QCD Monte Carlo model tuning studies in CMS

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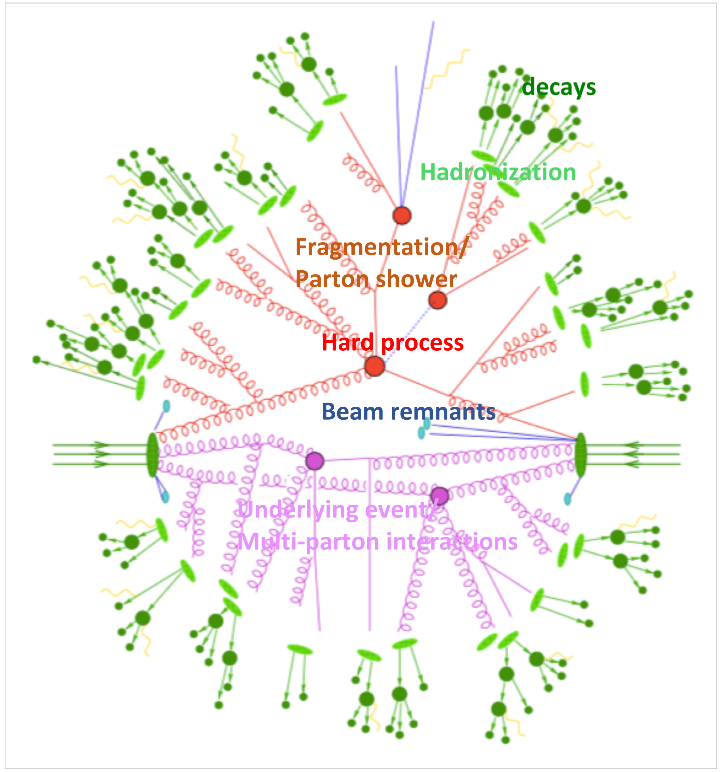
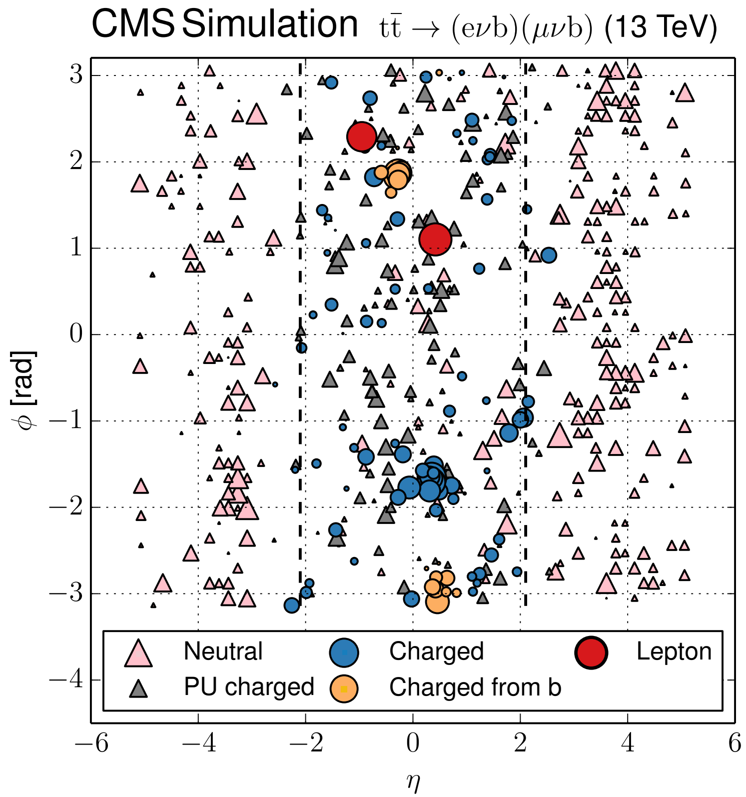
XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

Torino (Italy), 8-12 April 2019

Underlying Event



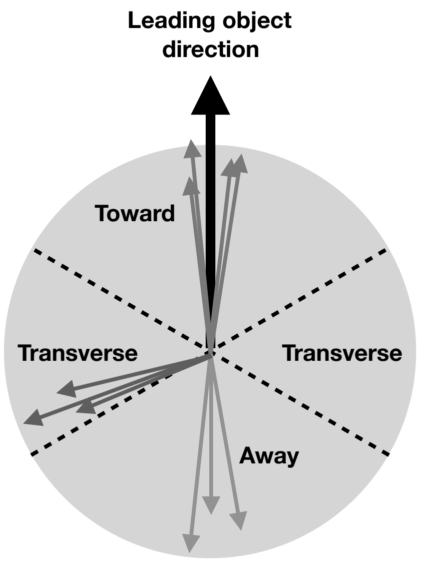
Gleisberg et al. JHEP02 (2004) 056



CMS, EPJ C 79 (2019) 123

- **UE**: activity in addition to the hard process
  - Consists of beam-beam remnants and multi-parton interactions + some contribution from the hard process
  - Requires modeling of BBR, MPI, hadronization, ISR, FSR.
  - Need to tune the adjustable parameters in MCs.

Comparisons of predictions for UE observables from previous tunes to 13 TeV data

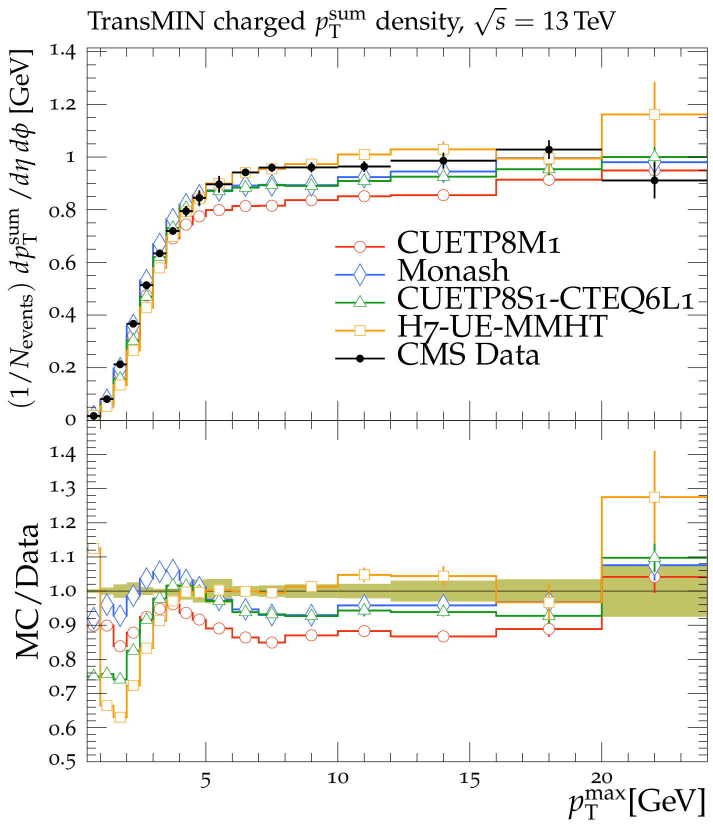


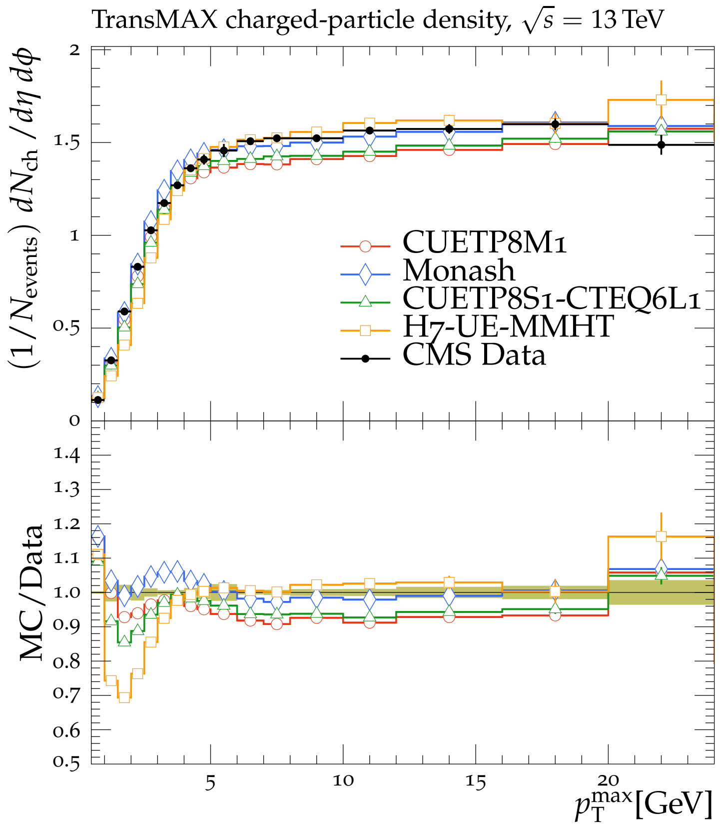
$p_T > 0.5\ GeV$

$|\eta| < 0.8$

$p_T^{max} = max(p_T^{trk,i})$

arXiv:1903.12179





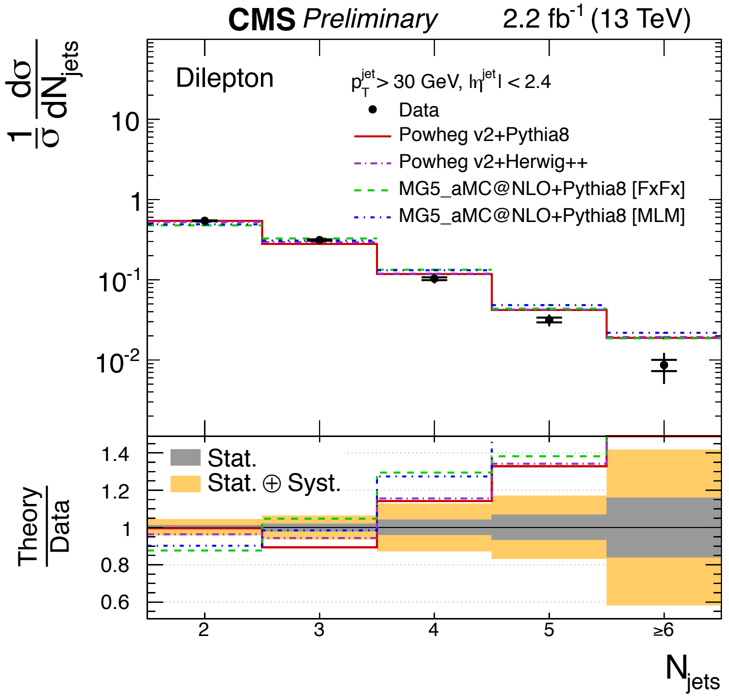
- Main CMS tune (CUETP8M1 based on Monash tune) used until 2017 analyses does not describe well the central values of the data at 13 TeV. EP JC 76 (2016) 155
- CUETP8M1: α_s and shower parameters kept as in Monash → $\alpha_s^{ISR/FSR}$=0.1365 despite the prefered values of 0.130 in LO and 0.118 in NLO matrix elements/ PDF sets.
  - α_s^{FSR} in Monash → by fitting Pythia8 predictions to LEP event shapes and α_s^{ISR} is just assumed to be the same as α_s^{FSR}.
  - α_s^{MPI} = 0.130 set to the value prefered in the LO PDF set.

