



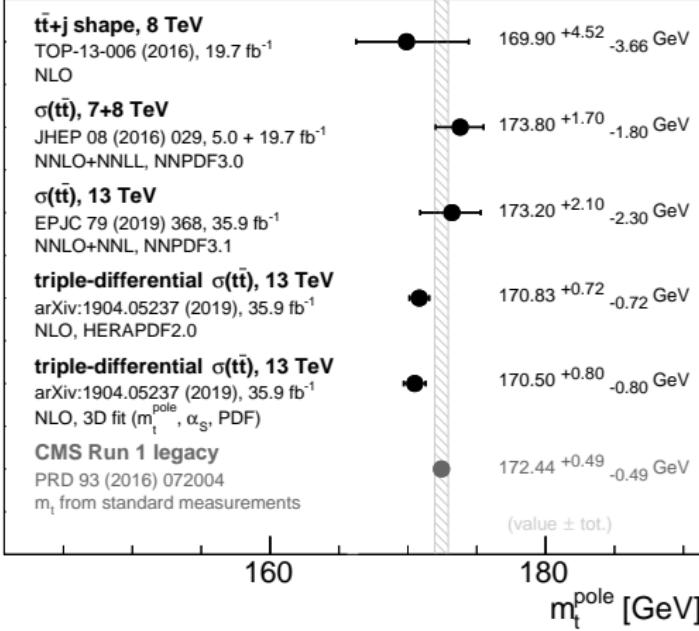
# CMS measurements of top quark pole mass

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on behalf of CMS Collaboration

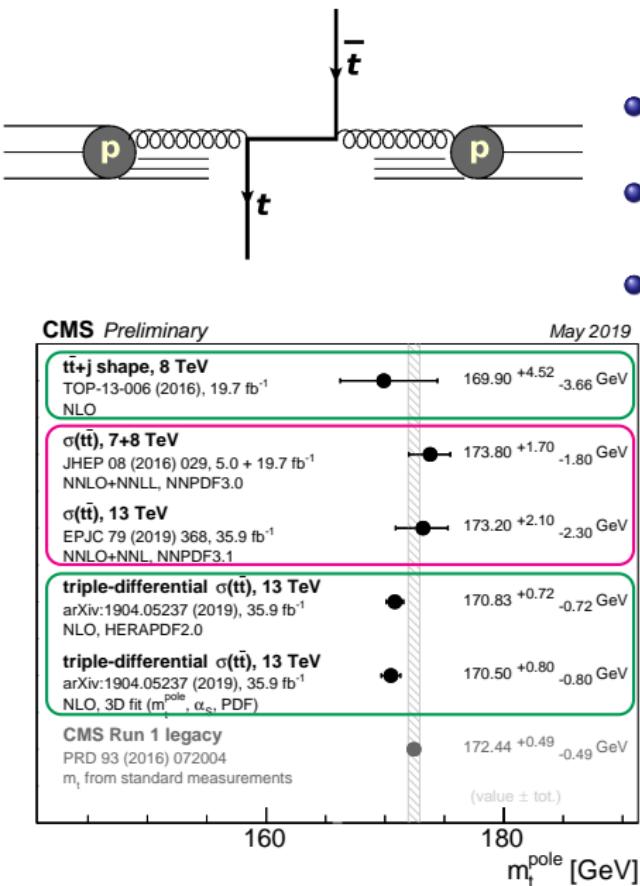
LHCTopWG Meeting, CERN  
28.05.2019

CMS Preliminary

May 2019



# Overview



- $m_t$  provides a hard scale  
→ ultimate probe of pQCD (NLO, aNNLO, NNLO, ...)
- Produced mainly via  $gg$   
→ constrain gluon PDF at high  $x$
- Production sensitive to  $\alpha_s$  and  $m_t^{\text{pole}}$   
→ constrain fundamental SM parameters

- ▶  $m_t^{\text{pole}}$  corresponds to the pole of propagator
- ▶  $m_t^{\text{pole}}$  is defined at any order of perturbation series, but carries intrinsic uncertainty  $\sim \Lambda_{\text{QCD}}$
- ▶ other mass definitions exist (e.g.  $\overline{\text{MS}}$ ) and influence convergence of perturbation series

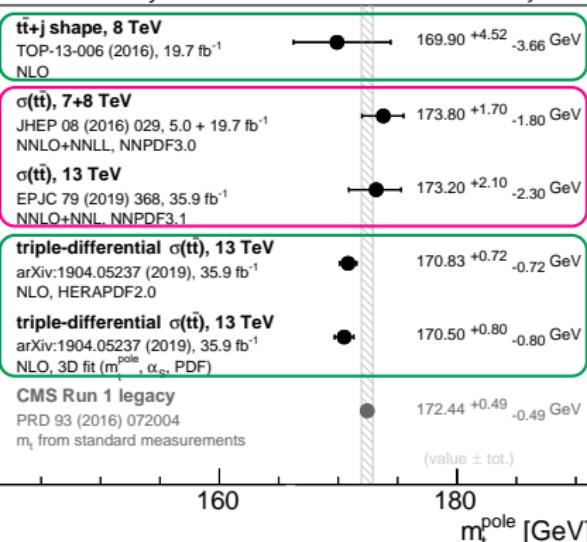
Extract  $m_t^{\text{pole}}$  from measured x-sections exploiting:

- (1) total rate:  $m_t^{\text{pole}} \nearrow \implies \sigma_{t\bar{t}} \nearrow$
- (2) threshold effects:  $m_t^{\text{pole}} \nearrow \implies \sigma_{t\bar{t}} \searrow$  at low  $M(t\bar{t})$  faster than at large  $M(t\bar{t})$
- (3) radiation effects: presence of hard jet enhances (2)

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## Definition of final state:

- inclusive in (1)
- parton or particle in (2), (3)
- if  $m_t^{\text{pole}}$  determined with PDFs and  $\alpha_s$ , particle level definition not possible because PS calculations are not interfaced to fitting tools, and PS complicate interpretation of  $\alpha_s$ , PDFs

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Available QCD calculations [at fixed order]:

- NNLO for (1)
- NLO for (2), (3)

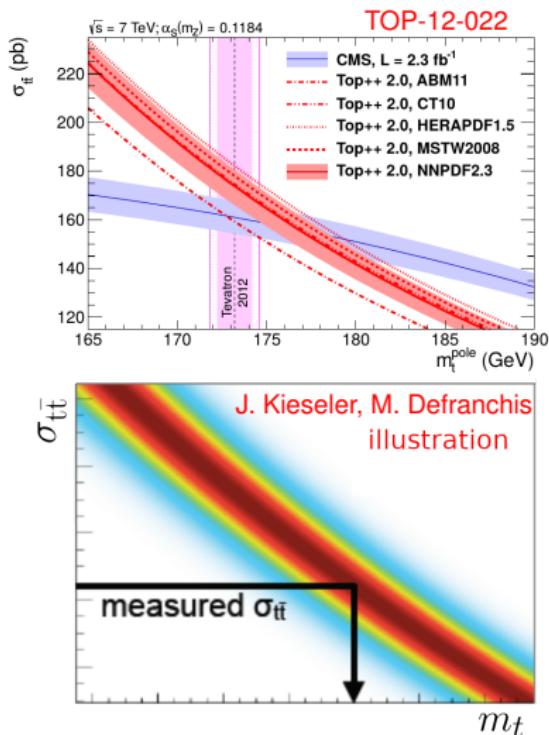
[NNLO for 1D  $M(t\bar{t})$  not yet provided publicly for  $m_t^{\text{pole}}$  scan]

## Interplay with other theory input parameters:

- strong correlation with  $\alpha_s$  and PDFs in (1):  $m_t^{\text{pole}}$  can be extracted only if  $\alpha_s$ , PDFs known
- greatly reduced in (2), (3):
  - either canceled effects (1D distributions)
  - or extra sensitivity (2D, 3D distributions)  
 $\rightarrow m_t^{\text{pole}}$  can be determined simultaneously with  $\alpha_s$  and PDFs

# Idea of simultaneous measurement of $\sigma(t\bar{t})$ and $m_t^{\text{MC}}$

- $m_t^{\text{pole}}$  can be extracted comparing measured  $\sigma(t\bar{t})$  to theoretical predictions which depend on  $m_t^{\text{pole}}$ , but ...
- ... measured  $\sigma(t\bar{t})$  depends on  $m_t^{\text{MC}}$  due to efficiency and acceptance corrections
- Dependence of measured  $\sigma(t\bar{t})$  on  $m_t^{\text{MC}}$  has to be taken into account:
  - ▶ assume  $m_t^{\text{MC}} = m_t^{\text{pole}} \pm 1 \text{ GeV}$  [TOP-12-022]
  - ▶ better: simultaneously measure  $\sigma(t\bar{t})$  and  $m_t^{\text{MC}}$  [PRL 116 (2016) 162001, TOP-17-001]



# TOP-17-001: strategy of simultaneous measurement of $\sigma(t\bar{t})$ and $m_t^{\text{MC}}$

Template fit to multi-differential distribution  
(2016 data, dilepton channel):

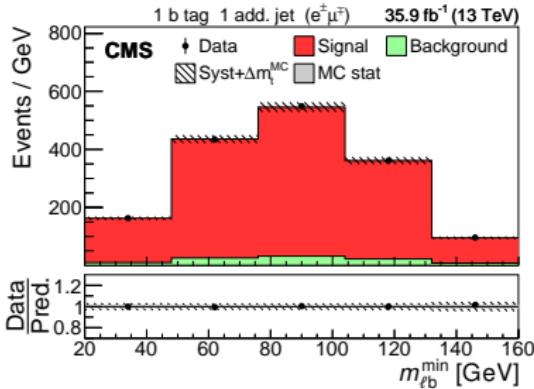
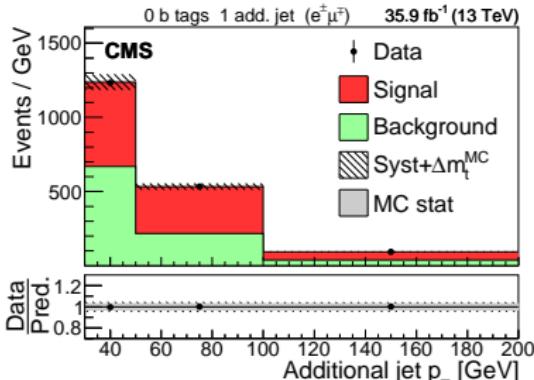
- b-tagged jet multiplicity  
→ constrain b-tagging efficiency
- non b-tagged (additional) jet multiplicity  
→ constrain model uncertainties due to QCD radiation
- $m_{lb}^{\min}$ , or  $p_T^{\text{jet}}$  (if no b-tagged jets)  
→ constrain  $m_t^{\text{MC}}$

$$\sigma_{t\bar{t}} = 815 \pm 2(\text{stat}) \pm 29(\text{syst}) \pm 20(\text{lumi}) \text{ pb}$$

main uncertainty: lumi (2.5%), lepton ID (2.5%)

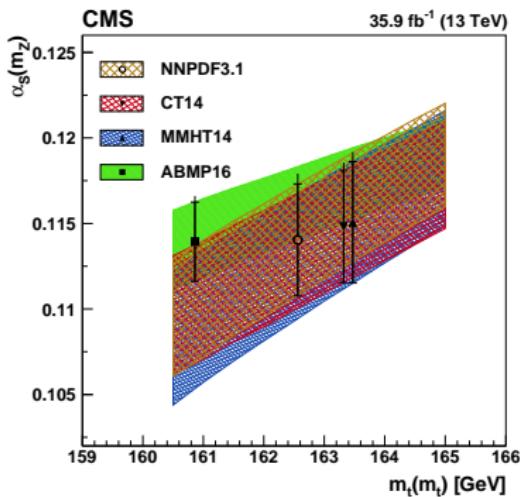
$$m_t^{\text{MC}} = 172.33 \pm 0.14(\text{stat})^{+0.66}_{-0.72}(\text{syst}) \text{ GeV}$$

main uncertainty: JES (570 MeV), MC stats (360 MeV)



# TOP-17-001: strategy of $\alpha_s$ , $m_t^{\text{pole}}$ , $m_t(m_t)$ extraction

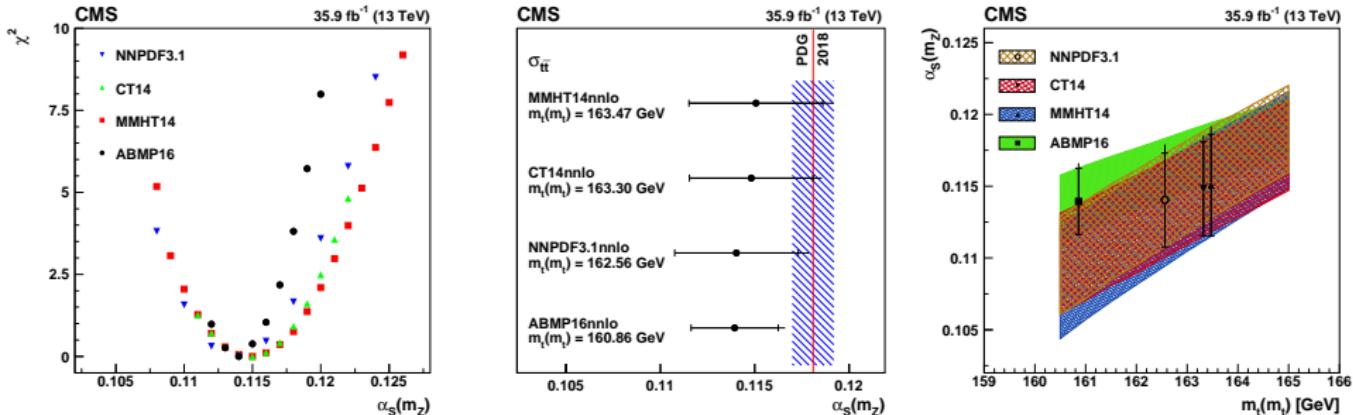
- Using NNLO [Hathor,  $m_t(m_t)$  and  $m_t^{\text{pole}}$ ] or NNLO+NNLO [TOP++,  $m_t^{\text{pole}}$ ] predictions
- Theoretical predictions
  - with growing  $\alpha_s$
  - with growing  $m_t^{\text{pole}}$  (or  $m_t(m_t)$ )
  - $\Rightarrow \alpha_s$  and  $m_t^{\text{pole}}$  are fully correlated, and only one parameter can be determined using  $\sigma_{t\bar{t}}$
  - ... in addition, predictions depend on PDFs



Strategy of data interpretation in TOP-17-001:

- (1) consider different PDF sets with values of  $m_t^{\text{pole}}$  ( $m_t(m_t)$ ) used in their determination  
→ extract  $\alpha_s$  @ NNLO
- (2) consider different PDF sets with values of  $\alpha_s$  used in their determination  
→ extract  $m_t(m_t)$  @ NNLO  
→ extract  $m_t^{\text{pole}}$  @ NNLO+NNLL

# TOP-17-001: extraction of $\alpha_s$



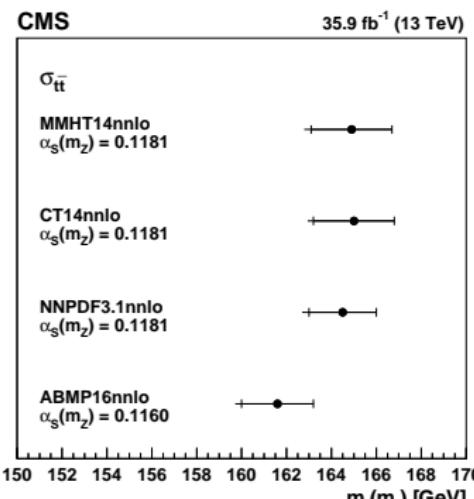
PDF set	$\alpha_S(m_Z)$
ABMP16	$0.1139 \pm 0.0023$ (fit + PDF) $^{+0.0014}_{-0.0001}$ (scale)
NNPDF3.1	$0.1140 \pm 0.0033$ (fit + PDF) $^{+0.0021}_{-0.0002}$ (scale)
CT14	$0.1148 \pm 0.0032$ (fit + PDF) $^{+0.0018}_{-0.0002}$ (scale)
MMHT14	$0.1151 \pm 0.0035$ (fit + PDF) $^{+0.0020}_{-0.0002}$ (scale)

- 2–3% precision
- currently:  
fit+PDF unc. > NNLO scale unc.

