# Quarkonium production in p+p and p+A collisions

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Based on works done with:
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6th workshop of the APS Topical Group on Hadronic Physics,
Baltimore, MD, April 10th, 2015

# Historical review of quarkonium production

0. **1974 Discovery of $J/\psi$**
   E598 Collaboration (1974)
   SLAC-SP-017 Collaboration (1974)

1. **1974 - CSM and CEM**

   Color Singlet Model: fine until 1994, $\psi'$ surplus — Einhorn, Ellis (1975), Chang (1980), Berger, Jone (1981), …

   Color Evaporation Model: (see Ramona Vogt's talk) — Fritzsch (1977), Halzen (1977), …

2. **1994 - NRQCD**

   ① 1994-2004 NRQCD@LO — Bodwin, Braaten, Lepage, 9407339, …

   √ Self consistent, explain $\psi'$ surplus

   × Polarization puzzle, double charmonium, …

   ② 2005-2014 NRQCD@NLO — Zhang, Gao, Chao, 0506076, …

   √ B-factories and hadron colliders, separately

   × High $p_T$, low $p_T$, …

It was proved that both CSM and CEM are special cases in NRQCD framework.

Bodwin, Braaten, Lee, 0504014

3. **2014 -**

   High $p_T$: collinear factorization, SCET — Kang, Qiu, Sterman, 1109.1520; Fleming, Leibovich, Mehen, Rothstein 1207.2578; Kang, YQM, Qiu, Sterman, 1401.0923, …

   (see Hong Zhang's talk)

   Low $p_T$: CGC+NRQCD — Kang, YQM, Venugopalan, 1309.7337; Qiu, Sun, Xiao, Yuan, 1310.2230; YQM, Venugopalan , 1408.4075; YQM, Venugopalan, Zhang, 1503.07772

# Outline

I. Success and failure of NLO NRQCD calculation

II. CGC+NRQCD framework

III. Quarkonium production at p+p

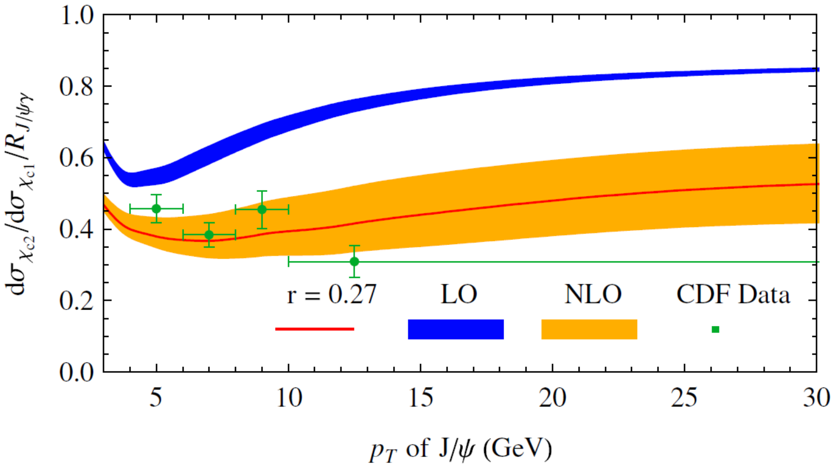
IV. Quarkonium production at p+A

# A successful example: $\chi_{cJ}$@hadron colliders

- **NRQCD framework:** (see Hong Zhang and Thomas Mehen's talk)

- **$\chi_{cJ}$ production:** $d\sigma_{\chi_{cJ}} \approx d\hat{\sigma}_{{}^3P_J^{[1]}} \langle O\left({}^3P_0^{[1]}\right)\rangle + (2J+1) d\hat{\sigma}_{{}^3S_1^{[8]}} \langle O\left({}^3S_1^{[8]}\right)\rangle$
  - $\langle O\left({}^3P_0^{[1]}\right)\rangle$: can be determined by potential model
  - $\langle O\left({}^3S_1^{[8]}\right)\rangle$: the only free parameter, fit from Tevatron $d\sigma_{\chi_{c2}}/d\sigma_{\chi_{c1}}$ data

