Production of $\chi_c\, \chi_c$ pairs in proton-proton collisions in k_T-factorization and collinear approaches

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- Anna Cisek, WS & Antoni Szczurek, Phys.Rev. D97 (2018) no.11, 114018
- Izabela Babiarz, WS & Antoni Szczurek, Phys.Rev. D99 (2019) no.7, 074014

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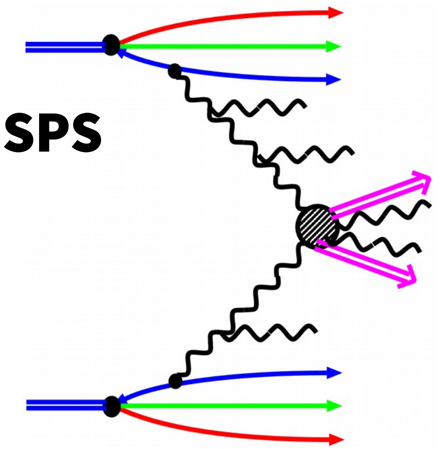
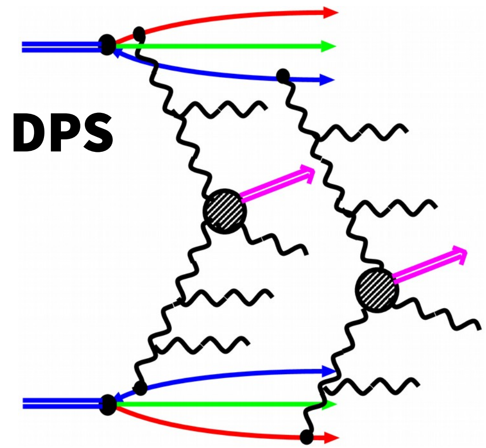
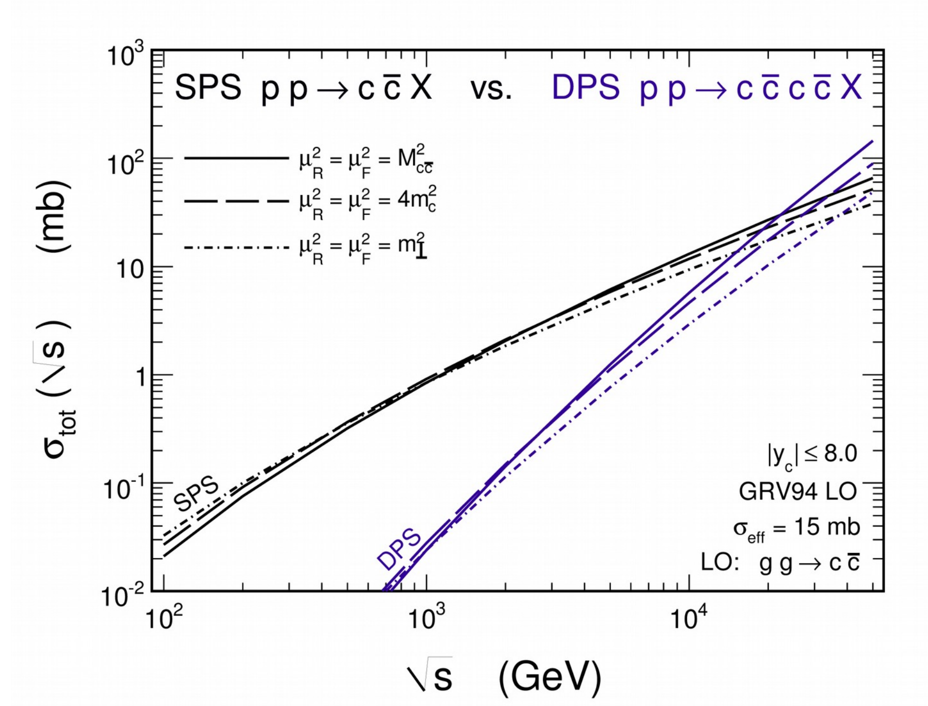
Single vs. double parton scattering





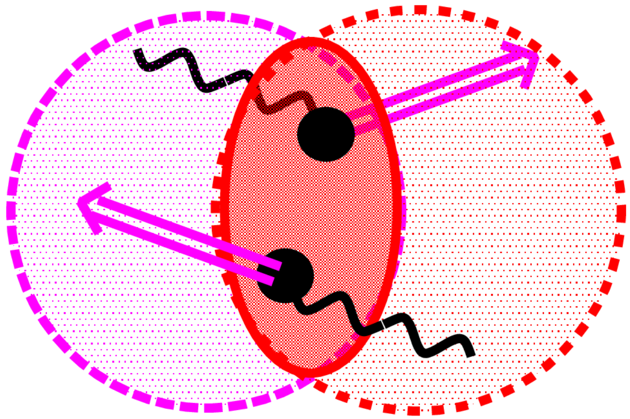


- Production of heavy quark pairs mainly through *single hard scattering* $gg \rightarrow Q\bar{Q}$
- At LHC energies multiple hard scatterings in one pp-collision become important
- DPS **especially prominent in charm sector** → large cross sections & access from perturbative QCD [Luszczak, Maciula & Szczurek (2012), Kom, Kulesza & Stirling (2011)]

DPS & the effective cross section

$$T_{NN}(\mathbf{b}) = \int d^2\mathbf{s}\, t_N(\mathbf{s}) t_N(\mathbf{b}-\mathbf{s})$$

$$\frac{1}{\sigma_{\rm eff}} = \int d^2\mathbf{b}\, T^2_{NN}(\mathbf{b})$$



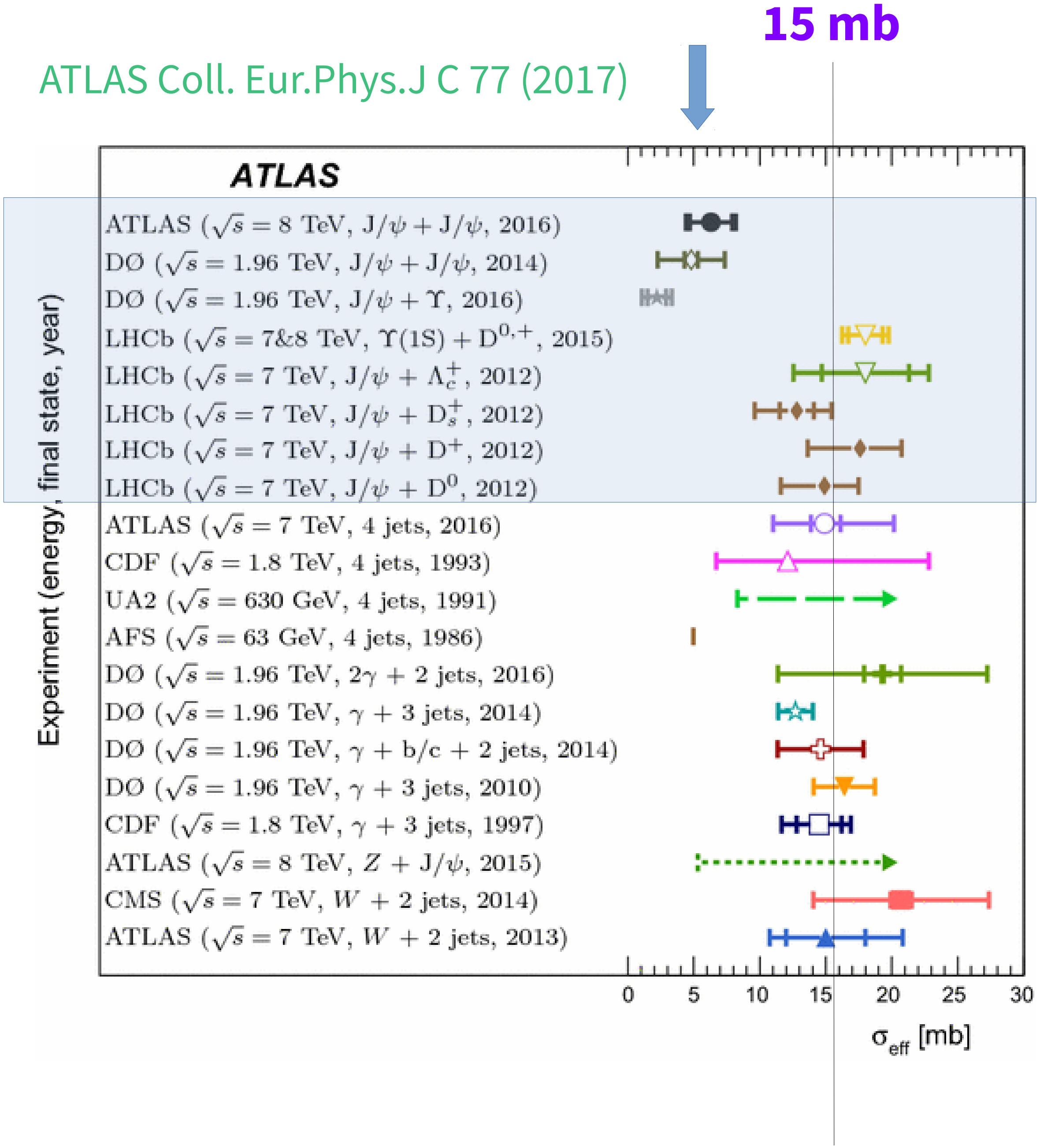
Normalization of DPS is controlled by the "***effective cross section***" & measures the overlap of parton clouds in the transverse plane.

