DPI in pp and pA collisions

Daniele Treleani

University of Trieste & INFN

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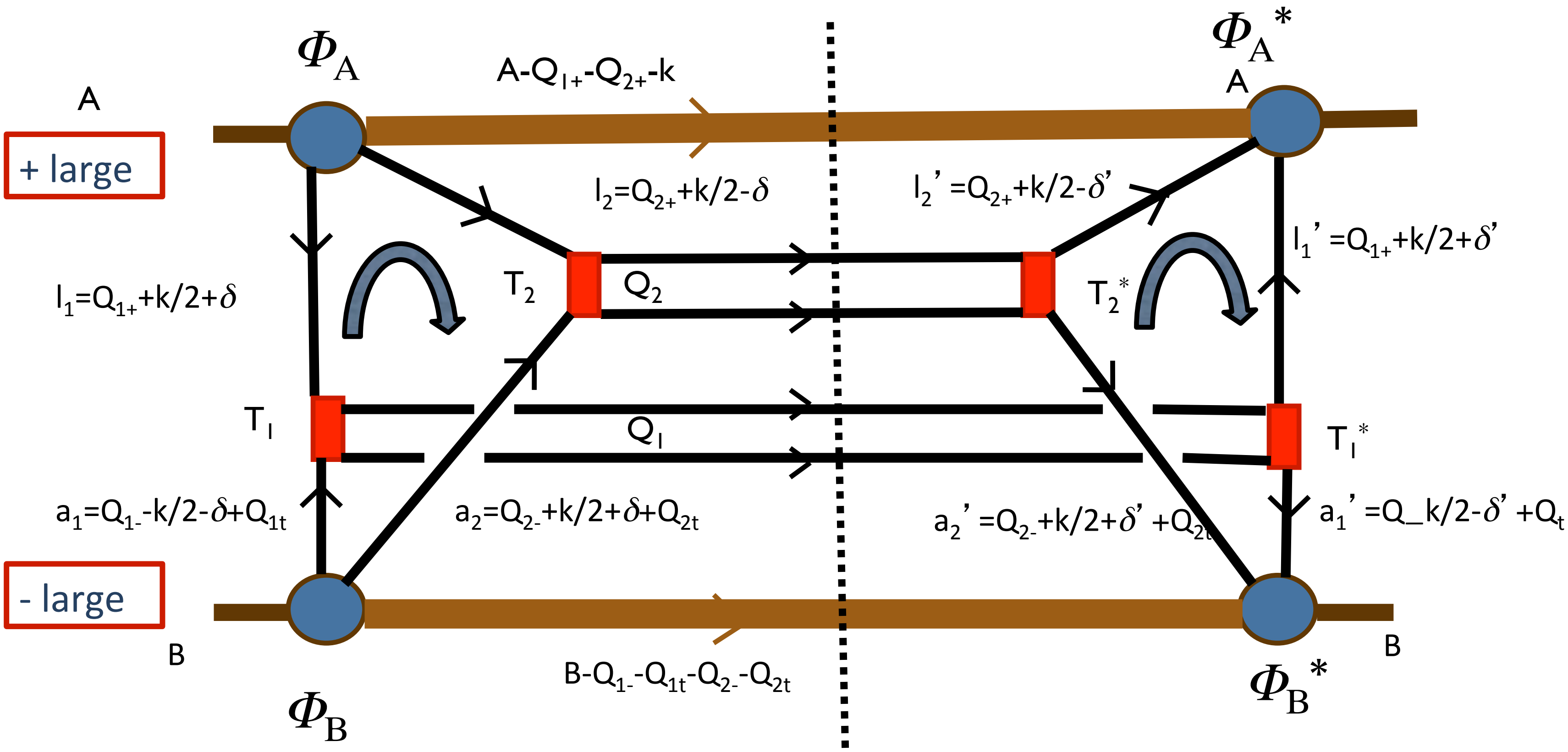
  - Experimental evidences
  - $b\bar{b}$ and $b\bar{b}b\bar{b}$ production in pp collisions at the LHC
- DPI in pA collisions:
  - Most natural expectations and hadron structure

