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Measurement of Double Parton Scattering at LHC with the CMS experiment

Ankita Mehta[*†]
Panjab University, INDIA
E-mail: ankita.mehta@cern.ch

Double parton scattering is measured in different channels using the CMS experiment at the CERN LHC. Data from pp collisions collected at 7 and 8 TeV center-of-mass energy are used. Several final states are investigated to identify and measure the signature of double parton scattering in inelastic events. Parameters are extracted from the data that are suited in an optimal way to distinguish double parton scattering from various backgrounds. Multivariate analysis techniques are exploited to maximize the sensitivity.

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[*]Speaker.
[†]On behalf of the CMS collaboration.

1. Introduction

In high energy proton-proton (pp) collisions at LHC, due to the composite nature of protons, it is possible to have two or more distinct hard parton-parton interactions occurring simultaneously in a single pp collision. At fixed final state invariant masses, such cross sections tend to increase with collision energy because partons with successively lower momentum fraction x and rapidly varying flux, are being probed [1]. Multiple soft parton-parton collisions are called Multiple parton interactions (MPI), while those in which only a single pair of partons produce a hard scattering are referred as Single Parton Scattering (SPS) [2]. Large hadronic activity is observed in the soft regime, characterized by small transverse momenta (p_T) of the produced particles. For relatively large p_T values, the observation of MPI will mostly focus on two simultaneous scatterings, i.e. on Double parton scattering (DPS) [3][4][5].

2. Effective cross section

The effective cross section, $\sigma_{\rm eff}$, is a measure of the transverse distribution of partons inside the colliding hadrons and their overlap in a collision. If X and Y are two independent processes, with σ_X and σ_Y as their production cross sections respectively, $\sigma_{\rm eff}$ can be written in terms of these single process cross sections and cross section for these processes to occur simultaneously ($\sigma^{\rm DPS}_{\rm X+Y}$) as:

$$\sigma_{\rm eff} = \frac{\rm m{*}\sigma(X){*}\sigma(Y)}{\sigma^{\rm DPS}_{\rm X+Y}}$$

where “m” is the symmetry factor $\rm m = \frac{1}{2}$, if processes “X” and “Y” are identical otherwise one. CMS has adopted a three-step strategy in order to perform the extraction of this parameter; first of all, variables sensitive to the DPS contribution, corrected at the stable particle level, are measured followed by a study of templates for the signal (DPS) and the background (SPS) to obtain the fraction of each of them that best fits the data. This fraction is then used to extract $\sigma_{\rm eff}$.

3. DPS using W + 2jets events

A DPS process leads to a W + 2jets final state when one hard interaction produces a W boson and the second one produces 2jets in the same collision [6][7]. Events containing W + 2jets produced from a single parton scattering (SPS) contribute an irreducible background. This analysis makes use of the full 2011 data sample, corresponding to an integrated luminosity of 5 $\rm fb^{-1}$ and requires the presence of at least one muon candidate at the trigger level. The selection criteria is summarized in Table. 1. For the case of the W + 2jets process one can define the fraction of DPS

Table 1: Phase space definition for visible cross section at particle-level.

Exactly one muon with $p_T > 35$ GeV/c and $\lvert\eta\rvert < 2.1$
W transverse mass > 50 GeV/c, $E_T^{\rm Miss} > 30$ GeV/c, jets with $p_T > 20$ GeV/c

events as $f_{\rm DPS} = N'^{\rm DPS}_{\rm W+2j}/N'_{\rm W+2j}$, where $N'_{\rm W+2j}$ and $N'^{\rm DPS}_{\rm W+2j}$ are the yields of the W bosons associates with two jets and DPS, respectively. $\sigma_{\rm eff}$ can be reformulated as:

