Systematic study of the energy loss in QGP at RHIC-PHENIX

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Puerto Vallarta

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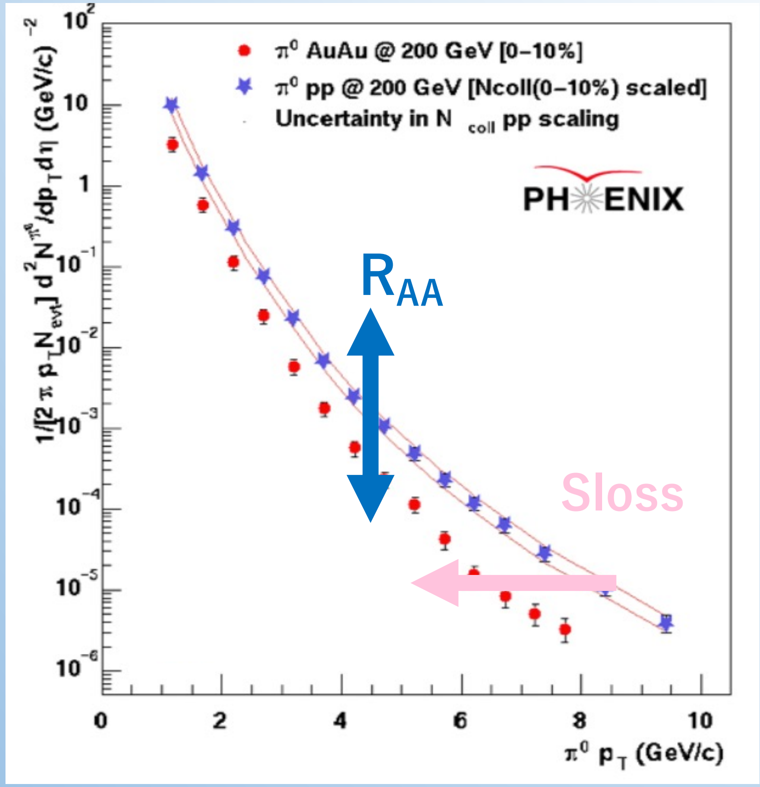
- Charged hadron energy loss
  - Inclusive fractional momentum loss (S_{loss})
  - Azimuthal-angle-dependent S_{loss}
- Heavy flavor energy loss
  - R_{AA}
  - V_2

Charged hadron energy loss

Findings 1: Yield Suppression

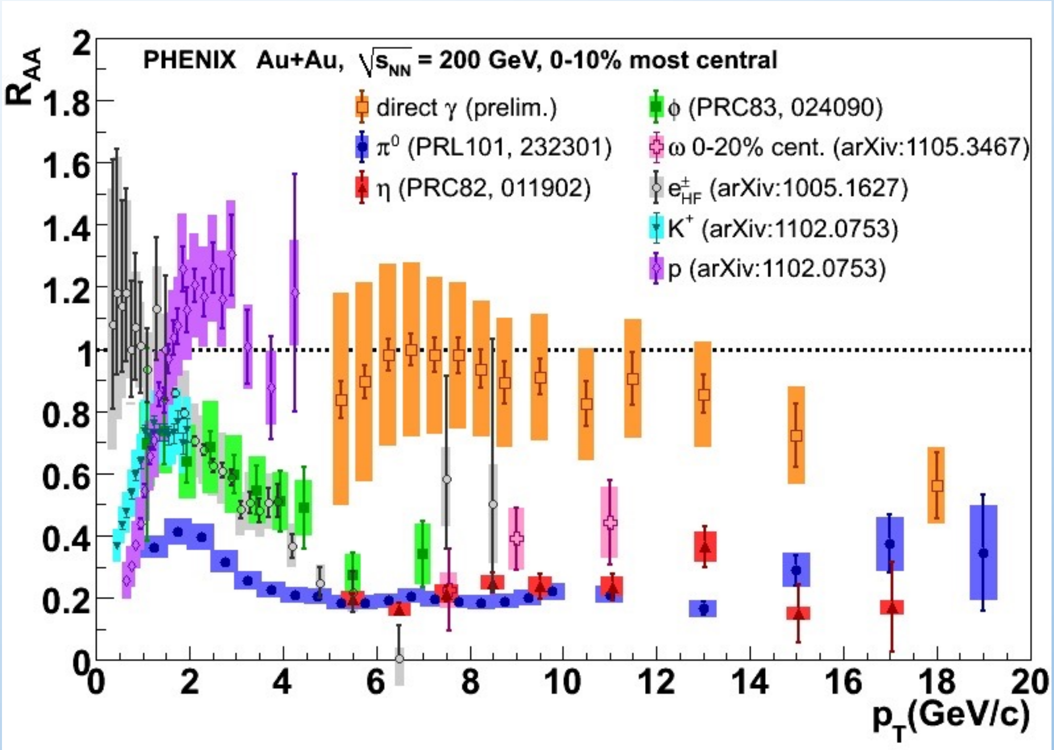
R_{AA}: Nuclear modification factor

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA}\rangle \sigma_{pp}}$$



$R_{AA} = 1$ → No medium effects

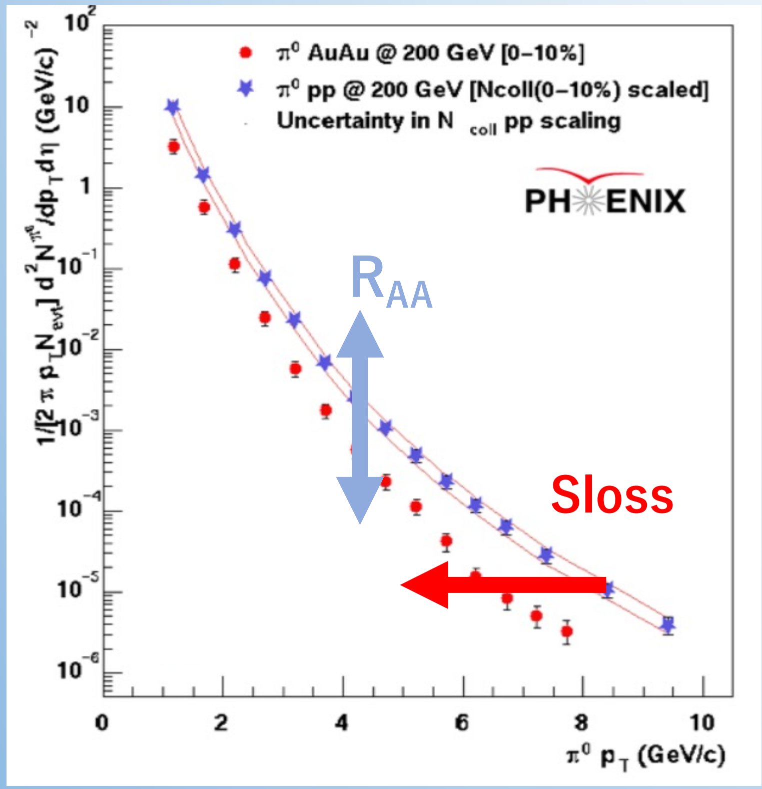
✔ $R_{AA} < 1$ → Suppression



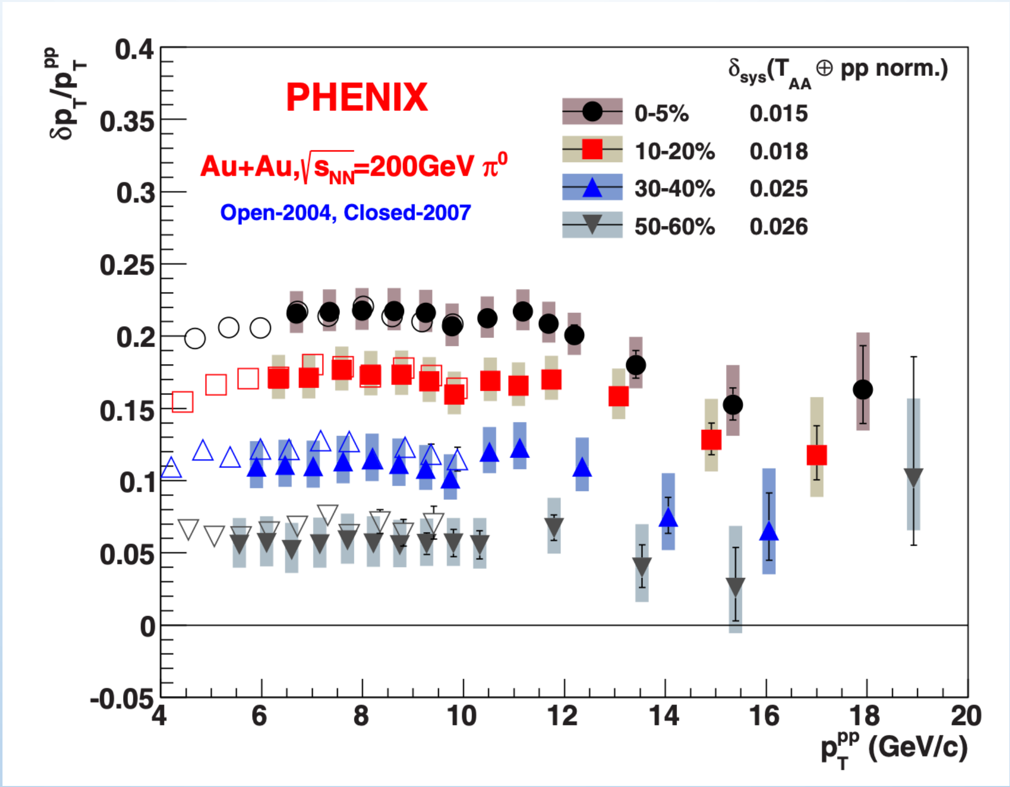
- High p_T hadron suppression has been observed.

Findings 2: Fractional momentum loss (s_{loss})

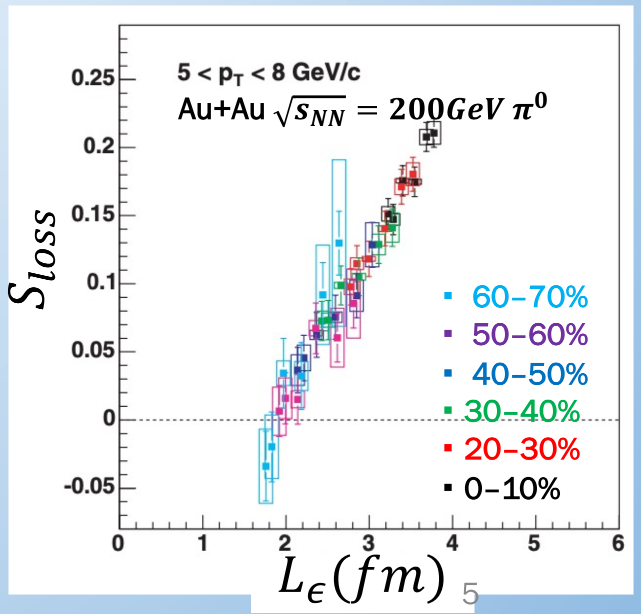
$$S_{loss} = \frac{p_T^{pp}(\text{scaled}) - p_T^{AA}}{p_T^{pp}(\text{scaled})}$$



Phys. Rev. C 93.024911 (2016)

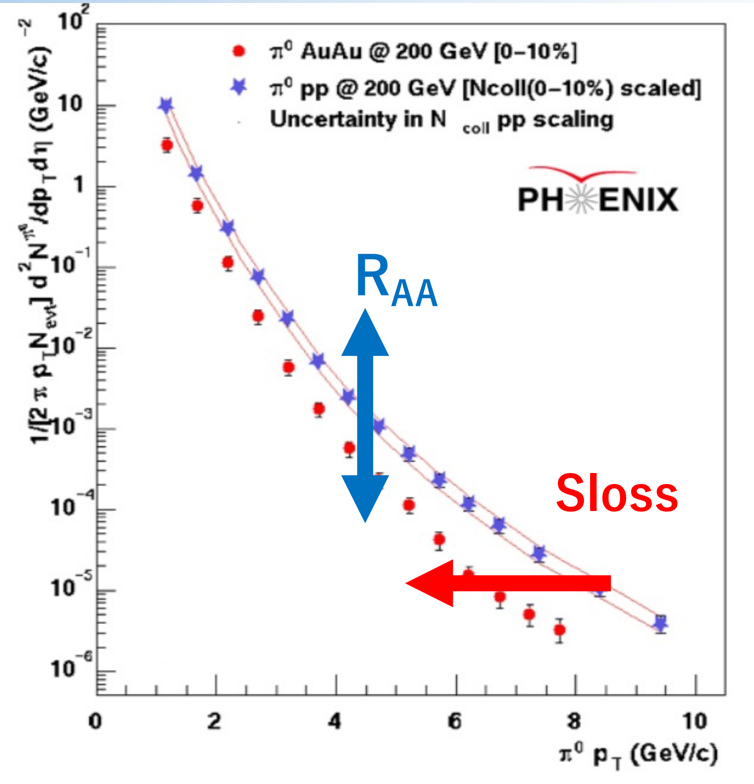


Phys. Rev. C.76.034904 (2007)



- S_{loss} doesn't have strong dependence on p_T.
- Larger S_{loss} is seen with larger reaction area which is coursed by more central collisions.
- S_{loss} depends on L_ϵ, an effective radius of the collision.

Motivation

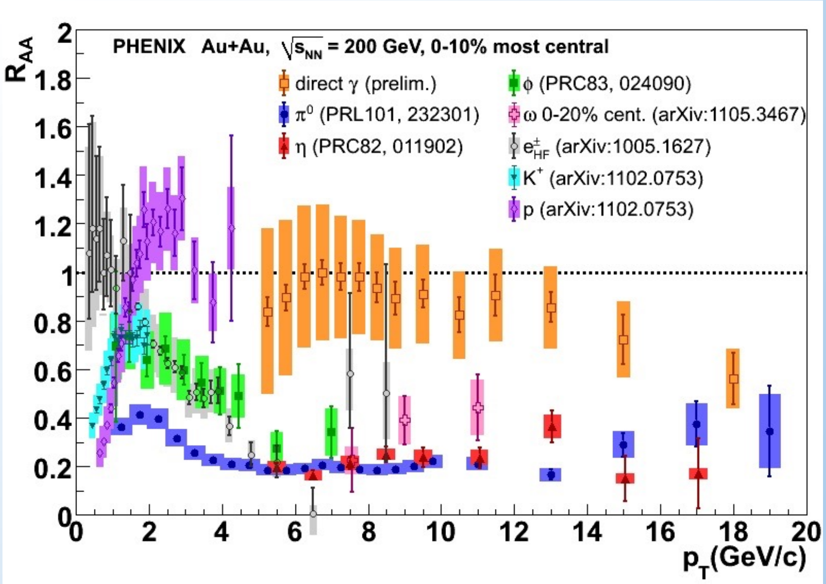


R_{AA}: Nuclear modification factor

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{pp}}$$

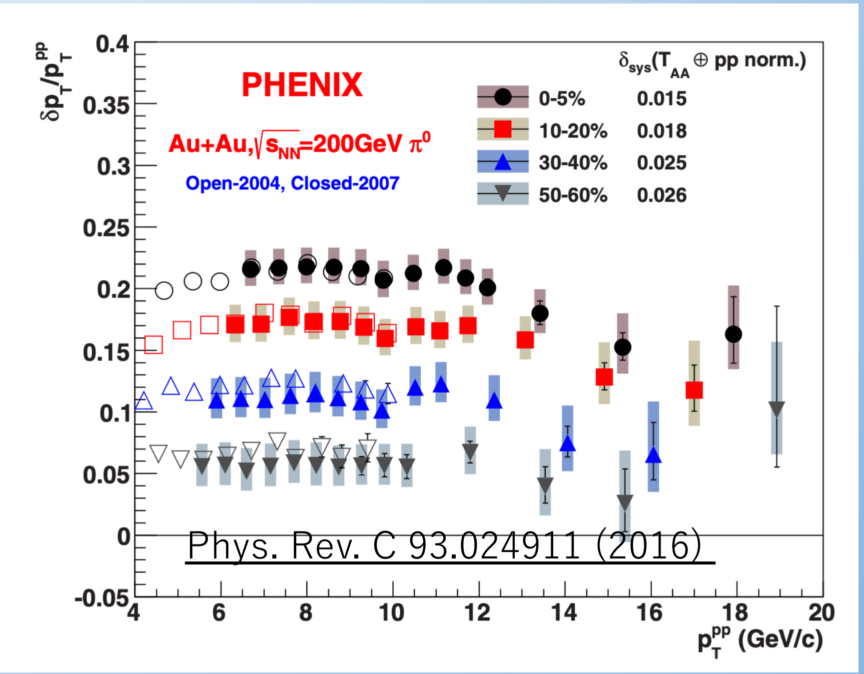
$R_{AA} = 1 \rightarrow$ No medium effects

✔ $R_{AA} < 1 \rightarrow$ Suppression



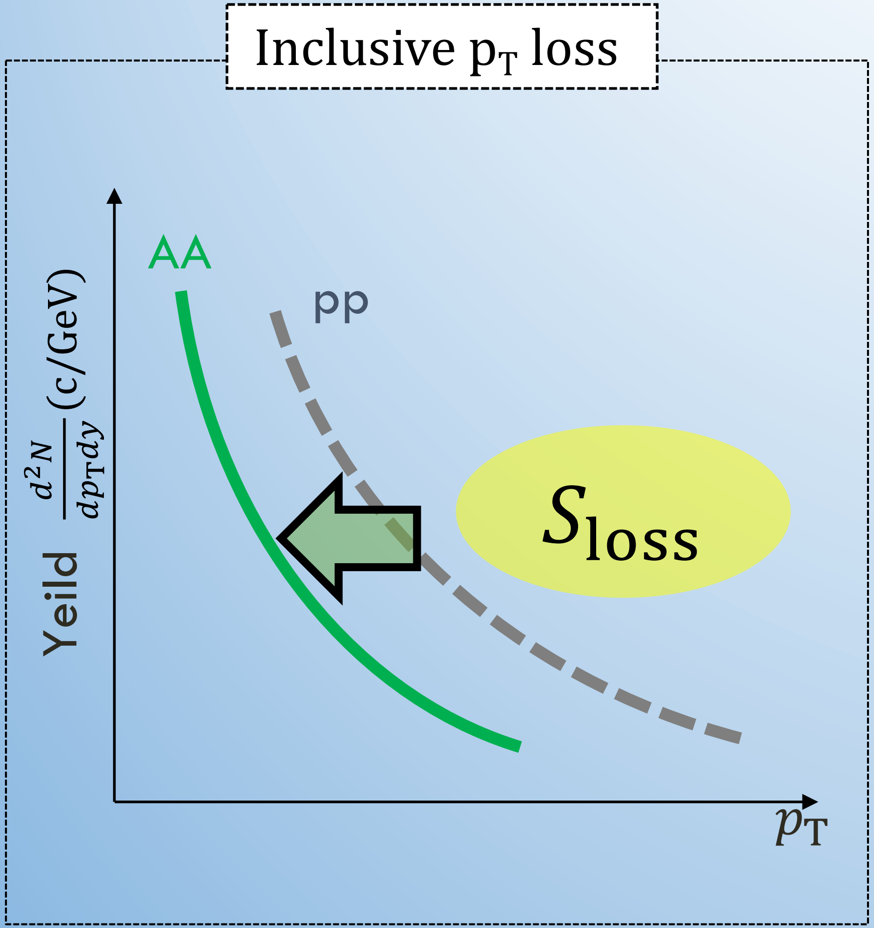
S_{loss}: the fractional momentum loss

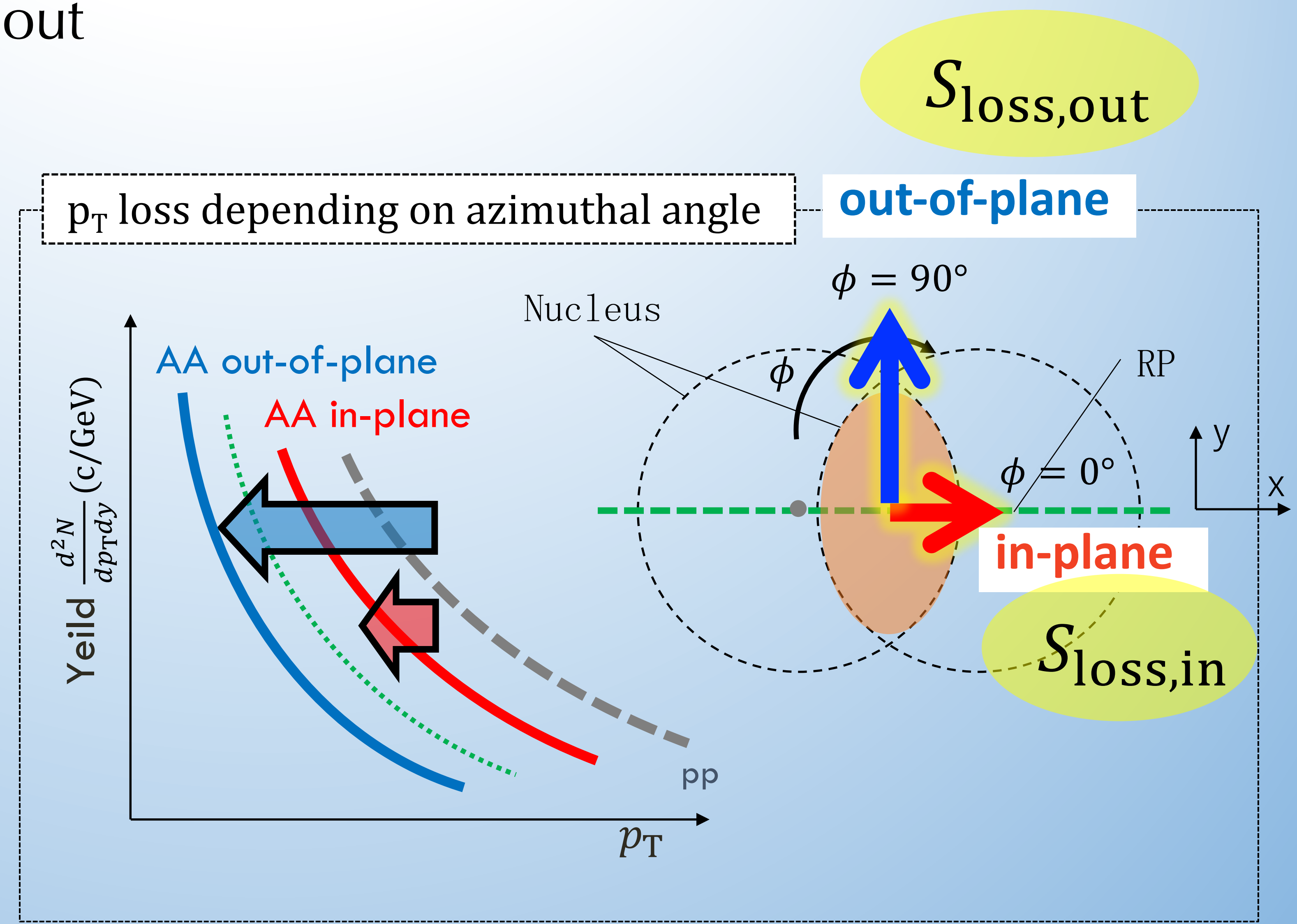
$$S_{loss} = \frac{p_T^{pp}(\text{scaled}) - p_T^{AA}}{p_T^{pp}(\text{scaled})}$$



To understand S_{loss} behavior better, we study the dependence of the size, density, and azimuthal angle of the reaction region in AA collision.