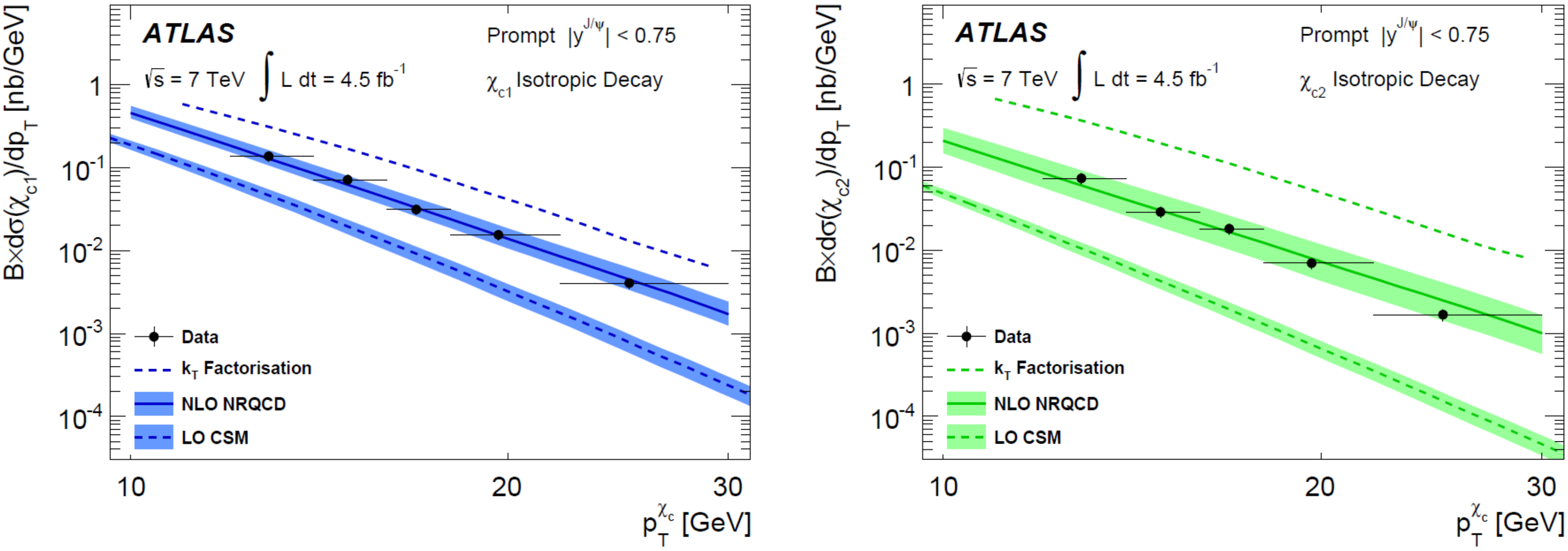
YQM, Wang, Chao, 1002.3987



# Predictions

## ➢ Comparison with new data

ATLAS, 1404.7035



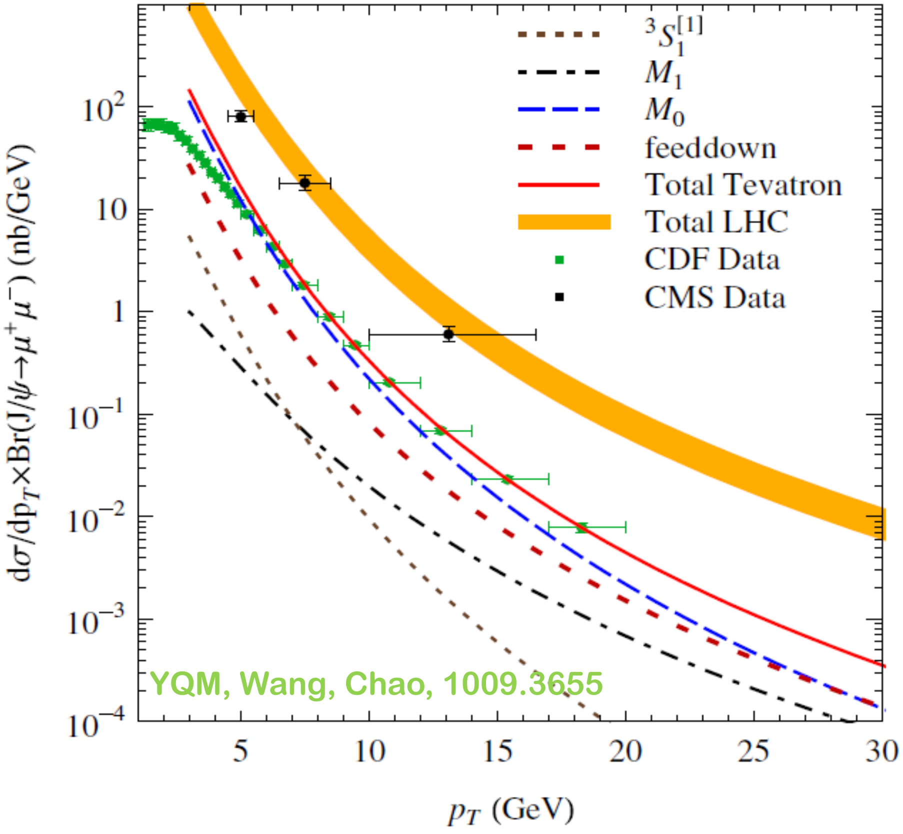

So far, the best **PREDICTION** in quarkonium production field!

# Low $p_T$ quarkonium production

- **Moderate $p_T$ region: fine**

- **Small $p_T$ region**

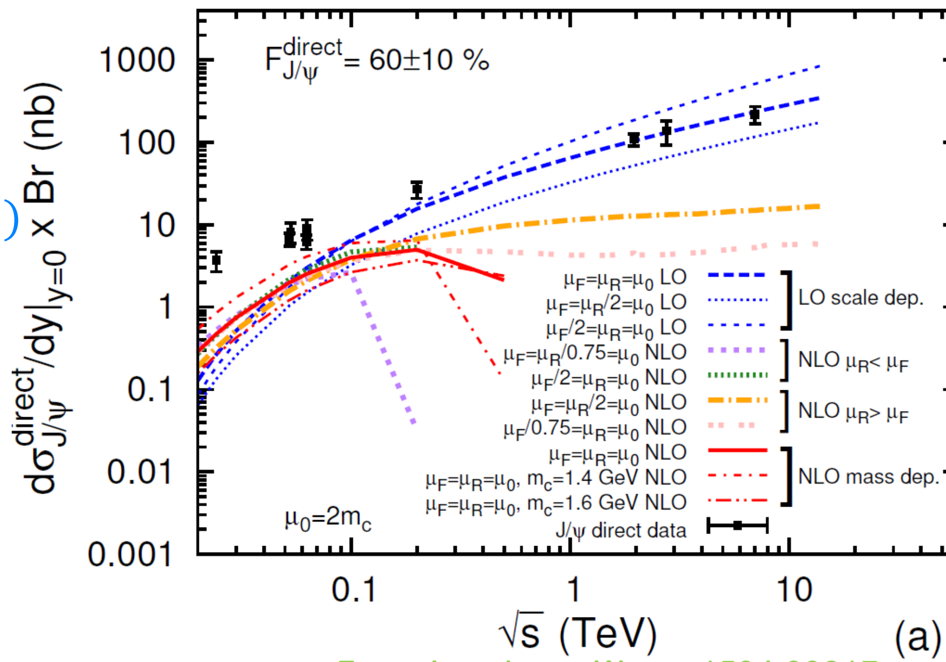
  - Far from understood
  - When $p_T \ll m_H$, fixed order gives $\frac{d\sigma}{dp_T} \propto \frac{1}{p_T}$, while data goes to zero
  - Dominate the cross section



# Small $p_T$ v.s. small $x$

- **Sudakov double logarithm** Berger, Qiu, Wang, 0404158; Sun, Yuan, Yuan, 1210.3432
  - Sudakov resummation of $\log^2(p_T/m_H)$ is needed at small $p_T$ regime
  - This resummation itself is still hard to explain the $J/\psi$ data

- **Total cross goes to negative at high energy**
  - Total cross section is free of $\log(p_T/m_H)$
  - The only large logarithm is $\log(x)$
  - Small-$x$ effect can be important!!!




Feng, Lansberg, Wang, 1504.00317

# CGC effective field theory

McLerran, Venugopalan, 9309289

## ➢ Color Glass Condensate

◊ A tool to deal with small-$x$ physics

◊ An effective field theory of QCD: separate $x < x_0$ configuration from $x > x_0$ configuration

◊ For small-$x$ configuration: large saturation scale, perturbatively calculable

◊ For large-$x$ configuration: $\Delta t^+ \sim \frac{1}{k^-} = \frac{2k^+}{k_\perp^2} \sim x$, life time of parton is long, determined before the collision, randomly distributed, CGC average

◊ JIMWLK evolution: guarantees the separation point $x_0$ independence

# CGC+CEM

Fujii, Gelis, Venugopalan, 0603099
Fujii, Watanabe, 1304.2221
Ducloue, Lappi, Mantysaari, 1503.02789