# TOP-17-001: extraction of $m_t(m_t)$ and $m_t^{\text{pole}}$

PDF set	$m_t(m_t)$ [GeV]
ABMP16	$161.6 \pm 1.6$ (fit + PDF + $\alpha_S$ ) $^{+0.1}_{-1.0}$ (scale)
NNPDF3.1	$164.5 \pm 1.6$ (fit + PDF + $\alpha_S$ ) $^{+0.1}_{-1.0}$ (scale)
CT14	$165.0 \pm 1.8$ (fit + PDF + $\alpha_S$ ) $^{+0.1}_{-1.0}$ (scale)
MMHT14	$164.9 \pm 1.8$ (fit + PDF + $\alpha_S$ ) $^{+0.1}_{-1.1}$ (scale)

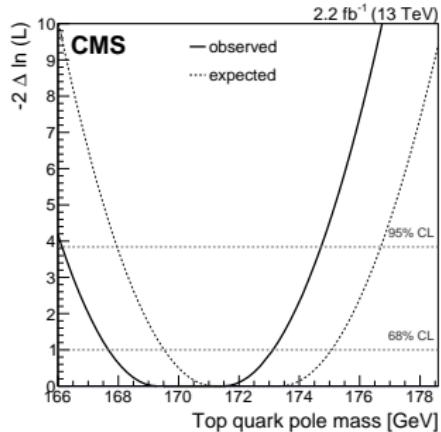
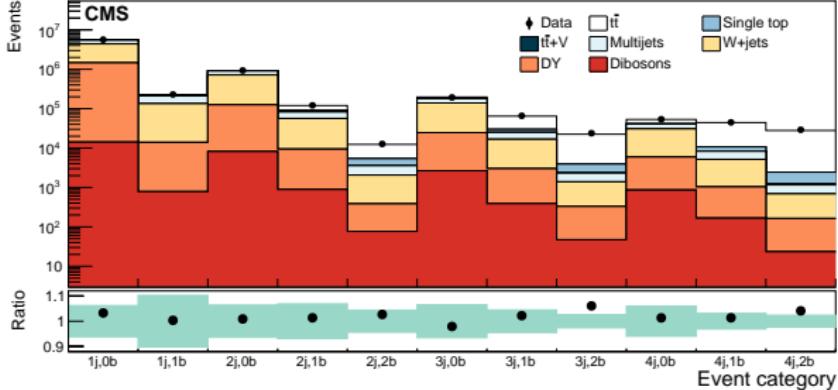
PDF set	$m_t^{\text{pole}}$ [GeV]
ABMP16	$169.9 \pm 1.8$ (fit + PDF + $\alpha_S$ ) $^{+0.8}_{-1.2}$ (scale)
NNPDF3.1	$173.2 \pm 1.9$ (fit + PDF + $\alpha_S$ ) $^{+0.9}_{-1.3}$ (scale)
CT14	$173.7 \pm 2.0$ (fit + PDF + $\alpha_S$ ) $^{+0.9}_{-1.4}$ (scale)
MMHT14	$173.6 \pm 1.9$ (fit + PDF + $\alpha_S$ ) $^{+0.9}_{-1.4}$ (scale)



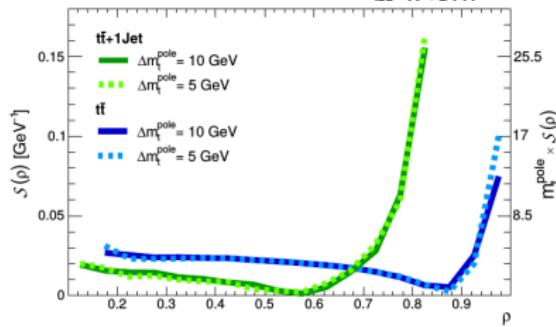
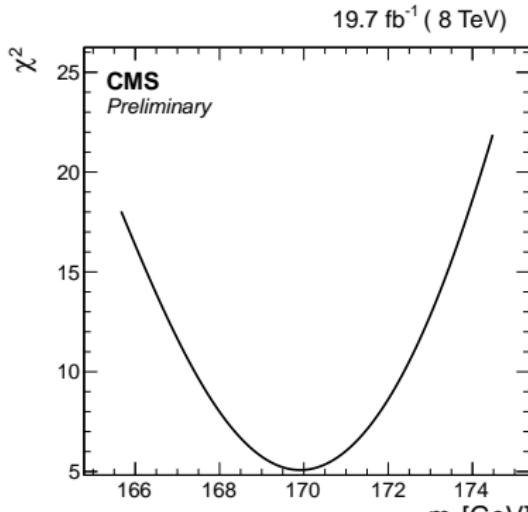
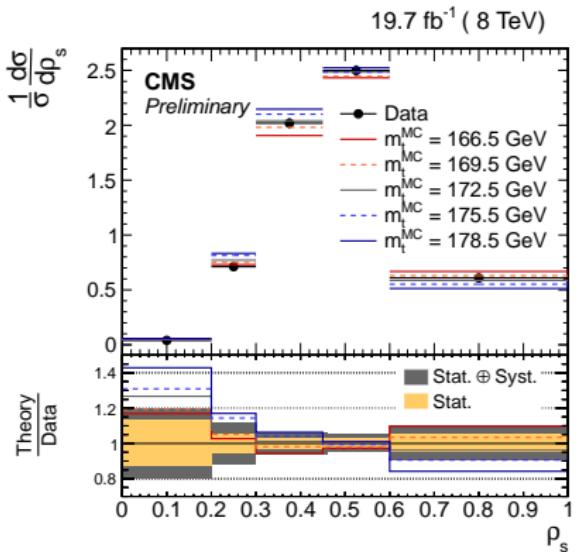
→  $\sim 1.2\%$  precision

→ larger  $m_t^{\text{pole}}$  scale uncertainties due to slower convergence of perturbative series for  $\sigma_{t\bar{t}}$   
[EPJ C74 (2014) 3167]

# TOP-16-006: measurement of $\sigma_{t\bar{t}}$ , $m_t^{\text{pole}}$



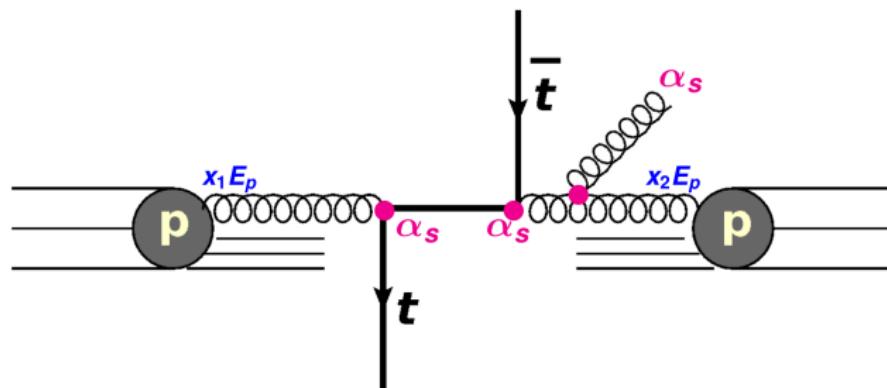
- $\sigma_{t\bar{t}}$  extracted from likelihood fit in event categories in l+jets channel using 2015 data
- $\sigma_{t\bar{t}} = 888 \pm 2(\text{stat})^{+26}_{-28}(\text{syst}) \pm 20(\text{lumi}) \text{ pb}$
- $m_t^{\text{pole}} = 170.6 \pm 2.7 \text{ GeV}$



- $\rho_s = \frac{2m_0}{s_{t\bar{t}+\text{jet}}}$ ,  $s_{t\bar{t}+\text{jet}} = M(t\bar{t}j)$ : effectively  $M(t\bar{t}j)$
- using Run-1 data of 19.7 fb<sup>-1</sup> and dilepton channel
- dominant systematic uncertainties: MadGraph scale variations and PS matching [BACKUP]
- fit using POWHEG+PYTHIA simulation:

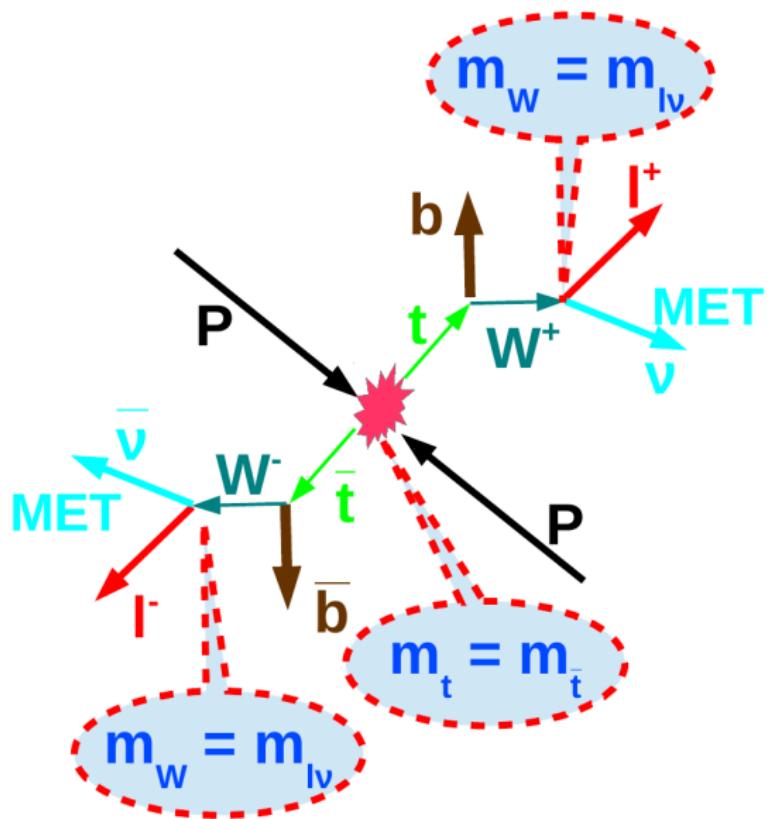
$$m_t^{\text{pole}} = 169.9 \pm 1.1(\text{stat}) + 2.5^{+3.6}_{-3.1}(\text{syst})^{+3.6}_{-1.6}(\text{theo}) \text{ GeV}$$

## TOP-18-004: idea of 3D measurement



Final state explored to get ultimate constraints on theory parameters:

- $x_1 x_2 = M(t\bar{t})^2/s$ ,  $x_1/x_2 = e^{y(t\bar{t})}$   
→  $M(t\bar{t})$  and  $y(t\bar{t})$  constrain PDFs
- $\sigma(t\bar{t} + \text{jet})/\sigma(t\bar{t}) \propto \alpha_s$   
→  $N_{\text{jet}}$  constrains  $\alpha_s$
- $M(t\bar{t})^{\min} = 2m_t^{\text{pole}}$   
→  $M(t\bar{t})$  constrains  $m_t^{\text{pole}}$
- $g$  and  $\alpha_s$  interplay via QCD evolution in PDF fits  
→ constraining PDFs  $\Leftrightarrow$  constraining  $\alpha_s$



- Measured input: leptons, jets, MET
- Unknowns:  $\bar{p}_\nu, \bar{p}_{\bar{\nu}}$  (6)
- Constraints:
  - $m_t, m_{\bar{t}}$  (2)
  - $m_{W^+}, m_{W^-}$  (2)
  - $(\bar{p}_\nu + \bar{p}_{\bar{\nu}})_T = \text{MET}$  (2)

## Two variants:

### (1) Full reconstruction:

- recover  $t, \bar{t}$
- use all constraints

### (2) Loose reconstruction:

- recover  $t\bar{t}$  only
- $m_t$  constraints not used:  
 $\sigma \neq \sigma(m_t^{\text{MC}})$   
 $\rightarrow$  reliable to extract  $m_t^{\text{pole}}$   
**crucial point for  $m_t^{\text{pole}}$  measurement! [BACKUP]**

## Data interpretation consists of two parts:

(1) comparison theory vs data using external PDF sets:

- ▶ extracting  $\alpha_s$  keeping  $m_t^{\text{pole}}$  fixed
- ▶ extracting  $m_t^{\text{pole}}$  keeping  $\alpha_s$  fixed

→ this presents  $\alpha_s$ ,  $m_t^{\text{pole}}$  extraction from  $t\bar{t}$  data only

(2) simultaneous fit of PDFs,  $\alpha_s$  and  $m_t^{\text{pole}}$  using  $t\bar{t}$  and HERA DIS:

→ this presents fully consistent extraction of  $\alpha_s$ ,  $m_t^{\text{pole}}$  and PDFs, but using also HERA data

