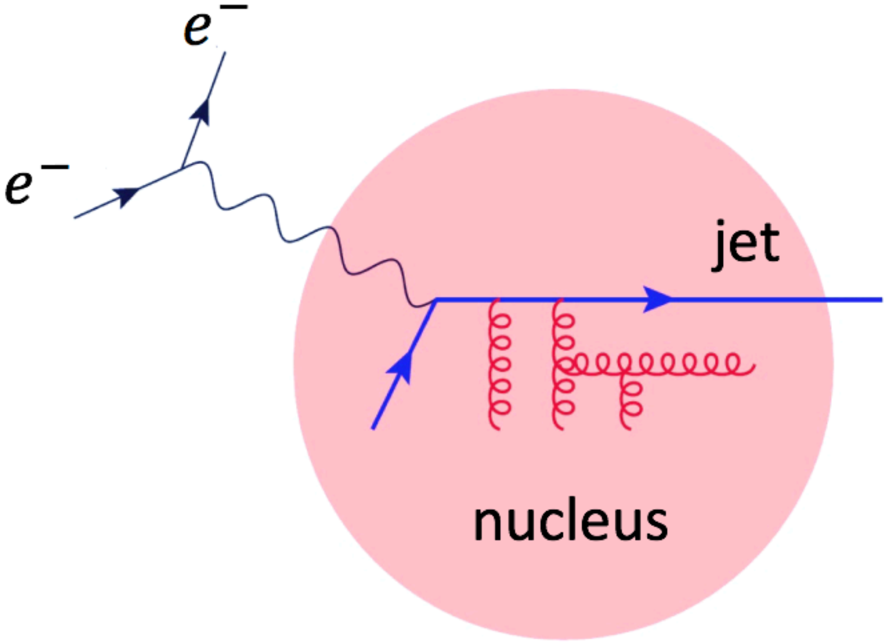
Kinematics dependent jet transport coefficient in cold nuclear matter



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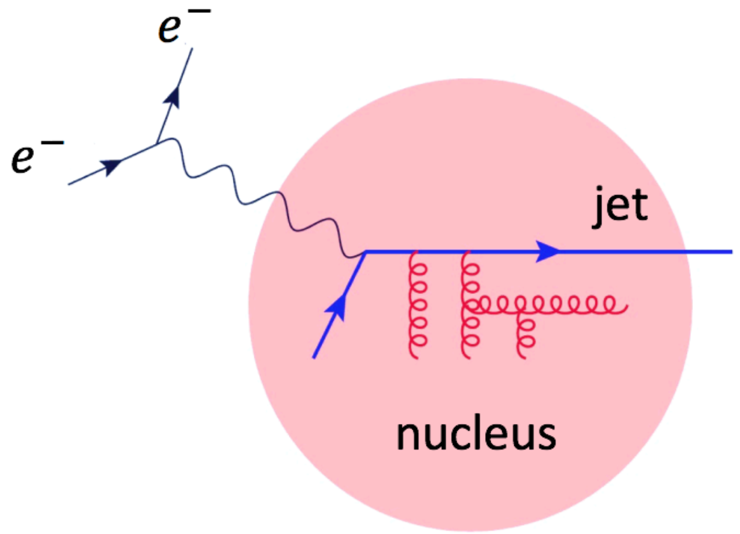
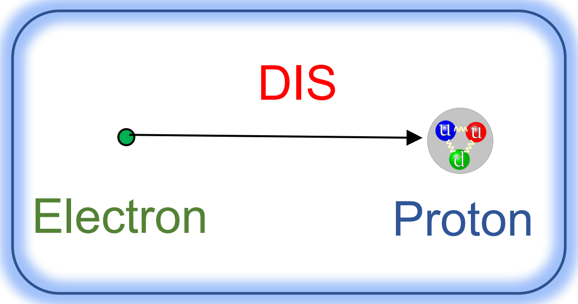
Santiago de Compostela 05.05.2022

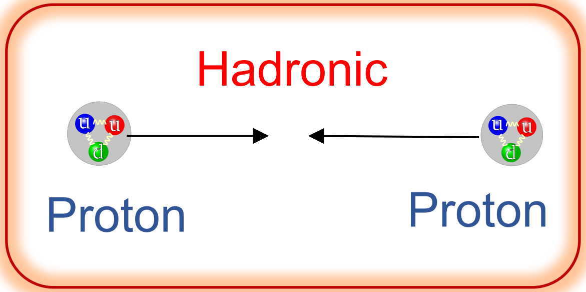
Outline

- Jets as a hard probe of nuclear matter property
  ---- from quark-gluon plasma (QGP) to cold nuclear matter (CNM).
- Extracting jet transport coefficient $\hat{q}$ in CNM.
  ---- A global analysis of world data within high-twist factorization.
- Results: kinematics dependent $\hat{q}$ and its uncertainty.
- Jet energy dependence of $\hat{q}$
- Future study at EIC /RHIC/ LHC.
- Summary.

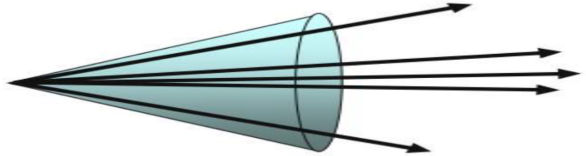


Jets as a hard probe of nuclear matter property

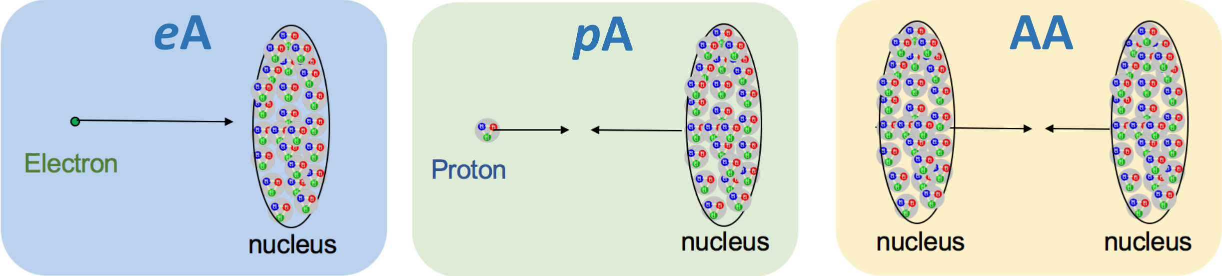




Hard scattering processes :
energetic partons in initial and/or final states.

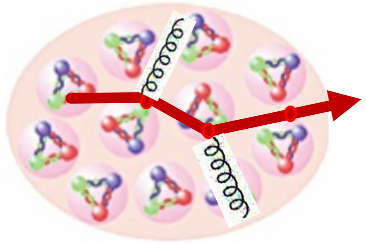


Replacing hadron with nucleus

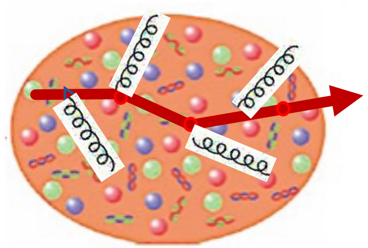


The presence of nuclear-medium environments
in high-energy eA, pA and AA collisions.

Jet encounters nuclear medium

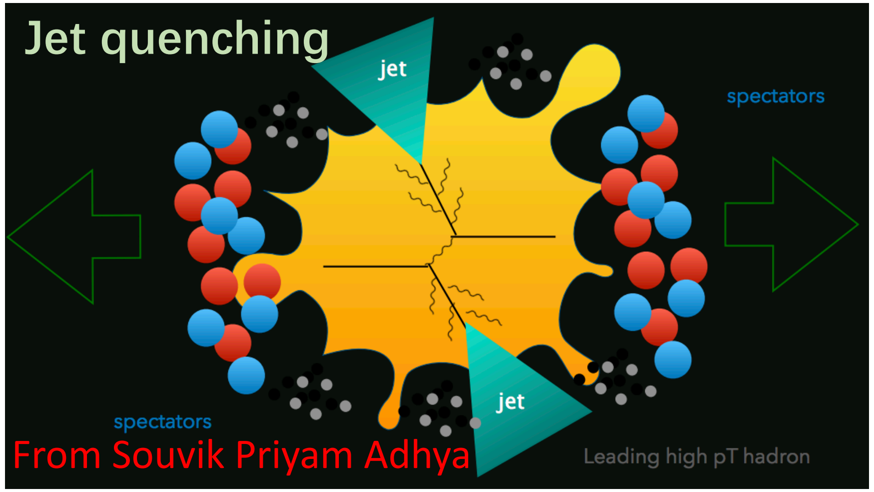


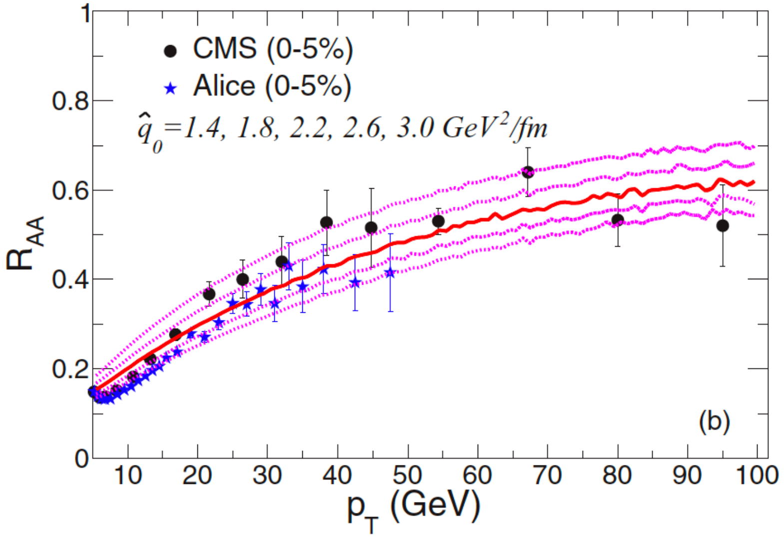
Cold nuclear matter
(Confined)



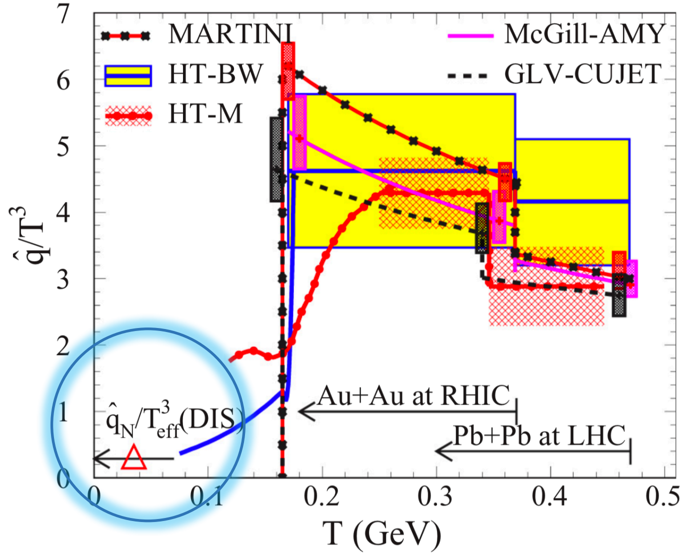
Quark gluon plasma
(Deconfined)

Jet quenching in heavy-ion collisions



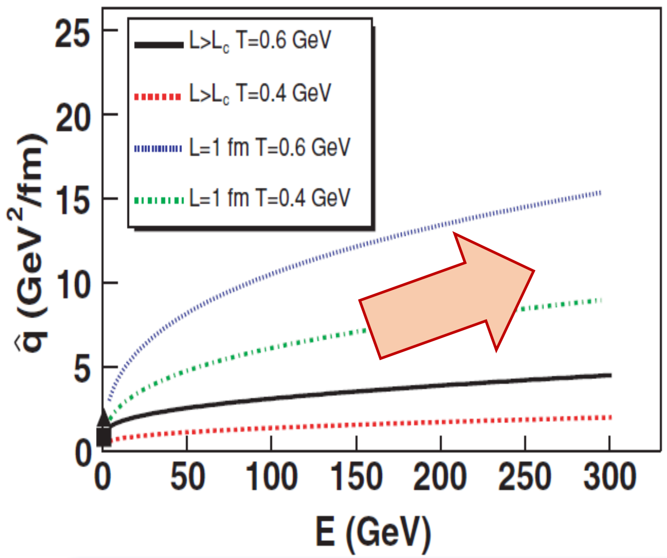


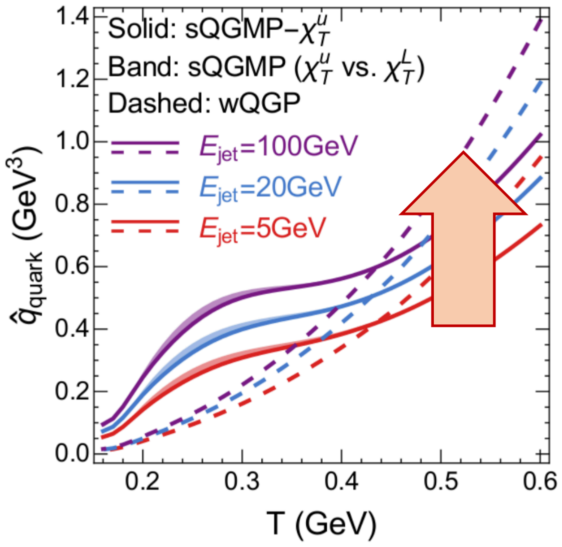
JET, PRC 90, 014909 (2014)

