Double Parton Scattering Measurements at the CMS Experiment

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Overview

Double parton scattering (DPS)

DPS experiments at CMS

- Measurements of Z bosons plus jets using variables sensitive to double-parton scattering in proton-proton collisions at $\sqrt{s}$ = 13 TeV

- Study of double-parton scattering in inclusive production of four jets with low transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV

- Observation of triple J/ψ production in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Double parton scattering

- Apart from single parton scattering (SPS), MPI possible in pp collisions → Double parton scattering (DPS) simples form
- DPS cross section described by the **DPS pocket-formula**

$$\sigma_{A,B}^{DPS} = \frac{m}{2} \frac{(\sigma_A \cdot \sigma_B)}{\sigma_{eff}}$$

  - A, B are two independent processes
  - Combinatorial factor m = 1 for identical and m = 2 for non-identical processes
  - Effective cross section parameter σ_{eff} → Reflects correlation between the processes A and B
- σ_{eff} is independent of final state in this approach
- Pocket formula is only valid in inclusive production [1]

- Pocket formula assumes NO correlations between partons coming from the same hadron

- DPS is expected to become increasingly important at higher and higher centre-of-mass energies
- DPS processes can be important backgrounds in SM and new physics measurements
- Better knowledge of DPS contributes to a more complete understanding of hadronic interactions

[1] Michael H. Seymour and Andrzej Siodmok. Extracting σ eff from the LHCb double-charm measurement, arXiv:1308.6749 [hep-ph]

Measurements of Z bosons plus jets using variables sensitive to double-parton scattering in proton-proton collisions at $\sqrt{s}$ = 13 TeV

CMS-SMP-20-009, arXiv:2105.14511

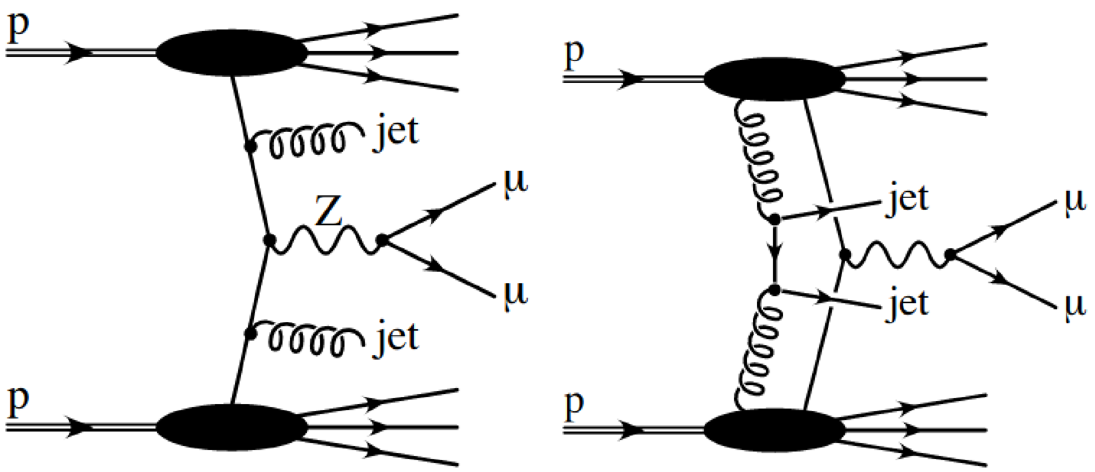
Event topology and observables

- Two topologies and multiple observables considered (only Z→μμ)
  - Z + ≥1 jet
    - Azimuthal angle between jet and Z boson

