Quarkonia at small-x and gluon saturation / relation to diffraction

Kazuhiro Watanabe
(Subatech)

Physics Opportunities with Heavy Quarkonia at the EIC, CFNS, 10/25/2021

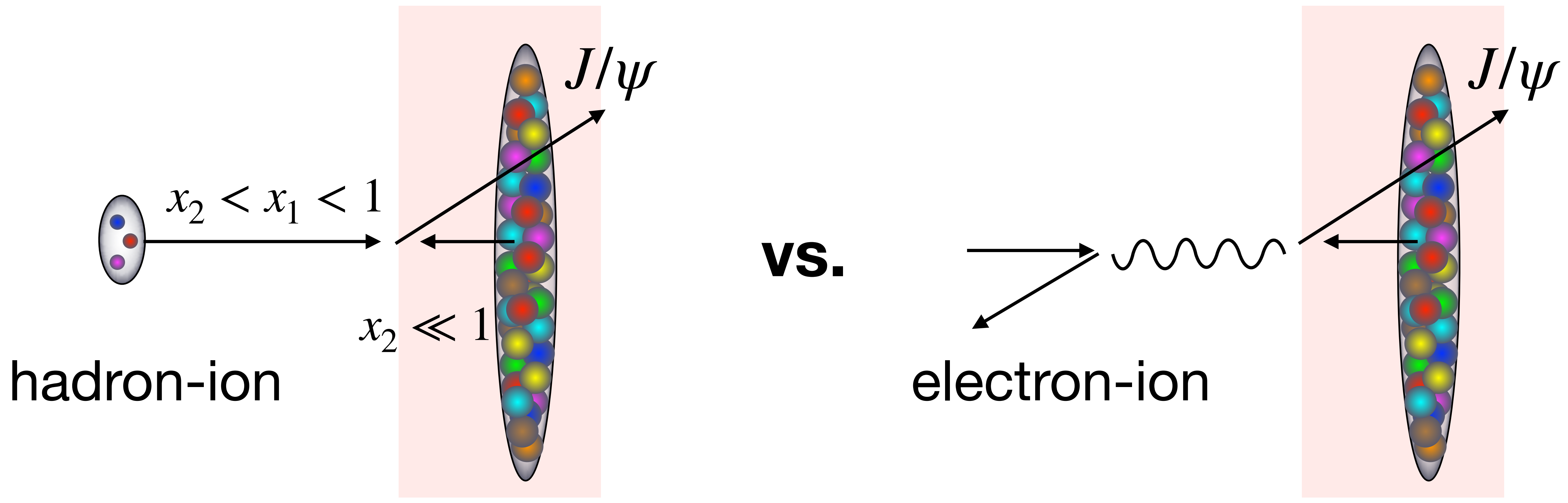
Outline
- Onia production in (almost) pp collisions
- Onia production in (almost) pA collisions
- Diffractive events

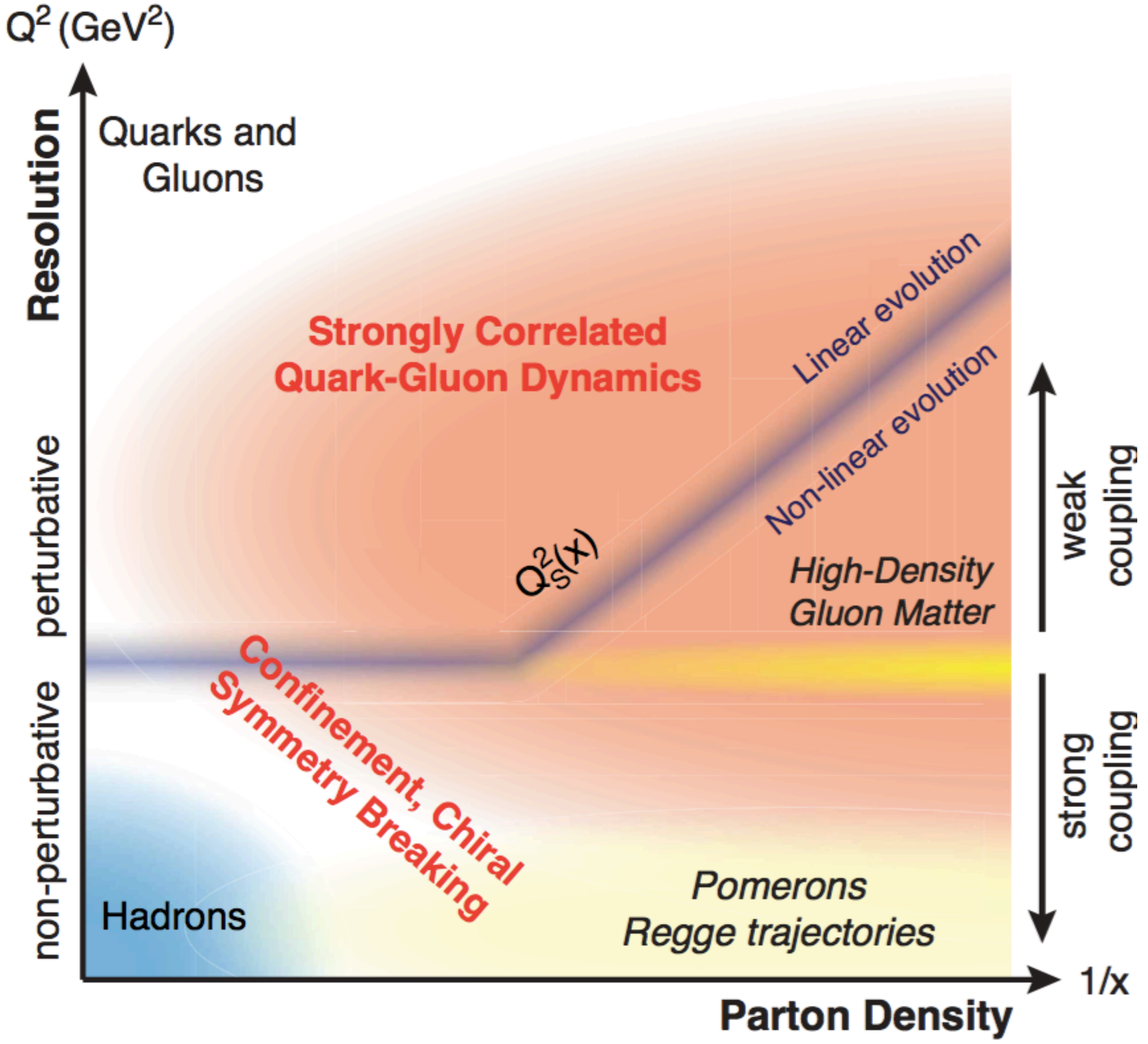
cnrs IN2P3 Subatech

Hunting the nucleus for gluon saturation at the EIC

Quarkonium production at the EIC could tell us:

- 1D configuration of small-x gluons in nuclei, i.e. nuclear PDFs
- 3D gluon TMDs (k_T dep.) and GPDs (b dep.) at small-x
- Gluon saturation : the question is which is the most efficient way to assess it.



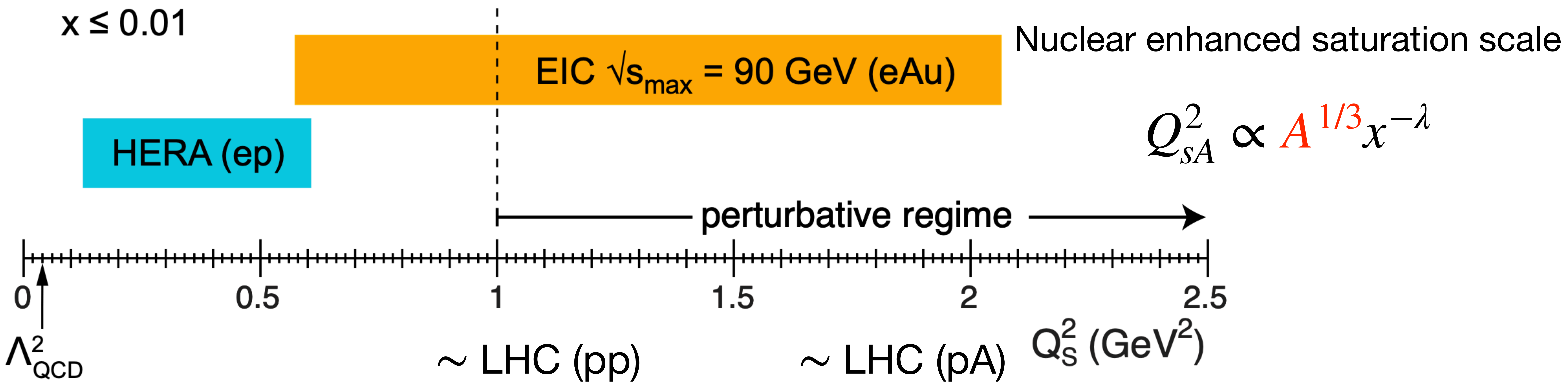


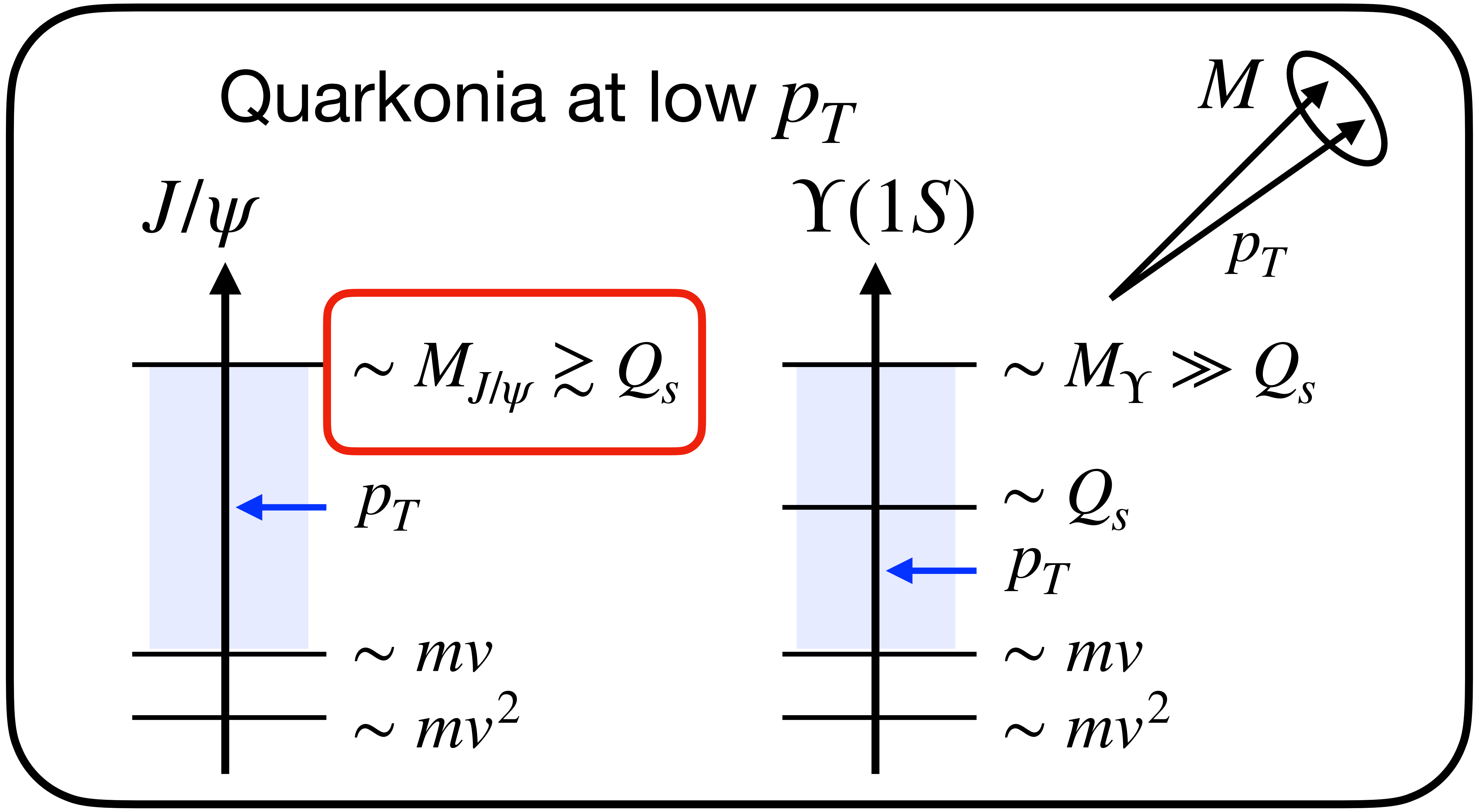
➢ Hadronic (pp) and hadron-ion (pA) collision provide an important benchmark for EIC (ep/eA).

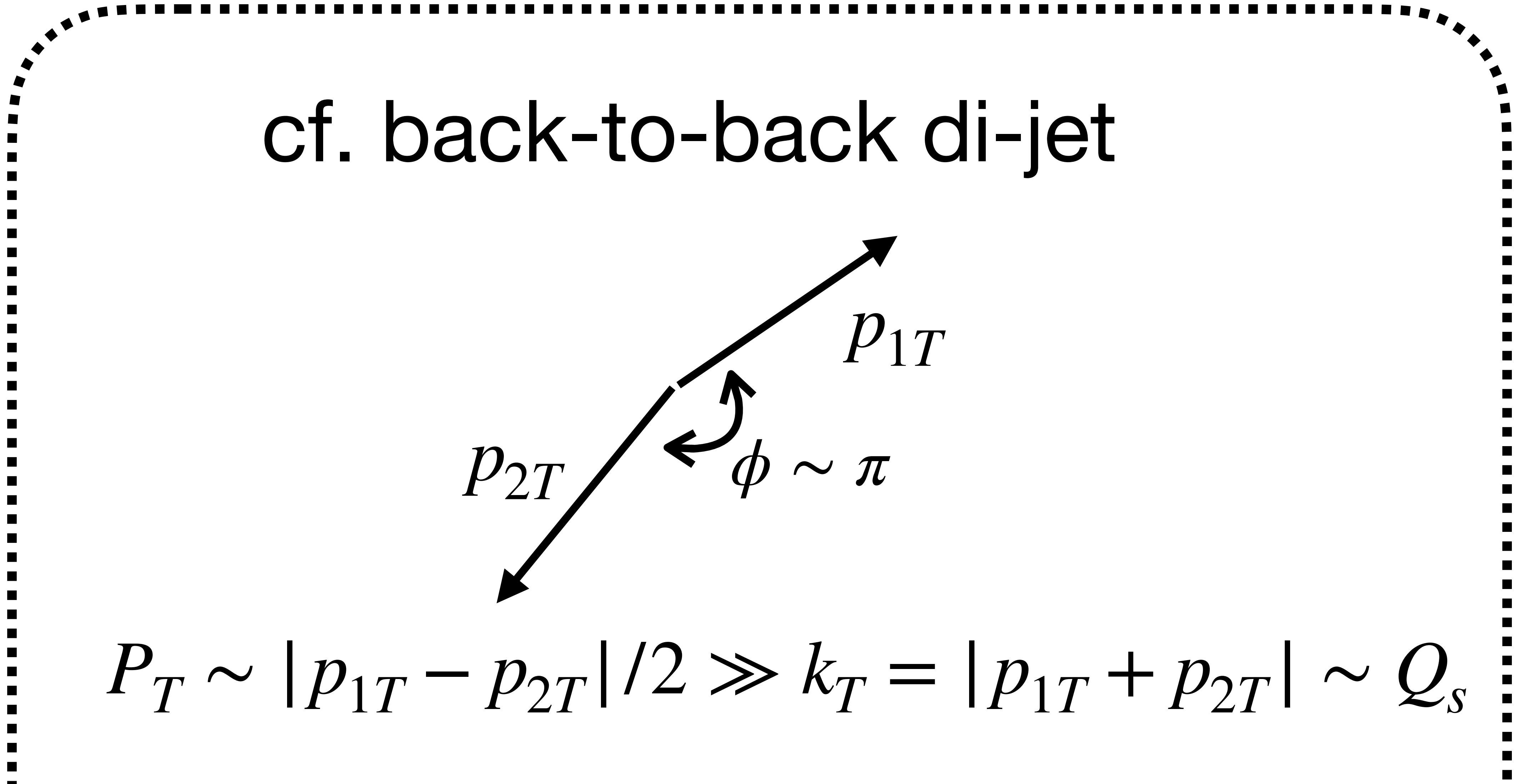
➢ Inclusive/Exclusive forward quarkonium production should be sensitive to nonlinear QCD dynamics at small-x.

Quarkonium production with multi-scales

HERA data are used to fit input parameters in theory.