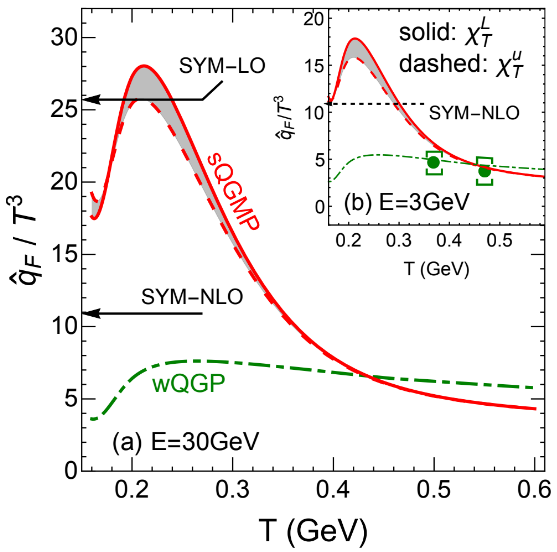


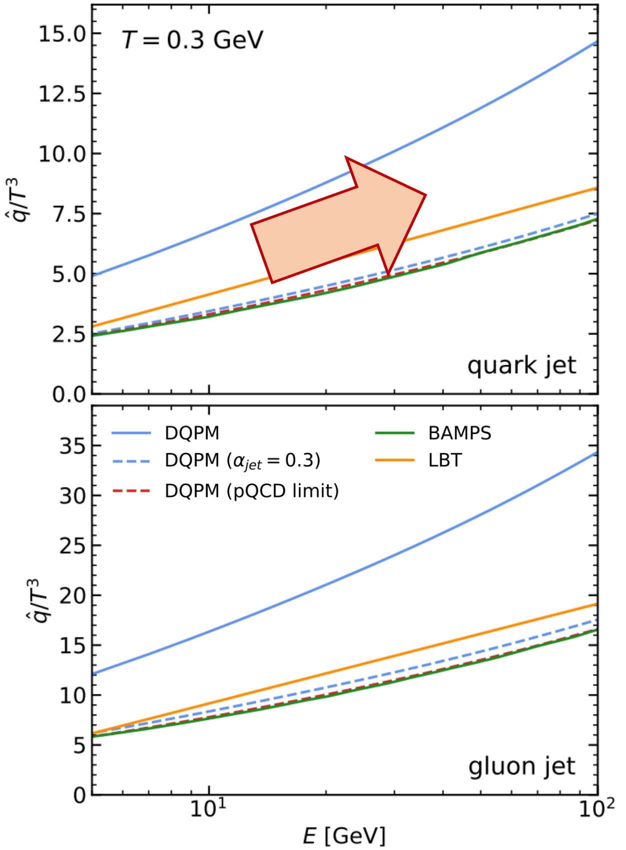
- $\hat{q}$ is an important **non-perturbative** input in jet-quenching models.
- Transverse momentum broadening per unit length for propagating parton.
- Characterize **interaction strength** between hard probe and nuclear medium.
- **Medium property** is encoded in $\hat{q}$.

$\hat{q}$ for quark-gluon plasma: jet energy dependence









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

$$\hat{q}_R = \frac{4\pi^2 C_R}{N_c^2-1}\rho \int_0^{\mu^2} \frac{d^2 q_T}{(2\pi)^2} \int dx\, \delta\left(x - \frac{q_T^2}{2p^-\langle k^+\rangle}\right) \times \alpha_s(q_T^2)\phi(x, q_T^2),$$

A. Kumar, A. Majumder, C. Shen PRC 101, 034908 (2020)

$$\hat{q}(\mu^2, q^-) = \frac{1}{L^-}\int d^2k_\perp k_\perp^2 \frac{d^2\hat{\sigma}}{d^2k_\perp}\int_0^{L^-} dy^-\rho(y^-) \times \int_{(k_\perp^2/2p^+q^-)}^{1} dx_N G(x_N, \mu^2).$$

M. Gyulassy, QM19, 2012.06151

S. Shi, J. Liao, M. Gyulassy, 1808.05461

$$\hat{q}_F(E,T) = \int_0^{6ET} dq_\perp^2 \frac{2\pi}{(\boldsymbol{q}_\perp^2 + f_E^2\mu^2(\boldsymbol{z}))(\boldsymbol{q}_\perp^2 + f_M^2\mu^2(\boldsymbol{z}))}\rho(T) \times \Big\{ [C_{qq}f_q + C_{qg}f_g]\cdot[\alpha_s^2(\boldsymbol{q}_\perp^2)]\cdot[f_E^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] + [C_{qm}(1-f_q-f_g)]\cdot[1]\cdot[f_M^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})]\Big\},$$

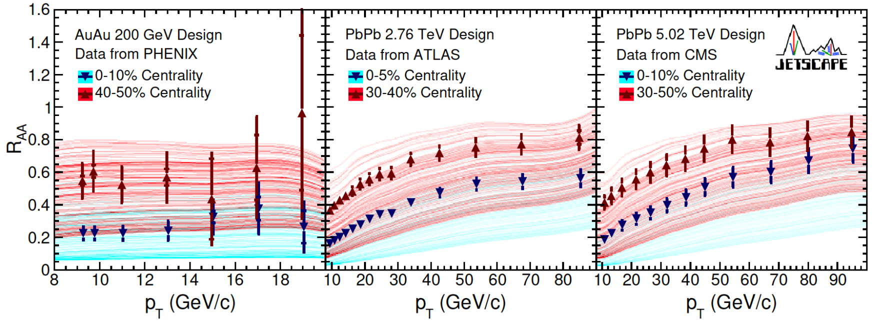
I. Grishmanovskii et al., 2204.01561

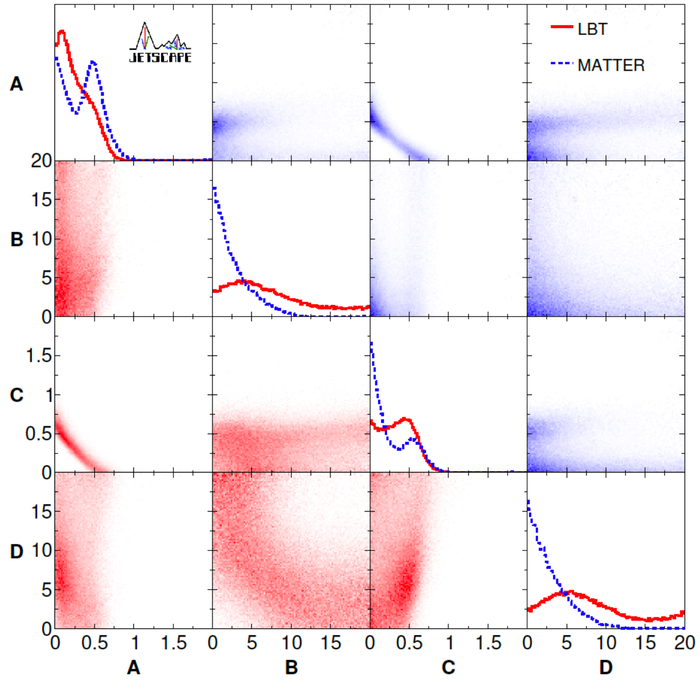
Gluon density in medium is usually used in theoretical descriptions.

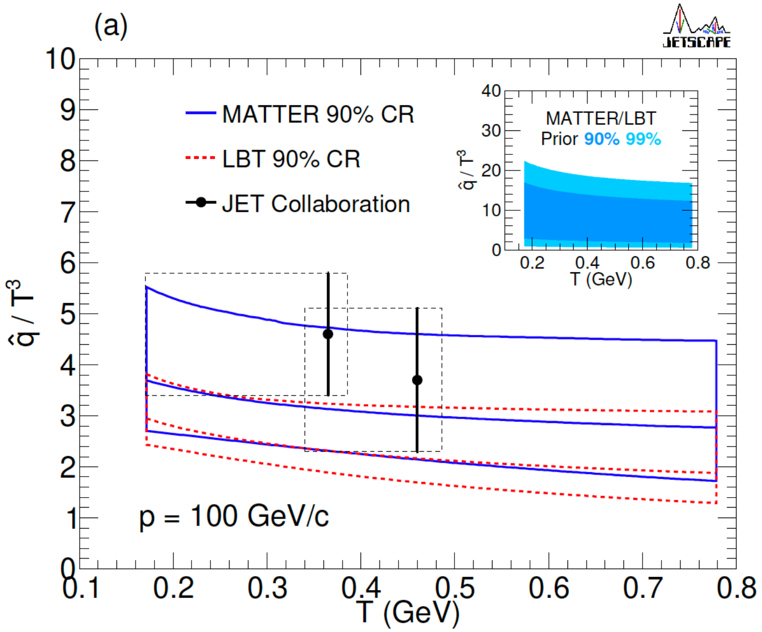
An increase with jet energy can be observed in general.

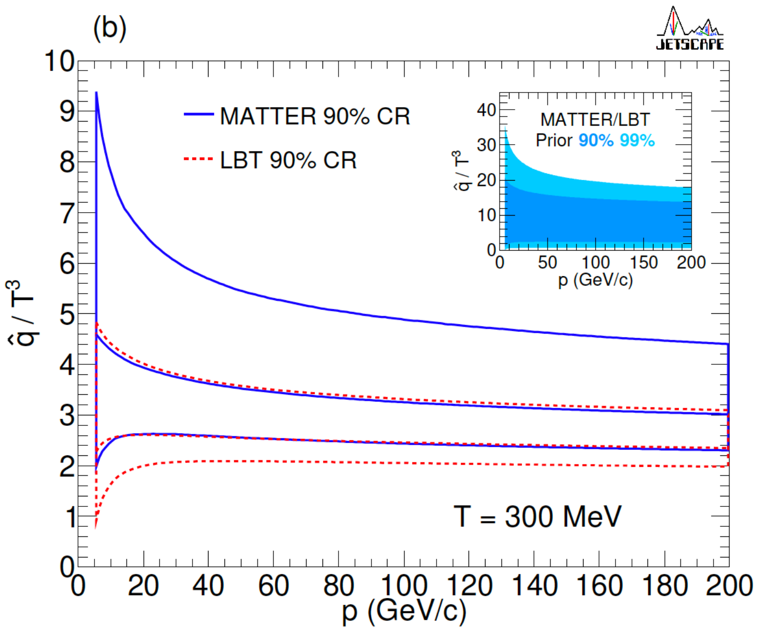
$\hat{q}$ for quark-gluon plasma from Bayesian analysis

JETSCAPE, PRC **104**, 024905 (2021)









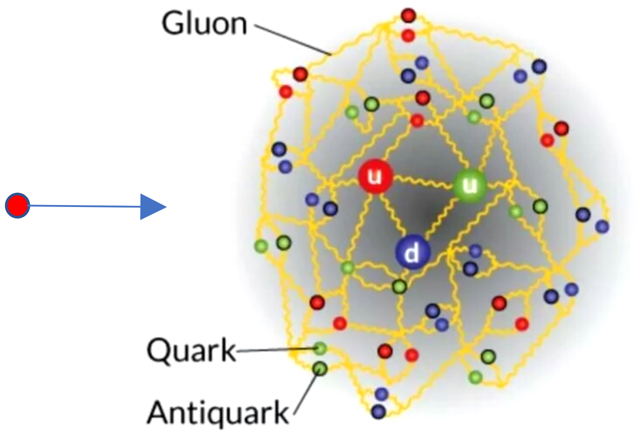
Consistent with JET

No clear energy dependence

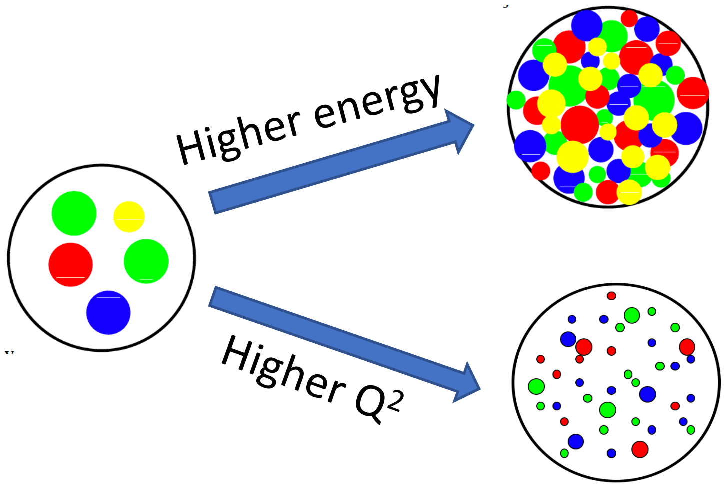
$$\frac{\hat{q}(Q,E,T)|_{Q_0,A,C,D}}{T^3} = 42C_R\frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2\left\{\frac{A\left[\ln\left(\frac{Q}{\Lambda}\right)-\ln\left(\frac{Q_0}{\Lambda}\right)\right]}{\left[\ln\left(\frac{Q}{\Lambda}\right)\right]^2}\theta(Q-Q_0)+\frac{C\left[\ln\left(\frac{E}{T}\right)-\ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}\right\}.$$

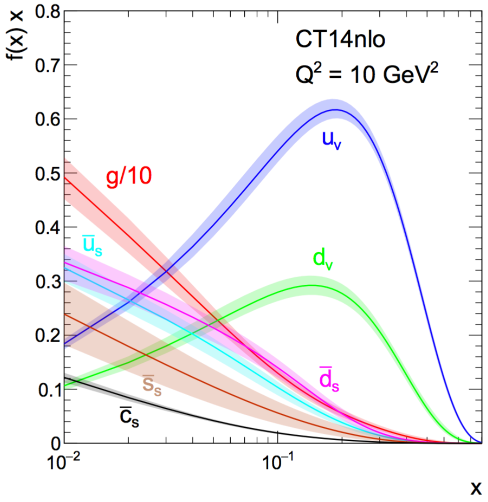
May be limited by both Exp. data and parametrization form.
The dependence on jet energy is not yet fully understood.

