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Top Quark Event Modelling and Generators in CMS

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for the CMS Collaboration

TOP 2017
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Top Quark and QCD

- Top quark measurements
 - Test and understand QCD effects → ultimate precision in top quark mass, its interpretation and in other properties.
 - Beyond standard model effects
- This talk: a sub-set of recent measurements and studies from CMS.

All public top physics results from CMS at:
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>

Precision of Top Quark Pair Measurements

- Top quark pair cross section measurements better than NNLO+NNLL precision:
~5.5%.

JHEP 08 (2016) 029,
arXiv:1701.06228,
EPJ-C 77 (2017) 172

- Run I Direct Top Quark Mass Measurements Combination: precision ~0.3% with dominant uncertainties:

- Hadronization (b hadronization modeling and effect on jet energy scale)
- modeling of hard scattering,
- jet energy calibration and pile-up

- Run I Alternative Top Quark Mass Measurements Combination: precision ~0.4% with dominant uncertainties:

CMS-PAS-TOP-15-012

- JEC
- hadronization (JEC: flavor, b jet modelling)
- QCD scales
- PS-ME matching
- Top quark pT
- UE/PDF

Some theory uncertainties (hadronization, top pT, underlying event, ...) may be improved.

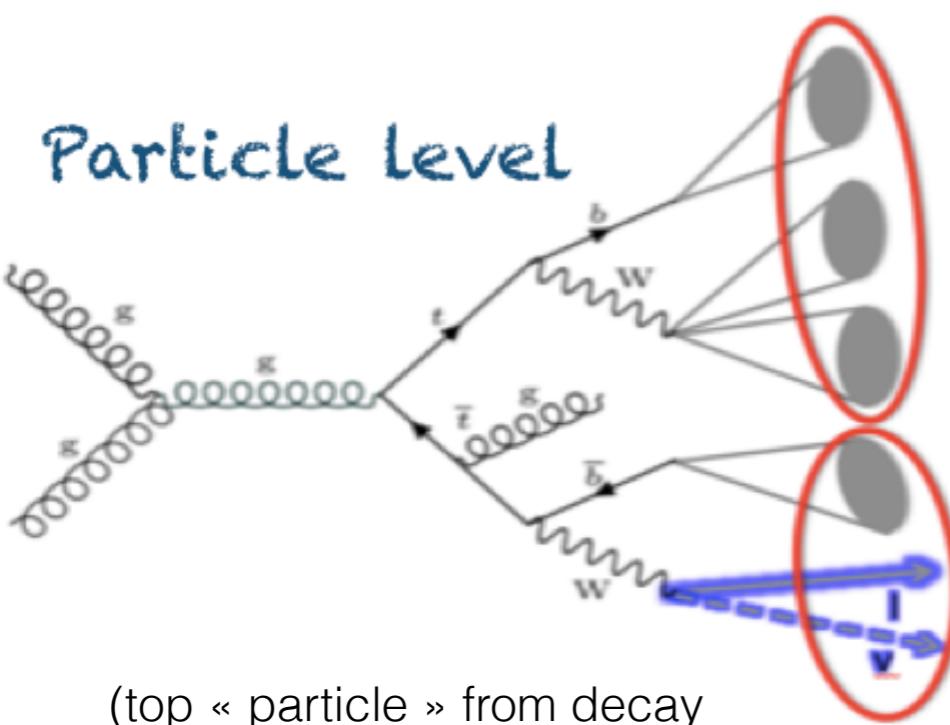
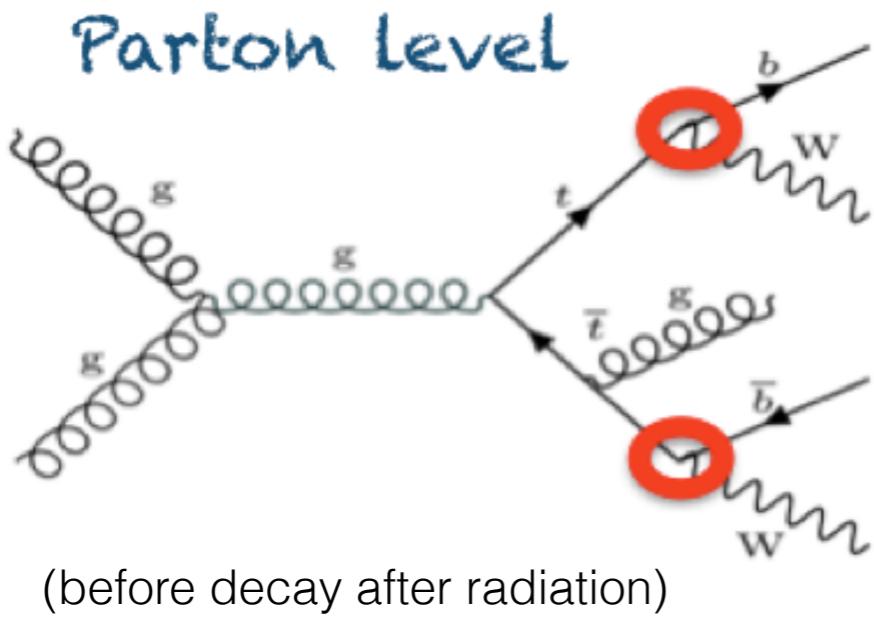
Goal/expectation for HL-LHC Direct top mass measurements < 0.1% precision.

Improving Uncertainties

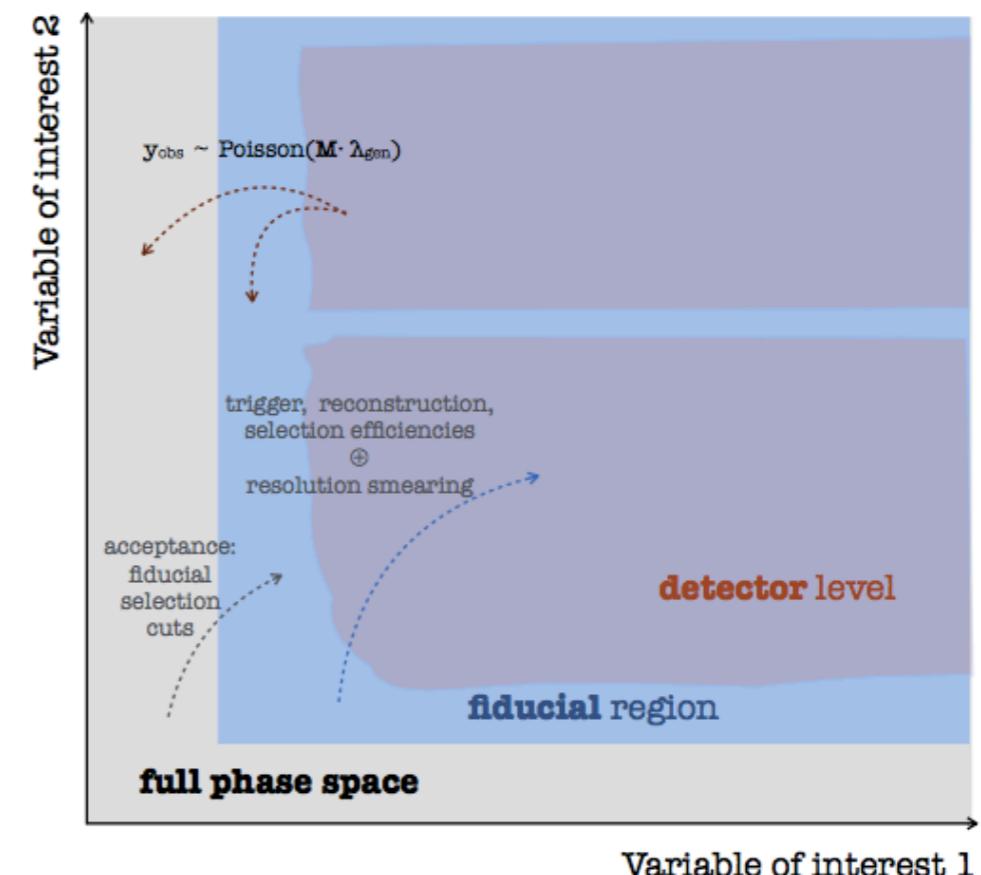
- Test ME+PS configurations and tunes using well-defined differential measurements.
- Detailed studies of each source of modeling uncertainty.
- Measurements (e.g. top mass) in different phase-space regions.
- ...

Improving uncertainties: Object Definitions for Top Particle

CMS-NOTE-2017-004

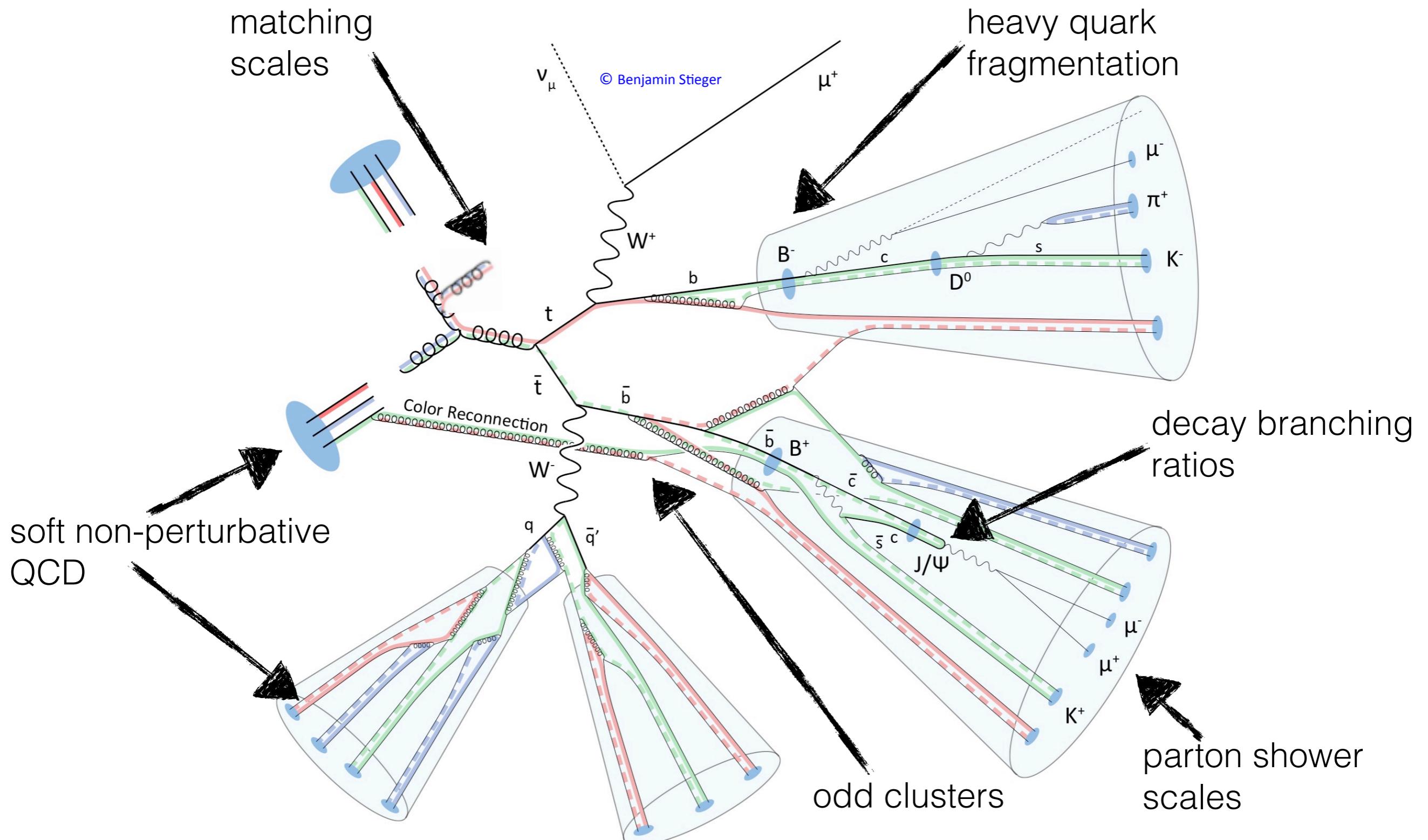


- Fundamental aspect of performing current and future measurements of top quark differential production cross sections: Use well-defined objects in simulations —> Construct tops only from observed final-state = particle level top.
- Parton level top ill-defined - more so at NLO
- finite width of the top quark for off-shell production and interference with the backgrounds.