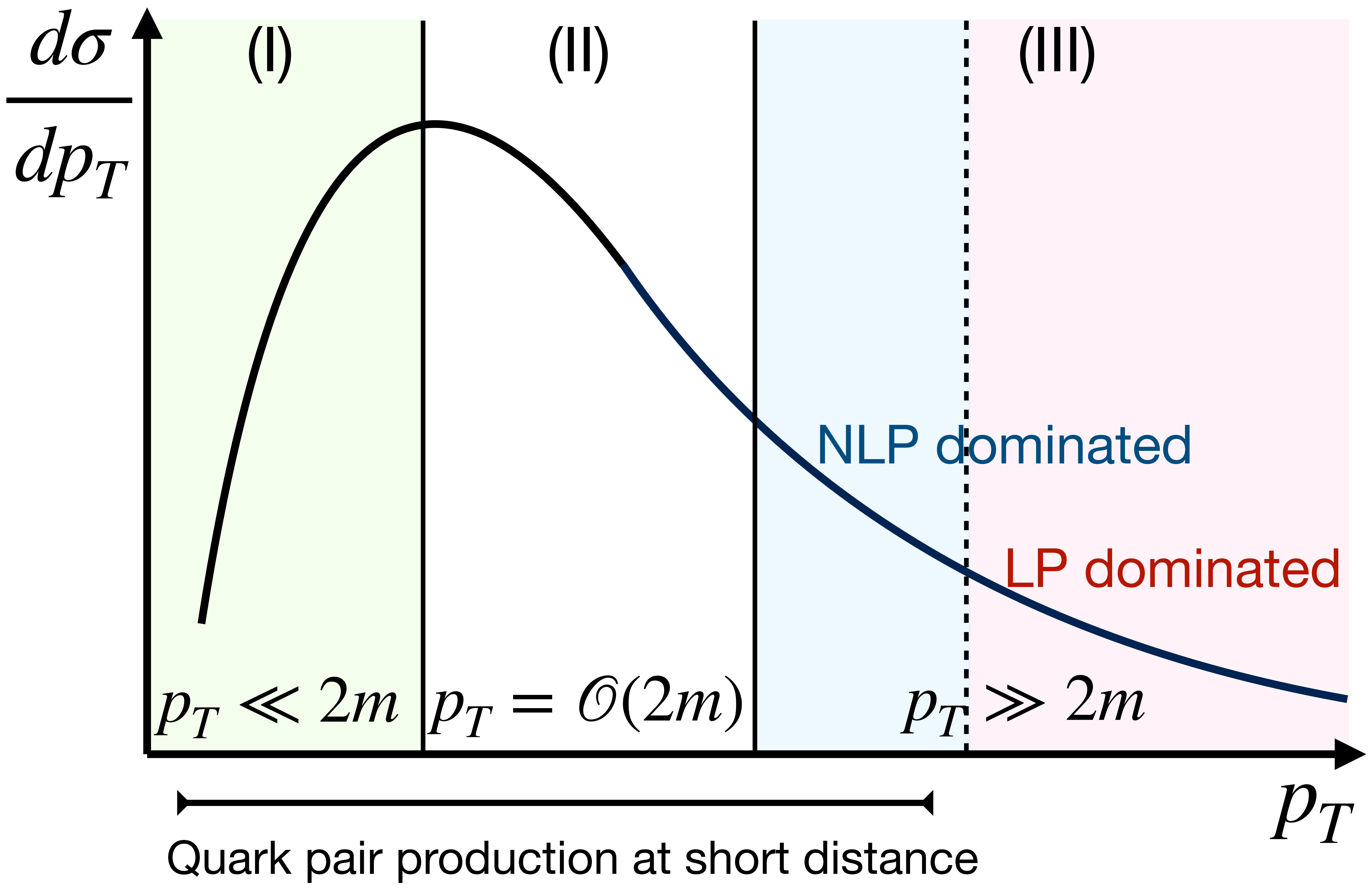




J/ψ + jet is a higher order process in the CGC framework.

p+p collisions

p_T distribution of hadronic quarkonium production



(I) TMD factorization + CEM or NRQCD

Berger, Qiu and Wang, PRD 71, 034007 (2005)
Sun, Yuan and Yuan, PRD88, 054008 (2013)

CGC framework + CEM or NRQCD (forward)

Ma, Venugopalan, PRL113, 19, 192301 (2014)
KW, Xiao, PRD92, 11, 111502 (2015)

(II) NRQCD factorization

Butenschoen, Kniehl, PRD84, 051501 (2011)
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012)
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013)

(III) QCD factorization w/ Fragmentation Functions

Kang, Qiu and Sterman, PRL108, 102002 (2012)
Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014)
Ma, Qiu, Sterman, Zhang, PRL113, 14, 142002 (2014)

Matching between (I) and (II):

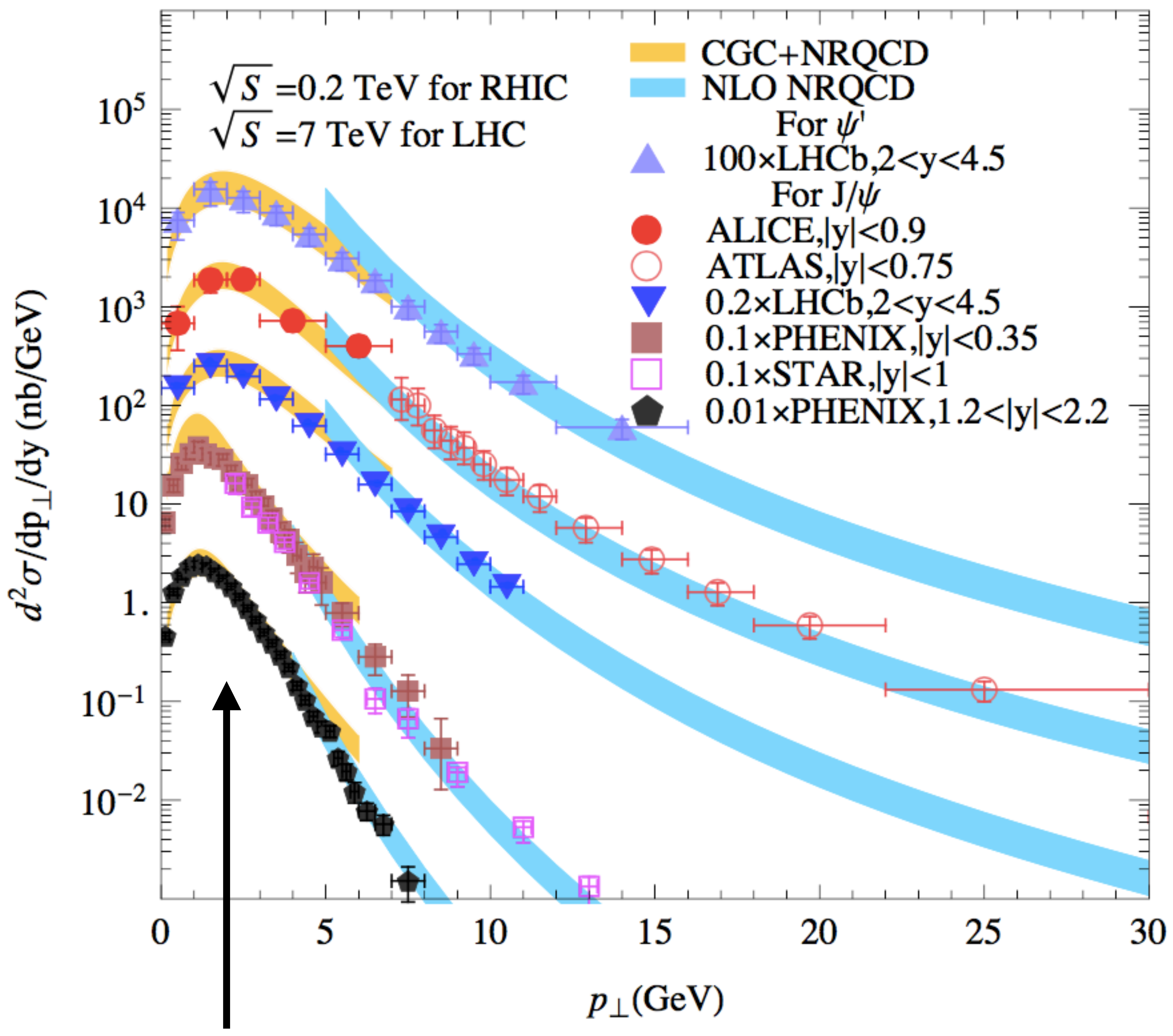
$$\frac{d\sigma_{A+B\to\psi+X}(m\neq 0)}{d^2p_\perp dy} = \boxed{\frac{d\sigma^{\text{Resum}}_{A+B\to\psi+X}(m\neq 0)}{d^2p_\perp dy}} - \frac{d\sigma^{\text{Asym}-(n)}_{A+B\to\psi+X}(m\neq 0)}{d^2p_\perp dy} + \frac{d\sigma^{\text{NRQCD}-(n)}_{A+B\to\psi+X}(m\neq 0)}{d^2p_\perp dy}$$

Large $\ln(1/x)$ corrections

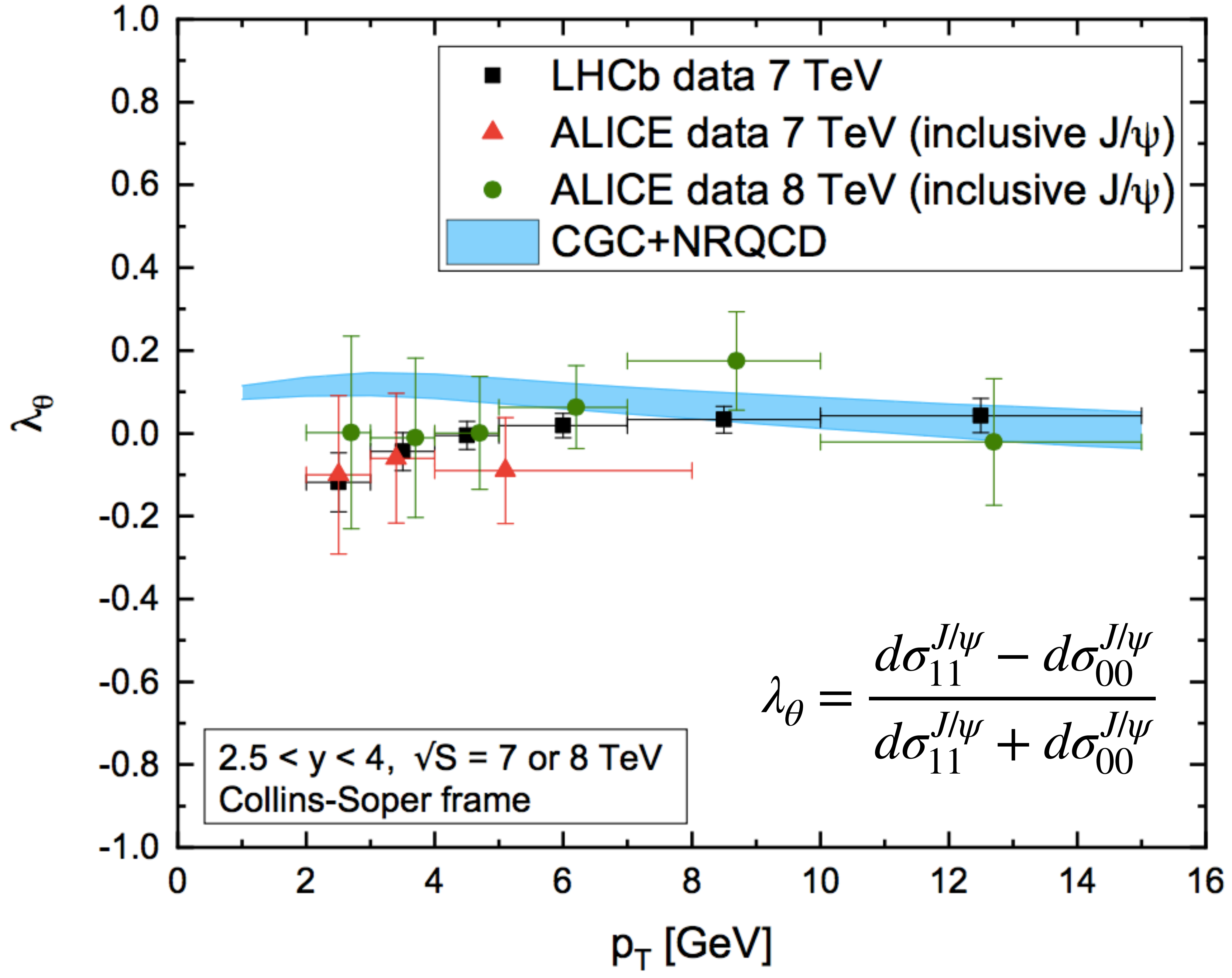
Production → Jean-Philippe Lansberg (Mon. 25)
TMD factorization → Thomas Mehen (Mon. 25)

Forward J/ψ production and polarization

Ma, Venugopalan, PRL113, 19, 192301 (2014)



Ma, Stebel and Venugopalan, JHEP12, 057 (2018)

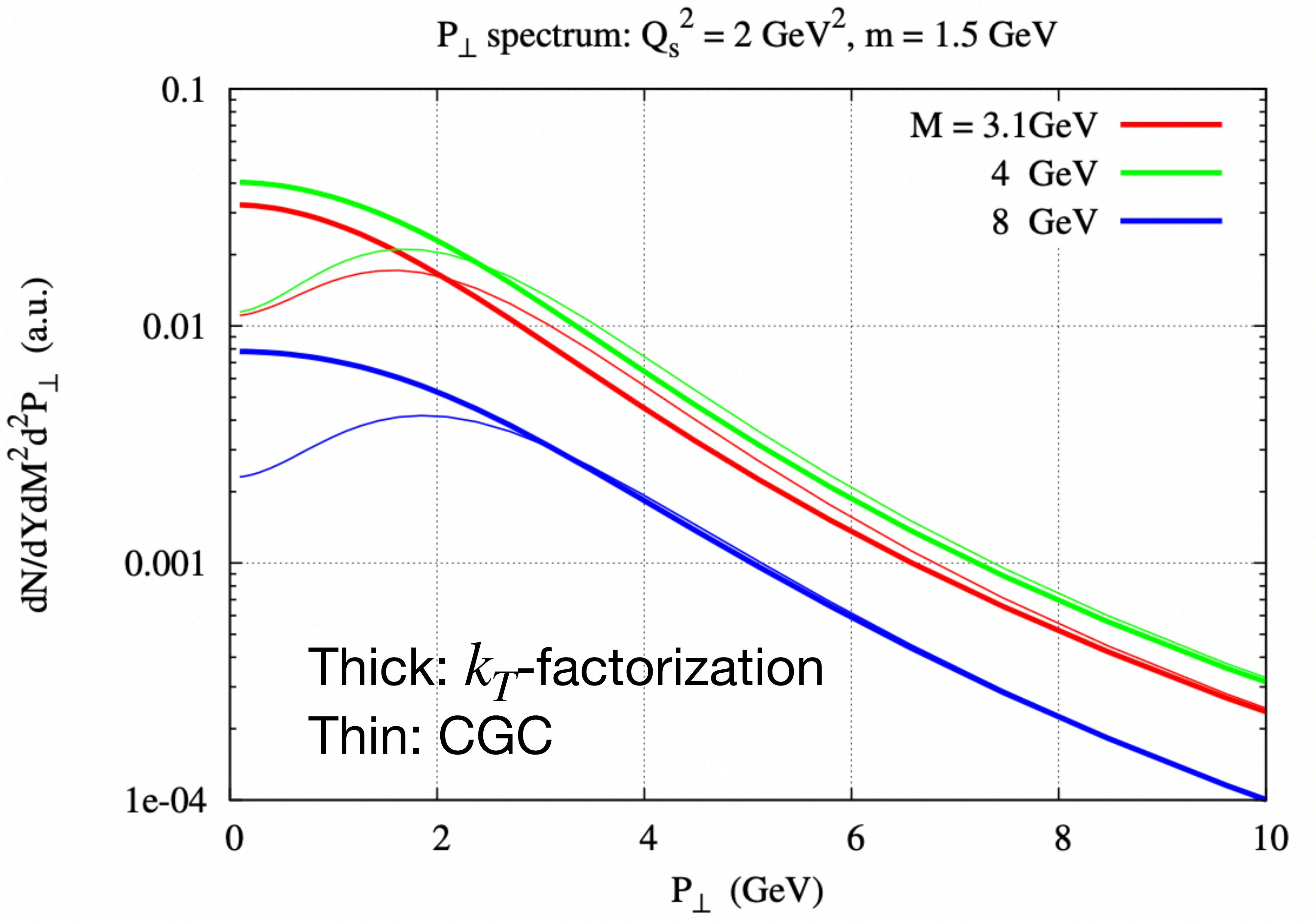


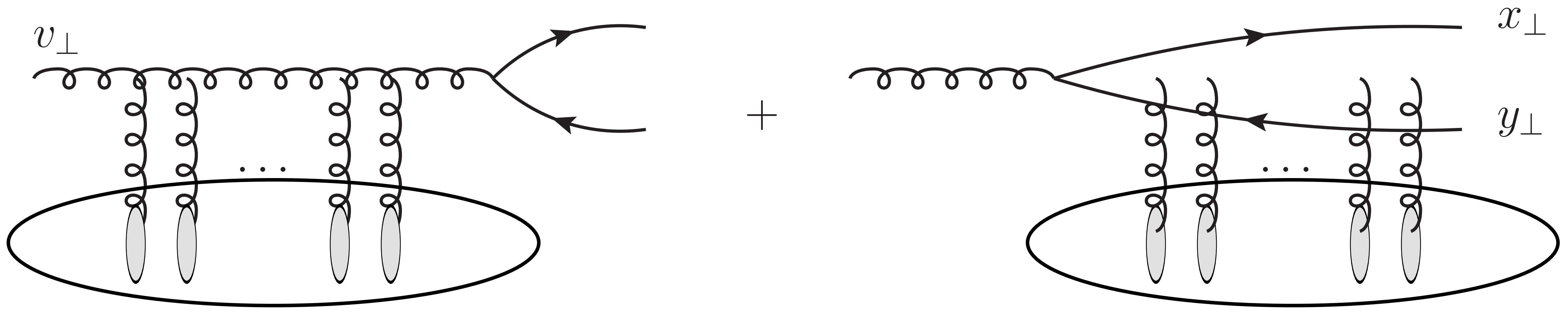
- ➢ The MV-model + JIMWLK evolution gives a good parametrization of the unpolarized gluon distribution at small-x.
- ➢ Positive definite LDMEs are used.

LDMEs extraction → Yan-Qing Ma (Mon. 25)

Multiple-scattering (twist) corrections

Fujii, Gelis and Venugopalan, NPA 780, 146 (2006)





Higher twist corrections (encoded in Wilson lines) modify the p_T spectrum of quarkonium at $p_T^2 \lesssim Q_s^2$.