pp collisions: Present approach and open problems

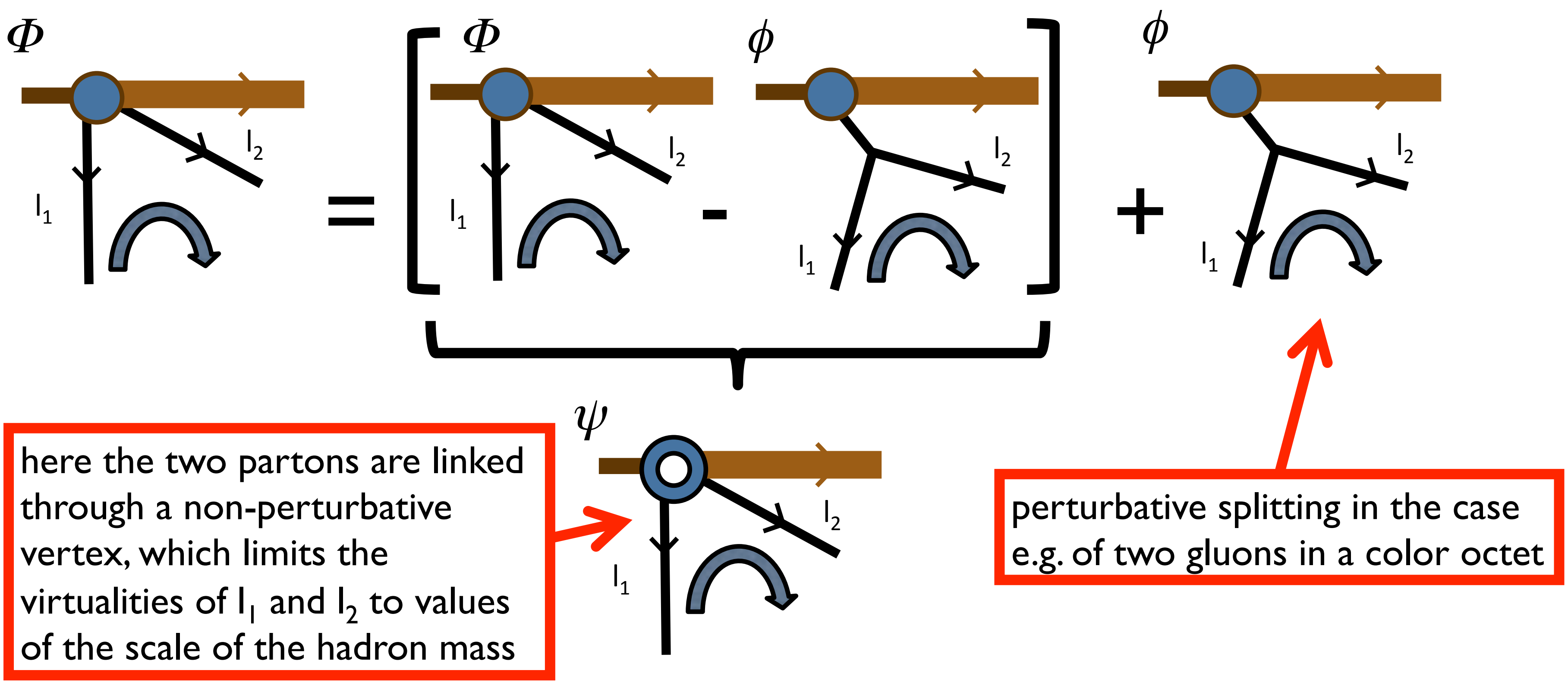
- In a Double Parton Interaction two different pairs of partons interact with large momentum transfer exchange in the same inelastic event.



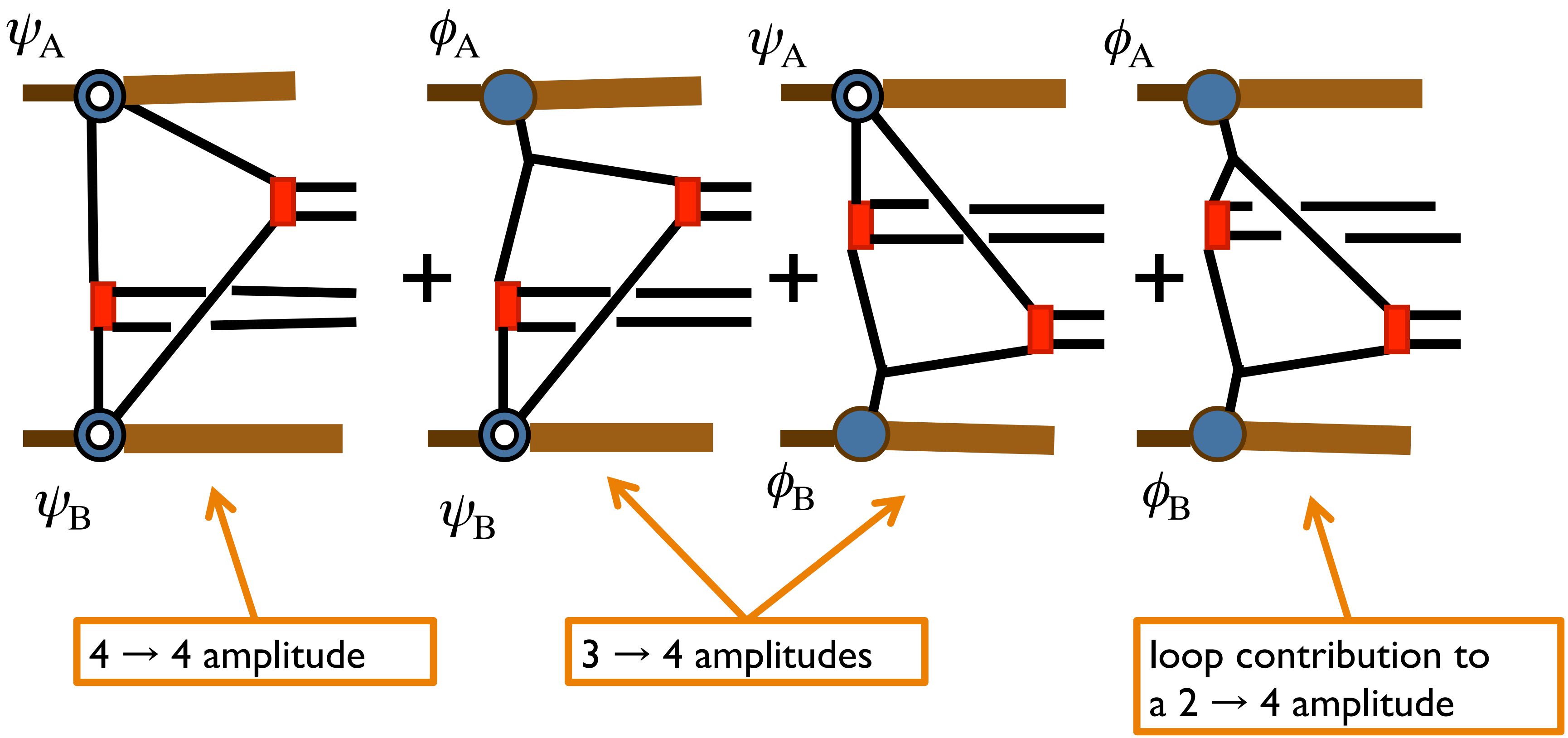
The cross section can be expressed as a contribution to the forward elastic scattering amplitude, which is characterized by two independent loops where initial state momenta of the partonic interactions are integrated independently in the amplitude of the process and in its complex conjugate.

