# Monte Carlo modeling and tuning in CMS

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on behalf of the CMS Collaboration

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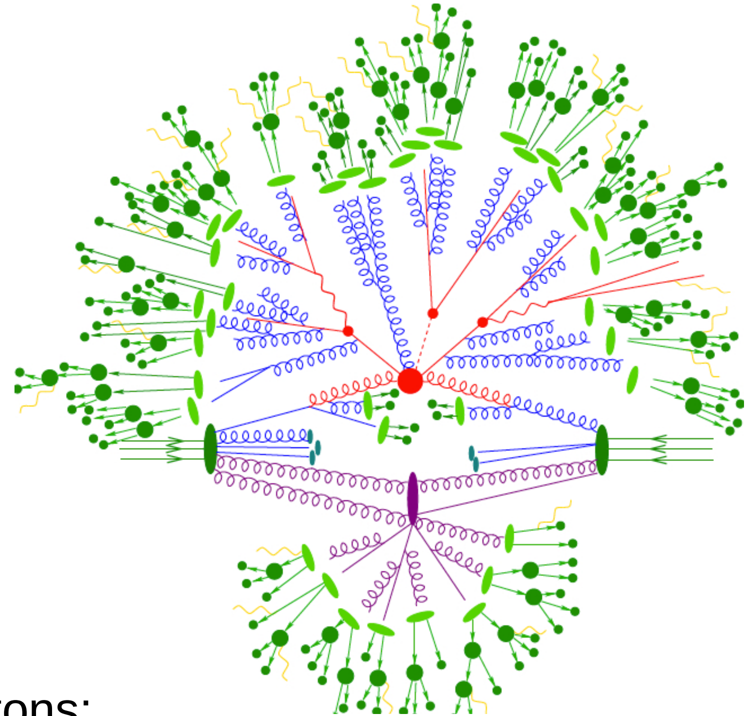
# Simulating a hadron-hadron collision

**Monte Carlo (MC) event generators** simulate

- Hard scattering matrix element (ME)
- Parton showers (PS) / radiation
- Hadronization / hadron decays
- Multiple-parton interactions (MPI)
- Beam remnants



→ **"Underlying event"** (UE)
involving color exchange between partons;
color fields may be rearranged → color reconnection (CR)

Commonly used **MC generators in CMS** include

| | |
|---|---|
| **`Powheg`, `MadGraph5_aMC@NLO`** | for fixed-order ME calculations |
| **`Sherpa`** | multipurpose |
| **`Pythia`, `Herwig`** | multipurpose, but often used to interface parton shower and UE simulation to ME |

# Tuning parton shower generators

Underlying event, parton shower development, hadronization (~ lower scales)
**not always calculable in perturbative QCD**

→ modeling governed by **phenomenological parameters** that can be **"tuned"**

**Pythia 8.2** GEN-17-001

| Parameter description | Range considered |
|---|---|
| MPI threshold [GeV], `pT0Ref`, at $\sqrt{s} = \sqrt{s_0}$ | 1.0–3.0 |
| Exponent of $\sqrt{s}$ dependence, $\epsilon$ | 0.0–0.3 |
| Matter fraction contained in the core | 0.1–0.95 |
| Radius of the core | 0.1–0.8 |
| Range of color reconnection probability | 1.0–9.0 |

**Herwig 7.1** GEN-19-001

new

| Parameter | Range |
|---|---|
| $p_{\perp,0}^{\min}$ (GeV) | 1.0–5.0 |
| $b$ (GeV) | 0.1–0.5 |
| $\mu^2$ ($\mathrm{GeV}^{-2}$) | 0.5–2.7 |
| $p_{\mathrm{reco}}$ | 0.05–0.90 |

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  *lower threshold → more MPI, i.e. more UE activity*

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Exponent

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- Overlap distribution between two colliding protons
  *larger / denser overlap → more MPI*

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Inverse proton radius squared

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- Color reconnection probability
  *large value → tends to reduce final particle multiplicities*

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**Parton distribution functions (PDF), strong coupling ($\alpha_S$)** affect predictions too

**Tuning** performed by **fitting predictions to data** using `Rivet` + `Professor`

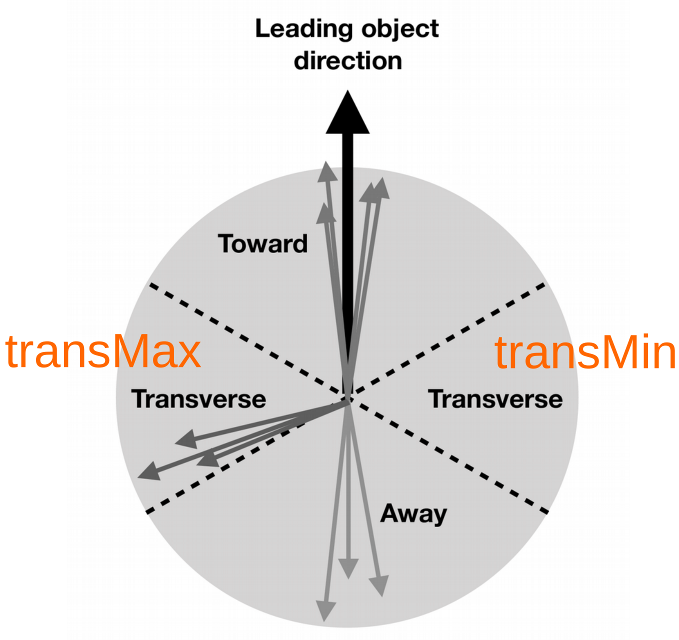
$$\chi^2(p) = \sum_{\mathcal{O}} w_{\mathcal{O}} \sum_{i \in \mathcal{O}} \frac{(f^i(p) - \mathcal{R}_i)^2}{\Delta_i^2}$$

$p$ = tuning parameters
$f^i$ = predicted bin content from parametrization
$R_i$ = measured bin content
$O$ = binned observable