➢ Remark on twist corrections in the CGC framework

TMD + kinematic twist $\mathcal{O}(k_t/Q)$ = Improved TMD

Improved TMD + higher-body genuine twist $\mathcal{O}(Q_s/Q)$ = CGC

k_t : off-shellness in short distance parts

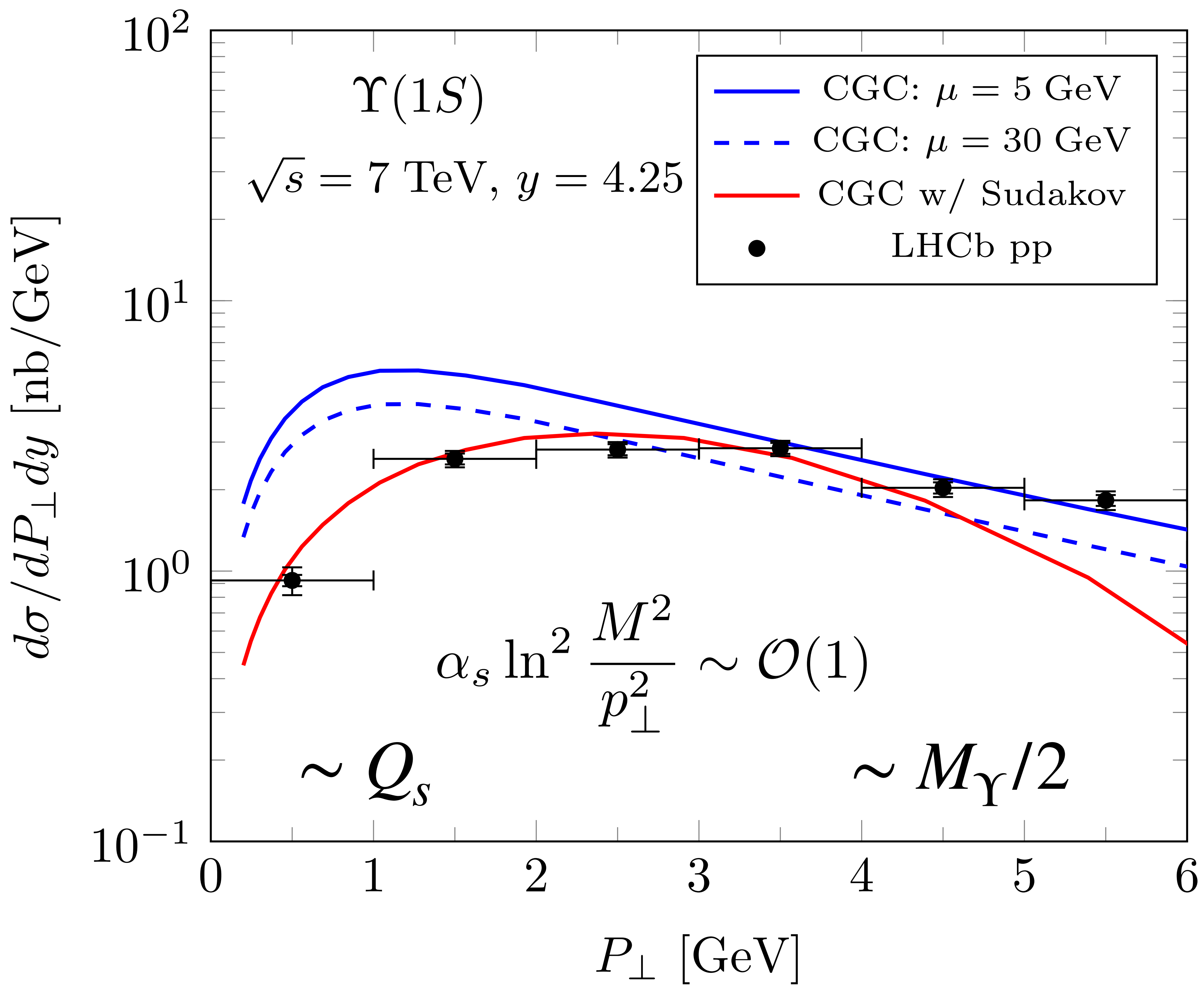
Q : a hard scale.

Altinoluk, Boussarie and Kotko, JHEP05, 156 (2019).
Mantysaari, Mueller, Salazar and Schenke, PRL124, no.11, 112301 (2020).
Fujii, Marquet and **KW**, JHEP12, 181 (2020).
Altinoluk, Marquet and Taels, JHEP06, 085 (2021).
Boussarie, Mantysaari, Salazar and Schenke, [arXiv:2106.11301 [hep-ph]].
…

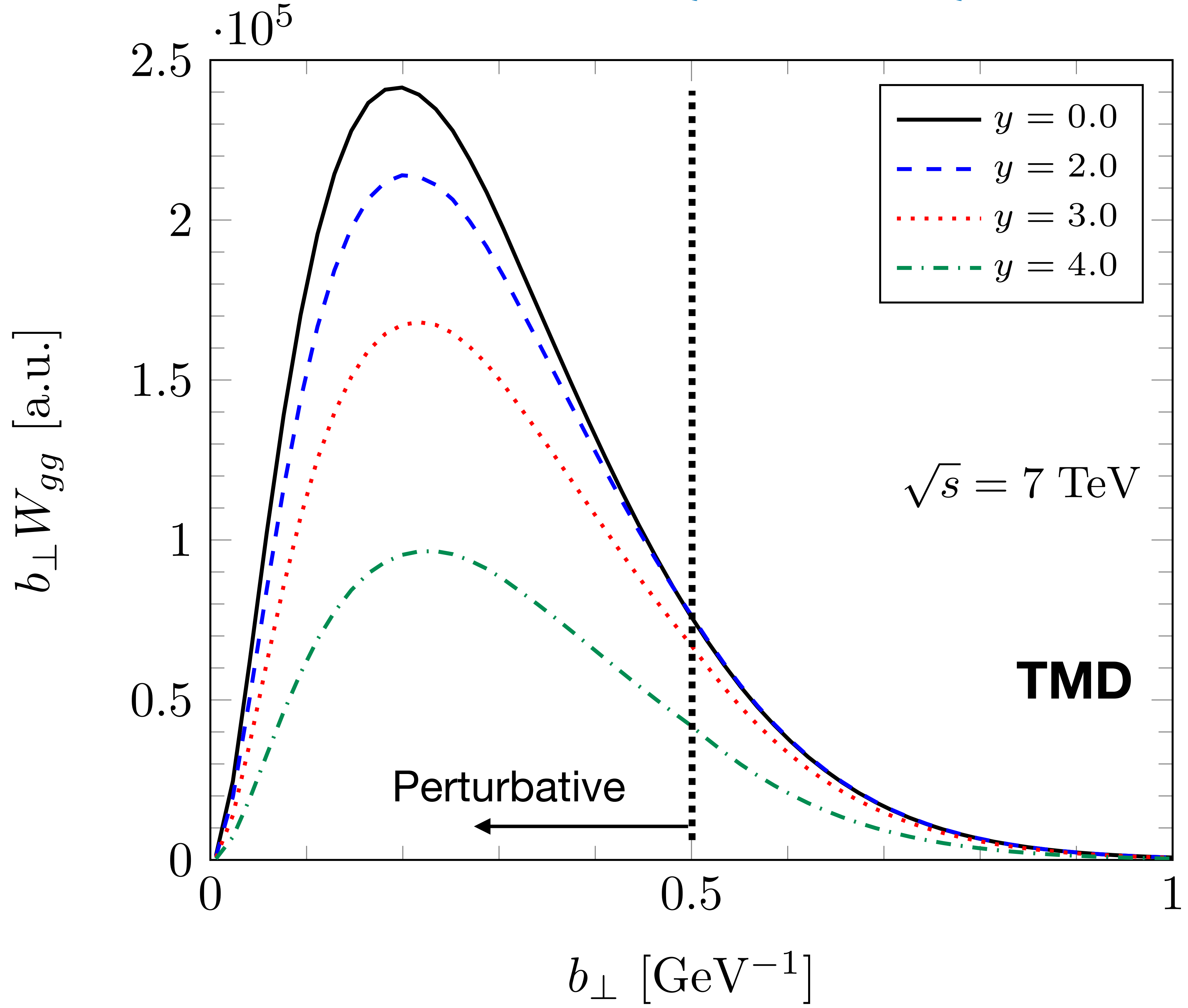
Extensively studied for dijet/dihadron production in pA/eA

Υ production as a crosscheck: small-x and large Q^2

KW, Xiao, PRD92 (2015) 11, 111502



Qiu, **KW**, PoS QCDEV2017 (2017) 024



- ➢ Forward bottomonium probes $x \sim 10^{-4} - 10^{-5}$, giving $Q_s^2 \sim 1\text{GeV}^2$.
- ➢ Initial state soft-collinear parton shower effect (Sudakov: CSS evolution) is important. Even at forward rapidity, there is the perturbative shower effect.

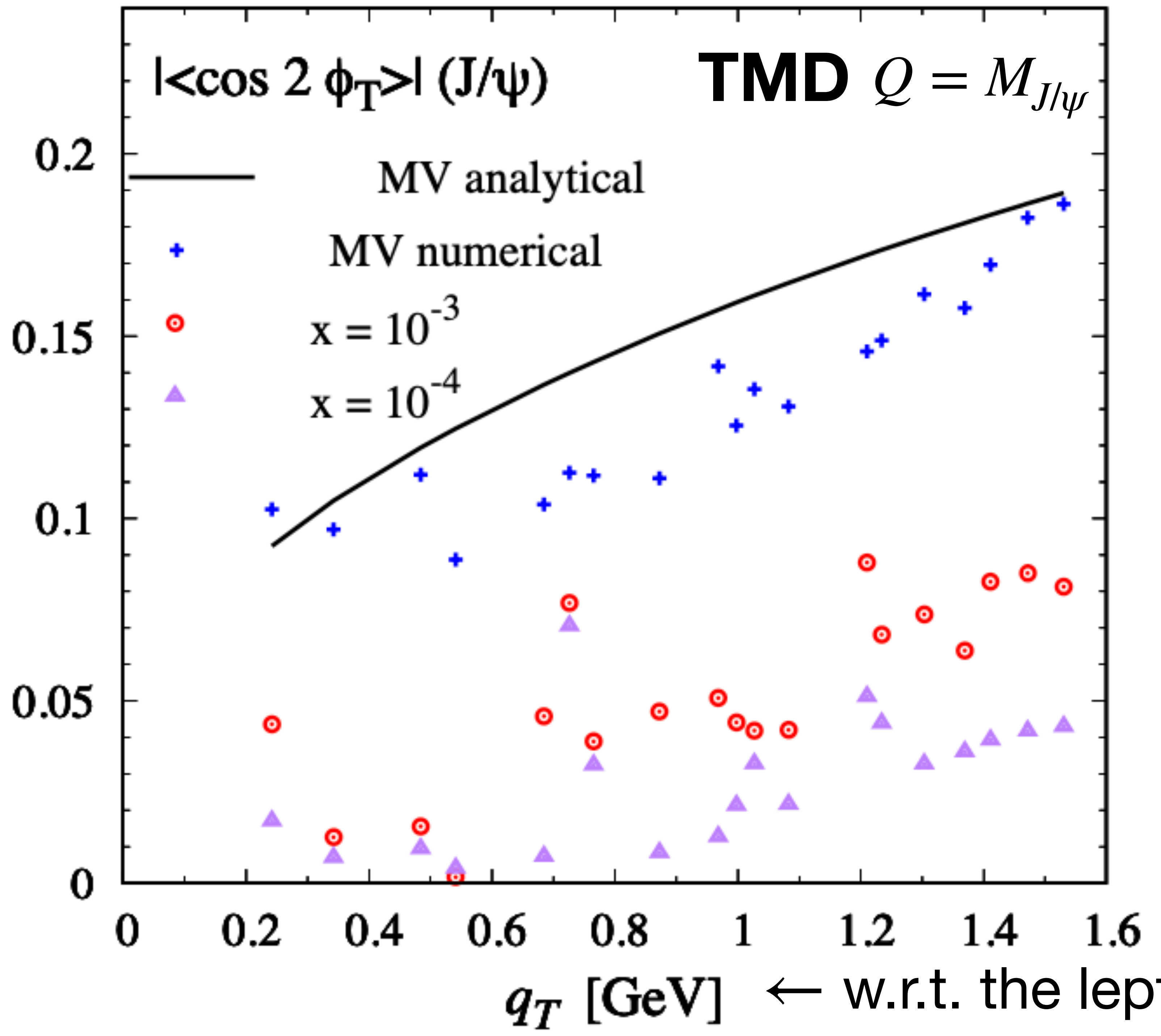
$$\left.\frac{d\sigma_{A+B\to Q\bar{Q}+X}}{d^2P_\perp^2 dy}\right|_{\text{resum}} \propto \int \frac{db_\perp}{2\pi} J_0(P_\perp b_\perp) b_\perp W_{gg} d\hat{\sigma}_{gg\to Q\bar{Q}}$$

Benchmark for further study at the EIC

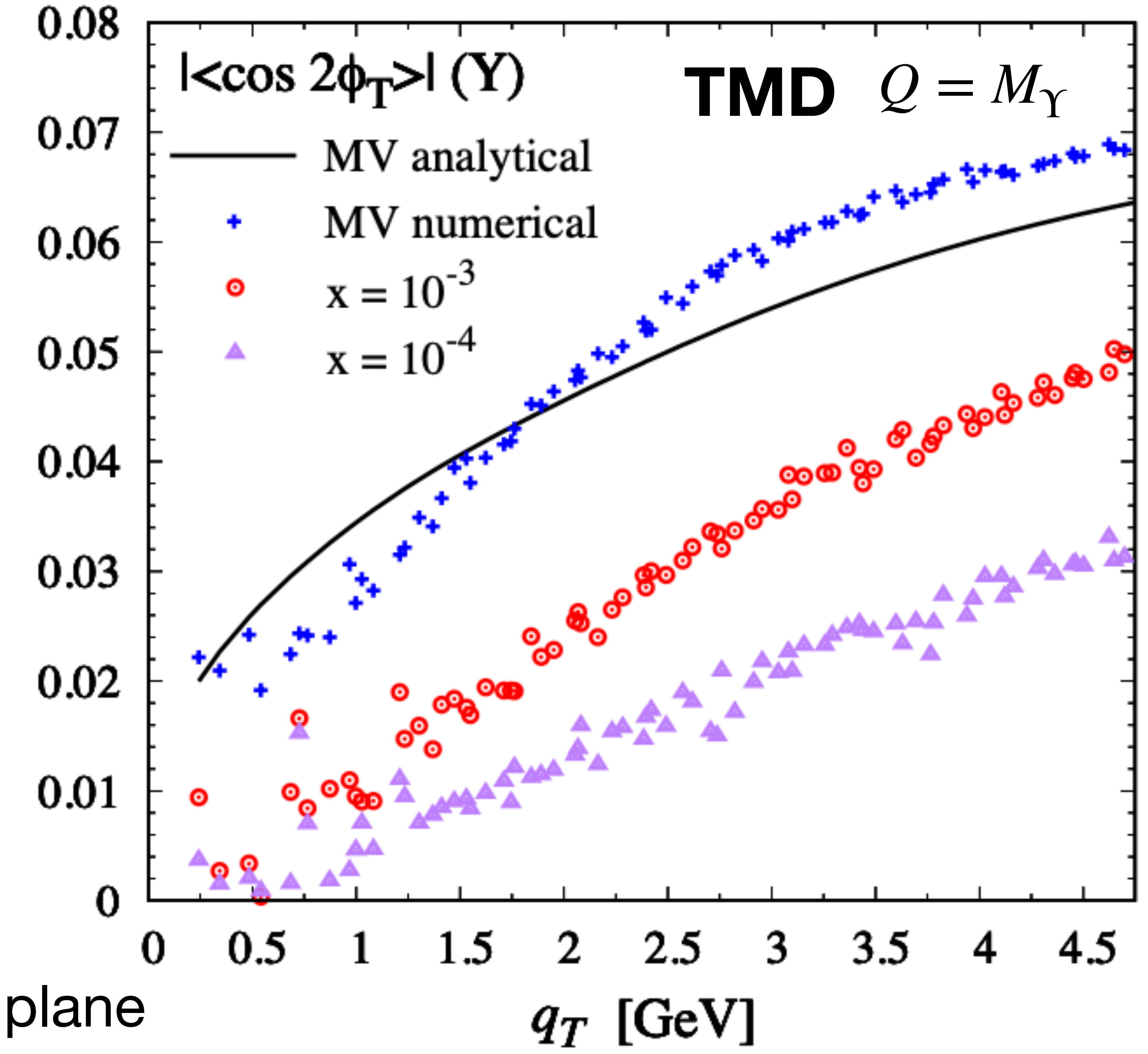
$$e + p \to e + J/\psi(\Upsilon) + X$$

Bacchetta, Boer, Pisano and Taels, Eur. Phys. J. C 80, no.1, 72 (2020)

$$\langle \cos 2\phi_T \rangle \propto \frac{h_\perp^g(x, q_T^2)}{f_1^g(x, q_T^2)}$$



← w.r.t. the lepton plane



Unpolarized and linearly polarized Weizsäcker-Williams in the unpolarized proton in MV model lead to:

$$\frac{p_T^2}{2M_p^2}\frac{h_1^{\perp g}(x, \boldsymbol{p}_T^2)}{f_1^g(x, \boldsymbol{p}_T^2)} = \frac{\int \mathrm{d}r \frac{J_2(p_T r)}{r \ln(\frac{1}{r^2\Lambda^2}+e)} \left(1 - e^{-\frac{r^2}{4}Q_{sg0}^2 \ln\left(\frac{1}{r^2\Lambda^2}+e\right)}\right)}{\int \mathrm{d}r \frac{J_0(p_T r)}{r} \left(1 - e^{-\frac{r^2}{4}Q_{sg0}^2 \ln\left(\frac{1}{r^2\Lambda^2}+e\right)}\right)}$$

