Nuclear effects in eA and pA collisions

Hongxi Xing
邢宏喜

QCD物理暨国家自然科学基金重大项目交流会
7月17-25, 威海

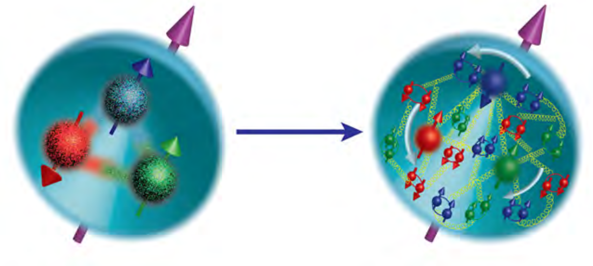
Outline

- Introduction
- Incoherent multiple scattering in pA
- Jet quenching in eA
- Transverse momentum broadening in eA and pA
- Summary

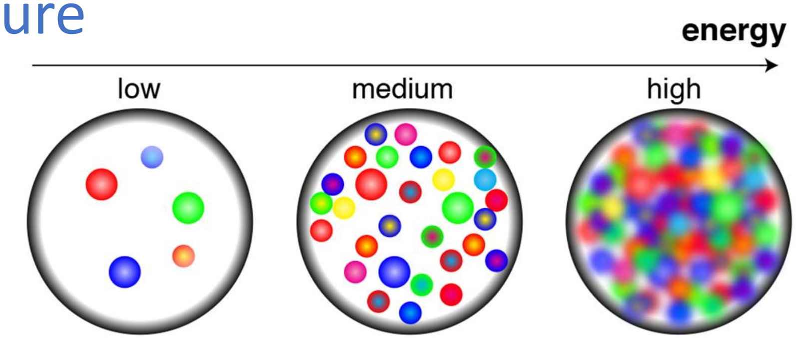
Key questions at EIC, EicC

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

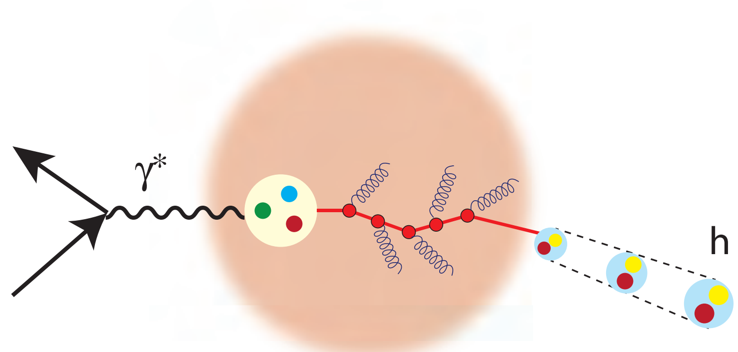
See Feng Yuan's talk



- ❑ Nuclear structure

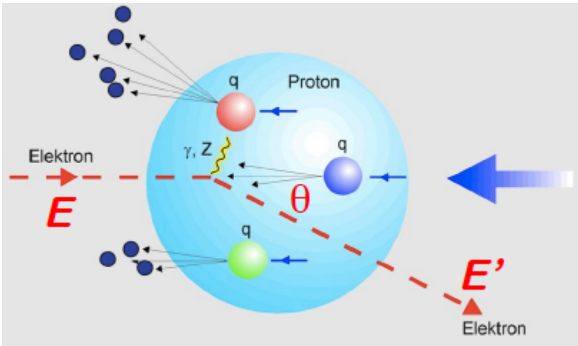


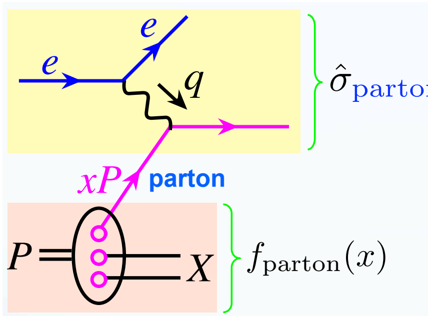
- ❑ Quarks and gluons inside nuclei



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**

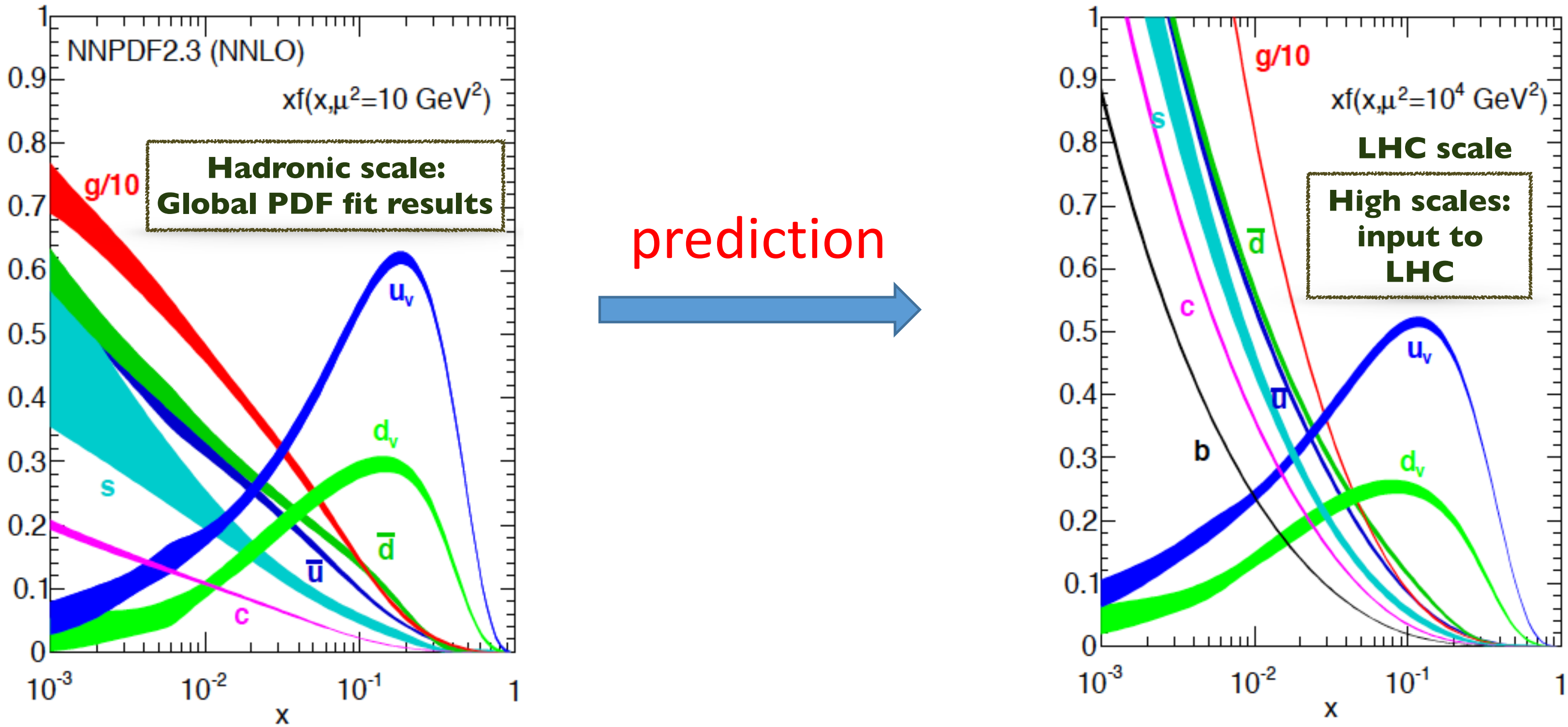
QCD factorization theorem is the corner stone of high energy physics!

The predictive power of pQCD

- Predict the proton inner structure with higher resolution scale

$$\sigma_{\text{proton}}(Q) = f_{\text{parton}}(x) \otimes \hat{\sigma}_{\text{parton}}(Q)$$

Universal (measured) **calculable**



Proton structure is encoded in the Parton Distribution Functions (PDFs)
PDFs: probability density for finding a parton in a proton with momentum fraction x.

Multiple scattering expansion

❑ Generalized factorization theorem

perturbative expansion →

Multiple scattering expansion ↓

$$\sigma^h_{phys} = \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x) \longrightarrow \text{leading twist}$$

$$+ \frac{1}{Q}\left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x) \longrightarrow \text{twist-3}$$

$$+ \frac{1}{Q^2}\left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x) \longrightarrow \text{twist-4}$$

$$+ \ldots$$

- High twist effects = power corrections = multiple scattering contributions
- What's the size of the next power corrections?

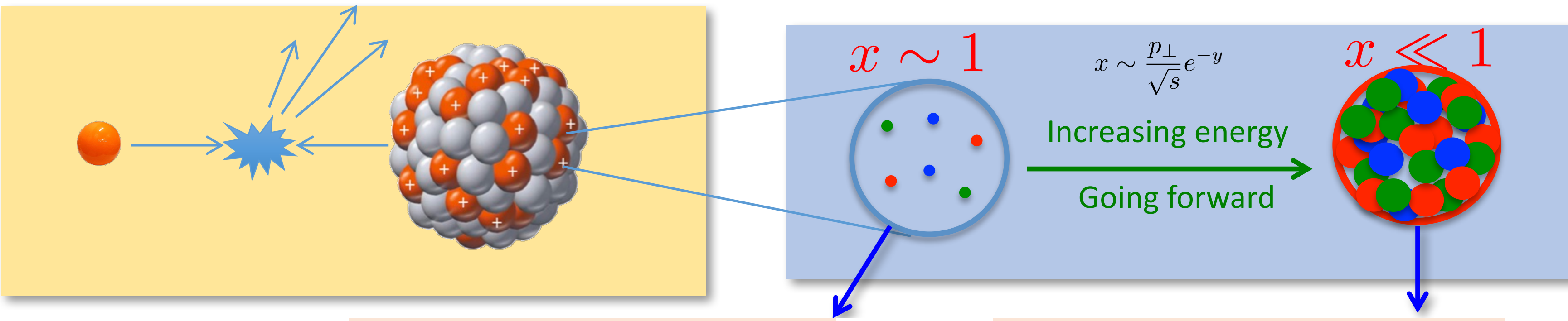
  in general small compare to leading power term
- Observables

  leading power vanishes - SSAs

  nuclear enhanced power correction $\frac{1}{Q^2} \rightarrow \frac{A^{1/3}}{Q^2}$