- A Double Parton Interaction cross section therefore is not diagonal as a function of initial state momenta.

- It is convenient to distinguish two different contributions in the non-perturbative vertices :



- The amplitude thus splits into 4 different pieces, the first 3 introduce a non perturbative dimensional factor in the cross section and are thus of interest to DPIs, the 4th tem is a higher order correction to the 2 → 4 parton scattering amplitude :



Due to the mass scale in ψ, the loop integrations, on the light cone '+' and '-' integration variables are kinematically decoupled in the upper and in the lower part of the forward scattering amplitude diagram.
In the case of the 4 $\rightarrow$ 4 scattering process, the integrations on δ_+ and δ_- can thus be done independently:

$$\int \frac{\psi_A}{l_1^2 l_2^2} T_1 T_2 \frac{\psi_B}{a_1^2 a_2^2} d\delta_- d\delta_+ \approx \left(\int d\delta_- \frac{\psi_A}{l_1^2 l_2^2}\right) \times \left\{T_1 T_2\right\} \times \left(\int d\delta_+ \frac{\psi_B}{a_1^2 a_2^2}\right)$$

$$\equiv \Psi_A \times \left\{T_1 T_2\right\} \times \Psi_B$$

and, through the functions Ψ_A and Ψ_B, one can introduce the Double parton distributions, which allow expressing the cross section as a factorized product of two almost independent partonic interactions.

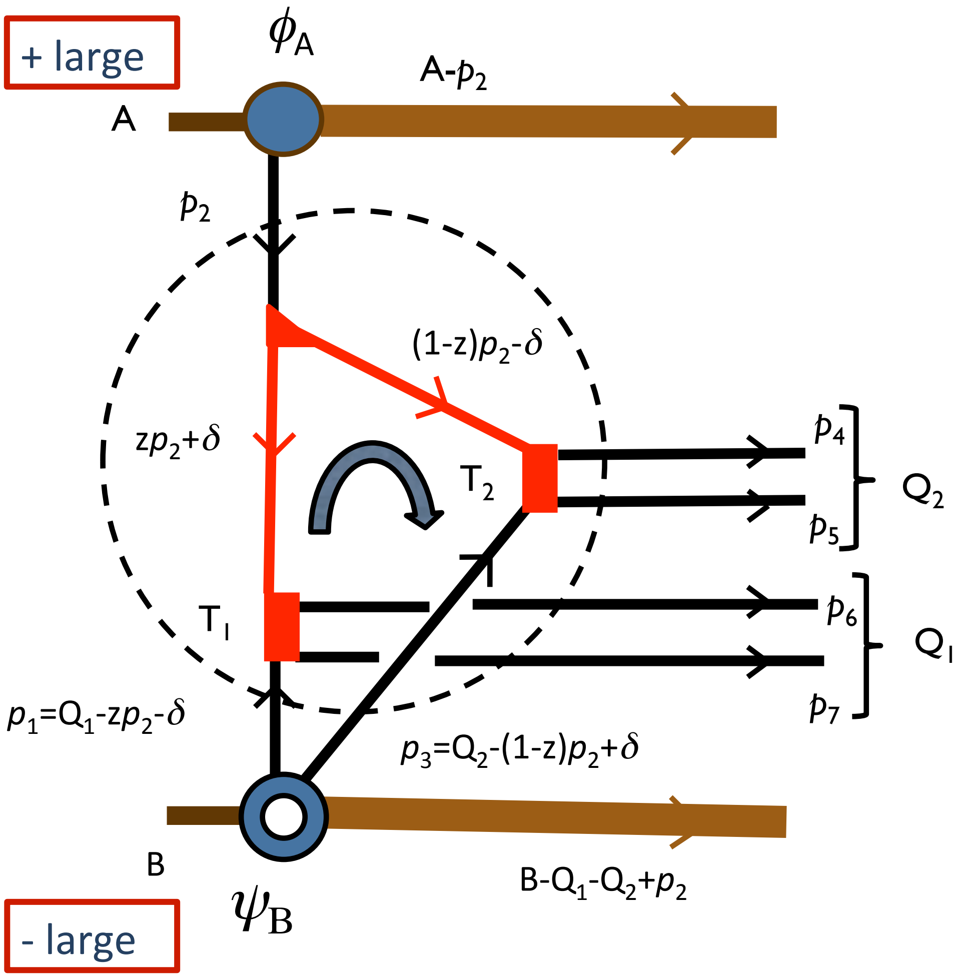
The case of the 3 $\rightarrow$ 4 contributions is more elaborate. When looking at Feynman diagrams, one finds that, in the case of all gluons, the number of diagrams to be considered for the 7-gluon amplitude is huge: 2485 at tree level. In the zero mass case, tree level amplitudes are nevertheless successfully worked out with the Spinor-Helicity formalism.

In the spinor helicity formalism the amplitude is expressed by a sum of gauge invariant 'color ordered' amplitudes.

Contributions to the 3 $\rightarrow$ 4 parton processes are given by terms with at least two three-particle singularities in the external momenta.

