Heavy flavor and quarkonium production in the forward region

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Exploration of small-x structure of nuclei and signals of saturation in forward measurements at the LHC
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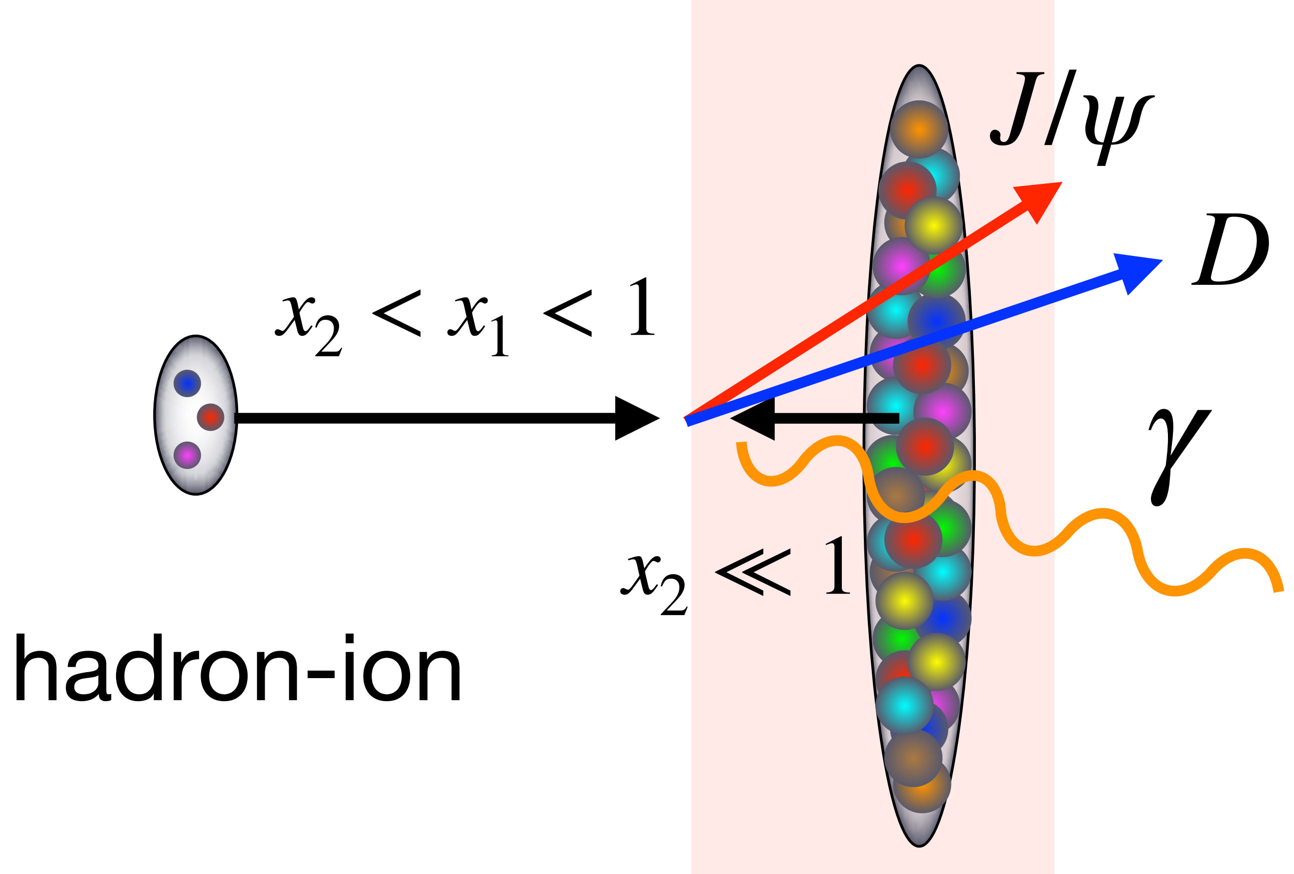
Motivation

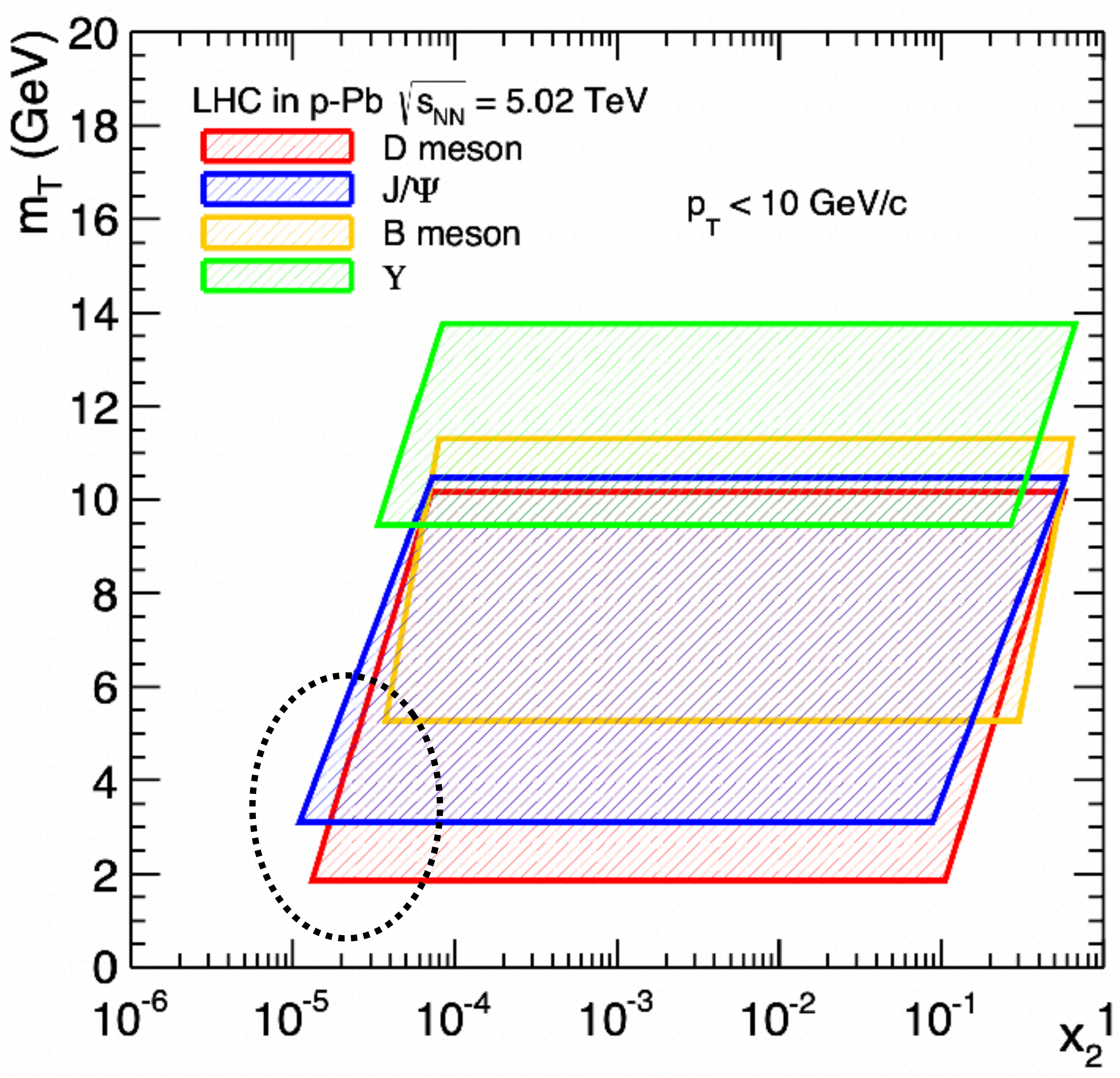


- Forward HF and Onium production are sensitive to the gluon content of hadrons/nuclei, probing gluons of $x_2 = 10^{-5} \sim 10^{-4}$.

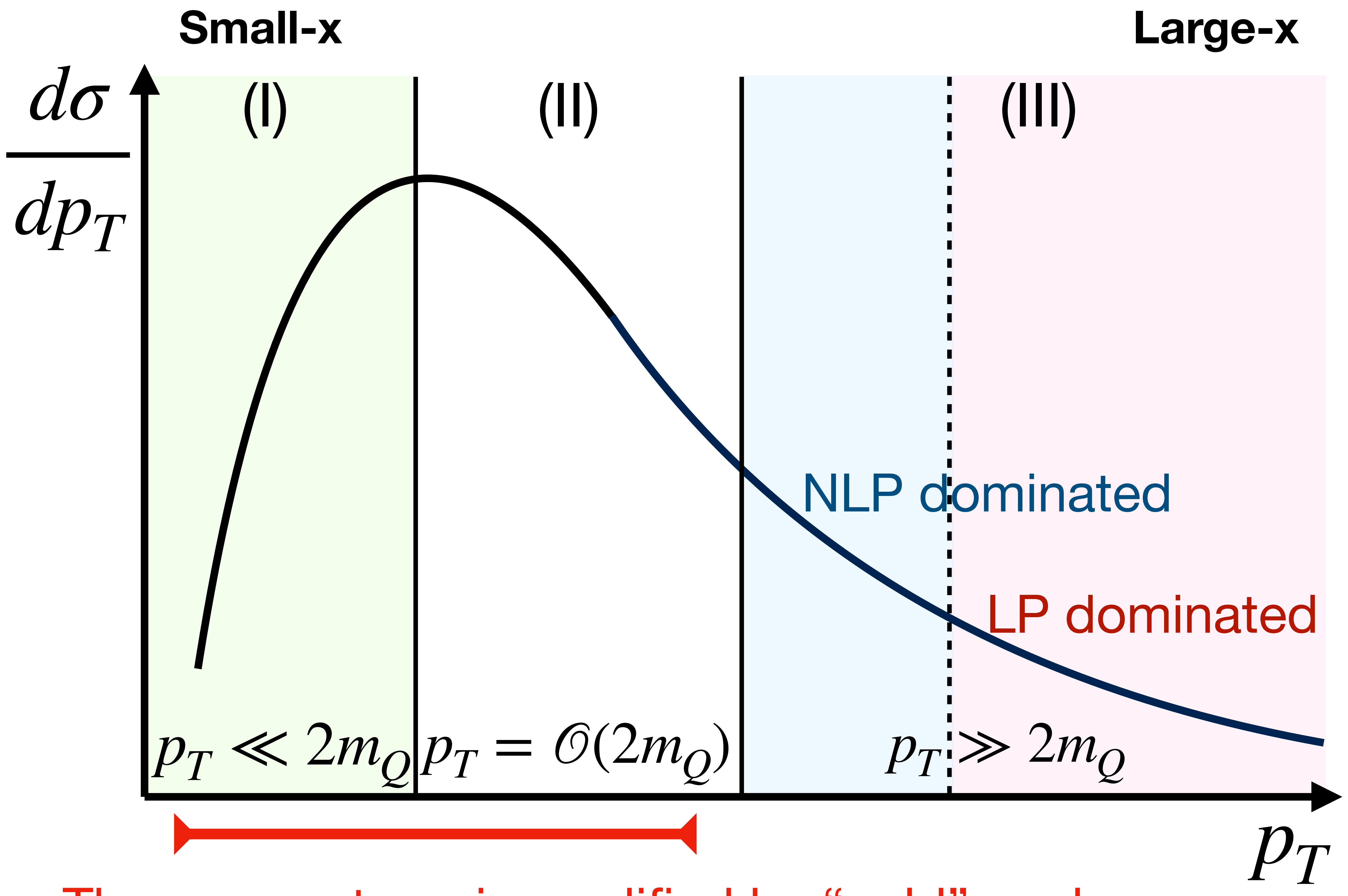
- HF at LHCb $(2 < y < 4)$ and Onium at ALICE/LHCb $(2 < y < 4)$ are important complementary to Hadron/Photon at FoCal $(3 < y < 6)$. We should study various observables extensively.

