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Minimum Bias & Underlying Events Overview of Measurements and MC Tuning @CMS

Weijie Jin

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Outline

- **Testing and understanding the models of QCD interactions with hadronic jet productions**
  (SMP-21-003, https://arxiv.org/abs/2210.16139)
  - Measurement of the **Z+jets differential cross section**
    - Jet multiplicity & azimuthal correlations measurement in slices of pT(Z) bins
  - Theoretical comparisons
    - **Shower**: TMD parton shower + PB-TMD PDF(CASCADE 3) v.s. PYTHIA 8 shower+NNPDF NLO
      (Transverse Momentum Dependent) (Parton Branching method)
    - **ME**: NNLO(Z+0j) + higher order resummation (GENEVA) v.s NLO(≤1j, ≤2j) v.s. LO (≤3j, ≤4j) (MG5_aMC)

- **Generator description for minimum bias underlying events**
  - **PHYTHIA8 tunes with color reconnection** (CR) models based on CMS **underlying-event** data
    (GEN-17-002, https://arxiv.org/abs/2205.02905)

Z+jets differential cross section measurement

Motivation & Measurement

Drell-Yan processes can be measured **precisely in experiments** and calculated to **a high precision theoretically**

→ Clean to study the QCD corrections
→ Help us to understand the QCD modeling
→ Help to improve the generator descriptions of the QCD processes

↓

Analyse the kinematics of jets associated DY processes

Two **leptonic Z decay** channels:
- $Z \to e^+e^-$
- $Z \to \mu^+\mu^-$

Observables:
- Jet multiplicity
- $\Delta\Phi$(Z, leading jet 1)
- $\Delta\Phi$(leading jet 1, leading jet 2)

Measure in 3 pT(Z) regions:
- Low: pT(Z)<10GeV
- Intermediate: 30<pT(Z)<50GeV
- High: pT(Z)>100GeV

Remove detector effects:

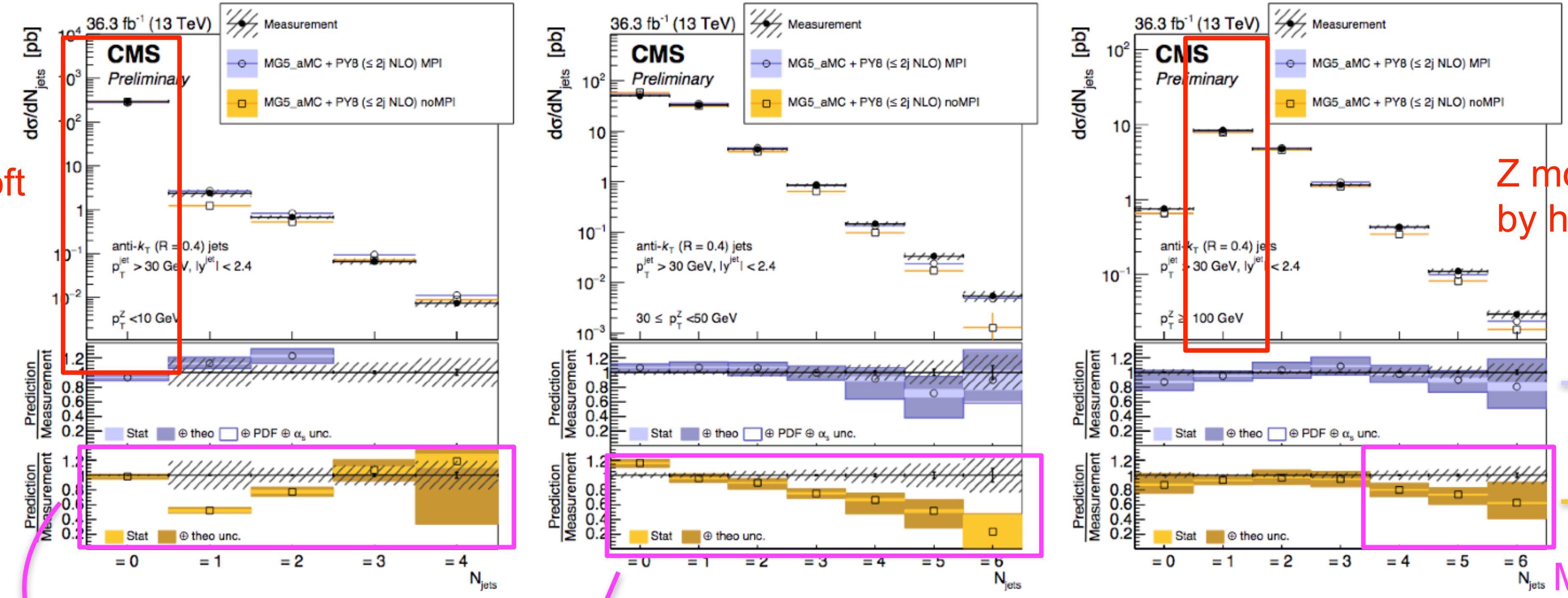
reco-level distributions $\xrightarrow{\text{unfold}}$ gen-level distributions

Z+jets differential cross section measurement

Results & Comprehension

#jets (pT>30GeV)

Z pT from soft radiations



Z mostly accompanied by hard jets

with MPI

without MPI

pT(Z)<10GeV

30GeV<pT(Z)<50GeV

pT(Z)>100GeV

MPI effects also in high #jet, high pT(Z) region

MPI contributes significantly in the low and medium Z pT region

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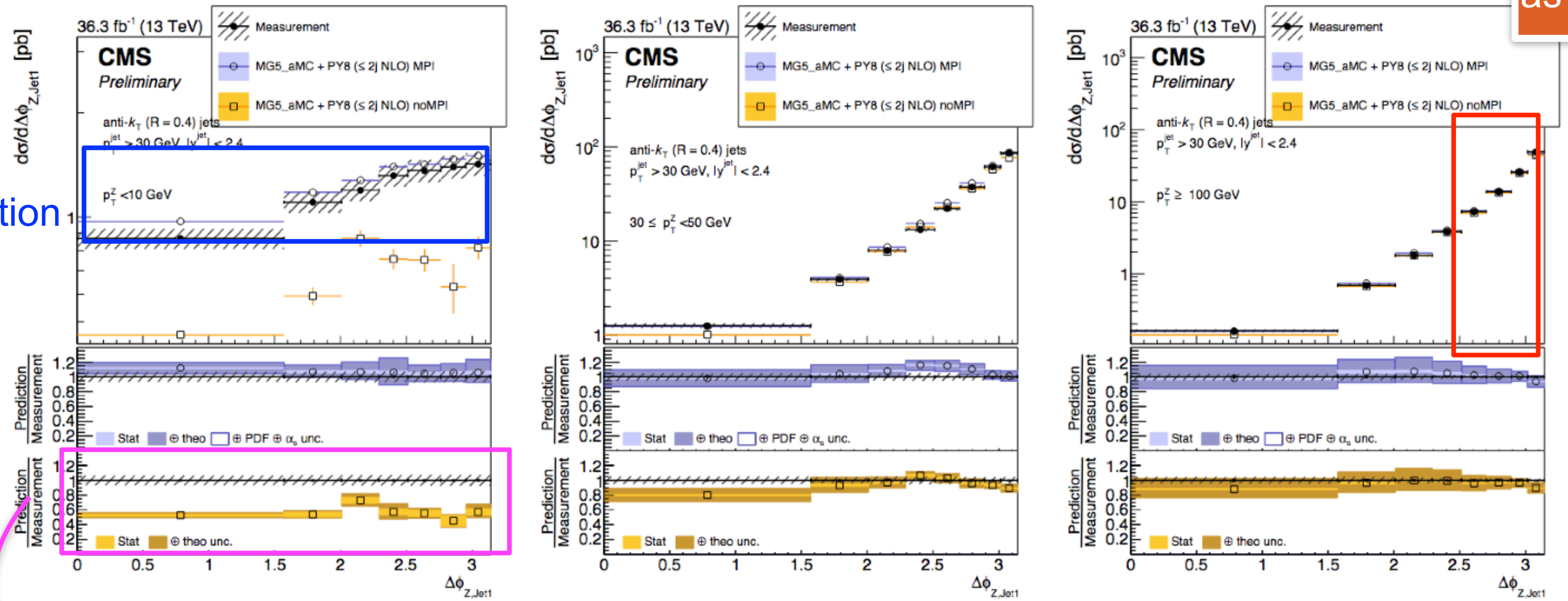
Z+jets differential cross section measurement