See Markus Seidel's poster

Ambiguities



Factorized Parton Shower/Hadronization Uncertainties

Source	Handle	Weights	Variation	Note/Reference
Shower scales	ISR scale (SpaceShower:renormMultFac)	No	0.5-2.0	FSR variations can be scaled down by $\sqrt{2}$ from LEP
	FSR scale (TimeShower:renormMultFac)	No	0.5-2.0	
ME-PS Matching	hdamp	No	hdamp=1.58m _t +0.66-0.59 m _t	see TOP-16-021
Soft QCD	UE parameters	No	CUETP8M2T4 up/down	See TOP-16-021 MPI & CR strength doesn't affect resonance decays
	MPI based, QCD-inspired, gluon move	No	different models	
Color reconnection (odd clusters)	momentum transfer from the b-quark to the B hadron: $x_b = p_T(B)/p_T(b\text{-jet})$	Yes	Vary Bower-Lund parameter within uncertainties from LEP/SLD fits	CR affecting resonance decays
Fragmentation	Pythia vs Herwig	No	Vary the JES independently per flavour for light, g, c, b.	see TOP-16-022 (re-weight x_b)
Flavor response/ hadronization	B semi-leptonic BR	Yes	vary semileptonic BR +0.77%/-0.45%	re-weight the fraction of semi-leptonic b jets by the PDG values (scale Λ_b to match PDG)
Decay tables				

Top Quark Pair Differential Cross Sections

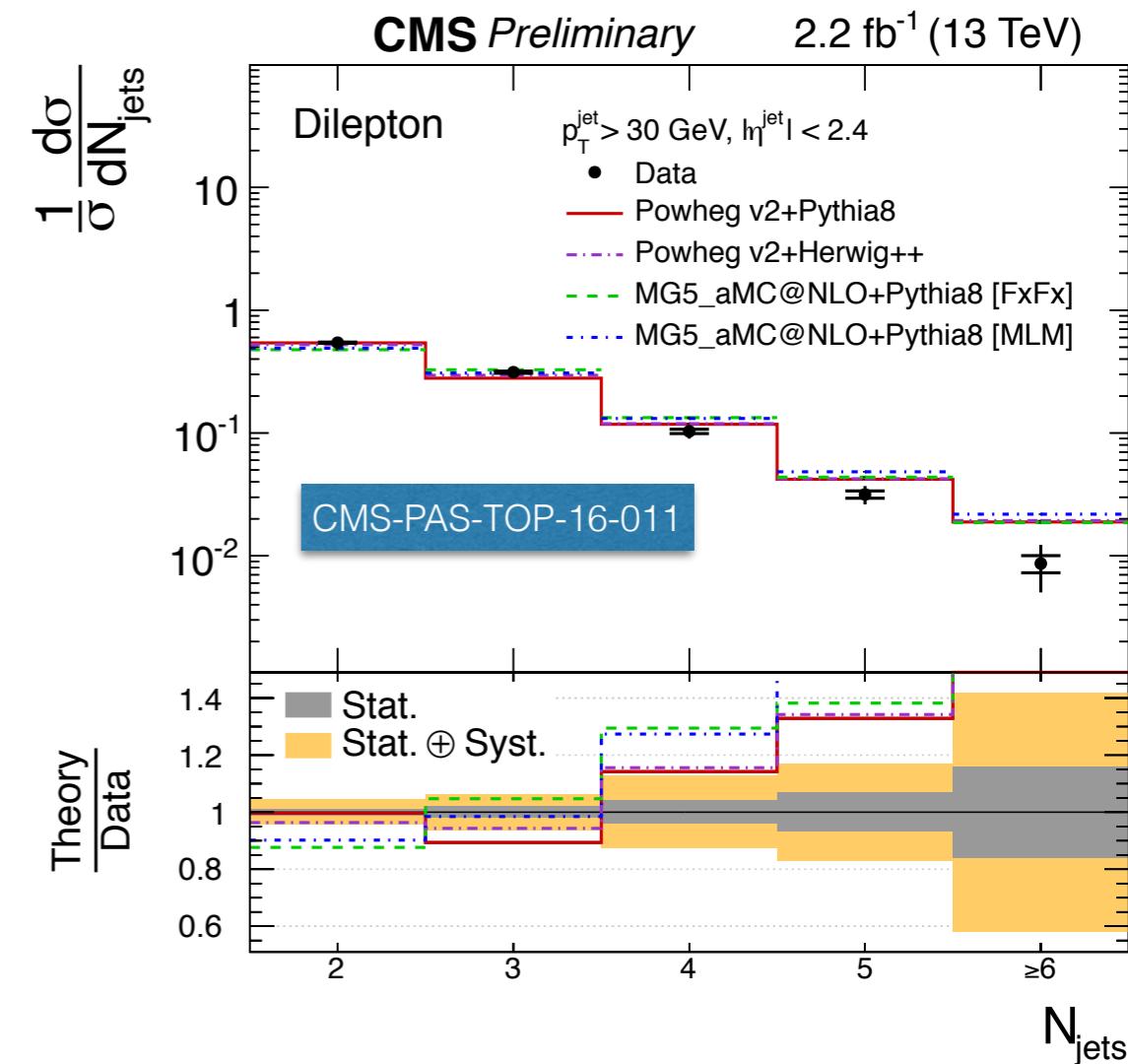
- Test QCD description of the top quark (both as signal and background)

CMS-PAS-TOP-12-041 (dilepton 8 TeV),
Phys. Rev. D 95 (2017) 092001 (l+jets 13 TeV)

- Test and tune new MCs (NLO ME + LO PS MC)

see Otto Hindrich's presentation

- POWHEG, MG5_aMC@NLO [FxFx, MLM] + Pythia8/Herwig
- Sherpa+OpenLoops+CS
- Differential distributions described reasonably well by NLO MCs at particle level [[arXiv:1708.07638](https://arxiv.org/abs/1708.07638), TOP-17-002], at parton level and NNLO calculations [PRD 95 (2017) 092001, TOP-17-002]
- Top p_T not well-described.
- High Njets not described using Monash based tunes $a_s^{\text{ISR}} = 0.1365$.

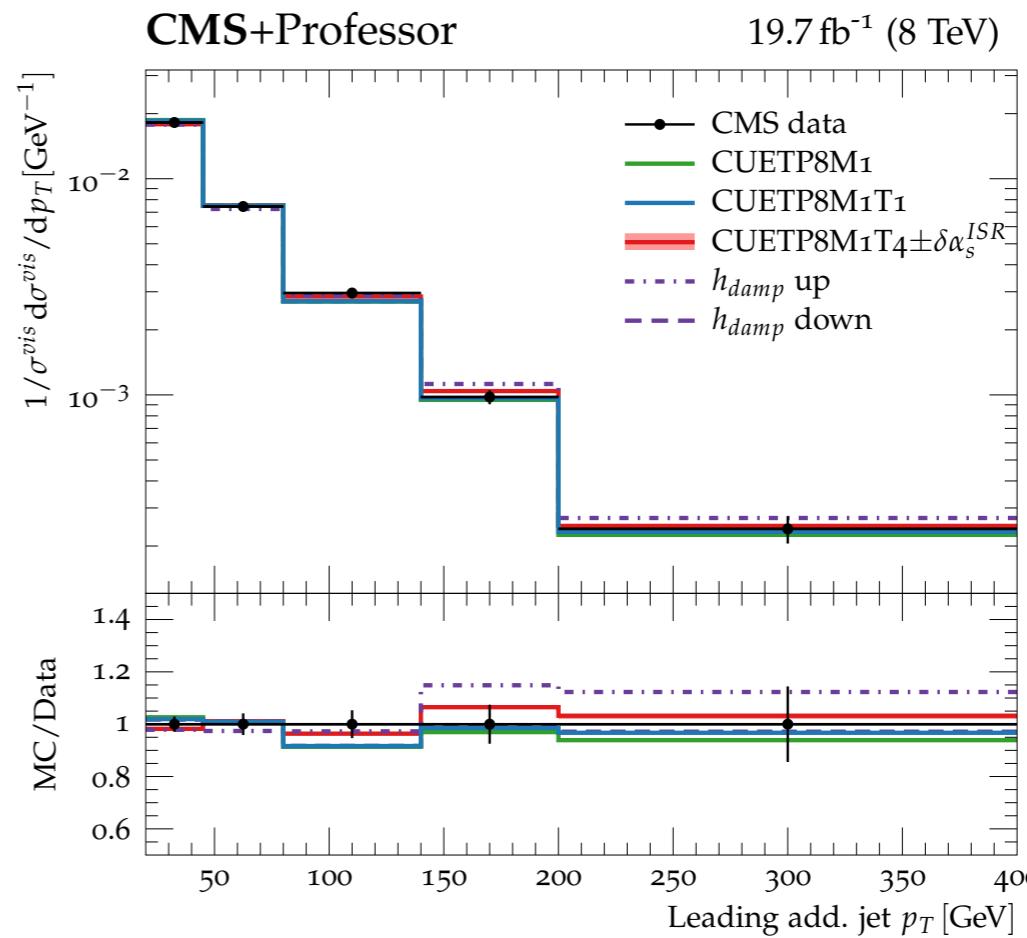
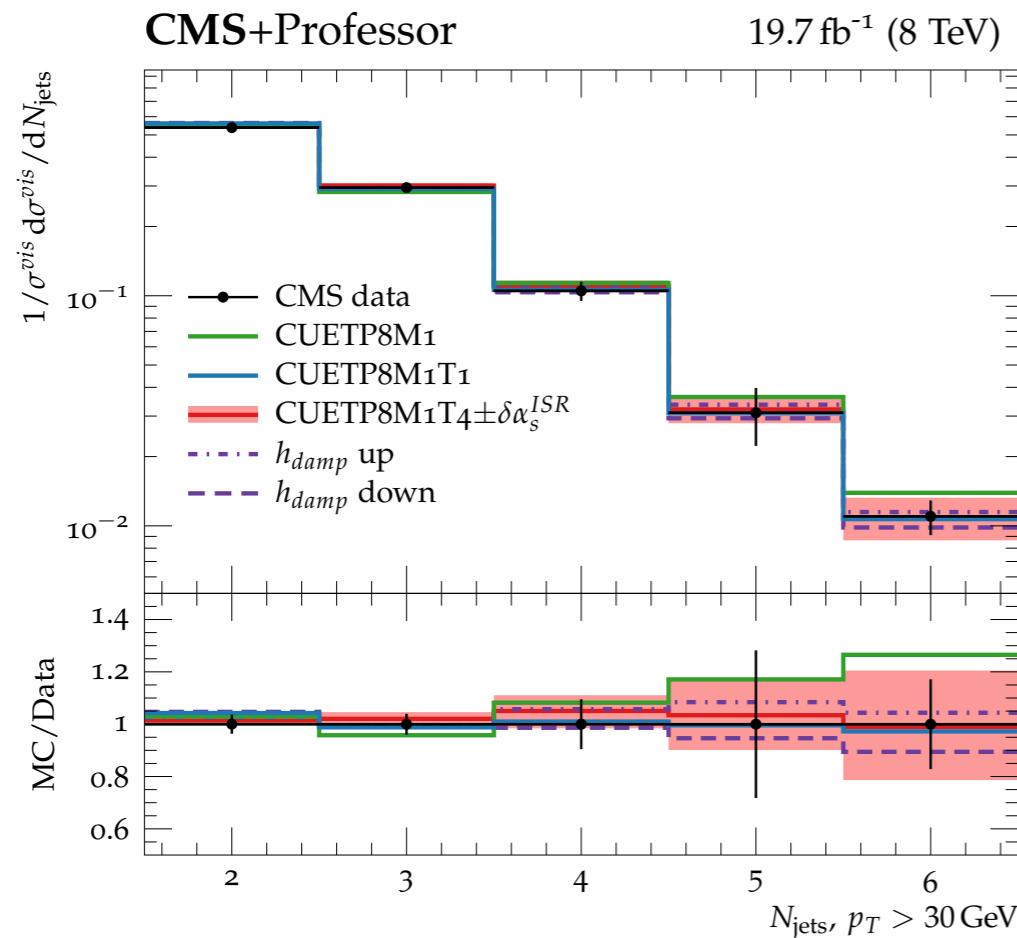


A Top Specific Event Tune

- Charged particle multiplicity and pT-sum densities (in the transverse region) => Can not constrain MPI and shower ISR simultaneously.
- First, tune shower a_s^{ISR}
 - ttbar jet kinematics => Sensitive to shower a_s^{ISR} but not so much to the UE.
 - Nominal ttbar simulation: Powheg+Pythia8 => include hdamp in the tuning.
- Then fit UE & MinBias data at 13 TeV to tune MPI parameters.
- Verify the tune with other processes.

