Hard Probes 2020
June 3rd

A global extraction of jet transport coefficient in cold nuclear matter & Predictions for future EIC experiments

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In collaboration with:

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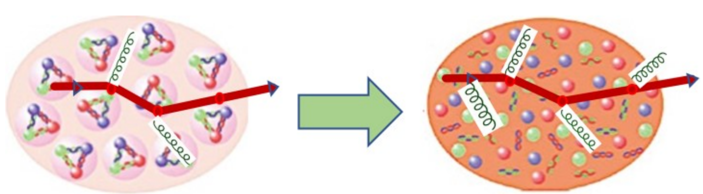

Cold nuclear matter Quark gluon plasma

PR, Z.-B. Kang, E. Wang, H. Xing, B.-W. Zhang
1907.11808, 2004.00027(QM19), in preparation

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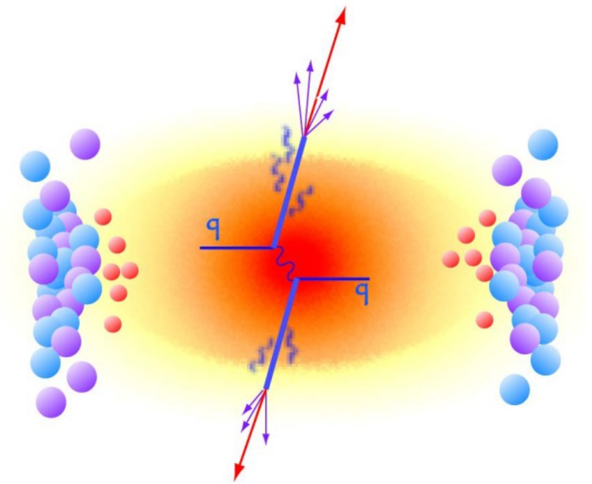
Questions

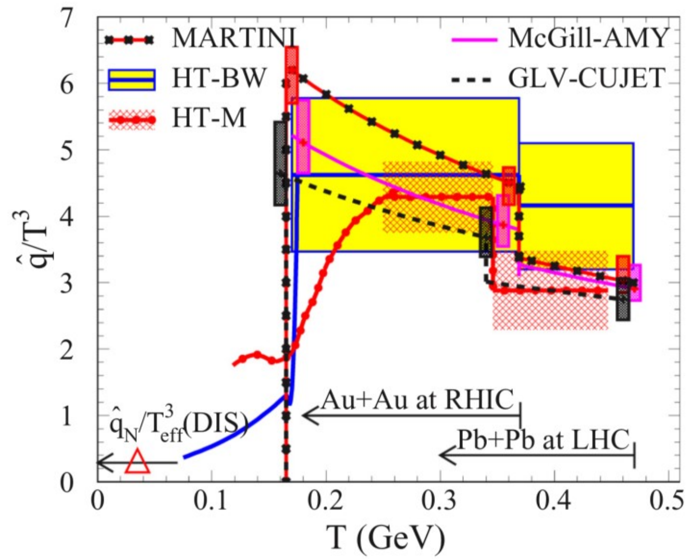
- Why study $\hat{q}$ for cold nuclear matter (CNM)?
- $\hat{q}$ in CNM: Universal for various types of processes?
- Describe global data within one framework?
- $\hat{q}$: constant or kinematics/scale dependent?
- How can future EIC experiments help us understand $\hat{q}$?

$\hat{q}$ for quark-gluon plasma



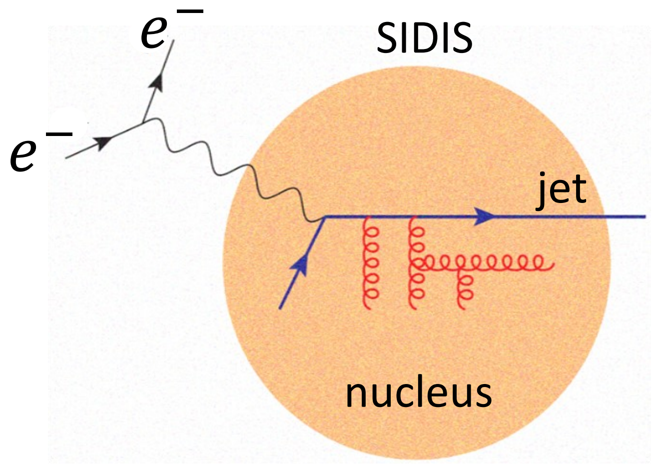
Jet quenching

JET, PRC 90, 014909 (2014)

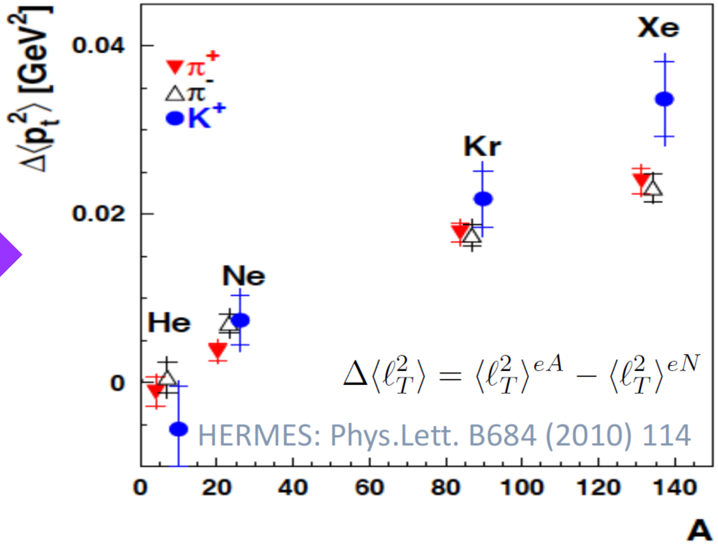


- $\hat{q}$ is an important **non-perturbative** input in jet-quenching models.
- Transverse momentum broadening per unit length for propagating parton.
- Characterize **interaction strength** between hard probe and nuclear medium.
- **Medium property** is encoded in $\hat{q}$.

$\hat{q}$ for cold nuclear matter



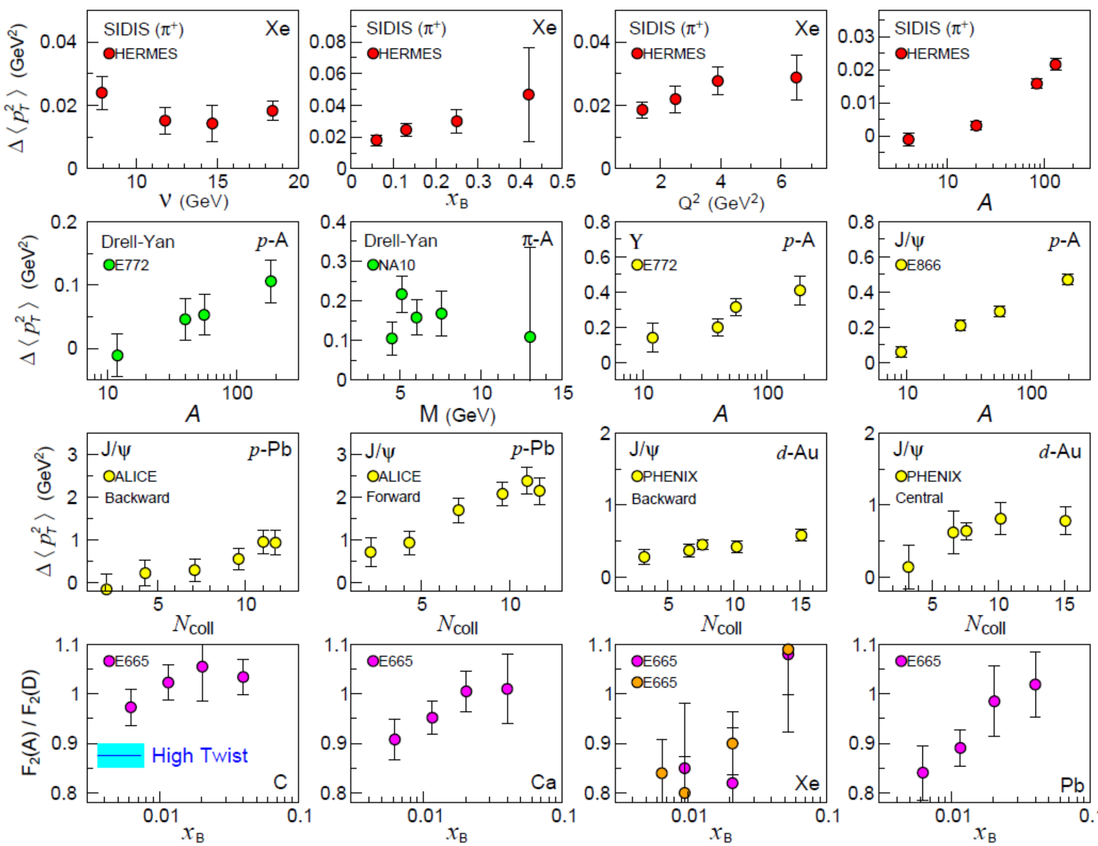
$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep}$$



- eA and pA collisions provide a **clean environment** for both experimental and theoretical study.
- Significant **transverse momentum broadening** in SIDIS, DY and heavy-quarkonium production has been observed.
- Jet-medium interactions for CNM and QGP can be studied with **same theoretical framework**.
- A comprehensive study of in $\hat{q}$ cold nuclear matter is needed! Is it a constant value as usually assumed?

What have we done?

Similar as what is usually done for parton distribution functions (PDFs), we do a global extraction of the $\hat{q}$ in cold nuclear matter from various types of observables.



Observable:

1. Transverse momentum (p_T) broadening for:

- Hadron production in semi-inclusive deeply inelastic *e*A scattering (**SIDIS**).
- **Drell-Yan** dilepton in pA collisions.
- Heavy **quarkonium** (J/ψ,Υ) production in pA collisions.

2. Nuclear modification of DIS structure functions:

- Dynamical **shadowing** effect.

