Nucleon Structure and soft QCD from CMS

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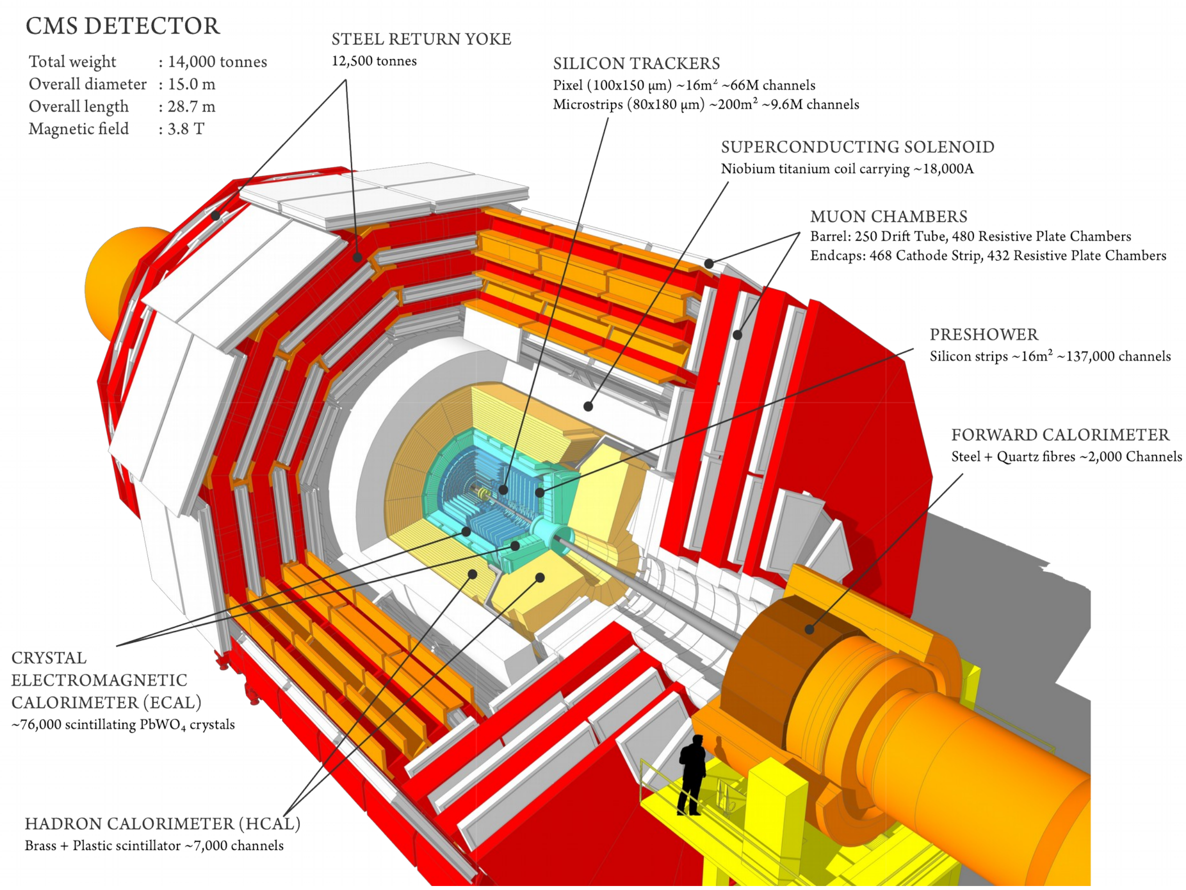
LHCP2021 (Online)
June 7-12, 2021

LHCP2021
The Ninth Annual Conference on Large Hadron Collider Physics

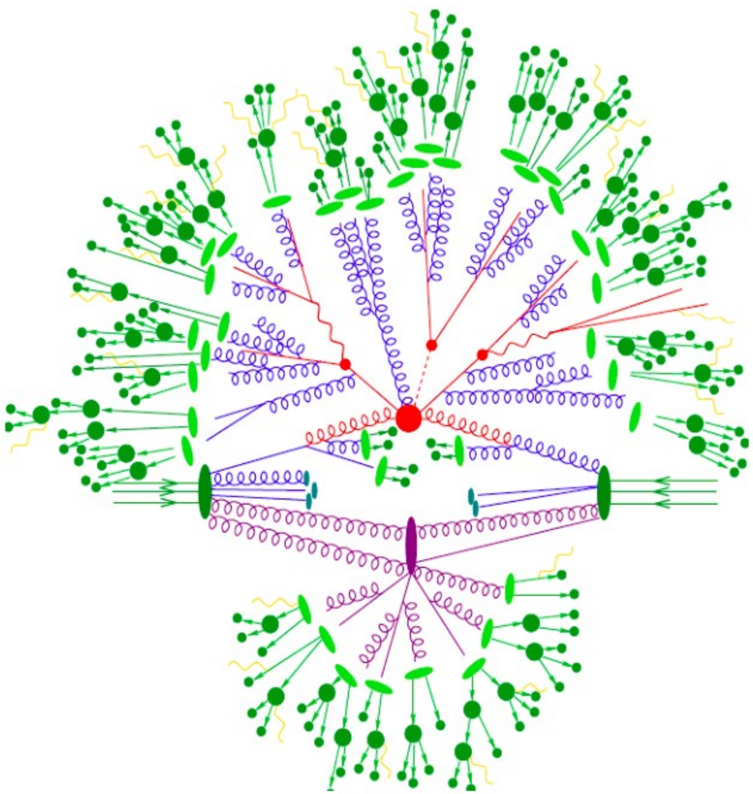
Outline

- **Introduction**
- **CMS Detector**
- **Soft QCD Measurements**
- **Diffractive Measurements**
- **Summary**



Introduction

- LHC collisions are complex: due to sub-structure of protons
- QCD: theory of strong interaction between interacting quarks and gluons of proton
  - Hard QCD – high p_T : PDFs, strong coupling, perturbation theory, ISR & FSR, parton shower
  - Soft QCD – low p_T : perturbative QCD approach not applicable
    -- Minimum bias events, Fragmentation/hadronization
    -- Underlying Event (ISR/FSR, BBR, MPI)
    -- Diffraction



Main Interaction

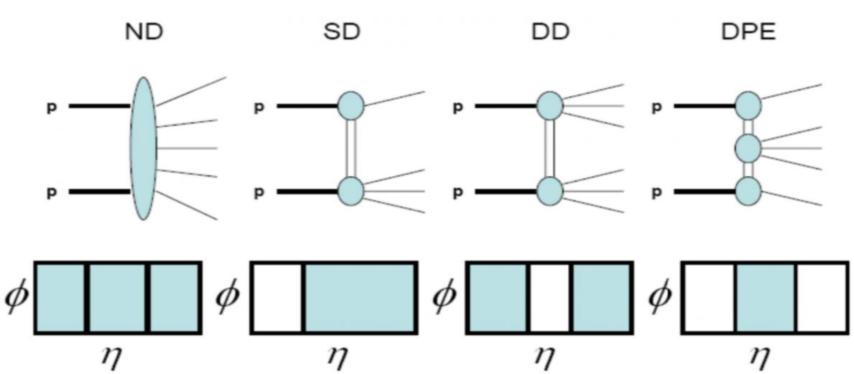
Radiation (ISR/FSR)

Fragmentation/Hadronization

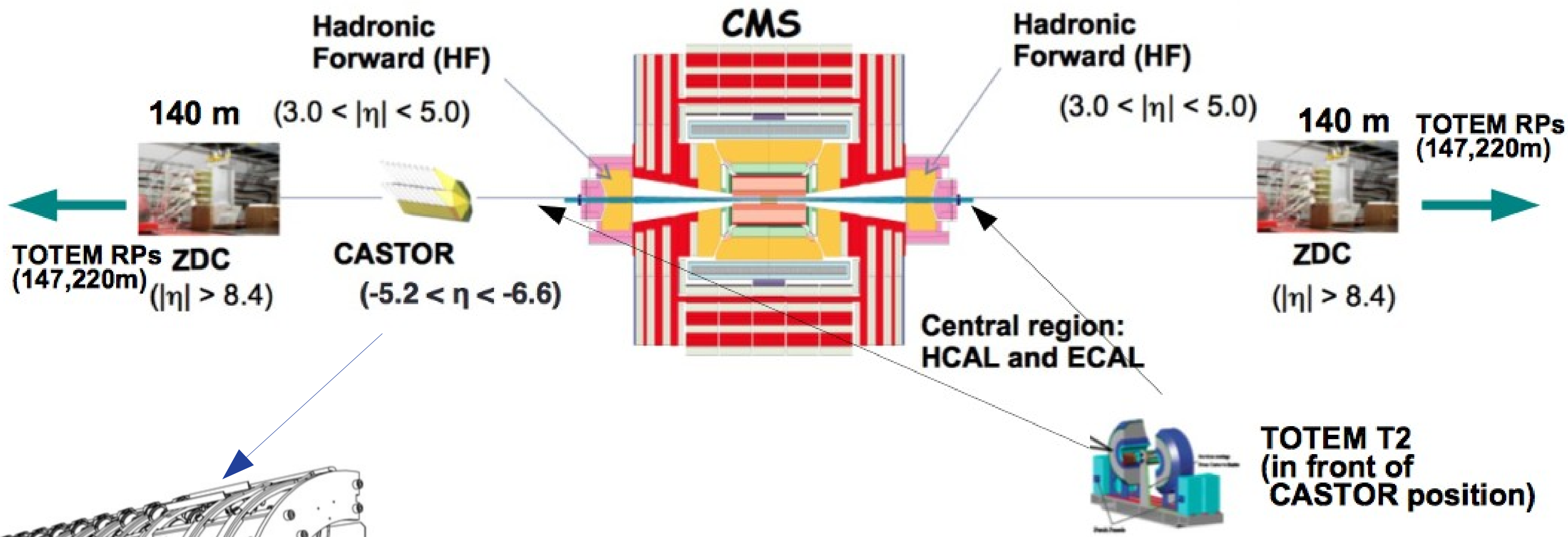
Multiple Parton Interactions (MPI)

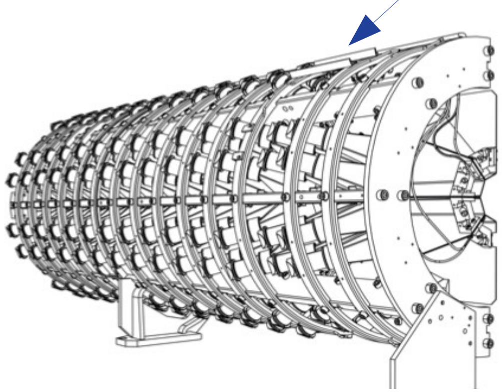
Beam remnant

- pp collisions: elastic or inelastic
- Inelastic collisions: diffractive or non-diffractive
- Diffractive processes dominate in forward regions



