ttbar Differential Distributions: Comparison to MCs and Interpretation

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TOP LHC WG Meeting
21 November 2016

Previous Run 2 MC Studies

- *Comparison of Monte Carlo generator predictions to ATLAS measurements of top pair production at 7 TeV*, **ATL-PHYS-PUB-2015-002**, http://cds.cern.ch/record/1981319
- *Simulation of top-quark production for the ATLAS experiment at √s =* 13 *TeV*, **ATL-PHYS-PUB-2016-004**, http://cds.cern.ch/record/2120417
- *Further studies on simulation of top-quark production for the ATLAS experiment at √s =* 13 *TeV*, **ATL-PHYS-PUB-2016-016**, http://cds.cern.ch/record/2205262
- *Comparisons of MC generator predictions for ttbar with data at √s= 8 TeV.* **CMS-PAS-TOP-15-011**, http://cds.cern.ch/record/2110635
- *Tuning α_s^{ISR} in Powheg+Pythia8 in the ttbar process*, Supplement to **CMS-PAPER-TOP-12-041**, http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-12-041/index.html#AddFig

New Studies

- *Studies of top-quark Monte Carlo modelling for Top2016*, **ATL-PHYS-PUB-2016-020**, https://cds.cern.ch/record/2216168
  - Optimization of Powheg+Pythia8 and Powheg+Herwig7 and comparisons with alternative setups.
  - Simulating interference effects between ttbar and single-top. ⟶ Discussion this afternoon.
- *Investigations of the impact of the parton shower tuning in Pythia 8 in the modelling of ttbar at √s=8 and 13 TeV*, **CMS-PAS-TOP-16-021**,
  - Tuning of Powheg+Pythia8 through ttbar and global event variables and comparisons with alternative setups.

- Most modelling studies rely on RIVET.
  - All of the ATLAS differential and other measurements and the necessary CMS measurements are available in Rivet and more are coming.

Monte Carlo For Run 2

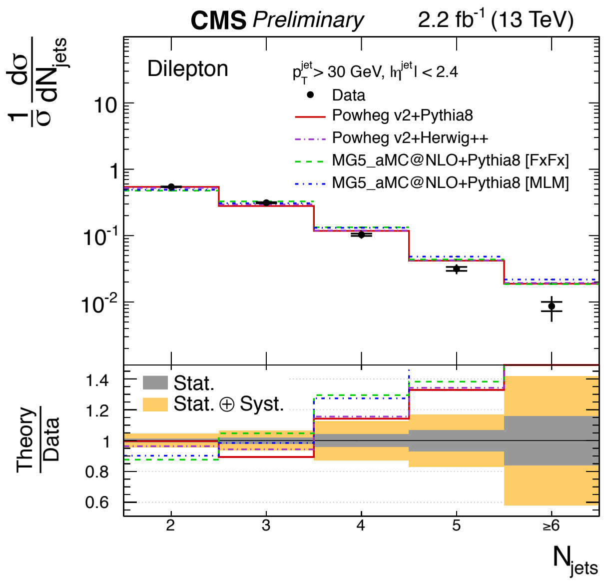
- Powheg_v2+Pythia8: ttbar [NLO], 1 jet [LO], ≥2 jets [PS]
- aMC@NLO + Pythia 8: ttbar [NLO], 1 jet [LO], ≥2 jets [PS]
- MG5_aMC@NLO + Pythia8 [MLM]: ttbar+0,1,2,3 jets [LO], ≥4 jets [PS]
- MG5_aMC@NLO + Pythia8 [FxFx]: ttbar+0,1,2 jets [LO], ≥3 jets [PS]
- Powheg+Herwig7: ttbar [NLO], 1 jet [LO], ≥2 jets [PS]
- Sherpa [MEPS@NLO]: ttbar+0,1,2 [NLO], ≥3 [LO]

Only ATLAS (for now)

- Event tunes: A14, CUETP8M1, CUETP8M2T4 (new), EE5C, H7UE, …
- Matching/merging: Powheg, MLM, FxFx, CKKW-L, MEPS@NLO, …

Jet Activity in ttbar Events

Jet Multiplicity at √s = 13 TeV and Shower α_s+h_{damp} Tuning



- Predictions overshoot the data for jet large multiplicities when out of the box parameters are used (in Monash-based tunes) .

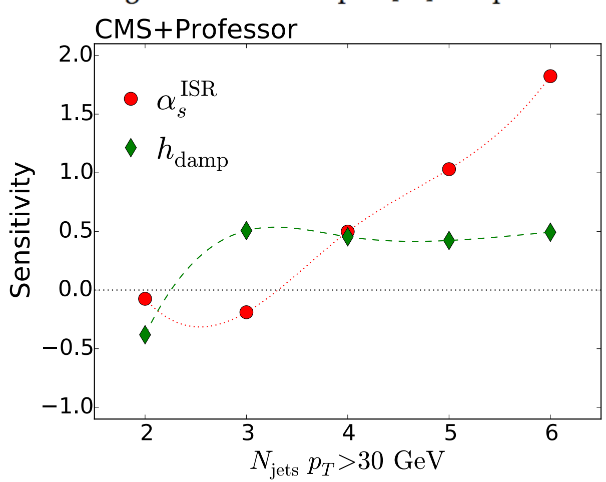
Monash Tune: Skands, Carrazza, Rojo, EPJ C 74 (2014) 1

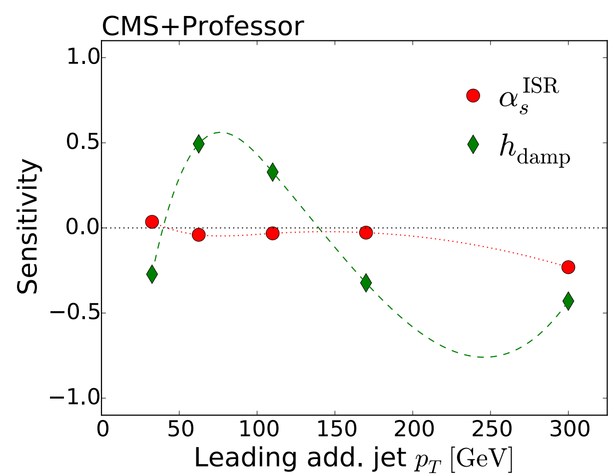
CMS-PAS-TOP-16-011

- POWHEG: hdamp (h_{damp}) is the model parameter that controls ME/PS matching and effectively regulates the high-p_{T} radiation by damping real emissions generated by POWHEG with a factor of $h^2_{\mathrm{damp}} / \left(p^2_{\mathrm{T}} + h^2_{\mathrm{damp}}\right)$. The default value is equal to the top-quark mass $m_t = 172.5$ GeV used in simulation.
- PYTHIA 8: `SpaceShower:alphaSvalue` (α_s^{ISR}) is the value of the strong coupling at m_Z used for the initial-state shower. The default value is $\alpha_s^{\mathrm{ISR}} = 0.1365$ obtained from tuning to LEP event shapes [22] is kept for the final-state shower.

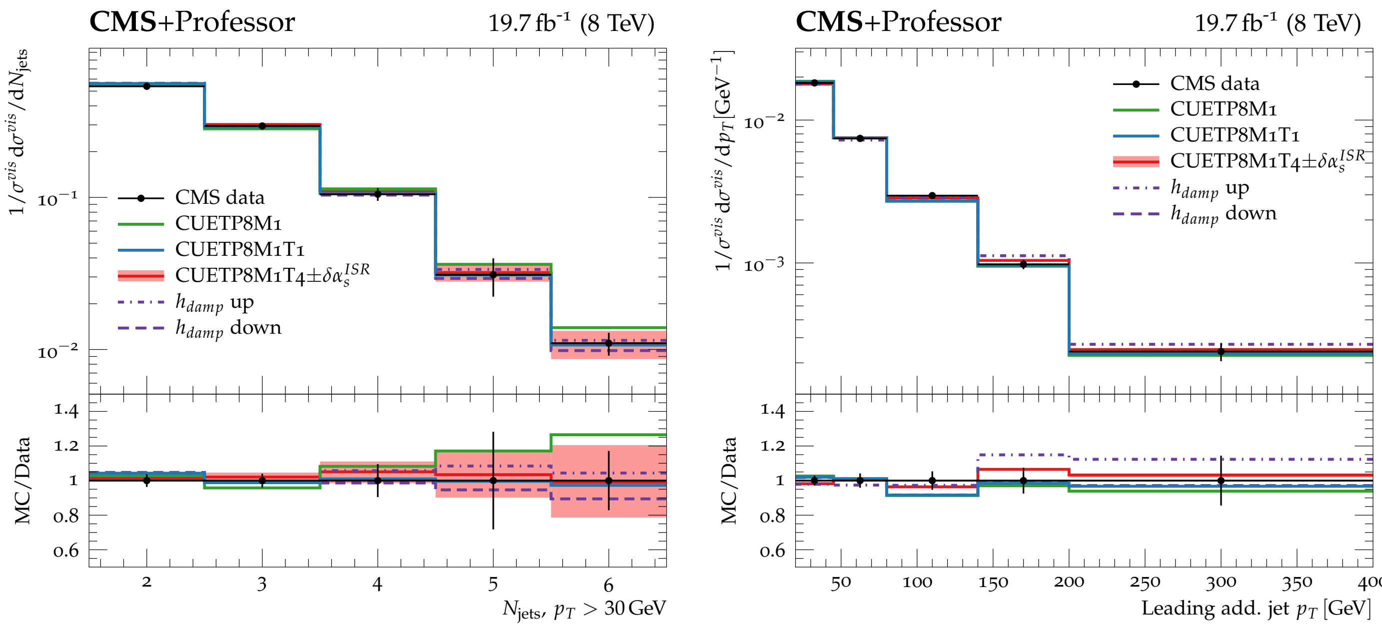
Effect on
→ 2-jet/3-jet events
→ Lead. add. Jet p_T

→ $N_{jets} > 3$





CMS Shower α_s+h_{damp} + UE Tuning



CMS-PAS-TOP-16-021

$$\alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$

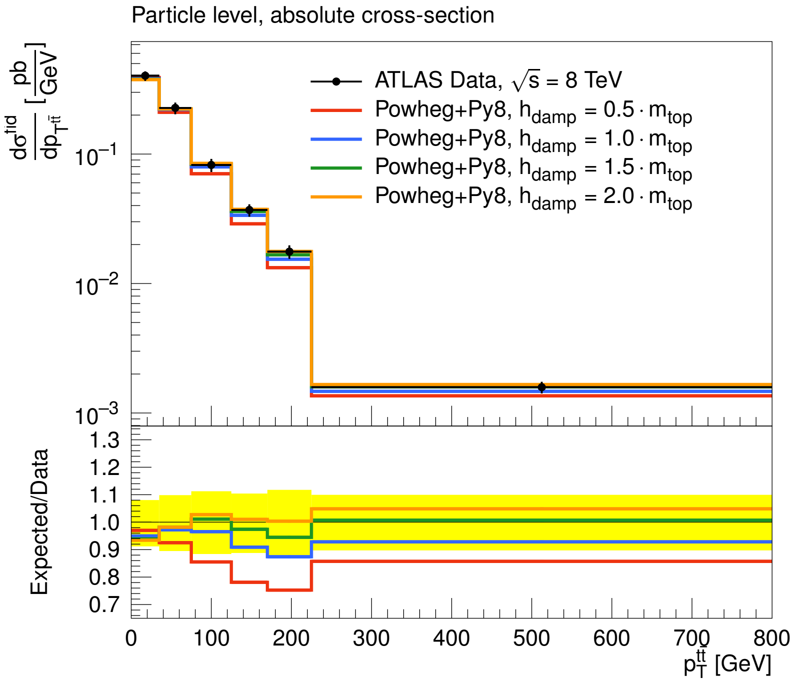
$$h_{damp} = 1.581^{+0.658}_{-0.585} \times m_t$$

