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Multiple parton scattering: From both theoretical and experimental point of views

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Summary. — In this paper, I will review the recent theoretical, phenomenological, and experimental progress of studying multiple parton scattering at the LHC in both proton-proton and heavy-ion collisions. I will then highlight two novel measurements and their theoretical interpretations: the first triple J/ψ production studies with the CMS detector for triple parton scattering, and the first double parton scattering measurement of J/ψ plus open charm and two open charm production in proton-lead collisions by the LHCb Collaboration.

1. – Introduction

Due to the compositeness nature of protons and nuclei, multiple parton interaction (MPI) is ubiquitous at hadron colliders such as the CERN LHC [1]. MPI is indispensable in scrutinising event activities and hadron multiplicities of observables measured at high-energy experiments, and therefore has been generally modelled in general-purpose Monte Carlo event generators, such as Pythia8 [2], Herwig7 [3] and Sherpa2 [4]. While most of the interactions lie in the non-perturbative regime, there is an non-negligible probability that more-than-one hard interactions can happen simultaneously in a single collision of the initial two hadrons, which we usually refer to as the "multiple parton scattering" (MPS). In the latter, the perturbation theory based on the factorisation approach is effective. MPS provides us with a new way to access the information of the multi-body parton structure of nucleons. The probability of each hard scattering subprocess scales as $\mathcal{O}(\frac{\Lambda^2_{\rm QCD}}{Q^2})$, where $\Lambda_{\rm QCD}$ is the intrinsic QCD scale and Q is the hard scale of the subprocess. Therefore, the inclusive N-parton scattering cross-section is normally $\mathcal{O}((\frac{\Lambda^2_{\rm QCD}}{Q^2})^{N-1})$ suppressed with respect to the single parton scattering (SPS) cross-section. This renders the experimental observation of MPS very challenging, and increasingly difficult for larger values of N. However, there are cases where the MPS processes are important to understand the signals and backgrounds in the analysis at hadron colliders, since MPS final states can involve jets, photons, $W^\pm/Z$ bosons, heavy-flavour hadrons and quarkonia, as well as leptons.

The factorisation theorem of double parton scattering (DPS) for colourless final state processes has been proven in refs. [5, 6]. For instance, the double Drell-Yan process $pp \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$ has the DPS factorisation formula:

$$
\begin{aligned}
\mathrm{d}\sigma^{\mathrm{DPS}}_{pp\to\ell_1^+\ell_1^-\ell_2^+\ell_2^-} &= \frac{1}{(1+\delta_{\ell_1\ell_2})^2}\sum_{i,j,k,l}\int \mathrm{d}x_1\mathrm{d}x_2\mathrm{d}x_1'\mathrm{d}x_2'\mathrm{d}^2\vec{b}_1\mathrm{d}^2\vec{b}_2\mathrm{d}^2\vec{b} \\
&\times \Gamma_{ij}(x_1,x_2,\vec{b}_1,\vec{b}_2)\mathrm{d}\hat{\sigma}_{ik\to\ell_1^+\ell_1^-}(x_1,x_1')\mathrm{d}\hat{\sigma}_{jl\to\ell_2^+\ell_2^-}(x_2,x_2')\Gamma_{kl}(x_1',x_2',\vec{b}_1-\vec{b},\vec{b}_2-\vec{b}),
\end{aligned}
\tag{1}
$$

where $\vec{b},\vec{b}_1,\vec{b}_2$ are the impact parameter of the two initial protons and of the partons with respect to the centres of their protons. The short-distance cross-sections $\mathrm{d}\hat{\sigma}$ can be perturbatively calculated, while the generalised double parton distribution Γ is largely unknown, which prevents the formula from being applicable directly in phenomenology. By taking several simplifications, Γ can be related to the well-known one-body parton distribution function (PDF) and the parton transverse form factor $F(\vec{b})$ of proton. This yields the well-known "pocket formula"

$$
\mathrm{d}\sigma_{pp\to\ell_1^+\ell_1^-\ell_2^+\ell_2^-} = \mathrm{d}\sigma_{pp\to\ell_1^+\ell_1^-}\mathrm{d}\sigma_{pp\to\ell_2^+\ell_2^-}/[(1+\delta_{\ell_1\ell_2})^2\sigma_{\mathrm{eff},pp}],
\tag{2}
$$

