QCD Monte-Carlo Model Tuning Studies with CMS Data at 13 TeV

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On behalf of the CMS Collaboration

12th December 2017

Outline

- Introduction
  - Why Monte Carlo event generators?
- CMS efforts for MC tuning
- Measurements for CMS tunes
- Summary

Why Monte Carlo event generators?

- Experiments rely on Monte Carlo event generators (PYTHIA, HERWIG, SHERPA, etc...)
  - calculate physical observables
  - pileup simulation
  - correct detector effects
  - apply unfolding
  - estimation of background
  - optimization of cuts for limit or discovery
  - deal with many processes ...

- In order to describe the data parameters used in MC programs need to be adjusted i.e. "tuned"
  - For example parameters used in PYTHIA :

- Multiple interaction parameters in Pythia

$$p_T^0(s) = p_T^{ref}\left(\frac{s}{s_{ref}}\right)^{\varepsilon}$$

extrapolation from lower energy

- Primordial k_T

Width of the gaussian used for modelling the parton primordial k_T inside the proton

- Parton shower

Strong coupling value
Regularization cut-off
Upper scale

- Hadronization

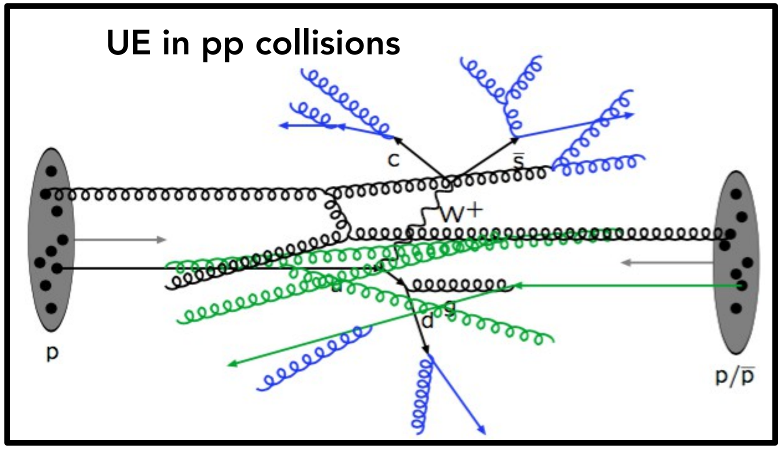
Length of fragmentation strings
Strange baryon suppression

Why and How MC tuning?

- **Why:**
  - Obtain correct description of the data
  - Good physics predictions
  - Correct evaluation of physics effects
- **How:**
  - Choose sensitive observables and corresponding parameters
  - Choose parameter ranges
  - Use predictions for different parameter choices and interpolation of the MC response
  - Look at Data-MC differences and minimize with parameter space
  - Avoid from over-tuning!

Underlying Event @ LHC

- The hard pp-collision at the LHC can be interpreted as a "hard scattering" between partons accompanied by the underlying event (UE).

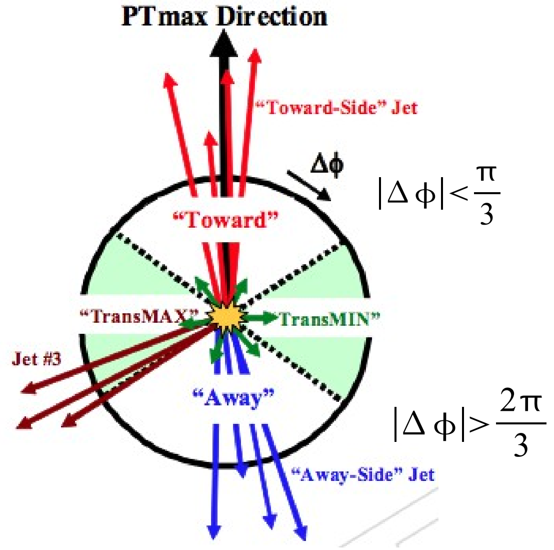


- UE consists of particles from
  - Beam-Beam Remnants (BBR)
  - Multiple Parton Interactions (MPI)
  - Soft Initial and final state radiation (ISR&FSR)

- UE is essentially semi-hard interaction, with typical scale~1-2 GeV

  (to be compared with soft interaction scale of Λ_{QCD} ~ 0.2 GeV)
  - needs phenomenological models for description
  - parameters in the models need adjustments
  - *TUNING* of Monte Carlo event generators

$|\Delta\phi| < \pi/3 \rightarrow$ TOWARD region
$\pi/3 < |\Delta\phi| < 2\pi/3 \rightarrow$ TRANSVERSE region
$|\Delta\phi| > 2\pi/3 \rightarrow$ AWAY region



- UE observables: TransMAX and TransMIN Charged Particle & PtSum Density
  - TransMIN very sensitive to MPI and BBR
  - TransMAX often contains a 3[rd] jet in events with hard ISR or FSR.
  - TransDIFF (TransMAX - TransMIN) very sensitive to ISR and FSR

