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Central exclusive production of selected charmonia in the light-front $k_\perp$-factorization approach

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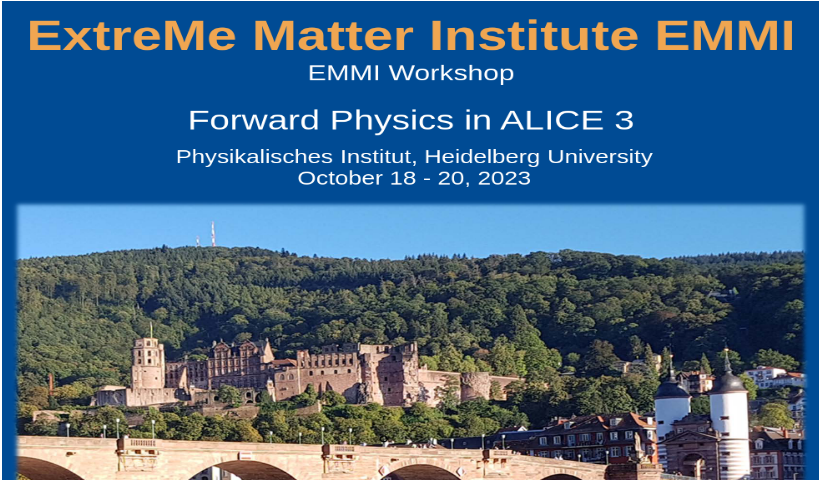
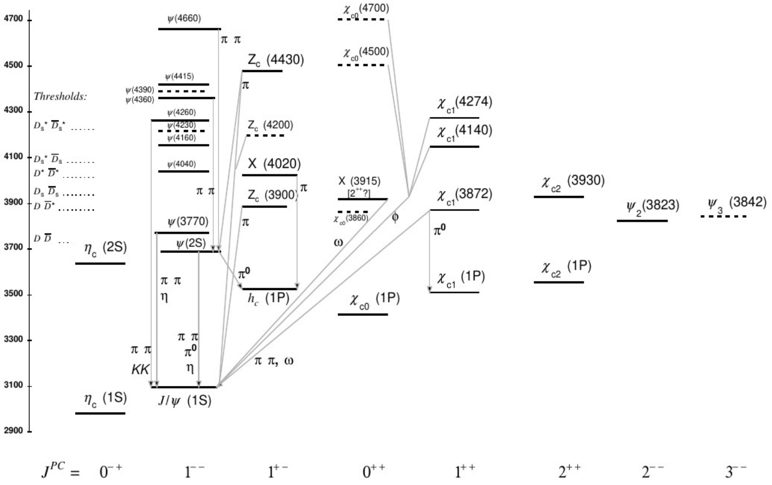
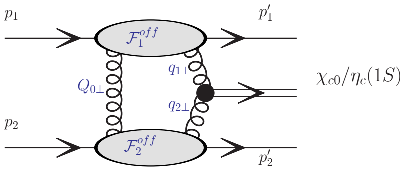


Introduction ⇒ $\eta_c(1S)$, χ_{c0} (1P)



mass spectra of $c\bar{c}$ states **P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)**

Introduction



Generic diagram for **central exclusive production** of η_c and χ_{c0}, *Phys.Rev.D*102, 114028(2020)

$\mathcal{V}^{c_1 c_2} \Rightarrow \mathcal{V}^{c_1 c_2}(g^* g^* \to \eta_c(1S))$

Prompt hadroproduction of $\eta_c(1S, 2S)$ *in the* k_T*-factorization approach*, *JHEP*02, 037(2020),

$\mathcal{V}^{c_1 c_2} \Rightarrow \mathcal{V}^{c_1 c_2}(g^* g^* \to \chi_{c0}(1P))$

Hadroproduction of scalar P-wave quarkonia in the light-front k_T *-factorization approach* *JHEP*06, 101(2020)

$$\mathcal{M} = \frac{s}{2}\pi^2 \frac{1}{2} \frac{\delta_{c_1 c_2}}{N_c^2 - 1} \int d^2 \boldsymbol{Q}\, \mathcal{V}^{c_1 c_2} \frac{\mathcal{F}_g^{\rm off}(x_1, x', \boldsymbol{Q}^2, \boldsymbol{q}_1^2, \mu^2, t_1) \mathcal{F}_g^{\rm off}(x_2, x', \boldsymbol{Q}^2, \boldsymbol{q}_2^2, \mu^2, t_2)}{\boldsymbol{Q}^2 \boldsymbol{q}_1^2 \boldsymbol{q}_2^2},$$

