QCD Monte-Carlo model tuning studies with CMS data at 13 TeV

Daniela Dominguez  … on behalf of CMS collaboration
Deutsches Elektronen Synchrotron

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Introduction & Tuning: basic concepts
A pp collision at the LHC can be interpreted as a hard scattering between partons accompanied by underlying event (UE) consisting of:

- Initial and final state radiation (Parton shower)
- Hadronization
- Multiple Parton Interactions (MPI)
- Beam Remnants

These contributions are not always calculable using pQCD.

There are free phenomenological parameters to determine!!! (TUNING!!)
The underlying event (UE) at the LHC

Many processes are included in the nomenclature *UE* at different scales, i.e.:

1. Semi-hard multiparton interactions
2. Double Parton Scattering (DPS)
3. Diffractive processes

How we deal with that?

**Monte Carlo event generators (PYTHIA, HERWIG, SHERPA...)**

Parameters need to be adjusted (tuned) to describe data:

- **MPI**: 
  \[ p_T^0 = p_T^{\text{ref}} (E/E_{\text{ref}})^\epsilon \]
  Primordial \( k_T \), i.e: width of the Gaussian used for modeling the parton primordial \( k_T \) inside the proton

- Colour reconnection
- Parton shower: Strong coupling value, Regularization cut-off upper scale
- Hadronization: Length of fragmentation strings
Tuning Strategy

Rivet+Professor
https://professor.hepforge.org/

- Choice of parameter ranges and sensitive observable.
- Predictions for different parameter choices and interpolation of the MC response.
- Data-MC difference and minimization over parameter space.

Before Run II
UE observable used

during RunII ..until now
UE observable & charge particle multiplicity in MB events used.
**UE Observable**

**Transverse regions:** $60^\circ < |\Delta \phi| < 120^\circ$

- "transMAX" and "transMIN" Charge Particle Density: number of charged particles ($p_t > 0.5\text{GeV}, |\eta| < 0.8$)
- "transMAX" and "transMIN" Charged PTsum Density: scalar $p_t$

**TransMAX**
max. jet activity, often contains the 3rd jet sensitive to MPI/BR + ISR/FSR

**TransMIN**
min. jet activity, sensitive to MPI/BR

**TransAVE, TransDIF**

\[
= \frac{(\text{TransMAX} + \text{TransMIN})}{2}
\]

\[
= \frac{(\text{TransMAX} - \text{TransMIN})}{2}
\]

**TransMIN** sensitive to MPI & BR

**TransAVE, TransDIF** sensitive to ISR/FSR

\[
\frac{<N_{ch}>}{\Delta \eta \Delta (\Delta \phi)} \cdot \sum \frac{<p_t>}{\Delta \eta \Delta (\Delta \phi)}
\]
CMS UE Tunes
based on Tevatron & LHC $\sqrt{s} = 7\text{TeV}$ data

**PYTHIA 6.4 Tune CUETP6S1 - CTEQ6L or HERAPDF1.5LO**
Start with Tune $Z2 \ast -lep$ and tune to the CDF $\text{PTmax} \ trans\text{MAX}$ and $\ trans\text{MIN}$ UE data at 300 GeV, 900 GeV, and 1.96 TeV and the CMS $\text{PTmax} \ trans\text{MAX}$ and $\ trans\text{MIN}$ UE data at 7 TeV.

**HERWIG++ Tune CUETHS1-CTEQ6L**: Start with the Seymour & Siodmok UE-EE-5C tune and tune to the CDF $\text{PTmax} \ trans\text{MAX}$ and $\ trans\text{MIN}$ UE data at 900 GeV, and 1.96 TeV and the CMS $\text{PTmax} \ trans\text{MAX}$ and $\ trans\text{MIN}$ UE data at 7 TeV.

**PYTHIA 8 Tune CUETP8S1, CTEQ6L or HERAPDF1.5LO & PYTHIA 8 Tune CUETP8M1-NNPDF2.3LO**
details next slide
First CMS Tunes (Run1 LHC)
**Pythia8 UE Tunes with RunI LHC + Tevatron Data**

\[ p\bar{p} \text{ collisions with } \sqrt{s} = 0.9, 1.96, 7 \text{ TeV} \]

using \textit{transMAX}, \textit{transMIN} charged-particle and \( \sum p_T \) densities as observable for performing the tune (EPJC 76 (2016) 155)

