Monte Carlo Modelling and Tuning in CMS

Vieri Candelise

University of Trieste and INFN

11th International Workshop on Multiple Partonic Interactions

Prague, Czech Republic

19/11/2019

Outline

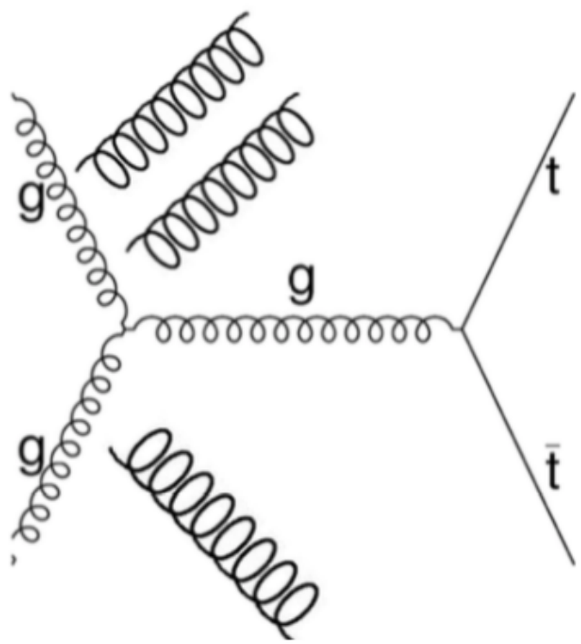
- Monte Carlo Modelling and Tuning in CMS: overview
- QCD parameters and Tuning Procedure

- Extraction of 5 new Pythia8 Tunes
- Validation and Comparisons on Several Physics Processes

Modelling and Tuning

Modelling Monte Carlo Generators at the LHC

useless to say: we (*often) rely* on Monte Carlo doing LHC physics



- Heavily dominated QCD-radiated / jets environment
- irreducible backgrounds - MC for searches
- achieve precision (NNLO) for SM measurements
- need higher accuracy precision on phenom. parameters

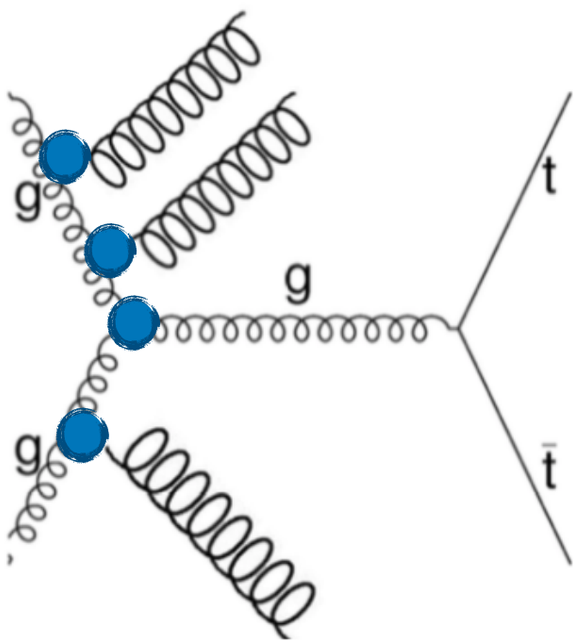
In CMS we use LO and NLO multi-leg generators matched with parton shower

- MadGraph5_aMC@NLO+Pythia8 MLM-merging — LO up to 4 partons — *W+jets, Z+jets…*
  MadGraph5_aMC@NLO+Pythia8 FxFx-merging — NLO up to 2 partons
- Powheg MiNLO +Pythia8 — NNLO up to 2 jets — *top, V+2J…*
- Sherpa, Herwig7… — NLO

Modelling and Tuning

Modelling Monte Carlo Generators at the LHC

strong coupling and parton density functions appear in many physics stages of pp collisions and can be evaluated at different orders in QCD



- PDFs and strong coupling orders ME, PS and MPI
- this poses problems of α_S orders ME/PS/MPI
- Order of strong coupling at FSR/ISR
- rapidity ordering effects

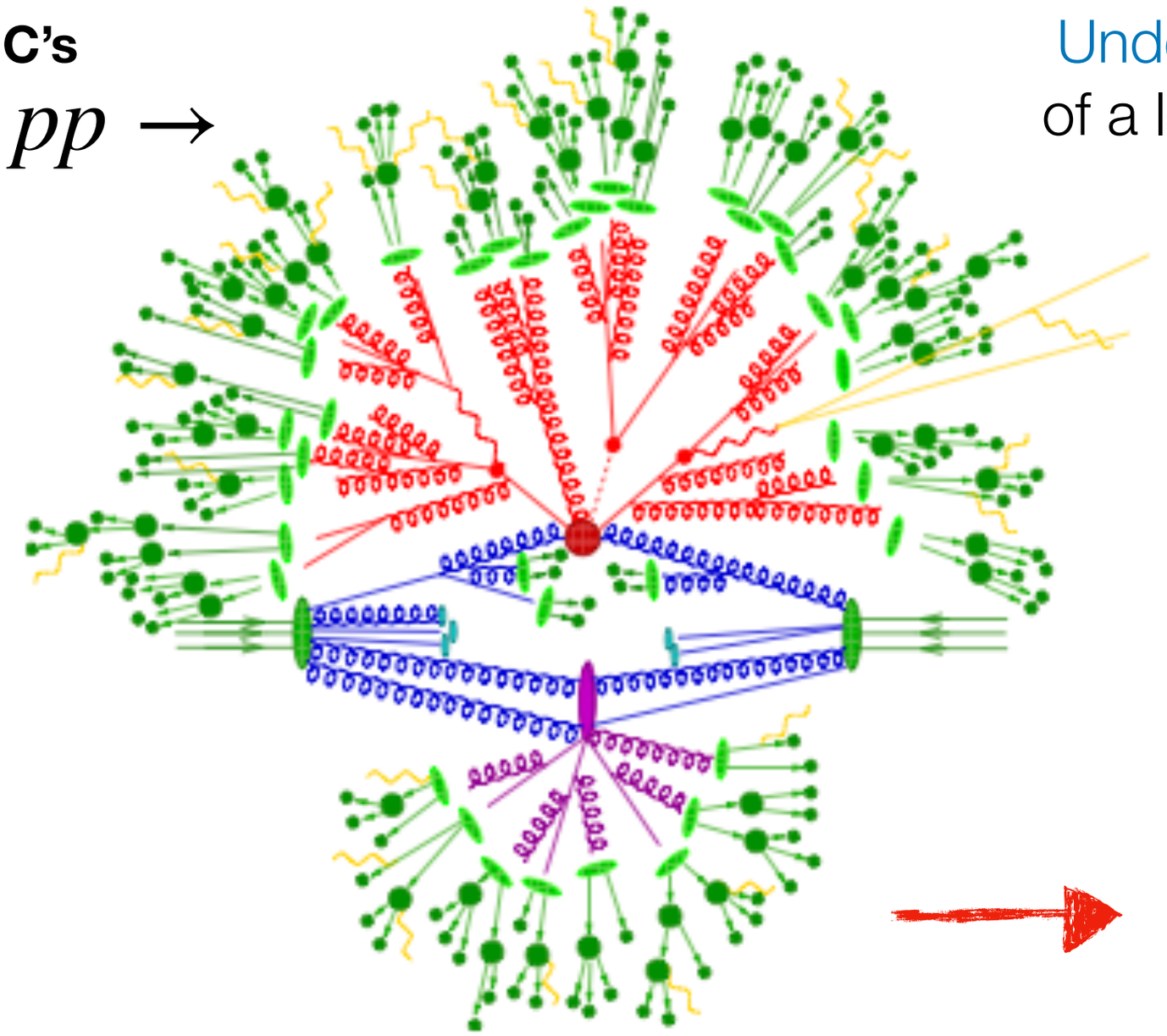
It is important to have tunes at different α_S and PDF orders (they can be very different!) and compare to data to understand their effect

why tuning? ⟶

The good old underlying event sketch

LHC's

$pp \rightarrow$



Underlying Event at the LHC consists of a lot of processes at different scales

hadronization modelling

initial/final state radiation (PS)

multiple parton interactions (UE)

beam remnants (primordial k_T)

Double Parton Scattering

Diffraction

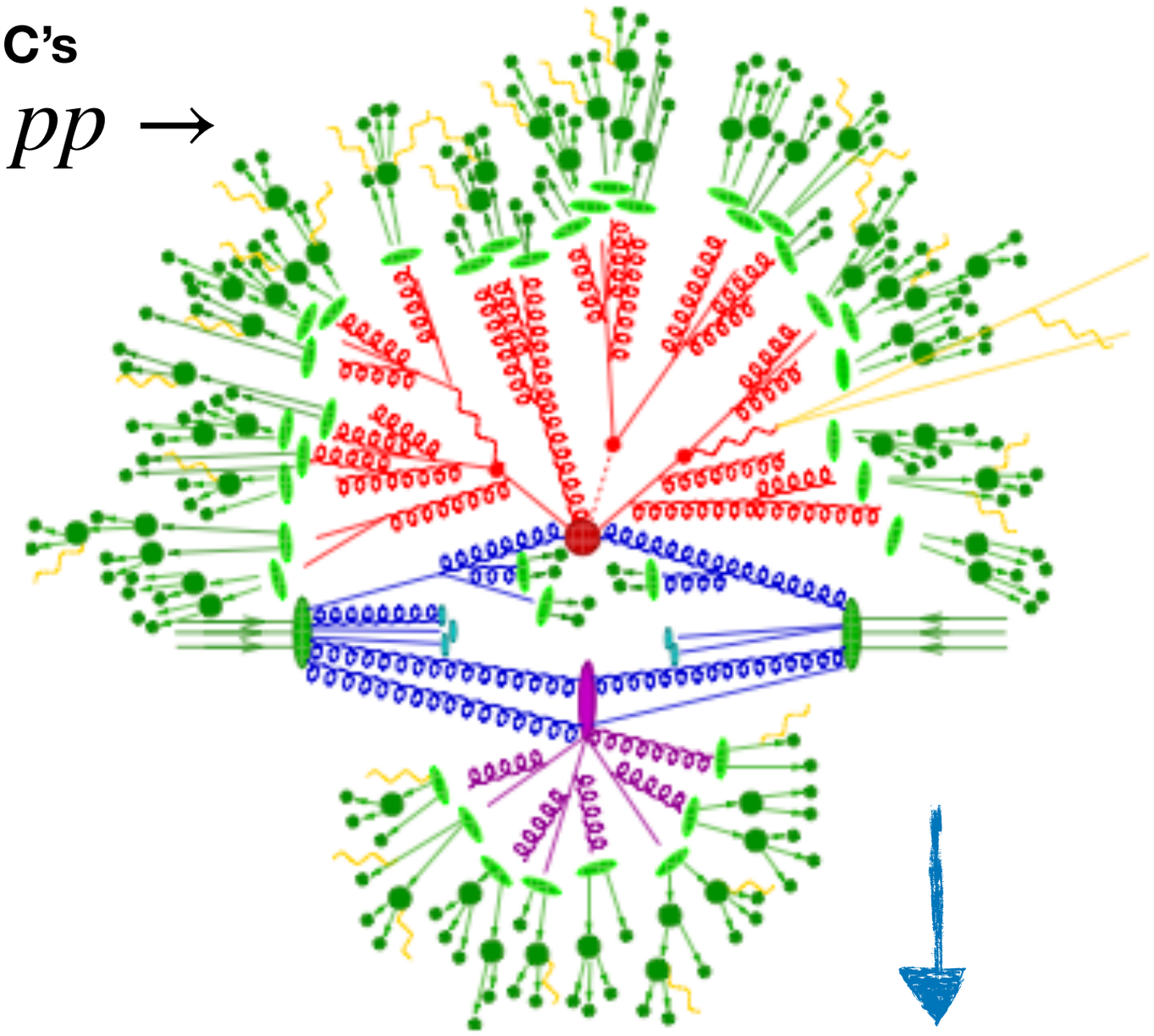
Semi-hard MPI processes

a rich physics relying on phenomenological parameters.
We need data to understand QCD

Several sensitive QCD parameters

LHC's

$pp \rightarrow$



MPI

$$p_T^0 = p_T^{ref} \cdot (E/E_{ref})^{\epsilon}$$

smooth cut to regularize pt->0 divergences

initial/final state radiation (PS)
strong coupling, regularization
upper scale…

hadronization modelling
length of fragmentation string,
strange baryon suppresion…

beam remnants (primordial kT)
width of the gaussian of the primordial
kT in the proton…

we use Professor as main tool to choose parameters ranges, make interpolation and minmization to extract the tunes

Tunes Extraction Procedure: tools

PROFESSOR
for tuning MC generators

https://professor.hepforge.org/
[v.2.5.2]

RIVET
for comparisons

https://rivet.hepforge.org/
[v.1.4.0]

common strategy, experiment
independent, flexible and reliable

"social"drawback: we need RIVET routines from analyses to make comparisons!

Tunes Extraction Procedure

We use CDF data at $\sqrt{s}$=1.96 TeV and CMS data with $\sqrt{s}$=7,13 TeV:

- charged particle and p_{Tsum} densities in *transMIN*, *transMax* vs p_{Tmax}
- charged-particle multiplicity vs η

