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Like-Sign W Boson Production at the LHC as a Probe of Double Parton Scattering

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ABSTRACT

Double parton scattering, i.e. two parton hard scattering processes in the same hadron-hadron collision, may constitute an important background for Higgs and other new particle searches at the LHC. We point out that like-sign W pair production provides a relatively clean way of searching for, and calibrating, double parton scattering at the LHC.

Recently [1] the importance of double parton scattering at the Large Hadron Collider (LHC) has been readdressed. In particular it has been pointed out [1] that double parton scattering may constitute a significant background to Higgs boson production and decay via the $b\bar{b}$ decay channel, which, for a Higgs mass below the W^+W^- threshold, is one of the most promising discovery channels. Of course, double scattering contributes to the background in many other processes, and similar analyses have been performed in the past for hadron collisions at lower energy [2]. However, the LHC and its discovery potential necessitates a very accurate estimation of backgrounds where double scattering may provide a significant contribution. Therefore it is essential to obtain a better quantitative understanding of double parton scattering and a more precise estimation of the effect.

The double (multiple) scattering occurs when two (many) different pairs of partons scatter independently in the same hadronic collision. From the theoretical point of view, the presence of double scattering is required to preserve unitarity in the high energy limit, i.e. when the distribution of partons with small momentum fractions within a hadron is high. In principle, double scattering probes correlations between partons in the hadron in the transverse plane, and thus provides important additional information on hadron structure [6]. If a scattering event is characterized by high centre-of-mass energy and relatively modest partonic subprocess energy, which happens for example in the production of heavy gauge bosons or a Higgs boson at the LHC, then parton-parton correlations can be assumed to be negligible. Such an assumption leads to a simple factorised expression for the double scattering cross section (in the case of two distinguishable interactions, a and b) [6]

$$\sigma_{\rm DS} = \frac{\sigma_a \sigma_b}{\sigma_{\rm eff}}\,. \tag{1}$$

Here σ_a represents the single scattering cross section

$$\sigma_a = \sum_{i,j} \int dx_A dx_B f_i(x_A) f_j(x_B) \hat{\sigma}_{ij\to a}\,, \tag{2}$$

with $f_i(x_A)$ being the standard parton distribution of parton i and $\hat{\sigma}_{ij\to a}$ representing the partonic cross section. If the two interactions are indistinguishable, double counting is avoided by replacing Eq. (1) with

$$\sigma_{\rm DS} = \frac{\sigma_a \sigma_b}{2\sigma_{\rm eff}}\,. \tag{3}$$

The parameter $\sigma_{\rm eff}$, the effective cross section, contains all the information about the non-perturbative structure of the proton in this simplified approach and corresponds to the overlap of the matter distributions in the colliding hadrons. The factorisation hypothesis appears to be in agreement with the experimental data from CDF [3] at the Tevatron $p\bar{p}$ collider. It is also believed that $\sigma_{\rm eff}$ is largely independent of the centre-of-mass energy of the collision and on the nature of the partonic interactions (for a detailed discussion the reader is referred to [6]). Therefore throughout this study we will use the value $\sigma_{\rm eff} = 14.5$ mb, as measured by CDF. [1]

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[1] Strictly speaking, this value refers to an exclusive measurement and therefore should be understood as an *upper* bound on $\sigma_{\rm eff}$.

Given the potential importance of double scattering as a background to new-physics searches at the LHC, it is important to be able to calibrate the effect, i.e. to measure $\sigma_{\rm eff}$ using a known, well-understood Standard Model process. In the case of single scattering processes, the benchmark process is W boson production, see for example Ref. [7]. [2] This suggests that W *pair* production could be used to calibrate double parton scattering. In the Standard Model, like-sign W pair production is much smaller than opposite-sign production, which suggests that the former channel is the best place to look for additional double scattering contributions.

The purpose of this note is to quantify the expected cross sections for like- and opposite-sign W pair production at the LHC, from both the single and double scattering mechanisms, and to explore differences in the distributions of the final state particles.

