Probing nucleon and nuclear structure at electron ion colliders

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第18届全国中高能核物理大会
6月22-25, 长沙

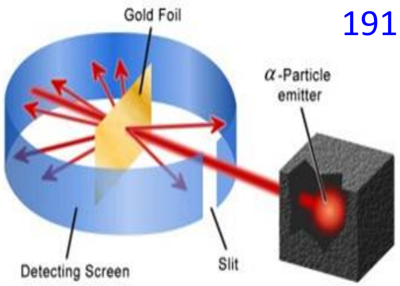
Outline

- Key questions in exploring nucleon/nuclear structure
  - How are the quarks and gluons distributed, and their interactions inside the nucleon/nuclei?
  - Sensitive observables: DIS, SIDIS, exclusive DIS, diffractive DIS…
- Theoretical tools
  - QCD factorization
  - Probe nucleon and nuclear structure at NLO
- Summary

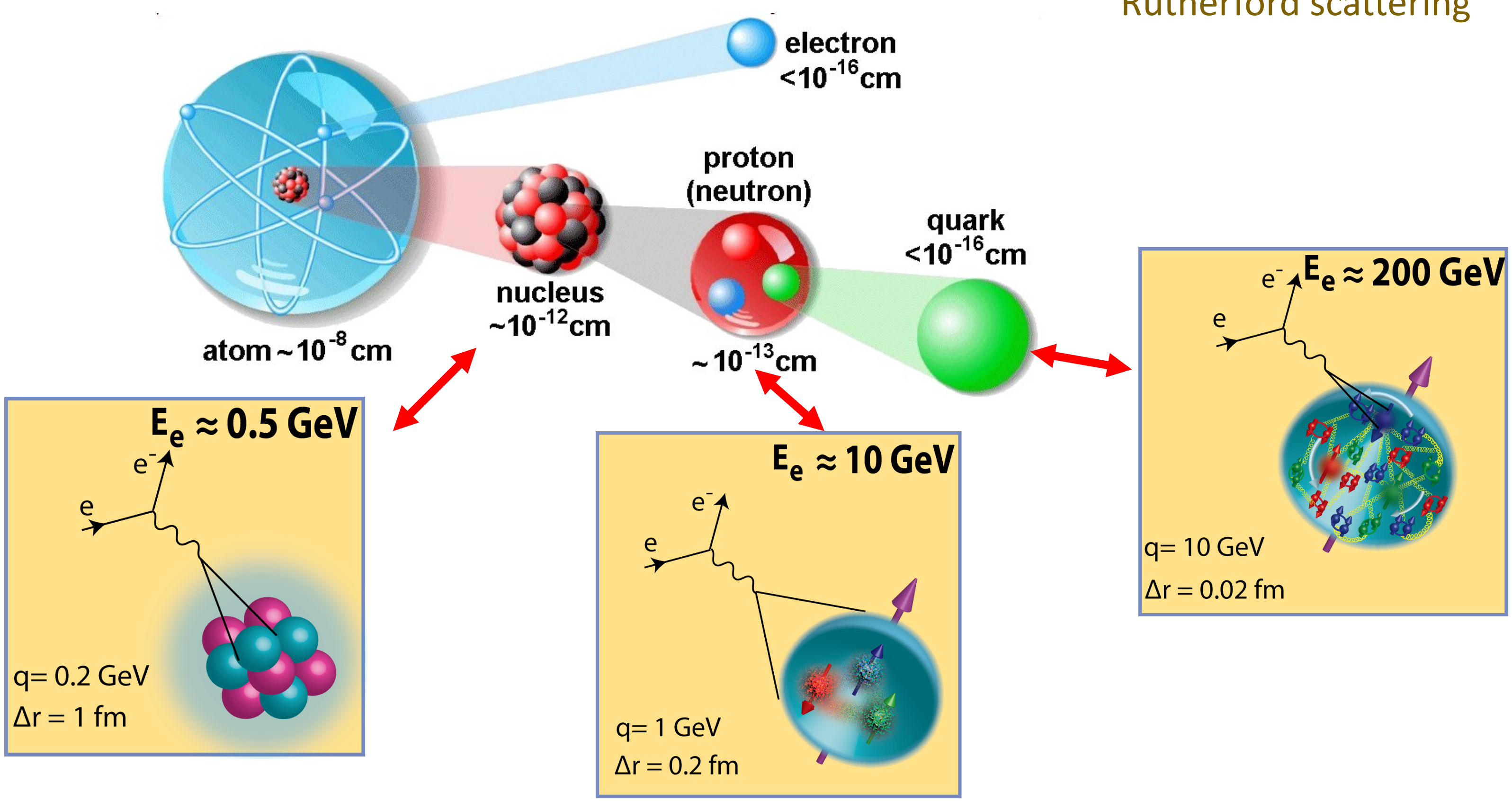
Revolution in our view of nuclear structure

- Long history in exploring the structure of matter
  - Atom: Dalton 1803
  - Nucleus: Rutherford 1911
  - Neutron: Chadwick 1932
  - Quark model: Gell-Mann and Zweig 1964
  - Parton: Feynman 1969
  - …

1911

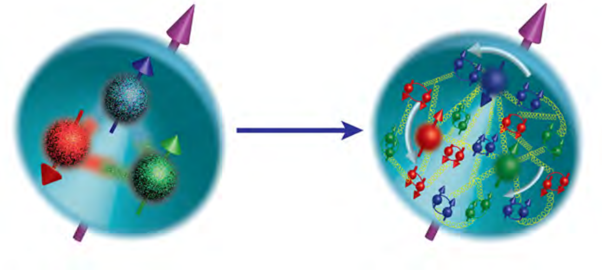


Rutherford scattering

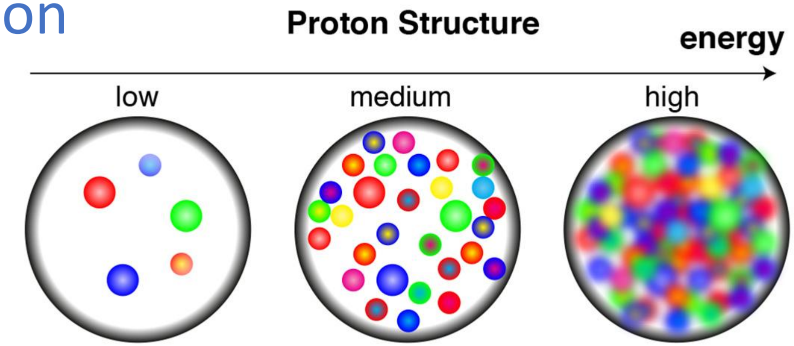


Key questions in modern era

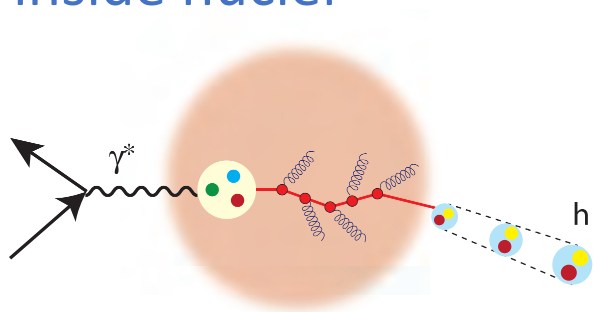
- How quarks and gluons distribute their momentum and spin inside the nucleon?



- Gluon saturation



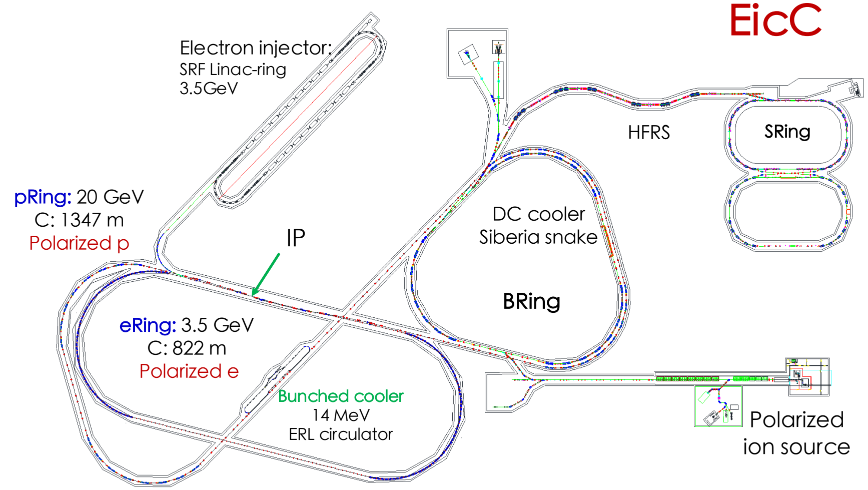
- Quarks and gluons inside nuclei

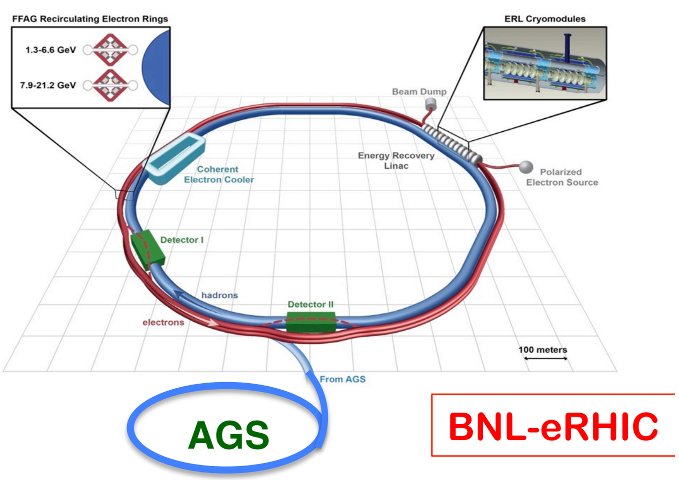


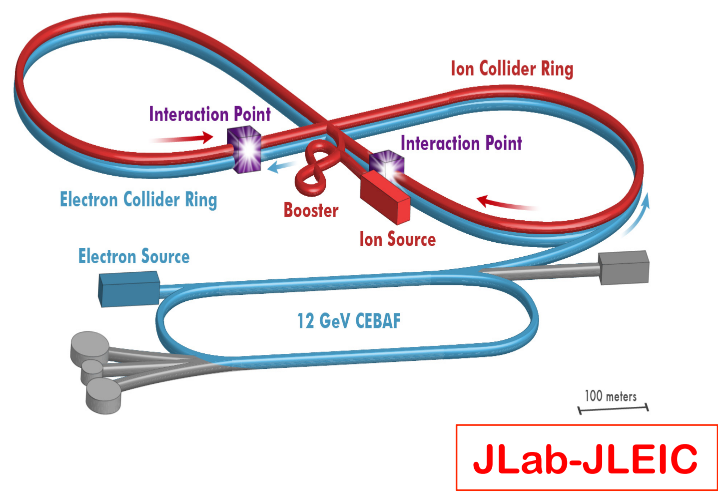
❑ Experimental facilities

See talk by Liang Yutie on Tuesday

JLab: electron-proton scattering (~GeV)



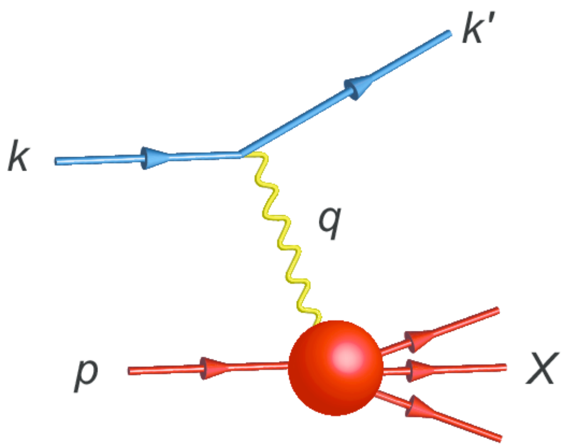




Future Electron-Ion Collider

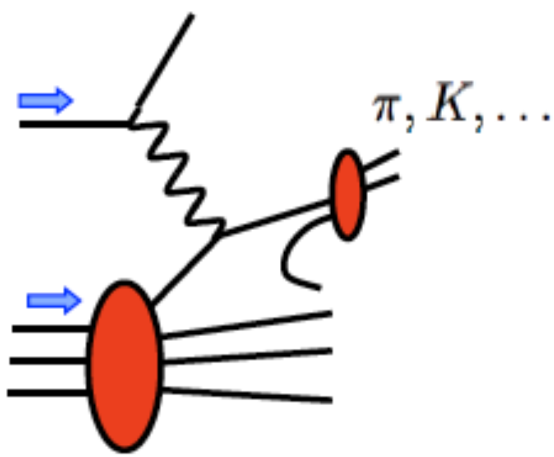
Observables in Electron Ion Collisions

❑ Deep inelastic scattering



- Only the scattered electron is detected.
- One hard scale, sensitive to the sum of PDFs, hard to probe flavor dependence.