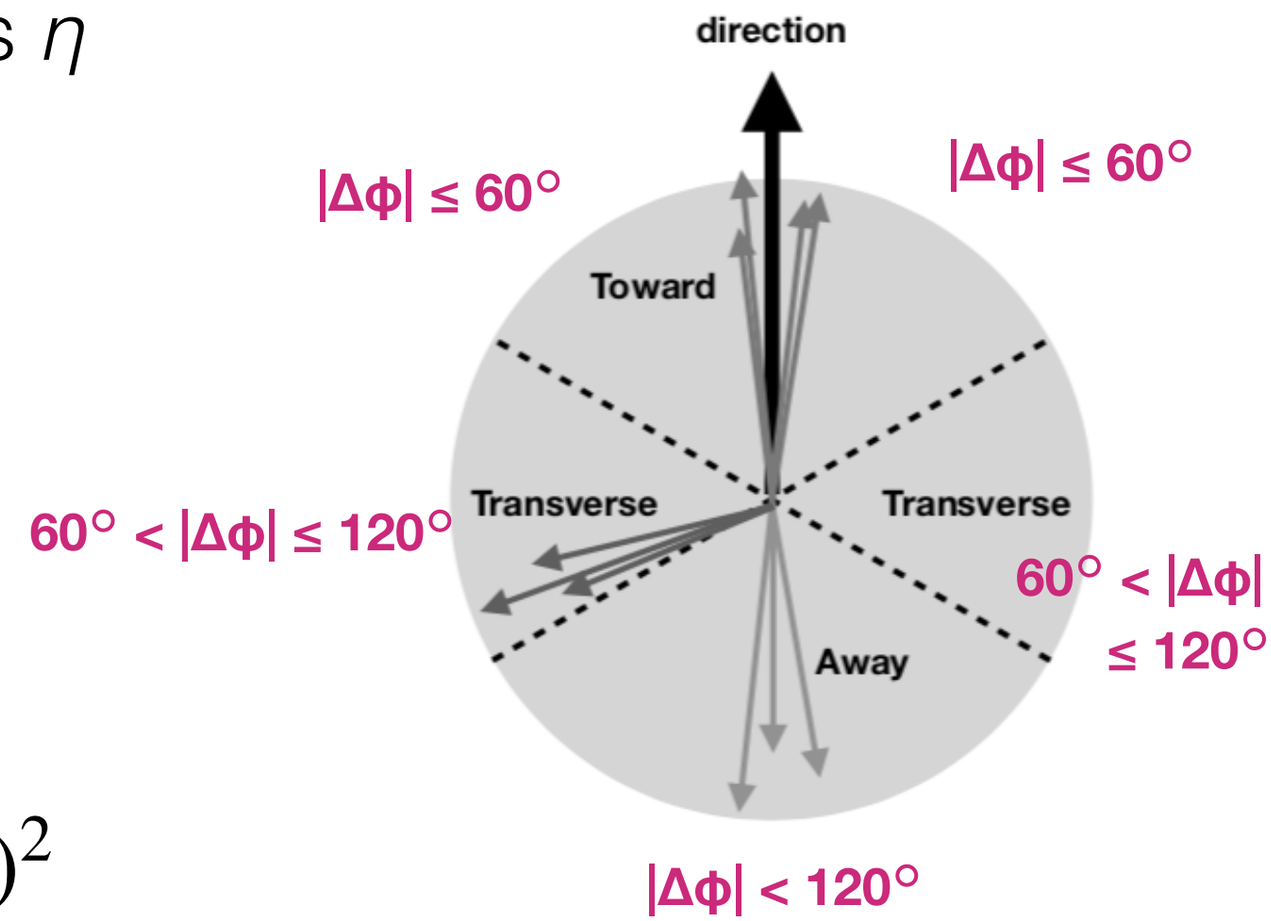
↓

Generate predictions points in a grid parameter space

↓

Tune data by minimizing

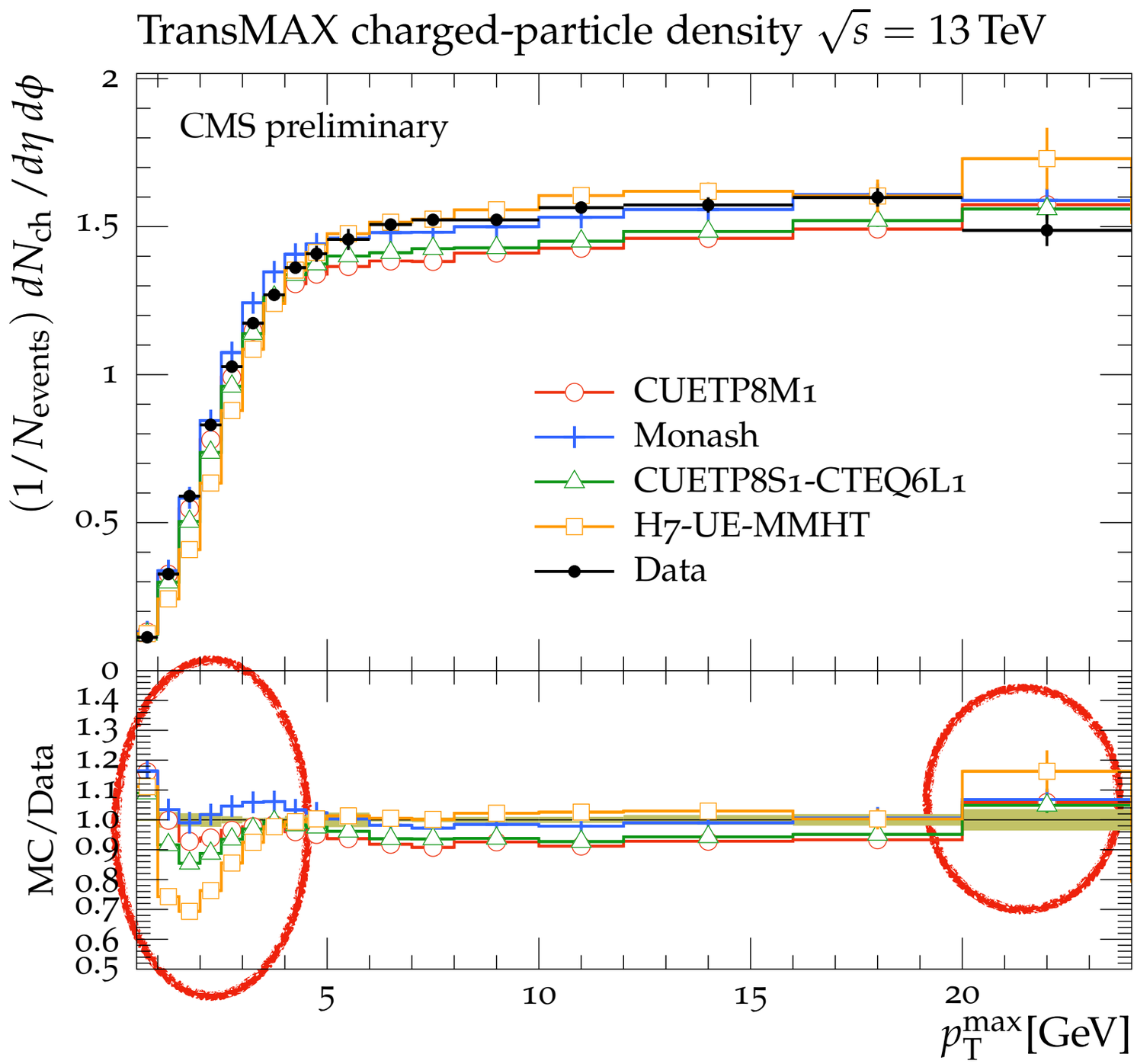
$$\chi^2(p) = \sum w_o \sum \frac{f^b(p) - R(b)^2}{\Delta_b^2}$$



MPI modelling: The overlap between two protons modelled by a double-gaussian

The 7 TeV Tunes Era

tested on 13 TeV data



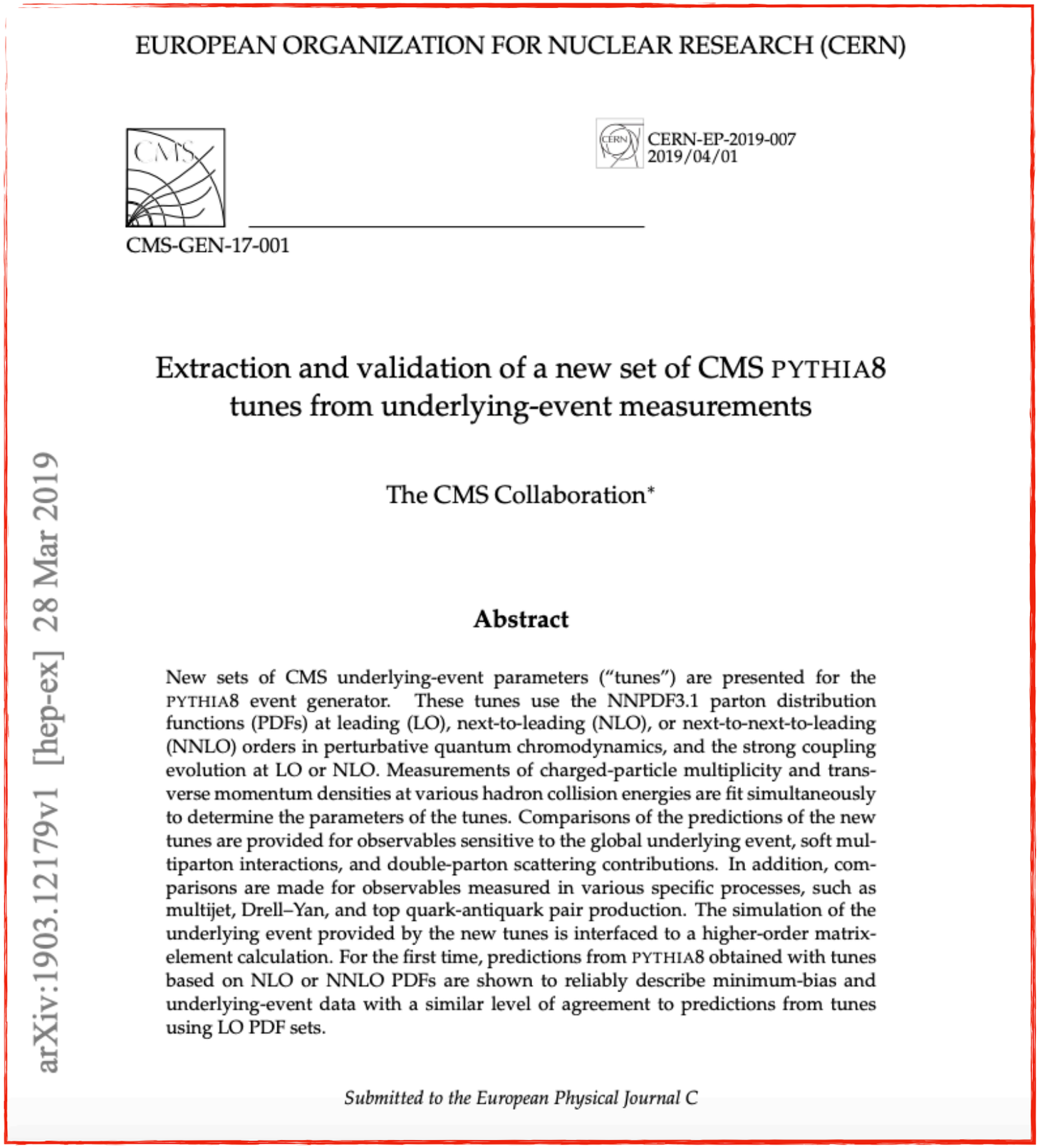
7 TeV CMS tunes were based on Monash tune

CMS official MC production used CUETP8M1 as default tune

none of the tunes describes both low p_T and high p_T particle mulitplicity from UE!

we need to explore deeper the QCD and evaluate the tune dependence on PDF/ α_S at higher orders…

The CMS "Tune Paper"



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-007
2019/04/01

CMS-GEN-17-001

Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements

The CMS Collaboration*

Abstract

New sets of CMS underlying-event parameters ("tunes") are presented for the PYTHIA8 event generator. These tunes use the NNPDF3.1 parton distribution functions (PDFs) at leading (LO), next-to-leading (NLO), or next-to-next-to-leading (NNLO) orders in perturbative quantum chromodynamics, and the strong coupling evolution at LO or NLO. Measurements of charged-particle multiplicity and transverse momentum densities at various hadron collision energies are fit simultaneously to determine the parameters of the tunes. Comparisons of the predictions of the new tunes are provided for observables sensitive to the global underlying event, soft multiparton interactions, and double-parton scattering contributions. In addition, comparisons are made for observables measured in various specific processes, such as multijet, Drell–Yan, and top quark-antiquark pair production. The simulation of the underlying event provided by the new tunes is interfaced to a higher-order matrix-element calculation. For the first time, predictions from PYTHIA8 obtained with tunes based on NLO or NNLO PDFs are shown to reliably describe minimum-bias and underlying-event data with a similar level of agreement to predictions from tunes using LO PDF sets.

Submitted to the European Physical Journal C

arXiv:1903.12179v1 [hep-ex] 28 Mar 2019

https://arxiv.org/pdf/1903.12179.pdf

- ★ a huge and complex collective effort!
- ★ under EPJC review
- ★ first attempt to deliver a P8 tune "tested" over several physics processes
- ★ Output of the work is a new set of 5 tunes

one tune will be chosen for the official CMS MC production based on performances

The CMS Pythia8 Tunes Family

PYTHIA 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
α_S^{ISR} value/order	0.1365/LO	0.130/LO
α_S^{FSR} value/order	0.1365/LO	0.130/LO
α_S^{MPI} value/order	0.130/LO	0.130/LO
α_S^{ME} value/order	0.130/LO	0.130/LO
MULTIPARTONINTERACTIONS:PT0REF [GeV]	2.4	2.3
MULTIPARTONINTERACTIONS:ECMPOW	0.1543	0.1391
MULTIPARTONINTERACTIONS:COREFRADIUS	0.5436	0.3755
MULTIPARTONINTERACTIONS:COREFRACTION	0.6836	0.3269
COLORRECONNECTION:RANGE	2.633	2.323
χ^2/dof	0.89	0.538

fixed inputs

outcome of the fit

The Leading Order Tunes CP1 and CP2

CP Tunes = CMS Pythia Tunes

The CMS Pythia8 Tunes Family

PYTHIA 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
α_S^{ISR} value/order	0.118/NLO	0.118/NLO	0.118/NLO
α_S^{FSR} value/order	0.118/NLO	0.118/NLO	0.118/NLO
α_S^{MPI} value/order	0.118/NLO	0.118/NLO	0.118/NLO
α_S^{ME} value/order	0.118/NLO	0.118/NLO	0.118/NLO
MultipartonInteractions:pT0Ref [GeV]	1.516	1.483	1.41
MultipartonInteractions:ecmPow	0.02266	0.02012	0.03344
MultipartonInteractions:coreRadius	0.5396	0.5971	0.7634
MultipartonInteractions:coreFraction	0.3869	0.3053	0.63
ColorReconnection:range	4.727	5.613	5.176
χ^2/dof	0.759	0.803	1.04

