Multiple production of W bosons in pp, pA and AA collisions

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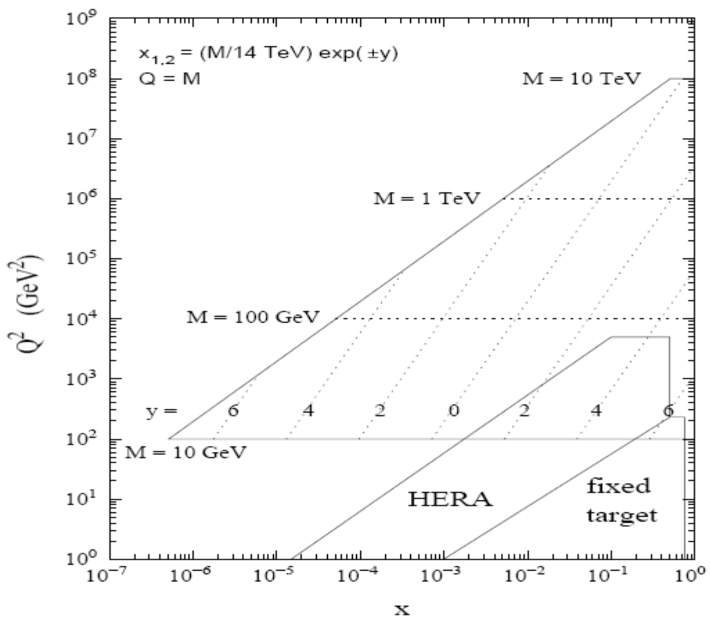
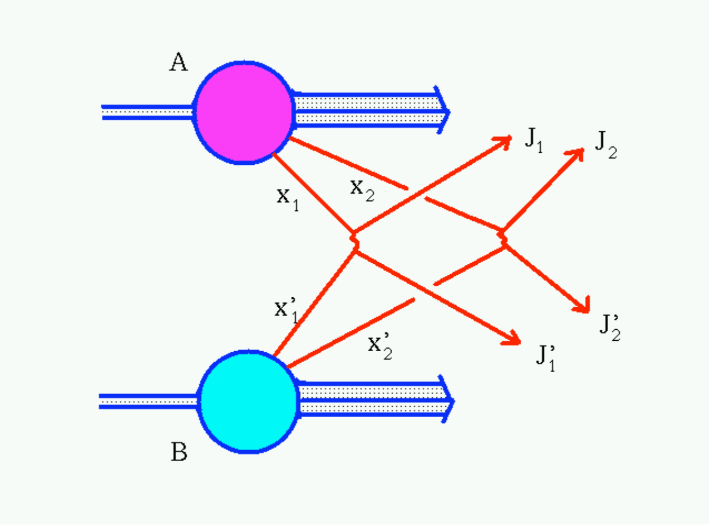
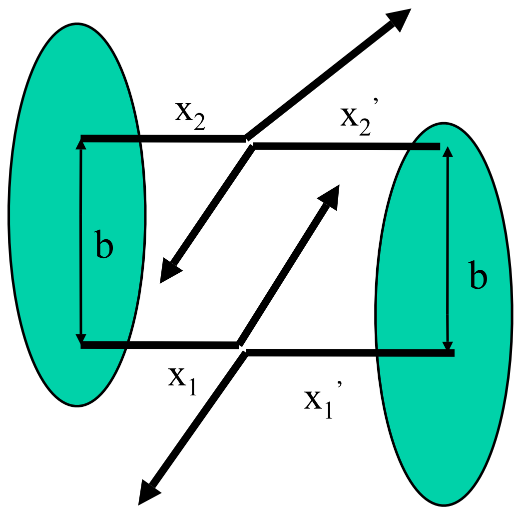
The rapid increase of the parton flux at small x causes a dramatic increase of all cross sections with large momentum transfer in pp collisions at the LHC.
In the case of production of jets one may easily exceed the value of the total inelastic cross section.



The problem with unitarity is solved by introducing multiple parton interactions.
The simplest case is **double parton scattering**



The hard interactions are well localized in the overlap region of the two interacting hadrons and, in a double parton collisions, the non-perturbative component is factorized into a function which depends on the two fractional momenta and on the relative transverse distance b



as a consequence, the inclusive double parton-scattering cross-section, for two parton processes A and B in a pp collision, is given by

$$\sigma^D_{(A,B)} = \frac{m}{2}\sum_{i,j,k,l}\int D_{ij}(x_1,x_2;b)\hat{\sigma}^A_{ik}(x_1,x'_1)\hat{\sigma}^B_{jl}(x_2,x'_2)D_{kl}(x'_1,x'_2;b)dx_1dx'_1dx_2dx'_2d^2b$$

where $D_{ij}(x_1,x_2,b)$ are the double parton distribution functions

The expression of the cross section simplifies considerably after neglecting correlations in the momentum fraction *x*. In such a case the two-body parton distributions are given by

$$D_{ij}(x_1, x_2; b) = D_i(x_1) D_j(x_2) F_i^j(b)$$

which leads, for the cross section, to the expression

$$\sigma^D_{(A,B)} = \frac{m}{2} \sum_{ijkl} \Theta^{ij}_{kl} \sigma^S_{ij}(A) \sigma^S_{kl}(B)$$

where

$$\Theta^{ij}_{kl} = \int d^2b\, F^i_k(b)\, F^j_l(b)$$

are geometrical coefficients with dimension an inverse cross section and depending directly on the transverse correlation of the different kinds of parton pairs in the hadron structure

In the simplest case the functions F_k^i do not depend on the indices *i, k* and the coefficients are all equal to a universal constant. The double parton scattering cross section is hence given by

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

The experimental indication is that the value of σ_{eff} is close to 10 mb, which sets the scale of values of σ_S where unitarity corrections are a large effect and need to be resummed. 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}

