# MONTE-CARLO MODELING AND TUNING STUDIES AT CMS

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ON BEHALF OF THE CMS COLLABORATION

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QCD DESCRIPTION AT CMS

- Achieved through the use of well-established Monte-Carlo (MC) tools
- Full-event generators often replaced by factorized MC generation:
  - Matrix-element, i.e. up to parton-level
  - Parton shower (mostly Pythia8)
  - Applications for particle decays (e.g. EvtGen, Tauola) → not in this talk
  - Use of staged generation requires dealing with physics effects (e.g. «matching») and more complex interfacing with CMS software

- A very important ingredient of generation: underlying event (UE) → activity in addition to the hard process
  - Consists of beam-beam remnants and multi-parton interactions plus some contribution from the hard process
  - Requires modeling of MPI, hadronisation, ISR, FSR
  - Need to tune adjustable parameters in MCs
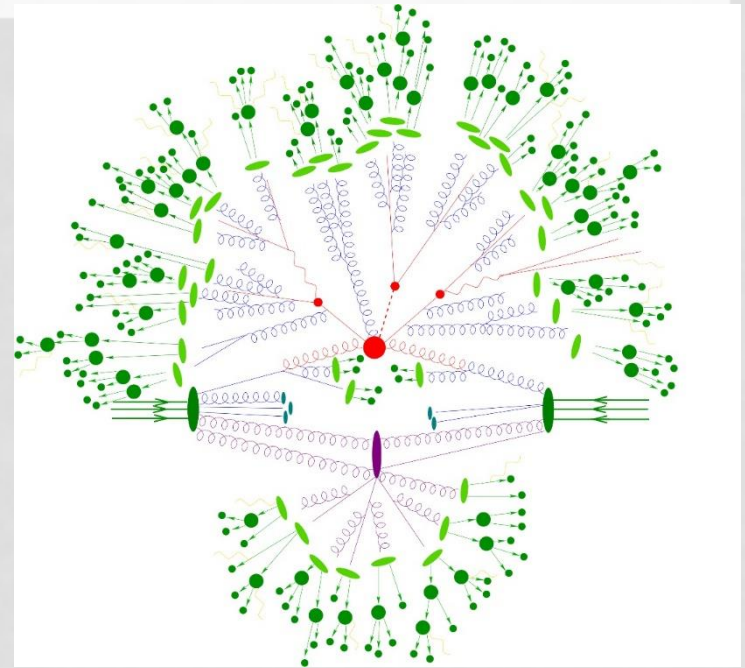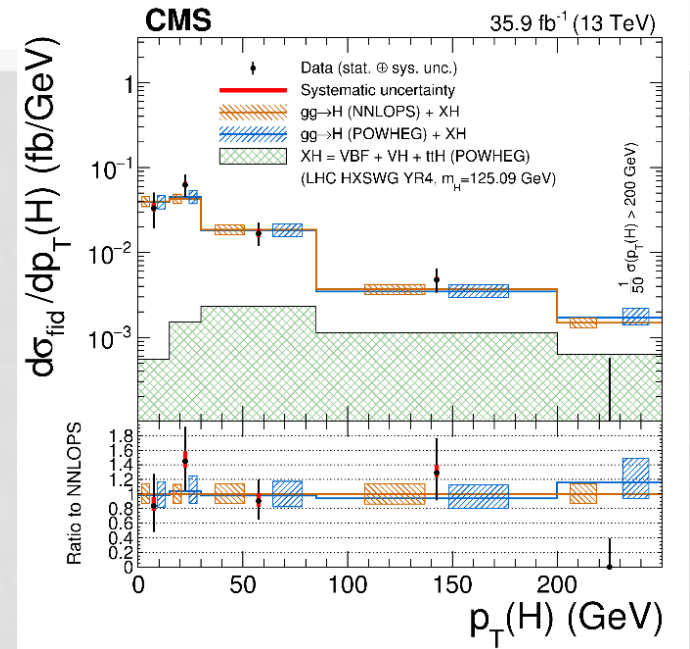
MATRIX-ELEMENT GENERATORS
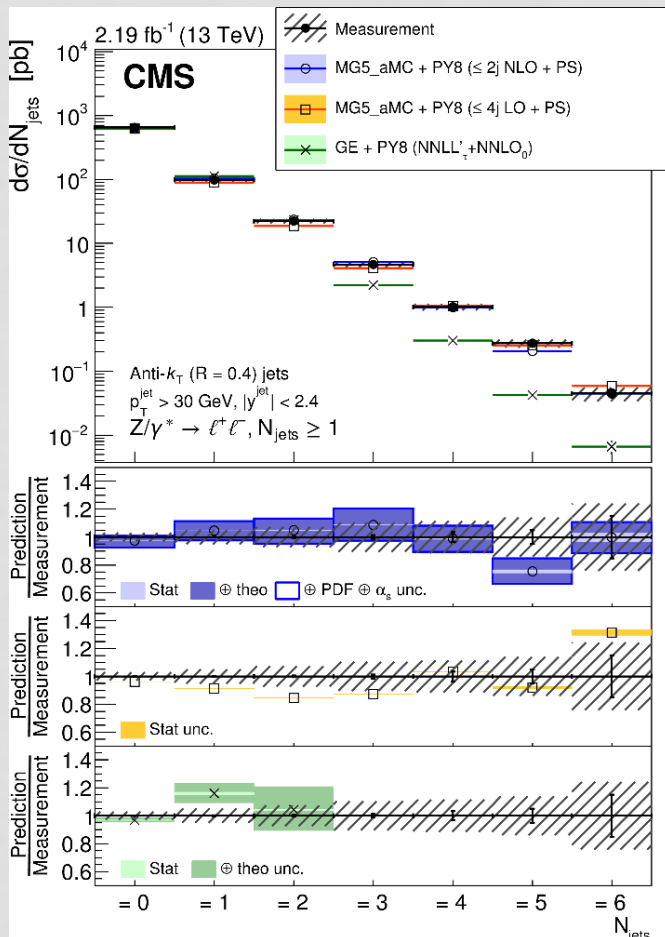
CMS collab., EPJC 78 (2018) 965

