Theories for heavy quarkonium production

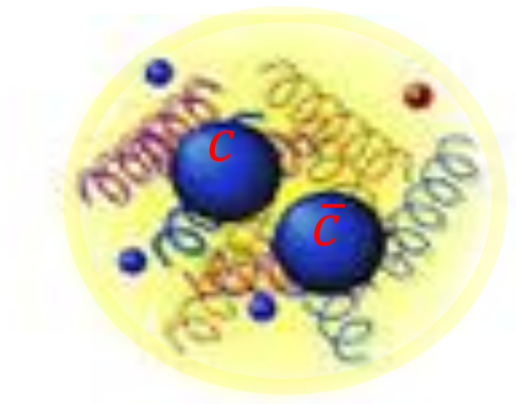
Yan-Qing Ma

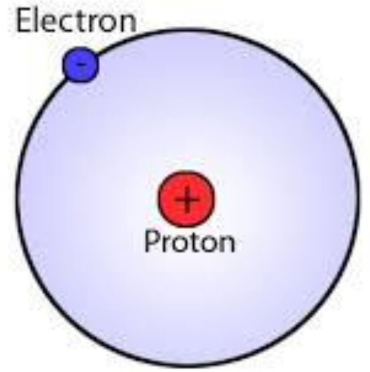
Peking University

QCD study group 2016,
Shanghai Jiao Tong University, Shanghai, Apr. 2nd, 2016

- **Bound state of $Q\bar{Q}$ pair under strong interaction**

Eg: $J/\psi\ \ \psi', \chi_{cJ}, \Upsilon(nS), \chi_{bJ}(nP) \cdots$





- ✓ **The simplest system in QCD: two-body problem**
- ✓ **"Hydrogen atom in QCD", "an ideal laboratory in QCD"**

Property

- **A non-relativistic QCD system: $v \ll 1$**

  Charmonium: $v^2 \approx 0.3$

  Bottomonium: $v^2 \approx 0.1$

- **Multiple well-separated scales :**

$$\left.\begin{array}{ll} \text{Quark mass:} & M \\ \text{Momentum:} & Mv \\ \text{Energy:} & Mv^2 \end{array}\right\} \quad M \gg Mv \gg Mv^2 \sim \Lambda_{QCD}$$

- **Involving both perturbative and nonperturbative physics**

- **Production: ideal to understand hadronization, to study QGP**

Historical theories for quarkonium production

1. 1974 - Discovery of J/ψ, CSM and CEM

CSM: IR divergence, ψ' surplus — Einhorn, Ellis (1975), Chang (1980), Berger, Jone (1981), ...

CEM: wrong for ratio — Fritzsch (1977), Halzen (1977), ...

2. 1994 - NRQCD

Bodwin, Braaten, Lepage, 9407339, ...

No divergence up to now, solving many puzzles

Plain NRQCD fails when $p_T \gg M$ or $p_T \ll M$, leak all order proof

3. 2014 -

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

Low p_T: CGC+NRQCD — Kang, YQM, Venugopalan, 1309.7337; Qiu, Sun, Xiao, Yuan, 1310.2230, ...

...........: ?????

Outline

I. NRQCD: what we learned from NLO?

II. High p_T: collinear factorization up to NLP

III. Low p_T: CGC+NRQCD

IV. Improved CEM: Renaissance of CEM? (New)

Mainly talk about production in hadron colliders!

NRQCD Factorization

Bodwin, Braaten, Lepage, 9407339

➢ Factorization formula

$$d\sigma_\psi = \sum_{i,j,n} \int \underbrace{dx_1 dx_2 \boxed{G_{i/A} G_{j/B}}}_{\Lambda_{QCD}} \times \underbrace{\boxed{\hat{\sigma}[ij \to c\bar{c}[n] + X]}}_{m_c} \times \underbrace{\boxed{\langle O_n^\psi \rangle}}_{m_c v}$$

Parton distribution function
Long distance ($\sim 1/\Lambda_{\mathrm{QCD}}$)

Hadronization (LDMEs)
Long distance ($\sim 1/(m_c v)$)
input .

Production of heavy quark pair
Short distance ($\sim 1/m_c$)
perturbative calculable.

➢ LO NRQCD: polarization puzzle

- Dominated by ${}^3S_1^{[8]}$, LO NRQCD predicts transversely polarized J/ψ, contradicts with CDF data

CDF, 0704.0638

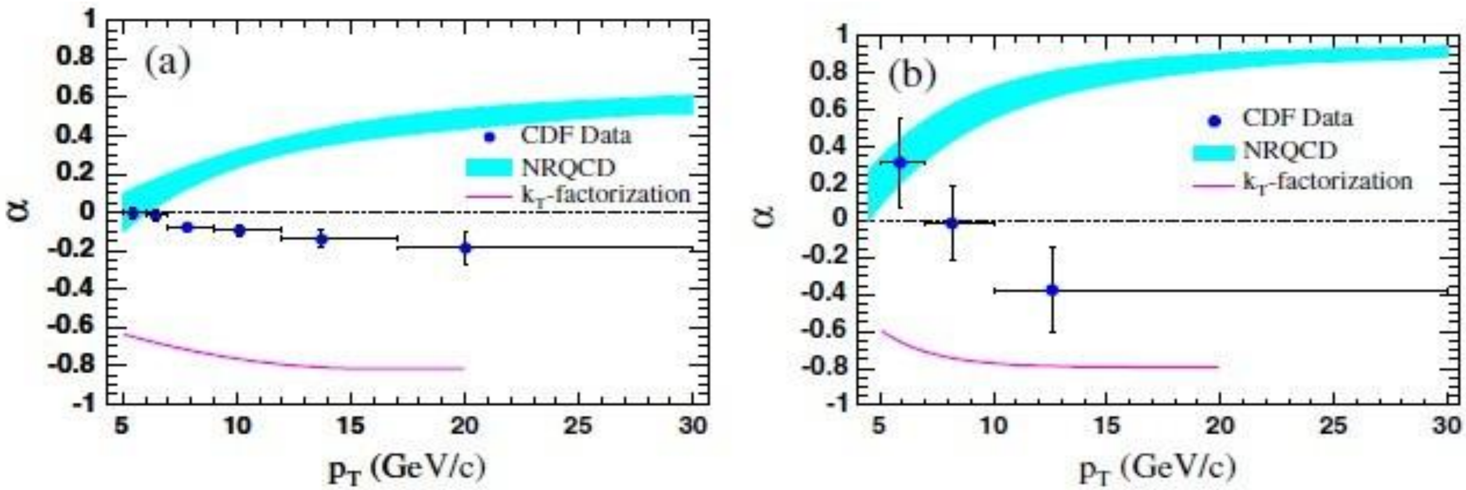


FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

History of high order calculation: pp collision

- 0703113: Campbell, Maltoni, Tramontano

NLO, cross section, S-wave

- 0802.3727: Gong, Wang

NLO, polarization, S-wave

- 0806.3282: Artoisenet, Campbell, Lansberg, Maltoni, Tramontano

$\mathrm{NNLO}^{\star}$, S-wave

- 1002.3987: YQM, Wang, Chao
- 1009.3655: YQM, Wang, Chao
- 1009.5662: Butenschöen, Kniehl

Complete NLO (S- and P-wave), cross section

- 1201.1872: Butenschöen, Kniehl
- 1201.2675: Chao,YQM,Shao,Wang,Zhang
- 1205.6682: Gong,Wan,Wang,Zhang

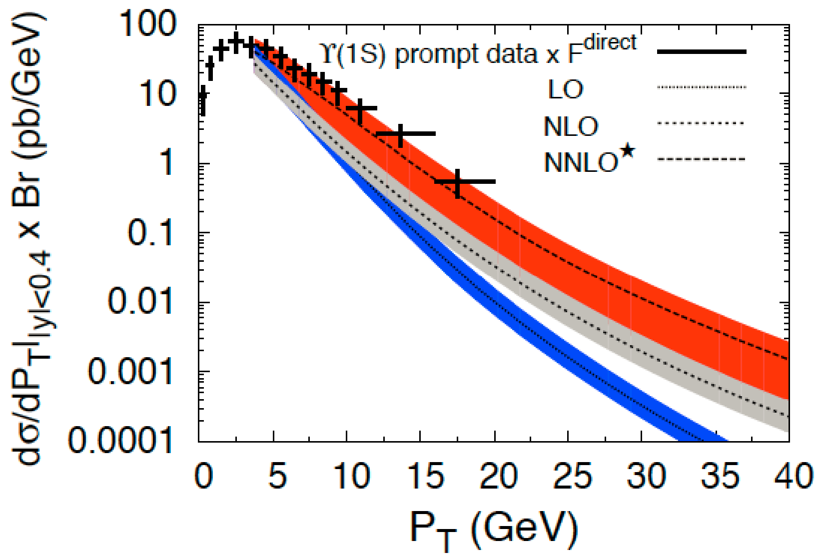
Complete NLO (S- and P-wave), with polarization

NOT fully comprehensive!!!

Discovery (1): large correction at high p_T

➢ S-wave ($^3S_1^{[1]}$):

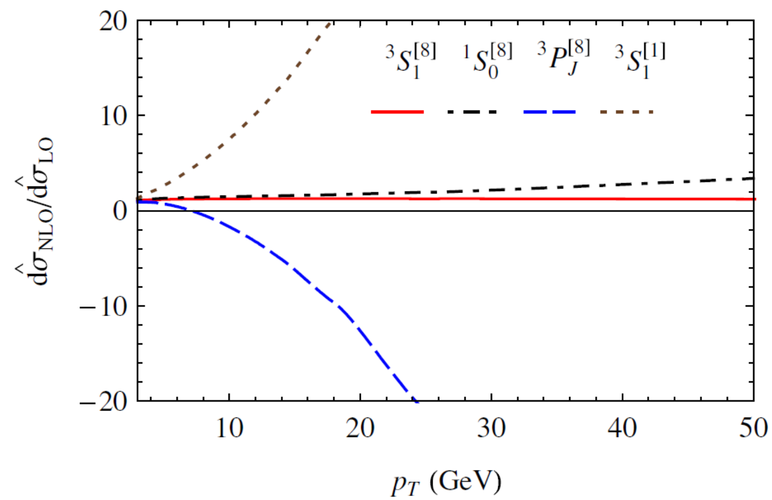
- Large corrections are found for NLO and NNLO*



Campbell, Maltoni, Tramontano, 0703113,
Artoisenet, Campbell, Lansberg, Maltoni, Tramontano, 0806.3282

➢ P-wave ($^3P_{J=0,1,2}^{[1,8]}$):

- Large NLO corrections are found for both CS and CO channel



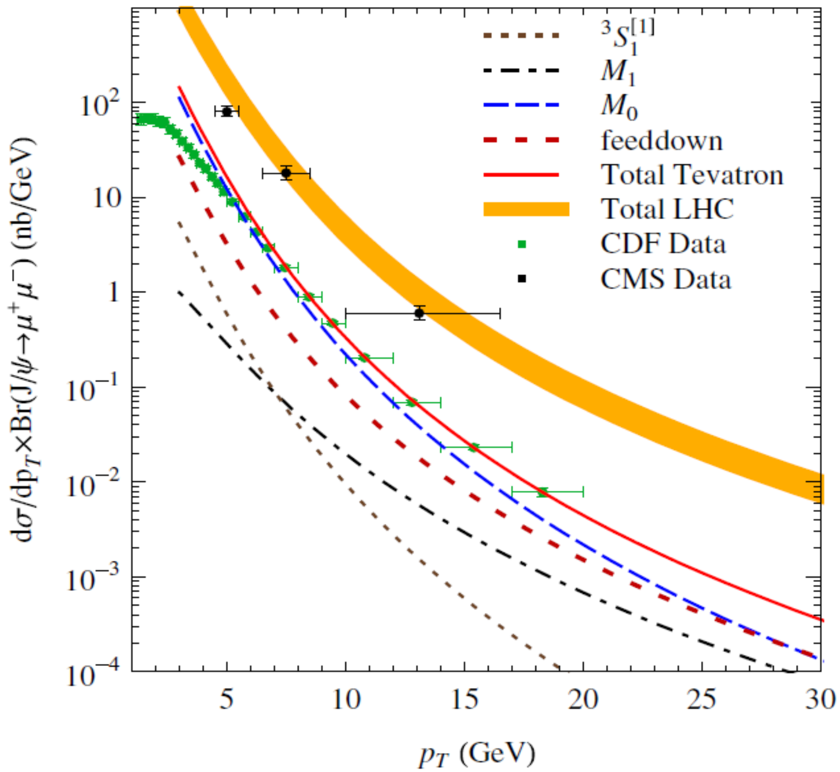
YQM, Wang, Chao, 1002.3987
YQM, Wang, Chao, 1009.3655
Butenschöen, Kniehl, 1009.5662

