POLYTECH
Peter the Great St. Petersburg
Polytechnic University

ЯДРО 2025

LXXV International Conference «NUCLEUS – 2025. Nuclear physics, elementary particle physics and nuclear technologies»

Azimuthal dependence of the fractional parton energy loss in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

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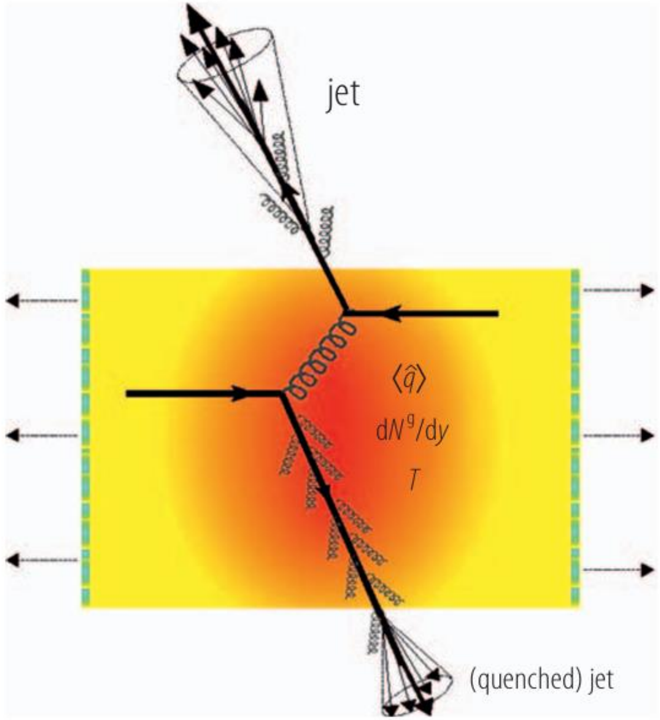
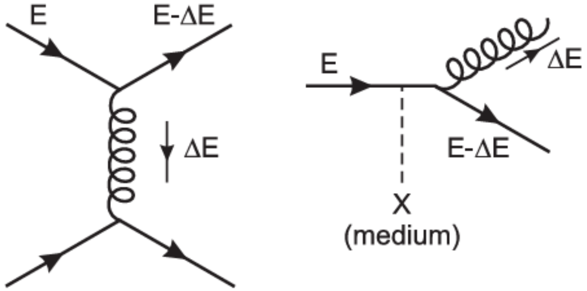
Energy loss of hard partons in the medium

The production of partons (quarks and gluons) as a result of hard scattering of nucleons:

$$p_T, m \gtrsim Q_0\big(= \mathcal{O}(1\ GeV)\big) \gg \Lambda_{QCD}(\approx 0.2 GeV)$$

Integral energy loss: $\Delta E = f(E_{in}, M, T, \alpha_s, L)$





1. Nuclear modification factor:

$$R_{AB}(p_T) = \frac{1}{\langle N_{coll}\rangle}\frac{d^2N_{AB}^{\pi^0}/dp_T dy}{d^2N_{pp}^{\pi^0}/dp_T dy}$$

$\langle N_{coll}\rangle$ – average number of inelastic binary nucleon-nucleon interactions for the given centrality

2. Fractional parton energy loss

$$S_{loss} = \frac{\Delta E}{E_{in}} \Rightarrow S_{loss} = \frac{p_T^{pp} - p_T}{p_T^{pp}} = \frac{\Delta p_T}{p_T^{pp}}$$

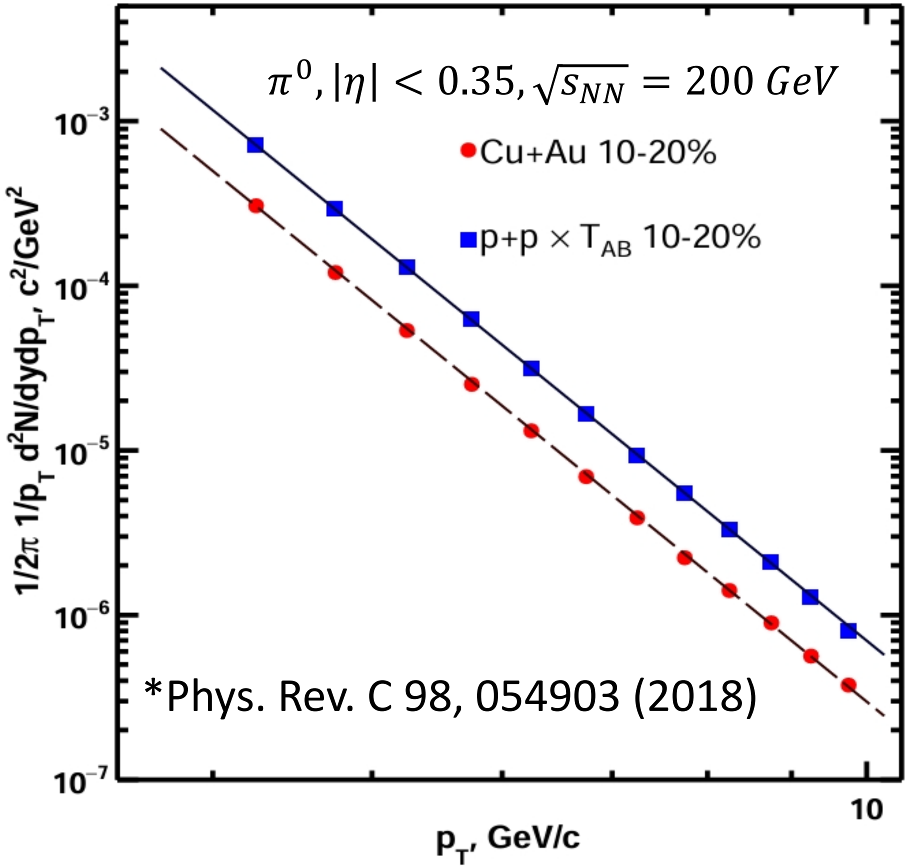
$p_T(p_T^{pp})$ – average transverse momentum of hadrons in A+B (p+p) collisions at fixed invariant yield

$R_{AA} > 1$ $(S_{loss} < 0)$ → increase in the yield of hadrons (the parton absorbs energy);
$R_{AA} < 1$ $(S_{loss} > 0)$ → decrease in the yield of hadrons (the parton loses energy in the medium);
$R_{AA} \approx 1$ $(S_{loss} \approx 0)$ – absence/compensation of collective effects (no energy loss is observed).