- NLO QCD event generation is now standard (mostly POWHEG and MadGraph5_aMCatNLO, recently SHERPA becoming more widely used)
- Specific cases where LO is still used:
  - Final states with large particle multiplicities (e.g. V + 4jets)
  - NP signals where NLO calculations are not available/implemented
  - Final states with complicated final-state kinematics (e.g. anomalous H-boson couplings with full tensor structure)
  - …etc.

MATRIX-ELEMENT GENERATORS

- **Beyond NLO**
  - Several NNLO calculators used for comparison with unfolded data (FEWZ, MATRIX etc.)
  - Event generation only for specific processes (e.g. SM gg → H), mostly obtained through the NNLOPS method in POWHEG
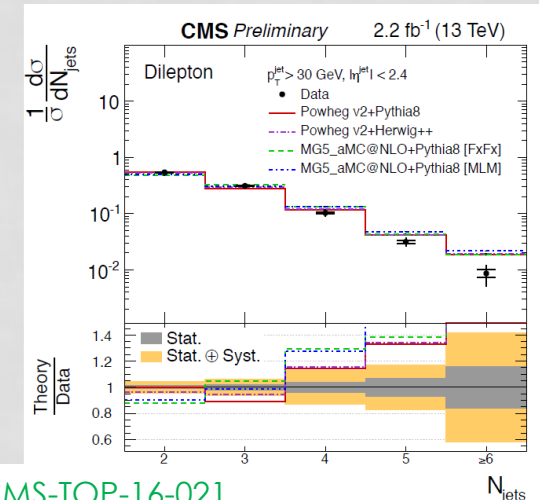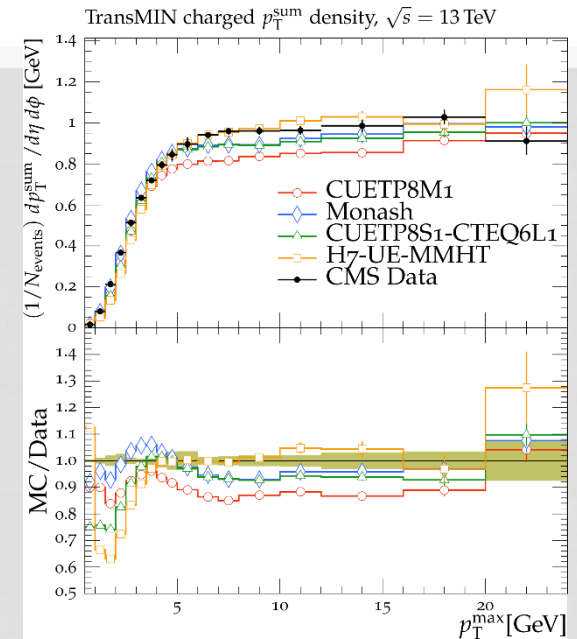

CMS collab., JHEP 11 (2017) 047

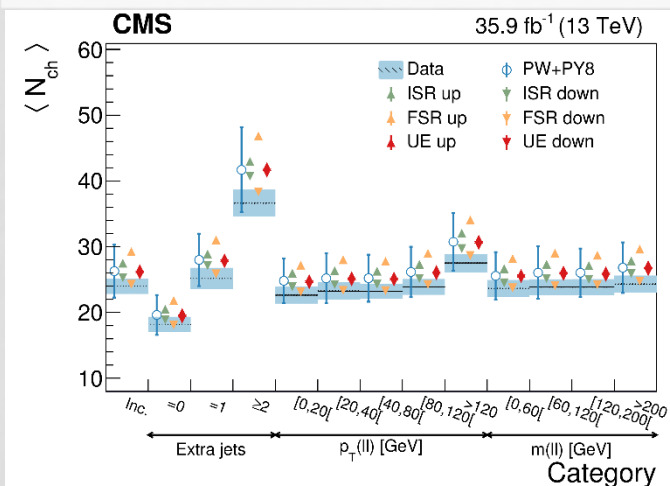- **Matrix-element (ME) uncertainties**
  - Uncertainties via QCD scale and PDF-variation reweighting now implemented in most generators
  - Significant computing improvements on both MCs and CMS implementation allowed storing of large number of weights