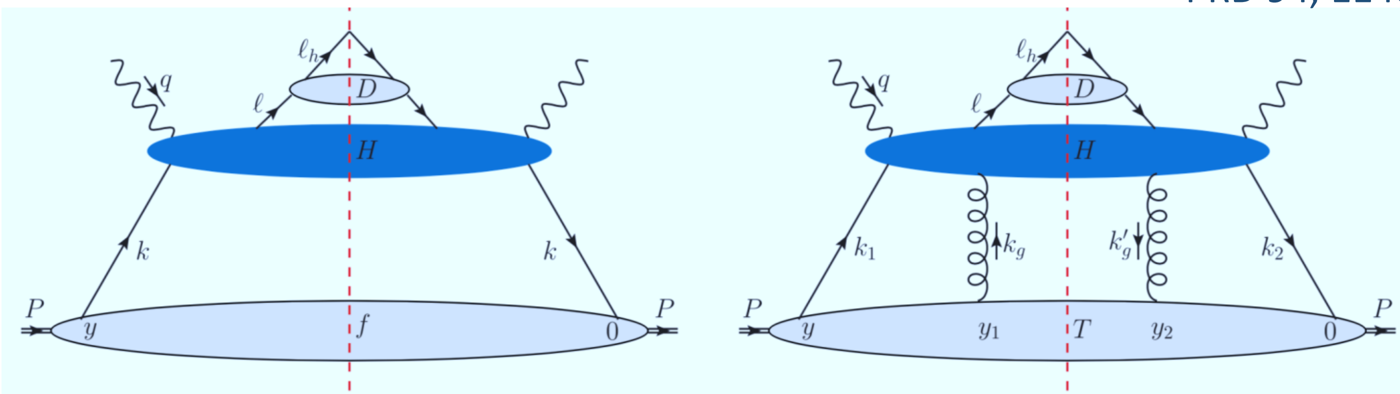
Theoretical framework for parton multiple scattering in nuclear medium:

Higher-twist (HT) expansion

Multiple parton scattering in HT framework

Transverse momentum broadening in semi-inclusive deeply inelastic scattering (SIDIS)

Kang, Wang, Wang, Xing,
PRL 112, 102001 (2014)
PRD 94, 114024 (2016)



Single scattering   Double scattering

Twsit-4 quark-gluon correlation function:

$$T_{qg}(x) = \int \frac{dy^-}{2\pi} e^{ixp^+y^-} \int \frac{dy_1^- dy_2^-}{4\pi} \theta(-y_2^-)\theta(y^- - y_1^-)\langle p_A | F_\alpha^+(y_2^-)\bar{\Psi}_q(0)\gamma^+\Psi_q(y^-)F^{\alpha+}(y_1^-)|p_A\rangle$$

Transverse momentum broadening:

$$\Delta\langle p_T^2\rangle \approx \int dp_T^2 p_T^2 \frac{d\sigma^D}{dPS\, dp_T^2} / \frac{d\sigma^S}{dPS} = \frac{4\pi^2\alpha_s z_h^2}{N_c} \frac{\sum_q e_q^2 T_{qg}(x,\mu^2) D_{h/q}(z_h,\mu^2)}{\sum_q e_q^2 f_{q/A}(x,\mu^2) D_{h/q}(z_h,\mu^2)}$$

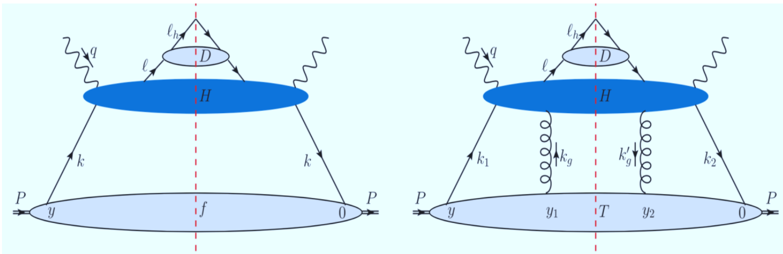
Expressed with $\hat{q}$:

$$T_{qg}(x,\mu^2) \approx \frac{9R_A}{8\pi^2\alpha_s} f_{q/A}(x,\mu^2)\, \hat{q}(x,\mu^2)$$

Approximation of a large and loosely bound nucleus

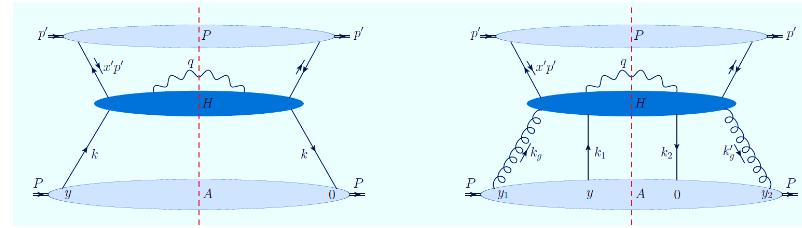
Multiple parton scattering in HT framework

1. pT broadening in SIDIS



Single scattering　　Double scattering

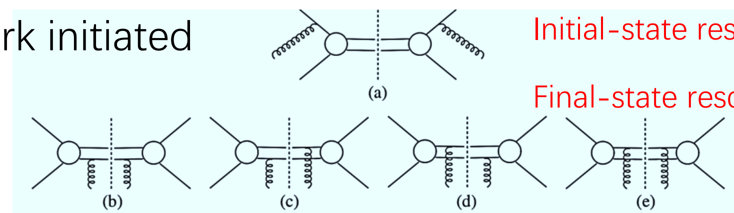
2. pT broadening in Drell-Yan in pA



Single scattering　　Double scattering

3. pT broadening of heavy quarkonium in pA

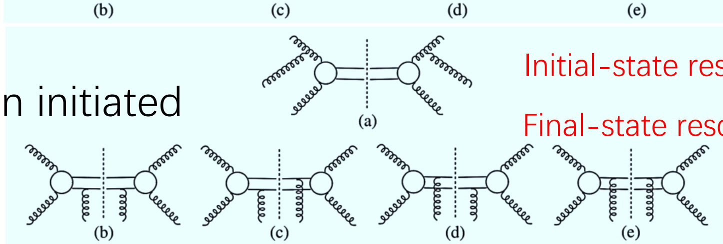
Quark initiated



Initial-state rescattering

Final-state rescattering

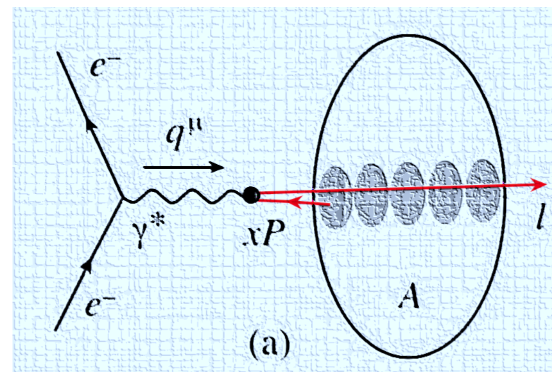
Gluon initiated



Initial-state rescattering

Final-state rescattering

4. Dynamical shadowing in DIS

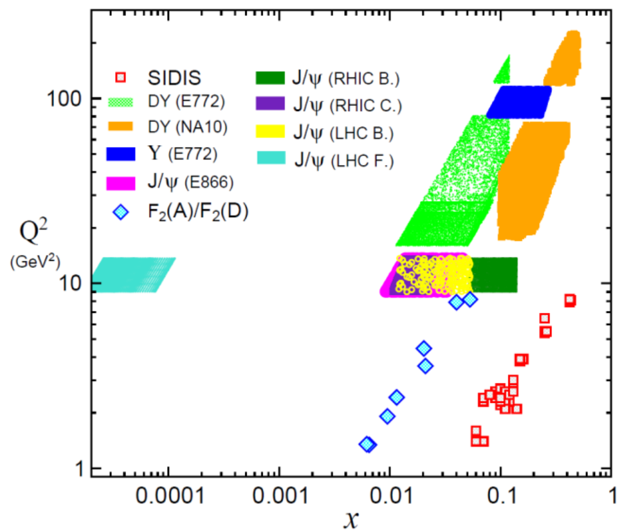


$$R(x,Q^2)=\frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}$$

All these cold nuclear medium modifications are calculated within higher-twist framework.

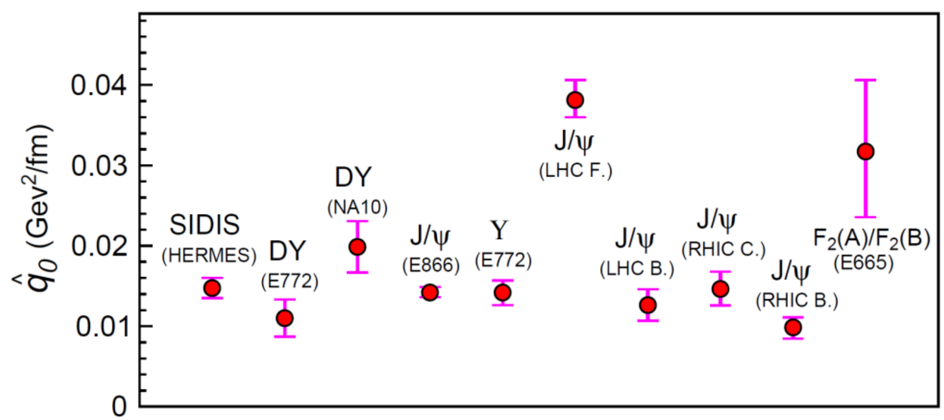
Extract $\hat{q}$ & study its kinematic dependence

Range of kinematics and probing scale (x and Q^2) covered by chosen data:



A test with a constant transport coefficient:

$$\hat{q} = \hat{q}_0$$



- A **constant** $\hat{q}$ can hardly describe different processes (or same process but in different kinematic regions) simultaneously.
- The fitted $\hat{q}$ values for individual observable can even **differ by a factor of 2 -- 4**.
- Indicating a non-trivial **kinematics and probing scale** (x and Q^2) dependence of $\hat{q}$.

Extract $\hat{q}$ & study its kinematic dependence

Parametrization of $\hat{q}(x, Q^2)$:

$$\hat{q}(x, Q^2) = \hat{q}_0 \alpha_s(Q^2) x^{\alpha} (1-x)^{\beta} [\ln(Q^2/Q_0^2)]^{\gamma}$$

4 parameters to be constrained by data:

$$\hat{q}_0,\ \alpha,\ \beta,\ \gamma$$

experiment	data type	data points	χ^2 (constant $\hat{q}$)	χ^2 $[\hat{q}\,(x_B, Q^2)]$
HERMES	SIDIS (p_T broad.)	156	218.5	189.7
FNAL-E772	DY (p_T broad.)	4	2.69	1.65
SPS-NA10	DY (p_T broad.)	5	6.86	6.47
FNAL-E772	Υ (p_T broad.)	4	2.33	2.67
FNAL-E866	J/ψ (p_T broad.)	4	2.03	2.45
RHIC	J/ψ (p_T broad.)	10	44.4	31.0
LHC	J/ψ (p_T broad.)	12	87.3	4.8
FNAL-E665	DIS (shadowing)	20	23.7	21.46
TOTAL:		215	387.9	260.2

χ^2/NDP=1.21

Table 1. Data sets used in the global analysis, and the χ^2 values with a constant $\hat{q}$ and $\hat{q}(x_B, Q^2)$, respectively.

Total χ^2 decreases with kinematic dependence taken into account.

