Multiple scattering in collisions of p+p and UPC of heavy ions

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QCD - Old Challenges and New Opportunities

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Multi-particle final states at the LHC

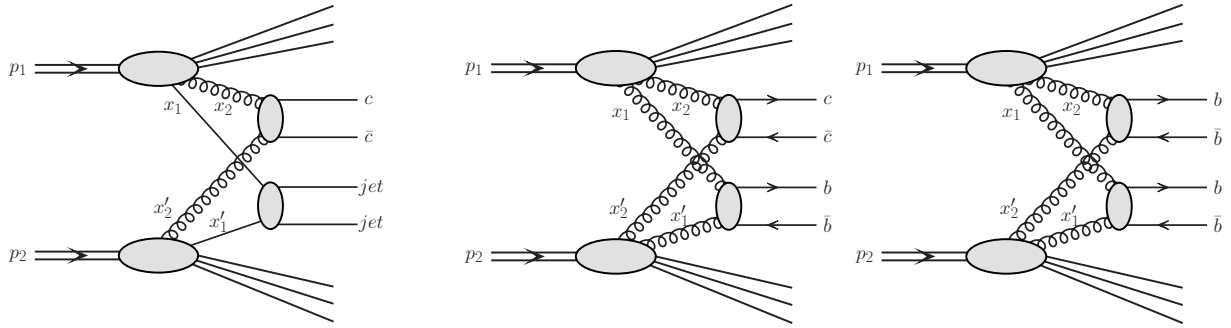
The high luminosity already achieved at the LHC potentially allows to study more complicated final states and opens new possibilities in testing dynamics of pQCD processes

Our interest: phenomena of Multiple-Parton Interactions (MPI)

During last years: Double-Parton Scattering (DPS) effects in $pp-$collisions

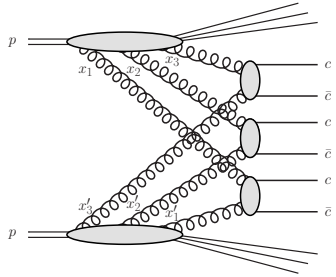
- $pp \to c\bar{c}c\bar{c}\ X$ (supported by the LHCb double charm data)
- $pp \to 4\text{jets}\ X$ (needs dedicated experimental analyses)

Very recently: $pp \to c\bar{c} + 2\text{jets}\ X$, $pp \to c\bar{c}b\bar{b}\ X$, $pp \to b\bar{b}b\bar{b}\ X$



Can we observe some evidence of DPS effects in these cases?

A step beyond the DPS: Triple-parton scattering (TPS) in $pp \to c\bar{c}c\bar{c}c\bar{c}\ X$



Can we observe some evidence of TPS effects at the LHC in the case of triple charm production?

General Theoretical Framework

The cross section for production of $a_1 + \ldots + a_n$ final state in *n*-parton scattering in h_1 h_2 collisions can be written, somewhat formally, as

$$\sigma_{h_1 h_2 \to a_1 \ldots a_2} = \left(\frac{m}{n!}\right) \sum_{i_1,\ldots,i_n,j_1,\ldots,j_n} \int \Gamma_{h_1}^{i_1\ldots i_n}\left(x_1,\ldots,x_n;\mathbf{b}_1,\ldots,\mathbf{b}_n;\mu_1^2,\ldots,\mu_n^2\right)$$
$$\sigma_{a_1}^{i_1,i_1'}(x_1,x_1',\mu_1^2)\ldots\sigma_{a_n}^{i_n,i_n'}(x_n,x_n',\mu_n^2)$$
$$\Gamma_{h_2}^{j_1\ldots j_n}\left(x_1',\ldots,x_n';\mathbf{b}-\mathbf{b}_1,\ldots,\mathbf{b}-\mathbf{b}_n;\mu_1^2,\ldots,\mu_n^2\right)$$
$$dx_1\ldots dx_n dx_1'\ldots dx_n' d^2b_1\ldots d^2b_n d^2b\ . \qquad (1)$$

Above $\Gamma_{h_i}^{i_1,\ldots i_2}\left(x_1,\ldots x_n;\mathbf{b_1},\ldots,\mathbf{b_n},\mu_1^2,\ldots,\mu_n^2\right)$ are n-parton distributions in the impact parameter space.

Theoretical ideas, continuation

$x_1, \ldots, x_n$ are momentum fractions of partons in h_1
$x'_1, \ldots, x'_n$ are momentum fractions of partons in h_2.
$\mu_1^2, \ldots, \mu_n^2$ are scales for first, ..., n-th scattering,
$\mathbf{b}_1, \ldots, \mathbf{b}_n$ are impact parameters for the first, ..., n-th scattering.
Of course the following conditions must be fulfilled:

$$x_1 + \ldots + x_n < 1 \quad , \quad x'_1 + \ldots + x'_n < 1 \, . \tag{2}$$

They are imposed as extra condition.
The combinatorial prefactor takes into account identities of the produced final states.
$\Gamma_h^{i_1,\ldots,i_n}$ encodes the three-dimensional parton structure.
(Including density of partons in the transverse plane.)
Do we know n-parton distributions? Not really.
We know double-parton distributions
Krzysztof Golec-Biernat lecture

Theoretical ideas, continuation

The impact parameter n-parton distributions can be translated to momentum n-parton distributions as:

$$\Gamma_h^{i_1,\ldots,i_n}\left(x_1,\ldots,x_n;\mathbf{b}_1,\ldots,\mathbf{b}_n;\mu_1^2,\ldots,\mu_n^2\right) = D_h^{i_1,\ldots,i_n}\left(x_1,\ldots,x_n,\mu_1^2,\ldots,\mu_n^2\right)\cdot f(\mathbf{b}_1)\ldots f(\mathbf{b}_n) \tag{3}$$

where $f(\mathbf{b}_i)$ describes the transverse parton density of the hadron (universal function, assumption of independent partons)

This approach neglects correlations in b-space (!)

Both nonperturbative and perturbative correlations are possible in general.

This was not well studied.

Theoretical ideas, continuation

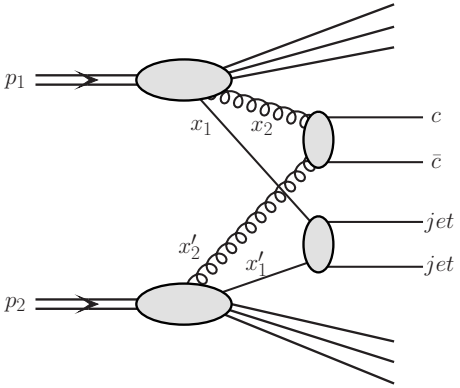
From b-space to momentum space:

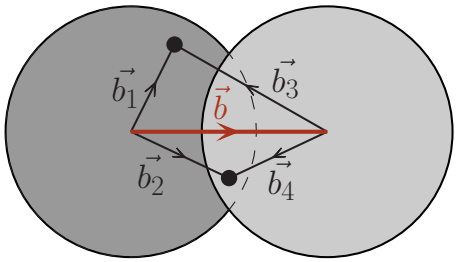
$$\sigma_{h_1 h_2 \to a_1 + \ldots + a_n} = \left(\frac{m}{n!}\right) \frac{\sigma^{SPS}_{h_1 h_2 \to a_1} \ldots \sigma^{SPS}_{h_1 h_2 \to a_n}}{\sigma_{eff}^{n-1}} \,. \tag{4}$$

Here σ_{eff}^{n-1} is a nonperturbative parameter that can be calculated in a model.

Snigirev has shown how to calculate it from partonic profiles.

Double-parton scattering (DPS) mechanism





DPS in general form for $pp \to c\,\bar{c}\,k\,l\,X$:

$$d\sigma^{DPS} = \frac{1}{2} \cdot \sum_{i,j,k,l} \Gamma_{ig}(b, x_1, x_2; \mu_1^2, \mu_2^2)\, \Gamma_{jg}(b, x_1', x_2'; \mu_1^2, \mu_2^2)$$
$$\times\, d\sigma_{ij\to kl}(x_1', x_1, \mu_1^2) \cdot d\sigma_{gg\to c\bar{c}}(x_2, x_2', \mu_2^2)\; dx_1\, dx_2\, dx_1'\, dx_2'\, d^2b$$

DPDF - emission of one parton with assumption that second parton is also emitted

$$\Gamma_{i,j}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2)\; F_j(x_2, \mu_2^2)\; F(b; x_1, x_2, \mu_1^2, \mu_2^2)$$

- longitudinal and transverse correlations between two partons
- spin, flavor and color correlations
- formal theory: *e.g.* Diehl, Ostermeier, Schafer, JHEP 03, 089 (2012)
  difficult for phenomenological studies

Factorized ansatz (pocket-formula)

In a simple probabilistic picture process initiated by:

two simultaneous hard parton-parton scatterings in one proton-proton interaction

$$\sigma^{DPS} = \frac{1}{\sigma_{eff}} \cdot \sum_{i,j,k,l} \sigma^{SPS}(i\,j \to k\,l) \cdot \sigma^{SPS}(g\,g \to c\,\bar{c})$$

two subprocesses are not correlated and do not interfere

- $\sigma_{eff} \Rightarrow$ model parameter $\Rightarrow$ normalization of σ^{DPS}

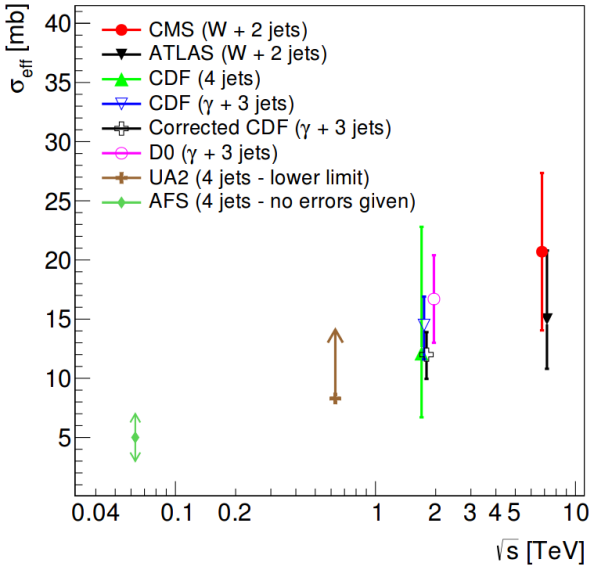
Double-parton scattering (DPS) mechanism

Factorized ansatz (pocket-formula)

- a good approximation for small-x partons
- color/flavor correlations suppressed in evolution (Kasemets et al., Phys. Rev. D91, 014015 (2015))
- spin (polarization) correlations very small (Echevarria et al. JHEP 04, 034 (2015))

Separation of longitudinal and transverse degrees of freedom

- DPDFs in multiplicative form: $\Gamma_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2) F_j(x_2, \mu_2^2) F(b)$
- only transverse correlations taken into account
- $\sigma_{eff} = \left[\int d^2b \, (F(b))^2\right]^{-1}$, $F(b)$ - overlap of the matter distribution in transverse plane where b is a distance between both partons
- nonperturbative quantity with dimension of cross section, connected to transverse size of proton



- extracted from several experimental analyses
- in principle may not be universal
- detailed studies: Seymour, Siódmok, JHEP 10, 113 (2013)
- LHCb double charm data: $\sigma_{eff} = 21^{+7}_{-6}$ mb
- ATLAS 4jets data: $\sigma_{eff} = 14.9$ mb
- world average: $\sigma_{eff} \approx 15$ mb (large uncertainties)

A bit of formalism

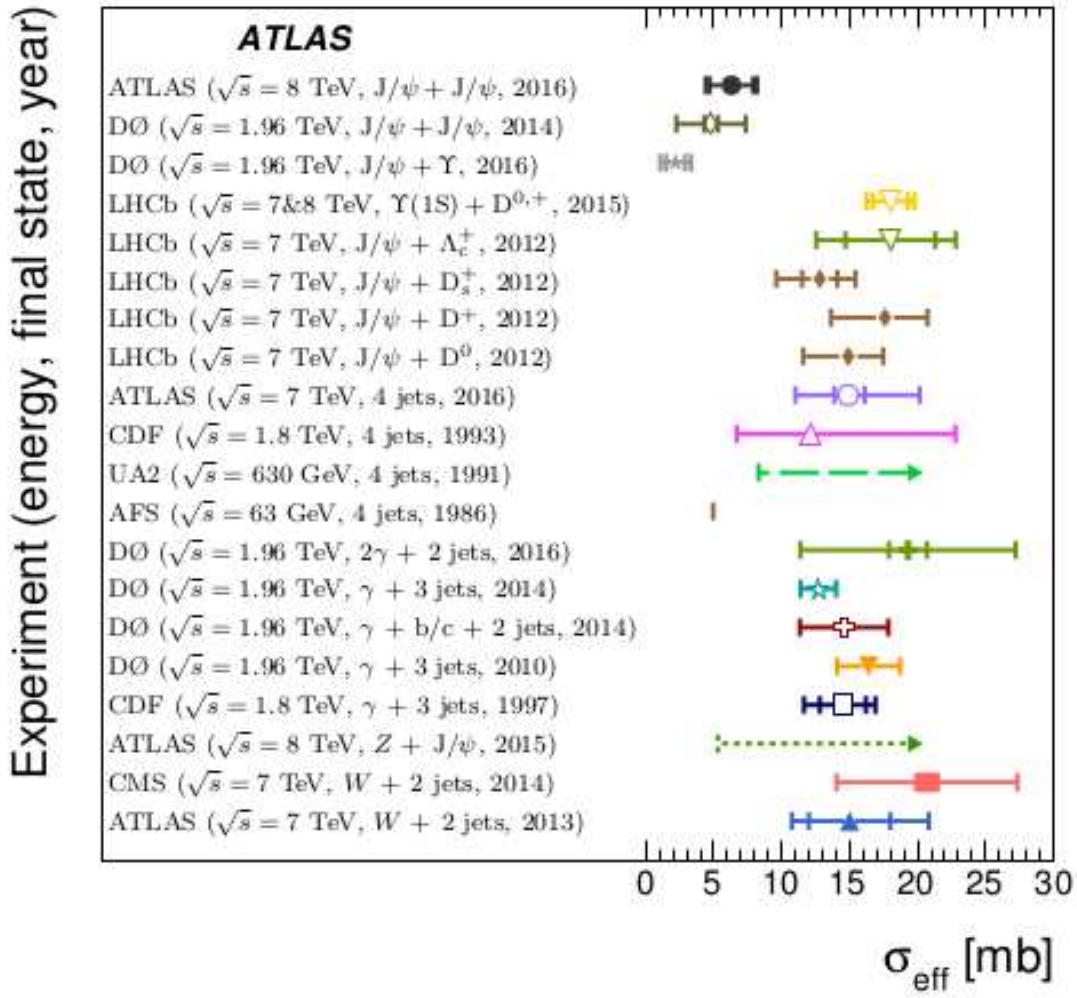
discussed a bit by K. Golec-Biernat

$$d\sigma^{DPS} = \frac{1}{2\sigma_{eff}} F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2) F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2) \, d\sigma_{gg\to c\bar{c}}(x_1, x_1', \mu_1^2) d\sigma_{gg\to c\bar{c}}(x_2, x_2', \mu_2^2) \; dx_1 dx_2 dx_1' dx_2' \, .$$

$F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$, $F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$
are called double parton distributions

dPDF are subjected to special evolution equations
single scale evolution: Snigirev
double scale evolution: Ceccopieri, Gaunt-Stirling

σ_{eff} from experiments



σ_{eff} may be process dependent

σ_{eff} encodes spatial overlap of four partons:
two from first hadron, two from the second hadron.
In general: $\sigma_{eff}(\ldots) = \sigma_{eff}^{ijkl}(\ldots)$
For instance σ_{eff}^{gggg}, $\sigma_{eff}^{gg q\bar{q}}$, $\sigma_{eff}^{q\bar{q}q\bar{q}}$. etc could be different

- $gggg$: important for $c\bar{c}c\bar{c}$, $J/\psi J/\psi$
- $q\bar{q}q\bar{q}$: important e.g. for W^+W^-
  (by adjusting σ_{eff} (very small) could almost describe H in this channel)

As a consequence σ_{eff} can be process dependent if we assume one universal σ_{eff} fitted to data within factorized ansatz.
In practice (at present) we cannot fit more than one σ_{eff} !!!
Not enought precision in calculation and data.
Parton distribution in b-space can be regular or irregular. σ_{eff} combines therefore both nonperturbative and perturbative effects
$\rightarrow$ very difficult to control.

Phenomenological models of factorization violation

DPD (double parton distribution)

Diehl, Kasemets, Keane, JHEP 1405, 118 (2014).

$$F_{ab}(x_1, x_2, \Delta\vec{b}) = \int d^2b \; f_a\left(x_1, \vec{b} + \Delta\vec{b}\right) f_b\left(x_2, \vec{b}\right) \; . \tag{5}$$

Single parton distribution:

$$f_a(x, \vec{b}) = f_a(x) \frac{1}{4\pi h_a(x)} \exp\left(\frac{-b^2}{4h_a(x)}\right) \tag{6}$$

The width with the Gaussian is sometimes parametrized as:

$$h_a(x) = a'_a ln(1/x) + B_a \; . \tag{7}$$

Then the double parton distribution is:

$$F_{ab}(x_1, x_2, \Delta\vec{b}) = f_a(x_1) f_b(x_2) \frac{1}{4\pi} h_{ab}(x_1, x_2) \exp\left(\frac{-(\Delta\vec{b})^2}{4h_{ab}(x_1, x_2)}\right) \; , \tag{8}$$

where

$$h_{a,b}(x_1, x_2) = h_a(x_1) + h_b(x_2) \; . \tag{9}$$

Remarks on correlations

I do not discuss:

- Parton-parton nonperturbative correlations
  Treleani et al.
  Strikman et al.
- Perturbative flavour, color, spin correlations
  Diehl et al.
  Rather formal formalism developed.
- Hot spots (partonic matter is not smooth)
  valence quarks, fluctuations

Many possible processes

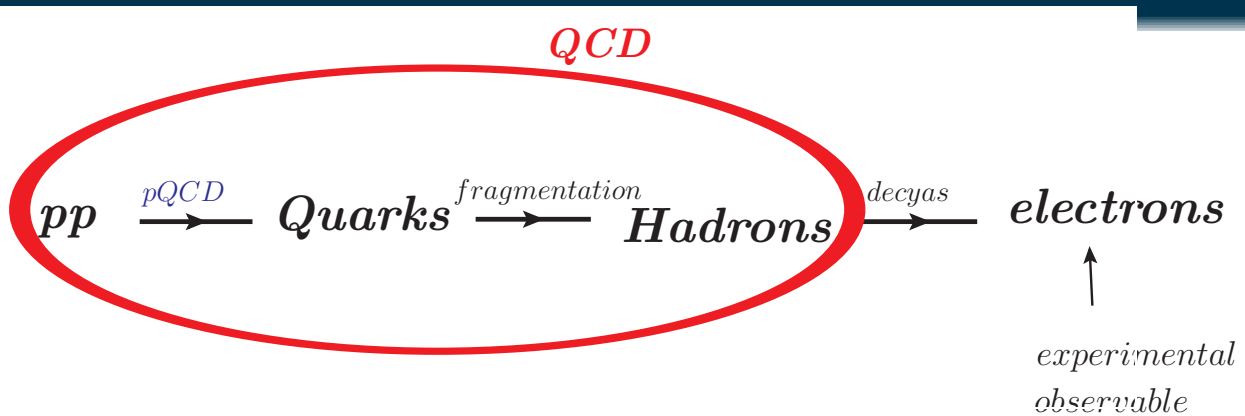
- Double Drell Yan process (small)
- Four jet production (in some regions of the phase space)
- W^+W^+ or W^-W^- production
  (very small, small branching fractions)
- $Q\bar{Q}Q\bar{Q}$
  $c\bar{c}c\bar{c}$ (extremely large)
- $J/\psi J/\psi$ (some controversy)
- Many other combinations
  (some will be discussed here)

Our studies of DPS and related processes

- $pp \to c\bar{c}c\bar{c}$ (mesons) (EXP)
- $pp \to jjjj$, background for Mueller-Navelet jets (EXP)
- $pp \to c\bar{c}j$ (mesons) SPS
- $pp \to c\bar{c}jj$ (mesons)
- $pp \to J/\psi J/\psi$ (EXP)
- $pp \to c\bar{c}b\bar{b}$ (mesons) (very recently)
- $pp \to b\bar{b}b\bar{b}$ (mesons) (very recently)

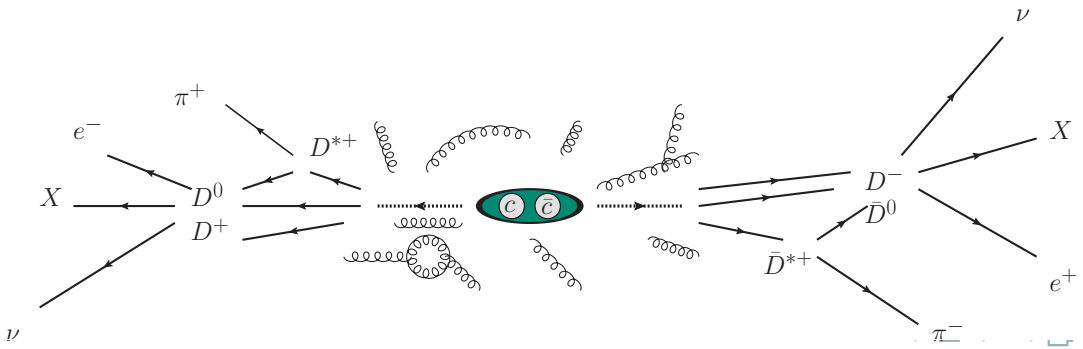
I will discuss now some of our results.

$Q\bar{Q}$, 3-step process



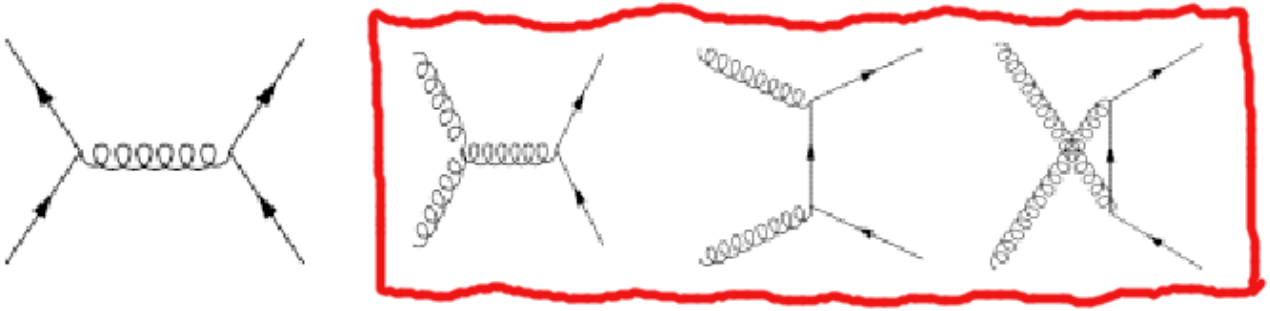
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

$$\frac{d\sigma^e}{dyd^2p} = \frac{d\sigma^Q}{dyd^2p} \otimes D_{Q\to H} \otimes f_{H\to e}$$

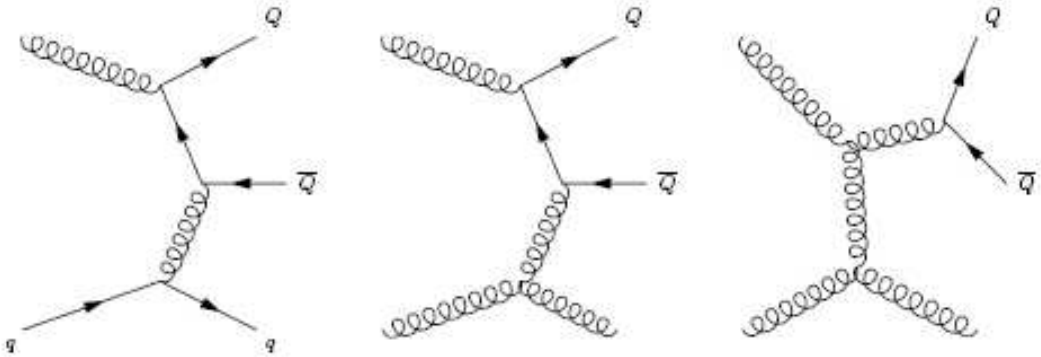


Dominant mechanisms of $Q\bar{Q}$ production

- Leading order processes contributing to $Q\bar{Q}$ production:

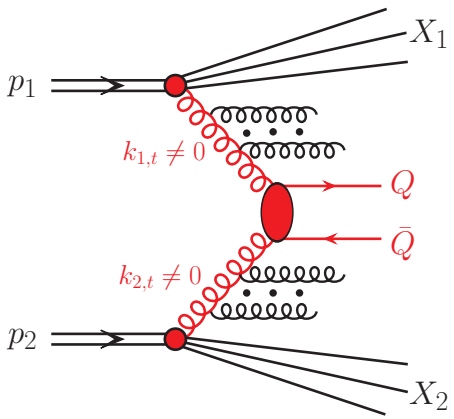


- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
- some of next-to-leading order diagrams:



NLO contributions $\longrightarrow$ K-factor

k_t-factorization (semihard) approach



- charm and bottom quarks production at high energies $\longrightarrow$ gluon-gluon fusion
- QCD collinear approach $\rightarrow$ only inclusive one particle distributions, total cross sections

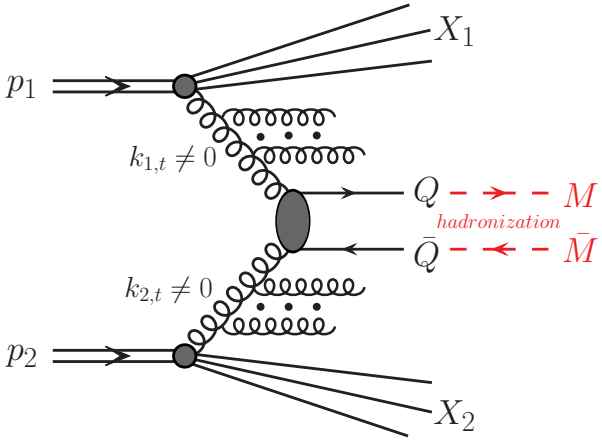
LO k_t-factorization approach $\longrightarrow$ $\kappa_{1,t}, \kappa_{2,t} \neq 0$
$\Rightarrow Q\bar{Q}$ correlations

- multi-differential cross section

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij\to Q\bar{Q}}|^2}$$
$$\times \quad \delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathcal{F}_i(x_1, \kappa_{1,t}^2)\, \mathcal{F}_j(x_2, \kappa_{2,t}^2)$$

- off-shell $\overline{|\mathcal{M}_{gg\to Q\bar{Q}}|^2}$ $\longrightarrow$ Catani, Ciafaloni, Hautmann (rather long formula)
- major part of NLO corrections automatically included
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated parton distributions
- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$,
  $x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2)$, where $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$.

