Multiple Production of W Bosons in pp and pA Collisions

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Abstract
The production of equal sign W boson pairs, through single and double parton collisions, are comparable in magnitude at the LHC. As a consequence of the strong anti-shadowing of MPI in interactions with nuclei, the double scattering contribution is further enhanced in the case of hadron-nucleus collisions

1 Multiple production of W bosons in proton-proton collisions

Multiple parton interactions are a manifestation of the unitarity problem caused by the rapid increase of the parton flux at small x, which leads to a dramatic growth of all cross sections with large momentum transfer in pp collisions at the LHC [5]. The critical kinematical regime may be identified by comparing the rate of double collisions with the rate of single collisions. When the two rates become comparable multiple collisions are no more a small perturbation and all multiple collisions become equally important, while the production of large p_t partons becomes a common feature of the inelastic event [10] [3]. In its simplest implementation [9] the double parton scattering cross section σ_D is given by

$$\sigma_D = \frac{1}{2}\frac{\sigma_S^2}{\sigma_{eff}} \tag{1}$$

where σ_S is the single scattering cross section. The problem with unitarity becomes hence critical in the kinematical domain where σ_S and the scale factor σ_{eff} are of the same order.

The experimental indication is that the value of σ_{eff} is close to 10 mb [1]. One might hence conclude that one should worry about multiple parton collisions only when the single scattering cross section becomes comparable with σ_{eff}. On the contrary multiple parton collisions may represent an important effect also in cases where the single scattering cross section is many orders of magnitude smaller that σ_{eff}. The consideration applies to the interesting case of the production of equal sign W boson pairs. The leptonic decay channel of W bosons, which leads to final states with isolated leptons plus missing energy, is in fact of great interest for the search of new physics [2].

The production of two equal sign W bosons is a higher order process in the Standard Model and two equal sign W bosons can be produced only in association with two jets [7]. At the lowest order there are 68 diagrams at $\mathcal{O}(\alpha_W^4)$ and 16 diagrams at $\mathcal{O}(\alpha_S^2\alpha_W^2)$ (some of the diagrams are shown in Fig.1) and, even though $\alpha_S > \alpha_W$, the strong and electroweak diagrams give comparable contributions to the cross section, which is infrared and collinear safe and can be evaluated without imposing any cutoff in the final state quark jets.

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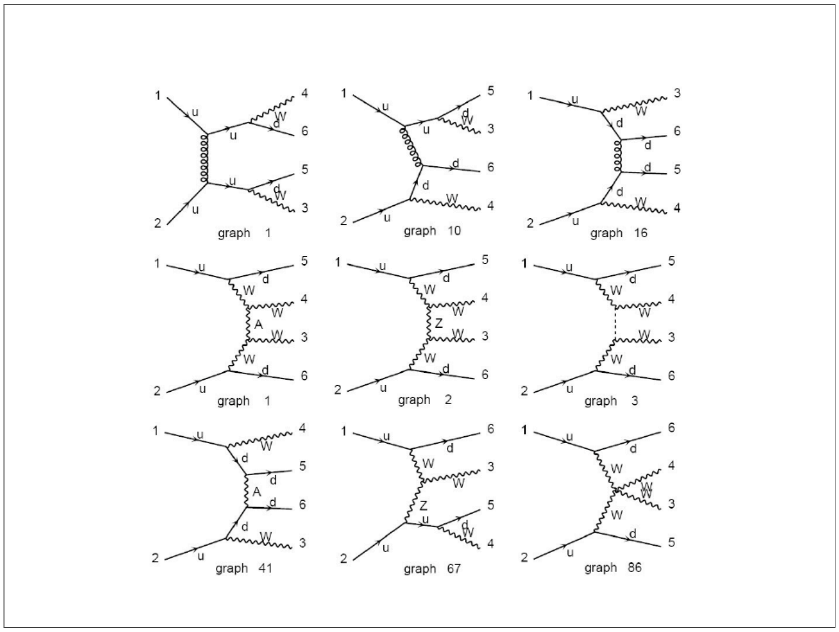

Fig. 1: Some of the three level diagrams which contribute to equal sign W pairs production

