



STUDY ON THE ENERGY LOSS OF LIGHT AND HEAVY QUARKS IN QGP AT PHENIX

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FOR THE PHENIX COLLABORATION

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MAR. 28TH 2023

HARD PROBES 2023 ASCHAFFENBURG

Contents

(1) Heavy flavor hadron energy loss

- R_{AA} Comparison of the light hadrons.

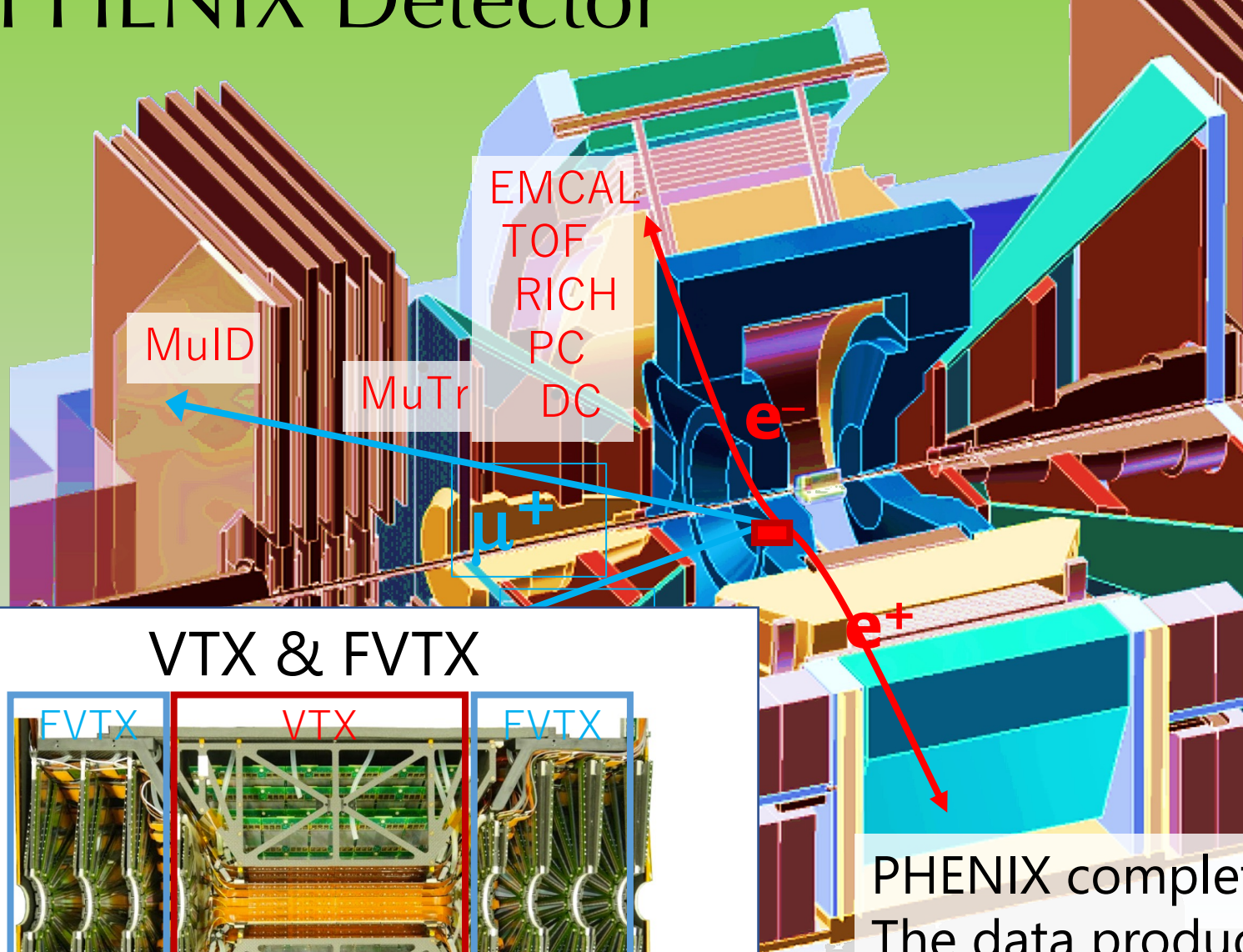
(2) Charged hadron energy loss

- **Inclusive fractional momentum loss (S_{loss})**
- **Azimuthal-angle-dependent S_{loss}**