In the kinematical configurations close to the two singularities, the interaction amplitude can in fact split in this way into two almost independent 2 $\rightarrow$ 2 sub-interaction amplitudes.

In the spinor-helicity formalism, all contributions of interest to the seven gluon amplitude can be obtained from four different color ordered amplitudes. The simplest color ordered amplitude is $A(1^-2^-3^-4^+5^+6^+7^+)=A|_a+A|_b+A|_c$, where the term $A|_c$, which corresponds to the figure below, is characterized by two three particle singularities: $A|_c \sim (P_{176})^{-2}(P_{345})^{-2}$



Analogously to the 4 → 4 case, to study the effect of the loop integration on the term $A|_c$, one can integrate on the loop integration variables δ_+ and δ_- by keeping into account of the dependence on δ_- only in the upper part of the loop and of the dependence on δ_+ only in the lower part of the loop. The integration on δ_+ thus defines the function Ψ_B and fixes the values of the fractional momenta z and $1 - z$, while the integration on δ_- is estimated with the singularities of the two propagators in the upper part of the loop.

Concerning the loop integration on the transverse variables, one may notice that the closest configuration to the mass shell, of the two intermediate gluons with momenta $(1\text{-}z)p_2 - \delta$ and $zp_2 + \delta$, is obtained when $\delta_t = 0$.
One is thus interested in the behavior of the integrand in the limit of small δ_t, where one finds that the integrand behaves as $1/\delta_t$

The integration of $A|_c$ in $d^2\delta_t$ thus washes out the singularity at $\delta_t = 0$.
As a consequence the amplitude is not enhanced in the configuration where the transverse momenta of the two pairs of large p_t partons are compensated pairwise.

Since $A|_c$ is summed coherently with $A|_a$ and $A|_b$ in the gauge invariant color orderd amplitude A and since $A|_c$ is not enhanced, the interferences of $A|_c$ with $A|_a$ and with $A|_b$ cannot be neglected and the contribution of $A|_c$ cannot be isolated in the final cross section.

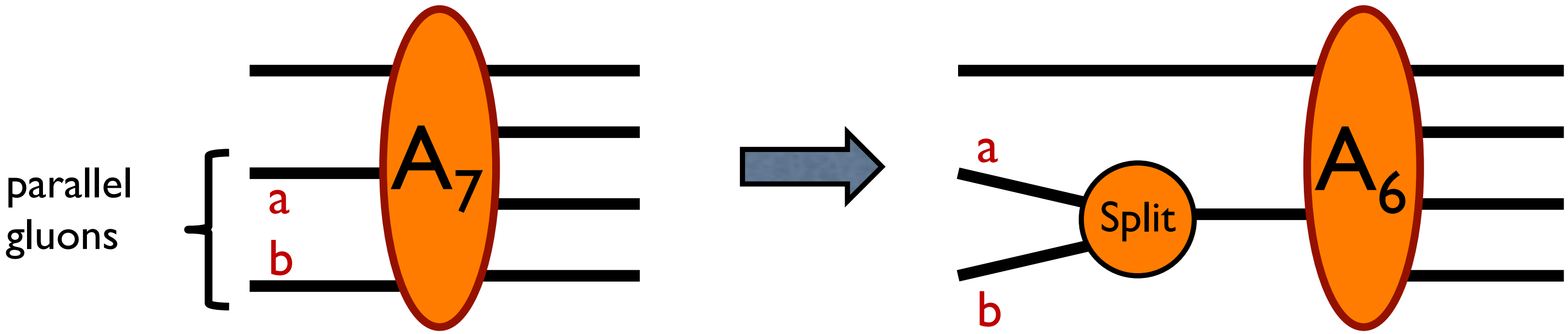
This property holds not only for the particular case of color ordered amplitude discussed above. It holds also for all other contributions, to the tree level 7-gluons amplitude, characterized by multi-particle singularities.

A further feature is that the complete 3 $\rightarrow$ 4 scattering amplitude results from the sum of all color ordered contributions. In the actual case of interest one has two gluons in the initial state, which are originated by the same hadron and which thus have a rather small relative transverse momentum.

The color ordered terms, where the almost parallel initial state gluons are cyclicaly-adjacent in the amplitude, are singular, in the invariant obtained by the sum of the two almost parallel momenta, and therefore give a leading contribution to the amplitude.

A main contribution to the 7-gluon amplitude, in the kinematics considered here, is therefore factorized into a fusion amplitude and a 6-gluon scattering amplitude, the latter with only two gluons in the initial state.

While initiated by three partons, a main contribution to the cross section is thus effectively given by a 2 $\rightarrow$ 4 , rather than by a 3 $\rightarrow$ 4 parton process.



pp collisions: Comments concerning the actual approach and open problems

In the kinematics of DPIs, a main contribution to the $3 \rightarrow 4$ parton processes is given by terms corresponding to the fusion of the two initial state partons, which originate from the same hadron.

In the 7 gluons tree level amplitude one finds terms, that contribute to the color ordered amplitudes, which can be factorized into a splitting amplitude and two almost on shell four partons (namely $2 \rightarrow 2$) scattering amplitudes.

