

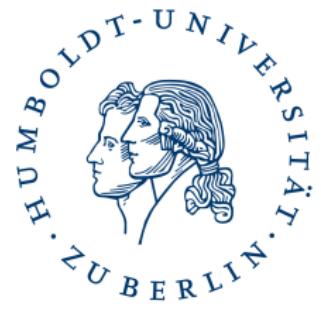
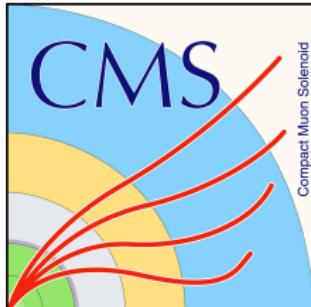
# Top quark pair-production cross-section measurements at LHC

Sergio Grancagnolo



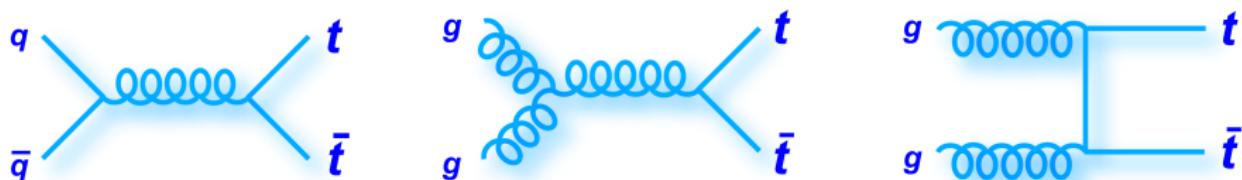
Humboldt-Universität zu Berlin

on behalf of  
ATLAS and CMS Collaborations  
DIS2019 - Turin

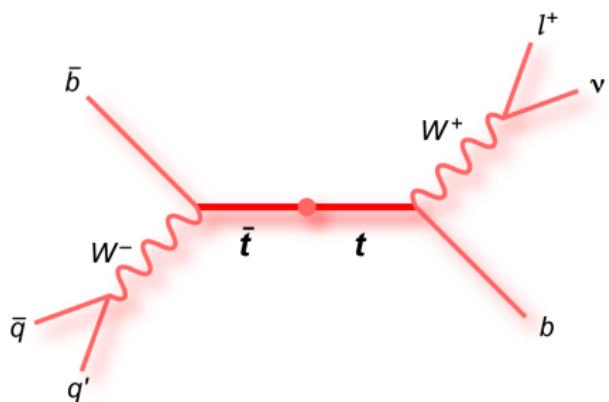


# Top quark pair production overview

$t\bar{t}$  production modes - LHC:  $\sim 8$  Hz with  $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  at  $\sqrt{s} = 13$  TeV

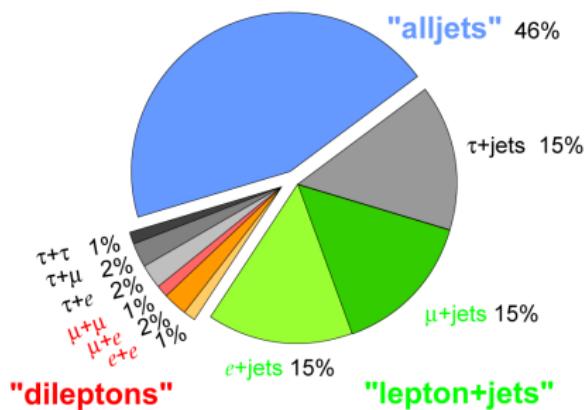


Decay  $t \rightarrow Wb \sim 100\%$



$t\bar{t}$  decay in  $\ell + \text{jets}$

Top Pair Branching Fractions



# Top quark measurements

## Motivation

- Top quark most massive known elementary particle
- Interactions EM, strongly, weakly, Higgs ( $t \rightarrow t + g/\gamma/Z/H$ )
- Cross section: test SM, probe BSM scenarios
- Constrain input parameters to QCD predictions

## Cross section methods and definitions

- Fiducial (close to detector acceptance), full phase space extrapolation
- Absolute or normalized to inclusive  $\sigma_{t\bar{t}}$
- Parton level (unfolding): consider partons  
(e.g. quarks before hadronisation)
- Particle level: consider stable particles from  
full ME+parton shower generators (w/ QCD+EWK FSR effects),  
no simulation of pile-up or interaction w/ the detector

# Most recent cross section measurements w/ LHC $pp$ collisions @ 13TeV

## CMS: full phase space, differential and multi-differential

- $t\bar{t}$  (two leptons channel:  $ee$ ,  $e\mu$ ,  $\mu\mu$ )
  - $\sigma_{t\bar{t}}$  used to determine top quark mass,  $\alpha_S$ , PDF
- More CMS results

## ATLAS: fiducial phase space and differential

- $t\bar{t} + \text{heavy flavour jets}$  (channels:  $e\mu$  and lepton+jets)
  - Test QCD predictions
  - Background of  $t\bar{t}H(H \rightarrow b\bar{b})$ , sensitive to relative contribution
- More ATLAS results

# CMS - $35.9 \text{ fb}^{-1}$ $pp$ collisions at 13 TeV (2016)

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

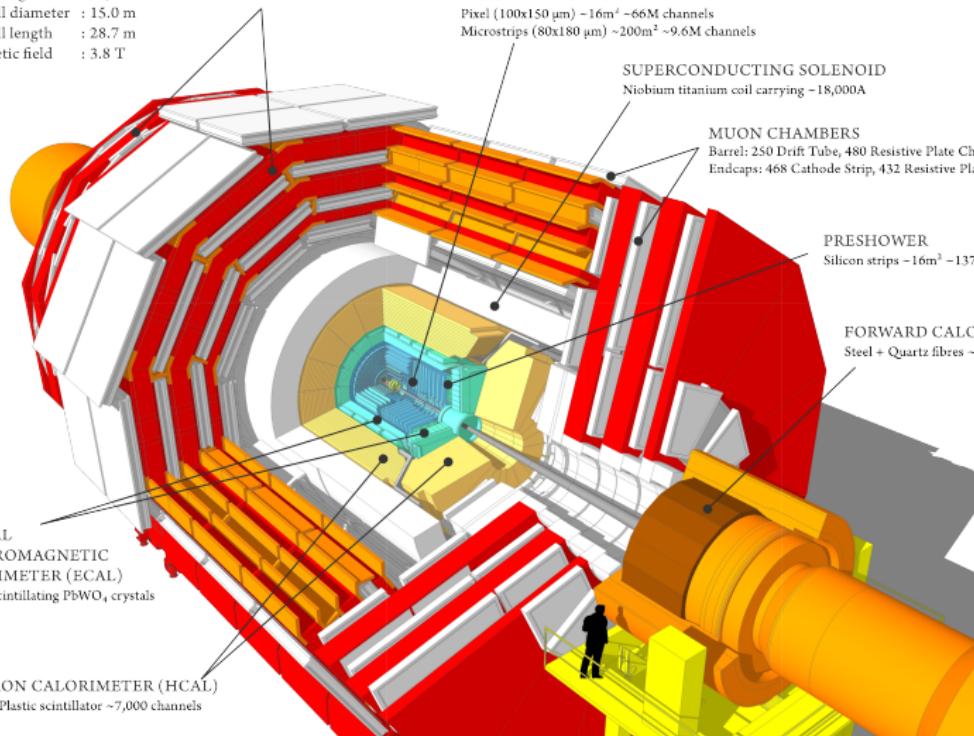
MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels

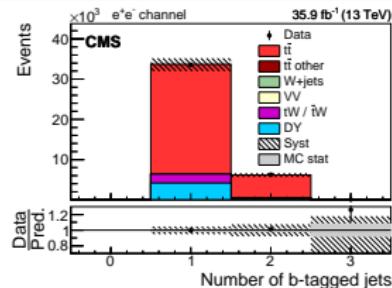
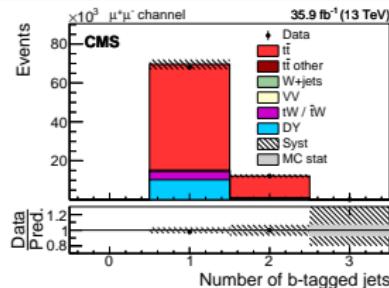
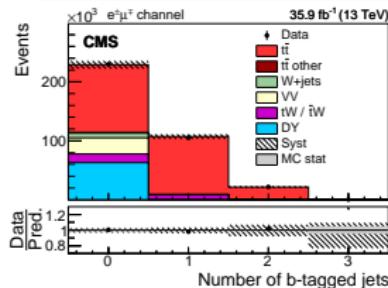


## Event selection

- $\geq 2$  leptons ( $e, \mu$ ), use highest  $p_T$  ones w/ opposite charge
- Include  $\tau$  decaying leptonically
- $b$ -tagging efficiency 41%,  $c$ -jets 2.2%, light-flavour 0.1%

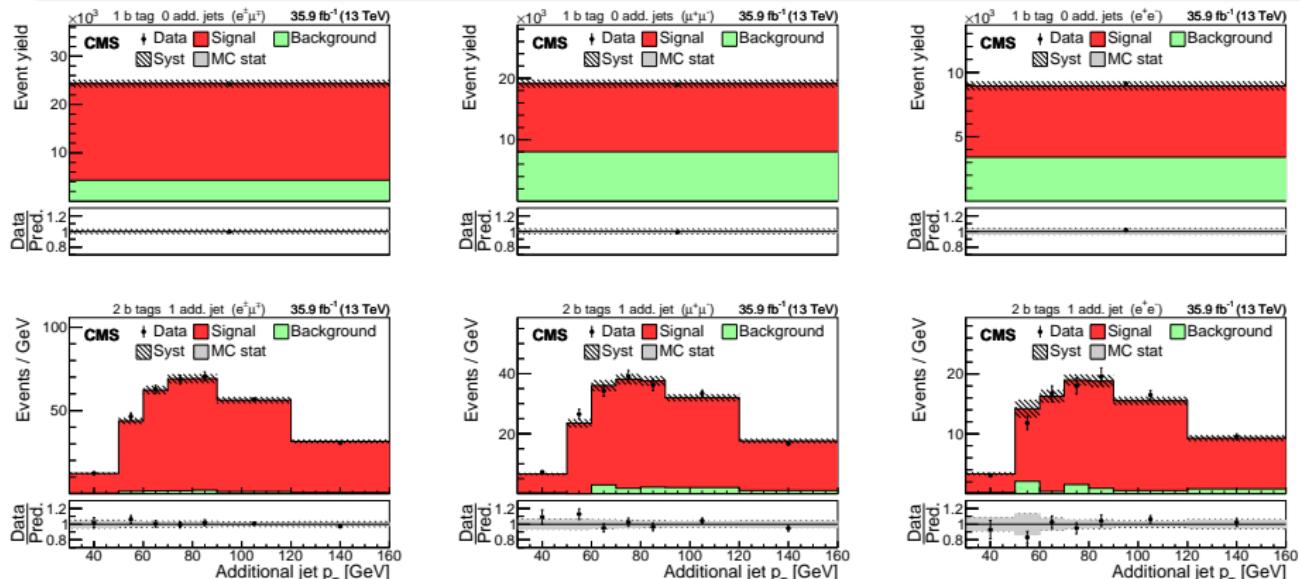
## Event classification by lepton and number of $b$ -tagged jets

- 4 categories: same-flavor ( $ee$  or  $\mu\mu$ ) w/ 1 or 2  $b$ -tagged jets
- 3 categories:  $e^\pm\mu^\mp$  w/ 1 or 2  $b$ -tags or other cases (0 or  $\geq 3$ )



# Additional categorization: 0, 1, 2, $\geq 3$ non $b$ -jets

- Constrain systematic uncertainties due to modelling

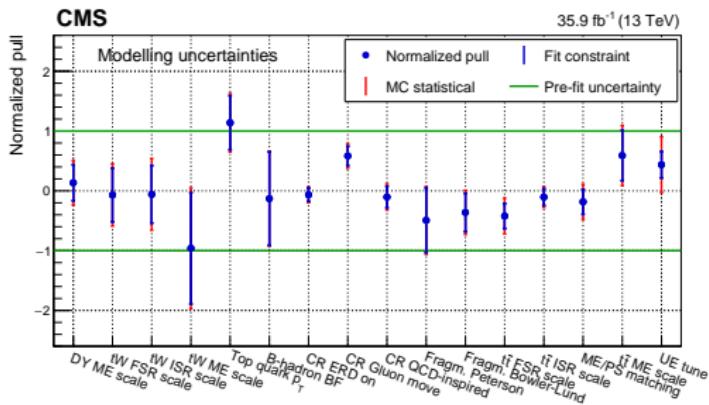


# Extrapolation to full phase space

Define acceptance  $A_{\ell\ell}$ ,  
include BR to leptons

Relative uncertainties  
from template fit  
Major contributions

$$\sigma_{t\bar{t}} = \frac{\sigma_{t\bar{t}}^{\text{vis}}}{A_{\ell\ell}}$$

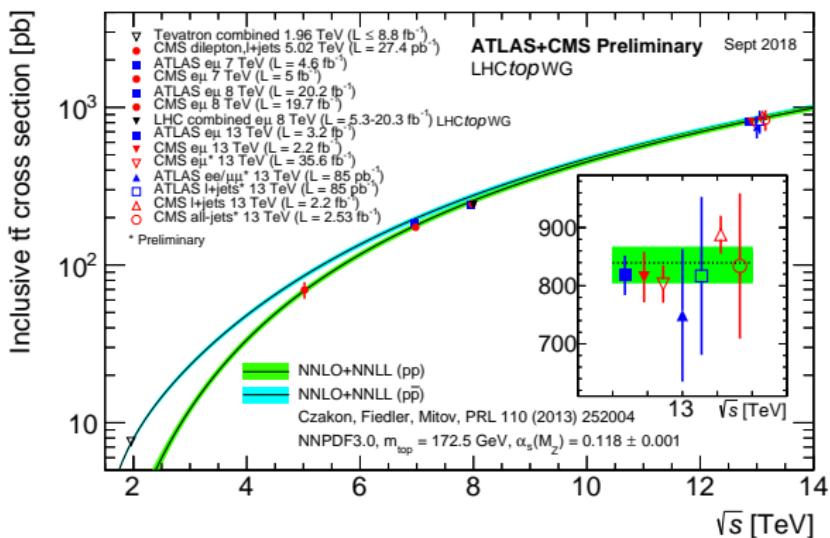
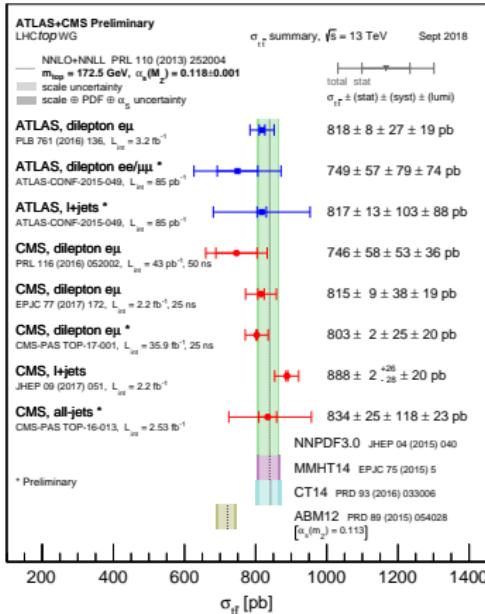


