Multiple parton scattering in eA and pA collisions

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The 11th workshop on hadron physics in China and opportunities worldwide

Outline

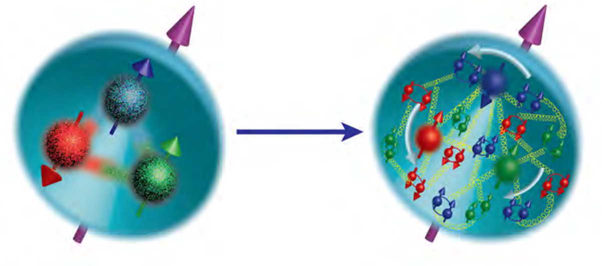
- Introduction
- Nuclear parton distribution functions
  - J/psi production as a probe of nuclear PDFs at EIC

    Wang, **HX**, arXiv:1909.xxxxx
- Multiple parton interaction in cold nuclear matter
  - Parton energy loss at EIC — Chang, Deng, Wang, **HX**, arXiv:1909.xxxxx
  - Incoherent multiple scattering in pA — Kang, Vitev, **HX**, 2019
  - Jet transport coefficient for cold nuclear matter

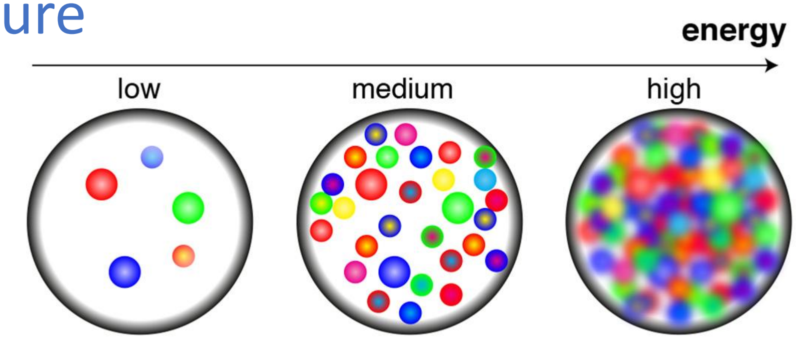
    Ru, Kang, Wang, **HX**, Zhang, arXiv:1907.11808
- Summary

Key questions at EIC, EicC

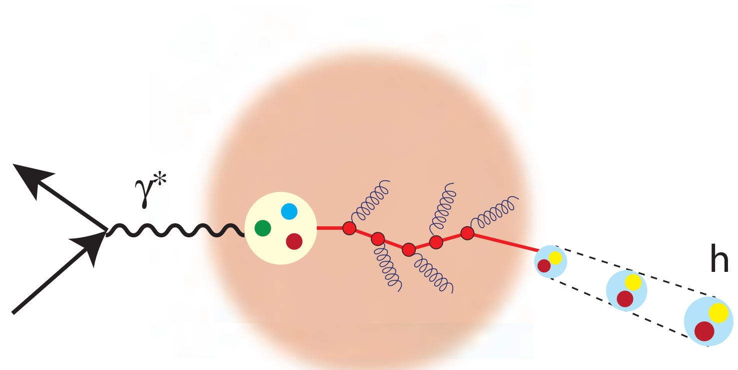
- How quarks and gluons distribute their momentum and spin inside the nucleon?



- Nuclear structure

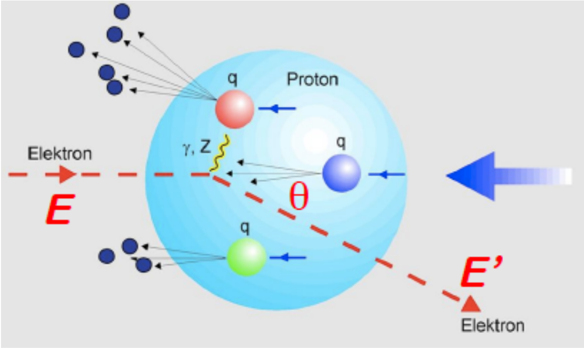


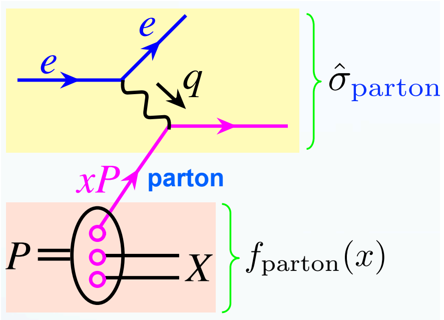
- Quarks and gluons inside nuclei



QCD factorization theorem

❑ Factorization in deep inelastic scattering





- Question: cross section involving identified hadron(s) is **not** infrared safe
  Hadronic scale ~ 1/fm is non-perturbative, the cross section is **not** perturbative calculable.

- Solution from theory advances: QCD factorization theorem

Cross Section = Infrared-Safe ⊗ Nonperturbative-distribution

Measured ↑ **Hard-probe** ↑ **Universal-hadron structure** ↑

QCD factorization theorem is the corner stone of high energy physics!

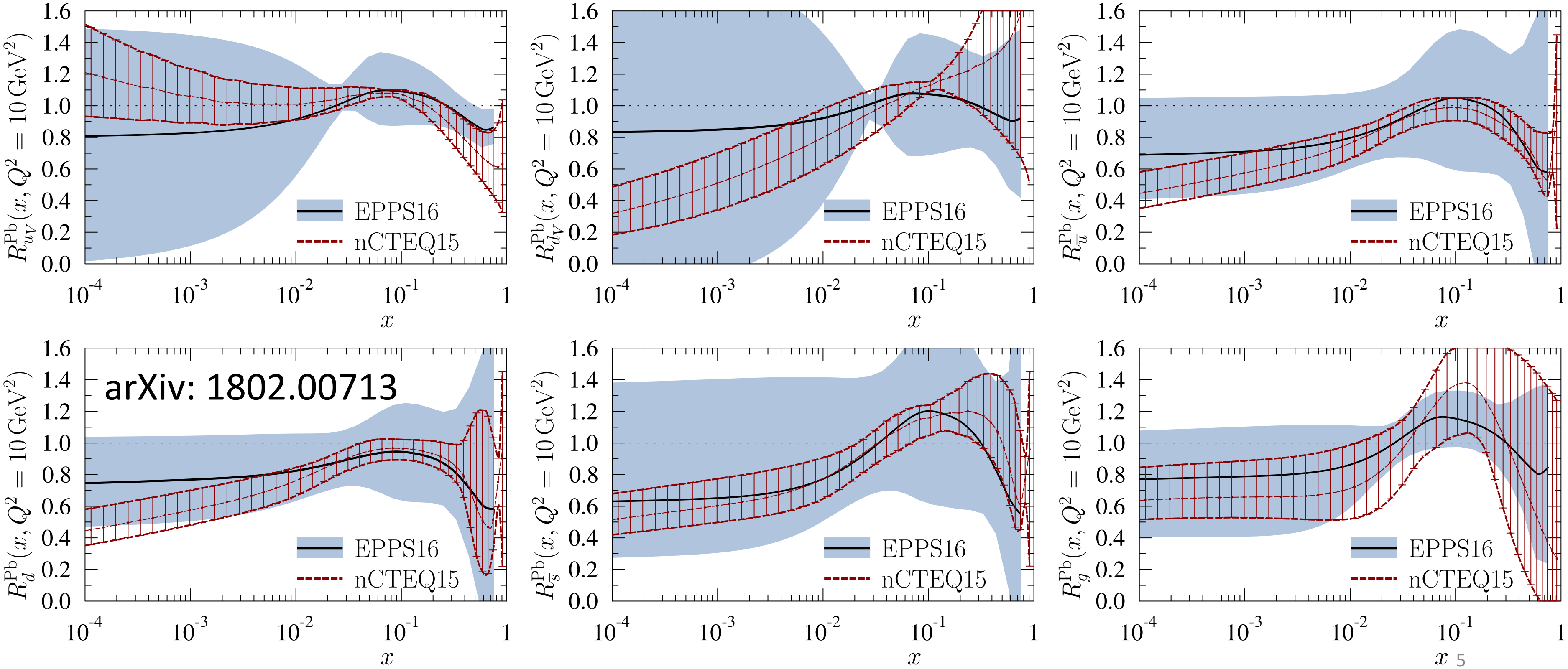
Nuclear effect - nuclear PDFs

Cross Section = **Infrared-Safe** ⊗ **Nonperturbative-distribution**

Measured — **Hard-probe** — **Universal-hadron structure**

Put all nuclear effects into nPDFs

- Current state of the art of nuclear PDFs – large uncertainty



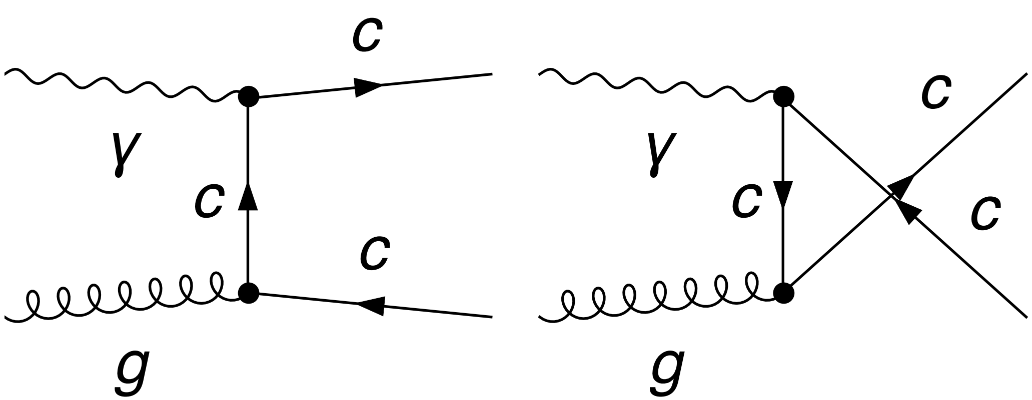
J/psi production in electron ion collisions

- NRQCD factorization formalism

$$\sigma = \sum_i \sum_n \int d\xi f_{i/A}(\xi, \mu^2) \hat{\sigma}_{e+i\to e+c\bar{c}[n]+X} \langle \mathcal{O}^{J/\psi}_{[n]} \rangle$$