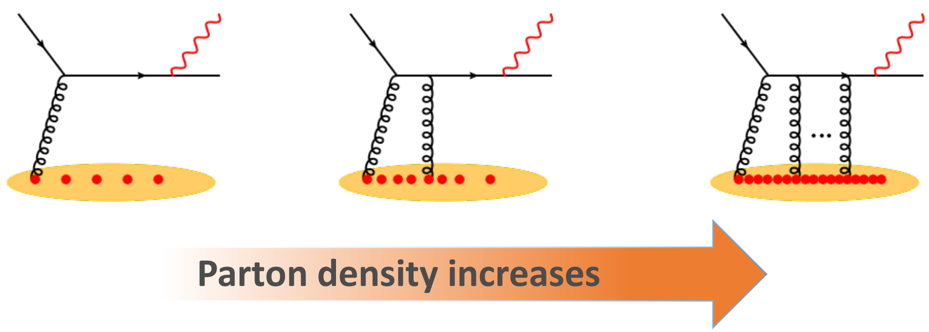
Multiple scattering in nuclear medium

❑ Multiple scattering in dilute and dense region

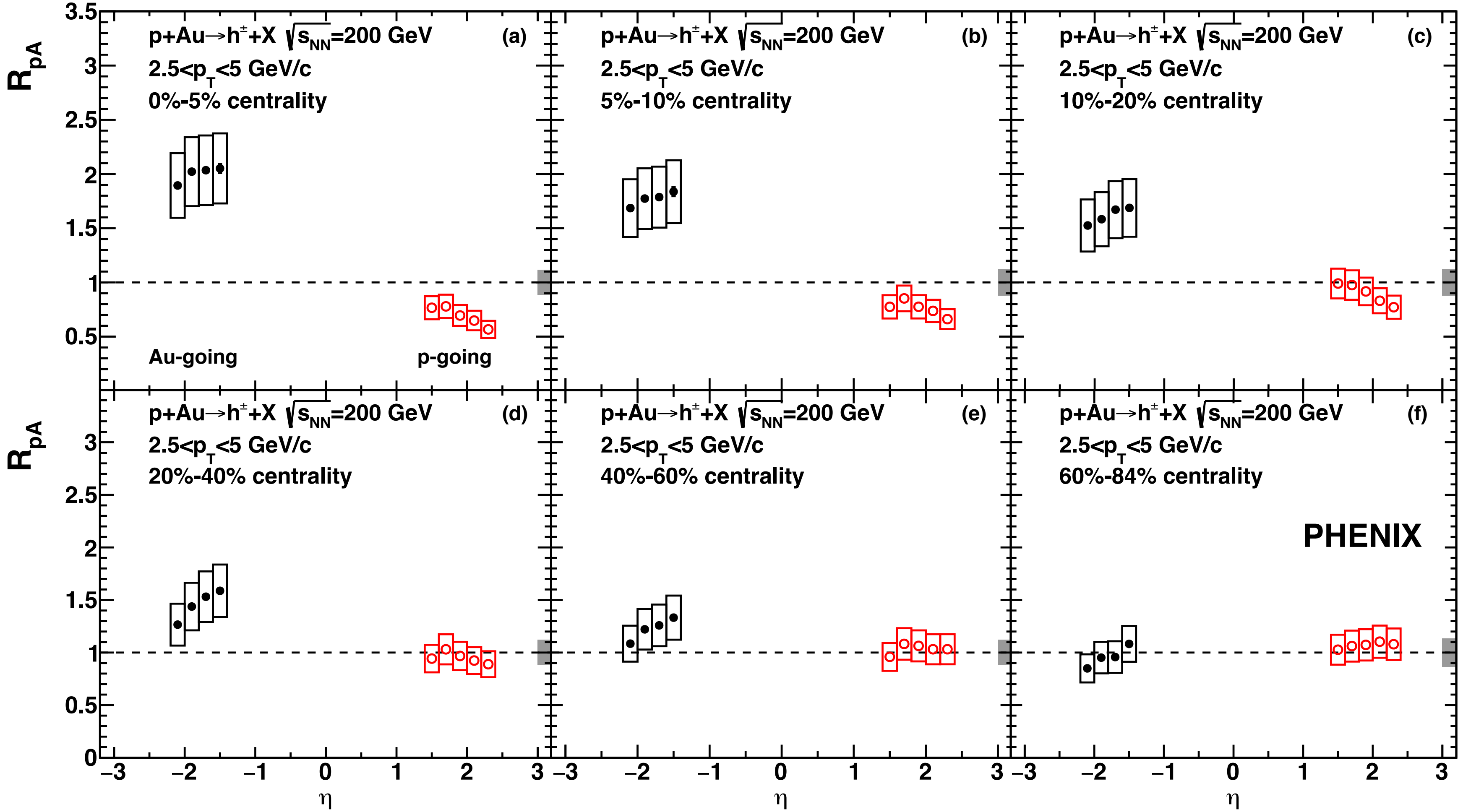


- A dilute system
- Probes interact independently

- A dense system
- Probes interact coherently



Looking forward and backward

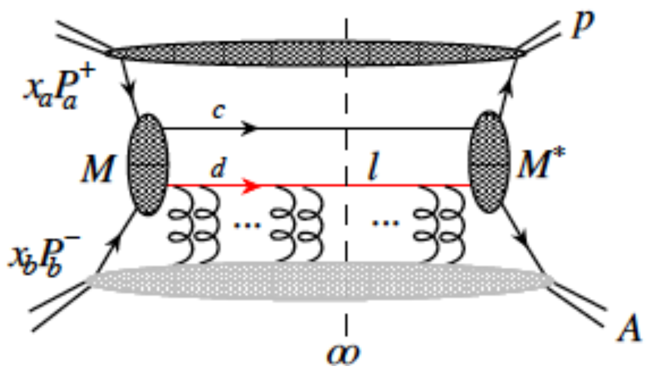


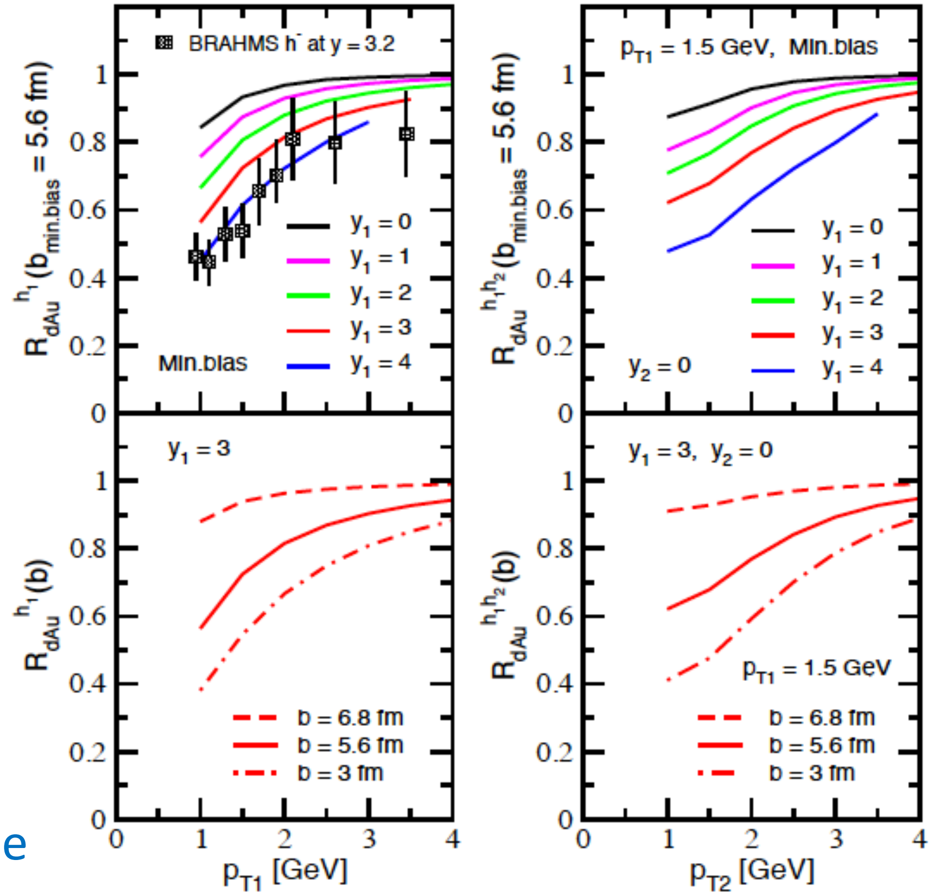
PHENIX Collaboration arXiv:1906.09928

Looking forward

- Coherent multiple scattering in small-x

I. Vitev, J. Qiu, PLB, 2006





Probing length:

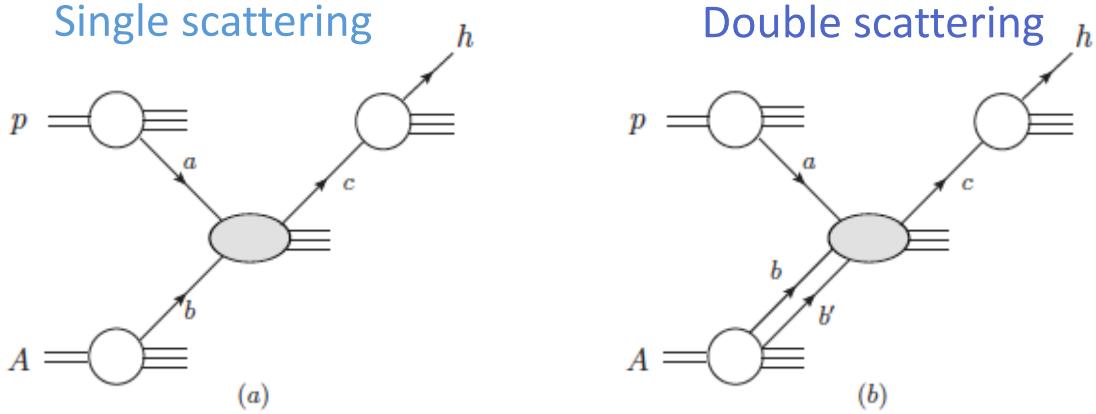
$$\frac{1}{Q} \sim \frac{1}{x_b P_b} \gg 2R\left(\frac{m}{p}\right)$$

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

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.

