Second conference on heavy ion collisions in the LHC era and beyond

# Heavy quark pair production in pA collisions at the LHC within the CGC framework


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work in collaboration with
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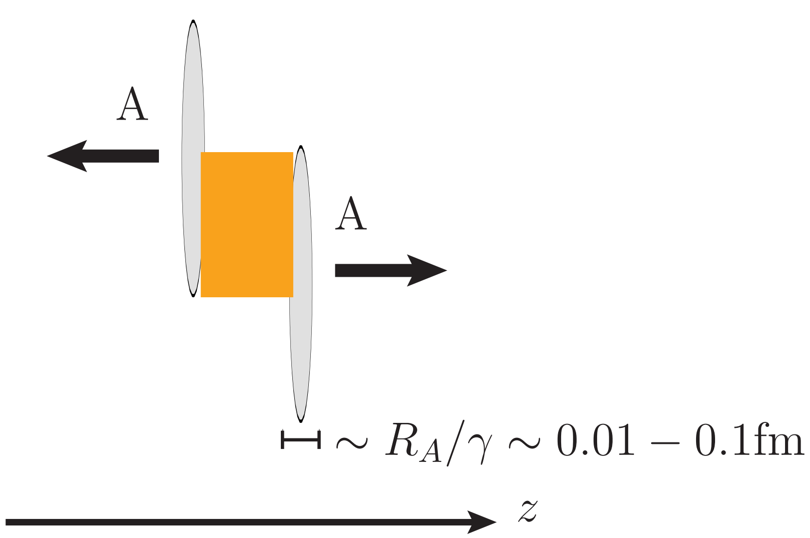
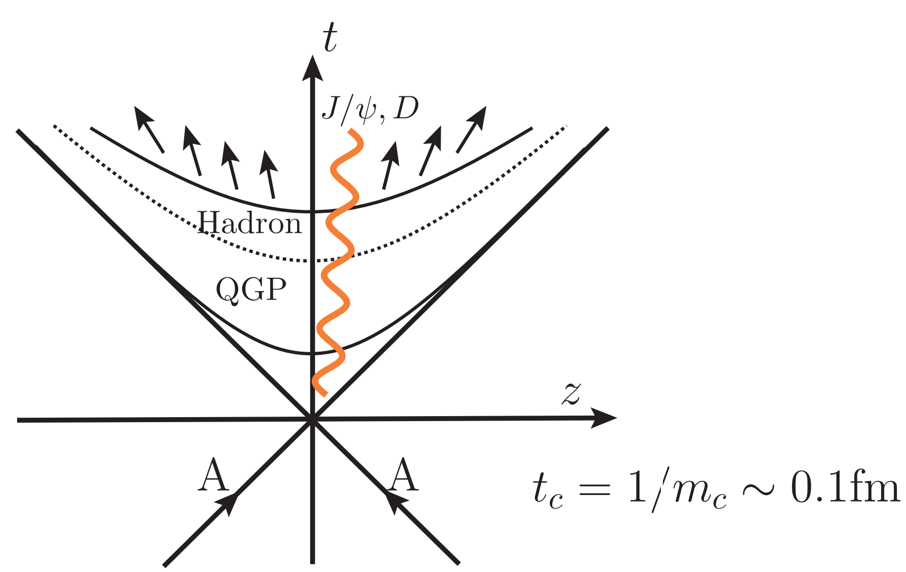
Talk Plan

1. Early work → Nucl.Phys.A915 (2013)
2. Recent Progress → arXiv:1507.06564[hep-ph]

# Heavy quark pair production in HIC

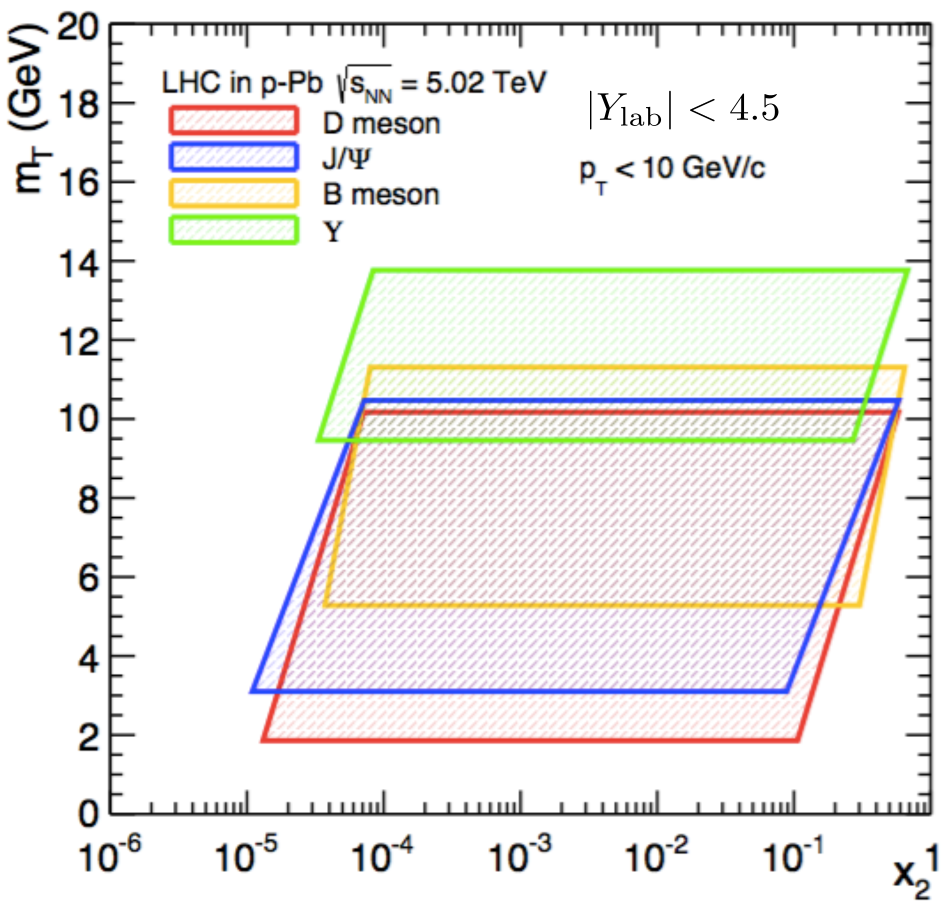
- The goals of ultrarelativistic heavy ion collisions (HICs) physics are to create quark-gluon plasma (QGP) and to understand its properties.
- Heavy quark pair is produced in initial hard process → Subsequent interactions reflect medium properties.
- Initial cold nuclear matter (CNM) effects, such as nPDF, energy loss, parton saturation, should be studied in pA collisions → A controlled baseline against AA.

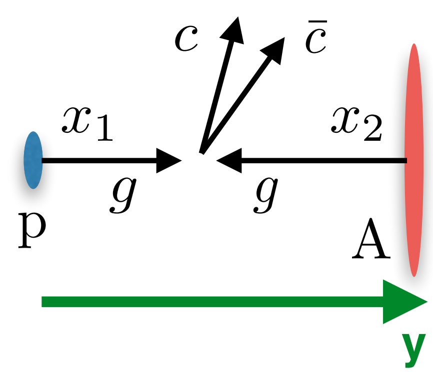


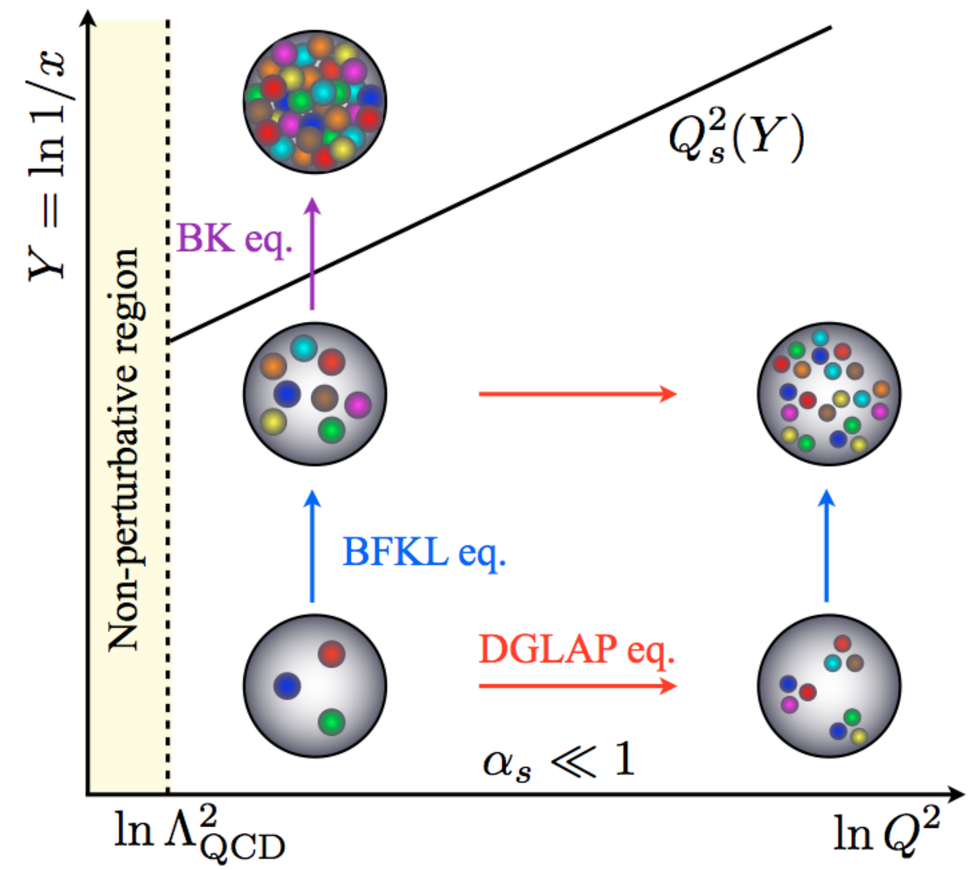



# The Hadron Tomography

arXiv:1506.03981[nucl-ex]