Results & Comprehension

ΔΦ(Z, leading jet 1) (pT(jet)>30GeV)

Dominated by **Z+jet** production, additional jets as **QCD corrections**

Weak correlation between Z & leading jet 1



Strong back-to-back correlation between Z & leading jet 1

pT(Z)<10GeV 30GeV<pT(Z)<50GeV pT(Z)>100GeV

Significant MPI contribution

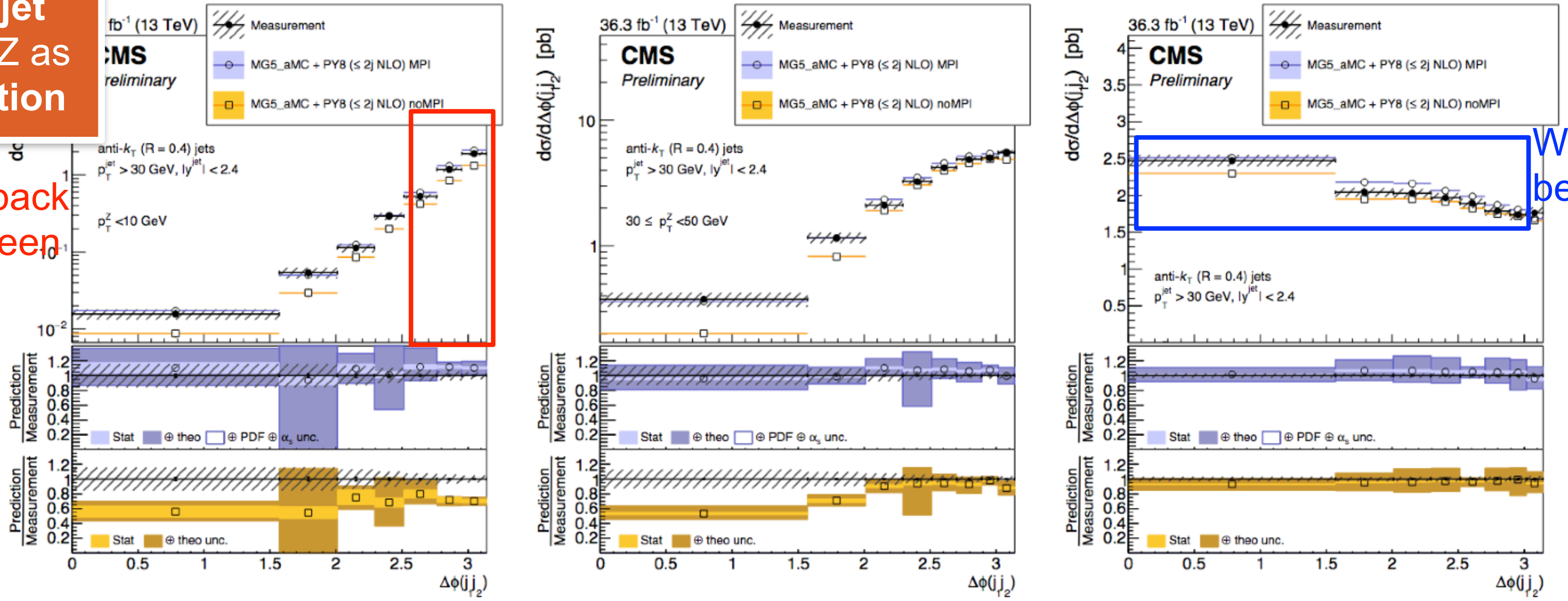
Z+jets differential cross section measurement

Results & Comprehension

ΔΦ(leading jet 1, leading jet 2) (pT(jet)>30GeV)

Dominated by **jet productions**, Z as an **EW correction**

Strong back-to-back correlation between the two jets



Weak correlation between the two jets

pT(Z)<10GeV | 30GeV<pT(Z)<50GeV | pT(Z)>100GeV

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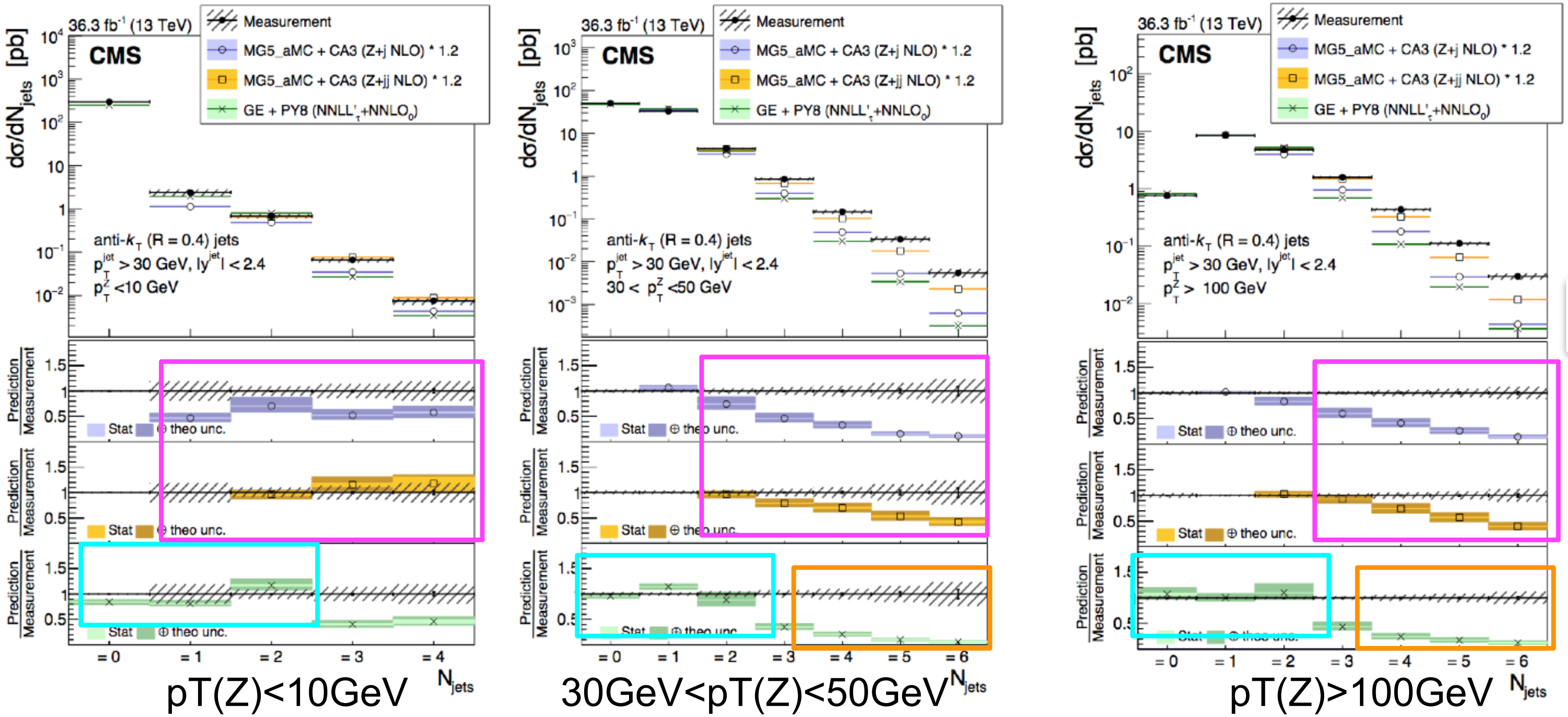
Z+jets differential cross section measurement

