Minimum Bias & Underlying Event: review of measurements and MC tuning at CMS

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Lisbon, Portugal

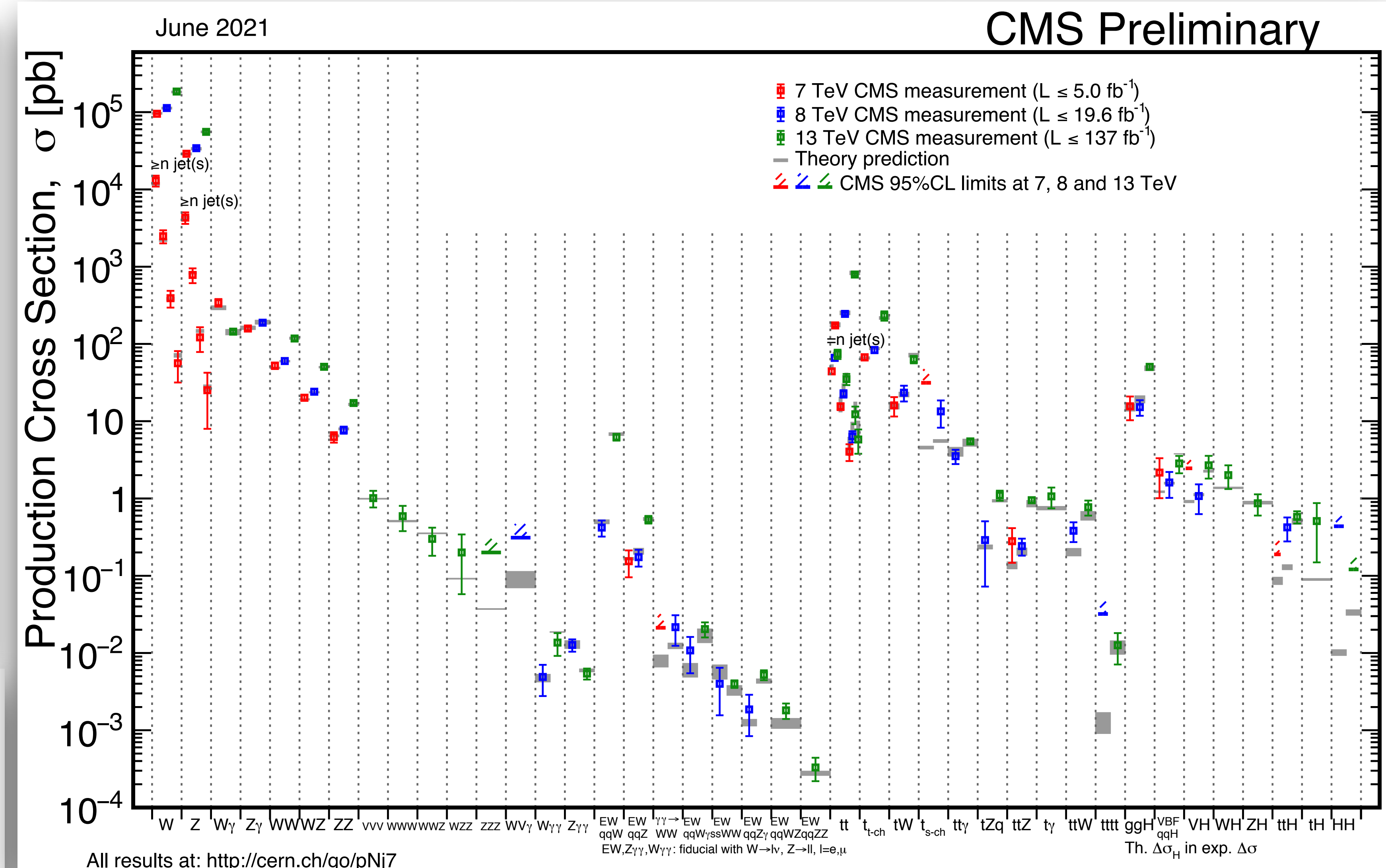
Skeletal Outline

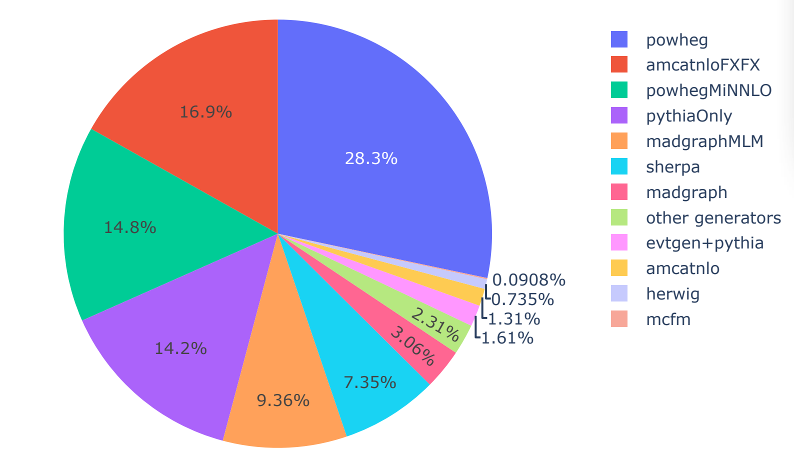
- The LHC as a precision machine
  - Examples of analyses from the top and diboson final states
- The underlying event description and color reconnection modeling
- Color reconnection tunes
  - Performance of the color reconnection tunes in PYTHIA8 NEW
- Studies of double parton scattering NEW
- Going beyond DGLAP NEW

- Focused on recent results where possible
- Emphasis on exploration of novel regions of phase space

Testing the Standard Model

- Inelastic collision cross section ~10^{11} pb
- Vector boson scattering (electroweak ZZ) ~10^{-3} pb
- At the LHC, 14 orders of magnitude probed in cross section
- Excellent agreement with predictions



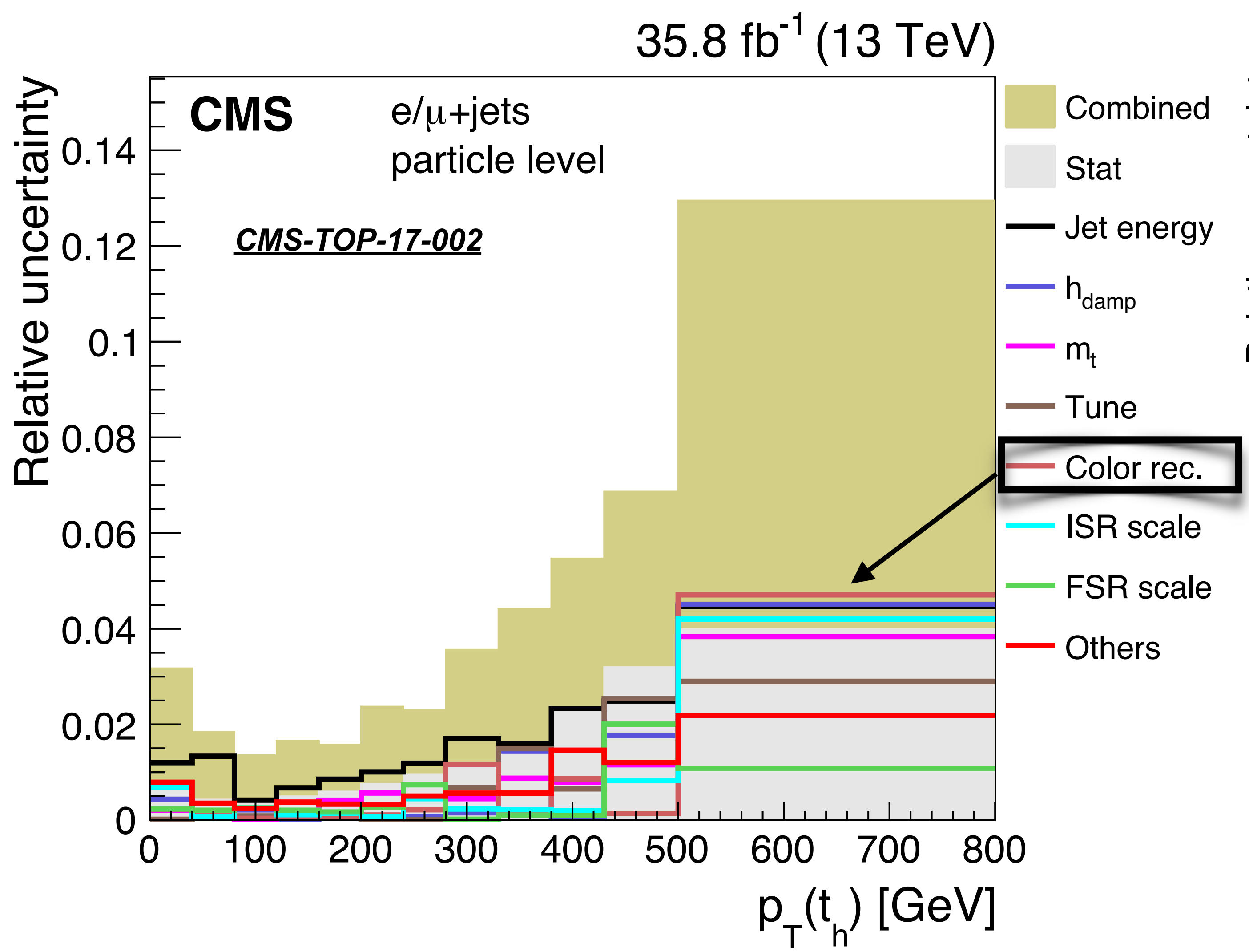


MC production split by events

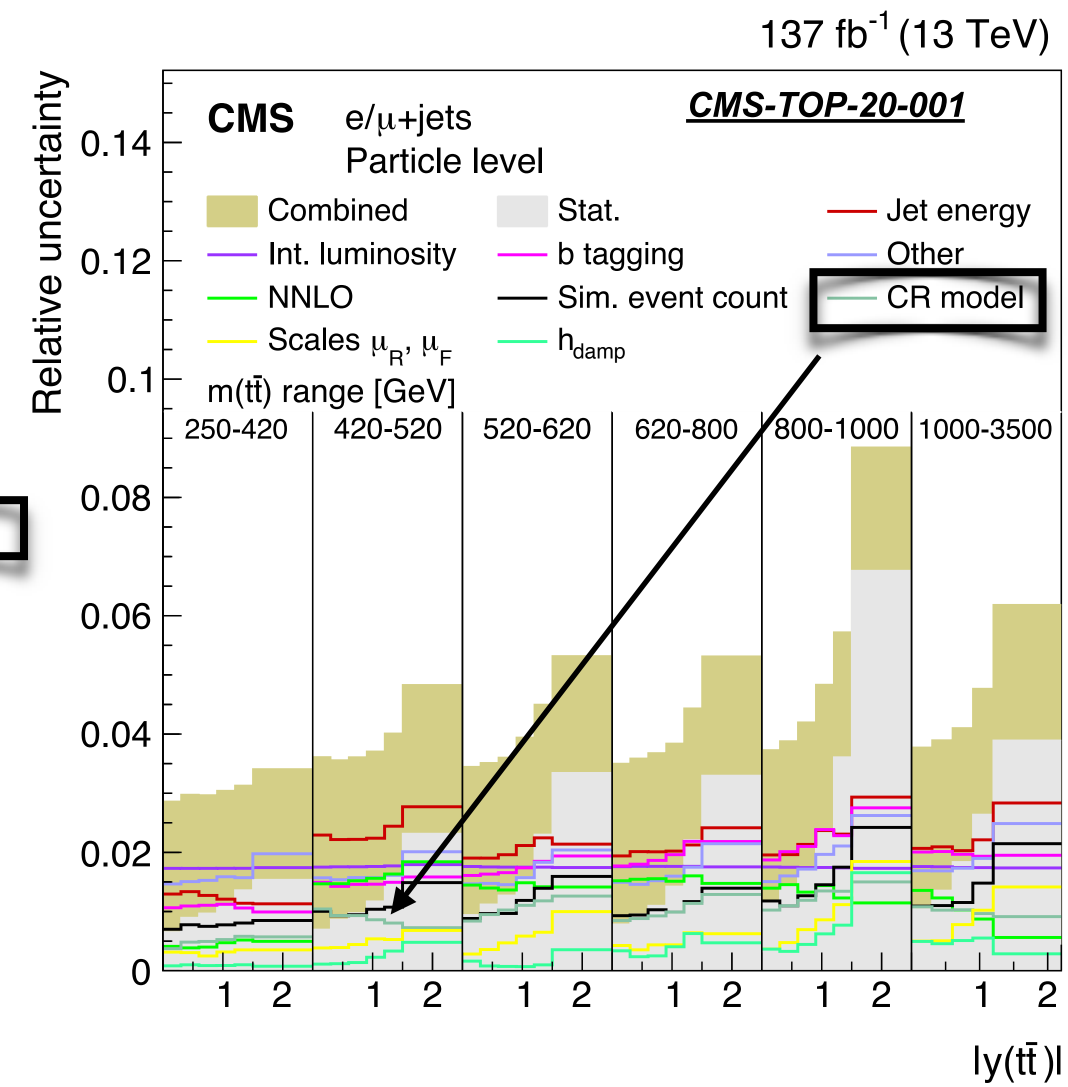
- Currently majority of samples generated at next-to-leading order at matrix element level
- In most cases, showered and hadronized with PYTHIA8