- At the LHC, HQ productions can be reflected of small-x information of dense gluon for the target hadron.
- Their typical transverse momentum is around the saturation momentum:

$$Q^2_{sA}(x_2) \sim A^{1/3} \left(\frac{0.01}{x_2}\right)^{0.3} \Lambda^2_{\rm QCD} \quad \rightarrow \text{a test of CGC}$$

# The CGC formula

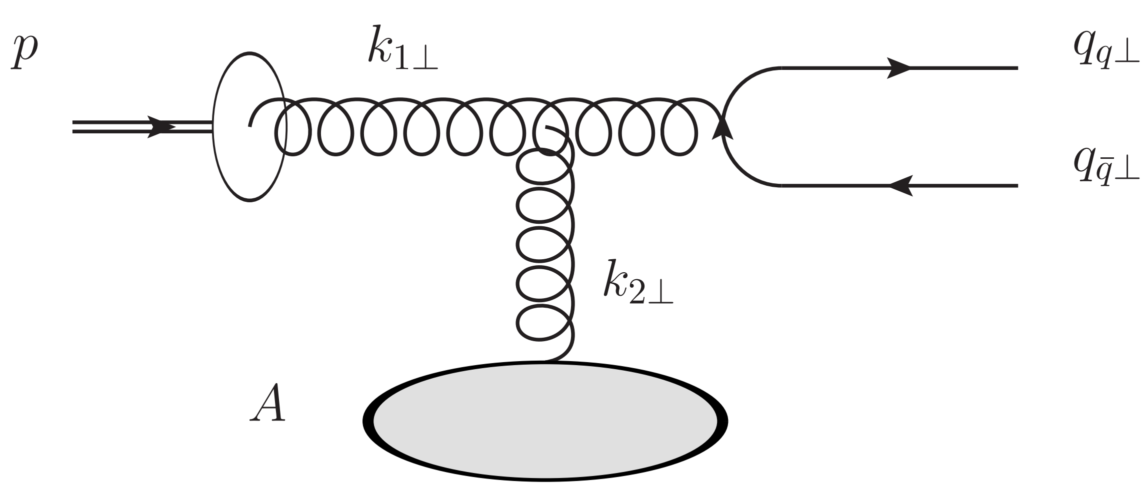
Blaizot, Gelis, Venugopalan, (2004)

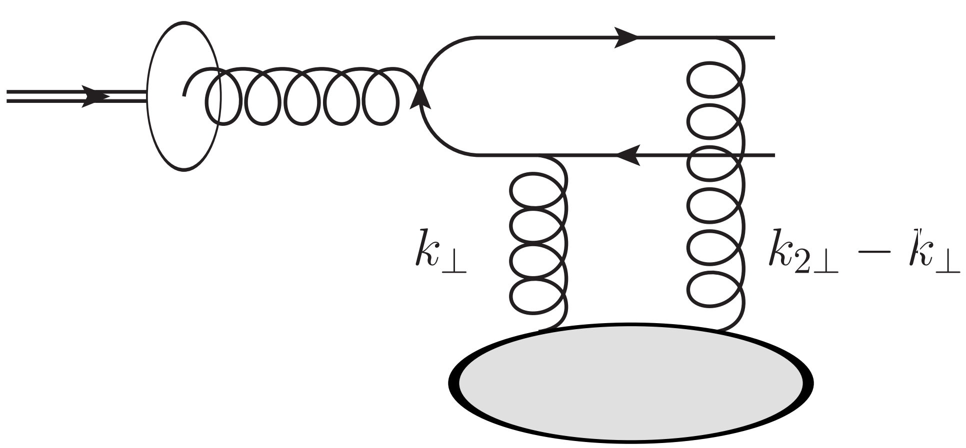
- kt-factorized formula

$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{(2\pi)^6 C_F}\int d^2k_{2\perp}d^2k_\perp \frac{\Xi(k_{1\perp},k_{2\perp},k_\perp)}{k_{1\perp}^2 k_{2\perp}^2}\ \varphi_{p,x_1}(k_{1\perp})\ \phi_{A,x_2}^{q\bar{q},g}(k_{2\perp},k_\perp)$$

- Hybrid (DHJ) formula : collinear/CGC (Forward regions)

$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int d^2k_\perp \frac{\Xi_{\rm coll}(k_{2\perp},k_\perp)}{k_{2\perp}^2}\ x_1 G(x_1,\mu)\ \phi_{A,x_2}^{q\bar{q},g}(k_{2\perp},k_\perp)$$



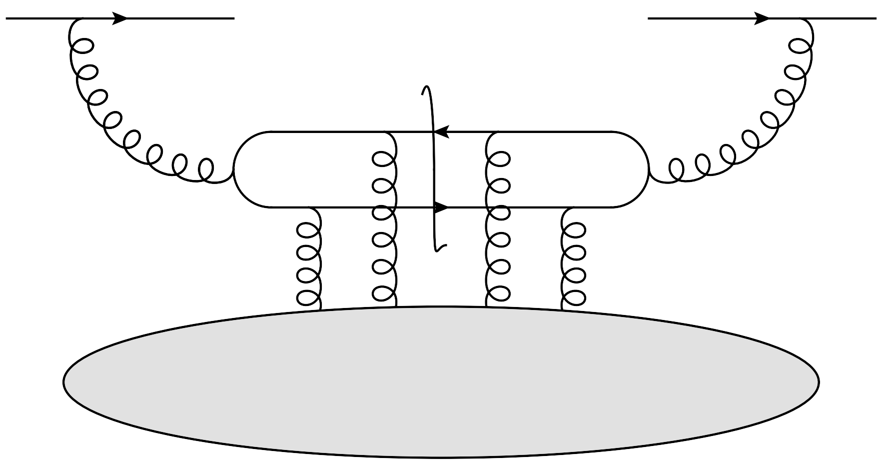

High energy limit : s → ∞

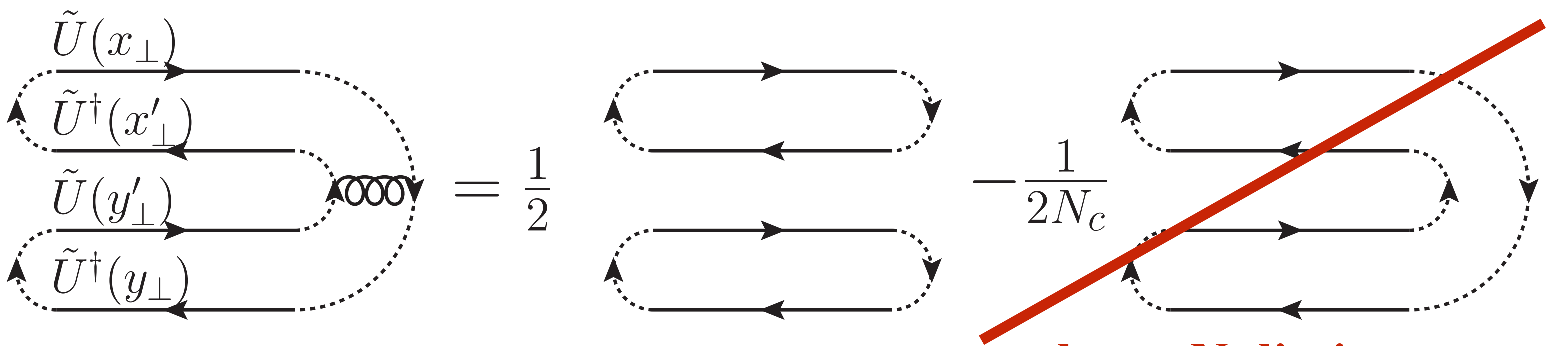
# The multipoint function

$$\phi^{q\bar{q},g}_{A,Y_g}(k_{2\perp},k_\perp) \propto \int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^4} e^{-ik_\perp\cdot x_\perp} e^{i(k_{2\perp}-k_\perp)\cdot y_\perp} S_{Y_g}(x_\perp)\, S_{Y_g}(y_\perp)$$

$$= F_{Y_g}(k_\perp)\, F_{Y_g}(k_{2\perp}-k_\perp)$$

$$Y_g = \ln\frac{1}{x_2}$$






- The multipoint function is the same in both CEM and color octet channel of NRQCD in large-Nc.
- Nuclear dependence is expected to be universal for quarkonium production.

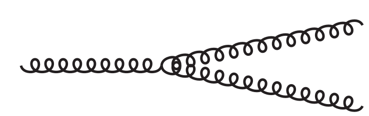
Qiu, Sun, Xiao and Yuan, PRD89(2014)

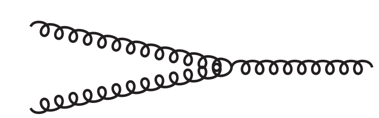
# Balitsky-Kovchegov equation

I.Balitsky (1996), Y.V.Kovchegov (1999)

- BK equation : Quantum evolution of dipole

$$\frac{d}{dY}N_Y(\vec{r}_\perp) = \int d\vec{r}_{1\perp}\mathcal{K}(\vec{r}_\perp,\vec{r}_{1\perp})\Big[\underbrace{N_Y(\vec{r}_{1\perp}) + N_Y(\vec{r}_{2\perp}) - N_Y(\vec{r}_\perp)}_{\text{BFKL cascade}} - \underbrace{N_Y(\vec{r}_{1\perp})\mathcal{N}_Y(\vec{r}_{2\perp})}_{\text{Recombination}}\Big]$$

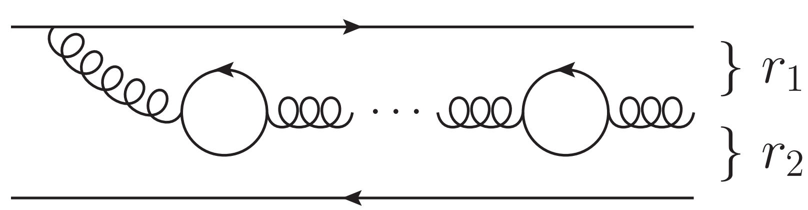




- The running coupling evolution kernel (rcBK)