$$\Delta\phi(Z, j_1) = |\phi_Z - \phi_{j_1}|$$

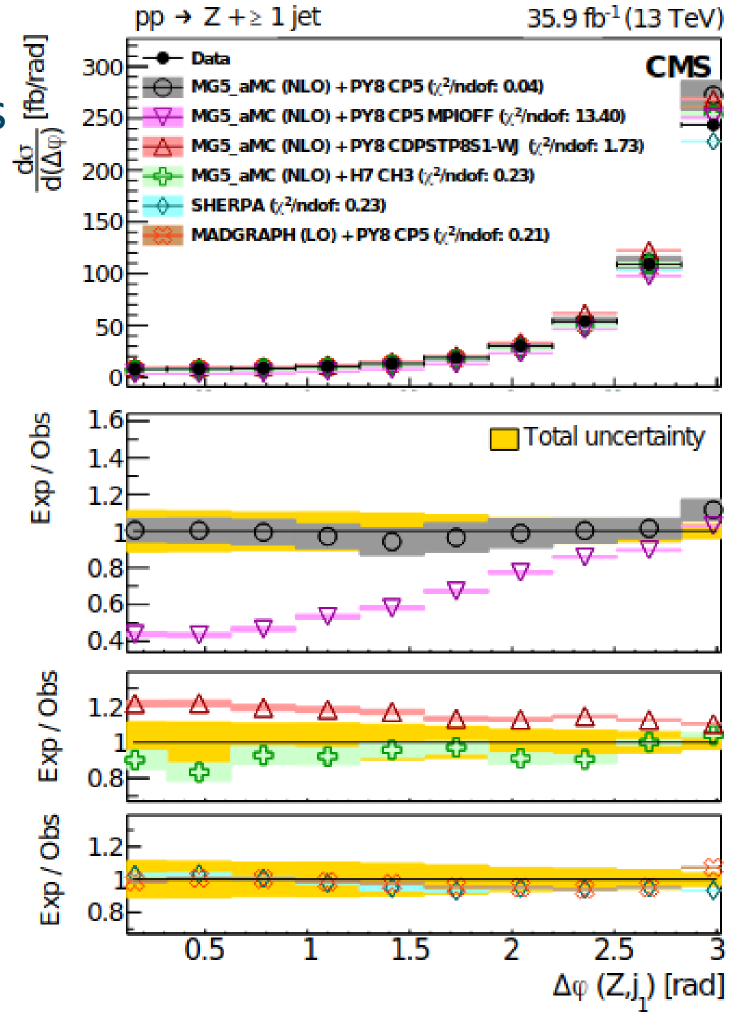
  - Z + ≥ 2 jets
    - Relative p_T imbalance between jet pair

$$\Delta_{rel}\, p_T(j_{1,} j_2) = \frac{|\vec{p}_{j_1} + \vec{p}_{j_2}|}{|\vec{p}_{j_1}| + |\vec{p}_{j_2}|}$$



Results: Z + ≥ 1 jet, Δφ(Z,j)

- Cross sections measured from data and compared to multiple MC model predictions
  - MG5_aMC (NLO) + Pythia8, CP5 overestimates SPS dominant regions
  - MG5_aMC (NLO) + Pythia, CP5 MPIOFF shows large discrepancy in DPS sensitive area
  - MG5_aMC (NLO) + Pythia8, CDPSTP8S1-Wj [1] overshoots cross section 10-20%
  - MG5_aMC (NLO) + Herwig7, CH3 undershoots DPS sensitive region



[1] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, Eur. Phys. J. C 76 (2016) 155, arXiv:1512.00815.

