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JMS Aster Plaza, Hiroshima, Japan

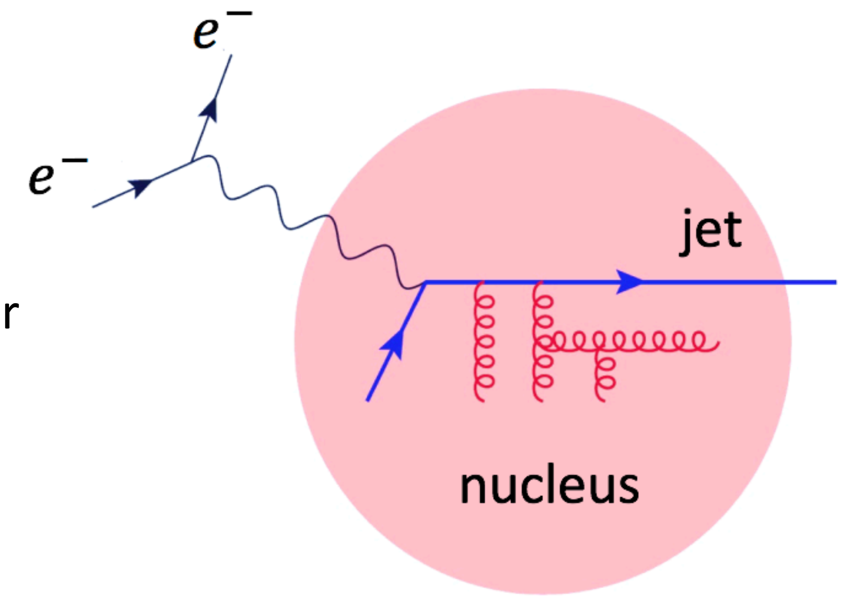
ATHIC2023

Probing jet transport coefficient of cold nuclear matter in electron-ion collisions

Peng Ru / 茹芃

School of Materials and New Energy & Institute of Quantum Matter

South China Normal University



In collaboration with:

Zhong-Bo Kang, Enke Wang, Hongxi Xing, Ben-Wei Zhang

Outline

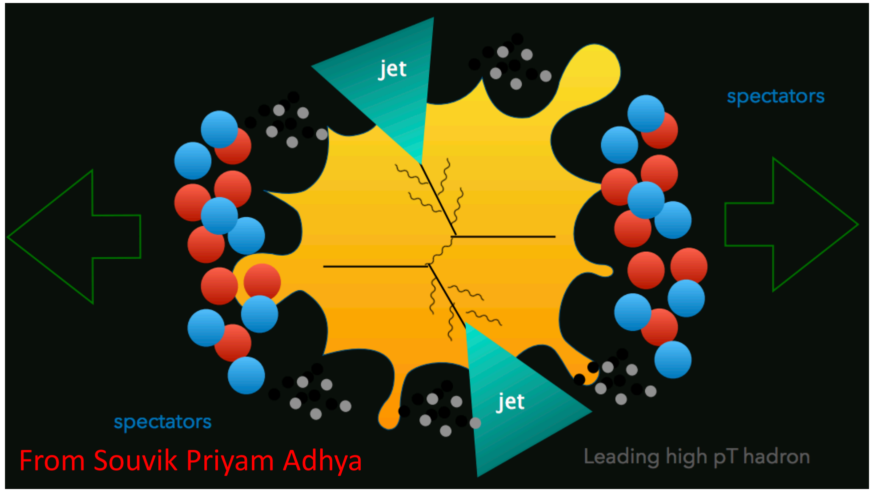
1. Motivation

2. Kinematics dependent $\hat{q}$ within high-twist factorization

3. Transverse momentum broadening/imbalance in electron-ion collisions

4. Summary

Jet quenching in heavy-ion collisions



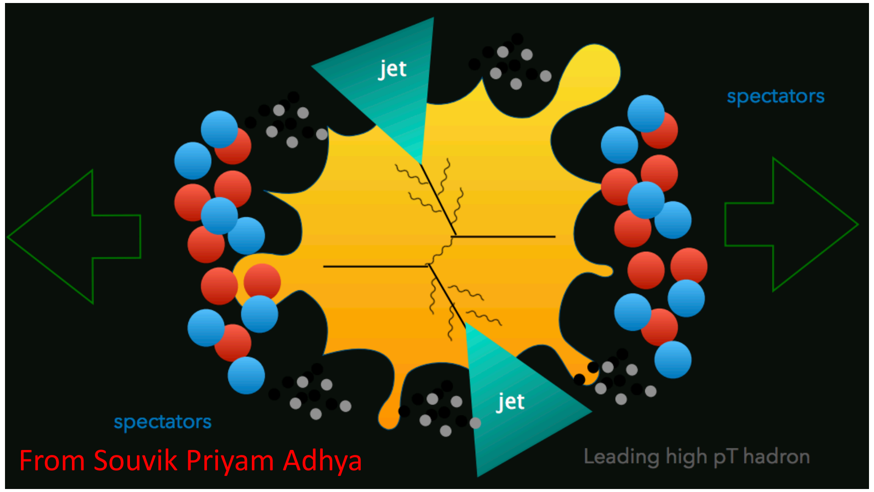
$\hat{q}$ is an important **non-perturbative** input in jet-quenching models.

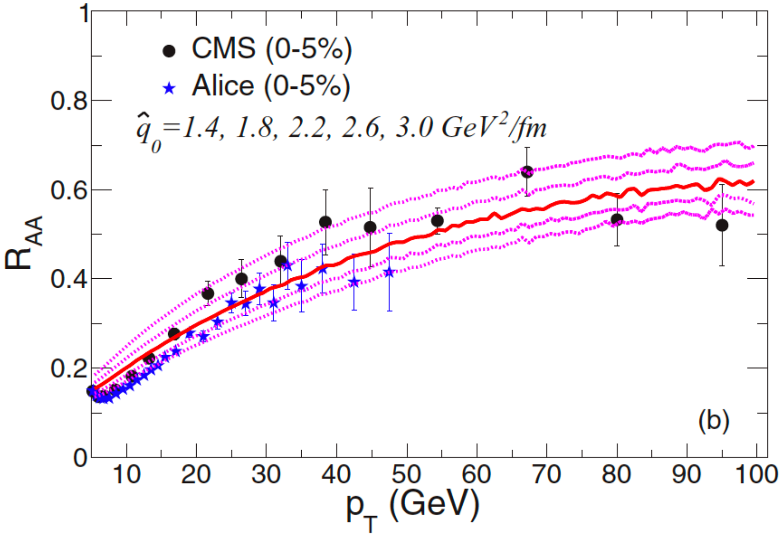
Transverse momentum broadening per unit length for propagating parton.

Characterize **interaction strength** between hard probe and nuclear medium.

Jet quenching in heavy-ion collisions

JET, PRC 90, 014909 (2014)





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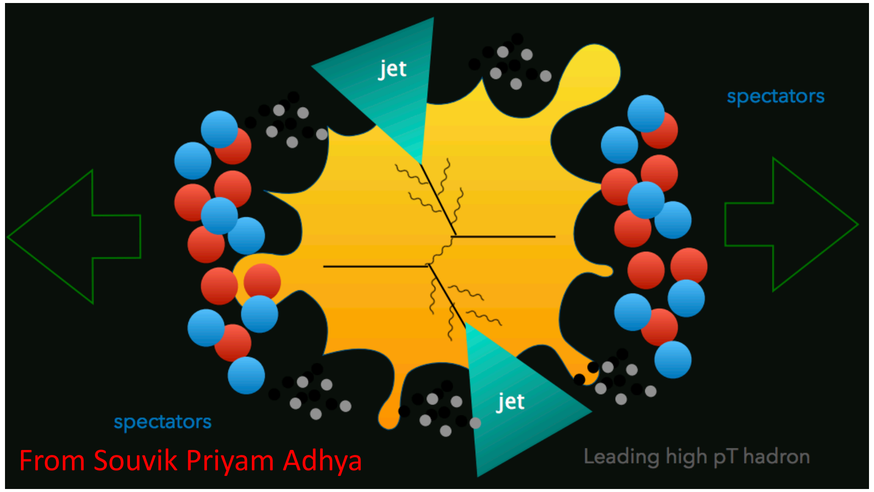

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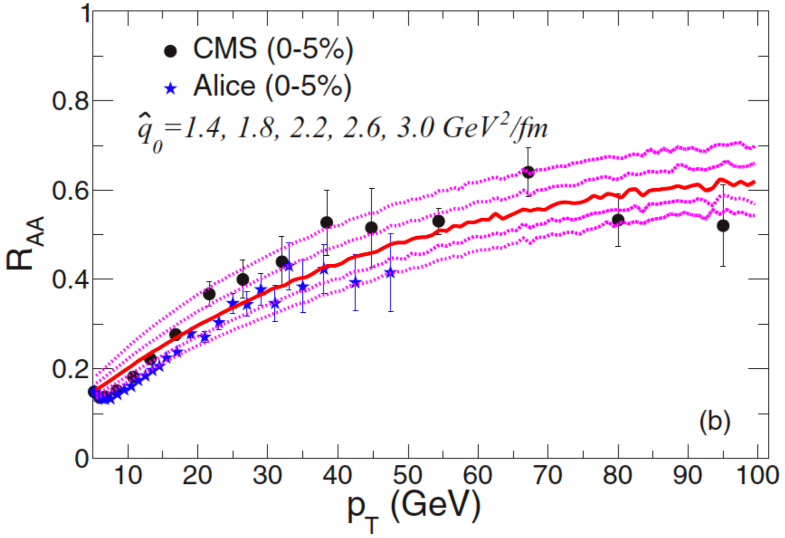

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$\hat{q}$ → Medium properties

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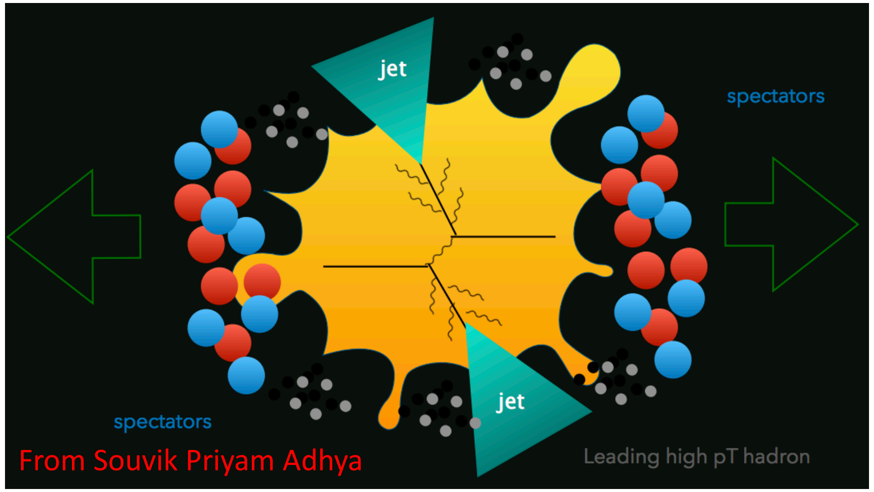