## ➢ CGC: production of $c\bar{c}$-pair

◊ Using CGC to calculate gluon distribution

◊ Small $x$ resummation is accounted by solving JIMWLK or BK evolution equations

## ➢ CEM:

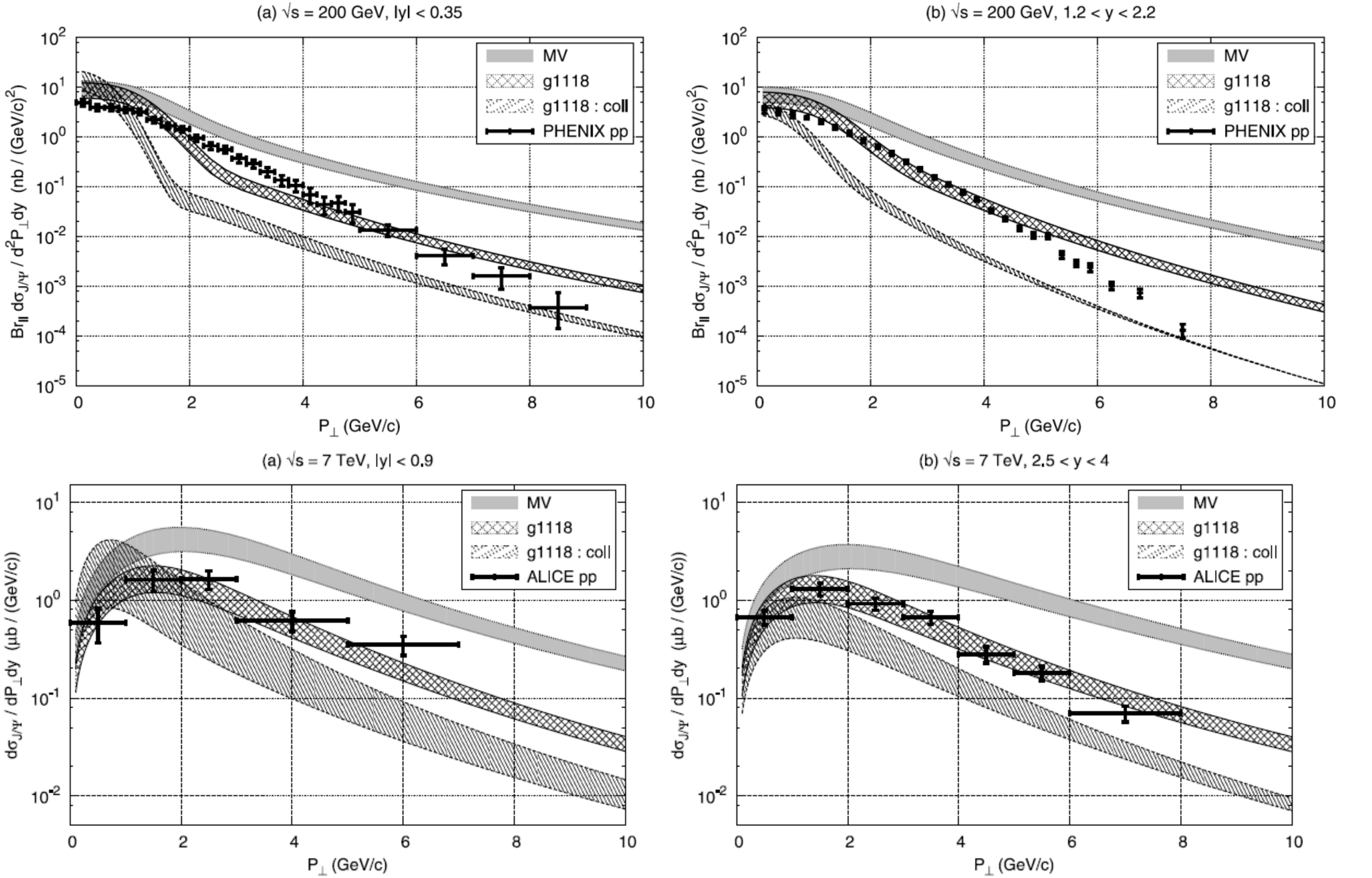
◊ A fixed fraction to become $J/\psi$ if the invariant mass of $c\bar{c}$-pair is below the $D$-meson threshold

$$\frac{d\sigma_{J/\psi}}{d^2\boldsymbol{p}_\perp dy} = F_{J/\psi} \int_{4m_c^2}^{4m_D^2} dM^2 \frac{d\sigma_{c\bar{c}}}{dM^2 d^2\boldsymbol{p}_\perp dy}$$

