127 ± 27pb

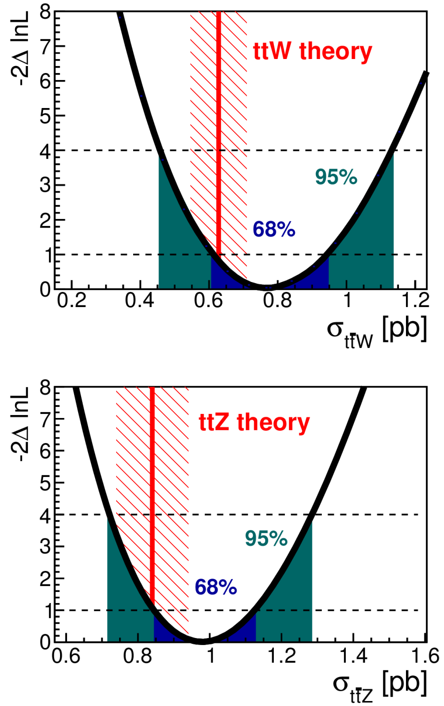
Main uncertainty: Fake photons

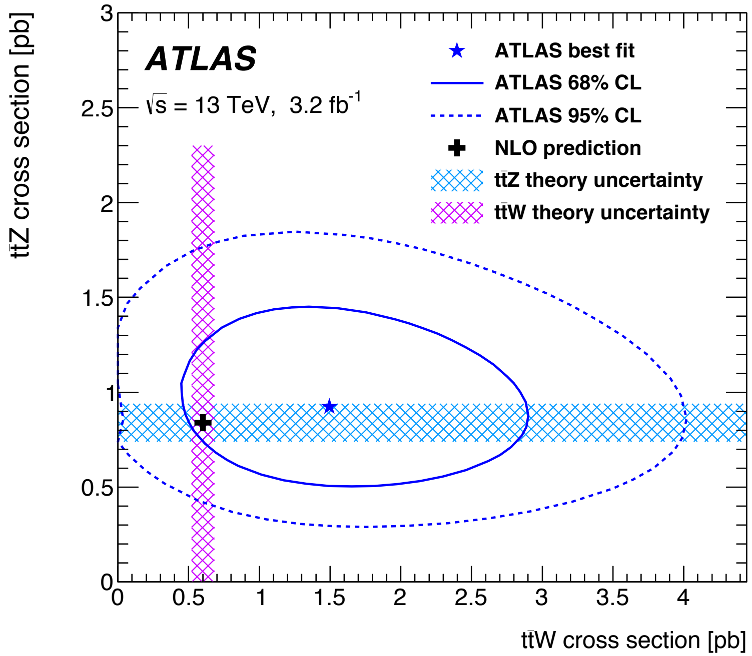
(LO) MadGraph, normalised to NLO prediction: $\sigma_{tt\gamma}$=151 ± 24pb



$t\bar{t} + W/Z$







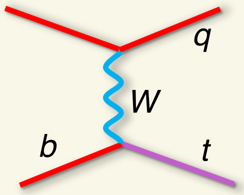
CMS 2l(SS)+jets, multi-l+jets, 13 TeV, 35.9 fb^{-1}:
arXiv:1711.02547

Statistics dominated. 29 event categories analyzed.
Constrains anomalous EFT operators.

ATLAS 13 TeV, 3.2 fb^{-1}
Eur.Phys.J. C77(2017)40
~Same channels used

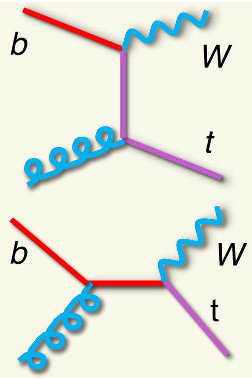
Single top production

t-channel



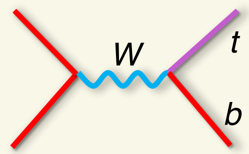
$\sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb}$

***tW*-channel**



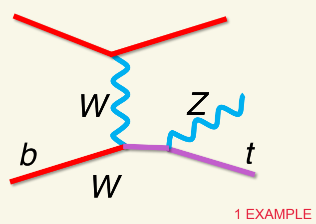
$\sigma(13\text{TeV}) = 72^{+4}_{-4}\text{pb}$

s-channel



$\sigma(13\text{TeV}) = 10.3^{+0.4}_{-0.4}\text{pb}$

***tZq* channel**
(rare SM process)



$\sigma(13\text{TeV}) = 0.8^{+0.05}_{-0.05}\text{pb}$

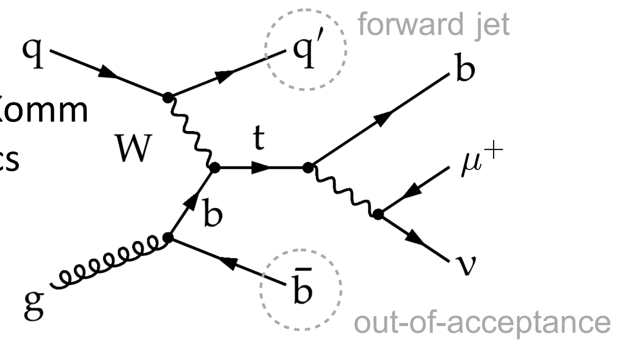
Thanks to
Marcel Vreeswijk
for graphics

From Hathor:
Comp.Phys.Comm.
191(2015)74

Tests SM Wtb vertex: New Constraints on anomalous EFT operators.

Huge background from $t\bar{t}$. Use MVA methods to get rid of it.

t channel

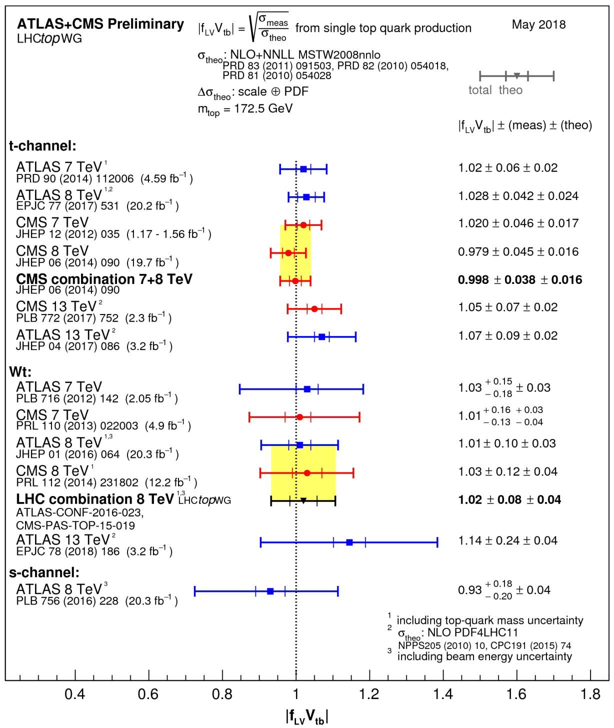


ATLAS 8 TeV 20.2 fb^{-1} EPJC 77 (2017) 531

$|f_{LV} V_{tb}| = 1.03^{+0.05}_{-0.04}$

R $t/\bar{t}$ = 1.72 ± 0.08

(NNPDF3.0 predicts 1.82 ± 0.04)



CMS 13 TeV 35.9 fb^{-1} CMS-PAS-TOP-17-011

SR: l + jets, split by #b-jets

$|f_{LV} V_{tb}|$ = 1.00 ± 0.05 ± 0.02(theo)

R $t/\bar{t}$ = 1.65 ± 0.02 ± 0.04

(NNPDF3.0 predicts 1.66 ± 0.02)

Main systematic: PS scale.

Also available:

Differential cross-sections:

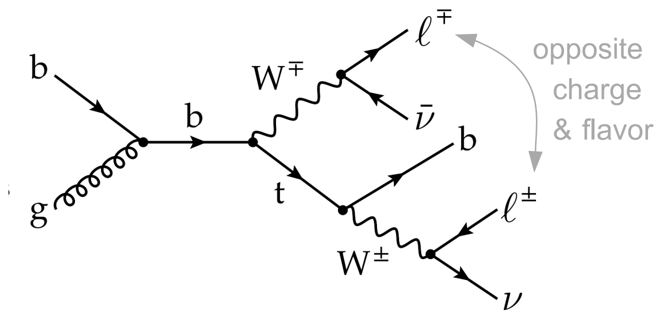
EPJC 77 (2017) 53, CMS-TOP-16-004

top/W polarization:

JHEP 1704 (2017) 124, JHEP 1604 (2016) 073

tW channel

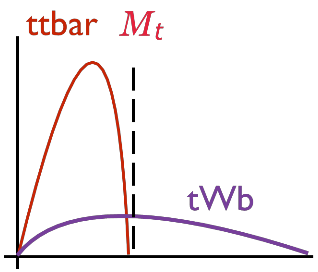
ATLAS 13 TeV, 36.1 fb^{-1}, 1806.04667
Final state is $l^+l^-b\bar{b} + X$
First study of prescriptions for separating
tW from $t\bar{t}$ amplitudes

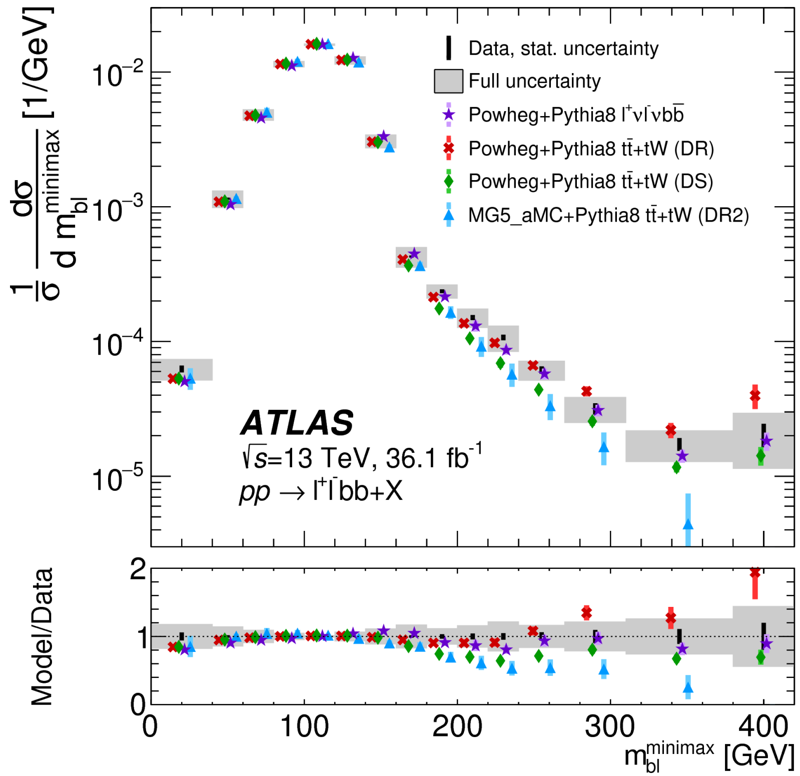


$$m_{b\ell}^{\mathrm{minimax}} \equiv \min\{ \max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

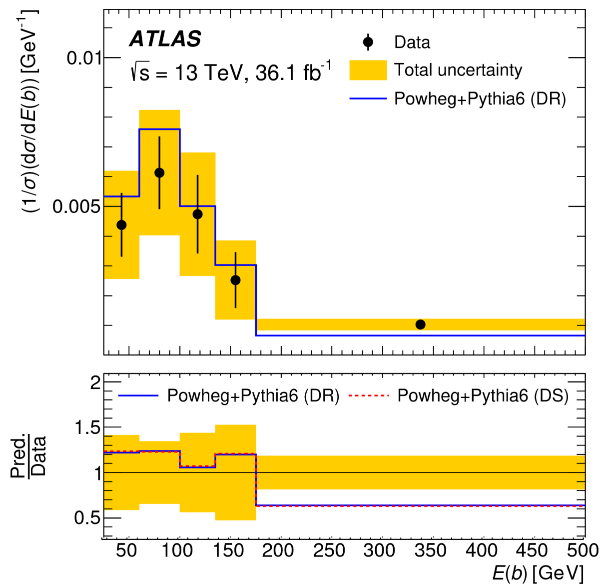
Nominal prescription: Diagram Removal
Alternative DS : Diagram Subtraction
Alternative DR2 : Remove only modulus sq.