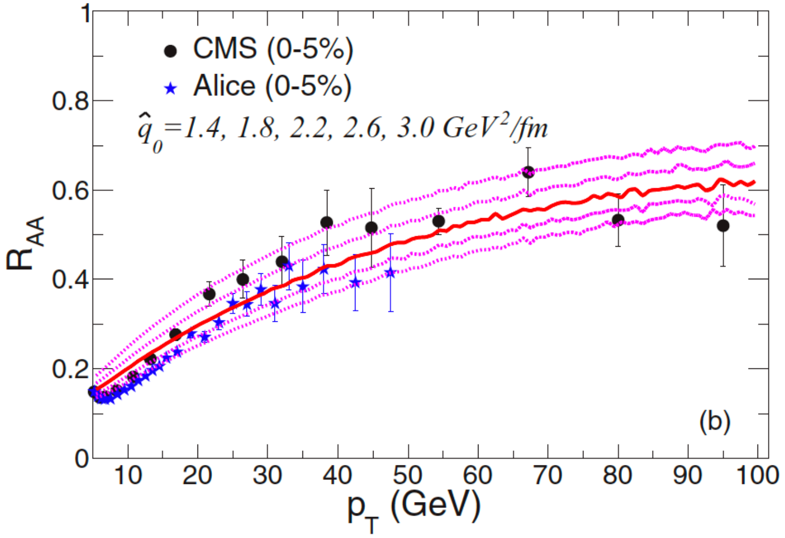

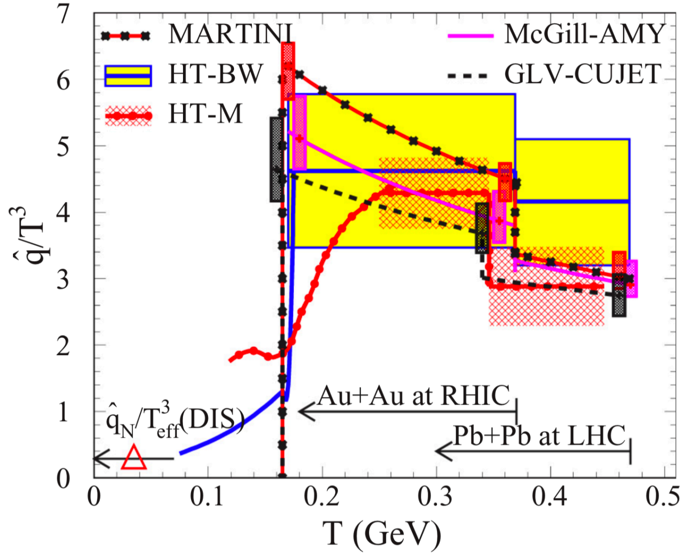

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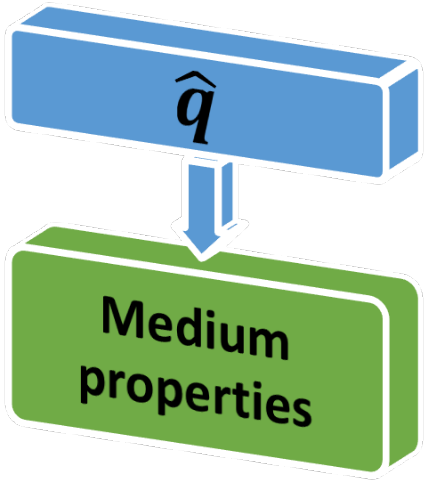
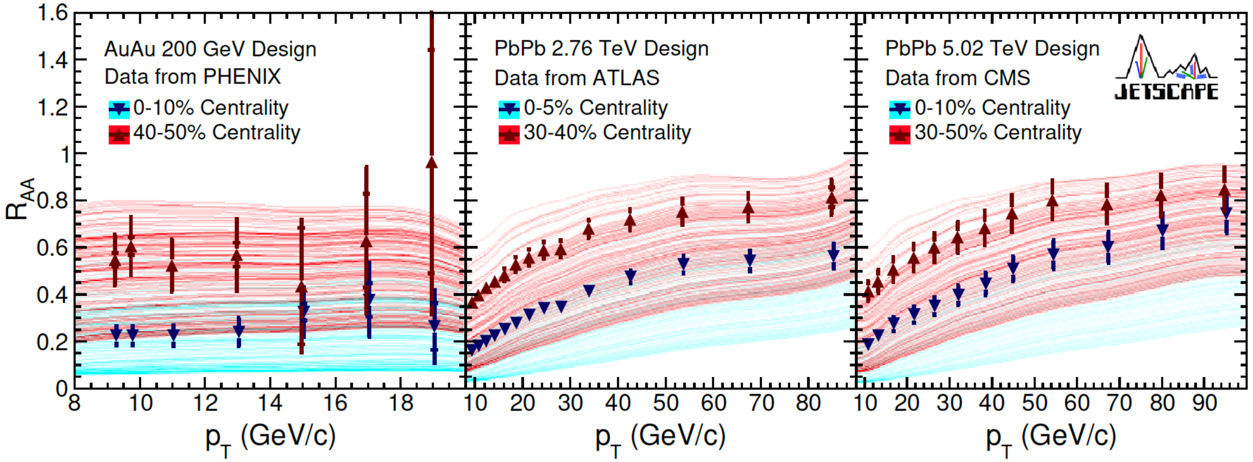
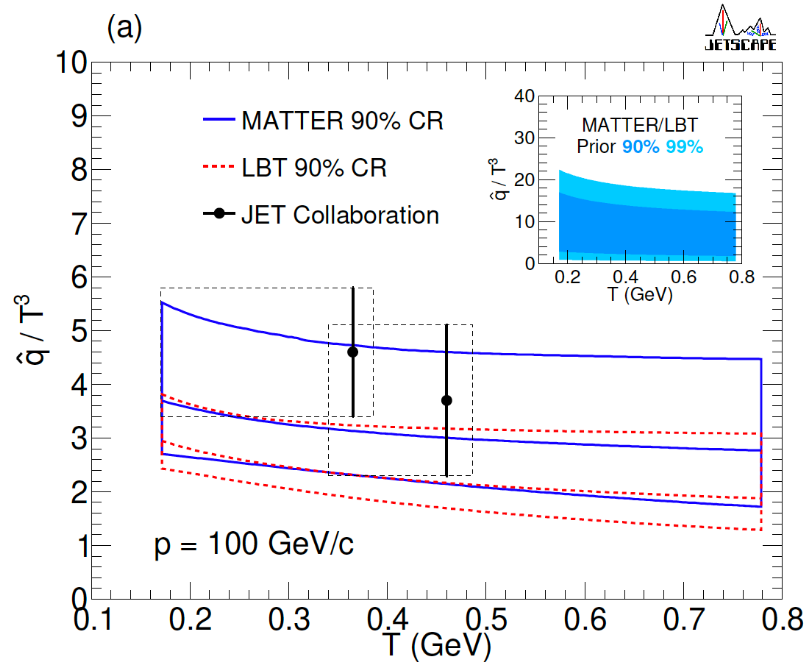


Temperature dependence of $\hat{q}$ from Bayesian analysis

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





Consistent with JET results.

Only a **weak** temperature dependence of $\hat{q}/T^3$ is found.

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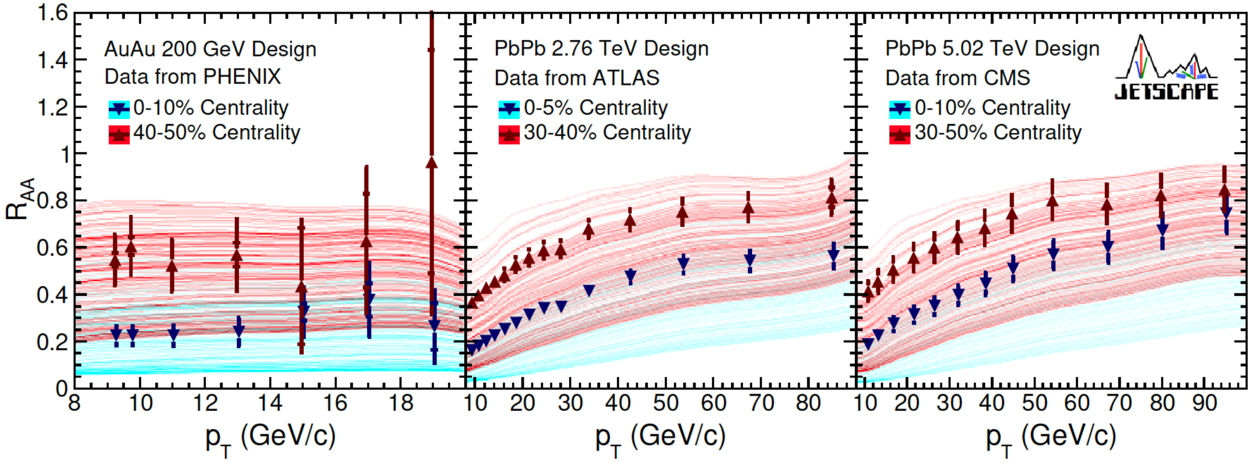

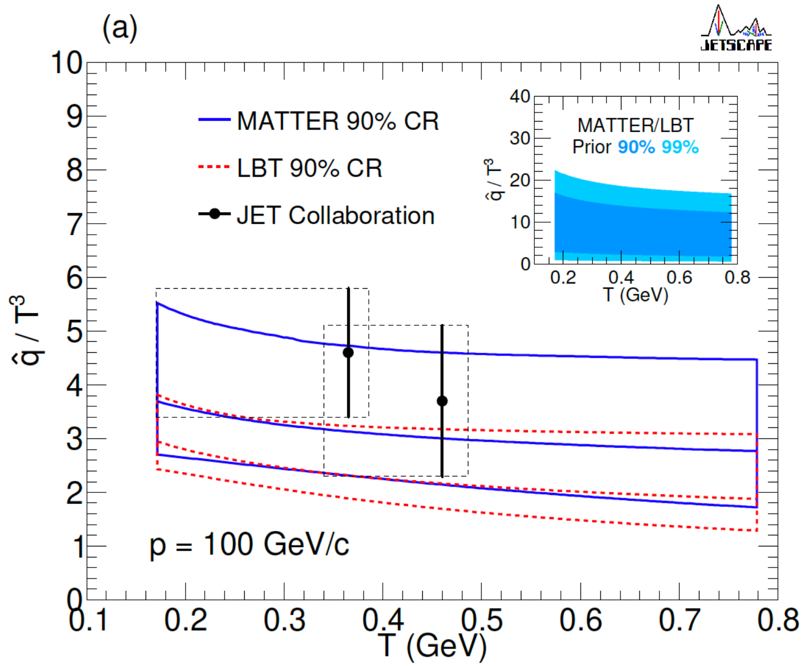

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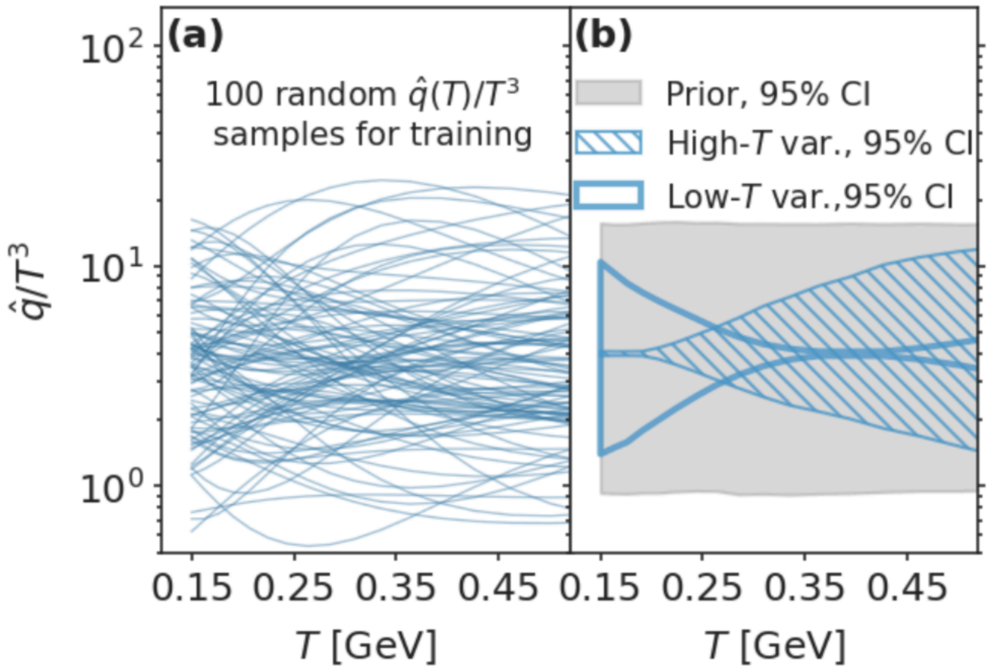
$$\frac{\hat{q}(Q,E,T)|_{Q_0,A,C,D}}{T^3} = 42C_R\frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2\left\{\frac{A\left[\ln\left(\frac{Q}{\Lambda}\right)-\ln\left(\frac{Q_0}{\Lambda}\right)\right]}{\left[\ln\left(\frac{Q}{\Lambda}\right)\right]^2}\theta(Q-Q_0)+\frac{C\left[\ln\left(\frac{E}{T}\right)-\ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]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

May be limited by parametrization form.

Temperature dependence of $\hat{q}$ from Bayesian analysis

M. Xie, W. Ke, H. Zhang, X.-N. Wang, 2206.01340 [hep-ph]



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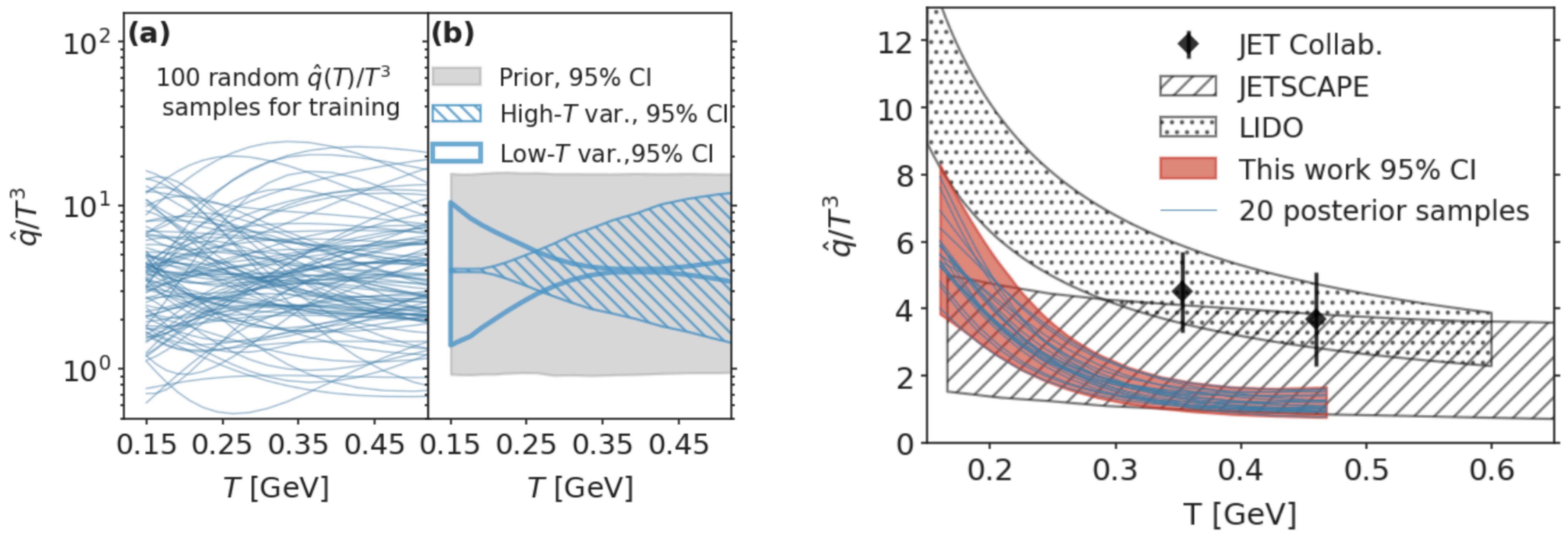
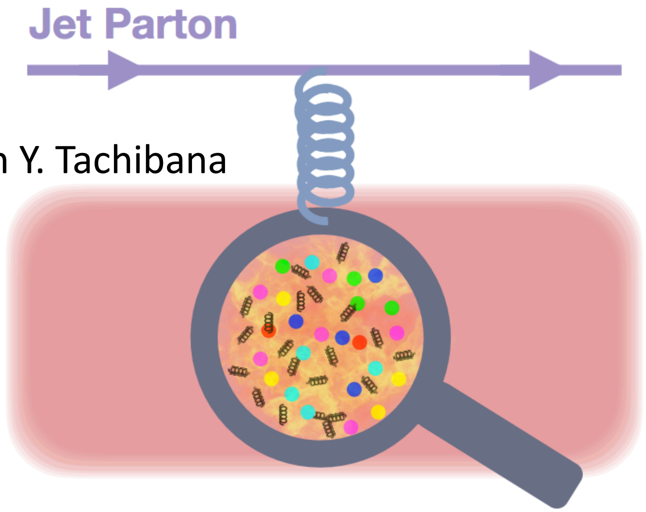


A **strong** temperature dependence can be observed by introducing a parametrization-free information field method.