Forward detectors at CMS



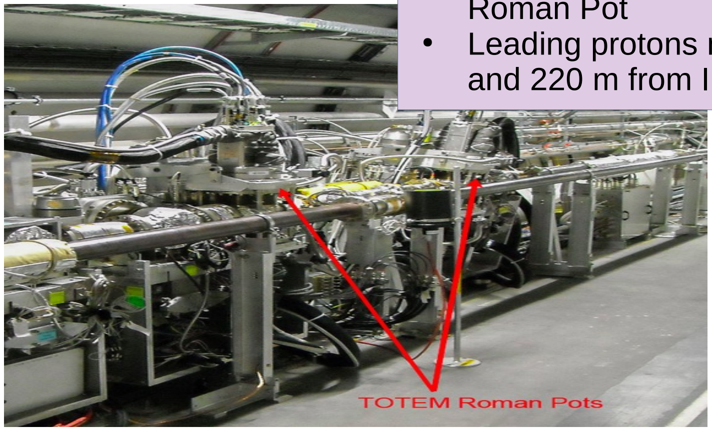


TOTal and Elastic Measurement (TOTEM)

- Dedicated for measuring total pp cross-section and understanding proton structure by elastic scattering
- Acceptance: $3.1 \leq |\eta| \leq 5$
- Consist of 2 near-beam telescopes: Roman Pot
- Leading protons measured at 147 m and 220 m from IP

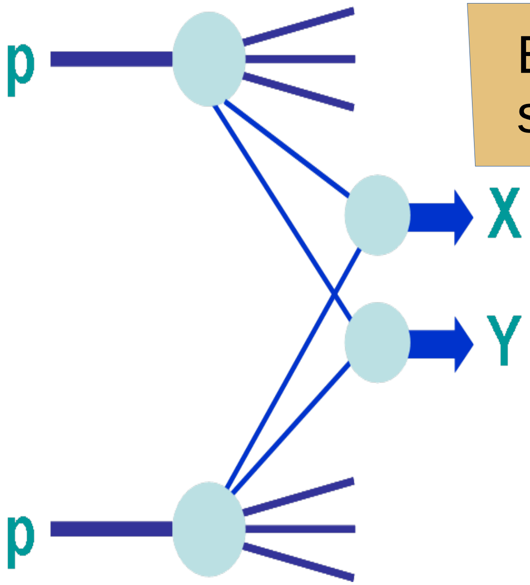
CASTOR at CMS

- CASTOR: EM-hadronic tungsten-quartz calorimeter at CMS
- Most forward conventional calorimeter deployed at the LHC, at 14 m from interaction point. Acceptance: $-6.6 \leq \eta \leq -5.2$
- Longitudinally 14-fold segmentation
- Transversally 16-fold segmentation
- CASTOR has no η segmentation! Consequence: measure energy of jets instead of p_T within its acceptance



Double Parton Scattering (DPS)

In general MPI is a softer contribution, → **Double Parton Scattering (DPS)**
But .....Some MPIs can be hard



Events where two hard parton-parton interactions occur in single proton-proton collisions

DPS cross-section $$\sigma_{eff} = \frac{m}{2} \cdot \frac{\sigma_X \cdot \sigma_Y}{\sigma^{DPS}_{X+Y}}$$

m = 1 when X = Y
m = 2 when X ≠ Y

- Background for rare processes, e.g. Higgs , SUSY etc
- Provides information on transverse partonic distribution of hadrons

DPS

- W + 2 Jets (JHEP03(2014)032
- γ + 3 Jets (CMS PAS FSQ-12-017)
- 4 Jets (Phys.Rev.D89(2014)092010)
- 2bjet+2jet (Phys.Rev.D94(2016)112005
- Double J/Ψ (JHEP09(2014)094)
- Same-sign WW (Eur. Phys. J. C 80, 41 (2020))

DPS studies using 4 jets and Z+Jets process are presented in this talk

DPS studies in 4-jets with low p_T at 13 TeV (CMS-PAS-20-007)

NEW

Observables

- Transverse momenta and pseudorapidity spectra of all the jets:
  - $p_{T,1}$, $p_{T,2}$, $p_{T,3}$ and $p_{T,4}$
  - η_1, η_2, η_3 and η_4
  - $p_{T,1}$ and η_1 in slides, others in backup
- Azimuthal angle of the soft jet pair: $\Delta\phi_{Soft} = |\phi_3 - \phi_4|$ → Back-to-back for DPS (peak around π)
- Combined minimum angle of 3 jets: $\Delta\phi_{3j}^{min} = min_{ijk}\{|\phi_i - \phi_j| + |\phi_j - \phi_k|\}$ → DPS (large value), SPS (random)
- Transversal momentum balance of the soft jet pair: $\Delta p_{T,soft} = \frac{|\vec{p}_{T,3}| + |\vec{p}_{T,4}|}{|\vec{p}_{T,3} + \vec{p}_{T,4}|}$ → Smaller value for DPS
- Maximum difference in pseudorapidity: $\Delta Y = max_{ij}\{|\eta_i - \eta_j|\}$ → larger value for DPS
- Azimuthal angle of the most remote jets: $\phi_{ij} = |\phi_i - \phi_j|$ for $\Delta Y = max_{ij}\{|\eta_i - \eta_j|\}$ → Strong correlation in SPS
- Azimuthal angle between the hardest and the softest jet pair (harder cuts needed): $\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}| \cdot |\vec{p}_{T,3} + \vec{p}_{T,4}|}\right)$ → DPS (random), SPS(peak at π)

Selection:

- Anti-k_T, R = 0.4
- Region I: $p_{T,1\ (2,3,4)}$ > 35 GeV (30,25,20 GeV)
- Region I: $p_{T,1\ (2,3,4)}$ > 50 GeV (30,30,30 GeV) for ΔS
- $|\eta_i| < 4.7$
- Asymmetric p_T cuts to enhance DPS sensitivity

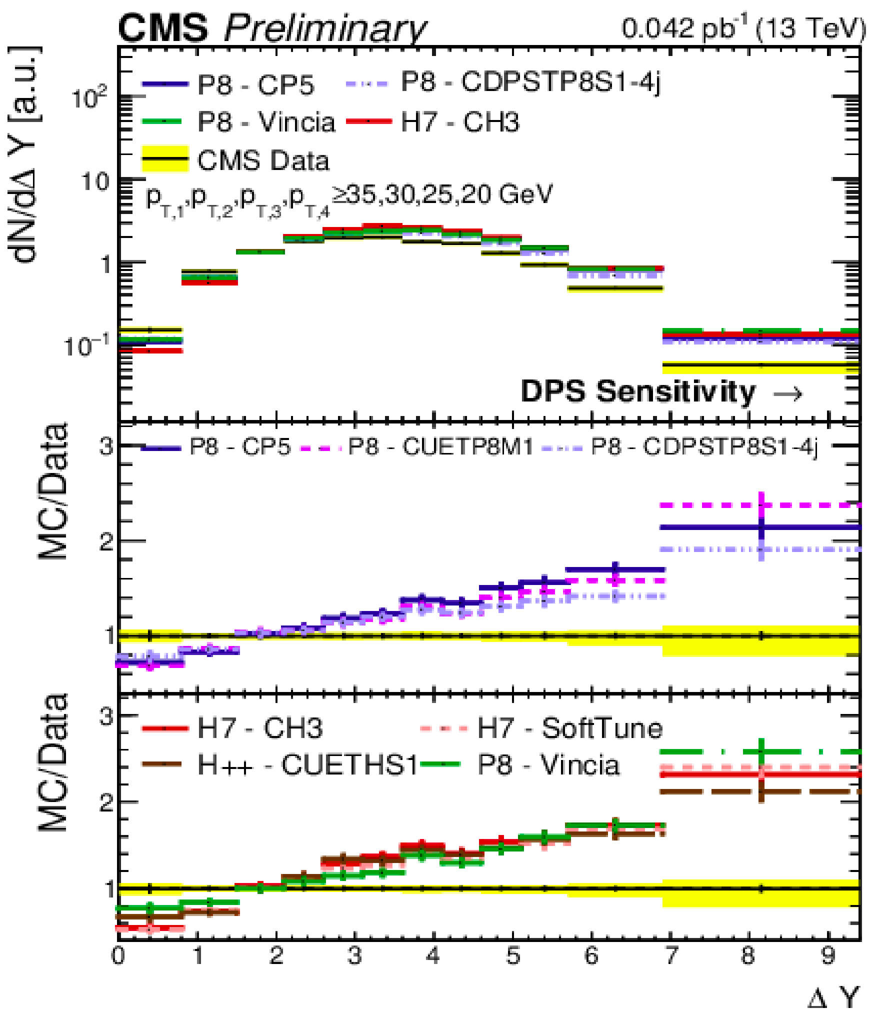
Workflow:

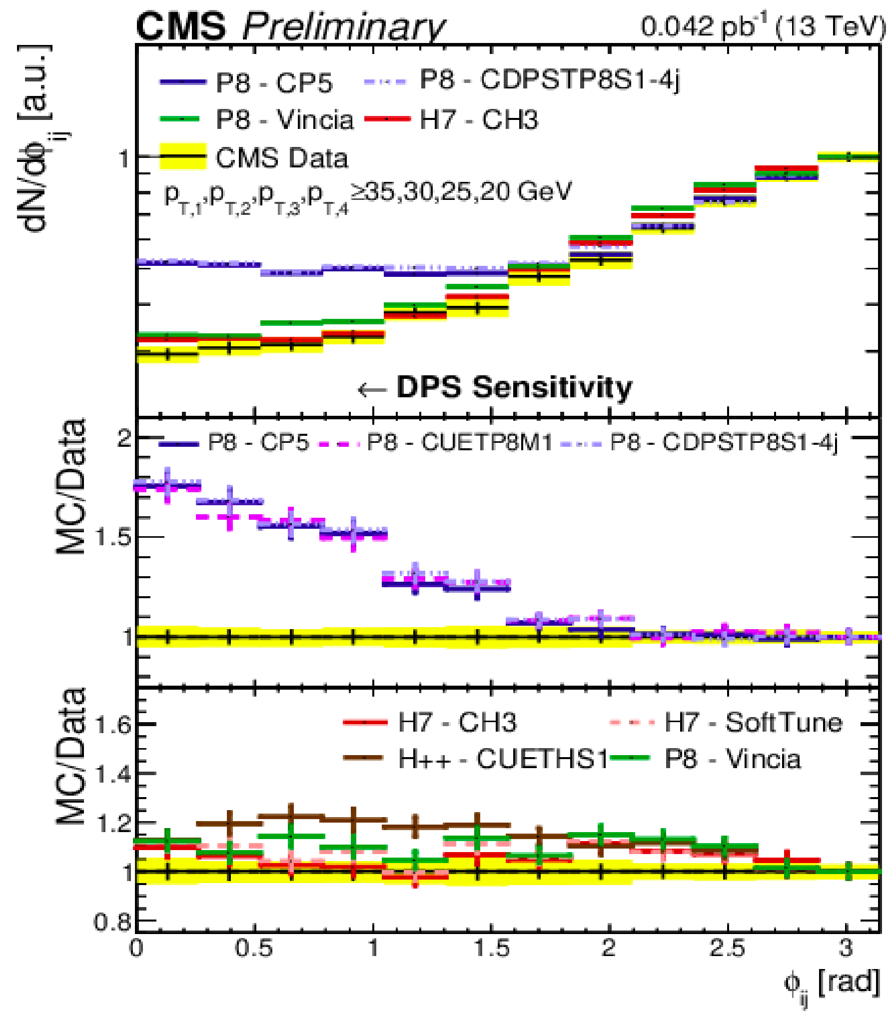
- Data distributions compared with:
  1. PYTHIA8 and HERWIG
  2. Multijet Models
  3. SPS+DPS Models
- Extraction of effective cross section

DPS studies in 4-jets with low p_T at 13 TeV (CMS-PAS-20-007)

NEW

- ΔY (left) and Φ_{ij} (right)
  - Normalization to first four bins for ΔY and the last bin for Φ_{ij}
- LO Models overshoot the data due to excess of forward/backward low p_T jets.
- Abs. cross-section prediction improves with NLO or high multiplicity ME (not true for all models)
- Φ_{ij} favor angular ordered/dipole antenna PS models over p_T-ordered showers.