CMS UE Tunes: PYTHIA8

EPJC 76 (2016) 155

- Use CDF and CMS data for the tunes
  - Select the leading charged particle (pTmax)
  - Use charged particles with $|\eta| < 0.8$ & $p_T > 0.5$ GeV.
- The software used for the tunes RIVET (A. Buckley et al, doi:10.1016/j.cpc.2013.05.021)
  PROFESSOR (A. Buckley et al. , Eur.Phys.J.C65(2010) 331357)
- Take PYTHIA8 Tune 4C as reference tune then construct two new UE tunes
  - using CTEQ6L1 (CUETPS1-CTEQ6L1)
  - using HERAPDF1.5LO (CUETP8S1-HERAPDF1.5LO)
  - varying the four parameters within the Tuning Range

PYTHIA8 Parameter	Tuning Range	Tune 4C (CTEQ6L1)	CUETP8S1 (CTEQ6L1)	CUETP8S1 (HERAPDF1.5LO)
MultipartonInteractions:pT0Ref [GeV]	1.0 - 3.0	2.085	2.101	2.000
MultipartonInteractions:ecmPow	0.0 - 0.4	0.19	0.211	0.250
MultipartonInteractions:expPow	0.4 -10.0	2.0	1.609	1.691
ColourReconnection:range	0.0 - 0.9	1.5	3.313	6.096

- By using the output from PYTHIA 8:
  - it is possible to predict the σ_{eff} value in the tune, defined by the UE parameters
  - PROFESSOR gives the eigentunes in order to get the uncertainties of the parameters

CMS UE Tunes: PYTHIA8, PYTHIA6 and HERWIG++

EPJC 76 (2016) 155)

- Combines updated fragmentation parameter for NNPDF2.3LO
  - NNPDF2.3LO has a gluon distribution @ small-x different than CTEQ6L1 & HERAPDF1.5LO
  - Affecting predictions especially in the forward region
- New tune PYTHIA8 CUETP8M1
  - using parameters of Monash Tune
  - Fitting two MPI energy dependence parameters to UE data @ s = 0.9, 1.96&7 TeV

PYTHIA8 Parameter	Tuning Range	Monash	CUETP8M1
PDF	-	NNPDF2.3LO	NNPDF2.3LO
MultipartonInteractions:pT0Ref [GeV]	1.0 - 3.0	2.280	2.402
MultipartonInteractions:ecmPow	0.0 - 0.4	0.215	0.252
MultipartonInteractions:expPow	-	1.85	1.6*
ColourReconnection:range	-	1.80	1.80**
MultipartonInteractions:ecmRef [GeV]	-	7000	7000**

- Two new PYTHIA6 UE tunes are constructed
  - Starting with Tune Z2*lep parameters,
  - Using CTEQ6L1 (CUETP6S1-CTEQ6L1)
  - Using HERAPDF1.5LO (CUETP6S1-HERAPDF1.5LO)
  - Not only MPI energy-dependence parameters but
    - the core-matter fraction PARP(83),
    - color reconnection (CR) strength PARP(78),
    - CR suppression PARP(77) are also varied.
- New HERWIG++ UE tune, CUETHppS1
  - obtained varying four parameters in table.
  - set MPI cut-off pT0 and ref. energy to Tune UE-EE-5C
  - vary MPI extrap. parameter

HERWIG++ Parameter	Tuning Range	UE-EE-5C	CUETHppS1
PDF	-	CTEQ6L1	CTEQ6L1
MPIHandler:Power	0.1 - 0.5	0.33	0.371
RemnantDecayer:colourDisrupt	0.1 - 0.9	0.8	0.628
MPIHandler:InvRadius [GeV^2]	0.5 - 2.7	2.30	2.255
ColourReconnector:ReconnectionProbability	0.1 - 0.9	0.49	0.528

CMS DPS Tunes

EPJC 76 (2016) 155

- We determined the MPI parameters by fitting to observables which involve correlations among outgoing objects in hadron collisions and sensitive to DPS

- The different kinematical configuration can be exploited to discriminate the two processes using the observables:

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\text{object}_1)\cdot\vec{p}_T(\text{object}_2)}{|\vec{p}_T(\text{object}_1)|\times|\vec{p}_T(\text{object}_2)|}\right)$$

$$\Delta^{\text{rel}} p_T = \frac{|\vec{p}_T^{\,\text{jet}_1} + \vec{p}_T^{\,\text{jet}_2}|}{|\vec{p}_T^{\,\text{jet}_1}| + |\vec{p}_T^{\,\text{jet}_2}|},$$

object_1: hard-jet pair
object_2 : soft-jet pair

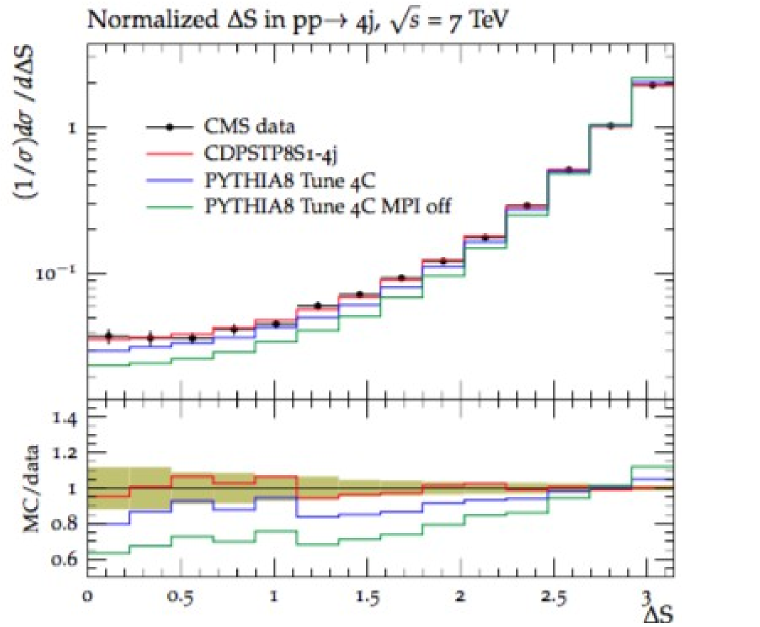
- Study of QCD evolution in W+2j & 4-jet production scenario
  - One of the two jet pairs is emitted by the hard scattering
  - Hard radiation can produce softer jets