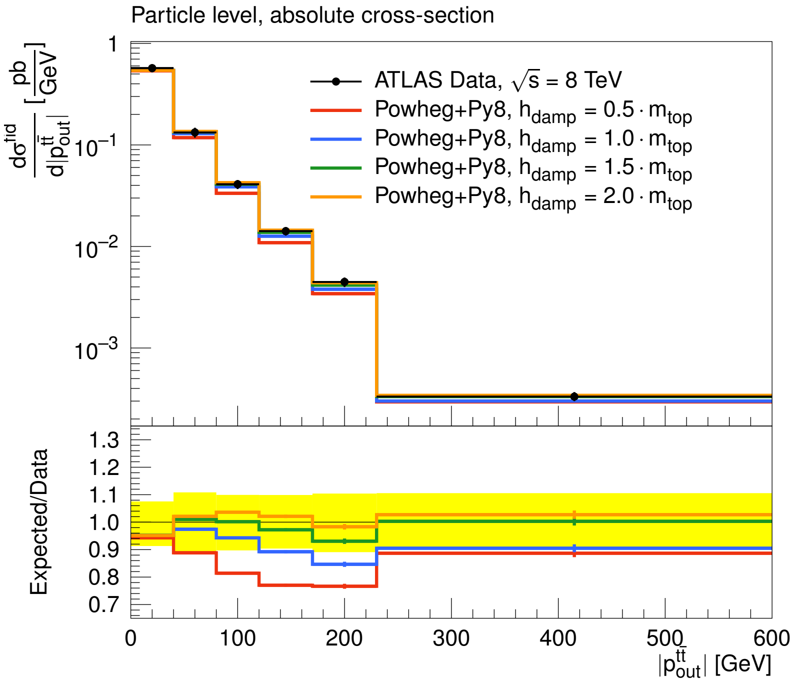
(pThard = 0, pTdef = 1)

- Fixing α_s to 0.1108, a new UE tune is derived optimizing MPI and color reconnection.
- Fit to UE observables at 13 TeV:
  - Charged-particle multiplicity vs leading track p_T and η.
  - Σp_T (in MIN & MAX regions) vs leading track p_T.
- Predictions with the new tune compared to independent measurements
- *New tune is used in Run 2 (2016) ttbar samples.*

ATLAS h_{damp} Tuning

ATL-PHYS-PUB-2016-020





$$h_{damp} = 1.5 \times m_t$$
$$\left(\alpha_s^{ISR} = 0.127\right)$$

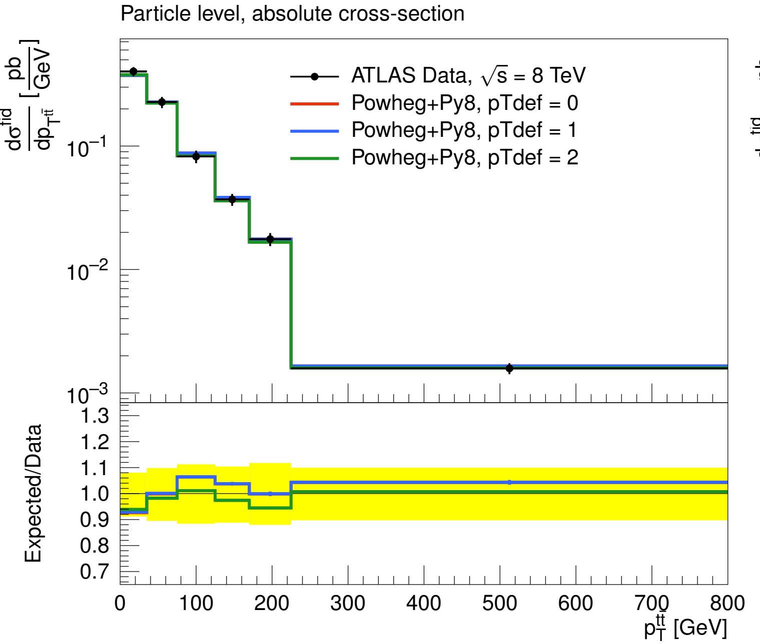
Out-of-plane momentum of $p_{t,had}$ w.r.t. $p_{t,lep}$ – beamline (z) plane.

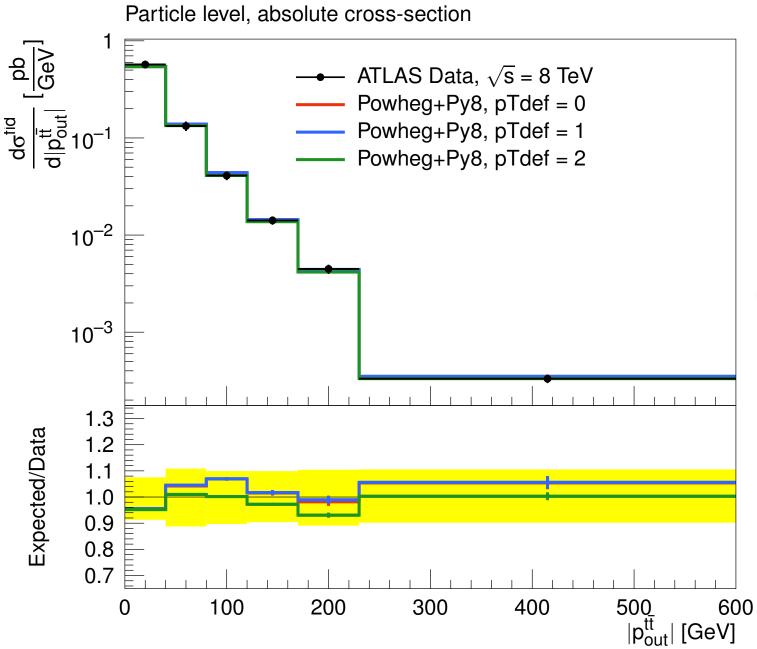
$$|p_{\rm out}^{t\bar{t}}| = \left| \vec{p}_{t,\rm had} \cdot \frac{\vec{p}_{t,\rm lep} \times \hat{z}}{|\vec{p}_{t,\rm lep} \times \hat{z}|} \right|$$

- h_{damp} compatible with run 1 tuning results.
- Both h_{damp}=m_t and =$1.5m_t$ give good agreement.
- ATLAS and CMS hdamp values compatible.

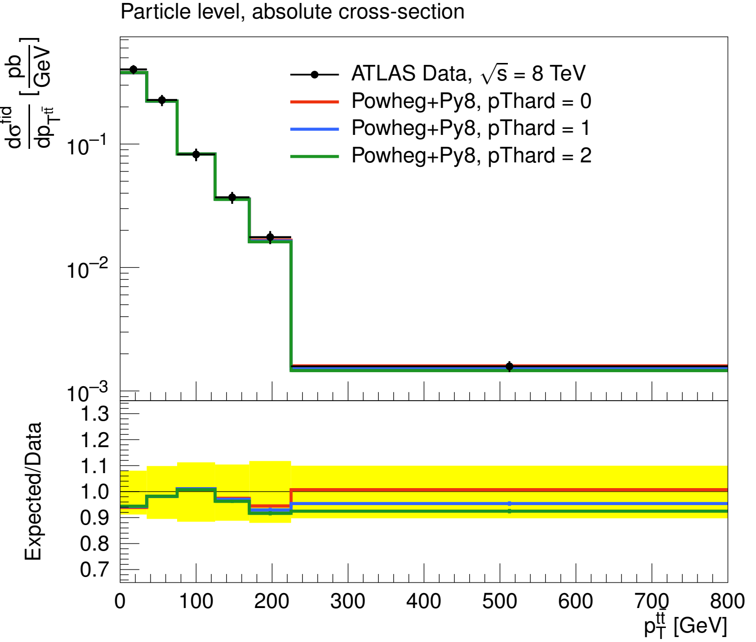
ATLAS h_{damp} Tuning

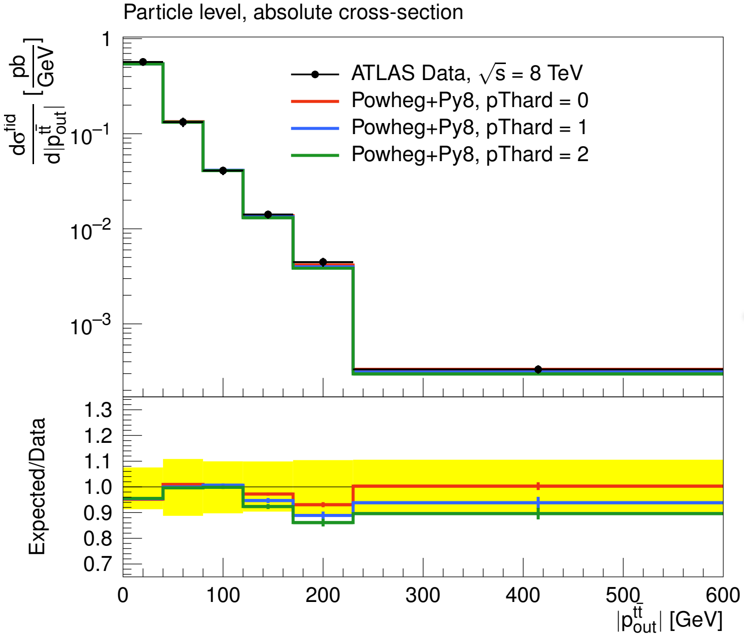
ATL-PHYS-PUB-2016-020





→ pTdef = 2





→ pThard = 0

Tuned Powheg+Pythia8 Parameters

ATLAS

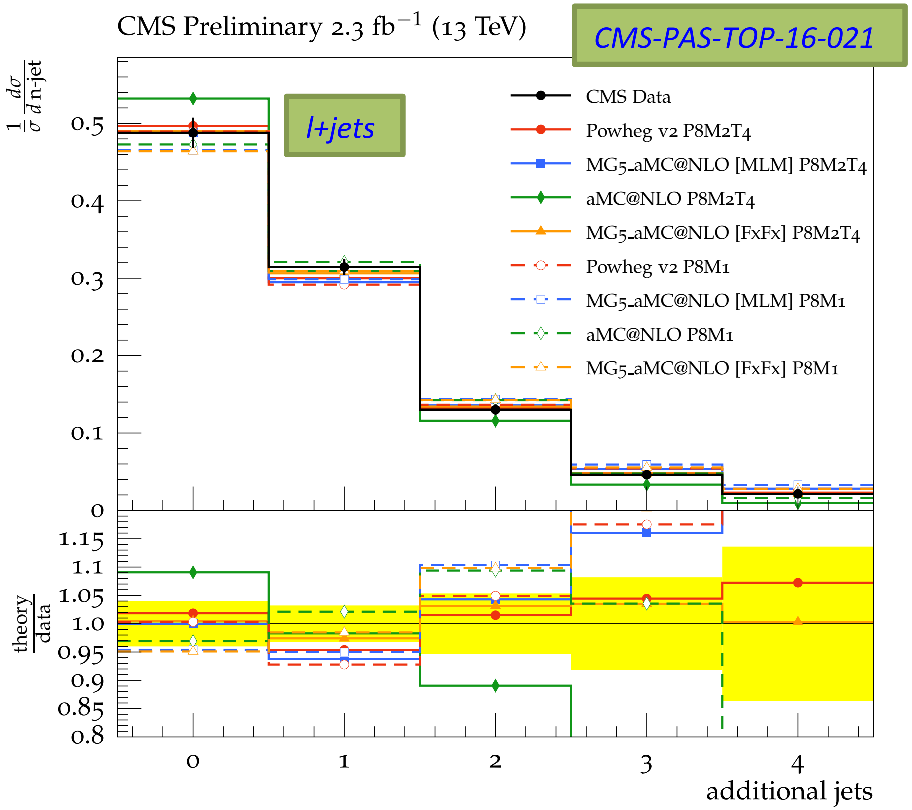
$$\alpha_s^{ISR} = 0.127$$
$$h_{damp} = 1.5$$
$$pThard = 0$$
$$pTdef = 2$$

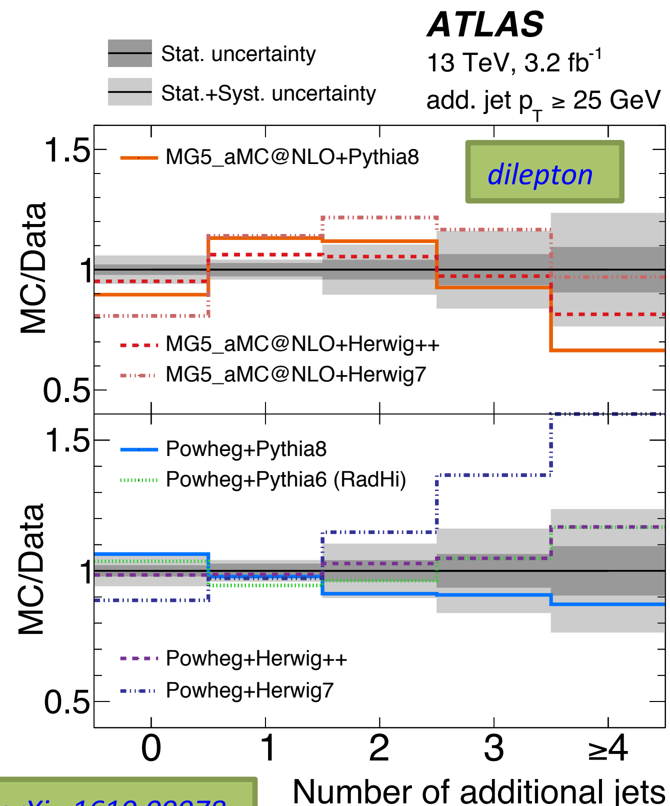
CMS

$$\alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$
$$h_{damp} = 1.581^{+0.658}_{-0.585} m_t$$
$$pThard = 0$$
$$pTdef = 1$$

→ In practice, since pythia and powheg definitions are not much different, the effect is small and the ATLAS plots in *ATL-PHYS-PUB-2016-020* confirm that.