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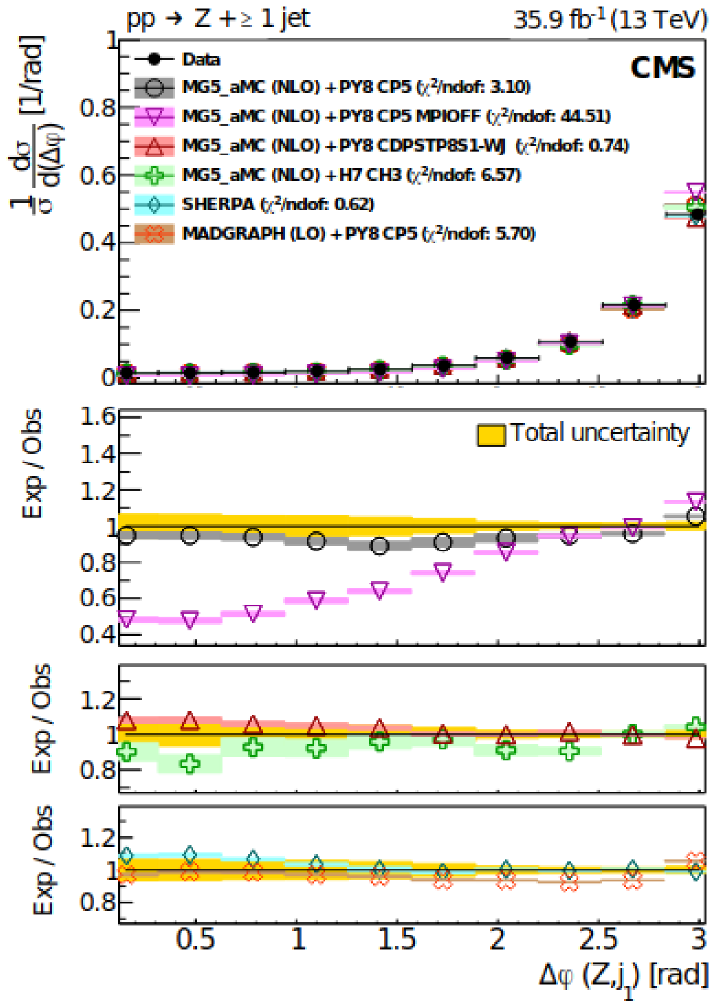
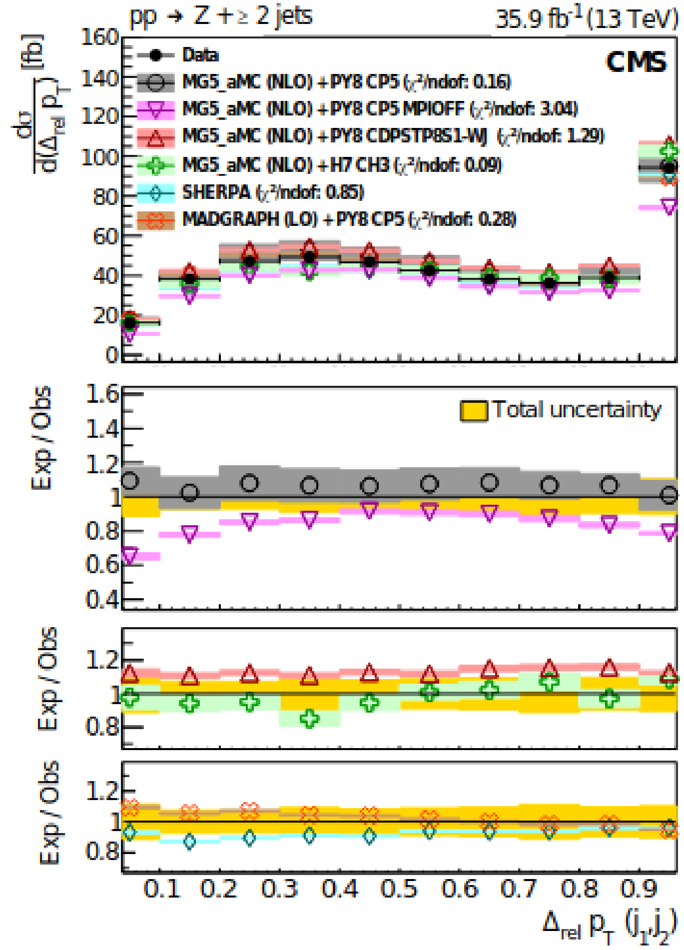
- Normalized cross sections
  → Good description of shape except for MG5_aMC (NLO) + Pythia, CP5 MPIOFF



[1] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, Eur. Phys. J. C 76 (2016) 155, arXiv:1512.00815.

