The x and scale dependence of the jet quenching parameter $\hat{q}$

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Based on: Bianchi et al. arXiv:1702.00481 [nucl-th]

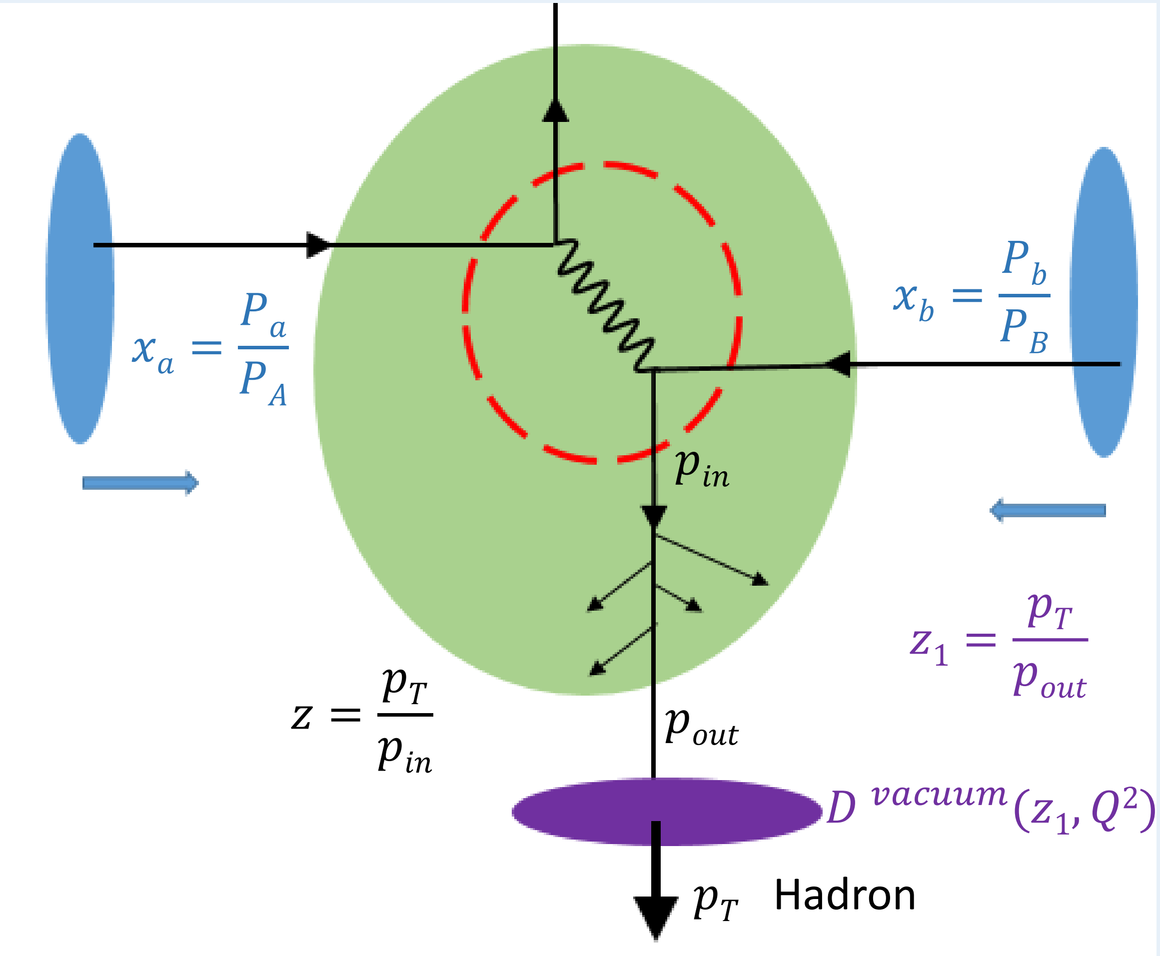
Outline

- Introduction to factorization of perturbative and non-perturbative physics
- Jet quenching parameter $\hat{q}$ puzzle
- Introduce x and scale dependence in $\hat{q}$ through QGP PDF
- Possible form of QGP PDF's
- R_{AA} and v_2 calculations at RHIC and LHC

Factorization of short and long-distance Physics

- ❑ **Work due to Collins, Soper, Sterman for pp collision**

- ❑ **Factorization assumed for High p_T hadron production in Heavy-ion Collision**



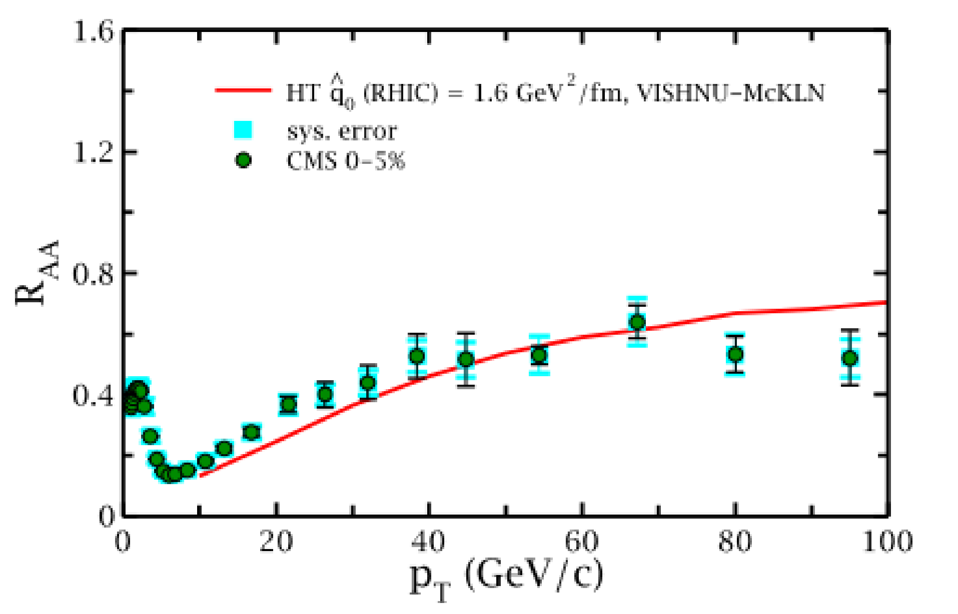
Jet Quenching Parameter

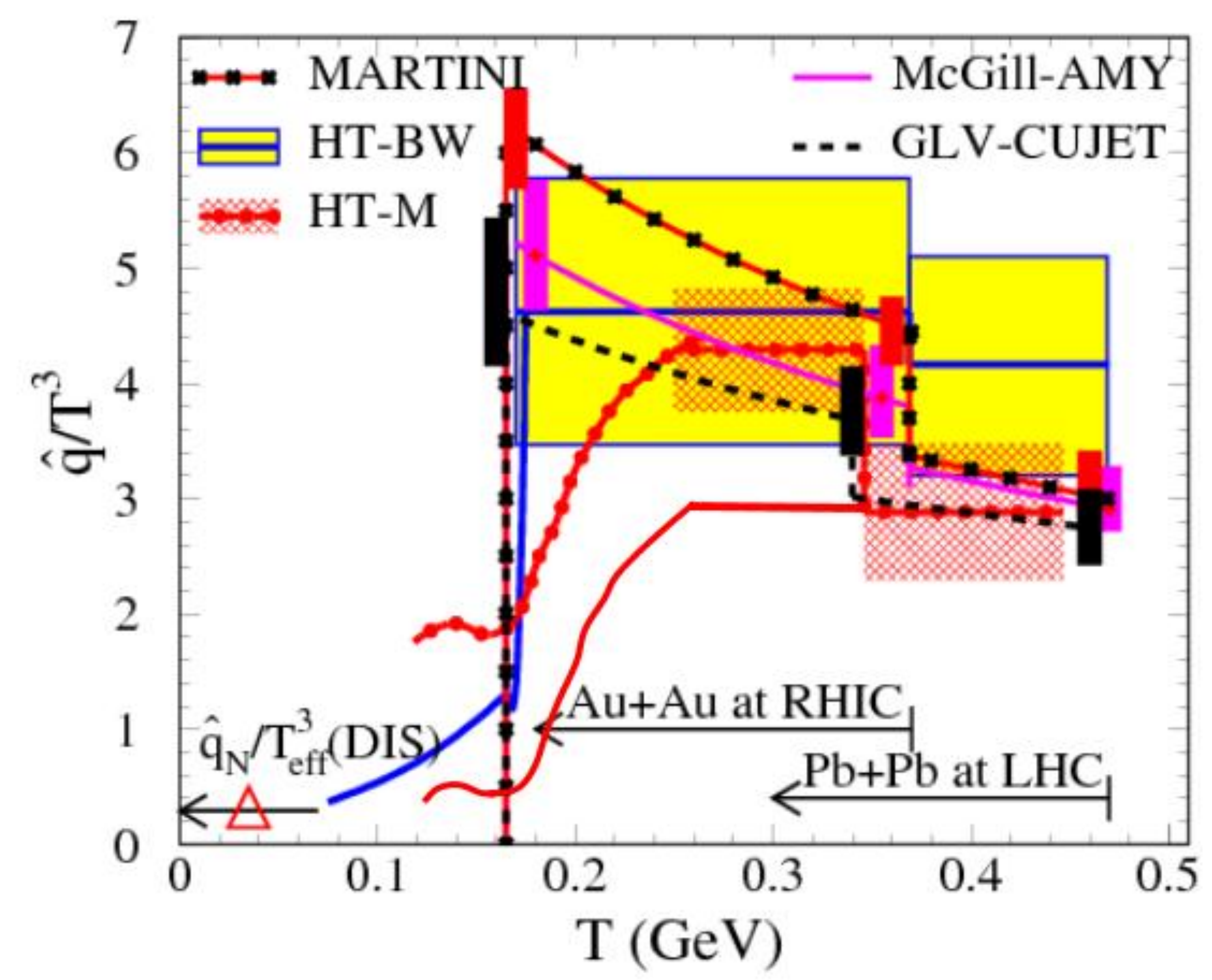
$$\hat{q}(T) = \frac{< k_\perp^2 >}{L}$$

(Universal Function)

$$\frac{d\sigma^{AB\to h+X}}{dy\, d^2p_T} \sim \int dx_a\, dx_b\, G_a^A(x_a, Q^2)\, G_b^B(x_b, Q^2)\, \frac{d\hat{\sigma}}{d\hat{t}}\, \widehat{D}^{med}_{modified}(z, Q^2)$$