Source	Uncertainty [%]
Lep id/iso	2.0
PDF	1.1
$tW$ bkgd	1.1
Lumi	2.5
MC stat	1.1
Total $\sigma_{t\bar{t}}^{\text{vis}}$	3.8
Extrapolation	
PDF	$\pm 0.8$
Top quark $p_T$	$\pm 0.5$
Total $\sigma_{t\bar{t}}$	$\pm 4.0$

# Final Results

## Total (extrapolated) cross-section

$$\sigma_{t\bar{t}} = 803 \pm 2(\text{stat}) \pm 25(\text{syst}) \pm 20(\text{lumi}) \text{ pb. Tot unc: 4\%}$$



Submitted to Eur. Phys. J. C

## Event selection

- Exactly 2 OS leptons ( $e^+e^-$ ,  $\mu^+\mu^-$ ,  $e^\pm\mu^\mp$ )
- $b$ -tagging efficiency  $\approx 79 - 87\%$ , light-flavour  $\approx 10\%$
- $p_T^{miss} > 40 \text{ GeV}$  ( $p_T^{miss} = -\sum p_T$  considering all event particles)
- Kinematic reconstruction algorithm (90% efficiency)

Selected final events (80.6% purity combined): 34890 ee, 150410 e $\mu$ , 70346  $\mu\mu$

## Absolute cross section

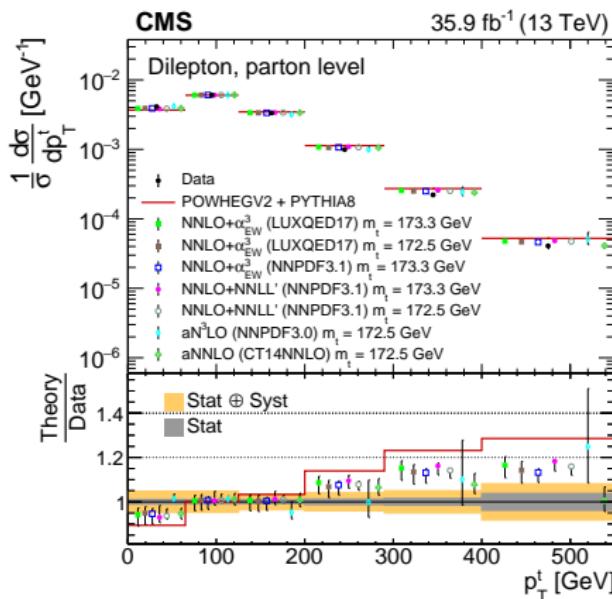
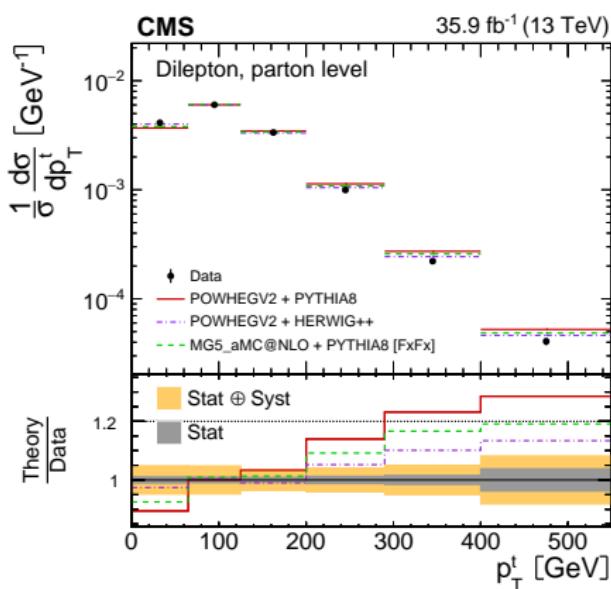
- Use relation  $\frac{d\sigma_i}{dX} = \frac{x_i}{\mathcal{L}\Delta_i^X}$  for observable X,  $\mathcal{L}$  integrated data luminosity
- Bin width  $\Delta_i^X$  optimised for purity and stability (both  $\approx 50\%$ )
- $x_i$ =signal events after background subtraction and corrections for detector efficiencies and acceptance and bin migration (regularised unfolding)

## Normalised cross section

- Divide absolute by total cross-section in same phase-space (sum over all bins of X variable)
- Avoid dependence on total inclusive  $\sigma_{t\bar{t}}$  used in MC normalisation

# Parton level $p_T^t$ (normalized)

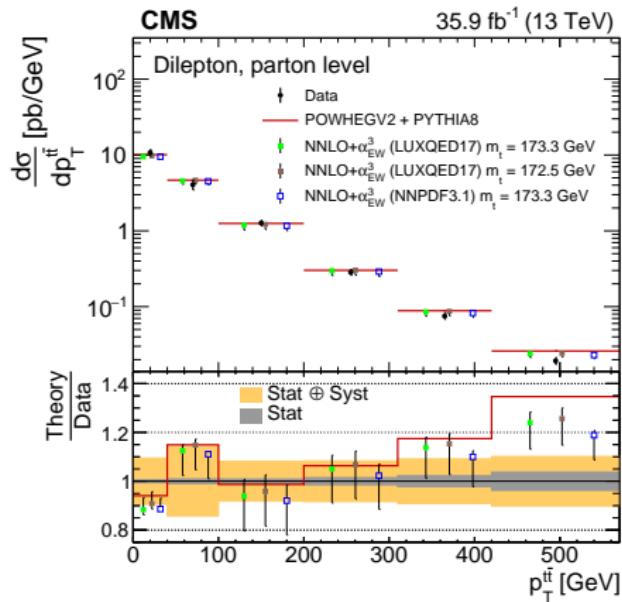
Sensitive to higher order QCD and EW correction in SM and BSM



Deficit at high  $p_T$  disappears when comparing w/  
fixed order NNLO theoretical predictions

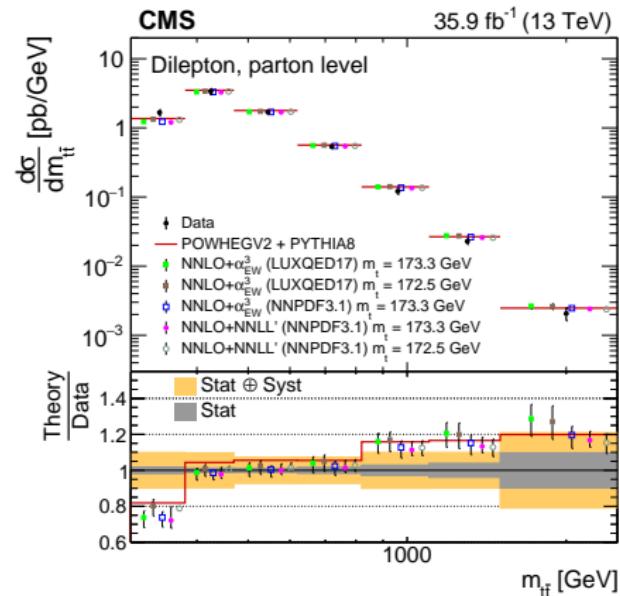
# Parton level full phase space $p_T^{t\bar{t}}$ , $m_{t\bar{t}}$ (absolute)

Sensitive to higher order terms in perturbative calculations



Slight deficit at high  $p_T^{t\bar{t}}$

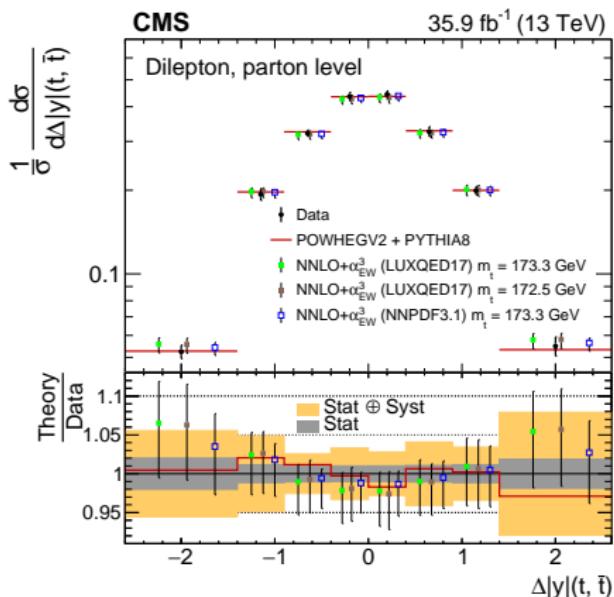
Might reduce gluon PDF uncertainty  
Sensitive to BSM  $t\bar{t}$  resonances



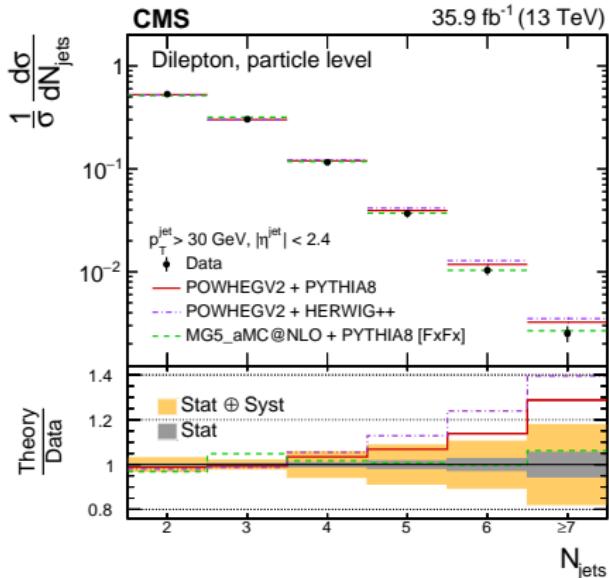
Low values: excess smaller for  $m_{top} = 172.5 \text{ GeV}$

# Parton level $\Delta|y|(t, \bar{t})$ , particle level $N_{jets}$ (normalized)

Allow extraction of charge asymmetries



Sensitive to higher order terms in perturbative calculations

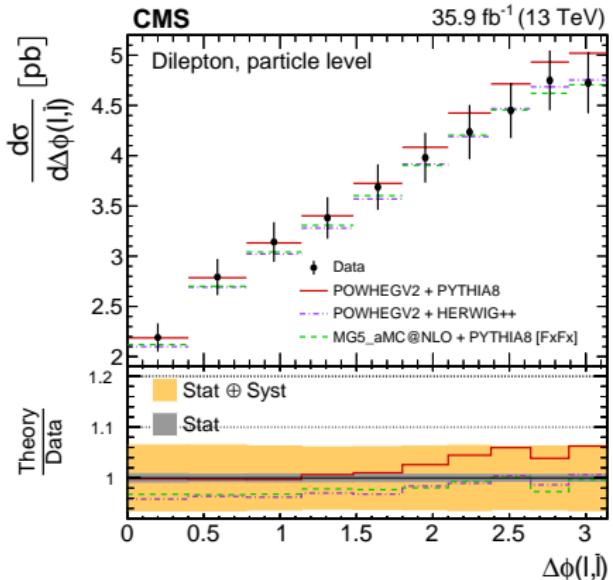
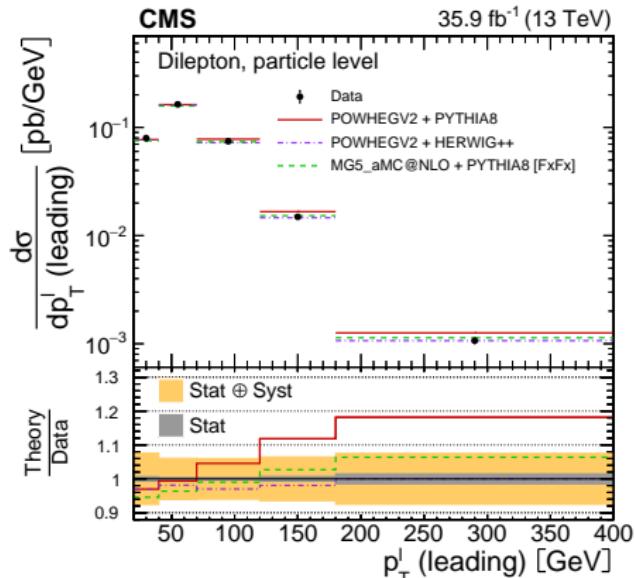


Data excess for  $N_{jets} \geq 4$   
(POWHEG+PYTHIA8, HERWIG++)