Why kinematic dependence is important

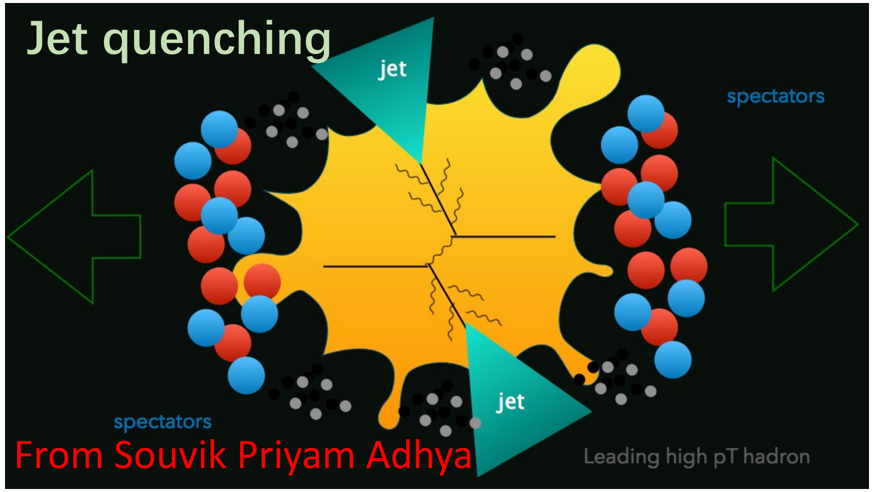


Kinematic dependence of
partonic structure of nucleon/nucleus:





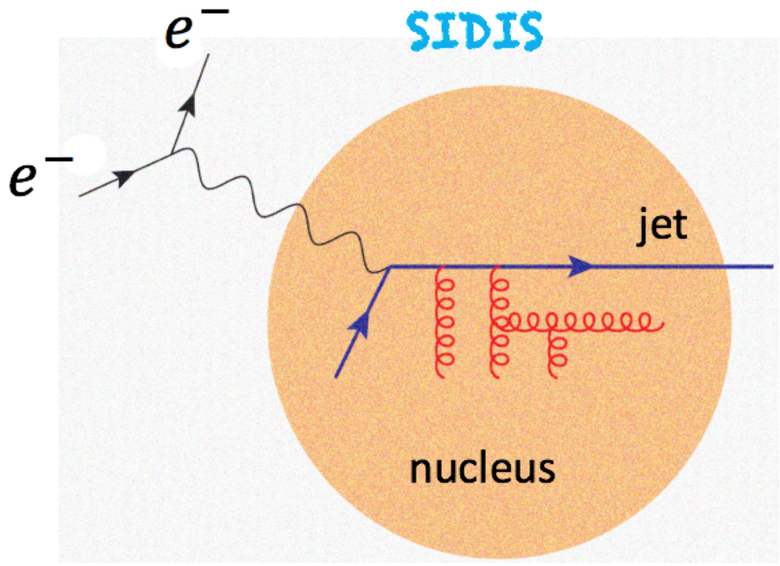
Nucleon structure:
global analysis based on factorization

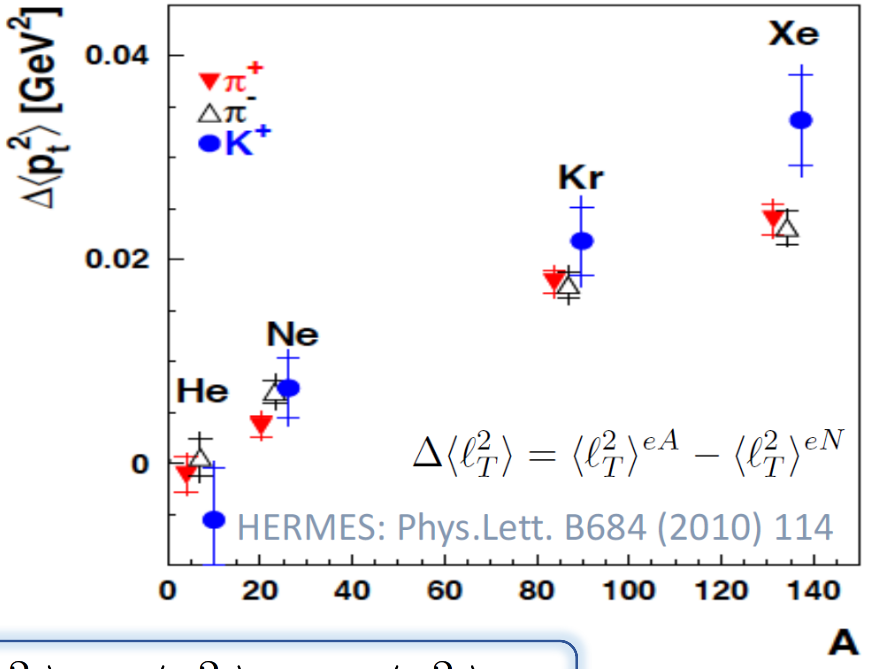


Jet as a probe of quark-gluon plasma.

Heavy-ion collision system is rather complicated.

$\hat{q}$ for cold nuclear matter



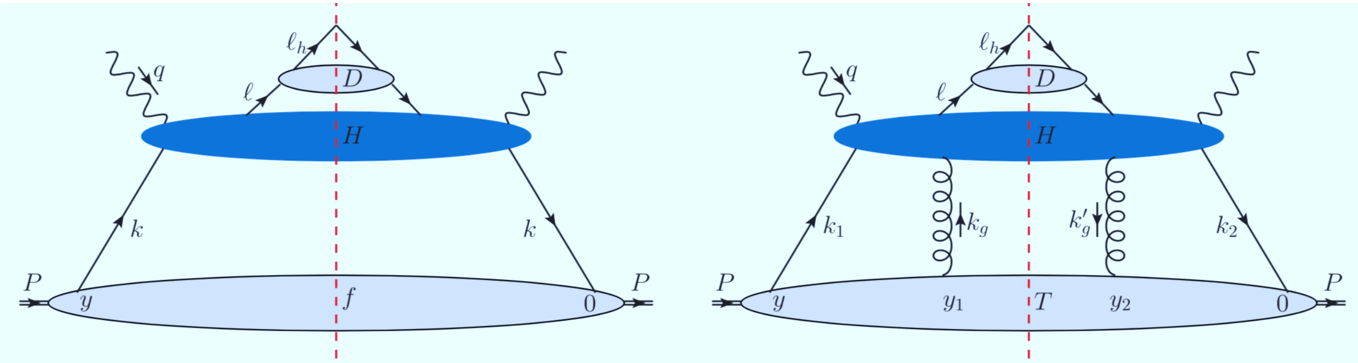


Transverse momentum broadening: $\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep}$

- 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 $\hat{q}$ in cold nuclear matter is needed!

Multiple parton scattering in HT framework

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



Single scattering Double scattering

Qiu & Sterman, NPB **353** (1991), **137** (1991) .
Luo, Qiu, Sterman, PLB **279** (1992).

perturbative expansion

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

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

power expansion

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

$$+ \ldots$$

For SIDIS:
Guo, Phys. Rev. D 58, 114033 (1998).
Kang, Wang, Wang, Xing, PRL 112, 102001 (2014).

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:

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

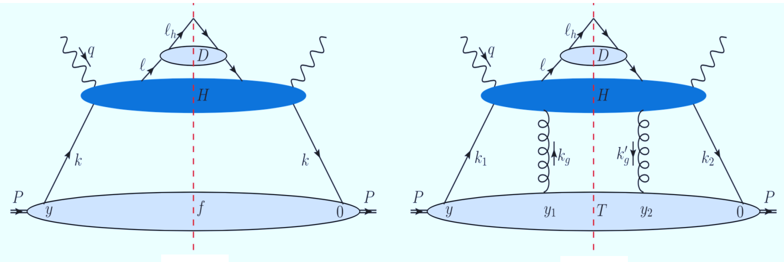
Expressed with $\hat{q}$:

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

Approximation of a large and loosely bound nucleus

Multiple parton scattering in HT framework

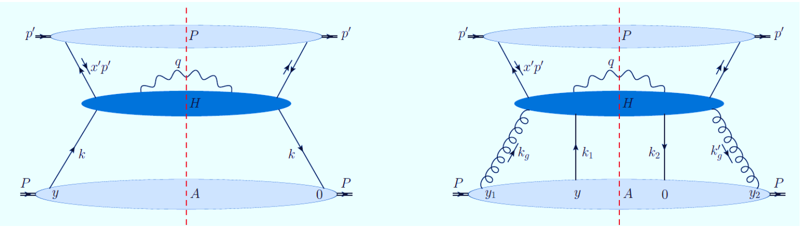
1. SIDIS



Single scattering | Double scattering

Guo (1998), Kang, et al.,(2014).

2. Drell-Yan (pA)

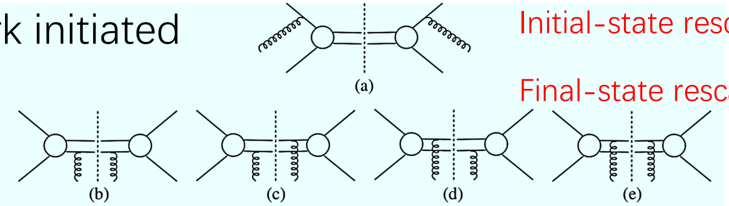


Single scattering | Double scattering

Kang & Qiu, PRD 77, 114027 (2008).

3. Heavy quarkonium (pA)

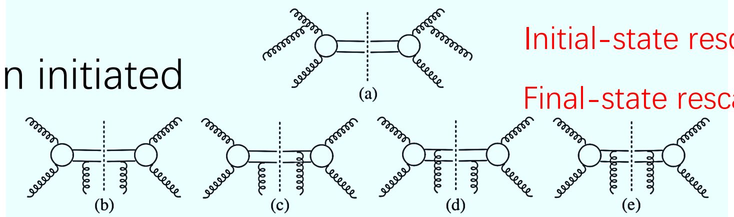
Quark initiated



Initial-state rescattering

Final-state rescattering

Gluon initiated

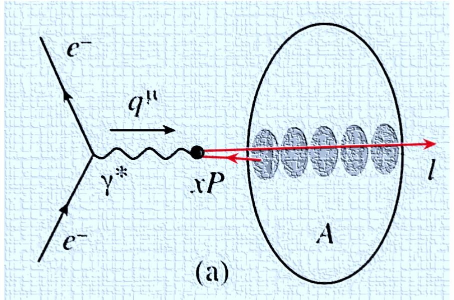


Initial-state rescattering

Final-state rescattering

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

4. Dynamical shadowing. (DIS)

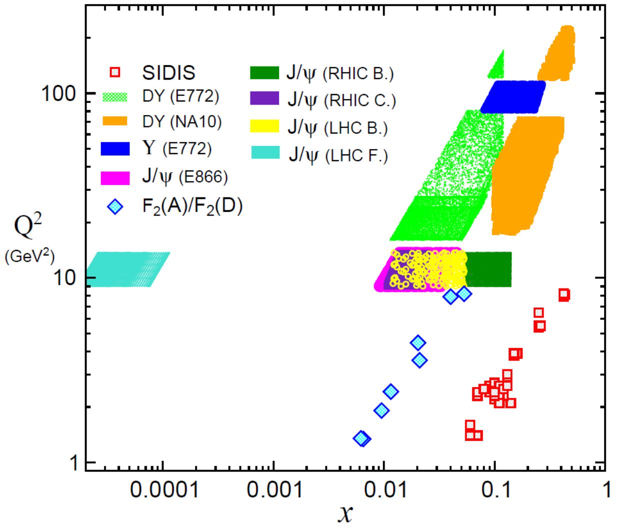


$$R(x,Q^2) = \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}$$

Qiu & Vitev, PRL **93**, 262301 (2004).