Theoretical Comparison

#jets (pT>30GeV)

TMD shower (CASCADE)
NNLL'+NNLO (GENEVA)



Lack of MPI

MG5_aMC(Z+j NLO)+CASCADE without MPI

MG5_aMC(Z+2j NLO)+CASCADE without MPI

GENEVA+PY8 (NNLL'+NNLO 0j)

Agree with data in low #jet bins

Miss higher order contributions in ME

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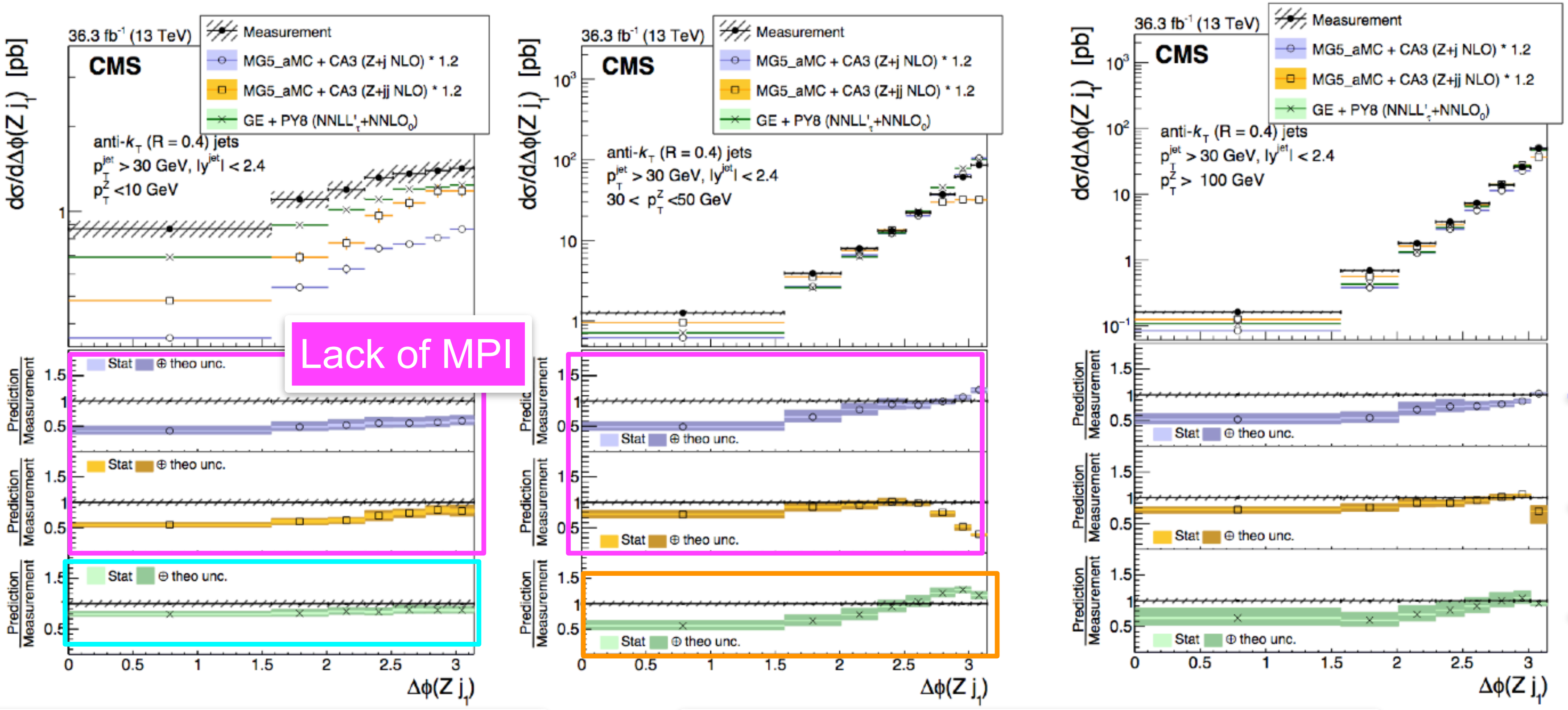
Z+jets differential cross section measurement

Theoretical Comparison

ΔΦ(Z, leading jet 1) (pT(jet)>30GeV)

TMD shower (CASCADE)
NNLL'+NNLO (GENEVA)



MG5_aMC(Z+j NLO)+CASCADE without MPI

MG5_aMC(Z+2j NLO)+CASCADE without MPI

GENEVA+PY8 (NNLL'+NNLO 0j)

Agree with data in low #jet bins

Miss higher order contributions in ME

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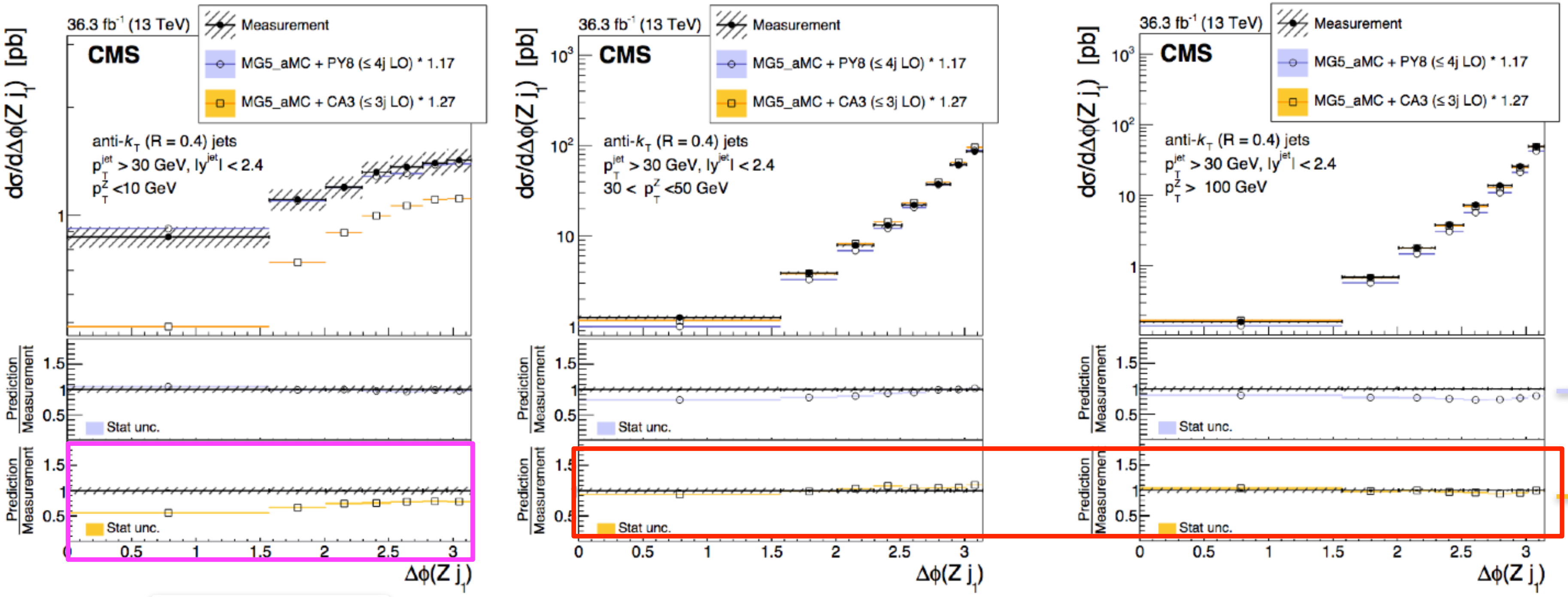
Z+jets differential cross section measurement

Theoretical Comparison

ΔΦ(Z, leading jet 1) (pT(jet)>30GeV)

ME at LO
Pythia / TMD shower (CASCADE)