Fragmentation functions technique



- fragmentation functions extracted from e^+e^- data
- often used: Braaten et al., Kartvelishvili et al., Peterson et al.
- rescalling transverse momentum at a constant rapidity (angle)

- from heavy quarks to heavy mesons:

$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

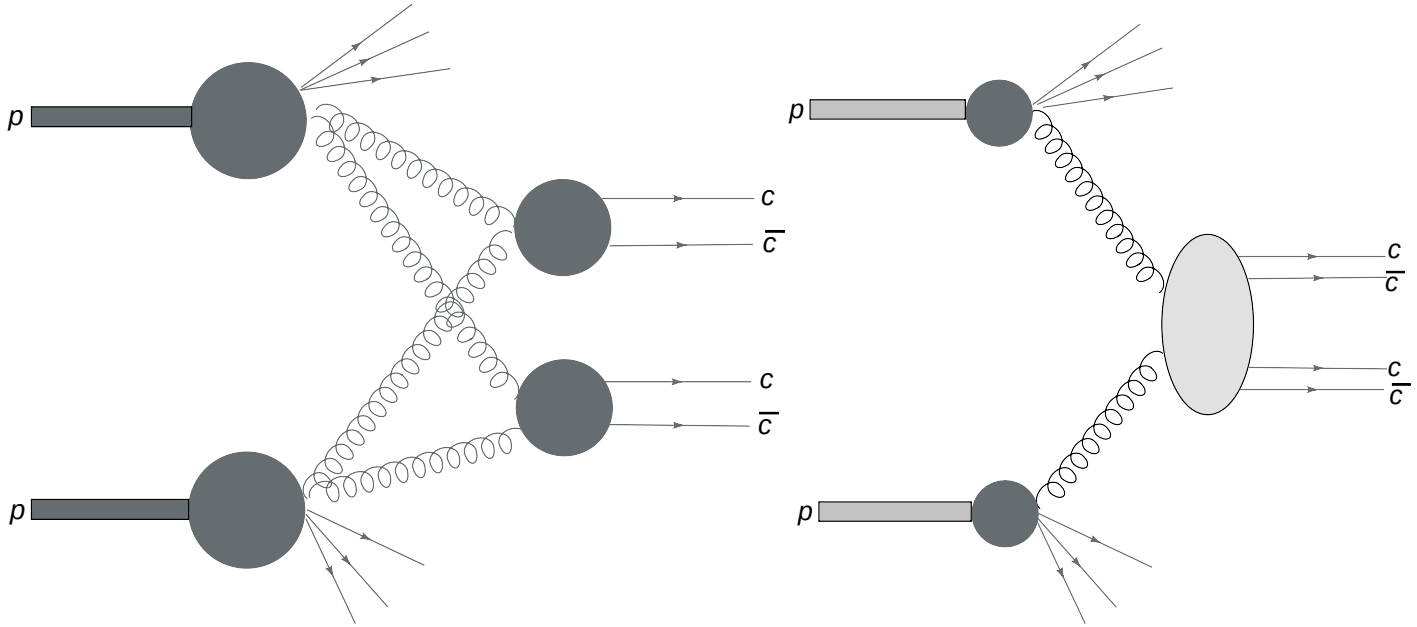
- **approximation:**

  rapidity unchanged in the fragmentation process $\rightarrow y_Q \approx y_M$

Production of D mesons in this framework:

Maciula, Szczurek, Phys. Rev. **D87** (2013) 094022.

Production of $c\bar{c}c\bar{c}$



Łuszczak, Maciuła, Szczurek, Phys. Rev. **D85** (2012) 014905.

Formalism

Consider reaction: $pp \to c\bar{c}c\bar{c}X$

Modeling double-parton scattering

Factorized form:

$$\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}} \sigma^{SPS}(pp \to c\bar{c}X_1) \cdot \sigma^{SPS}(pp \to c\bar{c}X_2).$$

In general σ_{eff} can depend on kinematics The simple formula above can be generalized to include differential distributions

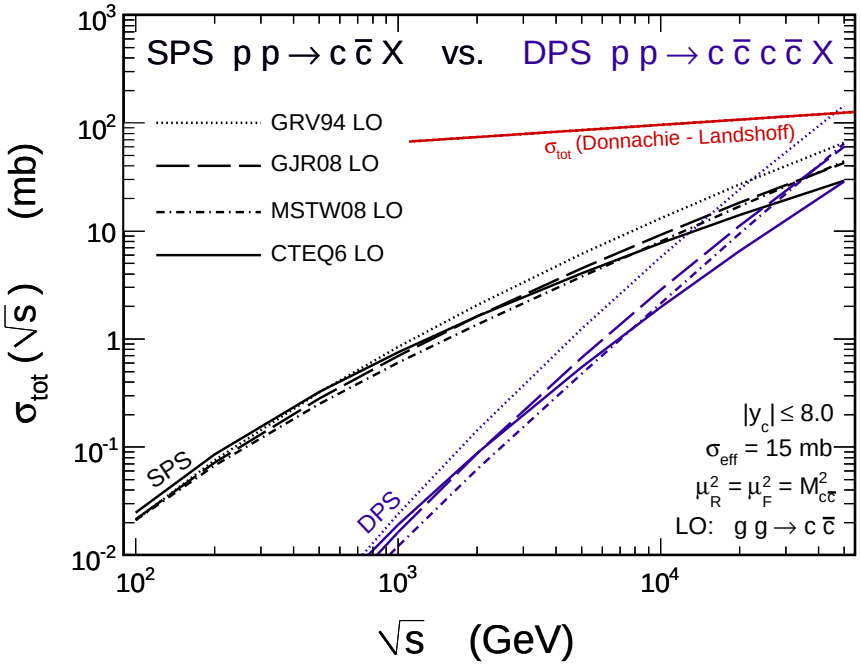
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 dy_2 d^2p_{1t}} \cdot \frac{d\sigma}{dy_3 dy_4 d^2p_{2t}} .$$

σ_{eff} is a model parameter (15 mb).

Found e.g. from experimental analysis of four jets (see also Siódmok et al.)

In principle does not need to be universal.

Energy dependence of $c\bar{c}c\bar{c}$ production



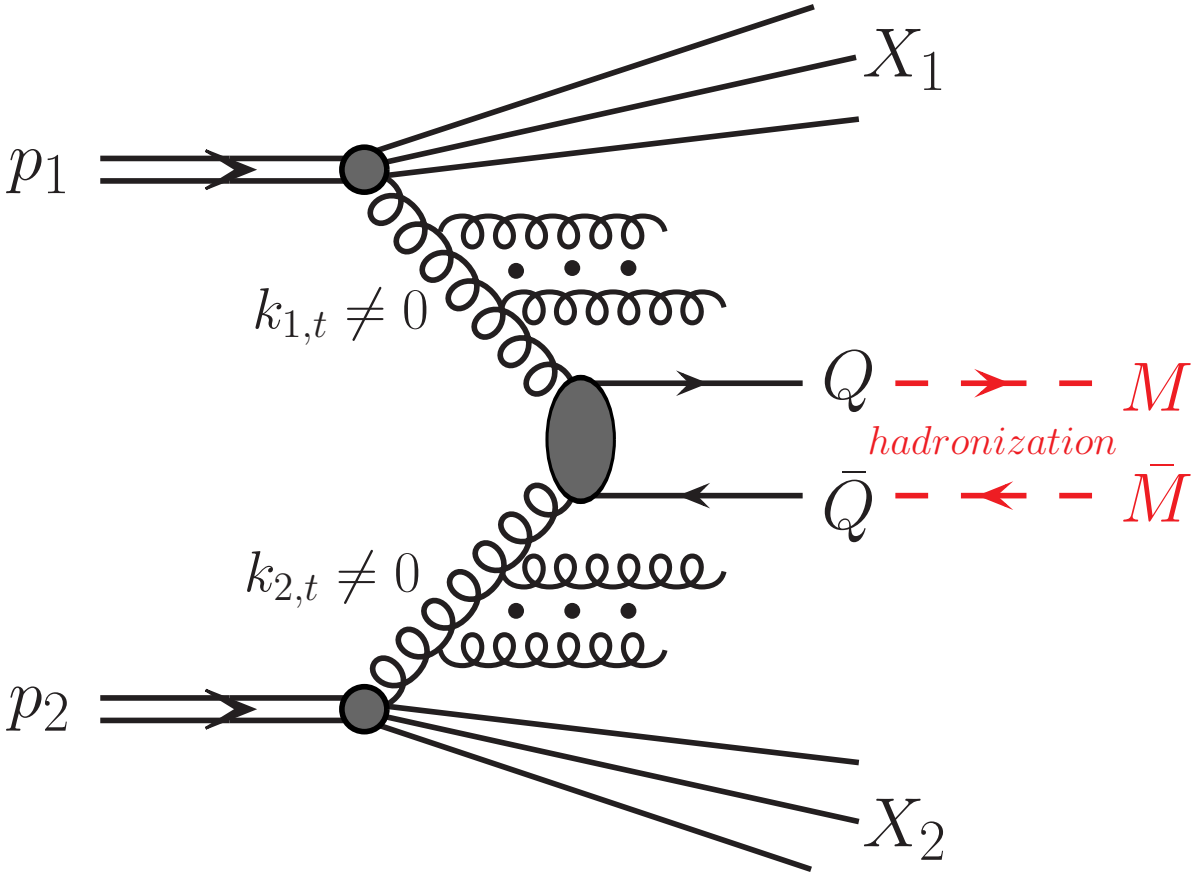
Luszczak,Maciula,Szczurek, Phys. Rev. **C86** (2012) 014905

spectacular result:

Already at the LHC production of two pairs as probable as production of one pair.

DPS in k_t-factorization

each step:



DPS in k_t-factorization

Generalize the LO collinear approach to k_t-factorization approach.

More complicated (more kinematical variables) as momenta of outgoing partons are less correlated

We need information about each quark and antiquark

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma}{dy_3 dy_3 d^2p_{3,t} d^2p_{4,t}} \tag{10}$$

DPS in k_t-factorization

Each individual scattering in the k_t-factorization approach

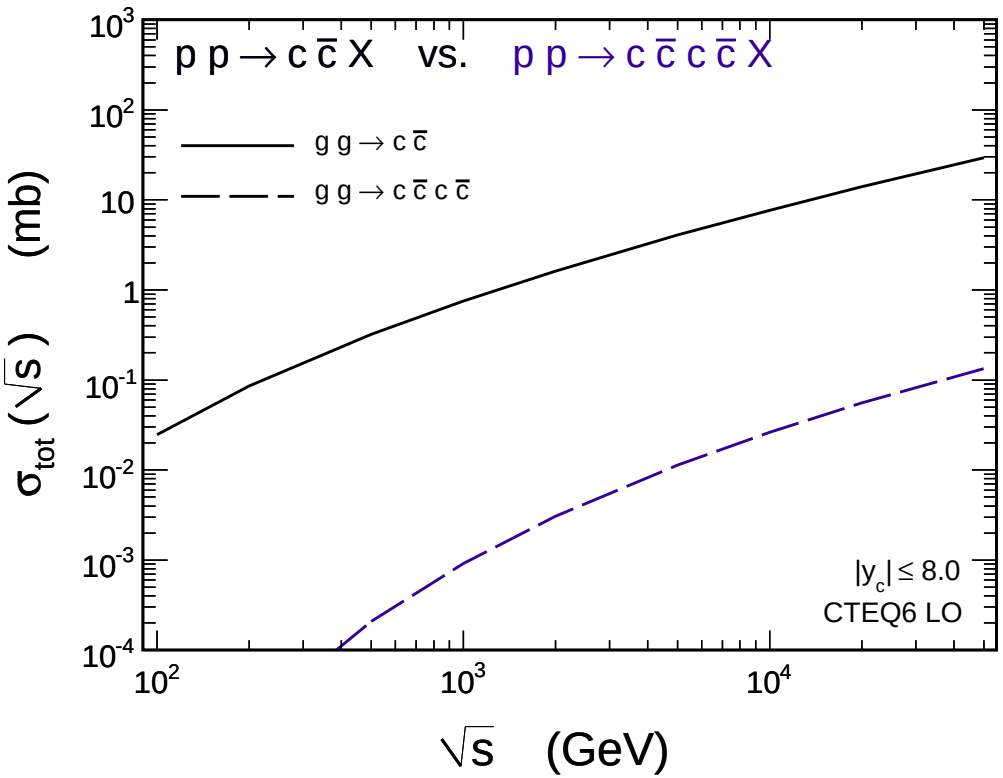
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2}$$
$$\int \overline{|\mathcal{M}_{off}|^2} \delta\left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}\right) \mathcal{F}\left(x_1, k_{1t}^2, \mu^2\right) \mathcal{F}\left(x_2, k_{2t}^2, \mu^2\right) \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi}$$

$$\frac{d\sigma}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{16\pi^2 \hat{s}^2}$$
$$\int \overline{|\mathcal{M}_{off}|^2} \delta\left(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t}\right) \mathcal{F}\left(x_3, k_{3t}^2, \mu^2\right) \mathcal{F}\left(x_4, k_{4t}^2, \mu^2\right) \frac{d^2k_{3t}}{\pi} \frac{d^2k_{4t}}{\pi}$$

Effectively 16 dimensions, Monte Carlo method

Maciula-Szczurek, hep-ph-1301.4469, Phys. Rev.**D87** (2013) 074039.

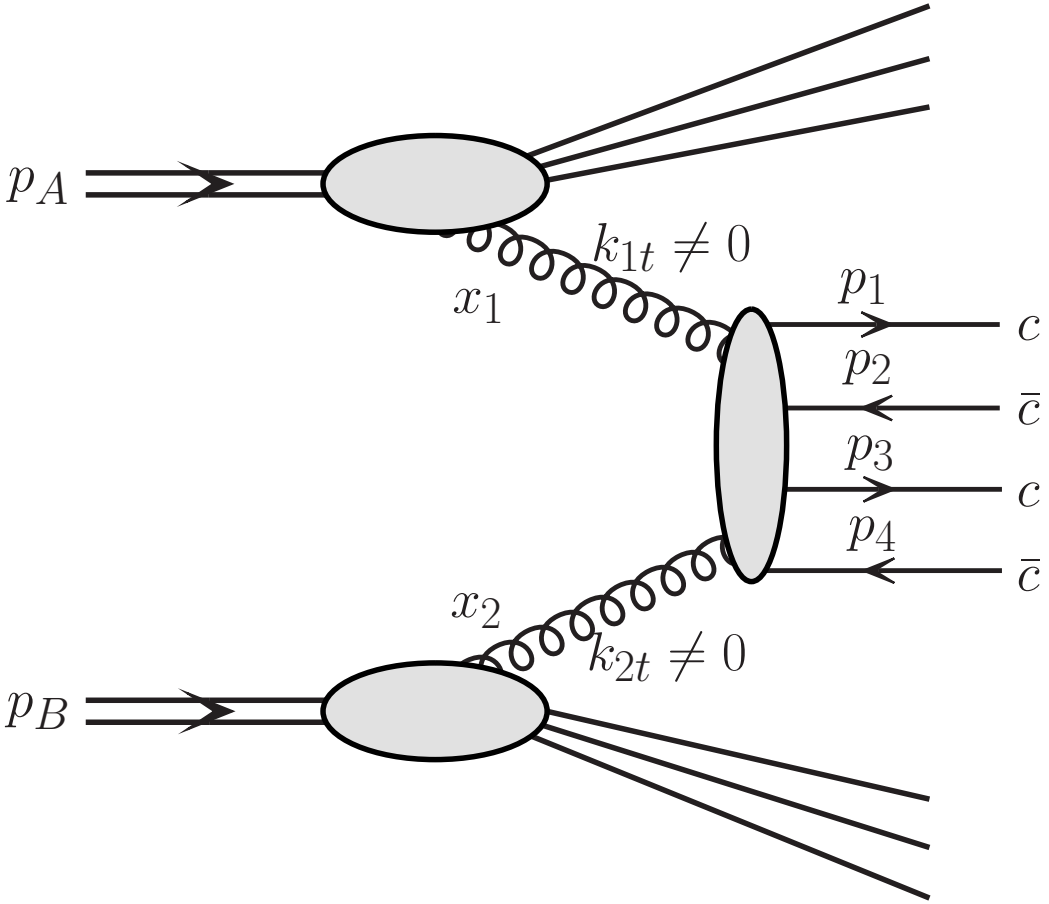
Single parton scattering 2 → 4 process?



Only about 1 % at high energies

Much smaller than DPS production of $c\bar{c}c\bar{c}$

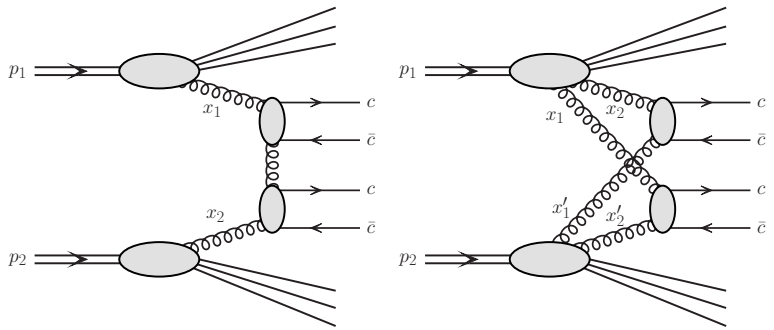
SPS in k_t-factorization approach



include gluon transverse momenta

A. van Hameren, R. Maciula and A. Szczurek, arXiv:1504.06490, Phys. Lett. **B748** (2015) 737.

SPS vs. DPS: Inclusive $c\bar{c}c\bar{c}$ LHCb at $\sqrt{s} = 7$ TeV



CHARM MESON-MESON pair production:

DD pairs – both mesons containing *c*-quarks

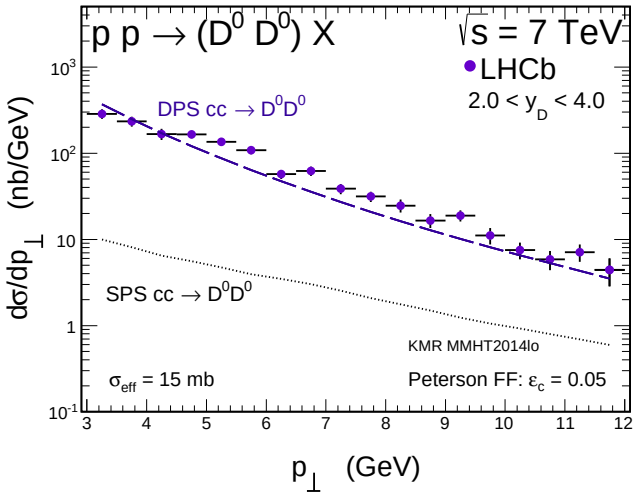
- impossible to be produced within standard SPS single $c\bar{c}$ mechanism
- SPS double charm very small

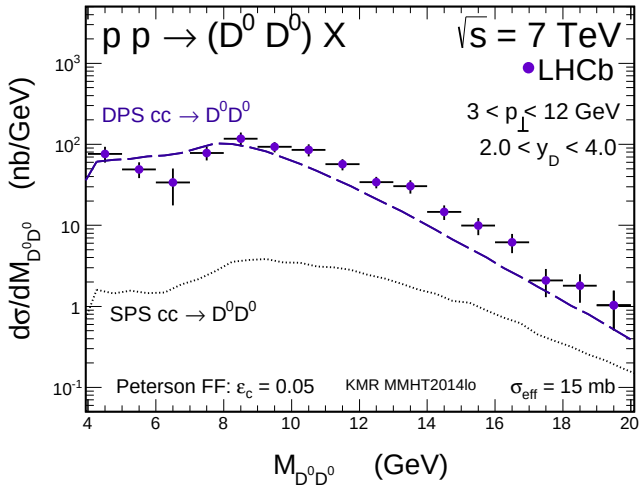
First measurement by LHCb: J. High Energy Phys. 06, 141 (2012)

Cross section much larger than the SPS predictions

$\Rightarrow$ clear evidence for DPS?

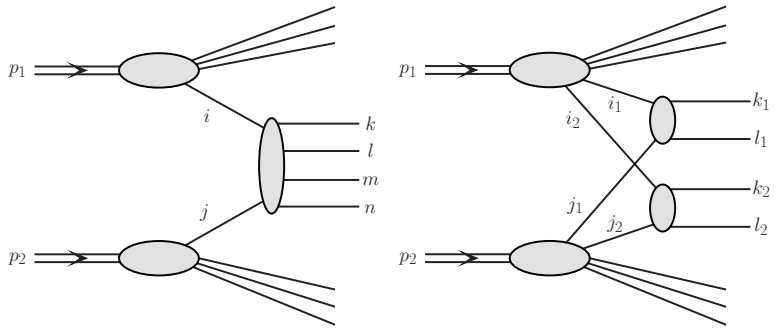
Mode	σ [nb]
D^0D^0	$690 \pm 40 \pm 70$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$





Łuszczak, Maciuła, Szczurek, Phys.Rev. D85 (2012) 094034
Maciuła, Szczurek, Phys.Rev. D87 (2013) no.7, 074039
Hameren, Maciuła, Szczurek, Phys.Rev. D89 (2014) no.9, 094019

SPS vs. DPS: Inclusive 4jets $\sqrt{s} = 13$ TeV



Optimal conditions for exploring DPS effects:

- keep jet-p_T's as low as possible:

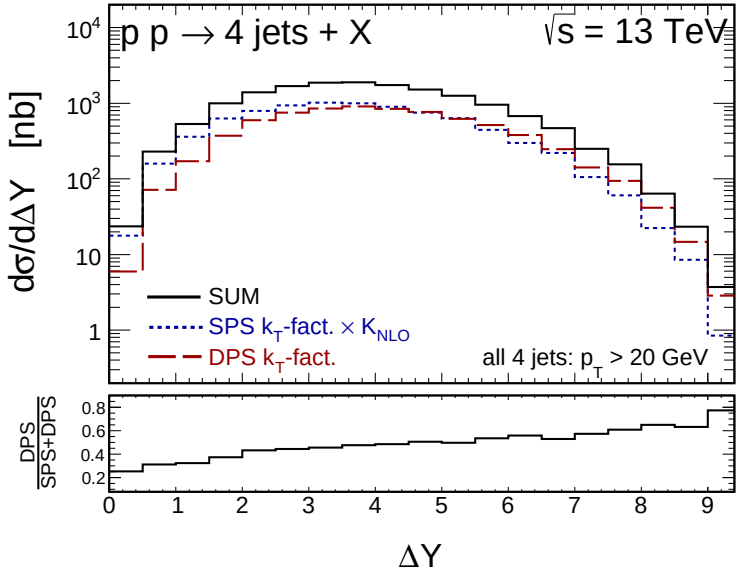
  symmetric: all 4 jets with $p_T > 20$ GeV

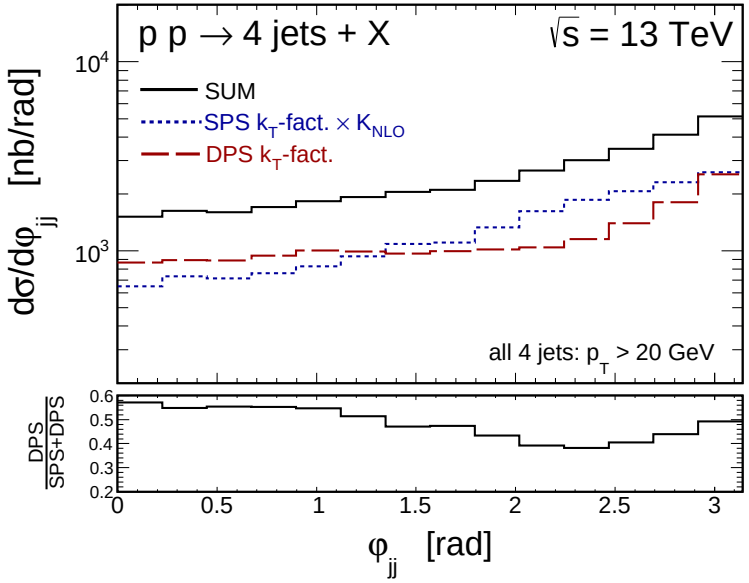
  asymmetric: 1st jet: $p_T > 35$ GeV

  $2^{nd}, 3^{rd}, 4^{th}$ jet: $p_T > 20$ GeV

- concentrate on jets most remote in rapidity

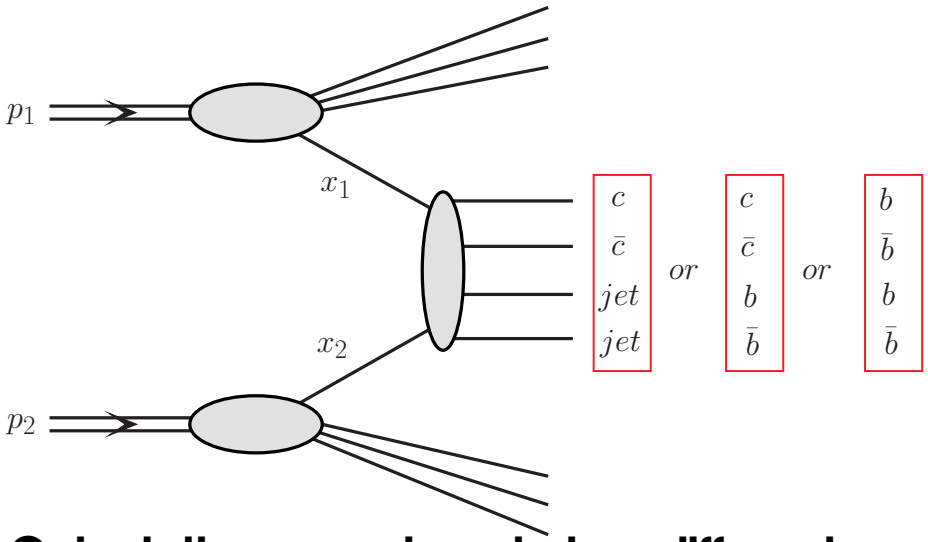
Maciuła, Szczurek, Phys.Lett. B749 (2015) 57-62
Kutak, Maciuła, Serino, Szczurek, Hameren, Phys.Rev. D94 (2016) no.1, 014019





- large rapidity distances between the most remote jets
- small azimuthal angles between the two jets most remote in rapidity

Single-Parton Scattering (SPS) mechanism



2 → 4 pQCD subprocesses:

9 channels for $c\bar{c} + 2\text{jets}$

$g\,g \to g\,g\,c\,\bar{c}$	$q\,\bar{q} \to q'\,\bar{q}'\,c\,\bar{c}$
$g\,g \to q\,\bar{q}\,c\,\bar{c}$	$q\,\bar{q} \to g\,g\,c\,\bar{c}$
$g\,q \to g\,q\,c\,\bar{c}$	$q\,q \to q\,q\,c\,\bar{c}$
$q\,g \to q\,g\,c\,\bar{c}$	$q\,q' \to q\,q'\,c\,\bar{c}$
$q\,\bar{q} \to q\,\bar{q}\,c\,\bar{c}$	