Revisiting Shower Parameters and Tunes

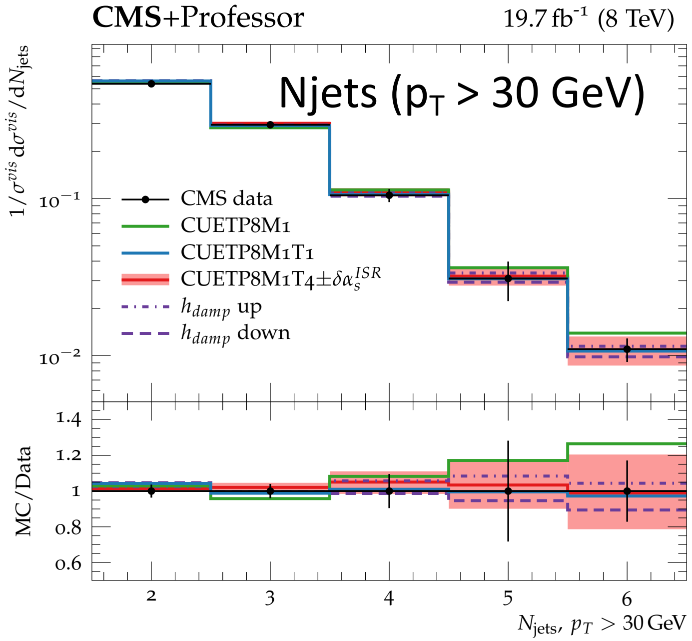
- Starting from parton shower in ttbar events — CMS-PAS-TOP-16-021
  → CUETP8M2T4 tune ($\alpha_s^{ISR} \sim 0.11$)
- UE in ttbar events at 13 TeV — EPJC 79 (2019) 123
  → $\alpha_s^{FSR} \sim 0.118$ agrees better with data.
- Jet substructure in ttbar events at 13 TeV — PRD98 (2018) 092014
  → $\alpha_s^{FSR} \sim 0.115$.
- New CMS tunes using (N)(N)LO PDF sets in PS — arXiv:1903.12179
  → CPX tunes (consistent treatment of PDF+α_s in matrix element and parton shower)
- UE in Z+jets events at 13 TeV — JHEP07 (2018) 032 and arXiv:1903.12179

CUETP8M2T4 Event Tune

CMS-PAS-TOP-16-021



- CUETP8M1 not only bad in describing the UE but its predictions overshoot the data for large jet multiplicities when out of the box parameters are used (in Monash-based tunes: α_s^{ISR}=0.1365)
- Effect also observed with 8 TeV data.



Tune α_s^{ISR} using 8 TeV ttbar Njets (using the parton-shower dominated region) and ttbar jet pT data →

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

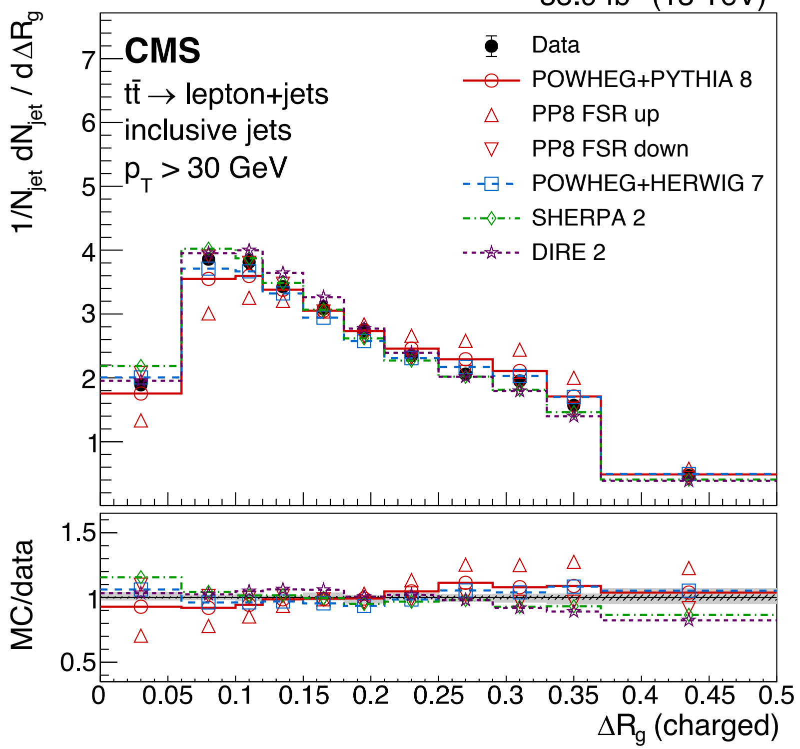
SpaceShower:RapidityOrdering=on

→ Significantly lower α_s^{ISR} cures the overshoot of CUETP8M1 at high jet multiplicities.
→ UE event tune starting with fixed lower α_s^{ISR} describes the UE & min-bias (and top quark) significantly data better.

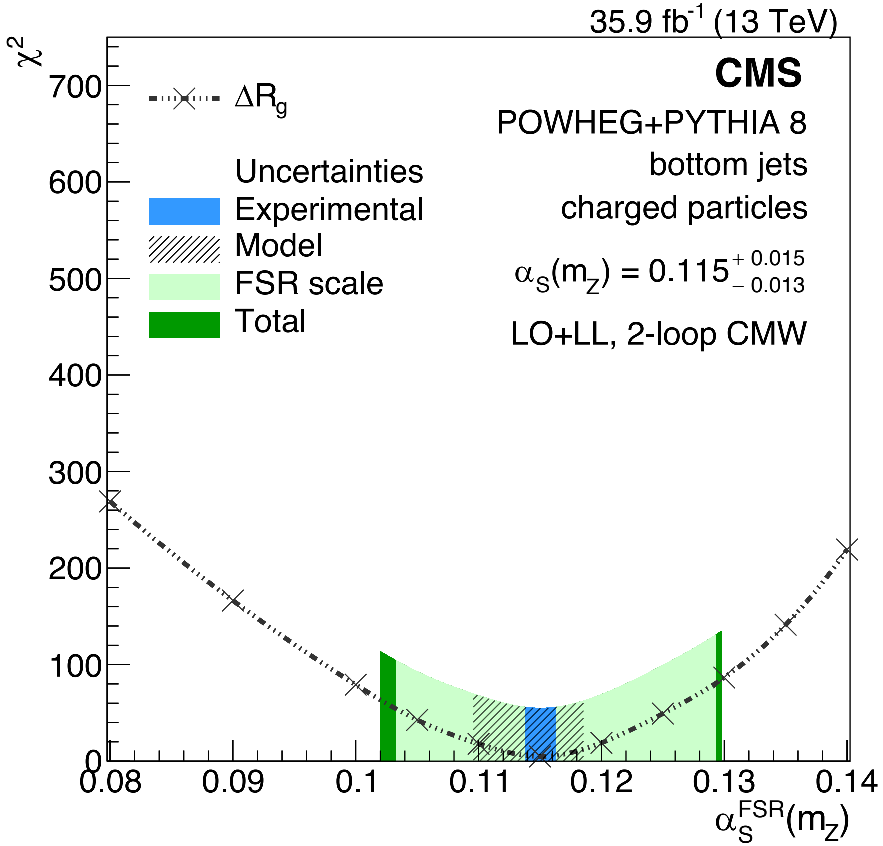
α_s^{FSR} from jet substructure in ttbar l+jets events

- Measured using charged+neutral and with only charged jet constituents (particle pT > 1 GeV).
- b, light, or gluon jet enriched samples.

PRD98 (2018) 092014



Angle between groomed subjets
at particle level (correlated to jet width)



Angle between groomed subjets
at particle level.

Pythia8:
CUETP8M2T4 for ttbar
CUETP8M1 for the rest.

None of the default tunes yield a good overall description of the data.

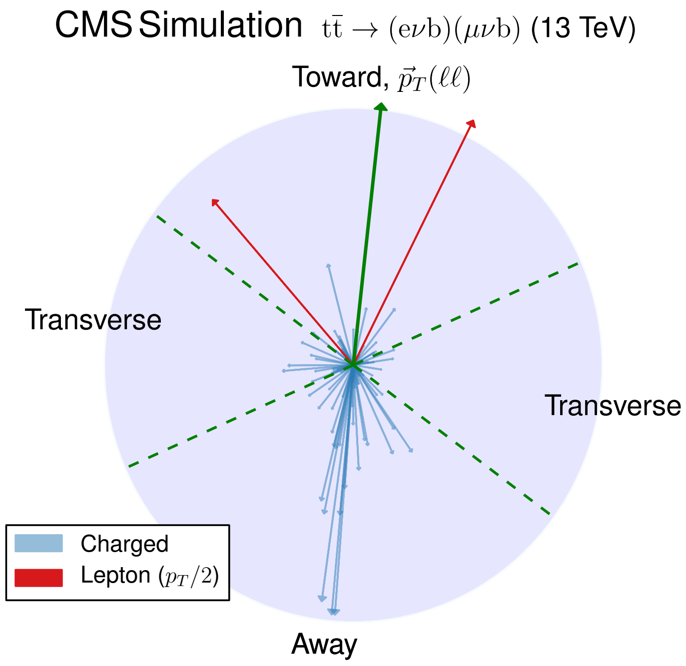
Powheg+Pythia8 with LO+LL, 2-loop :

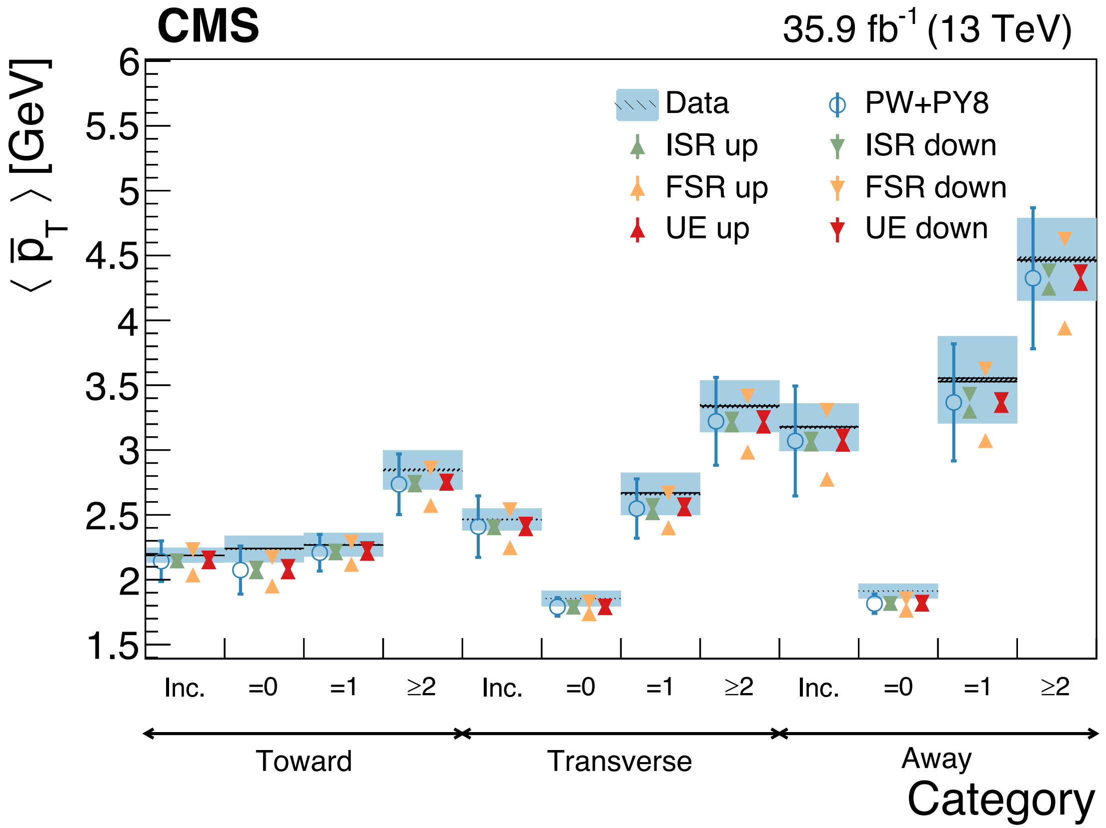
$$\alpha_s^{FSR}(M_Z) = 0.115^{+0.015}_{-0.013}$$

α_s^{FSR} from Underlying Event in ttbar

EPJC 79 (2019) 123

- Measurement of the UE for the first time at a scale of > $2m_t$.
- > 200 distributions investigated in different categories to enhance sensitivity to the modeling of MPI, color reconnection, $\alpha_s^{FSR}(M_Z)$ in Pythia8.
- Measurement unfolded to particle level.
- Good agreement of POWHEG+PYTHIA8 with CUETP8M2T4 in UE event regions.