Nonperturbative LDMEs

- Leading order

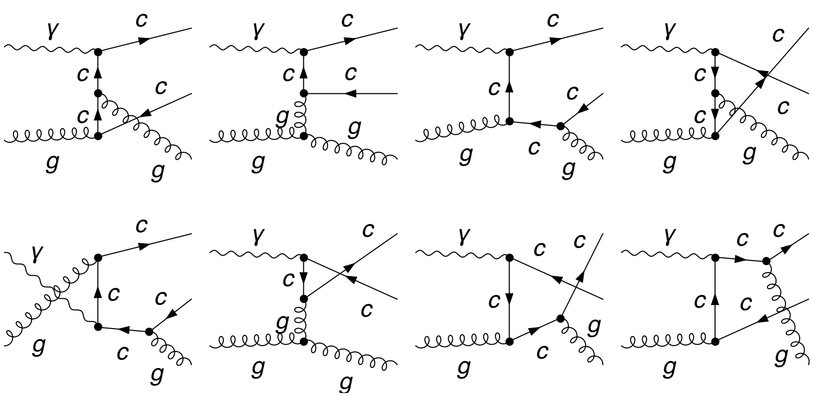


- Purely from gluon channel, very sensitive to initial state gluon distribution

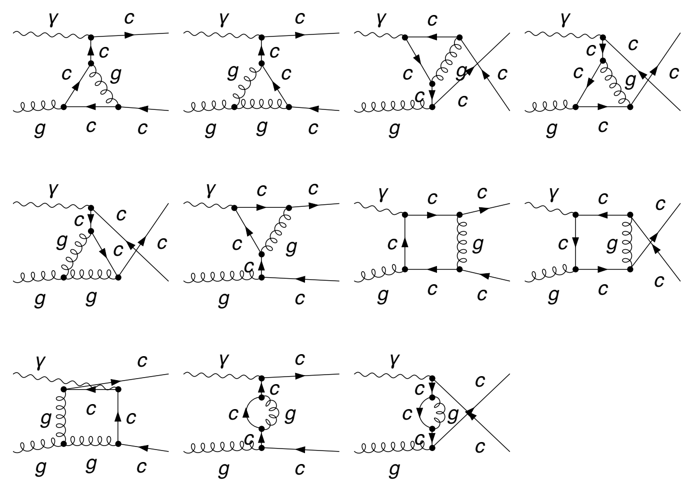
J/psi production in electron ion collisions

❑ Next-to-leading order

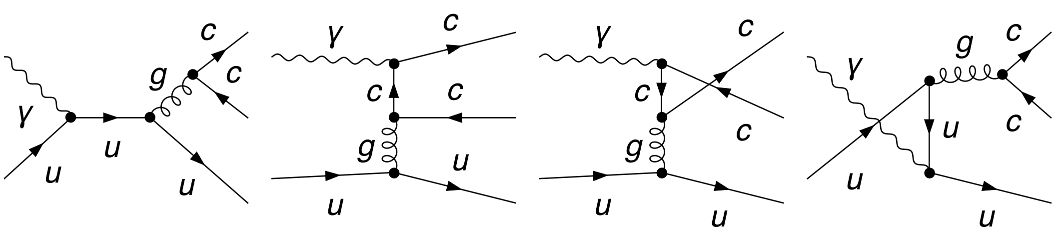
Xiang-Peng Wang, Hongxi Xing, 2019



gluon channel – real correction



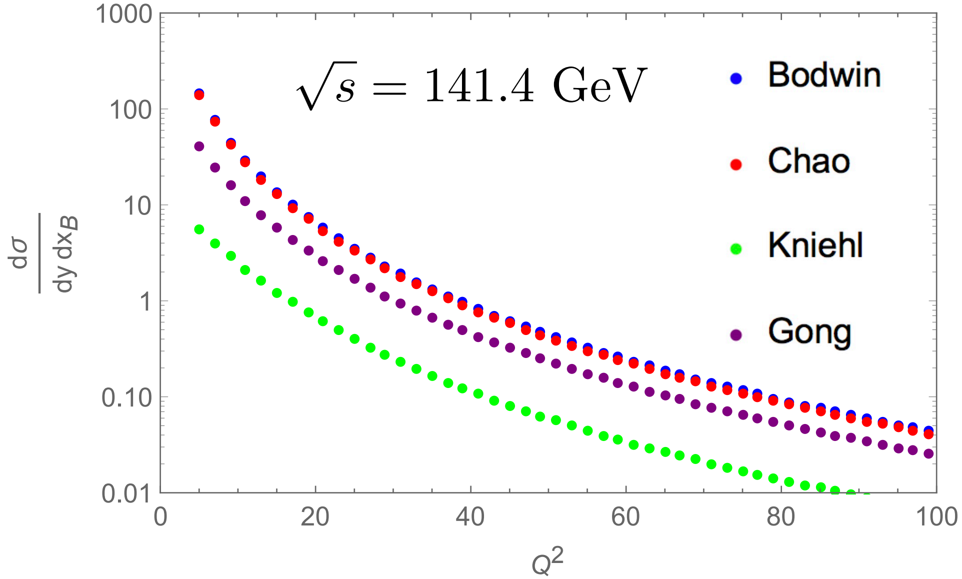
gluon channel – virtual correction

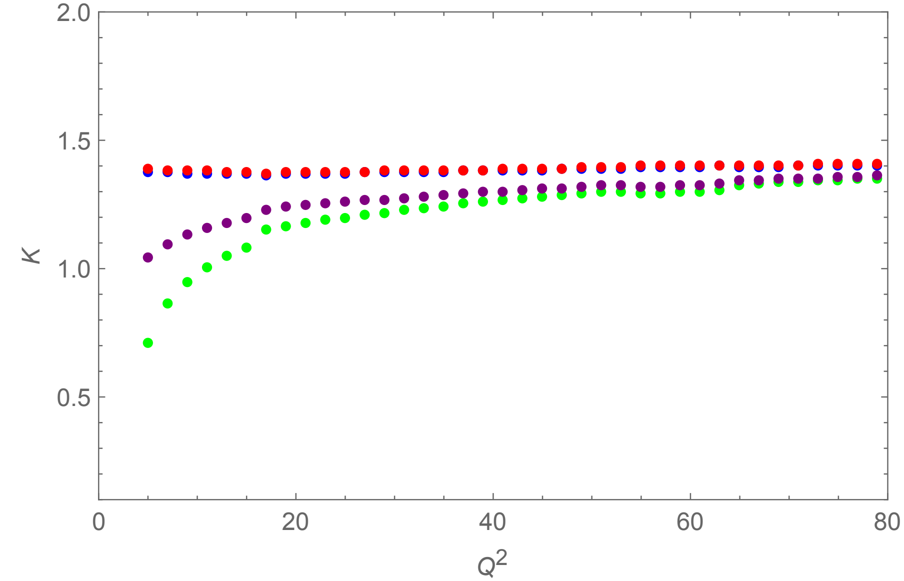


quark channel – real correction

J/psi production in electron ion collisions

❑ J/psi production at next-to-leading order



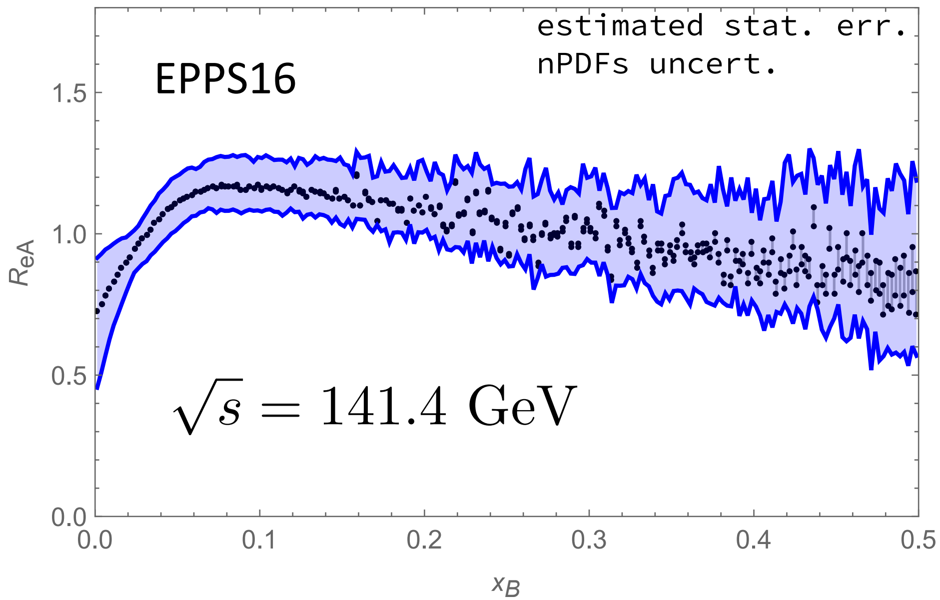


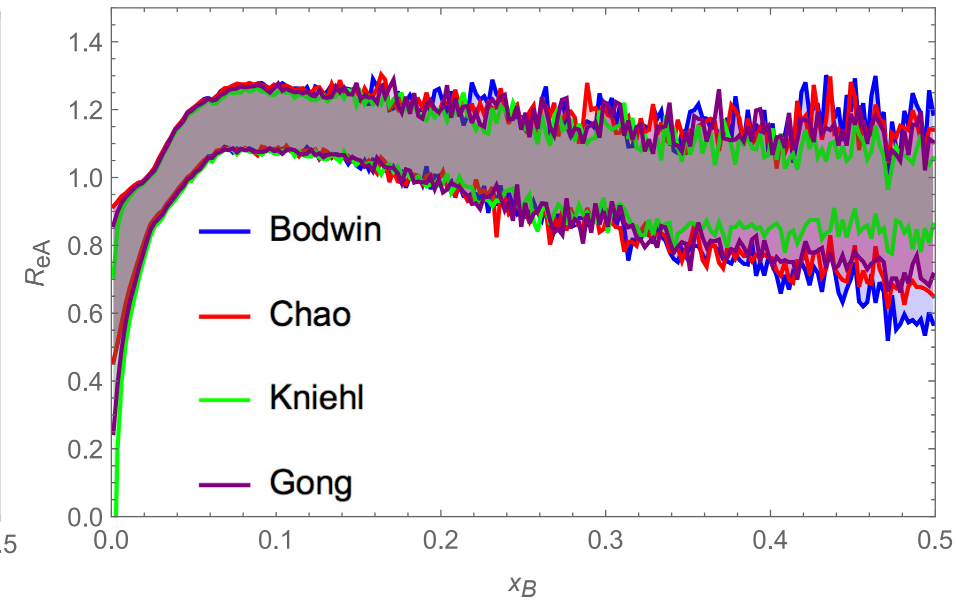
- Huge difference from four different parametrizations of LDMEs
- EIC and EicC will provide good opportunity to constrain LDMEs in NRQCD
- Next-to-leading order is important for precise prediction.