Puzzle: Jet Quenching Parameter $\hat{q}$ at RHIC and LHC



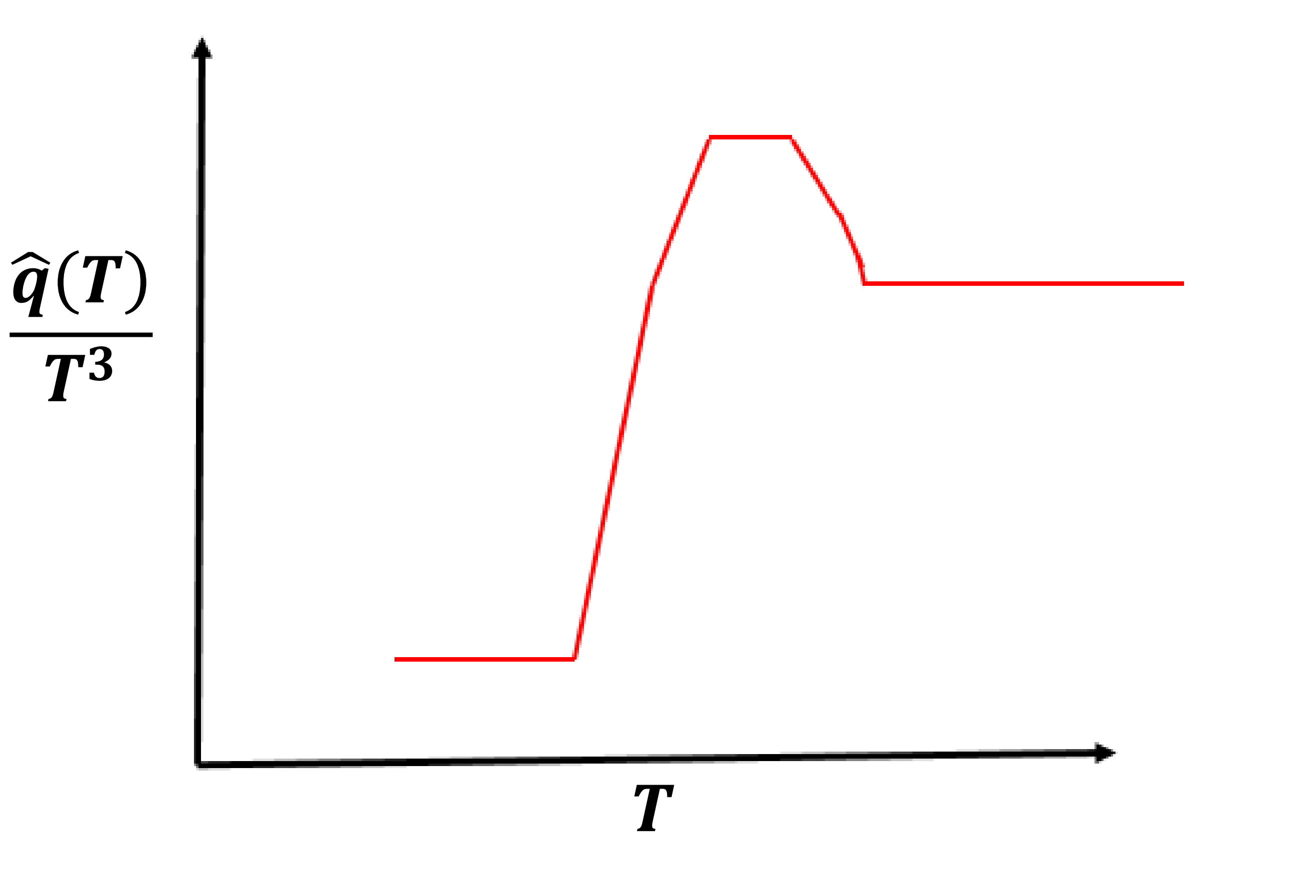


JET Collaboration (Burke et al.)

$$\hat{q}(\vec{r},t) = \frac{< k_\perp^2 >}{L} = q_0 \frac{S(\vec{r},t)}{S_0};$$

- ❑ **Has one Fitting parameter; Estimated through fitting one data point**
- ❑ **Fitting Parameter is higher at RHIC than at LHC!!**

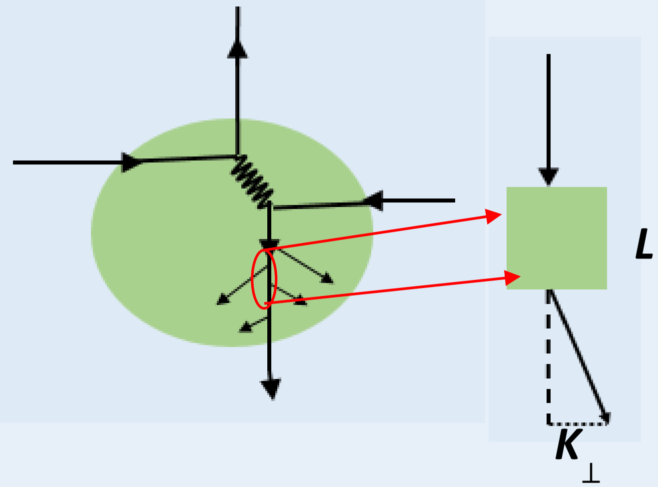
Puzzle: Jet Quenching Parameter $\hat{q}$ at RHIC and LHC



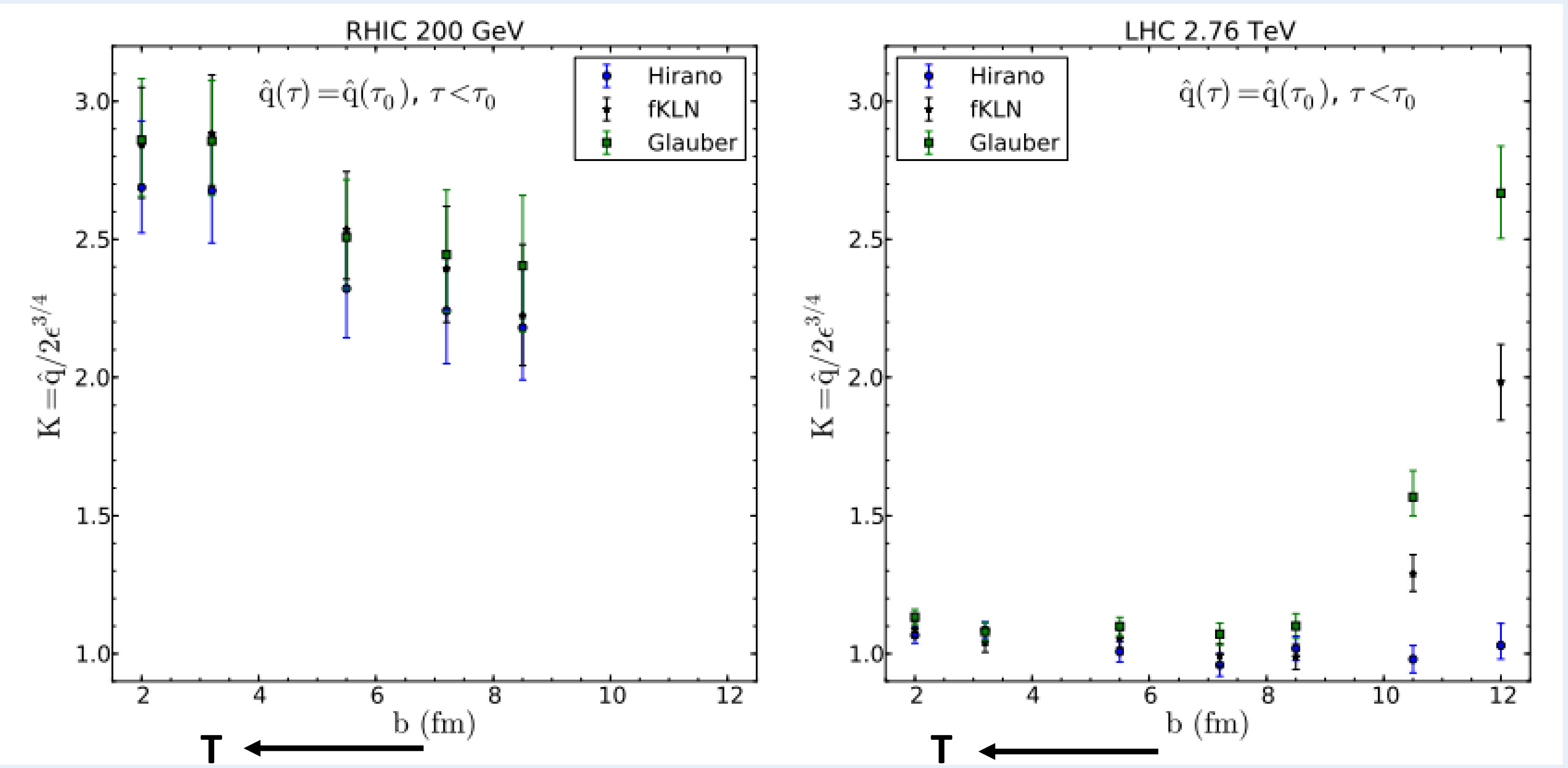
- A suggestion: $\frac{\hat{q}(T)}{T^3}$ has non-monotonic dependence on temperature

Xu, Liao and Gyulassy JHEP 1602 (2016) 169

Puzzle: Jet Quenching Parameter $\hat{q}$ at RHIC and LHC



$$\hat{q}(\vec{r}, t) = \frac{< k_{\perp}^2 >}{L} = K * 2\, \epsilon^{3/4};$$



Andres et al. 2016 (arxiv:1606.04837v2)

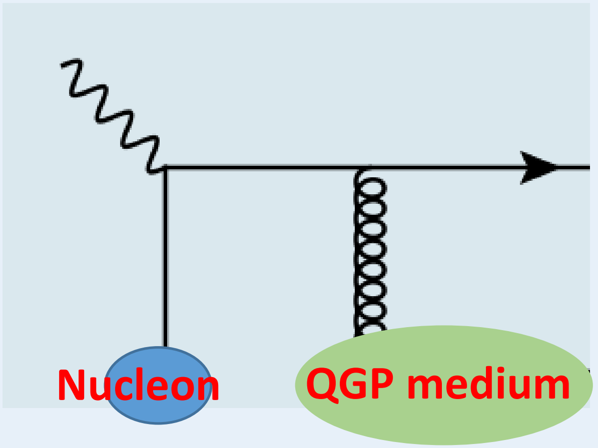
This ratio seems to depend on E_{cm} of Collision rather than medium properties.

If this ratio had temperature dependence, then the most central RHIC collision should have a similar value to semi-peripheral LHC data, but that's not the case

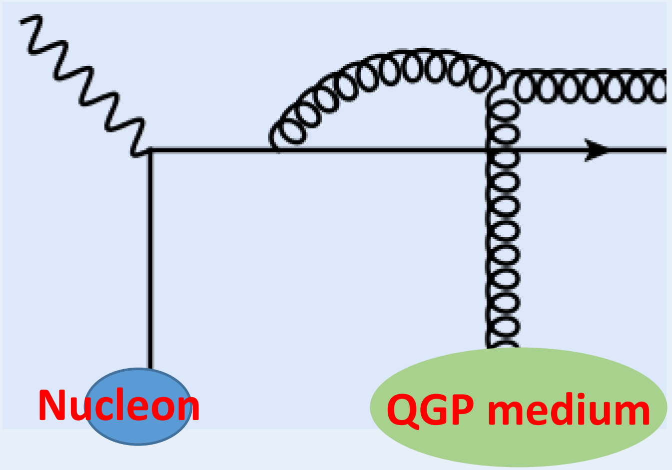
Ratio $\frac{\hat{q}}{T^3}$ at RHIC is 2~3 times higher than LHC!!

Physical Interpretation ?