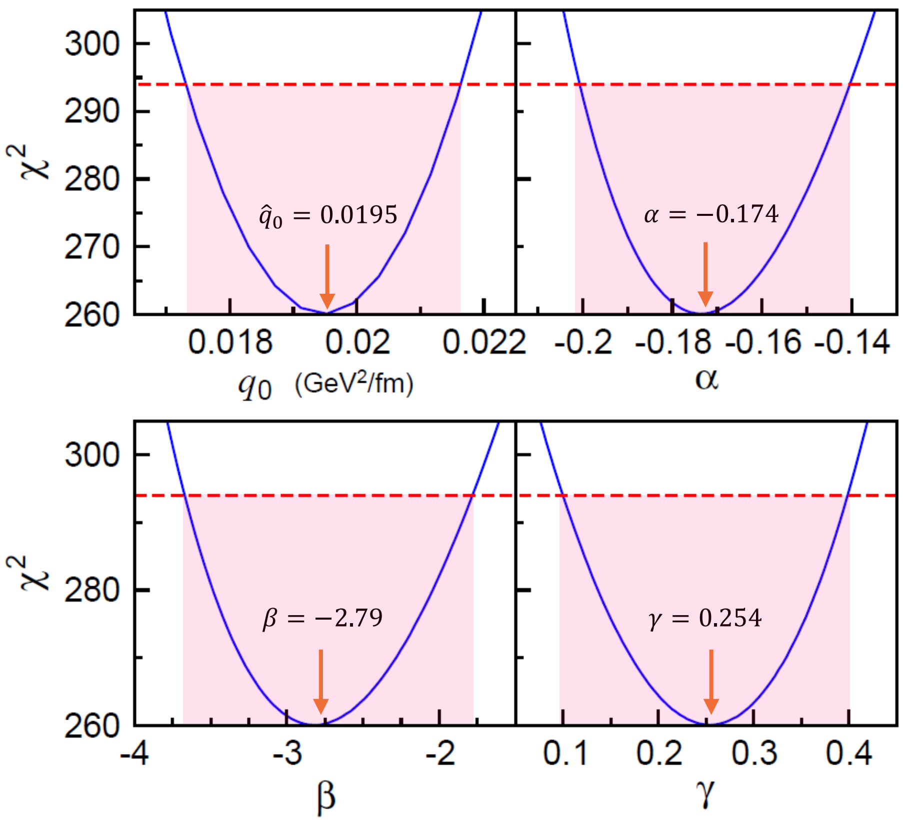
Extract $\hat{q}$ & study its kinematic dependence

Parametrization of $\hat{q}(x, Q^2)$:

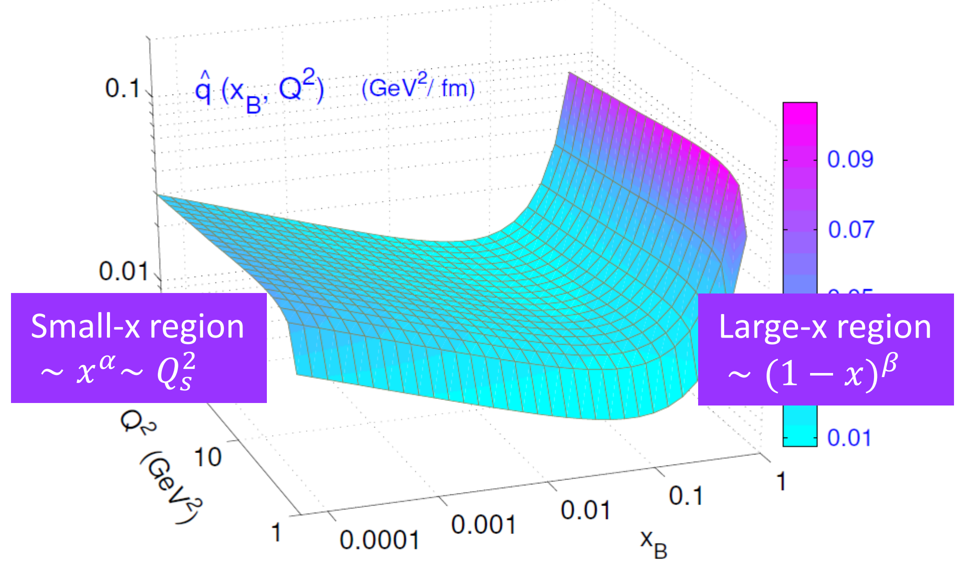
$$\hat{q}(x,Q^2) = \hat{q}_0 \alpha_s(Q^2) x^{\alpha} (1-x)^{\beta} [\ln(Q^2/Q_0^2)]^{\gamma}$$

4 parameters to be constrained by data:

$$\hat{q}_0,\ \alpha,\ \beta,\ \gamma$$



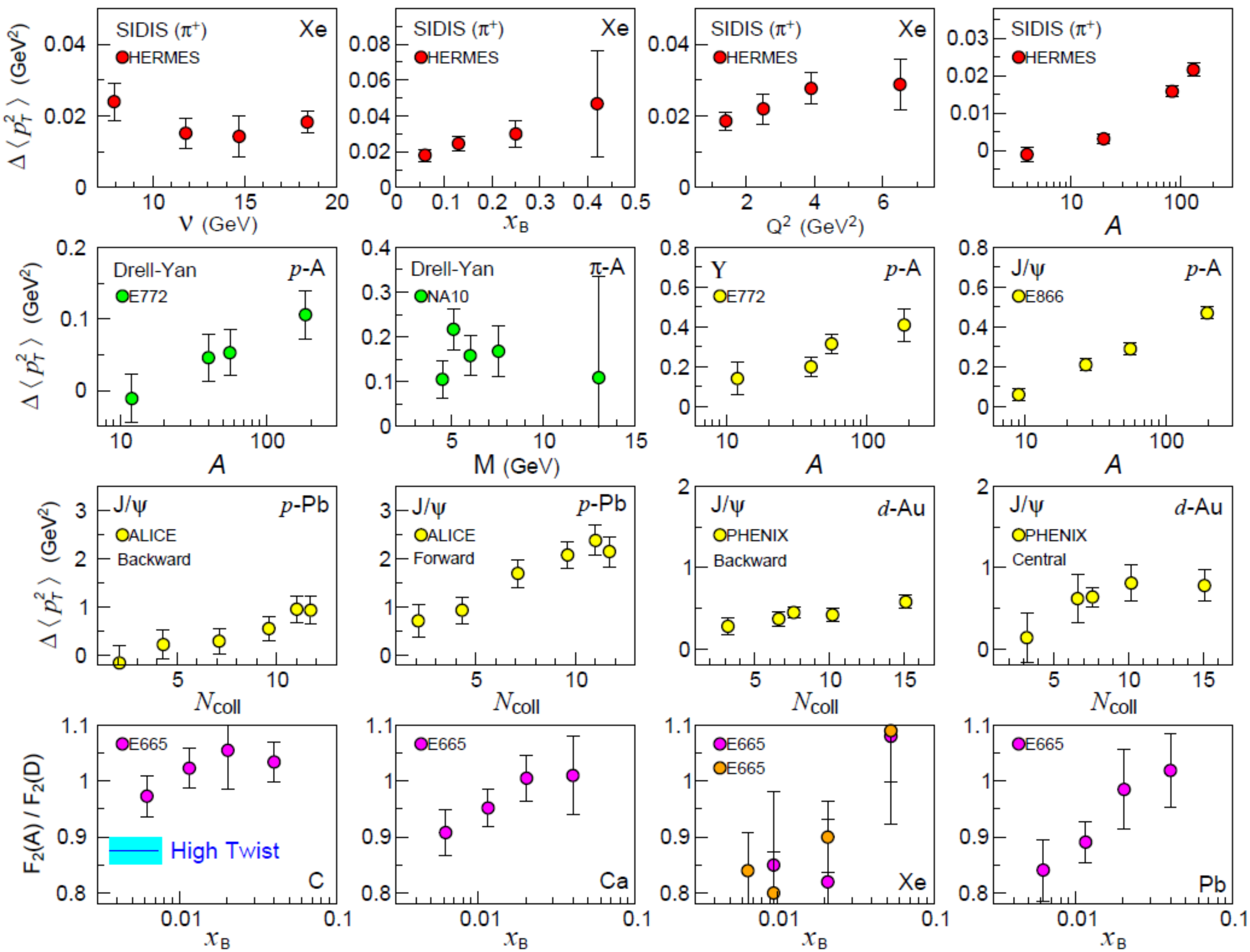
Optimal $\hat{q}(x_B, Q^2)$



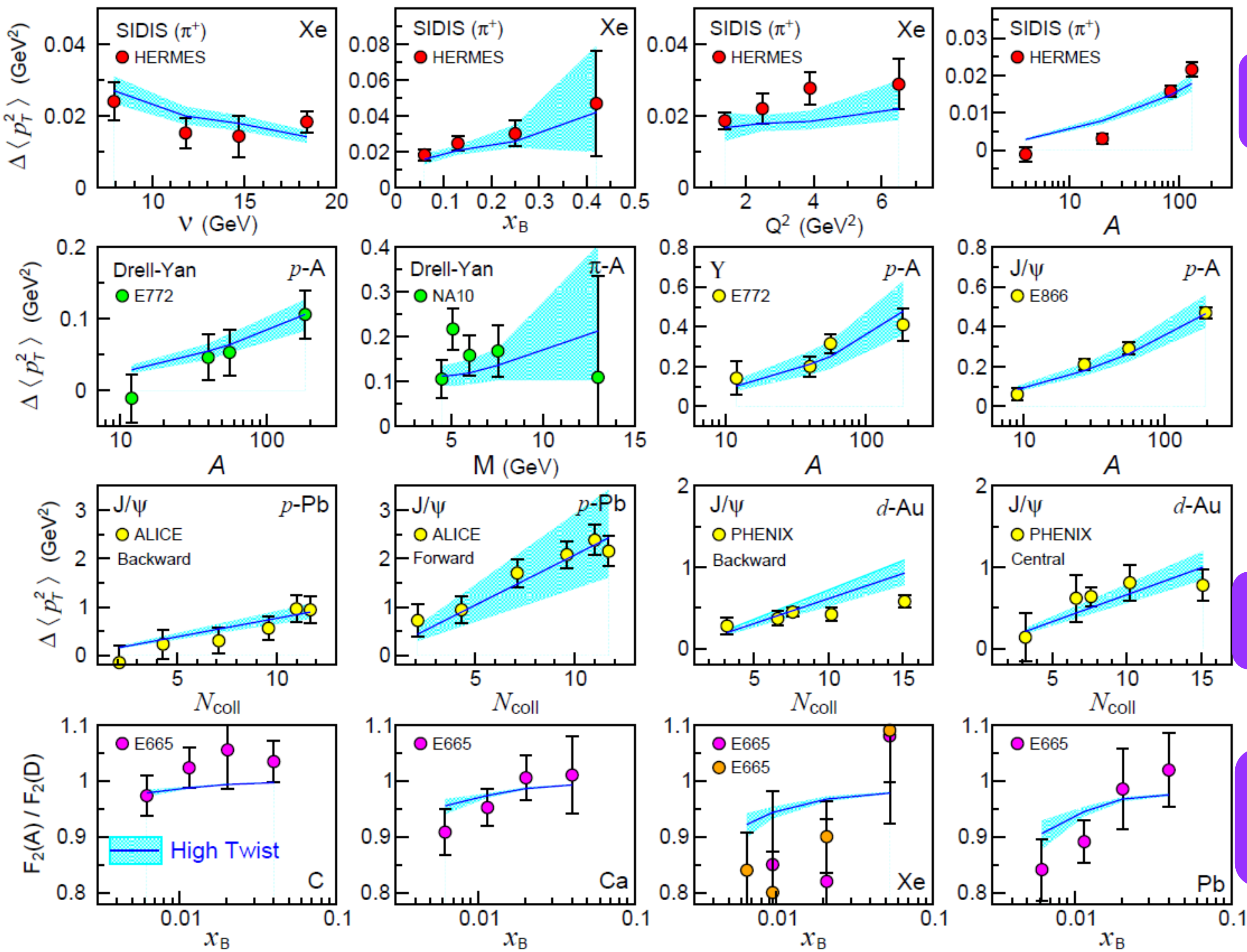
In a recent relevant work, (Arleo and Naïm, 2004.07188), $\hat{q}$ are extracted from DY and quarkonium data:

$$\hat{q}_A(x) = \hat{q}_0 \times \left(\frac{10^{-2}}{x}\right)^{\alpha} \qquad \alpha = 0.25 - 0.3$$