The LHC as a precision machine

Examples from the top sector



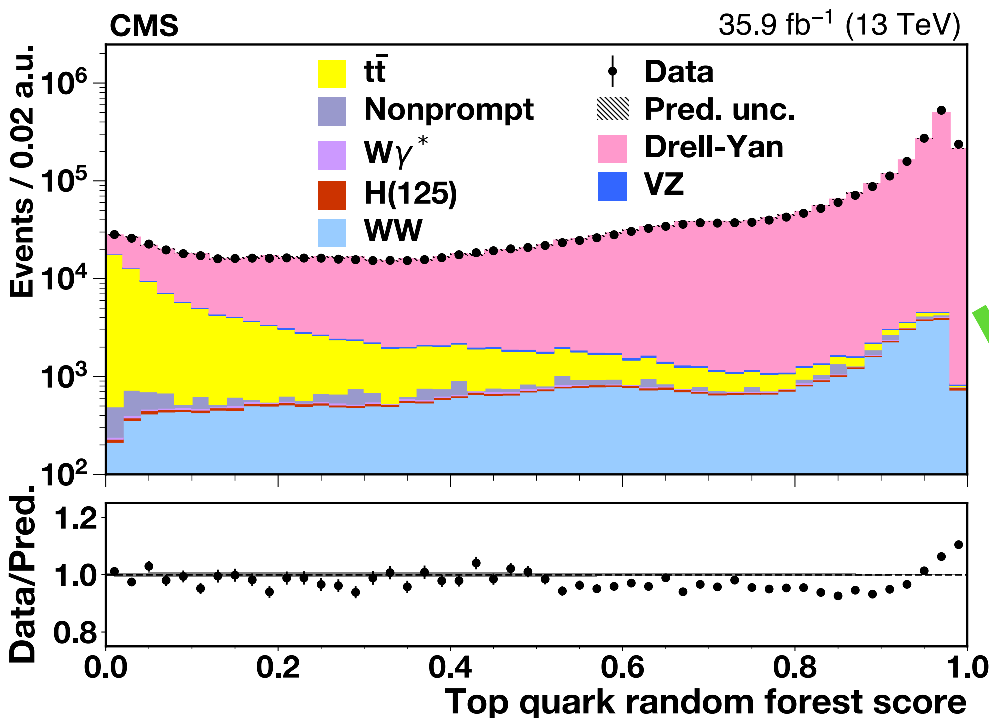
Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets channel

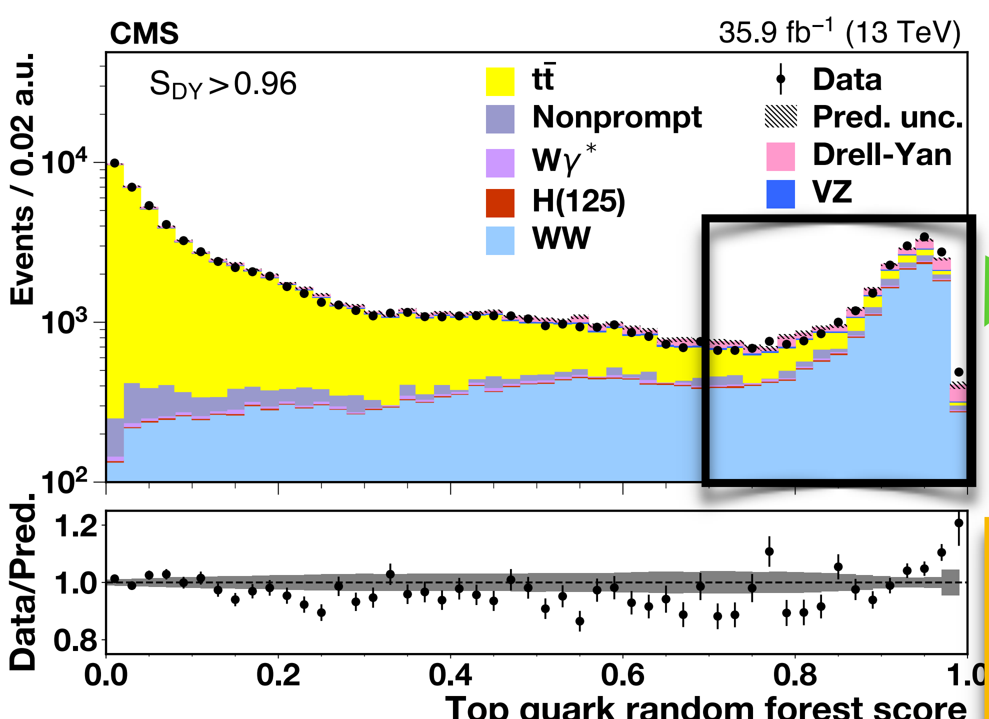


Measurement of differential tt production cross sections in the full kinematic range using lepton+jets events

- ☑ In many cases theoretical uncertainties (including modeling and cross section uncertainties) are (becoming) dominant
- ☑ Experimental uncertainties, such as those associated with the luminosity expected to be lower (~1%) at the HL-LHC (Beam Radiation, Instrumentation, and Luminosity (BRIL-TDR))

Using machine learning to probe inclusive regions of phase space: complements cut-based analyses



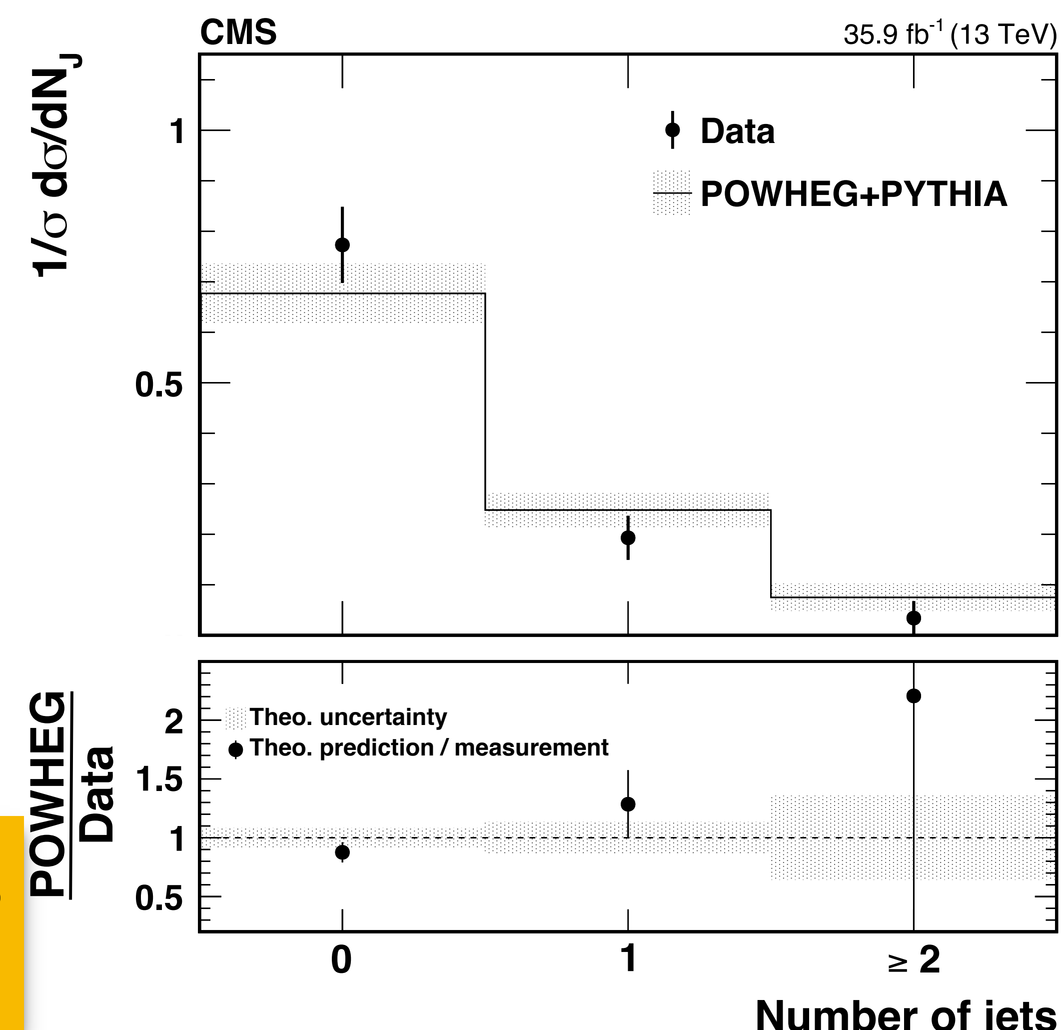


- Tension in WW cross section observed at both 8 TeV and early 13 TeV runs at the LHC

PhysRevD.102.092001

- Event selection in jet binned category sensitive to higher order QCD corrections
- Use of random forest discriminators helps mitigate backgrounds without constructing exclusive jet-binned event selection: complements cut-based approach

Fiducial cross section



Total cross section compared to NNLO prediction (with gg → WW incl.)

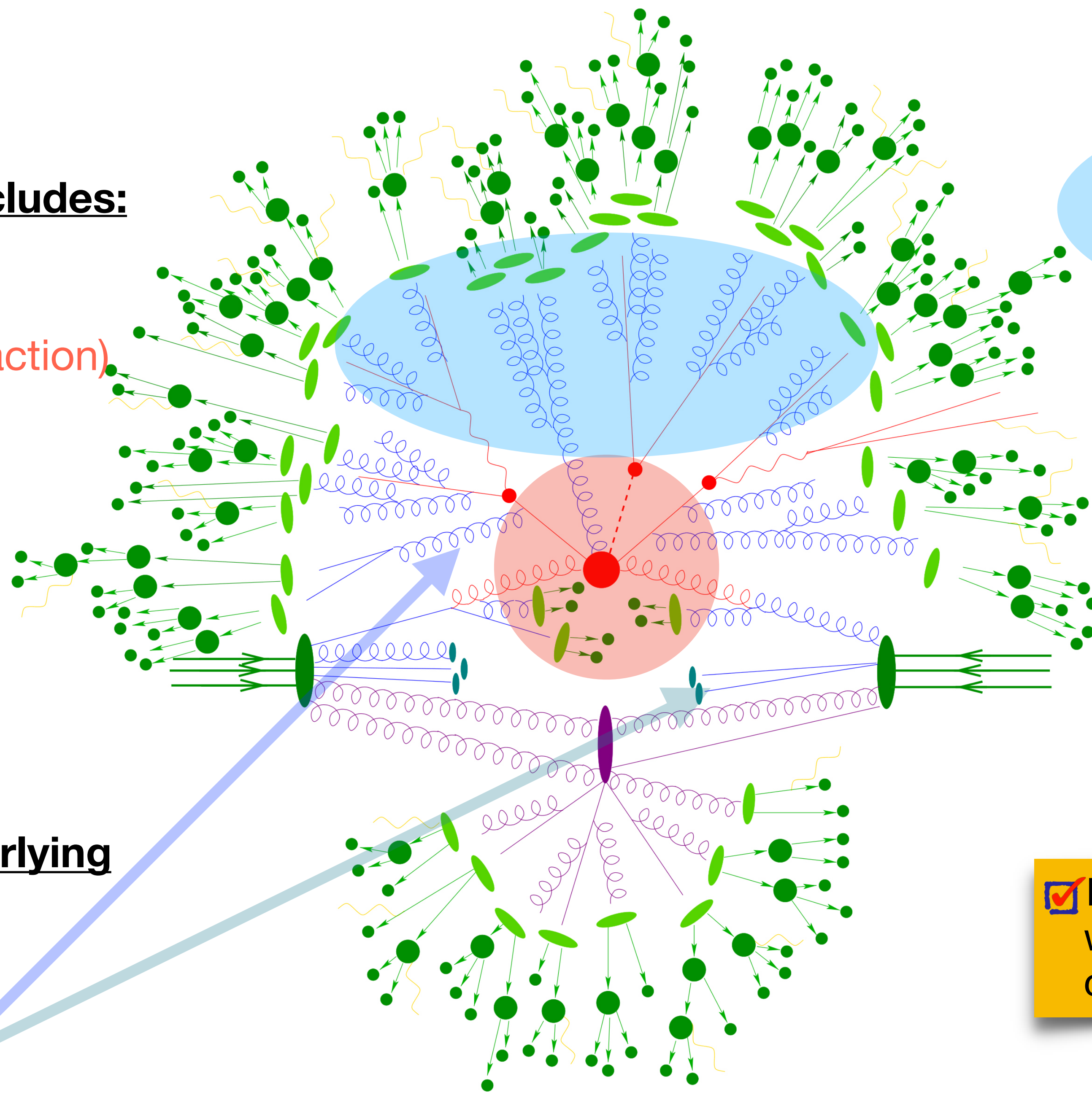
Components of the underlying events in the full event description

Full event description includes:

Initial state parton shower
Signal process (hard interaction)
Final state parton shower
Fragmentation
Hadron decays
Beam remnants
Underlying event

Components of the underlying event:

Initial state parton shower
Final state parton shower
Beam remnants



Parton shower
$\mathcal{O}$ **(1 TeV - 1 GeV)**

Hard process:
$\mathcal{O}$ **(1 TeV)**

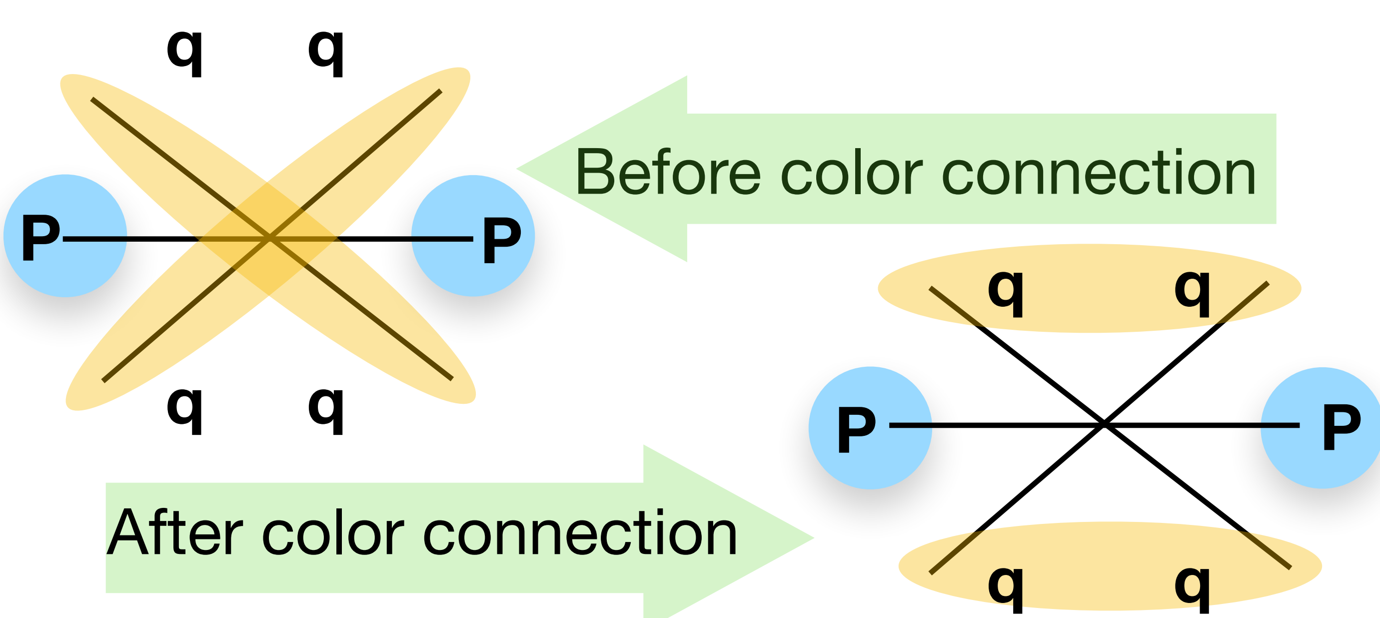
☑ Multiple parton interactions increase with √s (due to increased partonic content)

$\mathcal{O}$ **(1 GeV)** $\mathcal{O}$ **(1 TeV-10 GeV)** $\mathcal{O}$ **(1 TeV)** $\mathcal{O}$ **(1 TeV-10 GeV)** $\mathcal{O}$ **(1 GeV)**

non-perturbative perturbative non-perturbative

Color reconnection (CR)

- ☑ Color reconnection (CR) reconfigures color strings after parton shower
- ☑ Performed in the non-perturbative regime
- ☑ CR effects dominant in the low p_T region (p_T 2~5 GeV)
- ☑ Incorrect color associations can lead to large differences ⇒ unphysical
- ☑ Precision at the LHC necessitates an understanding of the color reconnection modeling



TOP-17-008

	δm_t^{hyb} [GeV]		
	all-jets	ℓ+jets	combination
Experimental uncertainties			
Method calibration	0.06	0.05	0.03
JEC (quad. sum)	0.15	0.18	0.17
– Intercalibration	−0.04	+0.04	+0.04
– MPFInSitu	+0.08	+0.07	+0.07
– Uncorrelated	+0.12	+0.16	+0.15
Jet energy resolution	−0.04	−0.12	−0.10
b tagging	0.02	0.03	0.02
Pileup	−0.04	−0.05	−0.05
All-jets background	0.07	–	0.01
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Modeling uncertainties			
JEC flavor (linear sum)	−0.34	−0.39	−0.37
– light quarks (uds)	+0.07	+0.06	+0.07
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Top quark p_T	+0.03	−0.01	−0.01
Underlying event	+0.17	−0.07	−0.06
Early resonance decays	+0.24	−0.07	−0.07
CR modeling (max. shift)	−0.36	+0.31	+0.33
– “gluon move” (ERD on)	+0.32	+0.31	+0.33
– “QCD inspired” (ERD on)	−0.36	−0.13	−0.14
Total systematic	0.70	0.62	0.61
Statistical (expected)	0.20	0.08	0.07
Total (expected)	0.72	0.63	0.61

Color reconnection (CR) tunes

GEN-17-002

- Color reconnection model based on modeling of multiple parton interactions **(MPI)**
- Regularized in PYTHIA8 with parameter p_{T0} (function of √s)
  - Energy dependence:

$$p_{T0}(\sqrt{s}) = p_{T0}^{\mathrm{ref}} \left(\frac{\sqrt{s}}{\sqrt{s_0}} \right)^{\epsilon}$$

Tunable parameter

Reference energy

  - Additional interactions from MPI function of parton distribution function (PDF), overlapping matter distribution of colliding hadrons (string width ~ hadronic width) and p_{T0}
- **MPI-based modeling** assigns a probability to each parton pair to reconnect with a harder system high p_T → less likely to be color connected

$$P = \frac{p^2_{\mathrm{T_{Rec}}}}{p^2_{\mathrm{T_{Rec}}} + p^2_T} \qquad p^2_{\mathrm{T_{Rec}}} = R \cdot p_{T_0}$$

- p_{TRec} is a regularization term prevents divergence of partonic cross sections at low p_T, R is a parameter

Color reconnection models

GEN-17-002

- **QCD inspired model** includes minimization of string length in addition to QCD color rules. Determines color-compatibility of a pair of dipoles iteratively. Causally connect produced strings through a string length measure (λ)

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

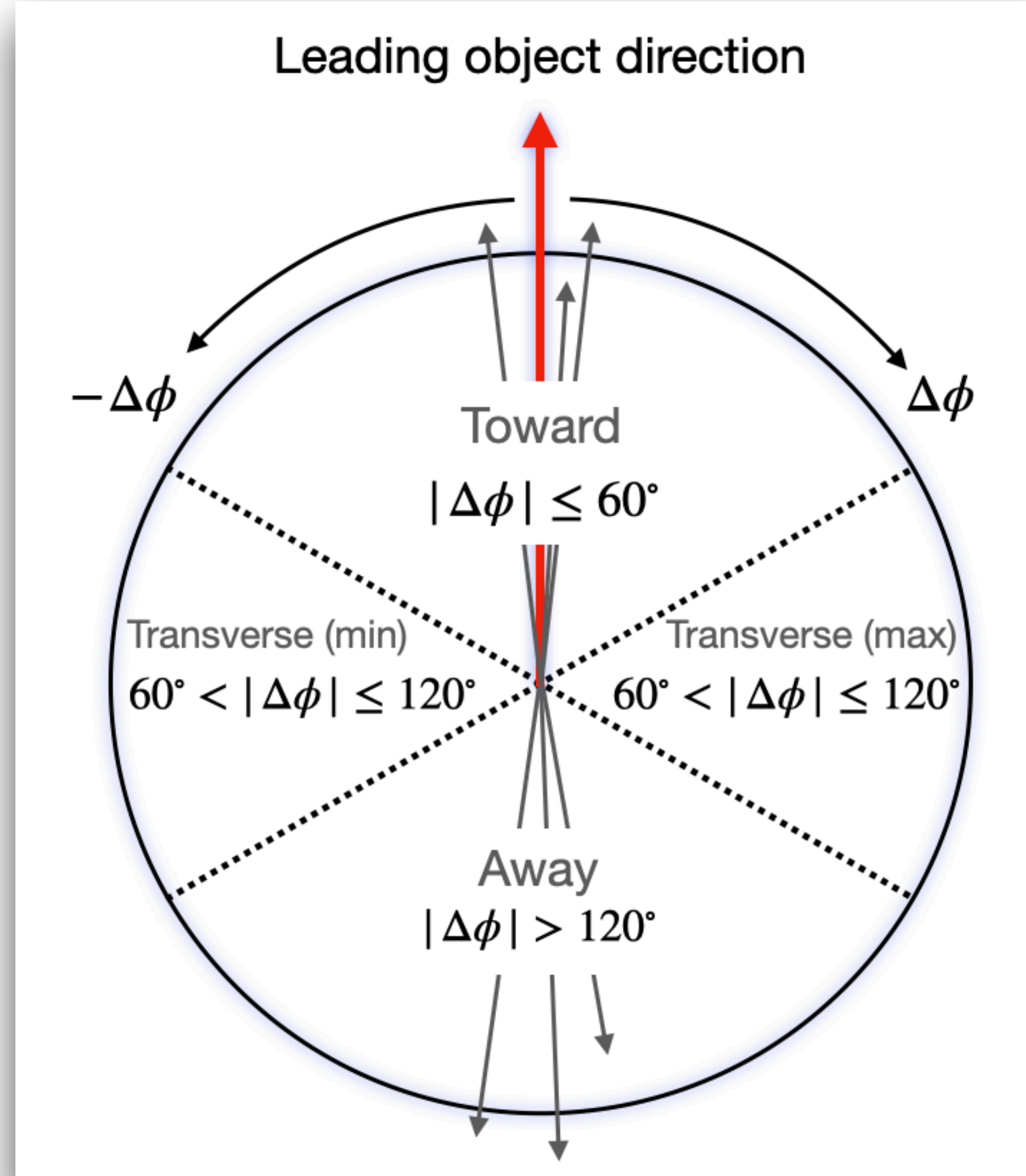
  - *m0* parameter determines whether a connection is favored, E_1 and E_2 represent energies of the colored partons (in the rest frame of the dipole)

- **Gluon move model:** Iteratively move each final-state gluon from a “string piece” of partons to another. Naive model does not include quark reconnection, implemented by including a “flip” mechanism (move quarks as well)

The Underlying event (UE)

GEN-17-002

- UE defined as activity not associated with particles originating from the hard scatter
- Generally studied in events that contain a hard scattering with pT ≳ 2 GeV
- Leading object defined on an event-by-event basis
- Φ regions relative to the leading object that are sensitive to the underlying event
- Azimuthal separation between charged particles and leading object $\Delta\Phi = \Phi - \Phi_{max}$ used to define sensitive regions



