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Effective fractional parton energy loss in U+U collisions at the energy of $\sqrt{s_{NN}}$ =193 GeV

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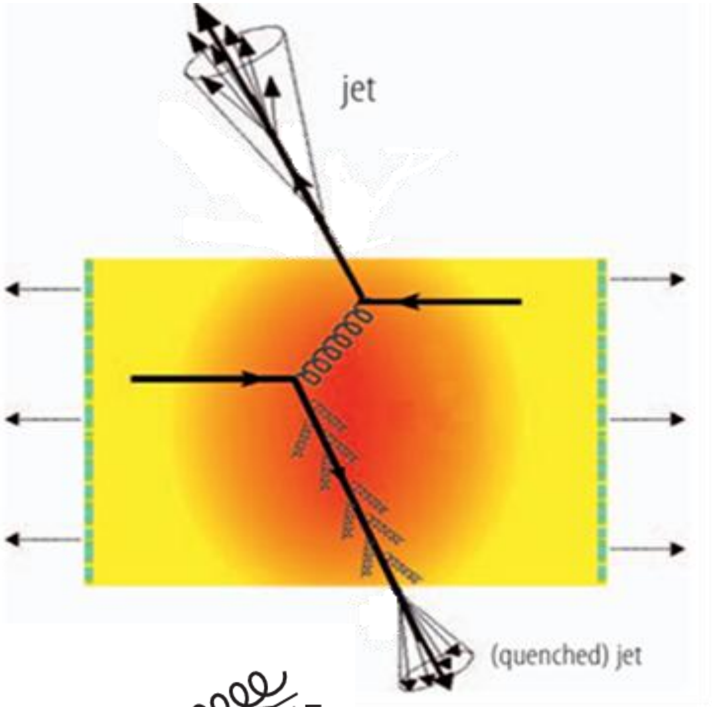
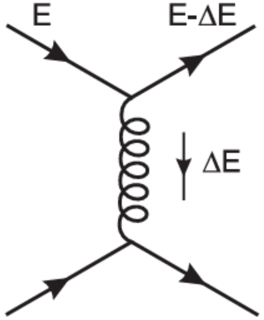
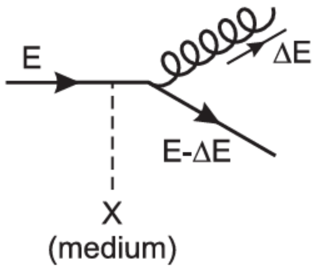
Quark-gluon plasma. Jet quenching.



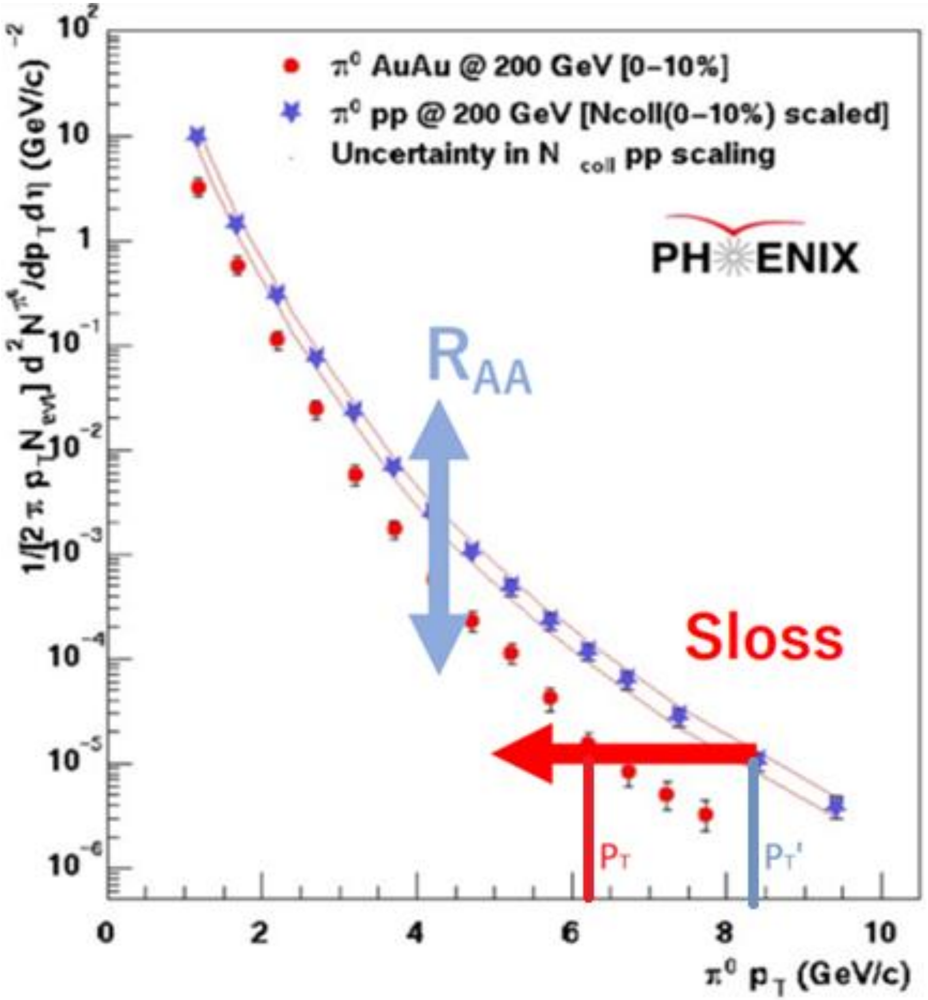




- Ultra-high energy density (>1 GeV/fm^3) in ultrarelativistic heavy ion collisions => asymptotically free quarks and gluons => quark-gluon plasma (QGP)
- QGP effects => jet quenching => a parton loses its energy while going through QGP => decreasing of the yields of the leading hadrons in a jet
- In general $\Delta E(E, m, T, \alpha_s, L)$
- $\Delta E = \Delta E_{\text{coll}} + \Delta E_{rad}$
- At high p_T (>5 GeV/c), energy loss through the gluonstrahlung prevails

