Event activity dependence of quarkonium production and polarization in small collision systems

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Self-introduction

- 2014: PhD from University of Tokyo, JP
  - ▸ Open/Hidden heavy flavor production in hadron-ion collisions

- 2014-2016: Postdoc, Central China Normal University, Wuhan, CN
  - ▸ Small-x factorization, Phenomenology of gluon saturation

- 2016-2018: Postdoc, Old Dominion University, Norfolk, USA
  mostly worked at Jefferson Lab

- 2018-2020: Postdoc, Jefferson Lab, Newport News, USA
  - ▸ QCD and TMD factorization, Hadronization of light and heavy particles

- 2021-present: Postdoc, Subatech, Nantes, FR
  - ▸ Energy loss mechanism in cold nuclear matter (ANR, COLDLOSS)

This presentation → Quarkonium, Small-x saturation

Quarkonium production in small collision systems

<u>Heavy ion collisions: Large systems</u>

J/ψ, Υ suppression due to the presence of QGP, strong flow effects

<u>Small systems</u>

- proton-proton (p+p): elementary process, production mechanism in vacuum
- proton-nucleus (p+A): cold nuclear matter (CNM) effects (shadowing, energy-loss, saturation)

※ e^+e^- and lepton-hadron/ion (EIC) collisions provide more clean test-grounds for studying quarkonium production mechanism.

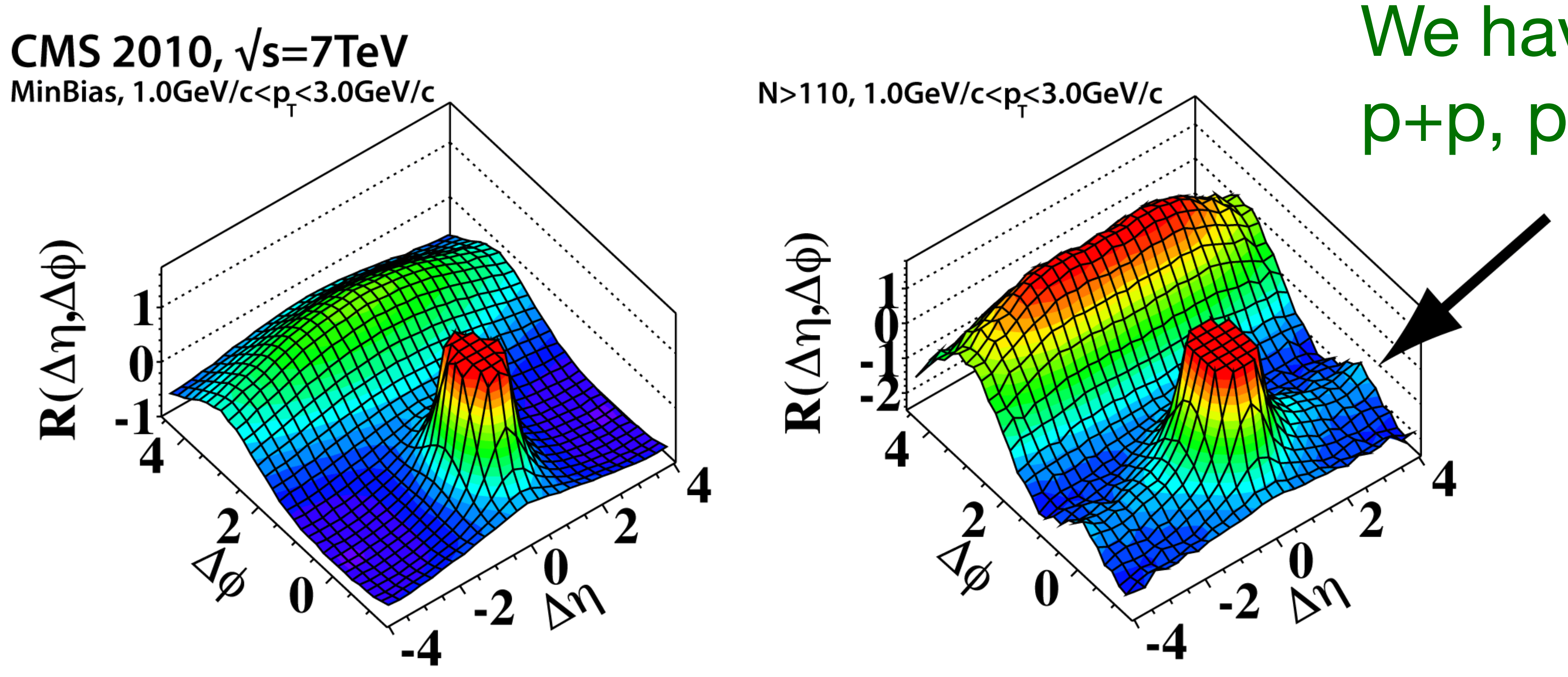
Small collision systems (p+p and p+A) give a baseline against large collision system (A+A), however, the QCD dynamics behind CNM effects is a long-standing issue.

One has to look into quarkonium production by considering

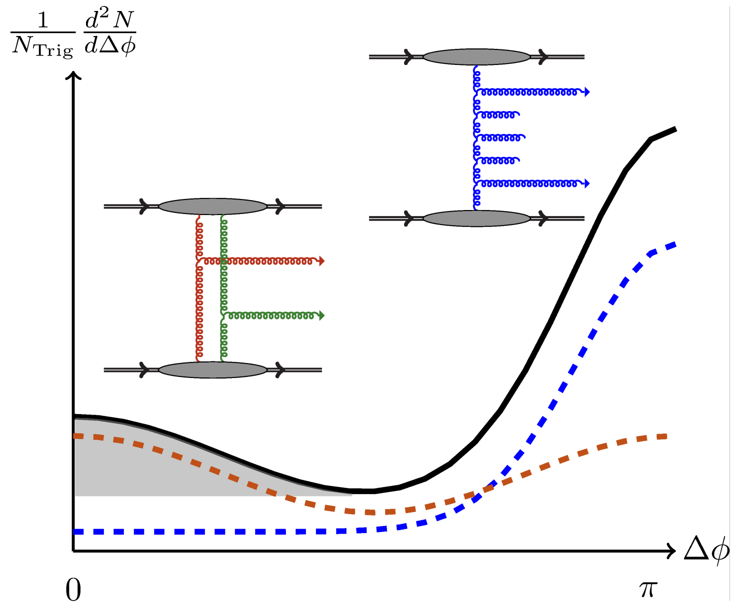
$\sqrt{s}$, y, $p_\perp$, m dependence, system size dependence, and event activity (multiplicity) dependence

Quarkonium production in high multiplicity events is a new puzzle to be addressed.

