MPI2017, Shimla, December 2017

Production of two pairs of J/ψ mesons and simultaneous production of D and B mesons in the context of double parton scattering

Antoni Szczurek [1,2]

[1]Institute of Nuclear Physics PAN Kraków
[2]University of Rzeszów

Introduction

- J/ψ the lightest quarkonium.
  Relatively large cross section.
- J/ψ a good probe of quark-gluon plasma.
- Long-standing problems in microscopic description of J/ψ distributions.
  Calculated cross sections much smaller than experimental ones.
- Color octet model was a "solution"
  But it was (is) rather fitted to the data.
- Higher-order collinear or k_t-factorization non-relativistic pQCD lead to larger cross sections.
- There is less and less room for color octet contributions.
- Do we need color-octet contributions ?
  Not clear in my opinion.

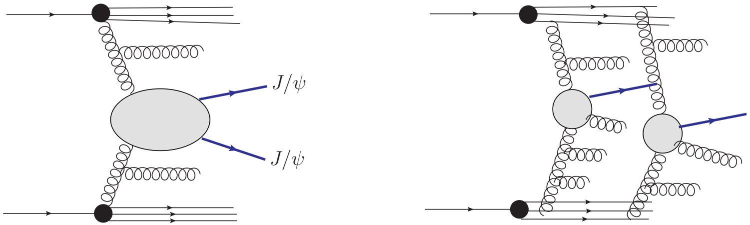
Single J/ψ production

We have done calculations of single J/ψ production within k_t-factorization and NRpQCD approach including:

- direct ($J/\psi g$) production
- feed-down from χ_c mesons

No fitting parameters (!)
A reasonable description of the midrapidity LHC data is possible.
Not much room for color octet contribution.
(Will not be discussed here.)
Here we concentrate on double J/ψ production.

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.

Our previous works on J/ψ

Our previous works on J/ψ:

A. Cisek, W. Schäfer and A. Szczurek, “Exclusive photoproduction of charmonia in $\gamma p \to Vp$ and $pp \to pVp$ reactions within k_t-factorization approach”,
JHEP **1504** (2015) 159. Phys. Rev. **D93** (2016) 074014.

A. Cisek, W. Schäfer and A. S., "Semiexclusive production of J/ψ mesons in proton-proton collisions", arXiv:1611.08210, in Phys.Lett.B.

A. Cisek and A. S., a paper in preparation

A. Cisek, W. Schäfer and A.S., a paper in preparation

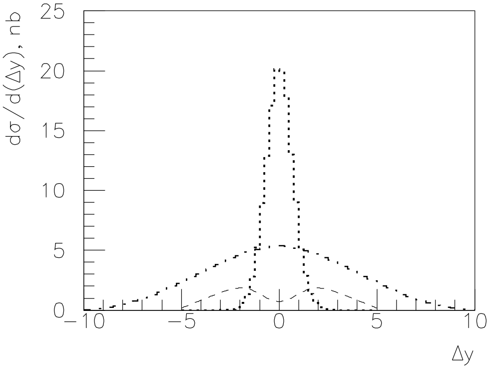
S.P. Baranov, A.M. Snigirev, N.P. Zotov, A. Szczurek and W. Schäfer, “Interparticle correlations in the production of J/ψ pairs in proton-proton collisions”, Phys. Rev. **D87** (2013) 034035.

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

New data become available recently:

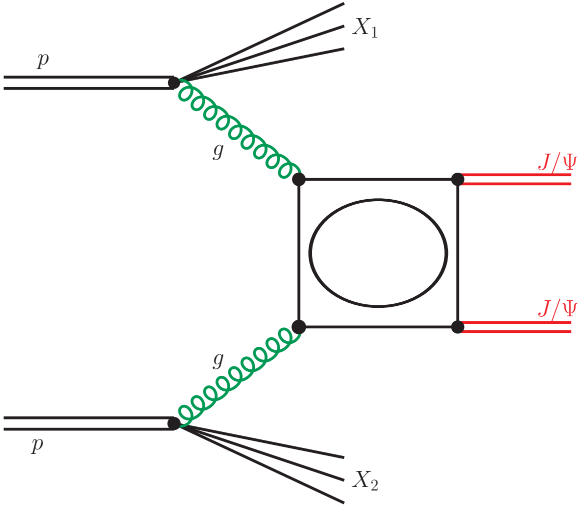
- Tevatron D0 data for $\sqrt{s}$ = 1.96 TeV (small σ_{eff} obtained)
- LHCb data ($\sqrt{s}$ = 7 TeV)
- CMS data for $\sqrt{s}$ = 8 TeV (running cuts, difficult to interprete)
- ATLAS data for $\sqrt{s}$ = 8 TeV (will be dicussed here)