CMS Shower $a_s + h_{\text{damp}}$ Tuning using Njets and Leading add. Jet P_T

CMS-PAS-TOP-16-021



SpaceShowerRapidityOrdering=on →

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

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

==> Significantly lower shower a_s curing the overshoot of CUETP8M1 at high jet multiplicities.
==> Tuning a_s (w/o h_{damp}) using the same data yields $\alpha_s^{\text{ISR}} = 0.115^{+0.021}_{-0.019}$

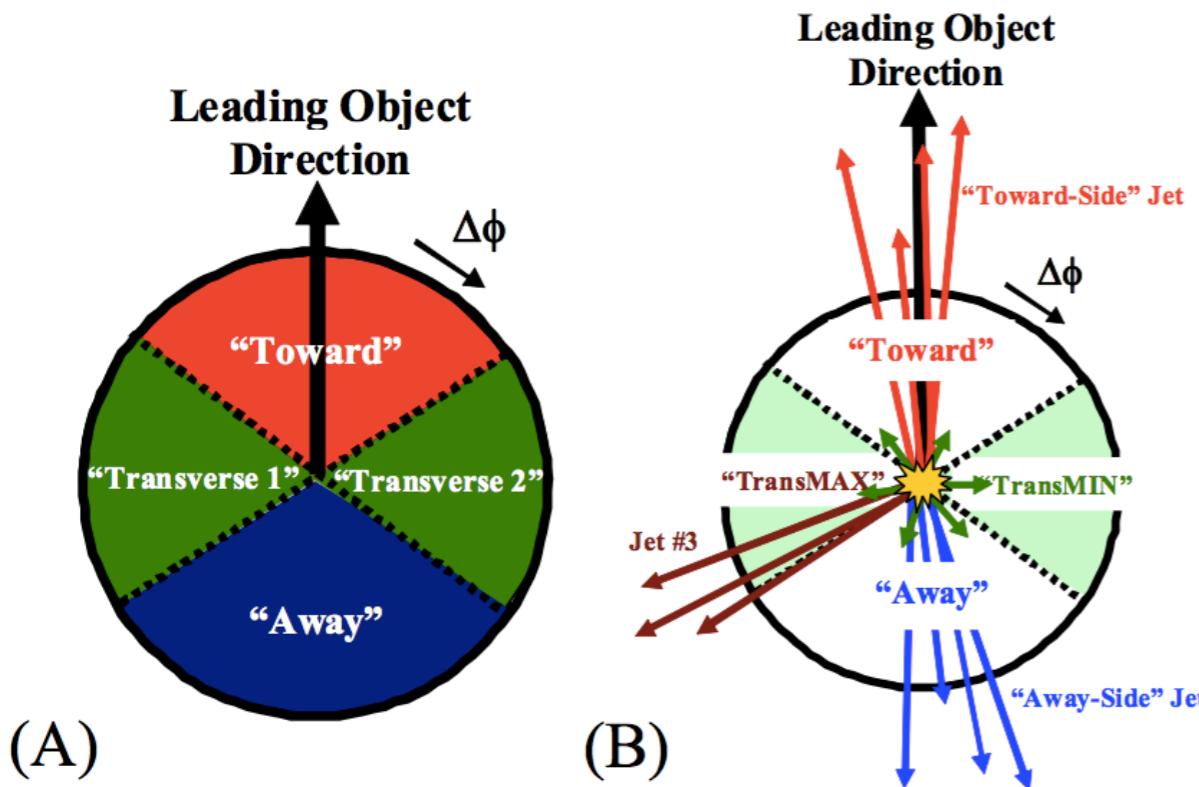
<http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-12-041/index.html#AddFig>

The New UE Tune

- Fixing the amount of ISR, a new UE tune is derived optimizing MPI parameters ==> Fit to 5 measurements
 - UE data ($pT > 0.5$ GeV, $|\eta| < 2$): Charged-particle and energy densities in TransMIN and TransMAX regions vs leading charged particle pT .
 - MB data ($pT > 0$): Charged-particle η distribution.

$$\frac{\langle \eta_{ch} \rangle}{\Delta\eta\Delta(\Delta\phi)}$$

$$\frac{\langle \sum p_T \rangle}{\Delta\eta\Delta(\Delta\phi)}$$



Transverse:

- * TransMax: maximum activity <= MPI/BR & ISR/FSR
- * TransMin: minimum activity <= MPI/BR
- * TransAve = (TransMax + TransMIN)/2
- * TransDIF = TransMax - TransMIN <= ISR/FSR

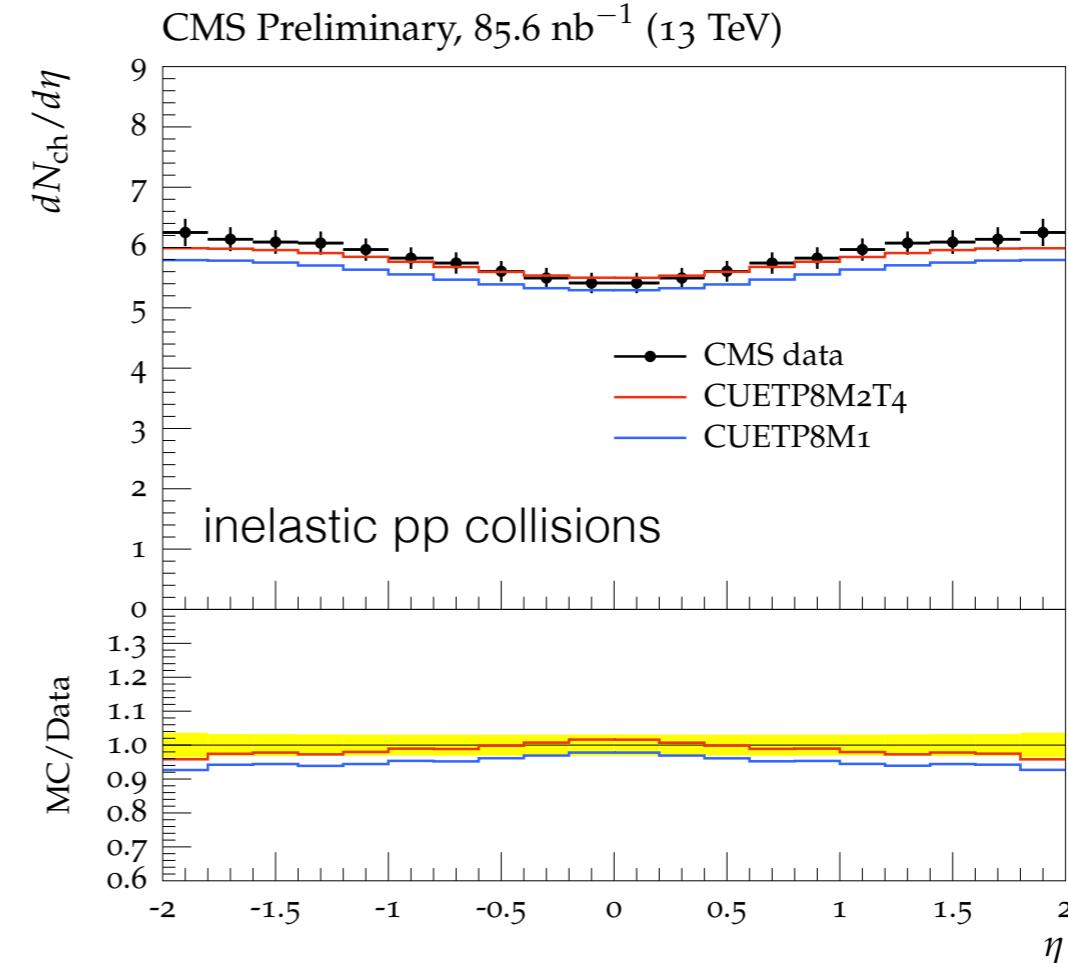
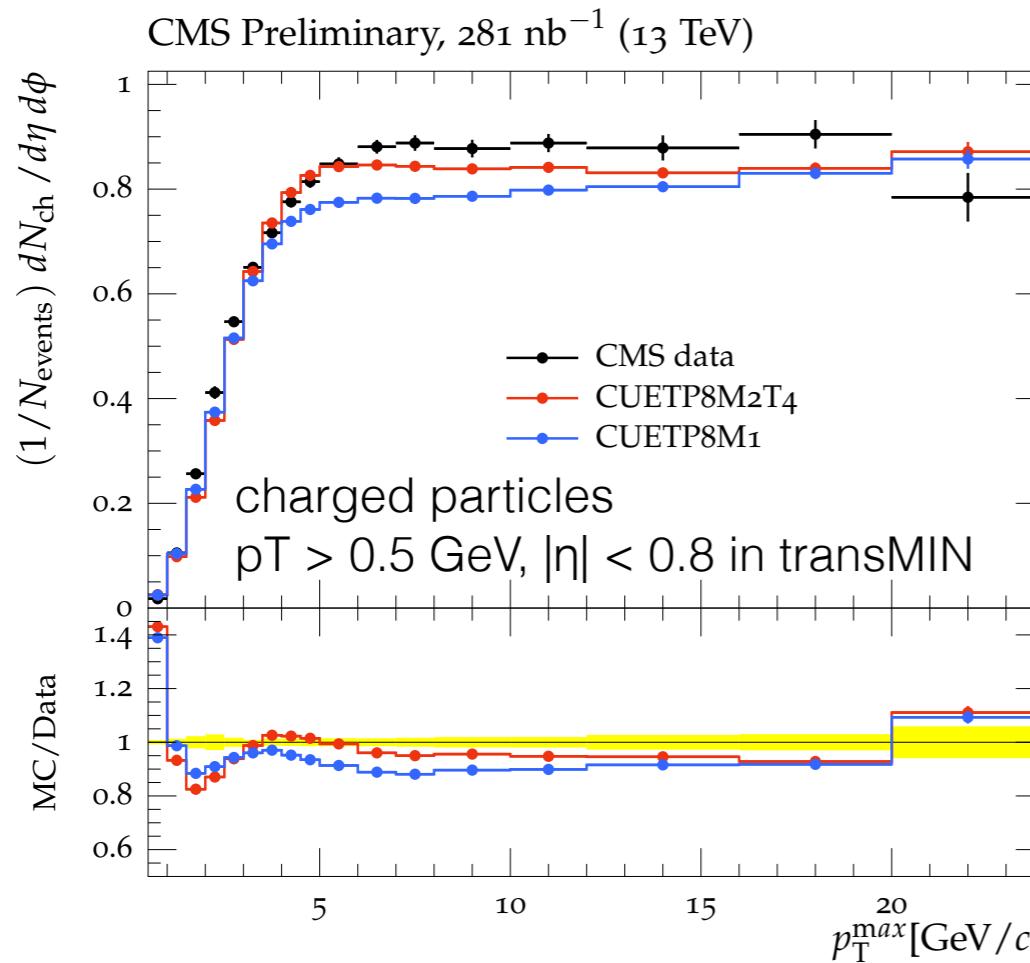
CMS-PAS-TOP-16-021

	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	Tuning ranges
MultipartonInteractions:expPow	1.6	1.6	1.0-3.0
ColourReconnection:range	1.8	6.6	0.4-10.0
			0.0-9.0