J/psi as a probe of nPDFs at EIC

❑ Nuclear modification factor at NLO

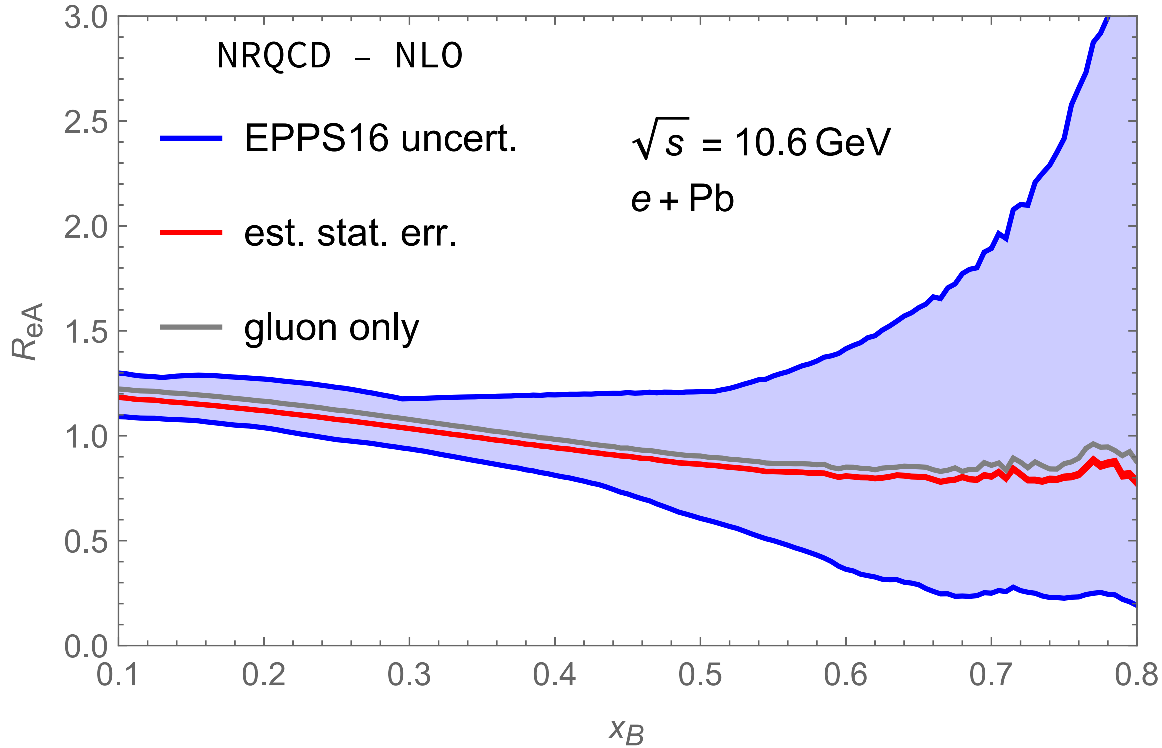
$$R_{eA} = \frac{d\sigma^{eA}/dQ^2dy}{d\sigma^{ep}/dQ^2dy}$$





- According to the designed high luminosity, the estimated statistical error is tiny for future EIC.
- The uncertainty due to nonperturbative LDMEs cancels in the ratio.

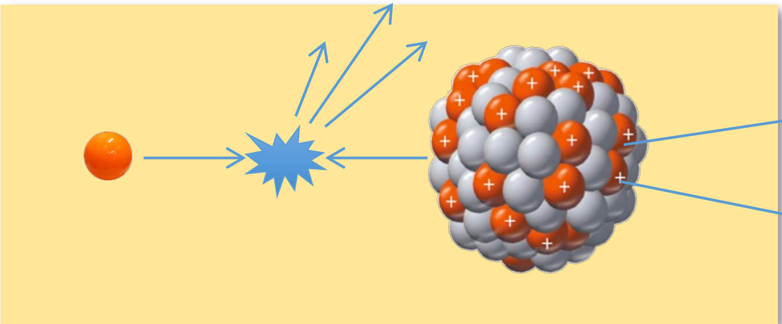
J/psi as a probe of nPDFs at EicC

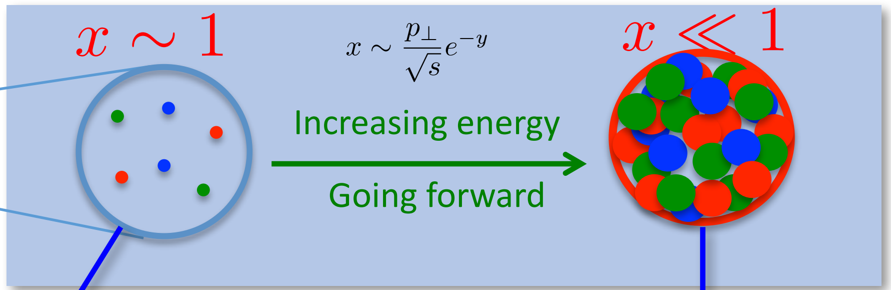


j/psi production can be served as a good channel to constrain nuclear gluon distribution function.

Multiple scattering in nuclear medium

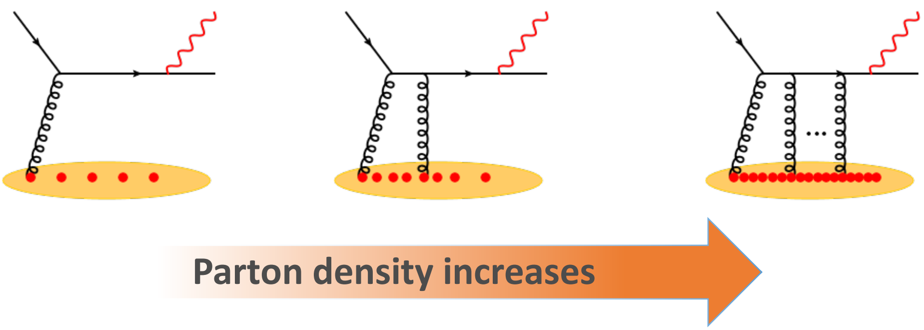
❑ Multiple scattering in dilute and dense region



