Double Parton Interactions in pp and pA collisions

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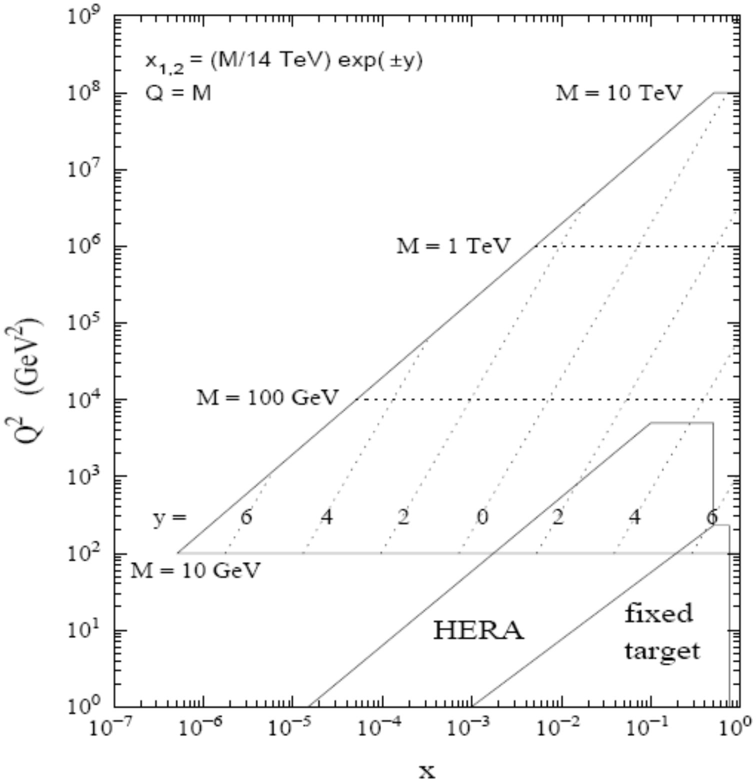
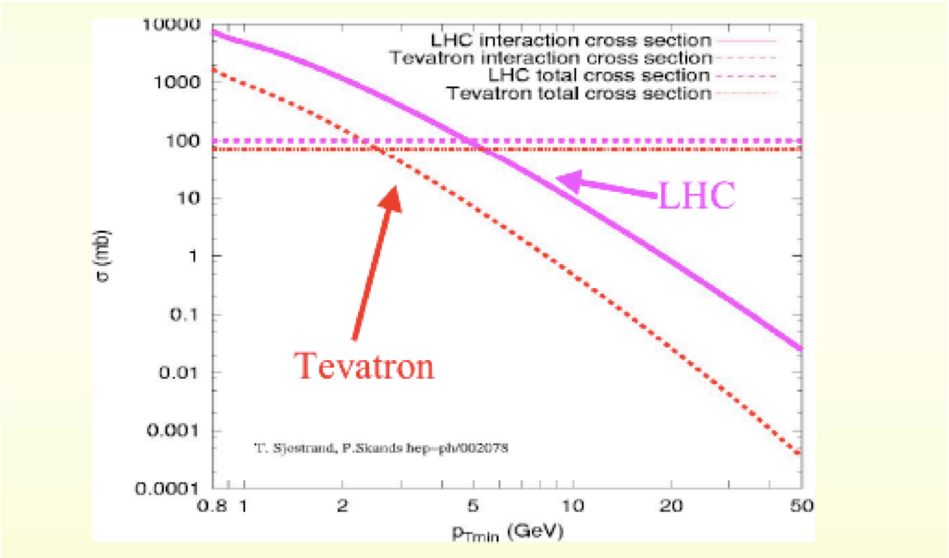
A unitarity problem at small x

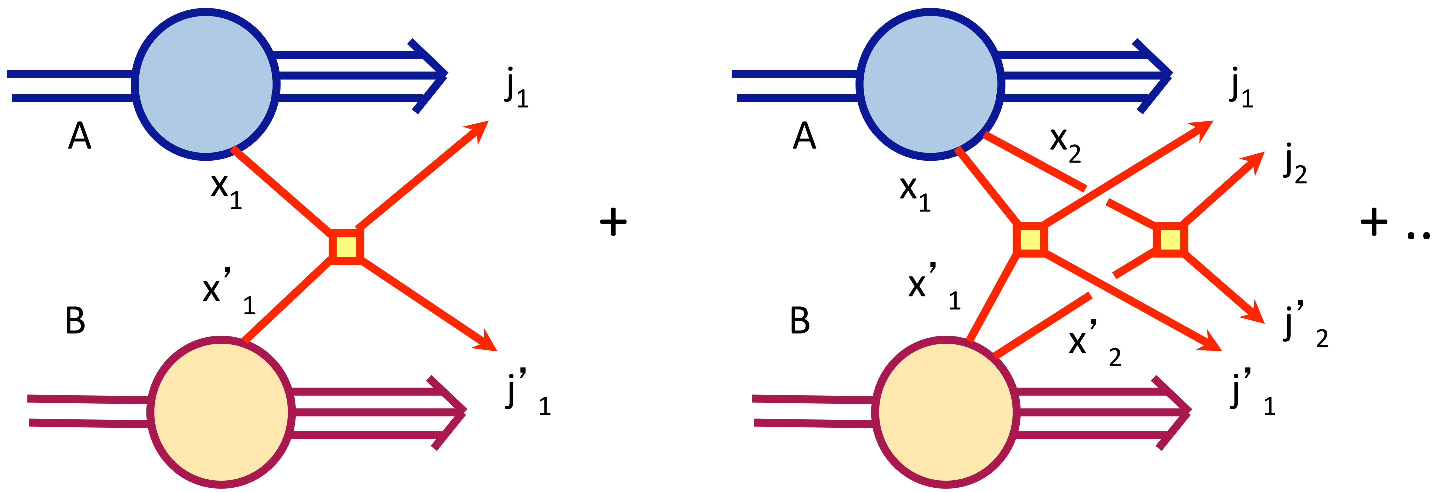
The rapid increase of the parton flux at small x causes a dramatic increase of all cross sections with large momentum transfer in pp collisions at the LHC.
In the case of production of jets, the inclusive cross section may exceed the value of the total inelastic cross section:





Multiple Parton Interactions

The unitarity problem is solved by introducinf the **Multiple Parton Interactions** (**MPI**)
For a given the final state, **MPI** are the processes which **maximize the incoming parton flux**



Unitarity is restored because the **inclusive cross section** counts the **multiplicity of interactions**. In this way, when the **average multiplicity** of interactions is **large,** the inclusive cross section is no more bounded by the value of the total inelastic cross section.

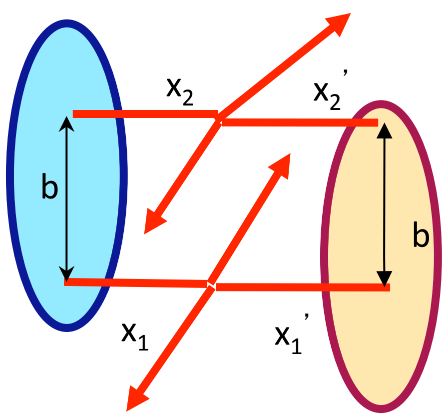
The simplest case of MPI is the **Double Parton Interaction** (**DPI**).