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

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

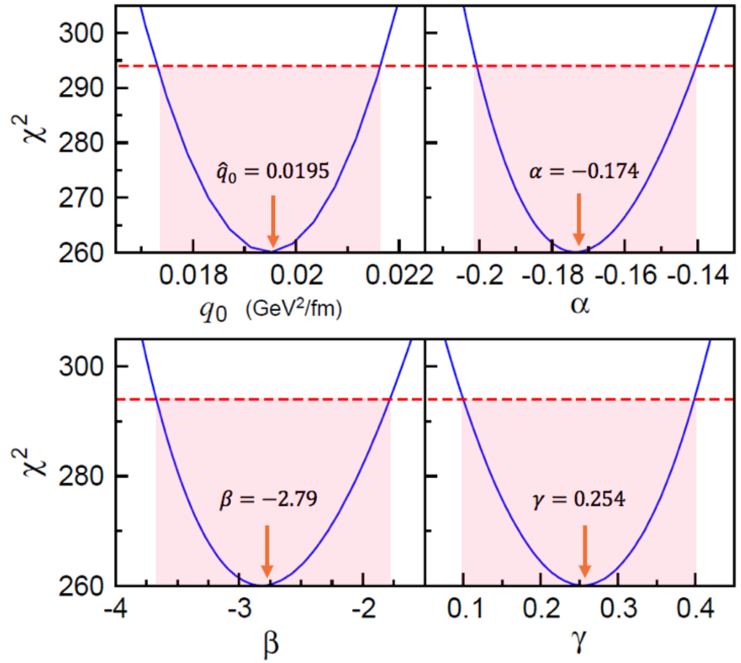


PR, Z.B. Kang, E. Wang, H. Xing and B.W. Zhang, PRD, L031901 (2021).

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

Also test constant $\hat{q} = \hat{q}_0$:



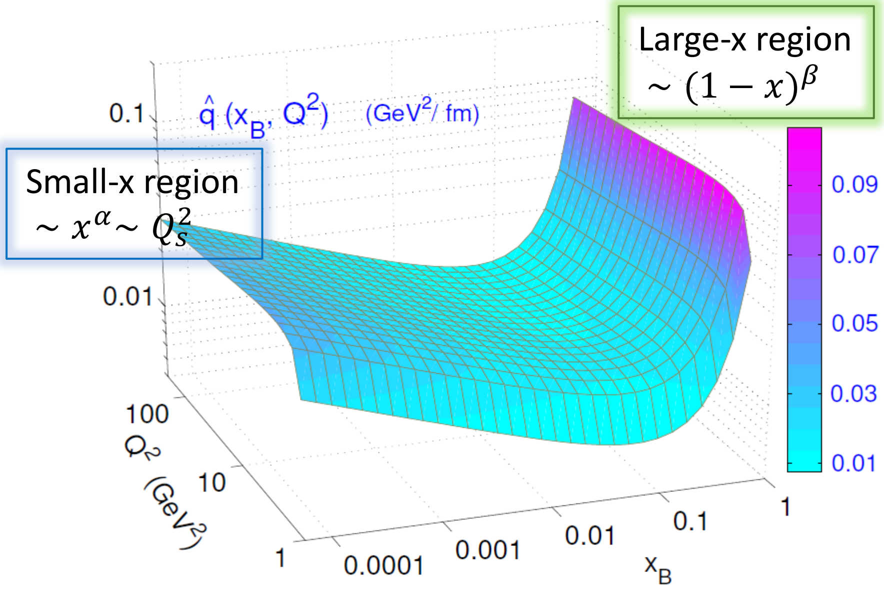
experiment	data type	data points	χ^2 (constant $\hat{q}$)	χ^2 [$\hat{q}(x_B, Q^2)$]
HERMES	SIDIS (p_T broad.)	156	218.5	189.7
FNAL-E772	DY (p_T broad.)	4	2.69	1.65
SPS-NA10	DY (p_T broad.)	5	6.86	6.47
FNAL-E772	Υ (p_T broad.)	4	2.33	2.67
FNAL-E866	J/ψ (p_T broad.)	4	2.03	2.45
RHIC	J/ψ (p_T broad.)	10	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	$\boxed{387.9}$	$\boxed{260.2}$

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.

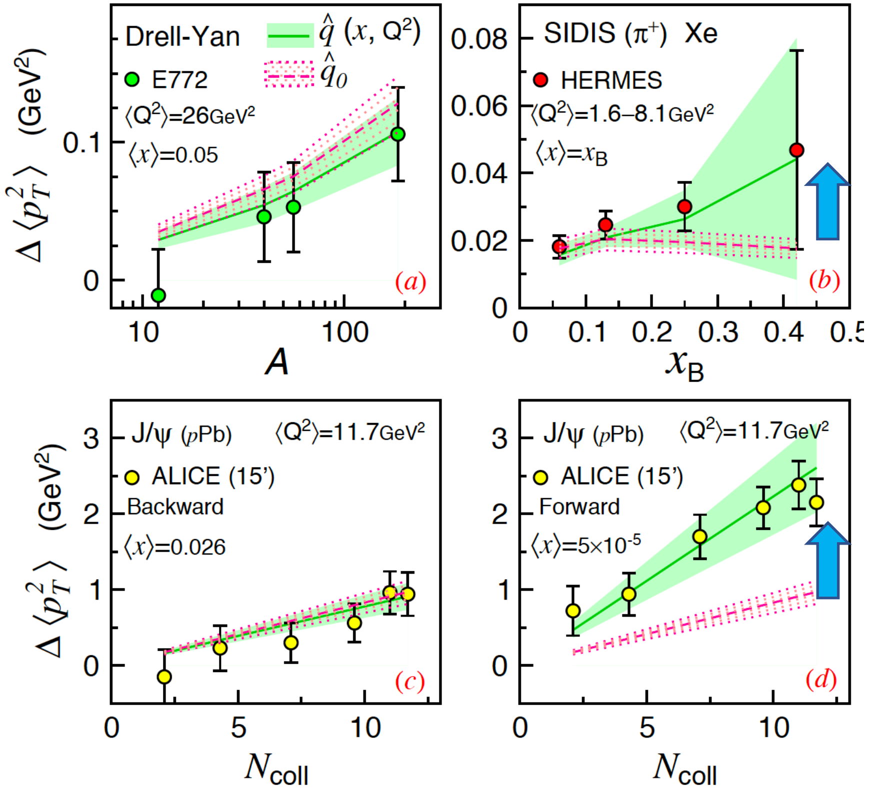
Extract $\hat{q}$ & study its kinematic dependence

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

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



$$\hat{q}_0 = 0.0191 \pm 0.0061\ \mathrm{GeV}^2/\mathrm{fm}, \quad \alpha = -0.182 \pm 0.050$$
$$\beta = -2.85 \pm 1.87, \quad \gamma = 0.264 \pm 0.169\,.$$



SIDIS in large-x region and J/psi in forward (small-x) region favor the enhanced broadening.

Seems consistent with recent study.

Arleo and Naïm, JHEP (2021)
Extraction from DY and quarkonium data:

$$\hat{q}_A(x) = \hat{q}_0 \times \left(\frac{10^{-2}}{x}\right)^{\alpha} \qquad \hat{q}_0 = 0.051 \sim 0.075 \qquad \alpha = 0.25 - 0.3$$

Y.-Y. Zhang, X.-N. Wang,
PRD **105** 034015 (2022)

$$\hat{q}_A^0(x_B, Q^2) = \frac{A^{1/3}}{2R_A} Q_{s0}^2(x_B, Q^2).$$

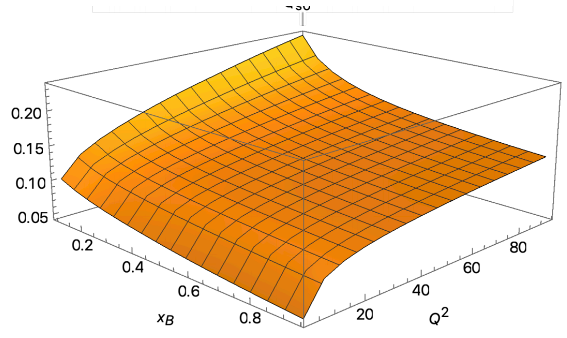
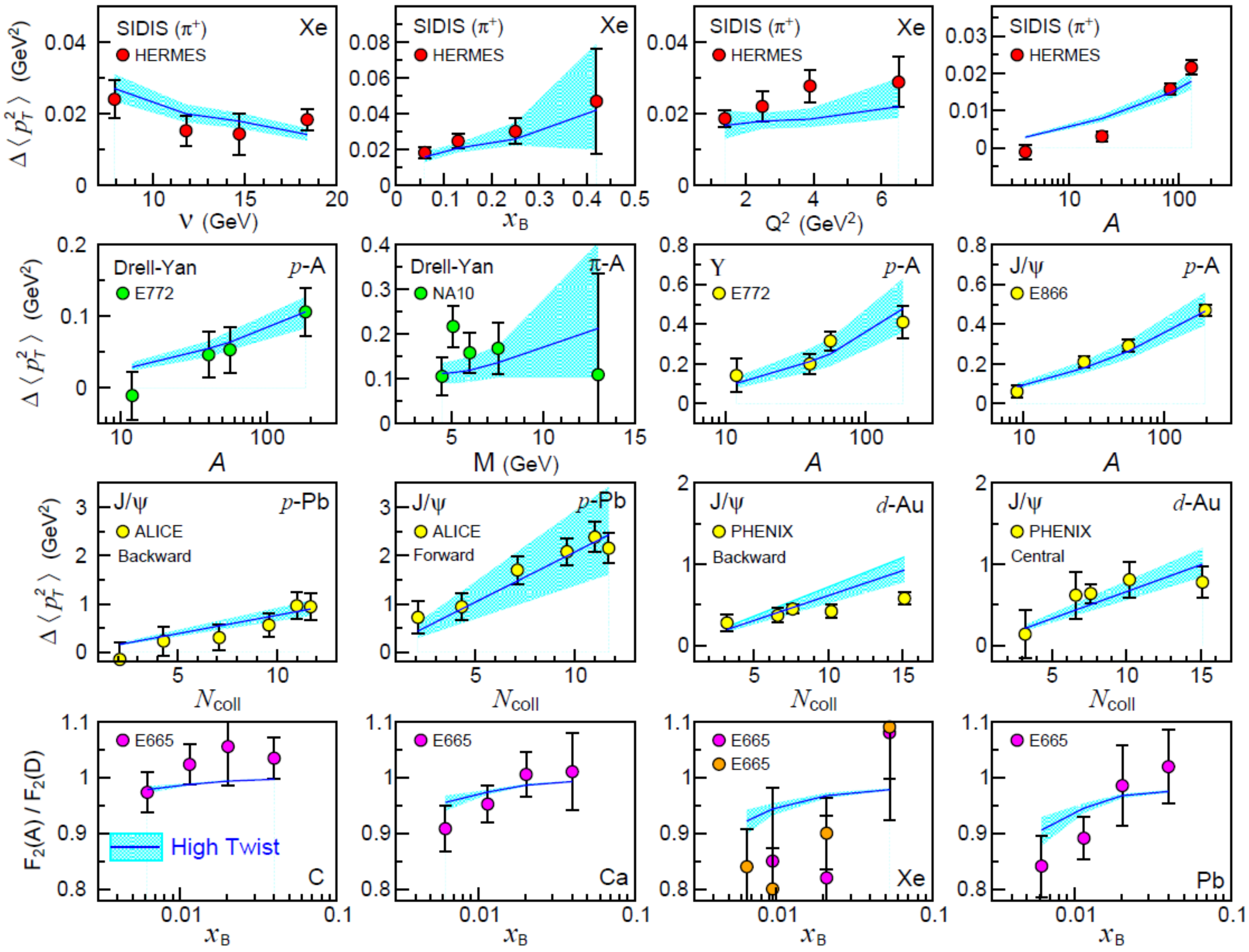
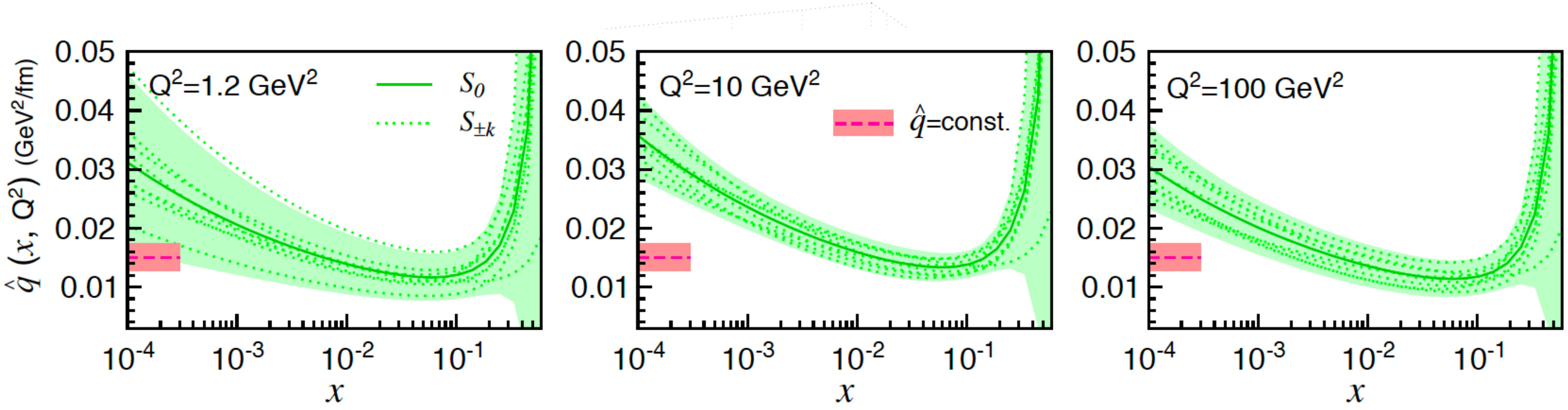


FIG. 5. The x_B and Q^2 dependence of the scaled saturation scale $Q_{s0}^2(x_B, Q^2)$ inside Pb from solving Eq. (29).