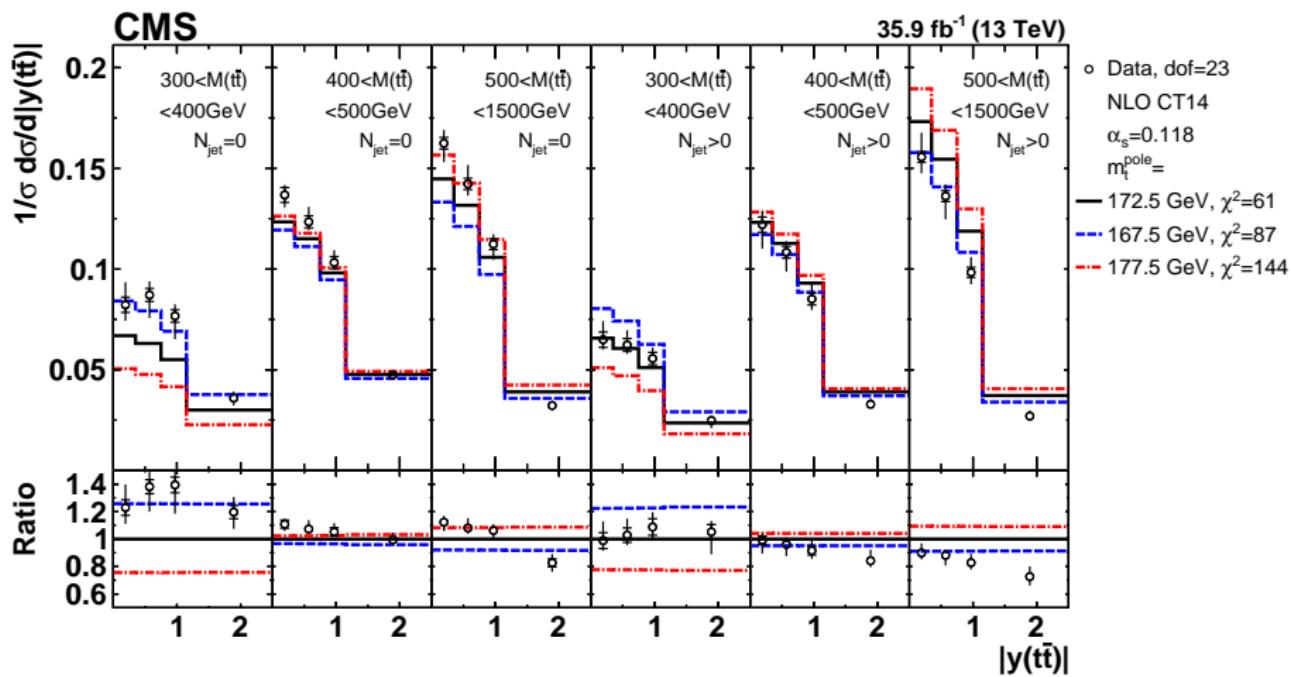
→ provides baseline for future global fits

## NLO calculations:

[MadGraph5\_aMC@NLO + aMCfast + ApollGrid + xFitter]

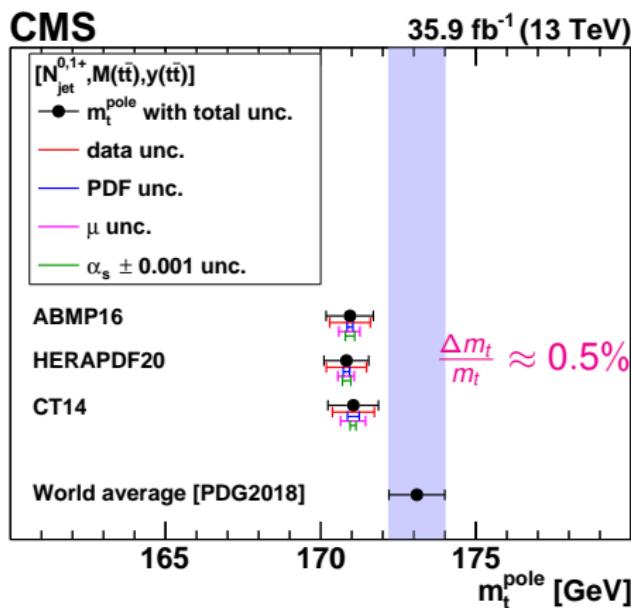
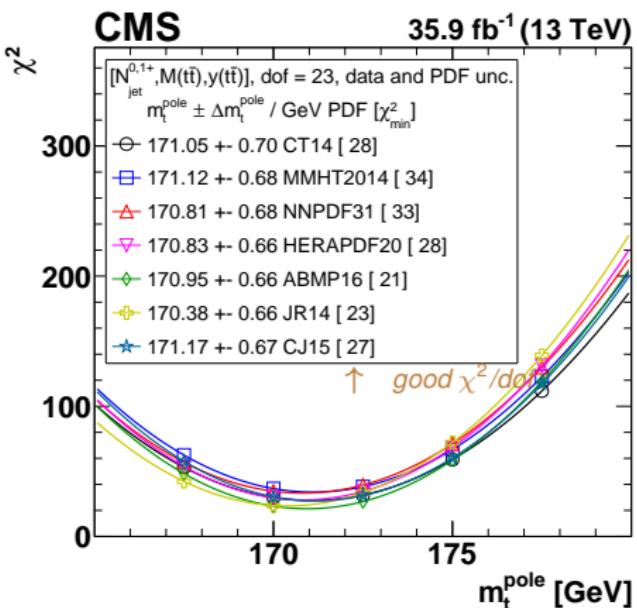
- For  $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ , using NLO for  $t\bar{t}$  of  $O(\alpha_s^3)$  and NLO for  $t\bar{t} + 1\text{jet}$  of  $O(\alpha_s^4)$ :
  - (1)  $\sigma^{\text{NLO}}(N_{\text{jet}} = 0) = \sigma^{\text{NLO}}(t\bar{t})[O(\alpha_s^3)] - \sigma^{\text{NLO}}(t\bar{t} + 1\text{jet})[O(\alpha_s^4)]$
  - (2)  $\sigma^{\text{NLO}}(N_{\text{jet}} > 0) = \sigma^{\text{NLO}}(t\bar{t} + 1\text{jet})[O(\alpha_s^4)]$
  - ▶ equivalent to comparing
    - ★  $\sigma^{\text{NLO}}(t\bar{t})[O(\alpha_s^3)]$  vs measured  $\sigma(t\bar{t})$  (just summing two equations above)
    - ★  $\sigma^{\text{NLO}}(t\bar{t} + 1\text{jet})[O(\alpha_s^4)]$  vs measured  $\sigma(t\bar{t} + 1\text{jet})$
    - ... (recall dijet and trijet measurements and  $R_{3/2}$ )
  - ▶ same for  $[N_{\text{jet}}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$ : using  $O(\alpha_s^3)$ ,  $O(\alpha_s^4)$  and  $O(\alpha_s^5)$  NLO calculations
- $\mu_r = \mu_f = H'/2$ ,  $H' = \sum_i m_{T,i}$  where the sum runs over all final-state partons ( $t, \bar{t}$  and up to three light partons in the  $t\bar{t} + 2$  jets calculations) and  $m_T = \sqrt{m^2 + p_T^2}$ . Uncertainties:
  - ▶  $\mu_r, \mu_f$  are varied by factor 2 (6 variations in total) coherently in all bins
  - ▶ alternative functional form  $\mu_r = \mu_f = H/2$ ,  $H = m_{T,t} + m_{T,\bar{t}}$   
→ mimics 'decorrelation' of scales, in particular for different bins of  $N_{\text{jet}}$
  - ▶ treated as external uncertainties: no nuisance parameters, no constraints by data
- NLO calculations are multiplied with non-perturbative corrections (< 5%) from parton to particle jet level (BACKUP)
- no NNLO corrections available for either of measured 2D or 3D distributions :-)

# TOP-18-004 [ $N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})$ ] compared to NLO pred. with diff. $m_t^{\text{pole}}$



- $m_t$  sensitivity comes from  $M(t\bar{t})$ , mainly 1st bin
- this method differs from extracting  $m_t^{\text{pole}}$  from total  $\sigma_{t\bar{t}}$ , and is similar to extracting  $m_t^{\text{pole}}$  from  $t\bar{t}j$  diff. x-section [EPJ C73 (2013) 2438, CMS-PAS-TOP-13-006, JHEP 1510 (2015) 121, 1905.02302]
- previous determination using this  $M(t\bar{t})$ : prelim. D0 results [FERMILAB-CONF-16-383-PPD]
- same sensitivity plots for  $\alpha_s$  and PDFs in BACKUP

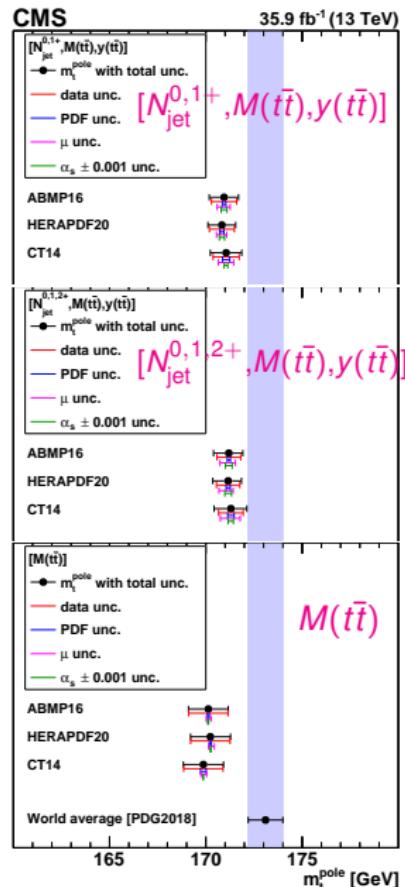
# TOP-18-004 extraction of $m_t^{\text{pole}}$ from $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$



- used  $\alpha_s$  from each PDF set ( $\alpha_s = 0.118$  in CT and HERAPDF,  $\alpha_s = 0.119$  in ABMP)
- precise determination of  $m_t^{\text{pole}}$  is possible using these data
- no significant dependence on PDF set
- these are our nominal observables, while several cross checks were done [next page]

# TOP-18-004 Cross checks

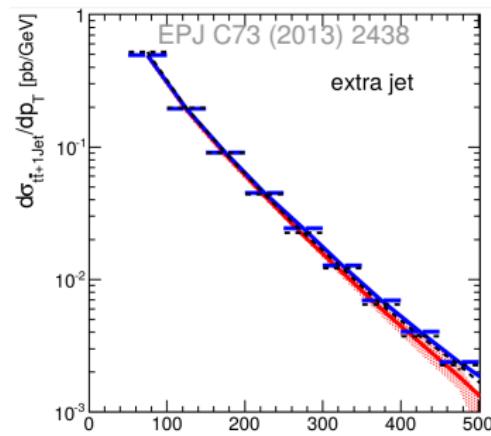
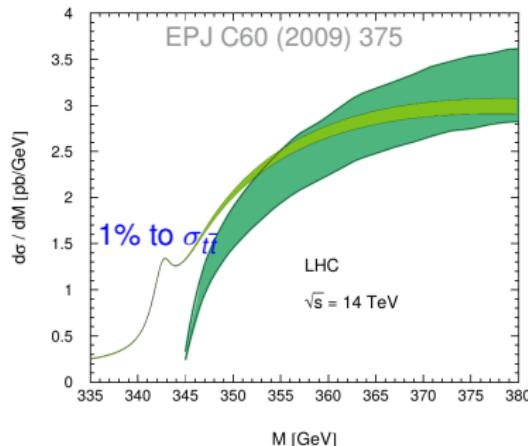
- using  $[N_{\text{jet}}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$
- using single-differential  $N_{\text{jet}}$ ,  $M(t\bar{t})$  or  $y(t\bar{t})$  cross sections
- using  $[p_T(t\bar{t}), M(t\bar{t}), y(t\bar{t})]$  cross sections with 2  $p_T(t\bar{t})$  bins
- using unnormalised cross sections
- consistent results obtained in all cross checks
- in this analysis, observables ( $\frac{1}{\sigma} \frac{d\sigma}{d\ldots}$ ) have been chosen to have **maximum sensitivity to QCD parameters and minimum experimental and scale uncertainties**



# TOP-18-004 Remarks on limitations in NLO theory calculations

NLO is the only available theory publicly available today, but there are limitations:

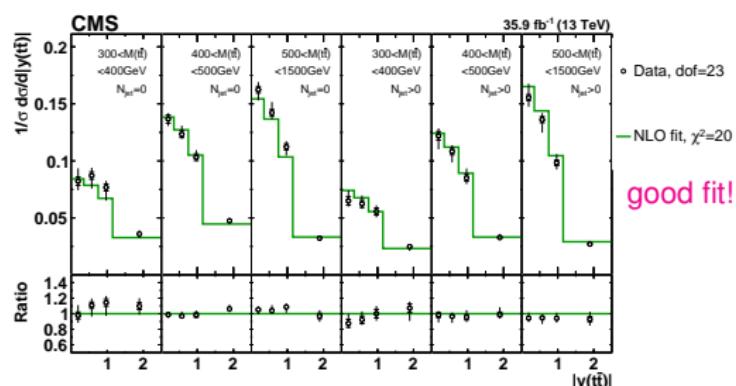
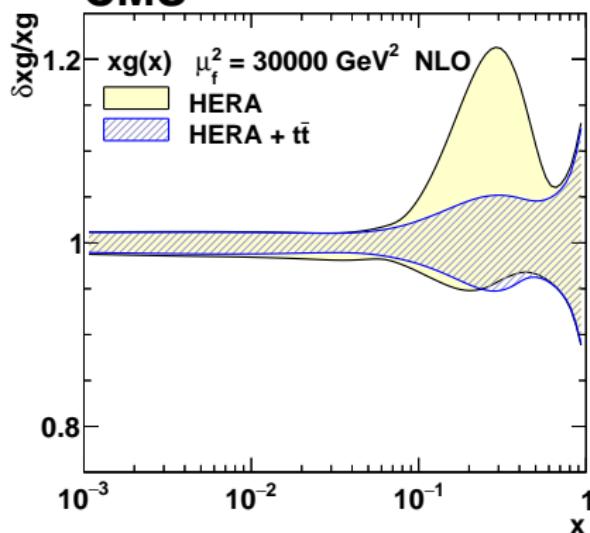
- impact of missing threshold resummation is  $\Delta m_t \sim 0.7$  GeV [Eur.Phys.J. C60 (2009) 375]
- impact of missing FSR resummation is  $\Delta m_t \sim 0.5$  GeV [Eur. Phys. J. C73 (2013) 2438]
  - ▶ in general, good agreement between NLO and NLO+PS [Fig. 1 in Eur. Phys. J. C73 (2013) 2438]
- EW corrections could be a few % near threshold [Phys. Rev. D91 (2015) 014020] [JHEP10 (2017) 186]
- **NNLO QCD corrections are needed**  
[NLO uncertainties are estimated by scale variations only: estimations of other numbers are too imprecise at the moment]



# TOP-18-004 Simultaneous PDF + $\alpha_s$ + $m_t^{\text{pole}}$ fit: results

- followed standard approach: using HERA DIS data only, or HERA +  $t\bar{t}$  data to demonstrate added value from  $t\bar{t}$  on PDF and  $\alpha_s$  determination
- settings follow HERAPDF2.0 fit (very similar to TOP-14-013), use xFitter-2.0.0
- input data: combined HERA DIS [1506.06042] +  $t\bar{t}$  (further details in BACKUP)