MG5_aMC(Z+4j LO)+PYTHIA8

MG5_aMC(Z+3j LO)+CASCADE without MPI

Lack of MPI

Otherwise it describes quite well

Z+jets differential cross section measurement
Theoretical Comparison

TMD (initial state) **parton shower** with **PB-TMD PDF**s (CASCADE)
- **close to data** in regions **not sensible to MPI**
- **not enough** to describe the phase space where **MPI** is important (mostly low pT(Z) regions)
- MPI models compatible with TMD shower is needed for improvement

NNLO ME(GENEVA) with higher order resummation (NNLL') + PYTHIA 8 shower
- Compatible with data and MC from other generators in **low #jet regions**
- Similar behavior as MG5_aMC(1j NLO)+TMD shower ← same order if #jet ≥ 1

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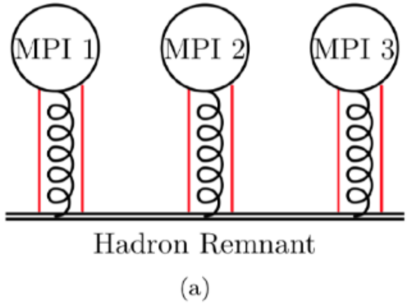
MC tune with color reconnection models for UE description

Color Reconnection Models

MC generation: **hard process** ⊗ **underlying events**

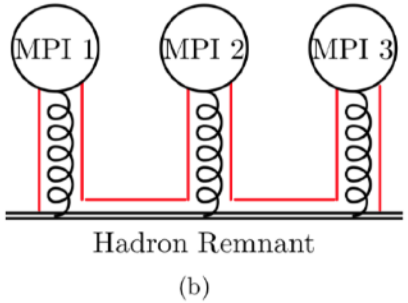
Initial/final state radiation (ISR/FSR)
Multi-parton interaction (MPI)
Beam-beam remnants (BBR)

#MPI **increases** with collision energy ↑ → Adds **more colored partons** to the final state



Leading color approximation

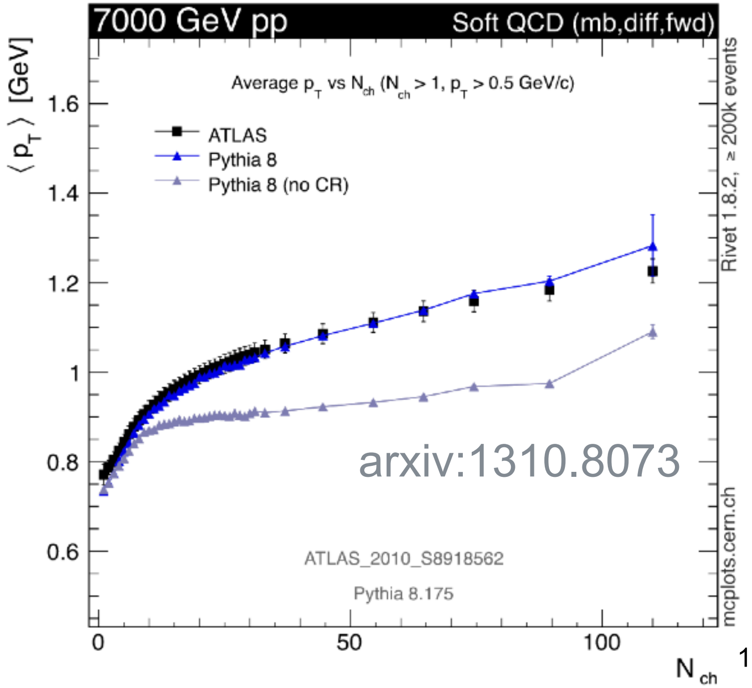
- MPIs are separate in color space
- No color lines between MPIs
- Total color charge is not optimal



Christiansen, J.R. & Skands, P.Z. J. High Energ. Phys. (2015) 2015: 3.

Color reconnection

- Reconnect color strings among different systems
- MPIs hadronize collectively
- First introduced by UA1 experiment to explain the rising trend of <pT>-Nch data

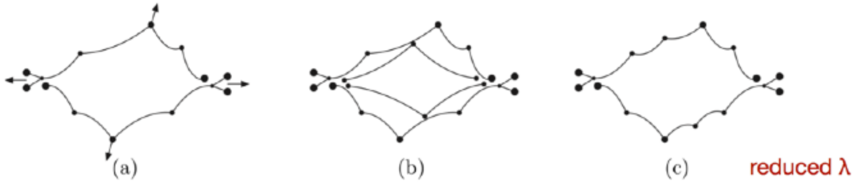


MC tune with color reconnection models for UE description

Color Reconnection Models (details in backup)

MPI-based CR model

- Reconnect color strings between partons
- Minimize the string length λ

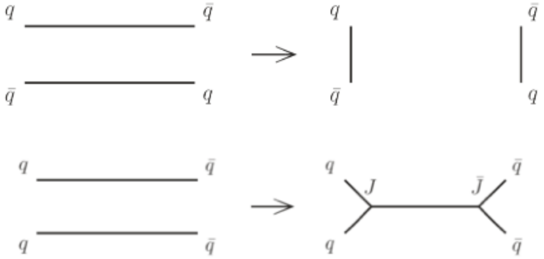


Tune:
- ColourReconnection:range

→ change reconnect probability

QCD-inspired CR model

- Switch dipole connections allowed by QCD color rules
- Shorten the string length λ
- Allow creation of junctions



Tune:
- ColourReconnection:m0

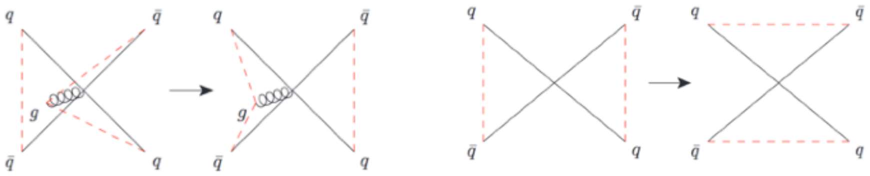
→ in string length definition
- ColourReconnection:junctionCorrection

→ correction for junction in string length
- ColourReconnection:timeDilationPar

→ time for strings to resolve and reconnect

Gluon-move CR model

- Move gluons' connection in string pieces
- Flip color lines between strings
- Shorten the string length



Tune:
- ColourReconnection:m2Lambda

→ in string length definition
- ColourReconnection:fracGluon

→ probability of a gluon move

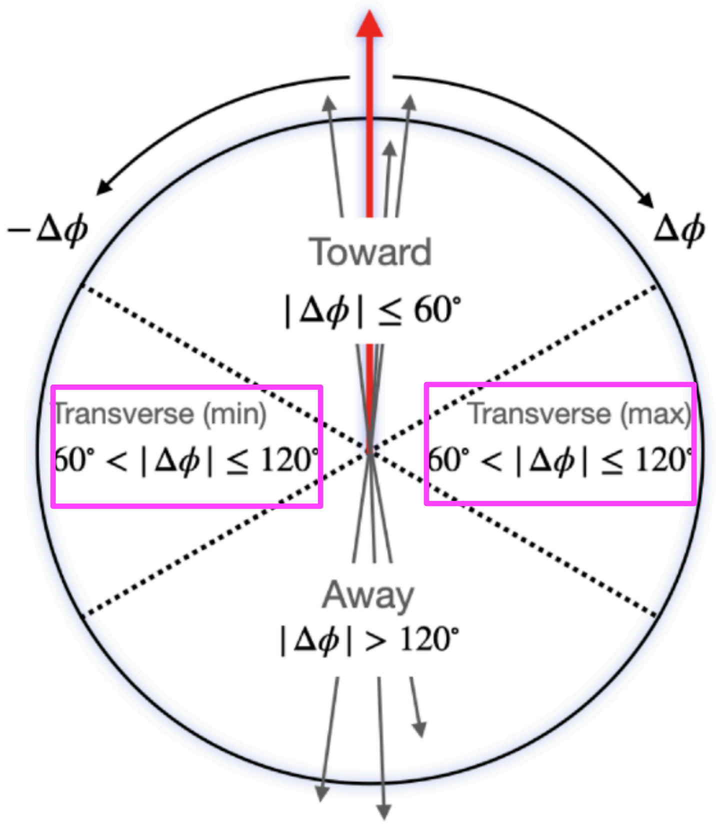
MC tune with color reconnection models for UE description