$$\frac{d\sigma_{\rm DPS}(pp\to abX)}{dy_a dy_b d^2\vec{p}_{aT} d^2\vec{p}_{bT}} = \frac{1}{1+\delta_{ab}} \frac{1}{\sigma_{\rm eff}} \frac{d\sigma(pp\to aX)}{dy_a d^2\vec{p}_{aT}} \frac{d\sigma(pp\to bX)}{dy_b d^2\vec{p}_{bT}} .$$

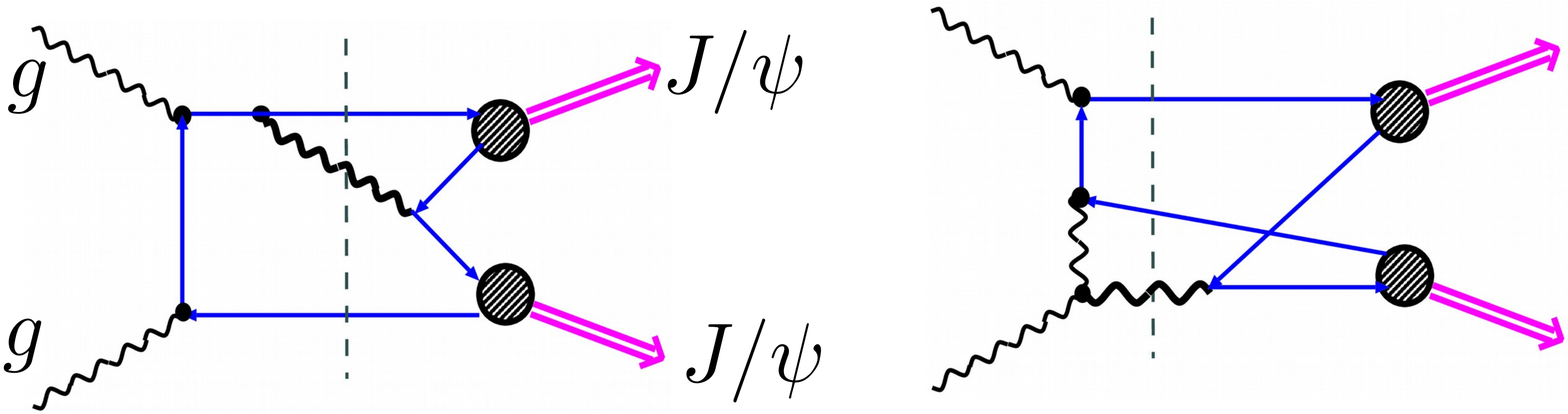
- Independent production: systems a & b are *completely uncorrelated in azimuth.*
- Each of the single particle spectra is a broad function of rapidity → *rapidity distance Δy between a & b has a very broad distribution!*
- Phenomenological models suggest: $\sigma_{\rm eff}$=15 mb.

Experimental results for σ_{eff}

- The universal **σ_{eff} = 15 mb** consistent throughout *except* for the J/ψ-pair production at ATLAS & D0.
- Could this be a hint for the failure of the *uncorrelated ansatz* for DPS?
- Or are we lacking in our understanding of J/ψ-pair production?
- **What kinematic variables really distinguish DPS & SPS ?**

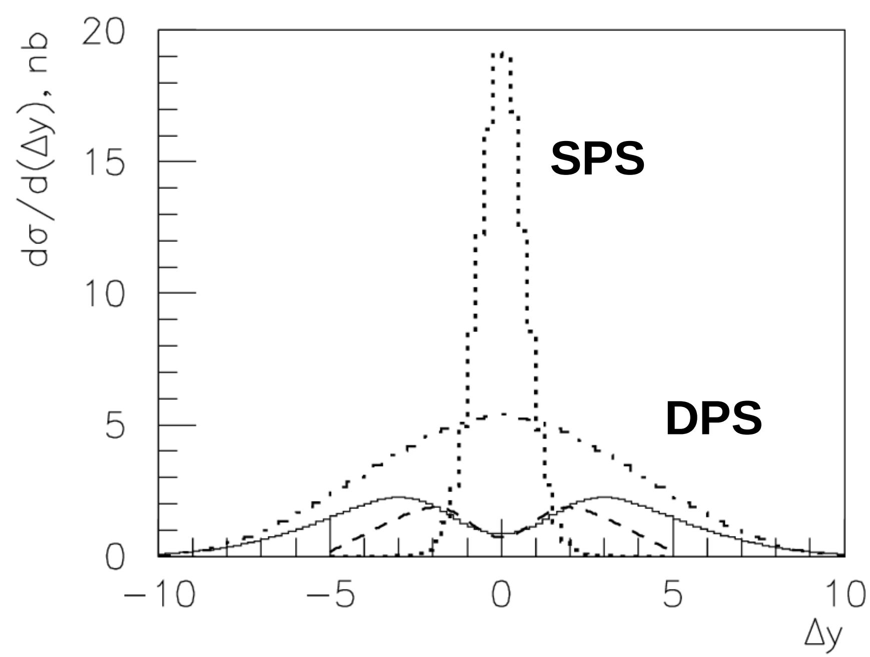


J/ψ pairs from SPS have small rapidity separation



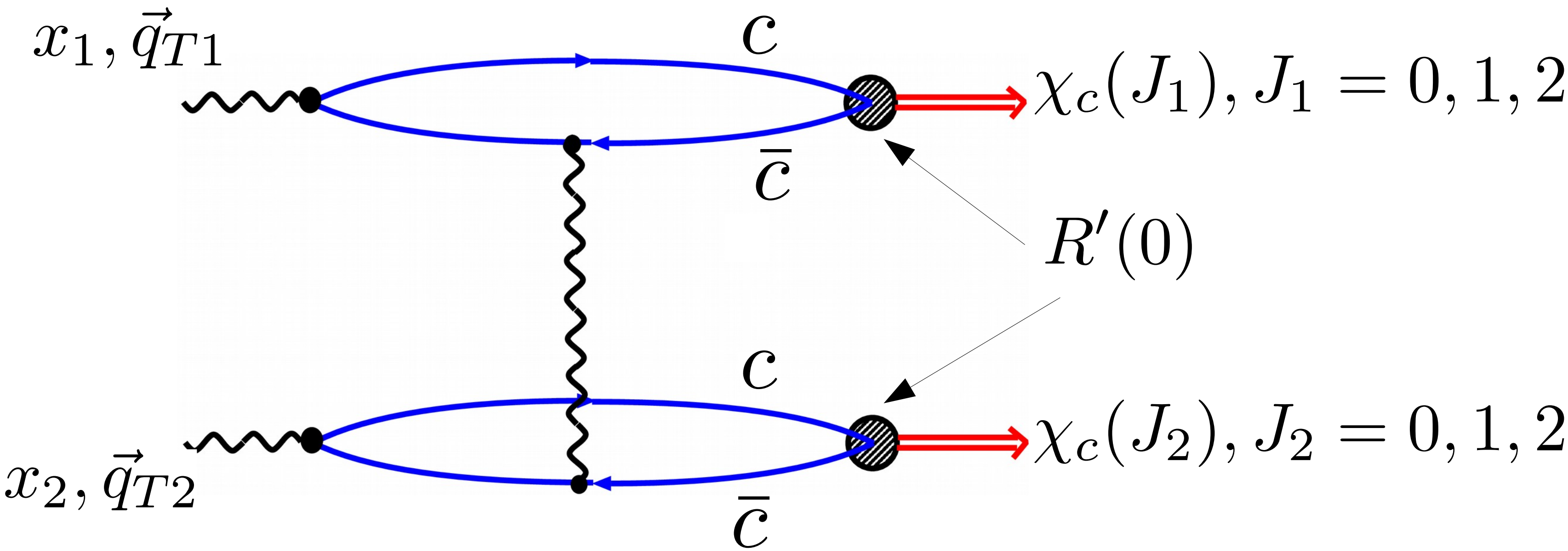
$$\sigma(g^* g^* \to J/\psi J/\psi) \propto \frac{1}{\hat{s}^3} \propto \exp[-3\Delta y]$$