Results: Z + ≥ 2 jets, $\Delta_{rel}p(j_1,j_2)$

- Cross sections measured from data and compared to multiple MC model predictions
  - Well described by most models, except:
    - MG5_aMC (NLO) + Pythia8, CP5 MPIOFF
    - MG5_aMC (NLO) + Pythia8, CDPSTP8S1-WJ
      → Overestimation up to 15%
    - MG5_aMC (NLO) + Herwig7, CH3
      → Some deviations



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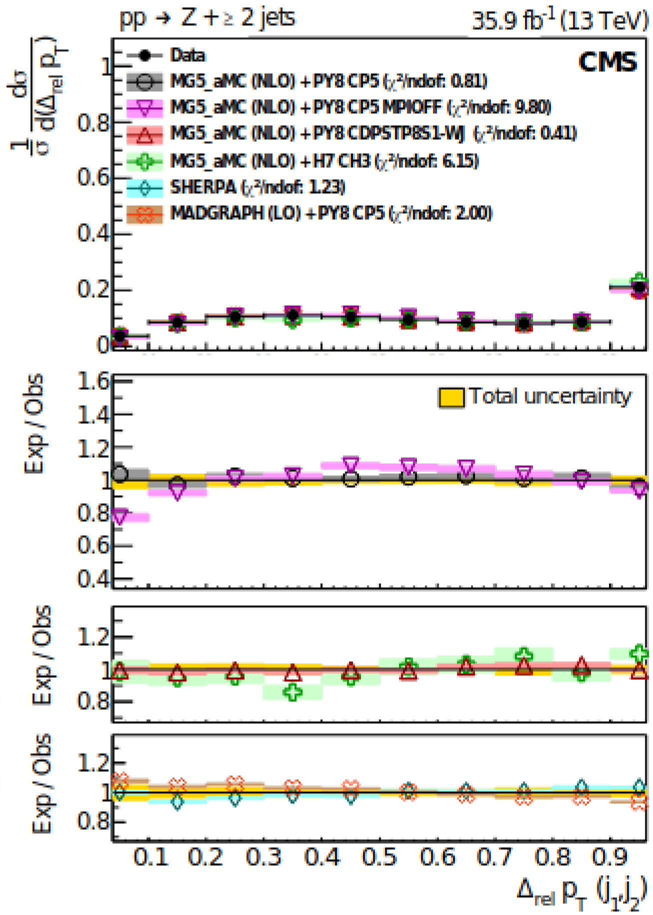
- Normalized cross section
  - MG5_aMC (NLO) + Pythia8, CDPSTP8S1-WJ describes shape well
  - Other models perform well with exception of some outliers



Conclusion

- Data shows significant sensitivity to MPI
  → Can serve as input to improve current models

- Observables are reasonably well described by Sherpa, MG5_aMC (LO and NLO) + Pythia8, CP5 and MG5_aMC (NLO) + Herwig7, CH3

- MG5_aMC (NLO) + Pythia 8, CDPSTP8S1-WJ deviates 10-20% but describes shape of observables well
  → Energy dependence in tune is modeled well

Study of double-parton scattering in inclusive production of four jets with low transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS-PAS_SMP-20-007

Event topology and observables

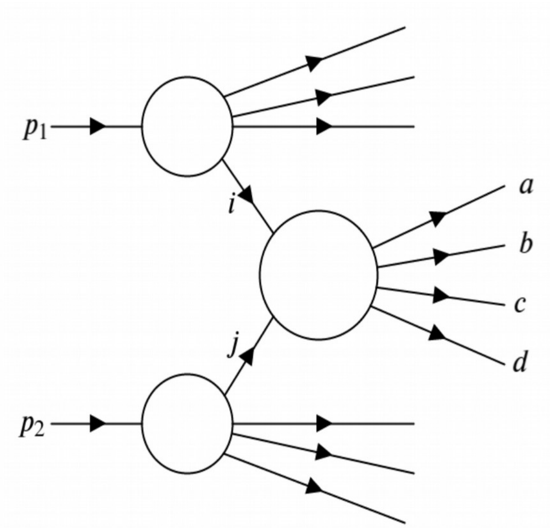
- Inclusive four jet production
  → Multijet final states can probe low-p_T and small-x regions