I.Balistky (2007)

$$\mathcal{K}_{\mathrm{run}}(\vec{r}_\perp,\vec{r}_{1\perp}) = \frac{\alpha_s(r^2)N_c}{2\pi^2}\left[\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$




rcBK is the state-of-the-art technology for phenomenologies

# Initial condition of the rcBK

- Parametrized initial condition at x=0.01: MV$^\gamma$ model

$$N_{Y=0}(r_\perp) = 1 - \exp\left[-\frac{(r^2 Q_{s0,\mathrm{p}}^2)^\gamma}{4}\ln\left(\frac{1}{\Lambda r}+e\right)\right] \qquad (*\Lambda = 0.241\mathrm{GeV})$$

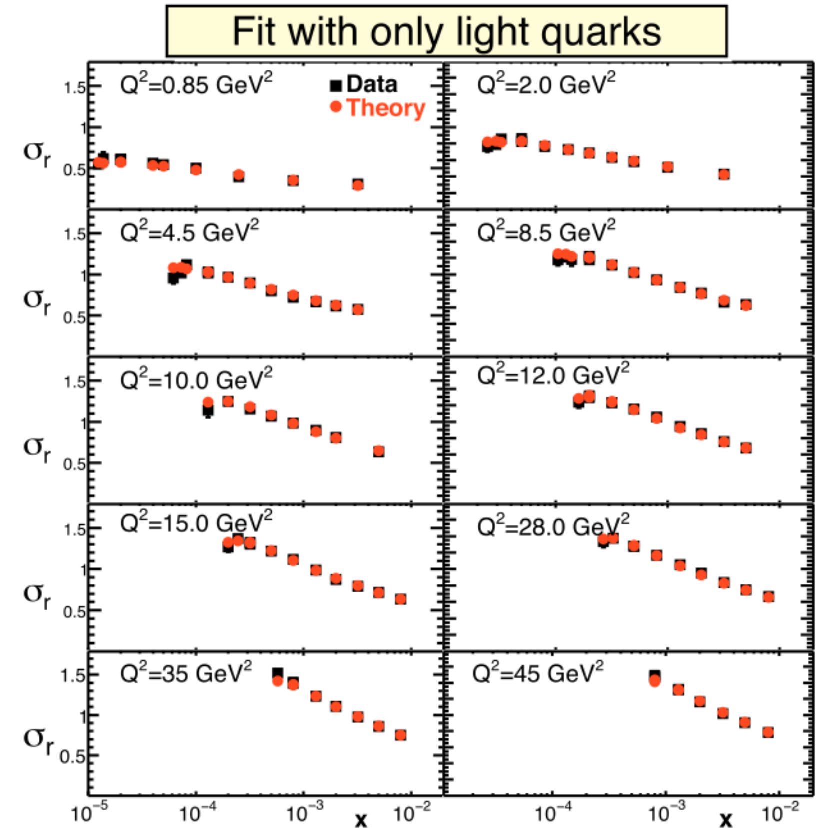
$$\alpha_s(r^2) = \left[b_0 \ln\left(\frac{4C^2}{r^2\Lambda^2}+a\right)\right]^{-1}$$

$$\alpha_s(r\to\infty) = \alpha_{fr}$$

Global analysis of DIS data

| set | $Q_{s0,\mathrm{p}}^2/\mathrm{GeV}^2$ | $\gamma$ | $\alpha_{fr}$ | $C$ | $\chi^2$/d.o.f. |
|---|---|---|---|---|---|
| MV$^\gamma$ | 0.1597 | 1.118 | 1.0 | 2.47 | ≈1.1 |

$\gamma$ controls the steepness of the gluon distribution at higher momentum $k_\perp > Q_{s0,p}$

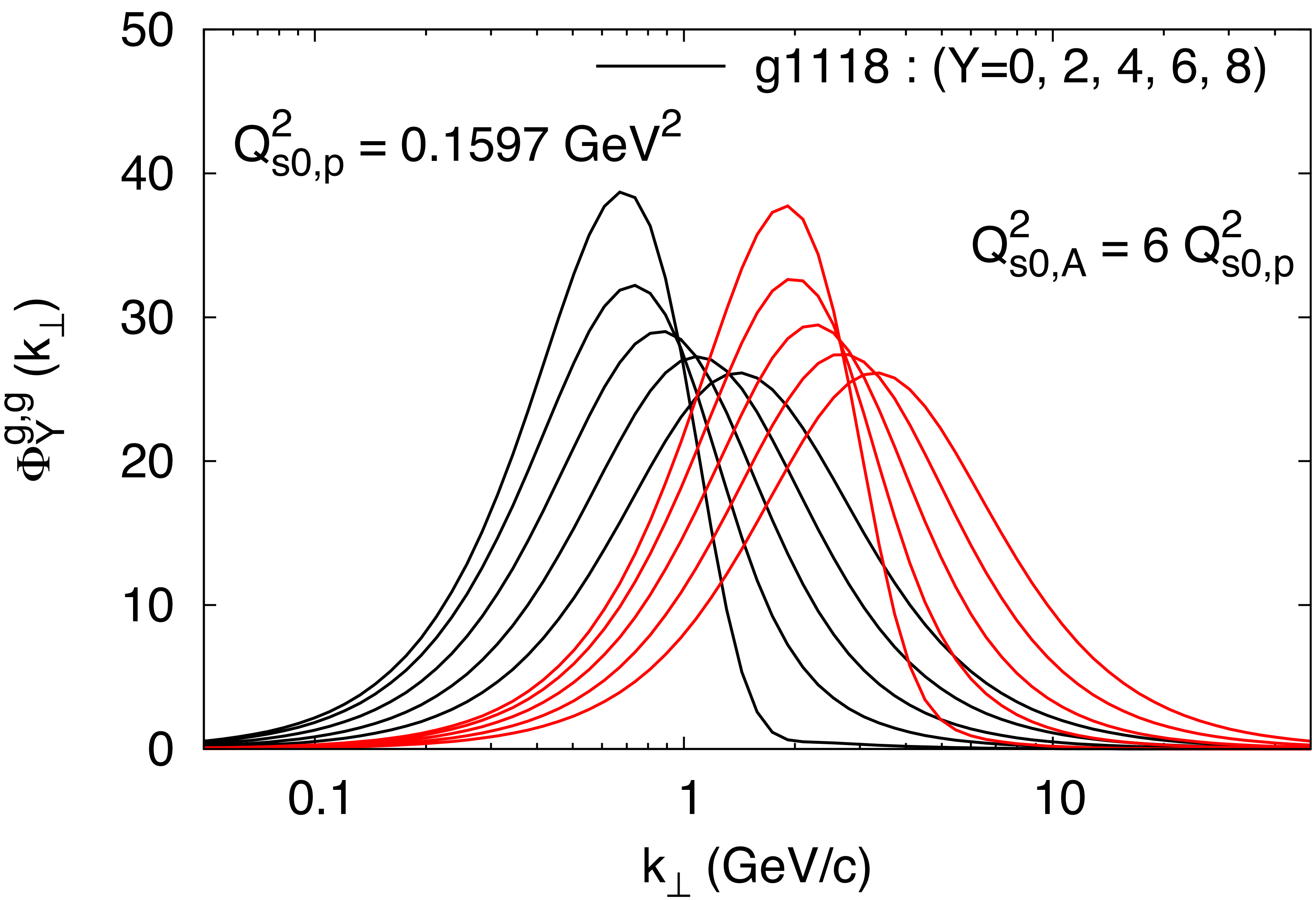



J.L.Albacete et al. (AAMQS) (2011)

cf. for rcBK:
Fujii, Itakura, Kitadono, Nara, JPG38(2011),
Albacete, Dumitru, Fujii, Nara, NPA897 (2013)

# Dipole gluon distribution function

$$\Phi_Y^{g,g}(k_\perp) \propto \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp \cdot x_\perp} S_Y(x_\perp) S_Y(x_\perp)$$