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



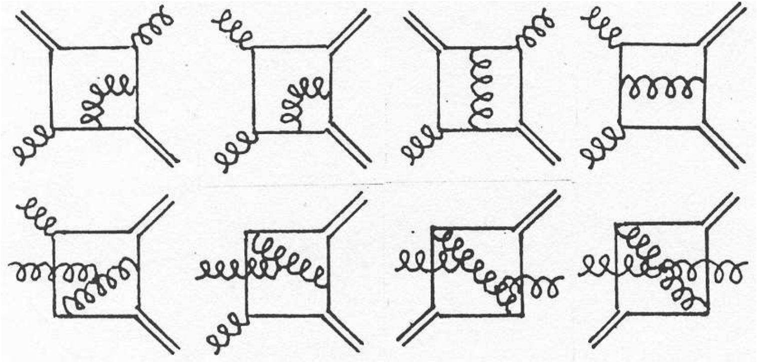
S.P. Baranov, A.M. Snigirev, N.P. Zotov, A. Szczurek and W. Schäfer, "Interparticle correlations in the production of J/ψ pairs in proton-proton collisions", Phys. Rev. **D87** (2013) 034035.

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



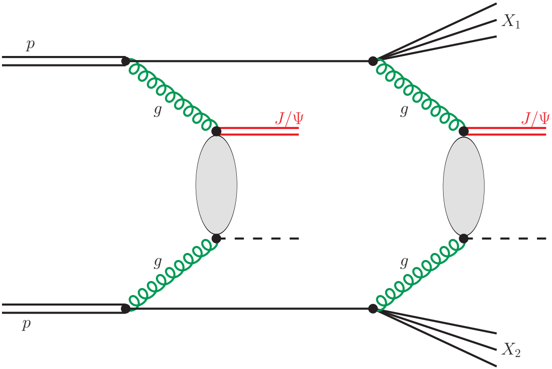
20 diagrams, box ($O(\alpha_s^4)$), $\sigma \propto |R(0)|^4$.

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



only some are shown

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



DPS ($O(\alpha_s^6)$)
But enhanced by higher powers of gluon distributions $g_1^2 g_2^2$ at high energy.

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

In k_t-factorization approach:

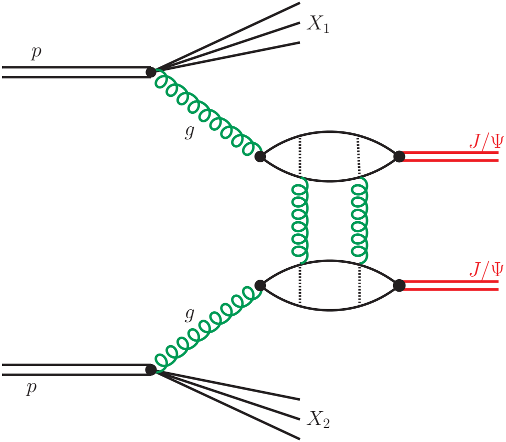
$$\frac{d\sigma(pp \to J/\psi J/\psi X)}{dy_{V_1} dy_{V_2} d^2p_{V_1,t} d^2p_{V_2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} \overline{|\mathcal{M}^{off-shell}_{g^*g^* \to J/\psi J/\psi}|^2}$$
$$\times \; \delta^2 \left(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{V_1,t} - \vec{p}_{V_2,t} \right) \mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2) \; . \quad (1)$$

The corresponding matrix elements squared for the $gg \to J/\psi J/\psi$ (box) is

$$|\mathcal{M}_{gg \to J/\psi J/\psi}|^2 \propto \alpha_s^4 |R(0)|^4 \; . \quad (2)$$

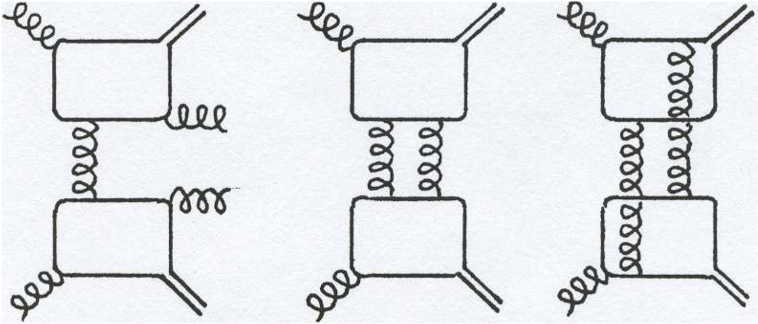
They were calculated e.g. by our collaborator S. Baranov.