The relationship between $S_{loss}(p_T)$ and $R_{AB}(p_T)$

p+p collisions: The invariant spectrum of π^0-mesons at p_T is described by a power function at $p_T > 4\ GeV/c$:

$$f_{pp}(p_T) = E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{dp_T dy} = Ap_T^{-n}$$



Cu+Au collisions: for the entire range of p_T (weighted sum of the Hagedorn function and the power function):

$$f_{CuAu}(p_T) = T(p_T)\frac{B}{\left(1+\frac{p_T}{p_0}\right)^b} + (1 - T(p_T))Cp_T^{-m}$$

$p_T > 4\ GeV/c$ (transition to the power form):

$$f_{CuAu}(p_T) = Cp_T^{-m}$$

"Parallel spectra": $\dfrac{d(\Delta p_T)}{dp_T} = \dfrac{\Delta p_T}{p_T} = \text{const}(p_T)$

$n = 8.1 \pm 0.1\ (p+p)$

$m = 8.02 \pm 0.07\ (0-10\%\ \text{Cu}+\text{Au})$

$m = 8.22 \pm 0.32\ (60-90\%\ \text{Cu}+\text{Au})$

Integral over the azimuthal angle values ($p_T > 4GeV/c$)

$$\boldsymbol{S_{loss}(p_T) = 1 - (R_{AB}(p_T))^{\frac{1}{n-2}}}$$

Azimuthal dependencies $R_{AA}(p_T,\Delta\varphi)$ and $S_{loss}(p_T,\Delta\varphi)$

The invariant spectrum of π⁰-mesons π⁰-mesons in Cu+Au collisions:

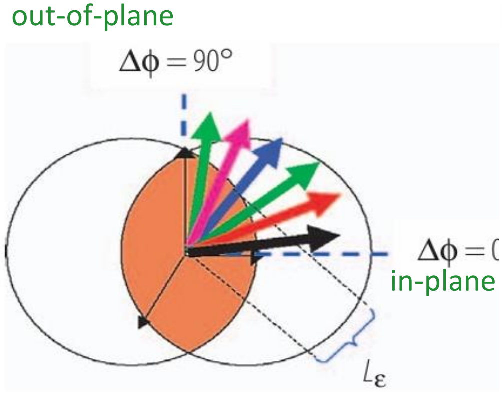
$$f_{CuAu}(p_T,\Delta\varphi,y)=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\underbrace{\left[1+\sum_{n=1}^{\infty}2v_n(p_T,y)\cos(n\Delta\varphi)\right]}_{\frac{2\pi}{N_0}f_{CuAu}(p_T,\Delta\varphi,y)}$$

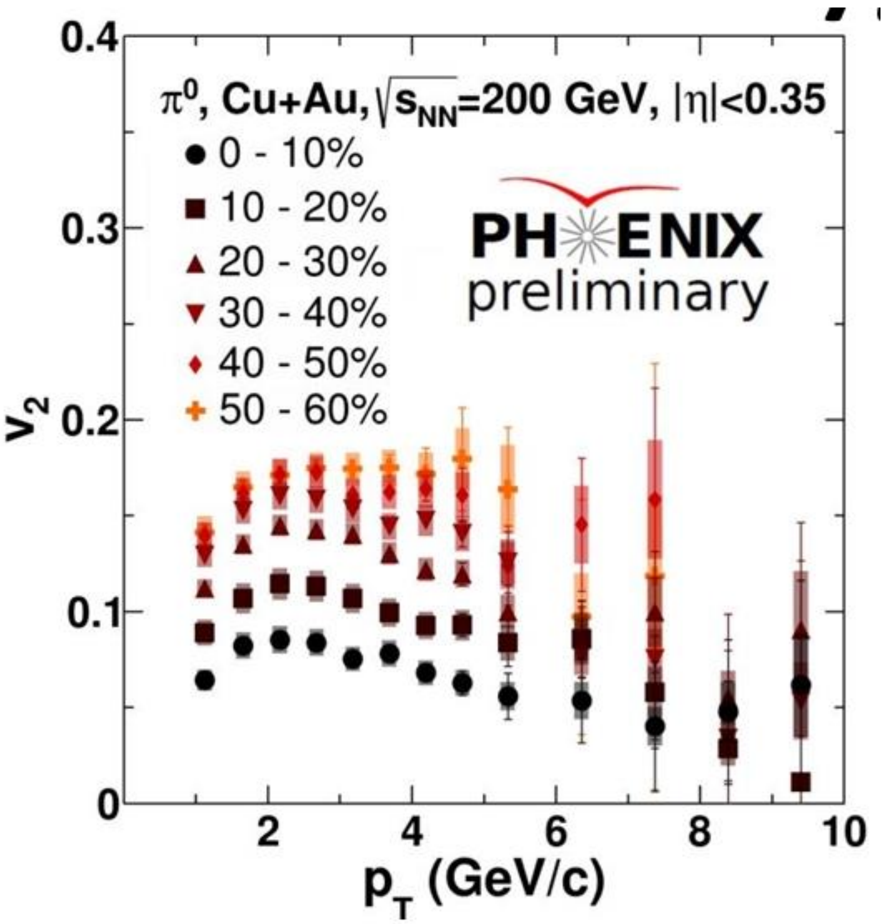
$\Delta\varphi=\varphi-\Psi_{RP}$, $v_n=\langle\cos(n\Delta\varphi)\rangle$, $v_2=\langle\cos(2\Delta\varphi)\rangle$ – elliptic flow