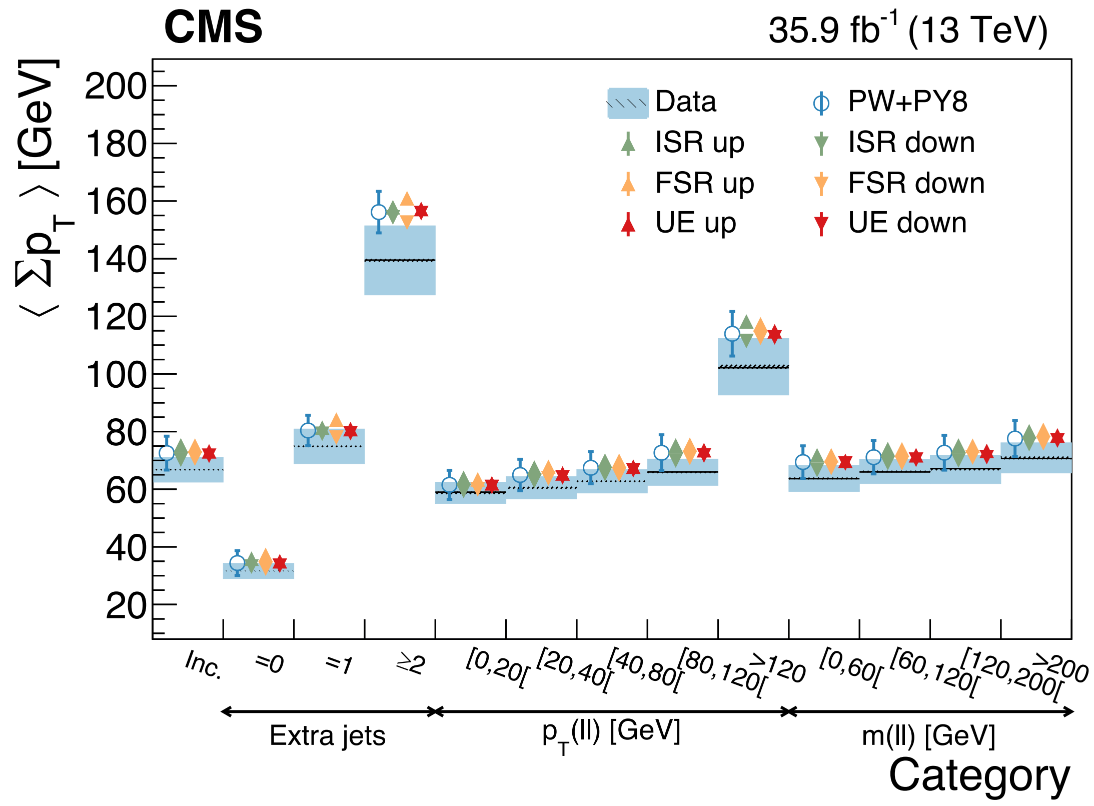


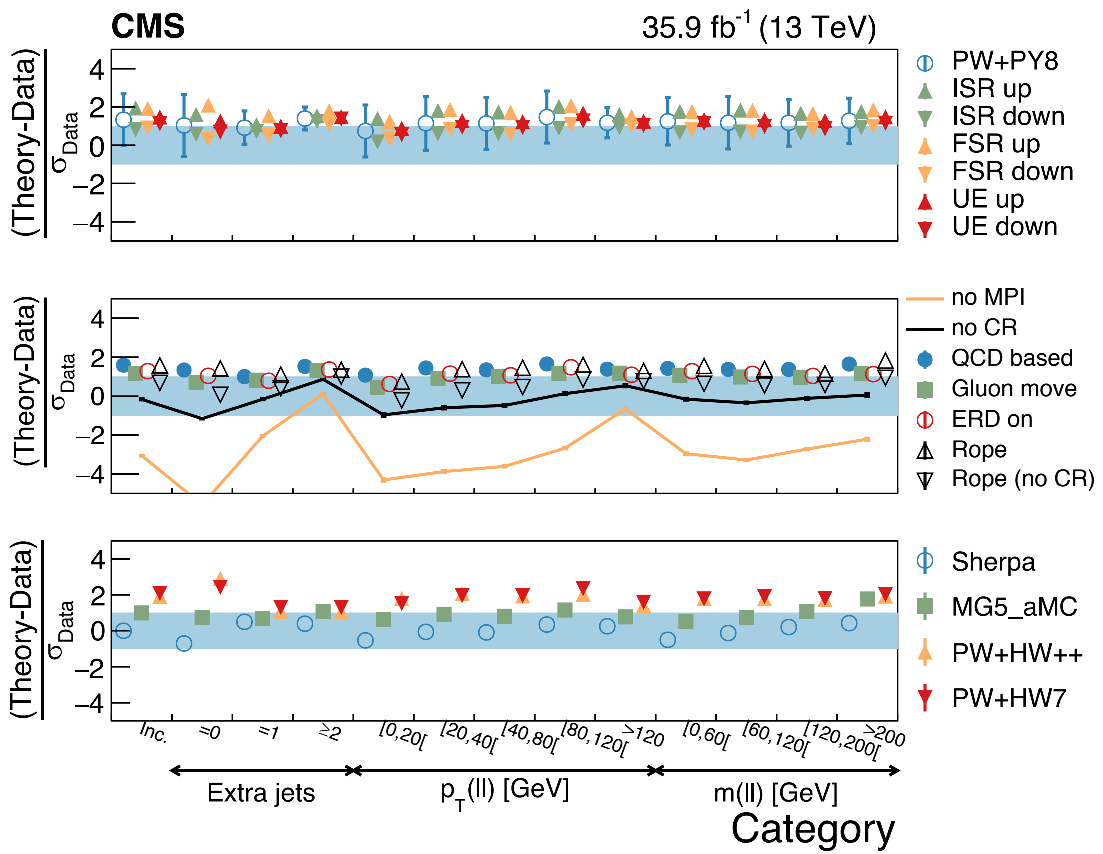


Underlying Event in ttbar Events

EPJC 79 (2019) 123

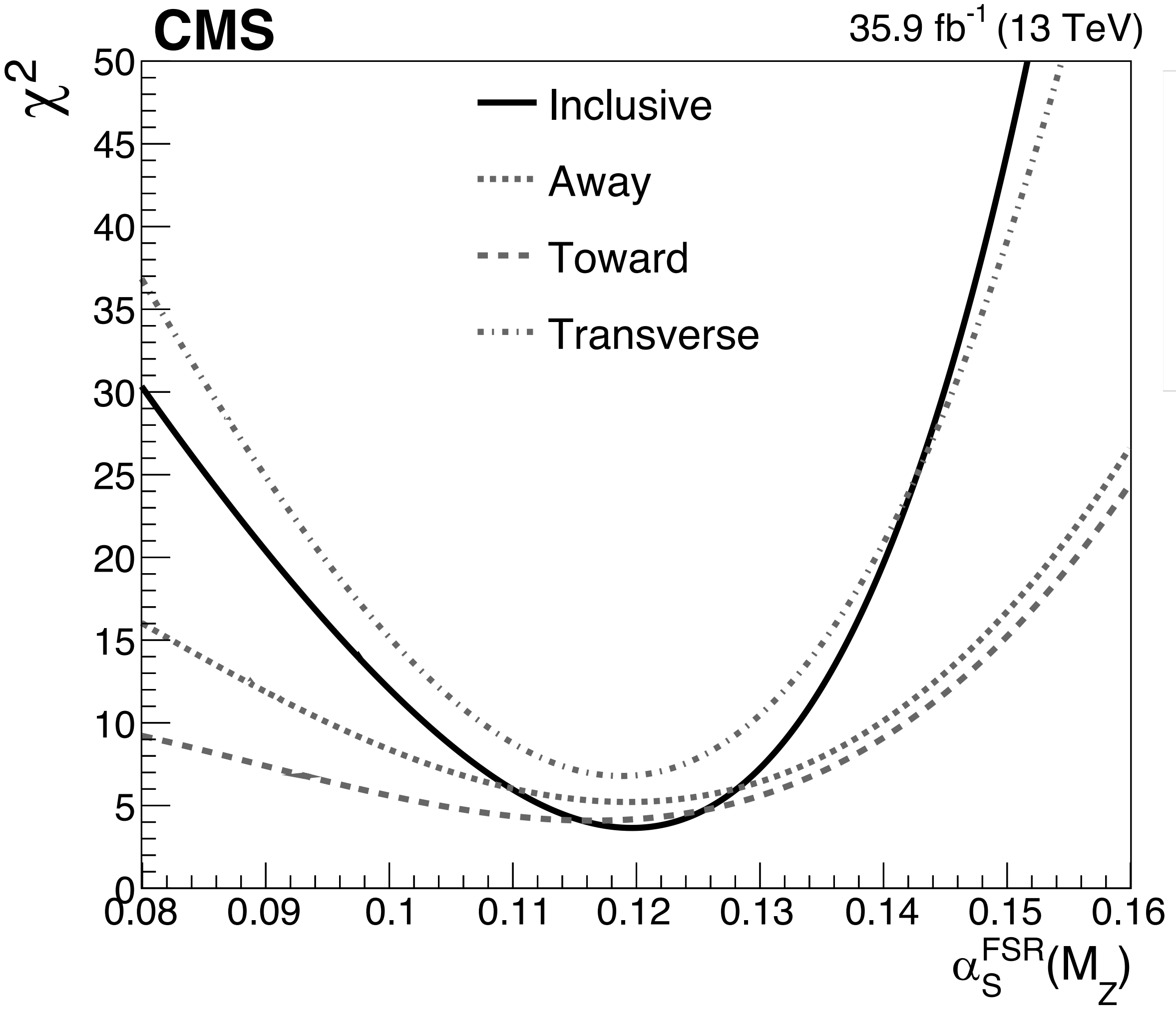
- Data disfavor default settings in HERWIG++, HERWIG7, and SHERPA → Need tuning.
- Choice of NLO ME generator (Powheg or MG5_aMC@NLO[FxFx] + Pythia8) doesn't impact UE in ttbar.
- Overall, these measurements characterize, for the first time, UE properties in ttbar production.
- *No deviation from universality hypothesis at energy scales > 350 GeV.*





α_s^{FSR} from Underlying Event in ttbar

EPJC 79 (2019) 123



$p_T(\ell\ell)$ region	Inclusive	Away	Toward	Transverse
Best fit $\alpha_S^{FSR}(M_Z)$	0.120	0.119	0.116	0.119
68% CI	[-0.006,+0.006]	[-0.011,+0.010]	[-0.013,+0.011]	[-0.006,+0.006]
95% CI	[-0.013,+0.011]	[-0.022,+0.019]	[-0.030,+0.021]	[-0.013,+0.012]
μ_R / M_Z	2.3	2.4	2.9	2.4
68% CI	[1.7,3.3]	[1.4,4.9]	[1.6,7.4]	[1.7,3.5]

- Data prefer $\alpha_s^{FSR}(M_Z)$~0.118 → significantly lower than assumed in Monash but similar to new (N)NLO tunes of CMS, i.e. CP3-5.
- Uncertainties correspond to a ~√2 variation of μ_R (instead of a ~2 variation).

α_s Consistency in ME and PS and PDF Choices

- PDF and $\alpha_s(M_Z)$ appear in ME, PS, and MPI models.
- $\alpha_s(M_Z)$ at (N)NLO = 0.118 (=world average) and LO = 0.130
- Different strategies are adopted
  - CMS & ATLAS tunes traditionally based on LO PDFs.
  - PYTHIA tunes are mostly based on LO PDFs.
  - Sherpa tunes are based on NNLO PDFs.
  - HERWIG7 provide tunes based on NLO PDFs (in which MPI is still based on LO PDF).
- Using the same PDF set and $\alpha_s(M_Z)$ value in the ME and in the simulation of the PS components in matched configurations advocated

  Cooper et al. EPJC72 (2012) 2078

  - i.e. If ME is at NLO, then use $N^{\geq 1}$LO PDF in ME and PS.
  - Effect depends on the configuration and process.