- We want to understand how HF/Onium production can bring us information on the saturation.

- In this talk, we will focus on inclusive HF/Onium production in pp and pA collisions at LHC.



Onium production at a glance



The p_T spectrum is modified by “cold” nuclear effects in pA collisions. HF as well.

(I) TMD factorization and CGC EFT + CEM or NRQCD

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

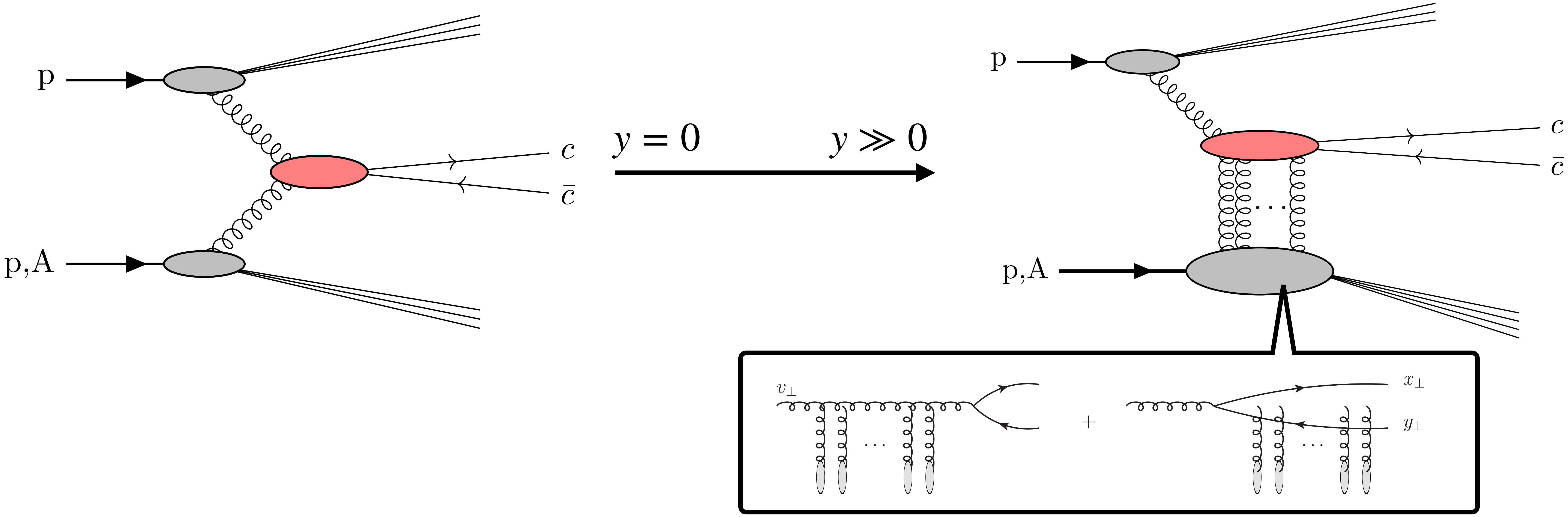
(III) QCD factorization w/ Fragmentation Functions

Kang, Qiu and Sterman, PRL108, 102002 (2012)
Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014)
Ma, Qiu, Sterman, Zhang, PRL113, 14, 142002 (2014)
Lee, Qiu, Sterman, **KW**, 2108.00305 and 22xx.xxxx.

- Two-step factorization: (i) $Q\bar{Q}$ production, (ii) **bound state formation**.
- We need to change the theoretical framework to describe the bound state formation according to a value of p_T.
- Constraining gluon PDF with Onium in a unified framework is a long-term goal.

Forward heavy quark production and CGC

- What happens to low p_T onium production in the forward region?



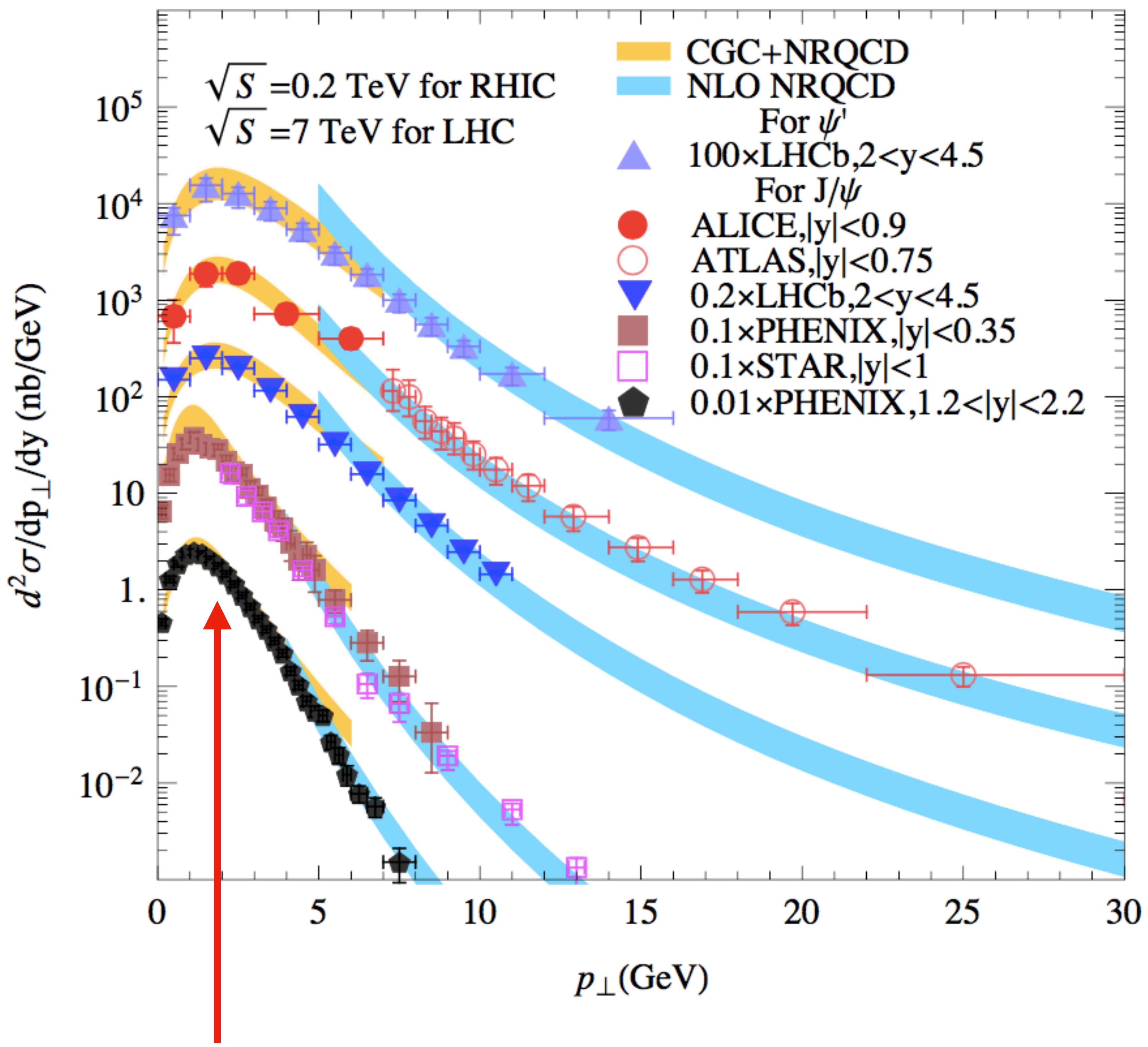
Bound state formation can be factorized: spectator interactions between onium and the target are suppressed by $1/p_{\|}$.

- **Multiple rescattering** with semi-classical fields.
- High $\sqrt{s}$, large y, low p_T lead to $\alpha_s \ln 1/x_2 = \mathcal{O}(1)$, which is resumed by solving BK-JIMWLK equation: **the same as hadron/photon production**.
- Weak coupling approach, the **CGC EFT**, is useful to pin down initial state effects on heavy quark production.