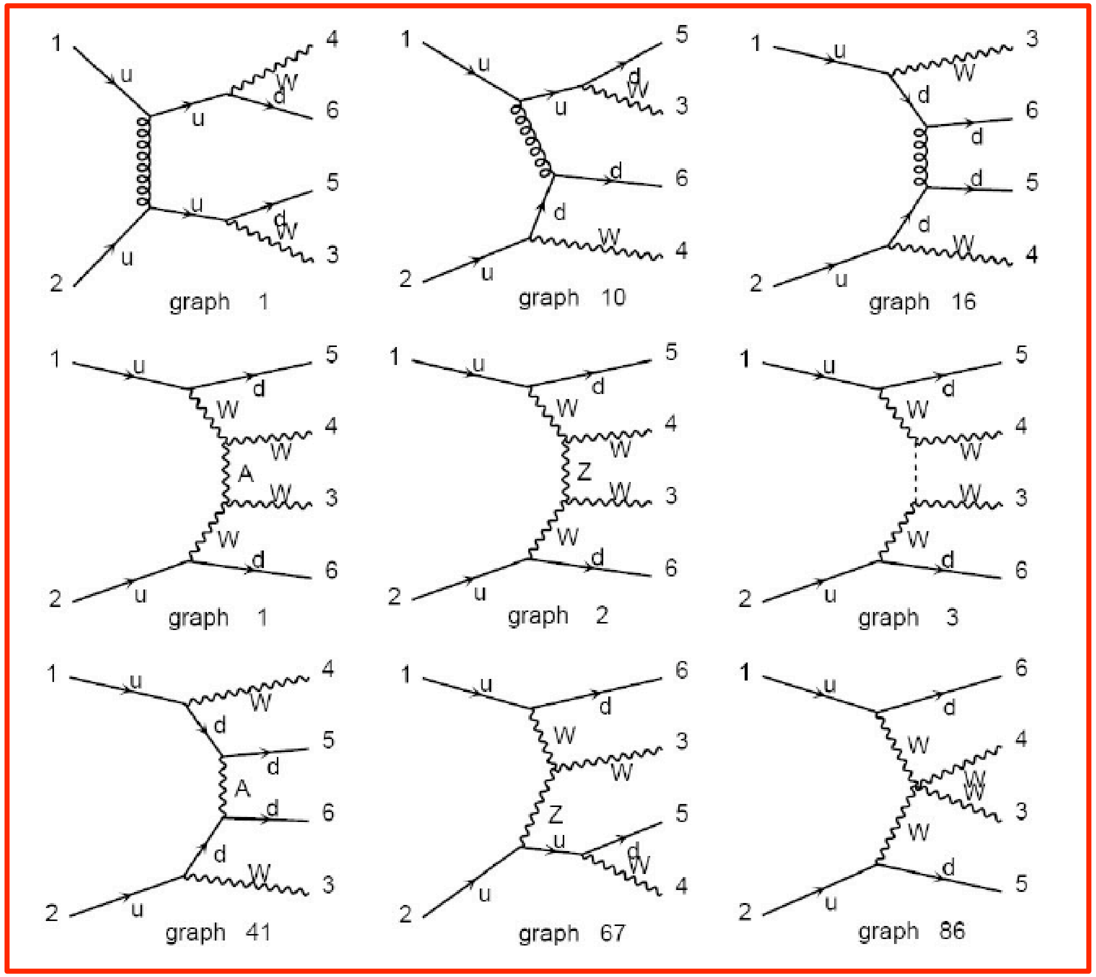
The consideration applies to the interesting case of the production of equal sign W boson pairs

Notice that the leptonic decay channel of W bosons, which leads to final states with isolated leptons plus missing energy, is very interesting for the search of new physics.

In the SM the production of **two equal sign W bosons is a higher order process.**
Two equal sign W bosons can in fact be produced only in association with two jets

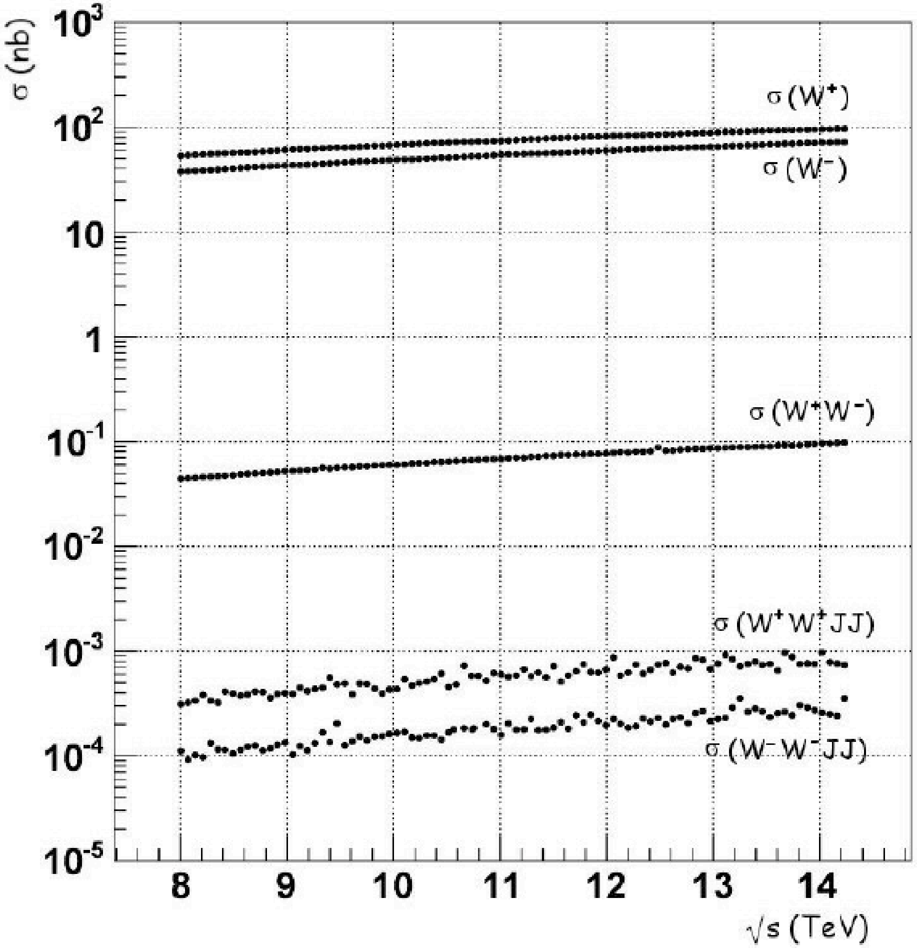
At the lowest order there are 68 diagrams at $\mathcal{O}(\alpha_W^4)$ and 16 diagrams at $\mathcal{O}(\alpha_S^2\alpha_W^2)$ and although $\alpha_S > \alpha_W$ the electroweak contribution is similar to the strong one.