The predicted rate of single W production at the LHC is naturally very high, resulting in a significant double scattering cross section. Since the W^+ and W^- single scattering cross sections are comparable in magnitude, the same will be true for the double scattering $\sigma_{\rm DS}(W^+W^+)$, $\sigma_{\rm DS}(W^-W^-)$ and $\sigma_{\rm DS}(W^+W^-)$ cross sections. However, for single scattering we would expect $\sigma(W^-W^-) < \sigma(W^+W^+) \ll \sigma(W^+W^-)$. The reason is that while the latter is $\mathcal{O}(\alpha_W^2)$ at leading order, same-sign inclusive W pair production is a mixed strong-electroweak process with leading contributions of $\mathcal{O}(\alpha_S^2\alpha_W^2)$ and $\mathcal{O}(\alpha_W^4)$. Hence we might expect that like-sign W pair production, with its relatively larger double scattering component, could give a clean measurement of $\sigma_{\rm eff}$.

The possibility of double scattering 'background' contributions to like-sign W pair production was noticed some time ago [4], when this process was considered as one of the most promising channels for searching for strong scattering in the electroweak symmetry breaking sector [5]. In these studies the double scattering contribution was treated as an unwanted background and suppressed by applying appropriate cuts.

We begin our analysis by calculating the total single-scattering cross sections for single W and (opposite-sign and like-sign) W pair production in pp and $p\bar{p}$ collisions at scattering energy $\sqrt{s}$. For consistency, we consider only *leading-order* cross sections for all processes studied, i.e. we use leading-order subprocess cross sections with leading-order parton distributions. [3]

As already noted, in the context of leading-order single parton scattering, opposite-sign W pair production in hadron-hadron collisions arises from the $\mathcal{O}(\alpha_W^2)$ subprocess

$$q + \bar{q} \to W^+ + W^- \tag{4}$$

In contrast, like-sign W pair production is an $\mathcal{O}(\alpha_S^2\alpha_W^2)$ or $\mathcal{O}(\alpha_W^4)$ process at leading order:

$$q + q \to W^+ + W^+ + q' + q' \tag{5}$$

with $q = u, c, \ldots$, $q' = d, s, \ldots$, together with the corresponding crossed processes. Charge conjugation gives a similar set of subprocesses for W^-W^- production. The Feynman diagrams split into two groups: the first set corresponds to the $\mathcal{O}(\alpha_S^2\alpha_W^2)$ gluon exchange process $qq \to qq$ where a single W is emitted from each of the quark lines, see Fig. 1(a). The second, $\mathcal{O}(\alpha_W^4)$, set contains analogous electroweak diagrams, i.e. $t-$channel γ or Z exchange, as well as WW scattering

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[2] It has even been suggested that this process could be used to measure the luminosity at the LHC.

[3] We note that the full $\mathcal{O}(\alpha_S^2)$ corrections to single W [8] and $\mathcal{O}(\alpha_S)$ corrections to W pair production [9] have been calculated.

