

# Differential Cross Sections of Global Event Variables of $t\bar{t}$ from ATLAS+CMS

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on behalf of the ATLAS and CMS collaboration

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# Outline

- Motivation
- MC Samples
- Definitions of Particle level objects
- (b) Jet and boosted jet multiplicity
- Additional jet multiplicity and  $\Delta R$  between two additional (b) jets
- Global event variables not relying on the kinematic reconstruction of the top quarks
- Conclusion

# Motivation of differential cross section

- It is crucial to understand the top quark process precisely in different phase spaces
  - $t\bar{t}$  is the main background/final state itself for BSM searches
  - Possible new physics can appear in any distribution, particular in high  $p_T$  region
- Measurement with respect to global event variables are complementary
  - Do not require kinematic reconstruction
  - Global event variables such as MET are sensitive to Dark Matter searches
- Measurement with additional jets, can check the validity of the QCD calculation involving a top quark pair plus additional quarks or gluons
  - Compare higher-order prediction against parton shower models
  - Better understanding of systematic uncertainties on the theory modeling

# MC samples at 13 TeV

ATLAS

Event generator	Parton shower	
POWHEG (v2)	Pythia 6 / Pythia 8	Default
POWHEG	Herwig++/Herwig7	
MadGraph5_aMC@NLO	Pythia 8 / Herwig++/Herwig7	
SHERPA	SHERPA tune	

- But not all of them are used to evaluate systematic uncertainties
- The details depends on dataset.

CMS

Event generator	Parton shower	
POWHEG (v2)	Pythia 8	Default
POWHEG	Herwig++	
MadGraph5_aMC@NLO	Herwig++/Pythia 8 with FxFx ( $t\bar{t} + 0, 1, 2j$ )	
MadGraph5 (LO)	Pythia 8 with MLM ( $t\bar{t} + 0, 1, 2, 3j$ )	
SHERPA	CS based on the SHERPA default tune	

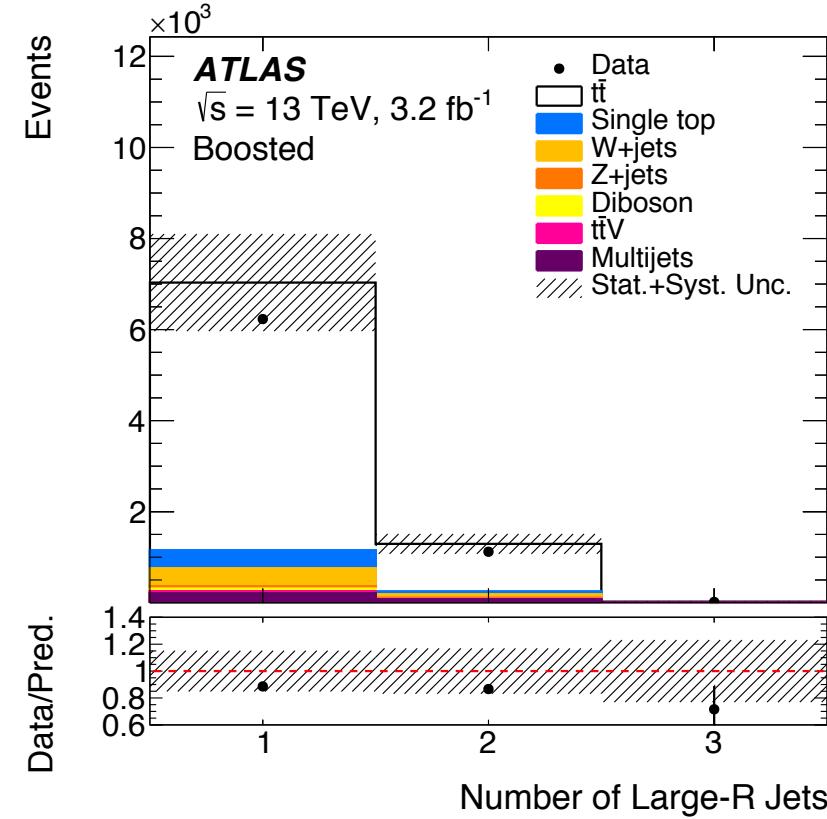
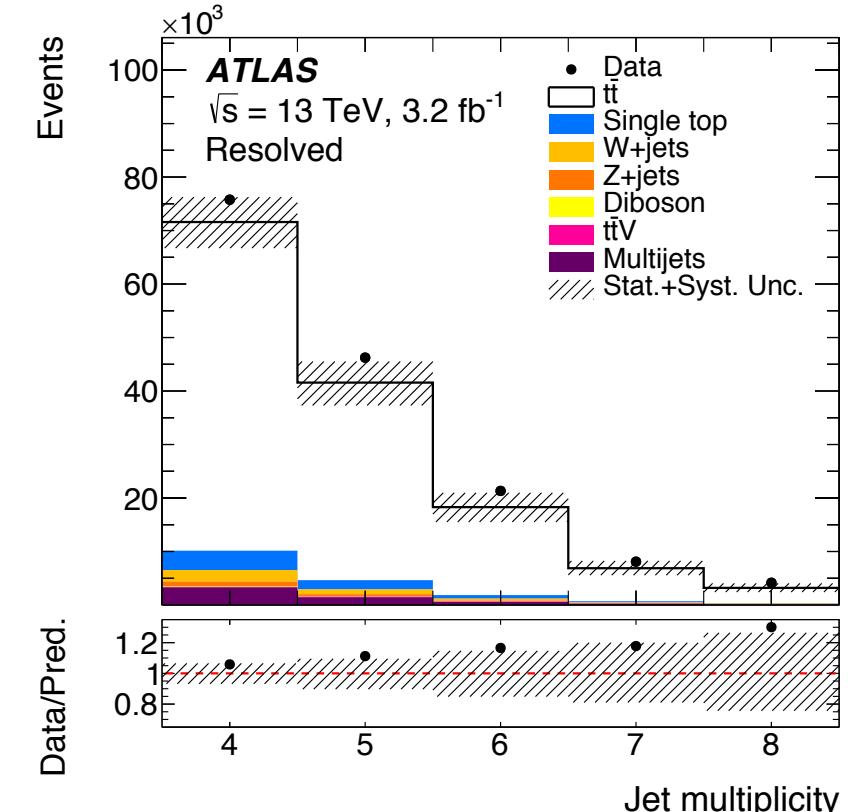
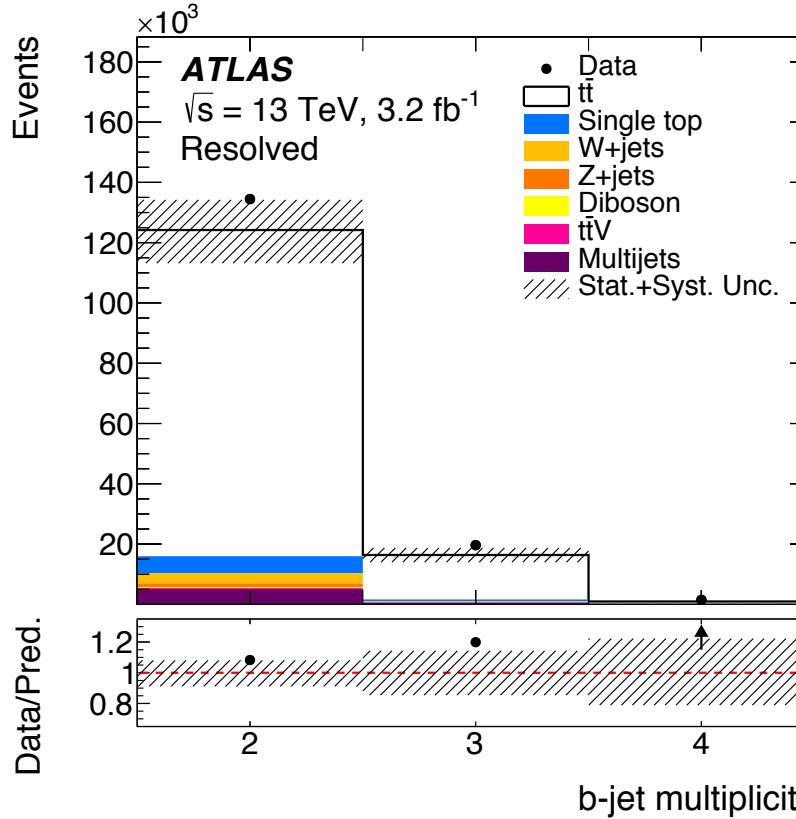
# Particle-level objects

- Decrease MC uncertainty from extrapolating to unmeasurable phase space
- Particle-level objects (harmonized between ATLAS and CMS, RIVET standard)
  - **Electrons and muons** :  $p_T > 25 \text{ GeV}$  and  $|\eta| < 2.5$ 
    - not originate from a hadron adding the four-momentum of all photons within  $\Delta R = 0.1$
  - **Jets** :  $p_T > 25 \text{ GeV}$  and  $|\eta| < 2.5$ 
    - clustering all stable particle except the selected  $e, \mu$  and radiated  $\gamma$  as well as neutrinos (but do include those from hadron decay) using the anti- $k_t$  algorithm with  $\Delta R=0.4$
    - **large-R jet** :  $300 \text{ GeV} < p_T < 1500 \text{ GeV}$ ,  $m > 50 \text{ GeV}$  and  $|\eta| < 2$
    - **top-tagged jets** :  $m(\text{large-R jet}) > 100 \text{ GeV}$ ,  $\tau_{32} < 0.75$
  - **b jets** : ghost matching technique - b hadron momentum is scaled down to a negligible value and included in the jet clustering
  - **MET** : vector  $p_T$  sum of all neutrinos from W/Z decays in the events