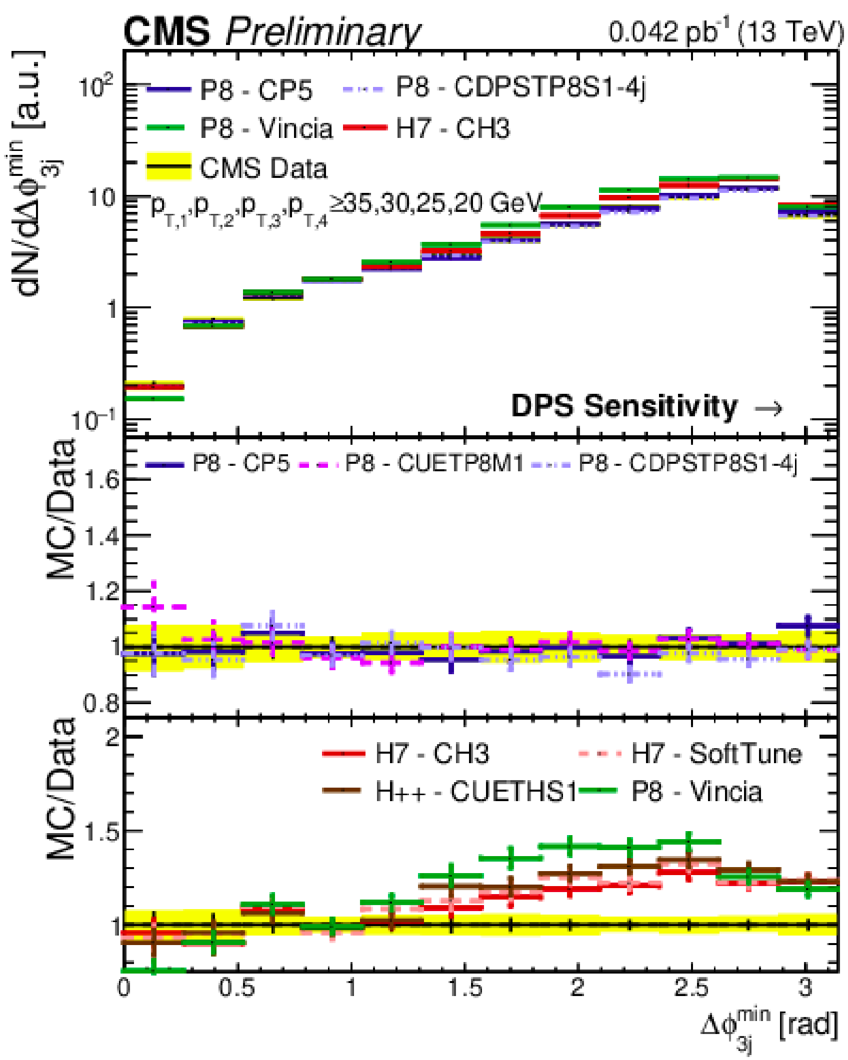


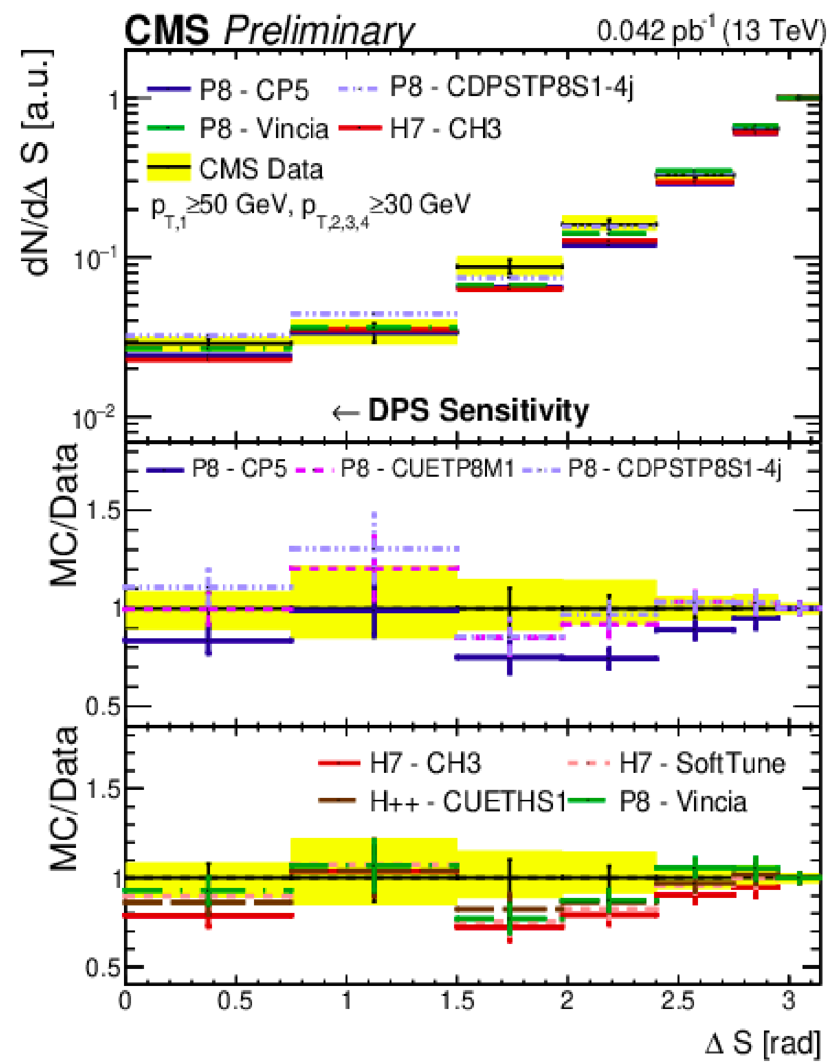
DPS studies in 4-jets with low p_T at 13 TeV (CMS-PAS-20-007)

- $\Delta\Phi_{3j}$ (left) and ΔS (right)
  - Normalization to first four bins for $\Delta\Phi_{3j}$ and the last bin for ΔS_j

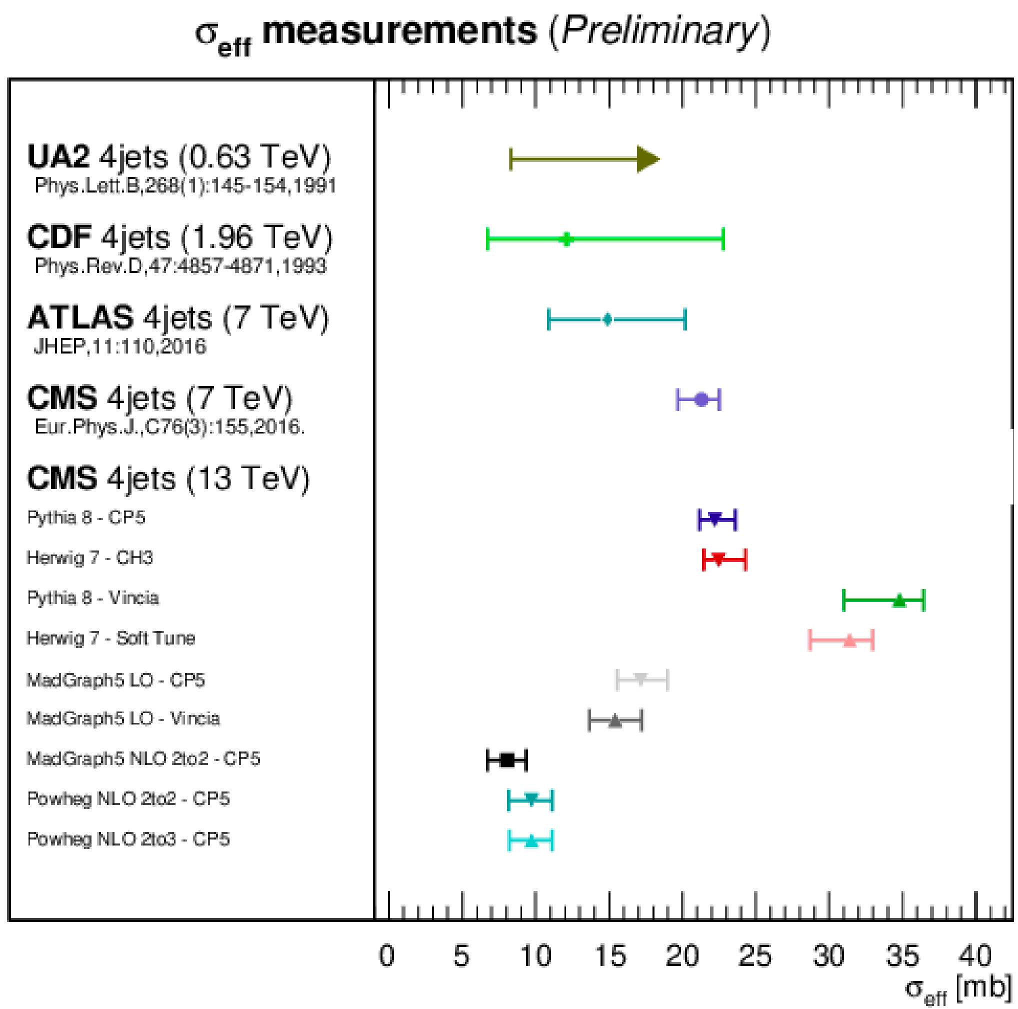
- Data favour p_T-ordered showers for LO models
- Less conclusive for NLO and/or higher-multiplicity ME

- Only distribution insensitive to PS modelling -- hence used for σ_{eff} extraction





DPS studies in 4-jets with low p_T at 13 TeV (CMS-PAS-20-007)



- Strong dependence of extracted value of σ_{eff} on the model to describe SPS contribution.
- NLO models with 2→2 and 2→3 ME yield smallest σ_{eff} (~10 mb) implying greater need of DPS contribution
- Including 4 partons in ME of SPS models introduce DPS-like correlat-ions in observables with σ_{eff} ~ 15 mb.
- Largest value of σ_{eff} (>~ 20 mb) found for LO models with 2→2 ME