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



16 diagrams, box ($O(\alpha_s^6)$) (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, "Interparticle correlations in the production of J/ψ pairs in proton-proton collisions", Phys. Rev. **D87** (2013) 034035

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



and many more ...

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

We have made calculations both in collinear and k_t-factorization approaches. In collinear approach:

$$\frac{d\sigma(pp \to J/\psi J/\psi}{dy_{V_1} dy_{V_2} d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \overline{|\mathcal{M}^{on-shell}_{gg \to J/\psi J/\psi}|^2} \times \; g(x_1, \mu_F^2) g(x_2, \mu_F^2) \; . \tag{3}$$

In our calculations we will use MSTW08 gluon distributions.

2g exchange mechanism

In high-energy approximation the elementary 2g-exchange process amplitude

$$\mathcal{M} \propto \hat{s} \int d^2\kappa \frac{\Phi_1^{nr}(\kappa_1)\Phi_2^{nr}(\kappa_2)}{(\kappa_1^2 + m_g^2)(\kappa_2^2 + m_g^2)} \; . \tag{4}$$

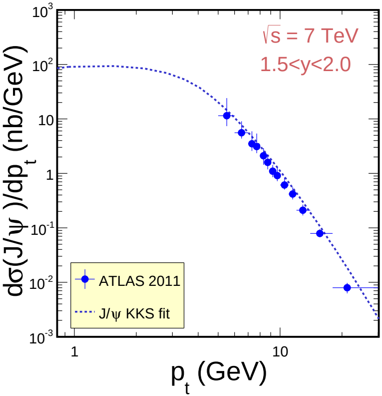
where nonrelativistic $g \to J/\psi$ impact factors:
$\Phi_k^{nr} \propto \sqrt{\Gamma_{V\to e^+e^-}}\alpha_s$ (k=1,2).
We take $m_g = 0$ (possible enhancement, but not in this corner of PS)
$\Phi_{\gamma\to V}^{nr}$ were calculated by Ginzburg,Panfil,Serbo 1987.
It was generalized to $g \to J/\psi$ transitions.

O(α_s^6) contribution !!!
(so far calculations upto O(α_s^5) in NLO) (Lansberg, Shao 2015)

experiment driven DPS

$$\frac{d\sigma(pp \to J/\psi g)}{dy_{J/\psi} dy_g d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} \overline{|\mathcal{M}^{eff}_{gg\to J/\psi g}|^2} \times \; g(x_1, \mu_F^2) g(x_2, \mu_F^2) \; . \quad (5)$$

Auxiliary final state "gluon" (could be massive).
We take parametrization by Kom-Kulesza-Stirling 2011 with MSTW08 PDF.



Experiment driven DPS

single parton scattering $\rightarrow$ double parton scattering
We assume factorized Ansatz.

$$\frac{d\sigma}{dy_1 d^2p_{1t} dy_2 d^2p_{2t}} == \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 d^2p_{1t}} \cdot \frac{d\sigma}{dy_2 d^2p_{2t}} \tag{6}$$

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???

$pp \to \chi_c \chi_c$

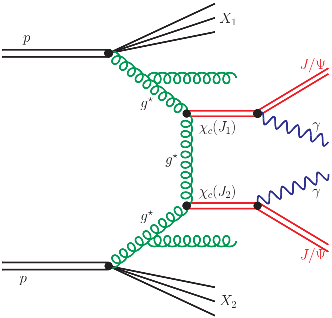


Figure: A diagrammatic representation of the leading order mechanisms for $pp \to \chi_c(J_1)\chi_c(J_2) \to (J/\psi + \gamma)(J/\psi + \gamma)$ reaction.