HT results with extracted $\hat{q}$



HT results with extracted $\hat{q}$



Increases with x at large x

$\sim A^{1/3}$

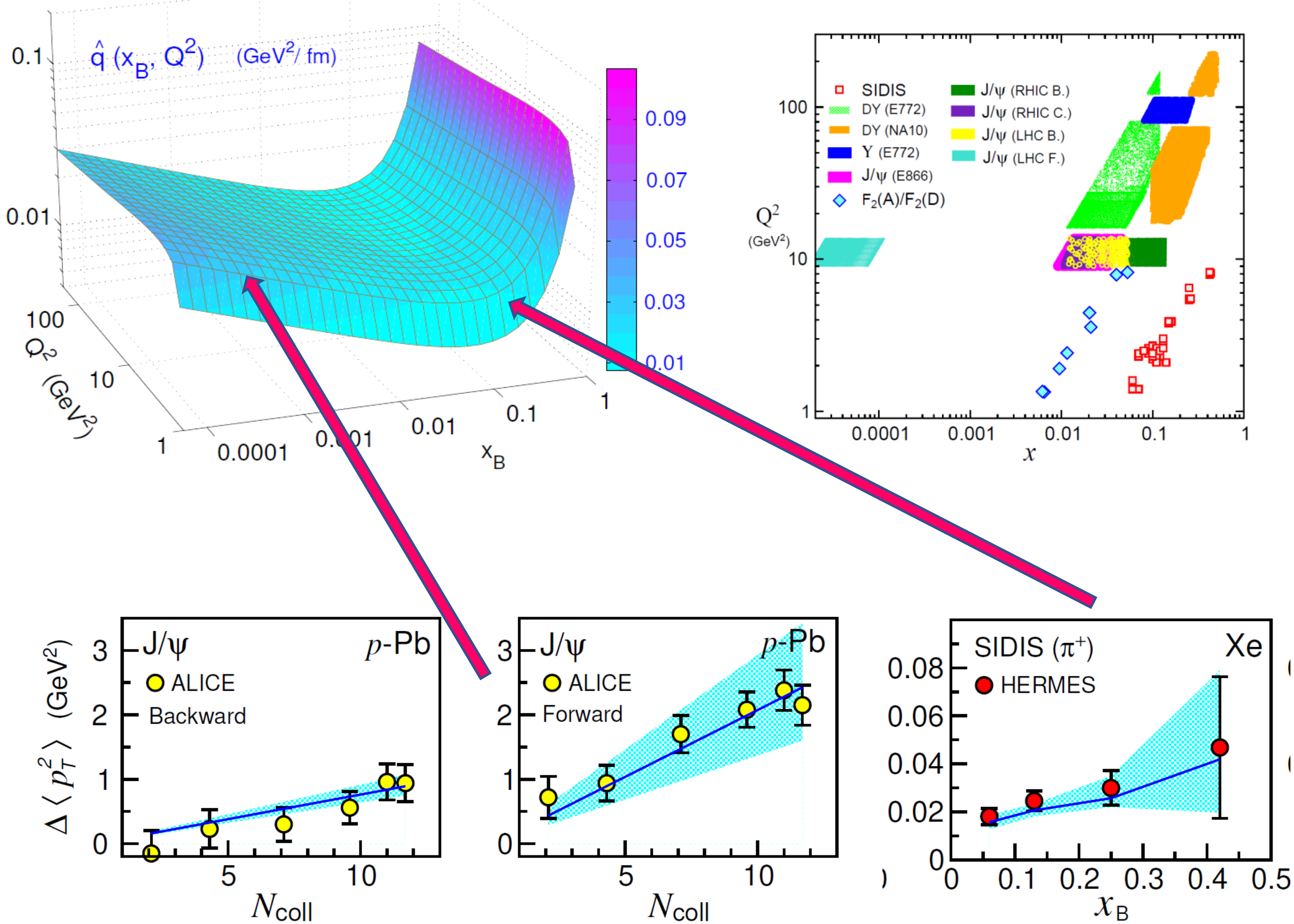
$\propto N_{coll}$

decreases with x at small x

Stronger shadowing for heavier nucleus

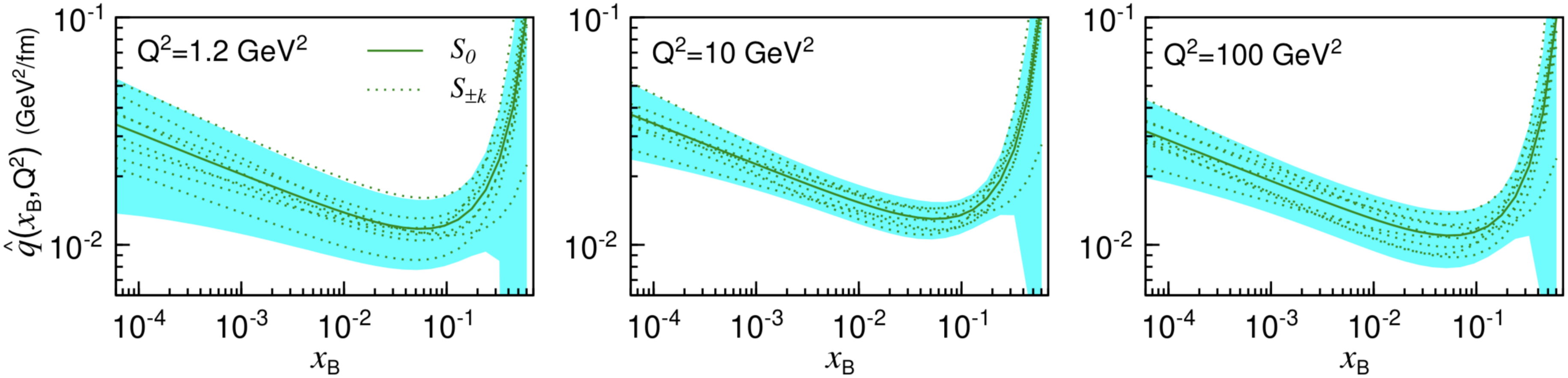
Kinematic dependence from the data

$$\hat{q}(x,Q^2)=\hat{q}_0\alpha_s(Q^2)x^{\alpha}(1-x)^{\beta}[\ln(Q^2/Q_0^2)]^{\gamma}$$



To make predictions for future measurement

In our previous work (1907.11808), the Lagrange multiplier method is used to evaluate the uncertainty of the observable, which is more robust but is not convenient to make further predictions with uncertainty.

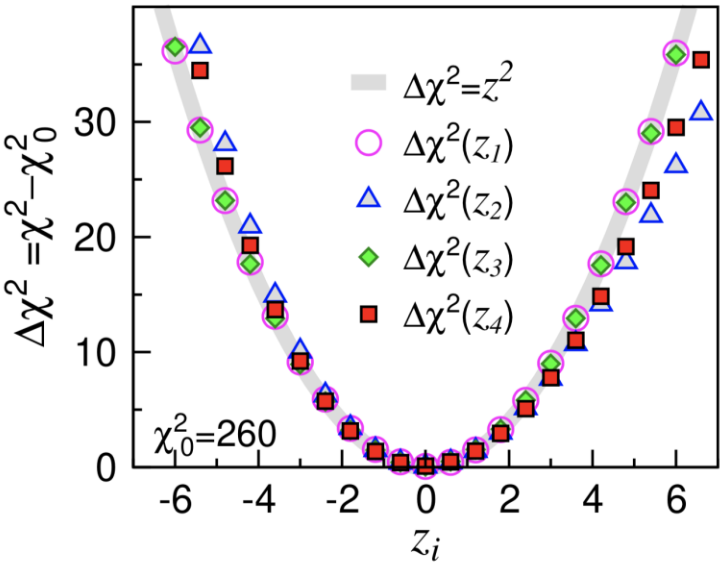


Recently, we have applied the Hessian matrix method [PRD,65,014011], which is widely used in the analysis of PDFs, to reanalysis the $\hat{\boldsymbol{q}}$ in cold nuclear matter.

Nine sets of $\hat{q}(x, Q^2)$ have been obtained, S_k,(k=-4,..0,..4), which can be used to evaluated the uncertainty of $\hat{\boldsymbol{q}}$ and predict observable with uncertainty in future.

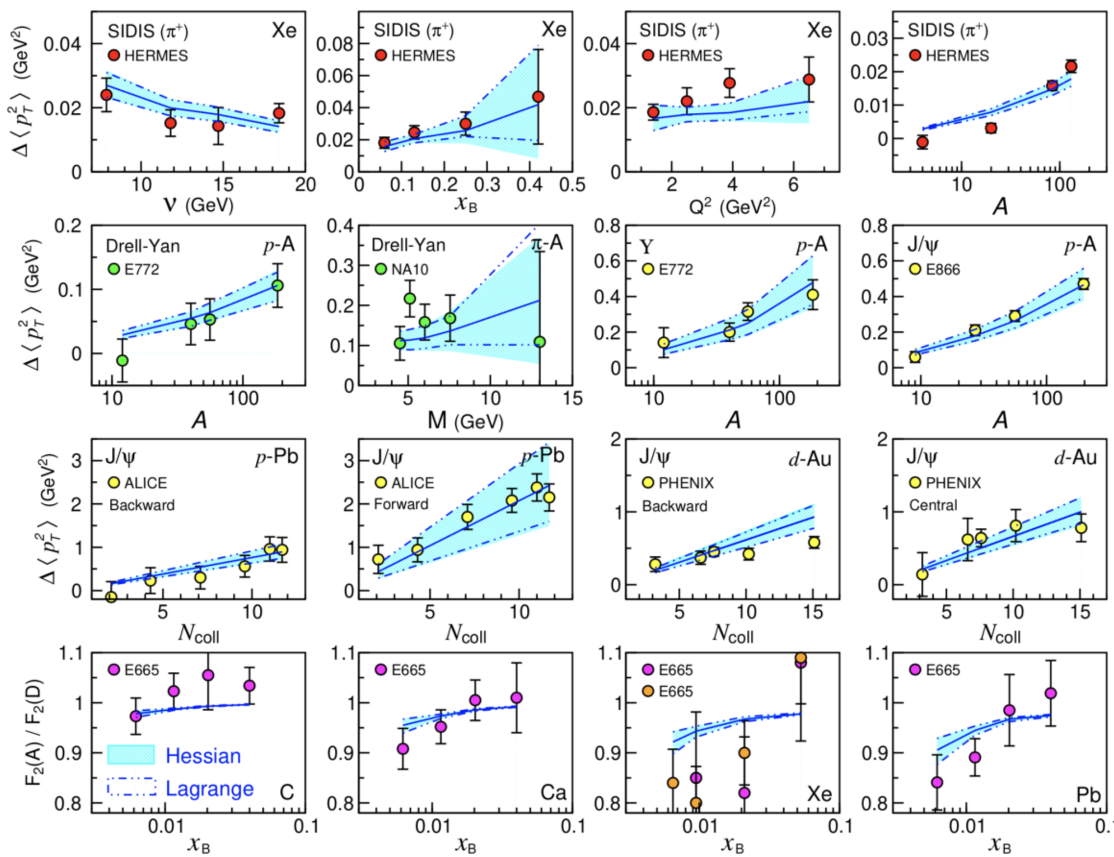
Reliability of the Hessian analysis

χ^2 vs. z_i (new basis)



The key of the Hessian method is to find a new set of parameter, z_i, in whose space the surfaces of any constant chi^2 are spheres. In an ideal case, the chi^2 would be a quadratic function of a z_i.