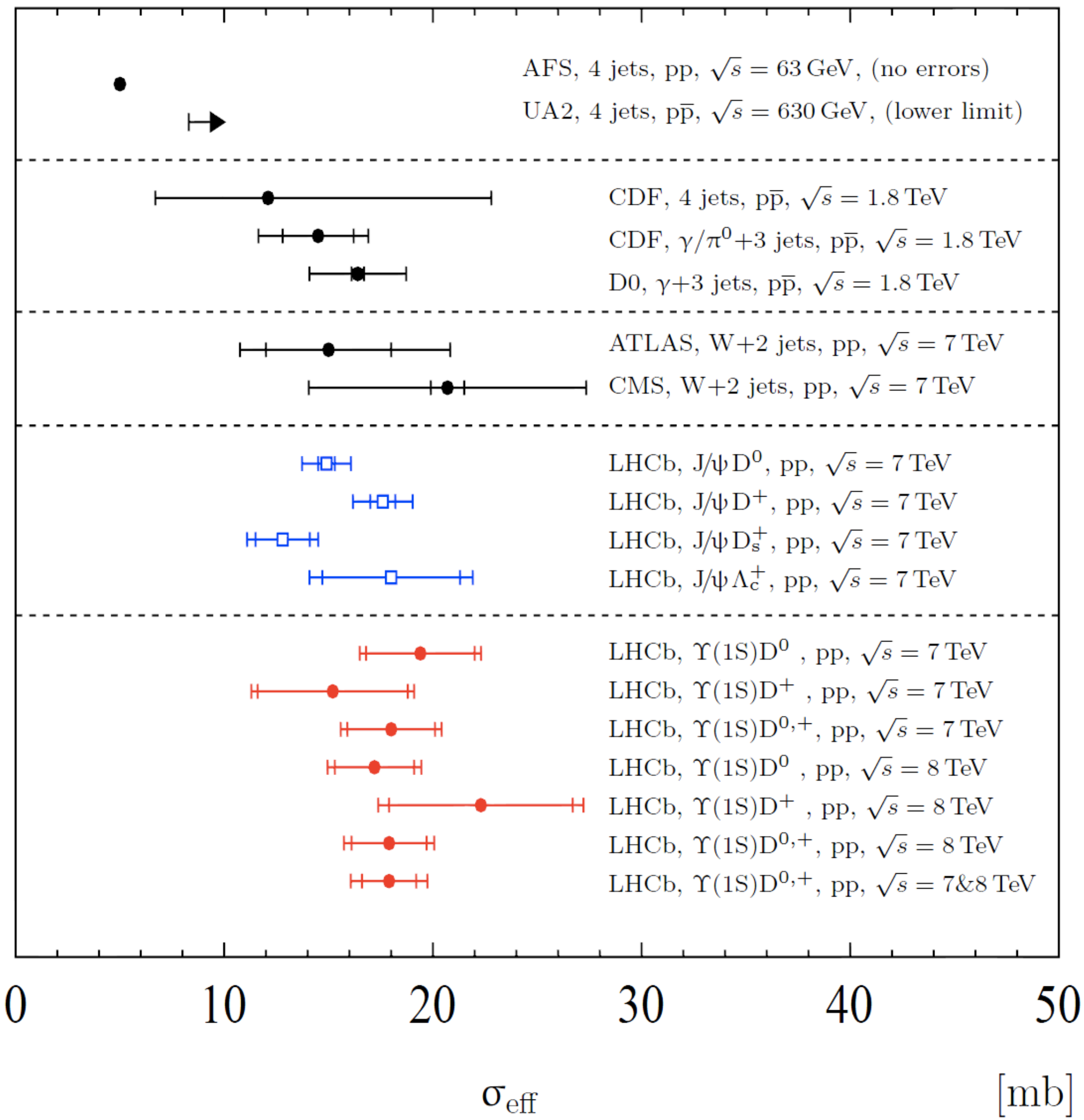
However these contributions to the amplitude

- are not enhanced in the configuration where the final state partons have transverse momenta balanced pair-wise because of the loop integration

- are not gauge invariant and thus interfere with the other contributions to the same (gauge invariant) color ordered amplitude, in such a way that they cannot be isolated in the final cross section

The main contribution of $3 \rightarrow 4$ to the final cross section is thus taken into account by including the fusion terms in the evolution of the hadronic distributions

