Searching for saturation with quarkonium production
CGC meets NRQCD for EIC

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POETIC workshop
February 28th, 2025

Based on 2409.04080 *[PRD 2024]*
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Outline

- Quarkonium production at RHIC and the LHC

  An overview of extant results

- Quarkonium production at the EIC

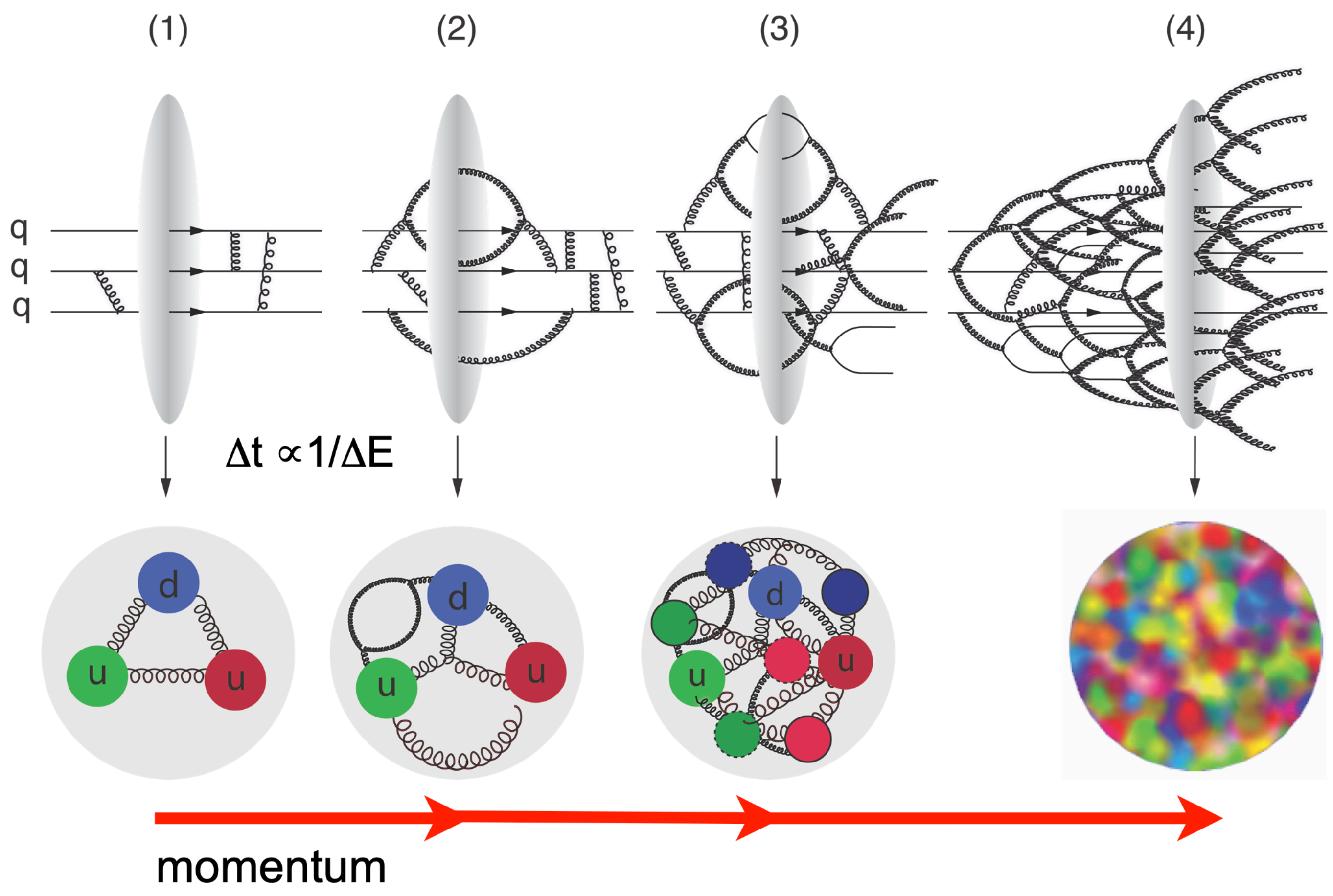
  Complete results from CGC + NRQCD

  Correspondence to TMD framework and beyond

  Taping into “genuine higher saturation corrections”

- Outlook

Quarkonium as a tool to search for gluon saturation



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

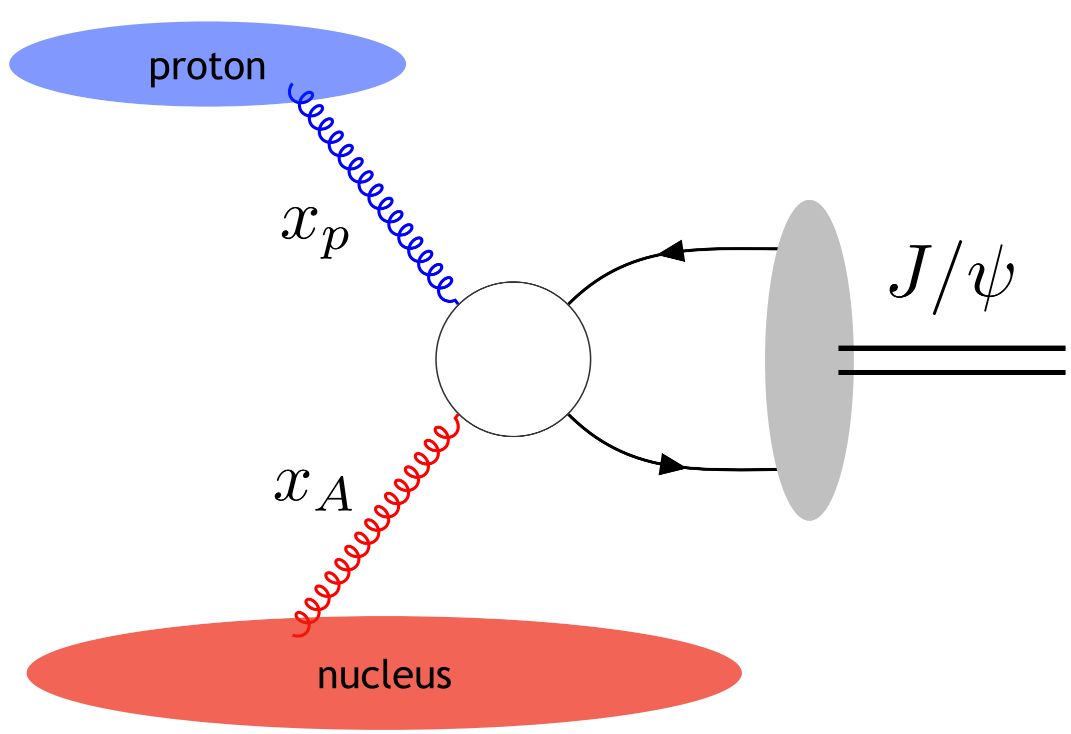
↓

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

↓

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

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



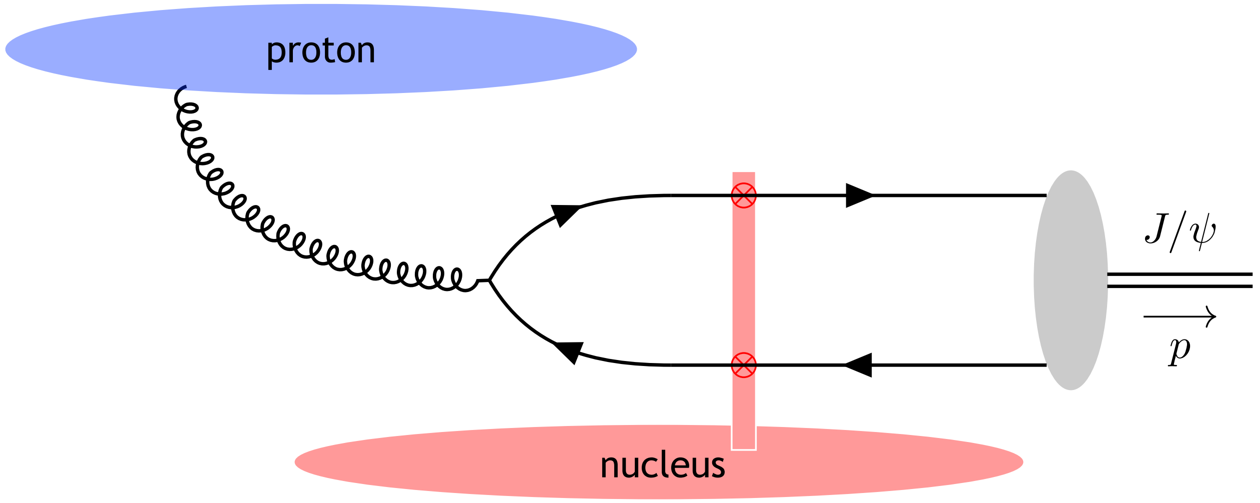
$$x_p = \sqrt{\frac{M_{J/\Psi}^2 + P_\perp^2}{s}} e^{Y} \qquad x_A = \sqrt{\frac{M_{J/\Psi}^2 + P_\perp^2}{s}} e^{-Y}$$

Forward production $Y \gg 1$

$$x_A \ll 1$$

Quarkonium production in proton-nucleus collisions

CGC meets NRQCD



Non-relativistic QCD

Non-perturbative LDME

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

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

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

Proton UGD/TMD — Perturbative factor — Nuclear-dependent (CGC)

Kang, Ma, Venugopalan, Zhang (JHEP 2013)