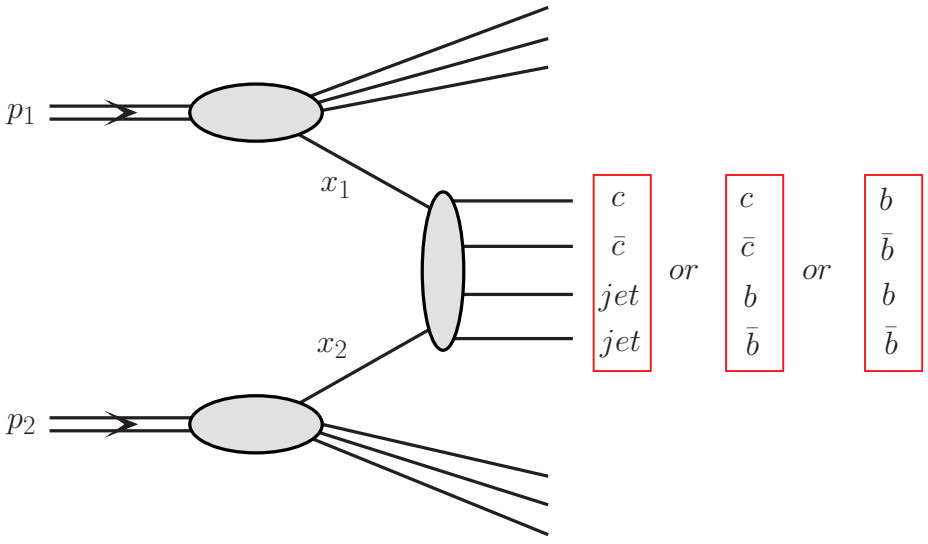
2 channels for $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$

$g\,g \to c\,\bar{c}\,b\,\bar{b}$	$q\,\bar{q} \to c\,\bar{c}\,b\,\bar{b}$
$g\,g \to b\,\bar{b}\,b\,\bar{b}$	$q\,\bar{q} \to b\,\bar{b}\,b\,\bar{b}$

Calculations are done in two different ways:

- LO collinear parton-model approach
- NEW: k_T-factorization approach with fully gauge-invariant tree-level 2 → 4 off-shell matrix elements
  - first time: off-shell initial state partons
  - exact kinematics from the very beginning and additional hard dynamics coming form transverse momenta of incident partons
  - part of higher-order (real) corrections included (depending on the model of unintegrated, transverse momentum dependent PDFs)

Single-Parton Scattering (SPS) mechanism



2 → 4 pQCD subprocesses:

9 channels for $c\bar{c} + 2\text{jets}$

$g\,g \to g\,g\,c\,\bar{c}$	$q\,\bar{q} \to q'\,\bar{q}'\,c\,\bar{c}$
$g\,g \to q\,\bar{q}\,c\,\bar{c}$	$q\,\bar{q} \to g\,g\,c\,\bar{c}$
$g\,q \to g\,q\,c\,\bar{c}$	$q\,q \to q\,q\,c\,\bar{c}$
$q\,g \to q\,g\,c\,\bar{c}$	$q\,q' \to q\,q'\,c\,\bar{c}$
$q\,\bar{q} \to q\,\bar{q}\,c\,\bar{c}$	

2 channels for $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$

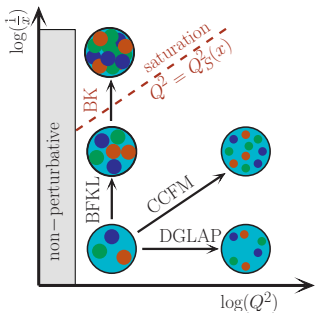
$g\,g \to c\,\bar{c}\,b\,\bar{b}$	$q\,\bar{q} \to c\,\bar{c}\,b\,\bar{b}$
$g\,g \to b\,\bar{b}\,b\,\bar{b}$	$q\,\bar{q} \to b\,\bar{b}\,b\,\bar{b}$

KaTie (A. van Hameren): https://bitbucket.org/hameren/KaTie arXiv:1611.00680

basics of the theory behind: Kutak, Kotko, Hameren, J. High Energy Phys. 01 (2013) 078;
Kutak, Salwa, Hameren, Phys.Lett. B727 (2013) 226-233

- complete Monte Carlo program for tree-level calculations of any process within the Standard Model
- any initial-state partons on-shell or off-shell
- scattering amplitudes are calculated numerically via Dyson-Schwinger recursion generalized also to tree-level off-shell amplitudes
- double-parton scattering available too!

Unintegrated parton distribution functions (uPDFs)

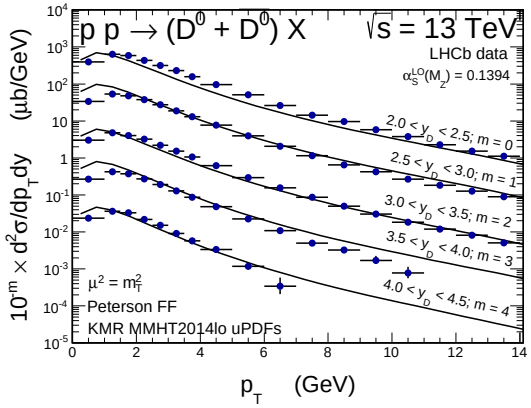


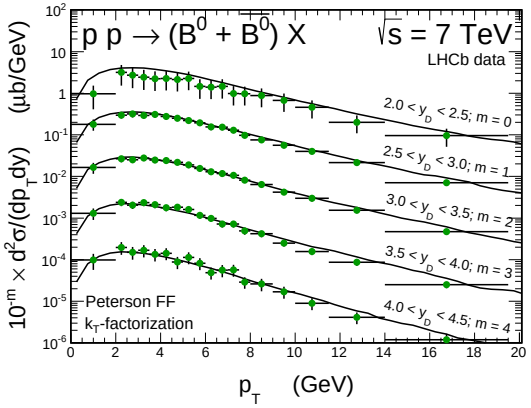
Most popular models:

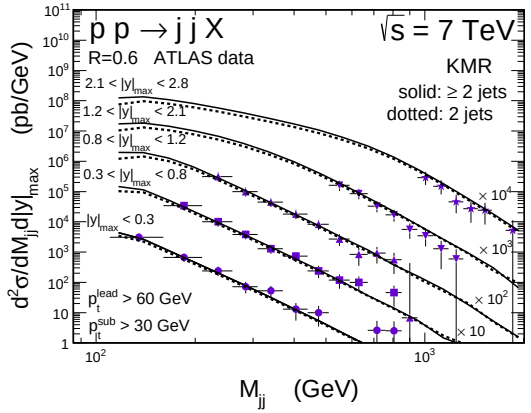
- Kwieciński, Jung (CCFM, wide range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small x-values)
- Kutak-Staśto (BK, saturation, only small x-values)

We use: Kimber-Martin-Ryskin (KMR) approach:

- calculated from collinear PDFs (most up-to-date PDF sets can be used)
- unintegrated quarks available (important for reliable predictions for jets)
- unique feature: possible additional hard emission from the uPDF (part of higher order corrections)



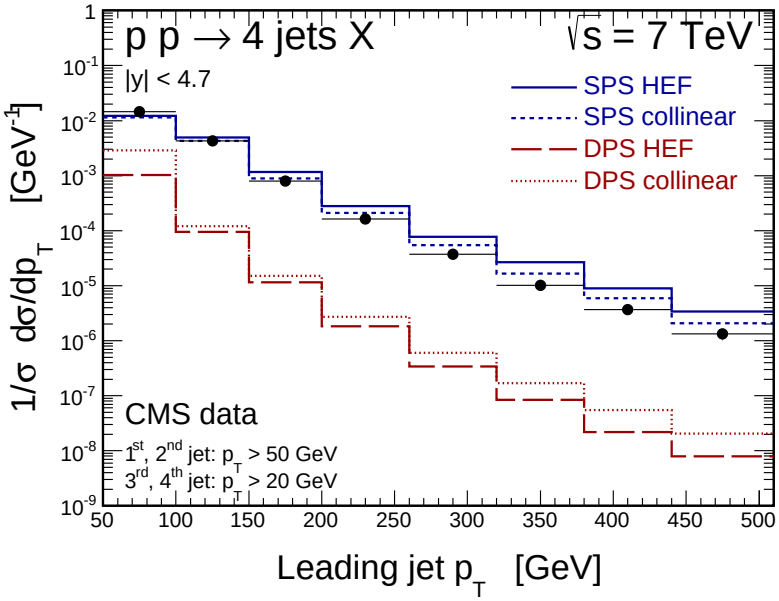


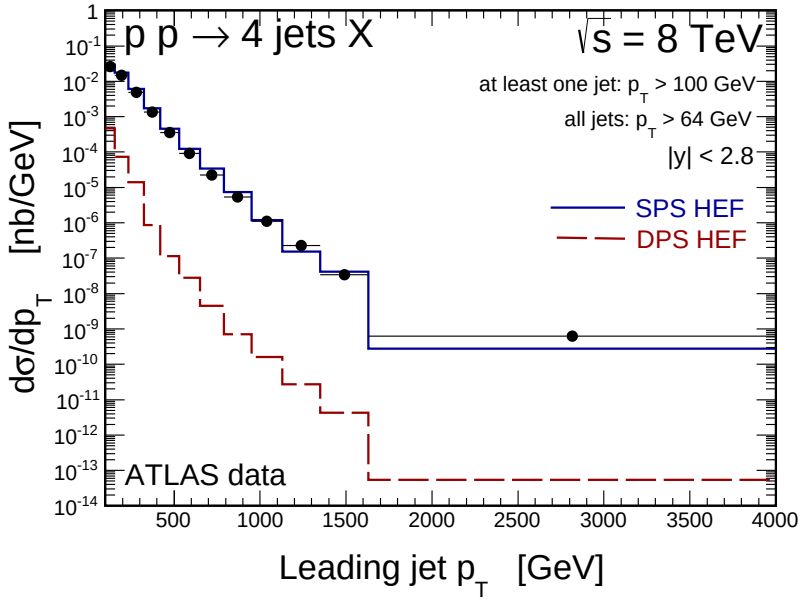


- works well for inclusive charm, bottom and inclusive dijet at the LHC
- good starting point for DPS predictions for $c\bar{c} + 2\text{jets}$, $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$

Inclusive 4jets CMS, ATLAS at $\sqrt{s} = 7, 8$ TeV

Testing SPS 2 → 4 calculations: KaTie + KMR uPDFs in multi-jet production

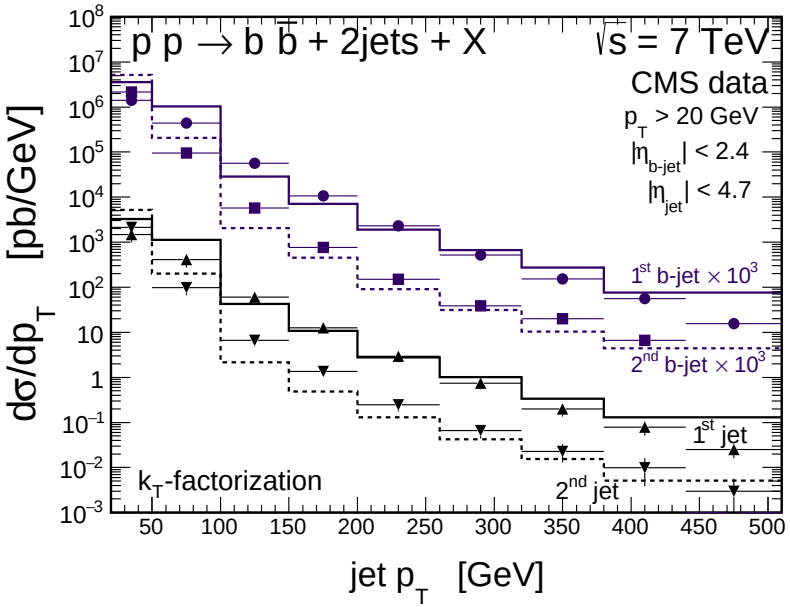


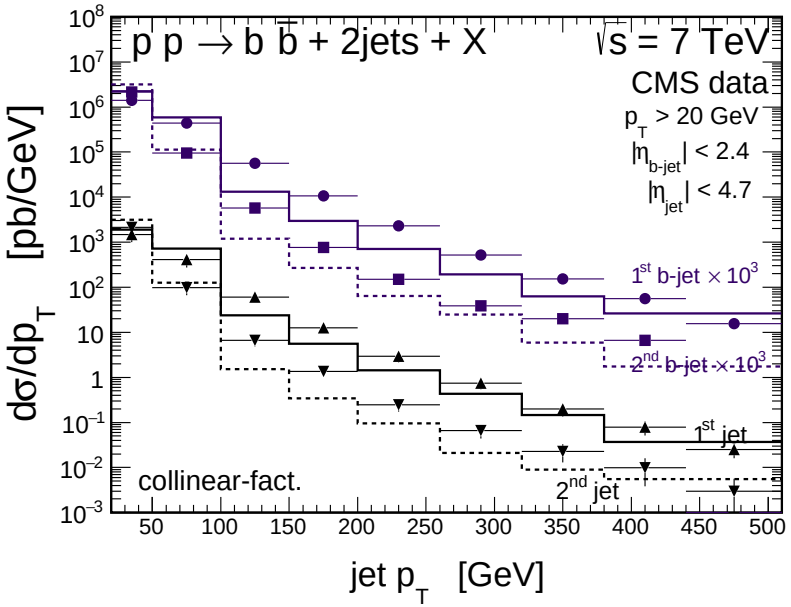


- CMS and ATLAS data described by the SPS mechanism
- DPS mechanism strongly suppressed by too hard jet-p_T cuts
- KaTie + KMR uPDFs gives reasonable description of the data sets

Inclusive $2b + 2j$ CMS at $\sqrt{s} = 7$ TeV

Testing SPS 2 → 4 calculations: KaTie + KMR uPDFs in multi-jet production





- CMS data described with the SPS mechanism
- DPS effects in hard-p_T b-flavour production are expected to be negligible
- KaTie + KMR uPDFs gives reasonable description of the data sets (p_T-slope better described than in the collinear case)

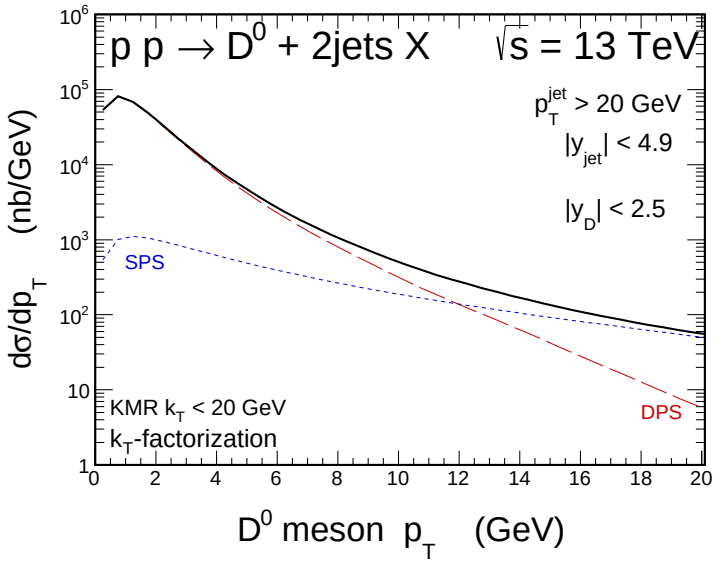
Inclusive $D^0 + 2\text{jets}$ $\sqrt{s} = 13$ TeV

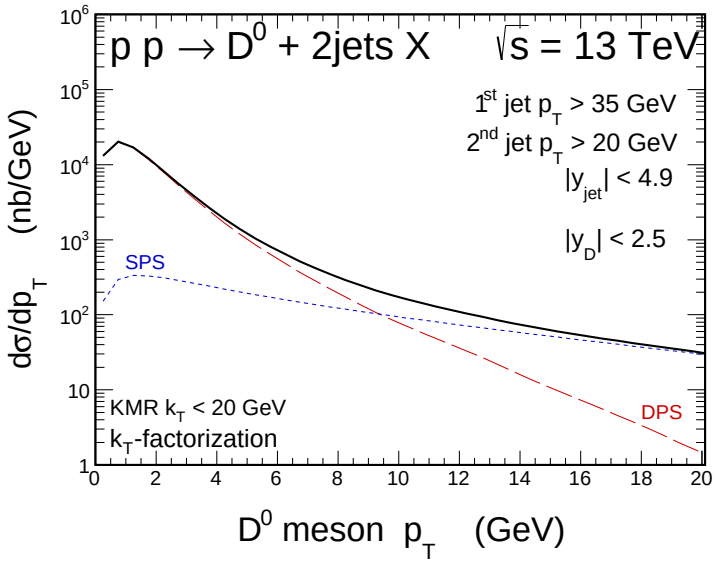
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

D^0 meson (or $\overline{D^0}$ antimeson): $|y| < 2.5$, $p_T > 3.5$ GeV both jets: $|y| < 4.9$, $R_{cone} = 0.5$

experimental jet-p_T mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20$ GeV	3.74	18.49	83 %
$p_T^{lead} > 35$ GeV, $p_T^{sub} > 20$ GeV	1.76	4.52	72 %
$p_T^{lead} > 50$ GeV, $p_T^{sub} > 35$ GeV	0.43	1.25	74 %

- large cross sections (μb)
- DPS dominated samples





Evident enhancement in the region of $p_T \lesssim 10$ GeV because of the presence of the DPS mechanism

Inclusive $D^0 + 2$jets $\sqrt{s} = 13$ TeV

The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

D^0 meson (or $\overline{D^0}$ antimeson): $|y| < 2.5$, $p_T > 3.5$ GeV both jets: $|y| < 4.9$, $R_{cone} = 0.5$

experimental jet-p_T mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
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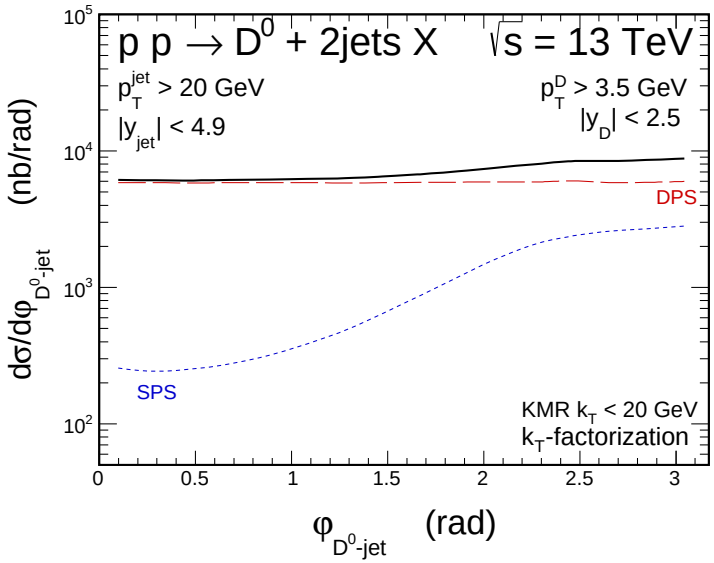
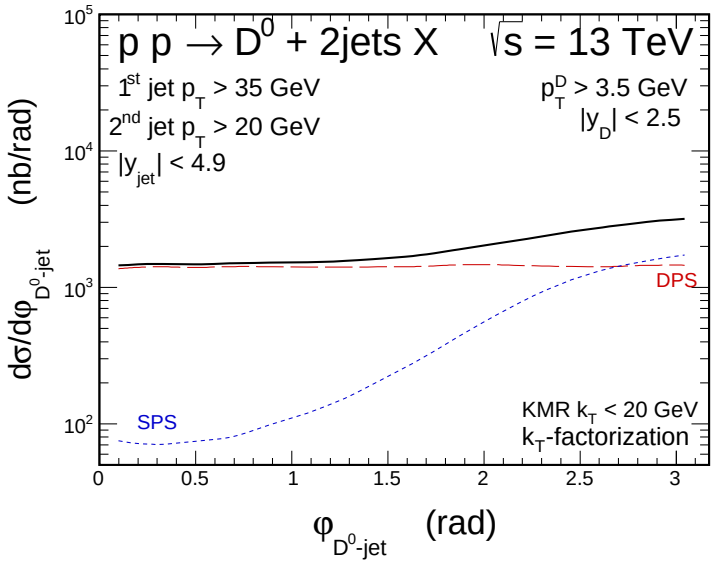
- large cross sections (μb)
- DPS dominated





Almost decorrelated distribution in $\varphi_{D^0\text{-}jet}$ azimuthal angle because of the presence of the DPS mechanism

Inclusive $D^0\overline{D^0} + 2\text{jets}$ $\sqrt{s} = 13$ TeV

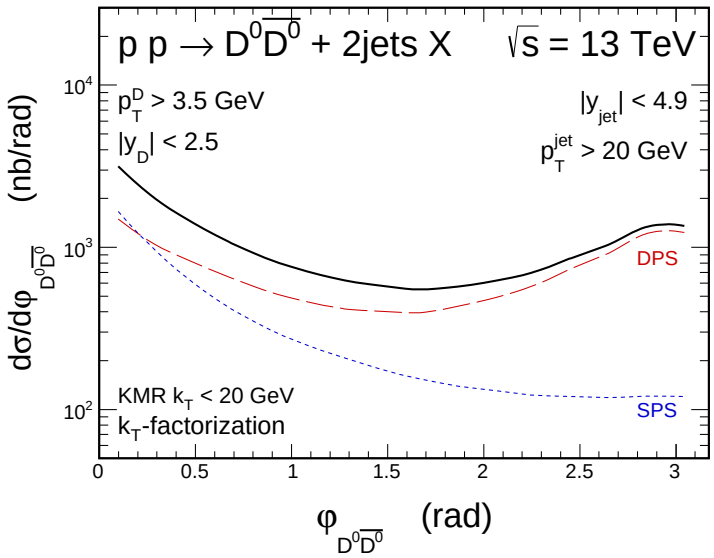
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

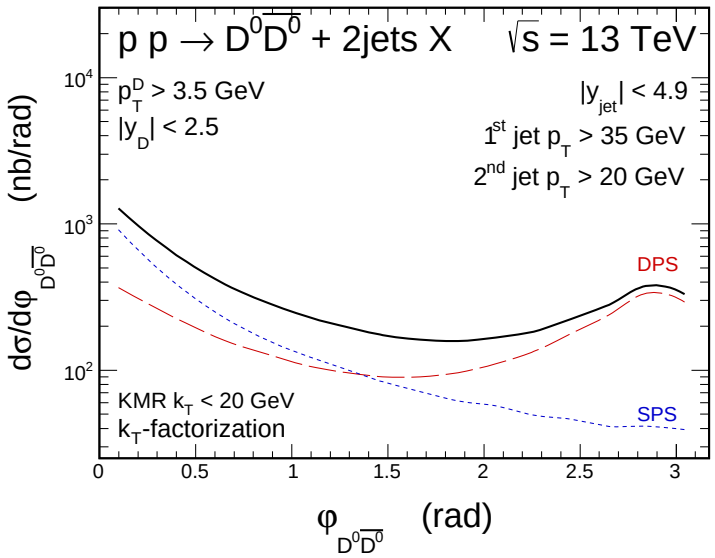
both, D^0 meson and $\overline{D^0}$ antimeson: $|y| < 2.5$, $p_T > 3.5$ GeV

both jets: $|y| < 4.9$, $R_{cone} = 0.5$

experimental jet-p_T mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20$ GeV	1.10	2.35	68 %
$p_T^{lead} > 35$ GeV, $p_T^{sub} > 20$ GeV	0.55	0.58	51 %
$p_T^{lead} > 50$ GeV, $p_T^{sub} > 35$ GeV	0.15	0.14	52 %

- smaller than in the single-D case but still large
- the relative DPS contribution slightly reduced





Evident enhancement in the region of $\varphi_{D^0\overline{D^0}} \gtrsim \frac{\pi}{2}$ because of the presence of the DPS mechanism

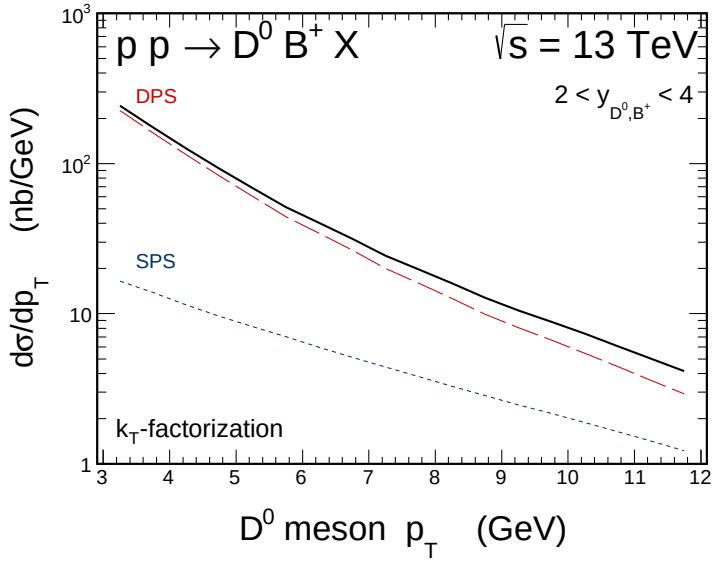
Inclusive D^0B^+ $\sqrt{s} = 7, 13$ TeV

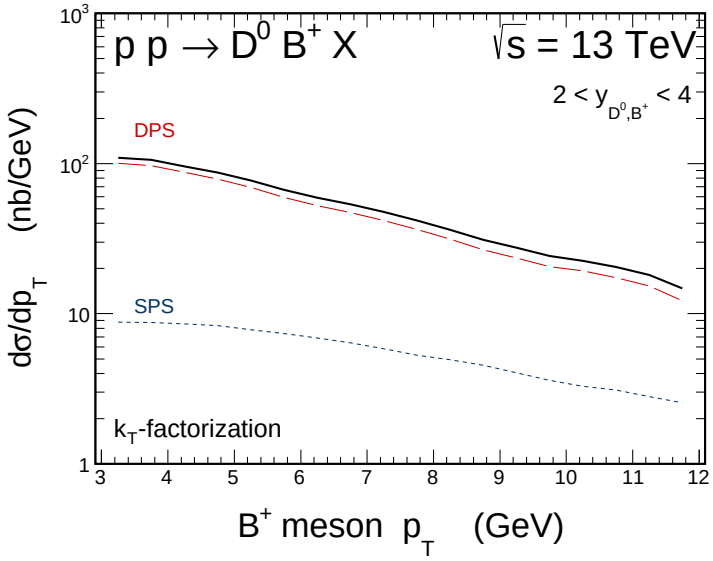
The calculated "visible" cross sections in nanobarns for the LHCb detector acceptance:

D^0 and B^+ meson (or $\overline{D^0}$ and B^- antimeson): $2 < y < 4$, $3 < p_T < 12$ GeV

Final state	Mechanism	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
$D^0B^+ + \bar{D}^0B^-$	DPS	115.50	418.79
	SPS	21.13	51.46

- large cross sections (nb)
- DPS dominated samples





Evident enhancement in the whole region of considered p_T's because of the presence of the DPS mechanism

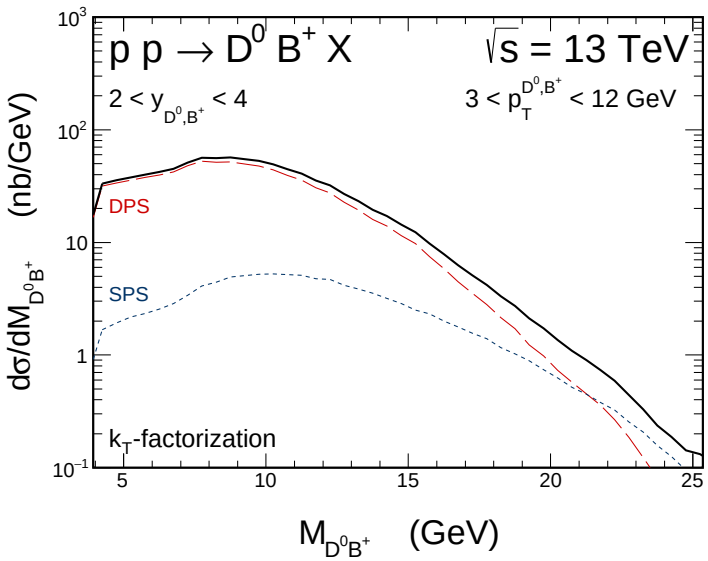
Inclusive D^0B^+ $\sqrt{s} = 7, 13$ TeV

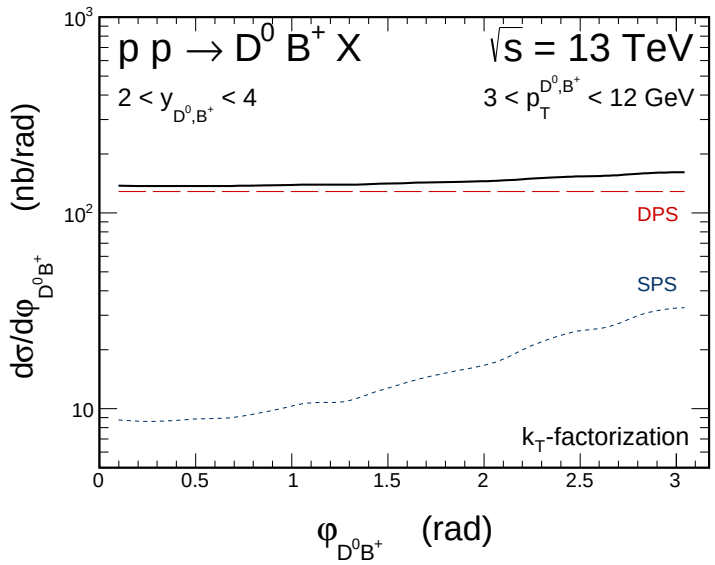
The calculated "visible" cross sections in nanobarns for the LHCb detector acceptance:

D^0 and B^+ meson (or $\overline{D^0}$ and B^- antimeson): $2 < y < 4$, $3 < p_T < 12$ GeV

Final state	Mechanism	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
$D^0B^+ + \bar{D}^0B^-$	DPS	115.50	418.79
	SPS	21.13	51.46

- large cross sections (nb)
- DPS dominated samples





- Evident enhancement in the region of $M_{D^0B^+} < 15$ GeV
- Almost decorrelated distribution in $\varphi_{D^0B^+}$ azimuthal angle

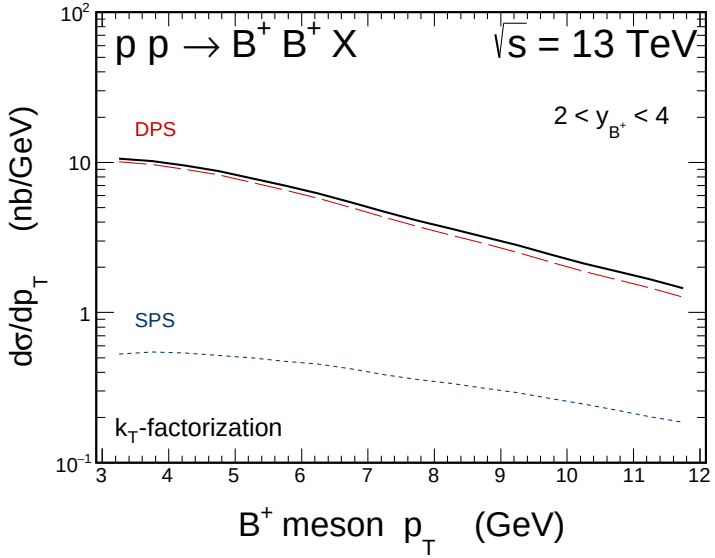
Inclusive B^+B^+ $\sqrt{s} = 7, 13$ TeV

The calculated "visible" cross sections in nanobarns for the LHCb detector acceptance:

both B^+ mesons (or both B^- antimesons): $2 < y < 4$, $3 < p_T < 12$ GeV

Final state	Mechanism	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
$B^+B^+ + B^-B^-$	DPS	11.04	43.40
	SPS	1.31	3.39

- large cross sections (nb)
- DPS dominated samples



Evident enhancement in the whole region of considered p_T's because of the presence of the DPS mechanism

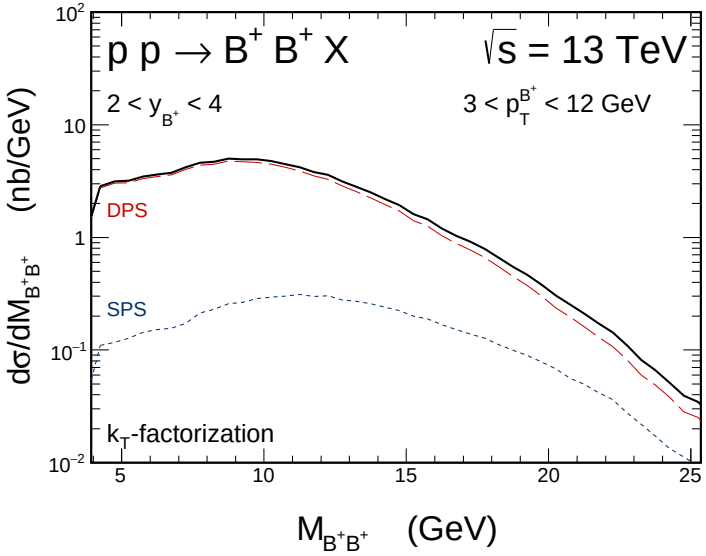
Inclusive B^+B^+ $\sqrt{s} = 7, 13$ TeV

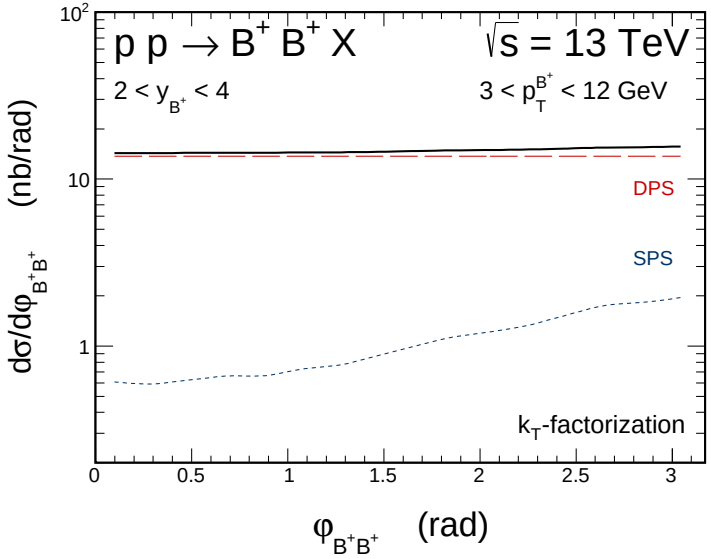
The calculated "visible" cross sections in nanobarns for the LHCb detector acceptance:

both B^+ mesons (or both B^- antimesons): $2 < y < 4$, $3 < p_T < 12$ GeV

Final state	Mechanism	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
$B^+B^+ + B^-B^-$	DPS	11.04	43.40
	SPS	1.31	3.39

- large cross sections (nb)
- DPS dominated samples

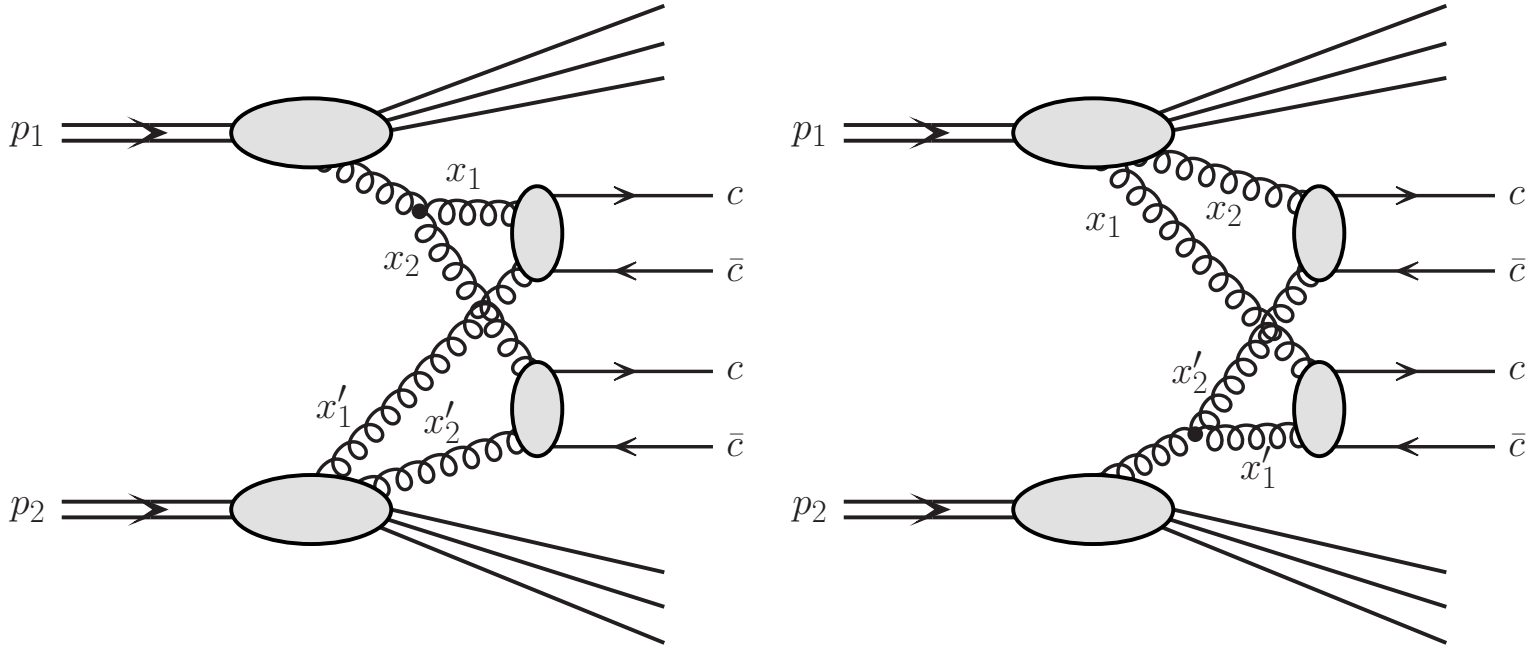




- Evident enhancement in the region of $M_{B^+B^+} < 20$ GeV
- Almost decorrelated distribution in $\varphi_{B^+B^+}$ azimuthal angle

Parton splitting mechanism

There are perturbative mechanisms not included in conventional DPS.



Gaunt, Maciuła, Szczurek, Phys. Rev. **D90** (2014) 054017.

A bit of formalism for parton splitting

Conventional DPS:

$$\sigma(2v2) = \frac{1}{2}\frac{1}{\sigma_{eff,2v2}}\int dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}\frac{1}{16\pi\hat{s}^2}\overline{|\mathcal{M}(gg\to c\bar{c})|^2}\, x_1 x_1' x_2 x_2' \times D^{gg}(x_1,x_2,\mu_1^2,\mu_2^2)\, D^{gg}(x_1,x_2,\mu_1^2,\mu_2^2)$$

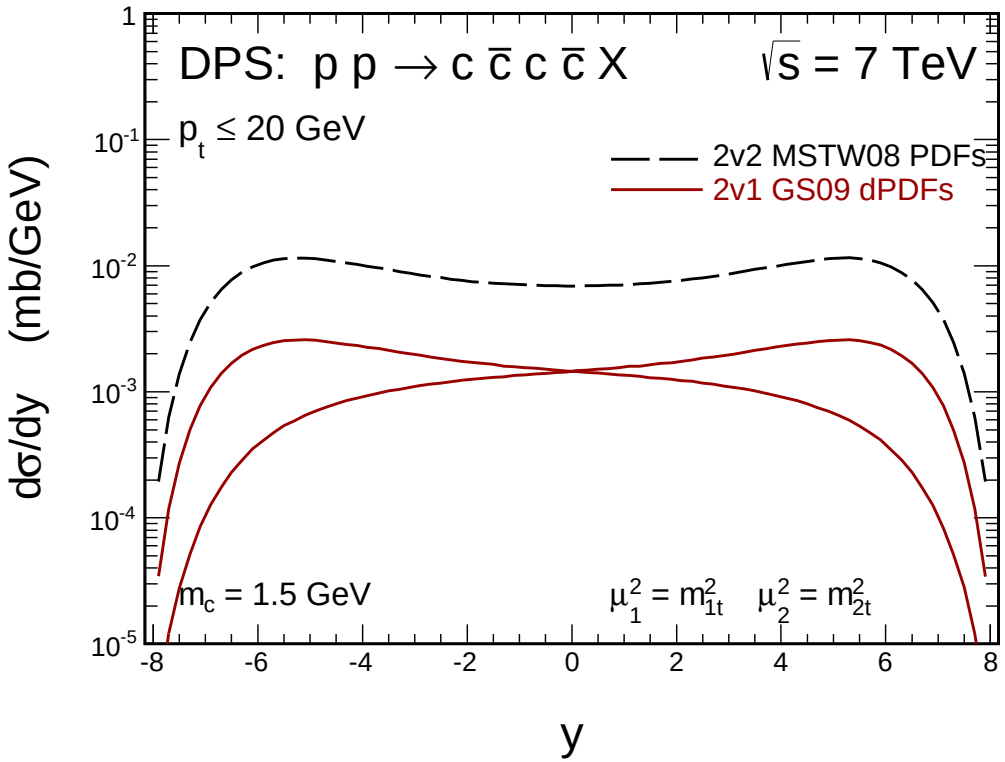
Parton splitting DPS

$$\sigma(2v1) = \frac{1}{2}\frac{1}{\sigma_{eff,2v1}}\int dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}\frac{1}{16\pi\hat{s}^2}\overline{|\mathcal{M}(gg\to c\bar{c})|^2}\, x_1 x_1' x_2 x_2' \times \left(\hat{D}^{gg}(x_1',x_2',\mu_1^2,\mu_2^2)D^{gg}(x_1,x_2,\mu_1^2,\mu_2^2) + D^{gg}(x_1',x_2',\mu_1^2,\mu_2^2)\hat{D}^{gg}(x_1,x_2,\mu_1^2,\mu\right.$$

There are two different normalization parameters. They are related in a geometrical picture.

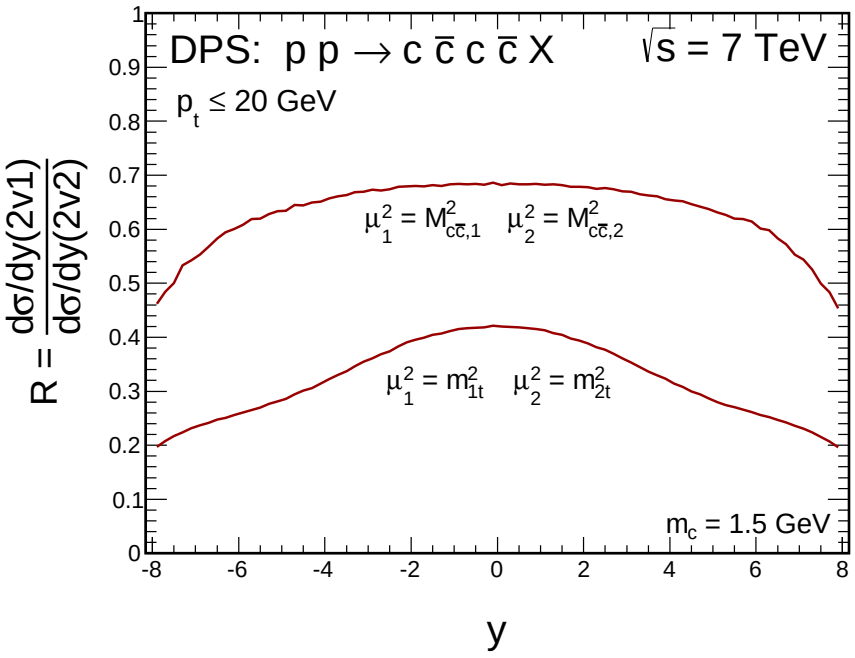
Presence of the two components leads to a dependence of effective parameter on different kinematical variables.

Parton splitting vs conventional DPS



Asymmetric 1*v*2 and 2*v*1 contributions

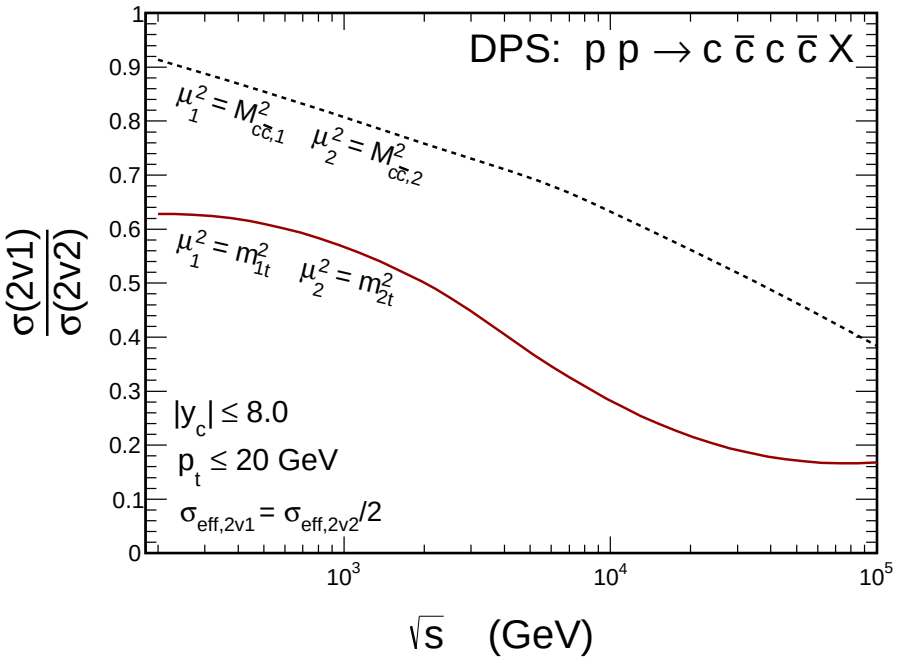
Parton splitting vs conventional DPS



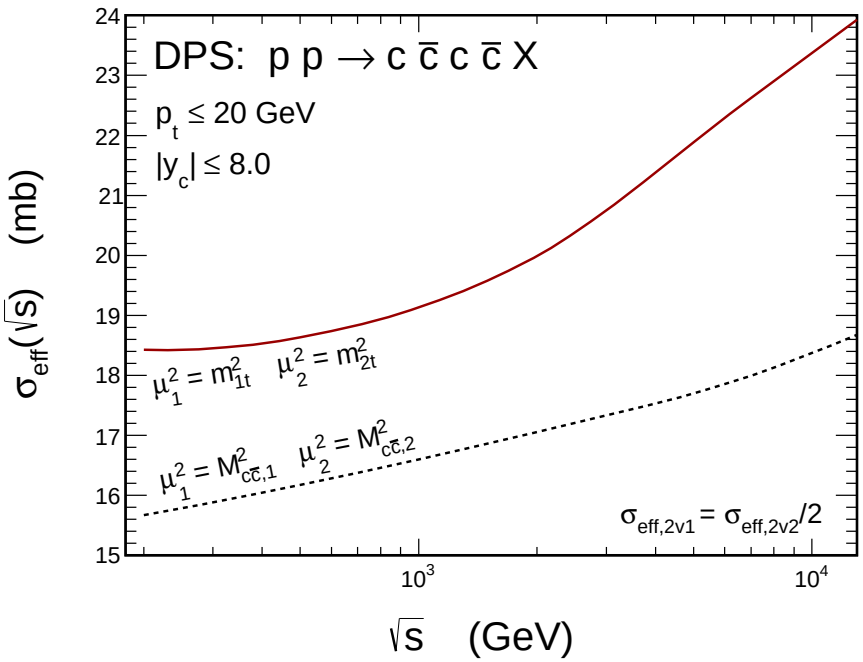
Rapidity and factorization scale dependence

There could be also transverse momentum dependence.

Parton splitting vs conventional DPS

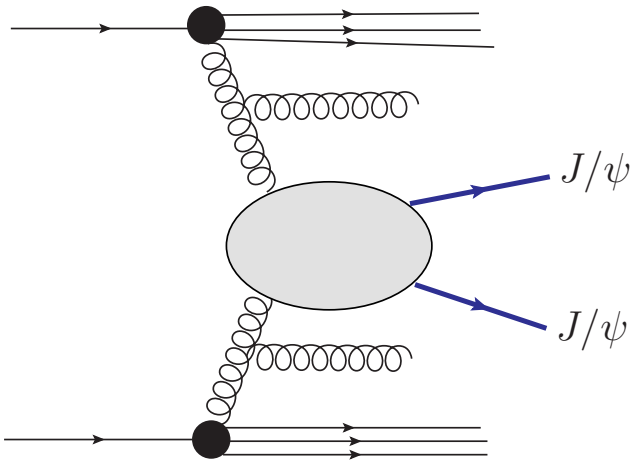


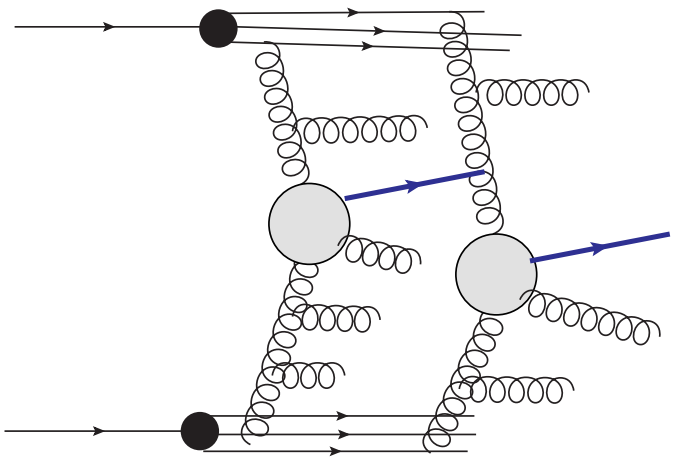
Parton splitting vs conventional DPS



σ_{eff} is no longer a constant

Mechanisms included for $J/\psi J/\psi$





Both single and double parton scattering contributions

Mechanisms included for $J/\psi J/\psi$

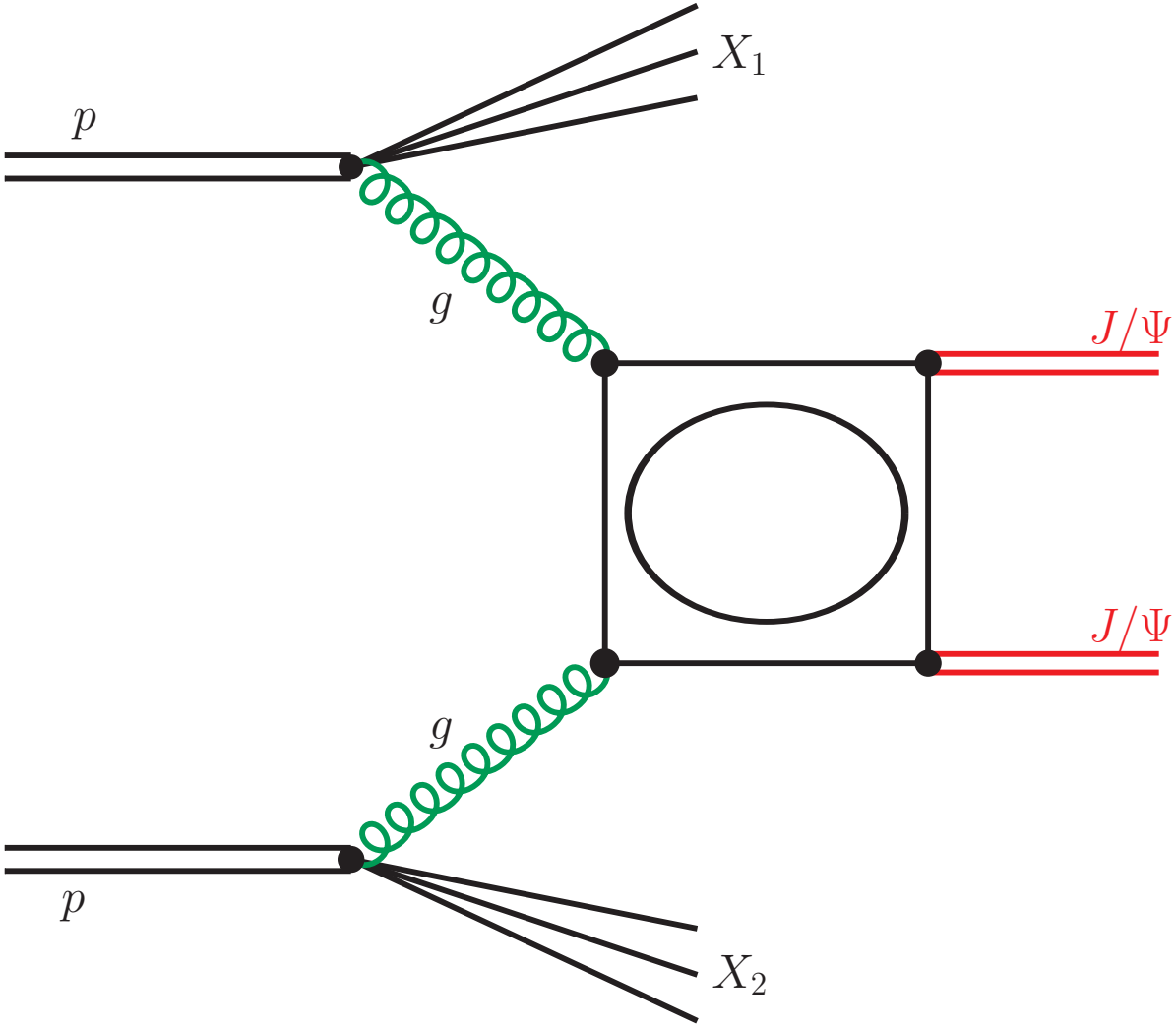
1. Leading order box contribution in k_t-factorization approach.
2. Double parton scattering mechanism (data driven).
3. Two-gluon exchange (collinear factorization).
4. Production of $\chi_c(J_1)\chi_c(J_2)$ and feed-down.