The corresponding **cross section** is **infrared and collinear safe** and can be evaluated without imposing any cutoff in the final state quark jets



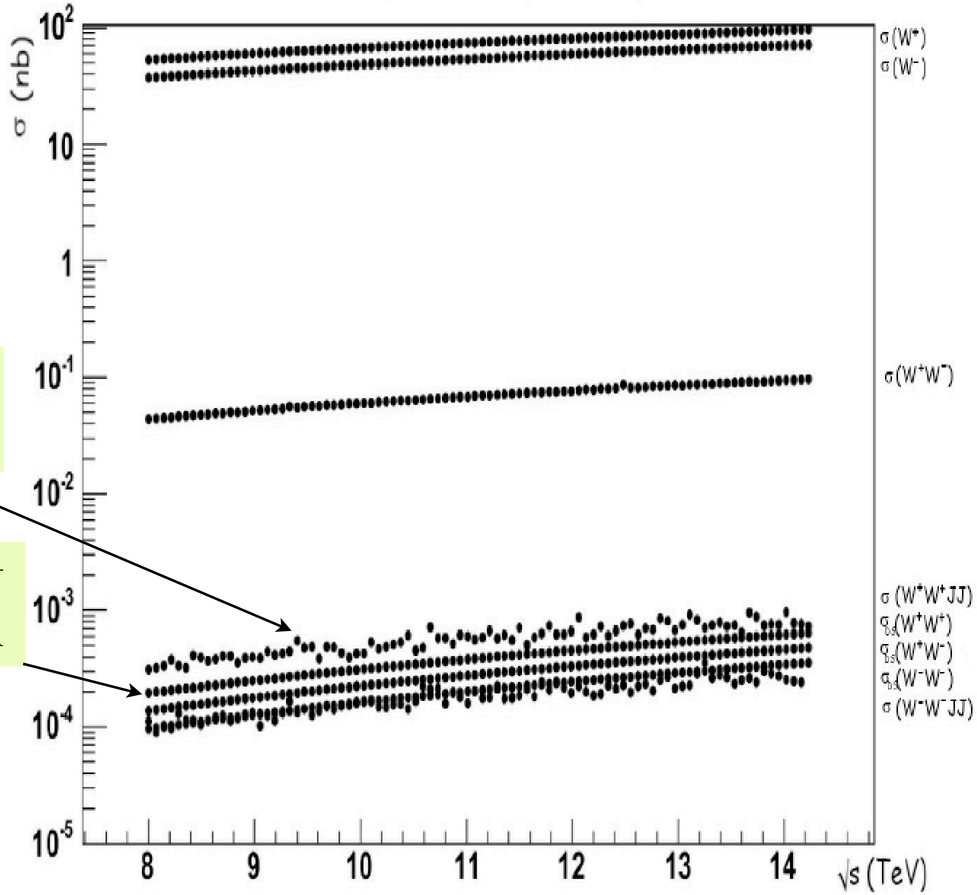
W production cross sections by single parton scattering in pp collisions as a function of the c.m. energy.

Notice that the cross section to produce two equal sign W bosons is **five orders of magnitude** smaller with respect to the cross section of single boson production



The **same reduction factor** is expected for W production **through multiple collisions** processes:

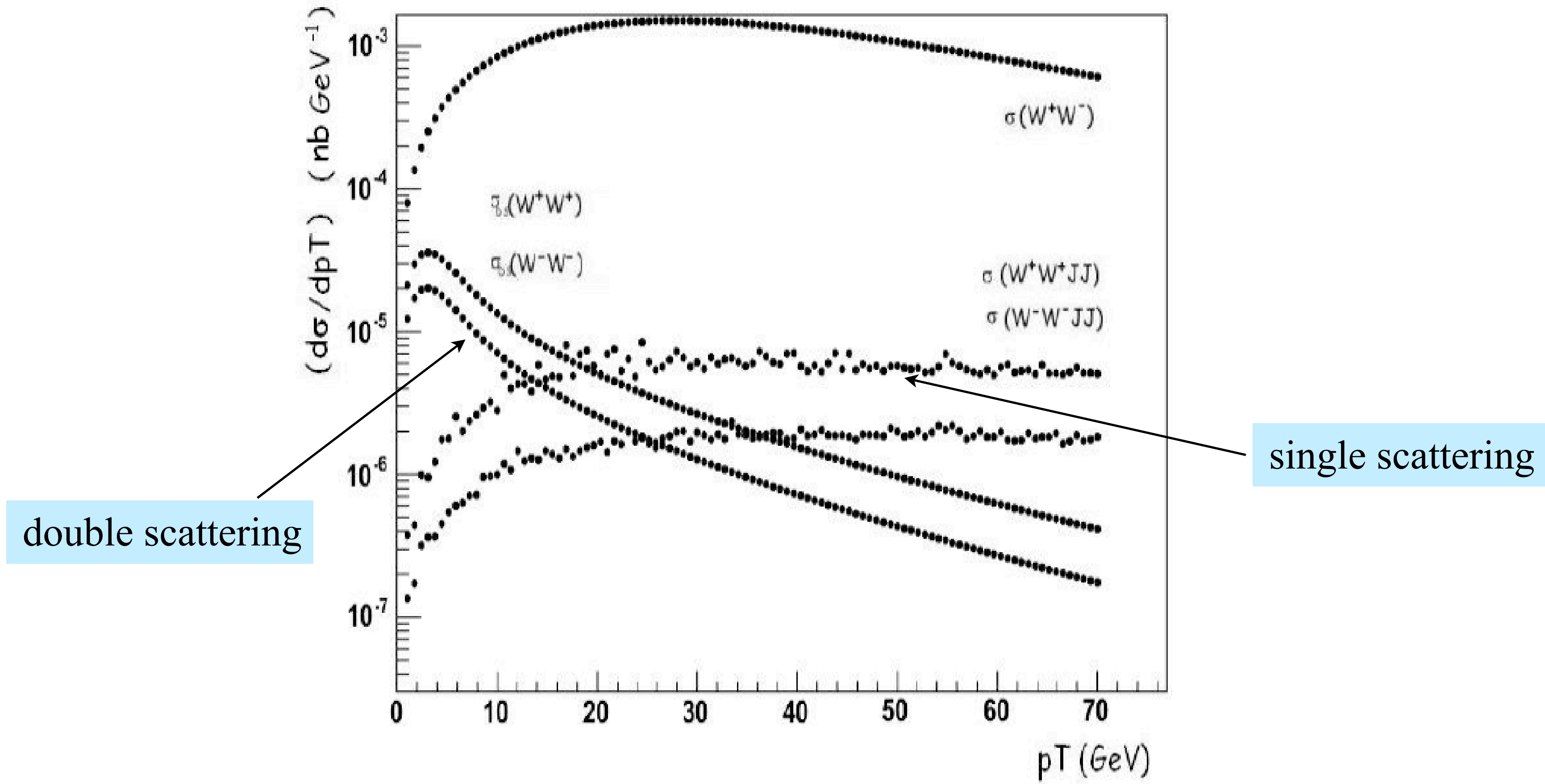
$$\sigma_{WW} = \frac{1}{2}\sigma_W \frac{\sigma_W}{\sigma_{eff}} \qquad\qquad \frac{\sigma_W}{\sigma_{eff}} \simeq \frac{10^2\text{nb}}{10\text{mb}} = 10^{-5}$$



