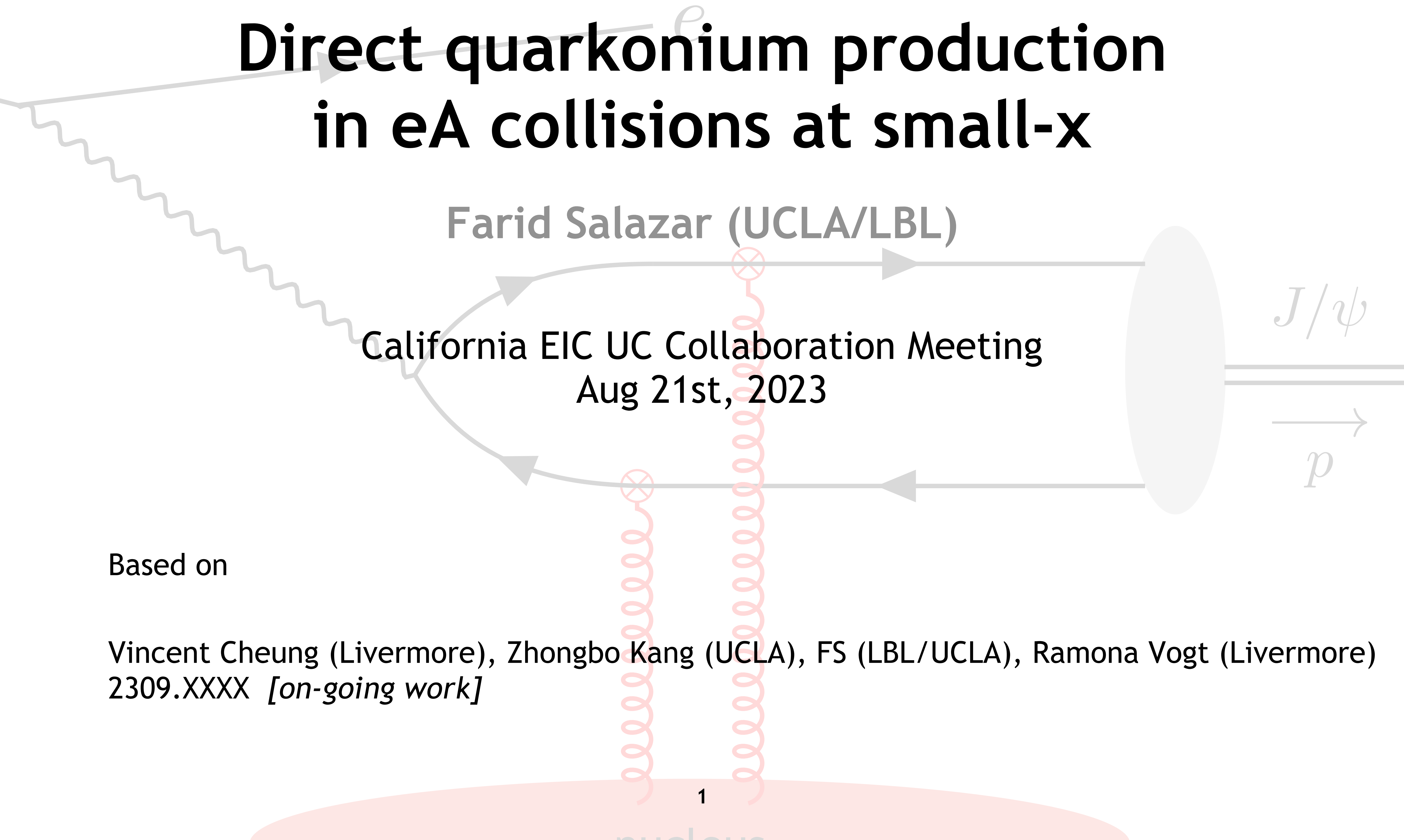
Direct quarkonium production in eA collisions at small-x

Farid Salazar (UCLA/LBL)

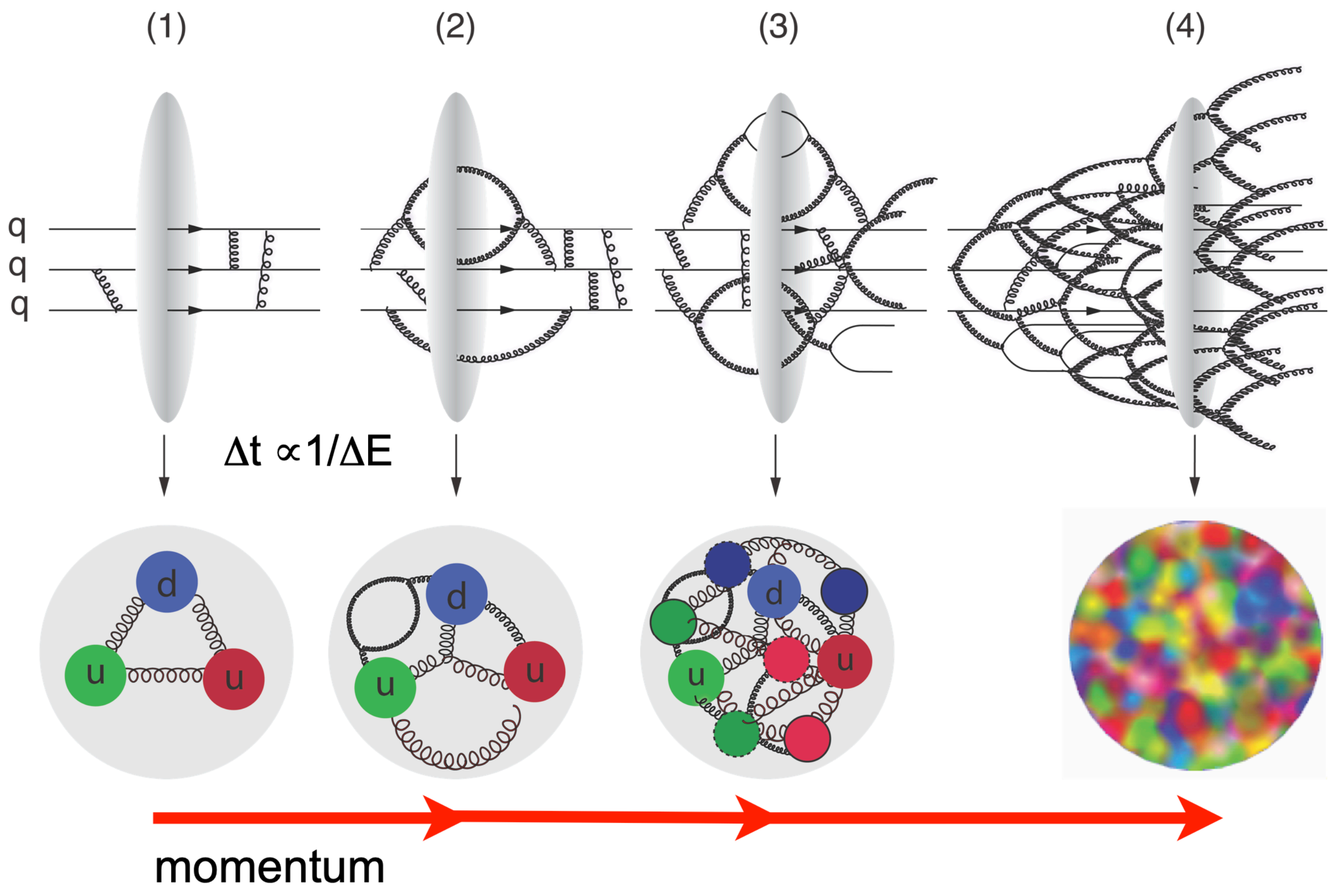


California EIC UC Collaboration Meeting
Aug 21st, 2023

Based on

Vincent Cheung (Livermore), Zhongbo Kang (UCLA), FS (LBL/UCLA), Ramona Vogt (Livermore)
2309.XXXX *[on-going work]*