Dependence on kinematic variables

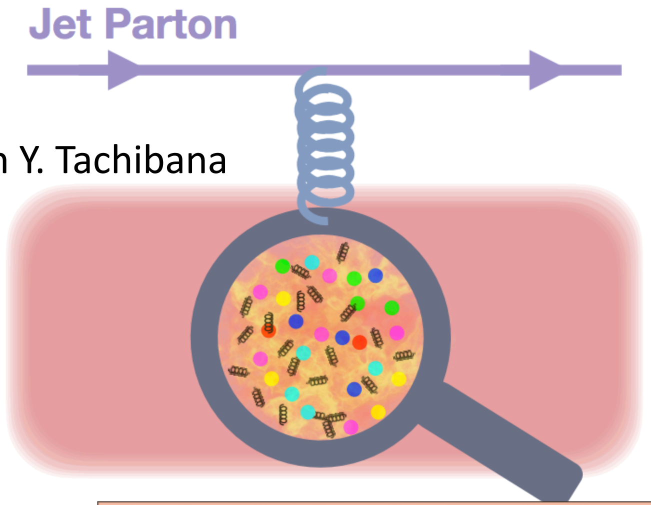


From Y. Tachibana

To decode more microscopic fine structures

Dependence of $\hat{q}$ on kinematic variables

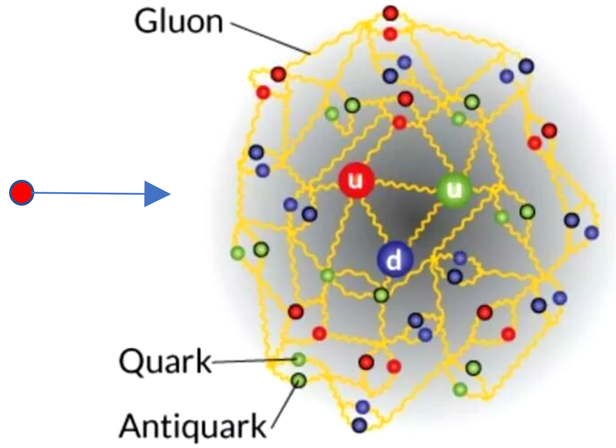
Dependence on kinematic variables

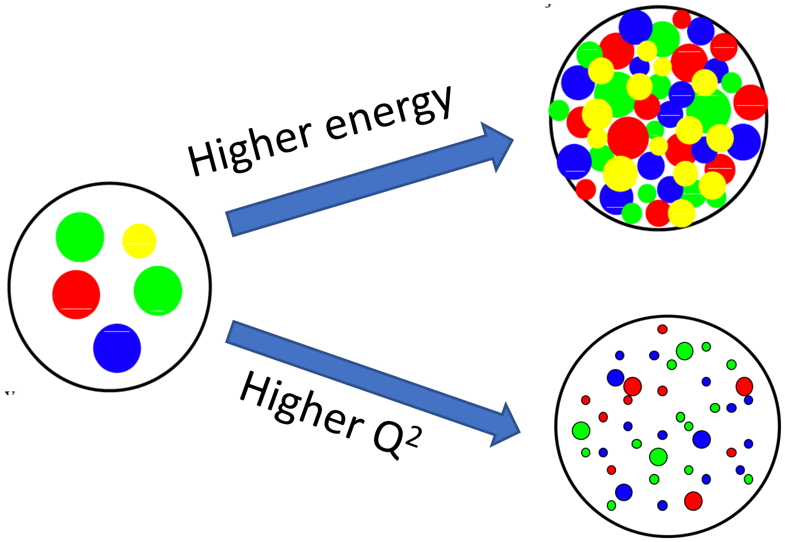


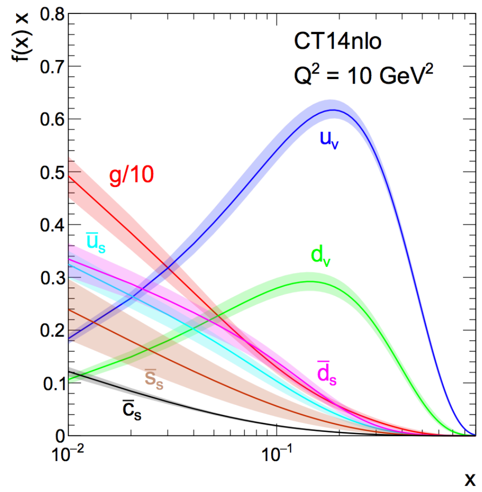
From Y. Tachibana

To decode more microscopic fine structures → **Dependence of $\hat{q}$ on kinematic variables**

An analogy: Kinematic dependence of partonic structure of nucleon/nucleus:



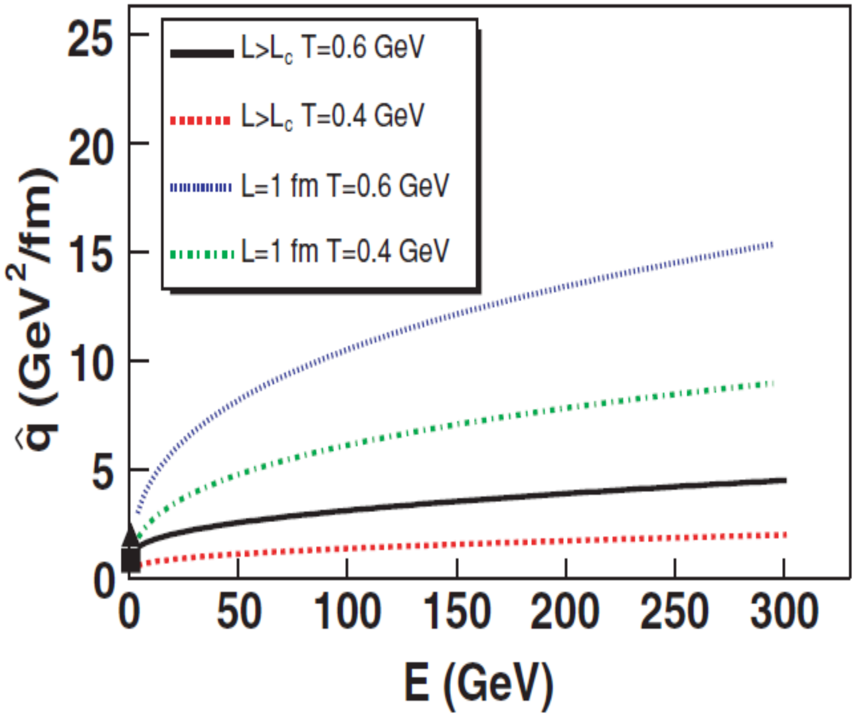




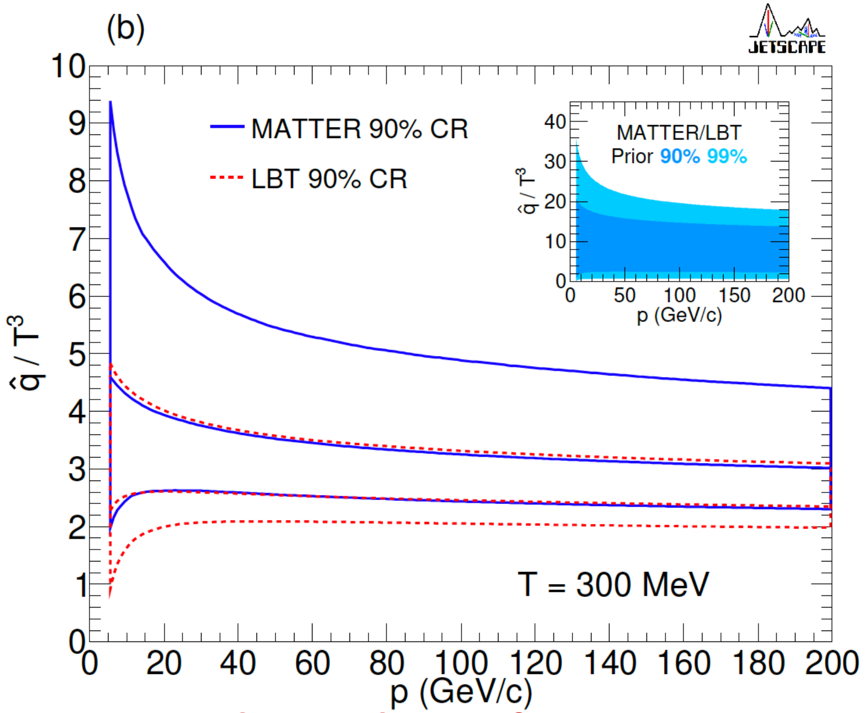
PDFs: global analysis based on factorization

Dependence of $\hat{q}$ on kinematic variables

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



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



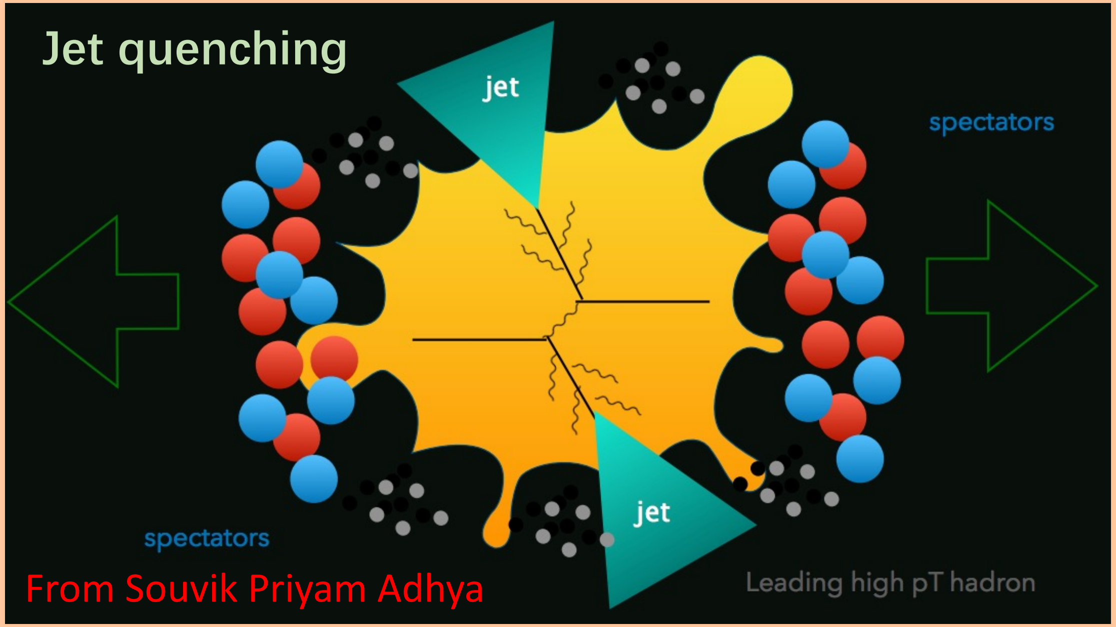
No clear energy dependence from Bayesian analysis.

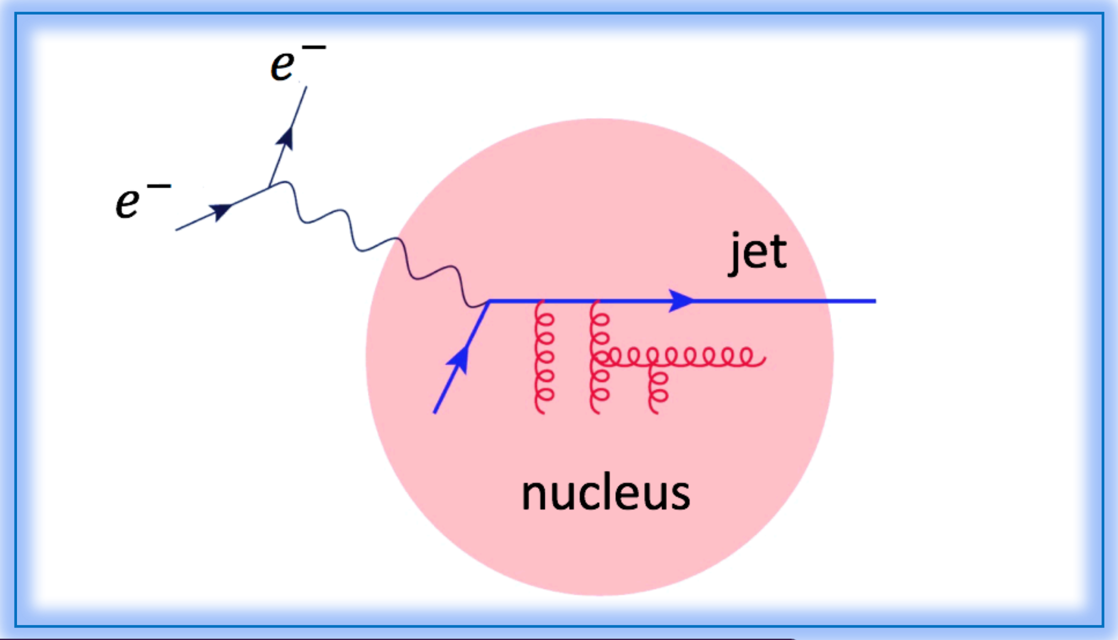
1. Complicated system: uncertainties in both theoretical and experimental sides.

2. Limitation of the parametrization form.

3. Need more suitable observable to reveal such subtle kinematic dependence.

An ideal place to study kinematic dependence of $\hat{q}$

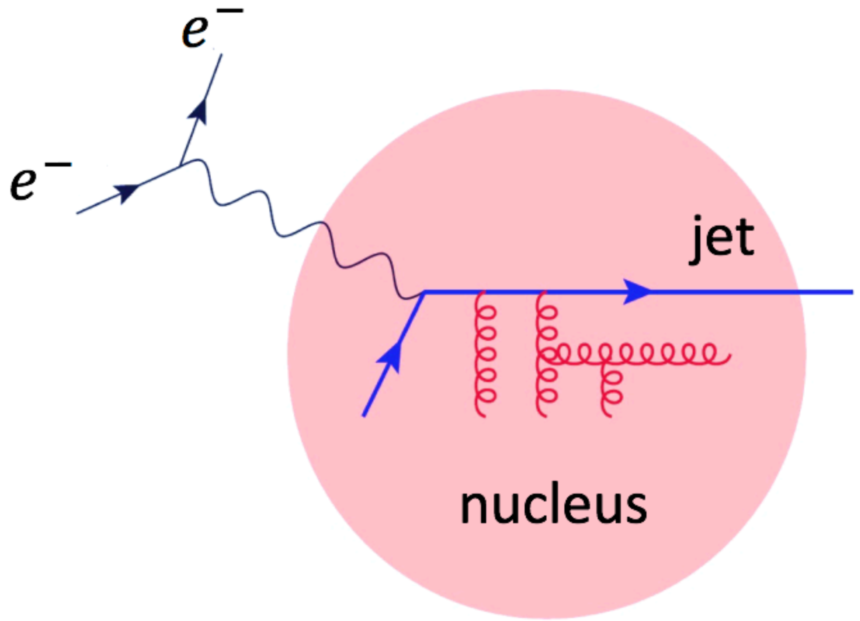


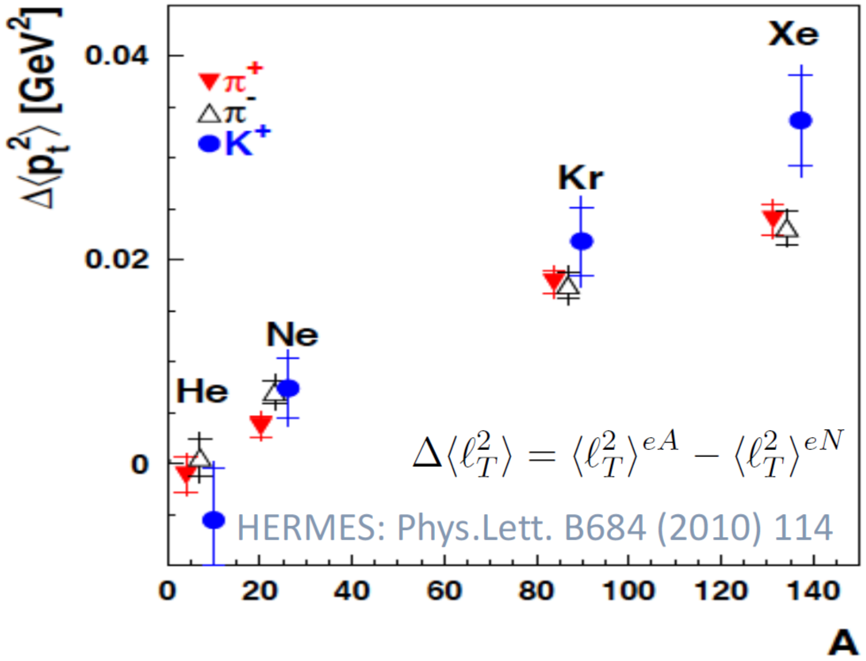


Advantages of eA/pA collisions:

- Less uncertainties in both theoretical and experimental sides.
- More controllable kinematics.
- May be instructive for jet quenching in AA.
- Opportunities from future high-precision EIC facilities.