Durham model of CEP, Int. J. Mod. Phys. A 29, 1430031 (2014), [arXiv:1405.0018 [hep-ph]]

$$\sigma = \frac{1}{2s} \frac{1}{2^8 \pi^4 s} \int |\mathcal{M}|^2 dt_1 dt_2 dy d\phi \,.$$

R. S. Pasechnik, A. Szczurek, and O. V. Teryaev, Phys. Rev. D 78, 014007 (2008),

$t_1 = (p_1 - p_1')^2$, $t_2 = (p_2 - p_2')^2$ and $\phi \in (0, 2\pi)$

$$\mathcal{V}^{ab}_{\mu\nu}(g^*g^* \to \chi_{c0}) = 4\pi\alpha_s \frac{\mathrm{Tr}[t^a t^b]}{\sqrt{N_c}} 2\mathcal{T}_{\mu\nu} = \frac{4\pi\alpha_s}{\sqrt{N_c}} \delta^{ab}\mathcal{T}_{\mu\nu} \,,$$

$$\mathcal{T} = n^+_\nu n^-_\mu \mathcal{T}_{\mu\nu} = |\boldsymbol{q_1}||\boldsymbol{q_2}| G_1(q_1^2, q_2^2) + (\boldsymbol{q_1}\cdot\boldsymbol{q_2}) G_2(q_1^2, q_2^2)\,,$$

$$G_1(\boldsymbol{q}_1^2, \boldsymbol{q}_2^2) = |\boldsymbol{q_1}||\boldsymbol{q_2}| \frac{4m_c}{\boldsymbol{q}_2^2} \int \frac{dz d^2\boldsymbol{k}}{z(1-z)16\pi^3} \psi_{\chi_{c0}}(z,\boldsymbol{k})\, 2z(1-z)(2z-1)\left[\frac{1}{\boldsymbol{l}_A^2+\varepsilon^2} - \frac{1}{\boldsymbol{l}_B^2+\varepsilon^2}\right]$$

$$G_2(\boldsymbol{q}_1^2, \boldsymbol{q}_2^2) = 4m_c \int \frac{dz d^2\boldsymbol{k}}{z(1-z)16\pi^3} \psi_{\chi_{c0}}(z,\boldsymbol{k})\left[\frac{1-z}{\boldsymbol{l}_A^2+\varepsilon^2} + \frac{z}{\boldsymbol{l}_B^2+\varepsilon^2}\right]$$

$$+ \frac{4m_c}{\boldsymbol{q}_2^2} \int \frac{dz d^2\boldsymbol{k}}{z(1-z)16\pi^3} \psi_{\chi_{c0}}(z,\boldsymbol{k}) 4z(1-z)\left[\frac{\boldsymbol{q_2}\cdot\boldsymbol{l}_A}{\boldsymbol{l}_A^2+\varepsilon^2} - \frac{\boldsymbol{q_2}\cdot\boldsymbol{l}_B}{\boldsymbol{l}_B^2+\varepsilon^2}\right],$$

$$\mathcal{V}^{ab}_{\mu\nu}(g^*g^* \to \eta_c) = (-i)4\pi\alpha_s \epsilon_{\mu\nu\alpha\beta} q^\alpha q^\beta \frac{\delta^{ab}}{2\sqrt{N_c}} 2I(\boldsymbol{q}_1^2, \boldsymbol{q}_2^2)\,,$$

where $I(\boldsymbol{q}_1^2, \boldsymbol{q}_2^2) = F_{\gamma^*\gamma^*\to\eta_c}(\boldsymbol{q}_1^2, \boldsymbol{q}_2^2)/(e_c^2\sqrt{N_c})$.