The resulting cross sections to produce W bosons and W boson pairs, by single parton scattering in pp interactions, are shown in Fig.2 as a function of the c.m. energy. As apparent in the figure (left upper panel) the cross section to produce two equal sign W bosons is five orders of magnitude smaller with respect to the cross section to produce a single W boson. The same reduction factor is expected for the production of two equal sign W bosons through a multiple collisions processes:

$$\sigma_{WW} = \frac{1}{2}\sigma_W \frac{\sigma_W}{\sigma_{eff}}, \qquad \frac{\sigma_W}{\sigma_{eff}} \simeq \frac{10^2\mathrm{nb}}{10\mathrm{mb}} = 10^{-5} \tag{2}$$

The argument above relies on the simplest expression of the double scattering cross section, obtained by assuming a factorized expression for the the double parton distributions, which is obviously inconsistent in the case of the valence because of the correlations induced by flavor conservation. In the actual case, given the large mass of the W bosons, one may expect important contributions of the valence also at the LHC. One may hence normalize the double parton distributions in such a way to satisfy the flavor sum rules and work out the double scattering cross section accordingly. The effect on the cross section is shown in the left lower panel of Fig.2, which shows that, at the LHC, the cross sections is reduced by about 20%.

The integrated rates of equal sign W boson pairs, by single and double parton collisions, are hence comparable in pp collisions at the LHC. The distribution in phase space is however rather different in the two cases.

In the right lower panel of Fig.2 we show the distribution of the produced Ws, as a function of their transverse momenta. The distribution in transverse momenta of the produced Ws is