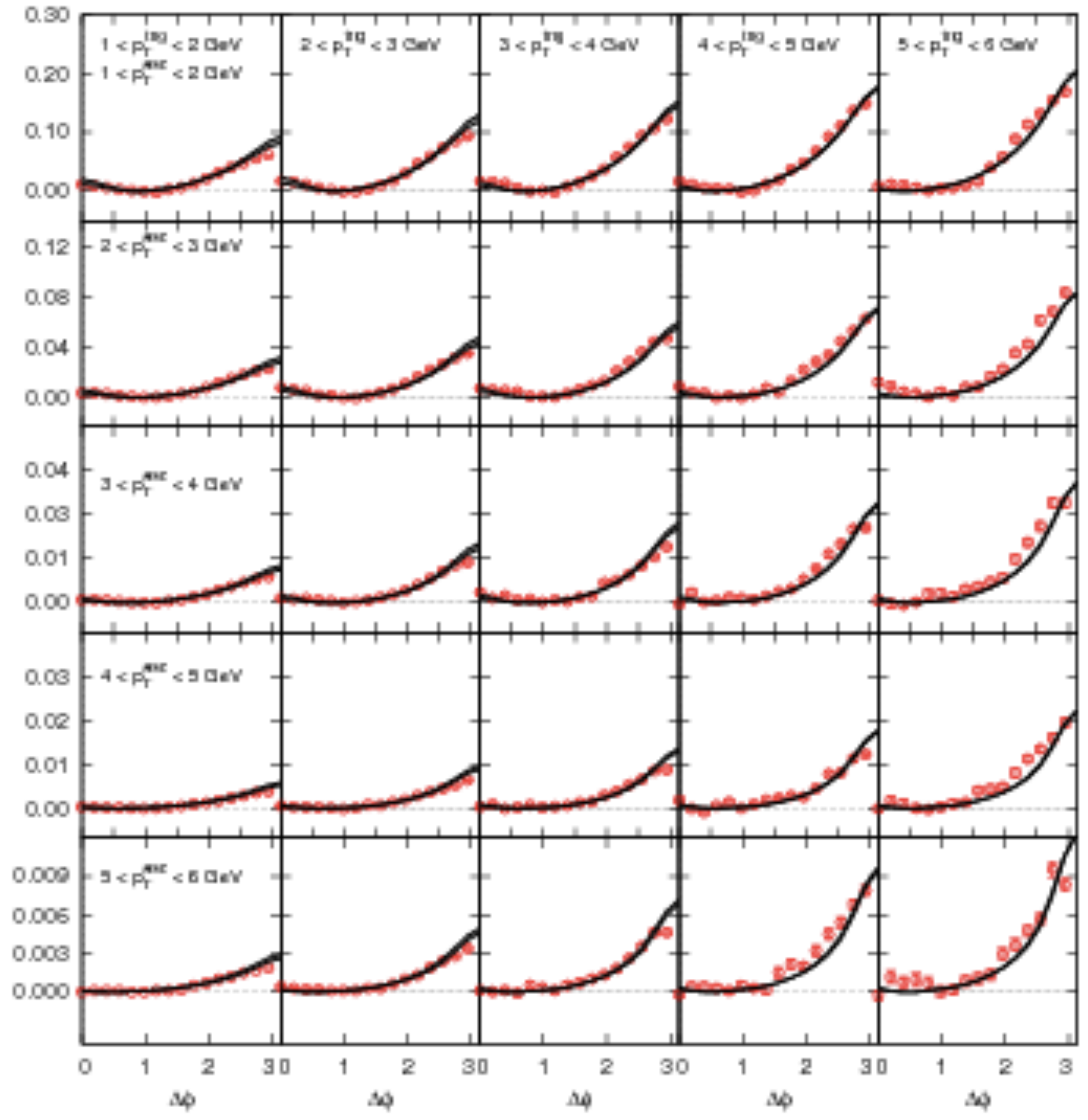
The ridge in small collision systems



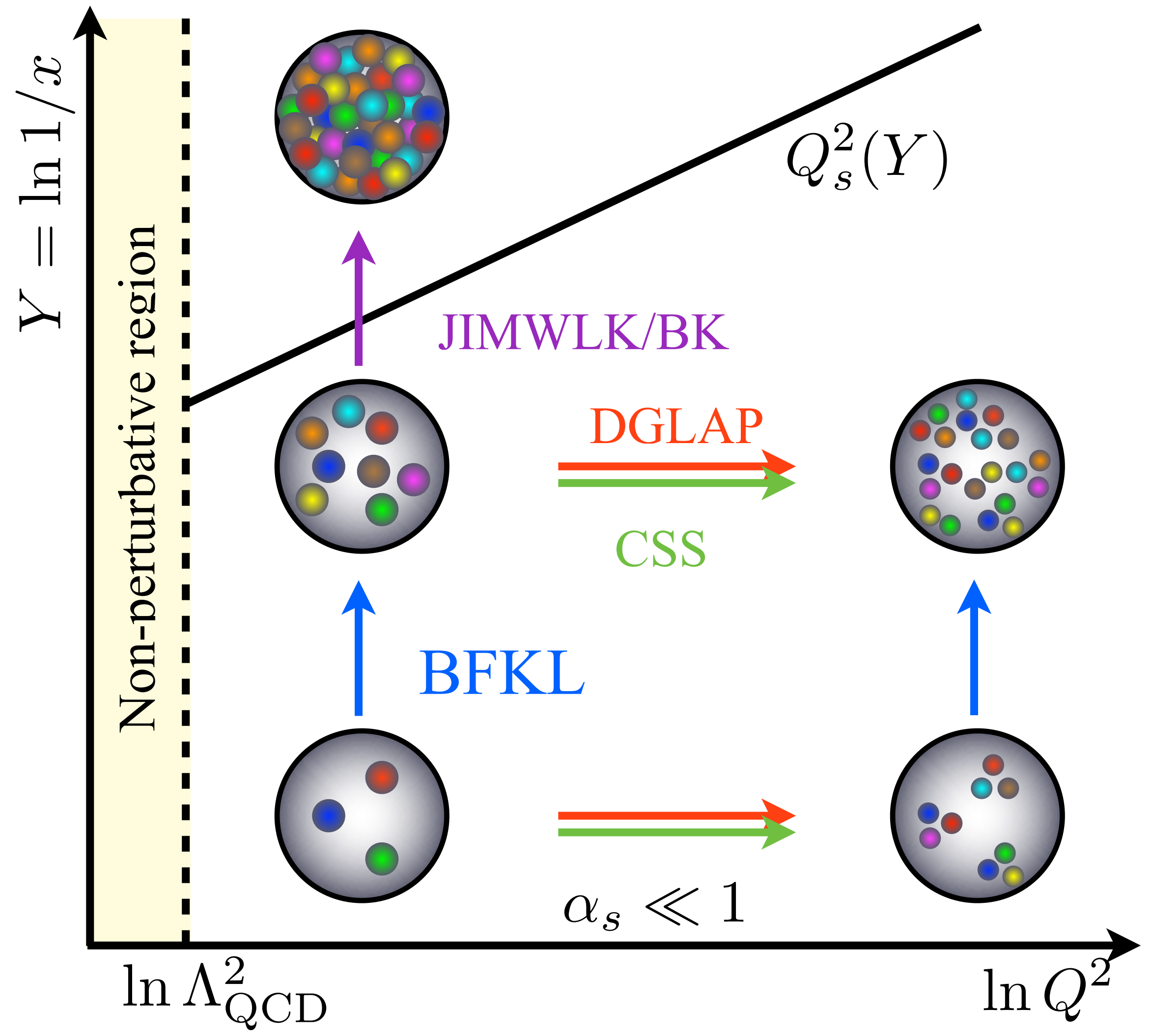
We have seen similar features in p+p, p+A, A+A collisions!