- NLO predictions significantly different from LO
- How reliable is the perturbative expansion?

collinear factorization, p_T expansion (Part II)

Discovery (2): failure at low p_T

- When $p_T \ll m_H$, fixed order gives $\frac{d\sigma}{dp_T} \propto \frac{1}{p_T}$, data goes to zero
- Naively, fixed order calculation can describe data with $p_T \gtrsim m_H$
- For J/ψ ($m_{J/\psi} = 3.1\mathrm{GeV}$) production, NLO calculation found only to well describe data with $p_T > 7\mathrm{GeV}$



YQM, Wang, Chao, 1009.3655
Gong,Wan,Wang,Zhang,1205.6682
Bodwin, Chung, Kim, Lee, 1403.3612
Faccioli,Knunz,Lourenco,Seixas,Wohri,1403.3970

- How to understand low p_T data? Saturation effect (Part III)

Discovery (3): J/ψ polarization

- Fit to J/ψ cross section requires a very small

$$\mathrm{M}_1 = \langle O\left({}^3\mathrm{S}_1^{[8]}\right)\rangle - 0.56\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

YQM, Wang, Chao, 1009.3655

- Transverse polarization proportional to

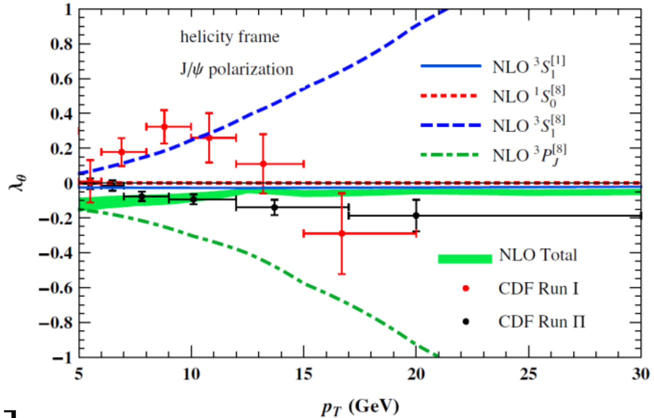
$$\mathrm{M'}_1 = \langle O\left({}^3\mathrm{S}_1^{[8]}\right)\rangle - 0.52\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

Chao,YQM,Shao,Wang,Zhang,1201.2675

- **Cross section requires small transverse polarization— consistent with data!!!**

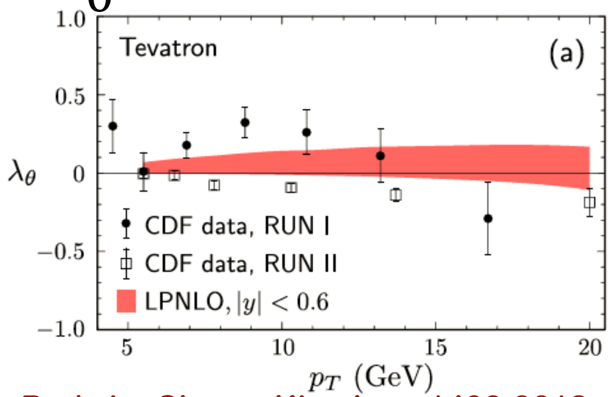
Explain J/ψ polarization

- Transverse polarization cancelled between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channel, ${}^1S_0^{[8]}$ may dominate

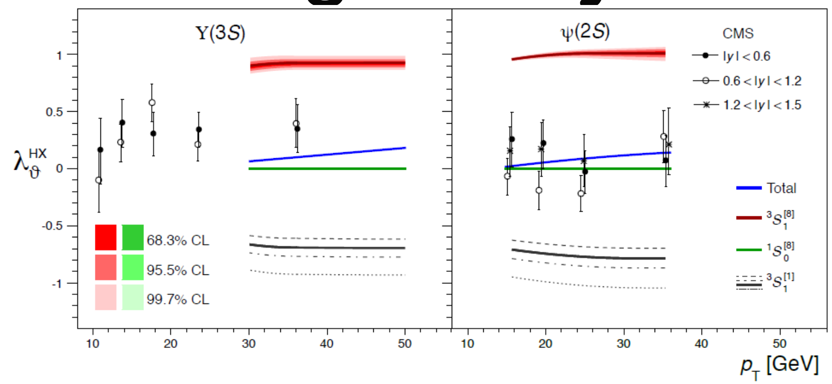


Chao,YQM,Shao,Wang,Zhang,1201.2675

- ${}^1S_0^{[8]}$ dominant mechanism: agreed by new studies



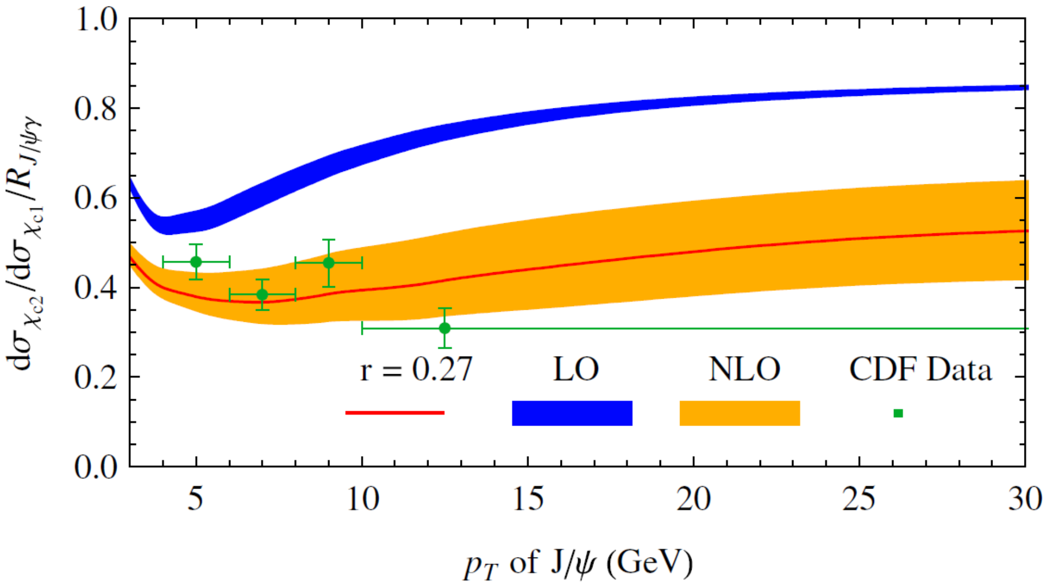
Bodwin, Chung, Kim, Lee, 1403.3612



Faccioli,Knunz,Lourenco,Seixas,Wohri,1403.3970

χ_{cJ}@hadron colliders

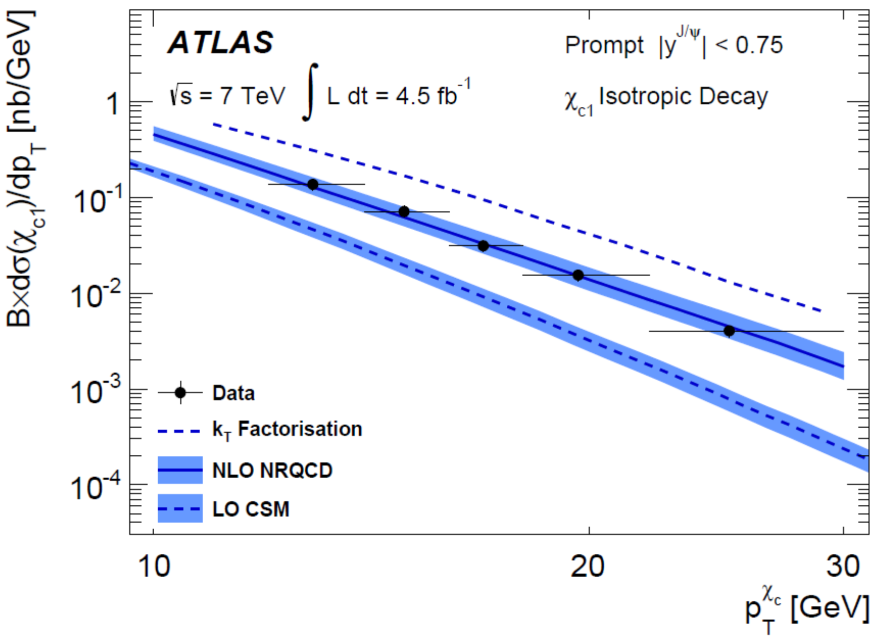
- **χ_{cJ} production:** $d\sigma_{\chi_{cJ}} \approx d\hat{\sigma}_{^3P_J^{[1]}} \langle O\left({}^3P_0^{[1]}\right)\rangle + (2J+1) d\hat{\sigma}_{^3S_1^{[8]}} \langle O\left({}^3S_1^{[8]}\right)\rangle$
  - $\langle O\left({}^3P_0^{[1]}\right)\rangle$: can be determined by potential model
  - $\langle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

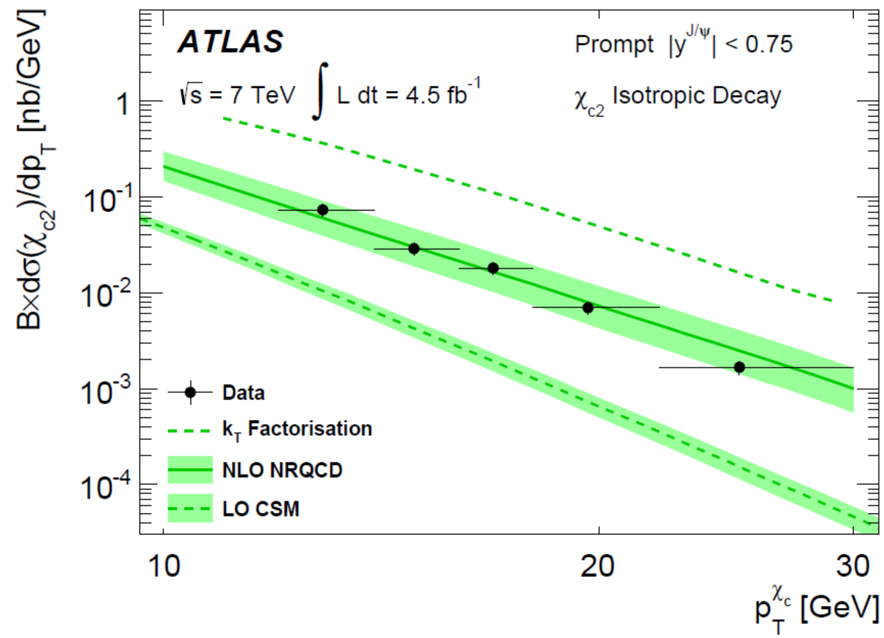


YQM, Wang, Chao, 1002.3987

➢ Comparison with new data

ATLAS, 1404.7035





Perfect agreement!