Description of the tunes

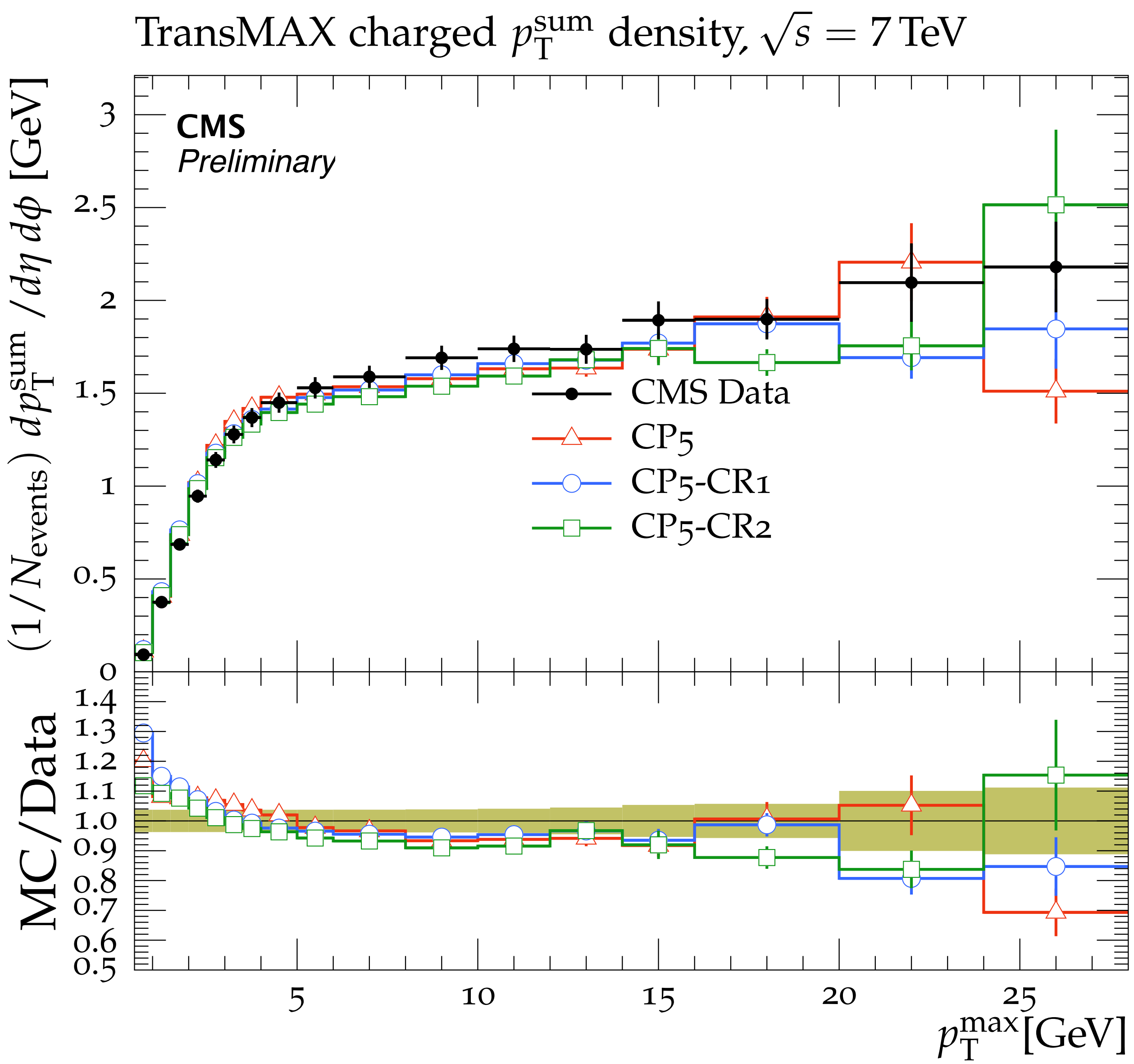
GEN-17-002

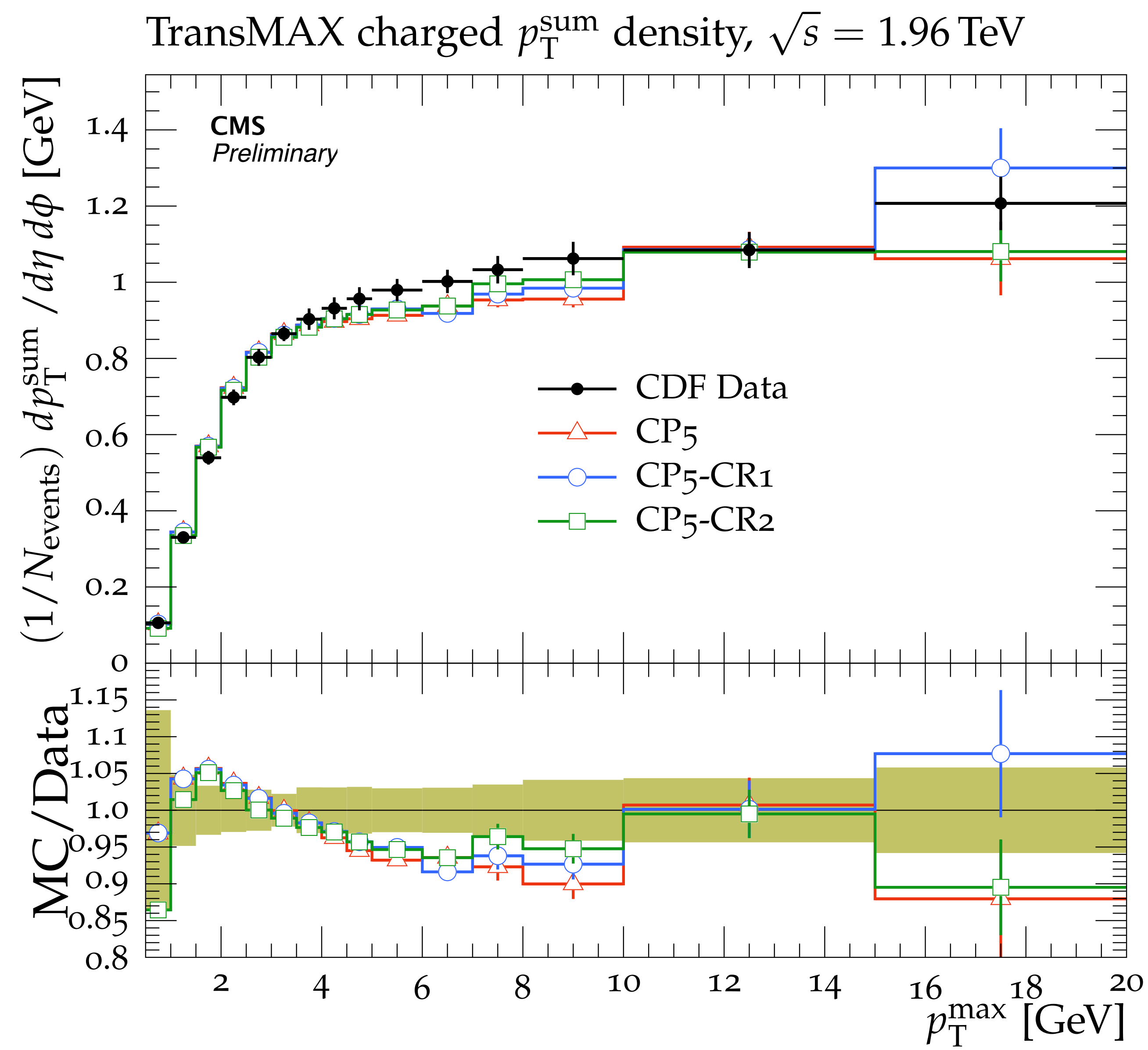
- **CR1 stands for the QCD-inspired model** and **CR2 stands for the gluon-move CR model**
  - Complements CP5 with color reconnection variations
- **CP5 default:** CP5 uses NNPDF31_nnlo_as_0118 PDF set, α_S = 0.118, and the MPI-based CR model

			CP5-CR1			CP5-CR2		
RIVET routine	$\sqrt{s}$ (TeV)	Distribution	Fit range (GeV)	N_{bins}	R	Fit range (GeV)	N_{bins}	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

Performance of the tune

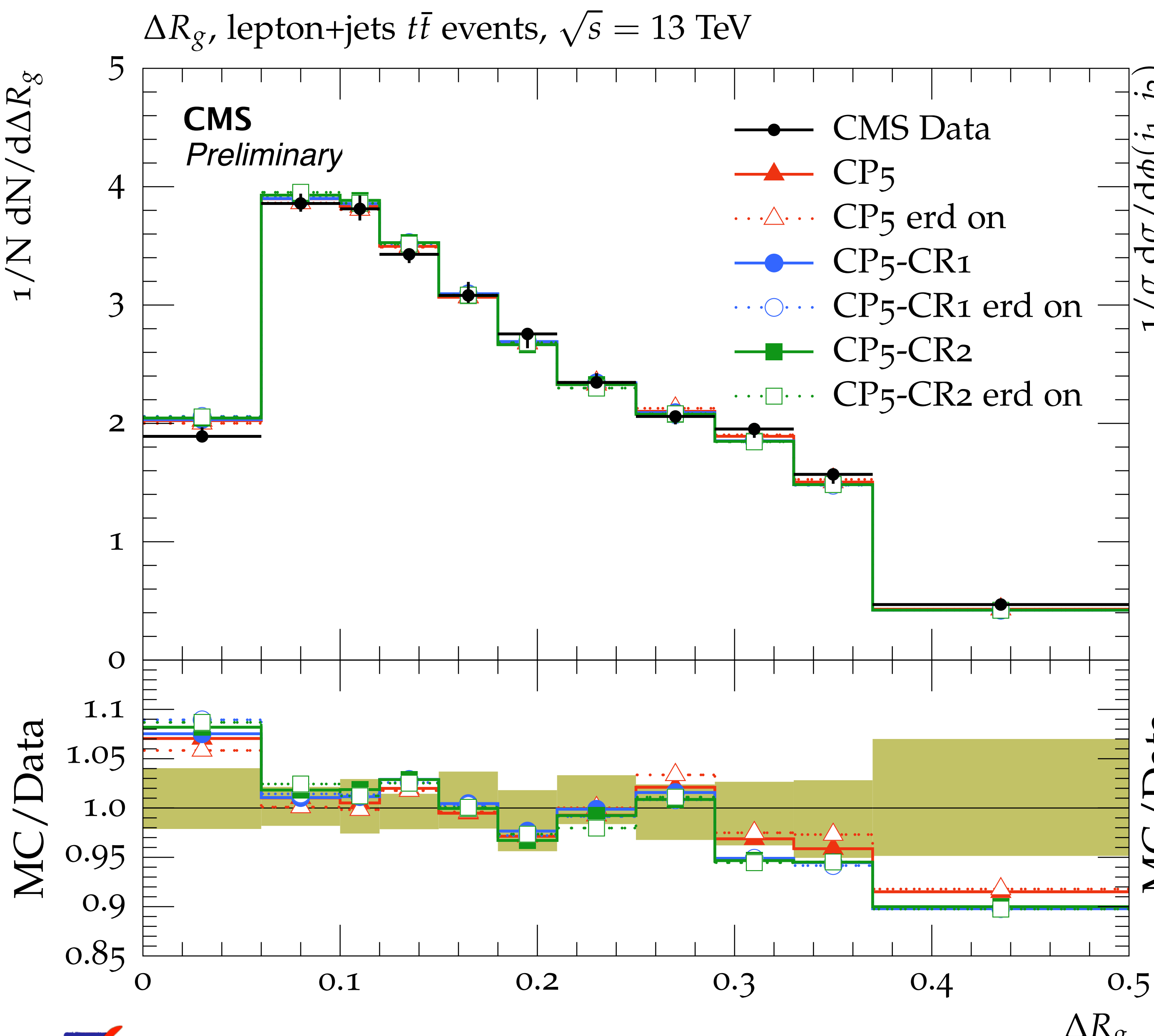
GEN-17-002



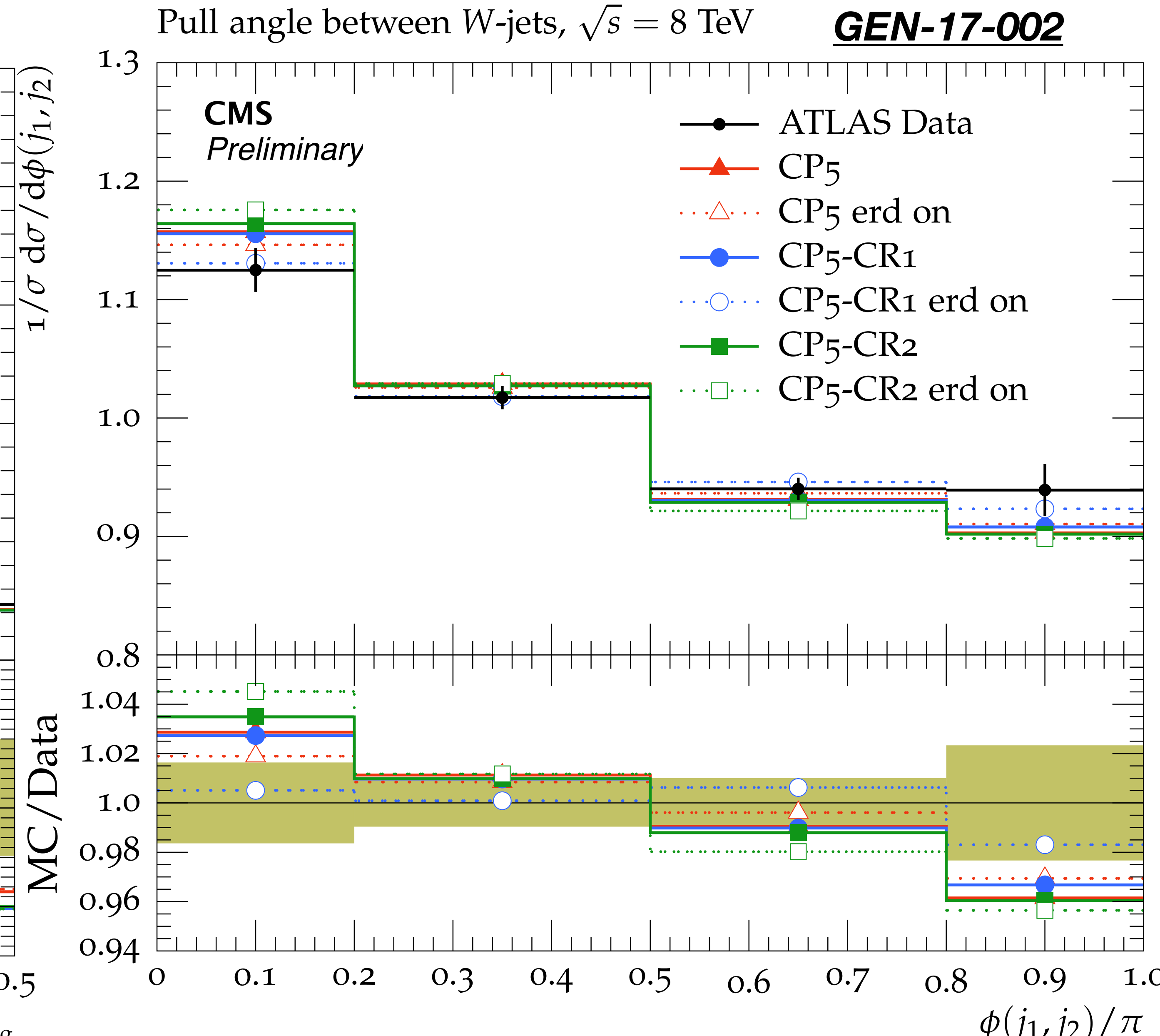


- Charged particle density in the transMAX region with CMS (left) and CDF (right) data
- Similar behavior seen at √s = 13 TeV and with ATLAS data
- Tunes perform well, inconsistencies seen in final states with charmed baryons (Λ)

Jet substructure variables in ttbar final states



GEN-17-002



- ☑ ΔR_g: angle between two groomed subjets
- ☑ $\Phi(j_1, j_2)/\pi$: pull angle between jets from the W-boson in top decays (using charged constituents of the jets)
- ☑ Early resonance decay (ERD) option: color reconnection before and after the top quark decay

Extraction of top-mass uncertainty using these new tunes

The top quark mass, m_t, and W mass, m_W, extracted by a fit to the predictions of the different PYTHIA8 tunes. The uncertainties in the m_t and m_W values correspond to the uncertainty in the fitted m_t and m_W.