Tune observables

To tune the CR parameters to UE observables

Identify UE constituents from the **azimuthal angles** in the transverse plane

- The **leading object** is often from **hard scatterings**
  - The "**toward**" region with Φ to leading object < 60˚ is **sensitive to hard scatterings**
  - The "**away**" region with Φ to leading object > 120˚ contains objects **recoiled from the leading object**
- **Underlying events** are those **not associated to hard scattering**
  - The "**transverse**" regions with Φ to leading object between 60˚ and 120˚ is **sensitive to UE**
  - **Observables** from kinematics in transverse regions **reflect UE modeling** -> **tune to them!**



Transverse plane of the collision

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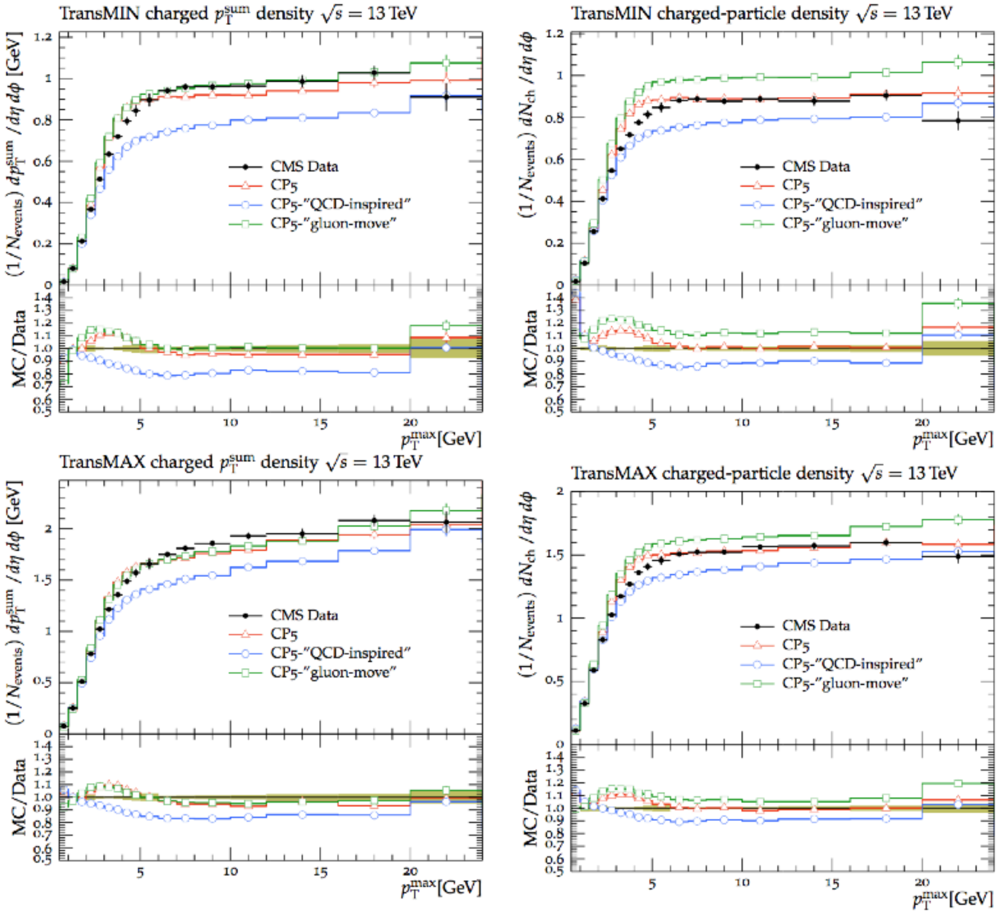
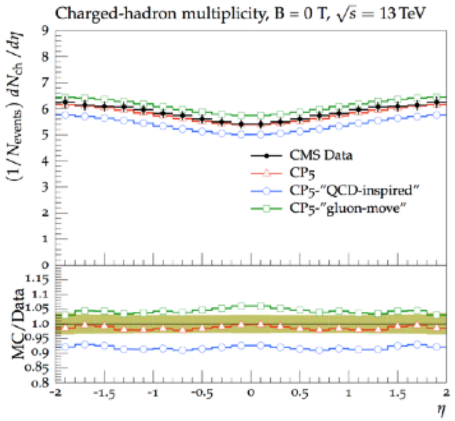
Tune observables



Charged particle density and **pT sum** in **transverse min/max** regions
Data collected in **various collision energies**:
1.96 TeV, 7 TeV, 13 TeV(shown left)

+ η distribution of charged hadron multiplicity (below)



MC tune with color reconnection models for UE description

Tune setup

QCD-inspired Gluon-move

RIVET routine	$\sqrt{s}$ (TeV)	Distribution	CP5-CR1 Fit range (GeV)	CP5-CR1 N_{bins}	CP5-CR1 R	CP5-CR2 Fit range (GeV)	CP5-CR2 N_{bins}	CP5-CR2 R
CMS_2015_I1384119	13	N_{ch} vs η		20	1		20	1
CMS_2015_PAS_FSQ_15_007	13	TransMIN charged p_T^{sum}	2–28	15	1	3–36	15	0.5
		TransMAX charged p_T^{sum}	2–28	15	1	3–36	15	0.5
		TransMIN N_{ch}	2–28	15	1	3–36	15	0.1
		TransMAX N_{ch}	2–28	15	1	3–36	15	0.1
CMS_2012_PAS_FSQ_12_020	7	TransMAX N_{ch}	3–20	10	1	3–20	10	0.1
		TransMIN N_{ch}	3–20	10	1	3–20	10	0.1
		TransMAX charged p_T^{sum}	3–20	10	1	3–20	10	0.1
		TransMIN charged p_T^{sum}	3–20	10	1	3–20	10	0.1
CDF_2015_I1388868	2	TransMIN N_{ch}	2–15	11	1	2–15	11	0.1
		TransMAX N_{ch}	2–15	11	1	2–15	11	0.1
		TransMIN charged p_T^{sum}	2–15	11	1	2–15	11	0.1
		TransMAX charged p_T^{sum}	2–15	11	1	2–15	11	0.1

Histogram of the observables

Weights for tuning

CP5: use **MPI-based** CR model
ColourReconnection:range =5.176
-> remove it in CR1 and CR2 tune