**CUETP8S1**

| PYTHIA8 Parameter | Tune Range | Tune 4C | CUETP8S1 | CUETP8S1 |
|-------------------|------------|---------|----------|----------|
| PDF               | —          | CTEQ6L  | CTEQ6L   | HERAPDF1.5LO |
| MultipartonInteractions:pt0Ref [GeV] | 1.0–3.0 | 2.085   | 2.101    | 2.000    |
| MultipartonInteractions:semPow  | 0.0–0.4  | 0.19    | 0.211    | 0.250    |
| MultipartonInteractions:emcPow   | 0.4–10.0 | 2.0     | 1.609    | 1.691    |
| ColourReconnection:range        | 0.0–9.0  | 1.5     | 3.313    | 6.096    |
| MultipartonInteractions:emcRef [GeV] | —       | 1800    | 1800*    | 1800*    |
| \( \chi^2/\text{dof} \)        | —         | 0.952   | 1.13     |          |

* Fixed at Tune 4C value.

Reference tune Pythia 8 Tune 4C

EPJ C 74 (2014) 3024

using different PDF sets:

CTEQ6L, HERAPDF1.5LO

**CUETP8M1**

| PYTHIA8 Parameter | Tuning Range | Monash | CUETP8M1 |
|-------------------|--------------|--------|----------|
| PDF               | —            | NNPDF2.3LO | NNPDF2.3LO |
| MultipartonInteractions:pt0Ref [GeV] | 1.0–3.0 | 2.280    | 2.402    |
| MultipartonInteractions:semPow  | 0.0–0.4  | 0.215    | 0.252    |
| MultipartonInteractions:emcPow   | —         | 1.6*     | 1.6*     |
| ColourReconnection:range        | —         | 1.80     | 1.80**   |
| MultipartonInteractions:emcRef [GeV] | —       | 7000    | 7000**   |
| \( \chi^2/\text{dof} \)        | —         | —       | 1.54     |

* Fixed at CUETP8S1-CTEQ6L1 value.

**CUETP8M1**

| PYTHIA8 Parameter | Tuning Range | Monash | CUETP8M1 |
|-------------------|--------------|--------|----------|
| PDF               | —            | NNPDF2.3LO | NNPDF2.3LO |
| MultipartonInteractions:pt0Ref [GeV] | 1.0–3.0 | 2.280    | 2.402    |
| MultipartonInteractions:semPow  | 0.0–0.4  | 0.215    | 0.252    |
| MultipartonInteractions:emcPow   | —         | 1.6*     | 1.6*     |
| ColourReconnection:range        | —         | 1.80     | 1.80**   |
| MultipartonInteractions:emcRef [GeV] | —       | 7000    | 7000**   |
| \( \chi^2/\text{dof} \)        | —         | —       | 1.54     |

* Fixed at CUETP8S1-CTEQ6L1 value.

** CUETP8M1**

Reference tune Pythia 8 Monash

JHEP 10 (2013) 113

one PDF set: NNPDF2.3LO PDF

only varying MPI-energy dependence parameters.
Charged particle mult. in the MIN reg (left) and MAX reg. (right) for CDF and LHC RunI data

Different versions changing PDF sets

Good description of MB and UE observable, as well as variables measured in the forward region and in the jet sector

Rising part and plateau region are well predicted by the new tune

(EPJC 76 (2016) 155)
Extrapolating results to RunII LHC Data
CUETP8M1 performance with RunII data

Good performance → confirmation of the understanding of the energy dependence cut off of the partonic cross section
Not optimal performance → inaccuracy of energy extrapolation included in the tune, need for a better PDF sets, etc ...

The tune describe quite well the MB and UE, as well as variables measured in the forward region and in the jet sectors....
BUT the performance is not optimal!

Jet multiplicity in top events was overestimated

This effect present in both 8TeV and 13TeV data

TOP-16-021
CUETP8M1 performance with RunII data (II)

None of the tunes reproduce the data perfectly!

\[ \sqrt{s} = 13 \text{ TeV} \]

**TOP plot:**

\[ dN/d\eta \]

**PLB 751 (2015) 143**

**BOTTOM plots:**

\[ N_{ch} \text{ vs } p_{T}^{\text{lead}} \]

CMS-FSQ-15-007

The energy dependence of the MPI fitted to lower energies is not optimal:

\[ p_{T}^{0} = p_{T}^{\text{ref}} (E/E_{\text{ref}})^{\epsilon} \]

Need for new Tune!!!
Re-Tuning efforts to describe RunII LHC

based on $\sqrt{s} = 8$ TeV Data
The following parameters are tuned to the jet multiplicity measured in dilepton events at 8 TeV:

- **POWHEG**: $h_{\text{damp}}$, controls ME/PS matching and effectively regulates the high-pt radiation by damping real emissions generated by POWHEG.
- **Pythia8 SpeceShower**: $\alpha_S^{\text{ISR}}$, value of the strong coupling at $m_Z$ used to initial-state shower.