Forward rapidity at RHIC

$$x_2 = 10^{-2} \sim 10^{-3}$$

↕

$$Q_{sp} < 1\text{GeV}$$

$$Q_{sA} \sim 2\text{GeV}$$

Forward rapidity at the LHC

$$x_2 = 10^{-4} \sim 10^{-5}$$

↕

$$Q_{sp} \sim 1\text{GeV}$$

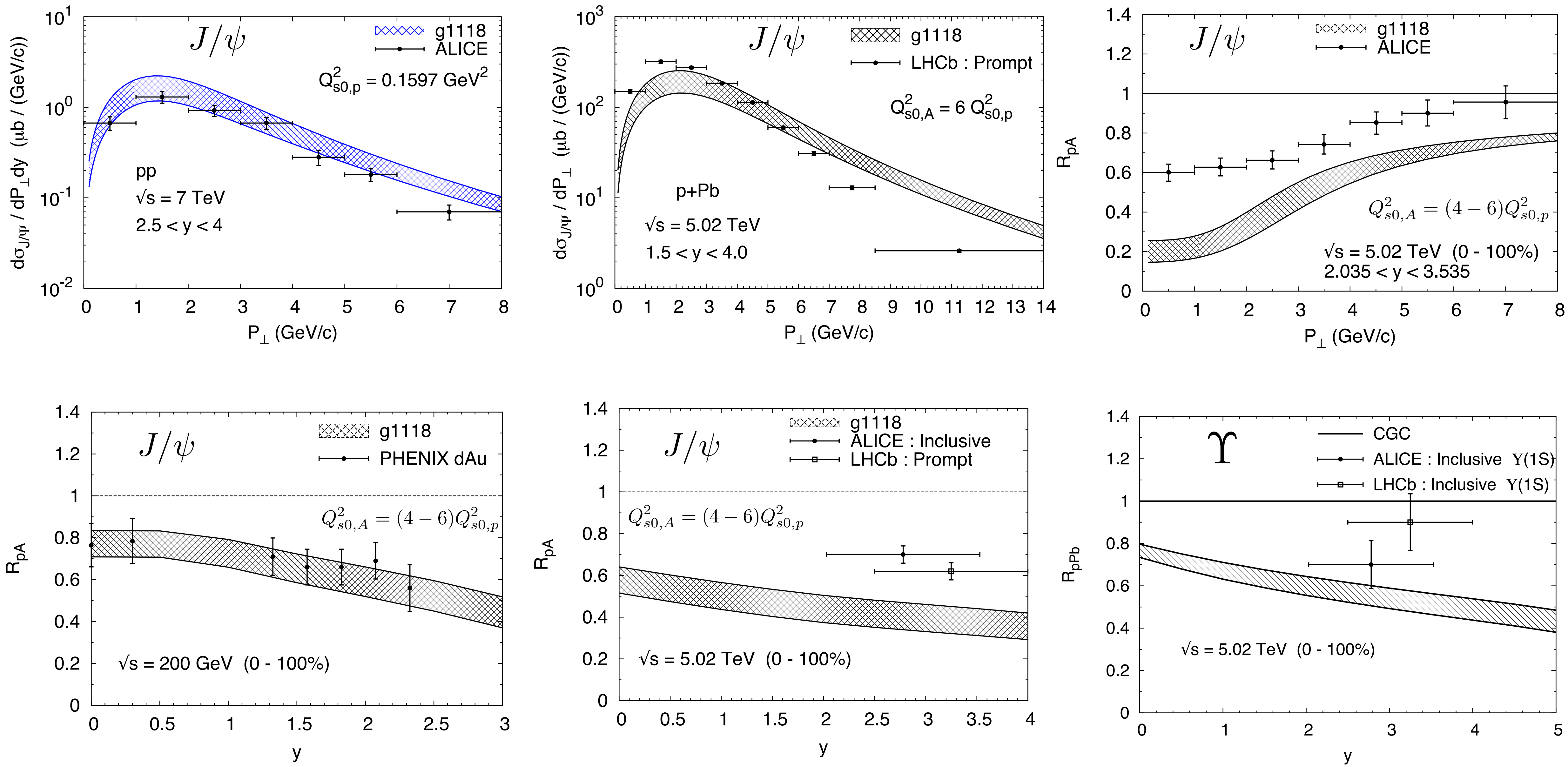
$$Q_{sA} \sim 3\text{GeV}$$

# Early CGC results 1

## Quarkonium

Fujii, KW, NPA915(2013)

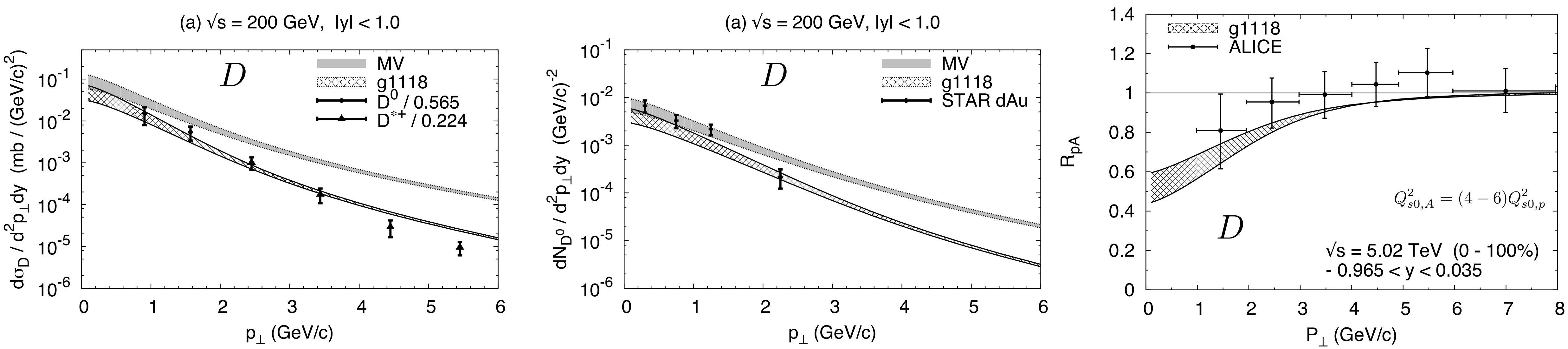
## Color evaporation model (CEM)



# Early CGC results 2

## Open heavy flavor

Fujii, KW, NPA920(2013)




- Open heavy flavor seems in good agreement with the data compared to quarkonium.

# $R_{pA}$ vs $Q_{s0}{}^2$

H. Fujii, K. Watanabe / Nuclear Physics A 915 (2013) 1–23 19

**Early results**

$$Q^2_{s0,A} = (4 \sim 6)Q^2_{s0}$$

**Another choice**

$$Q^2_{s0,A} = (2 \sim 3)Q^2_{s0}$$

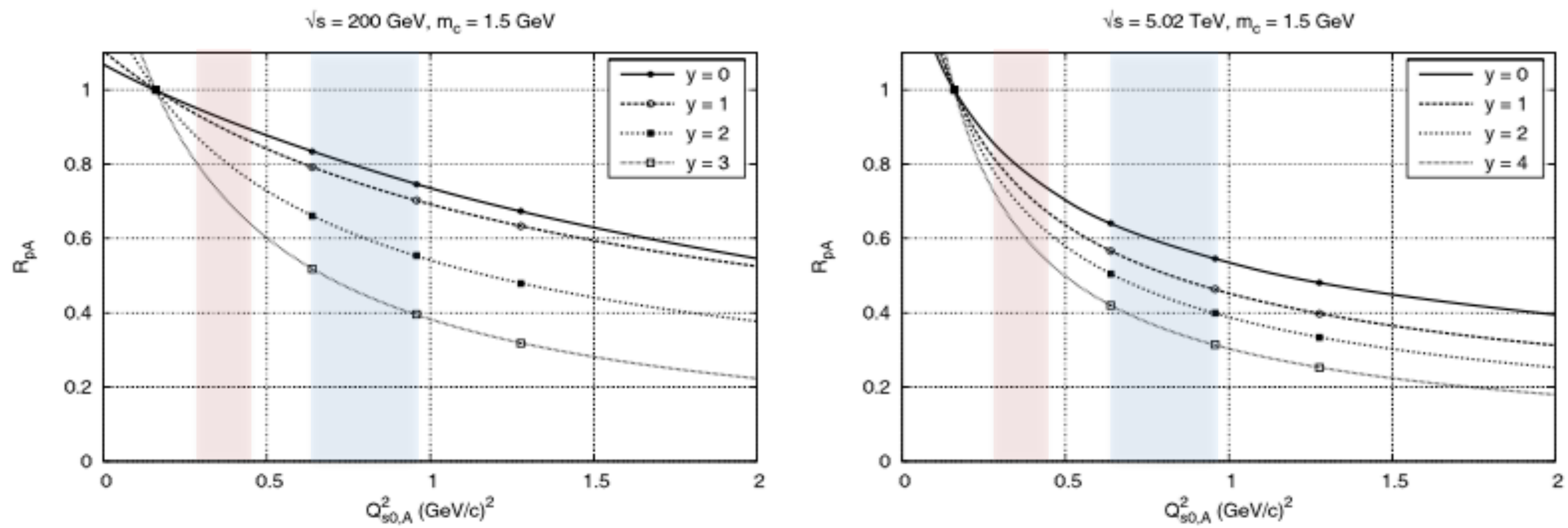



Fig. 14. Nuclear modification factor $R_{\mathrm{pA}}$ for $J/\psi$ as a function of $Q^2_{s0,A}$ at $y = 0, 1, 2$ and 3 for $\sqrt{s} = 200$ GeV (left) and at $y = 0, 1, 2$ and 4 for $\sqrt{s} = 5.02$ TeV (right). Fitted curves are also shown.

$$R_{\mathrm{pA}} = \frac{a}{(b + Q^2_{s0,A})^{\alpha}}$$

cf.
Ma, Venugopalan, and Zhang, arXiv:1503.07772,
Ducloue,Lappi, and Mantysaari, arXiv:1503.02789