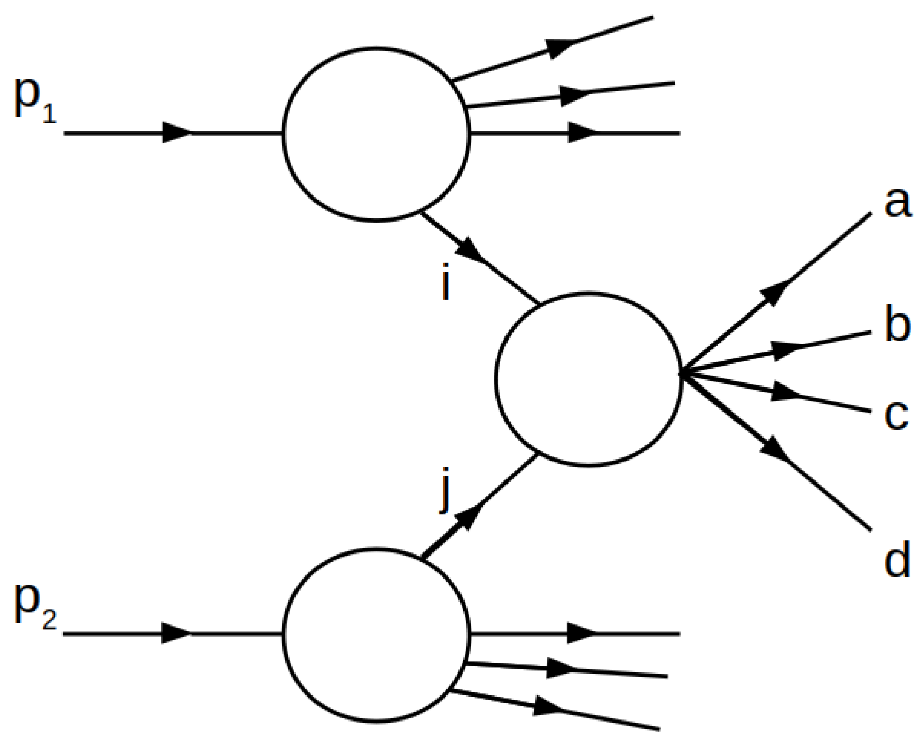
Tune	m_t [GeV]	Δm_t [GeV]	m_W [GeV]	Δm_W [GeV]	$\Delta m_t - 0.5 \times \Delta m_W$ [GeV]
CP5	171.93 ± 0.02	0	79.76 ± 0.02	0	0
CP5 erdOn	172.18 ± 0.03	0.25	80.15 ± 0.02	0.40	0.13
CP5-CR1	171.97 ± 0.02	0.04	79.74 ± 0.02	-0.02	0.05
CP5-CR1 erdOn	172.01 ± 0.03	0.08	79.98 ± 0.02	0.23	-0.04
CP5-CR2	171.91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

Allows comparison with TOP-17-007, factoring in shifts in Mw

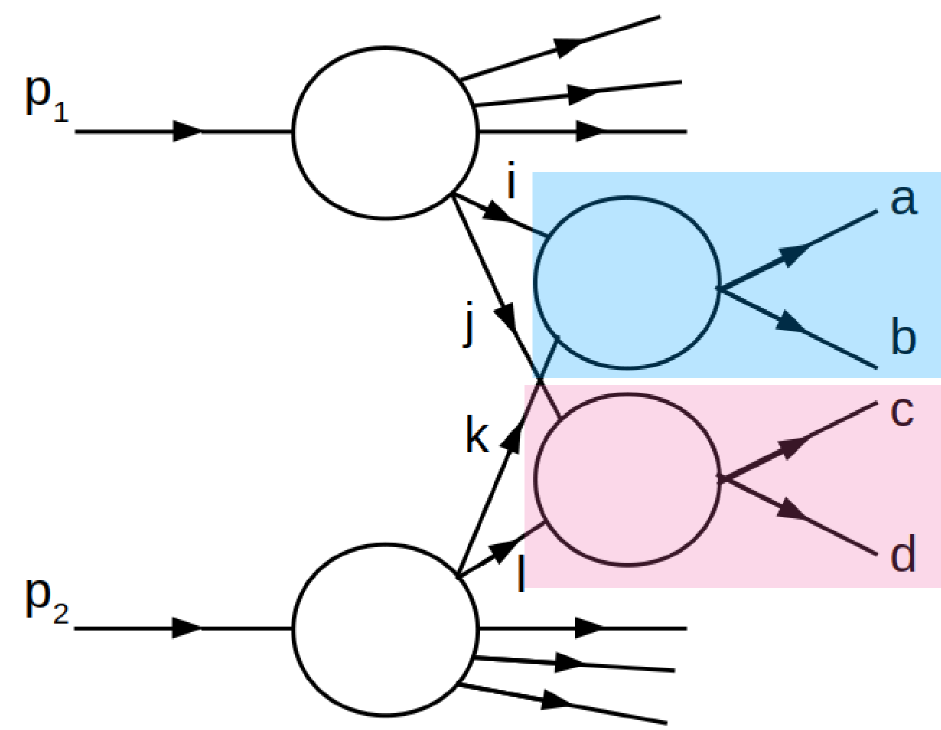
- ☑ Top-quark candidates constructed by a RIVET routine (kinematic requirements imposed and “dressed” leptons used)
- ☑ Largest deviation (from default CP5) found for CP5-CR2 erdon (0.32 GeV) ~ similar to what is observed in TOP-17-007

Double Parton Scattering: 4 jet production

https://arxiv.org/abs/2109.13822



Single parton scattering (SPS)



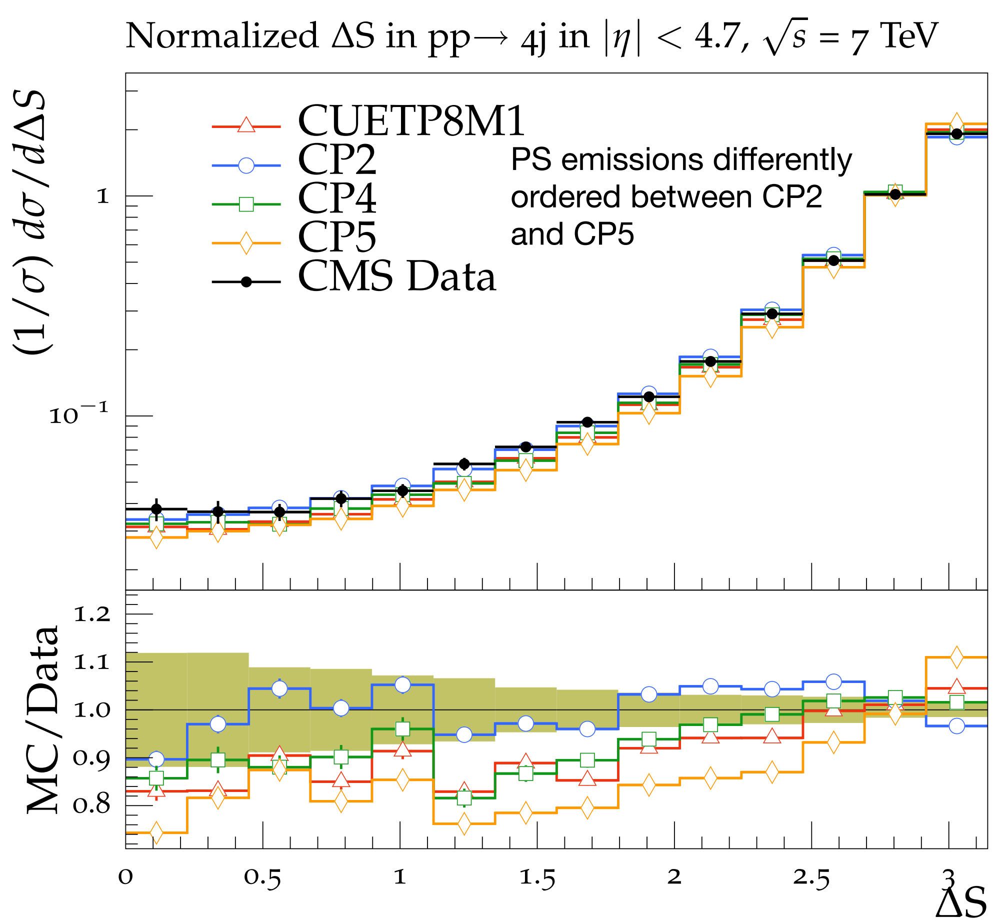
Double parton scattering (DPS)

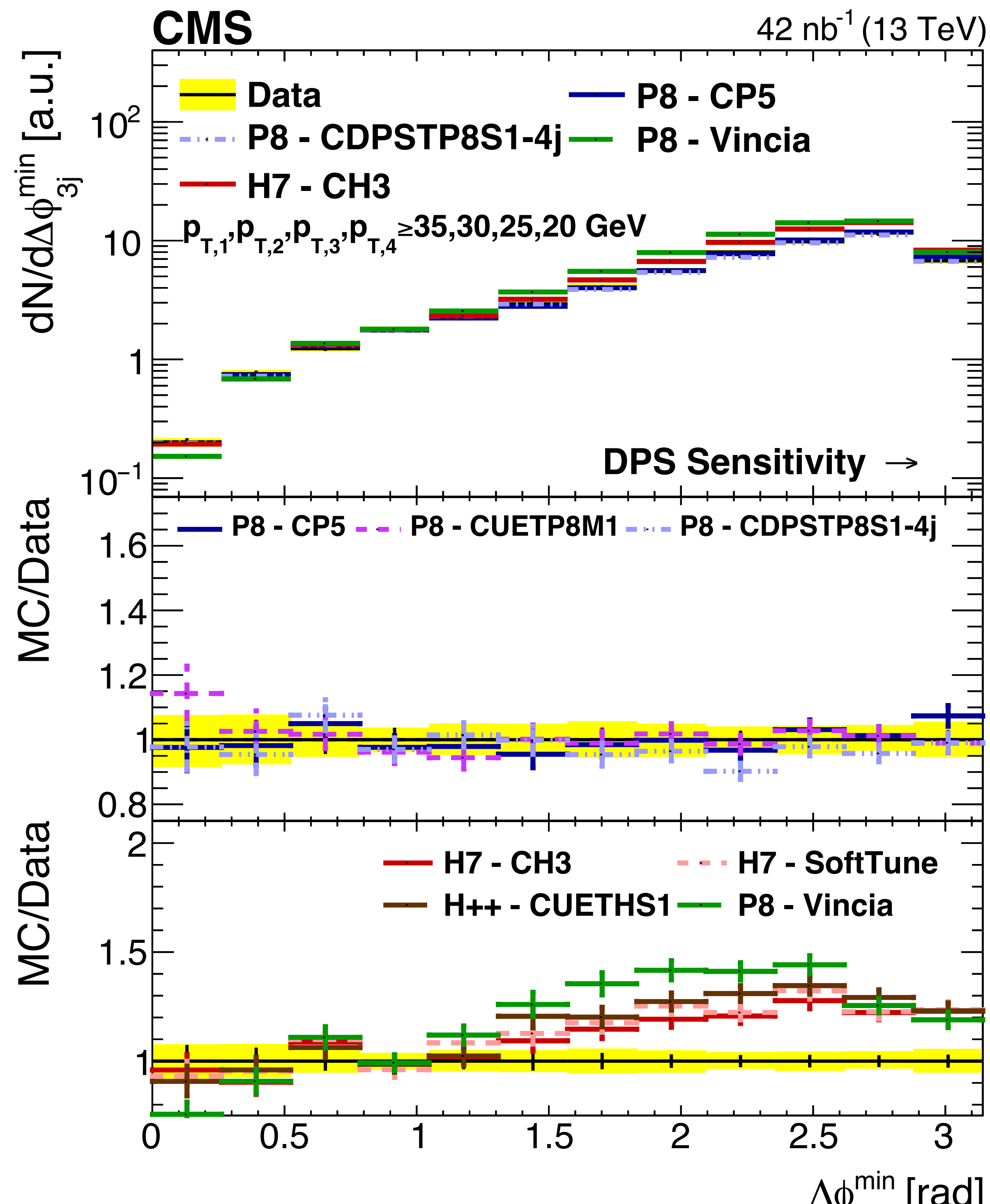
- ☑ In the case of SPS, one hard scattering produces the jets *a* through *d*
- ☑ Two jet pairs are created independently in a DPS event → different kinematic correlations than an SPS event

Double Parton Scattering: 4 jet production

Minimal combined azimuthal angular range of three jets (2 out of 3 jets likely to be back-to-back)

- ☑ Data shows preference for p_T ordered parton shower description (studies performed in GEN-17-001 in agreement)





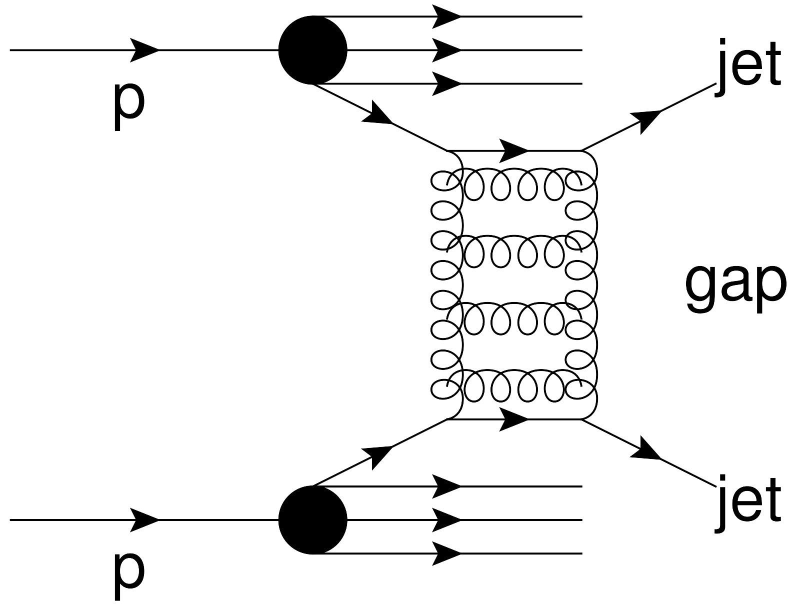
Azimuthal angular difference between the hard and the soft jet pairs