DPS studies using Z+jets process at 13 TeV (CMS-PAS-20-009)

NEW

Overview:

- First DPS measurement with Z+Jets at 13 TeV with Z decaying into dimuon.
- Medium Muon ID with $I_{rel} < 0.15$ (R=0.4), opp. charged muons with $p_T > 27$ GeV, $|\eta| < 2.4$
- Z mass window (71 GeV < $M_{\mu\mu}$ < 111 GeV)
- $p_T > 20$ GeV, $|\eta| < 2.4$, $\Delta R(\text{jet},\mu) > 0.4$, Medium PU MVA ID

Observables :
(motivated from prev. measurements)

- $Z + \geq 1$ jet events:
  - $\Delta\phi(Z, j_1)$, $\Delta^{\text{rel}}_{p_T}(Z, j_1) = \frac{|\vec{p}_T(Z)+\vec{p}_T(j_1)|}{|\vec{p}_T(Z)|+|\vec{p}_T(j_1)|}$.
- $Z + \geq 2$ jets events:
  - $\Delta\phi(Z, dijet)$., $\Delta^{\text{rel}}_{p_T}(Z, dijet) = \frac{|\vec{p}_T(Z)+\vec{p}_T(dijet)|}{|\vec{p}_T(Z)|+|\vec{p}_T(dijet)|}$
  - $\Delta^{\text{rel}}_{p_T}(j_1, j_2) = \frac{|\vec{p}_T(j_1)+\vec{p}_T(j_2)|}{|\vec{p}_T(j_1)|+|\vec{p}_T(j_2)|}$.

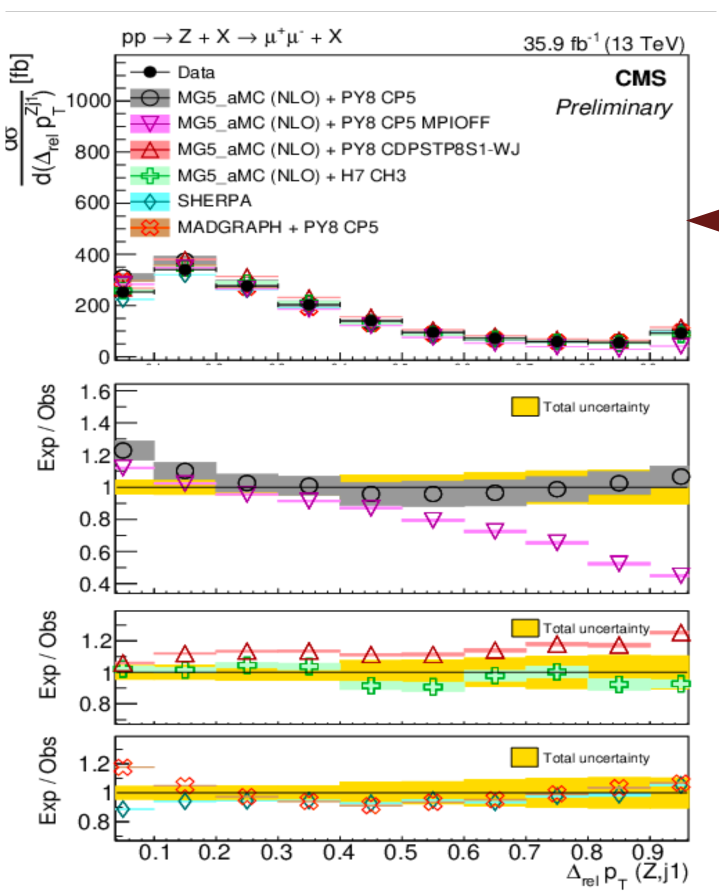
Cross-section (pb)		$Z + \geq 1$ Jets	$Z + \geq 2$ Jets
Measurement		158.5 ± 0.3 (stat) ± 7.0 (syst) ± 1.2 (theo) ± 4.0 (lumi) pb	44.8 ± 0.4 (stat) ± 3.7 (syst) ± 0.5 (theo) ± 1.1 (lumi) pb
MG5_aMC (NLO)	PYTHIA 8, CP5 tune	167.4 ± 9.7	47.0 ± 3.9
	PYTHIA 8, CDPSTP8S1-WJ tune	178.4 ± 0.3	50.5 ± 0.2
	HERWIG 7, CH3 tune	158.3 ± 1.1	44.4 ± 0.6
MADGRAPH + PYTHIA 8, CP5 tune (LO)		161.2 ± 0.1	45.3 ± 0.1
SHERPA (NLO+LO)		149.8 ± 0.2	41.6 ± 0.1

Measured integrated cross sections and comparison with different MC generators for Z + ≥ 1 jet and Z + ≥ 2 jet events

- Well described by SHERPA, MC@NLO+PYTHIA8 (tune CP5) and MC@NLO+HERWIG7 (tune CH3) predictions.
- MC@NLO+PYTHIA8 (DPS tune CDPSTP8S1) overestimate by 10-15%

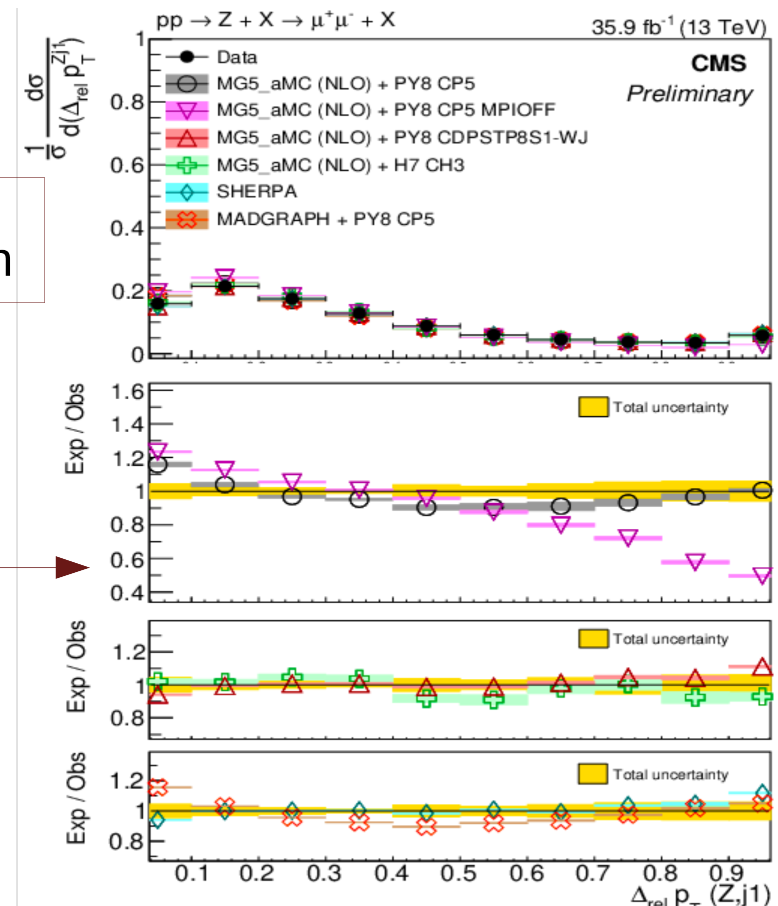
DPS studies using Z+jets process at 13 TeV (CMS-PAS-20-009)

- MC@NLO+P8 (MPI-OFF) is lower than measurement (by 50%) in lower $\Delta\Phi$ and high $\Delta_{rel}p_T$ region.
- MC@NLO+P8 (MPI-OFF), MC@NLO+H7 and SHERPA: behave similar while describing differential and area normalized distributions.
- MC@NLO+P8 CP5 (with MPI) describes diff. cross-section within uncertainty (except lower region of $\Delta_{rel}p_T$ (SPS dominated), but underestimates measurement in case of area-normalized distributions (except lower $\Delta_{rel}p_{T\ region}$).
- MC@NLO+P8 (CDPSTP8S1-WJ) fails to describe differential cross-section but describe shape of distribution within uncertainty) --> well modelled collision energy dependence of MPI parameters in tune



Differential cross-section

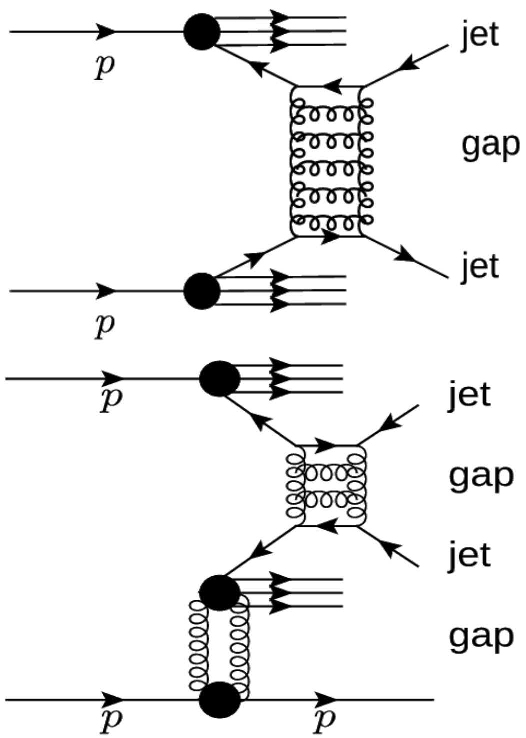
Area-normalized distribution

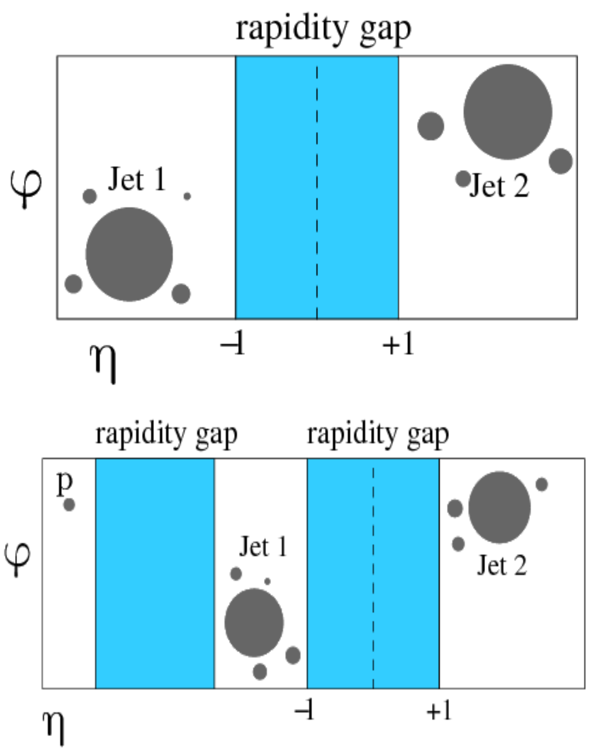


Hard color-singlet exchange in dijet events at 13 TeV (arxiV:2102.06945)