S_{loss}, $S_{loss,in}$ and $S_{loss,out}$





Analysis procedure

① In-plane spectra and out-of-plane spectra in A+A collision

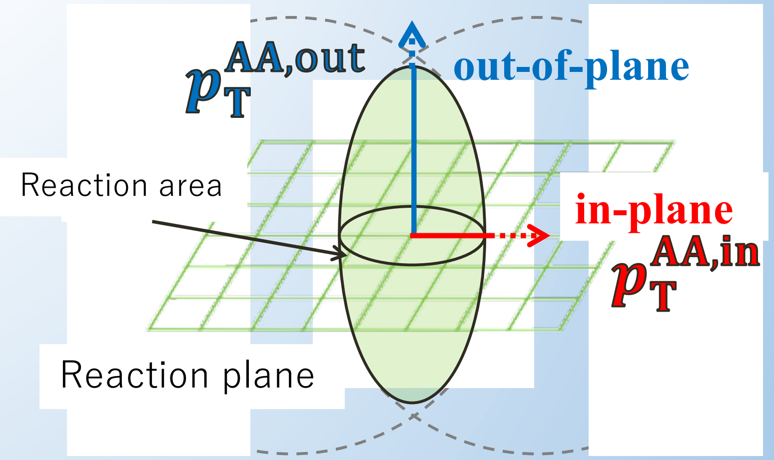
azimuthal distribution of generated particle $\frac{dN(\phi)}{d\phi} \propto 1 + 2v_2\cos 2\phi$

in-plane ($\phi = 0°$)

$$\left.\frac{d^2N}{dp_T dy}\right|_{\text{in}} = \frac{d^2N}{dp_T dy} \times (1 + 2v_2)$$

out-of-plane ($\phi = 90°$)

$$\left.\frac{d^2N}{dp_T dy}\right|_{\text{out}} = \frac{d^2N}{dp_T dy} \times (1 - 2v_2)$$



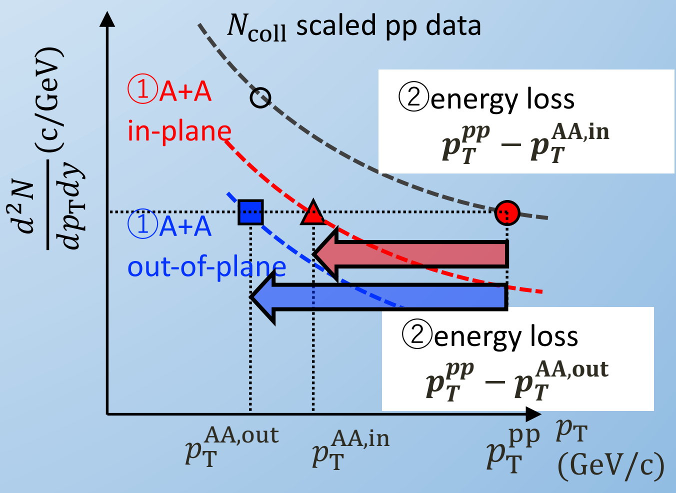
② The fractional momentum loss, $S_{\text{loss,in}}$ ($S_{\text{loss,out}}$), of in-plane (out-of-plane) using N_{coll} scaled pp data and in-plane spectra (out-of-plane spectra) in A+A collision

- The fractional momentum loss of in-plane:

$$S_{\text{loss,in}} = \frac{p_T^{\text{pp}} - p_T^{\text{AA,in}}}{p_T^{\text{pp}}}$$

- The fractional momentum loss of out-of-plane:

$$S_{\text{loss,out}} = \frac{p_T^{\text{pp}} - p_T^{\text{AA,out}}}{p_T^{\text{pp}}}$$

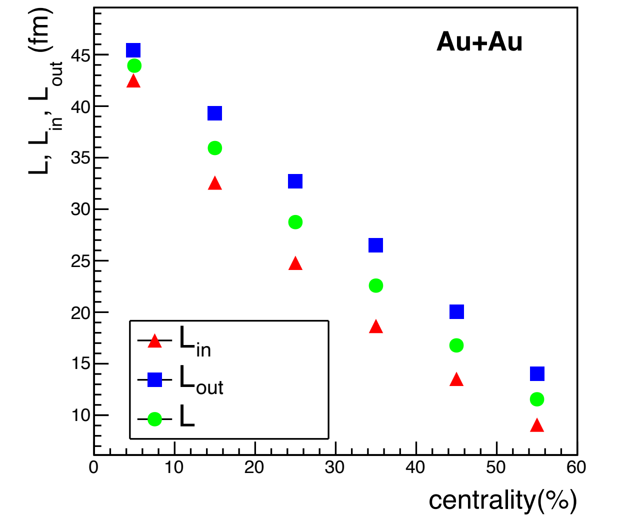


Parameters

L_{in}, L_{out}, L by Glauber MC

- Calculate the the distance from the collision center to the edge of reaction area. Reaction area is defined by participant distribution.

- In-plane path-length : L_{in}
- Out-of-plane path-length : L_{out}
- path-length: $L = \frac{\overline{L_{in}} + \overline{L_{out}}}{2}$



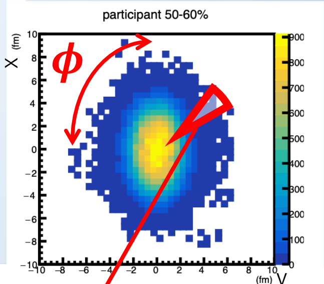
$N_{part\ in}$, $N_{part\ out}$ by Glauber MC

- Calculate the azimuthal distribution of participant

$$\frac{dN_{part}}{d\phi} \text{ vs. } \phi \qquad (\phi = \phi_{part} - \Psi_{RP})$$

ϕ_{part}: azimuthal angle of participant

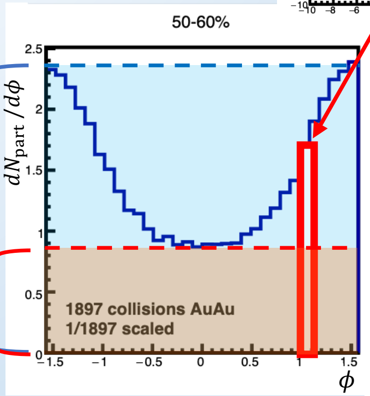
Ψ_{RP}: azimuthal angle of reaction plane

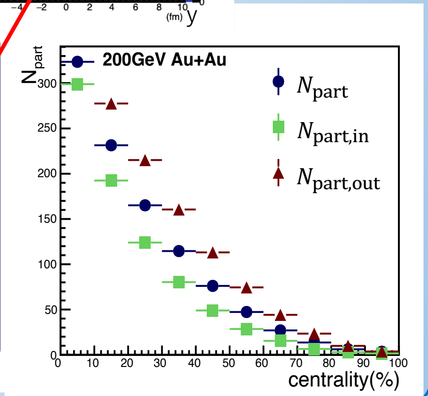


- in-plane $N_{part} \propto N_{part,in}$
- out-of-plane $N_{part} \propto N_{part,out}$

$N_{part,out}$

$N_{part,in}$





$\left.\frac{dN_{ch}}{d\eta}\right|_{in}$, $\left.\frac{dN_{ch}}{d\eta}\right|_{out}$

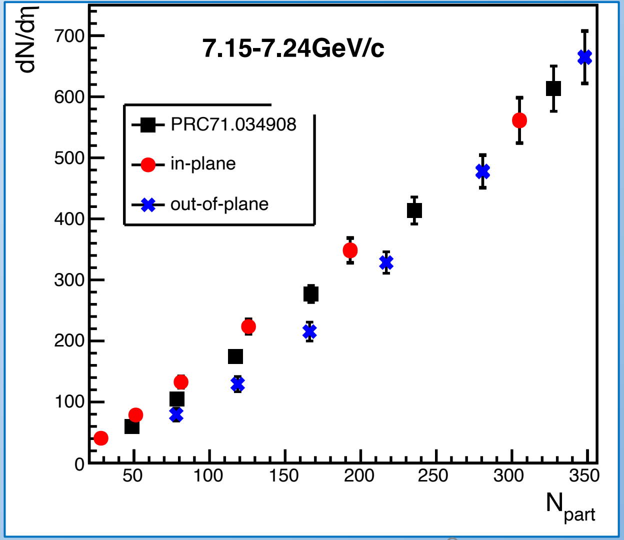
- Calculate $dN_{ch}/d\eta$ of in-plane and out-of-plane

- in-plane ($\phi = 0°$)

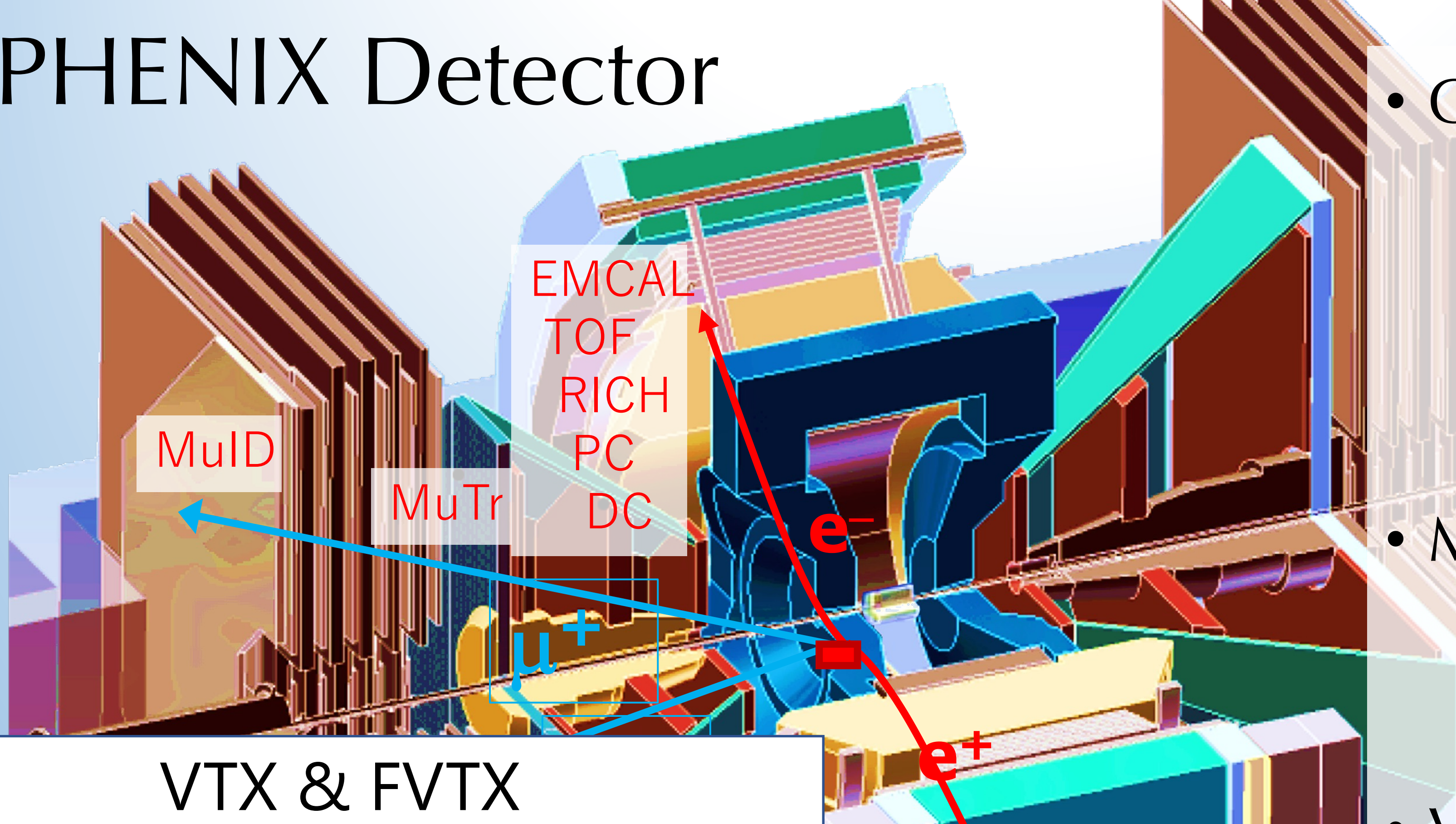
$$\left.\frac{dN_{ch}}{d\eta}\right|_{in} = \frac{dN_{ch}}{d\eta} \times (1 + 2v_2)$$

- out-of-plane ($\phi = 90°$)

$$\left.\frac{dN_{ch}}{d\eta}\right|_{out} = \frac{dN_{ch}}{d\eta} \times (1 - 2v_2)$$

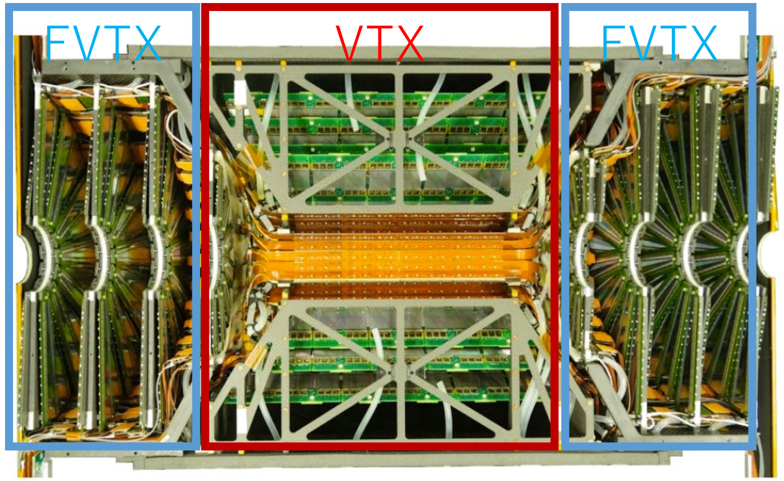


PHENIX Detector



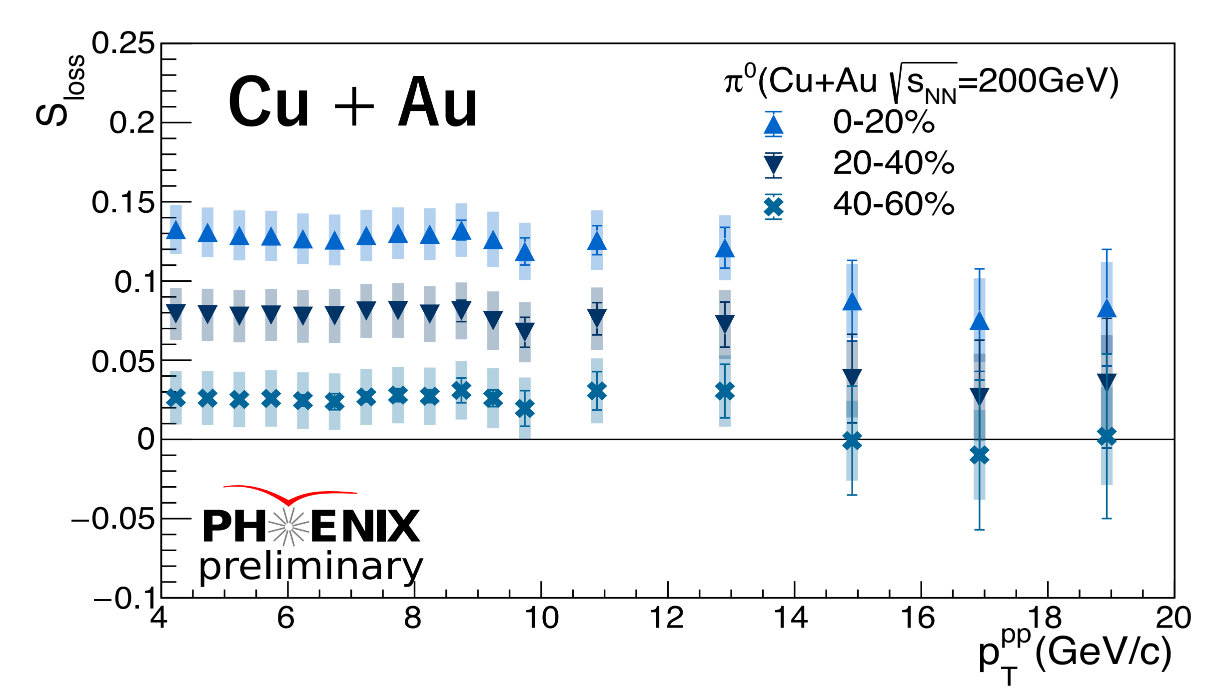
- Central Arms
  - |y|<0.35, ϕ~2·π/2
  - Electrons, γ, hadrons
    - DC, PC, RICH, EMCAL,TOF
- Muon Arms
  - 1.2~|y|<2.2, ϕ~2·π/2
  - Muons, Hadrons
- VTX-FVTX
  - Precise tracking for HF-ID

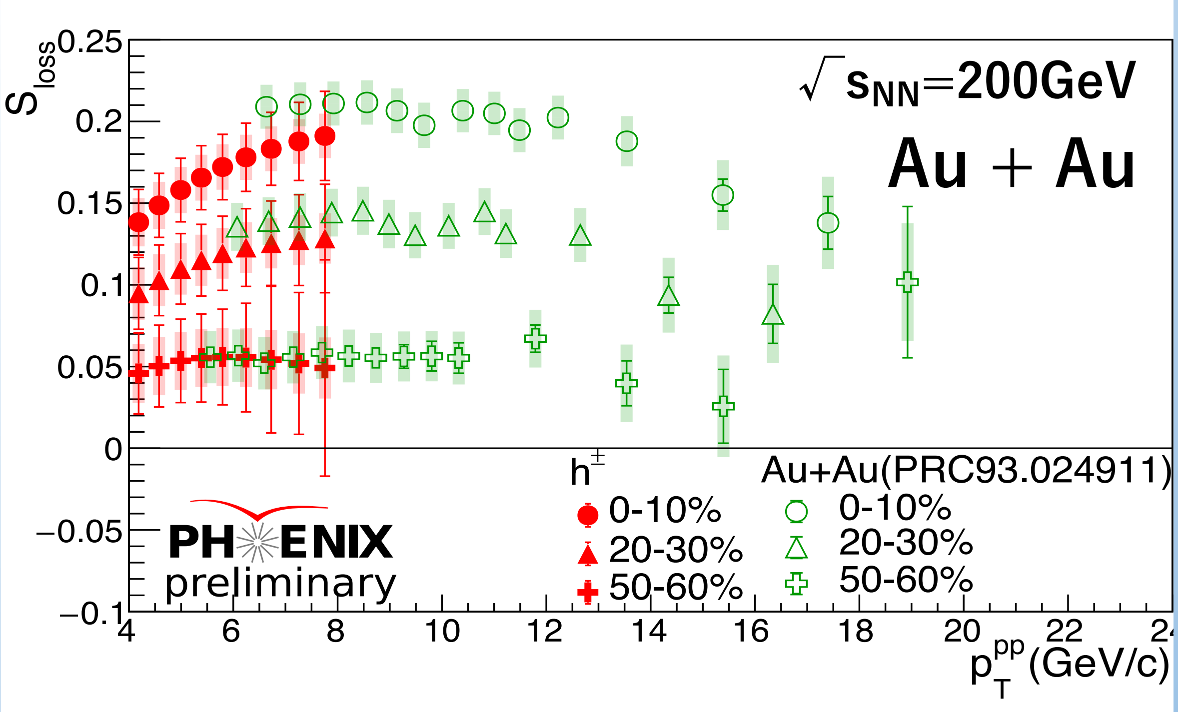
VTX & FVTX



PHENIX completed the data taking in 2016.
The data production completed.
Analyses are ongoing.

Result : S_{loss} vs. p_T





Collision size and density difference

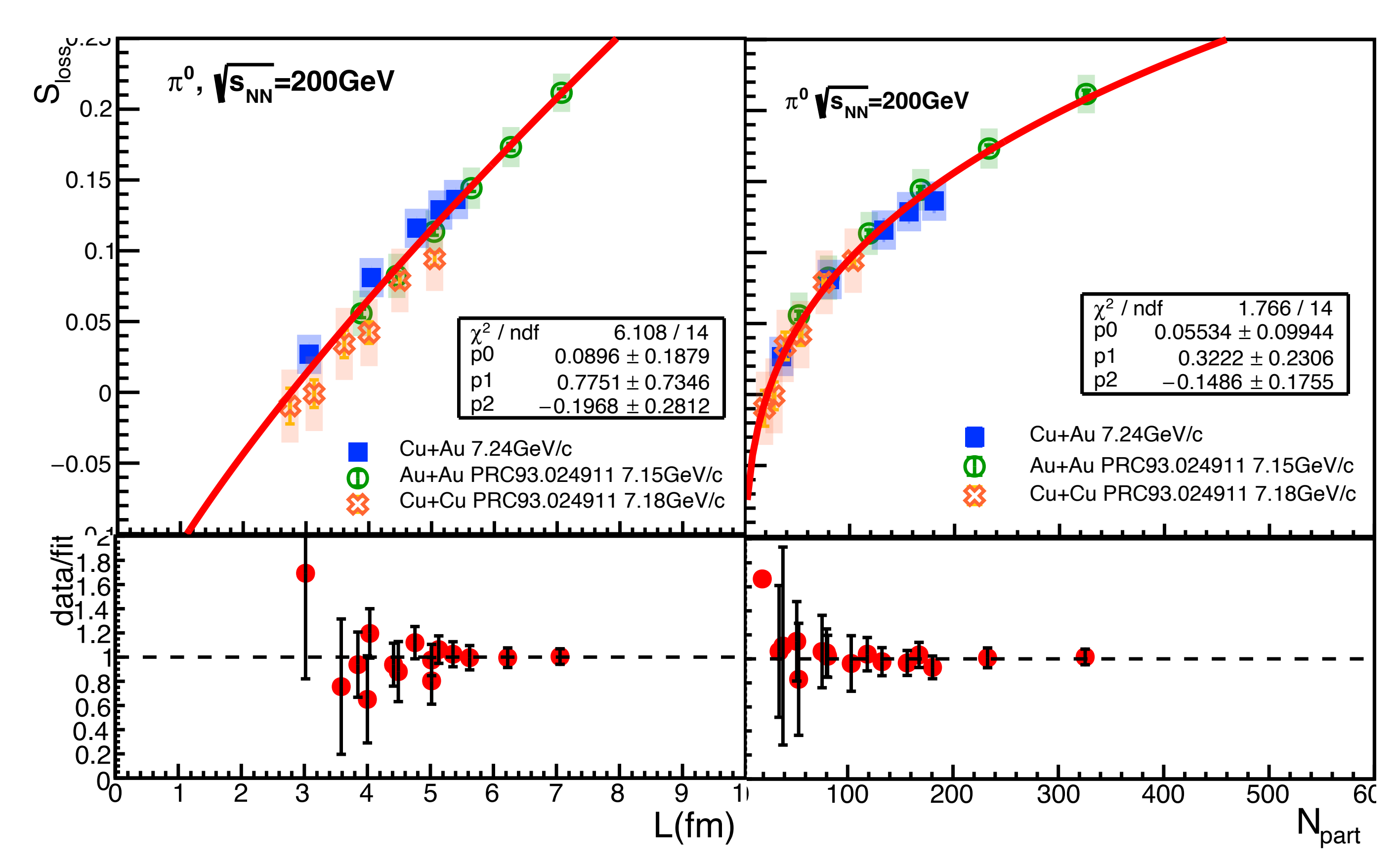
- No significant difference in the tendency of p_T dependence of S_{loss} between Cu+Au and Au+Au.

Particle species difference

- No significant difference in S_{loss} between charged hadrons and π^0s.

S_{loss} vs. L, N_{part} at Cu+Au, Au+Au, Cu+Cu

* Similar results for the measured p_T regions (4-10GeV/c).