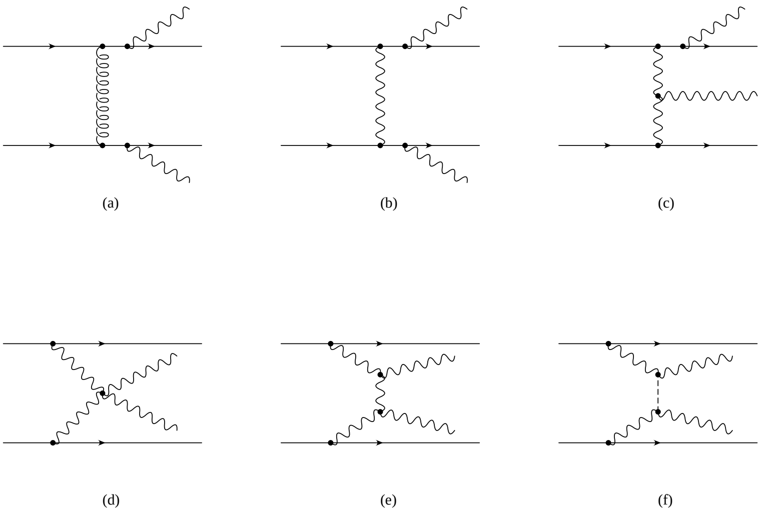

Figure 1: Examples of Feynman diagrams for the $uu \to W^+W^+dd$ scattering process, $\mathcal{O}(\alpha_S^2\alpha_W^2)$ (a) and $\mathcal{O}(\alpha_W^4)$ (b-f).

diagrams, including also a $t-$channel Higgs exchange contribution, see Fig. 1(b-f). Note that the corresponding cross sections are infra-red and collinear safe: the total rate can be calculated without imposing any cuts on the final-state quark jets. We would therefore expect naive coupling constant power counting to give the correct order of magnitude difference between the like-sign and opposite-sign cross sections, i.e. $\sigma(W^+W^+) \sim \alpha_{S,W}^2\ \sigma(W^+W^-)$. Given the excess of u quarks over d quarks in the proton, we would also expect $\sigma(W^+W^+) > \sigma(W^-W^-)$.

Figure 2 shows the total single W and W pair cross sections in proton–antiproton and proton–proton collisions as a function of the collider energy. No branching ratios are included, and there are no cuts on any of the final state particles. The matrix elements are obtained using MADGRAPH [10] and HELAS [11]. We use the MRST leading-order parton distributions from Ref. [13], and the most recent values for the electroweak parameters. [4] Note that for $p\bar{p}$ collisions, $\sigma(W^+) \equiv \sigma(W^-)$ and $\sigma(W^+W^+) \equiv \sigma(W^-W^-)$. The like-sign and opposite-sign cross sections differ by about two orders of magnitude, as expected. Despite the fact that $\alpha_S > \alpha_W$, the electroweak contribution to the single scattering like-sign WW production cross section is similar in size to the strong contribution. This is due to the relatively large number of diagrams (e.g. 68 for $uu \to W^+W^+dd$), as compared to the gluon exchange contribution (16 for the same process). A total annual luminosity of $\mathcal{L} = 10^5$ pb^{-1} at the LHC would yield approximately 65 thousand W^+W^+ events and 29 thousand W^-W^- events, before high-order corrections, branching ratios and acceptance cuts are included.

The production characteristics of the Ws in like- and opposite-sign production are somewhat different. In particular, the presence of two jets in the final state for the former leads to a broader

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[4] Note that the same-sign cross sections are weakly dependent on the Higgs mass: varying the mass from $M_H = 125$ GeV to $M_H = 150$ GeV leads to only a 2% change in the total rate at the LHC. We use $M_H = 125$ GeV as the default value.