# Observables sensitive to UE

Tunes extracted from relevant observables in unfolded **minimum-bias (MB) data**

= inelastic events collected with loose selection




- **Charged-particle multiplicity** ($N_{ch}$) **and scalar** $p_T$ **sum** ($p_T^{sum}$) **densities as function of** $p_T$ > 3 GeV **of leading object** (= track or charged-particle jet), in transverse regions
  CMS @ 7 + 13 TeV (+ 0.9 TeV for Herwig)
  (+ CDF @ 1.96 TeV for Pythia)
- $N_{ch}$ **as function of charged hadron** $\eta$
  CMS @ 13 TeV

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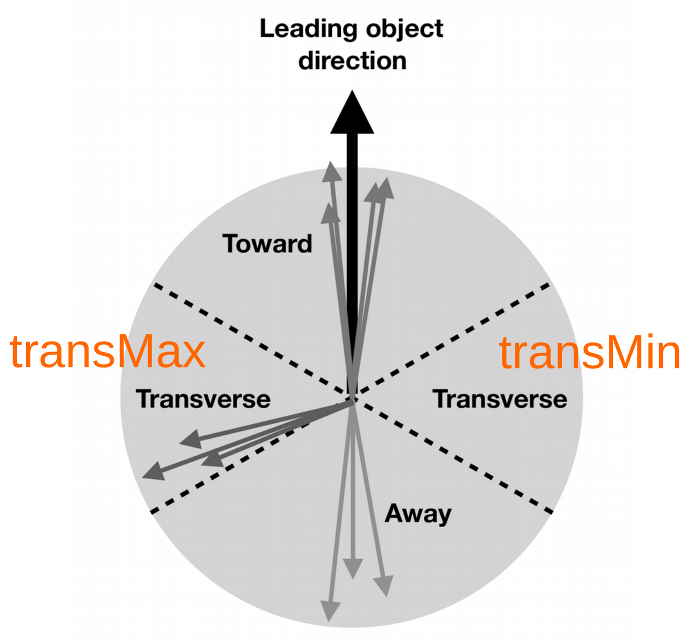


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**Components of hard scattering** such as hadronization and initial-state (ISR) and final-state radiation (FSR) **may affect UE-sensitive observables**

→ transMax more sensitive to ISR & FSR; transMin to MPI & beam remnants

Predictions obtained by **simulating non-diffractive + diffractive inelastic events** for each choice of tune parameters

Simulation with `Pythia 8` includes central diffraction

# Results of CMS Pythia 8 tunes

Different assumptions for **order of PDF** set, and **$\alpha_s$ value + running**

LO-PDF tunes

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

- Higher-order PDF used in NLO ME may motivate usage of higher-order PDF in PS / UE
- Different assumptions allow to **check consistency of matching order of PDF** used in ME and in tunes

(N)NLO-PDF tunes

| PYTHIA8 parameter | CP3 | CP4 | CP5 |
|---|---|---|---|
| PDF Set | NNPDF3.1 NLO | NNPDF3.1 NNLO | NNPDF3.1 NNLO |
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| 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 |
| $\chi^2$/dof | 0.76 | 0.80 | 1.04 |

Rapidity ordering of ISR reduces phase space for parton emissions

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**Significant differences between LO- and (N)NLO-based tunes** in value of $p_T^0$ and energy dependence, and amount of CR:

- Different shapes of gluon densities at small $x$
- $\alpha_s$ running

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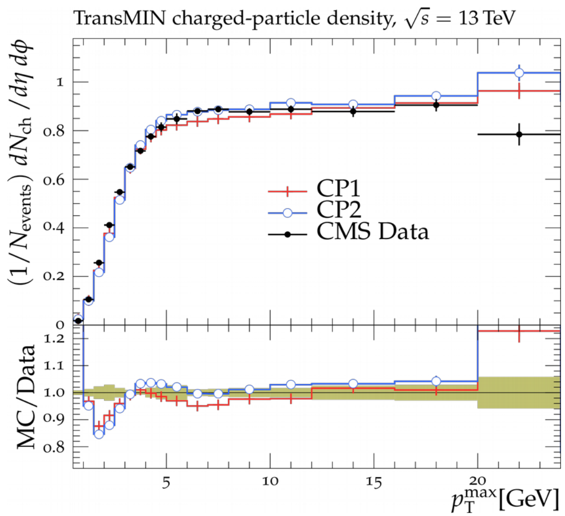
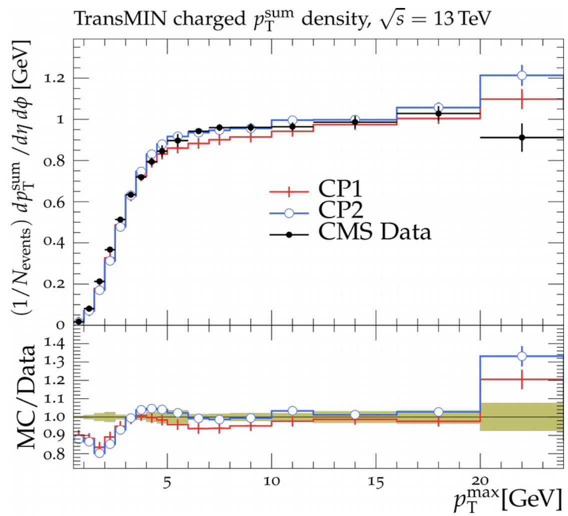
# Example observables used in Pythia 8 tuning