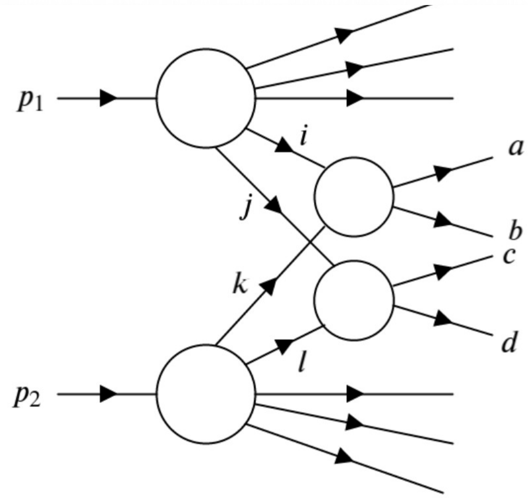
- Exploit differences in correlations between jets and jet pairs
  - Azimuthal angular difference between jets with largest pseudorapidity separation

$$\phi_{ij} = |\eta_i - \eta_j| \; for \; max_{i \neq j}(|\eta_i - \eta_j|)$$

  - Azimuthal angular difference between hard and soft jet pair

$$\Delta S = \arccos\left(\frac{(\overrightarrow{p_{T,1}} + \overrightarrow{p_{T,2}}) \cdot (\overrightarrow{p_{T,3}} + \overrightarrow{p_{T,4}})}{|\overrightarrow{p_{T,1}} + \overrightarrow{p_{T,2}}||\overrightarrow{p_{T,3}} + \overrightarrow{p_{T,4}}|}\right)$$