## (b) Jet multiplicity (ATLAS)

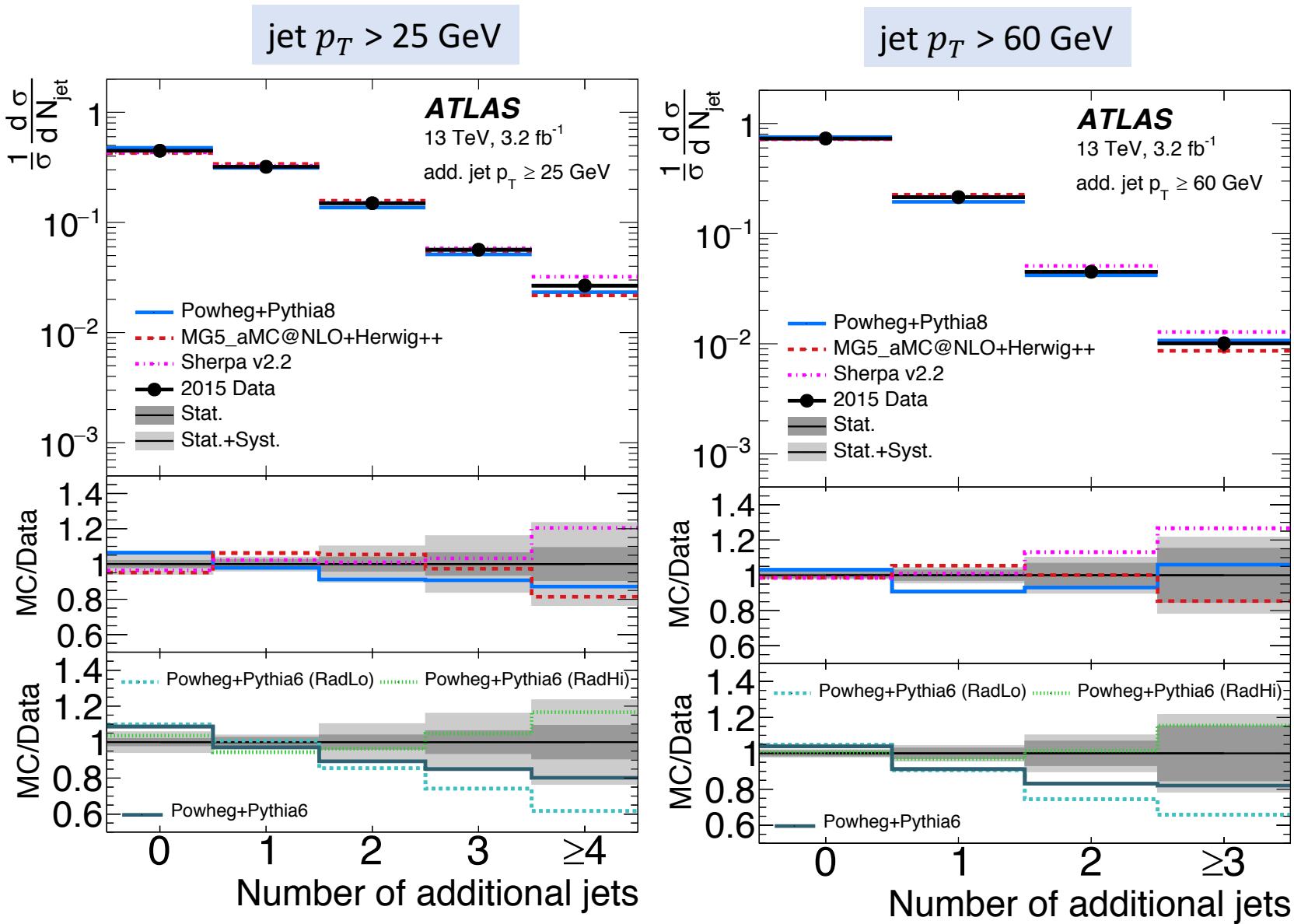
- b jet and jet multiplicity
- Resolved and boosted topology in the combined  $/+jets$  channel at detector level

arXiv:1708.00727



- Overall prediction has a tendency to underestimate data except the boosted topology
- The largest uncertainty comes from JES/JER and flavour tagging

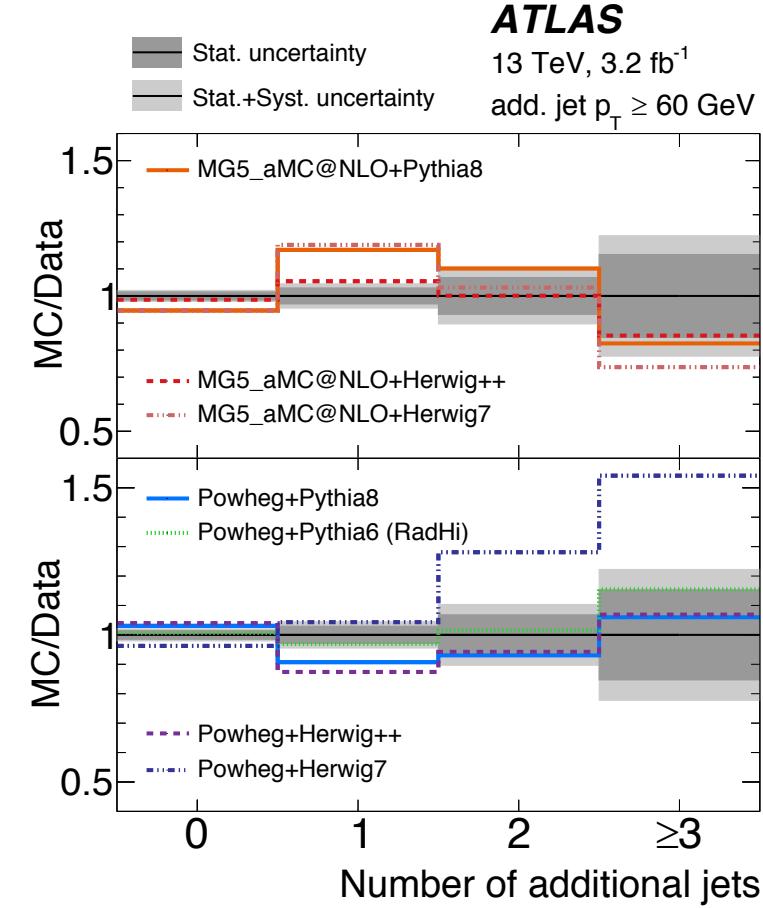
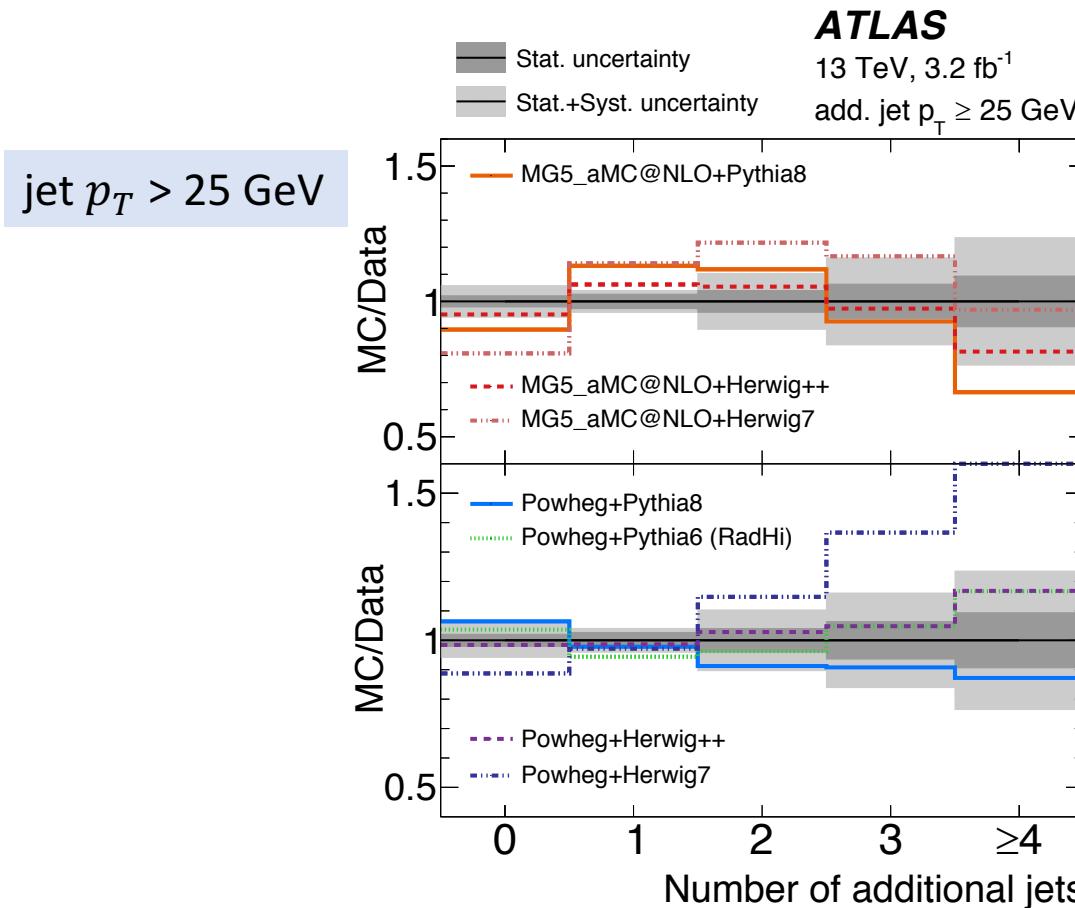
# Additional jets (ATLAS)



Eur. Phys. J. C77 (2017) 220

- Most of predictions are within uncertainties
- Slight deviations are visible
- Powheg+Pythia6 (low radiation variation of the Perugia 2012 tune) is lower than data in high multiplicity

# Additional jets (ATLAS)



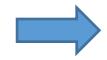
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jet  $p_T > 60 \text{ GeV}$

- Herwig7 predicts too many extra jets / MG5\_aMC@NLO requires more work
  - 0-and 1-extra jet bins point to difference between the POWHEG and aMC@NLO treatment of the hardest radiation while other bins in the parton-shower algorithm