- Box mechanism always has a parton with off-shellness growing with cm-energy, therefore strong energy dependence.
- Rapidity separation is an **excellent discriminator!**
- … but does this clean separation of SPS and DPS hold beyond the box-diagram mechanism?



rapidity distance between J/ψ's

Large rapidity distances in χ-pair production



- The *even C-parity* χ-states can be produced via the ***t-channel gluon exchange***. There is no divergence at small t as quark-antiquark pairs are color-neutral.
- Due to the vector exchange, cross section is constant at high energies
- The "box" contribution for χ-states is suppressed by a small parameter

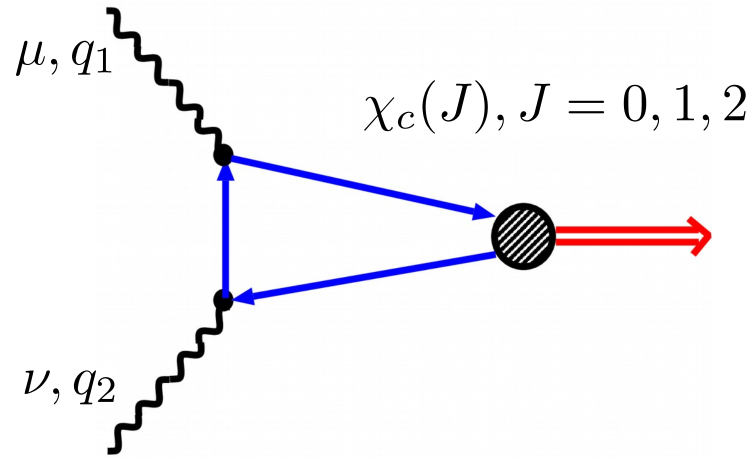
$$\left(\frac{|R'(0)|^2}{M_\chi^2 |R(0)|^2}\right)^2 \sim 10^{-3}$$

The g*g*→ χ vertices

A.Cisek, WS, A. Szczurek, Phys Rev D 97(2018)

$$V^{ab}_{\mu\nu}(J, J_z; q_1, q_2) = -i\, 4\pi\alpha_S\, \delta^{ab}\, \frac{2R'(0)}{\sqrt{\pi N_c M^3}}\, \sqrt{3}\cdot T_{\mu\nu}(J, J_z; q_1, q_2)\,,$$

$$T_{\mu\nu}(0,0;q_1,q_2) = \frac{1}{\sqrt{3}}\,\frac{M^2}{(2q_1\cdot q_2)^2}$$
$$\Big\{g_{\mu\nu}\Big(6(q_1\cdot q_2) - q_1^2 - q_2^2 + \frac{(q_2^2-q_1^2)^2}{M^2}\Big)$$
$$+\, q_{1\mu}q_{2\nu}\, 2\Big(\frac{q_1^2+q_2^2}{M^2} - 1\Big) + q_{2\mu}q_{1\nu}\, 2\Big(\frac{q_1^2+q_2^2}{M^2} - 3\Big)$$
$$+\, q_{1\mu}q_{1\nu}\frac{4q_2^2}{M^2} + q_{2\mu}q_{2\nu}\frac{4q_1^2}{M^2}\Big\}$$



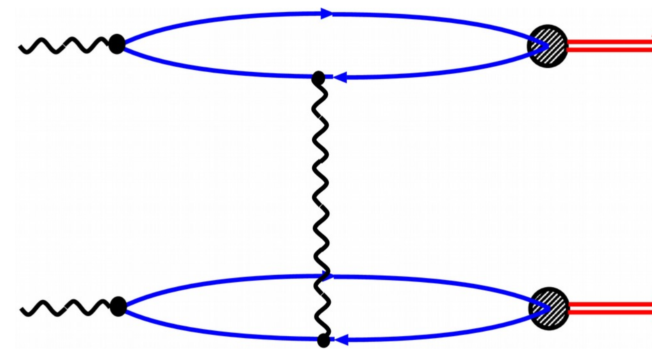
$$T_{\mu\nu}(1,J_z;q_1,q_2) = \frac{i}{\sqrt{2}M}\,\frac{1}{(q_1\cdot q_2)}\Big\{(q_1^2 - q_2^2)\epsilon_{\mu\nu\alpha\beta}(q_1+q_2)^\alpha\epsilon^\beta(J_z)$$
$$+\, \frac{q_1^2+q_2^2}{(q_1\cdot q_2)}(a_\mu q_{1\nu} - a_\nu q_{2\mu}) + 2(a_\nu q_{1\mu} - a_\mu q_{2\nu})\Big\}$$

$$a_\mu = \epsilon_{\mu\rho\alpha\beta}q_1^\rho q_2^\alpha \epsilon^\beta(J_z)\,.$$

$$T_{\mu\nu}(2,J_z;q_1,q_2) = \frac{-M^2}{(2q_1\cdot q_2)^2}\Big\{-g_{\mu\nu}(q_2-q_1)^\alpha(q_2-q_1)^\beta\epsilon_{\alpha\beta}(J_z) + 4(q_1\cdot q_2)\epsilon_{\mu\nu}(J_z)$$
$$+\, 2(q_2-q_1)^\alpha\epsilon_{\alpha\nu}(J_z)q_{2\mu} - 2(q_2-q_1)^\alpha\epsilon_{\alpha\mu}(J_z)q_{1\nu}\Big\}\,,$$

- All vertices fulfill the QED-like Ward identities and can be used for external spacelike off-shell gluons
- The vertex for the axial vector, J=1, vanishes for on-shell external photons/gluons, in agreement with Landau-Yang theorem