[d'Enterria, D. (2010). 6.4 Jet quenching. In: Stock, R. (eds) Relativistic Heavy Ion Physics. Landolt-Börnstein - Group I Elementary Particles, Nuclei and Atoms, vol 23. Springer, Berlin, Heidelberg]

Nuclear modification factors and effective fractional energy loss S_{loss}



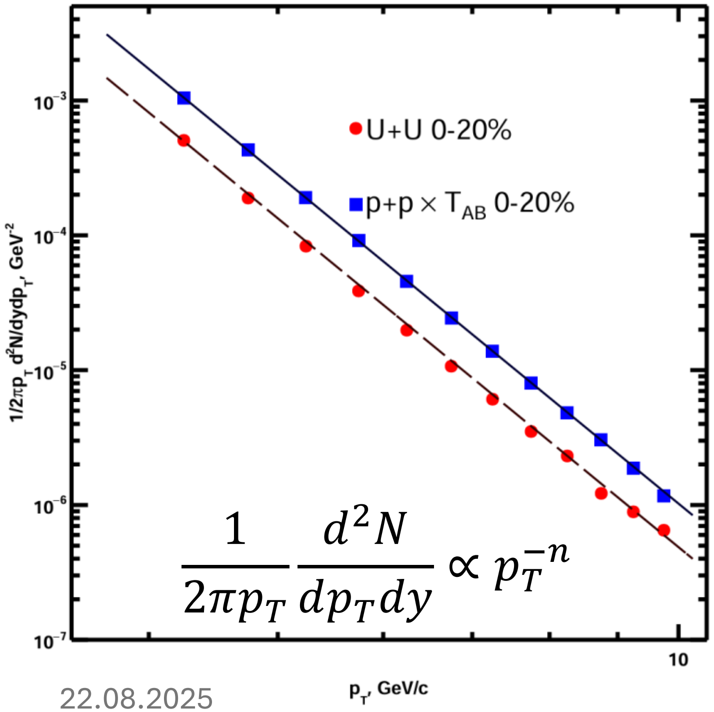
- The change in particle yields in heavy ion collisions compared to the pp-collisions is characterized by nuclear modification factors R_{AB}
- $\boldsymbol{R_{AB} = \frac{1}{\langle N_{coll}\rangle}\frac{d^2N_{AB}}{dp_T dy} / \frac{d^2N_{pp}}{dp_T dy}}$
- $\langle N_{coll}\rangle$ - the average number of binary inelastic nucleon-nucleon collisions
- The energy loss of particles in QGP is characterized by S_{loss}
- $\boldsymbol{S_{loss} = \frac{\Delta E}{E_{initial}} \approx \frac{p_T' - p_T}{p_T'} = \frac{\Delta p_T}{p_T'}}$
- p_T' - transverse momentum of π^0-mesons in p+p collisions
- p_T - transverse momentum of π^0- mesons in A+B collisions

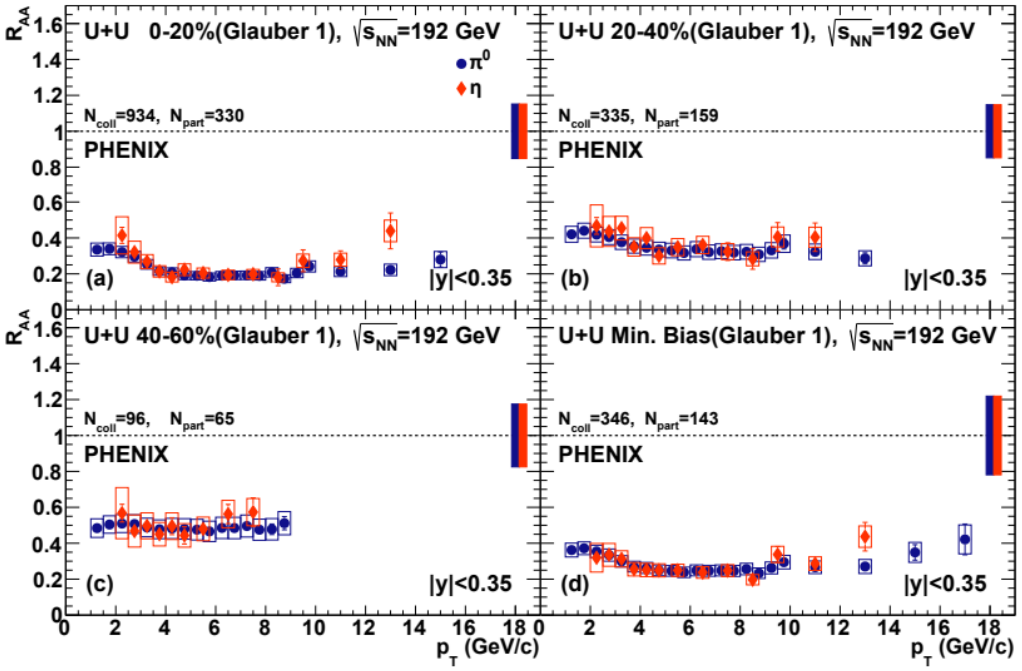
Relationship between R_{AB} and S_{loss}

If the spectra of π^0 in nucleus-nucleus collisions are parallel to the spectra of π^0 in proton-proton collisions (at least in some area of transverse momentum):

$$\frac{\Delta p_T}{p_T} \approx const \qquad \frac{d\Delta p_T}{dp_T} \approx const \qquad (p_T > 4\ GeV/c)$$

$$\boldsymbol{S_{loss}(p_T) = 1 - R_{AB}^{\frac{1}{n-2}}(p_T)} \approx const(p_T)$$ [PRC 76, 034904 (2007)]