PARTON SHOWERS AND UE

- Pythia8 used as main PS tool in CMS
- Non-uniform recipes for uncertainties used up to 2016
  - Pythia vs. Herwig difference in relevant variables
  - ME-consistent up and down μ_R variations…
- More recently:
  - PS weights added to MC generations

    Phys. Rev. D 94, 074005 (2016)

  - alternative PS methods (e.g. DIRE)

- UE tuning: an important ingredient
  - Up to 2016 CUETP8M1 tune used (derived from CMS data up to 7 TeV, based on LO PDFs)
  - Not so good agreement with basic UE variables at 13 TeV and jet multiplicity in tt events

TransMIN charged p_T^{sum} density, $\sqrt{s} = 13\,\text{TeV}$

- CUETP8M1
- Monash
- CUETP8S1-CTEQ6L1
- H7-UE-MMHT
- CMS Data

CMS Preliminary   2.2 fb⁻¹ (13 TeV)

CMS collab., CMS-TOP-16-021

7/10/2019   R. Covarelli

NEW APPROACHES TO UE TUNING


- CMS Pythia8 tunes traditionally based on LO PDFs
  - Use $\alpha_s(M_Z)$ at LO for ISR, FSR, MPI = 0.130
  - UE measurements in tt events prefer lower value

    CMS collab., EPJC 79 (2019) 123

- New approach: PDF and $\alpha_s(M_Z)$ consistency in ME, PS, and MPI
  - $\alpha_s(M_Z)$ at (N)NLO = 0.118
  - Following recommendation of using the same PDF set and $\alpha_s(M_Z)$ value in the ME and PS components in matched configurations

    EPJC, 72 (2012) 2078

    - i.e. If ME is at NLO QCD, then use $N^{\geq 1}$LO PDFs in ME **and** PS
    - CMS uses now NNLO PDFs as default for ME

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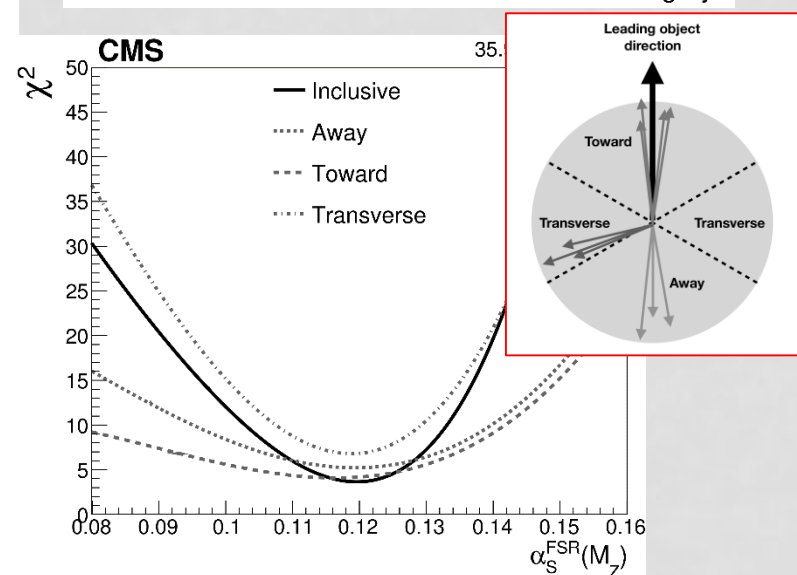
CMS TUNES WITH (N)NLO PDF

| PYTHIA8 parameter	CP3	CP4	CP5	
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO	Fixed inputs
$\alpha_S(m_Z)$	0.118	0.118	0.118	
SpaceShower:rapidityOrder	off	off	on	
MultipartonInteractions:EcmRef [GeV]	7000	7000	7000	
$\alpha_S^{ISR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO	
$\alpha_S^{FSR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO	
$\alpha_S^{MPI}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO	
$\alpha_S^{ME}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO	
MultipartonInteractions:pT0Ref [GeV]	1.52	1.48	1.41	Fitted parameters
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	

- **Data inputs:**
  - charged particle and Σp_T densities in "transMin" and "transMax" regions vs. p_T of the leading track (jet) at $\sqrt{s}$ = 1.96, 7, and 13 TeV
  - charged-particle multiplicity vs η at $\sqrt{s}$ = 13 TeV