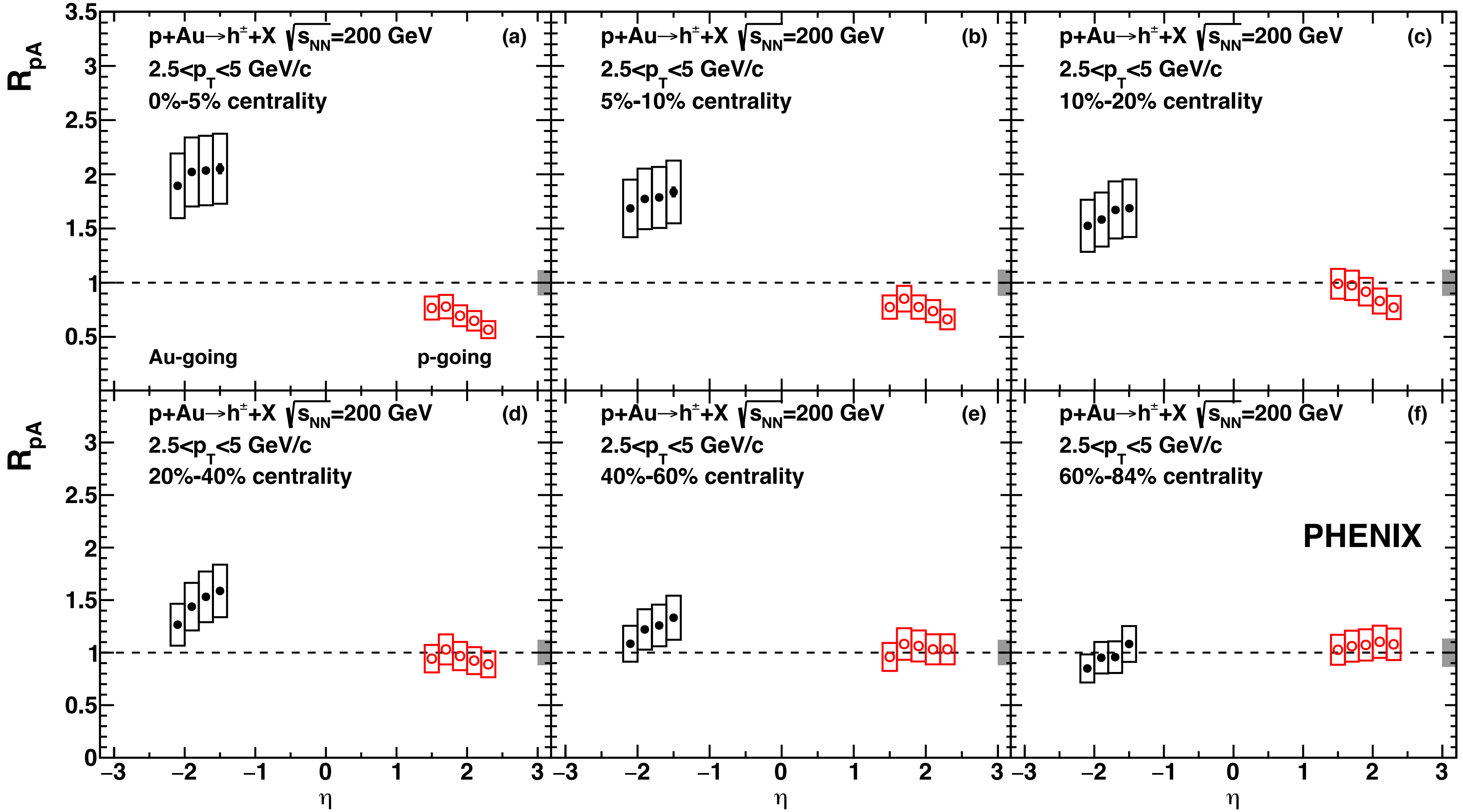


- A dilute system
- Probes interact independently

- A dense system
- Probes interact coherently



Looking forward and backward

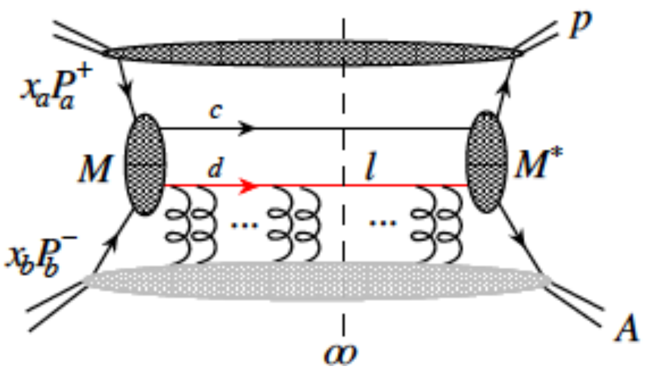


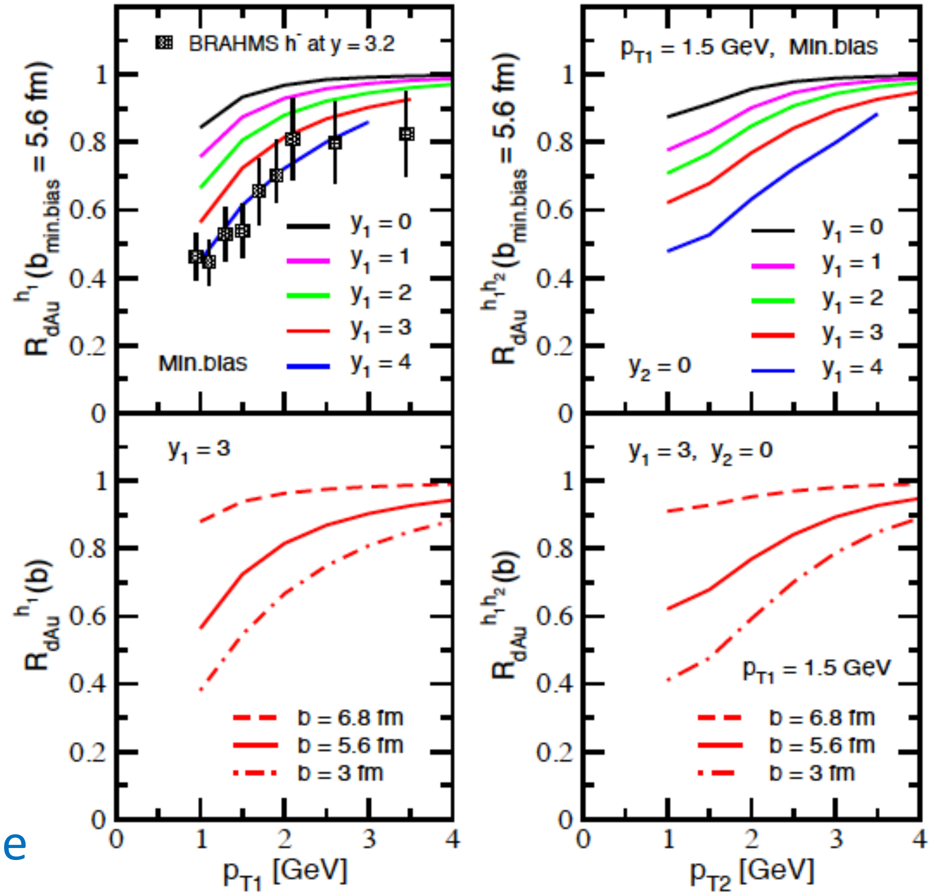
PHENIX Collaboration arXiv:1906.09928

Looking forward

- Coherent multiple scattering in small-x

I. Vitev, J. Qiu, PLB, 2006





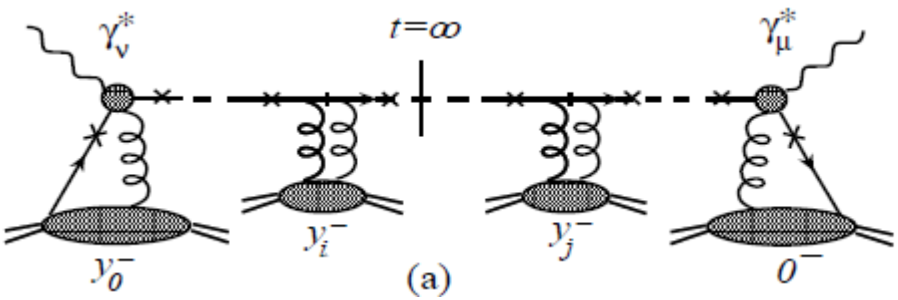
Probing length:

$$\frac{1}{Q} \sim \frac{1}{x_b P_b} \gg 2R\left(\frac{m}{p}\right)$$

In forward rapidity region, x_b is small, the probe interacts with the whole nucleus coherently.

Coherent multiple scattering – twist resummation

❑ Nuclear dynamic shadowing - structure function in DIS



$$F_T^A(x,Q^2) \approx \sum_{n=0}^{N} \frac{A}{n!}\left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n \frac{d^n F_T^{(\mathrm{LT})}(x,Q^2)}{d^n x}$$

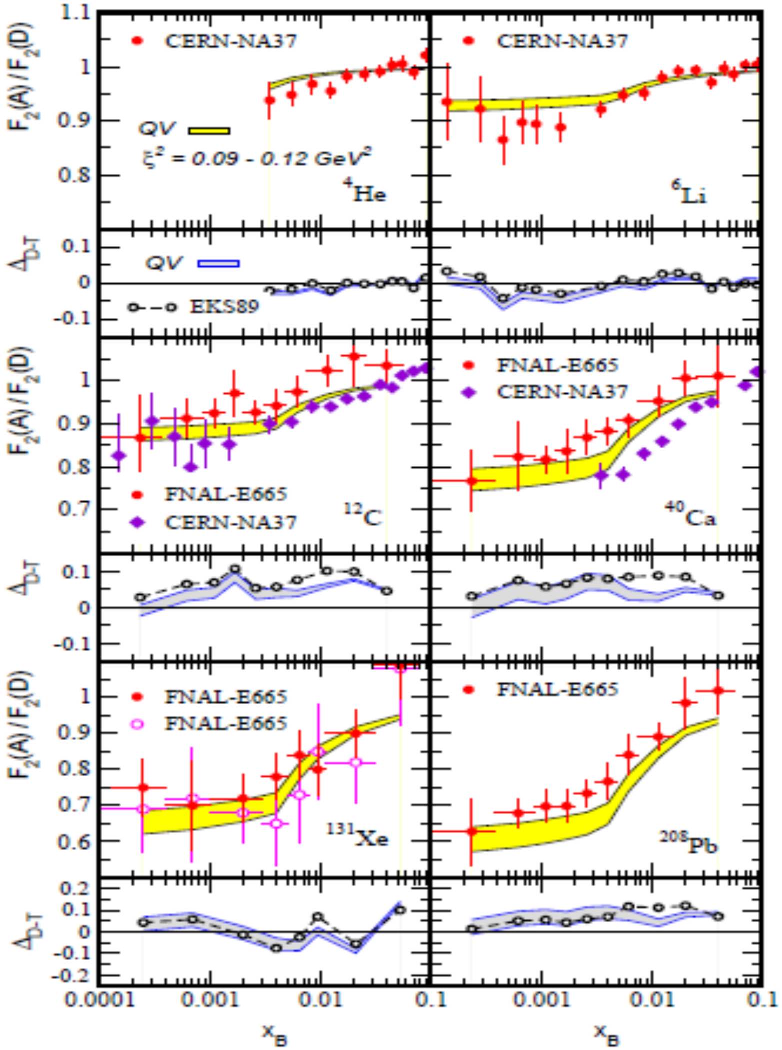
$$\approx A\, F_T^{(\mathrm{LT})}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2\right), \qquad (10)$$

$$\xi^2 = \frac{3\pi\alpha_s(Q^2)}{8\,r_0^2}\langle p|\,\hat{F}^2(\lambda_i)\,|p\rangle$$

$$= 0.09 - 0.12\ \mathrm{GeV}^2$$

Only one free parameter, related to qhat.

Opportunities to explore coherent multiple scattering (small x) in EIC and EicC?

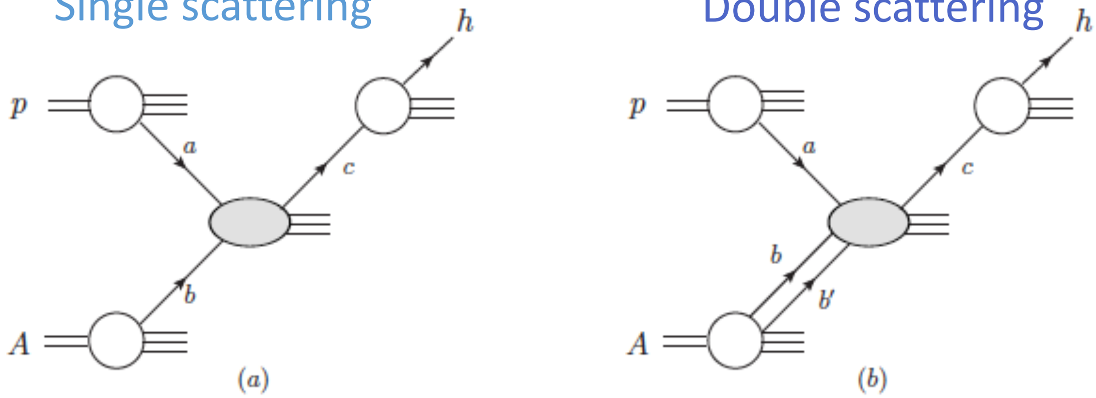


Qiu, Vitev , PRL, 2004

Looking backward

- Incoherent multiple scattering in p+A collisions

Single scattering Double scattering



Probing length: $$\frac{1}{Q} \sim \frac{1}{x_b P_b} < 2R\left(\frac{m}{p}\right)$$

In backward rapidity region, x_b is large. The probe interacts with the nucleus incoherently, we need to calculate multiple scattering contributions order by order, the leading contribution comes from double scattering.

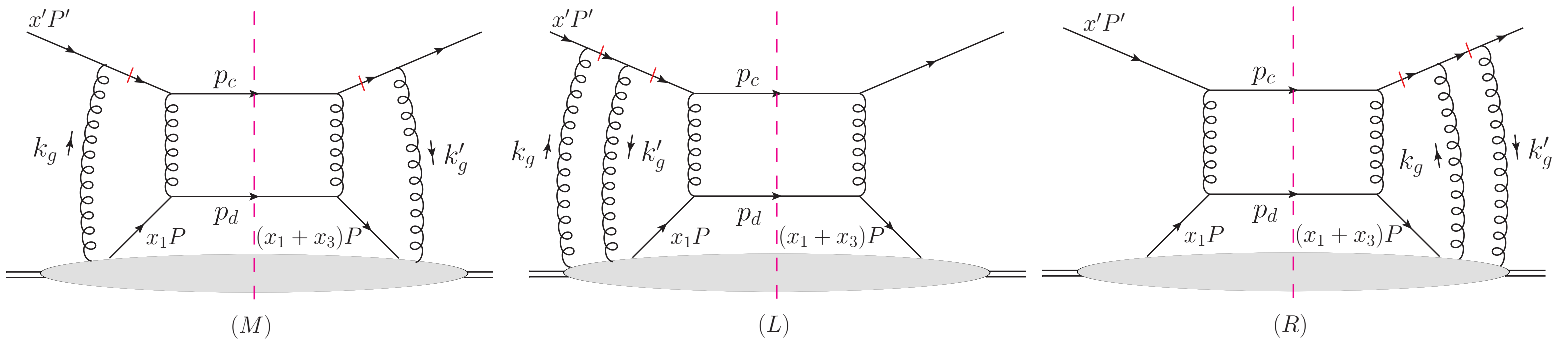
- multiple scattering expansion

$$d\sigma_{pA\to hX} = d\sigma^{(S)}_{pA\to hX} + d\sigma^{(D)}_{pA\to hX} + \cdots$$