The Next-to-Leading Order Tunes CP3, CP4, CP5

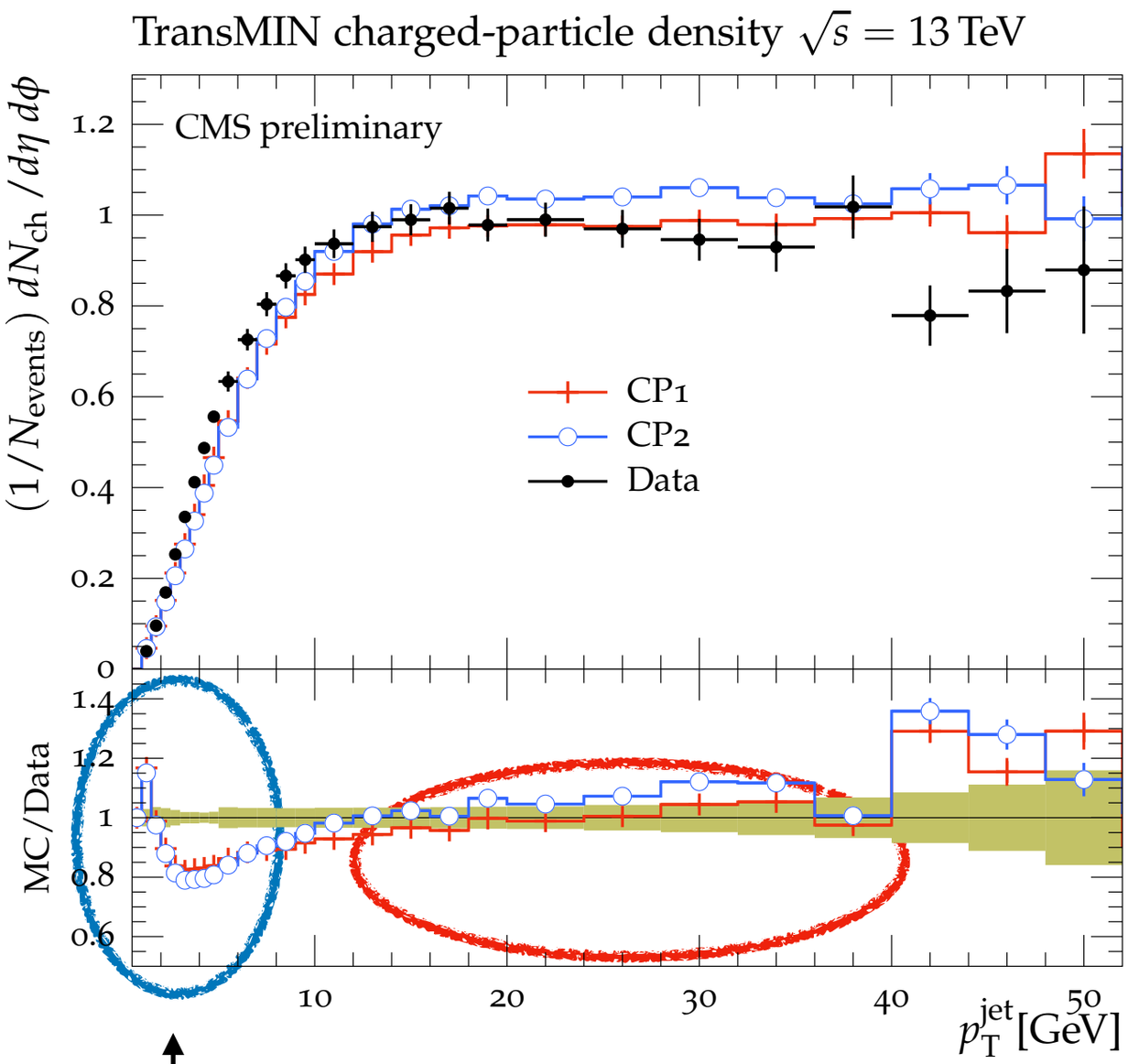
CP Tunes = CMS Pythia Tunes

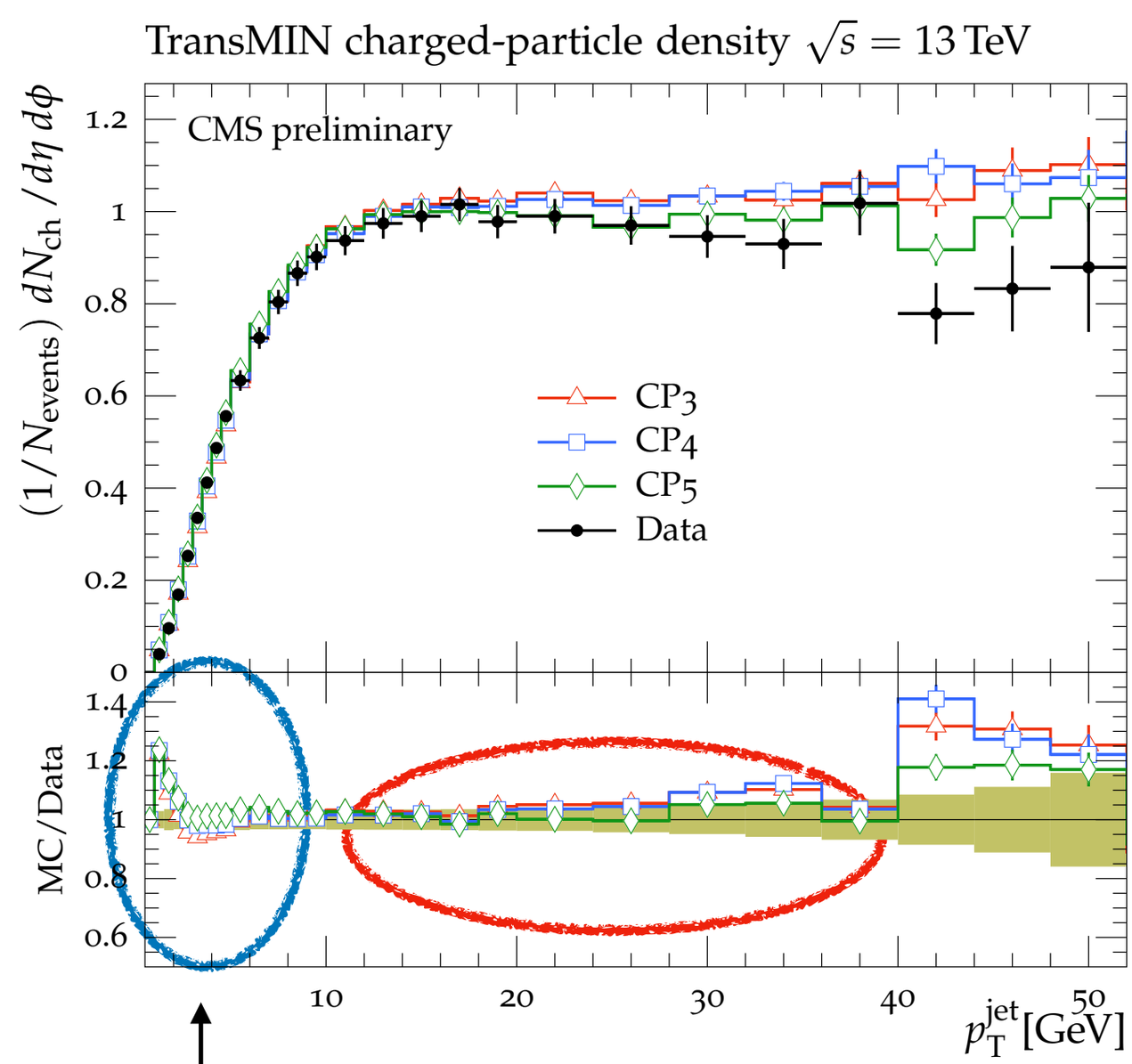
Test of the CP tunes

Underlying Events

all results taken from arXiv:1903.12179

leading charged particle jet in the TransMIN region

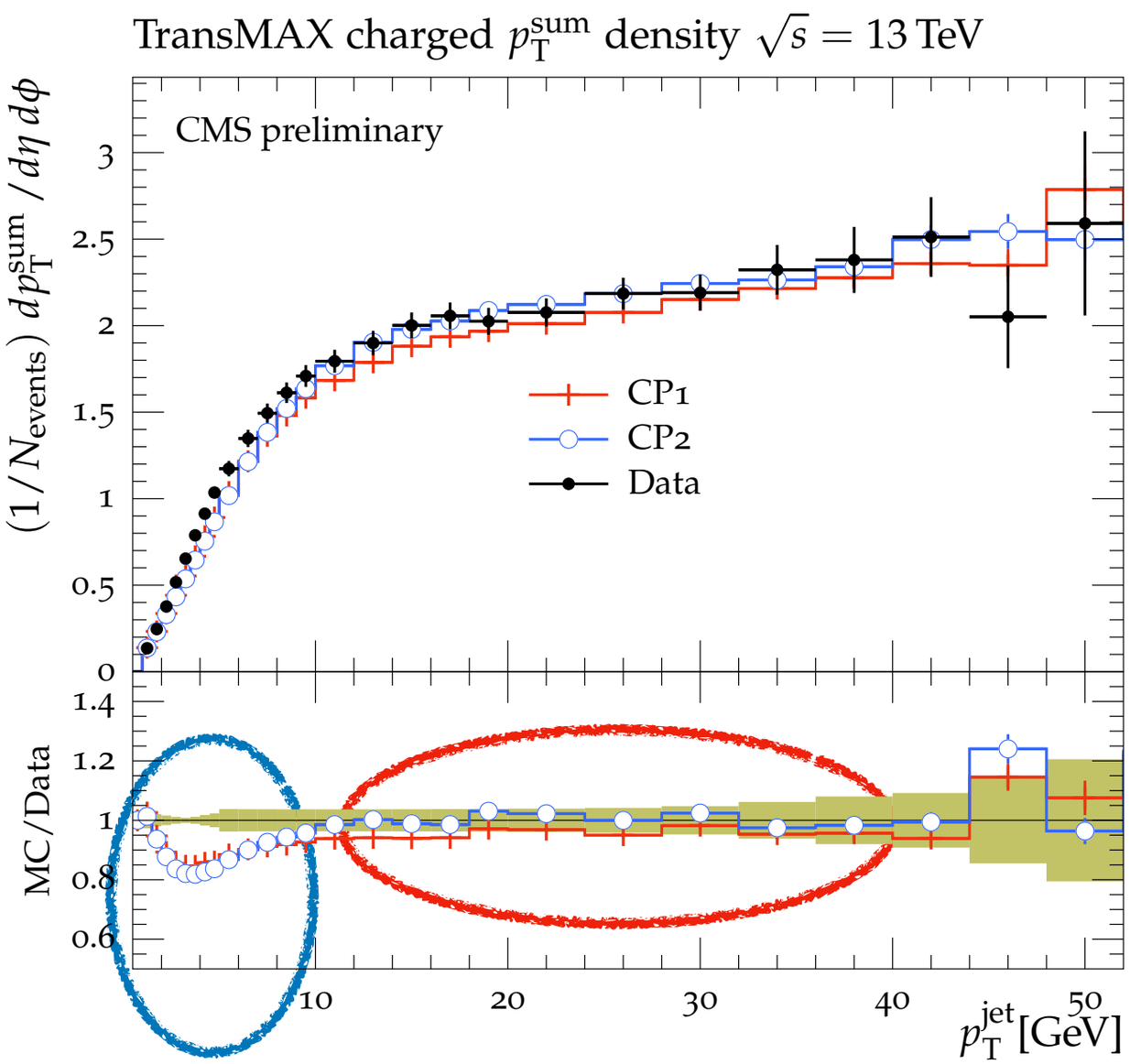


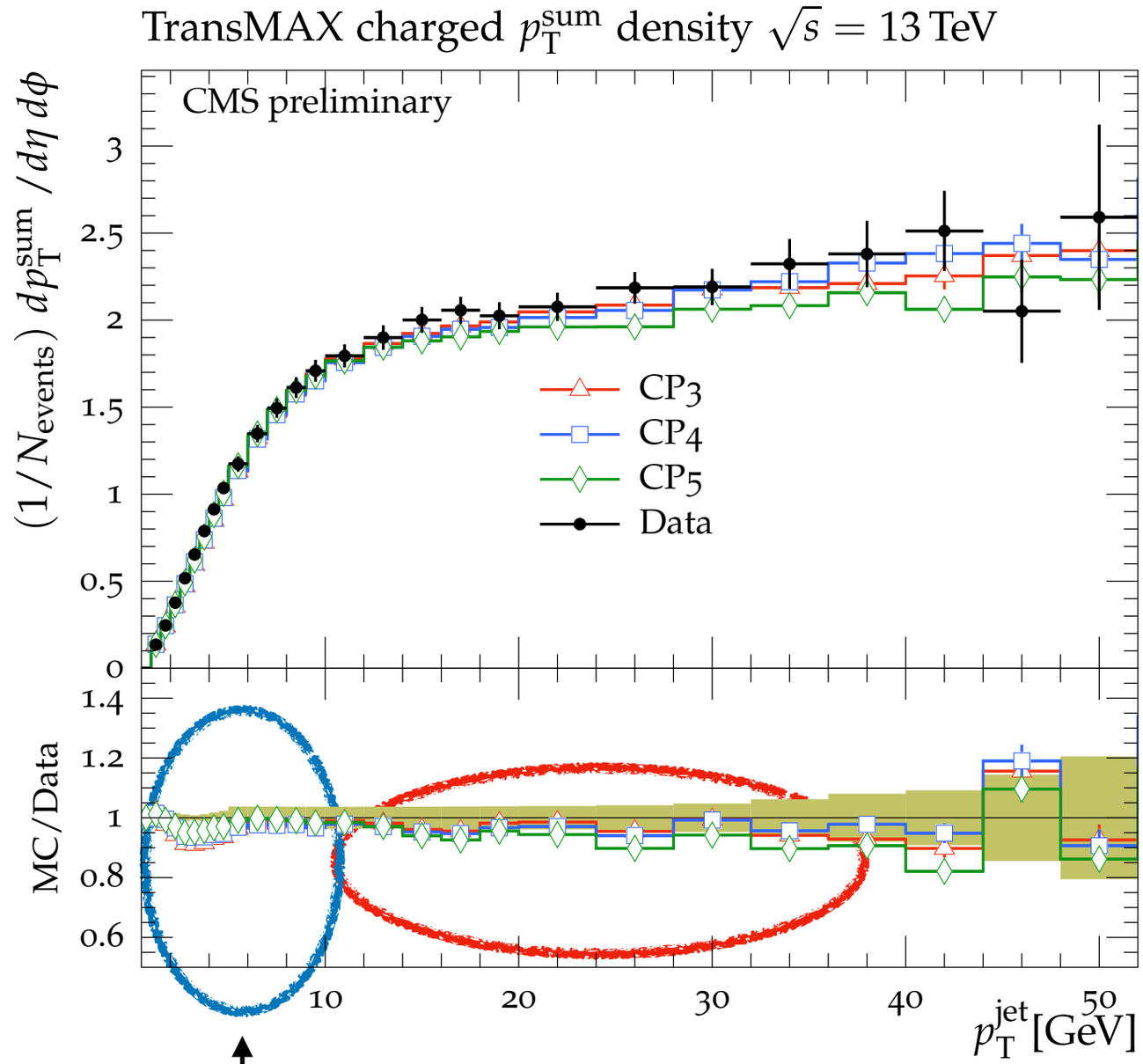


soft region: higher order PDF tunes (CP3, CP4, CP5) better agreement

soft region: up to 15% disagreement with LO tunes agreement ~ok after 10 GeV

leading charged particle jet in the TransMAX region





soft region: higher order PDF tunes (CP3, CP4, CP5) better agreement

soft region: up to 15% disagreement with LO tunes

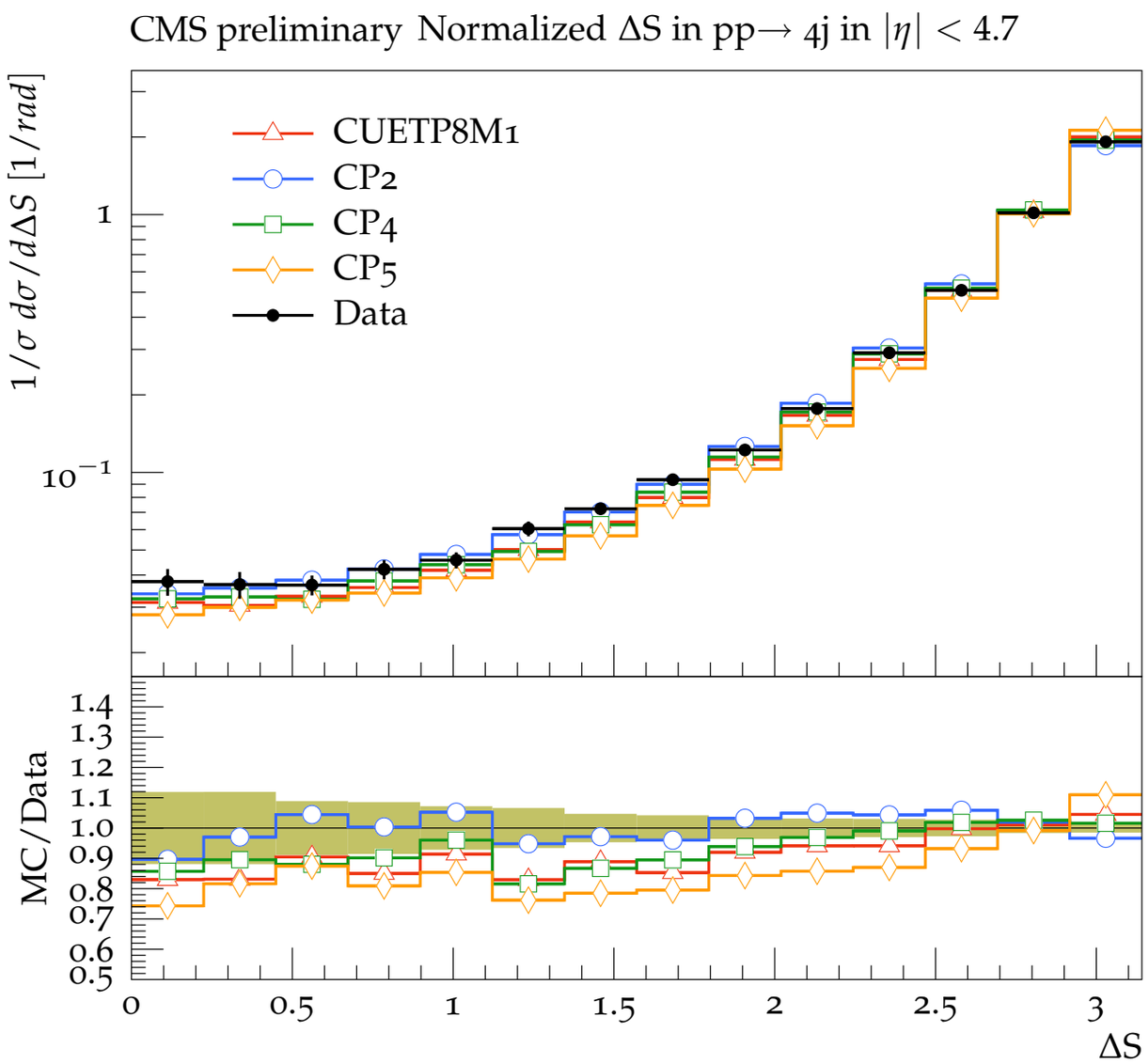
agreement ~ok after 10 GeV

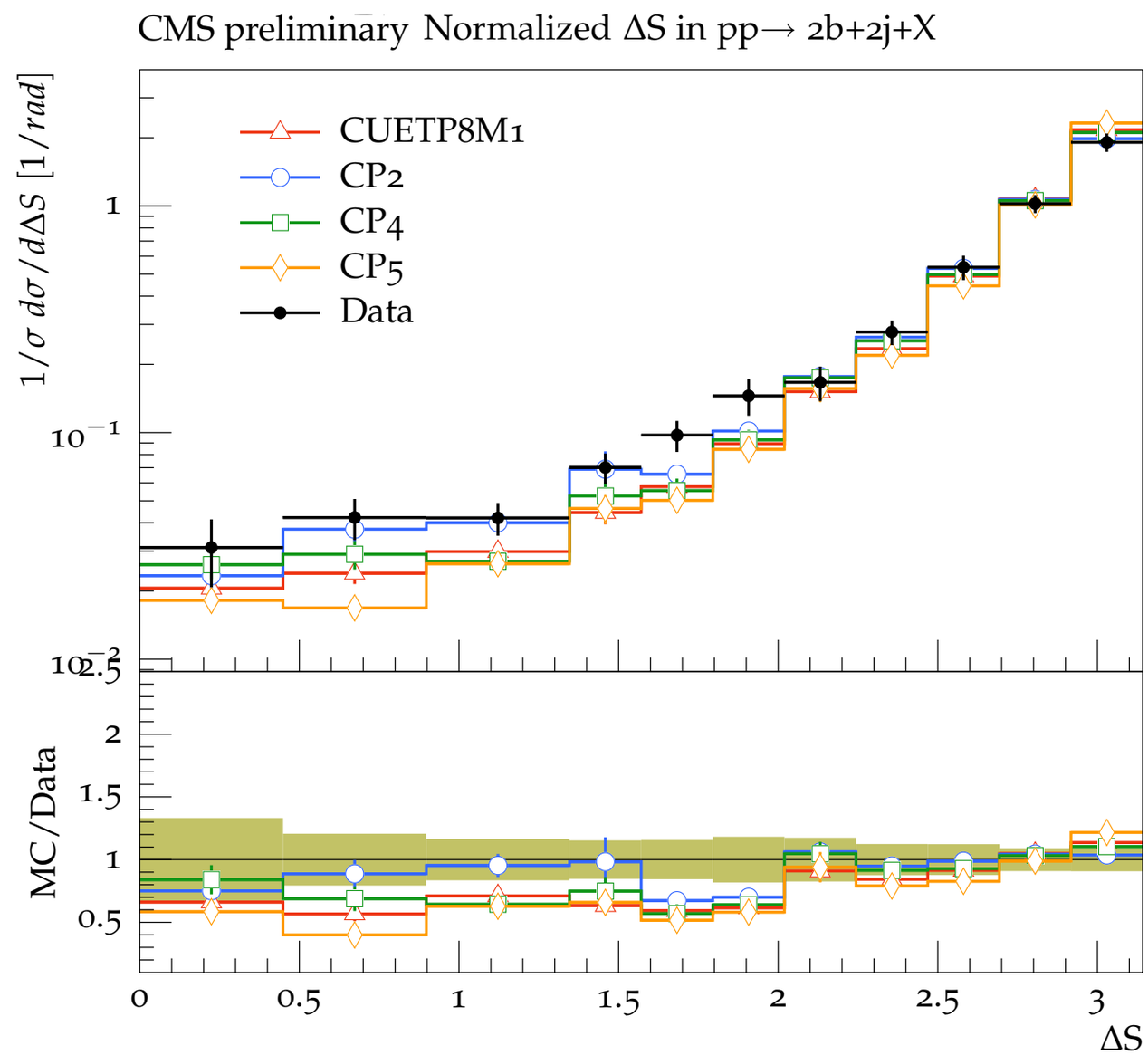
Test of the CP tunes

Double Parton Scattering