# Particle level leading $p_T^\ell$ , $\Delta\phi(\ell, \bar{\ell})$ (absolute)

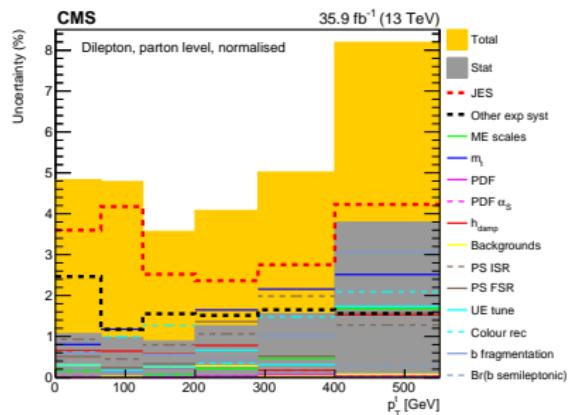
## Lepton kinematic observables

- Test top quark decay modeling
- Test spin correlations

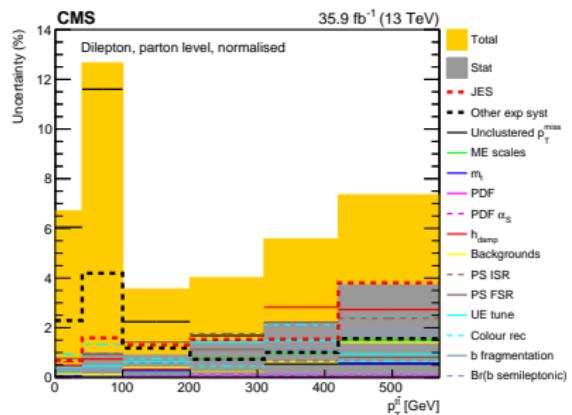


Constrain chromomagnetic dipole moment in EFT framework

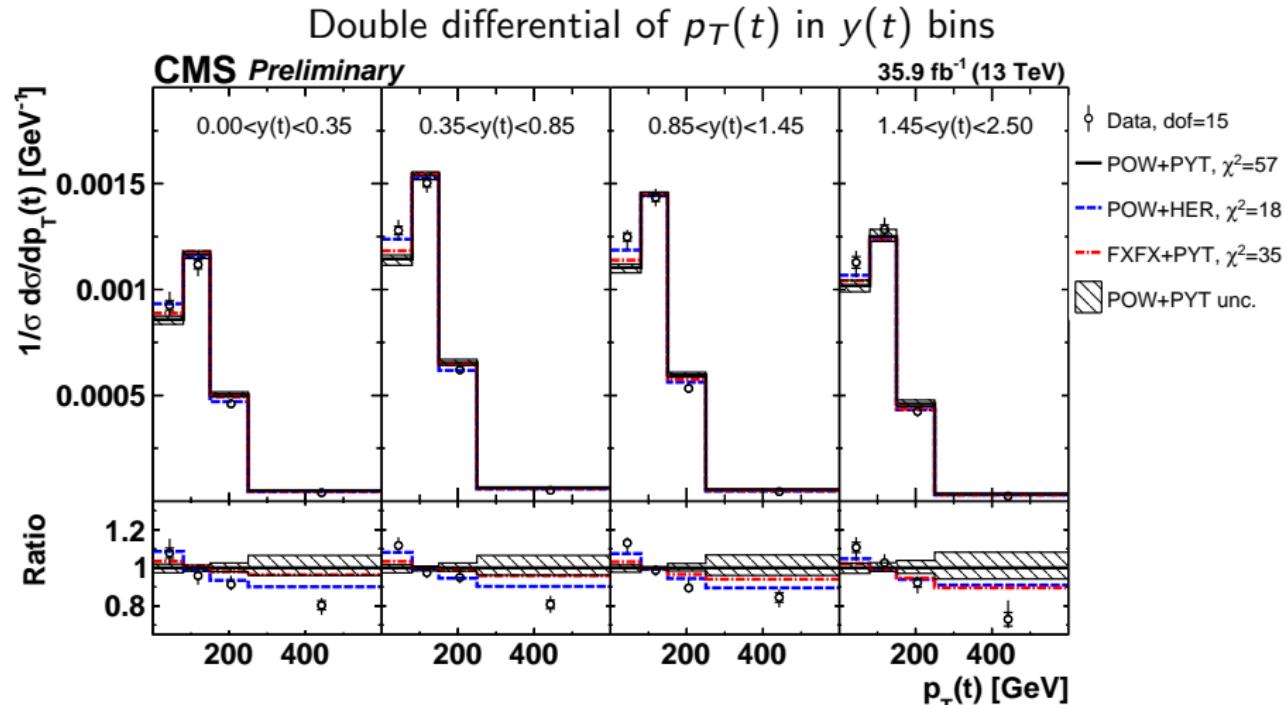
# Systematic uncertainties sources (normalised $p_T^t$ , $p_T^{t\bar{t}}$ )



Dominant contribution: JES



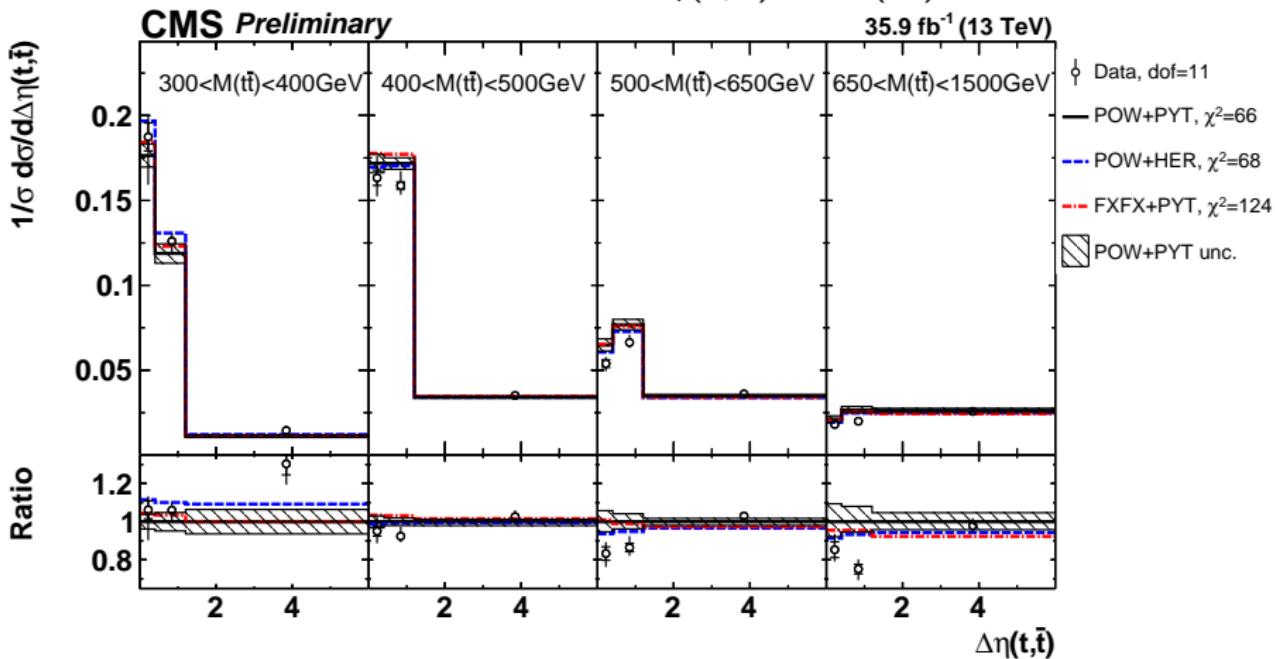
Dominant contribution:  
 $p_T^{\text{miss}}$  at lower bins



Data softer than predictions (POW-PYT worst, POW-HER well)

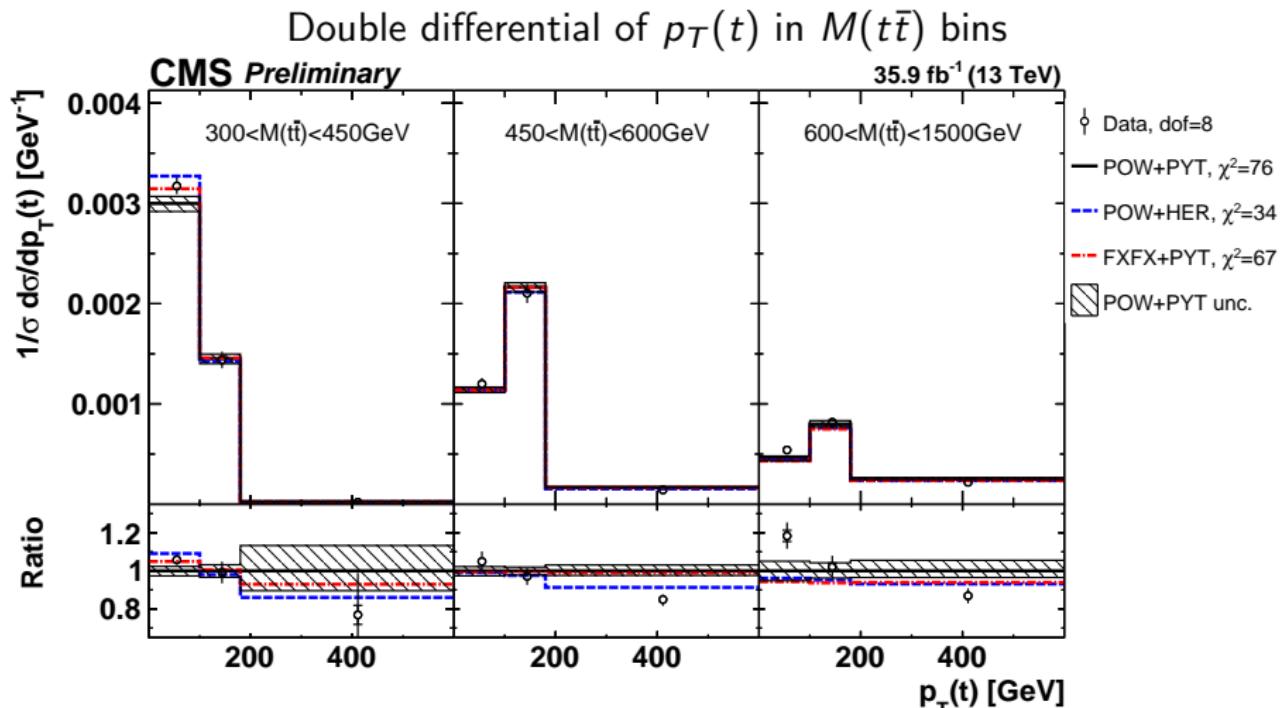
# Multi differential cross sections - CMS-PAS-TOP-18-004

Double differential of  $\Delta\eta(t, \bar{t})$  in  $M(t\bar{t})$  bins



Discrepancy for medium, high  $M(t\bar{t})$  bins, predictions too low  
(FXFX+PYT workst)

# Multi differential cross sections - CMS-PAS-TOP-18-004

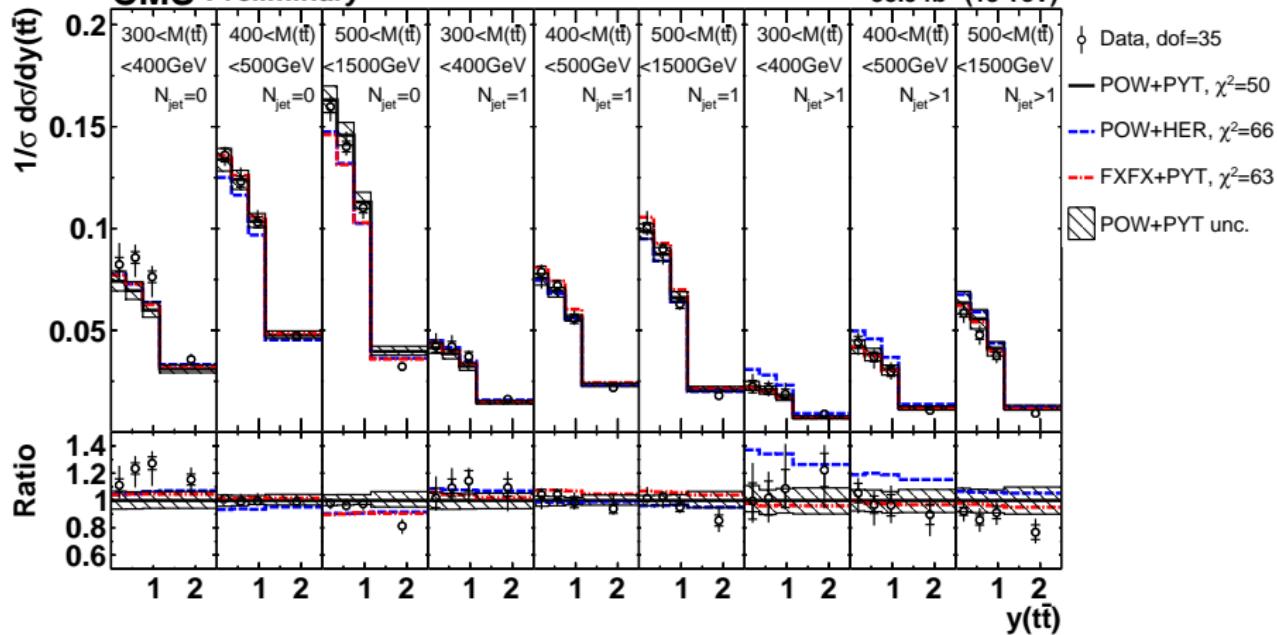


None describes data, too hard  $p_T(t)$  predicted, especially at high  $M(t\bar{t})$

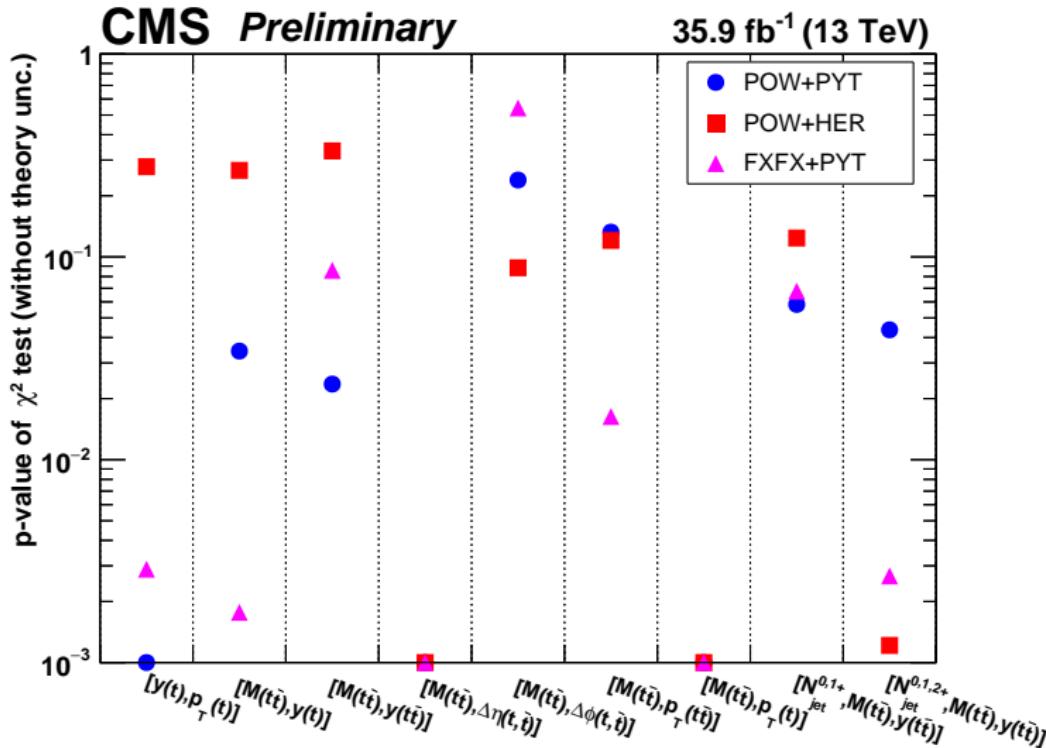
Triple differential of  $y(t\bar{t})$  in bins of  $M(t\bar{t})$  and  $N$  extra jets