$\hat{q}$ and transverse momentum broadening





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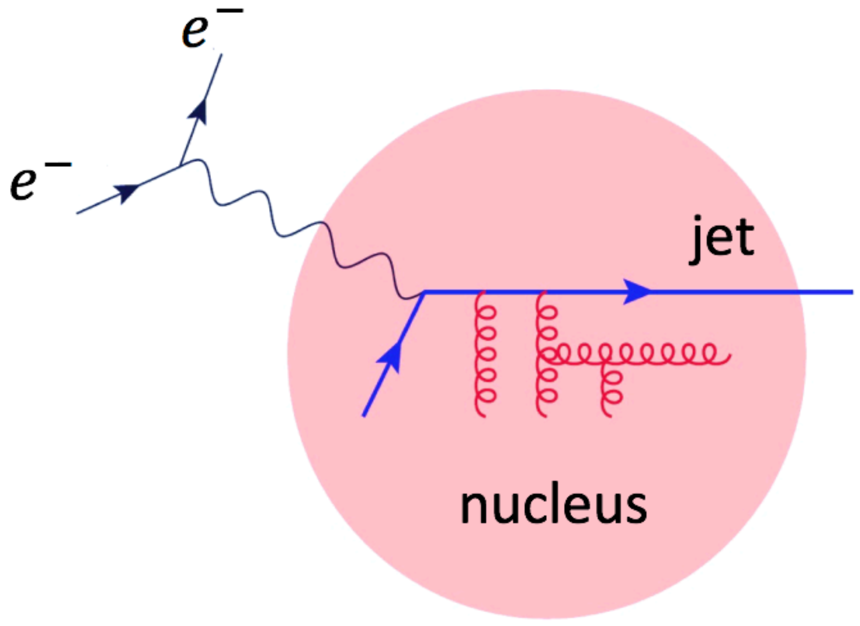
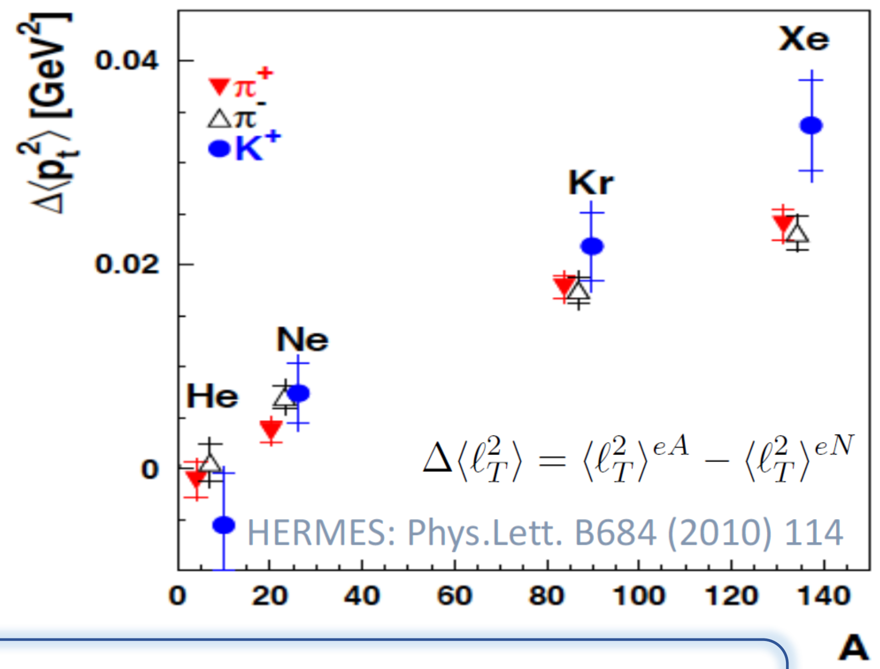




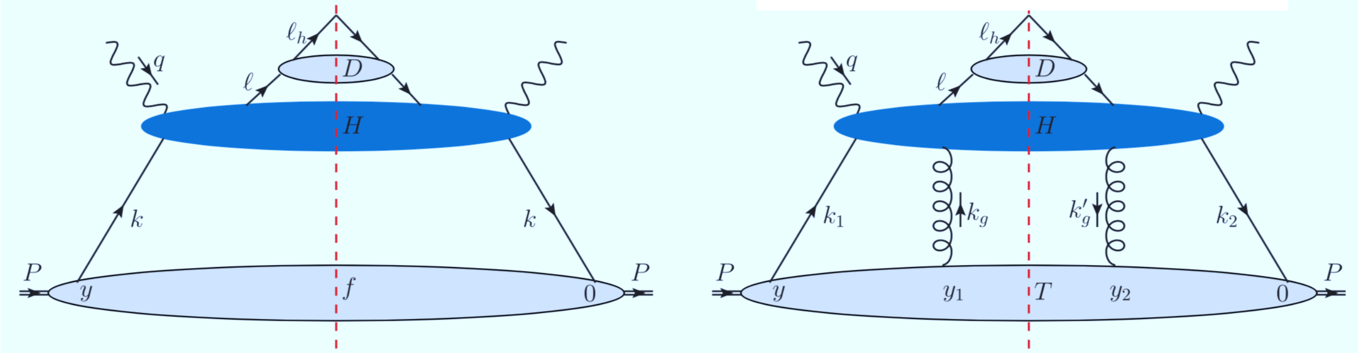
Transverse momentum broadening: $\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep}$

- The nuclear-effect observable most directly related to $\hat{q}$
- Increase with the mass number of the nuclear target

Multiple parton scattering in HT framework

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

$$d\sigma = d\sigma^S + d\sigma^D + \cdots$$



Single scattering　　　　Double scattering

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

perturbative expansion →

power expansion ↓

$$\sigma^h_{phys} = \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x) \longrightarrow \text{leading twist}$$
$$+ \frac{1}{Q}\left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x) \longrightarrow \text{twist-3}$$
$$+ \frac{1}{Q^2}\left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x) \longrightarrow \text{twist-4}$$
$$+ \ldots$$

For SIDIS:

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

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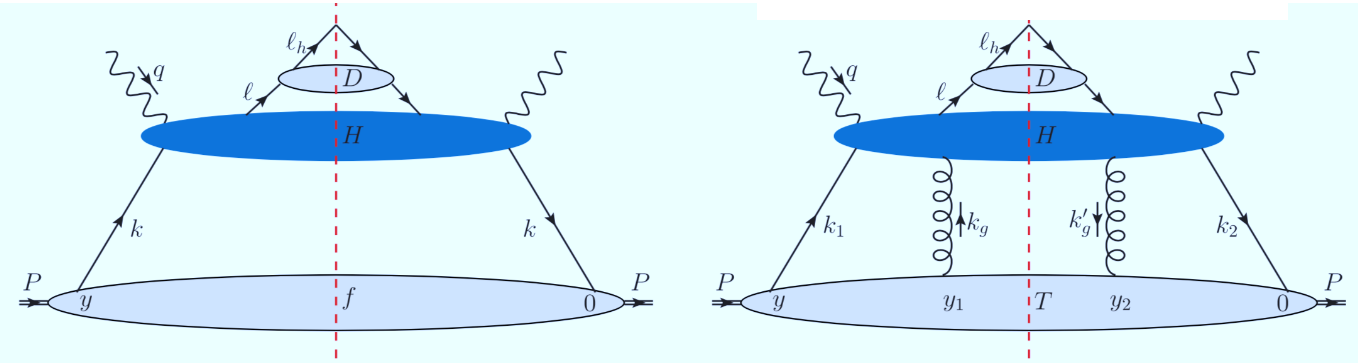

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Twsit-4 quark-gluon correlation function:

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

Transverse momentum broadening:

$$\Delta\langle p_T^2\rangle \approx \int dp_T^2 p_T^2 \frac{d\sigma^D}{dPS\, dp_T^2} \Big/ \frac{d\sigma^S}{dPS} = \frac{8\pi^2\alpha_s z_h^2 C_F}{N_c^2 - 1} \frac{\sum_q e_q^2 T_{qg}(x,\mu^2) D_{h/q}(z_h,\mu^2)}{\sum_q e_q^2 f_{q/A}(x,\mu^2) D_{h/q}(z_h,\mu^2)}$$

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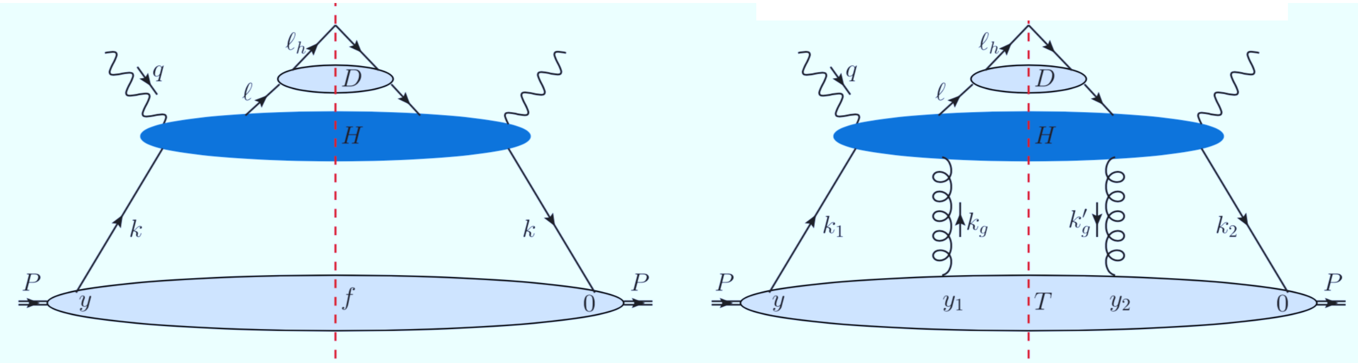

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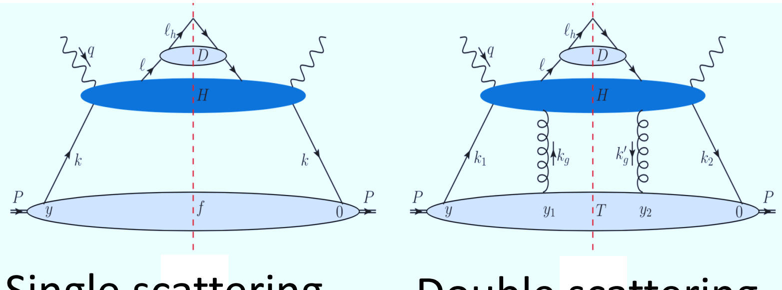
Expressed with $\hat{q}$:

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

Approximation of a large and loosely bound nucleus

Multiple parton scattering in HT framework

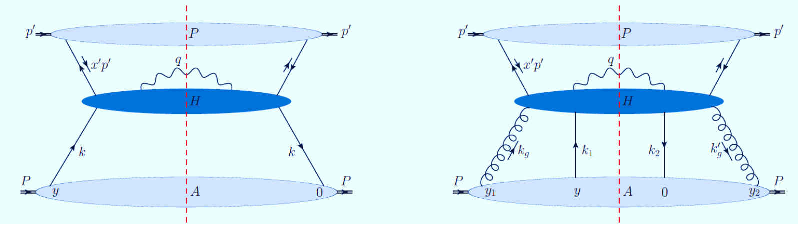
1. SIDIS



Single scattering Double scattering

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

2. Drell-Yan (pA)

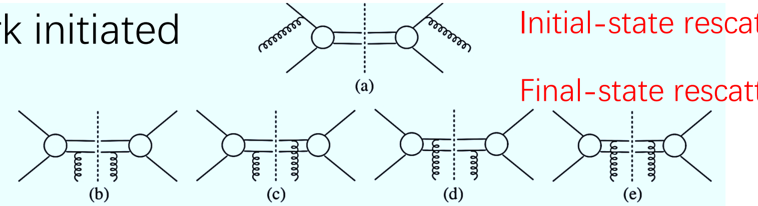


Single scattering Double scattering

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

3. Heavy quarkonium (pA)

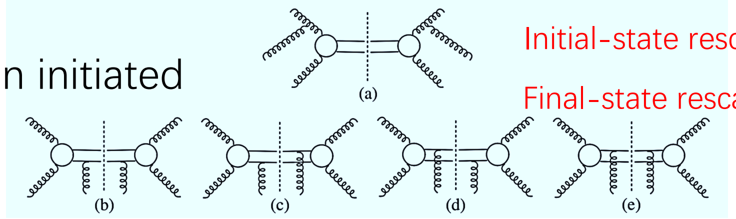
Quark initiated



Initial-state rescattering

Final-state rescattering

Gluon initiated

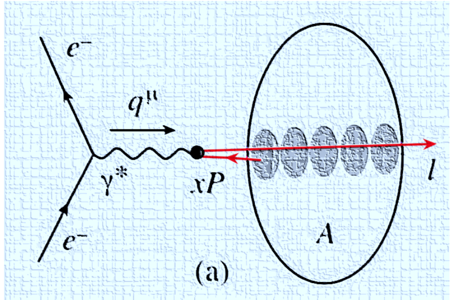


Initial-state rescattering

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).