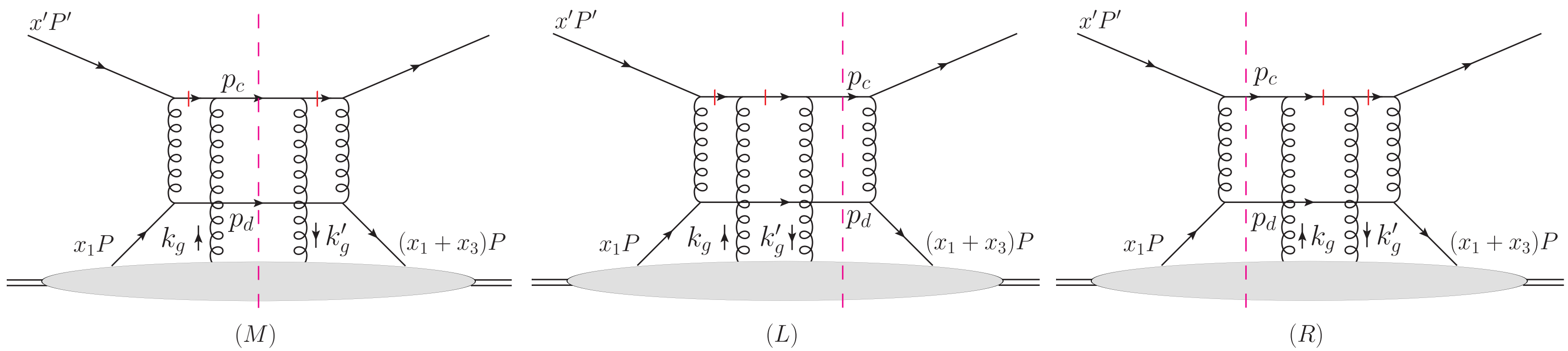
$$E_h \frac{d\sigma^{(S)}}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int \frac{dz}{z^2}D_{c\to h}(z)\int \frac{dx'}{x'}f_{a/p}(x')\int \frac{dx}{x}f_{b/A}(x)H^U_{ab\to cd}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u})$$

▪ Double scattering Feynman diagrams ($qq' \to qq'$ as an example)

Initial state double scattering



Final state double scattering



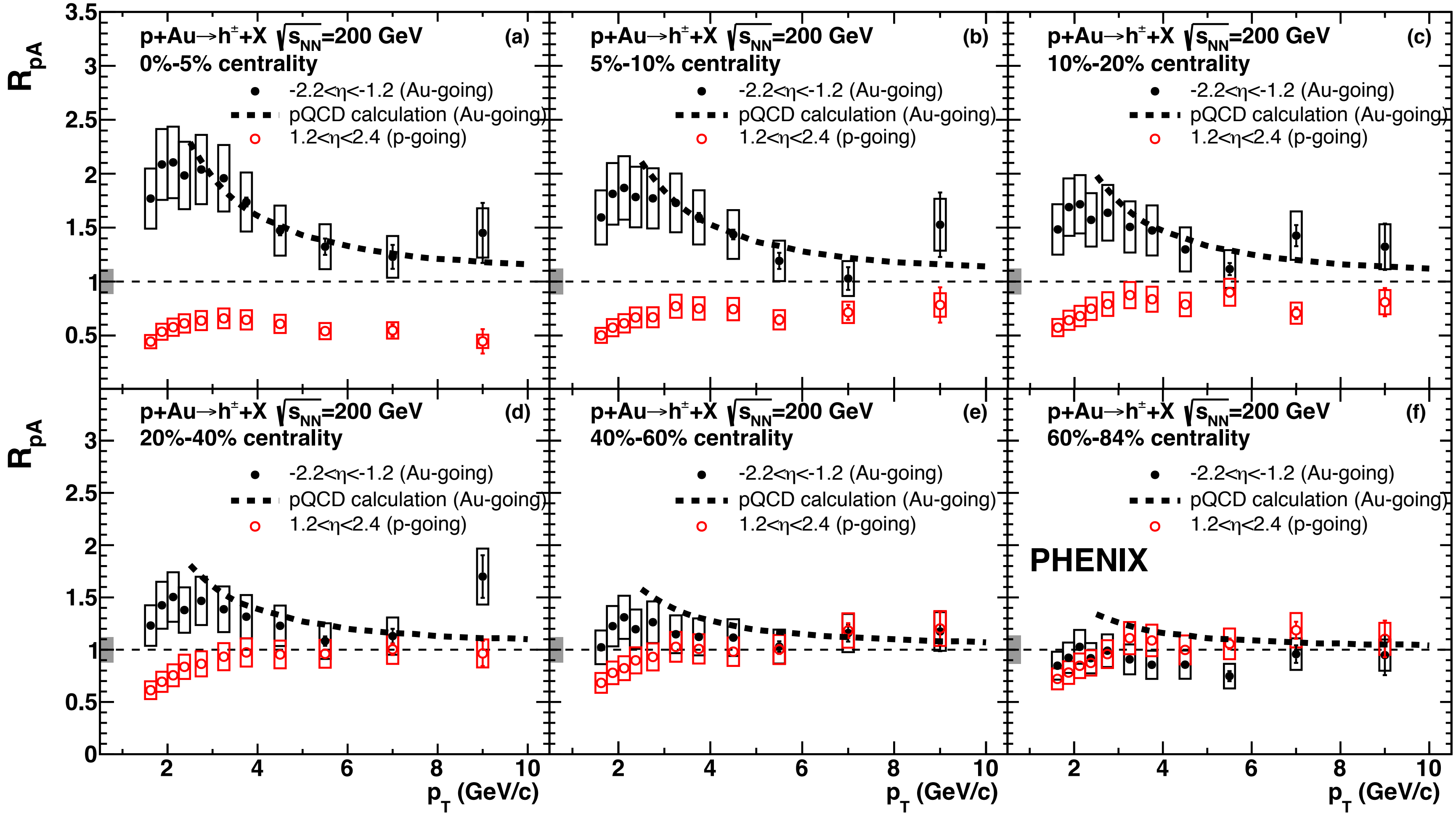
▪ Double scattering cross section (twist-4 contribution) Kang, Vitev, **HX**, PRD 2013

$$E_h \frac{d\sigma^{(D)}}{d^3P_h} = \left(\frac{8\pi^2\alpha_s}{N_c^2-1}\right) \frac{\alpha_s^2}{S} \sum_{a,b,c} \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} \delta(\hat{s}+\hat{t}+\hat{u})$$

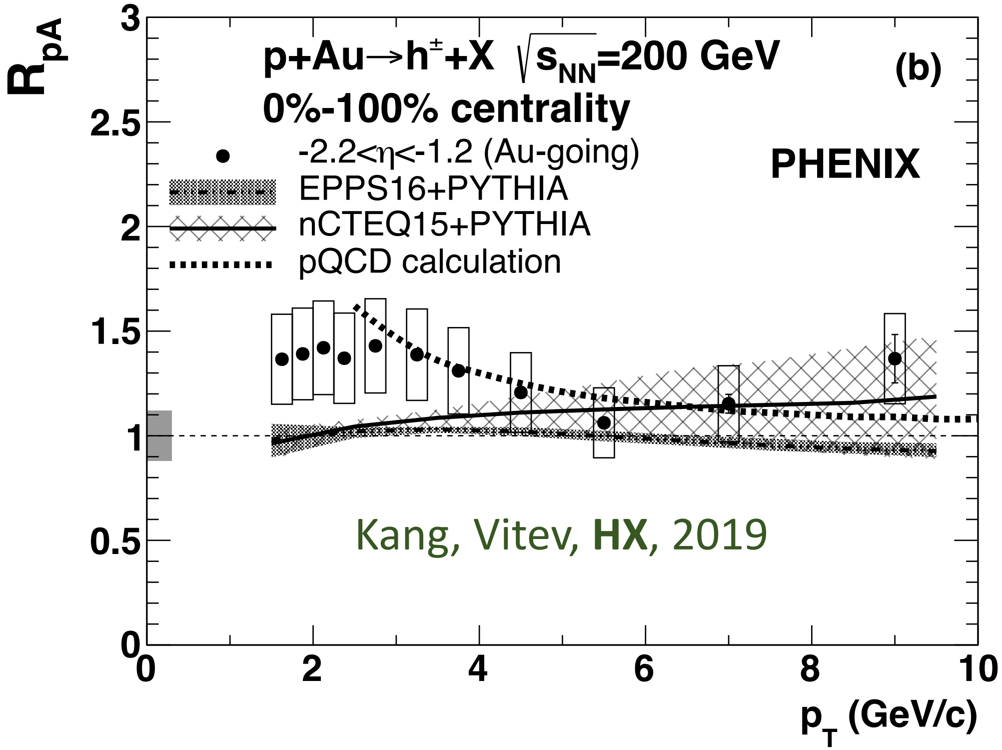
$$\times \sum_{i=I,F} \left[x^2 \frac{\partial^2 T_{b/A}^{(i)}(x)}{\partial x^2} - x \frac{\partial T_{b/A}^{(i)}(x)}{\partial x} + T_{b/A}^{(i)}(x) \right] c^i H^i_{ab\to cd}(\hat{s},\hat{t},\hat{u})$$

❑ Looking backward in PHENIX

Kang, Vitev, **HX**, 2019
PHENIX, arXiv: 1906.09928

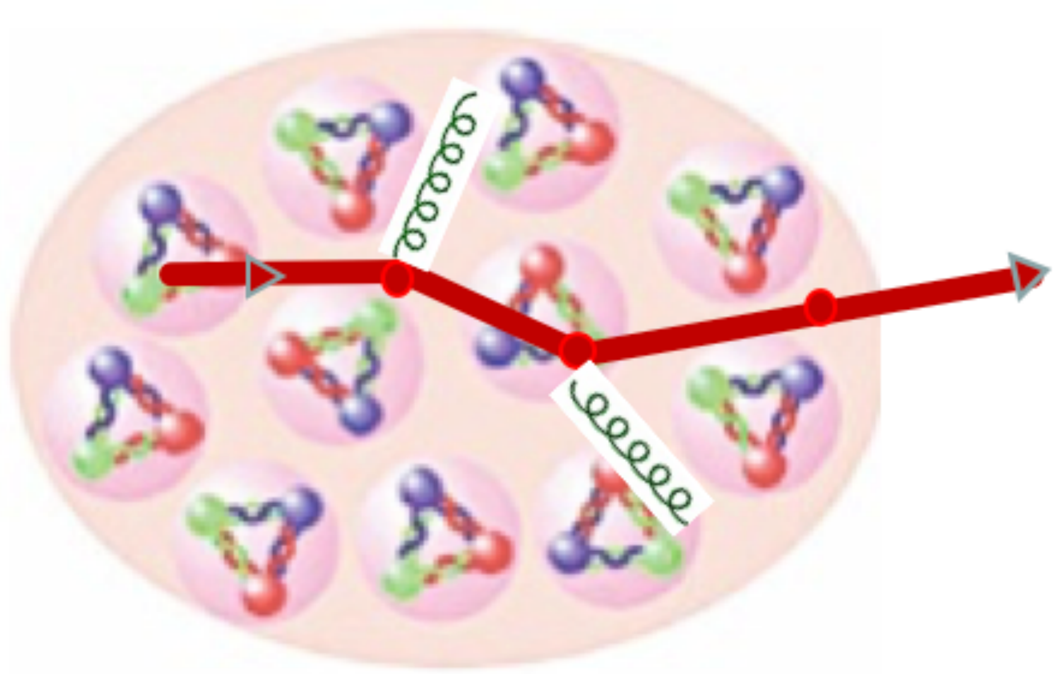


❑ Nuclear PDFs vs. incoherent multiple scattering



Explore incoherent multiple scattering (large x) in EicC?