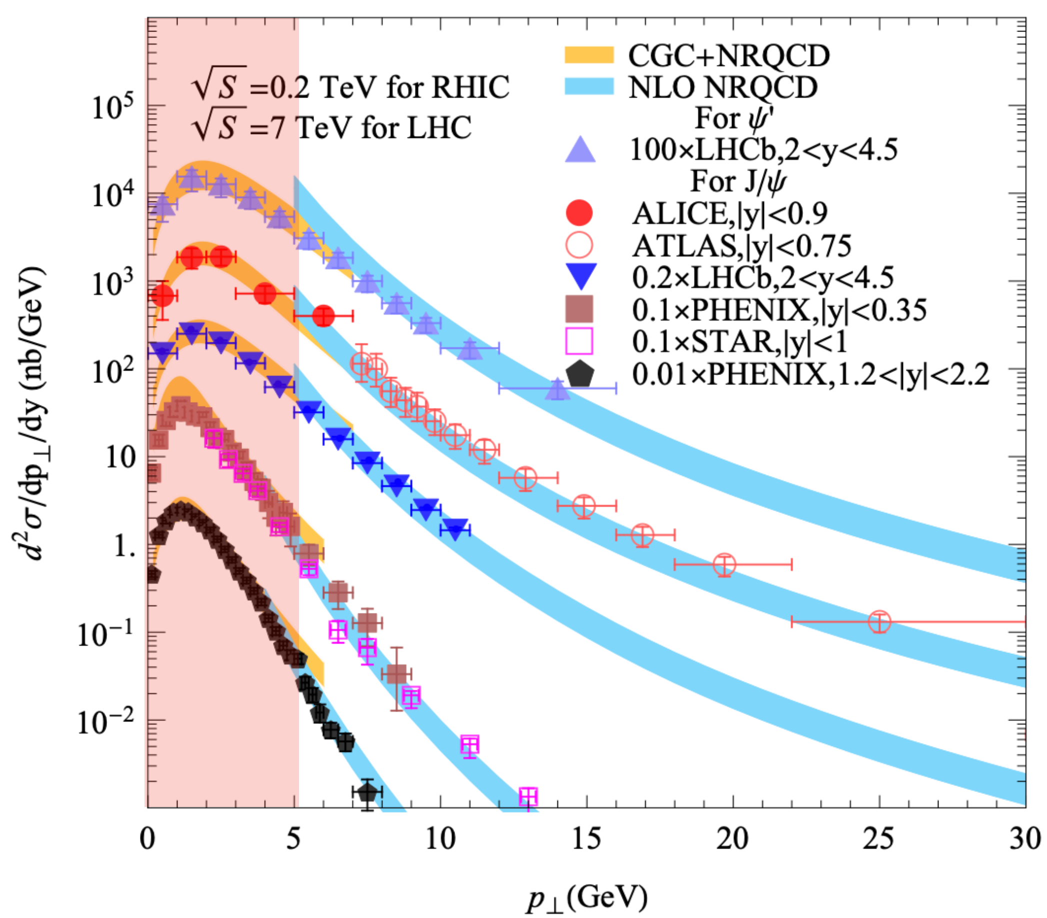
Confronting to RHIC and LHC data

Ma, Venugopalan (PRL 2014)

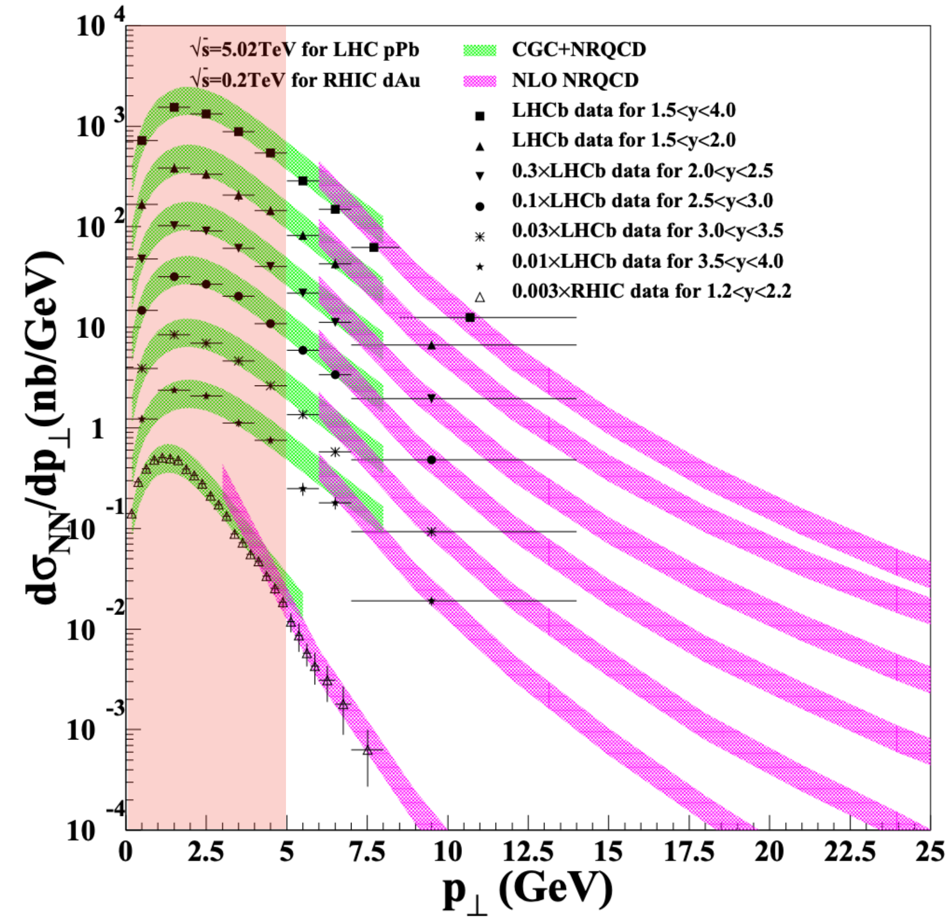
Ma, Venugopalan, Zhang (PRD 2015)

Transverse momentum distribution

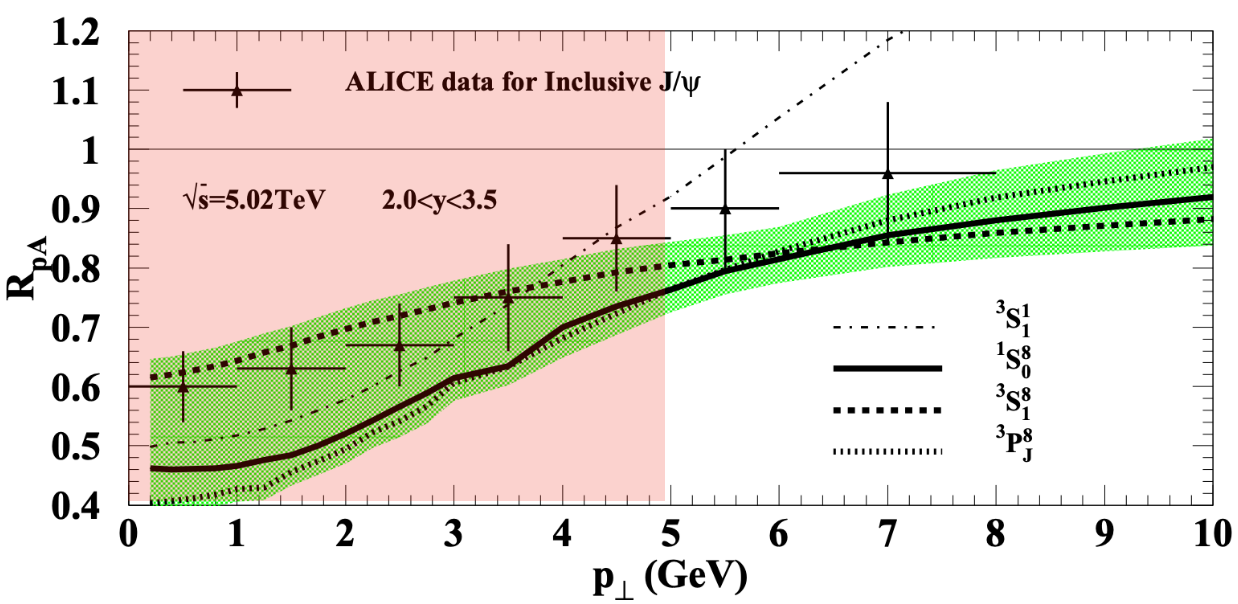
Proton-proton



Proton-nucleus



Nuclear modification Ratio



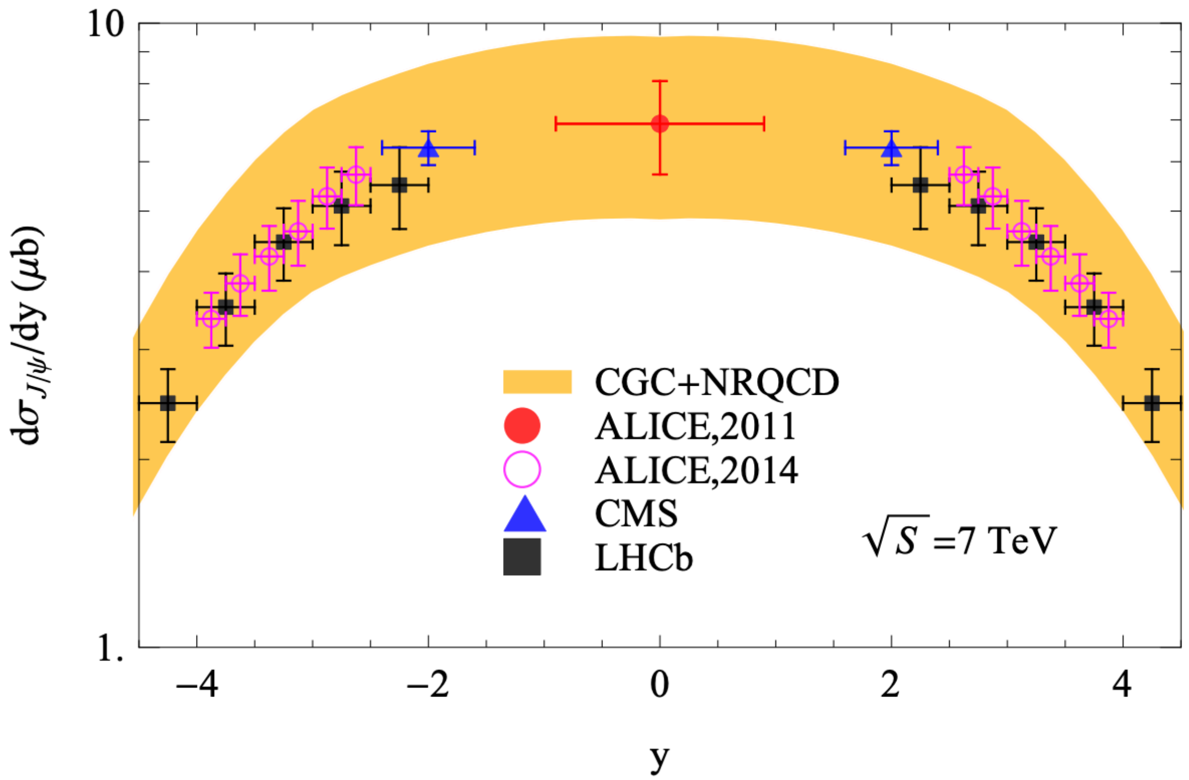
CGC provides good description of experimental data at low pT ($p_\perp \lesssim Q_s$)