all results taken from arXiv:1903.12179

$$\Delta S = \arccos \frac{\overrightarrow{p_{T,1}} \cdot \overrightarrow{p_{T,2}}}{|\overrightarrow{p_{T,1}}| \cdot |\overrightarrow{p_{T,2}}|}$$





- DPS observable tested over inclusive 4j and 2b+2j final states
- LO tunes better : different pT0ref value to simulate MPI
- DPS is very sensitive to rapidity ordering: need a specific tune

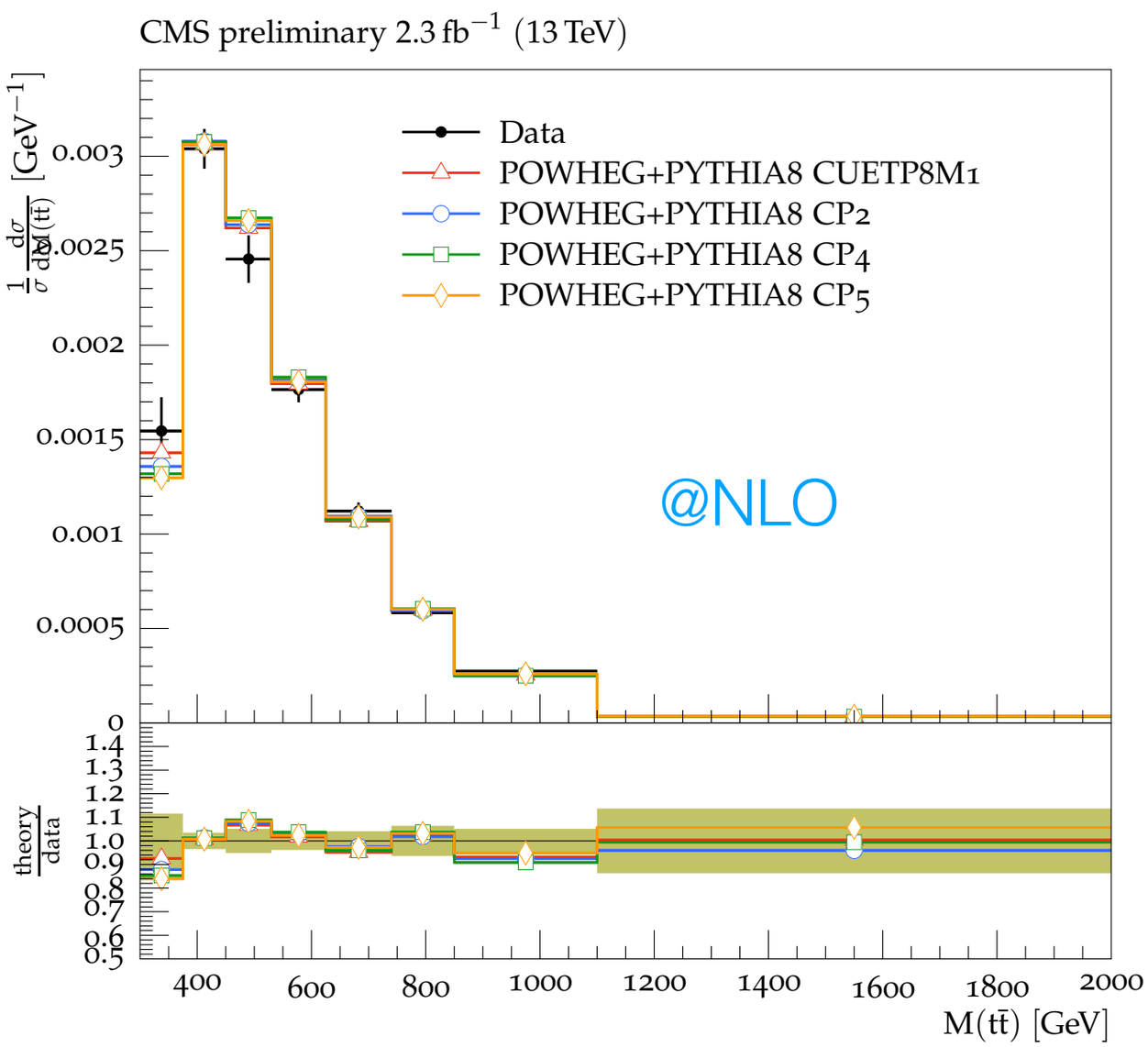
Test of the CP tunes

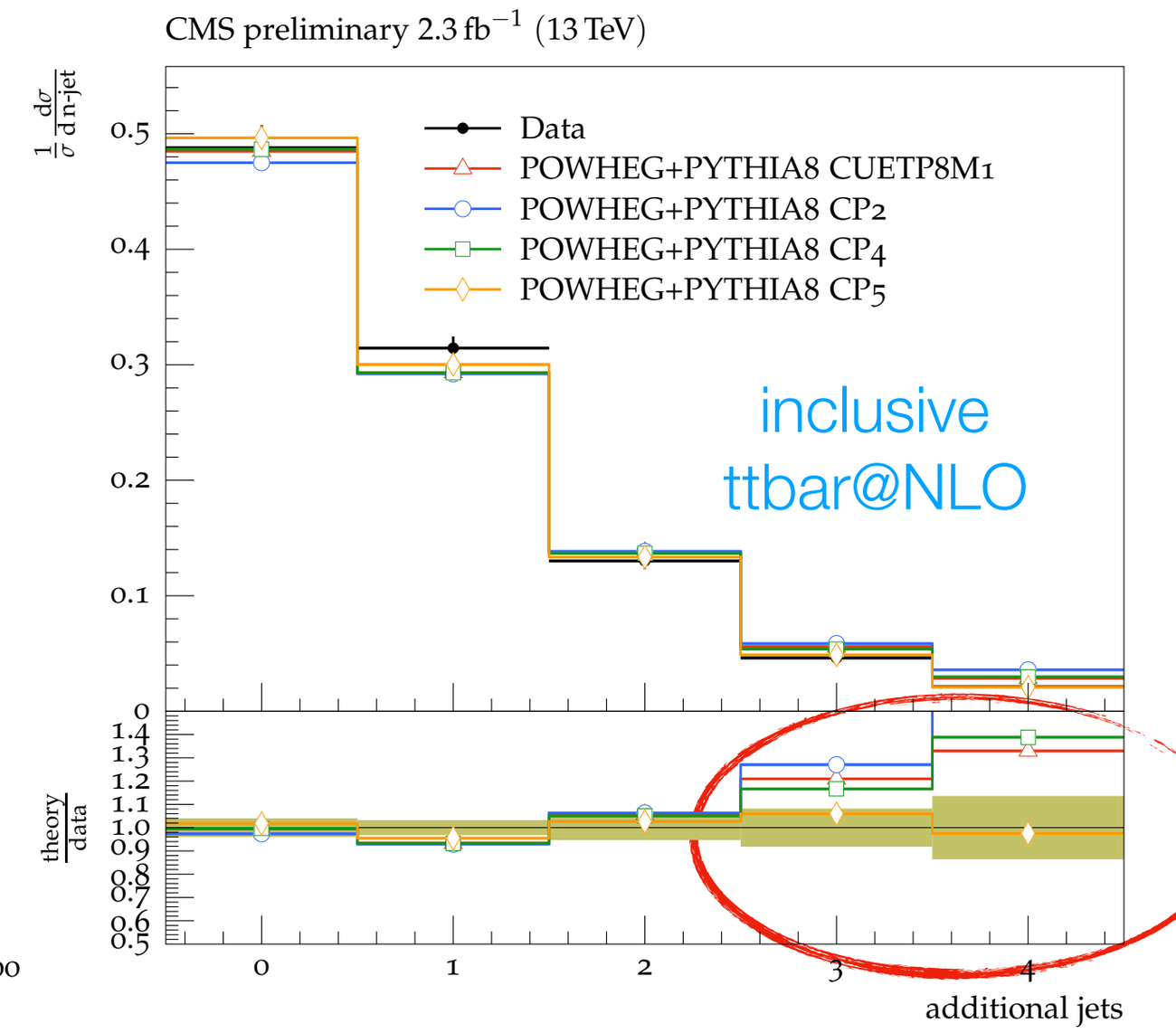
Top quark

all results taken from arXiv:1903.12179

Normalized ttbar cross section in bins of top quark mass and jet multiplicity

matrix element generation made by madgraph_aMC@NLO[FxFx] and Powheg





CP5 does the best job describing top data (effect of rapidityOrder ON)

CP4 overestimates higher multiplicities (effect of rapidityOrder OFF)

(all tunes describe higher multiplicities using MG5)