single scattering W^+W^+ production cross section

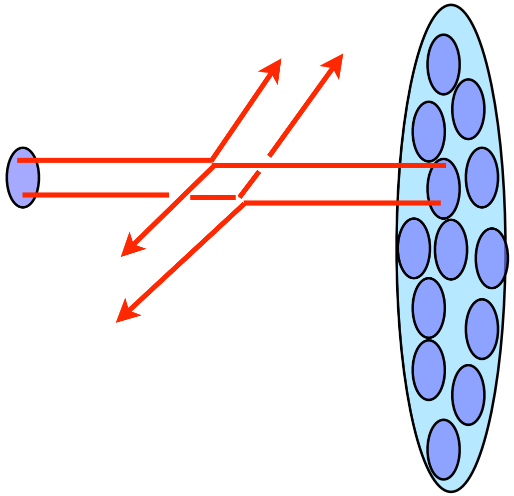
double scattering W^+W^+ production cross section

The two equal sign W bosons are distributed differently in phase space by the two production mechanisms, which may be separated with a cut of 15 GeV/c in the transverse momenta of the produced Ws



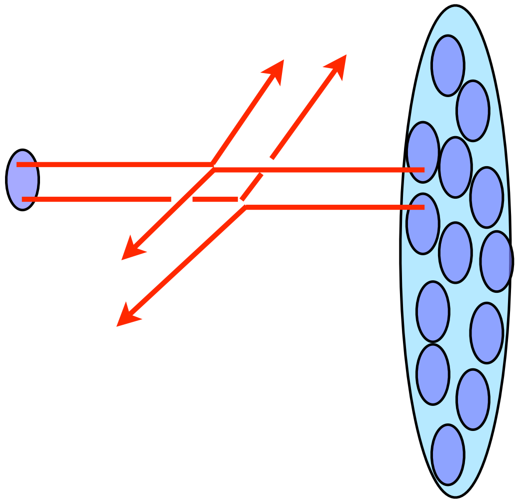
In pA collisions multiple parton interactions are enhanced by the presence of an additional contribution in the cross section, proportional to $A^{4/3}$

$$\sigma_D^A = \sigma_D^A\big|_1 + \sigma_D^A\big|_2$$



same A dependence of a single scattering process

$$\sigma_D^A\big|_1 = \frac{1}{2}\frac{\sigma_W^2}{\sigma_{eff}}\int d^2bT(b) \propto A$$