NRQCD: summary

- **Most puzzles can be understood qualitatively at NLO**
  - Including J/ψ polarization puzzle
- **Fails at very high p_T or very low p_T region**
  - Other methods are needed for these extreme regions
- **Leak all order proof of NRQCD factorization**
  - Factorization correct at least up to NNLO   Nayak, Qiu, Sterman, 0509021

Outline

I. NRQCD: what we learned from NLO?

II. High p_T: collinear factorization up to NLP

III. Low p_T: CGC+NRQCD

IV. Improved CEM: Renaissance of CEM? (New)

Collinear factorization for high p_T production

- When $p_T \gg m$, power expansion m^2/p_T^2 first, then α_s
- Leading power: collinear factorization, single parton fragmentation

Collins, Soper (1982)
Braaten, Yuan, 9303205
Nayak, Qiu, Sterman, 0509021

- NLP: important for heavy quarkonium produciton

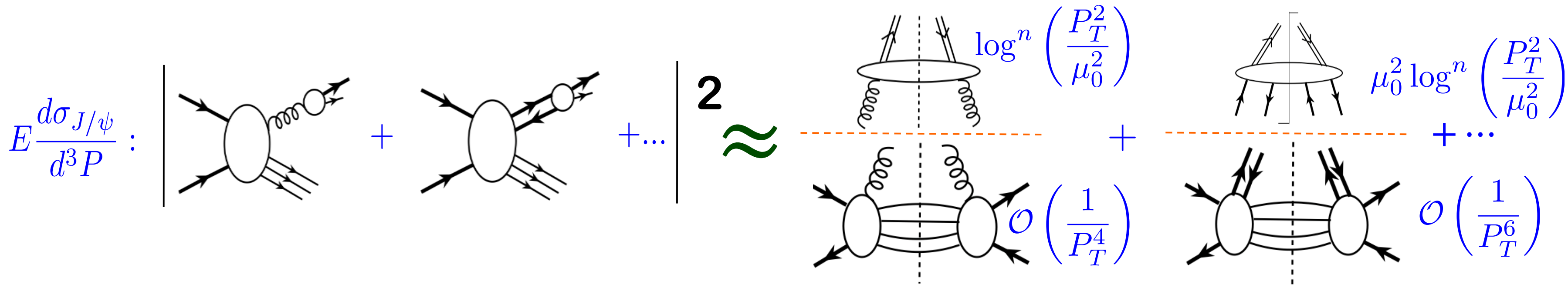
Kang, Qiu, Sterman, 1109.1520

- A rigorous collinear factorization method up to NLP

Kang, YQM, Qiu, Sterman, 1401.0923
Kang, YQM, Qiu, Sterman, 1411.2456

Collinear factorization approach

- **Ideas:**



- **Factorization correct to all order**

Qiu, Sterman (1991)
Kang, YQM, Qiu, Sterman, 1401.0923

Factorization

- **Factorization formalism:**

produce pair at $1/m_Q$

$$d\sigma_{A+B\to H+X}(p_T) = \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q)$$
$$+ \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z)$$
$$\otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q)$$
$$+ \mathcal{O}(m_Q^4/p_T^4)$$

produce pair at $1/p_T$

$\kappa = v, a, t$ **for spin, and** $1, 8$ **for color.**

Evolution

Kang, YQM, Qiu, Sterman, 1401.0923

➢ Independence of the factorization scale:

$$\frac{d}{d\ln(\mu)}\sigma_{A+B\to HX}(P_T)=0$$

➢ Evolution equations at NLP:

produce pair between $[1/p_T, 1/m_Q]$

$$\frac{d}{d\ln\mu^2}D_{H/f}(z,m_Q,\mu)=\sum_j\frac{\alpha_s}{2\pi}\gamma_{f\to j}(z)\otimes D_{H/j}(z,m_Q,\mu)$$
$$+\frac{1}{\mu^2}\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s^2}{(2\pi)^2}\Gamma_{f\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

$$\frac{d}{d\ln\mu^2}\mathcal{D}_{H/[Q\bar{Q}(c)]}(z,\zeta,\zeta',m_Q,\mu)=\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s}{2\pi}K_{[Q\bar{Q}(c)]\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')$$
$$\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

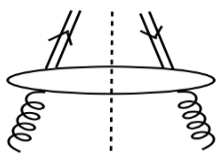
Large $\log(p_T/m)$: can be resumed by solving evolution equation

Predictive power

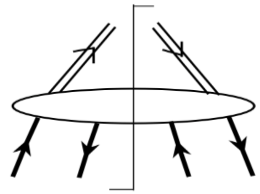
- **Calculation of short-distance hard parts in pQCD:** Kang, YQM, Qiu, Sterman, 1411.2456
  - Power series in α_s , without large logarithms
  - LO is now available for all partonic channels
- **Calculation of evolution kernels in pQCD:** Kang, YQM, Qiu, Sterman, 1401.0923
  - Power series in α_s, without large logarithms
  - LO is now available for both mixing kernels and pair evolution kernels of all spin states of heavy quark pairs
- **Universality of input fragmentation functions at the initial scale μ_0**

Input fragmentation function

- **FFs at μ_0: fit from data**
  - Complicated: different quarkonium states require different input distributions!
- **NRQCD factorization: plausible at $\mu_0 \sim m_Q$**



$D_{H/f}(z, m_Q, \mu_0)$



$\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z, \zeta, \zeta', m_Q, \mu_0)$

  - Apply NRQCD to the input distributions at initial scale

NLO is now available for all channels

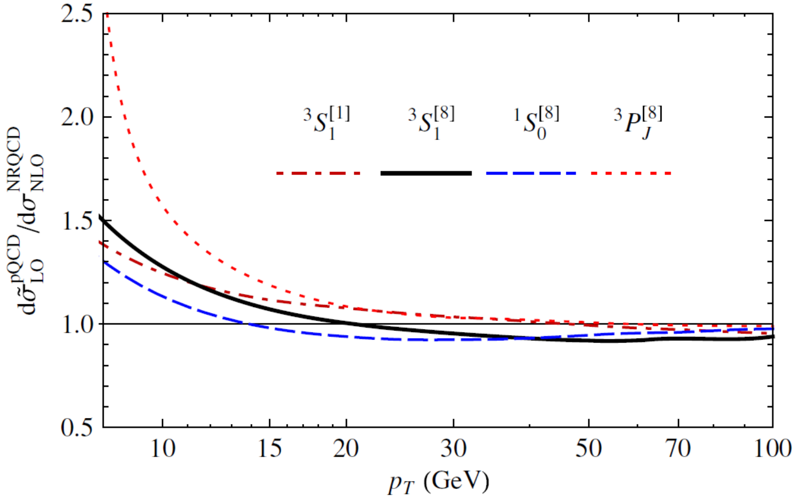
YQM, Zhang, Qiu, 1311.7078
YQM, Zhang, Qiu, 1401.0524
YQM, Zhang, Qiu, 1501.04556

  - For CS to CS channel, see also Deshan Yang's talk

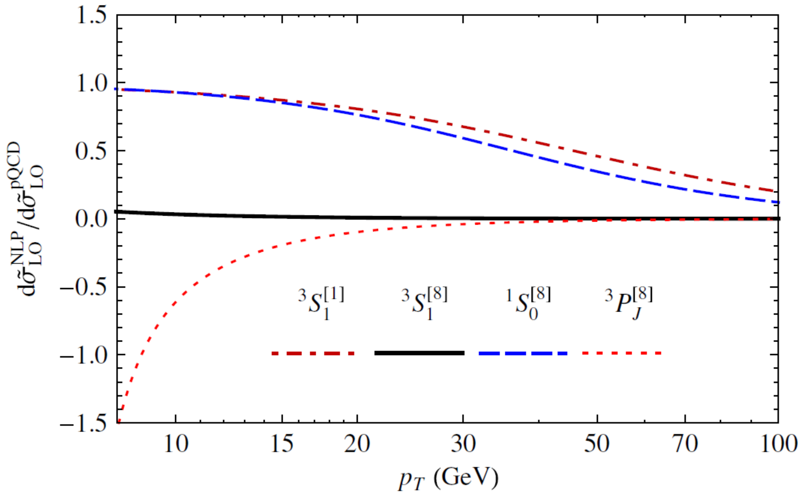
Reproducing plain NRQCD

YQM, Qiu, Sterman, Zhang, 1407.0383

➢ LO LP+NLP comparing with NLO NRQCD



- LO analytical results reproduce NLO NRQCD calculations (numerical) !



- LP dominates: $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels
- NLP dominates: $^1S_0^{[8]}$ and $^3S_1^{[1]}$ channels

Large p_T: summary

- The collinear factorization framework is ready to use, potentially better convergence

A lot of works to be done!

- Solving the double parton evolution equations

  Resummation of $\log(p_T/m)$

- Calculating hard parts to NLO

  Before resummation, potentially can reproduce NNLO NRQCD

- Global analysis, based on collinear factorization formalism including NLP and evolution

Outline

I. NRQCD: what we learned from NLO?

II. High p_T: collinear factorization up to NLP

III. Low p_T: CGC+NRQCD

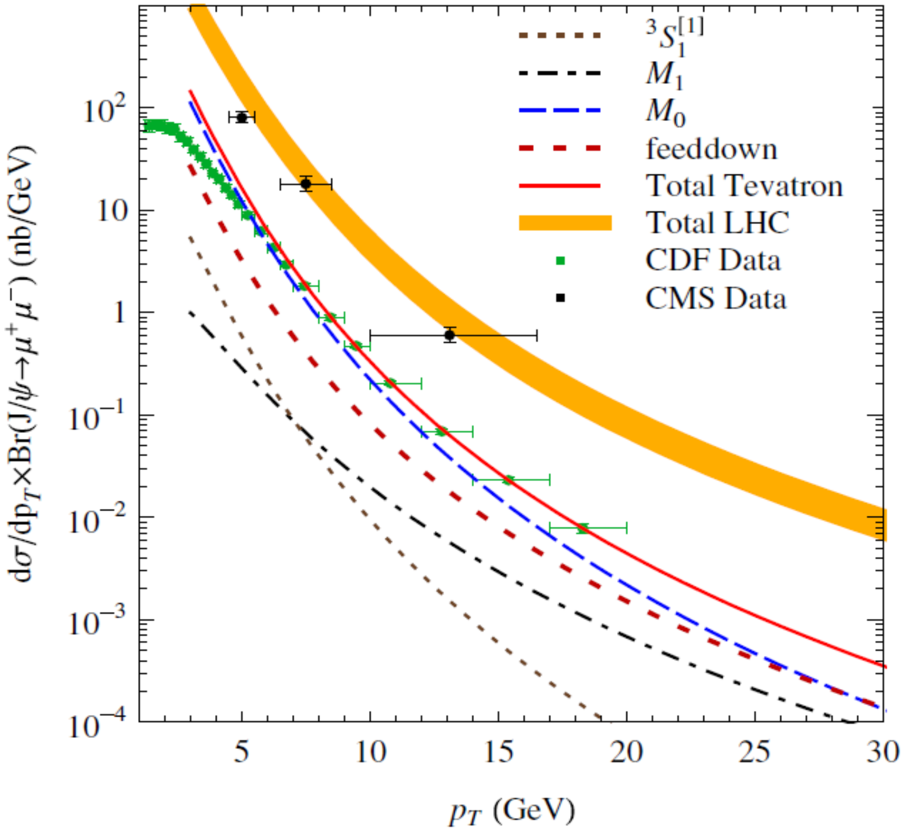
IV. Improved CEM: Renaissance of CEM? (New)

Low p_T quarkonium production

- **Moderate p_T region: fine**

- **Small p_T region**

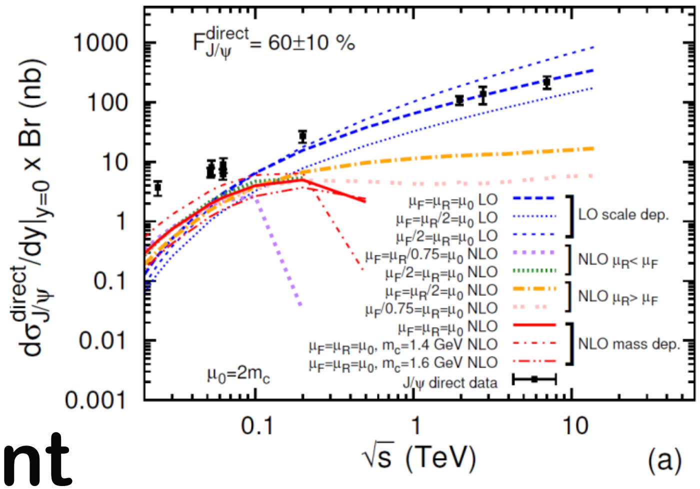
- When $p_T \ll m_H$, fixed order gives $\frac{d\sigma}{dp_T} \propto \frac{1}{p_T}$, data goes to zero
- Far from understood
- Dominate the total cross section