HT results with extracted $\hat{q}(x, Q^2)$

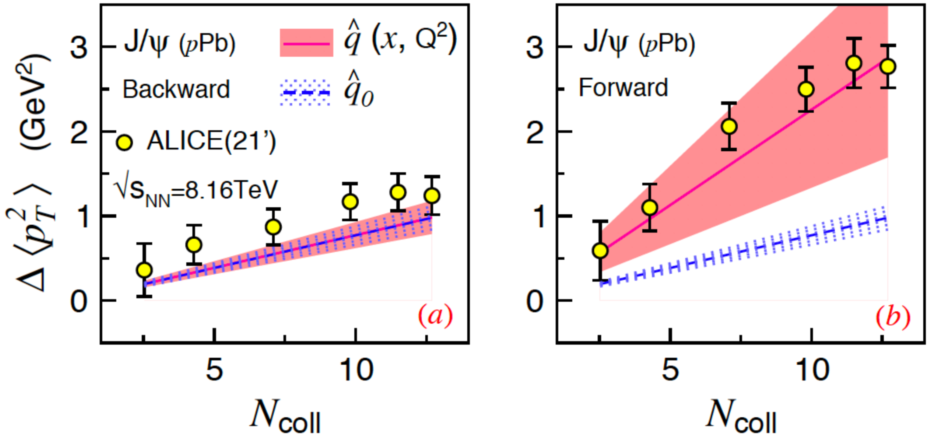


Determine uncertainties of $\hat{q}$

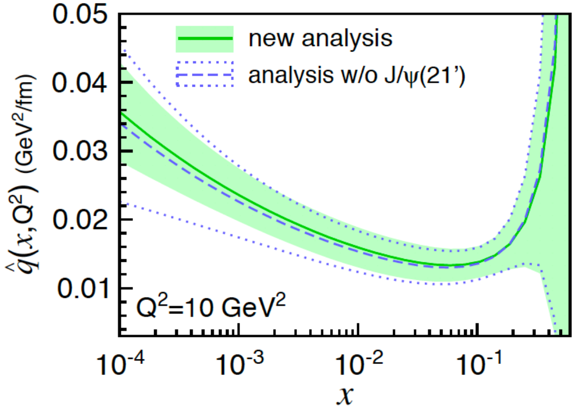


Hessian matrix method [PRD,65,014011, widely used in the analysis of PDFs, to determine the uncertainty of $\hat{\boldsymbol{q}}$ in cold nuclear matter. **Nine sets** S_k,(k=-4,..0,..4) of $\hat{q}(x, Q^2)$ for future theoretical predictions.

Test with new LHC data on Jpsi

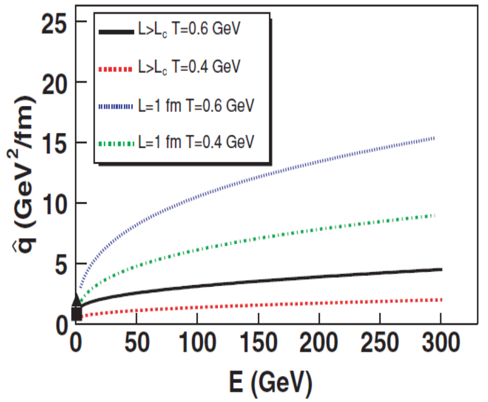


New data reduce uncertainty at small x

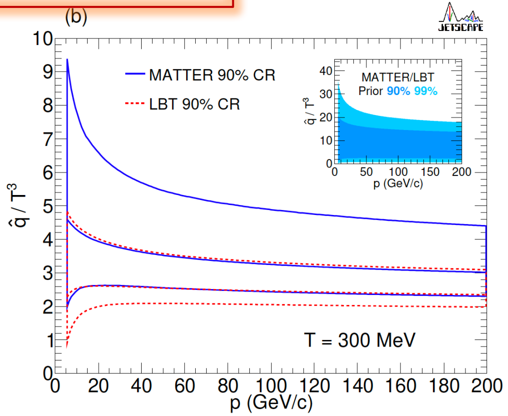


$\hat{q}$ for cold nuclear matter: jet energy dependence

For quark-gluon plasma

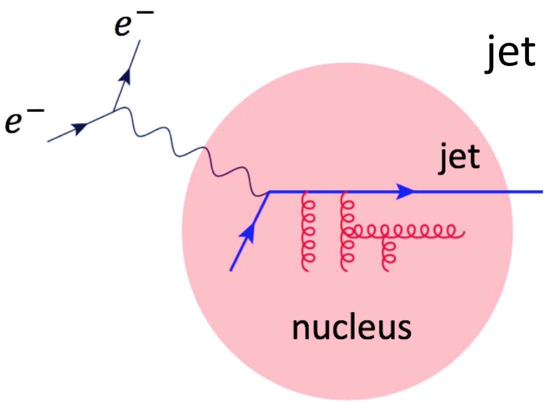


J. Casalderrey-Solana and X.-N. Wang, PRC **77**, 024902 (2008)



JETSCAPE, PRC **104**, 024905 (2021)

For cold nuclear matter

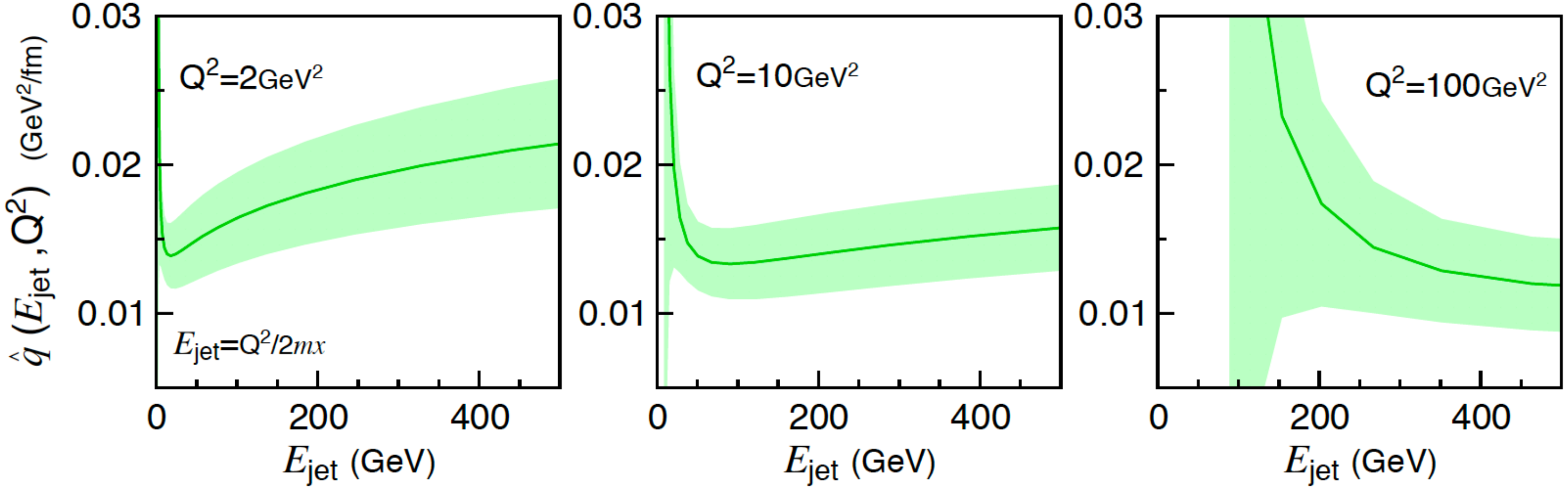


A common relation between jet energy and x & Q^2 in various processes

$$E_{\text{jet}} = \frac{Q^2}{2m_p x}$$

(jet energy in nucleus rest frame)

$$\hat{q}(x, Q^2) \to \hat{q}(E_{\text{jet}}, Q^2)$$

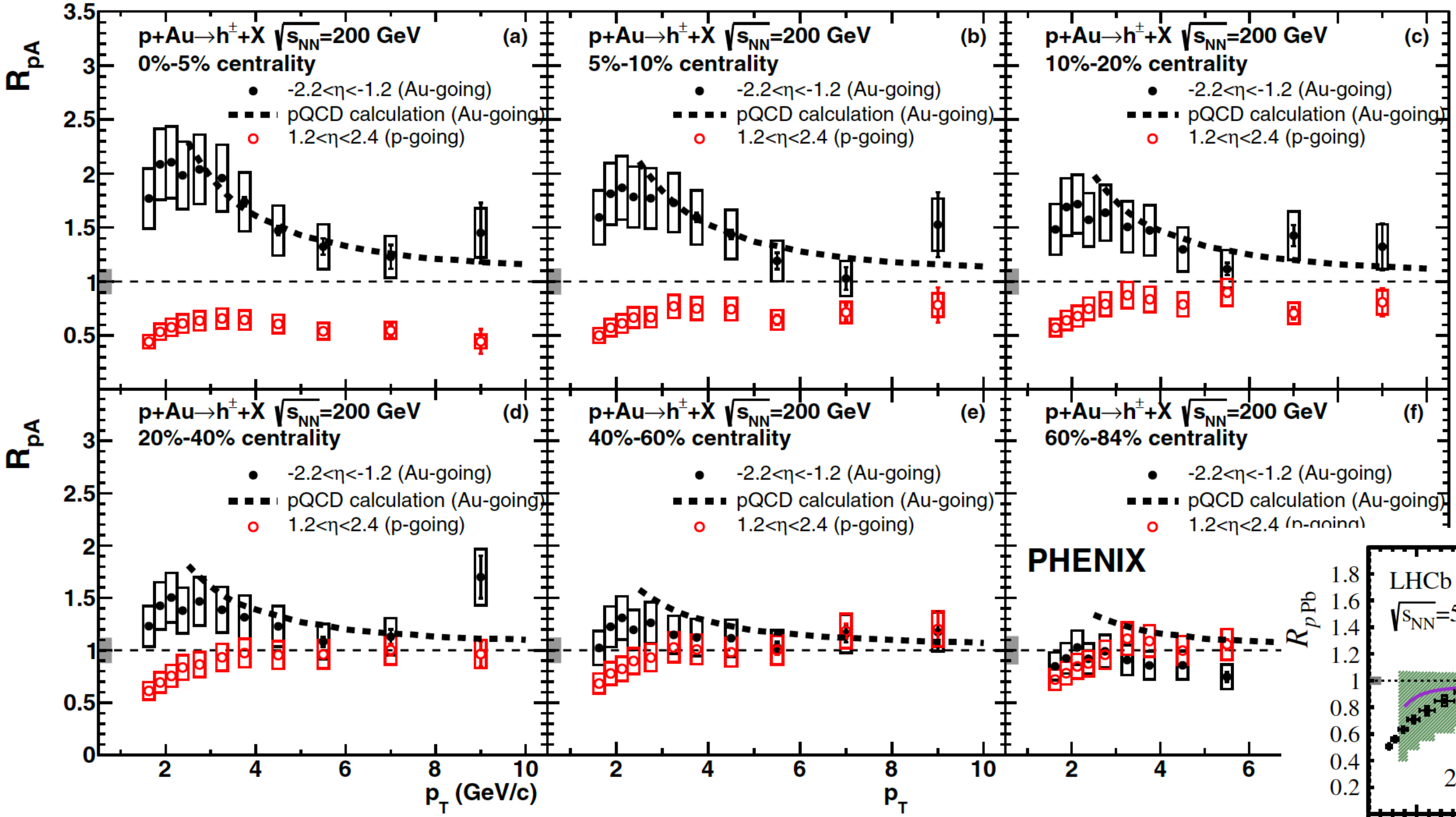


Increasing with jet energy at low Q^2.

Jet energy dependence is sensitive to resolution scale Q^2.

How to extend this knowledge to heavy-ion collisions is of interest.