**CMS Preliminary**

$35.9 \text{ fb}^{-1}$  (13 TeV)

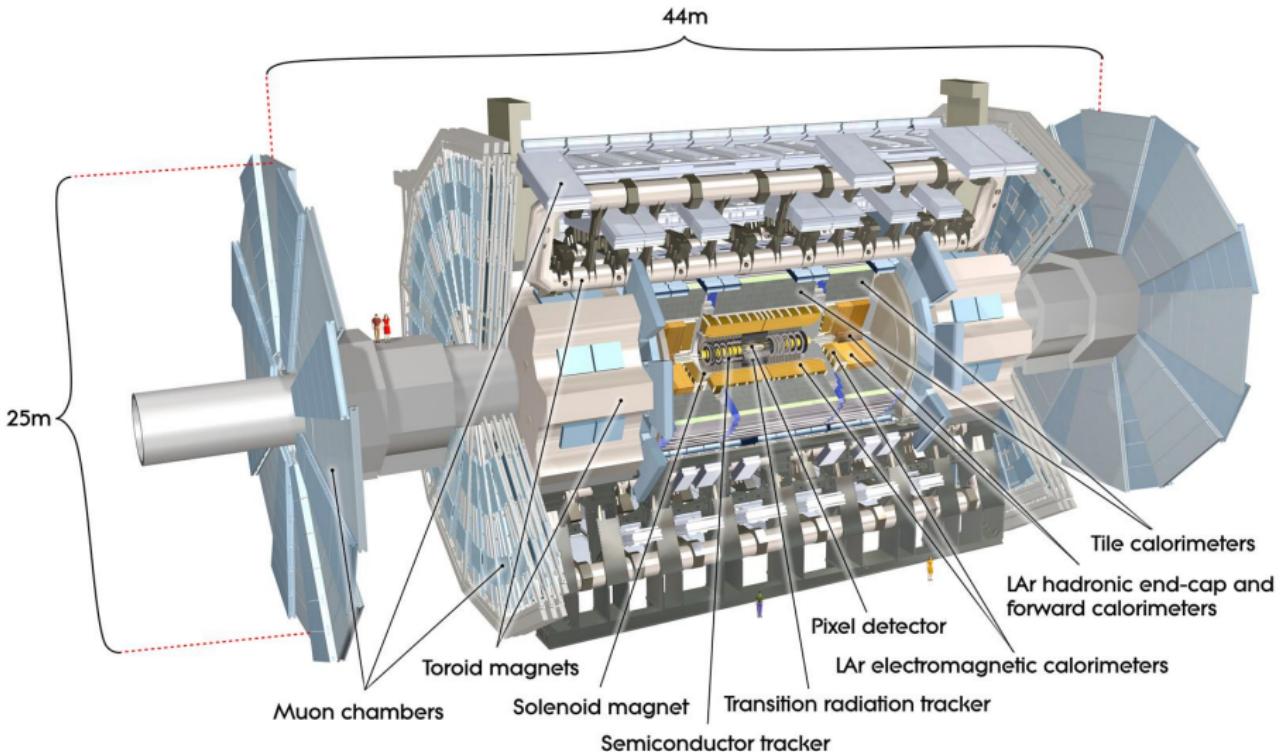


Only POW+PYT satisfactory. POW+HER too high for  $N_{\text{jet}} > 1$ .  
 FXFX-PYT worst at  $N_{\text{jet}} = 1$ .

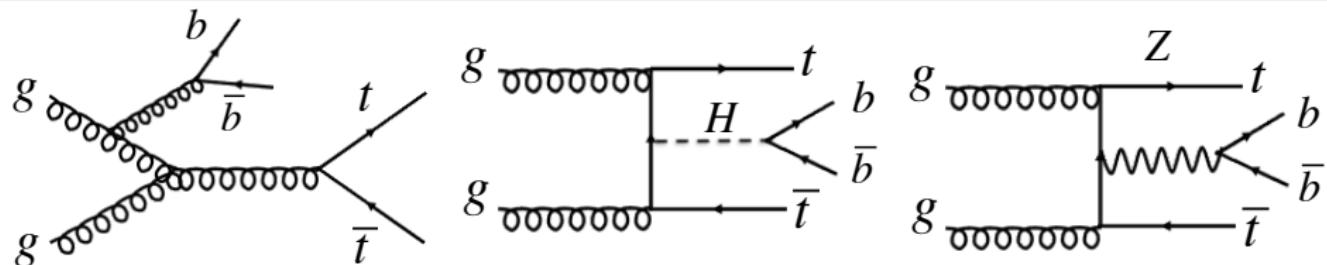


According to  $p$ -values, no prediction able to describe all distributions.

# ATLAS - $36.1 \text{ fb}^{-1}$ $pp$ collisions at 13 TeV (2015/2016)



# $t\bar{t}b$ , $t\bar{t}bb$ fiducial and differential cross sections - arXiv:1811.12113



## Single lepton triggers 2015 (2016)

- $p_T(e) > 24(26)$  GeV or  $p_T(\mu) > 20(26)$  GeV
- Complemented w/ higher  $p_T$ , loosening isolation

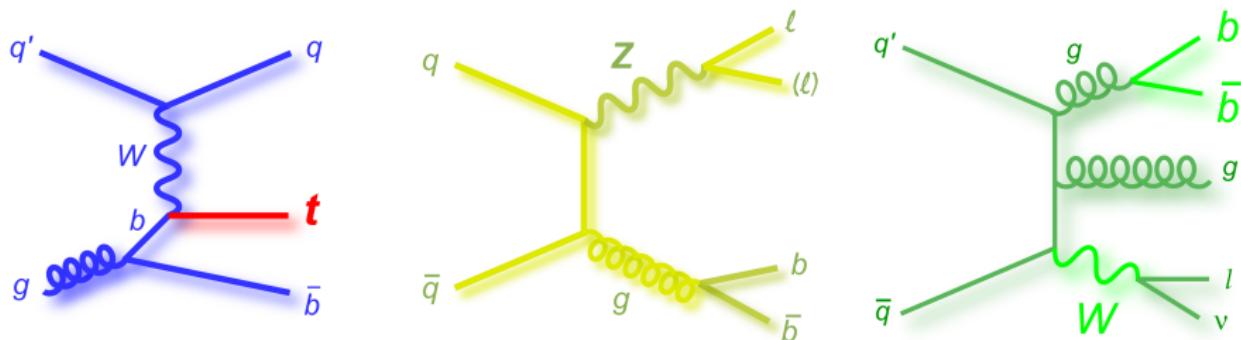
## Baseline event selection

- $e\mu$  channel
  - exactly one  $e$  and one  $\mu$ ,  $p_T > 27$  GeV, opposite charge
  - $\geq 2$  jets,  $\geq 2$   $b$ -jets among them (77% eff working point)
- $\ell + \text{jets}$  channel:
  - exactly one lepton ( $e$  or  $\mu$ ),  $p_T > 27$  GeV
  - $\geq 5$  jets,  $\geq 2$   $b$ -jets among them (60% eff working point)

# Backgrounds

Prompt leptons: estimated from MC simulations

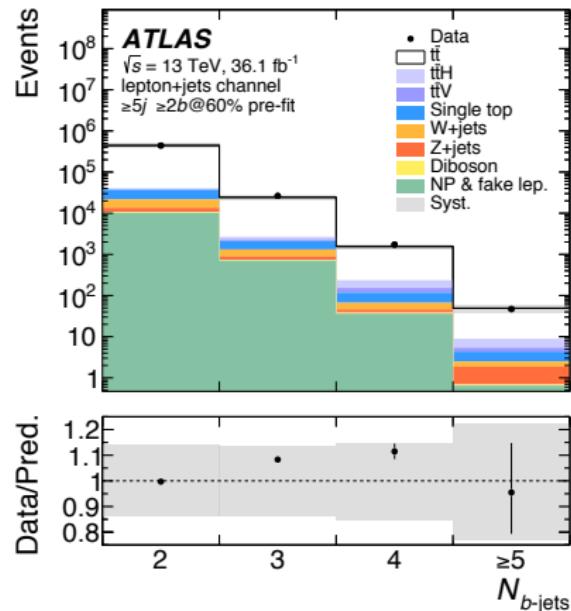
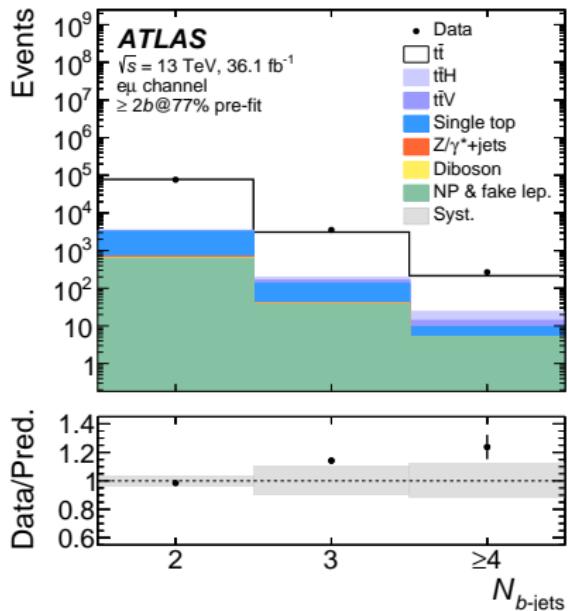
- Single top: 3% contribution of event yields (smaller in 4  $b$ -jets)
- Drell-Yan,  $Z/\gamma^*$ : scaled to data
- $W+\text{jets}$ : < 2% ( $> 3b$ -tagged jets)



non-prompt ( $b$  or  $c$ -hadrons) and  
fake leptons ( $\gamma$  conv,  $\mu$  from  $\pi/K$ ,  $e$  from mis-id jet)

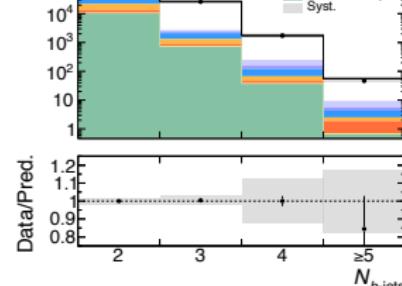
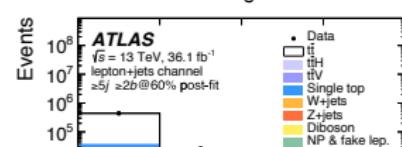
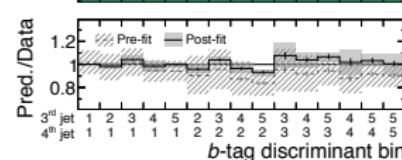
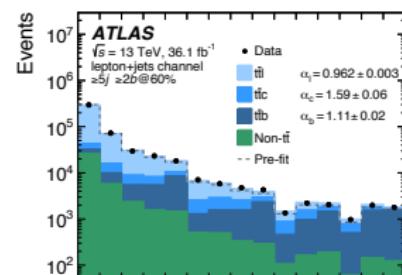
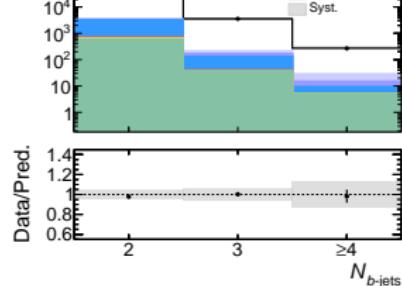
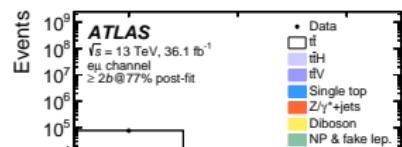
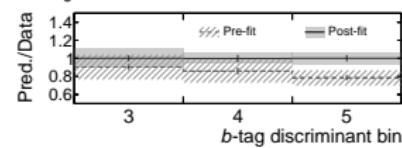
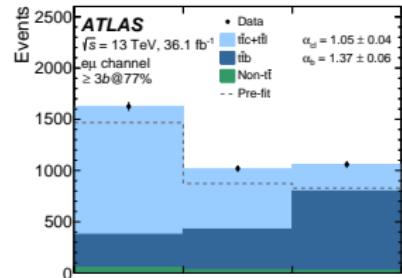
- Dilepton: combined data-driven and MC simulation
- $\ell+\text{jets}$ : matrix-method

# Data vs prediction after baseline selection

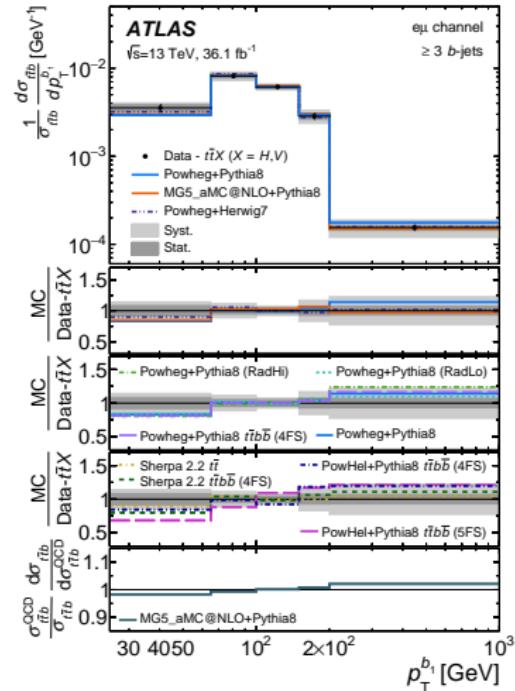
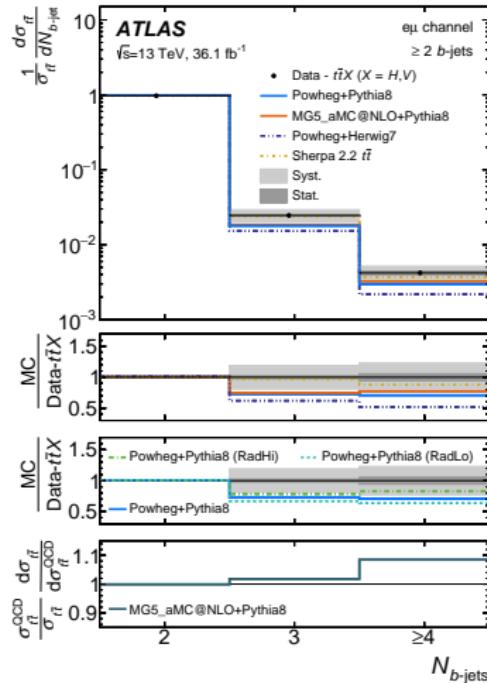