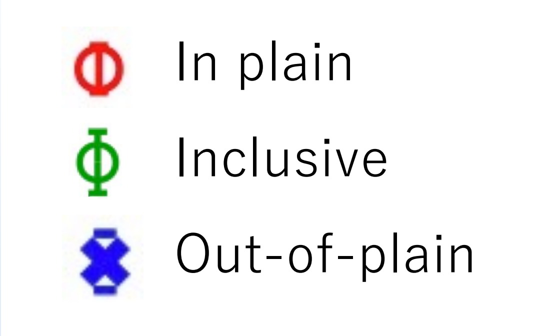
Different collision size and density

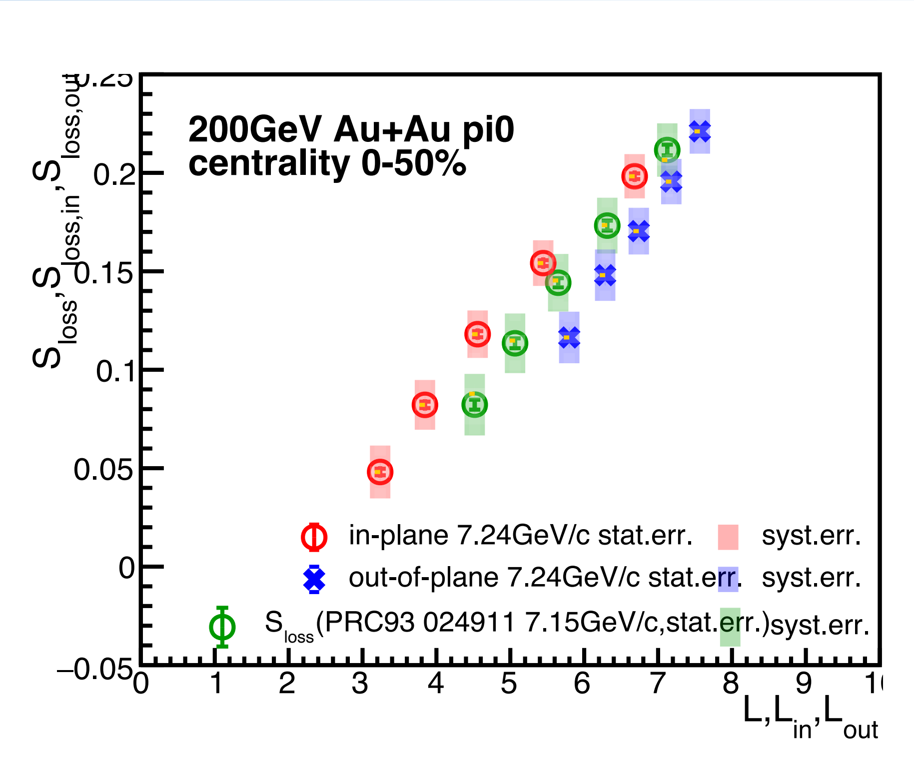
- No significant difference in the tendency of S_{loss} between Cu+Au, Au+Au, and Cu+Cu.
- S_{loss} draws one curve as a functions of N_{part} better than L with different collision systems.

→ How about looking at more details such as angle dependent S_{loss}

S_{loss} ,$S_{loss,in}$ $S_{loss,out}$ vs. L

*Similar results for the measured p_T regions (4-10GeV/c)



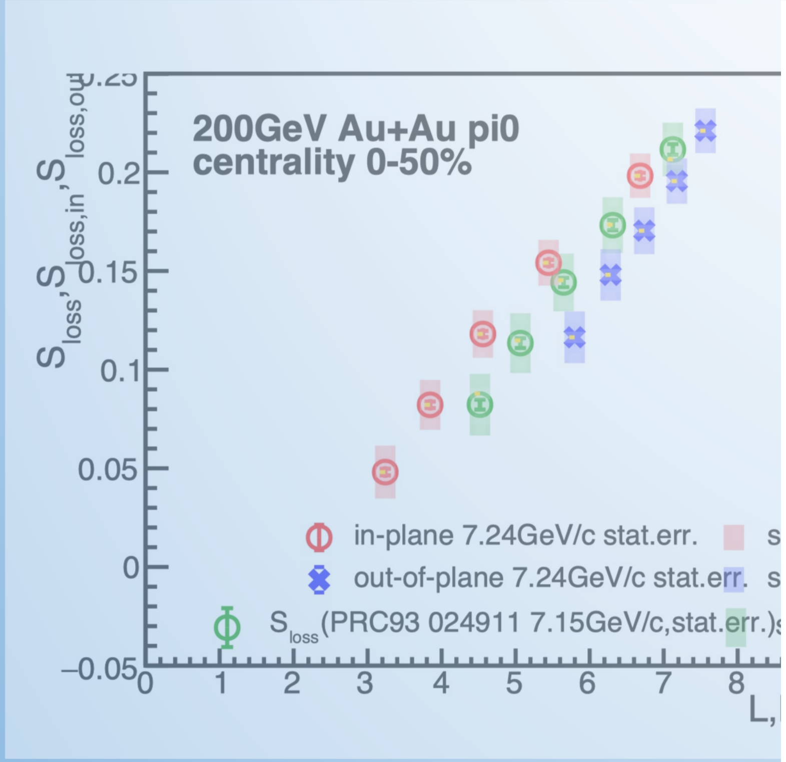


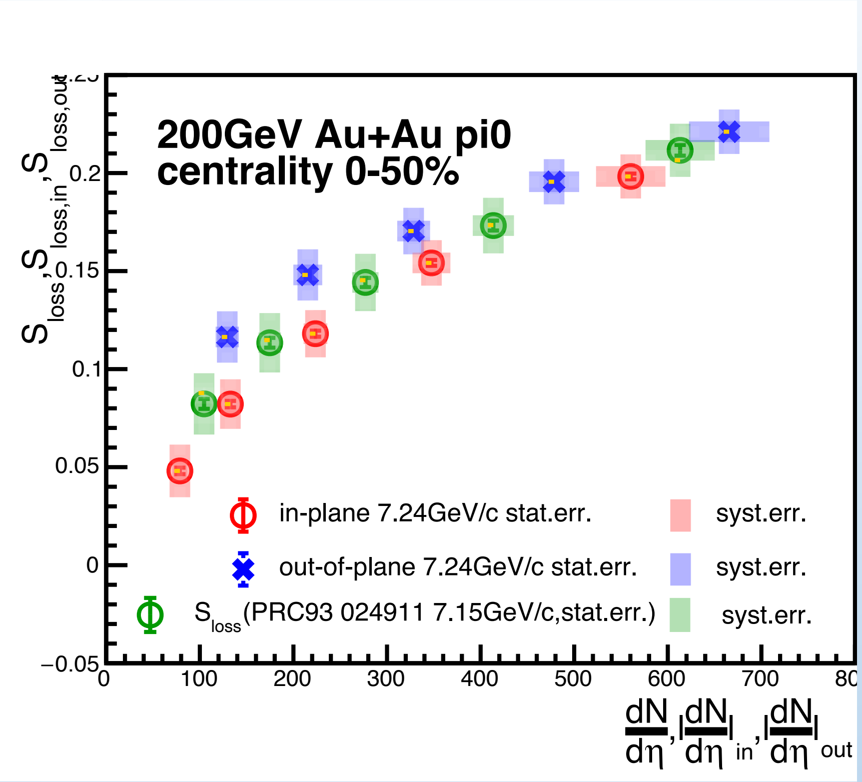
S_{loss} of in-plain and out-of-plain
- have similar tendency.
- but, doesn't follow the same curve as a function of L.

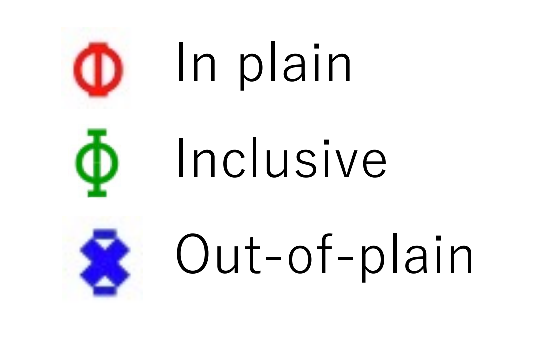
All three have different curves.

S_{loss} ,$S_{loss,in}$ $S_{loss,out}$ vs. L, $dN_{ch}/d\eta$

*Similar results for the measured p_T regions (4-10GeV/c)



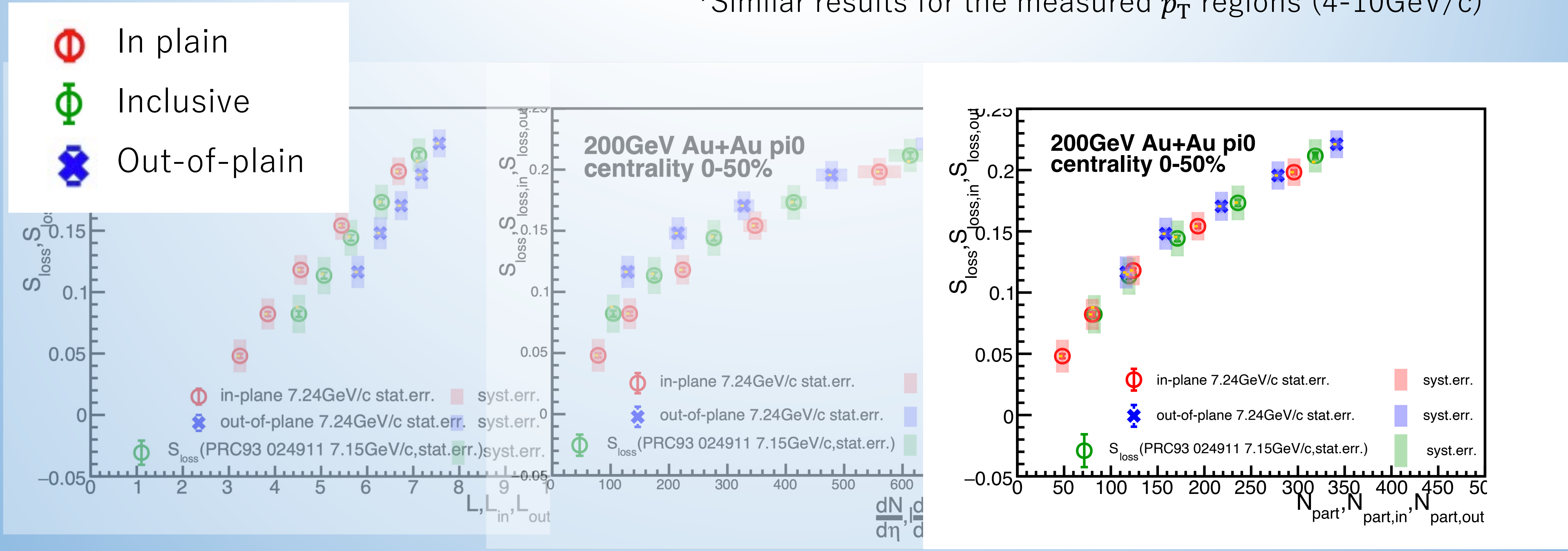




Same as L,
these three S_{loss} have similar trend but doesn't follow the same curve as a function of $dN_{ch}/d\eta$.

S_{loss} ,$S_{\text{loss,in}}$ $S_{\text{loss,out}}$ vs. L, $dN_{ch}/d\eta$, N_{part}

*Similar results for the measured p_T regions (4-10GeV/c)

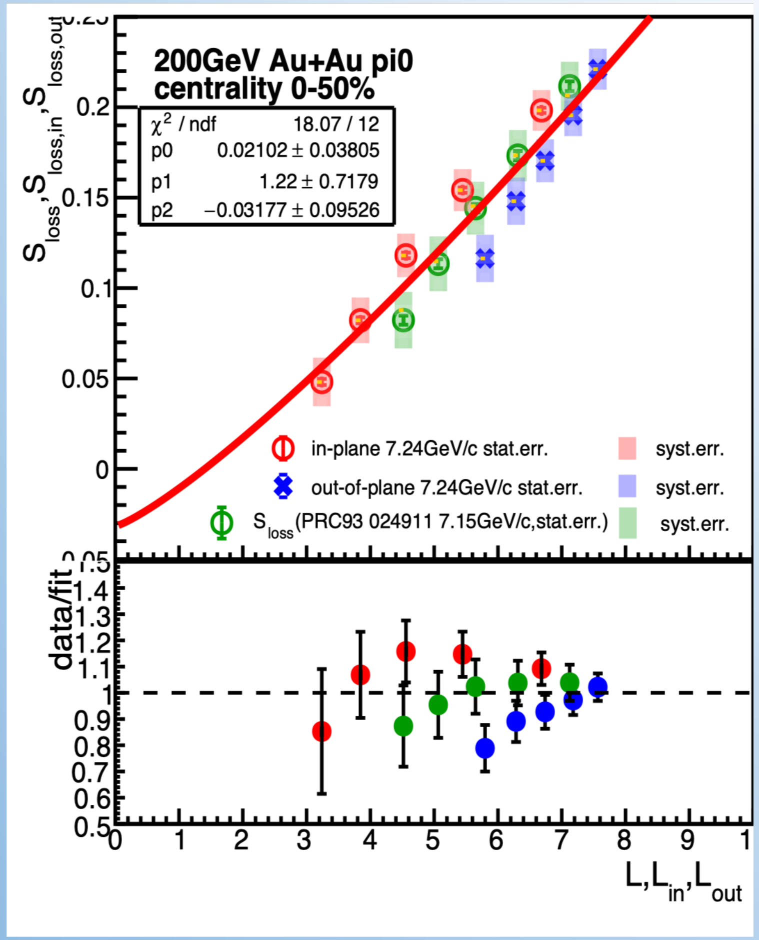


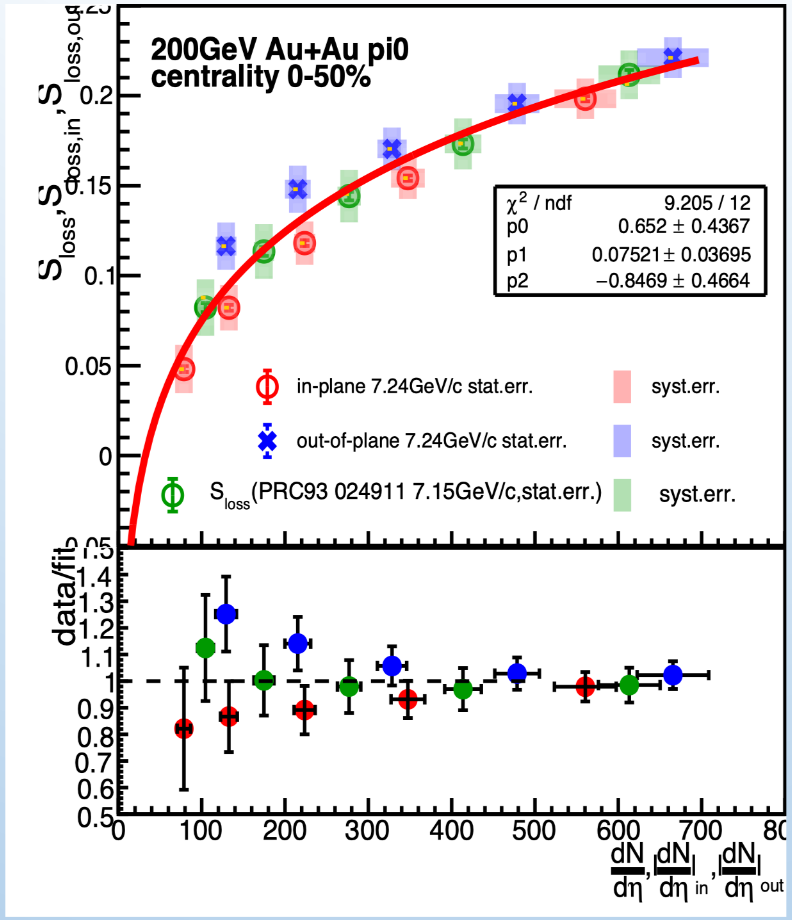
- S_{loss}, $S_{\text{loss,in}}$, $S_{\text{loss,out}}$ follow a curve most as a functions of N_{part} .

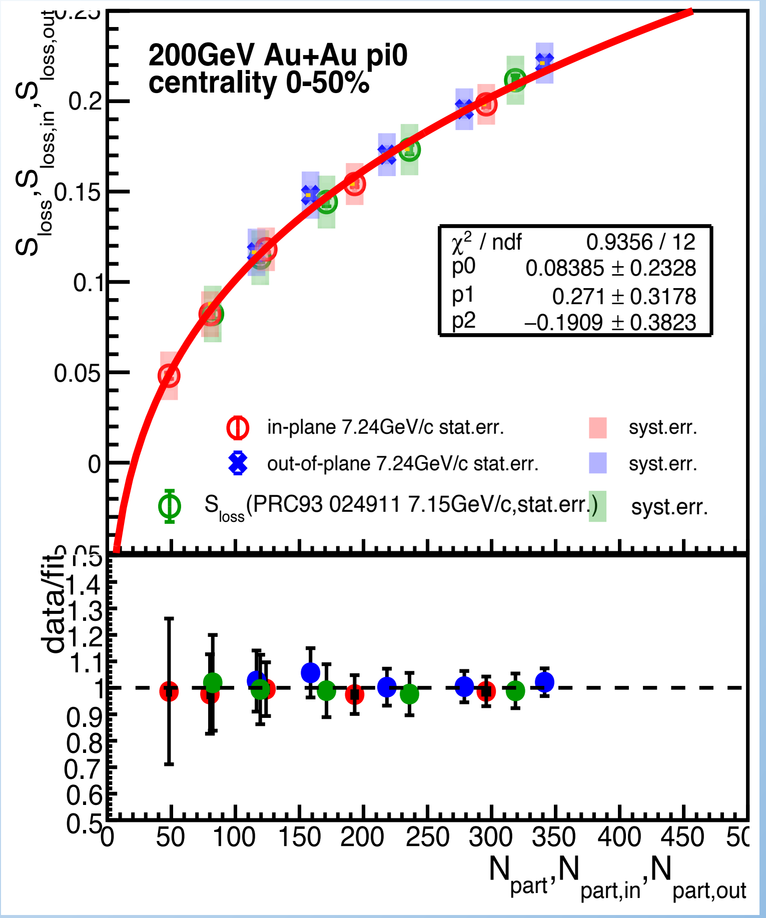
S_{loss} ,$S_{loss,in}$ $S_{loss,out}$ vs. L, $dN_{ch}/d\eta$, N_{part}

Fitting function
$f(x) = p0 * x^{p1} + p2$

*Similar results for the measured p_T regions (4-10GeV/c)







- S_{loss}, $S_{loss,in}$, $S_{loss,out}$ draw a curve as a functions of N_{part} better than L and dN/dη.

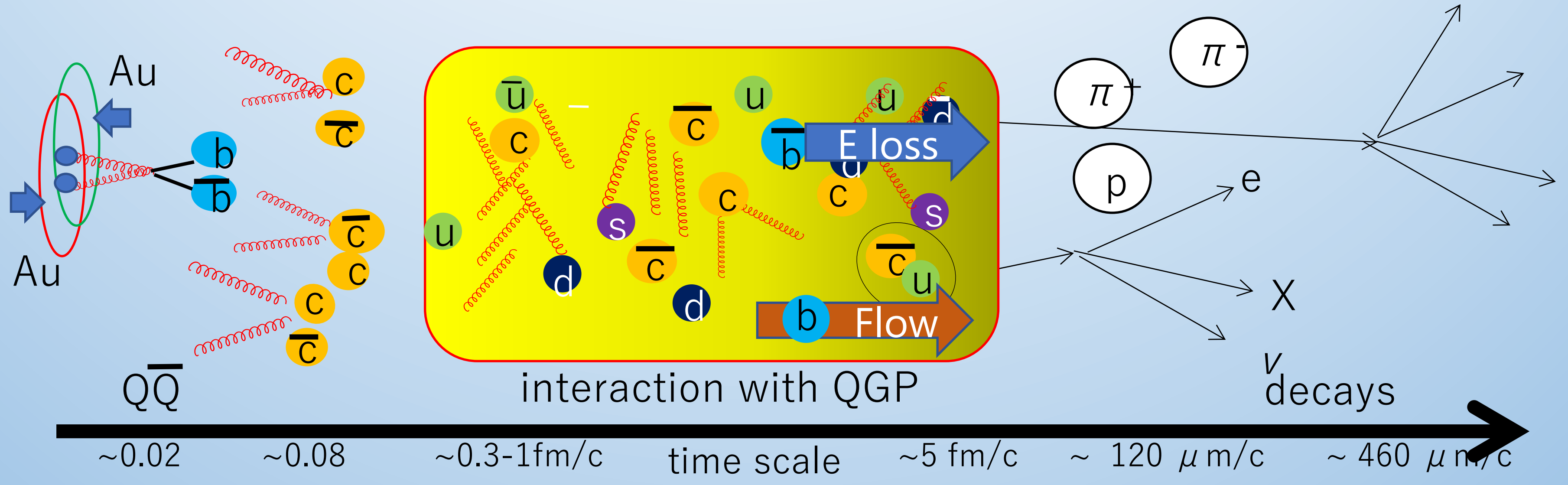
→ indicates the importance of initial particle density dependence.

Heavy flavor energy loss

Why heavy flavor, bottom & charm ?