CMS



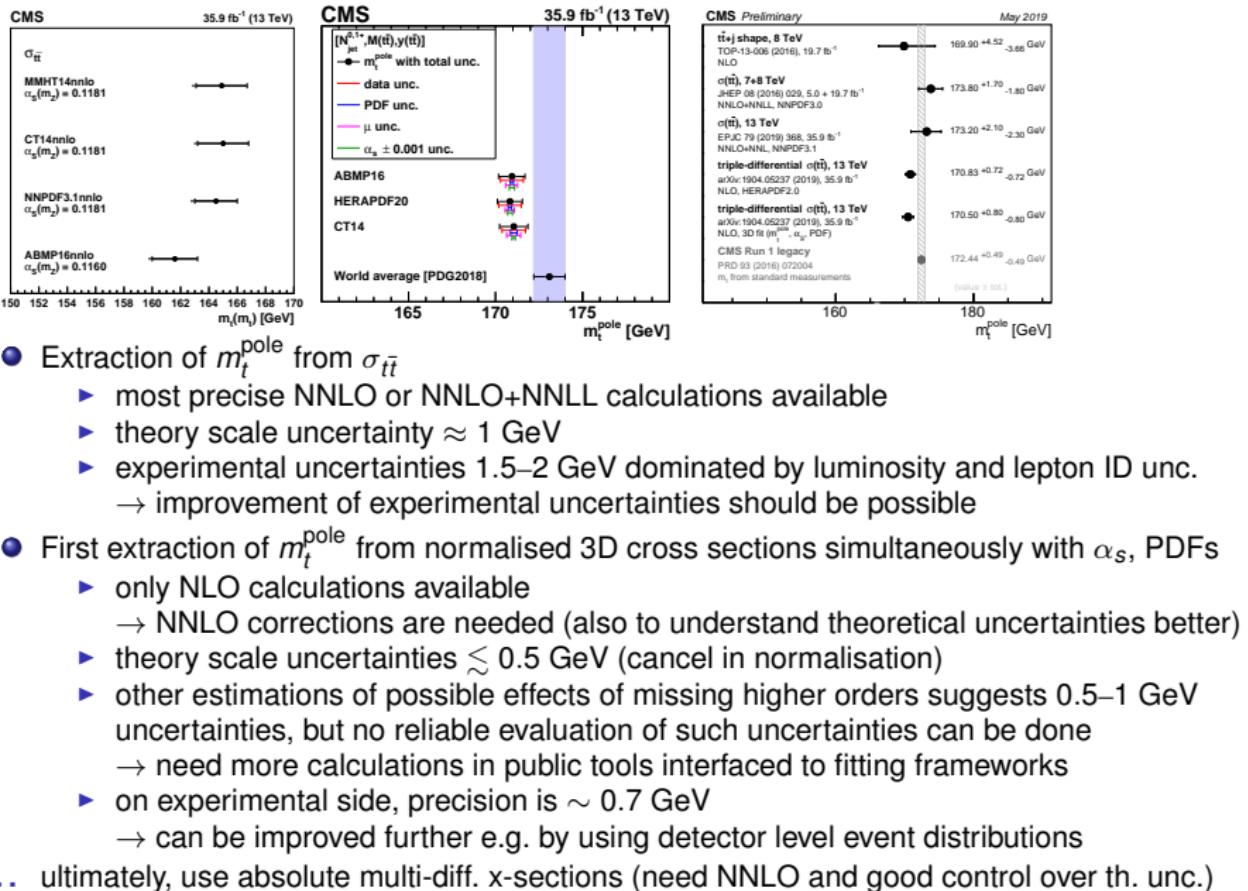
$$\alpha_s(M_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{mod})^{+0.0008}_{-0.0001}(\text{par})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit})^{+0.1}_{-0.1}(\text{mod})^{+0.0}_{-0.1}(\text{par})^{+0.3}_{-0.3}(\text{scale}) \text{ GeV} = 170.5 \pm 0.8(\text{total}) \text{ GeV}$$

## TOP-18-004: discussion of a few comments received recently

- The analysis uses exclusive  $N_{\text{jet}}$  bins, while jet veto introduces logarithmic corrections not accounted by fixed order predictions
  - No exclusive bins are used, but only inclusive  $\sigma(t\bar{t})$ ,  $\sigma(t\bar{t} + 1\text{jet})$ ,  $\sigma(t\bar{t} + 2\text{jets})$  (page 13). We will try to make a better description in the revised paper.
- Coherent scale variations in the predictions with different jet multiplicities may underestimate missing higher order effects
  - When estimating scale uncertainties, we adopt the alternative scale definition which specifically probes hard jets (page 13) and mimics incoherent scale variations.
- Was anything else done besides standard scale variation in order to estimate the errors?
  - Several consistency checks were done using different observables (page 16) and described in the paper. Consistent results were obtained.
  - Several effects were estimated (page 17) and discussed in the paper, though the estimations are too imprecise to be assigned as uncertainties (they are consistent with scale unc.).
- To estimate NNLO effects, one has to extract the mass using the POWHEG output at the shower level before hadronization, applied to data unfolded at the particle level
  - The full PDF+ $\alpha_s + m_t^{\text{pole}}$  fit with PS is not possible using existing tools. If done for  $m_t^{\text{pole}}$  only:
    - ▶ would not it be a MC mass with different uncertainties, given that one could tune PS to obtain a different result?
    - ▶ we use bins with different jet multiplicities, while POWHEG inclusive  $t\bar{t}$  does not have NLO accuracy for  $t\bar{t} + \text{jets}$ . Some multijet merging algorithm has to be used [→ extra unc.]?
    - ▶ somehow 'before hadronization' and 'particle level' sounds as contradiction

# Summary

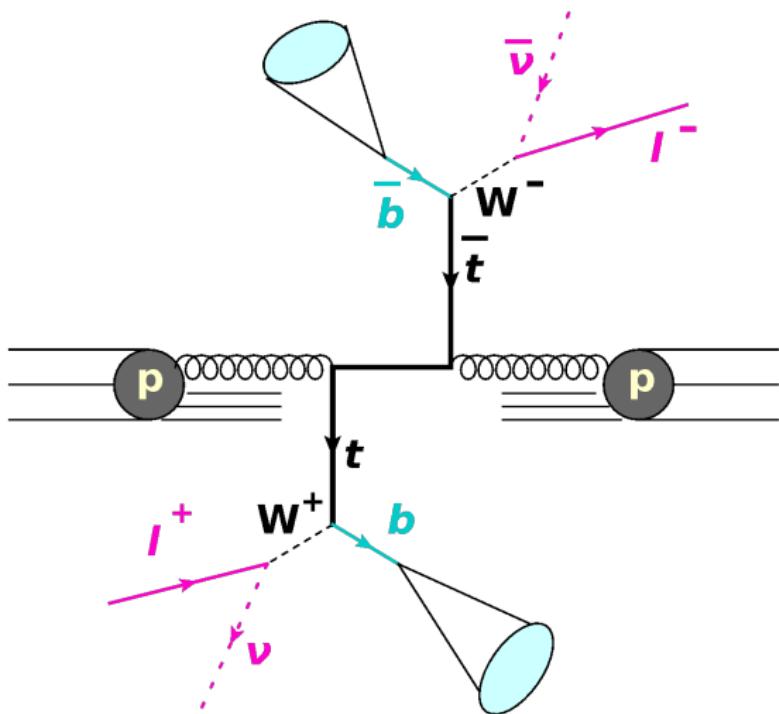


# BACKUP

# CMS-PAS-TOP-13-006 Systematic uncertainties

Source	$\Delta m_t$ [GeV]
POWHEG $t\bar{t}$ +jet modelling	-1.6 +3.6
Jet-Parton Matching	-0.1 +1.6
$Q^2$ Scale	+1.0 -2.8
ME/Showering	$\pm 0.4$
Color Reconnection	$\pm 0.7$
Underlying Event	$\pm 0.3$
PDF	+0.9 -0.1
Background	$\pm 1.0$
Jet Energy Scale	$\pm 0.1$
Jet Energy Resolution	$\pm 0.1$
Pile-Up	$\pm 0.3$
Trigger Eff.	< 0.1
Kinematic Reconstruction	< 0.1
Lepton Eff.	$\pm 0.1$
B-Tagging	$\pm 0.3$
Syst. uncertainty	+2.5 -3.1
Stat. uncertainty	$\pm 1.1$

# TOP-18-004 Event selection



**Follows 1D measurement:**  
CMS-TOP-17-014 (arXiv:1811.06625)

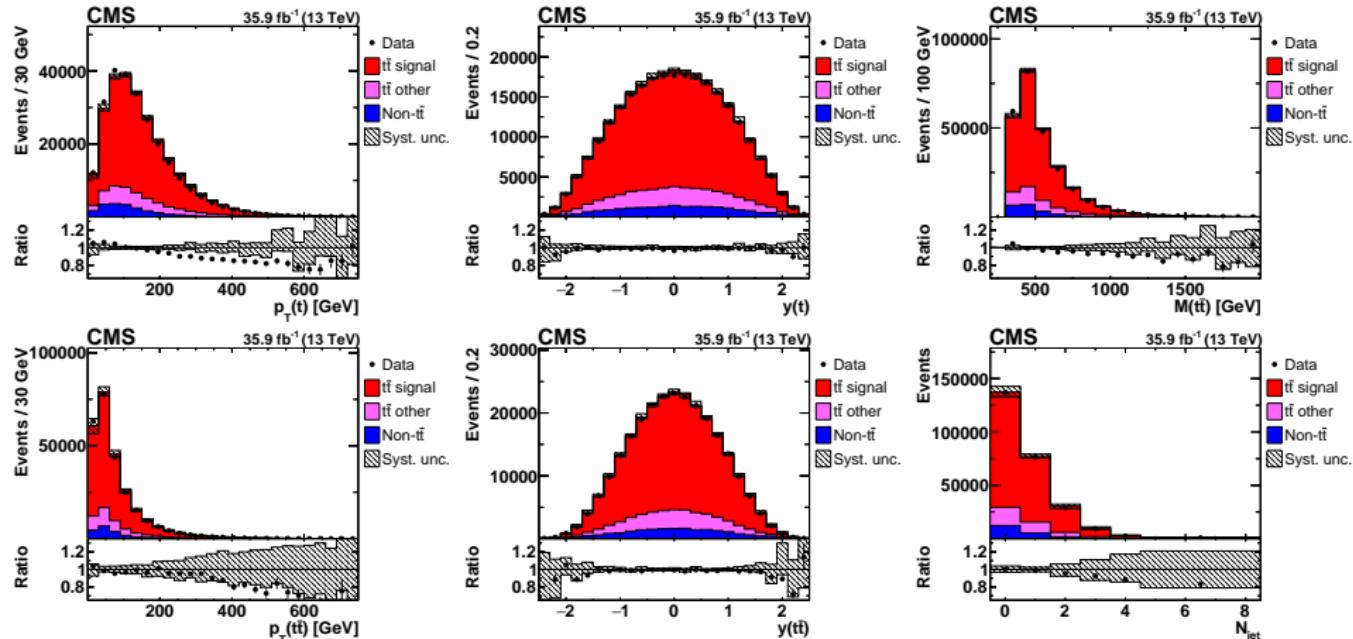
- **Leptons:**

- ▶ 2 isolated  $l^\pm/\bar{l}^\mp$
- ▶  $p_T > 20(25)$  GeV
- ▶  $|\eta| < 2.4$

- **Jets:**

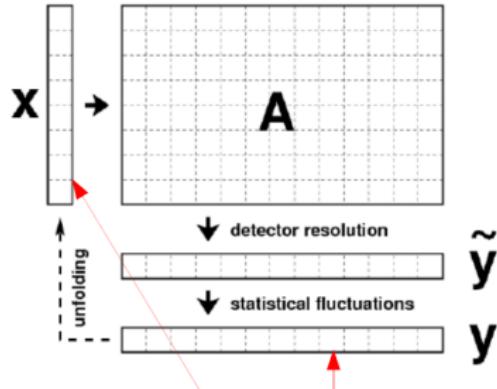
- ▶ at least 2 jets
- ▶  $p_T > 30$  GeV
- ▶  $|\eta| < 2.4$
- ▶ at least 1  $b$ -tagged

# TOP-18-004 Kinematic distributions



- $t\bar{t}$  signal MC: PowHEGv2 + PYTHIA8 (details in BACKUP)
- Overall good description of data within uncertainties
- Central MC predictions for  $p_T(t)$ ,  $p_T(t\bar{t})$ ,  $M(t\bar{t})$ ,  $N_{\text{jet}}$  are softer than data

# TOP-18-004 Unfolding



TUnfold [JINST 7 (2012) T10003]

$\chi^2$  minimisation with regularisation  
( $\approx 1\%$ )

2d distributions are mapped to 1d arrays

$$\chi^2 = (Y - AX)^T V_Y^{-1} (Y - AX) + \tau^2 (X - X_0)^T L^T L (X - X_0)$$

reco. data      unfolded distribution      regularization strength      regularization conditions (second derivative)

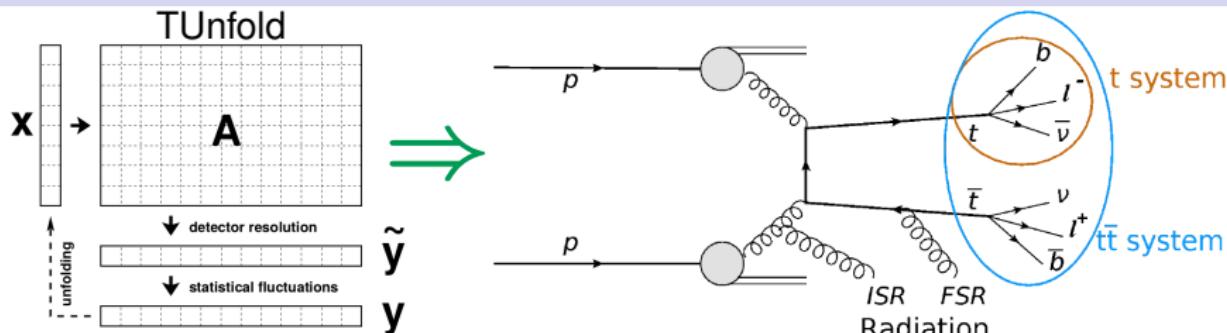
migration probability matrix      stat. errors of reco.      gen. distribution

$$Y = N_{\text{measured}} - N_{\text{Background}}$$

For each  $\Delta a^i$ :

$$\left( \frac{1}{\sigma} \frac{d\sigma}{db} \right)^{ij} = \frac{1}{\sigma} \cdot \frac{X^{ij}}{BR \cdot L \cdot \Delta b^j}$$

# TOP-18-004 Overview of measured cross sections



- **$t$  production:**
  - ▶  $[y(t), p_T(t)]$ : most simple
- **$t\bar{t}$  production:**
  - ▶  $[M(t\bar{t}), y(t\bar{t})]$ : most sensitive to PDFs (at LO  $x_{1,2} = \sqrt{\frac{M(t\bar{t})}{s}} e^{\pm y(t\bar{t})}$ )
  - ▶  $[M(t\bar{t}), p_T(t\bar{t})]$ : sensitive to radiation (at LO  $p_T(t\bar{t}) \equiv 0$ )
- **$t, t\bar{t}$  mixed:**
  - ▶  $[M(t\bar{t}), y(t\bar{t})]$ : sensitive to PDFs (at LO  $y(t\bar{t}) = (y(t) + y(\bar{t})) / 2$ )
  - ▶  $[M(t\bar{t}), \Delta\phi(t, \bar{t})]$ : sensitive to radiation (at LO  $\Delta\phi(t\bar{t}) \equiv \pi$ )
  - ▶  $[M(t\bar{t}), \Delta\eta(t, \bar{t})]$ : correlated with  $p_T(t)$  and may shed light on  $p_T(t)$  problem
  - ▶  $[M(t\bar{t}), p_T(t)]$ : may shed further light on  $p_T(t)$  problem
- **NEW  $t\bar{t}$  production with extra jets:**
  - ▶  $[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ : sensitive to  $\alpha_s$ ,  $m_t^{\text{pole}}$  and PDFs (nominal extraction)
  - ▶  $[N_{jet}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$ : sensitive to  $\alpha_s$ ,  $m_t^{\text{pole}}$  and PDFs (cross check)