Azimuthal dependencies ($p_T>4$ ГэВ/c):

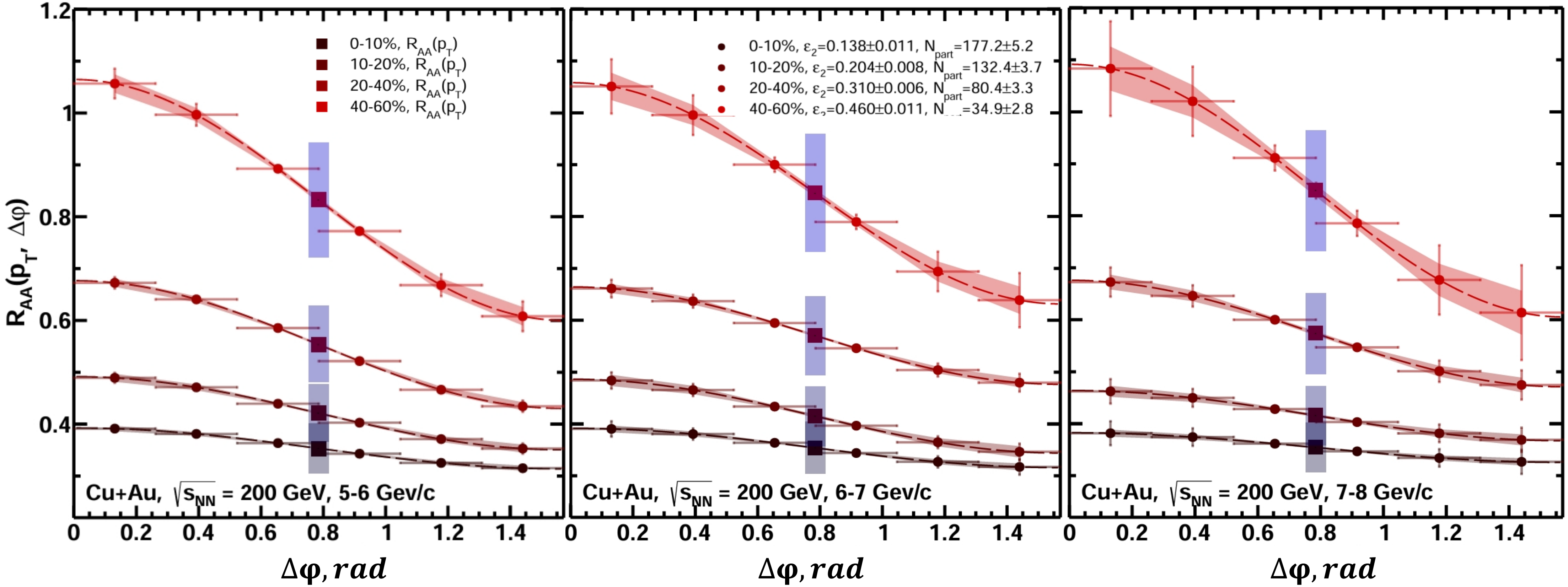
$$R_{AB}(\Delta\varphi,p_T)=\frac{2\pi}{N_0}f_{CuAu}(\Delta\varphi,p_T)\cdot R_{AB}(p_T)\approx$$
$$\approx\left(1+2v_2\cos(2\Delta\varphi)\right)\cdot R_{AB}(p_T)$$

$$S_{loss}(\Delta\varphi,p_T)=1-\left(R_{AB}(\Delta\varphi,p_T)\right)^{\frac{1}{n-2}}$$





$R_{AB}(N_{part}, p_T, \Delta\varphi)$ for π^0-mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



- $R_{AB}(\Delta\varphi)|_{N_{part}}, R_{AB}|_{N_{part}} \approx const(p_T)$
- $R_{AB}(N_{part})|_{p_T}$ increases when moving from central to peripheral collisions (with decreasing N_{part})
- The degree of anisotropy $R_{AB}(\Delta\varphi)$ increases when moving from central to peripheral collisions (with decreasing N_{part})
- $R_{AB}\left(\frac{\pi}{24}\right)|_{40-60\%} \gtrsim 1$

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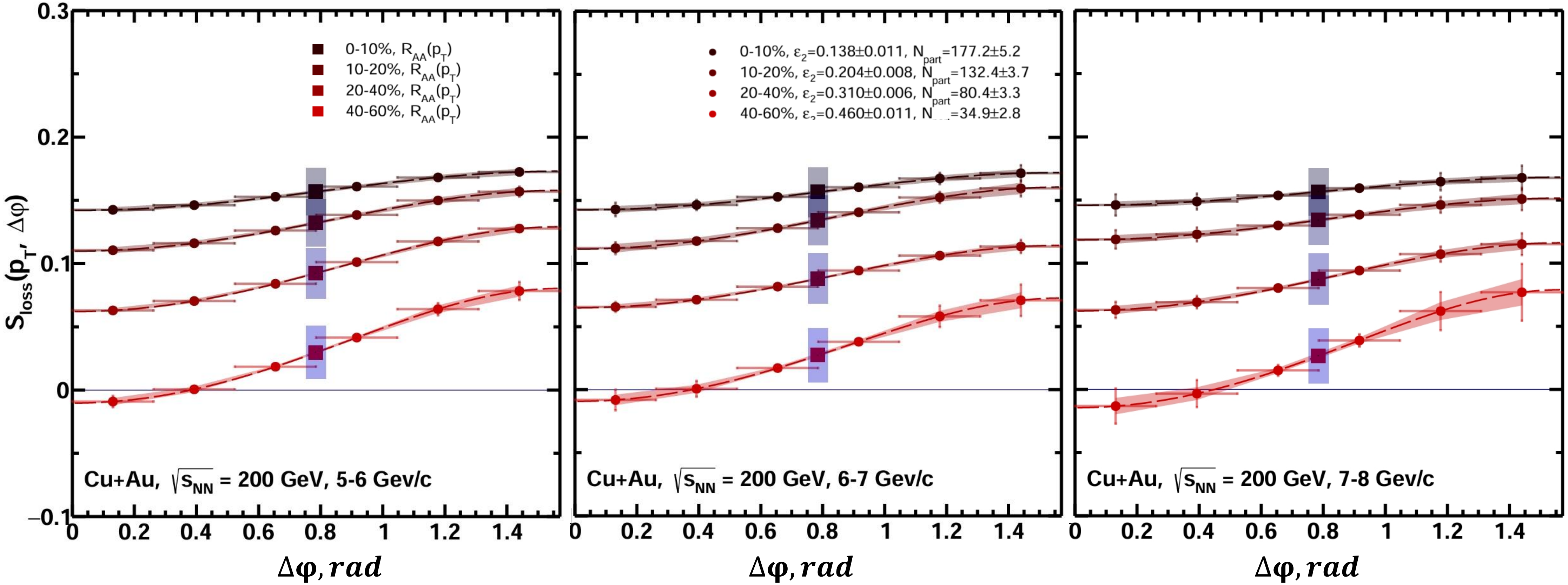