(3) Finer event classification

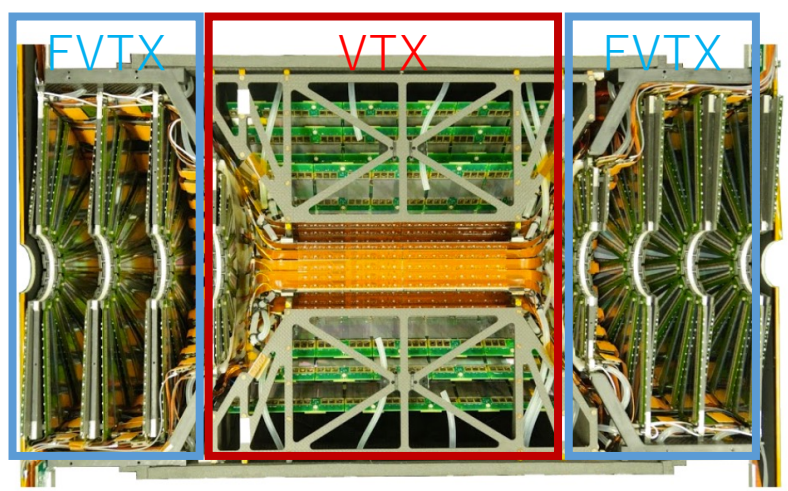
- $N_{spectator}$ and multiplicity

PHENIX Detector



- Central Arms
 - $|y| < 0.35$, $\phi \sim 2 \cdot \pi/2$
 - **Electrons**, γ , hadrons
 - DC, PC, RICH, EMCAL, TOF
- Muon Arms
 - $1.2 \sim |y| < 2.2$, $\phi \sim 2 \cdot \pi/2$
 - Muons, Hadrons
- VTX-FVTX
 - Precise tracking for HF-ID