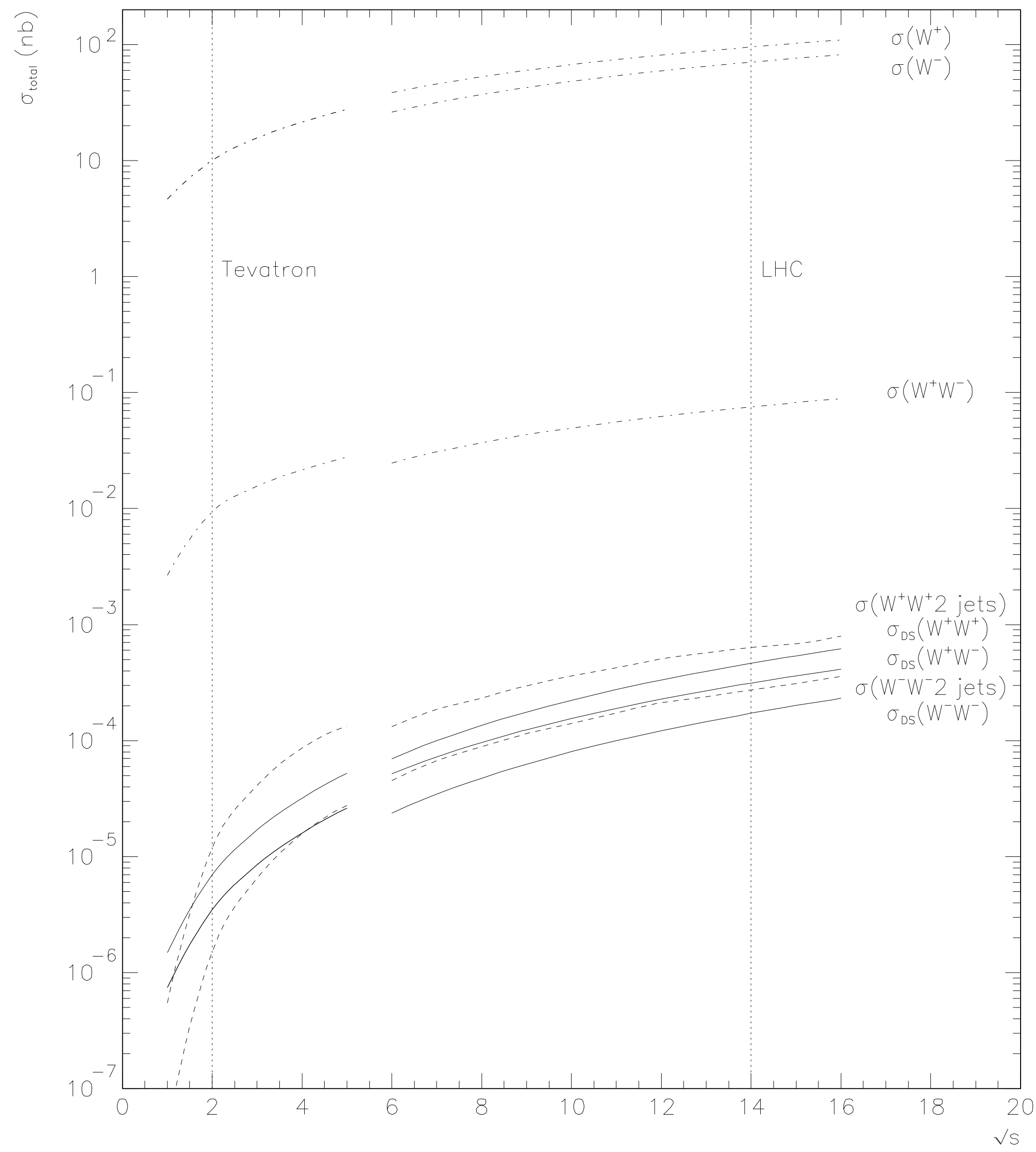

Figure 2: Total cross sections for single W and W pair production in pp and $p\bar{p}$ collisions. The dashed and dot-dashed lines correspond to single parton scattering, and the solid lines to double parton scattering assuming $\sigma_{\rm eff} = 14.5$ mb.

	$N(W^+W^-)$	$N(W^+W^+)$	$N(W^-W^-)$
single scattering	7,500,000	65,000	29,000
double scattering	46,000	31,000	17,000

Table 1: The expected number of WW events expected for $\mathcal{L} = 10^5$ pb^{-1} at the LHC from single and double scattering, assuming $\sigma_{\text{eff}} = 14.5$ mb for the latter.

transverse momentum distribution, as illustrated in Fig. 3. Also of interest is the jet transverse momentum distribution in $W^\pm W^\pm$ production, shown in Fig. 4. This indicates that a significant fraction of the jets would pass a detection p_T threshold, and could be used as an additional 'tag' for like-sign production. Of course one also expects large p_T jets in opposite-sign W production via higher-order processes, e.g. $q\bar{q} \to W^+W^-g$ at $\mathcal{O}(\alpha_S)$, but these have a steeply falling distribution reflecting the underlying infra-red and collinear singularities at $p_T = 0$.