$g^* g^* \to \chi_c$ vertex

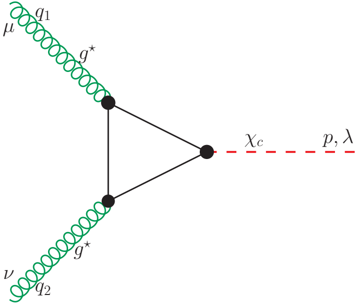
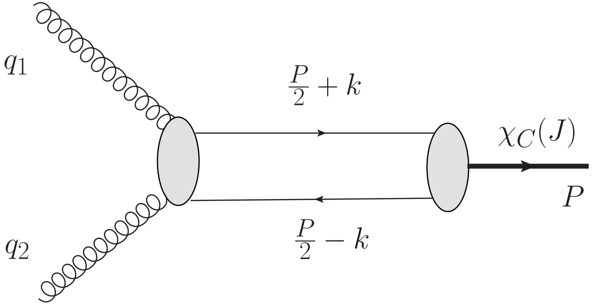


Figure: $g^* g^* \to \chi_c(\lambda)$ vertex being a building block of corresponding $g^* g^* \to \chi_c(J_1)\chi_c(J_2)$.

$$
\begin{aligned}
q_1^\mu T_{\mu\nu}(J, J_z) &= 0 \,, \\
q_2^\nu T_{\mu\nu}(J, J_z) &= 0 \,.
\end{aligned}
$$

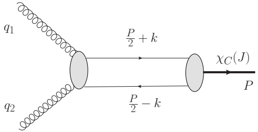
$g^*g^* \to \chi_c$ vertex



$$V^{ab}_{\mu\nu}(J,J_z;q_1,q_2) = 4\pi\alpha_S \frac{\mathrm{Tr}[t^a t^b]}{\sqrt{N_c}} \sqrt{\frac{2}{M}} \sum_{S_z,L_z} \int \frac{d^4k}{(2\pi)^3} \delta(k^0 - \frac{\vec{k}^2}{M}) \Psi_{1,L_z}(\vec{k})$$
$$\times \langle 1, S_z; 1, L_z ||| J, J_z \rangle \cdot \mathrm{Tr}[A_{\mu\nu} \Pi_{1,S_z}],$$

- NRQCD: expand in the relative momentum k.

$g^*g^* \to \chi_c$ vertex



The $g^*g^* \to Q\bar{Q}$ amplitude is (up to factors)

$$A_{\mu\nu} = \gamma_\mu \frac{\hat{p}_Q - \hat{q}_1 + m_Q}{(p_Q - q_1)^2 - m_Q^2} \gamma_\nu + \gamma_\nu \frac{\hat{p}_Q - \hat{q}_2 + m_Q}{(p_Q - q_2)^2 - m_Q^2} \gamma_\mu \, .$$

Projector onto spin-triplet:

$$\Pi_{S=1,S_z} = \frac{1}{2\sqrt{2}m_Q} \left(\frac{\hat{P}}{2} - \hat{k} - m_Q\right) \hat{\epsilon}(S_z) \left(\frac{\hat{P}}{2} + \hat{k} + m_Q\right).$$

- NRQCD: expand in the relative momentum k.

Elementary amplitudes

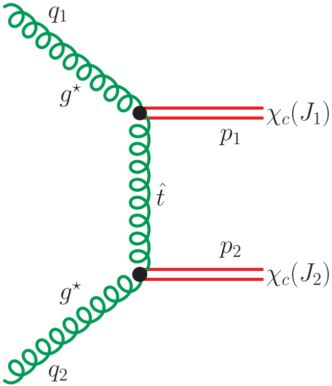


Figure: A diagrammatic representation of the generic $g^* g^* \to \chi_c(J_1)\chi_c(J_2)$ t-channel (left) and u-channel (right) amplitudes.

Elementary amplitudes

Now we wish to discuss the elementary $g^* g^* \to \chi_c(J_1)\chi_c(J_2)$ amplitudes $\mathcal{M}_{\mu\nu}(J_1 J_{1z}, J_2 J_{2z})$.

The generic amplitude for the $gg \to \chi_c(J_1)\chi_c(J_2)$ subprocess can be written as:

$$\begin{aligned} \mathcal{M}(\lambda_1, \lambda_2) = \epsilon_1^{\alpha}\epsilon_2^{\beta}[\quad & V_{\alpha\mu}^{\chi_c(J_1),t}(\lambda_1 \ldots)\frac{g^{\mu\nu}}{\hat{t}} V_{\beta\nu}^{\chi_c(J_2),t}(\lambda_2 \ldots) \\ + \quad & V_{\alpha\mu}^{\chi_c(J_2),u}(\lambda_2 \ldots)\frac{g^{\mu\nu}}{\hat{u}} V_{\beta\nu}^{\chi_c(J_1),u}(\lambda_1 \ldots)] \, . \end{aligned} \qquad (7)$$