Quarkonium as a tool to search for gluon saturation



Gluon occupancy is high at small-x (high-energy) and it saturates

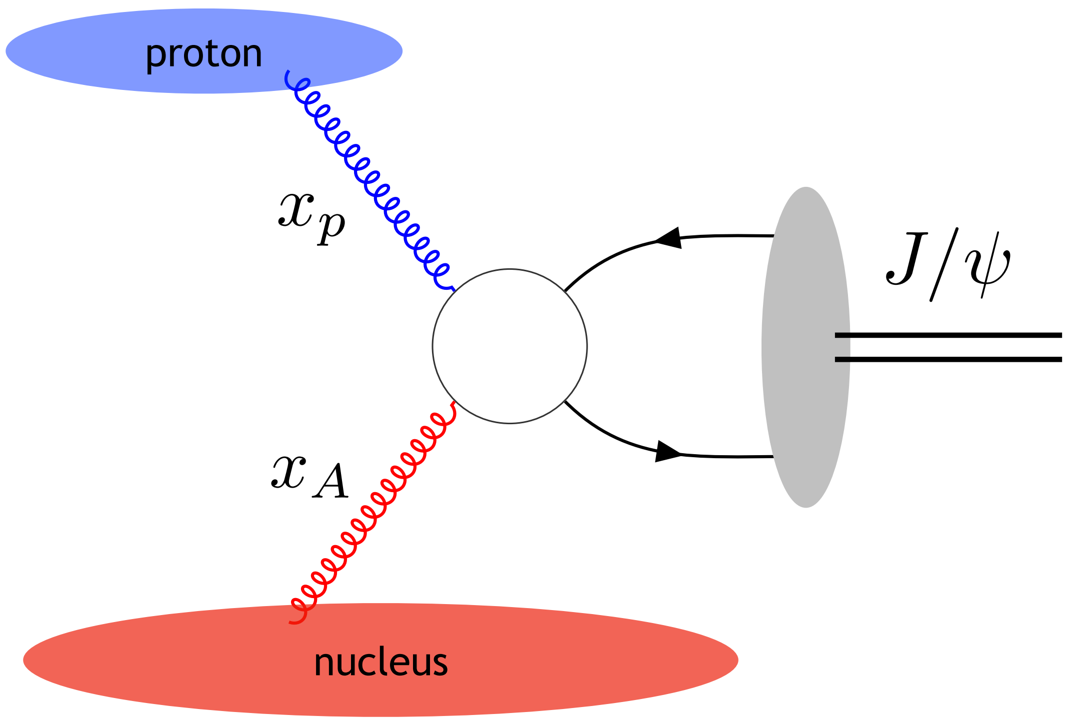
↓

Gluons with transverse momentum $k_\perp \lesssim Q_s$ (saturation scale) are suppressed

↓

Imprint on particle production in high-energy collisions at low $k_\perp$

$$Q_s^2 \propto \frac{A^{1/3}}{x^\lambda} \sim M^2_{J/\psi}$$



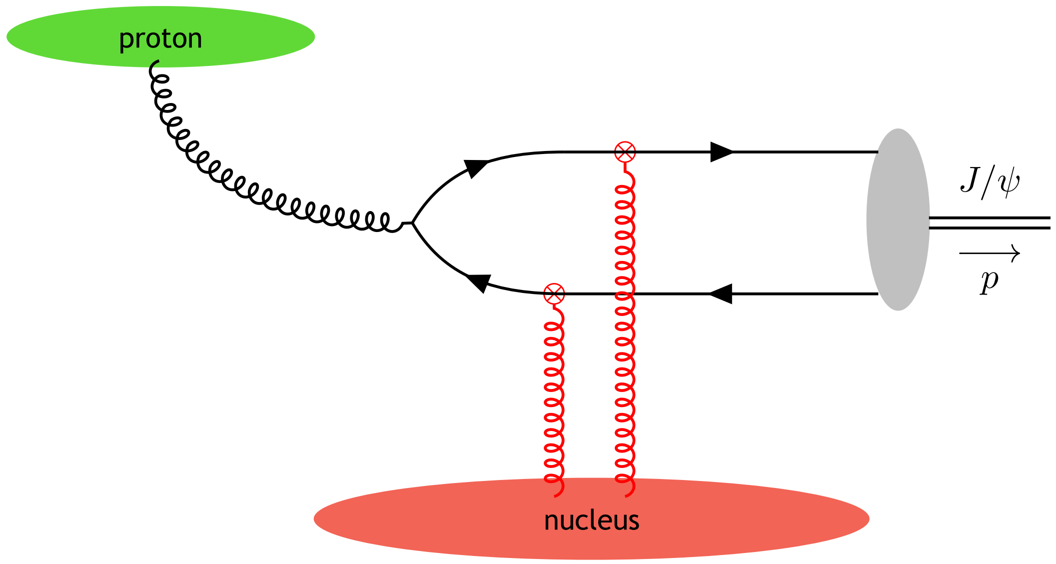
$$x_p = \sqrt{\frac{M^2_{J/\Psi} + P^2_\perp}{s}} e^{Y} \qquad x_A = \sqrt{\frac{M^2_{J/\Psi} + P^2_\perp}{s}} e^{-Y}$$

Forward production $Y \gg 1$

$$x_A \ll 1$$

Quarkonium production in proton-nucleus collisions

CGC meets NRQCD



Non-relativistic QCD

Non-perturbative LDME

$$\frac{d\sigma^{J/\psi}}{d\boldsymbol{p}_\perp^2\, d\eta} = \sum_\kappa \langle \mathcal{O}_\kappa^{J/\psi} \rangle \frac{d\hat{\sigma}^\kappa}{d\boldsymbol{p}_\perp^2\, d\eta}$$

Decompose contribution into specific quantum state of the heavy quark pair

$$\kappa = {}^{2S+1}L_J^{[c]}$$

S (spin), L (angular momentum), J (total angular momentum), c (color state)

Contributing to J/ψ production: ${}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$

Short-distance coefficients

$$\frac{d\hat{\sigma}^\kappa}{d\boldsymbol{p}_\perp^2\, d\eta} = g(x_p, \boldsymbol{k}_\perp) \otimes \widetilde{\Gamma}^\kappa(\boldsymbol{p}_\perp; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp, \boldsymbol{k}_\perp) \otimes \widetilde{\mathcal{G}}^\kappa(x_A, \boldsymbol{p}_\perp; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp)$$

Proton UGD/TMD

Perturbative factor

Nuclear-dependent (CGC)