LO-PDF tunes

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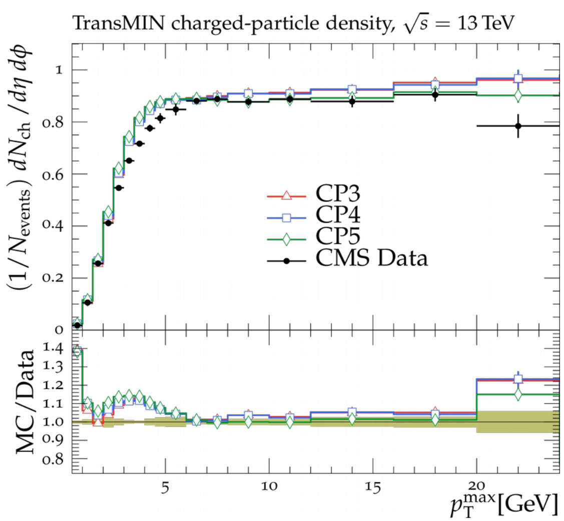
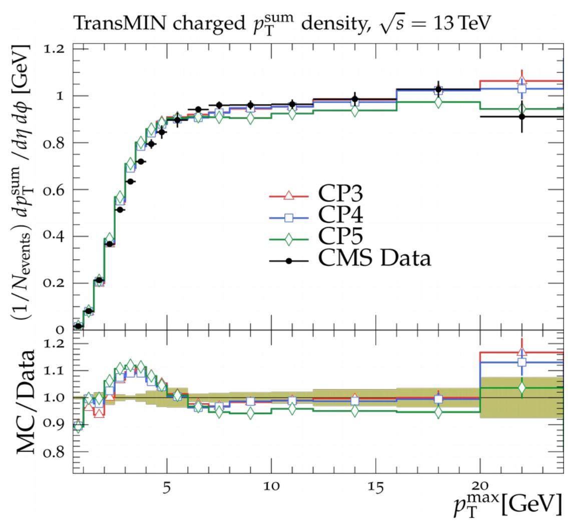



- **Rising part of spectrum: diffraction processes become more important**

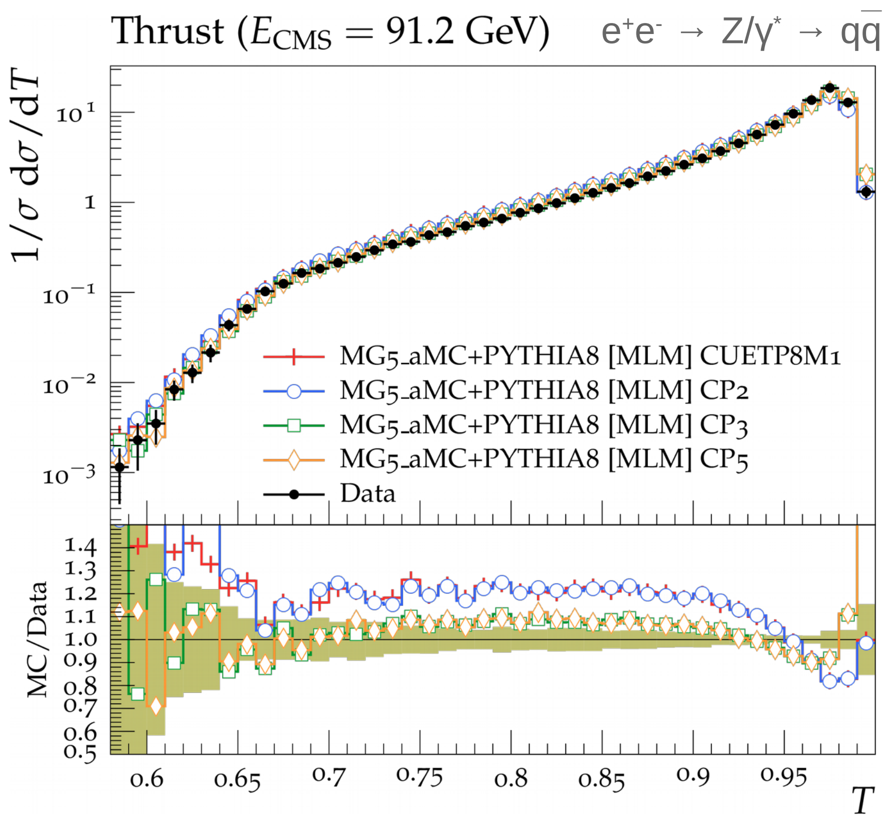
  → not always well described; $p_T^{max} < 3$ GeV not included in tuning

- No MB or UE observable where level of agreement between data and prediction from different tunes is significantly different

# Example validations of different Pythia 8 tunes

Ideally, UE tune is **universal** and describes wide range of processes & observables

**LEP event shape observables**




- Predictions from `MG5_aMC@NLO` + `Pythia 8` with up to 4 partons at ME
- Leptonic initial state → **observables particularly sensitive to $\alpha_s^{FSR}$**
- Thrust ($T$): dijet event $T \sim 1$, isotropic event $T \sim 0.5$
- **Tunes assuming lower $\alpha_s^{FSR}$ describe data better** (less FSR → less isotropic)

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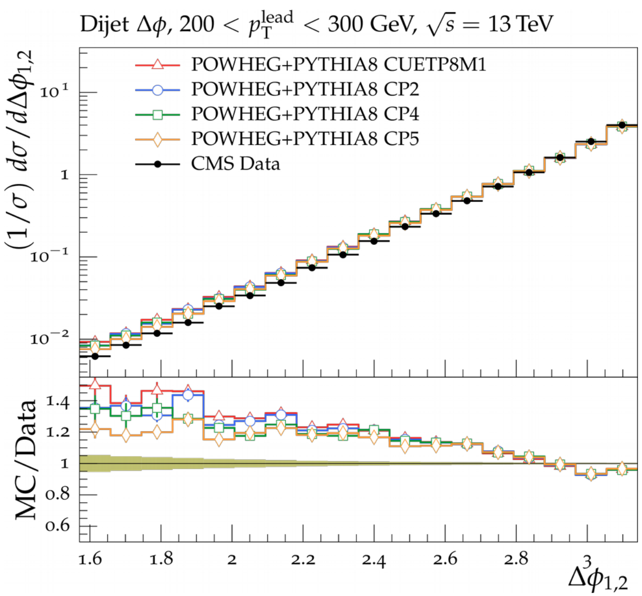
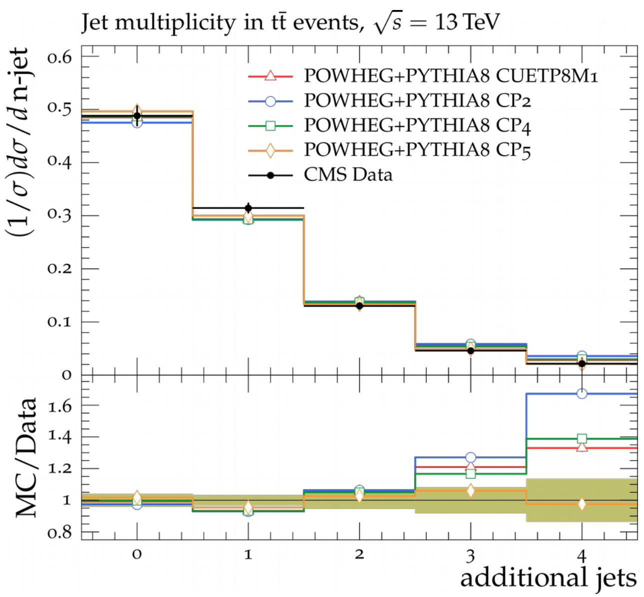
## Multijet final states