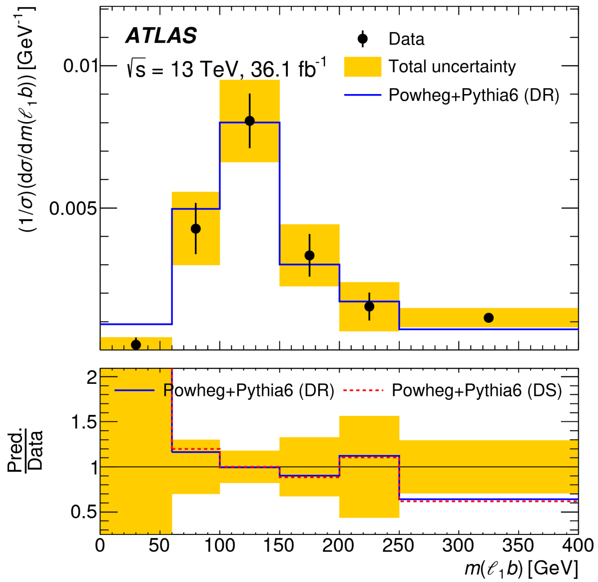
Powheg+Pythia8 : Abandon distinction between $t\bar{t}$ and $tW\bar{b}$. Full amplitude.





tW channel – differential and inclusive



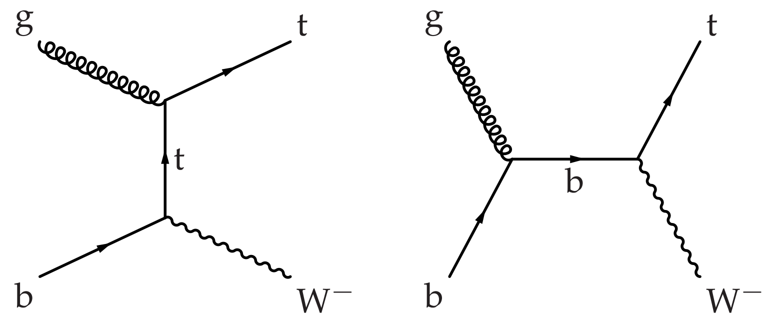


ATLAS 13 TeV, 36.1 fb^{-1}: EPJ C78 (2018) 186

SR: dilepton+b

Use BDT to reduce the large $t\bar{t}$ background.

Data>MC in high energy tails



CMS 13 TeV 35.9 fb^{-1}: arXiv:1805.07399

SR: eμ+b

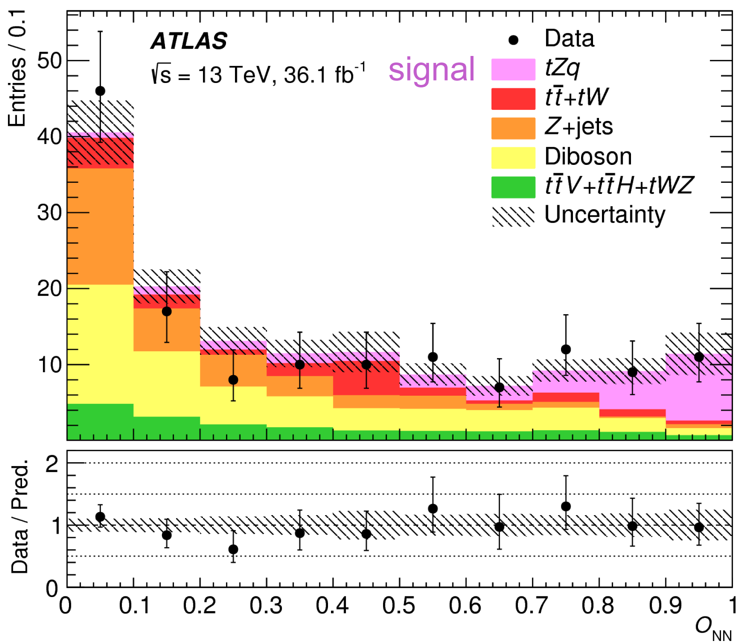
σ_{tW} = 63.1 pb ± 11%

Agrees with NLO prediction: 72 ± 4 pb

~3% sys uncertainty from each source:
(efficiencies, trigger, JES, lumi,
stat, pile-up, $t\bar{t}$ bkg)

Must reduce *all* to obtain substantial improvement.

Evidence for tZq



ATLAS 13 TeV, 36.1 fb^{-1}:

PLB 780 (2018) 557

SR: 3l + b + jet

tZq significance: 4.2σ (5.4 expected)

CMS 13 TeV, 35.9 fb-1:

PL B779 (2018) 358

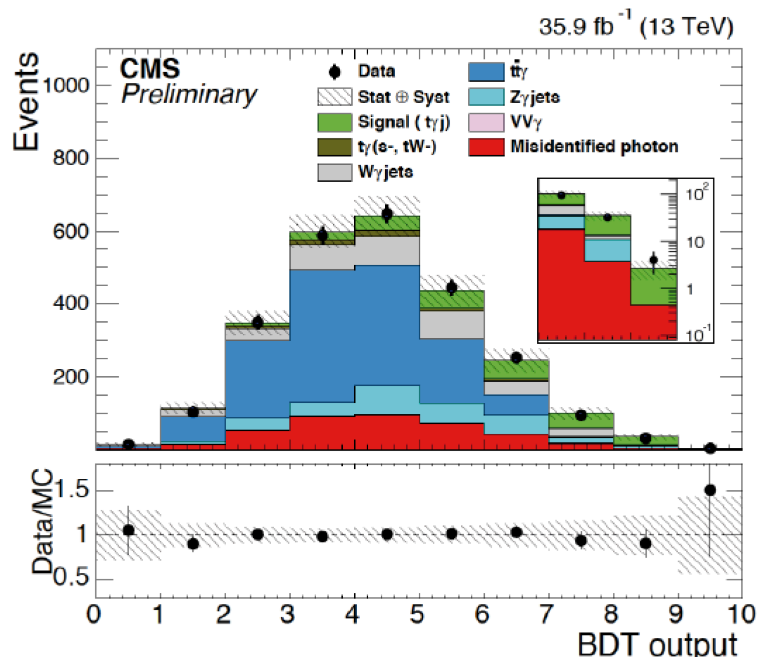
SR: 3l + b + jet(s)

tZq significance: 3.7σ (3.1 expected)

Evidence for tγq

CMS 13 TeV, 35.9 fb^{-1}: CMS-TOP-17-16

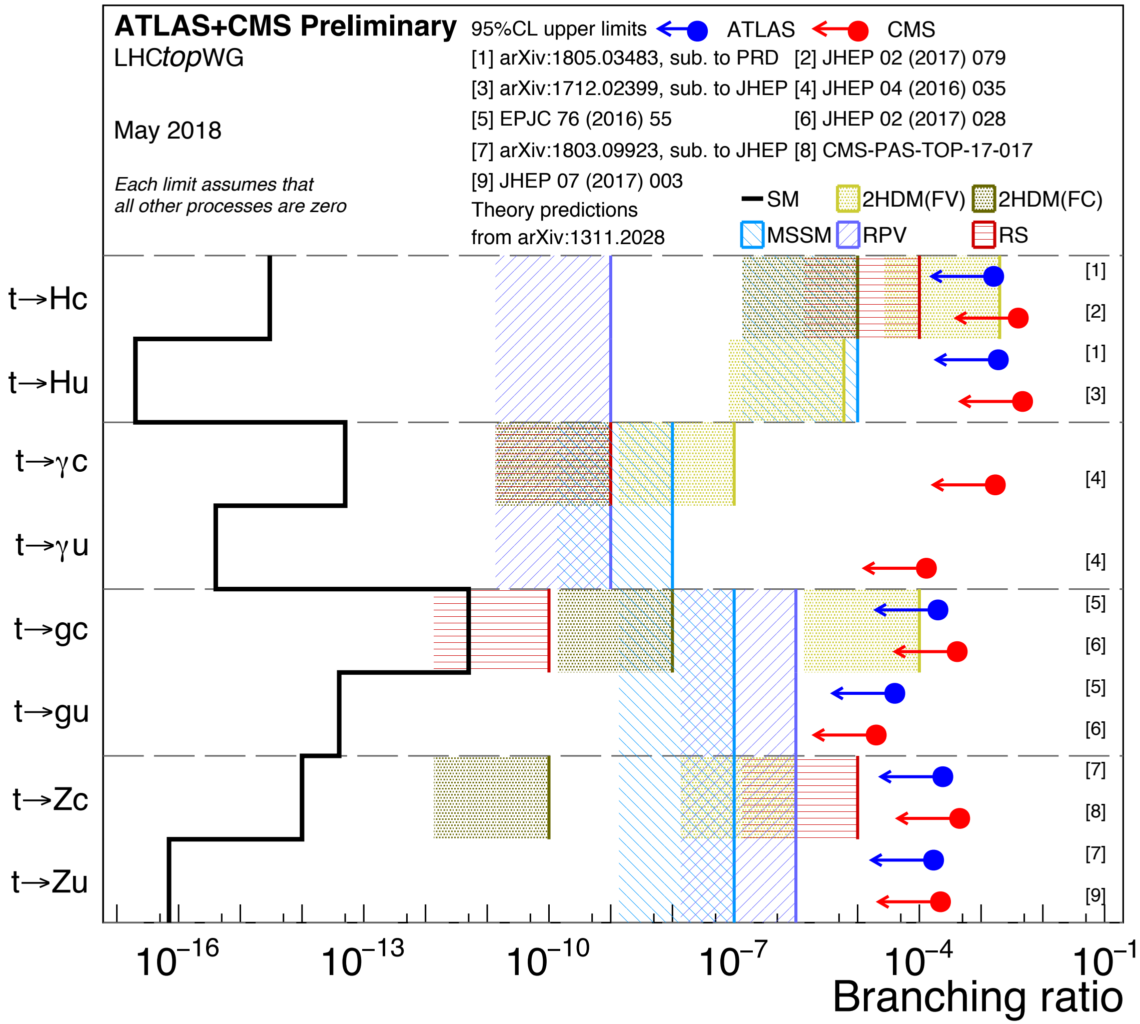
tγq significance: 4.3σ (3.0 expected)



FCNC summary

Starting to make contact with some BSM models

Full run2 will have much more exclusion power.

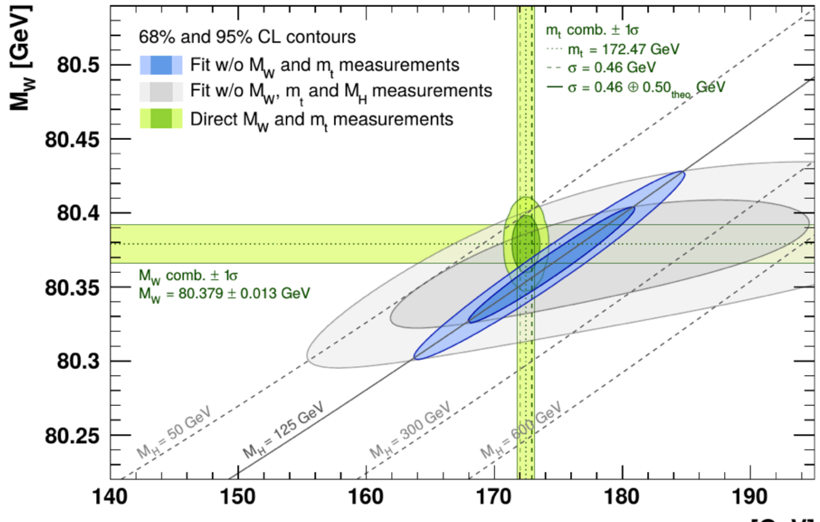


Top quark mass

- Very important test of the Standard Model.

- Measurements can be either *direct,* comparing mass-sensitive detector-level observables to MC templates calculated for different *top mass parameters*, m_{top}, in the generator,
- or they can be *indirect* from cross-section measurements that are predicted by NLO or NNLO calculations depending on the so-called *top pole mass,* m^{pole}, which is well defined theoretically as the mass of a free top.

- The relation between of m_{top} and m^{pole} is under debate and study, see eg CERN-TH-2017-266. The ambiguity is to a large extent covered by the reported systematic errors from varying scales, shower-matching and hadronization schemes.



arXiv: 1803.01853

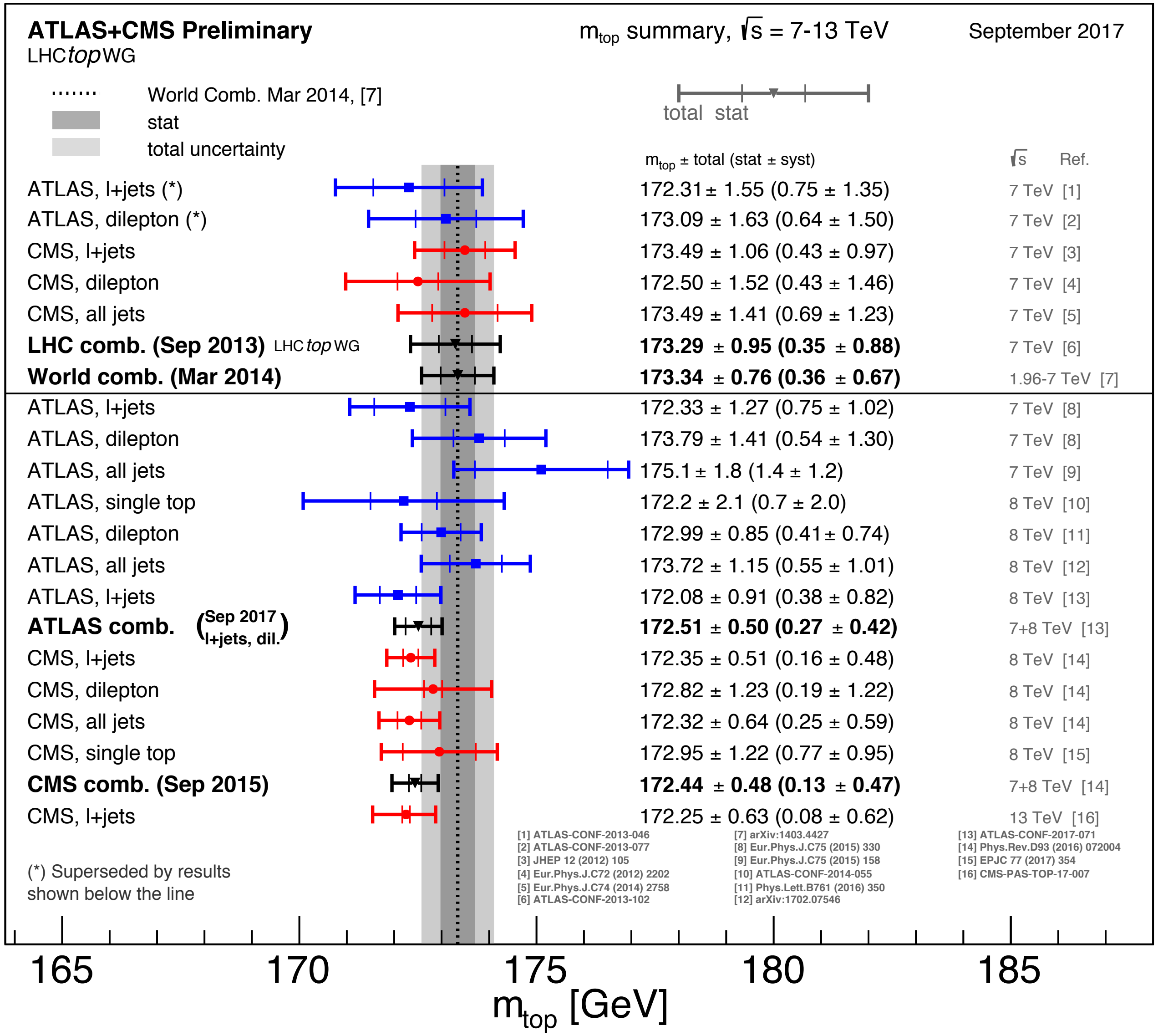
Direct top mass

Has now reached ~0.5 GeV prec.

