QCD chalenges, Trento February/March 2017

Inclusive double J/ψ production at the LHC

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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 at all color-octet contributions ?
  Not clear in my opinion.

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

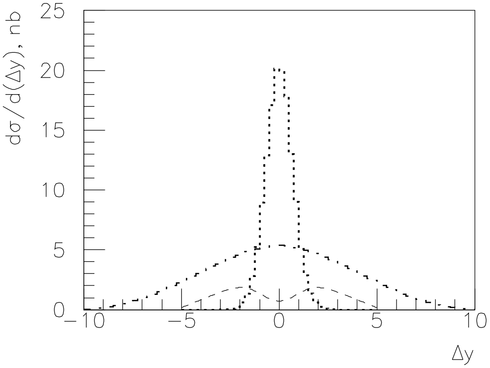
Our previous works on J/ψ:
A. Cisek, W. Schäfer and A. Szczurek, “Exclusive photoproduction of charmonia in $\gamma p \to Vp$ and $pp \to pVp$ reactions within k_t-factorization approach”,
JHEP **1504** (2015) 159. Phys. Rev. **D93** (2016) 074014.
A. Cisek, W. Schäfer and A. S., "Semiexclusive production 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:

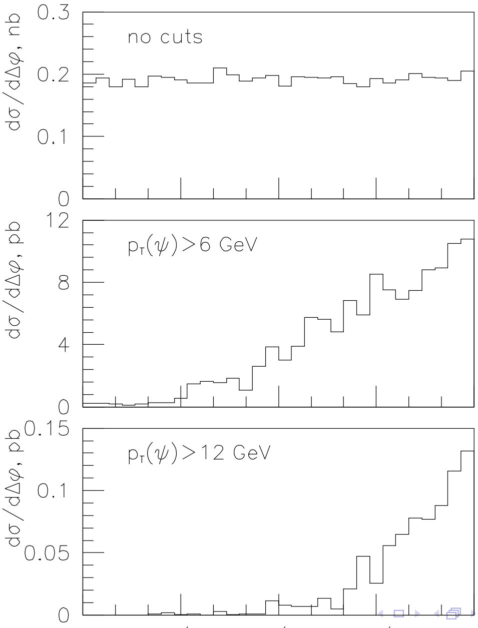
- Tevatron D0 data for $\sqrt{s}$ = 1.96 TeV (small σ_{eff} obtained)
- LHCb data ($\sqrt{s}$ = 7 TeV)
- CMS data for $\sqrt{s}$ = 8 TeV (running cuts, difficult to interprete)
- preliminary ATLAS data for $\sqrt{s}$ = 8 TeV (will be dicussed here)

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

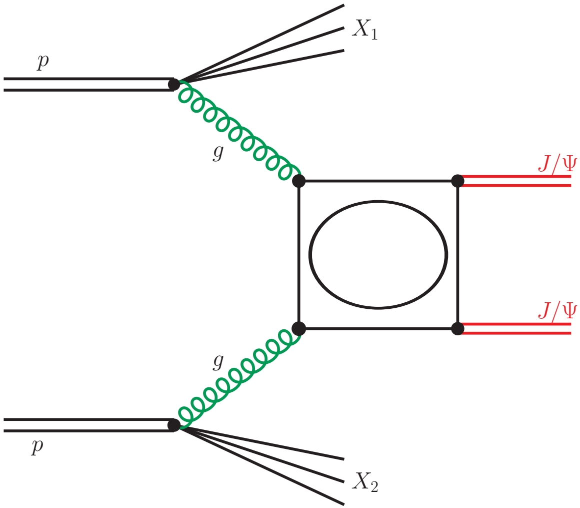


S.P. Baranov, A.M. Snigirev, N.P. Zotov, A. Szczurek and W. Schäfer, "Interparticle correlations in the production of J/ψ pairs in proton-proton collisions", Phys. Rev. **D87** (2013) 034035.