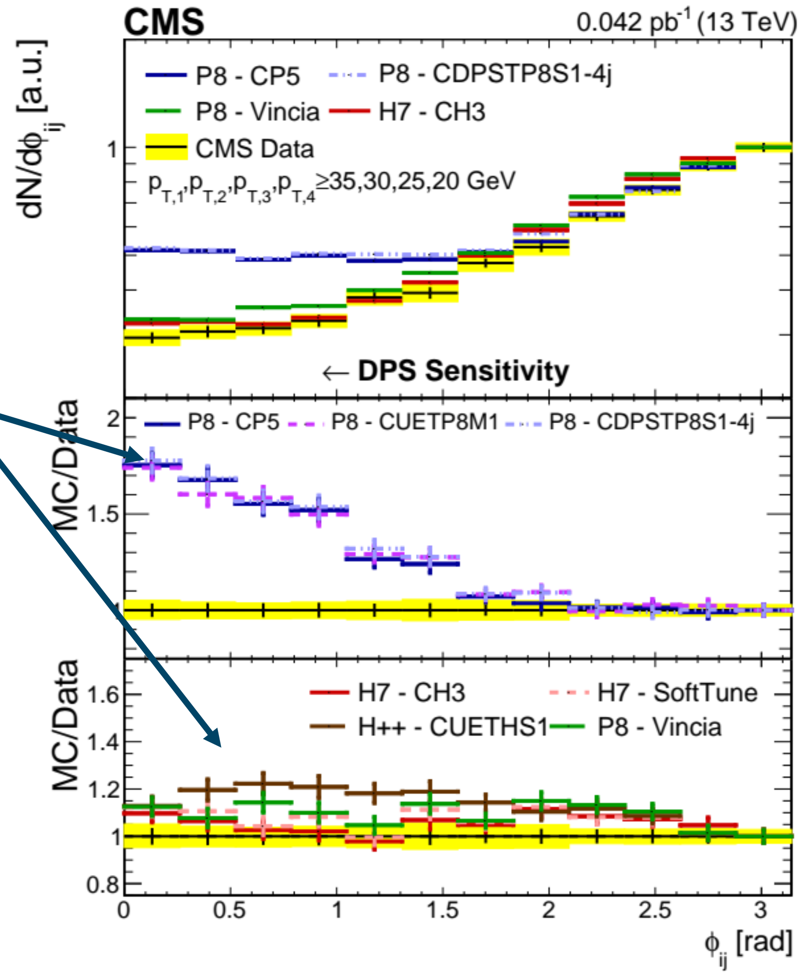


Results for φ_{ij}

- Normalized to bin at π
  → Least DPS sensitivity expected

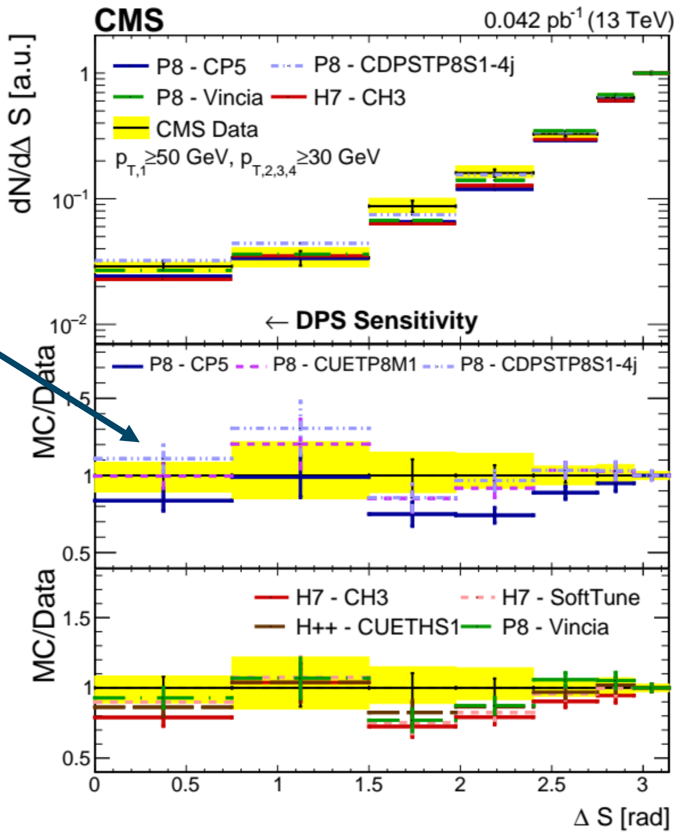
- Compared to LO models with 2→2 ME
  → Significant difference between p_T-ordered and angular-ordered/dipole antenna showers!

  → Improved description with angular-ordered/dipole-antenna shower



Results for ΔS

- Normalized to bin at π
  → Least DPS sensitivity expected
- Pythia and Herwig models: LO with 2→2 ME
  → Only CUETP8M1 and CDPSTP8S1-4j (dedicated DPS tune [1]) overshoot DPS-sensitive slope



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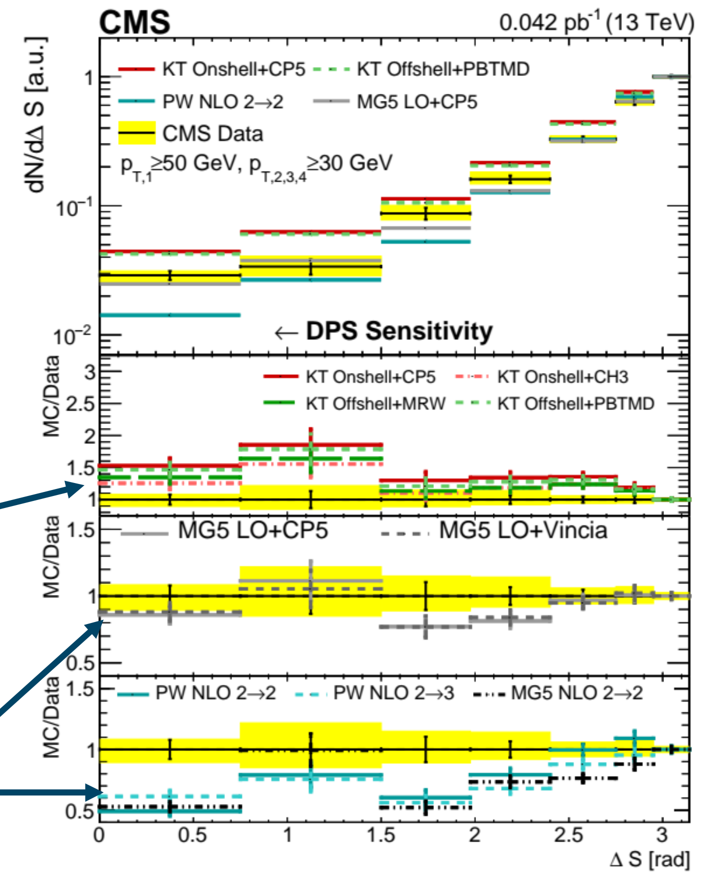
- Multijet models
  - KaTie: LO 2→4 ME
    - On-shell (DGLAP eq., PDFs)
    - Off-shell (CCFM eq., TMD PDFs)