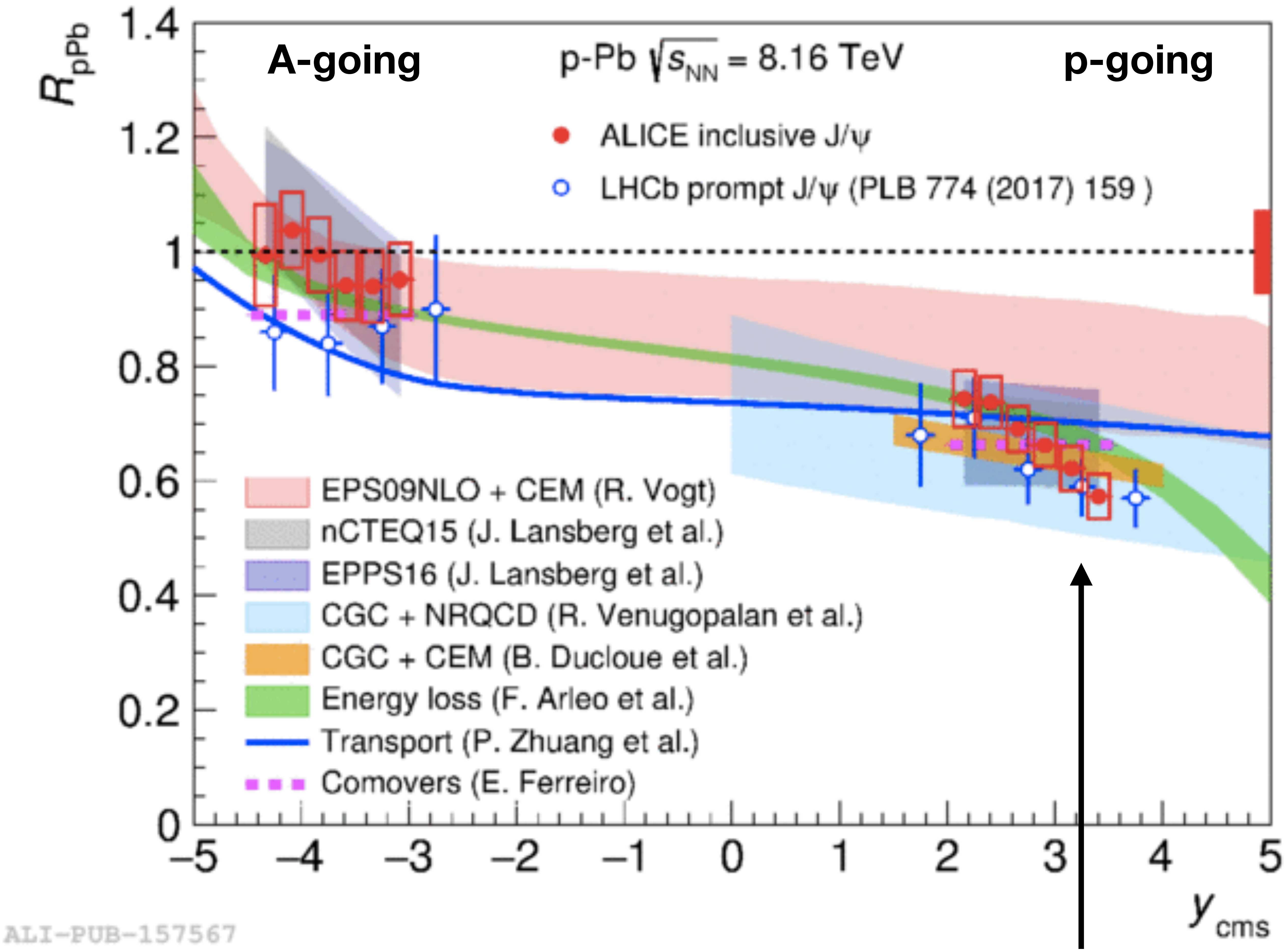
- ➢ Useful observables to fit LDMEs.
- ➢ How small are higher twist effects at low q_T?

p+A collisions

Nuclear suppression at forward rapdity

- ➢ Nuclear PDFs
  - Leading-twist shadowing.
- ➢ CGC / Energy loss
  - Saturation effect (multiple scattering).
- ➢ Comover interaction in final state
  - Partonic and hadronic soft interaction. Significant to excited states, such as $\psi(2S)$.

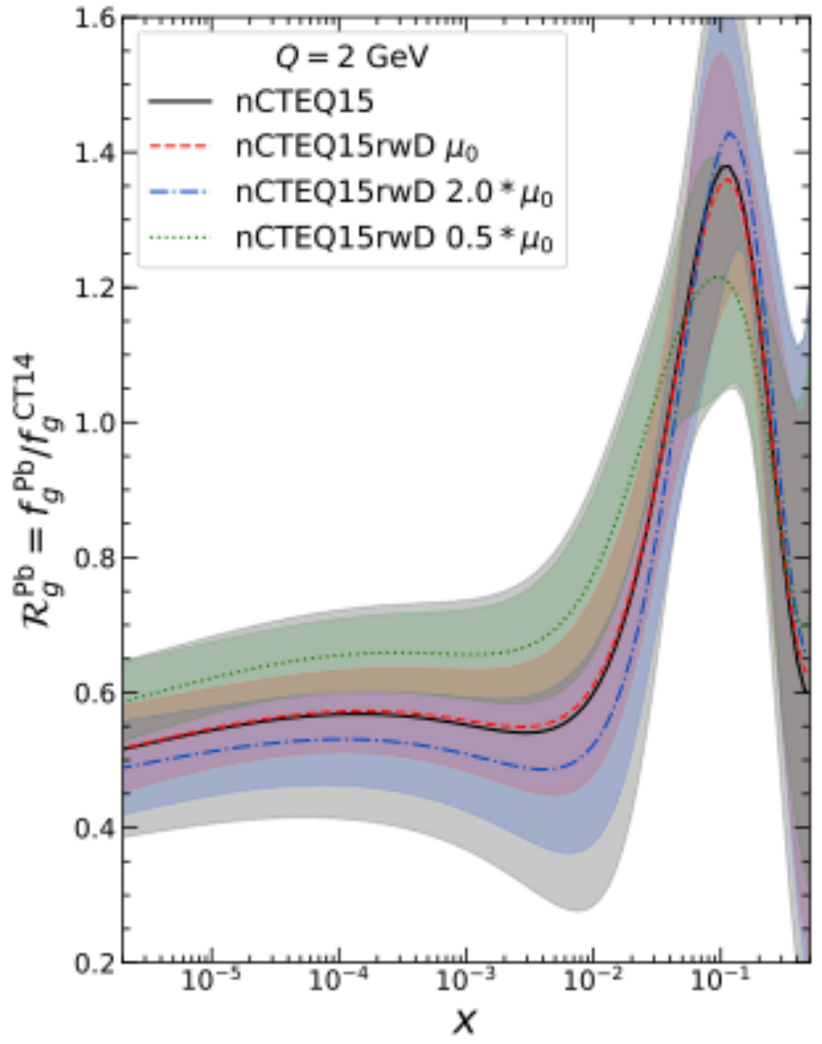
*There is no clear consensus about which is the dominant CNM effect yet.



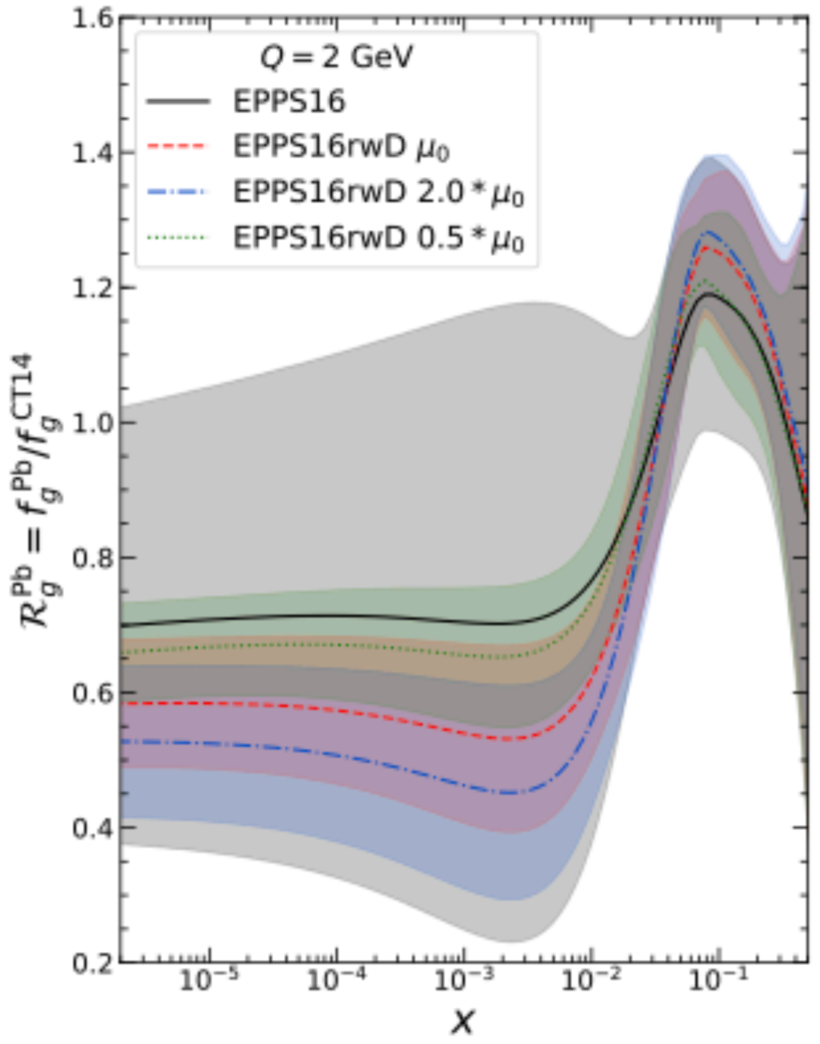
$$x_2 \sim M_{J/\psi} e^{-y} / \sqrt{s} = \mathcal{O}(10^{-5})$$

Exp. results → Rongrong Ma (Tue. 26)