- **NLO dijet ME** in `Powheg` merged with `Pythia 8`
- **Tunes based on NLO $\alpha_s$ running better** (lower $\alpha_s^{FSR}$ → less jet decorrelation) than tunes with LO running

## Top quark pair production




- Interfacing **NLO** `Powheg` or `MG5_aMC@NLO` ME with `Pythia 8`
- **$\alpha_s$ = 0.118 + rapidity ordering** of ISR (= CP5 tune) **favored** for `Powheg + Pythia 8`

# Results of CMS Herwig 7 tunes

Different assumptions for **order of PDF** set in UE, and **$\alpha_s$ value + running**

| | | SoftTune | CH1 | CH2 | CH3 |
|---|---|---|---|---|---|
| $\alpha_S(m_Z)$ | | 0.1262 | 0.118 | 0.118 | 0.118 |
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| MPI & remnants | PDF set | MMHT2014 LO | NNPDF3.1 NNLO | NNPDF3.1 LO | NNPDF3.1 LO |
| | $\alpha_S^{PDF}(m_Z)$ | 0.135 | 0.118 | 0.118 | 0.130 |
| $p_{\perp,0}^{min}$ (GeV) | | 3.502 | 2.322 | 3.138 | 3.040 |
| $b$ (GeV) | | 0.416 | 0.157 | 0.120 | 0.136 |
| $\mu^2$ (GeV$^{-2}$) | | 1.402 | 1.532 | 1.174 | 1.284 |
| $p_{reco}$ | | 0.5 | 0.400 | 0.479 | 0.471 |
| $\chi^2/N_{dof}$ | | 12.8 | 4.15 | 1.54 | 1.71 |

**NNLO PDF for parton shower**, consistent with PDF in ME calculations

**SoftTune**: tune performed by Herwig 7 authors using ATLAS data

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**NNLO PDF for parton shower**, consistent with PDF in ME calculations

**SoftTune**: tune performed by Herwig 7 authors using ATLAS data

- Lower $p_T{}^0$ and $b$ compared to SoftTune
  → **increased amount of MPI in CH tunes**
- **LO PDF for UE preferred** over NNLO PDF
- **Choice of $\alpha_s$ in PDF less important**,
  but $\alpha_s$ = 0.130 typically associated with LO PDF

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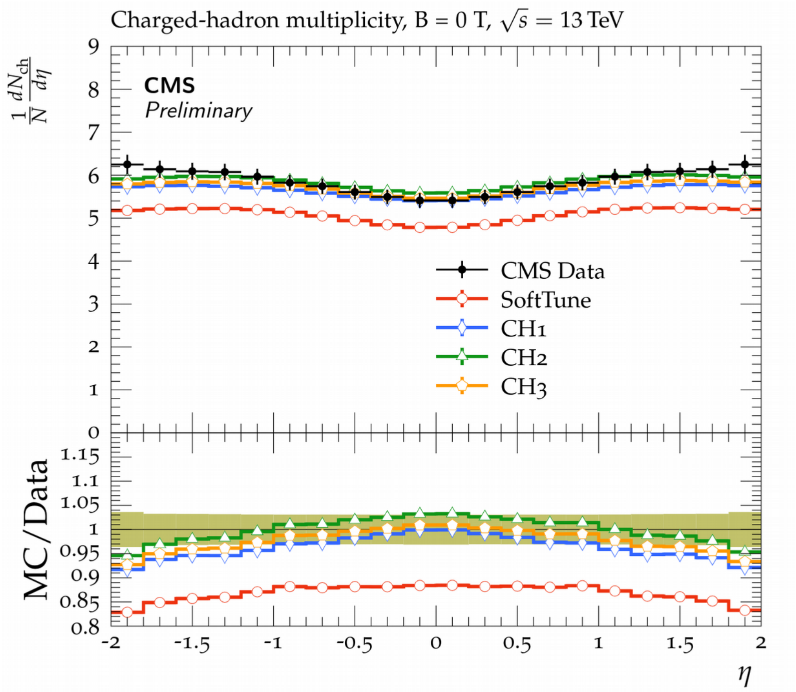
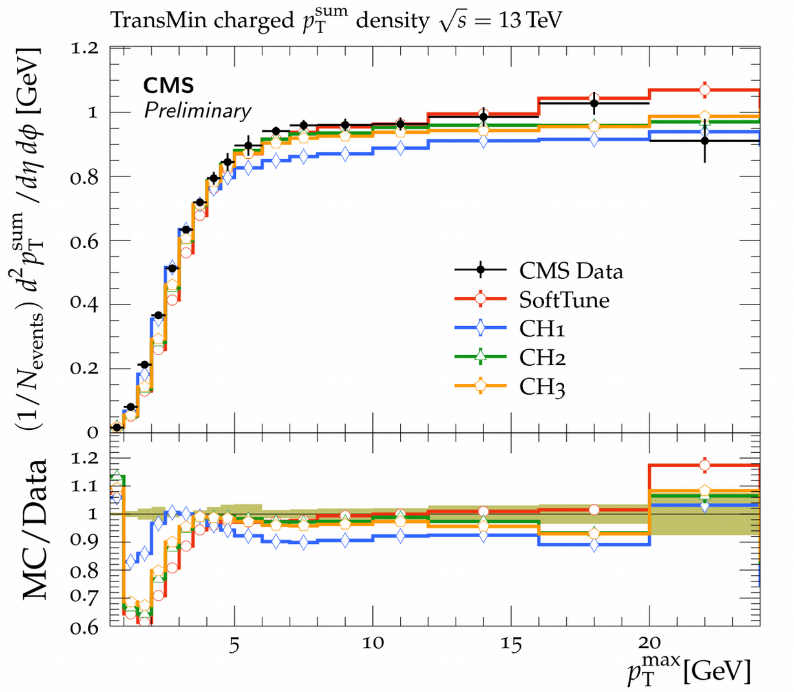


