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Results and perspectives on multi-parton interactions with CMS(*)

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Summary. — This contribution covers recent CMS experiment studies at the LHC, including the first direct observation of Double Parton Scattering (DPS) in same-sign WW boson production at $\sqrt{s} = 13$ TeV. Interest in DPS has shifted to flavour physics due to higher production cross-sections and better detector performance, enabling CMS to rival experiments like LHCb. Significant findings include the DPS signal in double Y analysis and double J/ψ production at $\sqrt{s} = 13$ TeV, which not only confirms the X(6900) resonance but highlights the DPS potential contribution. Additionally, the first observation of triple J/ψ production via Triple Parton Scattering (TPS).

1. – Introduction

The interaction between two protons can involve simultaneous interactions of multiple partons. As the centre-of-mass energy increases, the parton density increases, enhancing the probability of such interactions. Multi-parton interactions (MPI) can be categorised into two regimes: the soft regime, characterised by secondary hadronic activity, and the hard regime, which involves energetic scatterings between multiple pairs of partons.

In Single-Parton Scattering, the production of two or more particles occurs through a single interaction between two partons. Here, the kinematics are correlated, and additional gluon emissions are negligible. In contrast, Double-Parton Scattering involves the production of two particles through a double interaction between partons from the same protons (see fig.1). These scatterings are assumed to be uncorrelated. Although DPS is power-suppressed relative to SPS in terms of total cross-section, it can dominate in certain channels. DPS processes are described by the pocket formula:

$$\sigma_{DPS} = \frac{1}{m!}\frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{eff}}}$$

where m is the factorial factor 1 or 2 depending on the final state, the σ_A and σ_B are the cross-sections of individual SPS processes, and σ_{eff} represents a parameter incorporating the unknown correlations between partons within the proton.

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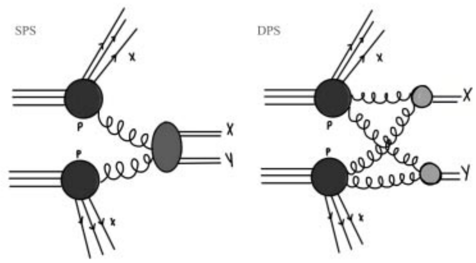

Fig. 1. – Left: generic diagram for a Single Parton Scattering. Right: generic diagram for a Double Parton Scattering.

2. – Same Sign WW: a golden channel for DPS

In recent years, the CMS experiment [1] at the LHC has made significant progress in understanding MPI, one example can be the same-sign W boson pair production (ss-WW) [2]. This final state is a gold channel for studying Double Parton Scattering (DPS) due to its exceptionally clean experimental signature and the strong suppression of contributions from Single-Parton Scattering (SPS).

The decays under consideration involve two leptons of the same sign plus the neutrinos (antineutrinos, accordingly to the lepton number conservation), such as $e^{\pm}\mu^{\pm}\nu_e\nu_\mu$ or $\mu^{\pm}\mu^{\pm}\nu_\mu\nu_\mu$. However, the analysis faces challenges from several principal backgrounds, including WZ events where both bosons decay leptonically, events featuring a W boson and a jet, as well as QCD events with multiple jets. Additionally, rare processes like SPS production of $W^{\pm}W^{\pm}$, VVV (where V is either W or Z), and ttV add complexity to the analysis.

Utilising data collected between 2016 and 2018 during Run 2 at the centre of mass energy of 13 TeV, totalling an integrated luminosity of 138 fb^{-1}, the total cross-section for ss-WW production was determined to be $80.7 \pm 11.2(\text{stat})^{+9.5}_{-8.6}(\text{syst}) \pm 12.1(\text{model})$ fb, while the fiducial cross-section was found to be 6.28 ± 0.81 (stat) ± 0.69 (syst) ± 0.37 (model) fb.

Of particular importance is the fiducial cross-section's correspondence to a signal significance of 6.2 standard deviations compared to the hypothesis of background only.