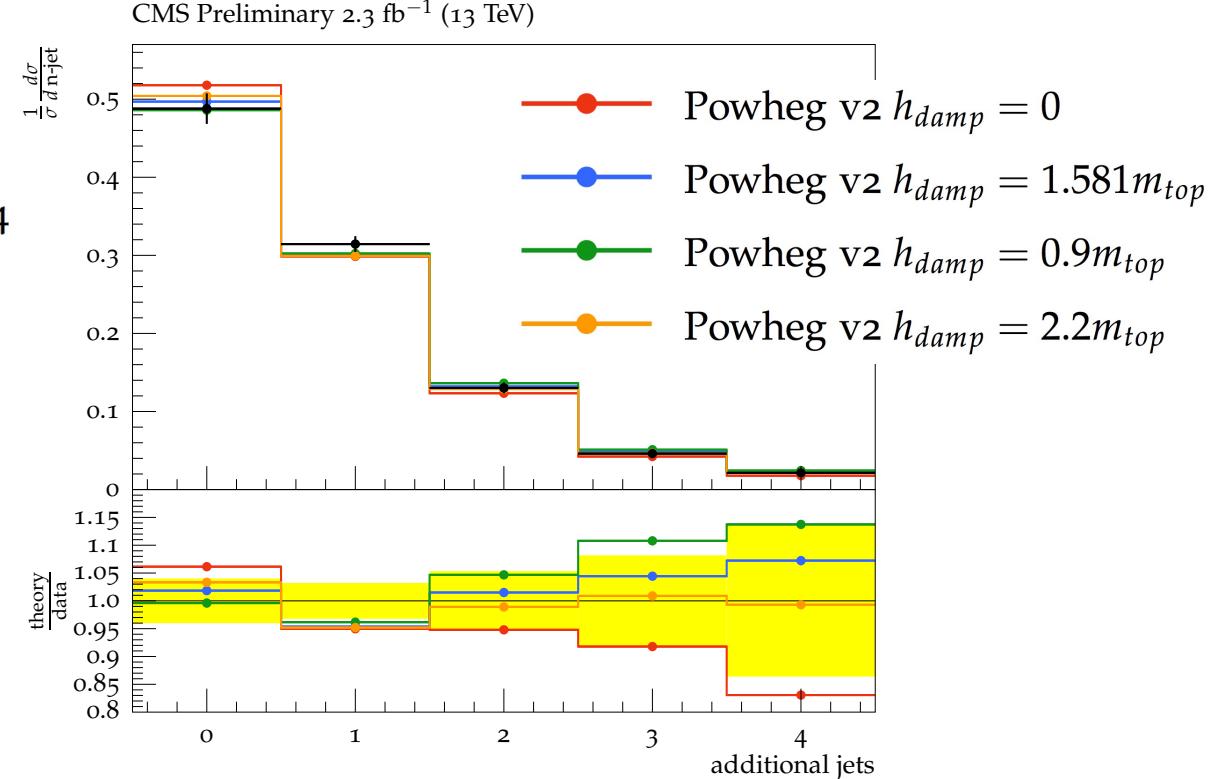
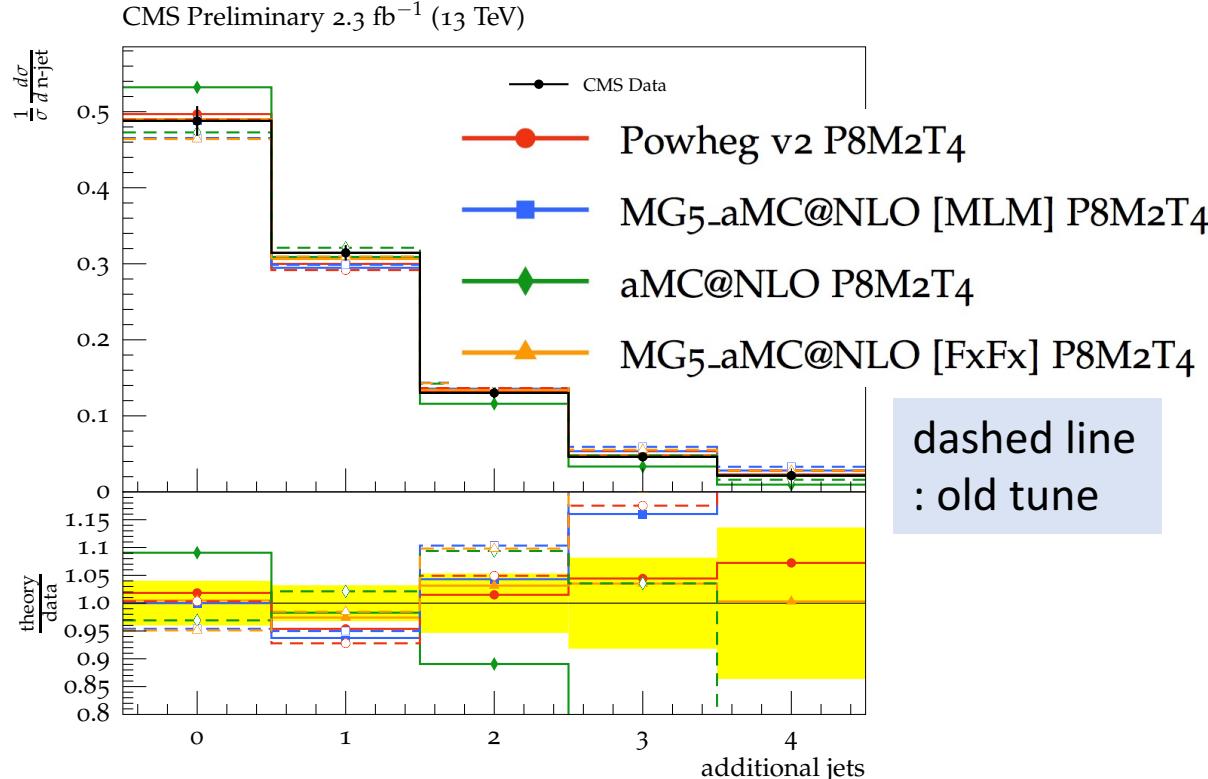
# Jet multiplicity in lepton + jets (CMS)

$$h_{\text{damp}} = 1.581^{+0.658}_{-0.585} \times m_t, \quad \alpha_s^{\text{ISR}} = 0.1108^{+0.0145}_{-0.0142}$$



Efe's talk , "Top quark modeling and Tuning"

CMS-PAS-TOP-16-021



- NLO generators agree with data within uncertainty
- LO order of MG5\_aMC@NLO (MLM) and aMC@NLO do not agree with data
- Data disfavors vanishing  $h_{\text{damp}}$

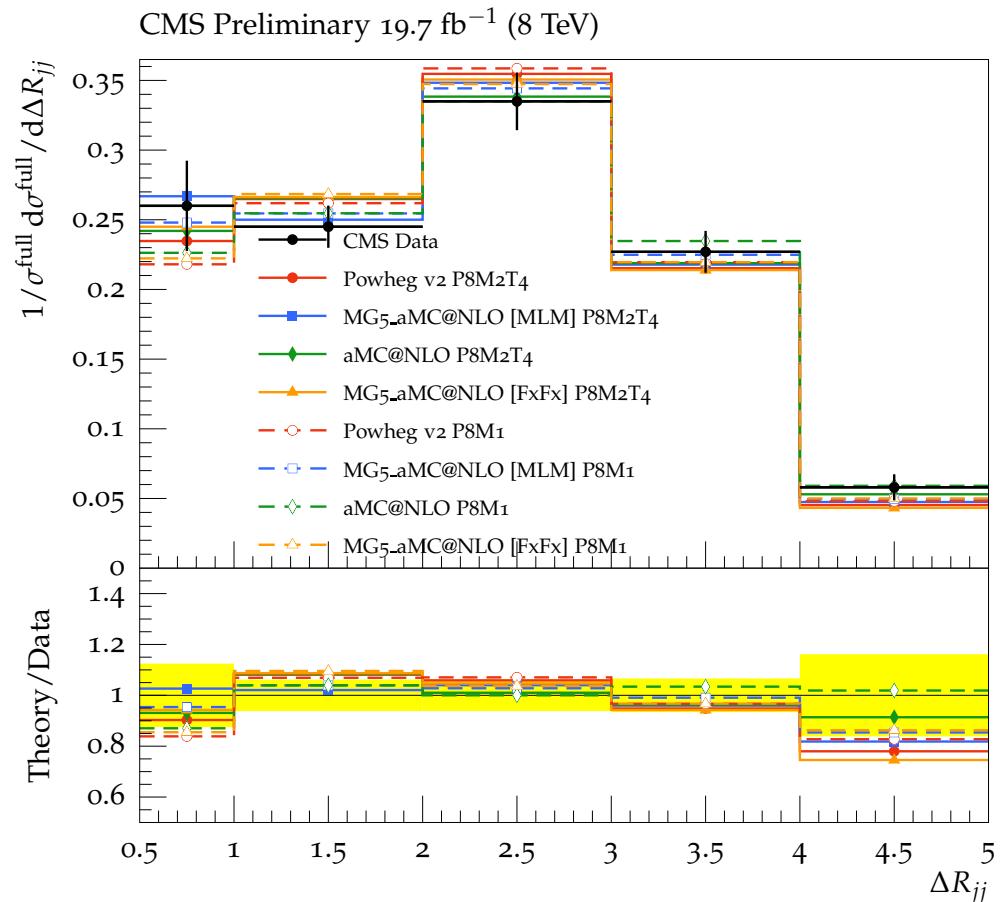
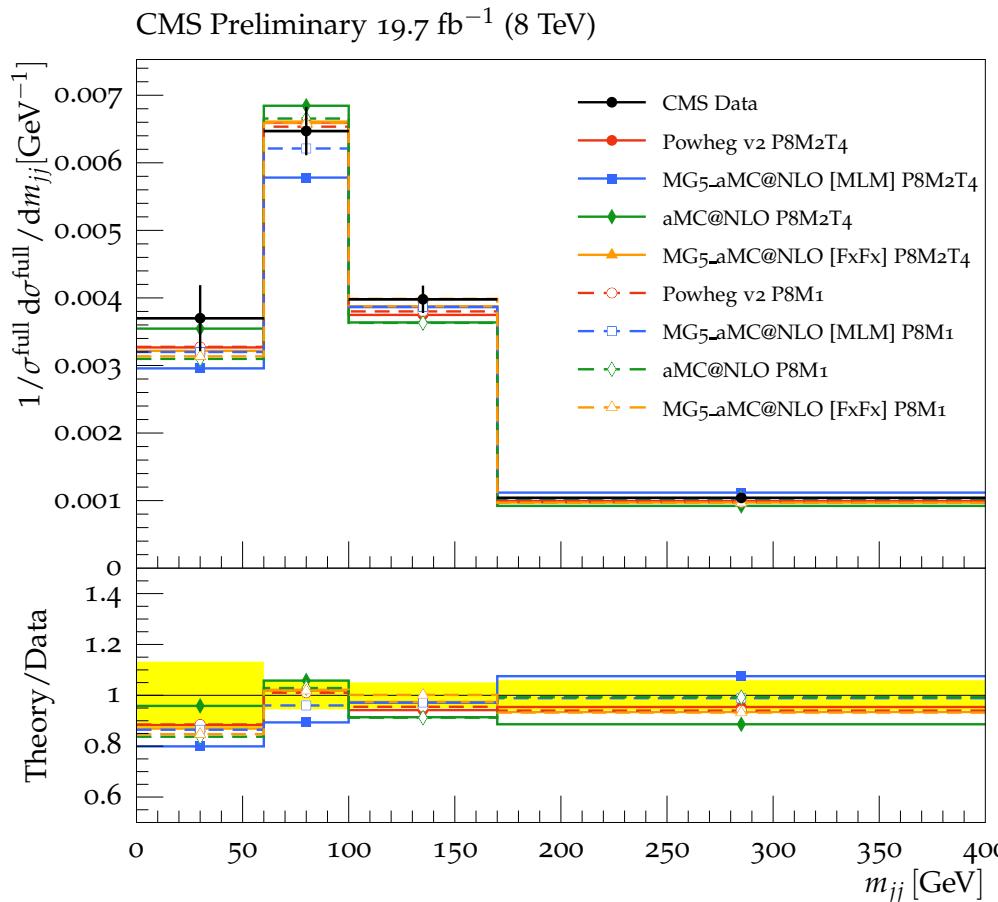
# $\Delta R_{jj}$ and $m_{jj}$ of additional jets (CMS)

- Normalized  $t\bar{t}$  cross sections in bins of invariant mass and the angular distance of the leading and second leading additional jets