One should keep into account that:

a) Given the large momentum transfer, hard interactions are localized in a space region much smaller as compared to the hadron size.
b) One should look at the processes which maximize the incoming parton flux

The hard component of the interaction is thus disconnected and, in the case of the **DPI**, one obtains the geometrical picture here below.

Notice that the non-perturbative components are factorized into functions which depend on two fractional momenta and on the **relative transverse distance *b* between the two interaction points.**



The non-perturbative input to DPI, namely the double parton distribution functions, contain therefore ***information on the hadron structure*** which is ***not accessible in a single scattering large p_t processes***

When neglecting spin and color, the inclusive double parton-scattering cross-section, for two parton processes A and B in a pp collision, is given by

$$\boxed{\sigma^D_{(A,B)} = \frac{m}{2}\sum_{i,j,k,l}\int D_{ij}(x_1,x_2;b)\hat{\sigma}^A_{ik}(x_1,x_1')\hat{\sigma}^B_{jl}(x_2,x_2')D_{kl}(x_1',x_2';b)dx_1dx_1'dx_2dx_2'd^2b}$$

where m is a symmetry factor (m=1 when A=B and m=2 when A is different from B)

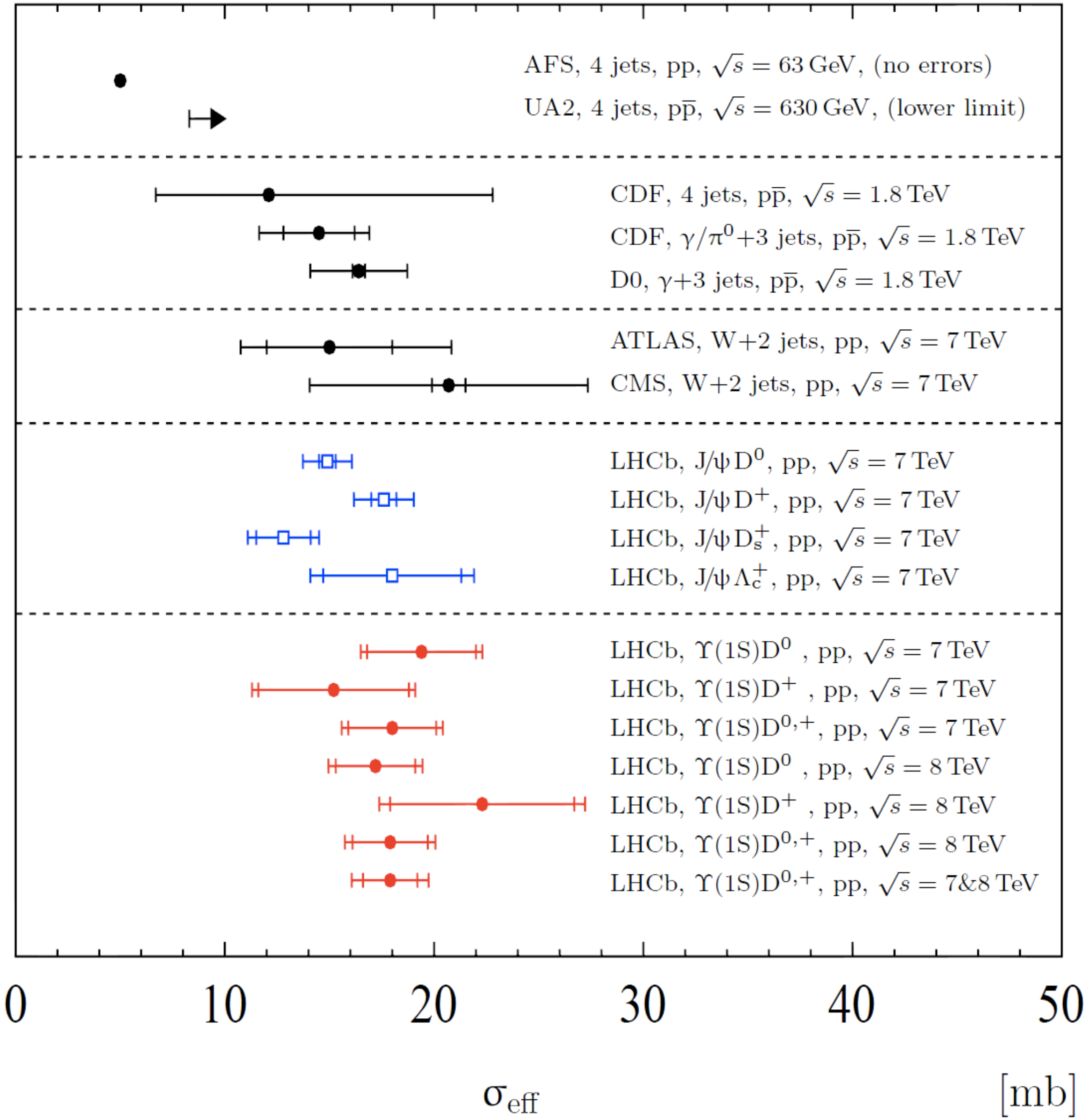
Notice that all dependence of σ^D on the final parton's transverse momenta is very well characterized and very strong, actually the square of the dependence of a single hard scattering cross section, which represents a rather non trivial experimental test of the MPI interaction dynamics.

One may thus introduce the "effective cross section" and express σ^D with the "pocket formula", utilized in the experimental analysis:

$$\boxed{\sigma^D_{(AB)} = \frac{m}{2}\frac{\sigma_A\sigma_B}{\sigma_{eff}}}$$

Of course the "pocket formula" makes sense only if, when comparing with experiment, σ_{eff} turns out to be weakly dependent on kinematics