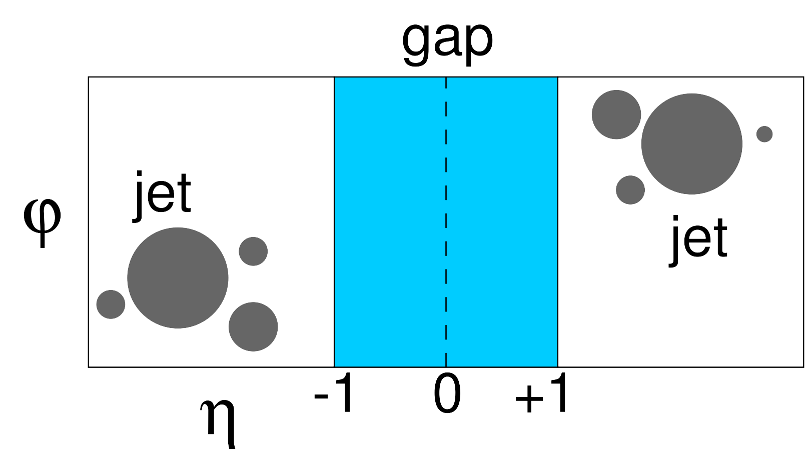
$$\Delta S = \arccos\left(\frac{(\vec{p}_{T,1}+\vec{p}_{T,2}).(\vec{p}_{T,3}+\vec{p}_{T,4})}{|\vec{p}_{T,1}+\vec{p}_{T,2}||\vec{p}_{T,3}+\vec{p}_{T,4}|}\right)$$

$$\Delta\phi_{3j}^{min} = \min\left\{|\phi_i-\phi_j|+|\phi_j-\phi_k| \,\middle|\, i,j,k\in[1,2,3,4], i\neq j\neq k\right\}$$

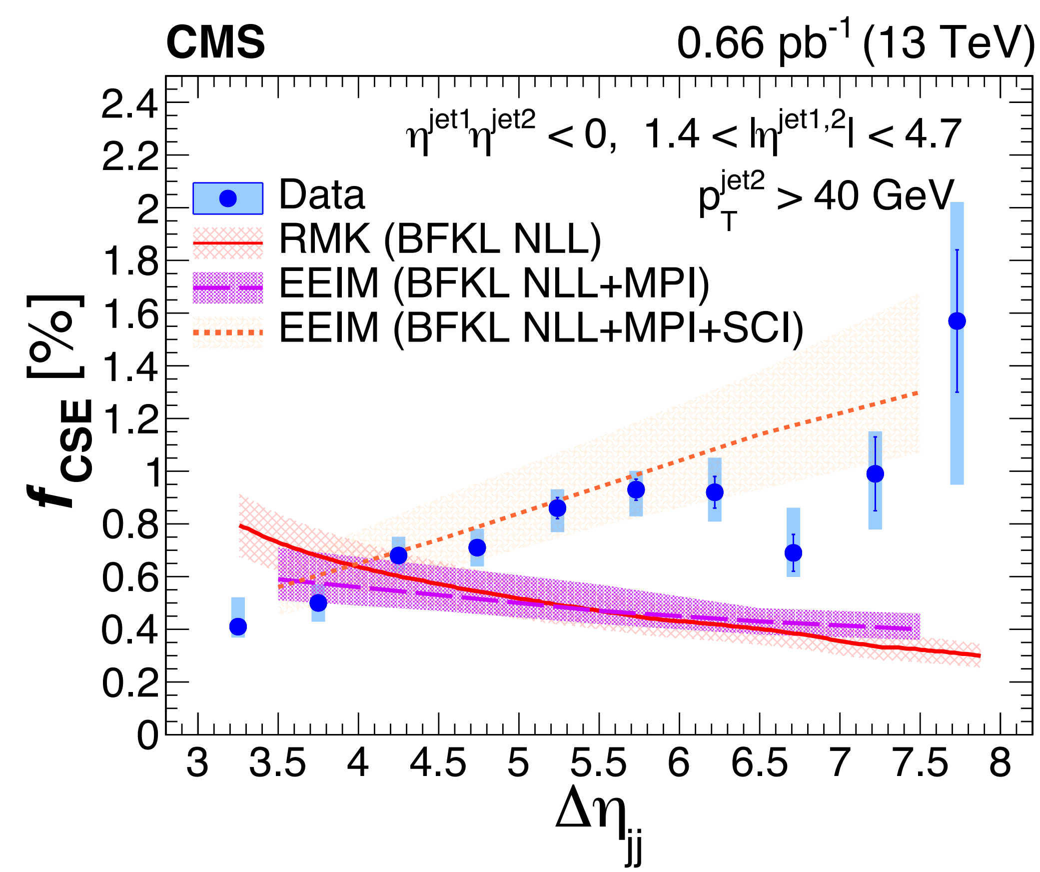
Parton shower description beyond DGLAP

Phys. Rev. D 104 (2021) 032009



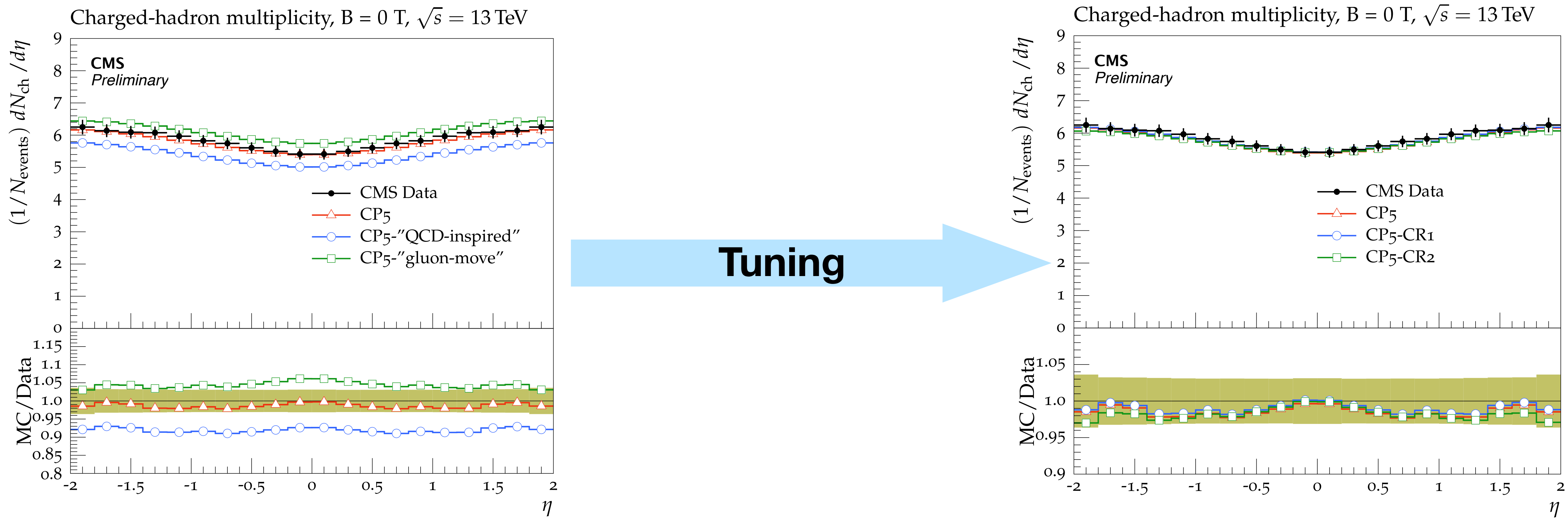


- 2 → 2 scattering: for values of Λ_{QCD}, where QCD is no longer strongly coupled, fixed order perturbation theory no longer valid
- Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution equation resums logarithmic terms to all orders in α_S → NLL accuracy
- In dijet production, BKFL dynamics expected to manifest when two jets are separated by a large rapidity interval



Conclusion

- Color reconnection tunes derived by constraining parameters with the use of $\sqrt{s}$ = 1.96, 7, and 13 TeV data
- These tunes do not improve the description of strange particle production: point to need for improved models of hadronization?
- Distribution of data in 4-jet production via double parton scattering point to slight preference for p_T ordered parton shower description
- Novel jet-gap-jet studies point to the need for going beyond DGLAP evolution equations

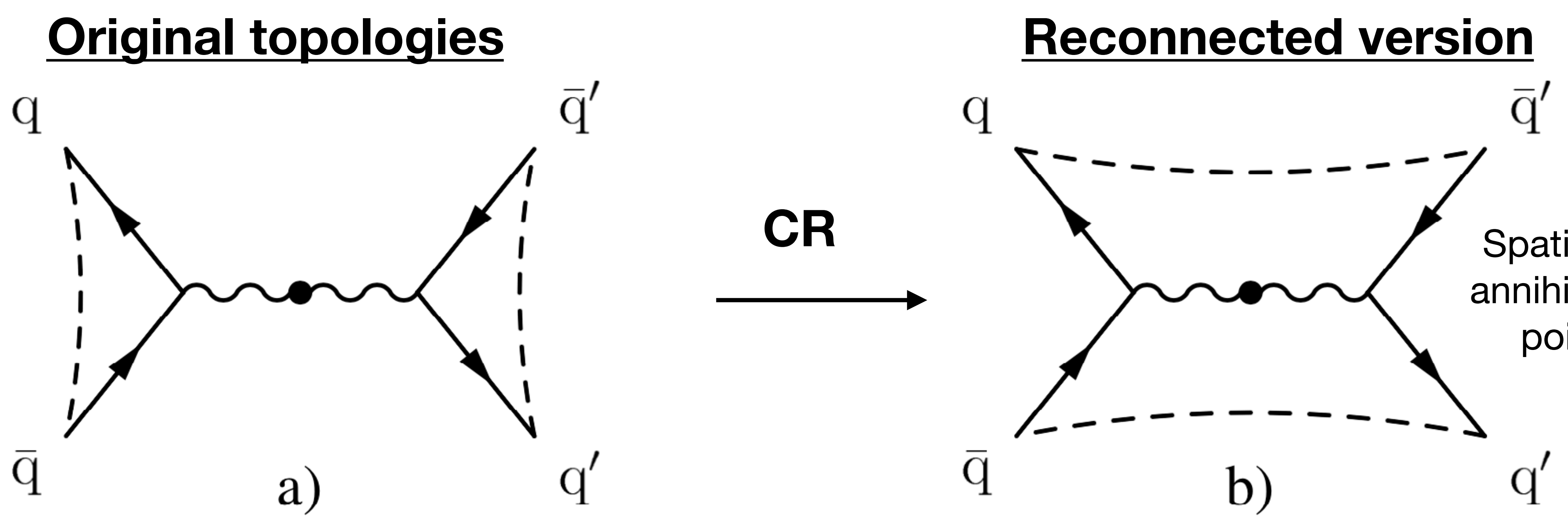


Additional studies not covered in this talk…

- ☑ GEN-19-001: description of the HERWIG tune
- ☑ GEN-17-001: description of the CPx tunes
- ☑ TOP-17-013: jet shape variables in ttbar final states
- ☑ TOP-17-015: Underlying event description in ttbar
- ☑ TOP-16-021: Exploration of the CUETP8M2T4 tune
- ☑ SMP-20-009: Underlying event description in Z+Jets final states

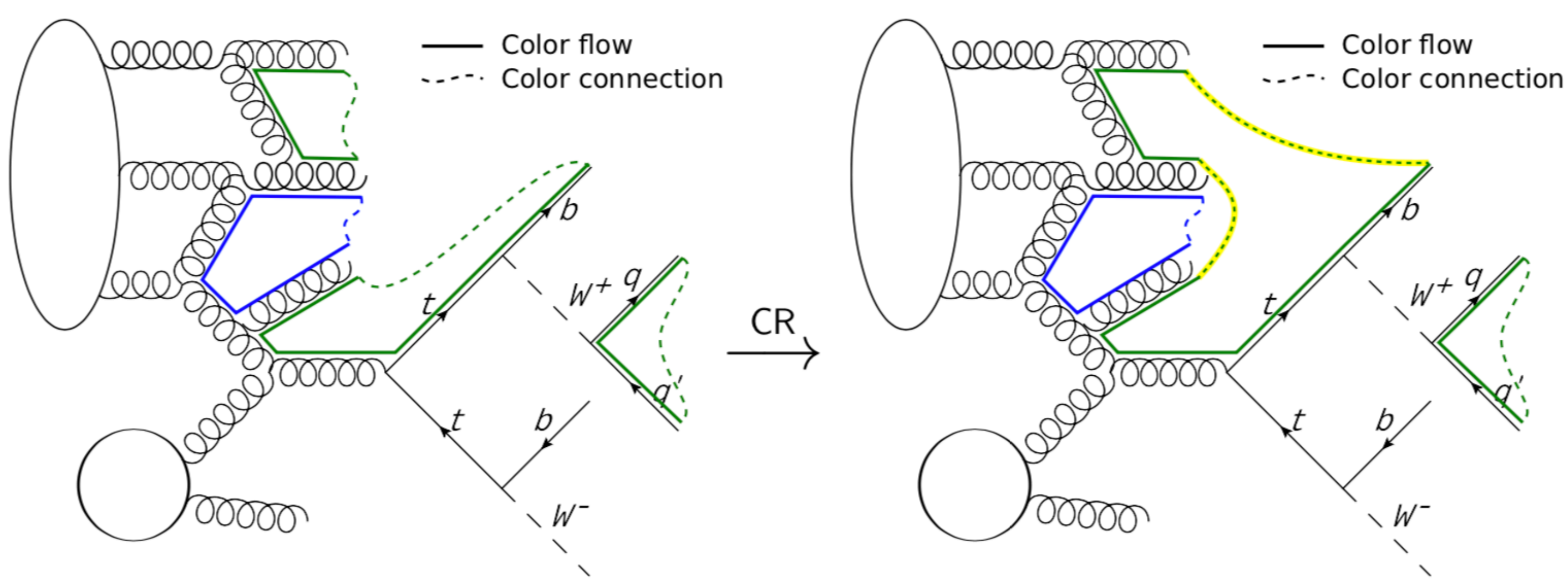
Additional Material

Color flows after reconnection



Spatial diagrams after annihilation, production point at the origin

Colour Annealing — A Toy Model of Colour Reconnections: M. Sandhoff , P. Skands



M. Seidel

Outline

- Sercan may also have a good overview which FSQ/QCD (or now SMP) analyses can be included in addition:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FSQ/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/UEMINB.html