Amplitudes & cross sections

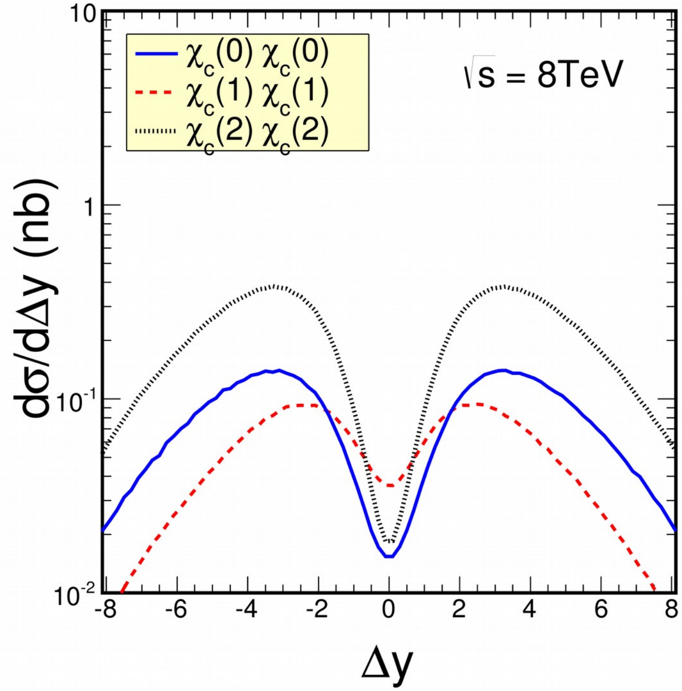


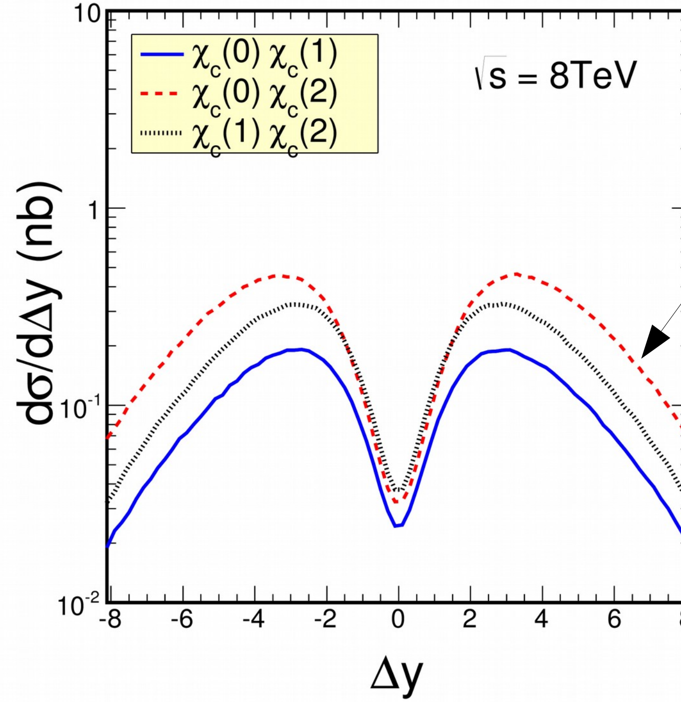
$$\mathrm{M}^{ab}_{\mu\nu}(J_1, J_{1z}, J_2, J_{2z}) = V^{ac}_{\mu\alpha}(J_1, J_{1z}; q_1, p_1 - q_1) \frac{-g^{\alpha\beta}\delta_{cd}}{\hat{t}} V^{db}_{\beta\nu}(J_2, J_{2z}; p_2 - q_2, q_2)$$
$$+ V^{ac}_{\mu\alpha}(J_2, J_{2z}; q_1, p_2 - q_1) \frac{-g^{\alpha\beta}\delta_{cd}}{\hat{u}} V^{db}_{\beta\nu}(J_1, J_{1z}; p_1 - q_2, q_1)\,,$$

$$\frac{d\sigma(pp \to \chi\chi X)}{dy_1 d^2\vec{p}_{1T} dy_2 d^2\vec{p}_{2T}} = \frac{1}{16\pi^2 (x_1 x_2 s)^2} \frac{1}{1 \underset{2}{+} \delta_{ij}} \int \frac{d^2\vec{q}_{1T}}{\pi \vec{q}^{\,2}_{1T}} \frac{d^2\vec{q}_{2T}}{\pi \vec{q}^{\,2}_{2T}} \overline{|\mathcal{M}^{\mathrm{off-shell}}_{g^* g^* \to \chi_c(i)\chi_{cJ}}|^2}$$
$$\times\ \delta^{(2)}\left(\vec{q}_{1T} + \vec{q}_{2T} - \vec{p}_{1T} - \vec{p}_{2T}\right) \mathcal{F}(x_1, \vec{q}^{\,2}_{1T}, \mu_F^2) \mathcal{F}(x_2, \vec{q}^{\,2}_{2T}, \mu_F^2)\ .$$

unintegrated gluon distributions

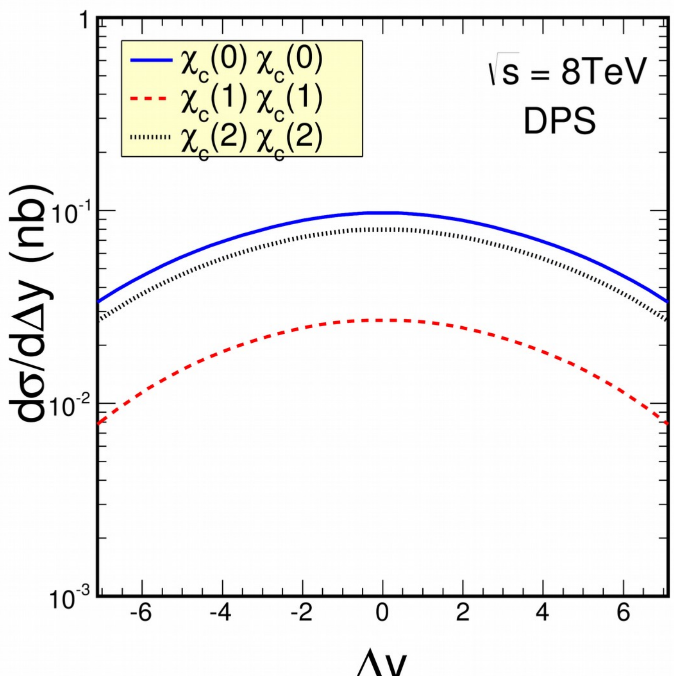
$$xg(x, \mu_F^2) = \int^{\mu_F^2} \frac{d\vec{q}^{\,2}_T}{\vec{q}^{\,2}_T} \mathcal{F}(x, \vec{q}^{\,2}_{1T}, \mu_F^2)$$