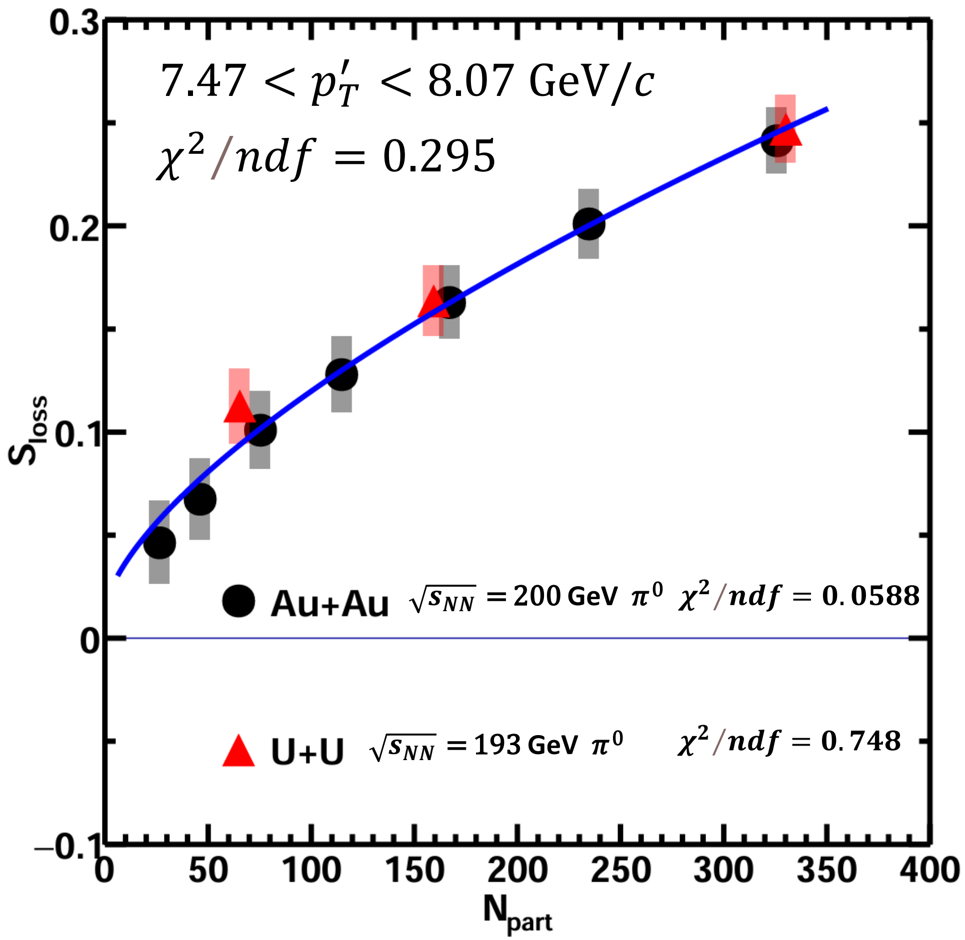


In many centrality classes, the nuclear modification factor is a constant with good accuracy at $p_T > 4\quad GeV/c$

[PRC 102, 064905 (2020)]

Dependence of S_{loss} on centrality for π^0 in U+U collisions

The values of R_{AB} for Au+Au are taken from [PRC 87, 034911 (2013)] to calculate the S_{loss} value for Au+Au



$$S_{loss}(N_{part}) = 1 - \left(R_{AB}(N_{part})\right)^{\frac{1}{n-2}}$$

N_{part} – the average number of nucleons that have experienced at least one inelastic collision.

Approximation:

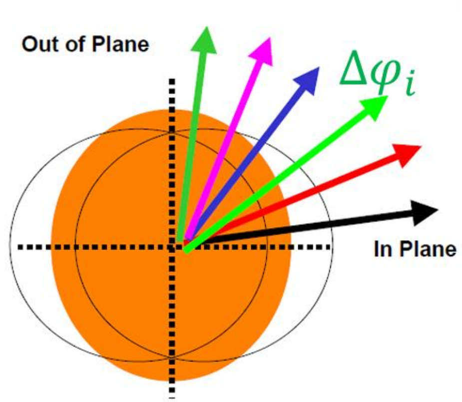
$$S_{loss} \approx k N_{part}^{2/3}$$

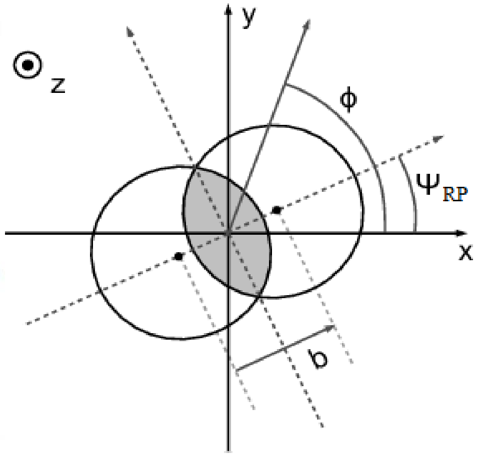
k – free parameter

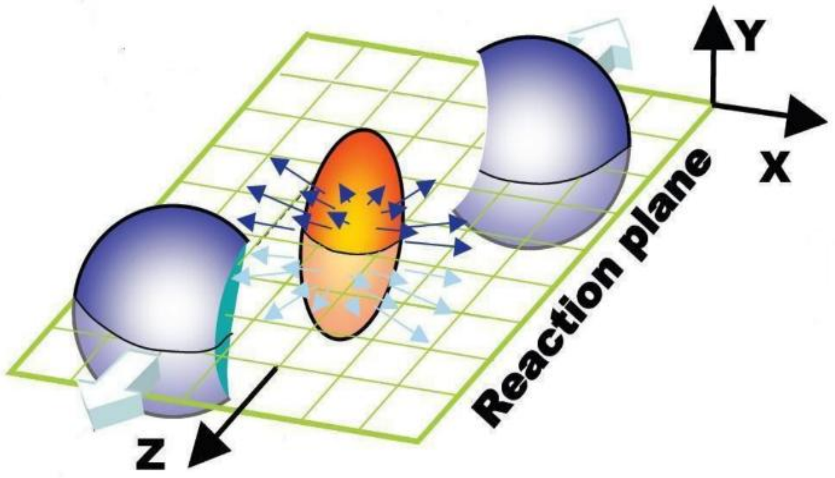
N_{part} - the average number of nucleons that have experienced at least 1 inelastic scattering