Confronting to RHIC and LHC data

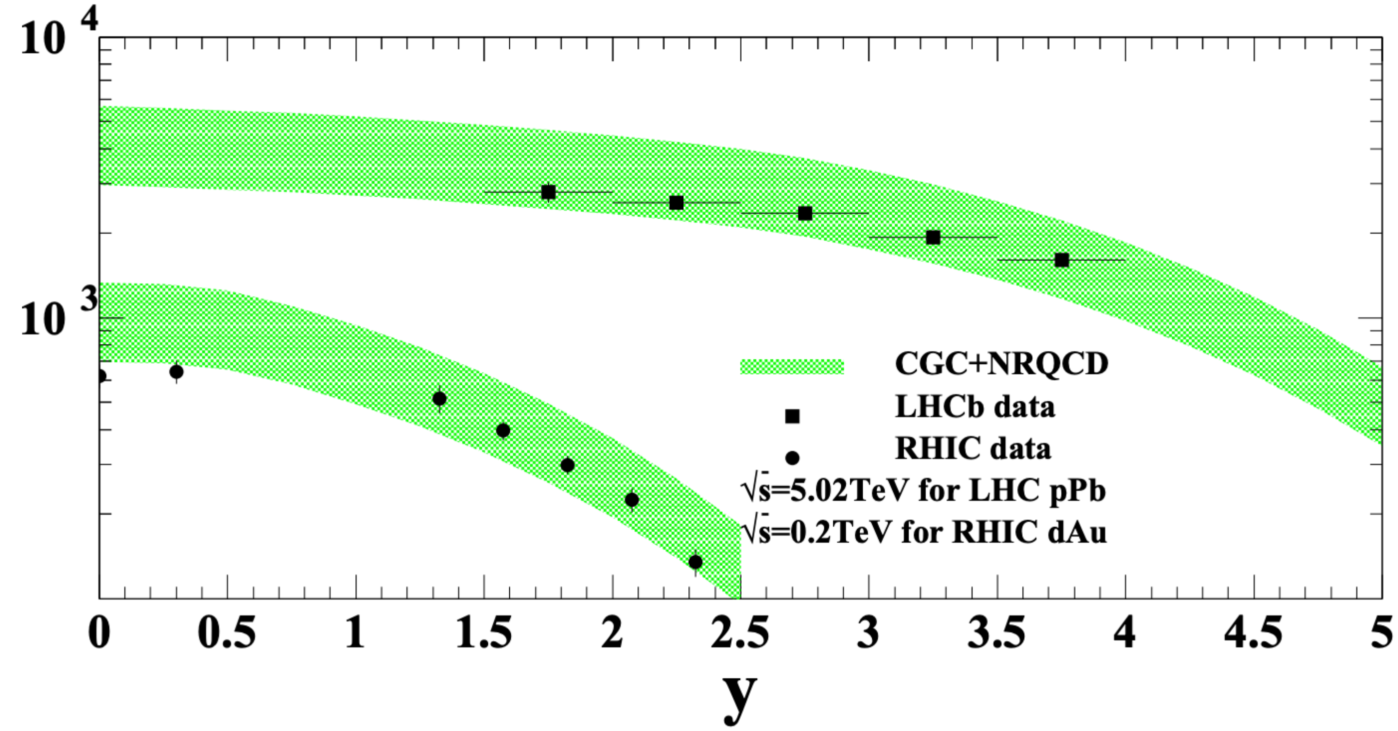
Ma, Venugopalan (PRL 2014)
Ma, Venugopalan, Zhang (PRD 2015)

Rapidity distribution and nuclear modification

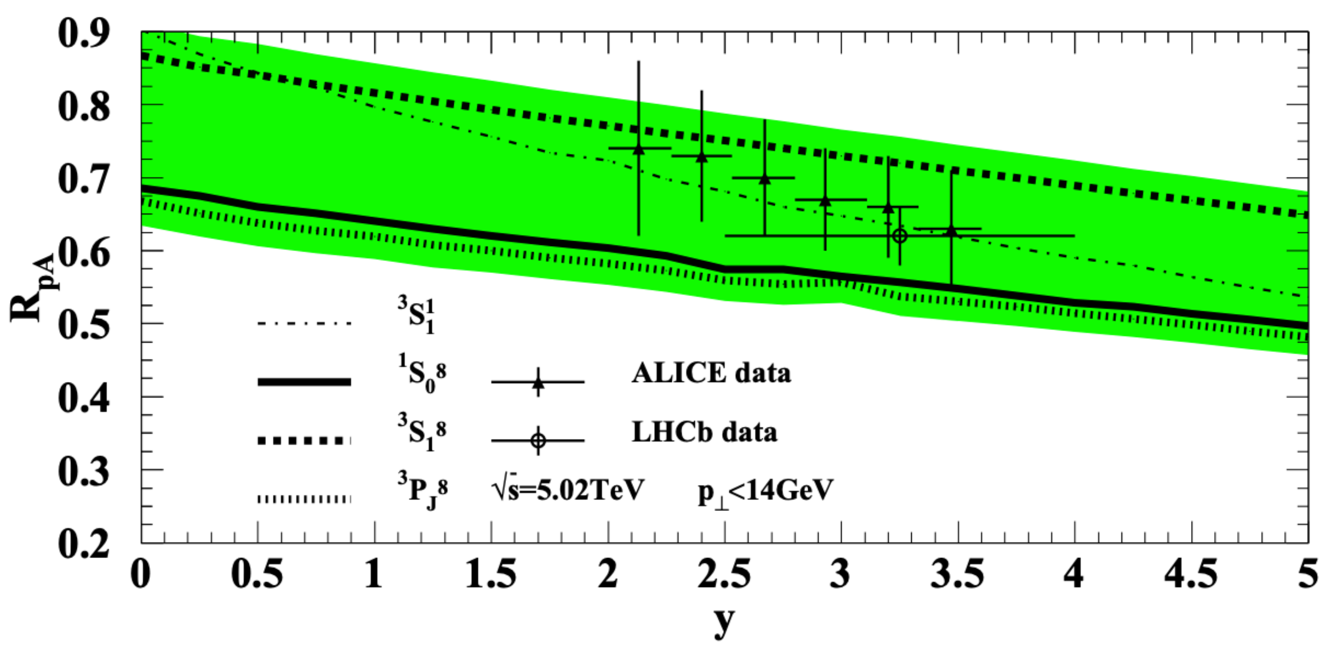
Proton-proton



Proton-nucleus



Nuclear modification Ratio

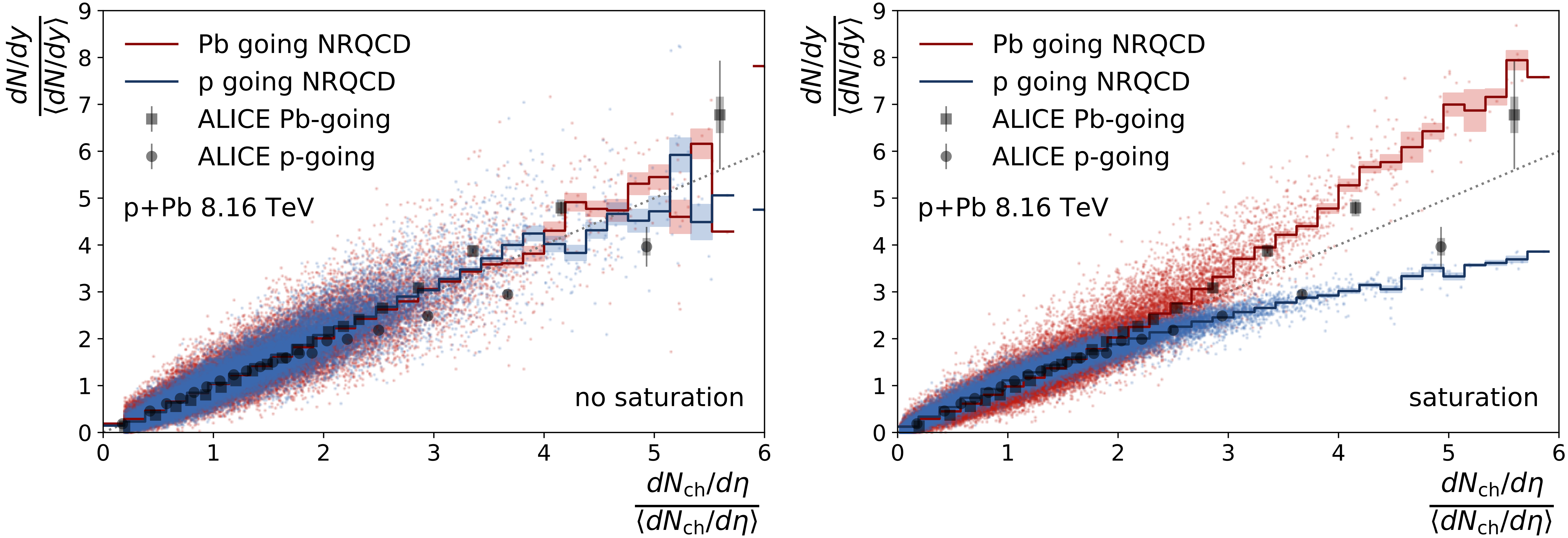


Rapidity distributions are integrated over $p_\perp$, low $p_\perp$ dominates the bulk of the cross-section