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

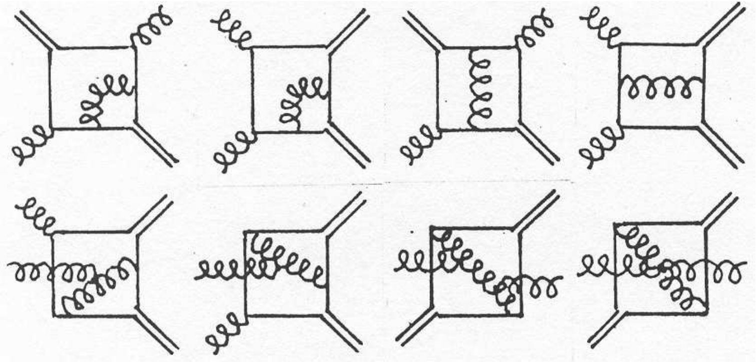


$pp \to J/\psi J/\psi$, box



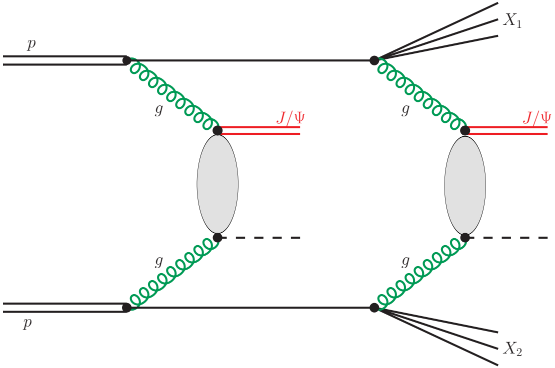
20 diagrams, box ($O(\alpha_s^4)$), $\sigma \propto |R(0)|^4$.

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



only some are shown

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

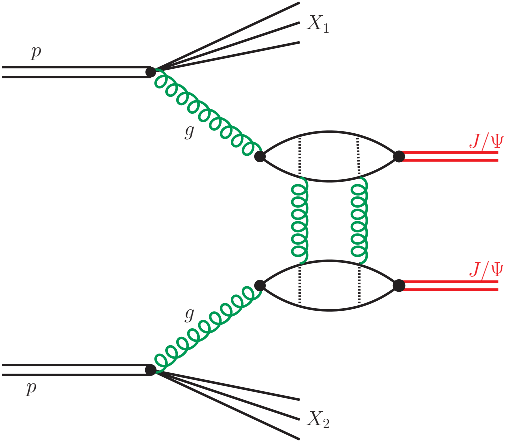
$$\frac{d\sigma(pp \to J/\psi J/\psi X)}{dy_{V_1} dy_{V_2} d^2p_{V_1,t} d^2p_{V_2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} \overline{|\mathcal{M}^{off-shell}_{g^*g^* \to J/\psi J/\psi}|^2}$$
$$\times \; \delta^2 \left(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{V_1,t}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

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

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

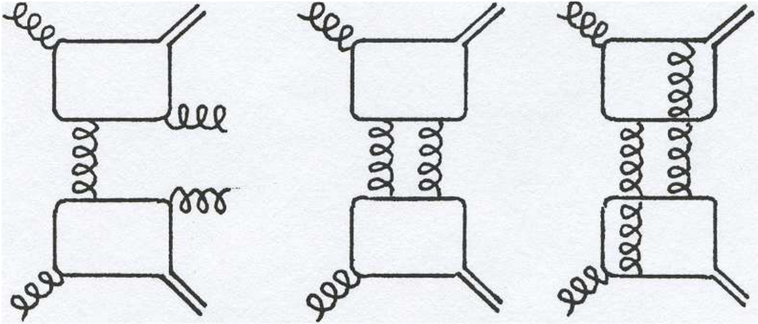
They were calculated e.g. by our collaborator S. Baranov.

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

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

In our calculations we will use MSTW08 gluon distributions.