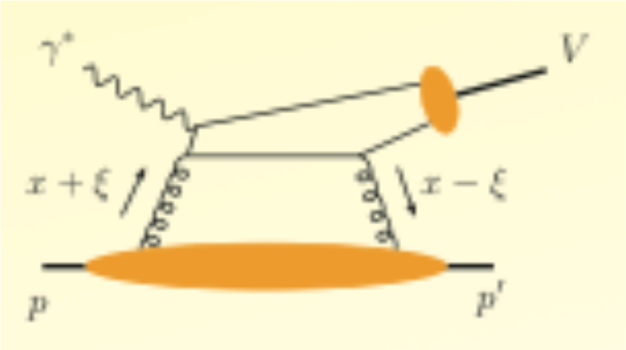
❑ Semi-inclusive deep inelastic scattering



- A specified hadron is identified.
- Two natural scales, sensitive to PDFs, using particular final state hadron to tag initial state parton flavor, and TMD.

Observables in Electron Ion Collisions

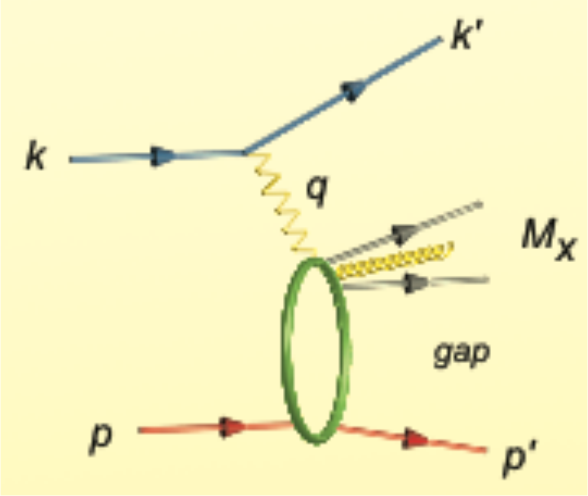
❑ Exclusive process



$$e + p \rightarrow e' + p' + V(J\psi)$$

- All final state particles are detected, the scattered proton remains intact.
- Sensitive to generalized parton distributions – 3D imagine of nucleon structure.

❑ Diffractive scattering



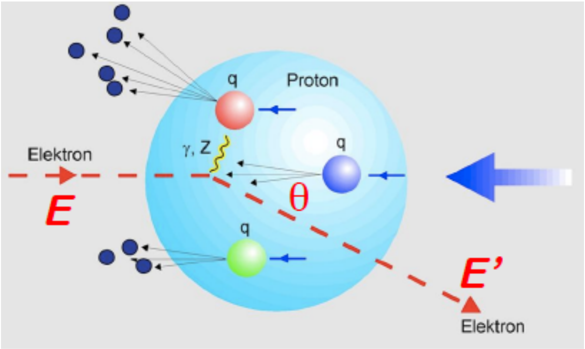
$$e + p \rightarrow e' + p' + X$$

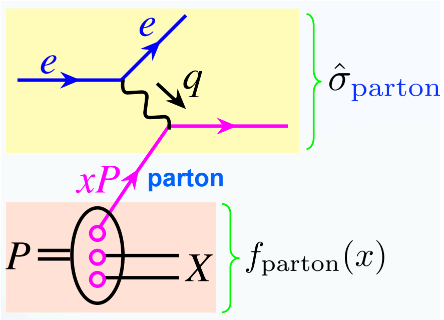
- The scattered proton remains intact.
- Color neutral exchange between beam electron and proton
- Large rapidity gap between X and the scattered proton.
- Sensitive to gluon saturation.

QCD factorization theorem

❑ Factorization in deep inelastic scattering

See talk by X. Ji tomorrow





- 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** ↑

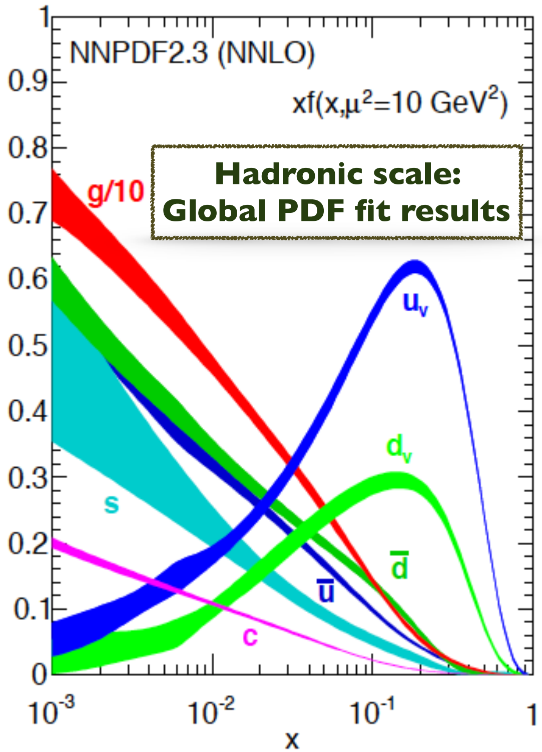
QCD factorization theorem is the corner stone of high energy physics!

The predictive power of pQCD

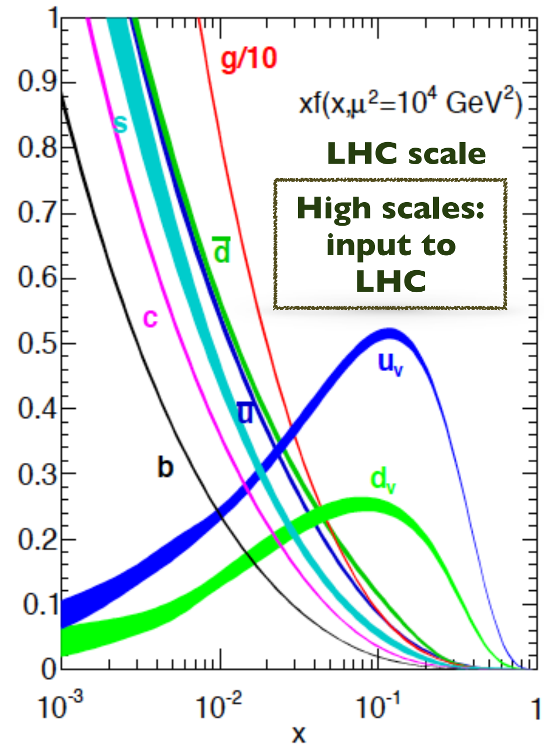
- Predict the proton inner structure with higher resolution scale

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

Universal (measured) **calculable**



prediction



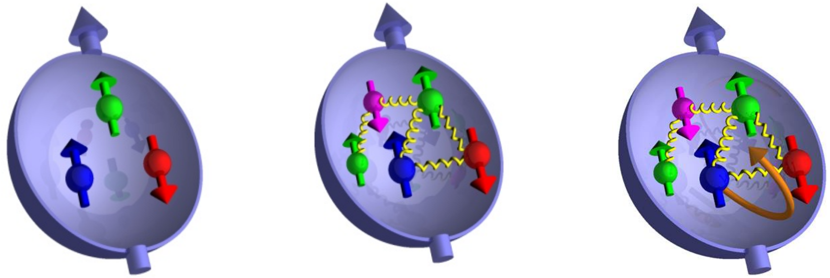
Proton structure is encoded in the Parton Distribution Functions (PDFs)
PDFs: probability density for finding a parton in a proton with momentum fraction x.

Nucleon structure - Spin

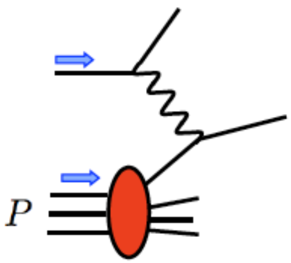
- Proton spin configuration

Jaffe, Manohar; Ji

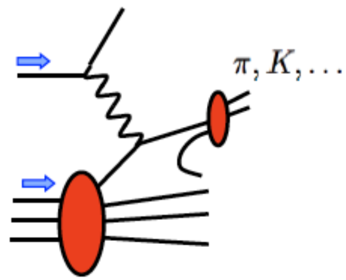
$$\frac{1}{2} = \frac{1}{2}\Delta\sum + \Delta G + L_q + L_g$$



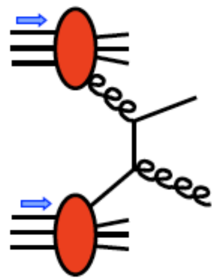
❑ Current knowledge about parton helicity distribution



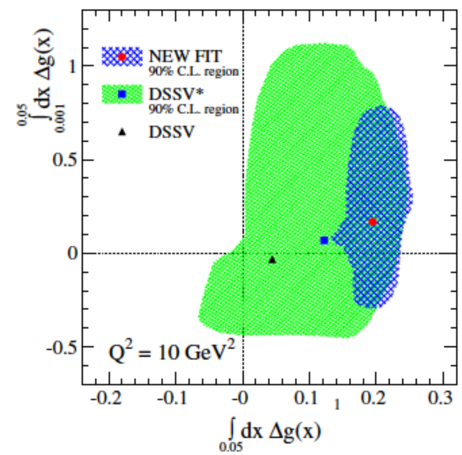
DIS

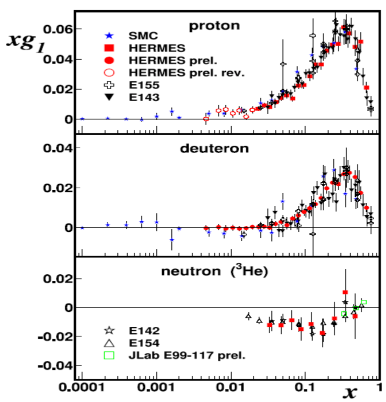


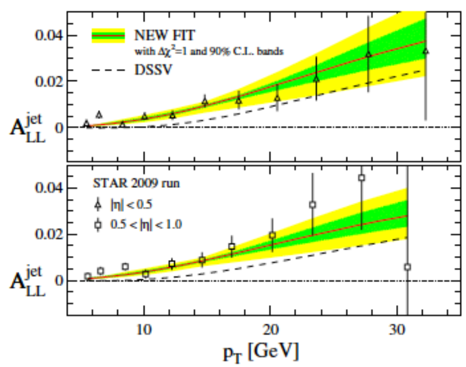
SIDIS

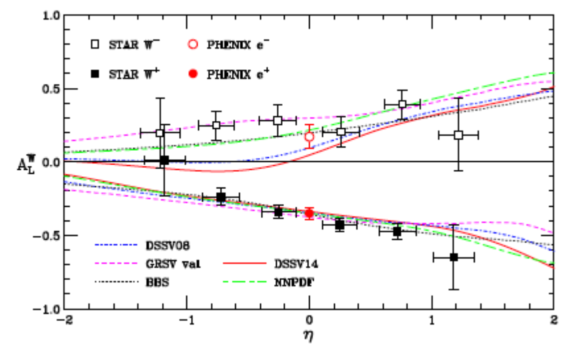


pp (RHIC)









quark spin $\Delta \sum = \int_0^1 dx \Delta f_q(x)$ ~30%

gluon spin $\Delta G = \int_0^1 dx \Delta f_g(x)$ ~20%

Orbital angular momentum, no conclusion yet.