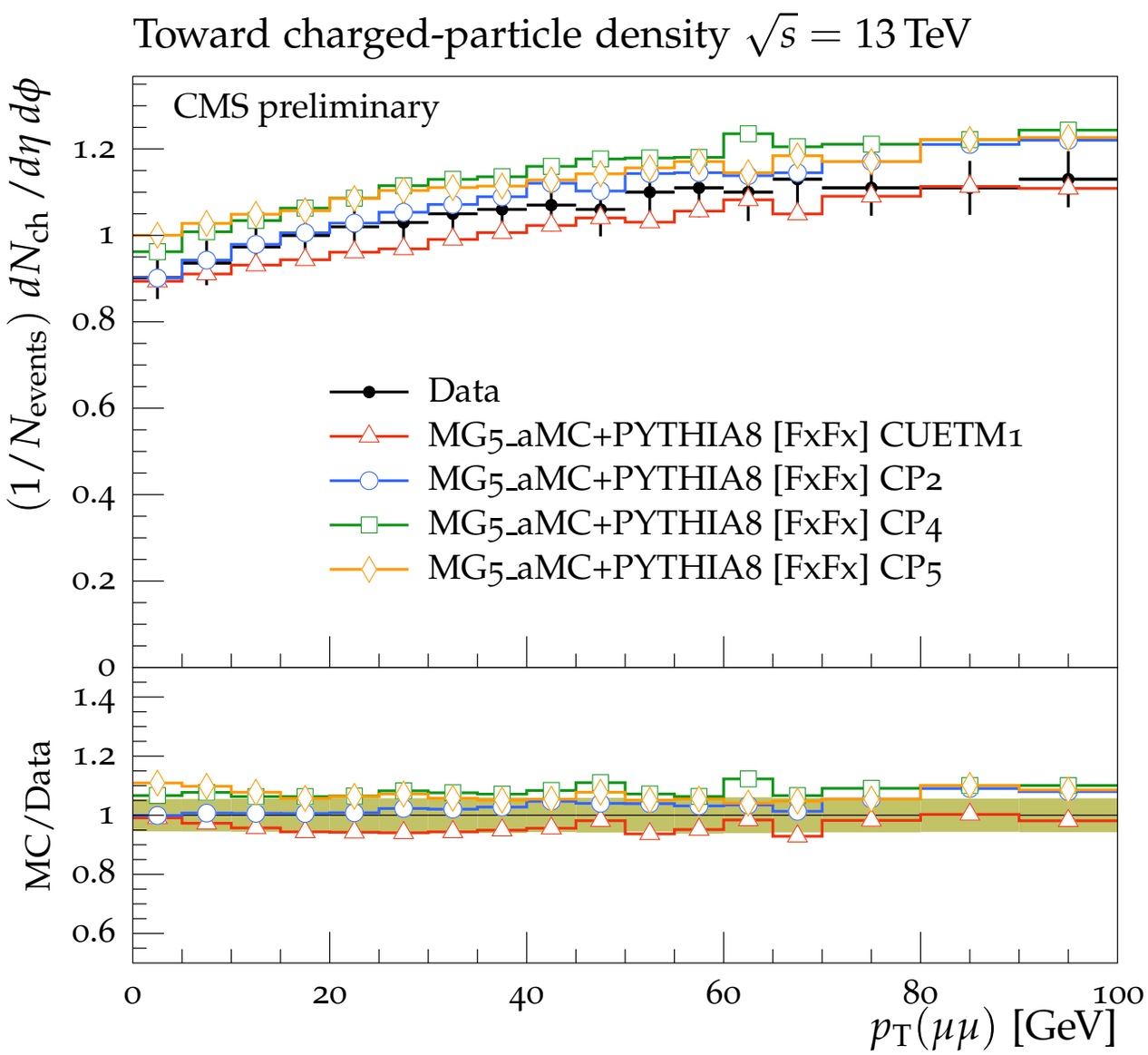
Test of the CP tunes

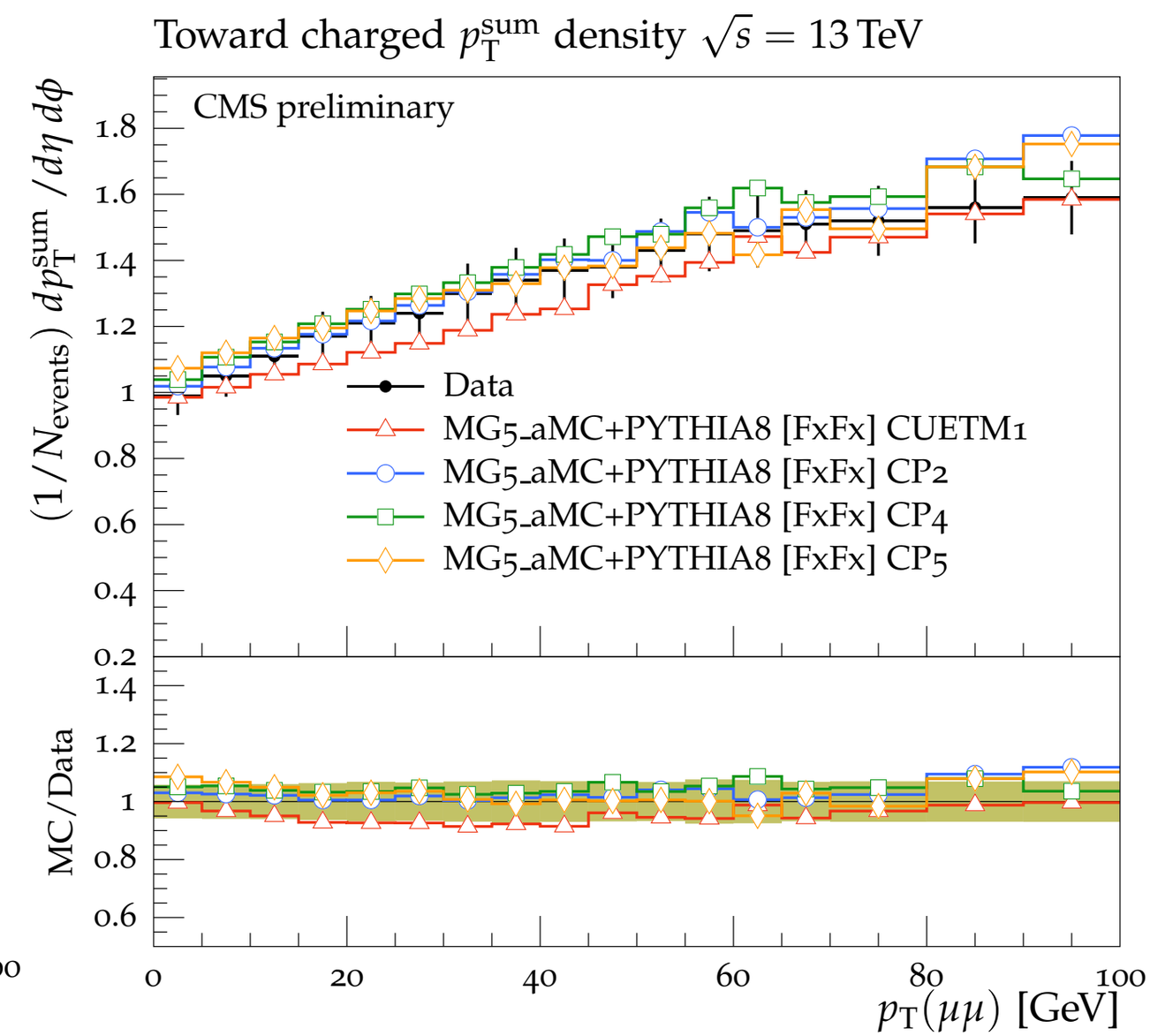
Jets & EW bosons

all results taken from arXiv:1903.12179

CP tunes in high p_T jets & EW bosons final states

UE in Z+jets matrix element generation made by madgraph_aMC@NLO [FxFx]





pT(μ)>20/10 GeV
|Mμμ-91| < 20 GeV
eta < 2

old-Monash based tune CUETPM1 not able to describe the Z

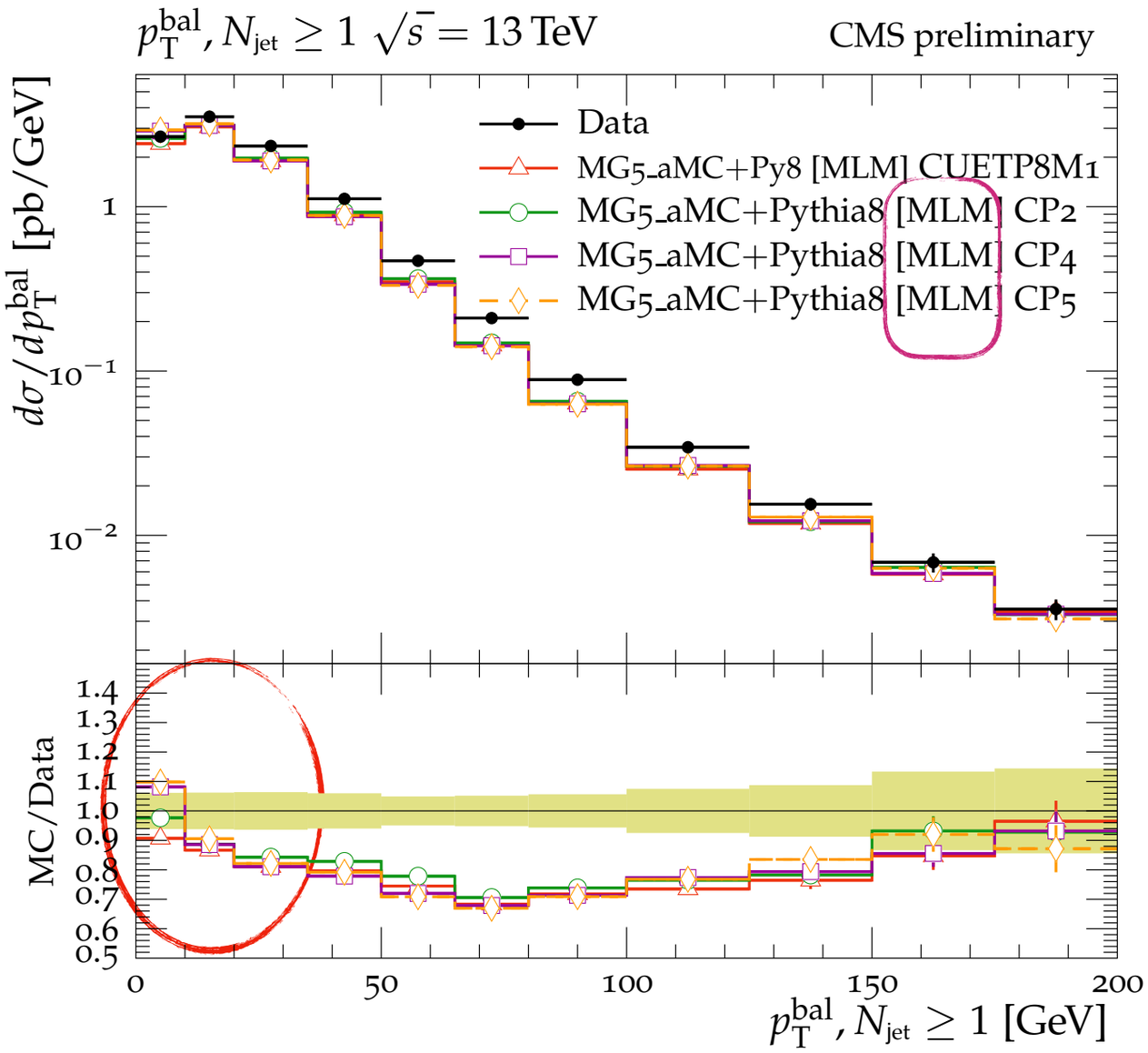
CP5 gives the average best description in all regions

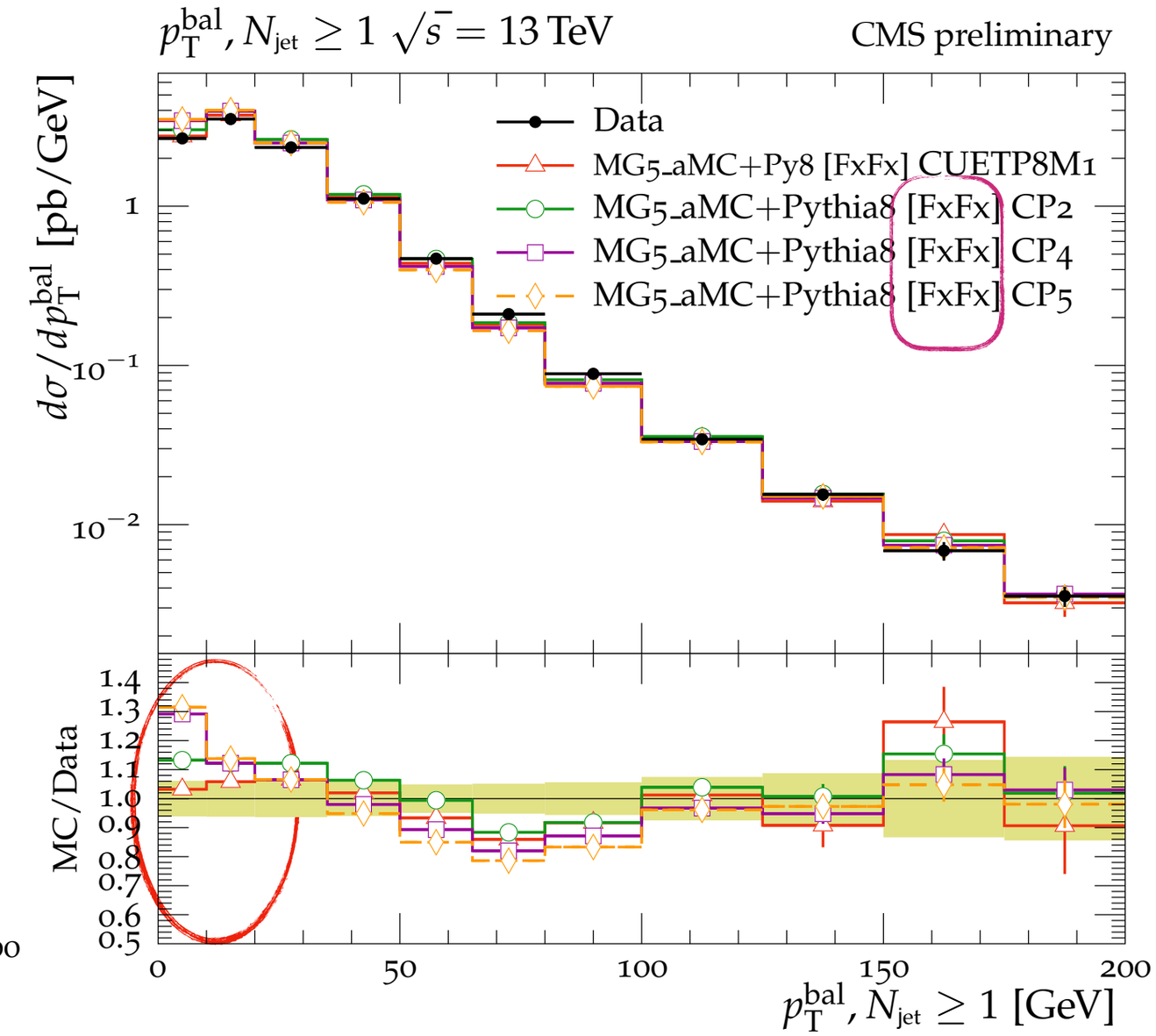
all tunes describe data

CP tunes in high p_T jets & EW bosons final states

hard QCD: Z+jets events with jet pt>30 GeV

matrix element generation made by madgraph_aMC@NLO[FxFx and MLM]



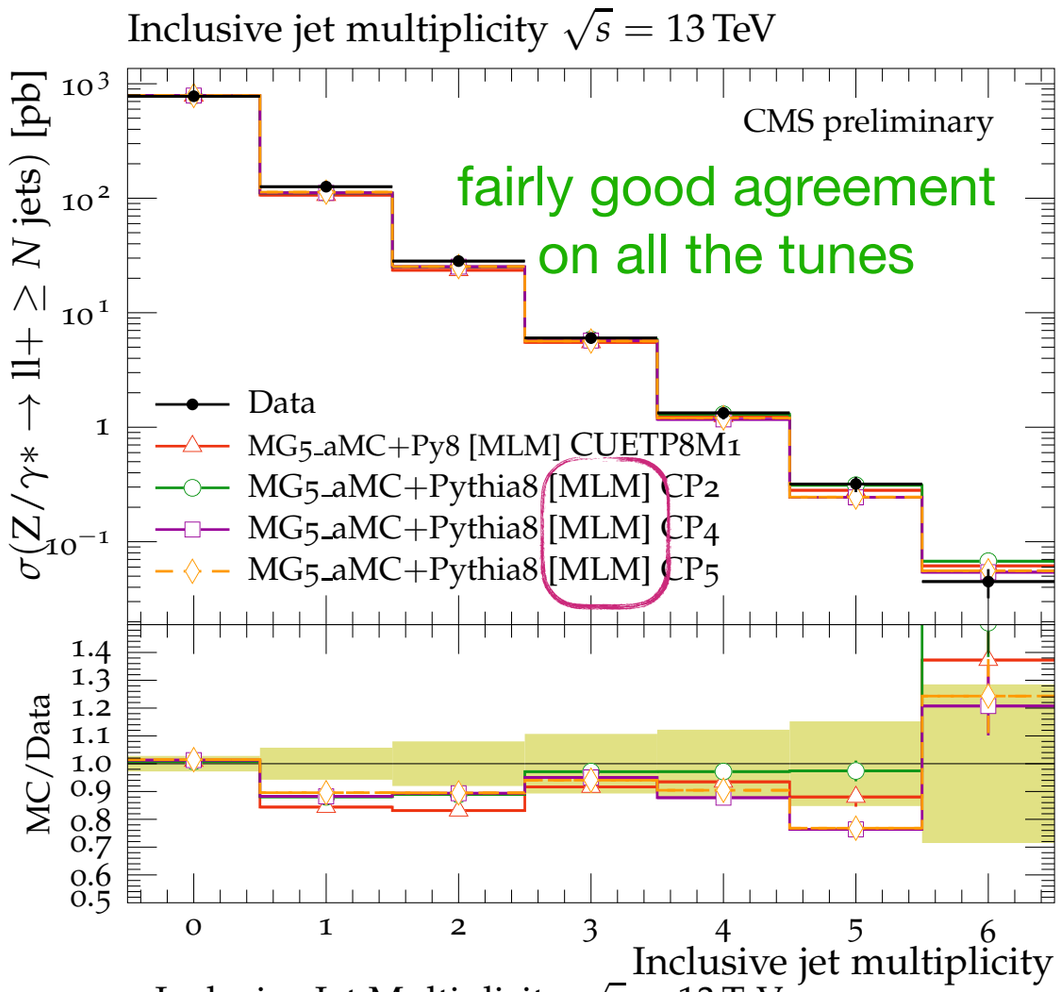


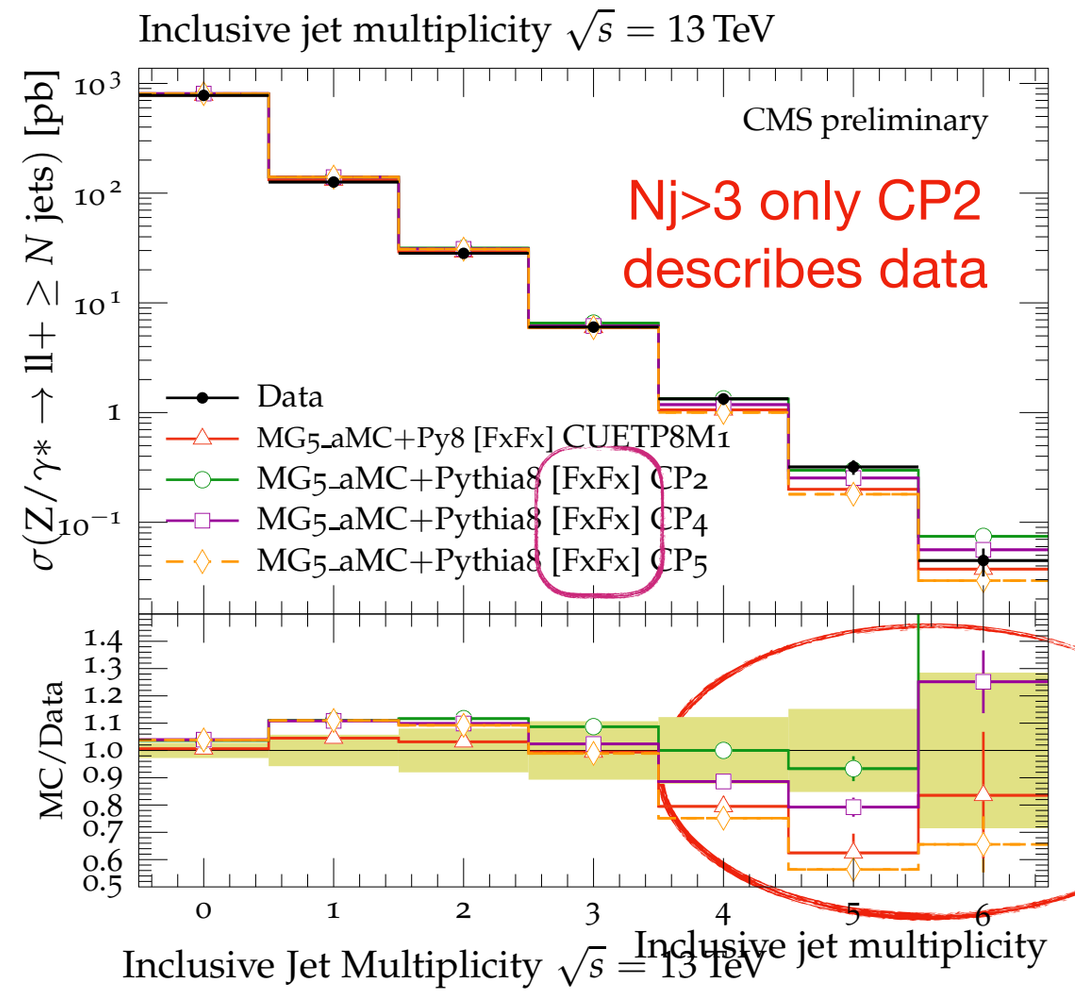
Z-J balance: hadronic activity not clustered in jets generate imbalance