8 TeV

CMS-PAS-TOP-16-021

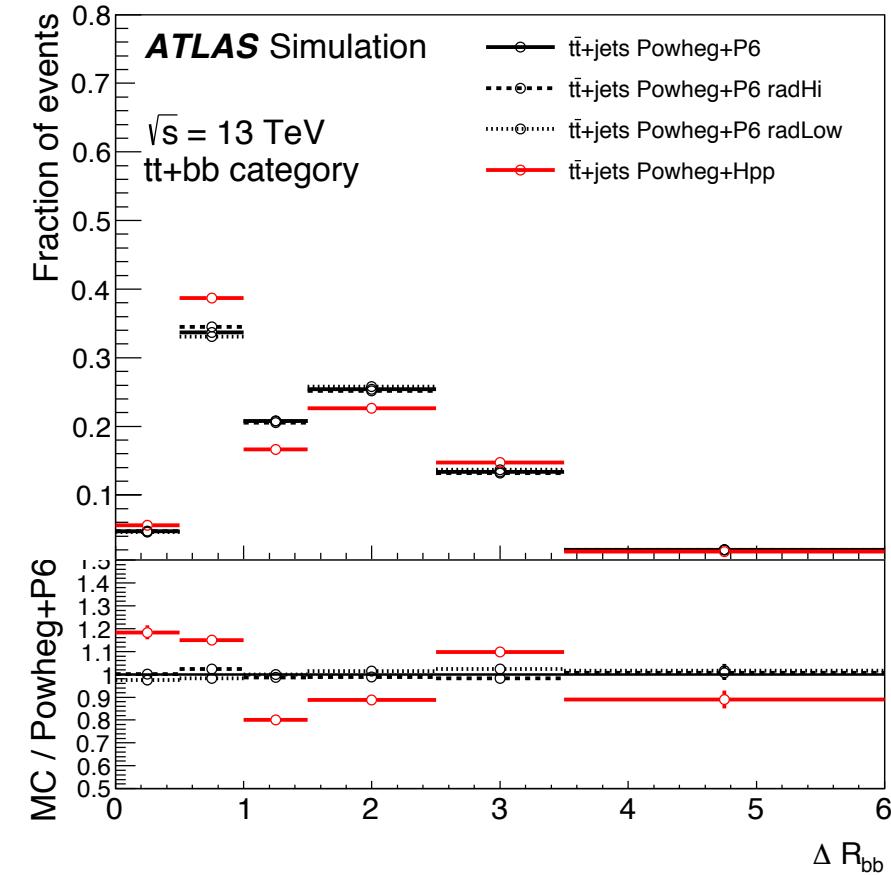
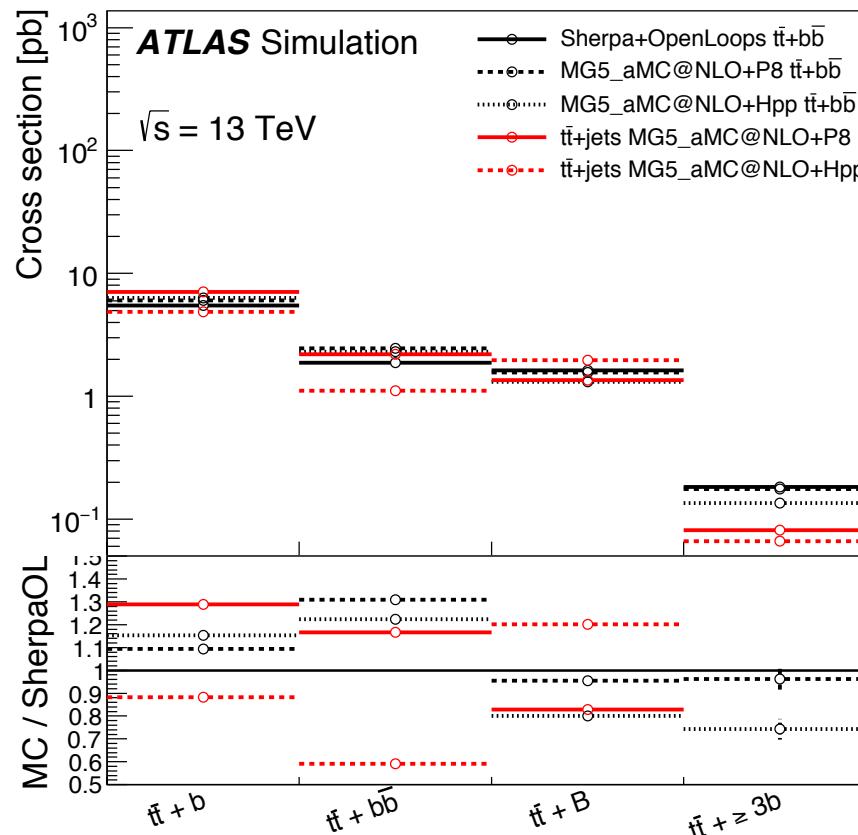
Data is from Eur. Phys. J. C 76 (2016) 379



# $\Delta R_{jj}$ of additional b jets (ATLAS)

- b jets are identified using  $\Delta R < 0.4$  matching with a b-hadron
- NLO predictions with 4F scheme (massive b-quarks) are compared
  - Sherpa + OpenLoops, MG5\_aMC@NLO + Herwig++/Pythia8

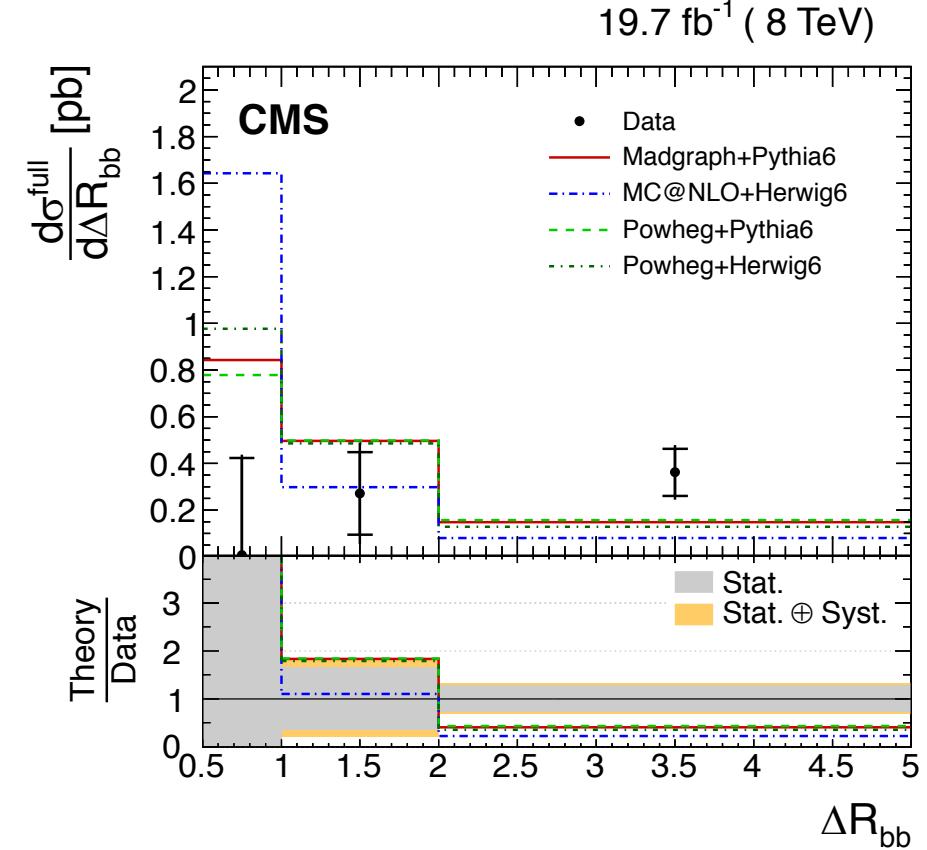
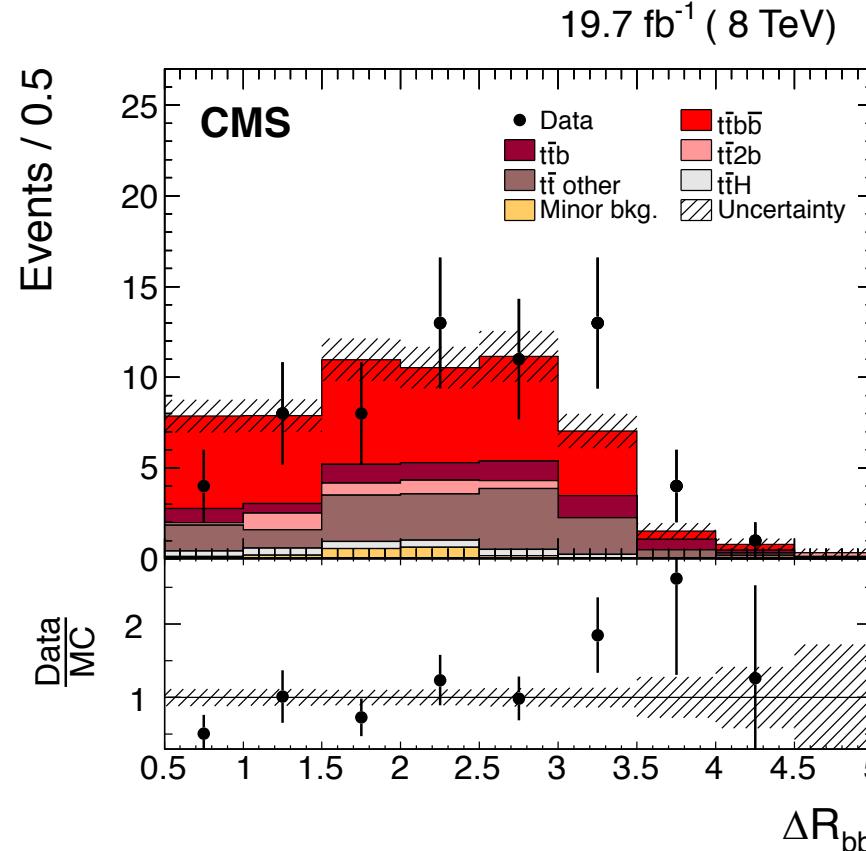
ATL-PHYS-PUB-2016-016