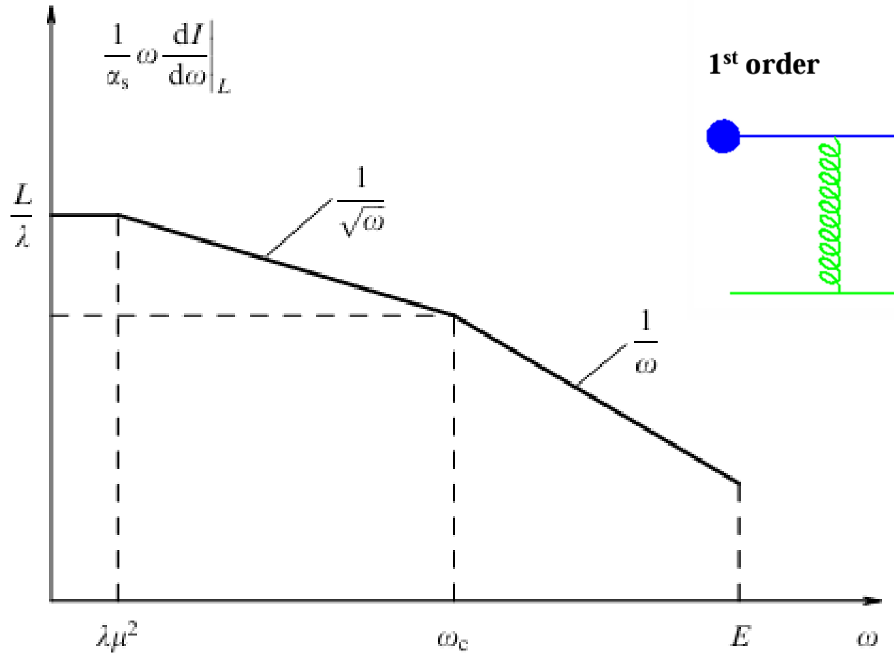
- $S_{loss}(\Delta\varphi)|_{N_{part}}, S_{loss}|_{N_{part}} \approx const(p_T)$
- $S_{loss}(N_{part})|_{p_T}$ decreases when moving from central to peripheral collisions (with decreasing N_{part})
- The degree of anisotropy $S_{loss}(\Delta\varphi)$ increases when moving from central to peripheral collisions (with decreasing N_{part})
- $S_{loss}\left(\frac{\pi}{24}\right)|_{40-60\%} \lesssim 0$

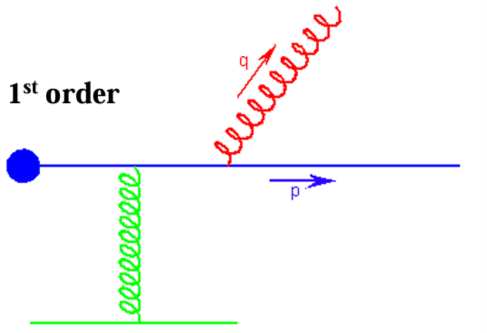
Radiative energy loss in the medium

pQCD calculations for light quarks and gluons $\left(E \gg \frac{M^2}{T}\right)$

Landau-Pomeranchuk-Migdal regime (LPM) ($L \gg \lambda$):

$$\omega \frac{dI_{rad}}{d\omega} \sim \alpha_s C_R \begin{cases} L/\lambda \\ \sqrt{\omega_c/\omega} \\ \omega_c/\omega \end{cases} \Rightarrow \Delta E_{rad}^{LPM} = \int^{E} \omega \frac{dI_{rad}}{d\omega} d\omega \sim \alpha_s C_R \begin{cases} L m_D^2, & \omega < \lambda m_D^2 \; (l_{form}^{vac} \sim \omega/m_D^2 < \lambda) \\ \omega_c, & \omega_c < \omega \\ \omega_c \ln(E/\omega_c), & \lambda m_D^2 < \omega < \omega_c \end{cases}$$





$\hat{q} \equiv \frac{\langle q_T^2 \rangle}{\lambda} = \frac{m_D^2}{\lambda}$ – the transport coefficient

m_D – the Debye mass ($m_D(T) \sim gT$)

λ – the mean free path

$\omega_c = \frac{\hat{q}L^2}{2} \cong \frac{2\langle \Delta E_{rad} \rangle}{\alpha_s C_R}$ – characteristic gluonstrahlung energy

For the dominant part of the spectrum:

$$\Delta E_{rad}^{LPM} \propto \alpha_s \hat{q} L^2$$

$$\Delta E_{rad}^{LPM} \propto \ln(E) \;\; (\omega_c < \omega)$$

Effective parton path-length

- The traversing partons can be produced at any initial point within the fireball;
- $T(\boldsymbol{r},\tau), \rho(\boldsymbol{r},\tau), m_D(\boldsymbol{r},\tau), \hat{q}(\boldsymbol{r},\tau) \Rightarrow$ including azimuthal anisotropy;
- The produced plasma is expanding with large longitudinal (transversal) velocities.

