Event Generator Tuning in the CMS Experiment

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(on behalf of the CMS Collaboration)

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CMS Event Generator Tunes (7 TeV)

UE tunes

CUETP8 S1/M1 (PYTHIA8)

S1 tunes based on 4C (CTEQ6L1)
- CUETP8S1-CTEQ6L1
- CUETP8S1-HERAPDF1.5LO

M1 tune based on Monash (NNPDF2.3LO)
- CUETP8M1

CUETP6S1 (PYTHIA6)

S1 tunes based on PYTHIA6 Z2*lep (CTEQ6L1)
- CUETP6S1-CTEQ6L1
- CUETP6S1-HERAPDF1.5LO

CUETHppS1 (HERWIG++)

CUETHppS1 tune using CTEQ6L1 based on Herwig++ Tune UE-EE-5C.
- CUETHppS1

DPS tunes

CDPSTP8 S1/S2 (PYTHIA8)

DPS observables in W+dijet and 4j events

- CDPSTP8S1-Wj
- CDPSTP8S1-4j

} only expPow tuned

- CDPSTP8S2-Wj
- CDPSTP8S2-4j

} all MPI+CR parameters tuned

expPow: matter overlap, most sensitive to σ_{eff}

[CMS-GEN-14-001], EPJC 76, 155 (2016)

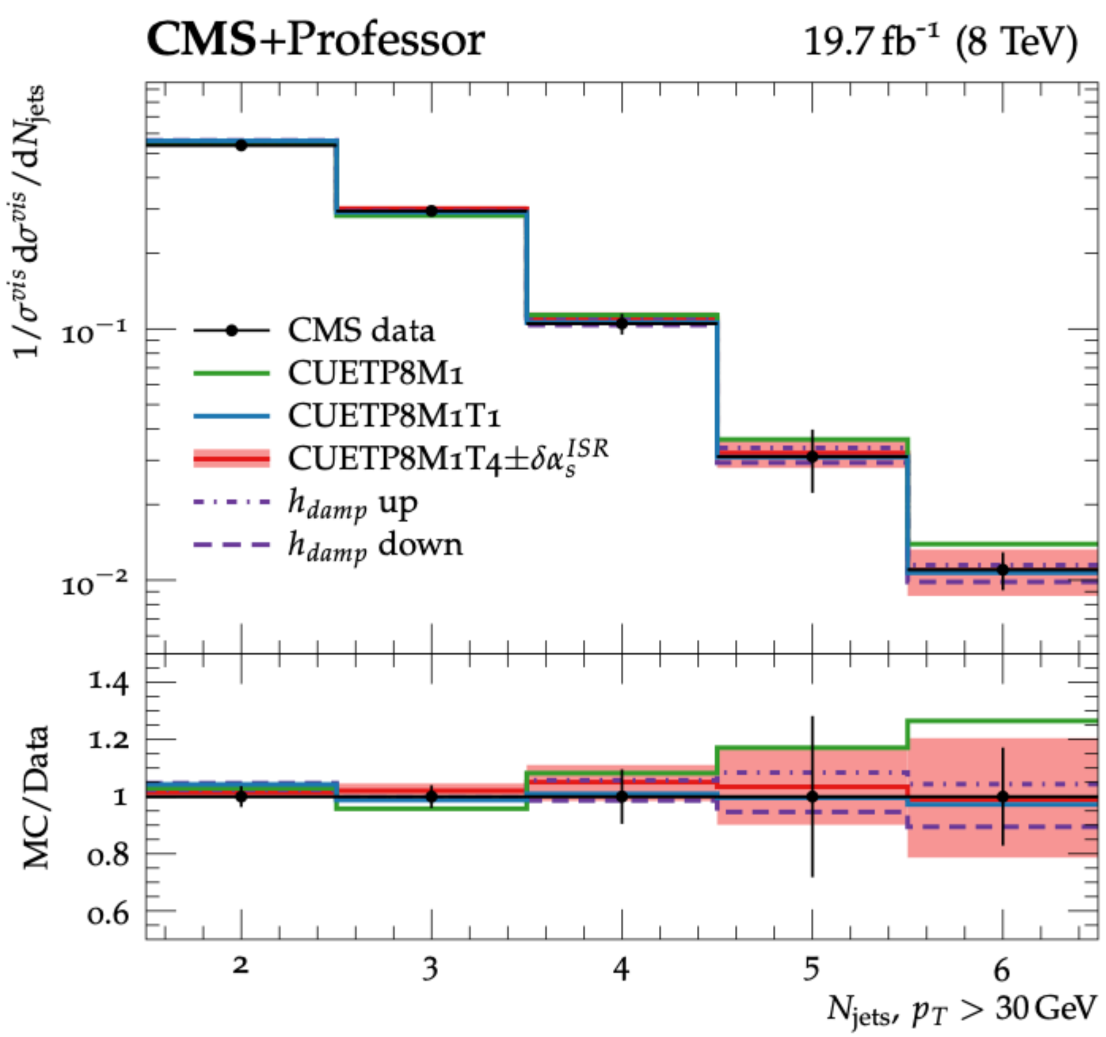
"CUET" stands for CMS Underlying Event tune
"CPDS" stands for CMS DPS (Double Parton Scattering) tune

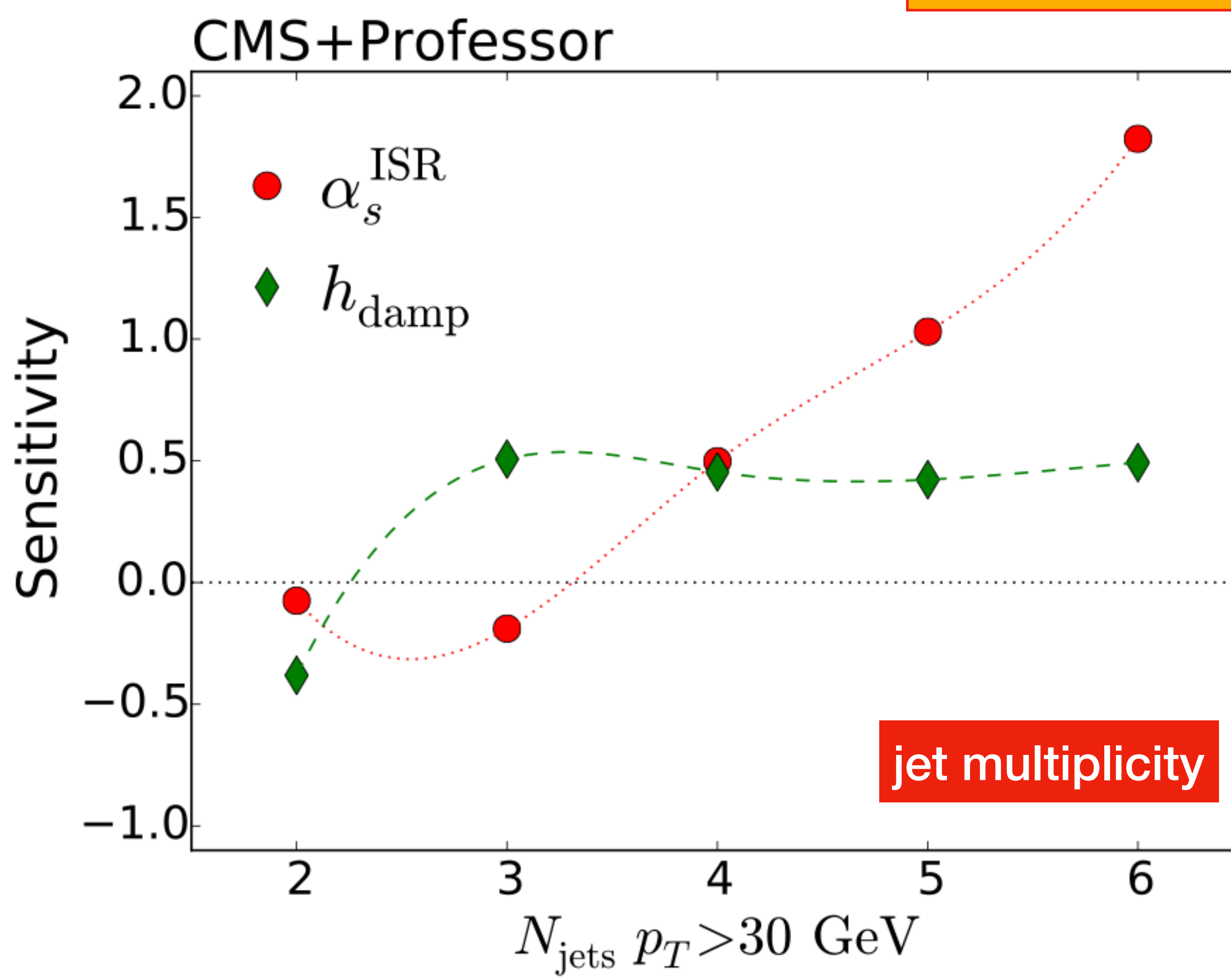
- **CUETP8M1** used for legacy production at 7 TeV
- tuning of MPI + CR parameters to MB & UE observables at 0.9, 1.96 (CDF), 7 TeV
- DPS tunes are obtained by tuning of MPI + CR parameters to DPS observables
- validation of the tunes at various final states and c.o.m. energies.
- studied predictions for 13 TeV
- provided tune uncertainties
- calculated σ_{eff} (DPS)
- Rivet + Professor