# CHARGED-PARTICLE AND P_T-SUM DENSITIES (13 TEV)
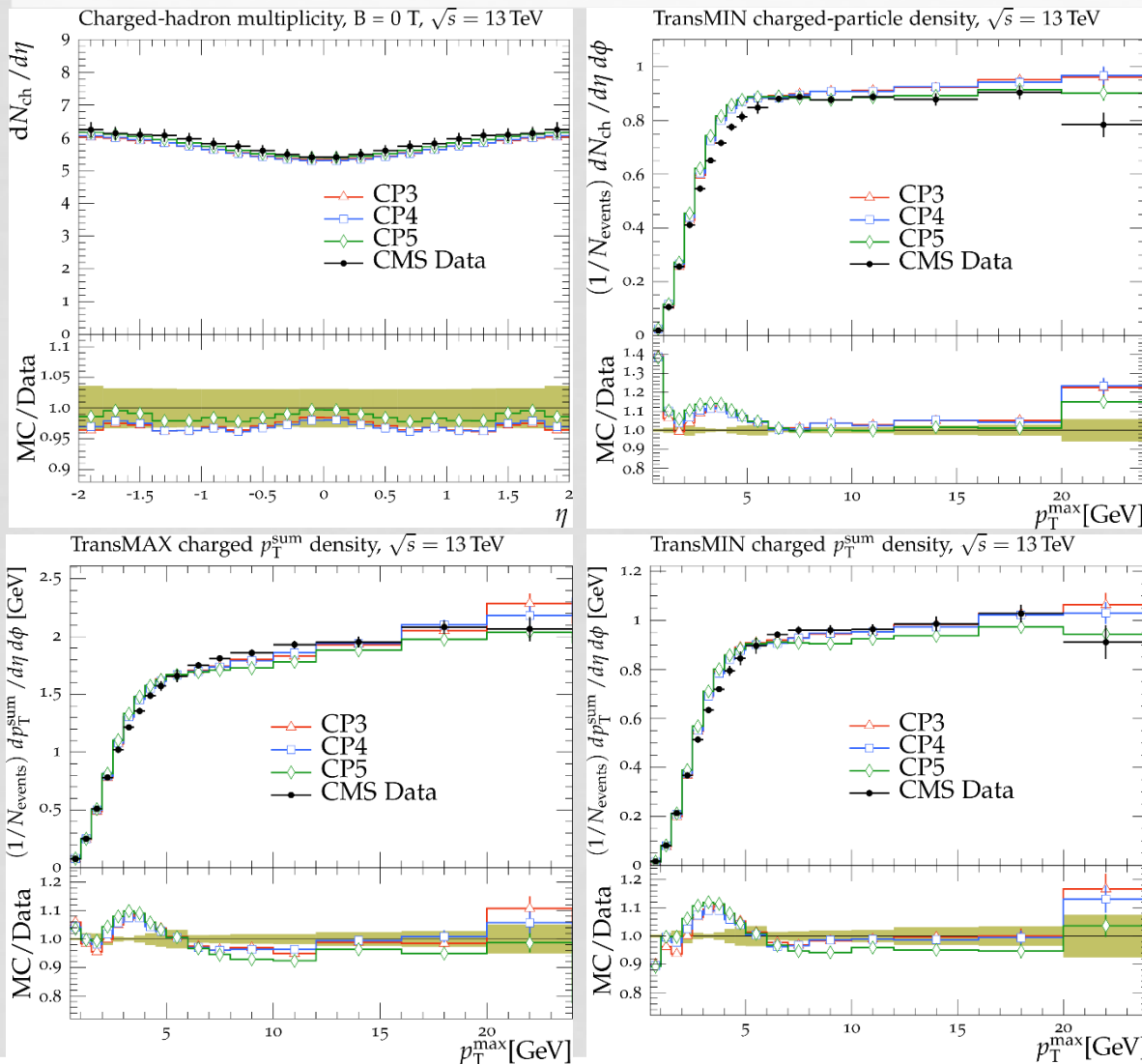
- **Minimum-bias data** (w/ and w/o B field)
- **Good agreement on dN_ch/dη in all** regions
- Still **10% disagreement** in minimum transverse region
  - **«Plateau» regions significantly improved w.r.t. CUETP8M1 tune**
  - Best normalization with **CP5 tune**