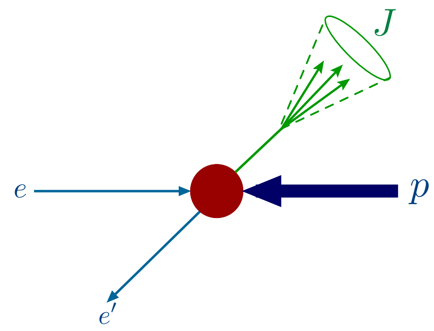
Inclusive jet production in DIS

❑ Inclusive jet production

- Integrate over outgoing lepton

  Hard scale: jet p_T

$$\ell + p \to jet + X$$



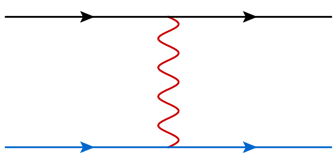
❑ QCD collinear factorization

Kang, Metz, Qiu, Zhou, 11

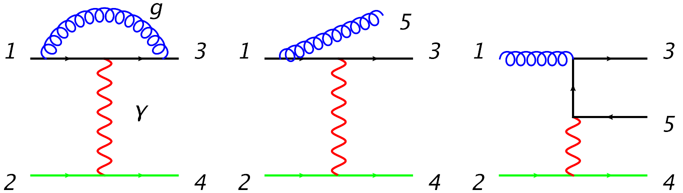
$$\sigma^{\ell+p\to jet+X} = \sum_{a,b} f_{a/\ell} \otimes f_{b/p} \otimes \hat{\sigma}^{a+b\to jet+X}$$

❑ Leading order is trivial

$$d\sigma^{LO} = \sum_q \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\left[f_{\ell/\ell}(x_1) f_{q/p}(x_2) d\hat{\sigma}^{(0)}_{q\ell} + f_{\ell/\ell}(x_1) f_{\bar{q}/p}(x_2) d\hat{\sigma}^{(0)}_{\bar{q}\ell}\right]$$



❑ Fully differential Next to leading order



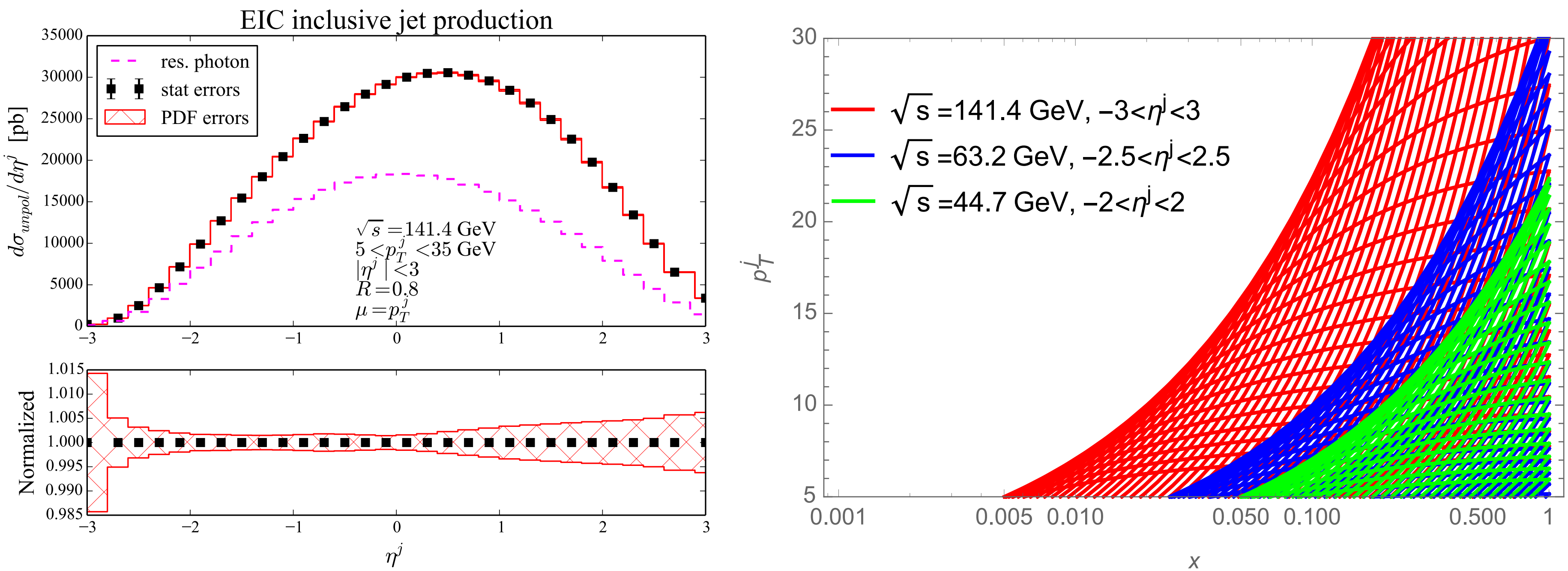
N-jettiness subtraction + dipole subtraction

R. Boughezal, F. Petriello, **HX**, PRD (2018)

EIC predictions

❑ NLO unpolarized cross section

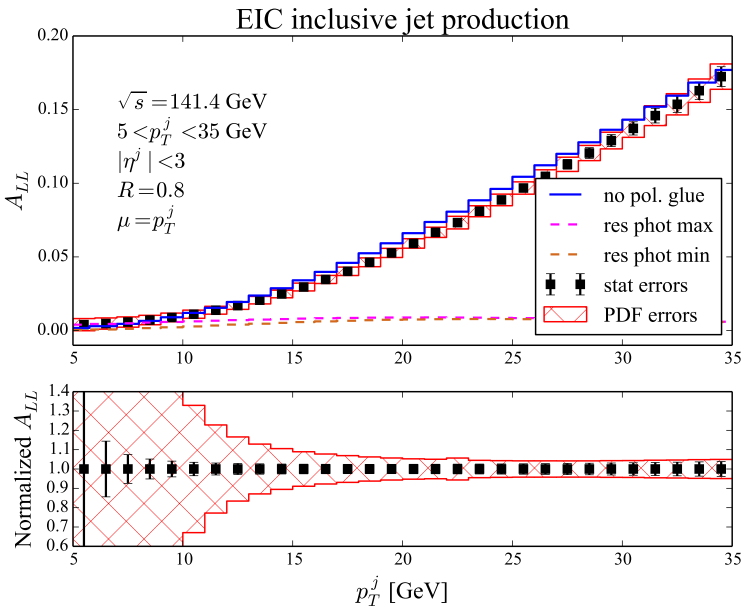
R. Boughezal, F. Petriello, **HX**, PRD (2018)

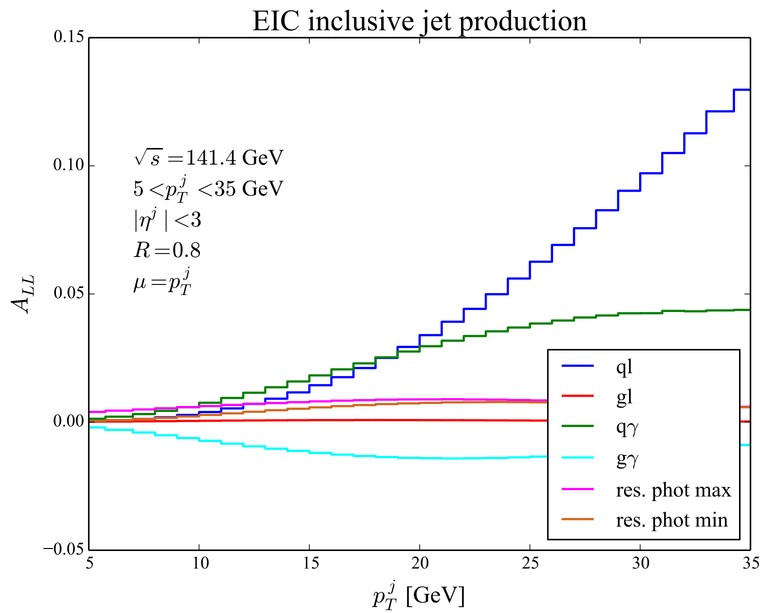


PDF uncertainty is small. Resolved photon channel is important in small pt region.

Double longitudinal asymmetry – pt distribution

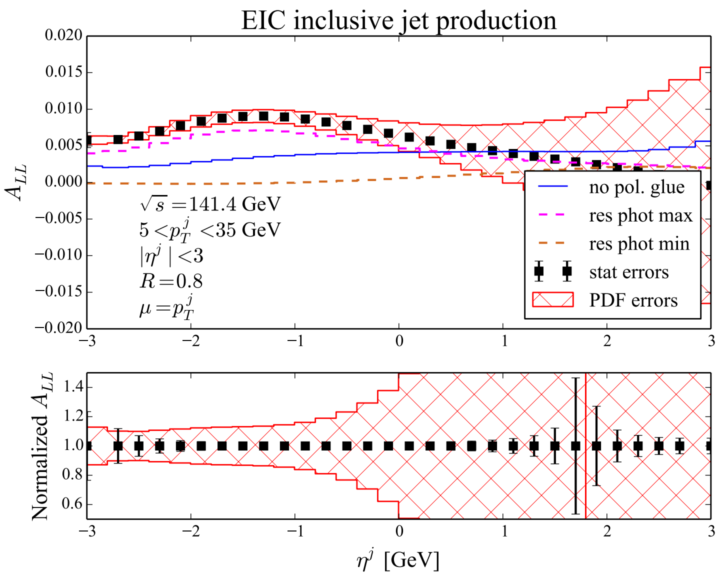
$$\mathcal{A}_{LL} = \frac{d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}}{d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}}$$

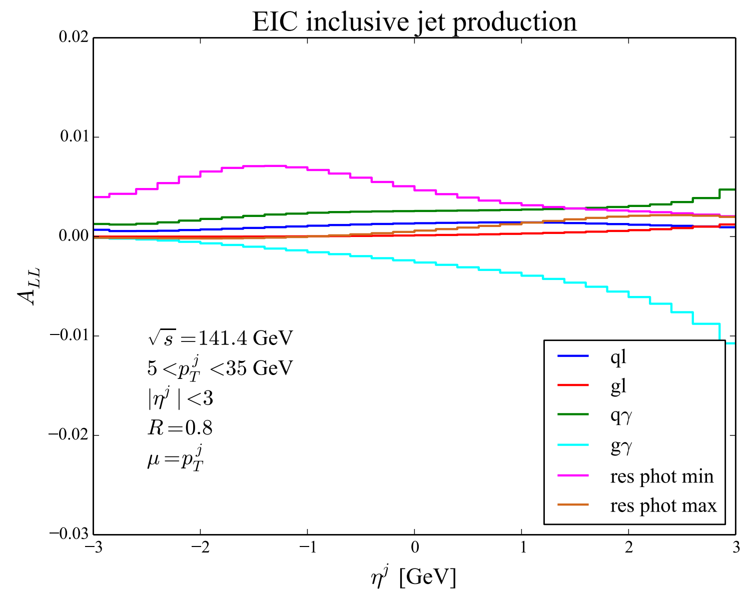




- Poor understanding of polarized PDF leads to larger PDF errors than that in unpolarized case.
- PDF errors are large in small pt region, but the asymmetry is small.
- The dominant contribution to the asymmetry at intermediate-to-high pt comes from the ql channel.
- The sensitivity to polarized gluon PDF occurs only for inclusive jet production.