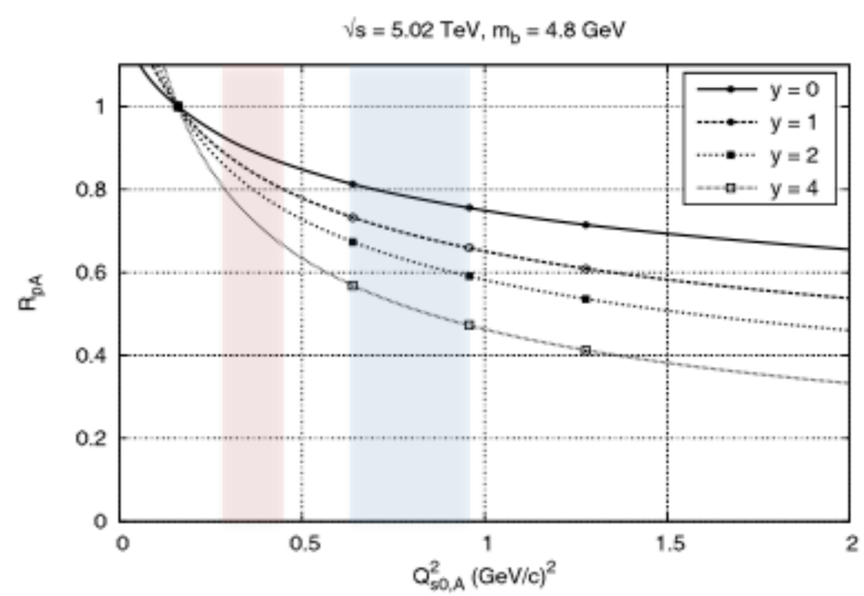
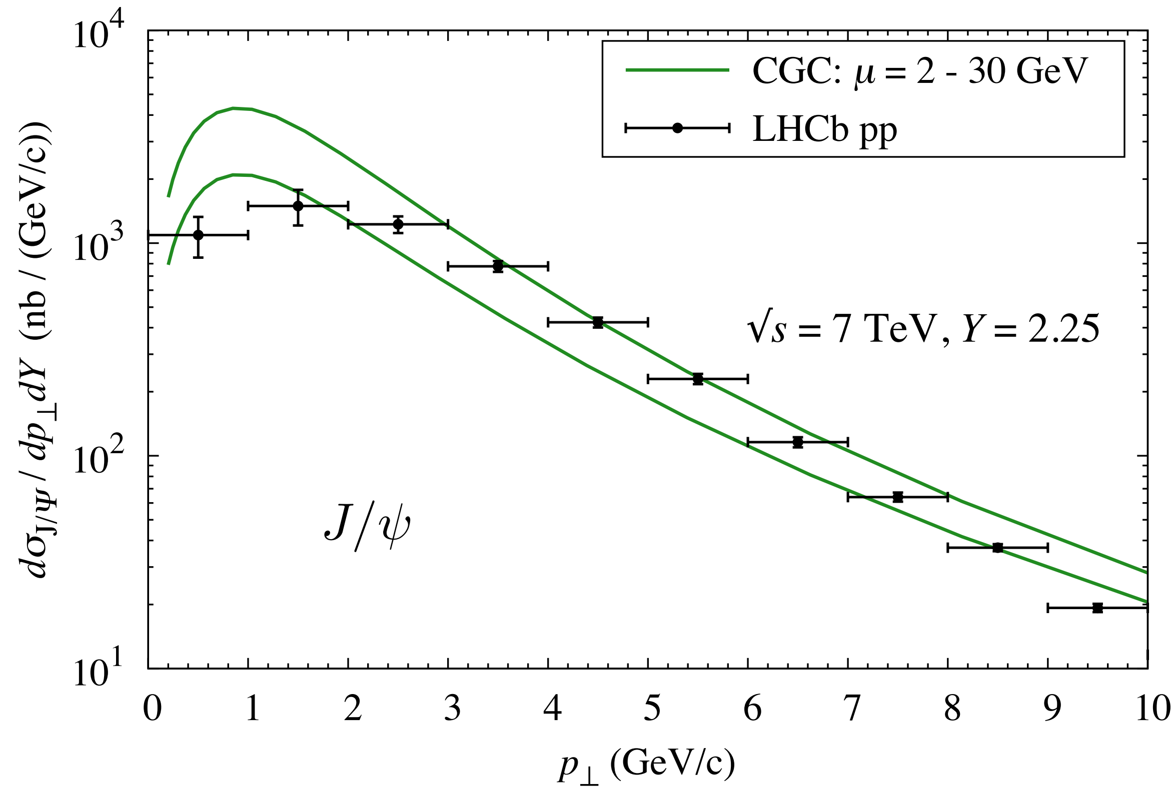
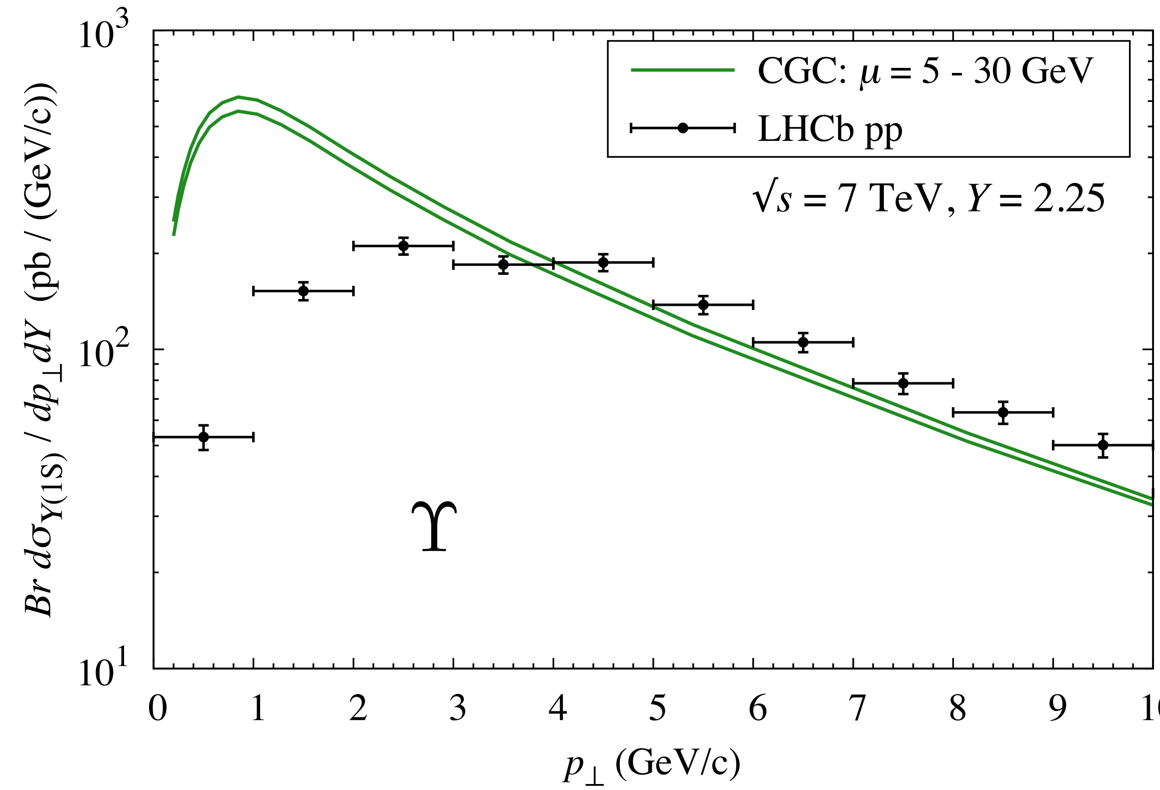



Fig. 15. Nuclear modification factor $R_{\mathrm{pA}}$ for $\Upsilon(1S)$ as a function of $Q^2_s$ at $y = 0, 1, 2$ and 4 at $\sqrt{s} = 5.02$ TeV.

# “LHCb puzzle”




These results are computed in hybrid formula.

- The saturation scale at the LHC is about 1GeV.
- What is the LHC data telling ?

# Two kinds of correction

- Small-x $\alpha_s N_c \ln \frac{1}{x_2} \sim \mathcal{O}(1)$ → BK eq.
- Low-pt $\alpha_s N_c \ln^2 \frac{M^2}{p_\perp^2} \sim \mathcal{O}(1)$ → Sudakov factor

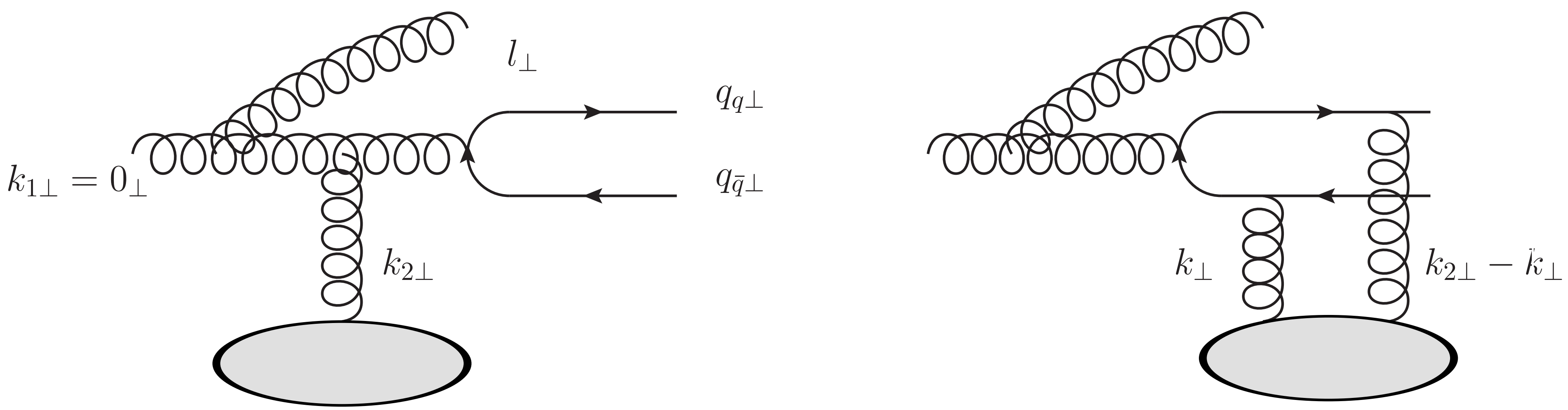
cf. Higgs boson production

Mueller, Xiao, and Yuan, PRL110(2013), PRD88 (2013)

- "Heavy" quarkonium production at low-pt is expected to be sensitive to the Sudakov factor : pt < M.