- $> 2b$ -tagged jets events underestimated
- correct  $c$ -jets and light jets prediction w/ data-driven scale factors

# b-tag discriminants and impact of scale factors

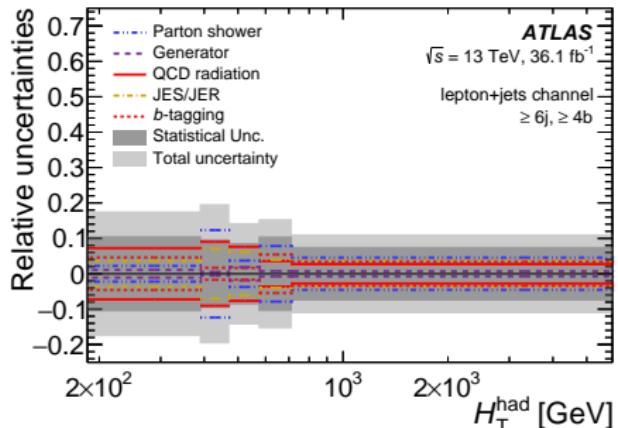
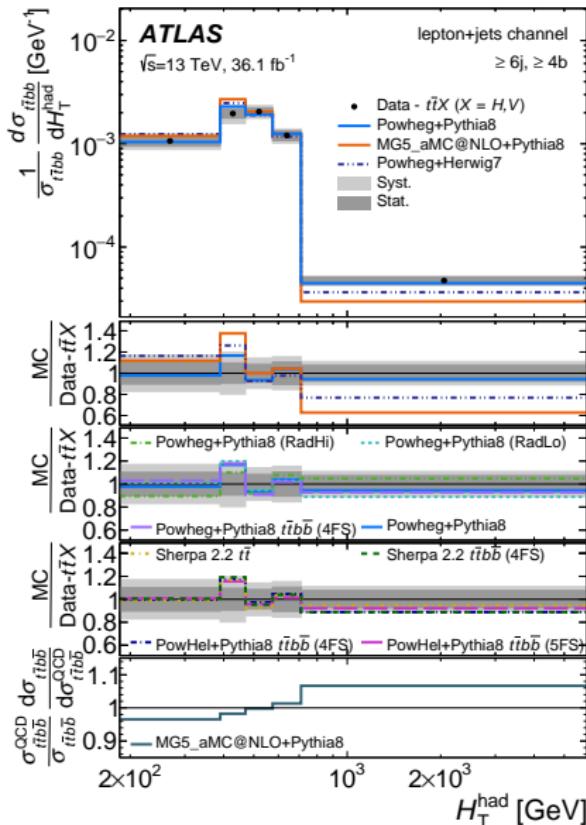


# $e\mu$ differential cross section ( $\# b\text{-jet}$ , $p_T^{b_1}$ )



- $N_{b\text{-jets}} \geq 4$ : 10% difference adding  $t\bar{t}H$ ,  $t\bar{t}Z$  contributions
- $p_T^{b_1}$ : Data well described except by PowHeI+Pythia8  $t\bar{t}b\bar{b}$  (5FS)

# $\ell + \text{jets}$ differential cross section and uncertainties ( $H_T^{\text{had}}$ )



- $H_T^{\text{had}}$ : Data well described, except MG5\_aMC@NLO+Pythia8
- Systematic uncertainties:
  - Parton shower modelling
  - Low region: QCD radiation scale (softer jet contribution)

# Fiducial cross section

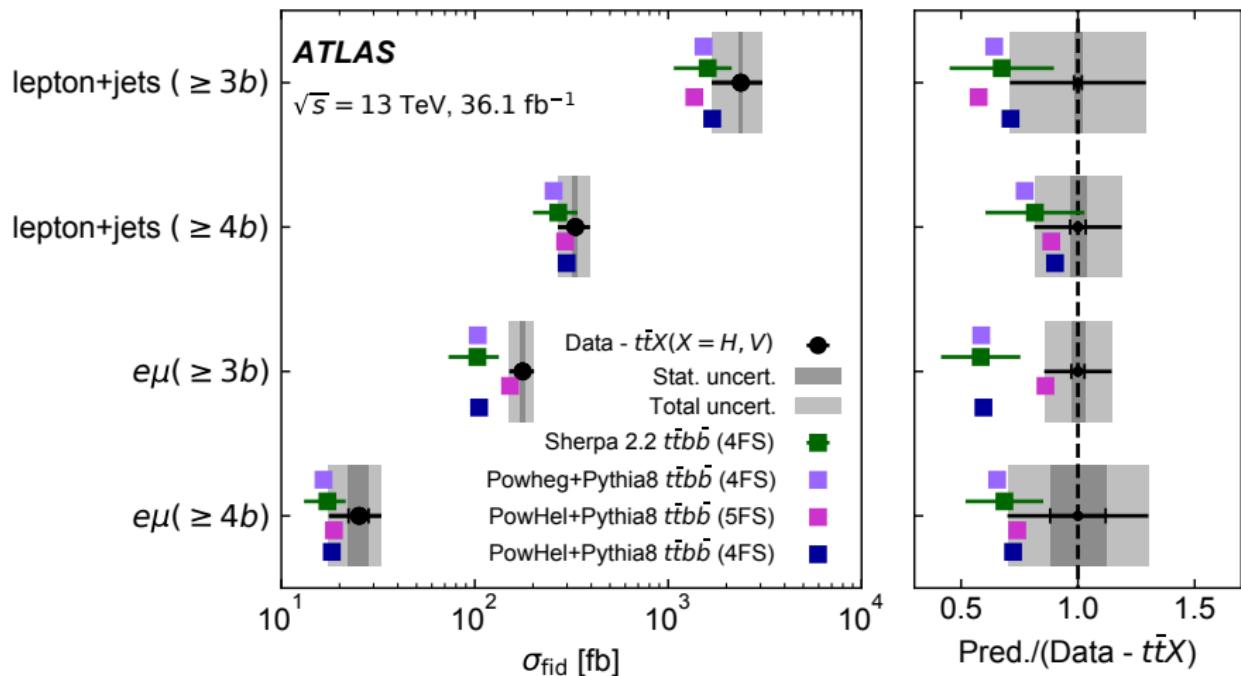
$$\sigma^{\text{fid}} = \int \frac{d\sigma^{\text{fid}}}{dX} dX = \frac{\sum N_{\text{unfold}}^i}{\mathcal{L}}$$

	$e\mu$ [fb]		lepton + jets [fb]	
	$\geq 3b$	$\geq 4b$	$\geq 5j, \geq 3b$	$\geq 6j, \geq 4b$
Measured	181 ± 5 (stat) ± 24 (syst)	27 ± 3 (stat) ± 7 (syst)	2450 ± 40 (stat) ± 690 (syst)	359 ± 11 (stat) ± 61 (syst)
$t\bar{t}X(X = H, V)$ MC	4	2	80	28
Measured – $t\bar{t}X$	177	25	2370	331
SHERPA 2.2 $t\bar{t}b\bar{b}$ (4FS)	$103 \pm 30$	$17.3 \pm 4.2$	$1600 \pm 530$	$270 \pm 70$
POWHEG+PYTHIA 8 $t\bar{t}b\bar{b}$ (4FS)	104	16.5	1520	260
PowHEL+PYTHIA 8 $t\bar{t}b\bar{b}$ (5FS)	152	18.7	1360	290
PowHEL+PYTHIA 8 $t\bar{t}b\bar{b}$ (4FS)	105	18.2	1690	300

# Systematic 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
Pile-up	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

# Measured fiducial vs predictions



Accepted by JHEP!

# Summary of last results with $36 \text{ fb}^{-1}$ at $13 \text{ TeV}$

## $t\bar{t}$ production cross section in dilepton events (CMS)

$$\sigma_{t\bar{t}} = 803 \pm 2(\text{stat}) \pm 25(\text{syst}) \pm 20(\text{lumi}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{th}} = 832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_S) \text{ pb}$$

- Agreement w/ expectations from SM calculation at NNLO

## $t\bar{t}$ differential cross section in dilepton events (CMS)

- As function of kinematic observables of  $t$  quarks and decay products,  $t\bar{t}$  and # jets, at particle and parton levels
- Significant disagreement observed between data and predictions for several observables
- Multi-differential: no MC describe well all distributions

## $t\bar{t} + \text{heavy flavours}$ fiducial and differential cross section (ATLAS)

- Performed in  $e\mu$  and lepton+jets events at particle level w/ 3 or 4  $b$ -jets
- Measured inclusive fiducial exceeds  $t\bar{t}bb\bar{b}$  predictions at NLO but are compatible within total uncertainties (smaller than predictions)
- Good agreement observed in differential measurements

# Backup

Some feynman diagrams from D0 experiment [webpage](#)

## Previous measurements - $t\bar{t}$ production cross section

### ATLAS ( $e\mu$ w/ $b$ -tagged jets in $pp$ )

- $\sqrt{s} = 7 \text{ TeV} (4.6\text{fb}^{-1})$   
 $\sigma_{t\bar{t}} = 182.9 \pm 3.1(\text{stat}) \pm 4.2(\text{syst}) \pm 3.6(\text{lumi}) \pm 3.3(\text{beam}) \text{ pb}$
- $\sqrt{s} = 8 \text{ TeV} (20.2\text{fb}^{-1})$   
 $\sigma_{t\bar{t}} = 242.9 \pm 1.7(\text{stat}) \pm 5.5(\text{syst}) \pm 5.1(\text{lumi}) \pm 4.2(\text{beam}) \text{ pb}$
- $\sqrt{s} = 13 \text{ TeV} (3.2\text{fb}^{-1})$   
 $\sigma_{t\bar{t}} = 818 \pm 8(\text{stat}) \pm 27(\text{syst}) \pm 19(\text{lumi}) \pm 12(\text{beam}) \text{ pb}$

### CMS ( $e\mu$ w/ $b$ -tagged jets in $pp$ )

- $\sqrt{s} = 7 \text{ TeV} (5\text{fb}^{-1})$   
 $\sigma_{t\bar{t}} = 173.6 \pm 2.1(\text{stat})^{+4.5}_{-4.09}(\text{syst}) \pm 3.8(\text{lumi}) \text{ pb}$
- $\sqrt{s} = 8 \text{ TeV} (19.7\text{fb}^{-1})$   
 $\sigma_{t\bar{t}} = 244.9 \pm 1.4(\text{stat})^{+6.3}_{-5.5}(\text{syst}) \pm 6.4(\text{lumi}) \text{ pb}$

# Previous measurements ( $pp$ ) - $t\bar{t}$ +heavy-jets cross section

## ATLAS

- $\ell\ell$  w/  $\geq 3$ b-tagged jets ( $4.7\text{fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$ )  
 $\sigma_{t\bar{t}+HF}/\sigma_{t\bar{t}+jet} = 6.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})$
- $e\mu$  and  $\ell+\text{jets}$  w/  $\geq 1$ b-tagged jets ( $20.3\text{fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ )  
 $\sigma_{t\bar{t}(\ell+jets)+\geq 1b} = 950 \pm 70(\text{stat})^{+240}_{-190}(\text{syst})\text{fb}$   
 $\sigma_{t\bar{t}(e\mu)+\geq 1b} = 50 \pm 10(\text{stat})^{+15}_{-10}(\text{syst})\text{fb}$

## CMS

- $t\bar{t}b, t\bar{t}bb$  - dilepton ( $19.7\text{fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ )
- $\ell\ell + 2$  jets ( $19.6\text{fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ )  
 $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003(\text{stat}) \pm 0.005(\text{syst})$
- $\ell\ell + 2$  jets ( $2.3\text{fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ )  
 $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003(\text{stat}) \pm 0.006(\text{syst})$   
 $\sigma_{t\bar{t}b\bar{b}} = 4.0 \pm 0.6(\text{stat}) \pm 1.3(\text{syst})\text{pb}$   
 $\sigma_{t\bar{t}jj} = 184 \pm 6(\text{stat}) \pm 33(\text{syst})\text{pb}$

# Event simulation

## $t\bar{t}$ (CMS)

- POWHEG (v.2), NLO (QCD) ME level,  $h_{\text{damp}} = 1.58m_t = 272.72 \text{ GeV}$ 
  - PYTHIA (v.8.219) w/ CUETP8M2T4 tune for PS and hadronisation
  - HERWIG++ (v.2.7.1) w/ EE5C tune for PS and hadronisation
- MadGRAPH5\_aMC@NLO (v.2.2.2) up to 2 extra partons at ME (NLO)
  - MADSPIN used for top quarks decays
  - PYTHIA for PS and hadronisation w/ [FxFx] prescription

## Backgrounds (CMS)

- DY,  $tW$ : POWHEG (v.2) w/ NNPDF3.0 PDF,  
PYTHIA (v.8.202) w/ CUETP8M2T4 tune
- $W+\text{jets}$ : MadGRAPH5\_aMC@NLO (v.2.2.2) w/ NNPDF3.0 PDF,  
PYTHIA (v.8.202) w/ CUETP8M1 tune
- $WW$ ,  $WZ$ ,  $ZZ$ : PYTHIA (v.8.2) w/ NNPDF2.3 PDF and CUETP8M1  
tune

# Common object selection - CMS

## Single lepton and dilepton triggers

- $p_T(e) > 27 \text{ GeV}$  or  $p_T(\mu) > 24 \text{ GeV}$
- ee:  $p_T(e) > 23(12) \text{ GeV}$ ,  $\mu\mu$ :  $p_T(\mu) > 17(8) \text{ GeV}$
- $e\mu$ :  $p_T(e) > 23$ ,  $p_T(\mu) > 8 \text{ GeV}$  or  $p_T(\mu) > 23$ ,  $p_T(e) > 12 \text{ GeV}$

## Particle-flow (PF) algorithm

- Combine information from various detectors
- Identify each individual particle
- Leading (subleading) leptons:  $p_T > 25(20) \text{ GeV}$ ,  $|\eta| < 2.4$
- Reject e in  $1.44 < |\eta| < 1.57$
- Relative Isolation  $\sum_{\Delta R=0.3(0.4)}^{PF} p_T / p_T^{e(\mu)} < 6(15)\%$
- Reject  $m_{\ell\bar{\ell}} < 20 \text{ GeV}$ ,  $76 < m_{\ell\bar{\ell}} < 106 \text{ GeV}$