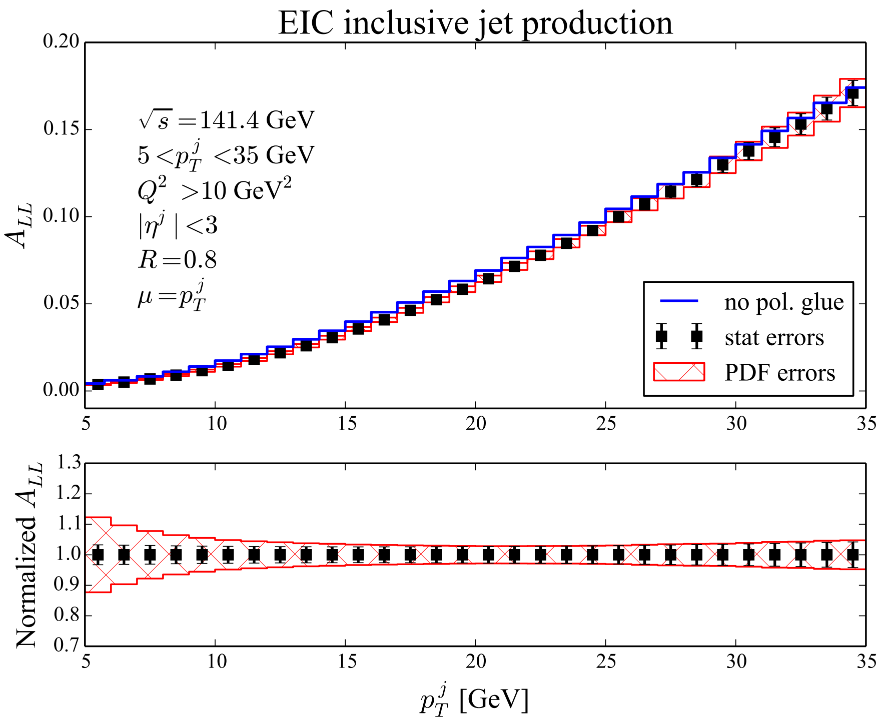
❑ Double longitudinal asymmetry – rapidity distribution

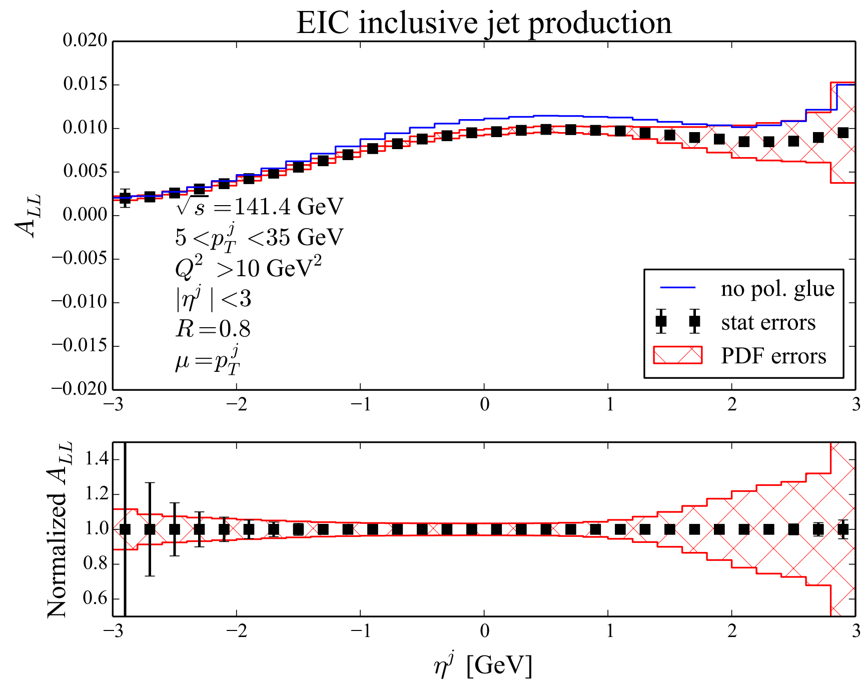




- The PDF errors are larger than stat errors indicate that EIC has the potential to improve our understanding of polarized PDFs.
- The increase of PDF errors at forward rapidity is due to the large uncertainty in the polarized PDFs at low Bjorken-x.
- Sensitive to polarized photon distributions.
- Sensitive to polarized gluon PDF.
- The smallness of the asymmetry will be a challenge for experimental measurements.

❑ Double longitudinal asymmetry – with Q2 cut





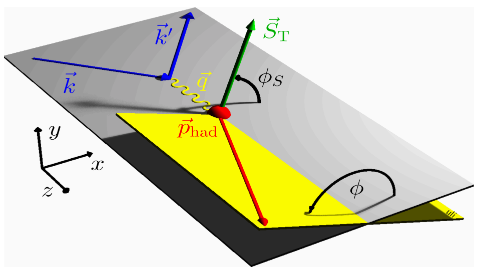
Indicates the advantage of inclusive jet measurements.

- Dihadron double longitudinal spin asymmetry in SIDIS, see talk by 杨维 on Monday.
- Jet event shape in EIC, see talk by Tanmay Maji on Monday.

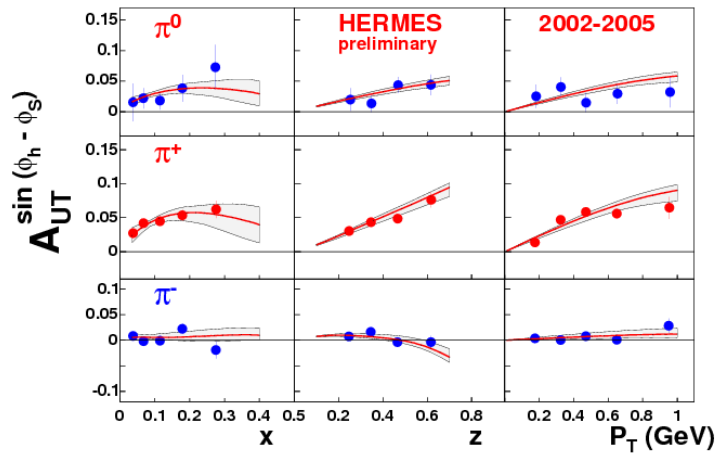
Nucleon structure – 3D imaging

- Single transverse spin asymmetry

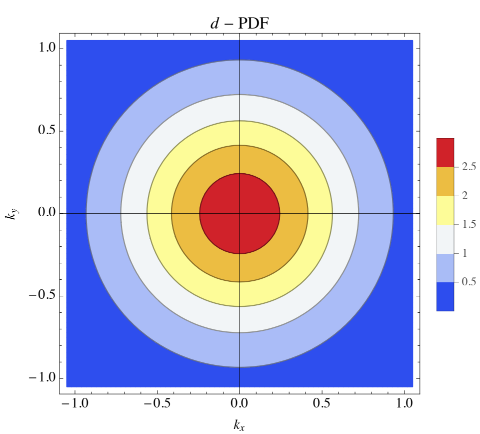
$$\Delta\sigma \propto A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S)$$



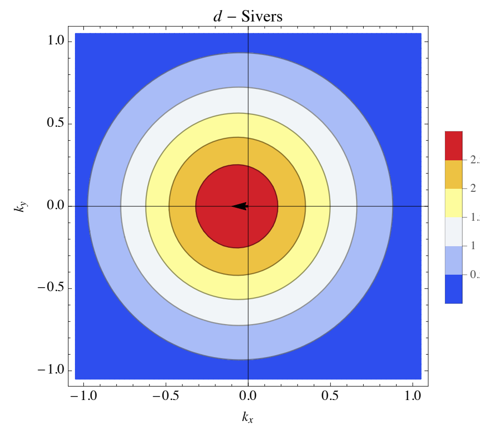
sensitive to parton's transverse motion



- Distortion from Sivers effect



Unpolarized

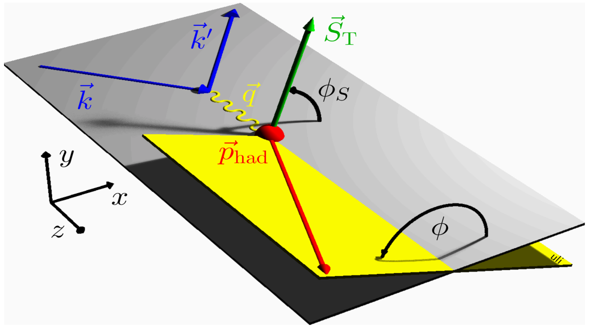


Transversely polarized

Transverse momentum weighted SSA in SIDIS

❑ Weighted cross section

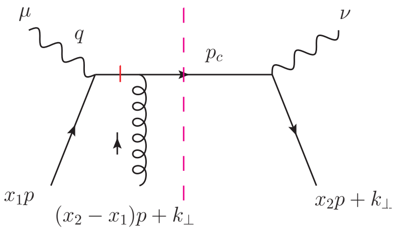
$$\frac{d\langle P_{h\perp}\Delta\sigma(S_\perp)\rangle}{dx_B dy dz_h} \equiv \int d^2P_{h\perp}\epsilon^{\alpha\beta}S_\perp^\alpha P_{h\perp}^\beta \frac{d\Delta\sigma(S_\perp)}{dx_B dy dz_h d^2P_{h\perp}}$$



❖ Only one scale – collinear factorization at twist 3

❑ Leading order

$$\frac{d\langle P_{h\perp}\Delta\sigma(S_\perp)\rangle}{dx_B dy dz_h} = -\frac{z_h\sigma_0}{2}\sum_q e_q^2 \int \frac{dx}{x}\frac{dz}{z} T_{q,F}(x,x) D_{q\to h}(z)\delta(1-\hat{x})\delta(1-\hat{z})$$

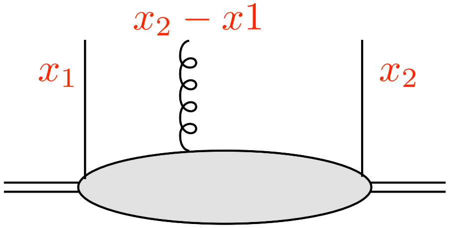


❑ Qiu-Sterman function

$$T_{q,F}(x_1,x_2) = \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_1P^+y_1^- + i(x_2-x_1)P^+y_2^-} \frac{1}{2}\langle PS|\bar{\psi}_q(0)\gamma^+\epsilon^{\alpha\beta}S_{\perp\alpha}F^+{}_\beta(y_2^-)\psi_q(y_1^-)|PS\rangle$$

Relation to Sivers function

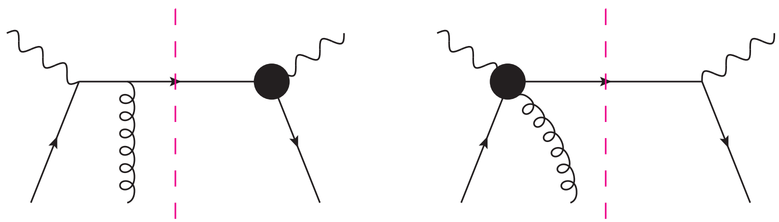
$$T_{q,F}(x,x) = \int d^2k_\perp \frac{|\vec{k}_\perp|^2}{M_h} f_{1T}^\perp(x,k_\perp^2)$$

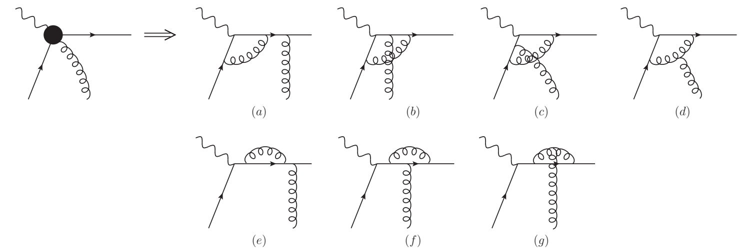


SSA in SIDIS at NLO

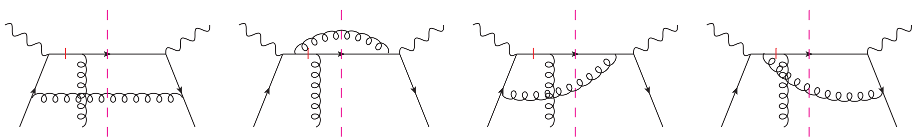
Kang, Vitev, **HX**, PRD, 2013

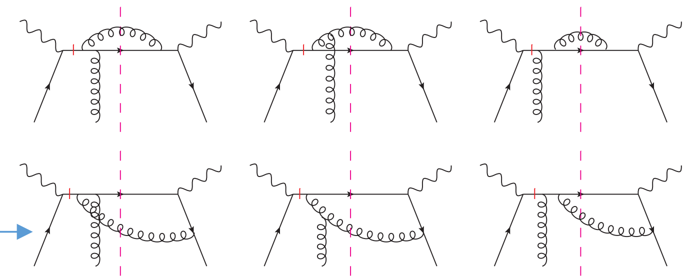
- Virtual correction





- Real correction





soft-pole

hard-pole →

- QCD evolution of Qiu-Sterman function

$$\frac{\partial}{\partial \ln \mu^2} T_{q,F}(x_B, x_B, \mu^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x} \Bigg\{ T_{q,F}(x, x, \mu^2) C_F \left[\frac{1+\hat{x}^2}{(1-\hat{x})_+} + \frac{3}{2}\delta(1-\hat{x}) \right] - N_c \delta(1-\hat{x}) T_{q,F}(x, x, \mu^2)$$
$$+ \frac{N_c}{2} \left[\frac{1+\hat{x}}{(1-\hat{x})_+} T_{q,F}(x, x\hat{x}, \mu^2) - \frac{1+\hat{x}^2}{(1-\hat{x})_+} T_{q,F}(x, x, \mu^2) \right] \Bigg\}.$$