Baseline:
Monash tune

Tuning ranges
1.0-3.0
0.4-10.0
0.0-9.0

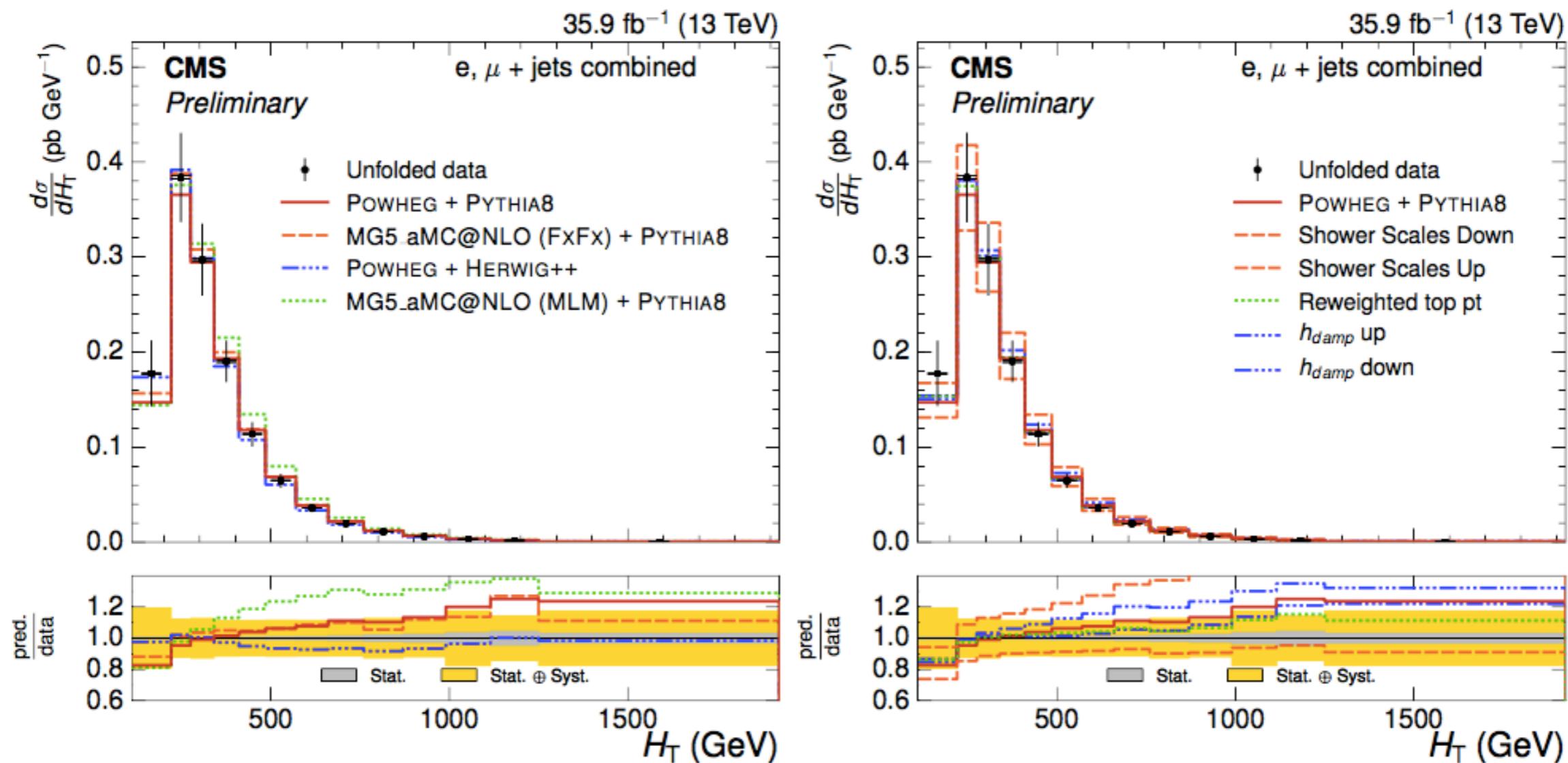
Performance of the New CMS Tune



CMS-PAS-TOP-16-021

- New tune describes UE and MB data at $\sqrt{s} = 13 \text{ TeV}$ simultaneously
- Performs well at $\sqrt{s} = 7 \text{ TeV}$ as well.
- Provides a better description of the plateau.
- Single-diffractive enhanced observables and inelastic cross sections not well described.

Performance of the New CMS Tune with Top Quark Data at 13 TeV

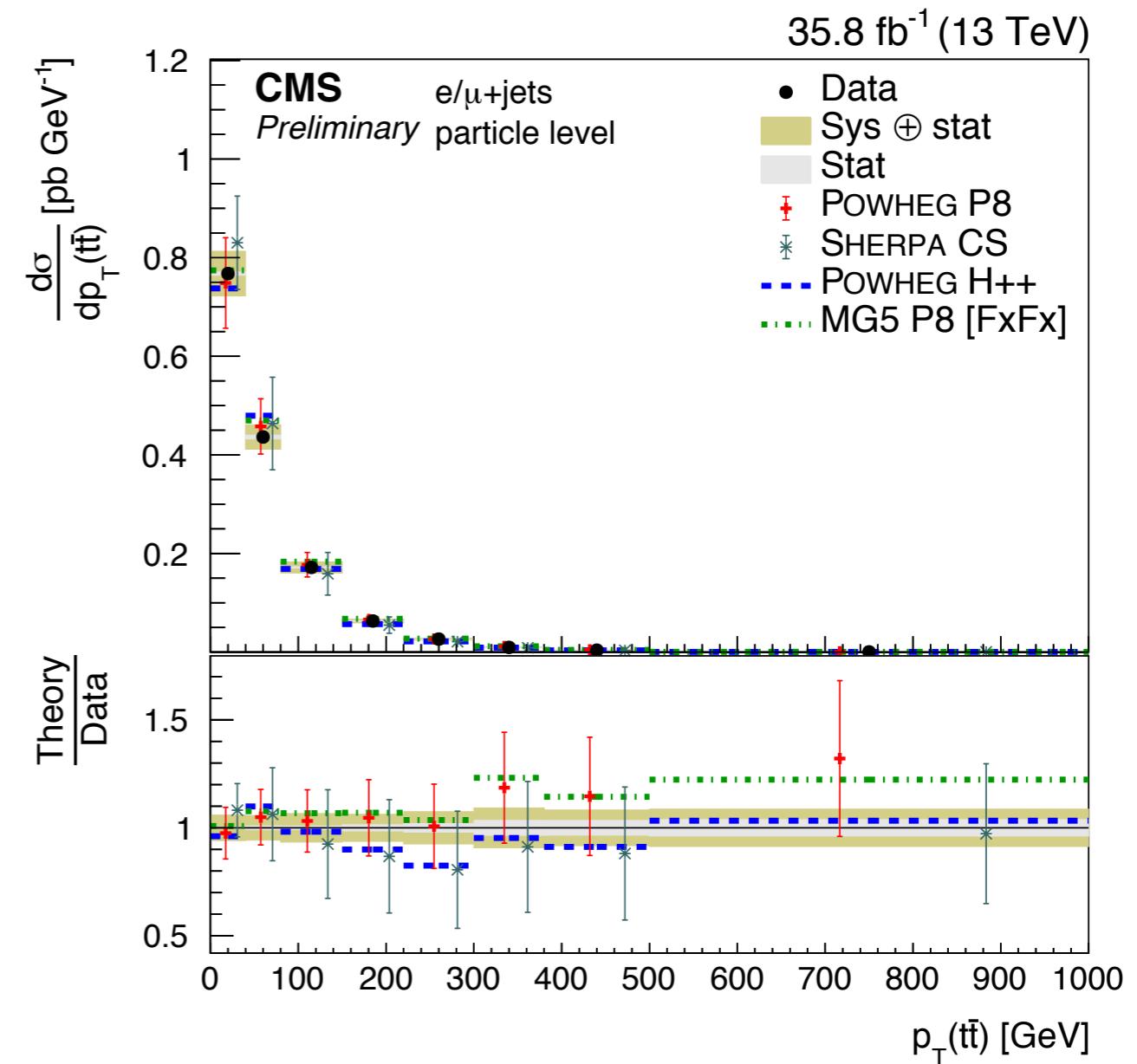
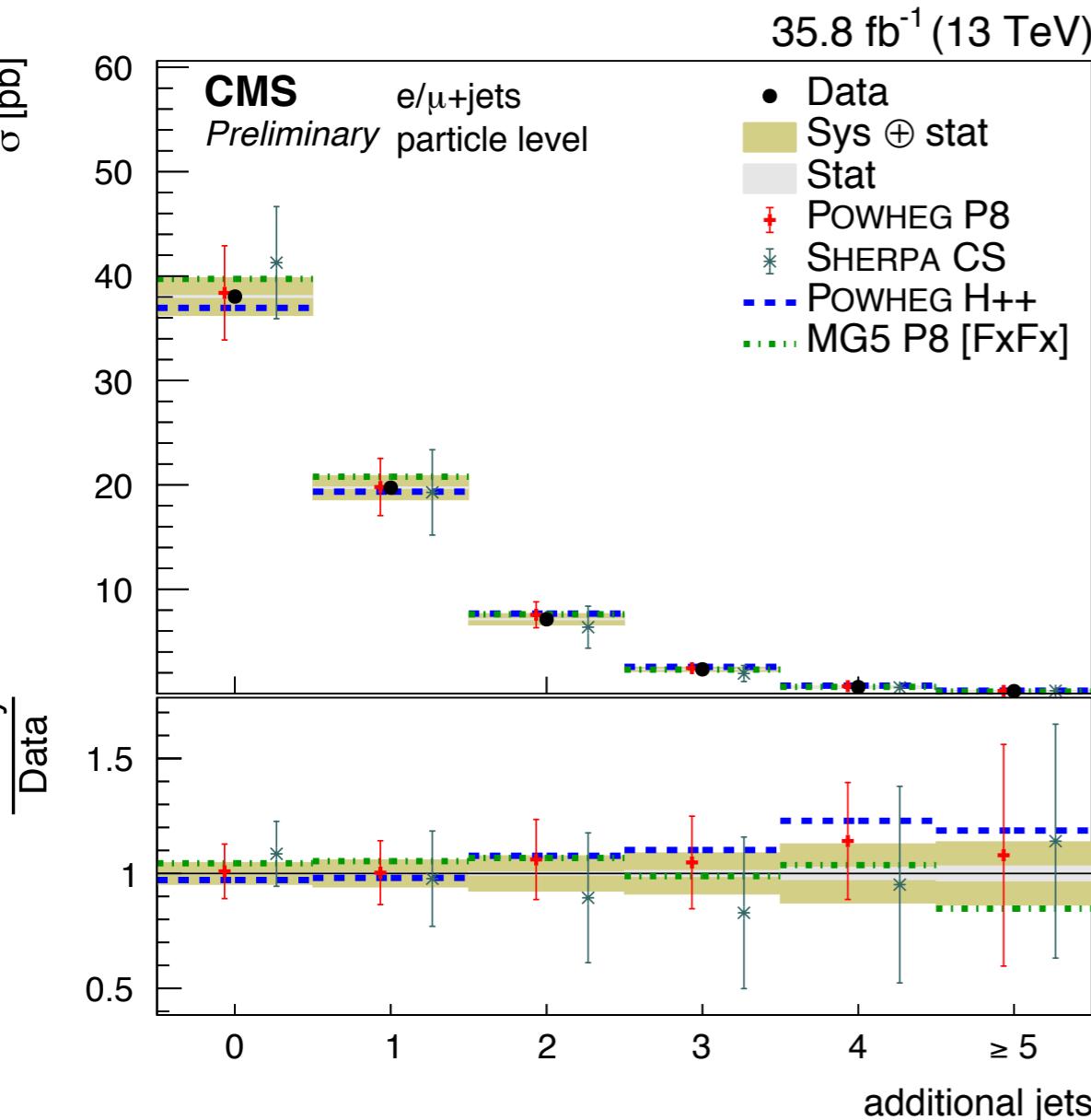


POWHEG + PYTHIA8		POWHEG + PYTHIA8 including simulation theory uncertainties		
	χ^2 / ndf	p-value	χ^2 / ndf	p-value
N_{jets}	2.5 / 6	0.87	2.4 / 6	0.88
p_T^W	10 / 7	0.19	6.6 / 7	0.48
p_T^{ℓ}	36 / 17	< 0.01	16 / 17	0.49
H_T	35 / 13	< 0.01	8.2 / 13	0.83
S_T	26 / 13	0.015	10 / 13	0.7
p_T^{miss}	7.2 / 6	0.3	4.7 / 6	0.58
All	116.7 / 62	< 0.01	47.9 / 62	0.91