# TOP-18-004 Systematic uncertainties

## Experimental uncertainties:

- JES (splitted in sources, also propagated to MET)
- JER
- b-tagging SFs
- lepton ID/ISO SFs
- triggers SFs
- pileup reweighting
- non- $t\bar{t}$  background normalisation varied by 30%
- lumi and branching ratios cancel for normalised cross section

## Model uncertainties:

- based on weights:
  - ▶ ME scales (envelope of 6 variations dominated by simultaneous  $\mu_r, \mu_f$  var.)
  - ▶ PDFs and  $\alpha_s$  (CT14 eigenvectors)
  - ▶ b-quark fragmentation (envelope of varied Bowler-Lund and Peterson funct.)
  - ▶ b-hadron branching ratios
- based on independent samples:
  - ▶  $m_t \pm 1$  GeV (using samples with  $\pm 3$  GeV → rescaled by 1/3)
  - ▶  $0.996m_t < h_{\text{damp}} < 2.239m_t$
  - ▶ ISR  $\mu$ , FSR  $\mu$  variations (latter rescaled by  $1/\sqrt{2}$ )
  - ▶ color reconnection: envelope of 3 samples with different tunes
  - ▶ underlying event tune variation

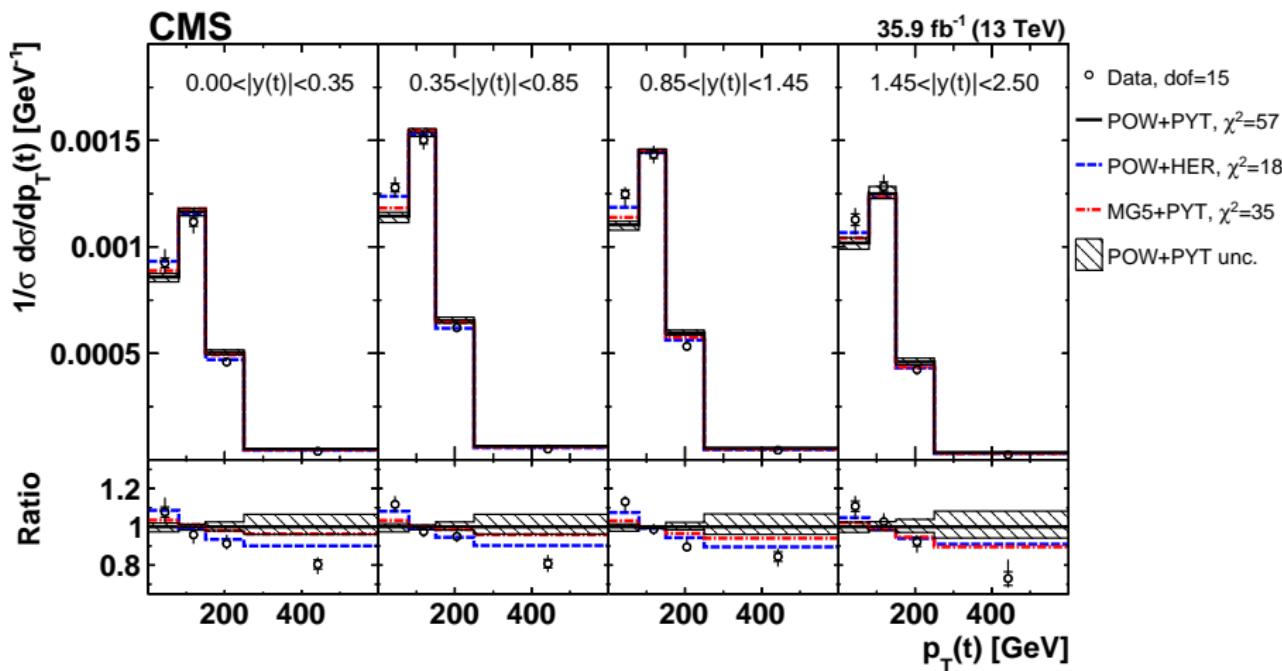
## TOP-18-004 MC predictions

- POWHEGv2 + PYTHIA8
  - ▶  $h_{\text{damp}} = 1.581 m_t$
  - ▶  $m_t = 172.5 \text{ GeV}$
  - ▶ CUETP8M2T4 tune [CMS-PAS-TOP-16-021]
- POWHEGv2 + HERWIG++
  - ▶  $h_{\text{damp}} = 1.581 m_t$
  - ▶  $m_t = 172.5 \text{ GeV}$
  - ▶ EE5C tune [JHEP10 (2013) 113]
- MG5\_AMC@NLO + PYTHIA8
  - ▶ FxFx prescription for  $t\bar{t}$ ,  $t\bar{t} + 1 \text{ jet}$ ,  $t\bar{t} + 2 \text{ jets}$  @ NLO [JHEP12 (2012) 061]
  - ▶  $m_t = 172.5 \text{ GeV}$
  - ▶ CUETP8M2T4 tune [CMS-PAS-TOP-16-021]

## TOP-18-004 overview of results

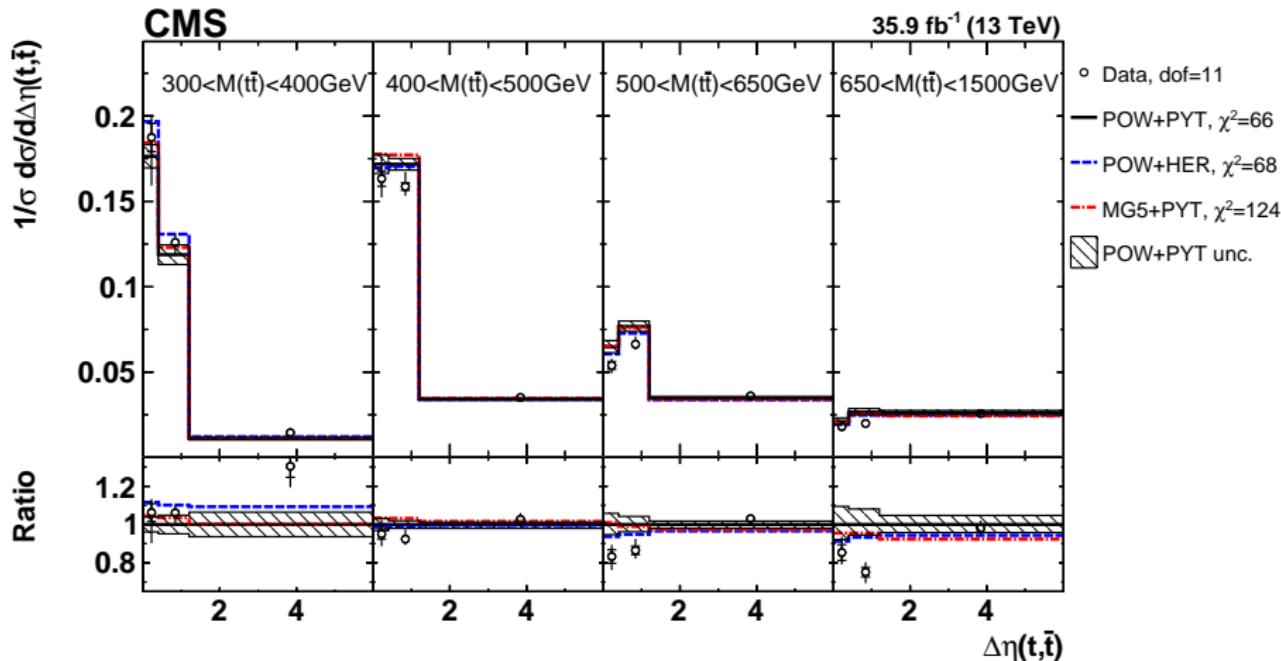
- Measured seven 2D and two 3D cross sections
- All cross sections are provided at parton level for  $t\bar{t}$  (before  $t$  decay) but particle level for jets
  - ▶ corrections particle → parton level (e.g. for FO predictions) derived from MC ( $\lesssim 5\%$ )
- 2D and 3D cross sections are compared to MC predictions (details in BACKUP)
  - ▶ POWHEGv2 + PYTHIA8, CUETP8M2T4 ('POW-PYT')
  - ▶ POWHEGv2 + HERWIG++, EE5C ('POW-HER')
  - ▶ MG5\_AMC@NLO + PYTHIA8 [FxFx], CUETP8M2T4 ('FXFX-PYT')
- Each comparison is quantified by  $\chi^2$  which takes into account data statistical and systematical unc. (list in BACKUP), their correlation, and cross section normalisation
  - ▶ resulted  $\chi^2$  are translated into  $p$ -values and compared on one plot  
(caveat: no theory uncertainties →  $p$ -value have limited value)
- Further, 3D cross sections are exploited for  $\alpha_s + m_t$  +PDF extraction using NLO (highest order available for  $t\bar{t}$  + jets) calculations
  - ▶ sensitivity to PDFs from  $M(t\bar{t}), y(t\bar{t})$  ( $x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp [\pm y(t\bar{t})]$ )
  - ▶ sensitivity to  $\alpha_s$  from  $N_{jet}$  and  $M(t\bar{t}), y(t\bar{t})$  (PDFs)
  - ▶ sensitivity to  $m_t$  from  $M(t\bar{t})$  via threshold and cone effects

# TOP-18-004 2D x-sections [ $y(t), p_T(t)$ ]



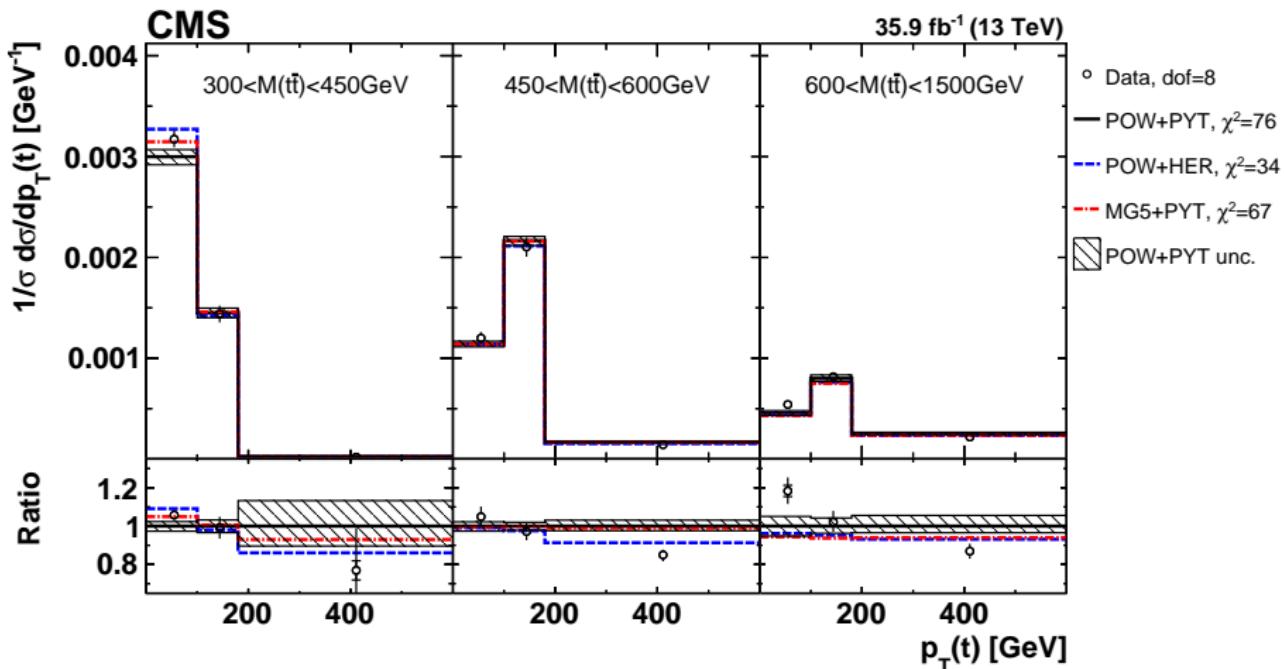
- 'POW-PYT' and 'FXFX-PYT' predict softer  $p_T(t)$  in entire  $y(t)$  range
- better description by 'POW-HER'

# TOP-18-004 2D cross sections [ $M(t\bar{t})$ , $\Delta\eta(t,\bar{t})$ ]



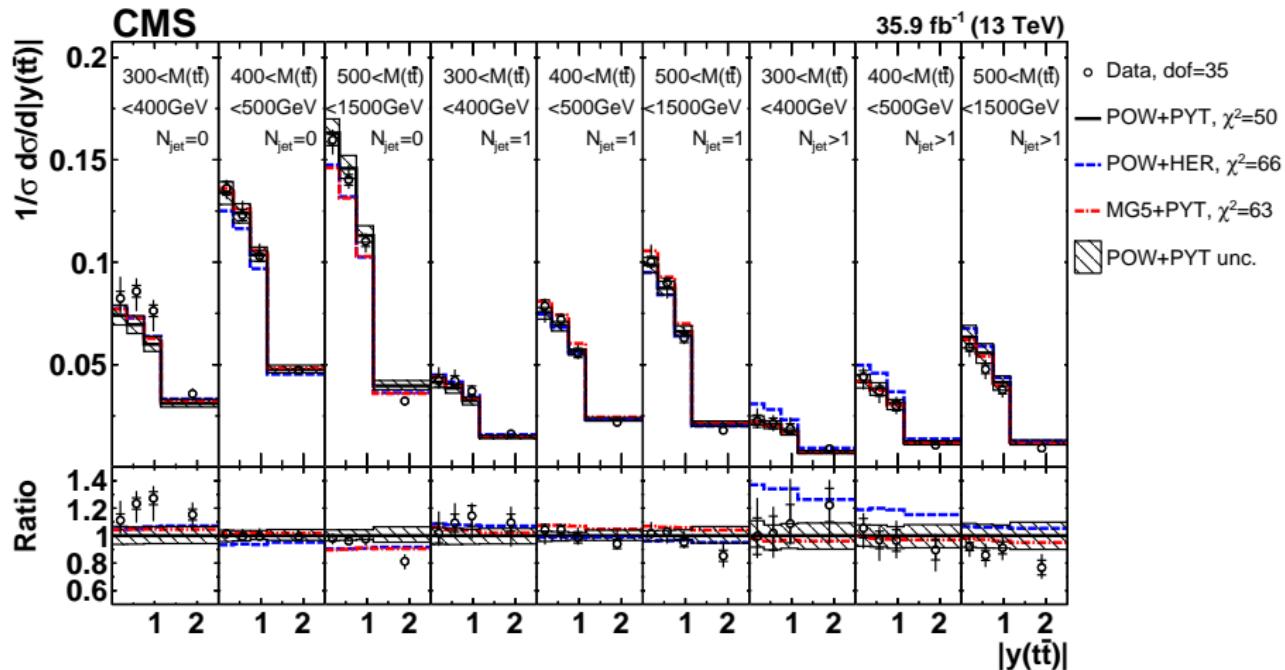
- predicted  $\Delta\eta(t, \bar{t})$  are too low at medium and high  $M(t\bar{t})$
- at large  $M(t\bar{t})$ ,  $t$  and  $\bar{t}$  have a larger  $\eta$  separation than in MC: correlated with a lower  $p_T(t)$
- bad description by all MC central predictions, strongest disagreement for 'FXFX-PYT'