LO VS. (N)NLO PDF ORDER
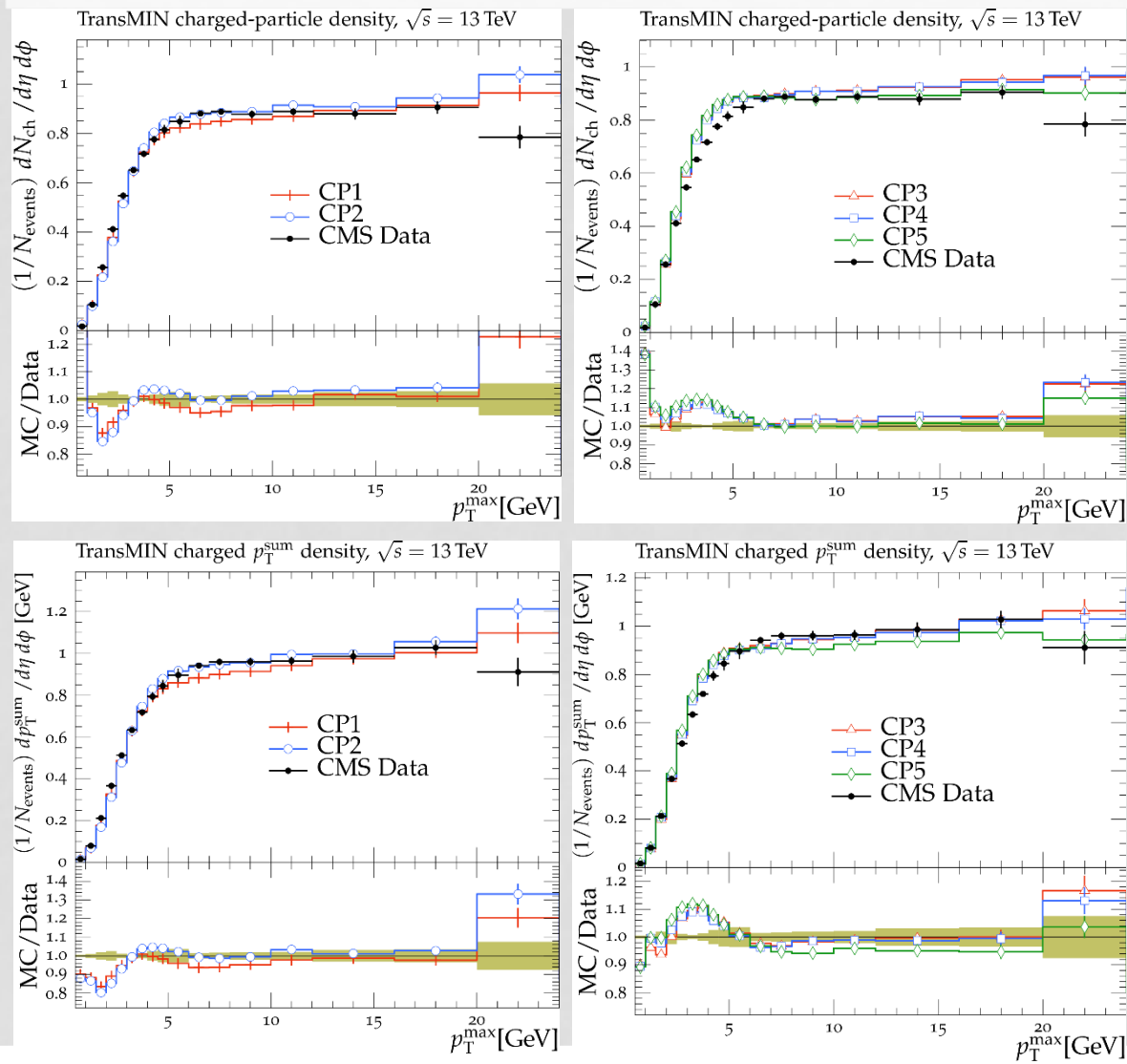
- Cross-check tunes (CP1-2) use same data inputs but LO PDFs