PoS(EPS-HEP2015)447

$$\sigma_{\text{eff}} = \frac{\text{R}}{\text{f}_{\text{DPS}}}.\sigma'_{2\text{j}}$$

where R is the ratio of the yield of W bosons associated with zero jets and the yields associated with DPS, $\text{R} = \text{N}'_{\text{W}+0\text{j}}/\text{N}'_{\text{W}+2\text{j}}$ and $\sigma'_{2\text{j}}$ is the particle-level cross section for W-boson production for dijet events. Thus, the determination of the effective cross section reduces to a measurement of R, $\sigma'_{2\text{j}}$ and f_{DPS}. Several observables which might be sensitive to discriminate DPS events from the SPS ones have been defined based on the back to back topology of DPS events:

- the normalized p_{T} balance between the two selected jets:

$$\Delta^{\text{rel}}\text{p}_{\text{T}} = \frac{|\vec{\text{p}_{\text{T}}}(\text{j1})+\vec{\text{p}_{\text{T}}}(\text{j2})|}{|\vec{\text{p}_{\text{T}}}(\text{j1})|+|\vec{\text{p}_{\text{T}}}(\text{j2})}$$

- the azimuthal angle between the W and the dijet system:

$$\Delta\text{S} = \arccos\left(\frac{\vec{\text{p}_{\text{T}}}(\mu,\text{E}_{\text{T}}^{\text{Miss}}).\vec{\text{p}_{\text{T}}}(\text{j1,j2})}{|\vec{\text{p}_{\text{T}}}(\mu,\text{E}_{\text{T}}^{\text{Miss}})|.|\vec{\text{p}_{\text{T}}}(\text{j1,j2})|}\right)$$

where $\vec{\text{p}_{\text{T}}}(\text{j1})$ and $\vec{\text{p}_{\text{T}}}(\text{j2})$ are the transverse momentum vectors of the leading and sub-leading jet respectively. $\vec{\text{p}_{\text{T}}}(\mu,\text{E}_{\text{T}}^{\text{Miss}})$ and $\vec{\text{p}_{\text{T}}}(\text{j1},\text{j2})$ are the combined transverse momentum vectors of $(\mu,\text{E}_{\text{T}}^{\text{Miss}})$ and the two jets, respectively.

3.1 Unfolding and comparison with simulations

The distributions of the DPS-sensitive observables for the selected events are corrected for selection efficiencies and detector effects. The unfolding to the stable particle level, is carried out for the shapes of the $\Delta^{\text{rel}}\text{p}_{\text{T}}$ and ΔS.Various simulations at particle level are compared with the fully corrected DPS-sensitive observables as shown in Fig. 1. The $\Delta^{\text{rel}}\text{p}_{\text{T}}$, ΔS distributions are properly described by MADGRAPH 5 + PYTHIA 8. The NLO predictions for W + 2jets production obtained with POWHEG 2 + PYTHIA 6 also satisfactorily describe the data. PYTHIA 8 simulation underestimates the measurements due to missing higher order processes. Without MPI, the LO and NLO predictions fail to describe data.

3.2 Determination of the effective cross section

The fraction of W + 2jets events produced by DPS is extracted by performing a template fit using the signal and background templates to the fully corrected distributions of $\Delta^{\text{rel}}\text{p}_{\text{T}}$ and ΔS. The fitted value of the DPS fraction (f_{DPS}) is:

$$\text{f}_{\text{DPS}} = 0.055 \pm 0.002 \text{ (stat.) } \pm 0.014 \text{ (syst.)}$$

The ratio, R is measured to be:

$$\text{R} = 27.8 \pm 0.2 \text{ (stat.) } \pm 3.3\text{(syst.)}$$

The cross section for events with exactly two jets with $\text{p}_{\text{T}} > 20$ GeV/c and $|\eta| < 2.0$ is:

$$\sigma'_{\text{eff}} = 0.0409 \pm 0.0004 \text{ (stat.) } \pm 0.0061 \text{ (syst.) mb}$$

Combining the values of R, f_{DPS}, σ'_{eff}, σ_{eff} is determined to be:

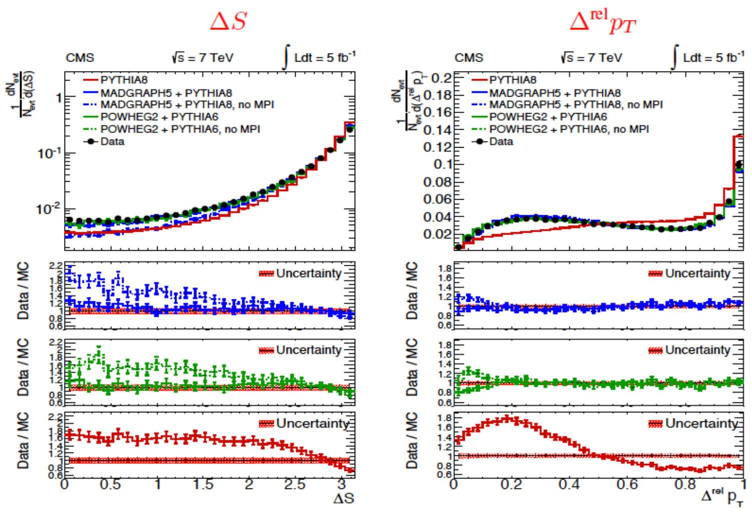

Figure 1: Fully corrected data distributions, normalized to unity, for ΔS, $\Delta^{\text{rel}}p_{\text{T}}$ together with the several MC predictions.

$$\sigma_{\text{eff}} = 20.7\ \pm\ 0.8(\text{stat.}) \pm\ 6.6\ (\text{syst.})\ \text{mb}$$

Fig. 2 shows a comparison of the effective cross sections obtained using different processes at various center-of-mass energies. From the experimental results, a firm conclusion on the energy dependence of σ_{eff} cannot be drawn because of the large systematic uncertainties. The CMS measurement is consistent with previous measurements performed at the Tevatron and by the ATLAS Collaboration at the LHC.

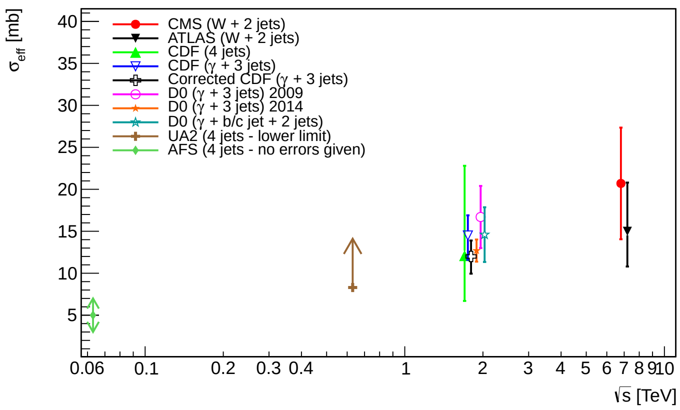

Figure 2: Center-of-mass energy dependence of σ_{eff} measured by different experiments using different processes.

4. DPS using 2b-jets + 2jets events

Measurements of differential cross sections for the production of at least four jets, two of them initiated by a b-quark, in pp collisions are presented as a function of the transverse momentum p_T and pseudorapidity η, together with the correlations in azimuthal angle and the p_T-balance among the jets [8]. The data sample was collected in 2010 at $\sqrt{s}$ =7 TeV with the CMS detector at LHC with an integrated luminosity of 3 pb^{-1}. Events with at least four jets with p_T > 20 GeV are selected. To study the production of pairs of different flavored jets via DPS the two highest p_T jets are associated in the “b-quark jet pair”(bottom), while the remaining two compose the “light-quark jet pair”(light). Fig. 3 shows the differential normalized cross sections as a function of the azimuthal angle, ΔS between the two dijet pairs (most DPS-sensitive observable), defined as:

$$\Delta S = \arccos\left(\frac{\vec{p_T}(\text{bottom}_1,\text{bottom}_2).\vec{p_T}(\text{light}_1,\text{light}_2)}{|\vec{p_T}(\text{bottom}_1,\text{bottom}_2)|.|\vec{p_T}(\text{light}_1,\text{light}_2)|}\right)$$

The measured distribution is compared to predictions of POWHEG + PYTHIA 8, MADGRAPH + PYTHIA 8, PYTHIA 6, PYTHIA 8 and HERWIG ++. ΔS is not well described by any prediction: in particular, all of them, except HERWIG ++ and PYTHIA 8 in a lesser extent, underestimate the region at values of ΔS < 2. This study shows the need for multiple parton interaction (MPI) contributions in the simulation in order to describe correlation observables between jets.