2g exchange mechanism

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

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

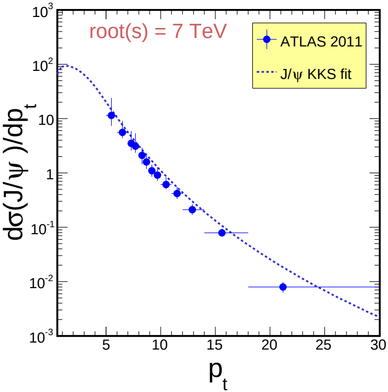
where nonrelativistic $g \to J/\psi$ impact factors:
$\Phi_k^{nr} \propto \sqrt{\Gamma_{V \to e^+e^-}}\alpha_s$ (k=1,2).
We take $m_g = 0$ (possible enhancement, but not in this corner of PS)
$\Phi_{\gamma \to V}^{nr}$ were calculated by Ginzburg,Panfil,Serbo 1987.
It was generalized to $g \to J/\psi$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

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

experiment driven DPS

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

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 were 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???

$pp \to \chi_c \chi_c$

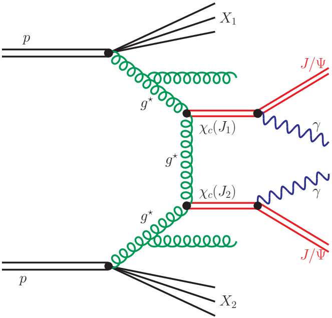


Figure: A diagrammatic representation of the leading order mechanisms for $pp \to \chi_c(J_1)\chi_c(J_2) \to (J/\psi + \gamma)(J/\psi + \gamma)$ reaction.

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

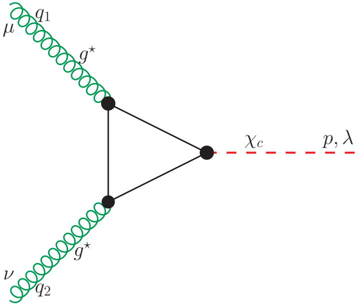


Figure: A diagrammatic representation of the $g^*g^* \to \chi_c(\lambda)$ vertex being a building block of corresponding $g^*g^* \to \chi_c(J_1)\chi_c(J_2)$.

Elementary amplitudes

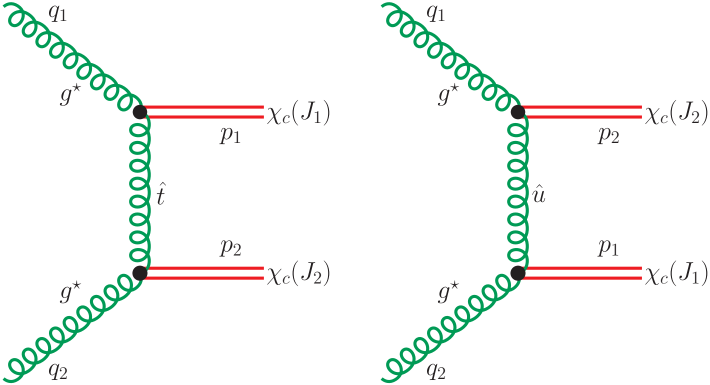


Figure: A diagrammatic representation of the generic $g^* g^* \to \chi_c(J_1)\chi_c(J_2)$ t-channel (left) and u-channel (right) amplitudes.