Jet propagation through QGP medium

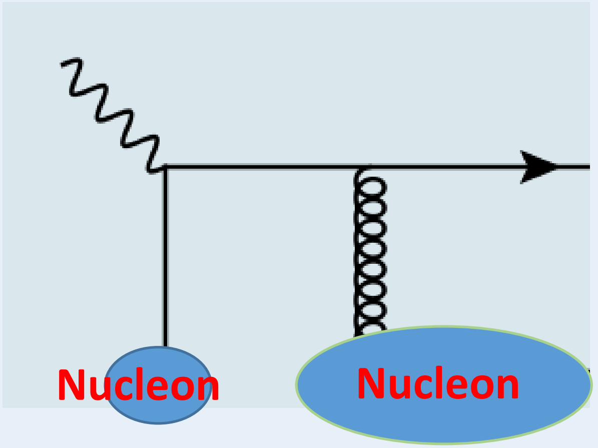


Glauber-gluon exchange

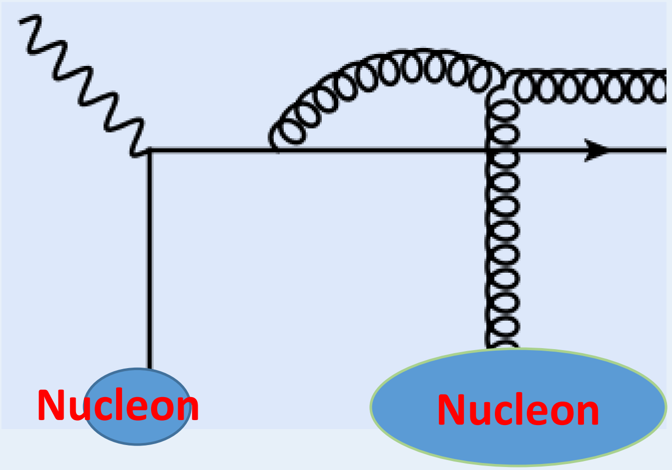


Collinear gluon emission
Glauber-gluon exchange
from gluon

Jet propagation through nucleus



Glauber-gluon exchange



Collinear gluon emission
Glauber-gluon exchange
from gluon

Single-gluon Scattering Diagram

(In light-cone coordinate)

$q^2 = (q^0)^2 - (\vec{q})^2 < 0$

$q = Q\left(\frac{-1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$

$p_1 \sim Q(1, \lambda^2, \lambda)$

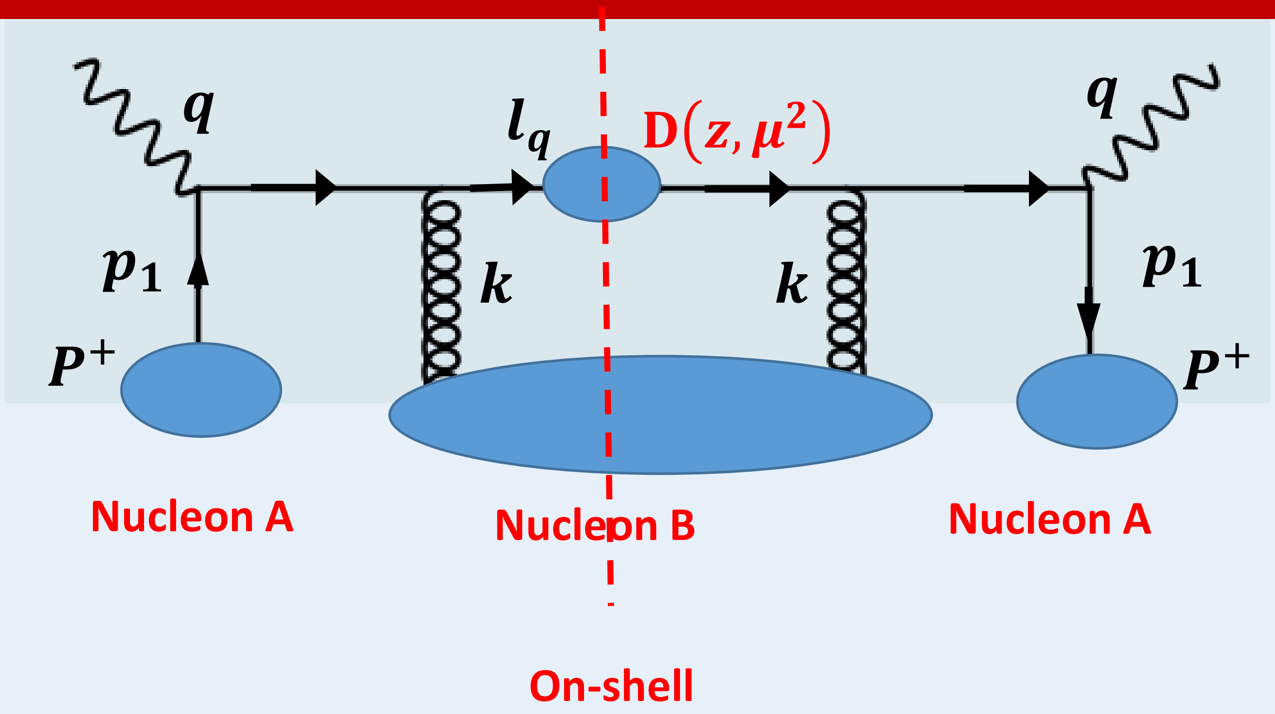
Glauber Gluons

$k \sim Q(\lambda^2, \lambda^2, \lambda)$

Jet Quenching Parameter

$$\hat{q}(\vec{r}, t) = \frac{< l_{q\perp}^2 >}{L}$$

$$\vec{l}_{q\perp} = \vec{k}_\perp$$



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$p_1 \sim Q(1, \lambda^2, \lambda)$

$l_q \sim Q(\lambda^2, 1, \lambda)$

$k \sim Q(\lambda^2, \lambda^2, \lambda)$

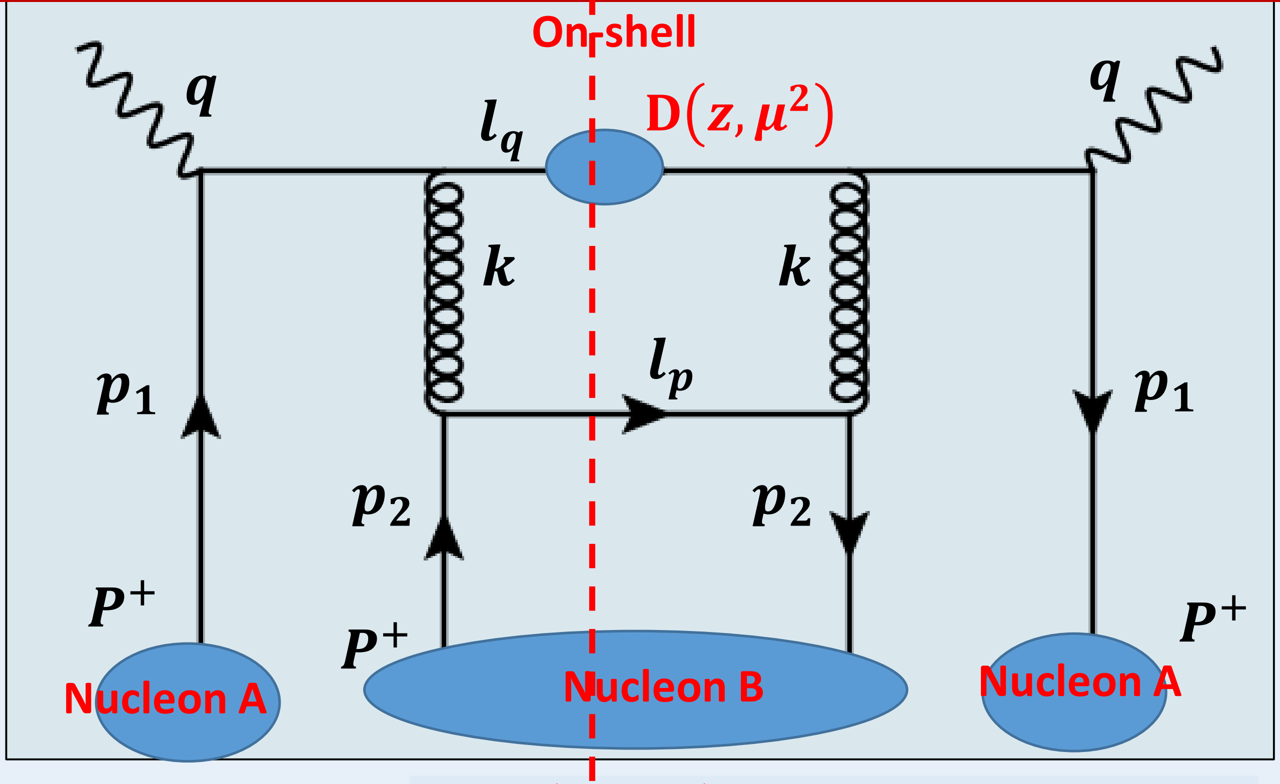
$p_2 \sim Q(1, \lambda^2, \lambda)$

$l_p \sim Q(1, \lambda^2, \lambda)$

Jet Quenching Parameter

$$\hat{q}(\vec{r}, t) = \frac{< l_{q\perp}^2 >}{L}$$

$$\vec{l}_{q\perp} = \vec{k}_\perp = -\vec{l}_{p\perp}$$



$f(x_N, \mu^2)$ = **Nucleon B PDF**

x **for nucleon N:** $x_N = \frac{p_2^{\ +}}{P^+}$

Range of x: $\frac{\vec{l}_{q\perp}^{\,2}}{2q^- P^+} < x_N < 1$

$$\int_0^{2q^-P^+} \frac{dl_{q\perp}^2}{l_{q\perp}^2} = \int_0^{\mu^2} \frac{dl_{q\perp}^2}{l_{q\perp}^2} + \int_{\mu^2}^{2q^-P^+} \frac{dl_{q\perp}^2}{l_{q\perp}^2}$$

$$\mu^2 < \vec{l}_{q\perp}^{\,2} < 2q^- P^+$$

$\Rightarrow$ **Scale dependence in** $f(x_N, \mu^2)$

Radiated-gluon Scattering from nucleus

(In light-cone coordinate)

Glauber Gluons

$q^2 = (q^0)^2 - (\vec{q})^2 < 0$

$q = \left(\frac{-Q}{\sqrt{2}}, \frac{Q}{\sqrt{2}}, 0\right)$

$k \sim Q(\lambda^2, \lambda^2, \lambda)$

$p_1 \sim Q(1, \lambda^2, \lambda)$ $\quad p_2 \sim Q(1, \lambda^2, \lambda)$

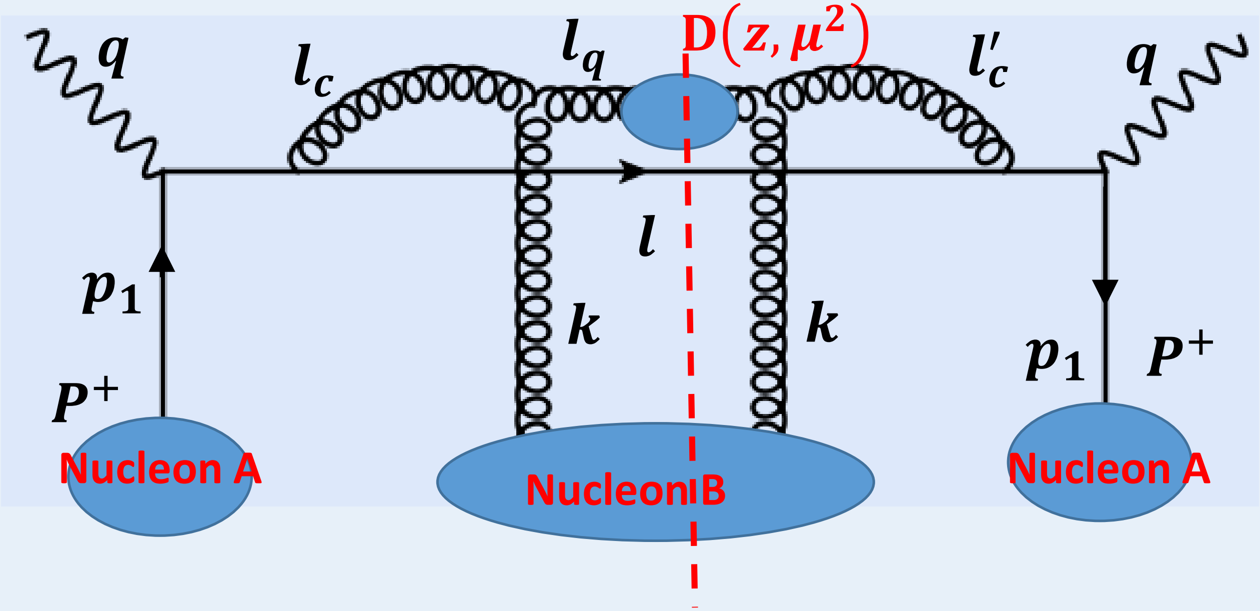
$l_q \sim Q(\lambda^2, 1, \lambda)$ $\quad l_p \sim Q(1, \lambda^2, \lambda)$