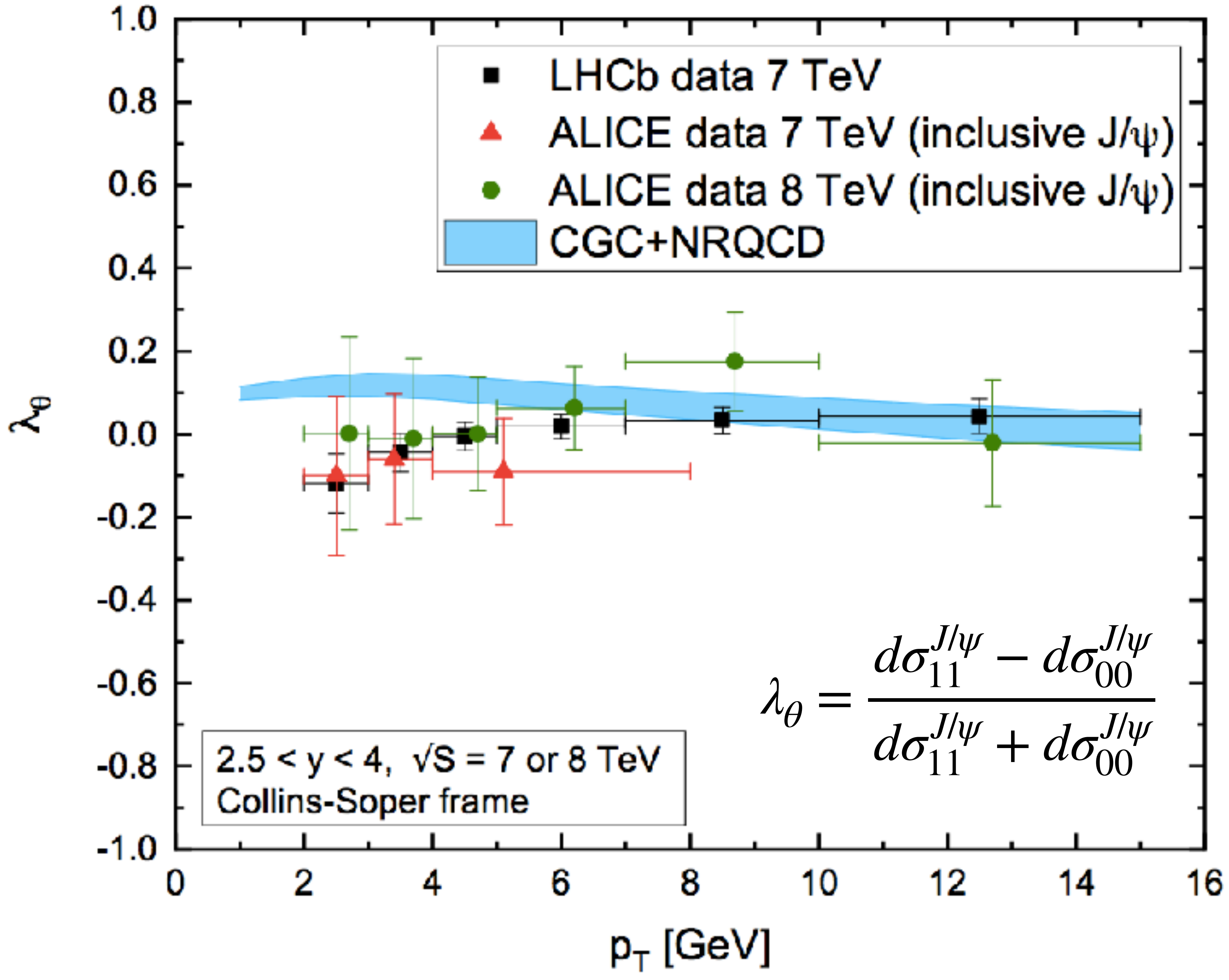
  - # of net gluons (xf_g) in the target is large at small-x → $\alpha_s(Q_s) \ll 1$

Forward J/ψ production and polarization

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

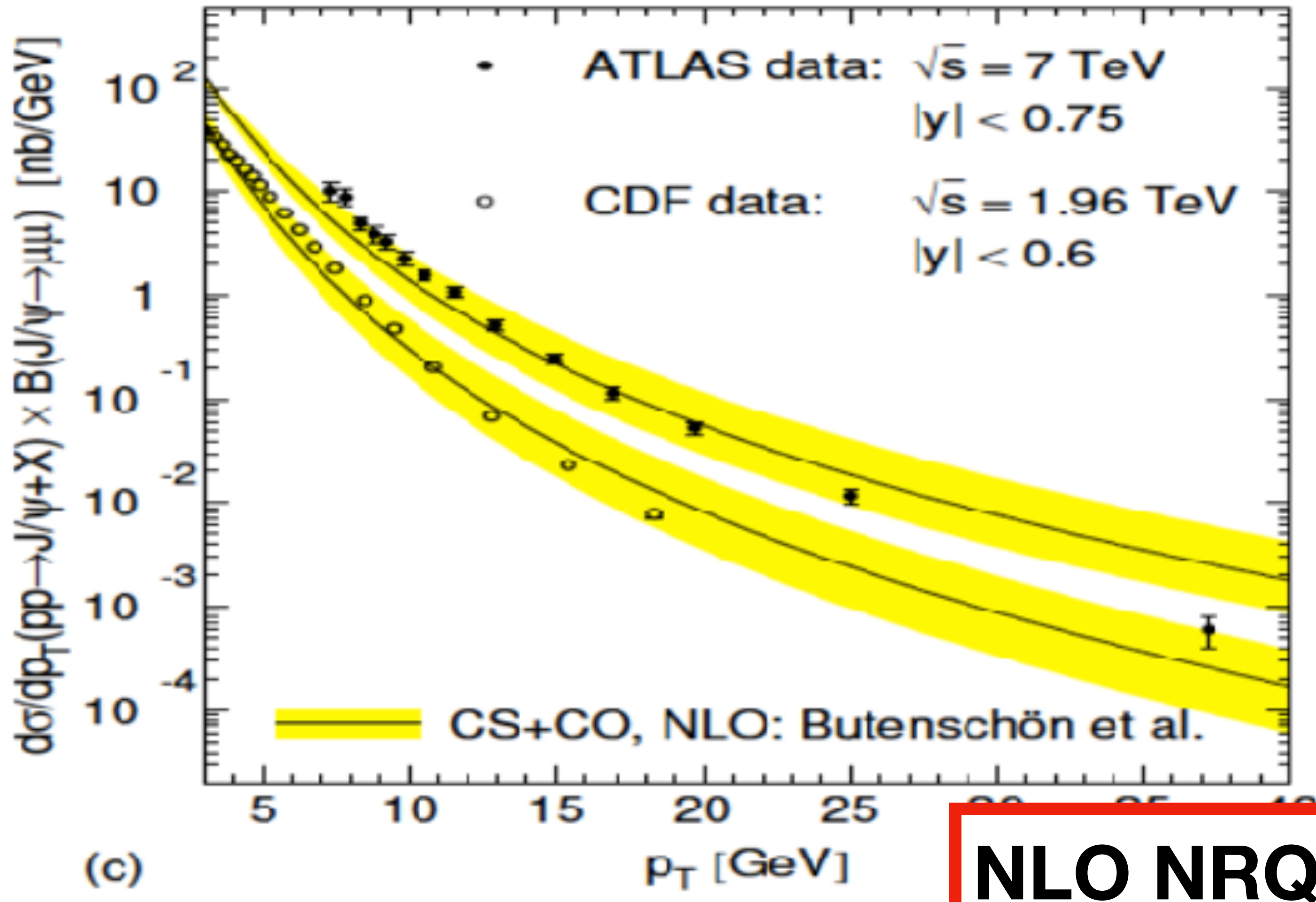


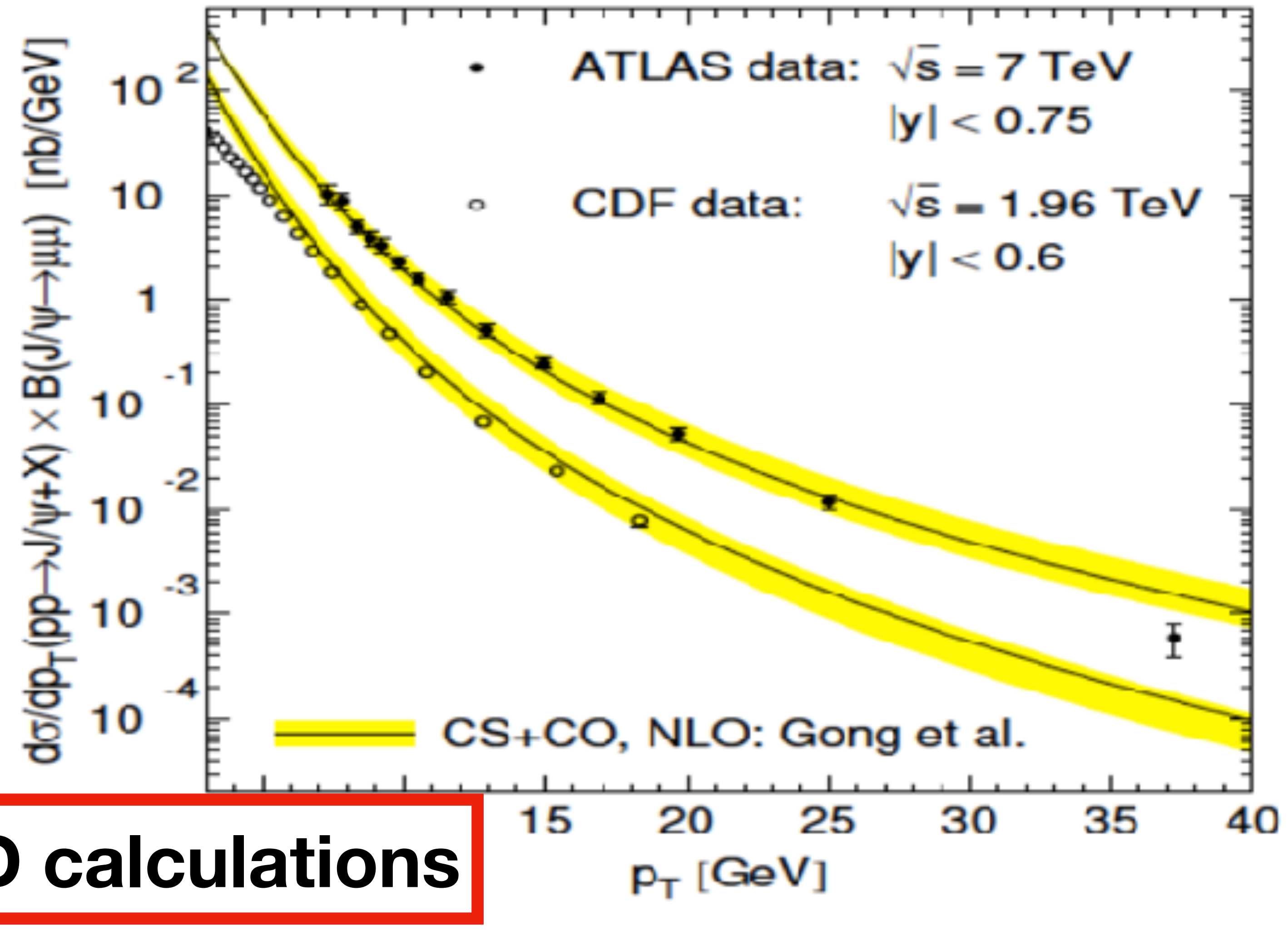
Ma, Stebel and Venugopalan, JHEP12, 057 (2018)