Future study: charge hadron RpA in large-x region

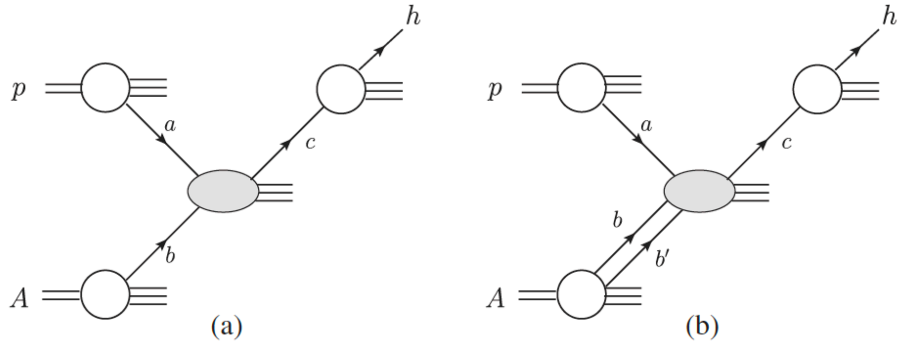


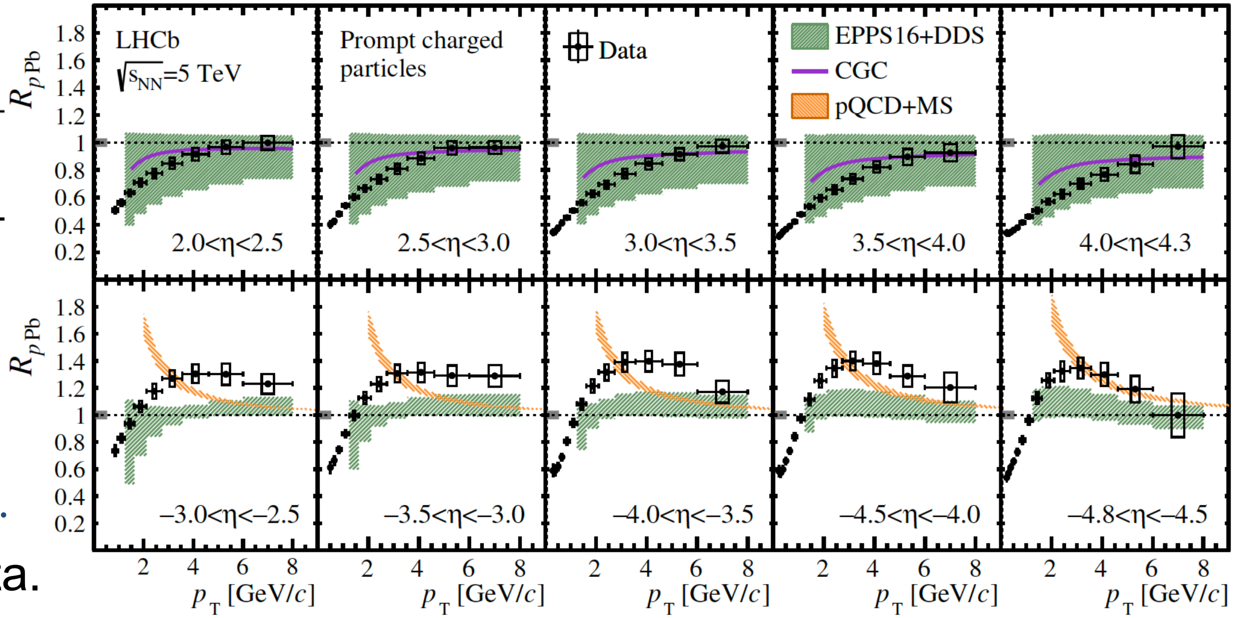
PHENIX, PRC 101, 034910 (2020).

May include this data set in global analysis.

Incoherent multiple scattering enhances the hadron yields in large-x region.

Kang, Vitev, Xing, PRD 88, 054010 (2013)



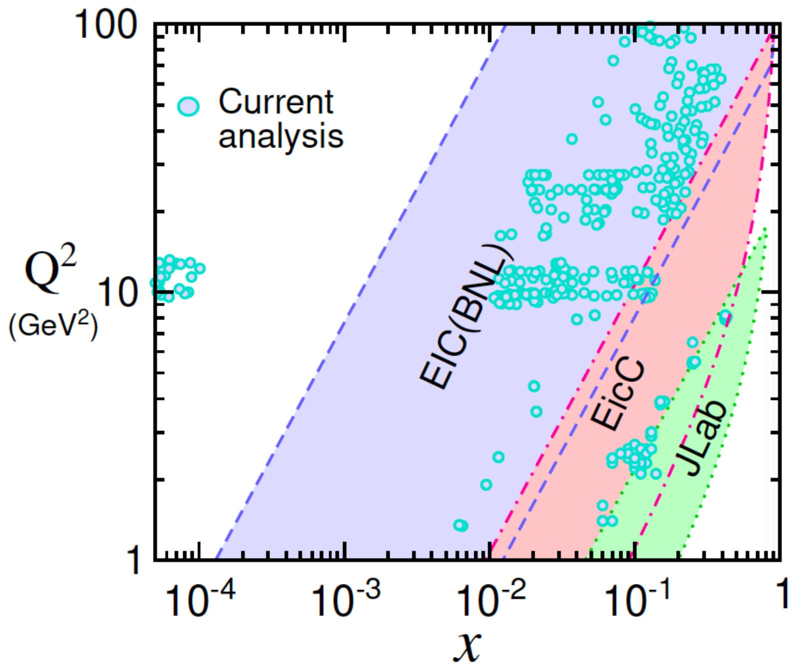


LHCb, PRL 128, 142004 (2022).

More challenges in describing LHCb data.

How will EIC deepen our understanding

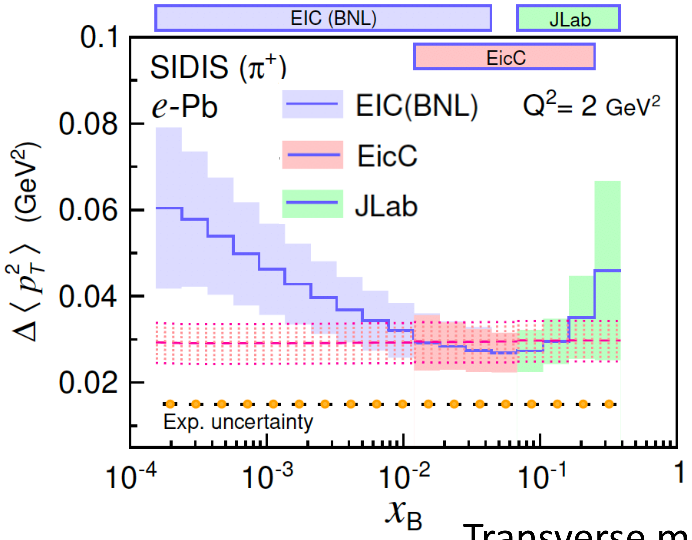
Kinematics coverage of future EIC facilities

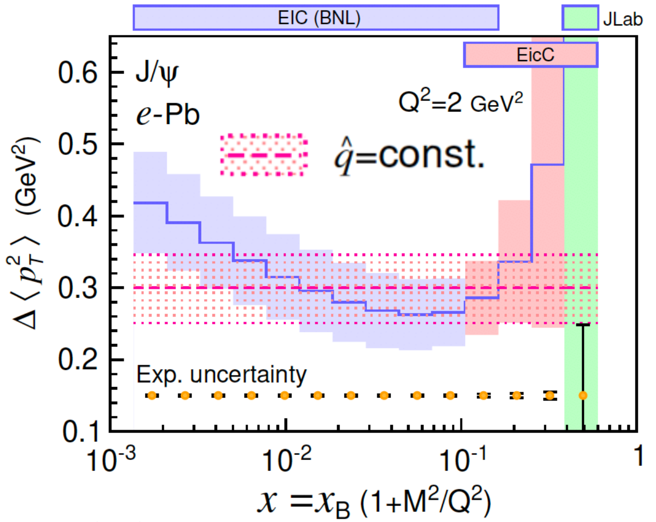


The future EIC experiments, e.g., at EIC (BNL), JLab and EicC (China) will largely extend the coverage of kinematic region and improve the accuracy of the measurement.

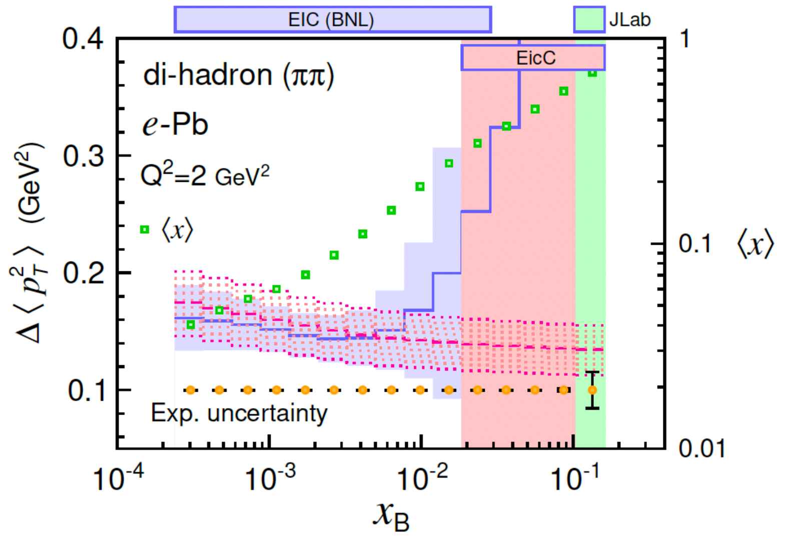
PR, Z.B. Kang, E. Wang, H. Xing and B.W. Zhang, in preparation

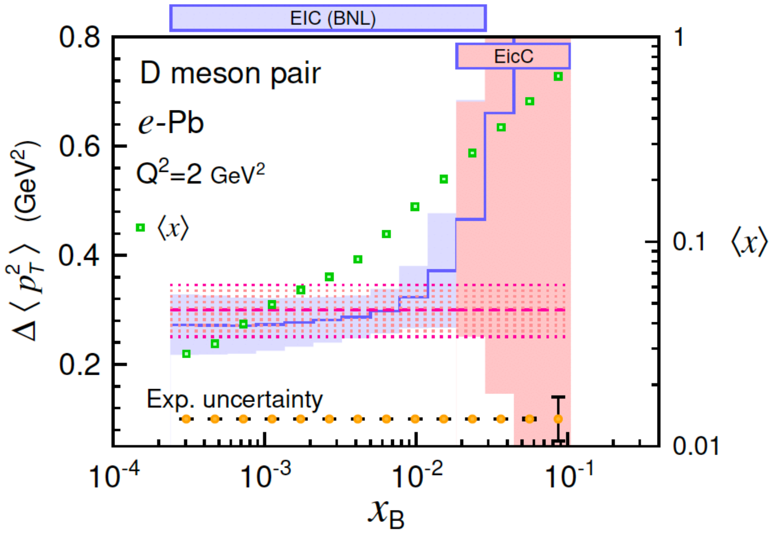
Transverse momentum broadening





Transverse momentum imbalance





Summary

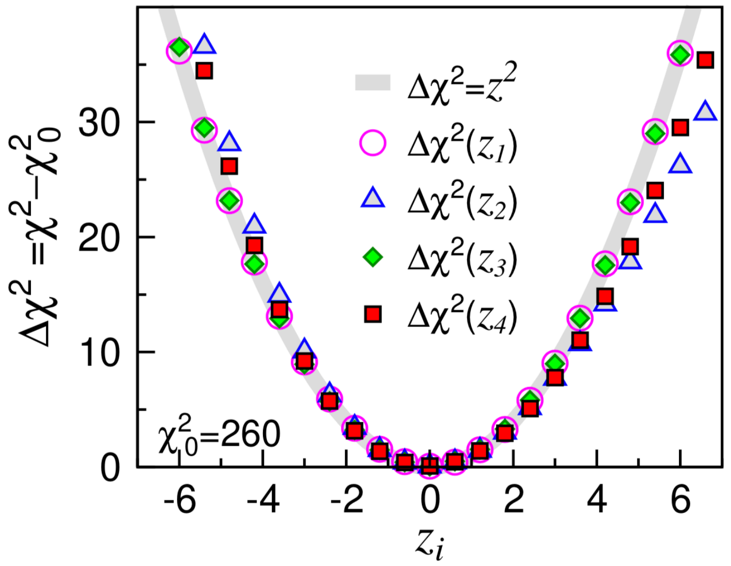
- A universal non-trivial kinematic dependence of $\hat{q}$ is suggested by the first global analysis of transverse momentum broadening in cold nuclear matter.
- High-twist framework is able to describe the included various types of data.
- Uncertainties of of $\hat{q}$ are determined through Hessian analysis: useful for future theoretical predictions.
- May be informative for $\hat{q}$ in QGP. -- Jet energy dependence?
- Future measurements are expected to examine the results and provide powerful constraints.

Thank you for your attentions!
Thank the organizers!