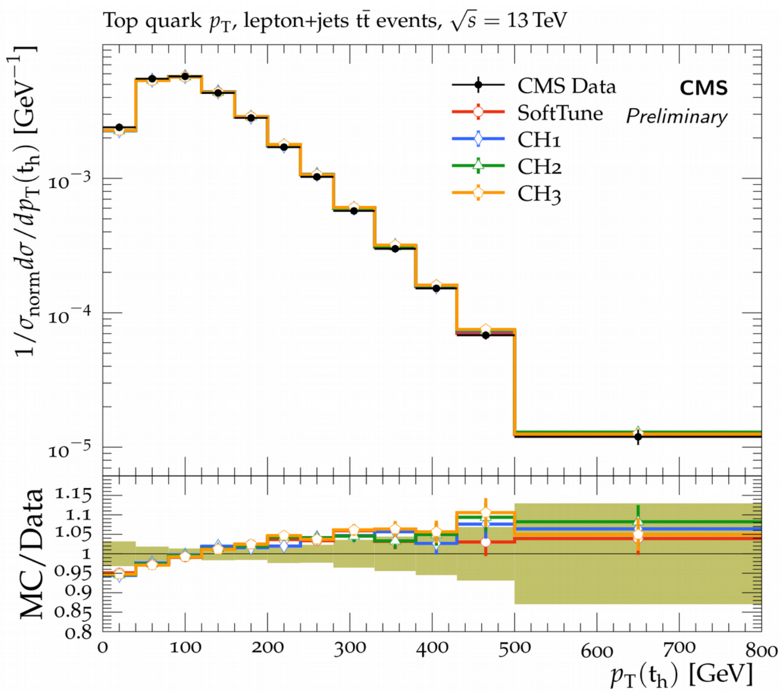

- **CH tunes increase amount of MPI** w.r.t SoftTune

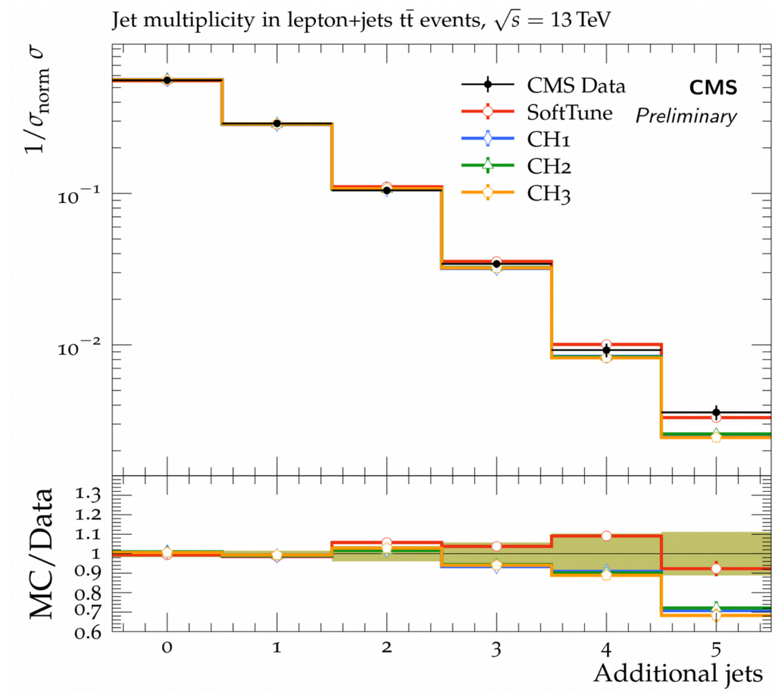
- CH tunes show typically **good agreement in plateau** of $N_{ch}$ or $p_T^{sum}$ density spectrum

- **Rising part** of spectrum (diffraction processes become more important) **not included in tuning procedure**

# Example validations of different Herwig 7 tunes

## Top quark pair production



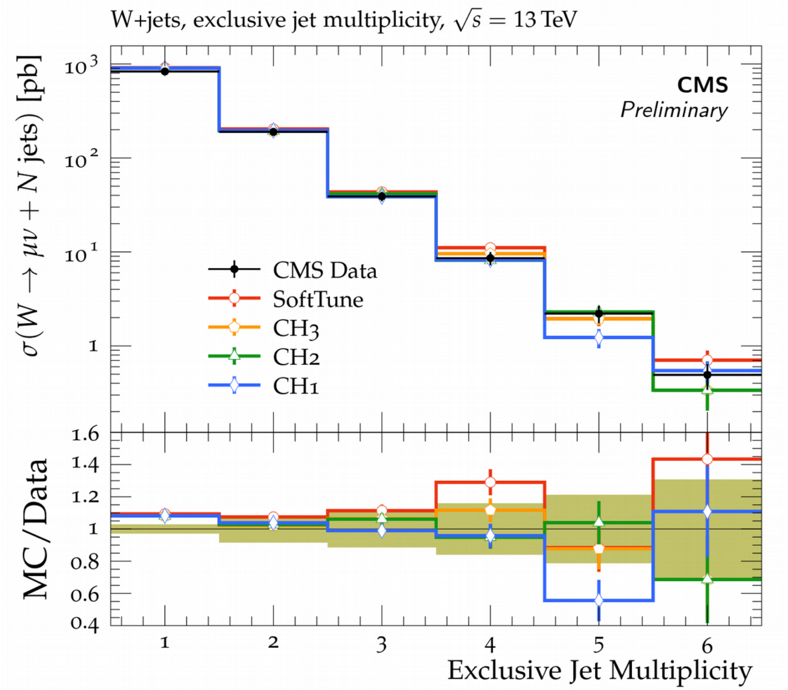




- **NLO ME** calculation with NNLO PDF set, `Powheg + Herwig 7`
- **Kinematic properties well described**