- b and c are mainly created by initial collisions at RHIC energy
  - Production can be calculated by pQCD
- Their p_T and angular distributions can be modified in QGP
  - Suffer energy loss and flow effects –

Mc~1.3GeV, Mb~4.5GeV >> T_{QGP} ~400MeV, Λ_{QCD} ~200MeV

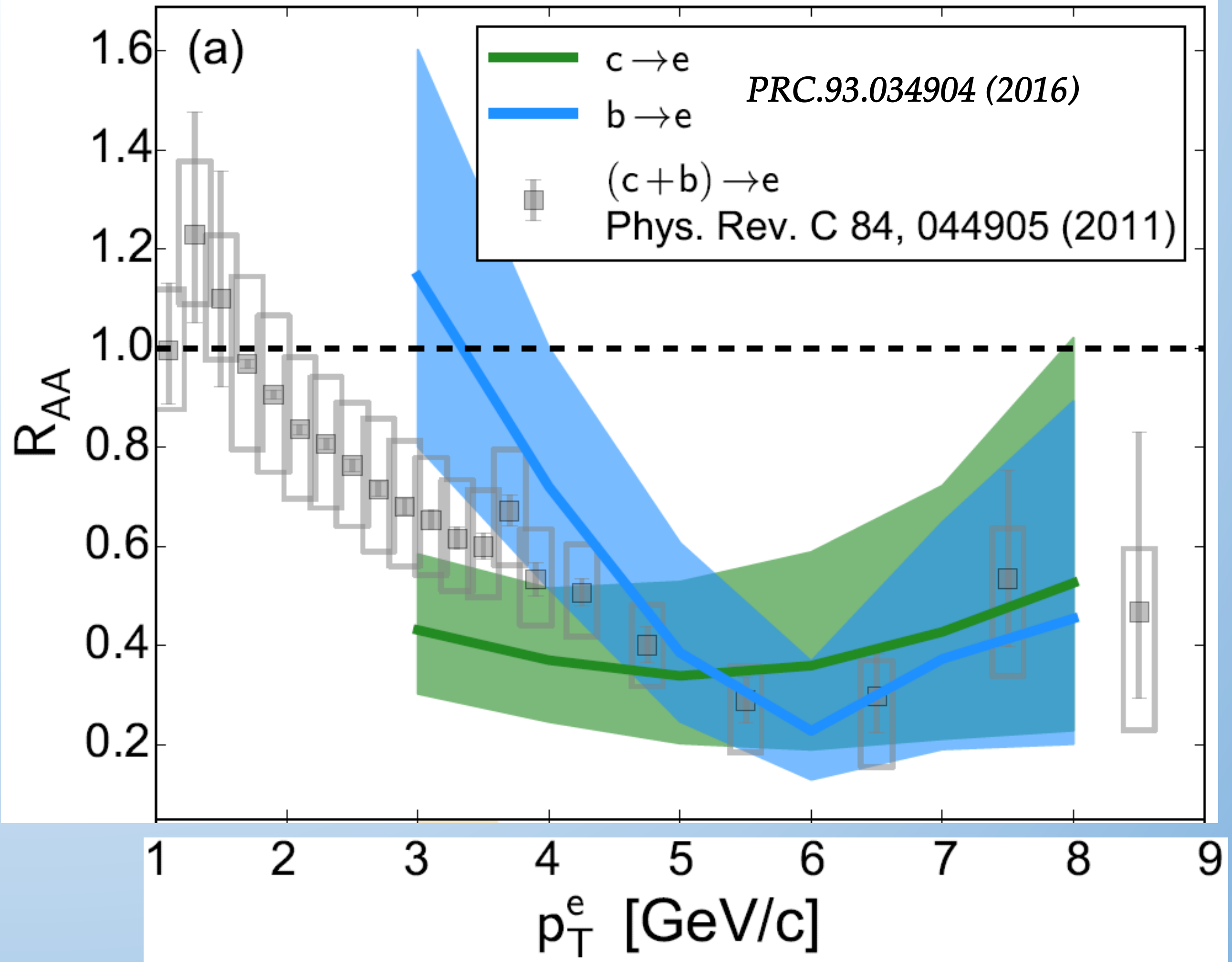


Modification of Heavy flavor shows the property of QGP

Findings1 : Heavy flavor suppression

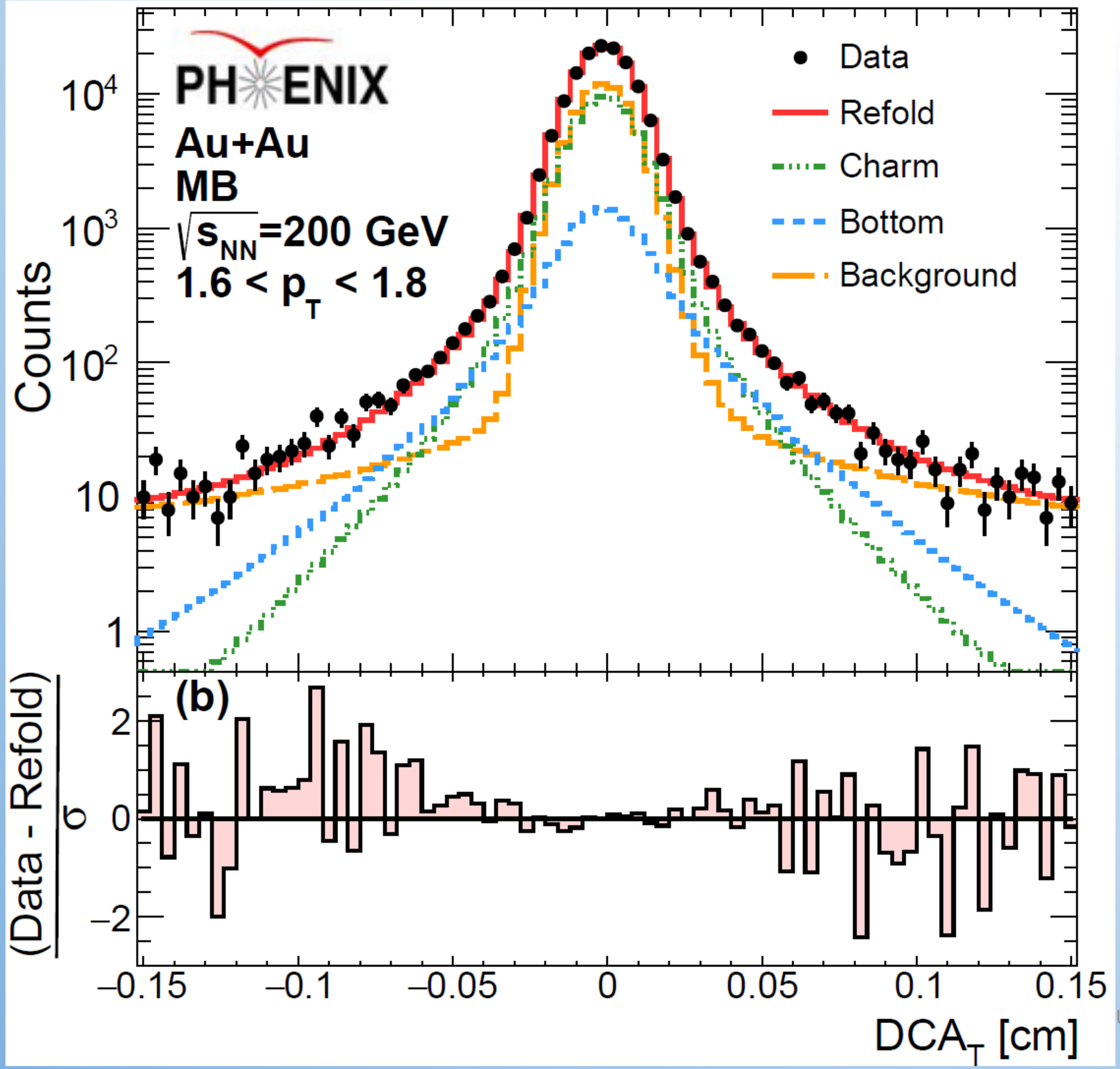
$$R_{AA} = \frac{Yield(Au+Au)}{Ncoll \ * Yield(p+p)}$$

- PHENIX observes strong suppression of hf electron.
- Successfully separated b and c components.



Bottom and charm separation

arXiv:2203.17058

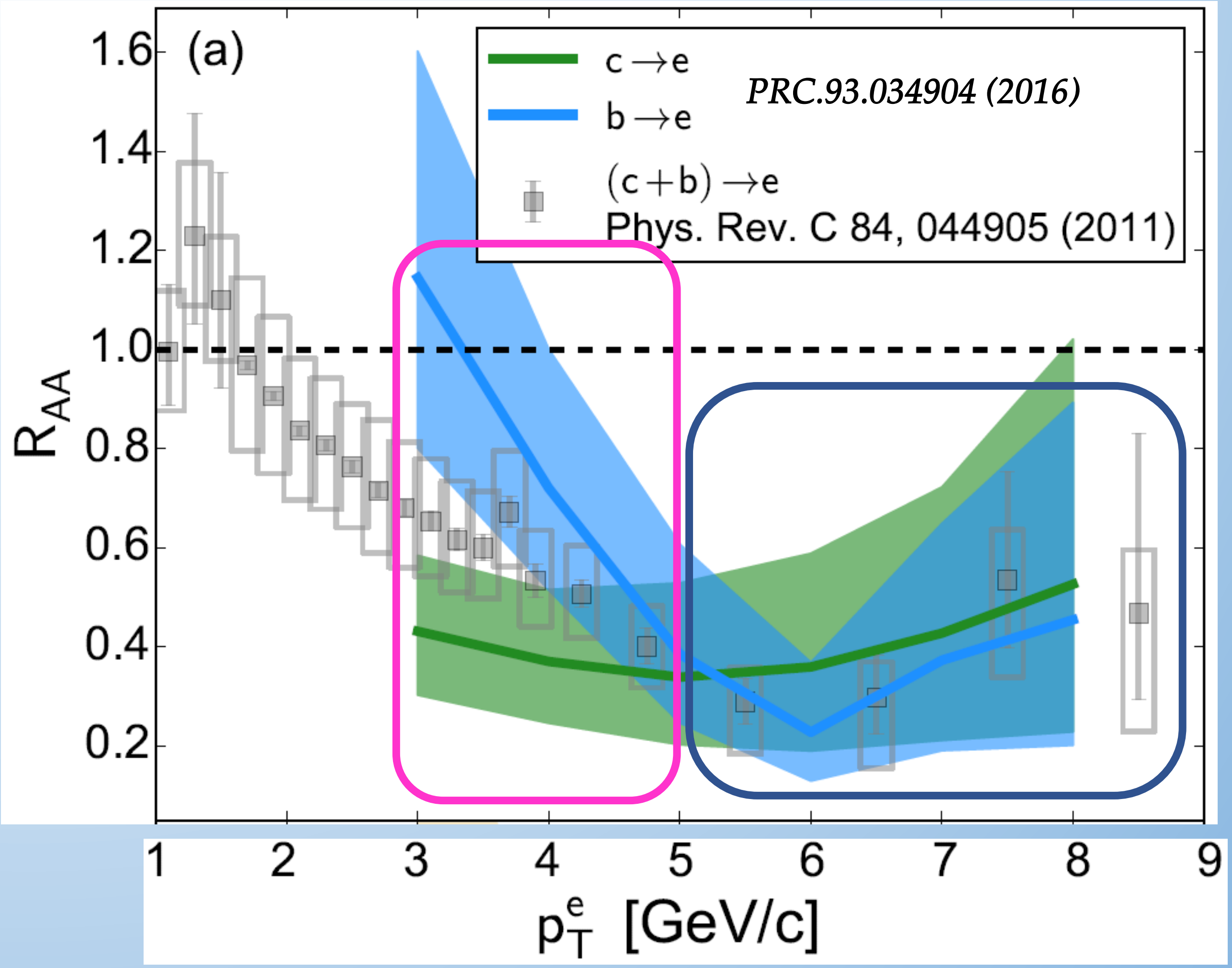


- Au+Au 200 GeV in 2014
  - 17 B events = 3 times larger than 2011
- Electrons from charm and bottom hadron decays
- Charm and bottom separation using the distance-of-closest-approach (DCA) and p_T distribution
- Bayesian unfolding method:
  - Separates charm and bottom contribution in electrons
  - Extract charm and bottom hadron yields

Findings2 : HF Mass dependence of suppression

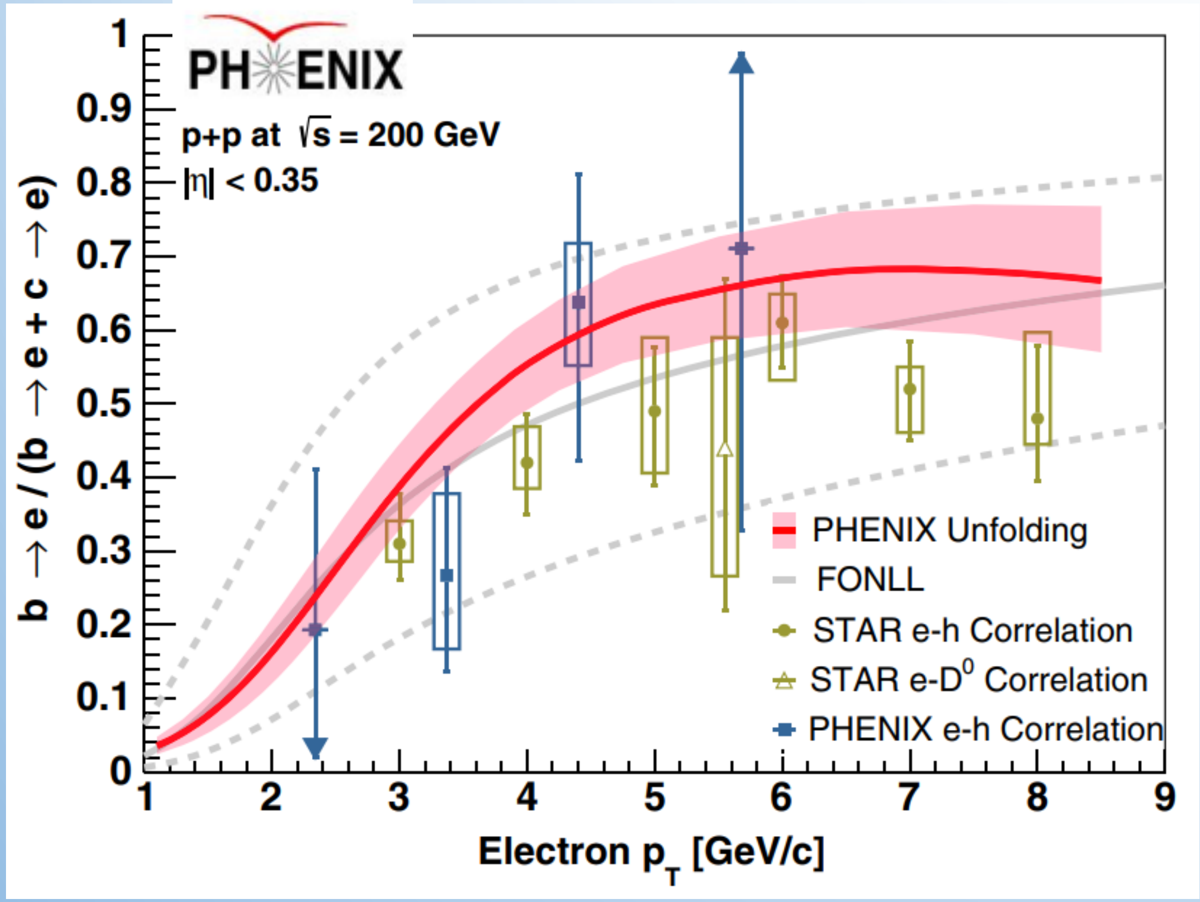
$$R_{AA} = \frac{Yield(Au + Au)}{Ncoll \; * Yield(p + p)}$$

- Both are suppressed at high p_T
  - $R_{AA}(b) \sim R_{AA}(c) < 1$ at high p_T
- B is less suppressed at low p_T
  - $R_{AA}(b) > R_{AA}(c)$ at low p_T
- Consistent with the expected mass ordering
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Radiative loss @ high p_T
- Coll. & Rad. loss @ low p_T
- To understand energy loss of the mass dependence more, we need systematic study
  - Centrality dependence
  - Azimuthal anisotropy

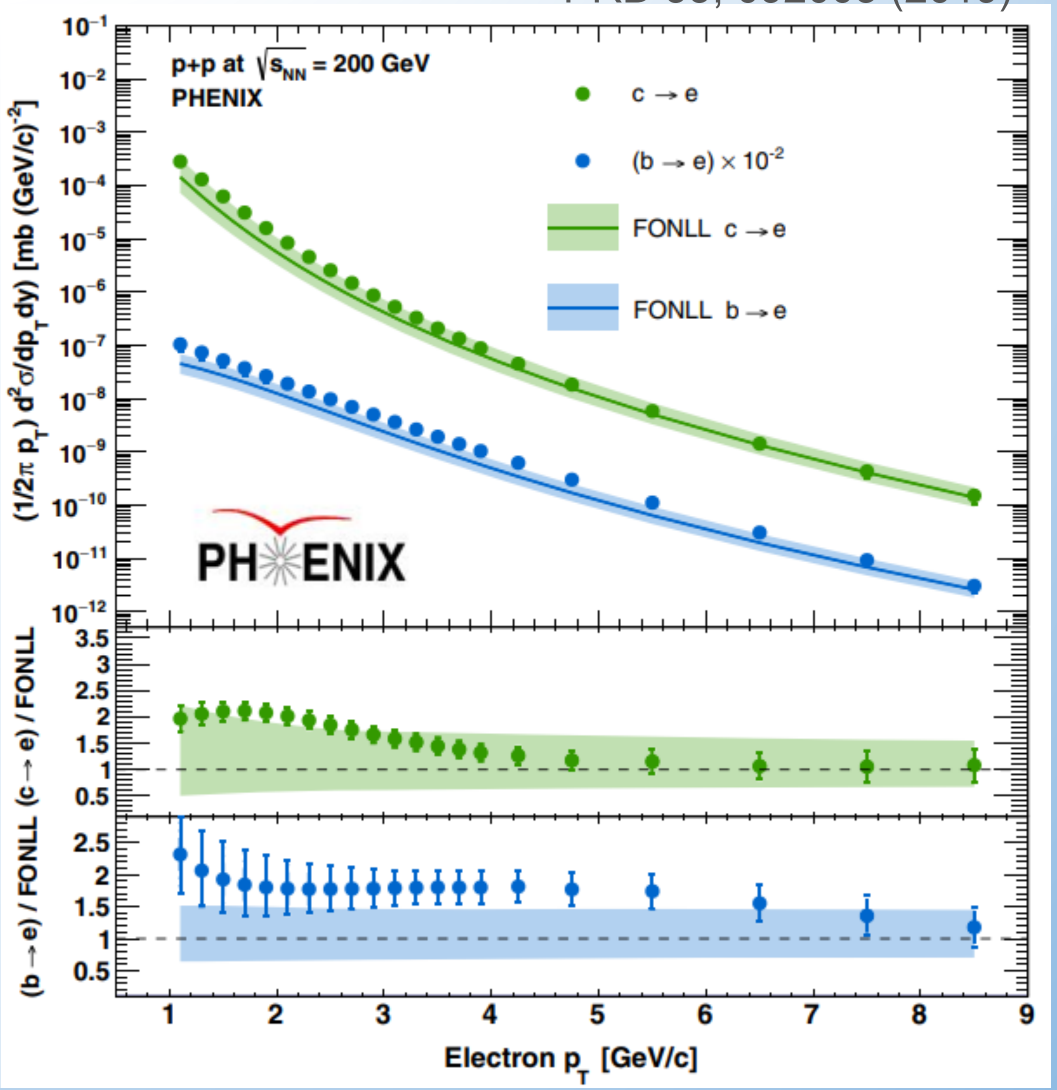


Updated p+p baseline : Bottom Electron Fraction

PRD **99**, 092003 (2019)



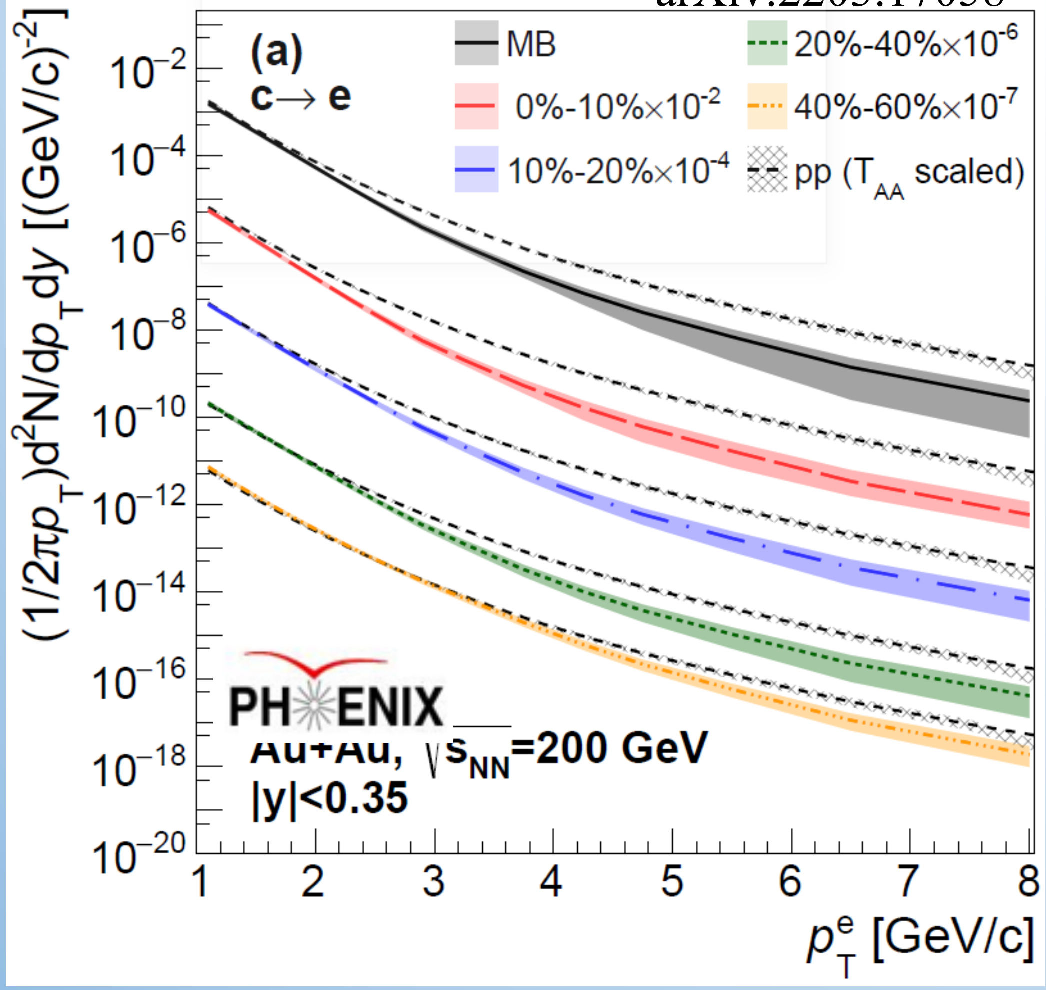
PRD **99**, 092003 (2019)



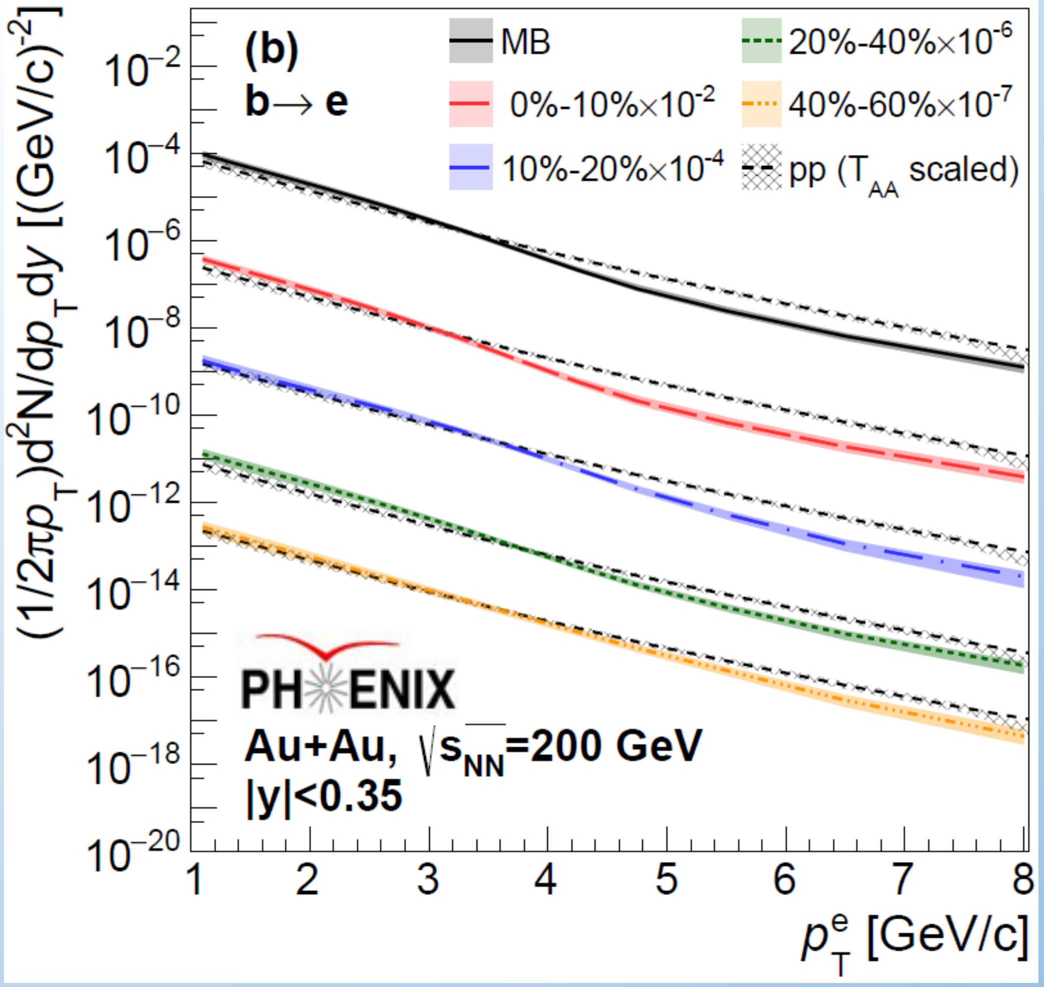
- New p + p baseline of bottoms and charms available w/ p_T = 1~8 GeV/c