# CGC+CEM: p+p

**Bad agreement:**

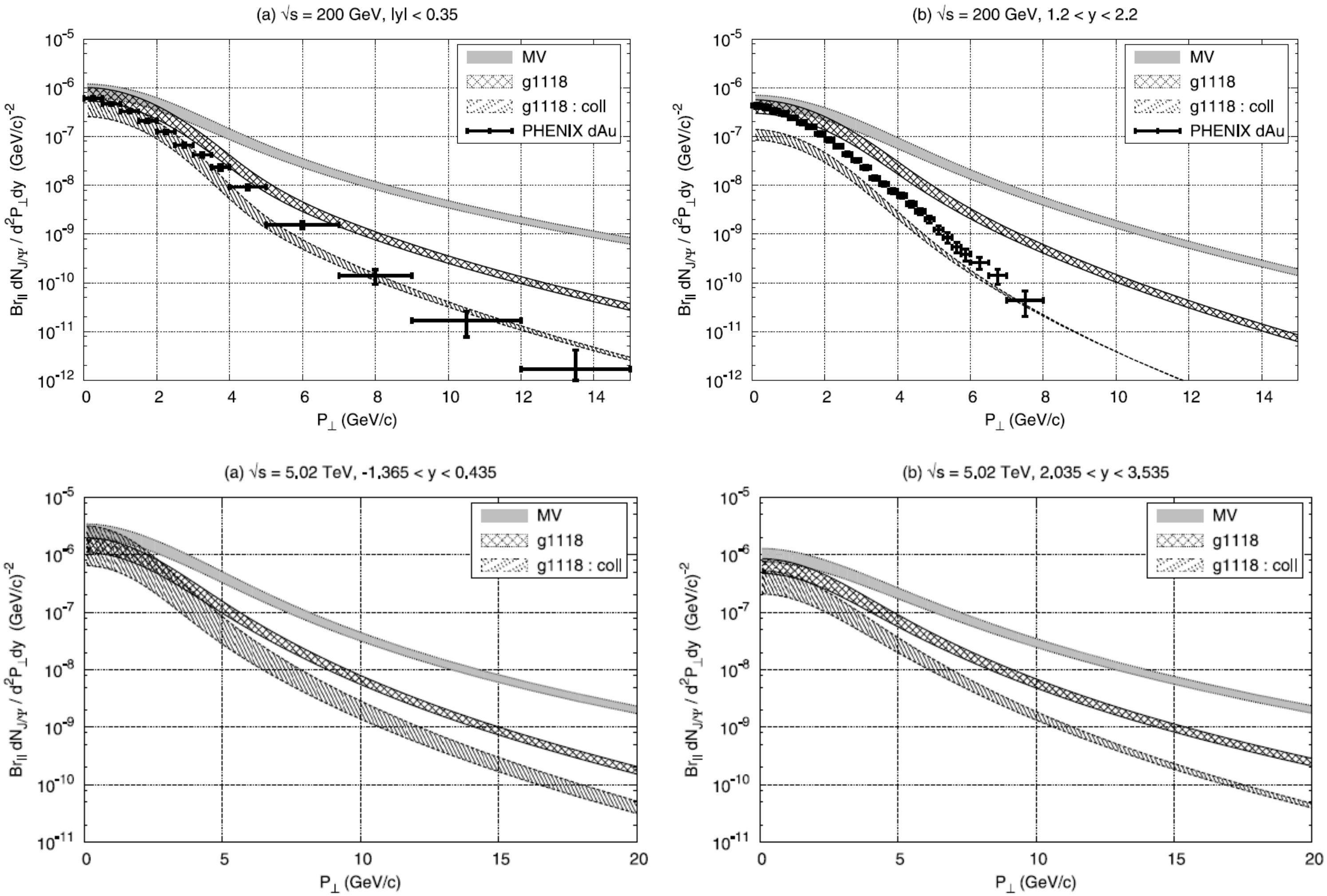
Fujii, Watanabe, 1304.2221



# CGC+CEM: p+A

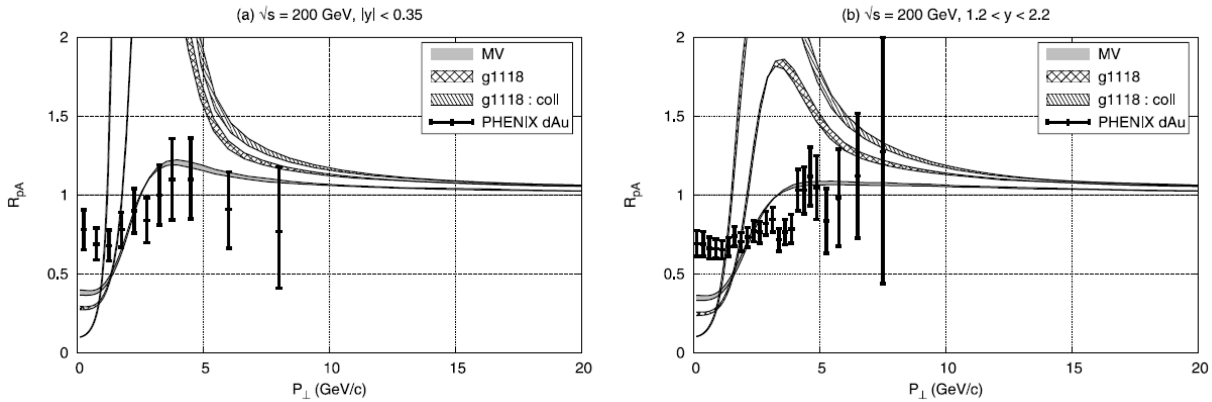
**Bad agreement:**

Fujii, Watanabe, 1304.2221



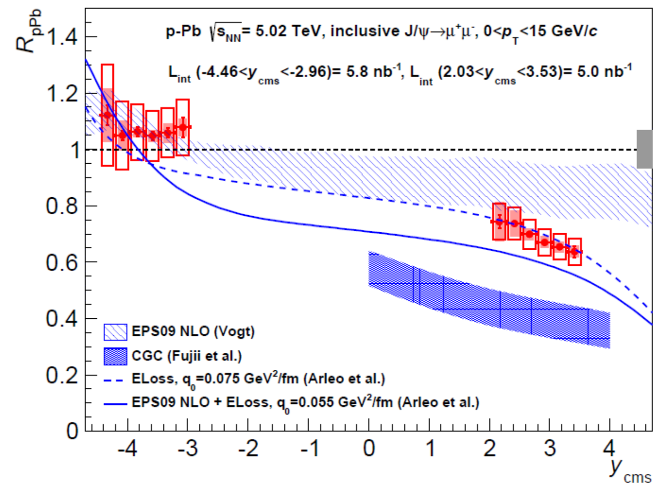
# CGC+CEM: $R_{pA}$

- **RHIC:**




Fujii, Watanabe, 1304.2221

- **LHC:**
  - ◊ Disagree with data
  - ◊ Rule out the CGC method???



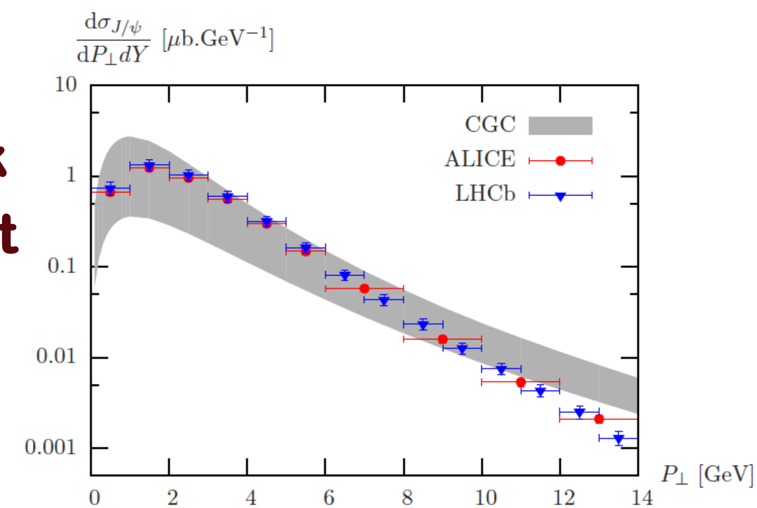

ALICE, 1308.6726

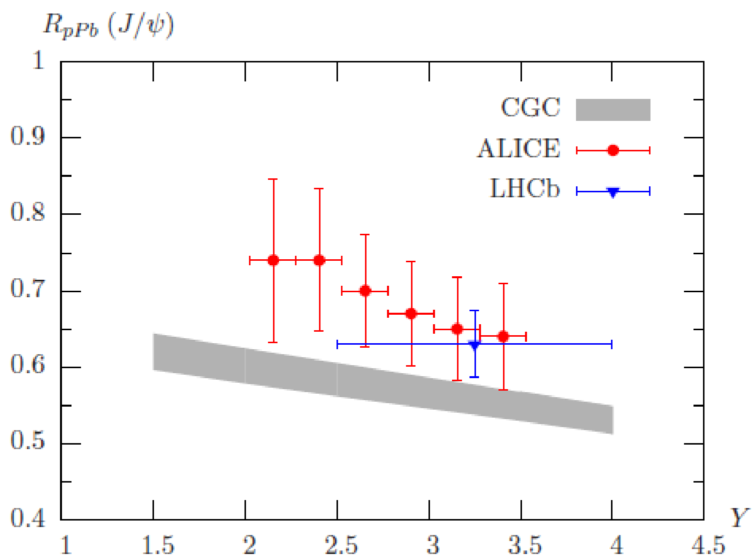
are also shown. Within our uncertainties, both the model based on shadowing only and the coherent energy loss approach are able to describe the data, while the CGC-based prediction overestimates the observed suppression. None of these models include a suppression related to the break-up of the $c\bar{c}$ pair.

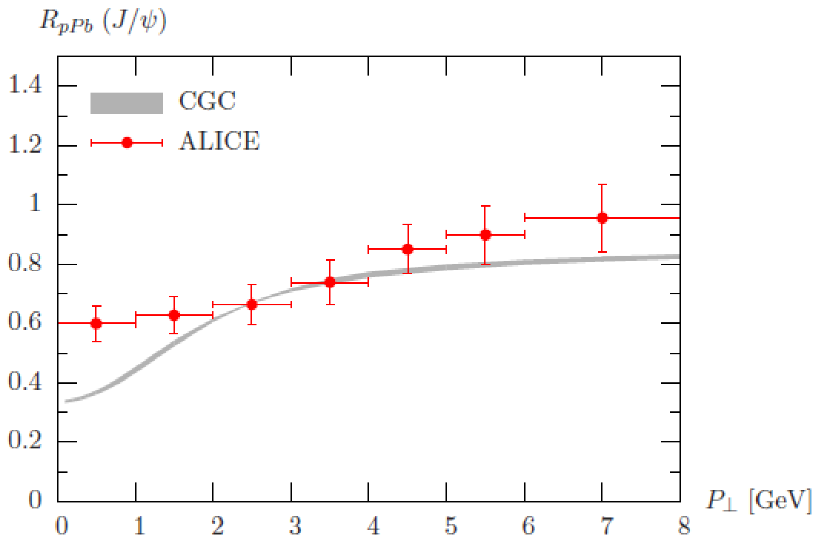
# CGC+CEM: improved

Ducloue, Lappi, Mantysaari, 1503.02789

- Using the collinear "hybrid" frame work
- Introduce impact-parameter-dependent initial condition
- Marginally describe data