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

CUETP8M2T4 (α_s^{ISR} + h_{damp} tuning)

[CMS-TOP-16-021





Additional jet multiplicity (Njets) in ttbar depends on α_s^{ISR} and ME/PS matching hdamp

- CUETP8M2T4: based on CUETP8M1.
- tuning of Powheg+Pythia ISR to ttbar events at 8 TeV + retune of MPI parameters to 13 TeV (ecmPow fixed to the value of CUETP8M1)
- Describes Njets in ttbar better than Powhegv2 + PYTHIA8 CUETP8M1.
- $\alpha_s^{\text{ISR}} = 0.1108^{+0.0145}_{-0.0142}$ (cf. in CUETP8M1 (Monash-based) tune α_s^{ISR} = 0.1365)

CMS Event Generator Tunes (13 TeV)

UE tunes

CP (**C**MS **P**YTHIA8) tunes

[CMS-GEN-17-001], EPJC 80, 4 (2020)

- CP1 / CP2: NNPDF 3.1 LO + α_S = 0.1365/0.130 (Monash/PDF value)
- CP3 / CP4 / CP5: NNPDF 3.1 (N)NLO + α_S = 0.118 consistent with PDF and ME

CH (**C**MS **H**erwig7) tunes

[CMS-GEN-19-001], EPJC 81, 312 (2021)

NNPDF 3.1 NNLO PDF for PS.

$\alpha_S(m_Z)$ = 0.118, $\alpha_S^{PDF}(m_Z)$ = 0.118; LO or NNLO for MPI and beam remnants;

- CH1: NNLO
- CH2: LO
- CH3: LO

Colour Reconnection (CR) tunes

CP **CR** (**C**olour **R**econnection) tunes

[CMS-GEN-17-002], arXiv:2205.02905, accepted by EPJC

- CP5-CR1 (QCD-inspired CR model)
- CP5-CR2 (gluon-move CR model)

LO CR tunes:

- CP1-CR1
- CP2-CR1

- **CP5** used for legacy production at 13 TeV
- tuning of MPI + CR parameters to MB & UE observables at 1.96 (CDF), 7, and 13 TeV
- better description of the data when $\alpha_S^{ISR}(m_Z)$=0.118 is used (i.e. CP3-CP5 tunes)
- validation of the tunes at various final states and c.o.m. energies.
- up/down tunes
- Rivet + Professor + MCPLOTSCMS

UE model: main parameters

$$p_\perp^{\min} = p_{\perp,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b,$$

E_0: reference energy
b: energy dependence of $p_\perp^{\min}$

$$\langle n\rangle = A(d)\sigma(s), \qquad A(d) = \frac{\mu^2}{96\pi}(\mu d)^3 K_3,$$

$\langle n\rangle$: mean number of additional interactions

μ^2 : inverse proton radius squared

In PYTHIA8: a double Gaussian matter distribution, with the two free parameters *coreRadius* and *coreFraction*.

1. **p_T threshold parameter** ($p_\perp^{\min}$) to govern transition between soft and hard interactions.
   lower threshold → more MPI (UE activity).
2. **energy dependence** of $p_\perp^{\min}$
3. **overlap distribution between two colliding protons**
   denser overlap → more MPI.
   (μ^2 in Herwig, coreFraction/coreRadius in PYTHIA8)
4. **colour reconnection probability**

HERWIG 7.1

Parameter	HERWIG 7 configuration parameter
$p_{\perp,0}^{\min}$ (GeV)	/Herwig/UnderlyingEvent/MPIHandler:pTmin0
b	/Herwig/UnderlyingEvent/MPIHandler:Power
μ^2 (GeV^{-2})	/Herwig/UnderlyingEvent/MPIHandler:InvRadius
p_{reco}	/Herwig/Hadronization/ColourReconnector:ReconnectionProbability

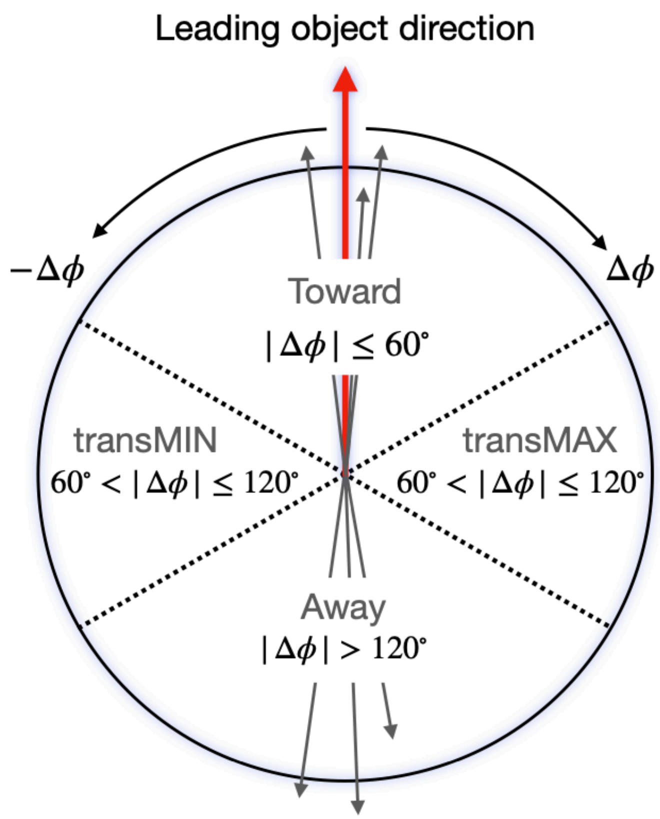
p_{reco}: Colour reconnection probability for accepting a proposed reconnection. Plain CR model (default).