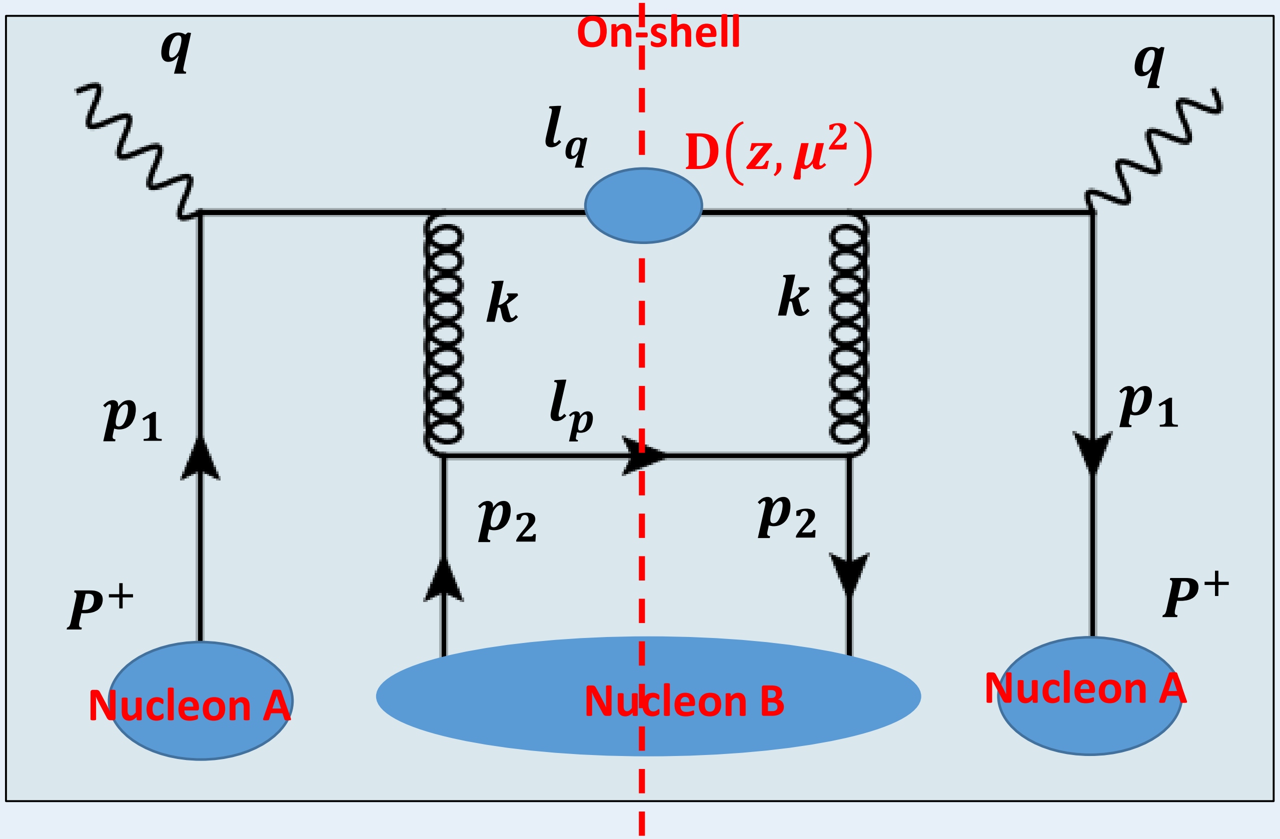
Jet Quenching Parameter

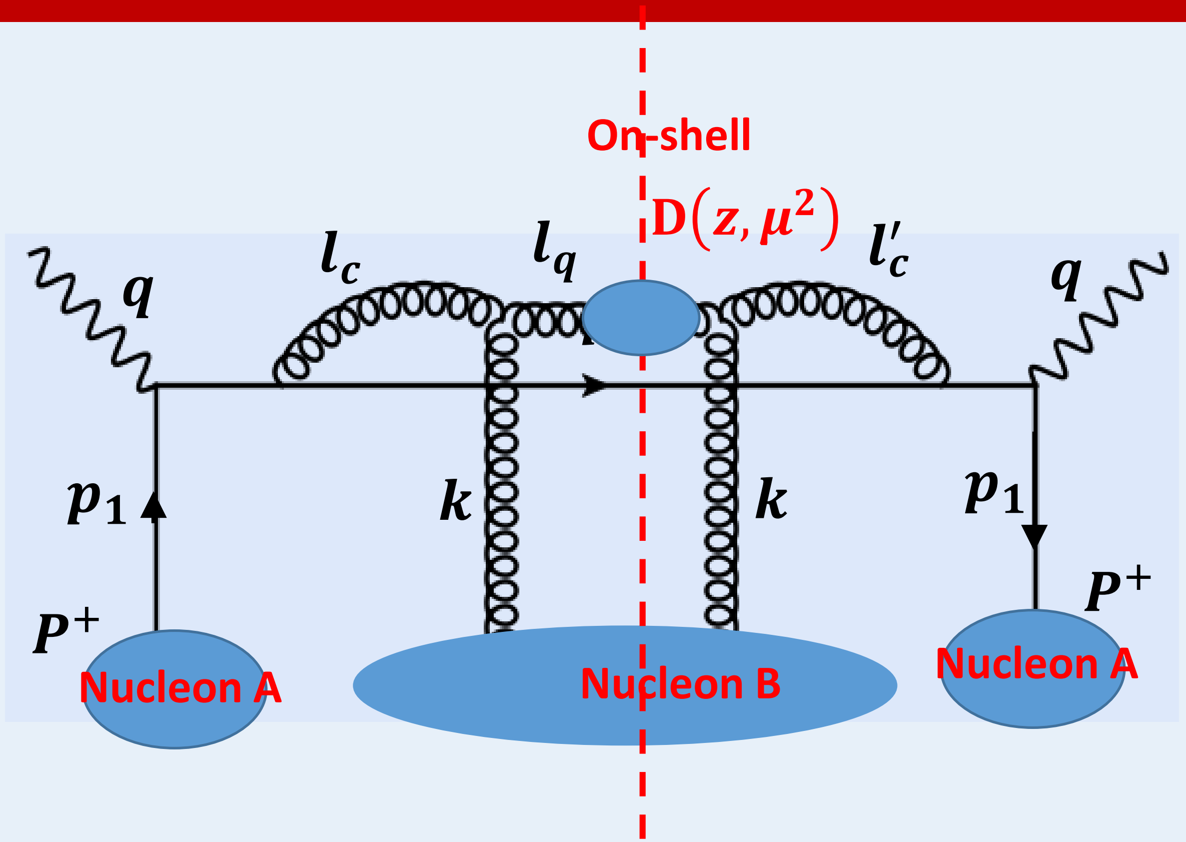
$$\hat{q}(\vec{r}, t) = \frac{< l_{q\perp}^2 >}{L}$$

In regime

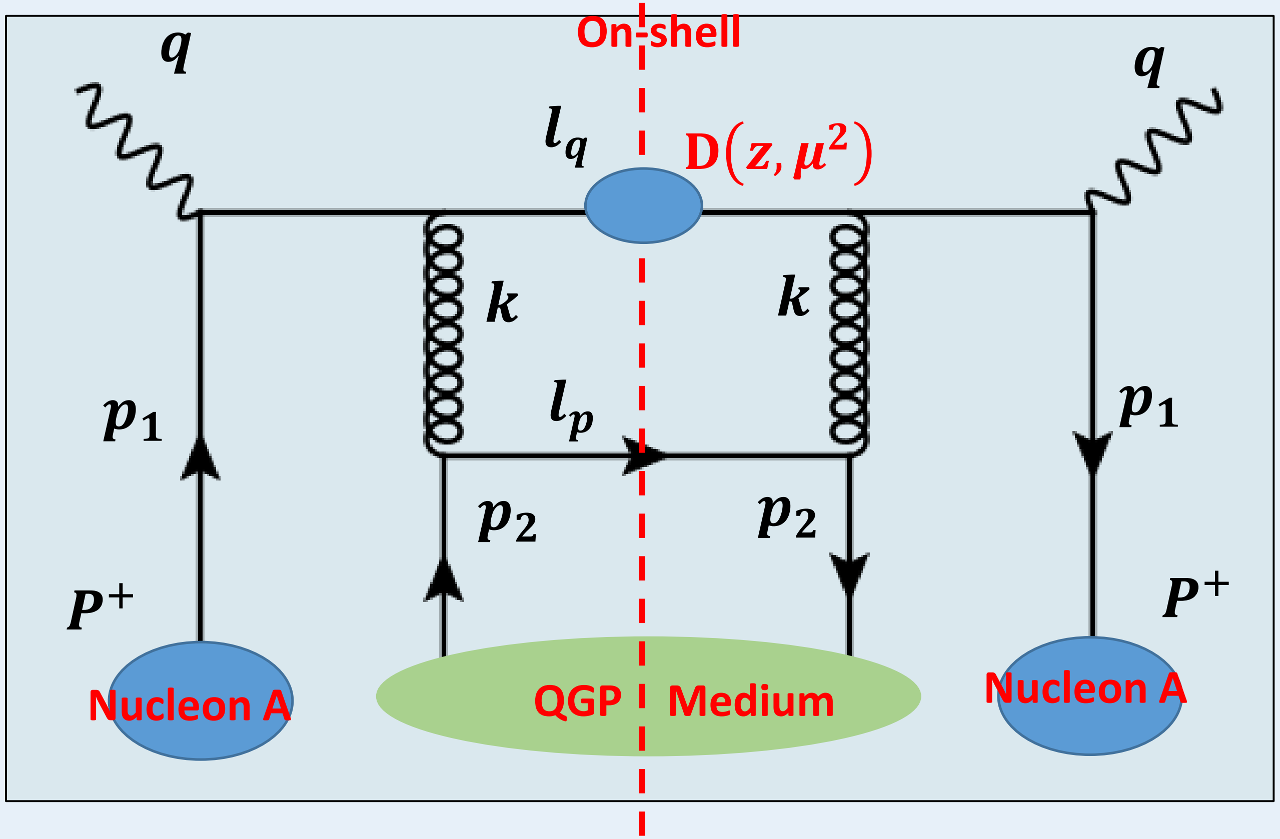
$\vec{l}_{q\perp}, \vec{l}_{\perp} \gg \vec{k}_{\perp}$