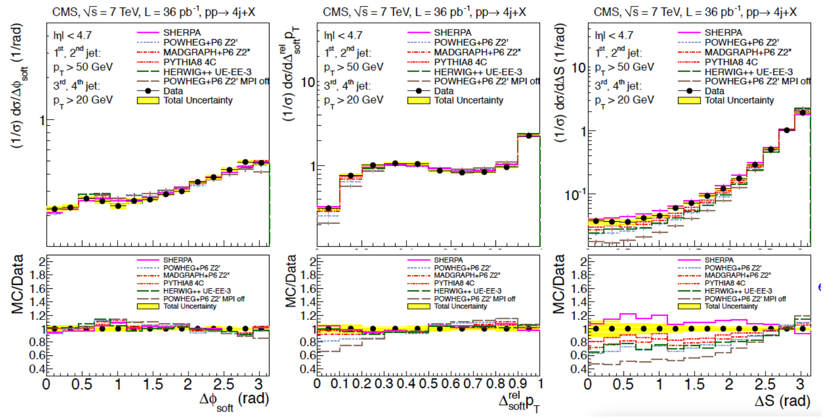

Figure 3: Normalized cross sections unfolded to the stable particle level as a function of ΔS, compared to different MC predictions.

5. DPS using photon + 3jets events

Distributions sensitive to DPS are investigated in the photon + 3jets final state in pp collisions at a $\sqrt{s}$ = 7 TeV [9]. The analyzed data sample corresponds to an integrated luminosity of 36 pb^{-1}, collected by the CMS detector in 2010. The measurement requires the transverse momentum p_T > 75 GeV for the leading (highest p_T) photon and the leading jet and p_T > 20 GeV for the other jets. The photon source of DPS signal events can be direct photons and fragmentation photons. Events containing photon + 3jets produced from SPS or misidentified photon +3jets caused by decays of π^0 and η mesons constitute an irreducible background. Fig. 4 shows the normalized differential cross section as a function of the azimuthal angle between the p_T vectors of the photon-jet pair and the dijet pair defined as:

$$\Delta S = \Delta\phi(\vec{p_T}(\gamma, \text{jet1}), \vec{p_T}(\text{jet2}, \text{jet3}))$$

where γ, jet1, jet2, and jet3 stand for the leading photon, the leading jet, the second leading jet, and the third leading jet, respectively. The predictions of PYTHIA 8, MADGRAPH + PYTHIA 8 and SHERPA are compatible with the measured distribution. Switching off the MPI simulation for MADGRAPH + PYTHIA and SHERPA causes about 5-10 % differences. The reason the MPI causes only small changes in ΔS is due to various background components which reduce the possible sensitivity for the DPS signal contribution.

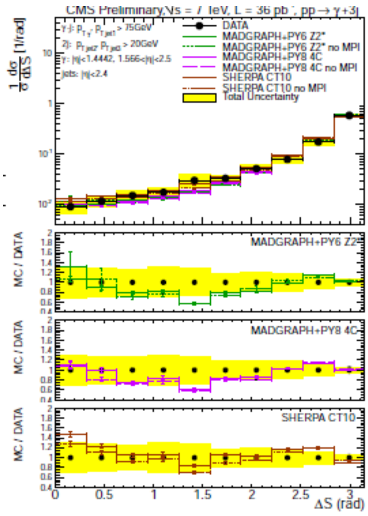

Figure 4: Normalized differential cross sections as a function of ΔS compared to different MC predictions.

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