3. – Final states with heavy quarks

In recent years, the focus of research has transitioned towards flavour physics, moving away from final states characterised by harder kinematics such as jets and electroweak bosons. This transition is motivated by the higher production cross-sections and enhanced detector performance, enabling CMS to compete with specialised experiments like LHCb. In this frame, the analysis aimed to measure the cross-section for the production of Υ(1S)Υ(1S) pairs [3], extrapolate the DPS contribution, and search for a new resonance in the Υ(1S) + $\mu\mu$ final state. In the region where both Υ(1S) have $|\eta| < 2$, the cross-section for pair production was found to be $\sigma = 79 \pm 11(\text{stat}) \pm 6(\text{syst}) \pm 3\,\text{pb}$. In the region between 17.5 and 19.5 GeV (approximately four times the mass of the b quark), a new limit for the production cross-section decaying into Υ(1S) + $\mu\mu \to \mu\mu$ + $\mu\mu$ was set. The kinematics of the DPS process differ from those of SPS. We expect a

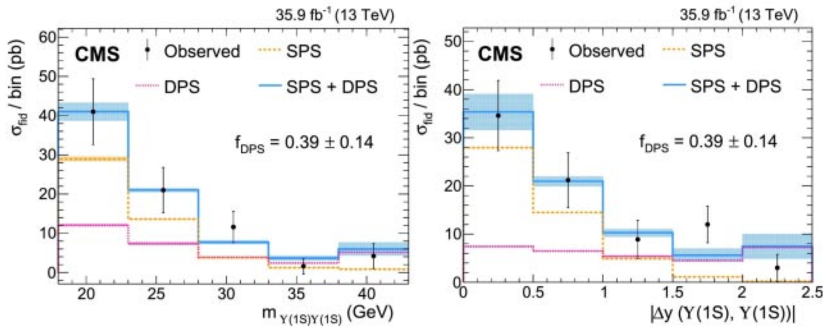

Fig. 2. – Measured fiducial cross section (black dots) in bins of $m_{\Upsilon(1\ S)\Upsilon(1\ S)}$ (right) $|\Delta y(\Upsilon(1\ S), \Upsilon(1\ S))|$ (left). The last bin includes the overflow. The SPS and DPS distributions predicted from the simulation are overlaid using the f_{DPS} value extracted from the fit to the $|\Delta y(\Upsilon(1\ S), \Upsilon(1\ S))|$ distribution. The shaded areas around the SPS and DPS predictions indicate the theoretical uncertainties, which are often smaller than the thickness of the dashed lines. The shaded area around the total distribution corresponds to the uncertainty in the measurement of $f_{\mathrm{DPS.}}$. The solid line shows the sum of the SPS and DPS contributions with the best-fit f_{DPS} [3].

greater rapidity separation $|\Delta y(\Upsilon(1S), \Upsilon(1S))|$ between the mesons and a higher invariant mass $m(\Upsilon(1S), \Upsilon(1S))$. By calculating the differential cross-sections, the fraction of DPS events can be obtained as follows:

$$f_{DPS}(|\Delta y(\Upsilon(1S), \Upsilon(1S))|) = 0.39 \pm 0.14$$

$$f_{DPS}(m(\Upsilon(1S), \Upsilon(1S))) = 0.27 \pm 0.22$$

These results include both statistical uncertainties (which are dominant) and theoretical uncertainties (see fig. 2).

In 2020, LHCb [4] announced a new narrow resonance in the $J/\psi\ J/\psi$ mass spectrum, designated as X(6900). This peak has been interpreted as a four-quark bound state (tetraquark). Both ATLAS [5] and CMS [6] subsequently repeated the same analysis. CMS analysed the data collected during Run 2, corresponding to an integrated luminosity of 135 fb^{-1} at a centre-of-mass energy of 13 TeV. The J/ψ mesons were reconstructed in the di-muon channel, requiring their invariant mass to be between 2.95 and 3.25 GeV with $p_T > 3.5$ GeV. One of the main background sources in the di-J/ψ analysis of Run 2 is DPS, which is expected to contribute about 25% to the background (see fig. 3). In the region above 11 GeV for $m_{J/\psi J/\psi}$, the DPS contribution is expected to dominate. Previously, CMS published an analysis of the di-J/ψ channel using data collected during Run 1 at a centre-of-mass energy of 7 TeV [7]. Even there, the importance of including the DPS contribution was evident.