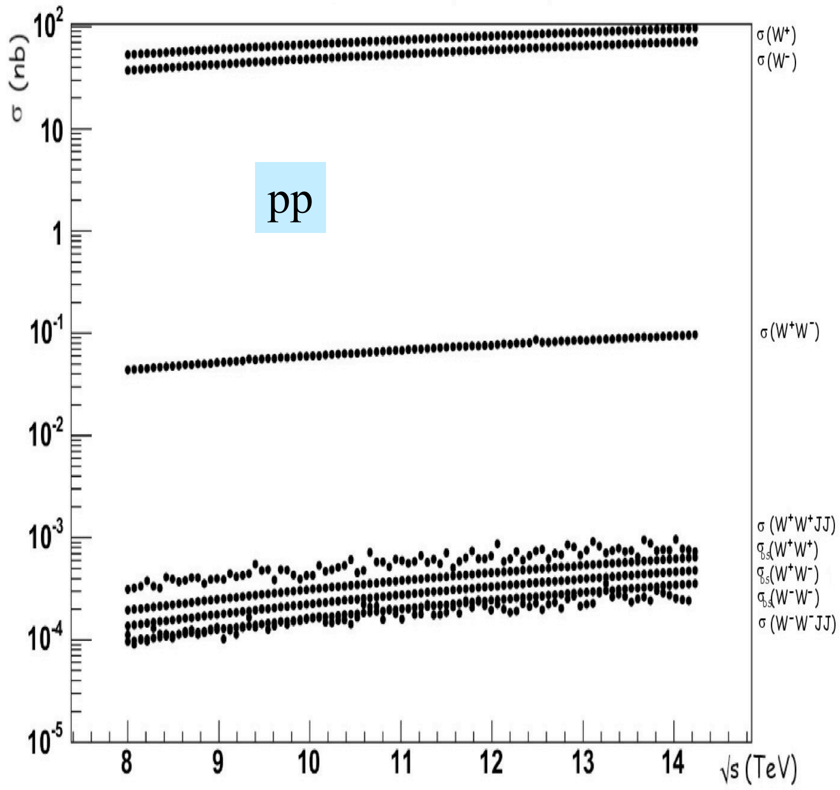


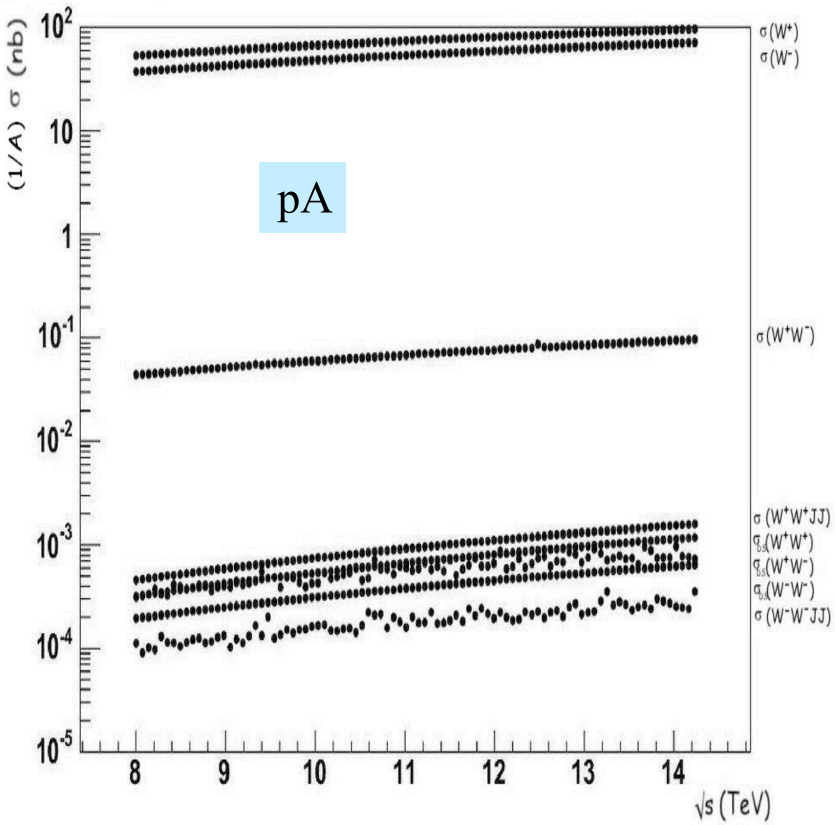
$$\sigma_D^A\big|_2 = \frac{1}{2}\sigma_W^2\int d^2bT^2(b) \propto A^{4/3}$$

notice the stronger A dependence

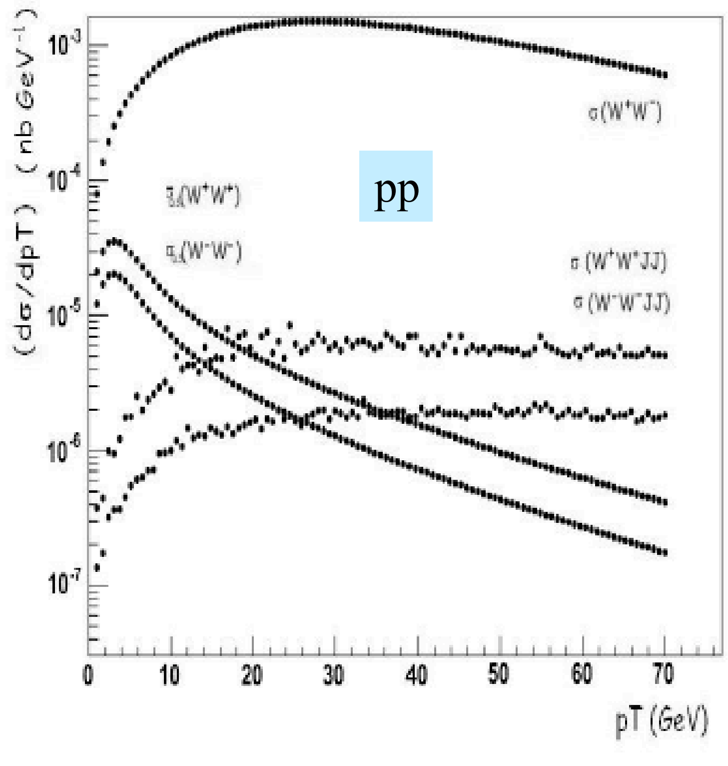
Notice that the presence of the term proportional to $A^{4/3}$ in the double scattering cross section gives rise to a **very strong antishadowing effect**

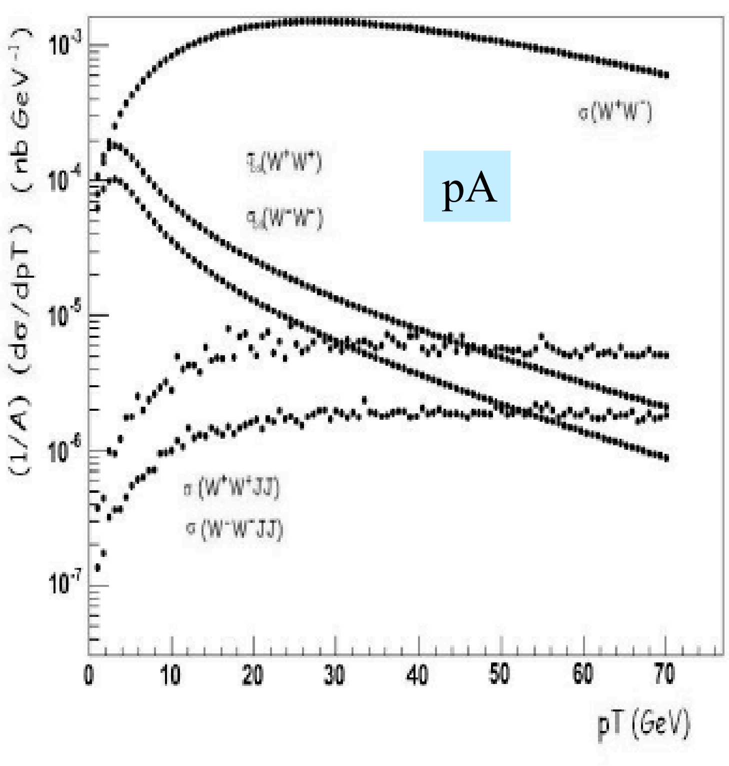
The effect is shown in the figures below, where the W production cross sections are compared in pp and in pA collisions, after dividing by the atomic mass number A





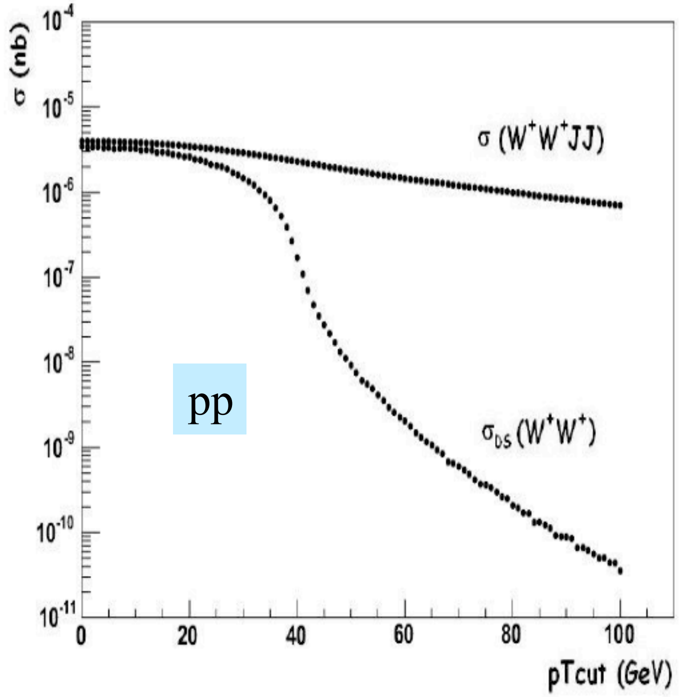
In the case of pA collisions the distribution in transverse momenta of the W^+W^+ bosons is dominated by the contribution of multiple parton interactions down to transverse momenta of 40 GeV/c