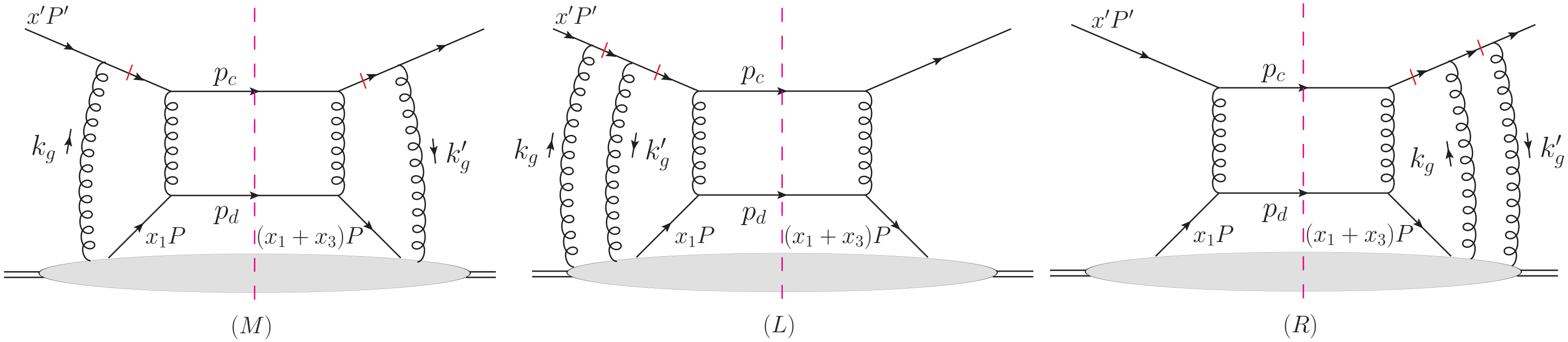
- multiple scattering expansion

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

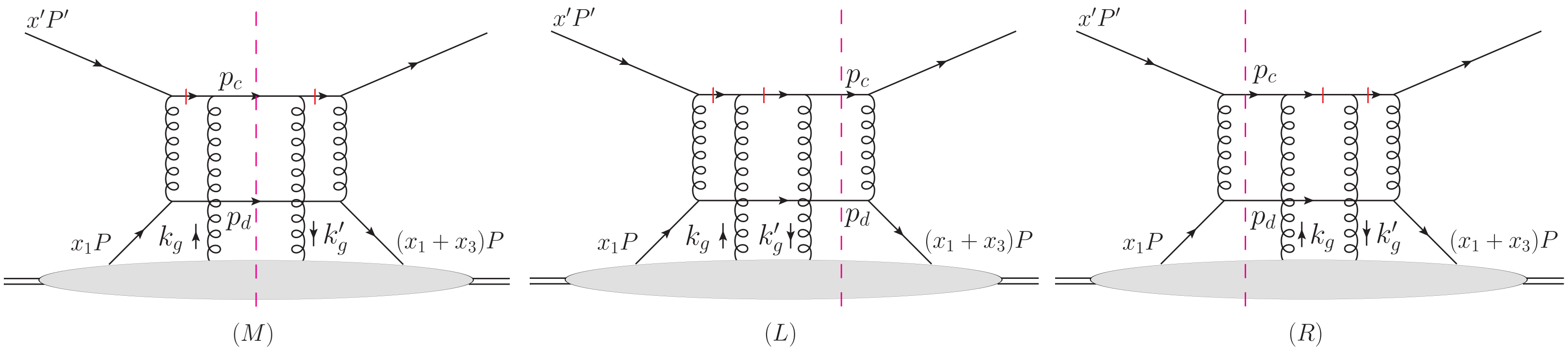
$$E_h \frac{d\sigma^{(S)}}{d^3P_h} = \frac{\alpha_s^2}{S} \sum_{a,b,c} \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) H^U_{ab\to cd}(\hat{s},\hat{t},\hat{u}) \delta(\hat{s}+\hat{t}+\hat{u})$$

- ## 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)

$$E_h \frac{d\sigma^{(D)}}{d^3P_h} \propto \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{a/p}(x') \int dx_1 dx_2 dx_3 T(x_1, x_2, x_3) \left(-\frac{1}{2} g^{\rho\sigma}\right) \left[\frac{1}{2} \frac{\partial^2}{\partial k_\perp^\rho \partial k_\perp^\sigma} H(x_1, x_2, x_3, k_\perp)\right]_{k_\perp}$$

- Final result (incoherent multiple scattering)

Kang, Vitev, **HX**, PRD 2013

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

double scattering hard factor

$$c^I = -\frac{1}{\hat{t}} - \frac{1}{\hat{s}}$$

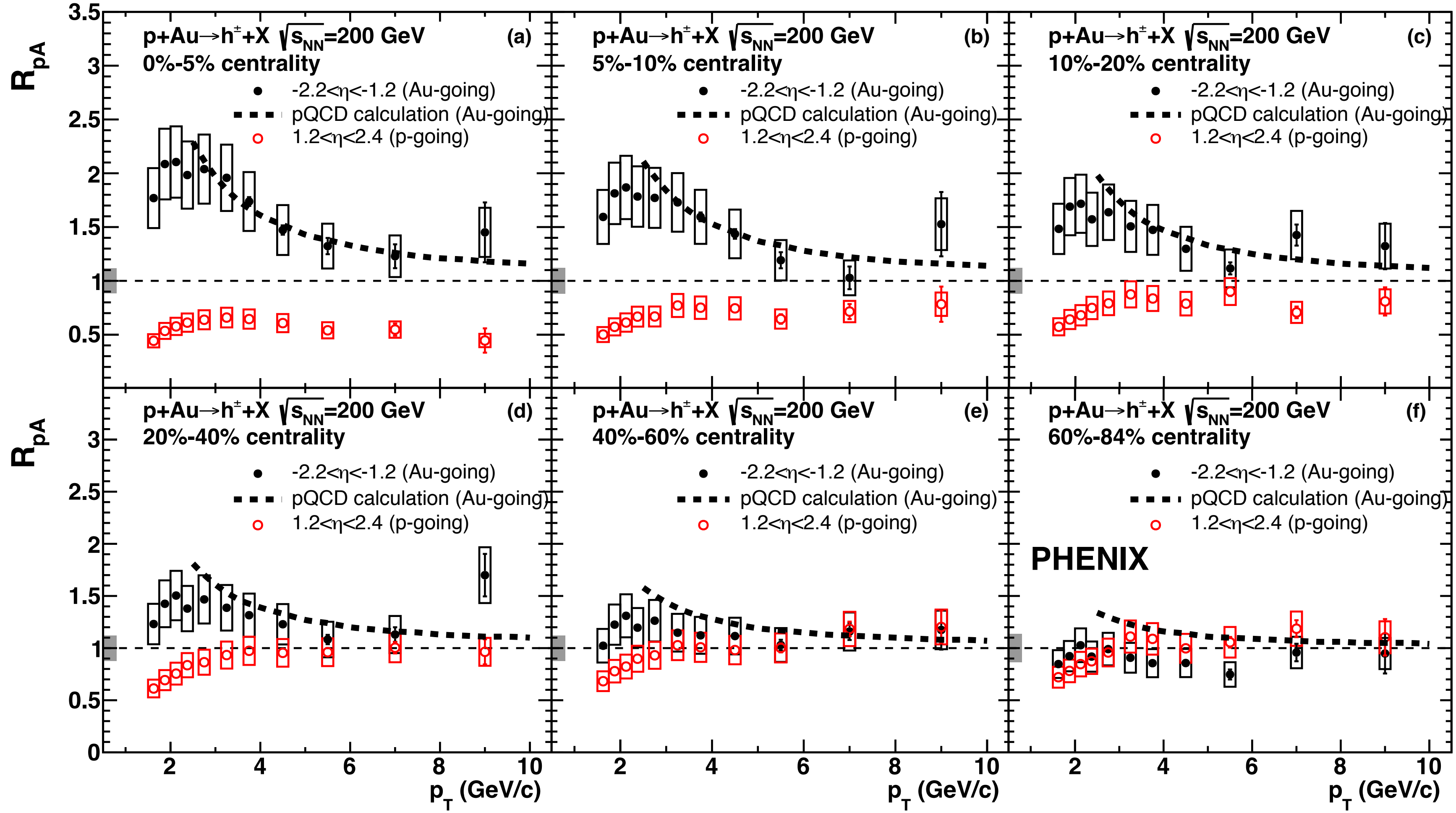
$$c^F = -\frac{1}{\hat{t}} - \frac{1}{\hat{u}}$$

$$H_{ab\to cd}^I = \begin{cases} C_F H_{ab\to cd}^U & \text{a=quark} \\ C_A H_{ab\to cd}^U & \text{a=gluon} \end{cases}$$ (a: incoming)