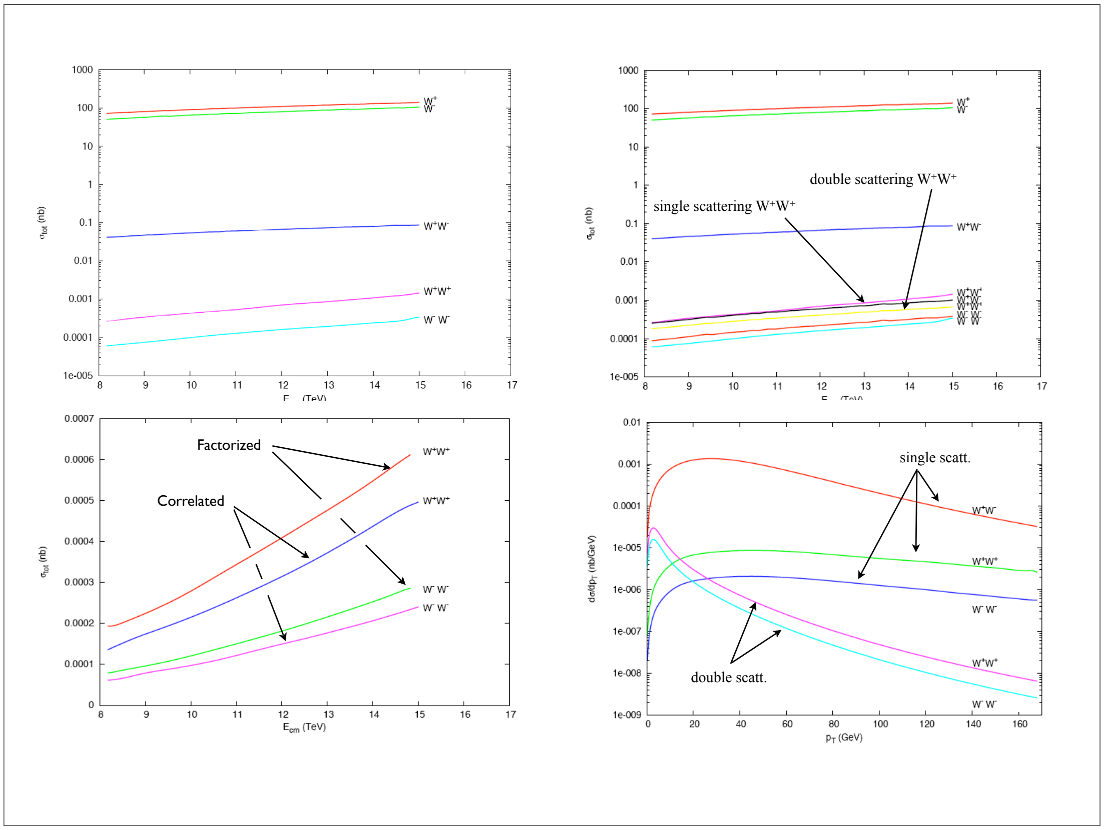

Fig. 2: *Upper left panel*: W production cross sections by single parton scattering in pp interactions as a function of the c.m. energy. *Upper right panel*: W and W pairs production cross sections in pp interactions by double and by single parton collisions. *Lower left panel*: W pairs production cross sections by double parton collisions with correlated and uncorrelated parton densities in the case of pp interactions. *Lower right panel*: W pairs densities in transverse space in the case of single and of double parton collisions in pp interactions.

obtained by following the recipe of the "Poor Man's shower model" of Barger and Phillips [4] and using as a smearing function at low p_t the expression in Eq.15 of [8]. The two contributions may be separated with a cut of 15 GeV/c in the transverse momenta of the produced Ws. In Fig. 3 we show how the W^+ bosons (left panels) and their decay electrons (right panels) are distributed in transverse momentum and rapidity. The case of double parton collisions is shown in the upper panels, while the case of single parton collisions is shown in the lower panels. In the case of a double parton collision, the W bosons are mainly produced with small transverse momenta, while the rapidity distribution of the W boson reminds the momentum of the originating up quarks. The distributions of the final state charged leptons is peaked at the same rapidity of the parent W boson and at a transverse momentum corresponding to 1/2 of the W boson mass.

In the case of single parton collisions (lower panels of Fig.3) the Ws and the corresponding decay leptons have a much broader distribution in p_t and rapidity and the characteristic peaks of the double scatterings are completely absent. The two contributions are hence disentangled very easily by adopting appropriate cuts in rapidity and transverse momenta of the finally observed charged leptons.