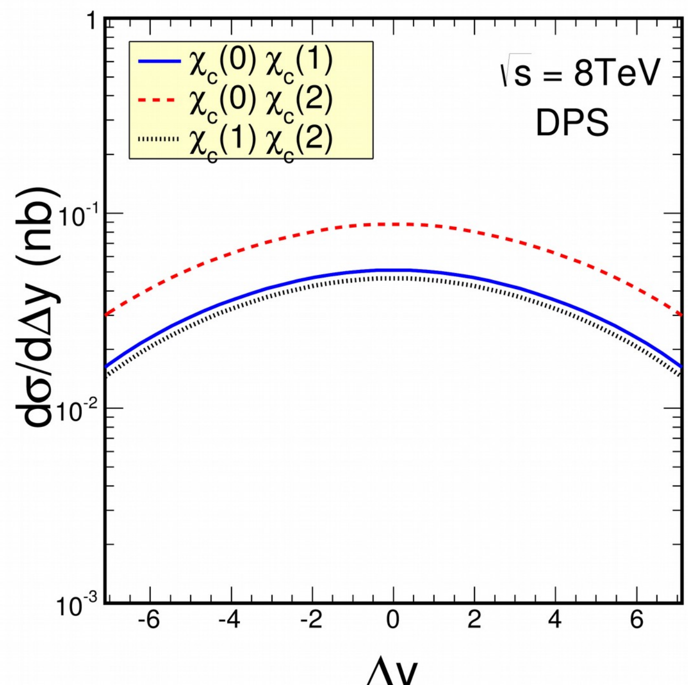




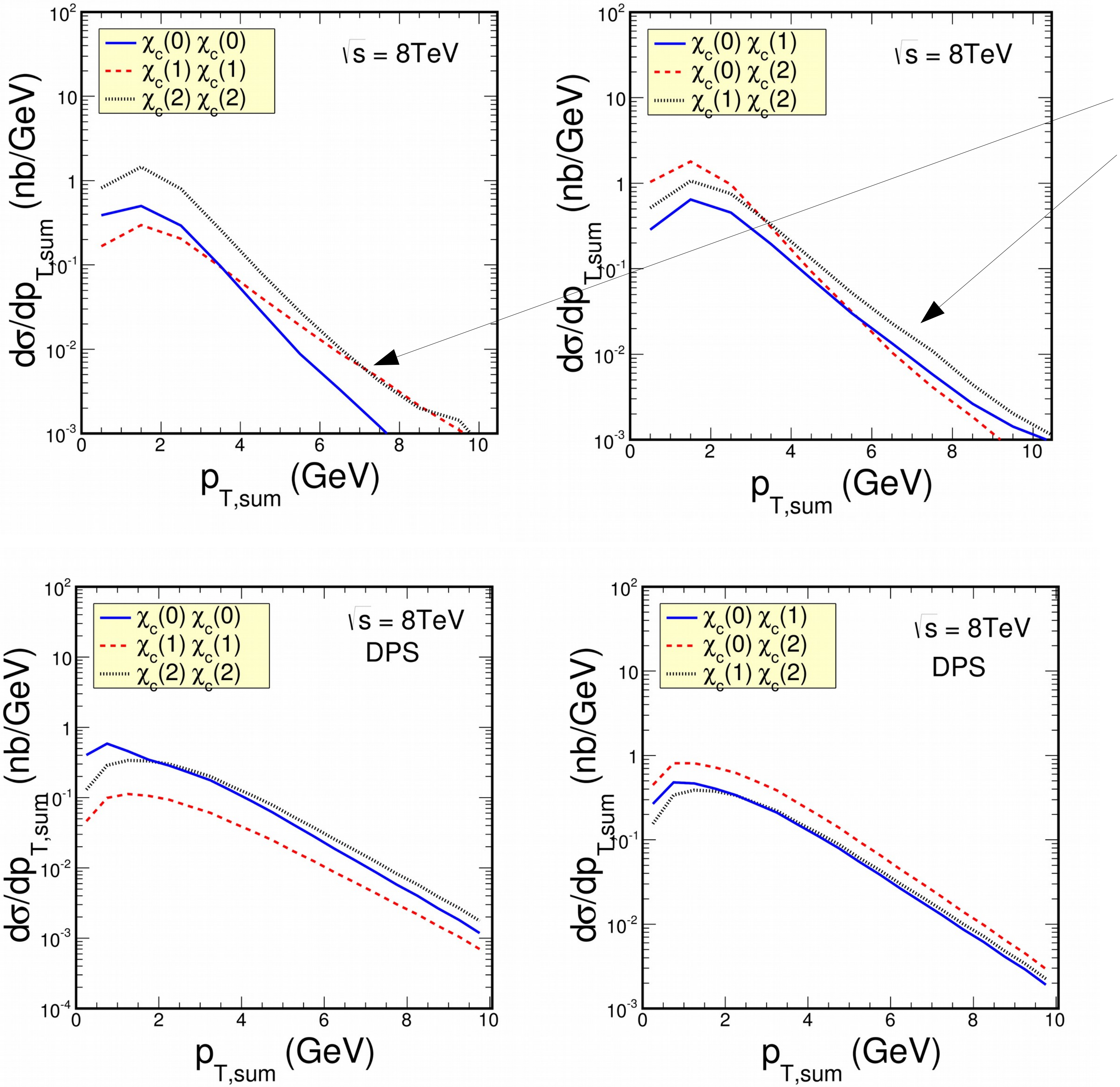
drop induced by large-x gluons

- SPS & DPS of the similar magnitude (**with σ_{eff}=15 mb**).
- Deep dip in SPS distribution





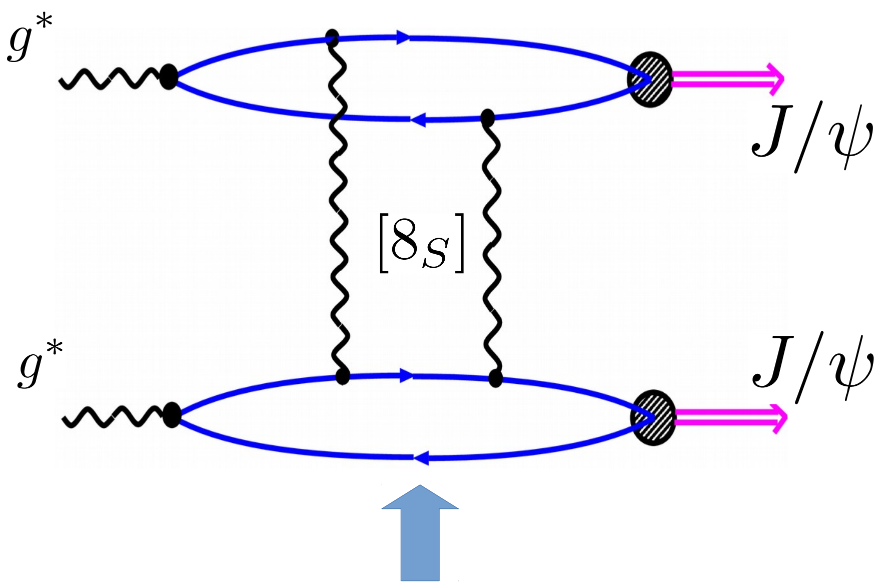
A.Cisek, WS, A. Szczurek, Phys Rev D 97(2018)

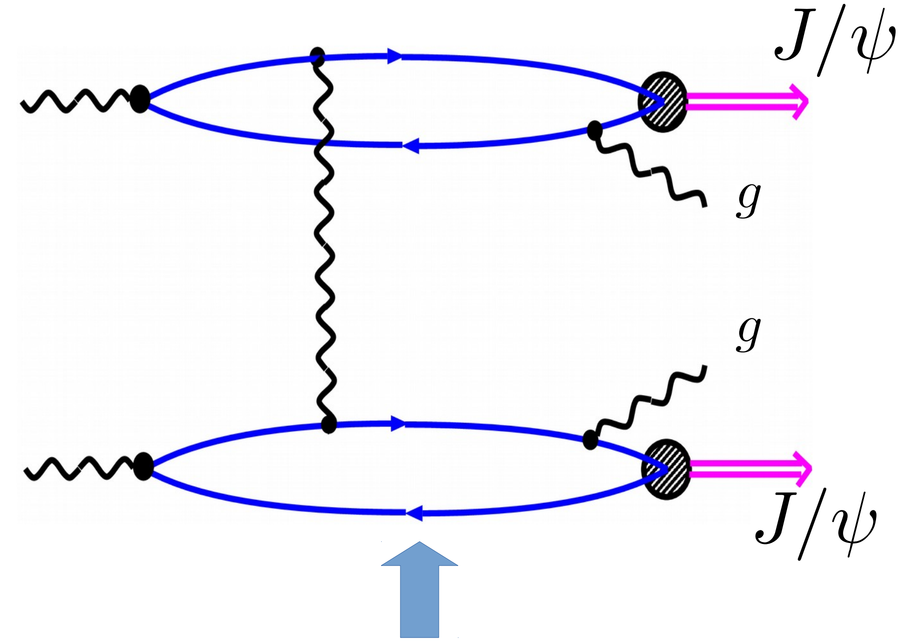


SPS: presence of $\chi_c(1)$ induces harder spectrum

A.Cisek, WS, A. Szczurek, Phys Rev D97 (2018)

g*g*→ J/ψ J/ψ processes that survive at high Δy



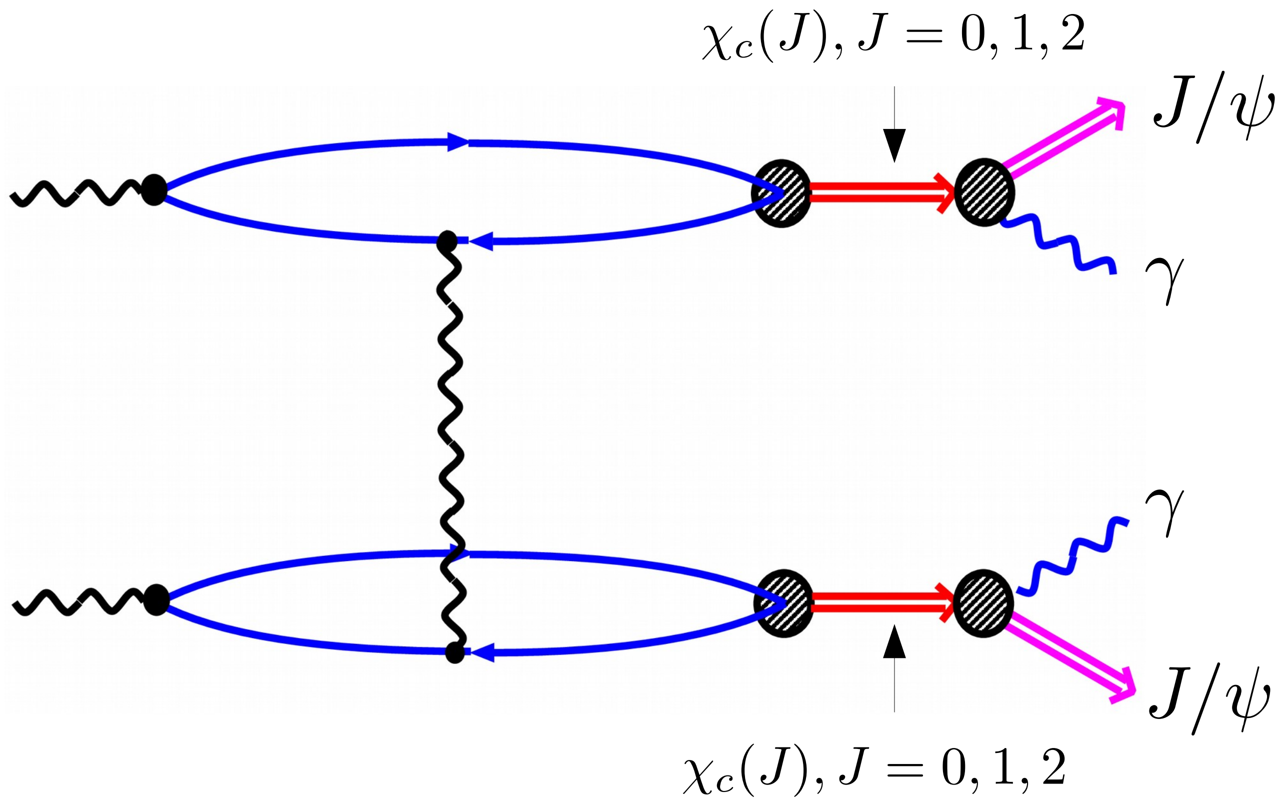


- "quasi-diffractive" exchange of 2 gluons in symmetric color octet
- A type of "colored Pomeron", purely imaginary amplitude very similar to 2 gluon exchange in γγ-scattering [Ginzburg, Panfil & Serbo 1988].