$pp \to J/\psi J/\psi$

New data become available recently:

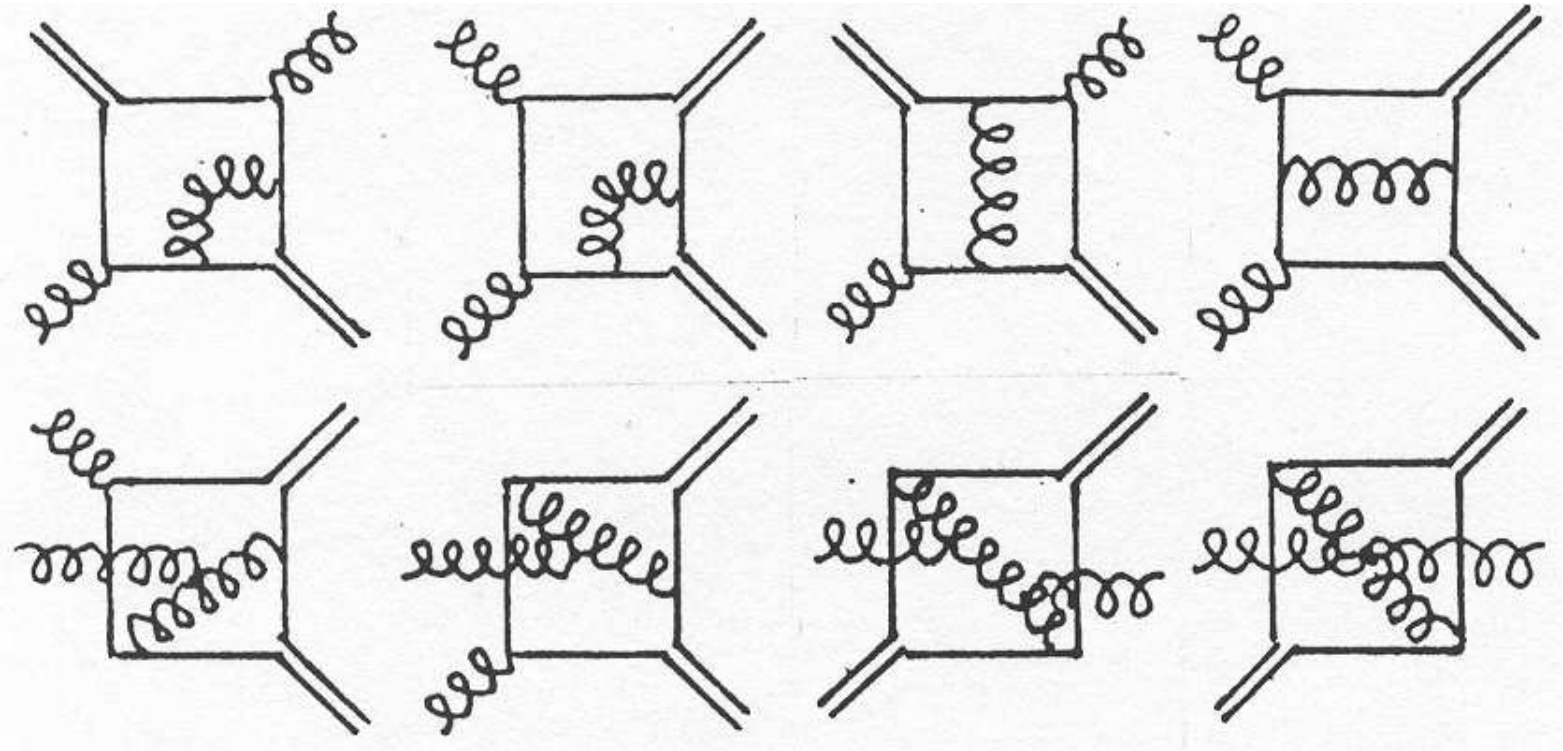
- Tevatron D0 data for $\sqrt{s}$ = 1.96 TeV (small σ_{eff} obtained)
- LHCb data ($\sqrt{s}$ = 7 TeV)
- CMS data for $\sqrt{s}$ = 8 TeV (running cuts, difficult to interprete)
- preliminary ATLAS data for $\sqrt{s}$ = 8 TeV (will be dicussed here)

$pp \to J/\psi J/\psi$, box



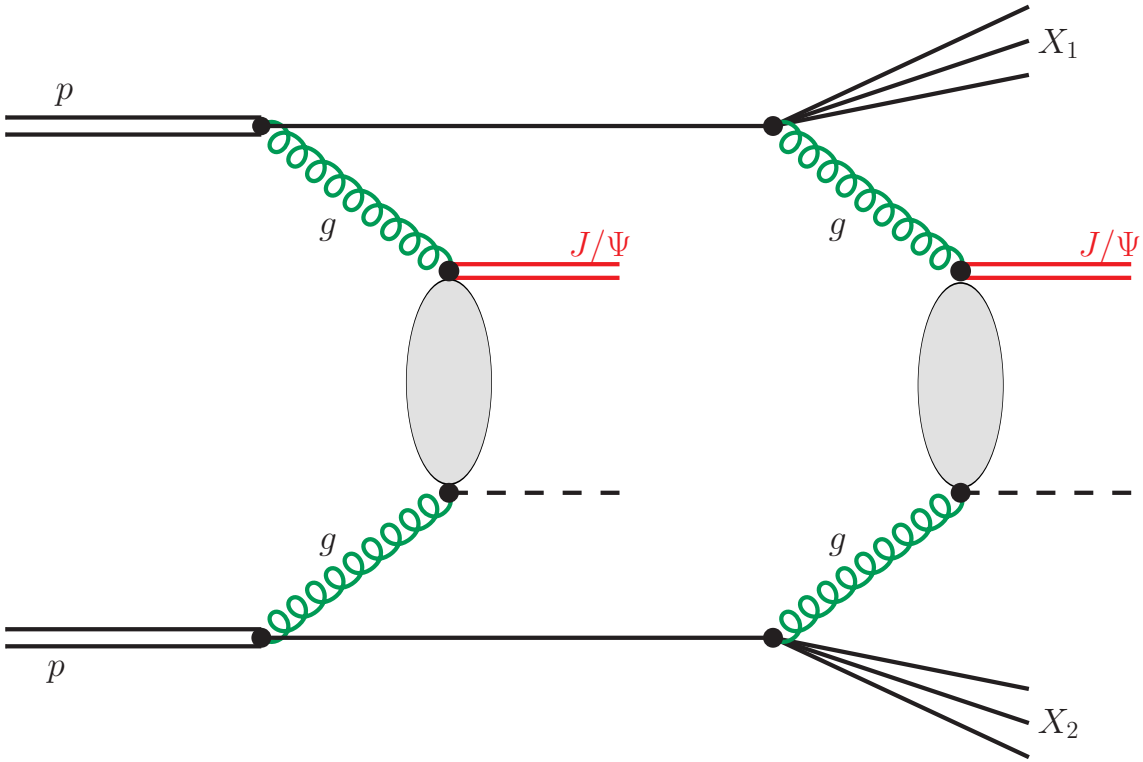
20 diagrams: box ($\mathcal{O}(\alpha_s^4)$), $\sigma \propto |R(0)|^4$

$pp \to J/\psi J/\psi$, box



only some are shown

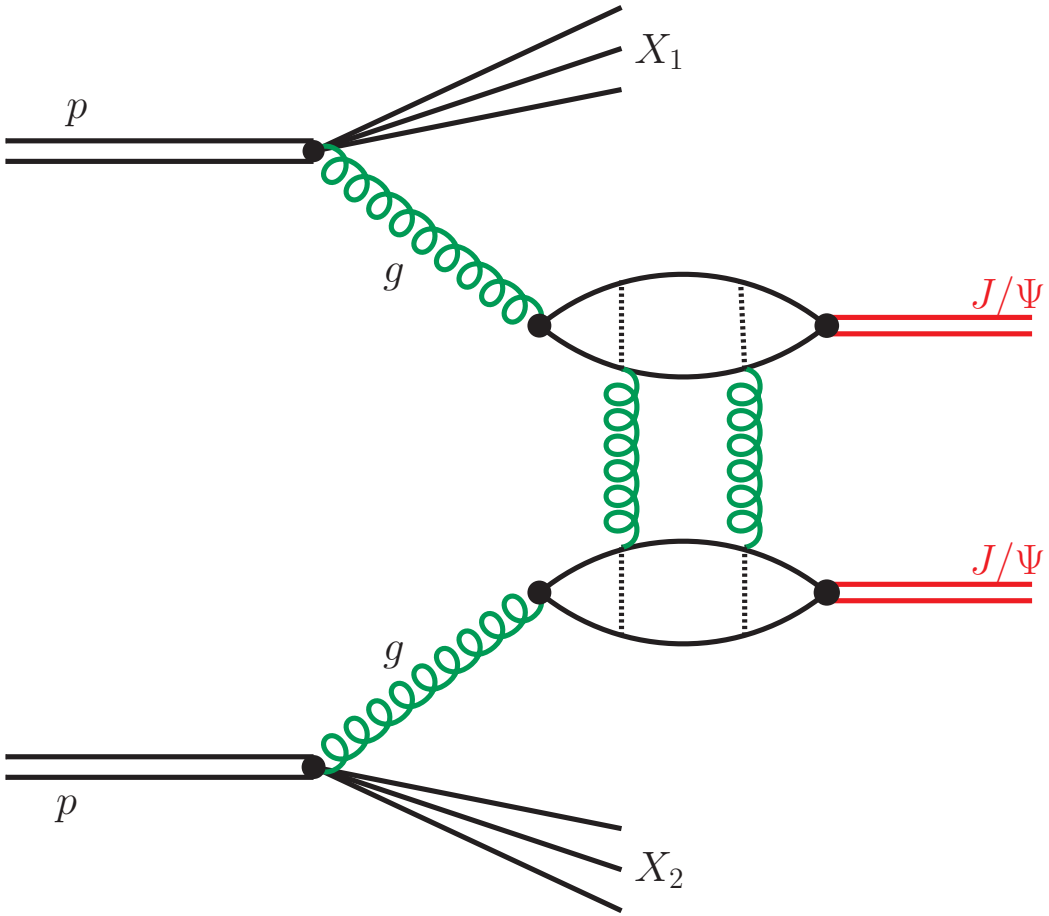
$pp \to J/\psi J/\psi$, double parton scattering



DPS ($O(a_s^6)$)

But enhanced by higher powers of gluon distributions $g_1^2 g_2^2$ at high energy.

framepp $\to J/\psi J/\psi$, 2g exchange (NNLO)



16 diagrams, box ($O(a_s^6)$) (high-order)

from $\gamma\gamma \to J/\psi J/\psi$ to $gg \to J/\psi J/\psi$ first included in:

S.P. Baranov, A.M. Snigirev, N.P. Zotov, A. Szczurek and W. Schäfer,

$pp \to \chi_c \chi_c$

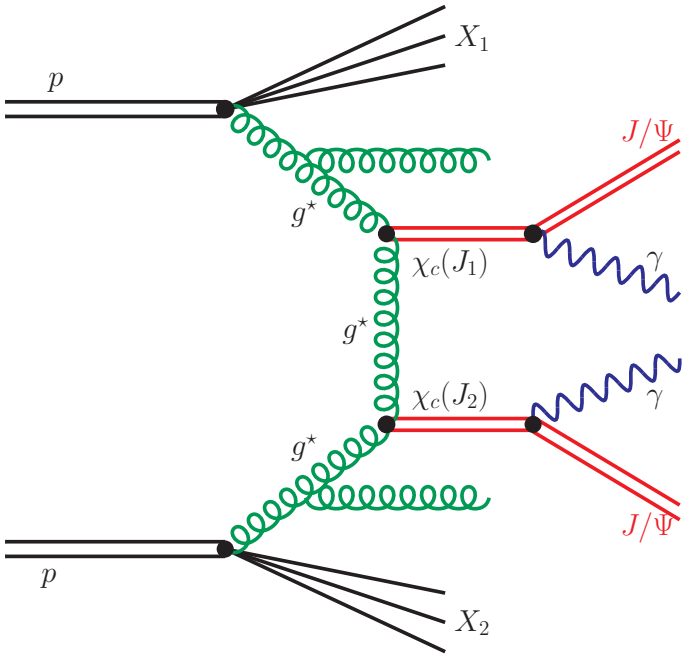


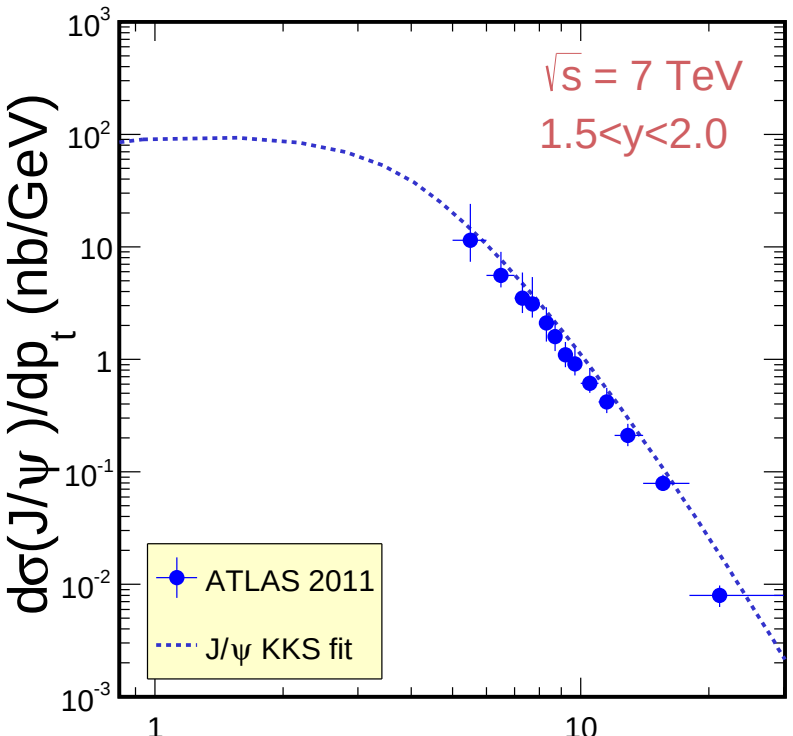
Figure: A diagrammatic representation of the leading order mechanisms for $pp \to \chi_c(J_1)\chi_c(J_2) \to (J/\psi + \gamma)(J/\psi + \gamma)$ reaction.

Experiment driven DPS

$$\frac{d\sigma(pp \to J/\psi g)}{dy_{J/\psi} dy_g d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \overline{|\mathcal{M}^{eff}_{gg\to J/\psi g}|^2} \times \quad g(x_1, \mu_F^2) g(x_2, \mu_F^2) \ . \qquad (13)$$

Auxiliary final state "gluon" (could be massive).

We take parametrization by Kom-Kulesza-Stirling 2011 with MSTW08 PDF.



Experiment driven DPS

single parton scattering → double parton scattering

We assume factorized Ansatz.

$$\frac{d\sigma}{dy_1 d^2p_{1t} dy_2 d^2p_{2t}} == \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 d^2p_{1t}} \cdot \frac{d\sigma}{dy_2 d^2p_{2t}} \tag{14}$$

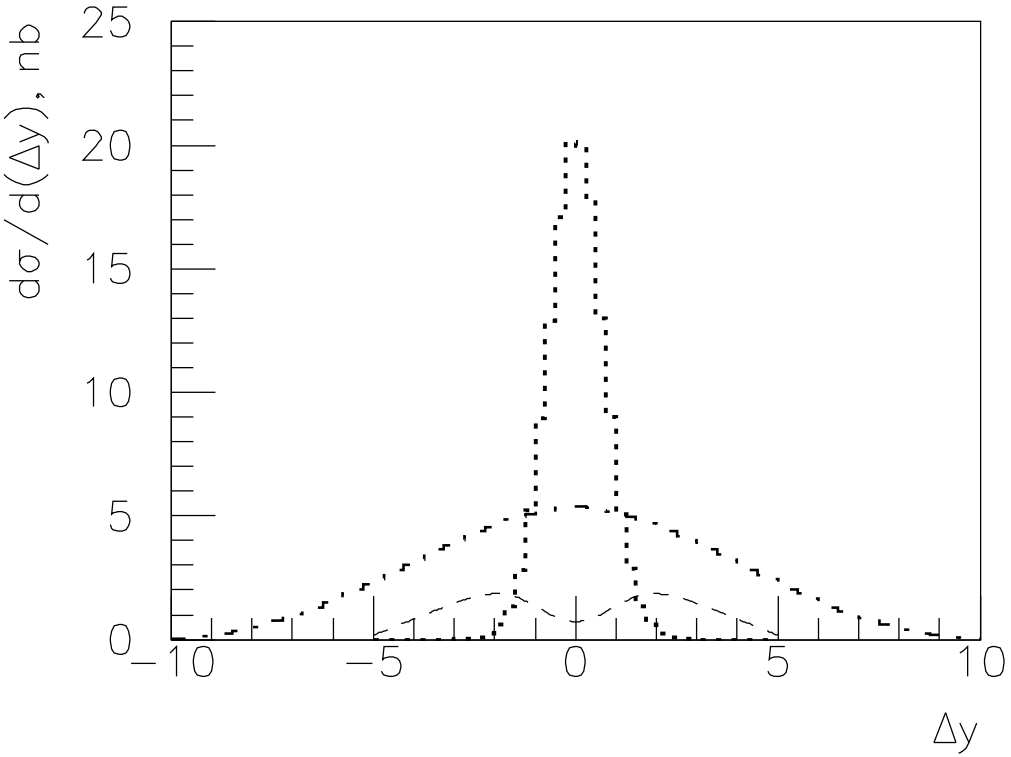
single J/ψ distributions are parametrized.

σ_{eff} in principle a free parameter responsible for the overlap of partonic densities of colliding protons.

σ_{eff} = 15 mb is world average for different reactions.

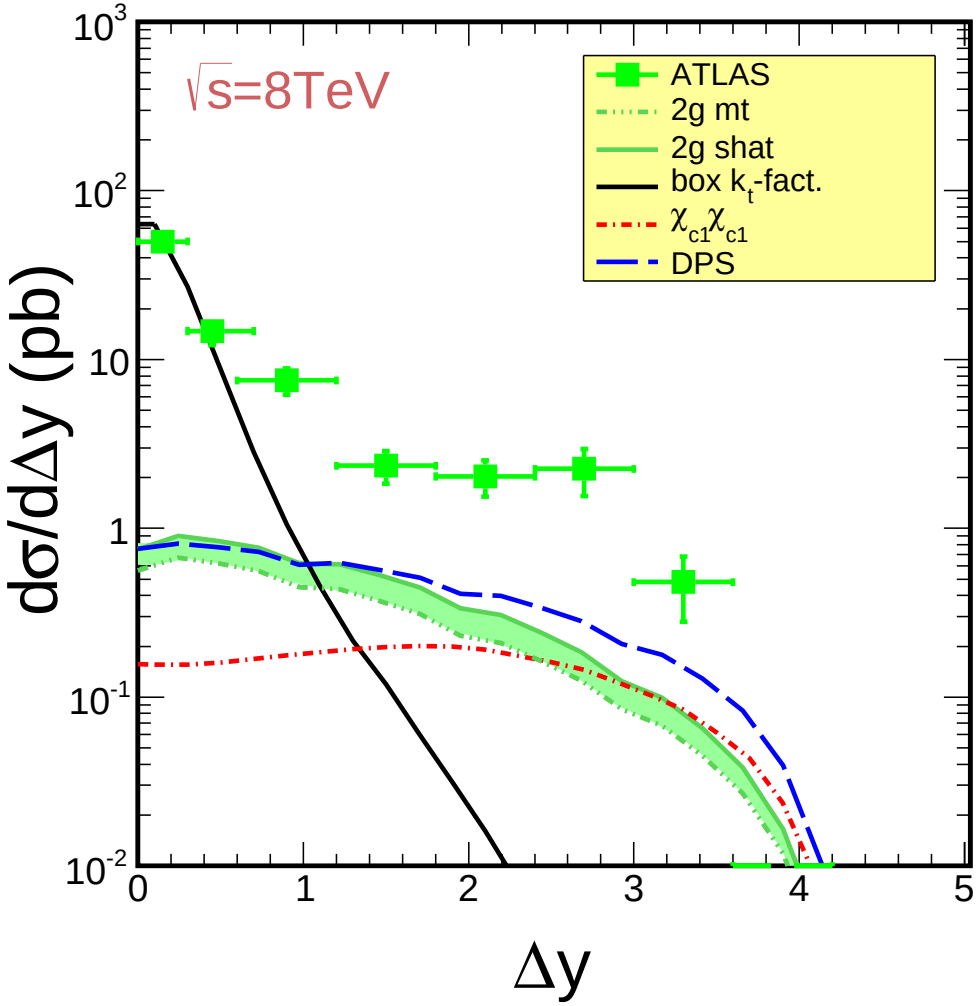
Much smaller value was obtained for double quarkonia production???

$pp \to J/\psi J/\psi$, LHCb



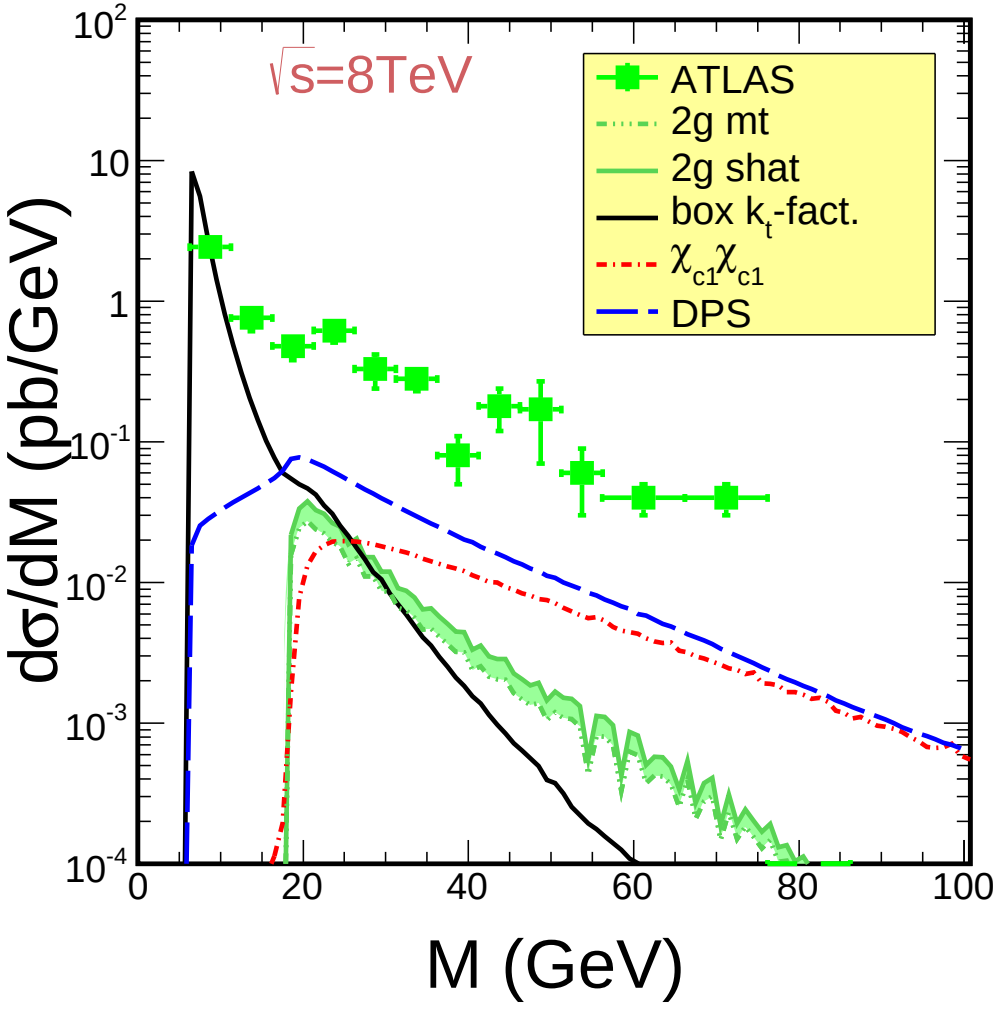
S.P. Baranov, A.M. Snigirev, N.P. Zotov, A. Szczurek and W. Schäfer, ``Interparticle correlations in the production of J/ψ pairs in proton-proton collisions'', Phys. Rev. **D87** (2013) 034035.