Dusling, Venugopalan, 1302.7018



- Even when flow effect is absent, p+p and p+A data can be described in the CGC framework; correlations from initial state interactions.



At high energies, gluon fields behave like classical: $A \sim 1/g$

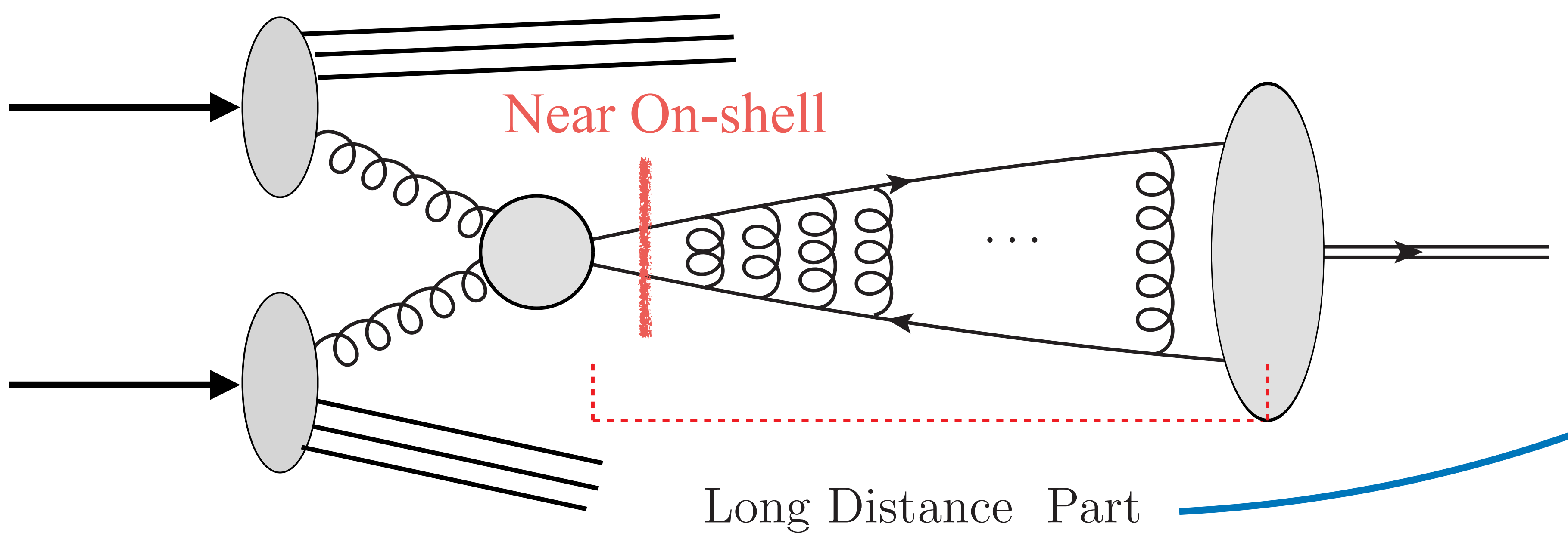
$$\frac{dN_{ch}}{dy} \sim \int d^2b_\perp d^2k_\perp \langle AA \rangle \sim \frac{S_\perp Q_s^2}{\alpha_s}$$

Rare lumpy partons configuration
$\leftrightarrow$ large Q_s $\leftrightarrow$ High multiplicity

Collectivity of multi-particle production have been studied in the CGC approach.
See, e.g., Dusling, Mace, Venugopalan, 1705.00745 , …

Can we explain N_{ch} dependence of quarkonium production in the CGC framework?