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

Anisotropy of colliding nuclei







- The region of nuclear overlap is azimuthally asymmetric with respect to the angle Ψ_{RP}
- The path-length of a parton in QGP, color charge density and other characteristics are anisotropic => different energy losses
- Angular distribution of particles:

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\varphi - \Psi_{RP})\right)$$

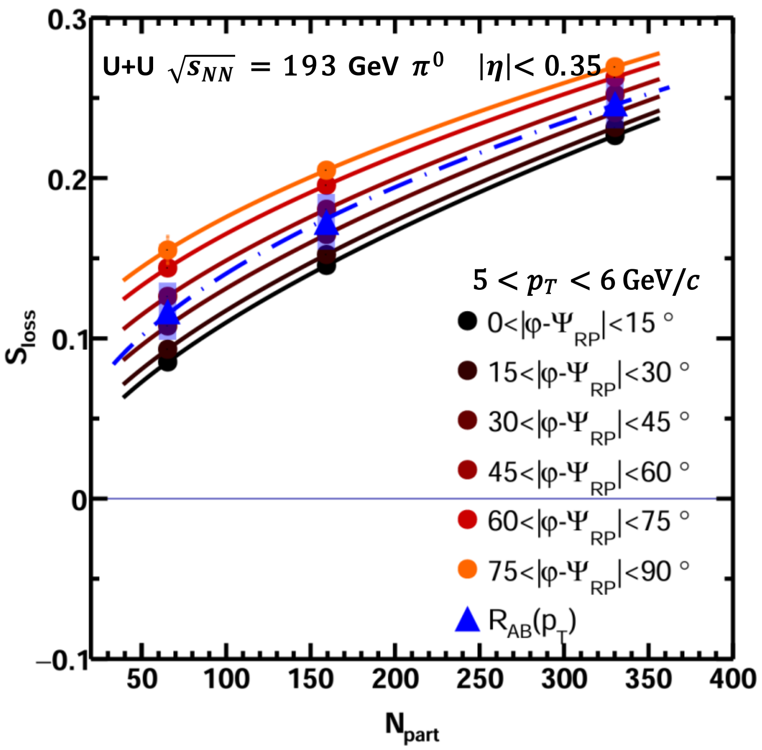
- The main contribution to the anisotropy – second harmonic – elliptic flow v_2
- Energy losses and particle yields depend on the azimuthal angle [PRC 76, 034904 (2007)] :

$$\boldsymbol{R_{AB}(p_T, \Delta\varphi) \approx (1 + 2v_2(p_T)\, cos(2\Delta\varphi))R_{AB}(p_T)}$$

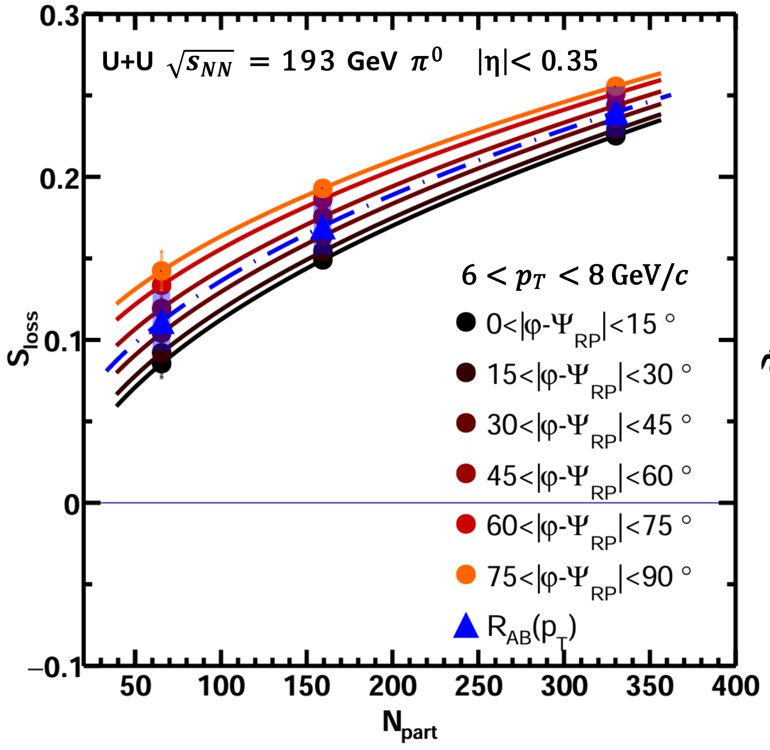
$$\boldsymbol{S_{loss}(p_T, \Delta\varphi) = 1 - R_{AB}^{\frac{1}{n-2}}(p_T, \Delta\varphi)}$$

- Naïve expectations:
  - Losses are minimal in the reaction plane ($\Delta\varphi = 0°$)
  - If $\Delta\varphi = 90^{\circ}$ losses are maximal