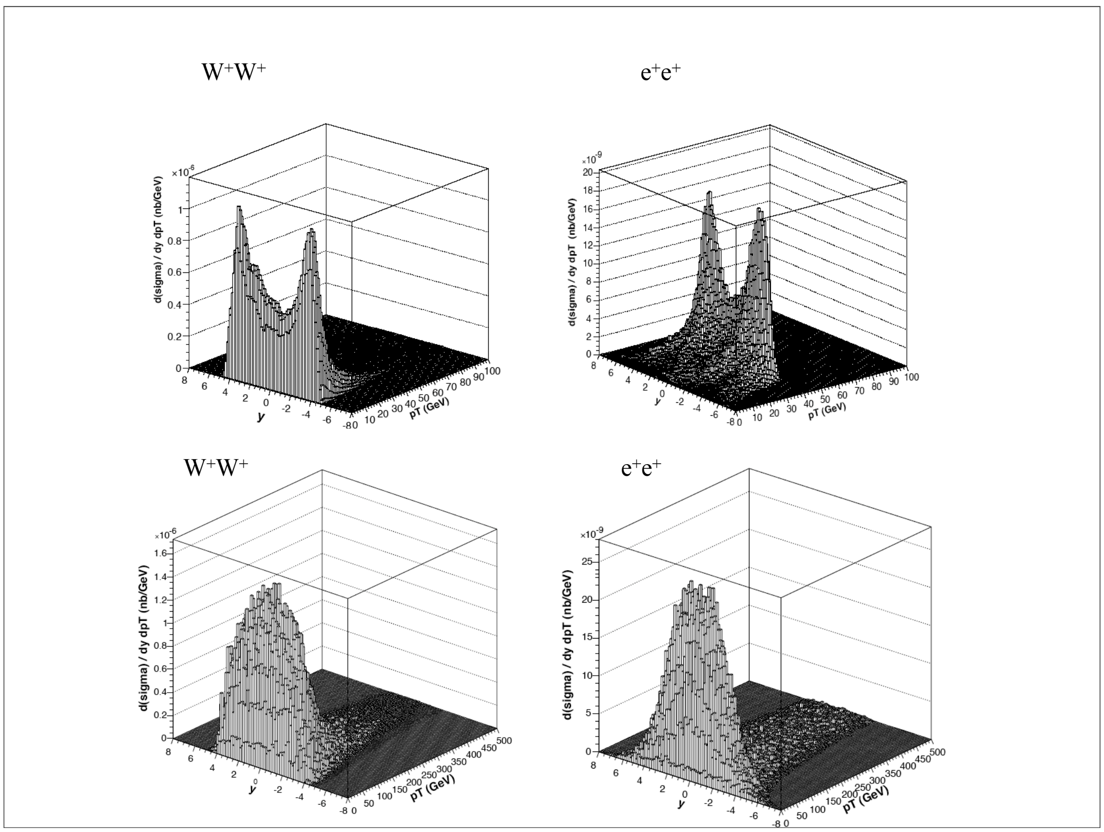

Fig. 3: W^+W^+ and e^+e^+ pairs distribution in transverse momentum and rapidity, in the case of single parton collision (upper panels) and of double parton collisions (lower panels) in proton-proton collisions.

2 Multiple production of W bosons in proton-nucleus collisions

As pointed out in [11], a major feature of MPI in hadron-nucleus collisions is the strong anti-shadowing. Double parton collisions may in fact be amplified by a factor 2 or 3 on heavy nuclei as compared with the corresponding cross section in hadron-nucleon collisions multiplied by the atomic mass number A. Notice that for, say, values of x of the order of 10^{-3} and for values of $Q^2 > 10\,\mathrm{GeV}^2$, the usual nuclear shadowing correction is a much smaller effect and corresponds to a reduction of the cross section not larger than 10% even on heavy nuclei [6]. The effect is schematically illustrated in Fig. 4, where non additive corrections to the nuclear structure functions are neglected, in such a way that each nuclear parton may be associated to a given parent nucleon. As shown in Fig.4, in proton-nucleus interactions one may hence distinguish two different contributions to the double parton scattering cross section, depending wether the two nuclear partons undergoing the interactions are originated by one or by two different target nucleons.

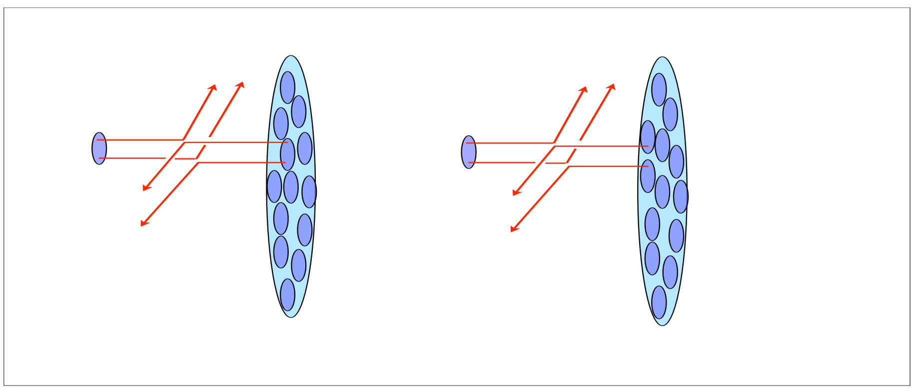

Fig. 4: W production cross sections by single parton scattering in pp collisions as a function of the c.m. energy.

The cross section may thus be written as the sum of two terms

$$\sigma_D^A = \sigma_D^A|_1 + \sigma_D^A|_2 \tag{3}$$

and

$$\sigma_D^A|_1 = \frac{1}{2}\frac{\sigma_W^2}{\sigma_{eff}}\int d^2b T(b) \propto A, \qquad \sigma_D^A|_2 = \frac{1}{2}\sigma_W^2 \int d^2b T^2(b) \propto A^{4/3}$$

The anti-shadowing effect is apparent in Fig.5, where the W production cross sections in proton-proton collisions are compared with the cross sections in proton-nucleus collisions (after dividing by the atomic mass number A). In the upper panels one compares the cross sections as a function of the c.m. energy, while in the lower panels one compares the distributions in transverse momenta of the two W^+ bosons. The region where double parton collisions dominate now extends to transverse momenta of the order of 40 GeV/c.