# TOP-18-004 2D cross sections [ $M(t\bar{t}), p_T(t)$ ]



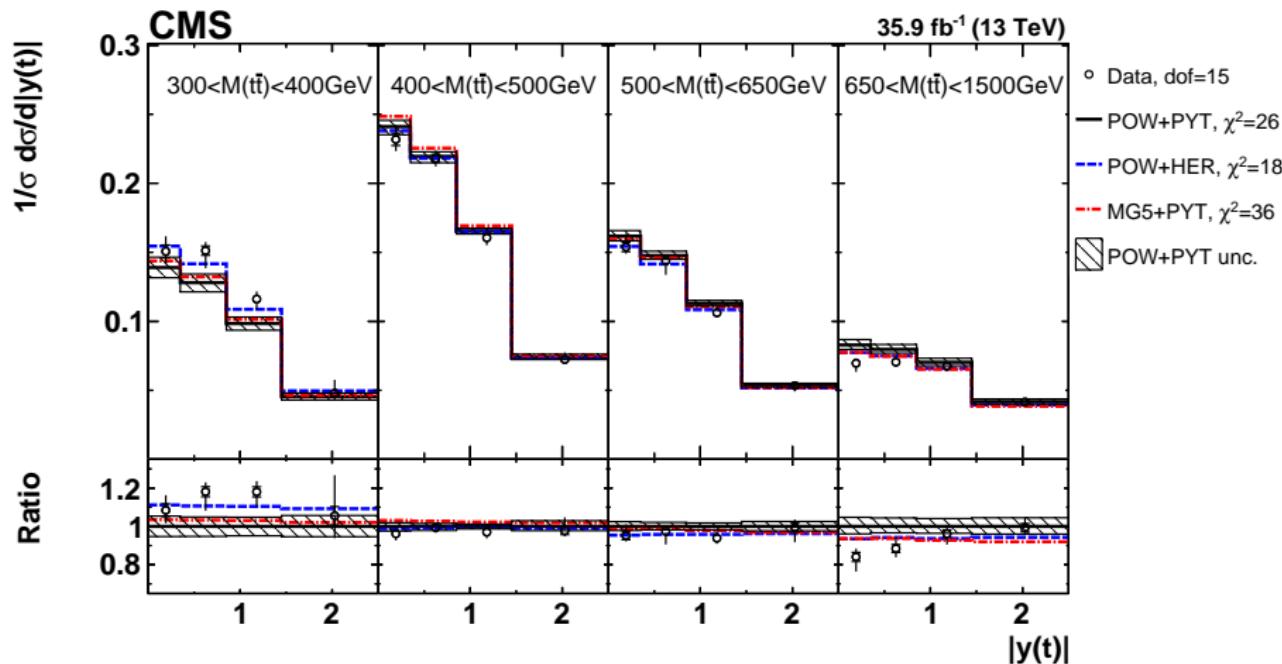
- bad description by all MC, strongest disagreement for 'POW-PYT'
- notice: 'POW-HER' describes  $p_T(t)$  in entire  $y(t)$  range well, but predicts too hard  $p_T(t)$  at high  $M(t\bar{t})$

# TOP-18-004 3D cross sections [ $N_{\text{jet}}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})$ ]



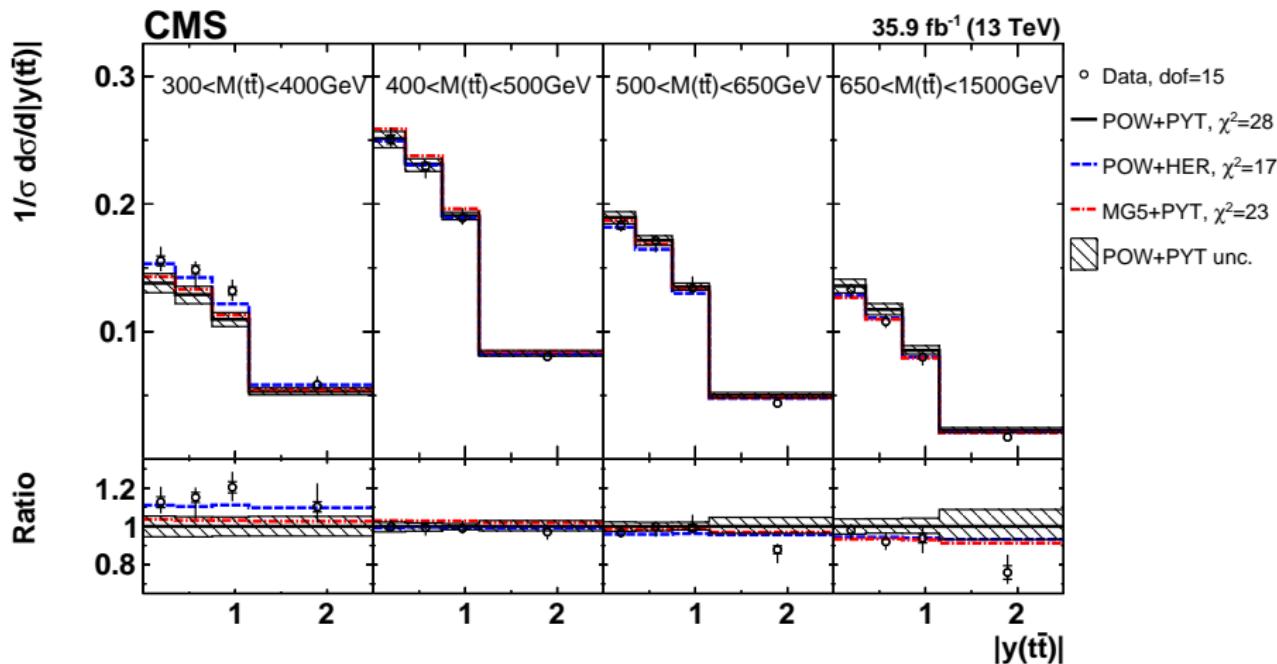
- only ‘POW-PYT’ is in satisfactory agreement with data
- ‘POW-HER’ predicts too high cross section at  $N_{\text{jet}} > 1$
- ‘FXFX-PYT’ describes worse  $M(t\bar{t})$  at  $N_{\text{jet}} = 1$
- ... more plots in BACKUP

# TOP-18-004 2D x-sections [ $M(t\bar{t})$ , $y(t)$ ]



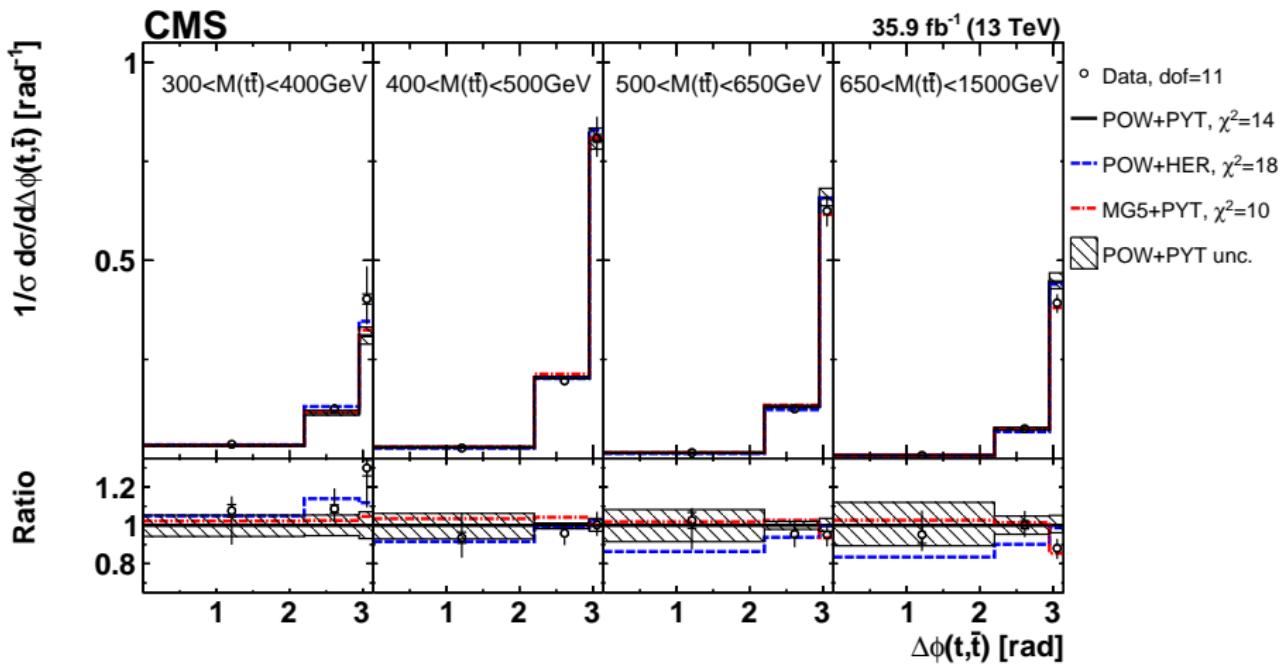
- MC is more central than data at largest  $M(t\bar{t})$
- best description by 'POW-HER' (mainly  $M(t\bar{t})$  slope)

# TOP-18-004 2D cross sections [ $M(t\bar{t})$ , $y(t\bar{t})$ ]



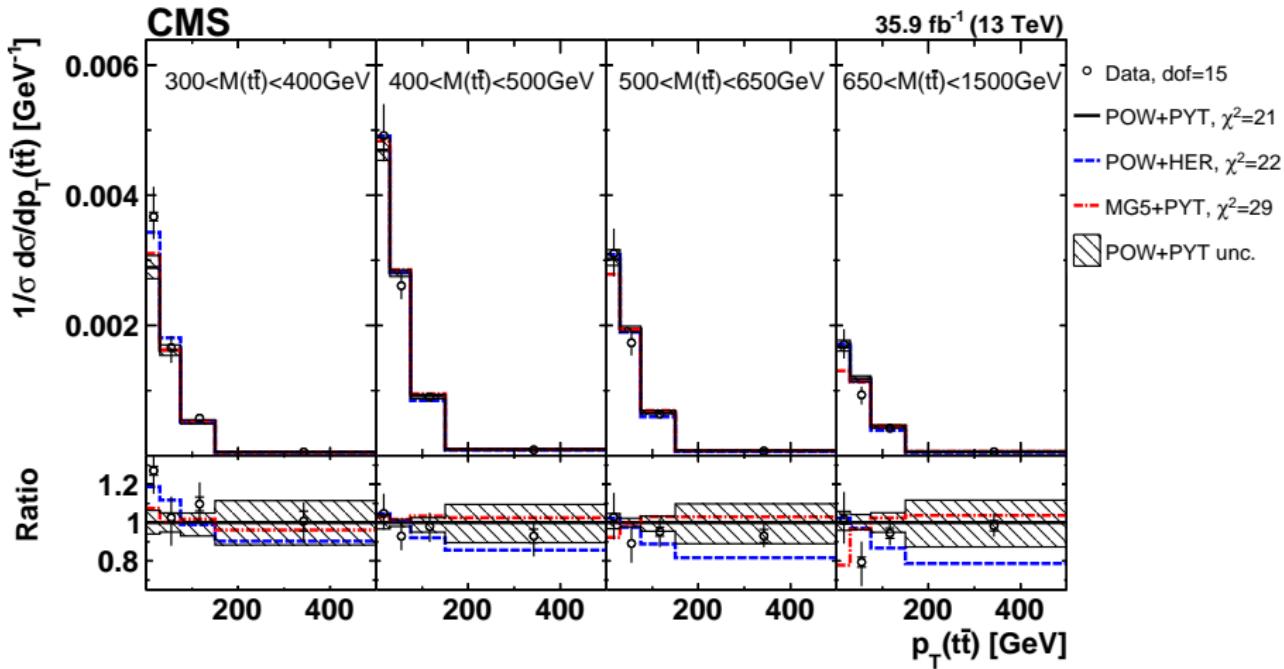
- MC is (somewhat) less central than data at largest  $M(t\bar{t})$
- best description by 'POW-HER' (mainly  $M(t\bar{t})$  slope)