  → Too decorrelated, due to sole use of 2→4 ME

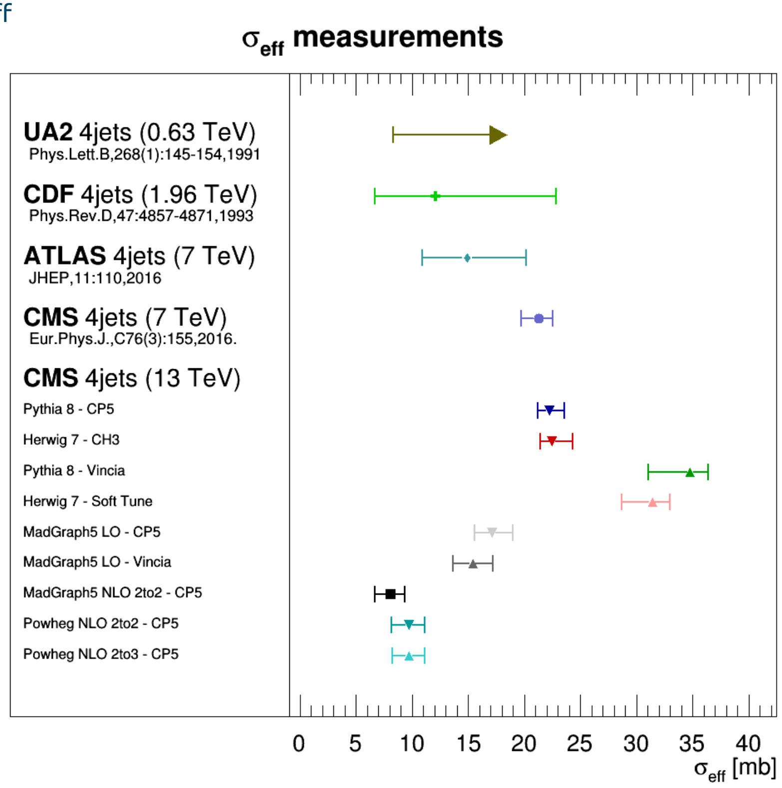
  - All other MG5_aMC (LO) 2→2,3,4 ME, MG5_aMC (NLO) 2→2 ME and Powheg (NLO) 2→2/2→3 undershoot DPS sensitive slope



Extraction of σ_{eff}: template method

- Fit background and signal template to data to determine DPS cross section using least-squares minimization
  - Background template: LO 2→2 and multijet MC samples with room for DPS contribution
  - Signal template: constructed from data
  - DPS cross section determined
    → Pocket formula allows for determination σ_{eff}

- Clear model dependence observed!
  - Pythia8, VINCIA and Herwig7, SoftTune use older PDF and UE tune
  - Pythia8, CP5 and Herwig7, CH3 agree with CMS measurement at 7 TeV
  - MG5_aMC (LO) 2→2,3,4 + Pythia8, CP5 and Pythia8, VINCIA samples agree with ATLAS measurement at 7 TeV
  - MG_aMC (NLO) 2→2 + Pythia8, CP5 and Powheg (NLO) 2→2 and 2→3 + Pythia8, CP5



Conclusion

- Measurements show excellent sensitivity to DPS, parton shower effects, influence of the ME, …
  → Important input to improve models

- Interplay between DPS and parton shower
  → Parton shower can simulate DPS!