4. – Three J/ψ in one go

The natural progression from Double Parton Scattering (DPS) is Triple Parton Scattering (TPS). Similar to DPS, TPS considers three pairs of interacting partons and their

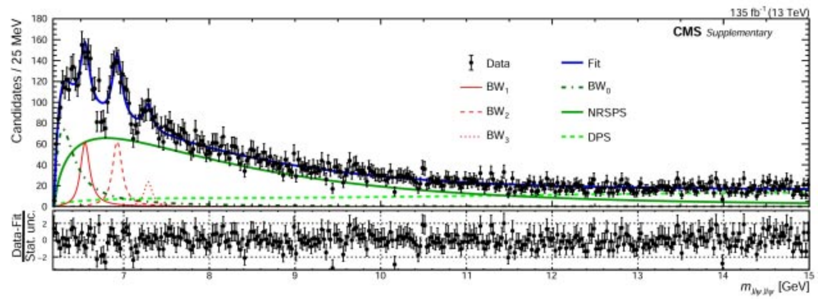

Fig. 3. – In the di-J/ψ invariant mass spectrum we observe that over 11 Gev the DPS contribution is dominant [6].

interaction products as completely independent. A pocket formula formally describes this process:

$$\sigma_{\mathrm{TPS}}^{pp\to\psi_1\psi_2\psi_3+X} = \left(\frac{m}{3!}\right)\frac{\sigma_{\mathrm{SPS}}^{pp\to\psi_1+X}\sigma_{\mathrm{SPS}}^{pp\to\psi_2+X}\sigma_{\mathrm{SPS}}^{pp\to\psi_3+X}}{\sigma_{\mathrm{eff,TPS}}^2}$$

where $m = 1, 3$ or 6 (depending on whether all three, two or none of the ψ_i states are identical). In the absence of parton correlations, the effective cross-section $\sigma_{\mathrm{eff,TPS}}$ is closely related to its DPS counterpart via $\sigma_{\mathrm{eff,TPS}} = \kappa\sigma_{\mathrm{eff,DPS}}$, with κ of order unity. To date, only one analysis of TPS has been conducted, published by CMS in 2023, which studied the simultaneous production of three J/ψ mesons [9]. Analysing all the data collected during Run 2, corresponding to an integrated luminosity of 133 fb^{-1}, CMS identified 5 signal events and 1 background event. The expected contributions from SPS, DPS, and TPS to the measurement of the triple-J/ψ cross-section are 6%, 74%, and 20% respectively, meaning that 1 event, out of the 5 observed, is produced via TPS. This is the first observation for this process so far. The fiducial cross-section is $\sigma = 272^{+141}_{-104}$ (stat) ± 17 (syst) fb, the effective cross-section for DPS is $\sigma_{\mathrm{eff,DPS}} = 2.7^{+1.4}_{-1.0}(\mathrm{exp})^{+1.5}_{-1.0}(\mathrm{theo})$mb, and the effective cross-section for TPS is $\sigma_{\mathrm{eff,TPS}} = (0.82 \pm 0.11)\sigma_{\mathrm{eff,DPS}}$, where the effective cross-section is based on theoretical prediction and not extrapolated from the data.

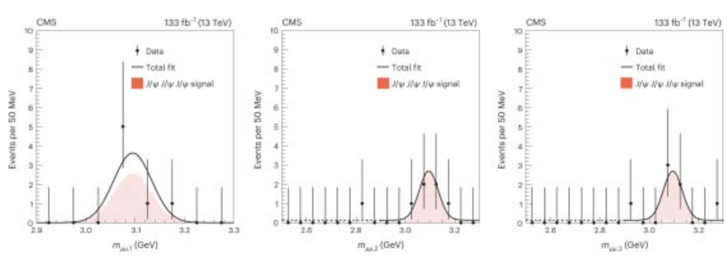

Fig. 4. – The three distributions are ordered, left to right, by decreasing pair p_T. The data are represented by the points with the vertical bars showing the (Poisson) statistical uncertainties. The solid (dotted) curve shows the overall fit to the data (in the extended mass range, discussed in the main text), and the red-shaded area shows the fitted signal yield. The horizontal bin width is indicated on the vertical axis legend [9].