- **CH tunes underestimate high jet multiplicity**: lower $\alpha_S$ than SoftTune, but scale uncertainties expected to be large at high muliplicity

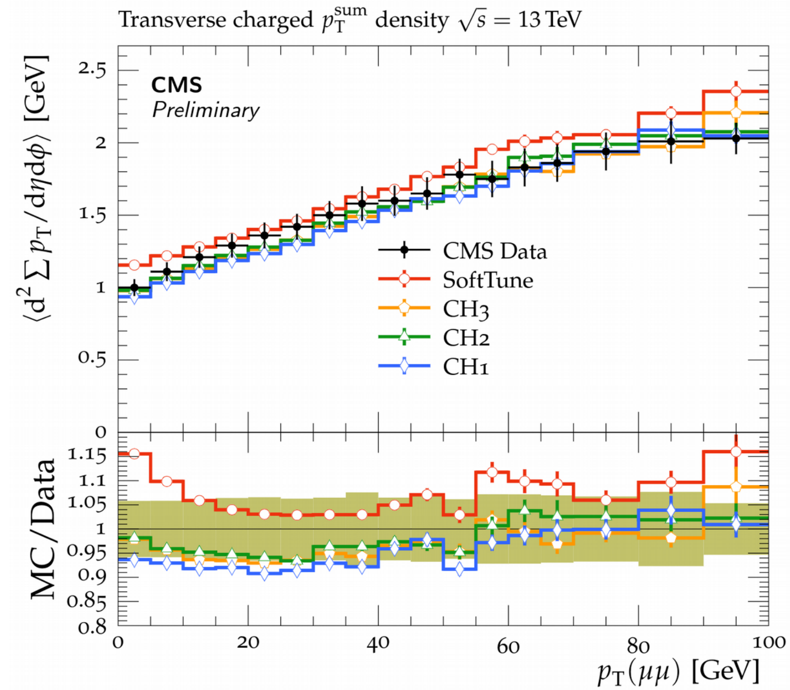
# Example validations of different Herwig 7 tunes

## W/Z + jets production




- **NLO ME** calculations up to 2 additional partons
`MG5_aMC@NLO + Herwig 7[FxFx]`
- ME (PS) dominates at low (high) jet multiplicity
- **Similar description by all tunes**

## UE in Z + jets production




- Checks UE description at higher scales than MB data
- **CH tunes describe data well**

# Summary

**CMS extracted and validated sets of tunes** for the UE simulation,
by fitting predictions to UE-sensitive observables in MB events at various $\sqrt{s}$

**`Pythia 8`** GEN-17-001

- New tunes improve on older `Pythia` tunes extracted at lower $\sqrt{s}$
- Predictions based on higher-order PDF shown to give reliable description of MB and UE measurements
- CP5 tune provides good overall description, most used in CMS

**`Herwig 7`** GEN-19-001 new

- First dedicated `Herwig 7` tunes with CMS data
- Derived tunes with different assumptions on PDF and $\alpha_S$ in UE
- Good overall description;
CH3 tune will be used in CMS

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**`Pythia 8`** GEN-17-001

- New tunes improve on older `Pythia` tunes extracted at lower $\sqrt{s}$
- Predictions based on higher-order PDF shown to give reliable description of MB and UE measurements
- CP5 tune provides good overall description, most used in CMS

**`Herwig 7`** GEN-19-001 new

- First dedicated `Herwig 7` tunes with CMS data
- Derived tunes with different assumptions on PDF and $\alpha_S$ in UE
- Good overall description; CH3 tune will be used in CMS

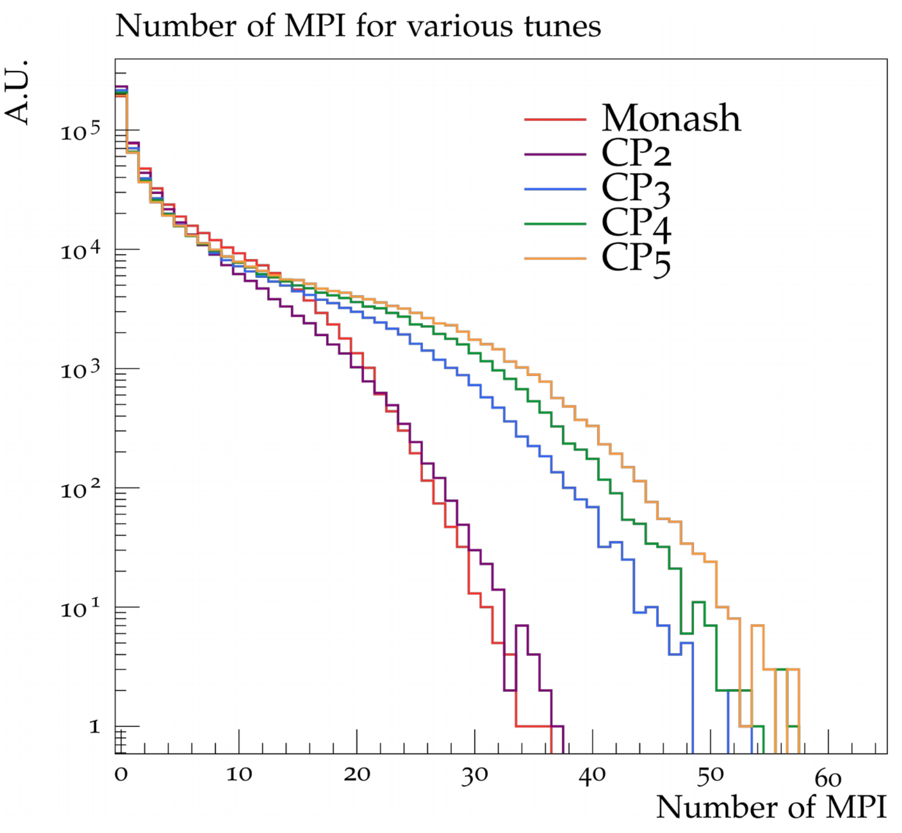
UE simulation from new tunes **interfaced with higher-order and multileg ME** provide good description