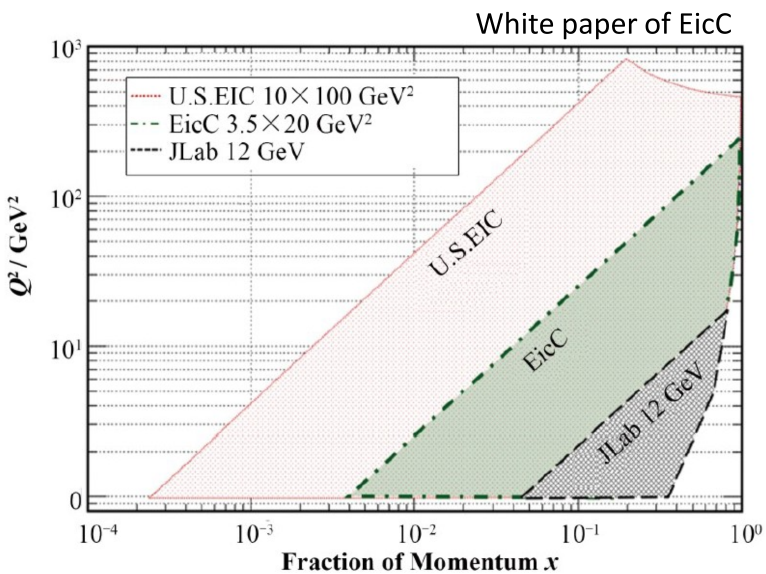
Comparison between Hessian approach and Lagrange multiplier method



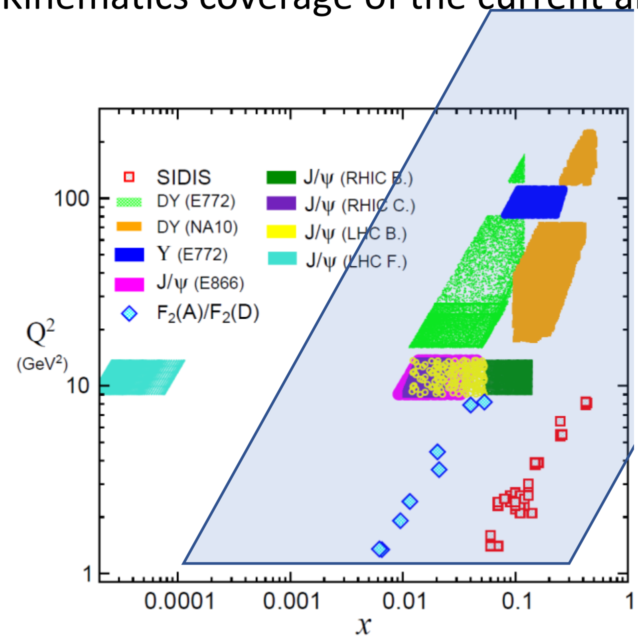
Good agreement between two methods.

How will EIC deepen our understanding

Kinematics coverage of future EIC facilities



Kinematics coverage of the current analysis



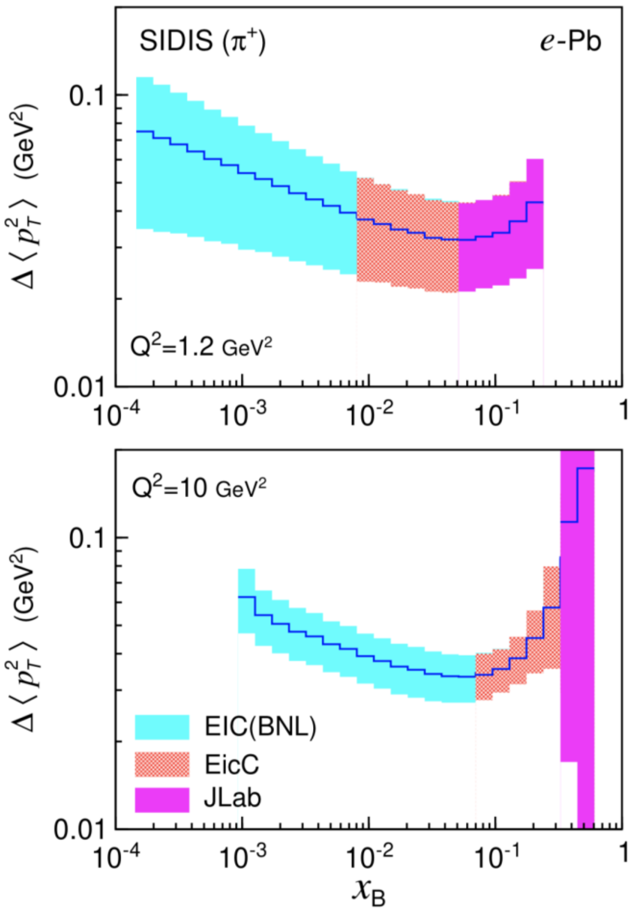
The future EIC experiments, e.g., EIC (BNL), JLab and EicC (China) will largely extend the coverage of kinematic region.