Comparing the "pocket formula" with data



$$\sigma^D_{(AB)} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

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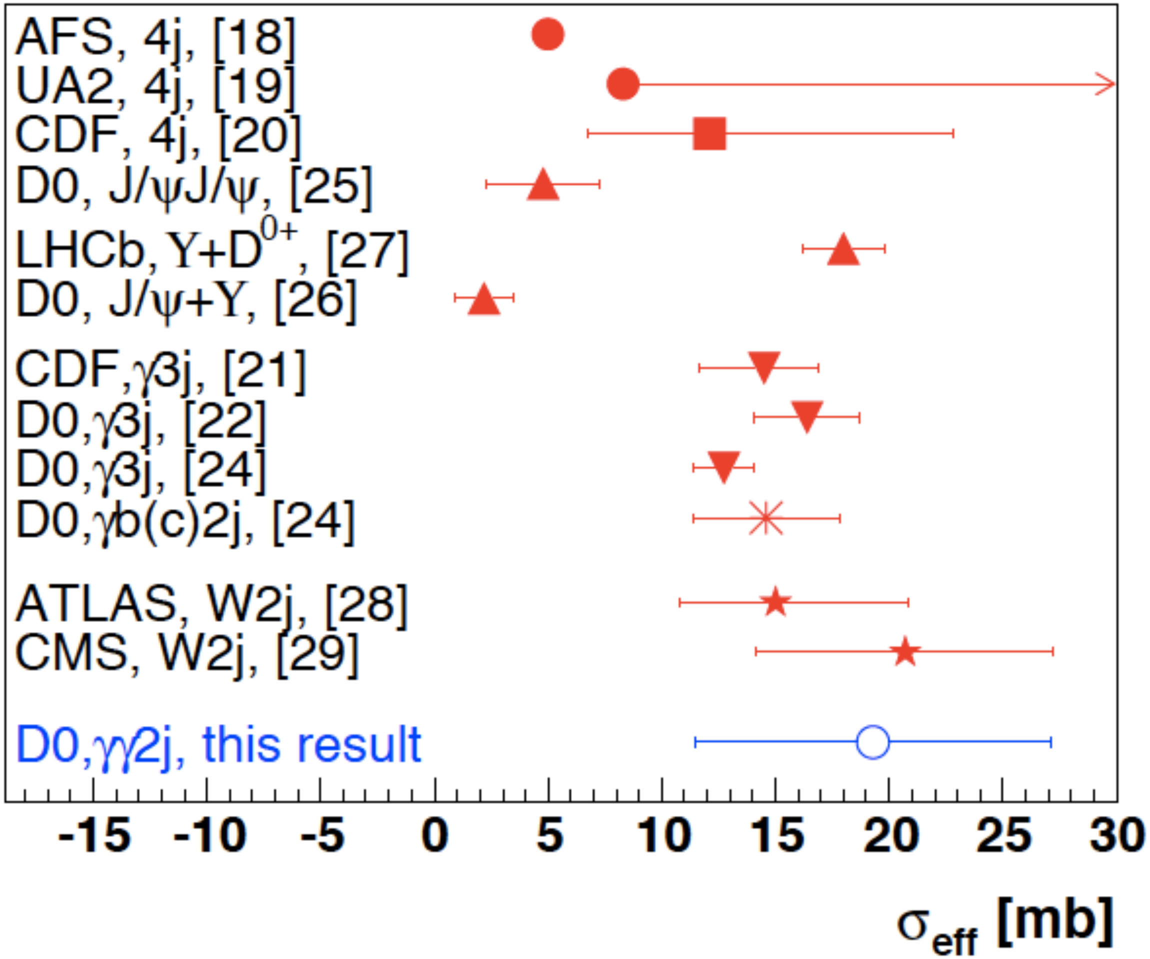

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[22] V. M. Abazov *et al.* (D0 Collaboration), *Double parton interactions in $\gamma + 3$ jet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, Phys. Rev. D **81**, 052012 (2010).

[23] V. M. Abazov et al. (D0 Collaboration), *Azimuthal decorrelations and multiple parton interactions in $\gamma + 2$ jet and $\gamma + 3$ jet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, Phys. Rev. D **83**, 052008 (2011).

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[26] V. M. Abazov *et al.* (D0 Collaboration), *Evidence for simultaneous production of J/ψ and Υ mesons*, arXiv:1511.02428.

[27] R. Aaij *et al.* (LHCb Collaboration), *Production of associated Υ and open charm hadrons in pp collisions at $\sqrt{s} = 7$ and 8 TeV via double parton scattering*, arXiv:1510:05949.

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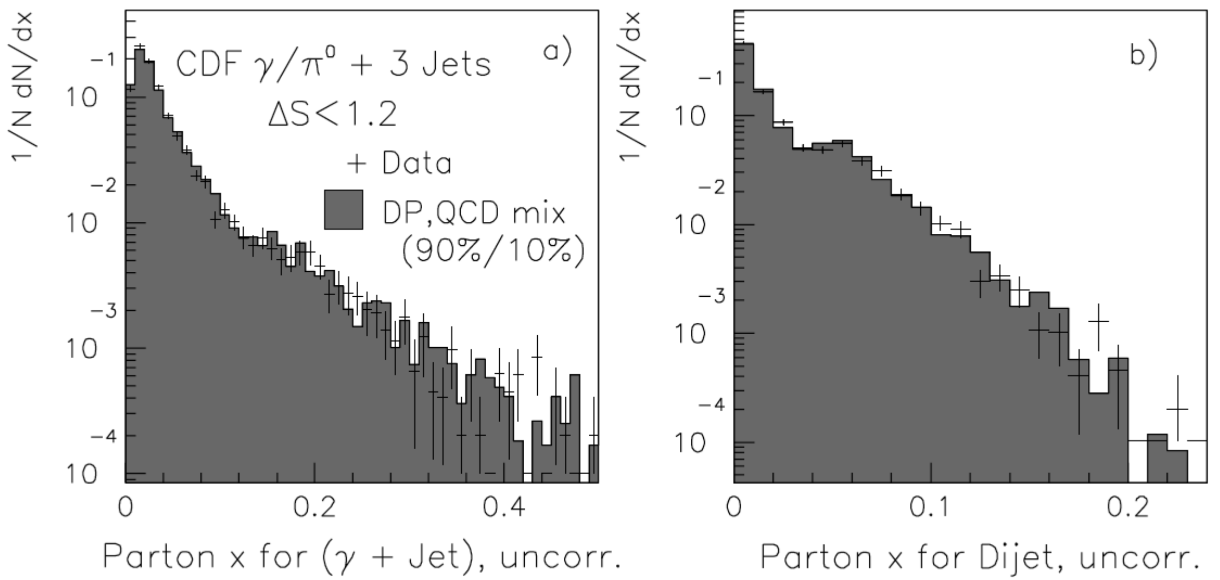
Dependence of σ_{eff} on x

F. Abe et al. [CDF Collaboration], Phys. Rev. D 56, 3811(1997).



Distributions of x are plotted in Figs. 20(a) and 20(b), along with a prediction obtained by applying the DS < 1.2 selection to the admixture 90% MIXDP+10% PYTHIA.
No systematic deviation of the DP rate vs x, and thus **no x dependence to σ_{eff}**, is apparent over the x range accessible to this analysis (0.01 – 0.40 for the photon+jet scattering, 0.002–0.20 for the dijet scattering).