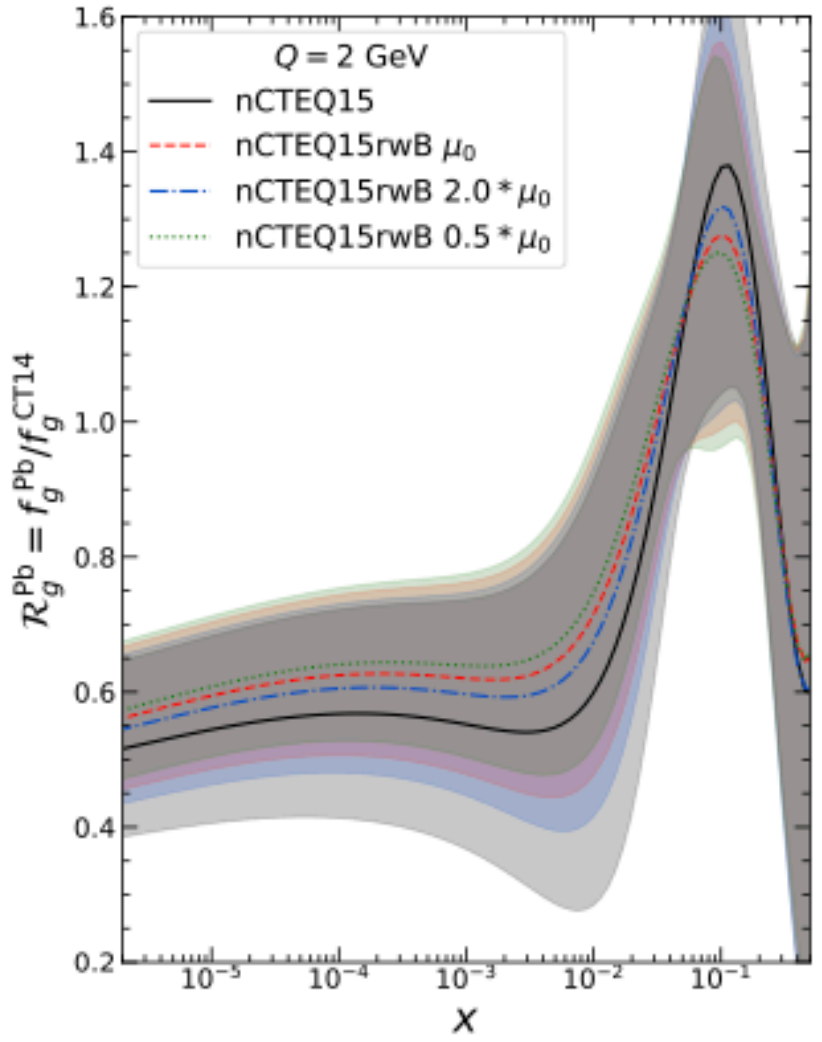
Constraining gluon nPDF with J/ψ



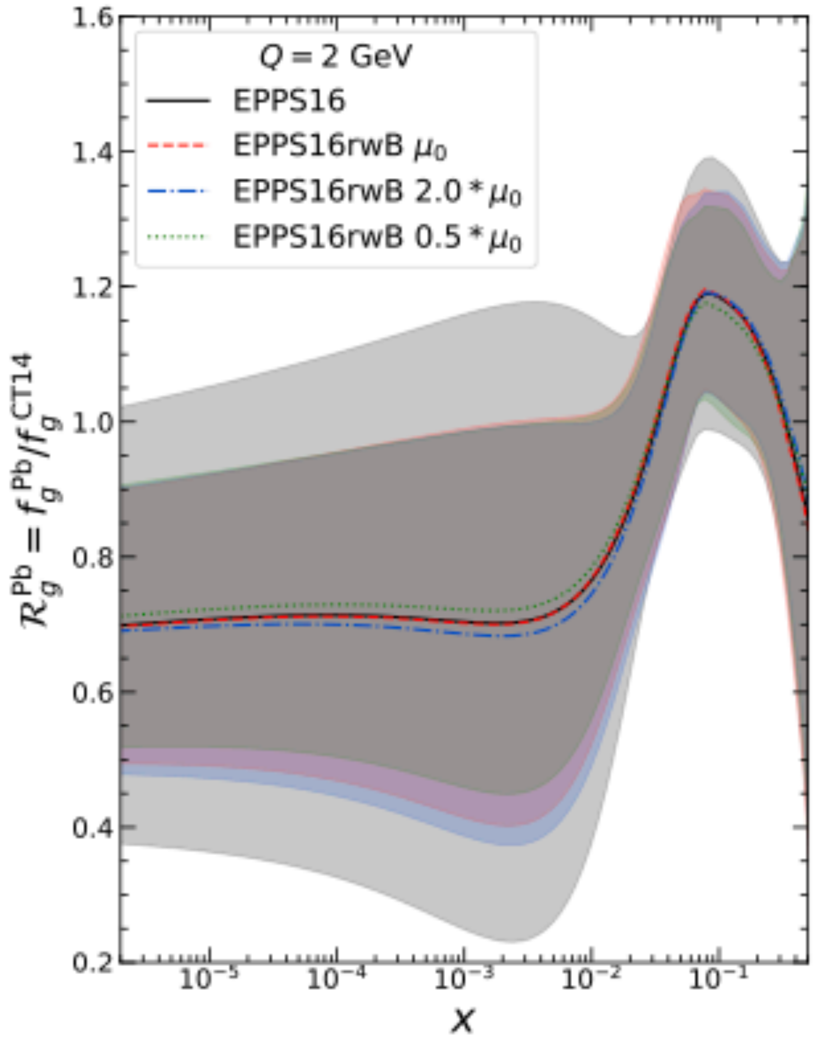
(a) *D*-reweighted nCTEQ15



(b) *D*-reweighted EPPS16



(c) $B \to J/\psi$-reweighted nCTEQ15

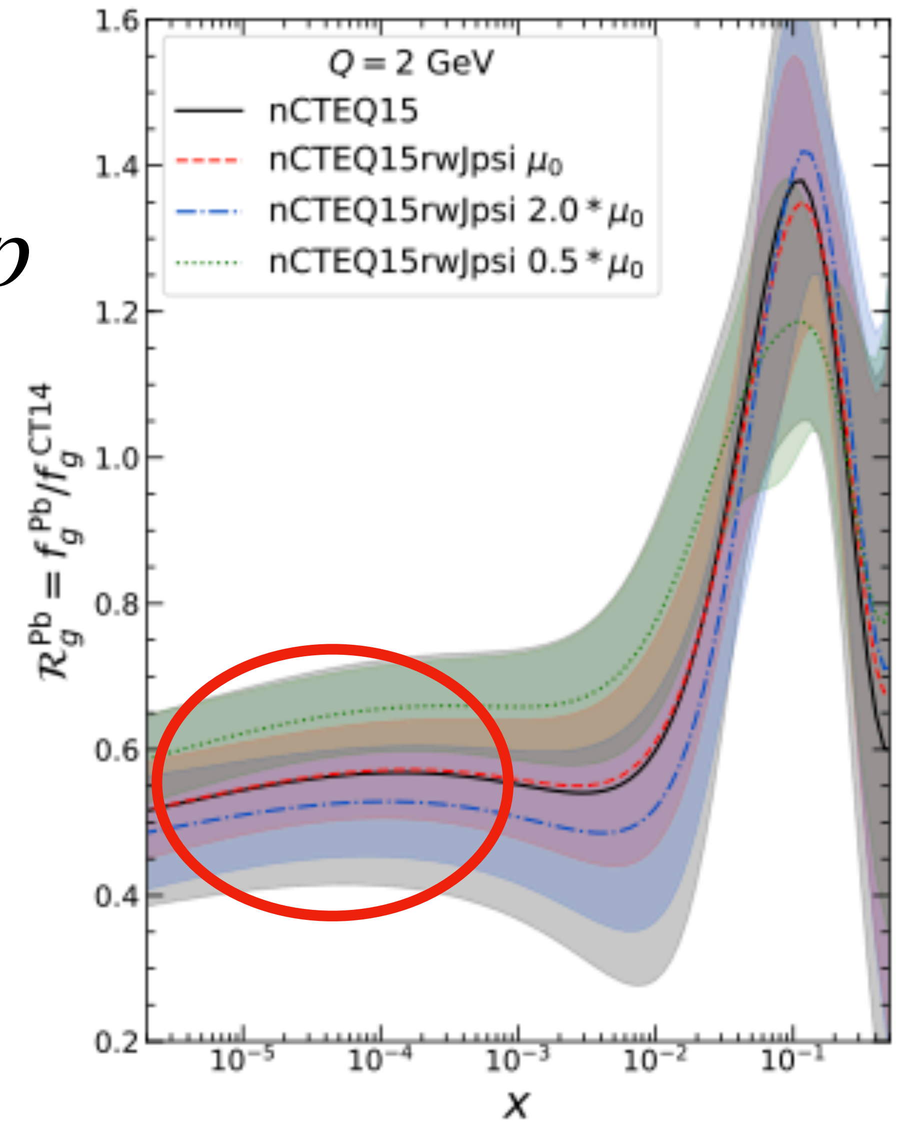


(d) $B \to J/\psi$-reweighted EPPS16

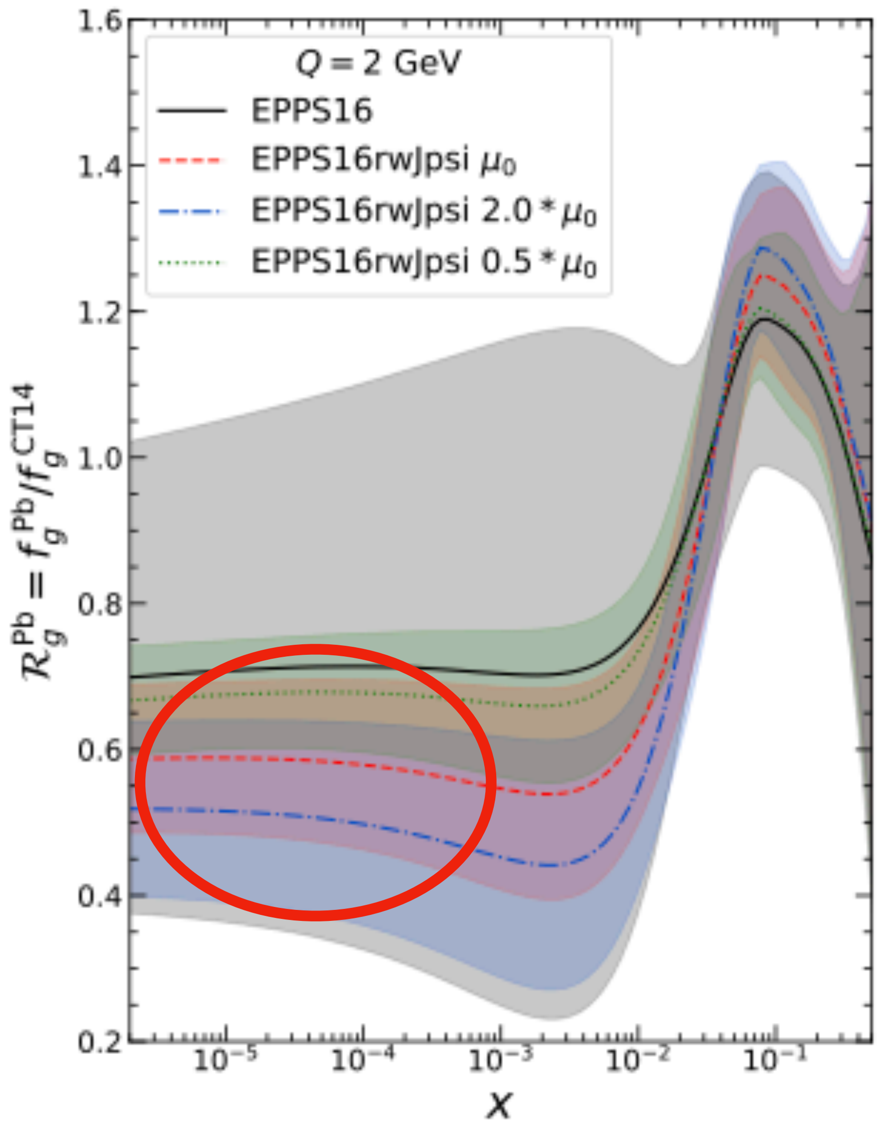
- ➢ Leading-twist gluon nPDF shows strong depletion at small-x after taking into account heavy flavor and quarkonium production data in pA collisions.
- ➢ Need to understand the impact of the saturation effect on the fitting of nPDFs.

Kusina, Lansberg, Schienbein and Shao, PRD104, no.1, 014010 (2021)

$$R_g = f_{g/A}/f_{g/p}$$



(e) J/ψ-reweighted nCTEQ15



(f) J/ψ-reweighted EPPS16

nPDFs → Pit Duwentaester (Mon. 25)

Nuclear p_T broadening

A direct access to the gluon saturation scale

$$\Delta\langle p_T^2\rangle_{pA/eA} = \langle p_T^2\rangle_{pA/eA} - \langle p_T^2\rangle_{pp/ep}$$

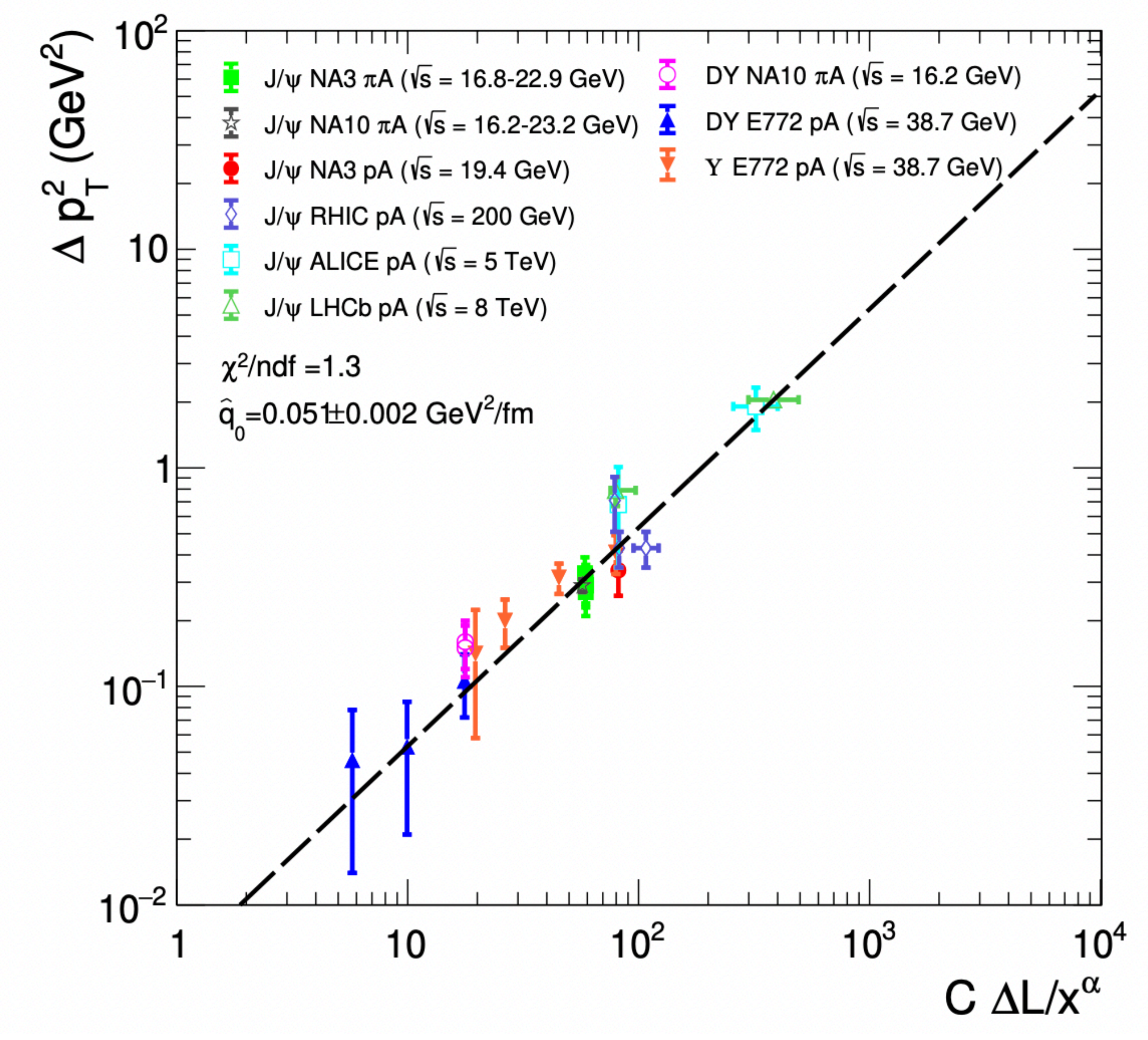
$$\langle p_T^2\rangle_{pA/eA} = \boxed{\langle p_T^2\rangle_{vac}} + \boxed{\hat{q}L_A}$$

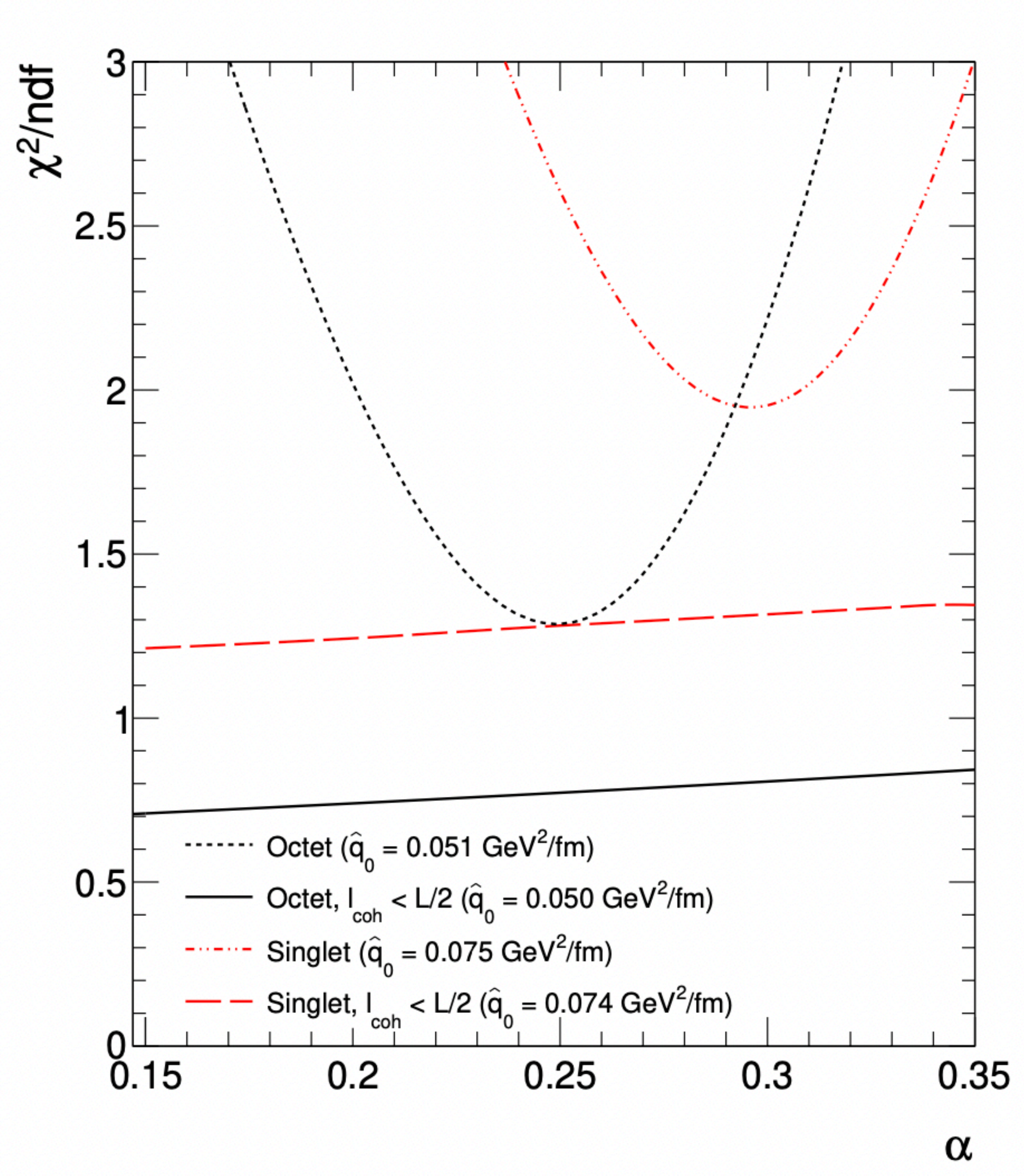
Medium independent

Multiple scattering effect in cold nuclear medium

Baier, Dokshitzer, Mueller, Peigne and Schiff, NPB484, 265 (1997)
Liou, Mueller, and Wu, NPA916, 102 (2013)
Blaizot and Mehtar-Tani, NPA929, 202 (2014)
…

$\hat{q}$: transport coefficient in cold nuclear matter $\rightarrow$ $\hat{q} = Q_s^2/L$ at small-x.





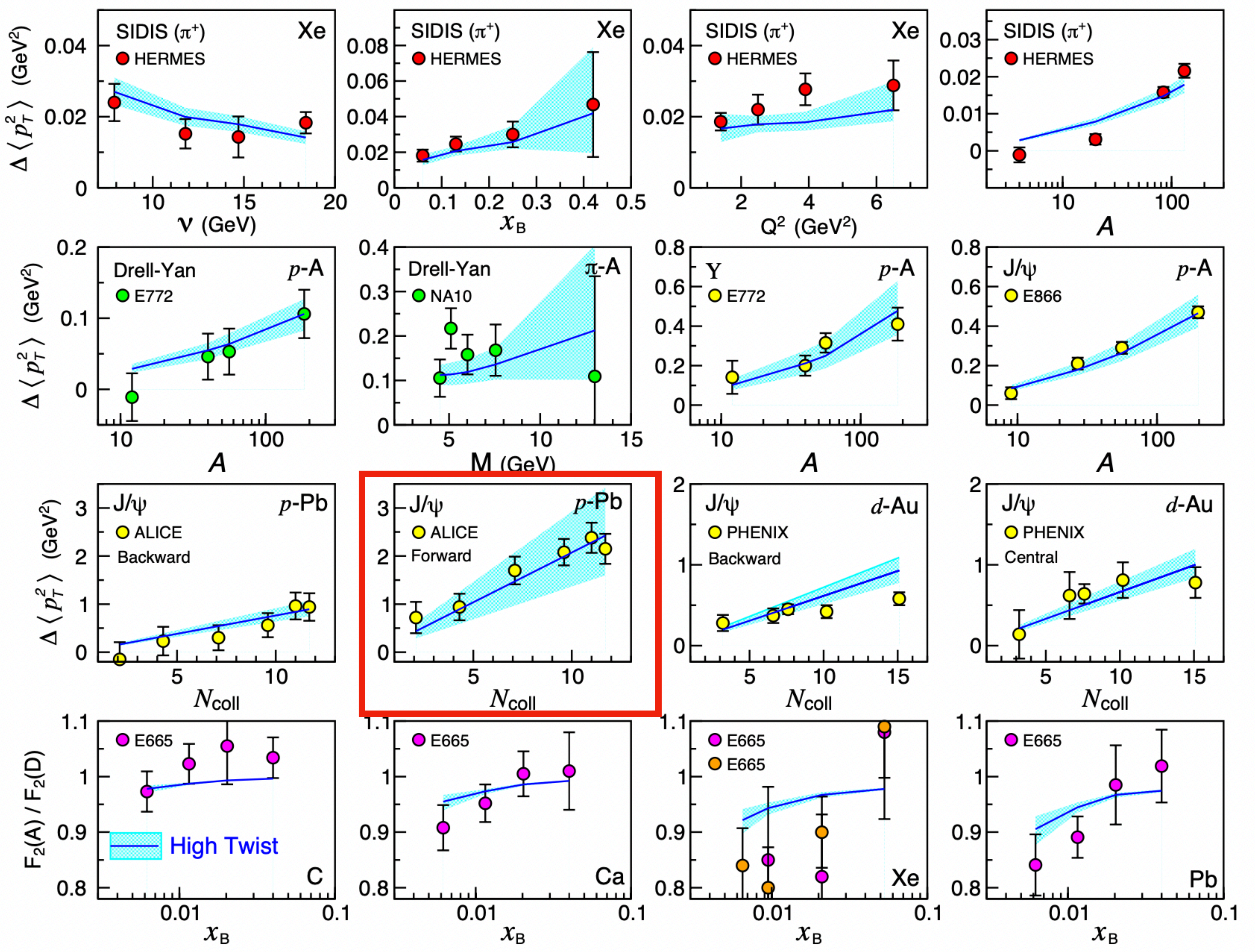
- Assuming quarkonium is produced as color octet states: $\hat{q}(x) \propto x^{-0.25}$.
- The x-dependence is consistent with geometrical scaling fit at HERA.