Elementary amplitudes

Now we wish to discuss the elementary $g^*g^* \to \chi_c(J_1)\chi_c(J_2)$ amplitudes.
For example the amplitude for the $gg \to \chi_c(0)\chi_c(0)$ subprocess can be written as:

$$\mathcal{M}^{00} = \epsilon_1^{\alpha}\epsilon_2^{\beta}\left(\frac{g^{\mu\nu}}{\hat{t}}V_{\alpha\mu}^{\chi_c(0),t}(...)V_{\beta\nu}^{\chi_c(0),t}(...) + \frac{g^{\mu\nu}}{\hat{u}}V_{\alpha\mu}^{\chi_c(0),u}(...)V_{\beta\nu}^{\chi_c(0),u}(...)\right) \tag{7}$$

Elementary amplitudes

The amplitude for the $gg \to \chi_c(1)\chi_c(1)$ subprocess in a tensorial form can be written as:

$$\mathcal{M}^{11}_{\gamma\delta} = \epsilon_1^{\alpha}\epsilon_2^{\beta}\left(\frac{g^{\mu\nu}}{\hat{t}}V^{\chi_c(1),t}_{\alpha\mu,\gamma}(...)V^{\chi_c(1),t}_{\beta\nu,\beta}(...) + \frac{g^{\mu\nu}}{\hat{u}}V^{\chi_c(1),u}_{\alpha\mu,\gamma}(...)V^{\chi_c(1),u}_{\beta\nu,\beta}(...)\right) \tag{8}$$

Then the helicity amplitude can be obtained from the tensorial representation as:

$$\mathcal{M}^{11}(\lambda_1,\lambda_2) = \epsilon^{*}_{\chi_c(1),1}(p_1,\lambda_1)\epsilon^{*}_{\chi_c(1),2}(p_2,\lambda_2)\mathcal{M}^{11}_{\gamma\delta}\ . \tag{9}$$

Elementary amplitudes

The k_t-factorization amplitude can be written conveniently using the so-called nonsense polarization vectors for off-shell gluons and carteasian polarization vectors for final χ_c mesons. The corresponding formula reads

$$M^{i,j}_{g^* g^* \to \chi_c(1) \chi_c(1)} = e_{1\alpha} e_{2\beta} T^{\alpha\beta,\mu\nu} \epsilon^{i}_{3\mu} \epsilon^{j}_{4\nu} \; , \qquad (10)$$

or more precisely

$$M^{i,j}_{g^* g^* \to \chi_c(1) \chi_c(1)} = e_{1\alpha} e_{2\beta} T_t^{\alpha\beta,\mu\nu} \epsilon^{i}_{3\mu} \epsilon^{j}_{4\nu} + e_{1\alpha} e_{2\beta} T_u^{\alpha\beta,\mu\nu} \epsilon^{i}_{3\nu} \epsilon^{j}_{4\mu} \; , \qquad (11)$$

where i and j are the carteasian polarizations of $\chi_c(1)$ mesons and T is a tensorial representation of the amplitude.

Elementary amplitudes

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:

$$\begin{aligned} q_1^{\alpha}\mathcal{M}_{\alpha\beta\gamma\delta} &= 0, \\ q_2^{\beta}\mathcal{M}_{\alpha\beta\gamma\delta} &= 0, \\ p_1^{\gamma}\mathcal{M}_{\alpha\beta\gamma\delta} &= 0, \\ p_2^{\delta}\mathcal{M}_{\alpha\beta\gamma\delta} &= 0. \end{aligned} \tag{12}$$

Elementary amplitudes

Finally we wish to discuss also production of tensor χ_c mesons. The $g^* g^* \to \chi_c(2)$ vertex, being a building block of corresponding amplitudes for two χ_c meson production, can be written as:

$$V_{\mu\nu}(2, J_z; q_1, q_2) = ...R'_P(0)\; \delta^{ab}\; T_{\mu\nu}(2, J_z; q_1, q_2) \qquad (13)$$

where

$$T_{\mu\nu}(2, J_z; q_1, q_2) = \frac{-16M^2}{(2q_1 \cdot q_2)^2}\Big(\; - \; g_{\mu\nu}(q_2 - q_1)^\alpha (q_2 - q_1)^\beta \epsilon_{\alpha\beta}(J_z) + 4(q_1 \cdot$$
$$+ \; 2(q_2 - q_1)^\alpha \epsilon_{\alpha\nu}(J_z) q_{2,\mu} - 2(q_2 - q_1)^\alpha \epsilon_{\alpha\mu}$$