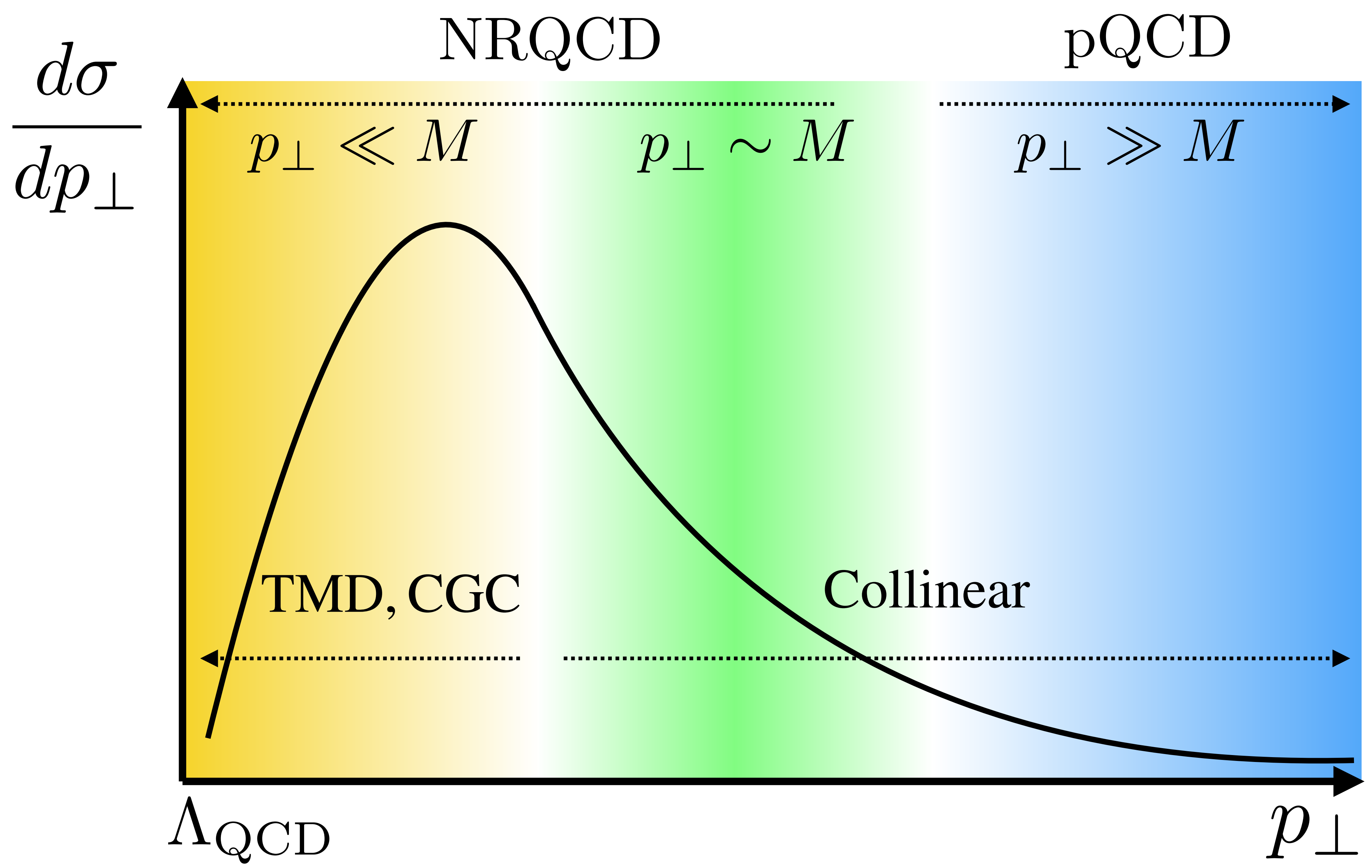
Hadronic quarkonium production at a glance



Nonperturbative bound state formation part:

- Color Singlet Model (CSM)
- Color Evaporation Model (CEM)
- Non-Relativistic QCD (NRQCD)
- pQCD Fragmentation function (only when $p_\perp \gg m$)

For J/ψ production, soft interactions between $c\bar{c}$ and beam remnants can be suppressed by $1/p_\perp$ or $1/p_{||}$ (forward rapidity).



High $p_\perp$: Collinear factorization

$$d\hat{\sigma} \approx f_{i/p}(x_1) \otimes f_{j/p}(x_2) \otimes H_{ij\to c\bar{c}+X}(m, p_\perp) + \mathcal{O}\left(\frac{\Lambda}{p_\perp}, \frac{\Lambda}{m}\right)$$