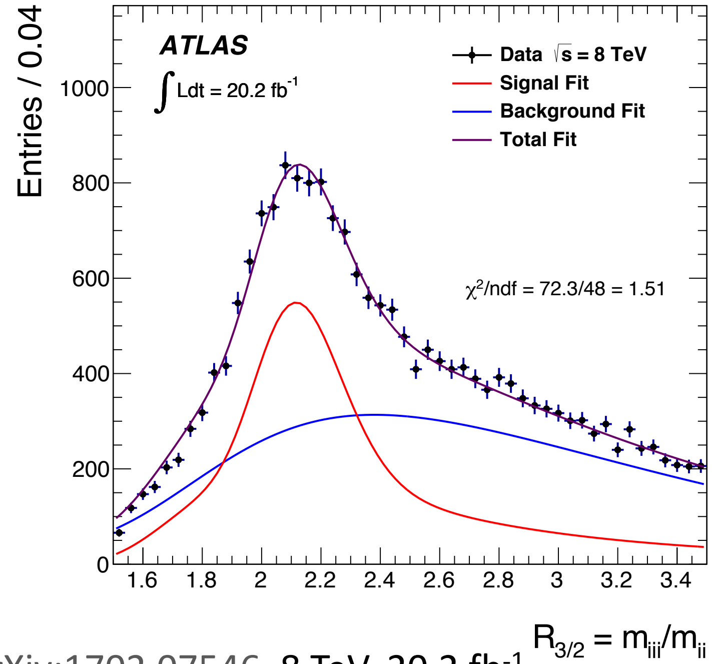
Latest:

ATLAS 8 TeV, 20.2 fb^{-1}, all jets (12)
ATLAS 8 TeV, 20.2 fb^{-1}, l+jets (13)
CMS 13 TeV, 35.9 fb^{-1}, l+jets
arXiv:1805.01428

Very latest:
CMS 13 TeV, 35.9 fb^{-1}, all jets
CMS-PAS-TOP-17-008



Direct top mass – all jets: $t\bar{t} \rightarrow W^{+}bW^{-}\bar{b} \rightarrow q\bar{q}'bq''\bar{q}'''\bar{b}$



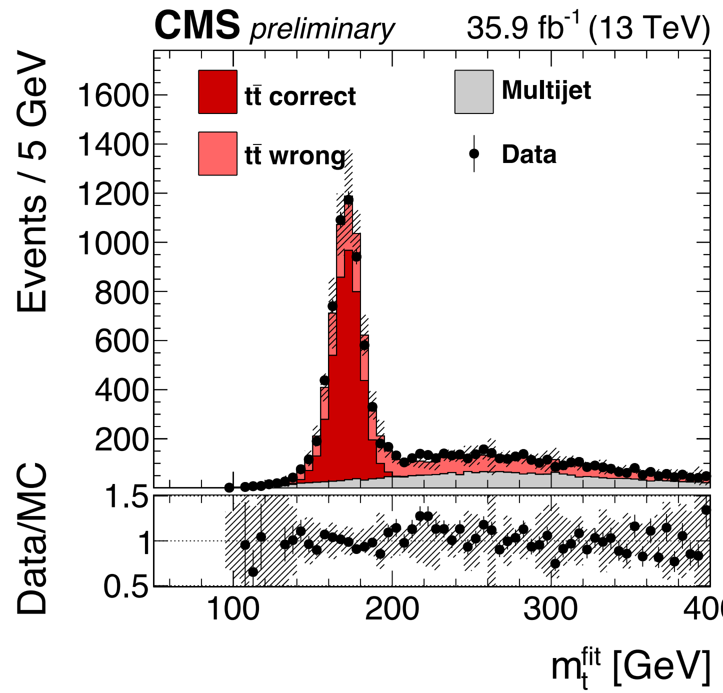
arXiv:1702.07546, 8 TeV, 20.2 fb^{-1}

m_{top} = 173.2 ± 0.55 ± 1.01 GeV

Jet assignments to top from chisquared kinematic fit

Fit 3-jet over 2-jet mass

Main systematics: hadronization, JES, bJES



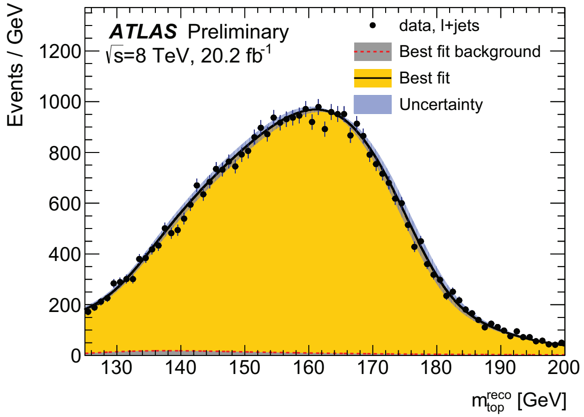
CMS-PAS-TOP-17-008, 13 TeV 35.9 fb^{-1}

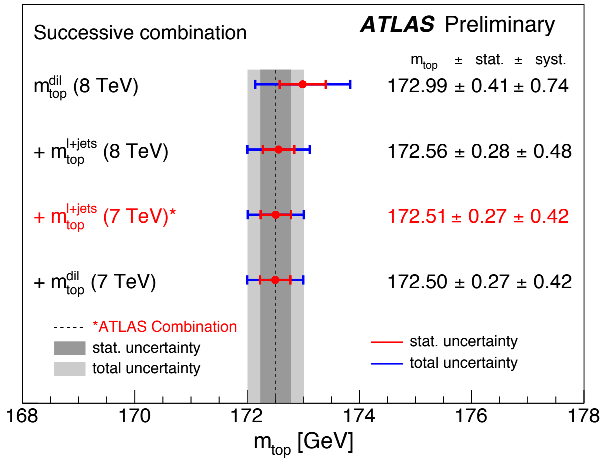
m_{top} = 172.34 ± 0.20(stat+JES) ± 0.76 GeV

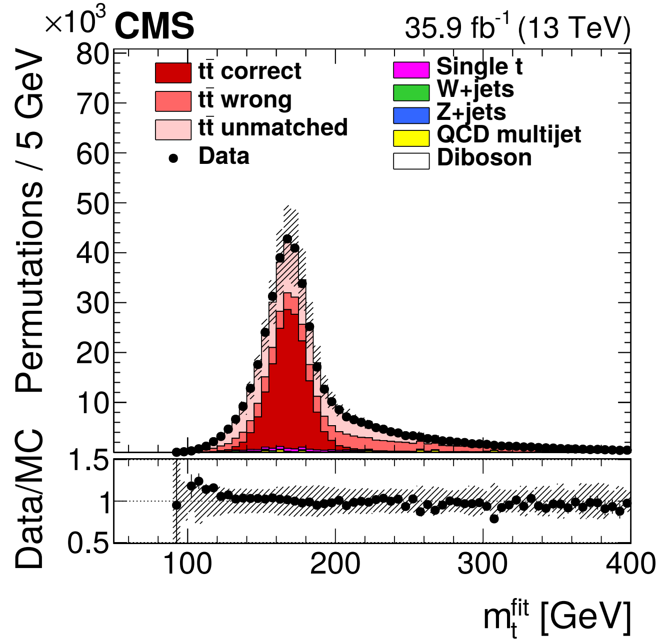
Simultanous ideogram fit of m_{top} and JES.

New Colour Reconnection variation contributes 0.36 GeV to the systematic uncertainty.

Direct top mass – l+jets: $t\bar{t} \to W^+ bW^- \bar{b} \to q\bar{q}' b\ell\bar{\nu}\bar{b}$







ATLAS-CONF-2017-071, 8 TeV, 20.2 fb^{-1}
m_{top} = 172.08 ± 0.39 ± 0.82 GeV
Parton assignments from kinematic fit.
Fit m_{top} and Jet Energy Scale simultanously.

Main systematics: JES, bJES , b-tagging.
Some partly cancel in the combination
with the dilepton and 7 TeV results.

arXiv:1805.01428, 13 TeV 35.9 fb^{-1}
m_{top} = 172.25 ± 0.08 ± 0.62 GeV
Simultanous ideogram fit of m_{top} and JES.
Main systematics: flavor dependent JES
New Colour Reconnection variation contributes
0.31 GeV to the systematic uncertainty.

Indirect top mass (m^{pole})

- EPJ C77 (2017) 804
  ATLAS 8 TeV, 20.2 fb^{-1}, eμ , (1/σ)dσ/dX

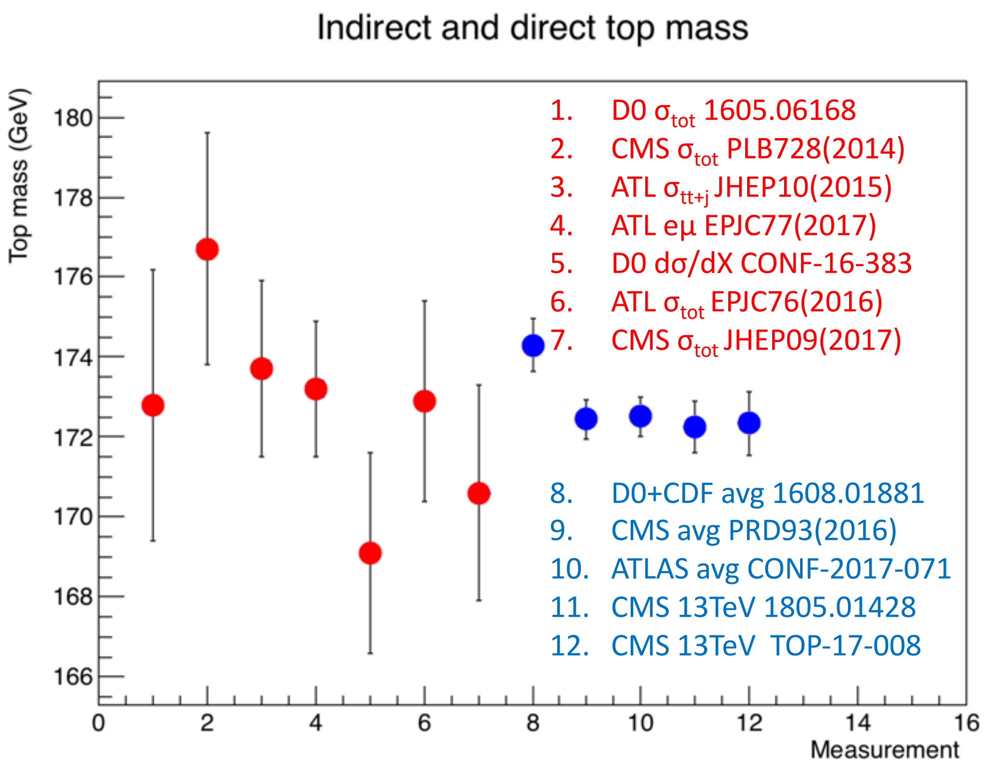
  Fit MCFM NLO templates to
  the shapes of 8 eμ observables
  (basically with no jet requirements):
  m^{pole} = 173.2 ± 1.2(exp) ± 1.2(theo) GeV
  Main systematics: QCD scales (ISR/FSR)

- JHEP 09 (2017) 051
  CMS 13 TeV, 2.2 fb^{-1}, l+jets

  Extract m^{pole} = 170.6±2.7 GeV
  from σ_{tt} = 888pb ±3.9% using Top++ and CT14