Confronting to RHIC and LHC data

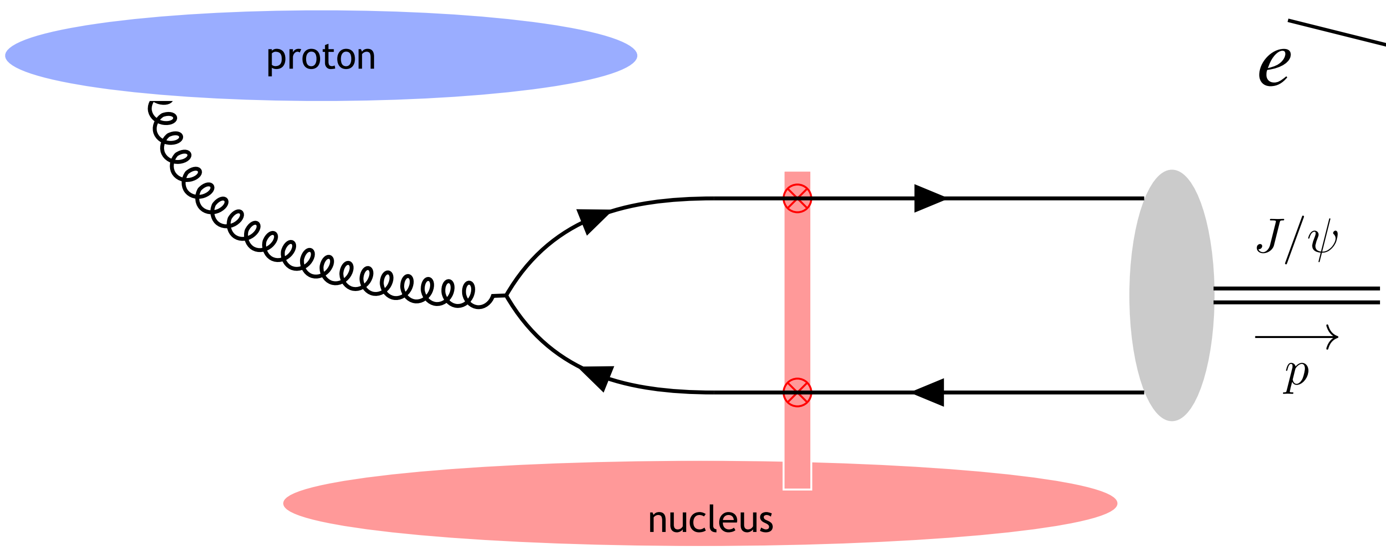
J/ψ multiplicity vs charged hadron multiplicity

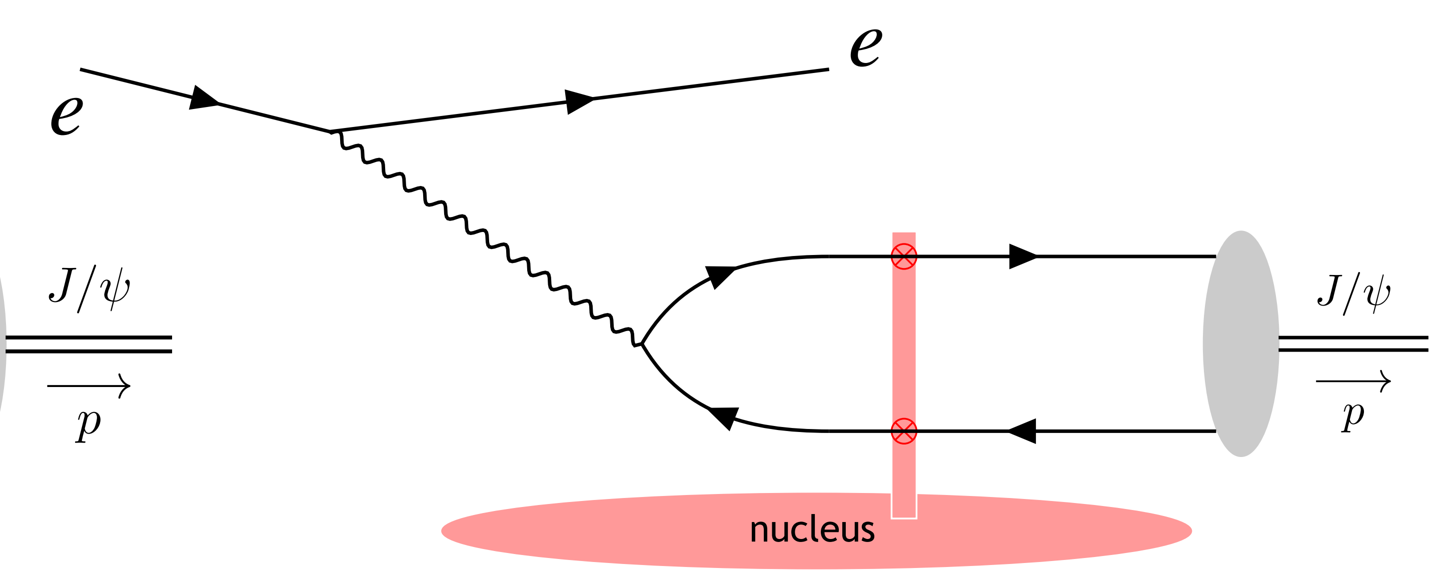
FS, Schenke, Soto-Ontoso (PLB 2022)



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

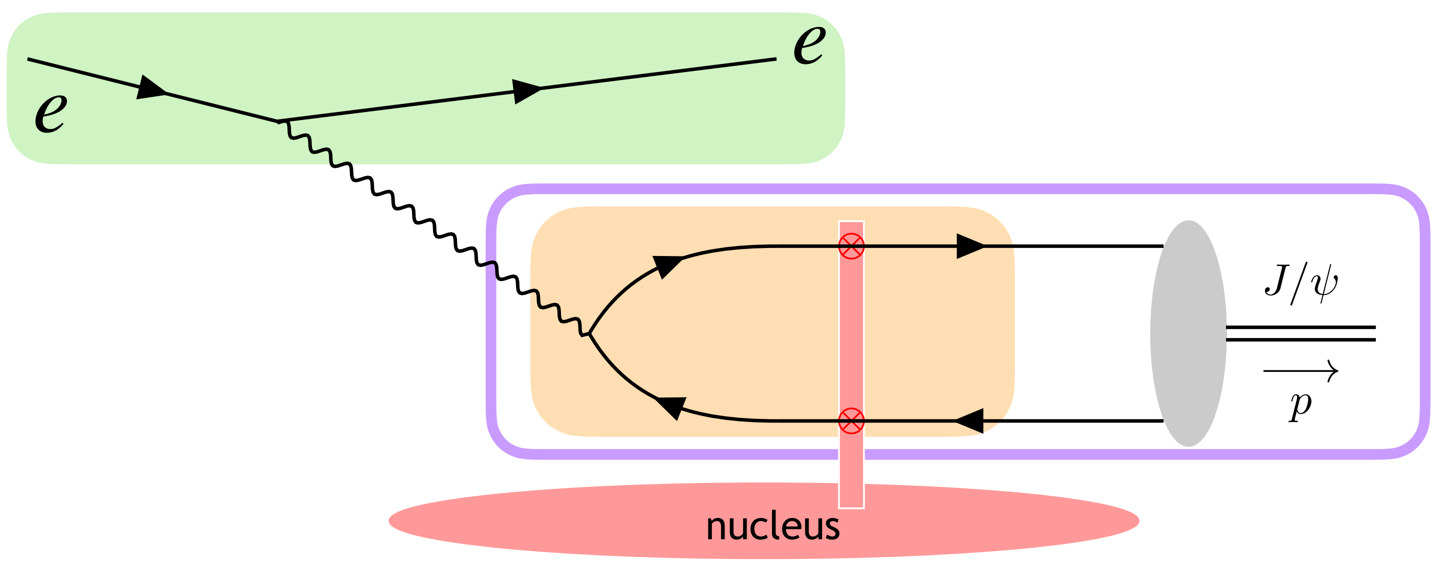
Surprisingly, calculations [in CGC] hadn’t been done yet, not even at LO…

Motivated our work in Cheung, Kang, FS, Vogt (PRD 2024)

Quarkonium production in electron-nucleus collisions

Lepton-hadron decomposition in polarization basis

Breit frame:



Following *Mantysaari, Roy, FS, Schenke (PRD 2020)*, decompose the DIS cross-section in terms of $\gamma^* A$

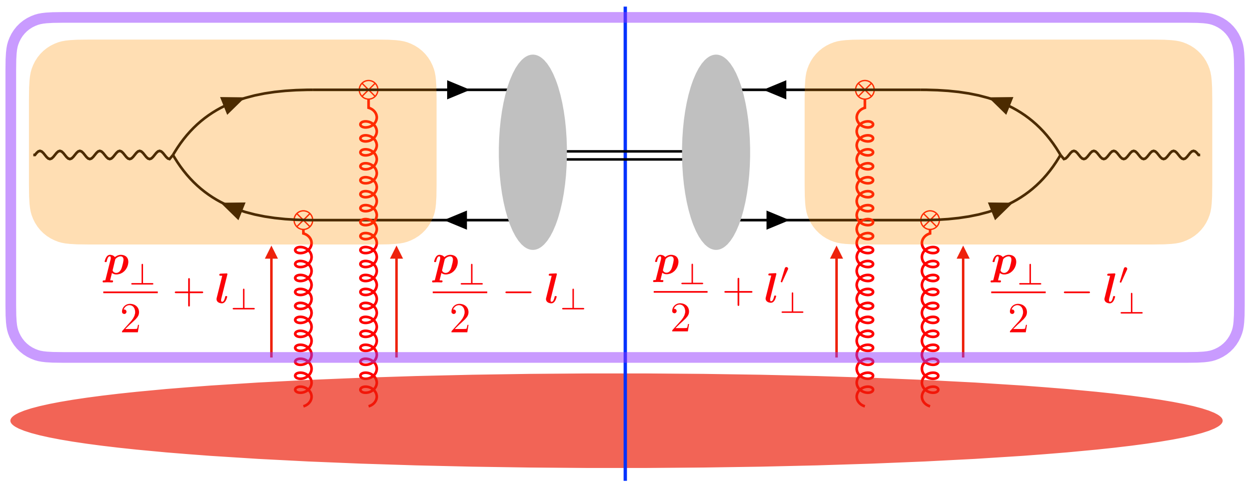
$$\frac{\mathrm{d}\sigma^{J/\psi}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}y\mathrm{d}\boldsymbol{p}_\perp^2\,\mathrm{d}\phi_{eJ/\psi}} = \frac{\alpha_{\mathrm{em}}}{2\pi^2 y x_{\mathrm{Bj}}} \left\{ f_{\mathrm{L}}(y)\frac{\mathrm{d}\sigma_{\mathrm{L}}^{J/\psi}}{\mathrm{d}\boldsymbol{p}_\perp^2} + f_{\mathrm{T}}(y)\frac{\mathrm{d}\sigma_{\mathrm{T}}^{J/\psi}}{\mathrm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