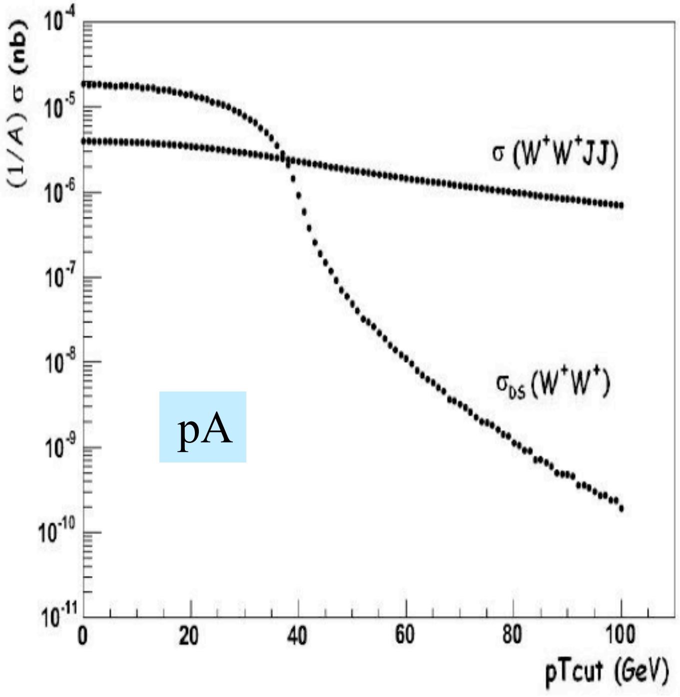




Cross sections of e^+e^+ production, through W^+W^+ production and decay (by single and double parton interactions), in pp (left figure) and pA collisions (right figure) as a function of the minimum transverse momentum p_t^{cut} of each positron.

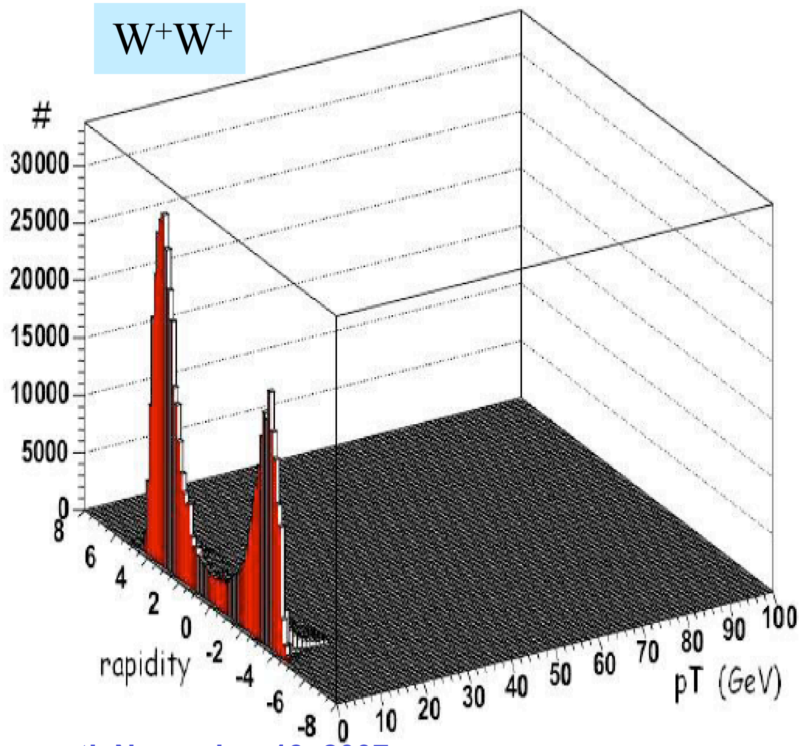
The **antishadowing** effect is apparent in the comparison of the two figures. In the case of pA collisions the cross section has been divided by the atomic mass number A.

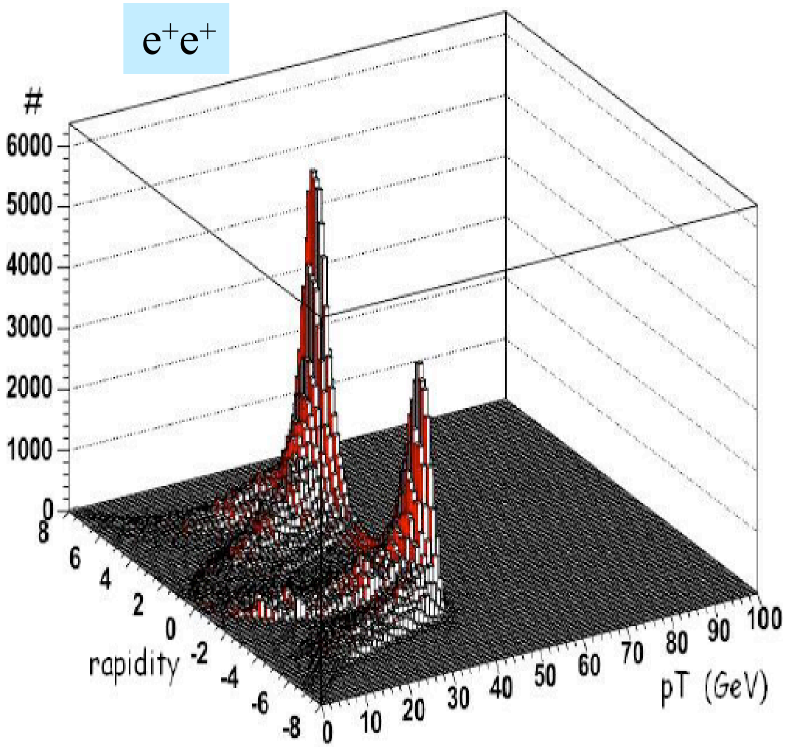




Distribution in phase space in the case of ***double parton collisions***

Distribution in transverse momentum and rapidity of the **W^+ bosons (left figure)** and of the **decay leptons (right figure)** in pA collisions.
The W bosons are produced with with small transverse momentum while the rapidity distribution of the W boson reminds the momentum of the originating up quark. The asymmetry between the two peaks is due to the different content of up quarks in the proton and in the pp, pn and nn nuclear pairs, which undergo the double interaction process. 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.