New CMS Tunes using LO PDF

arXiv:1903.12179

PYTHIA8 parameter	CP1	CP2	
PDF Set	NNPDF3.1 LO	NNPDF3.1 LO	Fixed inputs
$\alpha_S(m_Z)$	0.130	0.130	
`SpaceShower:rapidityOrder`	off	off	
`MultipartonInteractions:EcmRef` [GeV]	7000	7000	
$\alpha_S^{\mathrm{ISR}}(m_Z)$ value/order	0.1365/LO	0.130/LO	
$\alpha_S^{\mathrm{FSR}}(m_Z)$ value/order	0.1365/LO	0.130/LO	
$\alpha_S^{\mathrm{MPI}}(m_Z)$ value/order	0.130/LO	0.130/LO	
$\alpha_S^{\mathrm{ME}}(m_Z)$ value/order	0.130/LO	0.130/LO	
`MultipartonInteractions:pT0Ref` [GeV]	2.4	2.3	Fitted parameters
`MultipartonInteractions:ecmPow`	0.15	0.14	
`MultipartonInteractions:coreRadius`	0.54	0.38	
`MultipartonInteractions:coreFraction`	0.68	0.33	
`ColorReconnection:range`	2.63	2.32	
χ^2/dof	0.89	0.54	

New CMS Tunes using (N)NLO PDFs

arXiv:1903.12179

PYTHIA8 parameter	CP3	CP4	CP5
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118	0.118	0.118
`SpaceShower:rapidityOrder`	off	off	on
`MultipartonInteractions:EcmRef` [GeV]	7000	7000	7000
$\alpha_S^{\mathrm{ISR}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{\mathrm{FSR}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{\mathrm{MPI}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{\mathrm{ME}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
`MultipartonInteractions:pT0Ref` [GeV]	1.52	1.48	1.41
`MultipartonInteractions:ecmPow`	0.02	0.02	0.03
`MultipartonInteractions:coreRadius`	0.54	0.60	0.76
`MultipartonInteractions:coreFraction`	0.39	0.30	0.63
`ColorReconnection:range`	4.73	5.61	5.18
χ^2/dof	0.76	0.80	1.04

Fixed inputs

Fitted parameters

New CMS Tunes using (N)NLO PDFs

arXiv:1903.12179

PYTHIA8 parameter	CP3	CP4	CP5
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118	0.118	0.118
`SpaceShower:rapidityOrder`	off	off	on
`MultipartonInteractions:EcmRef` [GeV]	7000	7000	7000
$\alpha_S^{\mathrm{ISR}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{\mathrm{FSR}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{\mathrm{MPI}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{\mathrm{ME}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
`MultipartonInteractions:pT0Ref` [GeV]	1.52	1.48	1.41
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`ColorReconnection:range`	4.73	5.61	5.18
χ^2/dof	0.76	0.80	1.04

Fixed inputs

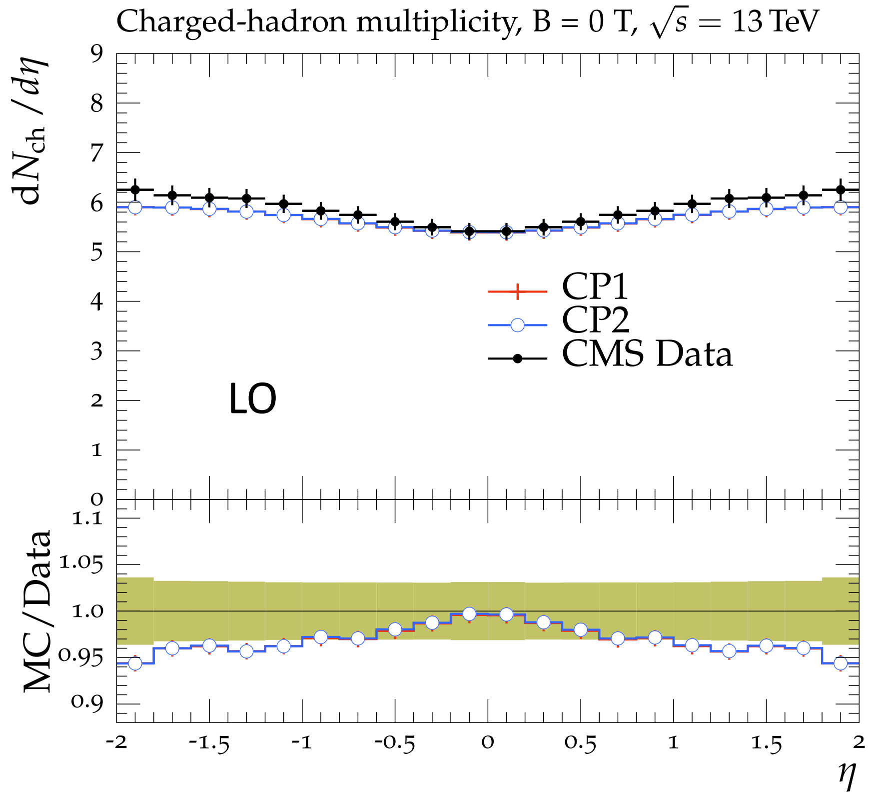
Fitted parameters

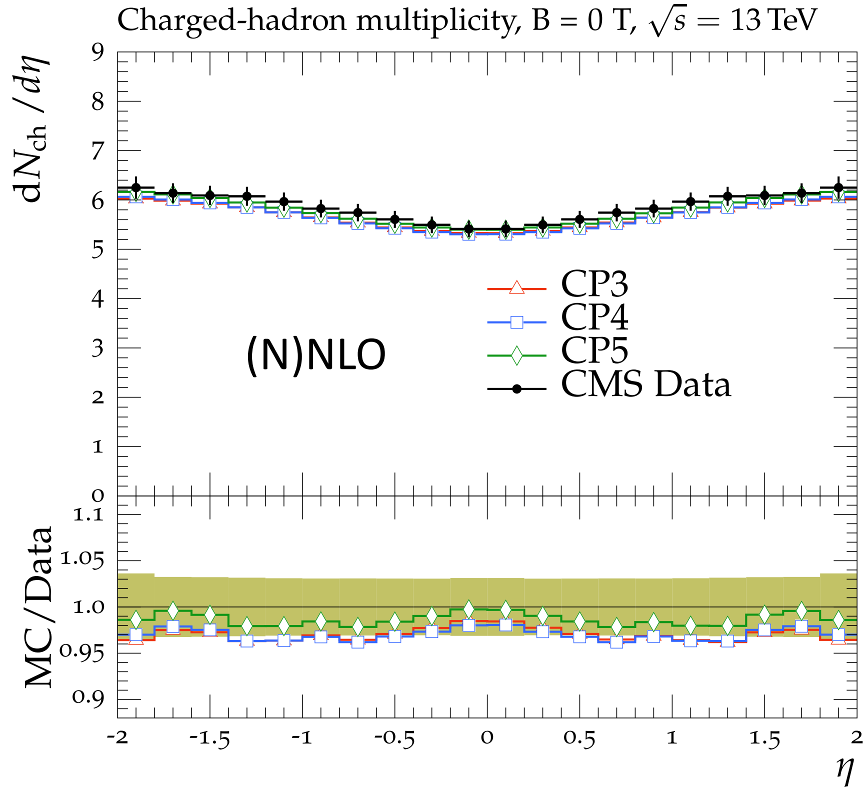
The overlap between two protons modelled by a double-gaussian --> better reproduce 7 TeV CMS data

CMS-PAS-FSQ-12-020

Data used for the fits:
charged particle and p_T^{sum} densities in transMIN, transMax vs p_T^{max} at √s = 1.96, 7 and 13 TeV.
+ charged-particle multiplicity vs η at √s=13 TeV.

α_s Consistency in ME and PS and PDF Choices – MinBias



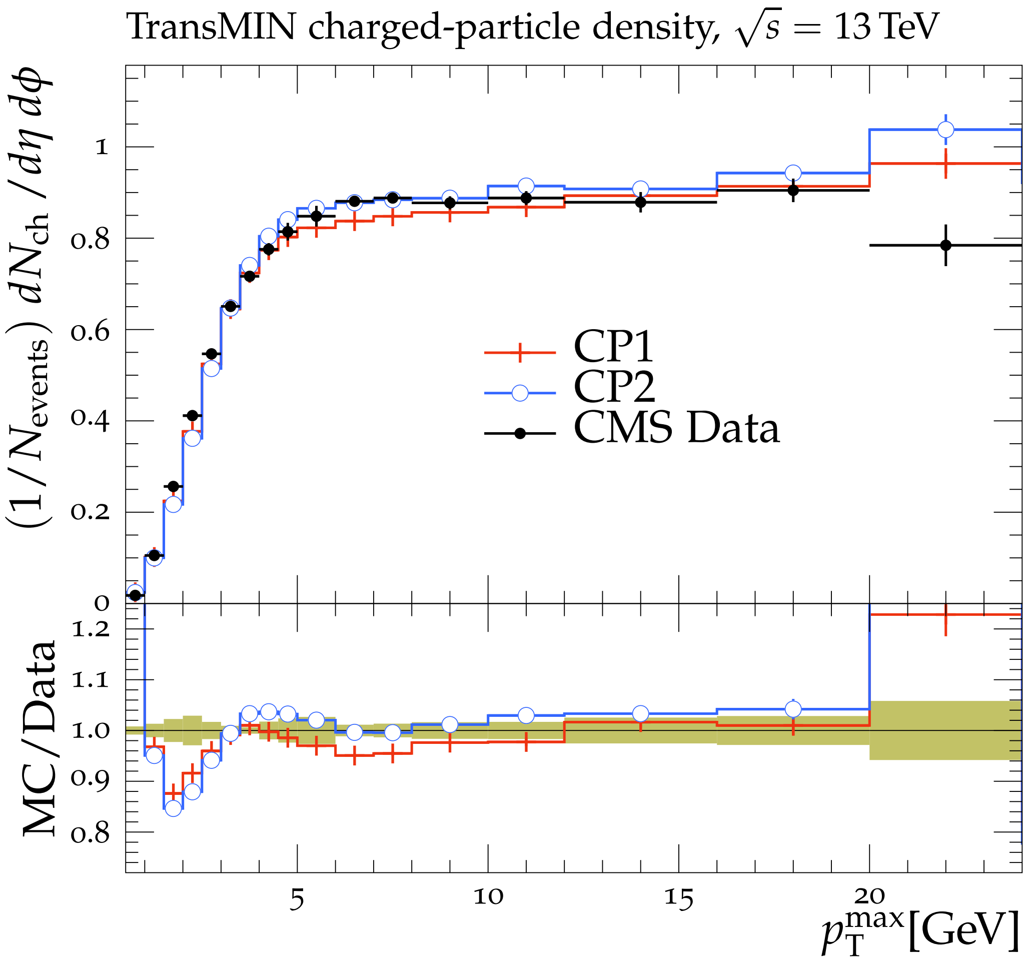


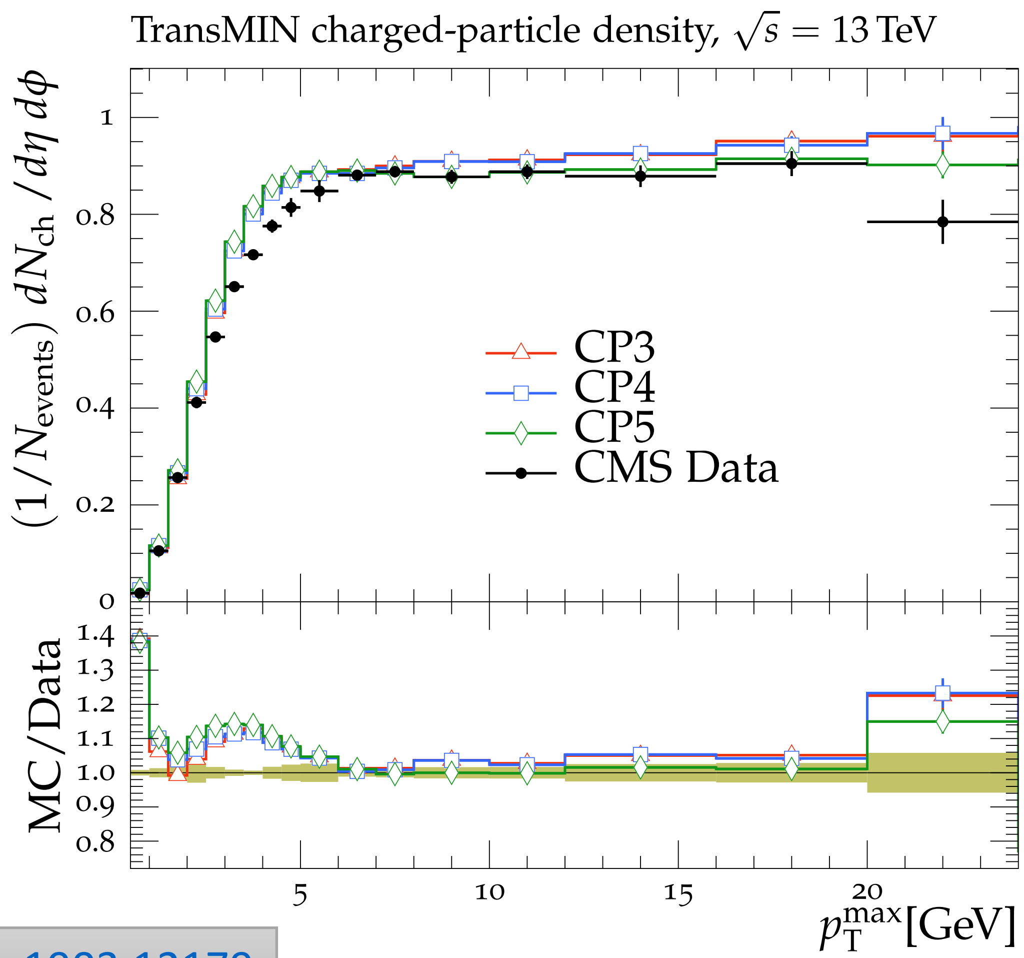
arXiv:1903.12179

$$|\eta| < \ 2, B = 0\ Tesla$$

- Central values of min-bias data are described within ~5% of uncertainties by tunes with LO, NLO, and NNLO NNPDF3.1 sets.
  - Central values of the LO-PDF-tunes worse description of data for |η|>1.5