Backup

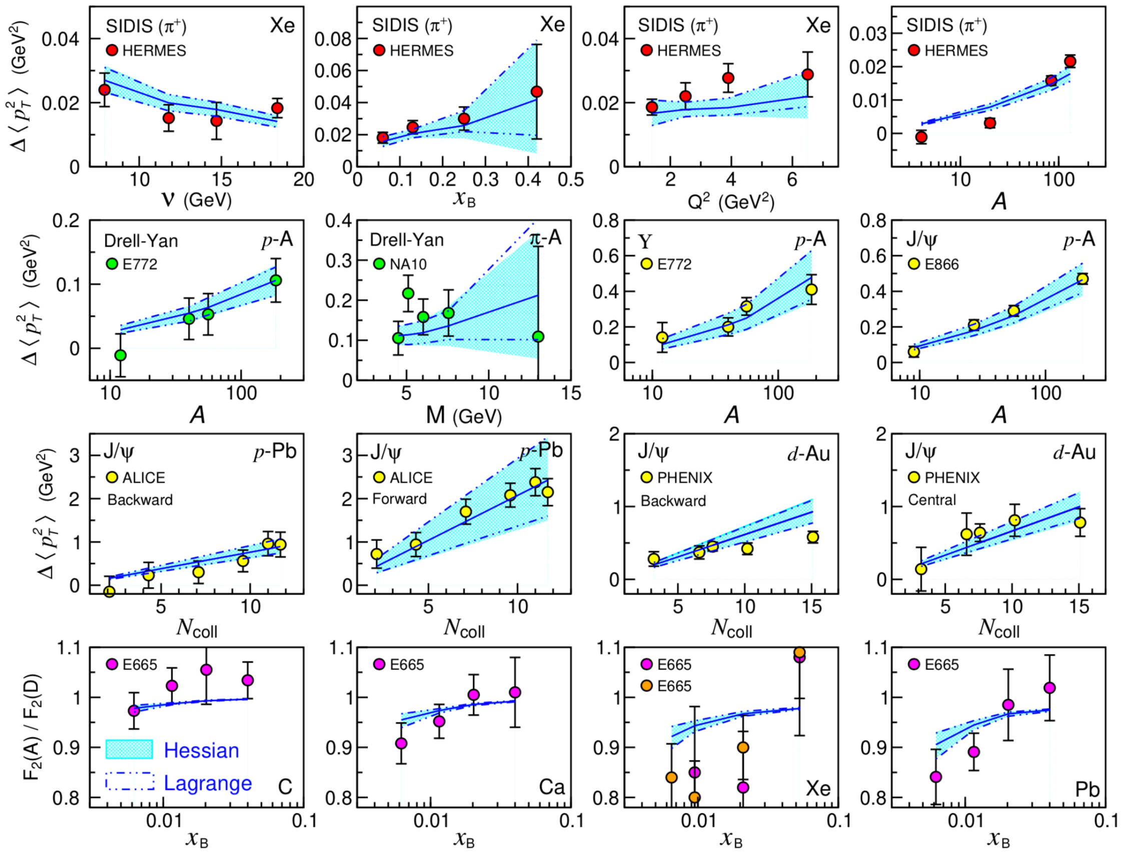
Reliability of the Hessian analysis

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.

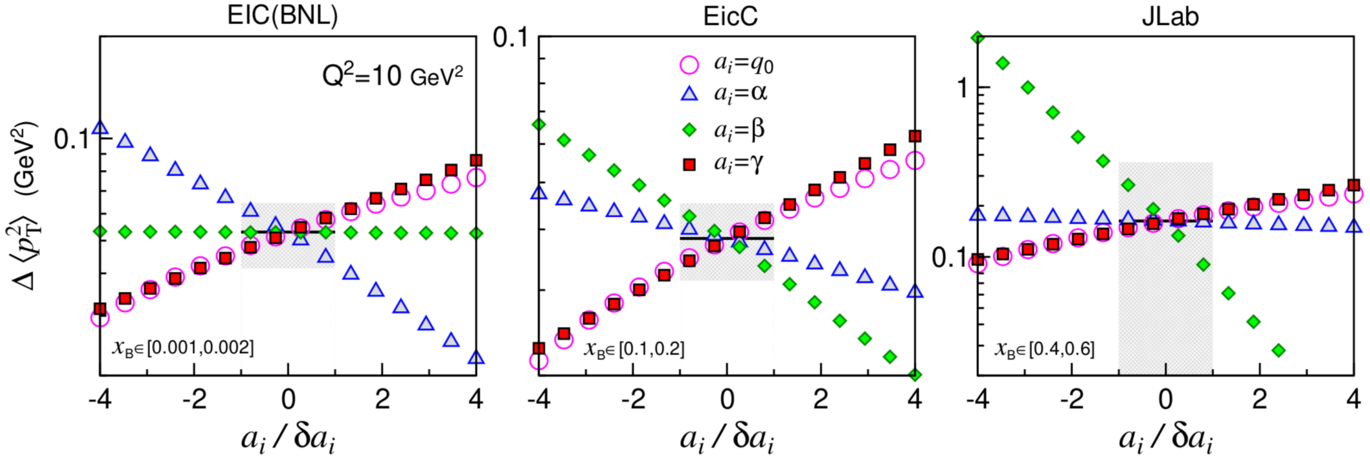
Comparison between Hessian approach
and Lagrange multiplier method



Good agreement between two methods.

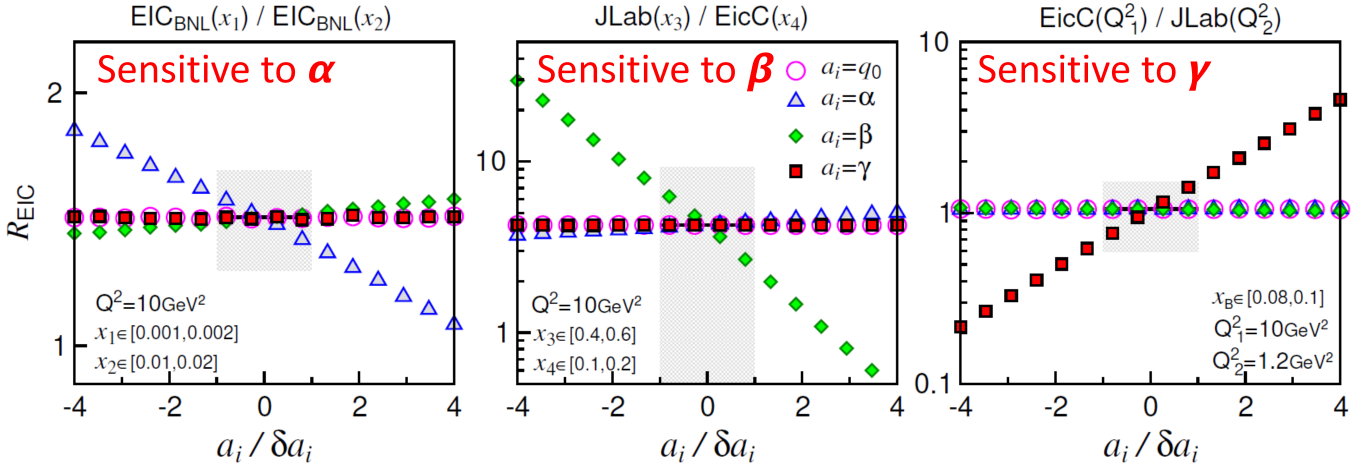
How will EIC deepen our understanding

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



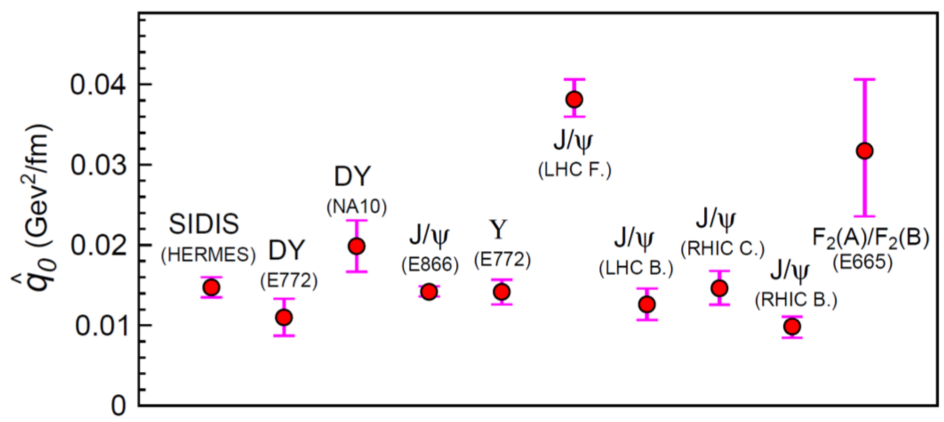
The **combination** (e.g., ratio) of different kinematic regions can effectively **reduce** the number of sensitive parameters.

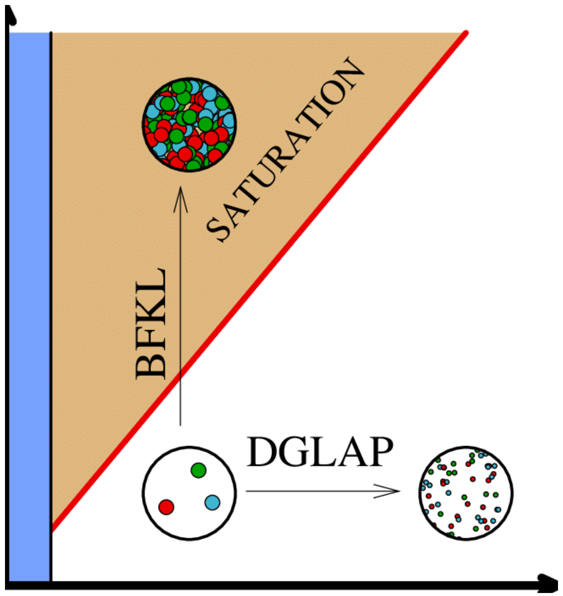
$$\hat{q}(x,Q^2)=\hat{q}_0\alpha_s(Q^2)x^{\alpha}(1-x)^{\beta}[\ln(Q^2/Q_0^2)]^{\gamma}$$

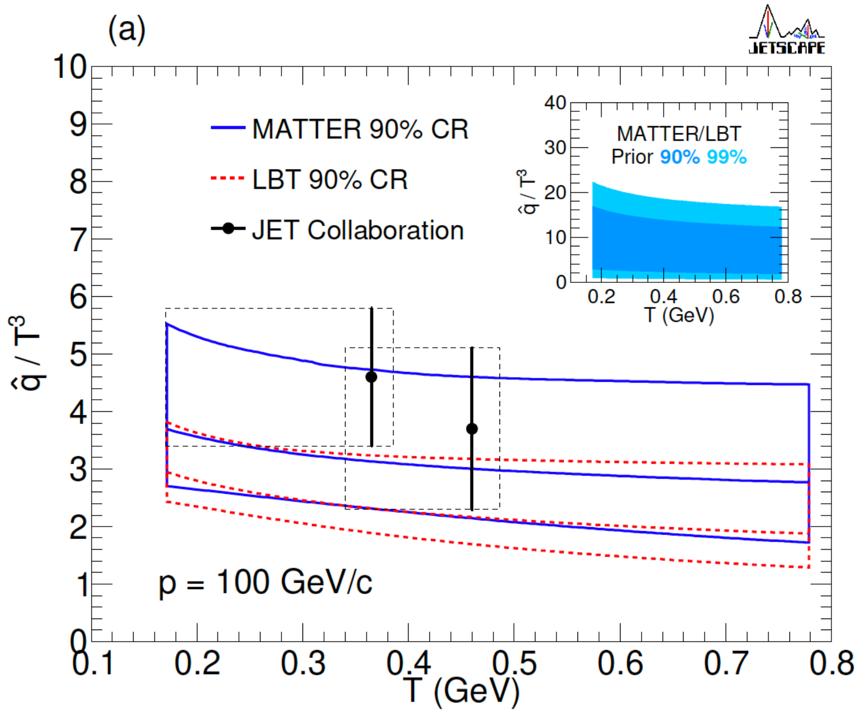


A test with a constant transport coefficient:

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







$$
\begin{aligned}
\eta/s &= \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p\rangle_a \lambda_a^{\perp} \\
&= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle S_{ab}\rangle/2} dq_\perp^2 \frac{4q_\perp^2}{\langle S_{ab}\rangle}\frac{d\sigma_{ab}}{dq_\perp^2}\right)^{-1} \\
&= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T, E=3T/2)\ .
\end{aligned}
$$

S. Shi, J. Liao, M. Gyulassy, 1808.05461

$$
\frac{\eta}{s}\left\{\begin{matrix}\approx\\ \gg\end{matrix}\right\} 1.25\frac{T^3}{\hat{q}} \qquad \left\{\begin{matrix}\text{for weak coupling,}\\ \text{for strong coupling.}\end{matrix}\right.
$$

A. Majumder, B. Muller and Xin-Nian Wang, hep-ph/0703082

Parametrization of kinematic dependence

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

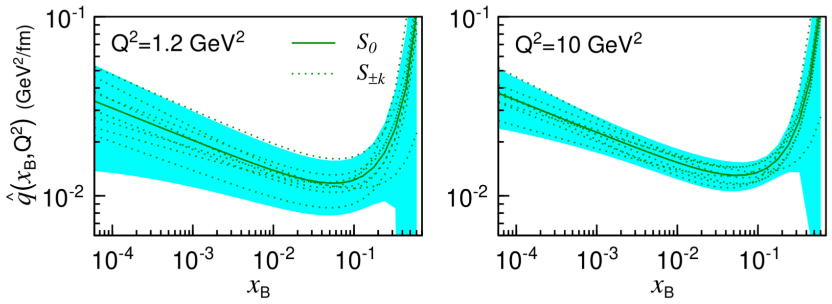
See also the talk by H. Xing at QM19

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:

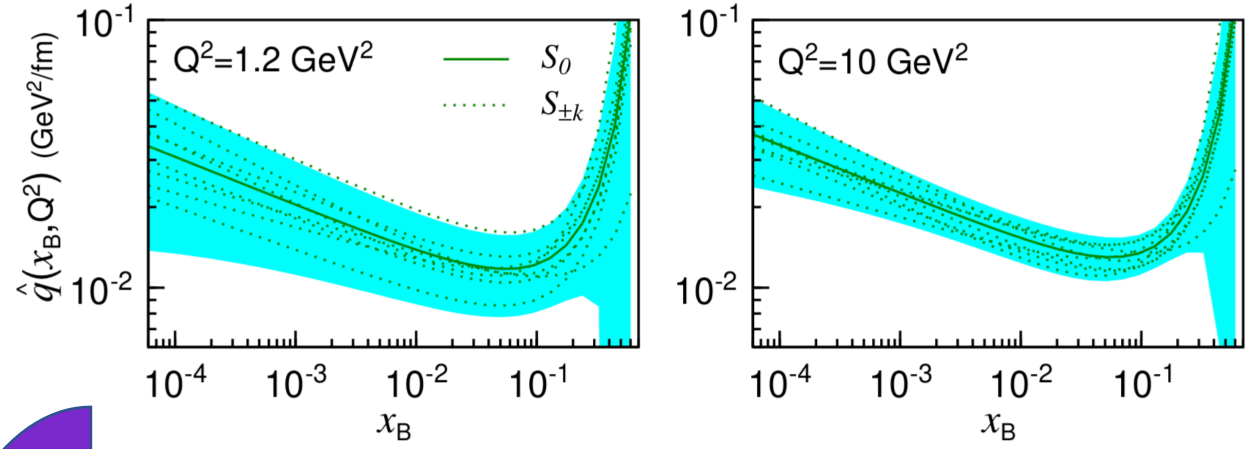
J. Pumplin, et al, CTEQ6, JHEP07(2002)012

The functional form that we use is

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

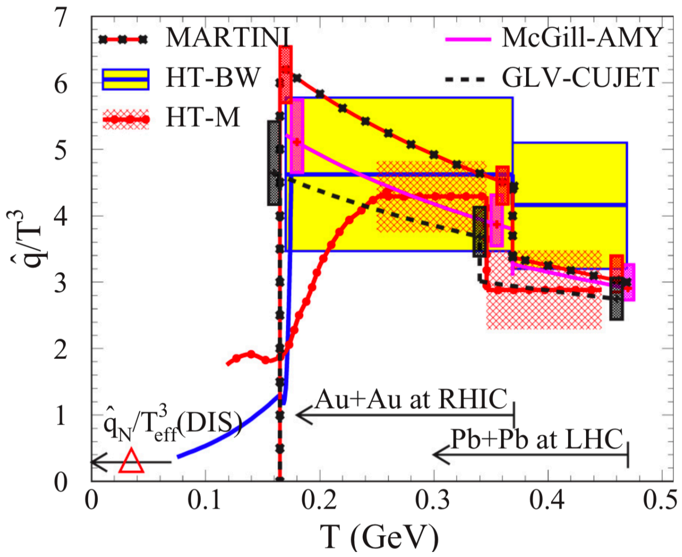
with independent parameters for parton flavor combinations $u_v \equiv u - \bar{u}$, $d_v \equiv d - \bar{d}$, g, and $\bar{u} + \bar{d}$. We assume $s = \bar{s} = 0.2\,(\bar{u} + \bar{d})$ at Q_0. The form (2.4) is "derived" by including a 1:1 Padé expansion in the quantity $d[\log(xf)]/dx$. This logarithmic 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.

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



In CNM

~ X 30-100



In QGP

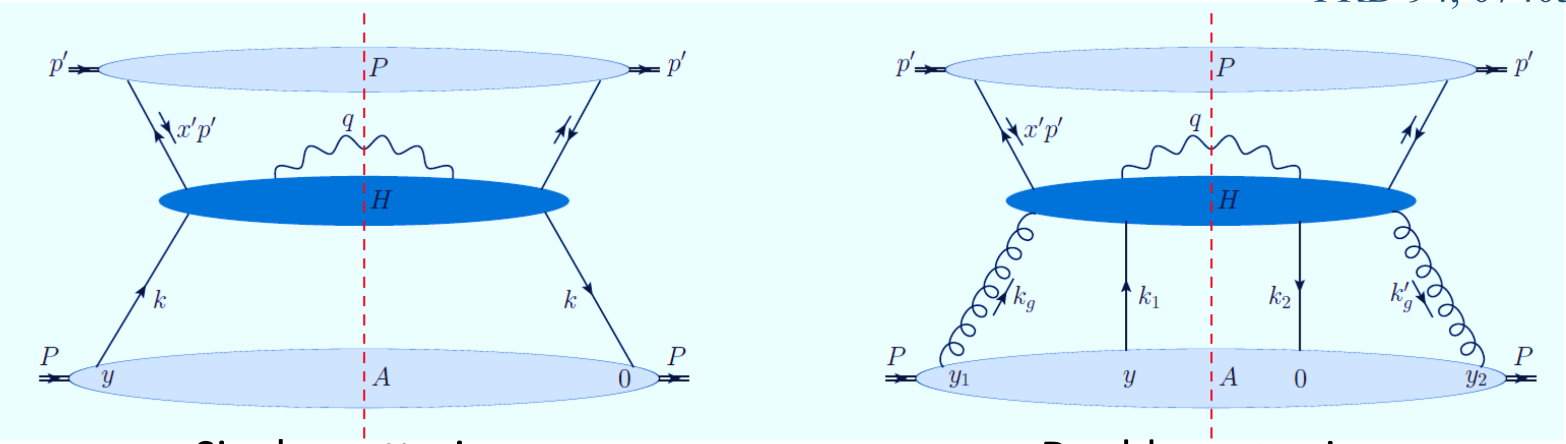
JET, PRC 90, 014909 (2014)

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

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:

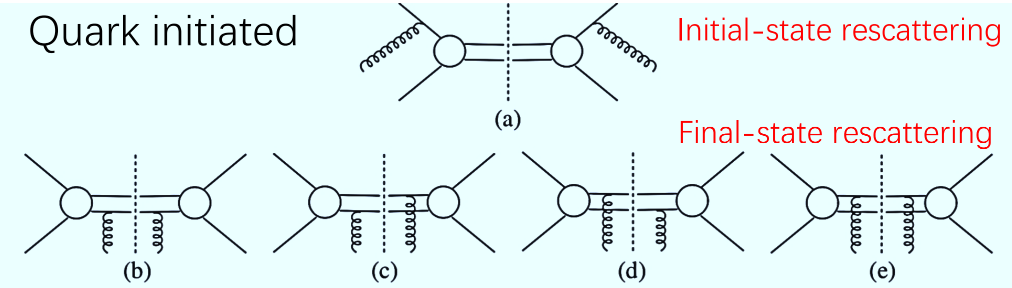
$$\Delta\langle p_T^2\rangle = \frac{4\pi^2\alpha_s}{N_c}\frac{\sum_q e_q^2\int\frac{dx'}{x'}f_{\bar{q}/p}(x',\mu^2)T_{qg}(x,\mu^2)}{\sum_q e_q^2\int\frac{dx'}{x'}f_{\bar{q}/p}(x',\mu^2)f_{q/A}(x,\mu^2)} \approx \frac{3R_A}{2}\frac{\sum_q e_q^2\int\frac{dx'}{x'}f_{\bar{q}/p}(x',\mu^2)f_{q/A}(x,\mu^2)\,\hat{q}(x,\mu^2)}{\sum_q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

Multiple parton scattering in HT framework

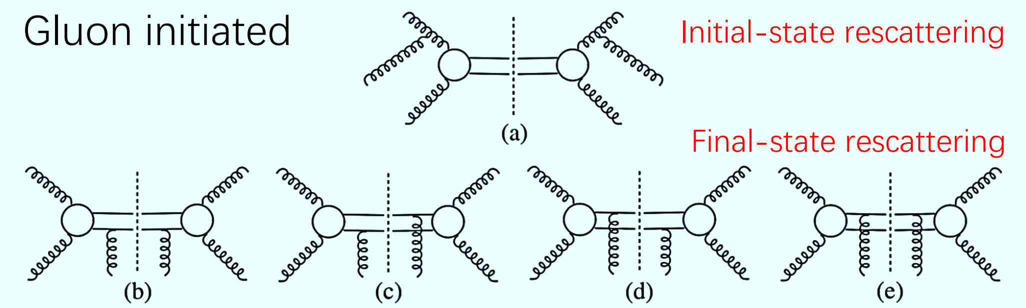
Transverse momentum broadening of heavy quarkonium($J/\psi, \Upsilon$) production in pA

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

Quark initiated



Gluon initiated



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:

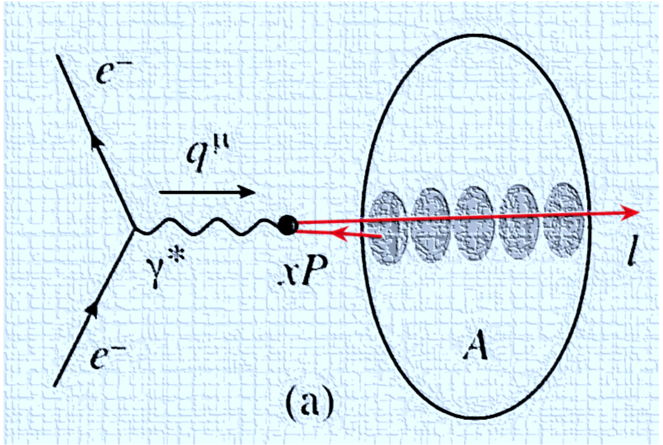
$$\Delta\langle p_T^2\rangle^{NRQCD} = \frac{3R_A\,\hat{q}_0}{2}\frac{(1+C_A/C_F)\sigma_{q\bar{q}}^{(0)}+2C_A/C_F\sigma_{gg}^{(0)}+\sigma_{q\bar{q}}^{(1)}/C_F}{\sigma_{q\bar{q}}^{(0)}+\sigma_{gg}^{(0)}}$$

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



Nuclear modification ratio:

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

Qiu, Vitev, PRL 93, 262301 (2004)

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

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

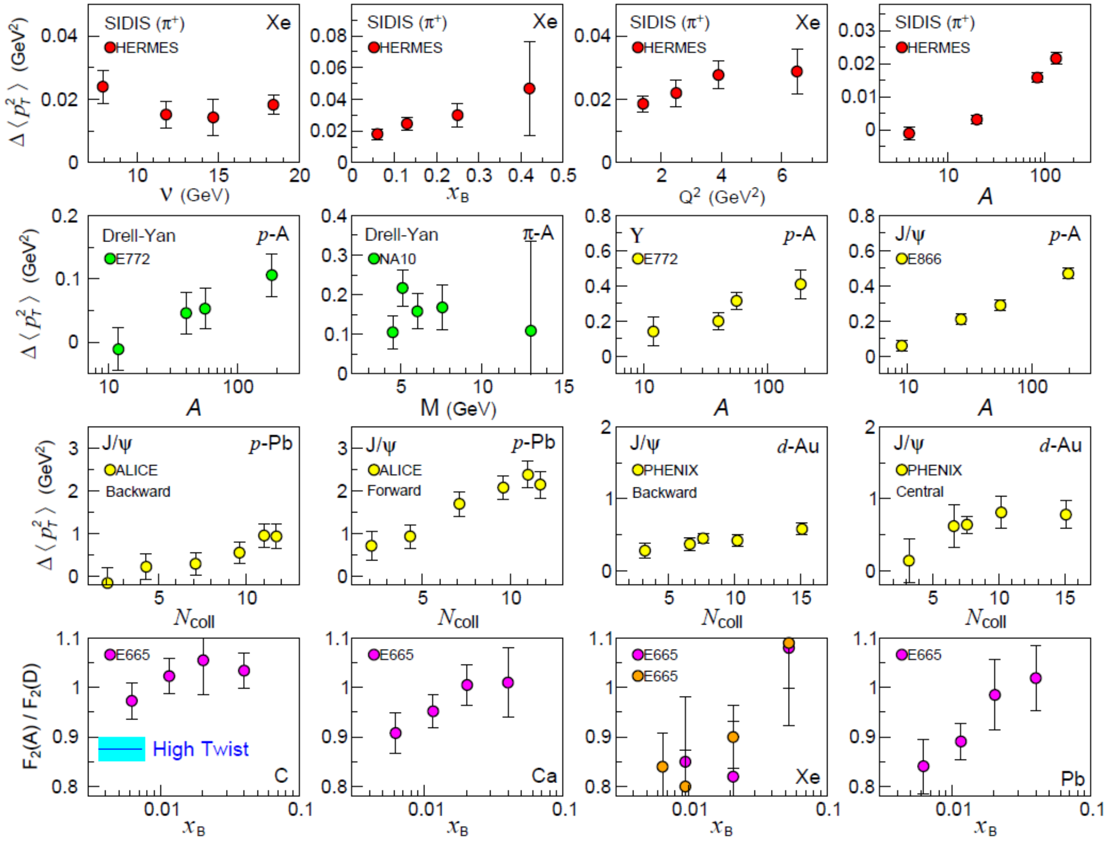
$$F_T^{(\mathrm{LT})}(x,Q^2) = \frac{1}{2}\sum_f Q_f^2 \phi_f(x,Q^2) + \mathcal{O}(\alpha_s),$$

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

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

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