**STEP 1** POWHEG+Pythia8 in top events (8 TeV Data):
Using jet multiplicity and $p_t$ of the additional jet distributions, parameters are tuned: $\alpha_S$ is tuned to lower values (**0.1108**)  
UE parameters are fixed using values from CUETP8M1

**CUETP8M1T4** (intermediate tune)

**STEP 2** Pythia8 in UE/MB using 13 TeV Data:
Once the $\alpha_S$ (ISR) is extracted (fixed to $\alpha_S = 0.1108$), a new UE/MB tune is derived. Parameter of energy dependence fixed to the value in CUETP8M1 (no energy dependence).

**CUETP8M2T4**
Intermediate tune: CUETP8M1T4  TOP-16-021

![Graphs showing CMS+Professor comparisons](image)

Improves the description of $t\bar{t}$ kinematics and overall description of observable at $\sqrt{s} = 8$ TeV & $\sqrt{s} = 13$ TeV. (arXiv:1803.0399)
Charge Particle Multiplicity in the MIN region and $dN/d\eta$ at 13TeV

the new tune describes better the plateau region

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP-16-021/index.html#AddFig

But: Single-Diffractive enhance observable and inelastic cross sections
not well described
Need for new tune!
Colour Reconnection tunes efforts
New CR tunes

New tunes are performed with two different CR models: 

- **QCD inspired** \( (HEP08 \ (2015) \ 003) \)
- **Gluon Move** \( arXiv:1506.09085 \)

**Tuning Strategy**

**Baseline:** CUETP8M2T4 (top specific tune)

Tuning in addition some color reconnection parameters:

- QCD-inspired model: junctionCorrection, timeDilationPar, m0
- Gluon-move model: m2Lambda

UE/MB observable used at 13 TeV Data.

**Very important in model dependence systematic uncertainties in the estimation of the top mass!!!**

TOP-17-007
Remarks: Very difficult to describe the rising part of the spectrum at 13 TeV
Most recent efforts for Tuning based in $13\,\text{TeV}$ Data

The five CP Tunes (CmsPythia Tune)
Strategy

Discussions on the order of PDF sets in parton shower and the matching of the PDF in the PS and in the ME brings the idea of new set of tunes.

1. **Tuning of ISR** $\alpha_S$ **values and** $hdamp$ **for POWHEG+PYTHIA8 simulation based on top events.** The UE parameters were fixed to CUETP8M1 tune.

2. **Full UE retuning starting from the new values of ISR** $\alpha_S$ **and switching to latest NNPDF3.1 set.**

Main idea: test the effect of using different PDF orders of NNPDF sets in Pythia8 among other parameters variations.
## CmsPythia tunes at 13 TeV

| Tune | PDF set & running order, $\alpha_s(M_Z)$ | ISR/FSR $\alpha_s$ |
|------|-----------------------------------------|---------------------|
| CP0  | NNPDF30 at LO/LO, 0.13                  | 0.1108/0.1365       |
| CP1  | NNPDF31 at LO/LO, 0.1365                | 0.13                |
| CP2  | NNPDF31 at LO/LO, 0.13                  | 0.13                |
| CP3  | NNPDF31 at NLO/NLO, 0.118               | 0.118               |
| CP4  | NNPDF31 at NNLO/NLO, 0.118              | 0.118               |
| CP4  | NNPDF31 at NNLO/NLO, 0.118              | 0.118               |
Minimum Bias events

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

Rivet: ATLAS_2017_I1509919, $\sqrt{s} = 13$ TeV, $|\eta| < 2.5$, $p_T > 0.5$ GeV with at least one of the charged particle with $p_T > 1$ GeV

Distributions most sensitive to MPI, biggest problems not using a LO PDF.

The data are described at the same level by tunes with LO, NLO, and NNLO PDF NNPDF3.1 sets.
Summary and conclusion

Monte Carlo models contain free phenomenological parameters that need to be tuned to describe properly new data.

- New Tunes in CMS used in LHC data Run II were presented.
- New Tunes for Pythia8 are ready and show good performance at 13 TeV data (also at 8 TeV).
- Effects on different choices of PDF and $\alpha_S$ in UE simulation are investigated.
Thanks for your attention!!!!