1. <u>Definition of L_{ef}</u>

Time-averaged transport coefficient along the direction of propagation of the parton:

$$\langle\hat{q}\rangle(b,\Delta\varphi) = \frac{2}{L^2}\int_{\tau_0}^{\tau_0+L} (\tau - \tau_0)\hat{q}(\tau)d\tau$$

τ_0 is the formation time of the expanding system

L – medium length along the propagation

The following effective quantities are introduced:

$$I_0(b,\Delta\varphi) = \langle\hat{q}\rangle L_{\text{eff}}(b,\Delta\varphi) \equiv \int_0^\infty \hat{q}(\tau)d\tau \qquad I_1(b,\Delta\varphi) = \omega_{c\,\text{eff}}(b,\Delta\varphi) \equiv \frac{1}{2}\langle\hat{q}\rangle L_{\text{eff}}^2 = \int_0^\infty \tau\hat{q}(\tau)d\tau$$

The effective parton path-length is determined as follows:

$$L_{\text{eff}}(b,\Delta\varphi) = \frac{2I_1(b,\Delta\varphi)}{I_0(b,\Delta\varphi)} \qquad L_{\text{eff}}(b) = \frac{2I_1(b)}{I_0(b)}$$

Effective parton path-length

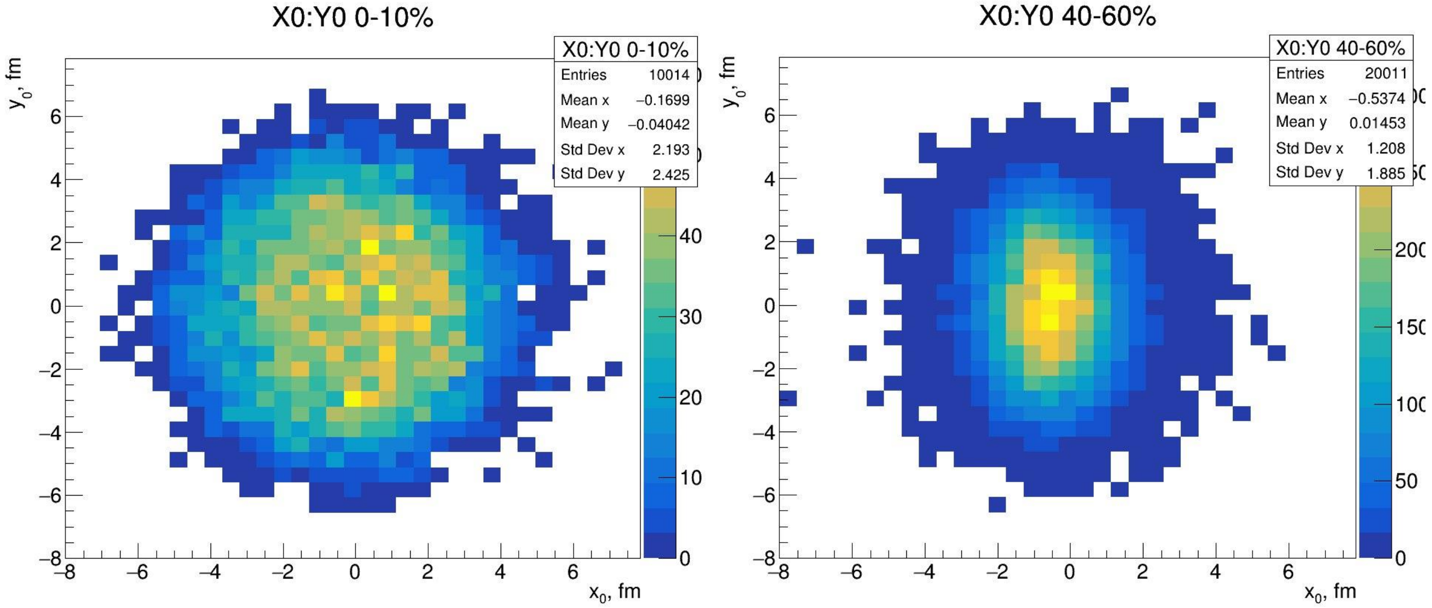
2. <u>Glauber model</u>

The local transport coefficient $\hat{q}(\tau; b)$ is proportional to the participant density in the transverse plane $\rho_{part}(\tau; b)$ ($\hat{q}(\tau; b) \propto \rho_c(\tau; b) \propto \rho_{part}(\tau; b)$):

$$\hat{q}(\tau; b) = \rho_c(\tau; b) \int d^2 q_T q_T^2 \frac{d\sigma}{d^2 q_T} = k(b)\rho_{part}(\tau; b)$$

$$\rho_{part}(\tau; b) = \rho_{part}(x_0 + \beta\tau\cos(\varphi_0 - \psi_2), y_0 + \beta\tau\sin(\varphi_0 - \psi_2); b)$$

A parton creation point (x_0, y_0) and the direction of movement φ_0 is generated in a plane transverse to the reaction plane



Density decreases with distance from the center

$$f(x_0, y_0) = A\rho_{coll}(x_0, y_0)$$

Isotropic distribution:

$$f(\varphi_0) = \frac{1}{2\pi}$$

Effective parton path-length

3. Longitudinal (1D) expansion of the plasma

$$\rho_c(\tau) = \rho_c(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{\alpha} \Rightarrow (\alpha = 1\ - \text{Bjorken expansion}) \Rightarrow \rho_c(\tau) = \rho_c(\tau_0)\frac{\tau_0}{\tau} \Rightarrow \Delta E \propto L$$