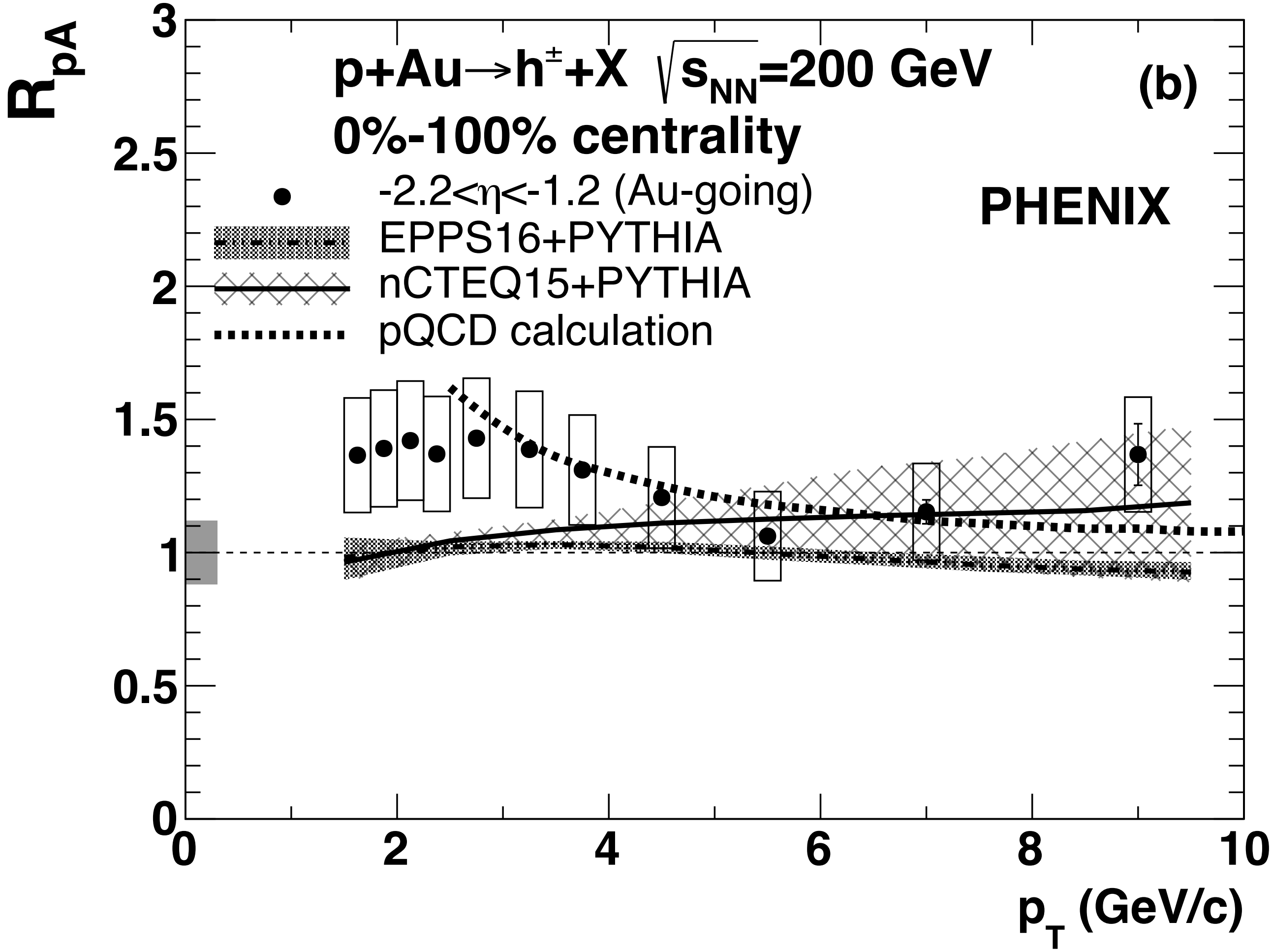
$$H_{ab\to cd}^F = \begin{cases} C_F H_{ab\to cd}^U & \text{c=quark} \\ C_A H_{ab\to cd}^U & \text{c=gluon} \end{cases}$$ (c: outgoing)

❑ Looking backward in PHENIX

Kang, Vitev, HX 2019
PHENIX, arXiv: 1906.09928



❑ Nuclear PDFs vs. incoherent multiple scattering

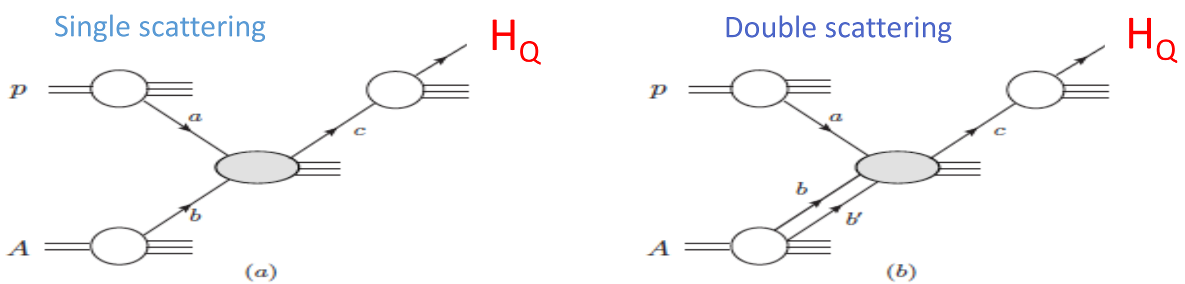


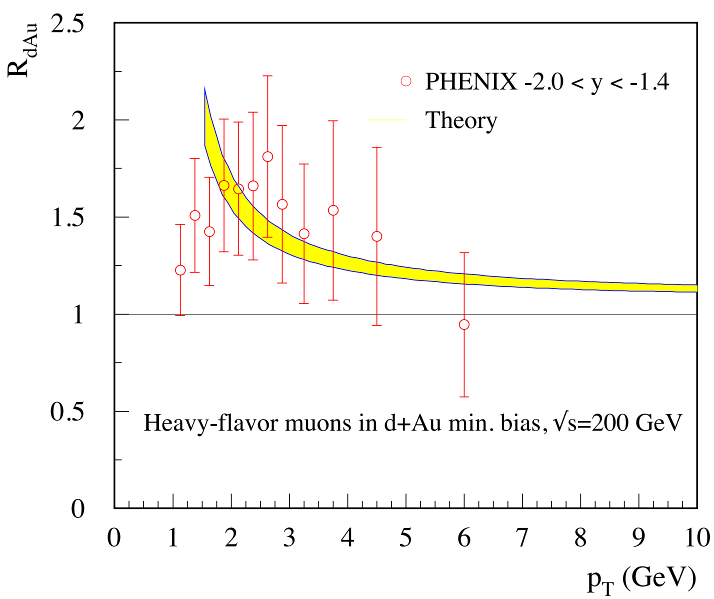
Looking backward – heavy flavor

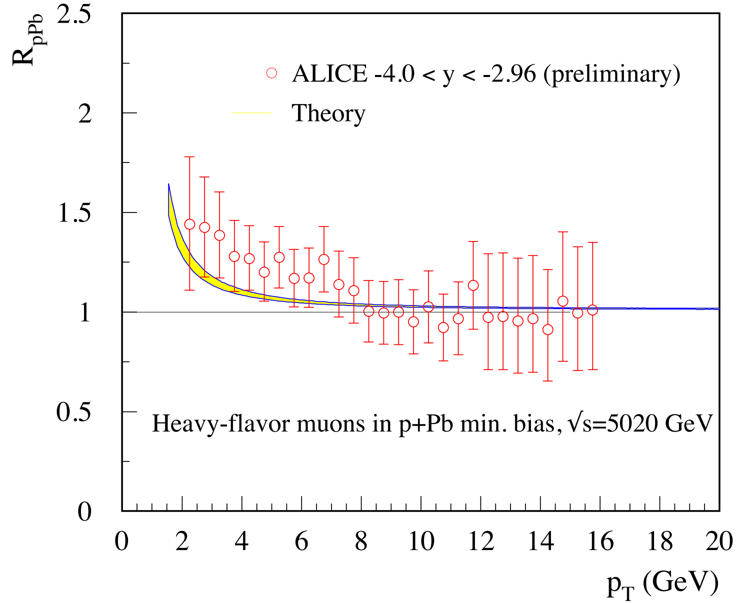
- Incoherence multiple scattering in heavy meson production