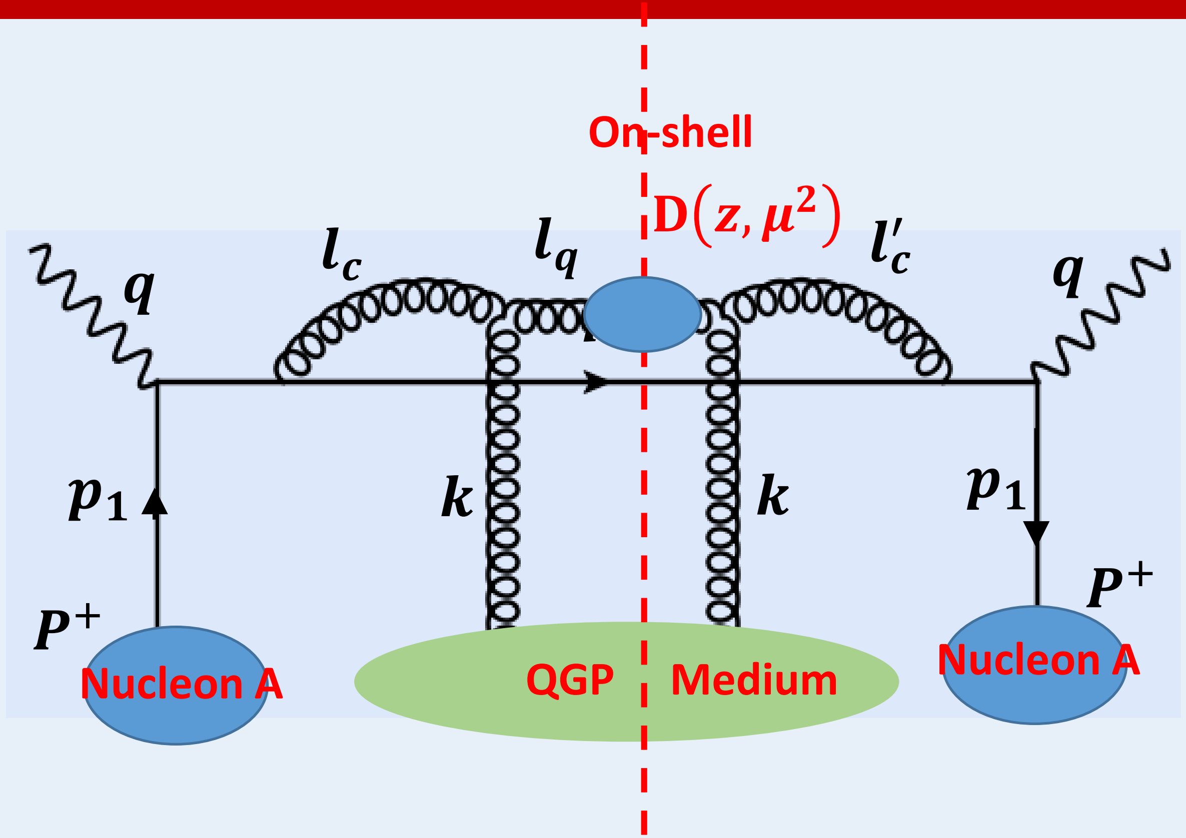



On-shell
q
q
l_q
$D(z,\mu^2)$
k
k
l_p
p_1
p_1
p_2
p_2
P^+
P^+
Nucleon A
Nucleon B
Nucleon A

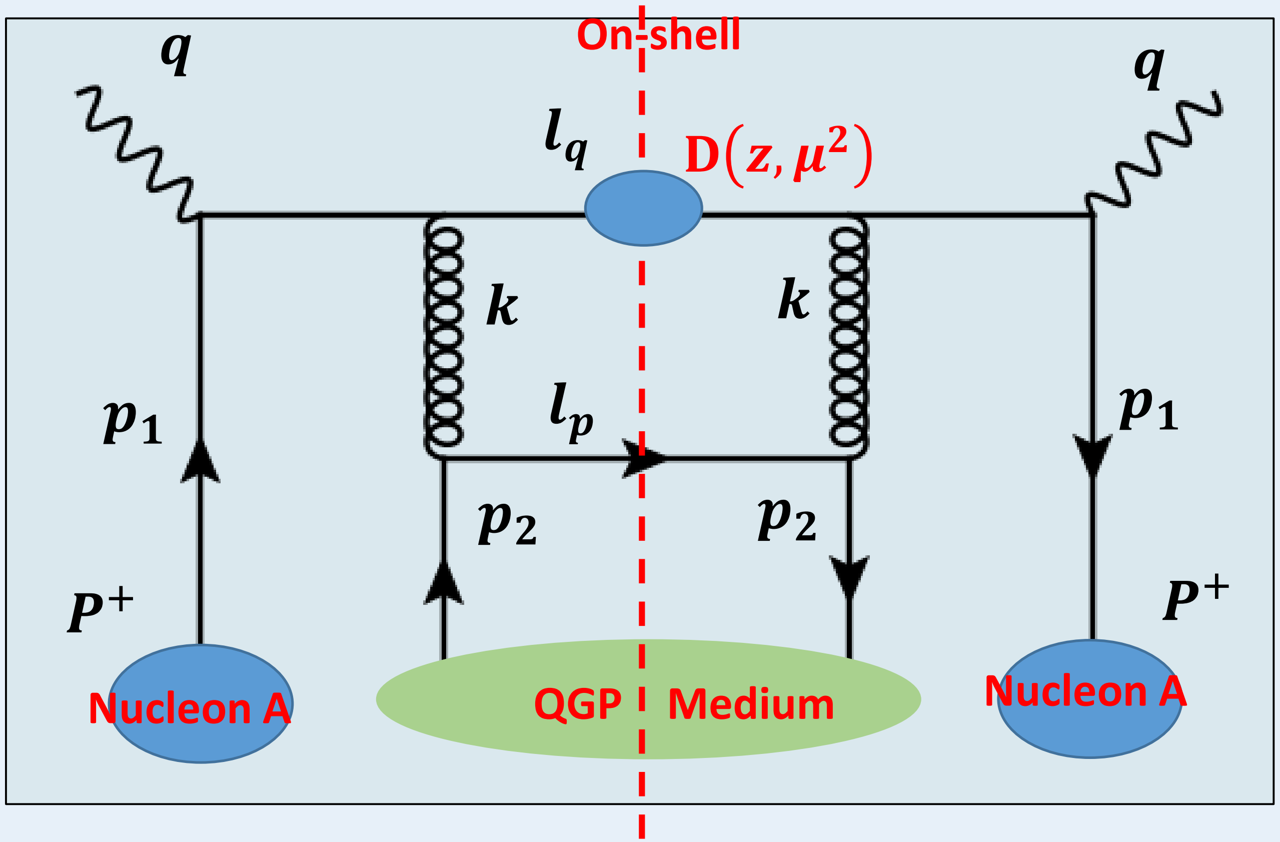

On-shell
$D(z,\mu^2)$
l_c
l_q
l'_c
q
q
k
k
p_1
p_1
P^+
P^+
Nucleon A
Nucleon B
Nucleon A

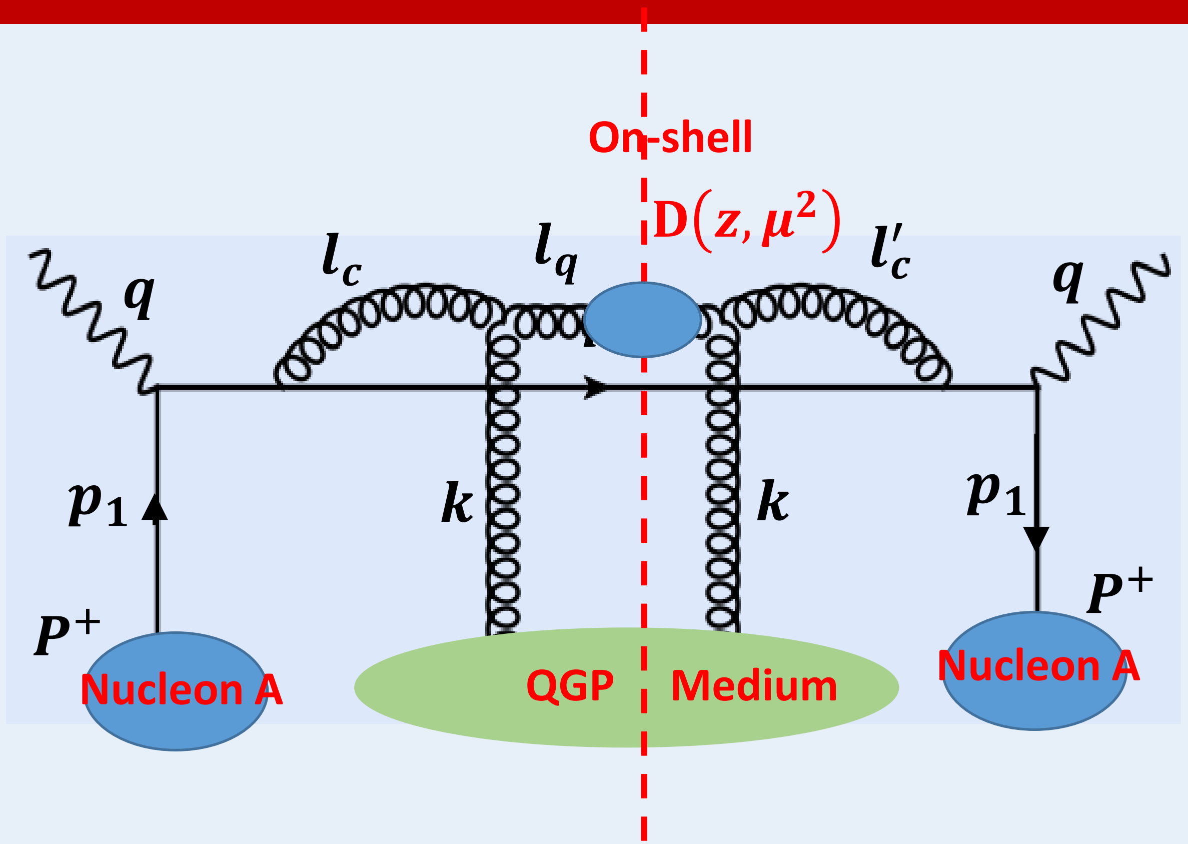
x for quark-gluon plasma





x for quark-gluon plasma

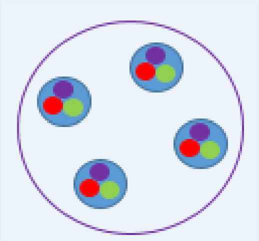




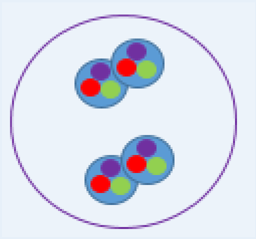
$f(x_N, \mu^2)$ = Quark – gluon plasma PDF

$x_N = \frac{p_2{}^+}{P^+}$?? ; Mass of QGP degree of freedom ??