# $\Delta R_{jj}$ of additional b jets (CMS)

- Herwig6 has different behavior: smaller dR between two b jets

Eur. Phys. J. C 76 (2016) 379



- Correct assignment is difficult in case of 4 b jets
- Need more statistics

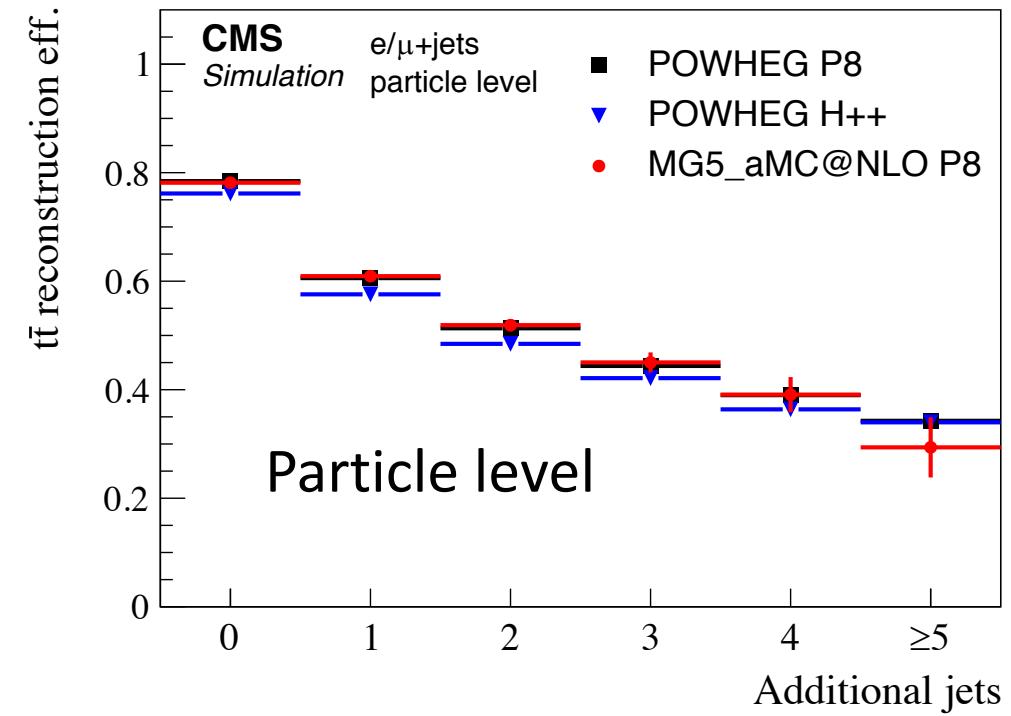
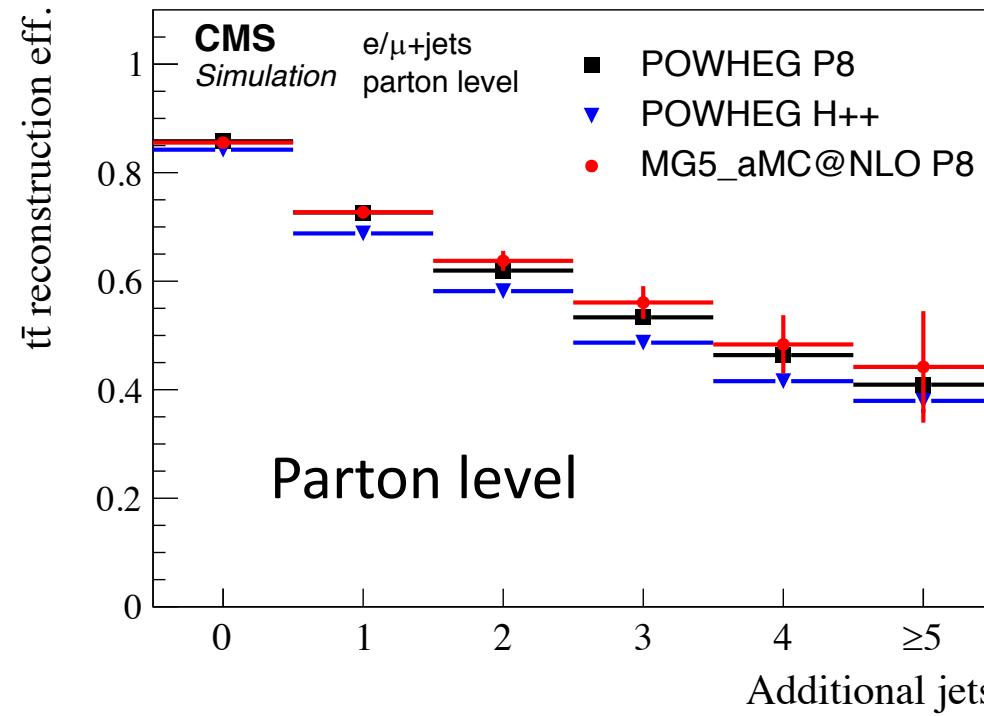
# Additional jets in lepton + jets (CMS)



- Only one electron or muon :  $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.1$
- No additional lepton :  $p_T > 15 \text{ GeV}$ ,  $|\eta| < 2.4$
- At least four jets :  $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.4$
- At least two b-tagged jets

$36 \text{ fb}^{-1}$

CMS-PAS-TOP-17-002



Number of permutation increases → more likely select a wrong permutation

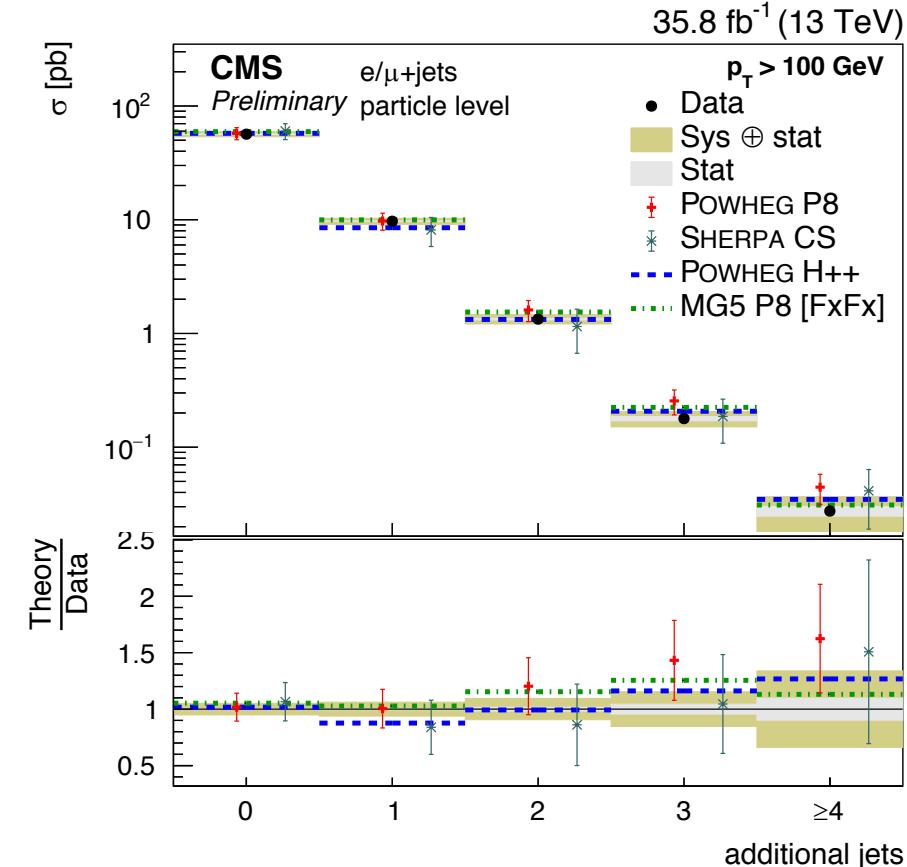
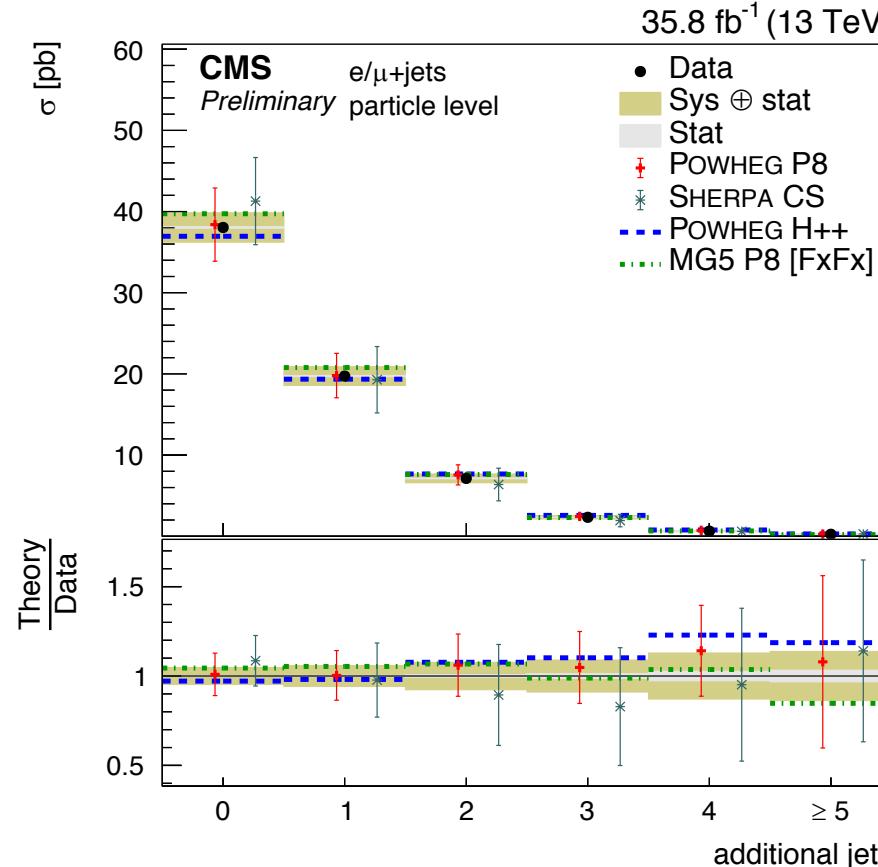
# Additional jets in lepton + jets (CMS)