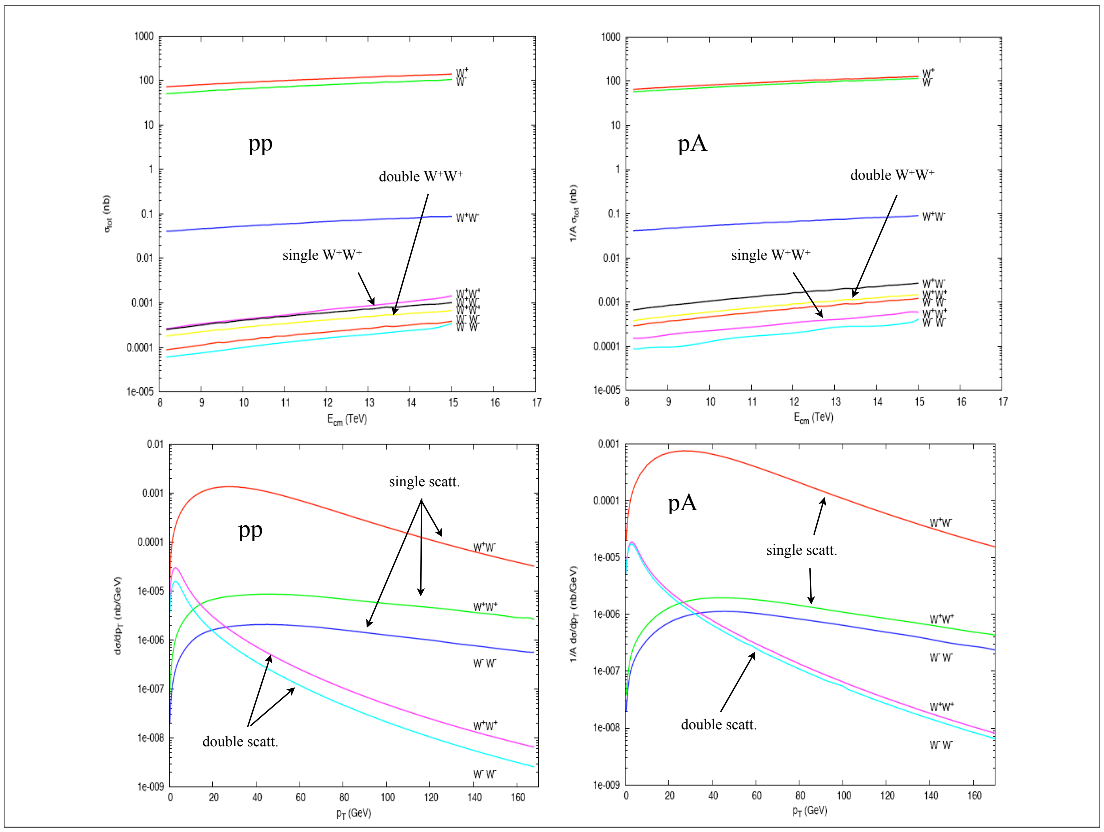

Fig. 5: W and W pairs production in proton-proton and proton-nucleus collisions. Integrated cross sections as a function of the c.m. energy (upper panels) and distributions in transverse space (lower panels).

In the upper panels of Fig.6 (left and right respectively) we show the distributions in transverse momentum and rapidity of the W^+ bosons and of the decay leptons in pA collisions. The W bosons are produced with a small transverse momentum, while the rapidity distribution of the W boson reminds the momentum of the originating up quark. The asymmetry in rapidity is due to the different content of up quarks in the proton as compared with the content of up quarks in the pairs of nucleons of the target nucleus undergoing the process (pp, pn and nn). The distributions of the final charged leptons is peaked at the same rapidity of the parent W boson and, as in the case of proton-proton interactions, at a transverse momentum corresponding to 1/2 of the W boson mass.