$$I(\boldsymbol{q}_1^2, \boldsymbol{q}_2^2) = 4m_c \int \frac{dz d^2\boldsymbol{k}}{z(1-z)16\pi^3} \psi_{\eta_c}(z,\boldsymbol{k}) \Big\{ \frac{1-z}{(\boldsymbol{k}-(1-z)\boldsymbol{q}_2)^2 + z(1-z)\boldsymbol{q}_1^2 + m_c^2}$$

$$+ \frac{z}{(\boldsymbol{k}+z\boldsymbol{q}_2)^2 + z(1-z)\boldsymbol{q}_1^2 + m_c^2} \Big\},$$

Off-diagonal gluons

KMR off-diagonal gluon:
Int. J. Mod. Phys. A 29, 1430031 (2014),
[arXiv:1405.0018 [hep-ph]],
Eur. Phys. J. C 35, 211–220 (2004)

$$\mathcal{F}^{\rm off}_{g,\rm KMR}(x_i, x', Q^2_\perp, q^2_{i\perp}, \mu^2, t_i) =$$

$$R_g \frac{d}{d\ln q^2_\perp}\left[xg(x, q^2_\perp)\sqrt{T_g(q^2_\perp, \mu^2)}\right]_{q^2_\perp = Q^2_\perp} F(t)\,,$$

$Q^2_{i\perp} = \min(Q^2_\perp, q^2_{i\perp})$, $i = 1, 2$ - Durham prescription

$Q^2_{i\perp} = \sqrt{Q^2_\perp q^2_{i\perp}}$ $i = 1, 2$ - BPSS prescription

CDHI off-diagonal gluon:
Eur. Phys. J. C 61, 369–390 (2009)

$$\mathcal{F}^{\rm off}_{g,\rm CDHI}(x_i, x', Q^2_\perp, q^2_{i\perp}, \mu^2, t_i) =$$

$$R_g\left[\frac{\partial}{\partial \log \bar{Q}^2}\sqrt{T_g(\bar{Q}^2, \mu^2)}\, xg(x, \bar{Q}^2)\right]\cdot \frac{2Q^2_\perp q^2_\perp}{Q^4_\perp + q^4_\perp}\cdot F(t)\,,$$

$$F(t) = \exp\left(\frac{bt}{2}\right), \quad b = 4\,\mathrm{GeV}^{-2}\,,$$

PST off-diagonal:
Phys. Rev. D 78, 014007 (2008).

$$\mathcal{F}^{\rm off}_{g,\rm PST}(x_i, x', Q^2_\perp, q^2_{i\perp}, \mu^2, t_i) =$$

$$\sqrt{Q^2_\perp f^{\rm GBW}_g(x', Q^2_\perp) q^2_\perp f^{\rm GBW}_g(x, q^2_\perp)}\sqrt{T_g(q^2_\perp, \mu^2)}\, F(t)\,,$$

$$f^{\rm GBW}_g(x, q^2_\perp) = \frac{3\,\sigma_0}{4\pi^2 \alpha_s} R^2_0\, q^2_\perp \exp[-R^2_0\, q^2_\perp]\,,$$

*J.HighEnergyPhys.*03(2018)102.

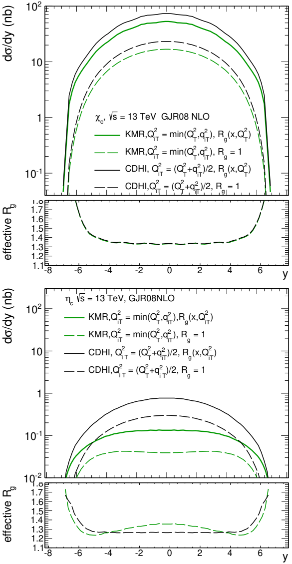
$$f^{RS}_g(x, |\boldsymbol{q}|) = \boldsymbol{q}^2 \frac{\sigma_0}{\alpha_s}\frac{N_c}{8\pi^2}\int_0^\infty r dr\, J_0(|\boldsymbol{q}|r)\left(1 - \frac{\sigma(x, r)}{\sigma_0}\right).$$