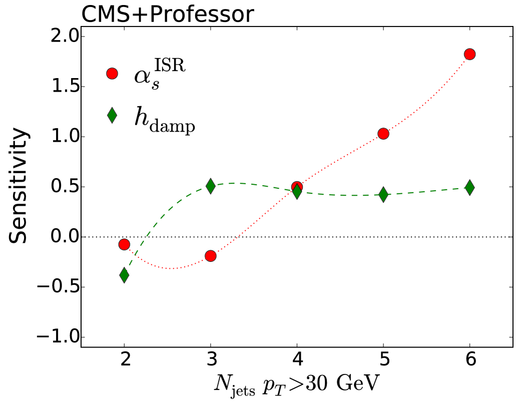
- **Very latest**: FERMILAB-CONF-16-383-PPD
  D0 1.96 TeV, 9.7 fb^{-1}, l+jets

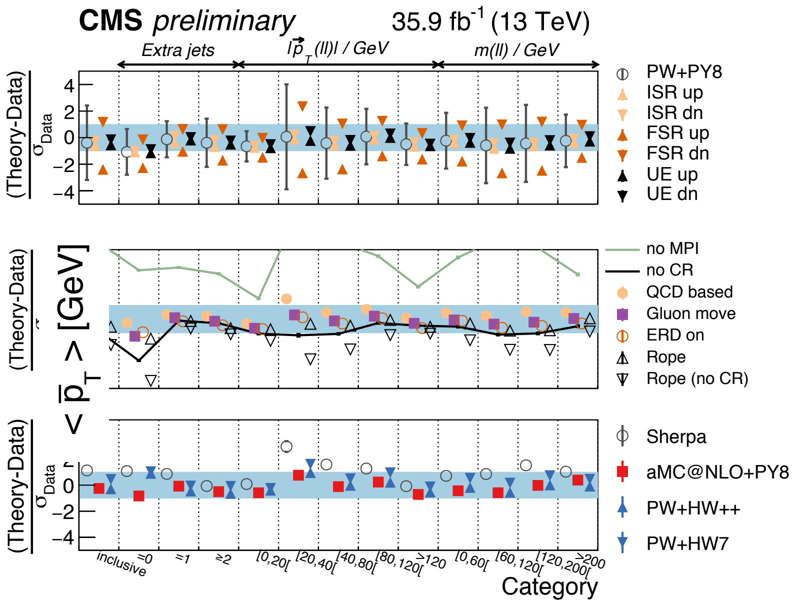
  Compare $\sigma_{tt}(m^{pole})$ and $d\sigma/dp_T(t)$ with NNLO calc:
  m^{pole} = 169.1 ± 2.5 GeV



No evidence at all for any systematic shift between m_{top} and m^{pole}, but a 1 GeV shift cannot be excluded either.

Shower model tuning





CMS-PAS-TOP-16-021, 8 TeV, 19.7 fb^{-1} (dilepton, l+jets).

The N_{jets} observable is sensitive to the parameters:

h_{damp}=1.6 ± 0.6 x m_t α_S^{ISR} = 0.111 ± 0.015

These values are used in PY8 tune (CUETP8M2T4) for Run2.

arXiv:1807.02810, 13 TeV, 35.9 fb^{-1} (μe + 2 b-jets)

Study observables N^{ch}, P_T^{ch} etc. in UE.

Classify events based on N_{jets}, p_T^{ll} and m_{ll}

PY8 performs well - MPI indispensable ingredient.

The analysis is sensitive to FSR:

α_S^{FSR} = 0.120 ± 0.006

CMS-PAS-TOP-17-13, (l+jets)

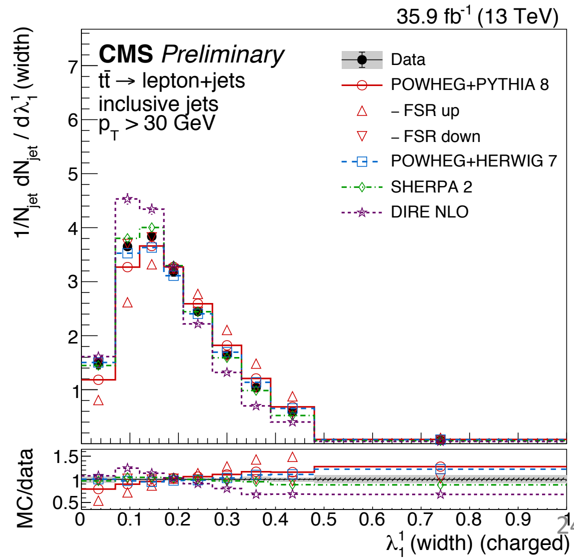
Jet width prefers

α_S^{FSR} = 0.123 ± 0.002 in PY8

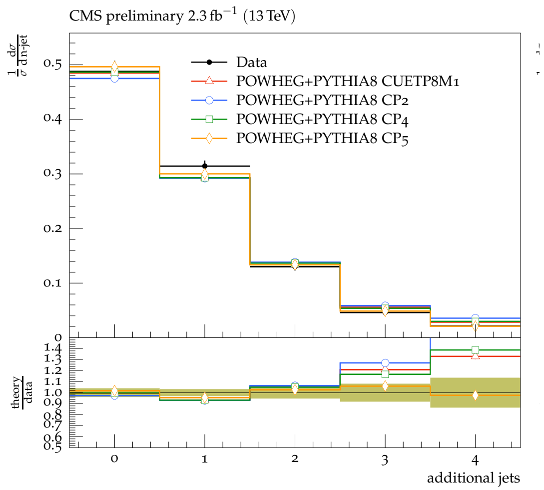
(note that Monash tune had

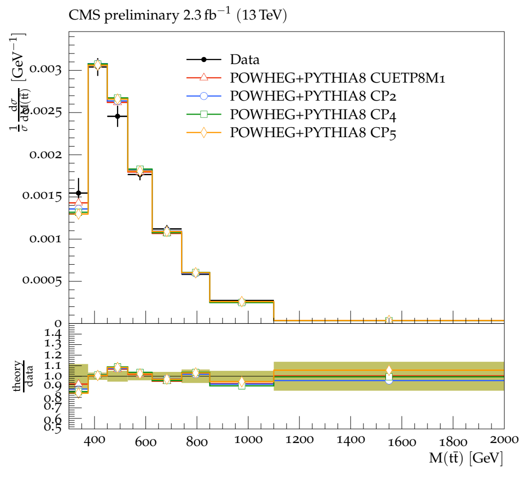
$\alpha_S^{ISR} = \alpha_S^{FSR}$ = 0.1365

- using NNPDF2.3LO)



Shower model tuning





CMS-PAS-GEN-17-01, 13 TeV, (Min Bias).

The UE parameters in PYTHIA8 have been tuned for the first time with the NLO and NNLO versions of NNPDF:

PYTHIA parameter	CP3	CP4	CP5
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(M_Z)$	0.118	0.118	0.118
SpaceShower:rapidityOrder	off	off	on
MultipartonInteractions:EcmRef [GeV]	7000	7000	7000
α_S^{ISR} value/order	0.118/NLO	0.118/NLO	0.118/NLO
α_S^{FSR} value/order	0.118/NLO	0.118/NLO	0.118/NLO
α_S^{MPI} value/order	0.118/NLO	0.118/NLO	0.118/NLO
α_S^{ME} value/order	0.118/NLO	0.118/NLO	0.118/NLO
MultipartonInteractions:pT0Ref [GeV]	1.516	1.483	1.41
MultipartonInteractions:ecmPow	0.02266	0.02012	0.03344
MultipartonInteractions:coreRadius	0.5396	0.5971	0.7634
MultipartonInteractions:coreFraction	0.3869	0.3053	0.63
ColorReconnection:range	4.727	5.613	5.176
χ^2/dof	0.759	0.803	1.04

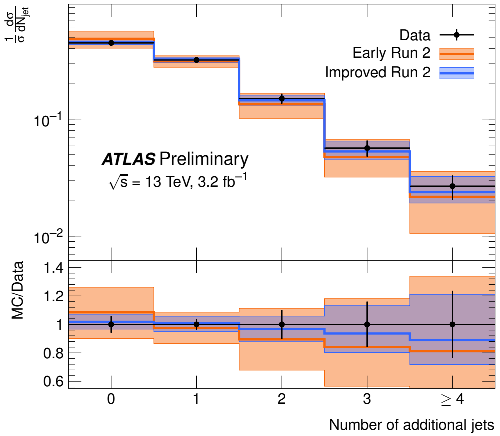
This comparison with MB and a variety of UE's at collision energies of 1.96, 7 and 13 GeV shows a similar level of agreement as with LO PDF tunings.

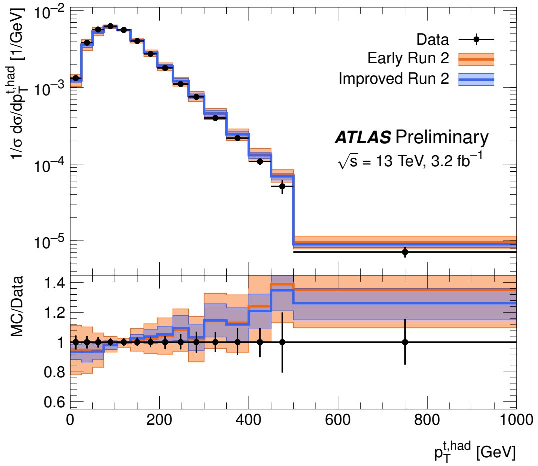
In particular, the top data are well reproduced – without these data having been used in the tuning.

Shower model tuning

ATLAS-PHYS-PUB-2018-009

The $t\bar{t}$ signal models used in early Run2 analysis have been significantly improved both regarding the realism of the nominal generator and the systematics resulting from the alternative generators.





New Run2 setup for ATLAS analysis

Source of Uncertainty	Samples	Procedure
Nominal	Powheg+Pythia8	N/A
NLO+PS matching	Powheg+Pythia8 vs. MadGraph5_aMC@NLO+Pythia8	$\pm\lvert\Delta\rvert$
Parton Shower and Hadronization Model	Powheg+Pythia8 vs. Powheg+Herwig7	$\pm\lvert\Delta\rvert$
Additional Radiation	Powheg+Pythia8 A14 (Var. 3c up, $\mu_{R,F} = 0.5, h_{\text{damp}} = 3.0\ m_{\text{top}}$ vs. Var. 3c down, $\mu_{R,F} = 2.0, h_{\text{damp}} = 1.5\ m_{\text{top}}$)	Δ

Summary

- Precise modelling of top quark production and decay, and precise measurements of top quark production and properties, are among LHC's most powerful instruments for probing fundamental physics.
- The present measurements are generally, but not in all details, consistent with SM NLO and NNLO simulations.
- The total Run2 sample will be a factor of 4 larger than the data investigated up to now and offer many new opportunities.
- Summarizing all measurements in the EFT framework has just started. This is promising for pointing out new research directions.

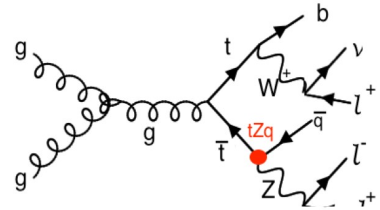
Backup slides

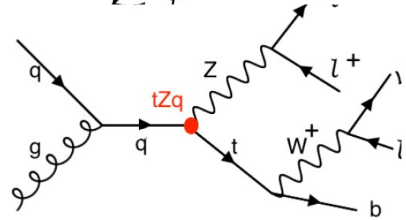
FCNC top decay t->qZ

ATLAS 13 TeV, 36.1 fb^{-1}: arXiv:1803.09923
Uses tt_{bar} -> (blν)(qll) topology
Extracts signal from m(llq) , m(lν) and m(lνb)

Br(t->Zu) < 1.7 10^{-3} (2.4 10^{-3} expected)
Br(t->Zc) < 2.2 10^{-3} (3.3 10^{-3} expected)

Main sys: signal model, large non-prompt bkg





CMS 13 TeV, 35.9 fb^{-1}: CMS-PAS-TOP-17-017
Includes also single top channel
Extracts signal from a BDT

Br(t->Zu) < 2.4 10^{-3} (1.5 10^{-3} expected)
Br(t->Zc) < 4.5 10^{-3} (3.7 10^{-3} expected)

Also interpretation in terms of EFT parameters available

FCNC top decay t->qH

ATLAS 13 TeV, 36.1 fb^{-1}
JHEP 10(2017)129 H->γγ:
Br(t->Hu) < 2.5 10^{-3} (1.7 10^{-3} expected)
Br(t->Hc) < 2.2 10^{-3} (1.6 10^{-3} expected)

arXiv:1805.03483 H->VV->leptons
Br(t->Hu) < 1.9 10^{-3} (1.5 10^{-3} expected)
Br(t->Hc) < 1.6 10^{-3} (1.5 10^{-3} expected)

Main sys: signal model
large non-prompt bkg

CMS 13 TeV, 35.9 fb^{-1}
arXiv:1712.02399
Uses H->bb_{bar}. Fits btag distributions.