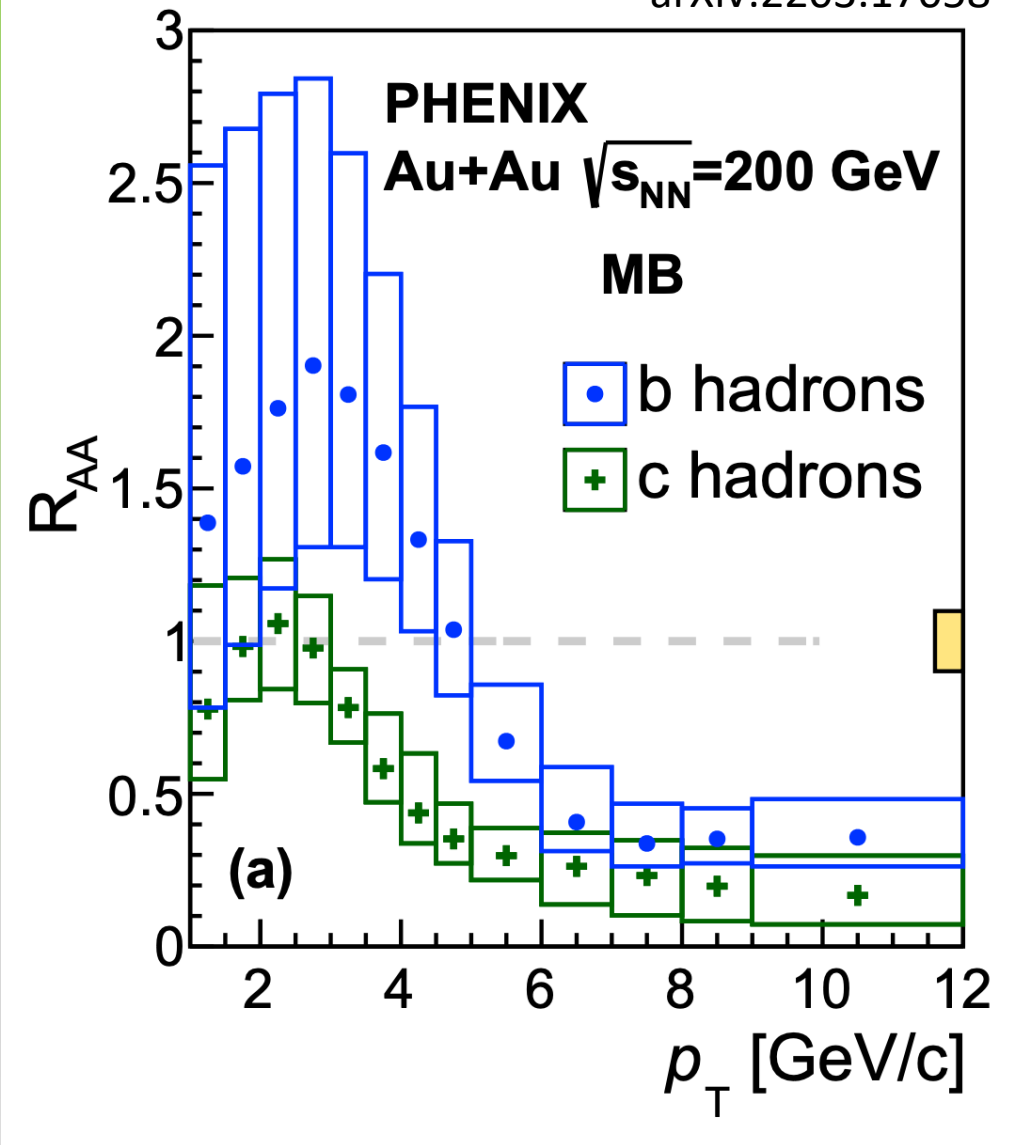
VTX & FVTX



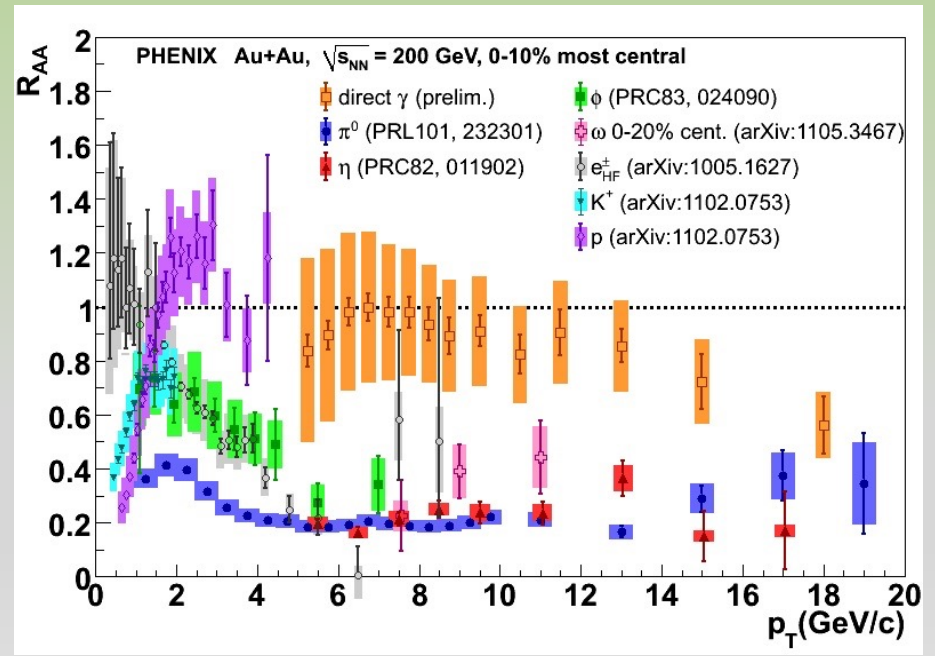
PHENIX completed the data taking in 2016.
The data production completed.
Analyses are ongoing.