First results, with muon cuts



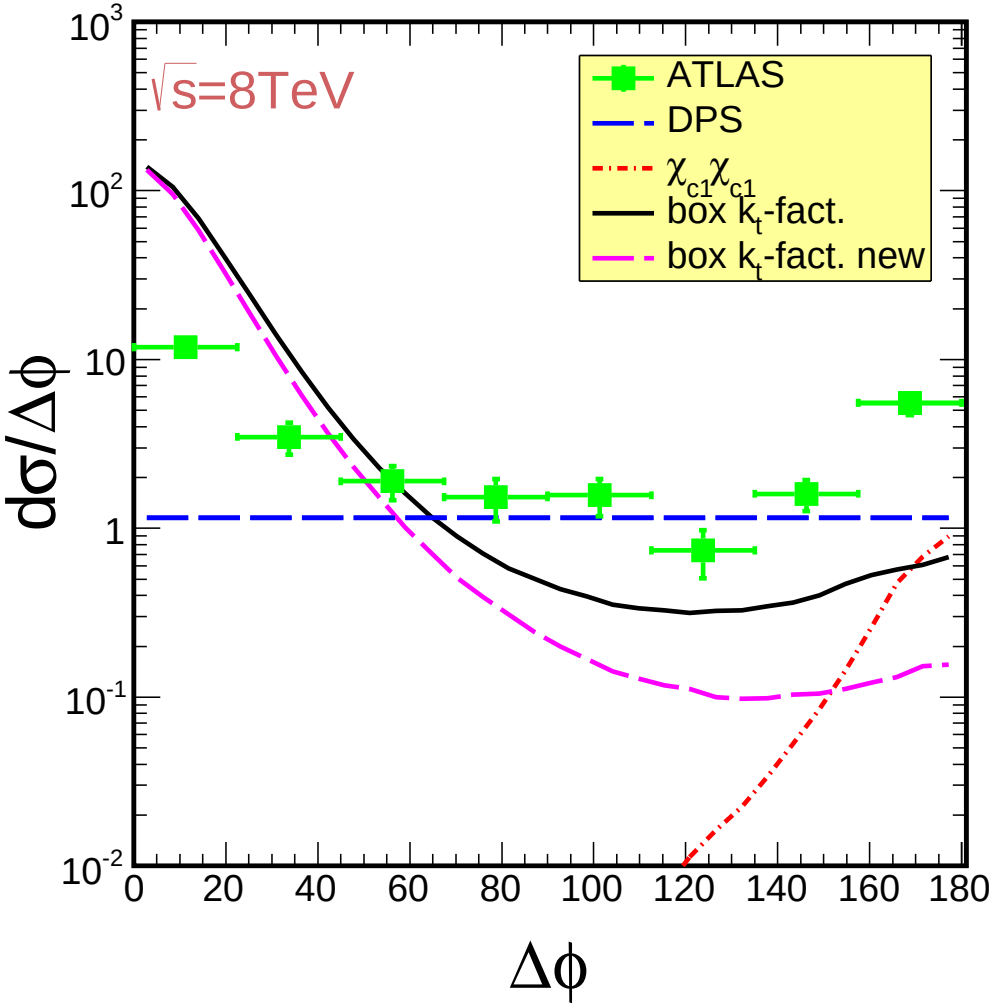
simultaneous decay of both J/ψ in Monte Carlo approach

First results, with muon cuts



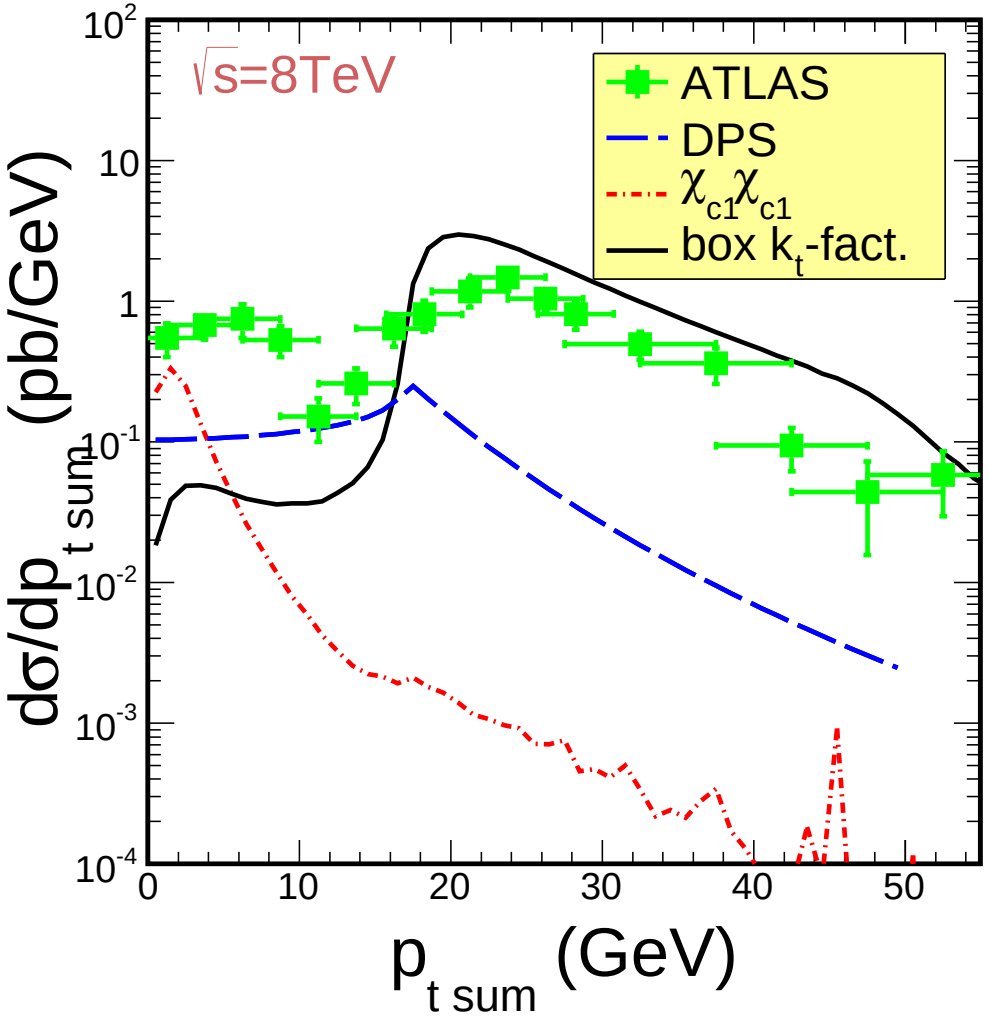
$p_{t,\mu} > 2.5$ GeV

First results, with muon cuts

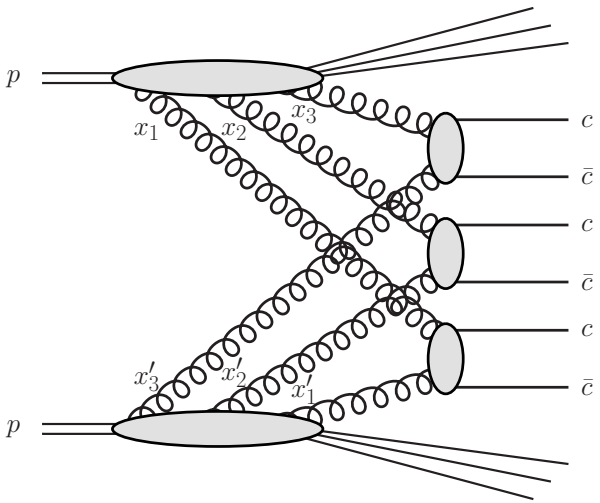


$p_{t,\mu} > 2.5$ GeV

First results, with muon cuts



Triple charm in triple-parton scattering (TPS)



First theoretical analysis for charm quarks:

d'Enterria, Snigirev, Phys.Rev.Lett. 118, no. 12, 122001 (2017)

- a generic expressions to compute TPS cross sections
- total charm quark cross sections in NNLO collinear approach

Our calculations:

Maciuła, Szczurek, Phys.Lett. B772 (2017) 849-853

- analysis for triple D meson production
- k_t-factorization approach
- differential distributions

Factorized ansatz for TPS (pocket-formula)

In a simple probabilistic picture process initiated by:

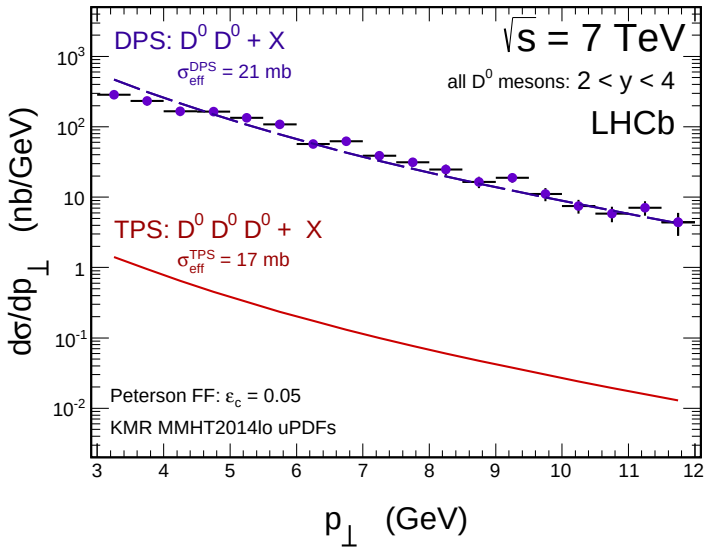
three simultaneous hard parton-parton scatterings in one proton-proton interaction

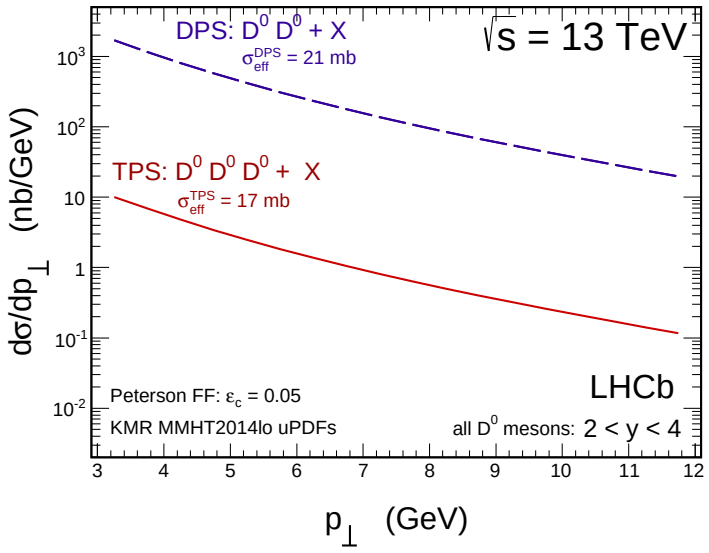
$$\sigma^{\rm TPS}_{pp\to c\bar{c}c\bar{c}c\bar{c}} = \left(\frac{1}{3!}\right) \frac{\sigma^{\rm SPS}_{pp\to c\bar{c}} \cdot \sigma^{\rm SPS}_{pp\to c\bar{c}} \cdot \sigma^{\rm SPS}_{pp\to c\bar{c}}}{\sigma^2_{\rm eff,TPS}}$$

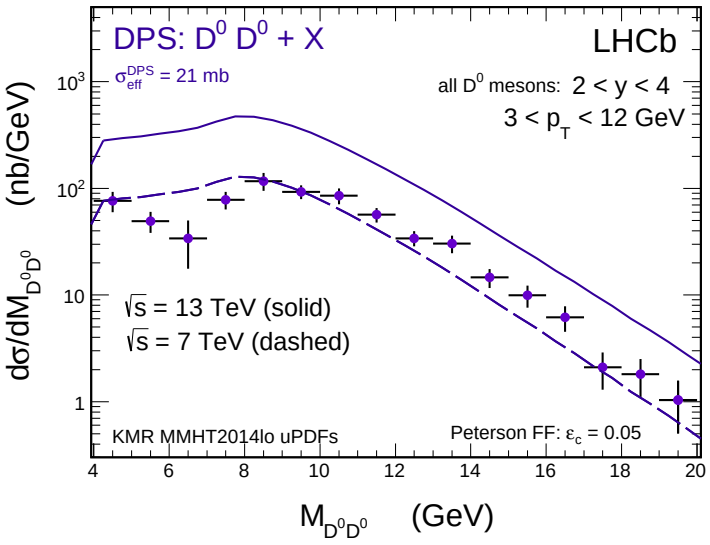
three subprocesses are not correlated and do not interfere

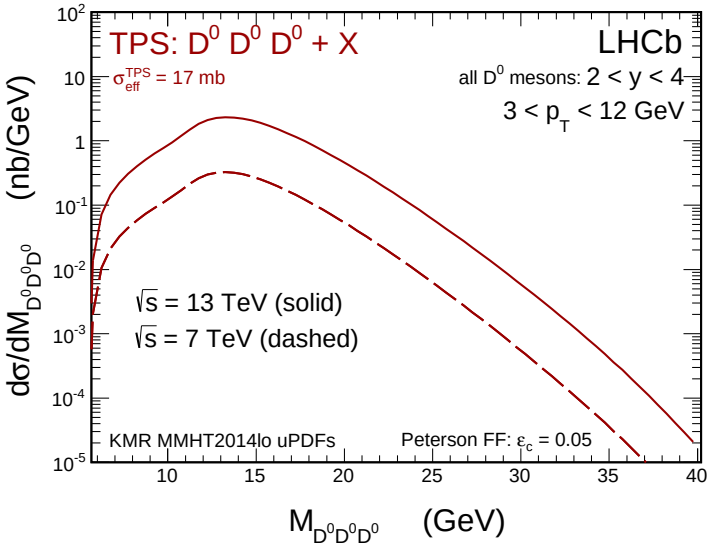
- $\sigma_{\rm eff,TPS} = k \times \sigma_{\rm eff,DPS}$, with $k = 0.82 \pm 0.11$
- $\sigma_{\rm eff,DPS} = 21$ mb (extracted from LHCb data) $\Rightarrow \sigma_{\rm eff,TPS} = 17$ mb

Inclusive $D^0 D^0 D^0$ $\sqrt{s} = 7, 13$ TeV









Inclusive $D^0D^0D^0$ $\sqrt{s} = 7, 13$ TeV

The integrated cross sections for double and triple D^0 meson production (in nb) within the LHCb acceptance: $2 < y_{D^0} < 4$ and $3 < p_T^{D^0} < 12$ GeV calculated in the k_T-factorization approach.

Final state	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
DPS: $\sigma(D^0D^0 + X)$	784.74	2992.91
TPS: $\sigma(D^0D^0D^0 + X)$	2.38	17.71

Number of events for different values of the feasible integrated luminosity in the LHCb experiment for the calculated cross sections

$\sqrt{s}$	Integrated Luminosity	DPS (D^0D^0)	TPS ($D^0D^0D^0$)
7 TeV	355 pb^{-1}	0.43×10^6	51
	1106 pb^{-1}	1.34×10^6	159
13 TeV	1665 pb^{-1}	7.70×10^6	1789
	5000 pb^{-1}	23.11×10^6	5374

- a few thousands of events of triple D^0 production at $\sqrt{s} = 13$ TeV

Conclusions

Formalism:

- The formalism exists in principle but difficult in reliable applications.
- Mixture of perturbative and nonperturbative effects (difficult) (multiparton correlations, hot spots, evolution of DPS or TPS).
- Factorizied Ansatz used in practical applications.
- σ_{eff} the only nonperturbative parameter
  Can be calculated from models or fitted to experimental data.
  Can be different for different flavours (W^+W^- production).
- Surprisingly similar value obtained from fits to different data.
  Exception: double quarkonium production at larger p_t.
- Sometimes single parton scattering is not well under control (e.g. $J/\psi J/\psi$).
- Many processes possible a priori.
  Processes with charm production are the best for studying DPS.

Conclusions, recent results

We have studied recently if and how the DPS effects can be observed at the LHC for different reactions in the sector of open heavy mesons:
$pp \to D^0 + 2\text{jets } X, pp \to D^0 \bar{D}^0 + 2\text{jets } X$

- cross sections of the order of microbarns at $\sqrt{s} = 13$ TeV within the ATLAS detector acceptance
- regions of phase space where the DPS component clearly dominates over SPS one are identified

$pp \to D^0 B^+ X, pp \to B^+ B^+ X$

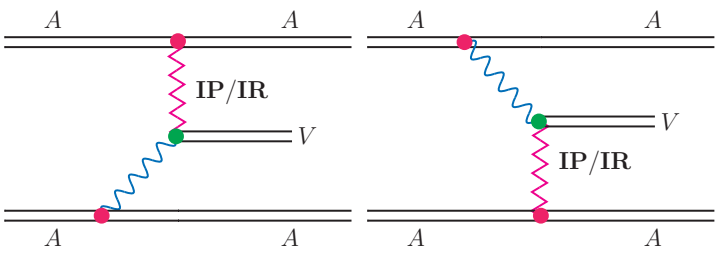
- cross sections of the order of hundreds ($D^0 B^+$) and tens ($B^+ B^+$) nanobarns at $\sqrt{s} = 13$ TeV within the LHCb detector acceptance
- DPS components dominate in the LHCb fiducial volume of the phase space.

We have presented first estimation of the triple-parton scattering production of triple open charm meson:
$pp \to D^0 D^0 D^0 X$

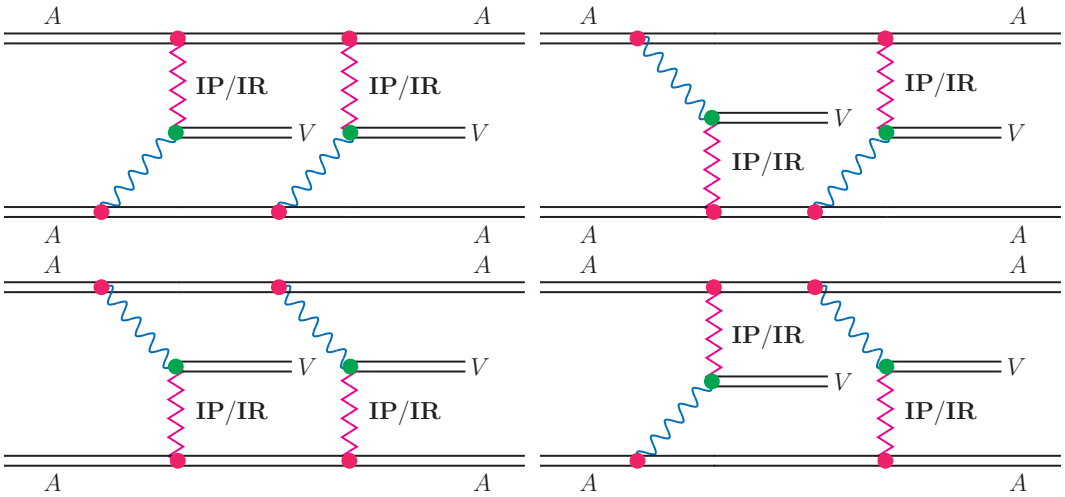
- a few thousands of events of triple D^0 production can be observed at $\sqrt{s} = 13$ TeV within the LHCb detector acceptance

Vector mesons production

- Single ρ^0 & J/ψ production



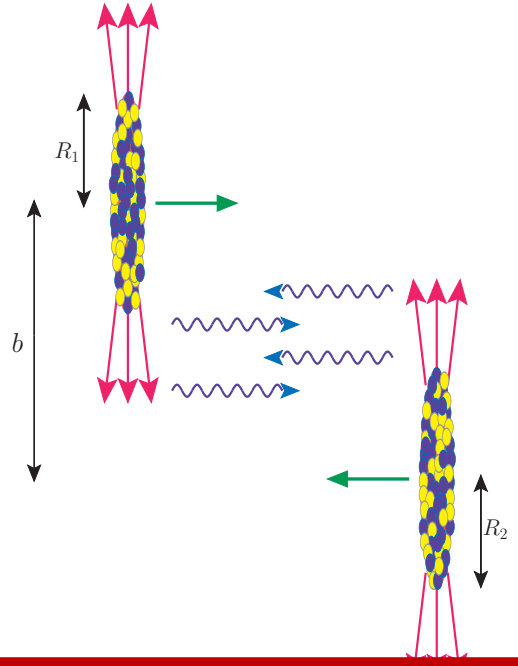
- Double-scattering mechanism



$\mathrm{Br}(\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-) \simeq 100\%$

STAR, CMS & ALICE data

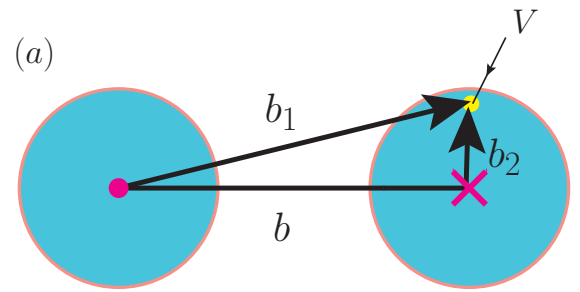
Equivalent Photon Approximation



The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.

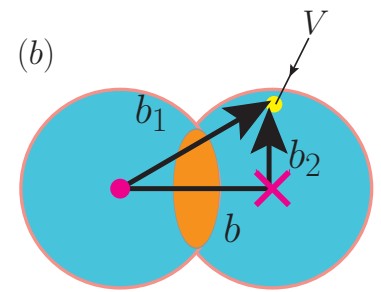
UltraPeriheral Collisions

$$b > R_{min} = R_1 + R_2$$

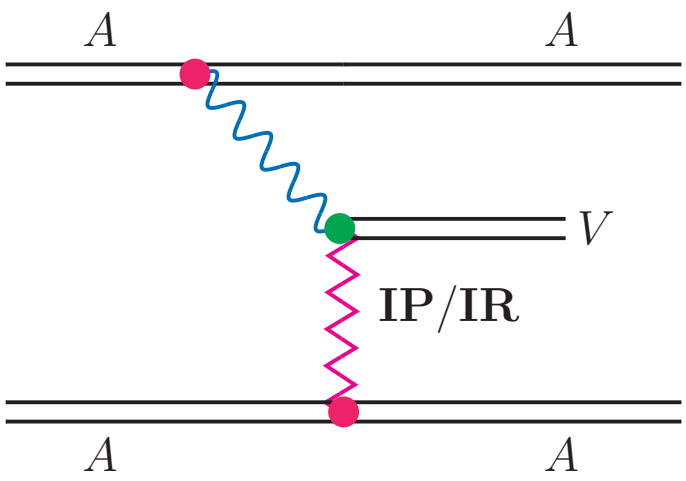


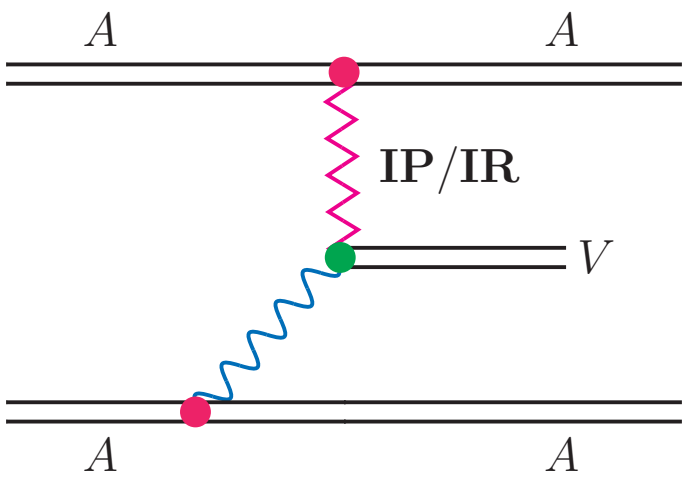
semi-central Collisions

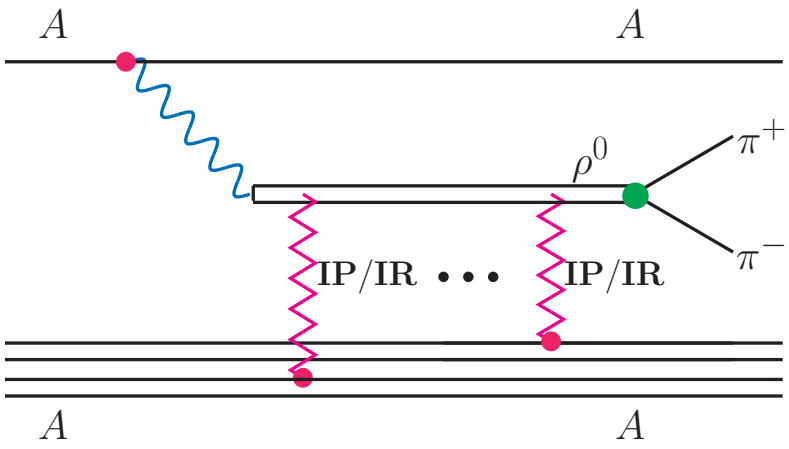
$$b \leq R_{min}$$

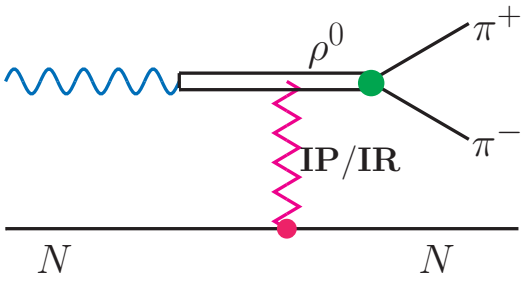


Photoproduction of vector meson



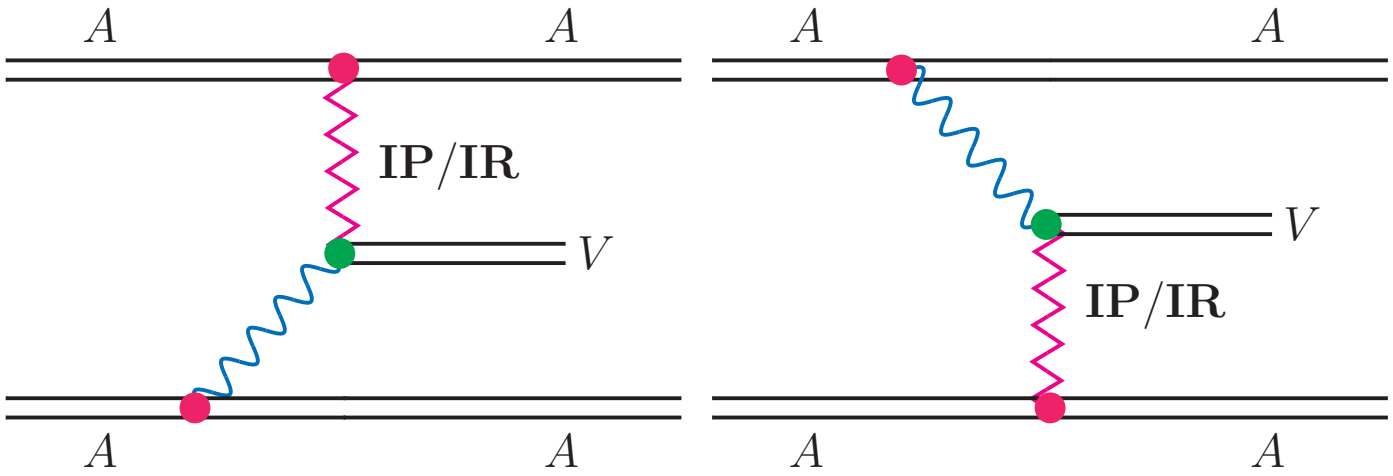






Parameters fixed to describe HERA data
we expect: $\frac{d\sigma(\gamma n \to Vn)}{dt} \approx \frac{d\sigma(\gamma p \to Vp)}{dt}$

Single vector meson production



$$\frac{d\sigma_{A_1A_2\to A_1A_2V}}{d^2b\,dy} = \frac{dP_\gamma(b,y)}{dy} + \frac{dP_\gamma(b,y)}{dy} \tag{15}$$

$$\frac{dP_{1/2}(b,y)}{dy} = \omega_{1/2}N(\omega_{1/2},b)\sigma_{\gamma A_{2/1}\to VA_{2/1}}(W_{\gamma A_{2/1}}) \tag{16}$$

- point-like $F(q) = 1$
- realistic $F(q) = \frac{4\pi}{q}\int \rho(r)\sin(qr)\,r\,dr$
- monopole $F(q) = \frac{\Lambda^2}{\Lambda^2+q^2}$ $\Lambda = \sqrt{\frac{6}{\langle r^2\rangle}}$