CP5-CR1
m0
timeDilationPar
junctionCorrection

CP5-CR2
m2Lambda
fracGluon

+ retun MPI parameters
ecmPow
pT0Ref
coreRadius
coreFraction

Tuned in this paper

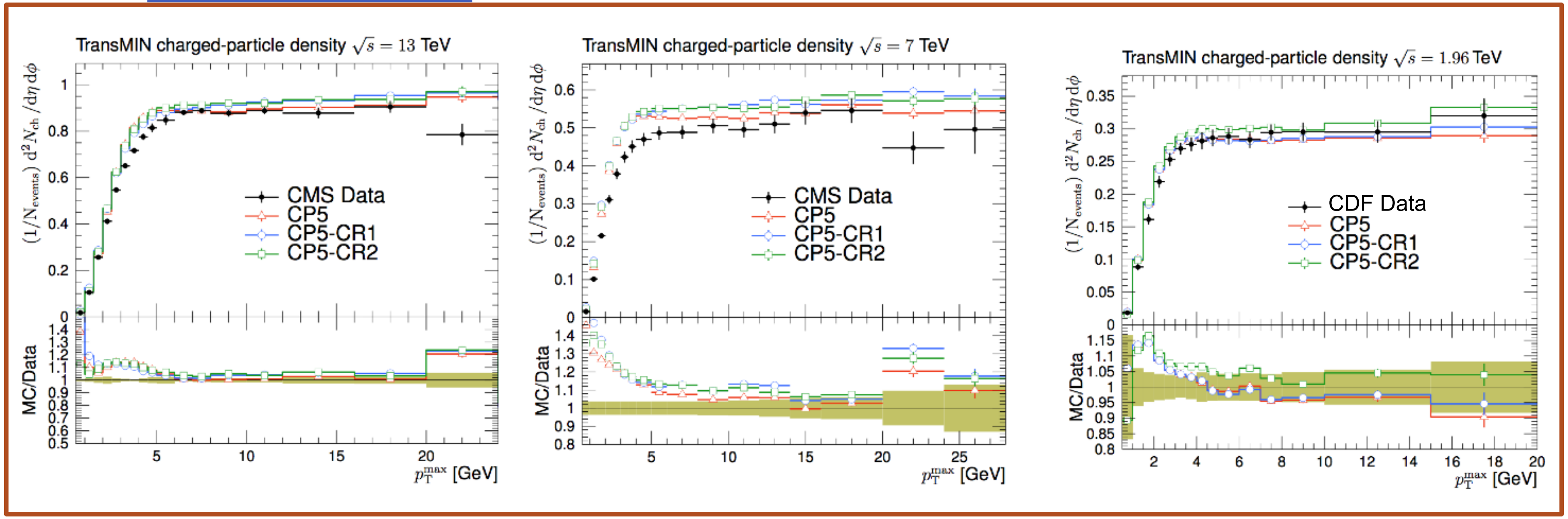
Algorithm:

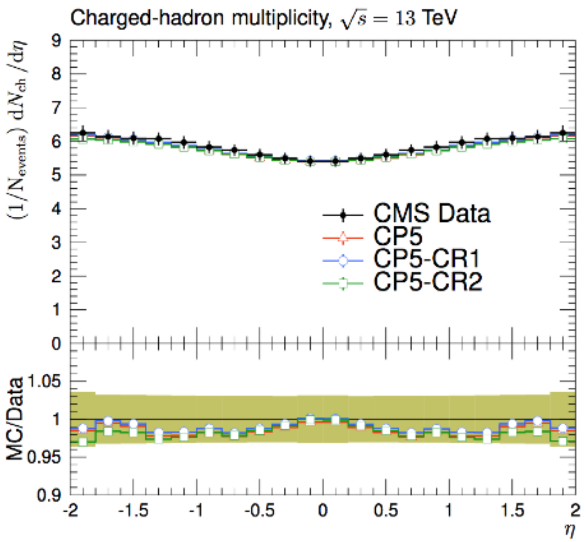
- **Generate predictions** in ~200 points in the parameter space
- **Interpolate** bin values as polynomials of the parameters
- **Minimize** the MC-data difference

$$\chi^2(p) = \sum_{O} w_O \sum_{b \in O} \frac{(f^b(p) - R_b)^2}{\Delta_b^2}$$

MC tune with color reconnection models for UE description

Performance



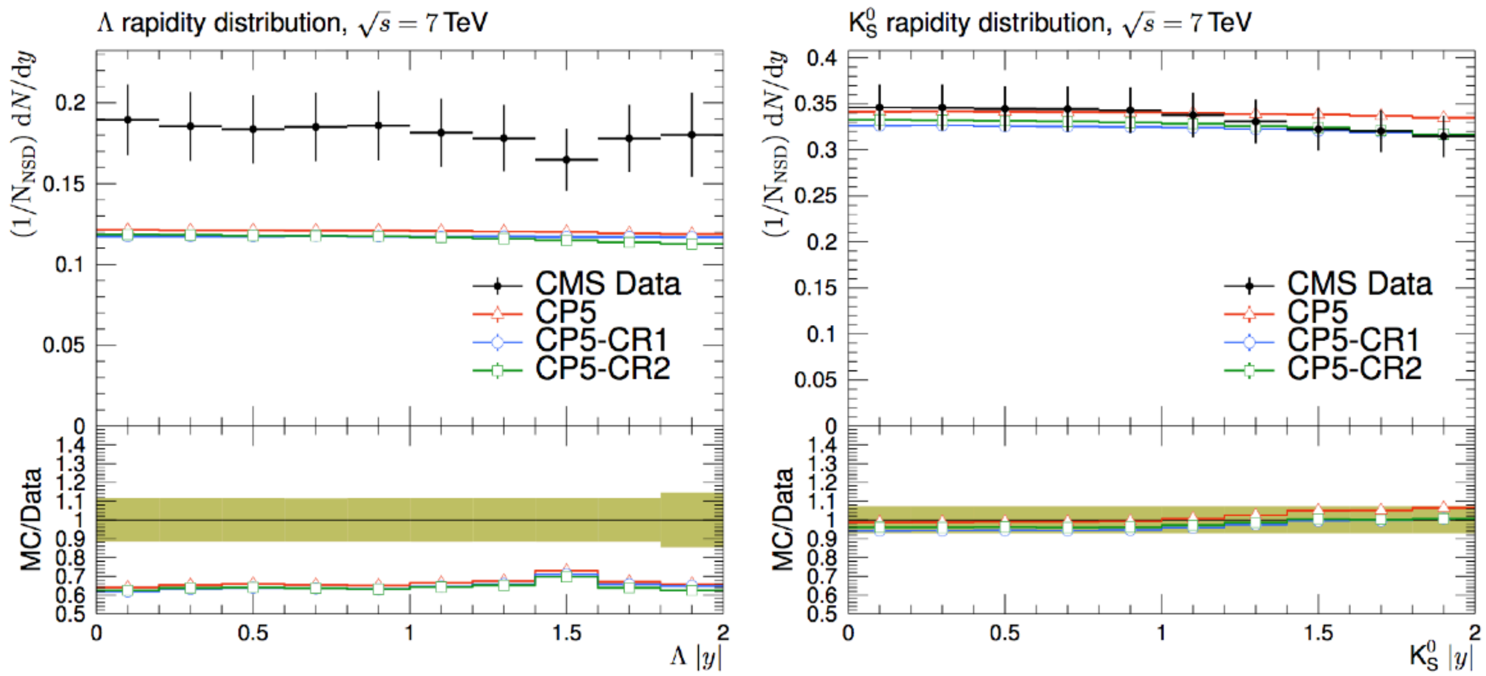


Nch v.s. η (13 TeV)

- Charged particle density in transMIN under 13 TeV, 7 TeV and 1.96 TeV energies compared to CMS and CDF data
- Similar behaviors for charged particle density and pTsum in transMAX

Tunes perform well and consistent with CP5

MC tune with color reconnection models for UE description
Performance



Christiansen, Skands, JHEP08(2015)003 : new Pythia8 CR models could **improve the description of Λ / K_S^0 in pp collisions**

- All the CR models **underestimate the Λ by ~40%**
- All the tunes **describe the K_S^0 measurement well**

May need other hadronization models to improve it

C. Bierlich, G. Gustafson, and L. Lönnblad, "A shoving model for collectivity in hadroniccollisions", 2016
C. Bierlich, "Rope hadronization and strange particle production", Eur. Phys. J. Web Conf.171 (2018) 14003