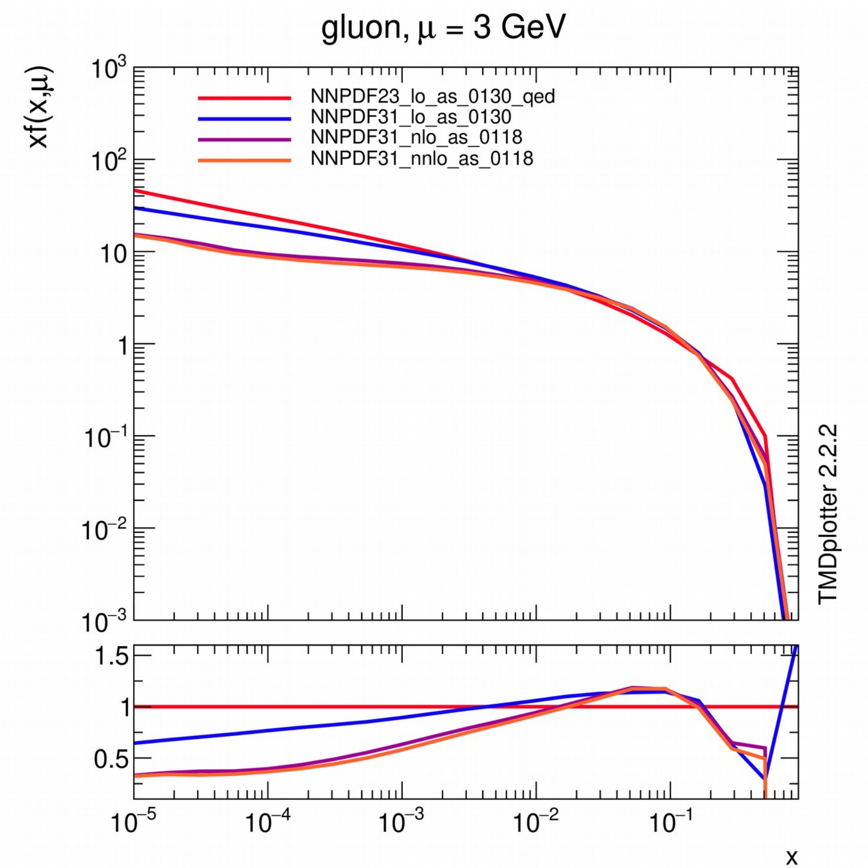
**Extensive validation**: event-shape observables, MB & UE simulation not used in tuning, multijet events, top quark pairs, W/Z production, double-parton scattering

**Tunes + uncertainties widely used** in Run 2 CMS measurements and searches

# Backup

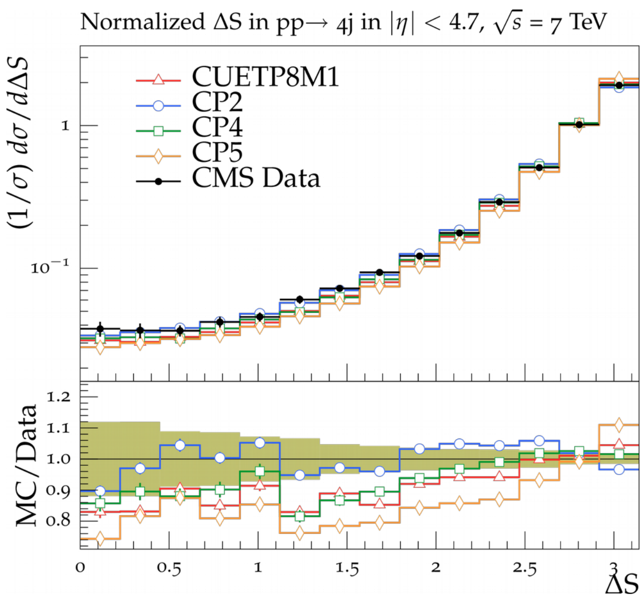
# Number of MPI and gluon PDF in CP tunes



# More validations of different Pythia 8 tunes

## Double-parton scattering (DPS)

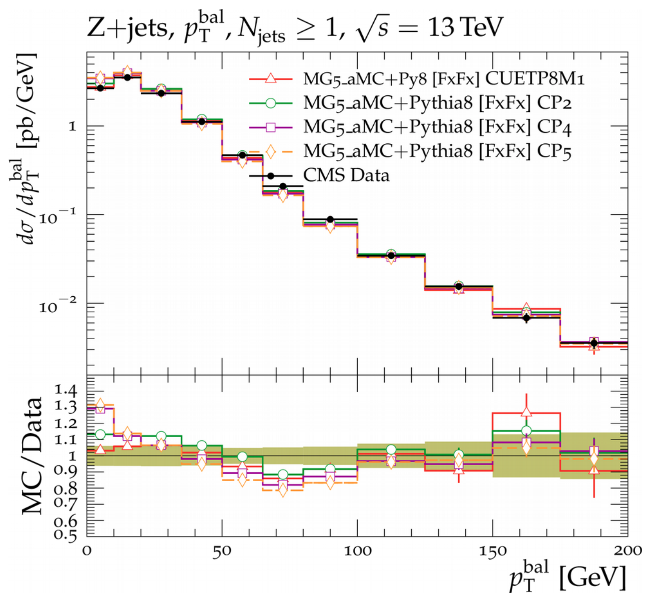



- **Topology in transverse plane** sensitive to contribution from DPS
- ΔS observable relates production planes of the hard and soft jet pairs