Elementary amplitudes, gauge invariance

Because of properties of our $g^*g^* \to \chi_c(1)$ vertices the tensorial amplitudes for the $g^*g^* \to \chi_c(1)\chi_c(1)$ fulfill the following relations:

$$\begin{aligned} q_1^\alpha \mathcal{M}_{\alpha\beta\gamma\delta} &= 0, \\ q_2^\beta \mathcal{M}_{\alpha\beta\gamma\delta} &= 0, \\ p_1^\gamma \mathcal{M}_{\alpha\beta\gamma\delta} &= 0, \\ p_2^\delta \mathcal{M}_{\alpha\beta\gamma\delta} &= 0. \end{aligned} \tag{8}$$

or

$$\begin{aligned} \mathcal{M}_{\mu\nu}(J_1 J_{1z}, J_2 J_{2z}) q_1^\mu &= 0\ , \\ \mathcal{M}_{\mu\nu}(J_1 J_{2z}, J_2 J_{2z}) q_2^\nu &= 0\ . \end{aligned}$$

Cross section

From the general rules of nonrelativistic pQCD:

$$\sigma_{pp\to\chi_c\chi_c} \propto \alpha_s^4 |R'_P(0)|^4 \tag{9}$$

The cross section sensitive to the choice of renormalization scale and the wave function.

$$\Gamma(\chi_c(0^+) \to \gamma\gamma) = \frac{27 e_c^4 \alpha_{em}^2}{(m_{\chi_c(0)}/2)^4} |R'_P(0)|^2 \; . \tag{10}$$

Use PDG data.

Combined branching fractions

Table: Combined decay branching fractions for different combinations of intermediate $\chi_c(J_1)\chi_c(J_2)$ dimeson states.

	$\chi_c(0)$	$\chi_c(1)$	$\chi_c(2)$
$\chi_c(0)$	$1.44\ 10^{-4}$	0.0035	0.002
$\chi_c(1)$	0.0035	0.12	0.07
$\chi_c(2)$	0.002	0.07	0.035

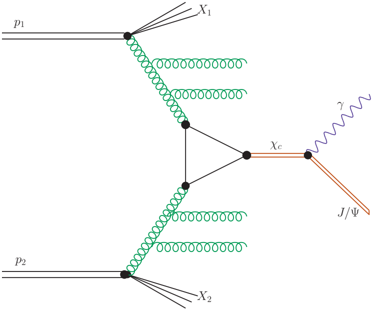
$pp \to \chi_c \chi_c$ cross section

The k_t-factorization approach the corresponding differential cross section can be written as:

$$\frac{d\sigma(pp \to \chi_c \chi_c X)}{dy_{M_1} dy_{M_2} d^2p_{M_1,t} d^2p_{M_2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} \overline{|\mathcal{M}^{off-shell}_{g^*g^* \to \chi_c \chi_c}|^2}$$
$$\times \; \delta^2 \left(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{V_1,t} - \vec{p}_{V_2,t} \right) \mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2) \; . \quad (11)$$

The x_1 and x_2 are calculated from χ_c's transverse masses and rapidities in the standard way.

$pp \to \chi_c$



$\sigma_{k_t-fact} < \sigma_{coll}$ for $\chi_c(0), \chi_c(2)$
$\sigma_{k_t-fact} > \sigma_{coll} = 0$ for $\chi_c(1)$
We reproduce formulae of Kniehl, Vasin, Saleev.

$pp \to \chi_c \chi_c$, prelimianary results

Table: Cross sections in nb for production of different $\chi_c(J_1)\chi_c(J_2)$ dimeson states for the full phase space for $\sqrt{s}$ = 8 TeV.

ATLAS	$\chi_c(0)$	$\chi_c(1)$	$\chi_c(2)$
$\chi_c(0)$	1.32	1.71	4.24
$\chi_c(1)$	....	0.84	2.88
$\chi_c(2)$	....	....	3.45

$pp \to \chi_c\chi_c$, results

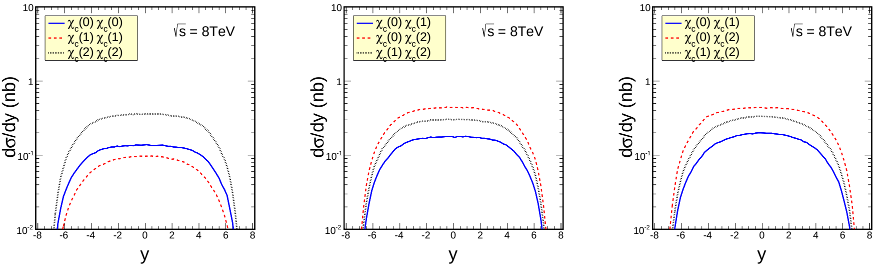


Figure: Rapidity distributions of quarkonia for different spin combinations.