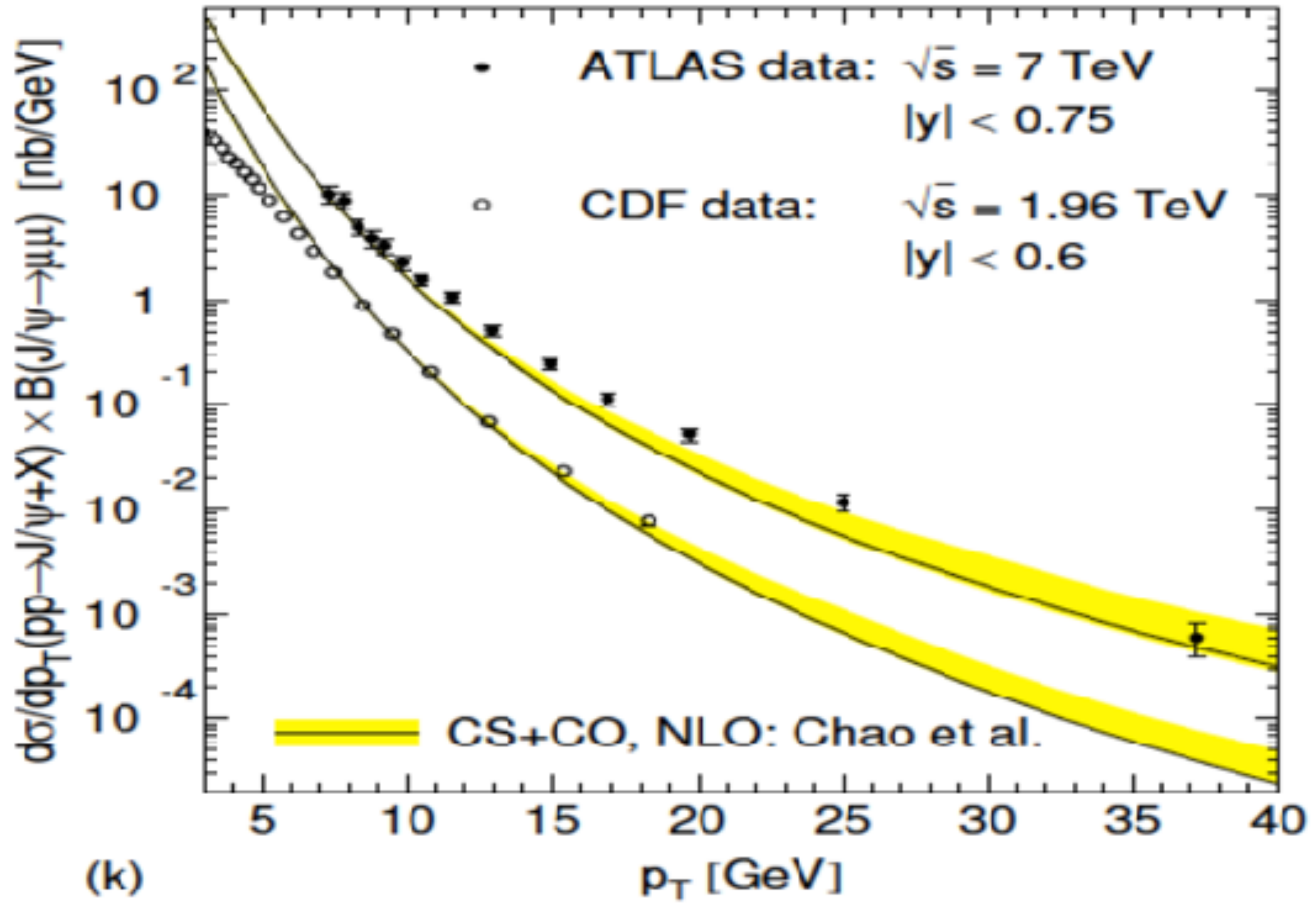
- The CGC framework with the running coupling BK evolution provides a good parametrization of the gluon TMD distribution function at small-x.
- **Assumption:** BFKL evolution ≫ DGLAP evolution when $\mu \sim m_Q \sim p_T \sim Q_s$.
- Long-Distance-Matrix-Elements (LDMEs) are crucial inputs: ${}^1S_0^{[8]}$ state is significant.

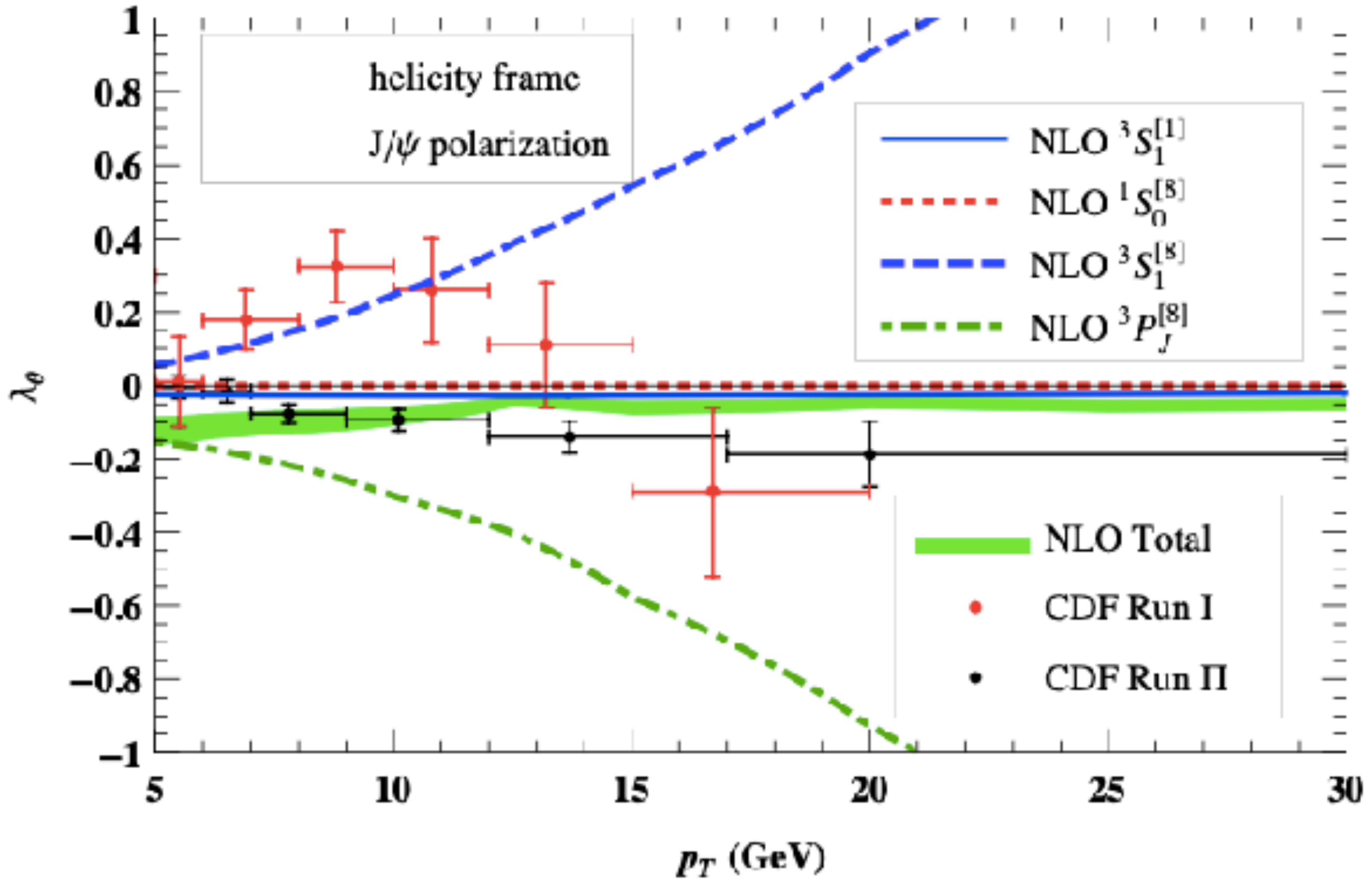
Remarks: The long-standing puzzle





NLO NRQCD calculations





	$\langle \mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle \mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle \mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle \mathcal{O}(^3P_0^{[8]})\rangle/m_c^2$ 10^{-2} GeV^3
Bodwin et al	-	9.9	1.1	0.49
Butenschoen et al	1.32	3.04	0.16	-0.30
Chao et al	1.16	8.9	0.30	0.56
Gong et al	1.16	9.7	-0.46	-0.95

Butenschoen, Kniehl, PRD84, 051501 (2011),
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012)
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013),
Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014).

Fitted LDMEs should be universality, however:

- Numbers are not the same
- Not even the sign

We still don't understand which intermediate states of the quark pair are more significant.

Note: CGC calculations customarily use Chao's set of LDMEs.

e^+e^-, ep, pp help us resolve these issues.

Onium suppression in pA collisions

We expect that $Q_{sA}^2 > Q_{sp}^2$ results in onium suppression in pA, which is seen at LHC; however, other nuclear effects are also sizable.

➢ Nuclear PDFs

- Leading-twist shadowing.