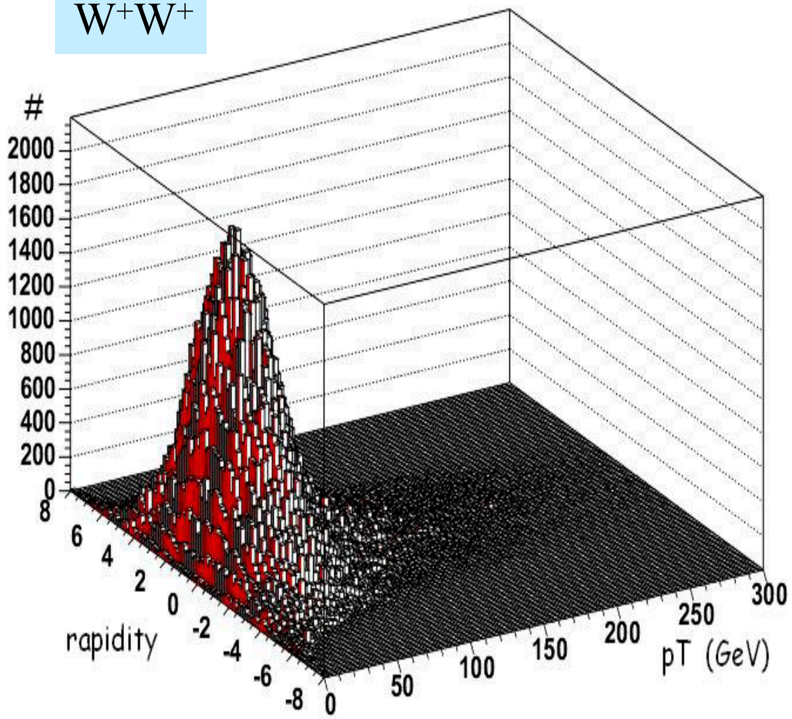




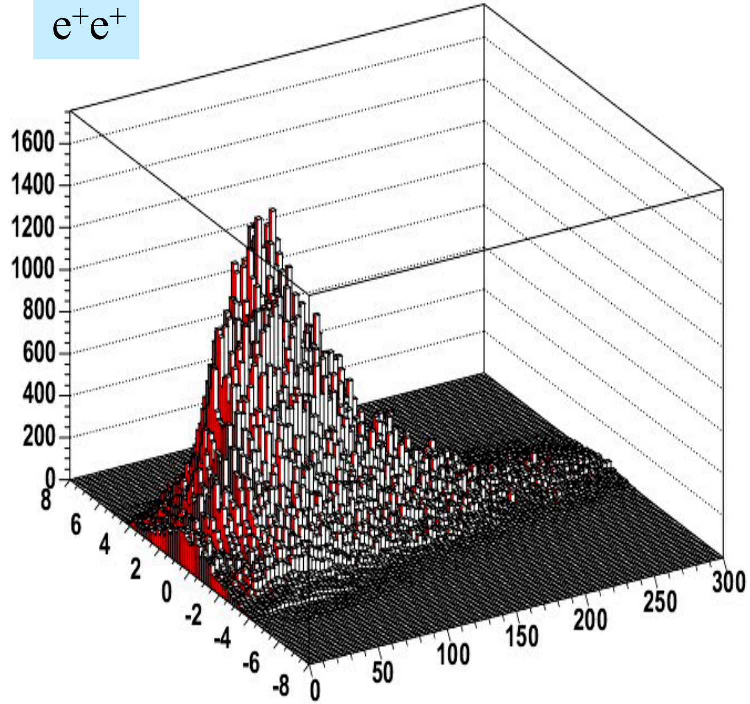
Distribution in phase space in the case of ***single parton collisions***

Distribution of **equal sign W bosons (left figure)** and of the **decay leptons (right figure)** generated by single parton collisions in pA interactions as a function of rapidity and transverse momentum.