We turn now to the double parton scattering cross sections. As discussed above, we estimate these by simply multiplying the corresponding single scattering cross sections and normalising by σ_{eff} for the like-sign W pair production and $2\sigma_{\text{eff}}$ for the opposite-sign case. The factorisation assumption holds since the energy required to produce a vector boson is much lower than the overall centre of mass energy. Figure 2 shows the resulting total $\sigma_{\text{DS}}(W^+W^-)$ and $\sigma_{\text{DS}}(W^\pm W^\pm)$ cross sections as a function of $\sqrt{s}$. The opposite-sign single scattering and double scattering cross sections differ by two orders of magnitude. However for like-sign W^+W^+ (W^-W^-) production the double scattering scattering contribution is only a factor 2.1 (1.7) smaller than the single scattering contribution. Additionally, a double scattering event signature differs significantly from the single scattering case. In particular, the W transverse momentum distribution from double scattering has a very pronounced, steep peak for small values of p_T (see Fig. 3), inherited from the single scattering p_T distribution [5], in contrast to the broader single-scattering distributions. Obviously, similar features will characterize the p_T spectra of leptons originating from W decay, allowing for additional discrimination between double and single scattering events.

The absolute rate of like-sign W^+W^+ and W^-W^- pair production therefore provides a relatively clean measure of σ_{eff} at LHC energies. Table 1 summarizes the number of expected events in the various WW channels (recall these are leading-order estimates only, with no branching ratios), assuming $\sigma_{\text{eff}} = 14.5$ mb. However, since the absolute event rates shown in Table 1 are sensitive to overall measurement and theoretical uncertaintities, it may be more useful to consider cross section *ratios*. Consider for example the ratio of the like- to opposite-sign event rates

$$\begin{aligned}\mathcal{R} &= \frac{N(W^+W^+) + N(W^-W^-)}{N(W^+W^-)} \\ &= \frac{\sigma(W^+W^+) + \sigma(W^-W^-) + (2\sigma_{\text{eff}})^{-1}\left[\sigma(W^+)^2 + \sigma(W^-)^2\right]}{\sigma(W^+W^-) + \sigma_{\text{eff}}^{-1}\sigma(W^+)\sigma(W^-)}\end{aligned} \qquad (6)$$

with both single and double scattering contributions included. The ratio $\mathcal{R}$ for the LHC is shown as a function of σ_{eff} in Fig. 5. The limit $\sigma_{\text{eff}} \to \infty$ corresponds to the (very small) single scattering

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[5] We are assuming here that the non-perturbative 'intrinsic' transverse momentum distributions of the two partons participating in the double parton scattering are uncorrelated.