(14)

Elementary amplitudes

J_z above is a projection of the spin 2 to a chosen axis. The spherical polarization tensors for tensor $\chi_c(2)$ mesons, that appear above, fulfill the following orthogonality relation:

$$\epsilon^*_{\mu\nu}(\lambda_1)\epsilon^{\mu\nu}(\lambda_2) = \delta_{\lambda_1\lambda_2} \tag{15}$$

The above vertex functions are used then to calculate for instance amplitude for the partonic $g^*g^* \to \chi_c(2)\chi_c(2)$ subprocess. The tensorial representation of the amplitude can be then written as

$$\begin{aligned} A_{\mu_1\mu_2}(q_1 q_2, p_3, p_4; \lambda_3\lambda_4) &= V^{t,1}_{\mu_1\nu_1}(p_3,\lambda_3)\left(\frac{-g_{\nu_1\nu_2}}{\hat{t}}\right)V^{t,2}_{\nu_2\mu_2}(p_4,\lambda_4) \\ &+ V^{u,1}_{\mu_1\nu_1}(p_4,\lambda_4)\left(\frac{-g_{\nu_1\nu_2}}{\hat{u}}\right)V^{u,2}_{\nu_2\mu_2}(p_3,\lambda_3) \end{aligned} \tag{16}$$

Cross section

From the general rules of nonrelativistic pQCD:

$$\sigma_{pp\to\chi_c\chi_c} \propto \alpha_s^4 |R'_P(0)|^4 \tag{17}$$

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

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

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

Table: Cross sections in pb for production of different $\chi_c(J_1)\chi_c(J_2)$ dimeson states for the ATLAS fiducial volume: -2.1 $< y_1, y_2 <$ 2.1 and $p_t >$ 8.5 GeV. The numbers are obtained in the k_t-factorization approach. the second number (in parantheses) is obtained in the collinear-factorization approach. In all cases the gauge invariant matrix elements discussed in the present paper were used.

ATLAS	$\chi_c(0)$	$\chi_c(1)$	$\chi_c(2)$
$\chi_c(0)$	0.68	2.4	not yet
$\chi_c(1)$	2.4	19.6	not yet
$\chi_c(2)$	not yet	not yet	1.2

$pp \to \chi_c \chi_c$ cross section

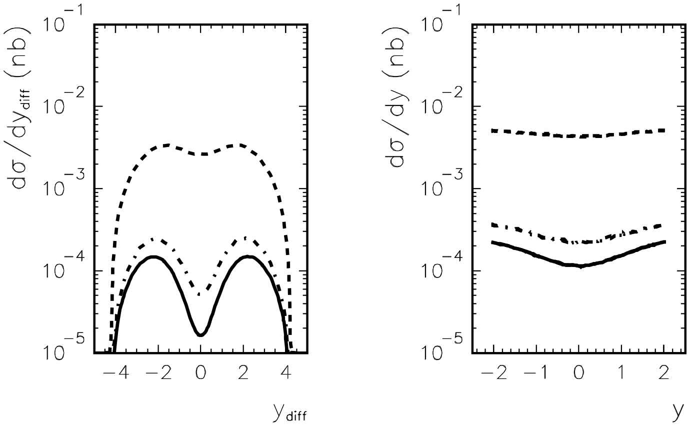
The k_t-factorization approach the corresponding differential cross section can be written as:

$$\frac{d\sigma(pp \to \chi_c \chi_c X)}{dy_{M_1} dy_{M_2} d^2p_{M_1,t} d^2p_{M_2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} \overline{|\mathcal{M}^{off-shell}_{g^*g^* \to \chi_c \chi_c}|^2}$$