Multiple parton scattering in HT framework

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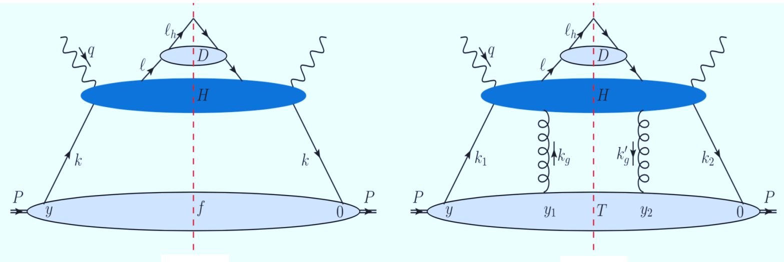

Single scattering Double scattering

Guo (1998), Kang, et al.,(20

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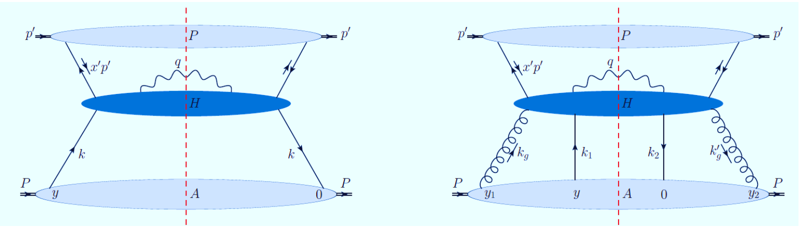

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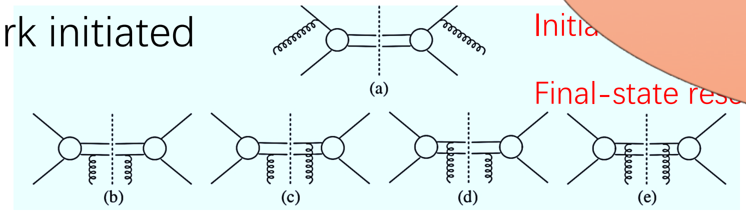
D 77, 114027 (2008).

A Common parameter:

$\hat{q}$ in CNM

3. Heavy quarkoni

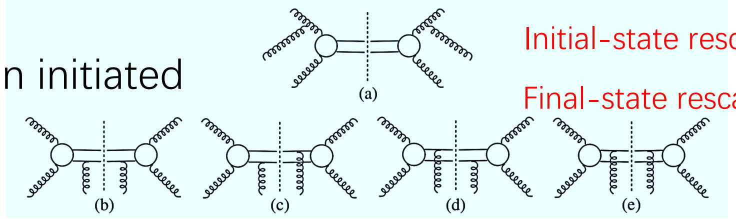
Quark initiated



Initia

Final-state res

Gluon initiated



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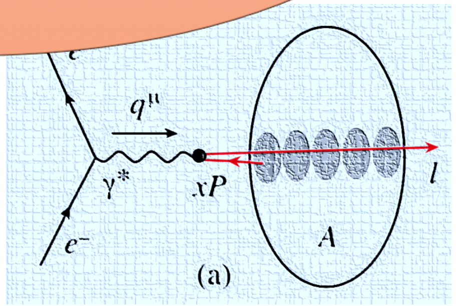
(DIS)



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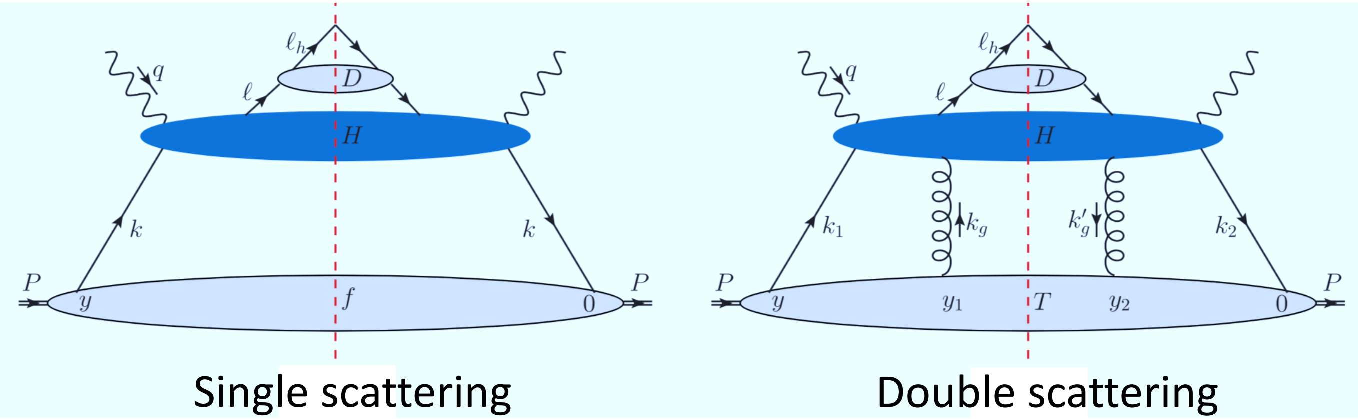
Multiple parton scattering in HT framework

Generalizing co-linear factorization to multiple scattering (higher twist)



Parton distribution function $f_q(x, Q^2)$ → $T_{qg}(x, Q^2)$ Quark-gluon correlation function

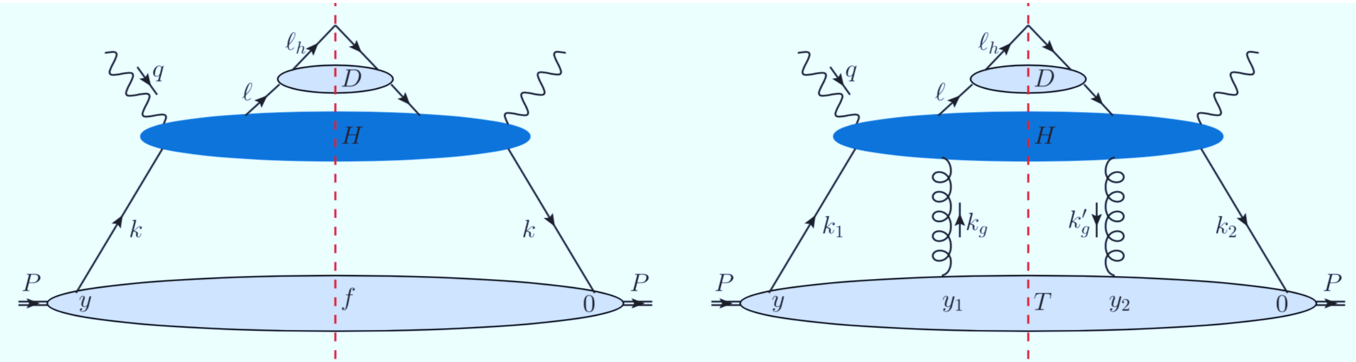
HT factorization verified to NLO

LO: Guo, Phys. Rev. D 58, 114033 (1998).

NLO: Kang, Wang, Wang, Xing, PRL 112, 102001 (2014).

Multiple parton scattering in HT framework

Generalizing co-linear factorization to multiple scattering (higher twist)



Single scattering

Double scattering

Parton distribution function $f_q(x, Q^2)$ → $T_{qg}(x, Q^2)$ Quark-gluon correlation function

HT factorization verified to NLO

LO: Guo, Phys. Rev. D 58, 114033 (1998).

NLO: Kang, Wang, Wang, Xing, PRL 112, 102001 (2014).

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

Dependence on Kinematic variables (x, Q^2) is natrually included.

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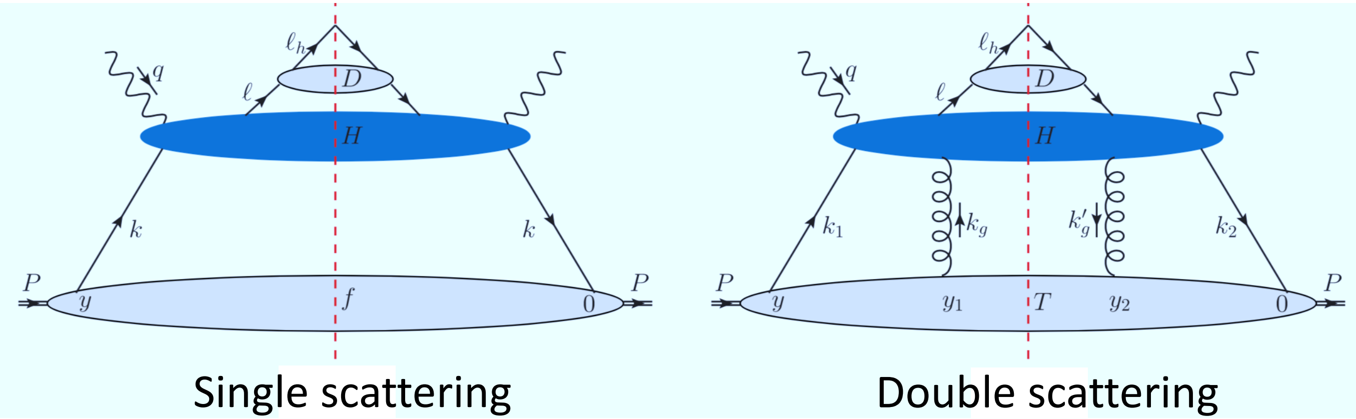

Measurement of $\Delta\langle p_T^2\rangle$ at certain values of Bjorken x_B and scale Q^2

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

Parton distribution function $f_q(x, Q^2)$ → $T_{qg}(x, Q^2)$ Quark-gluon correlation function

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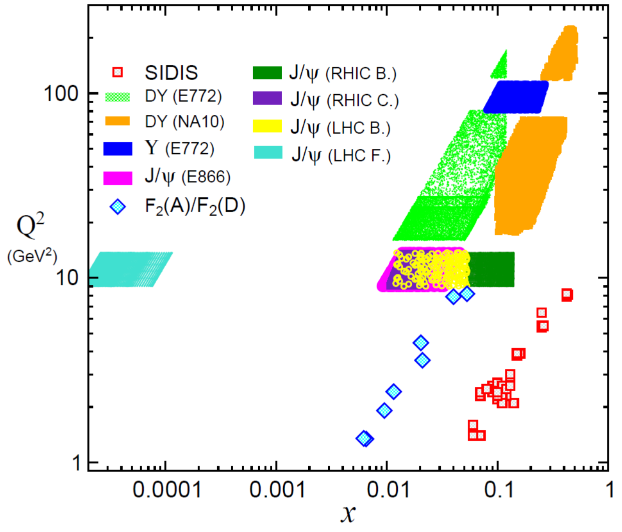
Extract $\hat{q}$ & study its kinematic dependence

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

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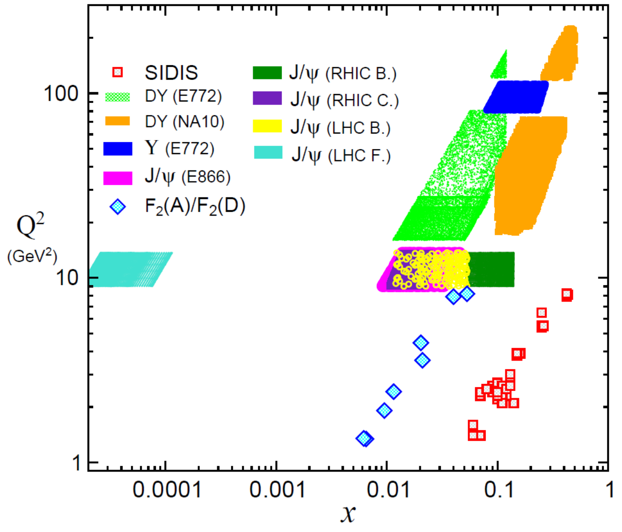

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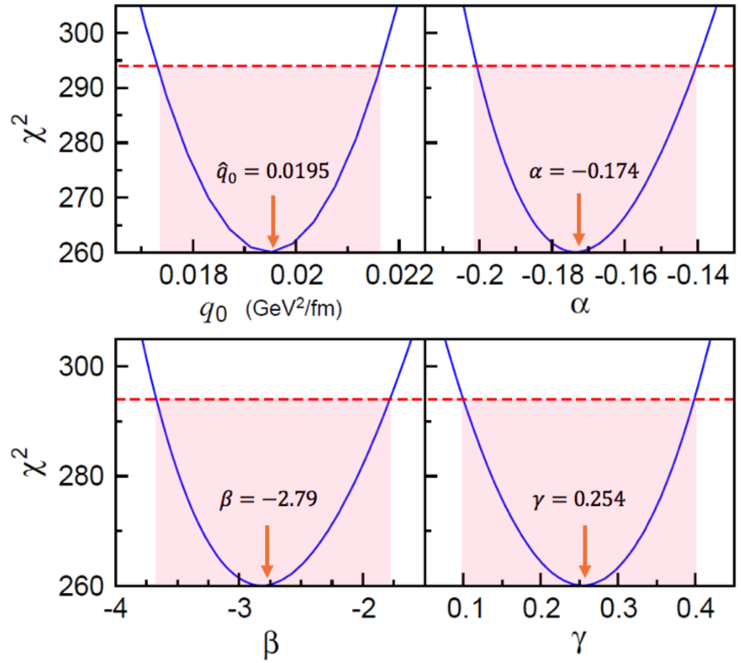
Also test constant $\hat{q} = \hat{q}_0$:

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	387.9	260.2

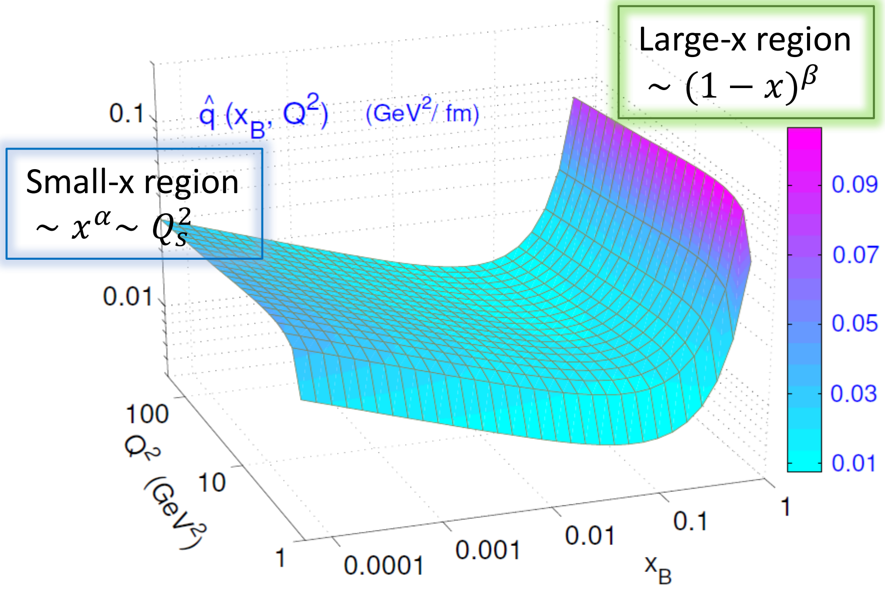
Table 1. Data sets used in the global analysis, and the χ^2 values with a constant $\hat{q}$ and $\hat{q}(x_B, Q^2)$, respectively.