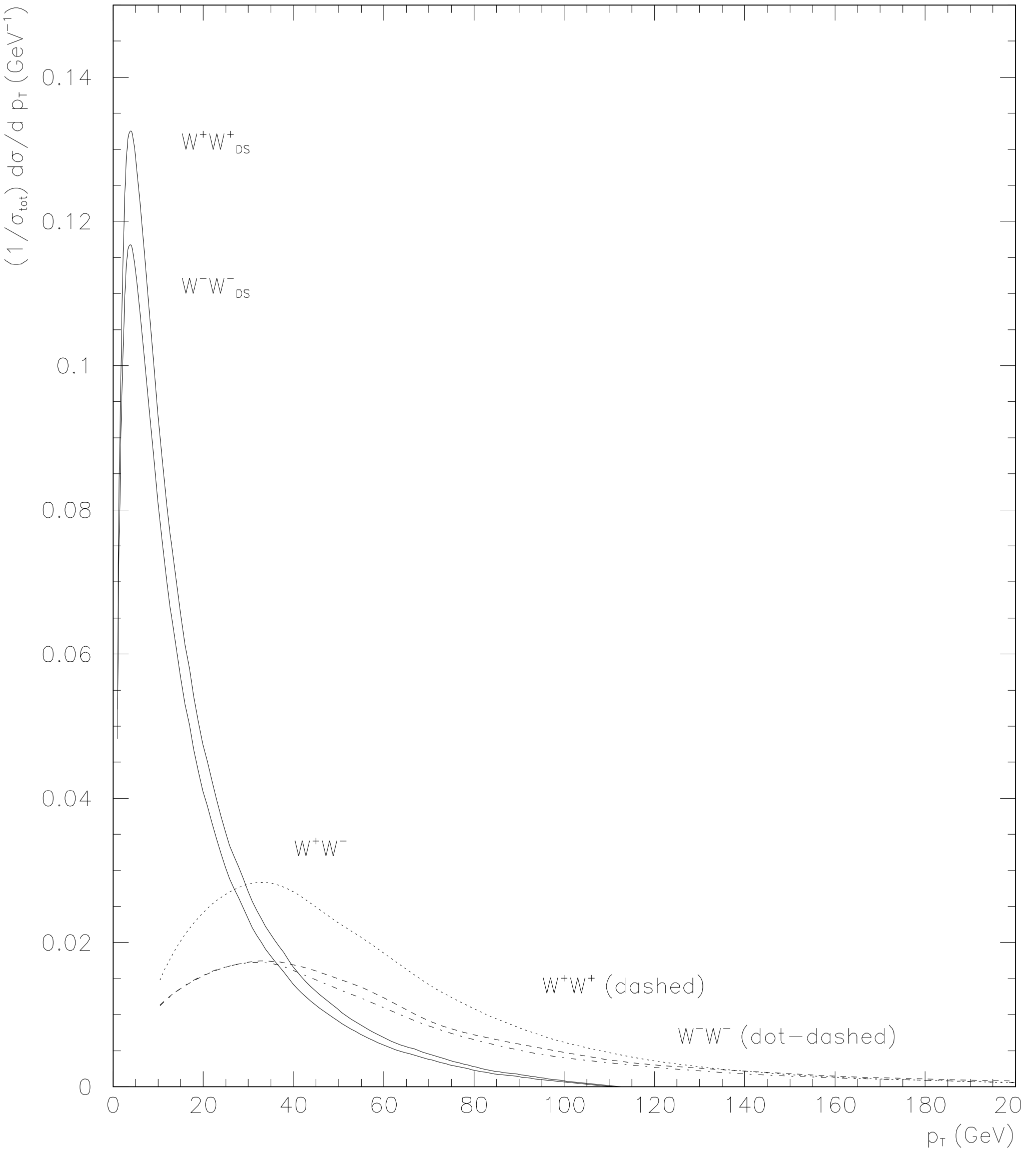

Figure 3: Transverse momentum distributions for W^+W^+, W^-W^-, W^+W^- (dashed, dot-dashed and dotted lines, respectively) single parton scattering and W^+W^+, W^-W^- double parton scattering (solid lines) at the LHC. The double scattering predictions are obtained using the p_T-space resummation method [14] (with neither smearing nor matching included).