Br(t->Hu) < 4.7 10^{-3} (3.4 10^{-3} expected)
Br(t->Hc) < 4.7 10^{-3} (4.4 10^{-3} expected)

All these limits are larger than expected…

Plenty of possible improvements:
- Will have x4 more Run2 data
- Will have better tuning @ 13 TeV
- Some channels not explored yet
- EFT-style analysis just started

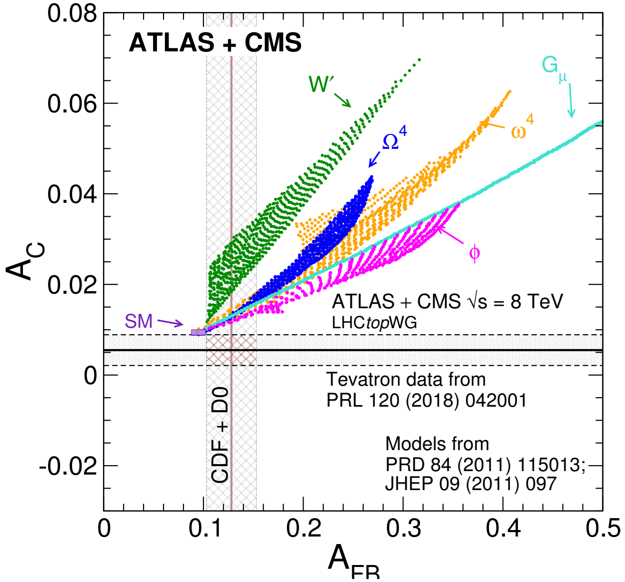
Top charge asymmetry – LHC Combination

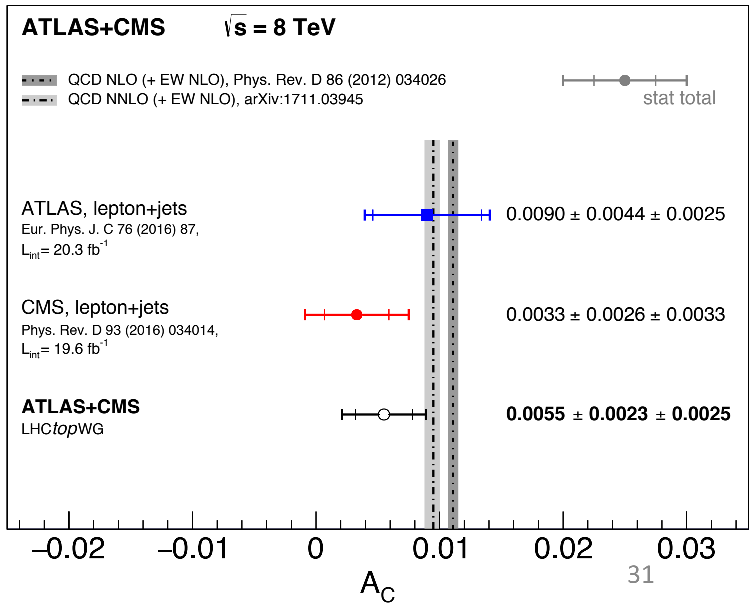
While the Tevatron could measure A_{FB} in ttbar events, LHC can measure

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

JHEP 04 (2018) 033

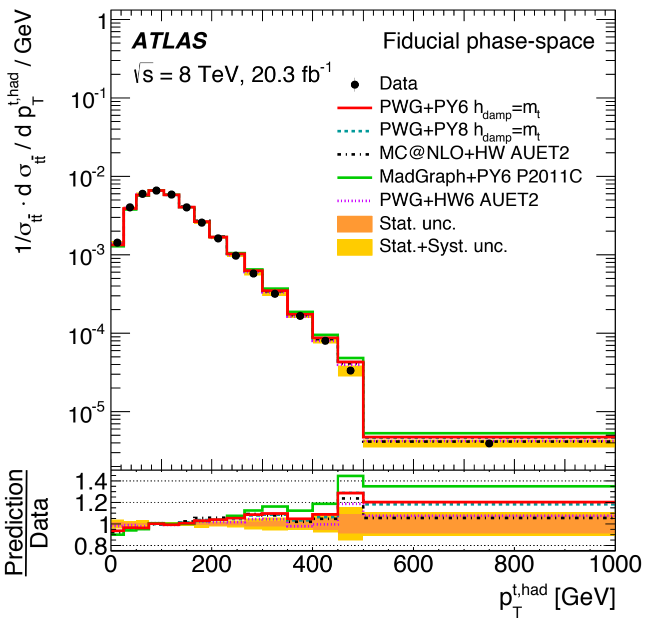
Expected to be non-zero due to higher order interference effects.
The LHC run 1 combination can exlude many exotic models.

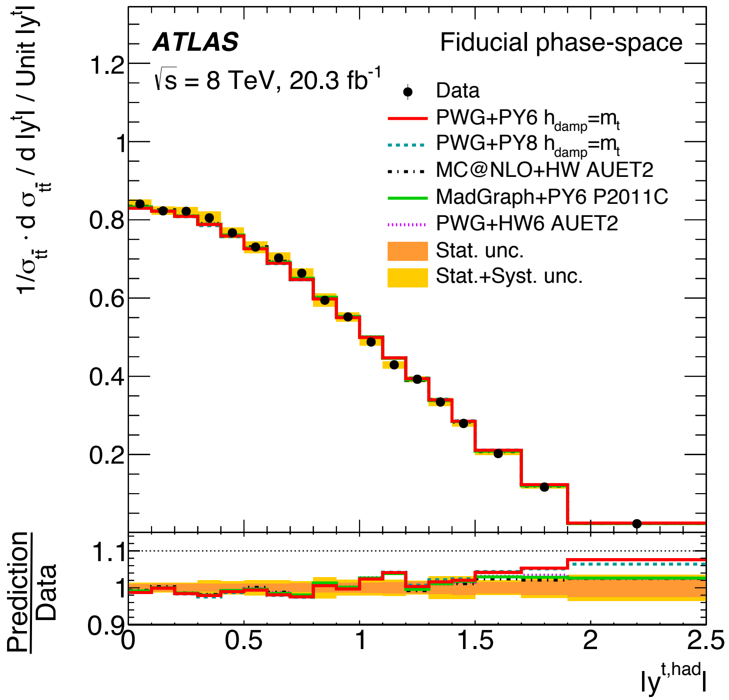




Differential tt_{bar} cross-sections @ 8 TeV

ATLAS particle level



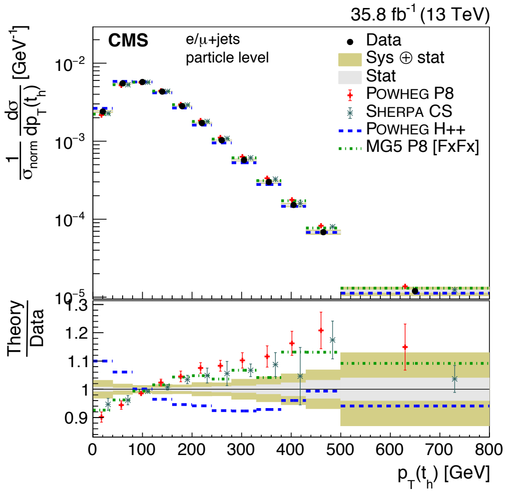


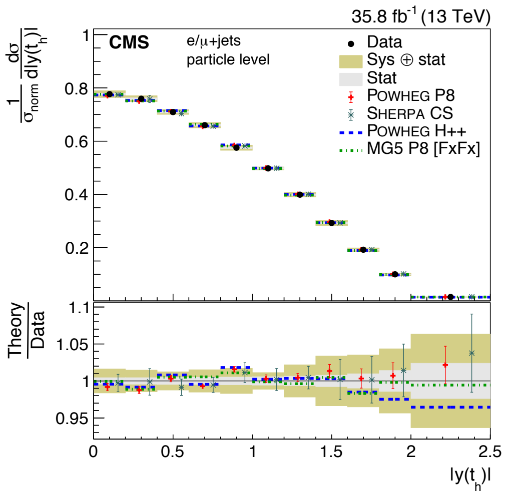
l+jets

Eur. Phys. J. C76 (2016) 538

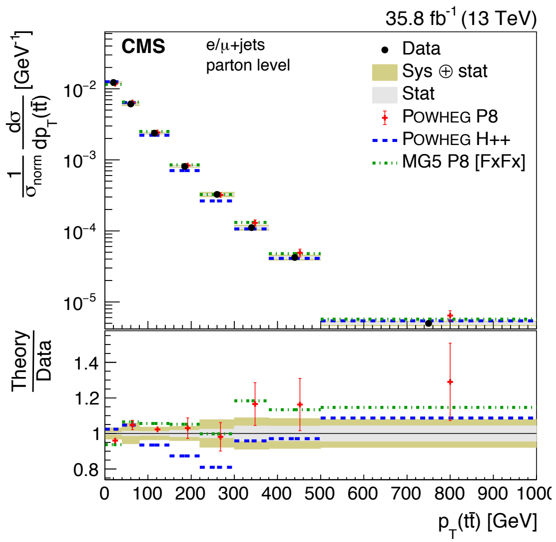
Differential tt_{bar} cross-sections @ 13 TeV

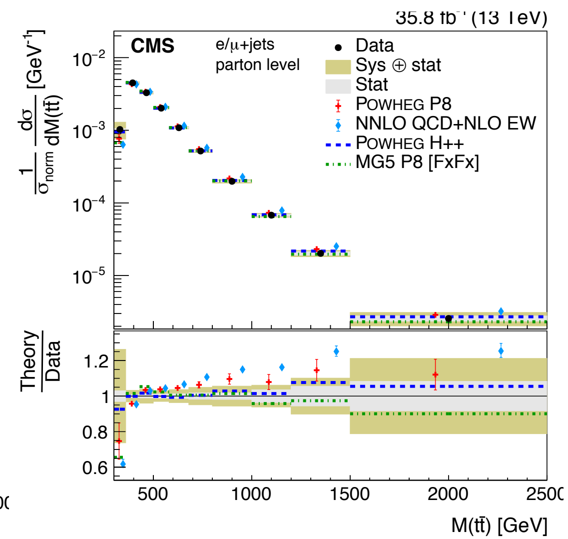
particle level





parton level



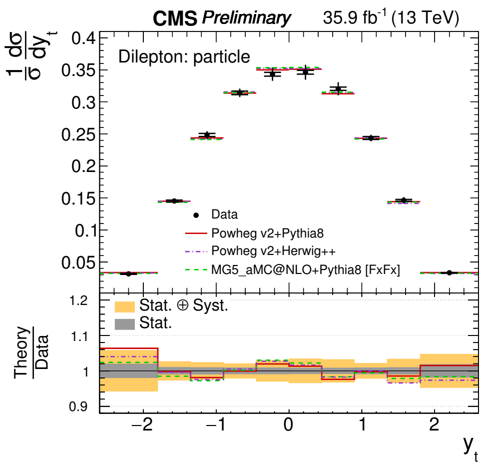


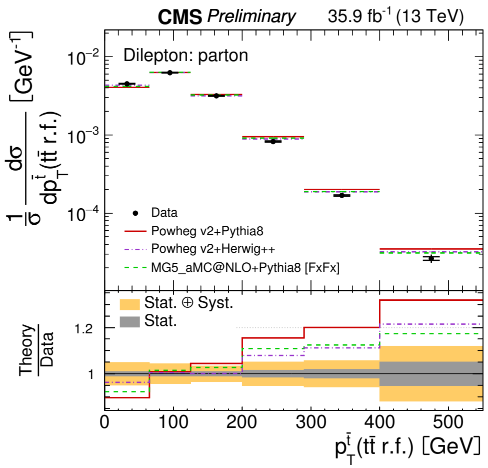
CMS l + jets, 13 TeV, 35.8 fb^{-1}

PRD 97 (2018)) 112003

Differential tt_{bar} cross-sections @ 13 TeV

top rapidity

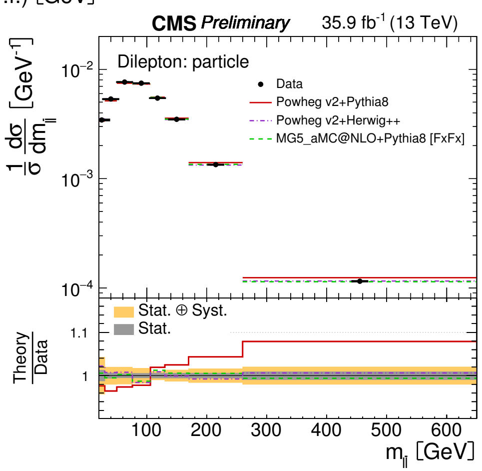


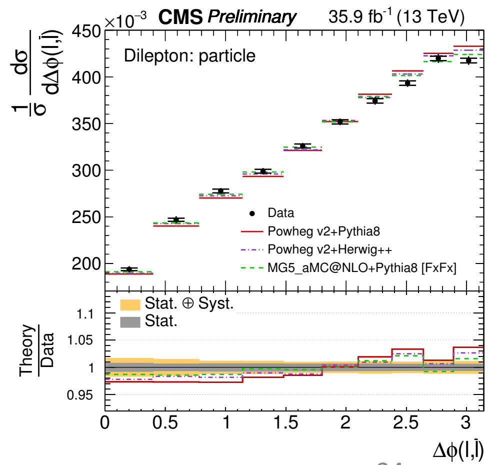


pT (top in tt rest frame)