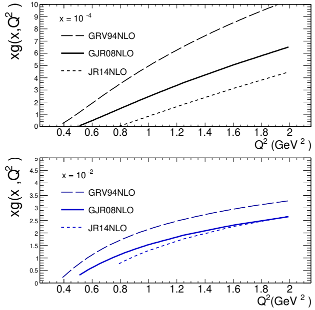
*Phys.Rev.D*88, 074016(2013)

$$T_g(q^2_\perp, \mu^2) = \exp\left[-\int_{q^2_\perp}^{\mu^2}\frac{d\boldsymbol{k}^2_\perp}{\boldsymbol{k}^2_\perp}\frac{\alpha_s(k^2_\perp)}{2\pi} \times \int_0^{1-\Delta}\left[zP_{gg}(z) + \sum\nolimits_q P_{qg}(z)\right]dz\right],$$

$$\mu^2 = M^2 + q^2_\perp\,.$$

Effective skewedness correction





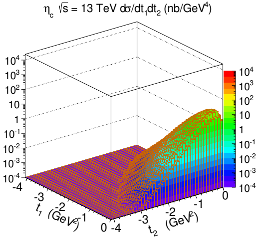
Shuvaev prescription

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+4)},$$

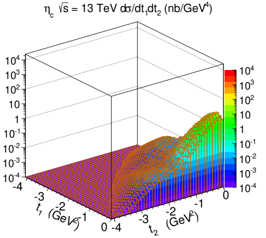
$$\lambda = \frac{d}{d\ln(1/x)}\left[\ln\left(xg(x, q_\perp^2)\right)\right].$$

η_c - distribution in $t_1 \times t_2$, $\sqrt{s} = 13\,TeV$

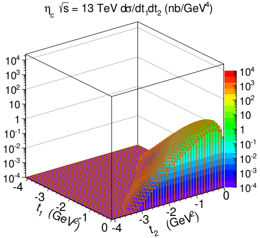
- in the limit $t_1, t_2 \to 0$ the CEP vertex vanishes $\Rightarrow$ the cross-section is heavily suppressed relatively to χ_{c0}
- On the other hand the cross-section strongly depends on $\Psi_S(0)$, while χ_{c0} $\Psi'_P(0)$



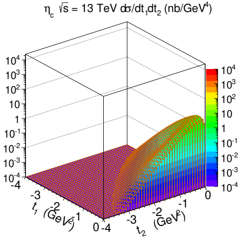
CDHI



BPSS

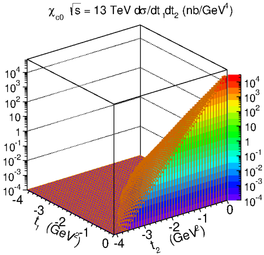


KMR -Durham model

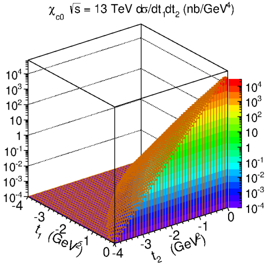


PST

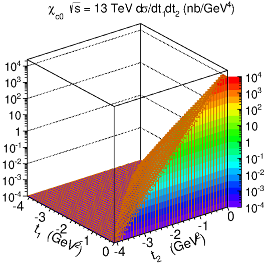
χ_{c0} - distribution in $t_1 \times t_2$, $\sqrt{s} = 13\,TeV$