- Multiplicities of the additional jets are reasonably modeled by POWHEG+PYTHIA8

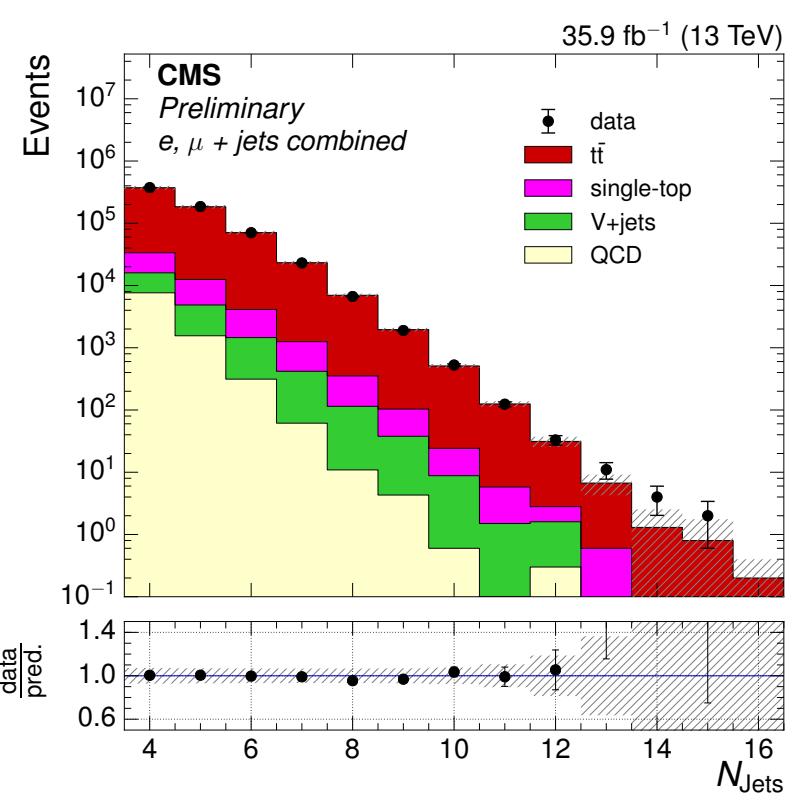
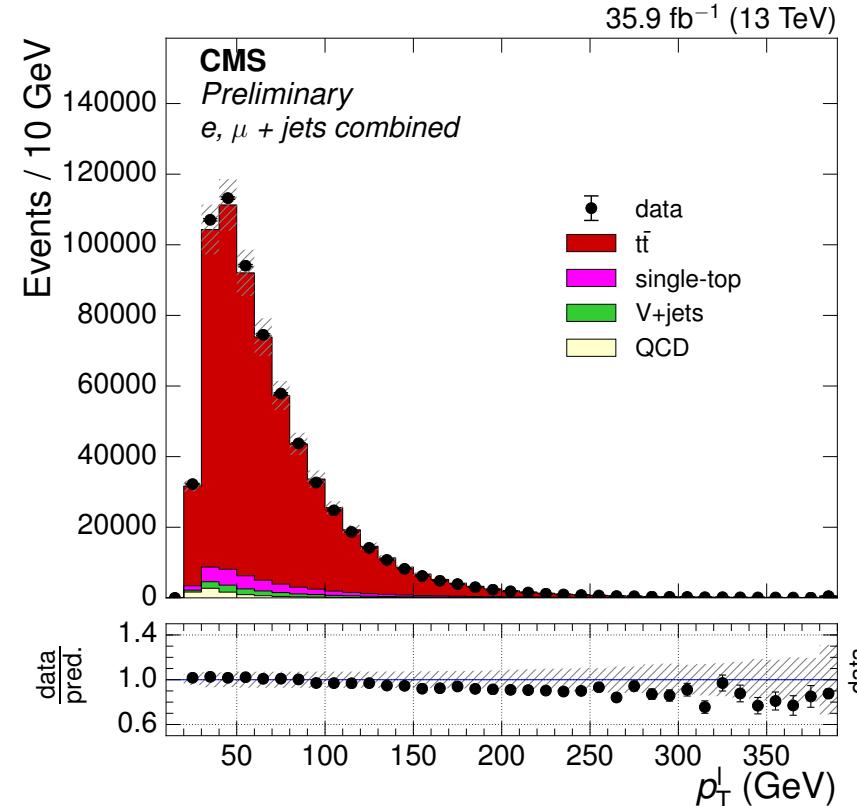
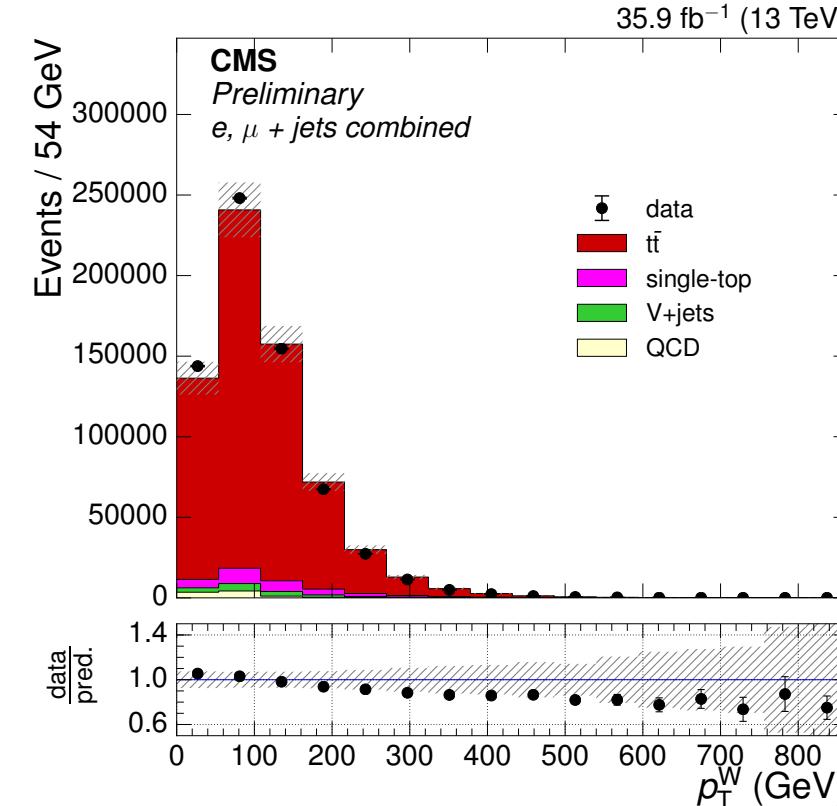
36  $fb^{-1}$

CMS-PAS-TOP-17-002



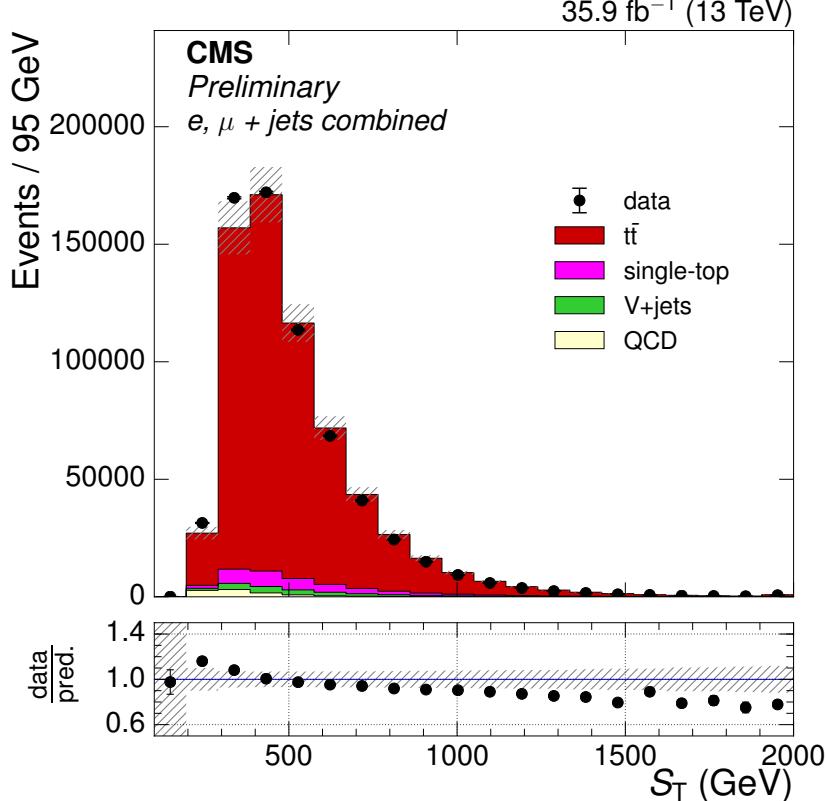
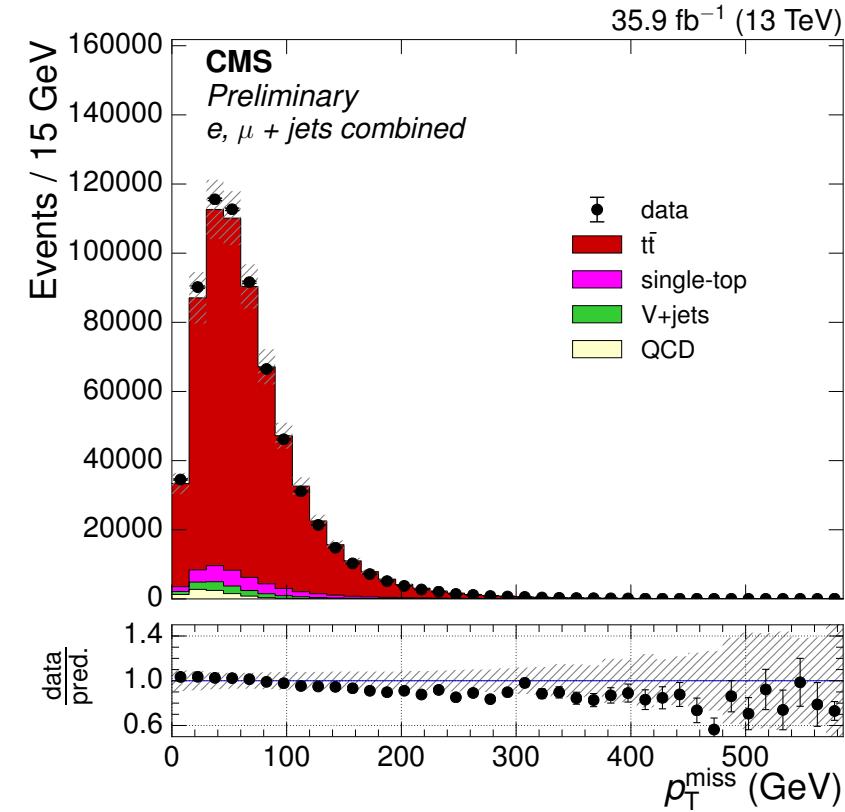
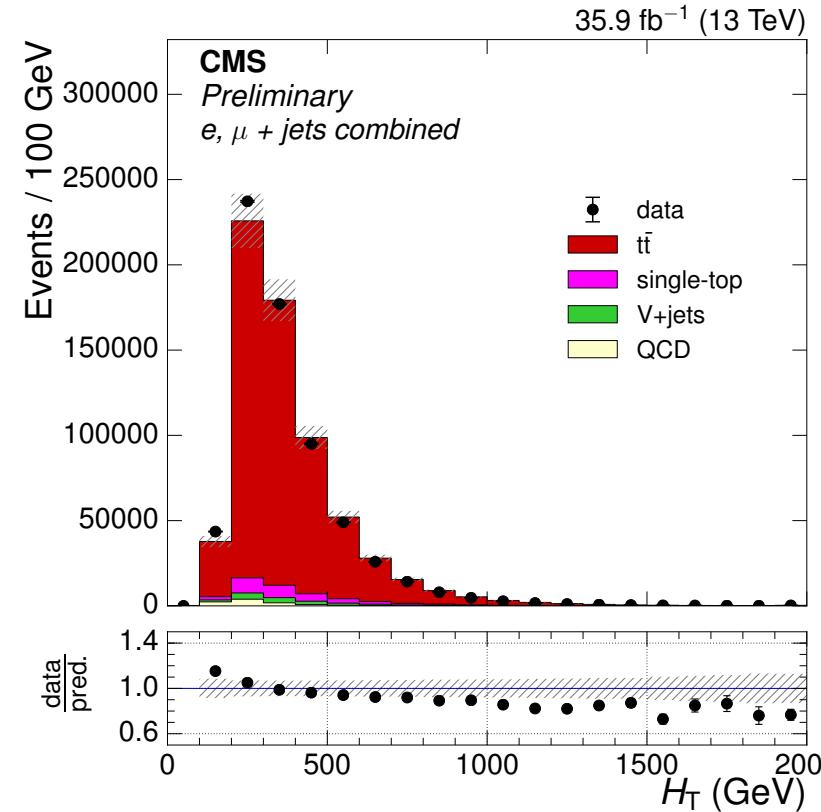
- SHERPA prediction has been compared
- MG5\_aMC@NLO + PYTHIA8 has the best agreement