Small p_T v.s. small x

Berger, Qiu, Wang, 0404158
Sun, Yuan, Yuan, 1210.3432
Watanabe, Xiao, 1507.06564

- **Sudakov double logarithm**
  - Sudakov resummation: $\log^2(p_T/m_H)$ important at small p_T regime
  - Sudakov resummation can be dominant for Υ production
  - But, itself still hard to describe the J/ψ production
- **Why $\log^2(p_T/m_H)$ resummation is not enough?**
  - Total cross section is free of $\log(p_T/m_H)$
  - Total cross section can be negative
  - Fixed order NRQCD fails to explain data



Feng, Lansberg, Wang, 1504.00317

- **Small-x effect can be important**
  - The only large logarithm is $\log(x)$

CGC effective field theory

➢ Color Glass Condensate

McLerran, Venugopalan, 9309289

- A tool to deal with small-x physics
- An effective field theory of QCD: separate $x < x_0$ configuration from $x > x_0$ configuration
- Small-x configuration: large saturation scale, perturbatively calculable
- 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+NRQCD

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

➢ 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

➢ 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

Dilute-dense formula at LO

Kang, YQM, Venugopalan, 1309.7337

- Short distance for CS channels in CGC

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

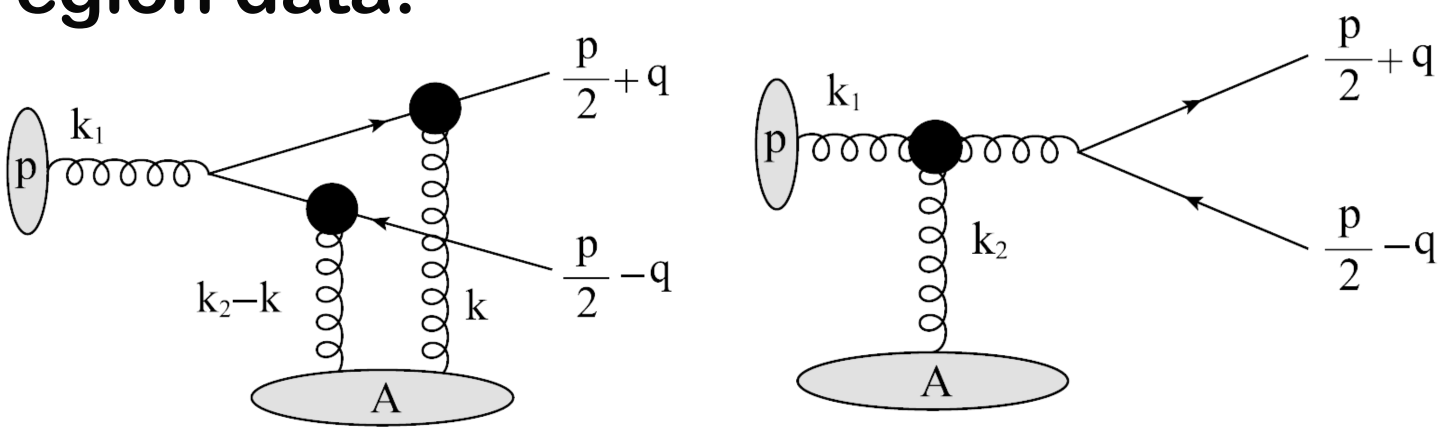
- Short distance for CO channels in CGC

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

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

High p_T and NLO

- **With LO calculation: can only describe small p_T region data!**



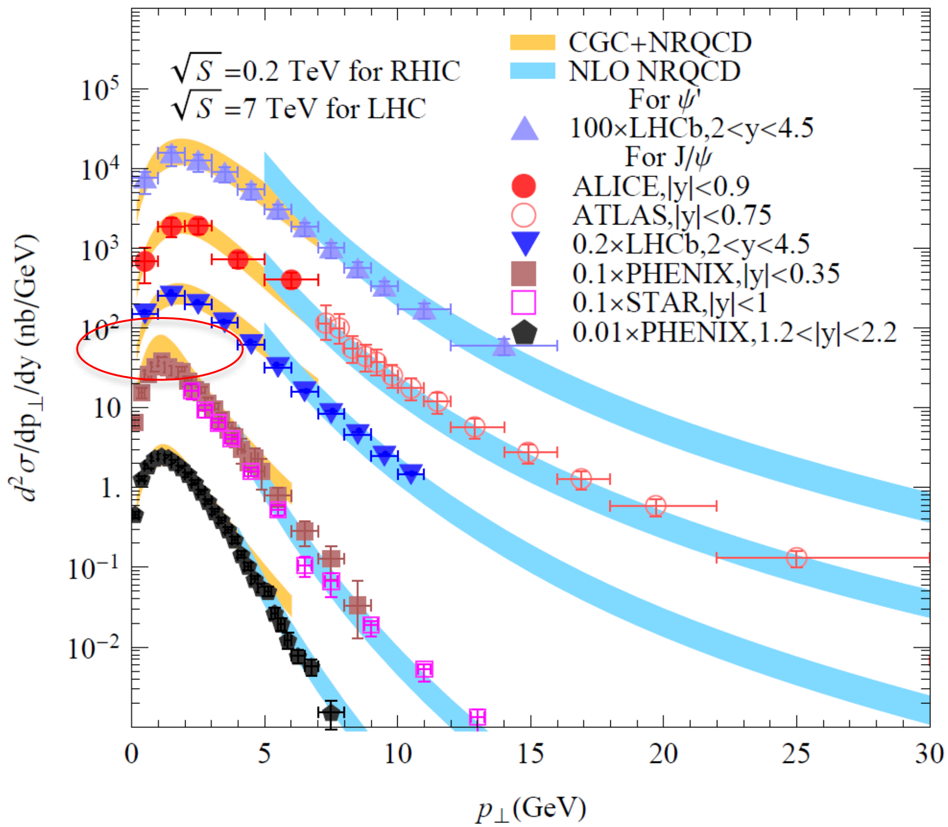
- ✓ No final state radiation
- ✓ Correct only if initial state radiation dominate (p_T can not be much larger than the saturation scale)

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

J/ψ@p+p: p_T dependence

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/ψ production at all p_T region can be described now!

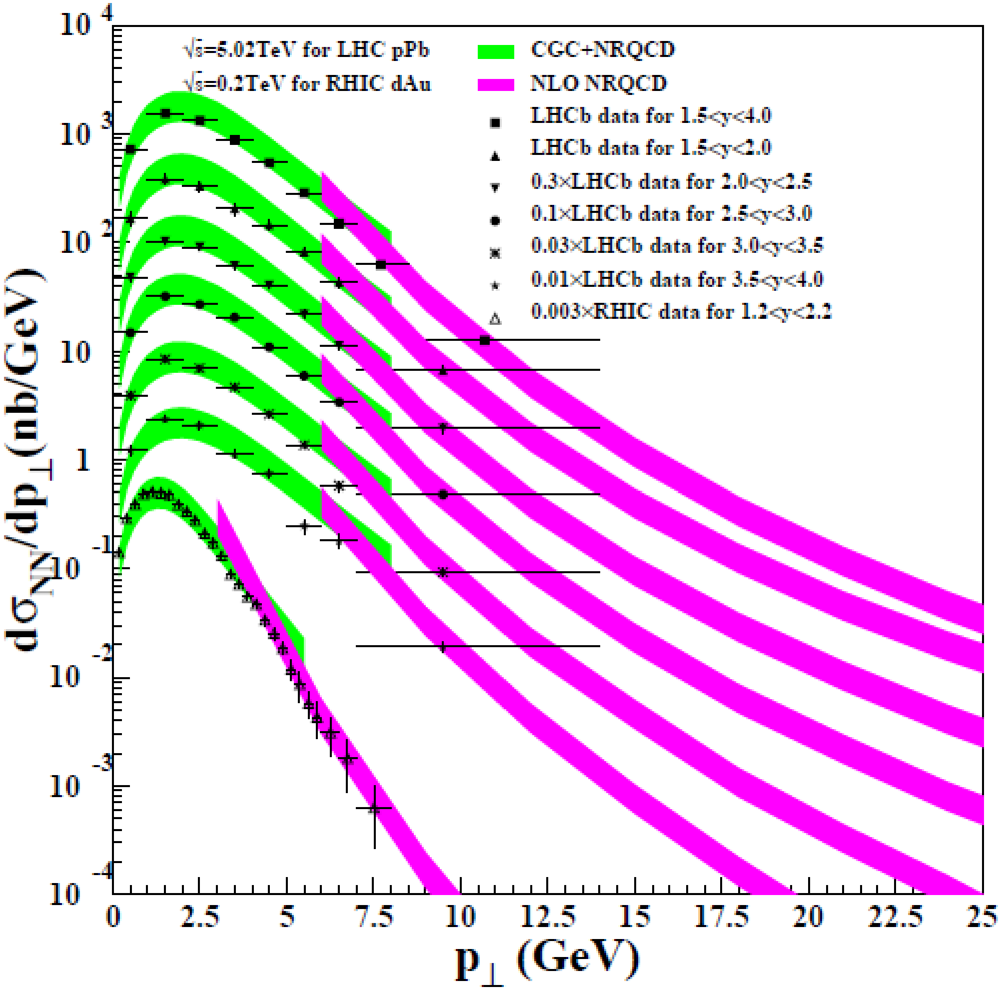
◆ RHIC data at central rapidity: agreement is not very good

◆ As expected: CGC+NRQCD good for high energy and forward rapidity

J/ψ@p+A: p_T dependence

YQM, Venugopalan, Zhang, 1503.07772

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



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

  - ✓ J/ψ production at all p_T region can be described

Small p_T: summary

- NRQCD+CGC: rigorous method for small p_T
  - Good description for J/ψ production at p+p and p+A collisions
  - Is there a rigorous method for A+A collision?
- To descripe Υ production, Sudakov resummation is needed
  - Sudakov resummation in CEM+CGC： Watanabe, Xiao, 1507.06564
  - How to resum in NRQCD+CGC?
- Apply for other quarkonium states is possible

  Plenty of data at LHC
- NLO calculation in CGC+NRQCD framework is important!!

Outline

I. NRQCD: what we learned from NLO?

II. High p_T: collinear factorization up to NLP

III. Low p_T: CGC+NRQCD

IV. Improved CEM: Renaissance of CEM? (New)

CEM

➢ CEM:

◆ A fixed fraction to become ψ if the invariant mass of $c\bar{c}$-pair is below the D-meson threshold