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

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

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



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

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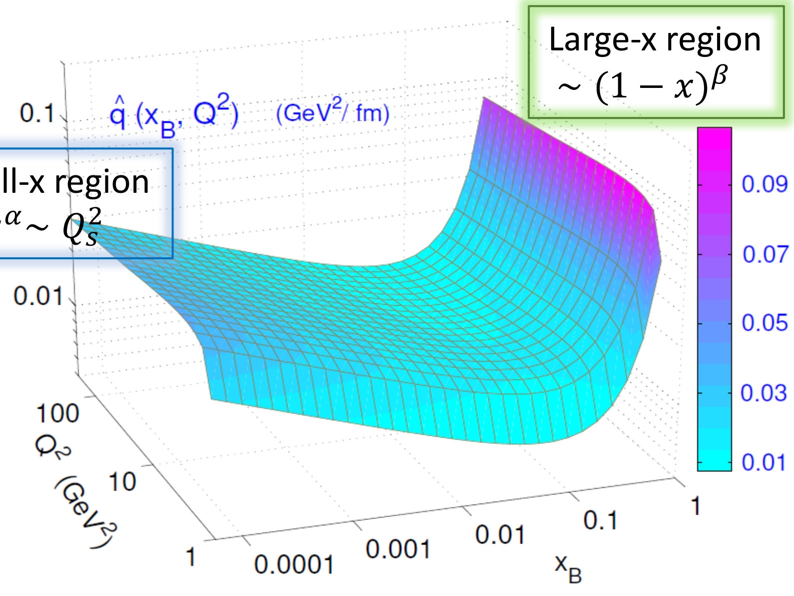
Small-x region $\sim x^{\alpha} \sim Q_s^2$

Large-x region $\sim (1-x)^{\beta}$



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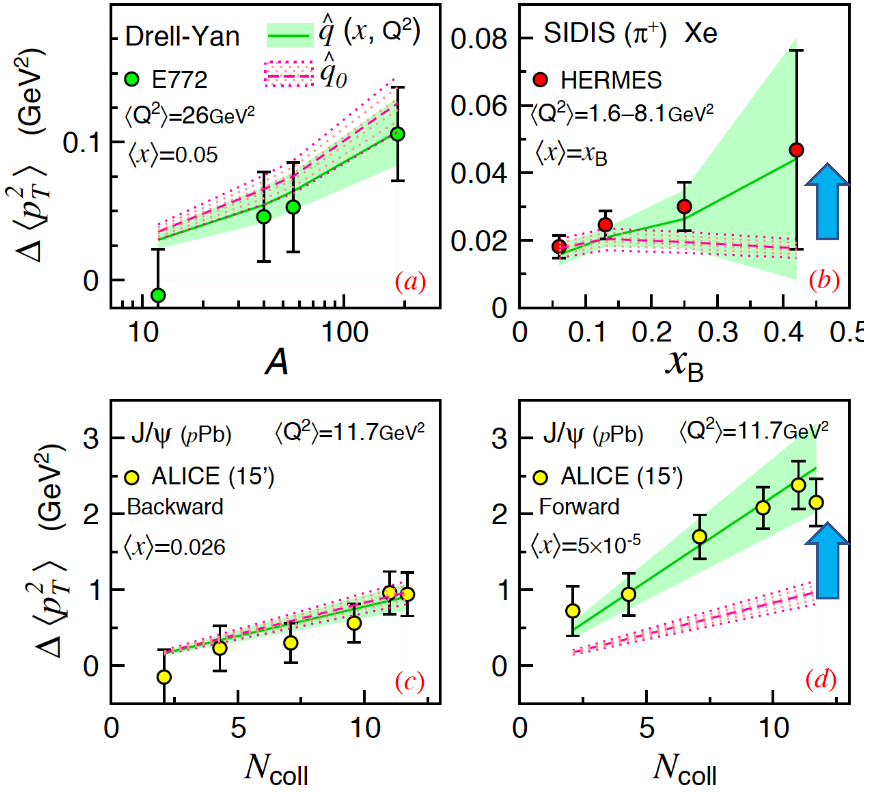

SIDIS in large-x region and
J/psi in forward (small-x) region
favor the enhanced broadening.

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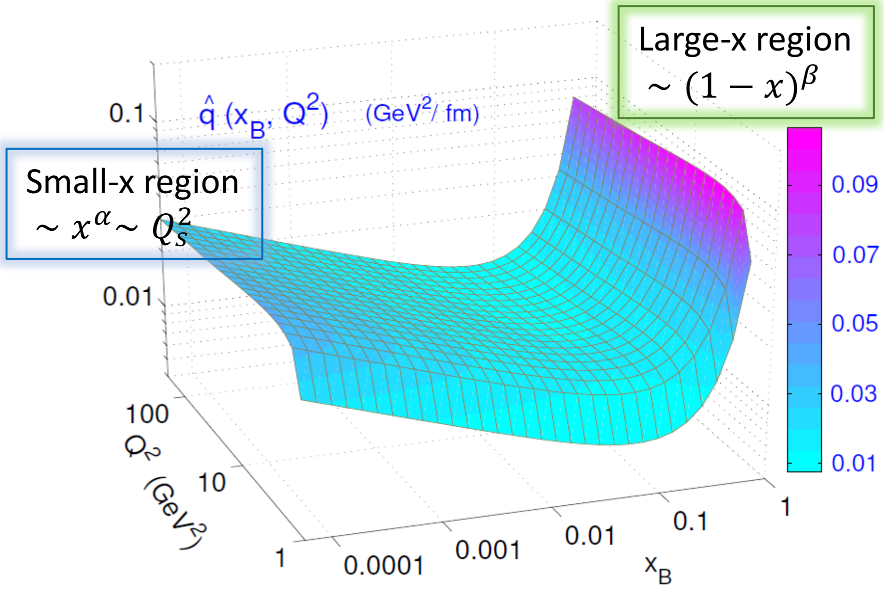

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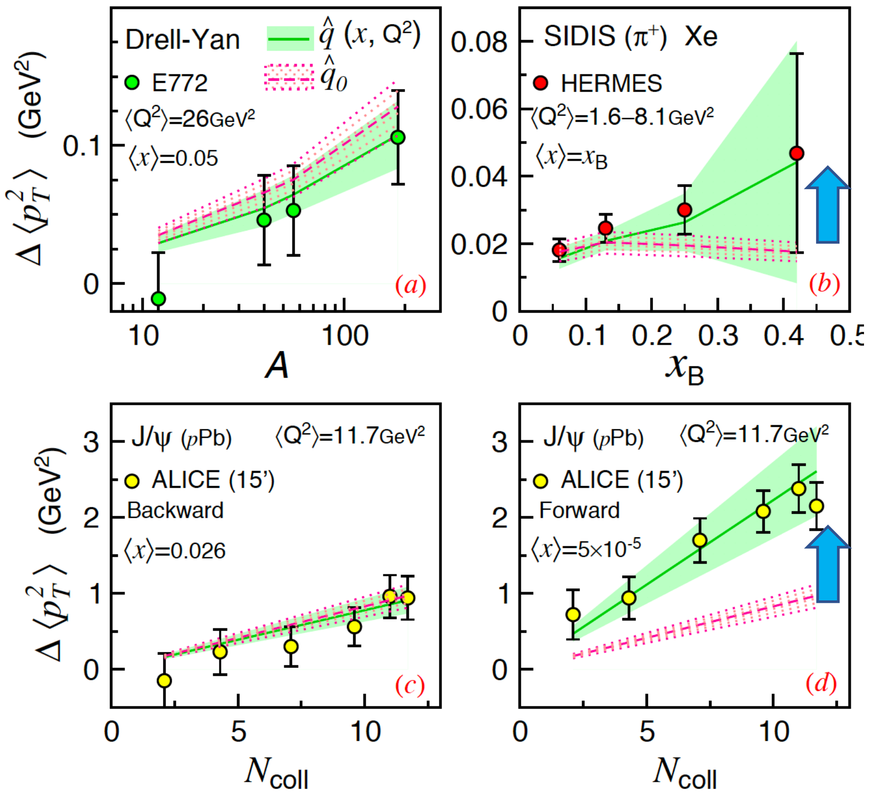


SIDIS in large-x region and
J/psi in forward (small-x) region
favor the enhanced broadening.

Seems consistent with recent study.

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

$$\hat{q}_A(x) = \hat{q}_0 \times \left(\frac{10^{-2}}{x}\right)^\alpha \qquad \hat{q}_0 = 0.051\sim0.075$$
$$\alpha = 0.25 - 0.3$$

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

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

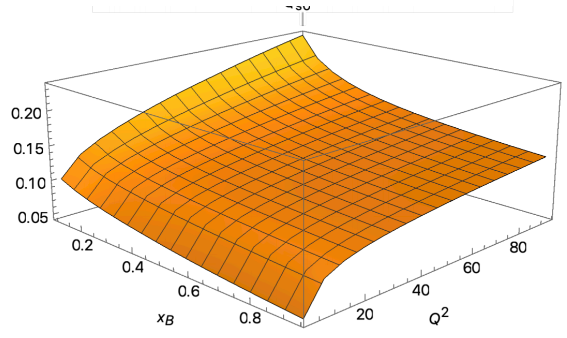
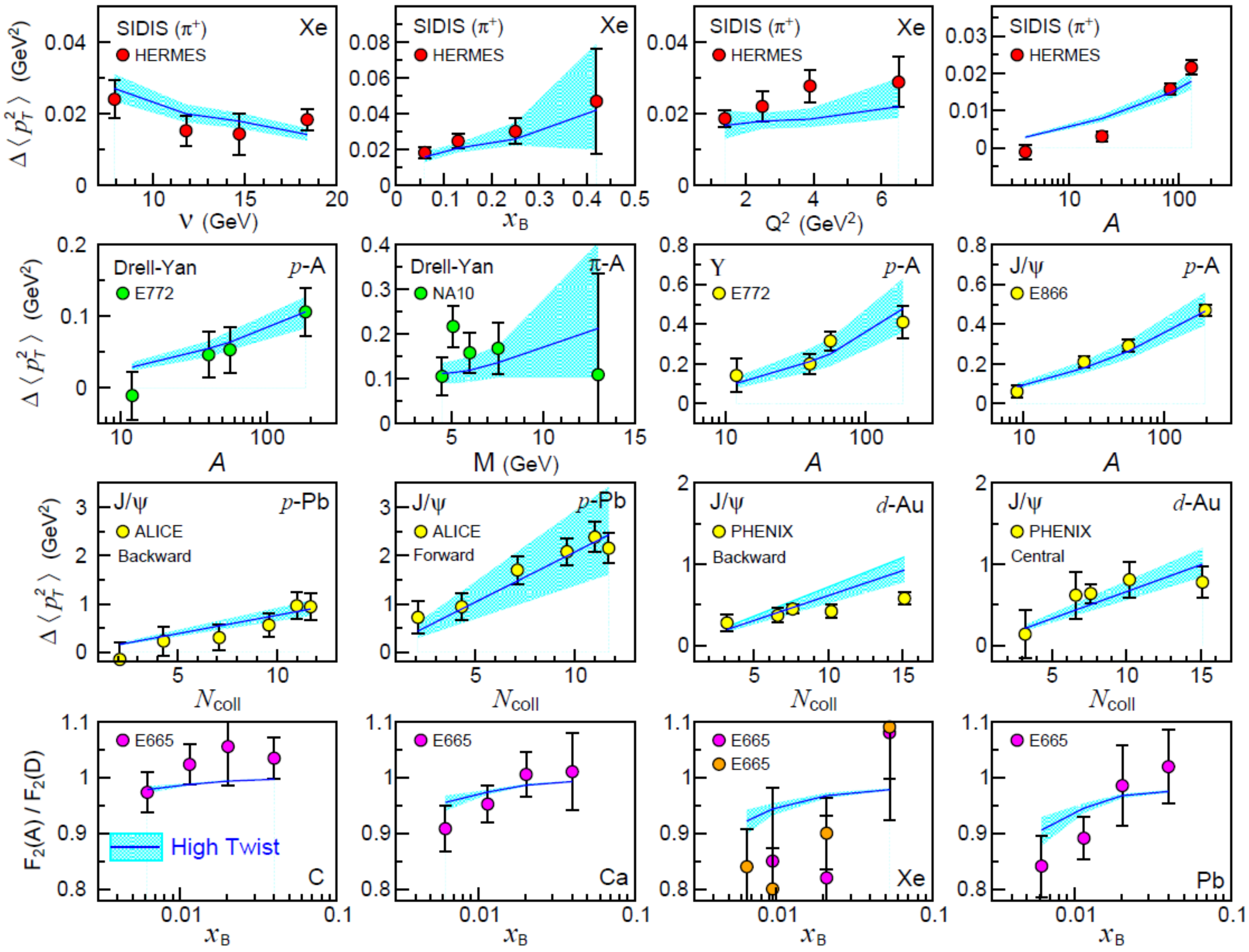
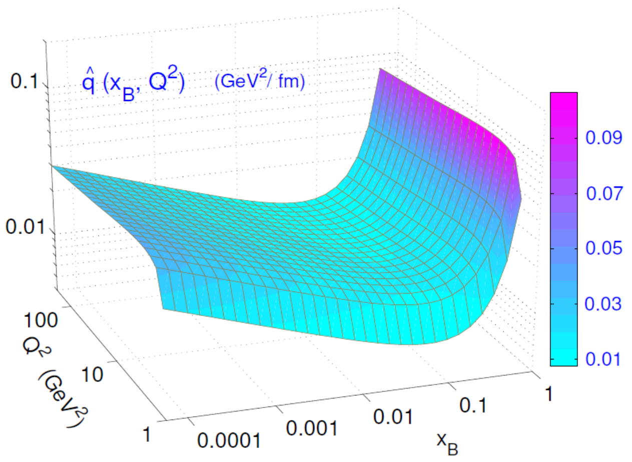


FIG. 5. The x_B and Q^2 dependence of the scaled saturation scale $Q_{s0}^2(x_B, Q^2)$ inside Pb from solving Eq. (29).

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



Determine uncertainties of $\hat{q}$



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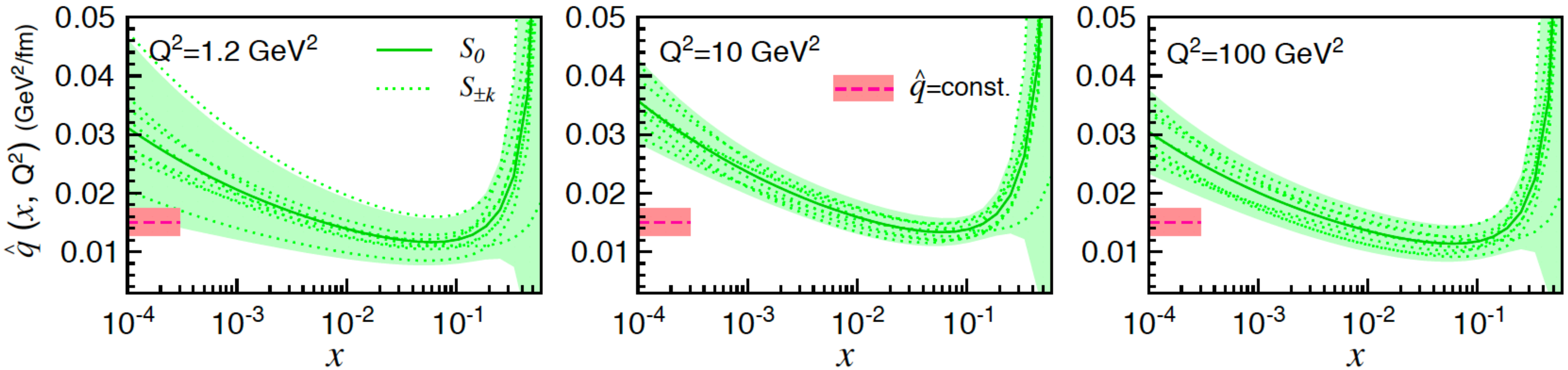

Hessian matrix method [PRD,65,014011, widely used in the analysis of PDFs, to determine the uncertainty of $\hat{q}$ in cold nuclear matter. **Nine sets** S_k,(k=-4,..0,..4) of $\hat{q}(x, Q^2)$ for future theoretical predictions.