Accepted by PRD

- Events with two high-p_T jets separated by a pseudorapidity gap (interval void of particle activity).
  - DGLAP dynamics largely suppressed
  - allow to study BFKL pomeron exchange (color singlet exchange = two gluon t-channel exchange)





- Central gap can be destroyed by soft-parton interactions.
  - Parametrized by means of gap survival probability ($|S|^2 \sim 10^{-2}$-10^{-1})

- In pp collisions with intact protons, soft-parton activity is largely reduced
  -- Central gap more likely to "survive"

- Analysis Strategy:
  - Study jet-gap-jet in inclusive dijet production in pp collisions at 13 TeV with CMS
  - Study jet-gap-jet events with leading protons in pp collisions at 13 TeV (subset of CMS only dijet sample + forward protons detected with TOTEM roman pots): studied first time experimentally

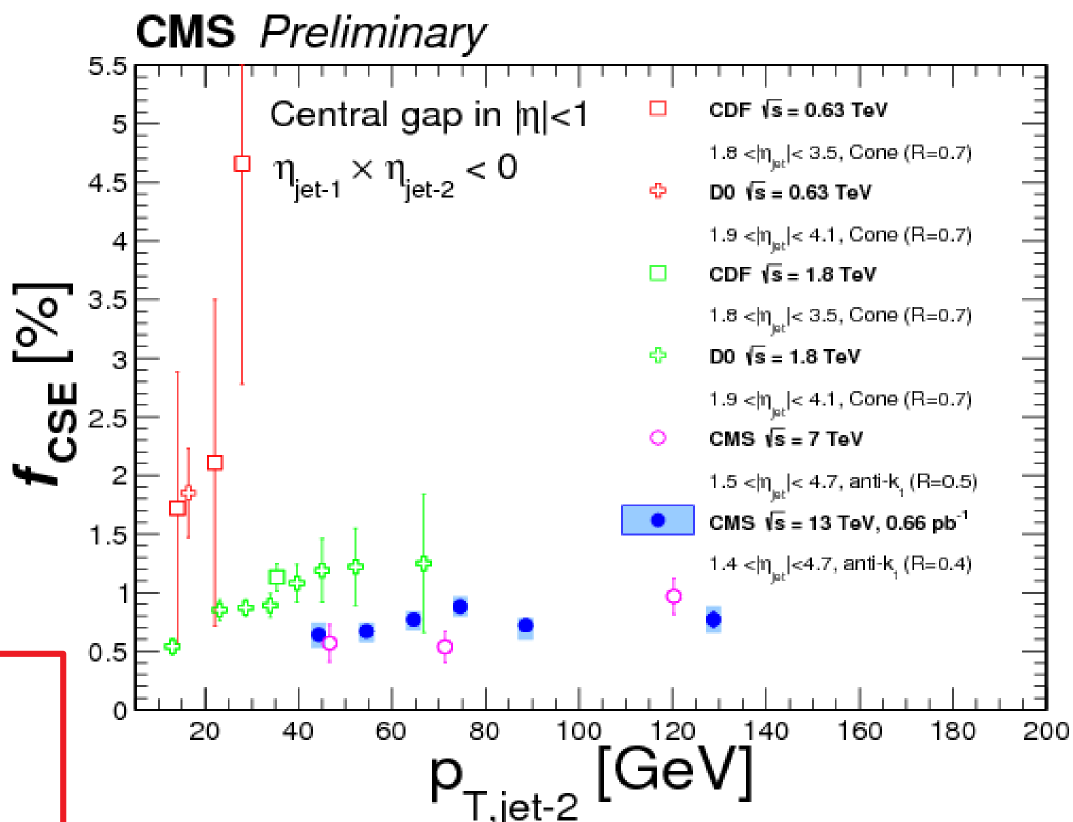
Hard color-singlet exchange in dijet events at 13 TeV (arxiV:2102.06945)

Accepted by PRD

Event Selection

- Particle-flow anti-k_T jets R=0.4
- 2 leading jets p_T > 40 GeV each
- Leading jet $1.4<|\eta_{jet}|<4.7$, and $\eta_{jet-1} \times \eta_{jet-2} < 0$ --> favours t-channel exchange

Pseudorapidity gap: charged particle multiplicity b/w leading 2 jets (p_T>200 MeV, $|\eta|<1$)



Fraction of dijet events produced by color-singlet exchange f_{CSE}:

$$f_{CSE} = \frac{N(N_{tracks}<3) - N_{bkg}(N_{tracks}<3)}{N_{all}} = \frac{colour\ singlet\ exchange\ dijet\ events}{all\ dijet\ events}$$

f_{CSE} is measured as a function of $\Delta\eta_{jj}$, $p_{T,jet-2}$, $\Delta\phi_{jj}$

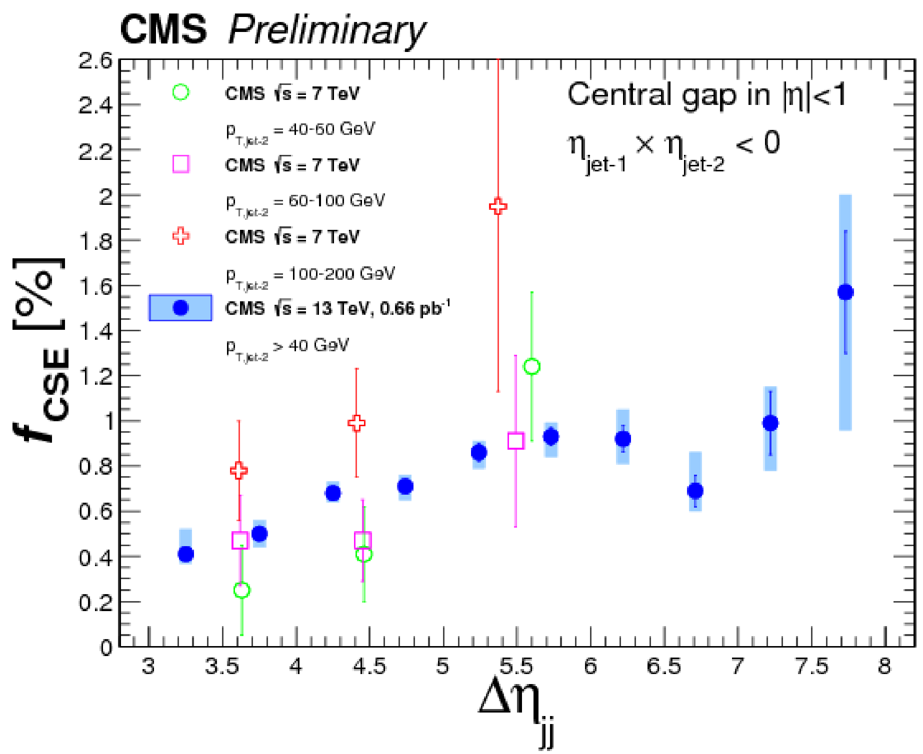
- Gap survival probability $|S^2|$ is expected to decrease with increasing COM, due to increase in spectator parton activity with COM.

- Within uncertainties, gap fractions stop decreasing with COM (7 TeV to 13 TeV), in contrast to trend observed at lower energies 0.63 TeV --> 1.8 TeV --> 7 TeV

Hard color-singlet exchange in dijet events at 13 TeV (arxiV:2102.06945)

Accepted by PRD

- f_{CSE} vs $\Delta\eta_{jj}$ expands the reach in pseudorapidity separations covered in the earlier 7 TeV measurements,
- Trend of increasing f_{CSE} vs $\Delta\eta_{jj}$ observed @7 TeV is confirmed @13 TeV
- Extends the range previously explored towards large values of $\Delta\eta_{jj}$



Jet-gap-jet events with intact protons:

- First observation of this process experimentally
- Hard color singlet exchange fraction f_{CSE} is $2.91 \pm 0.70(stat)^{+1.01}_{-0.94}$ larger than that in standard jet-gap-jet events.

Summary

- An overview of some representative soft QCD and diffractive measurements has been presented.
- LHC has provided access to a large phase space as well as a new energy scale for understanding various aspects of QCD.
- CMS has a rich physics program which is perfect testing ground for QCD models:
  - Improve our picture of nucleon structure and hadron collision, as well as its universality
- Energy measurements in the very forward rapidity regions indicate some interesting potential to further improve the underlying event model predictions
- Still more measurements and efforts as well as LHC Run3 preparations on-going. Stay Tuned!

Thanks for your attention!


Backup
Ctrl

Extraction Strategy of σ_{eff} (1)

- Before extraction of σ_{eff} from the pocket formula
  - Define the processes A and B $\sigma^{DPS}_{A,B} = \frac{m}{2} \frac{\sigma_A \cdot \sigma_B}{\sigma_{eff}}$
  - Extract method

- 4-jet DPS event when 1, 2 ,3 jets come from process A and 3, 2, 1 jets come from process B resp.
  - Define A and B as inclusive single jet processes → $\sigma_A = \sigma_{jet}(p_T \geq 50\,GeV)$, $\sigma_B = \sigma_{jet}(p_T \geq 30\,GeV)$
  - Lowest threshold jet trigger = 30 GeV
    → Extraction in region II performed
- Rapidity cross sections of processes A and B measured from data!

- Combining events from A and B into a DPS event
  - Veto condition for overlapping jets
  - 4-jet efficiency ε_{4j}= 0.32441 ± 0.00053 (stat.) found
  - → Combination rate of events from A and B that result in a 4-jet event passing the region II selection criteria
  - Pure DPS data sample is formed, same is done for Pythia 8 and Herwig++ with CUETP8M1 and CUETHS1 tunes resp.

- Rewrite pocket formula, taking overlap of A and B into account:

$$\sigma^{DPS}_{A,B} = \frac{\epsilon_{4j}}{\sigma_{eff}} \left(\frac{1}{2} \sigma_A^2 + \sigma_A \cdot (\sigma_B - \sigma_A) \right) = \frac{\epsilon_{4j} \sigma_A \sigma_B}{\sigma_{eff}} \left(1 - \frac{1}{2} \frac{\sigma_A}{\sigma_B} \right)$$

Extraction Strategy of σ_{eff} (2)

- Before extraction of σ_{eff} from the pocket formula
  - Define the processes A and B
  - Extract method

$$\sigma_{A,B}^{DPS} = \frac{\epsilon_{4j}\sigma_A \sigma_B}{\sigma_{eff}}\left(1 - \frac{1}{2}\frac{\sigma_A}{\sigma_B}\right)$$

- Template method for determination DPS cross section

$$\sigma^{Data}(\Delta S) = f_{DPS} \cdot \sigma_{DPS}^{Data}(\Delta S) + (1 - f_{DPS}) \cdot \sigma_{SPS}^{MC}(\Delta S)$$

  - ΔS fount to be least affected by parton showers (see results), used in extraction!
  - TFractionFitter class: likelihood fit using Poisson statistics
  - Optimal value of the fraction of DPS events in data (f_{DPS}) determined

- Background template: SPS MC models
- Signal template:
  - ΔS_{DPS} determined from pure DPS data sample
  - Fully corrected through same exact unfolding procedure as other observables
  - → Constructed pure DPS MC samples used for unfolding

- DPS cros section from f_{DPS}: $\sigma_{A,B}^{DPS} = f_{DPS} \int \sigma^{Data}(\Delta S) d(\Delta S)$

→ DPS is simplest form of multiple partonic interactions (MPI), expected Calculation of σ eff possible with DPS cross section as input in the pocket-formula!