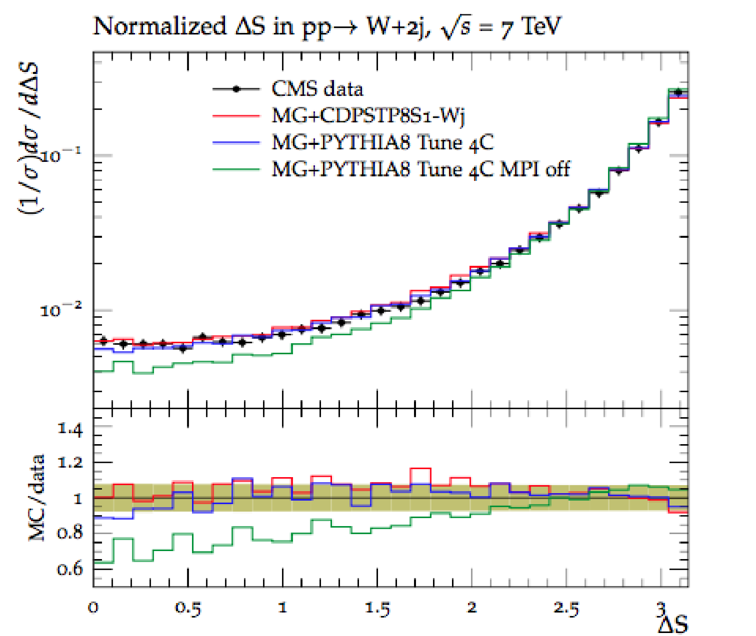
- Studies of SPS and DPS contributions performed with PYTHIA8 generator tune 4C:
  - MPI contribution switched off for SPS (CDPSTP8S1-Wj)
  - Two hard scatterings @ parton level forced to happen w/o PS (CDPSTP8S2-Wj)

- Compatible with the value measured by CMS using the template method

$$\sigma_{\text{eff}} = 20.6 \pm 0.8\ (\text{stat}) \pm 6.6\ (\text{sys})\ \text{mb}$$

PYTHIA Parameter	TUNE 4C	CDPSTP8S1-4j	CDPSTP8S2-4j
PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1
Predicted σ_{eff} (in mb)	30.3	$21.3^{+1.2}_{-1.6}$	$19.0^{+4.7}_{-3.0}$