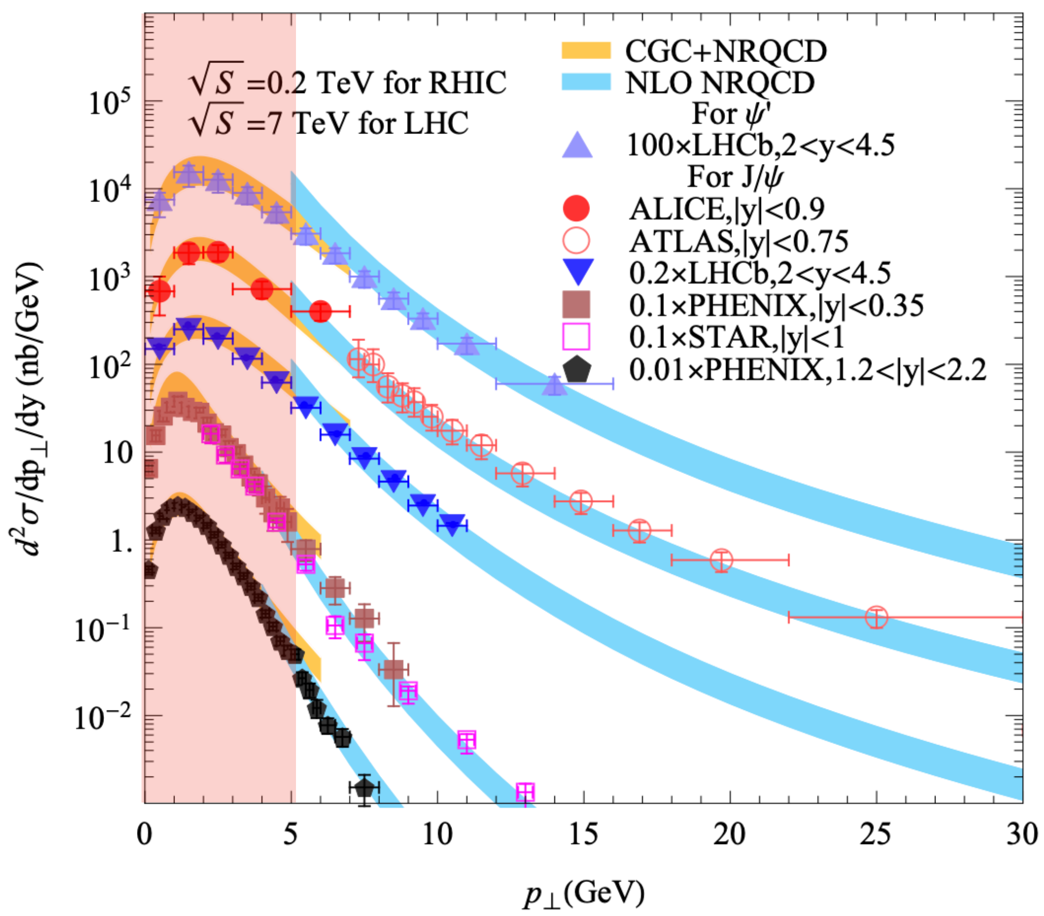
Kang, Ma, Venugopalan, Zhang (JHEP 2013)

Confronting to RHIC and LHC data

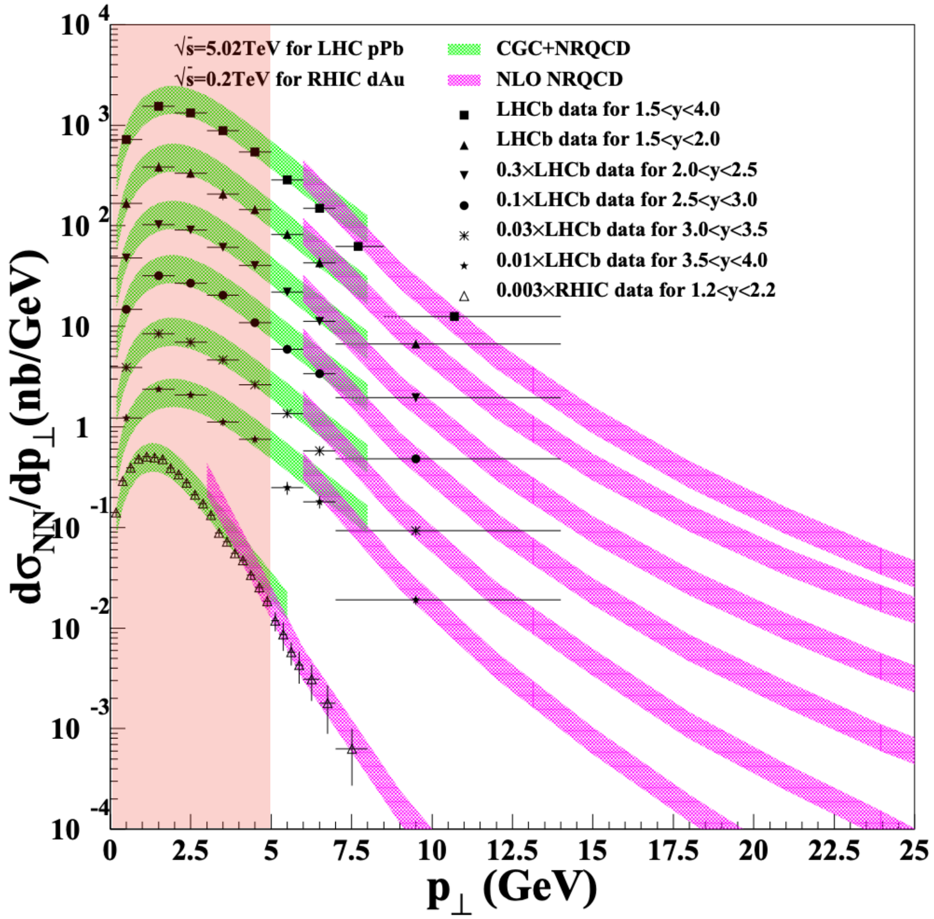
Ma, Venugopalan (PRL 2014)
Ma, Venugopalan, Zhang (PRD 2015)