α_s Consistency in ME and PS and PDF Choices –Underlying Event



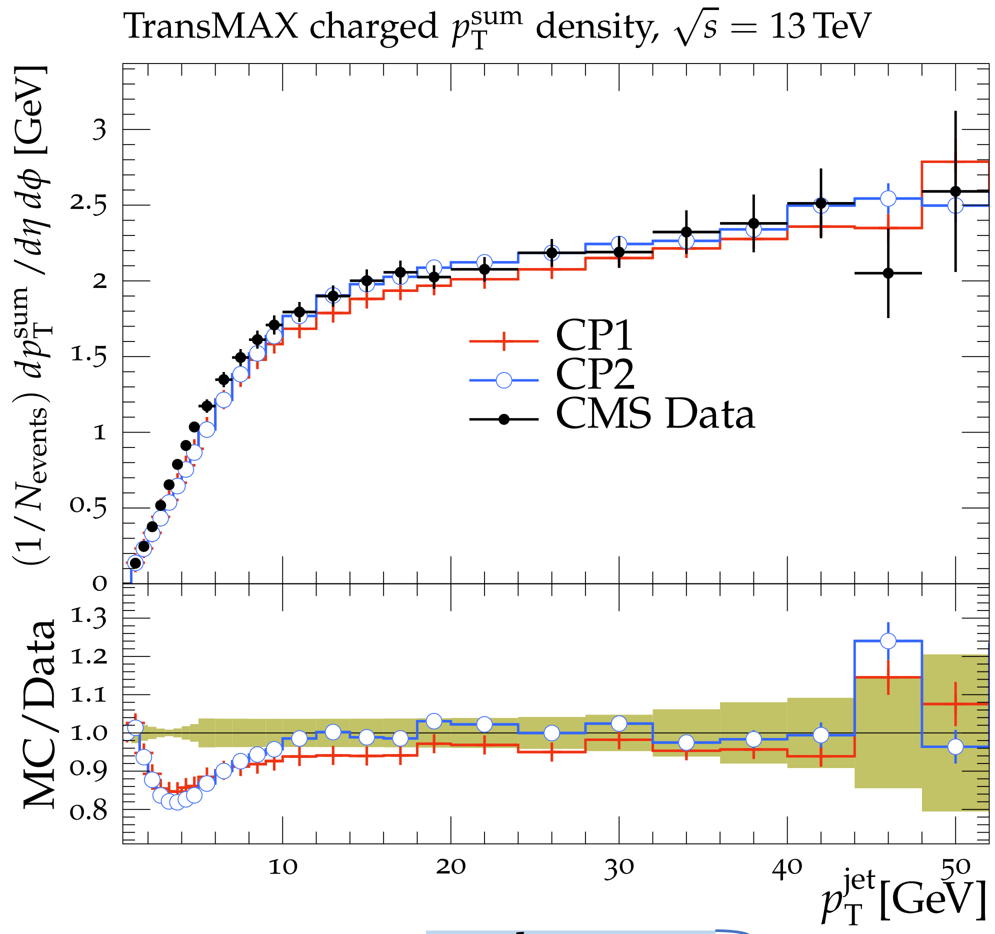


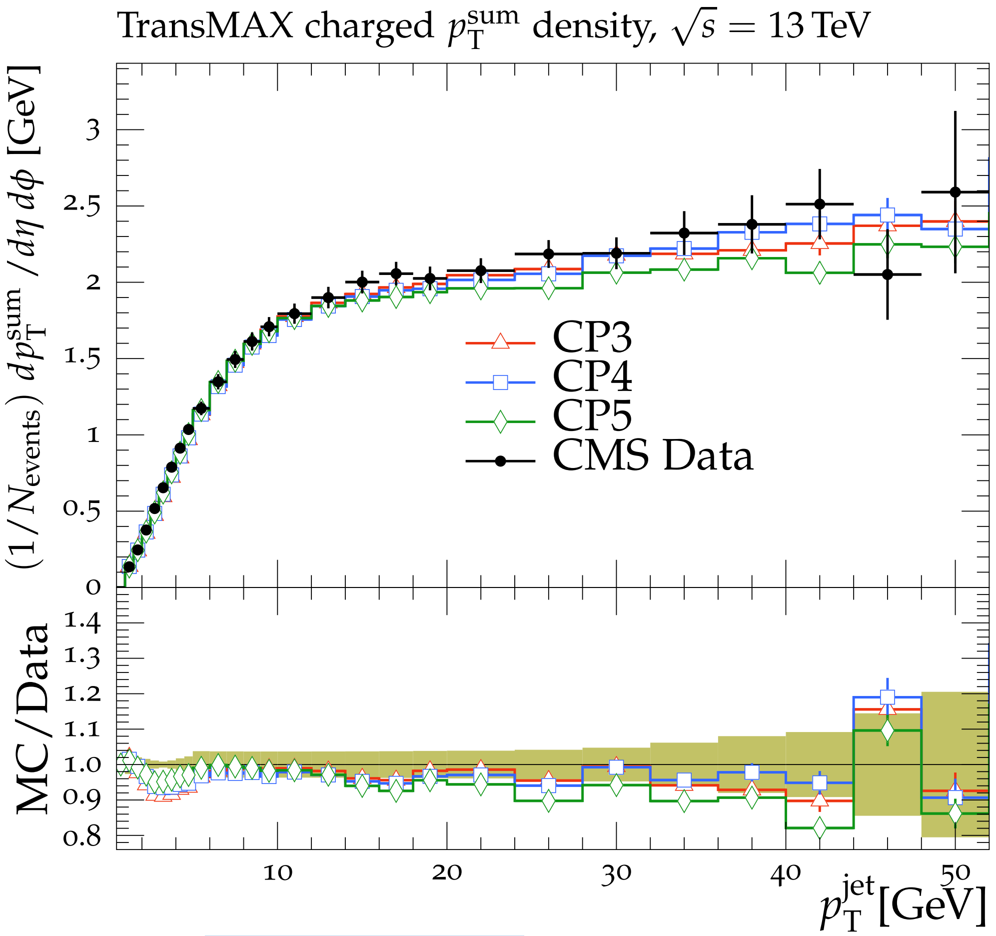
arXiv:1903.12179

- 13 TeV UE data are described at the same level by tunes with LO, NLO, and NNLO NNPDF3.1 sets.

CPX and UE

arXiv:1903.12179





$p_T^{trk} > 0.5$

$|\eta^{trk}| < 2.5$

SISCone0.5 jet

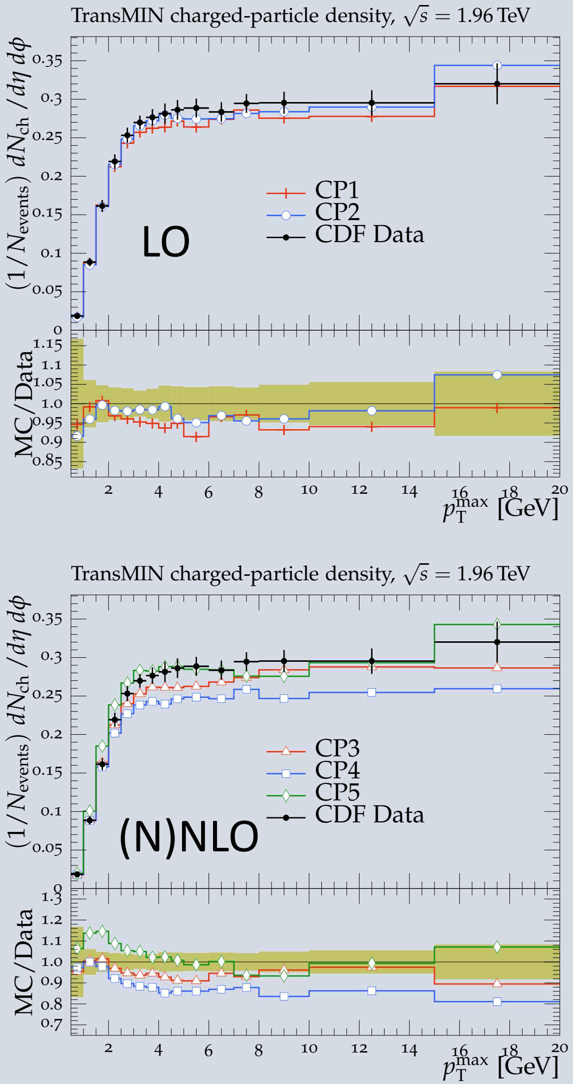
$p_T^{jet} > 1GeV$

$|\eta^{jet}| < 2$

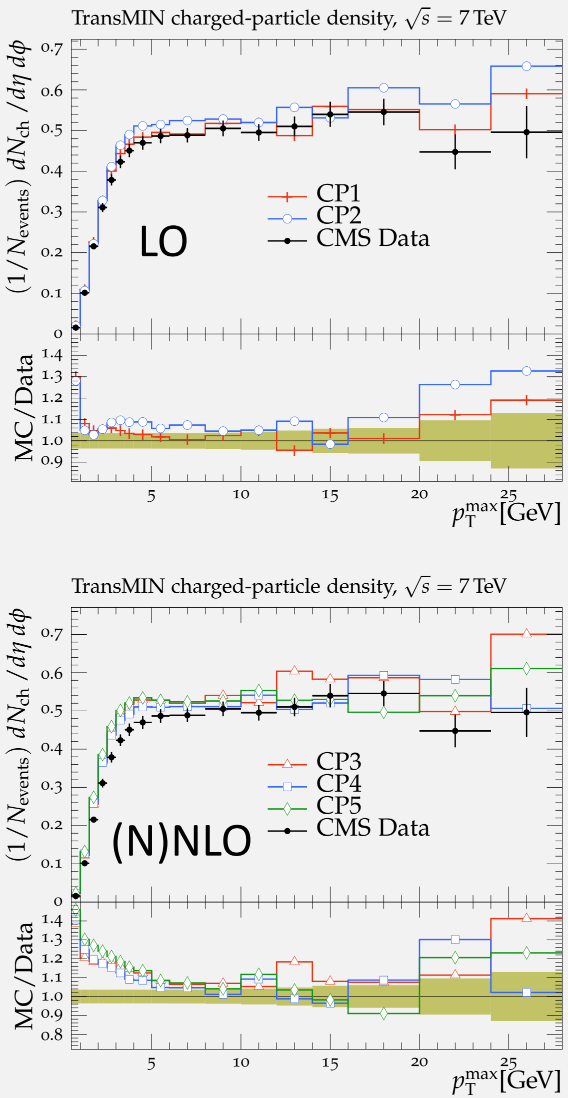
- Lower pT better described by (N)NLO PDF tunes.

CPX and Energy Dependence

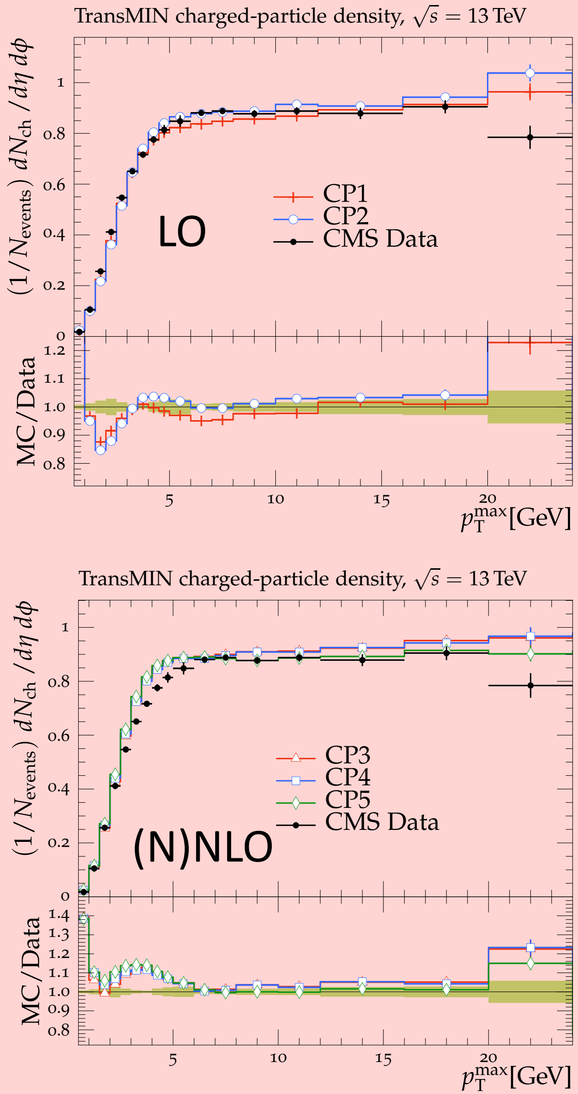
√s=1.96 TeV



√s=7 TeV



√s=13 TeV



- All predictions reproduce well the central values of UE observables at 1.96, 7, and 13 TeV.
- LO-PDF tunes slightly better in describing the energy dependence.