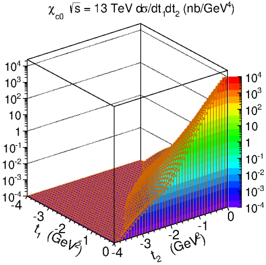
CDHI



BPSS



Durham



PST

Total cross-section $pp \to p\eta_c p$

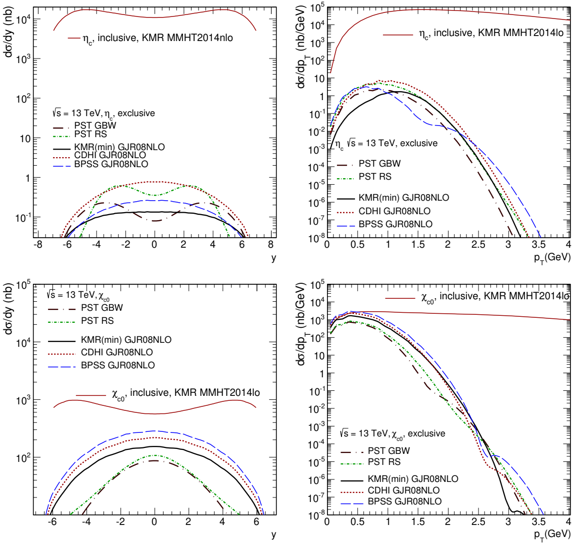
KMR Skewed gluon, $0.8\mathrm{GeV}^2 \leq Q^2_{0T}$, JR14NLO	$\sigma_{\rm tot}$ [nb], $R_g = 1.0$	$\sigma_{\rm tot}$ [nb], $R_g(x, Q^2_{iT})$
CDHI, $Q^2_{iT} = (Q^2_T + q^2_{iT})/2.$	1.1	2.4
KMR, $Q^2_{iT} = \sqrt{Q^2_T \cdot q^2_{iT}}$	0.39	1.2
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT})$	0.13	0.25
KMR Skewed gluon, $0.5\mathrm{GeV}^2 \leq Q^2_{0T}$, GJR08NLO	$\sigma_{\rm tot}$ [nb], $R_g = 1.0$	$\sigma_{\rm tot}$ [nb], $R_g(x, Q^2_{iT})$
CDHI, $Q^2_{iT} = (Q^2_T + q^2_{iT})/2.$	2.2	5.6
KMR, $Q^2_{iT} = \sqrt{Q^2_T \cdot q^2_{iT}}$	0.52	2.1
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT}), 0.5\mathrm{GeV}^2 \leq Q^2_{0T}$	0.44	1.3
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT}), 0.8\mathrm{GeV}^2 \leq Q^2_{0T}$	0.22	0.45
KMR Skewed gluon, $0.4\mathrm{GeV}^2 \leq Q^2_{0T}$, GRV94NLO	$\sigma_{\rm tot}$ [nb], $R_g = 1.0$	$\sigma_{\rm tot}$ [nb], $R_g(x, Q^2_{iT})$
CDHI, $Q^2_{iT} = (Q^2_T + q^2_{iT})/2.$	$1.2 \cdot 10^2$	$7.8 \cdot 10^3$
KMR, $Q^2_{iT} = \sqrt{Q^2_T \cdot q^2_{iT}}$	2.2	$1.3 \cdot 10^3$
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT}), 0.4\mathrm{GeV}^2 \leq Q^2_{0T}$	2.8	$1.0 \cdot 10^1$
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT}), 0.8\mathrm{GeV}^2 \leq Q^2_{0T}$	1.25	2.9
PST Skewed gluon	$\sigma_{\rm tot}$ [nb]	-
PST, GBW	1.9	-
PST, RS	4.1	

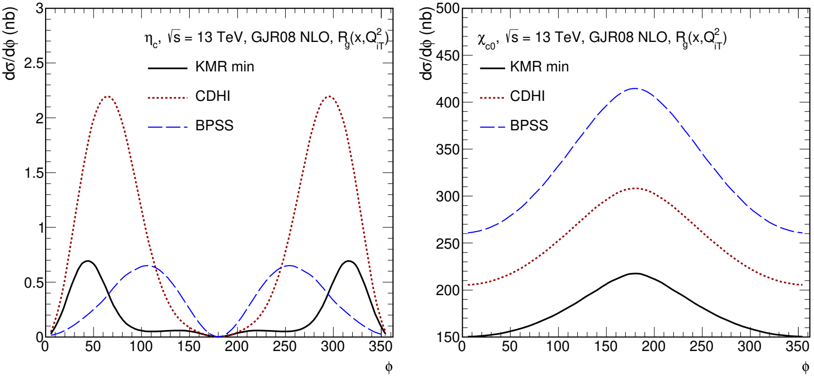
Total cross-section $pp \to p\chi_{c0}p$