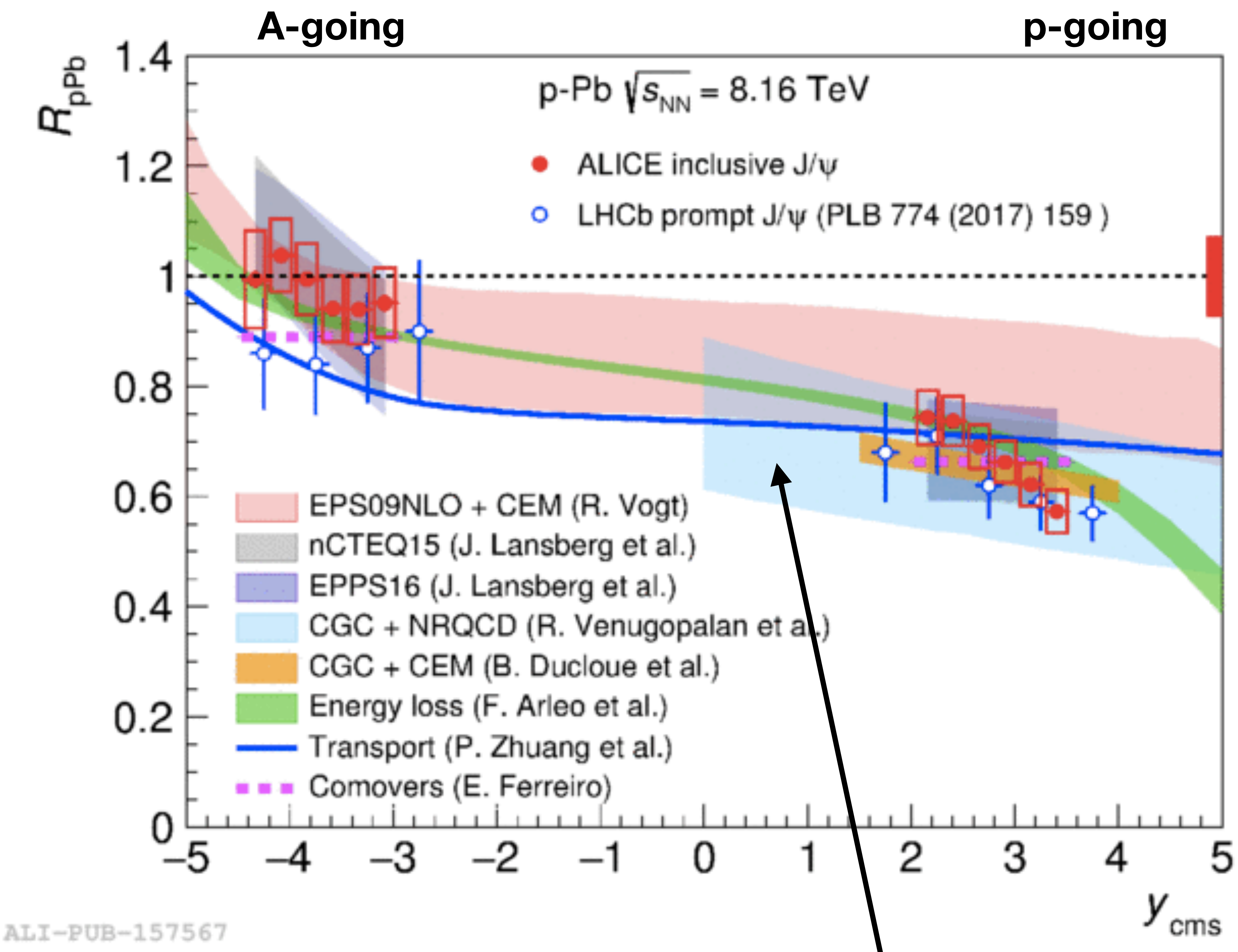
➢ Fully coherent energy loss (FCEL)

- Difference between induced gluon spectrum in pp and pA.

➢ Comover interaction in final state

- Partonic or hadronic soft interaction.

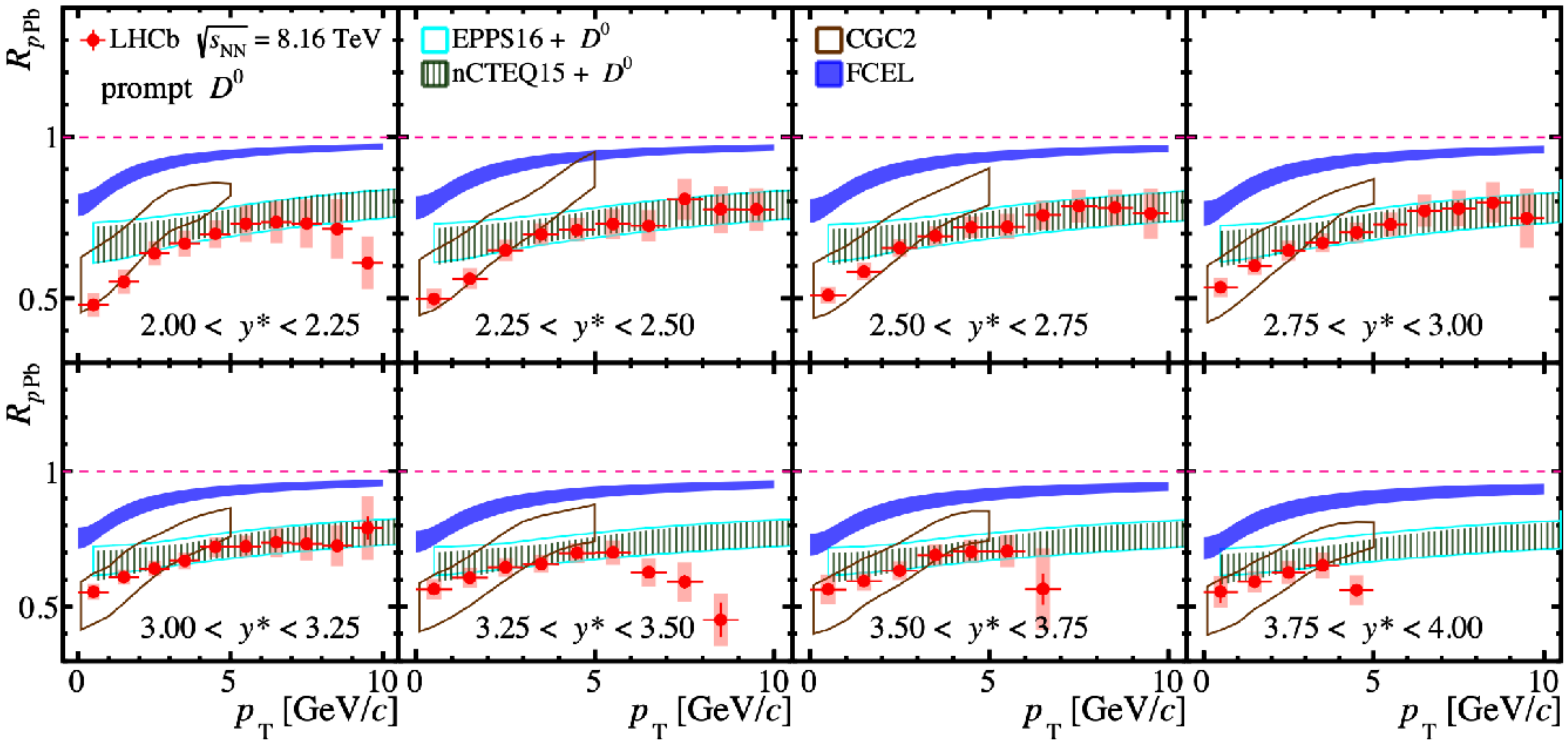
- The band of CGC+NRQCD is mainly caused by uncertainty about **LDMEs**.
- More theoretical work is needed to disentangle or combine distinct nuclear effects and reduce uncertainties about models including LDMEs.



$Q_{sA}^2 = 2Q_{sp}^2$ at $x_0 = 0.01$, plugged into the boundary condition of rcBK eq. Q_{sp}^2 is fitted by DIS data.

Forward D-meson suppression in pA collisions

LHCb collaboration, [arXiv:2205.03936 [nucl-ex]].



- The band of CGC is mainly caused by $Q^2_{sA} = (2\text{-}3) \times Q^2_{sp}$ at $x_0 = 0.01$. Ma, Tribedy, Venugopalan, **KW**, PRD98, no.7, 074025 (2018)
- $Q^2_{sA} \sim 2Q^2_{sp}$ at large-x reproduces **both** forward J/ψ and D suppression in MB pA collisions.