Transverse momentum distribution

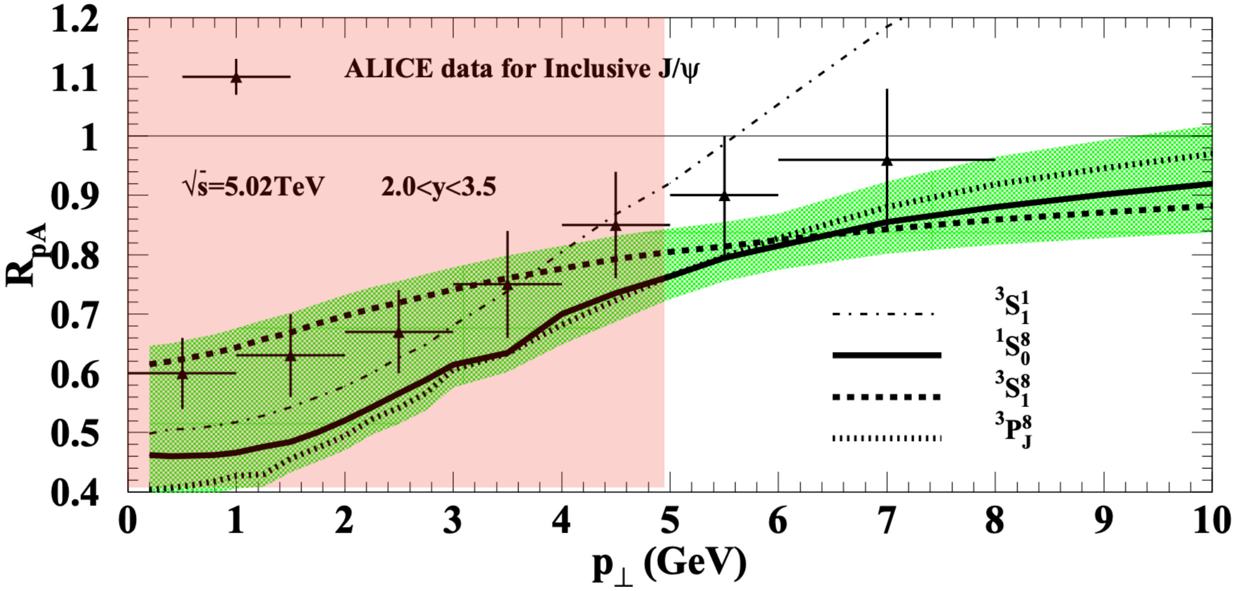
Proton-proton



Proton-nucleus



Nuclear modification Ratio



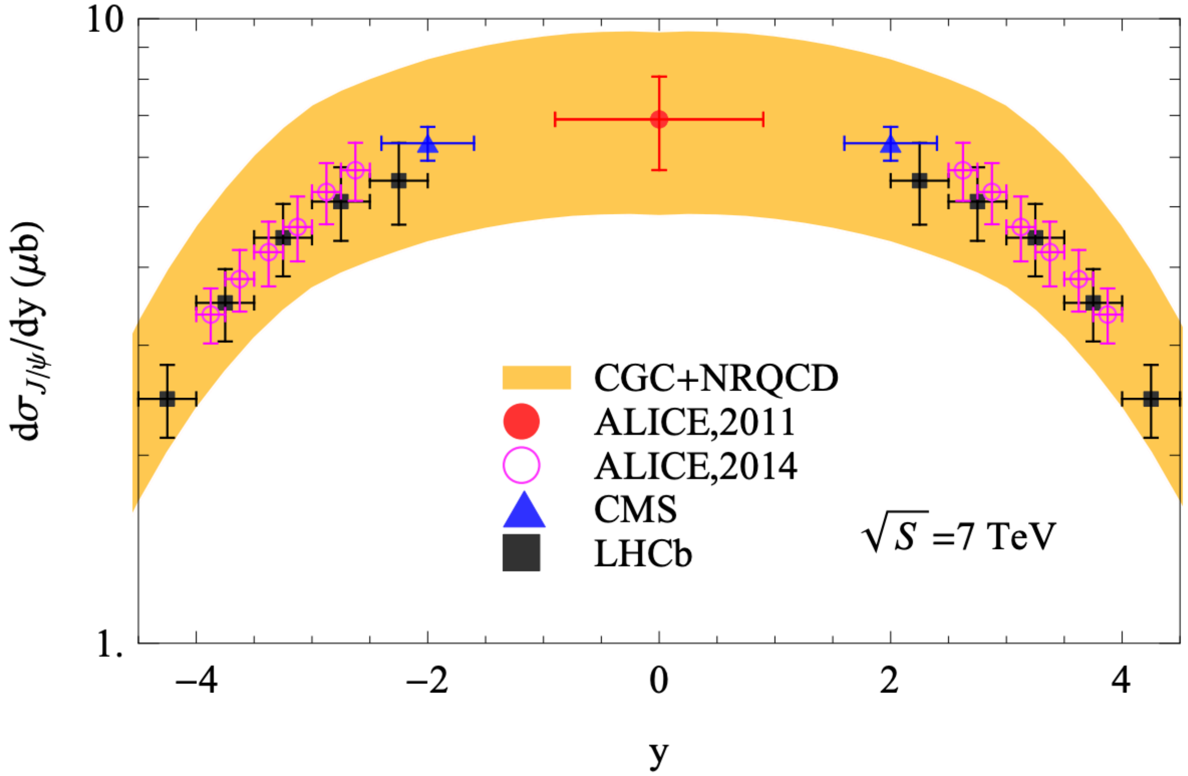
CGC provides good description of experimental data at low pT ($p_\perp \lesssim Q_s$)

Confronting to RHIC and LHC data

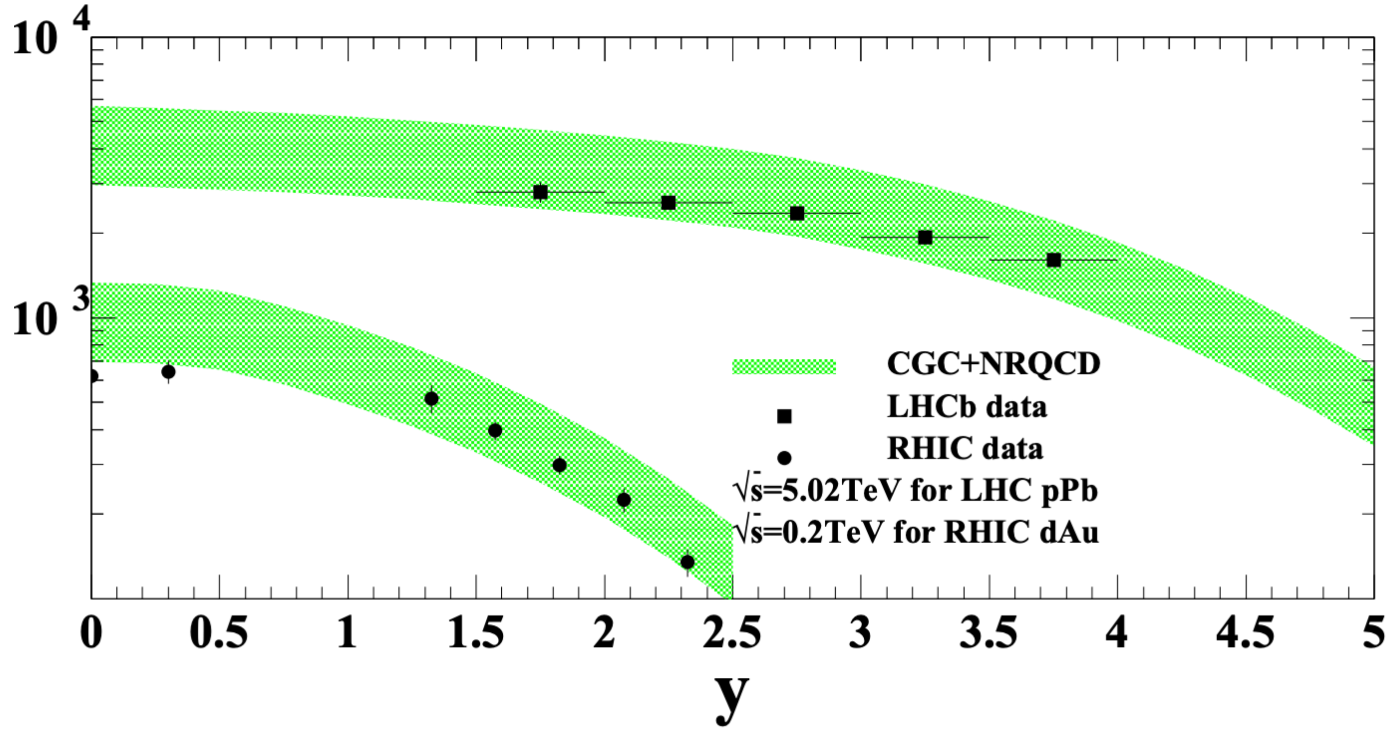
Ma, Venugopalan (PRL 2014)
Ma, Venugopalan, Zhang (PRD 2015)