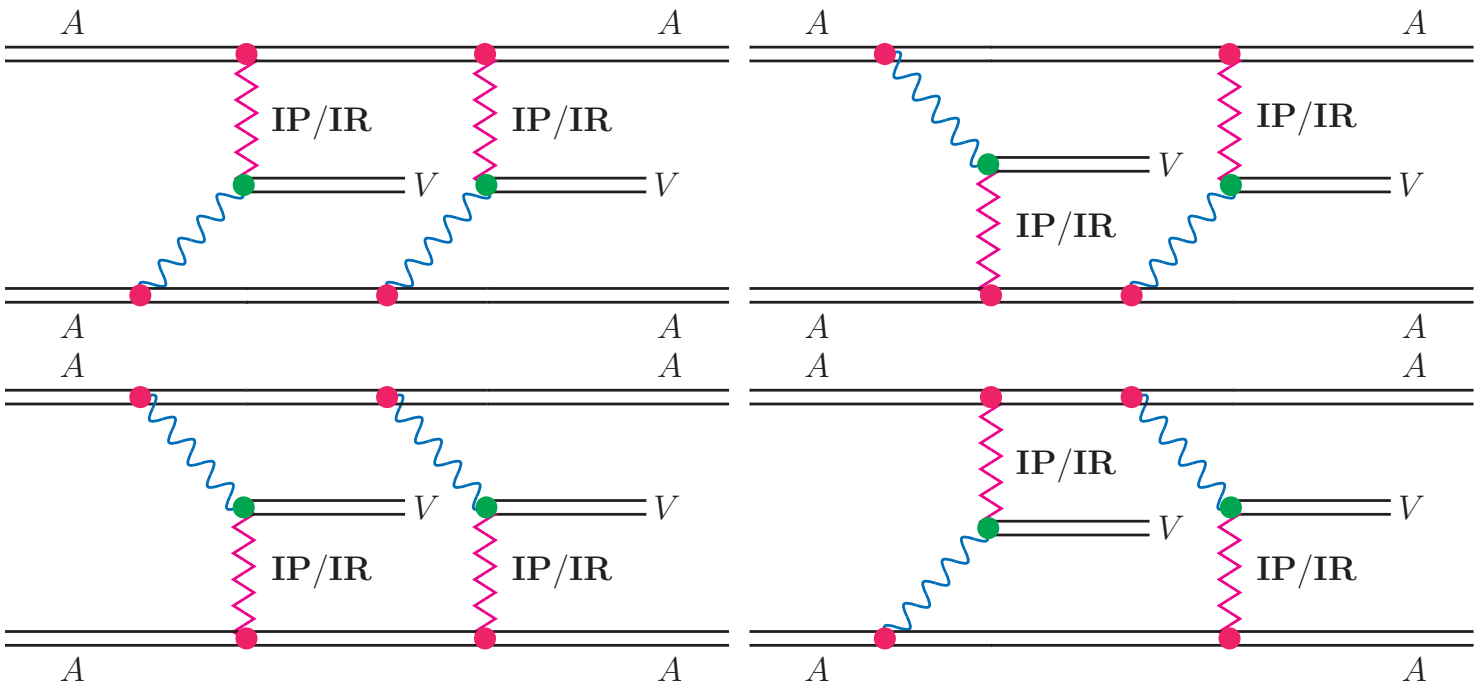
$\gamma A \to VA$

$\frac{d\sigma_{\gamma p \to Vp}(t=0)}{dt}$ ← HERA data

- $\sigma_{tot}^{CM}(VA) = \int d^2\mathbf{r}\,(1 - \exp(-\sigma_{tot}(Vp)T_A(\mathbf{r})))$
- $\sigma_{tot}^{QM}(VA) = 2\int d^2\mathbf{r}\left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(Vp)T_A(\mathbf{r})\right)\right)$

$$\sigma_{\gamma A \to VA}(W_{\gamma A_{2/1}}) = \frac{d\sigma_{\gamma A \to VA}(t=0)}{dt}\int_{-\infty}^{t_{max}} dt\left|F_A(t)\right|^2$$

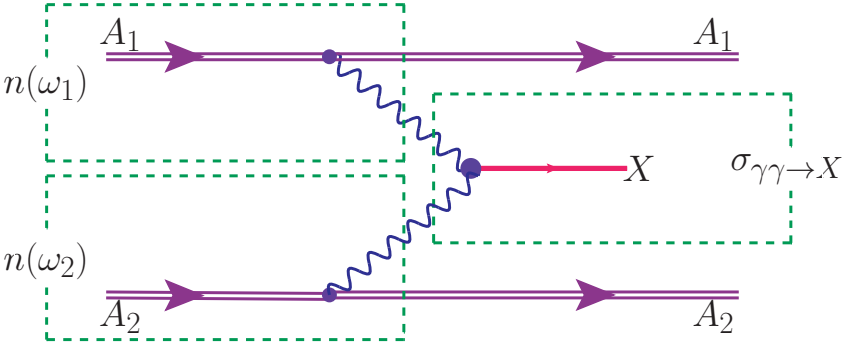
Double-scattering mechanism



$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2\rho^0\rho^0}}{\mathrm{d}y_1\mathrm{d}y_2} = \frac{1}{2}\int\left(\frac{\mathrm{d}P_\gamma(b,y_1)}{\mathrm{d}y_1} + \frac{\mathrm{d}P_\gamma(b,y_1)}{\mathrm{d}y_1}\right) \times \left(\frac{\mathrm{d}P_\gamma(b,y_2)}{\mathrm{d}y_2} + \frac{\mathrm{d}P_\gamma(b,y_2)}{\mathrm{d}y_2}\right)\mathrm{d}^2b$$

(ρ^0's have negligibly small transverse momenta)

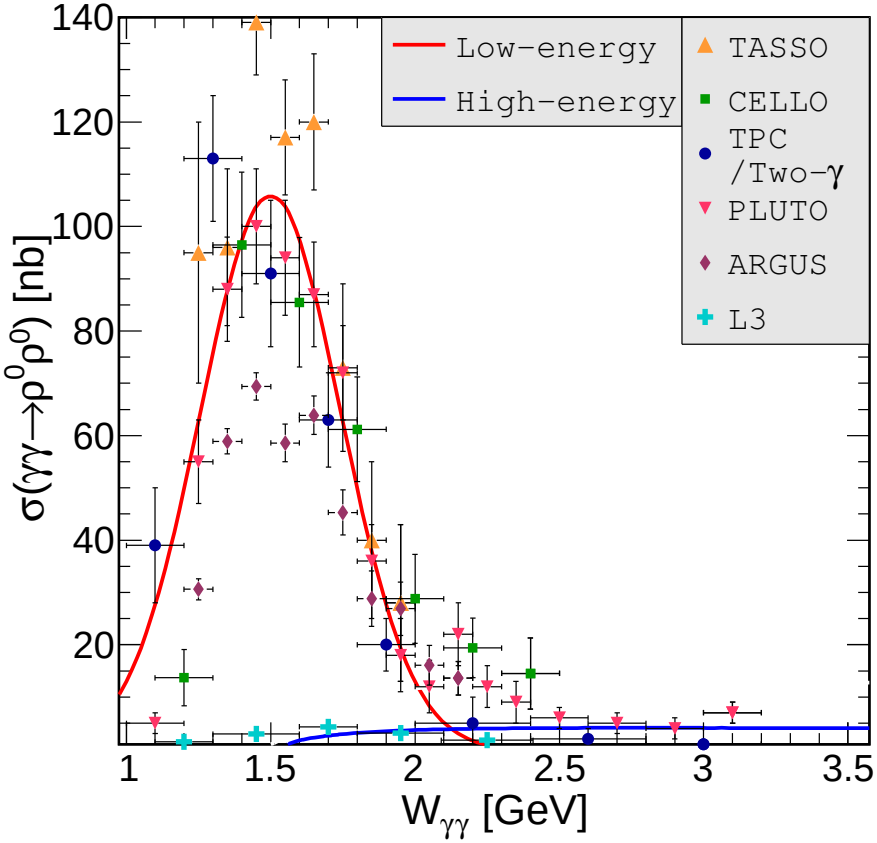
$AA \to AA\rho^0\rho^0$ - $\gamma\gamma$ fusion



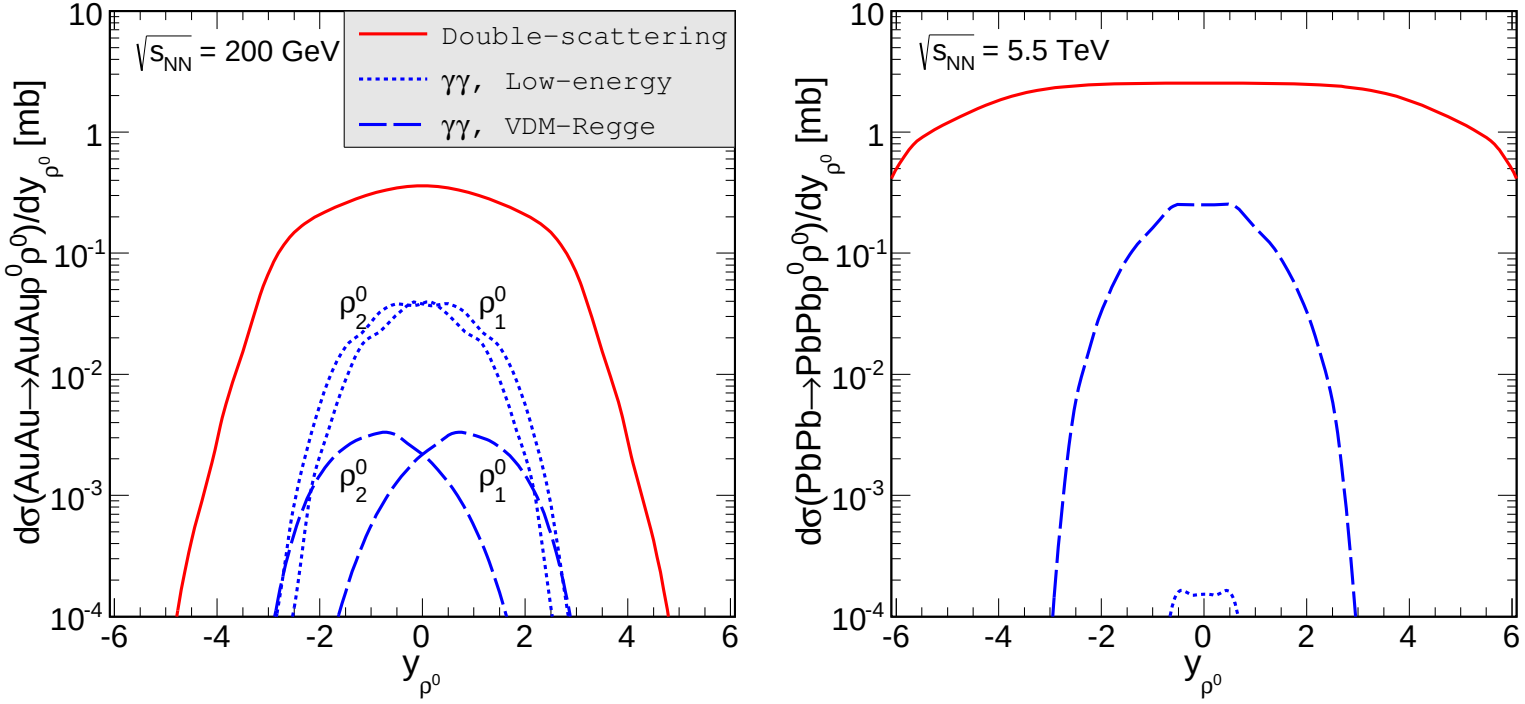
$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b)$$

Reference:

M. Kłusek, W. Schäfer and A. Szczurek, Phys.Lett. **B674** (2009) 92,
''Exclusive production of $\rho^0\rho^0$ pairs in $\gamma\gamma$ collisions at RHIC''
+ back-up slide



Double-scattering mechanism vs $\gamma\gamma$ fusion

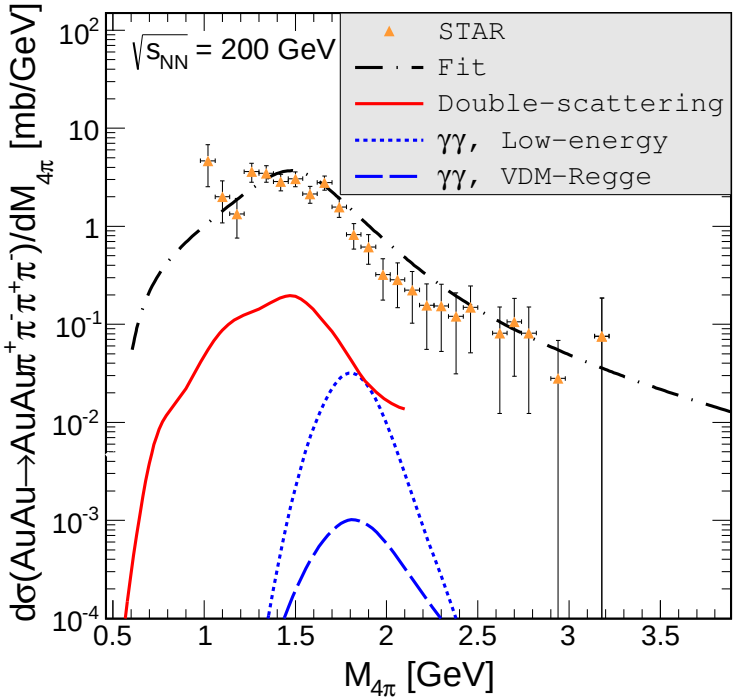


Reference:

M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. **C89** (2014) 024912
''Double-scattering mechanism in the exclusive $AA \to AA\rho^0\rho^0$ reaction in ultrarelativistic collisions'',

$\pi^+\pi^-\pi^+\pi^-$ production @ RHIC

$|\eta_\pi| < 1$

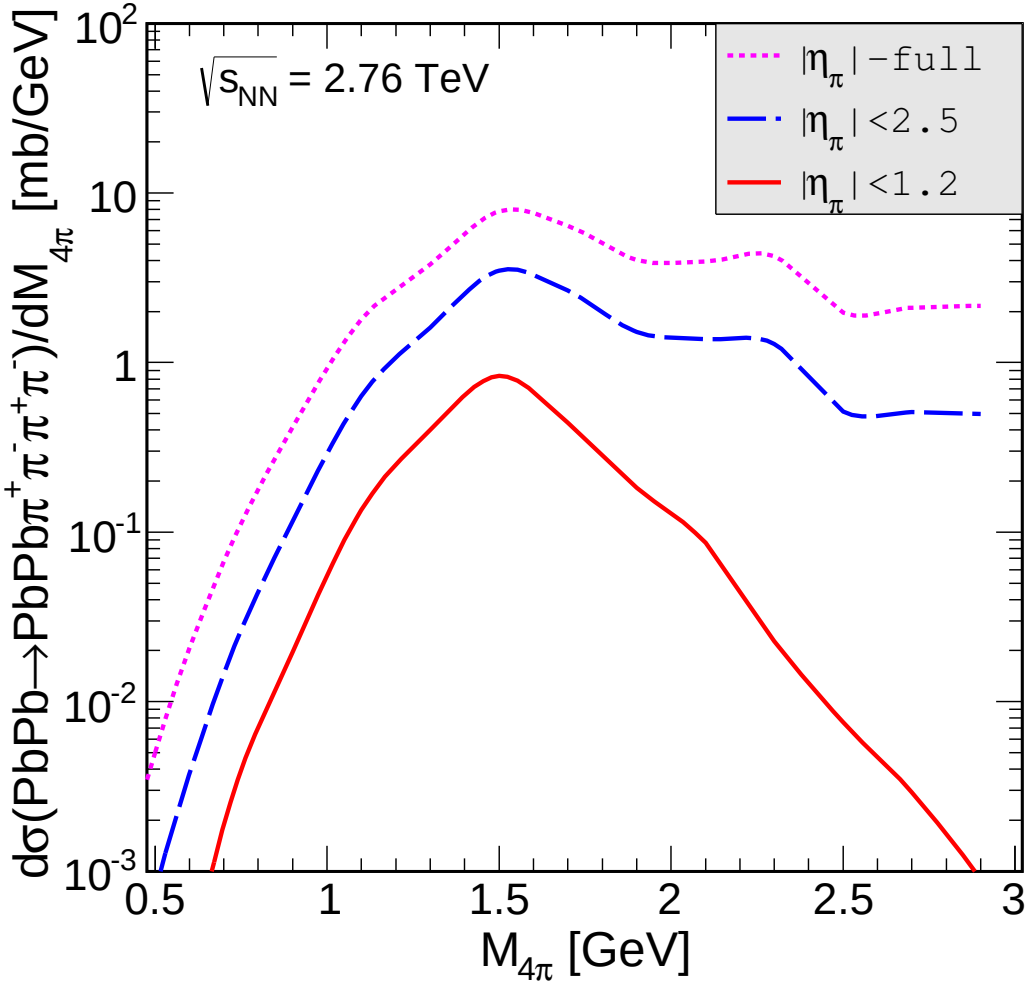


missing mechanisms:

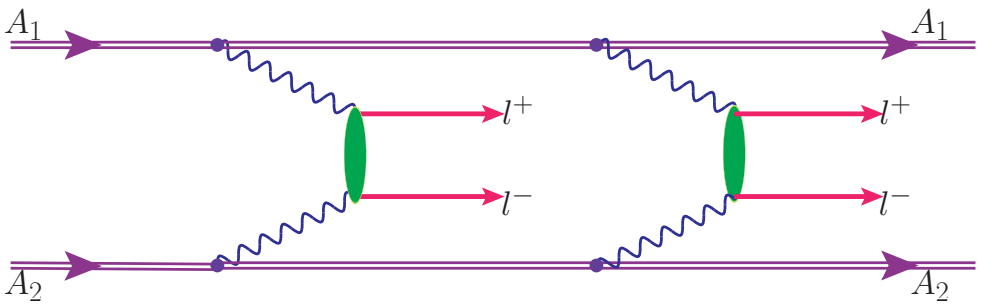
$AA \to AA\rho^0(1450) \to 4\pi$

$AA \to AA\rho^0(1700) \to 4\pi$

$\pi^+\pi^-\pi^+\pi^-$ production @ LHC



Four-lepton production



$$\sigma_{A_1A_2\to A_1A_2l^+l^-} = \int P_{\gamma\gamma\to l^+l^-}(b)\,\mathrm{d}^2b$$

$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2l^+l^-}}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}p_t} = \int \frac{\mathrm{d}P_{\gamma\gamma\to l^+l^-}(b;\,y_1,y_2,p_t)}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}p_t}\mathrm{d}^2b$$

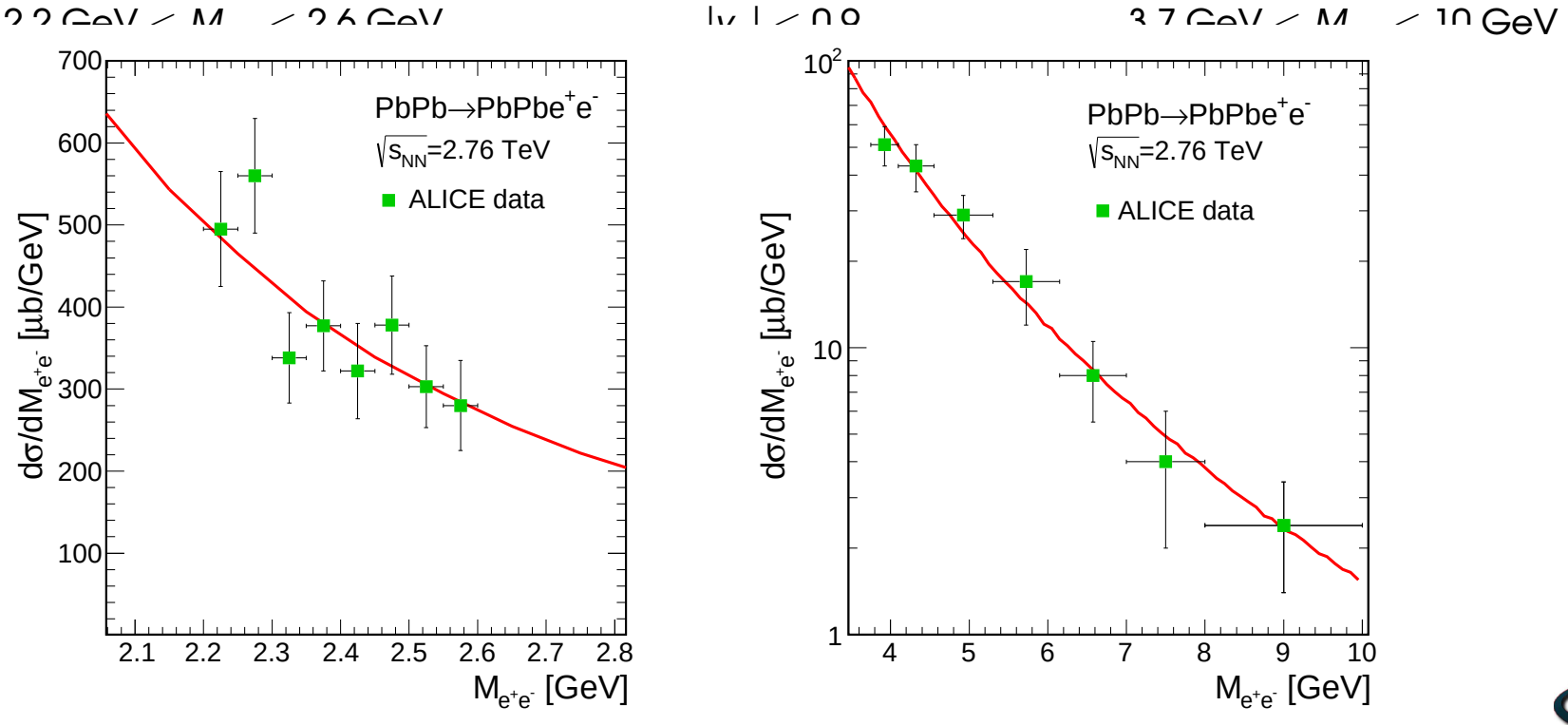
$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2l_1^+l_2^-l_3^+l_4^-}}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}y_3\mathrm{d}y_4} = \frac{1}{2}\int \frac{\mathrm{d}P_{\gamma\gamma\to l^+l^-}(b;\,y_1,y_2,p_{t,min})}{\mathrm{d}y_1\mathrm{d}y_2} \times \frac{\mathrm{d}P_{\gamma\gamma\to l^+l^-}(b;\,y_3,y_4,p_{t,min})}{\mathrm{d}y_3\mathrm{d}y_4}\mathrm{d}^2b$$

$AA \to AAe^+e^-$ - calculations vs. data

226

ALICE Collaboration (Abbas, E. et al.),
Charmonium and e^+e^- pair photoproduction at mid-rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,

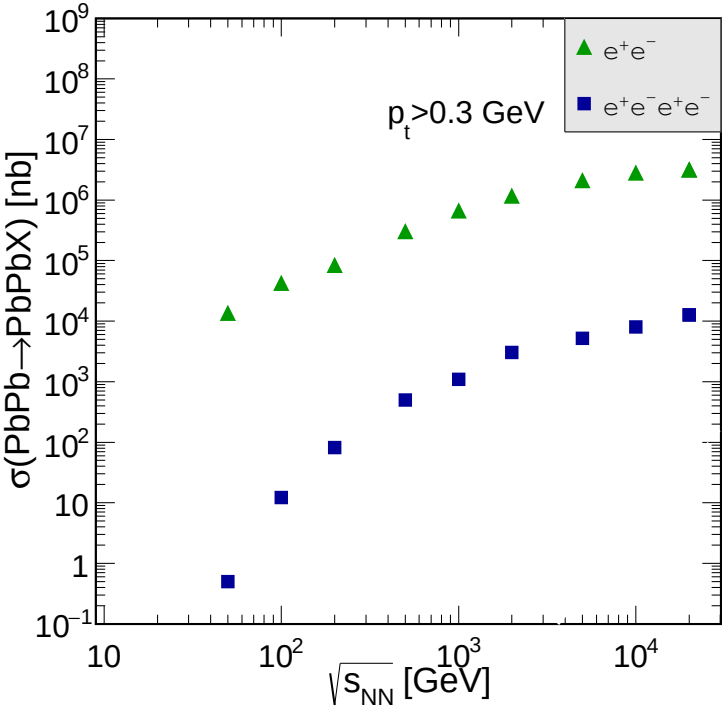
Eur. Phys. J. **C73** (2013) 2617



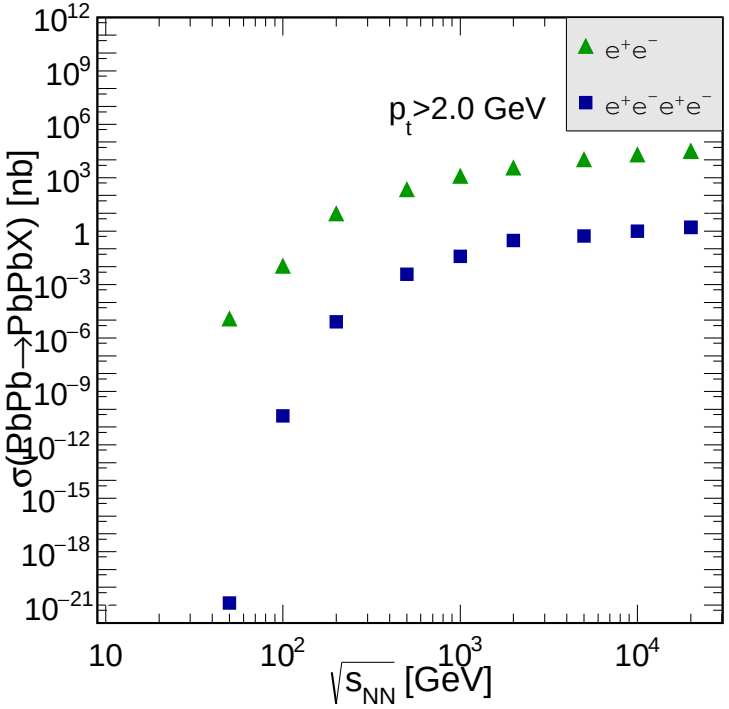
Good description of single pair production ⇒ two e^+e^- pair production