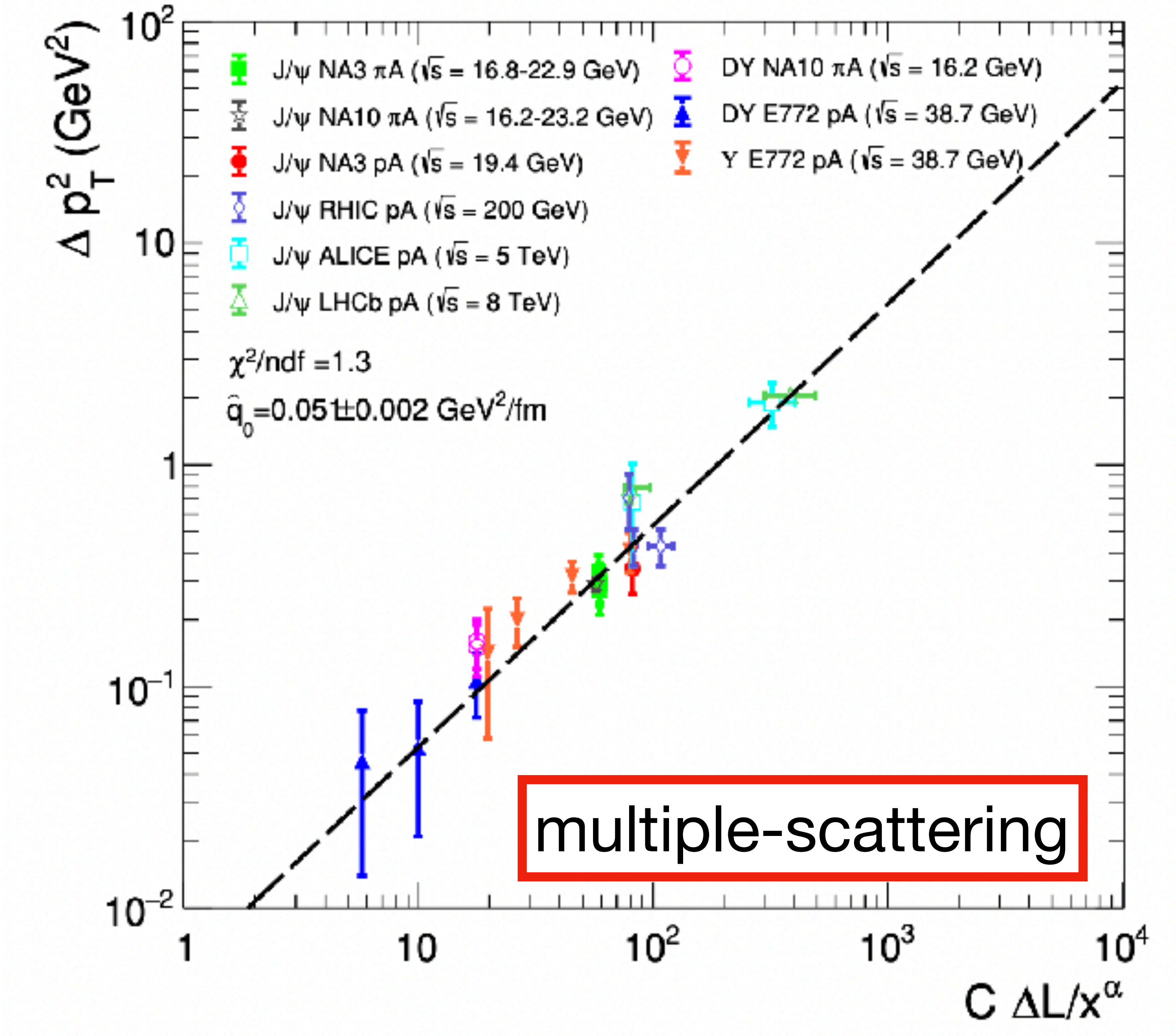
Nuclear p_T broadening

$$\Delta\langle p_T^2\rangle_{pA} = \langle p_T^2\rangle_{pA} - \langle p_T^2\rangle_{pp} = \hat{q}(x)L_A \sim Q_{sA}^2$$

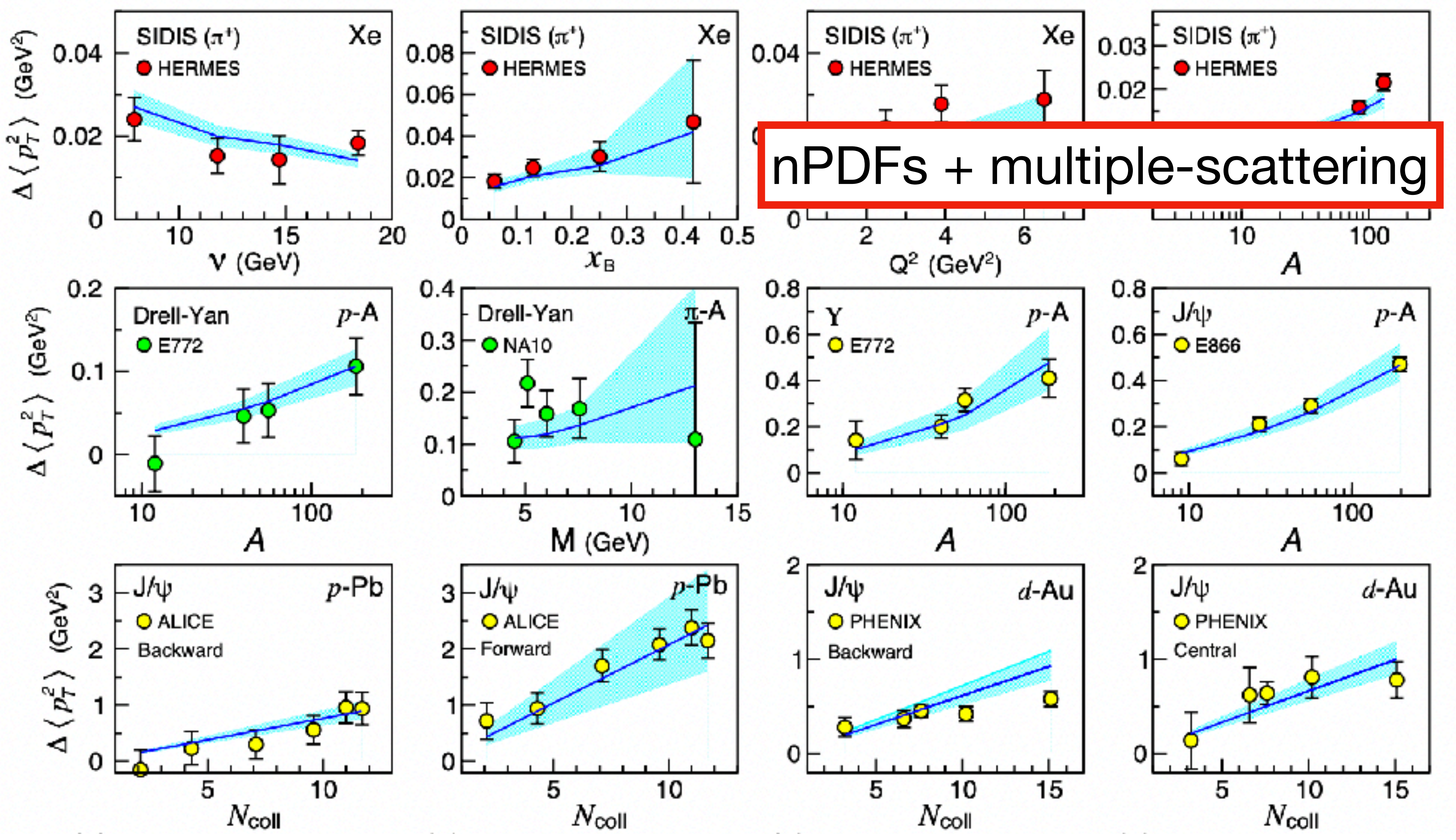
Small-x limit

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

Arleo and Naïm, JHEP07, 220 (2020)