Rapidity distribution and nuclear modification

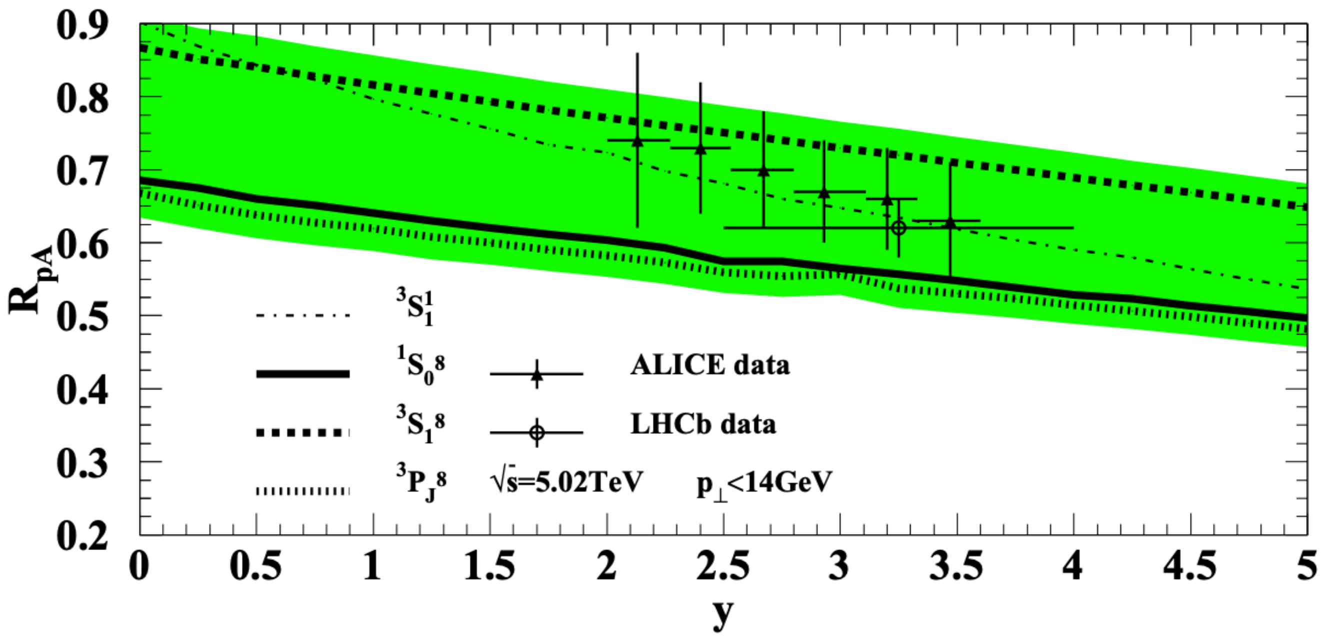
Proton-proton



Proton-nucleus



Nuclear modification Ratio

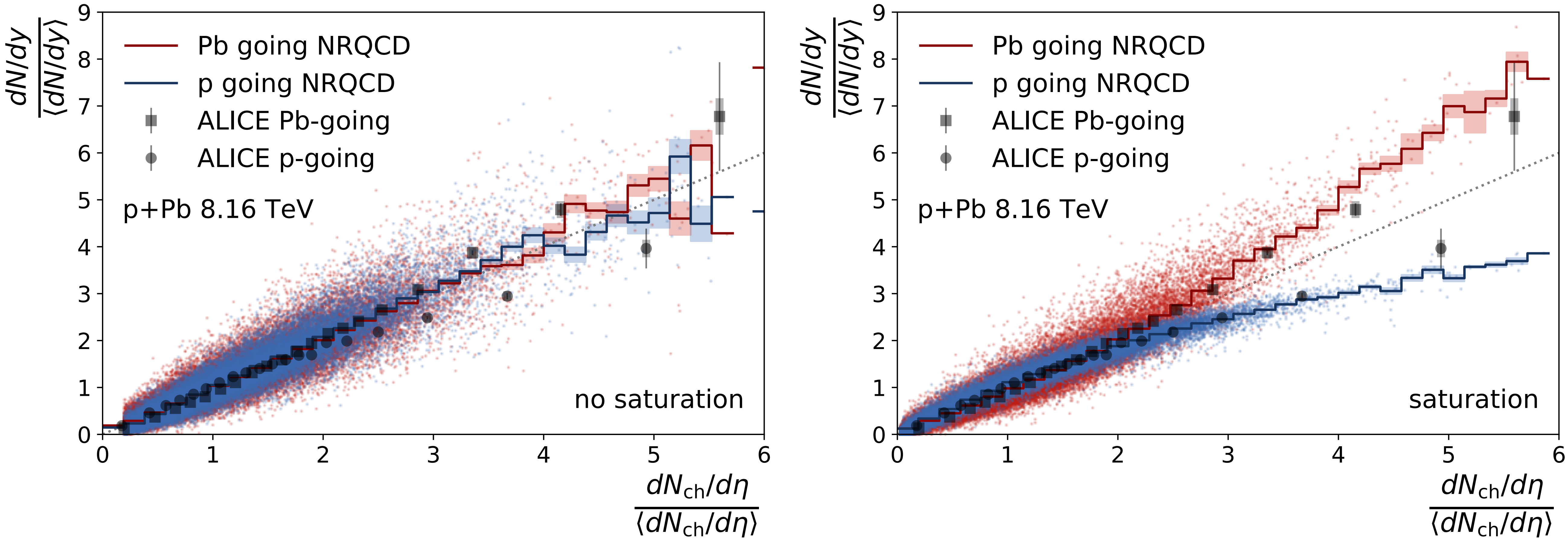


Rapidity distributions are integrated over $p_\perp$, low $p_\perp$ dominates the bulk of the cross-section

Confronting to RHIC and LHC data

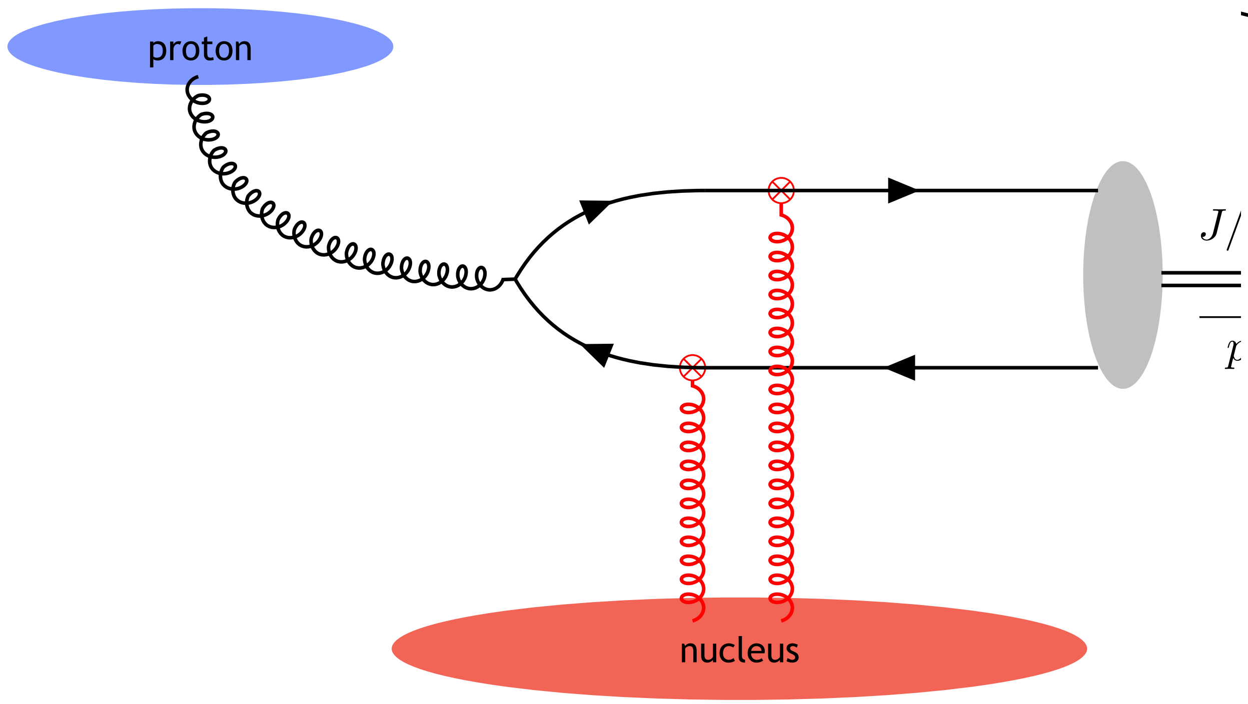
J/ψ multiplicity vs charged hadron multiplicity