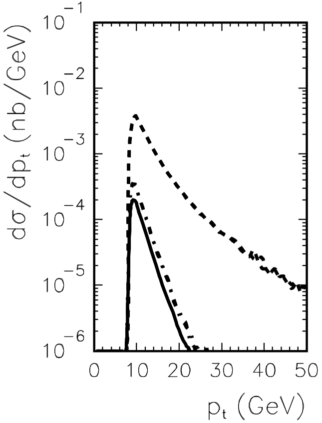
$$\times \; \delta^2 \left(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{V_1,t} - \vec{p}_{V_2,t} \right) \mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2) \,. \quad (18)$$

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

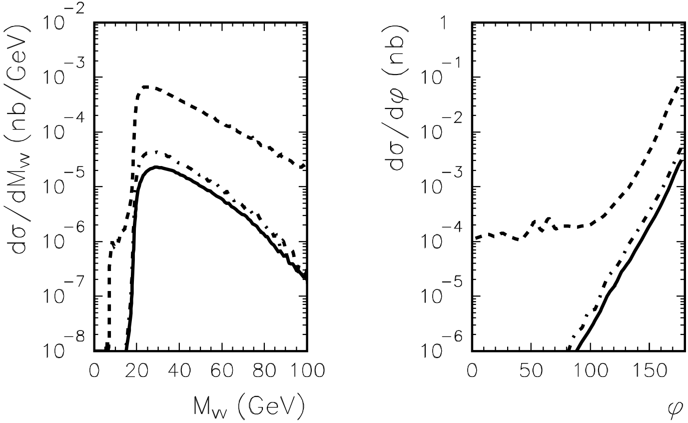
$pp \to \chi_c \chi_c$, prelimianary results



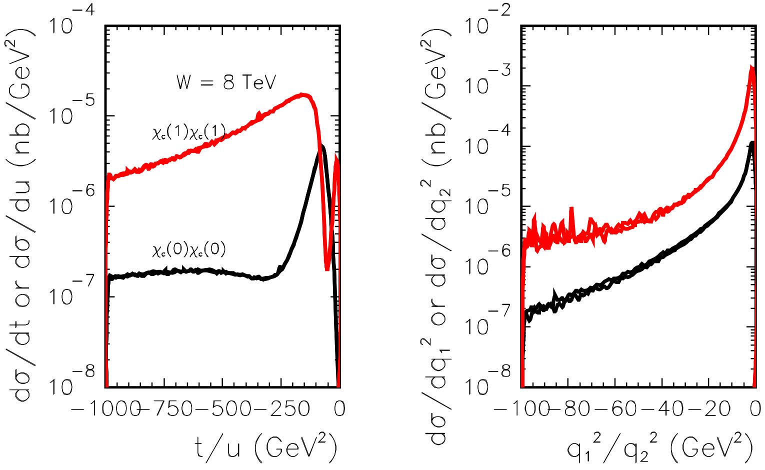
$pp \to \chi_c \chi_c$, preliminary results