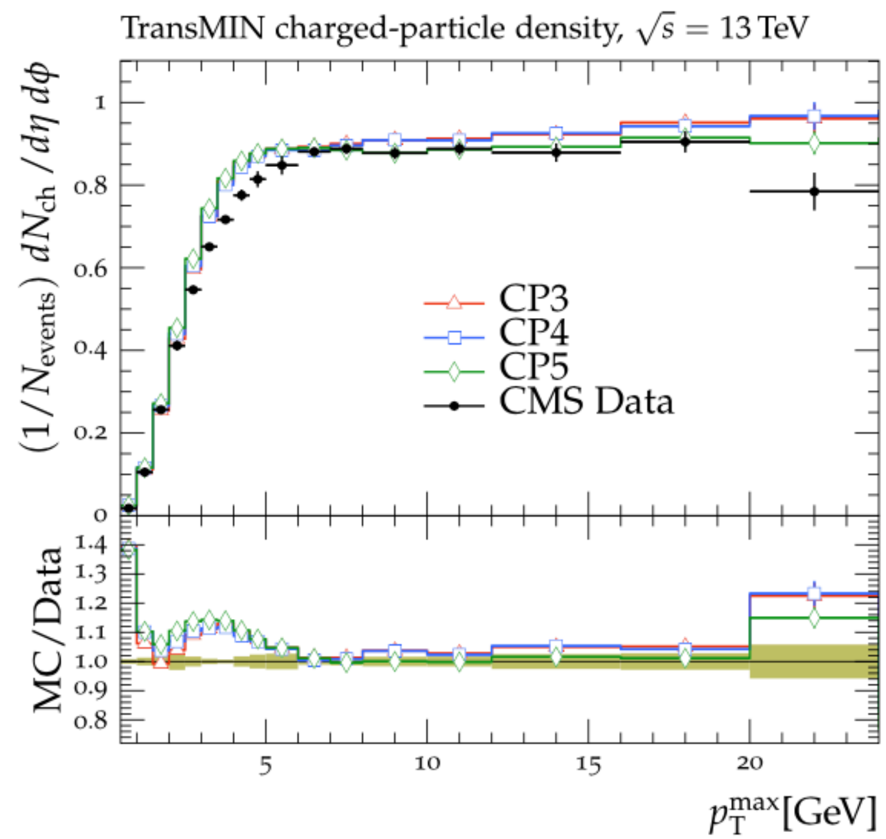
PYTHIA 8.2

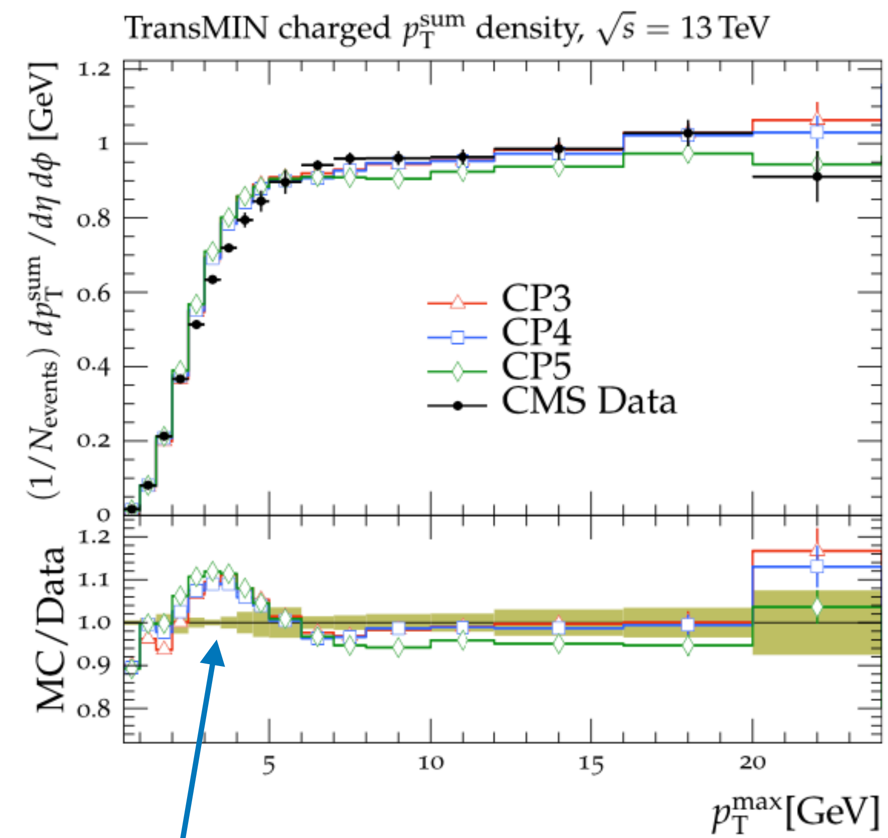
Parameter description	Name in PYTHIA8
MPI threshold (GeV), `pT0Ref`, at $\sqrt{s} = \sqrt{s_0}$	`MultipartonInteractions:pT0Ref`
Exponent of $\sqrt{s}$ dependence, ϵ	`MultipartonInteractions:ecmPow`
Matter fraction contained in the core	`MultipartonInteractions:coreFraction`
Radius of the core	`MultipartonInteractions:coreRadius`
Range of color reconnection probability	`ColorReconnection:range`

ColourReconnection:range probability for accepting a proposed reconnection. MPI-based model (default).

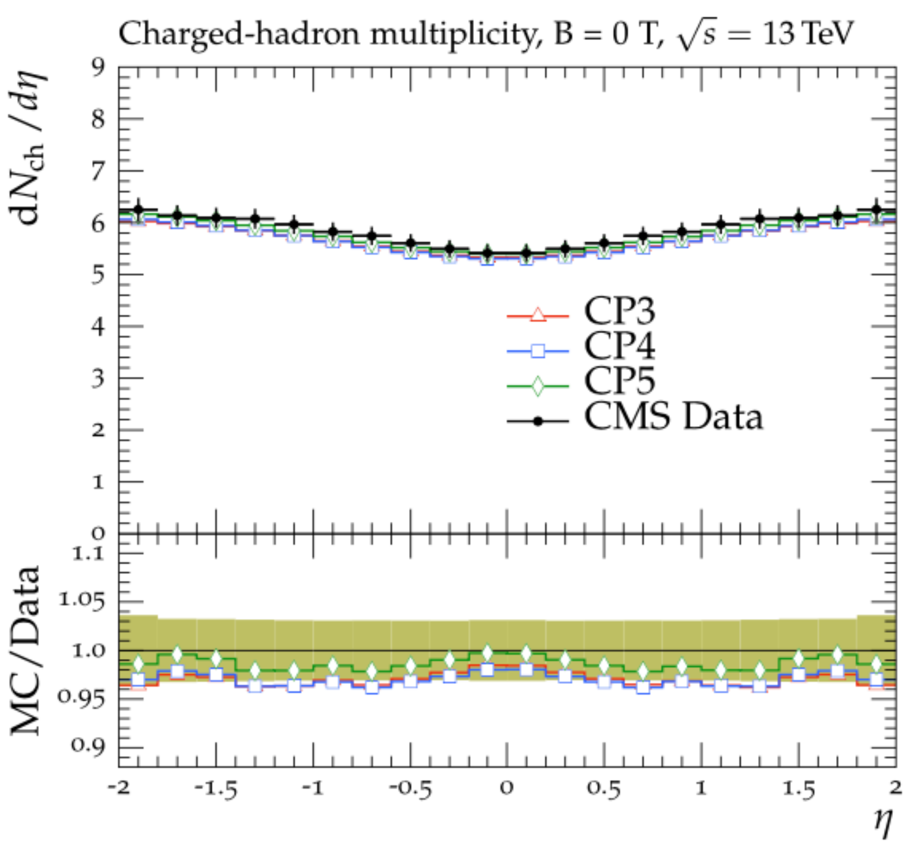
CMS UE tunes: tuning procedure







p_T^{max} < 3 GeV excluded from the fits (diffractive contributions)



Observables used in tuning:

- $dN_{ch}/d\eta$ at 13 TeV
- Charged-particle density and p_T^{sum} density in TransMIN and TransMAX regions @1.96 (0.9 TeV for Herwig7), 7, and 13 TeV.

minimize the χ² function:

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

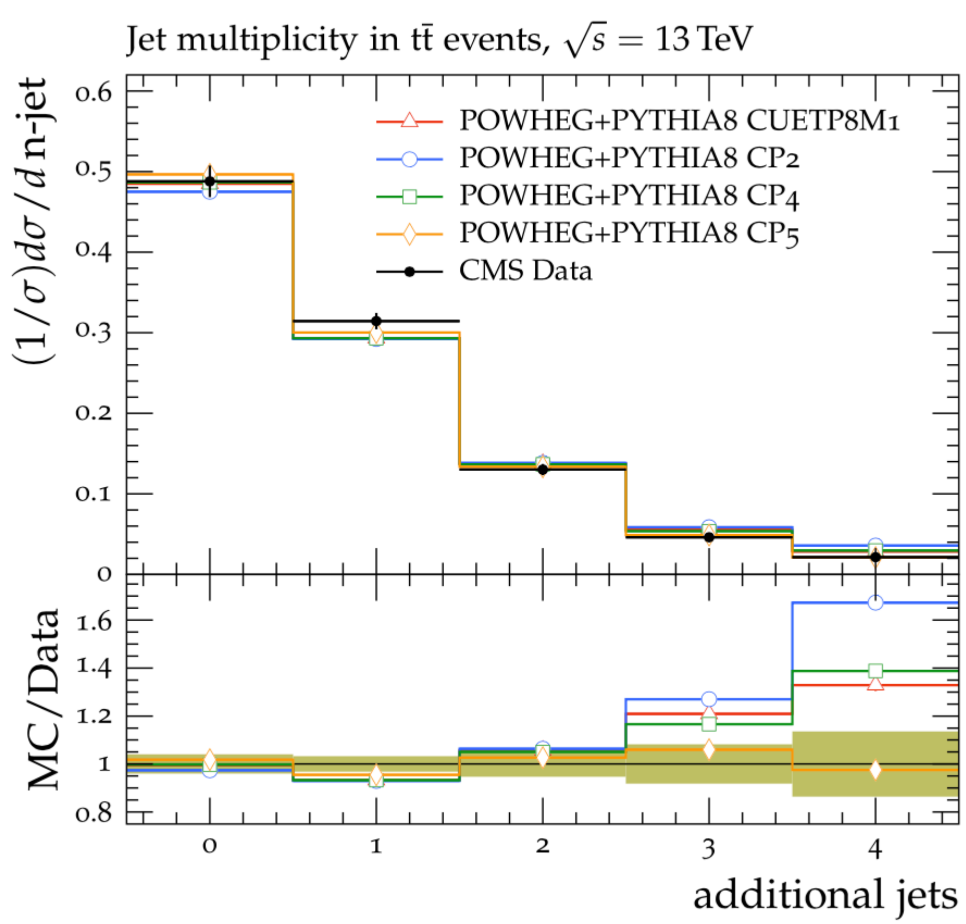
R_i: measured bin content of bin i of observable O.
$f^i(p)$: predicted bin content.
p: tuning parameters.
w: weight