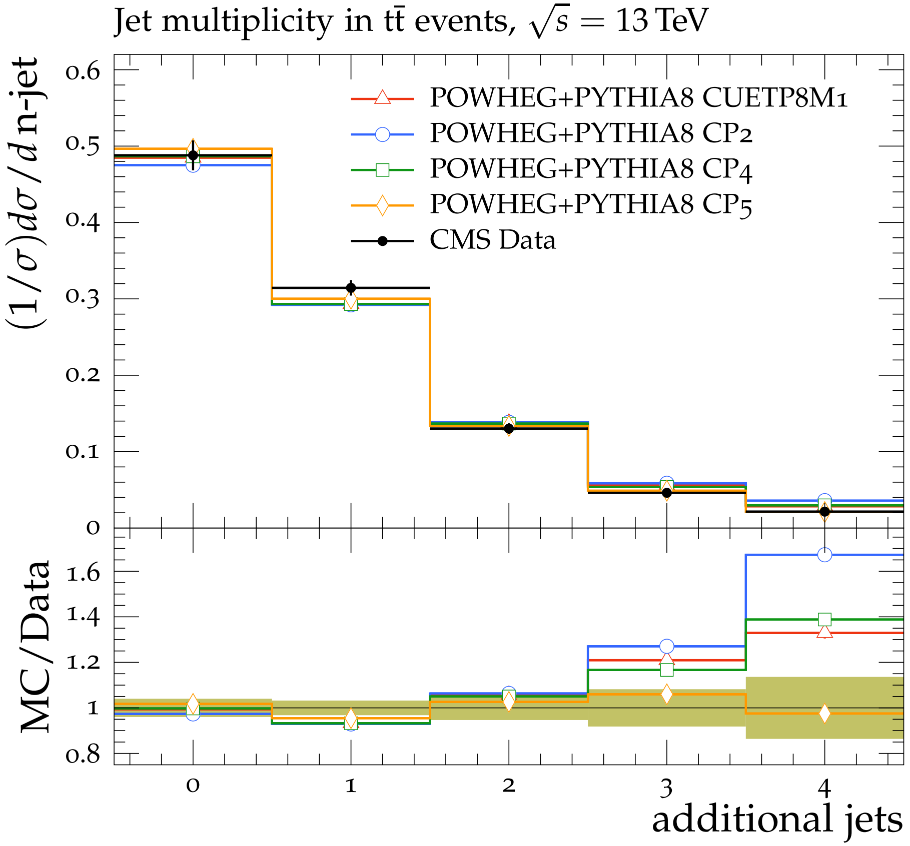
CPX and ttbar

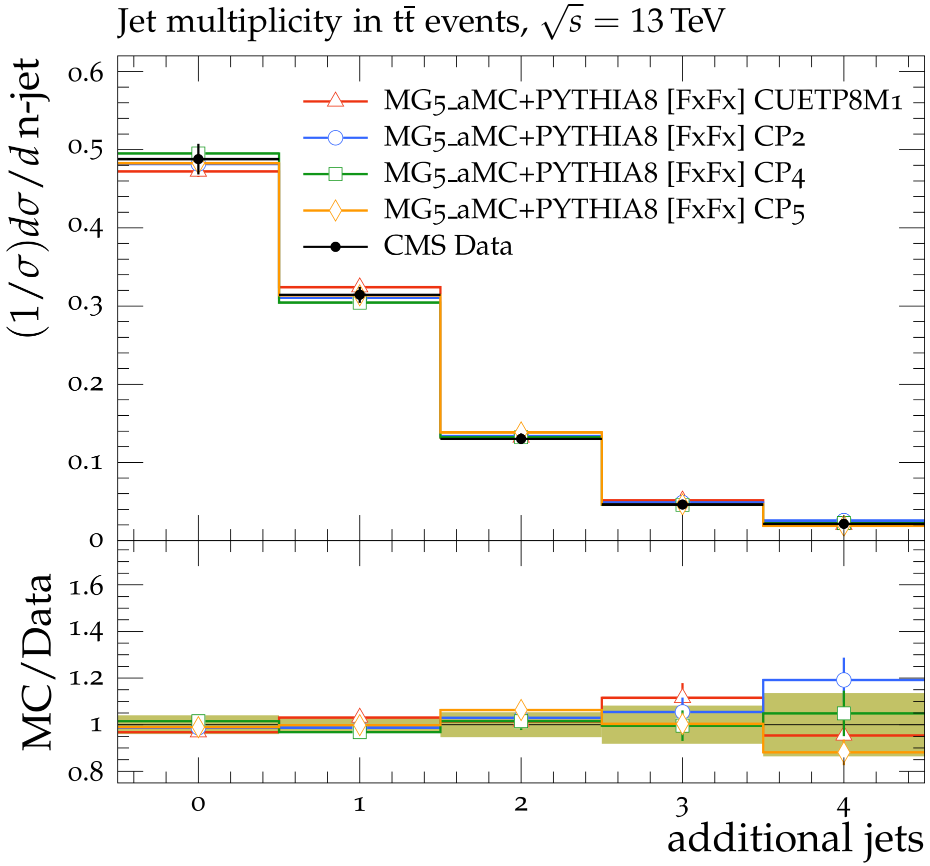
arXiv:1903.12179

Matrix elements:

- POWHEG: inclusive ttbar at NLO, additional jet at LO
  - hdamp tuned using 8 TeV data and CP5 tune
- MG5_aMC[FxFx]: ≤ 2 parton at NLO 3rd at LO
- NNPDF3.1 NNLO
  $\alpha_s(m_Z)$=0.118 for both cases

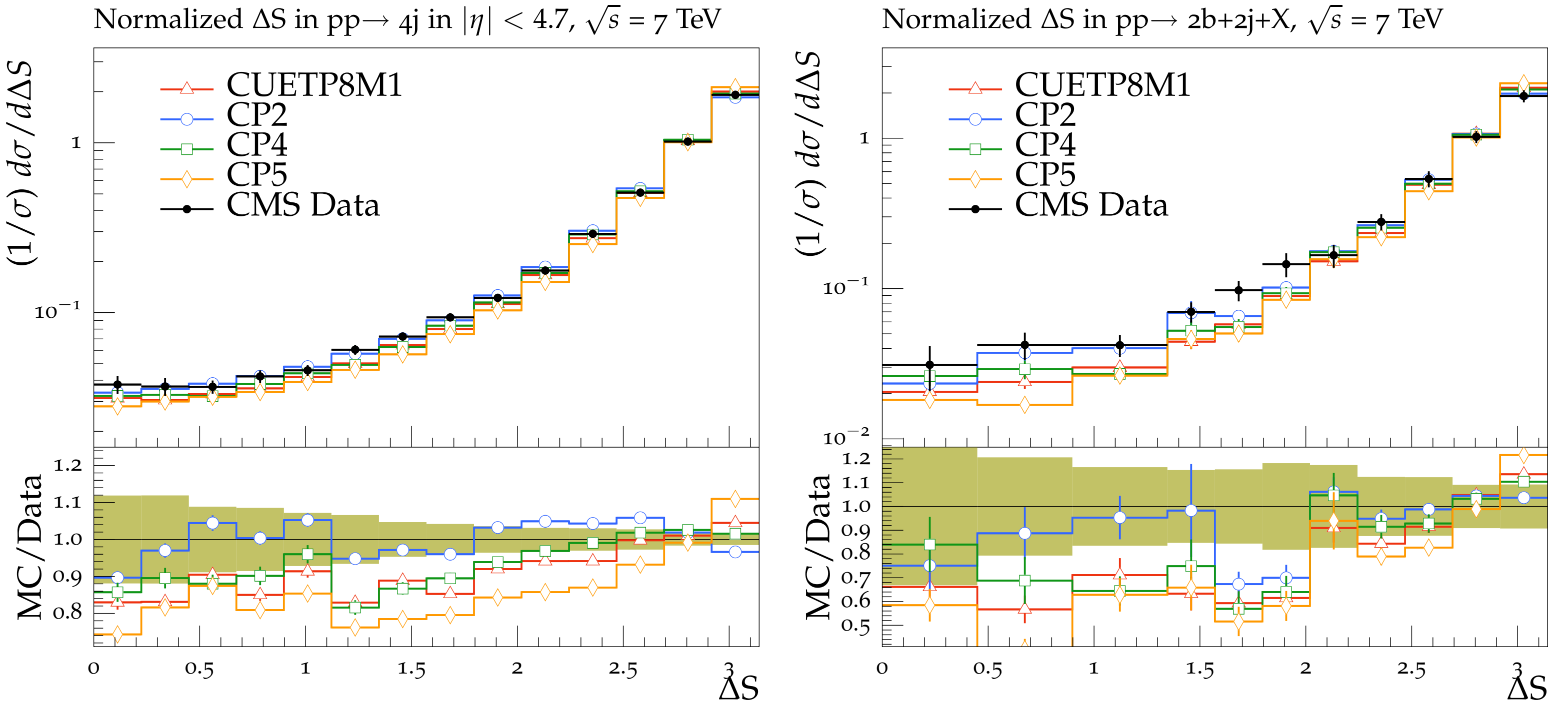
$$\mu_R = \mu_F = m_T^t = \sqrt{m_t^2 + p_T^2}$$





- CP5 (and CUETP8M2T4) → RapidityOrdering for ISR = on
  - Makes a big difference in POWHEG+PYTHIA8
- All predictions equivalently good for MG5_aMC+PYTHIA8 [FxFx]

CPX and double parton scattering



Final state	Generator	$\sigma_{\rm eff}$ [mb] ($\sqrt{s} = 7$ TeV)
4j	PYTHIA8	$19.0^{+4.7}_{-3.0}$ [5]
2b2j	PYTHIA8	$23.2^{+3.3}_{-2.5}$ [64]

	$\sqrt{s} = 7$ TeV $\sigma_{\rm eff}$ [mb]	$\sqrt{s} = 13$ TeV $\sigma_{\rm eff}$ [mb]
CP1	$26.3^{+1.0}_{-1.7}$	$27.8^{+1.1}_{-1.4}$
CP2	$24.7^{+1.0}_{-1.6}$	$26.0^{+1.0}_{-1.3}$
CP3	$24.1^{+1.0}_{-1.5}$	$25.2^{+1.0}_{-1.3}$
CP4	$23.9^{+1.0}_{-1.5}$	$25.3^{+1.1}_{-1.4}$
CP5	$24.0^{+1.0}_{-1.6}$	$25.3^{+1.0}_{-1.3}$

arXiv:1903.12179

$$\Delta S = \arccos\left(\frac{\vec{p}_{\rm T,1}\cdot\vec{p}_{\rm T,2}}{|\vec{p}_{\rm T,1}||\vec{p}_{\rm T,2}|}\right)$$

- DPS effective cross sections from the individual measurements and different tunes compatible within ~1σ.
- (N)NLO PDF tunes or RapidityOrdering gives worse predictions for DPS sensitive observables for CPX tunes.
- CUETP8M1 already not good (although LO and even w/o rapidity ordering)