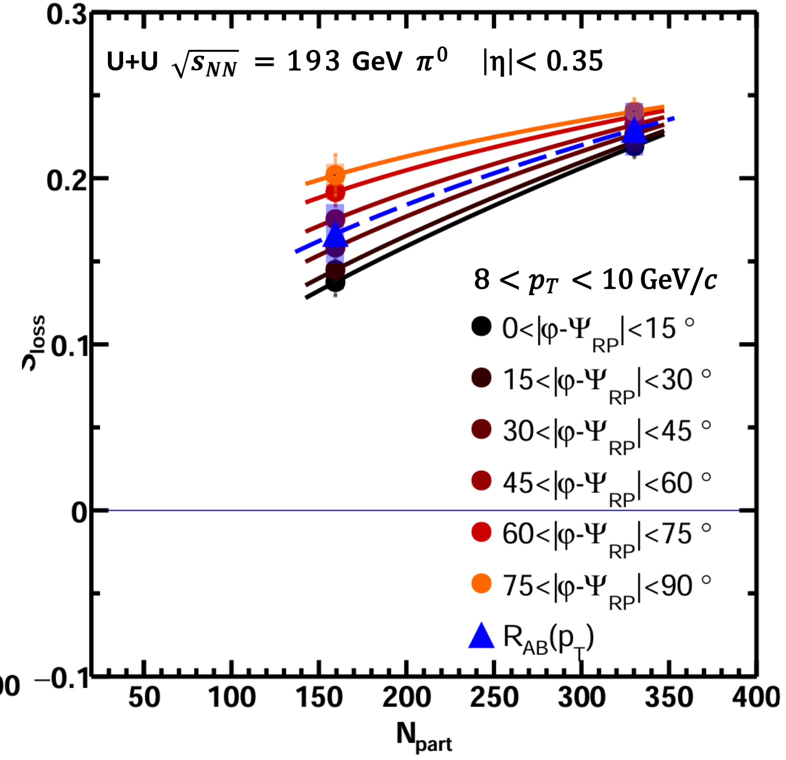
Dependence of S_{loss} of π^0 on N_{part} for different $\Delta\varphi$ in U+U collisions



$S_{loss} \uparrow$ if $N_{part} \uparrow$

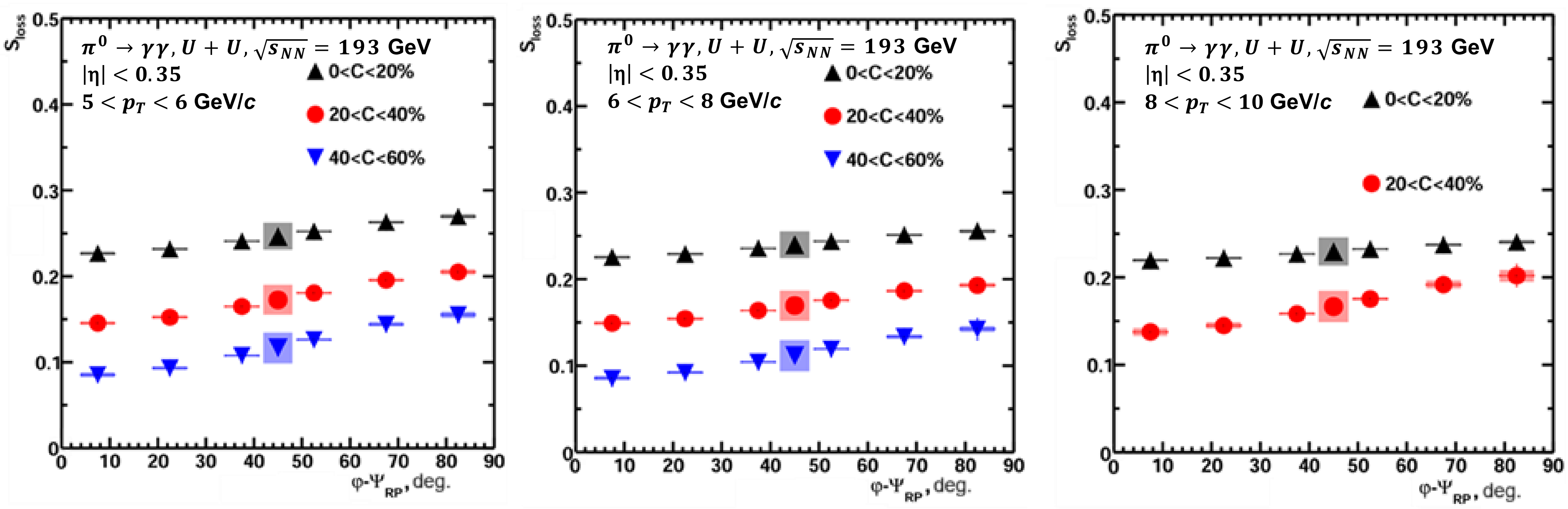


$S_{loss} \uparrow$ if $\Delta\varphi \uparrow$ as expected



The variation of $S_{loss} \uparrow$ if $N_{part} \downarrow$

Dependence of S_{loss} of π^0 on $\Delta\varphi$ in U+U collisions



Dependence of energy losses on the parton path length

- The parton path-length in the QGP and the various characteristics of the QGP itself are anisotropic => there is $S_{loss}(\Delta\varphi)$ => it's possible to express $S_{loss}(L)$
- At high p_T, radiative losses prevail
- For thin media $(L \ll \lambda)$ – Bete-Heitler spectrum:

$$\omega \frac{dI_{rad}}{d\omega} \approx \frac{\alpha_S \hat{q} L^2}{\omega} \qquad \Delta E_{rad}^{BH} \approx \alpha_S \hat{q} L^2 \ln\left(\frac{E}{m_D^2 L}\right)$$

- Thick media $(L \gg \lambda)$ – Landau-Pomeranchuk-Migdal spectrum:

$$\omega \frac{dI_{rad}}{d\omega} \approx \alpha_S \begin{cases} \sqrt{\frac{\hat{q} L^2}{\omega}} & (\omega < \omega_c) \\ \frac{\hat{q} L^2}{\omega} & (\omega > \omega_c) \end{cases} \qquad \Delta E_{rad}^{LPM} \approx \alpha_S \begin{cases} \hat{q} L^2 \\ \hat{q} L^2 \ln\left(\frac{E}{m_D^2 L}\right) \end{cases}$$

First expectation: $\boldsymbol{\Delta E \propto L^2}$

$\hat{q}$ – the transport coefficient, m_D – the Debye mass , ω – the energy of a gluon

[d'Enterria, D. (2010). 6.4 Jet quenching. In: Stock, R. (eds) Relativistic Heavy Ion Physics. Landolt-Börnstein - Group I Elementary Particles, Nuclei and Atoms, vol 23. Springer, Berlin, Heidelberg]