KMR Skewed gluon $0.8\,\mathrm{GeV}^2 \leq Q^2_{0T}$, JR14NLO	σ_{tot} [nb], $R_g = 1.0$	σ_{tot} [nb], $R_g(x, Q^2_{iT})$
CDHI, $Q^2_{iT} = (Q^2_T + q^2_{iT})/2.$	$0.42 \cdot 10^3$	$1.1 \cdot 10^3$
KMR, $Q^2_{iT} = \sqrt{Q^2_T \cdot q^2_{iT}}$	$0.36 \cdot 10^3$	$0.94 \cdot 10^3$
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT})$	$0.20 \cdot 10^3$	$0.52 \cdot 10^3$
KMR Skewed gluon $0.5\,\mathrm{GeV}^2 \leq Q^2_{0t}$, GJR08NLO	σ_{tot} [nb], $R_g = 1.0$	σ_{tot} [nb], $R_g(x, Q^2_{iT})$
CDHI, $Q^2_{iT} = (Q^2_T + q^2_{iT})/2.$	$0.46 \cdot 10^3$	$1.57 \cdot 10^3$
KMR, $Q^2_{iT} = \sqrt{Q^2_T \cdot q^2_{iT}}$	$0.64 \cdot 10^3$	$2.1 \cdot 10^3$
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT})$	$0.34 \cdot 10^3$	$1.1 \cdot 10^3$
KMR Skewed gluon $0.4\,\mathrm{GeV}^2 \leq Q^2_{0T}$, GRV94NLO	σ_{tot} [nb], $R_g = 1.0$	σ_{tot} [nb], $R_g(x, Q^2_{iT})$
CDHI, $Q^2_{iT} = (Q^2_T + q^2_{iT})/2.$	$1.88 \cdot 10^3$	$9.02 \cdot 10^3$
KMR, $Q^2_{iT} = \sqrt{Q^2_T \cdot q^2_{iT}}$	$3.03 \cdot 10^3$	$13.4 \cdot 10^3$
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT}), 0.4\mathrm{GeV}^2 \leq Q^2_{0T}$	$1.4 \cdot 10^3$	$6.1 \cdot 10^3$
KMR, $Q^2_{iT} = \min(Q^2_T, q^2_{iT}), 0.8\mathrm{GeV}^2 \leq Q^2_{0T}$	$0.75 \cdot 10^3$	$3.9 \cdot 10^3$
PST Skewed gluon	σ_{tot} [nb]	-
PST prescription, GBW	$0.44 \cdot 10^3$	-
PST prescription, RS	$0.52 \cdot 10^3$	-

$Br(\chi_{c0} \to J/\Psi\,\gamma) = (1.40 \pm 0.05)\%$ $\qquad$ $Br(\chi_{c1} \to J/\Psi\,\gamma) = (34.3 \pm 1.0)\%$

Exclusive vs. inclusive distributions





$$|\mathcal{M}(g^* g^* \to \eta_c)|^2 \sim \sin^2(\phi)$$

Absorptive correction to $pp \to pVp$ processes

$$\mathcal{M}(Y, y, \boldsymbol{p}_1, \boldsymbol{p}_2) = \mathcal{M}^{(0)}(Y, y, \boldsymbol{p}_1, \boldsymbol{p}_2) - \delta\mathcal{M}(Y, y, \boldsymbol{p}_1, \boldsymbol{p}_2),$$

$$\mathcal{M}^{(0)}(Y, y, \boldsymbol{p}_1, \boldsymbol{p}_2) = i\, s\Phi_1(\boldsymbol{p}_1) R_{\mathbf{P}}(Y - y, \boldsymbol{p}_1^2) \times V(\boldsymbol{p}_1, \boldsymbol{p}_2) R_{\mathbf{P}}(y, \boldsymbol{p}_2^2)\Phi_2(\boldsymbol{p}_2)$$

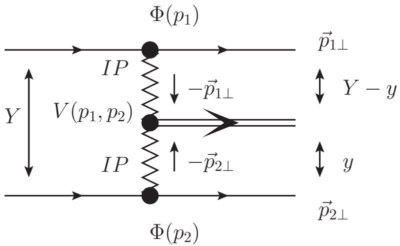
$$\delta\mathcal{M}(Y, 0, \boldsymbol{p}_1, \boldsymbol{p}_2) = \int \frac{d^2\boldsymbol{k}}{2(2\pi)^2}\, T(s, \boldsymbol{k}) \exp\left(-\frac{1}{2} B_D(\boldsymbol{p}_1 + \boldsymbol{k})^2 \right) \exp\left(-\frac{1}{2} B_D(\boldsymbol{p}_2 - \boldsymbol{k})^2 \right) \times V(\boldsymbol{p}_1 + \boldsymbol{k}, \boldsymbol{p}_2 - \boldsymbol{k})$$

$$T(s, \boldsymbol{k}) = \sigma_{\rm tot}^{pp}(s) \times \exp\left(-\frac{1}{2} B_{\rm el}(s) \boldsymbol{k}^2 \right)$$