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

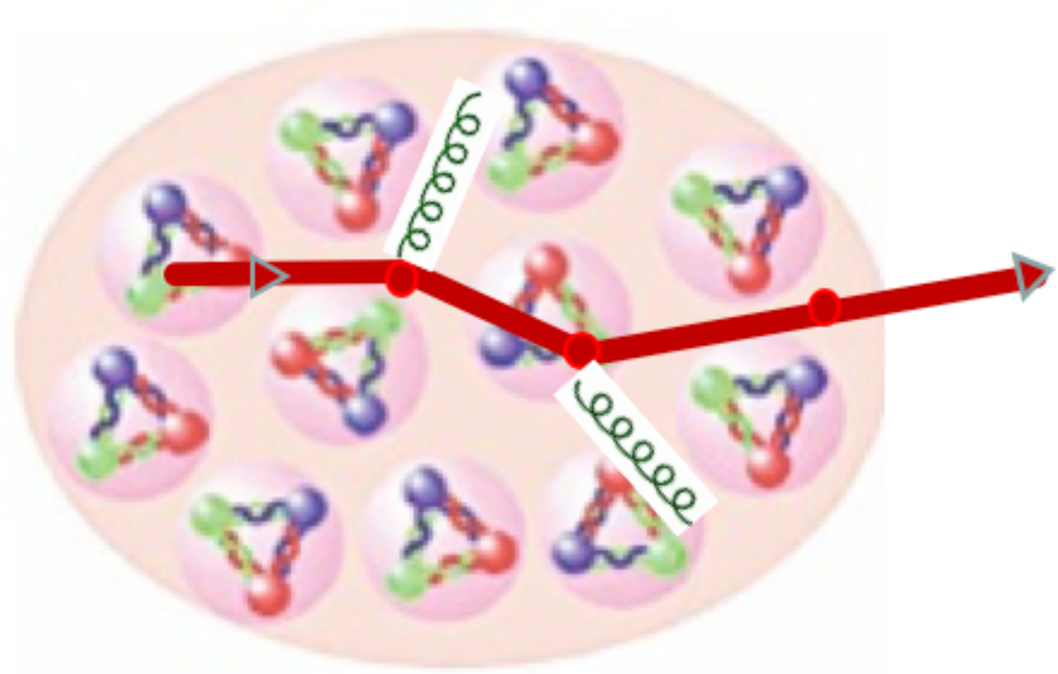
Kang, Vitev, **HX**, PLB 2015







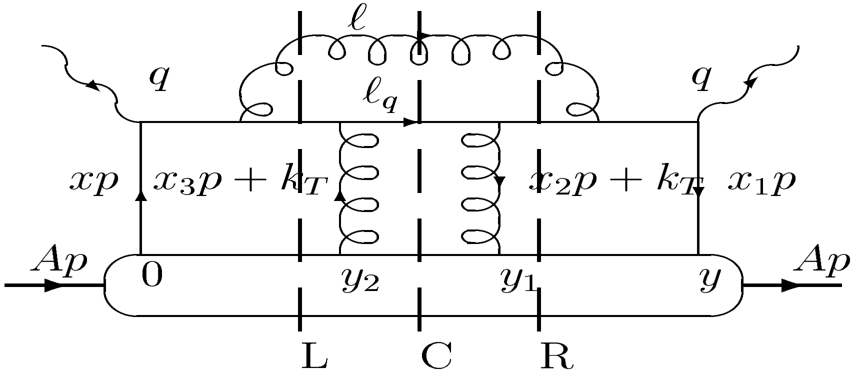
Parton energy loss in eA



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

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

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

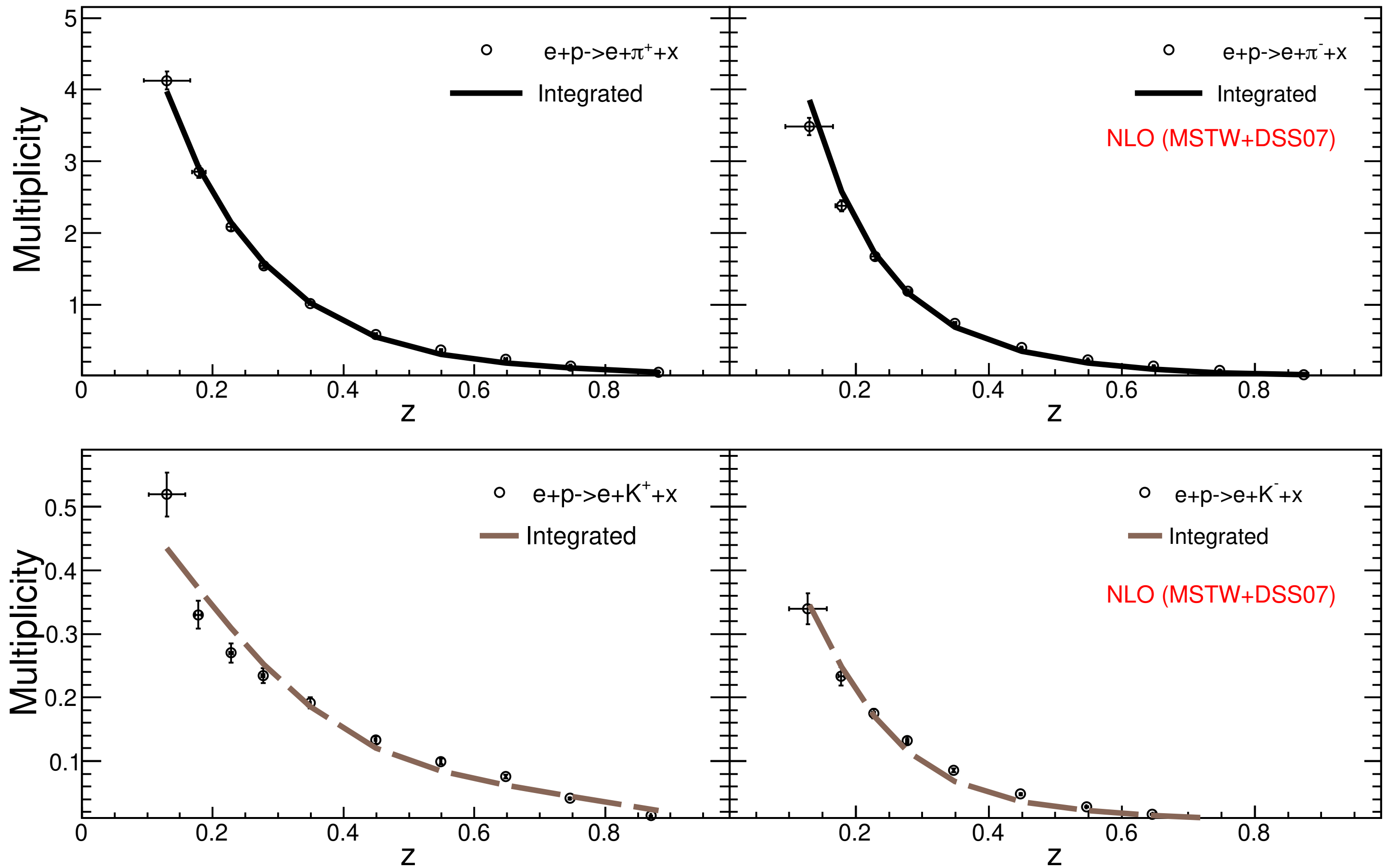
- Phenomenological extension to study jet quenching in heavy ion collisions. See talk by Guang-You Qin.

❑ Nuclear modification factor

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

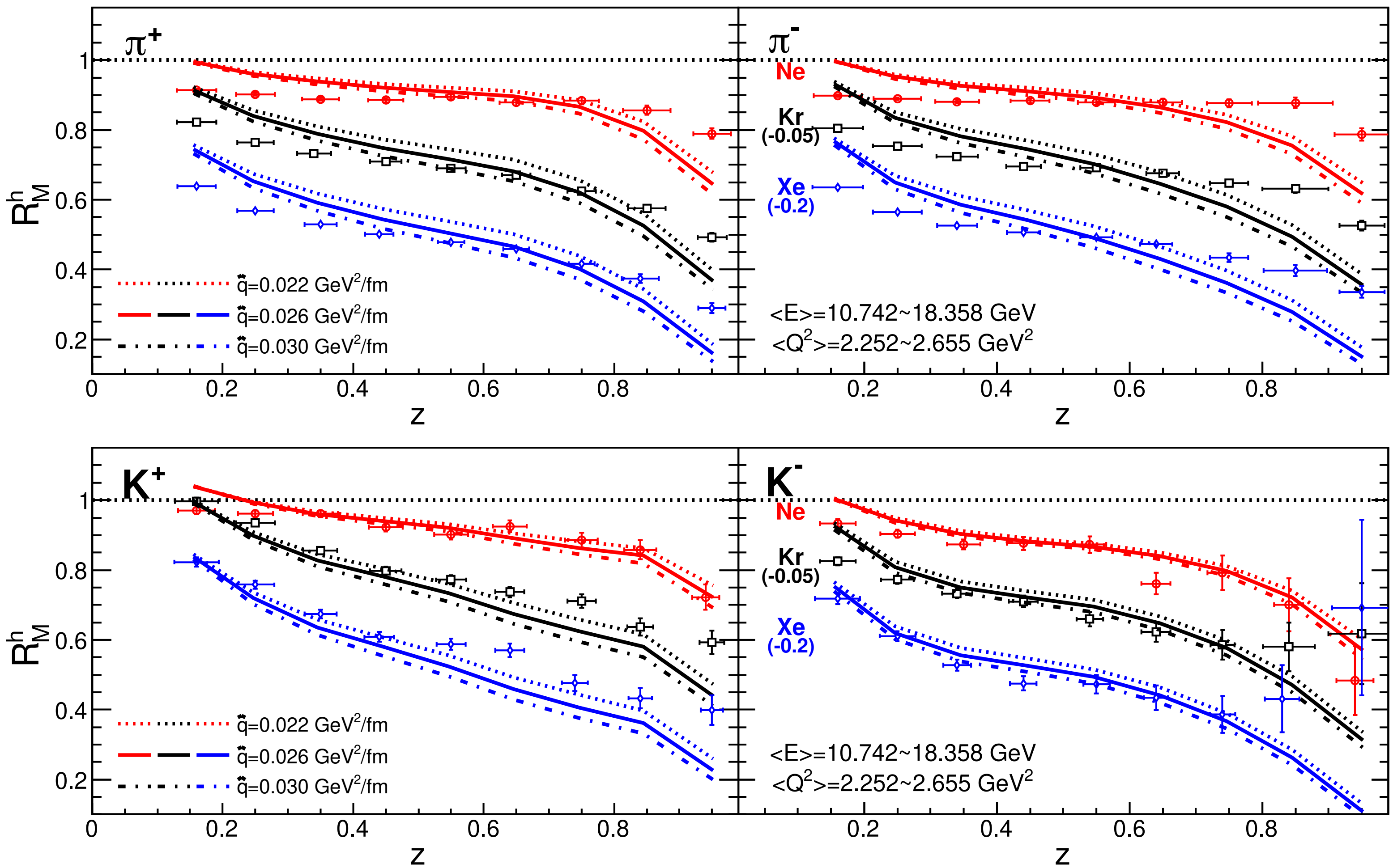
- ep baseline at NLO

Chang, Deng, Wang, **HX**, et al. 2019, 1908.xxxxx



- Medium effect in HERMES

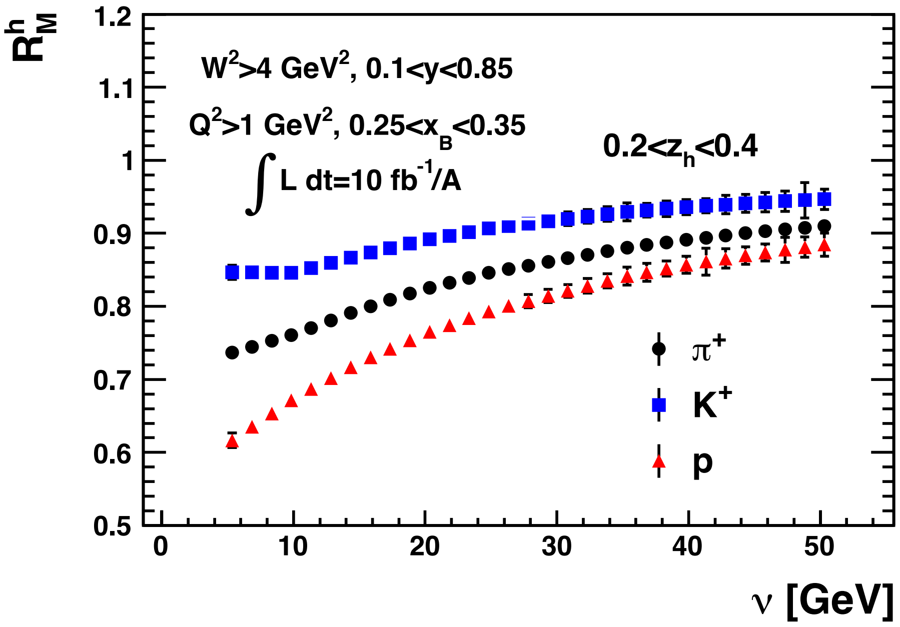
Chang, Deng, Wang, **HX**, et al. 2019, 1908.xxxxx