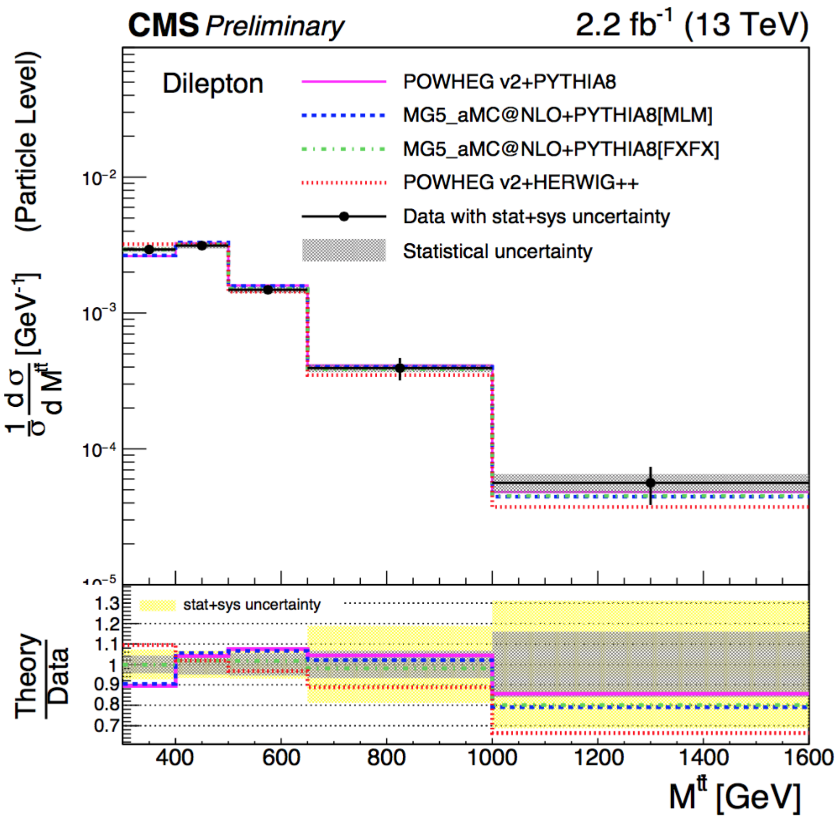
CMS efforts for tuning with Run II data

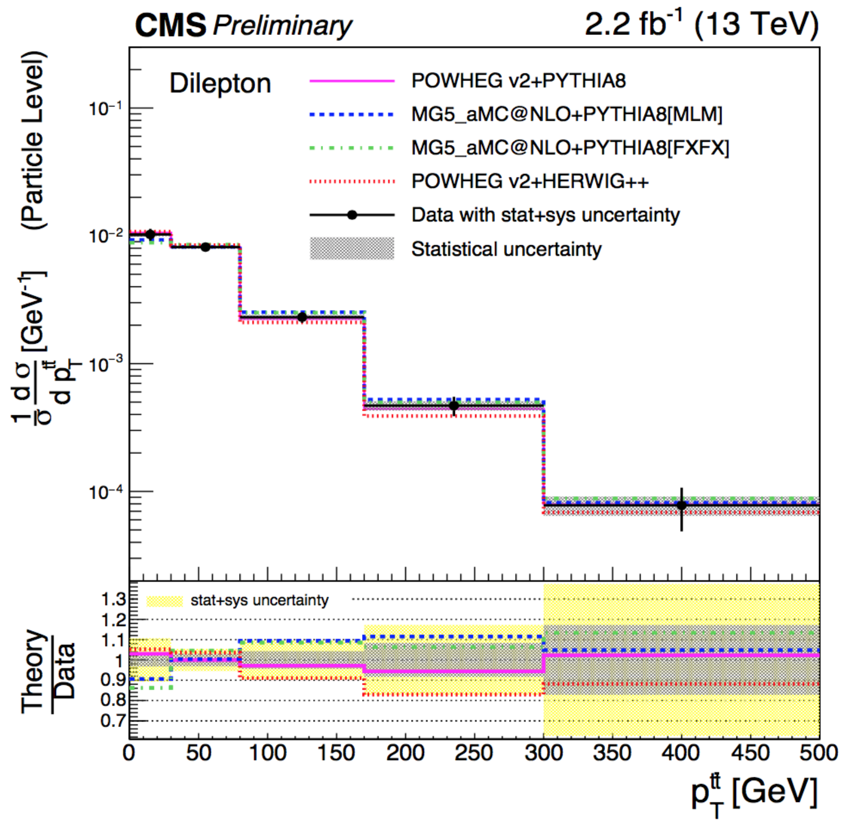
- Use similar strategy as done with CMS Run I data
  - Use UE observables i.e. charged particle multiplicity and p_T^{sum} densities (in the transverse region)
  - Tune perturbative parameter that determines inclusive event properties (α_S^{ISR})
  - Fit UE & MinBias data at 13 TeV to tune MPI parameters.
  - Verify the tune with various data (MinBias, DPS, UE, Drell-Yan, W/Z+jets, ...)
- New UE/MB tune at 13 TeV : CUETP8M2T4
  - CMS-GEN-17-001 paper in preparation

Differential Cross Sections of Top Quark Pair

- Provides a good test of perturbative QCD calculations.
- Gives opportunity to test and tune new MCs (NLO ME + LO PS MC)

CMS TOP-16-007





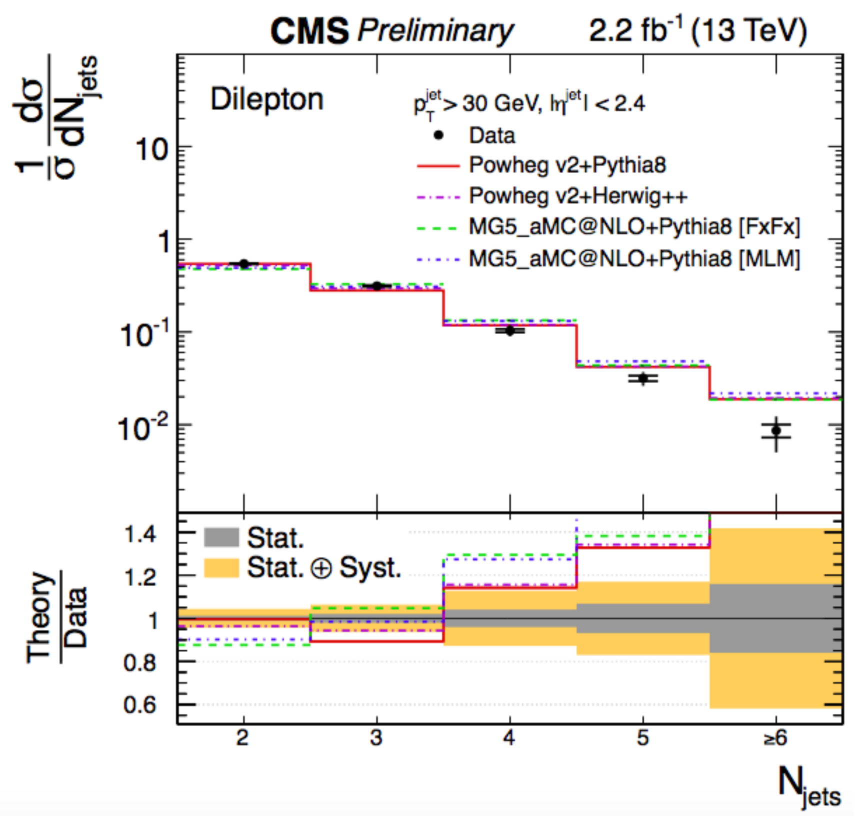
- POWHEG +HERWIG++ prediction better describes the data than the predictions interfaced with PYTHIA 8, with the exception of the M^{tt} distribution.