$\phi_{eJ/\psi}$ is the relative azimuthal angle between electron and J/ψ

Quarkonium production in electron-nucleus collisions

CGC meets NRQCD

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



Regge limit (small-x):

$$Q^2, M^2_{J/\psi}, p^2_\perp \ll s$$

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

LDME for J/ψ production

Short-distance coefficients

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

Spin and polarization-dependent perturbative factor (20 functions)

Nuclear-dependent CGC distribution (Octet and Singlet)

Singlet computed by *Lappi, Mäntysaari, Penttala (PRD 2020)*

$$\widetilde{\mathcal{G}}^\kappa(x_A, \boldsymbol{p}_\perp; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp)$$

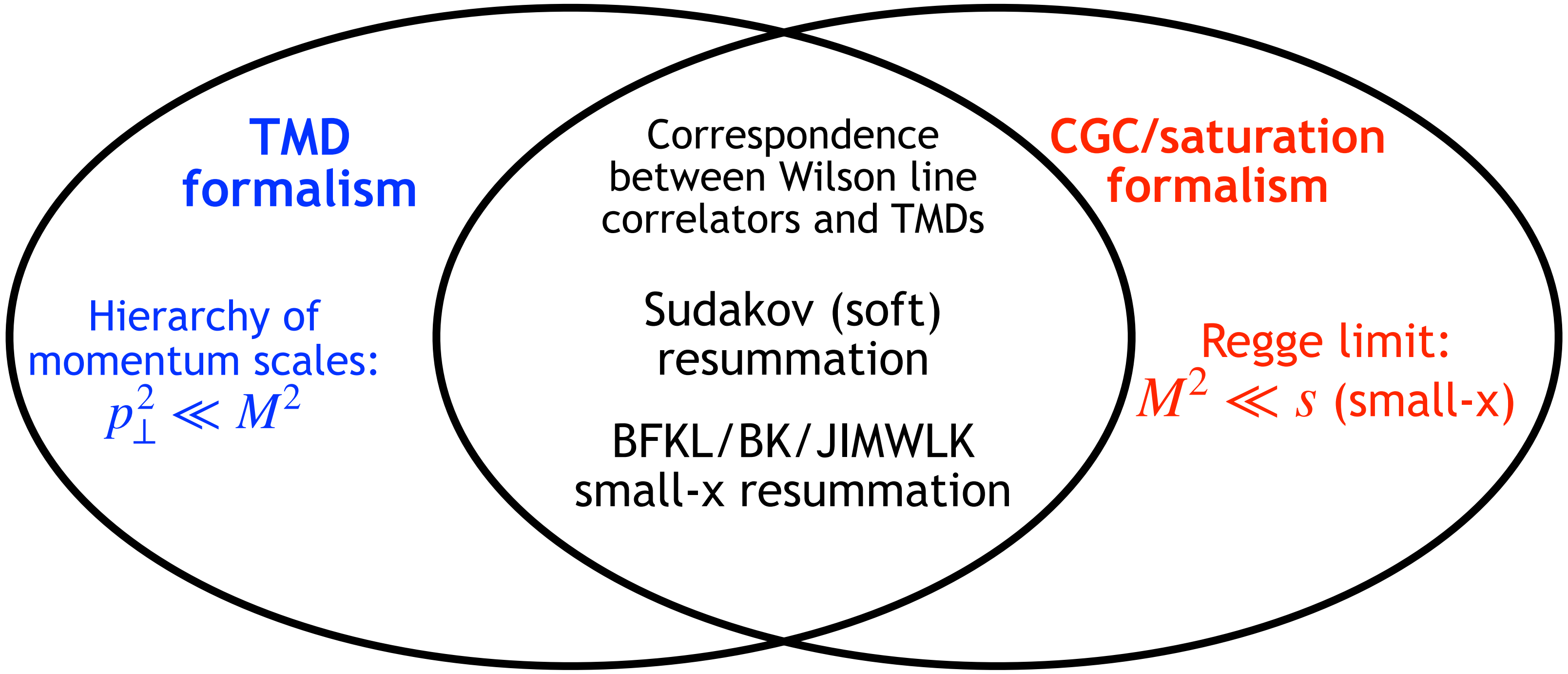
Built from Wilson lines. Encodes all the multiple interactions of the quark-antiquark pair with the nucleus. Implicitly depends on the saturation scale $Q_s(x_A)$

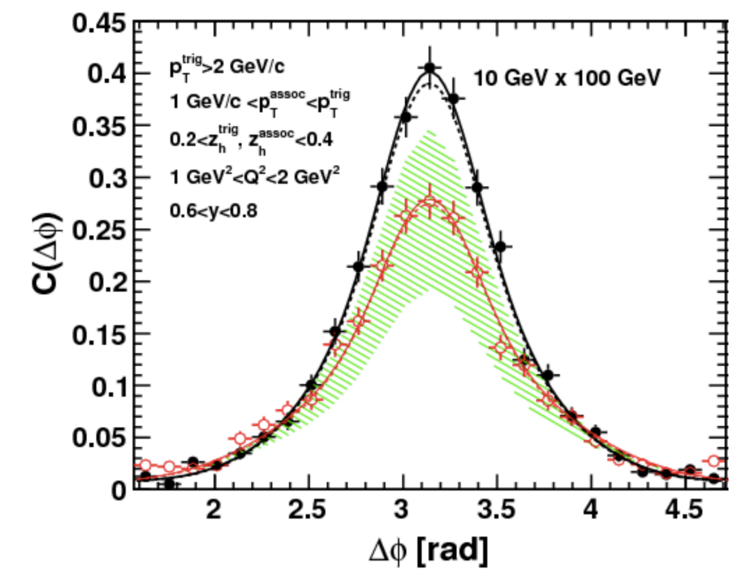
Cheung, Kang, FS, Vogt (PRD 2024)

Intermezzo: CGC and TMD correspondence

Dominguez, Marquet, Xiao, Yuan (PRD 2011)

For a variety of processes dijet in eA/pA, photon + jet in pA





Elucidating correspondence TMD and CGC

Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren (JHEP 2015)

Altinoluk, Boussarie, Kotko (JHEP 2019)

Boussarie, Mehtar-Tani (JHEP 2020)

Numerical studies for dijet in eA and pA

Mäntysaari, Mueller, FS, Schenke (PRL 2020)

Fujii, Marquet, Watanabe (JHEP 2021)

Boussarie, Mäntysaari, FS, Schenke (PRD 2021)

Interplay between Sudakov and small-x resummation

Mueller, Xiao, Yuan (PRD 2013)

Taels, Altinoluk, Beuf, Marquet (JHEP 2022)

Caucal, FS, Schenke, Venugopalan (JHEP 2022, JHEP 2023)

Full NLO TMD factorization for dijets and dihadrons in eA

Caucal, FS, Schenke, Stebel , Venugopalan (PRL 2024)

Caucal, FS (JHEP 2024)

Quarkonium production in electron-nucleus collisions

TMD factorization at small-x

Our result for Short-distance coefficients in CGC + NRQCD

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

In the limit: $Q_s^2 \ll Q^2 + M^2_{J/\psi}$ and $\boldsymbol{p}^2_{\perp} \ll Q^2 + M^2_{J/\psi}$

Momentum-space expansion

$$\widetilde{\Gamma}^{\kappa}_{\lambda}(\boldsymbol{p}_{\perp}, Q; \boldsymbol{l}_{\perp}, \boldsymbol{l}'_{\perp}) \approx \frac{\partial^2 \widetilde{\Gamma}^{\kappa}_{\lambda}(\boldsymbol{p}_{\perp}, Q; \boldsymbol{l}_{\perp}, \boldsymbol{l}'_{\perp})}{\partial \boldsymbol{l}^{\alpha}_{\perp} \partial \boldsymbol{l}'^{\alpha'}_{\perp}} \boldsymbol{l}^{\alpha}_{\perp} \boldsymbol{l}'^{\alpha'}_{\perp}$$

TMD factorization

Hard factor

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

Weizsäcker-Williams TMD at small-x, implicitly depends on Q_s

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

The non-vanishing contributions in TMD are: ${}^3P_1$ and ${}^3P_2$ (for longitudinally pol photon) and ${}^1S_0$ and ${}^3P_J$ (for for transversely pol photon, Tflip)

Cheung, Kang, FS, Vogt (PRD 2024)

Quarkonium production in electron-nucleus collisions

Improved TMD factorization at small-x

Our result for Short-distance coefficients in CGC + NRQCD

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

In the limit: $Q_s^2 \ll Q^2 + M^2_{J/\psi}$

Expansion following *Boussarie, Mehtar-Tani (PRD 2021), Boussarie, Mantysaari, FS, Schenke (PRD 2021)*

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

Weizsäcker-Williams TMD at small-x, implicitly depends on Q_s

“Improved ”Hard factor hard factor resums all corrections $p_{\perp}^2/(Q^2 + M^2_{J/\psi})$

Improved TMD only valid at leading power in $Q_s^2/(Q^2 + M^2_{J/\psi})$

Cheung, Kang, FS, Vogt (PRD 2024)