CPX and Z+Jets

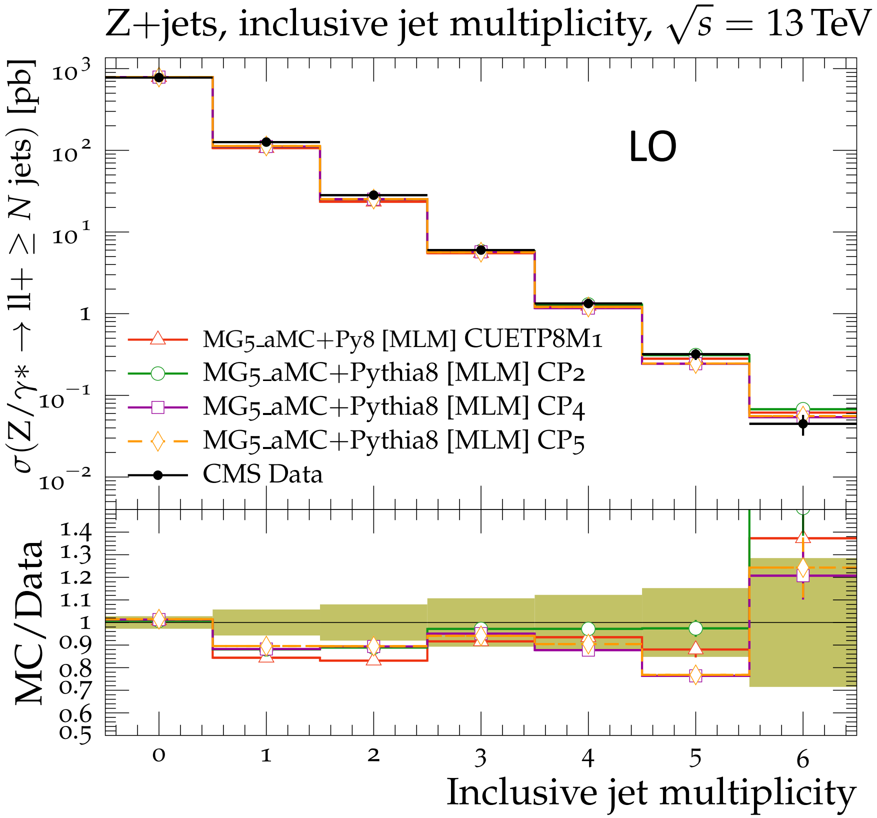
arXiv:1903.12179

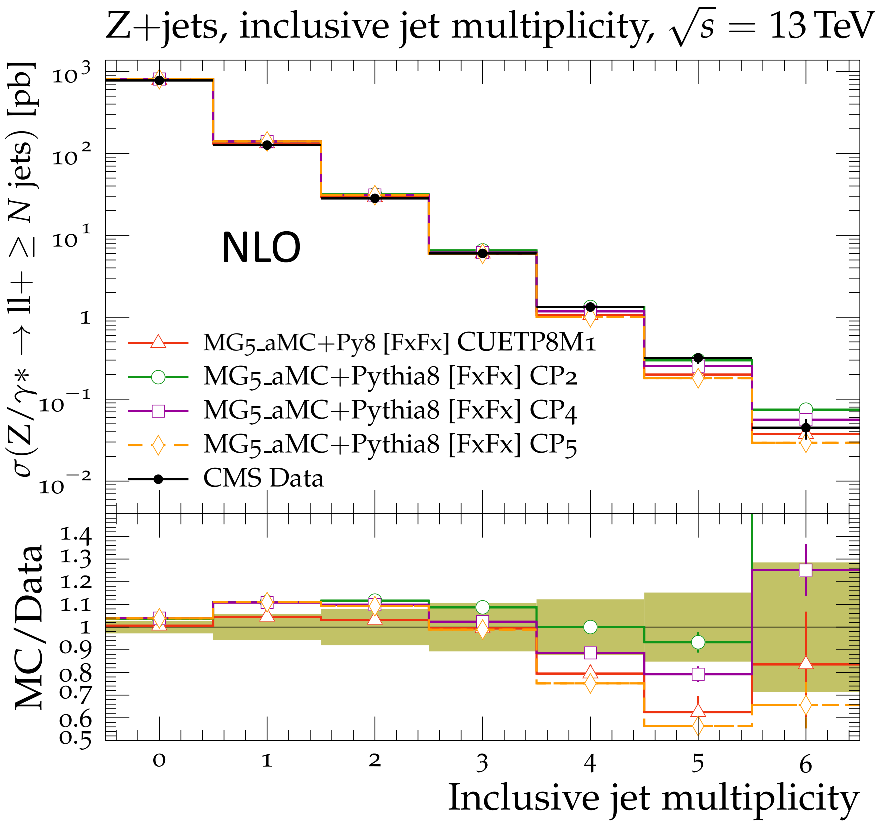
Matrix elements:

- LO: ≤ 3 partons
- NLO: ≤ 2 parton at NLO 3rd at LO
- NNPDF3.1 NNLO $\alpha_s(m_Z)$=0.118 for both cases

$$p_T^{\ell\ell} > 20\ GeV,\ |y^{\ell\ell}| < 2.4,\ |m^{\ell\ell} - 20| < 91\ GeV$$

$$p_T^{jet} > 30\ GeV,\ |y^{jet}| < 2.4$$





- Little sensitivity to the tune for low multiplicities.
- All tunes describe the central values of Njets reasonably well.
- CP2 has a slightly better description of the central values.
- CUETP8M1 and CP5 undershoot the data at the PS dominated region with at least 4 jets.

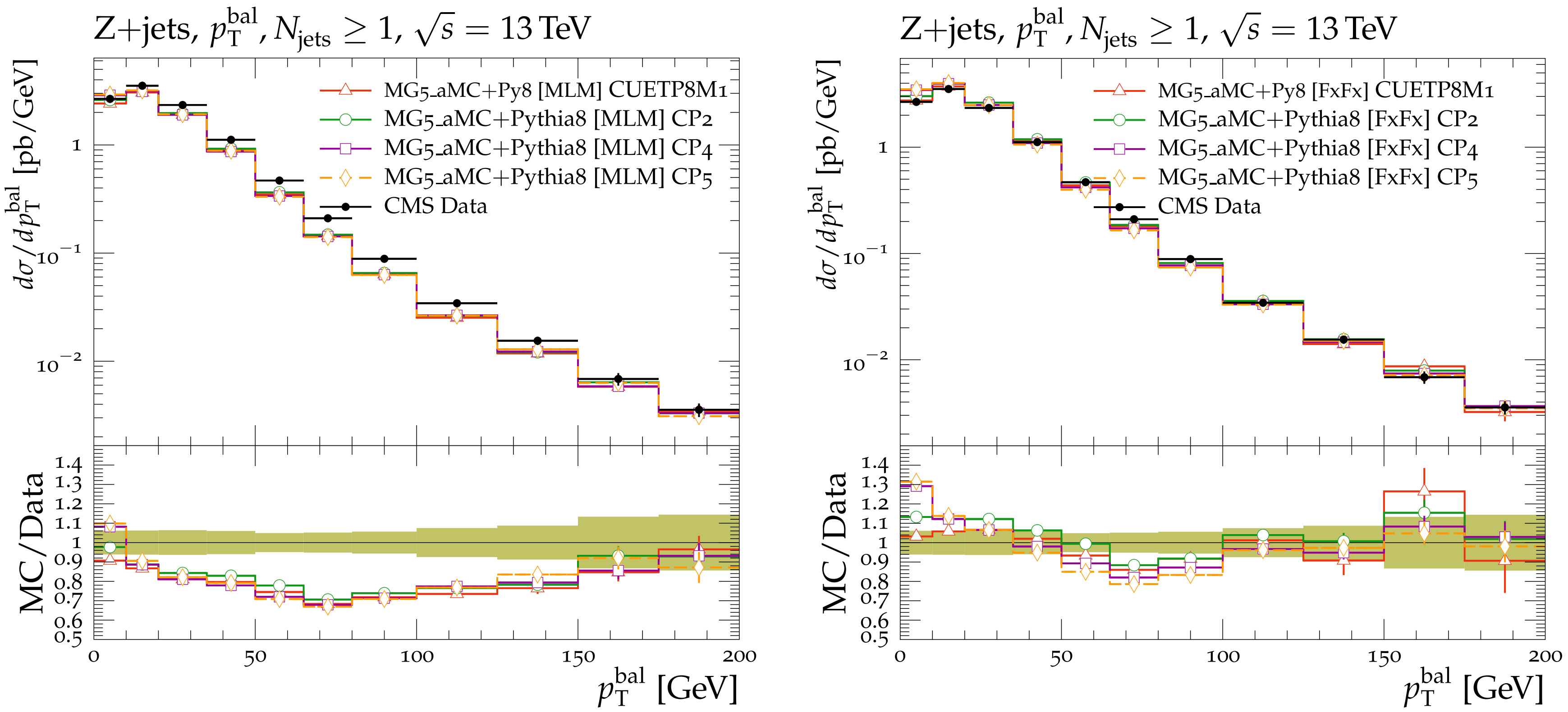
CPX and Z+Jets

arXiv:1903.12179

$$p_T^{bal} = |\vec{p}_T(Z) + \Sigma_{jets}\vec{p}_T(j_i)|$$

$$p_T^{jet} > 30\ GeV,$$
$$|y^{jet}| < 2.4$$

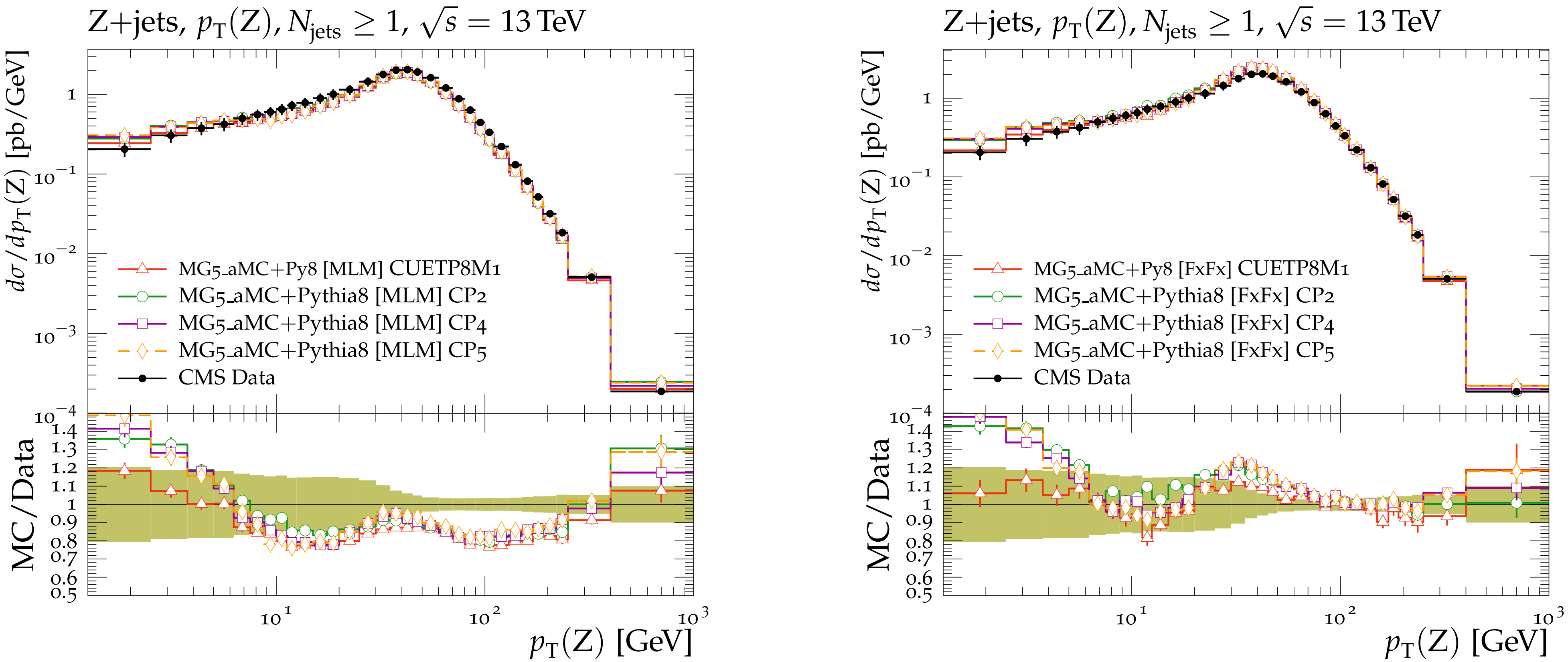
- Hadronic activity not clustered in jets → imbalance
  - Main contribution from forward jets
  - Gluon radiation wit pT>30 GeV not clustered.



- Different predictions from tunes $p_T^{bal} < 20$ GeV.
  - In this region LO-PDF tunes better describe the data for FxFx.