Number of Additional Jets



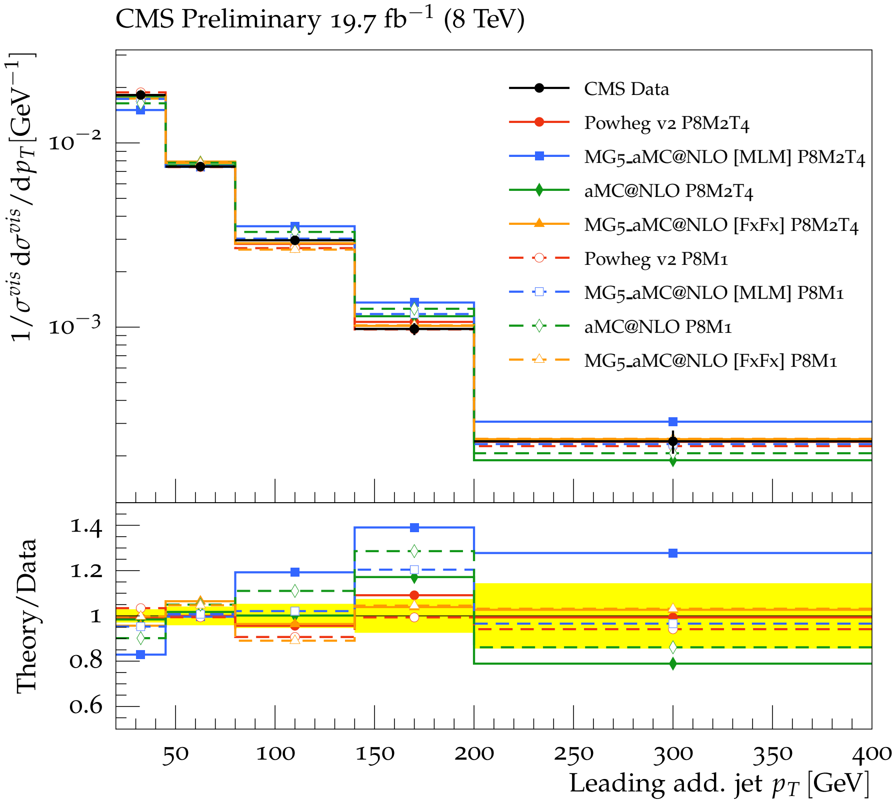


arXiv:1610.09978

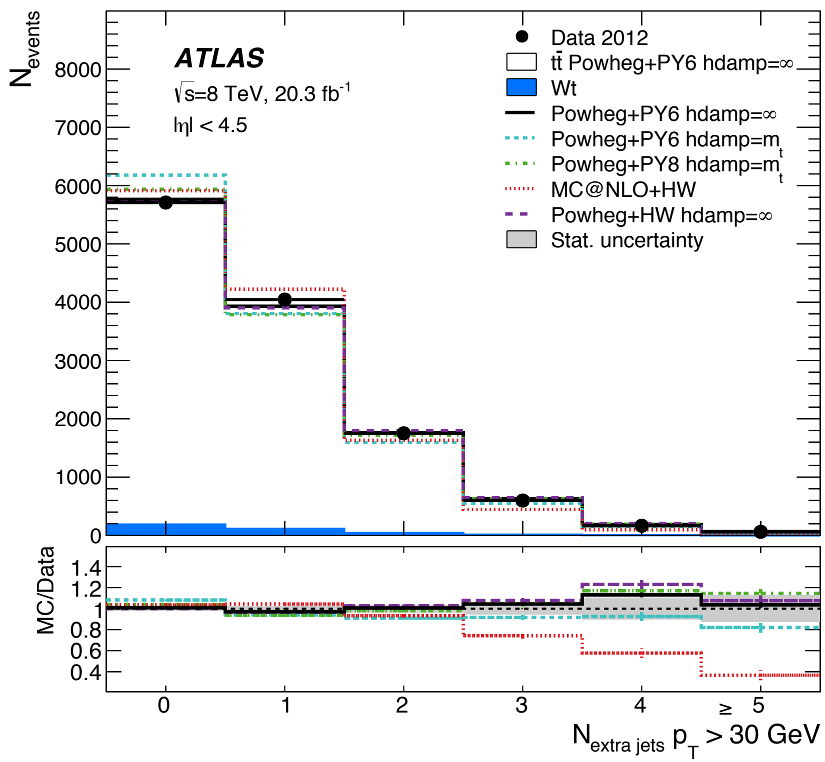
- Powheg works well.
- MG5_aMC@NLO [FxFx]+Pythia8 → Almost as good as good as Powheg
  - Dedicated studies needed to tune MG5_aMC@NLO considering matching options.
- MG5_aMC@NLO [MLM] and aMC@NLO + Pythia8 with the new CMS tune → Not good
- Need to better understand Powheg/Mg5_aMC@NLO + Herwig7

Leading Additional Jet p_T

CMS-PAS-TOP-16-021

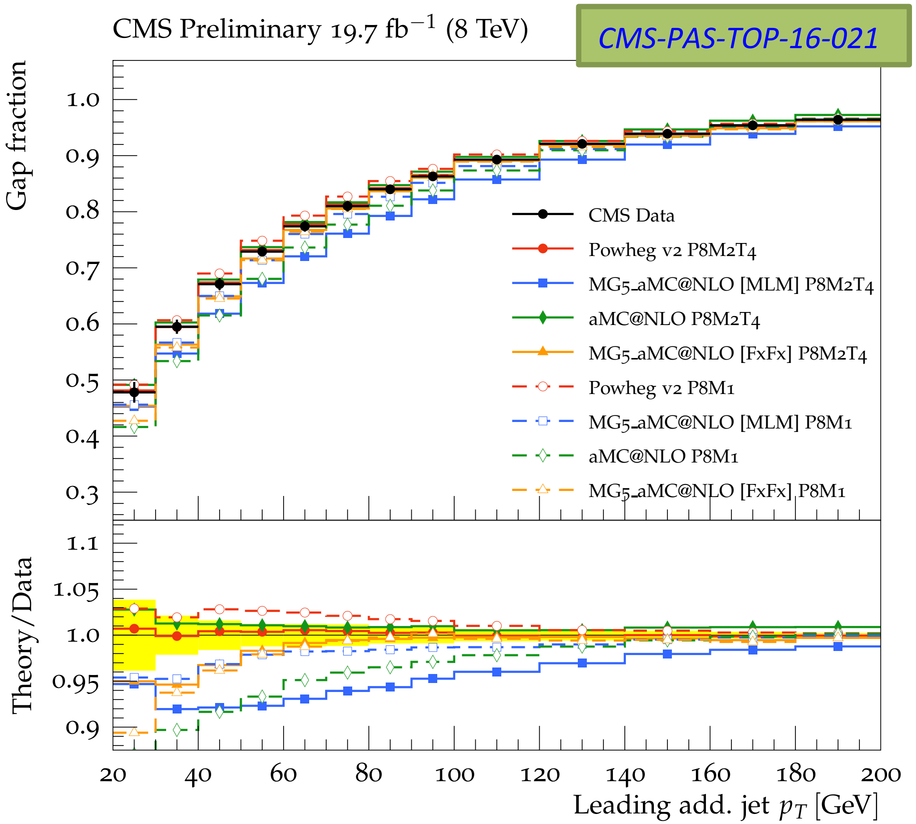


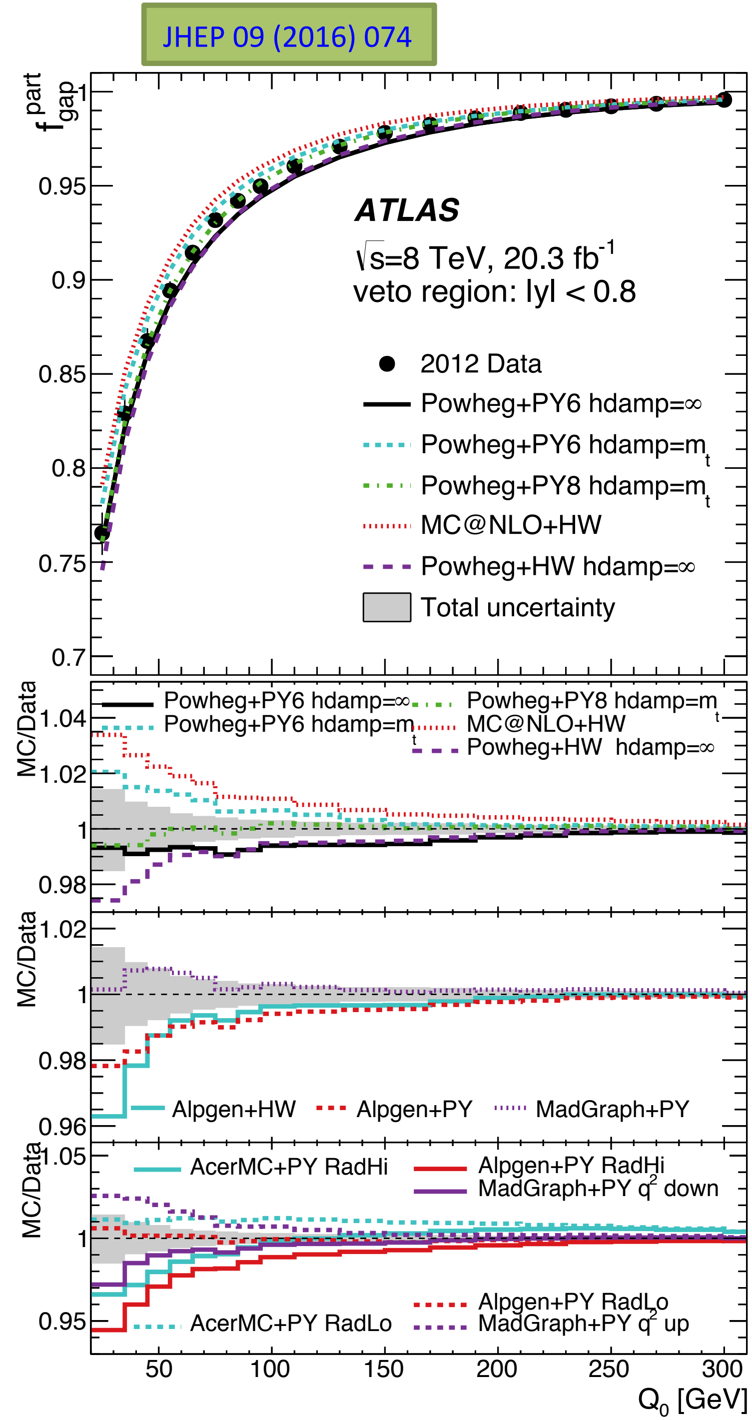
JHEP 09 (2016) 074



- All good
  - except MLM and aMC@NLO w/ the new CMS tune.
  - Except MC@NLO+HW (which also predicts significantly soft pt jet spectra).