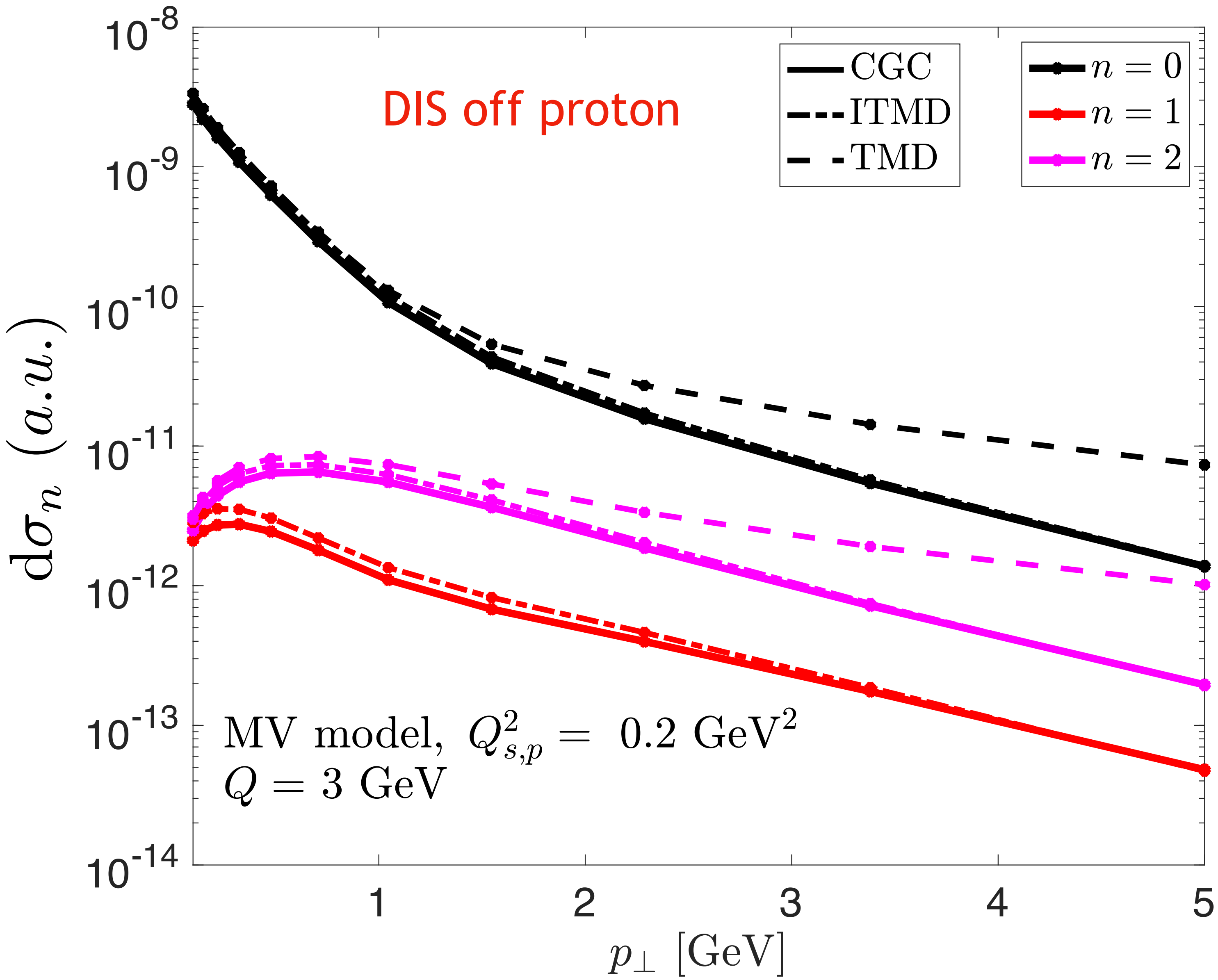
Quarkonium production in electron-nucleus collisions

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

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

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

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



We use MV model (semi-classical) for Wilson line correlators and the gluon WW distribution. For proton we have $Q_s^2 = 0.2\ \mathrm{GeV}^2$

Small saturation scale -> ITMD reproduces well full CGC

The behavior of pT spectrum from ITMD:

$\ln(Q_s^2/p_\perp^2)$ 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 $p_\perp \gg Q^2 + M_{J/\psi}^2$ kT factorization

Cheung, Kang, FS, Vogt (PRD 2024)

Quarkonium production in electron-nucleus collisions

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

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

Solid line= full CGC
Dashed-solid= Improved TMD
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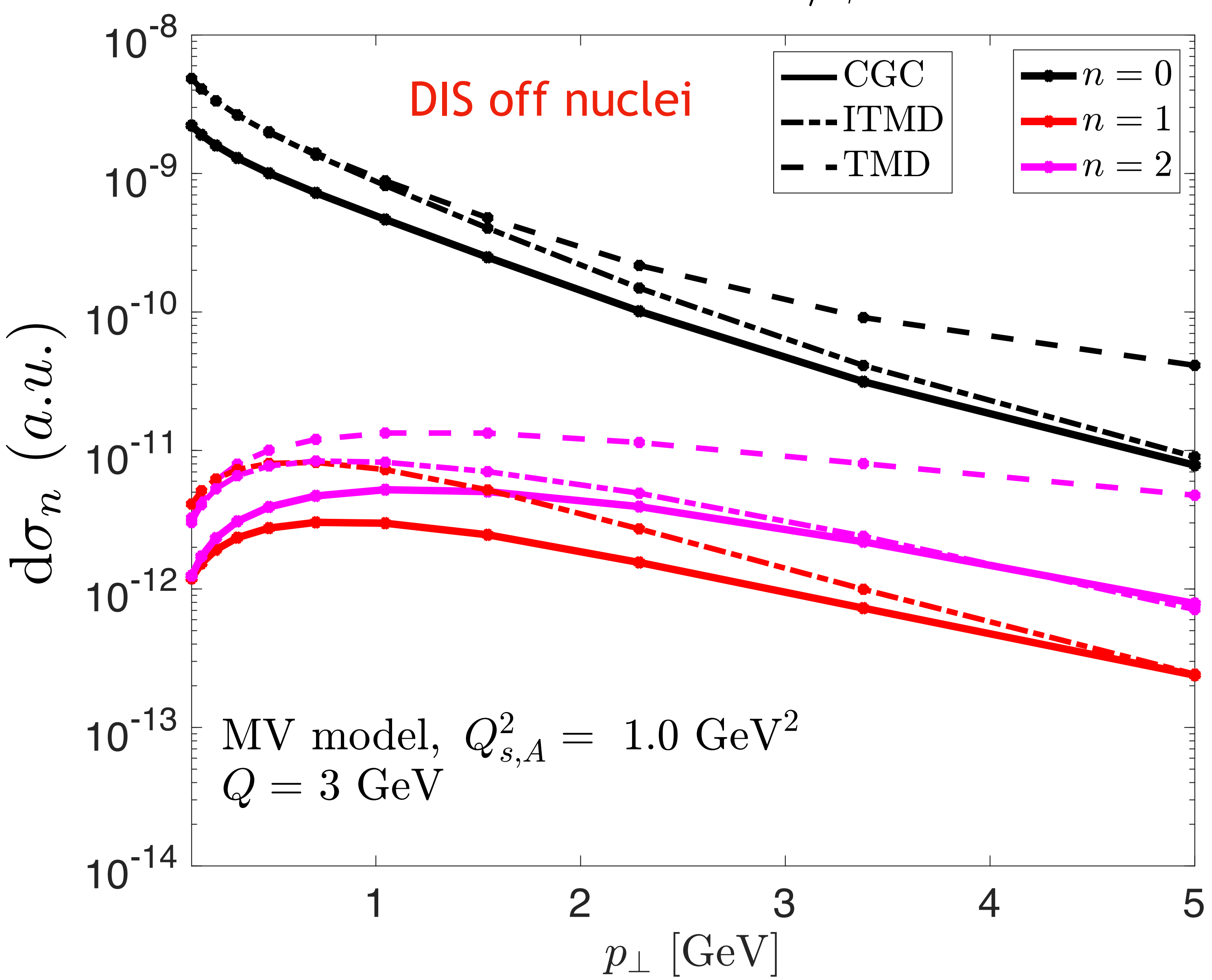
$$e + A \to e + J/\psi + X$$



We use MV model (semi-classical) for Wilson line correlators and the gluon WW distribution. For proton we have $Q_s^2 = 0.2$ GeV^2

Further suppression of the spectrum in full CGC result from "genuine higher saturation contributions" that scale as $Q_s^2/(Q^2 + M^2_{J/\psi})$