5. – Summary

In this contribution, we presented the significant progress made by the CMS experiment at the LHC in understanding MPI over the past few years. One of the most notable achievements is the direct observation of double parton scattering (DPS) in the production of same-sign W bosons (ssWW) at $\sqrt{s} = 13$ TeV. In recent years, research focus has shifted towards flavour physics, moving away from final states with harder kinematics such as jets and electroweak bosons.

This shift is driven by higher production cross-sections and improved detector performance, allowing CMS to compete with specialised experiments like LHCb. Notable measurements include the DPS signal in the double Y analysis and the measurement of double J/ψ production at $\sqrt{s} = 13$ TeV, which confirmed the X(6900) resonance. These findings also demonstrate the potential for DPS studies in this channel. Moreover, the first observation of triple J/ψ production has provided evidence for Triple Parton Scattering (TPS).

However, several open questions remain, such as the determination of the effective cross-section values and the reasons behind their variability (see fig. 5). Understanding how these values depend on the type of process, kinematics, and energy is essential for advancing our knowledge in this field. Finally, these studies are crucial for enhancing our comprehension of the internal structure of protons and the dynamics of high-energy collisions. They also prepare us to meet the challenges posed by future explorations at the highest energy frontiers, contributing to our fundamental understanding of particle physics.

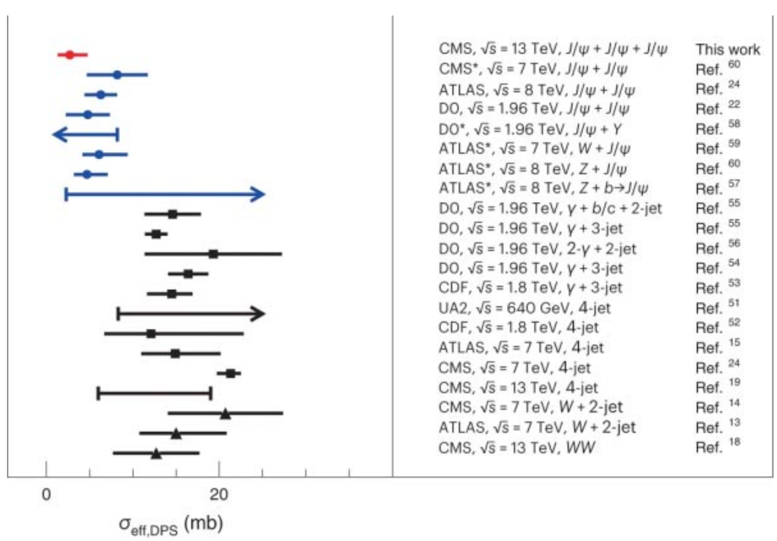

Fig. 5. – The sigma effective are compared. The arrows indicate lower (or upper) limits at 95%(68%) confidence level. For the experimental results marked with a star, more recent theoretical reinterpretations based on more accurate calculations of the corresponding SPS cross-section are plotted [9].

REFERENCES

[1] The CMS Collaboration, *JINST*, **3** (2008) S08004.
[2] The CMS Collaboration, *Phys. Rev. Lett.*, **131** (2023) 091803.
[3] The CMS Collaboration, *Phys. Lett. B*, **808** (2020) 135578.
[4] The LHCb Collaboration, *Sci. Bull.*, **65** (2020) 1983.
[5] The ATLAS Collaboration, *Phys. Rev. Lett.*, **131** (2023) 151902.
[6] The CMS Collaboration, *Phys. Rev. Lett.*, **132** (2024) 111901.
[7] The CMS Collaboration, *JHEP*, **2014** (2014) 94.
[8] The CMS collaboration, *JHEP*, **2021** (2021) 225.
[9] The CMS Collaboration, *Nat. Phys.*, **19** (2023) 338.