CMS-PAS-TOP-16-014

see Taejong Kim's presentation

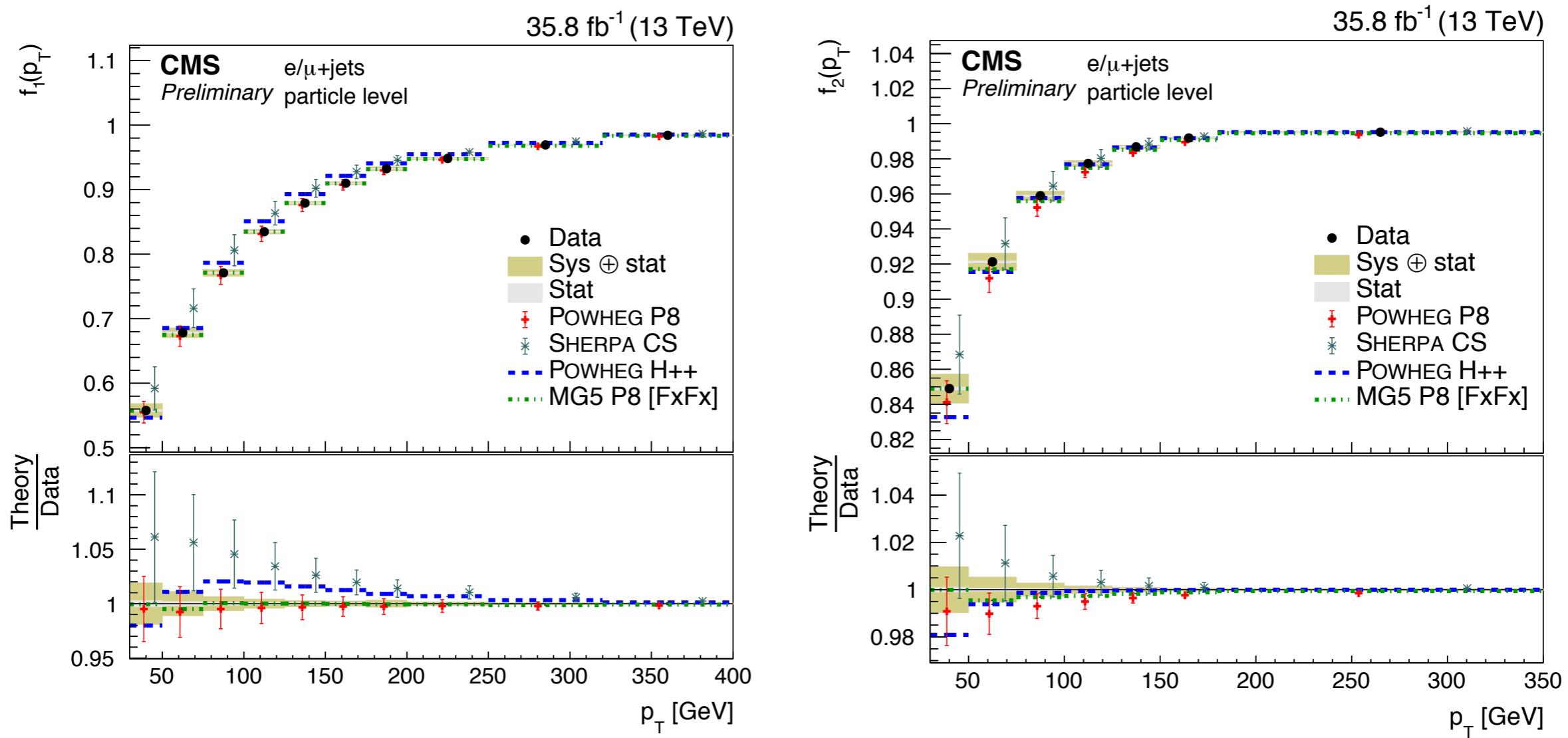
Top Quark Differential Distributions w/ the new Pythia8 tune and w/ different configurations at 13 TeV



see Otto Hindrich's presentation

CMS-PAS-TOP-17-002

Top Quark Differential Distributions w/ the new Pythia8 tune and w/ different configurations at 13 TeV



- All distributions (except top pT) described well with Powheg and MG5_aMC@NLO [FxFx] + Pythia8 with the CUETP8M2T4 tune.
 - Best agreement with FxFx.
- Sherpa+OpenLoops w/ CS parton shower with the default Sherpa tune → show larger discrepancies w.r.t. data but large QCD scale uncertainties.

α_s Consistency in ME and PS and PDF Choices

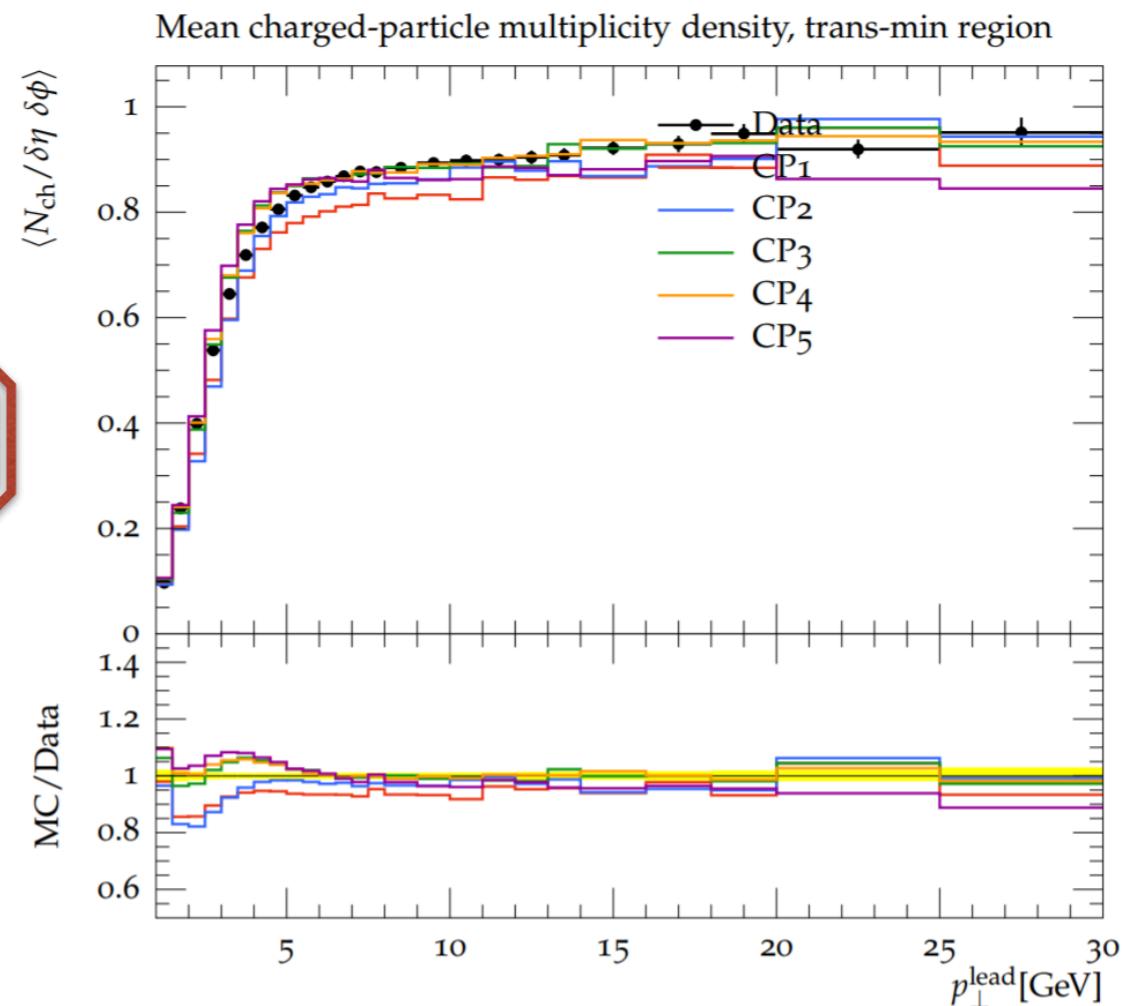
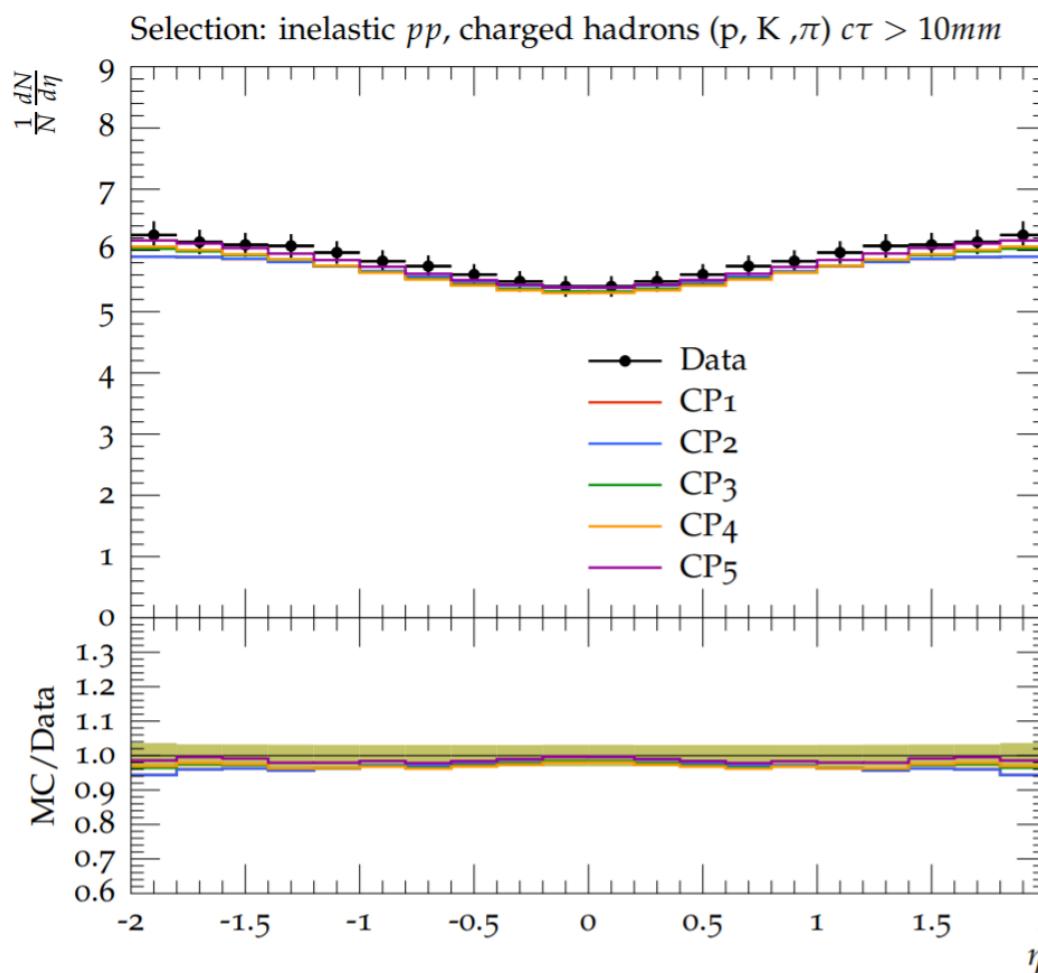
- Pythia (LO PDF), Herwig (NLO PDF), and Sherpa (NNLO PDF) have different PDF choices for parton showers
- Match PDF and α_s in the PS and in the ME.
- Discussions on the order of PDF sets in parton showers (cfr. last LHC and the Standard Model: Physics and Tools Meeting [presentations](#))
- We would like to match the PDF and α_s in ME and in the PS, and to have LO PDF for MPI to make sure small x-gluon is physical.
- We test the effect of using different PDF orders of NNPDF sets in PYTHIA8 among other parameter variations.
 - CP1: NNPDF3.1 LO ($\alpha_s=0.130$)
 - CP2: NNPDF3.1 LO ($\alpha_s=0.130$)
 - CP3: NNPDF3.1 NLO ($\alpha_s=0.118$)
 - CP4: NNPDF3.1 NLO ($\alpha_s=0.118$)
 - CP5: NNPDF3.1 NNLO ($\alpha_s=0.118$)

Currently not possible
to set different PDFs in
MPI and PS in Pythia.

Minbias and Underlying Event

- Rivet:
CMS_2015_I1384119, 0
Tesla, $\sqrt{s} = 13$ TeV, $|\eta| < 2$

- Rivet: ATLAS_2017_I1509919, $\sqrt{s} = 13$ TeV, $|\eta| < 2.5$, $pT > 0.5$ GeV with at least one of the charged particles $pT > 1$ GeV
- Transmin most sensitive to MPI (where we might expect to have the biggest problems not using a leading order PDF)



- UE/Min-Bias data are described at the same level by tunes with LO, NLO, and NNLO PDF NNPDF3.1 sets.
- It would still be good if Pythia8 allows setting different PDFs for PS and MPI (as e.g. in Herwig7)

$\sqrt{s} = 13 \text{ TeV}$ Top Mass

CMS-PAS-TOP-17-007



$172.25 \pm 0.08 \text{ (stat + JSF)} \pm 0.62 \text{ (syst) } GeV$

- Consistent with Run I result —> No impact from the new reference generator or changes in the experiment
- Dominant systematic uncertainties
 - Hadronization modeling (flavor-dependent JEC; b-jet modelling)
 - pQCD Modeling (ME generator: Powheg vs MG5_aMC@NLO[FxFx] ; FSR PS scale)
 - Soft QCD modeling (color reconnection modelling: default Pythia8 vs QCD inspired and gluon move models.)