Gap Fraction

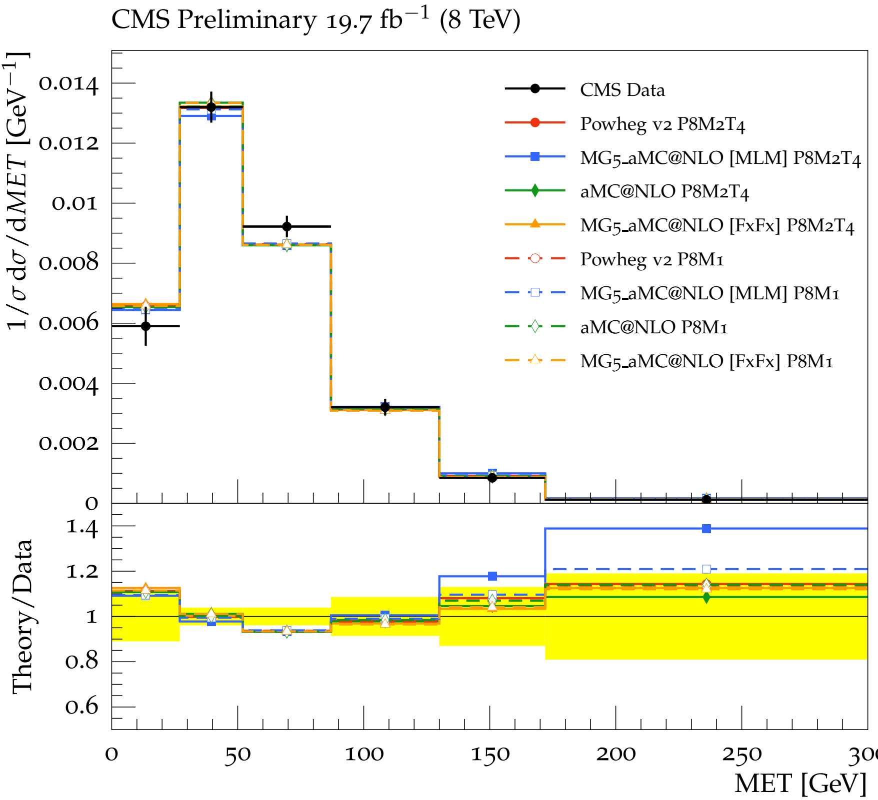


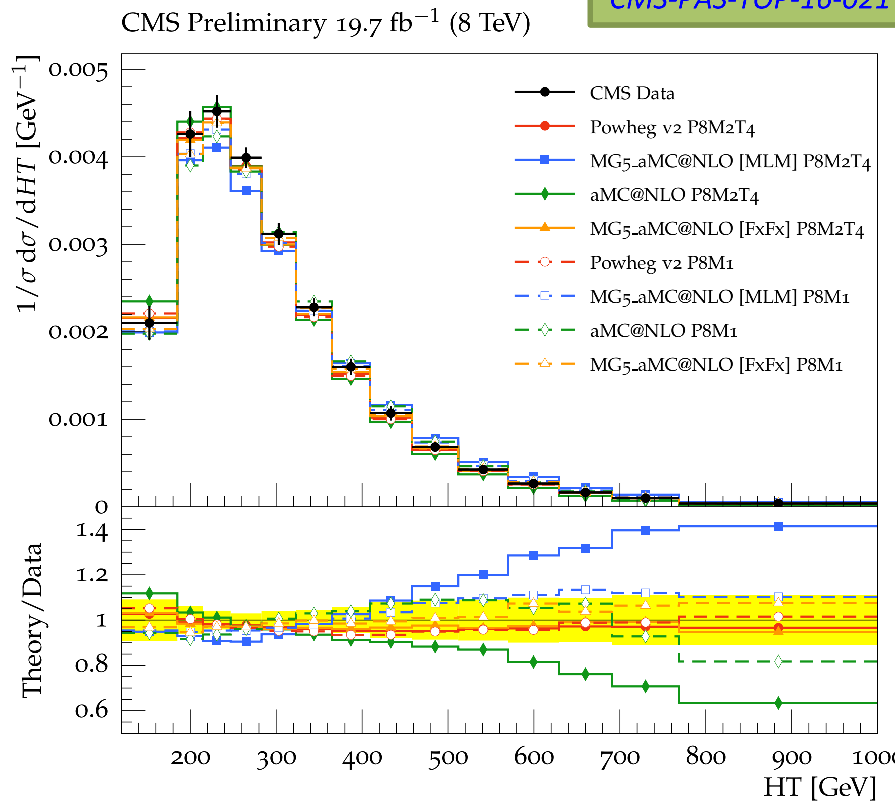


- Gap fraction = fraction of events that don't contain additional jets above a threshold.
  - Best description by
    - Powheg+Pythia8 with the new CMS tune.
    - Powheg +Pythia8 and Alpgen+Pythia (RadLo) with the ATLAS A14 tune.

Global Event Variables

CMS-PAS-TOP-16-021



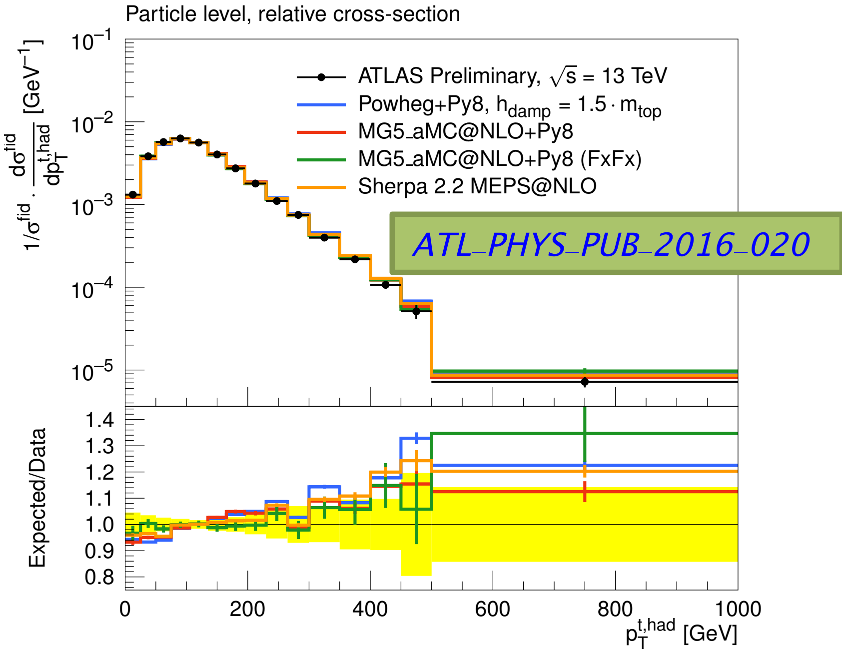


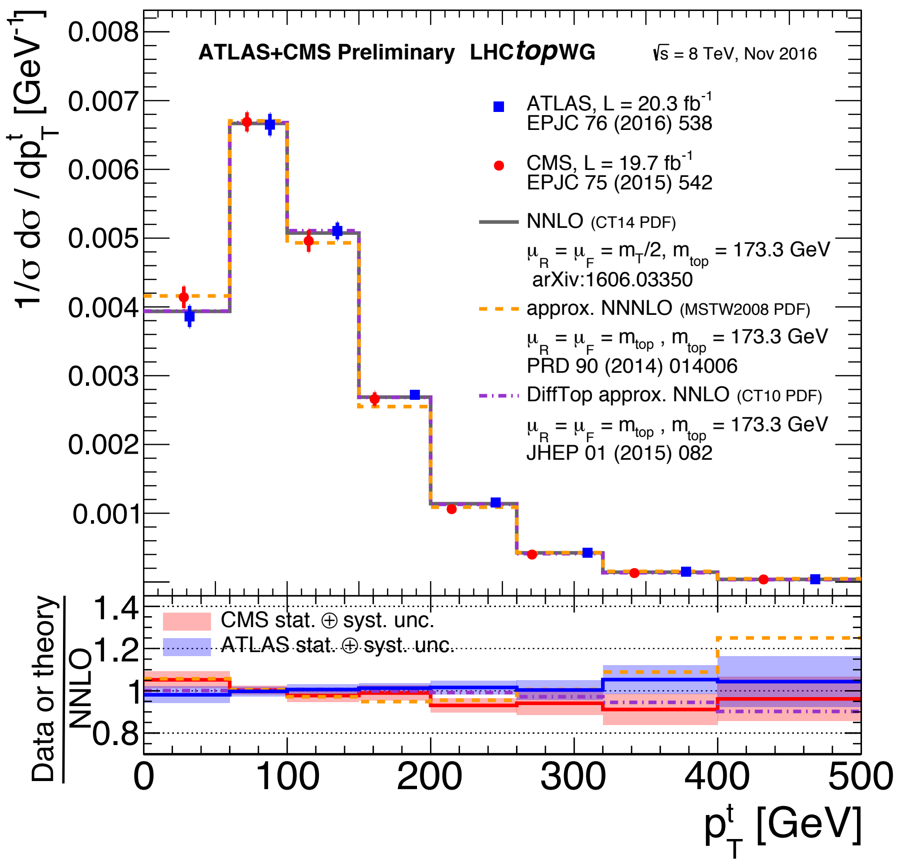
- Distributions important in new physics searches (and some top mass measurements, e.g. tt+jets, ..).
- All unchanged except MLM and aMC@NLO with the new tune.
  - No bias for searches using MET.
  - Search analyses relying on Njets, pT(ttbar) or pT(lead. Add. jet() in ttbar-like process may need particular attention.

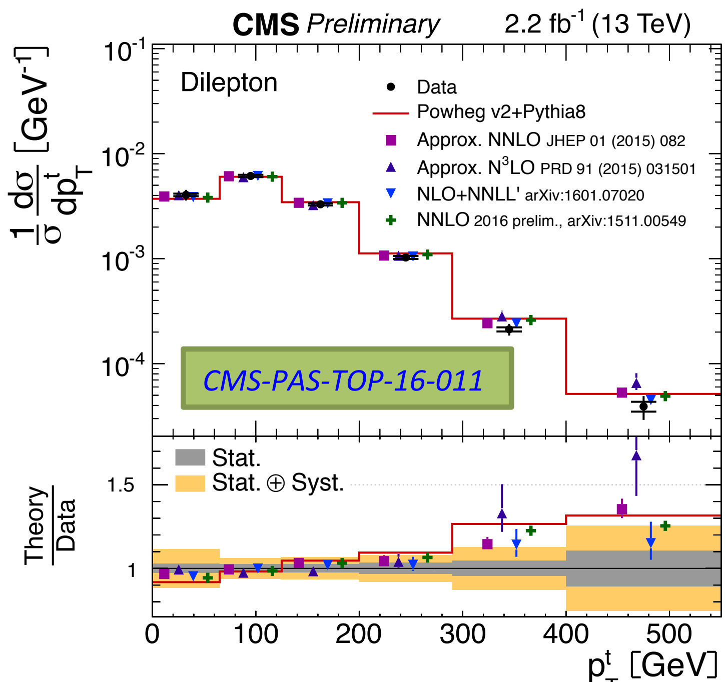
Top Quark and ttbar Kinematics

The Top Quark p_T

- LHC Run 1 "discovery": harder spectrum in LO/NLO+PS predictions than in data.
  - NLO+NNLL/NNLO→ significantly better description of top p_T.
- Similar behavior @ 13 TeV