❑ Fully analytical calculation at next-to-leading order

LO

$$
\frac{d\langle P_{h\perp}\Delta\sigma(S_\perp)\rangle}{dx_B\,dy\,dz_h} = -\frac{z_h\sigma_0}{2}\sum_q e_q^2\int_{x_B}^1\frac{dx}{x}\int_{z_h}^1\frac{dz}{z}T_{q,F}(x,x,\mu^2)D_{q\to h}(z,\mu^2)\delta(1-\hat{a}tx)\delta(1-\hat{a}tz)
$$

$$
\begin{aligned}
&-\frac{z_h\sigma_0}{2}\frac{\alpha_s}{2\pi}\sum_q e_q^2\int_{x_B}^1\frac{dx}{x}\int_{z_h}^1\frac{dz}{z}D_{q\to h}(z,\mu^2)\Bigg\{\ln\left(\frac{Q^2}{\mu^2}\right)\left[\delta(1-\hat{x})T_{q,F}(x,x,\mu^2)P_{qq}(\hat{z})\right.\\
&\left.+\delta(1-\hat{z})P_{qg\to qg}\otimes T_{q,F}(x,x\hat{x},\mu^2)\right]\\
&+x\frac{d}{dx}T_{q,F}(x,x,\mu^2)\frac{1}{2N_c}\left[\frac{1-\hat{z}}{\hat{z}}+\frac{(1-\hat{x})^2+2\hat{x}\hat{z}}{\hat{z}(1-\hat{z})_+}-\delta(1-\hat{z})\left((1+\hat{x}^2)\ln\frac{\hat{x}}{1-\hat{x}}+2\hat{x}\right)\right]\\
&+T_{q,F}(x,x,\mu^2)\delta(1-\hat{z})\frac{1}{2N_c}\left[(2\hat{x}^2-\hat{x}-1)\ln\frac{\hat{x}}{1-\hat{x}}-2\left(\frac{\ln(1-\hat{x})}{1-\hat{x}}\right)_+ +\frac{2\hat{x}(2-\hat{x})}{(1-\hat{x})_+}+2\frac{\ln\hat{x}}{1-\hat{x}}\right.\\
&+T_{q,F}(x,x,\mu^2)\delta(1-\hat{x})C_F\left[-(1+\hat{z})\ln\hat{z}(1-\hat{z})+2\left(\frac{\ln(1-\hat{z})}{1-\hat{z}}\right)_+ -\frac{2\hat{z}}{(1-\hat{z})_+}+2\frac{\ln\hat{z}}{1-\hat{z}}\right]\\
&+T_{q,F}(x,x,\mu^2)\frac{1}{2N_c\hat{z}}\left[\frac{2\hat{x}^3-3\hat{x}^2-1}{(1-\hat{x})_+(1-\hat{z})_+}+\frac{1+\hat{z}}{(1-\hat{x})_+}-2(1-\hat{x})\right]\\
&+T_{q,F}(x,x\hat{x},\mu^2)\delta(1-\hat{z})\frac{N_c}{2}\left[\ln\frac{\hat{x}}{1-\hat{x}}+2\left(\frac{\ln(1-\hat{x})}{1-\hat{x}}\right)_+ -2\frac{\ln\hat{x}}{1-\hat{x}}-\frac{1+\hat{x}}{(1-\hat{x})_+}\right]\\
&+T_{q,F}(x,x\hat{x},\mu^2)\frac{1+\hat{x}\hat{z}^2}{(1-\hat{x})_+(1-\hat{z})_+}\left(C_F+\frac{1}{2N_c\hat{z}}\right)-T_{q,F}(x,x,\mu^2)6C_F\delta(1-\hat{x})\delta(1-\hat{z})\Bigg\}
\end{aligned}
$$

NLO

All finite, perfect for numerical calculation!

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

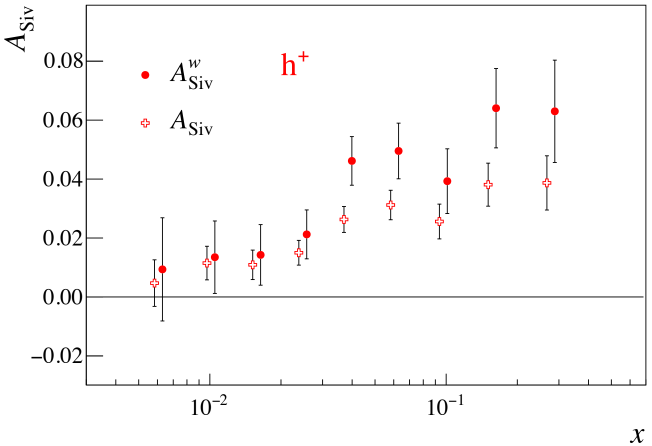
COMPASS measurement

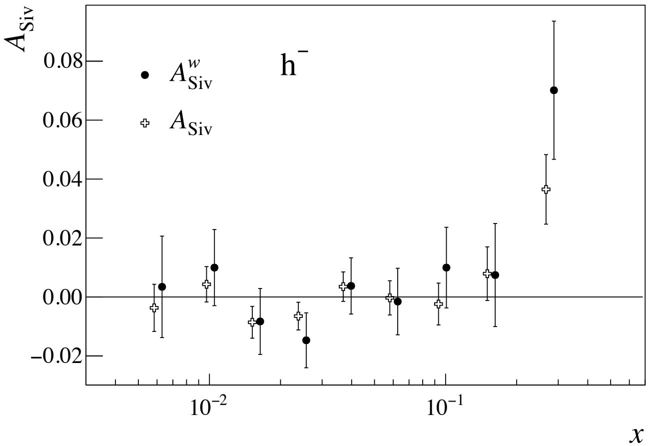
Measurement of P_T-weighted Sivers asymmetries in leptoproduction of hadrons

The COMPASS Collaboration

Abstract

The transverse spin asymmetries measured in semi-inclusive leptoproduction of hadrons, when weighted with the hadron transverse momentum P_T, allow for the extraction of important transverse-momentum-dependent distribution functions. In particular, the weighted Sivers asymmetries provide direct information on the Sivers function, which is a leading-twist distribution that arises from a correlation between the transverse momentum of an unpolarised quark in a transversely polarised nucleon and the spin of the nucleon. Using the high-statistics data collected by the COMPASS Collaboration in 2010 with a transversely polarised proton target, we have evaluated two types of P_T-weighted Sivers asymmetries, which are both proportional to the product of the first transverse moment of the Sivers function and of the fragmentation function. The results are compared to the standard unweighted Sivers asymmetries and used to extract the first transverse moments of the Sivers distributions for u and d quarks.



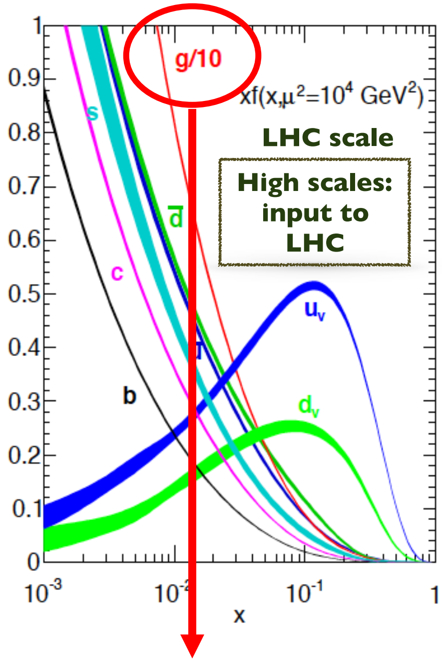


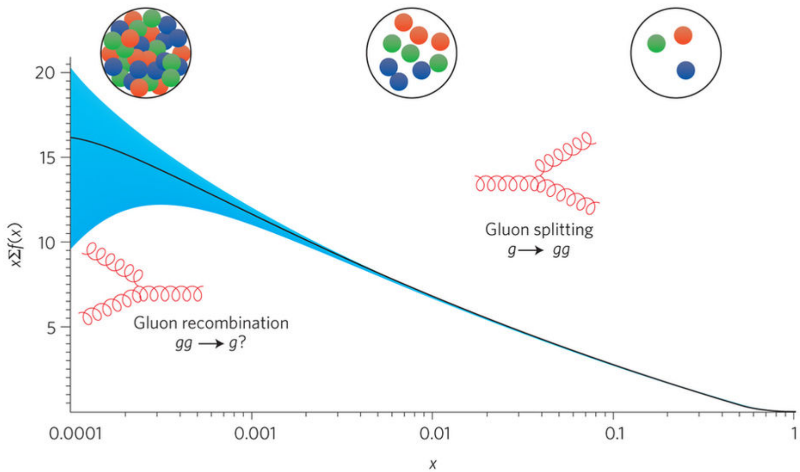
NLO description of Sivers asymmeties, **HX**, in preparation.

Nuclear structure in small-x

Dense region - gluon saturation

❑ Parton density in small-x region

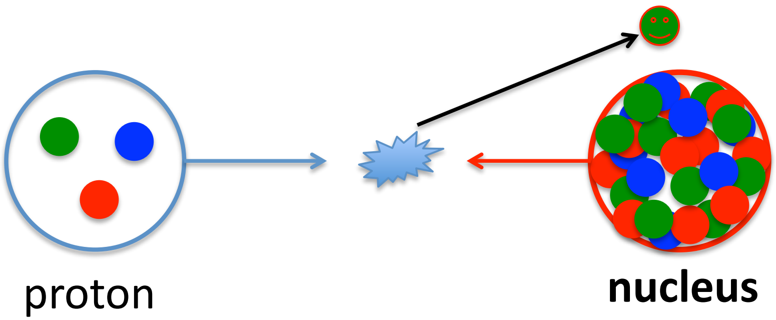


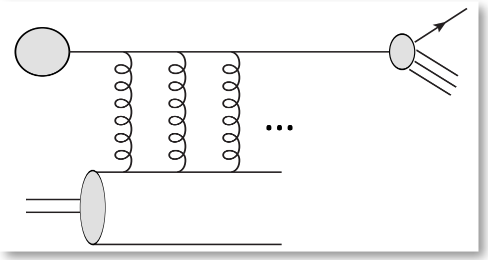


- ❖ Gluon density grows dramatically in small-x region.
- ❖ Such fast growth would violate the fundamental principle of unitarity.
- ❖ Gluon recombination process needs to be taken into account.