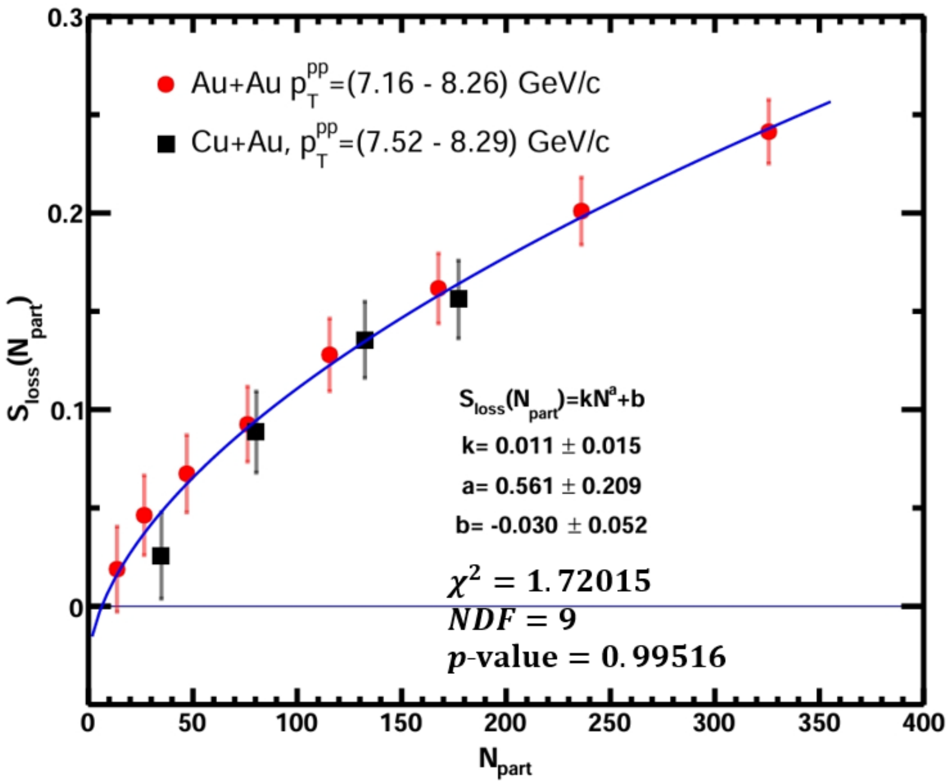
The regularized form:

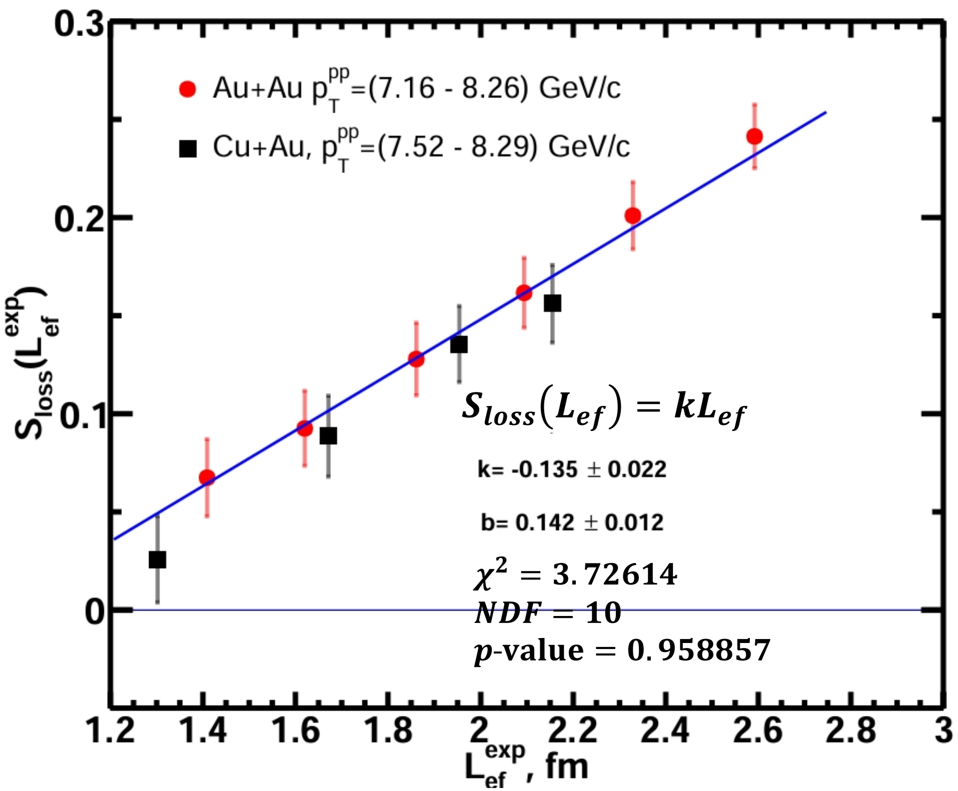
$$\rho_c(\tau) = \rho_{c0}\left(\frac{\tau^2/\tau_0^2}{1+\tau^2/\tau_0^2}\right)\left(\frac{\tau_0}{\tau}\right)$$

We have the following formula for calculation $L_{\mathrm{ef}}(b, \Delta\varphi)$:

$$L_{\mathrm{ef}}(b,\Delta\varphi) = \frac{2\int_0^{\infty} \beta^2 \tau \rho_{part}(x_0 + \beta\tau\cos(\Delta\varphi)\,, y_0 + \beta\tau\sin(\Delta\varphi)\,; b)\left(\frac{\tau^2/\tau_0^2}{1+\tau^2/\tau_0^2}\right)\left(\frac{\tau_0}{\tau}\right)\, d\tau}{\int_0^{\infty} \beta \rho_{part}(x_0 + \beta\tau\cos(\Delta\varphi)\,, y_0 + \beta\tau\sin(\Delta\varphi)\,; b)\left(\frac{\tau^2/\tau_0^2}{1+\tau^2/\tau_0^2}\right)\left(\frac{\tau_0}{\tau}\right)\, d\tau}$$

$S_{loss}(L_{ef})$ for π^0-mesons in Cu+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