Low $p_\perp$: TMD factorization

$$d\hat{\sigma} \approx f_{i/p}(x_1, k_\perp) \otimes f_{j/p}(x_2, k_\perp) \otimes H_{ij\to c\bar{c}+X}(m) + \mathcal{O}\left(\frac{p_\perp}{m}\right)$$

Low $P_\perp$ at small-x: CGC framework

$$d\hat{\sigma} \approx f_{i/p}(x_1, k_\perp) \otimes f_{j/p}(x_2, k_\perp) \otimes H_{ij\to c\bar{c}+X}(m) + \mathcal{O}\left(\frac{Q_s}{p_\perp}, \frac{Q_s}{m}, \cdots\right)$$

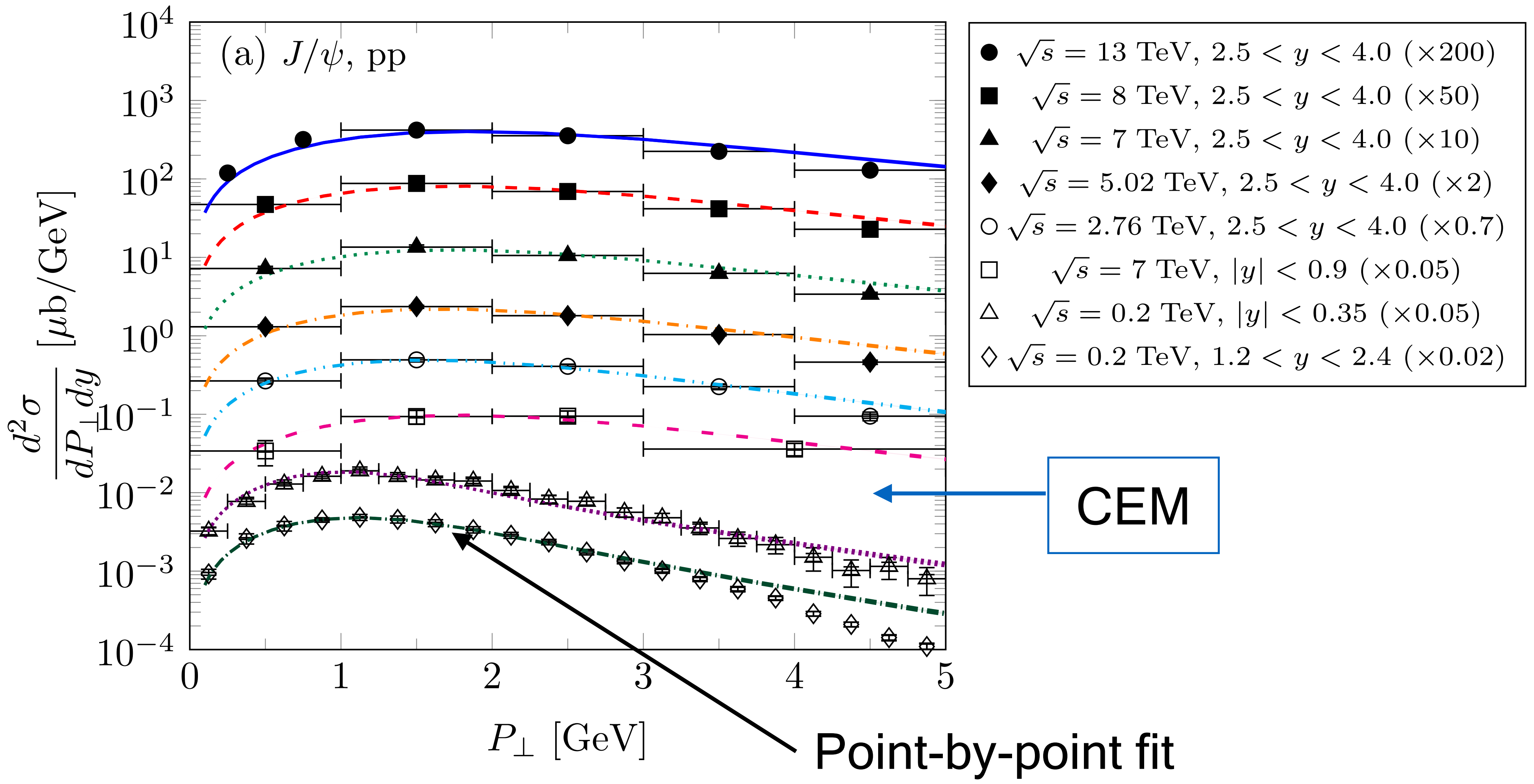
Power corrections must be important especially when Q_s gets harder.