$pp \to \chi_c \chi_c$, preliminary results



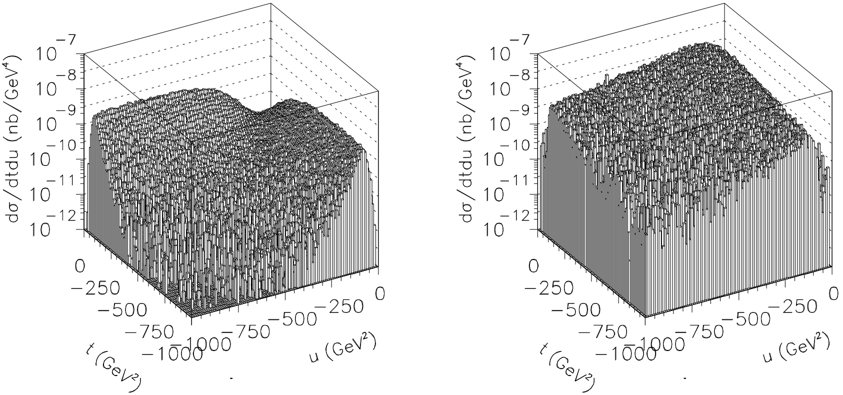
t, u distributions



$|\hat{t}| \ll |q_1^2|, |q_2^2|$ or $|\hat{u}| \ll |q_2^2|, |q_2^2|$

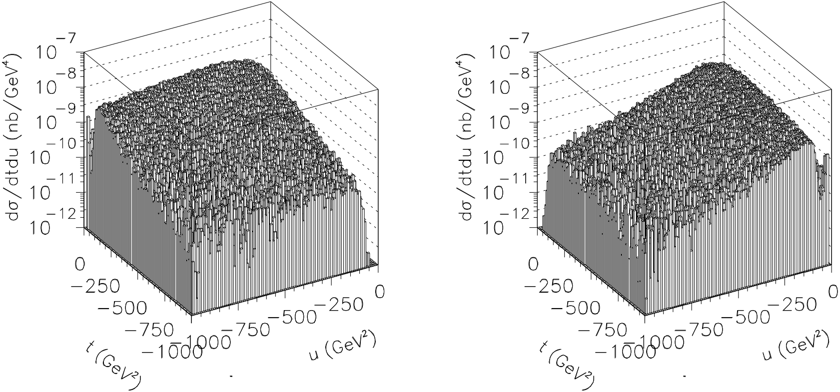
Enhancement of very large $|\hat{t}| and |\hat{u}|$ for $\chi_c(1)\chi_c(1)$

t x u distributions



Interference effect for $\chi_c(1)\chi_c(1)$?

t x u distributions



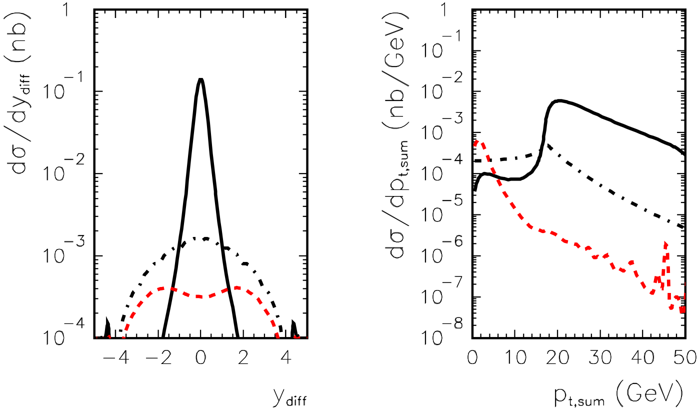
t diagram and *u* diagram separately

Not really interference (about 30%)

$pp \to \chi_c(1)\chi_c(1)$, 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
$(q_1^2 = 0, \hat{t} = 0), (q_1^2 = 0, \hat{u} = 0), (q_2^2 = 0, \hat{u} = 0), (q_2^2 = 0, \hat{u} = 0)$
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.

Comparison of different mechanisms



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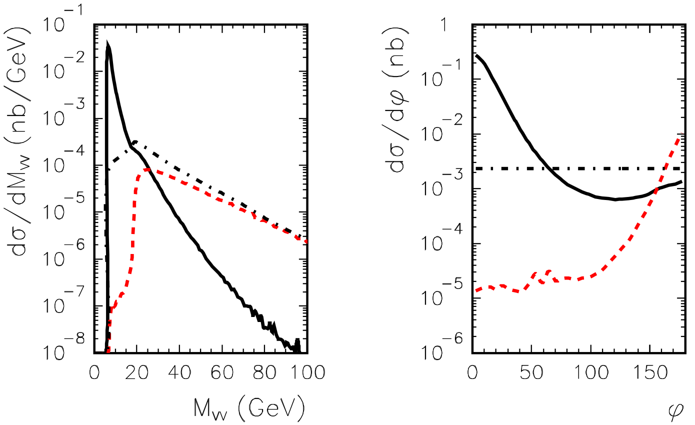
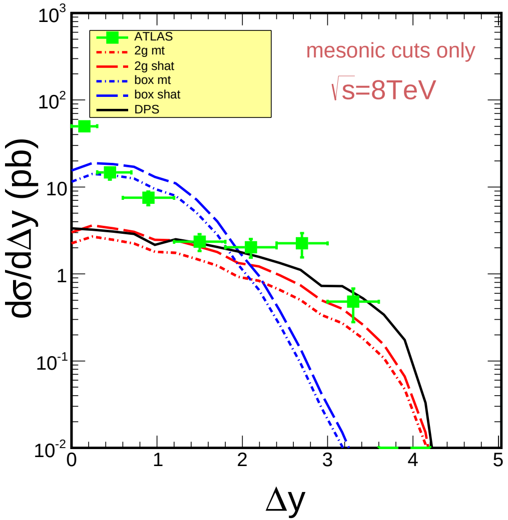