Pythia 8, Herwig++ and Herwig 7 (1)

- Pythia 8
  - CUETP8M1, CDPSTP8S1-4j (GEN-14-001), CP5 tunes
  - **p_T-ordered parton shower**
- Pythia 8 with Vincia showering
  - Standard Pythia 8.3 tune
  - **dipole-antenna showering in Pythia 8**
- Herwig++
  - CUETHS1 tune
  - **Angular-ordered parton shower**
- Herwig 7
  - CH3, SoftTune tunes
  - **Angular-ordered parton shower**

Sample	Tune	σ_{I} (μb)	σ_{II} (μb)
Data	-	$2.77 \pm 0.02\ ^{+0.68}_{-0.55}$	$0.61 \pm 0.01\ ^{+0.12}_{-0.10}$
PYTHIA 8	CUETP8M1	5.03	1.07
PYTHIA 8	CP5	4.07	0.84
PYTHIA 8	CDPSTP8S1-4j	7.06	1.28
PYTHIA 8+VINCIA	Standard PYTHIA 8.3	4.66	0.97
HERWIG++	CUETHS1	4.35	0.83
HERWIG 7	CH3	4.82	0.98
HERWIG 7	SoftTune	5.34	1.07

MultiJet Samples (1)

- MadGraph5
  - 2 LO samples, 2→2,3,4 MEs combined, showered with Pythia 8 with the CP5 tune and with Pythia 8 with Vincia showering
  - NLO 2→2 sample, showered with Pythia with CP5 tune
- PowhegBox
  - NLO 2→2 and NLO 2→3 samples
  - Showered with Pythia interfaced with the CP5 tune
- KaTie is tree-level ME generator
  - On-shell production showered with Pythia 8 and Herwig 7
  - Off-shell production possible, showered with Cascade → Initial states receive non-zero k_T, used with different TMD PDFs
  - LO 2→4 ME for all samples
  - Generation of pure DPS sample possible

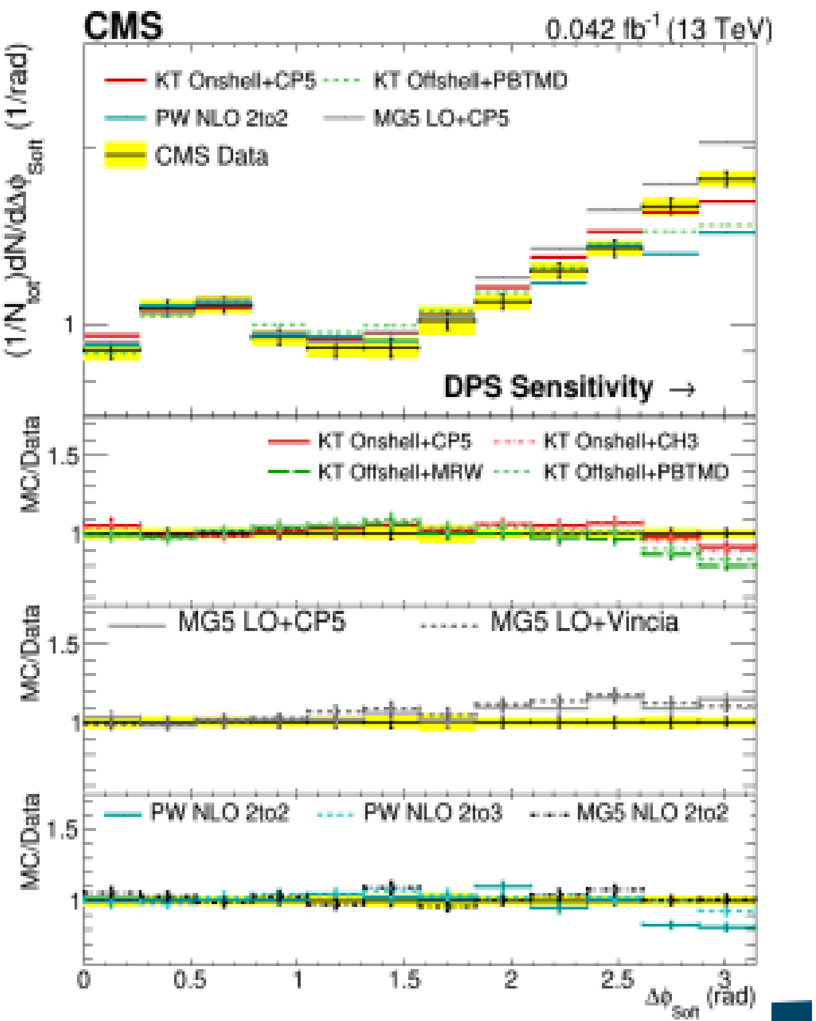
Sample	Tune/TMD	σ_1 (μb)	σ_{11} (μb)
Data	-	$2.77 \pm 0.02\ ^{+0.68}_{-0.55}$	$0.61 \pm 0.01\ ^{+0.12}_{-0.10}$
KaTie on-shell, PYTHIA 8	CP5	4.23	2.87
KaTie on-shell, HERWIG 7	CH3	3.56	2.25
KaTie off-shell, CASCADE	MRW	2.40	1.46
KaTie off-shell, CASCADE	PBTMD	2.57	1.56
MadGraph 5 LO $2 \to 2, 3, 4$, PYTHIA 8	CP5	2.69	1.26
MadGraph 5 LO $2 \to 2, 3, 4$, PYTHIA 8+Vincia	Standard PYTHIA 8.3	1.93	0.90
MadGraph 5 NLO $2 \to 2$, PYTHIA 8	CP5	2.12	1.03
POWHEG NLO $2 \to 2$, PYTHIA 8	CP5	3.50	1.62
POWHEG NLO $2 \to 3$, PYTHIA 8	CP5	2.55	1.22

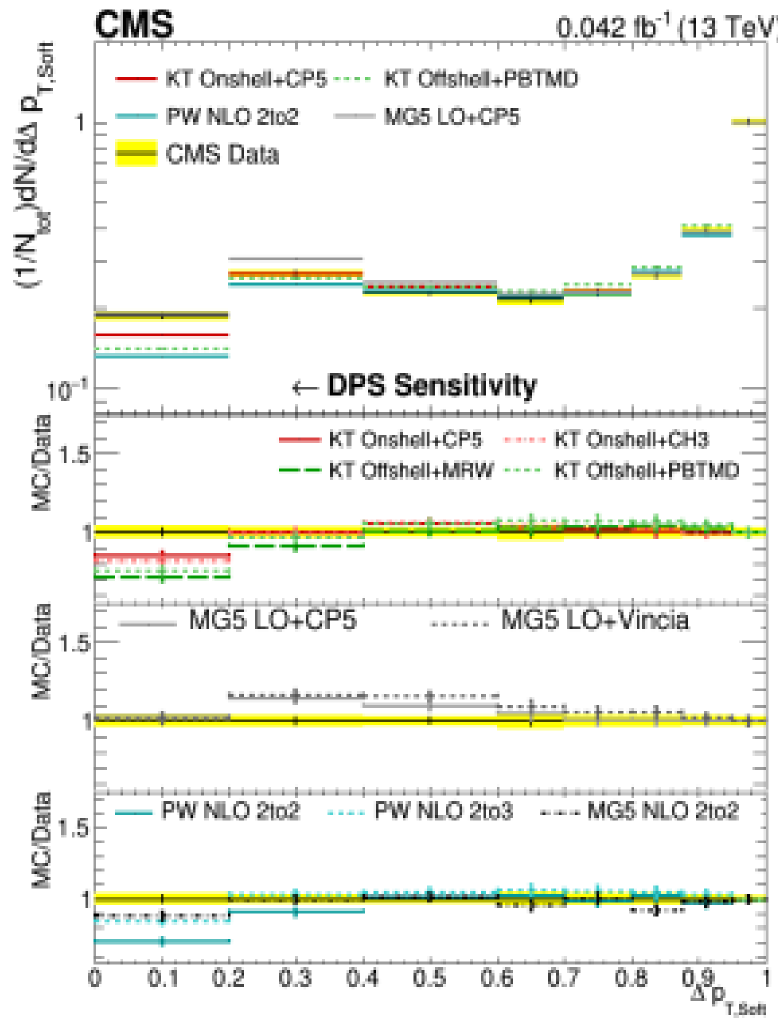
MultiJet Samples (3)

- $\Delta\phi_{Soft}$ (left) and $\Delta p_{T,Soft}$ (right)

- All MadGraph models overshoot DPS-sensitive slope
- All KaTie and Powheg models indicate need for DPS contribution

- Both MadGraph LO models overshoot DPS-sensitive slope
- All KaTie and NLO models indicate need for DPS contribution





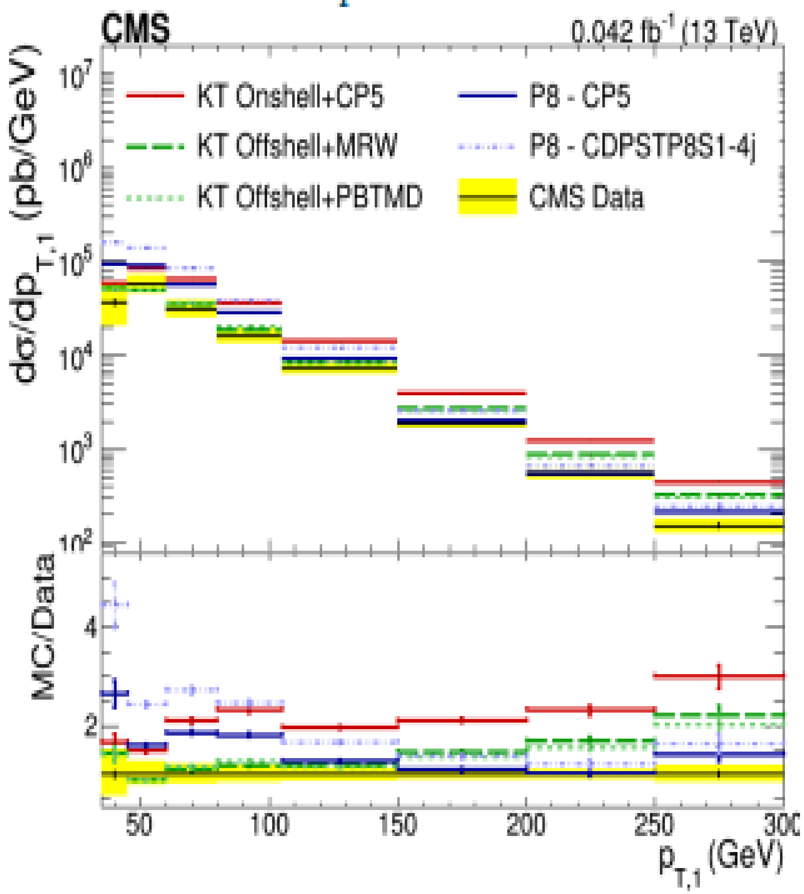
SPS+DPS Samples (1)