The transition to the effective parton path-length

- The efficiency of parton energy loss may vary along the way
- Parton may not be created in the center of the QGP
- QGP is expanding
- Therefore, the effective (rather than the real) parton path-length in a homogenized effective QGP is considered [Eur. Phys. J. C 38, 461–474 (2005)]

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

$$I_0(b,\Delta\varphi) = \langle\hat{q}\rangle L_{eff}(b,\Delta\varphi) = \int_0^{\infty}\hat{q}(\tau)d\tau$$

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

$$\boldsymbol{L_{eff} = \frac{2I_1}{I_0}}$$

Effective path-length in Glauber model

$$\hat{q}(\tau, b) \propto \rho_c(\tau, b) \propto \rho_{part}(\tau, b)$$

- Parton creation point (x_0, y_0) and its direction of movement φ_0 are generated in Glauber model

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

- ρ_{part} is maximal in the center of overlap area and decreases towards the edges
- Longitudinal QGP expansion – Bjorken expansion [Phys. Rev. C 80, 054907 (2009)]:

$$\rho_c(\tau) = \rho_c(\tau_0)\frac{\tau_0}{\tau}$$

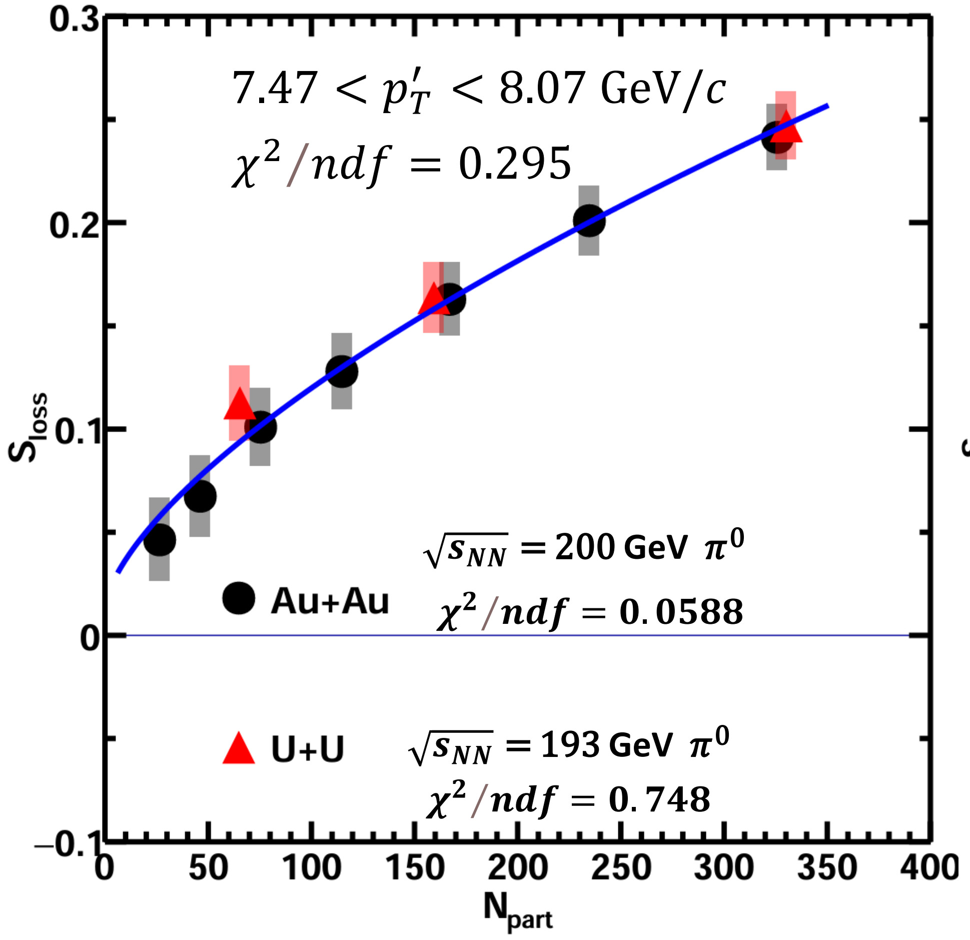
- Regularized form:

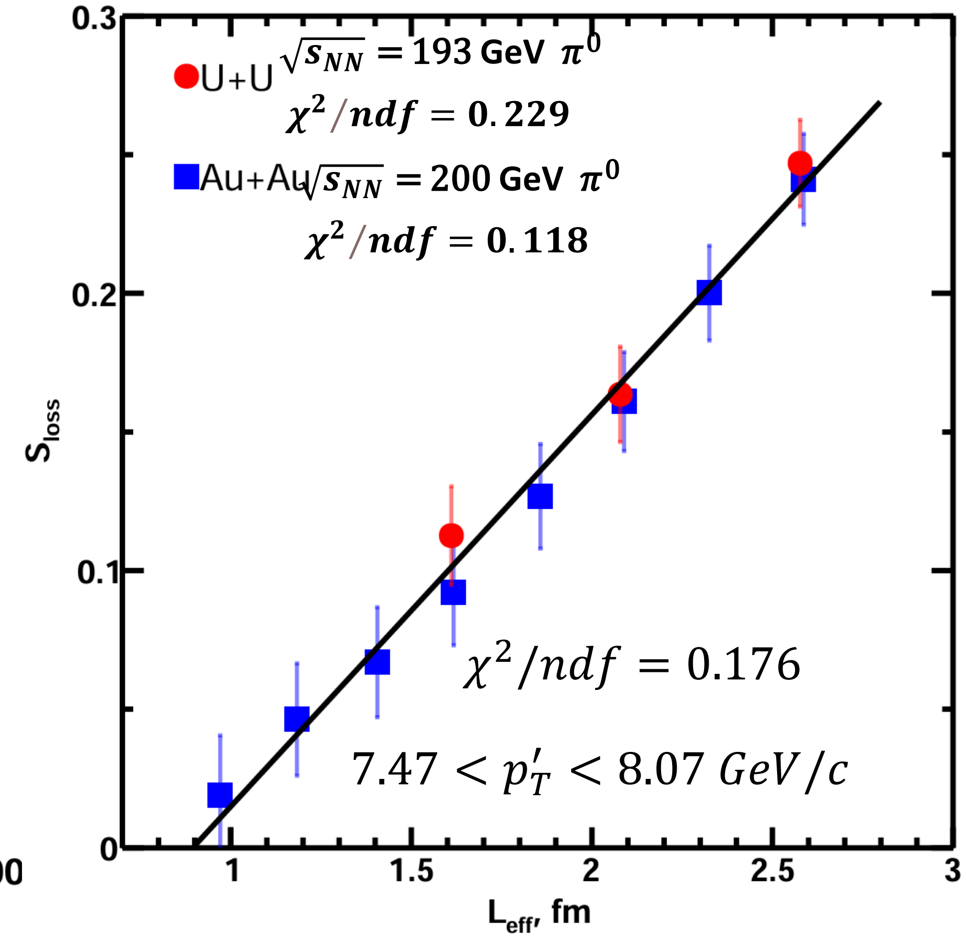
$$\rho_c(\tau) = \rho_{c0}\frac{\tau/\tau_0}{1 + \tau^2/\tau_0^2}$$