# CGC+NRQCD

Kang, YQM, Venugopalan, 1309.7337
Qiu, Sun, Xiao, Yuan, 1310.2230

- **CGC: production of $c\bar{c}$-pair**
  - Using CGC to calculate gluon distribution
  - Small $x$ resummation is accounted by solving JIMWLK or BK evolution equations

- **NRQCD factorization:**

Control the formation of quarkonium from $Q\bar{Q}$-pair

$$d\sigma_H = \sum_\kappa d\hat{\sigma}^\kappa \langle \mathcal{O}_\kappa^H \rangle$$

- Via many channels, both CS and CO

# Dilute-dense formula

Kang, YQM, Venugopalan, 1309.7337

- **Short distance for CS channels in CGC**

$$\frac{d\hat{\sigma}^{\kappa}}{d^2\boldsymbol{p}_\perp dy} \overset{\text{CS}}{=} \frac{\alpha_s \pi R_A^2}{(2\pi)^7 (N_c^2-1)} \int_{\boldsymbol{k}_{1\perp}} \frac{\varphi_{p,y_p}(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2} \int_{\boldsymbol{\Delta}_\perp, \boldsymbol{r}_\perp, \boldsymbol{r}'_\perp} e^{-i(\boldsymbol{p}_\perp - \boldsymbol{k}_{1\perp})\cdot\boldsymbol{\Delta}_\perp} \times \left( Q_{\frac{\boldsymbol{r}_\perp}{2}, \boldsymbol{\Delta}_\perp + \frac{\boldsymbol{r}'_\perp}{2}, \boldsymbol{\Delta}_\perp - \frac{\boldsymbol{r}'_\perp}{2}, -\frac{\boldsymbol{r}_\perp}{2}} - D_{\boldsymbol{r}_\perp} D_{\boldsymbol{r}'_\perp} \right) \Gamma_1^{\kappa},$$

- **Short distance for CO channels in CGC**

$$\frac{d\hat{\sigma}^{\kappa}}{d^2\boldsymbol{p}_\perp dy} \overset{\text{CO}}{=} \frac{\alpha_s (\pi R_A^2)}{(2\pi)^7 (N_c^2-1)} \int_{\boldsymbol{k}_{1\perp}, \boldsymbol{k}_\perp} \frac{\varphi_{p,y_p}(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2} \mathcal{N}(\boldsymbol{k}_\perp) \mathcal{N}(\boldsymbol{p}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_\perp) \Gamma_8^{\kappa}$$

- **Scope of application:**
  - High energy p+A or p+p collision
  - Quarkonium produced in forward rapidity region

# Comparison with other methods

## ➢ Quasi-classical approximation

Kang, YQM, Venugopalan, 1309.7337

$$Q_{x_\perp x'_\perp y'_\perp y_\perp} \approx D_{x_\perp - y_\perp} D_{x'_\perp - y'_\perp} - \frac{\ln(D_{x_\perp - y'_\perp} D_{x'_\perp - y_\perp}) - \ln(D_{x_\perp - x'_\perp} D_{y_\perp - y'_\perp})}{\ln(D_{x_\perp - y_\perp} D_{x'_\perp - y'_\perp}) - \ln(D_{x_\perp - x'_\perp} D_{y_\perp - y'_\perp})} \times \left( D_{x_\perp - y_\perp} D_{x'_\perp - y'_\perp} - D_{x_\perp - x'_\perp} D_{y_\perp - y'_\perp} \right).$$

$$\frac{d\sigma^{J/\psi}}{d^2 \boldsymbol{p}_\perp dy} \overset{\text{CSM}}{=} (\pi R_A^2) x_p f_{p/g}(x_p, Q^2) \int_{\boldsymbol{\Delta}_\perp, \boldsymbol{r}_\perp, \boldsymbol{r}'_\perp} \frac{e^{i \boldsymbol{p}_\perp \cdot \boldsymbol{\Delta}_\perp}}{4(2\pi)^4} \Phi(r_\perp) \Phi(r'_\perp) \times \frac{4 \boldsymbol{r}_\perp \cdot \boldsymbol{r}'_\perp}{(\boldsymbol{r}_\perp + \boldsymbol{r}'_\perp)^2 - 4\Delta_\perp^2} \left\{ e^{-\frac{Q_s^2}{16}[(\boldsymbol{r}_\perp - \boldsymbol{r}'_\perp)^2 + 4\Delta_\perp^2]} - e^{-\frac{Q_s^2}{8}(r_\perp^2 + {r'_\perp}^2)} \right\}$$

Our CS channel reproduce the work: Dominguez, Kharzeev, Levin, Mueller, Tuchin, 1109.1250

## ➢ CEM has only CO contributions in large $N_c$ limit

Only dipoles are involved in CEM calculation. No quadrupole.

# Parameters for p+p

## An approximation for quadrupole

YQM, Venugopalan, 1408.4075

$$Q_{x_\perp x'_\perp y'_\perp y_\perp} \approx D_{x_\perp - x'_\perp} D_{y'_\perp - y_\perp} - D_{x_\perp - y'_\perp} D_{x'_\perp - y_\perp} + D_{x_\perp - y_\perp} D_{x'_\perp - y'_\perp}$$
$$+ \frac{1}{2} (D_{x_\perp - y'_\perp} D_{x'_\perp - y_\perp} - D_{x_\perp - y_\perp} D_{x'_\perp - y'_\perp})$$
$$\times (D_{x'_\perp - y_\perp} - D_{y'_\perp - y_\perp} + D_{y'_\perp - x_\perp} - D_{x'_\perp - x_\perp})$$

- ✓ Self-consistent: exact when any two adjacent positions coincide
- ✓ Checked: a good approximation to the quadrupole

## Dipole distributions:

- Dipole distribution at initial scale ($x = x_0 = 0.01$): using MV model
- All parameters are fixed from fits to the HERA DIS data