KW and Xiao, arXiv:1507.06564

# The CGC formula with the Sudakov factor



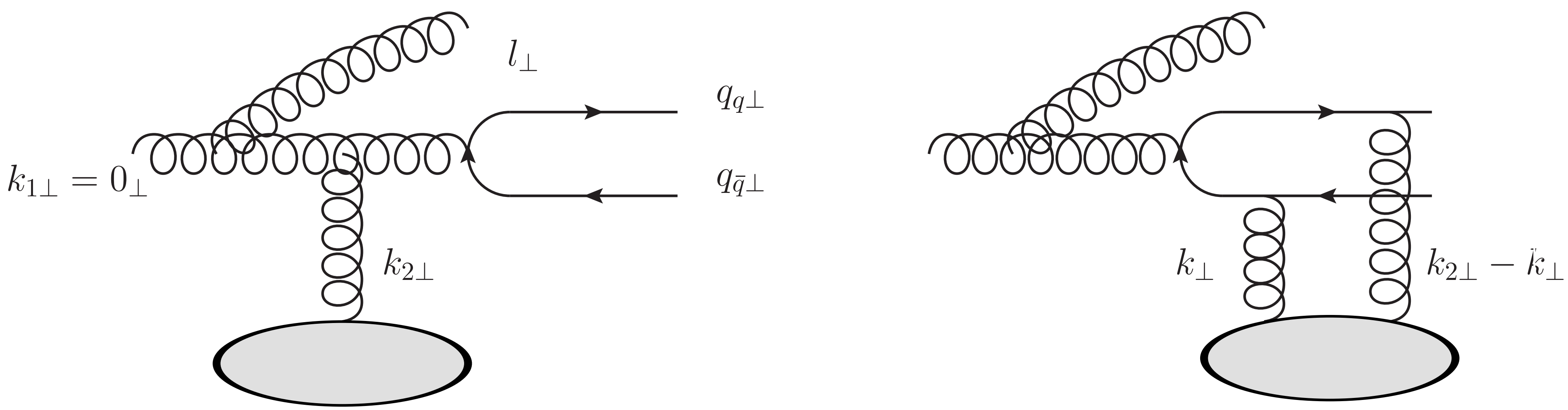

- **Improved** Hybrid formula

$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\rm coll}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2}\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp)$$

$$\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp) \propto F_{Y_g}(k_\perp) F_{Y_g}(k_{2\perp} - k_\perp + l_\perp) F_{\rm Sud}(l_\perp)$$

$$F_{\rm Sud}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp\cdot l_\perp} e^{-S_{\rm Sud}(M,b_\perp)} x_1 G\left(x_1, \frac{c_0}{b_\perp}\right)$$

# The CGC formula with the Sudakov factor




- **Improved** Hybrid formula

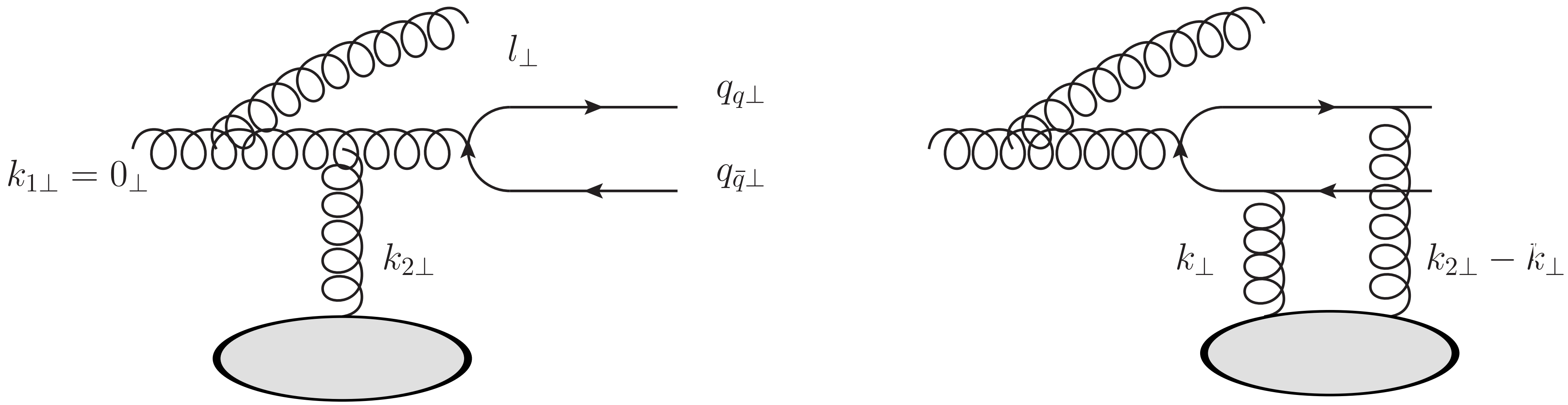
$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\text{coll}}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2}\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp)$$

**BK**

$$\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp) \propto \boxed{F_{Y_g}(k_\perp) F_{Y_g}(k_{2\perp} - k_\perp + l_\perp)} F_{\text{Sud}}(l_\perp)$$

$$F_{\text{Sud}}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp \cdot l_\perp} e^{-S_{\text{Sud}}(M,b_\perp)} x_1 G\left(x_1, \frac{c_0}{b_\perp}\right)$$

# The CGC formula with the Sudakov factor




- **Improved** Hybrid formula

$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\rm coll}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2}\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp)$$

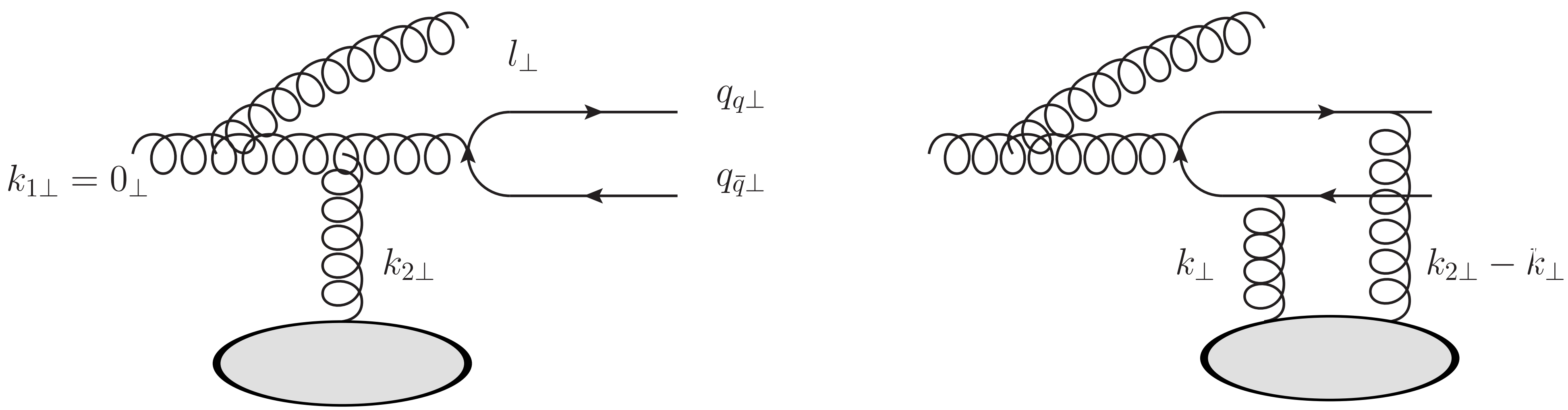
**BK**

$$\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp) \propto F_{Y_g}(k_\perp) F_{Y_g}(k_{2\perp} - k_\perp + l_\perp) F_{\rm Sud}(l_\perp)$$

$$F_{\rm Sud}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp \cdot l_\perp} e^{-S_{\rm Sud}(M,b_\perp)} x_1 G\left(x_1, \frac{c_0}{b_\perp}\right)$$

**Sudakov**

# The CGC formula with the Sudakov factor




- **Improved** Hybrid formula

$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\mathrm{coll}}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2}\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp)$$

BK

$$\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp) \propto F_{Y_g}(k_\perp) F_{Y_g}(k_{2\perp} - k_\perp + l_\perp) F_{\mathrm{Sud}}(l_\perp)$$

$$F_{\mathrm{Sud}}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp \cdot l_\perp} e^{-S_{\mathrm{Sud}}(M,b_\perp)} x_1 G\left(x_1, \frac{c_0}{b_\perp}\right)$$

Sudakov

DGLAP (CTEQ6M)

# Collins-Soper-Sterman (CSS) formalism

$$S_{\text{Sud}}(M,b) = S_{\text{perp}}(M,b_\star) + S_{\text{NP}}(M,b)$$

CSS, NPB250(1985)

$$b_\star = b/\sqrt{1+(b/b_{\max})^2}$$

small-b: $b_\star \sim b$

large-b: $b_\star \sim b_{\max} = 0.5\ \text{GeV}^{-1}$

- Perturbative form factor (small-b)

Sun, Yuan, and Yuan, PRD 88(2013)

$$S_{\text{perp}}(M,b) = \int_{c_0/b^2}^{M^2} \frac{d\mu^2}{\mu^2}\left[A\ln\left(\frac{M^2}{\mu^2}\right) + B\right]$$