Dependence of σ_{eff} on Q^2

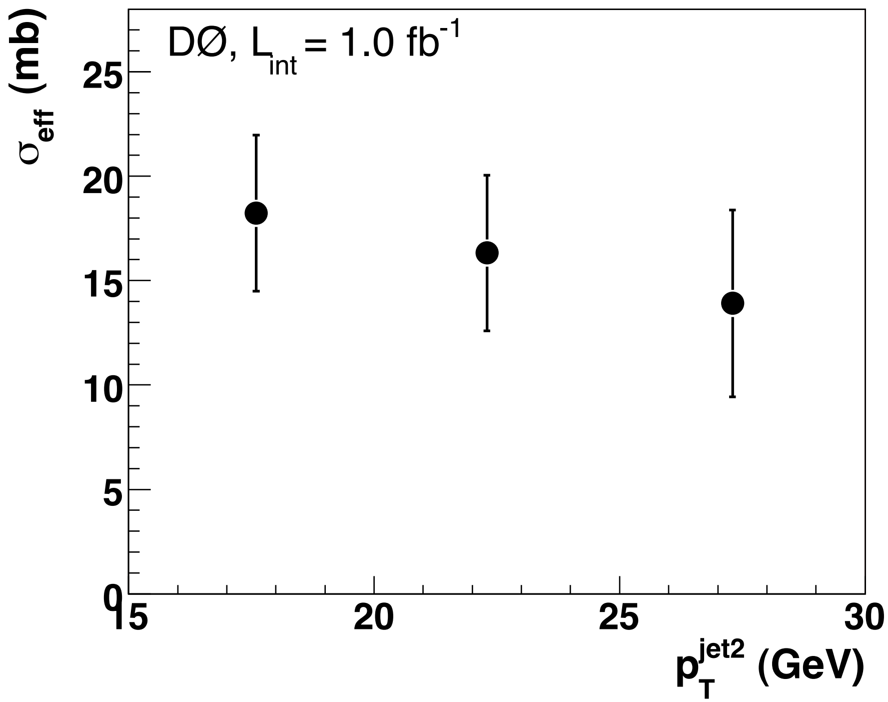


FIG. 11: Effective cross section $\sigma_{\rm eff}$ (mb) measured in the three $p_T^{\rm jet2}$ intervals.

D0 Collaboration, Phys.Rev. D81 (2010) 052012

Some comments

When σ_A is small the ratio σ_A/σ_{inel} is the probability of having the process A in a inelastic collision. By writing (for A different from B) $\sigma^D_{(AB)}=\sigma^A\,\sigma^B/\sigma_{eff}$, the effective cross section thus plays the role of the inelastic cross section in a biased case.

Within still large experimental errors, the observed values of the effective cross section are approximately constant (~ 15 mb) and do not seem to depend on

- the C.M. energy (Fermilab, LHC)
- the reaction channel (4j, γ3j, $\gamma\gamma$2j, γb(c)2j, Wjj)
- the values of x and Q^2

There is on the contrary a clear indication that the effective cross section is sizably smaller (~ 2-4 mb) in the case of J/Ψ J/Ψ and J/Ψ Υ production

Notice that σ_{eff} is sizably smaller as compared with σ_{inel}
=> evidence of strong partonic correlations in the hadron structure

σ_{eff} and partonic correlations

One may write the double parton distribution functions as

$$\Gamma(x_1, x_2;\ b) = G(x_1, x_2) f_{x_1 x_2}(b), \qquad G(x_1, x_2) = K_{x_1 x_2} G(x_1) G(x_2)$$

where f is normalized to one and the transverse scales, characterizing f, may still depend on fractional momenta.

$$\int f_{x_1 x_2}(b) d^2 b = 1 \qquad G(x) = \langle n \rangle_x, \qquad G(x_1, x_2) = \langle n(n-1) \rangle_{x_1, x_2}$$

$$K_{x_1 x_2} = \frac{\langle n(n-1) \rangle_{x_1, x_2}}{\langle n \rangle_{x_1} \langle n \rangle_{x_2}}$$

In the simplest case one would have $K_{xx'} = 1$ which, after integrating on b, would be the case of a Poissonian multi-parton distribution in multiplicity.

In *pp* one thus has

correlations in multiplicity

$$\sigma^{pp\ (A,B)}_{double}(x_1,x_1',x_2,x_2') = \frac{m}{2}K_{x_1x_2}K_{x_1'x_2'}G(x_1)\hat\sigma_A(x_1,x_1')G(x_1') \times G(x_2)\hat\sigma_B(x_2,x_2')G(x_2')\int f_{x_1x_2}(b)f_{x_1'x_2'}(b)db$$

$$= \frac{m}{2}\frac{K_{x_1x_2}K_{x_1'x_2'}}{\pi\Lambda^2(x_1,x_1',x_2,x_2')}\sigma_A(x_1,x_1')\sigma_B(x_2,x_2')$$

(effective cross section)$^{-1}$

where $$\int f_{x_1x_2}(b)f_{x_1'x_2'}(b)db = \frac{1}{\pi\Lambda^2(x_1,x_1',x_2,x_2')}$$

typical transverse interaction area

$$\sigma^{pp\ (A,B)}_{double} = \frac{m}{2}\frac{\sigma_A\sigma_B}{\sigma_{eff}}$$

while all new information on the hadron structure is summarized in a single figure: the value of σ_{eff}

Limiting case

$$\Gamma(x_1,x_2;\ b) = G(x_1,x_2)f_{x_1x_2}(b), \qquad G(x_1,x_2) = K_{x_1x_2}G(x_1)G(x_2) \qquad K_{x_1x_2} = \frac{\langle n(n-1)\rangle_{x_1,x_2}}{\langle n\rangle_{x_1}\langle n\rangle_{x_2}}$$

a) partons are not correlated in multiplicity => one has

$$\boxed{K_{x_1x_2} = 1}$$

b) partons are not correlated in the transverse coordinates => one may write:

$$\Gamma(x;b) = G(x)f_x(b), \qquad \int f_x(b)d^2b = 1 \qquad \boxed{f_{x_1,x_2}(b) = \int f_{x_1}(b')f_{x_2}(b-b')d^2b'}$$

Two gluon form factor

In this way one however obtains $\sigma_{\text{eff}} = \pi\Lambda^2 = 32$ **mb**, which is about **a factor 2 too large** as compared with available experimental evidence

⇨ Either ***K*** **is NOT** equal to **1** or $\pi\Lambda^2$ **is NOT** equal to **32 mb** or both

$$\sigma_{eff}(x_1, x'_1, x_2, x'_2) = \frac{\pi\Lambda^2(x_1, x'_1, x_2, x'_2)}{K_{x_1x_2}K_{x'_1x'_2}}$$

The experimental indication is that the effective cross section depends only weakly on fractional momenta.

⇒ **weak dependence of Λ and *K* on fractional momenta**

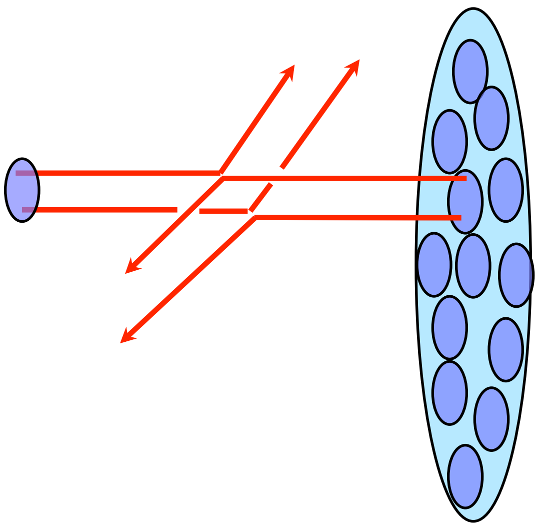
Since all new information on the hadron structure is summarized by a single quantity,