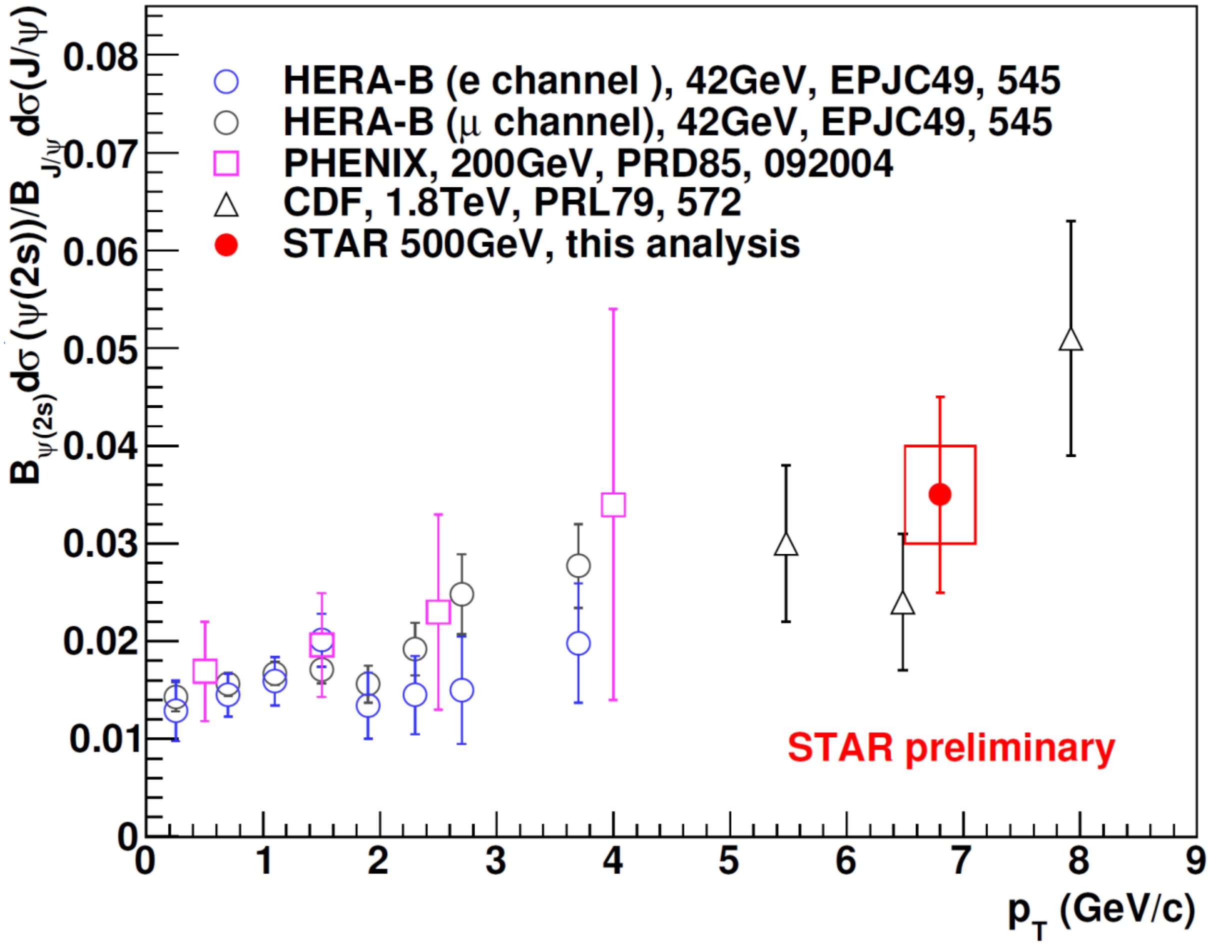
$$\frac{d\sigma_\psi(P)}{d^3P} = F_\psi \int_{2m_c}^{2M_D} dM \frac{d\sigma_{c\bar{c}}(M,P)}{dM\, d^3P}$$

➢ Nice features of CEM:

1. Simply and intuitive
2. Factorization holds to all order in α_s Collins, Soper, Sterman, NPB(1986)
3. Naturally predicts quarkonium to be unpolarized

CEM: wrong for ratio

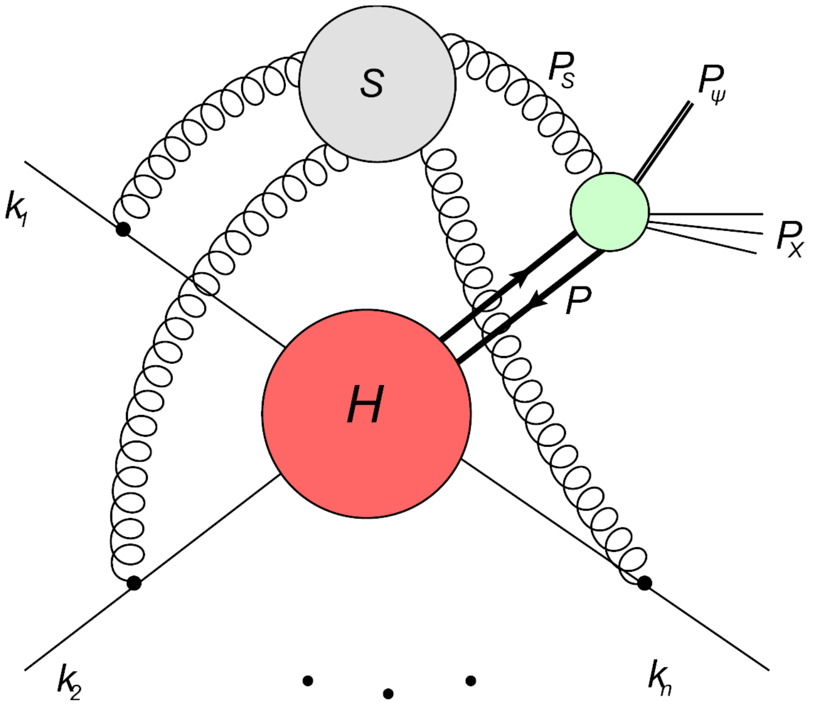
➢ **But** Wrong prediction for ratio of two quarkonia: constant



Picture

YQM, Vogt, In progress

➢ General diagram



- P_S: **exchanged soft gluons**
- P_X: **emitted soft gluons**
- $P = P_S + P_X + P_\psi$

Kinematics

- **Expectation values**

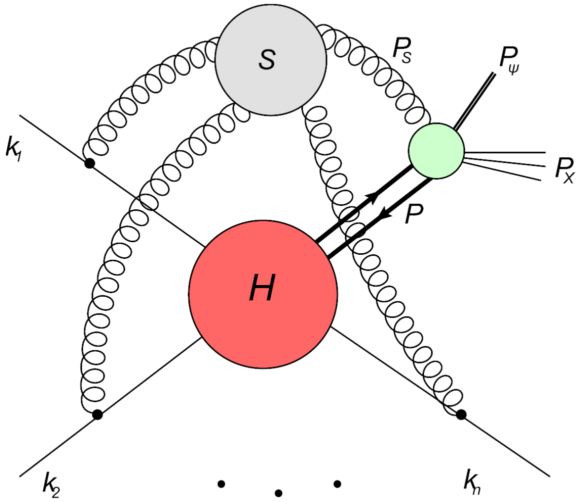
$$P = (M, 0,0,0)$$

$$\langle P_S \rangle = (\langle P_S^0 \rangle, 0,0,0)$$

$$\langle P_X \rangle = (\langle P_X^0 \rangle, 0,0,0)$$

$$\langle P_\psi \rangle = (\langle P_\psi^0 \rangle, 0,0,0)$$

YQM, Vogt, In progress



- $\langle P_S^0 \rangle \approx 0$: **energy of exchanged soft gluons**
- $\langle P_X^0 \rangle > 0$: **energy of emitted soft gluons**

- **Lower limit for M**

$$M > M - \langle P_X^0 \rangle = \langle P_\psi^0 \rangle > M_\psi$$

On average, hadronization of quarkonium happens by only emitting energy!

Improved CEM

- **More precisely**

YQM, Vogt, In progress

$$\langle P_\psi \rangle = \frac{\mathrm{M}_\psi}{M} P + O(\Lambda_{\mathrm{QCD}}^2/M)$$

- **The model:**

$$\frac{d\sigma_\psi(P)}{d^3P} = F_\psi \int_{M_\psi}^{2M_D} d^3P' dM \frac{d\sigma_{c\bar{c}}(M,P')}{dM d^3P'} \delta^3(P - \frac{M_\psi}{M} P')$$

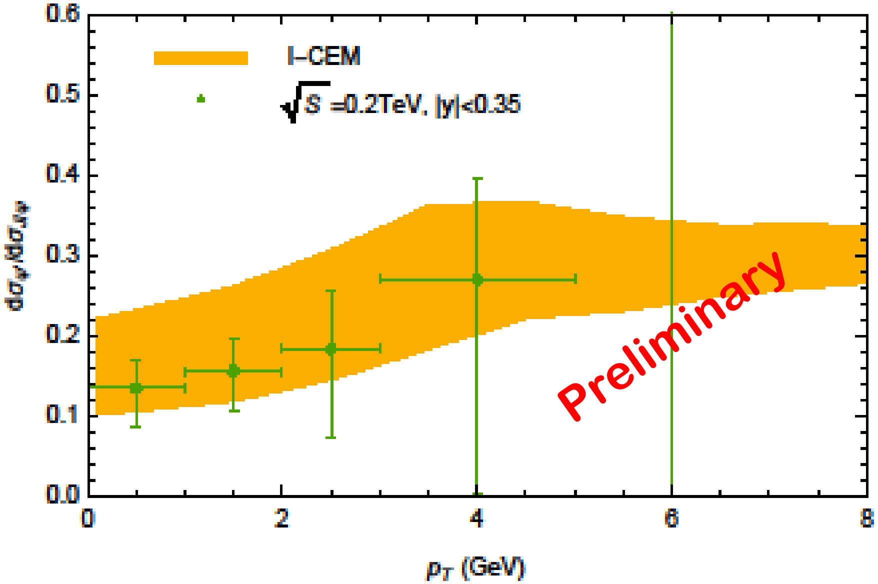
Comparing with traditional CEM

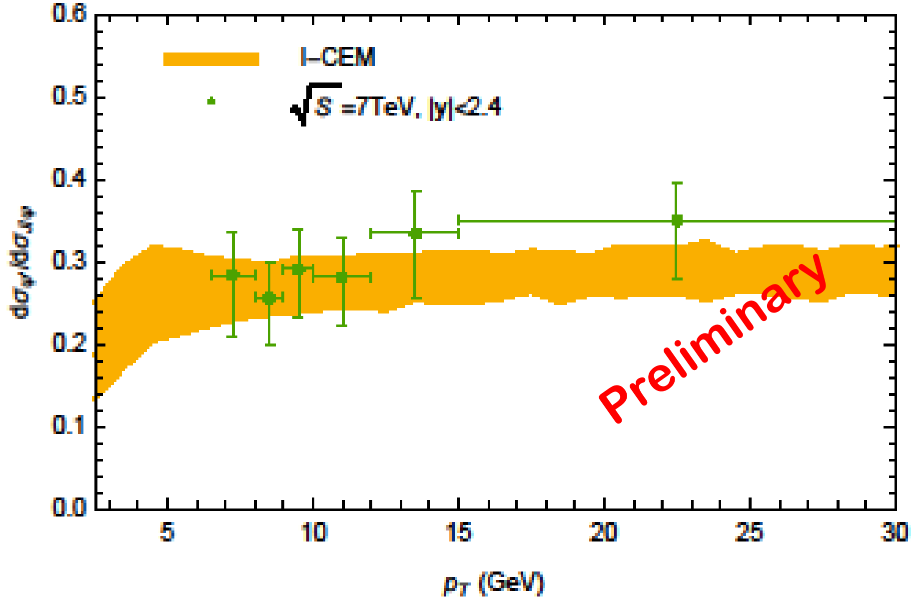
$$\frac{d\sigma_\psi(P)}{d^3P} = F_\psi \int_{2m_c}^{2M_D} dM \frac{d\sigma_{c\bar{c}}(M,P)}{dM d^3P}$$

Comparing with data

YQM, Vogt, In progress

- Ratio explained by I-CEM!





Improved CEM: summary

- Inherit all nice features of CEM
  - Simple, factorization, polarization

- Can describe cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi}$

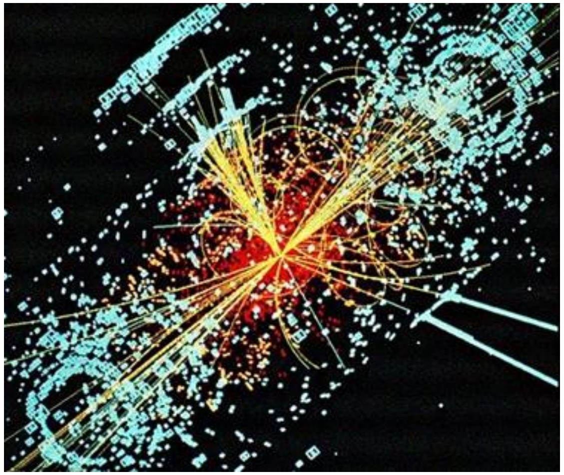
- More studies are needed!

Thank you!