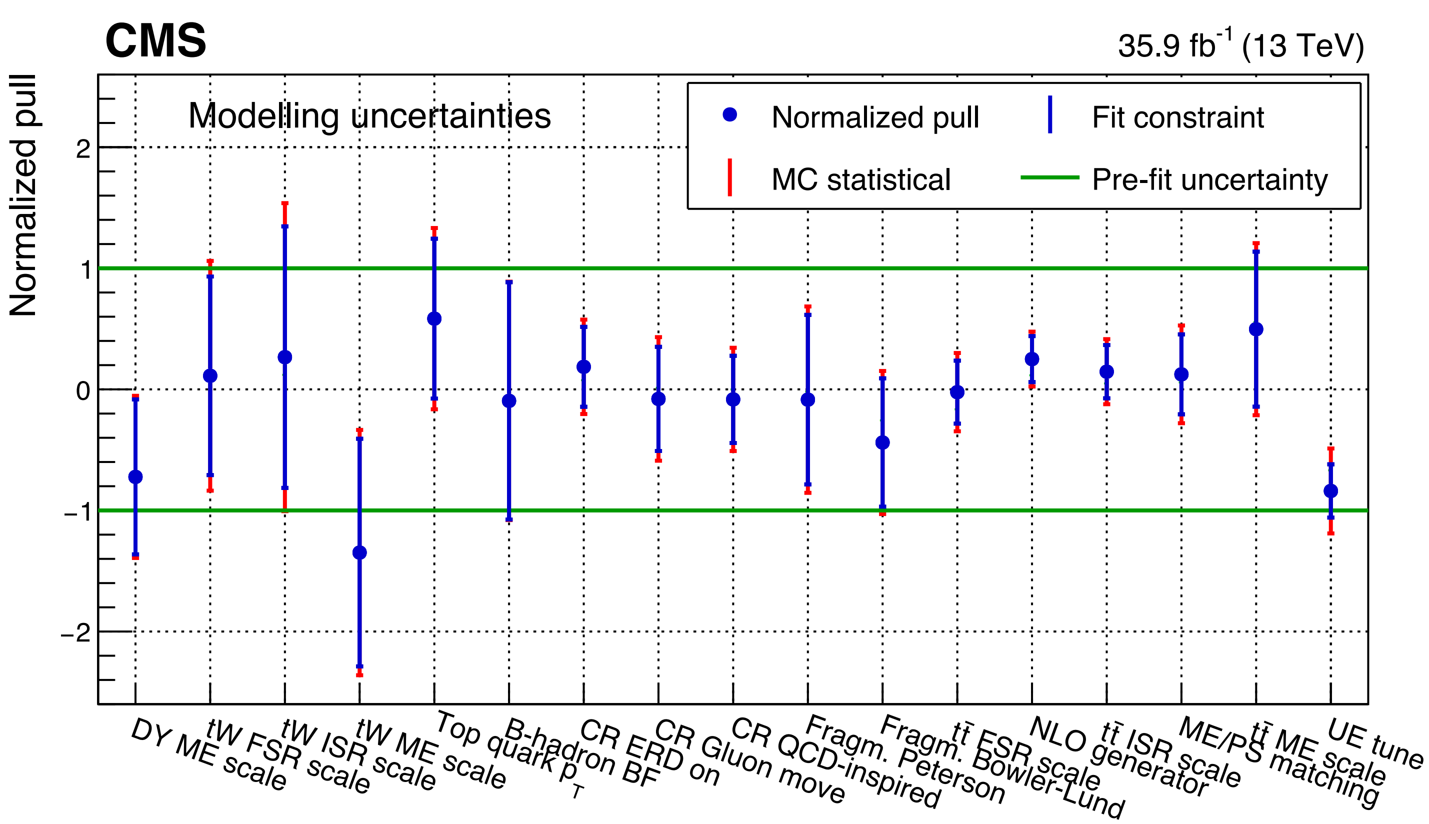
  - There are also some others mentioned in this Moriond talk: https://cms-mgt-conferences.web.cern.ch/conferences/pres_display.aspx?cid=2964&pid=22500http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-19-006/index.html (Sercan may comment if this falls in the topic of your talk)
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-17-015/ (UE in ttbar)

- DPS at 13 TeV (SMP-20-007)

- SMP-19-006

The LHC as a precision machine

Simultaneous measurement of the top quark mass (m_t) and cross section (σ_{tt}) in dilepton top events



TOP-17-001

Does not show the effect of variation of the top p_T directly; shows the uncertainty in the unfolding

Measurement of the top mass in all-jets final state and combination with lepton+jets channel

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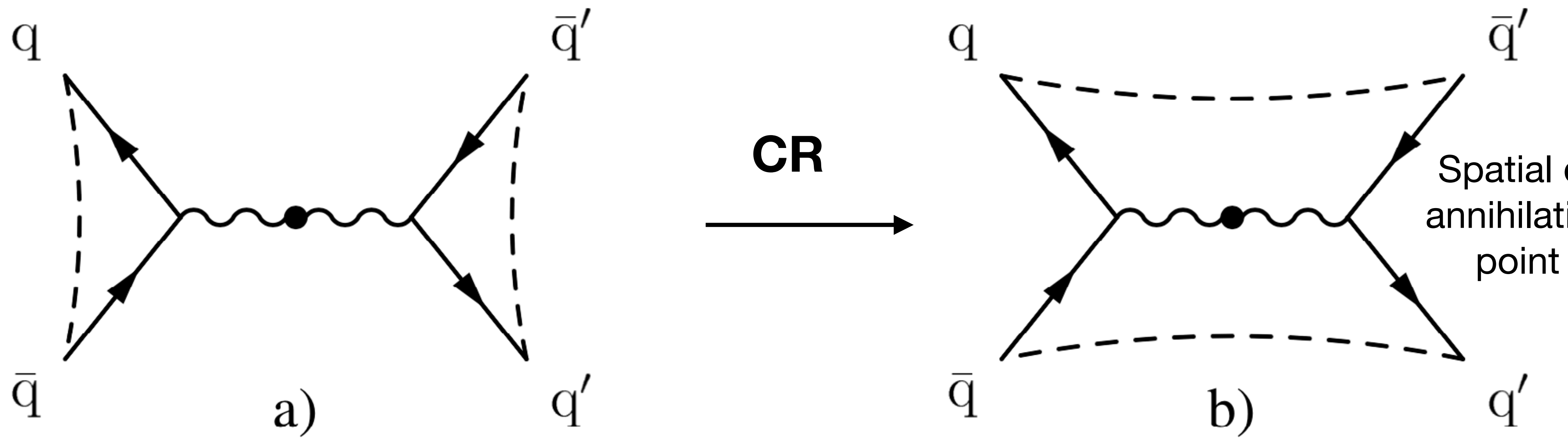
TOP-17-008

Color reconnection (CR)

Original topology | **Reconnected version**



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- ☑ Incorrect color associations can lead to large differences ⇒ unphysical
- ☑ Precision at the LHC necessitates an understanding of the color reconnection modeling (particularly relevant for top-based final states)

Color reconnection (CR) tunes

- CR effects dominant in the low p_T region (p_T 2~5 GeV)
  - Leads to discrepancy in the prediction of tunes with respect to data
- UL description of ttbar events requires inclusion of color reconnection

Description of underlying event tunes

The settings, used in the determination of the new CMS PYTHIA8 UE tunes, are as follows:

- Tune CP1 uses the NNPDF3.1 PDF set at LO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR equal to, respectively, 0.13, 0.13, 0.1365, and 0.1365, and running according to an LO evolution.
- Tune CP2 is a slight variation with respect to CP1, uses the NNPDF3.1 PDF set at LO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR contributions equal to 0.13, and running according to an LO evolution.
- Tune CP3 uses the NNPDF3.1 PDF set at NLO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR contributions equal to 0.118, and running according to an NLO evolution.
- Tune CP4 uses the NNPDF3.1 PDF set at NNLO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR contributions equal to 0.118, and running according to an NLO evolution.
- Tune CP5 has the same settings as CP4, but with the ISR emissions ordered according to rapidity.

GEN-17-001

Description of the tunes GEN-17-002

The MPI-related parameters that are kept free in both CP5-CR1 and CP5-CR2 tunes are:

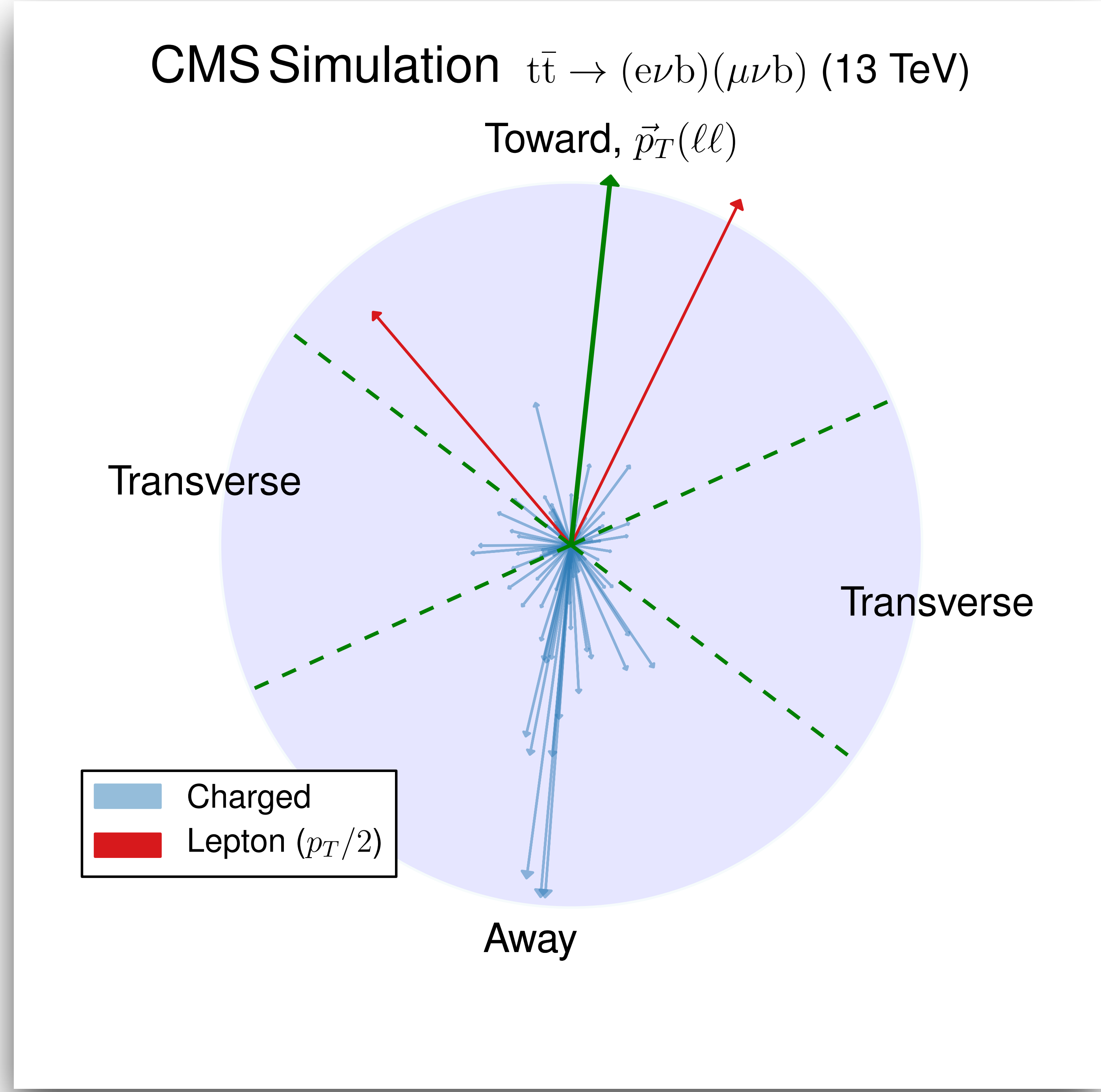
- `MultipartonInteractions:pT0Ref`, the parameter included in the regularisation of the partonic QCD cross section. It sets the lower scale of the MPI contribution;
- `MultipartonInteractions:ecmPow`, the exponent of the $\sqrt{s}$ dependence;
- `MultipartonInteractions:coreRadius`, the width of the core when a double Gaussian matter profile is assumed for the overlap distribution between the two colliding protons. A double Gaussian form identifies an inner, dense part, which is called core, and an outer less dense part;
- `MultipartonInteractions:coreFraction`, the fraction of quark and gluon content enclosed in the core when a double Gaussian matter profile is assumed.

