Nucleon Structure and soft QCD from CMS

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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

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

- **Main Interaction**
  - Radiation (ISR/FSR)
  - Fragmentation/Hadronization
  - Multiple Parton Interactions (MPI)
  - Beam remnant
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 $\eta$ segmentation! Consequence: measure energy of jets instead of $p_T$ within its acceptance
Double Parton Scattering (DPS)

In general MPI is a softer contribution, 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 $X \neq Y$

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

- W + 2 Jets (JHEP03(2014)032)
- $\gamma + 3$ Jets (CMS PAS FSQ-12-017)

- 2bjet+2jet (Phys.Rev.D94(2016)112005)
- Double J/Ψ (JHEP09(2014)094)

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)**

**Observables**

- Transverse momenta and pseudorapidity spectra of all the jets:
  - \( p_{T,1}, p_{T,2}, p_{T,3} \) and \( p_{T,4} \)
  - \( \eta_1, \eta_2, \eta_3 \) and \( \eta_4 \)
  - \( p_{T,1} \) and \( \eta_1 \) in slides, others in backup
- Azimuthal angle of the soft jet pair: \( \Delta \phi_{\text{soft}} = |\phi_3 - \phi_4| \) → Back-to-back for DPS (peak around \( \pi \))
- Combined minimum angle of 3 jets: \( \Delta \phi_{3j}^{\text{min}} = \min_{ijk} \{ |\phi_i - \phi_j| + |\phi_j - \phi_k| \} \) → DPS (large value), SPS (random)
- Transversal momentum balance of the soft jet pair: \( \Delta p_{T,\text{soft}} = \frac{|\vec{p}_{T,3} + \vec{p}_{T,4}|}{|\vec{p}_{T,3} + \vec{p}_{T,4}|} \) → 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):
  \[ \Delta S = \arccos \left( \frac{\vec{p}_{T,1} \cdot \vec{p}_{T,2} + \vec{p}_{T,3} \cdot \vec{p}_{T,4}}{||\vec{p}_{T,1}|| \cdot ||\vec{p}_{T,2}|| \cdot ||\vec{p}_{T,3}|| \cdot ||\vec{p}_{T,4}||} \right) \] → DPS (random), SPS (peak at \( \pi \))

**Selection:**
- Anti-\( k_T \), \( R = 0.4 \)
- Region I: \( p_{T,1} (2,3,4) > 35 \text{ GeV} \) (30,25,20 GeV)
- Region I: \( p_{T,1} (2,3,4) > 50 \text{ GeV} \) (30,30,30 GeV) for \( \Delta S \)
- \( |\eta| < 4.7 \)
- 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)

- $\Delta Y$ (left) and $\Phi_{ij}$ (right)
  - Normalization to first four bins for $\Delta Y$ and the last bin for $\Phi_{ij}$
- 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)
- $\Phi_{ij}$ 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 $\Delta S$ (right)
- Normalization to first four bins for $\Delta \Phi_{3j}$ and the last bin for $\Delta S$
- 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 $\sigma_{eff}$ extraction
DPS studies in 4-jets with low $p_T$ at 13 TeV (CMS-PAS-20-007)

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

- First DPS measurement with Z+Jets at 13 TeV with Z decaying into dimuon.
- Medium Muon ID with $I_{\text{rel}} < 0.15$ (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:
  - $\Delta\phi(Z, j_1)$, $\Delta_{\text{rel}}^{Z,j_1}(Z, j_1) = \frac{|\vec{p}_T(Z) + \vec{p}_T(j_1)|}{|\vec{p}_T(Z)| + |\vec{p}_T(j_1)|}$
- $Z + \geq 2$ jets events:
  - $\Delta\phi(Z, \text{dijet})$, $\Delta_{\text{rel}}^{Z,\text{dijet}}(Z, \text{dijet}) = \frac{|\vec{p}_T(Z) + \vec{p}_T(\text{dijet})|}{|\vec{p}_T(Z)| + |\vec{p}_T(\text{dijet})|}$
  - $\Delta_{\text{rel}}^{\text{dijet}}(j_1, j_2) = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$

Measured integrated cross sections and comparison with different MC generators for $Z + \geq 1$ jet and $Z + \geq 2$ 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 ΔΦ and high Δ_{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 Δ_{rel}p_T (SPS dominated), but underestimates measurement in case of area-normalized distributions (except lower Δ_{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
Hard color-singlet exchange in dijet events at 13 TeV (arXiV:2102.06945)

- 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)  