Back up

Hadronization

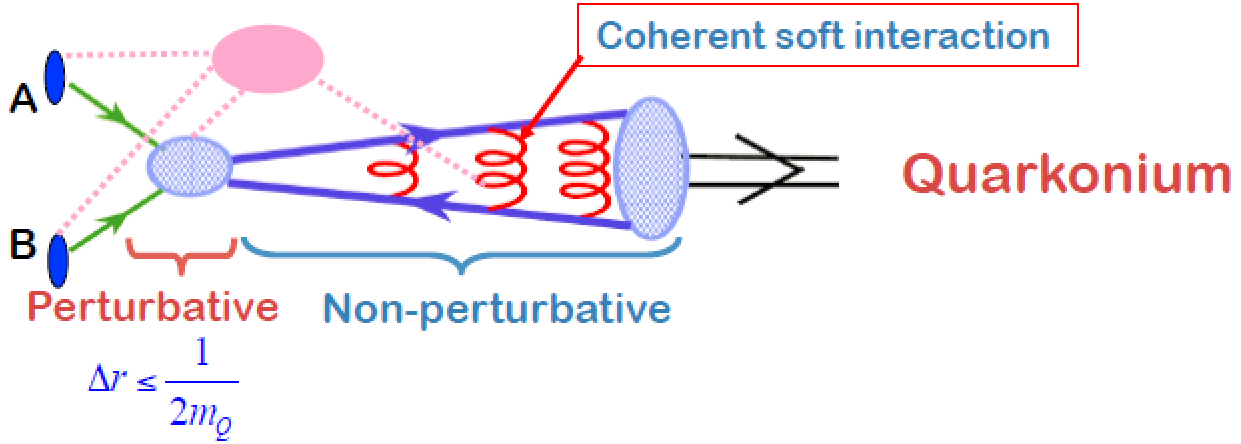
- **Produced at initial:**
  - Partons
- **Observed by detector:**
  - Hadrons



- **Hadronization in QCD**
- **Why hadronization? How hadronization?**
  - Study hadron production!

Factorization and hadronization models

➢ **Short-distance and long distance parts**



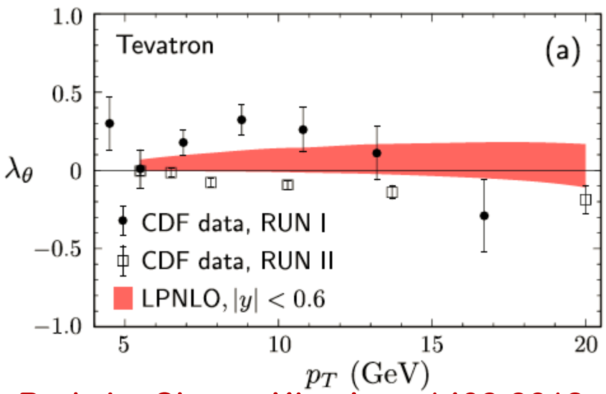
➢ **Approximation: on-shell pair + hadronization**

$$\sigma_{AB\to H+X} = \sum_n \int_n d\Gamma_{(Q\bar{Q})_n} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{(Q\bar{Q})_n}}\right] F_{(Q\bar{Q})_n\to H}(p_Q, p_{\bar{Q}}, P_H)$$

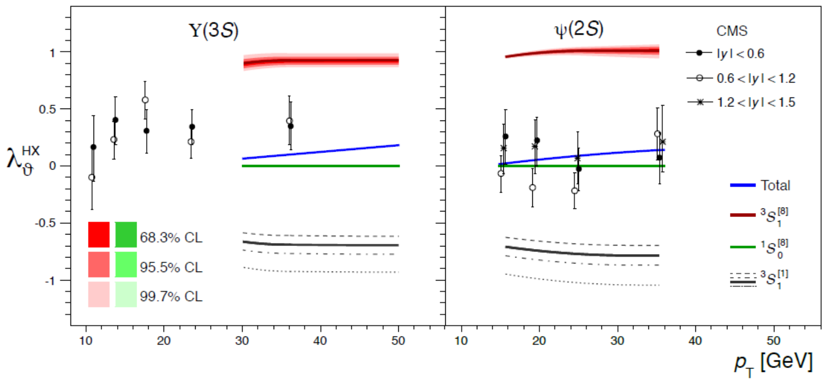
- **Hadronization: isolated from perturbative effects**
- **Different treatment for F: different factorization model**

J/ψ@hadron colliders

- ${}^1S_0^{[8]}$ **dominant mechanism:**
  - ✓ agreed by new studies



Bodwin, Chung, Kim, Lee, 1403.3612



Faccioli,Knunz,Lourenco,Seixas,Wohri,1403.3970

CGC+CEM

Fujii, Gelis, Venugopalan, 0603099
Fujii, Watanabe, 1304.2221
Ducloue, Lappi, Mantysaari, 1503.02789
Watanabe, Xiao, 1507.06564

➢ CEM:

- A fixed fraction to become J/ψ 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: production of $c\bar{c}$-pair

- Using CGC to calculate gluon distribution
- Small x resummation is accounted by solving JIMWLK or BK evolution equations

CGC+CEM

Fujii, Gelis, Venugopalan, 0603099
Fujii, Watanabe, 1304.2221
Ducloue, Lappi, Mantysaari, 1503.02789
Watanabe, Xiao, 1507.06564

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

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

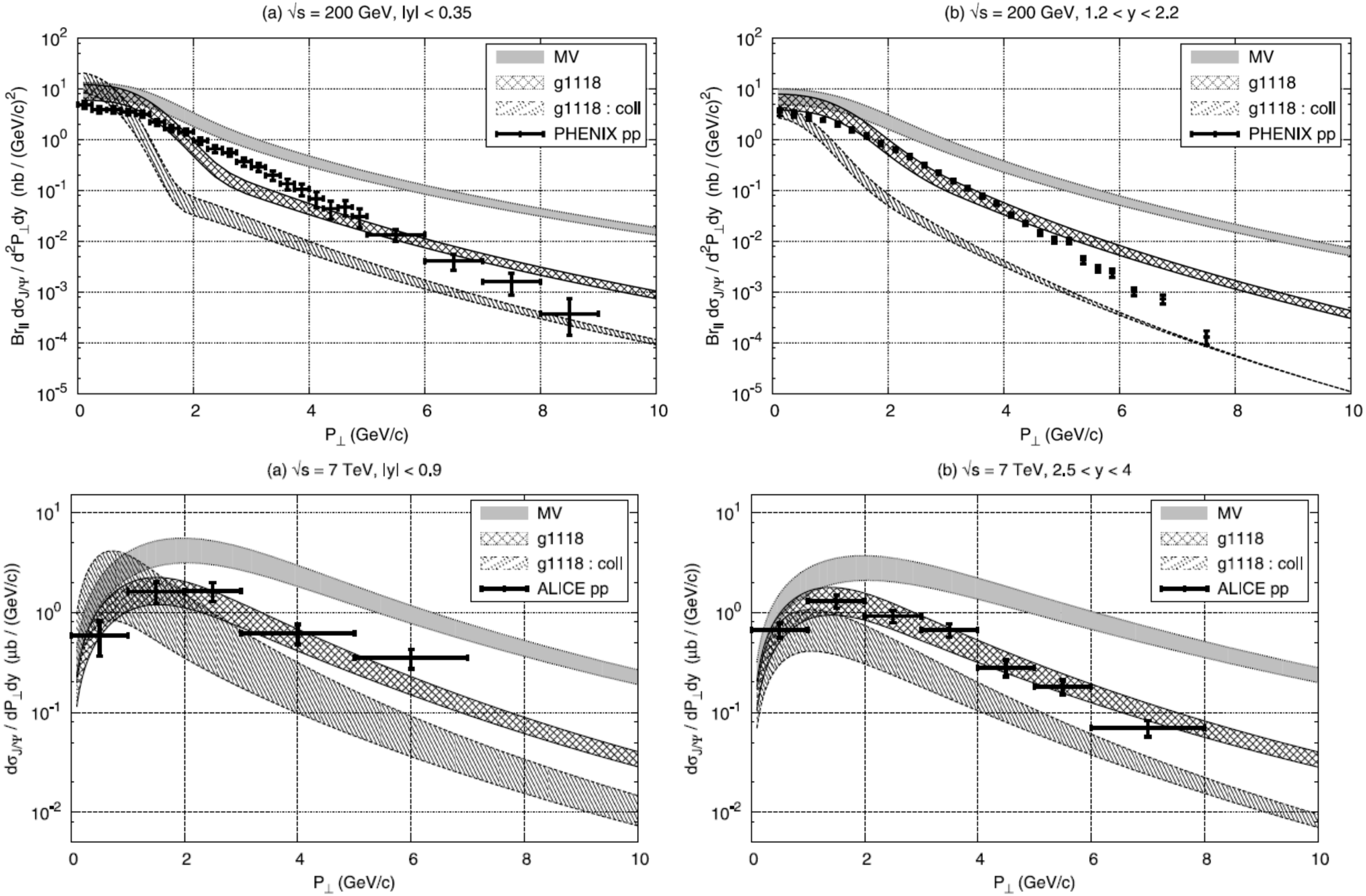
A simply and intuitive model

- **But**
  - Wrong prediction for the ratio of two quarkonia
  - Effectively dominated by ${}^3S_1^{[8]}$ channel in NRQCD language, overshoot data at hight p_T region
  - A special case of NRQCD
  - ....

CGC+CEM: p+p

Bad agreement:

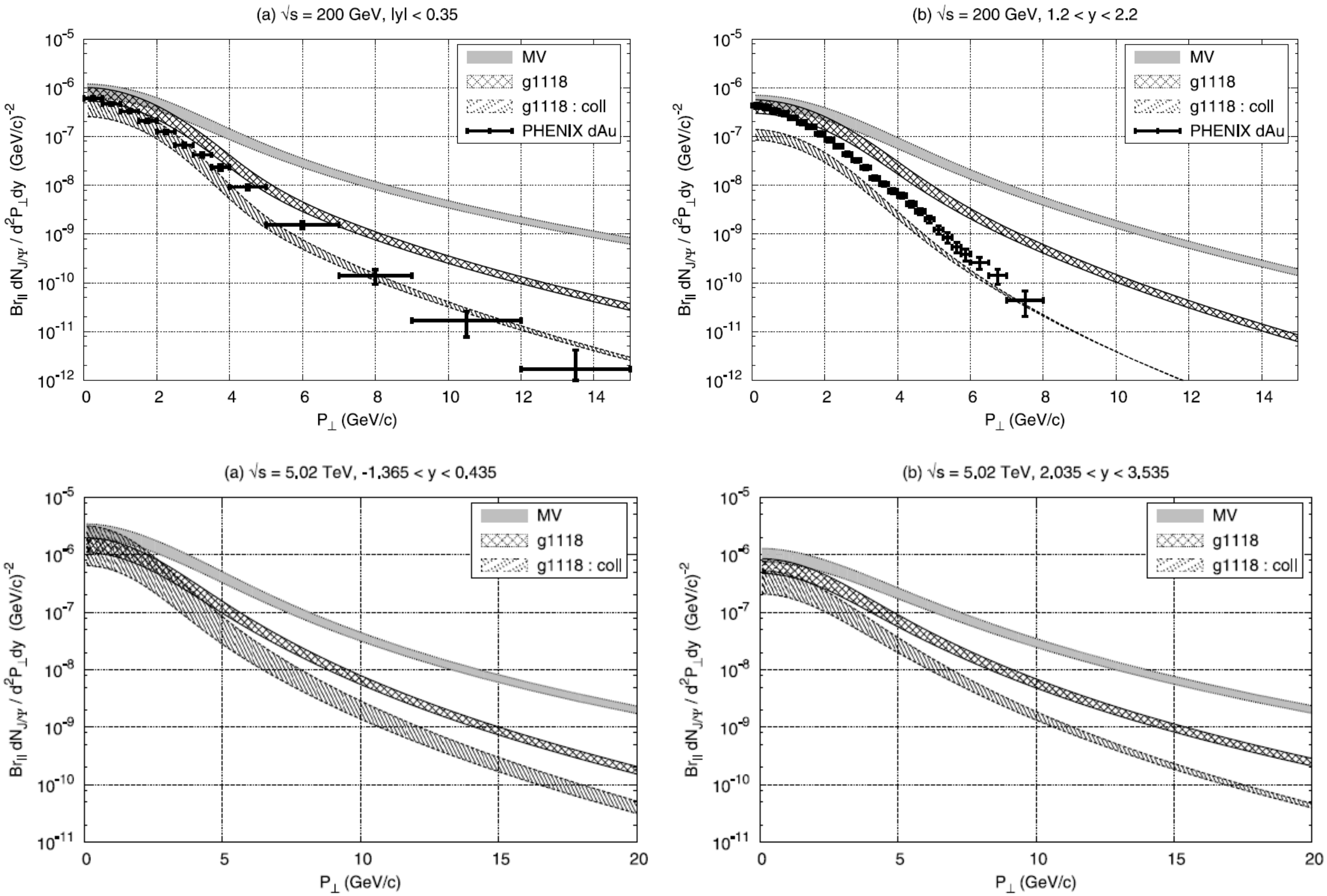
Fujii, Watanabe, 1304.2221



CGC+CEM: p+A

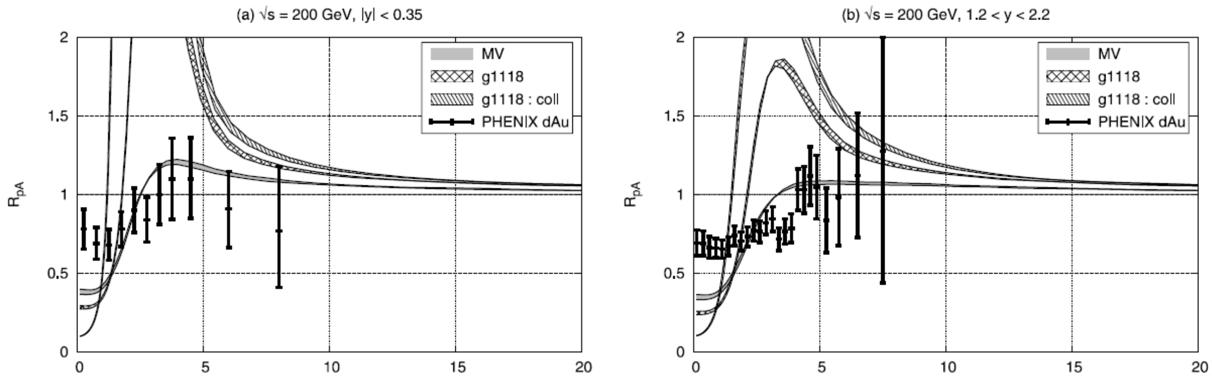
Bad agreement:

Fujii, Watanabe, 1304.2221



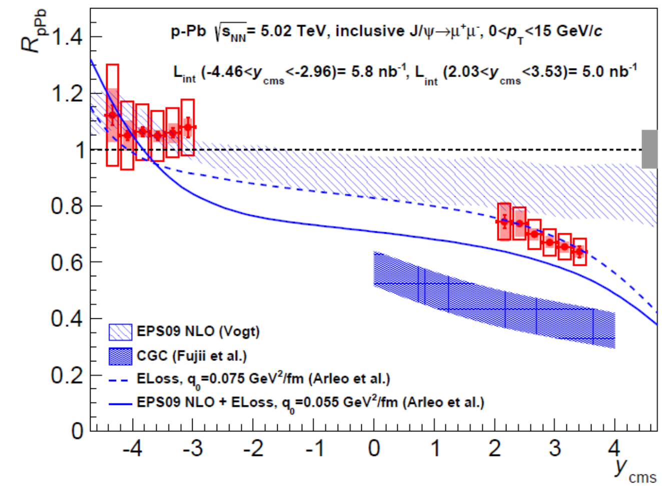
CGC+CEM: R_{pA}

- **RHIC:**



Fujii, Watanabe, 1304.2221

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



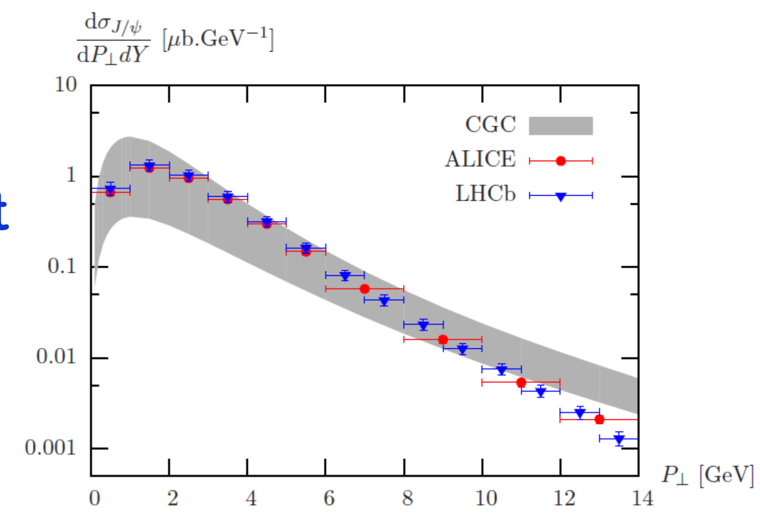
ALICE, 1308.6726

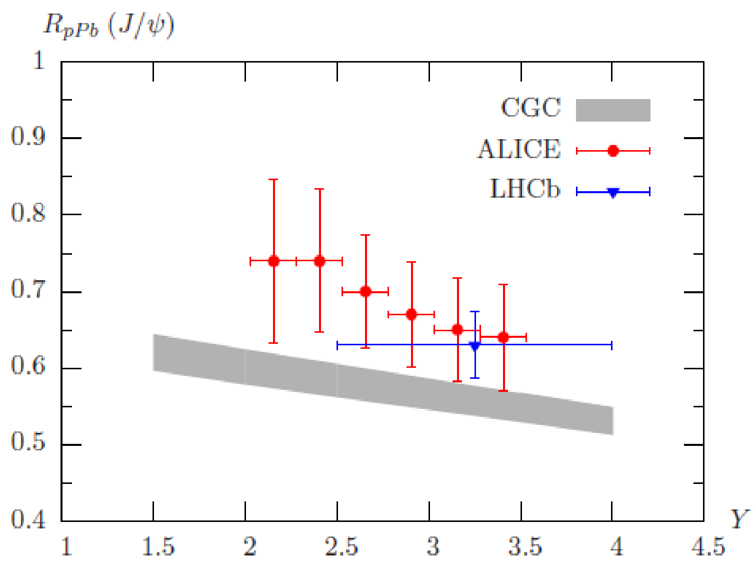
are also shown. Within our uncertainties, both the model based on shadowing only and the coherent energy loss approach are able to describe the data, while the CGC-based prediction overestimates the observed suppression. None of these models include a suppression related to the break-up of the $c\bar{c}$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

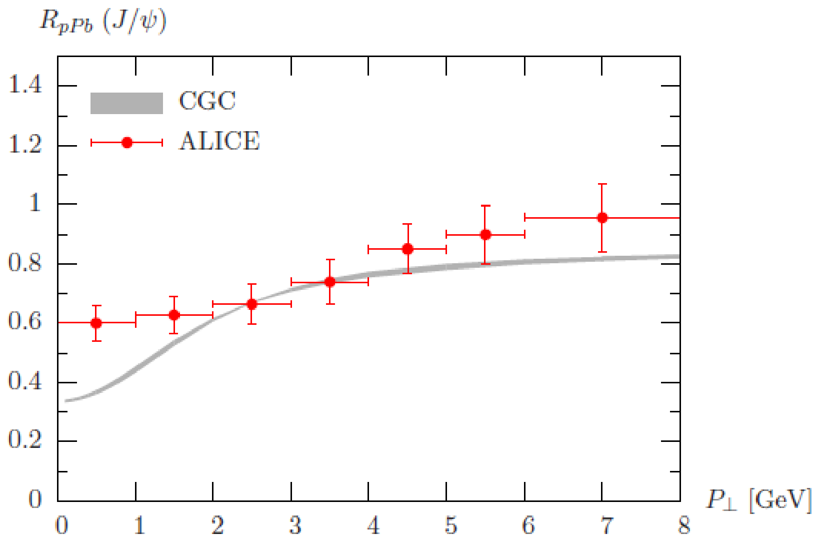
CGC+CEM: improved (1)

Ducloue, Lappi, Mantysaari, 1503.02789

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







CGC+CEM: improved (2)

◆ With small-p_T resummation

Watanabe, Xiao, 1507.06564

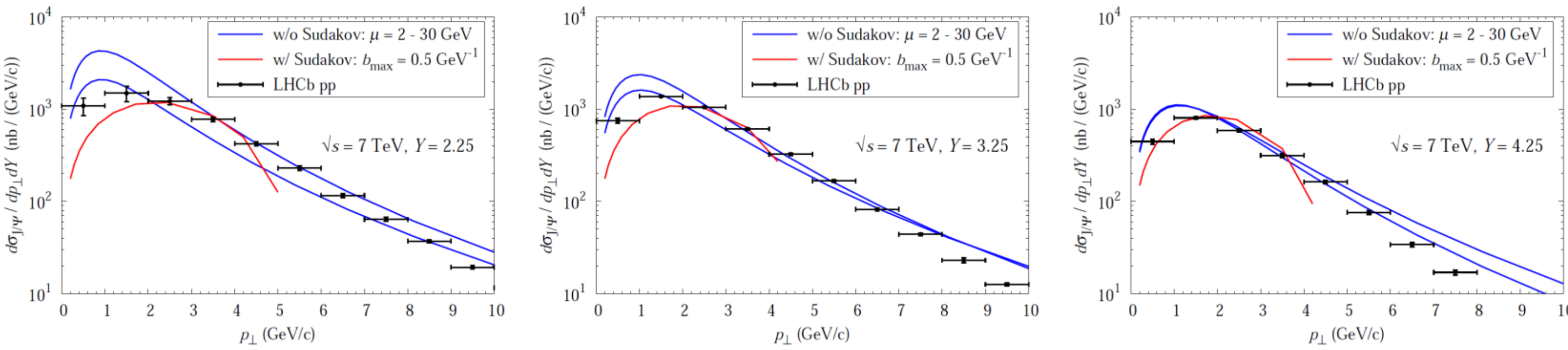


FIG. 1. Double differential cross section of J/ψ as a function of $p_\perp$ for $Y = 2.25$, 3.25, and 4.25 in pp collisions at $\sqrt{s} = 7$ TeV. Blue solid line is obtained by using Eq. (1) and the uncertainty band is coming from a change of factorization scales $(2 < \mu < 30$ GeV) for the collinear gluon distribution function. Red solid line denotes the result of Eq. 5 at $b_{\max} = 0.5$. We choose $F_{J/\psi} = 0.0975$ for Eq. (1) and 0.1495 for Eq. (5). The LHCb data for prompt production is taken from Ref. [16].

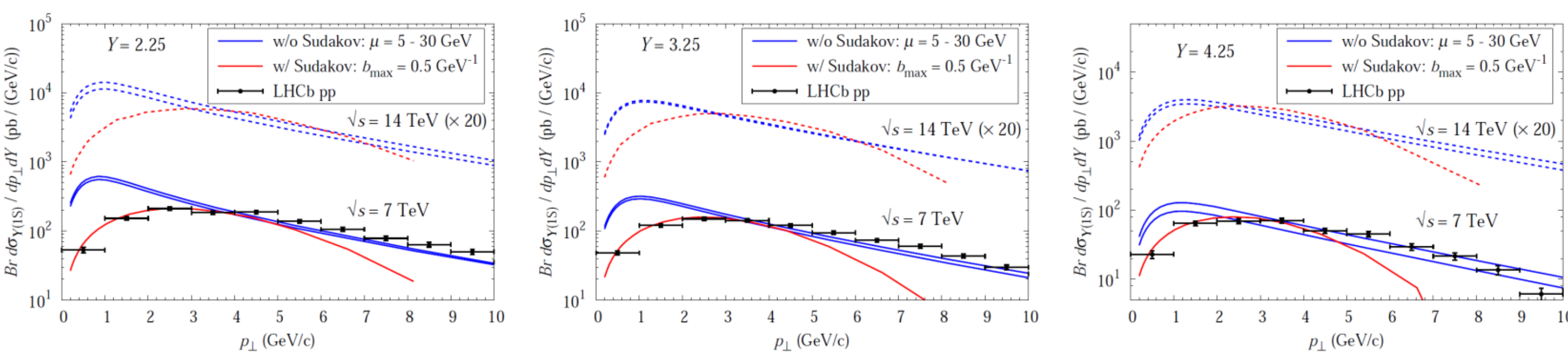


FIG. 2. Double differential cross section of $\Upsilon(1S)$ multiplied by a branching ratio of $\Upsilon(1S)$ decay into a lepton pair as a function of $p_\perp$ for $Y = 2.25$, 3.25, and 4.25 in pp collisions at $\sqrt{s} = 7$ TeV (solid lines) and 14 TeV (dotted lines). We choose $F_{\Upsilon(1S)} = 0.488$ for Eq. (1) and 0.390 for Eq. (5). The LHCb data is taken from Ref. [19].