Albacete, Dumitru, Fujii, Nara,1209.2001

- $R_p = 0.48$fm to match with collinear PDF at large $x$

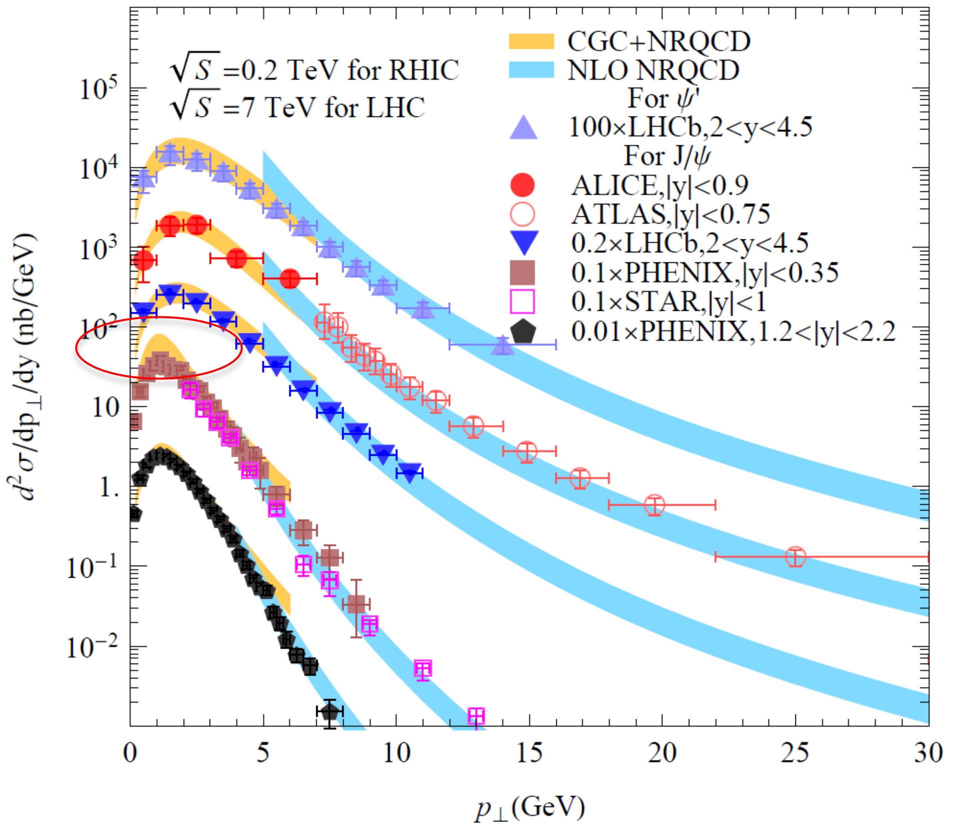
## NRQCD CO matrix elements

- Taken from fitting high $p_T$ data

Chao,YQM,Shao,Wang,Zhang,1201.2675

YQM, Venugopalan, 1408.4075

- **Agree with all small $p_T$ data**




- ✓ Evolution of peaks agree!
- ✓ At moderate $p_T$ region, smoothly matches with pQCD calculation: NLO NRQCD

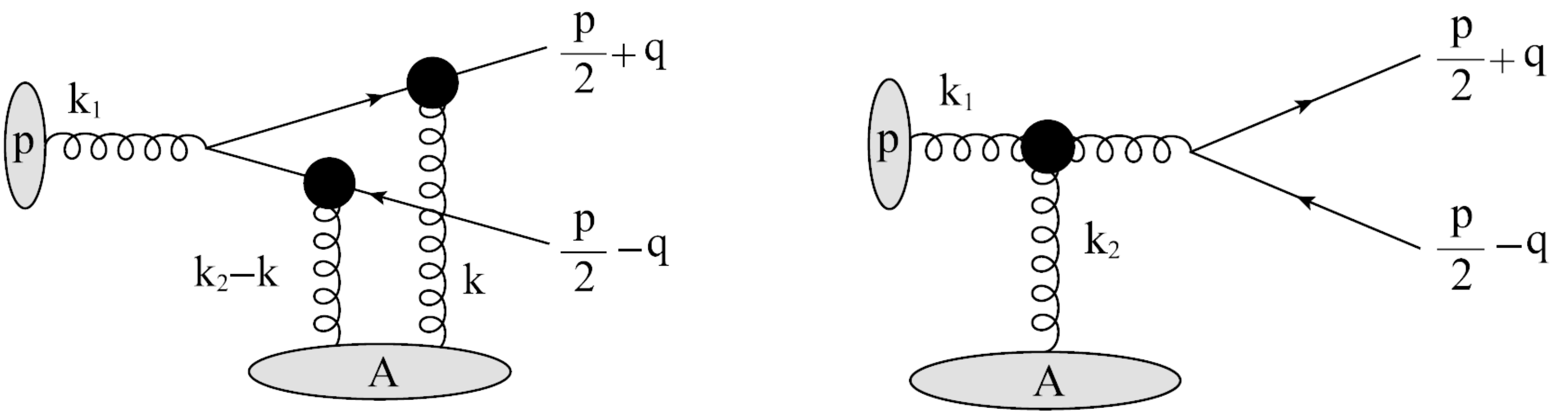
$J/\psi$ production at all $p_T$ region can be described now!

**RHIC data at central rapidity: agreement is not very good**

**As expected: CGC+NRQCD is good for small $x$ and forward rapidity**

# $J/\psi$@p+p: $p_T$ dependence (2)

➢ **LO formula can only describe small $p_T$ region data!**



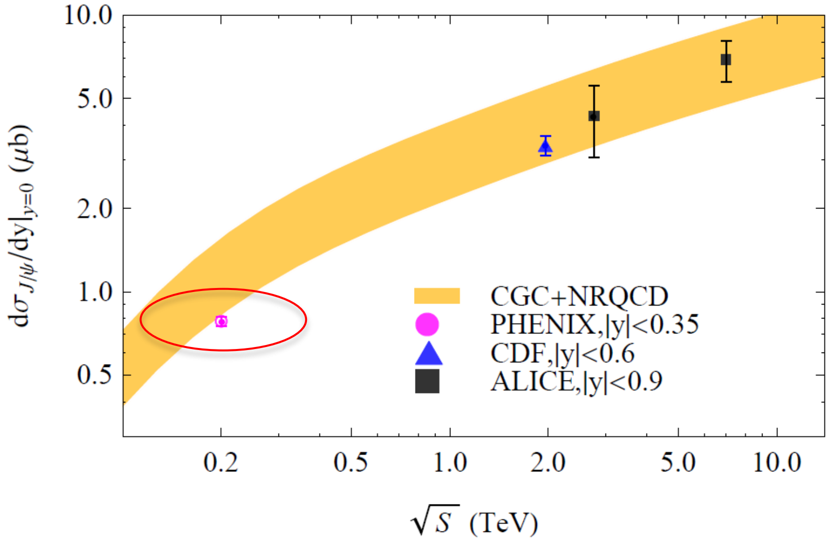

- ◊ No final state radiation
- ◊ Correct only if initial state radiation dominate ($p_T$ can not be much larger than the saturation scale)

➢ **NLO calculation is needed for CGC+NRQCD formula to give a consistent description of full $p_T$ region**

# $J/\psi$ @ p+p: $\sqrt{S}$ dependence

YQM, Venugopalan, 1408.4075

- **Good agreement with data**




  - Worst agreement with RHIC data at central rapidity

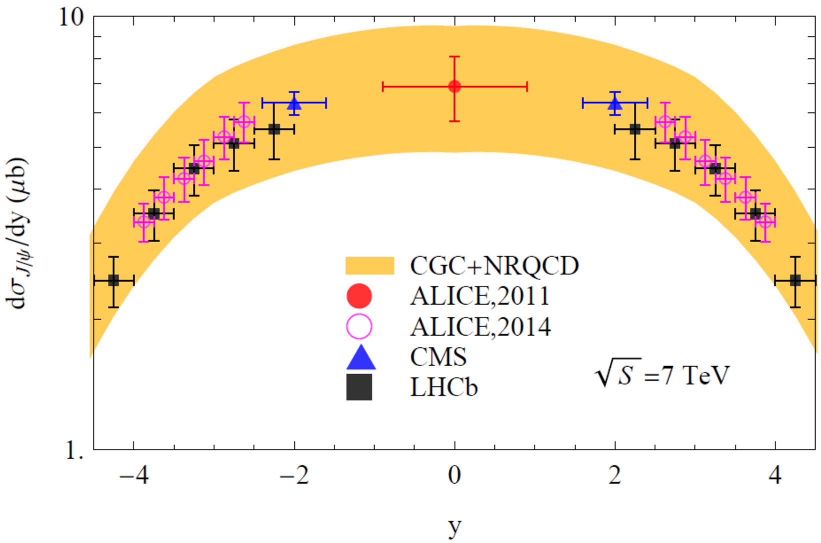
- **CS contribution is found to be only 10%**