$$A = \sum_{i=1} A^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$$

$$B = \sum_{i=1} B^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$$

At 1-loop calculation in NRQCD

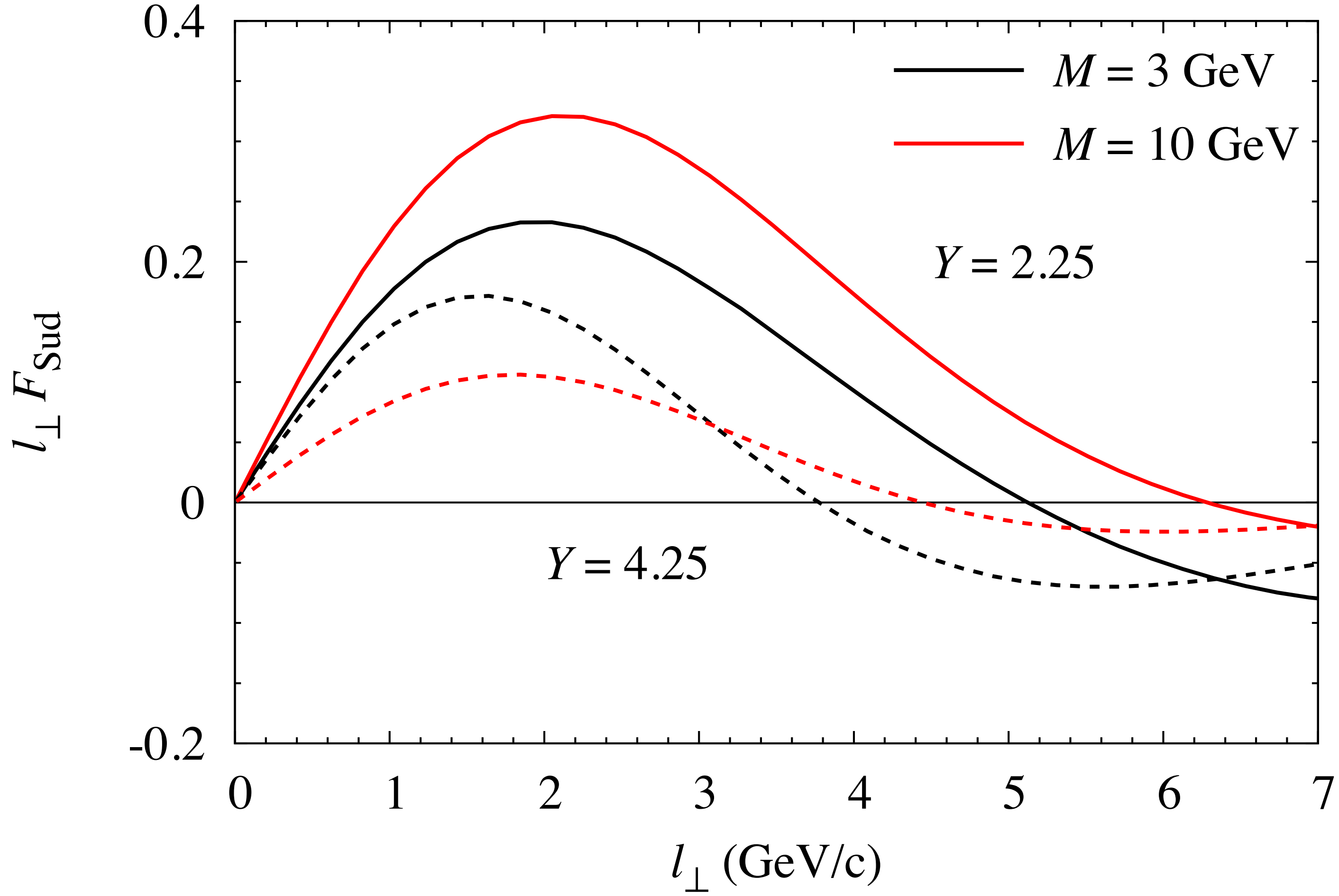
$$A^{(1)} = C_A \qquad B^{(1)} = -(b_0 + \frac{1}{2}\delta_{8c})N_c \qquad b_0 = \left(\frac{11}{6}N_c - \frac{n_f}{3}\right)\frac{1}{N_c}$$

- Non-Perturbative form factor (large-b) ←Determined by the data fitting

$$S_{\text{NP}}(M,b) = \exp\left[\frac{b^2}{2}\left(-g_1 - g_2\ln\left(\frac{M}{2Q_0}\right) - g_1 g_3\ln(100x_1x_2)\right)\right]$$

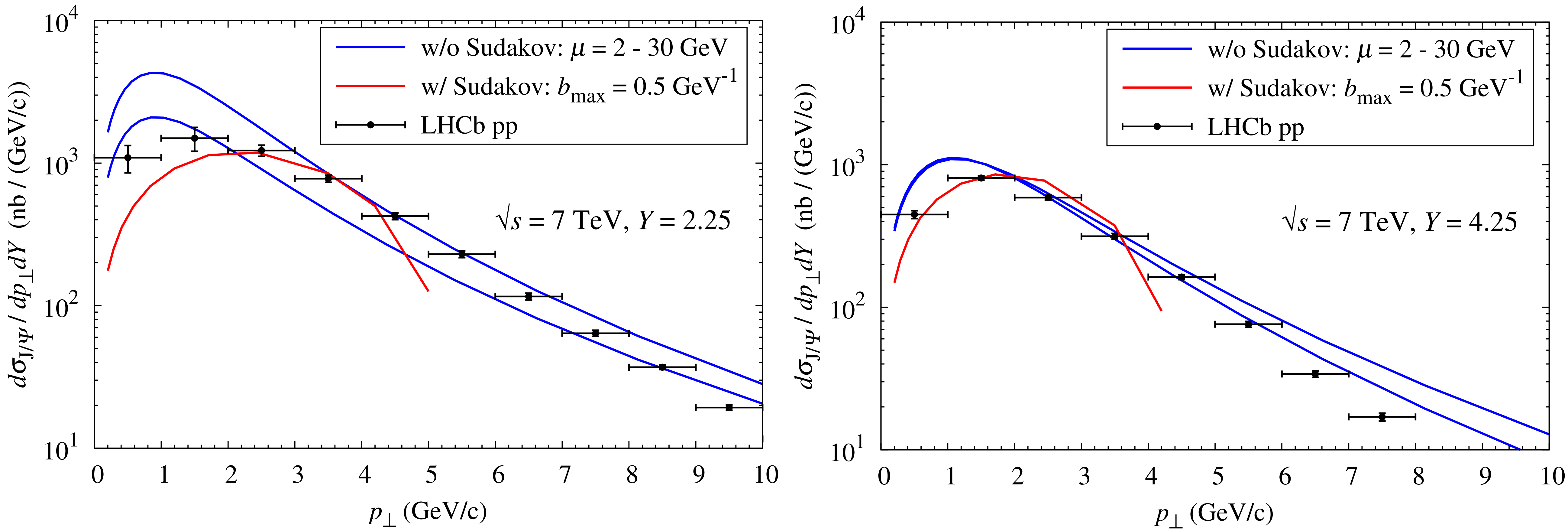
# The spectrum of soft gluons emission

$$F_{\rm Sud}(M,l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp\cdot l_\perp} e^{-S_{\rm Sud}(M,b_\perp)} x_1 G\left(x_1, \frac{c_0}{b_\perp}\right)$$



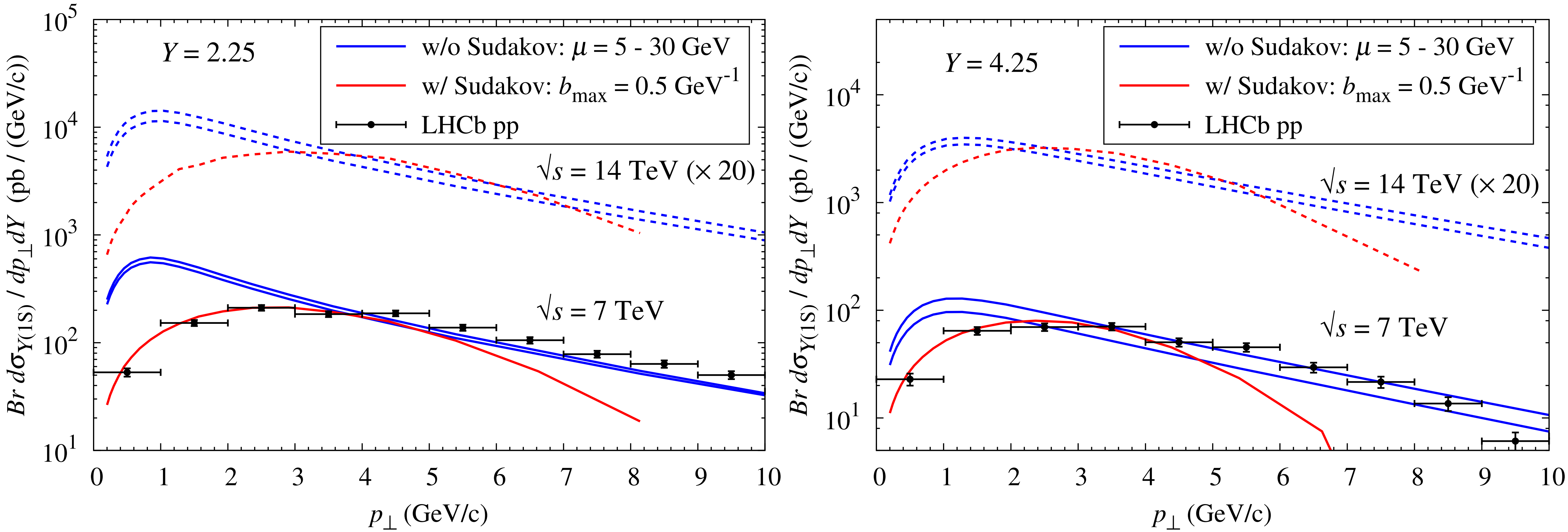

- Upsilon production : a large broadening of the distribution is expected.
- Soft gluon emissions carry away pt of the quarkonium about 1–2GeV.