- Very small contribution, vast region of phase space "blocked" for final state gluons

Baranov, Snigirev, Zotov, Szczurek & WS, Phys Rev D87 (2013)

Contribution of χ-pairs to J/ψ-pair production

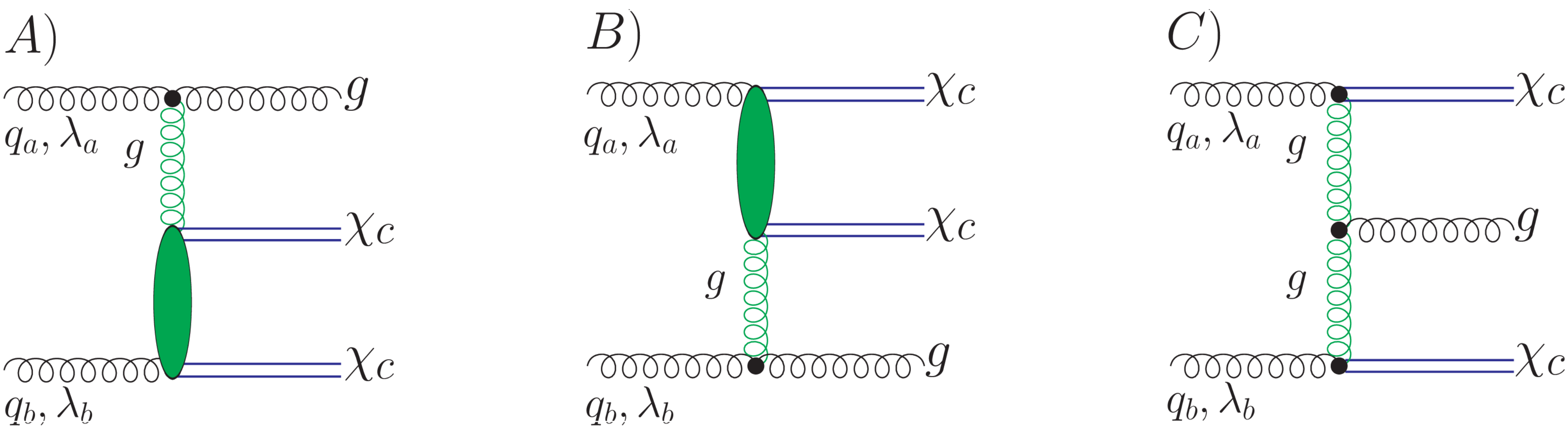


Br ($\chi_c(0) \to J/\psi\gamma$) = 1.26 ± 0.06%

Br ($\chi_c(1) \to J/\psi\gamma$) = 33.9 ± 1.2%,

Br ($\chi_c(2) \to J/\psi\gamma$) = 19.2 ± 0.7%

Associated production of χ_c pairs with a gluon

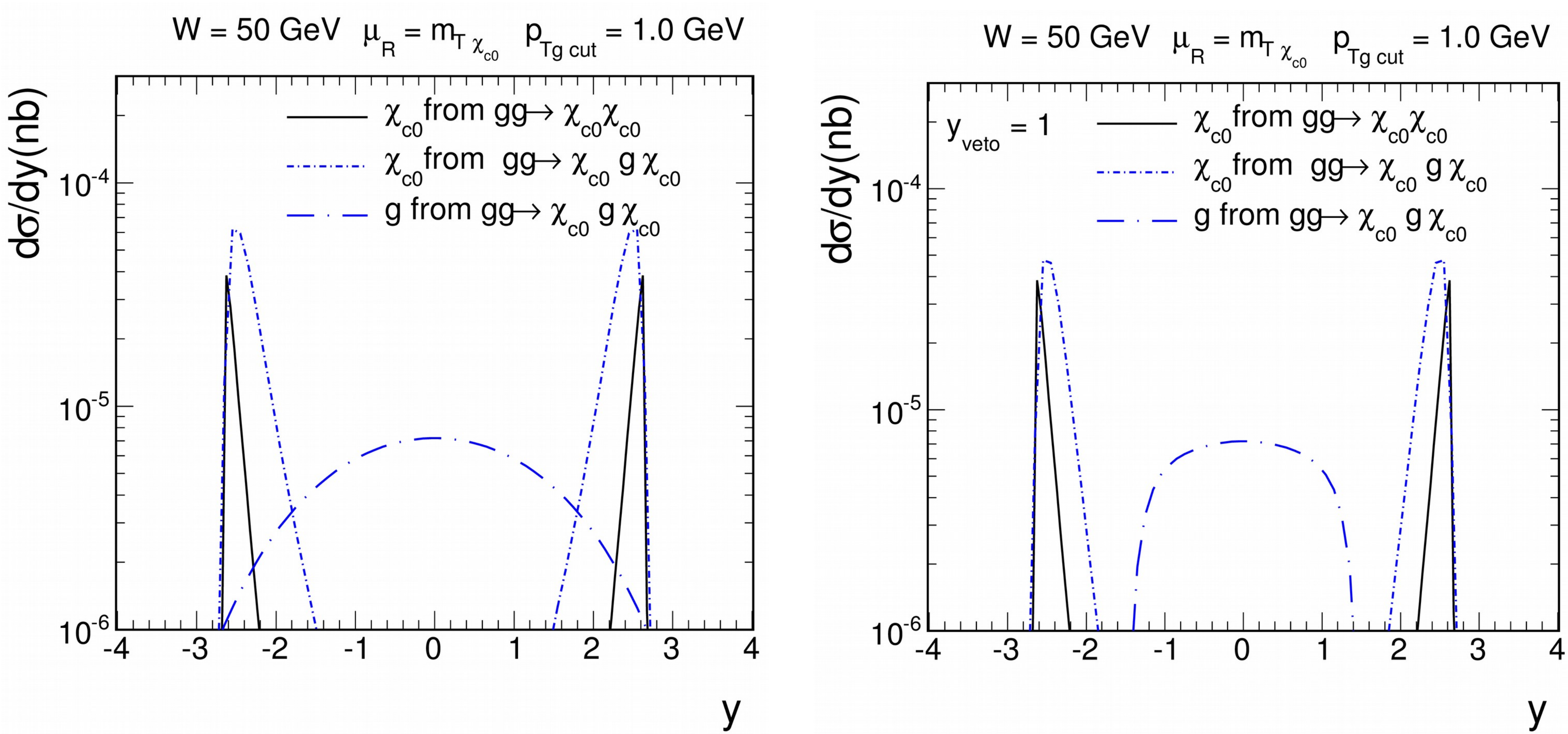


$$\mathcal{M}_A = i g_S f_{ab'c}\, 2q_a^+ \delta_{\lambda_a \lambda_g} \frac{1}{t_1}\, n^{+\mu'} \varepsilon^{\nu'}(\lambda_b, q_b) \mathcal{M}^{b'b}_{\mu'\nu'}(p_g - q_a, q_b; p_1, p_2)$$

$$\mathcal{M}_C = i g_S f_{a'b'c} V_1^{aa'}(q_a, p_1) \frac{1}{t_1} C^{\rho}(q_a - p_1, q_b - p_2) \varepsilon^*_{\rho}(\lambda_g, p_g) \frac{1}{t_2} V_2^{bb'}(q_b, p_2)$$

- Associated production with leading gluon (A&B) or central gluon (C) in collinear factorization
- Large rapidity distance between gluon and the mesons
- We can use Feynman rules e.g. from effective action of Lipatov et al.