First results, mesonic cuts only



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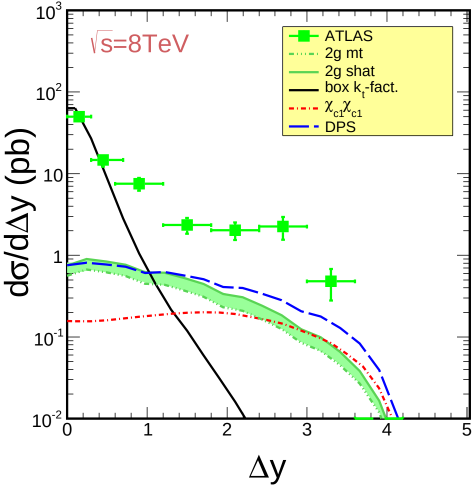
data include cuts on muons, this calculation not!

First results, with muon cuts

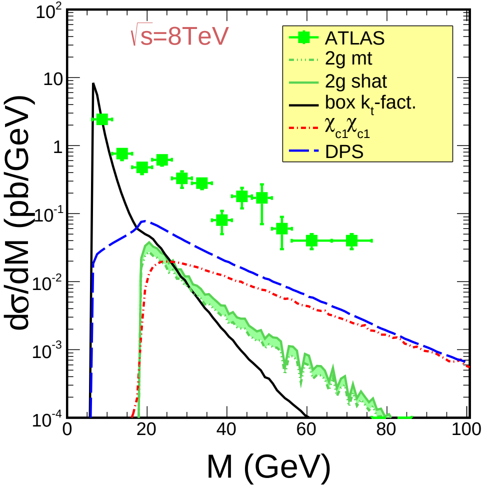


simultaneous decay of both J/ψ in Monte Carlo approach

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

ATLAS-CONF-2016-047

First results, with muon cuts



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

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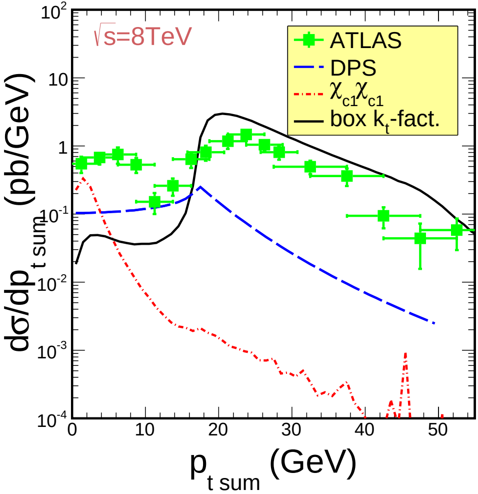
First results, with muon cuts



approximate inclusion of muonic cuts

ATLAS-CONF-2016-047

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.
- $\chi_c(J_1)\chi_c(J_2)$ were calculated.
  Dominance of $\chi_c(1)\chi_c(1)$ for the ATLAS cuts.
- 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 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.
  More work (test) clearly required.

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Thank You