with $\sigma_{\mathrm{eff},pp} = [\int \mathrm{d}^2\vec{b}(F(\vec{b}))^2]^{-1}$ and $\delta_{\ell_1\ell_2}$ being the Kronecker delta. The pocket formula is very predictive since the DPS cross-section solely depends on the single unknown parameter $\sigma_{\mathrm{eff},pp}$. Its size determines the normalisation of the DPS cross-section. The $\sigma_{\mathrm{eff},pp}$ values from different measurements in particular with the quarkonium final states have been summarised in fig. 1. Most of the phenomenological studies rely on it, and almost all the DPS experimental studies measure its value. However, there are several limitations in this simple formula. We refer the interested readers to sect.7 in ref. [7]. Nevertheless, from the phenomenological point of view, the pocket formula provides an excellent first approximation, and one can take any deviation with respect to experimental measurements as an indication of calling for a more rigorous calculation. From fig. 1, albeit being inconclusive, it is indicative that $\sigma_{\mathrm{eff},pp}$ disfavours a constant. However, we should bear in mind that not all SPS contributions in the $\sigma_{\mathrm{eff},pp}$ extractions are probably well under control. In addition, although the pocket formula is used to extract $\sigma_{\mathrm{eff},pp}$

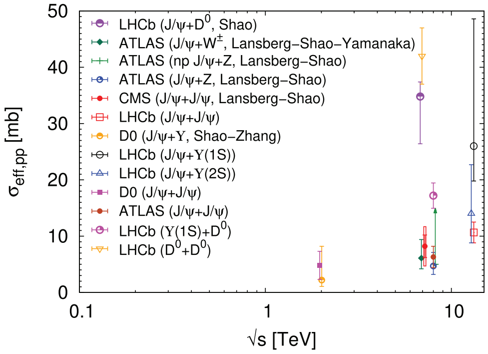

Fig. 1. – The summary of $\sigma_{\mathrm{eff},pp}$ extractions from quarkonium-associated production processes.

from different measurements, when confronting different measurements, we should bear in mind that $\sigma_{\text{eff},pp}$ is not necessarily a constant term and can be a function of many aspects in the measurements and also of the fact that the underlying assumptions in the pocket formula may apply more or less rigorously to the different measurements.

In the following, I will discuss two novel MPS observables that have been measured at the LHC.

2. – Triple parton scattering in proton-proton collisions

The first observable is the triple parton scattering (TPS) in proton-proton collisions. Analogous to the DPS pocket formula (2), we have the TPS pocket formula [8] for a generic process $pp \to f_1 f_2 f_3$:

$$\mathrm{d}\sigma^{\text{TPS}}_{pp\to f_1 f_2 f_3} = \frac{m}{3!}\frac{\prod_{i=1}^{3}\mathrm{d}\sigma_{pp\to f_i}}{\left(\sigma_{\text{eff},pp,3}\right)^2}, \tag{3}$$

where $\sigma_{\text{eff},pp,3} = [\int \mathrm{d}^2\vec{b}(F(\vec{b}))^3]^{-\frac{1}{2}}$ and m is the combinatorial factor accounting for the final state symmetry. From purely geometric considerations, $\sigma_{\text{eff},pp,3}$ is of the same order of magnitude as $\sigma_{\text{eff},pp}$. In particular, ref. [9] quantifies $\sigma_{\text{eff},pp,3} = (0.82 \pm 0.11)\,\sigma_{\text{eff},pp}$. A golden channel to study TPS proposed in ref. [10] is to look for the prompt triple J/ψ production at the LHC via the 6-muon final state. With our existing knowledge of single and double J/ψ production [11-14], the triple J/ψ process is predicted to be DPS and TPS dominant. It is expected that data collected so far by LHC experiments can be used to observe such a process, unless $\sigma_{\text{eff},pp}$ and $\sigma_{\text{eff},pp,3}$ are significantly larger than 10 mb. The CMS Collaboration carried out the first measurement at 13 TeV proton-proton collisions with the Run 2 data [15]. In order to increase the statistics, the measurement includes both the prompt J/ψ and the J/ψ particles from b decays. These totally involve 12 different channels. With the full Run 2 data collected by the CMS detector, the experiment observes 5 signal events and 1 background event leading to a fiducial cross-section estimate as $\sigma_{pp\to J/\psi J/\psi J/\psi X} = 272^{+141}_{-104}(\text{stat}) \pm 17(\text{syst})$ fb. Using the pocket formula and the theoretical inputs from the event generators of HELAC-Onia [16, 17], MadGraph5_aMC@NLO [18], and Pythia8.2 [19], it was possible to determine $\sigma_{\text{eff},pp} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb by assuming $\sigma_{\text{eff},pp,3} = (0.82 \pm 0.11)\,\sigma_{\text{eff},pp}$. With this assumption, 6 %, 74 %, and 20 % events are expected to be produced through SPS, DPS and TPS, respectively.