Charm and Bottom Electron yields in Au+Au

arXiv:2203.17058



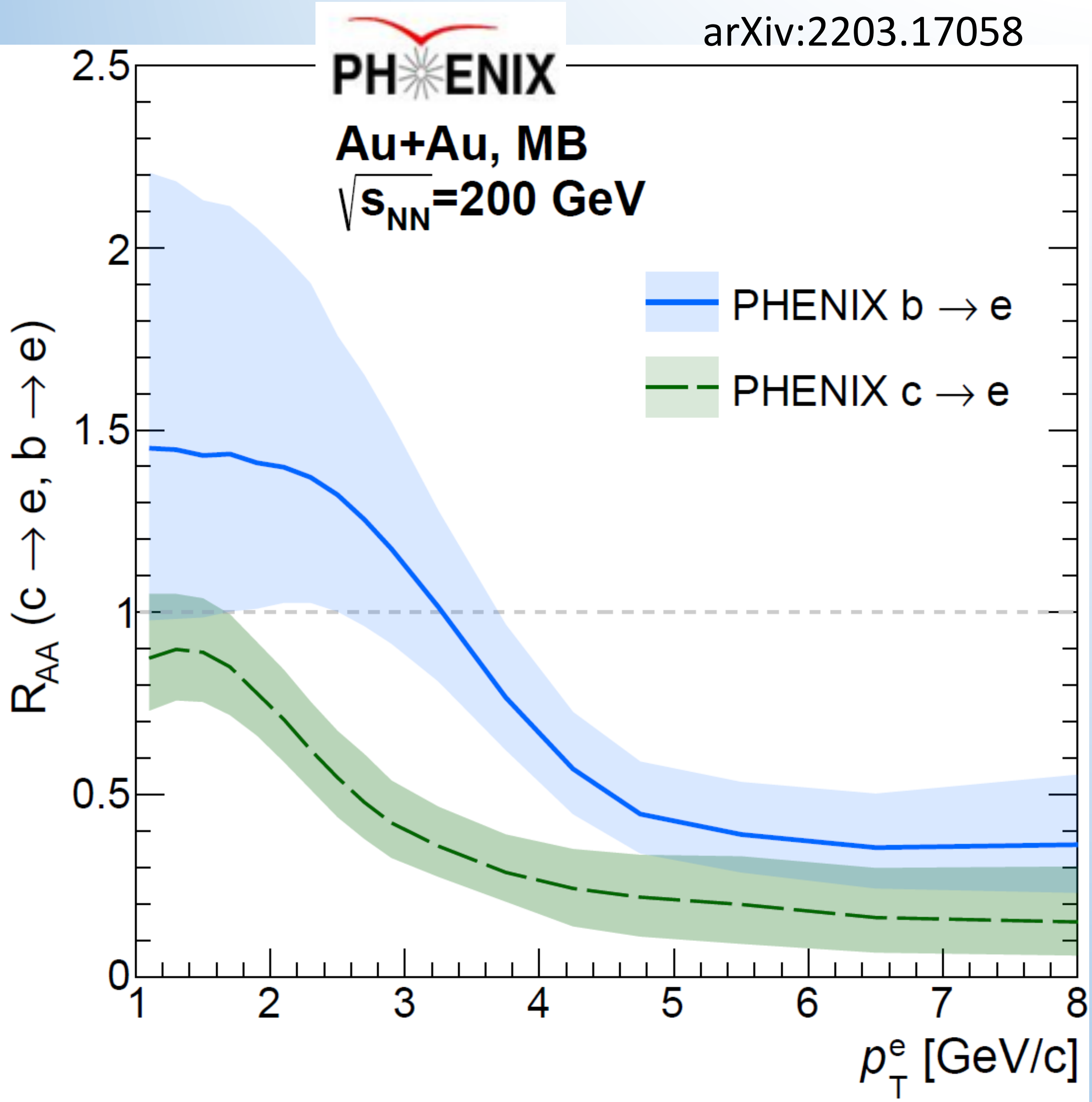
arXiv:2203.17058



- Yields in Au+Au are measured in MB, 0-10, 10-20, 20-40, 40-60%
- Show the difference from p+p scaled by T_{AA} at high p_T

$R_{AA}(b \to e)$ & $R_{AA}(c \to e)$ in Au+Au 200GeV

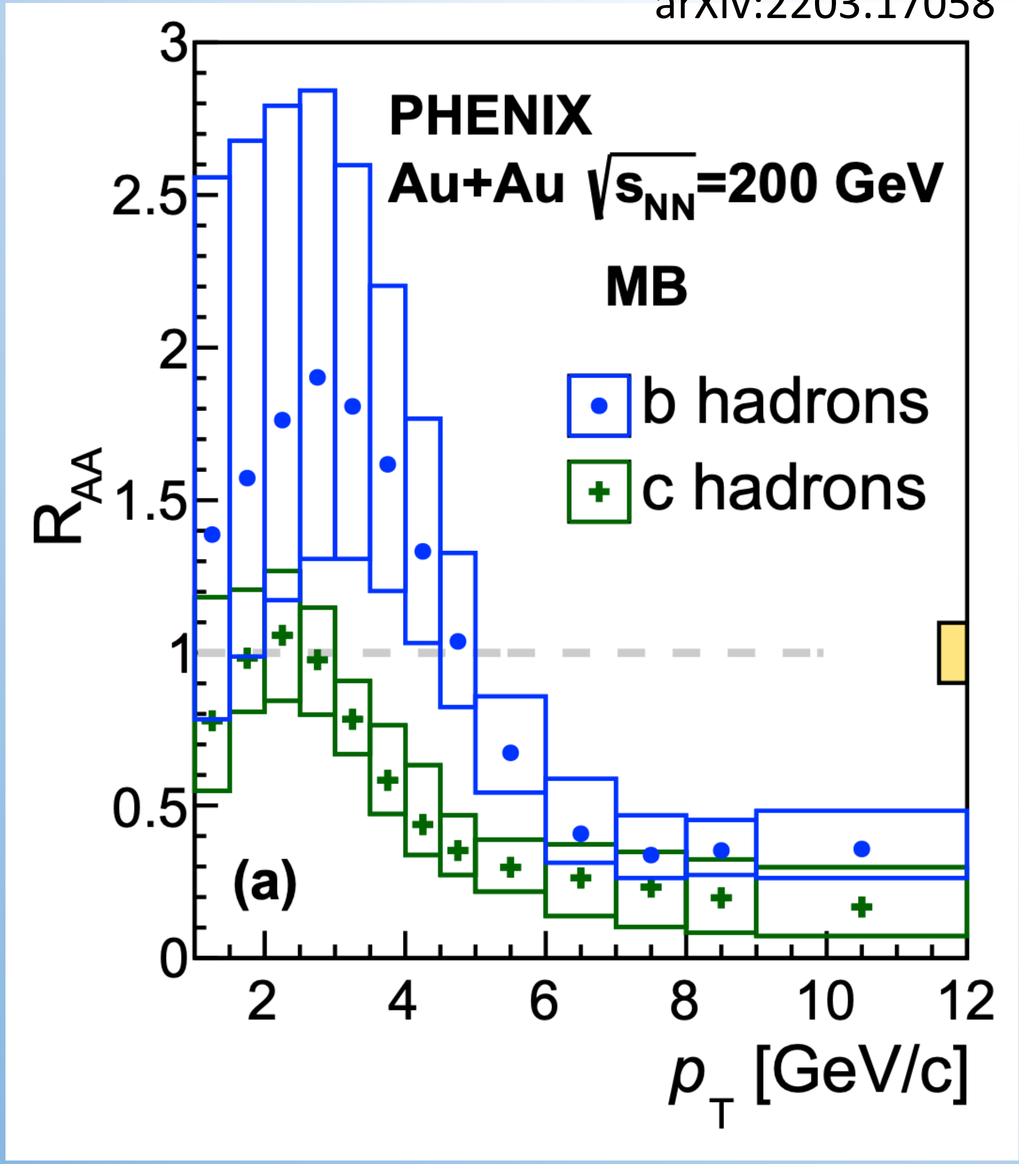
arXiv:2203.17058



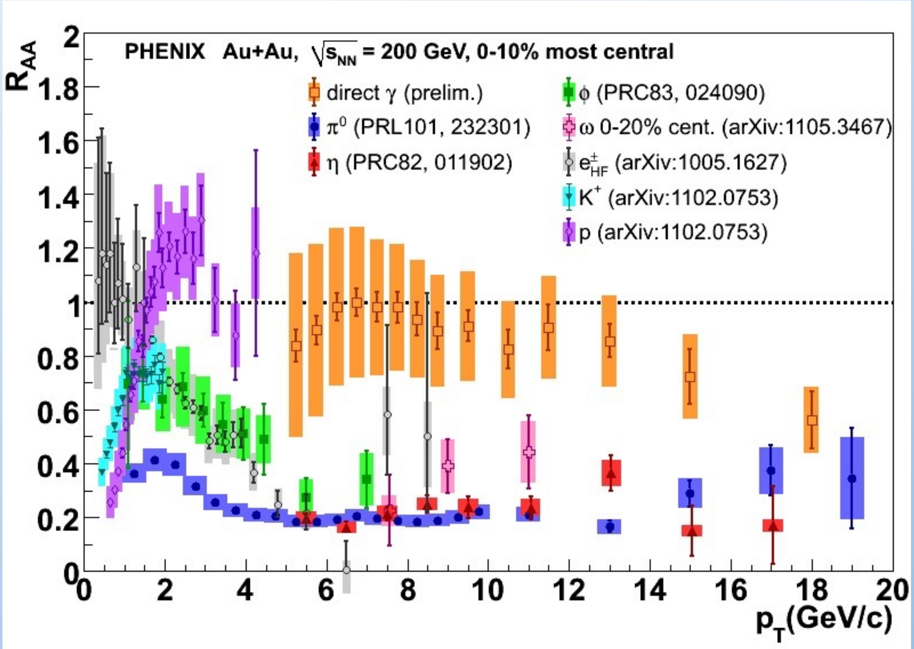
- Nuclear modification factor R_{AA}
  - Broad p_T range : 1 – 8 GeV/c
  - Smaller uncertainty with new p+p baseline
- Low p_T : R_{AA}(b->e) ~ R_{AA}(c->e) = 1
- Mid p_T : R_{AA}(b->e) > R_{AA}(c->e)
- High p_T: R_{AA}(b->e) ~ R_{AA}(c->e) < 1
- p_T dependence and mass dependence are seen.

Charm and Bottom hadron R_{AA}

arXiv:2203.17058

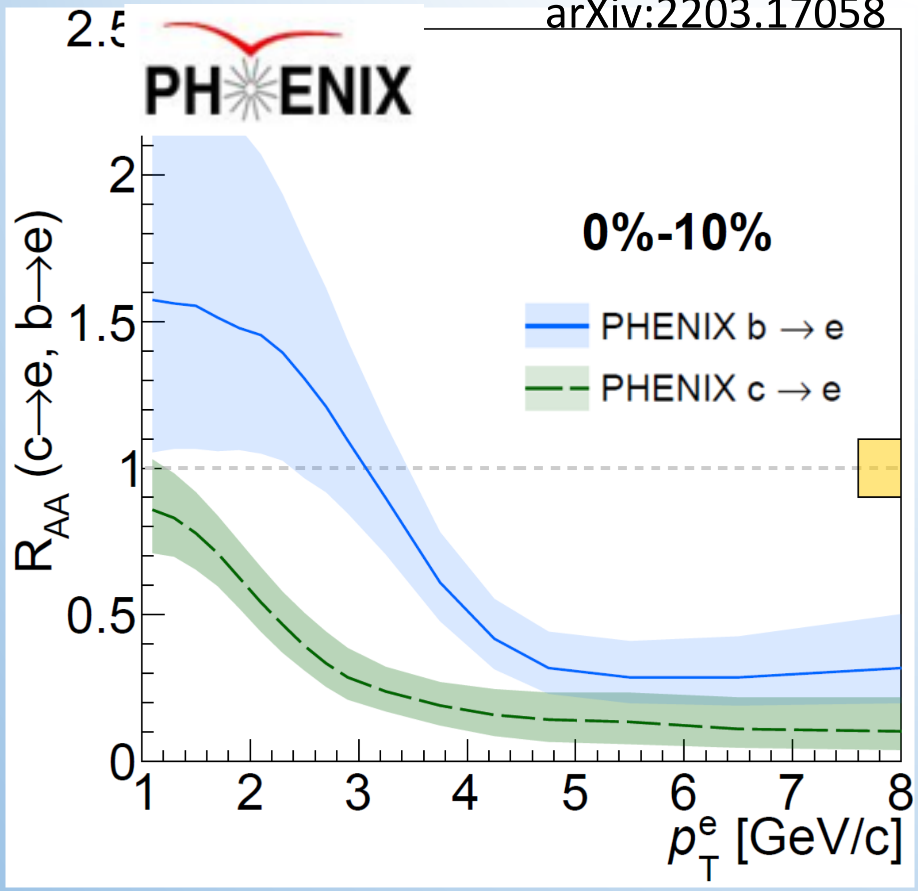


- Our unfolding method provides parent charm and bottom hadron yields.
- Charm and bottom hadron R_{AA} show same trend.
- No clear difference between c/b and u/d at high p_T



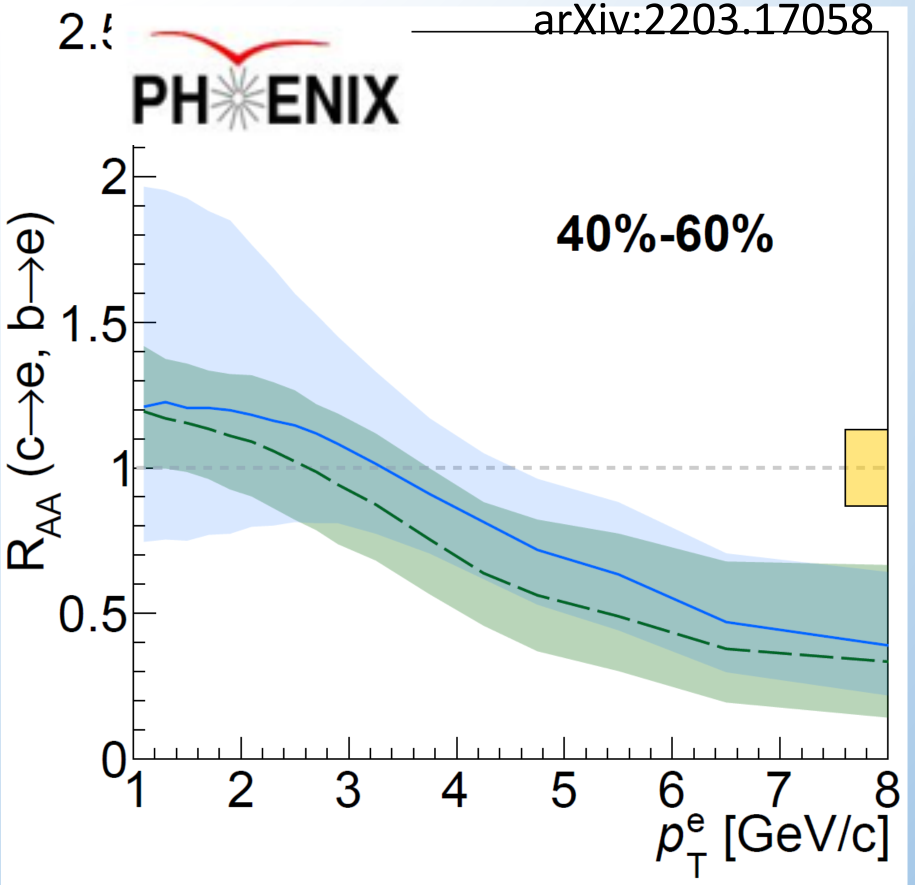
Centrality dependence of $R_{AA}(b\rightarrow e)$ & $R_{AA}(c\rightarrow e)$

arXiv:2203.17058



c and b are different and suppressed.

arXiv:2203.17058

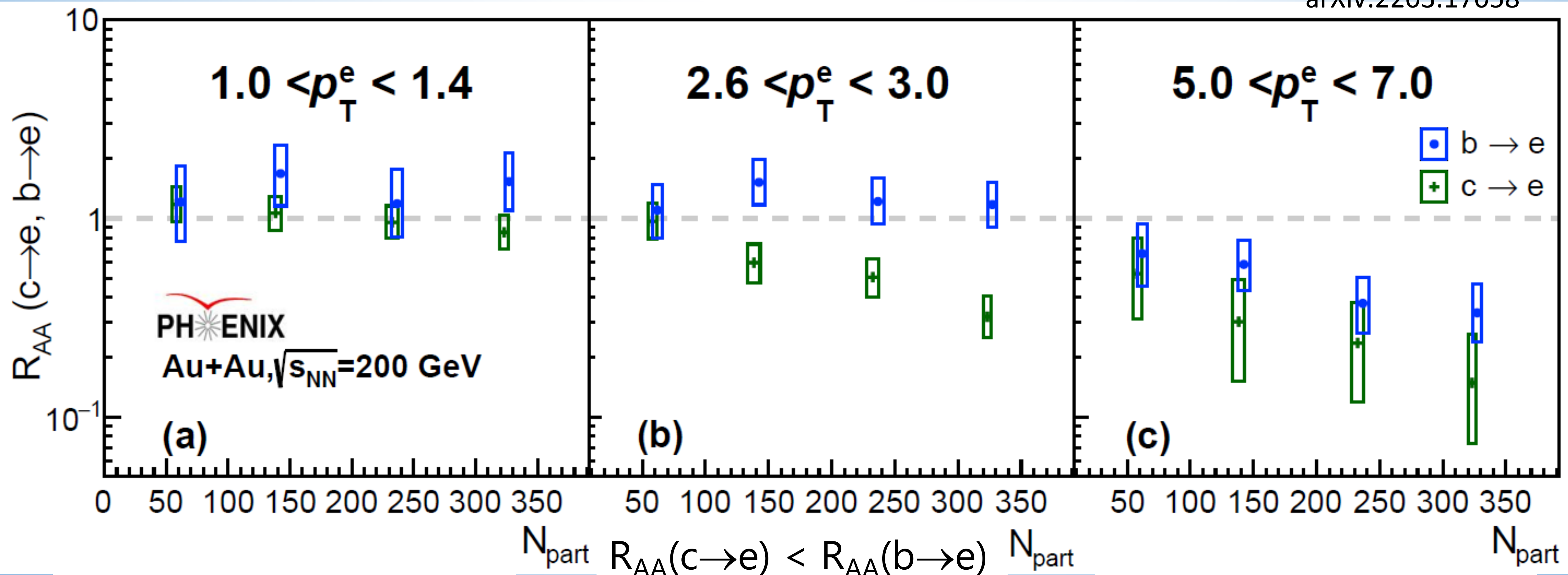


c and b are similar and less suppressed.

Centrality dependence of the energy loss is seen as expected.

Charm and Bottom R_{AA} vs. N_{part}

arXiv:2203.17058



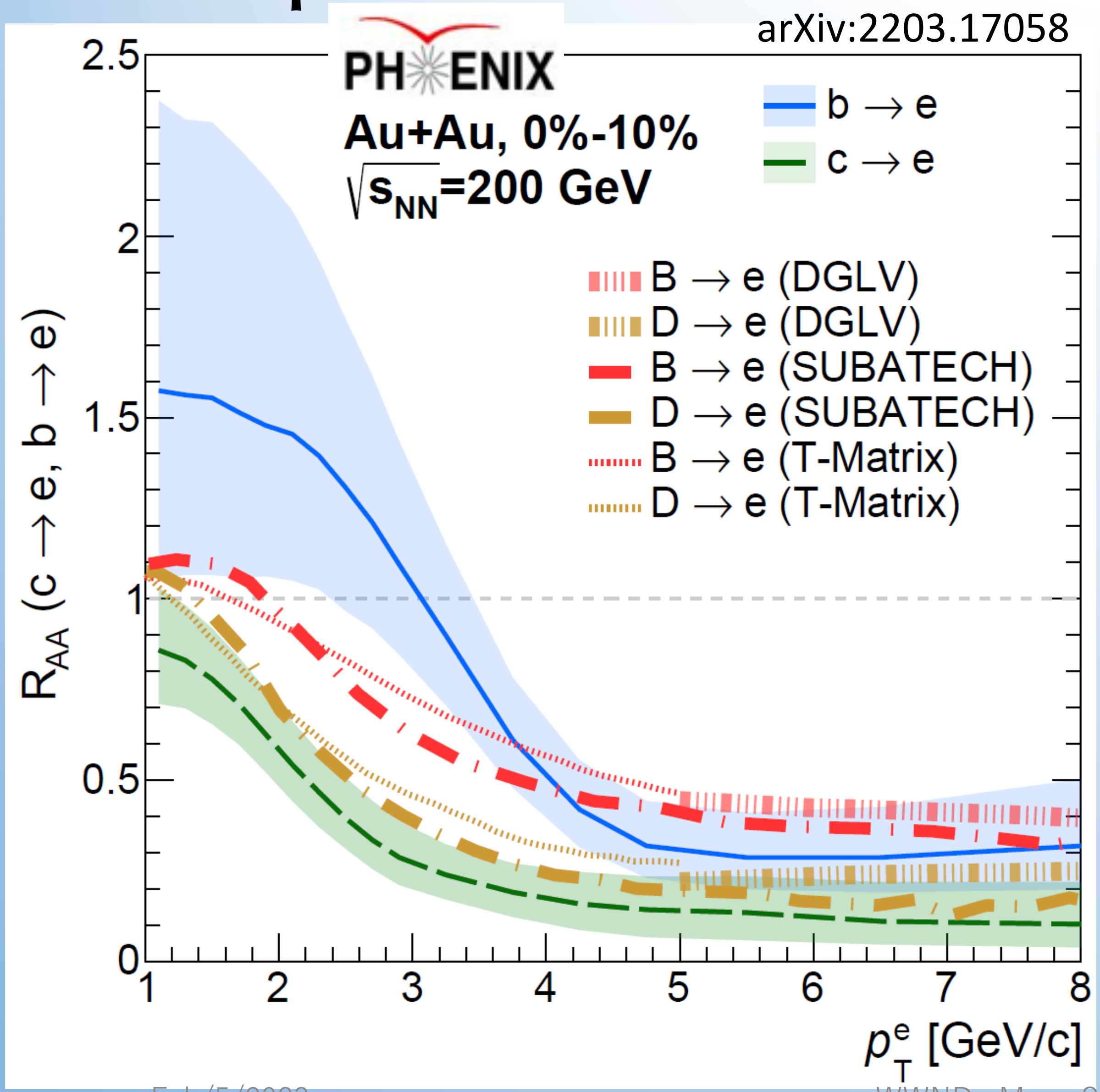
$R_{AA}(c \to e) \sim R_{AA}(b \to e) \sim 1$