A. Cisek, W. Schäfer and A. Szczurek, arXiv:1711.07366

$pp \to \chi_c \chi_c$, results

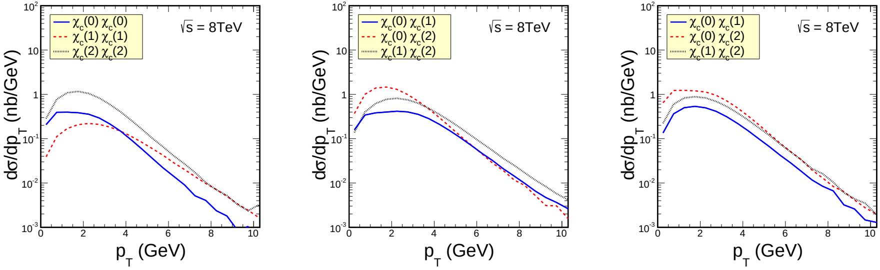


Figure: Transverse momentum distributions of quarkonia for different spin combinations.

A. Cisek, W. Schäfer and A. Szczurek, arXiv:1711.07366

$pp \to \chi_c\chi_c$, results

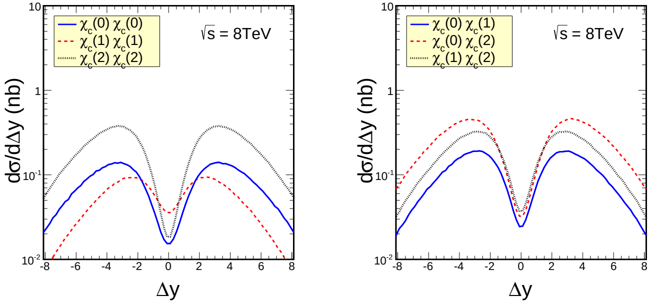


Figure: Distributions in the rapidity separation between χ_c's for different spin combinations.

A. Cisek, W. Schäfer and A. Szczurek, arXiv:1711.07366

$pp \to \chi_c \chi_c$, results

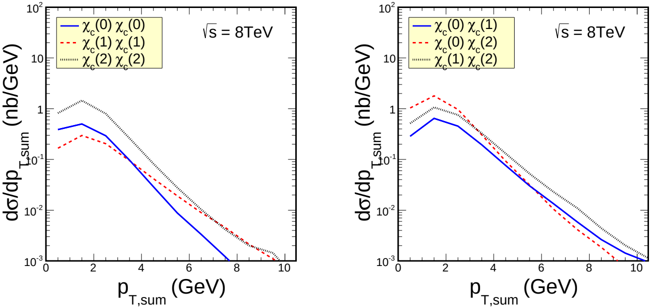


Figure: Distributions in the transverse momentum of quarkonium pairs for different spin combinations.

A. Cisek, W. Schäfer and A. Szczurek, arXiv:1711.07366

$pp \to \chi_c(i)\chi_c(j)$ contributions

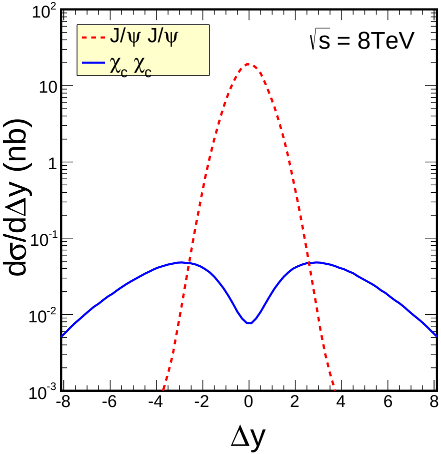
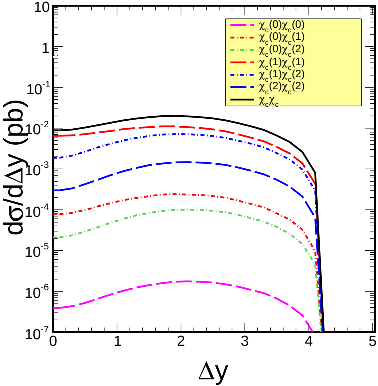


Figure: Distributions in the rapidity difference between two J/ψ (dashed line) and for the sum over all $\chi_c\chi_c$ combinations multiplied by combined branching fractions.