 - Significant differences but performances similar to tunes with NNLO PDFs

ENERGY DEPENDENCE
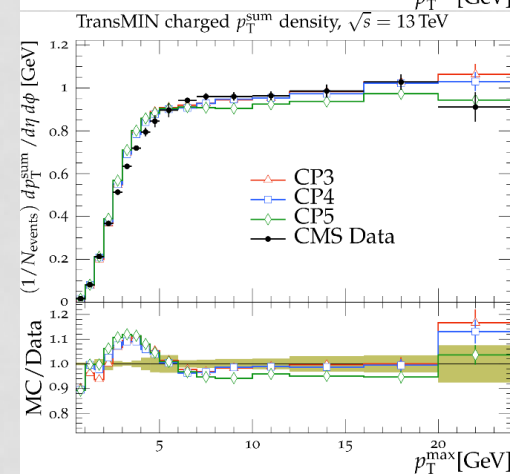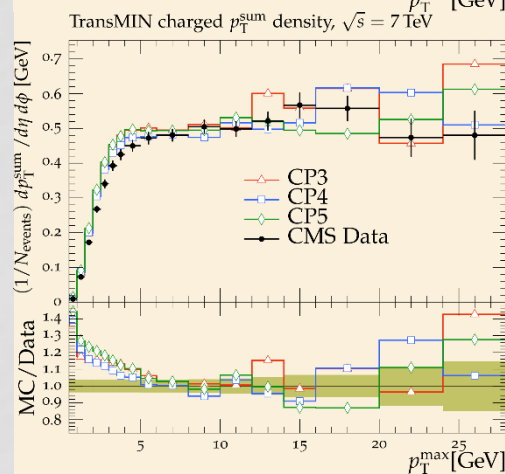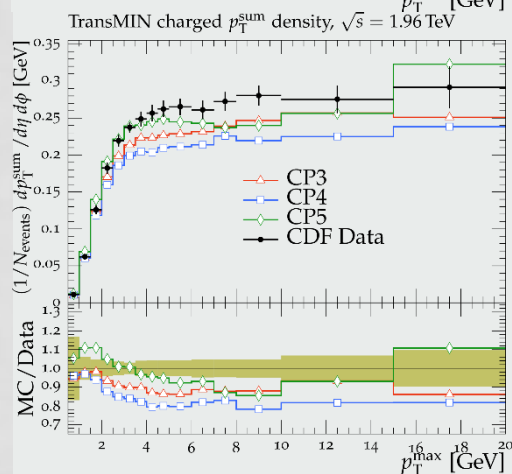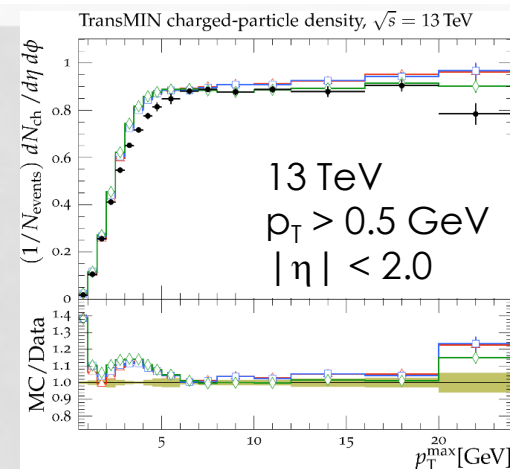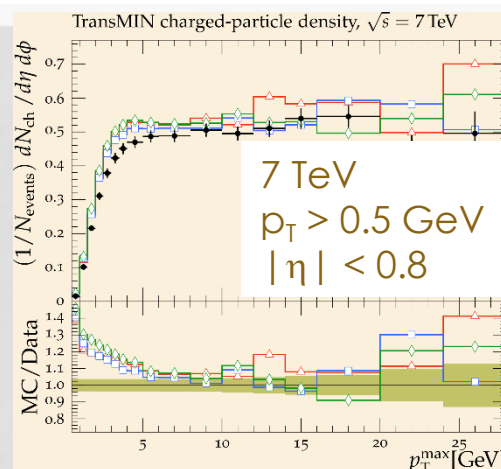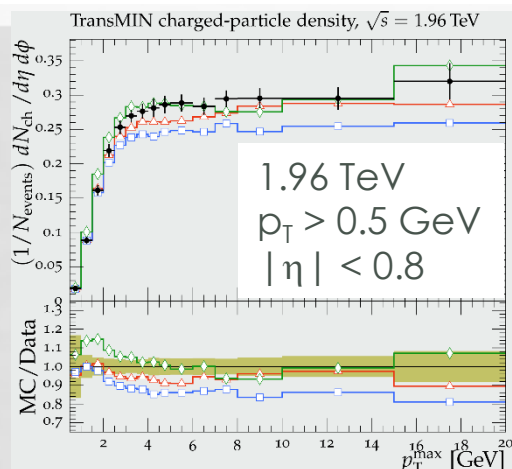
- CP5 tune more stable over √s

VALIDATION IN TT EVENTS

- ME generators
  - <u>Left:</u> POWHEG NLO inclusive
  - <u>Right:</u> MG5_aMC@NLO with FxFx merging: ≤ 2 partons at NLO
  - PDFs: NNPDF3.1 NNLO
  - $\alpha_s(m_Z)$ = 0.118 for both cases
  - $\mu = (m_t^2 + p_{Tt}^2)^{1/2}$
- «Standard» lepton+jets selection (with jet b-tagging), unfolded data
- In POWHEG description NNLO-PDF-based tunes show large improvement in the number of additional jets
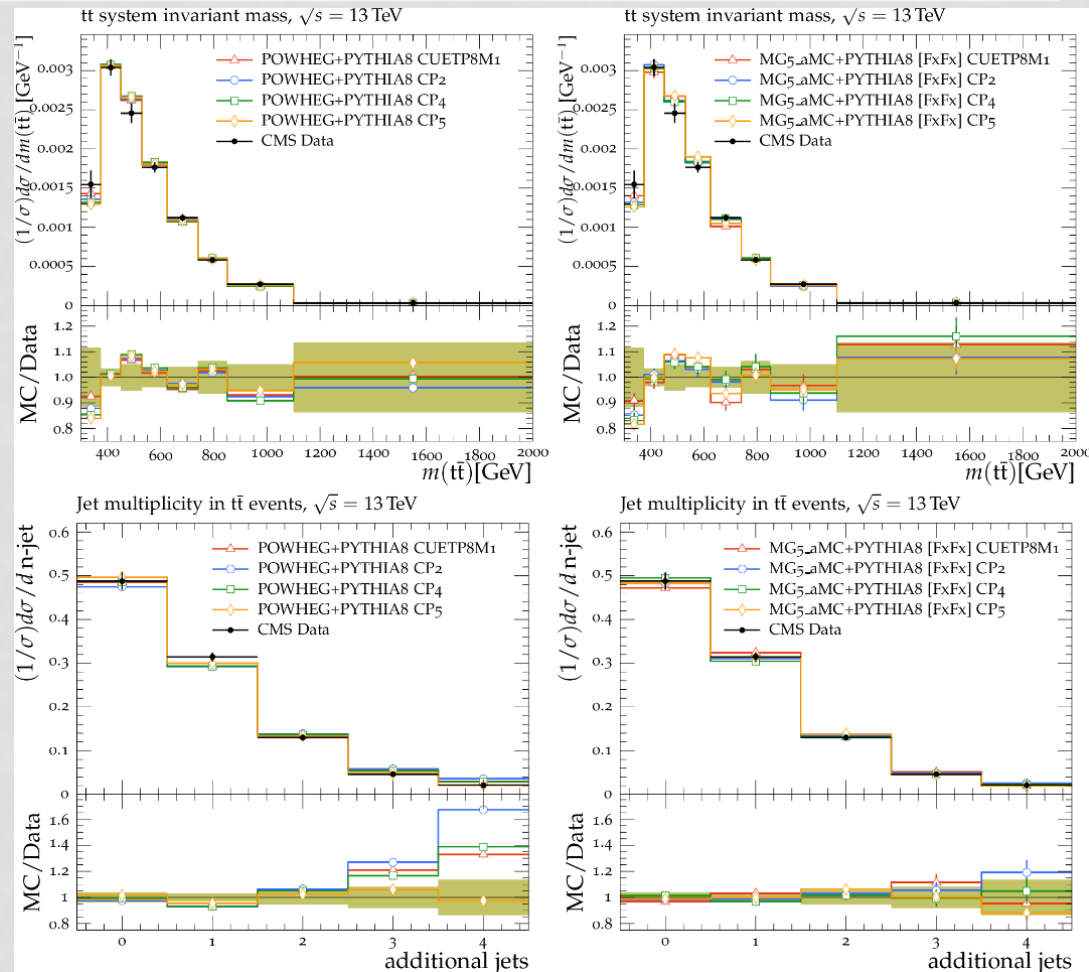
VALIDATION IN DRELL-YAN EVENTS