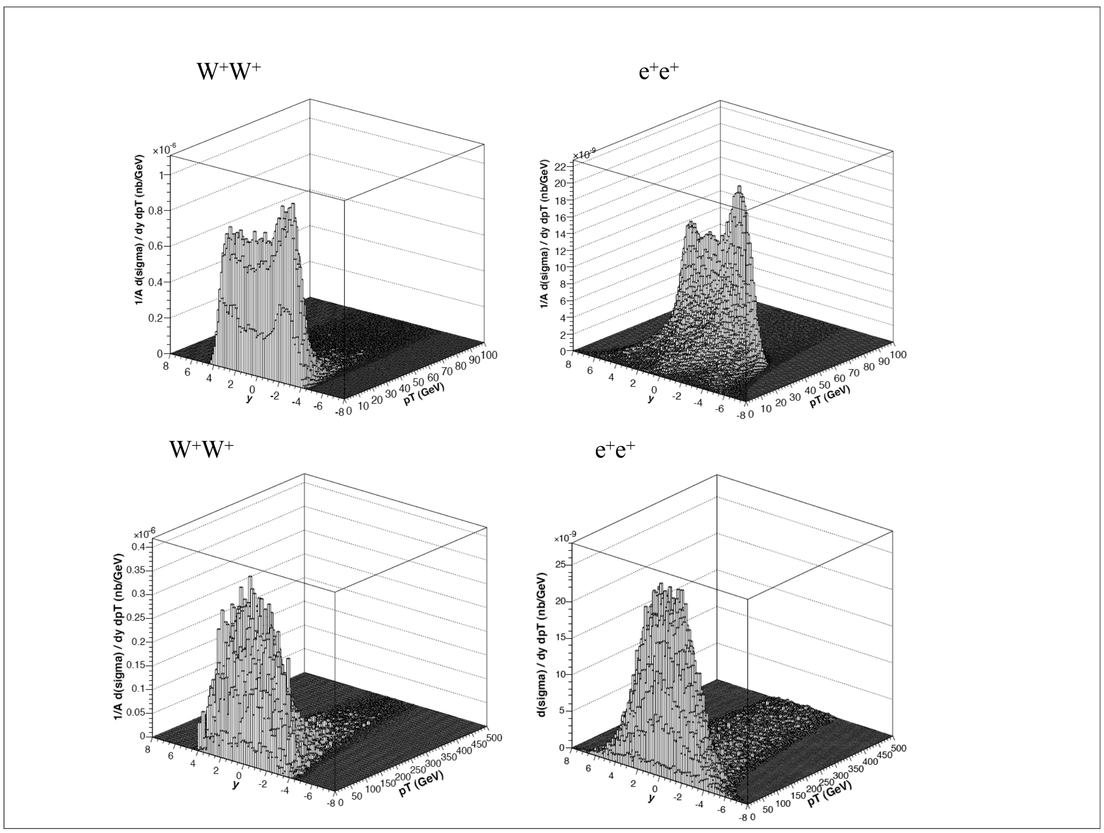

Fig. 6: W^+W^+ and e^+e^+ pairs distribution in transverse momentum and rapidity, in the case of single parton collision (upper panels) and of double parton collisions (lower panels) in proton-nucleus collisions.

The distributions of equal sign W bosons and of the decay leptons generated by single parton collisions in pA interactions are shown in the lower panels of Fig.6 (left and right respectively) as a function of rapidity and transverse momenta. The contribution of double collisions is overwhelming when selecting leptons with transverse momenta of the order of one half of the W mass.

3 Concluding summary

Equal sign W boson pairs are produced by a higher order process in the SM. As a consequence, the cross section to produce two W bosons with equal sign is more than two orders of magnitude smaller in pp collisions at the LHC, as compared with the cross section to produce two W bosons with opposite sign. An outcome is that the integrated cross sections, to produce two equal sign W bosons through single and double parton collisions, are similar in magnitude. The equal sign W bosons and the corresponding decay leptons are however distributed very differently in phase space by the two production mechanisms, which allows to disentangle the two contributions easily by looking at the distribution of the decay leptons.

As a consequence of the strong anti-shadowing of MPI in collisions with nuclei, the contribution of double scattering is greatly enhanced in the case of hadron-nucleus collisions.

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