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

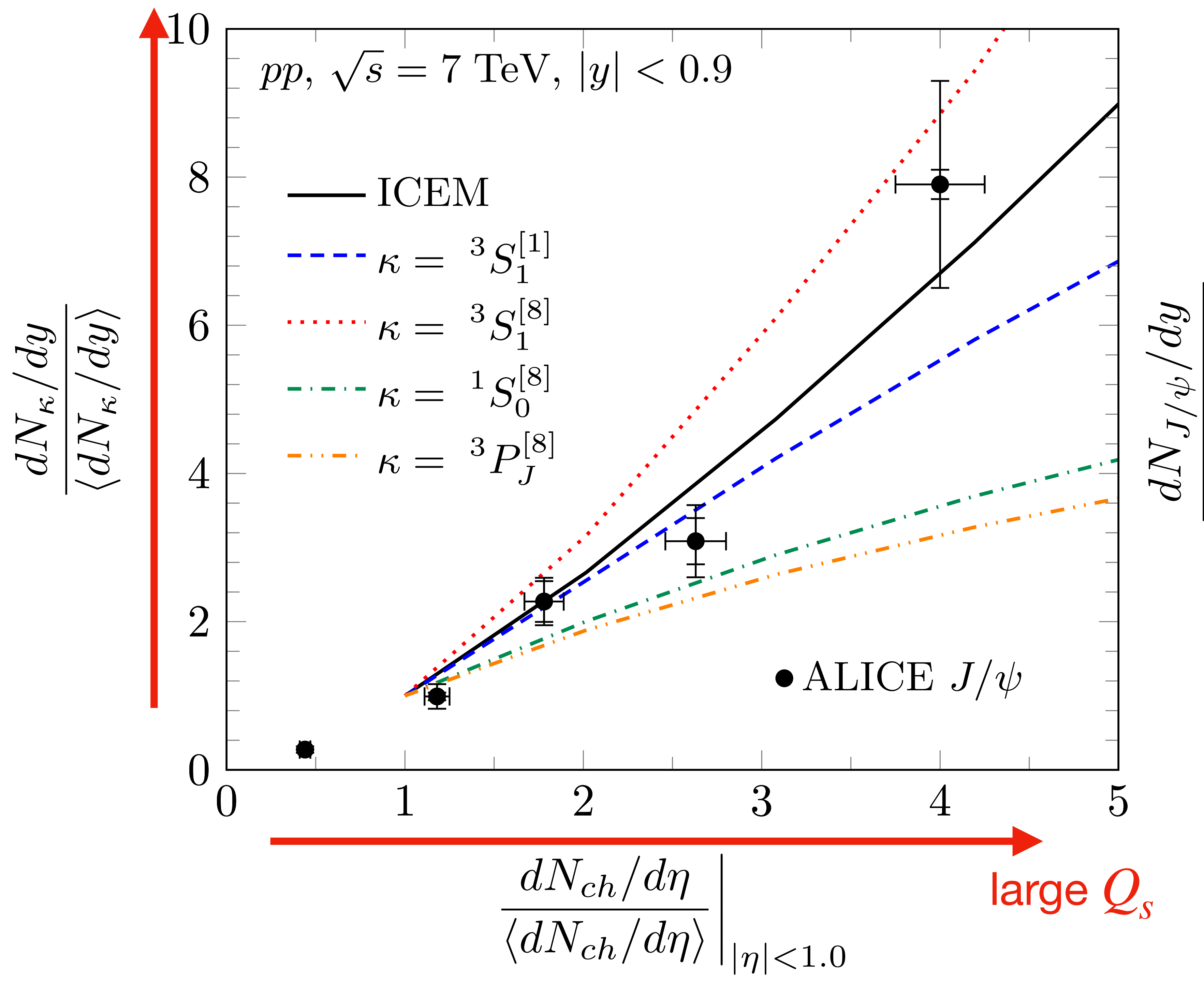


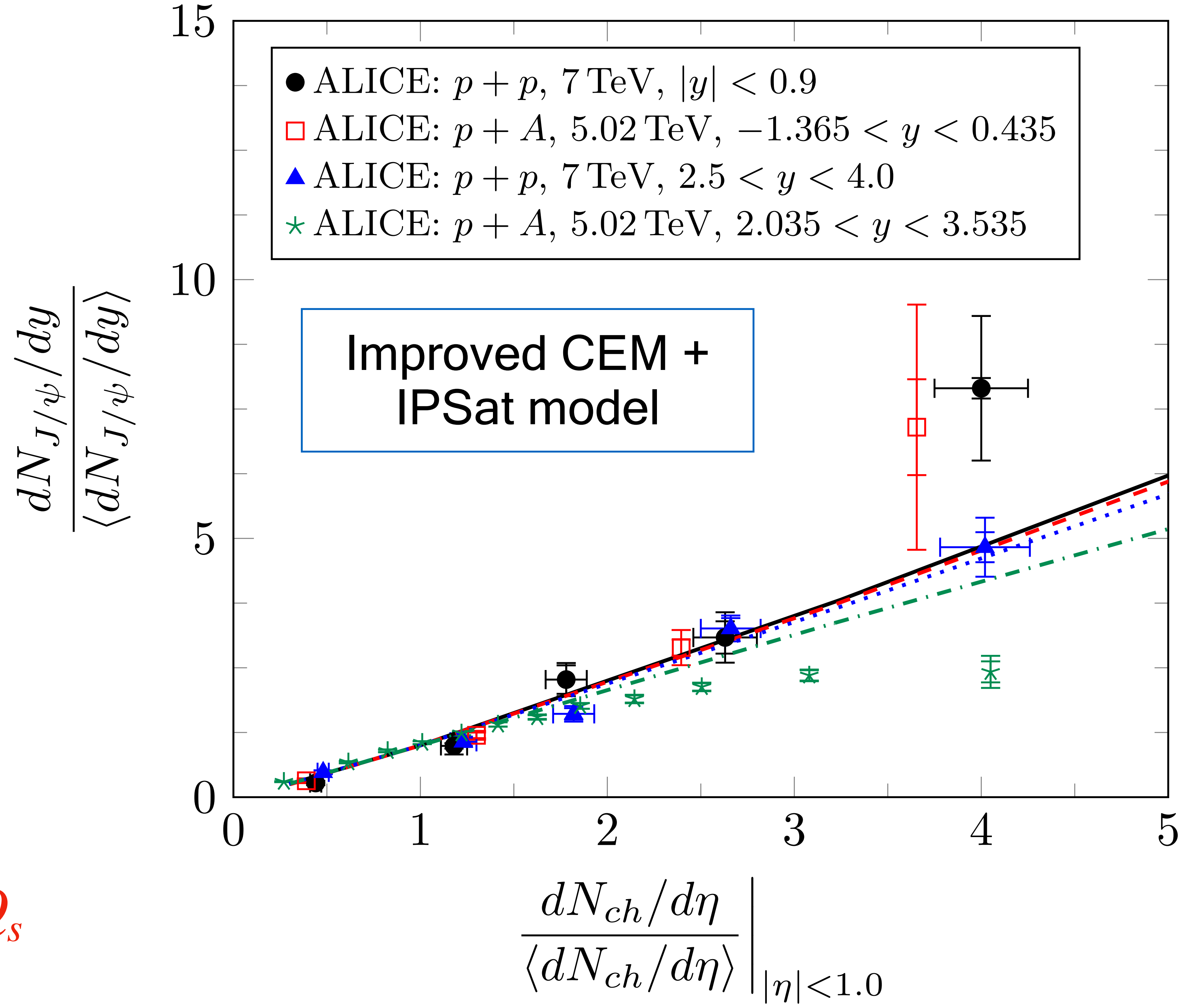
- $\hat{q}(x) \propto x^{-\alpha}$ with $\alpha = 0.25\text{-}0.30$ describes various data **from large-x to small-x.**
- Premature to say that the nonlinear saturation effect is seen. BFKL evolution could be seen.

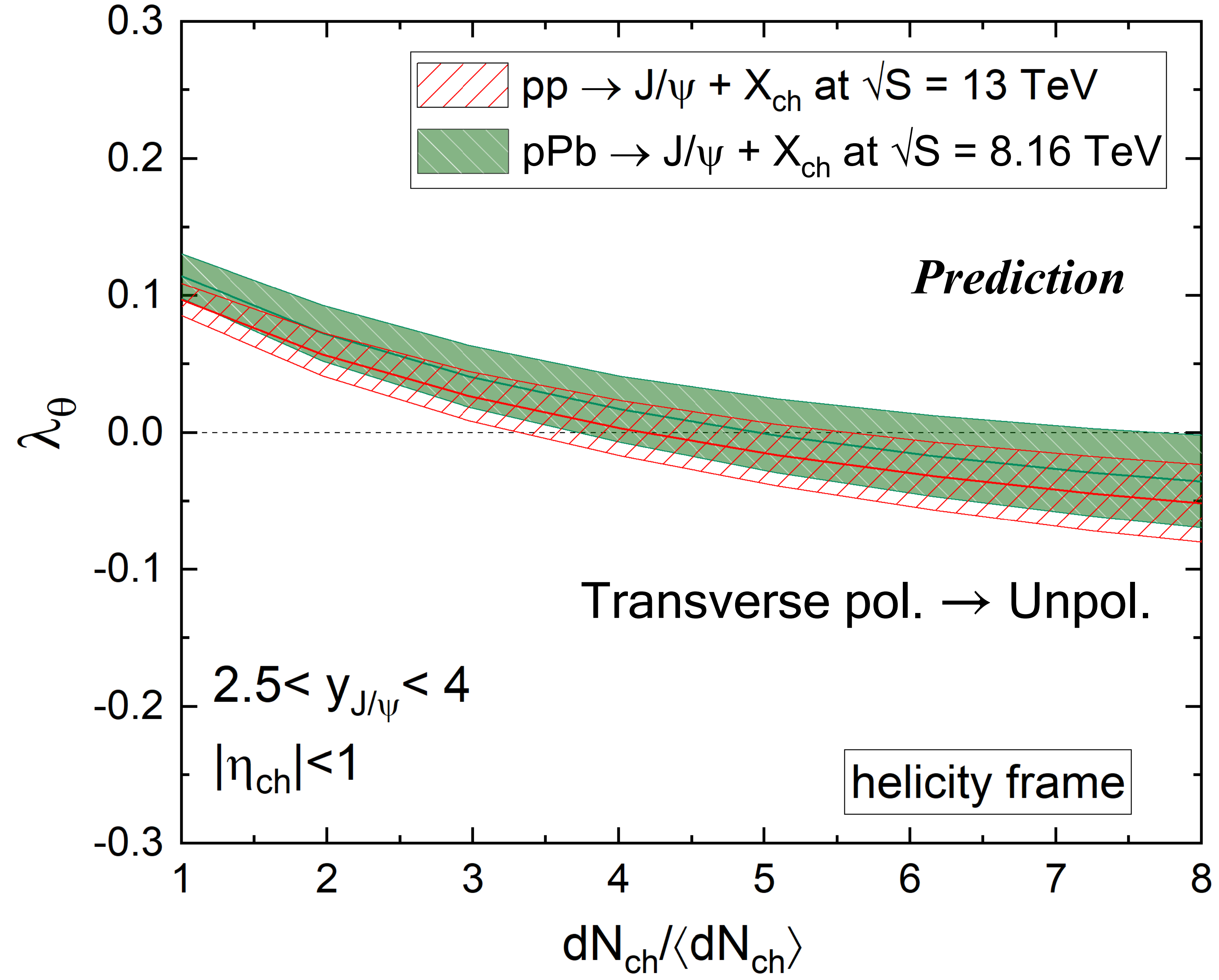
High multiplicity events in small systems

Ma, Tribedy, Venugopalan, **KW**, PRD98, no.7, 074025 (2018), NPA982, 747 (2019)
Ma, Stebel, Venugopalan, **KW**, PoSHardProbes2020, 066 (2021)

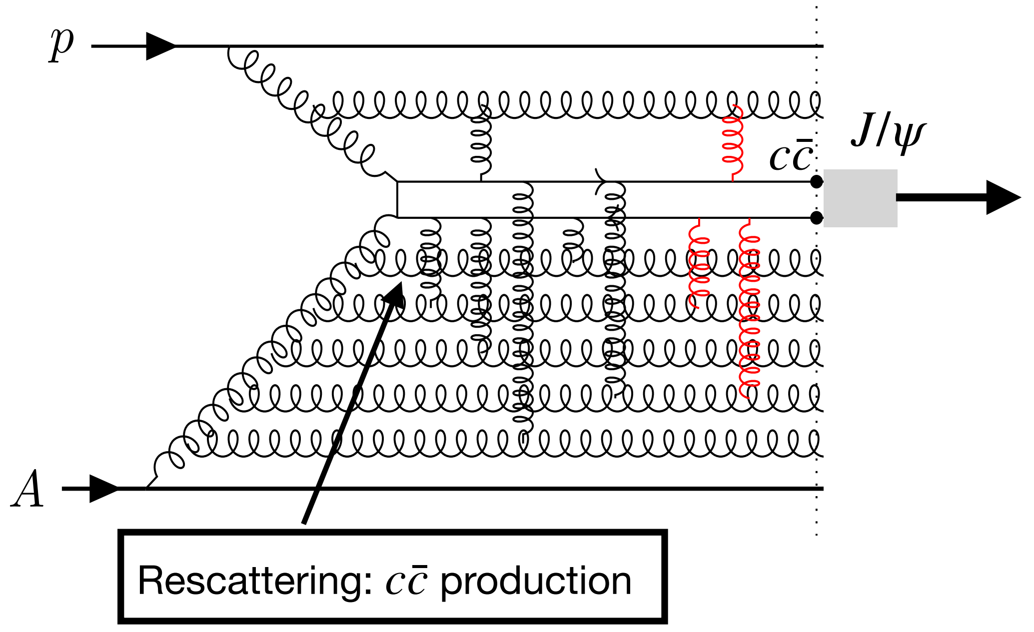
Stebel and **KW,** PRD104, no.3, 034004 (2021)







$$\frac{dN_{ch}}{d\eta} \sim \frac{S_\perp Q_s^2}{\alpha_s}$$



- The CGC EFT is applicable: High multiplicity → # of net gluons is large → $\alpha_s(Q_s) \ll 1$
- Rare partons configuration in hadrons/nuclei → **large Q_s** → **HM events.**
- Each intermediate state of the quark pair shows different N_{ch} dependence; Sensitive to the onium production mechanism.
- **Caveat**: The CGC framework reproduces the trend, but final state flow, CGC model dep., etc. affect the measurements.