(!) Only below 20 GeV we see differences among tunes

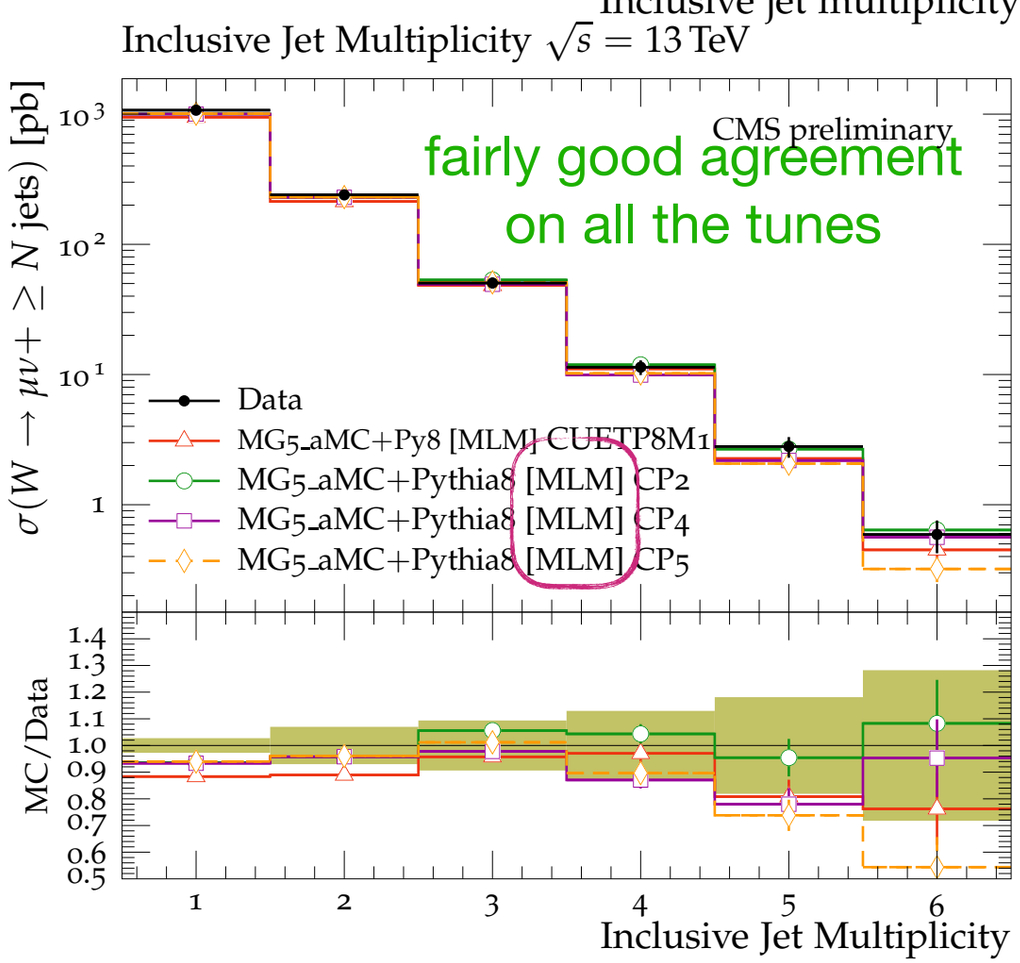
$$p_T^{bal} = |p_T(Z) + \sum_{jets} p_T^j|$$

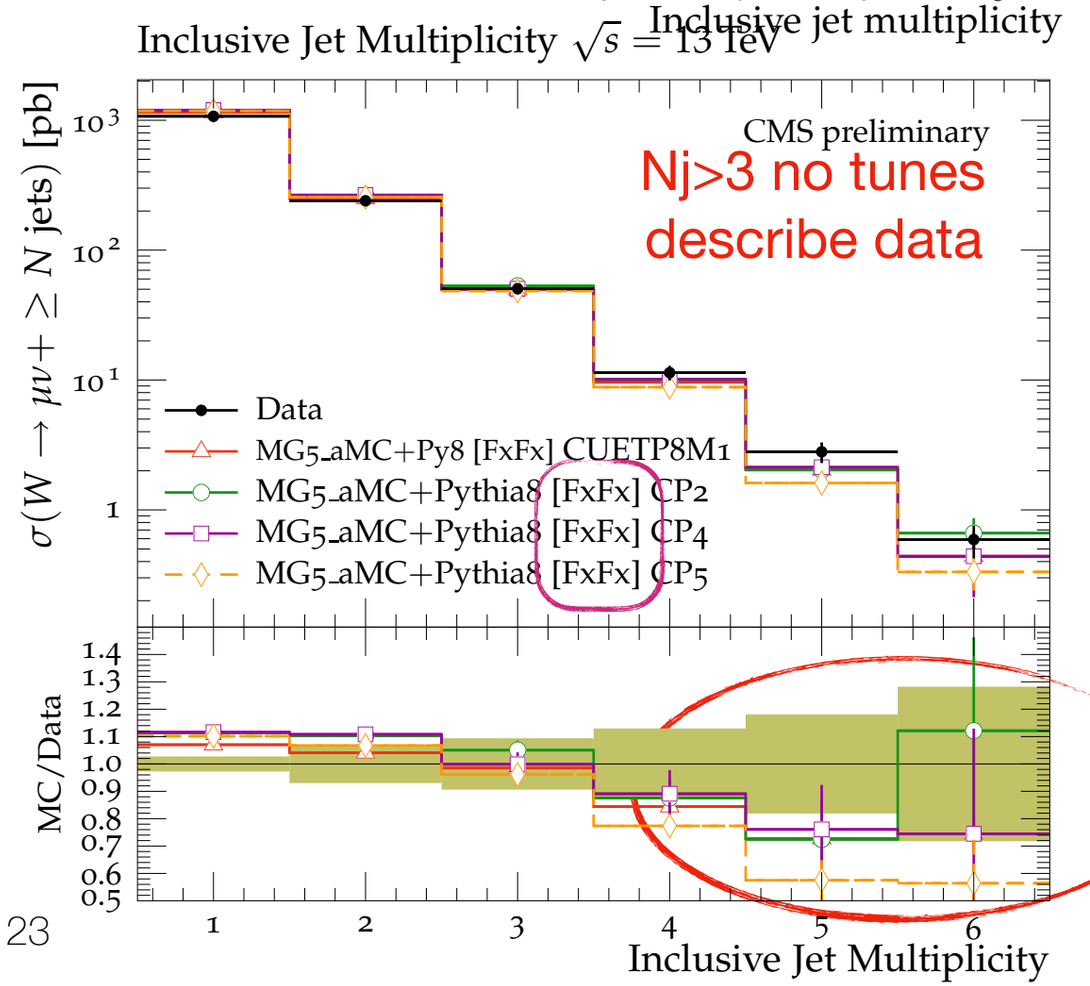
Inclusive Multiplicity in Z+jets





Inclusive Multiplicity in W+jets





Conclusions & Perspectives

- The extraction of the 5 CMS Pythia8 Tunes has been described
- The performances of the tunes have been tested over several physics processes: top, V+Jets, UE, DPS
- Strong coupling, PDF ordering in QCD play a role as well as the rapidity ordering in many cases
- The wide physics under test showed interesting inputs on the dependence of the tunes on QCD showering
- CMS is very active in this field! we are working on specific tunes: Herwig7, DPS, ColorReconnection and more…


CMS Experiment at the LHC, CERN
Data recorded: 2011-Sep-12 14:31:09.077784 GMT(16:31:09 CEST)
Run / Event: 176169 / 163929870
STAY TUNED!
CP
Chro.
DONNER
DT-2

backups

CP tunes in high p_T jets & EW bosons final states

for each CPn tune

Benchmark matrix elements used in V+jets in CMS

PDF: NNPDF3.1 @NNLO

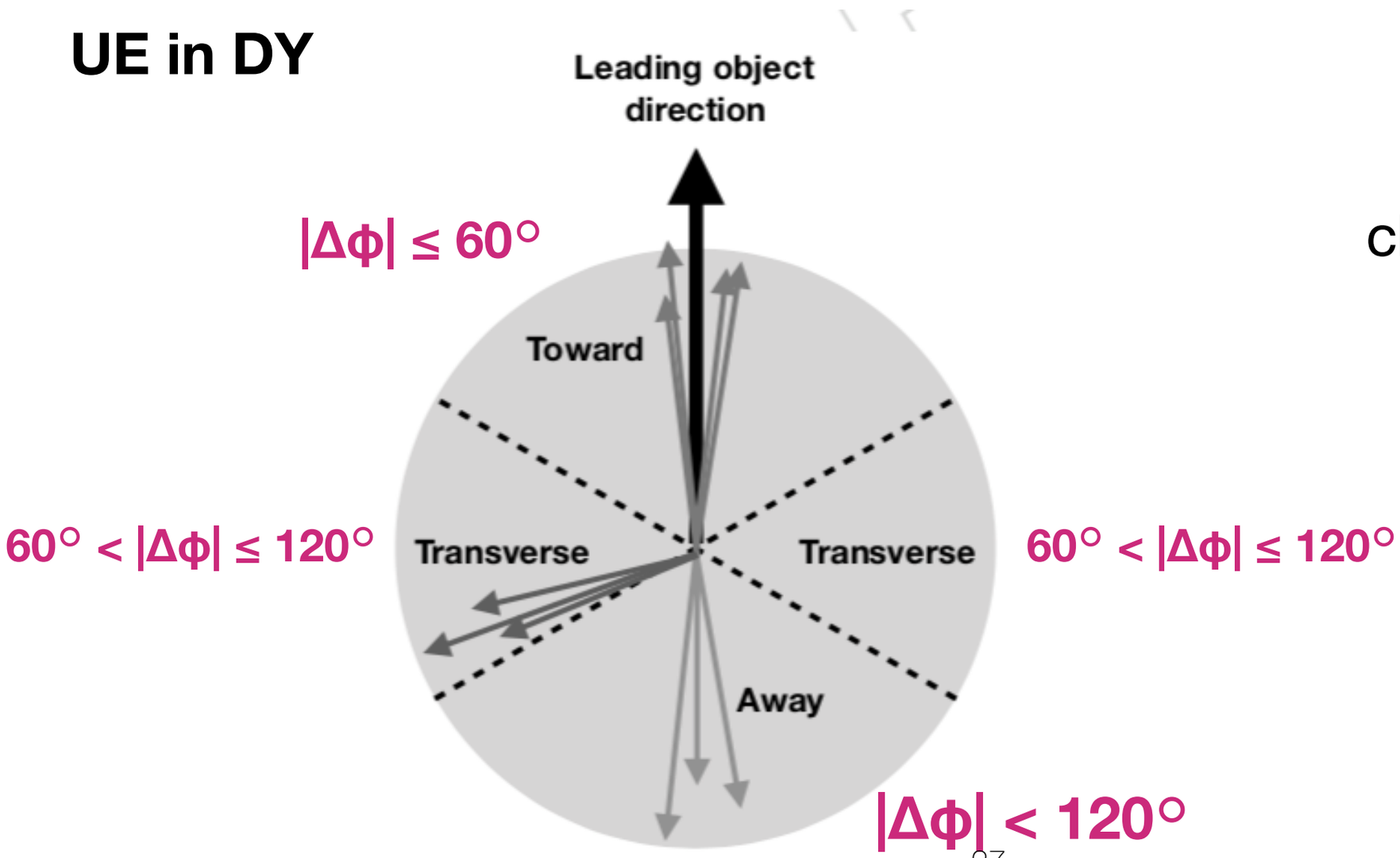
MadGraph5_aMC@NLO + Pythia8

$\alpha_S = 0.118$

LO-Mode kT–MLM merging scheme
0,1,2,3 partons

NLO-Mode FxFx merging scheme
up to 2 partons NLO

UE in DY



observables

charged particle density

charged pT sum

as a function of

Z boson properties

A brief CMS Tunes Chronology

In CMS we developed a set of tunes based on UE in Pythia8.

The (six) tunes differ by PDF order, α_S evolution and are extracted by fitting simultaneously charged-particle multiplicity and trans- verse momentum densities at various hadron collision energies

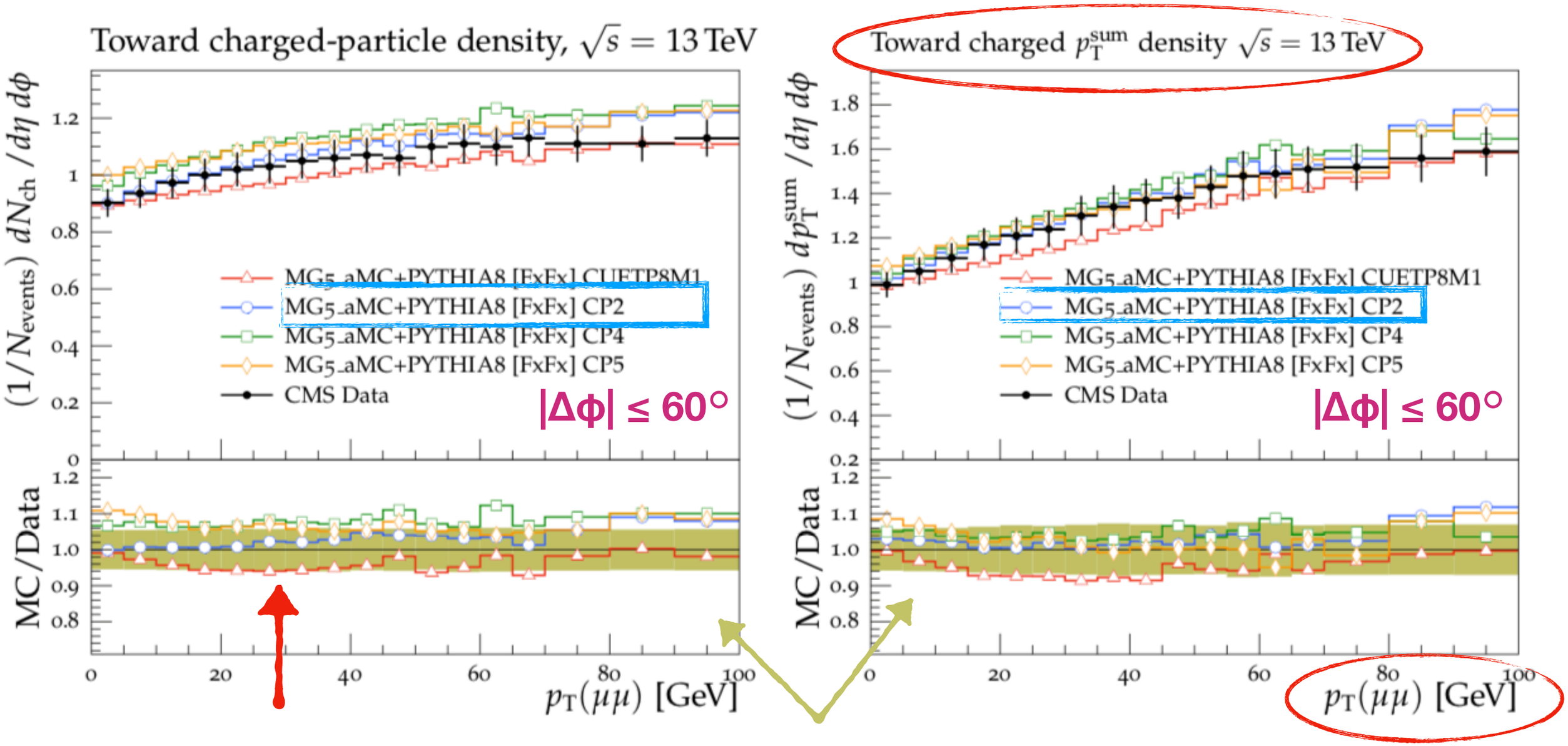
The idea was to obtain a tune for the official MC production that was tested over a variety of different final states, from soft to hard physics