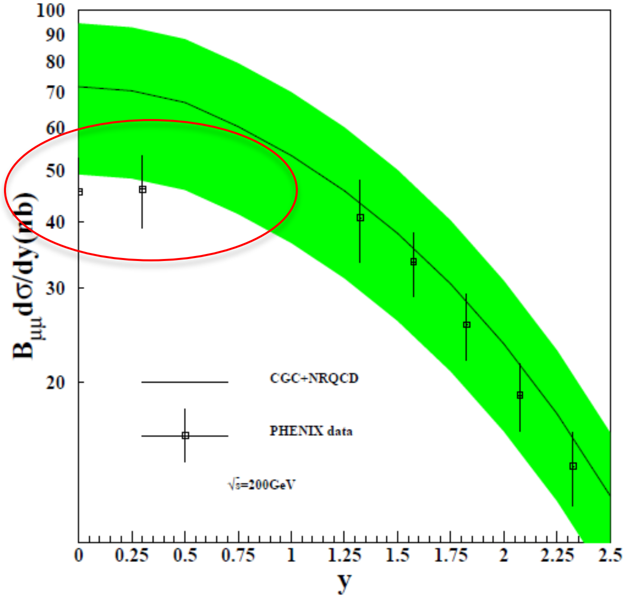
  - Large $p_\perp$: suppressed by $\frac{1}{p_T^2}$
  - Small $p_\perp$: suppressed by phase space

# $J/\psi$ @ p+p: $y$ dependence

- **Good agreement with data**

YQM, Venugopalan, 1408.4075




◊ Worst agreement with RHIC data at central rapidity

# Parameters for p+A

YQM, Venugopalan, Zhang, 1503.07772

- **Two free parameters: $Q_{s0,A}$ and $R_A$**

- **Self-consistent condition: $R_{pA} \to 1$ at high $p_T$ limit**

$$R_{pA} = \frac{d\sigma_{pA}}{A \times d\sigma_{pp}} \xrightarrow{\text{high } p_\perp} \frac{R_A^2}{AR_p^2} \frac{\widetilde{N}_{Y_A}^A(\boldsymbol{p}_\perp)}{\widetilde{N}_{Y_p}^A(\boldsymbol{p}_\perp)} \approx \frac{R_A^2}{AR_p^2} \frac{Q_{s0,A}^{2\gamma}}{Q_{s0,p}^{2\gamma}} = 1$$

  - ◊ $\gamma = 1$ in MV model, $Q_{s0,p}$ and $R_p$ are known from p+p case

- $Q_{s0,A}^2 = N \times Q_{s0,p}^2$

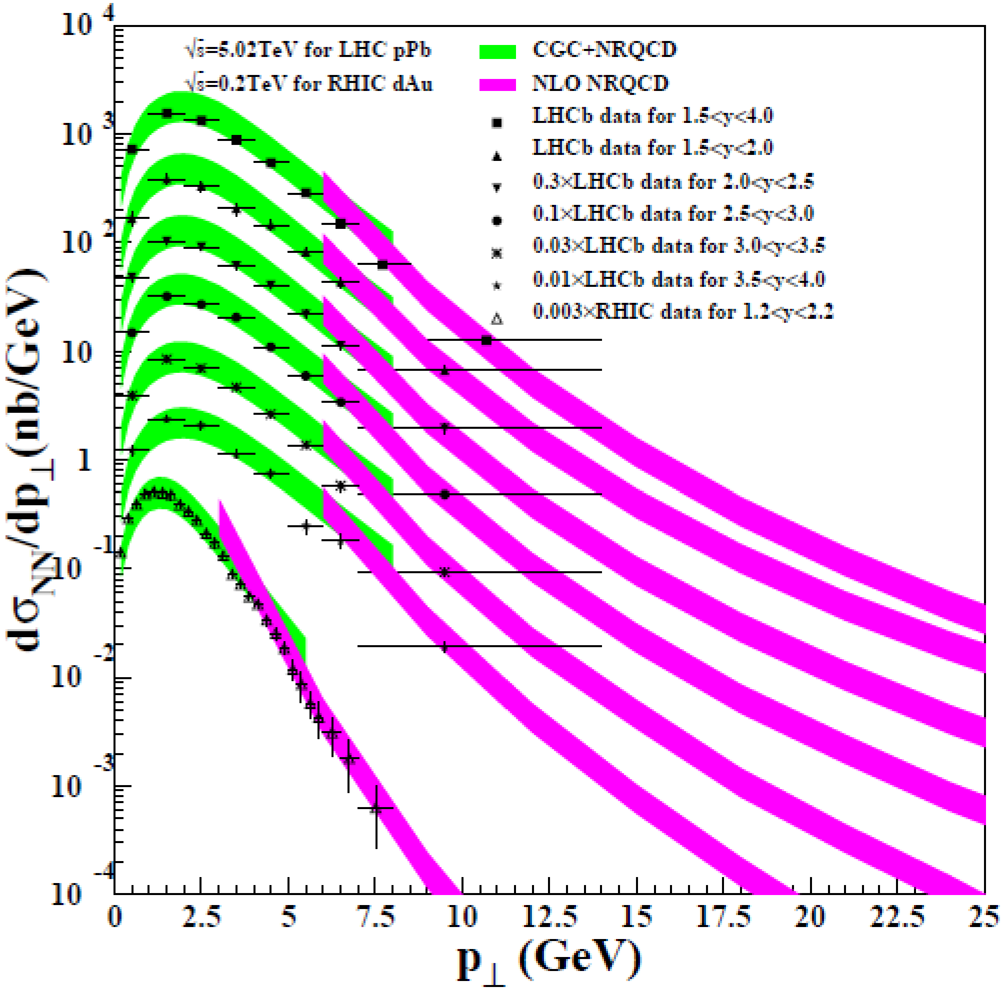
Dusling, Gelis, Lappi, Venugopalan, 0911.2720

  - ◊ Fitting HERA DIS data, $N \approx 3$ for $\gamma = 1.113$, and $N \approx 1.5$ for $\gamma = 1$
  - ◊ Set $N = 2$ as a tentative choice