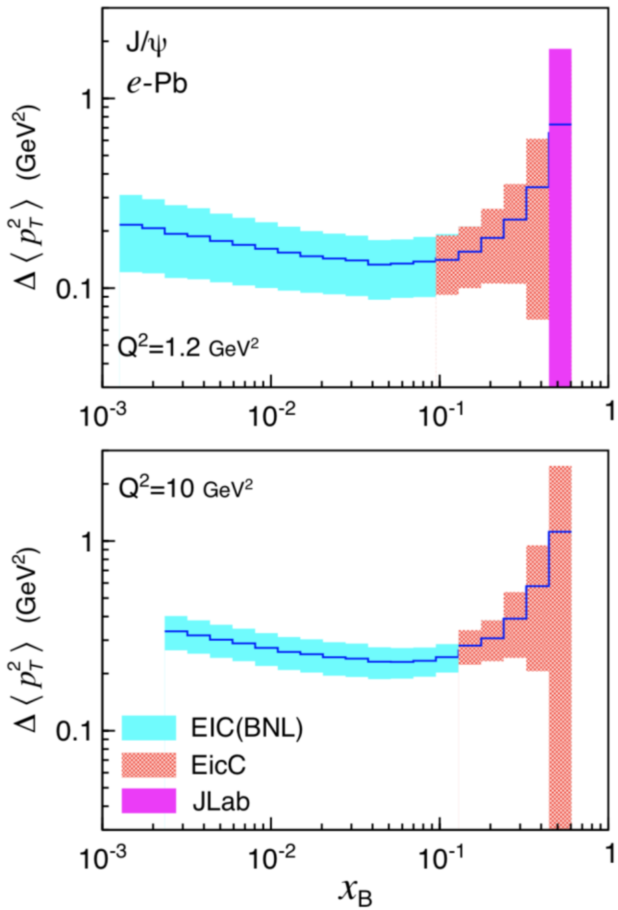
How will EIC deepen our understanding

Transverse momentum broadening for SIDIS and J/psi

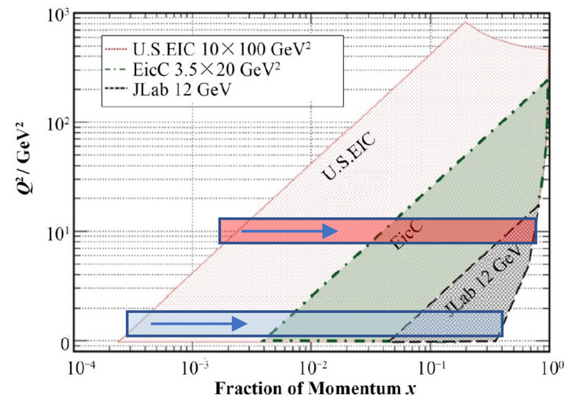
SIDIS

J/ψ



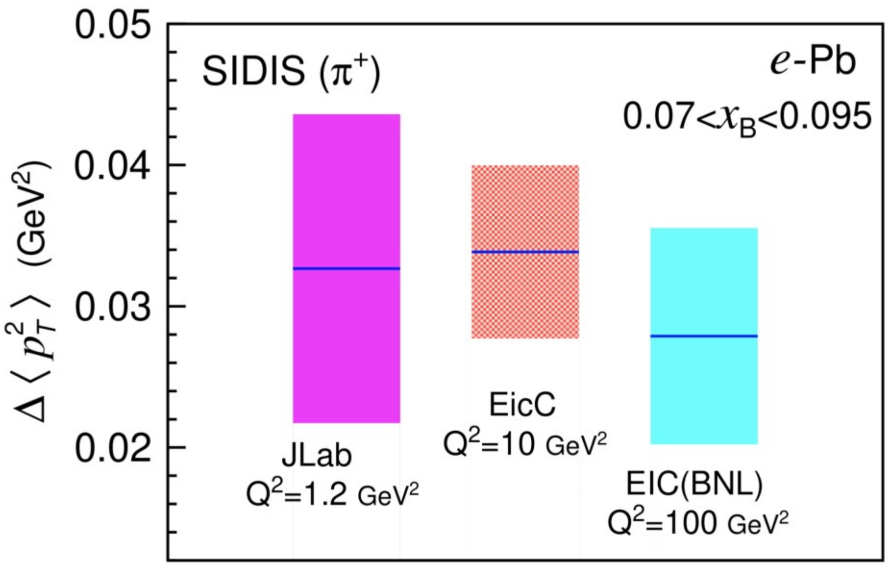


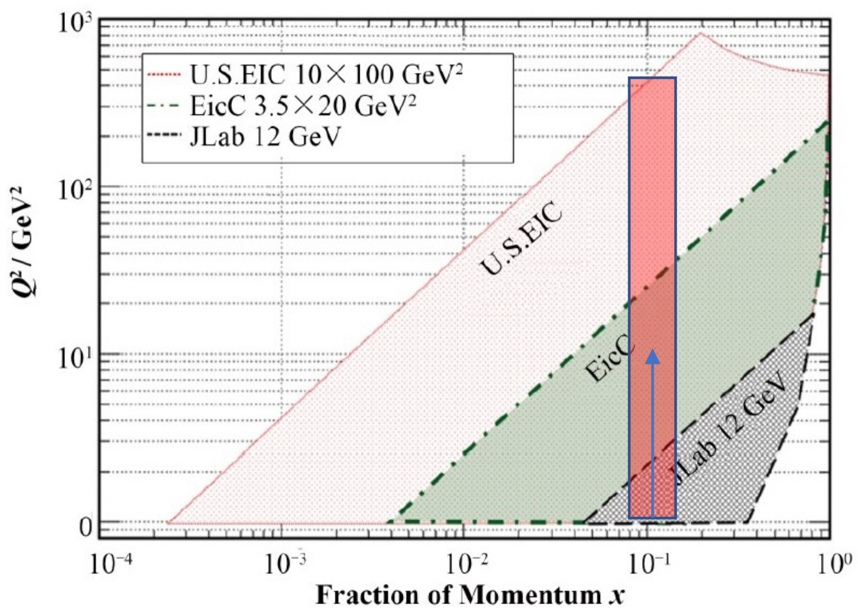
Bjorken-x scan



How will EIC deepen our understanding

Q^2 scan for SIDIS

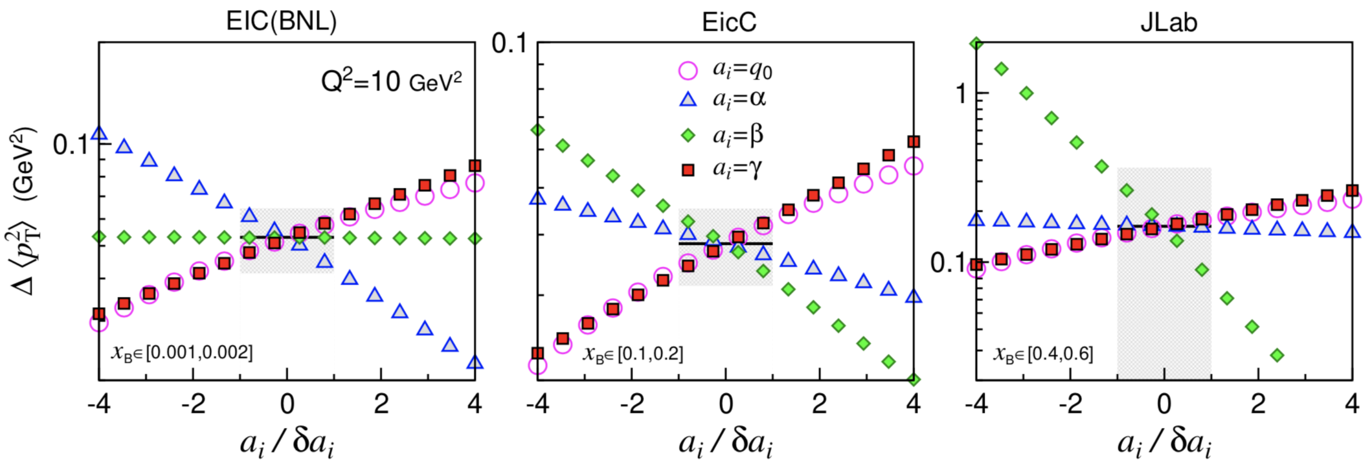




Measure the probing-scale evolution of $\hat{q}$

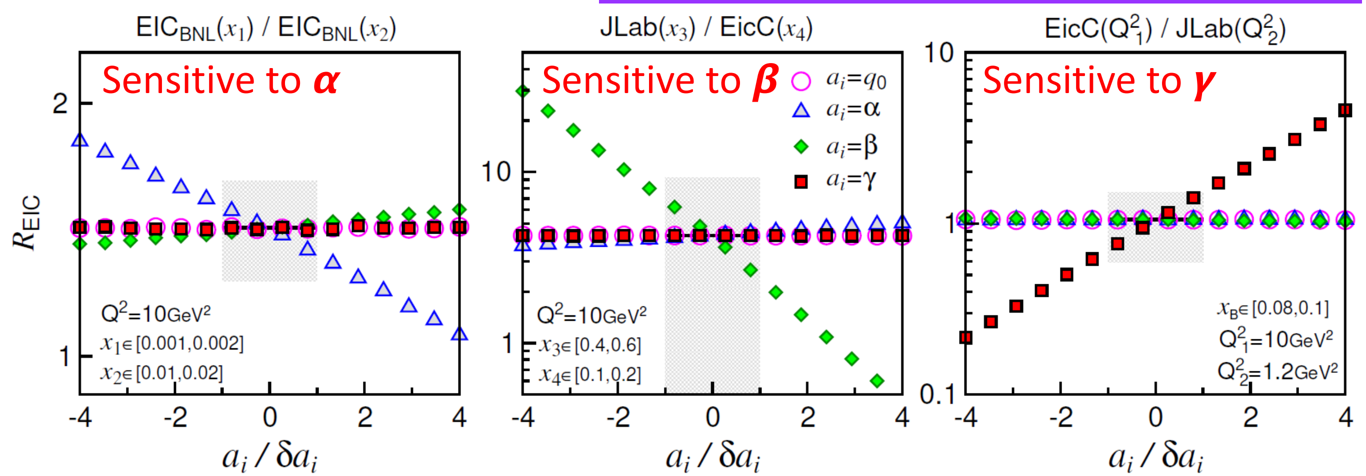
How will EIC deepen our understanding

The pT broadenings in different kinematic regions show different sensitivities to each parameter. Usually more than 3 sensitive parameters.



The **combination** (e.g., ratio) of different kinematic regions can effectively **reduce** the number of sensitive parameters.

$$\hat{q}(x, Q^2) = \hat{q}_0 \alpha_s(Q^2) x^{\alpha}(1-x)^{\beta}[\ln(Q^2/Q_0^2)]^{\gamma}$$



Summary

- A non-trivial x and Q dependence of $\hat{q}$ is indicated by the results. First quantitative evidence.
- Higher-twist framework is able to describe the included various types of data.
- The results may be informative for jet quenching in QGP.
  --Jet-energy dependence? (e.g., Casalderrey-Solana and Wang, PRC 77, 024902 (2008))
- In future, more data in a wider kinematic range may be useful to examine the results.
- Hessian analysis of $\hat{q}$ allow predictions with uncertainty for future measurement.
- Preliminary predictions for future EIC.

Thank you for your attentions!

Thank the organizers!

Backup

Parametrization of kinematic dependence

$$\hat{q}(x,Q^2) = \hat{q}_0 \alpha_s(Q^2) x^{\alpha} (1-x)^{\beta} [\ln(Q^2/Q_0^2)]^{\gamma}$$

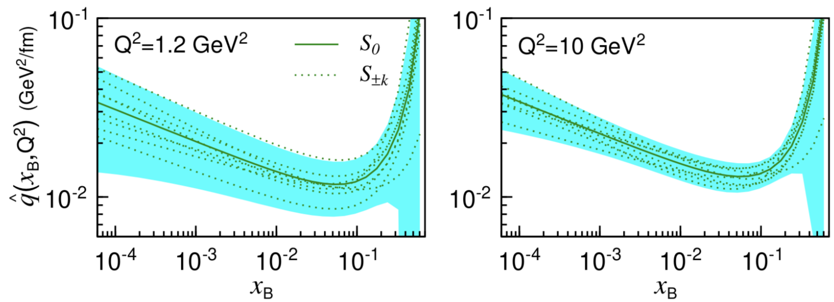
See also the talk by H. Xing at QM19

normalization

small-x saturation $\sim Q_s^2 \sim x^{\alpha}$

Large-x power correction

Scale dependence radiative corrections



Iancu, JHEP 10, 095 (2014)
Blaizot, Mehtar-Tani, Nucl. Phys. A929, 202 (2014).

Dokshitzer, Marchesini, Webber, Nucl. Phys. B469, 93 (1996),
Brodsky, hep-ph/0006310

Iancu, Venugopalan, hep-ph/0303204.
Kang, Qiu, Phys. Rev. D77, 114027 (2008)

Compared to the parametrization of PDFs:

J. Pumplin, et al, CTEQ6, JHEP07(2002)012

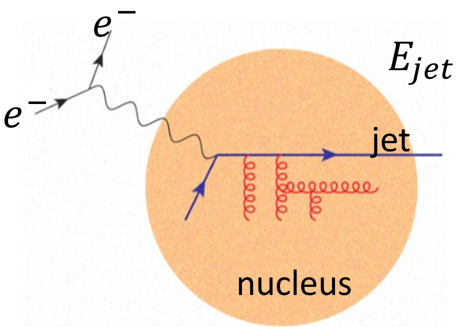
The functional form that we use is

$$x\, f(x,Q_0) = A_0\, x^{A_1}\, (1-x)^{A_2}\, e^{A_3 x}\, \left(1+e^{A_4}\, x\right)^{A_5} \tag{2.4}$$

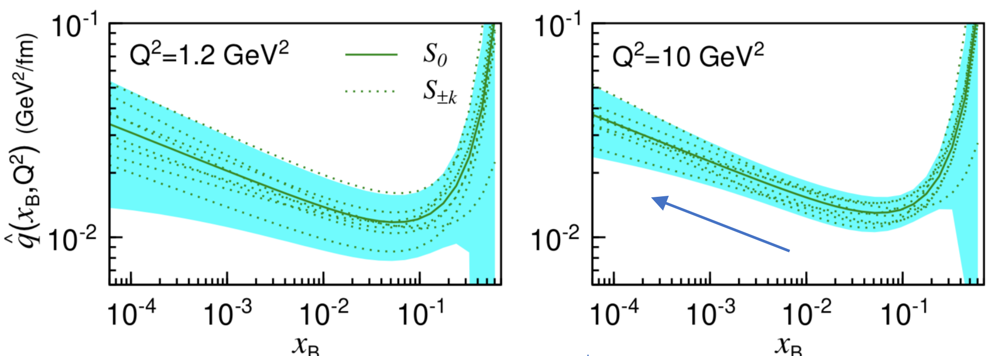
with independent parameters for parton flavor combinations $u_v \equiv u-\bar{u}$, $d_v \equiv d-\bar{d}$, g, and $\bar{u}+\bar{d}$. We assume $s=\bar{s}=0.2\,(\bar{u}+\bar{d})$ at Q_0. The form (2.4) is "derived" by including a 1:1 Padé expansion in the quantity $d[\log(xf)]/dx$. This logarithmic derivative has an especially simple form for the time-honored canonical parametrization $x\,f(x) = A_0\, x^{A_1}\, (1-x)^{A_2}$. For our parametrization there are poles at $x=0$ and $x=1$ to represent the singularities associated with Regge behavior at small x and quark counting rules at large x, along with a ratio of (linear) polynomials to describe the intermediate region in a smooth way.