Jet Multiplicity in Top Quark Pair Events

- Predictions overestimate the data for large jet multiplicities, when jets come from the parton shower!

CMS TOP-16-011

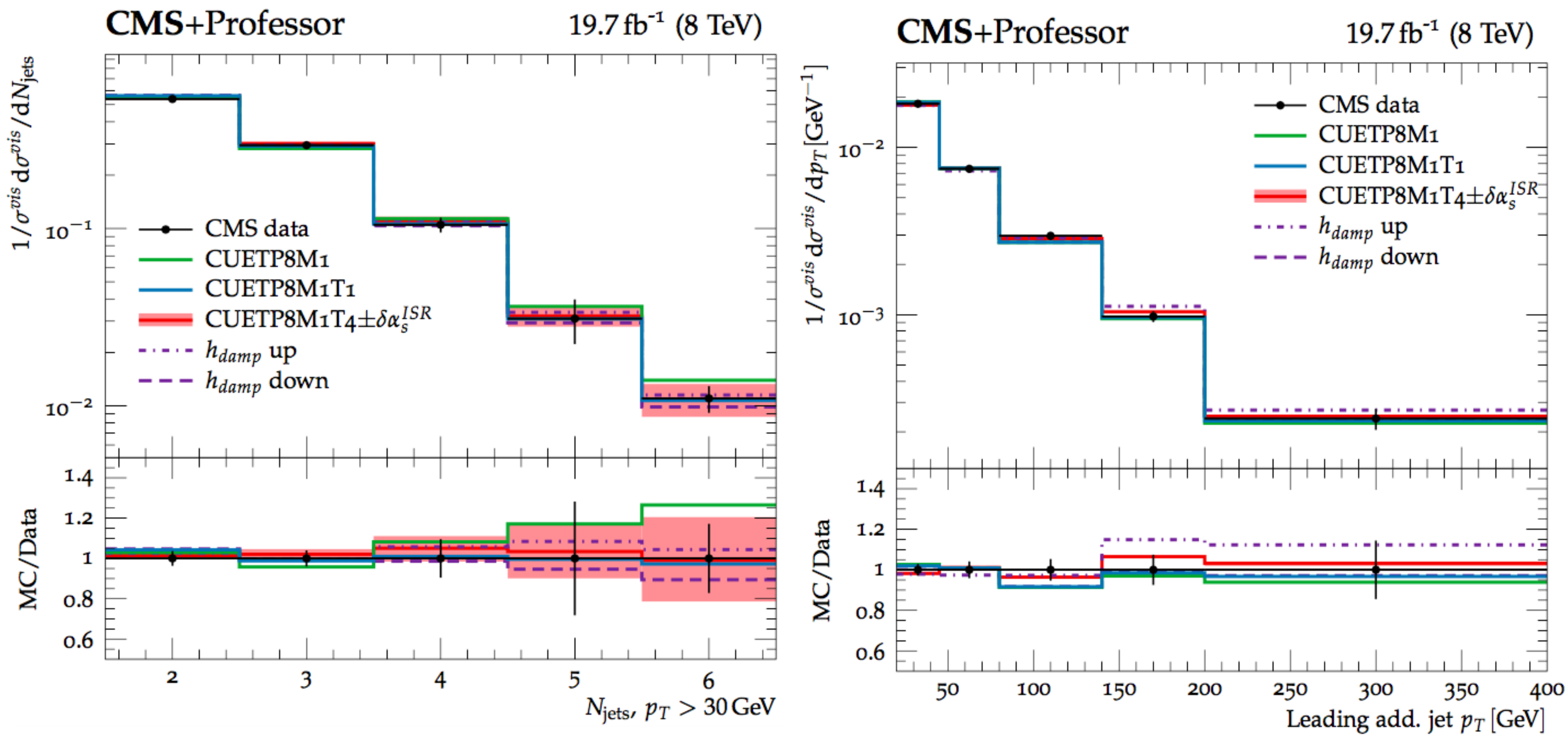
- Similar effect was observed at 8 TeV [CMS TOP-12-041]



Tuning of α_s+h_{damp}

CMS TOP-12-041 | CMS TOP-16-021

- Need for improvement of the jet multiplicity in top events



- Two parameters of the Pythia8 parton shower model are studied and tuned to the data:
  - **hdamp** : an internal parameter inside the POWHEG ME simulation, which regulates the amount of additional hard radiations
  - $\alpha_s^{ISR}(M_Z)$: strong-coupling constant at the mass of the Z boson for ISR

RESULTS:

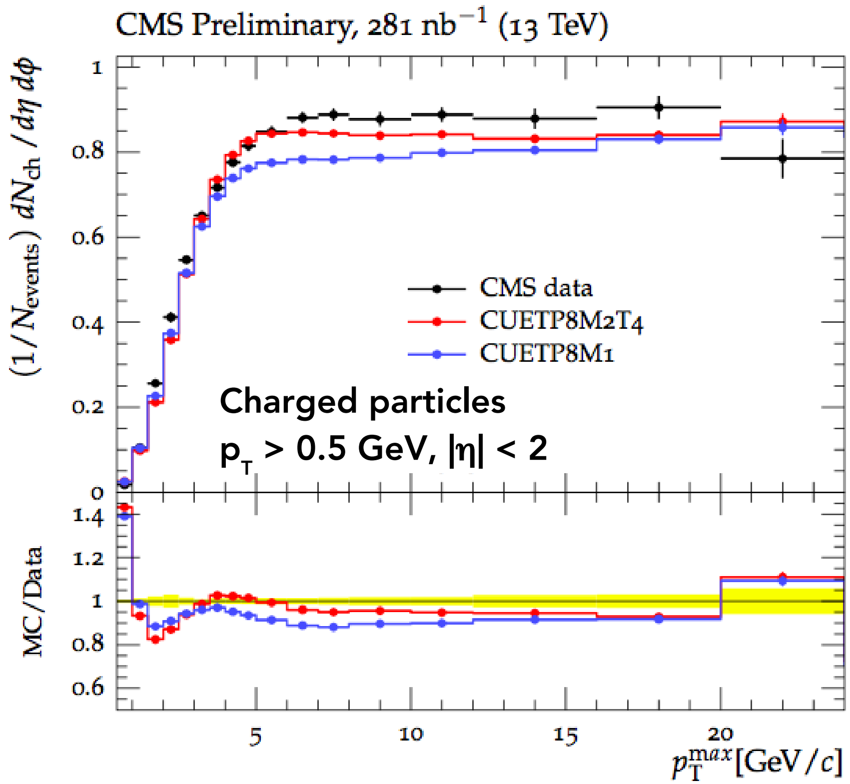
$$\alpha_S^{ISR} = 0.1108^{+0.0144}_{-0.0142}$$