The tunable CR parameters in the QCD-inspired model that are considered in the fit are:

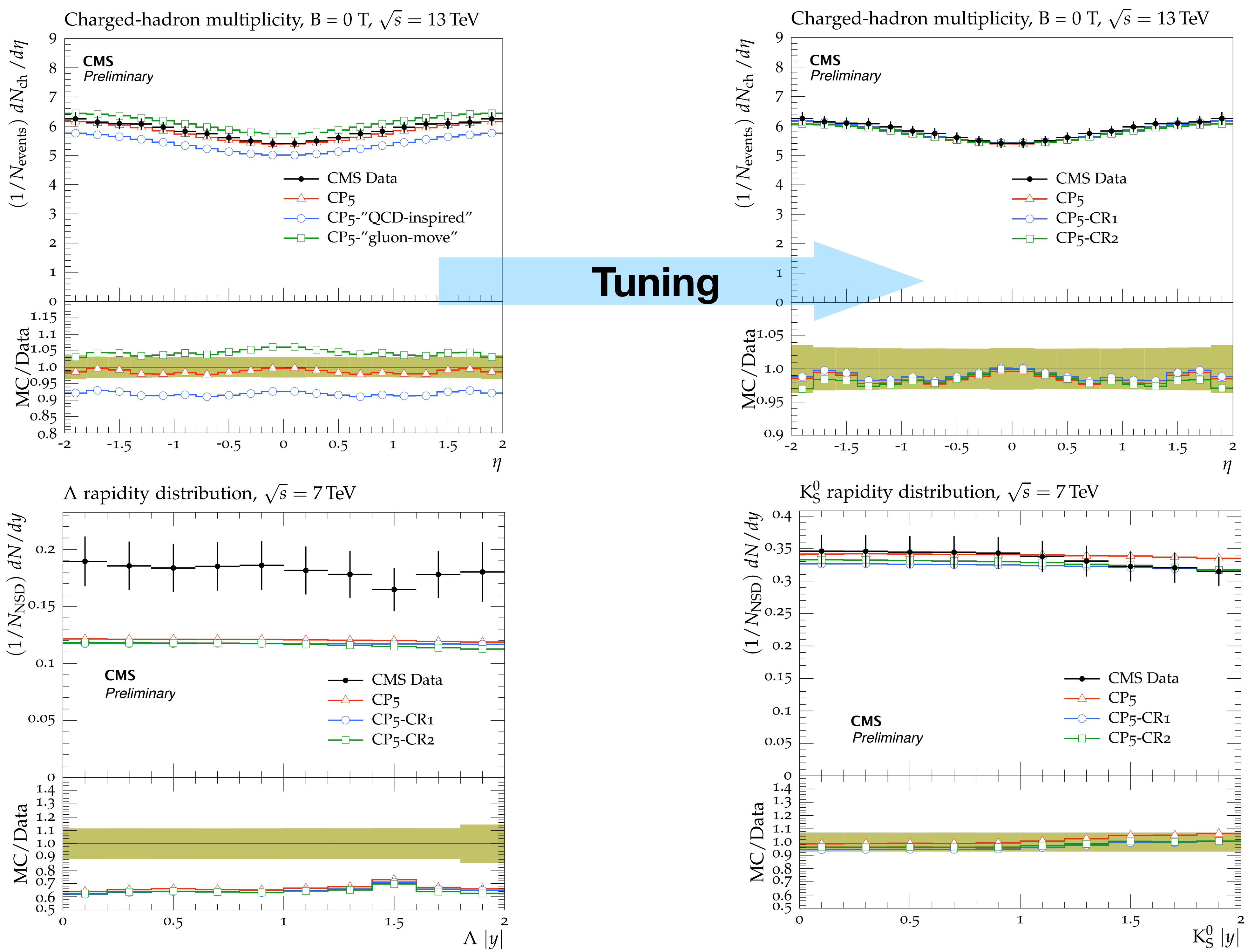
- `ColourReconnection:m0`, the variable that determines whether a possible reconnection is actually favoured in the λ measure in Eq. 3;
- `ColourReconnection:junctionCorrection`, the multiplicative correction for the junction formation, applied to the `m0` parameter;
- `ColourReconnection:timeDilationPar`, the parameter controlling the time dilation that forbids colour reconnection between strings that are not in causal contact.

For the CP5-CR1 tune, the parameters `StringZ:aLund`, `StringZ:bLund`, `StringFlav:probQQtoQ`, and `StringFlav:probStoUD`, relative to the hadronisation, proposed in [7], are also used in the initial settings. The first two of these parameters control the shape of the longitudinal fragmentation function used in the Lund string model in PYTHIA8,

Description of underlying event tune for top-based final states



Conclusion



Charged-hadron multiplicity, B = 0 T, $\sqrt{s}$ = 13 TeV
CMS
Preliminary
CMS Data
CP5
CP5-"QCD-inspired"
CP5-"gluon-move"
$(1/N_{events})\ dN_{ch}/d\eta$
MC/Data
η
Tuning
Charged-hadron multiplicity, B = 0 T, $\sqrt{s}$ = 13 TeV
CMS
Preliminary
CMS Data
CP5
CP5-CR1
CP5-CR2
$(1/N_{events})\ dN_{ch}/d\eta$
MC/Data
η
Λ rapidity distribution, $\sqrt{s}$ = 7 TeV
CMS
Preliminary
CMS Data
CP5
CP5-CR1
CP5-CR2
$(1/N_{NSD})\ dN/dy$
MC/Data
$\Lambda\ |y|$
K^0_S rapidity distribution, $\sqrt{s}$ = 7 TeV
CMS
Preliminary
CMS Data
CP5
CP5-CR1
CP5-CR2
$(1/N_{NSD})\ dN/dy$
MC/Data
$K^0_S\ |y|$

Double Parton Scattering: 4 jet production
Sensitive variables

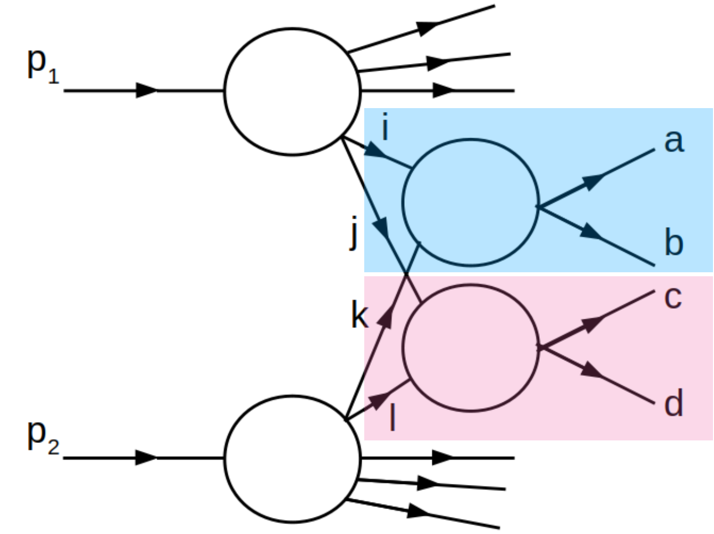
Jets sorted in decreasing p_T

- Azimuthal angular difference between the two softest jets (π for DPS)

$$\Delta\phi_{\mathrm{Soft}} = |\phi_3 - \phi_4|$$

- Minimal combined azimuthal angular range of three jets (2 out of 3 jets likely to be back-to-back)

$$\Delta\phi_{3j}^{\mathrm{min}} = \min\left\{ |\phi_i - \phi_j| + |\phi_j - \phi_k| \middle| i,j,k \in [1,2,3,4], i \neq j \neq k \right\}$$



- Maximum η difference between two jets

$$\Delta\Upsilon = \max\left\{ |\eta_i - \eta_j| \middle| i,j \in [1,2,3,4], i \neq j \right\}$$

- Azimuthal angular difference between the jets with the largest η separation

$$\phi_{ij} = |\phi_i - \phi_j| \quad \text{for} \quad \Delta\Upsilon = |\eta_i - \eta_j|$$

- Transverse momentum balance of the two softest jets

$$\Delta p_{\mathrm{T,Soft}} = \frac{|\vec{p}_{\mathrm{T},3} + \vec{p}_{\mathrm{T},4}|}{|\vec{p}_{\mathrm{T},3}| + |\vec{p}_{\mathrm{T},4}|}$$

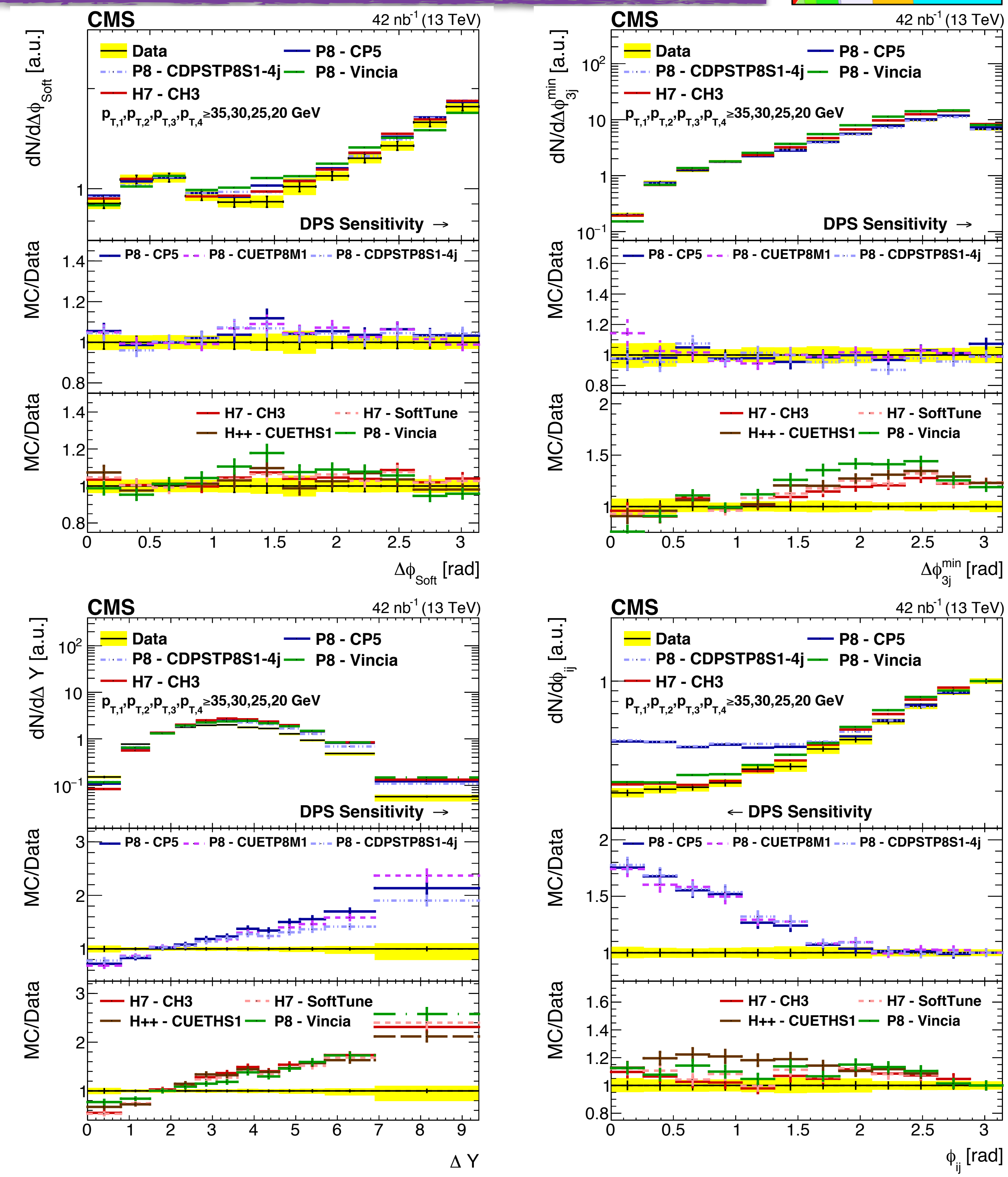
ΔS less correlated for DPS

- Azimuthal angular difference between the hard and the soft jet pairs

$$\Delta S = \arccos\left(\frac{(\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}).(\vec{p}_{\mathrm{T},3} + \vec{p}_{\mathrm{T},4})}{|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}||\vec{p}_{\mathrm{T},3} + \vec{p}_{\mathrm{T},4}|} \right)$$

Double Parton Scattering: 4 jet production

- Events generated with both PYTHIA8.240 and HERWIG
  - PYTHIA8.240 interfaced with CUETP8M1 (NNPDF2.3 LO), CP5 (NNPDF3.1 NNLO) and the CDPSTP8S1-4j tune
  - CDPSTP8S1-4j tune is a DPS tune (CTEQ6L1 PDFs)
    - MPI and DPS parameters derived from fit to data at $\sqrt{s}$ = 7 TeV
- PYTHIA8.301 sample generated with VINCIA : dipole ordered (NNPDF2.3 LO PDFs)
- HERWIG++ 2.71 with CUETHS1 tune (CTEQ6L1 PDFs)
- CH3 obtained through studies of underlying events (NNPDF3.1 NNLO PDF)
- **Data shows preference for p_T ordered parton shower description (studies performed in GEN-17-001 in agreement)**



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