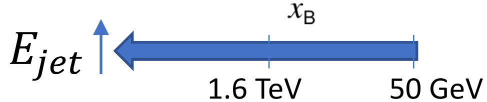
Jet-energy dependence of the $\hat{q}$ in CNM & QGP

In DIS, jet energy in the target rest frame:



$$E_{jet} = \nu = \frac{Q^2}{2mx_B}$$





$\hat{q}$ Increases with jet energy

J. Casalderrey-Solana and X.-N. Wang, PRC 77, 024902 (2008)

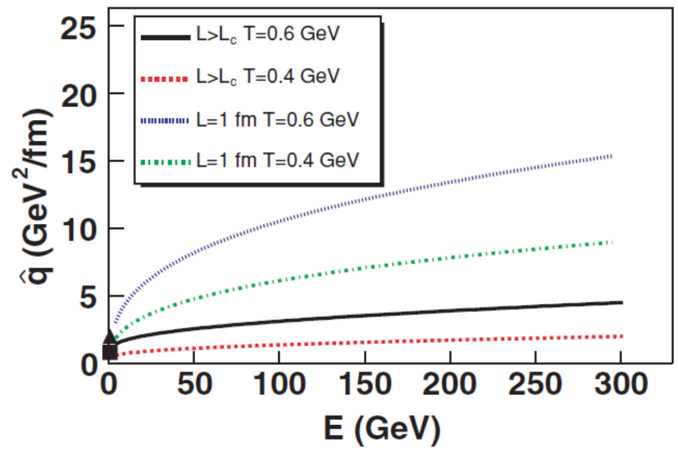
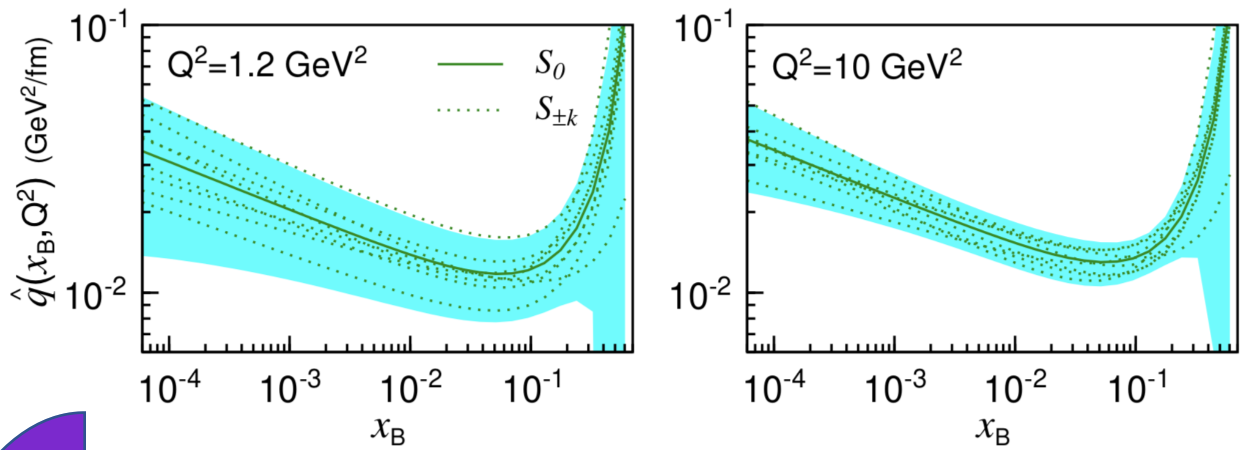


FIG. 6. (Color online) Jet quenching parameter $\hat{q}$ as a function of the jet energy. The square (triangle) marks the the value of $\hat{q}$ for thermal particle at $T = 0.4$ GeV ($T = 0.6$ GeV). Significant corrections to the energy dependence are expected at low energy which should approach their thermal value at $E = 3T$.

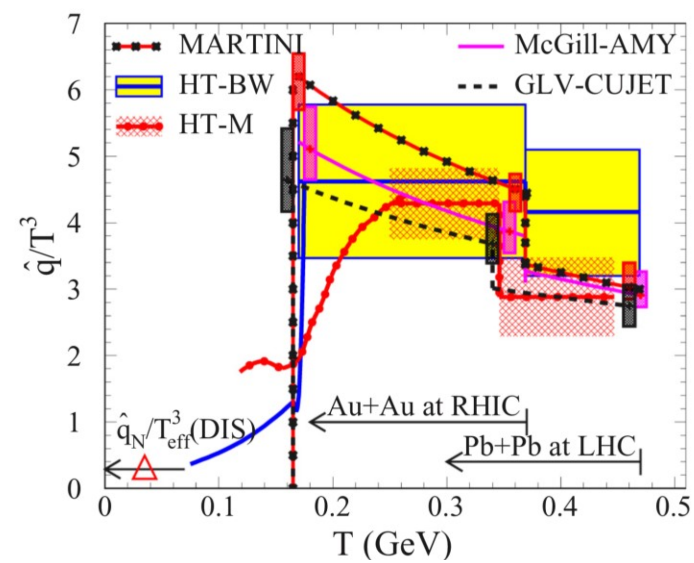
$\hat{q}$ Increases with jet energy in QGP

Compared to the $\hat{q}$ in QGP



In CNM

~ X 30-100



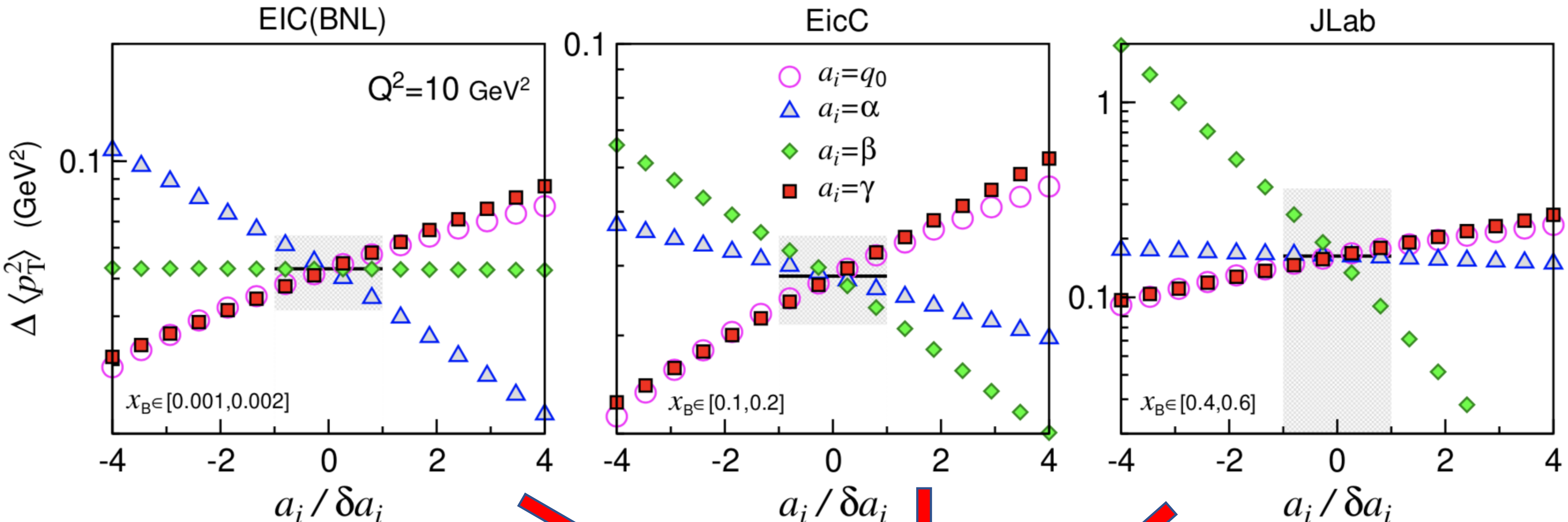
In QGP

JET, PRC 90, 014909 (2014)

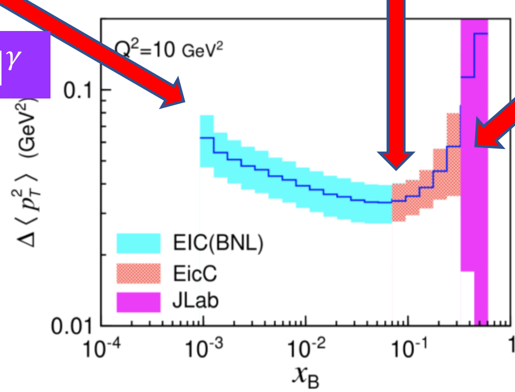
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{at} \quad \begin{array}{l} T = 370\ \mathrm{MeV}, \\ T = 470\ \mathrm{MeV}, \end{array}$$

How will EIC deepen our understanding

The pT broadenings in different kinematic regions show different sensitivities to each parameter. Usually, an observable is sensitive to more than 3 of the four parameters.



$$\hat{q}(x,Q^2) = \hat{q}_0\alpha_s(Q^2)x^{\alpha}(1-x)^{\beta}[\ln(Q^2/Q_0^2)]^{\gamma}$$