- ME generators
  - <u>Left:</u> MG5_aMC@NLO with MLM merging: ≤ 4 partons at LO
  - <u>Right:</u> MG5_aMC@NLO with FxFx merging: ≤ 2 partons at NLO
  - PDFs, $\alpha_s(m_Z)$, μ : same choice as for tt
- Selection:
  - Dilepton within 20 GeV of the Z mass
  - $p_{T\,jet}$ > 30 GeV
  - $|y_Z|$, $|\eta_{jet}|$ < 2.4
- Bad $p_T(Z)$ agreement for LO
- NLO describing well N_{jets} and $p_T(Z)$ for $p_T(Z)$ > 5 GeV
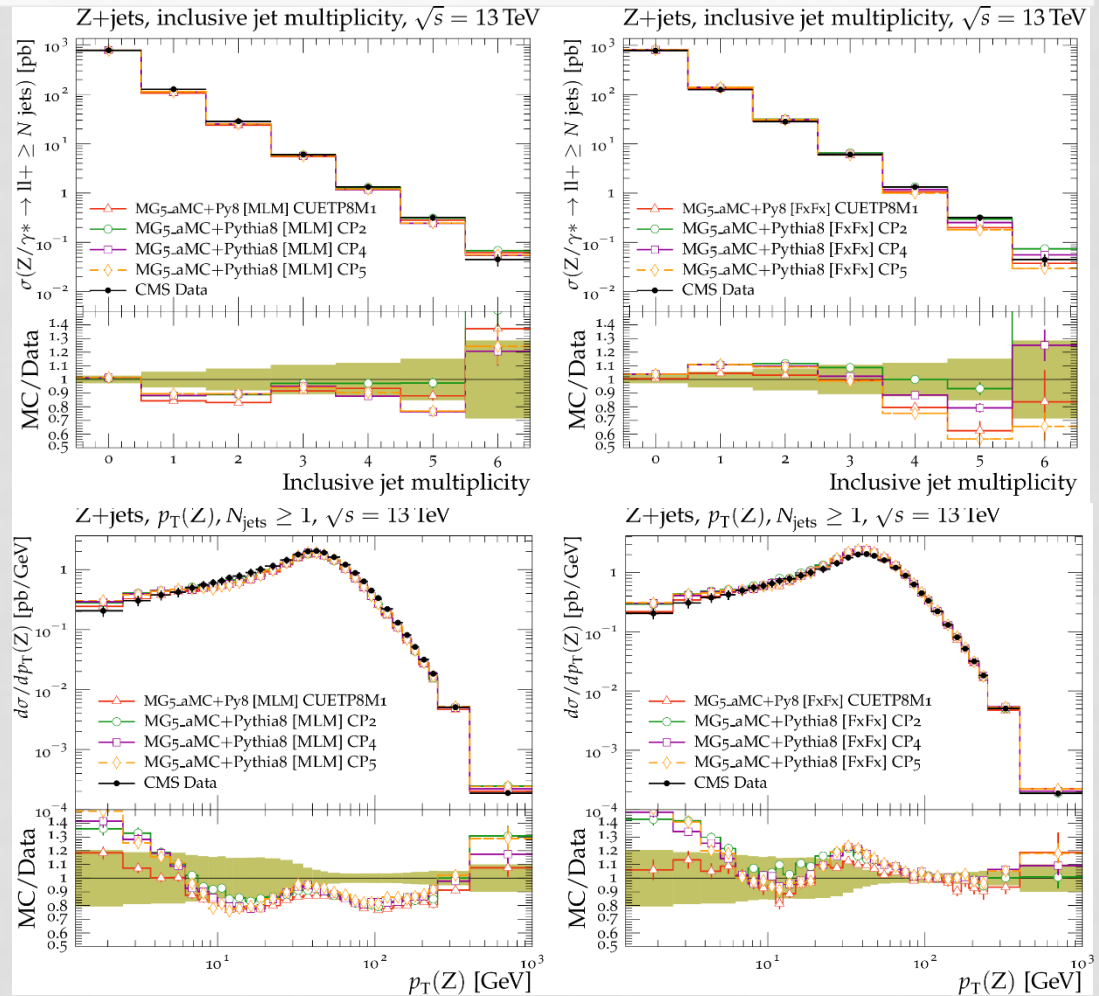
VALIDATION IN DPS