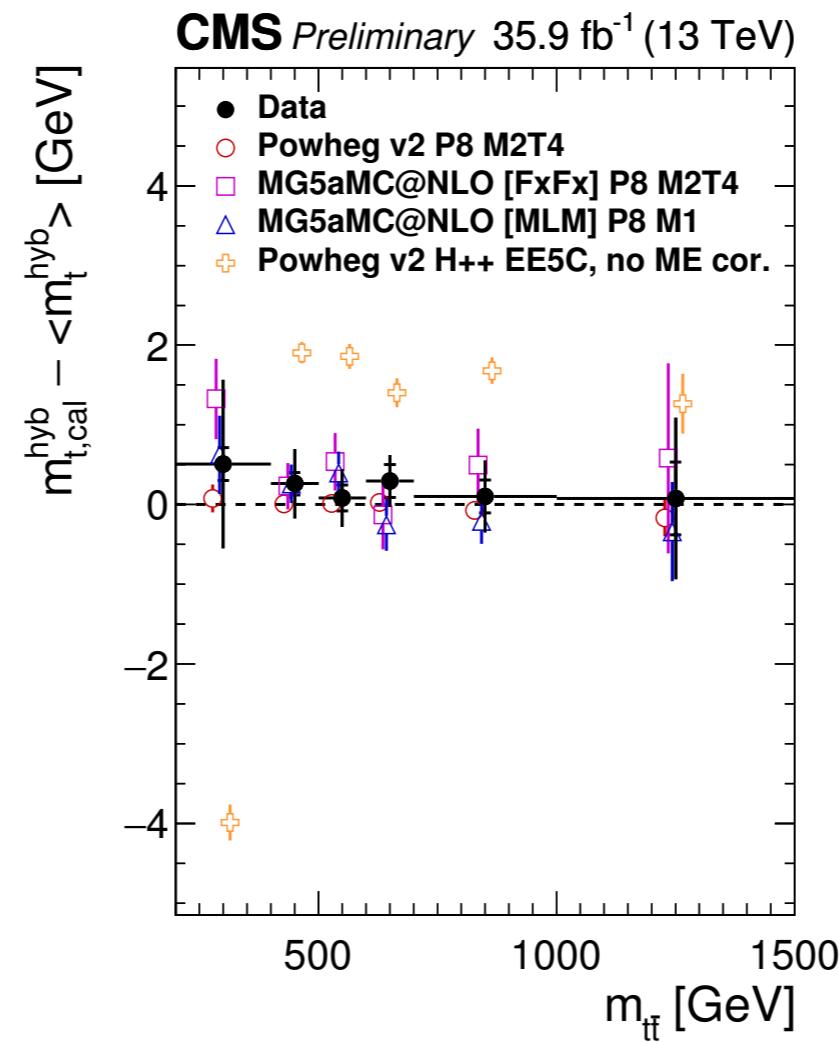
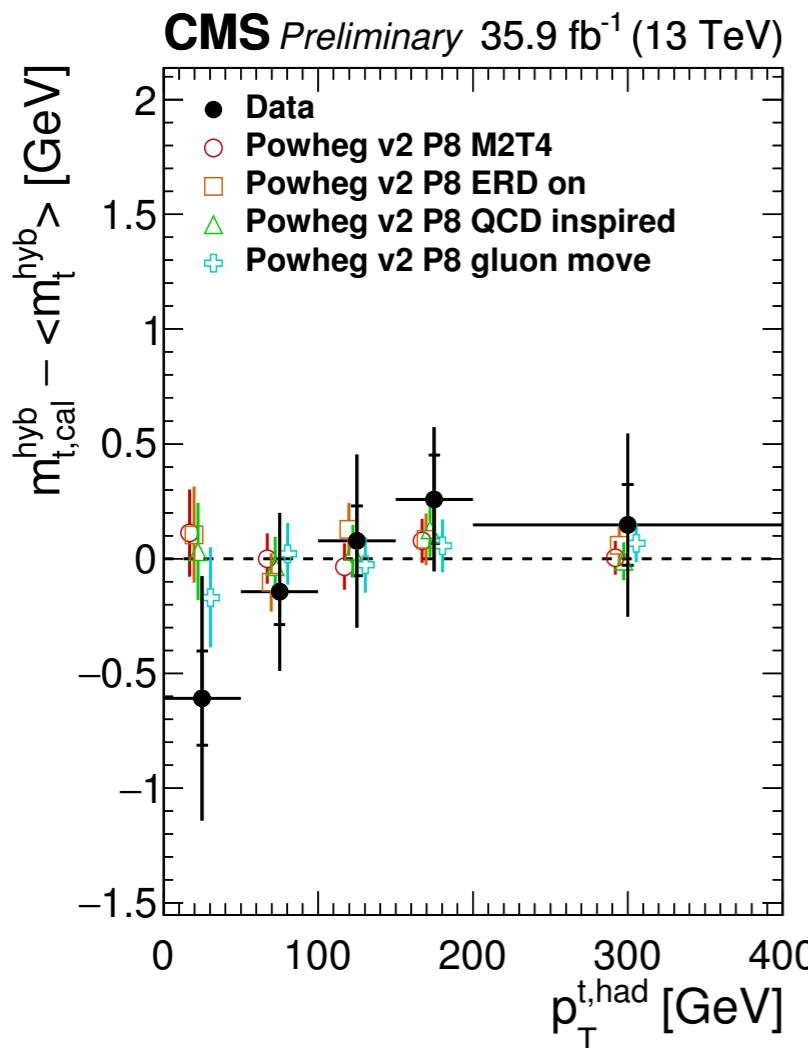
see Andrea Castro's presentation and
Nataliia Kovalchuk's poster

$\sqrt{s} = 13 \text{ TeV}$ Top Mass



- Effect of color reconnection on top decay productions \rightarrow ERD = on in Pythia8.
- Alternative color reconnection models in Pythia8:
 - QCD inspired: model with string formation beyond LO.
 - Gluon move: model in which gluons can be moved to another string.

CMS-PAS-TOP-17-007



- No indications of a kinematical bias.
Note: for Herwig++ ME corrections are off.
- Not much sensitivity to different color reconnection tunes.

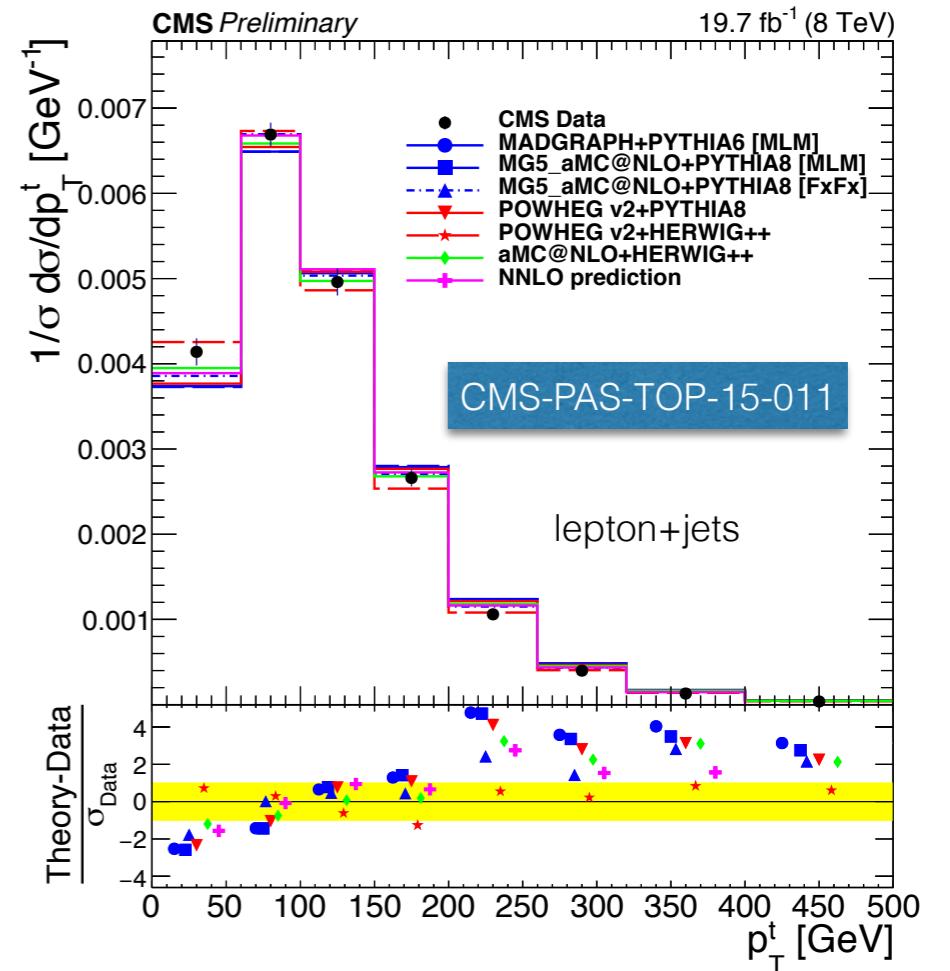
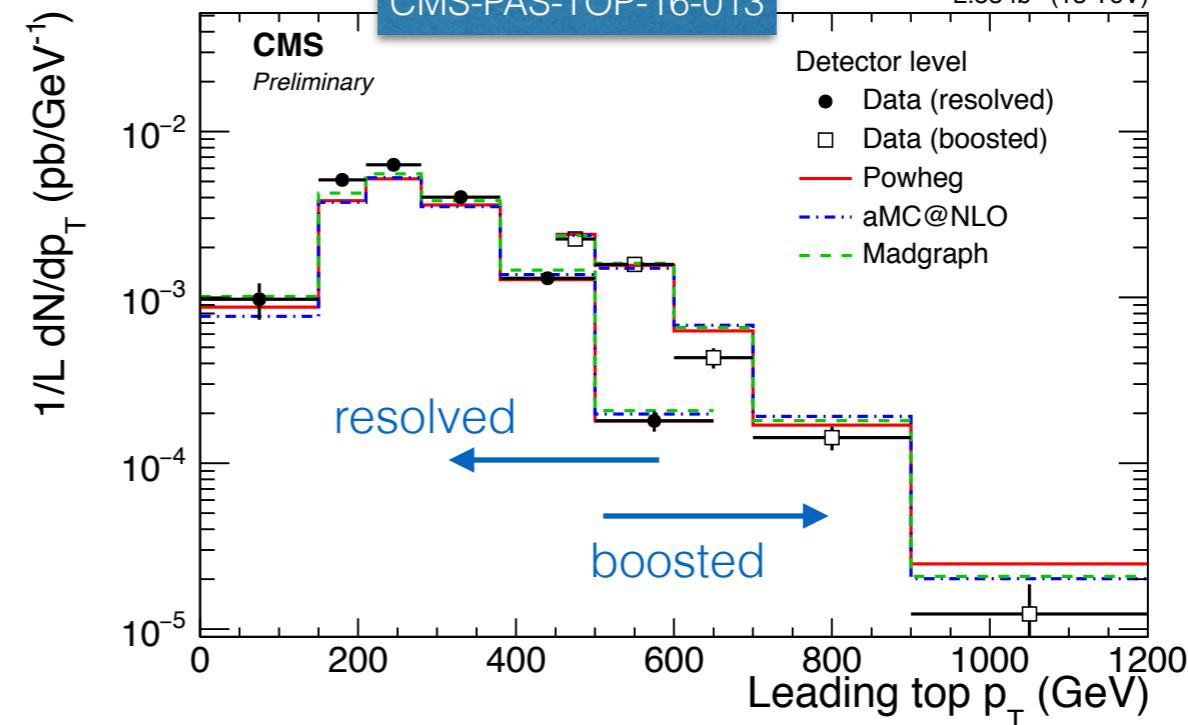
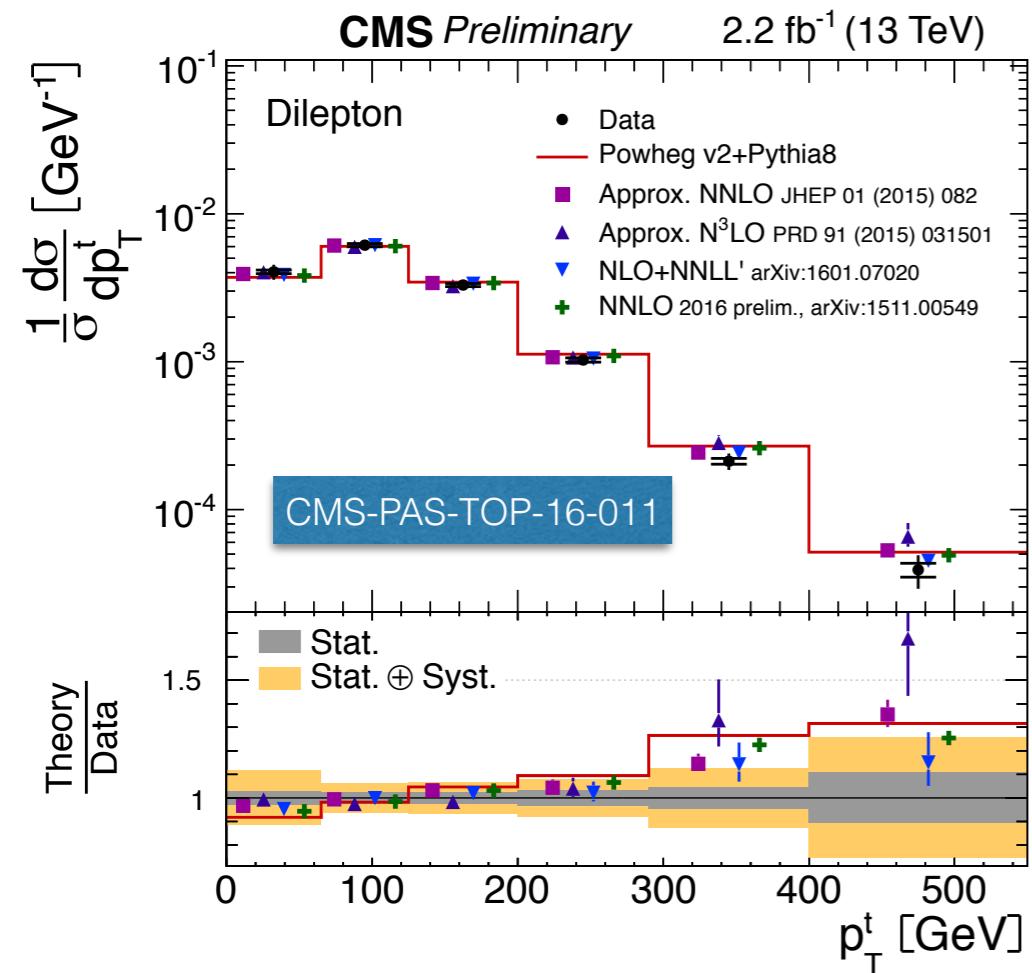
Summary and Conclusions