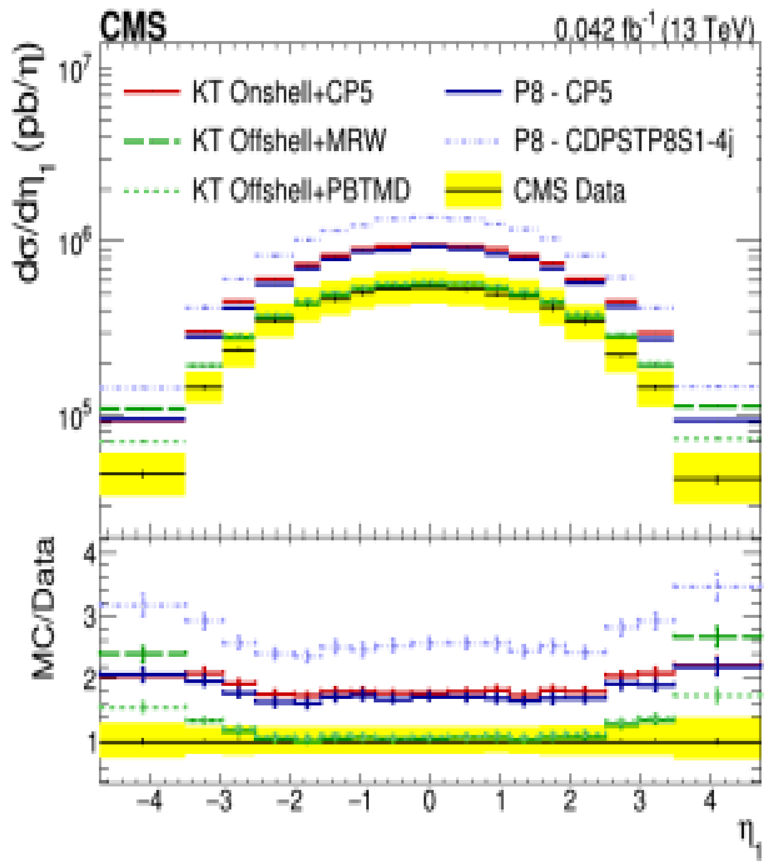
- Pythia 8
  - Pythia 8 allows generation of two times 2→2 ME at LO
  - σ_{eff} determined by UE parameters, not directly accessible
  - Pythia 8 with CP5 tune (SPS+DPS) sample
  - Pythia 8 with CDPSTP8S1-4j without DPS contribution
    → DPS is already in tune
- KaTie on- and off-shell
  - Include DPS contribution to SPS 2→4 ME at LO
  - Two times 2→2 ME at LO generated
  - σ_{eff} directly accessible, put to 21.3 mb (GEN-14-001)
  - On-shell sample hadronization only possible with Pythia 8
  - Off-shell samples with Cascade
    → DPS contribution through non-perturbative corrections from parton to hadron level

Sample	Tune/TMD	σ_{I} (μb)	σ_{II} (μb)
Data	-	$2.77 \pm 0.02\ ^{+0.68}_{-0.55}$	$0.61 \pm 0.01\ ^{+0.12}_{-0.10}$
SPS+DPS KaTie on-shell, PYTHIA 8	CP5	5.04	2.14
SPS+DPS KaTie off-shell, Cascade	MRW	3.11	0.95
SPS+DPS KaTie off-shell, Cascade	PBTMD	3.12	0.99
SPS+DPS PYTHIA 8	CP5	4.76	0.94
PYTHIA 8	CDPSTP8S1-4j	7.06	1.28

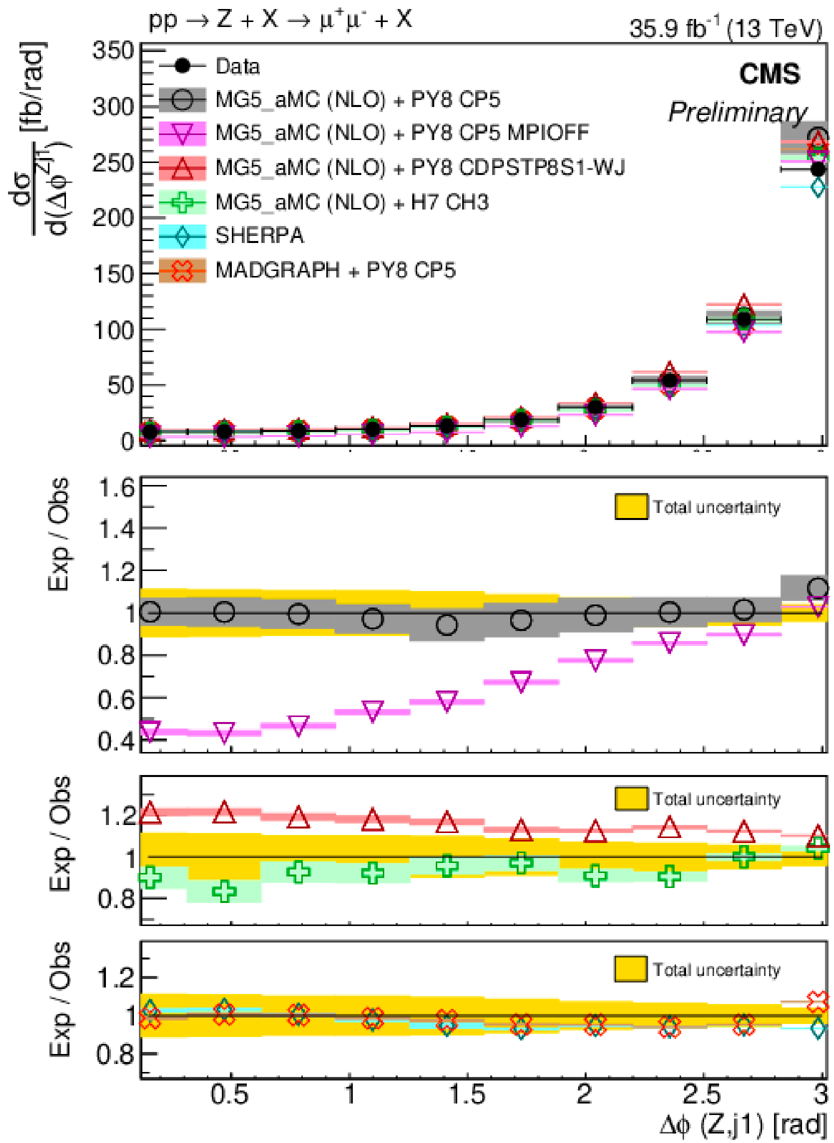
SPS+DPS Samples (2)

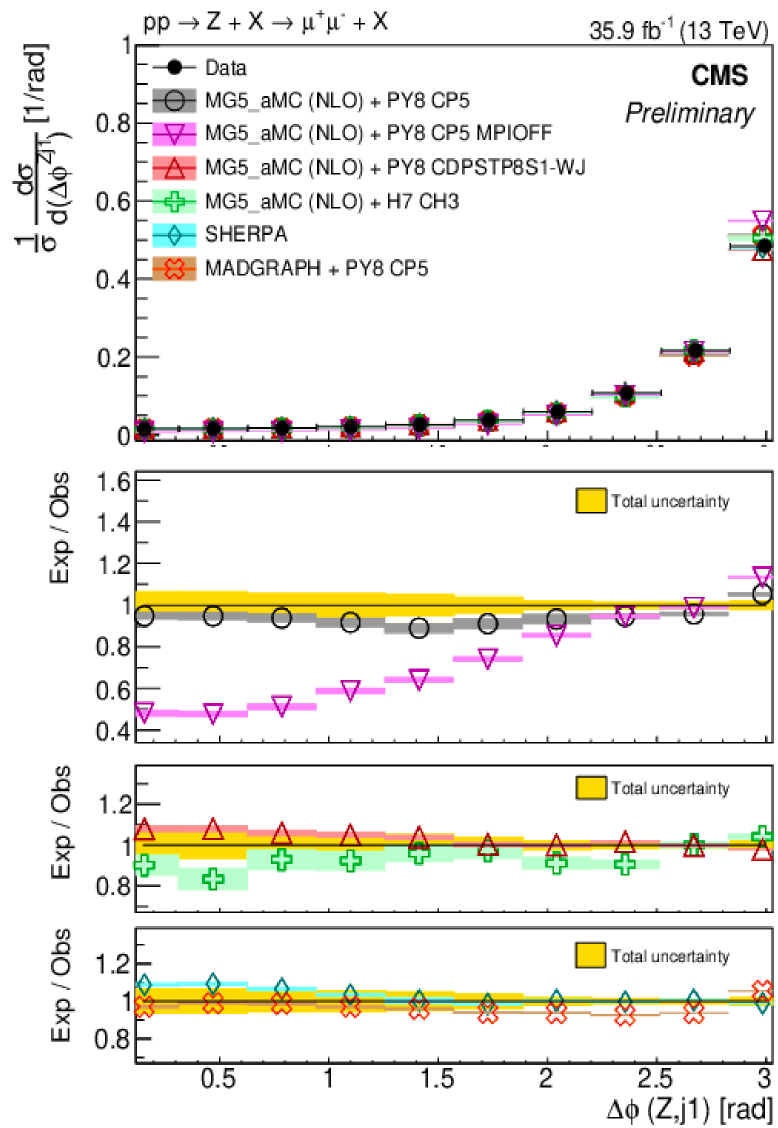
- $p_{T,1}$ (left) and η_1 (right)
  - Off-shell KaTie good description at low p_T (2→4 ME)
  - Pythia 8 with CP5 good description at high p_T (2→2 ME)
  - DPS contribution mainly at low p_T and forward/backward regions compared to SPS predictions