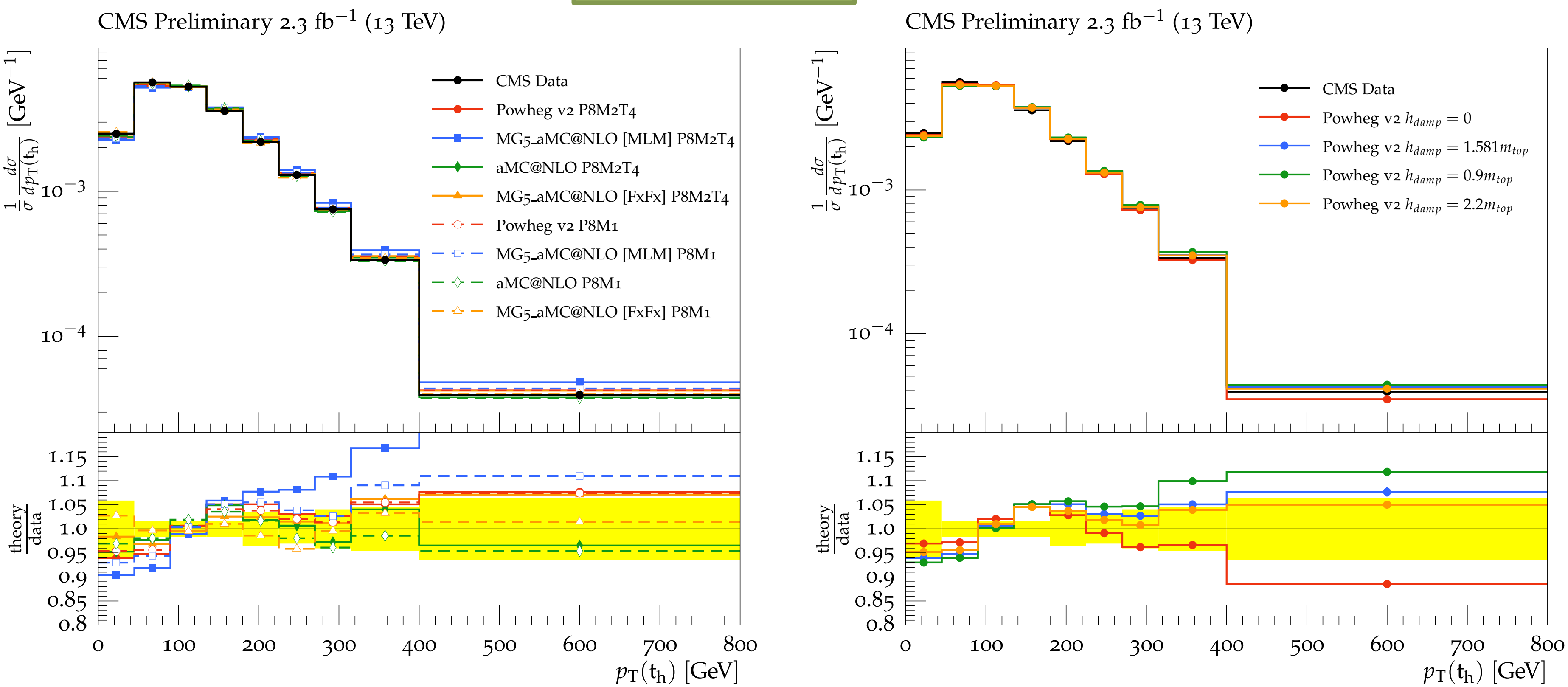






The Top Quark p_T

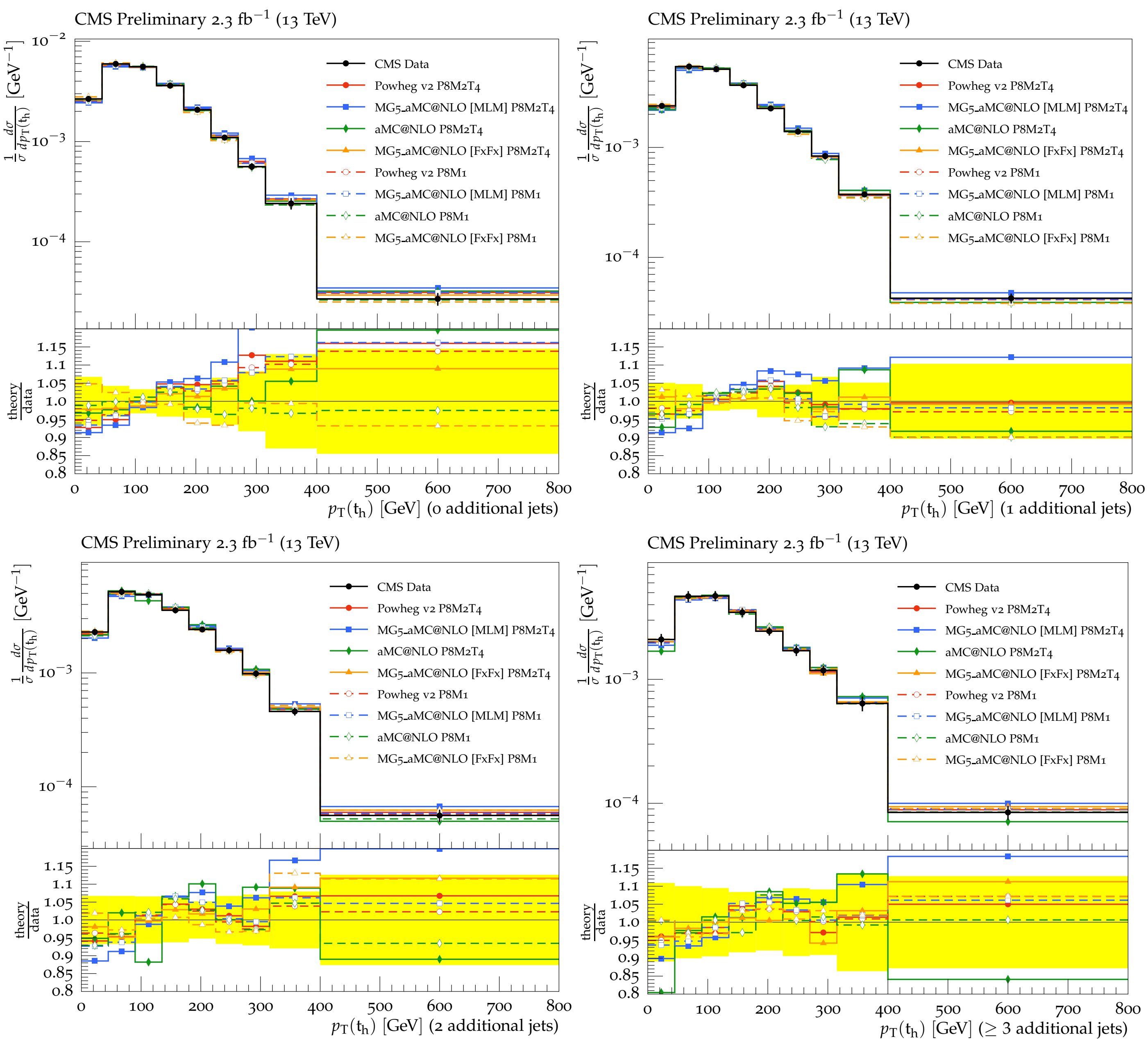
CMS-PAS-TOP-16-021



- NLO MCs show better agreement with data.
- Using NLO MCs with the new tune (or Powheg+Herwig7 shown later), top p_T reweighting uncertainty may already be reduced compared to Run 1?

The Top Quark p_T

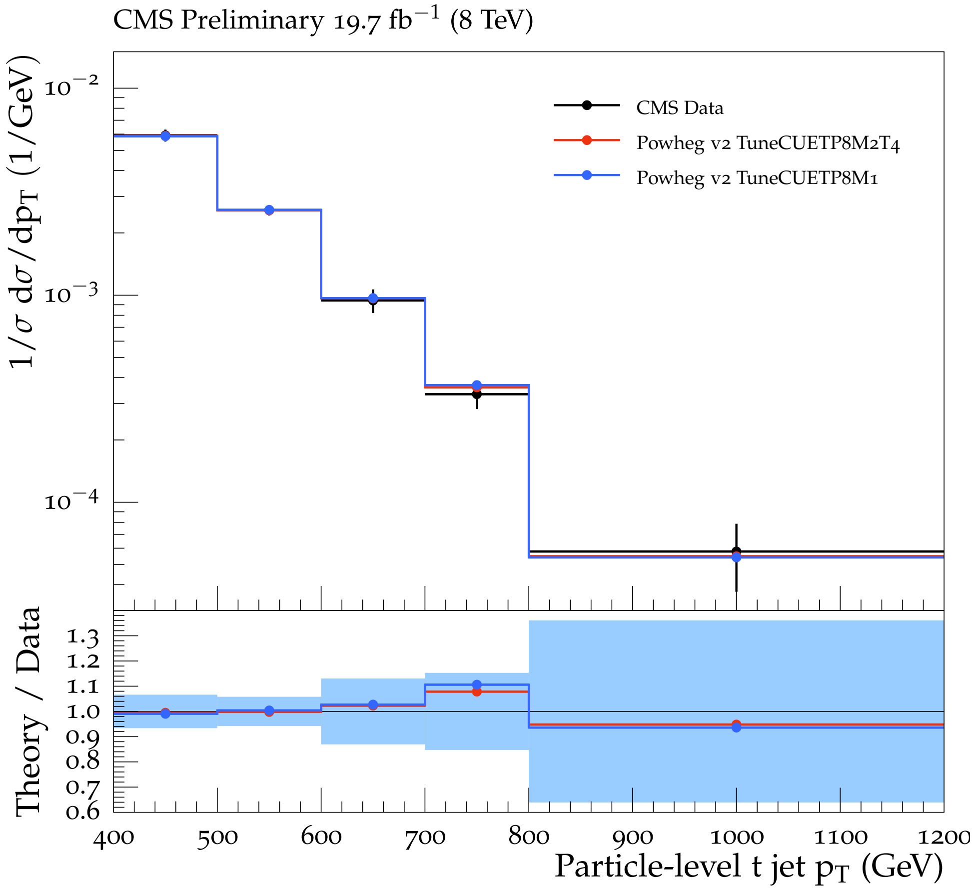
CMS-PAS-TOP-16-021



- For ≥1 additional jets, slope much smaller.