pp collisions: Experimental evidences



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

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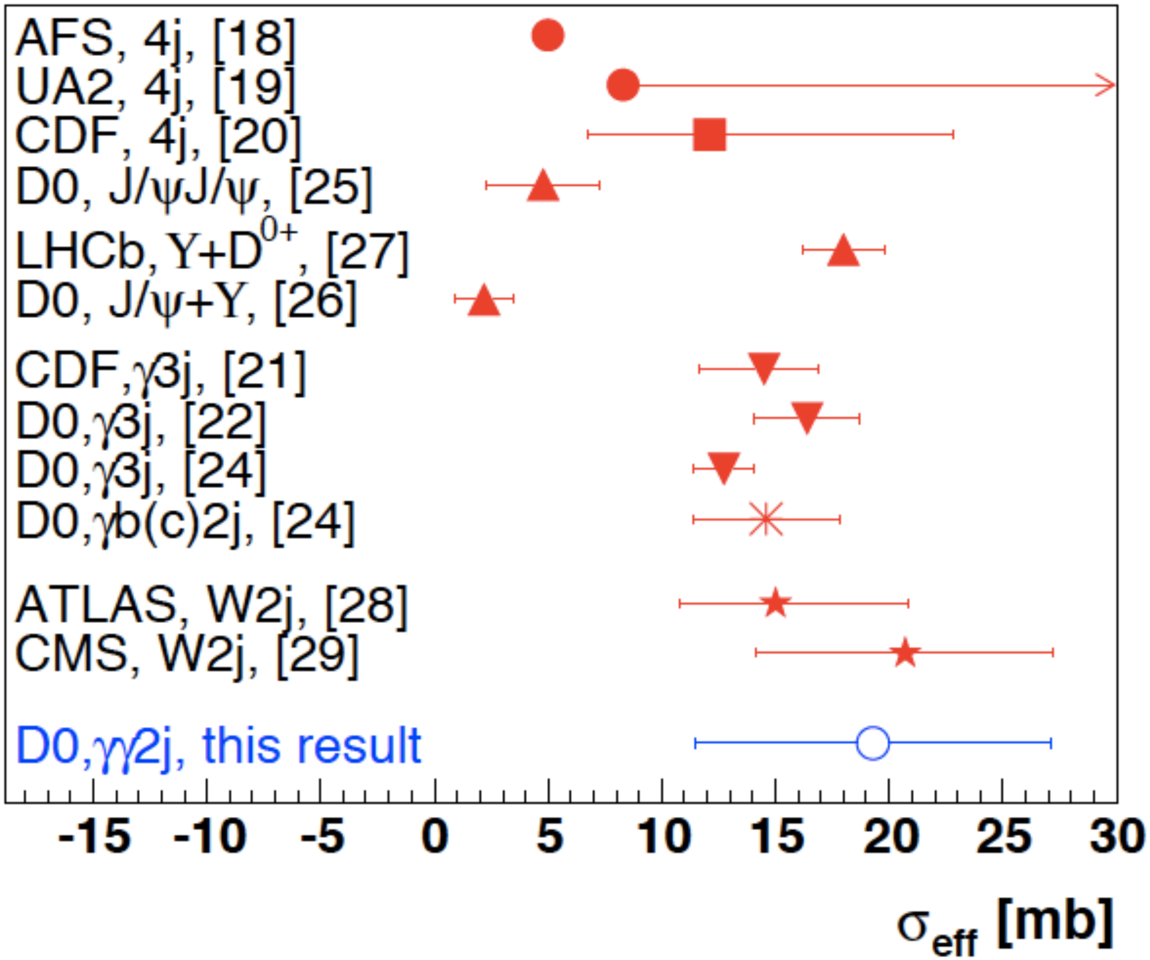

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pp collisions: Comments on the Experimental Evidences

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)

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 the indication from LHCb that, for J/Ψ D, J/Ψ Λ, ΥD production by DPIs, the value of the effective cross section is still of about 15 mb is in contradiction with the hypothesis that the effective cross section grows to values close to 30 mb at small transverse momenta, as assumed in PYTHIA.

$b\bar{b}$ and $b\bar{b}b\bar{b}$ production in pp collisions at the LHC

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.

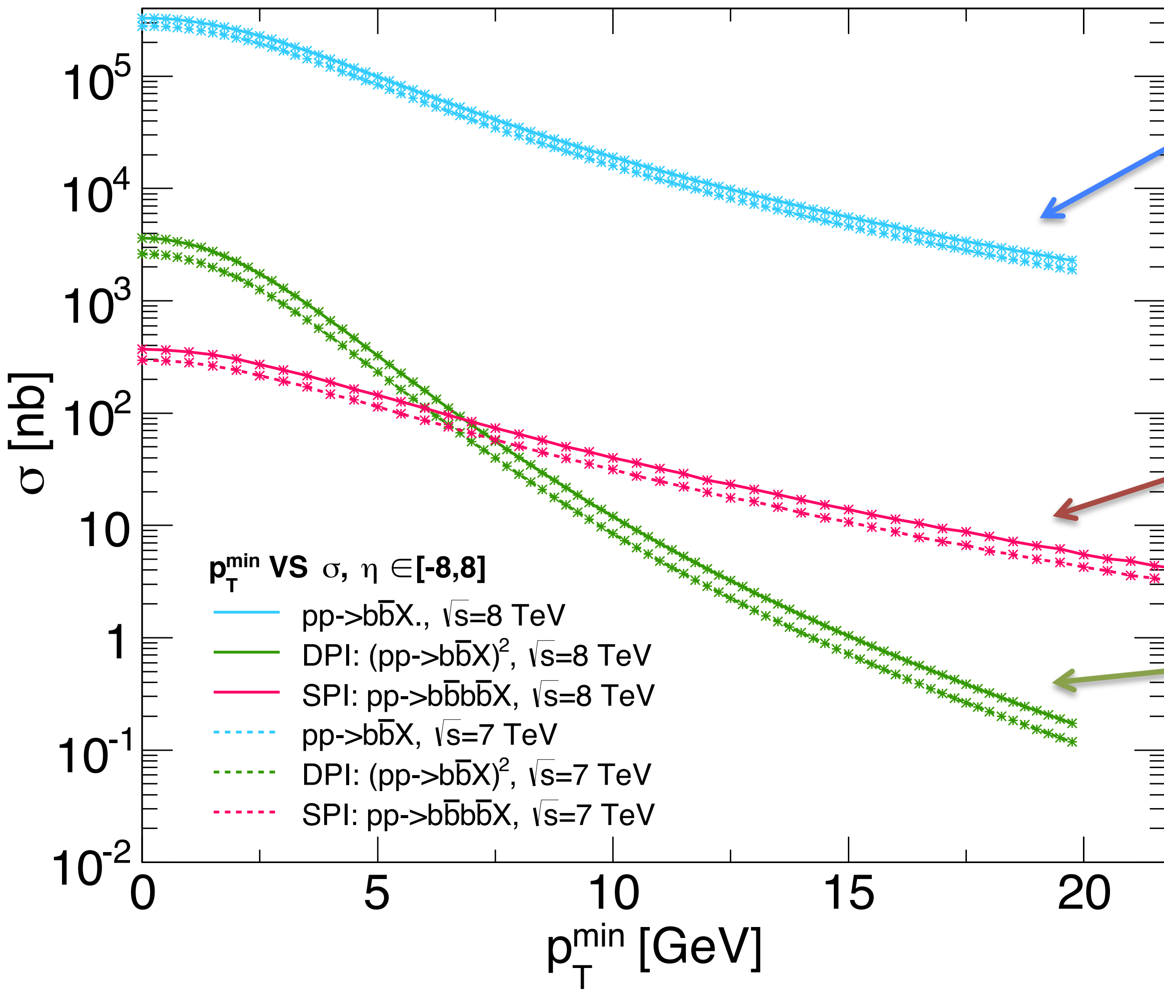
In *pp* collisions at 8 TeV c.m. energy, **the DPS contribution** to the integrated inclusive cross section is in fact expected to be **one order of magnitude larger** as compared to **the SPS contribution**.