M(ll)

Δϕ(ll)





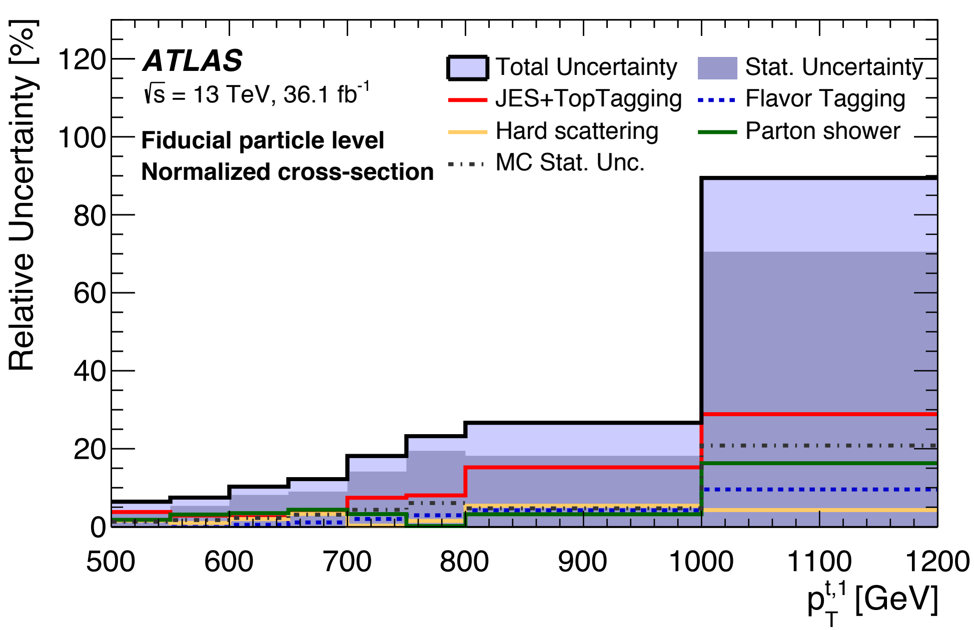
CMS dilepton, 13 TeV, 35.8 fb^{-1}

CMS-PAS-TOP-17-014

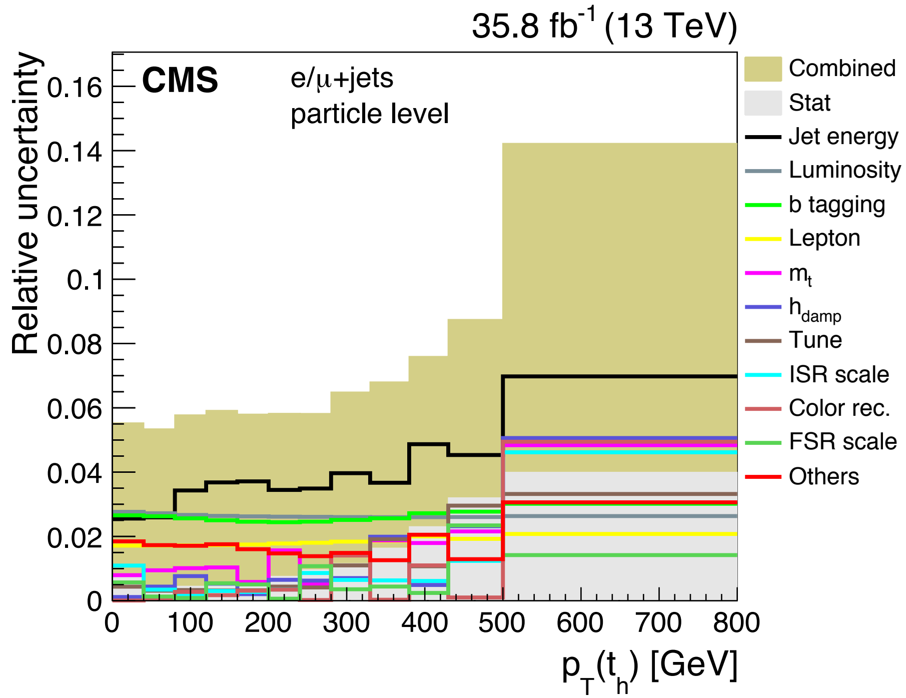
particle level

Differential tt_{bar} cross-sections @ 13 TeV - errors

ATLAS All-jet
PRD 98 (2018) 012003

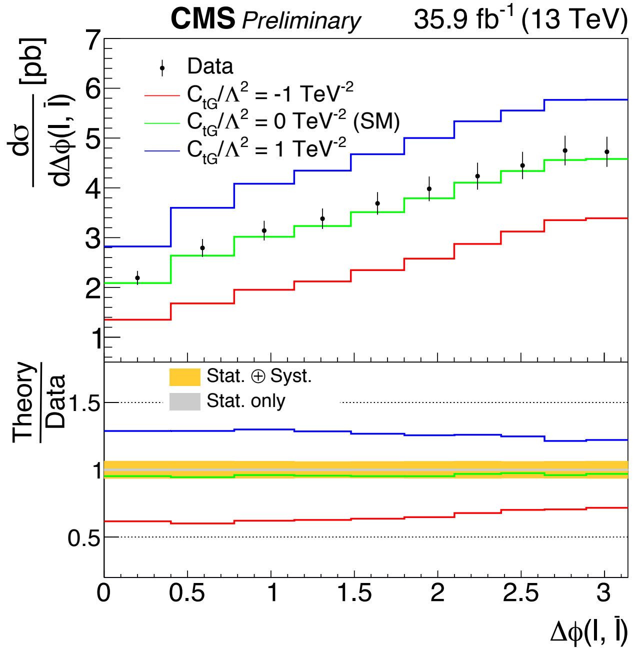


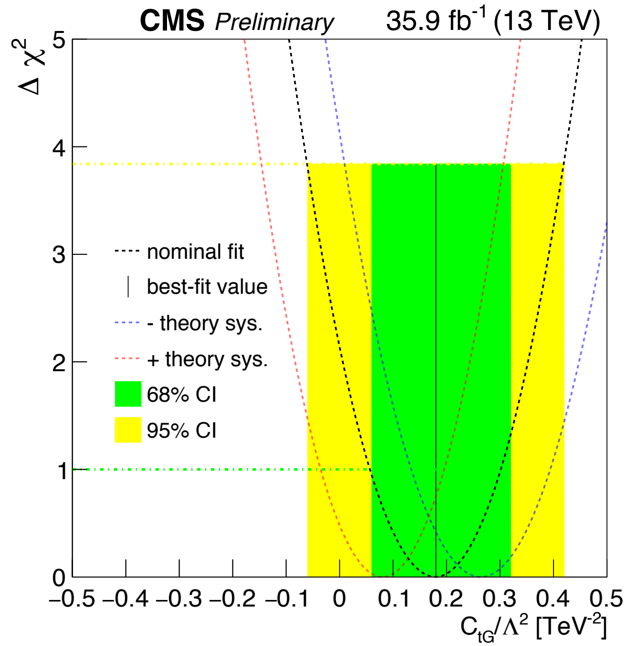
CMS lepton+jets
PRD 97 (2018)) 112003



$d\sigma/d\Delta\phi_{ll}$ and EFT

CMS-PAS-TOP-17-014





Particle level

ttbar->dilepton selection

Fiducial phase space

MG5_aMC@NLO +P8

CMS uses $\Delta\phi(l^+l^-)$ to constrain a chromomagnetic dipole EFT operator O_{tG} (see 1503.08841) which modifies the top-gluon interaction.

$t\bar{t}_{bar}$+W/Z - limits on EFG operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i + \cdots ,$$

Wilson coefficient	68% CL $[\text{TeV}^{-2}]$	95% CL $[\text{TeV}^{-2}]$
$\bar{c}_{\text{uW}}/\Lambda^2$	$[-1.6, 1.5]$	$[-2.2, 2.2]$
$\lvert\bar{c}_{\text{H}}/\Lambda^2 - 16.8\,\text{TeV}^{-2}\rvert$	$[3.7, 23.4]$	$[0, 28.7]$
$\widetilde{c}_{3\text{G}}/\Lambda^2$	$[-0.5, 0.5]$	$[-0.7, 0.7]$
$\bar{c}_{3\text{G}}/\Lambda^2$	$[-0.3, 0.7]$	$[-0.5, 0.9]$
$\bar{c}_{\text{uG}}/\Lambda^2$	$[-0.9, -0.8]$ and $[-0.3, 0.2]$	$[-1.1, 0.3]$
$\lvert\bar{c}_{\text{uB}}/\Lambda^2\rvert$	$[0, 1.5]$	$[0, 2.1]$
$\bar{c}_{\text{Hu}}/\Lambda^2$	$[-9.2, -6.5]$ and $[-1.6, 1.1]$	$[-10.1, 2.0]$
$\bar{c}_{2\text{G}}/\Lambda^2$	$[-0.7, 0.4]$	$[-0.9, 0.6]$

CMS 2l(SS)+jets, multi-l+jets 13 TeV, 35.9 fb^{-1}:
arXiv:1711.02547

tt_{bar}+bjets – in numbers (ATLAS-CONF-2018-029)

Uncertainties

Source	Fiducial cross-section phase space $e\mu$		lepton + jets	
	$\geq 3b$ unc. (%)	$\geq 4b$ unc. (%)	$\geq 5j, \geq 3b$ unc. (%)	$\geq 6j, \geq 4b$ unc. (%)
Data statistics	2.7	9.0	1.7	3.0
Luminosity	2.1	2.1	2.3	2.3
Jet	2.6	4.3	3.6	7.2
b-tagging	4.5	5.2	17	8.6
Lepton	0.9	0.8	0.8	0.9
Pileup	2.1	3.5	1.6	1.3
$t\bar{t}c$ fit variation	5.9	11	-	-
Non-$t\bar{t}$ bkg	0.8	2.0	1.7	1.8
Detector+background total syst.	8.5	14	18	12
Parton shower	9.0	6.5	12	6.3
Generator	0.2	18	16	8.7
ISR/FSR	4.0	3.9	6.2	2.9
PDF	0.6	0.4	0.3	0.1
$t\bar{t}V/t\bar{t}H$	0.7	1.4	2.2	0.3
MC sample statistics	1.8	5.3	1.2	4.3
$t\bar{t}$ modelling total syst.	10	20	21	12
Total syst.	13	24	28	17
Total	13	26	28	17

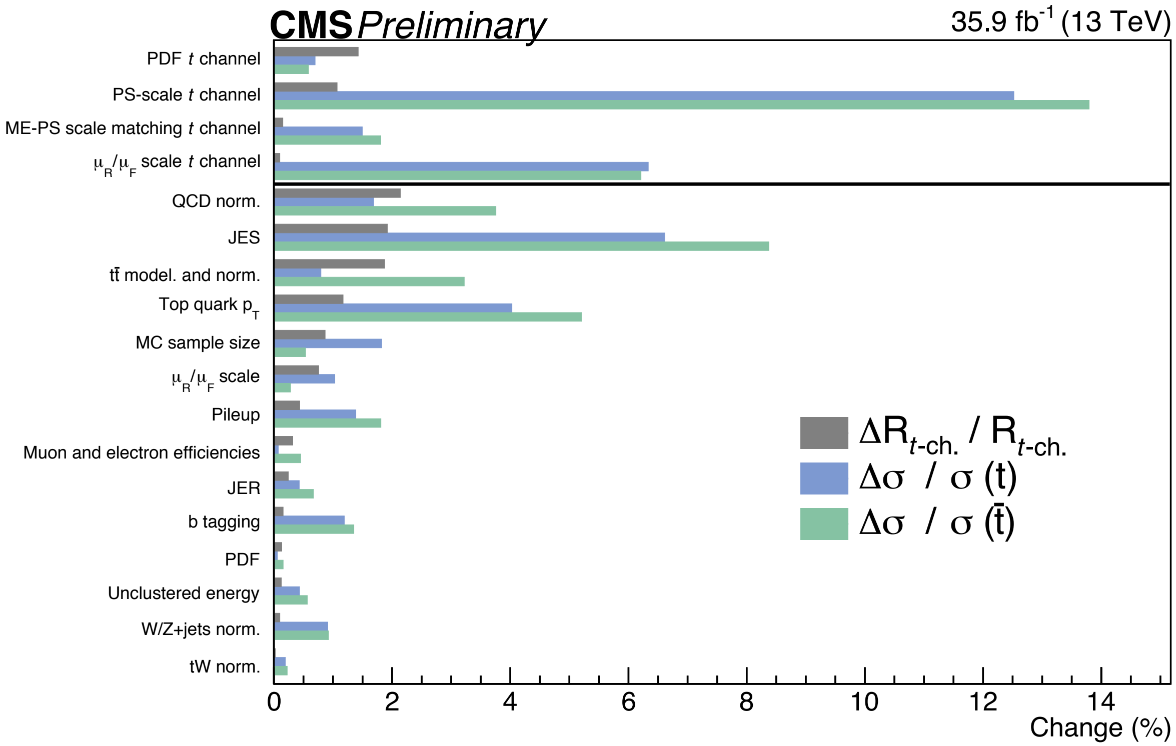
Number of b-jets. Data vs MC.