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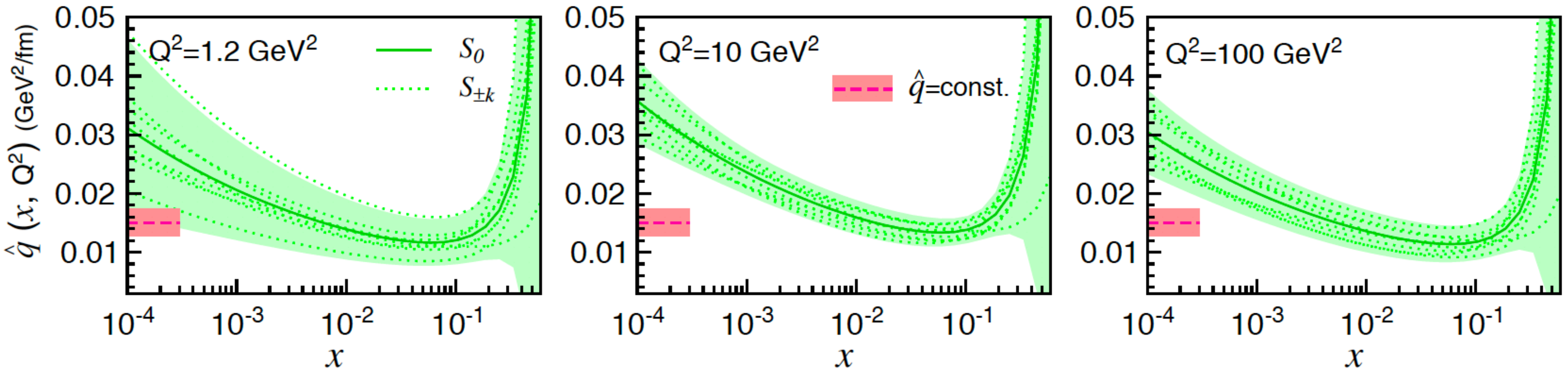

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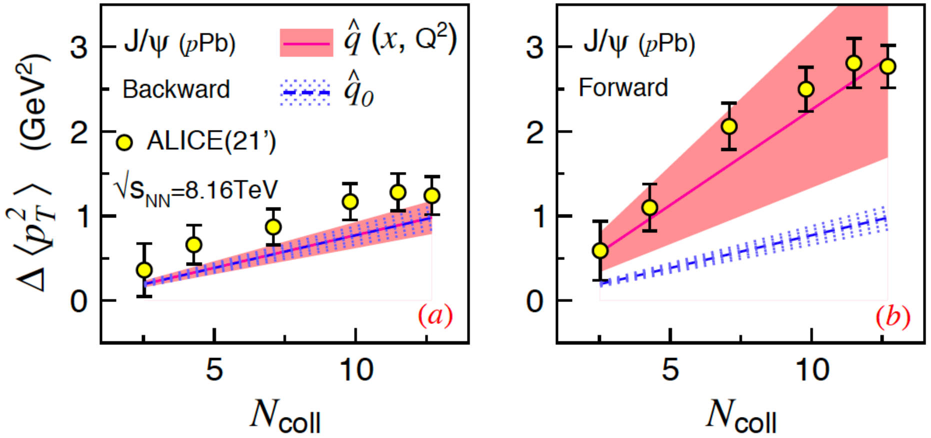
Test with new LHC data on Jpsi



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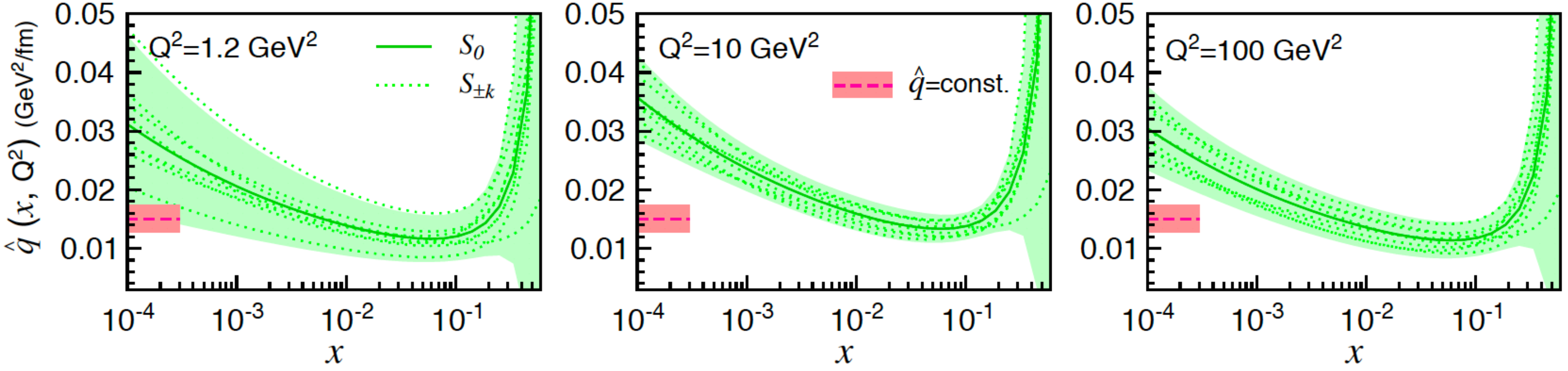

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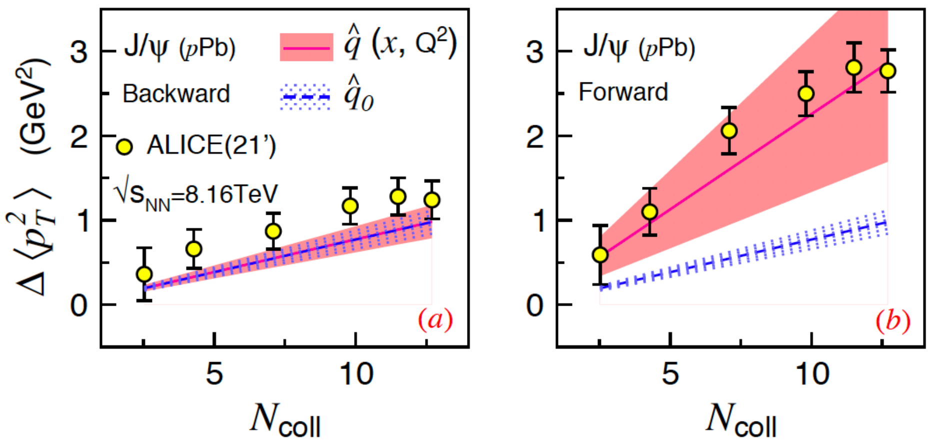
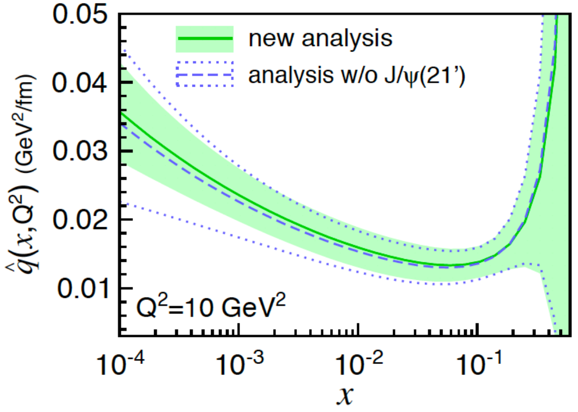
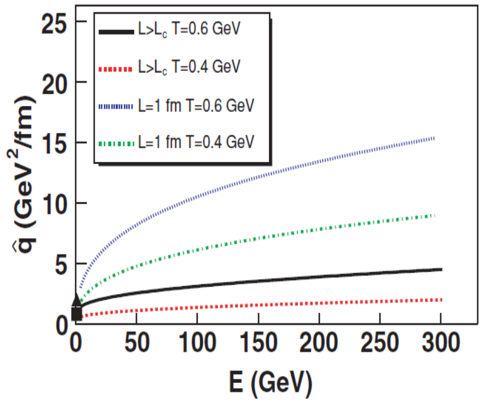


New data reduce uncertainty at small x

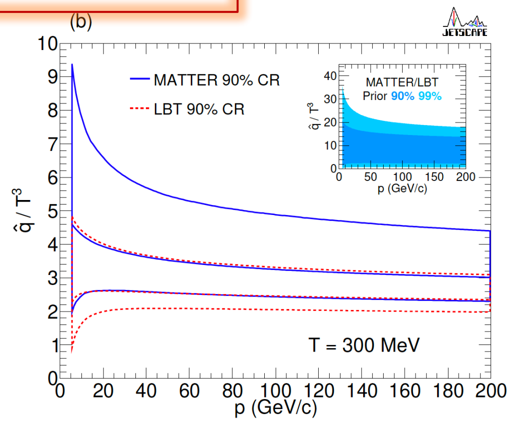


$\hat{q}$ for cold nuclear matter: jet energy dependence

For quark-gluon plasma



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



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

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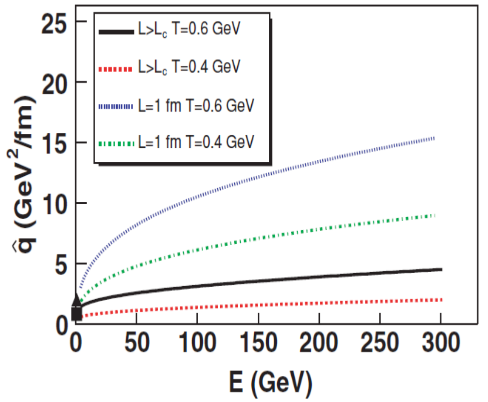

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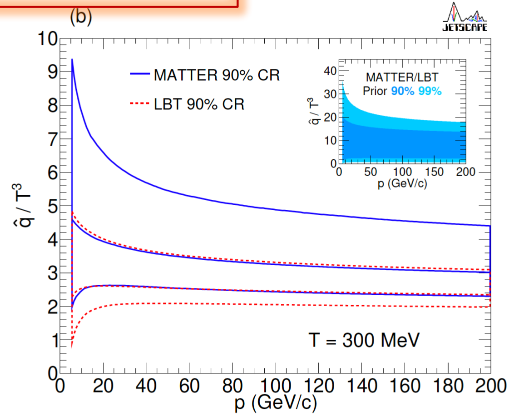
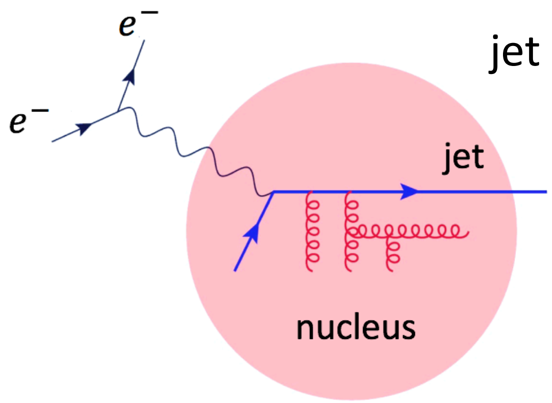


JETSCAPE, PRC **104**, 024905 (2021)

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)

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

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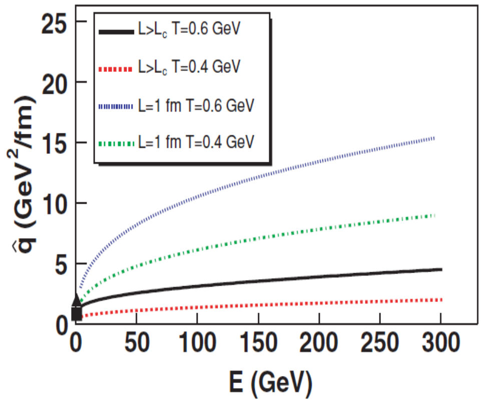

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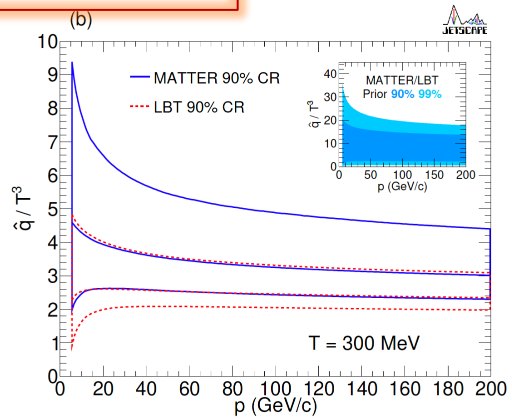
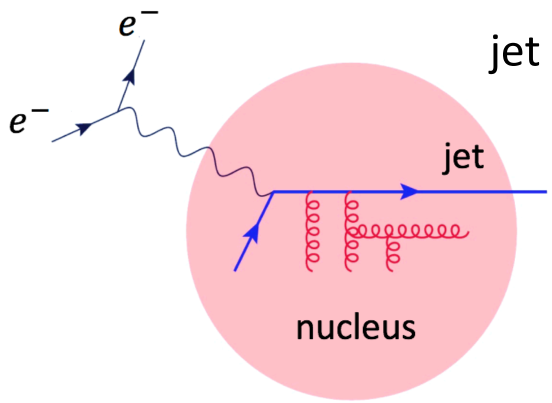


JETSCAPE, PRC **104**, 024905 (2021)