Associated production of χ_c pairs with a gluon



$$d\sigma(2 \to 3) = \frac{Y}{16\pi^2(N_c^2 - 1)} I_1(\vec{p}_{1\perp}) \mathcal{K}_r(\vec{p}_{1\perp}, -\vec{p}_{2\perp}) I_2(\vec{p}_{2\perp}) d^2\vec{p}_{1\perp} d^2\vec{p}_{2\perp}$$

- Rapidity spectra for Born-level pair production, and associated production with a central gluon
- Factorization in terms of impact factors and real emission BFKL vertex

I. Babiaerz, WS, A. Szczurek, Phys Rev D99 (2019)

Associated production of χ_c pairs with a gluon

I. Babiarz, WS, A. Szczurek, Phys Rev D99 (2019)

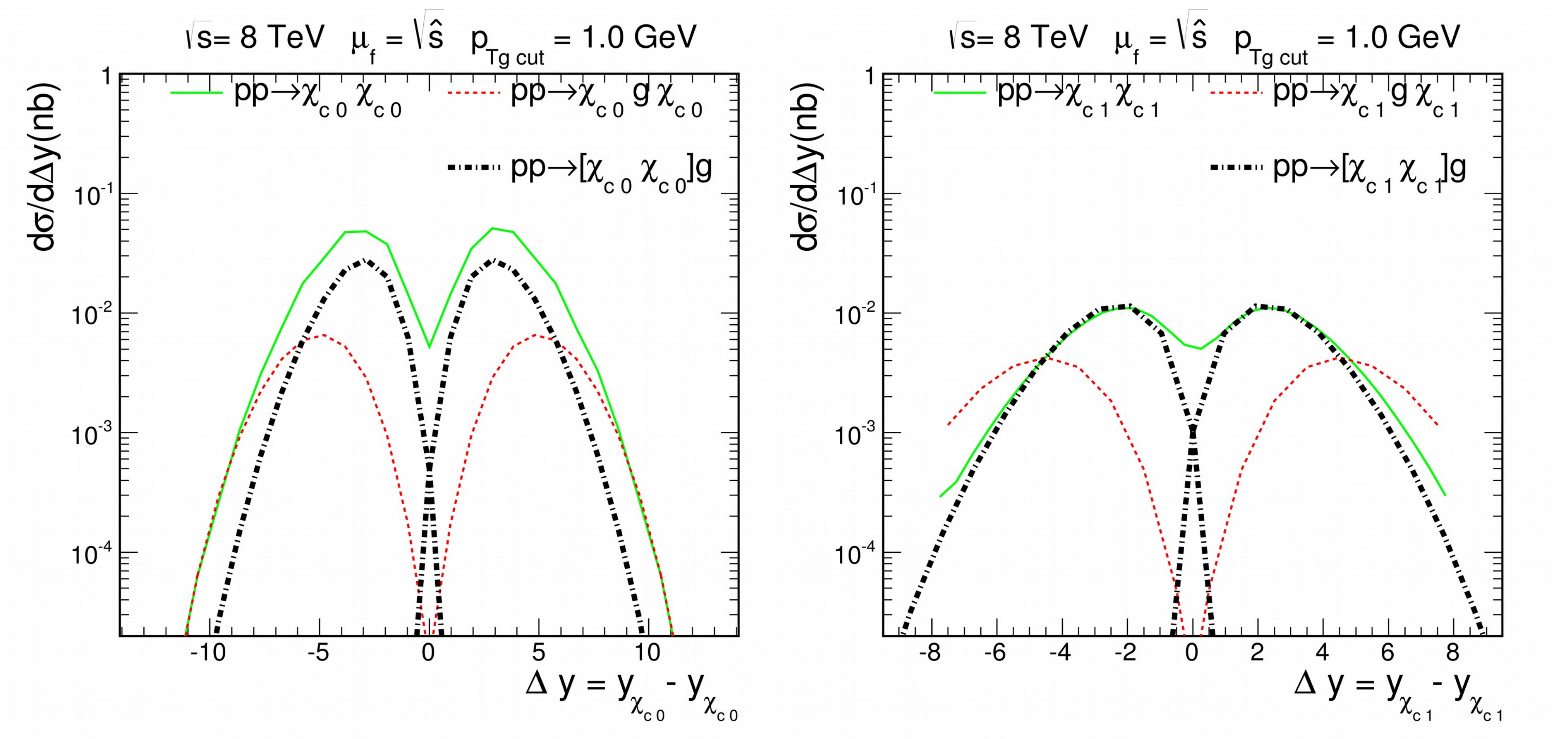
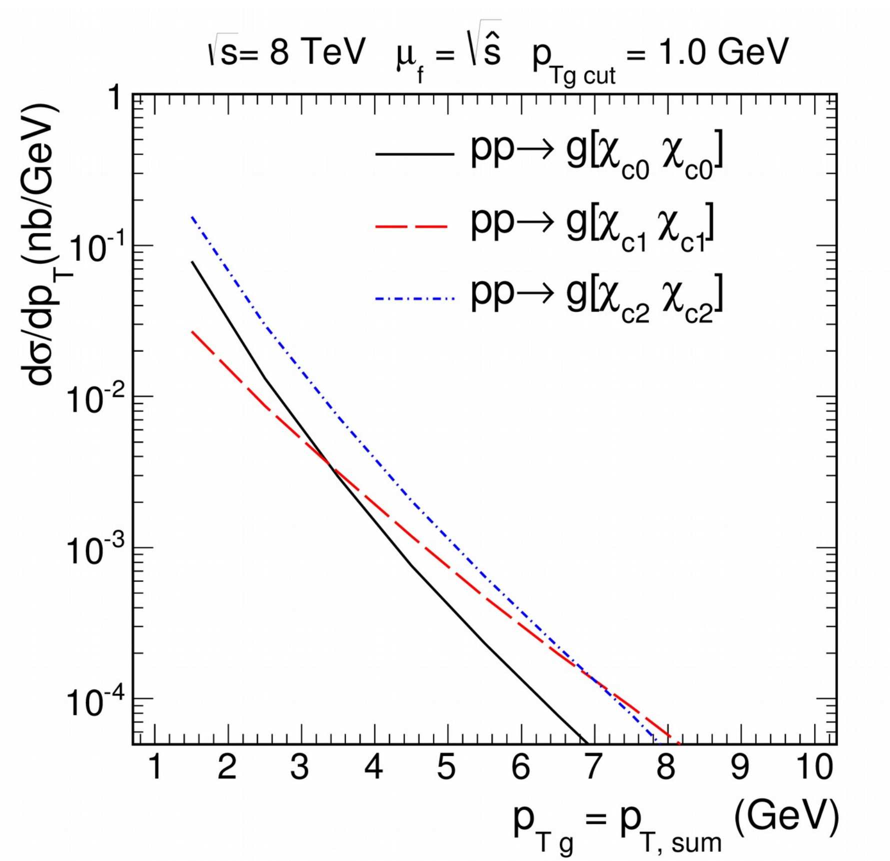
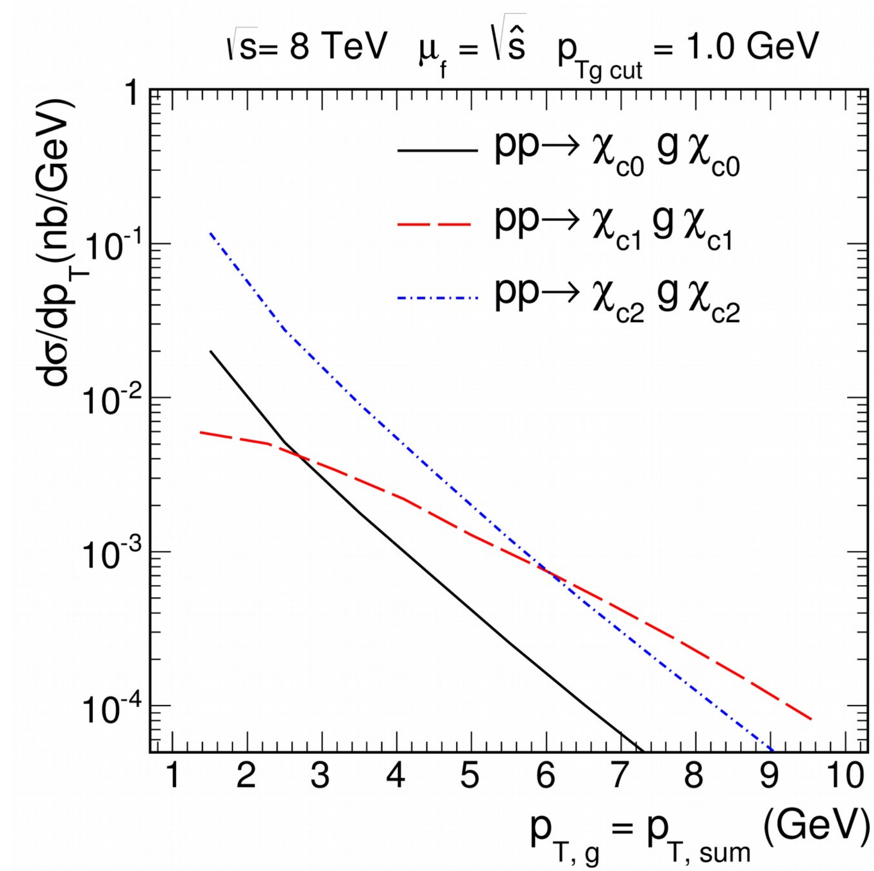