$R_{AA}(c \to e) < R_{AA}(b \to e) \sim 1$

$R_{AA}(c \to e) \sim R_{AA}(b \to e) < 1$

Centrality and p_T dependence are observed

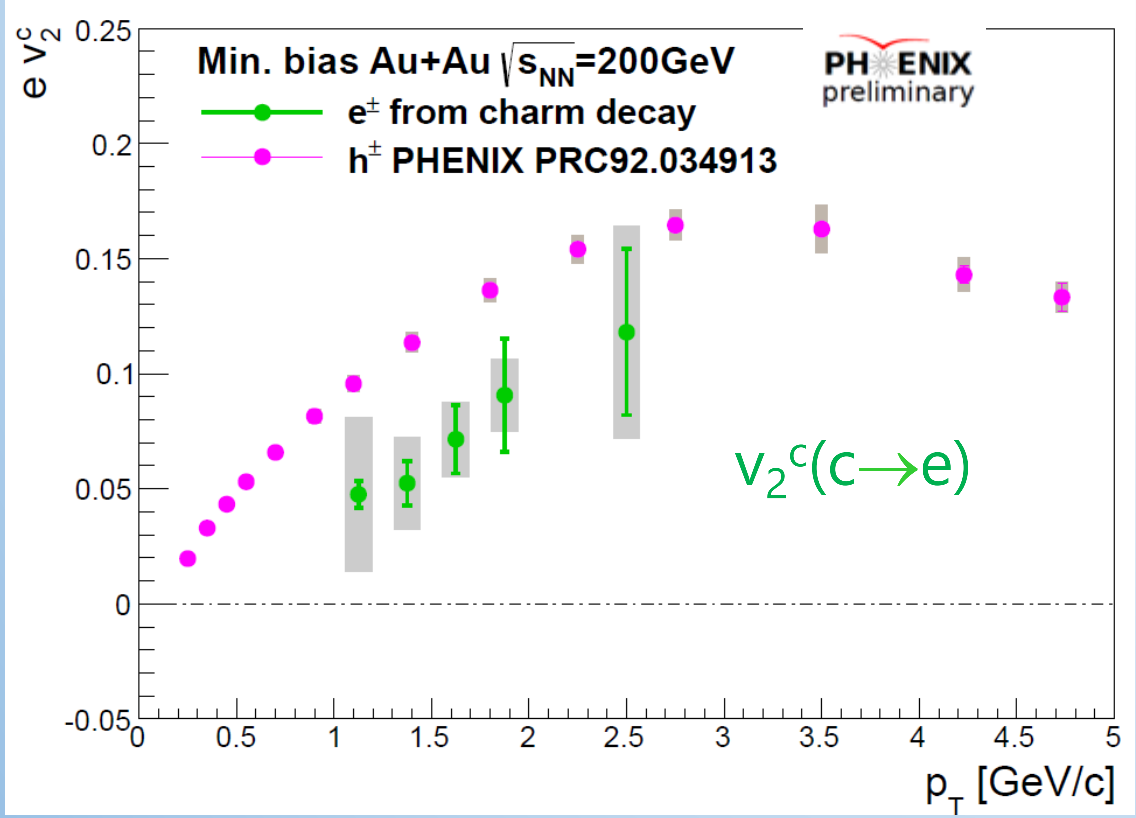
Comparison with Models

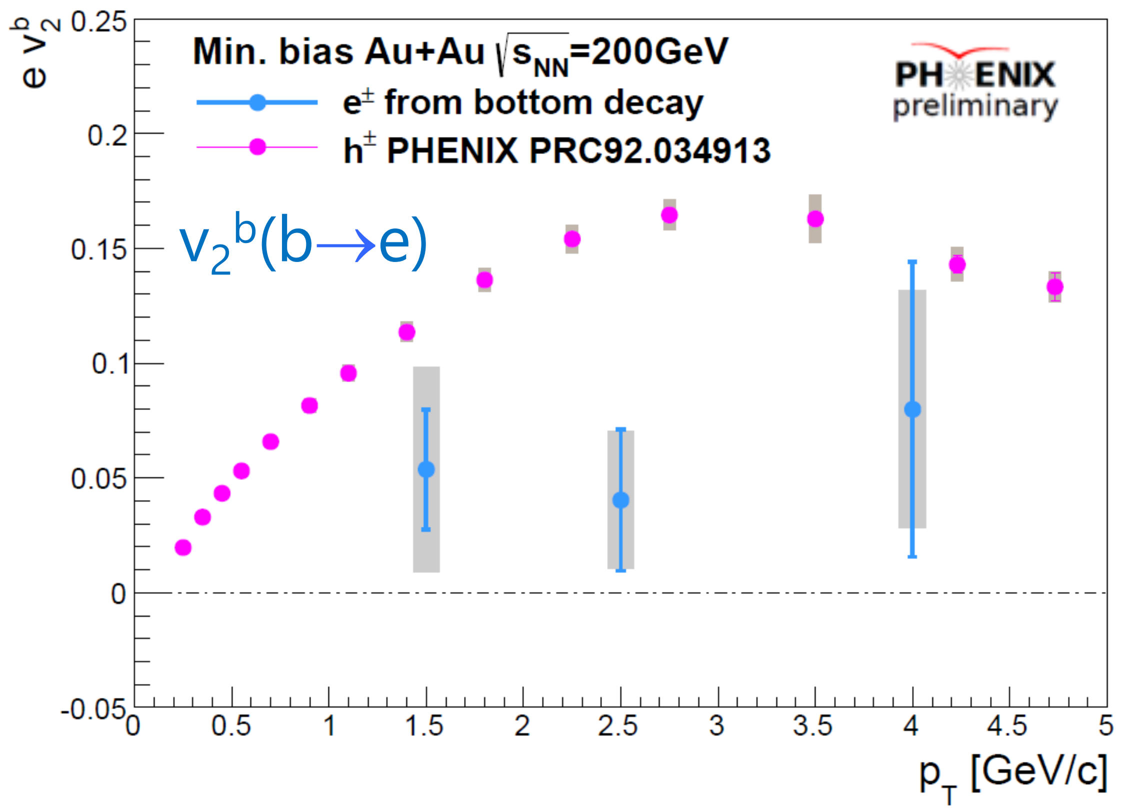


- 3 models
  - DGLV (Phys. Rev. C 90 034910)
    - E-loss + plasma w/ static potentials
  - SUBATECH (Phys. Rev. C 78 014904)
    - : E-loss + running coupling
  - T-Matrix + diffusion ($2\pi TD=4$) (Phys. Rev. Lett. 100 192301)
    - Strongly coupled QGP

- E-loss models agree with data at high p_T
- At low p_T
  - b models underestimates the data
  - c models slightly higher than data

$v_2^c(c \rightarrow e)$ and $v_2^b(b \rightarrow e)$ in Au+Au 200GeV





- v_2 $(c \rightarrow e)$ is positive with ~3.5 sigma
- $v_2(b \rightarrow e)$ indicates positive with 1.1 sigma
- Mass ordering is seen--> consistent with energy loss expectation.

Summary

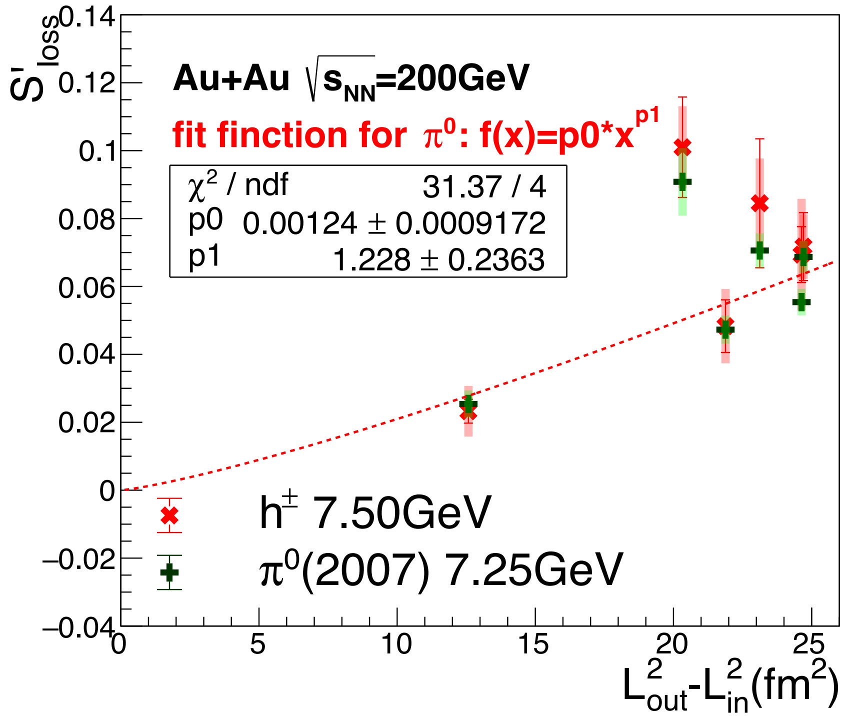
- To study energy loss in QGP, we measured S_{loss}, $S_{loss,in}$, $S_{loss,out}$ for π^0, h and R_{AA} and v_2 for separated c, b electrons.
  - No significant difference of the tendency on p_T dependence of S_{loss} between Cu+Au and Au+Au and between π^0 and h.
  - S_{loss}, $S_{loss,in}$, $S_{loss,out}$ vs. N_{part} follow a curve better than L and dN/dη. The initial particle density has important role.

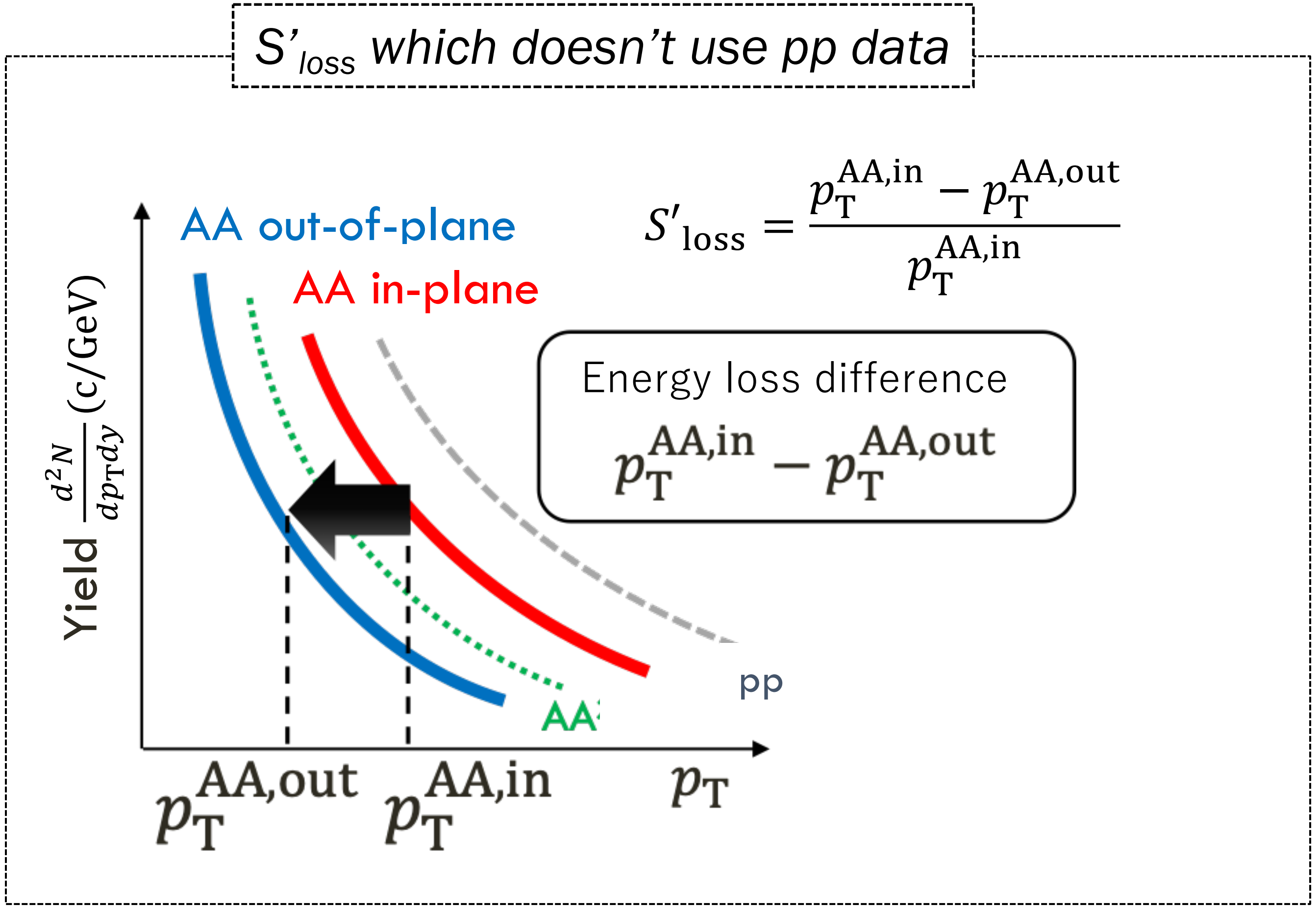
  - R_{AA} and v_2 for separated c,b electron show mass, p_T and centrality dependence, and the energy loss signal can be seen as expected.
  - At high p_T, more energy loss and larger v2 are seen with smaller mass (c more than b).

- No clear R_{AA} difference have been seen (yet?) between lf hadrons and hf hadrons. Need more study.

Back Up

S'_{loss} without pp collisions

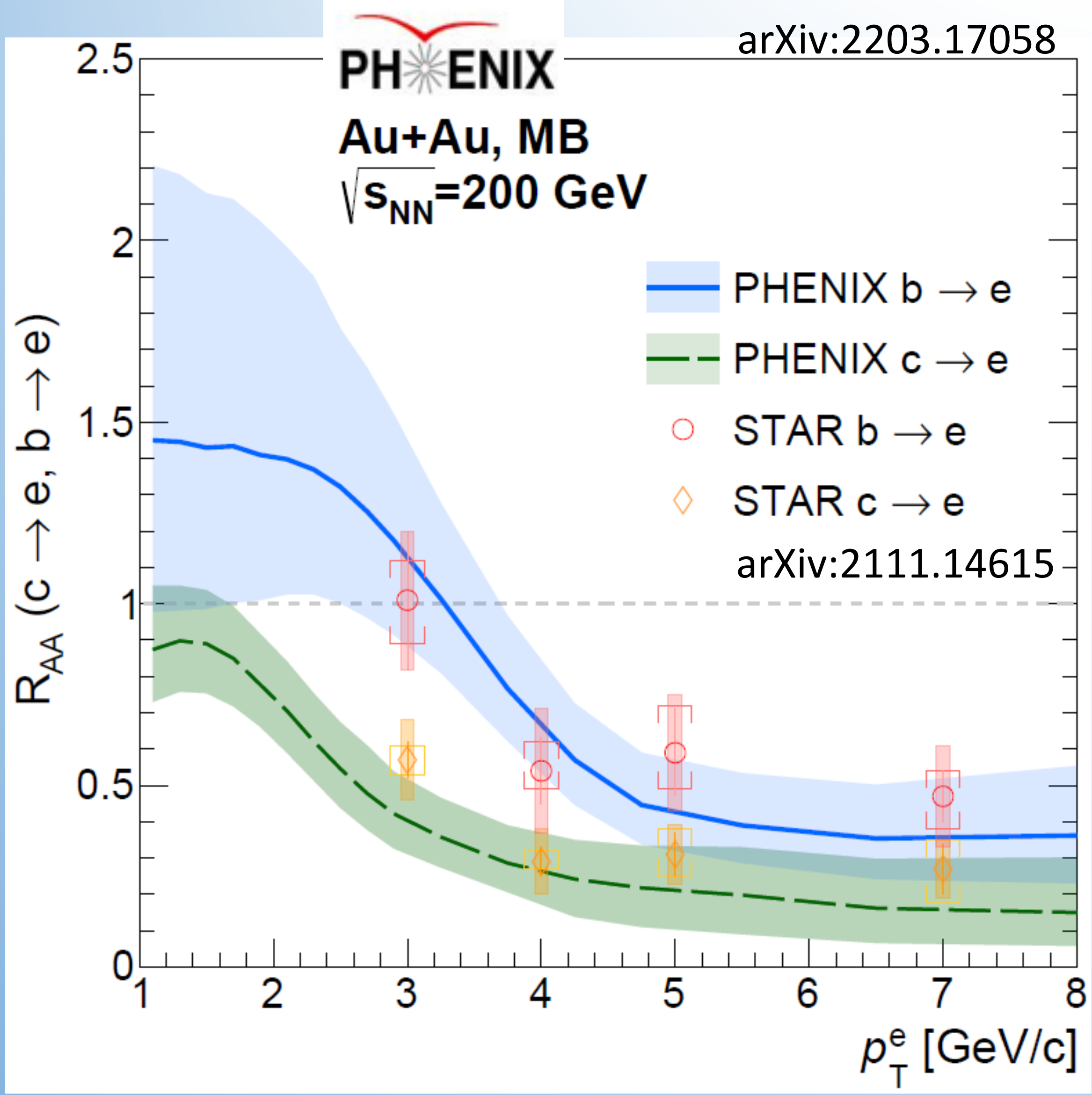




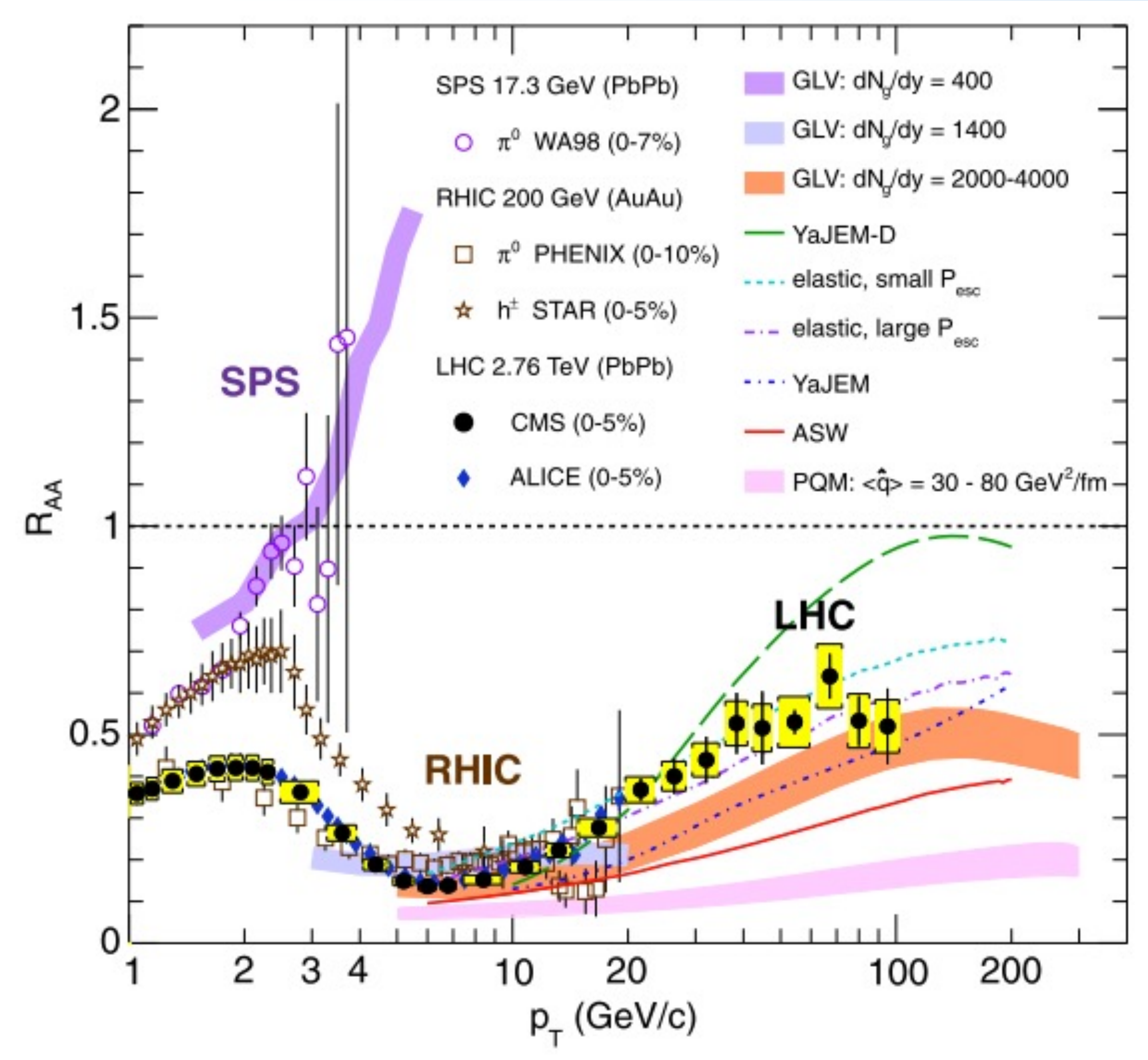
S'_{loss} vs. $L^2_{out} - L^2_{in}$

More detailed study about the function for S'_{loss} is needed.

$R_{AA}(b \rightarrow e)$ & $R_{AA}(c \rightarrow e)$ comparison with STAR 0-80%



- PHENIX MB and STAR 0-80% are in good agreement within uncertainties



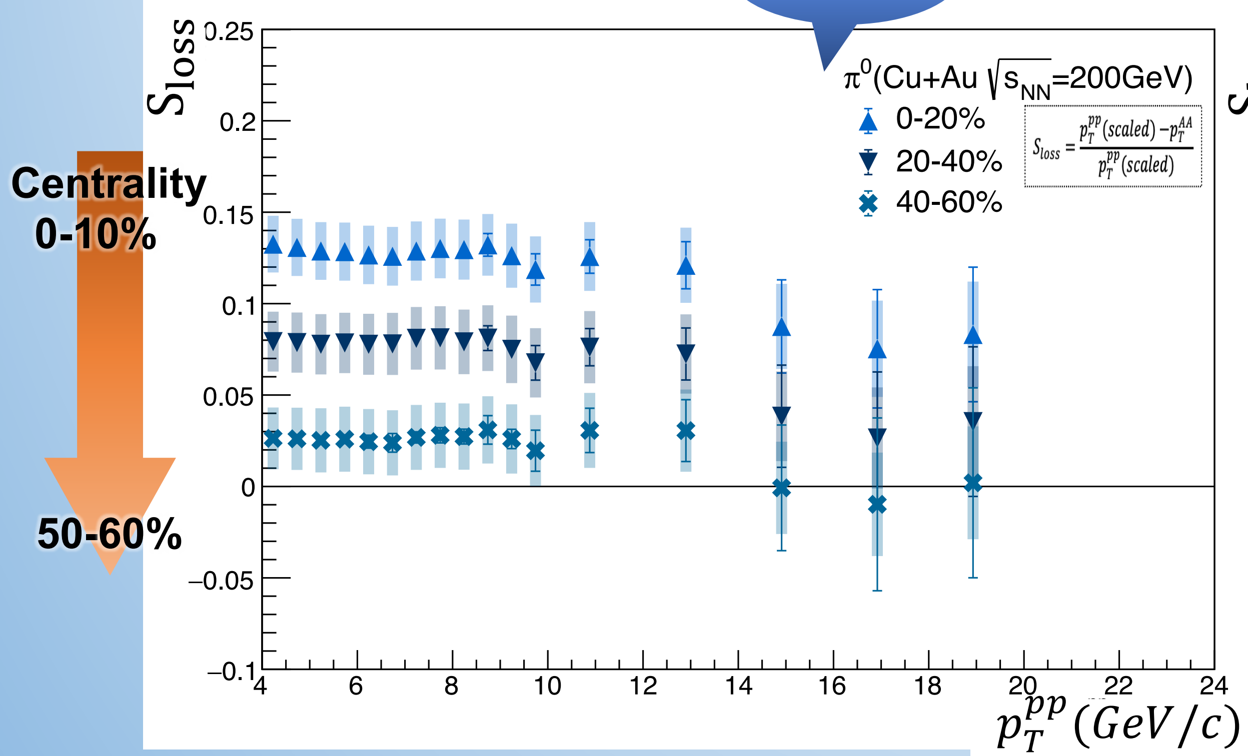
SPS 17.3 GeV (PbPb)
π⁰ WA98 (0-7%)
RHIC 200 GeV (AuAu)
π⁰ PHENIX (0-10%)
h± STAR (0-5%)
LHC 2.76 TeV (PbPb)
CMS (0-5%)
ALICE (0-5%)
GLV: dN_g/dy = 400
GLV: dN_g/dy = 1400
GLV: dN_g/dy = 2000-4000
YaJEM-D
elastic, small P_esc
elastic, large P_esc
YaJEM
ASW
PQM: <q̂> = 30 - 80 GeV²/fm
SPS
RHIC
LHC
R_AA
p_T (GeV/c)

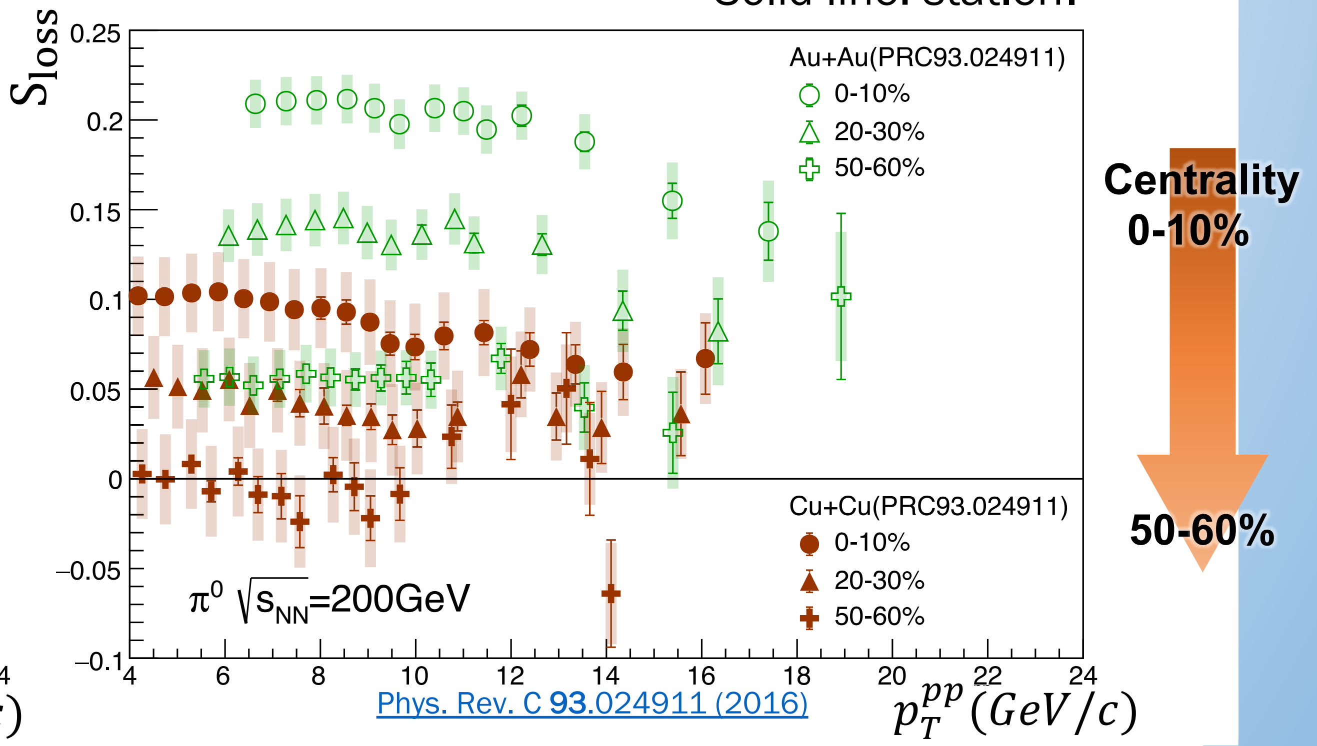
S_{loss} vs. p_T (π^0, Cu+Au)

$$S_{loss} = \frac{p_T^{pp}(scaled) - p_T^{AA}}{p_T^{pp}(scaled)}$$

Filled box: syst.err.
Solid line: stat.err.