$pp \to \chi_c(i)\chi_c(j)$ contributions for ATLAS kinematics

with $p_{i,t} > 8.5$ GeV, $-2.1 < y_i < 2.1$ cuts

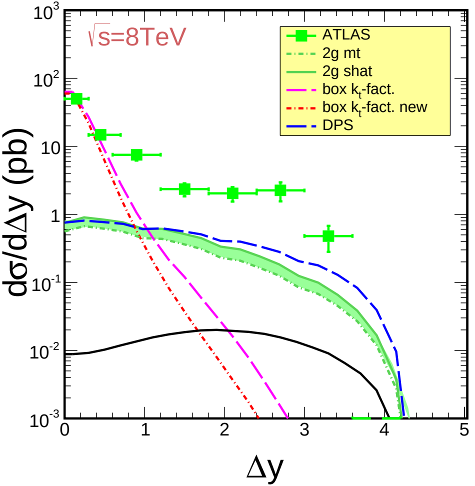


with branching fractions !!! $\chi_c(1)\chi_c(1)$ dominance !!!

$pp \to \chi_c(1)\chi_c(1)$, dominance

The dominance of the $\chi_c(1)\chi_c(1)$ requires extra discussion.
In contrast to the $g^*g^* \to \chi_c(1)$ amplitude, the amplitude for $g^*g^* \to \chi_c(1)\chi_c(1)$ does not vanish when $q_1^2 \to 0$ and $q_2^2 \to 0$. This can be understood by the fact that then neither $\hat{t}$ nor $\hat{u}$ (see diagram) have to vanish.
This means that we are alway far from
$(q_1^2 = 0, \hat{t} = 0), (q_1^2 = 0, \hat{u} = 0) and (q_2^2 = 0, \hat{u} = 0), (q_2^2 = 0, \hat{u} = 0)$
points, i.e. the Landau-Yang theorem is not active.
Even if we are close to one of such points and the t or u amplitudes are small, it does not happen simulataneously.

First results, with muon cuts

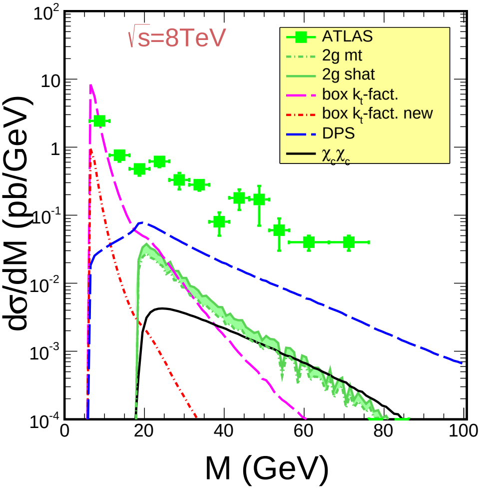


simultaneous decay of both J/ψ in Monte Carlo approach

-2.1 $< y_1, y_2 <$ 2.1, $p_t >$ 8.5 GeV

ATLAS-CONF-2016-047, Eur. Phys. J. **C77** (2017) 76.