Boosted Top Quark p_T

CMS-PAS-TOP-16-021



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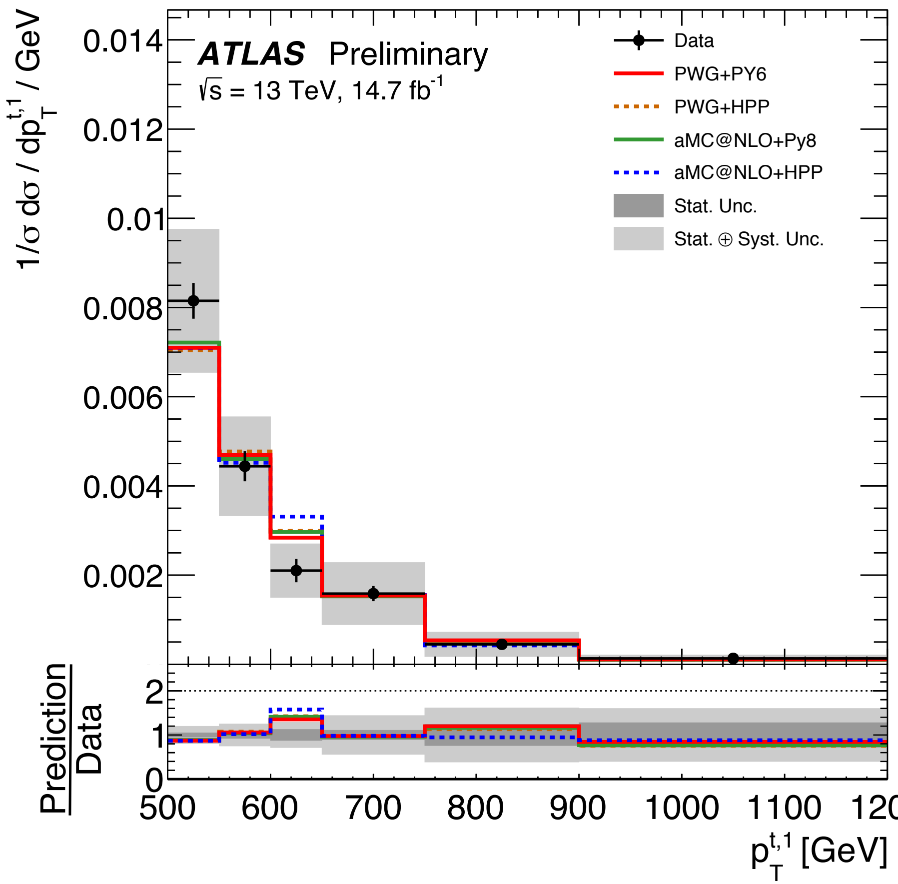
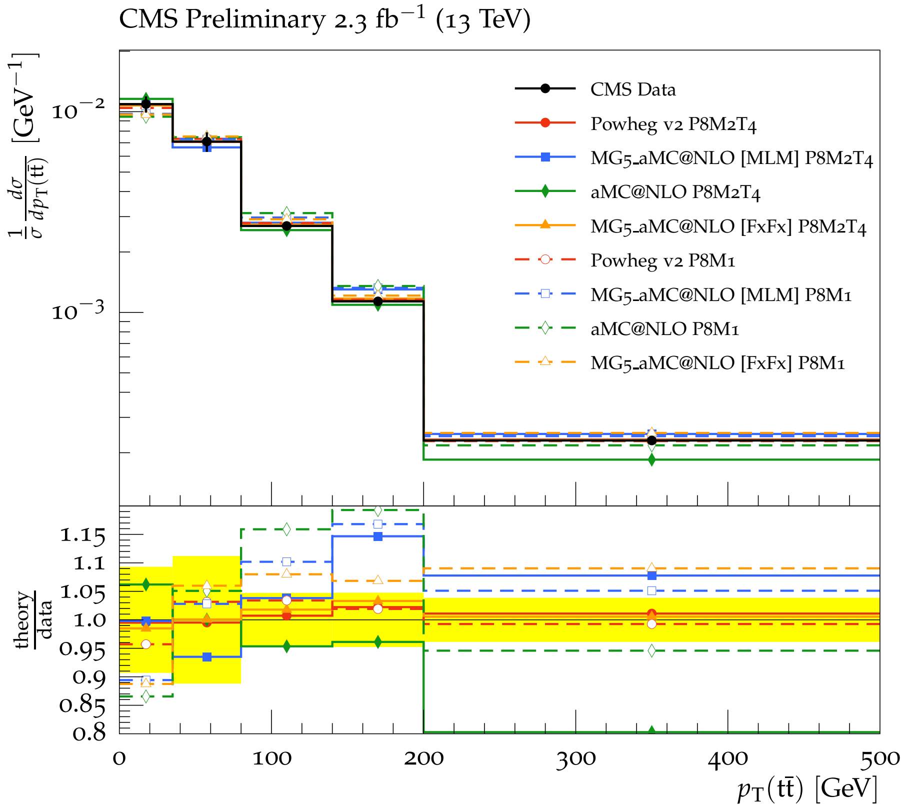


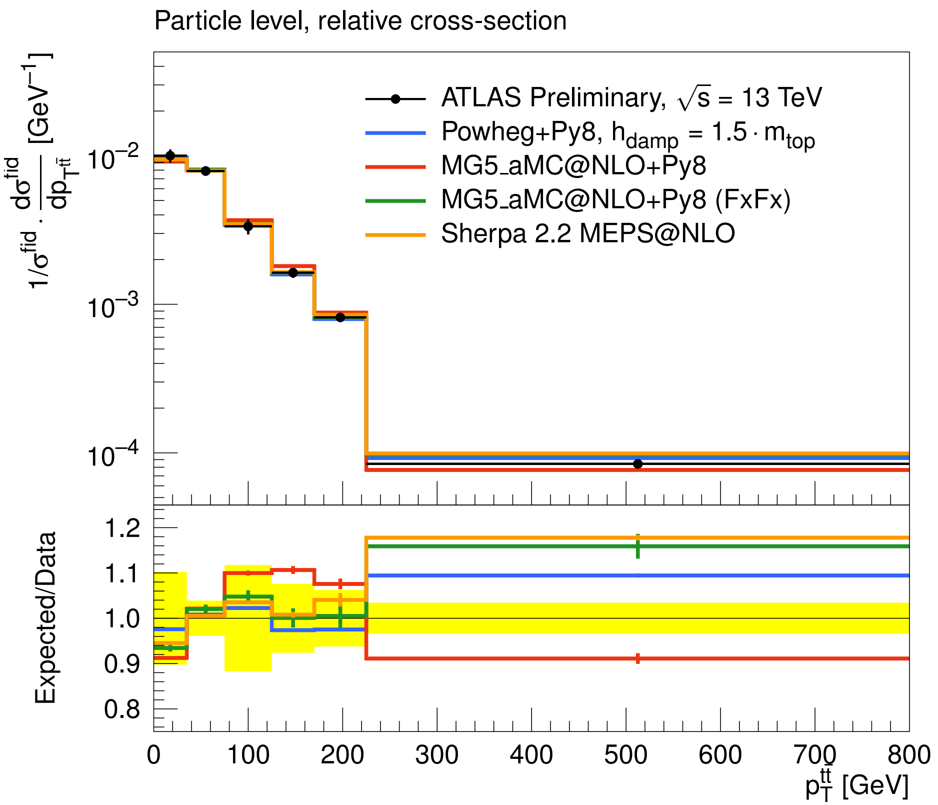
- No significant differences between different configurations.
- Old and new CMS tunes give same results.
- Large uncertainties cover the discrepancies.

Transverse Momentum of the ttbar System

CMS-PAS-TOP-16-021

ATL_PHYS_PUB_2016_020





- Powheg and FxFx with the new CMS tune very good
- ATLAS: MG5_aMC@NLO+Pythia8 with A14 or Sherpa → needs to be understood.
- aMC@NLO with the new CMS tune: large discrepancy at high momentum.
- h_{damp} variations with the new tune bracket the data.

ME and PS Consistency

α_s	MadGraph5 +Pythia6	MG5_aMC@NLO[FxFx] +Pythia8	Powhegv2 +Pythia8 ($1.58m_t$)	MG5_aMC@NLO[MLM] +Pythia8
ME	0.130	0.1180	0.1180	0.130
PS	0.127	0.1108	0.1108	0.1108

Describe most of the differential distributions from data well (except top p_T).

(consistent with ATL-PHYS-PUB-2016-020)

$\delta_{\alpha_s}^{ME,PS} \approx 17\%$

Does not describe the data well.

- Consistency of the α_s value in the PS and ME *may* be important for matched/merged emissions (also see Cooper et al. EPJ C72 (2012) 2078 that advocates this for MLM).
  - Powheg+Pythia: N/A powheg handles first emission, pythia all subsequent emissions.
  - aMC@NLO_Pythia [w/o merging]: applies to first emission
  - MG5_aMC@NLO+Pythia [FxFx & MLM]: applies to first ~3 emissions.

→ Set ME and PS α_s to the same value? → Sub-optimal for subsequent emissions?

→ Additional pythia developments may be needed.

→ Better predictive power of MG5_aMC@NLO over Powheg may become visible?

Scale Variations

Powheg+Pythia8 Scale Variations

- μ_R, μ_F coherent variations by x2 and Var3c down variation from A14 tune.
- μ_R, μ_F coherent variations by x0.5 and Var3c up variation from A14 tune.
- Var3c A14 variations ← α_s(ISR) variation (covers A14 eigentune variations).

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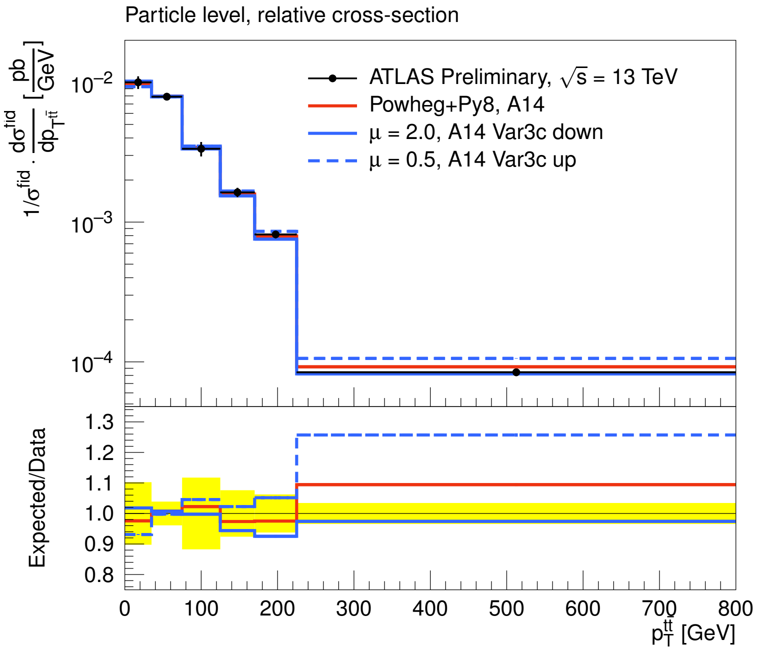
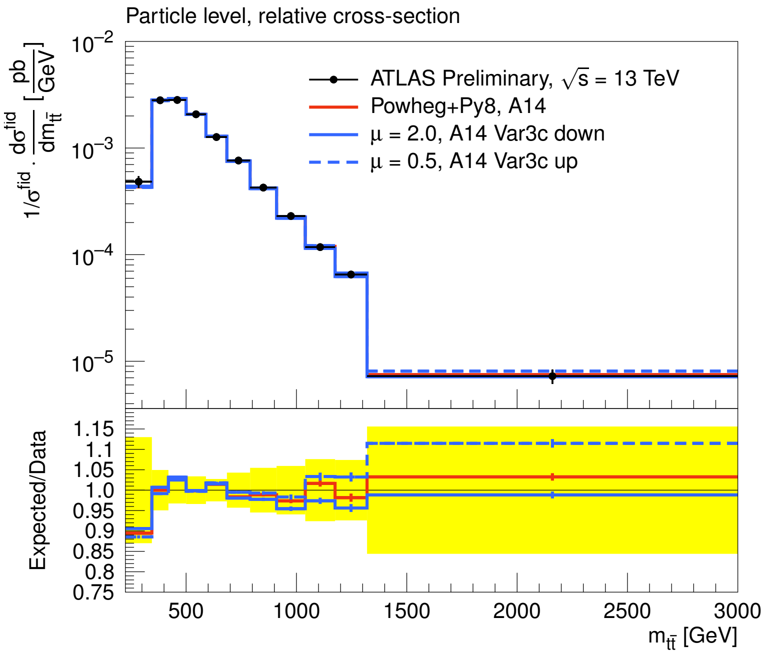




- At 8 and 13 TeV, variations partly bracket the data.
  - Variations smaller than data uncertainties for low bins and larger for high bins.
- Further studies necessary to determine the best setup for the radiation uncertainty.