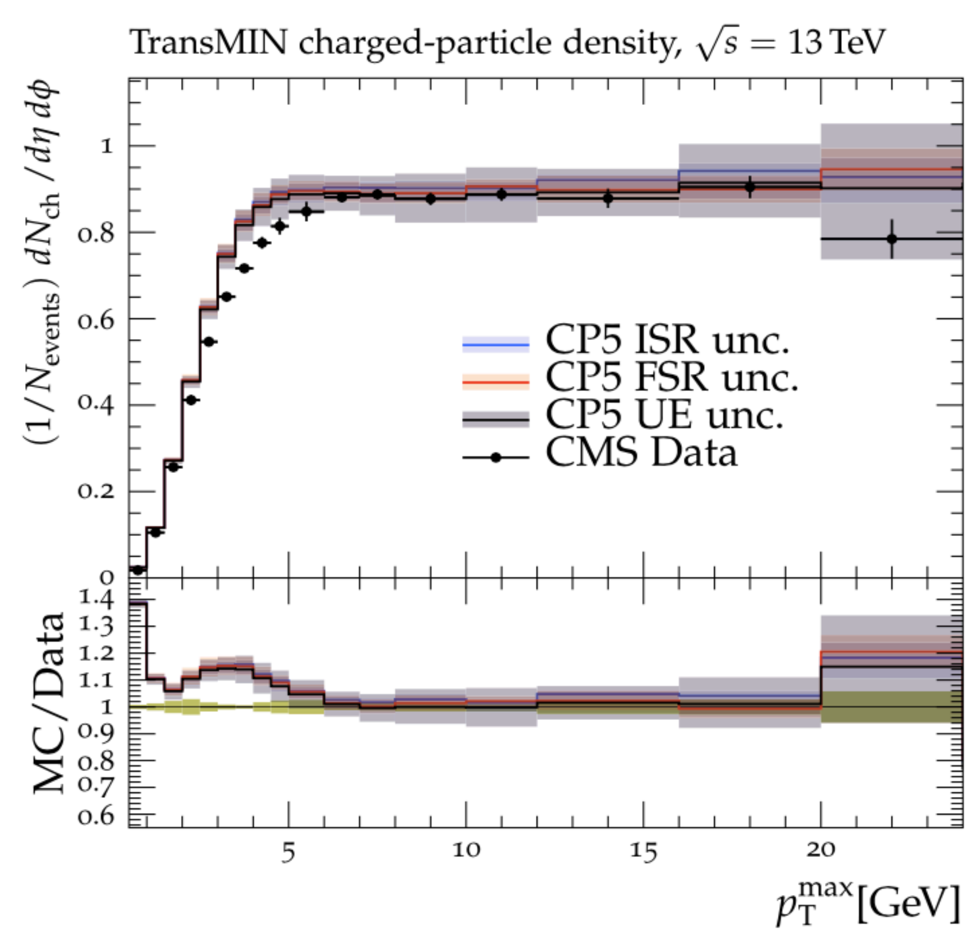
CP (CMS PYTHIA8) UE tunes

PYTHIA8 parameter	CP1	CP2	CP3	CP4	CP5
PDF Set	NNPDF3.1 LO	NNPDF3.1 LO	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.130	0.130	0.118	0.118	0.118
`SpaceShower:rapidityOrder`	Off	Off	Off	Off	On
`MultipartonInteractions:EcmRef` (GeV)	7000	7000	7000	7000	7000
$\alpha_S^{ISR}(m_Z)$ value/order	0.1365/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.1365/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.130/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.130/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
`MultipartonInteractions:pT0Ref` (GeV)	2.4	2.3	1.52	1.48	1.41
`MultipartonInteractions:ecmPow`	0.15	0.14	0.02	0.02	0.03
`MultipartonInteractions:coreRadius`	0.54	0.38	0.54	0.60	0.76
`MultipartonInteractions:coreFraction`	0.68	0.33	0.39	0.30	0.63
`ColorReconnection:range`	2.63	2.32	4.73	5.61	5.18
χ^2/dof	0.89	0.54	0.76	0.80	1.04

fitted parameters

- **CP5**: default CMS PYTHIA8 UE tune for 13 TeV. NNPDF 3.1 NNLO, $\alpha_S = 0.118$ for ISR, FSR, MPI, ME, consistent with PDF.
- *RapidityOrdering* for ISR reduces phase space for parton emission. Makes a big difference in POWHEG+PYTHIA8. Njets in ttbar best described by CP5.



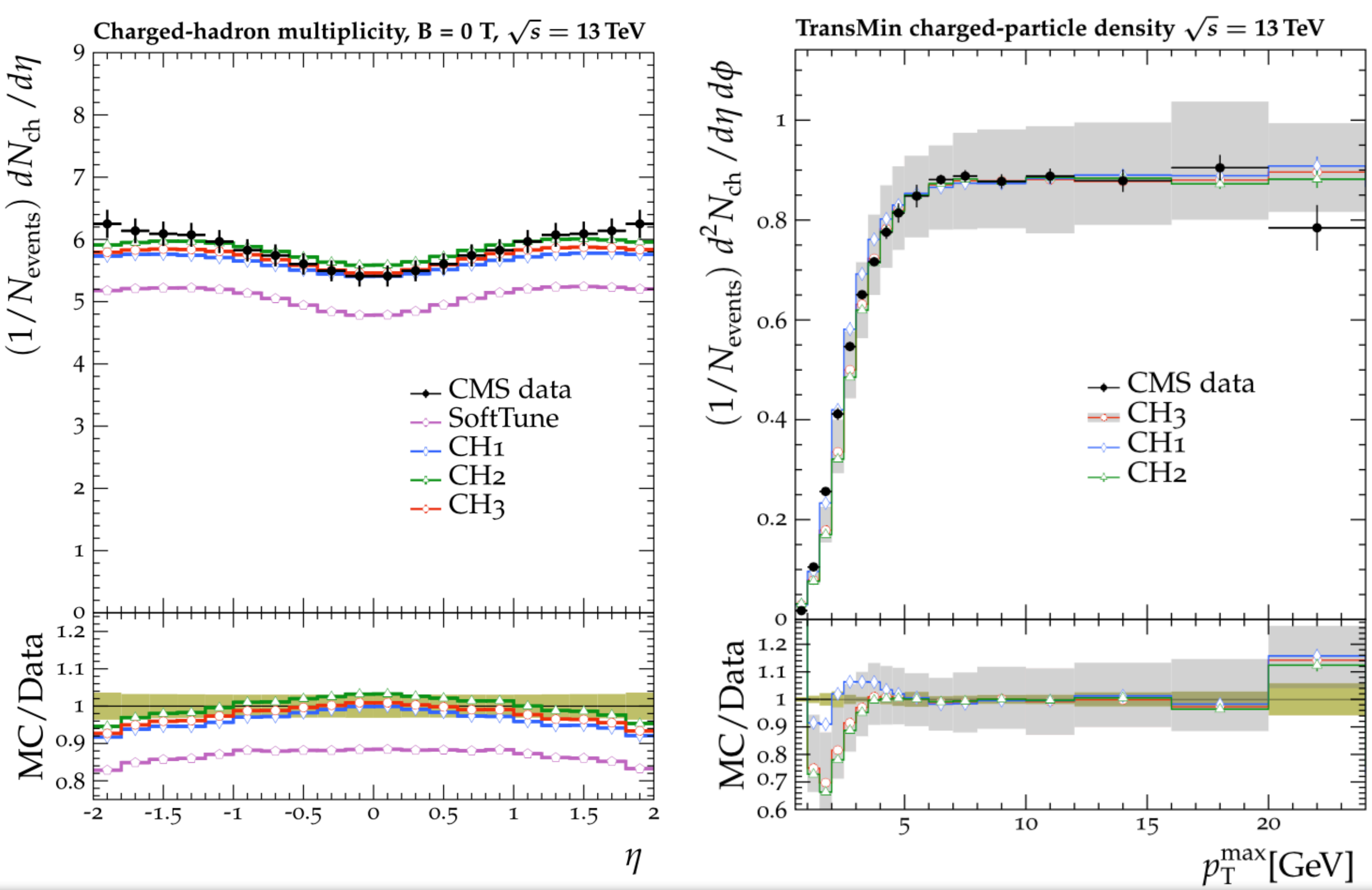


CH (CMS Herwig7) UE tunes

		SoftTune	CH1	CH2	CH3
$\alpha_S(m_Z)$		0.1262	0.118	0.118	0.118
PS	PDF set	MMHT2014 LO	NNPDF3.1 NNLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
	$\alpha_S^{PDF}(m_Z)$	0.135	0.118	0.118	0.118
MPI &	PDF set	MMHT2014 LO	NNPDF3.1 NNLO	NNPDF3.1 LO	NNPDF3.1 LO
remnants	$\alpha_S^{PDF}(m_Z)$	0.135	0.118	0.118	0.130
$p_{\perp,0}^{min}$ (GeV)		3.502	2.322	3.138	3.040
b		0.416	0.157	0.120	0.136
μ^2 (GeV^{-2})		1.402	1.532	1.174	1.284
p_{reco}		0.5	0.400	0.479	0.471
χ^2/N_{dof}		12.8	6.75	1.54	1.71

Equivalent to CP5

fitted parameters



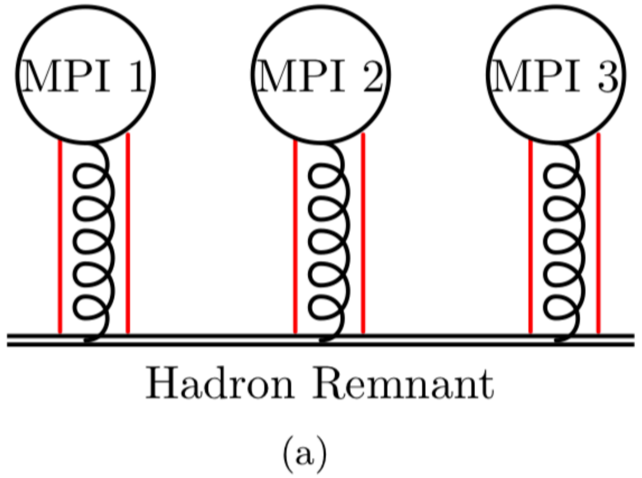
- LO PDF for MPI and beam remnants preferred over NNLO PDF
- Choice of α_s in PDF less important, but α_s = 0.130 is typically associated with LO PDF sets.
- **CH3 preferred choice over CH2.** Up/down tunes for CH3 provided.
- CH tunes increase amount of MPI w.r.t SoftTune. All CH tunes describe $dN_{ch}/d\eta$.