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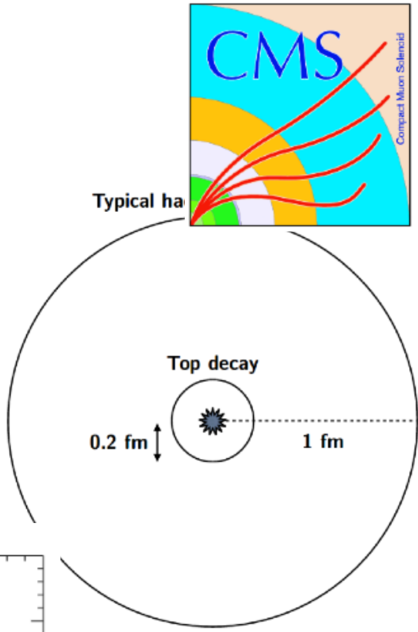
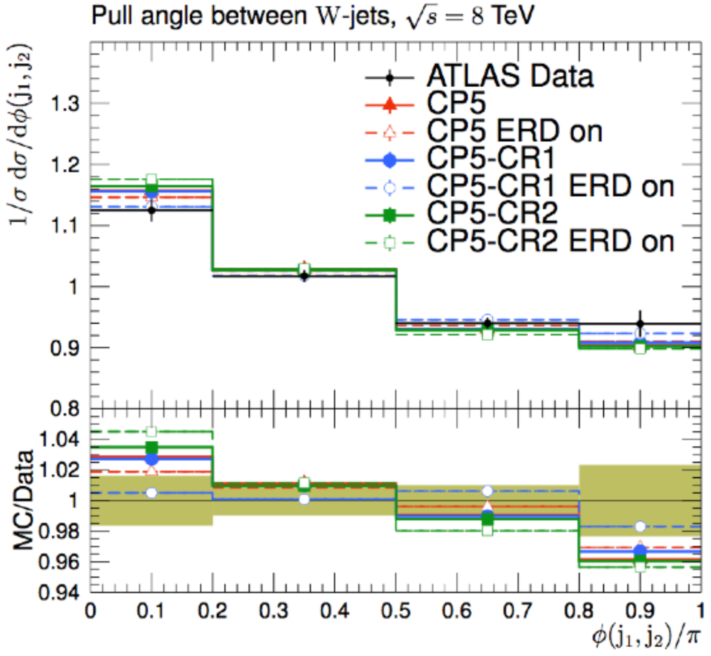


MC tune with color reconnection models for UE description

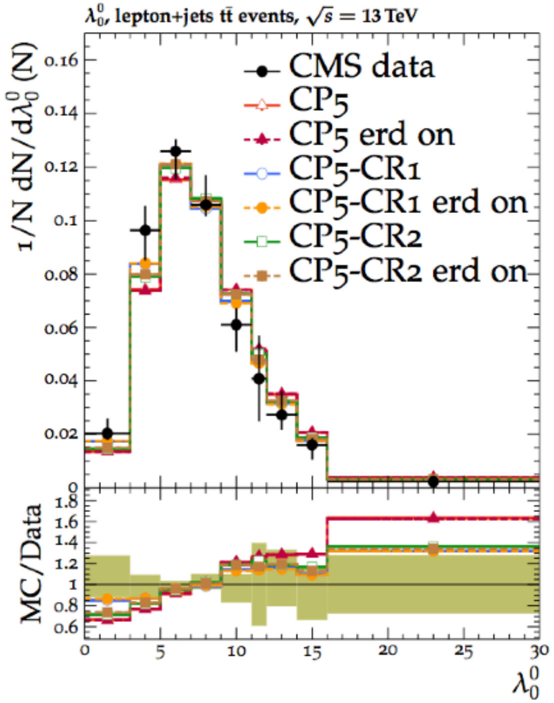
Performance

Jet substructure variables in ttbar

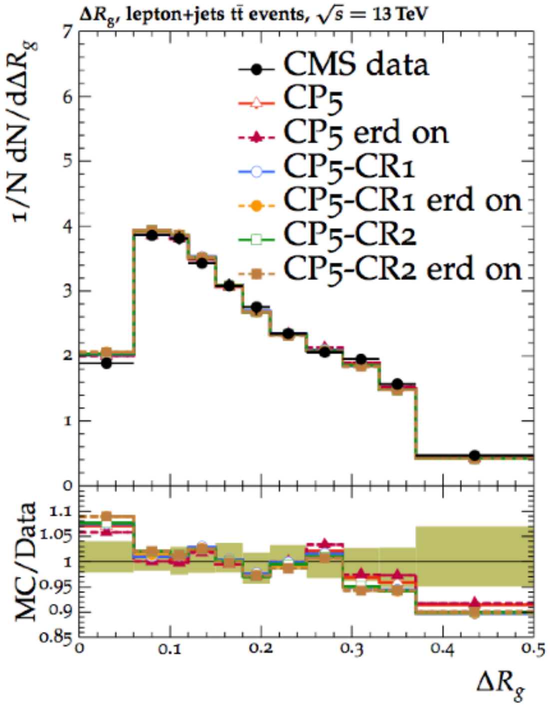
Top quarks decay before hadronize
-> **Early Resonance Decay** (ERD) option for top
-> ERD=on: color reconnect the decay products of top to other partons



Angle between W-jet from ttbar decay
-> sensitive to ERD
-> CR1 with ERD=on provides best description



Charged particle (pT>1 GeV) multiplicity



Angle between two groomed subjets

-> None of the tunes describes the data well
-> **Further studies needed for a better description**

MC tune with color reconnection models for UE description

Extraction of top-mass uncertainty

CR contributes most in the **uncertainties of top mass** measurement

Estimation strategy: compare the results with different CR model + ERD=on/off

-> their differences used as uncertainty

-> **not very "physical" without dedicate CR tunes**

Extract the top mass uncertainty from tuned CR models:

- Simulation from these models were injected to the RIVET routine
- Construct the top candidates and fit the mass
- Estimate the uncertainty from their deviations from default CP5

Tune	m_t [GeV]	Δm_t [GeV]	m_W [GeV]	Δm_W [GeV]	$\Delta m_t - 0.5 \times \Delta m_W$ [GeV]
CP5	171.93 ± 0.02	0	79.76 ± 0.02	0	0
CP5 erdOn	172.18 ± 0.03	0.25	80.15 ± 0.02	0.40	0.13
CP5-CR1	171.97 ± 0.02	0.04	79.74 ± 0.02	-0.02	0.05
CP5-CR1 erdOn	172.01 ± 0.03	0.08	79.98 ± 0.02	0.23	-0.04
CP5-CR2	171.91 ± 0.02	-0.02	79.85 ± 0.02	0.10	-0.07
CP5-CR2 erdOn	172.32 ± 0.03	0.39	79.90 ± 0.02	0.14	0.32

Largest deviation (0.32 GeV) is similar to TOP-17-007 result

Summary

Z+jets differential XS measurement

- Kinematics of **hadronic jet production** in **multiple pT(Z)** regions ← various EW v.s. QCD contributions
- Evaluate the performances of **multiple theoretical models**
  → physics in parton shower and MPI

MC tune with color reconnection effects to UE data

- **Improve the color reconnection** models in PYTHIA 8
- Inputs for the modeling of **strange particle production**
  → CR does not fix the Λ spectrum
  → We need other hardonization models
- Useful for evaluating the **systematic uncertainty from CR** (top mass measurement)
  → More sophisticated CR models with tuned parameters
  → The uncertainty from these CR models are more “physical”

Backup

Z+jets differential cross section measurement
Theoretical Models

- Models with Transverse Momentum Dependent (TMD) parton density and shower (CASCADE3)
- Models merging NLO ME with higher partonic jet multiplicity merged with shower & hadronization (MadGraph5 aMC@NLO + PYTHIA8)
- Models with resummed predictions at NNLO (GENEVA)

Z+jets differential cross section measurement
Event selection

Data: CMS 2016 data, luminosity 36.3 fb^{-1}

Z -> μ+μ- and **Z -> e+e-**:
- Muons and electrons are reconstructed with particle flow algorithm
- PF **isolation** requirements for the leptons
- Lepton pairs with **opposite charge**
- Detector restrictions on **pT** and **η**
  - pT(μ1) > 25 GeV, pT(μ2) > 20 GeV, |η|<2.4
  - pT(e1) > 20 GeV, |η| < 1.442 or 1.566 < |η| < 2.4
- **Z mass** around the resonance: 76 GeV < m(l+l-) < 106 GeV

Jet reconstruction:
- Clustered with anti-kT, R=0.4
- Isolation from lepton candidates from Z decay: ΔR(l,j)>0.4
- Pileup and jet energy corrections