Powheg+Pythia8 Scale Variations

CMS-PAS-TOP-16-021

- μ_R, μ_F variations by x2/0.5 (Q^2)
- PS scale from ISR and FSR independent variations (Run 2 2016 samples)
  - 'TimeShower:renormMultFac = 4.0/0.25', # FSR up/down (Q^2)
  - 'SpaceShower:renormMultFac = 4.0/0.25',# ISR up/down (Q^2)

PS=

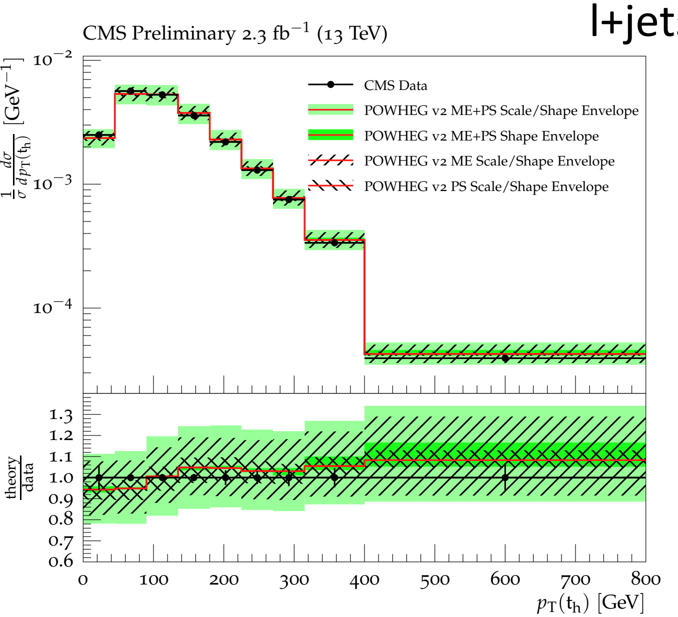
ISR up & FSR down

ISR down & FSR up

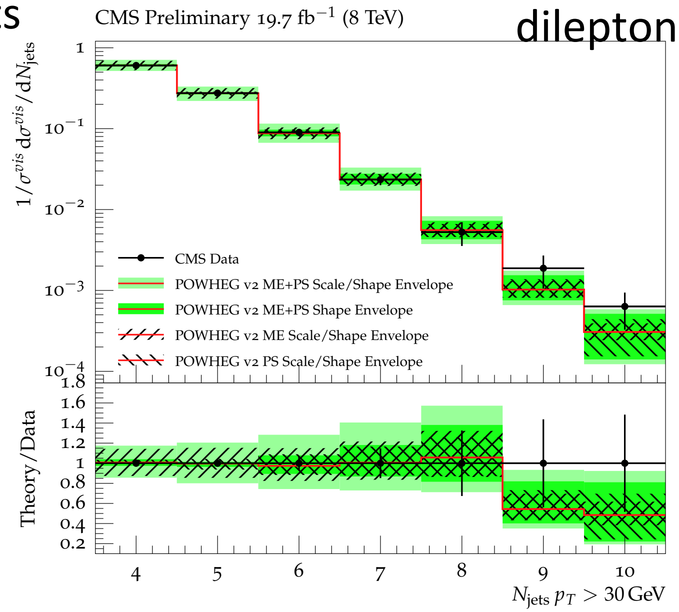
ISR & FSR up

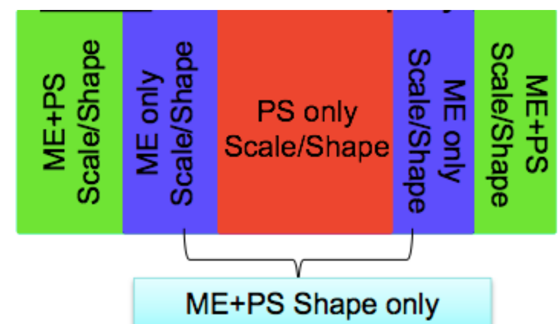
ISR & FSR down

l+jets



dilepton





- ME scale variations affect more normalization scale factor than shape
- PS scale variations affect more shape but observable dependent
  - FSR: larger flat normalization scale factor w.r.t. ISR and affects top kinematics
  - ISR: larger shape variation w.r.t. FSR and affects jet multiplicity and H_T.

Powheg+Herwig7

- h_{damp}=1.5m_t slightly better as in Powheg+Pythia8.
- Several treatments of global momentum recoil at the end of the showering for the angular-ordered Herwig7 using KinematicsReconstructor:ReconstructionOption

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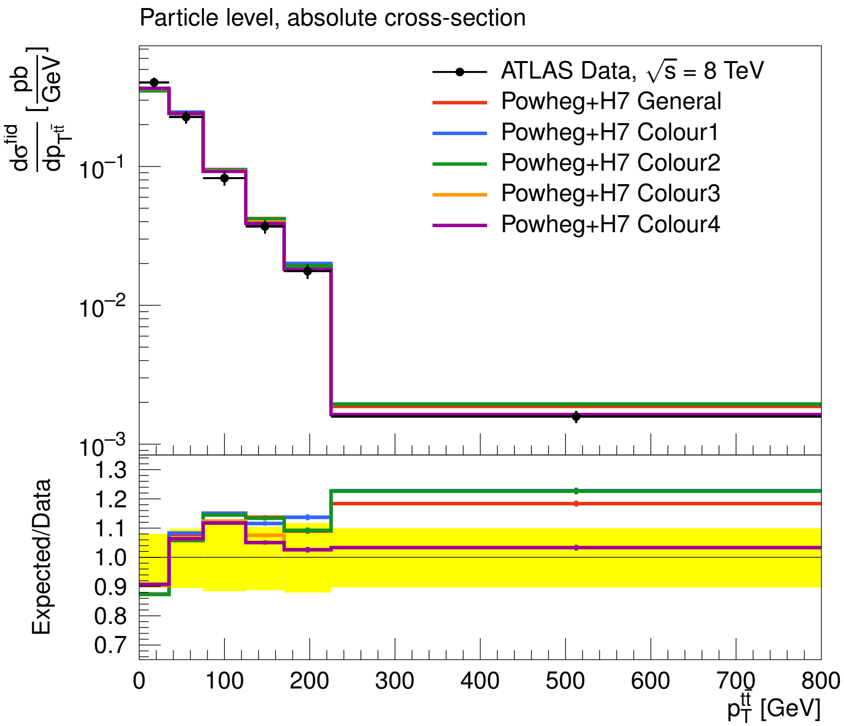
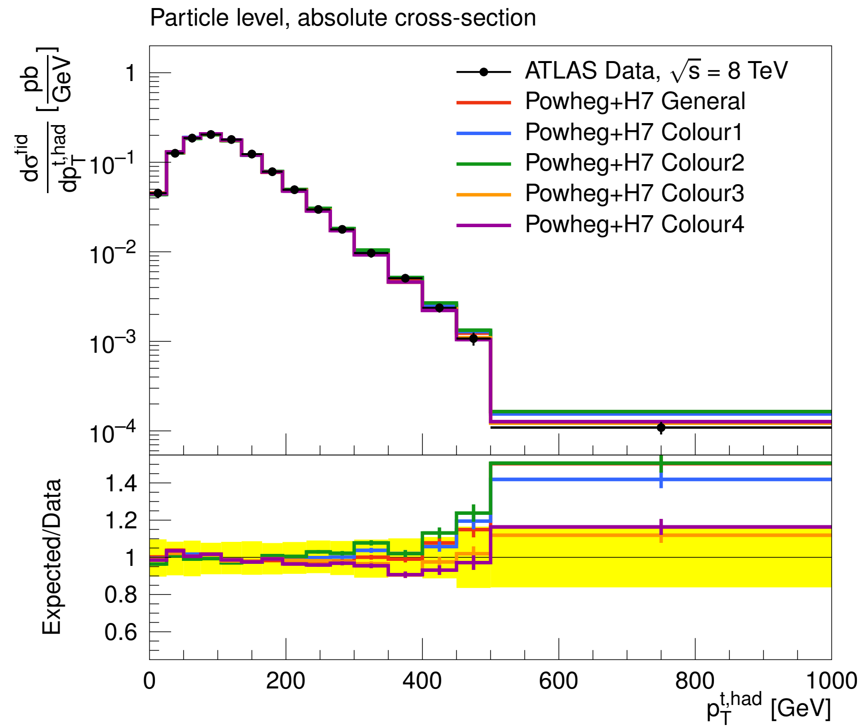




- The recommended Herwig7 setting "Colour3" has the best performance (Colour4 is good as well).

  - `Colour3` Make the most use possible of the colour structure of the process to determine the reconstruction procedure. Do the colour connections in order of the p_T's emitted in the shower starting with the hardest. The colour partner is fully reconstructed at the same time.

Summary and Next Steps

- Tuning Powheg+Pythia8 for ttbar by both ATLAS and CMS → lower α_s^{ISR} and h_{damp}=1.5m_t
  - All distributions described well (except top p_T, but description better than in run 1)
  - No bias on MET, HT and other variables but one should be careful using jet activity variables in searches using these tunes.
- MG5_aMC@NLO+Pythia8 [FxFx] good description of most distributions with the new CMS tune and ATLAS A14 tune (except e.g. at high momentum in the ATLAS p_T[ttbar]).
- Herwig7 studies
  - ATLAS studies → Good description of many variables with the recommended settings except jet multiplicity.
  - Detailed CMS Herwig7 studies is needed as well.
- Better understanding of radiation uncertainties by ATLAS and CMS but further studies needed to find the best method to determine the radiation uncertainties.

Summary and Next Steps

- Full understanding of NLO MC.
  - Matching parton shower and matrix element
    - Need to better understand the required consistency between ME and PS
    - Predictive powers of NLO MCs need to be better understood.
    - Sherpa also needs more studies and knobs to help assigning shower and radiation uncertainties.
  - pp→WbWb generation
  - …

Summary and Next Steps

- Single top differential distributions and comparisons
- EvtGen to have generator-independent b-tagging efficiencies.
- Perturbative/Non-perturbative effects through / tuning differential top mass measurements
- Constrain theory uncertainties through
  - UE, b-fragmentation, jet shapes, … in ttbar events
- Dedicated studies for searches
  - e.g. ttγγ/ttγ+jets/ttbb for ttH
  - Focus on modeling for rare top processes
- Differential ttV, spin correlation, asymmetry measurements

Bonus

ATLAS Setups

ME Gen.	PS/UE Gen.	ME PS/UE PDF	PS Tune	Matching (Merging)
Powheg-Box r2330.3	Pythia 6.427	CT10 CTEQ6L1	P2012	Powheg ($h_{damp} = m_{top}$)
Powheg-Box r3026 (v2)	Pythia 8.210	NNPDF3.0NLO NNPDF2.3LO	A14	Powheg (h_{damp} = 0.5-2.0 m_{top})
Powheg-Box r2330.3	Herwig 7.0.1	CT10 MMHT2014lo68cl	H7-UE-MMHT	Powheg
MadGraph5_aMC@NLO 2.3.3	Pythia 8.212	NNPDF3.0NLO NNPDF2.3LO	A14	MC@NLO
MadGraph5_aMC@NLO 2.3.3	Pythia 8.210	NNPDF3.0NLO NNPDF2.3LO	A14	MC@NLO (FxFx, μ_Q = 70 GeV)
Sherpa 2.2	Sherpa	NNPDF3.0NNLO	Default	MC@NLO (MEPS@NLO, Q = 30 GeV)

CMS Setups

ME generator	POWHEG v2	aMC@NLO	MG5_aMC@NLO	MG5_aMC@NLO
ME mode	hvq	Inclusive	FxFx Merging	MLM
ME pQCD level	$t\bar{t}$ [NLO] 1 jet [LO]	$t\bar{t}$ [NLO] 1 jet [LO]	$t\bar{t}$ +0,1,2 jets [NLO] 3 jets [LO]	$t\bar{t}+0,1,2,3$ jets [LO]
$\mu_R = \mu_F$	m_T^t	$\sum_{t,\bar{t}} m_T/2$	$\sum_{t,\bar{t},\text{jets}} m_T/2$	$\sum_{t,\bar{t},\text{jets}} m_T/2$
PS	PYTHIA 8.219	PYTHIA 8.219	PYTHIA 8.219	PYTHIA 8.219
Tune	CUETP8M2T4	CUETP8M2T4	CUETP8M2T4	CUETP8M2T4
Tune	CUETP8M1			
ME PDF	NNPDF3.0 [35]	NNPDF3.0	NNPDF3.0	NNPDF23 [36]
ME α_s	0.118	0.118	0.118	0.130
Other	$h_{damp} = 1.581 m_t$ $h_{damp} = m_t$ $ptsqmin = 0.8$ GeV $pThard = 0$ $pTdef = 1$			
q_{cut} (8 TeV)	-	-	30 GeV	60 GeV
q_{cut} (13 TeV)	-	-	40 GeV	80 GeV
Other (8 TeV)		-	$q_{cut}^{ME} = 10$ GeV	$x_{qcut} = 20$ GeV
Other (13 TeV)		-	$q_{cut}^{ME} = 20$ GeV	$x_{qcut} = 20$ GeV

Shower α_s Tuning

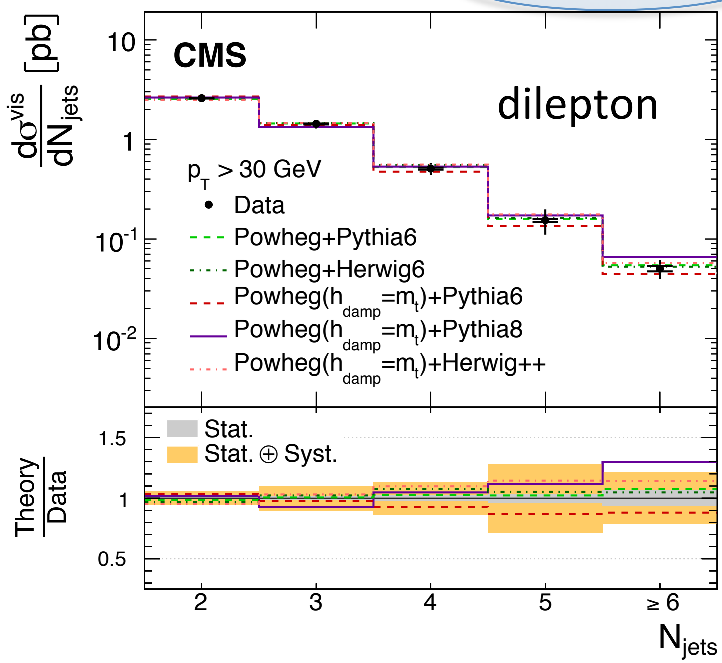
- Discrepancies at high Njets → non-optimal parton shower α_s.
- Tuning with PROFESSOR software
- Use $N_{jets} > 3$ where jets predominantly originate from the parton shower.