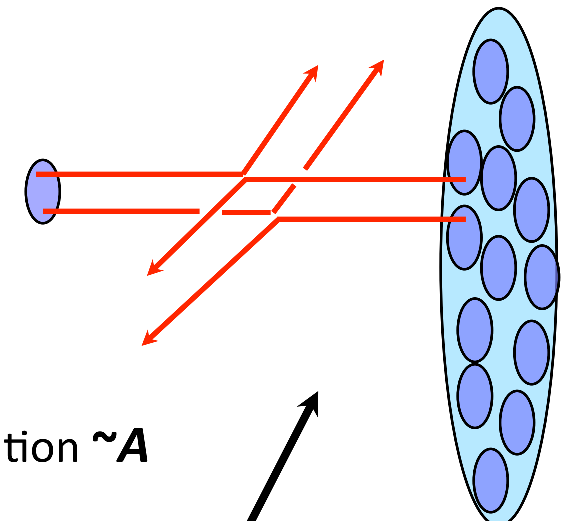
⇒ **the effective cross section does not provide enough information to discriminate between Λ and *K*.**

To obtain additional information on multi-parton correlations one may study MPI in *pA* collisions.
In the case of a double parton interaction, in a collision of a proton with a nucleus, the effects of longitudinal and transverse correlations are in fact different when a single nucleon or both target nucleons participate in the hard process.

DPI in pA collisions

In the case of DPS in *p-A* collisions one may have a double parton scattering against a single or against two different target nucleons:





Impulse Approximation **~*A***

Anti-shadowing correction **~ *A*$^{4/3}$**

$$\boxed{\sigma_D^A = \sigma_D^A\big|_1 + \sigma_D^A\big|_2}$$

WJJ production in p-A collisions

When <u>neglecting the effects of the interference terms</u>, which can produce a 10% correction, one obtains a simple expression for the DPI cross section:

single - scattering

double - scattering contribution

$$\begin{cases} \sigma^{pA}(WJJ) = \sigma_S^{pA}(WJJ) + \sigma_D^{pA}(WJJ) \\ \sigma_D^{pA}(WJJ) = \sigma_D^{pA}(WJJ)\big|_1 + \sigma_D^{pA}(WJJ)\big|_2 \end{cases}$$

labels 1 and 2 in refer to the number of active target nucleons

$$\begin{cases} \sigma_D^{pA}(WJJ)\big|_1 = \dfrac{1}{\sigma_{eff}}\left[Z\sigma_S^{pp}(W)\sigma_S^{pp}(JJ) + (A-Z)\sigma_S^{pn}(W)\sigma_S^{pn}(JJ)\right] \\ \sigma_D^{pA}(WJJ)\big|_2 = K\left[\dfrac{Z}{A}\sigma_S^{pp}(W) + \dfrac{A-Z}{A}\sigma_S^{pn}(W)\right]\sigma_S^{pp}(JJ)\displaystyle\int T(b)^2 d^2b \end{cases}$$

anti-shadowing contribution

nuclear thickness function
=> the contribution grows as $A^{4/3}$

linear with A, same as in *pp*

the hadronic transverse size gives the correct dimensionality to $\sigma_D|_1$ through σ_{eff}

$$\sigma_D^{pA}(WJJ)\big|_1 = \frac{1}{\sigma_{eff}}\left[Z\sigma_S^{pp}(W)\sigma_S^{pp}(JJ) + (A-Z)\sigma_S^{pn}(W)\sigma_S^{pn}(JJ)\right]$$

$$\sigma_D^{pA}(WJJ)\big|_2 = K\left[\frac{Z}{A}\sigma_S^{pp}(W) + \frac{A-Z}{A}\sigma_S^{pn}(W)\right]\sigma_S^{pp}(JJ)\int T(b)^2 d^2b$$

related to the multiplicity of pairs of partons in the projectile, for a Poissonian *K*=1

the correct dimensionality to $\sigma_D|_2$ is provided by the nuclear radius through the nuclear thickness function

grows as $A^{4/3}$

The two contributions probe different features of the double interaction. In particular, in the case of a heavy nucleus, the anti-shadowing term is proportional to the multiplicity of pairs of partons of the projectile.

Expectations

a) K ^{2} **= 1** and $\pi\Lambda^2 = \sigma_{\text{eff}}$ (No correlation in multiplicity)

$$\frac{\sigma_D^{pA}|_2}{\sigma_D^{pA}|_1} \approx 2$$

[**200% anti-shadowing correction !**]

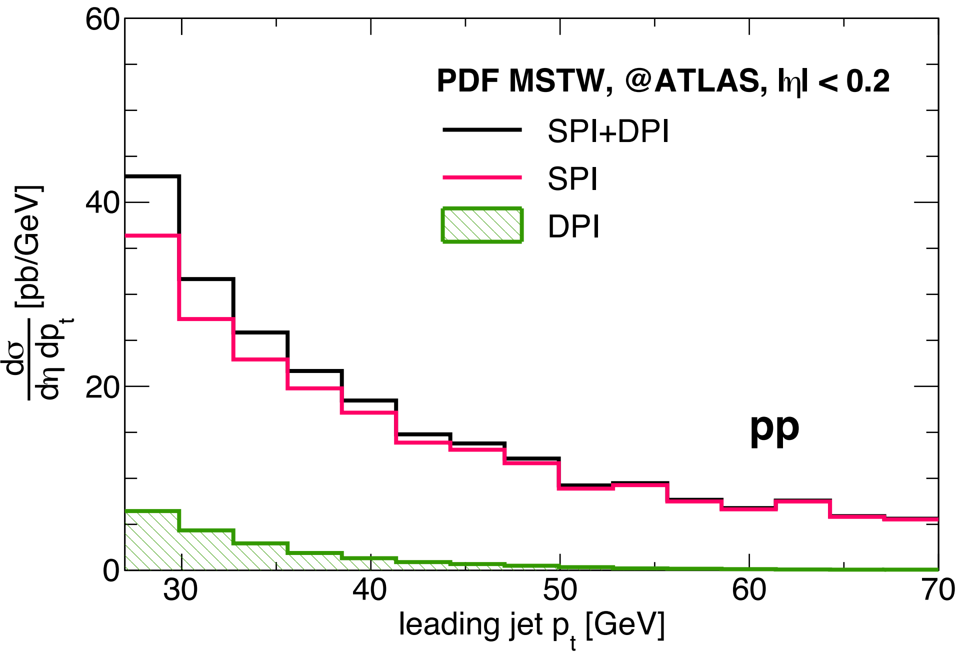
b) K ^{2} **= 2** and $\pi\Lambda^2 = K^2\sigma_{\text{eff}}$ (No correlations in the transverse coordinates)