Generators	$N_{b\text{-jets}}$: [2, 3, $\geq 4b$] χ^2 / NDF	p-value	$N_{b\text{-jets}}$: [3, $\geq 4b$] χ^2 / NDF	p-value
***eμ* channel**				
Powheg+Pythia 8	22.4 / 2	< 0.01	0.03 / 1	0.85
MadGraph5_aMC@NLO+Pythia 8	17.9 / 2	< 0.01	< 0.01 / 1	0.97
Sherpa 2.2 $t\bar{t}$	1.89 / 2	0.39	0.19 / 1	0.67
Sherpa 2.2 $t\bar{t}b\bar{b}$ (4FS)	-	-	0.19 / 1	0.67
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (5FS)	-	-	13.6 / 1	< 0.01
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	-	-	2.10 / 1	0.15
Powheg+Herwig 7	46.0 / 2	< 0.01	0.48 / 1	0.49
Powheg+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	-	-	0.12 / 1	0.73
Powheg+Pythia 8 (RadHi)	12.3 / 2	< 0.01	0.01 / 1	0.91
Powheg+Pythia 8 (RadLo)	32.4 / 2	< 0.01	0.08 / 1	0.78

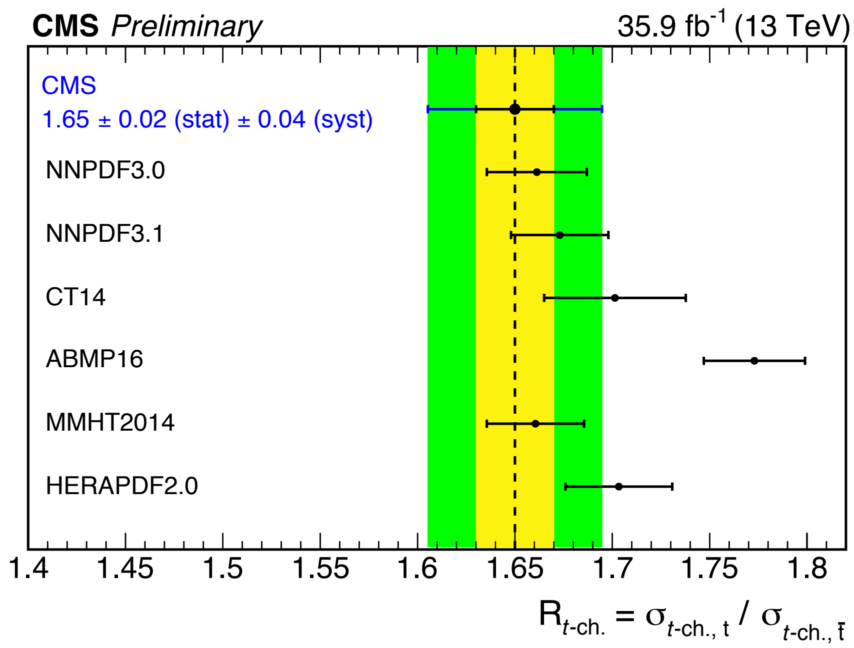
Single top – t channel

CMS-PAS-TOP-17-011

Uncertainties



PDF's vs Rmeas

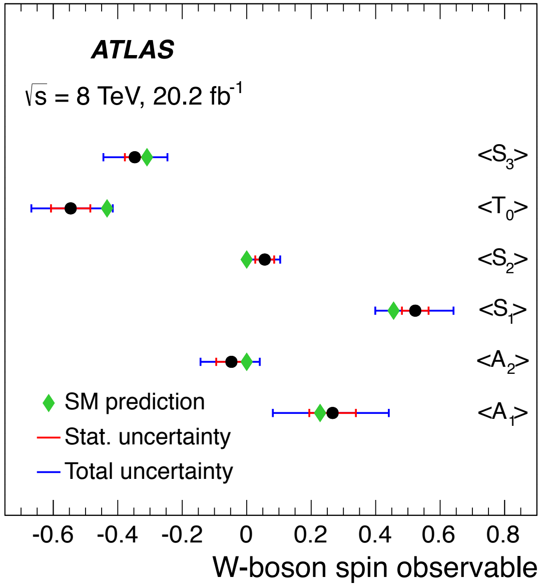


t channel: t,W polarization in t->Wb, W->l ν

W spin: Lepton angles in W rest frame

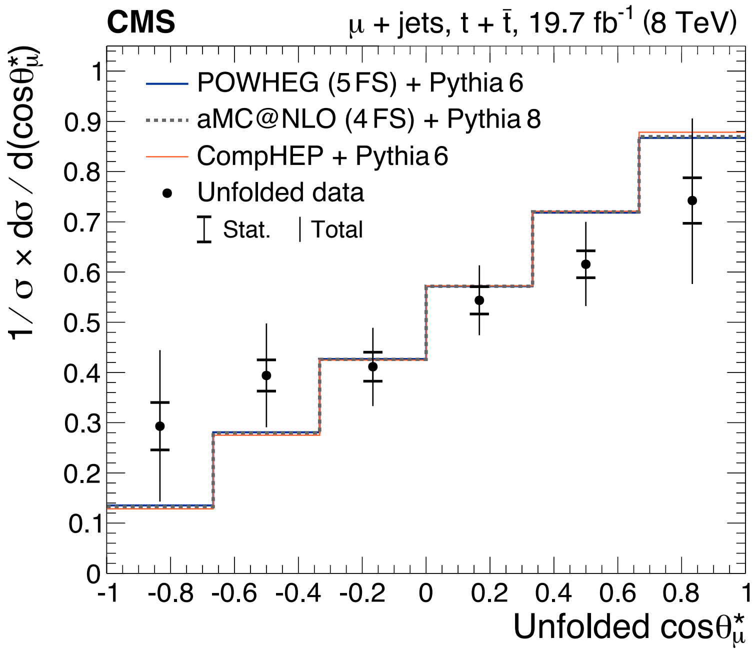
$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_\ell^*)d\phi_\ell^*} = \frac{3}{8\pi}\left\{\frac{2}{3}+\frac{1}{\sqrt{6}}\langle T_0\rangle\left(3\cos^2\theta_\ell^*-1\right)+\langle S_3\rangle\cos\theta_\ell^* + \langle S_1\rangle\cos\phi_\ell^*\sin\theta_\ell^* + \langle S_2\rangle\sin\phi_\ell^*\sin\theta_\ell^* - \langle A_1\rangle\cos\phi_\ell^*\sin 2\theta_\ell^* - \langle A_2\rangle\sin\phi_\ell^*\sin 2\theta_\ell^*\right\}.$$

arXiv: 1702.08309

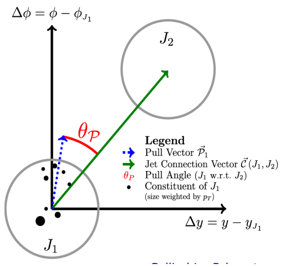


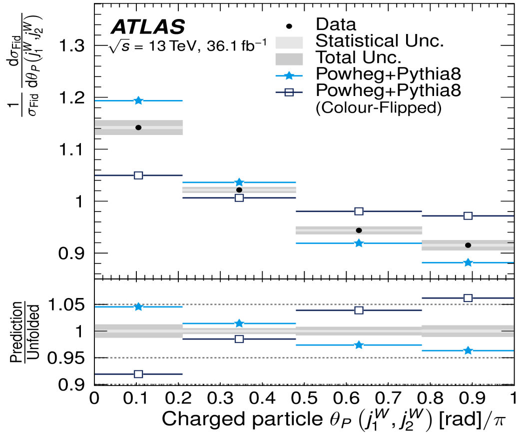
Top spin: angle between lepton and q' in top frame

arXiv:1511.02138

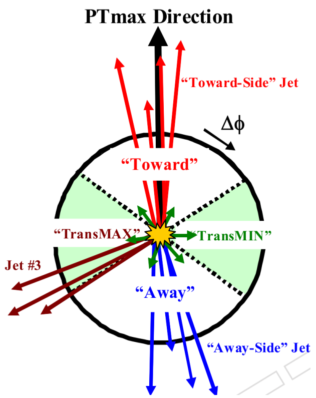


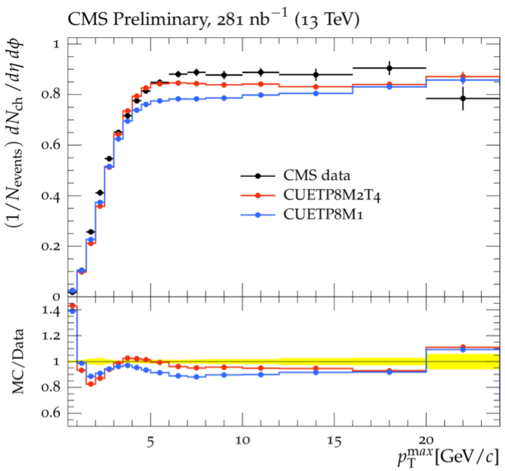
Colour reconnection





ATLAS 1805.02935, 13 TeV, 36.1 fb^{-1}, l+jets.
ATLAS used the jet pull vector to test CR models.
Jet pull angle poorly modelled by PY8 (HW7 and PY6 fits better).
An exotic colour flow model (octet W) is disfavoured.





CMS-PAS-TOP-16-021 suppl, 13 TeV, 281 nb^{-1}, Minimum Bias
CMS tested two alternative CR schemes ("QCD inspired" and "gluon move") in a low p_T "jet-less" region.
In the m_{top} measurement they contribute about 300 MeV uncertainty.

Direct top mass – All-jets

ATLAS:arXiv:1702.07546, 8 TeV, 20.2 fb^{-1}

Source of uncertainty	Δm_{top} [GeV]
Monte Carlo generator	0.18 ± 0.21
Hadronisation modelling	0.64 ± 0.15
Parton distribution functions	0.04 ± 0.00
Initial/final-state radiation	0.10 ± 0.28
Underlying event	0.13 ± 0.16
Colour reconnection	0.12 ± 0.16
Bias in template method	0.06
Signal and bkgd parameterisation	0.09
Non all-hadronic $t\bar{t}$ contribution	0.06
ABCD method *vs.* ABCDEF method	0.16
Trigger efficiency	0.08 ± 0.01
Lepton/E_T^{miss} calibration	0.02 ± 0.01
Overall flavour-tagging	0.10 ± 0.00
Jet energy scale (JES)	0.60 ± 0.05
b-jet energy scale (bJES)	0.34 ± 0.02
Jet energy resolution	0.10 ± 0.04
Jet vertex fraction	0.03 ± 0.01
Total systematic uncertainty	1.01
Total statistical uncertainty	0.55
Total uncertainty	1.15

CMS-PAS-TOP-17-008, 13 TeV 35.9 fb^{-1}

	2D		1D	hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.06	0.2	0.06	0.06	0.2
JEC (quad. sum)	0.18	0.3	0.73	0.15	0.2
- Intercalibration	−0.04	−0.1	+0.12	−0.04	−0.1
- MPFInSitu	−0.03	−0.0	+0.22	+0.08	+0.1
- Uncorrelated	−0.17	−0.3	+0.69	+0.12	+0.2
Jet energy resolution	−0.12	+0.4	+0.18	−0.03	+0.3
b tagging	0.02	0.0	0.01	0.02	0.0
Pileup	−0.06	+0.1	+0.00	−0.04	+0.1
Background	0.10	0.1	0.03	0.07	0.1
Trigger	+0.04	−0.1	−0.04	+0.02	−0.1
Modeling of hadronization					
JEC Flavor (linear sum)	−0.35	+0.1	−0.31	−0.34	+0.0
- light quarks (uds)	+0.10	−0.1	−0.01	+0.07	−0.1
- charm	+0.03	−0.0	−0.01	+0.02	−0.0
- bottom	−0.29	−0.0	−0.29	−0.29	−0.0
- gluon	−0.19	+0.2	+0.03	−0.13	+0.2
b jet modeling (quad. sum)	0.09	0.0	0.09	0.09	0.0
- b frag. Bowler-Lund	−0.07	+0.0	−0.07	−0.07	+0.0
- b frag. Peterson	−0.05	+0.0	−0.04	−0.05	+0.0
- semi-leptonic B decays	−0.03	−0.0	−0.03	−0.03	−0.0
Modeling of perturbative QCD					
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scale	0.05	0.0	0.04	0.04	0.0
ME/PS matching	+0.32 ± 0.20	−0.3	−0.05 ± 0.14	+0.24 ± 0.18	−0.2
ME generator	+0.29 ± 0.34	+0.1	+0.36 ± 0.24	+0.31 ± 0.30	+0.1
ISR PS scale	+0.17 ± 0.17	−0.2	+0.13 ± 0.12	+0.12 ± 0.14	−0.1
FSR PS scale	+0.22 ± 0.12	−0.2	+0.11 ± 0.08	+0.18 ± 0.11	−0.1
Top quark p_T	+0.03	−0.0	+0.02	+0.03	−0.0
Modeling of soft QCD					
Underlying event	+0.16 ± 0.19	−0.3	−0.07 ± 0.14	+0.10 ± 0.17	−0.2
Early resonance decays	+0.02 ± 0.28	+0.4	+0.38 ± 0.19	+0.13 ± 0.24	+0.3
CR modeling (max. shift)	+0.41 ± 0.29	−0.4	−0.43 ± 0.20	−0.36 ± 0.25	−0.3
- "gluon move" (ERD on)	+0.41 ± 0.29	−0.4	+0.10 ± 0.20	+0.32 ± 0.25	−0.3
- "QCD inspired" (ERD on)	−0.32 ± 0.29	−0.1	−0.43 ± 0.20	−0.36 ± 0.25	−0.1
Total systematic	**0.88**	**1.0**	**1.10**	**0.76**	**0.7**
Statistical (expected)	0.21	0.2	0.16	0.20	0.1
Total (expected)	**0.91**	**1.0**	**1.11**	**0.79**	**0.7**