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

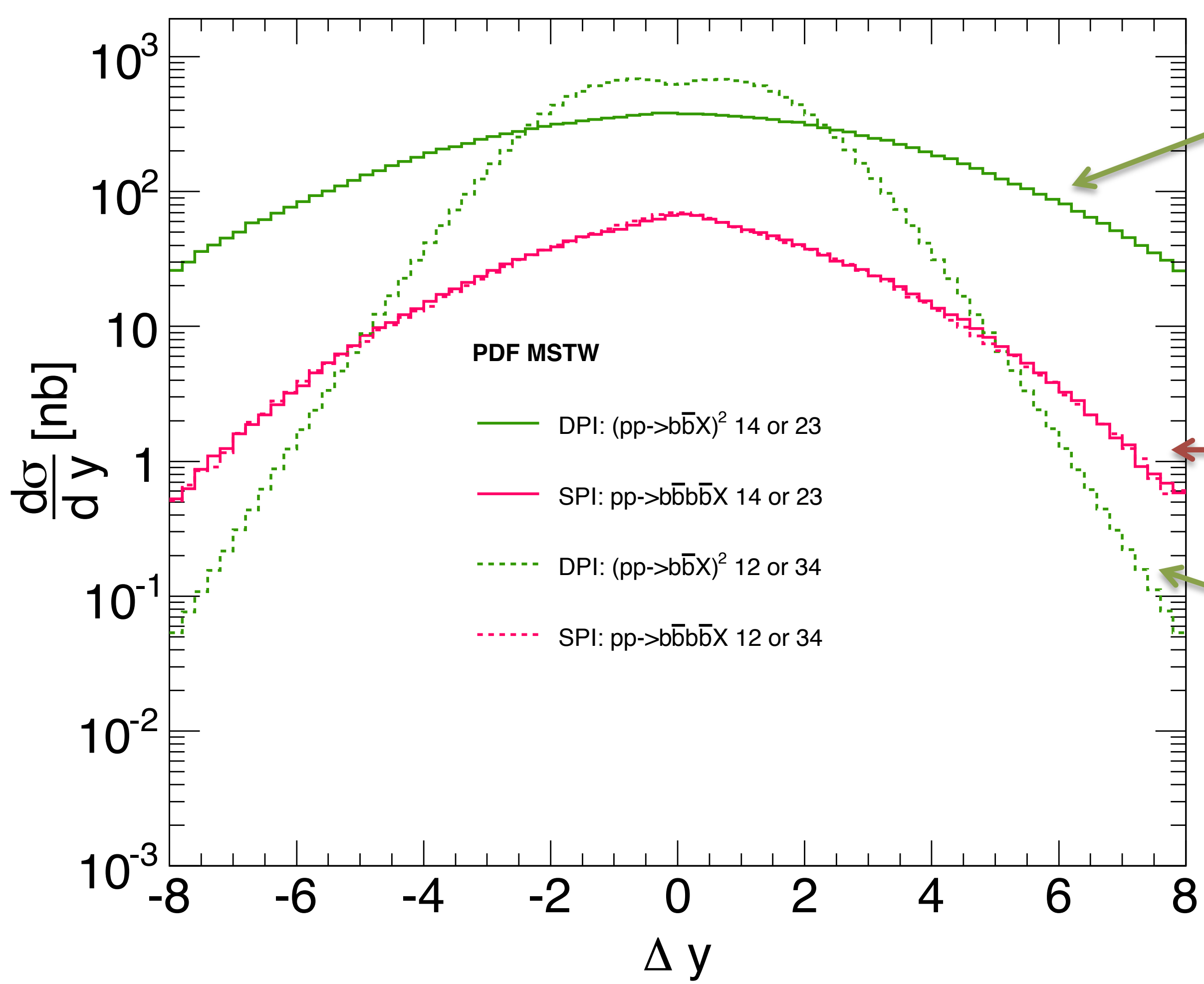


$b\bar{b}$ production: Integrated cross section, with $p_T > p_T^{min}$

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

$b\bar{b}b\bar{b}$ production by double parton scattering: 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