New!





Phys. Rev. C **93**.024911 (2016)

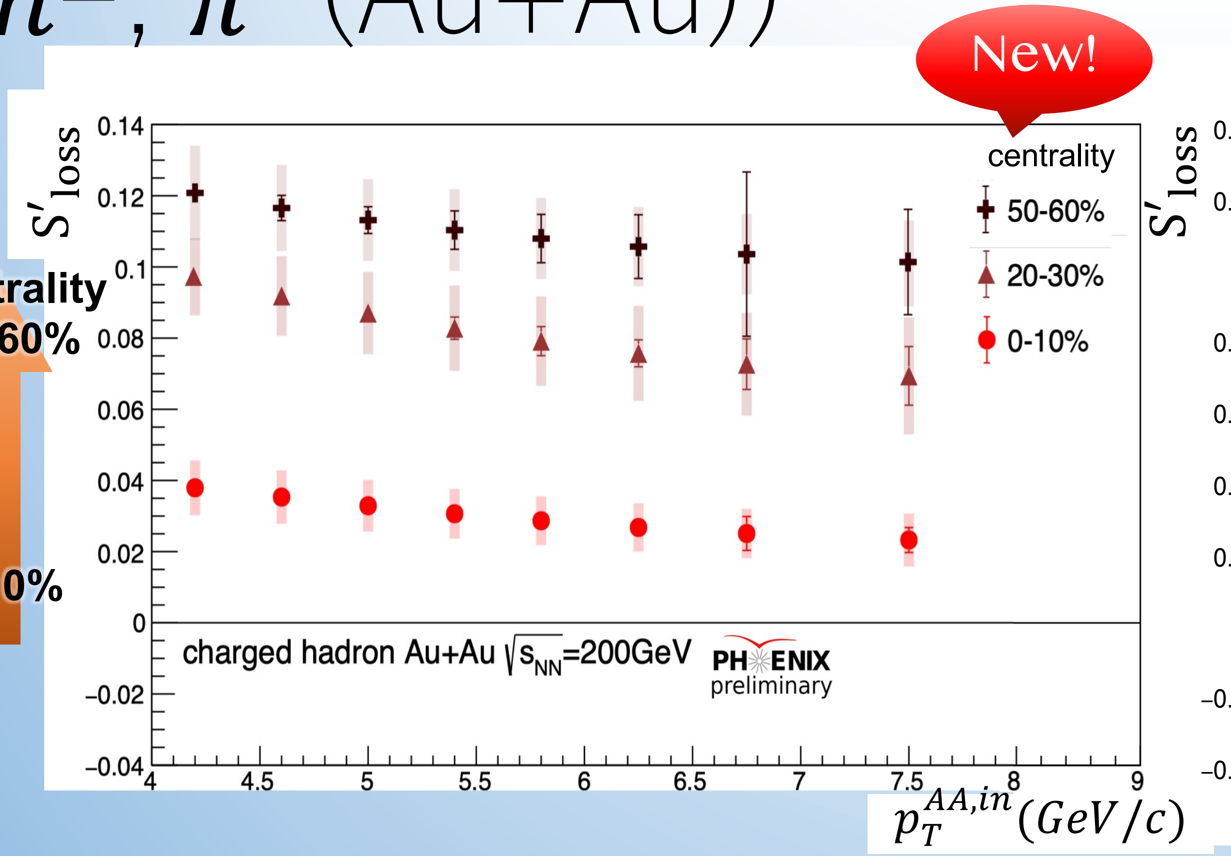
- S_{loss} for π^0s in Cu+Au is almost constant up to p_T ~12 GeV and decreases at higher p_T.
- S_{loss} decreases as centrality increases.
- S_{loss} vs. p_T shows the same tendency in Au+Au, Cu+Cu, and Cu+Au

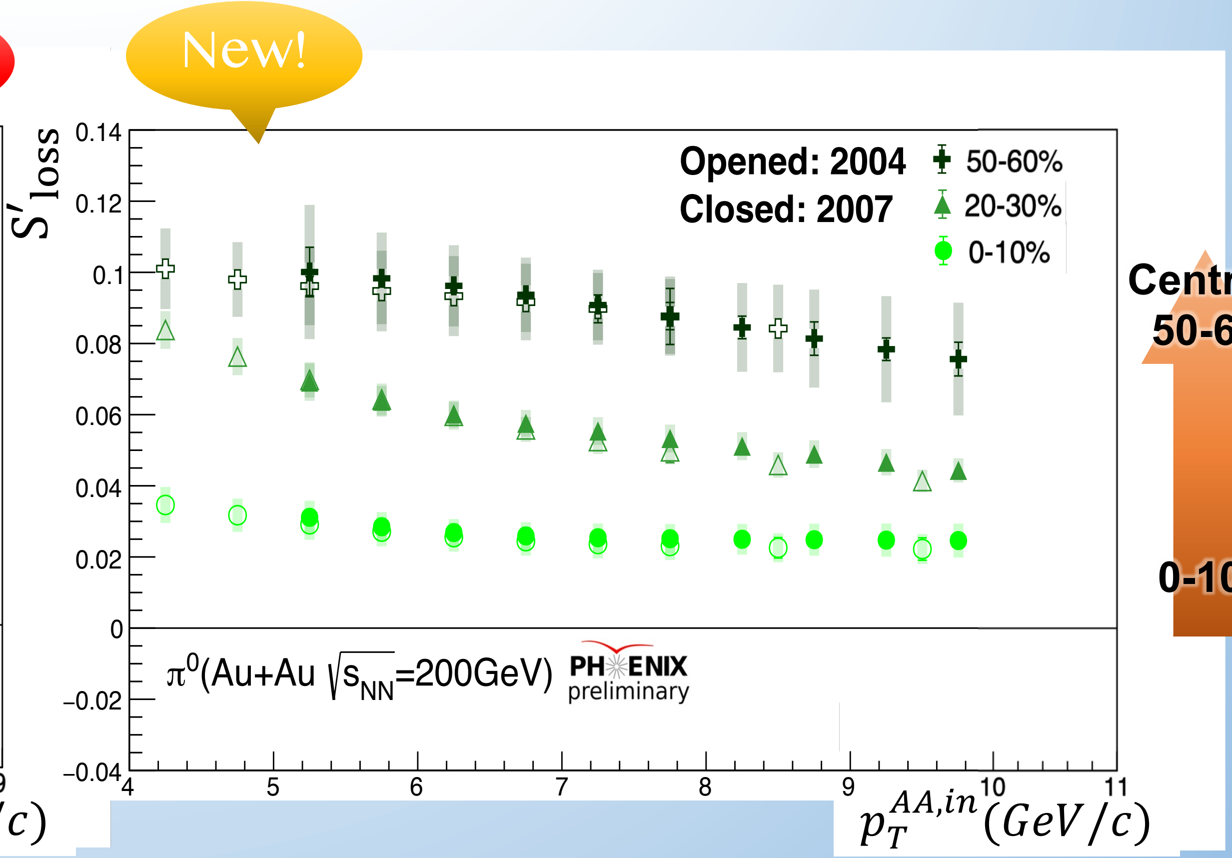
asymmetric collisions

S'_{loss} VS. p_T ($h^{\pm}$, π^0(Au+Au))

Filled box: syst.err.
Solid line: stat.err.

$$S'_{loss} = \frac{p_T^{AA,in} - p_T^{AA,out}}{p_T^{AA,in}}$$



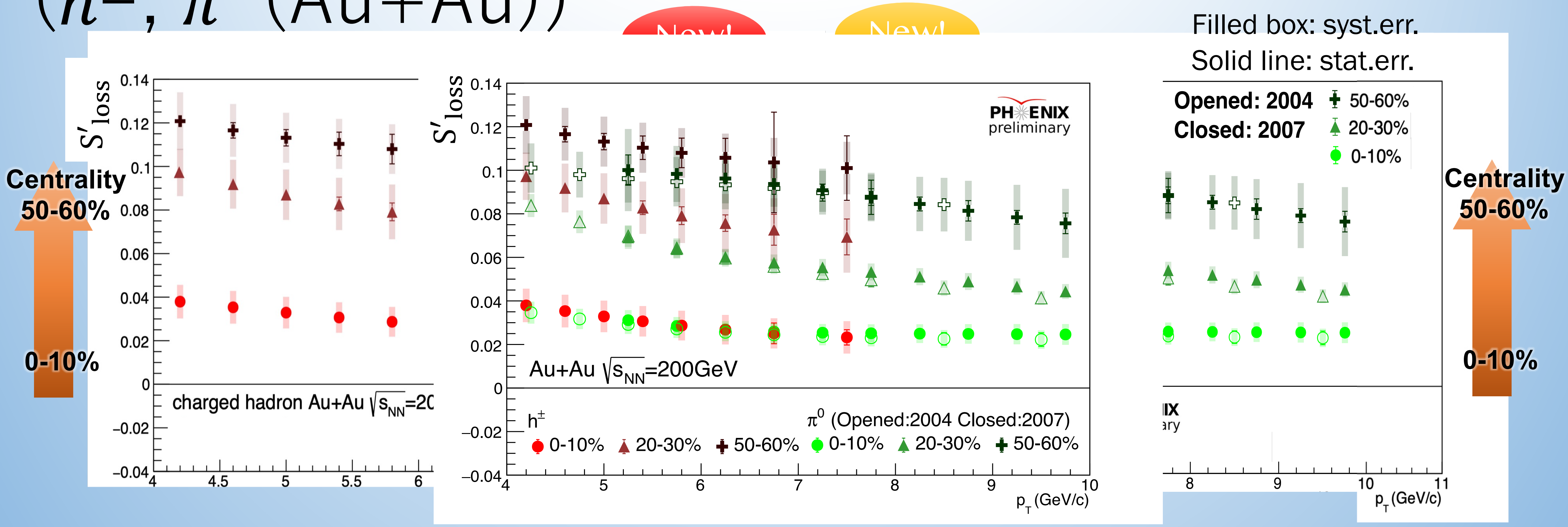


Centrality 50-60%
0-10%

- S'_{loss} for h$^{\pm}$s and π^0s slightly decrease up to p_T ~6 GeV and seems to be almost constant at higher p_T.
- S'_{loss} increases as centrality increases.
- There is no significant difference between $h^{\pm}s$ and π^0s.

S'_{loss} vs. p_T ($h^{\pm}$, π^0(Au+Au))

$$S'_{loss} = \frac{p_T^{AA,in} - p_T^{AA,out}}{p_T^{AA,in}}$$



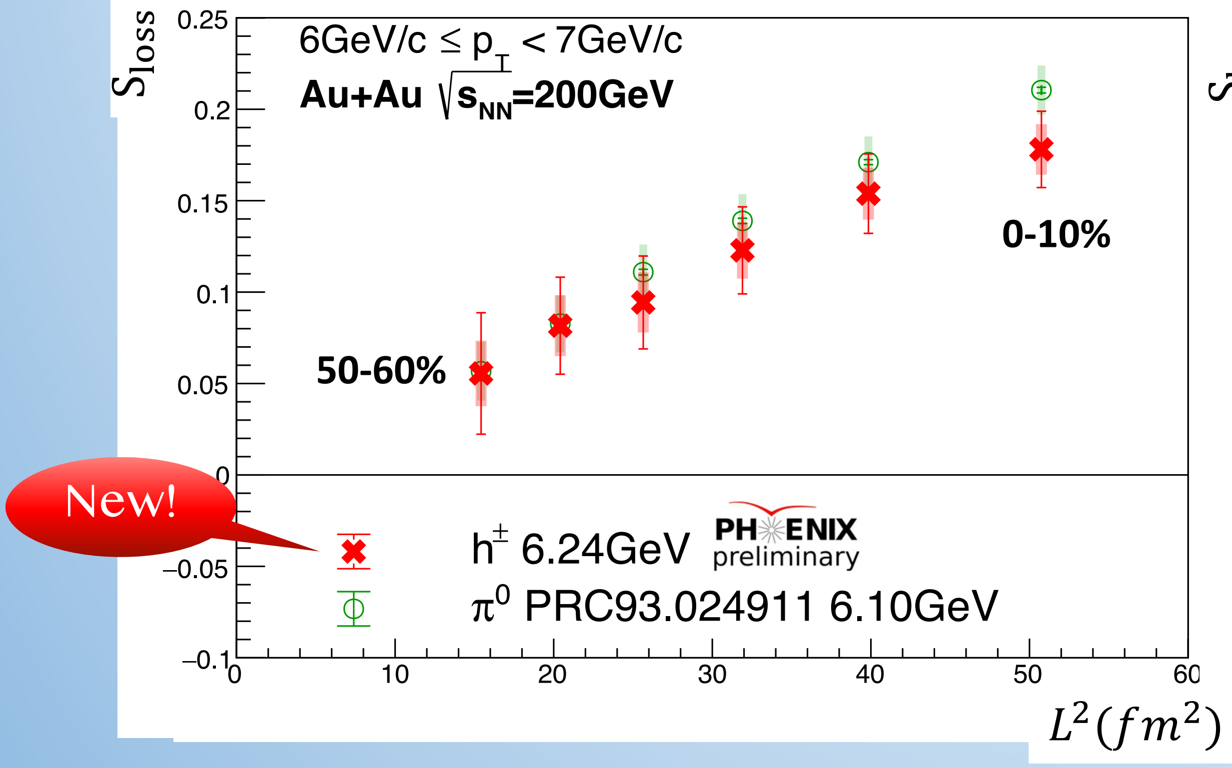
- S'_{loss} for $\mathrm{h}^{\pm}$s and π^0s slightly decrease up to p_T ~6 GeV and seems to be almost constant at higher p_T.
- S'_{loss} increases as centrality increases.
- There is no significant difference between $h^{\pm}s$ and π^0s.

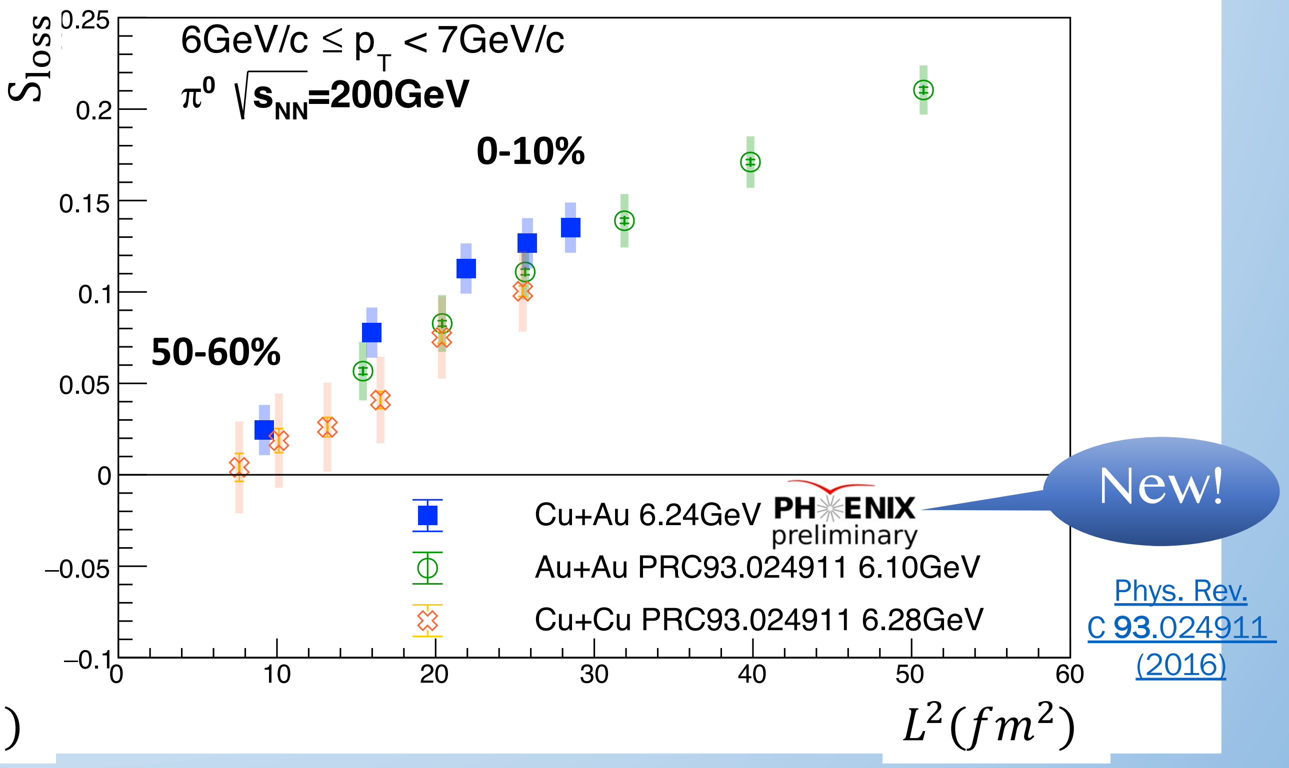
S_{loss} VS. L^2 ($h^{\pm}$(Au+Au), π^0(Cu+Au))

Filled box: syst.err.
Solid line: stat.err.

$$S_{loss} = \frac{p_T^{pp}(scaled) - p_T^{AA}}{p_T^{pp}(scaled)}$$

$$L^2 = \left(\frac{L_{out} + L_{in}}{2}\right)^2$$





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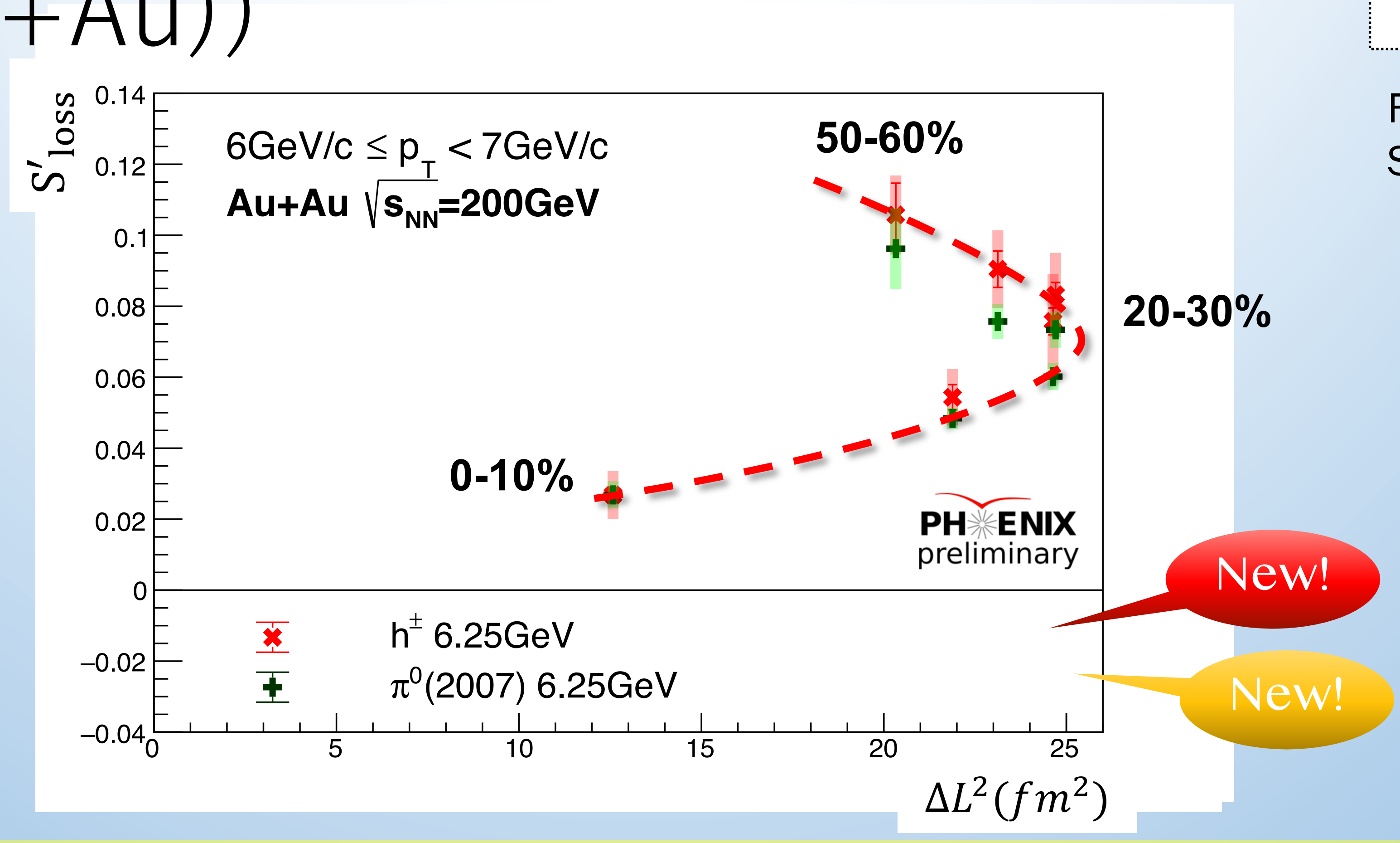
- S_{loss} is proportional to $\mathbf{L^2}$ for both $h^{\pm}s$ and π^0s, and it is common in Au+Au, Cu+Cu, and Cu+Au.
- It implies the gluon radiation loss is dominant.

S'_{loss} vs. $\Delta L^2 (= L^2_{out} - L^2_{in})$ $(h^{\pm}, \pi^0$(Au+Au))

$$S'_{loss} = \frac{p_T^{AA,in} - p_T^{AA,out}}{p_T^{AA,in}}$$

$$\Delta L^2 = L^2_{out} - L^2_{in}$$

Filled box: syst.err.
Solid line: stat.err.