Coherent multiple scattering – gluon saturation

❑ Single inclusive hadron production in proton-nucleus collisions





- In proton beam going direction

$x_p = \frac{p_\perp}{z\sqrt{s}} e^{y}$ → $x_p p_a \gg k_{Ta}$ → Probing valance quark – DGLAP evolution

$x_g = \frac{p_\perp}{z\sqrt{s}} e^{-y}$ → $x_g p_b \sim k_{Tb}$ → Probing dense gluon – BK evolution

- Hybrid (dilute-dense) factorization formalism

$$\sigma \sim x_p f_{q/p}(x_p) \otimes H \otimes \mathcal{F}(x_g, k_\perp) \otimes D_{h/q}(z)$$

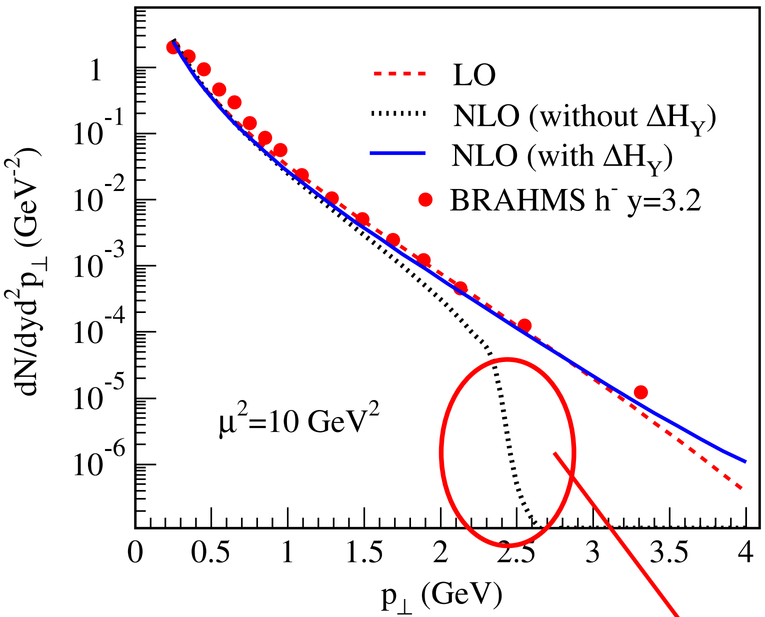
❖ All multiple scatterings become equally important, need to be resummed.

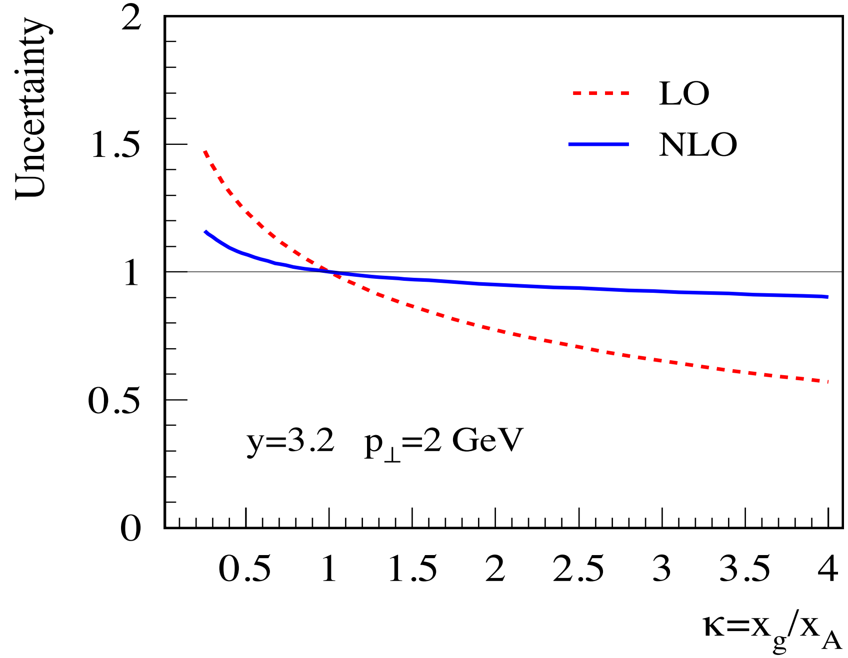
❖ Coherent multiple scattering are encoded in the so-called unintegrated gluon distribution (UGD) $F(x, k_T)$

PRL 113, 062002 (2014) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2014

Next-to-Leading-Order Forward Hadron Production in the Small-x Regime: The Role of Rapidity Factorization

Zhong-Bo Kang,[1] Ivan Vitev,[1] and Hongxi Xing[1,2]

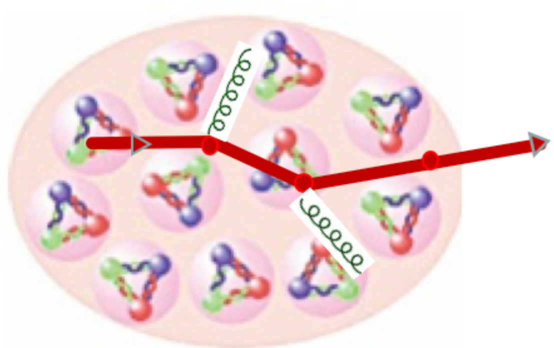




Puzzle in small-x physics, negative cross section.

- We solved the negative cross section puzzle!
- Better description of the experimental data at NLO.
- More stable theoretical control at NLO.
- NLO: highest precision in small-x physics.

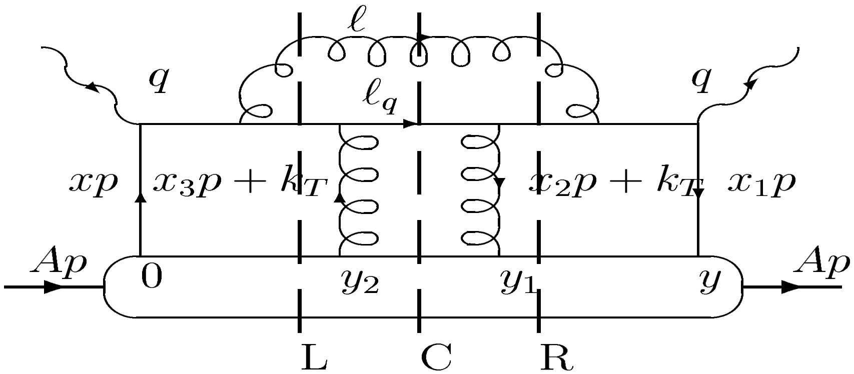
Parton energy loss in cold nuclear matter



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

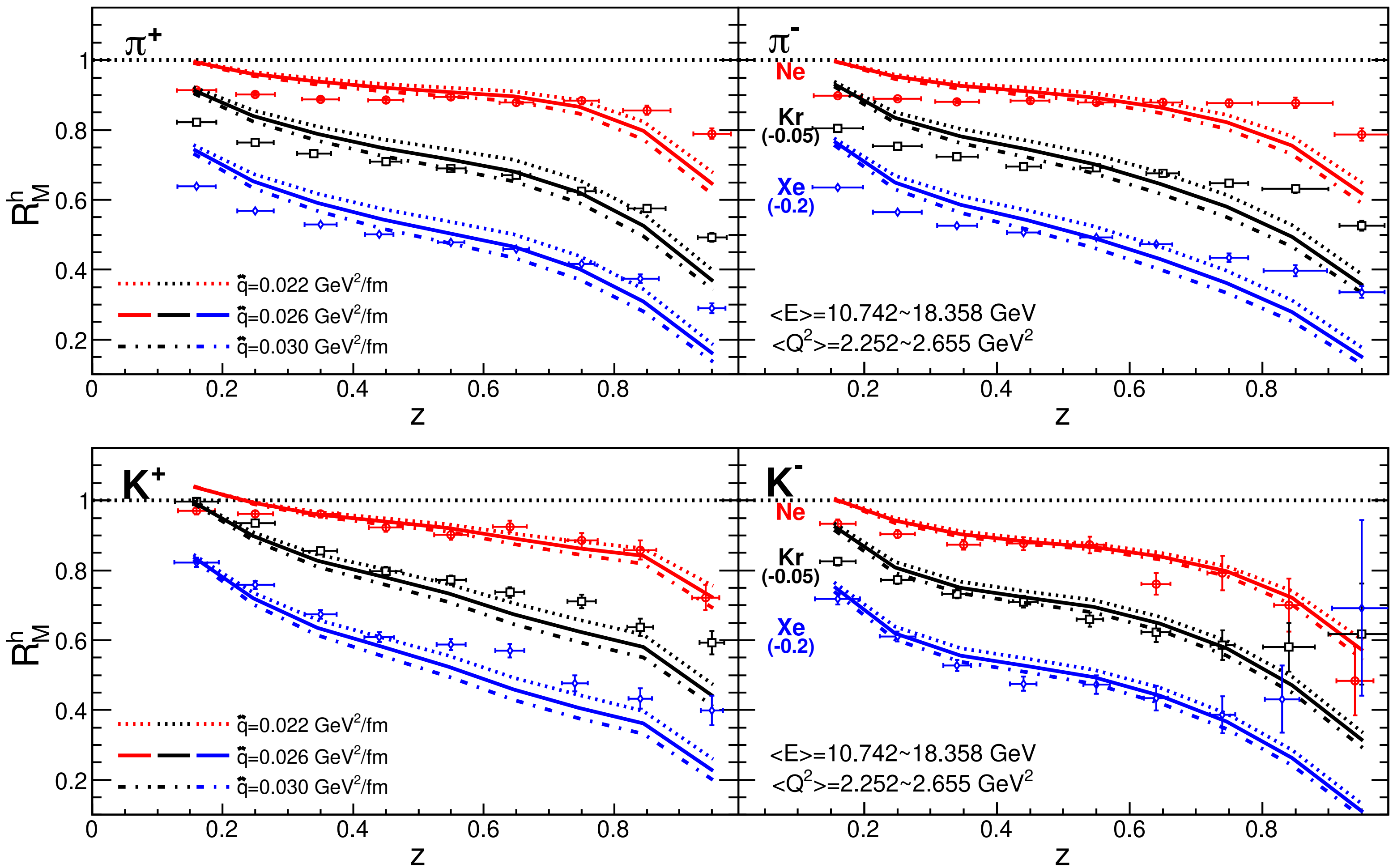
$$\frac{\partial \widetilde{D}_{q\to h}(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi}\int_{z_h}^{1}\frac{dz}{z}\Big[\widetilde{\gamma}_{q\to qg}(z,x,x_L,\mu^2)\widetilde{D}_{q\to h}(z_h/z,\mu^2) + \widetilde{\gamma}_{q\to gq}(z,x,x_L,\mu^2)D_{g\to h}(z_h/z,\mu^2)\Big] .$$

- Phenomenological extension to study jet quenching in heavy ion collisions. See talk by Ben-Wei Zhang.