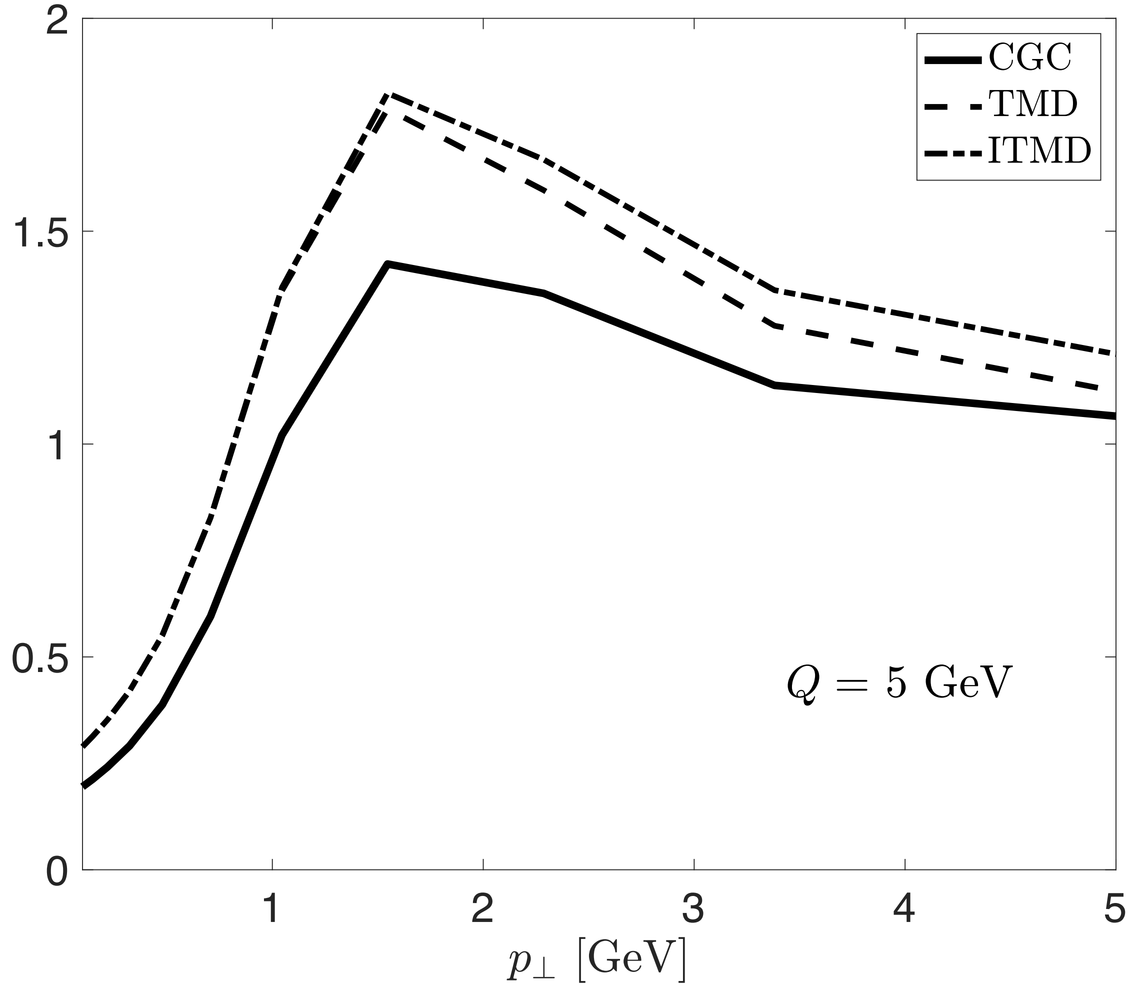
Similar effect was observed in dijets in *Boussarie, Mantysaari, FS, Schenke* (PRD 2021). However, **"genuine saturation corrections" in J/ψ production are stronger than in dijets** since $M^2_{J/\psi} \ll M^2_{dijet}$

Cheung, Kang, FS, Vogt (PRD 2024)

Quarkonium production in electron-nucleus collisions

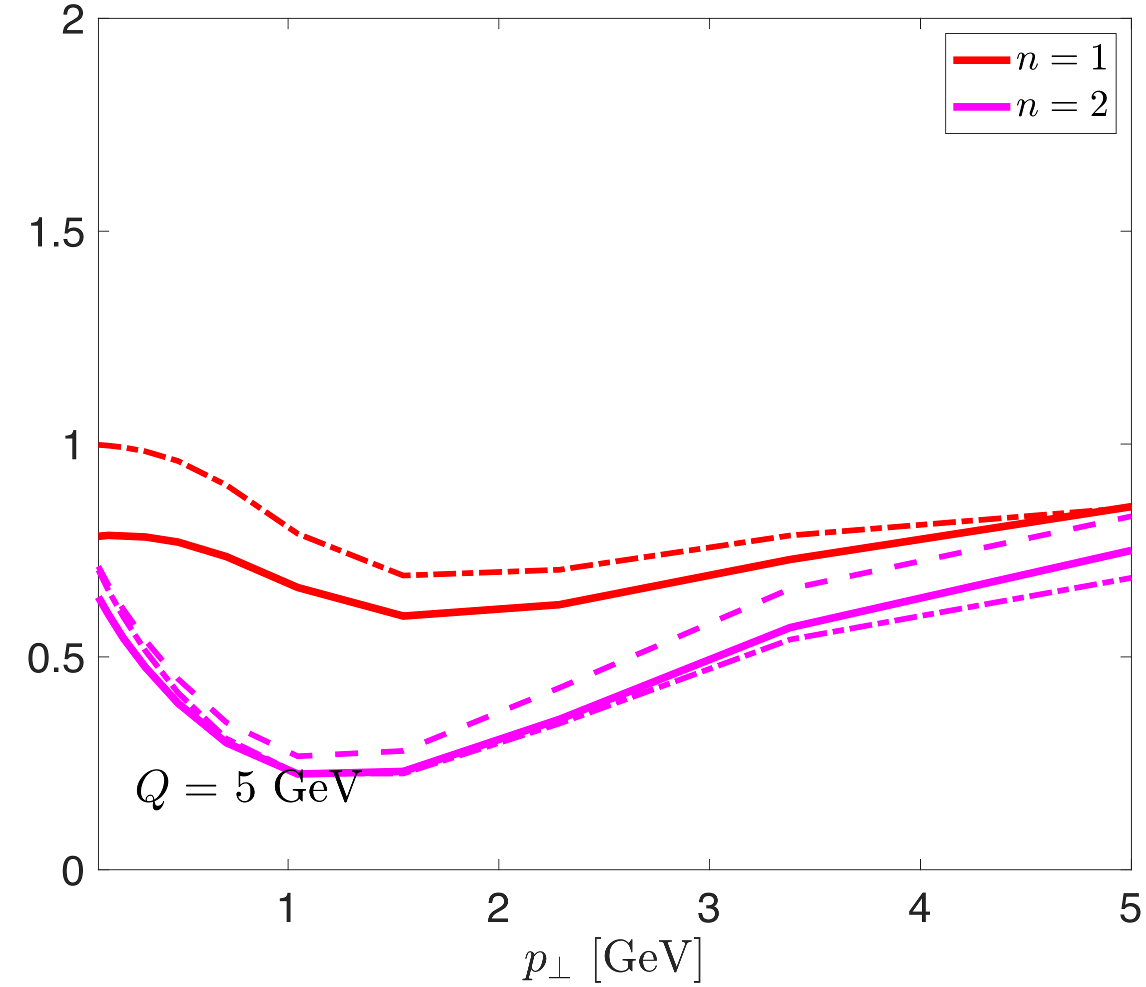
Nuclear modification ratio eA vs ep

$$R_{eA} = \frac{1}{A}\frac{\mathrm{d}\sigma_{eA}}{\mathrm{d}\sigma_{ep}}$$



Full CGC displays further suppression in the nuclear modification factor as compared to TMD and ITMD.

$$R_{eA}[v_n] = \frac{v_n(eA)}{v_n(ep)}$$



CGC, TMD, and ITMD give similar predictions for ratio of anisotropies

Cheung, Kang, FS, Vogt (PRD 2024)

Summary and Outlook

- Past

  CGC + NRQCD provided 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 eA and UPCs within CGC + NRQCD

  We studied the connection between CGC to TMDs

  J/ψ production has better sensitivity to genuine higher saturation corrections than dihadron/dijet production

- Future

  Can we provide a good description of HERA data? UPCs? Predictions for EIC?

  More realistic calculation (Sudakov, JIMWLK evolution, small-x initial conditions, uncertainty due to non-perturbative LDMEs, relativistic corrections)

  Study polarized J/ψ production

  Extend our results to NLO [First steps in this direction Zhongbo Kang, FS and Emilie Li, JHEP 2024]

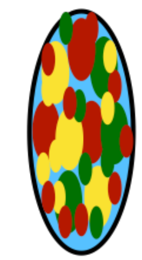
Back-up slides

Color Glass Condensate

McLerran, Venugopalan (PRD 1993)

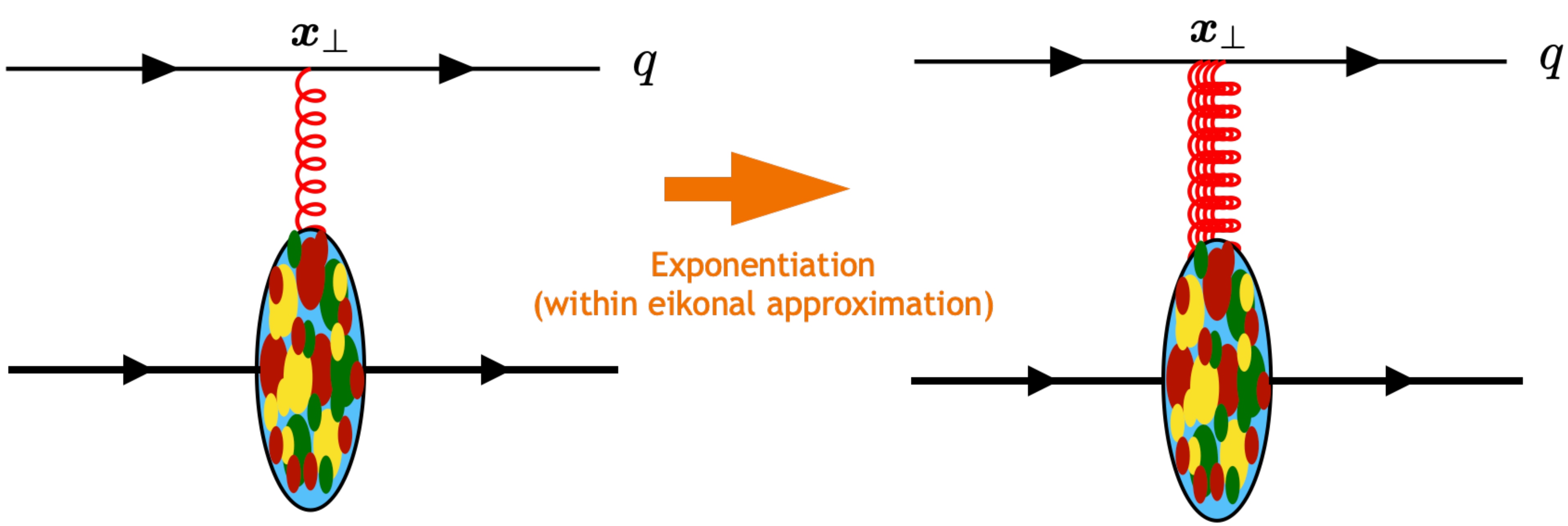
- **Effective field theory** for small-x gluons sourced by large-x partons