Direct top mass – l+jets

ATLAS-CONF-2017-071, 8 TeV, 20.2 fb[-1]

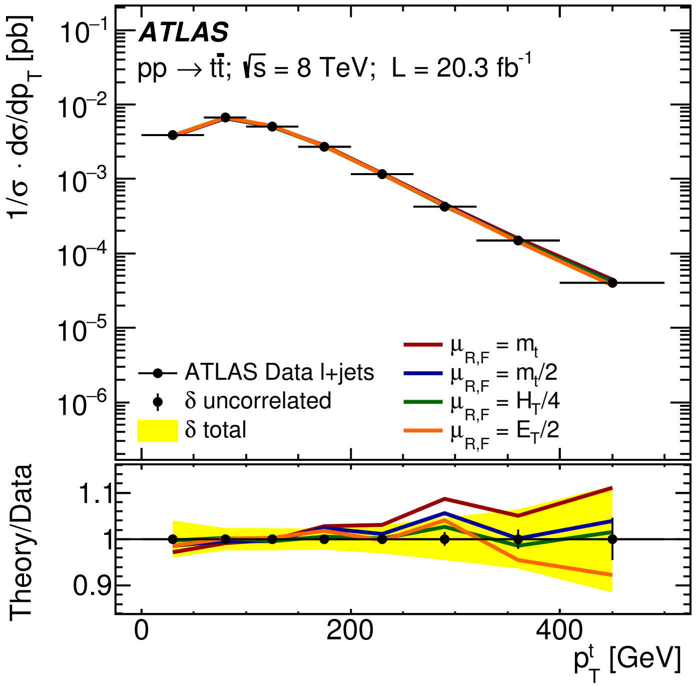
	$\sqrt{s}$ = 7 TeV		$\sqrt{s}$ = 8 TeV	
	m_{top}^{dil} [GeV]	m_{top}^{l+jets} [GeV]	m_{top}^{dil} [GeV]	m_{top}^{l+jets} [GeV]
Results	173.79	172.33	172.99	172.08
Statistics	0.54	0.75	0.41	0.39
– *Stat. comp.* (m_{top})		0.23		0.11
– *Stat. comp.* (JSF)		0.25		0.11
– *Stat. comp.* (bJSF)		0.67		0.35
Method	0.09 ± 0.07	0.11 ± 0.10	0.05 ± 0.07	0.13 ± 0.11
Signal Monte Carlo generator	0.26 ± 0.16	0.22 ± 0.21	0.09 ± 0.15	0.16 ± 0.17
Hadronisation	0.53 ± 0.09	0.18 ± 0.12	0.22 ± 0.09	0.15 ± 0.10
Initial- and final-state QCD radiation	0.47 ± 0.05	0.32 ± 0.06	0.23 ± 0.07	0.08 ± 0.11
Underlying event	0.05 ± 0.05	0.15 ± 0.07	0.10 ± 0.14	0.08 ± 0.15
Colour reconnection	0.14 ± 0.05	0.11 ± 0.07	0.03 ± 0.14	0.19 ± 0.15
Parton distribution function	0.11 ± 0.00	0.25 ± 0.00	0.05 ± 0.00	0.09 ± 0.00
Background normalisation	0.04 ± 0.00	0.10 ± 0.00	0.03 ± 0.00	0.08 ± 0.00
W/Z+jets shape	0.00 ± 0.00	0.29 ± 0.00	0	0.11 ± 0.00
Fake leptons shape	0.01 ± 0.00	0.05 ± 0.00	0.07 ± 0.00	0
Jet energy scale	0.75 ± 0.08	0.58 ± 0.11	0.54 ± 0.04	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.68 ± 0.02	0.06 ± 0.03	0.30 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.19 ± 0.04	0.22 ± 0.11	0.09 ± 0.05	0.20 ± 0.04
Jet reconstruction efficiency	0.07 ± 0.00	0.12 ± 0.00	0.01 ± 0.00	0.02 ± 0.01
Jet vertex fraction	0.00 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.09 ± 0.01
b-tagging	0.07 ± 0.00	0.50 ± 0.00	0.04 ± 0.02	0.38 ± 0.00
Leptons	0.13 ± 0.00	0.04 ± 0.00	0.14 ± 0.01	0.16 ± 0.01
E_T^{miss}	0.04 ± 0.03	0.15 ± 0.04	0.01 ± 0.01	0.05 ± 0.01
Pile-up	0.01 ± 0.00	0.02 ± 0.01	0.05 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.31 ± 0.07	1.03 ± 0.08	0.74 ± 0.05	0.82 ± 0.06
Total	1.41 ± 0.07	1.27 ± 0.08	0.85 ± 0.05	0.91 ± 0.06

CMS arXiv:1805.01428, 13 TeV 35.9 fb[-1]

	2D approach		1D approach	Hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.05	<0.1	0.05	0.05	<0.1
JEC (quad. sum)	0.13	0.2	0.83	0.18	0.3
– InterCalibration	(−0.02)	(<0.1)	(+0.16)	(+0.04)	(<0.1)
– MPFInSitu	(−0.01)	(<0.1)	(+0.23)	(+0.07)	(<0.1)
– Uncorrelated	(−0.13)	(+0.2)	(+0.78)	(+0.16)	(+0.3)
Jet energy resolution	−0.08	+0.1	+0.04	−0.04	+0.1
b tagging	+0.03	<0.1	+0.01	+0.03	<0.1
Pileup	−0.08	+0.1	+0.02	−0.05	+0.1
Non-$t\bar{t}$ background	+0.04	−0.1	−0.02	+0.02	−0.1
Modeling uncertainties					
JEC Flavor (linear sum)	0.42	0.1	0.31	0.39	<0.1
– light quarks (uds)	(+0.10)	(−0.1)	(−0.01)	(+0.06)	(−0.1)
– charm	(+0.02)	(<0.1)	(−0.01)	(+0.01)	(<0.1)
– bottom	(−0.32)	(<0.1)	(−0.31)	(−0.32)	(<0.1)
– gluon	(−0.22)	(+0.3)	(+0.02)	(−0.15)	(+0.2)
b jet modeling (quad. sum)	0.13	0.1	0.09	0.12	<0.1
– b frag. Bowler–Lund	(−0.07)	(+0.1)	(−0.01)	(−0.05)	(<0.1)
– b frag. Peterson	(+0.04)	(<0.1)	(+0.05)	(+0.04)	(<0.1)
– semileptonic B decays	(+0.11)	(<0.1)	(+0.08)	(+0.10)	(<0.1)
PDF	0.02	<0.1	0.02	0.02	<0.1
Ren. and fact. scales	0.02	0.1	0.02	0.01	<0.1
ME/PS matching	−0.08	+0.1	+0.03	−0.05	+0.1
ME generator	+0.19 ± 0.14	+0.1	+0.29 ± 0.08	+0.22 ± 0.11	+0.1
ISR PS scale	+0.07 ± 0.09	+0.1	+0.10 ± 0.05	+0.06 ± 0.07	<0.1
FSR PS scale	+0.24 ± 0.06	−0.4	−0.22 ± 0.04	+0.13 ± 0.05	−0.3
Top quark p_T	+0.02	−0.1	−0.06	−0.01	−0.1
Underlying event	−0.10 ± 0.08	+0.1	+0.01 ± 0.05	−0.07 ± 0.07	+0.1
Early resonance decays	−0.22 ± 0.09	+0.8	+0.42 ± 0.05	−0.03 ± 0.07	+0.5
Color reconnection	+0.34 ± 0.09	−0.1	+0.23 ± 0.06	+0.31 ± 0.08	−0.1
Total systematic	**0.72**	**1.0**	**1.09**	**0.62**	**0.8**
Statistical (expected)	0.09	0.1	0.06	0.08	0.1
Total (expected)	**0.72**	**1.0**	**1.09**	**0.62**	**0.8**

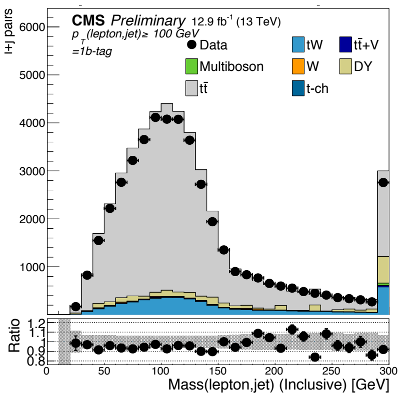
Indirect top mass – eμ

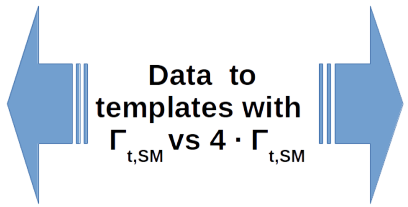
- EPJ C77 (2017) 804, 8 TeV, 20.2 fb^{-1}

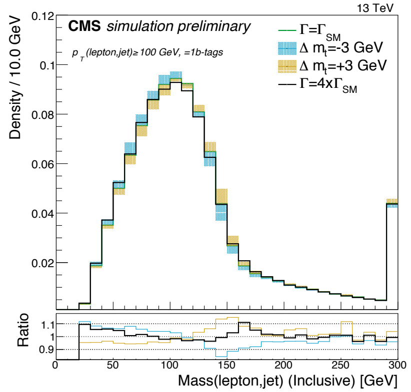


Template	p_T^ℓ	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
χ^2/N_{dof}	8.1/8	7.5/7	13.9/10	8.0/6	12.5/8
m_t [GeV]	168.4 ± 2.3	173.0 ± 2.1	170.6 ± 4.2	169.4 ± 2.0	166.9 ± 4.0
Data statistics	± 1.0	± 0.9	± 2.0	± 0.9	± 1.3
Expt. systematic	± 1.6	± 1.0	± 3.1	± 1.6	± 1.5
PDF uncertainty	± 1.0	± 0.2	± 1.6	± 0.6	± 3.4
$t\bar{t}$ generator	± 0.4	± 1.4	± 1.4	± 0.4	± 1.1
QCD radiation	± 0.7	± 0.8	± 0.5	± 0.2	± 0.2
Moment 1	p_T^ℓ	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
m_t [GeV]	168.2 ± 2.9	172.4 ± 3.8	166.6 ± 6.5	168.4 ± 2.9	160.8 ± 7.9
Data statistics	± 1.0	± 1.0	± 2.4	± 1.1	± 2.2
Expt. systematic	± 2.1	± 1.6	± 3.8	± 2.1	± 3.1
PDF uncertainty	± 1.2	± 0.3	± 2.9	± 1.1	± 6.7
$t\bar{t}$ generator	± 0.2	± 1.3	± 3.4	± 0.2	± 2.0
QCD radiation	± 1.2	± 3.0	± 1.4	± 1.1	± 0.2
Moment 2	p_T^ℓ	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
m_t [GeV]	168.1 ± 3.2	172.2 ± 4.5	166.9 ± 6.9	167.9 ± 3.3	159.9 ± 9.2
Data statistics	± 1.2	± 1.1	± 2.8	± 1.3	± 2.6
Expt. systematic	± 2.3	± 2.0	± 4.3	± 2.4	± 3.4
PDF uncertainty	± 1.3	± 0.4	± 3.3	± 1.3	± 7.8
$t\bar{t}$ generator	± 0.4	± 1.2	± 3.2	± 0.4	± 2.4
QCD radiation	± 1.2	± 3.7	± 0.7	± 1.3	± 0.2
Moment 3	p_T^ℓ	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
m_t [GeV]	168.3 ± 3.5	172.0 ± 5.6	166.4 ± 9.1	167.6 ± 3.8	160.9 ± 9.5
Data statistics	± 1.5	± 1.4	± 4.2	± 1.6	± 3.0
Expt. systematic	± 2.5	± 2.6	± 6.0	± 2.7	± 3.7
PDF uncertainty	± 1.5	± 0.6	± 4.1	± 1.4	± 7.8
$t\bar{t}$ generator	± 0.6	± 1.1	± 3.5	± 0.7	± 2.4
QCD radiation	± 1.1	± 4.6	± 0.2	± 1.4	± 0.2

Direct top width







CMS 13 TeV, 12.9 fb^{-1}, l+jets
CMS-PAS-TOP-16-019
Fits NLO templates to m(lb):
$0.6 < \Gamma < 2.5$ GeV at 95% conf
Main systematics: Signal modelling

ATLAS 8 TeV, 20.2 fb^{-1}, l+jets
Eur.Phys.J C78 (2018) 129
Fits NLO templates to m(lb) and $\Delta R_{min}(j_b,j_l)$
$\Gamma = 1.76 \pm 0.33\ ^{+0.79}_{-0.68}$ GeV

The NNLO SM prediction is 1.322 GeV.
A 1 TeV stop would change this by ~1%, (see hep-ph/0109291).
We are far from this kind of precision.