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

- **Best described by CP2 tune** due to different amount of MPI

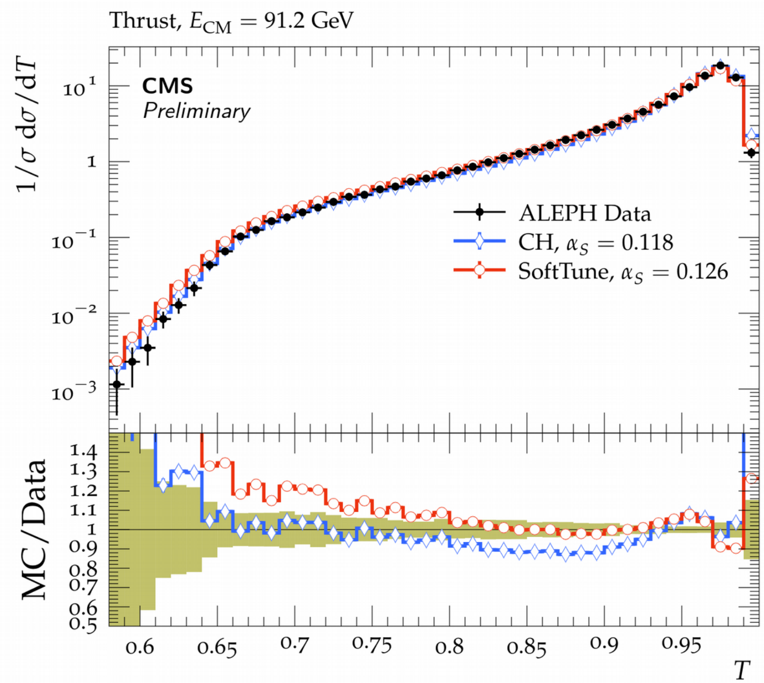
## W/Z + jets production




- `MG5_aMC@NLO + Pythia 8` at **LO** [MLM] or **NLO** [FxFx]
- **Some observables** such as $p_T$ balance between Z boson and jet, and $p_T$(Z), **best described by CP2**

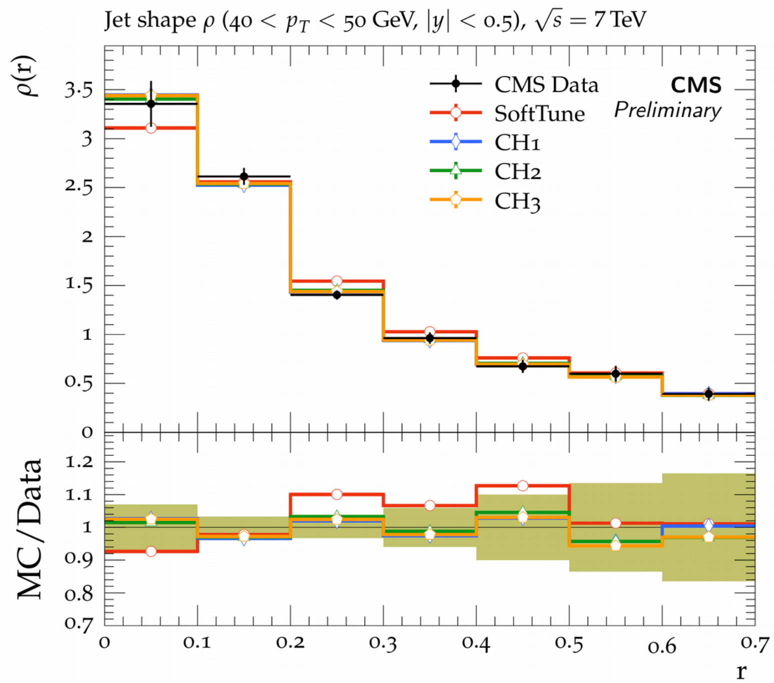
# More validations of different Herwig 7 tunes

## LEP event shape observables




- CH tunes underestimate number of events with $0.8 < T < 0.95$, but SoftTune predicts too many isotropic events (low values $T < 0.8$)

## Inclusive jet production




- Probing **jet substructure**
- **Jet shape ρ(r):** average fraction of $p_T$ of jet constituents contained inside annulus with inner (outer) radius r–0.1 (r+0.1)
- **CH tunes describe data well**

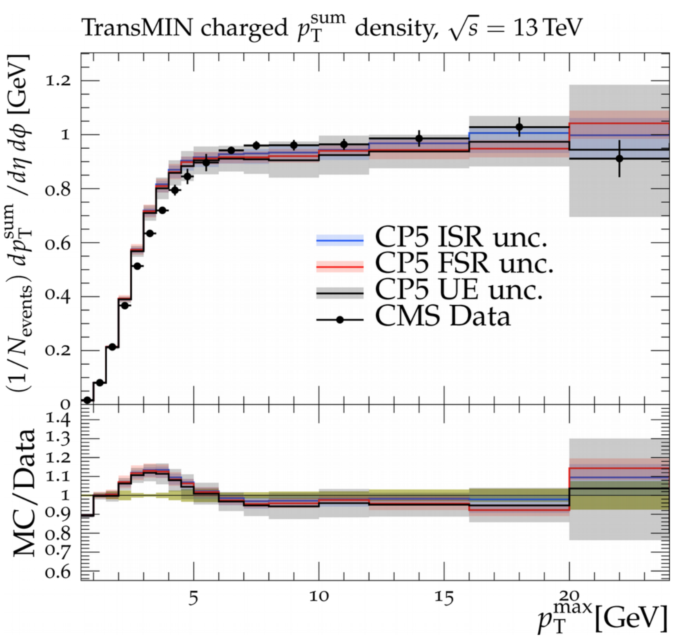
# UE tune uncertainties

**Two tune variations** (“up” and “down”)

- Constructed from 2*n* eigentunes (n = number of tuning parameters)
- Summing differences in quadrature in each bin
- Variations fitted to obtain the two sets of tune parameters

→ Simplifies **uncertainty estimation for CMS analyses** while still replicating combination of all 2*n* eigentunes

**Pythia 8**




**Herwig 7**