- Probing top differential spectra and UE to understand and improve top quark event modelling and generators (and top as background)
- Moved to factorized parton shower and hadronization uncertainties to understand each source better.
- A top specific tune is derived and used.
 - All distributions (except top pT) described well with Powheg and MG5_aMC@NLO [FxFx] + Pythia8 with the CUETP8M2T4 tune.
- Sherpa+OpenLoops w/ CS parton shower with the default Sherpa tune → show larger discrepancies in the central values w.r.t. data.
- UE/Min-Bias data are described at the same level by tunes with LO, NLO, and NNLO PDF NNPDF3.1 sets.
 - Higher order NNPDF3.1 sets (with $\alpha_s = 0.118$) can be consistently used in the ME and Pythia8.
- Top mass measurement
 - No impact from the new reference generator, tune or changes in the experiment
 - No bias when mass is measured in bins of top observables.

Bonus

The Top Quark p_T

- LHC Run I « discovery »: harder spectrum in LO/NLO + PS predictions than in data
 - NNLO+NNLL: significantly better description.
- Similar behaviour at Run II and in boosted top.



Jet Multiplicity at $\sqrt{s} = 13$ TeV and Shower a_s+h_{damp} Tuning

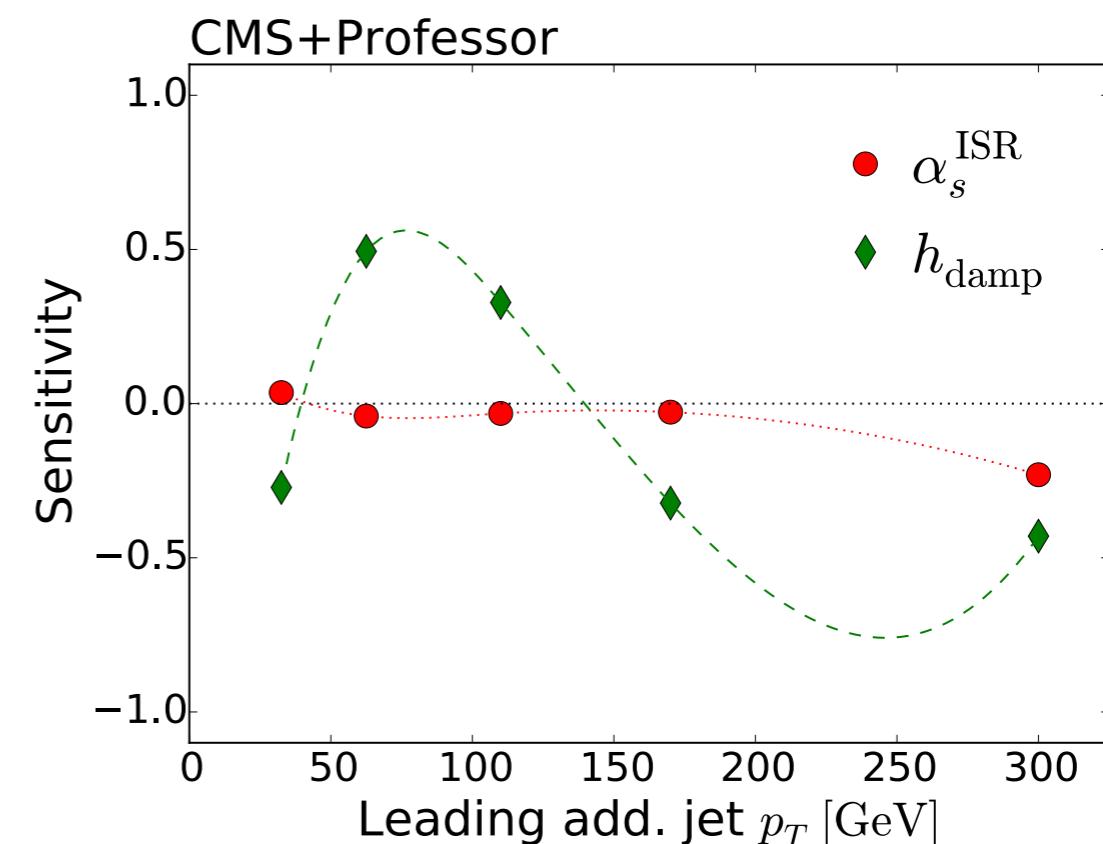
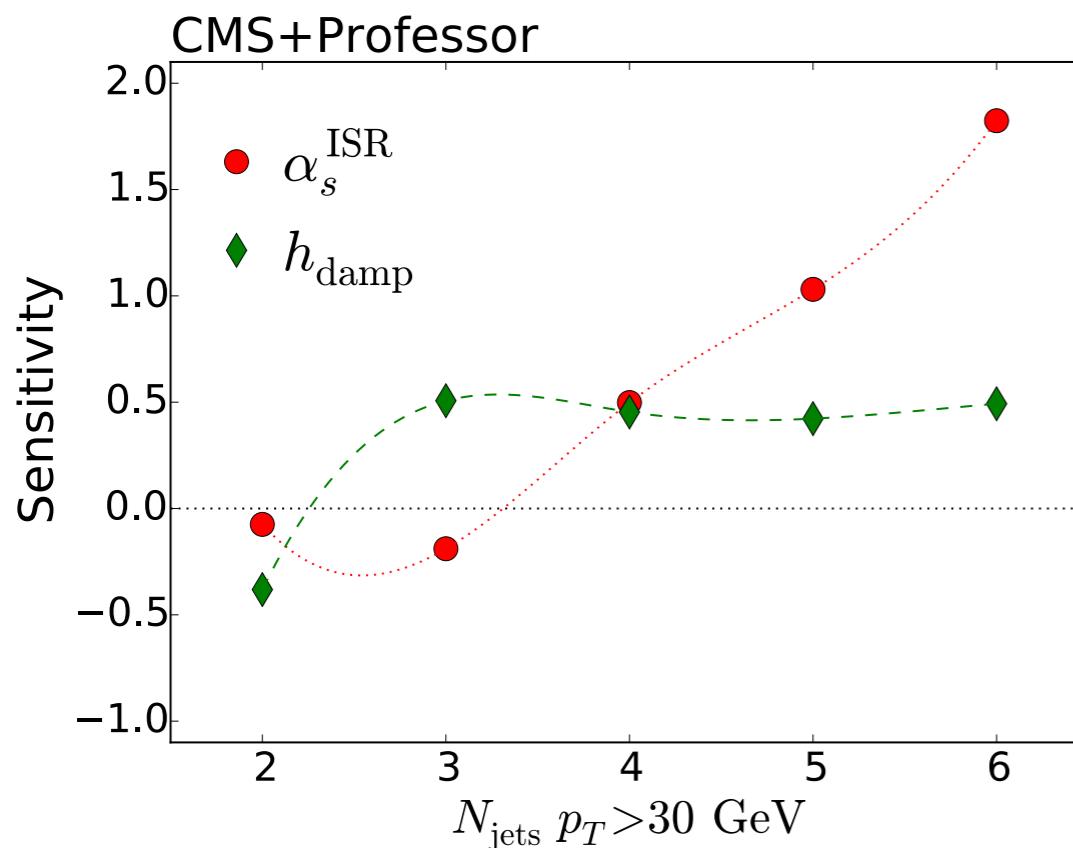
CMS-PAS-TOP-16-021

- POWHEG: h_{damp} (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 $h_{\text{damp}}^2 / (p_T^2 + h_{\text{damp}}^2)$. 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 $\alpha_s^{\text{ISR}} = 0.1365$ obtained from tuning to LEP event shapes [22] is kept for the final-state shower.

$$S = \frac{dMC(p)}{dp} \times \frac{p_c}{MC(p_c)}$$

bin value for a parameter value p
and p_c is a reference parameter point.

- 2-/3-jet events
- Lead. add. jet p_T
- $N_{\text{jets}} > 3$ where jets predominantly originate from the parton shower in Powheg+Pythia8



Particle Level Comparisons

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
$p_T(t_h)$	15.9/12	0.197	7.21/12	0.844	29.5/12	< 0.01
$ y(t_h) $	1.96/11	0.999	1.48/11	1.000	2.23/11	0.997
$p_T(t_\ell)$	27.0/12	< 0.01	22.3/12	0.034	80.2/12	< 0.01
$ y(t_\ell) $	4.55/11	0.951	5.07/11	0.928	4.99/11	0.932
$M(t\bar{t})$	5.83/10	0.829	2.40/10	0.992	9.07/10	0.525
$p_T(t\bar{t})$	4.96/8	0.761	28.9/8	< 0.01	41.2/8	< 0.01
$ y(t\bar{t}) $	5.93/10	0.821	6.63/10	0.760	8.61/10	0.570
$ y(t_h) \text{ vs. } p_T(t_h)$	35.7/44	0.810	29.6/44	0.953	64.1/44	0.025
$M(t\bar{t}) \text{ vs. } y(t\bar{t}) $	25.9/35	0.867	24.2/35	0.914	56.2/35	0.013
$p_T(t_h) \text{ vs. } M(t\bar{t})$	47.4/32	0.039	57.2/32	< 0.01	73.2/32	< 0.01
	SHERPA		POWHEG+H++		MG5_aMC@NLO+P8 FxFx	
$p_T(t_h)$	13.5/12	0.335	32.1/12	< 0.01	17.4/12	0.137
$ y(t_h) $	2.32/11	0.997	4.89/11	0.936	3.16/11	0.988
$p_T(t_\ell)$	39.4/12	< 0.01	21.8/12	0.040	47.7/12	< 0.01
$ y(t_\ell) $	5.54/11	0.902	4.04/11	0.969	7.22/11	0.781
$M(t\bar{t})$	2.86/10	0.985	52.8/10	< 0.01	5.45/10	0.859
$p_T(t\bar{t})$	68.7/8	< 0.01	46.8/8	< 0.01	21.3/8	< 0.01
$ y(t\bar{t}) $	12.1/10	0.276	18.6/10	0.046	8.13/10	0.616
$ y(t_h) \text{ vs. } p_T(t_h)$	48.3/44	0.305	116/44	< 0.01	44.9/44	0.434
$M(t\bar{t}) \text{ vs. } y(t\bar{t}) $	41.5/35	0.208	219/35	< 0.01	55.7/35	0.014
$p_T(t_h) \text{ vs. } M(t\bar{t})$	66.5/32	< 0.01	152/32	< 0.01	48.9/32	0.028