CMS-PAS-TOP-16-014

 $p_T$  of the leptonically decaying W $p_T$  of the lepton

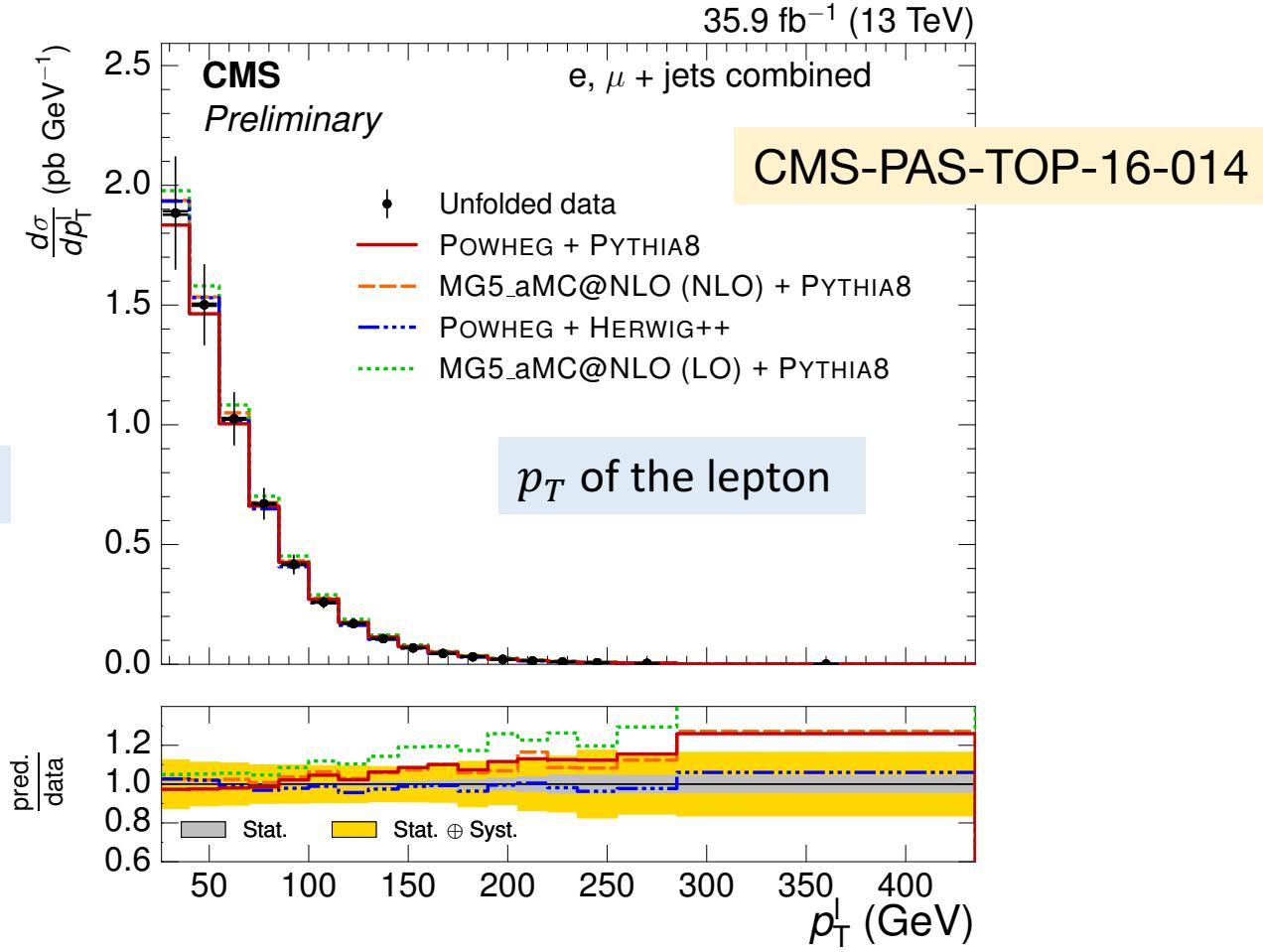
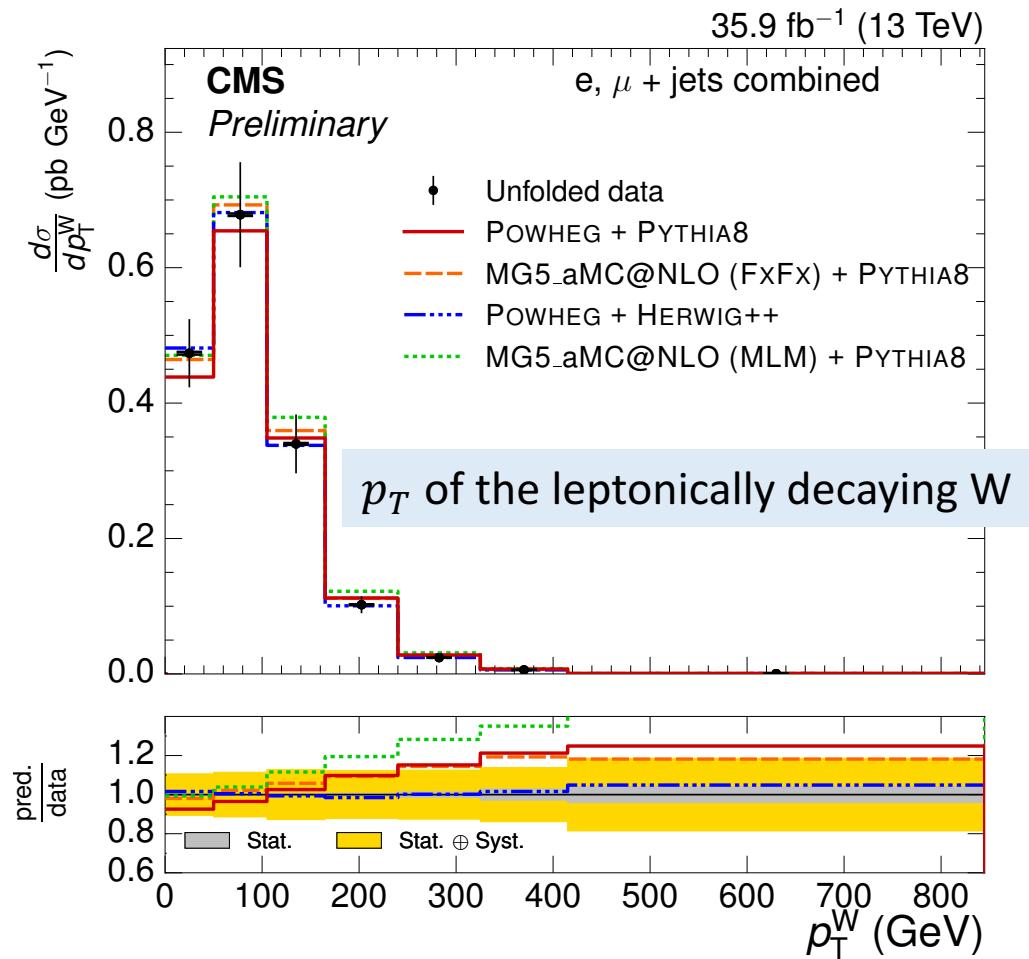
number of jets

CMS-PAS-TOP-16-014

Scalar sum of the jet  $p_T$ 

Missing transverse momentum

Sum of  $H_T$ ,  $p_T^{\text{miss}}$  and  $p_T^l$

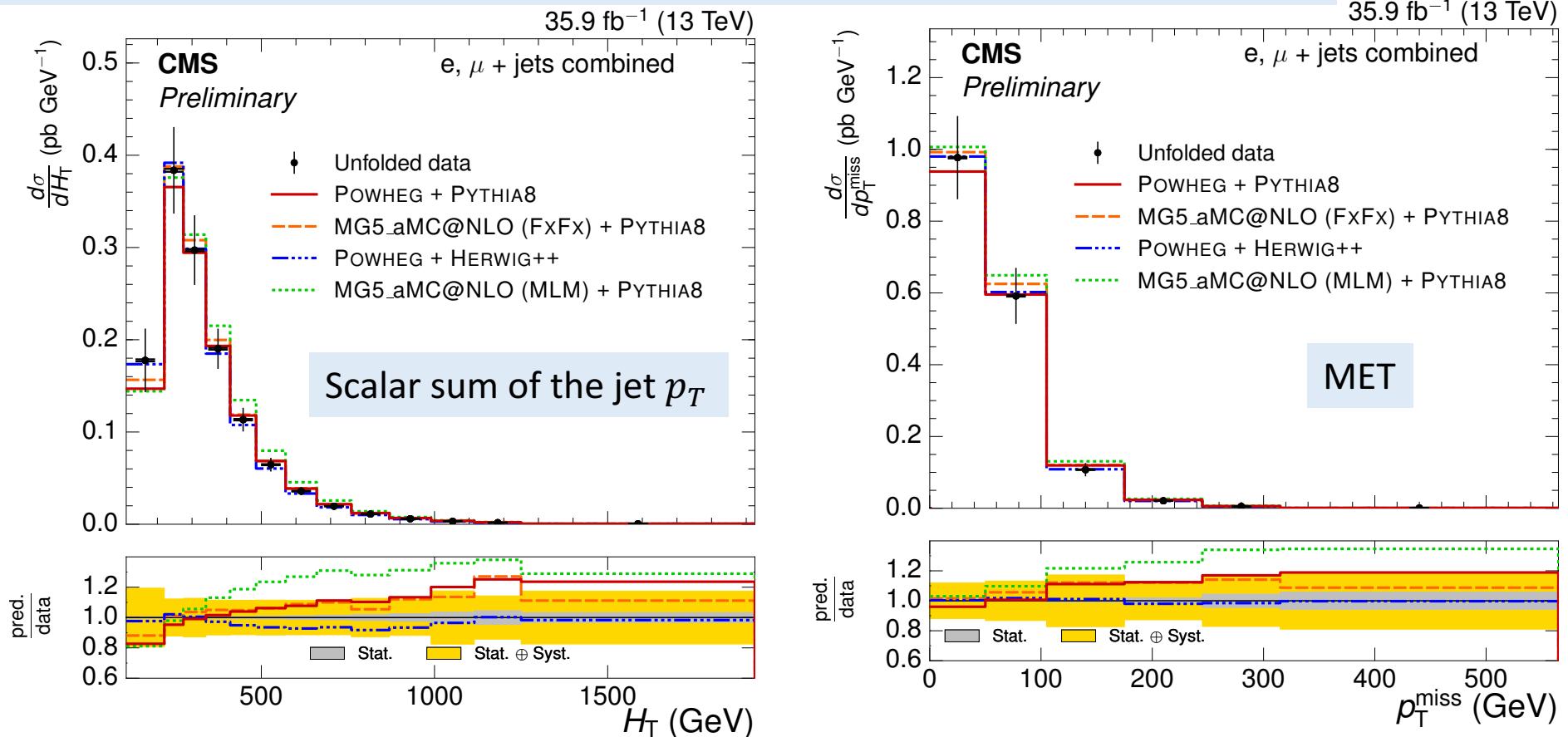


- MG5\_aMC@NLO (LO) simulation does not accurately describe distributions in data
- Three of other predictions have general agreement with data

Global variables in lepton + jets with  $36 \text{ fb}^{-1}$ 

- Using global variable distributions, a  $\chi^2$  test was performed
- POWHEG + PYTHIA8 has a general agreement ( $\chi^2/\text{ndf} = 100.4/62$ )