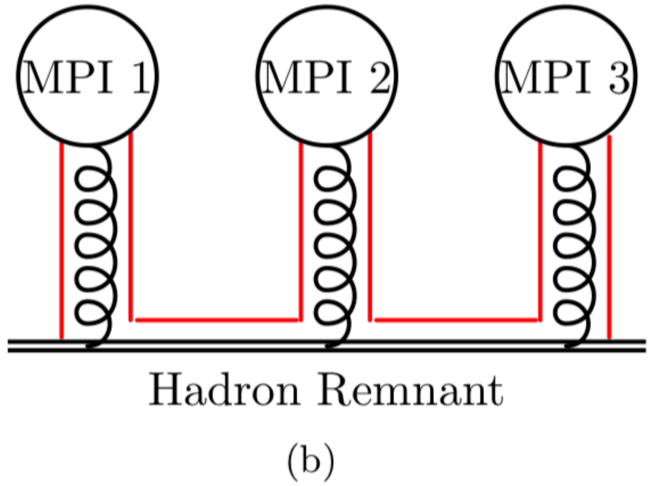
CP5 based CR (Colour Reconnection) tunes

[CMS-GEN-17-002], arXiv:2205.02905

Eur. Phys. J. C
Accepted: 16 May 2023

What is Colour Reconnection?





Leading colour (LC) approximation:

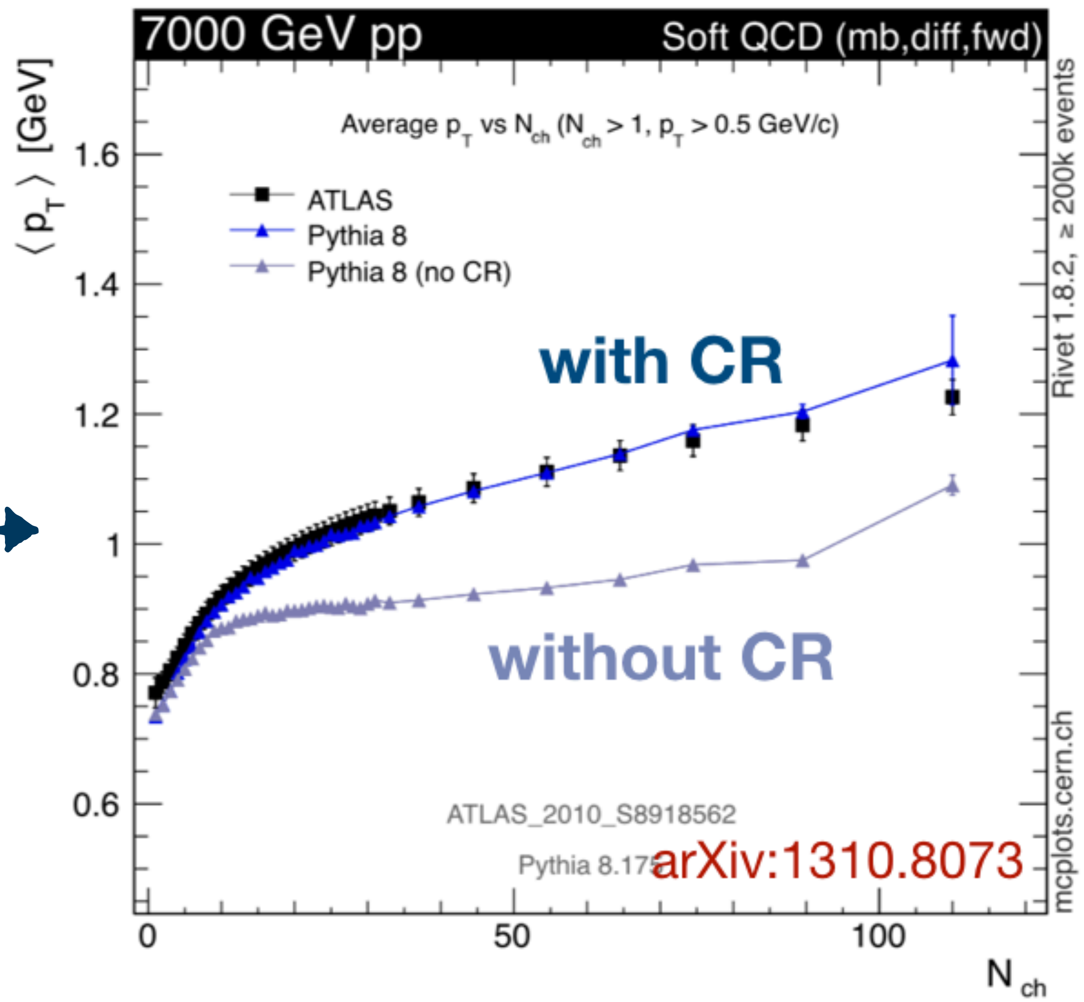
- Each MPI is viewed as separate from all other systems in colour space.
- No strings stretched between different MPI systems.

Color reconnection allows different MPI systems to be colour-connected to each other. **MPI hadronize collectively**.

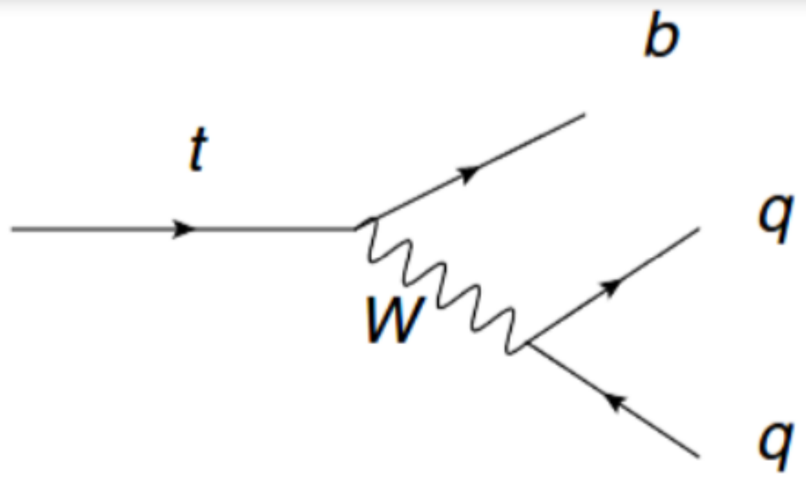
Christiansen, J.R., Skands, P.Z. JHEP, 2015, 3

Rising trend of ⟨p⊥⟩ vs N_{ch}:

- first observed by UA1 [***Nucl. Phys. B335 (1990)***]
- Colour reconnection is needed to describe the data.

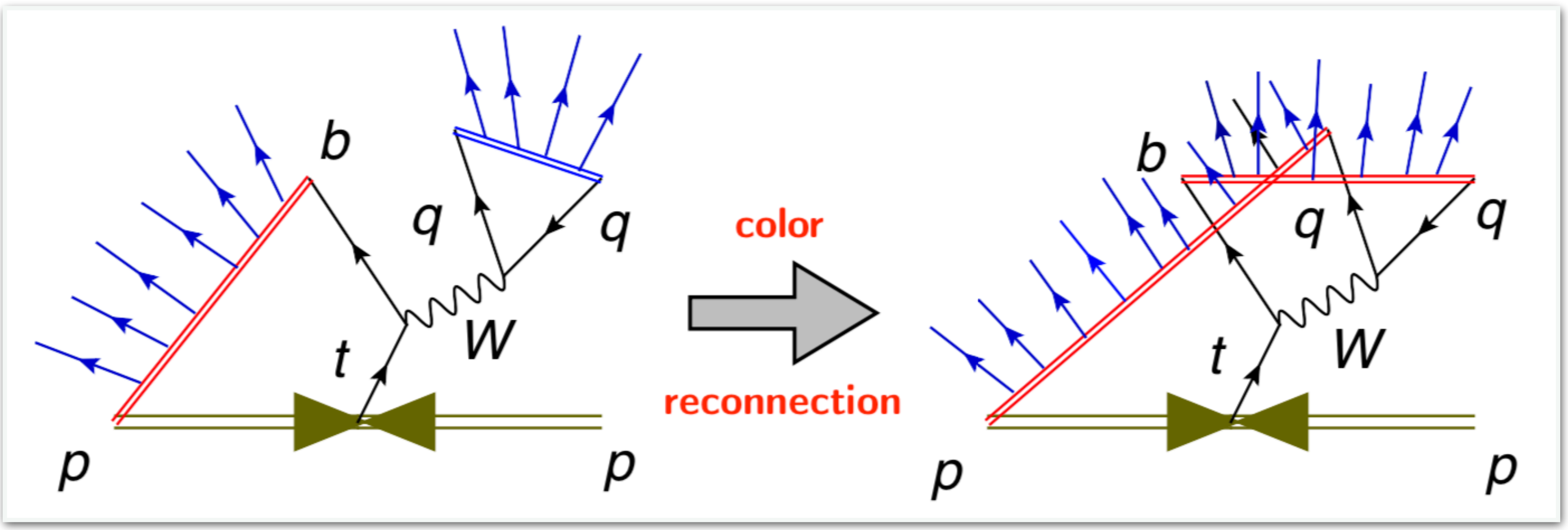


Effect of CR on m_{top}



$$t \to bW \to bq\bar{q}$$

$$\widehat{m}^2_{\text{top}} = (p_{\text{b}} + p_{\text{j1}} + p_{\text{j2}})^2$$



Credits: Spyros Argyropoulos
JHEP11 (2014) 043

$$m^2_{\text{top}} \neq (p_{\text{b}} + p_{\text{j1}} + p_{\text{j2}})^2$$

Typical hadronization scale is around 1 fm → But top quark travels ~0.2 fm before it decays.