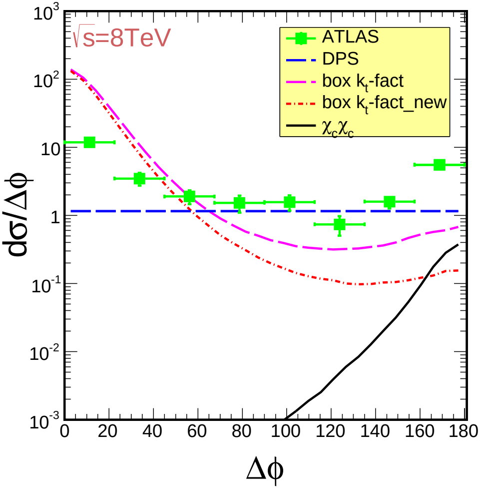
First results, with muon cuts



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

ATLAS-CONF-2016-047, Eur. Phys. J. **C77** (2017) 76

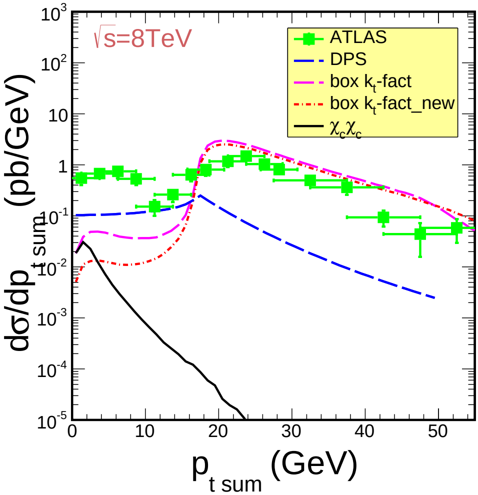
First results, with muon cuts



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

ATLAS-CONF-2016-047, Eur. Phys. J. **C77** (2017) 76

First results, with muon cuts

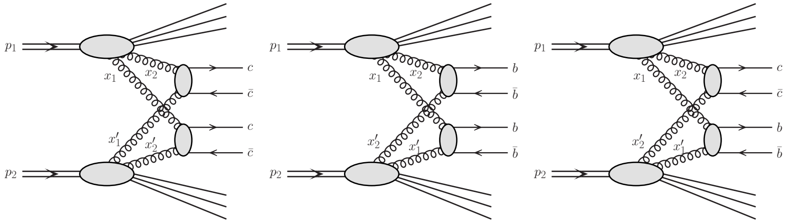


approximate inclusion of muonic cuts

ATLAS-CONF-2016-047, Eur. Phys. J. **C77** (2017) 76

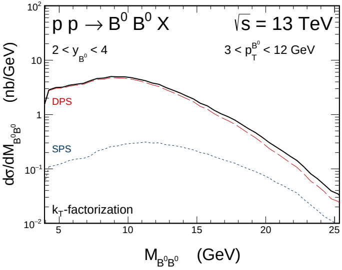
Heavy quark/meson DPS production

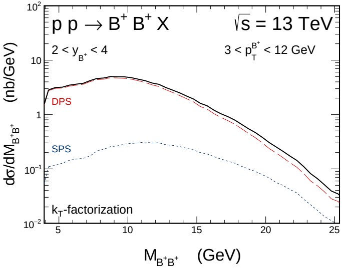
in preparation ... (with Rafal Maciuła)



The first process was studied both theoretically and experimentally
Both DPS and SPS calculated within k_t-factorization with the KMR UGDF.

Double BB meson production





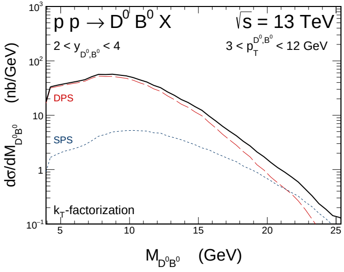
Peterson fragmentation functions

DPS $\gg$ SPS

Similar situation as for $D^0 D^0$ measured by the LHCb

but much smaller cross section (difficult)

Double *DB* meson production



Peterson fragmentation functions

DPS $\gg$ SPS

Similar situation as for $D^0 D^0$ measured by the LHCb

relatively large cross section !!!

Conclusions, double J/ψ production

- We have tried several mechanisms of double quarkonium production.
- Leading-order contribution in k_t-factorization.
- two-gluon exchange in collinear approach.
  go to k_t-factorization (enhancement?).
- Double parton scattering calculated based on experimental data for single J/ψ production.
- $\chi_c(J_1)\chi_c(J_2)$ in k_t-factorization were calculated for the first time.
  Dominance of $\chi_c(1)\chi_c(1)$ for the ATLAS cuts.
- For large rapidity distance between two χ_c mesons – ladder exchange (BFKL resummation) ?
- Clear signature of double parton scattering mechanism.
- $\sigma_{eff} \sim 5$ mb found from experimental analyses may be too small due to missing contributions (included in our calculation).
  The two-gluon exchange and double χ_c production mechanisms have some characteristics similar as DPS.
- There seems to be still some room for other mechanisms.
  We have a list of processes to be included.

Conclusions, double J/ψ production

- We have tried several mechanisms of double quarkonium production.
- Leading-order contribution in k_t-factorization.
- two-gluon exchange in collinear approach.
  go to k_t-factorization (enhancement?).
- Double parton scattering calculated based on experimental data for single J/ψ production.
- $\chi_c(J_1)\chi_c(J_2)$ in k_t-factorization were calculated for the first time.
  Dominance of $\chi_c(1)\chi_c(1)$ for the ATLAS cuts.
- For large rapidity distance between two χ_c mesons – ladder exchange (BFKL resummation) ?
- Clear signature of double parton scattering mechanism.
- $\sigma_{eff} \sim 5$ mb found from experimental analyses may be too small due to missing contributions (included in our calculation).
  The two-gluon exchange and double χ_c production mechanisms have some characteristics similar as DPS.
- There seems to be still some room for other mechanisms.
  We have a list of processes to be included.