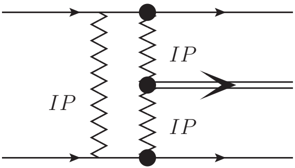
$\sqrt{s} = 13\,\mathrm{TeV} \Rightarrow \sigma_{\rm tot}^{pp} = (110.6 \pm 3.4)\,\mathrm{mb}$, $B_{\rm el} = (20.36 \pm 0.19)\,\mathrm{GeV}^{-2}$

G. Antchev *et al.* [TOTEM Collaboration],

Eur. Phys. J. C ***79**, no.2, 103 (2019)*

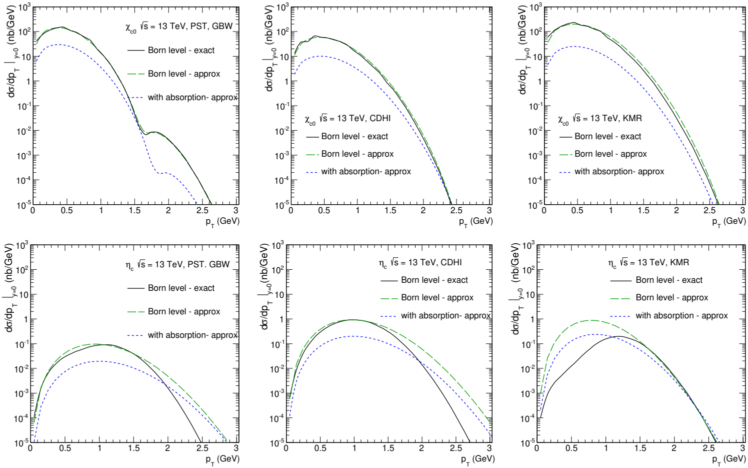


Born level diagram



absorptive correction

Absorptive correction - results



Gap surival probability at mid rapidity

χ_{c0}	$\frac{d\sigma}{dy}_{\rm tot}\vert_{y=0}$ [nb]	$\frac{d\sigma}{dy}^{\rm abs}_{\rm tot}\vert_{y=0}$ [nb]	$S^2_{y=0}$
PST GBW	17	3.7	0.22
PST RS	21	4.5	0.21
CDHI GJR08NLO	42	7.5	0.18
KMR GJR08NLO	29	3.7	0.13
BPSS GJR08NLO	61	8.0	0.13

η_c	$\frac{d\sigma}{dy}_{\rm tot}\vert_{y=0}$ [nb]	$\frac{d\sigma}{dy}^{\rm abs}_{\rm tot}\vert_{y=0}$ [nb]	$S^2_{y=0}$
PST GBW	1.8×10^{-2}	3.9×10^{-3}	0.22
PST RS	9.0×10^{-3}	1.9×10^{-3}	0.21
CDHI GJR08NLO	1.8×10^{-1}	4.0×10^{-2}	0.22
KMR GJR08NLO	1.3×10^{-1}	3.0×10^{-2}	0.23
BPSS GJR08NLO	5.8×10^{-2}	2.2×10^{-2}	0.38

$$S^2 \equiv \frac{d\sigma/dy\Big|_{y=0}}{d\sigma_{\rm Born}/dy\Big|_{y=0}}$$

Summary

- Transition amplitude for $g^* g^* \to \eta_c$ and $g^* g^* \to \chi_{c0}$ was calculated using light-cone wave functions of $c\bar{c}$ states in the framework of potential models.
- We also proposed a way to calculate the soft effects (in the region of small gluon transverse momenta) using the GBW or RS UGDs, which were obtained from the respective color dipole cross sections and a simple (PST) prescription for its off-diagonal extrapolation.
- Central exclusive processes in proton-proton colisions are sensitive to the low scale, especially η_c, which is the main uncertainties in the results.
- In our calculation of absorptive corrections, we restricted ourselves to the so-called elastic rescattering correction.
- Depending on the gluon distribution used, we obtain for the χ_c the gap survival values of $S^2 = (0.13 - 0.21)$, while for the η_c production, they are somewhat higher, $S^2 = (0.21 - 0.38)$.