Particle Level Comparisons

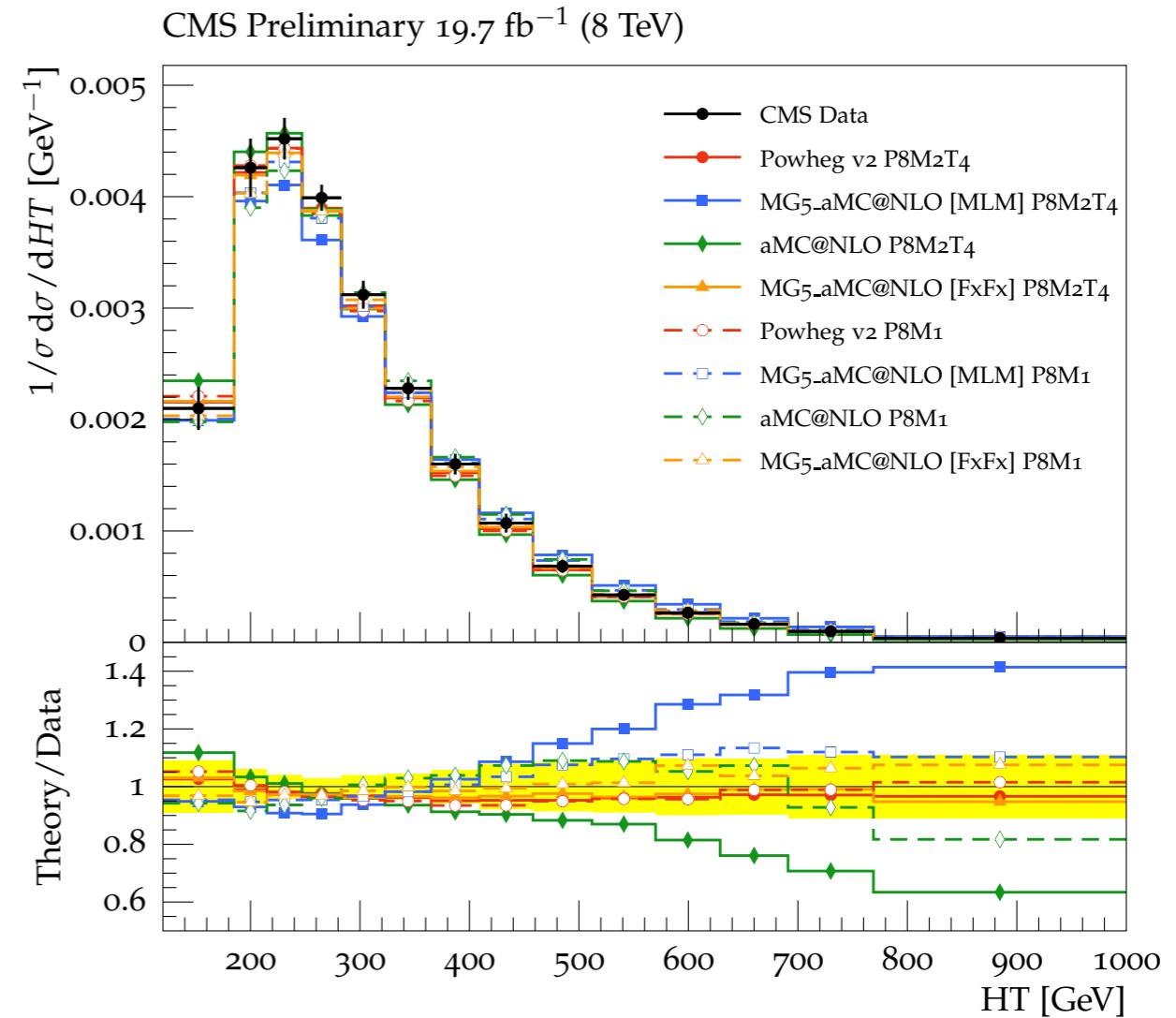
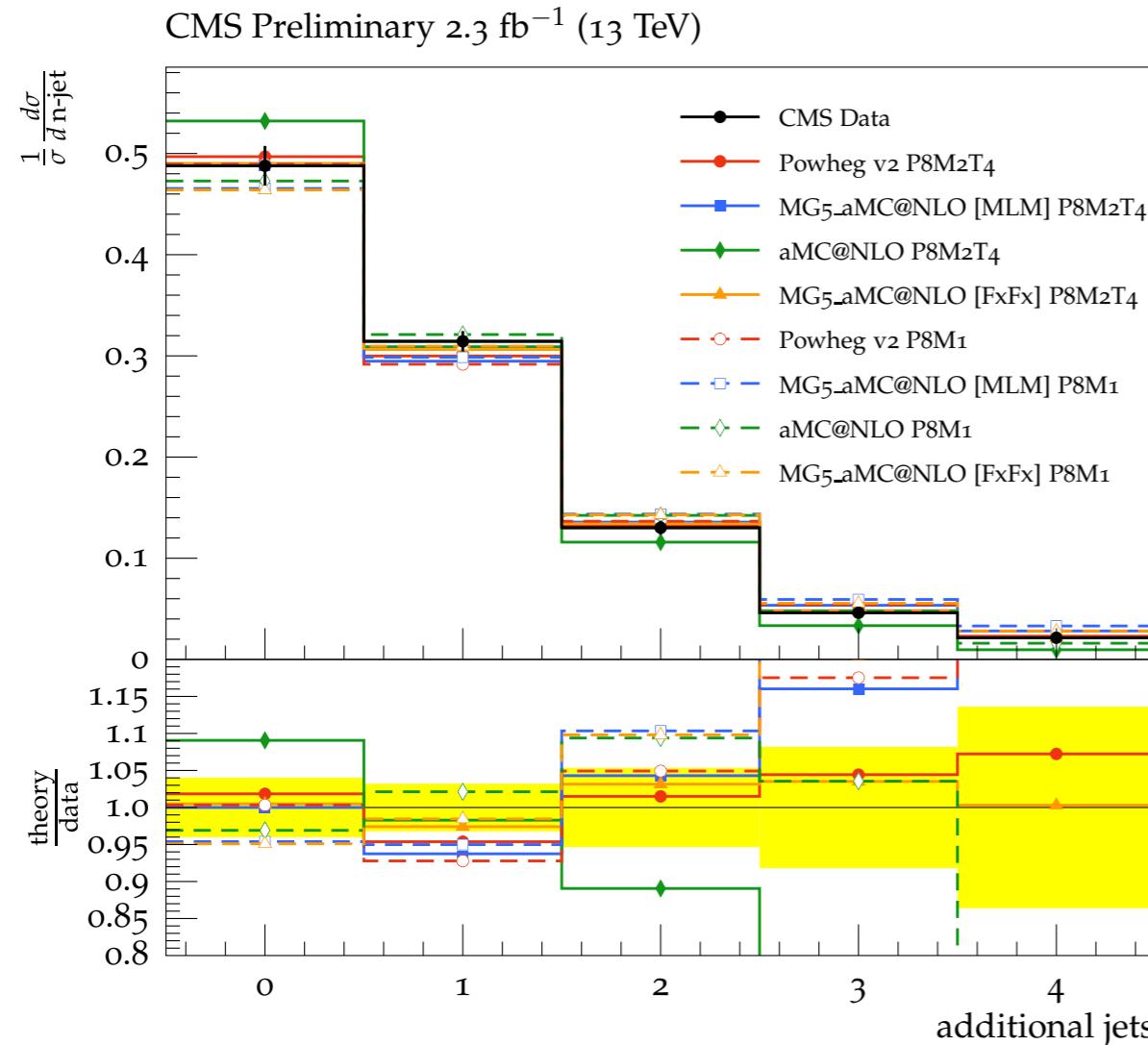
Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
Additional jets	1.52/6	0.958	27.3/6	< 0.01	10.1/6	0.121
Additional jets vs. $M(t\bar{t})$	27.5/36	0.845	68.9/36	< 0.01	38.8/36	0.345
Additional jets vs. $p_T(t_h)$	35.1/44	0.830	64.6/44	0.023	71.6/44	< 0.01
Additional jets vs. $p_T(t\bar{t})$	64.6/29	< 0.01	181/29	< 0.01	175/29	< 0.01
$p_T(\text{jet})$	70.2/47	0.016	374/47	< 0.01	133/47	< 0.01
$ \eta(\text{jet}) $	120/70	< 0.01	174/70	< 0.01	171/70	< 0.01
ΔR_{j_t}	60.9/66	0.655	215/66	< 0.01	168/66	< 0.01
ΔR_t	64.0/62	0.405	229/62	< 0.01	121/62	< 0.01
	SHERPA		POWHEG+H++		MG5_aMC@NLO+P8 FxFx	
Additional jets	63.0/6	< 0.01	34.1/6	< 0.01	11.1/6	0.086
Additional jets vs. $M(t\bar{t})$	112/36	< 0.01	300/36	< 0.01	55.1/36	0.022
Additional jets vs. $p_T(t_h)$	88.5/44	< 0.01	230/44	< 0.01	53.4/44	0.156
Additional jets vs. $p_T(t\bar{t})$	285/29	< 0.01	223/29	< 0.01	122/29	< 0.01
$p_T(\text{jet})$	768/47	< 0.01	624/47	< 0.01	111/47	< 0.01
$ \eta(\text{jet}) $	214/70	< 0.01	259/70	< 0.01	133/70	< 0.01
ΔR_{j_t}	334/66	< 0.01	959/66	< 0.01	67.0/66	0.441
ΔR_t	316/62	< 0.01	483/62	< 0.01	78.9/62	0.073

CMS-PAS-TOP-17-002

Monte Carlo for Run II

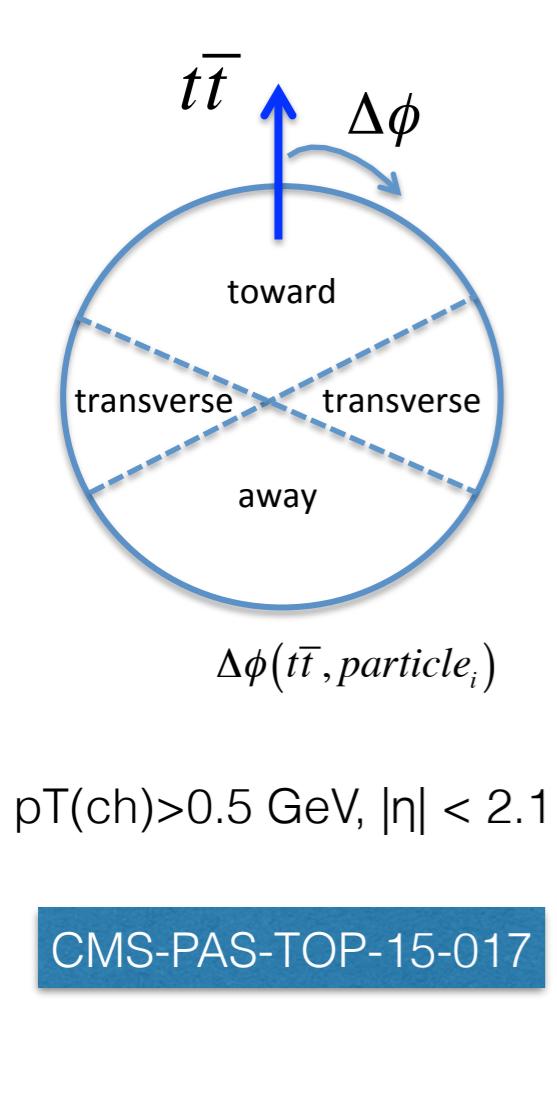
ME+PS	NLO	LO	PS
aMC@NLO + Pythia8	= 0 jet	= 1 jet	≥ 2 jets
Powheg + Pythia8/Herwig	= 0 jet	= 1 jet	≥ 2 jets
MG5_aMC@NLO + Pythia8 [MLM]	-	≤ 3 jets	≥ 4 jets
MG5_aMC@NLO + Pythia8 [FxFx]	≤ 2 jets	= 3 jets	≥ 4 jets
Sherpa+OpenLoops+CS	≤ 1 jet	≤ 4 jets	≥ 5 jets

Performance of the New CMS Tune with Top Quark Data



- Powheg+Pythia8 with the new tune describes the top quark data very well (except top p_T)
- MG5_aMC@NLO [FxFx] with the new tune describes the data as well as Powheg+Pythia8 (top p_T and except gap fraction).
- MG5_aMC@NLO [MLM] and aMC@NLO + Pythia8 with the new tune does not describe the top quark data in general.
- Global event variables do not get modified significantly with the change of a_s^{ISR} (except with Mg5_aMC@NLO [MLM] and aMC@NLO).

UE in ttbar Events



- Fair agreement between Powheg + Pythia8 CUETP8M1 tune predictions.
- UE is sensitive to QCD scales / ISR.
- A complete measurement of UE in ttbar events may lead to more precise top mass with better understood systematics.