# J/ψ in pp



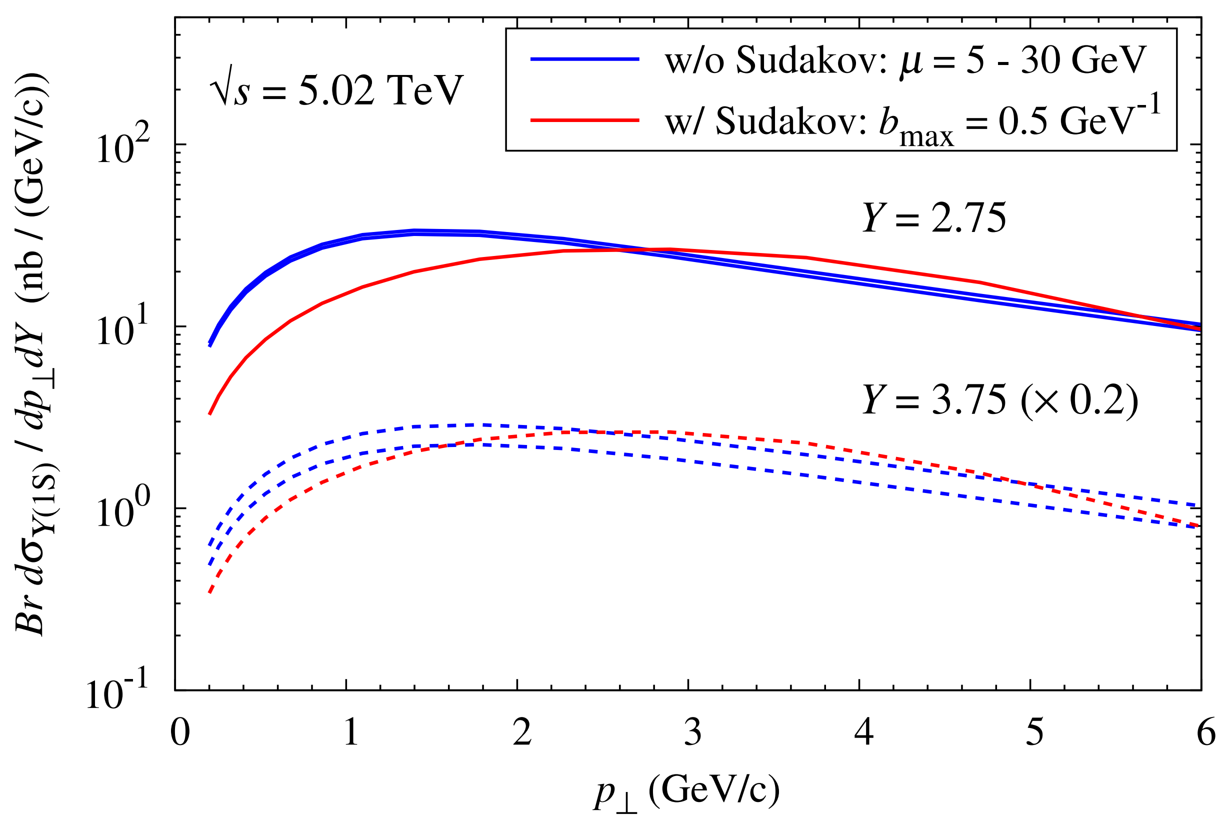

- The results are roughly in agreement with the data.
- The Sudakov resummation is not applicable at pt > 4, 5GeV.
- When pt ~ M, we should switch to the fixed order CGC calculation, which is responsible for the large pt region of the spectrum.

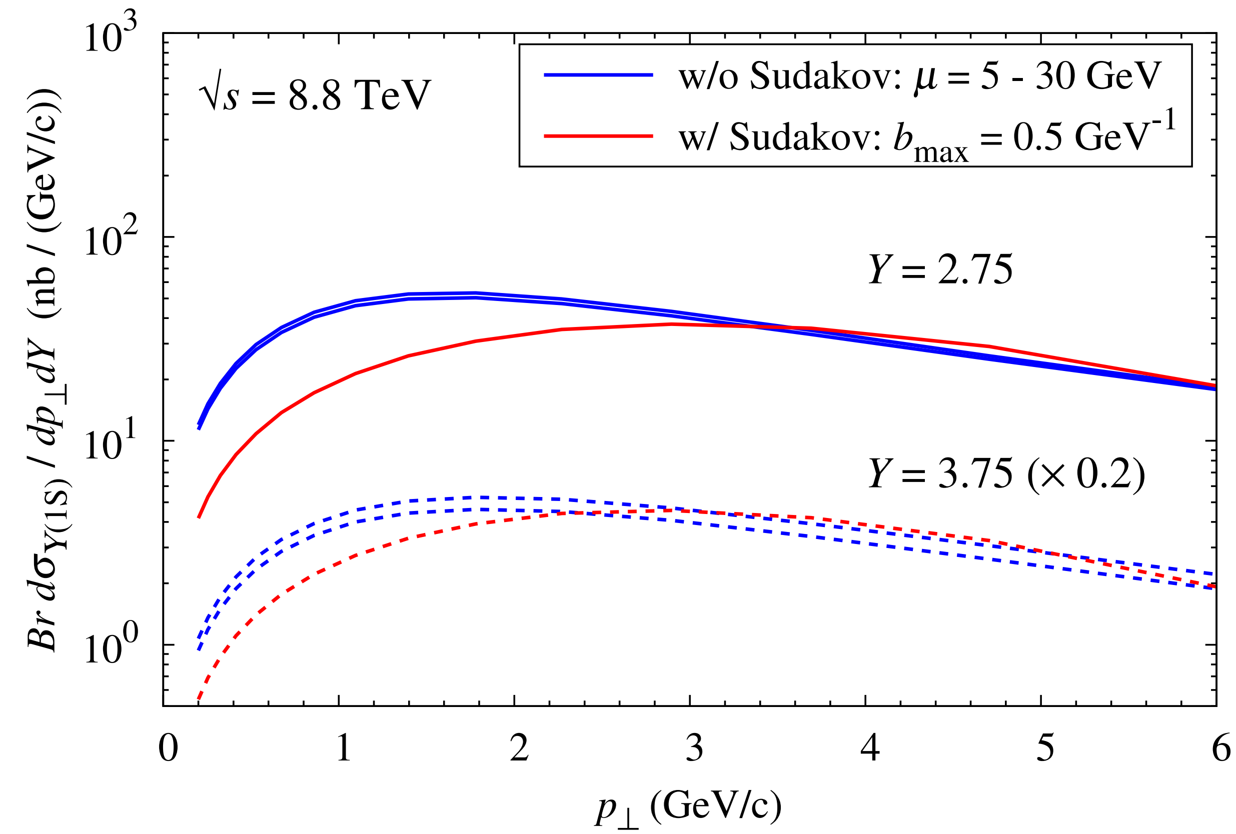
# Υ(1S) in pp




- We can reproduce the data points very well due to the gluon cascade.
- The peak is located at pt = 1 GeV → 3 GeV (w/ Sudakov).
- The Sudakov factor in association with large M gives additional strong broadening of the pt distributions for Upsilon production.

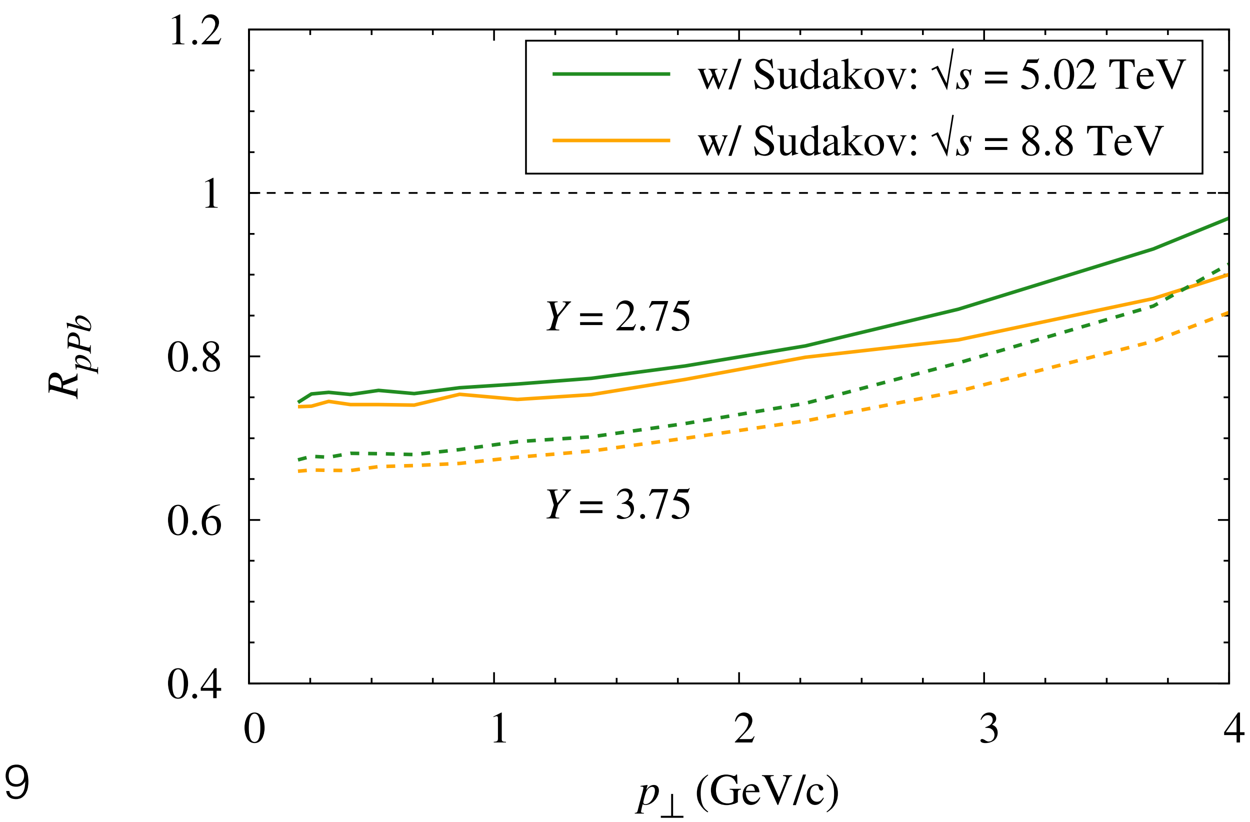
# Predictions of Υ(1S) in pPb




The initial condition $Q^2_{sA,0} = 3Q^2_{s,0}$

- The Sudakov effect in pA collisions is less pronounced as compared to pp.
- Nuclear modification factor can be modest at low pt.



# Summary

- Heavy quark pair production in pA can probe the dense gluon structure.
- We have demonstrated both the small-x resummation and low-pt resummation are essential to understand the LHC data → NLO corrections are not small.
- The effect of the Sudakov factor

| J/ψ in pp | Υ in pp | Υ in pPb |
|---|---|---|
| △ | ◎ | △ |

- The large-pt broadening of quarkonium due to initial soft gluon emission could be seen in the other model such as CGC+NRQCD.