# TOP-18-004 2D x-sections [ $M(t\bar{t})$ , $\Delta\phi(t,\bar{t})$ ]



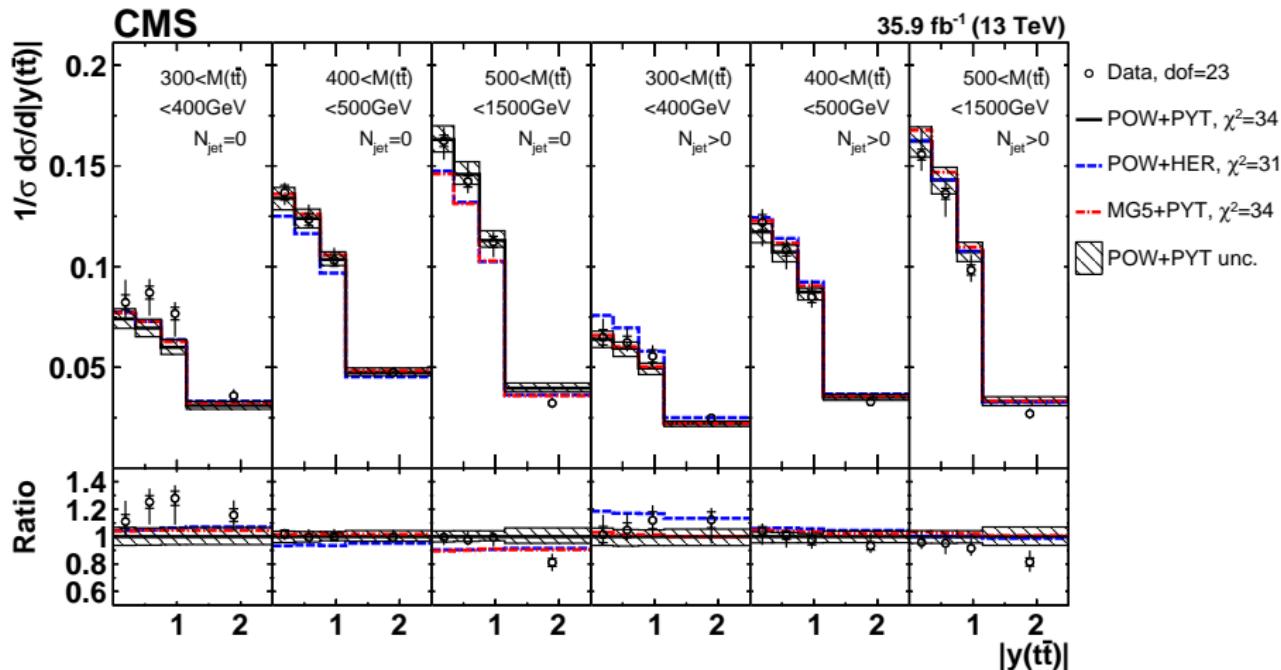
→ all MC describe data well

# TOP-18-004 2D x-sections [ $M(t\bar{t})$ , $p_T(t\bar{t})$ ]



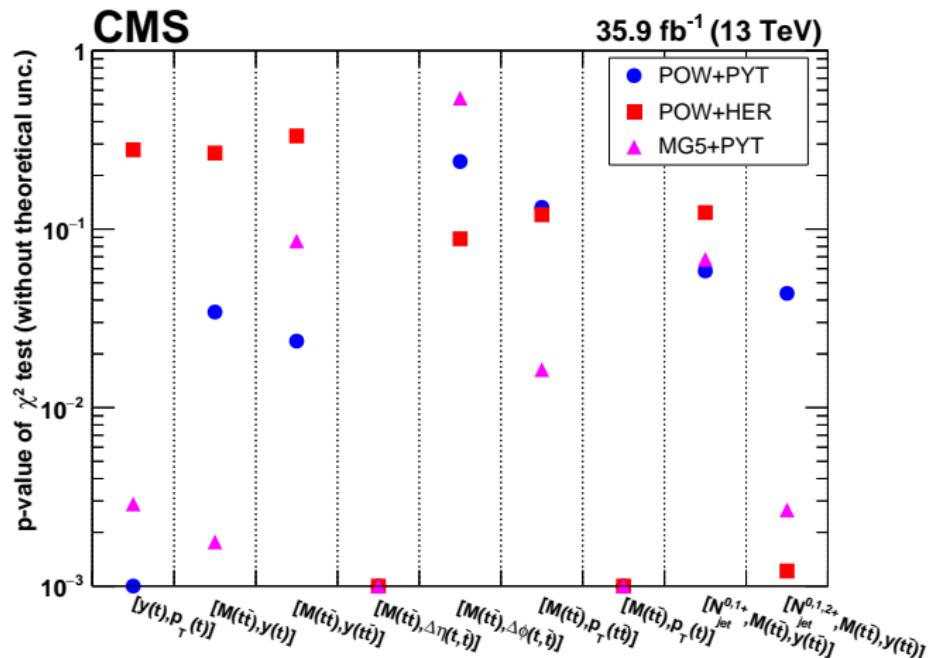
→ all MC describe data well, but 'FXFX-PYT' predicts too hard  $p_T(t\bar{t})$  at highest  $M(t\bar{t})$

# TOP-18-004 3D x-sections [ $N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})$ ]



→ all MC describe data well

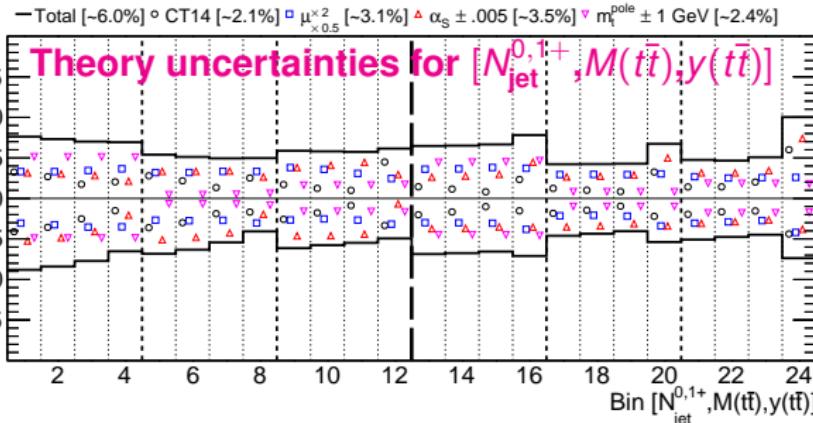
# TOP-18-004 summary of comparison to MC models



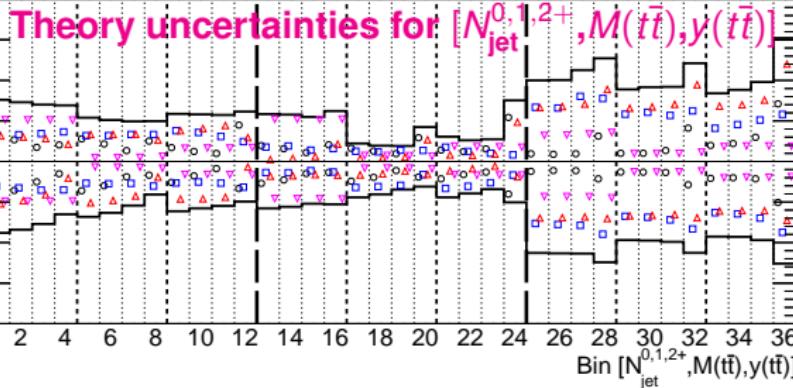
- none of central MC predictions is able to describe all distributions, in particular  $[M(t\bar{t}), \Delta\eta(t, \bar{t})]$ ,  $[M(t\bar{t}), p_T(t)]$
- overall, best description is provided by ‘POW-PYT’ and ‘POW-HER’:
  - ▶ ‘POW-HER’ describes better distributions probing  $p_T(t)$
  - ▶ ‘POW-PYT’ describes better distributions probing  $N_{\text{jet}}$  and radiation

# TOP-18-004 Data and theory uncertainties $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$

Uncertainty [%]



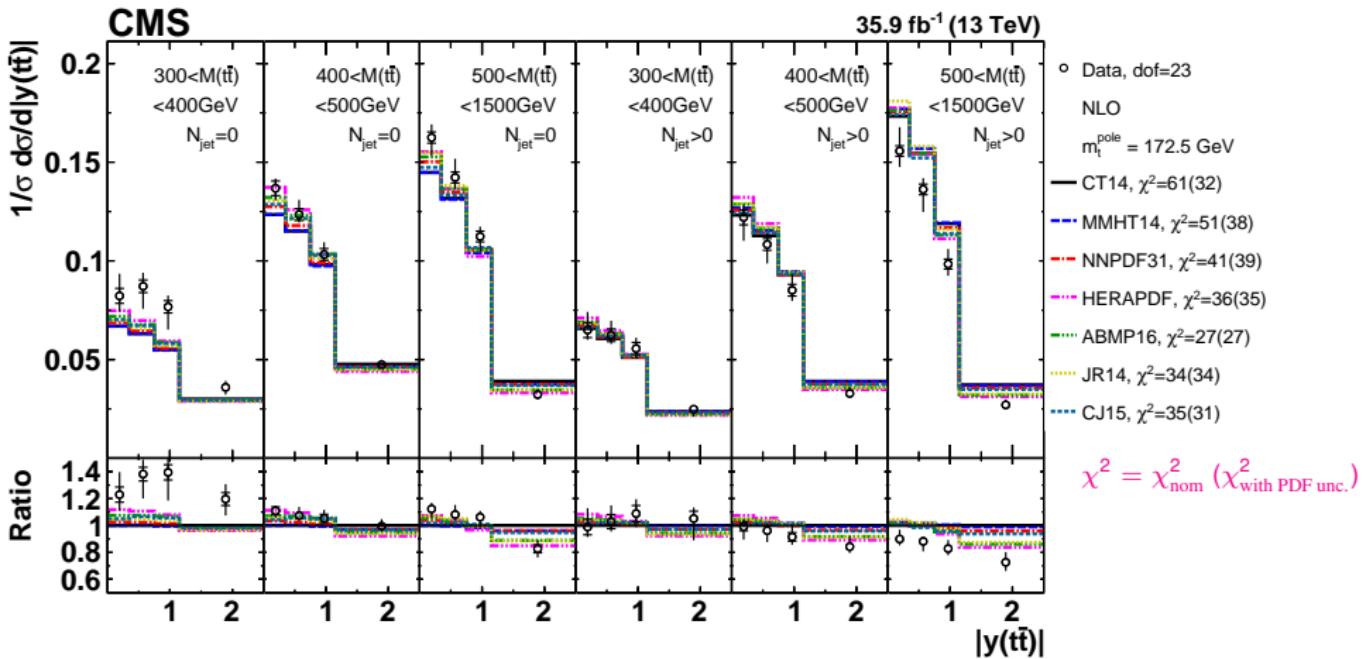
— Total [-6.0%] ◦ CT14 [-2.1%] □  $\mu_{x,0.5}^{-2}$  [-3.1%] ▲  $\alpha_s \pm .005$  [-3.5%] ▽  $m_t^{\text{pole}} \pm 1 \text{ GeV}$  [-2.4%]



— Total [-7.0%] ◦ CT14 [-2.2%] □  $\mu_{x,0.5}^{-2}$  [-3.9%] ▲  $\alpha_s \pm .005$  [-4.0%] ▽  $m_t^{\text{pole}} \pm 1 \text{ GeV}$  [-2.4%]

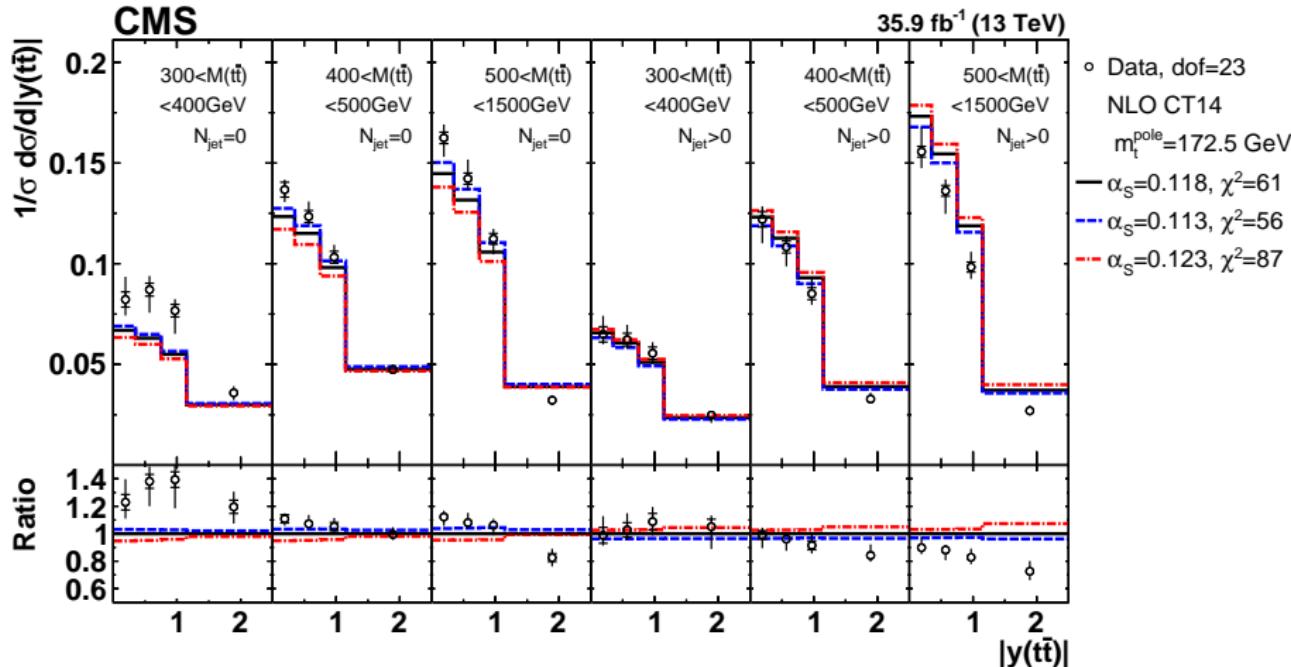
- Bins are grouped for  $y(t\bar{t})$ ,  $M(t\bar{t})$  and  $N_{\text{jet}}$  (separated by different vertical lines)
- NLO scale uncertainties are comparable to PDF,  $\alpha_s$  and  $m_t$  uncertainties  
→ data can constrain PDF,  $\alpha_s$  and  $m_t$
- Scale uncertainties are considerably smaller for  $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$   
→  $[N_{\text{jet}}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$  is used for cross check only

# TOP-18-004 [ $N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})$ ] compared to NLO pred. with diff. PDFs



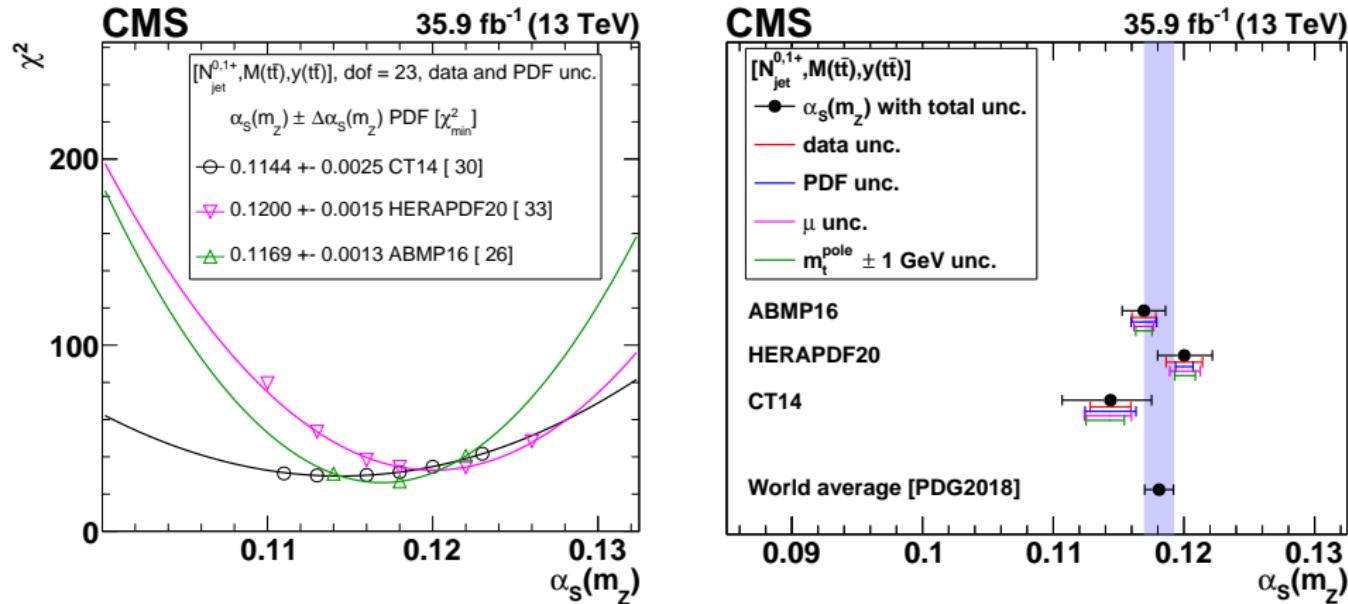
- description depends on PDFs → data are sensitive to PDFs
- All modern PDF sets considered:
  - MMHT2014, ABMP16: total  $\sigma(t\bar{t})$  data
  - NNPDF3.1: total and differential (Run-I)  $\sigma(t\bar{t})$  data
  - other PDFs: no  $t\bar{t}$  data