## Jets and b-tagging

- anti- $k_t$  clustering  $\Delta R = 0.4$  radius
- Calibrated ( $p_T, \eta$ ), in situ correction, pileup offset
- $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.4$
- Hadronised  $b$ -quarks identified w/ secondary vertex algorithms

# Template fit to $b$ -tags multiplicity in dilepton categories

Visible  $t\bar{t}$  cross section  $\sigma_{t\bar{t}}^{vis}$

- Constraint to the lepton identification efficiencies
- Constraint to the  $b$ -jet selection efficiency
- Signal and background templates from simulation
- Accessible detector fiducial volume phase space

Poisson Likelihood function

- Nuisance parameters:  $\vec{\lambda} = (\lambda_1, \dots, \lambda_J)$  from systematic uncertainties
- $\nu_i = s_i(\sigma_{t\bar{t}}^{vis}, \vec{\lambda}) + \sum_k b_k^{MC}$ : expected events in bin  $i$ .  $n_i$ : observed
- $\pi(\lambda_j)$ : penalty term for  $\lambda_j$  nominal value deviation (gaussian prior)

$$L = \prod_i \frac{e^{\nu_i} \nu_i^{n_i}}{n_i!} \prod_j \pi(\lambda_j)$$

# Final Results

## Visible cross-section

$$\sigma_{t\bar{t}}^{\text{vis}} = 25.61 \pm 0.05(\text{stat}) \pm 0.75(\text{syst}) \pm 0.64(\text{lumi}) \text{ pb. Tot unc: } 3.8\%$$

## Total (extrapolated) cross-section

$$\sigma_{t\bar{t}} = 803 \pm 2(\text{stat}) \pm 25(\text{syst}) \pm 20(\text{lumi}) \text{ pb. Tot unc: } 4\%$$

## Theoretical cross-section (NNLO+NNLL)

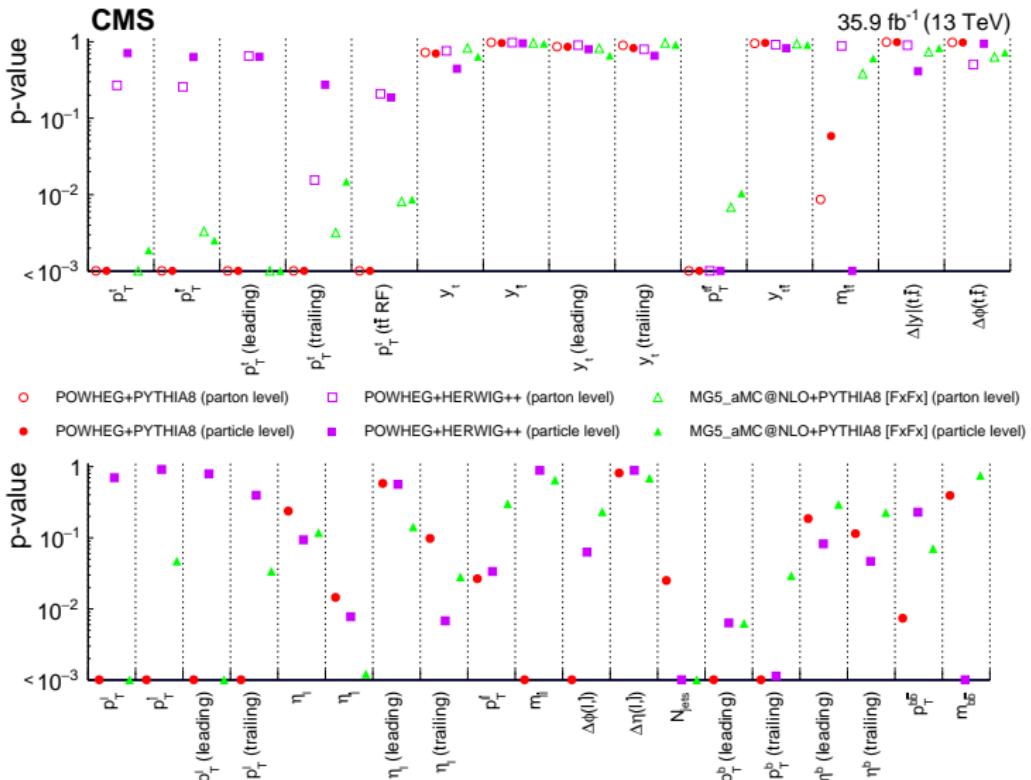
$$\sigma_{t\bar{t}}^{\text{th}} = 832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_S) \text{ pb. Tot unc: } {}^{+4.8\%}_{-5.5\%}$$

## Total (event counting) cross-section

$$\sigma_{t\bar{t}} = 804 \pm 2(\text{stat}) \pm 31(\text{syst}) \pm 20(\text{lumi}) \text{ pb. Tot unc: } 4.6\%$$

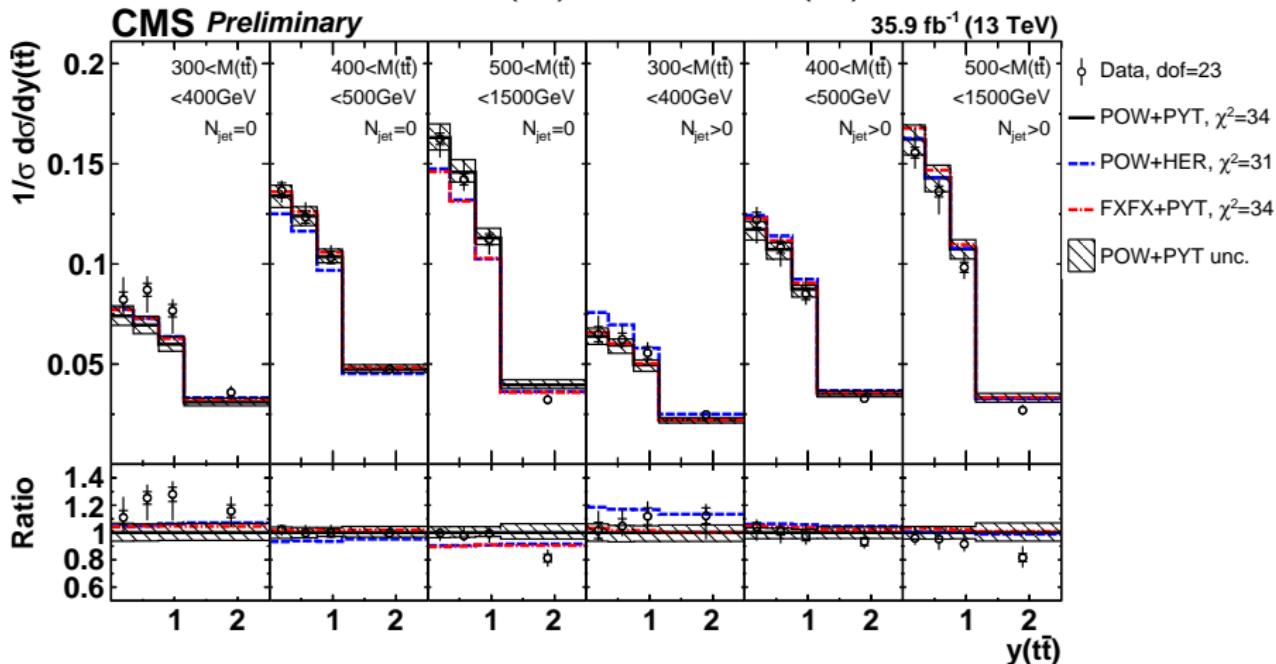
Submitted to Eur. Phys. J. C

# Data vs MC (normalised measurements $p$ -values)



# Multi differential cross sections - CMS-PAS-TOP-18-004

Triple differential of  $y(t\bar{t})$  in bins of  $M(t\bar{t})$  and  $N$  extra jets



Good description by all MC models when splitting between 0 or more jets

# Flavour composition of additional jets in $t\bar{t}$ events

## Binned maximum-likelihood fit w/ Poisson likelihood

- Events reco w/  $> 3b$ -jets (77% WP):  
50% w/ 3  $b$ -jets at particle level  
the rest w/  $\geq 1c$ - or light- mis-id jet
- Large uncertainties on mis-tag rates
- Use template fits to estimate  $t\bar{t}c$ ,  $t\bar{t}$ +light
- Discriminate using  $b$ -tagging efficiency bins defined by WPs

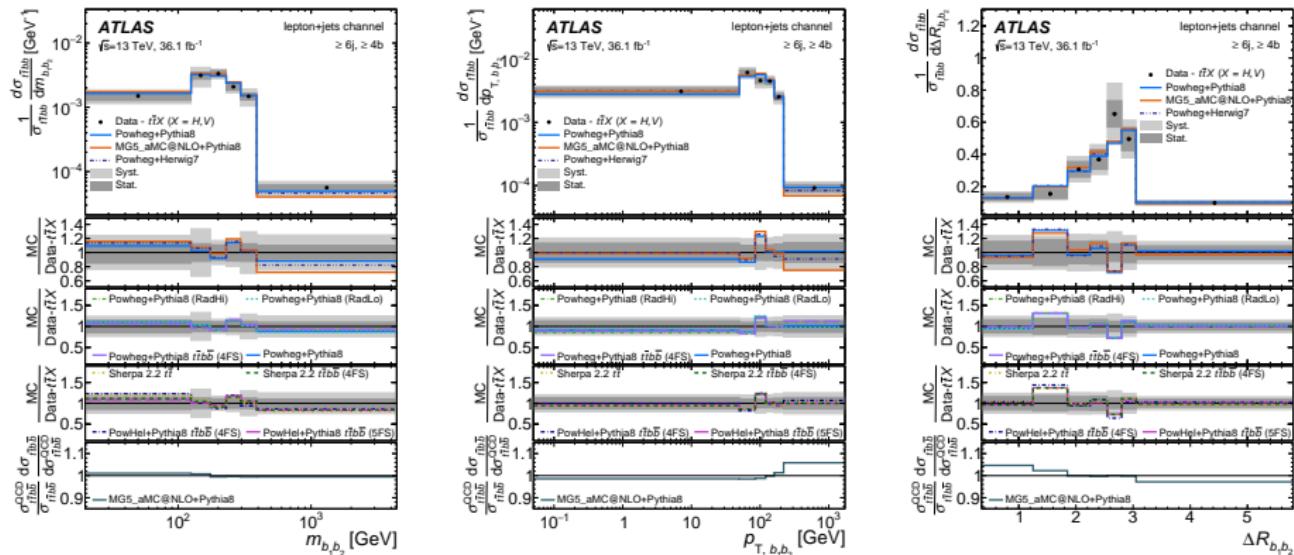
## Expected events and Scale factors

- $e\mu$  channel:  $\alpha_b N_{t\bar{t}b}^k + \alpha_{cl}(N_{t\bar{t}c}^k + N_{t\bar{t}l}^k) + N_{non-t\bar{t}}^k$   
 $\alpha_b = 1.37 \pm 0.06$ ,  $\alpha_{cl} = 1.05 \pm 0.04$  (stat only)
- $\ell+$ jets channel:  $\alpha_b N_{t\bar{t}b}^k + \alpha_c N_{t\bar{t}c}^k + \alpha_l N_{t\bar{t}l}^k + N_{non-t\bar{t}}^k$   
 $\alpha_b = 1.11 \pm 0.02$ ,  $\alpha_c = 1.59 \pm 0.06$ ,  $\alpha_l = 0.962 \pm 0.003$  (stat only)

$t\bar{t}+$ heavy flavour jets fiducial and differential cross-sections

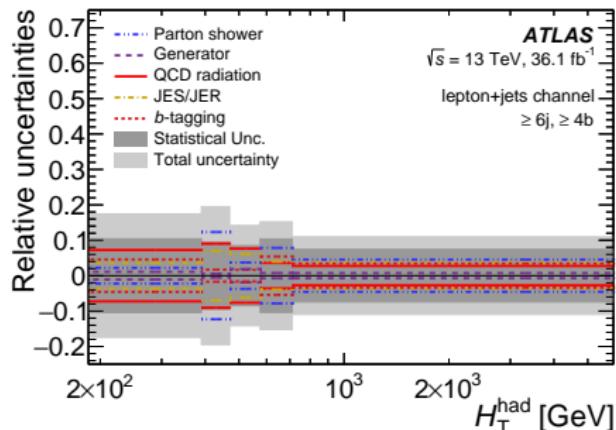
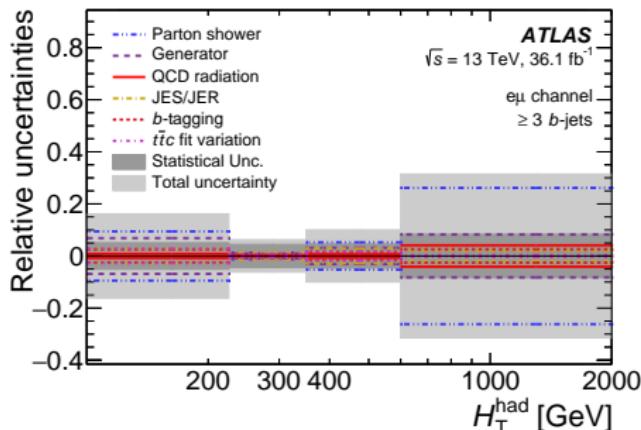
# $\ell + \text{jets}$ differential cross section ( $m_{b_1 b_2}$ , $p_{T_{b_1 b_2}}$ , $\Delta R_{b_1 b_2}$ )

$$\frac{d\sigma^{\text{fid}}}{dX^i} = \frac{N^i_{\text{unfold}}}{\mathcal{L}\Delta X^i} = \frac{1}{\mathcal{L}\Delta X^i f_{\text{eff}}^i} \sum_j \mathcal{M}_{ij}^{-1} f_{\text{matching}}^j f_{\text{accept}}^j f_{t\bar{t}b}^j (N_{\text{data}}^j - N_{\text{non-t\bar{t}-bkg}}^j)$$



$t\bar{t} + \text{heavy flavour jets}$  fiducial and differential cross-sections

# Relative systematic uncertainties (th and exp)



- $H_T^{\text{had}}$ : Parton shower modelling dominant
- Low  $H_T$  region: QCD radiation scale (softer jet contribution)