One of the six tunes was selected as the main “official” one for CMS Run2 MC production

A huge paper containing the validation of the tune, methodology and cross checks was prepared (arxiv:903.12179 under EPJC review)

CP tunes in high p_T jets & EW bosons final states

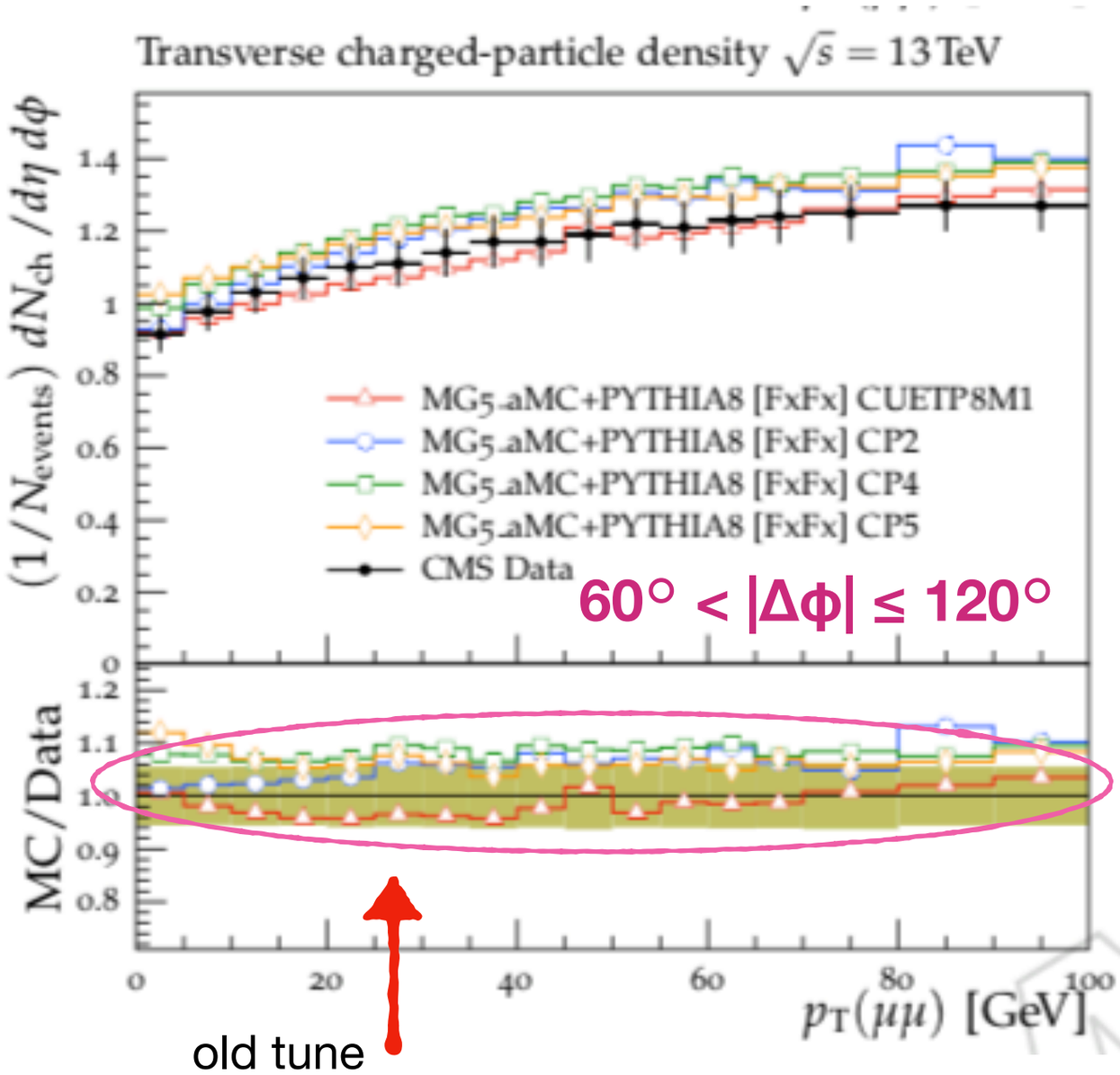
Towards region

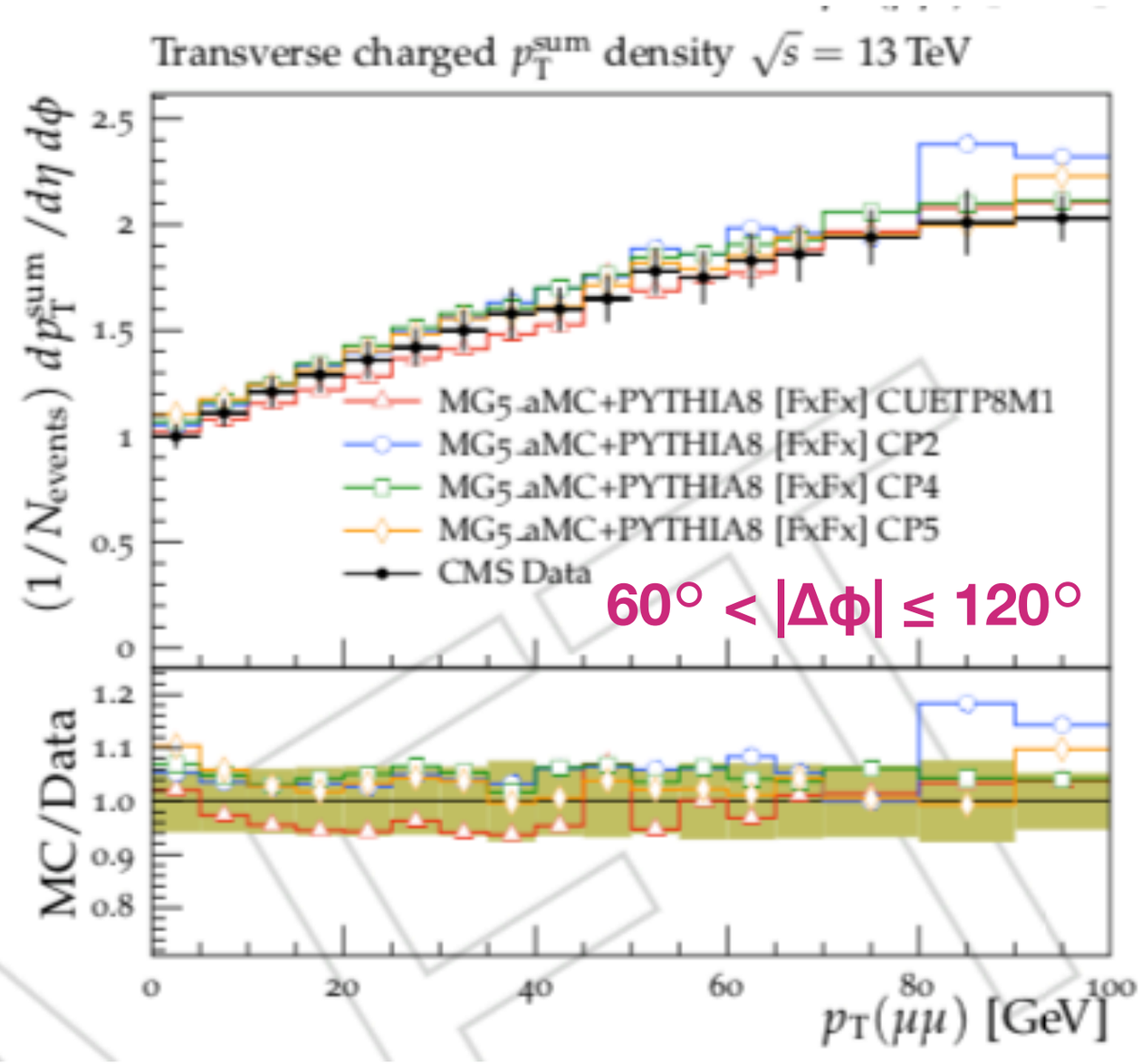


old-Monash-LO tune

band: total experimental uncertainty of the data

CP tunes in high p_T jets & EW bosons final states





Transverse region: CPs are improving the description wrt CUETP8M (but still ~10% off in the central region)

CP tunes in high p_T jets & EW bosons final states

phase space

Z-events: leptons $p_T > 20$ GeV and $|y| < 2.4$ and the dilepton mass lies in a ±20 GeV window around 91 GeV.

W-events: leptons $p_T > 20$ GeV and $|y| < 2.4$ and MT > 50 GeV

$\Delta R(l, j) > 0.4$

Jets anti-kT04 clustered with pT > 30 GeV and $|y| < 2.4$

observables data VS MG5aMC@NLO+P8CPn both MLM&FxFx

- ★ Jet Multiplicity (inclusive, >=Nj & exclusive =Nj)

  k_T–MLM predictions of the jet multiplicity have little sensitivity to the UE and PS tunes

- ★ pT balance Z-jet

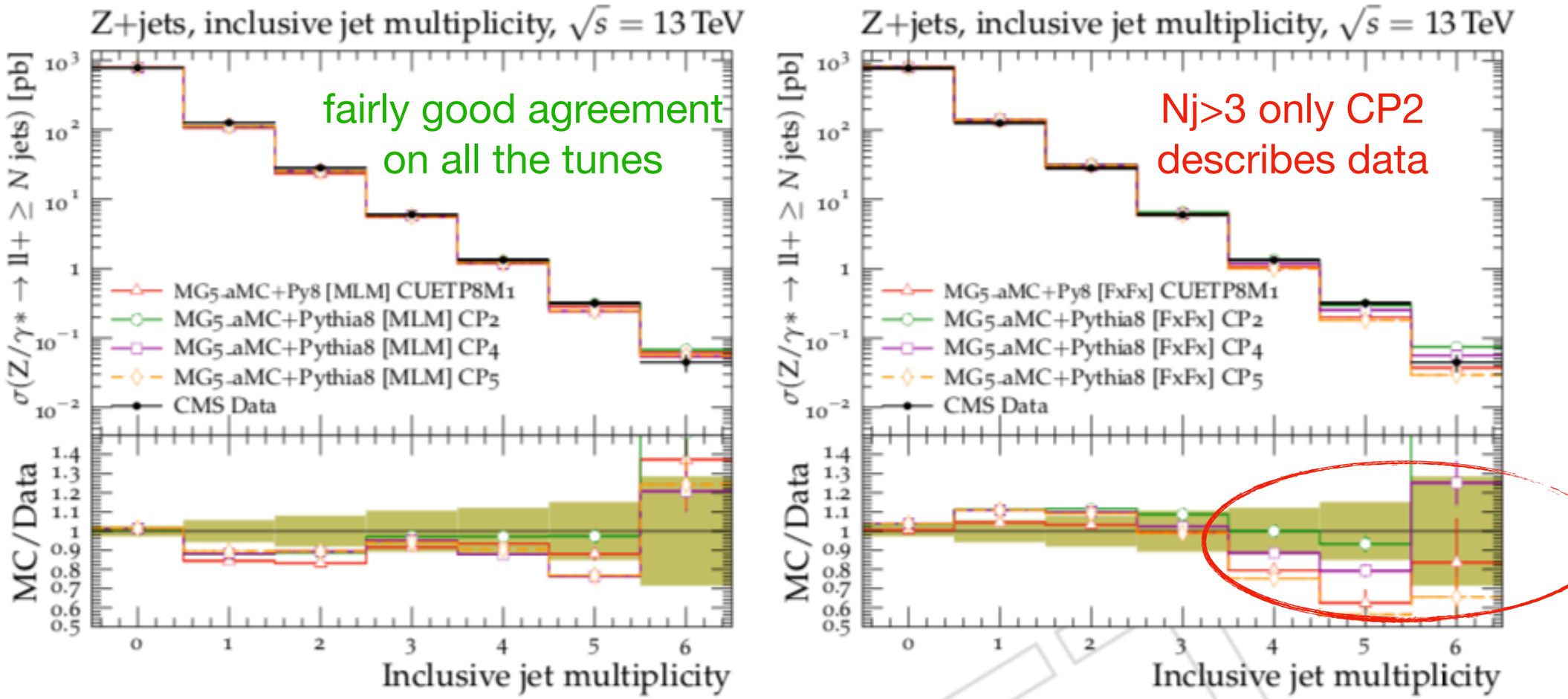
  sensitive to the UE and PS tunes

$$p_T^{bal} = |p_T(Z) + \sum_{jets} p_T^j|$$

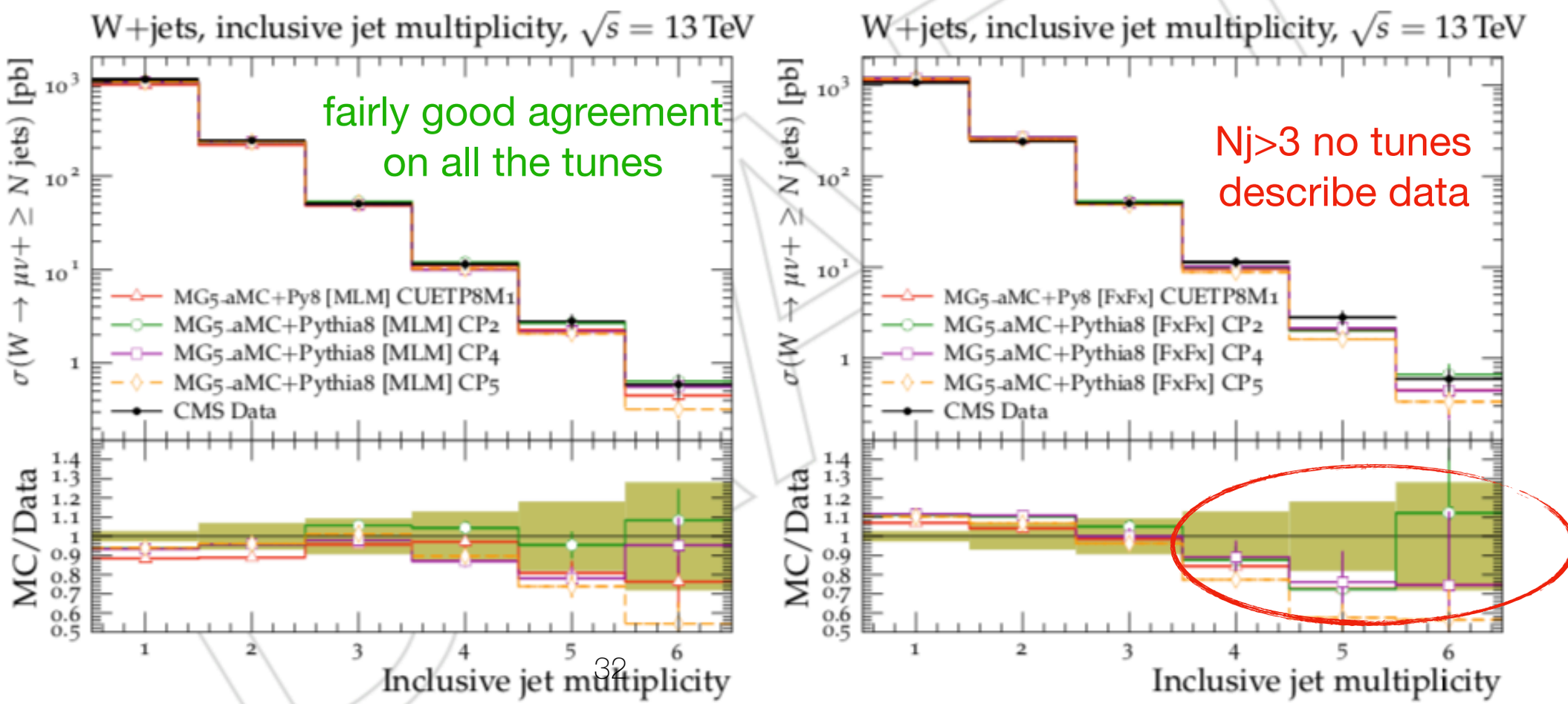
- ★ Z boson momentum (for Z+>=1j)