In PYTHIA8 (Early Resonance Decay (ERD))

- **ERD = off**: top quark can colour reconnect to other partons.
- **ERD = on**: the decay products of the top quark can colour reconnect to other partons.

CR models in PYTHIA8

I. MPI-based *(G. Gustafson, Acta Phys. Polon. B40, 1981 (2009))*

Reconnection probability (single tunable parameter)

$$P_{\text{rec}}(p_{\text{T}}) = \frac{(R_{\text{rec}} \cdot p_{\text{T0}})^2}{R_{\text{rec}} \cdot p\text{T0} + p_{\text{T}}^2}$$

Reduce λ by adding partons of the lower-pT system to the strings defined by the higher-pT system.

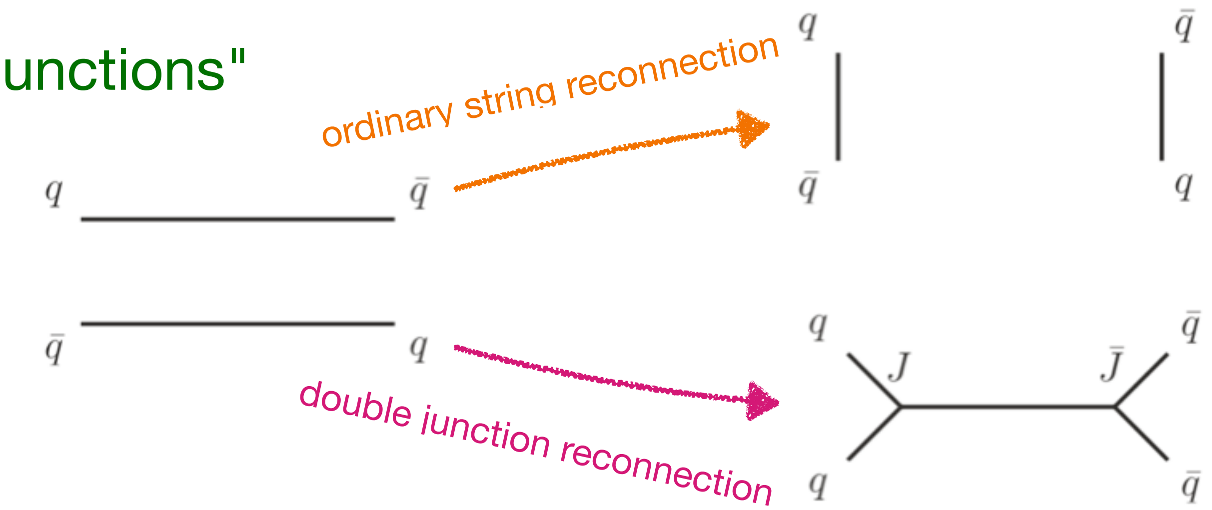
$p_{\text{T}} \downarrow \Rightarrow P_{\text{rec}} \uparrow$

softer systems easier to reconnect

II. QCD-inspired *(Christiansen, J.R., Skands, P.Z. JHEP, 2015, 3)*

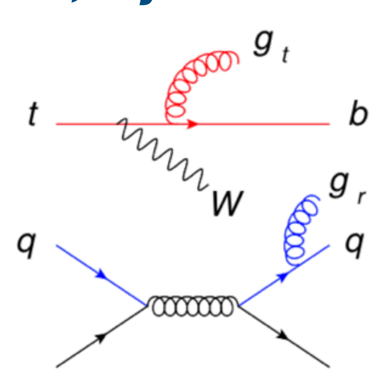
- Another approach for reconnection ⇒ introduce "junctions"
- More realistic; colour topologies defined by the SU(3) colour algebra.
- Improves description of baryon production.

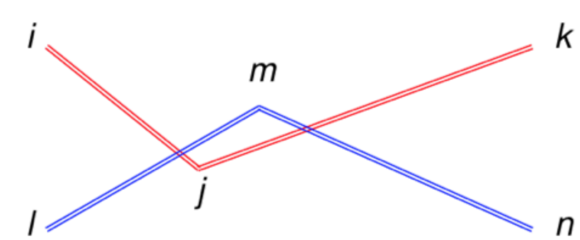
various types of junction reconnections available...



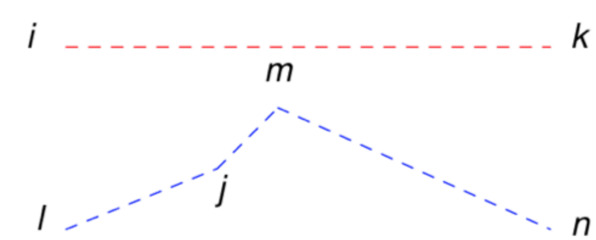
III. gluon-move *(Argyropoulos, S., Sjöstrand, T., JHEP, 2014, 43)*

A gluon can be moved from one string to another if it leads to a smaller total string length λ.





original configuration



resulting configuration after moving the gluon (reduced λ)

CP5-CR tunes settings

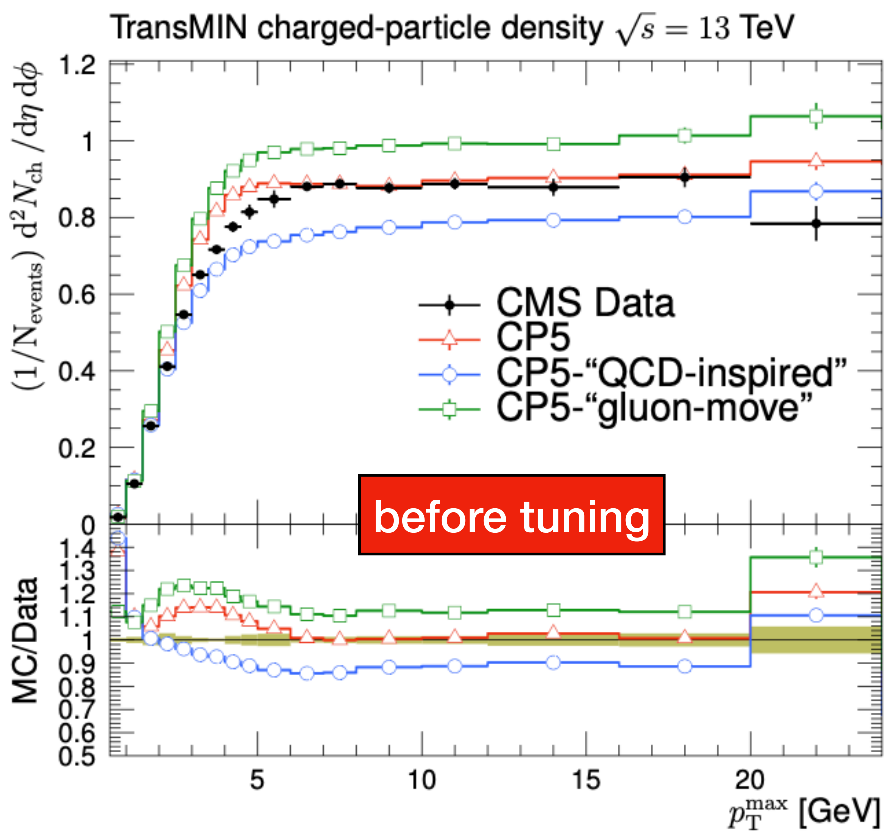
Replace the MPI-based CR model used in the CP5 with the QCD-inspired (CR1) and gluon-move (CR2) models, respectively, and tune the MPI + CR parameters.