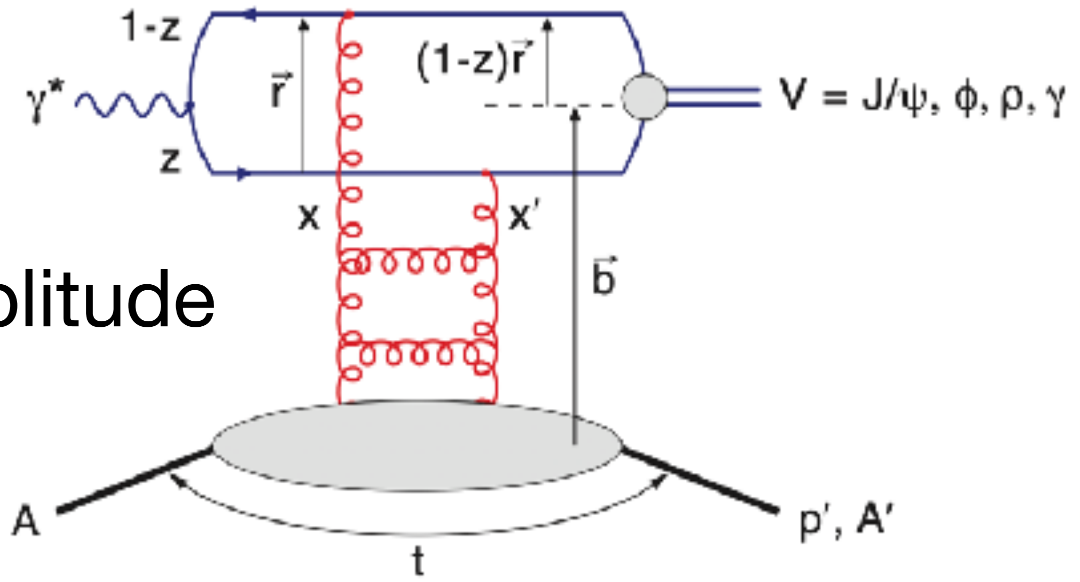
Summary

- Forward HF/Onium production is an interesting arena to study initial state multiple rescattering effects in the target.
- The CGC framework describes forward J/ψ and D suppression in pA collisions, which constrains the nuclear saturation scale at large-x.
- The saturation is elusive; we find no clear sign of the saturation from data on the J/ψ's p_T broadening and high multiplicity events so far.
- We need to comprehensively study the bound state formation in e^+e^-, ep, and pp collisions, while further constraints on saturation effects will be obtained from forward J/ψ and D production at ALICE and LHCb, which should be compared to hadron/photon production data from FoCal.

Thank you!

Appendix

Coherent J/ψ production in UPC



Dipole amplitude

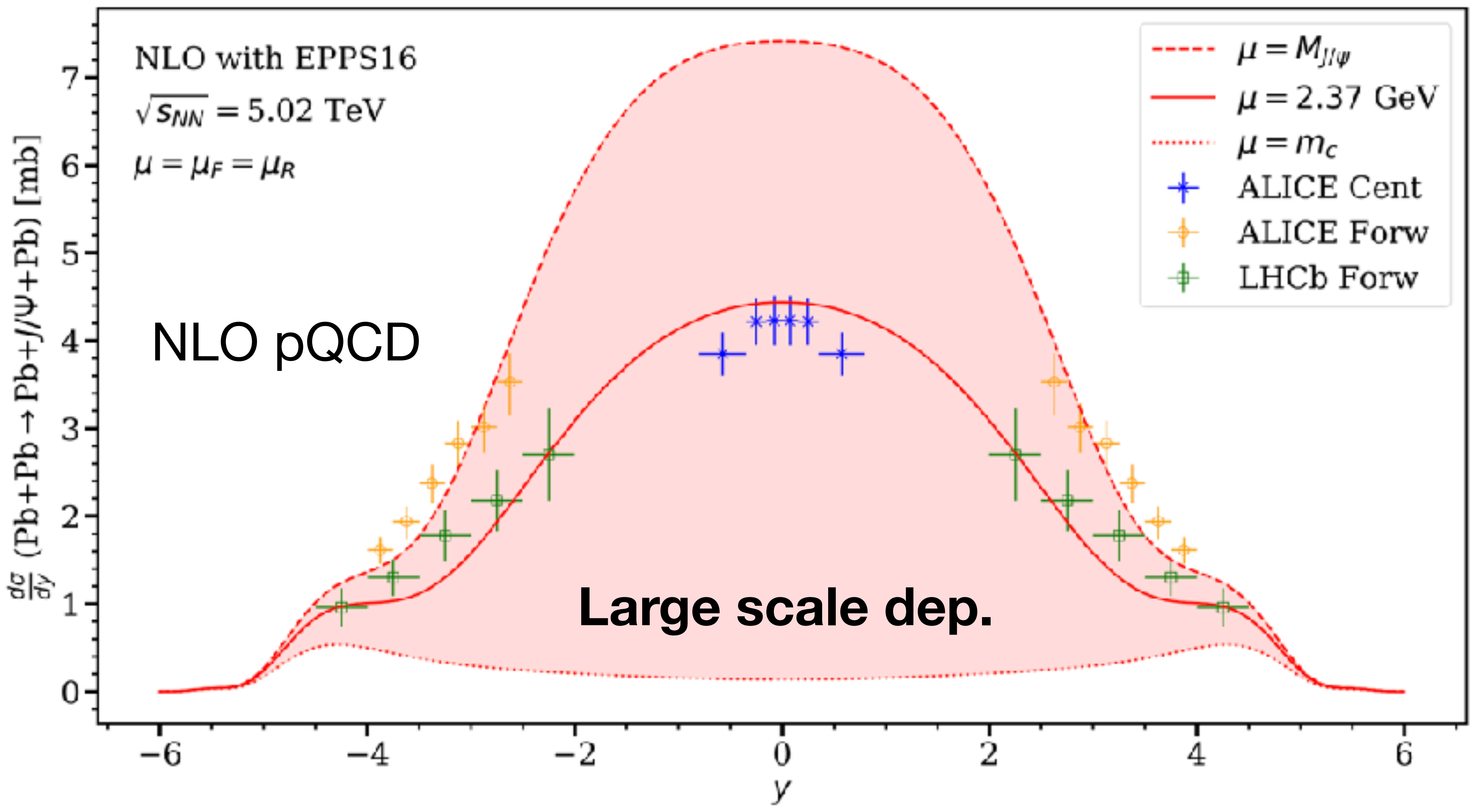
Fig. from Toll and Ullrich, PRC87, no.2, 024913 (2013)

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

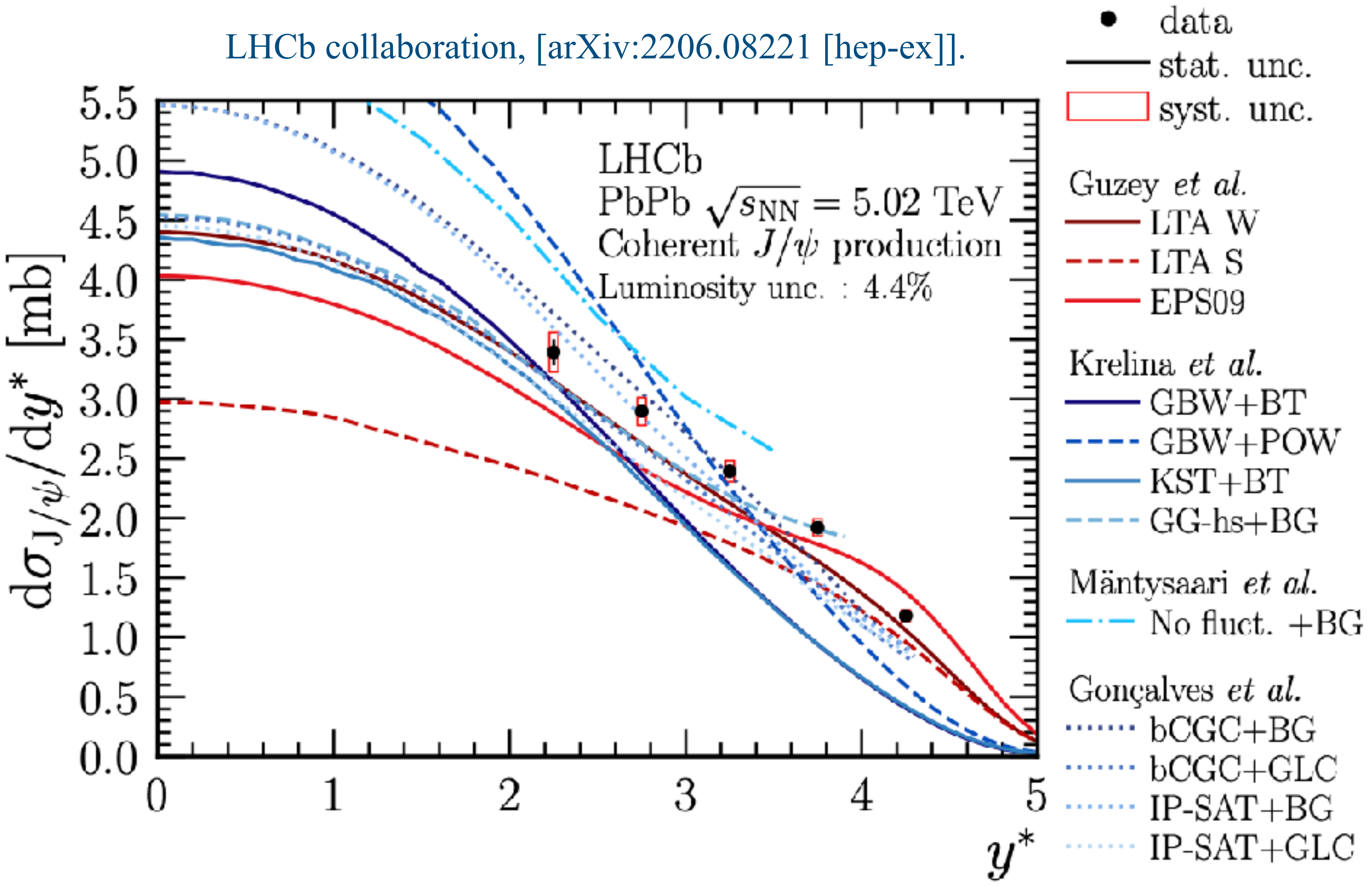
Sensitive to nuclear gluon distribution

No nuclear absorption in final state

Eskola, Flett, Guzey, Löytäinen, Paukkunen, [arXiv:2203.11613 [hep-ph]].



LHCb collaboration, [arXiv:2206.08221 [hep-ex]].



- Large theoretical uncertainties about GPDs, LF wave function, and so forth.
- Any model calculations cannot be ruled out by data comparison.