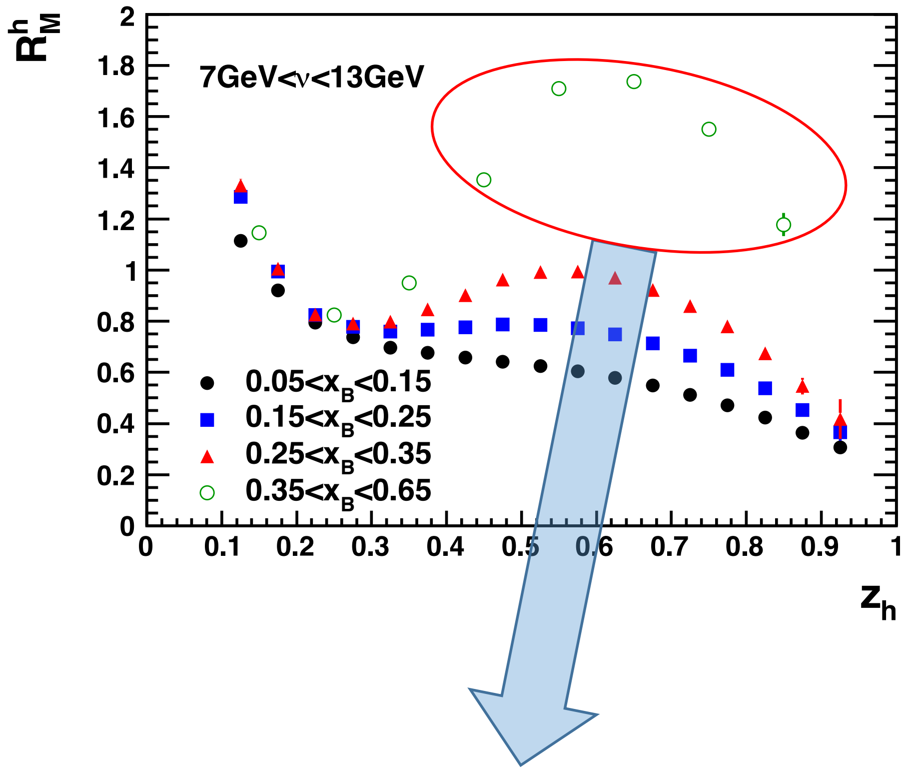


NLO ep baseline + parton energy loss

Predictions for EicC

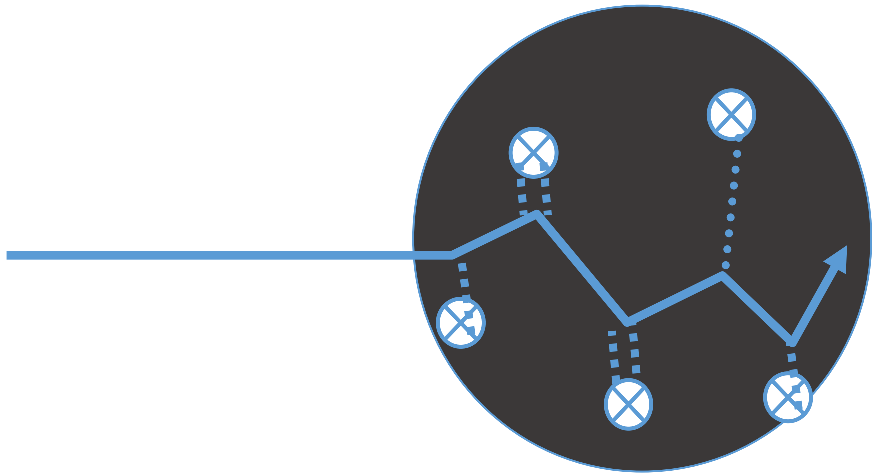
❑ Searching for Eloss and flavor conversion





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

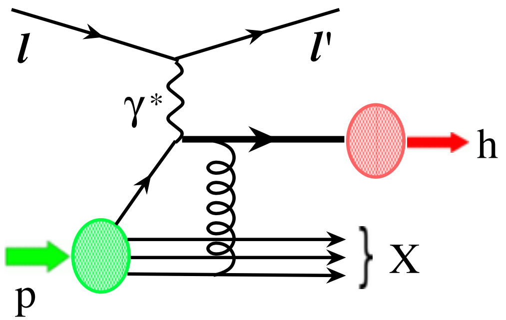
Transverse momentum broadening in eA and pA



A good observable to probe nuclear medium

❑ Transverse momentum broadening

Guo, 1998; Guo, Qiu 2000



- Sensitive to nuclear quark-gluon quantum correlation

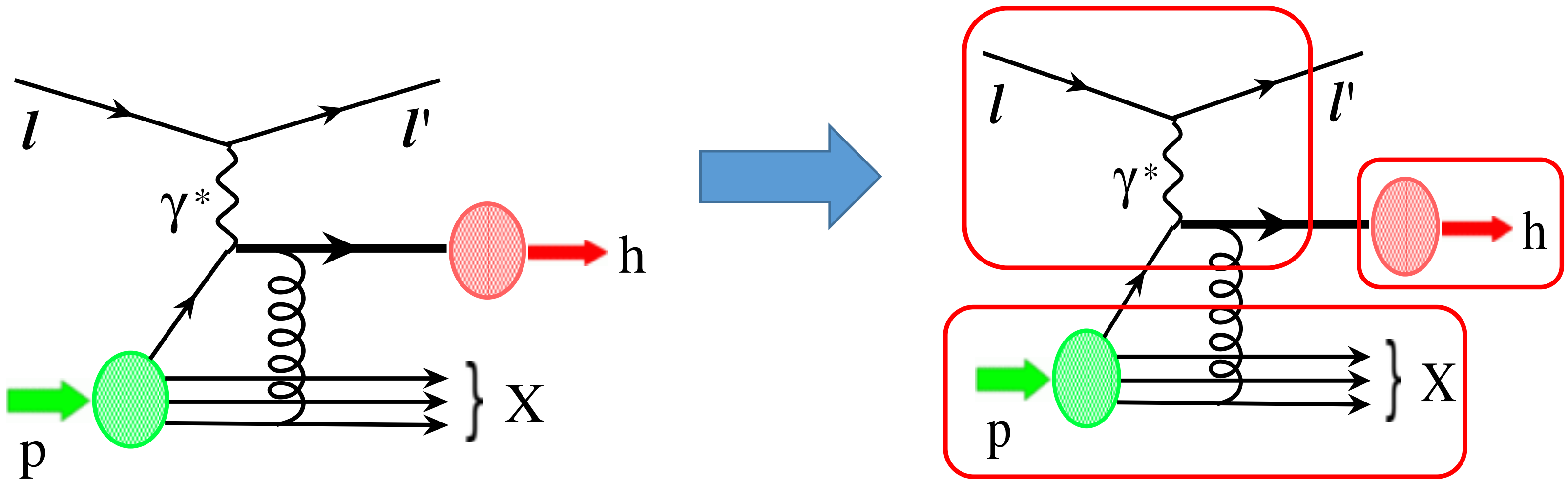
$$\Delta\langle \ell_{hT}^2\rangle = \langle \ell_{hT}^2\rangle_{eA} - \langle \ell_{hT}^2\rangle_{ep} = \left(\frac{4\pi^2\alpha_s}{N_c} z_h^2\right) \frac{\sum_q e_q^2 T_{qg}(x_B,0,0) D_{h/q}(z_h)}{\sum_q e_q^2 f_{q/A}(x_B) D_{h/q}(z_h)}$$

- ❖ A direct probe of the nuclear quark-gluon quantum correlation
- ❖ Characterize the fundamental nuclear QCD structure
- ❖ Phenomenological applications to investigate properties of quark-gluon plasma

PRL 112, 102001 (2014) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2014

Next-to-Leading Order QCD Factorization for Semi-Inclusive Deep Inelastic Scattering at Twist 4

Zhong-Bo Kang,[1] Enke Wang,[2] Xin-Nian Wang,[2,3] and Hongxi Xing[1,2,4]



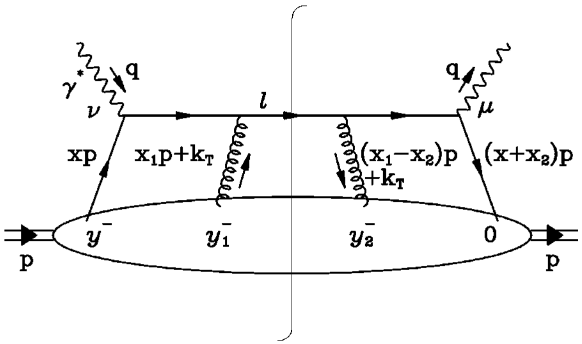
✓ **First time proof of QCD factorization theorem for double scattering at NLO**

$$\frac{d\langle \ell_{hT}^2 \sigma \rangle}{dz_h} \propto D_{q/h}(z,\mu^2) \otimes H^{LO}(x,z) \otimes T_{qg}(x,0,0,\mu^2)$$
$$+ \frac{\alpha_s}{2\pi} D_{q/h}(z,\mu^2) \otimes \boxed{H^{NLO}(x,z,\mu^2)} \otimes T_{qg(gg)}(x,0,0,\mu^2)$$

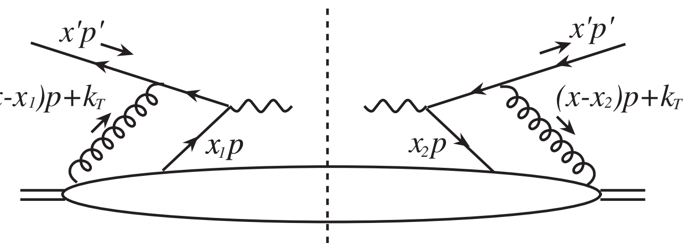
Multiple scattering hard probe and medium properties can be factorized!!!