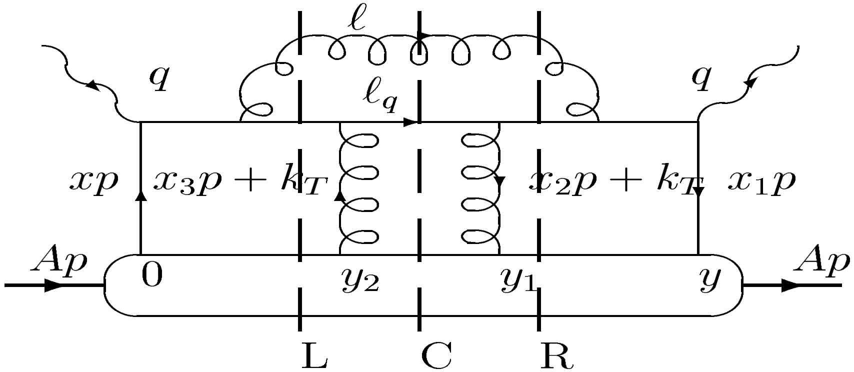
Parton energy loss in eA



Cold nuclear matter

Parton energy loss in cold nuclear matter

Medium induced gluon radiation – twist 4 contribution



Guo, Wang, 2002
Zhang, Wang, Wang, 2004
Du, Wang, HX, Zong, 2018
…

Medium modified fragmentation functions

$$\frac{\partial \tilde{D}_q^h(z_h, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{z_h}^{1}\frac{dz}{z}\left[\tilde{\gamma}_{q\to qg}(z,Q^2)\tilde{D}_q^h(\frac{z_h}{z},Q^2) + \tilde{\gamma}_{q\to gq}(z,Q^2)\tilde{D}_g^h(\frac{z_h}{z},Q^2)\right], \quad (1)$$

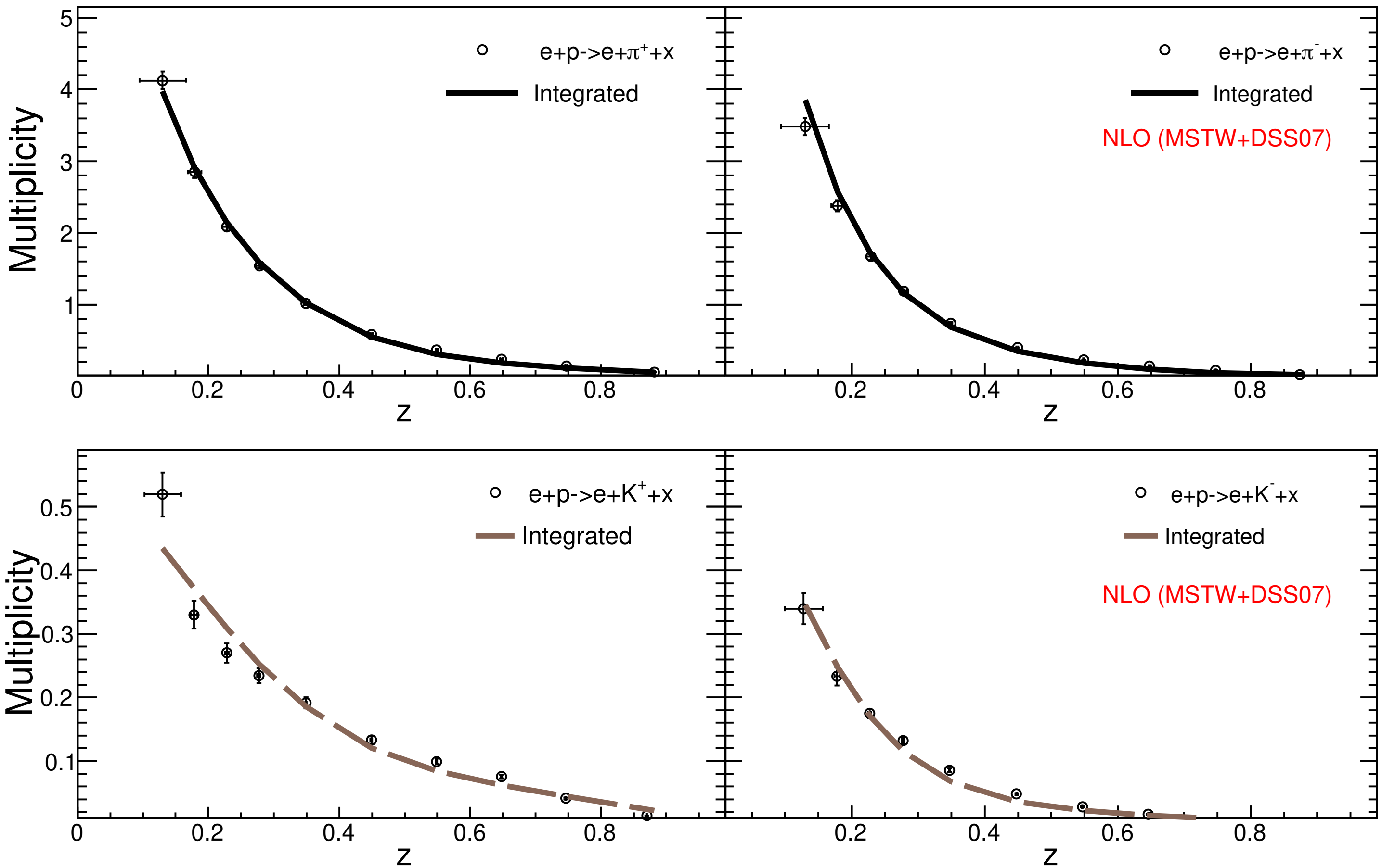
$$\frac{\partial \tilde{D}_g^h(z_h, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{z_h}^{1}\frac{dz}{z}\left[\tilde{\gamma}_{g\to gg}(z,Q^2)\tilde{D}_g^h(\frac{z_h}{z},Q^2) + \sum_{q=1}^{2n_f}\tilde{\gamma}_{g\to q\bar{q}}(z,Q^2)\tilde{D}_q^h(\frac{z_h}{z},Q^2)\right], \quad (2)$$

Nuclear modification factor

$$R_A^h(\nu, Q^2, z) = \left[\frac{N^h(\nu, Q^2, z)}{N^e(\nu, Q^2)}\right]_A \Big/ \left[\frac{N^h(\nu, Q^2, z)}{N^e(\nu, Q^2)}\right]_D$$