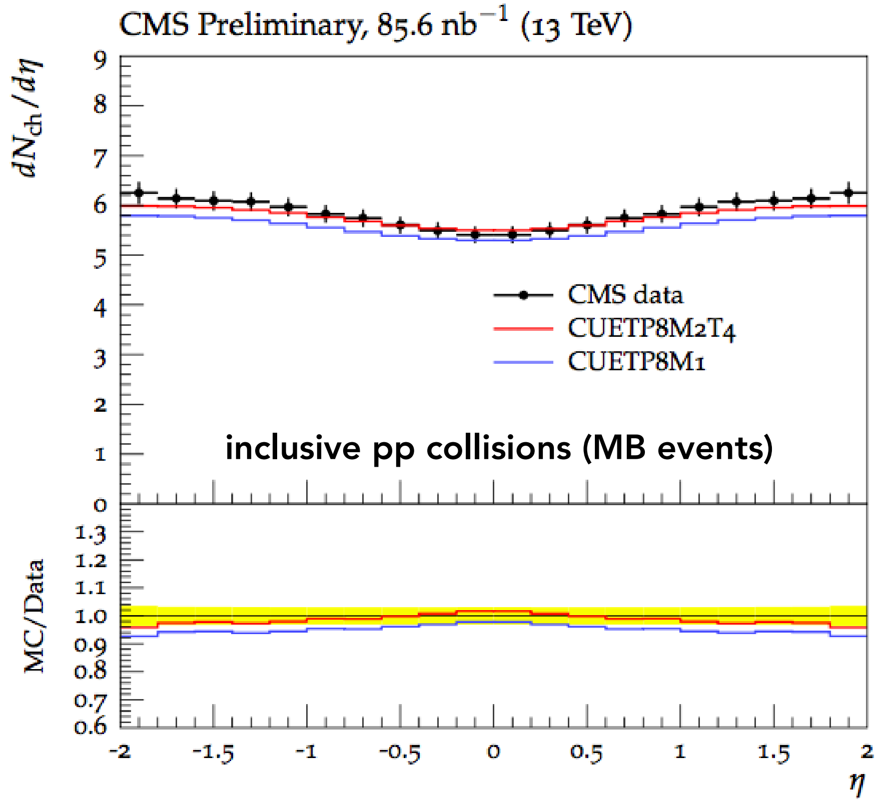
$$h_{damp} = 1.581^{+0.658}_{-0.585}$$

Performance of new CMS Tune

Underlying event at 13 TeV

CMS TOP-16-021



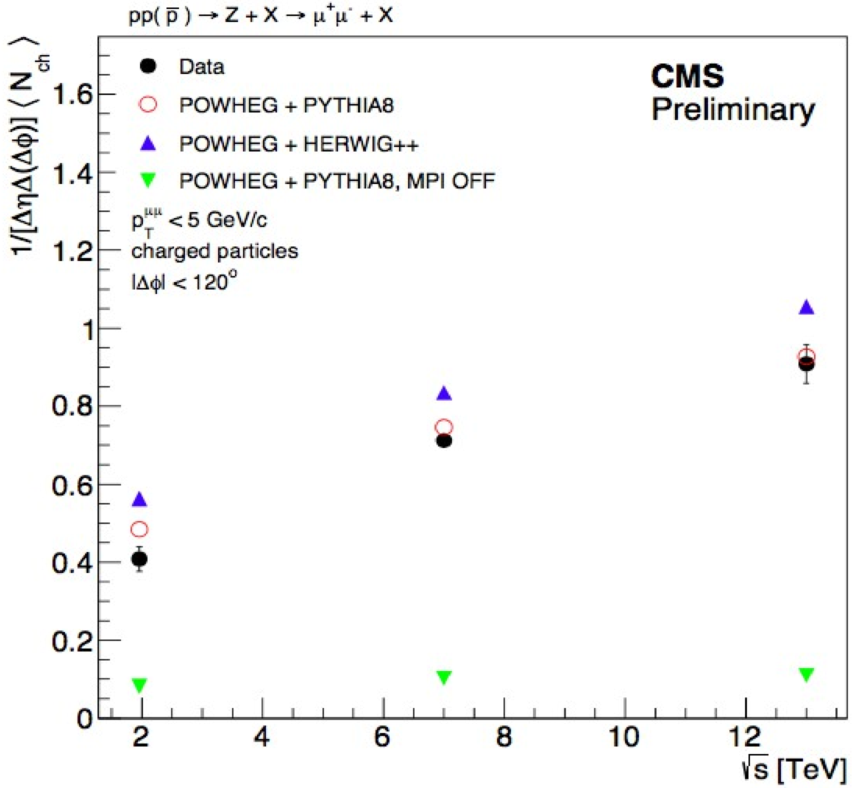


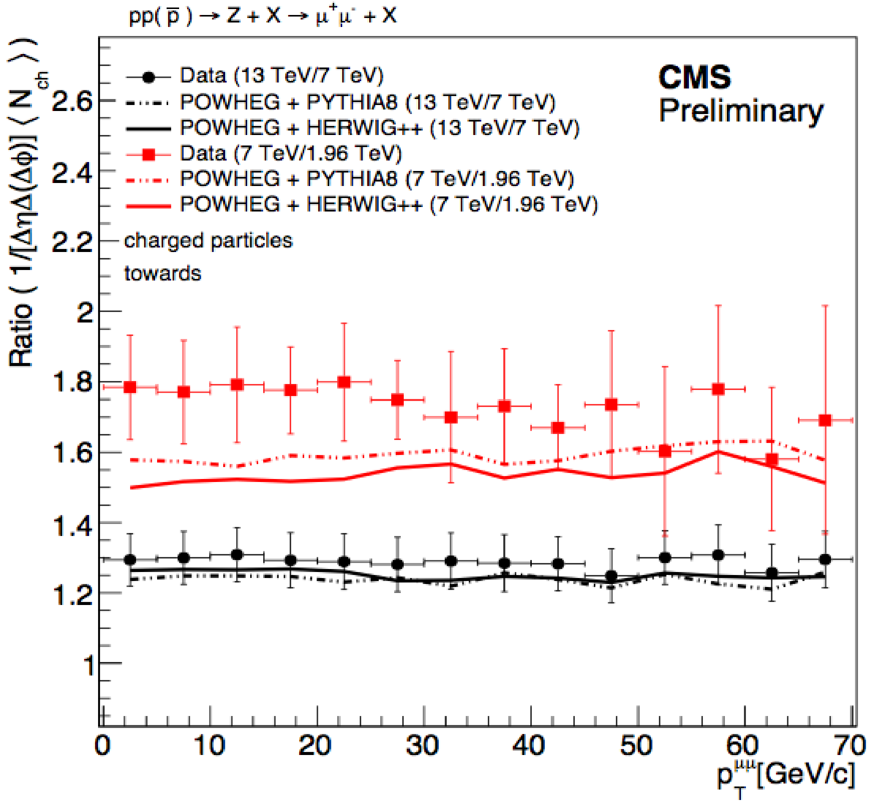
- Fixing the α_s^{ISR} to 0.1108, we derived a new tune, CUETP8M2T4
- New tune describes UE and MB data at $\sqrt{s}$ = 13 TeV simultaneously
- Performs well at $\sqrt{s}$ = 7 TeV as well.
- Provides a better description of the plateau
- Single-diffractive enhanced observables and inelastic cross sections not well described
- Comparisons with other processes, UE and DPS observables and tuning for Herwig7

Performance of new CMS Tune (II)

UE in Z+jets Events

CMS-FSQ-16-008





- UE activity increases with √s
- Better description by POWHEG+PYTHIA8

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

Test of higher order PDF positiveness

- Motivation:
  - to match the PDF in PS and in the ME, and to have LO PDF for MPI to make sure small x-gluon is physical (setting different PDFs in MPI and PS in Pythia not possible yet!)
  - to 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)