Assumption: large logs in x is predominant over logs in Q^2.

J/ψ production in minimum bias events

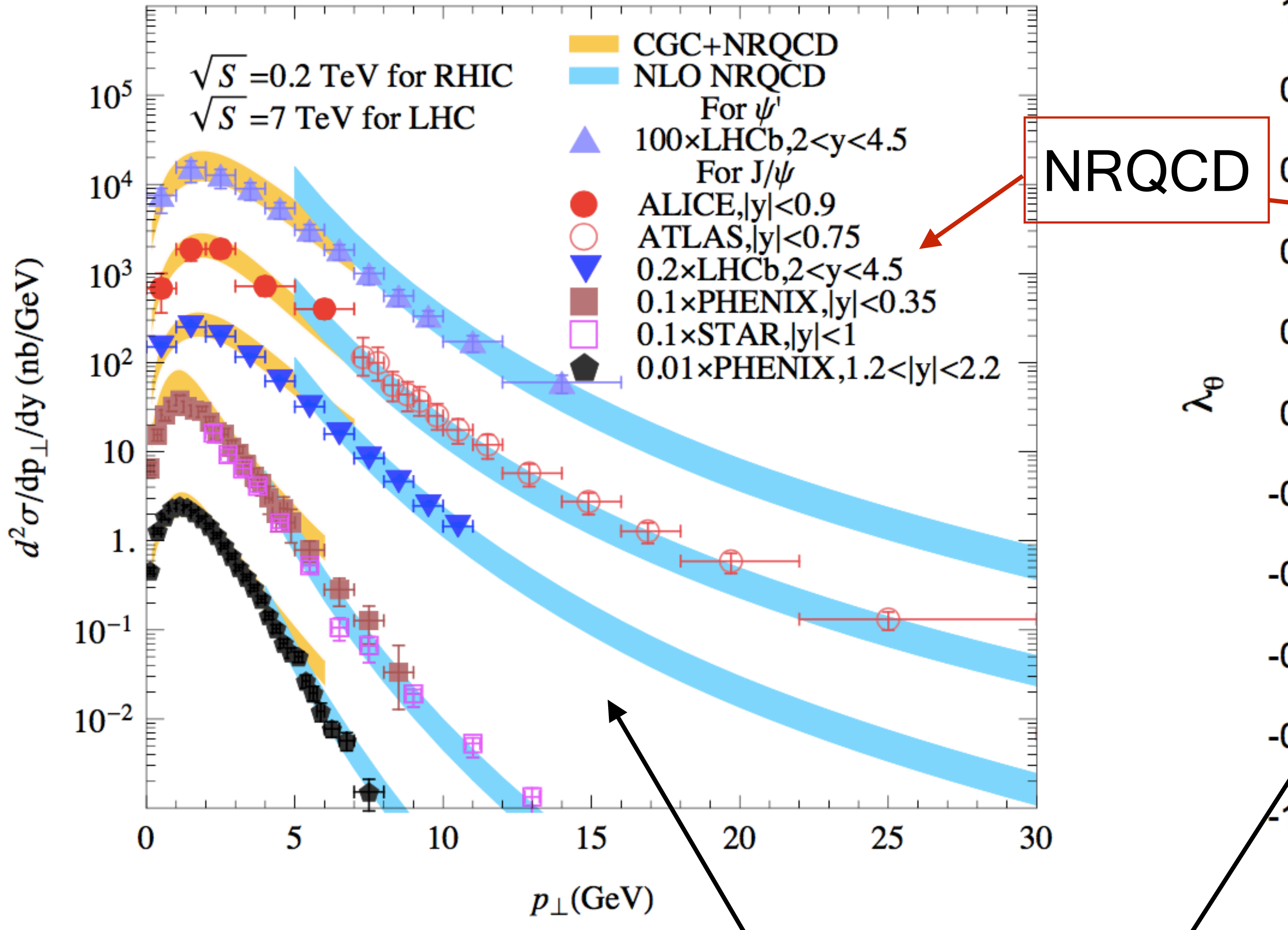
pp collisions

Ma, Venugopalan, KW, Zhang, 1707.07266



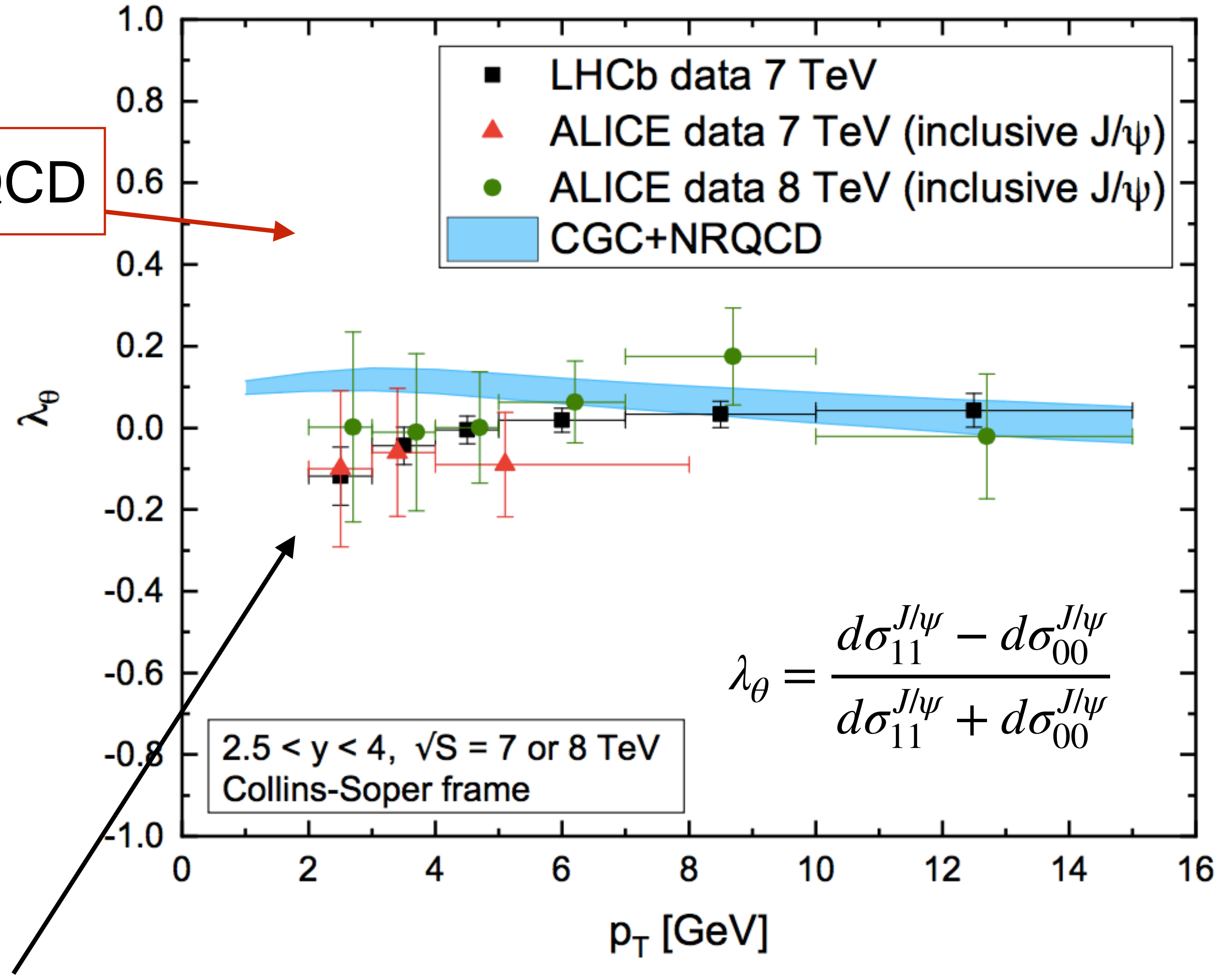
The CGC gives a good parametrization of the transverse momentum dependent (TMD) gluon distribution function at small-x.

Ma, Venugopalan, 1408.4075



$$\langle \mathcal{O}^{J/\psi}[^1S_0^{[8]}]\rangle = 0.089 \pm 0.0098 \mathrm{GeV}^3$$
$$\langle \mathcal{O}^{J/\psi}[^3S_1^{[8]}]\rangle = 0.0030 \pm 0.0012 \mathrm{GeV}^3$$
$$\langle \mathcal{O}^{J/\psi}[^3P_0^{[8]}]\rangle/m_c^2 = 0.0056 \pm 0.0021 \mathrm{GeV}^3$$