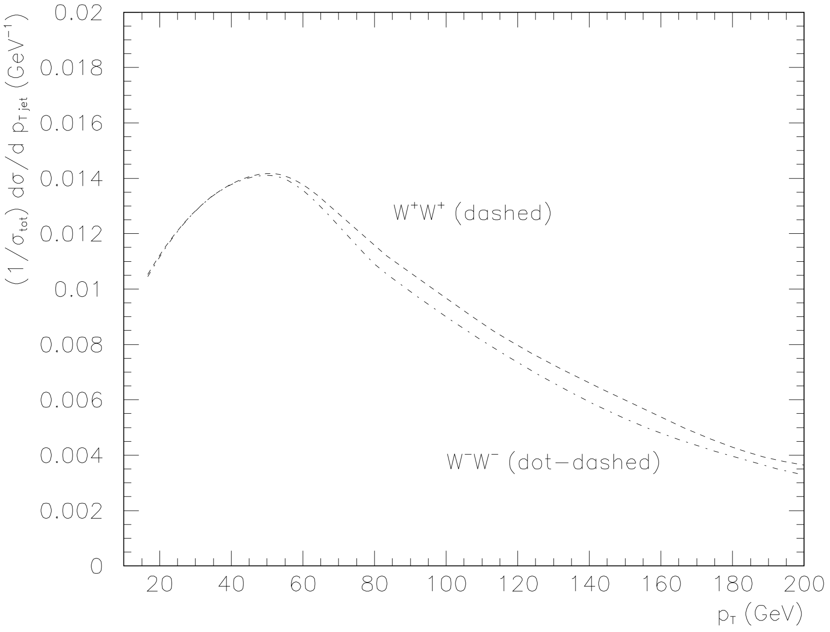

Figure 4: Jet transverse momentum distributions in like-sign single scattering WW production.

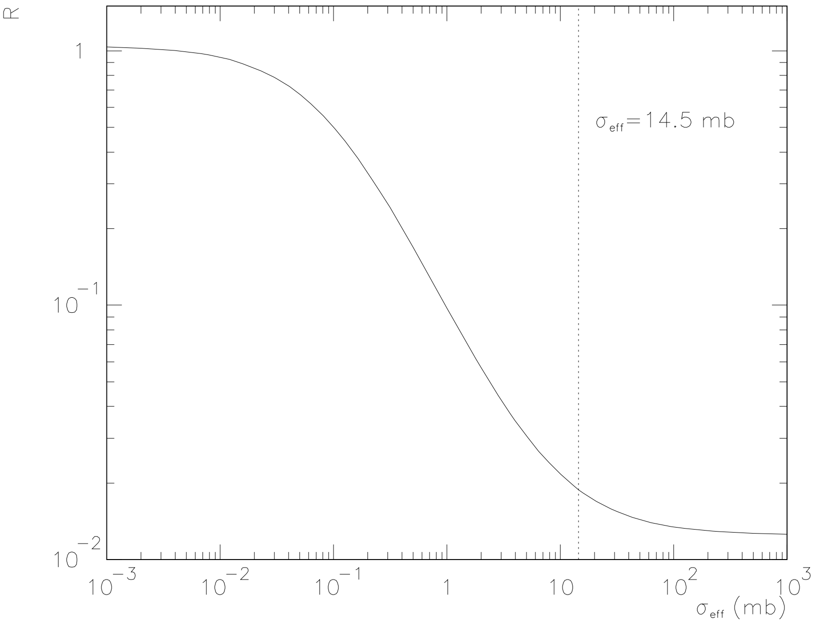

Figure 5: The dependence of the ratio $\mathcal{R}$ of like-sign to opposite-sign W pair event rates on the effective cross section $\sigma_{\rm eff}$ at the LHC.

ratio, $\mathcal{R} = 0.0125$ while $\sigma_{\rm eff} \to 0$ corresponds to the ratio (≈ 1.05) of the *single* W production cross sections in pp collisions. The CDF measured value [3] of $\sigma_{\rm eff} = 14.5$ mb gives $\mathcal{R} = 0.019$.

In conclusion, we have shown that like-sign W pair production provides a relatively clean environment for searching for and calibrating double parton scattering at the LHC. A measurement of $\sigma_{\rm eff}$ from this process would allow the double scattering backgrounds to new physics searches to be calibrated with precision. In this brief study we have concentrated on overall total event rates. An interesting next step would be to perform more detailed Monte Carlo studies of the various production processes, taking into account the W decays, experimental acceptance cuts, etc. In fact it would not be difficult to devise additional cuts to enhance the double scattering contribution. We see from Fig. 3, for example, that a cut of $p_T(W) < \mathcal{O}(20 \text{ GeV})$ would remove most of the single scattering events while leaving the double scattering contribution largely intact.

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