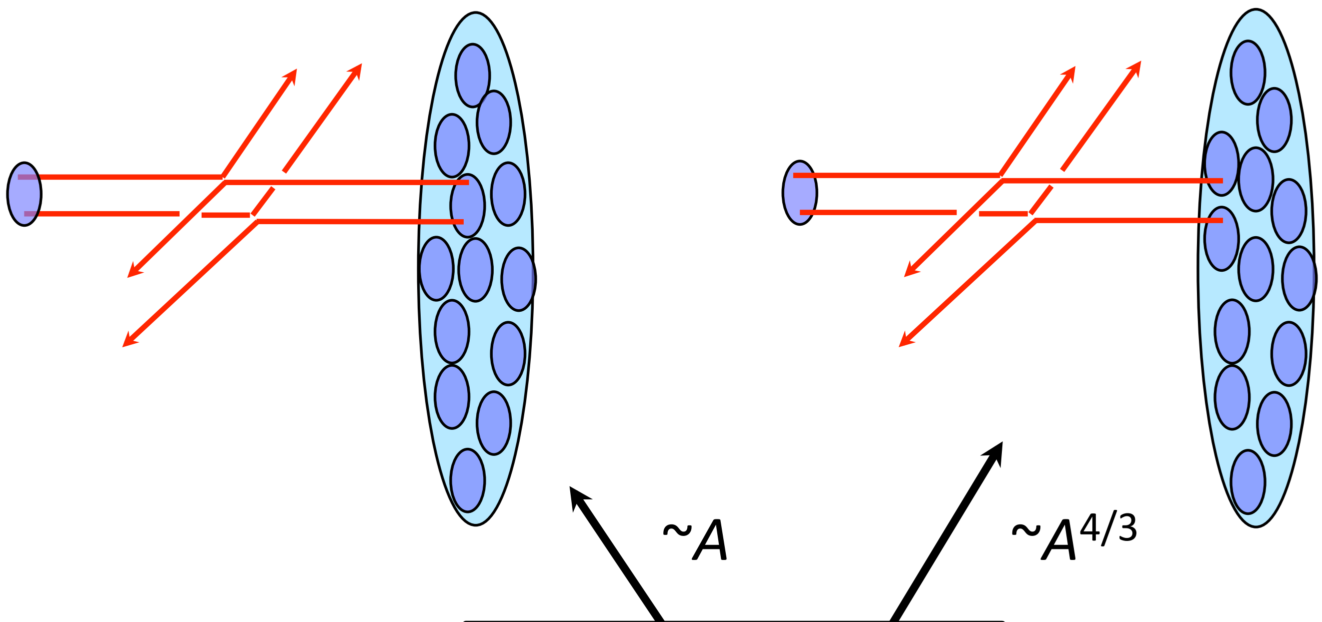
Double parton scattering: correlation between two b-quarks originated in two different elementary interactions

Single parton scattering

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

DPI in pA collisions: Most natural expectations and hadron structure

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:



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

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

single - scattering contribution

double - scattering contribution

$$\sigma^{pA}(b\bar{b}b\bar{b}) = \sigma^{pA}_S(b\bar{b}b\bar{b}) + \sigma^{pA}_D(b\bar{b}b\bar{b})$$
$$\sigma^{pA}_D(b\bar{b}b\bar{b}) = \sigma^{pA}_D(b\bar{b}b\bar{b})\big|_1 + \sigma^{pA}_D(b\bar{b}b\bar{b})\big|_2$$

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

$$\sigma^{pA}_D(b\bar{b}b\bar{b})\big|_1 = \frac{A}{2\sigma_{eff}}\left[\sigma^{pp}_S(b\bar{b})\right]^2$$
$$\sigma^{pA}_D(b\bar{b}b\bar{b})\big|_2 = K\frac{1}{2}\left[\sigma^{pp}_S(b\bar{b})\right]^2 \times \int T(B)^2 d^2B$$

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}

$$\sigma_D^{pA}(b\bar{b}b\bar{b})\Big|_1 = \frac{A}{2\sigma_{eff}}\left[\sigma_S^{pp}(b\bar{b})\right]^2$$

$$\sigma_D^{pA}(b\bar{b}b\bar{b})\Big|_2 = K\frac{1}{2}\left[\sigma_S^{pp}(b\bar{b})\right]^2 \times \int T(B)^2 d^2B$$

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

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

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.

$$\sigma_D^{pA}(b\bar{b}b\bar{b})\Big|_1 = \frac{A}{2\sigma_{eff}}\left[\sigma_S^{pp}(b\bar{b})\right]^2$$

Double scattering against a single target nucleon, it's linear with A

$$\sigma_D^{pA}(b\bar{b}b\bar{b})\Big|_2 = K\frac{1}{2}\left[\sigma_S^{pp}(b\bar{b})\right]^2 \times \int T(B)^2 d^2B$$

Double scattering against two different target nucleons, it grows as $A^{4/3}$

By measuring the amount of anti-shadowing one obtains information on *K*, namely on the correlation in multiplicity of the multi-parton distribution.

One may estimate that *K* may vary between 1 and √2

For *K*=1 (no correlation in multiplicity) one obtains $\frac{\sigma_D^{pA}|_2}{\sigma_D^{pA}|_1} \approx 2$ (200% anti-shadowing correction)

For *K*= √2 one obtains $\frac{\sigma_D^{pA}|_2}{\sigma_D^{pA}|_1} \approx 3$ (300% anti-shadowing correction)

Comments on $b\bar{b}b\bar{b}$ production in pp and pA collisions at the LHC

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**.

In ***p-Pb*** **collisions the dominand contribution** to $b\bar{b}b\bar{b}$ production is **due to** the "**anti-shadowing** contribution" to DPS, where two target nucleons play and active role in the production process.

The value of **the DPS cross section** for $b\bar{b}b\bar{b}$ production, in *p-Pb* collisions at 8 TeV proton-nucleon c.m. energy, **may range between 1 and 2 mb**.
By comparison, the expected $b\bar{b}b\bar{b}$ production cross section due to **the leading QCD mechanism,** in *p-Pb* collisions at 8 TeV proton-nucleon c.m. energy, **may be** about 80 μb, namely **20 – 30 times smaller**.

By measuring the amount of anti-shadowing one obtains information on the multi-parton correlation in the hadron structure.

Thank you