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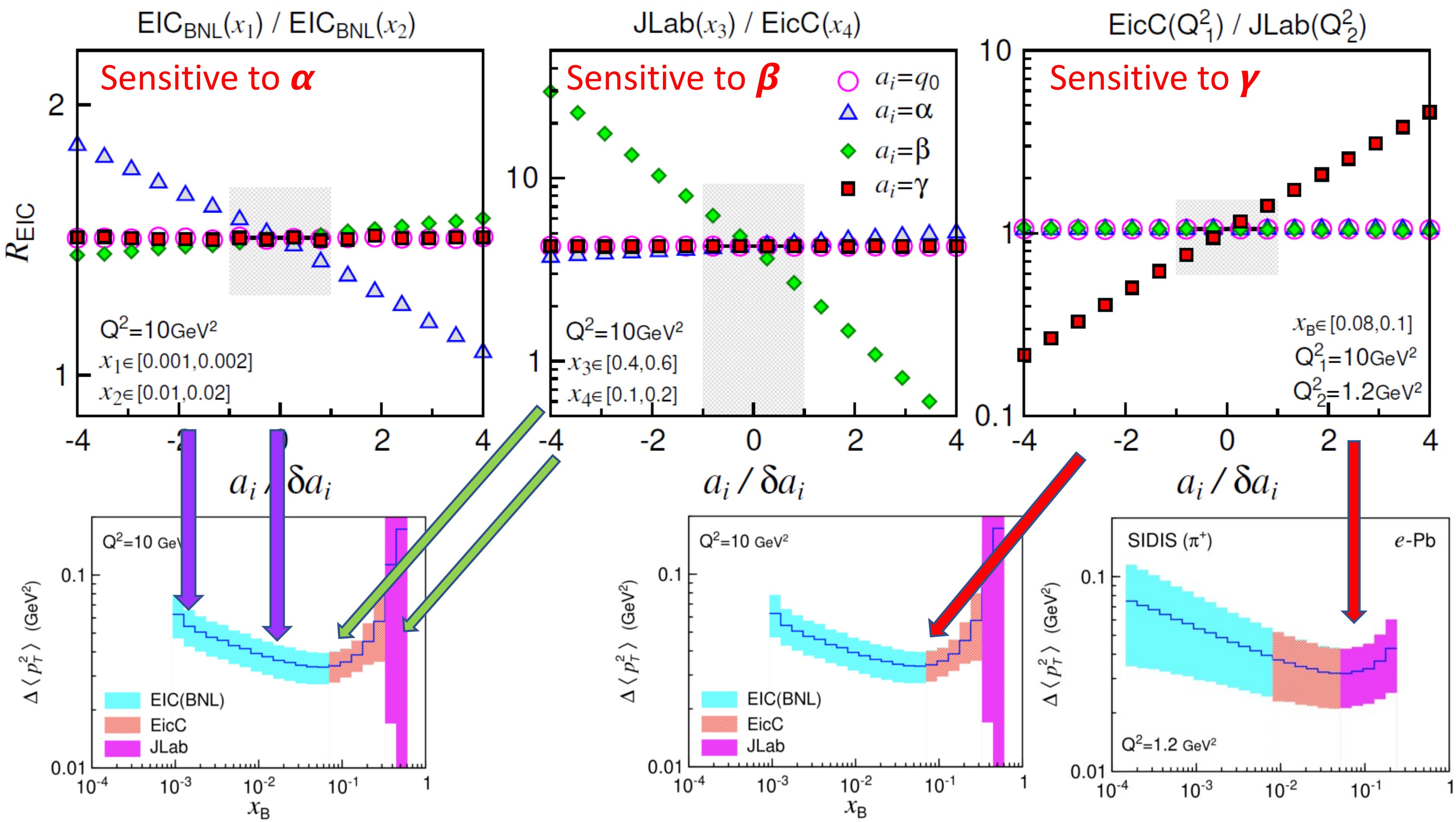
The **combination** (e.g., ratio) of different kinematic regions can effectively **reduce** the number of sensitive parameter.

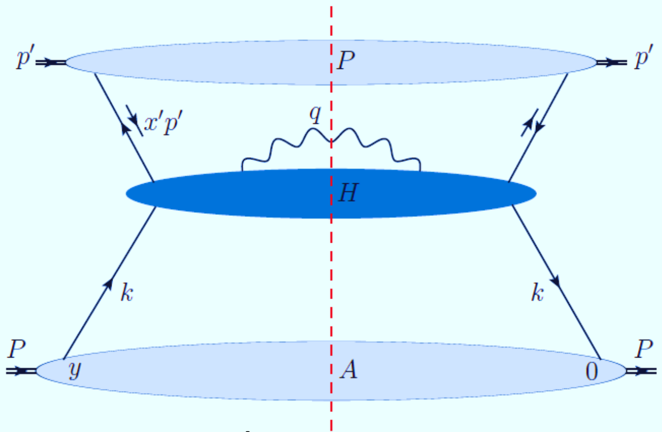
$$\hat{q}(x,Q^2)=\hat{q}_0\alpha_s(Q^2)x^{\alpha}(1-x)^{\beta}[\ln(Q^2/Q_0^2)]^{\gamma}$$



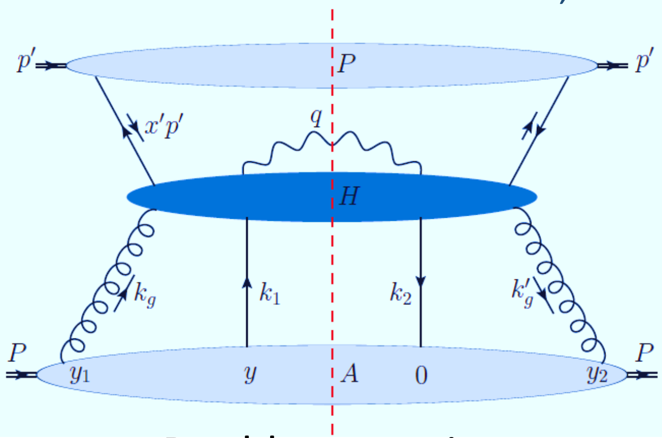
Multiple parton scattering in HT framework

Transverse momentum broadening for Drell-Yan (DY) dilepton production in pA

Kang, Qiu, PRD 77, 114027 (2008)
Kang, Qiu, Wang, Xing, PRD 94, 074038 (2016)



Single scattering



Double scattering

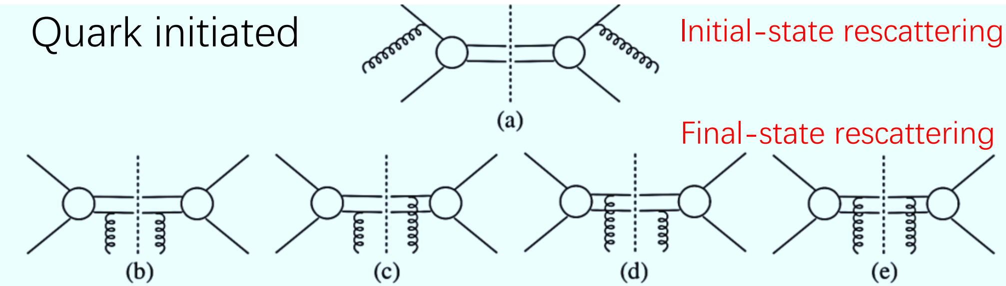
Transverse momentum broadening:

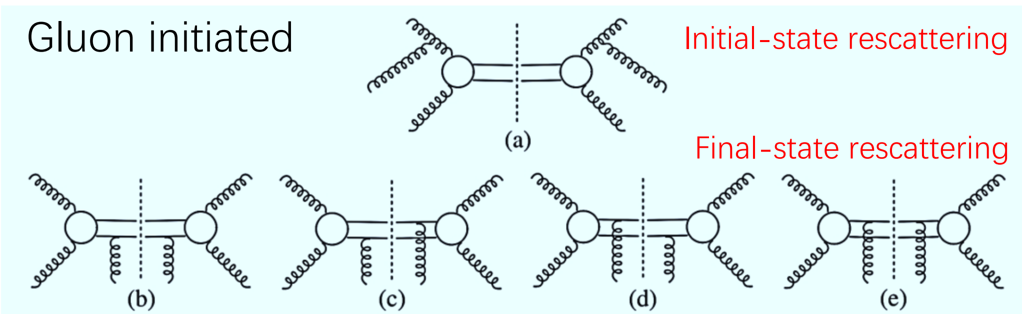
$$\Delta\langle p_T^2\rangle = \frac{4\pi^2\alpha_s}{N_c}\frac{\sum_q e_q^2\int \frac{dx'}{x'} f_{\bar{q}/p}(x',\mu^2)T_{qg}(x,\mu^2)}{\sum_q e_q^2\int \frac{dx'}{x'} f_{\bar{q}/p}(x',\mu^2)f_{q/A}(x,\mu^2)} \approx \frac{3R_A}{2}\frac{\sum_q e_q^2\int \frac{dx'}{x'} f_{\bar{q}/p}(x',\mu^2)f_{q/A}(x,\mu^2)\,\hat{q}(x,\mu^2)}{\sum_q e_q^2\int \frac{dx'}{x'} f_{\bar{q}/p}(x',\mu^2)f_{q/A}(x,\mu^2)}$$

Multiple parton scattering in HT framework

Transverse momentum broadening of heavy quarkonium(J/ψ, Υ) production in pA

Kang, Qiu,
PRD 77, 114027 (2008)
PLB 721, 277 (2013)





Transverse momentum broadening:

Color Evaporation model:

$$\Delta\langle p_T^2\rangle^{CEM} = \frac{3R_A\,\hat{q}_0}{2}\frac{(1+C_A/C_F)\sigma_{q\bar{q}} + 2C_A/C_F\sigma_{gg}}{\sigma_{q\bar{q}}+\sigma_{gg}}$$

NRQCD effective theory:

$$\Delta\langle p_T^2\rangle^{NRQCD} = \frac{3R_A\,\hat{q}_0}{2}\frac{(1+C_A/C_F)\sigma_{q\bar{q}}^{(0)} + 2C_A/C_F\sigma_{gg}^{(0)} + \sigma_{q\bar{q}}^{(1)}/C_F}{\sigma_{q\bar{q}}^{(0)}+\sigma_{gg}^{(0)}}$$

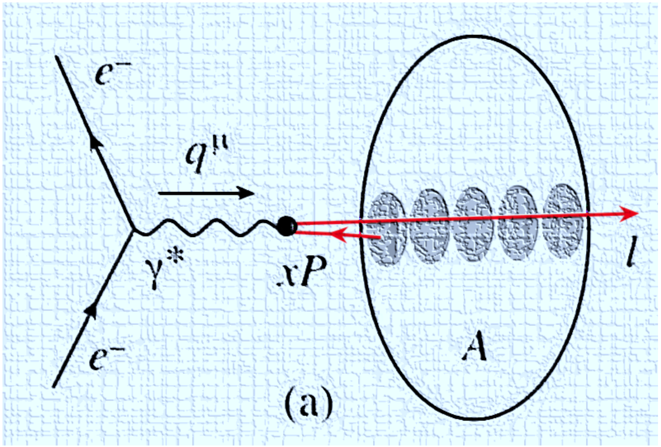
Twsit-4 gluon-gluon correlation function:

$$T_{gg}(x) = \int\frac{dy^-}{2\pi}e^{ixp^+y^-}\int\frac{dy_1^- dy_2^-}{2\pi}\theta(-y_2^-)\theta(y^- - y_1^-)\frac{1}{xp^+}\langle p_A|F_\alpha^+(y_2^-)F^{\sigma+}(0)F_\sigma^+(y^-)F^{\alpha+}(y_1^-)|p_A\rangle$$

Multiple parton scattering in HT framework

Dynamical shadowing in DIS nuclear structure function

Qiu, Vitev, PRL 93, 262301 (2004)



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

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

$$F_L^A(x,Q^2) \approx A F_L^{(\mathrm{LT})}(x,Q^2) + \sum_{n=0}^{N} \frac{A}{n!}\left(\frac{4\xi^2}{Q^2}\right) \times \left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n \frac{d^n F_T^{(\mathrm{LT})}(x,Q^2)}{d^n x}$$

$$\approx A F_L^{(\mathrm{LT})}(x,Q^2) + \frac{4\xi^2}{Q^2} F_T^A(x,Q^2),$$

Nuclear modification ratio:

$$R_{AD}(x,Q^2) = \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}$$

$$F_T^{(\mathrm{LT})}(x,Q^2) = \frac{1}{2}\sum_f Q_f^2 \phi_f(x,Q^2) + \mathcal{O}(\alpha_s)$$

$$F_L^{(\mathrm{LT})}(x,Q^2) = \mathcal{O}(\alpha_s),$$

$$F_2(x,Q^2) = 2x[F_L(x,Q^2) + F_T(x,Q^2)]$$