Transverse momentum broadening in CNM

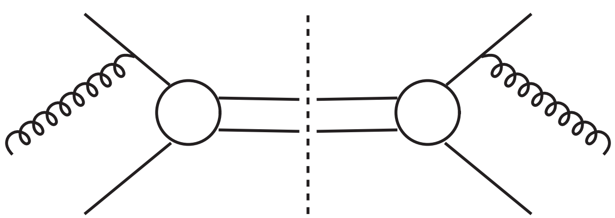
- Transverse momentum broadening in eA and pA collisions



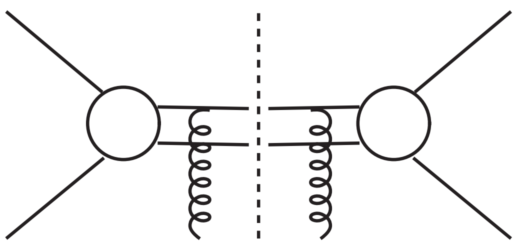
SIDIS (LO, NLO)
Kang, Wang, Wang, Xing 2014



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



Heavy quarkonium
Initial state multiple scattering
(CEM, NRQCD)



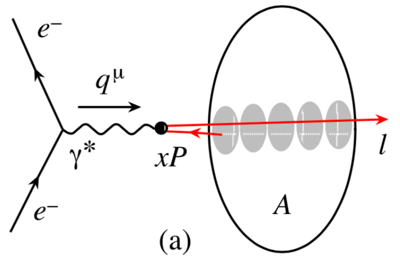
Heavy quarkonium
Final state multiple scattering
(CEM, NRQCD)

Kang, Qiu, 2008,2012

- Dynamical shadowing – small x

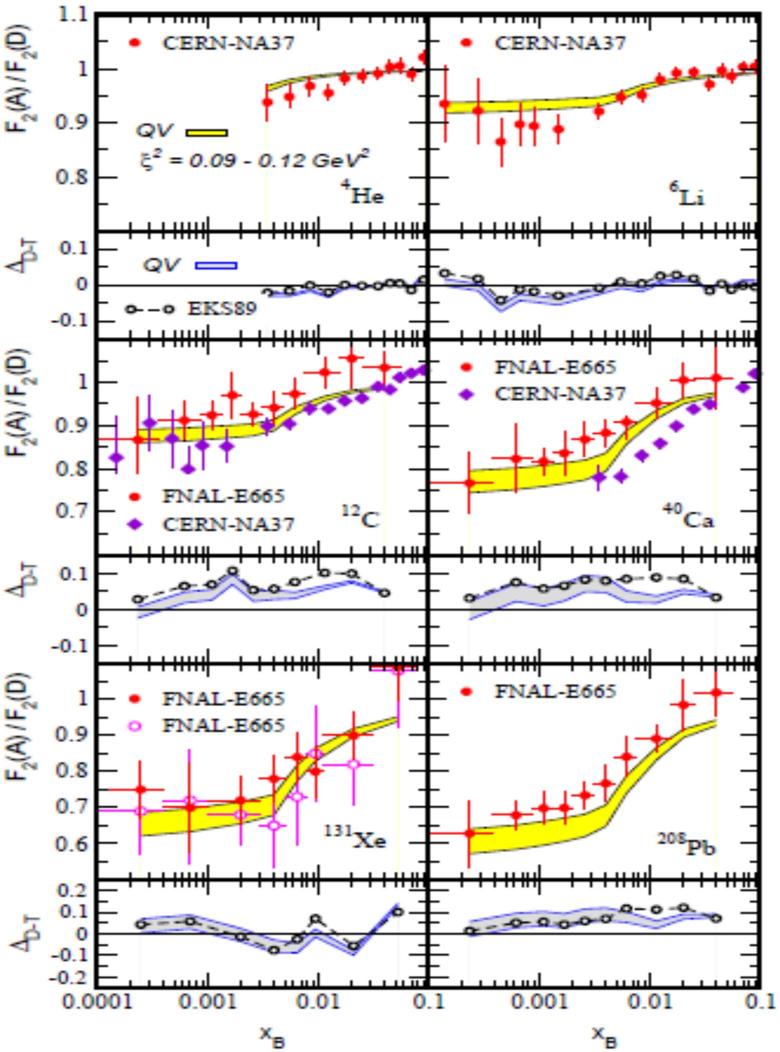
Qiu, Vitev , PRL, 2004

Coherent multiple scattering



Summing nuclear enhanced multiple scattering

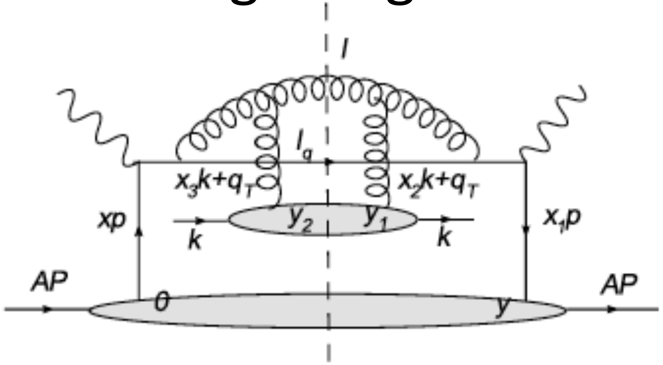
$$F_T^A(x,Q^2) \approx \sum_{n=0}^{N} \frac{A}{n!}\left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n \frac{d^n F_T^{(\mathrm{LT})}(x,Q^2)}{d^n x}$$
$$\approx A\, F_T^{(\mathrm{LT})}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2\right), \qquad (10)$$



❑ Parametrization of jet transport coefficient

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

- 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

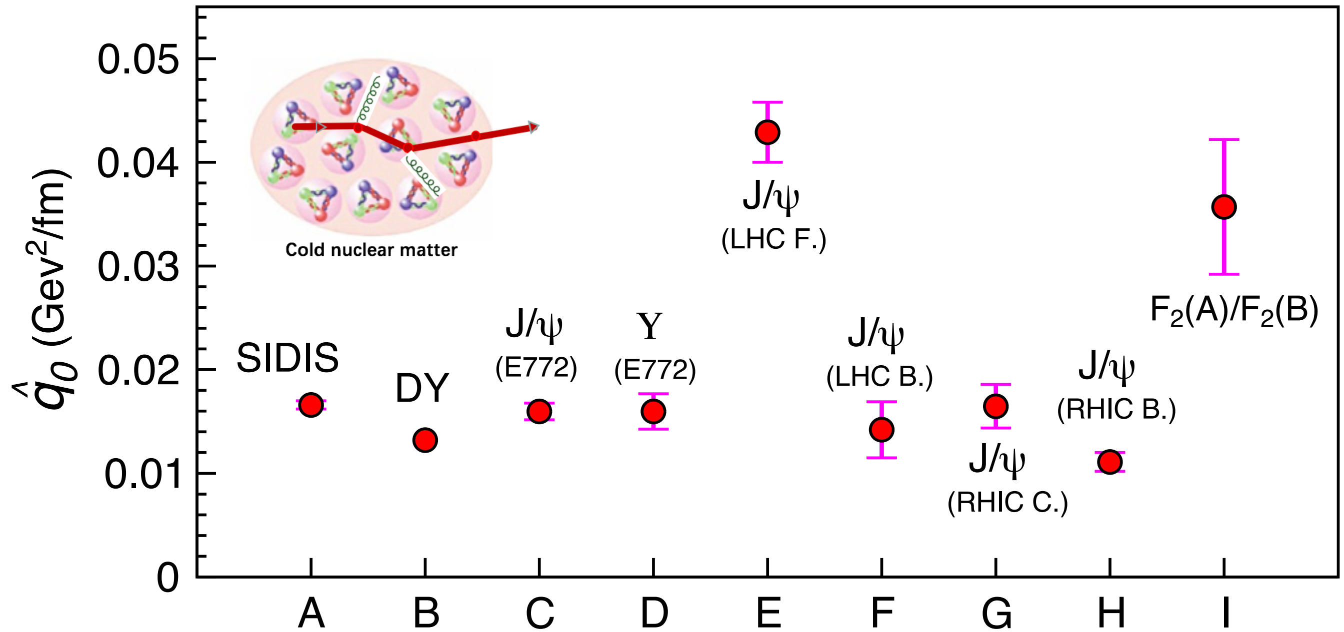
Small-x saturation

Large-x power correction

Scale dependence

Global analysis of the world data

- Non-universality of medium property (jet transport parameter) ?