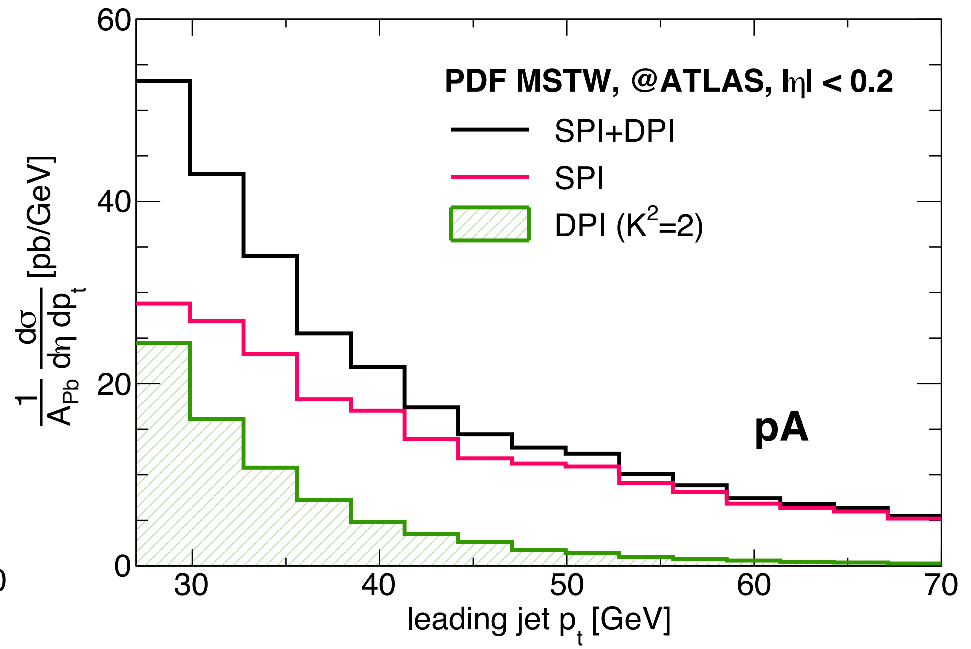
$$\frac{\sigma_D^{pA}|_2}{\sigma_D^{pA}|_1} \approx 3$$

[**300% anti-shadowing correction !**]

A more detailed information from the transverse spectra:

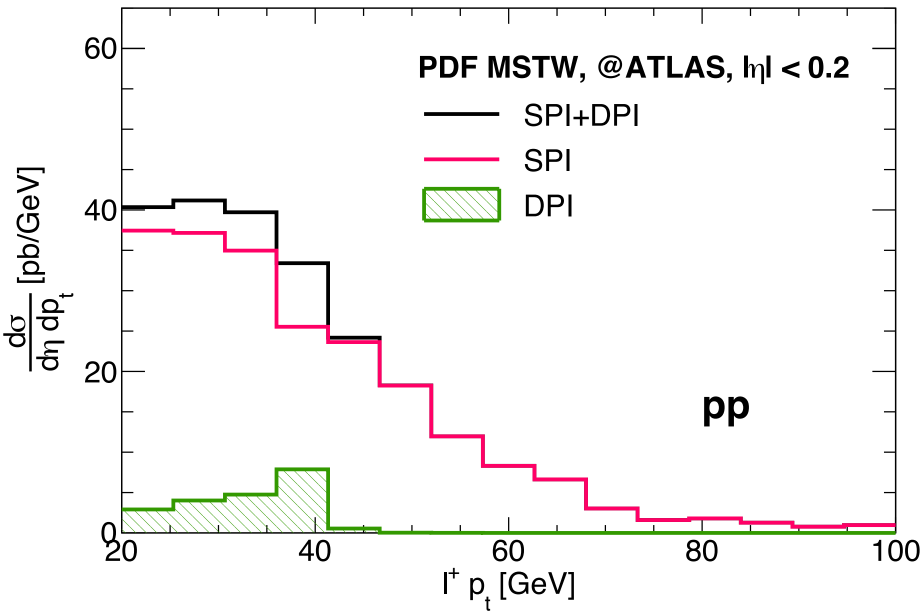
p_t spectrum of the leading jet in *p-p* and in *p-Pb*

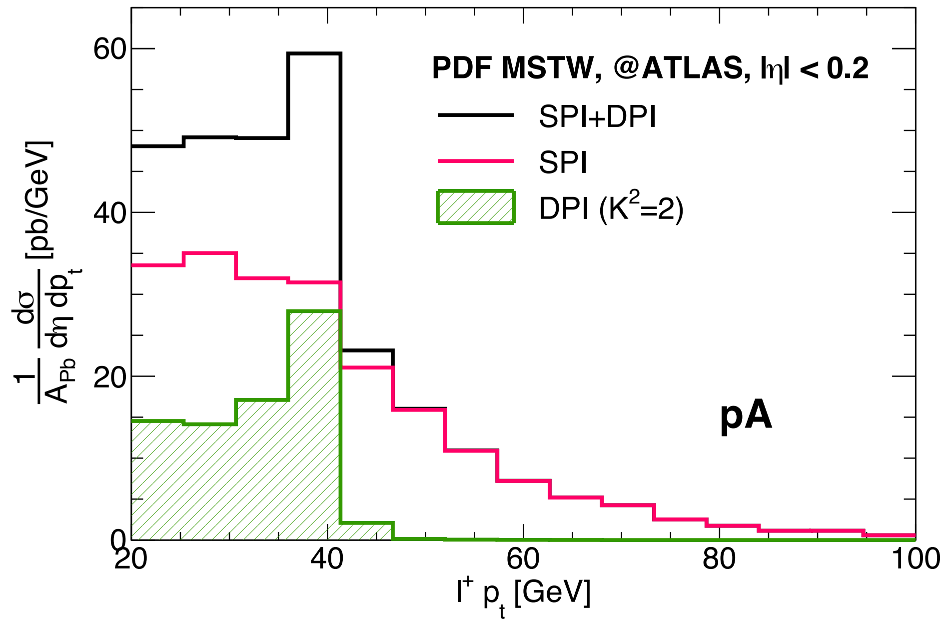




The shape in p_t of the leading jet is very different in *p-p* and in *p-Pb* for $p_t < 40$ GeV

p_t spectrum of the W decay-lepton in *p-p* and in *p-Pb*





While the spectrum does not change much in *p-p* collisions, the effect in *p-Pb* collisions is dramatic and one expects an increase of about 90% at p_t ~ 40 GeV

Concluding summary

MPI are a feature of growing importance in high energy hadronic collisions
DPI have been observed and studied in a large variety of reactions

The rate of DPI is characterized by σ_{eff} which, within the still rather large experimental errors and with few noticeable exceptions, seems to be independent on the different reaction channels and on kinematics.

DPI are directly related to parton correlations in the hadron structure

Important information on parton correlations can be obtained by the joint study of DPI in pp and pA collisions

Thank you

MPI are implemented in all Monte Carlo codes, which simulate high energy hadronic collisions.