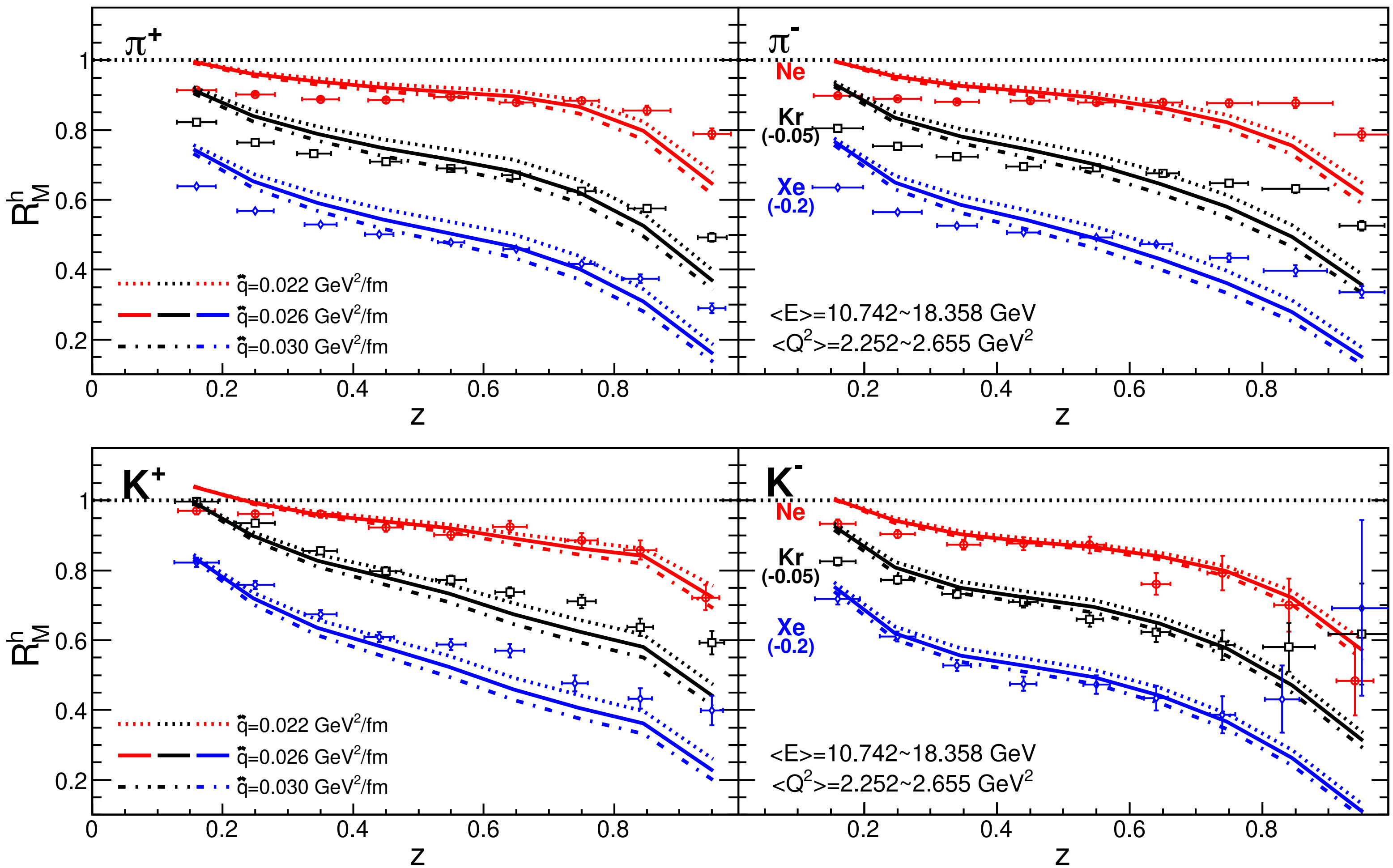
- ep baseline at NLO

Chang, Deng, Wang, **HX**, 1909.xxxxx



- Medium effect in HERMES

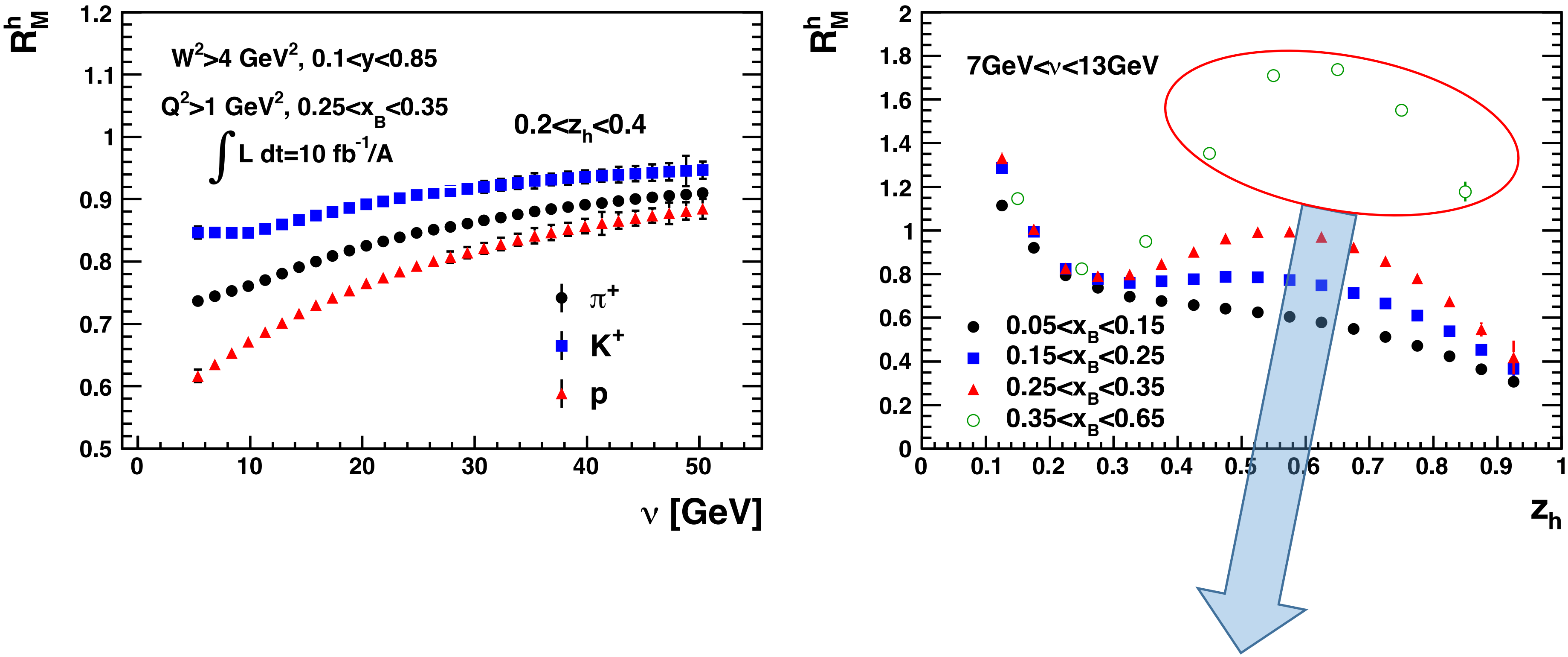
Chang, Deng, Wang, **HX**, 1909.xxxxx



NLO ep baseline + parton energy loss

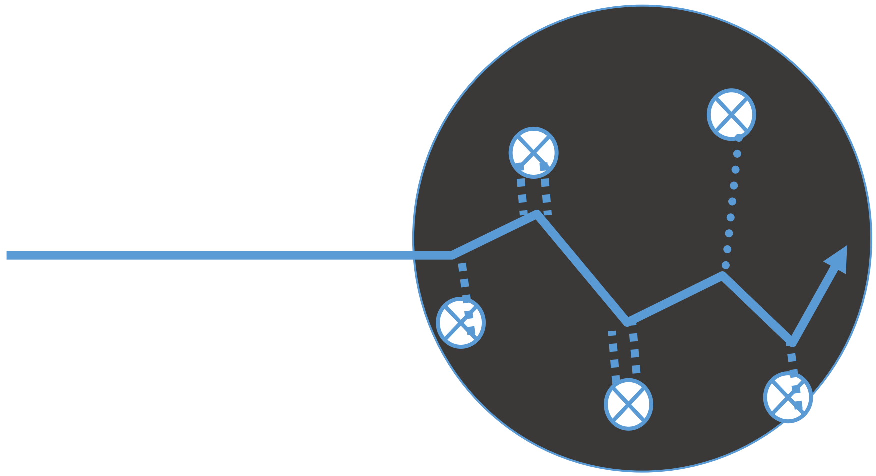
Predictions for EicC

❑ Searching for Eloss and flavor conversion



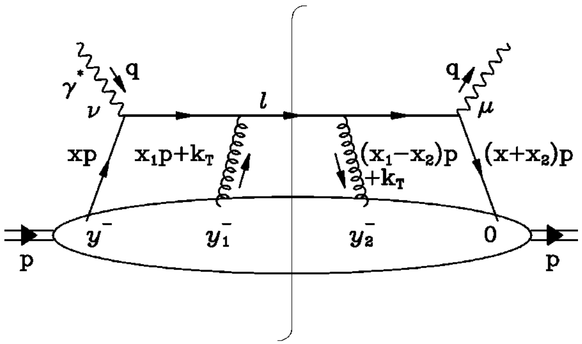
Medium induced flavor conversion leads to enhancement of K^- production yield.

Transverse momentum broadening in eA and pA

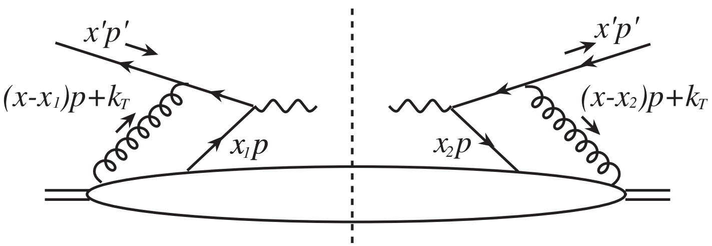


Transverse momentum broadening in CNM

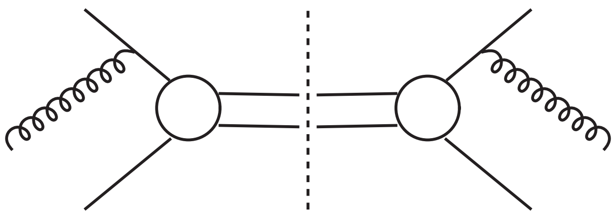
❑ Transverse momentum broadening in eA and pA collisions



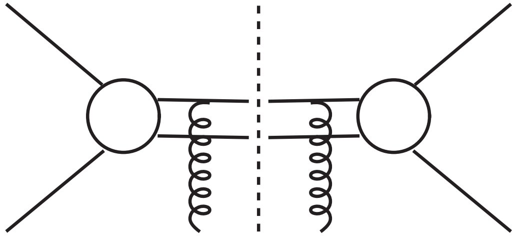
SIDIS (LO, NLO)
Kang, Wang, Wang, Xing 2014



Drell-Yan (LO, NLO)
Kang, Qiu, Wang, Xing 2016



Heavy quarkonium
Initial state multiple scattering
(CEM, NRQCD)



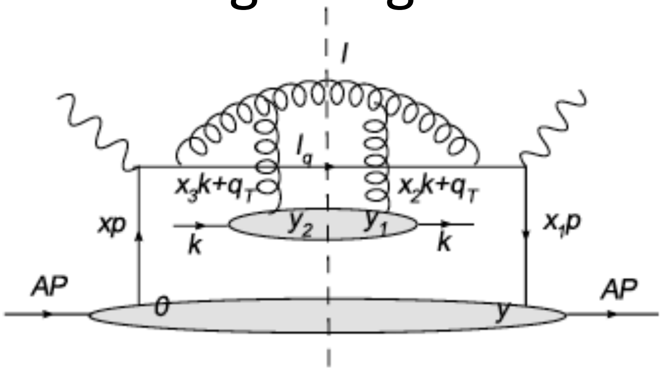
Heavy quarkonium
Final state multiple scattering
(CEM, NRQCD)

Kang, Qiu, 2008,2012

Parametrization of jet transport coefficient

$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep} \sim T_{qg/gg}(x,0,0)$$

- Considering a large and loosely bound nucleus



$$T_{qg}(x,0,0,\mu^2) \approx \frac{N_c}{4\pi^2\alpha_s} f_{q/A}(x,\mu^2)\hat{q}(x,\mu)$$

- Kinematic and scale dependence of qhat

$$\hat{q}(x,\mu^2) = \hat{q}_0\,\alpha_s(\mu^2)\,x^\alpha(1-x)^\beta \ln^\gamma(\mu^2/\mu_0^2)$$