TABLE 1. Values of total cross sections for particular processes for $\sqrt{s} = 8\,\text{TeV}$.

χ_{c2}	σ_{total}	χ_{c1}	σ_{total}	χ_{c0}	σ_{total}
$pp \to \chi_{c2}\chi_{c2}$	0.62 nb	$pp \to \chi_{c1}\chi_{c1}$	$8.60 \cdot 10^{-2}$ nb	$pp \to \chi_{c0}\chi_{c0}$	0.40 nb
$pp \to [\chi_{c2}\chi_{c2}]g$	0.19 nb × 2	$pp \to [\chi_{c1}\chi_{c1}]g$	$4.07 \cdot 10^{-2}$ nb × 2	$pp \to [\chi_{c0}\chi_{c0}]g$	0.10 nb × 2
$pp \to \chi_{c2}g\chi_{c2}$	0.16 nb	$pp \to \chi_{c1}g\chi_{c1}$	$1.78 \cdot 10^{-2}$ nb	$pp \to \chi_{c0}g\chi_{c0}$	0.03 nb

Associated production of χ_c pairs with a gluon





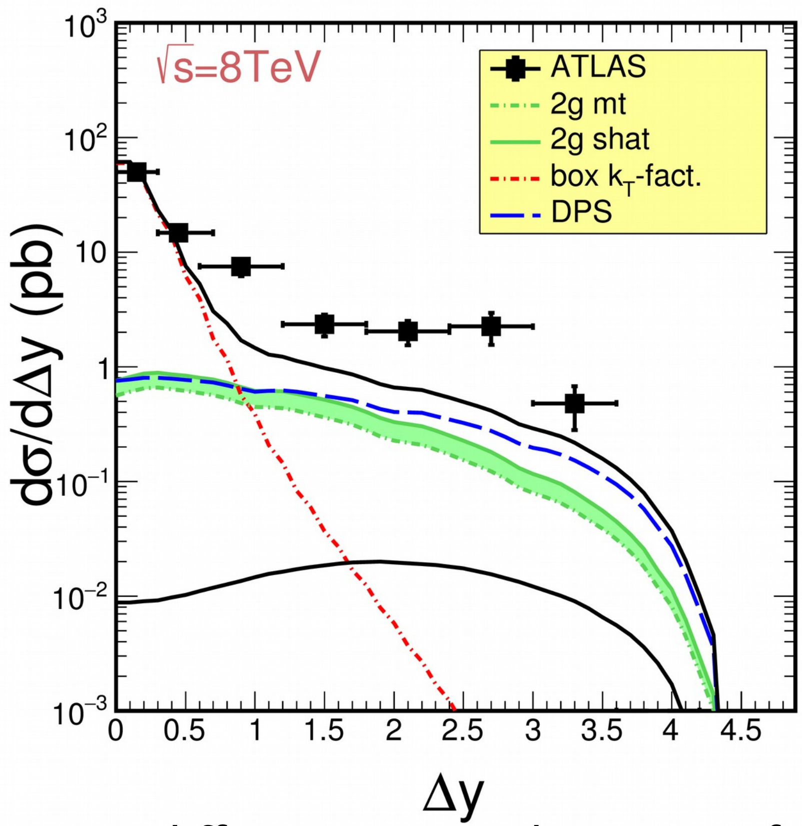
- Transverse momentum of leading gluon (left) and central gluon (right).
- J=1 state has harder large momentum tail, and central gluon distribution differs from the one for J=0,2.

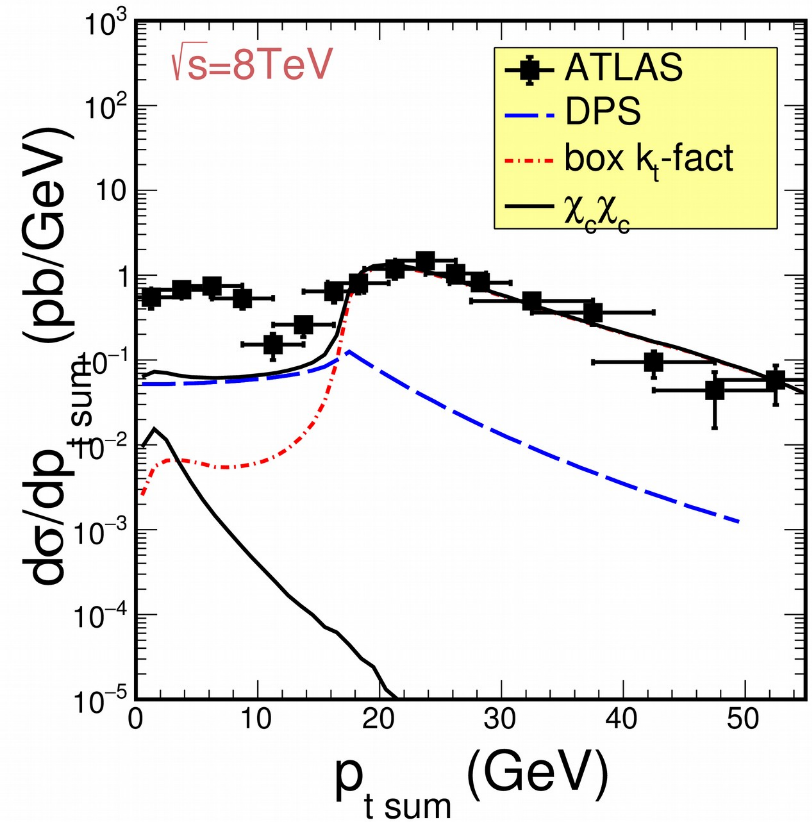
I. Babiarz, WS, A. Szczurek, Phys Rev D99 (2019)

ATLAS data on J/ψ J/ψ

ATLAS Coll. Eur.Phys.J C 77 (2017)

- cuts on J/ψ: $|y^{J/\psi}| < 2.1$, $p_T^{J/\psi} > 8.5\,\mathrm{GeV}$.
- additional muon cuts: $|\eta^\mu| < 2.3$, $p_T^\mu > 2.5\,\mathrm{GeV}$, $2.8 < M_{\mu\mu} < 3.4\,\mathrm{GeV}$.





- Quasi-diffractive 2g-exchange & χ-feed-down nicely mimic DPS in the
- Δy distribution
- Unfortunately they are lacking in pair transverse momentum
- Here we used **σ_{eff}=15 mb.**
- Similar situation for CMS data.

Summary

- Large DPS contribution in the charm sector → charmonium pair production as a probe of DPS
- Observation of small σ_{eff} leads to the quest for SPS mechanisms that *survive at large pair invariant mass/large rapidity distance Δy.*
- χ_c-pairs are produced via single t & u-channel gluon exchange → broad distributions in Δy
- Two-gluon exchange in $gg \to J/\psi J/\psi$ and feed-down from $\chi_c \chi_c$ *very much **mimic the behaviour of DPS*** but seem to be too small in strength to replace it.
- In collinear factorization, one needs to include 2→ 3 processes to recover kT-factorization results
- Additional enhancement from production of central gluons in the BFKL-like kinematics.