In Monte Carlo codes, one assumes that in hadronic collisions MPI are independent one from another, in such a way that the distribution in the number of partonic interactions is Poissonian, with average number depending on the impact parameter of the collision:

probability of having *N* partonic interactions, in a hadronic collision with impact parameter *b*

$$P_N(b) = \frac{\langle N(b)\rangle^N}{N!} e^{-\langle N(b)\rangle}$$

contribution of all MPI to the total inelastic cross section

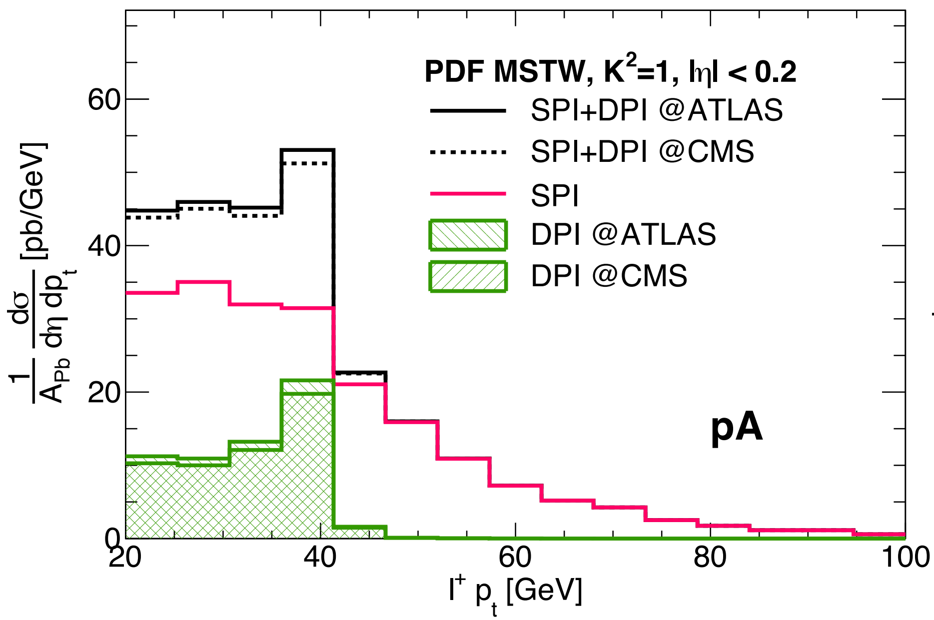
$$\sigma_{hard} = \sum_{N=1}^{\infty} \int d^2b \frac{\langle N(b)\rangle^N}{N!} e^{-\langle N(b)\rangle} = \int d^2b \Big[1 - e^{-\langle N(b)\rangle}\Big]$$

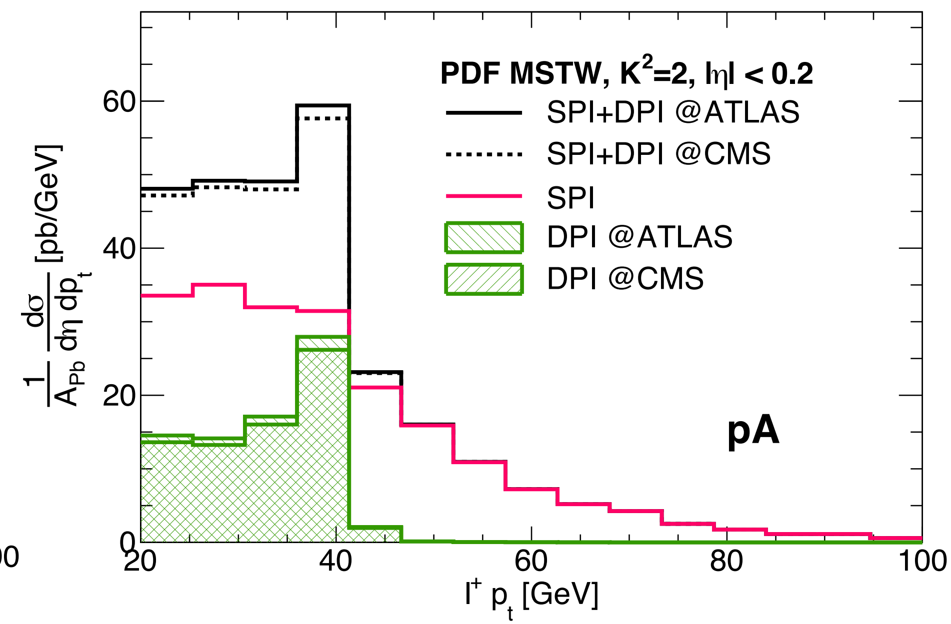
inclusive cross section: here partonic interactions contribute with their multiplicity

$$\sigma_{incl} = \sum_{N=1}^{\infty} \int d^2b\, N \frac{\langle N(b)\rangle^N}{N!} e^{-\langle N(b)\rangle}$$

$$= \int d^2b \langle N(b)\rangle \equiv \int G_A(x)\hat{\sigma}(xx')G_B(x')dxdx'$$

p_t spectrum of the W decay-lepton in *p-Pb*: dependence on *K* and on the measured value of σ_{eff} in *p-p* collisions





The spectra in *p-Pb* collisions do not change much, when σ_{eff} increases from 15 to 20 mb in *p-p* collisions. The effect of increasing K^2 from 1 to 2 is on the contrary sizable and, in *p-Pb* collisions, one expects an increase from 60 to 90 % of the observed cross section at p_t ~ 40 GeV

The rate of DPI is particularly large in the case of multiple production of heavy quark pairs

By estimating the DPS cross section with the “pocket formula” one obtains that, at the LHC, the inclusive production of two $b\bar{b}$ pairs is dominated by DPS.