W^+W^+

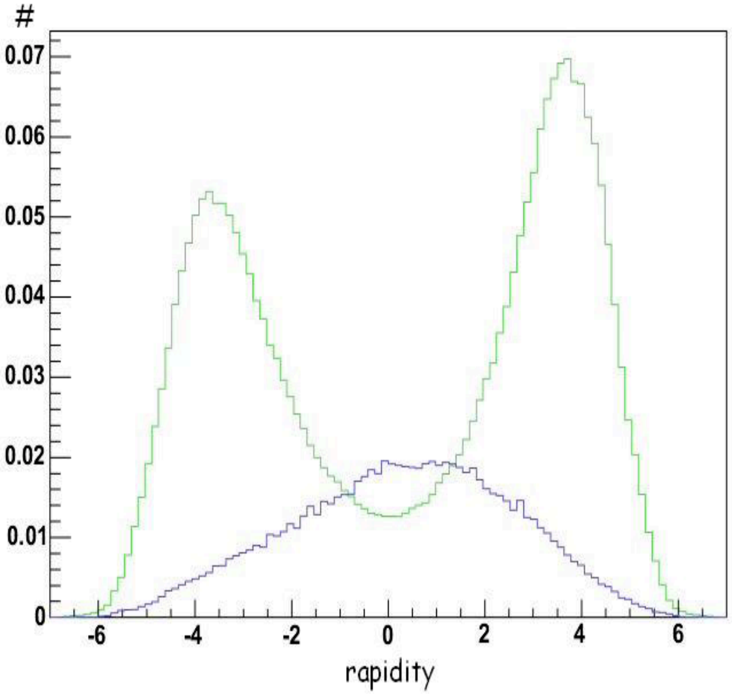


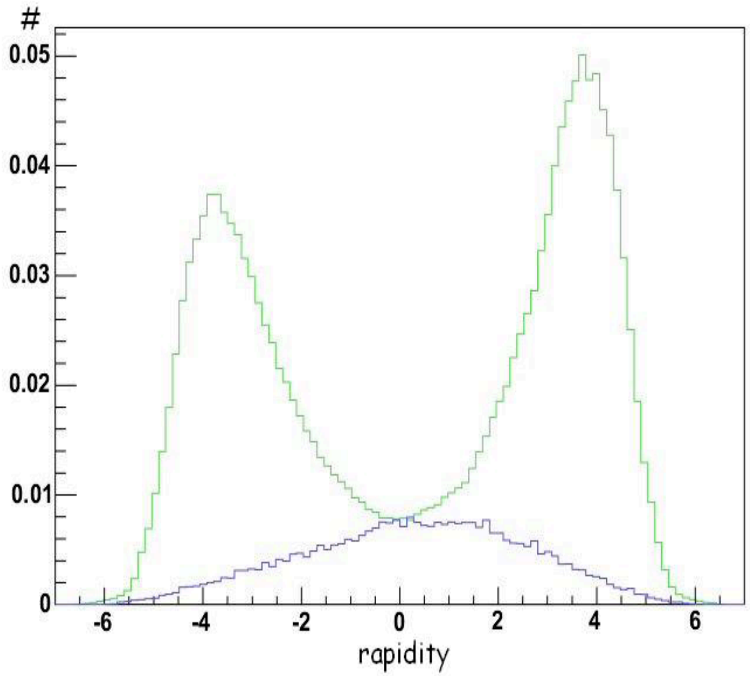
e^+e^+



Distribution in rapidity of charged leptons in the intervals 33 GeV/c < pt < 45 GeV/c (left panel) and 39 GeV/c < pt < 42 GeV/c (right panel). The **green histograms** refer to the contribution of **double parton interactions**, the **blue histograms** refer to the contribution of **single parton interaction**.

***The contribution from double scattering may hence be easily disentangled*.**





Antishadowing is a general feature of multiple parton interactions and the effect is obviously greatly enhanced in the case of AA collisions.

In **pp collisions** the production cross section of **equal sign W boson pairs** is more than **two orders of magnitude smaller,** as compared with the cross section of opposite sign W boson pairs production.

In AA collisions the contribution of multiple parton interactions to equal sign W boson pairs production is greatly enhanced.

As a result, in **AA collisions equal sign W boson pairs are produced with a rate similar to the rate of production of opposite sign W boson pairs**

Single and double parton scattering contributions to the W^+W^- production cross section compared with the double parton scattering cross section in a **central Pb-Pb collision at the LHC**

$$\left.\frac{d\sigma(W^+W^-)}{d^2b}\right|_{b=0} = 35\frac{\text{nb}}{\text{fm}^2}$$

← single scattering

$$\left.\frac{d\sigma(W^+W^-)}{d^2b}\right|_{b=0} = 87\frac{\text{nb}}{\text{fm}^2}$$

Double parton scattering contributions to the W^+W^+ production cross section in a **central Pb-Pb collision at the LHC**

$$\left.\frac{d\sigma(W^+W^+)}{d^2b}\right|_{b=0} = 62\frac{\text{nb}}{\text{fm}^2}$$

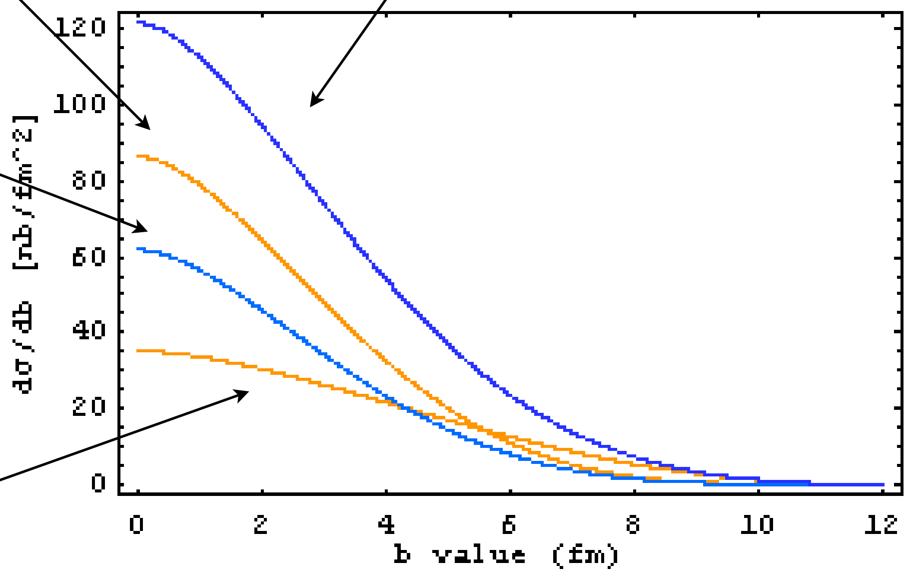
← double scattering

W^+W^- and W^+W^+ production cross sections as a function of the impact parameter b, in Pb-Pb collisions at the LHC

W^+W^- production cross section

W^+W^- production, double scattering contribution

W^+W^+ production cross section



W^+W^- production, single scattering contribution

Concluding summary

Equal sign W boson pairs are produced by a **higher order process** in the SM.

As a consequence, in **pp collisions** at the LHC, the cross section to produce **two equal sign W bosons** is more than **two orders of magnitude smaller,** as compared with the cross section to produce two opposite sign W boson.

In **pp collisions** at the LHC, the cross sections to produce **two equal sign W bosons**, through **single and double parton collisions**, are **similar in magnitude**

The two equal sign W bosons and the corresponding decay leptons are however **distributed very differently in phase space** by the two production mechanisms

Differently with respect to the more conventional single scattering large p_T processes, the **double parton scattering** processes are **anti-shadowed in collisions with nuclei**. Correspondingly the rate of two equal sign W bosons production is significantly increased in pA collisions.

The anti-shadowing effect is greatly enhanced in AA collisions. As a consequence **in AA collisions equal sign and opposite sign W boson pairs are produced with similar rates**.

Status of CMS Analyses on Multiple Parton Interactions Processes

1) Underlying Event in Jet and Drell-Yan Events at the LHC
2) Minimum Bias at the LHC (Multiplicities, P_T spectra)
3) Double Parton Scattering at the LHC
4) Tuning of Monte Carlo Models

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