Arleo and Naïm, JHEP07, 220 (2020)

Global data analysis of $\hat{q}$ for cold nuclear medium

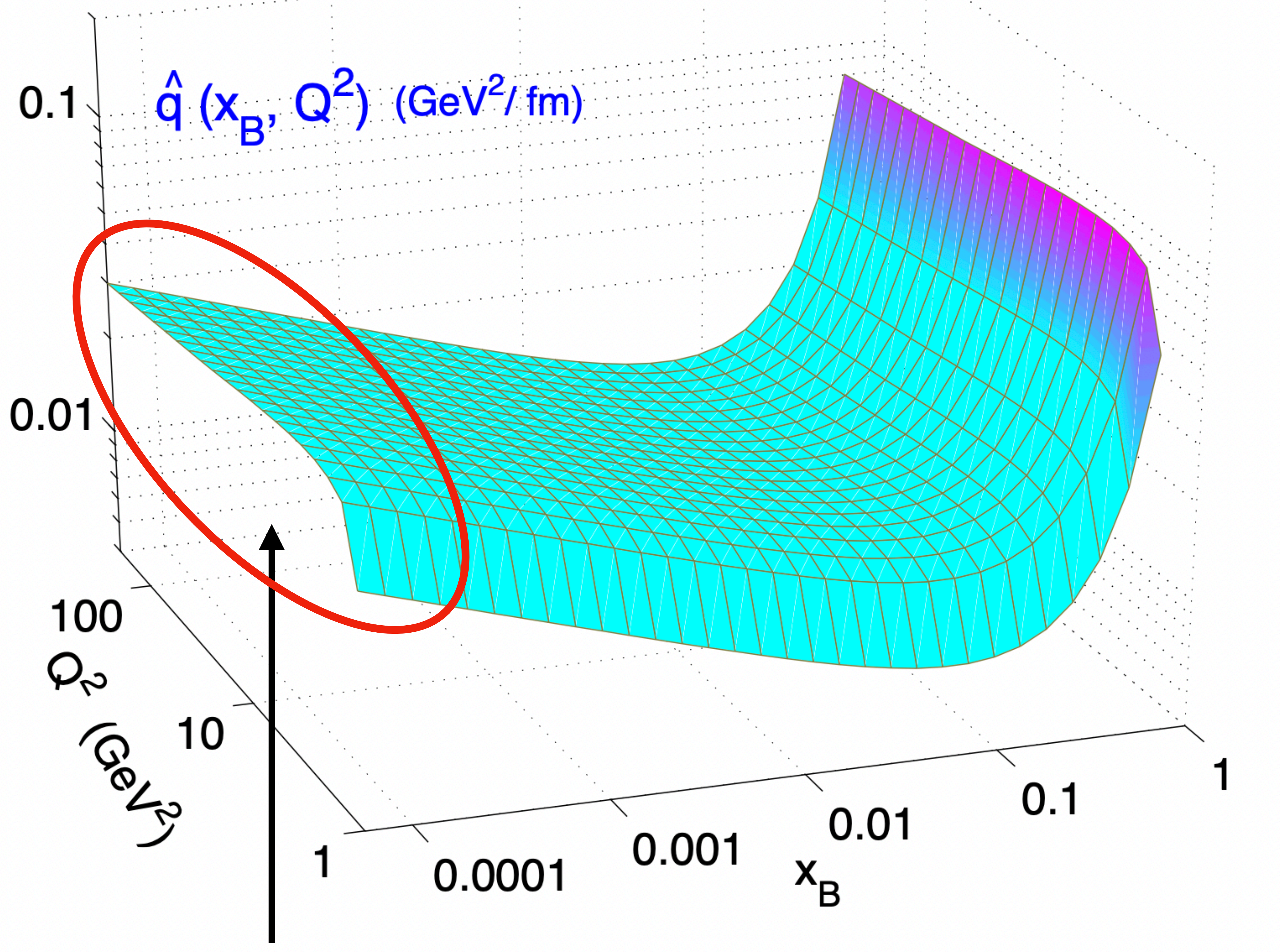
Global data analysis based on QCD factorization
(nPDFs + higher twist)

Ru, Kang, Wang, Xing and Zhang, PRD103, no.3, L031901 (2021)



$$\chi^2_{\rm dof} = 1.21$$

e.g. SIDIS: $T_{qg}(x,0,0,\mu^2) \propto f_{q/A}(x,\mu^2)\hat{q}(x,\mu^2)$

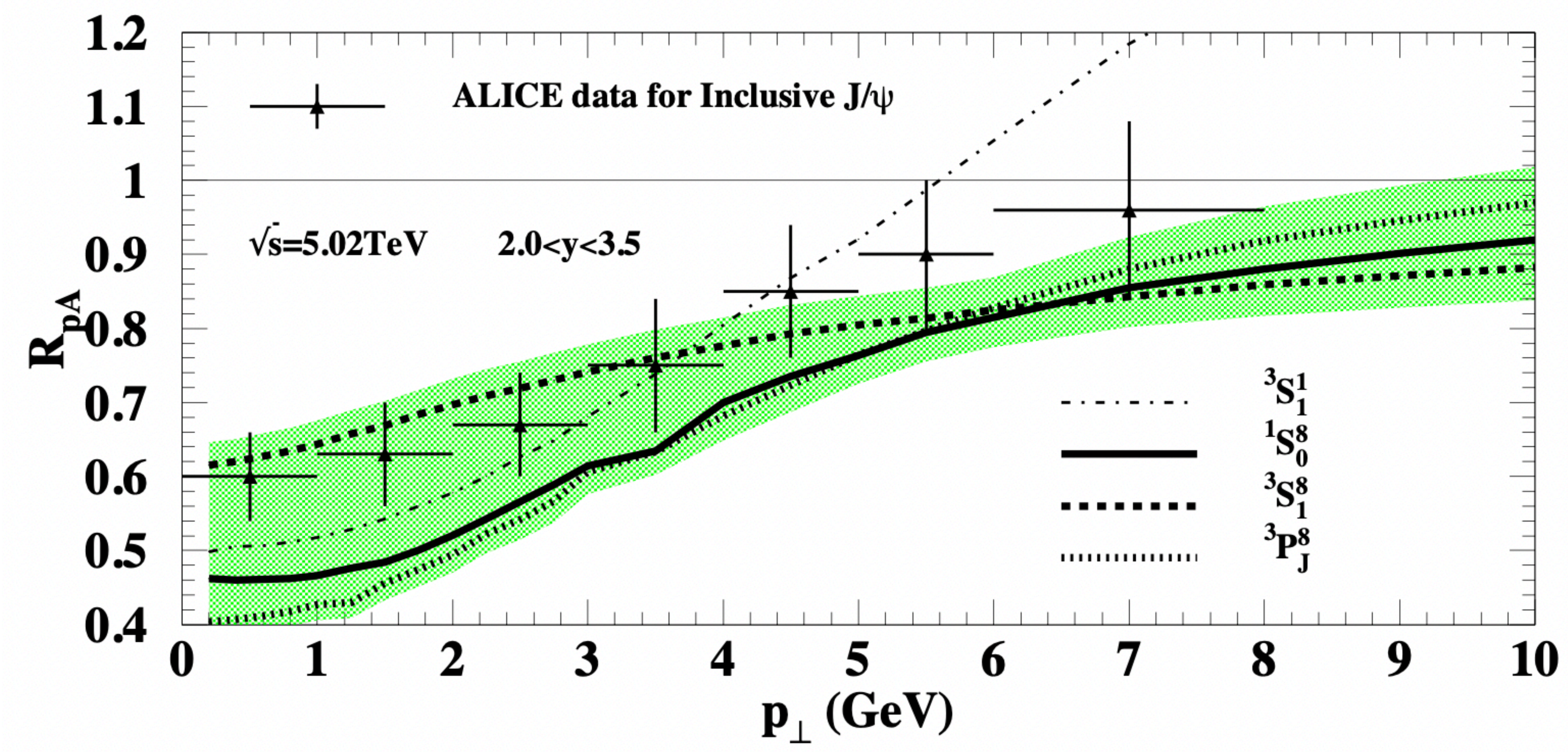


Consistent with the feature of the gluon saturation.

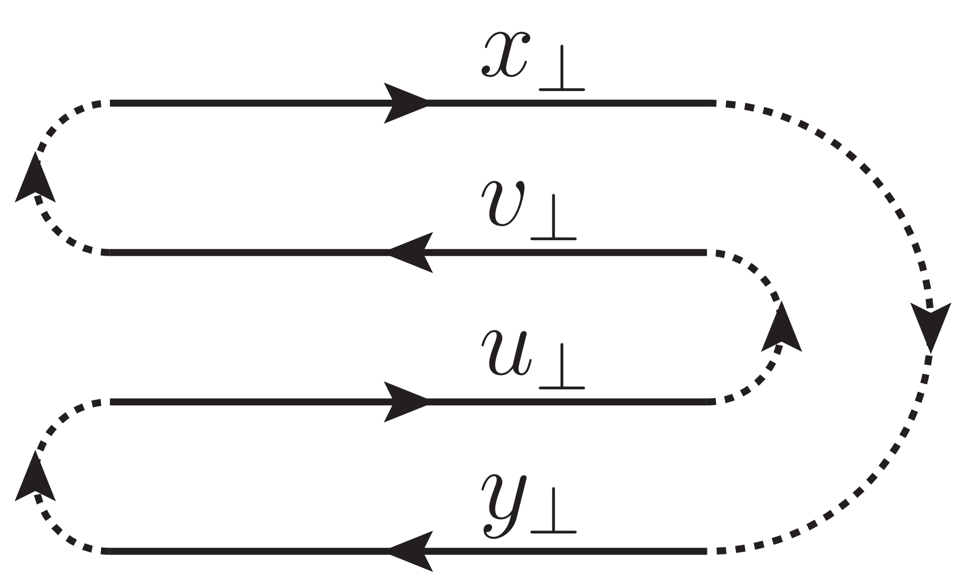
$$\hat{q}(x) \propto x^{-0.17}$$

Nuclear dependence in the CGC framework

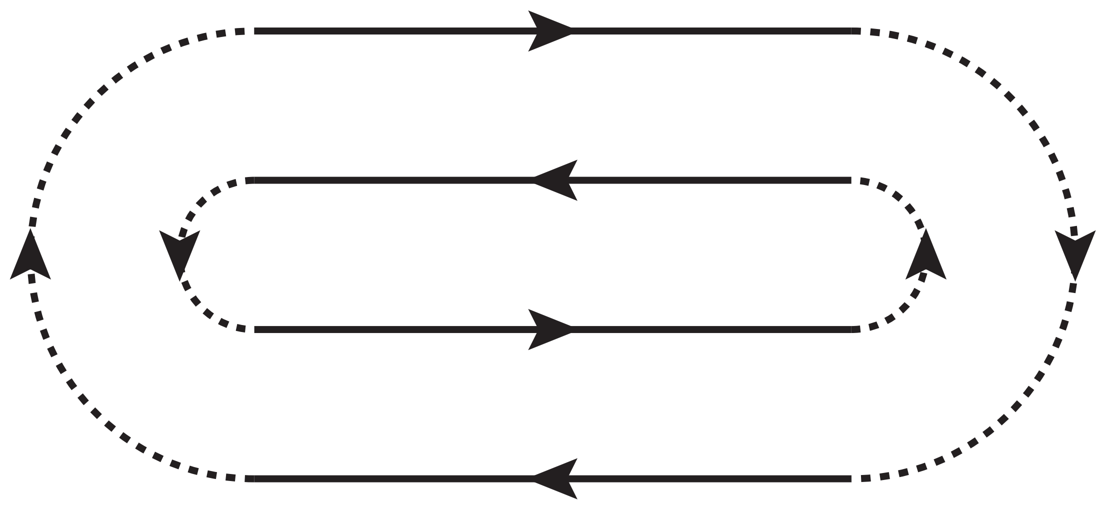
Ma, Venugopalan and Zhang, PRD92, 071901 (2015)



Color Singlet: quadrupole



Color Octet: double dipole



- ➢ Increasing the target size, the nuclear enhanced saturation effect is different in each intermediate state.
- ➢ For finite N_c, complicated process dependent Wilson line correlators are involved.
- ➢ Relative weights between LDMEs control the strength of the nuclear suppression as well as the nuclear broadening.

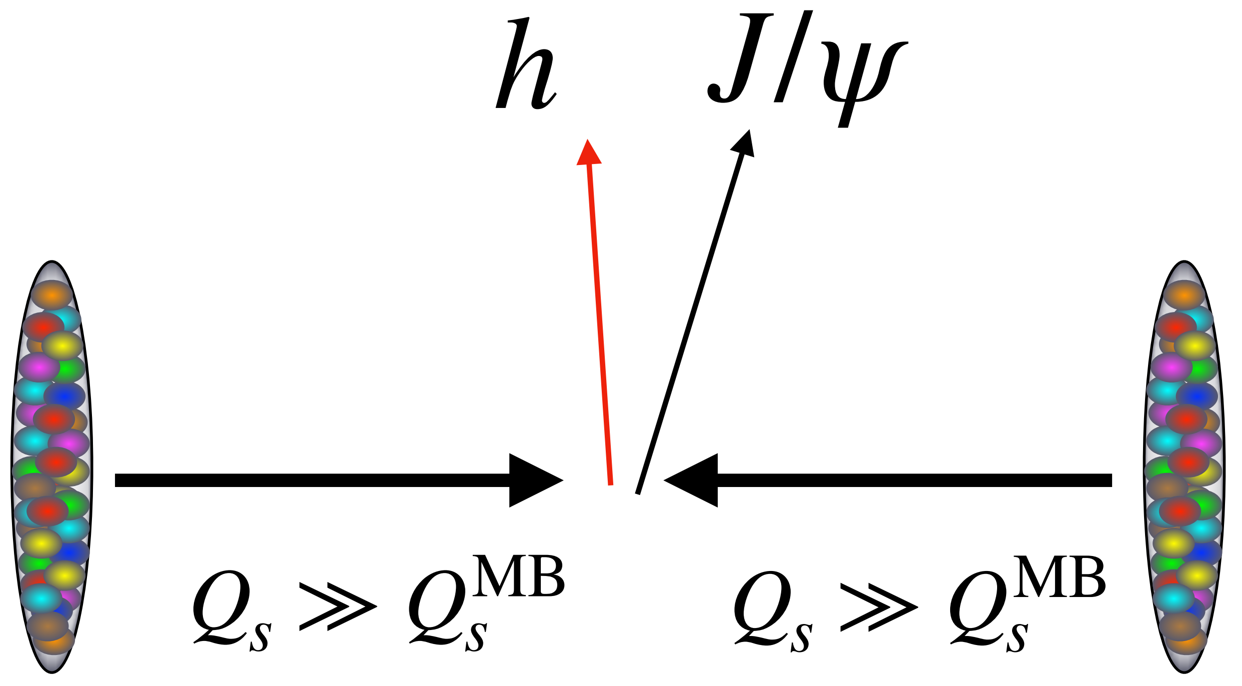
High multiplicity events in small systems.

➢ Unique opportunity at hadron colliders. Lower multiplicity is expected at the EIC.

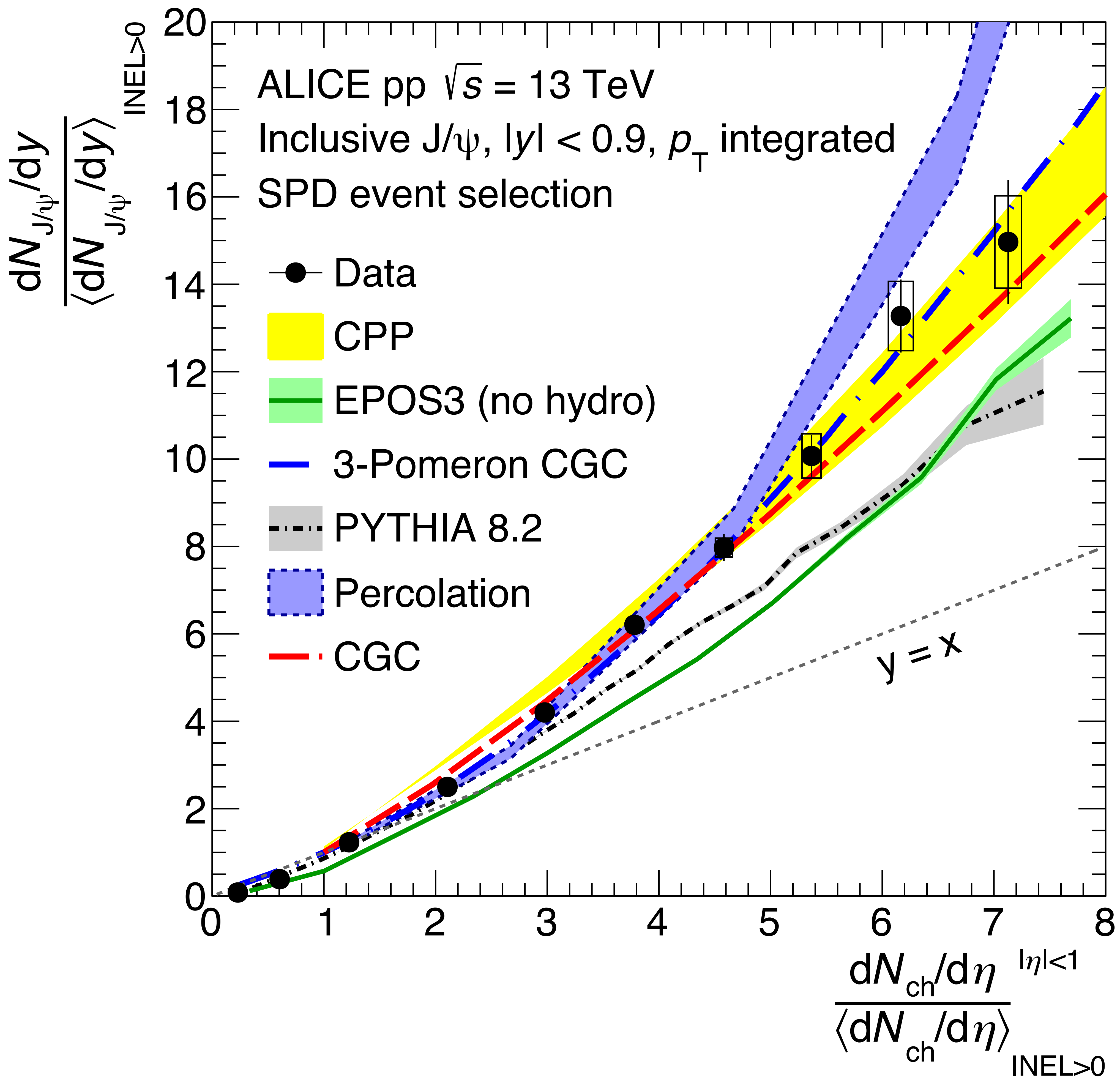
➢ Quarkonium yield and hadron multiplicity are sensitive to initial state fluctuation: rare parton configurations, giving larger $Q_s \gg Q_s^{\mathrm{MB}}$.