# TOP-18-004 [ $N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})$ ] compared to NLO pred. with diff. $\alpha_s$



- $\alpha_s$  sensitivity comes from different  $N_{\text{jet}}$  bins
- also (indirect) sensitivity comes from  $[M(t\bar{t}), y(t\bar{t})]$  via sensitivity to PDFs

# TOP-18-004 extraction of $\alpha_s$ from $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$



- used  $m_t^{\text{pole}} = 172.5$  GeV in ME for all PDF sets (ABMP16 fitted  $m_t^{\text{pole}} = 171.44$  GeV)
- precise determination of  $\alpha_s$  is possible using these data
- significant dependence on PDF set observed (correlation between  $g$  and  $\alpha_s$ )

## TOP-18-004 Definition of extra jets (not from top decay)

- NLO predictions for inclusive  $t\bar{t}$ ,  $t\bar{t} + 1$  jet and  $t\bar{t} + 2$  jets computed and compared to data using MadGraph5\_aMC@NLO + aMCfast + ApplGrid + xFitter
- particle-level jet definition used in measurement, further corrected to parton level using separate MC PowHEGv2 + PYTHIA8 simulations
  - ▶  $p_T(j) > 30 \text{ GeV}$ ,  $|\eta(j)| < 2.4$
  - ▶ ‘Particle level’: particle jets (no  $\nu$ ) required to be isolated within  $\Delta R > 0.4$  from  $l$  and  $b$  from  $t\bar{t}$
  - ▶ Parton level: standalone PowHEGv2 + PYTHIA8 generated without
    - (1) top decays:  $C_{\text{def}} = \sigma_{\text{no } l,b \text{ from } t\bar{t}} / \sigma_{\text{no } t\bar{t}}$
    - (2) hadronisation:  $C_{\text{had}} = \sigma_{\text{with had.}} / \sigma_{\text{no had.}}$
    - (3) MPI:  $C_{\text{MPI}} = \sigma_{\text{with MPI}} / \sigma_{\text{no MPI}}$
- $C_{\text{NP}} = \sigma_{\text{no } l,b \text{ from } t\bar{t}} / \sigma_{\text{no } t\bar{t}, \text{had.,MPI}}$  [ $C_{\text{NP}} \approx C_{\text{def}} \times C_{\text{had}} \times C_{\text{MPI}}$ ]
- theoretical predictions = NLO  $\times C_{\text{NP}}$
- similar procedure used in jet measurements (although without excluding decay products)

## TOP-18-004 Simultaneous PDF $+\alpha_s + m_t^{\text{pole}}$ fit: settings

- followed standard approach: using HERA DIS data only, or HERA +  $t\bar{t}$  data to demonstrate added value from  $t\bar{t}$  on PDF and  $\alpha_s$  determination
- settings follow HERAPDF2.0 fit (very similar to TOP-14-013), use xFitter-2.0.0
- input data: combined HERA DIS [1506.06042] +  $t\bar{t}$
- RTOPT,  $M_c = 1.47 \text{ GeV}$ ,  $M_b = 4.5 \text{ GeV}$ ,  $Q_{\min}^2 = 3.5^{+1.5}_{-1.0} \text{ GeV}^2$
- predictions for  $t\bar{t}$  data via MadGraph5\_aMC@NLO + aMCfast + ApplGrid,  
 $\mu_r = \mu_f = H_t/4$ ,  $H_t = \sqrt{m_t^2 + (p_T(t))^2} + \sqrt{m_t^2 + (p_T(\bar{t}))^2}$  varied by factor 2
  - dependence on  $\alpha_s$  and scales written in ApplGrid tables
  - dependence on  $m_t^{\text{pole}}$  derived by linear interpolation between tables generated with different values of  $m_t^{\text{pole}}$  (new feature for xFitter)
  - kinematic range probed by  $t\bar{t}$ :  $x = (M(t\bar{t})/\sqrt{s}) \exp[\pm y(t\bar{t})] \Rightarrow 0.01 \lesssim x \lesssim 0.1$
- 15-parameter form (backup) determined using parametrisation scan (one extra  $g$  parameter required by  $t\bar{t}$  data) at  $Q_0^2 = 1.9 \text{ GeV}^2$ ,  $f_s = 0.4 \pm 0.1$
- DGLAP NLO PDF evolution via QCNUM-17.01.14
- PDF uncertainties: fit ( $\Delta\chi^2 = 1$  via HESSE, cross checked with MC replica method), model and parametrisation; in addition for  $\alpha_s$  and  $m_t^{\text{pole}}$  scale uncertainties for  $t\bar{t}$  are considered

## TOP-18-004 Simultaneous PDF, $\alpha_s$ and $m_t^{\text{pole}}$ fit: PDF parametrisation

Determined using parametrisation scan:

$$x_g(x) = A_g x^{B_g} (1-x)^{C_g} (1+E_g x^2) - A'_g x^{B'_g} (1-x)^{C'_g},$$

$$x_{u_v}(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1+D_{u_v} x),$$

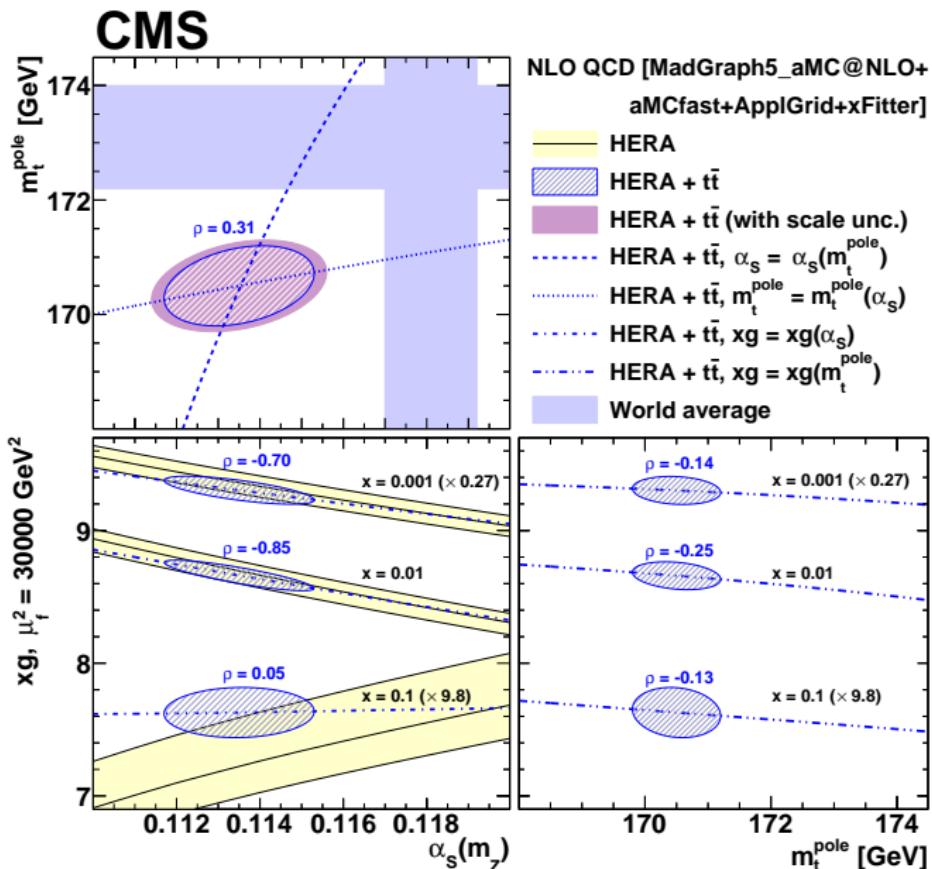
$$x_{d_v}(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1+D_{\bar{U}} x),$$

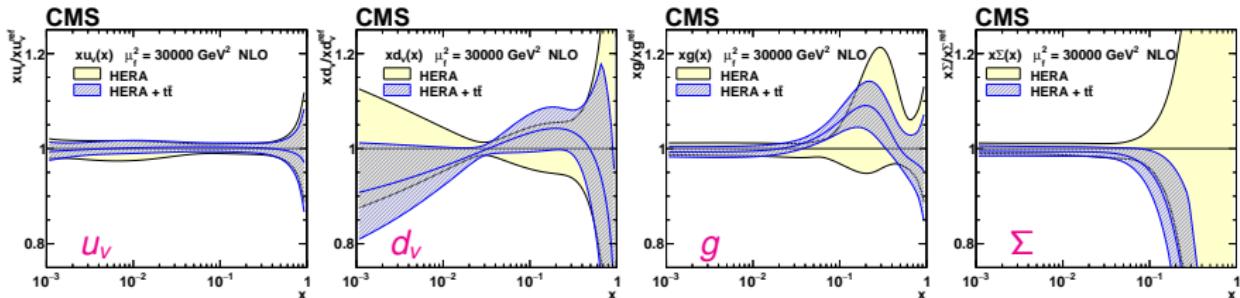
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}},$$

- additional gluon parameter ( $E_g$ ) required by new  $t\bar{t}$  data
- PDF parametrisation uncertainties given by  $A'_g = 0$  (13p) and  $E_g = 0$  (14p), and  $Q_0^2 = 1.9 \pm 0.3 \text{ GeV}^2$  variation

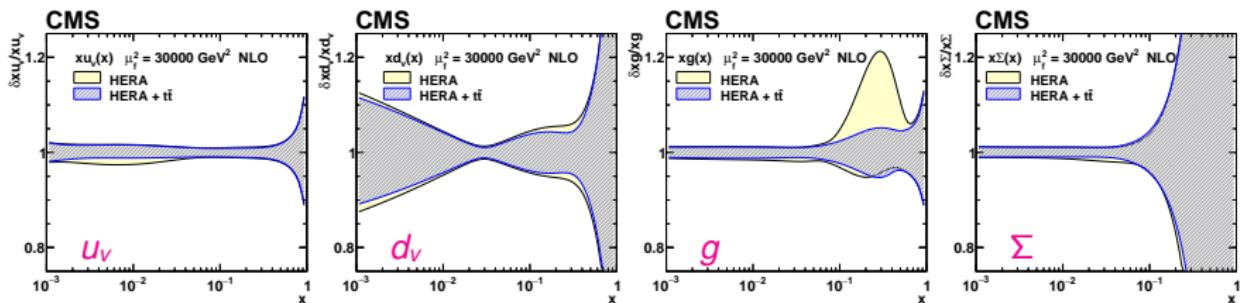
# TOP-18-004 Simultaneous PDF + $\alpha_s$ + $m_t^{\text{pole}}$ fit: $\alpha_s$ , $m_t^{\text{pole}}$ and g correlation



PDFs ( $\alpha_s$  in HERA-only fit set to  $\alpha_s = 0.1135 \pm 0.0016$ )

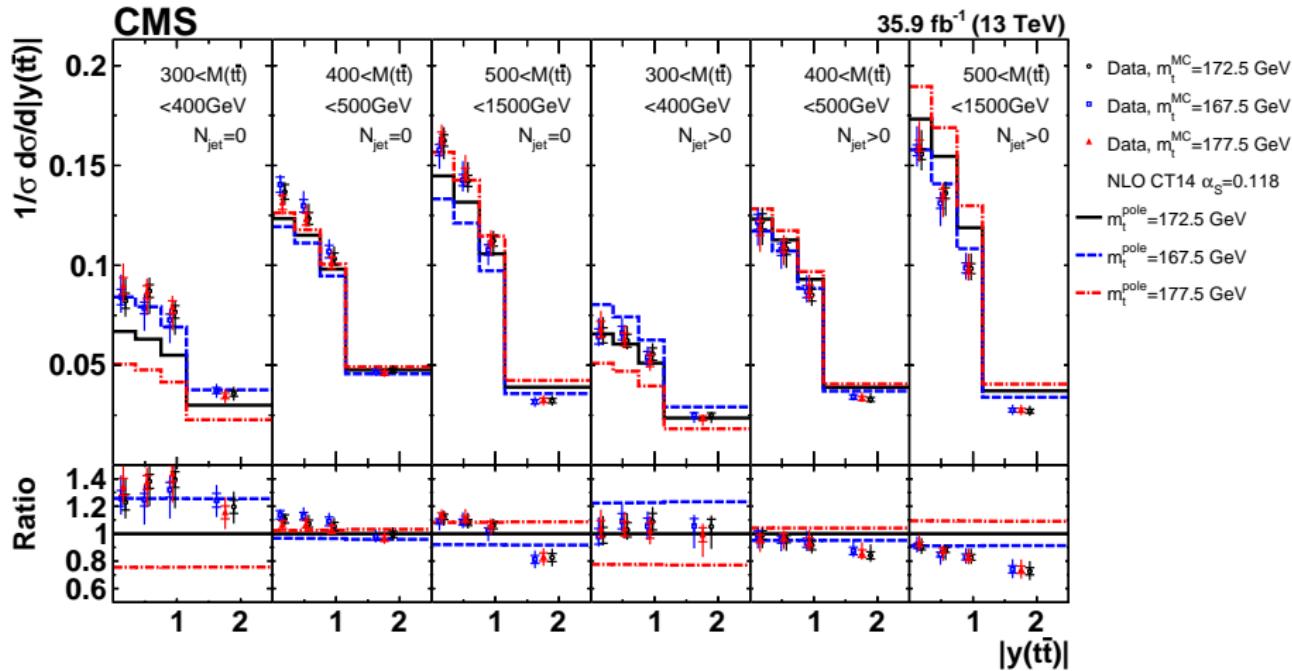


## Relative PDF uncertainties



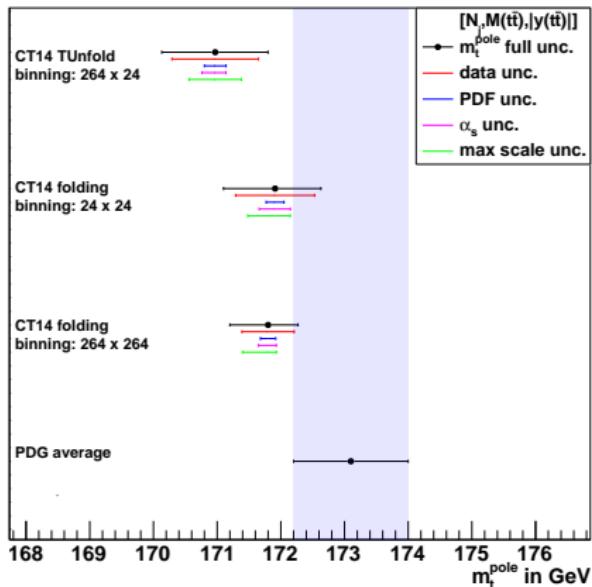
- reduced  $g$  uncertainty at high  $x$
- smaller impact on other distributions via correlations in the fit

# TOP-18-004 Dependence of measured cross sections on $m_t^{\text{MC}}$



# Extraction of $m_t^{\text{pole}}$ using CMS detector-level data

L. Materne, bachelor thesis "Differential Top-Pair Production Cross Section with the CMS Detector - Optimization of Measurement Information", Karlsruher Institut für Technologie (KIT), Bachelorarbeit, 2018 [ETP-Bachelor-KA/2018-11]



- 'CT14 TUnfold' is TOP-18-004
- 'CT14 folding' is obtained using data at detector level theoretical predictions which are folded with the response matrix