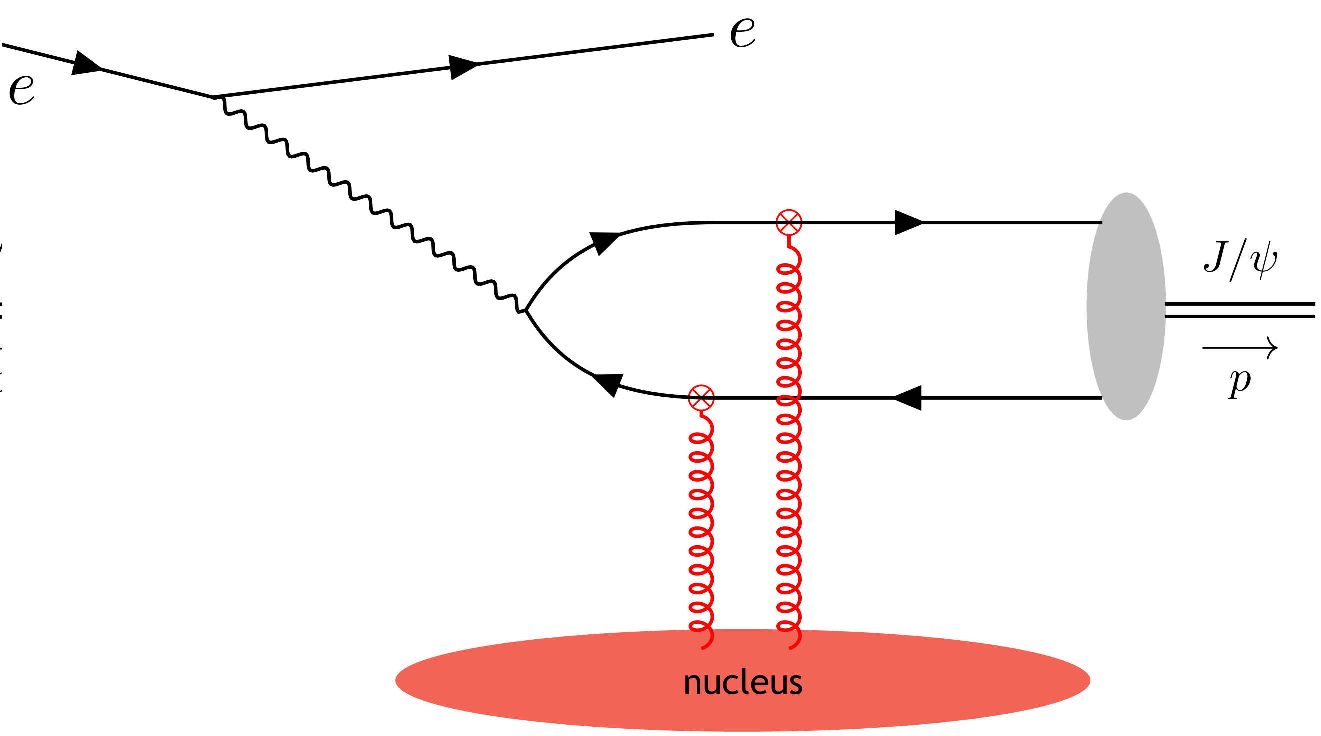
FS, Schenke, Soto-Ontoso *[PLB 2022]*



Sub-nuclear fluctuations in hotspots size and saturation scale provide a natural framework to generate different multiplicity classes that describe well LHC data

What about electron-nucleus deep inelastic scattering?





Replace the proton projectile by an electron

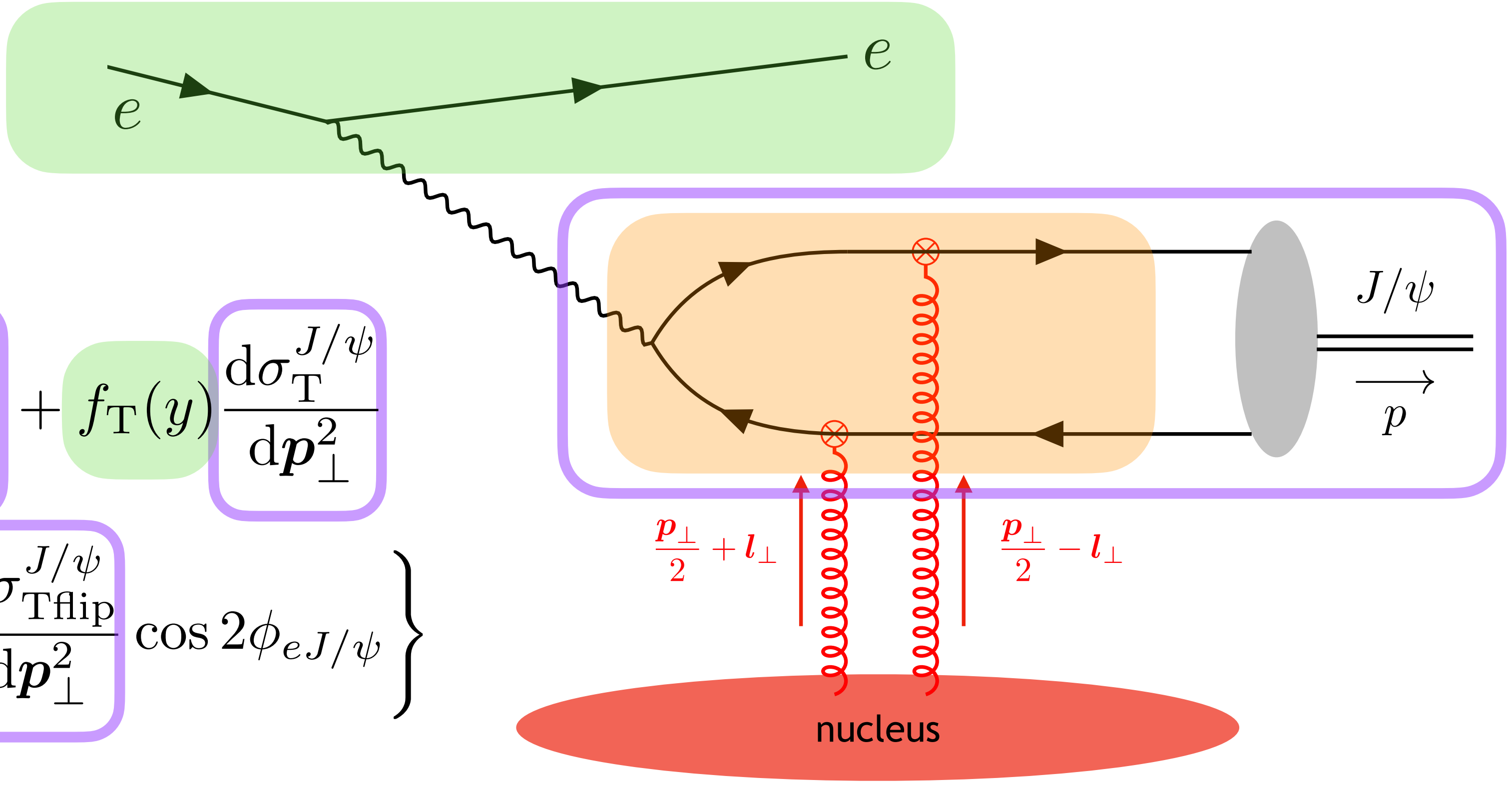
Reconstruct kinematics of the “projectile” photon
Electromagnetic probe -> cleaner theoretical calculation
Possible to measure at the future EIC