Parton energy loss in cold nuclear matter

❑ Medium effect in HERMES

Chang, **HX**, et al. 2019, 1907.xxxxx

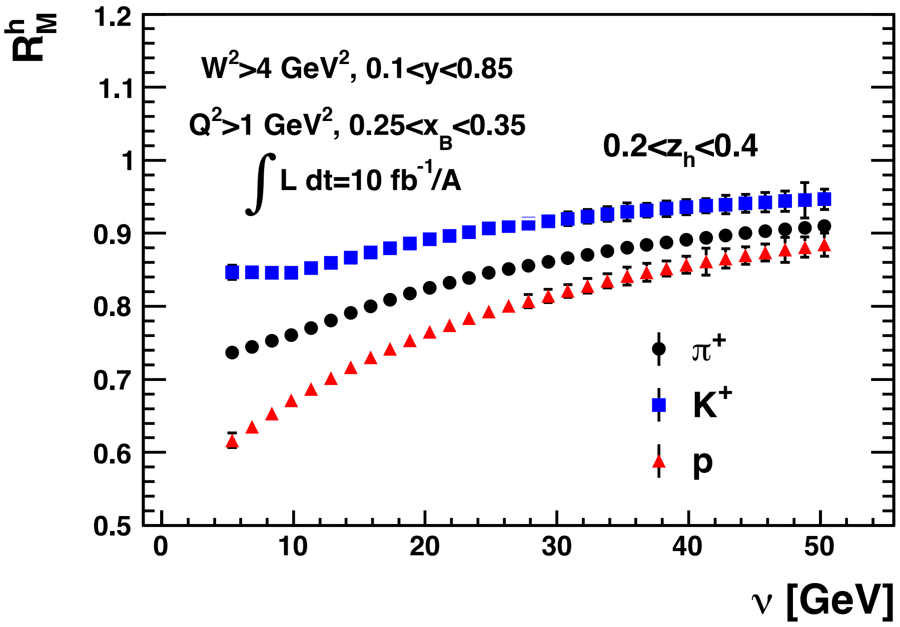


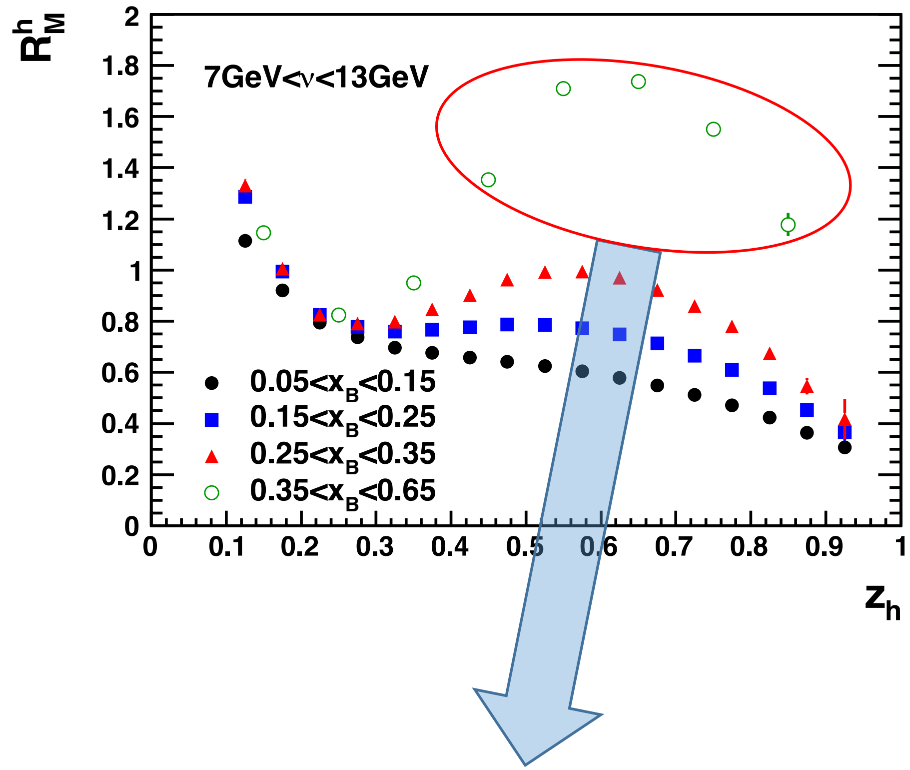
NLO ep baseline + medium effect

Parton energy loss in cold nuclear matter

- Predictions for EicC

Chang, **HX**, et al. 2019, 1907.xxxxx





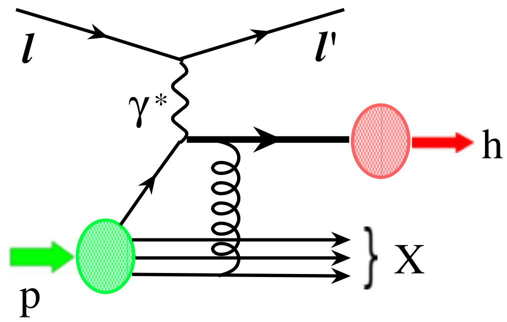
Medium induced flavor conversion leads to enhancement of K- production yield.

Transverse momentum broadening in CNM

A good observable to probe nuclear medium

Transverse momentum braodening

Guo, 1998; Guo, Qiu 2000



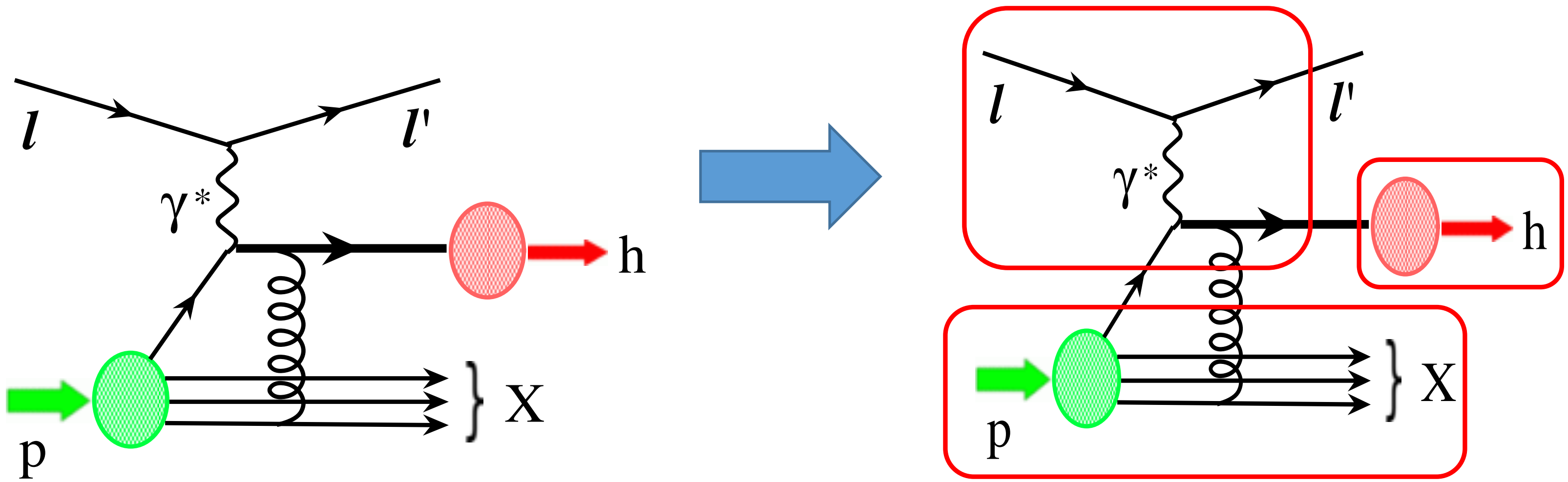
- Sensitive to nuclear quark-gluon quantum correlation

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

- 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

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]



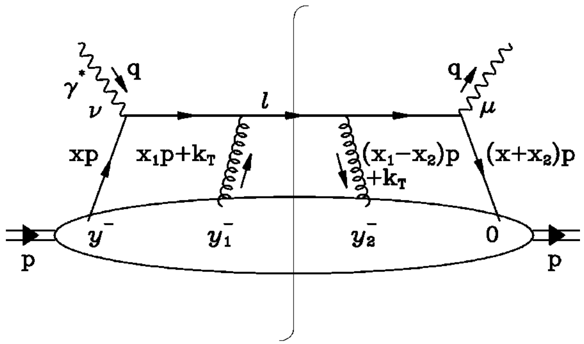
✓ **First time proof of QCD factorization theorem for double scattering at NLO**

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

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

Transverse momentum broadening in CNM

❑ Transverse momentum broadening in eA and pA collisions



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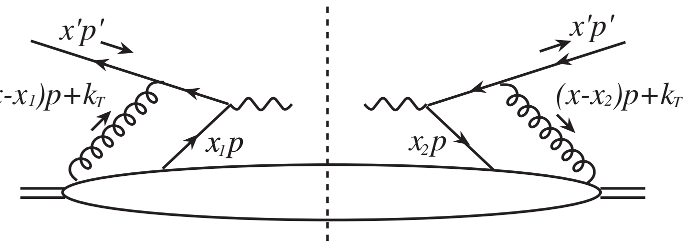
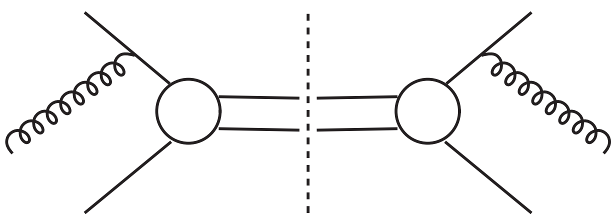
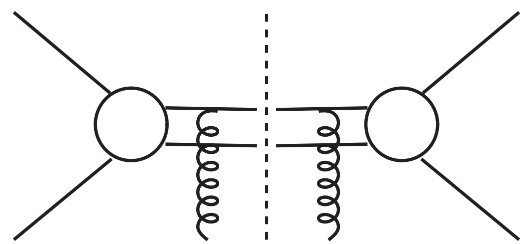


Drell-Yan



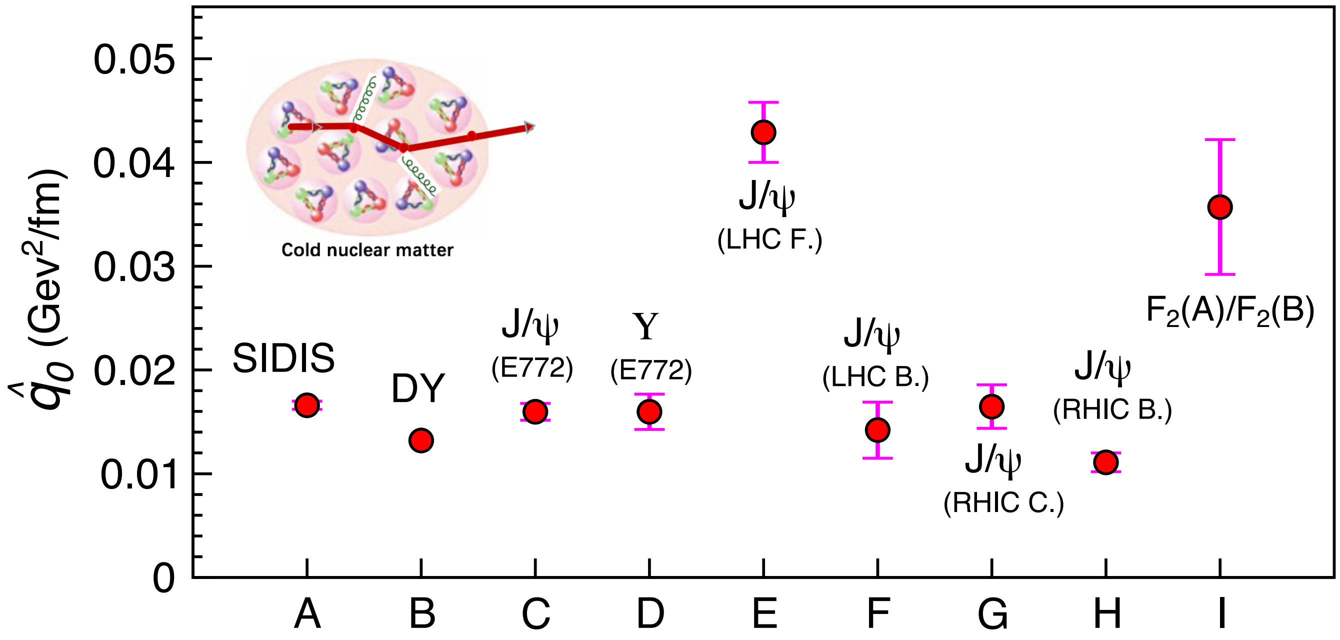
Heavy quarkonium
Initial state multiple scattering



Heavy quarkonium
Final state multiple scattering

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

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

jet transport parameter: jet transverse momentum broadening per unit length, characterizes the fundamental property of nuclear medium.