- Extraction of σ_{eff} for different models performed
  → Clear model dependence in the inclusive four jet topology
  → σ_{eff} is rather a model dependent parameter than an observable

Observation of triple J/ψ production in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS-PAS_BPH-21-004

Observation of triple J/ψ production

- Expected to be golden channel for DPS and triple parton scattering (TPS)
- TPS pocket formula similar to DPS pocket formula

$$\sigma^{TPS}_{A,B,C} = \frac{m}{3!}\frac{\sigma_A \sigma_B \sigma_C}{\sigma^2_{eff,TPS}}$$

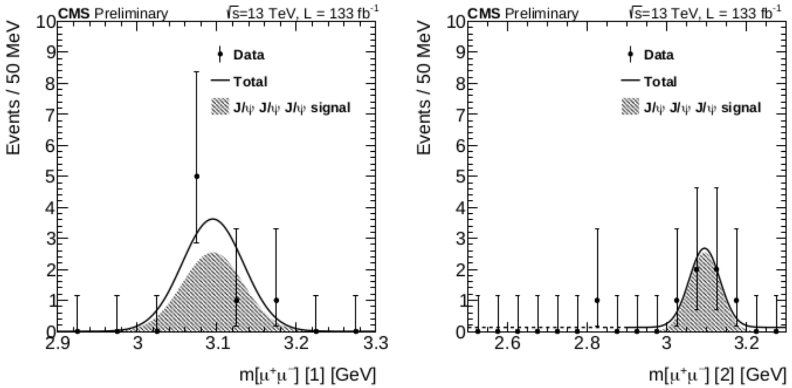
→ Only J/ψ→μμ in event selection

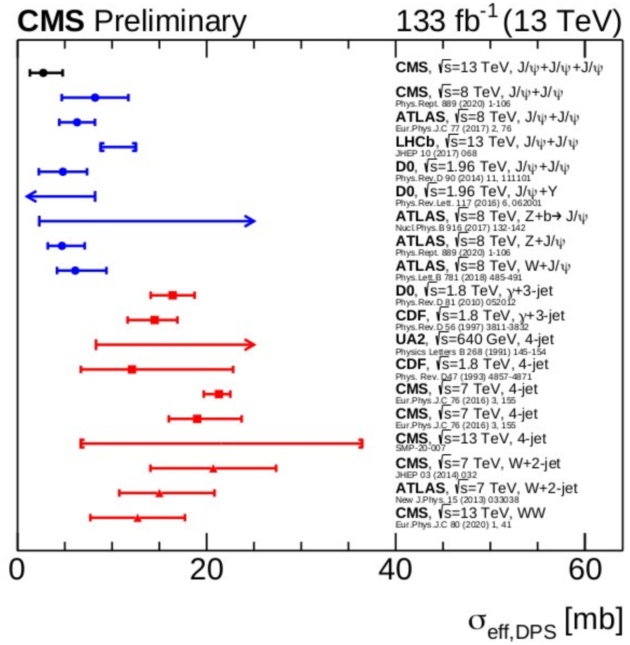
- 6 candidate events with 3 J/ψ observed
  - Mass distributions fitted with Gaussian →Significance > 5 std. dev., confirmed by multiple methods
- Cross section measured and $\sigma_{eff,DPS}$ extracted

$$\sigma_{pp \to J/\psi J/\psi J/\psi} = 272^{+141}_{-104}(stat) \pm 17(syst.)\,fb$$

$$\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}(\exp.)^{+1.5}_{-1.0}(theo.)\,mb$$

  - Agreement with older quarkonium measurements (~3-10 mb)
  - Smaller compared to measurements with different final state





Summary

- Measurements for different final states have been performed
  → First measurements in Z+jets and J/ψJ/ψJ/ψ final states

- Measurements show excellent sensitivity to DPS (and TPS)
  → Important input to improve MC models!

- Extraction of σ_{eff} has been performed
  - Inclusive 4 jet measurement shows strong model dependence
  - Triple J/ψ measurement shows agreement with older quarkonium measurements