Defining x in Parton distribution Function for QGP



Nucleus with energy 1 GeV per nucleon



x=1

x=0.5

Bjorken x for proton

$$x_B = \frac{Q^2}{2P.q}$$

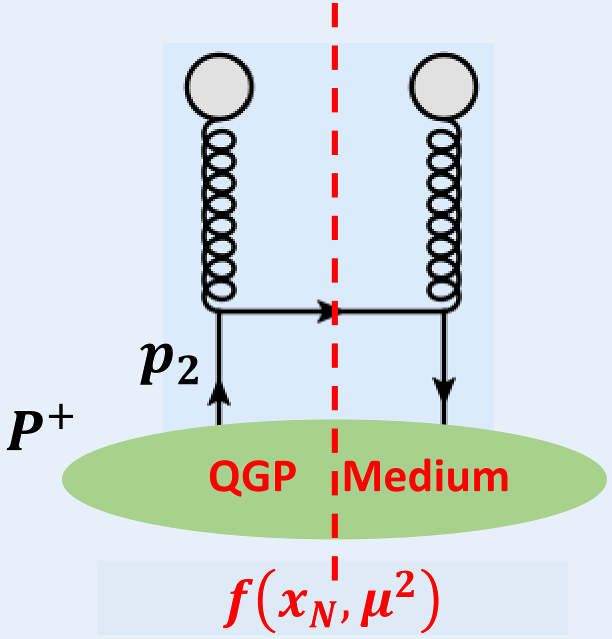
In the rest frame of proton

$$x_B = \frac{Q^2}{2ME} = \frac{\eta}{M}$$

PDF in Proton

$$f(x_B) = \int dy^- e^{ix_B P^+ y^-} \left\langle P \middle| \bar{\psi}(y^-) \frac{\gamma^+}{2} \psi \middle| P \right\rangle$$

$$g(\eta) = \int dy^- e^{i\eta y^-} \left\langle P \middle| \bar{\psi}(y^-) \frac{\gamma^+}{2} \psi \middle| P \right\rangle$$



- ❑ **For a Coupling Constant g and Temperature T Mass of QGP enclosing 1 degree of Freedom**

$$\Rightarrow M \simeq gT$$

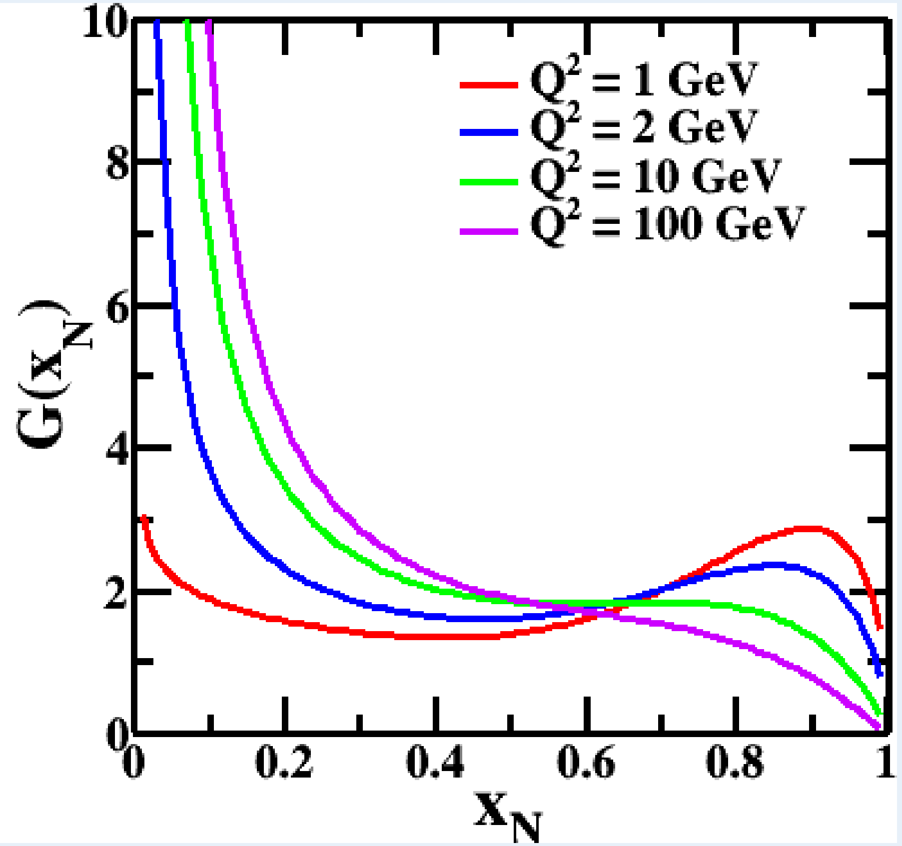
For instance T=400 MeV, $\alpha_s = 0.3 \rightarrow g = 2$

$$M \simeq 800 \text{ MeV}$$

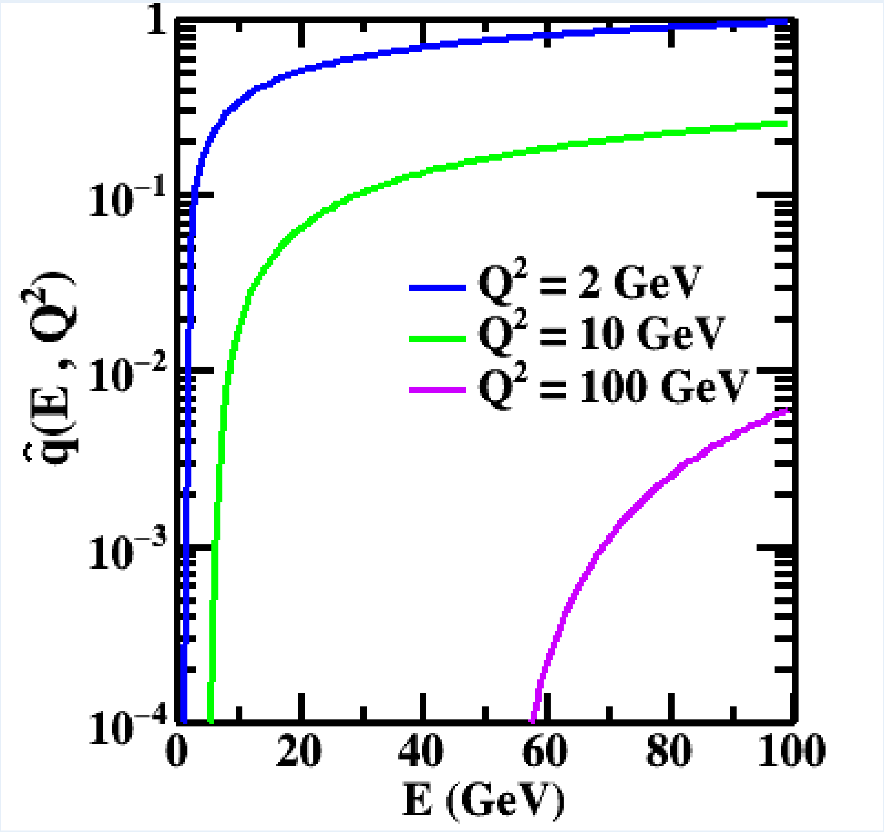
- ❑ **Upper Limit of $M = 1$ GeV**

Evolution of QGP PDF and $\hat{q}$ with Q^2

Input PDF: $G(x_N) = c(x_N)^a(1-x_N)^b$

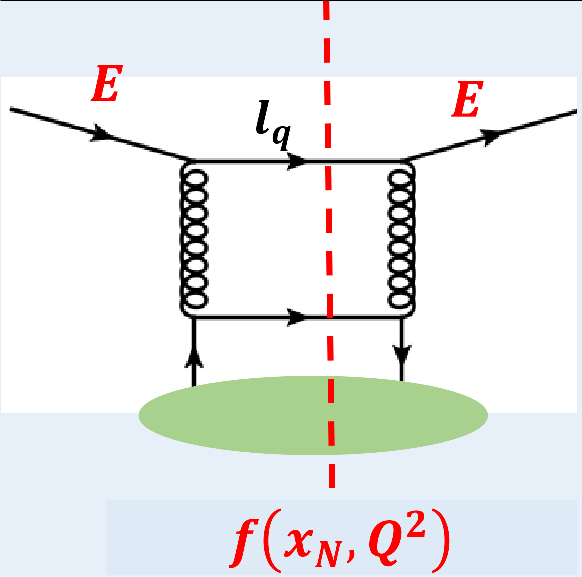


$\hat{q}$



Jet Quenching Parameter

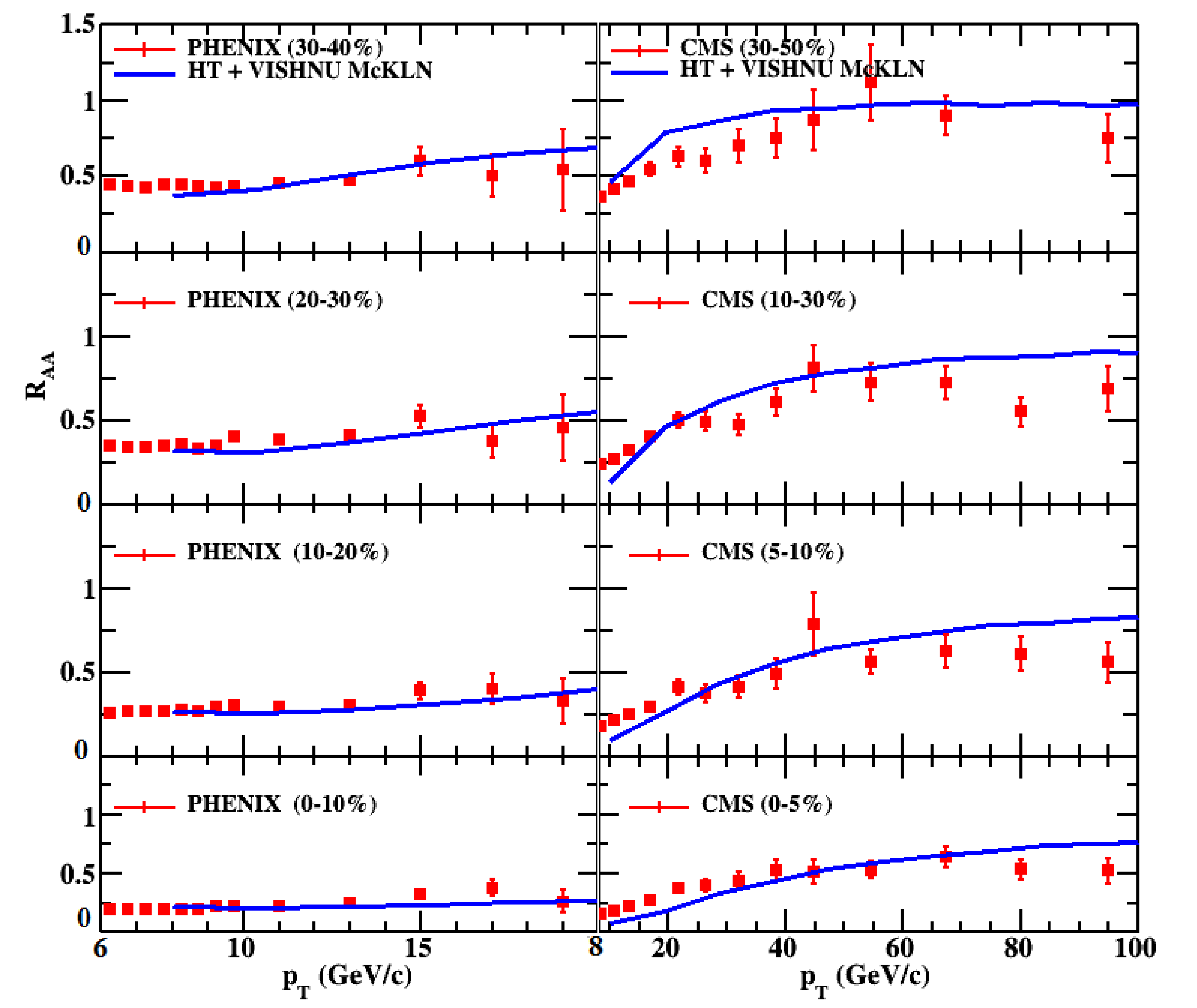
$$\hat{q}(\vec{r}, t) = \frac{< l_{q\perp}^2 >}{L}$$