CPX and Z+Jets

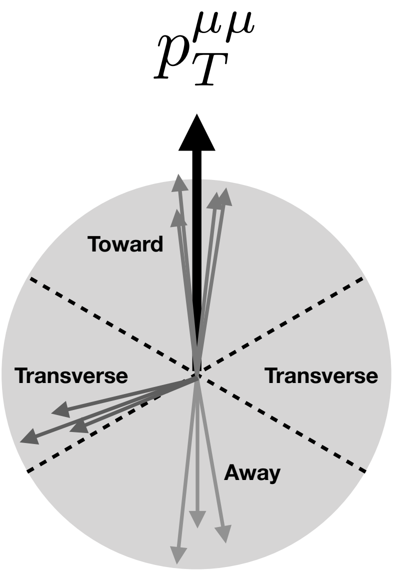
arXiv:1903.12179



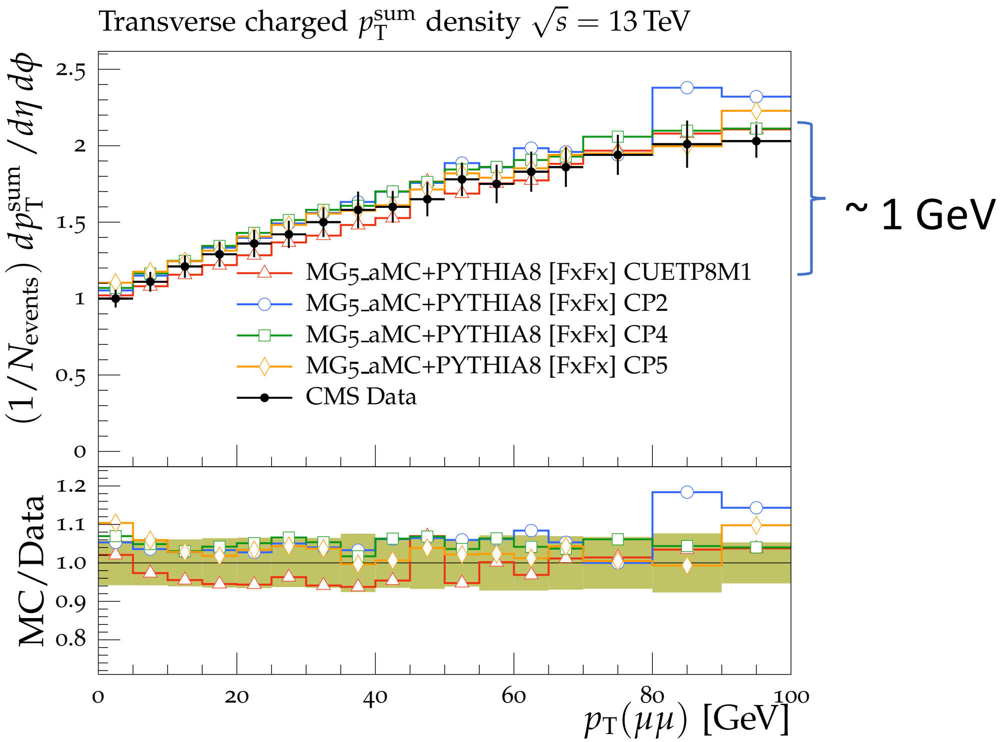
- MLM: poor agreement with data
- FxFx: all tunes give reasonable agreement for $p_T(Z)$> ~5 GeV
- $p_T(Z)$<10 GeV: description by CUETP8M1 is better

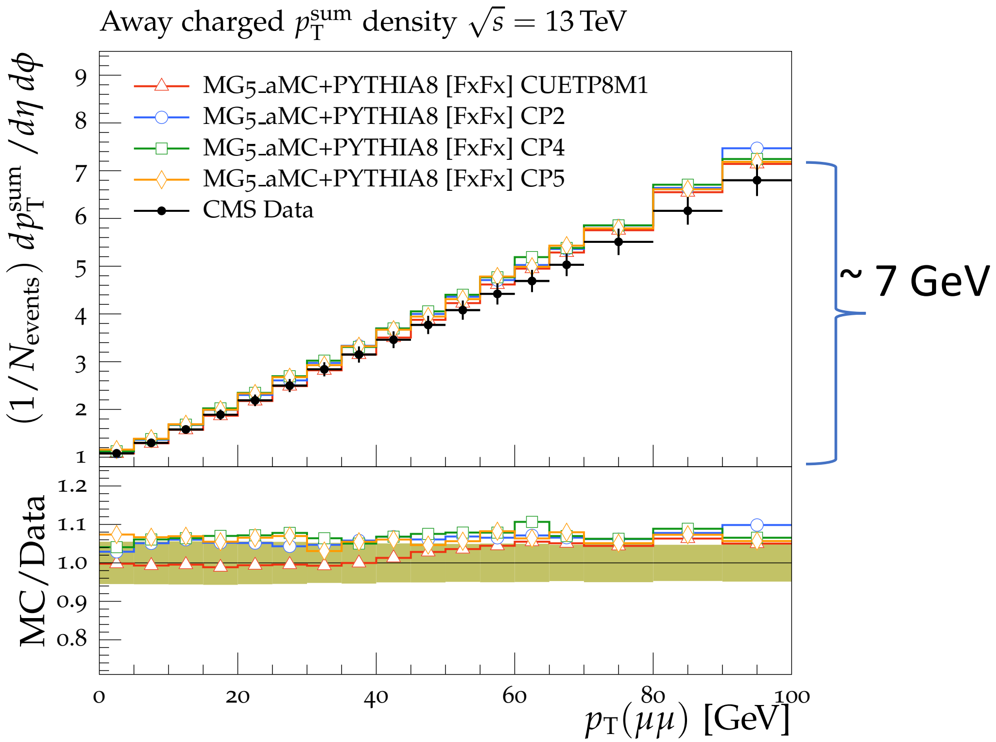
UE in Z+Jets Events

arXiv:1903.12179



$$p_T^{\mu} > 20, 10~GeV,$$
$$|M^{\mu\mu} - 20| = 91~GeV$$
$$p_T^{trk} > 0.5~GeV, |\eta| < 2$$





- Central values of the UE observables are, in general, well described by all tunes.
- Away region dominated by hadronic recoil system correlated with $p_T(\mu\mu)$
- UE≠0 when $p_T(\mu\mu)$→0 because of the large initial scale in Z boso events → significant overlap between transverse parton densities of the colliding protons → Larger # MPI
- UE activity becomes similar in different regions with $p_T(\mu\mu)$~0 ← activity in the three regions mostly due to varying ISR/FSR contributions.

Summary - 1

- New CMS tunes CUETP8M2T4 and CP1-5 describe the central values of the data better than CUETP8M1.
- ttbar data starting to help reduce modelling uncertainties.
- None of the tunes prior to CPX describe the ttbar jet sub-structure data
- ttbar jet data
    - Njets → $\alpha_S^{ISR}(M_Z)$ ~0.118 (also by azimuthal dijet correlation data)
    - groomed subjets → $\alpha_S^{FSR}(M_Z)$ ~ 0.118
- First ever measurement of underlying event in ttbar events.
    - Universality of UE up to energy scale of > 350 GeV tested.

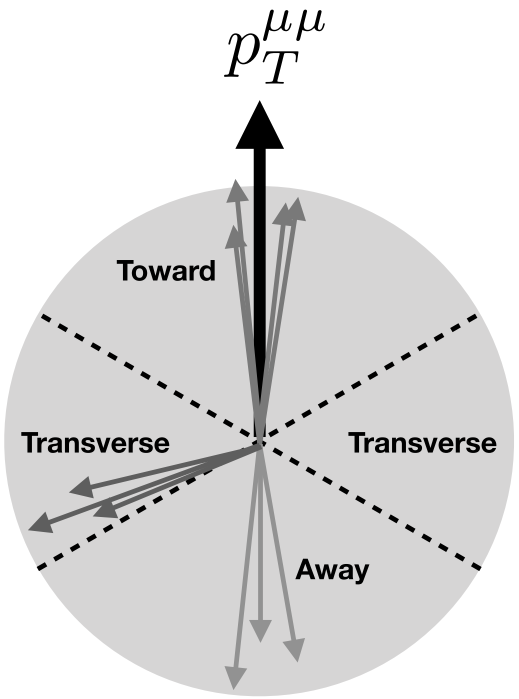
Summary - 2

- Tunes are tested for which $\alpha_S(M_Z)$ used for the hard scattering, ISR, FSR, and MPI are chosen consistently with the order of the PDF used.
- For the first time, predictions from PYTHIA8 with (N)NLO-PDF-based tunes are shown to reliably describe the central values of min-bias and underlying event data with similar or better level agreement to predictions from LO-PDF tunes.
- Irrespective of the order of NNPDF3.1 PDF order, predictions from CPX tunes reproduce the UE from 1.96-13 TeV reasonably well (and better than CUETP8M1).
- CPX tunes simultaneously describe the N_{ch} in diffractive and inelastic collisions.
- CPX tunes describe the min-bias data up to $|\eta| < 4.7$.
- No tune describes the very forward region ($-6.6 < \eta < -5.2$).
- New tunes tested against min-bias, UE, ttbar, DY, dijet, V+jets, DPS data.

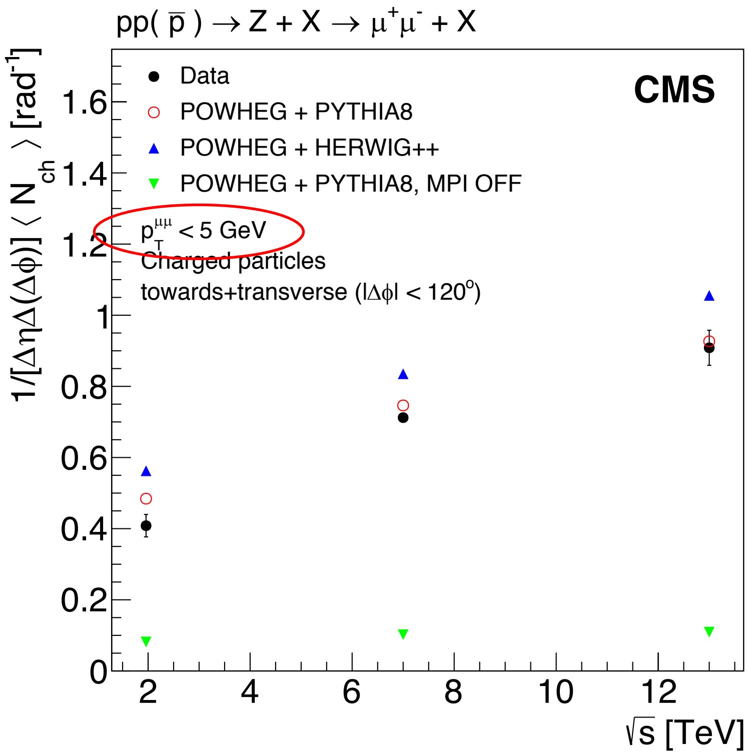
Additional Material

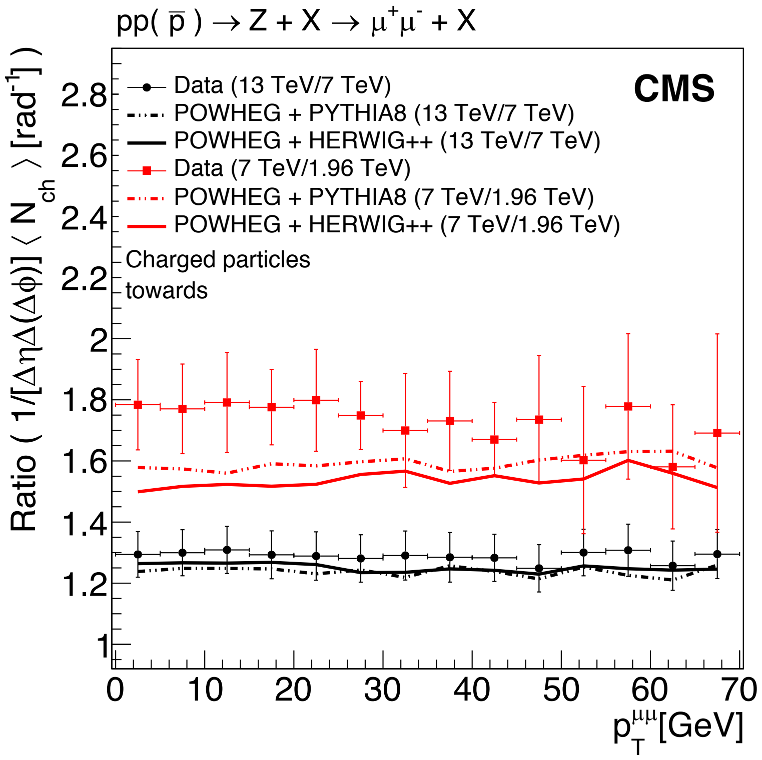
UE in Z+Jets Events

[JHEP07 (2018) 032]



$$p_T^{\mu} > 20, 10\ GeV,$$
$$|M^{\mu\mu} - 20| = 91\ GeV$$
$$p_T^{trk} > 0.5\ GeV, |\eta| < 2$$





- pT(μμ) < 5 GeV → Mainly MPI
  - very small contribution from radiation
- UE activity ~doubles w/ logarithmic increase from √s=1.96 to 13 TeV.
- Powheg+Pythia8 provides better description.

- The increase in UE from 7 to 13 TeV is described well by simulations but underestimate the UE evolution from 1.96 to 7 TeV