Global analysis of the world data

❑ Universality of medium property

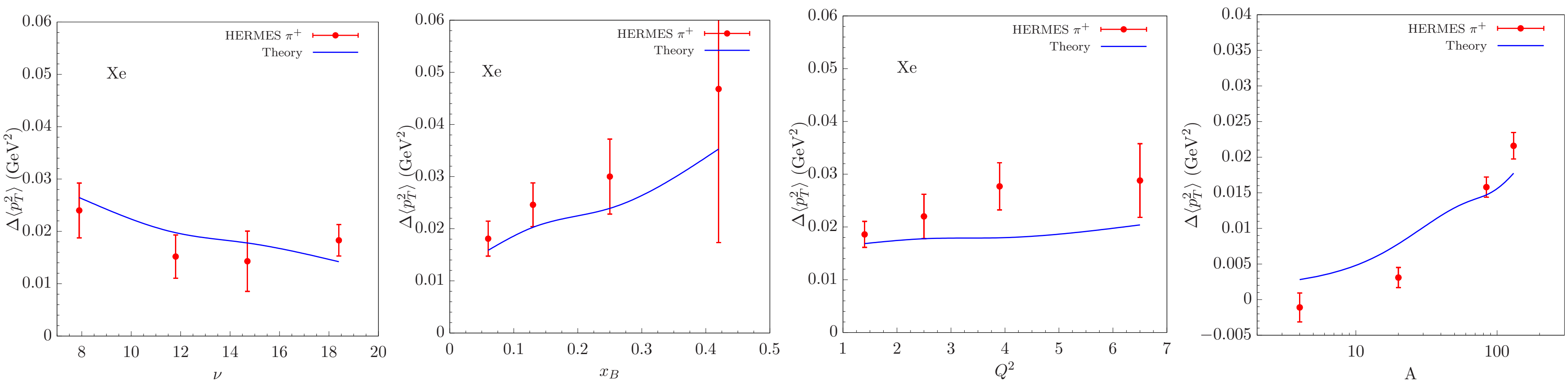
- Parametrization of qhat

$$\hat{q}(Q,x) = \hat{q}_0\ \alpha_s(Q^2)\ \left(\ln(Q^2)\right)^c\ x^a(1-x)^b$$

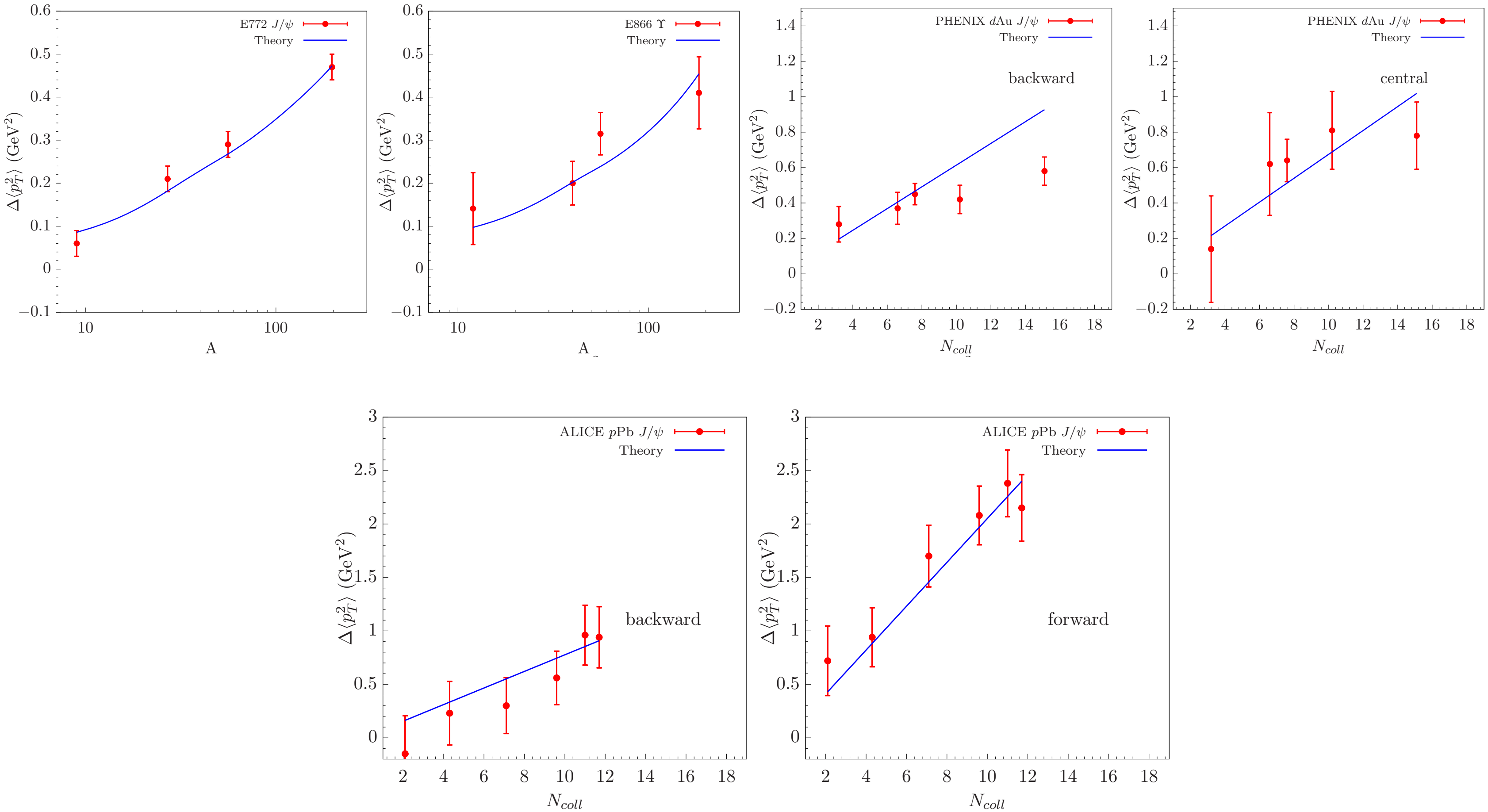
$$\chi^2/d.o.f\ (1.264)$$

$\hat{q}_0 = 0.0232$ GeV^2/fm
$a = -0.1666$
$b = -2.33$
$c = 0.2525$

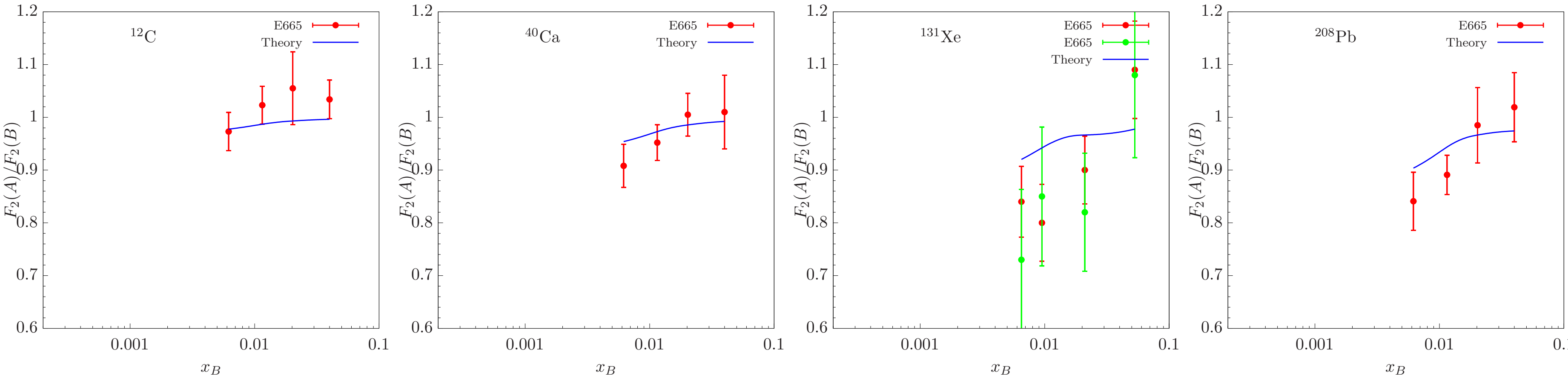
- Semi-inclusive deep inelastic scattering



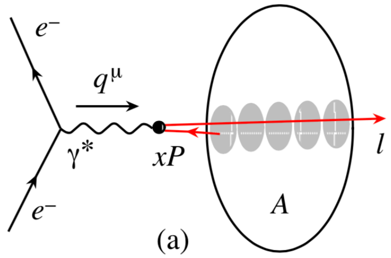
Vector boson production in pA collisions



Dynamical shadowing – small x



Coherent multiple scattering

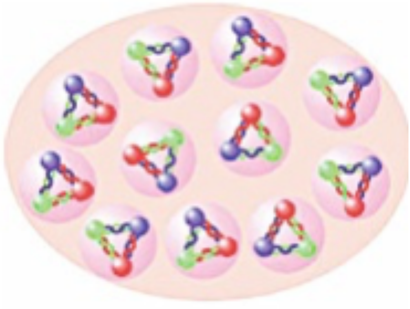


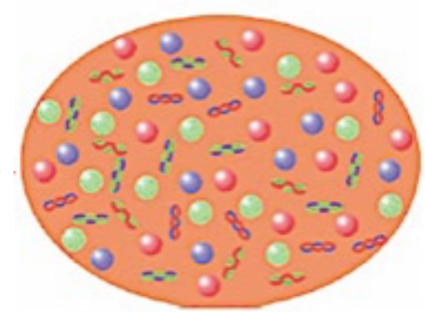
Summing nuclear enhanced multiple scattering

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

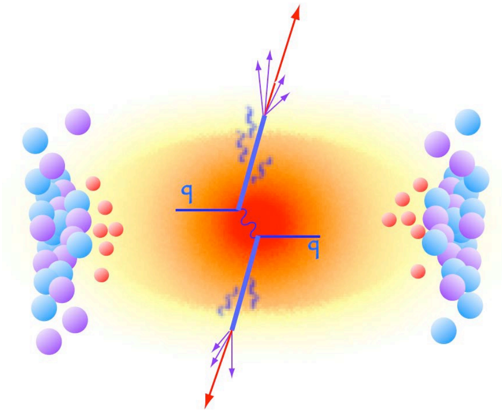
Phenomenological extension to QGP

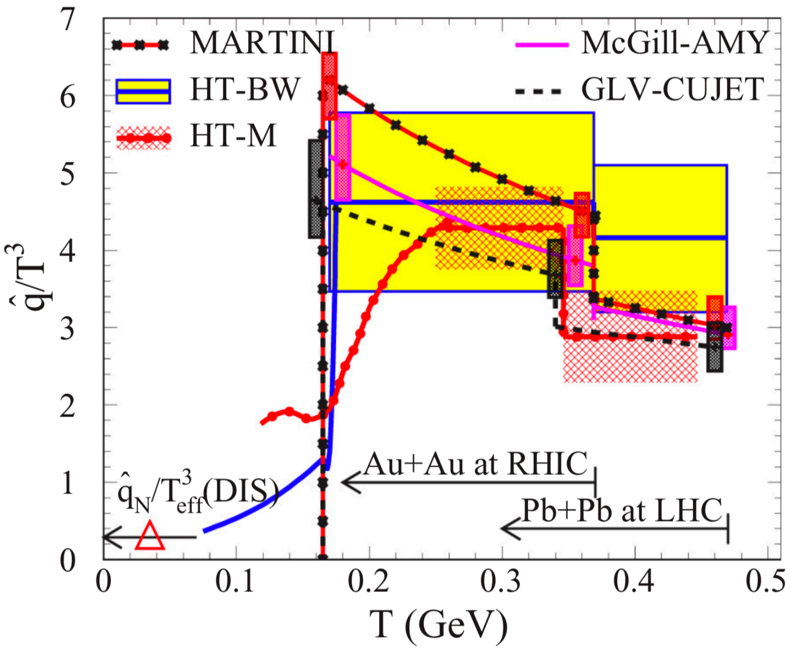
- Jet transport in hot dense medium





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





Summary

❑ Nucleon spin structure

- ❖ Inclusive jet production at NLO in EIC – 1D nucleon helicity distribution.
- ❖ Weighted Sivers asymmetry at NLO - 3D nucleon structure.

❑ Nuclear structure

- ❖ Small x at NLO.
- ❖ Parton energy loss and flavor conversion in cold nuclear matter.
- ❖ Global extraction of medium property by considering world data on transverse momentum broadening and dynamical shadowing.

❑ outlook

- ❖ Comprehensive Monte Carlo program to simulate electron ion collision at NNLO, provides the highest precision for EIC and EicC.

Summary Thanks for your attention!

Nucleon spin structure

- Inclusive jet production at NLO in EIC – 1D nucleon helicity distribution.
- Weighted Sivers asymmetry at NLO - 3D nucleon structure.

Nuclear structure

- Small x at NLO.
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outlook

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