For cold nuclear matter



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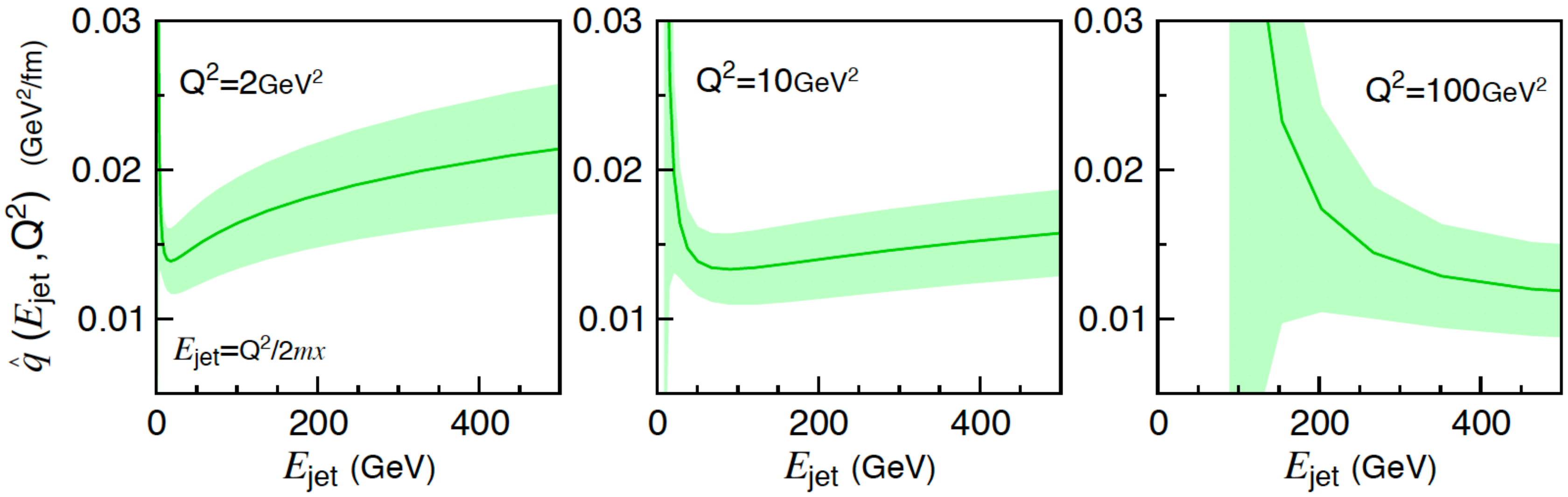


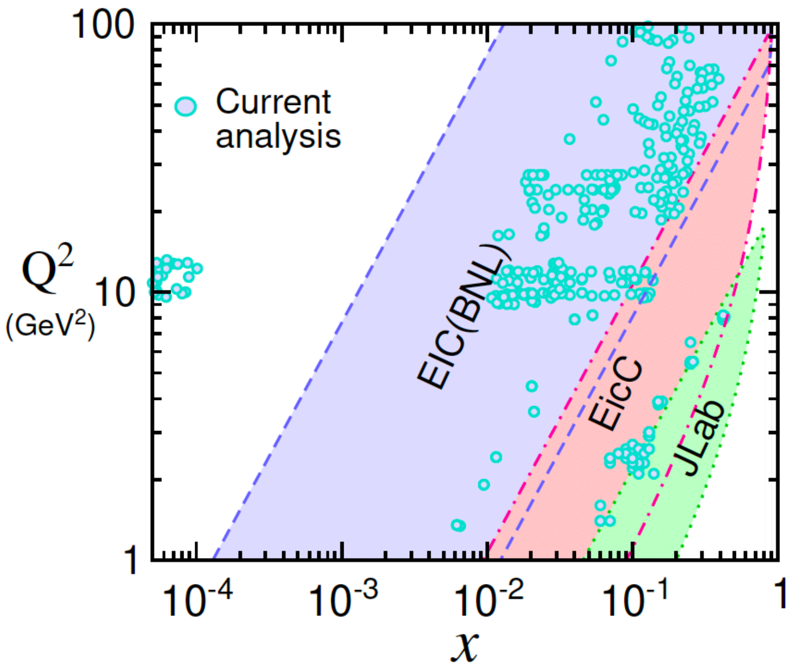
Increasing with jet energy at low Q^2.

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

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

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, 2302.02329

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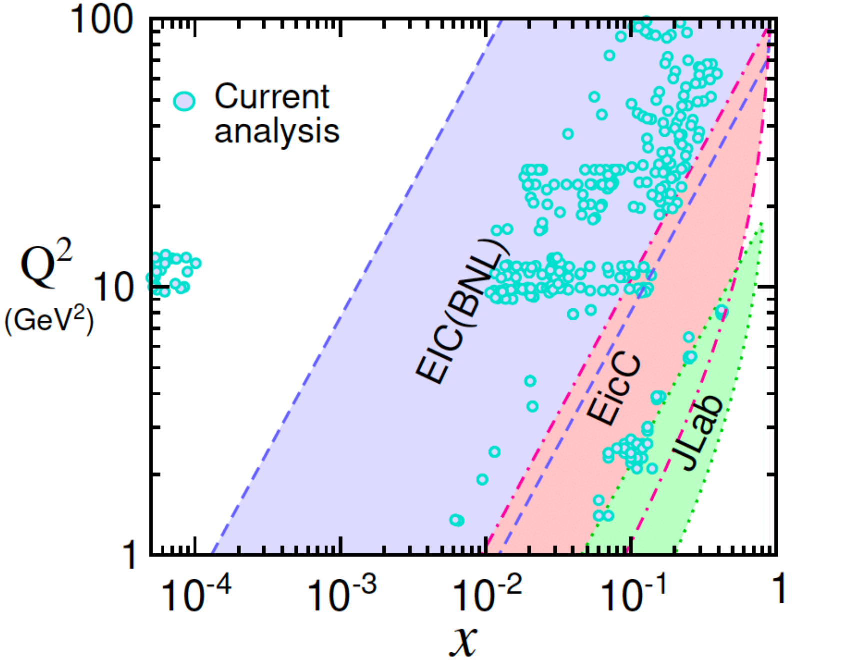

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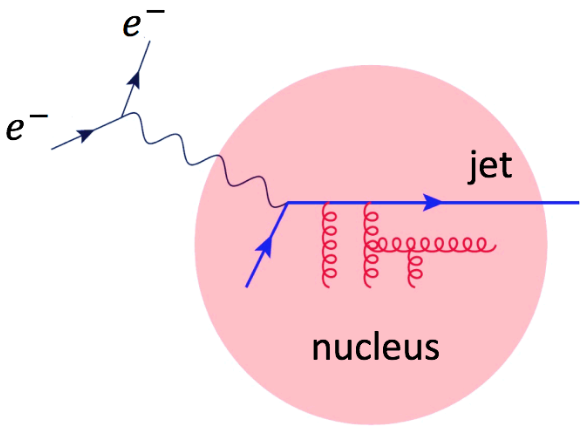
PR, Z.B. Kang, E. Wang, H. Xing and B.W. Zhang, 2302.02329

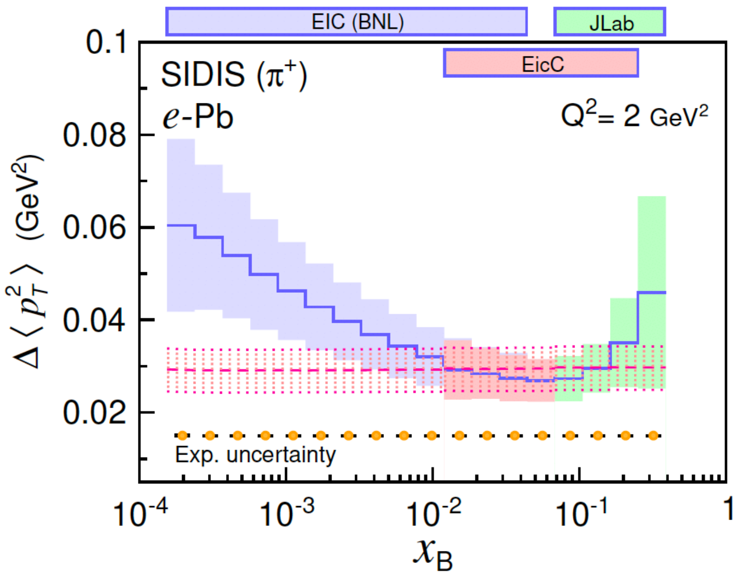
Transverse momentum broadening in SIDID

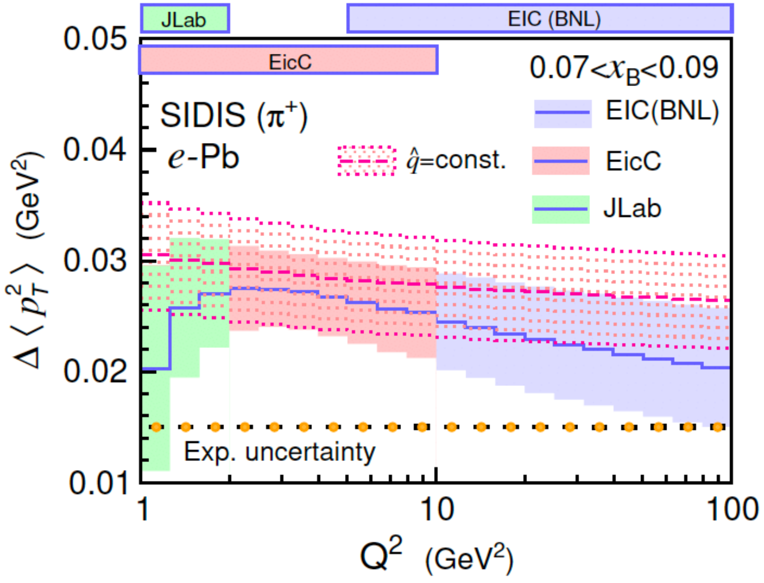


Abundant yield with nearly full kinematic coverage.

Quark jets dominate.

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



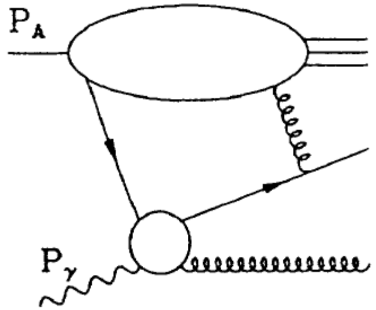


How will EIC deepen our understanding

Nuclear enhancement of transverse momentum imbalance of back-to-back particle pair

H. Xing, Z. B. Kang, I. Vitev and E. Wang, Phys. Rev. D 86, 094010 (2012)

For di-hadron

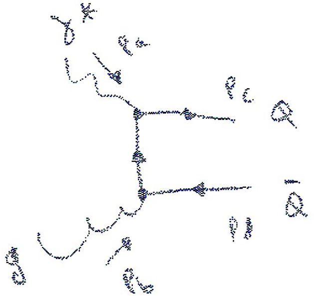


Mainly in mid- and large-x regions.

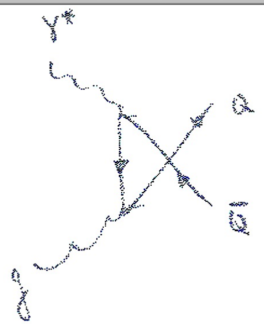
Both quark and gluon jets contribute.

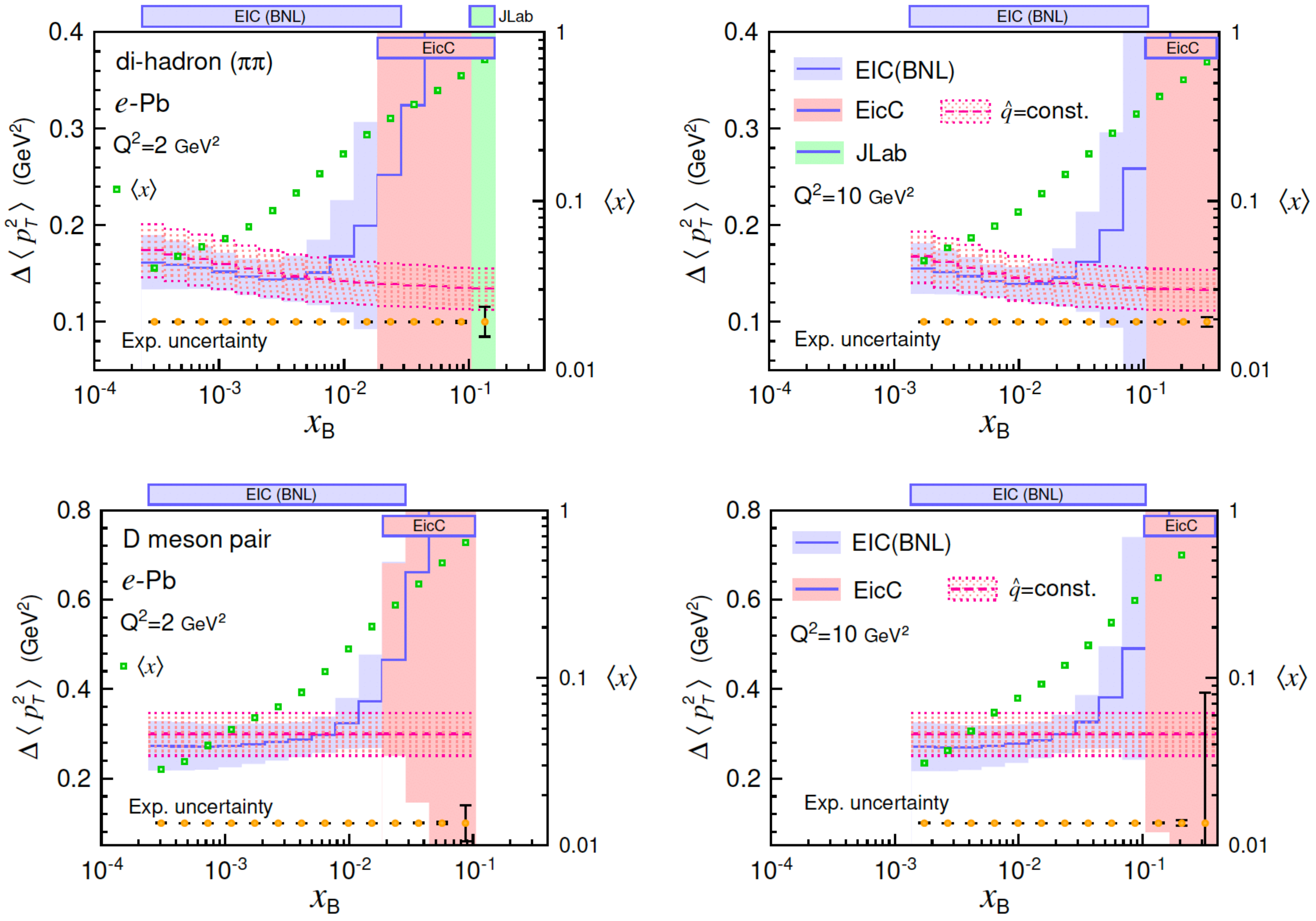
Reducing uncertainties of $\hat{q}(x, Q^2)$ at large-x

For heavy meson pair



Gluon jets dominate.





Summary

1. The possibility to gain the kinematic dependence of $\hat{q}$ in CNM through a global analysis

Similar as the standard PDFs.

2. A universal non-trivial kinematic (x, Q^2) dependence of $\hat{q}$:

Suggested by current data on transverse momentum broadening.

3. Jet energy dependence of $\hat{q}$:

May be sensitive to the probing scale.

4. Future EIC experiments in US and China:

Provide a precise image of $\hat{q}(x, Q^2)$

5. $\hat{q}(x, Q^2)$:

Not only useful for jet phenomena, but also the window to nucleus partonic structure (jet tomograghy).

Thank you!