3. – Double parton scattering in proton-lead collisions

The second new observable is DPS in heavy-ion collisions. Thanks to the geometric and combinatoric effects due to the multiple nucleons in the nucleus, it has been acknowledged that the DPS fraction will be enhanced in proton-nucleus (pA) or nucleus-nucleus collisions with respect to the proton-proton counterpart [20-25]. For instance, by assuming $\sigma_{\text{eff},pp} \simeq 15\,\text{mb}$, the DPS pA cross-sections scale as 3 times the number of nucleons A in a nucleus, while the SPS cross-sections only scale as the nuclear mass number A (modulo other nuclear matter effects). Of course, we need to take into account the nuclear matter effects, like gluon shadowing for heavy flavour and quarkonia [26, 27]. In fact, ref. [28] proposes that DPS in heavy-ion collisions can help to determine the impact-parameter–dependent nuclear parton distribution functions. The latter is the indispensable knowledge to decipher the centrality-dependent observables. The first DPS

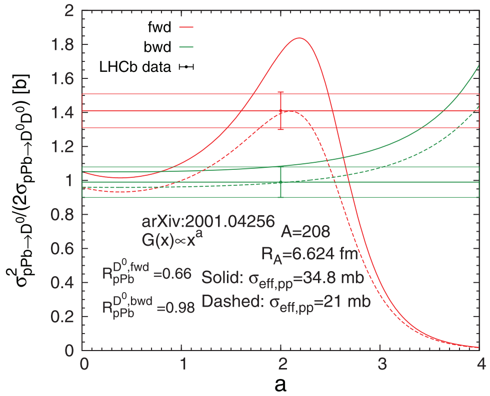

Fig. 2. – (Color online.) A theoretical interpretation of the cross-section $p\text{Pb} \to D^0D^0$ with impact-parameter–dependent gluon shadowing [28]. The LHCb measurement for the cross-section ratio in the forward (backward) rapidity is represented as the red (green) error bar. The theoretical calculations with different impact-parameter–dependent gluon shadowing with two $\sigma_{\text{eff},pp}$ values (solid and dashed lines) are compared with the LHCb data.

search in heavy-ion collisions has been carried out by the LHCb Collaboration in proton-lead collisions at $\sqrt{s_{\text{NN}}} = 8.16\,\text{TeV}$ [29]. The experiment measures both $p\text{Pb} \to D^0D^0$ and $p\text{Pb} \to J/\psi D^0$ and observes the $\sim 3A$ enhancement w.r.t. a similar pp measurement in DPS. However, the pure geometric effect cannot explain the rapidity dependence and the difference between $J/\psi D^0$ and D^0D^0 final states. It has been known that $J/\psi D^0$ receives a sizeable SPS contribution [30], while the SPS in D^0D^0 is negligible [31]. This can explain the difference between $J/\psi D^0$ and D^0D^0. If we consider the impact-parameter–dependent nuclear modification with the form of eq. (15) in ref. [28] and assume $G(\frac{T_A(\vec{b})}{T_A(\vec{0})}) \propto [\frac{T_A(\vec{b})}{T_A(\vec{0})}]^a$, the rapidity dependence of D^0D^0 cross-section can be understood as shown in fig. 2, where the LHCb data in the forward (red error bar) and backward (green error bar) rapidities have been compared with the theoretical calculations (solid and dashed curves for $\sigma_{\text{eff},pp} = 34.8$ mb and 21 mb, respectively) with the impact-parameter–dependent gluon shadowing [28]. From the plot, we can deduce that the data disfavour the exponent $a \sim 1$ but favour a slightly larger a, *i.e.*, a stronger $\vec{b}$ dependence. It would be certainly very interesting to see more DPS measurements in heavy-ion collisions in the future.

4. – Conclusion

The LHC program offers an unprecedented avenue to allow us to study MPS, building on a lot of theoretical, phenomenological and experimental progress achieved in the last decade. MPS is expected to reveal the first-ever multiple-body parton correlations in nucleons and nuclei. I have presented two results here. In particular, same-sign D^0 pair production in pPb collisions is a good candidate for new insights on MPS and on other peculiar aspects, like the impact-parameter–dependent gluon shadowing. I am looking forward to more attempts of the first-ever new measurements in the future, such as TPS in pPb and DPS in PbPb.

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