**t̄t+heavy flavour jets** fiducial and differential cross-sections

# $t\bar{t}$ differential cross section - JHEP 02 (2019) 149

## Event selection

- Exactly 2 OS leptons ( $e^+e^-$ ,  $\mu^+\mu^-$ ,  $e^\pm\mu^\mp$ )
  - Particle level:  $m_{\ell\ell} > 20$  GeV, do not include  $\tau$  decaying leptonically
- $\geq 2$  jets, at least one  $b$ -tagged (particle level:  $> 2b$ -jets)
  - $b$ -tagging efficiency  $\approx 79 - 87\%$ , light-flavour  $\approx 10\%$
- $p_T^{miss} > 40$  GeV ( $p_T^{miss} = - \sum p_T$  considering all event particles)

## Kinematic reconstruction algorithm (90% efficiency)

- Assume only neutrinos contribute to  $p_T^{miss}$
- $m_W = 80.4$  GeV,  $m_t = 172.5$  GeV
- Parton level:  $p_T^t$  after QCD radiation, before decay

## Smearing: randomly varying energies and directions within resolution

- Take  $\nu$  momenta solution yielding smallest  $m_{t\bar{t}}$
- Chosen solution w/ most  $b$ -tagged jets

# Differential cross section extraction

## Selected final events

- 34890 ee, 150410 e $\mu$ , 70346  $\mu\mu$
- Combines all three channels to reduce statistical uncertainties
- Estimated signal contribution to data is 80.6%

## Absolute cross section

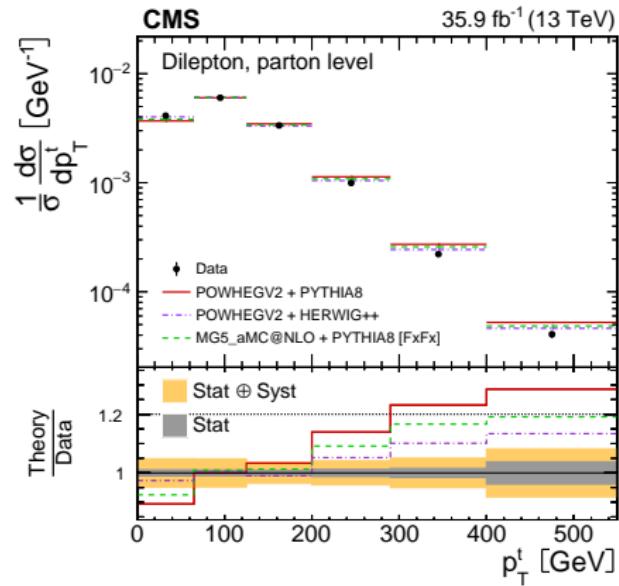
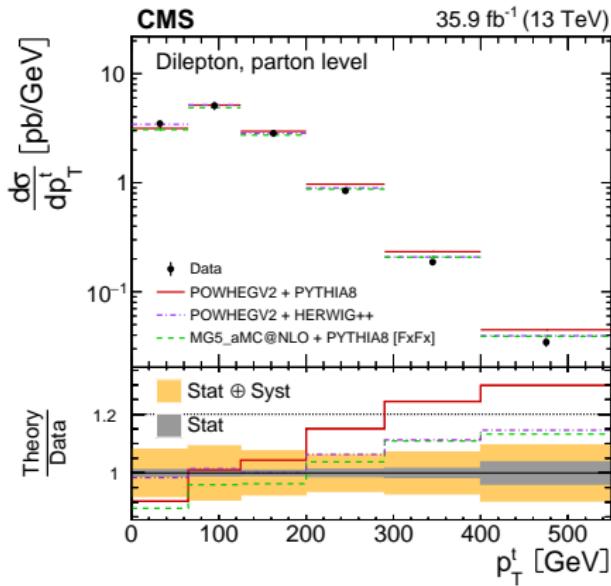
- Determined for X observable via relation  $\frac{d\sigma_i}{dX} = \frac{x_i}{\mathcal{L}\Delta_i^X}$
- $\mathcal{L}$  integrated data luminosity.  $\Delta_i^X$  bin width
  - Bin width optimised for purity and stability (both  $\approx 50\%$ )
- $x_i$ =signal events after background subtraction and corrections for detector efficiencies and acceptance and bin migration (regularised unfolding)

## Normalised cross section

- Obtained dividing absolute by total cross-section in same phase-space (sum over all bins of X variable)
- Avoid dependence on total inclusive  $\sigma_{t\bar{t}}$  used in MC normalisation

# Parton level $p_T^t$ (absolute and normalized)

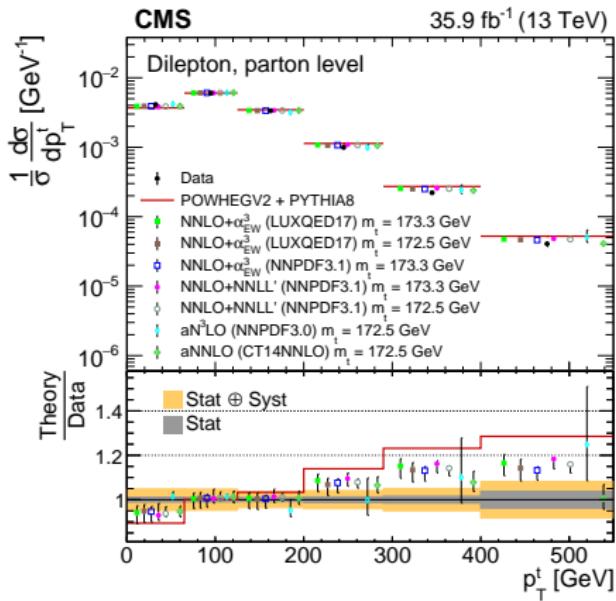
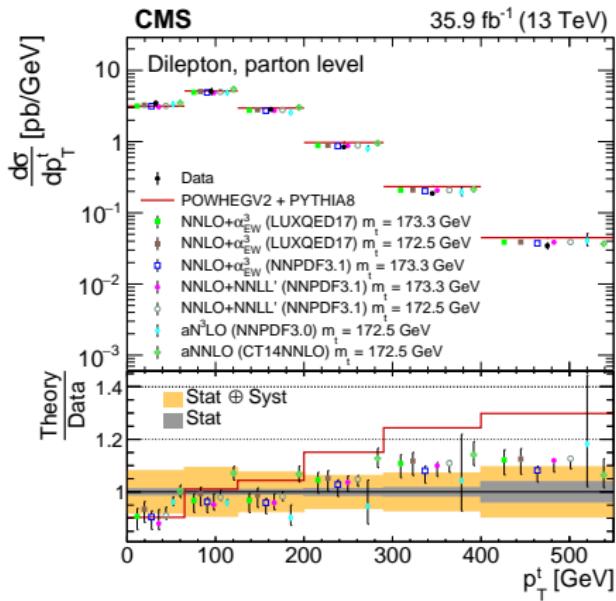
Sensitive to higher order QCD and EW correction in SM and BSM



Deficit at high  $p_T$

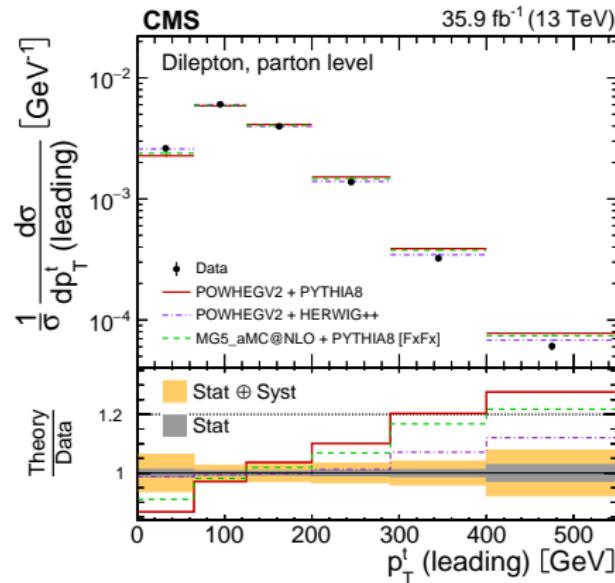
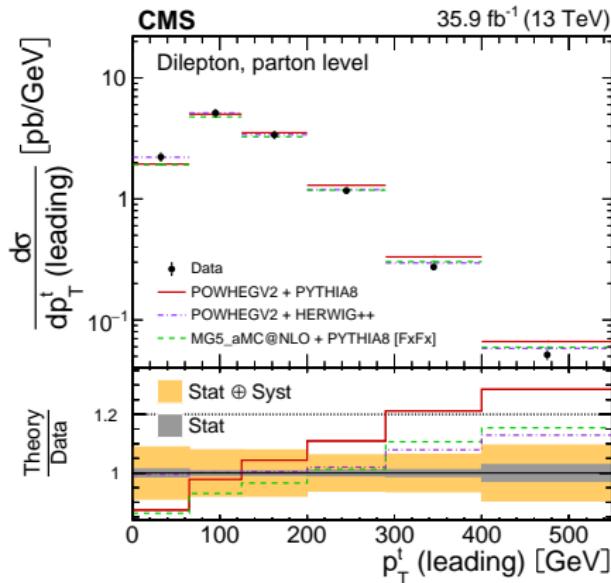
# Parton level $p_T^t$ (absolute and normalized)

Comparison w/ fixed order NNLO theoretical predictions



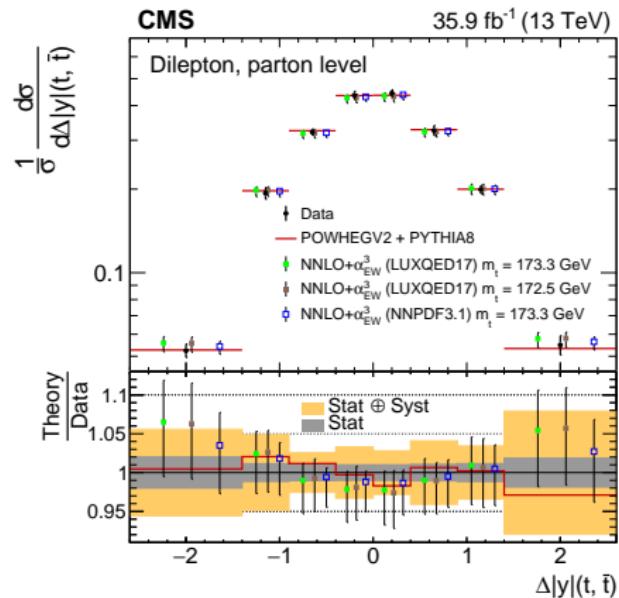
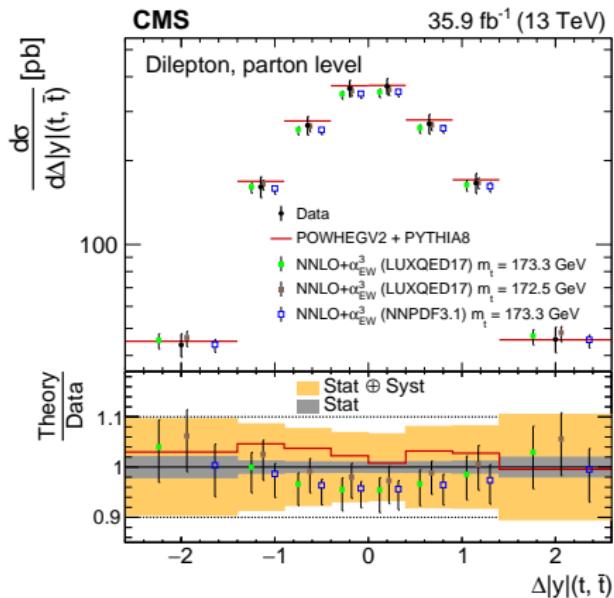
# Parton level leading $p_T^t$ (absolute and normalized)

Suppress effects of ISR, FSR



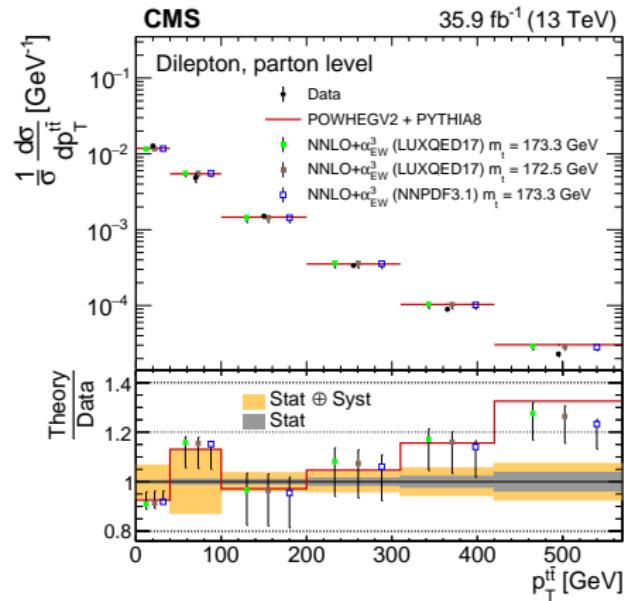
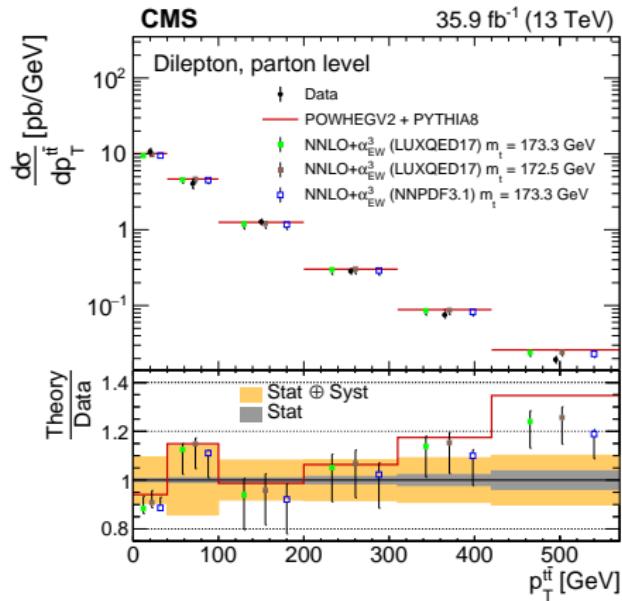
# Parton level $\Delta|y|(t, \bar{t})$ (absolute and normalized)