Color (QCD)
Glass (separation between slow and fast degrees of freedom)
Condensate (highly occupied system)



Large-x partons act as a classical color source which generates a background field A_{cl}

- **Multiple scattering** of partons with background field



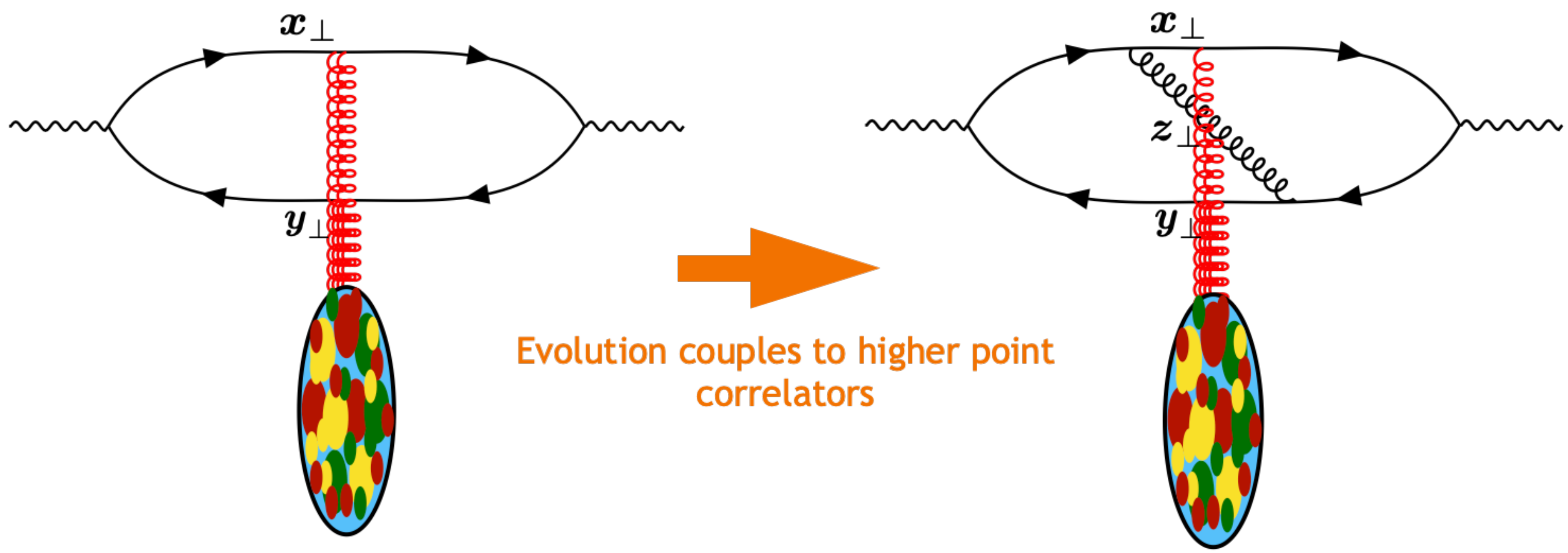
Ayala, Jalilian-Marian, McLerran, Venugopalan (PRD 1995) Balistky (NPB 1996)

High-energy scattering dofs = light-like Wilson line:

$$V(\boldsymbol{x}_\perp) = P\exp\left(ig\int \mathrm{d}x^- A^+_{\mathrm{cl}}(\boldsymbol{x}_\perp, x^-)\right)$$

Color Glass Condensate

- **Non-linear** renormalization group **evolution (BK-JIMWLK)**



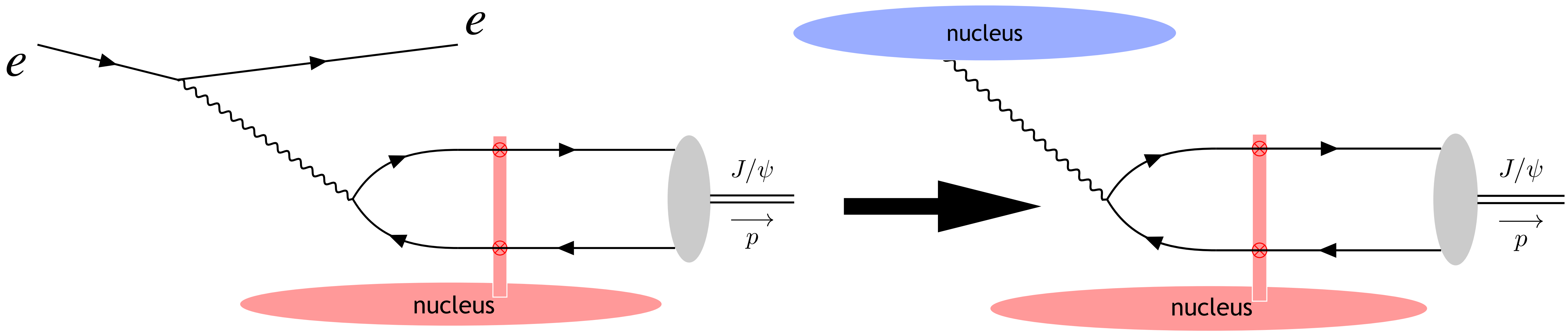
$$\mathrm{Tr}\left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp)\right] \qquad \mathrm{Tr}\left[V(\boldsymbol{x}_\perp)t^a V^\dagger(\boldsymbol{y}_\perp)t^b\right]U_{ab}(\boldsymbol{z}_\perp)$$

Balistky (1995), Kovchegov (1999)
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner (1996-2002)

- Fast fields are non-perturbative, slow fields evolve perturbatively

- **Probing CGC with dilute projectile**
  = pQCD embedded in strong gluon (non-perturbative) background field

What about UPCs?



Replace the photon source (electron -> nucleus)

Photon is quasi-real, take $Q^2 \to 0$ limit of our $\gamma^* A$ results (only transverse polarization survives)

Improved TMD regime of validity is very narrow: $Q_s^2 \ll M_{J/\psi}^2$

but for large nuclei at high energies $Q_s^2 \sim M_{J/\psi}^2$ Need full CGC calculation!

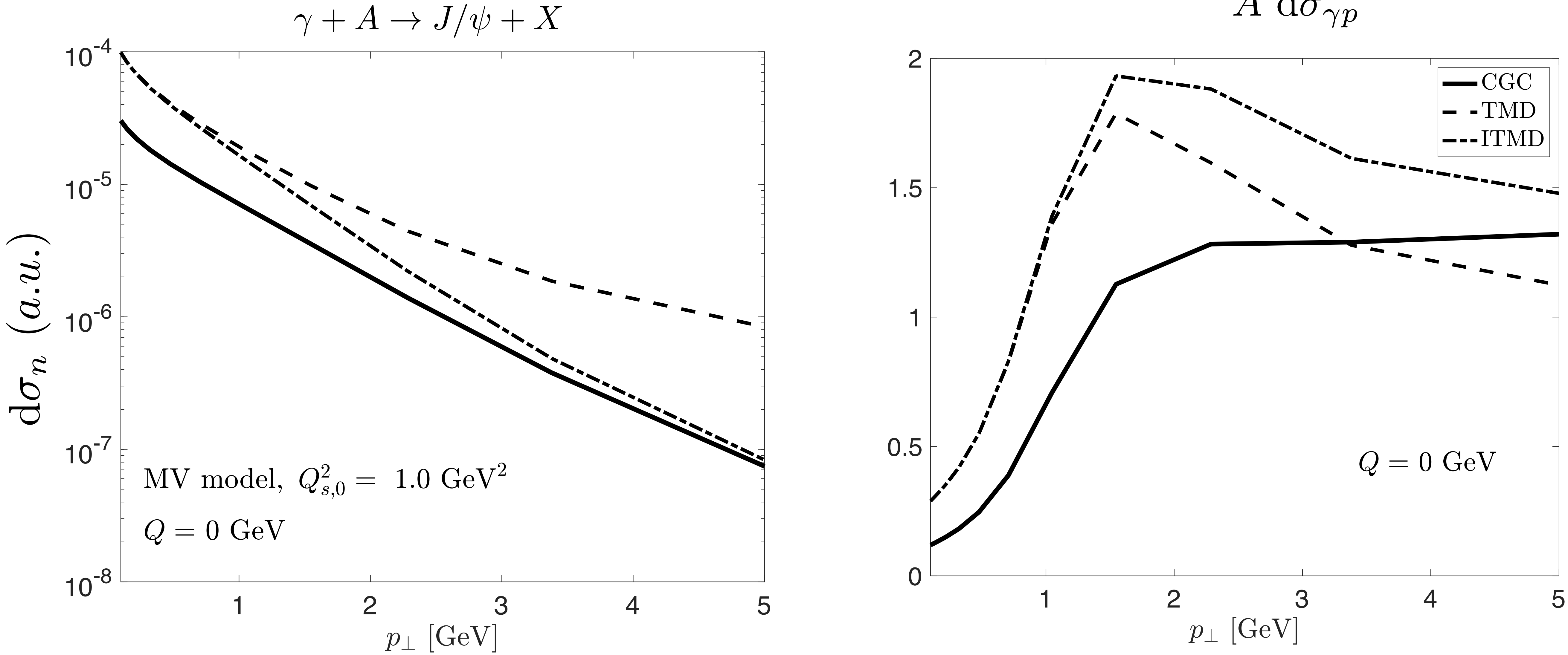
J/ψ production in UPCs could be very sensitive to **"higher genuine saturation corrections"** only present in the **full CGC calculation**

Better sensitivity than dijets since $M_{J/\psi}^2 \ll M_{dijet}^2$. Sudakov effect (soft radiation) should be smaller.

Quarkonium production in UPCs

Nuclear modification ratio in UPCs

$$R_{\gamma A} = \frac{1}{A}\frac{d\sigma_{\gamma A}}{d\sigma_{\gamma p}}$$



Genuine higher saturation contributions have the largest effect in photo-production (e.g. UPC) which cause a large suppression of the cross-section and the nuclear modification ratio at low pT