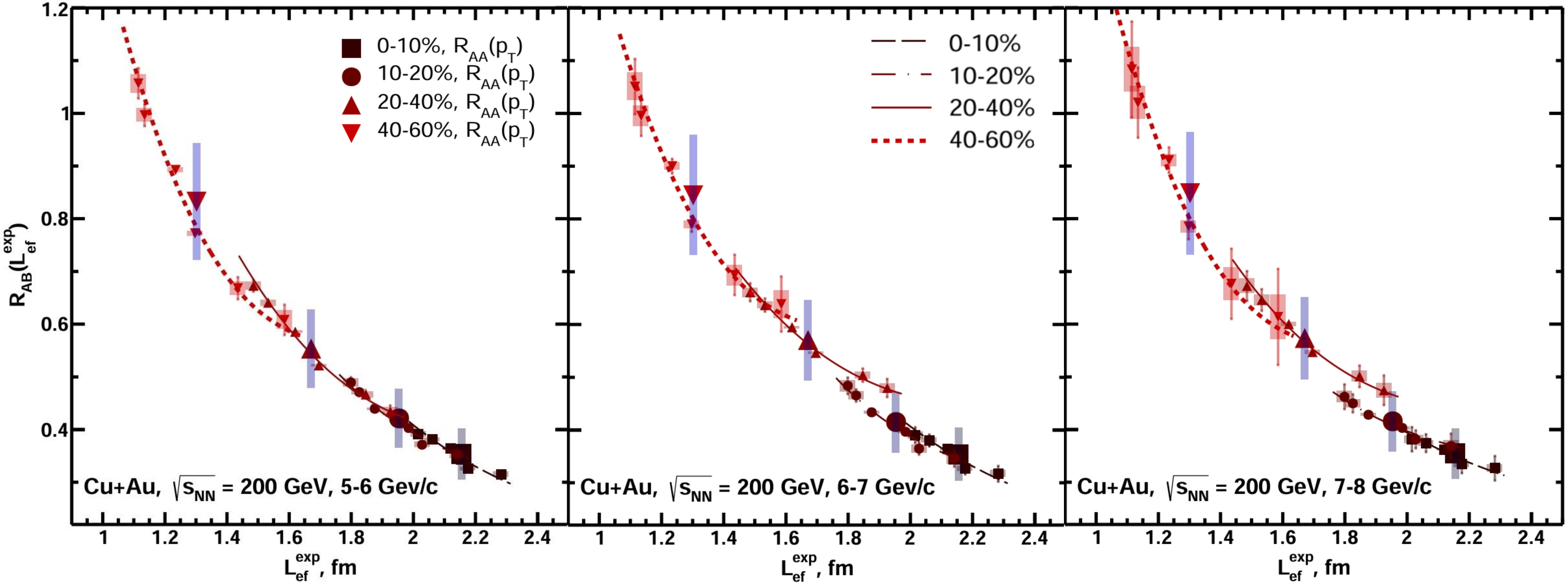


$S_{loss} = kN_{part}^{2/3}$

$S_{loss} = kL_{ef}$

$$\Delta E \propto \alpha_s^3 C_R \times \underbrace{\frac{1}{A_\perp}}_{\propto N_{part}^{2/3}} \times \underbrace{\frac{dN^g}{dy}}_{\propto \frac{dN_{ch}}{dy} \propto N_{part}} \times \underbrace{L}_{\propto N_{part}^{1/3}} \propto N_{part}^{2/3}$$

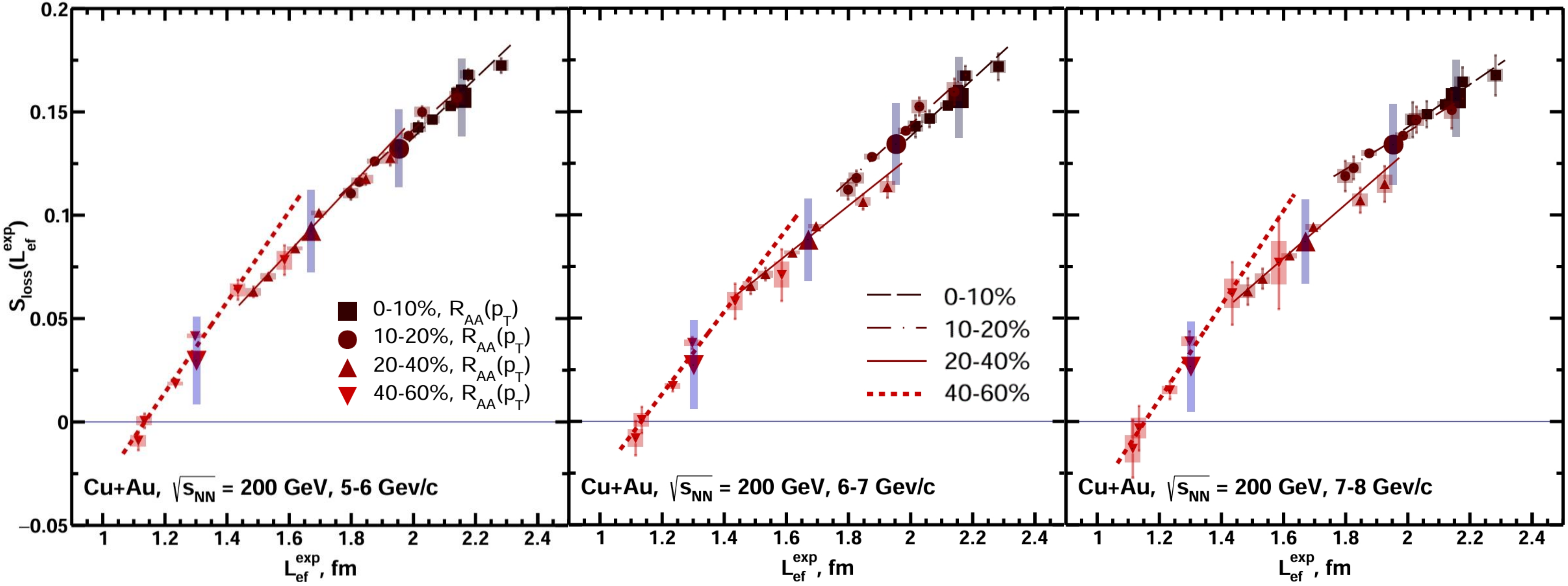
$R_{AA}(N_{part}, p_T, L_{ef})$ for π^0-mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