$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

$p_t > 0.3$ GeV

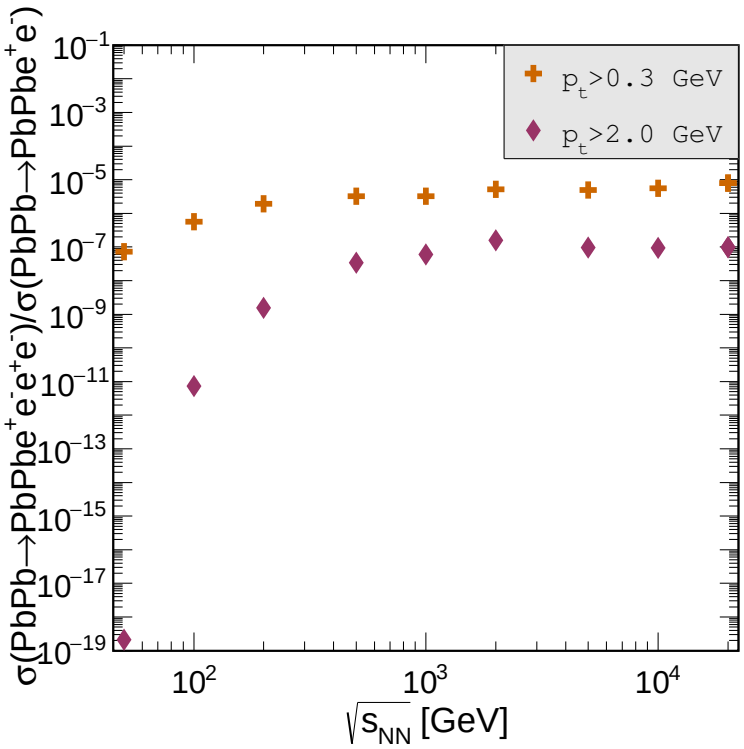


$p_t > 2.0$ GeV



$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

$$\frac{\sigma_{AA\to AAe^+e^-e^+e^-}}{\sigma_{AA\to AAe^+e^-}}$$



Ratio depends on $\sqrt{s_{NN}}$ and $p_{t,min}$

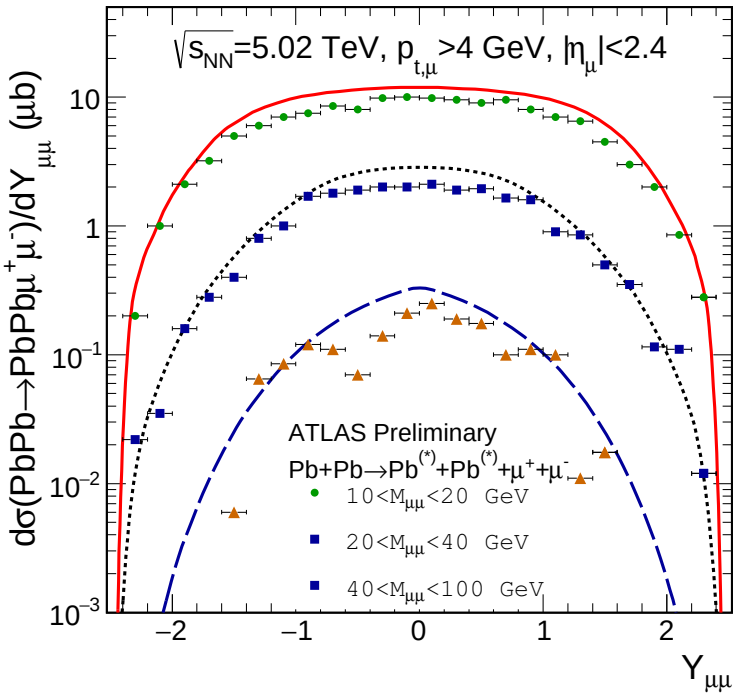
$AA \to AA\mu^+\mu^-$ - calculations vs. data

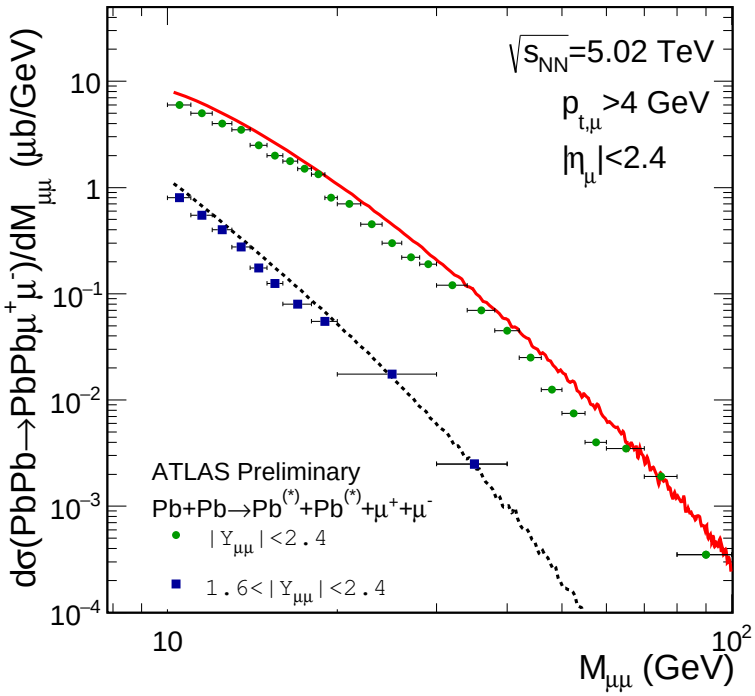
226

ATLAS Collaboration,
Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ *TeV with the ATLAS detector at the LHC,*

ATLAS-CONF-2016-025

$\frac{d\sigma}{dY_{\mu^+\mu^-}}$ $p_{t,\mu} > 4$ GeV, $|\eta_e| < 0.9$ $\frac{d\sigma}{dM_{\mu^+\mu^-}}$





AA→AA$\mu^+\mu^-$ - form factor

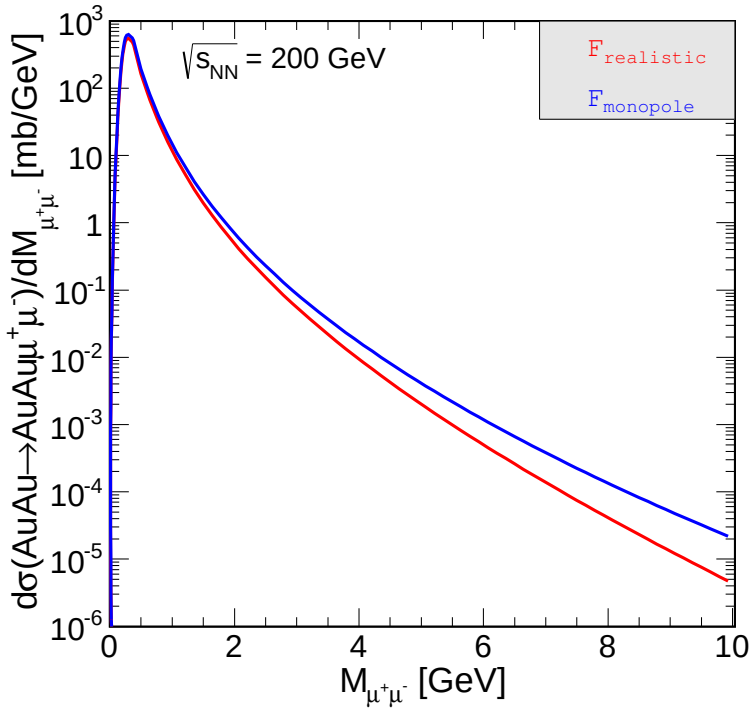
239

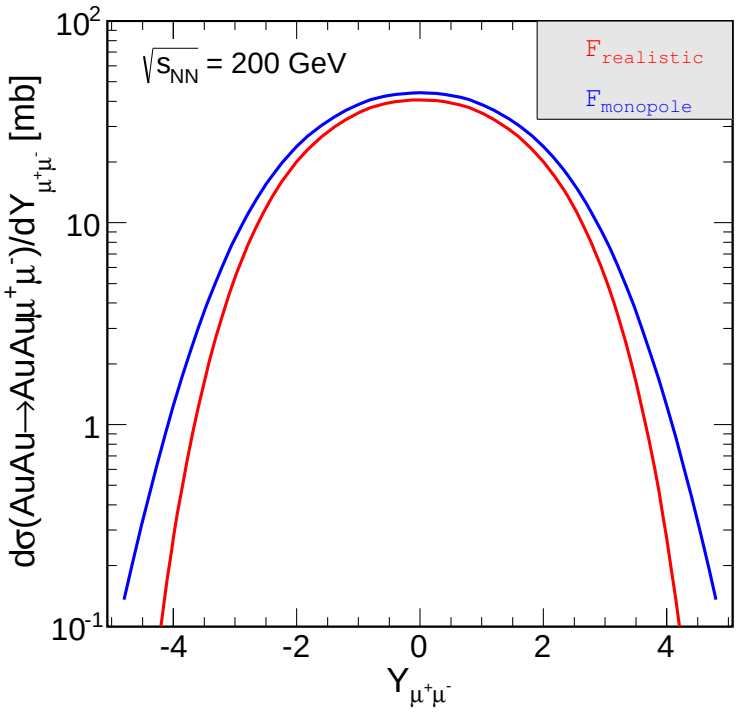
realistic

monopole

$M_{\mu^+\mu^-}$

$Y_{\mu^+\mu^-}$

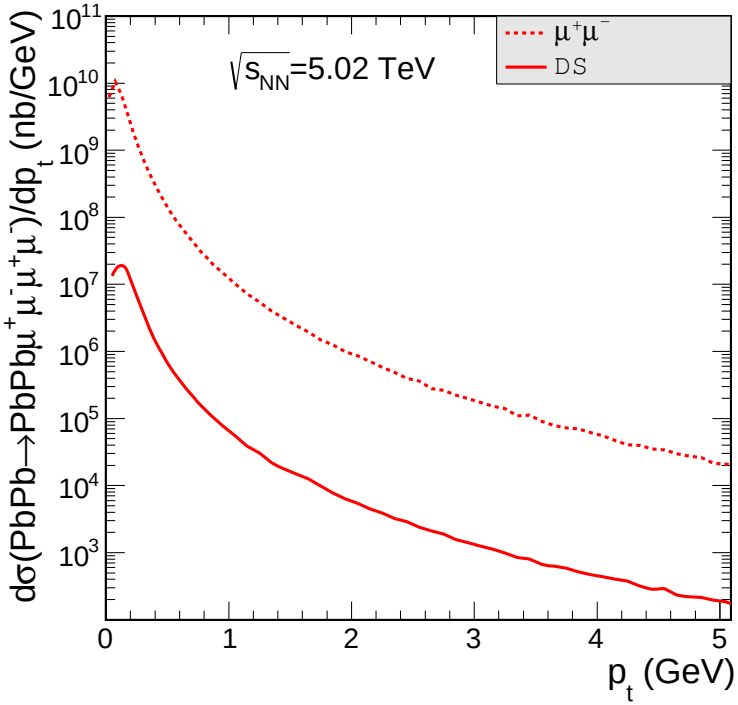




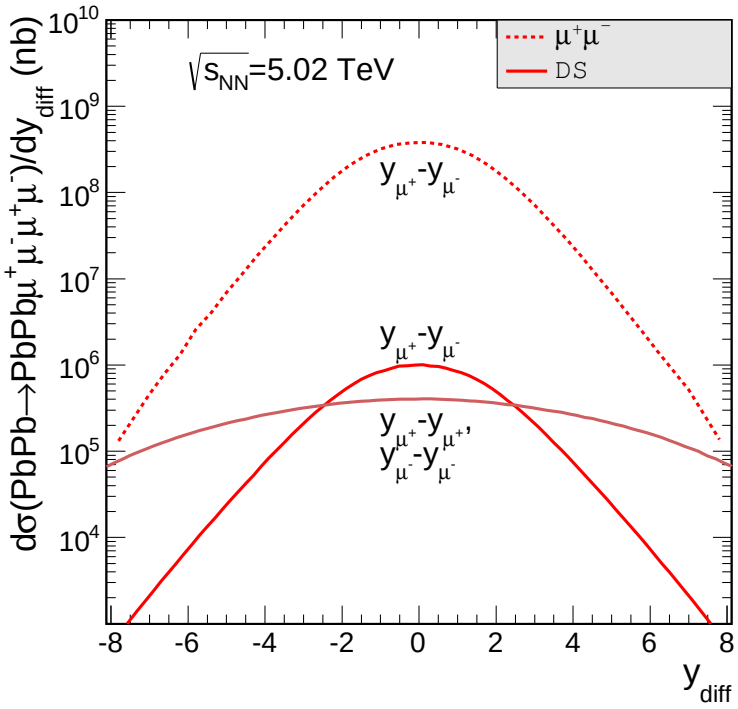
RHIC energy

$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

$p_{t,\mu}$



y_{diff}

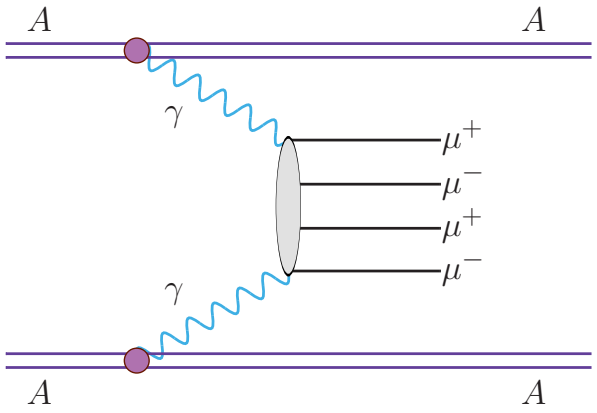


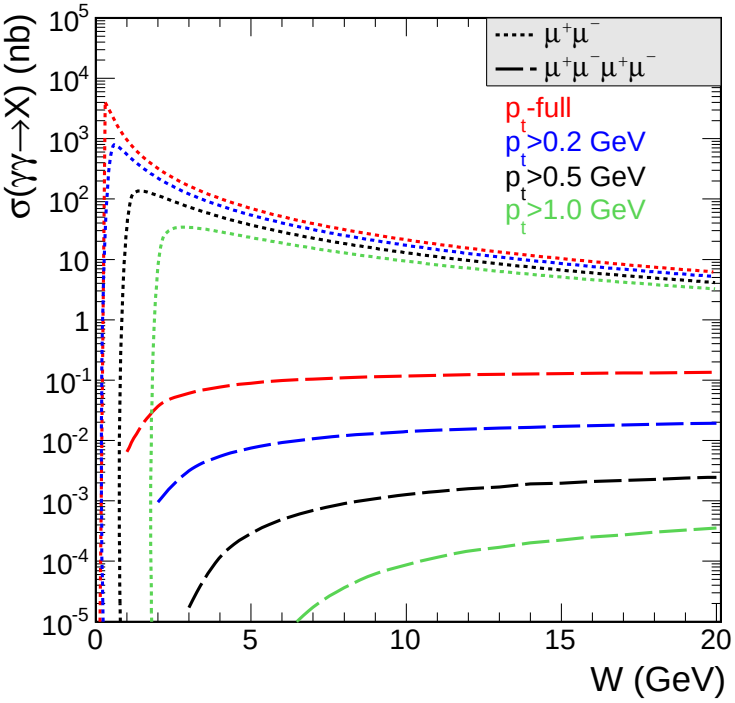
Similar like for electron-positron production: $\sigma_{\mu^+\mu^-} \simeq 1000 \times \sigma_{\mu^+\mu^-\mu^+\mu^-}$

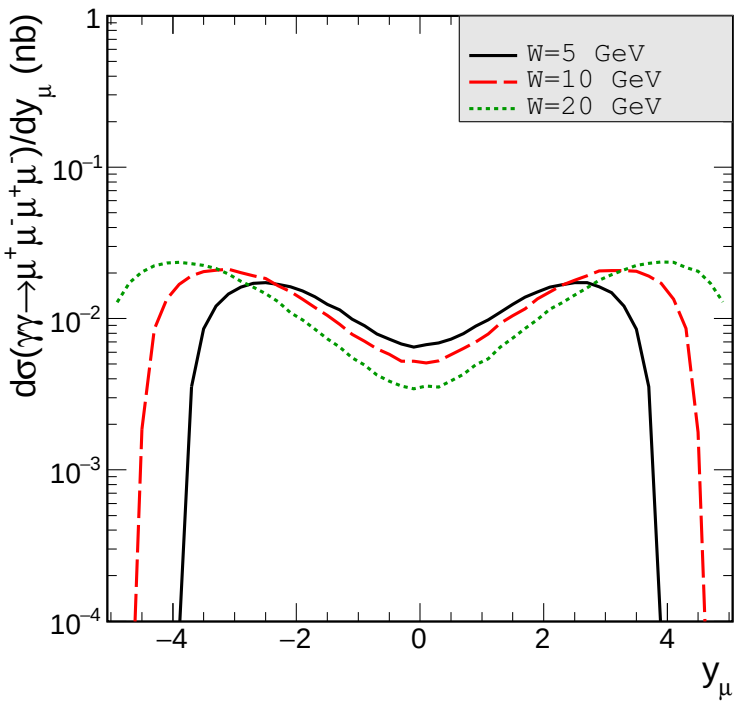
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - single scattering

$\Uparrow$

- an event generator that is specially designed
to deal with initial states that have an explicit transverse momentum dependence,
but can also deal with on-shell initial states.
is a parton-level generator for hadron scattering, but requires only a few adjustments
to deal with photon scattering.

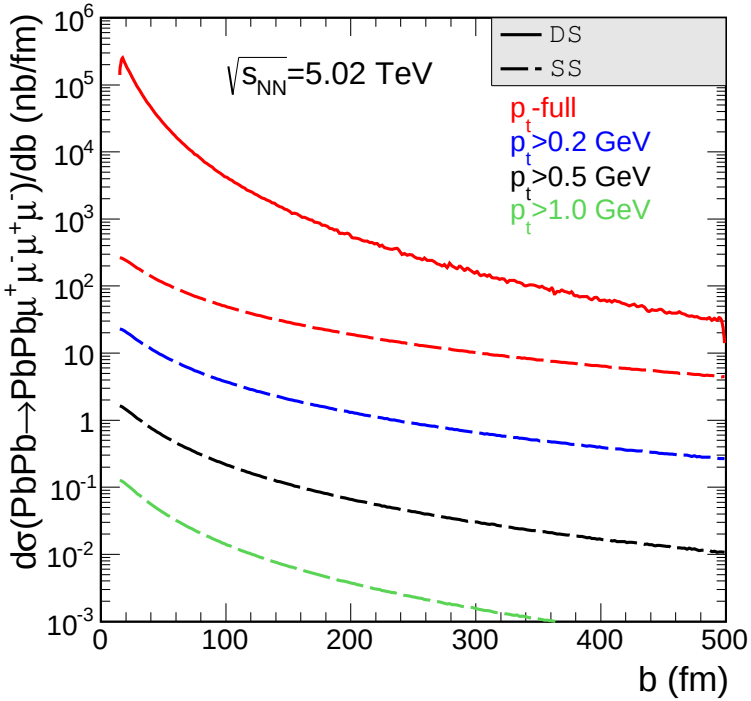






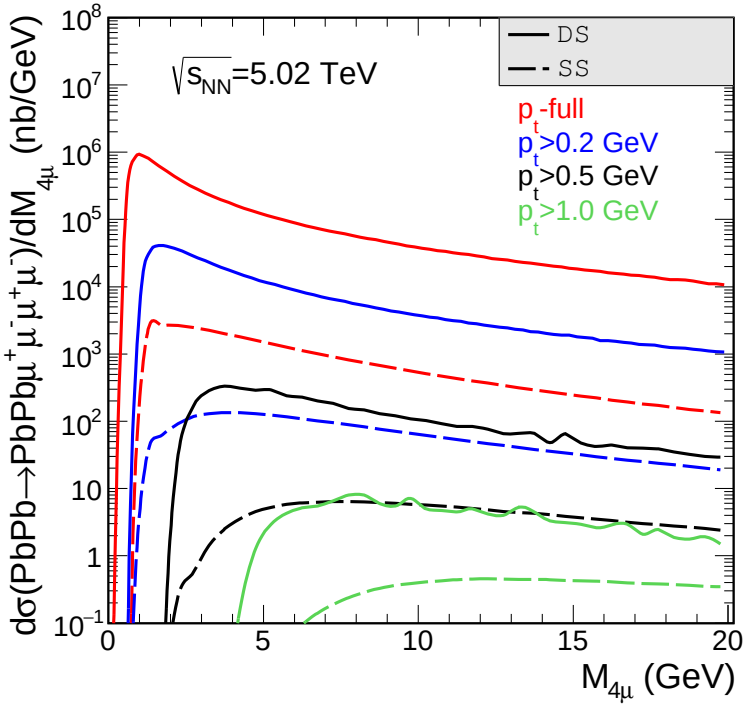
AA→AA$\mu^+\mu^-\mu^+\mu^-$

impact parameter



↑ purely theoretical distribution

$W_{\gamma\gamma} = M_{4\mu}$



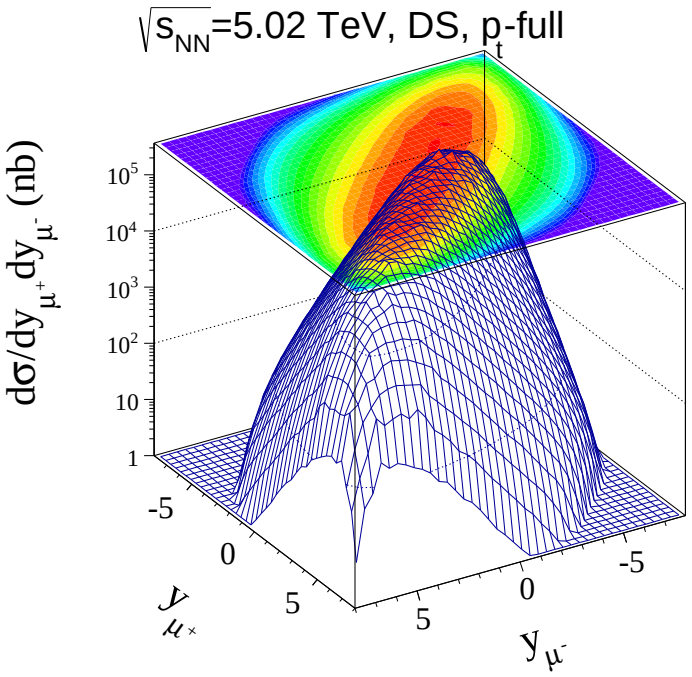
↑ DS dominates

It is difficult to isolate range of SS domination

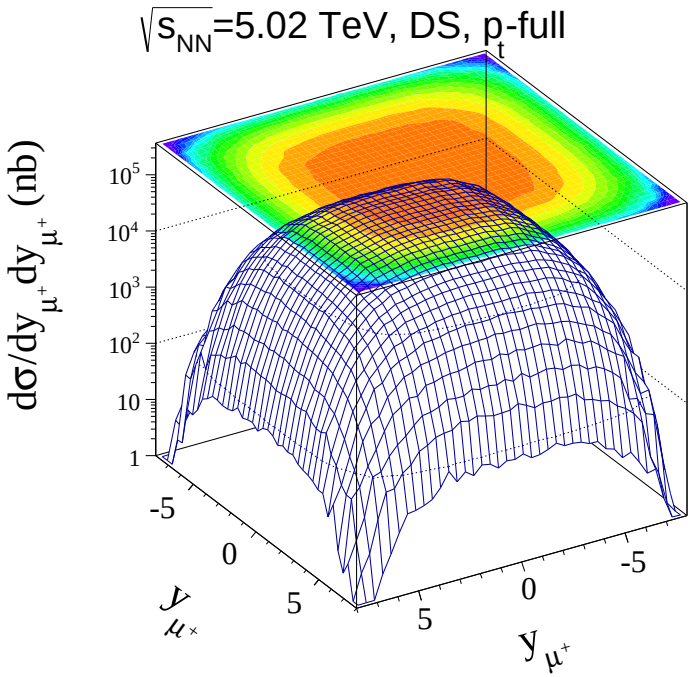
*DS - double-scattering mechanism
*SS - a NEW single-scattering mechanism

AA→AA$\mu^+\mu^-\mu^+\mu^-$

y_{μ^+} , y_{μ^-}

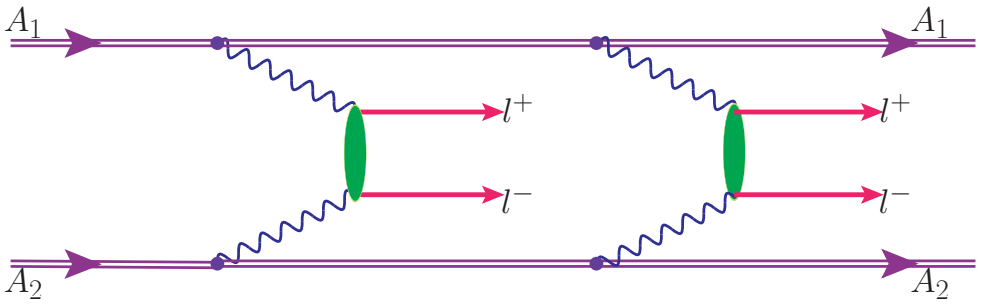


$y_{\mu^\pm}$, $y_{\mu^\pm}$



$p_{t,\mu_+} \simeq p_{t,\mu^-} \Rightarrow$ construction of similar distributions by ALICE or CMS?

Integrated cross sections



The number of counts for L_{int} = 1 nb^{-1}

(4μ), $\sqrt{s_{NN}} = 5.02$ TeV		$(4e)$, $\sqrt{s_{NN}} = 5.5$ TeV	
experimental cuts	N	experimental cuts	N
$\lvert y_i\rvert < 2.5$, $p_t > 0.5$ GeV	815	$\lvert y_i\rvert < 2.5$, $p_t > 0.5$ GeV	235
$\lvert y_i\rvert < 2.5$, $p_t > 1.0$ GeV	53	$\lvert y_i\rvert < 2.5$, $p_t > 1.0$ GeV	10
$\lvert y_i\rvert < 0.9$, $p_t > 0.5$ GeV	31	$\lvert y_i\rvert < 1.0$, $p_t > 0.2$ GeV	649
$\lvert y_i\rvert < 0.9$, $p_t > 1.0$ GeV	2	$\lvert y_i\rvert < 1.0$, $p_t > 1.0$ GeV	1
$\lvert y_i\rvert < 2.4$, $p_t > 4.0$ GeV	$\ll 1$		

CMS and ALICE $\Rightarrow p_{t,cut} = 1$ GeV

ALICE $\Rightarrow p_{t,cut} = 0.2$ GeV

ATLAS $\Rightarrow p_{t,cut} = 4$ GeV

Conclusions, part 2

- At the LHC double scattering possible even in UPC.
  Not yet identified.
- Double photoproduction of $\rho^0\rho^0$. Contribute to $\pi^+\pi^-\pi^+\pi^-$ production.
  Competition of $\rho' \to 4\pi$ and $\rho'' \to 4\pi$.
  ATLAS is a good candidate (rapidity separation).
- Double $\gamma\gamma$ production of $e^+e^-e^+e^-$ and $\mu^+\mu^-\mu^+\mu^-$.
  Measureable cross sections.
- Mixed contributions possible too (e.g. $\rho^0\mu^+\mu^-$).