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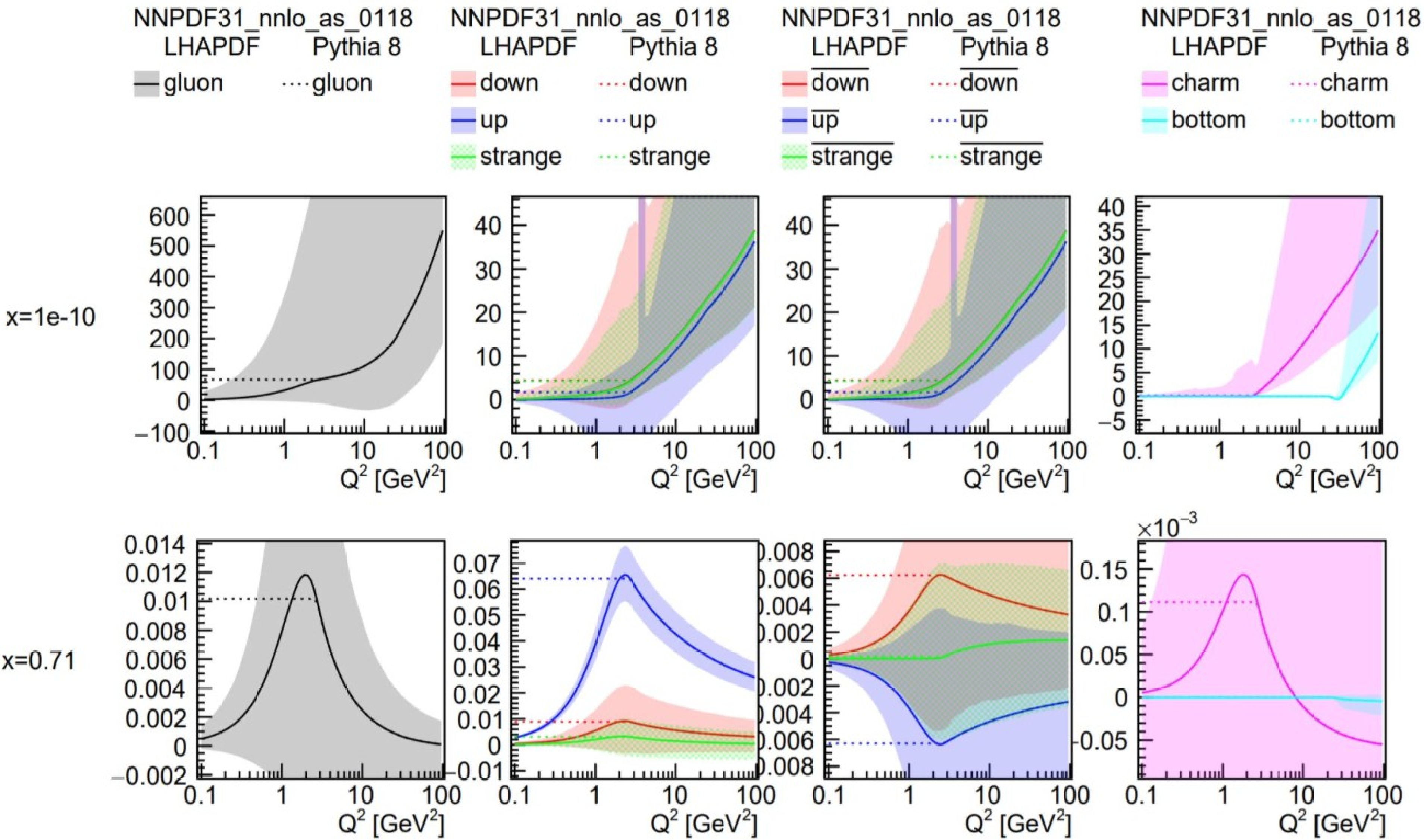

Summary

- LHC has provided various data samples to understand UE activities
- CMS has a rich tuning program for MC models
  - effort already started with Run I data (EPJC 76 (2016) 155)
  - still ongoing with Run II data
- A CMS top-specific Pythia8 is available
  - uses a lower value of ISR α_s, tuned to jet multiplicities in top events
  - describes UE and MB observables well
- UE/Min-Bias data are being studied tunes with LO, NLO, and NNLO PDF NNPDF3.1 sets.

- **Still more measurements and efforts on-going also intense preparation for the new tuning!**

Thank you for your attention!

BACKUP

UE Observables

- **TransMAX and TransMIN Charged Particle Density:**
  - Number of charged particles in the the maximum (minimum) of the two “transverse” regions as defined by the leading charged particle, p_T^{max}, divided by the area in η-ϕ space, $1.6\times2\pi/6$, averaged over all events with at least one particle with e.g. $p_T > 0.5$ GeV/c, $|\eta| < 0.8$.
- **TransMAX and TransMIN Charged Ptsum Density:**
  - Scalar p_T sum of charged particles in the the maximum (minimum) of the two “transverse” regions as defined by the leading charged particle, p_T^{max}, divided by the area in η-ϕ space, $1.6\times2\pi/6$, averaged over all events with at least one particle with e.g. $p_T > 0.5$ GeV/c, $|\eta| < 0.8$.

- **TransMIN very sensitive to MPI and BBR**
- **TransMAX often contains a 3rd jet in events with hard ISR or FSR.**
- **TransDIFF (TransMAX - TransMIN) very sensitive to ISR and FSR**

$|\Delta\phi| < \pi/3 \rightarrow$ TOWARD region
$\pi/3 < |\Delta\phi| < 2\pi/3 \rightarrow$ TRANSVERSE region
$|\Delta\phi| > 2\pi/3 \rightarrow$ AWAY region