R_{AA} at RHIC and LHC: Using QGP PDF as input

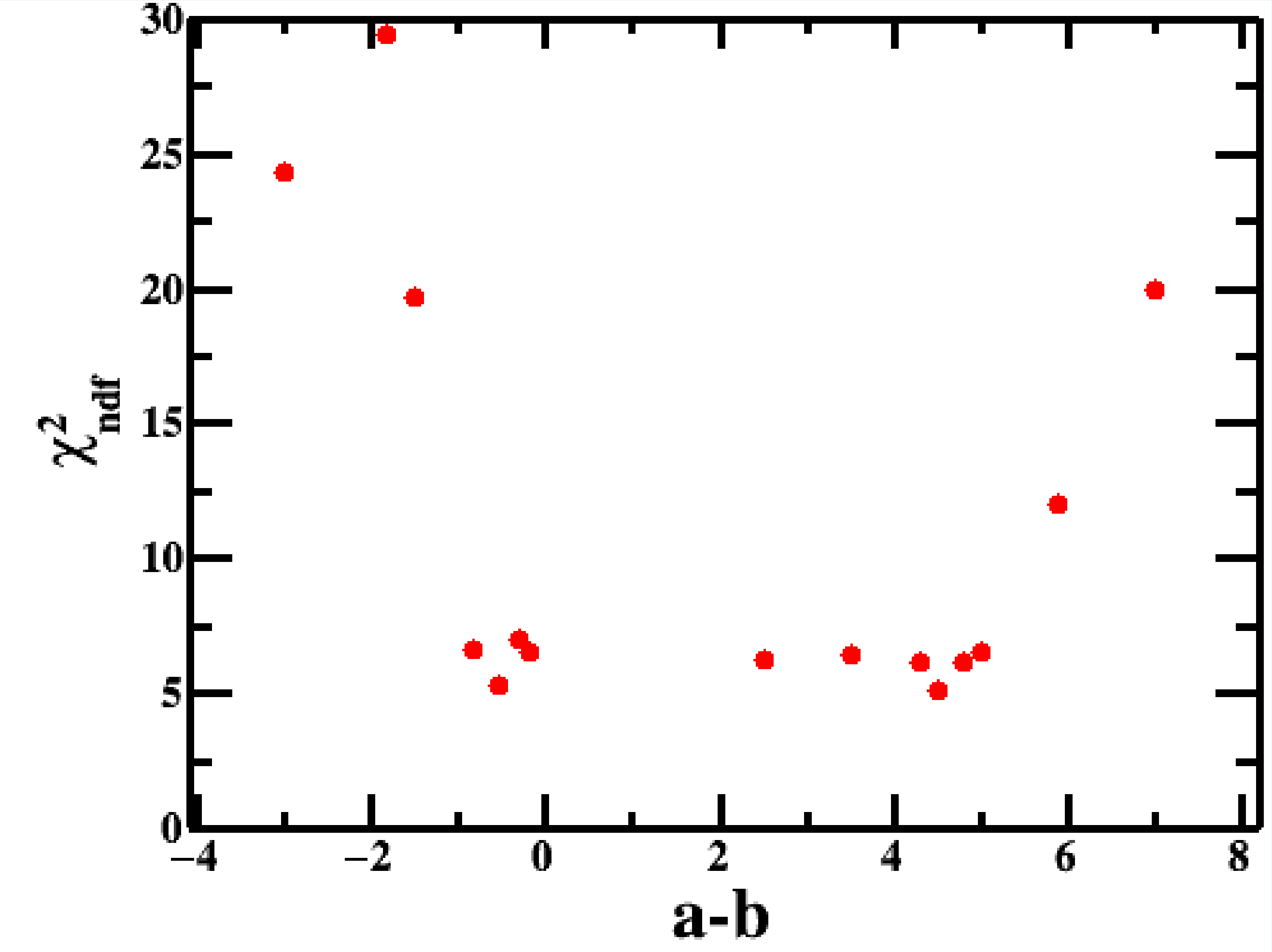
$$R_{AA} = \frac{\frac{d\sigma^{AA}}{dyd^2p_T}}{T_{AA}(b_{min}, b_{max})\frac{d\sigma^{pp}}{dyd^2p_T}}$$

- **No separate normalization is needed for RHIC and LHC data**
- **Combined χ^2_{ndf} = 5.6**



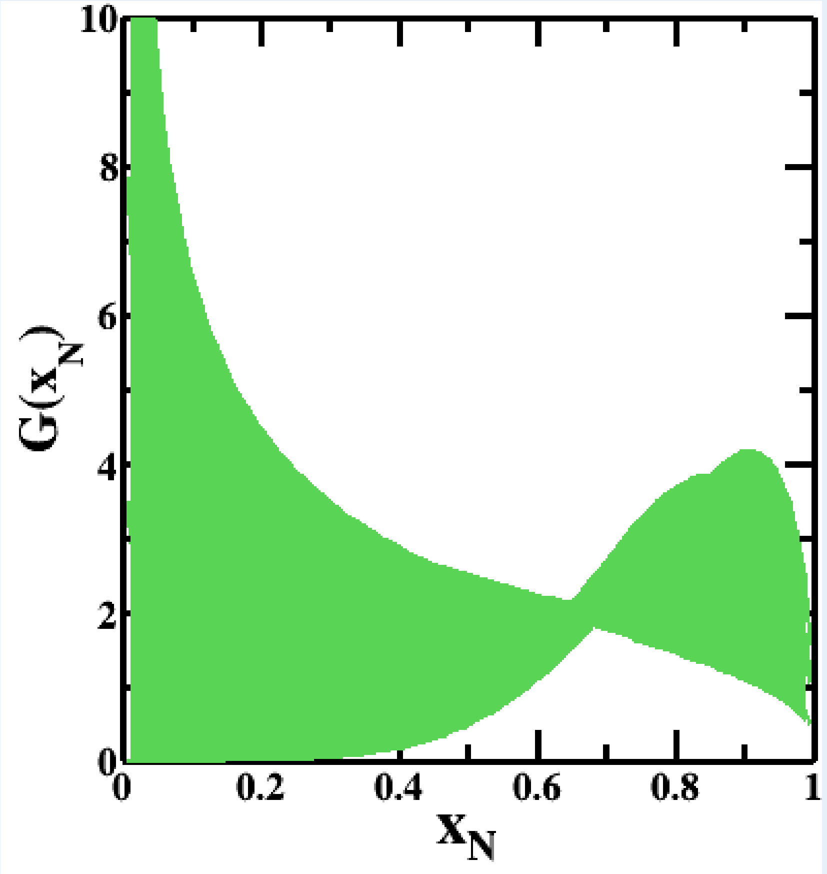
χ^2 analysis of R_{AA} for fits to RHIC and LHC data

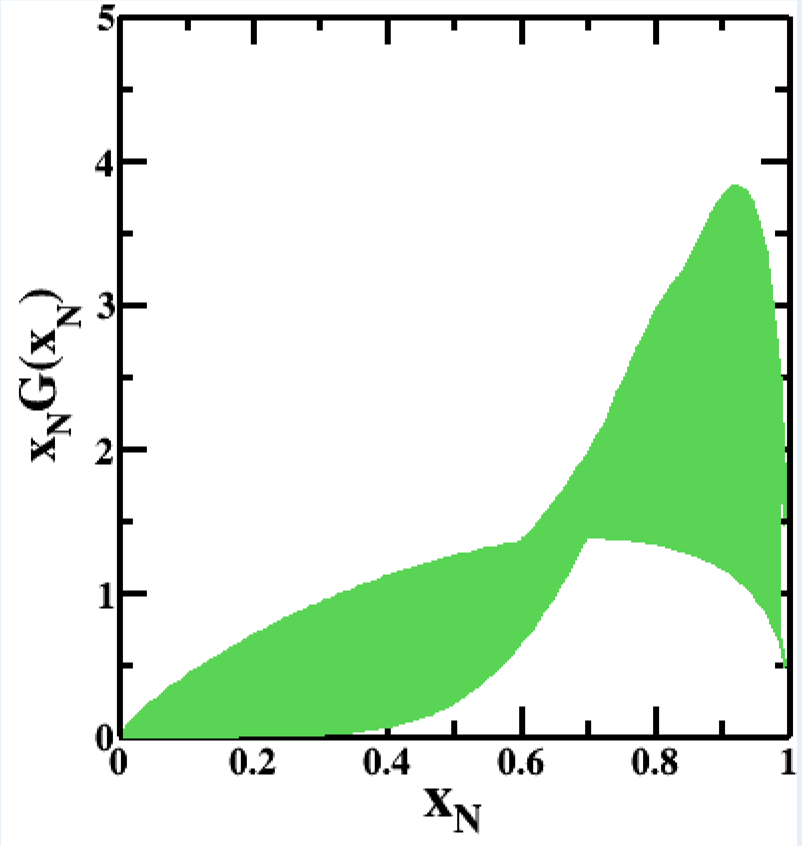
Input QGP PDF: $G(x_N) = c(x_N)^a(1-x_N)^b$



QGP Parton distribution function at Q^2=1 GeV^2

PDF′s $G(x_N) = c(x_N)^a(1 - x_N)^b$ which produces combined (RHIC and LHC) $\chi^2_{ndf} < 7.0$