  interesting to see the effect of the tune especially at low momentum

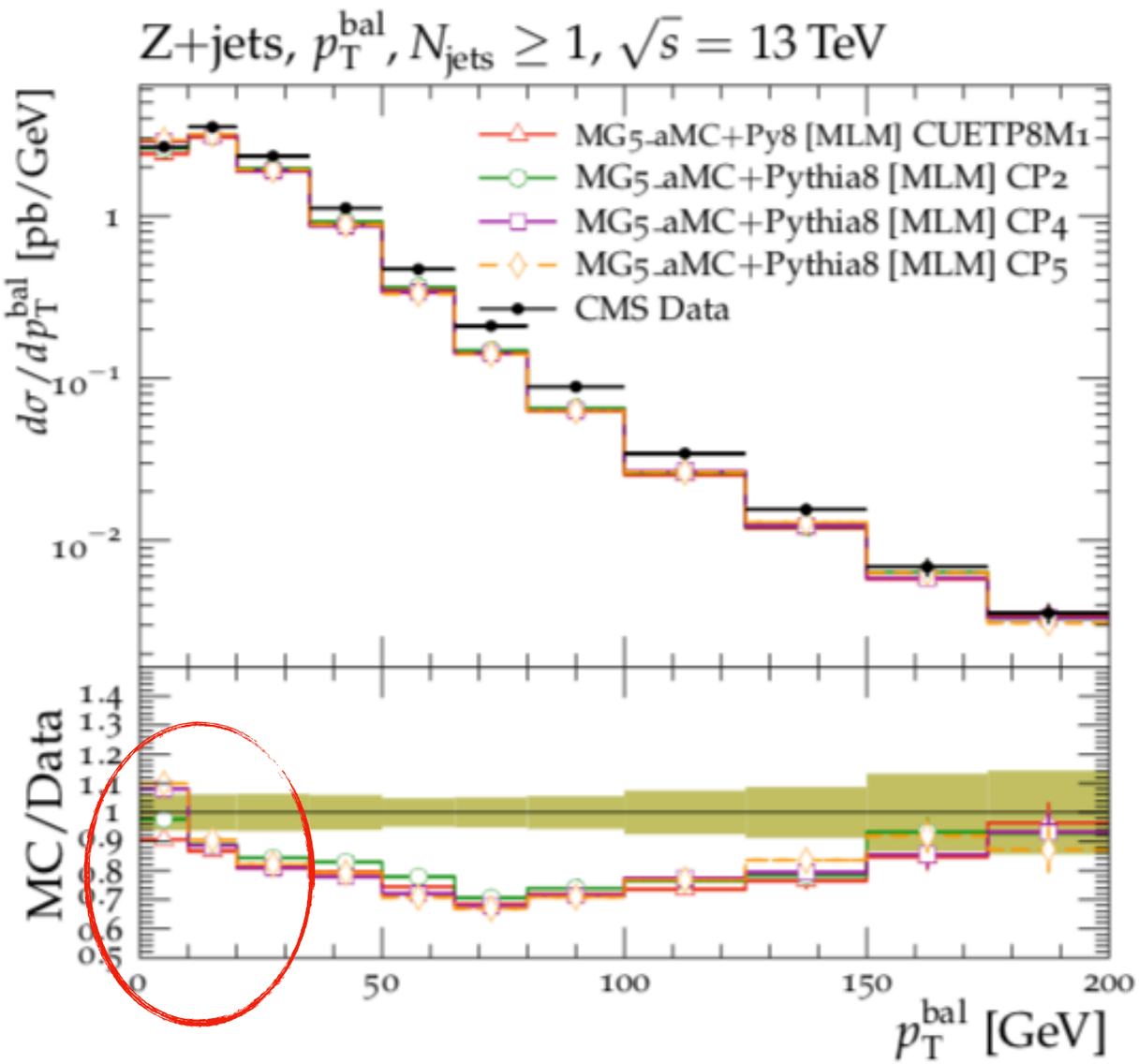
Jet-Z balance in Z+jets

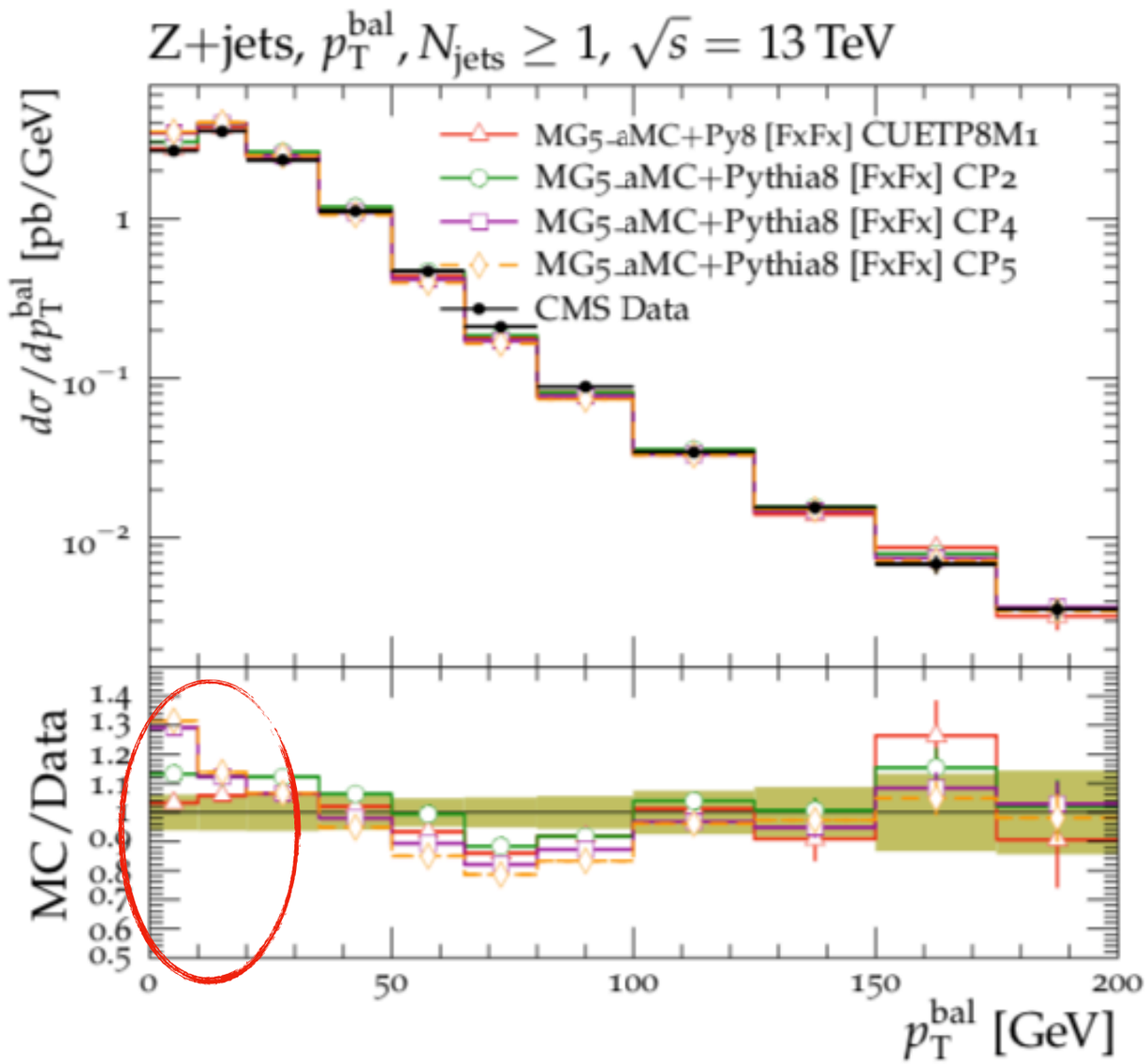


Jet-Z balance in W+jets



CP tunes in high p_T jets & EW bosons final states





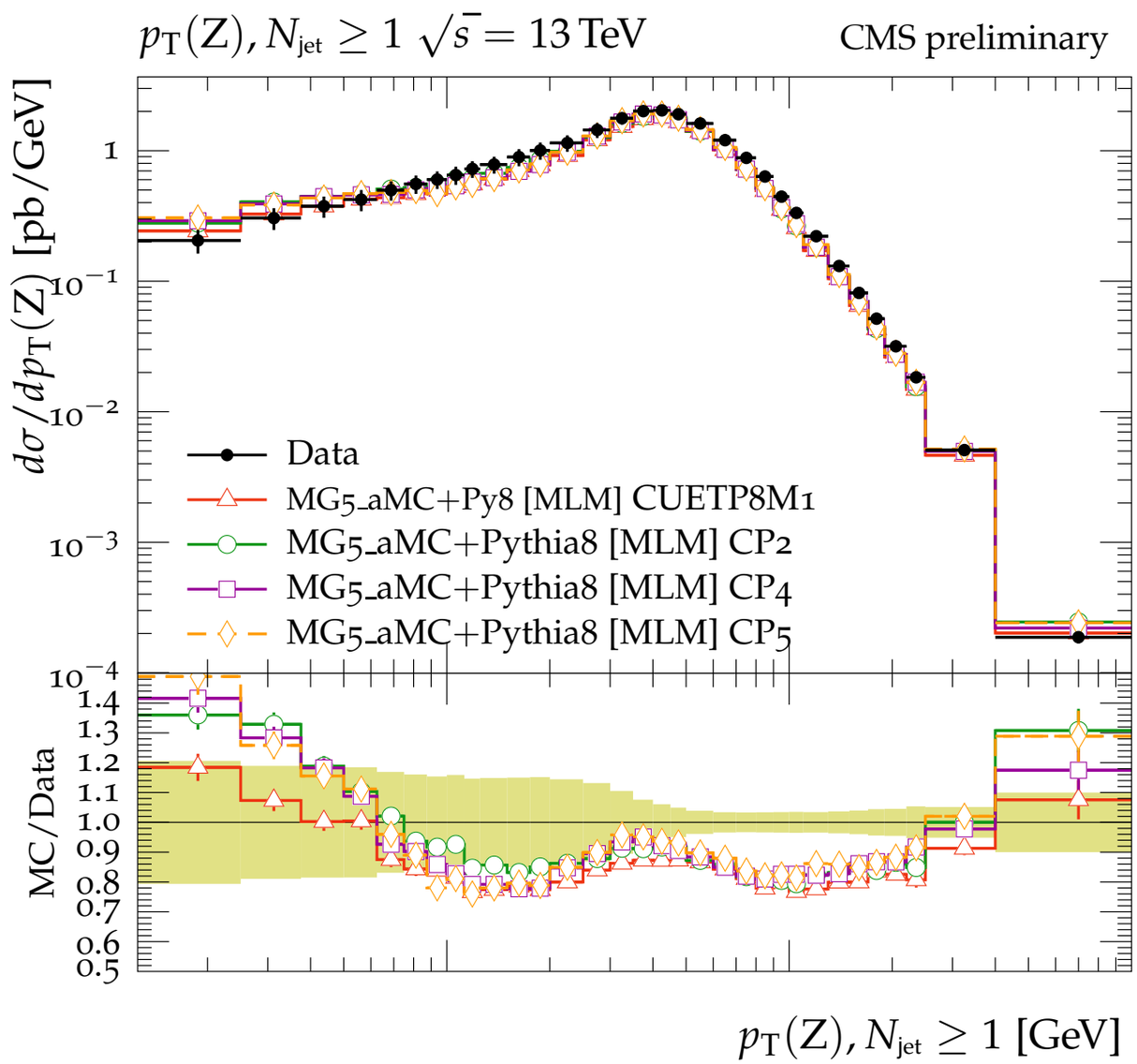
Jet-Z balance in Z+jets

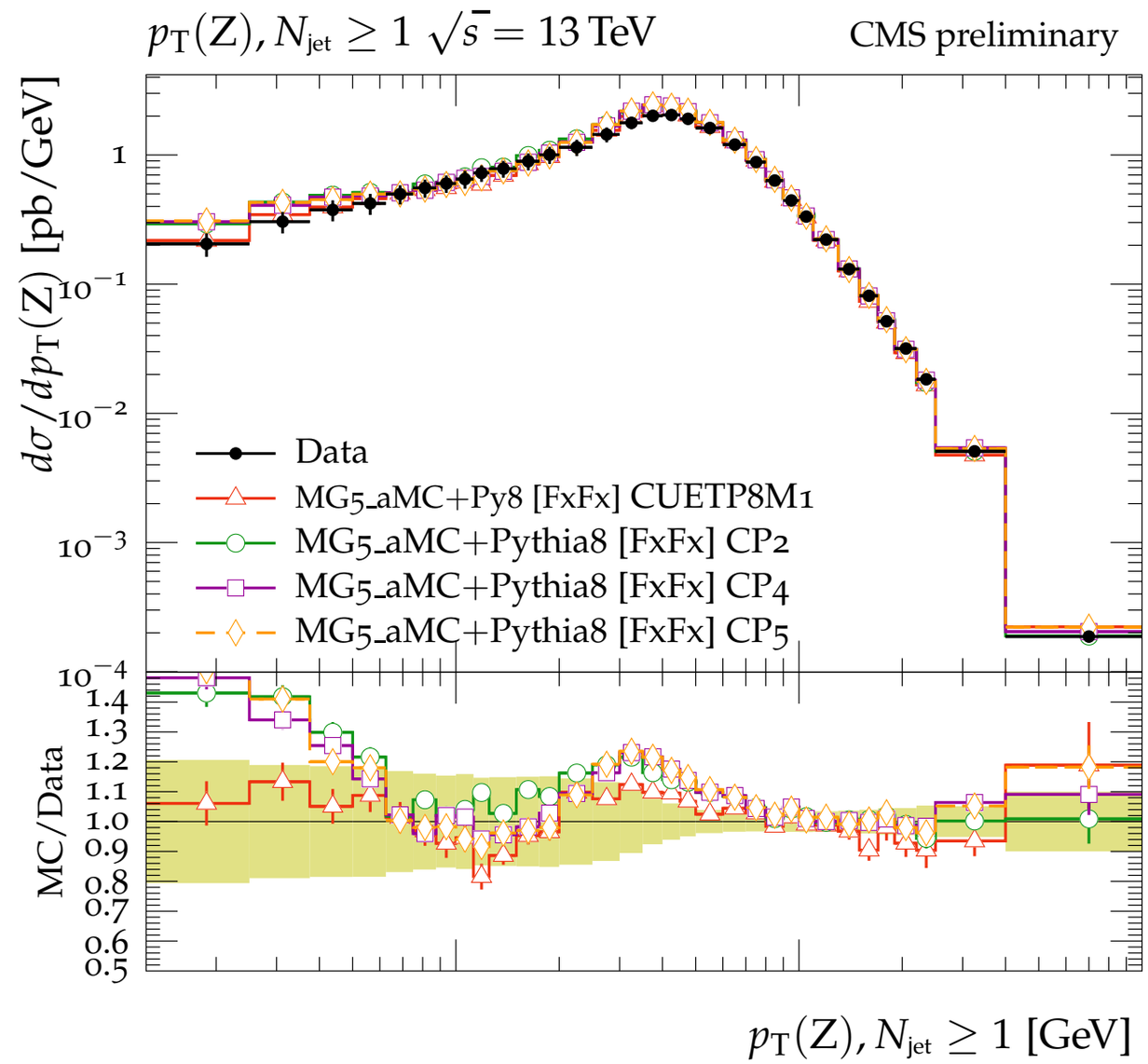
(!) Only below 20 GeV we see differences among tunes

CP tunes in high p_T jets & EW bosons final states

hard QCD: Z momentum in Z+jets events with jet pt>30 GeV

matrix element generation made by madgraph_aMC@NLO[FxFx and MLM]





- MLM: overall not able to describe the Z pt
- FxFx: all tunes give reasonable agreement around 5 GeV
- $p_T(Z)$<10 GeV: description by Monash-based CUETP8M1 is better