Surprisingly, calculations [in CGC] hadn’t been done yet, not even at LO…

Motivated our work in Cheung, Kang, FS, Vogt [2309.XXXX]

Quarkonium production in electron-nucleus collisions

CGC meets NRQCD



Direct J/ψ production in eA collision

$$\frac{\mathrm{d}\sigma^{J/\psi}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}y\mathrm{d}\boldsymbol{p}_\perp^2\,\mathrm{d}\phi_{eJ/\psi}} = \frac{\alpha_{\mathrm{em}}}{2\pi^2 y x_{\mathrm{Bj}}}\left\{ f_{\mathrm{L}}(y)\frac{\mathrm{d}\sigma_{\mathrm{L}}^{J/\psi}}{\mathrm{d}\boldsymbol{p}_\perp^2} + f_{\mathrm{T}}(y)\frac{\mathrm{d}\sigma_{\mathrm{T}}^{J/\psi}}{\mathrm{d}\boldsymbol{p}_\perp^2} \right.$$

$$\left. + f_{\mathrm{TL}}(y)\frac{\mathrm{d}\sigma_{\mathrm{TL}}^{J/\psi}}{\mathrm{d}\boldsymbol{p}_\perp^2}\cos\phi_{eJ/\psi} + f_{\mathrm{Tflip}}(y)\frac{\mathrm{d}\sigma_{\mathrm{Tflip}}^{J/\psi}}{\mathrm{d}\boldsymbol{p}_\perp^2}\cos 2\phi_{eJ/\psi} \right\}$$

Direct J/ψ production in $\gamma * A$ collision

$$\frac{\mathrm{d}\sigma_\lambda^{J/\psi}}{\mathrm{d}\boldsymbol{p}_\perp^2} = \sum_\kappa \langle \mathcal{O}_\kappa^{J/\psi}\rangle \frac{\mathrm{d}\hat{\sigma}_\lambda^\kappa}{\mathrm{d}\boldsymbol{p}_\perp^2}$$

$$\boxed{\frac{\mathrm{d}\hat{\sigma}_\lambda^\kappa}{\mathrm{d}\boldsymbol{p}_\perp^2} = \int \frac{\mathrm{d}^2\boldsymbol{l}_\perp}{2\pi}\int \frac{\mathrm{d}^2\boldsymbol{l}'_\perp}{2\pi}\widetilde{\Gamma}_\lambda^\kappa(\boldsymbol{p}_\perp, Q; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp)\widetilde{\mathcal{G}}_Y^\kappa(\boldsymbol{p}_\perp; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp)}$$

LDME for J/ψ production

Short-distance coefficients

Convolution manifestly breaks kT factorization

Spin and polarization-dependent perturbative factor (20 functions)

Nuclear-dependent CGC distribution (Octet and Singlet)

Quarkonium production in electron-nucleus collisions

kT factorization and the Weizsäcker Williams gluon distribution

Our result for Short-distance coefficients in CGC + NRQCD

$$\frac{\mathrm{d}\hat{\sigma}^{\kappa}_{\lambda}}{\mathrm{d}\boldsymbol{p}_{\perp}^{2}} = \int \frac{\mathrm{d}^{2}\boldsymbol{l}_{\perp}}{2\pi} \int \frac{\mathrm{d}^{2}\boldsymbol{l}'_{\perp}}{2\pi} \widetilde{\Gamma}^{\kappa}_{\lambda}(\boldsymbol{p}_{\perp}, Q; \boldsymbol{l}_{\perp}, \boldsymbol{l}'_{\perp}) \widetilde{\mathcal{G}}^{\kappa}_{Y}(\boldsymbol{p}_{\perp}; \boldsymbol{l}_{\perp}, \boldsymbol{l}'_{\perp})$$

Improved TMD limit $Q_s^2 \ll Q^2 + M_{J/\psi}^2$

Expansion following
Boussarie, Mehtar-Tani
(PRD 2021)

$$\frac{\mathrm{d}\hat{\sigma}^{\kappa}_{\lambda}}{\mathrm{d}\boldsymbol{p}_{\perp}^{2}} = \mathcal{H}^{\kappa}_{\lambda,\alpha\alpha'}(Q, \boldsymbol{p}_{\perp}) xG^{\alpha\alpha'}(x, \boldsymbol{p}_{\perp})$$

TMD limit $Q_s^2 \ll Q^2 + M_{J/\psi}^2$ and $\boldsymbol{p}_{\perp}^2 \ll Q^2 + M_{J/\psi}^2$

Reproduces results by
Bacchetta, Boer, Pisano and Taels
(EPJC 2018) within TMD factorization

$$\frac{\mathrm{d}\hat{\sigma}^{\kappa}_{\lambda}}{\mathrm{d}\boldsymbol{p}_{\perp}^{2}} = H^{\kappa}_{\lambda,\alpha\alpha'}(Q) xG^{\alpha\alpha'}(x, \boldsymbol{p}_{\perp})$$

→ Satisfies (generalized)
kT factorization

$$xG^{\alpha\alpha'}(x, \boldsymbol{p}_{\perp})$$

Weizsäcker-Williams
UGD or TMD at small-x

See e.g. Dominguez,
Marquet, Xiao, Yuan
(PRD 2013)

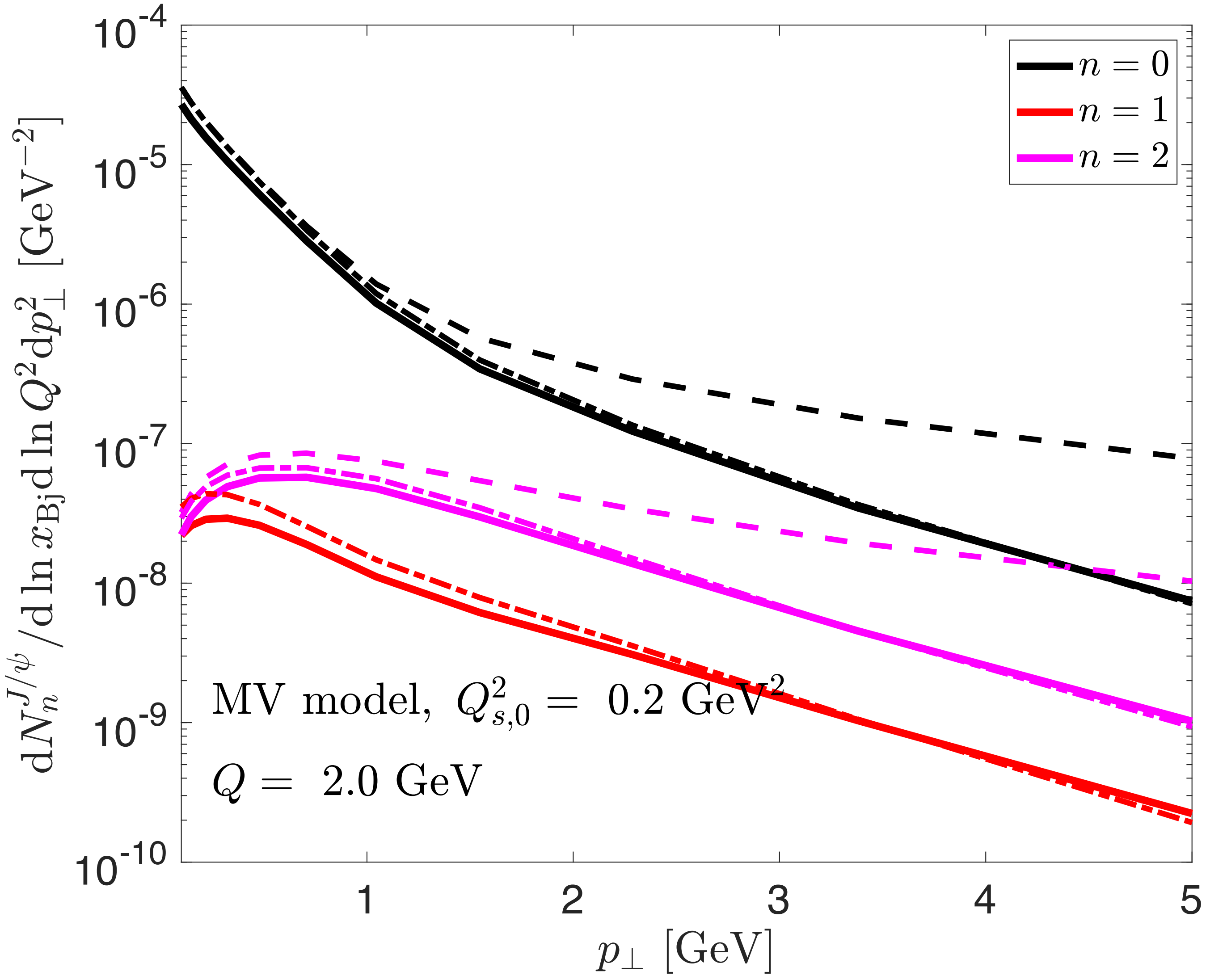
kT factorization breaking grows with saturation scale Q_s^2
(i.e. larger nuclei or larger energies)