- Losses: $\Delta E \propto L$ Not $\Delta E \propto L^2$!

$$L_{eff}(b, \Delta\varphi) = 2\beta\frac{\int_0^\infty \rho_{part}\left(\frac{\tau/\tau_0}{1+\tau^2/\tau_0^2}\right)\tau d\tau}{\int_0^\infty \rho_{part}\left(\frac{\tau/\tau_0}{1+\tau^2/\tau_0^2}\right)d\tau}$$

Dependence $S_{loss}(L_{eff})$ π^0 in U+U collisions





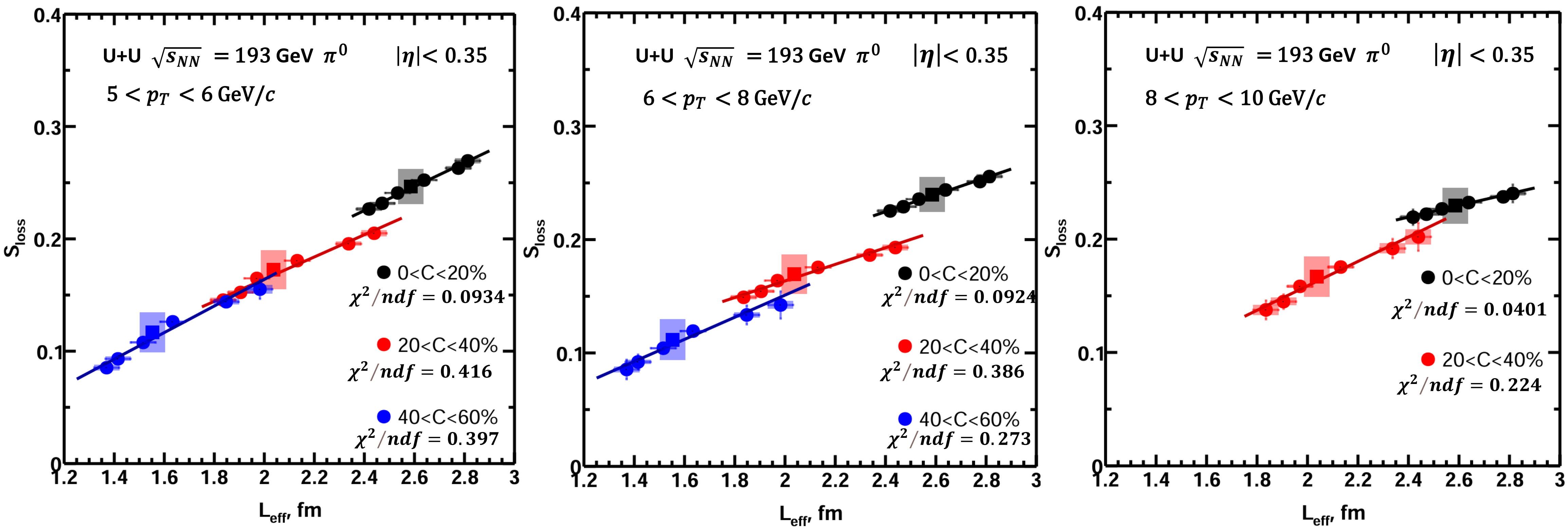
$\Delta E \propto L$

$S_{loss} = kL_{eff} + b$

The points of different systems fall on 1 straight line

The values of R_{AB} for Au+Au are taken from [PRC 87, 034911 (2013)] to calculate the S_{loss} value for Au+Au

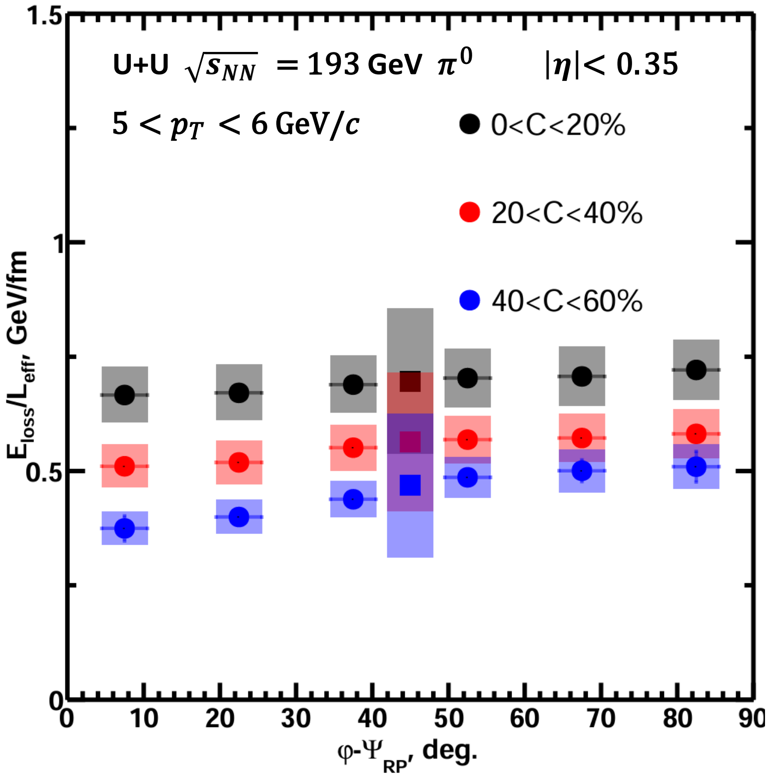
Dependence $S_{loss}(L_{eff})$ for different $\Delta\varphi$ of π^0 in U+U collisions