- The universal form $R_{AB} \propto (1-kL)^{n+1}$ for 0-10%, 10-20%, 20-40%

- Deviation from $R_{AB} \propto (1-kL)^{n+1}$ for 40-60%

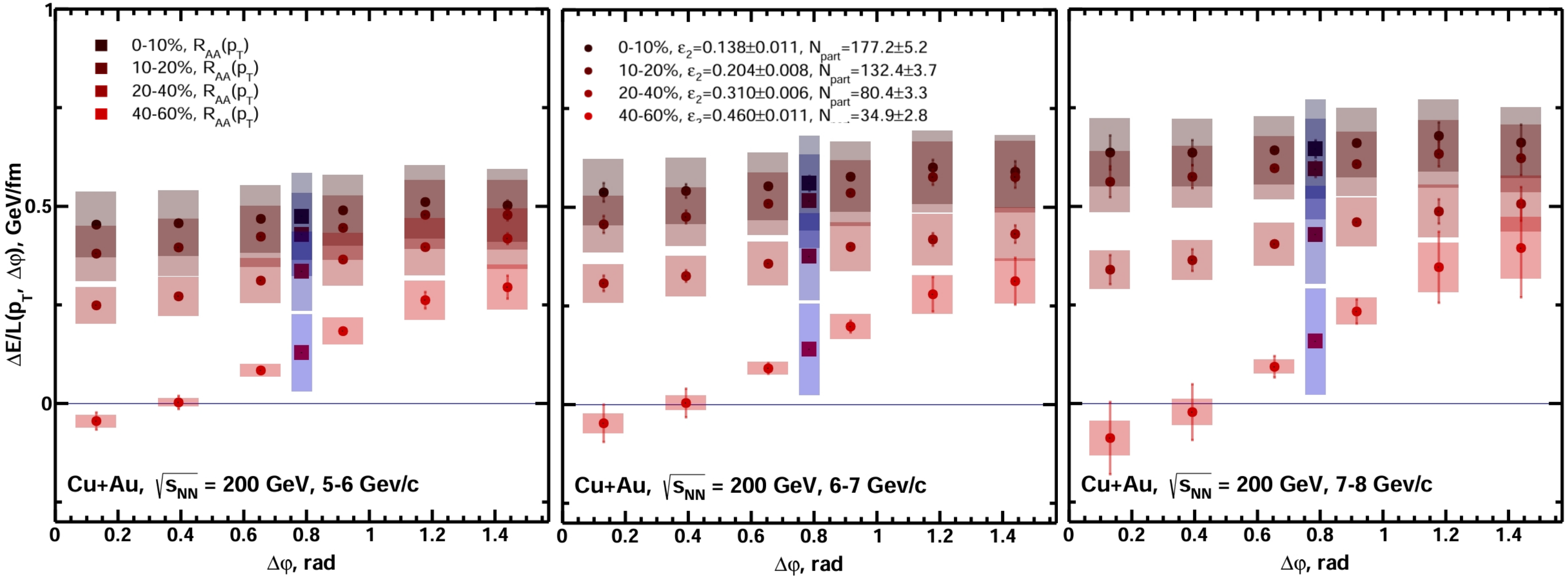
$S_{loss}(N_{part}, p_T, L_{ef})$ for π⁰-mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



- The universal form $S_{loss} \propto kL$ for 0-10%, 10-20%, 20-40%

- Deviation from $S_{loss} \propto kL$ for 40-60%

$\Delta E/L_{ef}(N_{part}, p_T, \Delta\varphi)$ for π^0-mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



- $\left.\frac{\Delta E}{L_{ef}}\right|_{max}^{5-6\ Gev/c} \sim 0.5\ GeV/fm$, $\left.\frac{\Delta E}{L_{ef}}\right|_{max}^{7-8\ Gev/c} \sim 0.7\ GeV/fm$ (0-10%)
- $\frac{\Delta E}{L_{ef}} \sim \mathrm{const}(\Delta\varphi)$ for 0-10%, 10-20%
- $\frac{\Delta E}{L_{ef}}$ varies slightly for 20-40%
- Significant anisotropy for 40-60%

Conclusions

- The form of dependencies $S_{loss}(N_{part})$, $S_{loss}(L_{ef})$ for Cu+Au matches with Au+Au,
$$S_{loss} \propto kN_{part}^{2/3},\ S_{loss} \propto kL_{ef}$$
- There is a clear azimuthal dependence $R_{AB}(\Delta\varphi)$ и $S_{loss}(\Delta\varphi)$ in the centralities 20-40% и 40-60%
- $R_{AB}\left(\frac{\pi}{24}\right)|_{40-60\%} \gtrsim 1, S_{loss}\left(\frac{\pi}{24}\right)|_{40-60\%} \lesssim 0$ in 40-60%
- The universal forms $R_{AB} \propto (1-kL)^{n+1}$and $S_{loss} \propto kL$ (for 0-10%, 10-20%, 20-40%)
- Deviation from $R_{AB} \propto (1-kL)^{n+1}$ and $S_{loss} \propto kL$ for 40-60%
- $\frac{\Delta E}{L_{ef}}$~const($\Delta\varphi$) for 0-10%, 10-20% (~0.7 GeV/fm for $p_T = 7-8\ Gev/c$)
- Significant anisotropy $\frac{\Delta E}{L_{ef}}$ for 40-60%
- In peripheral collisions there is significant anisotropy in the density distribution and other effects (corona effect etc.)

Thank you for your attention!