Allow extraction of charge asymmetries



# Parton level full phase space $p_T^{t\bar{t}}$ (absolute and normalized)

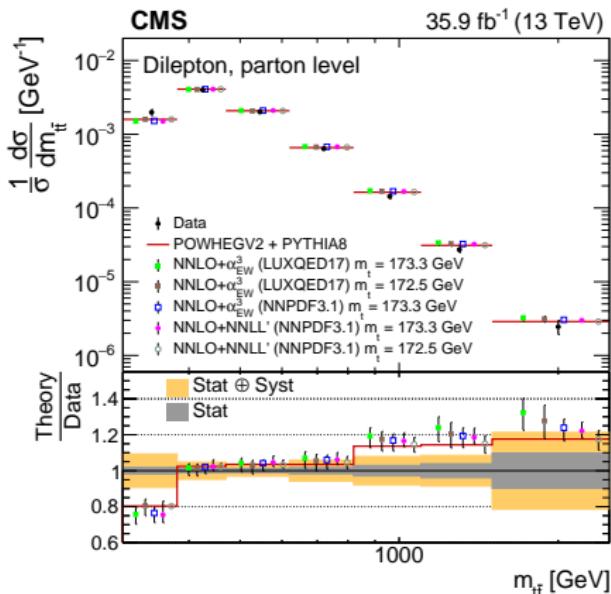
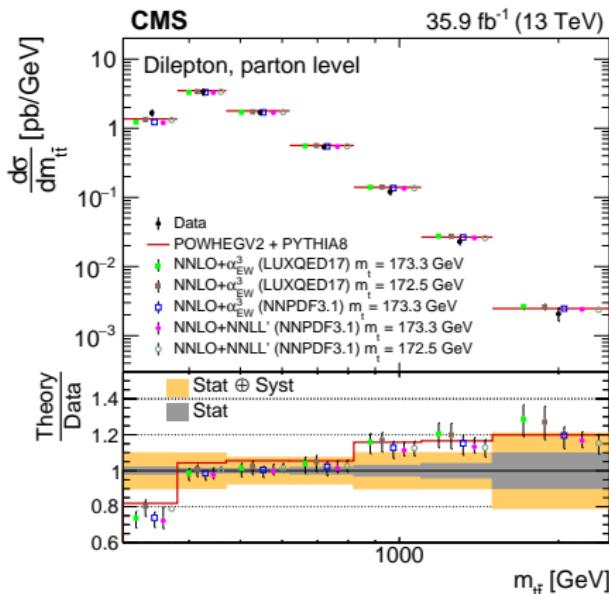
Sensitive to higher order terms in perturbative calculations



Slight deficit at high  $p_T^{t\bar{t}}$

# Parton level $m_{t\bar{t}}$ (absolute and normalized)

Potential to reduce gluon PDF uncertainties  
at large fractions of  $p$  longitudinal momentum carried by gluon



Small values: sensitive to  $m_{top}$

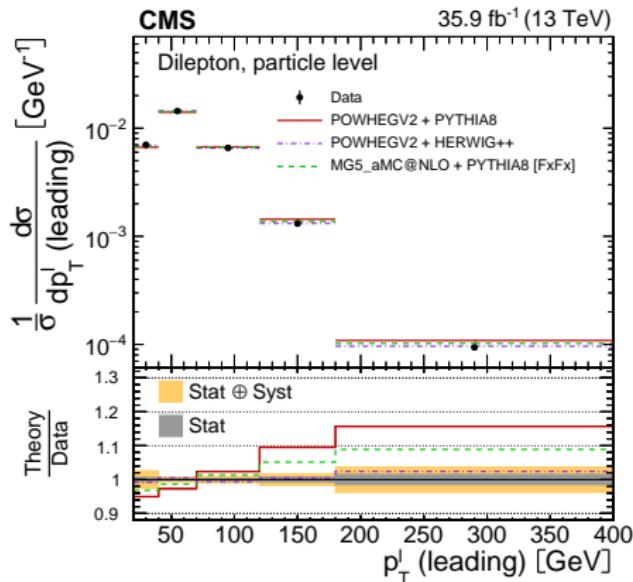
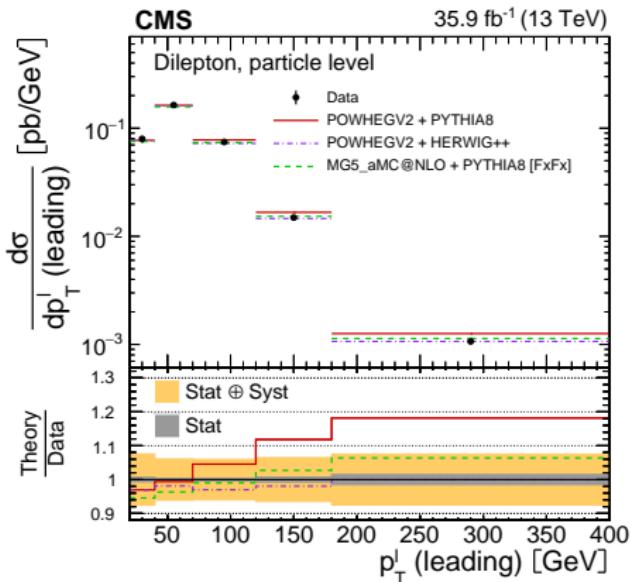
Large values: sensitive to BSM  $t\bar{t}$  resonances

Excess in lowest bin smaller for  $m_{top} = 172.5 \text{ GeV}$

# Particle level leading $p_T^\ell$ (absolute and normalized)

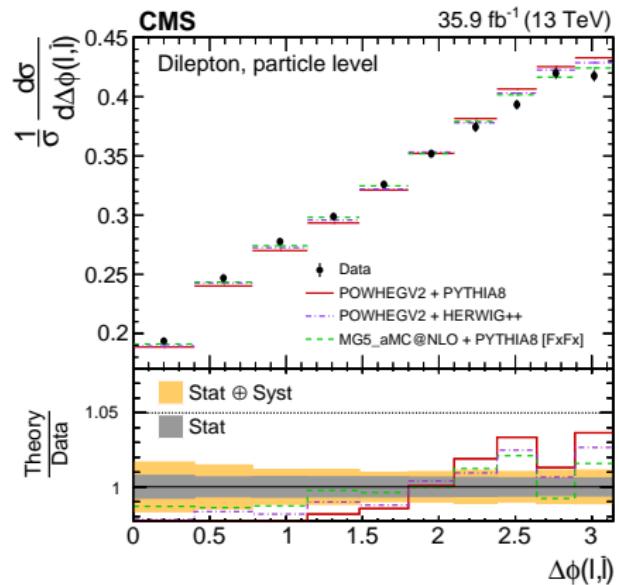
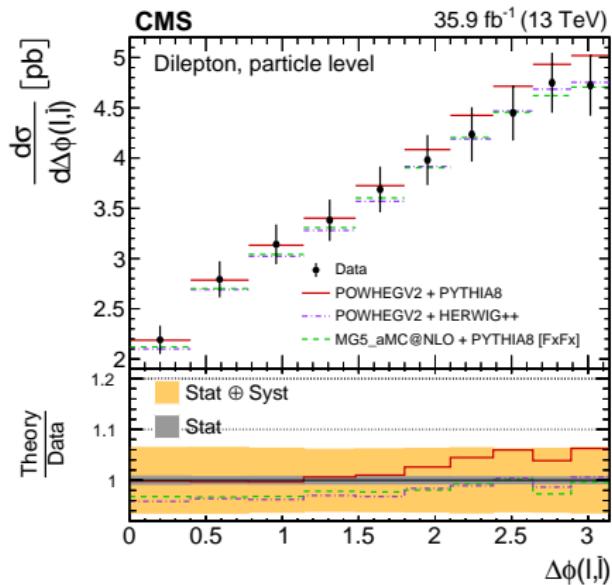
## Lepton kinematic observables

- Test modelling of top quark decays
- Test spin correlations



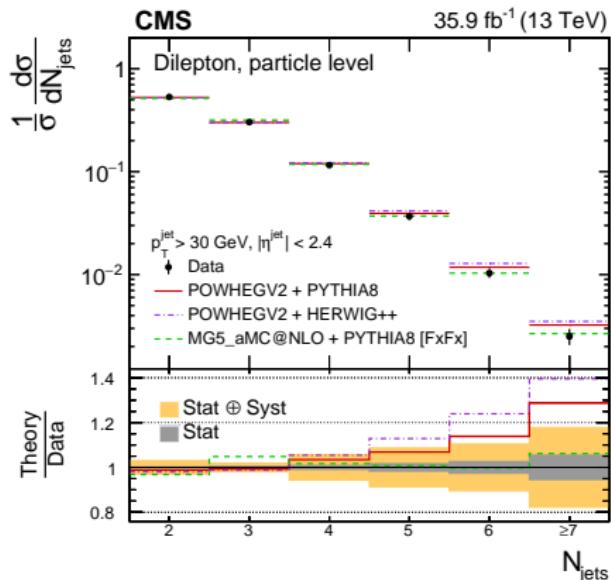
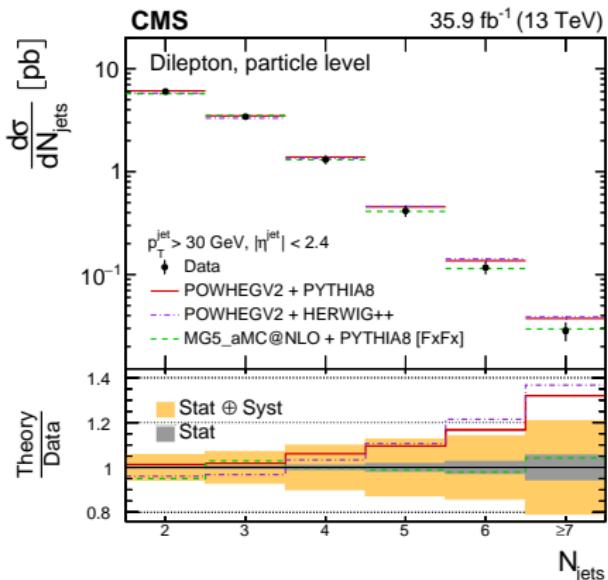
# Particle level $\Delta\phi(\ell, \bar{\ell})$ (absolute and normalized)

Constrain chromomagnetic dipole moment in EFT framework



# Particle level $N_{jets}$ (absolute and normalized)

Sensitive to higher order terms in perturbative calculations

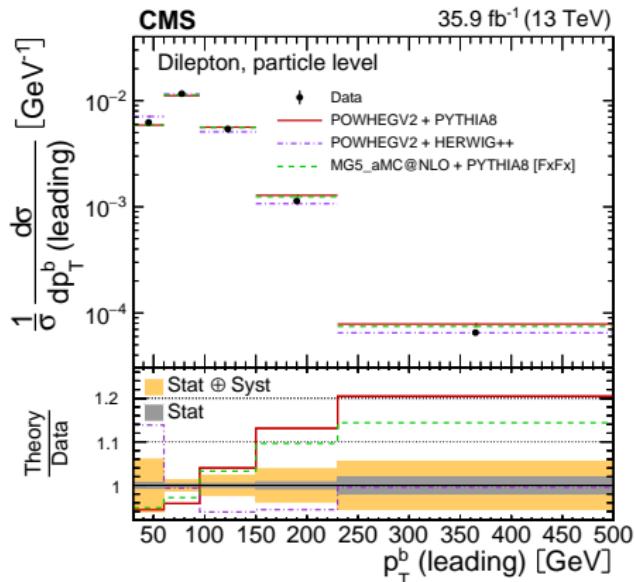
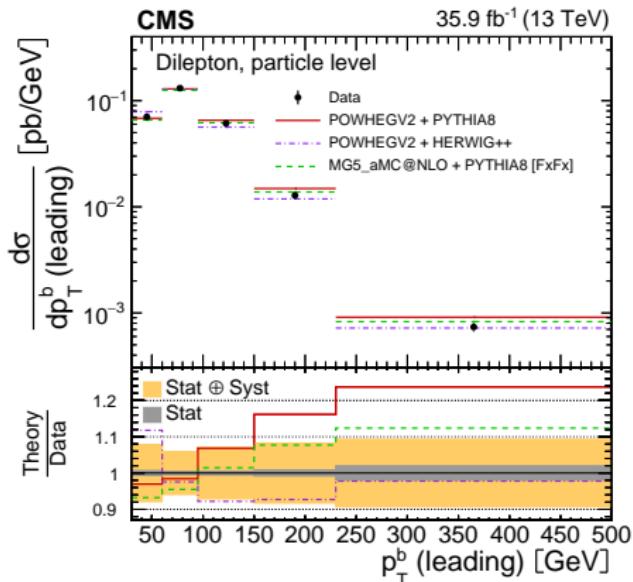


Increasing excess of data for  $N_{jets} \geq 4$  (POWHEG+PYTHIA8, HERWIG++)

# Particle level leading $p_T^b$ (absolute and normalized)

## $b$ -jet kinematic observables

- Test modelling of top quark decays
- Test parton shower hadronisation modelling



# Object Selection ATLAS - arXiv:1811.12113

## Primary vertex and Tracks

- $\geq 2$  tracks with  $p_T > 0.4$  GeV
- Largest  $|p_T|^2$  sum associated
- Quality tracks impact params:  $d_0$ ,  $z_0$

## Muons

- Consistent MS and ID good quality track match
- Medium quality,  $p_T > 25$  GeV,  $|\eta| < 2.5$
- Track  $p_T$  dependent isolation

## Electrons

- Track and calorimeter quality and match criteria,
- Tight,  $p_T > 25$  GeV,  $|\eta| < 2.47$
- Exclude  $1.37 < |\eta| < 1.52$
- Jet overlap removal  $\Delta R < 0.2$
- Track and energy  $p_T$  dependent isolation

## Jets

- anti- $k_t$  calo clustering  $\Delta R = 0.4$
- Calibrated ( $p_T, \eta$ ), in-situ correction
- $p_T > 25$  GeV,  $|\eta| < 2.5$
- $p_T > 60$  GeV,  $|\eta| < 2.4$  use JVT algo

## $b$ -jets

- Multivariate MV2c10
- Working points: 85%, 77%, 70%, 60% efficiencies for  $p_T > 20$  GeV
- Rejection: 3-35  $c$ -jets, 30-1500 light jets

## Overlap removal

- $e$  rejected if share track w/  $\mu$
- Rejected  $\Delta R = 0.2$  closest jet with  $e$
- $e$  rejected if any remaining jet within  $\Delta R = 0.4$
- Remove jet within  $\Delta R = 0.4$  of  $\mu$  if  $< 3$  tracks else remove  $\mu$