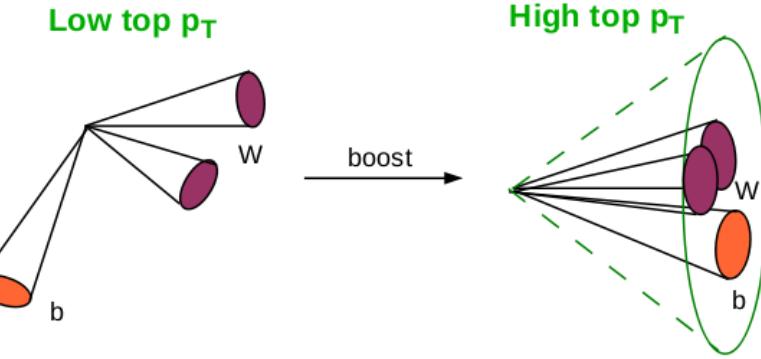
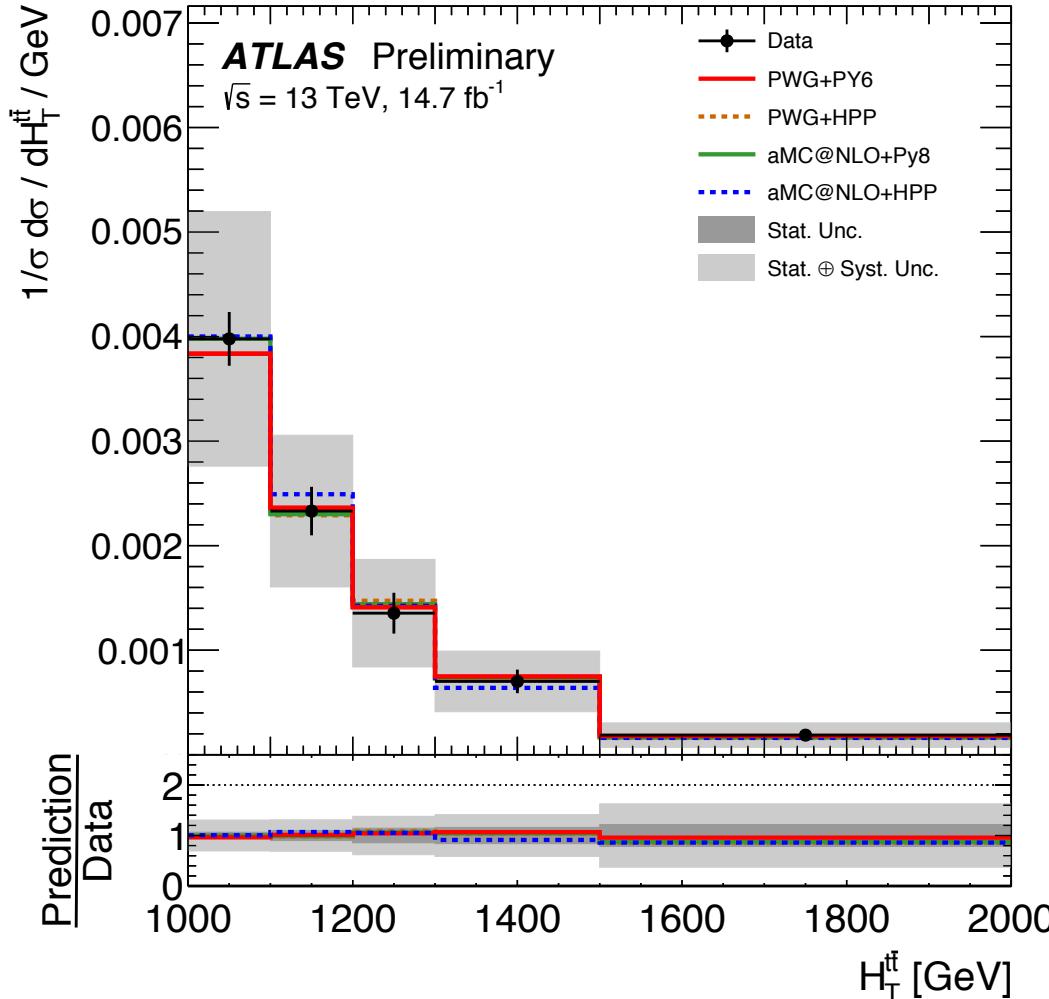
CMS-PAS-TOP-16-014



- POWHEG + HERWIG++ has the best agreement ( $\chi^2/\text{ndf} = 62.5/62$ )
- MG5\_aMC@NLO (NLO) + PYTHIA8 has a similar level of agreement ( $\chi^2/\text{ndf} = 75.9/62$ )

# Highly boosted top (ATLAS)

ATLAS-CONF-2016-100



- All hadronic channel
- $p_T^1 > 500 \text{ GeV}, p_T^2 > 350 \text{ GeV}$
- Boosted top quark S/B  $\sim 3$
- Conceivable to pursue more detailed study for high  $p_T$  SM

# Conclusion

- (b) Jet/additional jet multiplicity and global event variables are presented comparing with various MC predictions
- POWHEG+PYTHIA8 / POWHEG + HERWIG++ / MG5\_aMC@NLO (FxFx) has a general agreement with data
- When it comes to additional b jets, Herwig++ shows some deviations.
- No single simulation provides a good description of all variables simultaneously
- ATLAS+CMS differential measurements are available at 8 TeV and 13 TeV with high precision
- Need to compare with each other and improve theory modelling
- Many differential cross section measurements with more data of  $36\text{ }fb^{-1}$  are coming soon

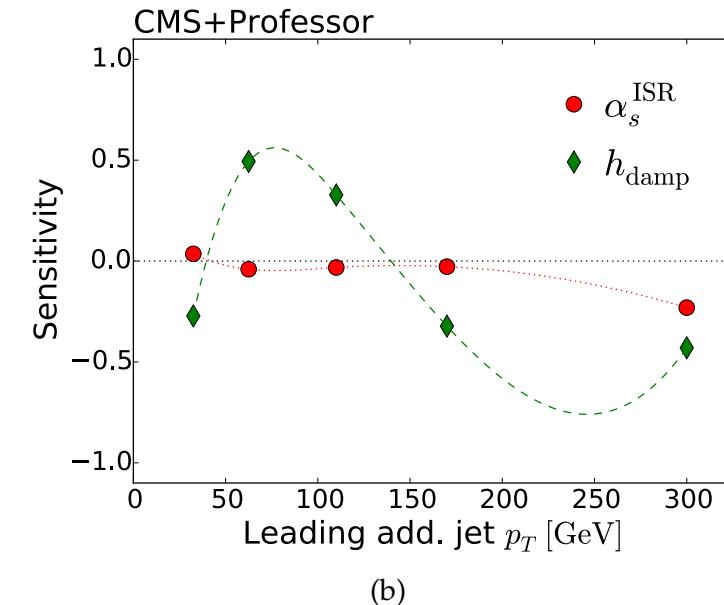
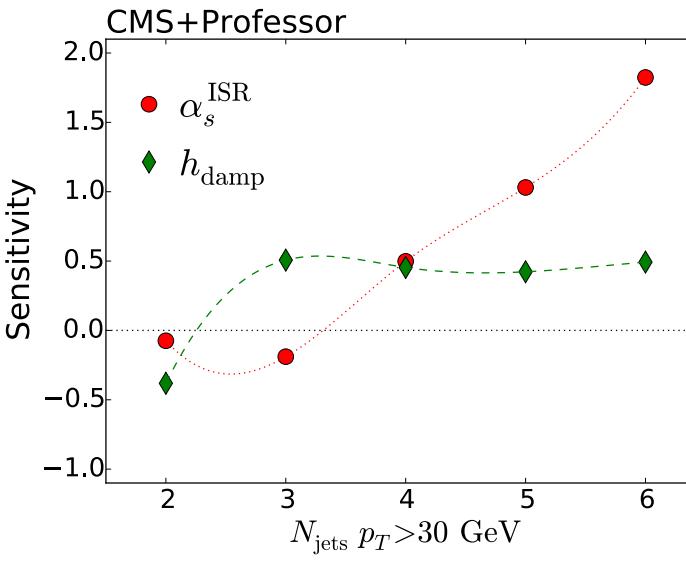
# Tuning with $\alpha_s^{ISR}$ and $h_{damp}$

POWHEG :  $h_{damp}$  = controls of the  $p_T$  of the first additional emission beyond the Born configuration (default is top quark mass 172.5 GeV)  
 → regulate the high- $p_T$  emission against top quark pair system recoils

CMS-PAS-TOP-16-021

damping real emission generated by POWHEG with a factor  $\frac{h_{damp}^2}{(p_T^2 + h_{damp}^2)}$

PYTHIA 8:  $\alpha_s^{ISR}$  is the value of the strong coupling at  $m_Z$  (default is 0.1365)



Tune using the 8 TeV data

$$h_{damp} = 1.581^{+0.658}_{-0.585} \times m_t, \quad \alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$

# Event categorization

- Particle level signal definition for  $t\bar{t}$ +heavy flavor

## CMS event categorization (dilepton)

### Visible phase space

$t\bar{t}jj : n_{leptons} = 2, n_{b-jets} \geq 2$  and  $n_{jets} \geq 4$

$t\bar{t}b\bar{b} : t\bar{t}jj + n_{b-jets} \geq 4$

$t\bar{t}bj : t\bar{t}jj + n_{b-jets} = 3$

$t\bar{t}c\bar{c} : t\bar{t}jj + n_{c-jets} \geq 2$

$t\bar{t}LF : t\bar{t}jj - t\bar{t}b\bar{b} - t\bar{t}bj - t\bar{t}c\bar{c}$

### Full phase space

$t\bar{t}jj : n_{jets \text{ not from top}} \geq 2$

$t\bar{t}b\bar{b} : t\bar{t}jj + n_{b-jets \text{ not from top}} \geq 2$

## ATLAS event categorization

Shorthand notation for the templates		Particle-level event requirements
$t\bar{t}b$ lepton-plus-jets		
$t\bar{t}b$		$n_{leptons} = 1, n_{jets} \geq 5$ and $n_{b-jets} \geq 3$
$t\bar{t}c$		$n_{leptons} = 1, n_{jets} \geq 5$ and $n_{b-jets} = 2$ and $n_{c-jets} \geq 1$
$t\bar{t}l$		other events
$t\bar{t}b e\mu$		
$t\bar{t}b$		$n_{jets} \geq 3$ and $n_{b-jets} \geq 3$
$t\bar{t}c$		$n_{jets} \geq 3$ and $n_{b-jets} \leq 2$ and $n_{c-jets} \geq 1$
$t\bar{t}l$		other events
$t\bar{t}bb$ dilepton fit-based		
$t\bar{t}bb$		$n_{jets} \geq 4$ and $n_{b-jets} \geq 4$
$t\bar{t}bX$		$n_{b-jets} = 3$
$t\bar{t}cX$		$n_{b-jets} = 2$ and $n_{c-jets} \geq 1$
$t\bar{t}lX$		other events



has to rely on MC mother particle information