➢ Data comparisons favor model calculations in the spirit of gluon saturation, but the status is still puzzling.

➢ Sensitive to LDMEs. More work is needed.



$$\frac{dN_{ch}}{d^2b_\perp} \propto Q_s^2$$



Ferreiro and Pajares, PRC86, 034903 (2012)
Ma, Tribedy, Venugopalan, **KW**, PRD98, 7, 074025 (2018)
Levin, Schmidt and Siddikov, Eur. Phys. J. C80, no.6, 560 (2020)
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Diffractive events

See talk by Mark Strikman (Tue. 26)

Coherent diffractive production

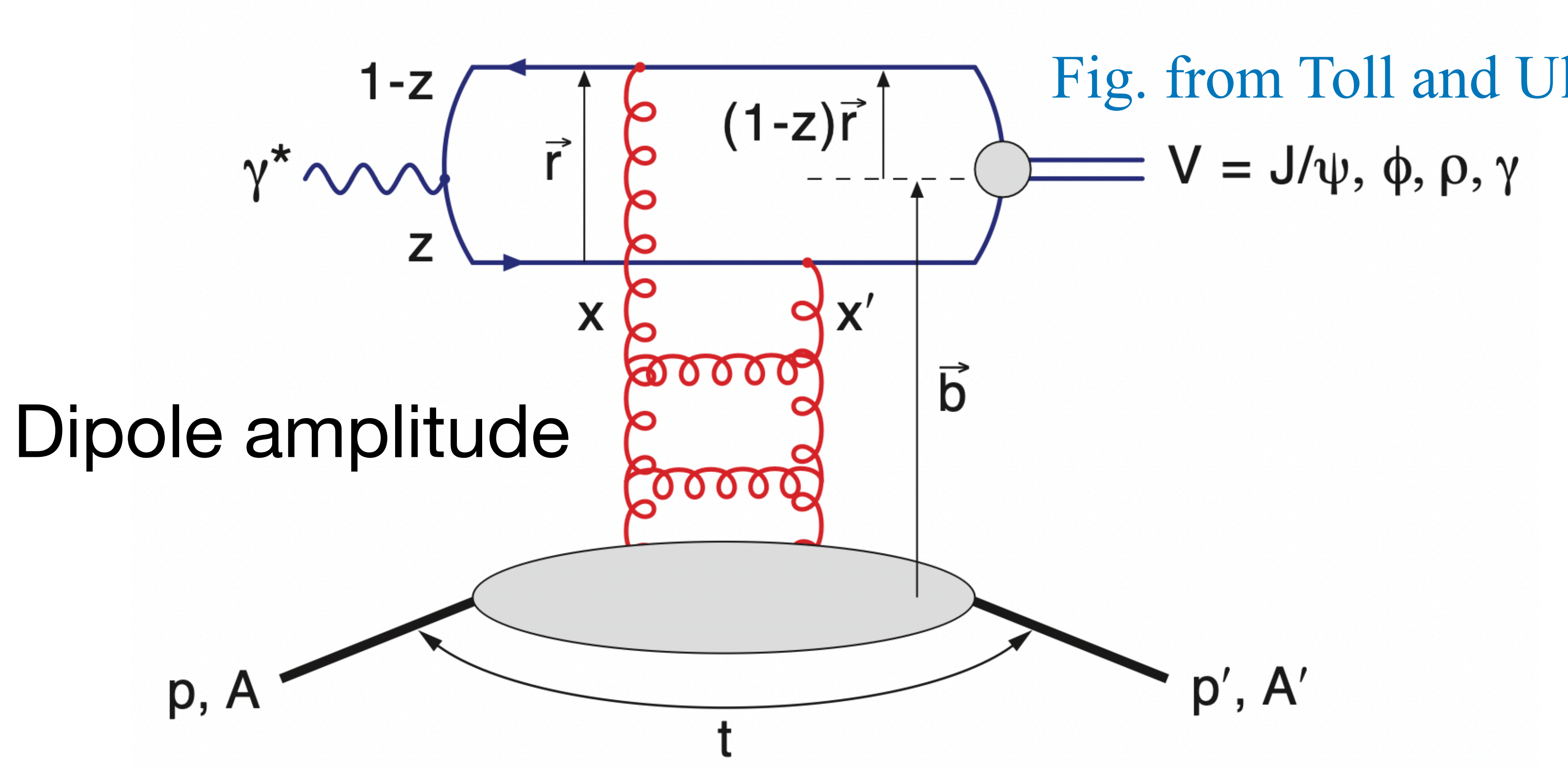
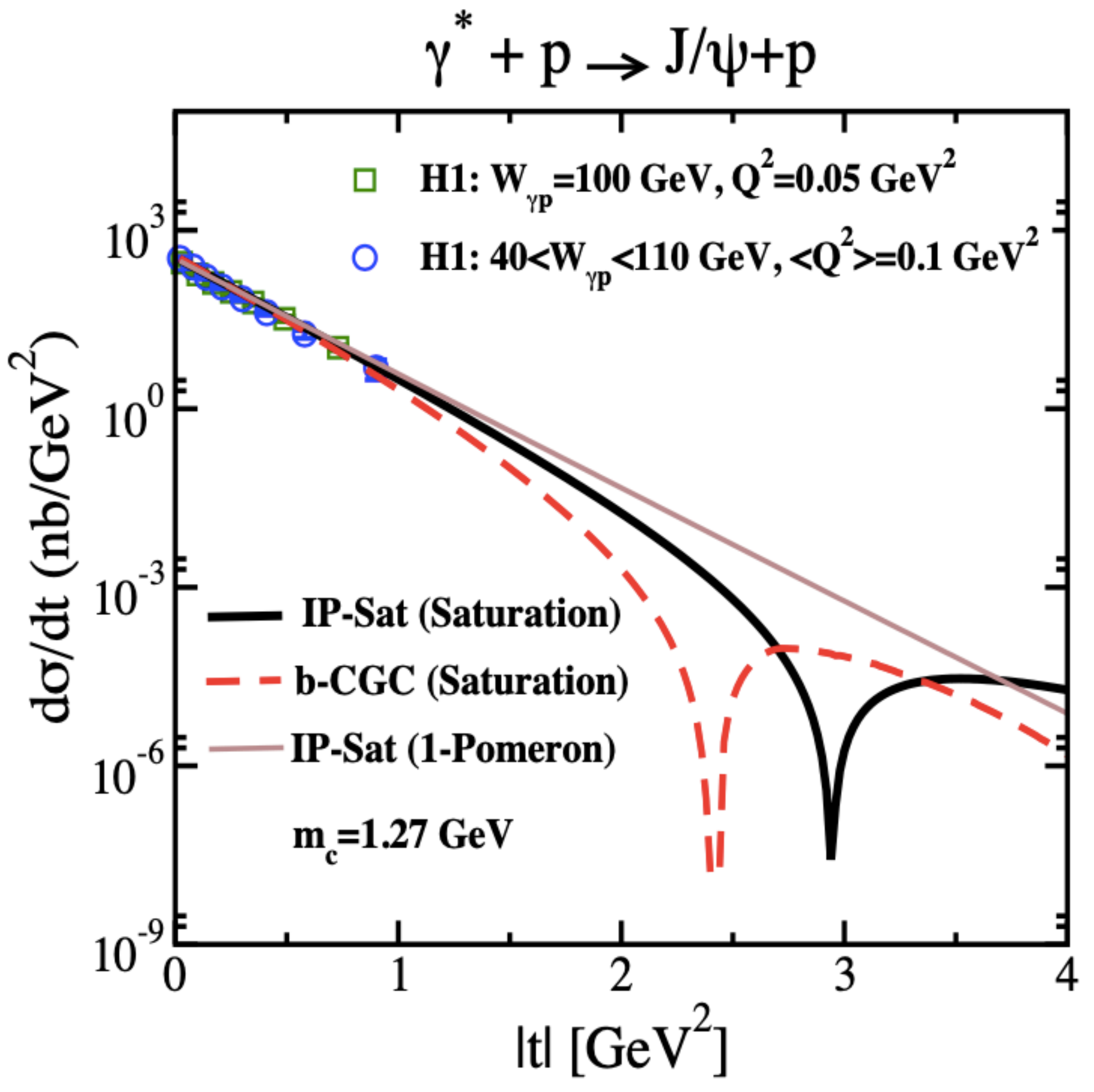


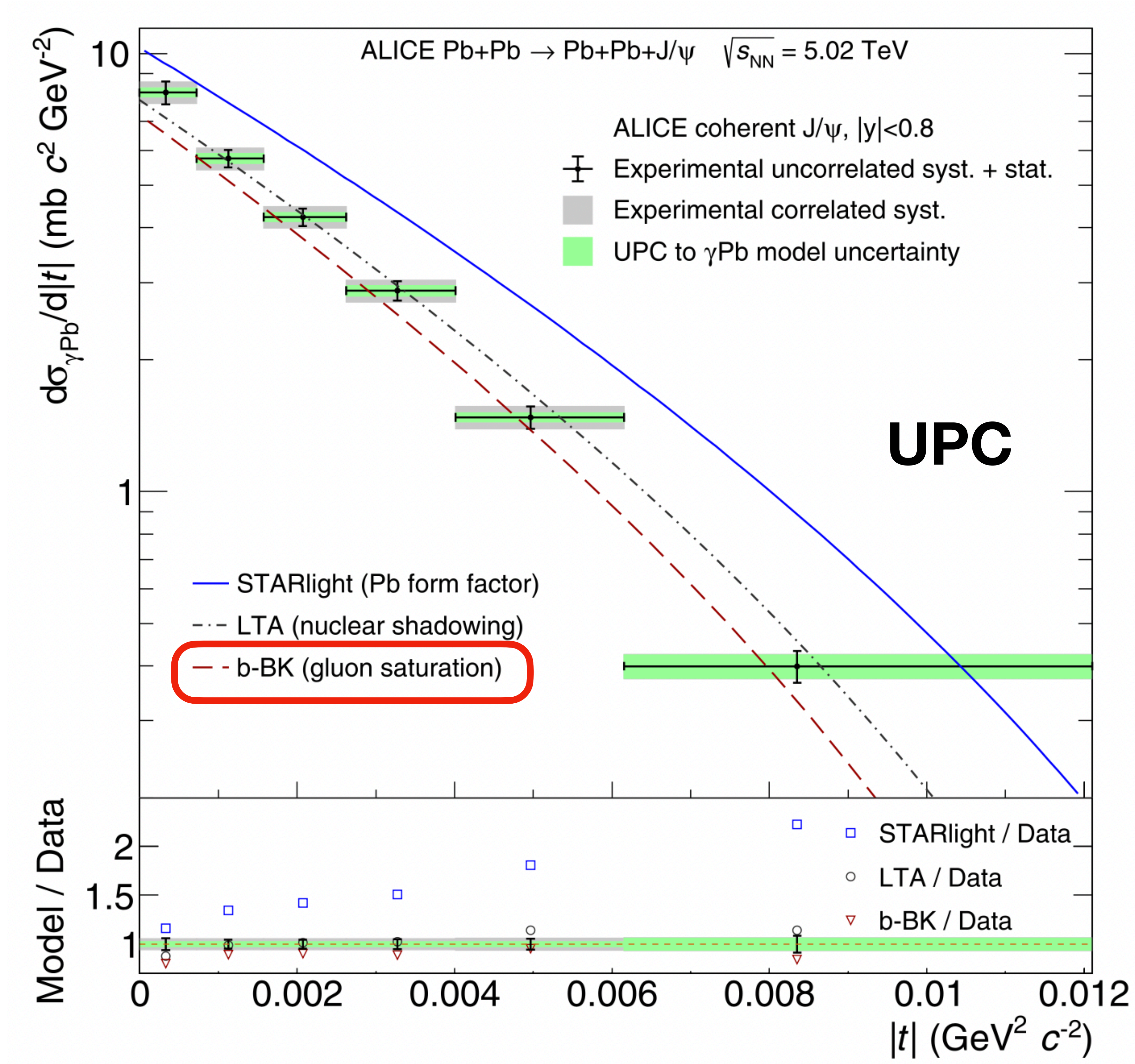
Fig. from Toll and Ullrich, PRC87, no.2, 024913 (2013)

$$\frac{d\sigma_{coh}^{\gamma^* p \to Vp}}{dt} \sim \left| \left\langle A_{T,L} \right\rangle_{\Omega} \right|^2$$

Sensitive to gluon distribution

Acharya et al. [ALICE], PLB817, 136280 (2021)





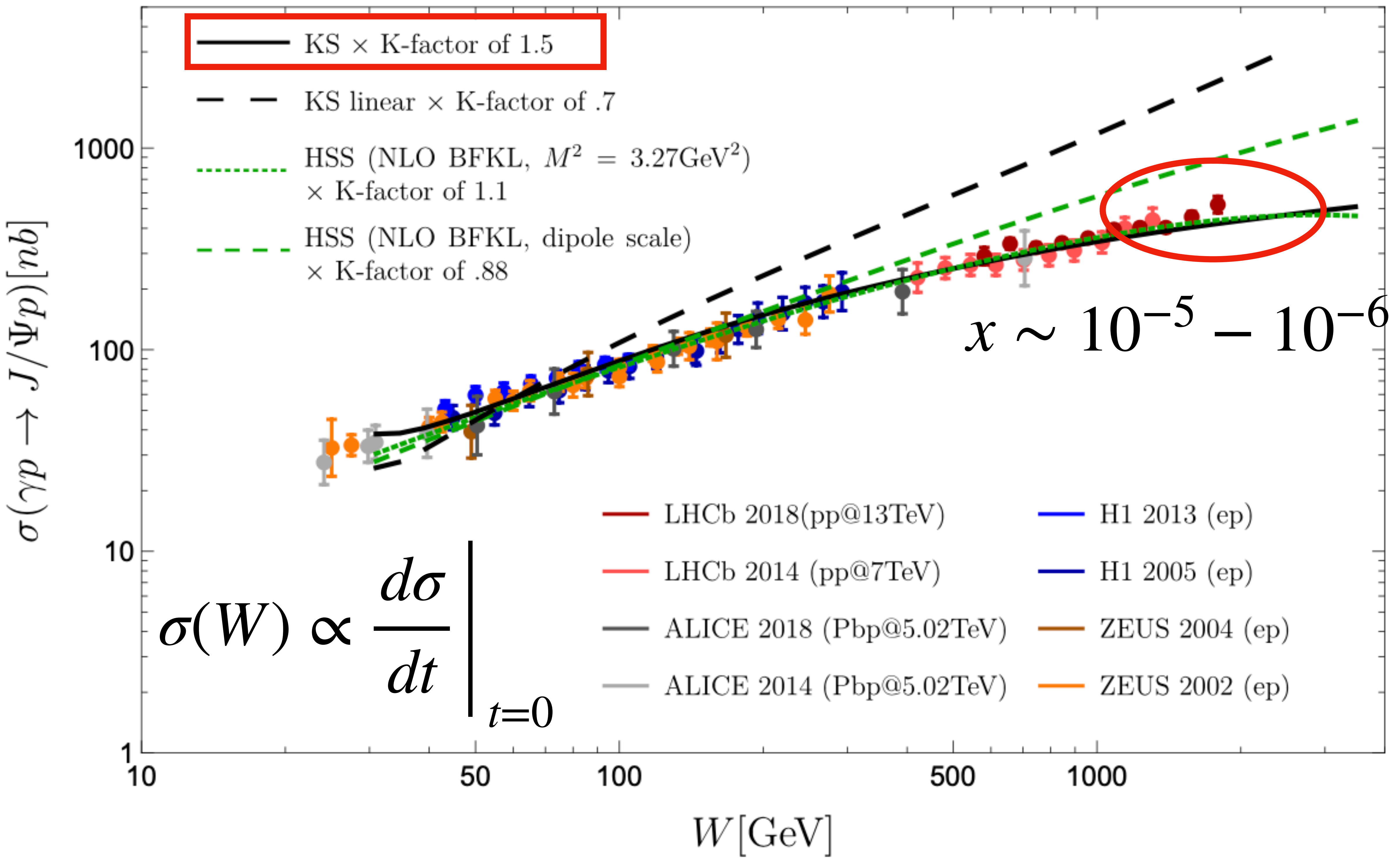
Armesto and Rezaeian, PRD90, no.5, 054003 (2014)