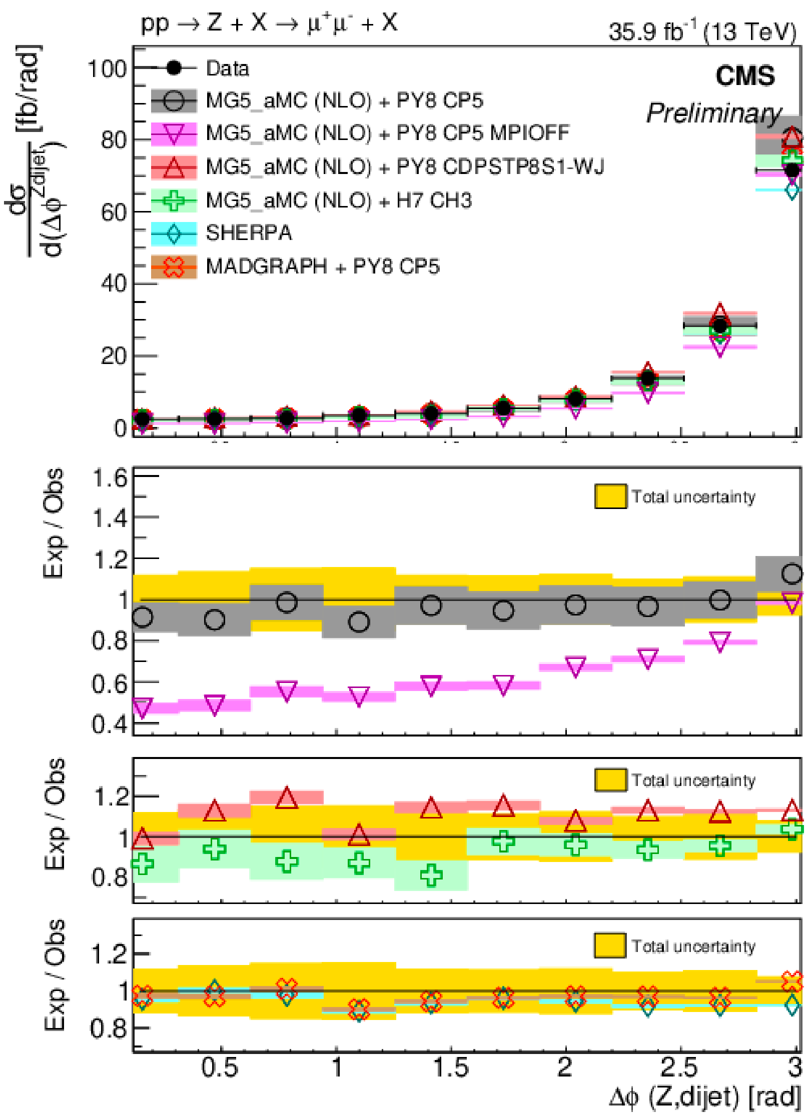


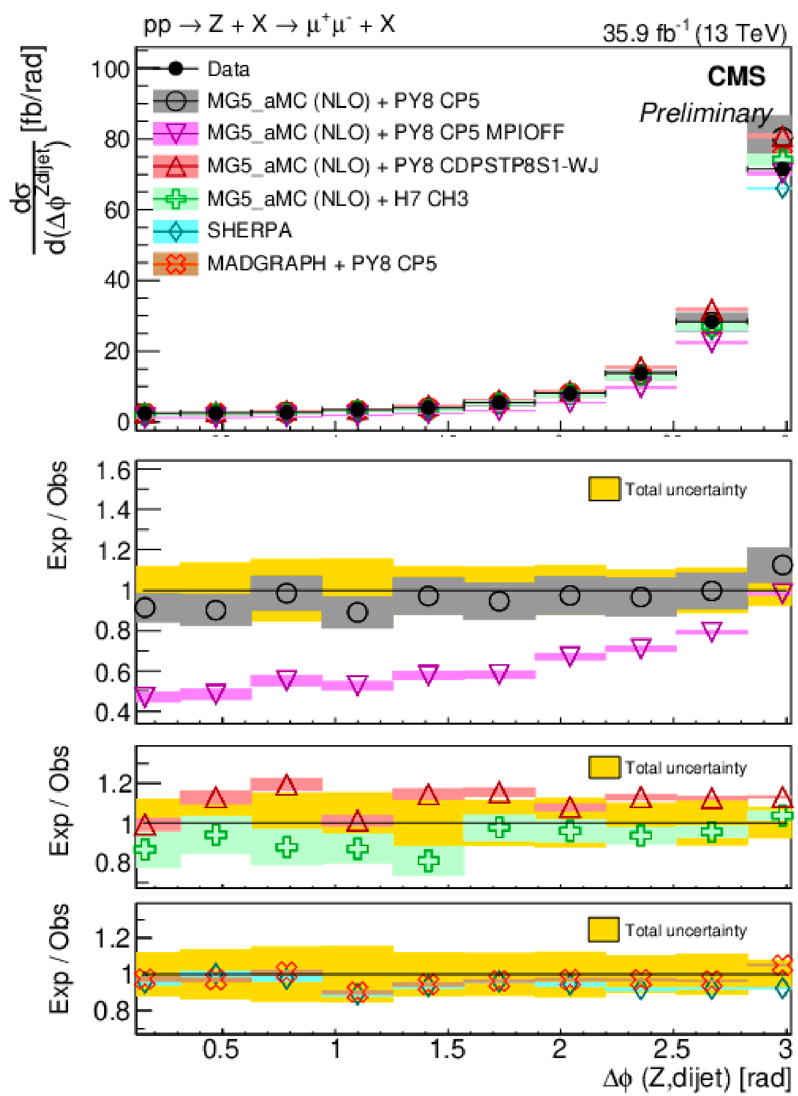
DPS studies using Z+jets process at 13 TeV (CMS-PAS-20-009)



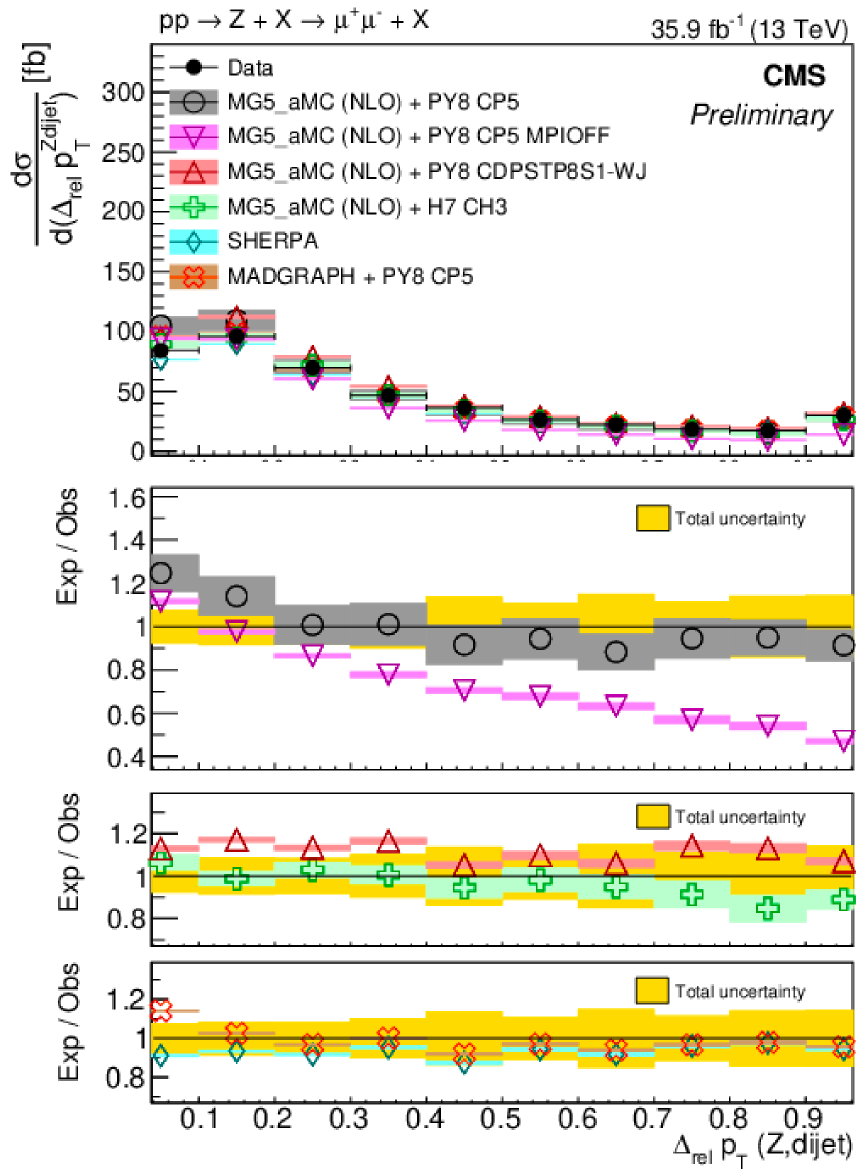


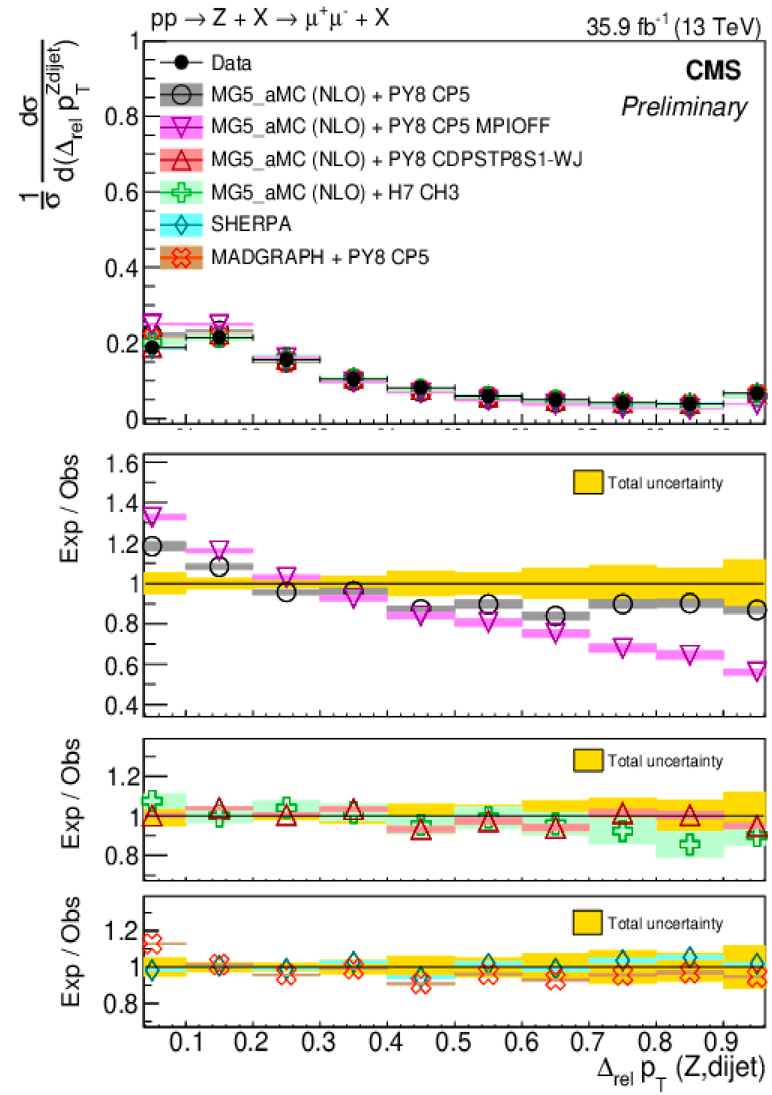
DPS studies using Z+jets process at 13 TeV (CMS-PAS-20-009)





DPS studies using Z+jets process at 13 TeV (CMS-PAS-20-009)





DPS studies using Z+jets process at 13 TeV (CMS-PAS-20-009)