Comparison with other methods

➢ Quasi-classical approximation

Kang, YQM, Venugopalan, 1309.7337

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

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

◆ 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

YQM, Venugopalan, 1408.4075

- **An approximation for quadrupole**

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

  - 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

Albacete, Dumitru, Fujii, Nara,1209.2001

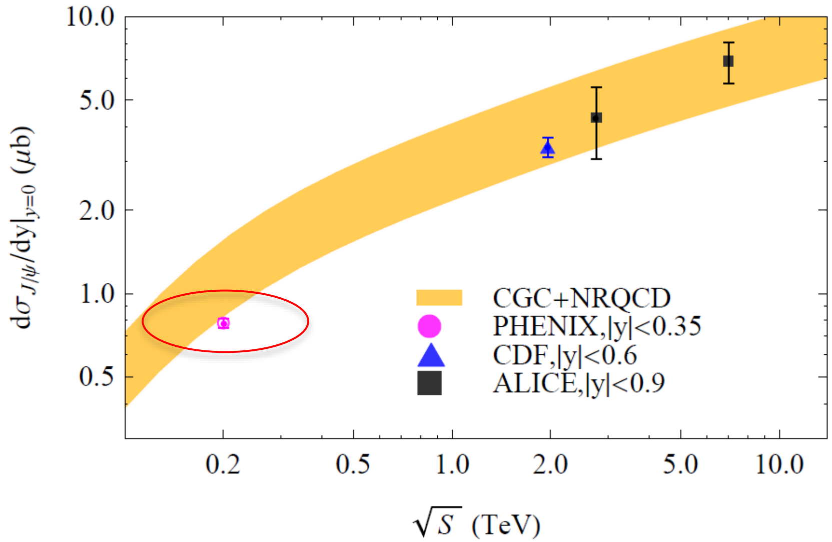
  - All parameters are fixed from fits to the HERA DIS data
  - $R_p = 0.48$fm to match with collinear PDF at large x

- **NRQCD CO matrix elements**
  - Taken from fitting high p_T data

Chao,YQM,Shao,Wang,Zhang,1201.2675

J/ψ @ p+p: $\sqrt{S}$ dependence

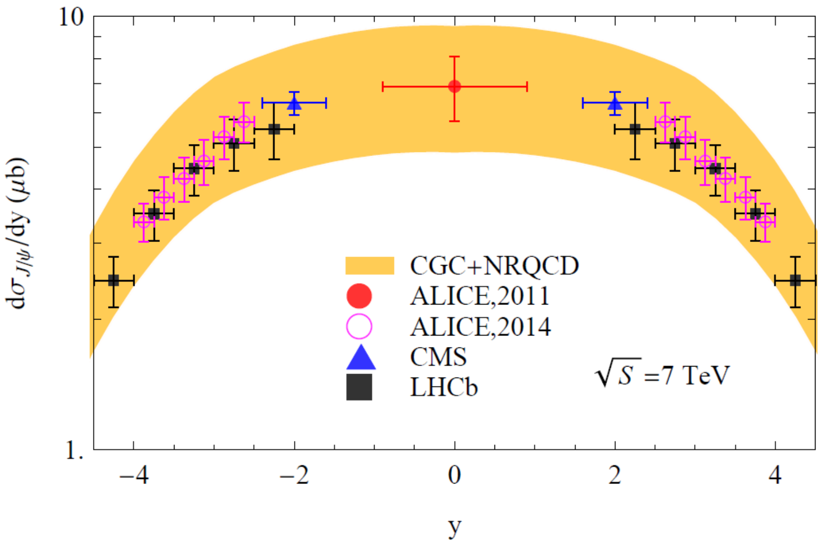
- **Good agreement with data**

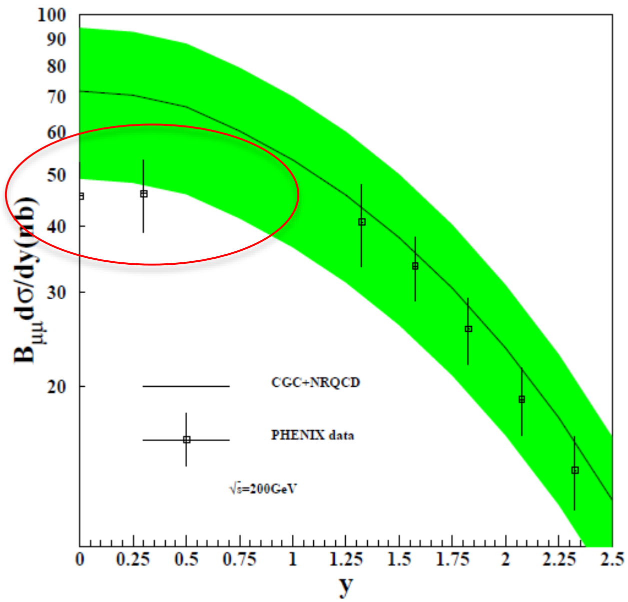


Worst agreement with RHIC data at central rapidity

J/ψ @ p+p: y dependence

➢ **Good agreement with**





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

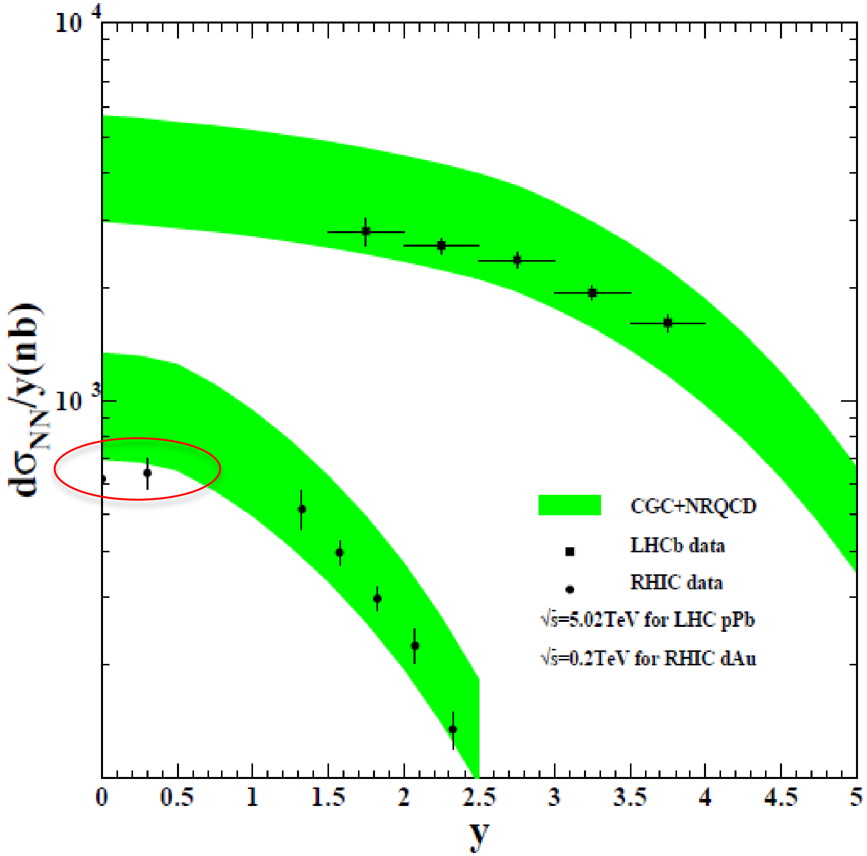
- $Q_{s0,A}^2 = N \times Q_{s0,p}^2$

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/ψ @ p+A: y dependence

- Good agreement with data



Worst agreement with RHIC data at central rapidity

R_{pA}

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

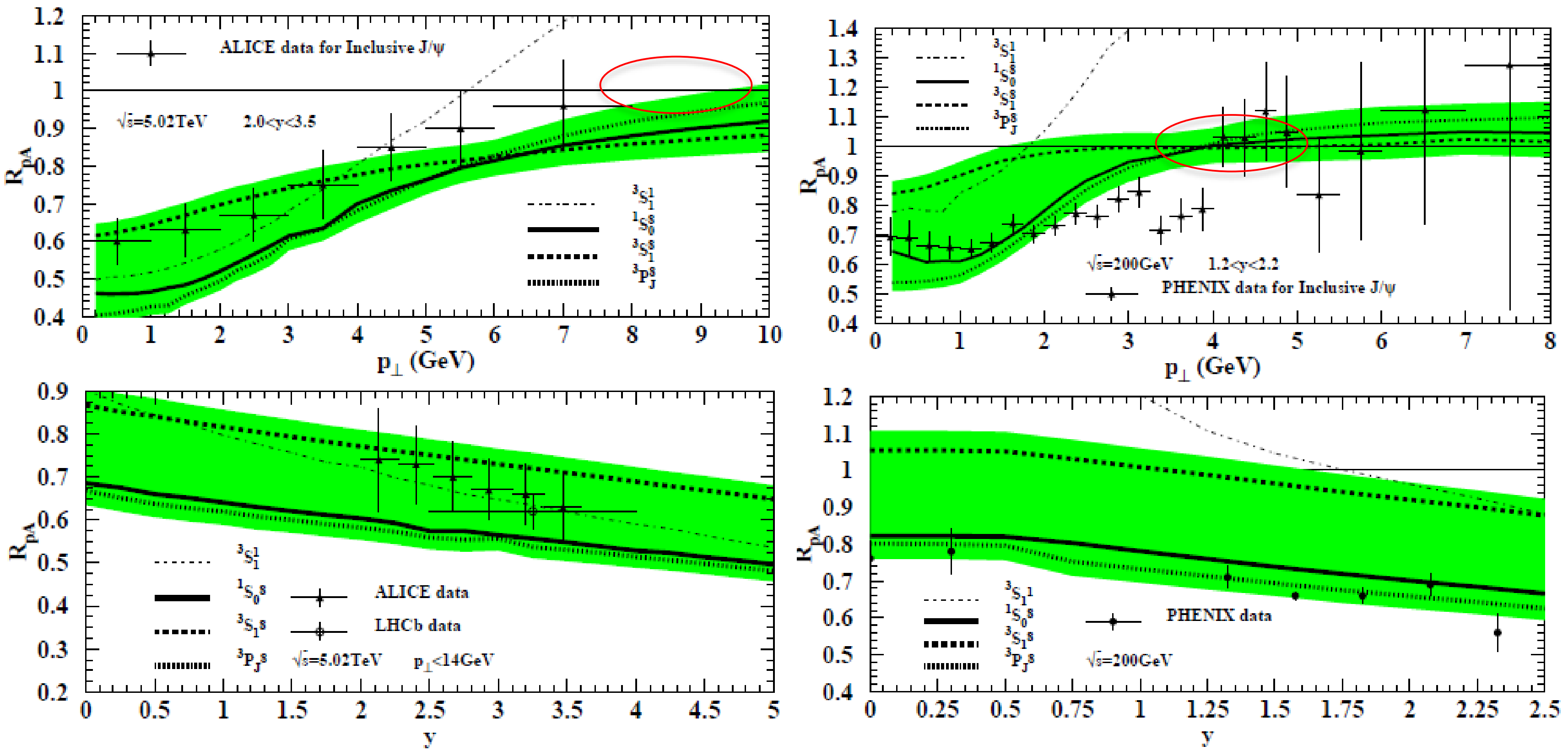
$$R_{pA} = \frac{d\sigma_{pA}}{A \times d\sigma_{pp}}$$

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

  - **Combining curves of all channels to provide the prediction for J/ψ**
  - **Results are independent of NRQCD matrix elements**
  - **R_{pA} calculated in this way is almost parameter-independent**

R_{pA}: p_T and y dependence

➢ **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