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 \rightarrow \text{favours t-channel exchange}
- Pseudorapidity gap: charged particle multiplicity b/w leading 2 jets (p_T>200 MeV, |\eta|<1)

\begin{align*}
\text{Fraction of dijet events produced by color-singlet exchange } f_{\text{CSE}}: \\
 f_{\text{CSE}} &= \frac{N(N_{\text{tracks}}<3) - N_{\text{bkg}}(N_{\text{tracks}}<3)}{N_{\text{all}}} \\
&= \frac{\text{colour singlet exchange dijet events}}{\text{all dijet events}}
\end{align*}

\( f_{\text{CSE}} \) 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)

- $f_{\text{CSE}}$ vs $\Delta \eta_{jj}$ expands the reach in pseudorapidity separations covered in the earlier 7 TeV measurements,
- Trend of increasing $f_{\text{CSE}}$ 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 $f_{\text{CSE}}$ is $2.91 \pm 0.70^{+1.01}_{-0.94} (\text{stat})$ 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!
Extraction Strategy of $\sigma_{\text{eff}}$ (1)

- Before extraction of $\sigma_{\text{eff}}$ from the pocket formula
  - Define the processes A and B
  - Extract method

\[ \sigma_{A,B}^{\text{DPS}} = \frac{m}{2} \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{eff}}} \]

- 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 →
  - 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 $\varepsilon_{4j} = 0.32441 \pm 0.00053$ (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:

\[ \sigma_{A,B}^{\text{DPS}} = \frac{\varepsilon_{4j}}{\sigma_{\text{eff}}} \left( \frac{1}{2} \sigma_A^2 + \sigma_A \cdot (\sigma_B - \sigma_A) \right) = \frac{\varepsilon_{4j} \sigma_A \sigma_B}{\sigma_{\text{eff}}} \left( 1 - \frac{1}{2} \frac{\sigma_A}{\sigma_B} \right) \]
Extraction Strategy of $\sigma_{\text{eff}}$ (2)

- Before extraction of $\sigma_{\text{eff}}$ from the pocket formula
  - Define the processes A and B
  - Extract method

- Template method for determination DPS cross section

\[
\sigma_{\text{Data}}^{\Delta S}(A) = f_{\text{DPS}} \cdot \sigma_{\text{DPS}}^{\Delta S} \cdot \Delta S + (1 - f_{\text{DPS}}) \cdot \sigma_{\text{MC}}^{\Delta S}
\]

- $\Delta S$ found 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 ($f_{\text{DPS}}$) determined

- Background template: SPS MC models
- Signal template:
  - $\Delta S_{\text{DPS}}$ determined from pure DPS data sample
  - Fully corrected through same exact unfolding procedure as other observables
  - $\rightarrow$ Constructed pure DPS MC samples used for unfolding

- DPS cross section from $f_{\text{DPS}}$:

\[
\sigma_{\text{DPS}}^{\Delta S} = f_{\text{DPS}} \int \sigma_{\text{Data}}^{\Delta S} d(\Delta S)
\]

$\rightarrow$ DPS is simplest form of multiple partonic interactions (MPI), expected Calculation of $\sigma_{\text{eff}}$ 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

<table>
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<th>Tune</th>
<th>$\sigma_1 (\mu b)$</th>
<th>$\sigma_2 (\mu b)$</th>
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<td>2.77 $\pm$ 0.02 $^{+0.68}_{-0.55}$</td>
<td>0.61 $\pm$ 0.01 $^{+0.12}_{-0.10}$</td>
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<td>HERWIG 7</td>
<td>SoftTune</td>
<td>5.34</td>
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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

<table>
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<tr>
<th>Sample</th>
<th>Tune/TMD</th>
<th>$\sigma_I$ (μb)</th>
<th>$\sigma_{II}$ (μb)</th>
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<td>2.77 ± 0.02</td>
<td>0.61 ± 0.01</td>
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<td>KaTie on-shell, Pythia 8</td>
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<td>2.55</td>
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MultiJet Samples (3)

- $\Delta \phi_{\text{Soft}}$ (left) and $\Delta p_{T,\text{Soft}}$ (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 $2 \rightarrow 2$ ME at LO
  - $\sigma_{\text{eff}}$ 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 $2 \rightarrow 4$ ME at LO
  - Two times $2 \rightarrow 2$ ME at LO generated
  - $\sigma_{\text{eff}}$ 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

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<th>$\sigma_{\text{II}}$ (µb)</th>
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SPS+DPS Samples (2)

- $p_{T,1}$ (left) and $\eta_1$ (right)
  - Off-shell KaTie good description at low $p_T$ ($2\rightarrow 4$ ME)
  - Pythia 8 with CP5 good description at high $p_T$ ($2\rightarrow 2$ 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)
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