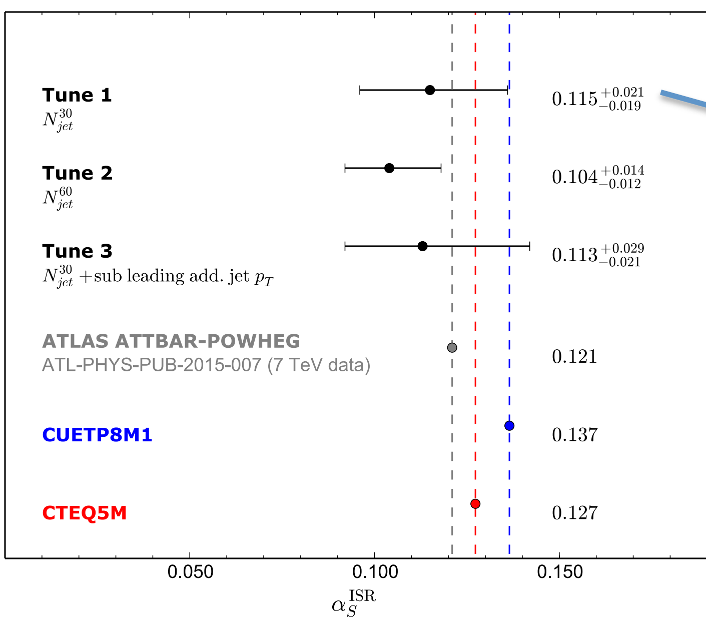
PYTHIA 8: SpaceShower:alphaSvalue (α_s^{ISR}) is the value of the strong coupling at m_Z used for the initial-state shower. The default value is $\alpha_s^{ISR} = 0.1365$ obtained from tuning to LEP event shapes [22] is kept for the final-state shower.

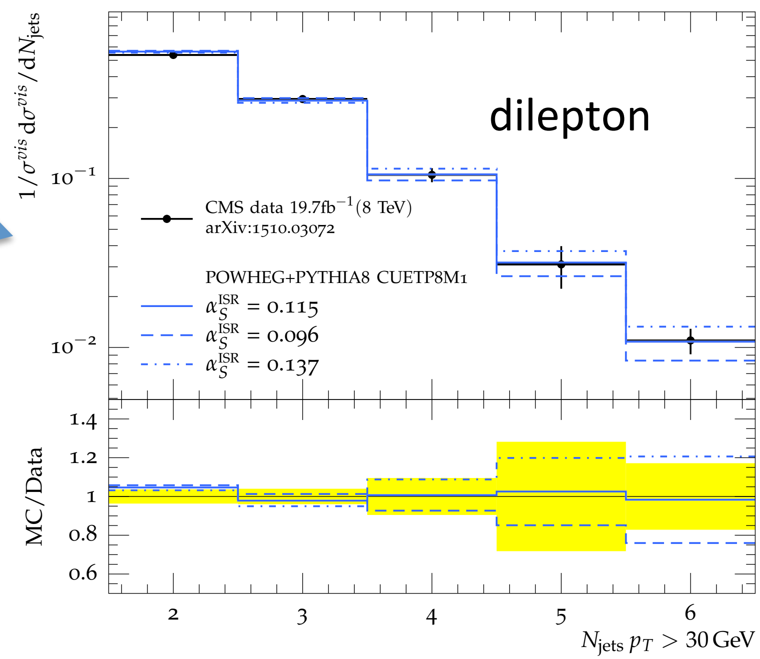
http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-12-041/index.html#AddFig

arXiv:1510.03072

19.7 fb^{-1} (8 TeV)







New CMS UE Tune

- Fixing α_s to 0.1108, a new UE tune is derived optimizing MPI and color reconnection.
- Fit to UE observables at 13 TeV:
  - Charged-particle multiplicity vs leading track p_T and η.
  - Σp_T (in MIN & MAX regions) vs leading track p_T.

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Table 3: The parameters of the old tune (CUETP8M1) and the new tune (CUETP8M2T4).

	CUETP8M1	CUETP8M2T4
Tune	pp 14	pp 14
Tune	ee 7	ee 7
MultipartonInteractions ecmPow	0.2521	0.2521
SpaceShower:alphaSvalue	0.1365	0.1108
PDF pSet LHAPDF6	NNPDF23_lo_qed_as_0130	NNPDF30_lo_as_0130
MultipartonInteractions:pT0Ref	2.40	2.20
MultipartonInteractions:expPow	1.6	1.6
ColourReconnection:range	1.8	6.6

* Z+jets.

- Forward energy flow as a function of pseudorapidity, $dE/d\eta$ [29];
- Central charged-particle multiplicity as a function of pseudorapidity, $dN/d\eta$ [30];
- UE observables, i.e. charged-particle multiplicity and Σp_T, in MIN and MAX regions, as a function of the leading jet p_T [27];

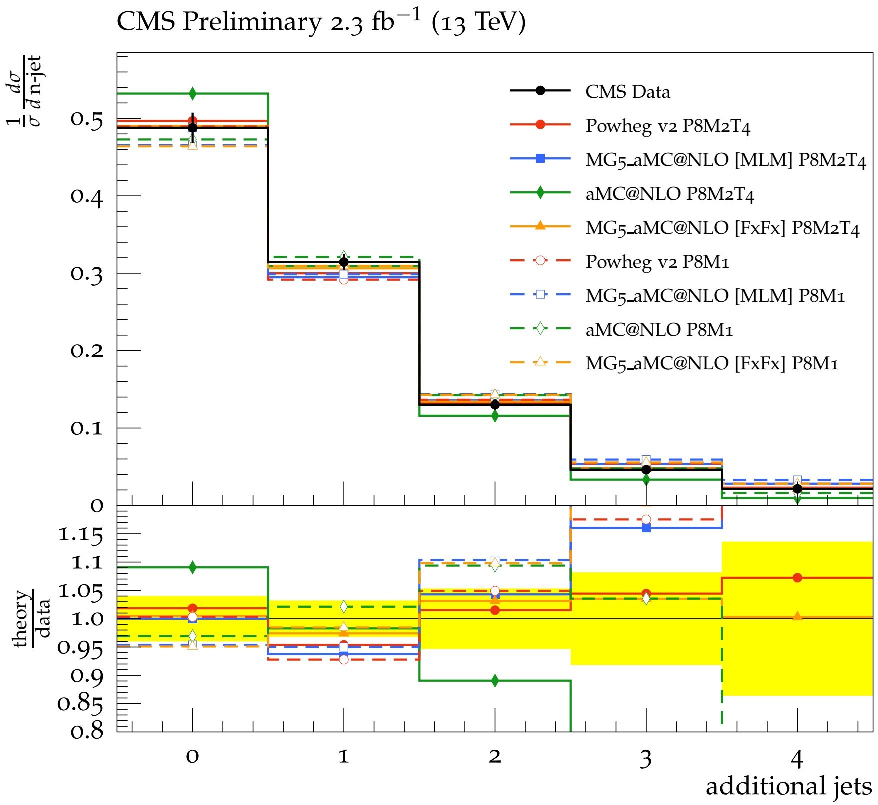
New tune is used in Run 2 (2016) ttbar samples.

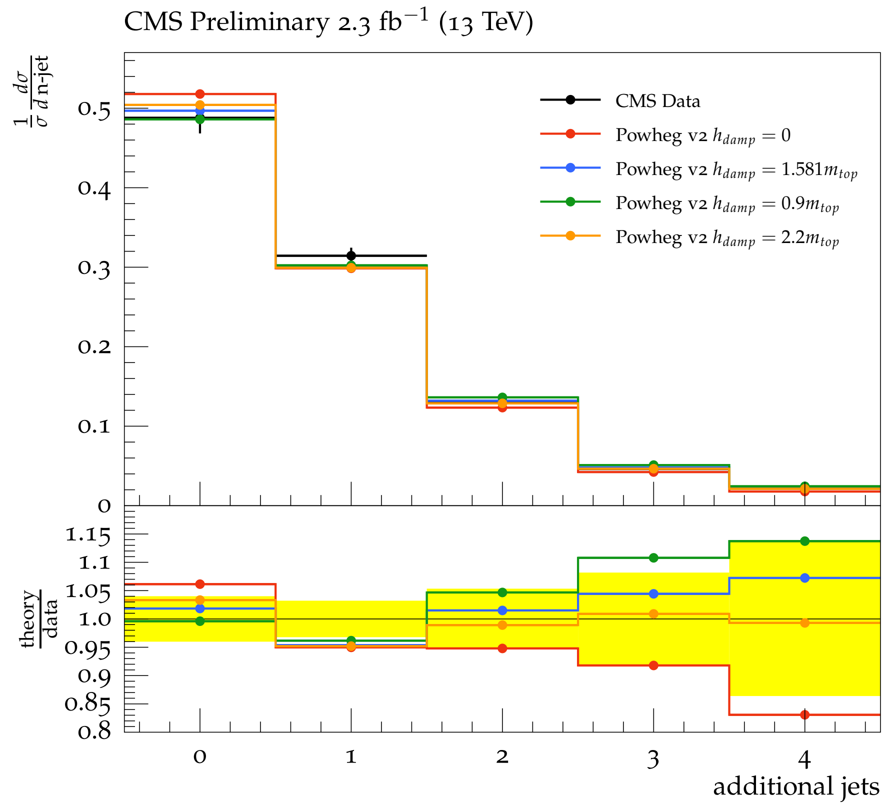
Powheg+Pythia8 Parameters

mode **POWHEG:pThard** (default = **0**; minimum = 0; maximum = 2)
Selection of the *pThard* scale. For events where there is no radiation, *pThard* is always set to be the SCALUP value of the LHA/LHEF standard.
option **0** : Set *pThard* equal to SCALUP.
option **1** : The *pT* of the POWHEG emission is tested against all other incoming and outgoing partons, with the minimal value chosen.
option **2** : The *pT* of all final-state partons is tested against all other incoming and outgoing partons, with the minimal value chosen.

mode **POWHEG:pTdef** (default = **0**; minimum = 0; maximum = 2)
Use of *pT* definitions.
option **0** : The POWHEG ISR *pT* definition for both ISR and FSR.
option **1** : The POWHEG ISR *pT* and FSR *d_ij* definitions.
option **2** : The PYTHIA definitions.

Various MC Predictions with the New CMS Tune





- (By definition) Powheg works well with the new tune.
  - hdamp needs to be finite
  - hdamp variations around the tuned ~ data uncertainties.
- MG5_aMC@NLO [FxFx] → Almost as good as good as Powheg
  - Dedicated studies needed to tune MG5_aMC@NLO considering matching options.
- MG5_aMC@NLO [MLM] and aMC@NLO → Not good

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