# $J/\psi$@p+A: $p_T$ dependence

YQM, Venugopalan, Zhang, 1503.07772

- **Agree with all small $p_T$ data, similar to p+p case**



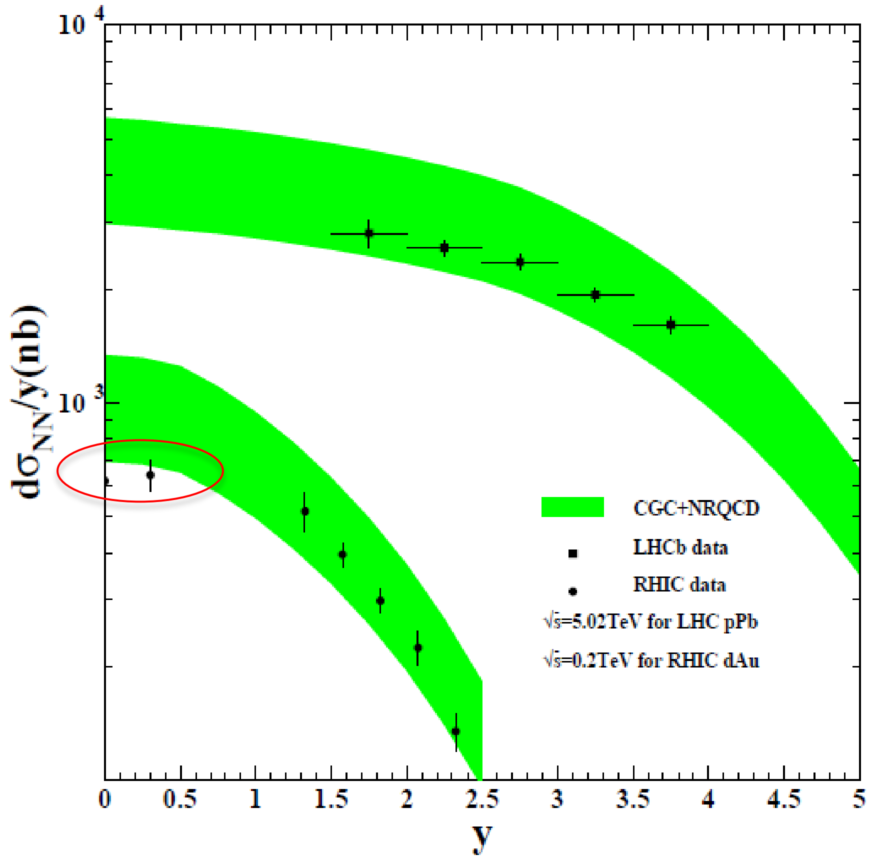

- ✓ Evolution of peaks agree!
- ✓ At moderate $p_T$ region, smoothly matches with pQCD calculation: NLO NRQCD

$J/\psi$ production at all $p_T$ region can be described

# $J/\psi$ @ p+A: $y$ dependence

- **Good agreement with data**

YQM, Venugopalan, Zhang, 1503.07772




◊ Worst agreement with RHIC data at central rapidity

# $R_{pA}$

YQM, Venugopalan, Zhang, 1503.07772

- **Many uncertainties can be cancelled in the ratio**

$$R_{pA} = \frac{d\sigma_{pA}}{A \times d\sigma_{pp}}$$

- **Calculate $R_{pA}$ for each NRQCD channel**

  - Combining curves of all channels to provide the prediction for $J/\psi$
  - Results are independent of NRQCD matrix elements

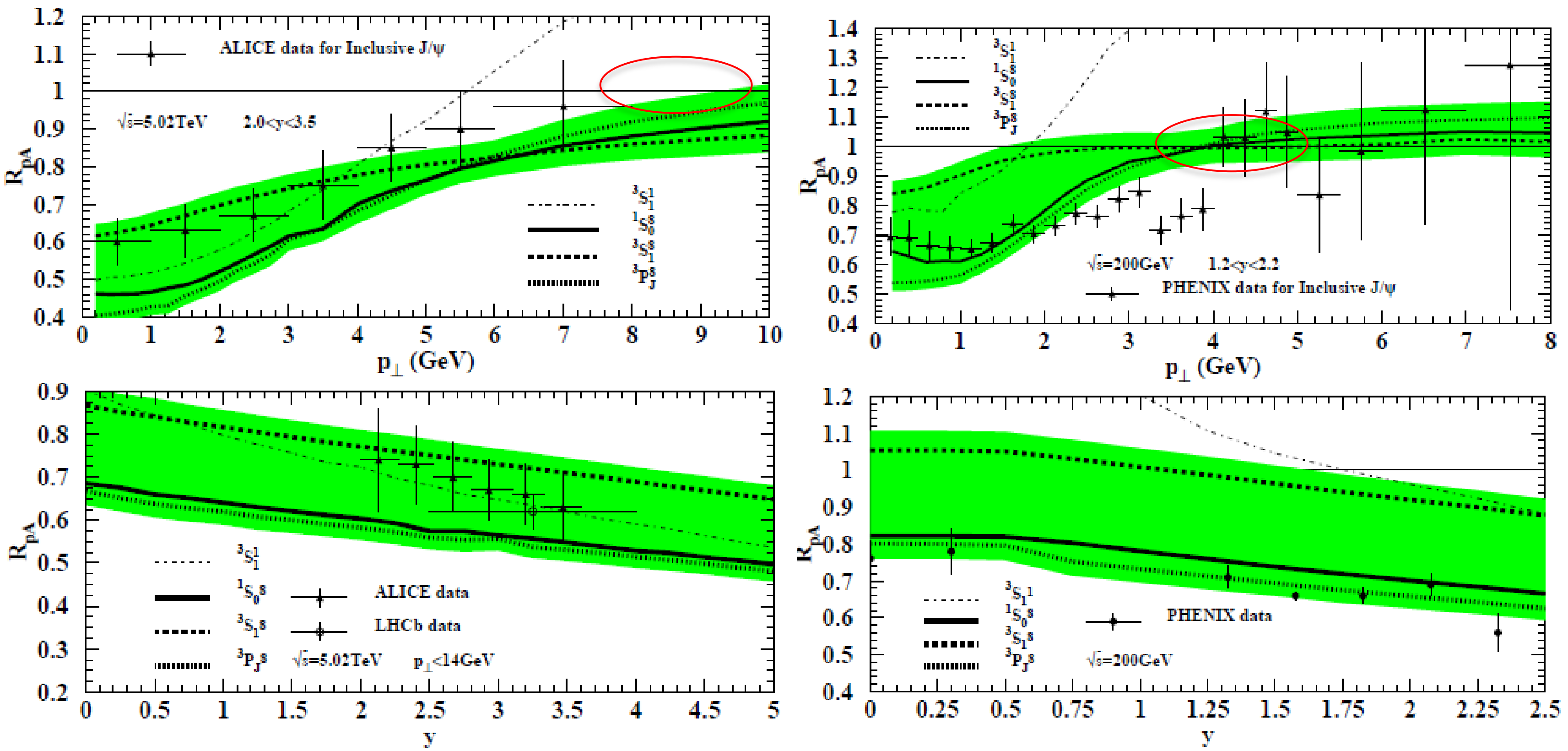
Note: By releasing the power counting for NRQCD matrix element, NRQCD factorization gives the most general formula for quarkonium production

$R_{pA}$ calculated in this way is almost $J/\psi$ production model independent

# $R_{pA}$: $p_T$ and $y$ dependence

YQM, Venugopalan, Zhang, 1503.07772

## ➢ Agreement with data




✓ $R_{pA} \to 1$ **at** $p_T \approx 9$**GeV at LHC and** $p_T \approx 4$**GeV at RHIC, both agree**

# Summary

- $J/\psi$ production at small $p_T$ region is sensitive to small-$x$ resummation
- Good description for $J/\psi$ production at both p+p and p+A collisions are obtained in the CGC+NRQCD framework
- Prediction for $R_{pA}$ is almost $J/\psi$ production model independent. The agreement provides a strong evidence for small-$x$ resummation effects for quarkonium production
- Apply for other quarkonium states is possible

  Plenty of data at LHC

- NLO calculation in CGC framework is important and needed!!

# Thank you!