Ma, Stebel, Venugopalan, 1809.03573



Fitted by high $p_\perp$ prompt J/ψ data at Tevatron

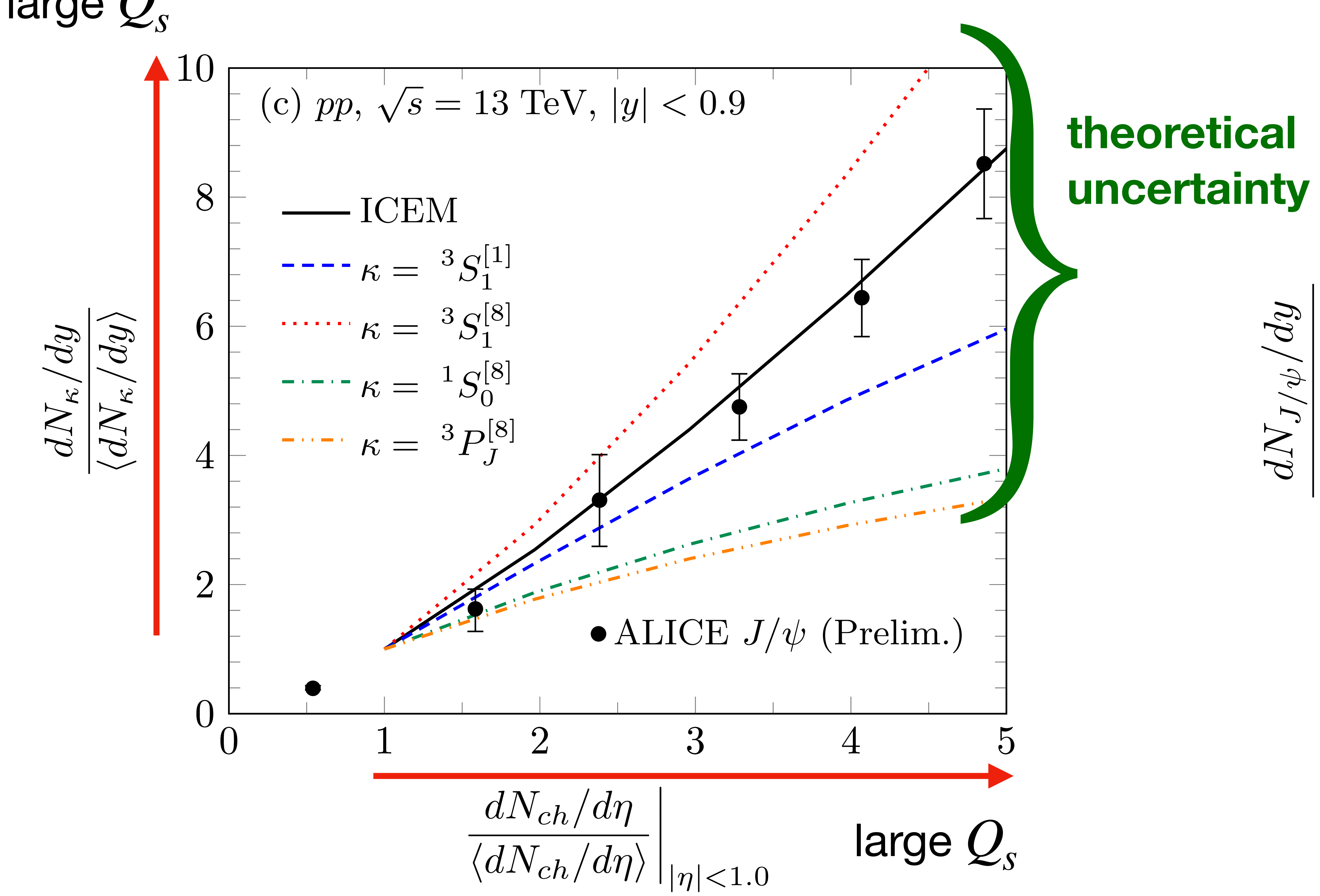
Chao, Ma, Shao, Wang, Zhang, 1201.2675

pA collisions

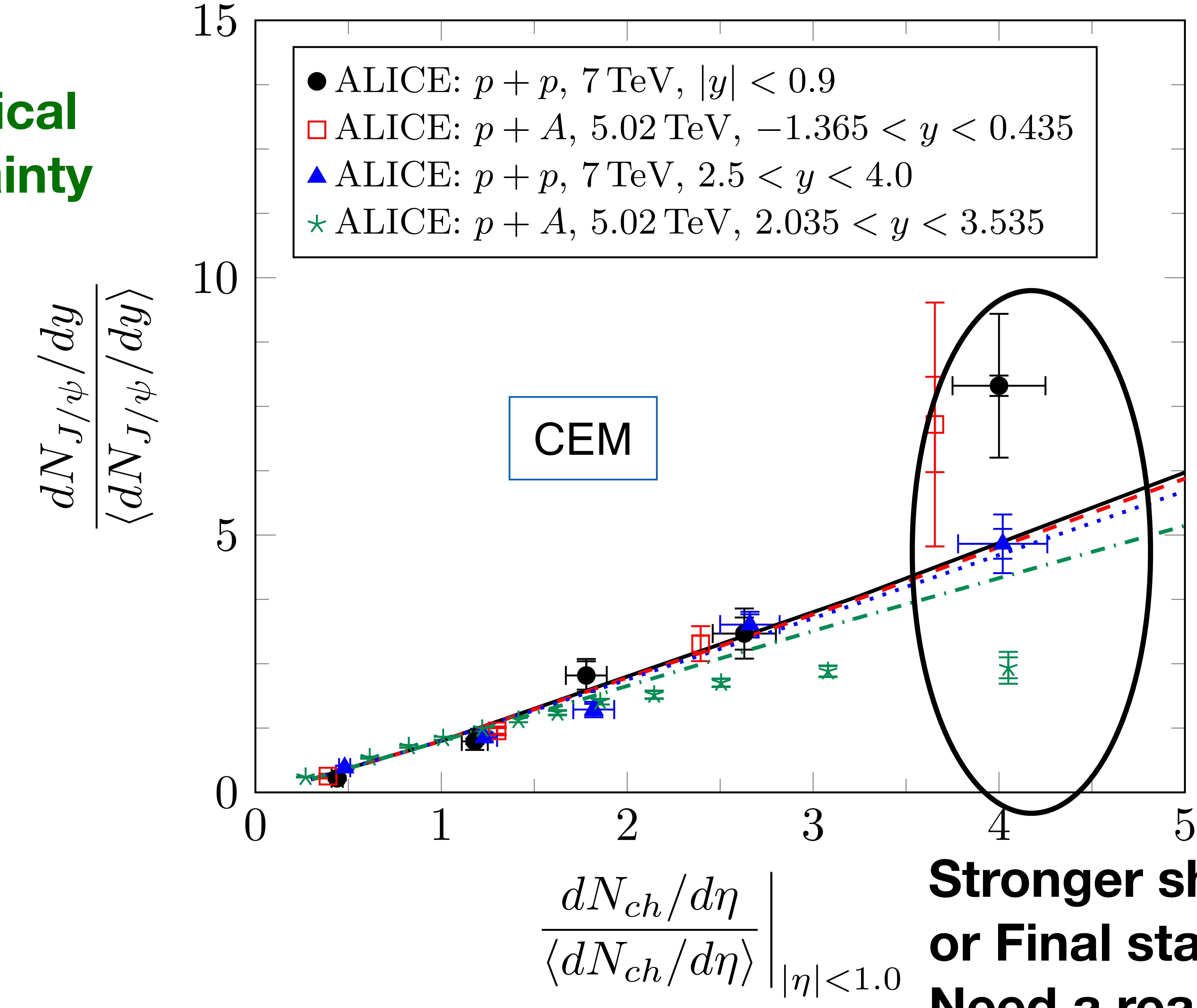
- The CGC computations now agree with data on $p_\perp$ spectra, R_{pA}. *Ma, Venugopalan, Zhang, 1503.07772, Ma, Venugopalan, KW, Zhang, 1707.07266*
- Elliptic flow v_2 can be obtained in the CGC. *Zhang, Marquet, Qin, Shi, Wang, Wei, Xiao, 2002.09878*

J/ψ production in high multiplicity events

Ma, Tribedy, Venugopalan, KW, 1803.11093, 1807.05655



Ma, Stebel, Venugopalan, KW, HP2020 proceedings
See also https://indico.cern.ch/event/751767/contributions/3770908/