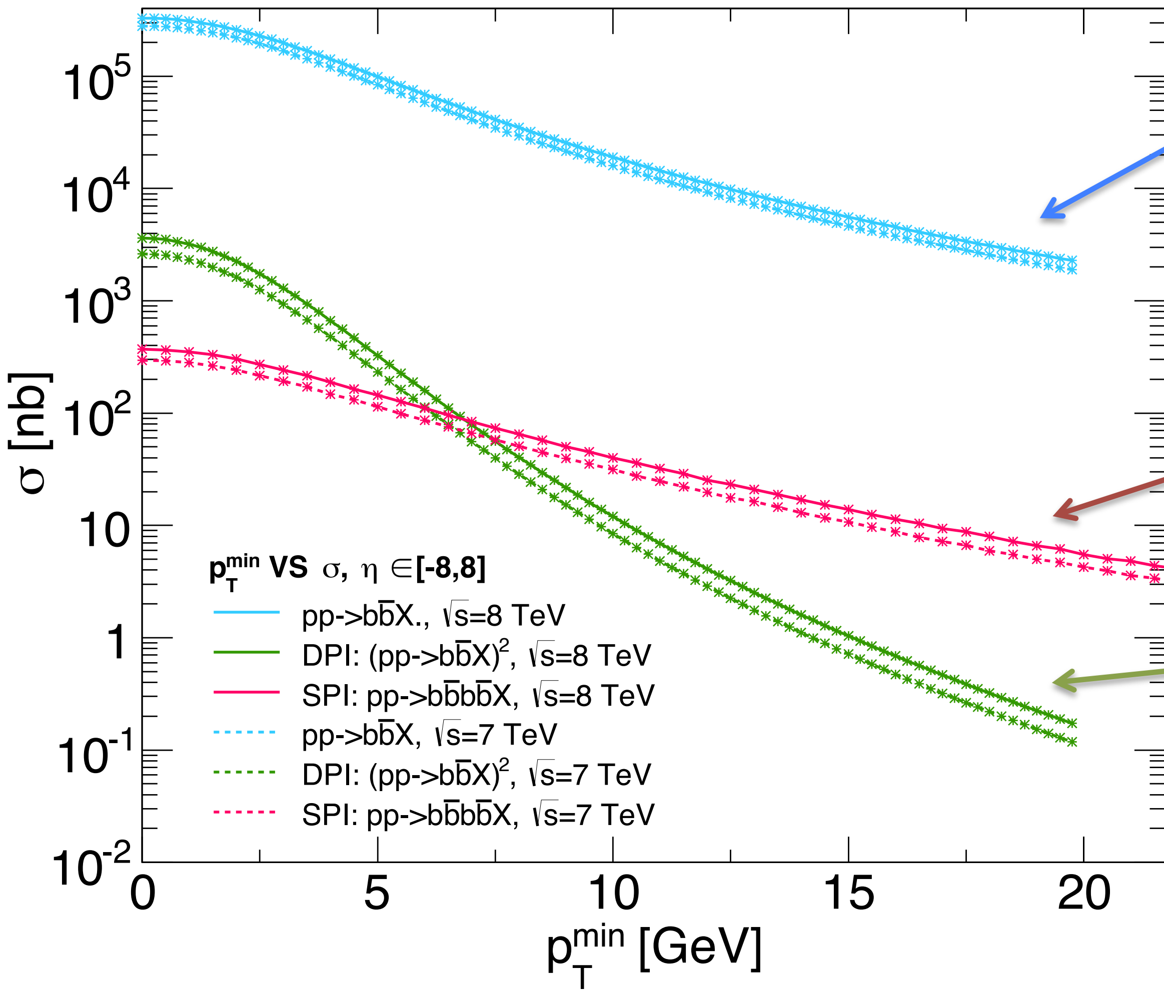
In *pp* collisions at 8 TeV c.m. energy, **the DPS contribution** to the integrated inclusive cross section is in fact expected to be **one order of magnitude larger** as compared to **the SPS contribution**.

The amount of $b\bar{b}b\bar{b}$ pairs produced in a *pp* collisions will thus exceed by a factor 10 the rate expected according with the leading QCD production mechanism.

Notice that **b quarks are produced strongly and decay weakly**. As a consequence **the integrated amount of heavy quarks**, produced in a hadronic collision, **does not depend on final state interactions**.

The integrated inclusive cross section to produce two $b\bar{b}$ pairs can thus provide a direct measurement of the DPS contribution to the cross section.

$b\bar{b}$ and $b\bar{b}b\bar{b}$ production in pp collisions at the LHC: Integrated cross sections

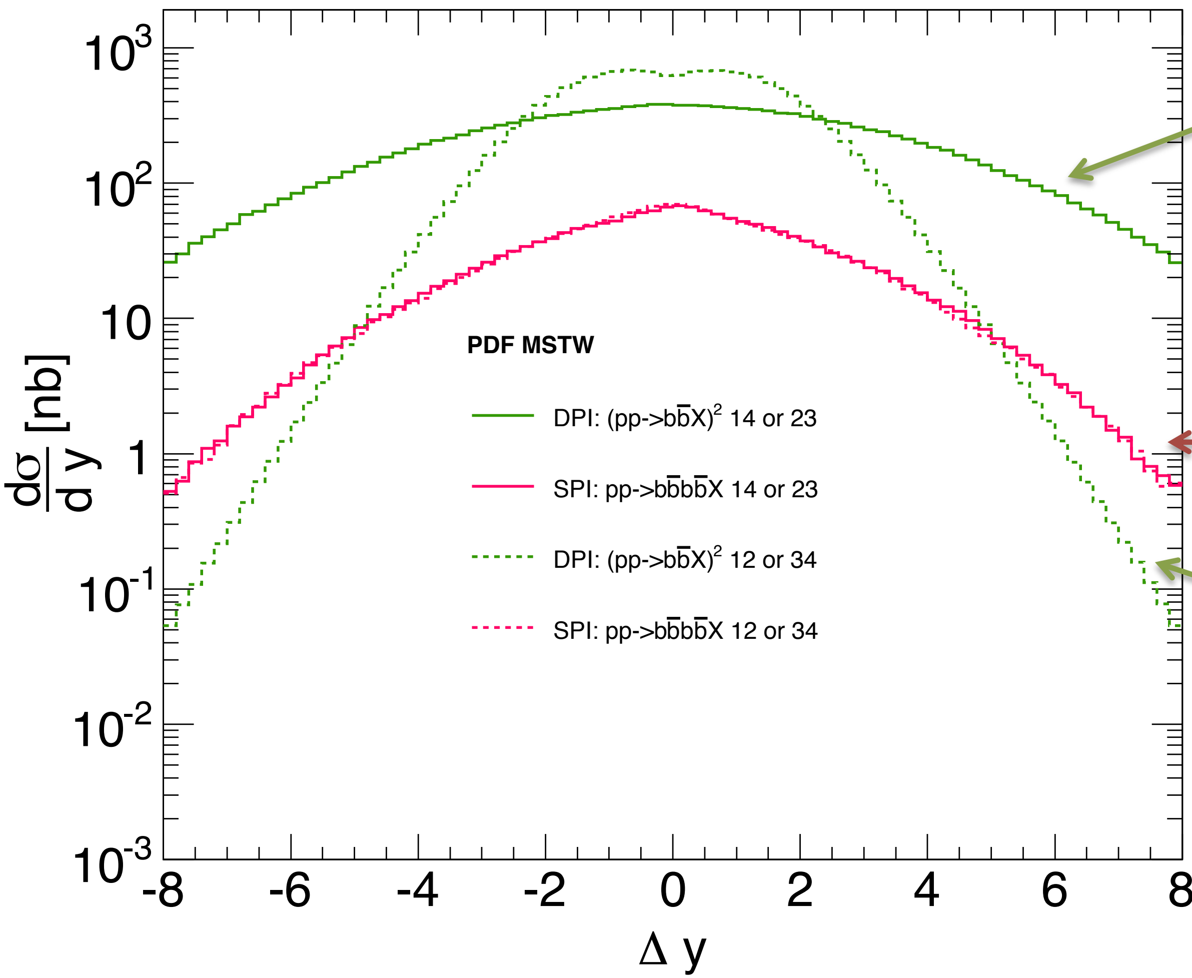


$b\bar{b}$ production: Integrated cross section, with $p_T > p_T^{min}$

$b\bar{b}b\bar{b}$ production by <u>single parton scattering</u>: Integrated cross section, with $p_T > p_T^{min}$

$b\bar{b}b\bar{b}$ production by <u>double parton scattering</u>: Integrated cross section, with $p_T > p_T^{min}$

$b\bar{b}b\bar{b}$ production in pp collisions at the LHC: Correlations in rapidity



Double parton scattering: correlation between two b-quarks originated in two different elementary interactions

Single parton scattering

Double parton scattering: correlation between two b-quarks originated in the same elementary interaction