Quarkonium production in electron-nucleus collisions

pT dependence: CGC vs kT factorization (TMD and ITMD)

$$\mathrm{d}N_n = \frac{1}{S_\perp}\int \frac{\mathrm{d}\phi_{eJ/\psi}}{2\pi}\mathrm{d}\sigma^{J/\psi}\cos(n\phi_{eJ/\psi})$$

$e+p \to e+J/\psi+X$



Solid line= full CGC
Dashed-solid= Improved TMD
Dashed = TMD

kT factorization (ITMD)

$\ln(Q_s^2/p_\perp^2)$ for $p_\perp^2 \lesssim Q_s^2$ TMD saturated

$/p_\perp^2$ for $Q_s^2 \ll p_\perp^2 \ll Q^2 + M_{J/\psi}^2$ TMD

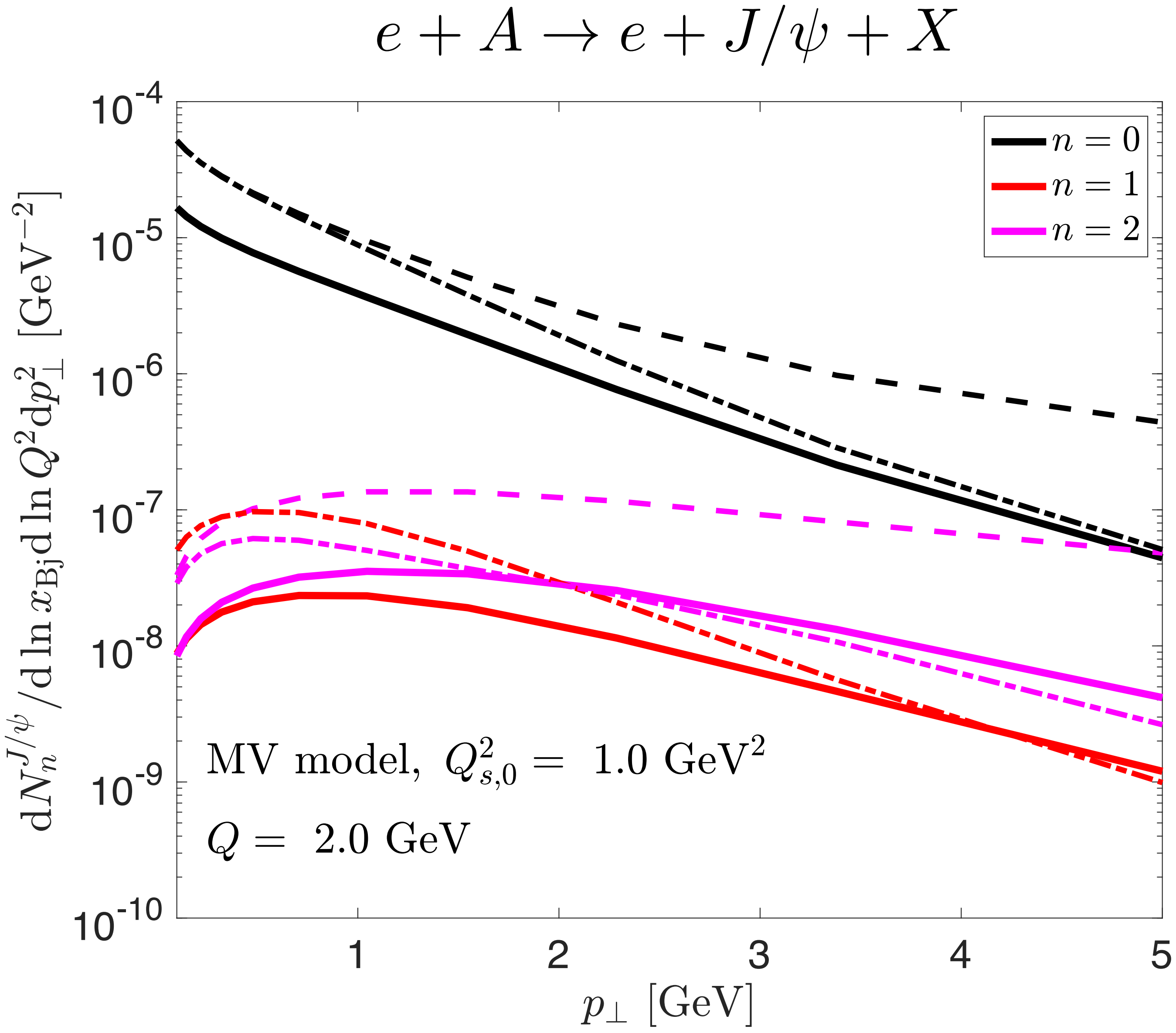
$1/p_\perp^4$ for $p_\perp \gg Q^2 + M_{J/\psi}^2$ collinear

Small saturation scale ->
little factorization kT breaking

Quarkonium production in electron-nucleus collisions

pT dependence: CGC vs kT factorization (TMD and ITMD)

$$\mathrm{d}N_n = \frac{1}{S_\perp}\int \frac{\mathrm{d}\phi_{eJ/\psi}}{2\pi}\mathrm{d}\sigma^{J/\psi}\cos(n\phi_{eJ/\psi})$$



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$\ln(Q_s^2/p_\perp^2)$ for $p_\perp^2 \lesssim Q_s^2$ TMD saturated

$1/p_\perp^2$ for $Q_s^2 \ll p_\perp^2 \ll Q^2 + M_{J/\psi}^2$ TMD

$1/p_\perp^4$ for $p_\perp \gg Q^2 + M_{J/\psi}^2$ collinear

Full CGC

Further suppression at low $p_\perp$ when $Q_s^2 \sim Q^2 + M_{J/\psi}^2$ due to kT factorization breaking

Summary and Outlook

- Past

  CGC + NRQCD provides good descriptions of rapidity and $p_\perp$ distribution, nuclear modification ratio, and multiplicity-dependence in high-energy pp and pA collisions at RHIC and LHC

- Present

  We computed direct quarkonium production in ep and eA, and carried our a numerical study focusing on deviations from kT factorization

- Future

  Can we provide a good description of HERA data? UPCs?

  Predictions for the EIC

  Study polarized J/ψ production

  Extend our results to NLO [ZK, FS and Emilie Li on-going work]