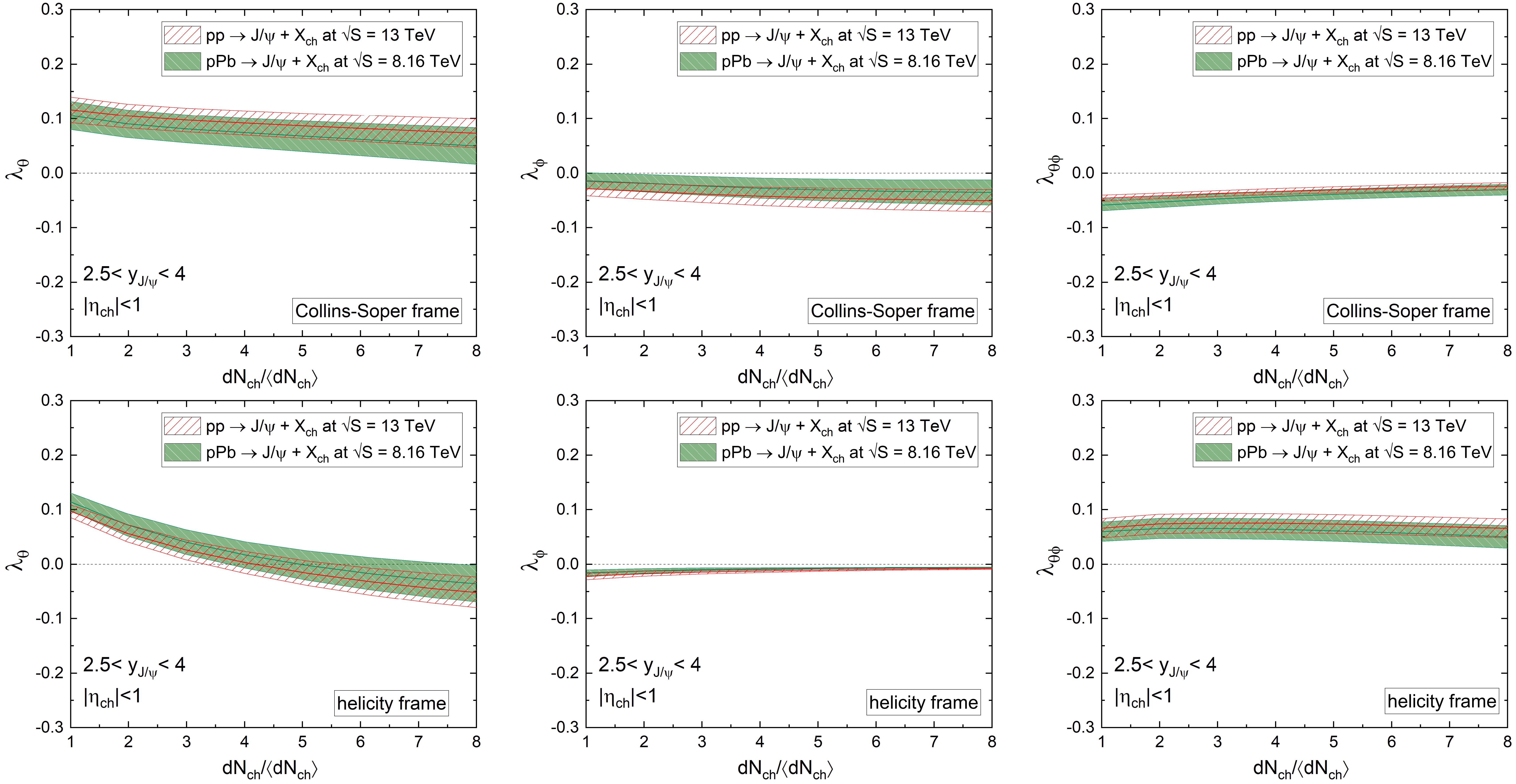
Stronger shadowing in pA?
or Final state interaction?
Need a realistic parameter tuning

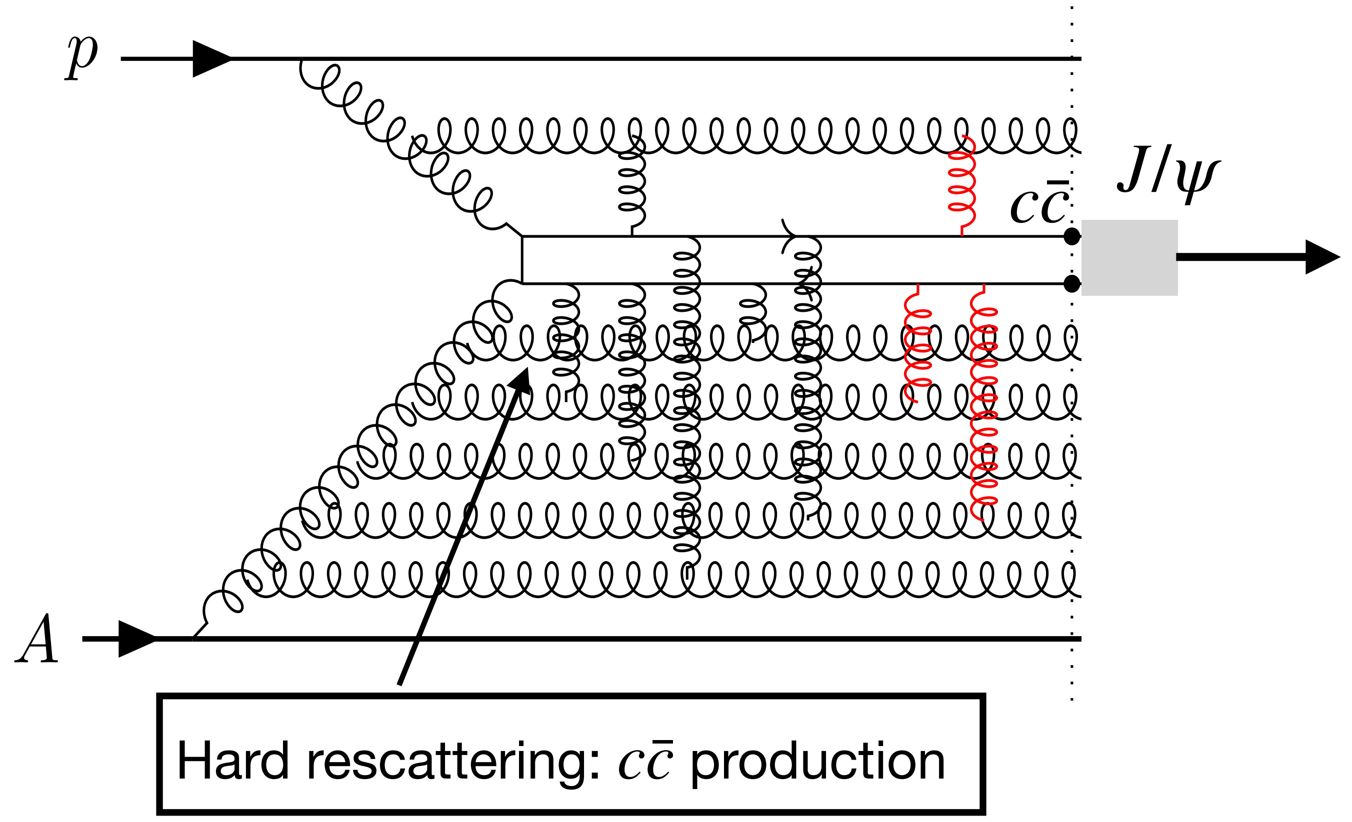
- The CGC framework can describe D-mesons vs. N_{ch} in p+p at mid rapidity — analogous to J/ψ.
- Self-normalized J/ψ yield has a system size dependence: important constraint to the CGC approach.

Predictions for J/ψ polarization vs. N_{ch}

$$\frac{d\sigma^{J/\psi(\to l^+l^-)}}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$

Stebel, KW, 2103.01724





As N_{ch} increases, J/ψ gets more unpolarized due to the strong multiple-rescattering at a short distance.
This is a benchmark work for further study.

Outlook

- We need to compare the dilute-dense CGC framework to a dense-dense framework (Glasma) to study multiple-rescattering effects systematically.

- We have to revisit centrality dependence of J/ψ production in MB pA collisions, $p_\perp$ cut dependence of J/ψ production in high multiplicity events, in addition, open heavy flavor production. *Stebel, Venugopalan, KW, in preparation*

Thank you!

Comments, questions are welcome!

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