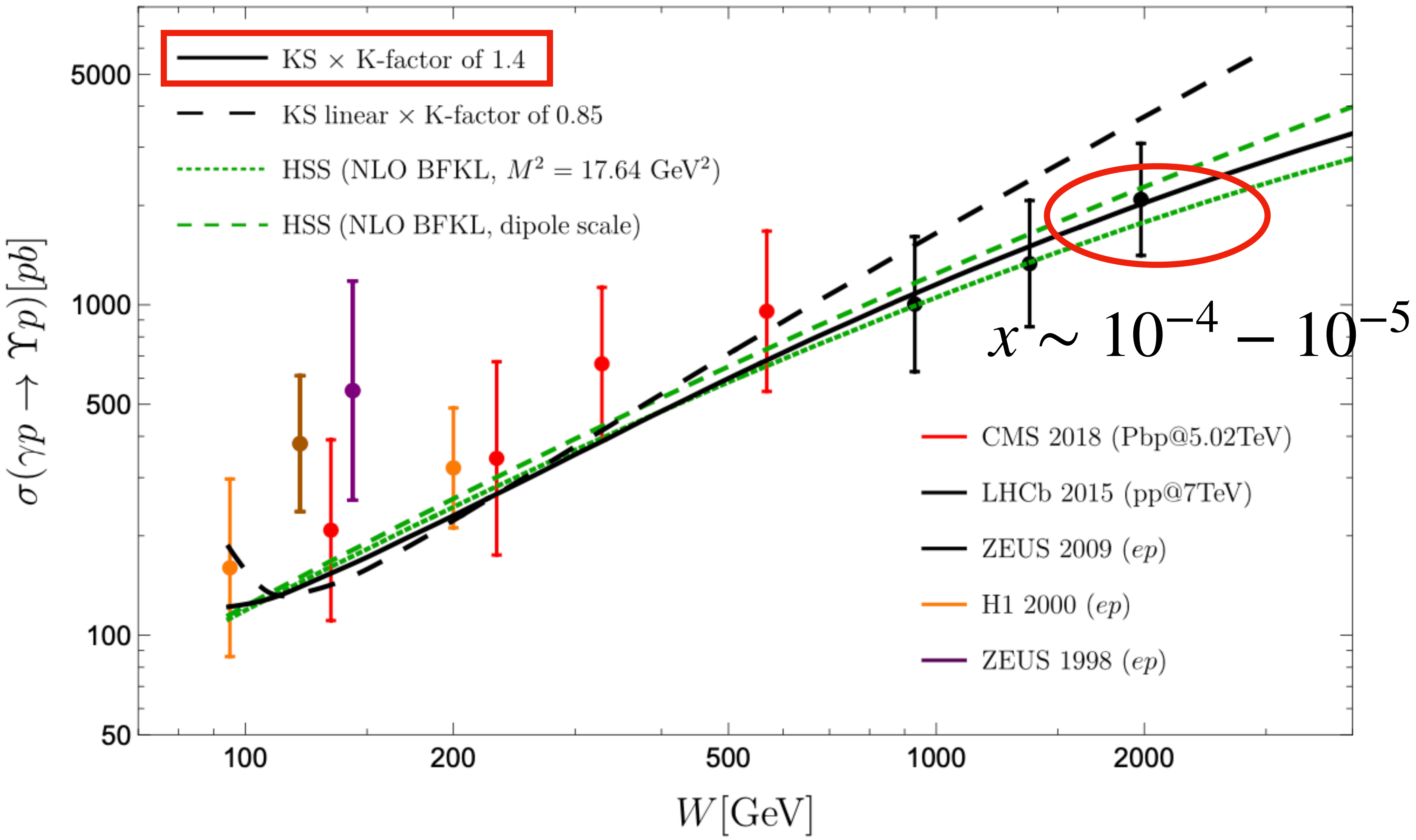
Bendova, Cepila, Contreras and Matas, PLB817, 136306 (2021)

Energy dependence of quarkonium photo-production

$x \simeq M_V^2/W^2$

Arroyo Garcia, Hentschinski and Kutak, PLB795, 569 (2019)





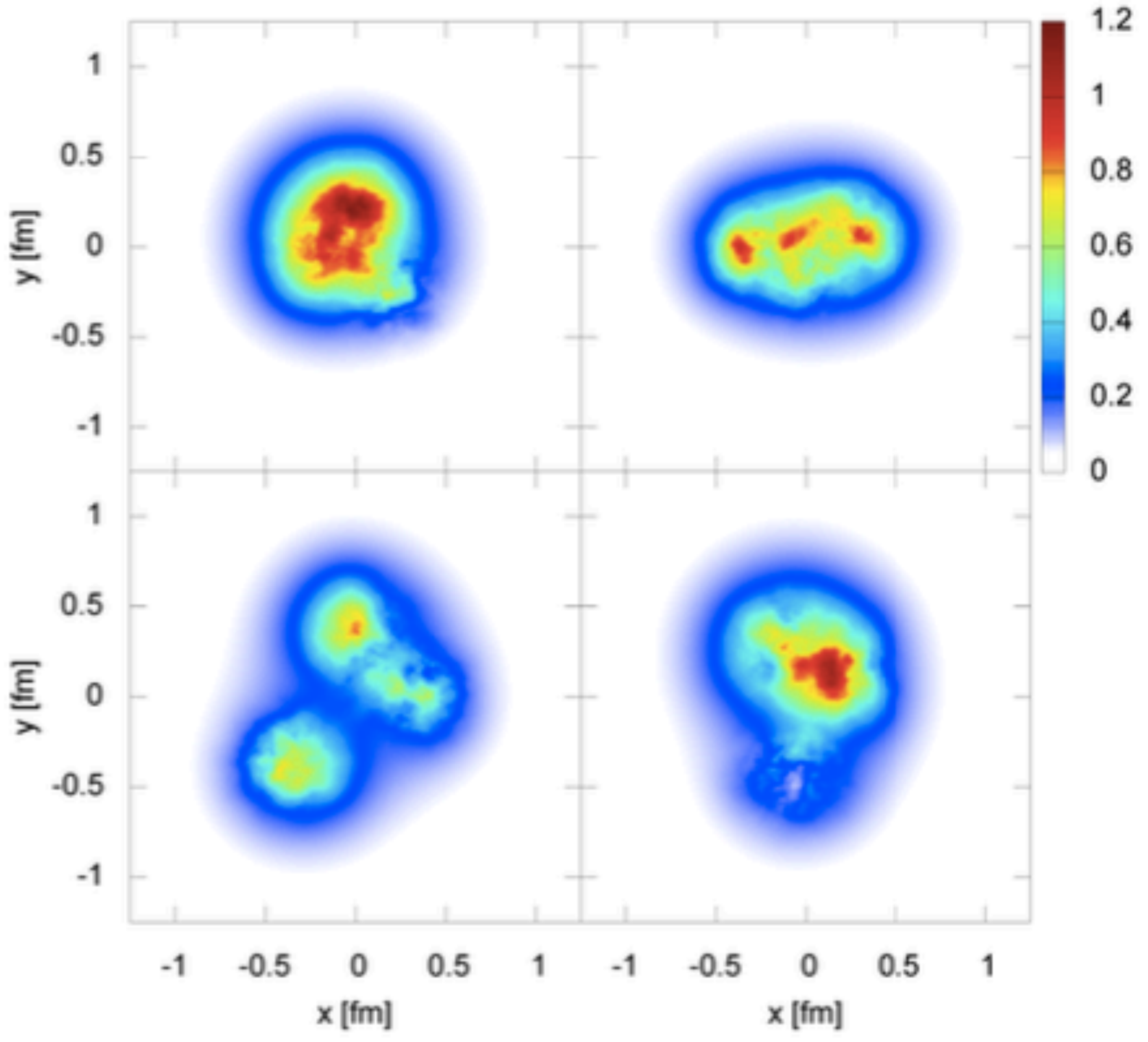
➢Without nonlinear recombination effect, the rapid growth of the gluon density in W results in the worse description of data.

➢ NLO BFKL evolution can also describe data, but it involves very large perturbative corrections.

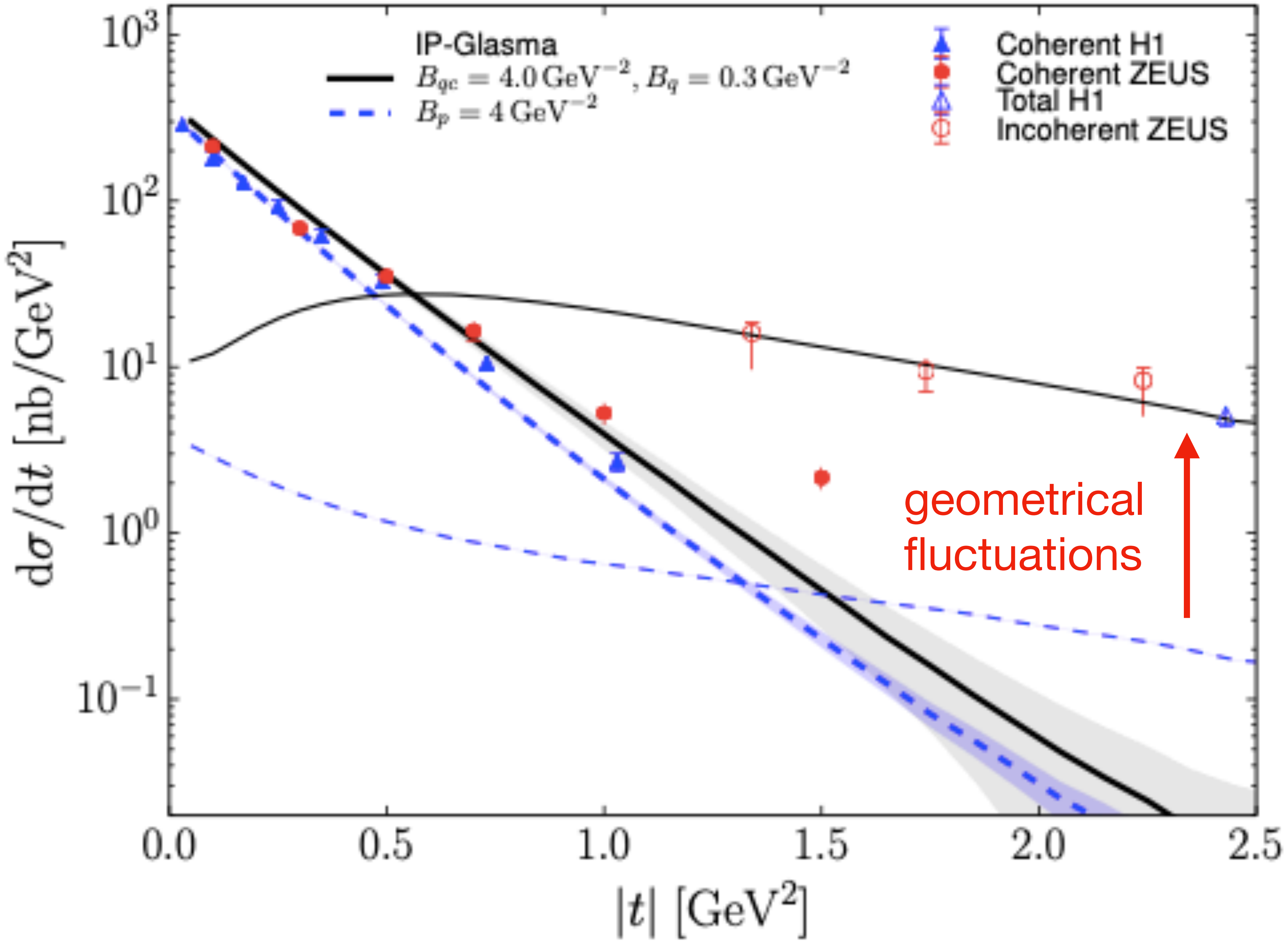
Incoherent diffractive production

$$\frac{d\sigma_{inc}^{\gamma^* p \to V p^*}}{dt} \sim \left\langle \left| A_{T,L} \right|^2 \right\rangle_\Omega - \left| \left\langle A_{T,L} \right\rangle_\Omega \right|^2$$

Offers a direct measure of the lumpiness of gluons



Mantysaari and Schenke, PRL117, no.5, 052301 (2016)

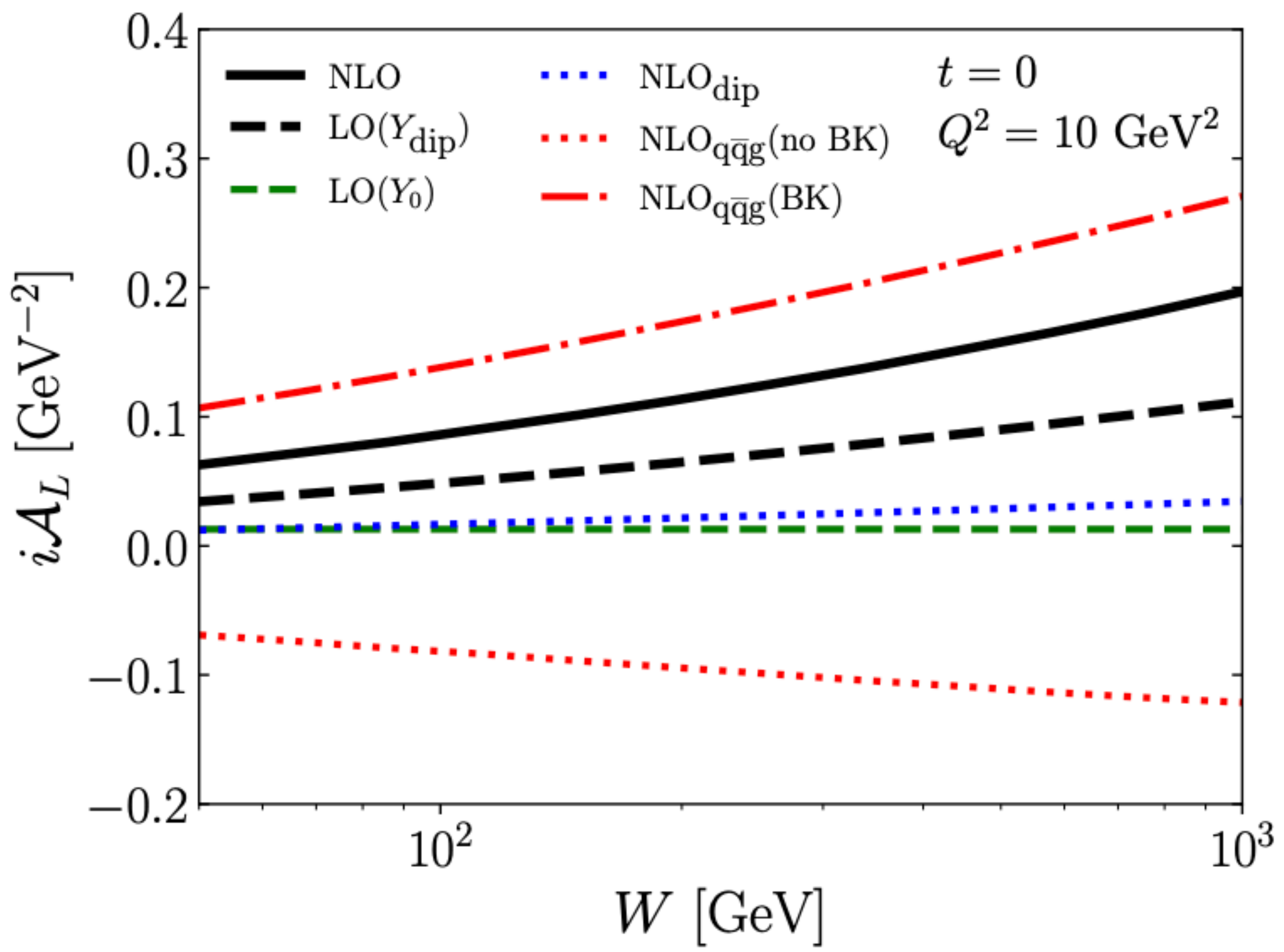


➢ Significant theoretical uncertainty in the production of vector mesons arises from the description of their light-cone wave function and the dipole amplitude.

Pushing business towards the NLO frontier

- ➢ Phenomenology of quarkonium production in pp/pA collisions in the CGC framework have been performed at LO level with leading logarithmic small-x evolution.
- ➢ Efforts are being made to push the precision to NLO level.
  - inclusive hadron production in pA
  - inclusive dijet (+ photon) in eA
  - exclusive dijet in eA
- ➢ NLO calculations for exclusive J/ψ production have been performed recently.
- ➢ Extensive NLO calculations for inclusive quarkonium production in pA/eA collisions are exciting tasks to complete in the next decade.

Chirilli, Xiao and Yuan, PRD86, 054005 (2012)
Altinoluk, Armesto, Beuf, Kovner, Lublinsky, PRD91, no.9, 094016 (2015)
KW, Xiao, Yuan and Zaslavsky, PRD92, no.3, 034026 (2015)
Ducloué, Lappi and Zhu, PRD93, no.11, 114016 (2016)
Liu, Ma and Chao, PRD100, no.7, 071503 (2019)
Liu, Kang and Liu, PRD102, no.5, 051502 (2020)
…
Roy and Venugopalan, PRD101, no.3, 034028 (2020)
Caucal, Salazar and Venugopalan, [arXiv:2108.06347 [hep-ph]]
Boussarie, Grabovsky, Ivanov, Szymanowski and Wallon, PRL119, no.7, 072002 (2017)
…



Mäntysaari and Penttala, PLB823, 136723 (2021)

Summary

➢ Gluon saturation at extremely small-x is an obligatory consequence of QCD, and the question is how it affects quarkonium production mechanism.

➢ Quarkonium production in pp/pA collisions provide important test grounds for exploring nonlinear QCD dynamics at small-x.

➢ Many calculations including the saturation effect seem consistent to data at colliders, but many questions remain.

➢ We need to push calculations to higher precision than ever and to deepen our understanding of small-x QCD further.

Thank you!