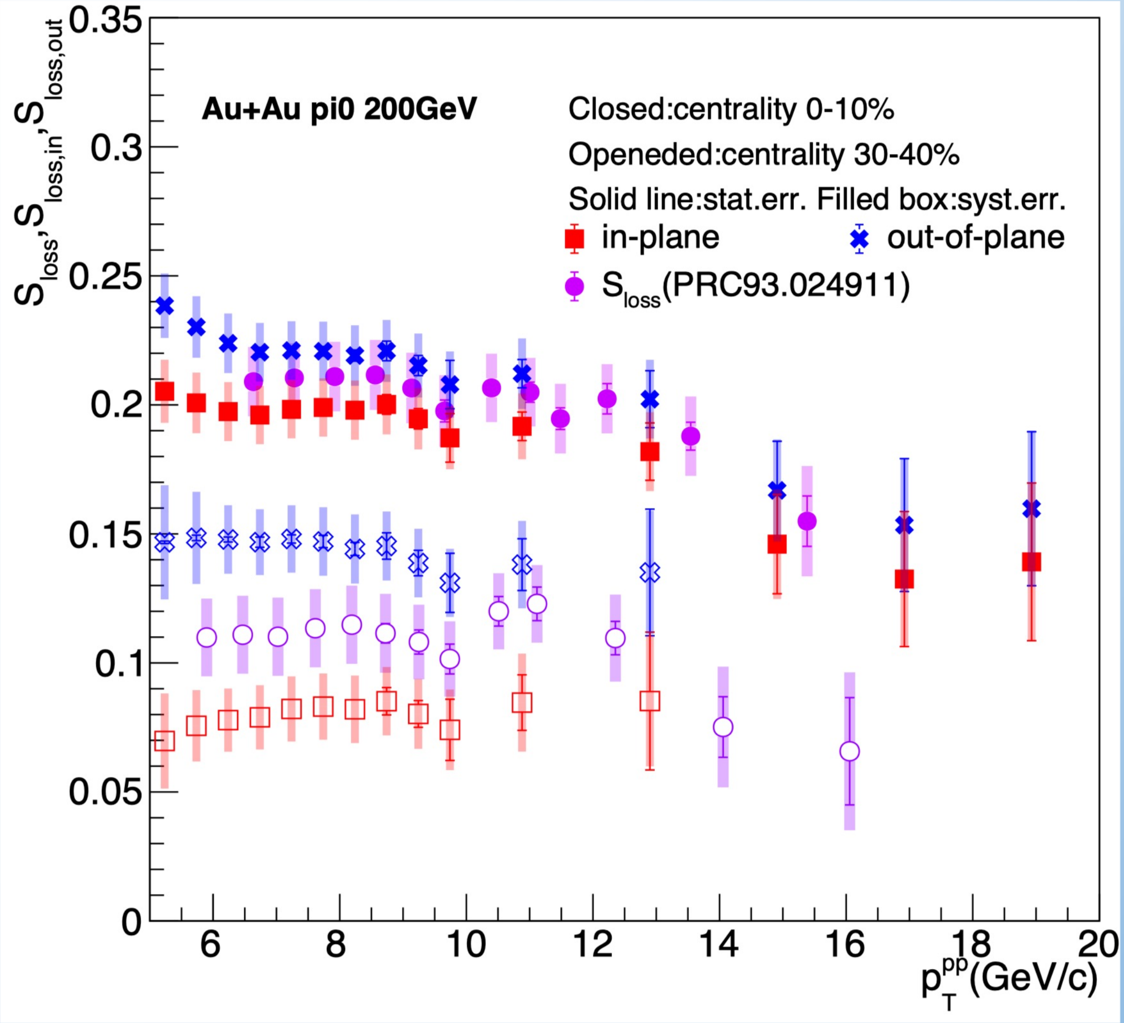
- S'_{loss} is not proportional to $L^2_{out} - L^2_{in}$.
- There is no significant difference between $h^{\pm}s$ and π^0s within uncertainty.

S'_{loss} exhibits a different tendency from S_{loss}!

$S_{loss,in}$, $S_{loss,out}$ vs. p_T

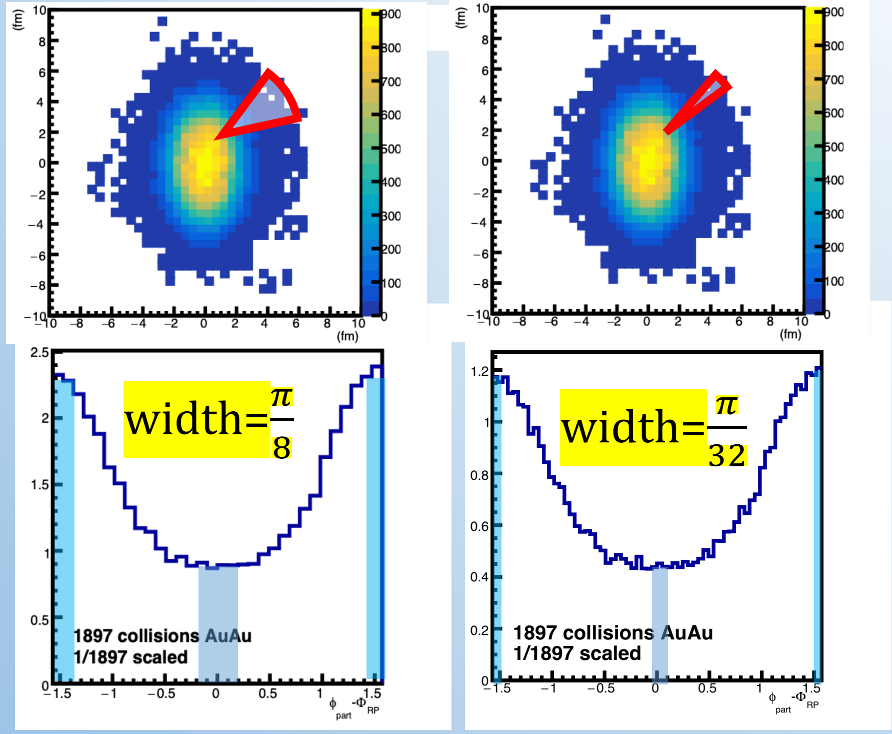
Different azimuthal angle

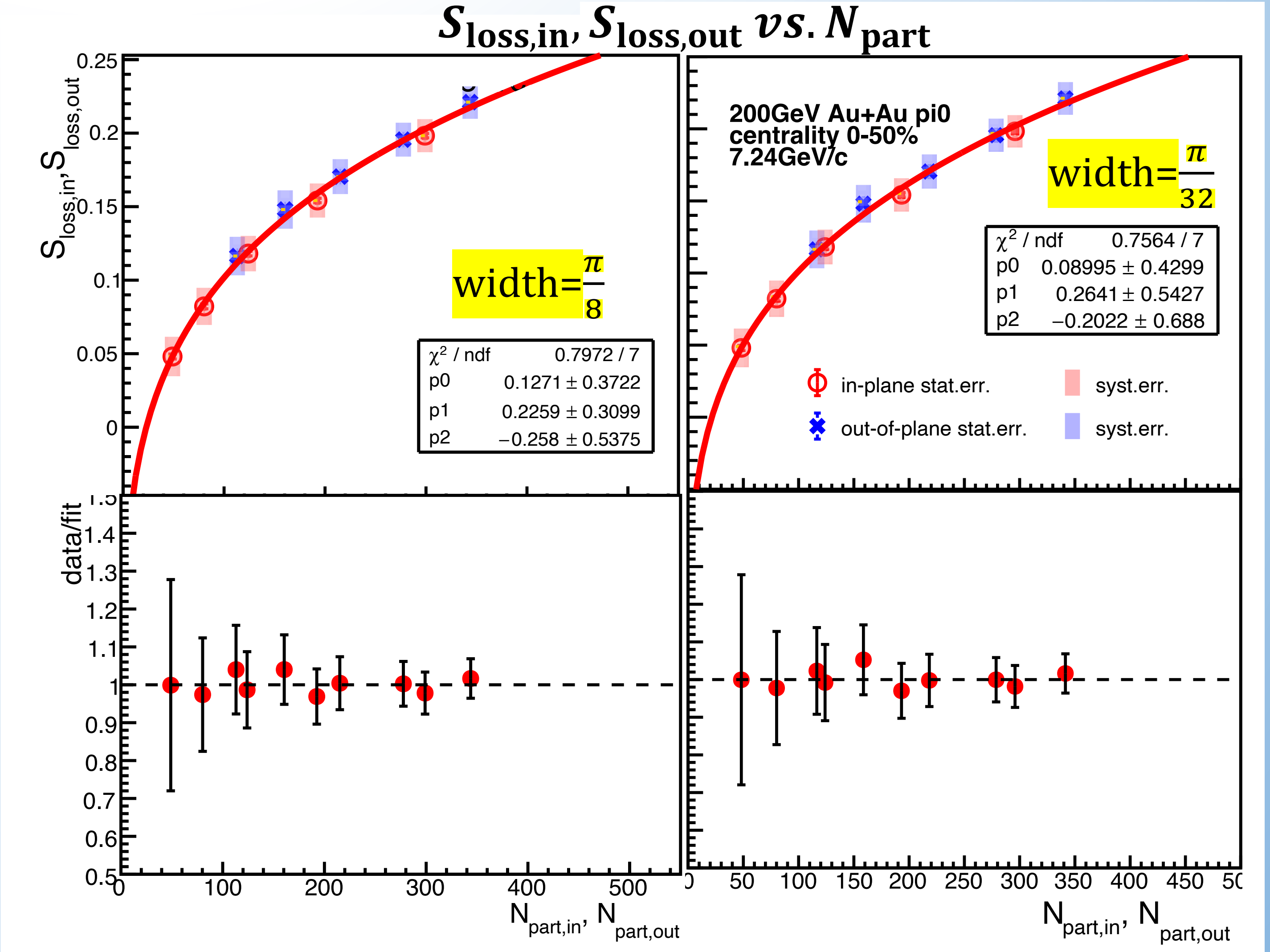
- The fractional momentum loss are different in the different azimuthal angle.
- Difference in the fractional momentum loss due to azimuthal angle, not seen in S_{loss}.
- The geometric anisotropy contributes to the energy loss mechanism in the QGP.



Systematic uncertainty from the caliculation of $N_{\mathrm{part,in}} N_{\mathrm{part,out}}$

- With different $N_{\mathrm{part,in\text{-}out}}$ width of the calculation



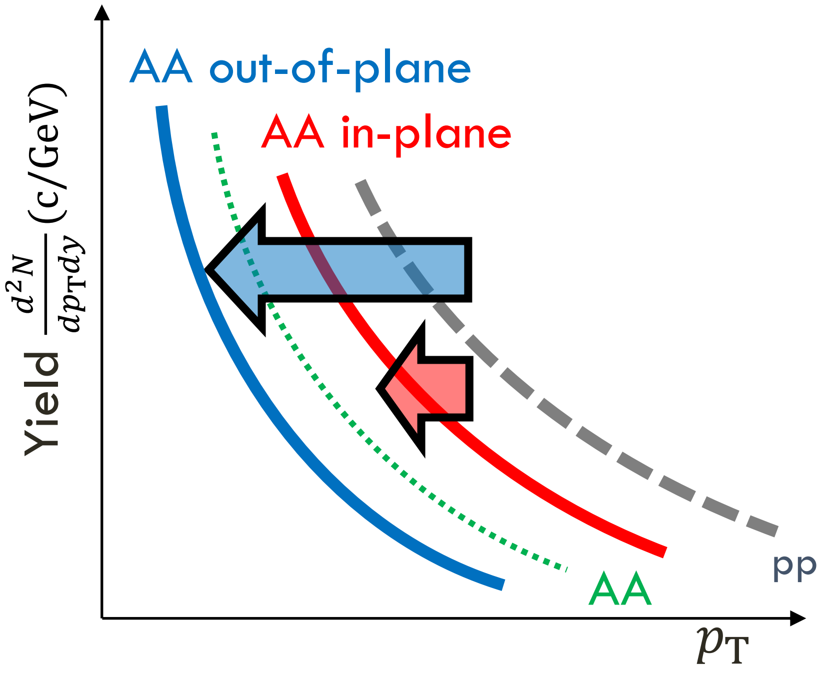


- No significant different of χ^2/ndf

- $N_{\mathrm{part,in}}, N_{\mathrm{part,out}}$ *and* N_{part} doesn't depend on the width of azimuthal bin.

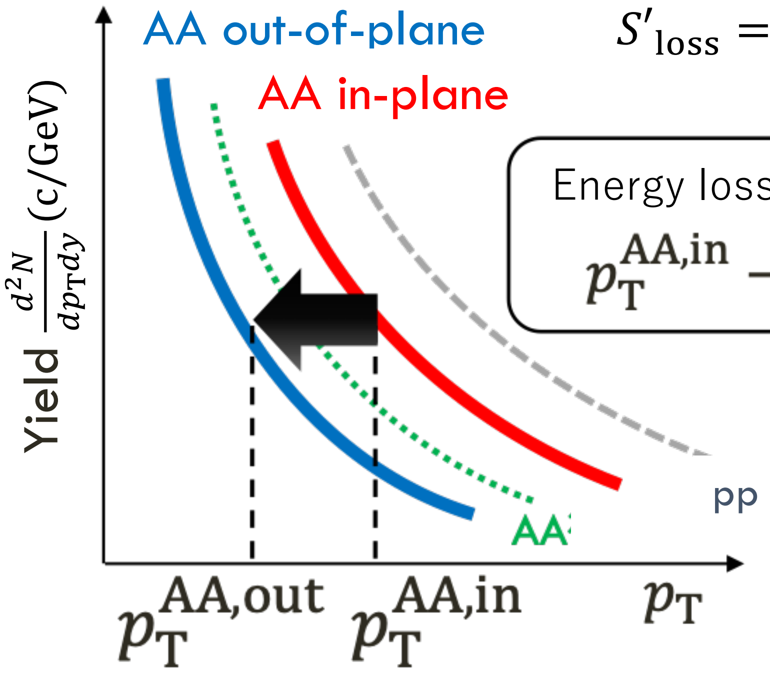
S'$_{loss}$ without pp collisions

S_{loss} depend on azimuthal angle



S'$_{loss}$ which doesn't use pp data

$$S'_{loss} = \frac{p_T^{AA,in} - p_T^{AA,out}}{p_T^{AA,in}}$$

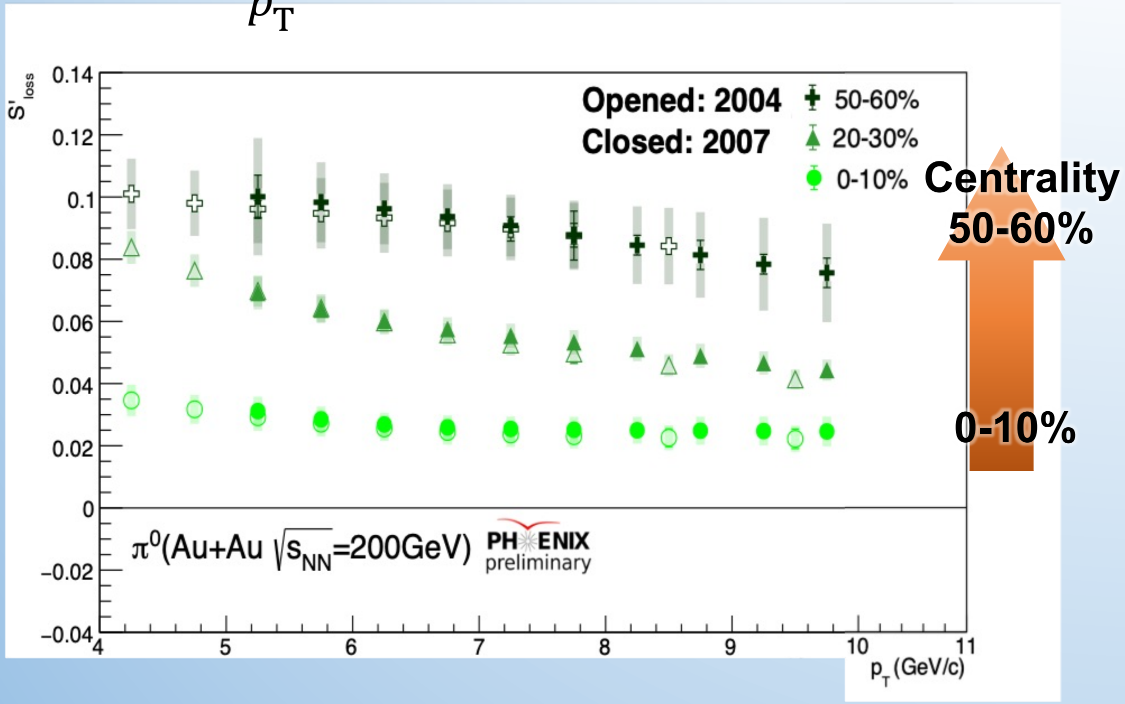


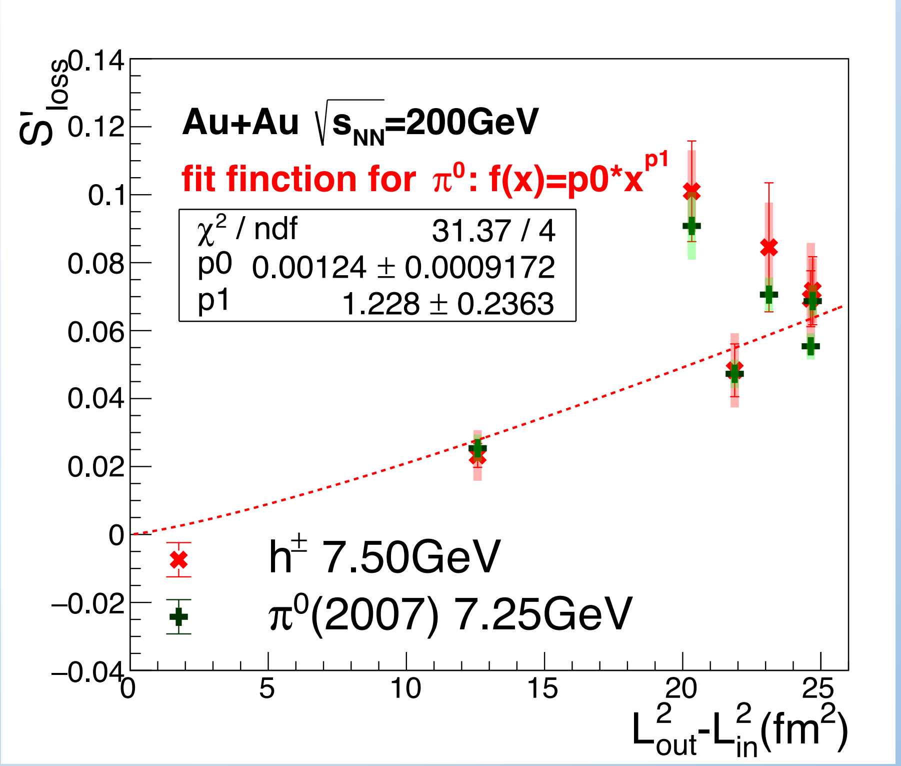
Energy loss difference

$p_T^{AA,in} - p_T^{AA,out}$

S'_{loss} (not use pp collision)

$$S'_{\text{loss}} = \frac{p_T^{\text{AA,in}} - p_T^{\text{AA,out}}}{p_T^{\text{AA,in}}}$$





S'_{loss} is roughly proportional to $L_{\text{out}}^2 - L_{\text{in}}^2$.
More detailed study about the function for S'_{loss} is needed.

Methods

<S_{loss}>

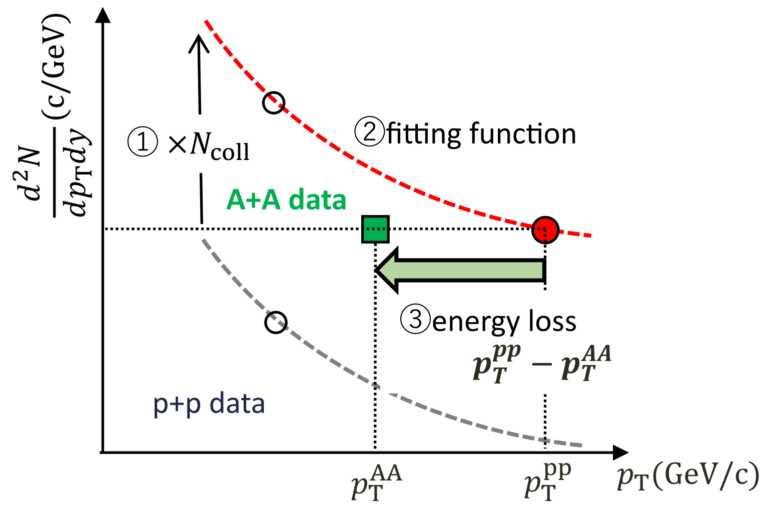
① scale spectra in p+p by binary collision number (N_{coll})

② get the fitting function of the scaled p+p spectra

③ The fractional momentum loss, S_{loss}, using the scaled pp data and spectra in A+A collision

- The fractional momentum loss:

$$S_{\text{loss}} = \frac{p_{\text{T}}^{\text{pp}} - p_{\text{T}}^{\text{AA}}}{p_{\text{T}}^{\text{pp}}}$$



<$S_{\text{loss,in}}$, $S_{\text{loss,out}}$>

① In-plane spectra and out-of-plane spectra in A+A collision

azimuthal distribution of generated particle	$\frac{dN(\phi)}{d\phi} \propto 1 + 2v_2\cos 2\phi$

in-plane ($\phi = 0°$)

$$\left.\frac{d^2N}{dp_Tdy}\right|_{\text{in}} = \frac{d^2N}{dp_{\text{T}}dy} \times (1 + 2v_2)$$

out-of-plane ($\phi = 90°$)

$$\left.\frac{d^2N}{dp_Tdy}\right|_{\text{out}} = \frac{d^2N}{dp_{\text{T}}dy} \times (1 - 2v_2)$$

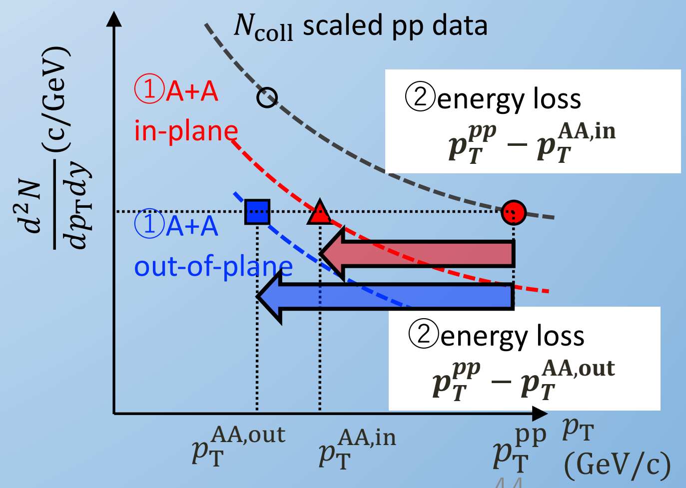
② The fractional momentum loss, $S_{\text{loss,in}}$($S_{\text{loss,out}}$), of in-plane (out-of-plane) using N_{coll} scaled pp data and in-plane spectra (out-of-plane spectra) in A+A collision

- The fractional momentum loss of in-plane:

$$S_{\text{loss,in}} = \frac{p_{\text{T}}^{\text{pp}} - p_{\text{T}}^{\text{AA,in}}}{p_{\text{T}}^{\text{pp}}}$$

- The fractional momentum loss of out-of-plane:

$$S_{\text{loss,out}} = \frac{p_{\text{T}}^{\text{pp}} - p_{\text{T}}^{\text{AA,out}}}{p_{\text{T}}^{\text{pp}}}$$



L dependences

- **S_{loss}: the fractional momentum loss of high-p_T hadrons**

$$S_{\text{loss}} = \frac{p_T^{pp}(\text{scaled}) - p_T^{AA}}{p_T^{pp}(\text{scaled})}$$

1. S_{loss} does not strongly depend on p_T, decreases as centrality increases. ([Phys. Rev. C. 93. 024911 (2016)])
2. S_{loss} increases with L_ϵ, an effective radius of the collision. ([Phys. Rev. C. 76. 034904(2007)])