normalization

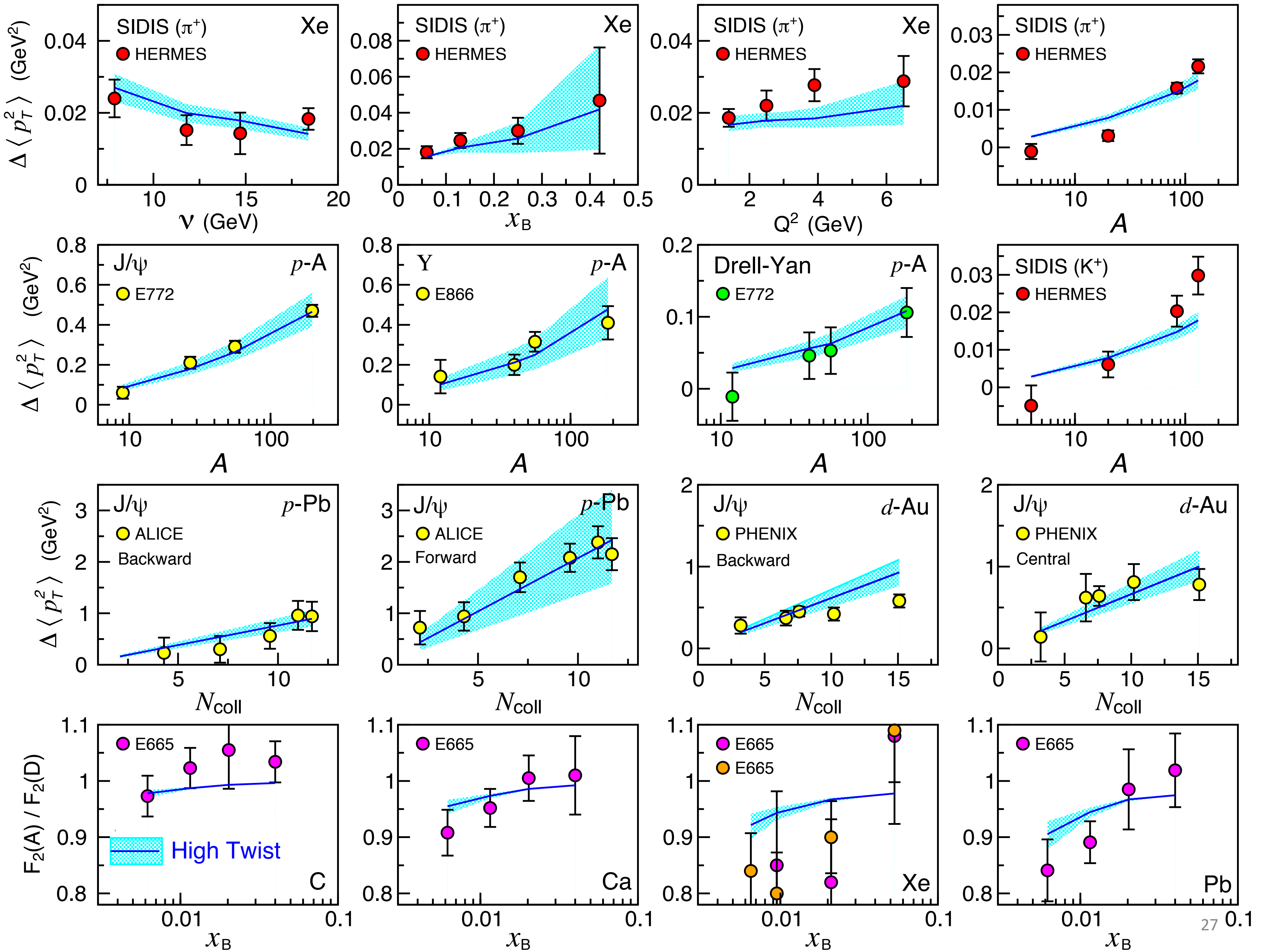
Small-x saturation

Scale dependence

Large-x power correction

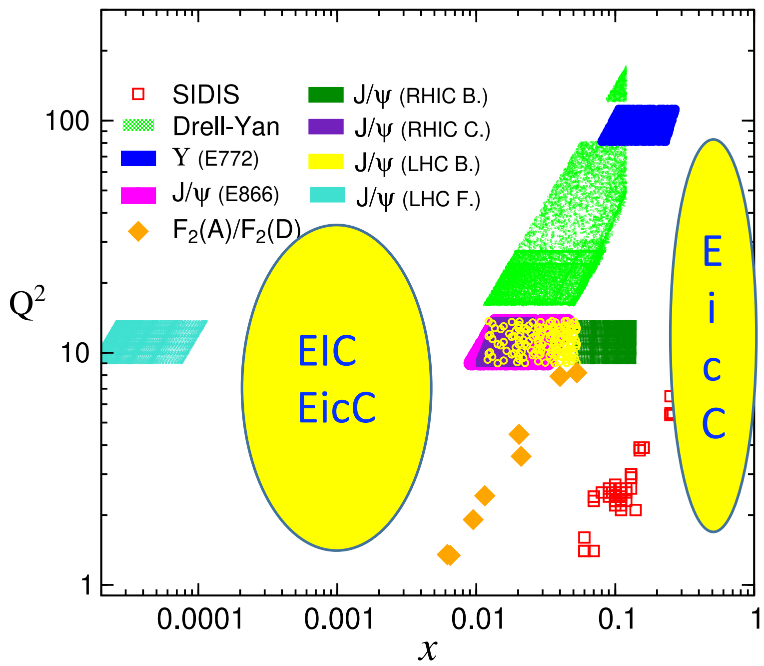
❑ Global analysis of world data

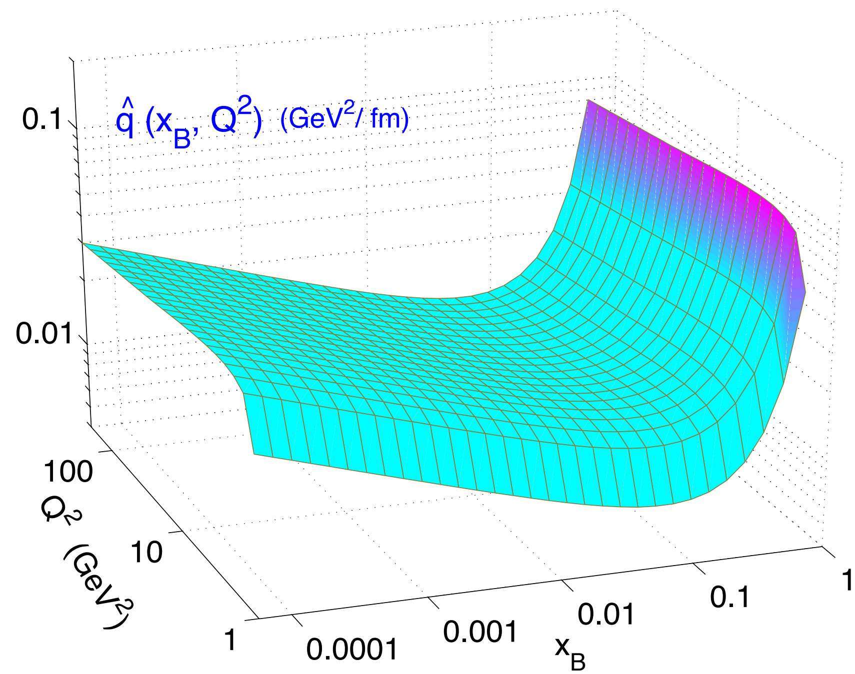
Ru, Kang, Wang, **HX**, Zhang, arXiv: 1907.11808



❑ Kinematic coverage and fitted qhat

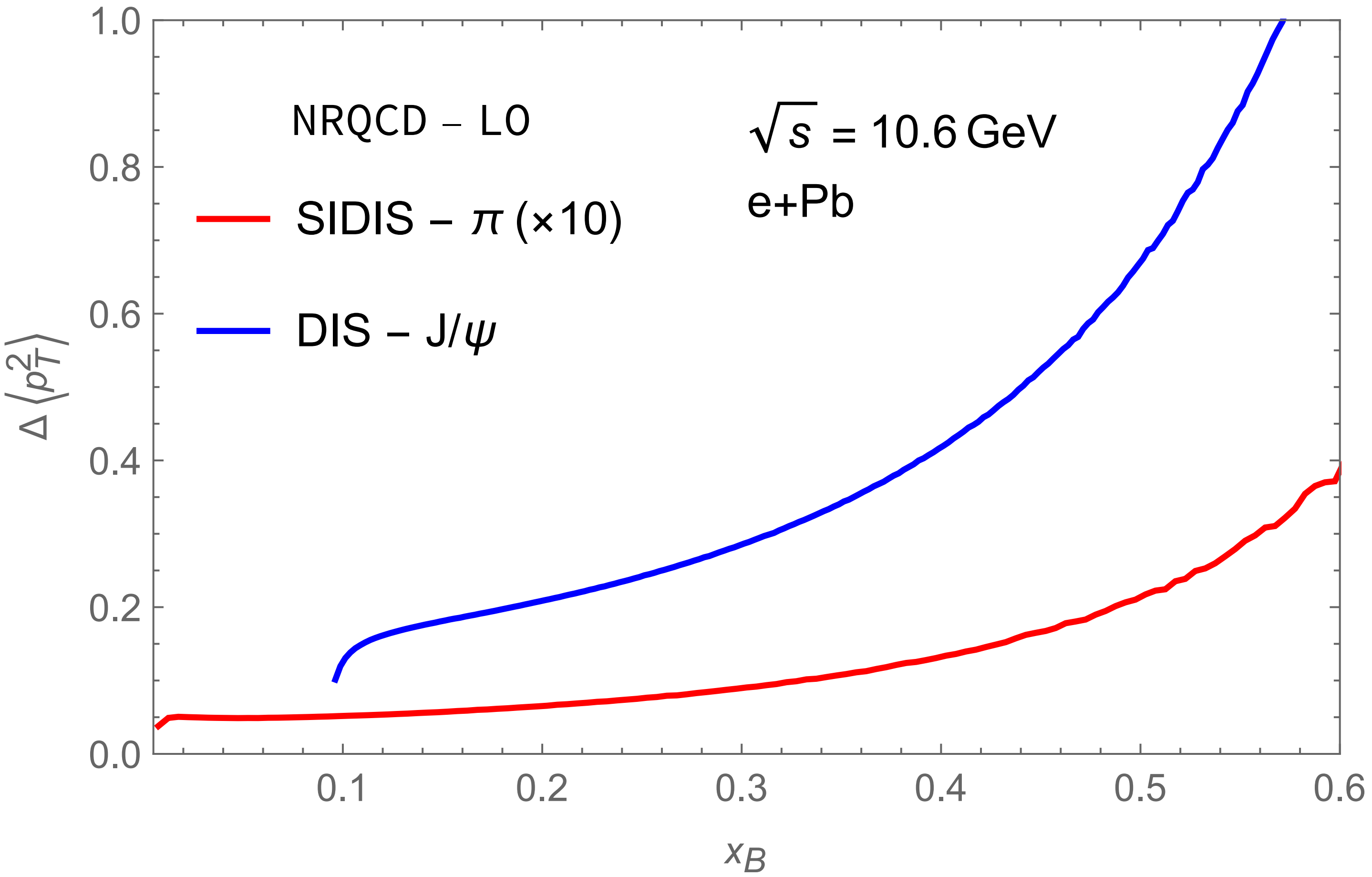
Ru, Kang, Wang, **HX**, Zhang, arXiv: 1907.11808





$$\hat{q}_0 = 0.02GeV^2/fm,\ \alpha = -0.17,\ \beta = -2.79,\ \gamma = 0.25$$

Transverse momentum broadening in EicC



Summary

Thanks for your attention!

- ❑ nuclear PDFs
  - ❖ j/psi production as a probe to nuclear PDFs in future EIC
- ❑ multiple parton interaction in cold nuclear matter
  - ❖ Incoherent multiple scattering at RHIC and LHC
  - ❖ Medium induced gluon radiation leads to parton eloss in eA
  - ❖ Medium induced flavor conversion leads to k^- enhancement in large xb and z region
- ❑ global extraction of qhat for cold nuclear matter
  - ❖ Global analysis on qhat from world data (SIDIS, DIS, DY, heavy quarkonium)
  - ❖ First time quantitative evidence of the universality of cold nuclear medium property