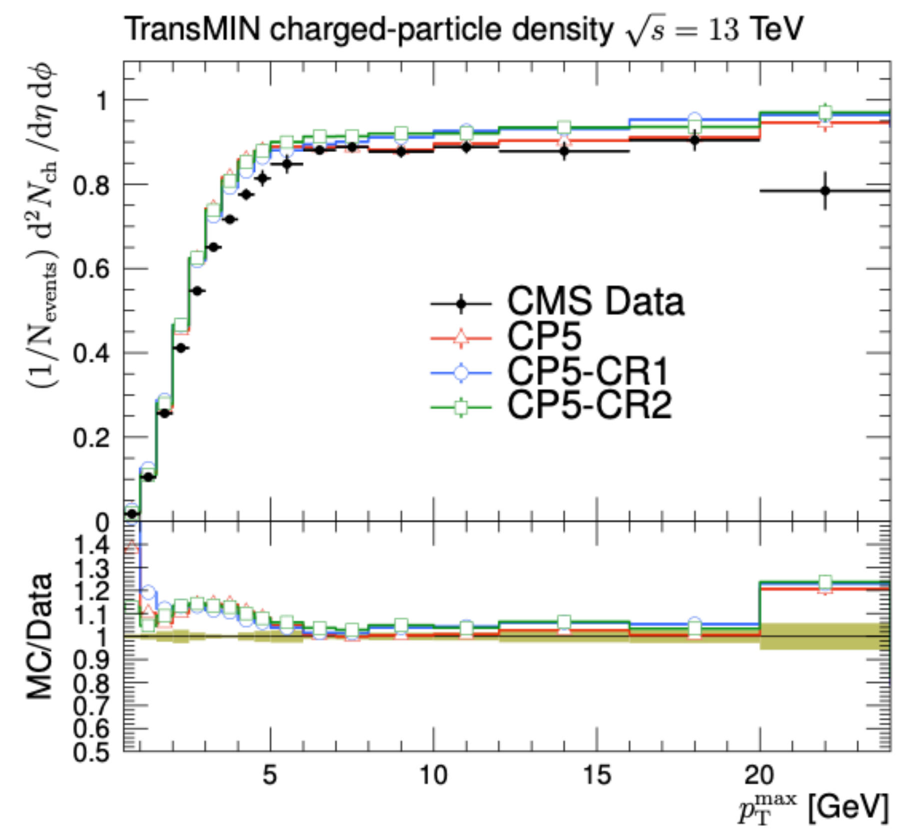
fixed parameters

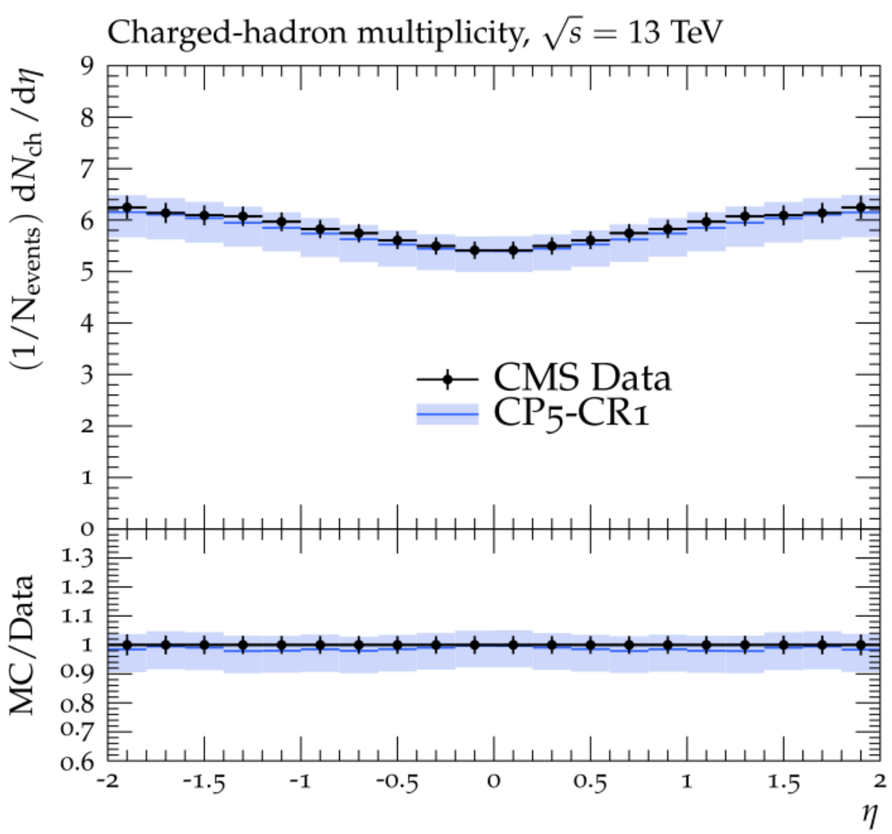
tuned parameters (CR + MPI)

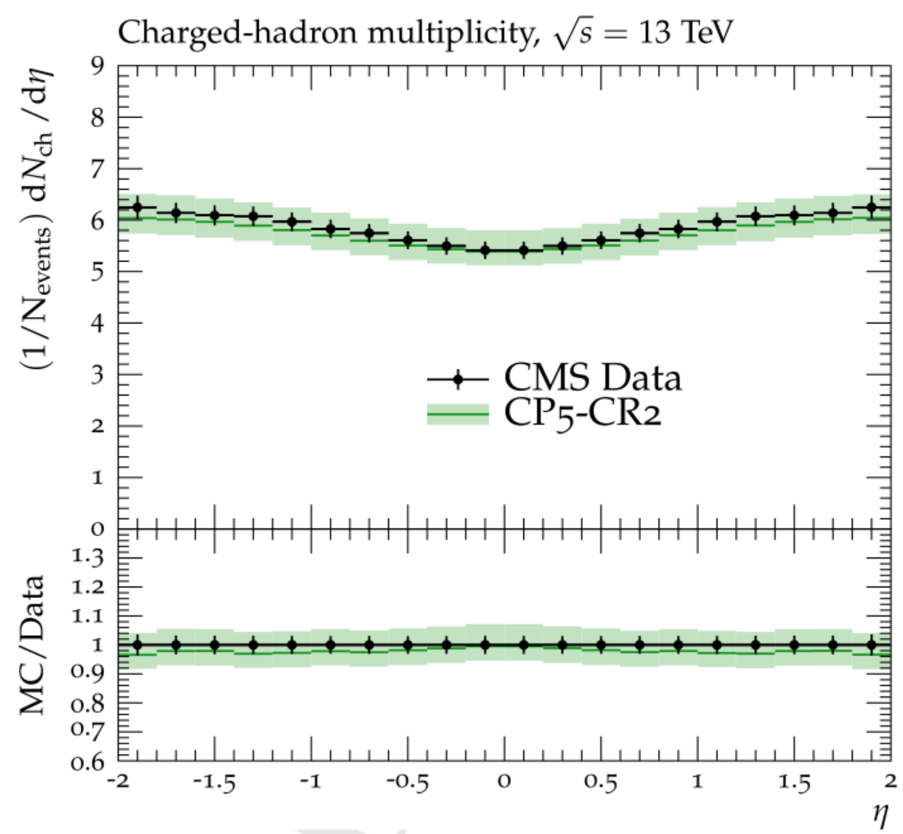
PYTHIA 8 parameter	CP5 [10]	CP5-CR1	CP5-CR2
PDF set	NNPDF3.1 NNLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118	0.118	0.118
`SpaceShower:rapidityOrder`	on	on	on
`MultipartonInteractions:ecmRef` [GeV]	7000	7000	7000
$\alpha_S^{ISR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
`StringZ:aLund`	—	0.38	—
`StringZ:bLund`	—	0.64	—
`StringFlav:probQQtoQ`	—	0.078	—
`StringFlav:probStoUD`	—	0.2	—
`SigmaTotal:zeroAXB`	off	off	off
`BeamRemnants:remnantMode`	—	1	—
`ColourReconnection:mode`	—	1	2
`MultipartonInteractions:pT0Ref` [GeV]	1.410	1.375	1.454
`MultipartonInteractions:ecmPow`	0.033	0.033	0.054
`MultipartonInteractions:coreRadius`	0.763	0.605	0.649
`MultipartonInteractions:coreFraction`	0.630	0.445	0.489
`ColourReconnection:range`	5.176	—	—
`ColourReconnection:junctionCorrection`	—	0.238	—
`ColourReconnection:timeDilationPar`	—	8.580	—
`ColourReconnection:m0`	—	1.721	—
`ColourReconnection:m2lambda`	—	—	4.917
`ColourReconnection:fracGluon`	—	—	0.993
N_{dof}	183	157	158
χ^{*2}/N_{dof}	1.04	2.37	0.89

CP5-CR tunes results









- Good description of plateau by all tunes. Low p_T part highly sensitive to diffractive contributions. Below ≈2-3 GeV is not included in the fits.
- New tunes perform better compared to tunes using default parameters of the new CR models.
- Tune uncertainties provided.

Top quark mass predicted by CP5-CR tunes

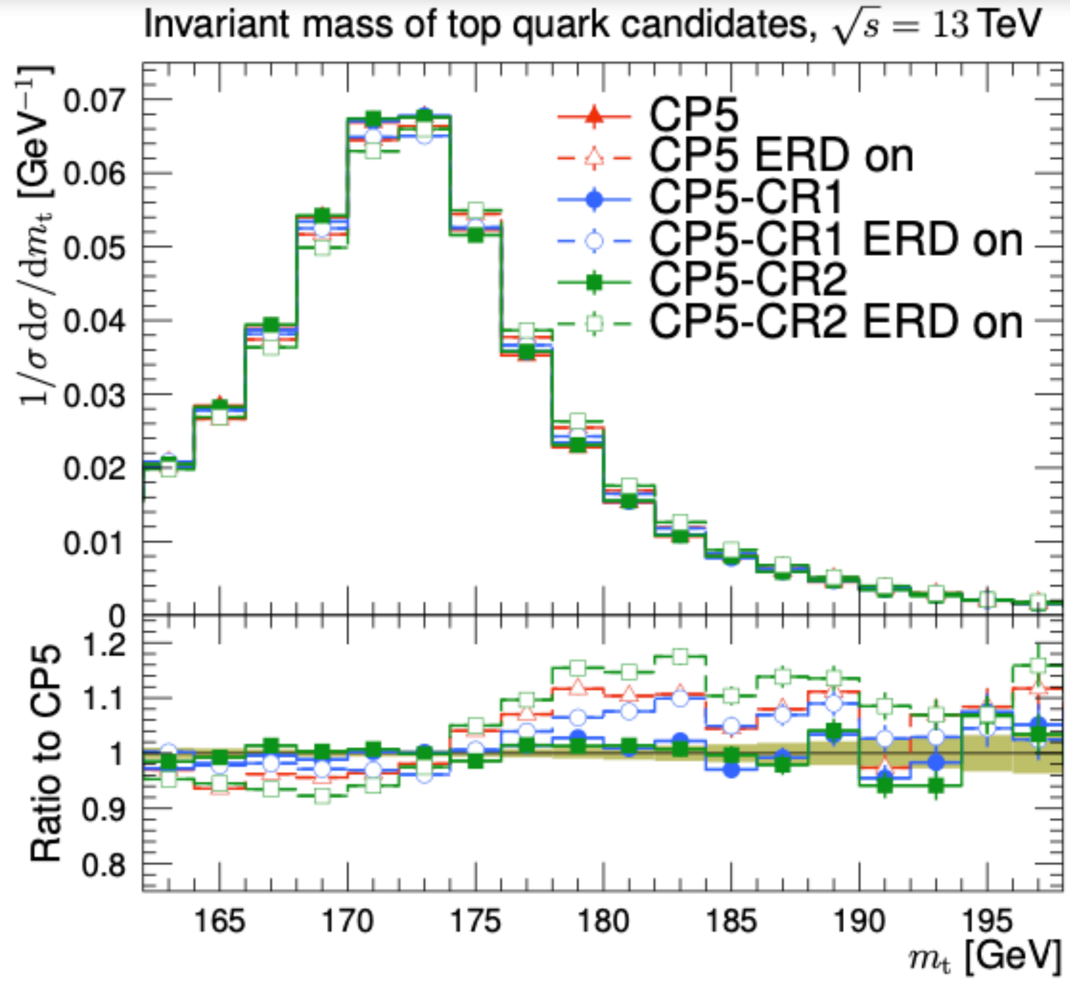
- Most precise measurement by CMS experiment combining the data at 7 and 8 TeV:

$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV},$$

  - Top/W mass values obtained by fitting a Gaussian function within an 8 GeV mass window around the corresponding mass peak.

$$\Delta m_t^{\text{hyb}} = \Delta m_t - 0.5\Delta m_W$$

Used in CMS-TOP-17-007 to estimate uncertainty on m_{top}



Tune	m_t [GeV]	Δm_t [GeV]	m_W [GeV]	Δm_W [GeV]	Δm_t^{hyb} [GeV]
CP5	171.93 ± 0.02	—	79.76 ± 0.02	—	—
CP5 ERD	172.18 ± 0.03	0.25	80.15 ± 0.02	0.40	0.05
CP5-CR1	171.97 ± 0.02	0.04	79.74 ± 0.02	−0.02	0.05
CP5-CR1 ERD	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 ERD	172.32 ± 0.03	0.39	79.90 ± 0.02	0.14	0.32

largest deviation from the predictions of CP5

- 0.32 GeV is similar to the shift (0.31 GeV) found in CMS-TOP-17-007 using CUETP8M2T4.

CP5 does not improve or degrade the precision of the top quark mass measurements.

Summary

- CMS has developed tunes for PYTHIA8, Herwig7, PYTHIA6, and Herwig++.
- Tunes validated in various final states and center-of-mass energies.
- Validation includes LEP event shape observables, multijet events, top quark pairs, W/Z production, double-parton scattering, forward observables, and more.
- Dedicated working group: PCGT (Physics Comparisons and Generator Tunes).
- TMG (Top Modeling and Generators) group also derives and tests tunes.
- Tools used: Rivet, Professor, MCPLOTSCMS.
- Recently employed tools: MCNTUNES, and Apprentice.

Backup

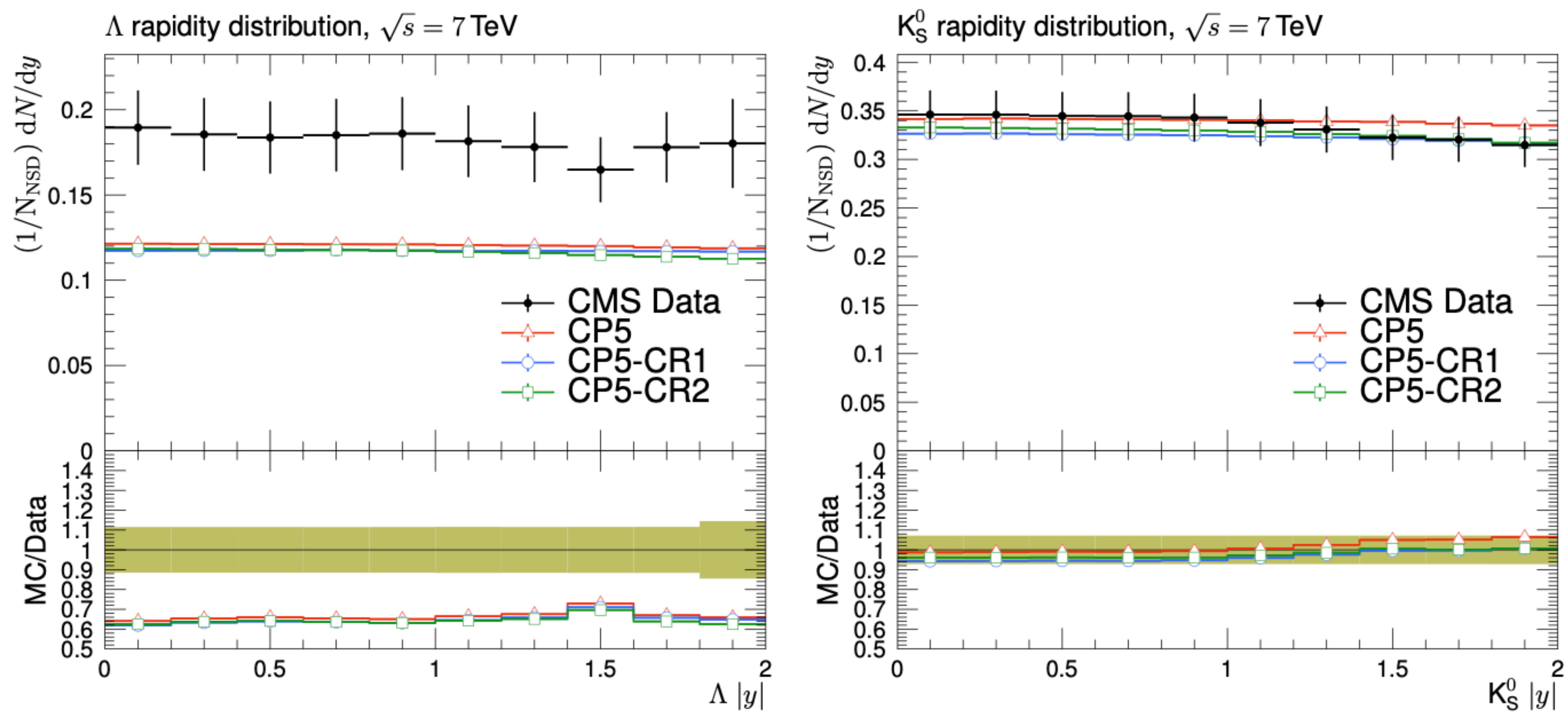
CUETP8M2T4 based CR tunes

Parameters	CUETP8M2T4	QCD inspired	gluon move
MultipartonInteractions:**pT0Ref**	2.20	2.17	2.30
MultipartonInteractions:**expPow**	1.60	1.31	1.35
MultipartonInteractions:**ecmRef**	7000	7000*	7000*
MultipartonInteractions:**ecmPow**	0.25	0.25*	0.25*
ColourReconnection:**range**	6.59	-	-
ColourReconnection:**junctionCorrection**	-	0.12 (1.20)	-
ColourReconnection:**timeDilationPar**	-	15.9 (0.18)	-
ColourReconnection:**m0**	-	1.2 (0.3)	-
ColourReconnection:**m2lambda**	-	-	1.9 (1.0)
ColourReconnection:**fracGluon**	-	-	1.0* (1.0)
ColourReconnection:**dLambdaCut**	-	-	0.0* (0.0)
PDF set	NNPDF30_LO [JHEP 04 (2015)]	NNPDF30_LO	NNPDF30_LO
SpaceShower:alphaSvalue	0.1108*	0.1108*	0.1108*
Goodness of fit/dof	1.89 [CMS-PAS-TOP-16-021]	1.06	1.69
* = value kept fixed in the fit			

- A study based on early UE tune of Run 2. Tunes have been used used in Ref.[1] to calculate the uncertainty on top mass due to the CR modeling.
- NNPDF3.0 LO PDF set.
- A simpler impact parameter profile for the incoming hadron beams is used, i.e., double Gaussion matter is not used.
- In gluon-move model, only m2Lambda parameter was tuned.

[1] CMS Collaboration, "Measurement of the top quark mass with lepton+jets final states using pp collisions at s = 13 TeV", *Eur. Phys. J. C* **78** (2018) 891.

Tune Performances: Strange particle productions (7 TeV)



- It is known that the LHC UE tunes do not perfectly describe strange particle production.
  - Shown in "Christiansen, J.R., Skands, P.Z. JHEP, 2015, 3" that new QCD-based CR model improves Λ/K^0_S versus rapidity production in pp collisions. The study is based on Monash tune with a different PDF set, alphas and MPI values from CP5. (Monash: NNPDF2.3 LO PDF set). Also, data at 13 TeV was not included in the tuning.

- After our tuning to existing data:
  - All CP5 tunes, regardless of the CR model, describe K^0_S versus rapidity very well.
  - Λ versus rapidity is underestimated by 30%. Therefore, Λ/K^0_S is not perfectly described.

MCPLOTSCMS

CMS version of http://mcplots.cern.ch/

Used for tuning and validation: particularly for tuning and validation of CP5-CR tunes and for the validation of CH tunes.