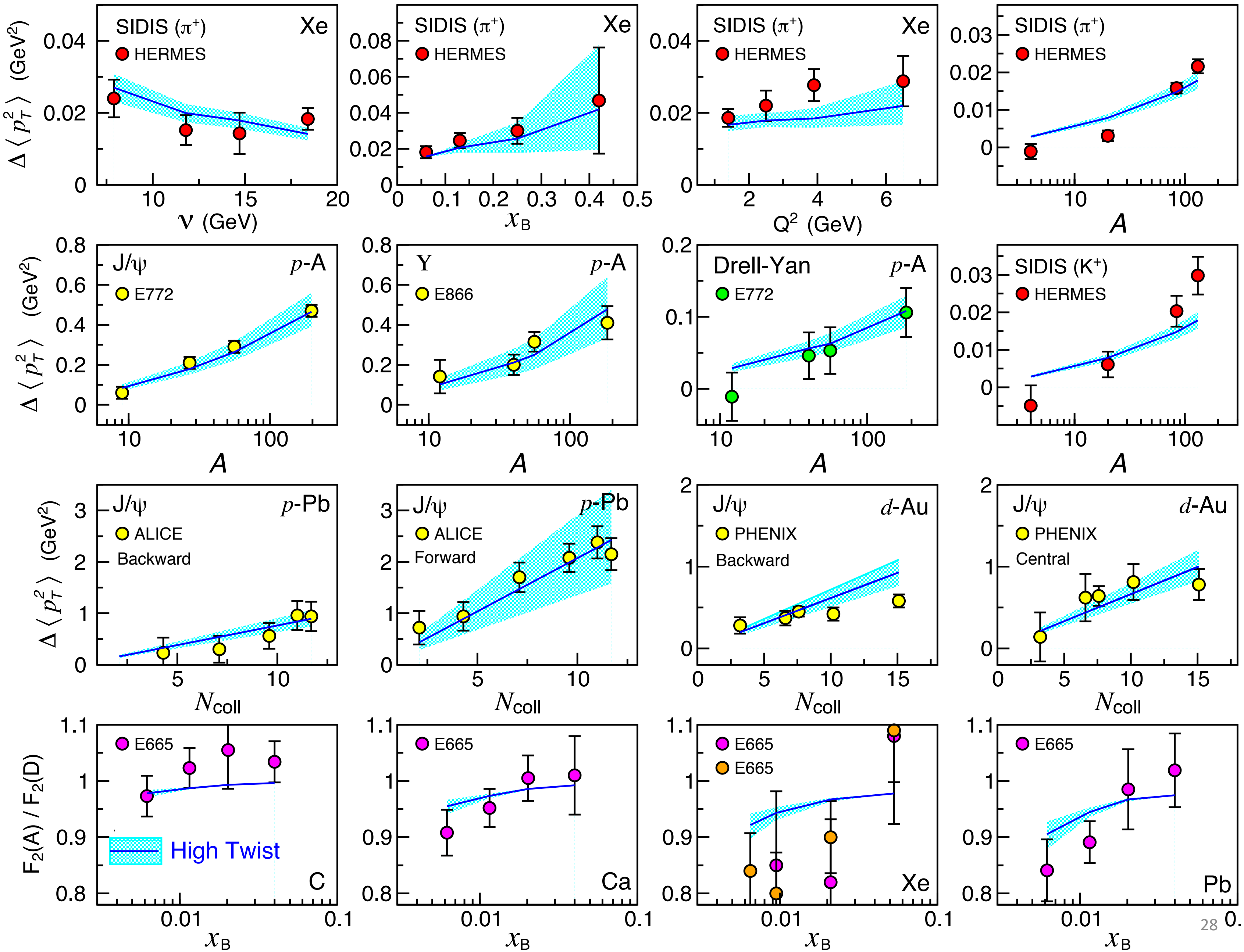
Peng Ru, **HX**, BW Zhang, ZB Kang, E Wang 2019, 1907.xxxxx

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

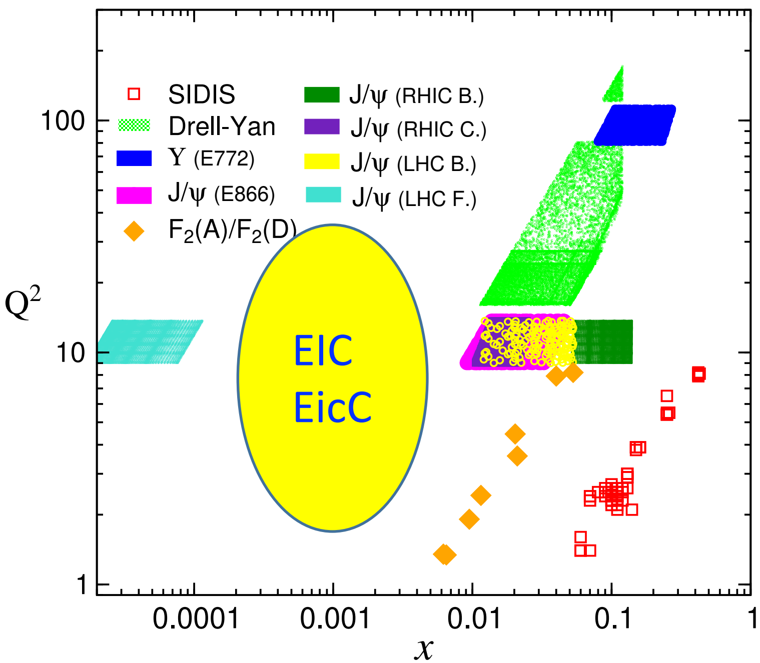
Test as usual: $\alpha = \beta = \gamma = 0$

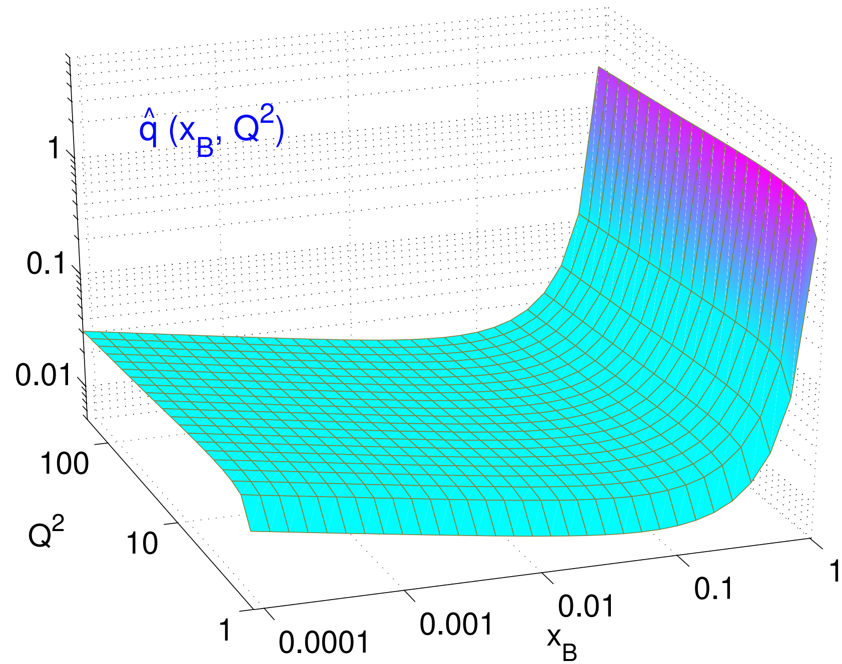
Inconsistent qhat from different process.

❑ Global analysis of world data



❑ Kinematic coverage and fitted qhat

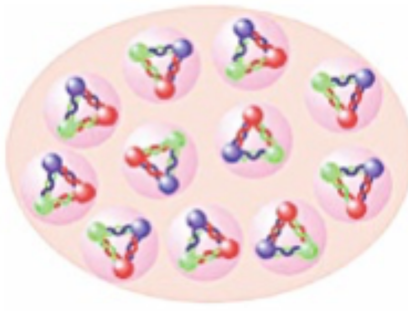


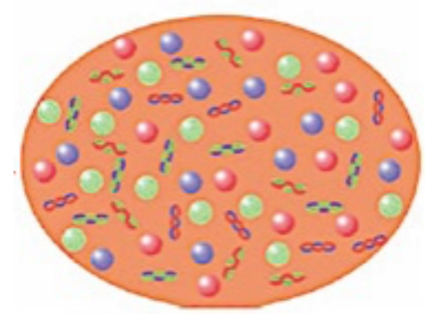


$$\hat{q}_0 = 0.022 GeV^2/fm,\ \alpha = -0.17,\ \beta = -2.73,\ \gamma = 0.25$$

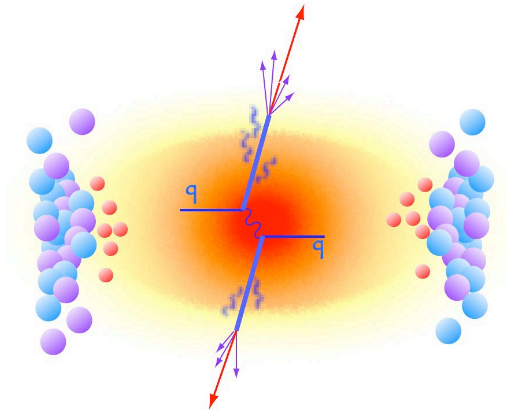
Phenomenological extension to QGP

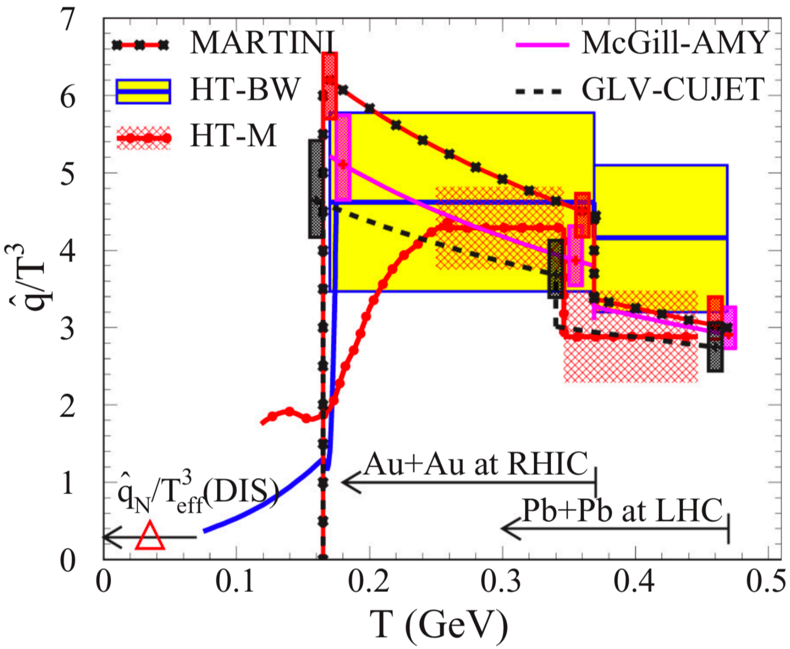
- Jet transport in hot dense medium





$$R_{AA}(p_T) = \frac{\langle N_{coll} \rangle^{-1} d\sigma^{AA} / dp_T}{d\sigma^{pp} / dp_T}$$





Summary

Thanks for your attention!

- Incoherent multiple scattering
  - Nuclear enhancement in backward rapidity in pA at RHIC and LHC
- Parton energy loss in cold nuclear matter
  - Medium induced gluon radiation leads to parton eloss in eA
  - Medium induced flavor conversion leads to k- enhancement in large xb and z region
- Transverse momentum broadening
  - Global analysis on qhat from world data (SIDIS, DIS, DY, heavy quarkonium)
  - First time quantitative evidence of the universality of cold nuclear medium property