Z+jets differential cross section measurement

Correction for detector effects -> Unfolding

Reco-gen correspondence: **response matrices** from MC template **MadGraph5 aMC@NLO (≤2j NLO)+Pythia8**
Algorithm: **iterative Bayesian** method implemented in RooUnfold
Backgrounds (tt, single top, double VB, W+jets, Z-> $\tau^+\tau^-$) are subtracted from data before unfolding

Reco-level differential XS → Stable particle-level differential XS
(leptons are dressed with collinear photons)

Uncertainties:

- Jet energy scale, jet energy resolution
- Trigger/lepton reconstruction/lepton identification efficiency
- Luminosity, pileup
- Unfolding uncertainty from MC models/MC statistics

MC tune with color reconnection models for UE description
PYTHIA 8 Implementation of CR

MPI-based CR model

First scattering
-> color connected
outgoing gluons

Another scattering
-> adds new strings

Reconnect the color strings
-> minimize the total string length λ

Reconnection probability **P**
for an MPI with **pT**

$$P = \frac{p_{T_{\mathrm{Rec}}}^2}{p_{T_{\mathrm{Rec}}}^2 + p_T^2}$$

$$p_{T_{\mathrm{Rec}}}^2 = R \cdot p_{T_0}$$

Energy-dependent damping parameter for MPI

pT↑ P↓ Harder processes are less likely to reconnect

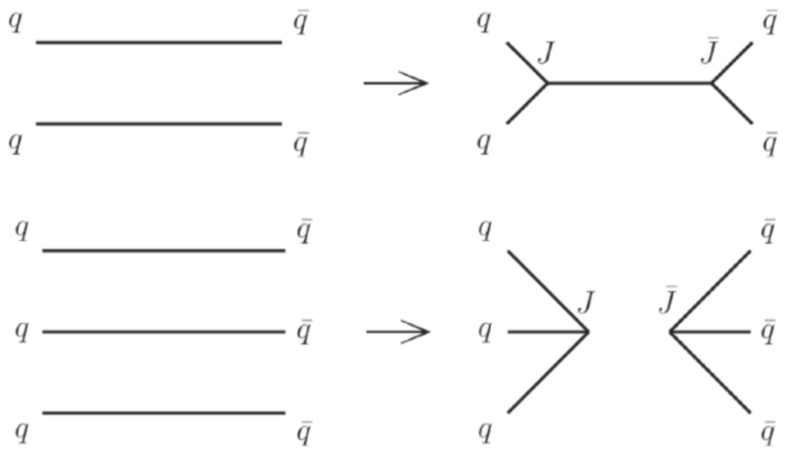
Tunable parameter
(**ColourReconnection:range** in PYTHIA8)

MC tune with color reconnection models for UE description
PYTHIA 8 Implementation of CR

QCD-inspired CR model

Construct dipoles allowed by **QCD color rules**

Switch if the reconnection **shortens the string length**



It allows the **creation of junctions**
-> accounts for higher order CR effects

Energy of the colored partons in the QCD dipole rest frame

String length $$\lambda = \ln\left(1 + \sqrt{2}\frac{E_1}{m_0}\right) + \ln\left(1 + \sqrt{2}\frac{E_2}{m_0}\right)$$

Tunable parameter

Free parameters in **PYTHIA8**:
ColourReconnection:m0 -> m0 parameter in λ
ColourReconnection:junctionCorrection
-> multiplicative correction to m0 for junctions
ColourReconnection:timeDilationPar
-> control the time of two strings to resolve and allow to reconnect

MC tune with color reconnection models for UE description
PYTHIA 8 Implementation of CR

QCD-inspired CR model

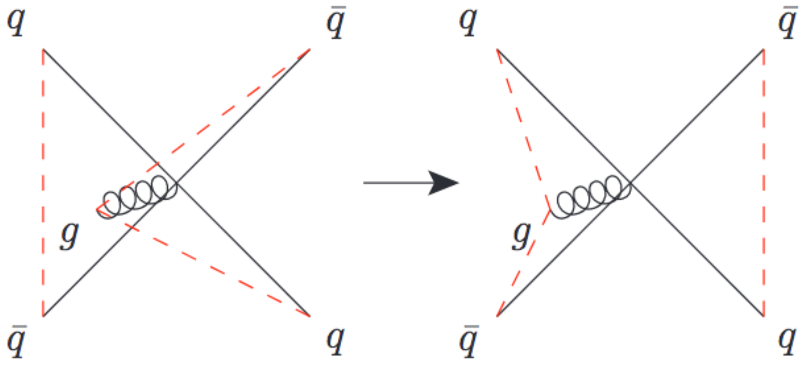
Only allow reconnection between strings with causal contact -> causal contact is controlled by models and parameters

mode **ColourReconnection:timeDilationMode** (default = **2**; minimum = 0; maximum = 5)
Disallow colour reconnection between strings that are not in causal contact; if either string has already decayed before the other string forms, there is no space-time region in which the reconnection could physically occur. The exact defintion of causal contact is not known, hence several possible defintions are included. They all include the boost factor, *gamma*, and the majority also rely on the typical hadronization scale, *r*, which is kept fixed at 1 fm. A tuneable dimensionless parameter is included, which can be used to control the overall amount of colour reconnection.
option **0** : All strings are allowed to reconnect.
option **1** : Strings are allowed to reconnect if *gamma < timeDilationPar* and all strings should be causally connected to allow a reconnection.
option **2** : Strings are allowed to reconnect if *gamma < timeDilationPar * mDip * r* and all strings should be in causal contact to allow a reconnection.
option **3** : Strings are allowed to reconnect if *gamma < timeDilationPar * mDip * r* and if a single pair of dipoles are in causal contact the reconnection is allowed.
option **4** : Strings are allowed to reconnect if *gamma < timeDilationPar * mDip' * r* and all strings should be in causal contact to allow a reconnection. mDip' is the invariant mass at the formation of the dipole (ie. the first time the colour tag appear in the perturbative expansion).
option **5** : Strings are allowed to reconnect if *gamma < timeDilationPar * mDip' * r* and if a single pair of dipoles are in causal contact the reconnection is allowed. mDip' is the invariant mass at the formation of the dipole (ie. the first time the colour tag appear in the perturbative expansion).

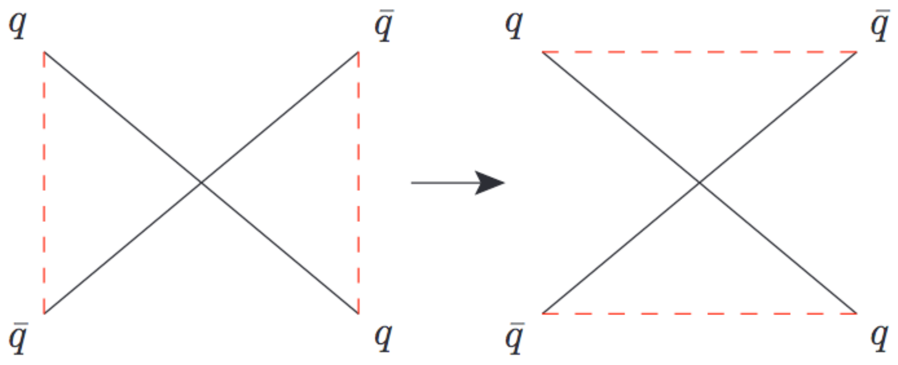
parm **ColourReconnection:timeDilationPar** (default = **0.18**; minimum = 0; maximum = 100)
This is a tuneable parameter for the time dilation. The definition can be seen above under `timeDilationMode`.

MC tune with color reconnection models for UE description
PYTHIA 8 Implementation of CR

Gluon-move CR model



Iteratively move final-state gluons between string pieces of partons



Flip color line of two strings if it reduces the string length

Free parameters in PYTHIA8:
- **ColourReconnection:m2Lambda** -> in string length definition
- **ColourReconnection:fracGluon** -> the probability of a gluon move