- Use CMS 4-jet and 2b-2jet events
- Test correlation variable ΔS → angle between the vectors of the hard di-jet (2b) and soft di-jet (2j) systems
- For the NNLO-PDF tunes:
  - Good agreement in fitted σ_{eff}
  - Not good in ΔS shapes
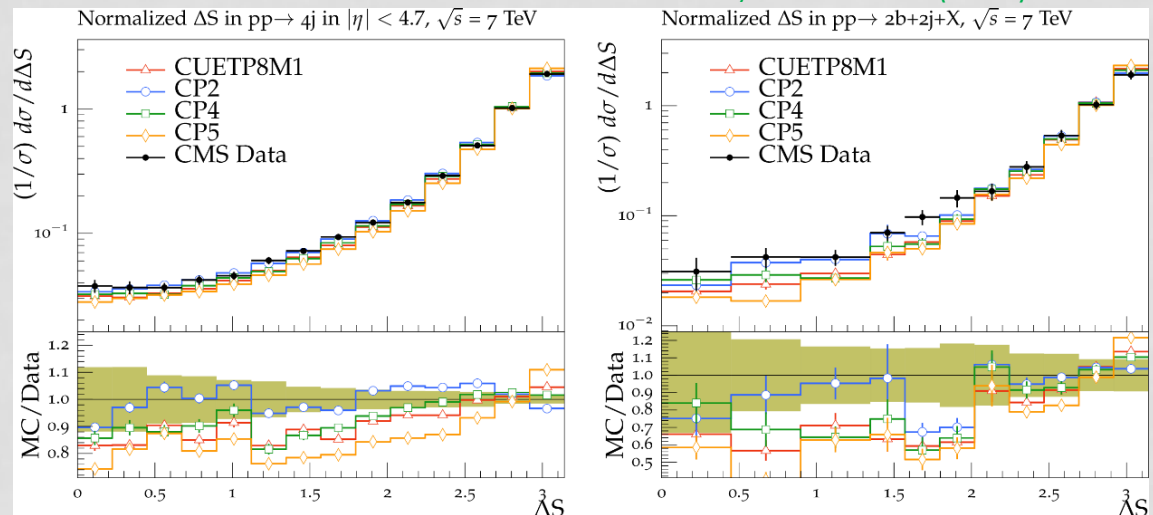   - LO ☺ > NNLO ☺ > rapidity ordering ☹

$$\sigma_{(A,B)}^{DPS} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

m = 1 for 4j
m = 2 for 2b2j

Data: CMS collab., Phys. Rev. D 89 (2014) 092010
CMS collab., Phys. Rev. D 94 (2016) 112005

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

	$\sqrt{s} = 7$ TeV σ_{eff} [mb]	$\sqrt{s} = 13$ TeV σ_{eff} [mb]
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	$24.0^{+1.0}_{-1.6}$	$25.3^{+1.0}_{-1.3}$

CONCLUSIONS

- Use of multi-stage MC generation up to NLO QCD + additional partons (NNLO for specific processes) now standard in CMS
  - Multiple physical / technical / computational challenges tackled
  - ME uncertainties well-established, PS uncertainties under validation
- New UE tunes are tested for which $\alpha_s(M_Z)$ and PDF order used for hard scattering, ISR, FSR, and MPI are chosen consistently
  - For the first time, predictions from Pythia8 with (N)NLO-PDF-based tunes are shown to reliably describe minimum-bias data with similar or better level agreement to predictions from LO-PDF tunes.
  - Irrespective of the NNPDF3.1 PDF order, predictions from CPX tunes reproduce the UE from 1.96 to 13 TeV data reasonably well (and better than CUETP8M1) up to |η| < 4.7
  - UE uncertainties also provided from fit («eigentunes»)
- New tunes tested against tt, Z+jets, and DPS data
  - CP5 (NNLO PDFs, rapidity ordering on) will be used as default for full-Run2 CMS MC modeling