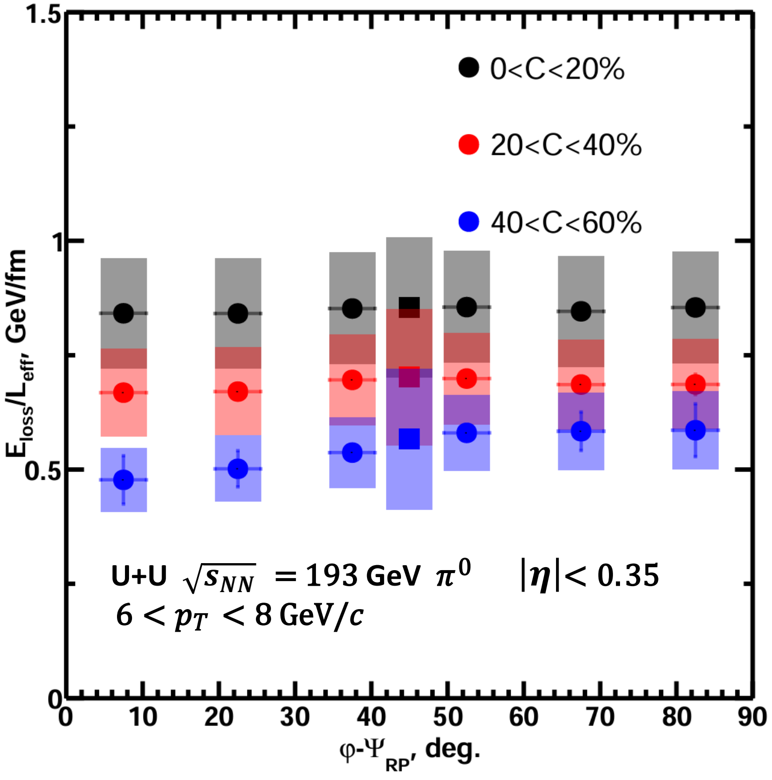
$S_{loss} \uparrow$ if $L_{eff} \uparrow$; $L_{eff} \uparrow$ if $\Delta\varphi \uparrow$

Dependence $E_{loss}/L_{eff}(\Delta\varphi)$ of π^0 in U+U collisions

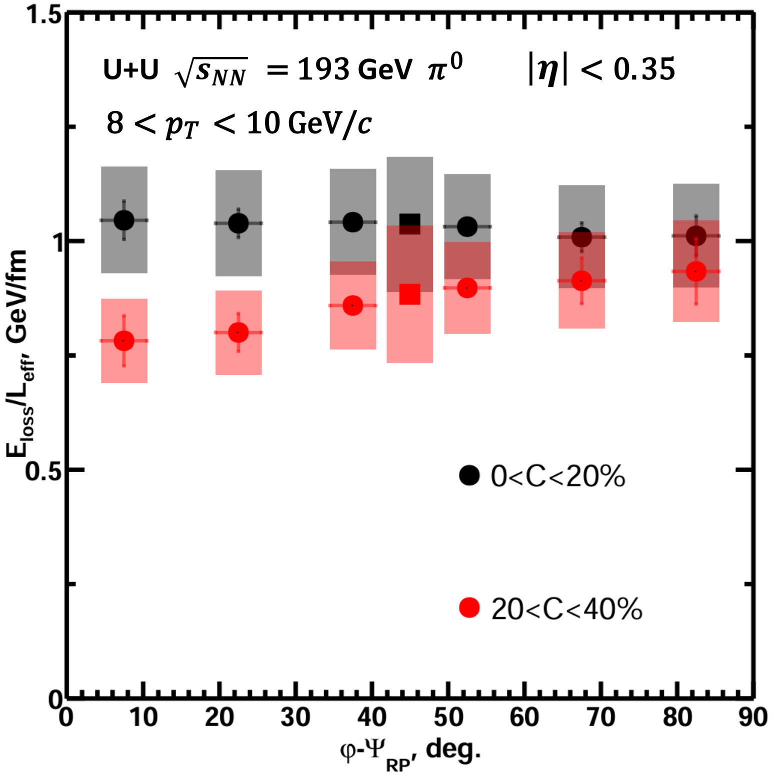
$$\Delta E = E_{loss} = S_{loss} p_T'$$



$E_{loss}/L_{eff} \approx constant(\Delta\varphi)$



$E_{loss}/L_{eff} \uparrow if\ N_{part} \uparrow$



$E_{loss}/L_{eff} \uparrow if\ p_T \uparrow$

Conclusion

- There are explicit dependencies $S_{loss}(N_{part})$, $S_{loss}(L_{eff})$, $S_{loss}(\Delta\varphi)$ and $S_{loss}(L_{eff}(\Delta\varphi))$
- Angle-inclusive losses $S_{loss}(L_{eff})$ and $S_{loss}(N_{part})$ dependencies have the same behavior for different collision systems (U+U, Au+Au):
  - $S_{loss} = kL_{eff} + b$
  - $S_{loss} = kN_{part}^{2/3}$
- $S_{loss}(L_{eff}(\Delta\varphi))$ are linear as expected
- $E_{loss}/\,L_{eff}(\Delta\varphi)$ is an almost constant value for every centrality class

Thank you for your attention!