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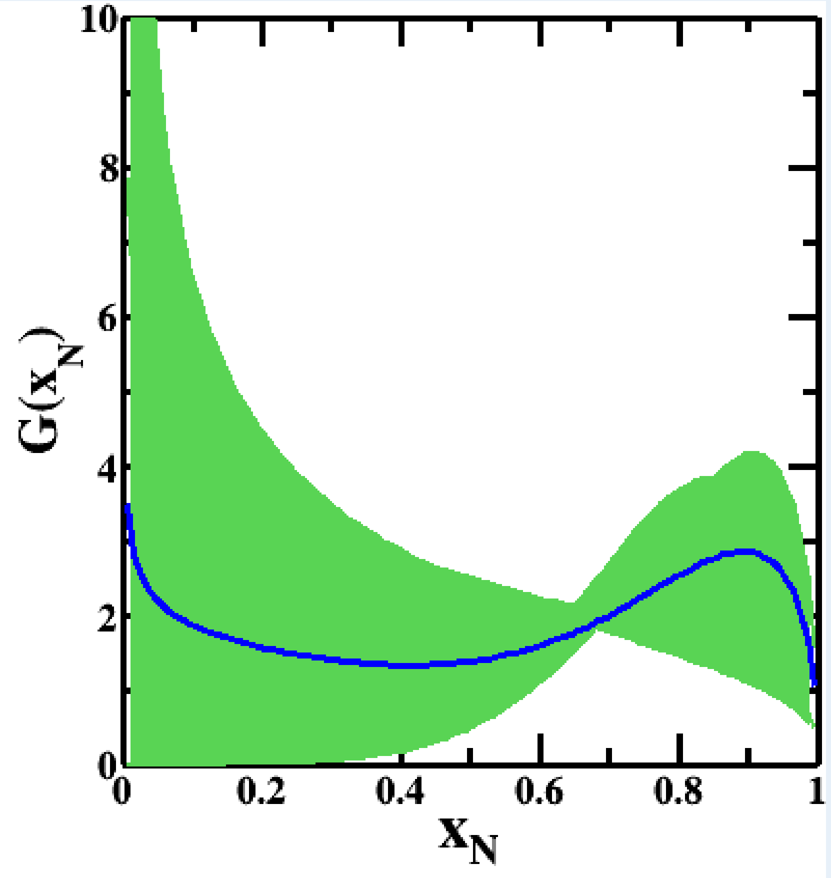
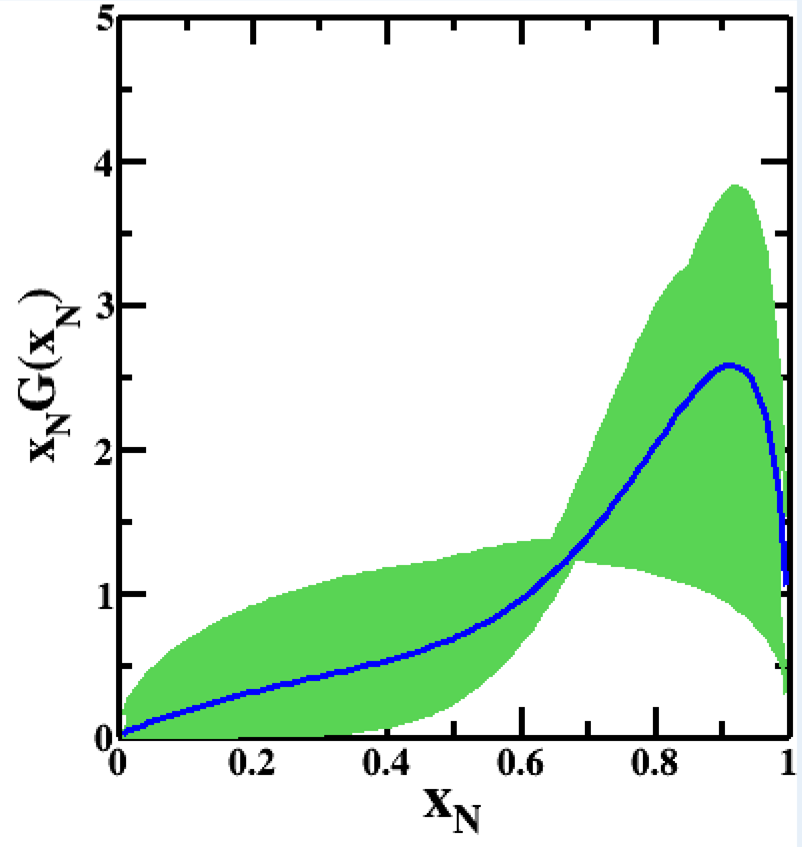
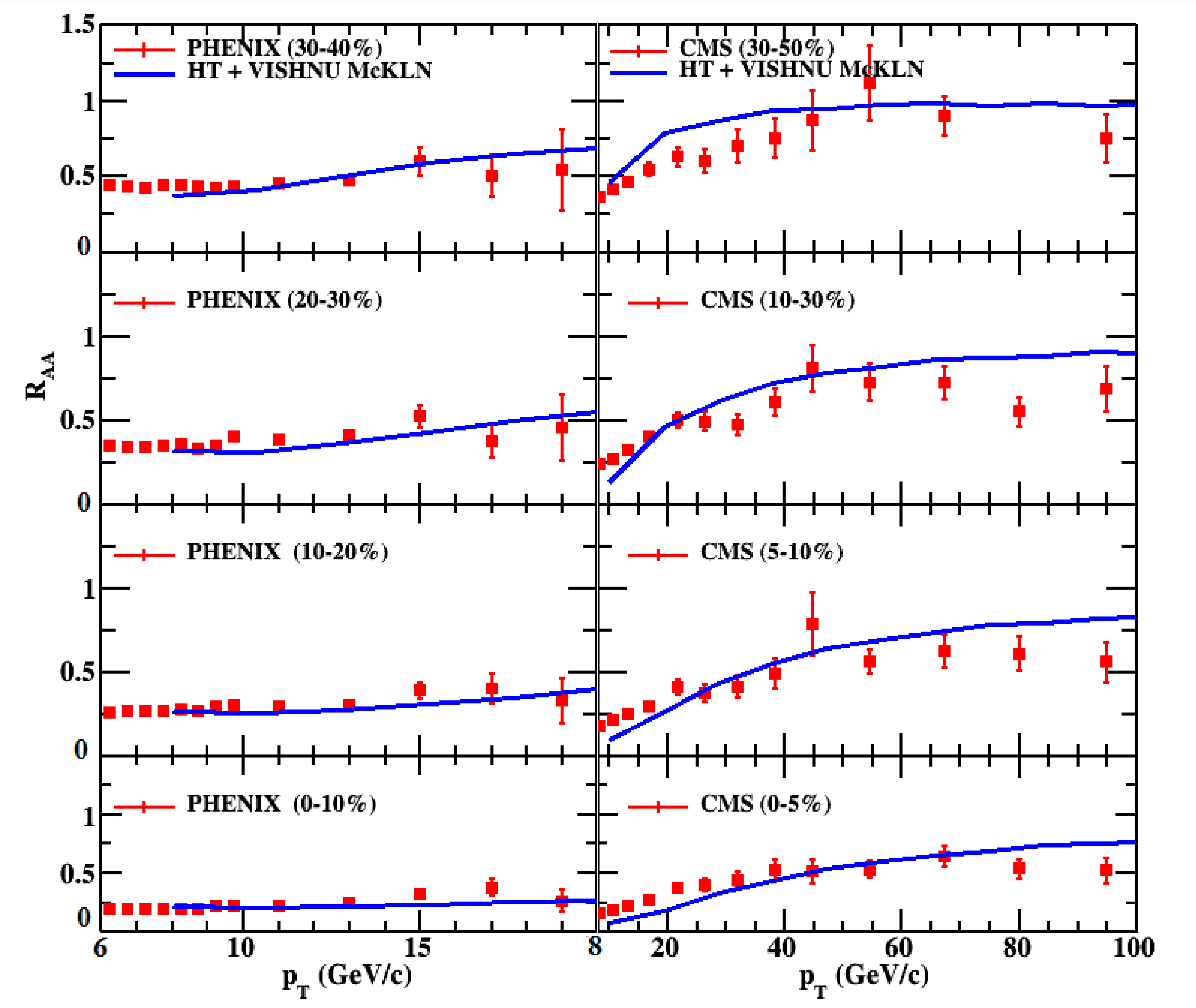




R_{AA} at RHIC and LHC: Using QGP PDF

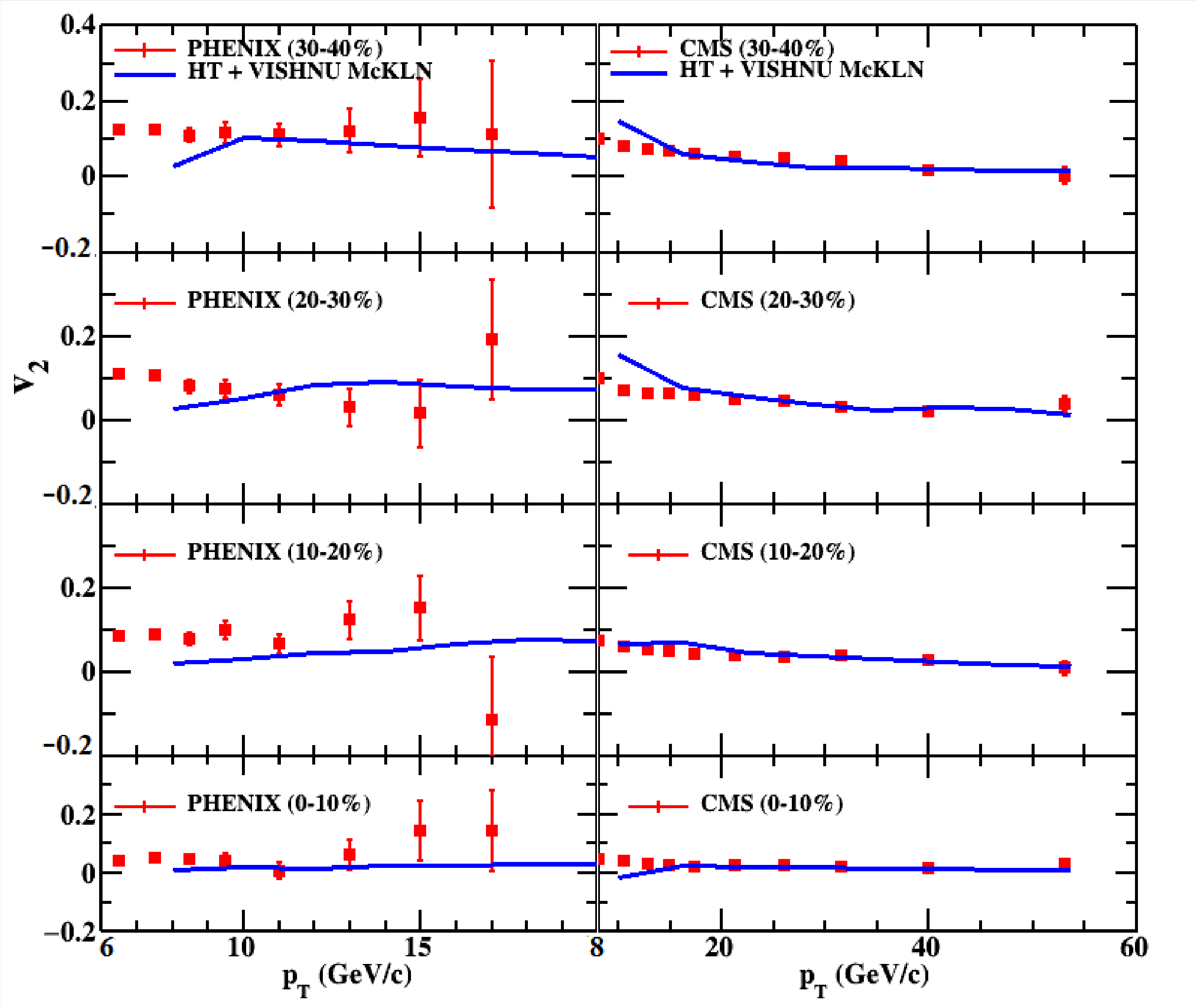
$$R_{AA} = \frac{\frac{d\sigma^{AA}}{dyd^2p_T}}{T_{AA}(b_{min}, b_{max})\frac{d\sigma^{pp}}{dyd^2p_T}}$$

- **No separate normalization is needed for RHIC and LHC data**
- **Elastic energy loss not included**
- **BFKL evolution for small x in PDF is not included**



Azimuthal anisotropy v_2 at RHIC and LHC

- **Using QGP PDF obtained from constraining R_{AA} observable**
- **No re-fitting is needed**



Summary and Future Work

- ❑ Solved the JET puzzle of $\hat{q}$ through x and scale dependence in addition to local temperature
- ❑ Estimated possible PDF's of QGP by constraining R_{AA} data.
- ❑ No separate fitting of $\hat{q}$ is required to explain the LHC and RHIC simultaneously

- ❑ Look for *ab-initio* formulation of $\hat{q}$ through expressing it in terms of expectation value of Field-Strength-Field-Strength Correlator calculated on Lattice using thermal field theory
- ❑ Implement elastic energy loss in jet quenching calculation
- ❑ BFKL evolution of PDF at small x