(1) Charm and Bottom hadron R_{AA} [See the talk by B. Blankenship on Wed](#)

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



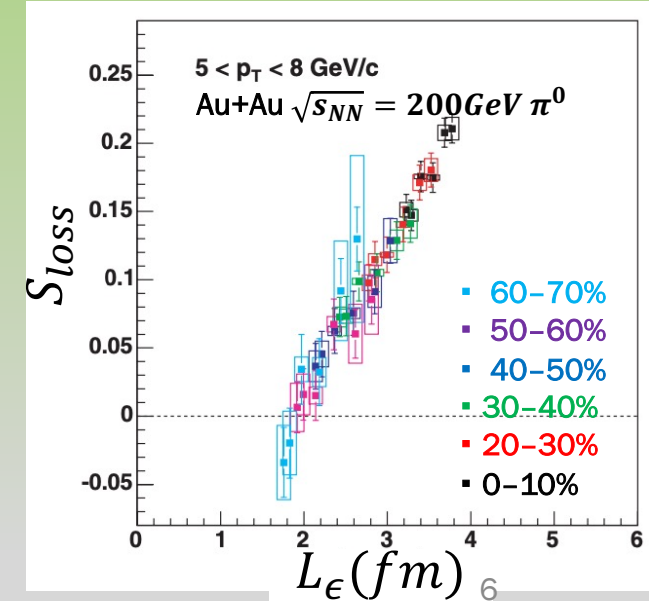
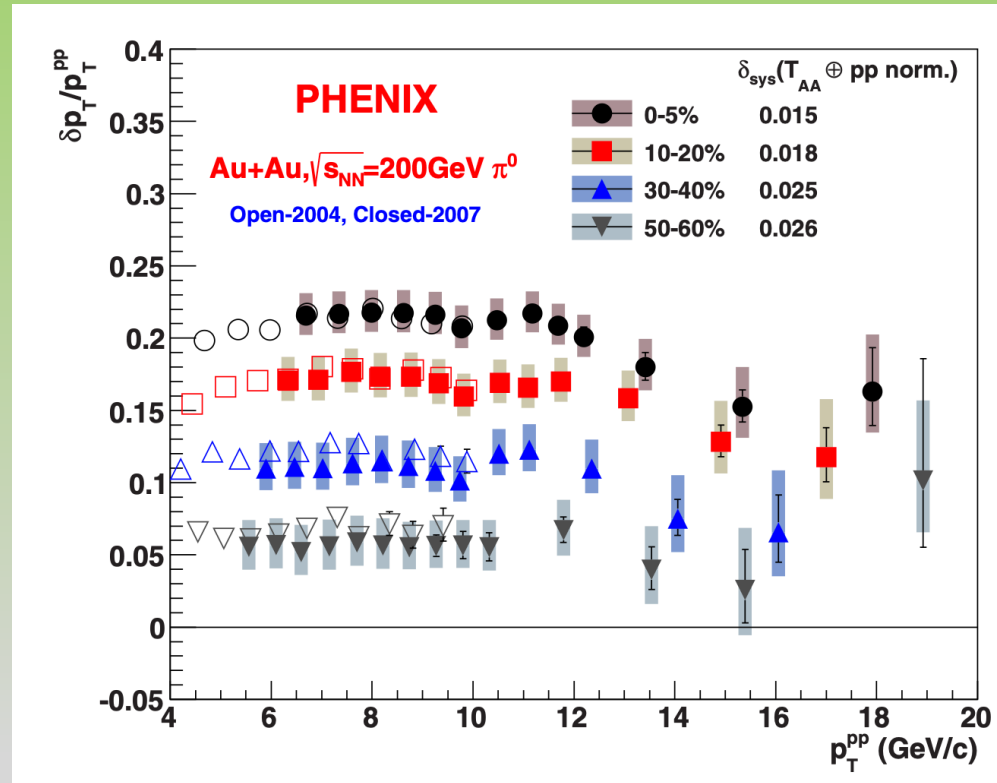
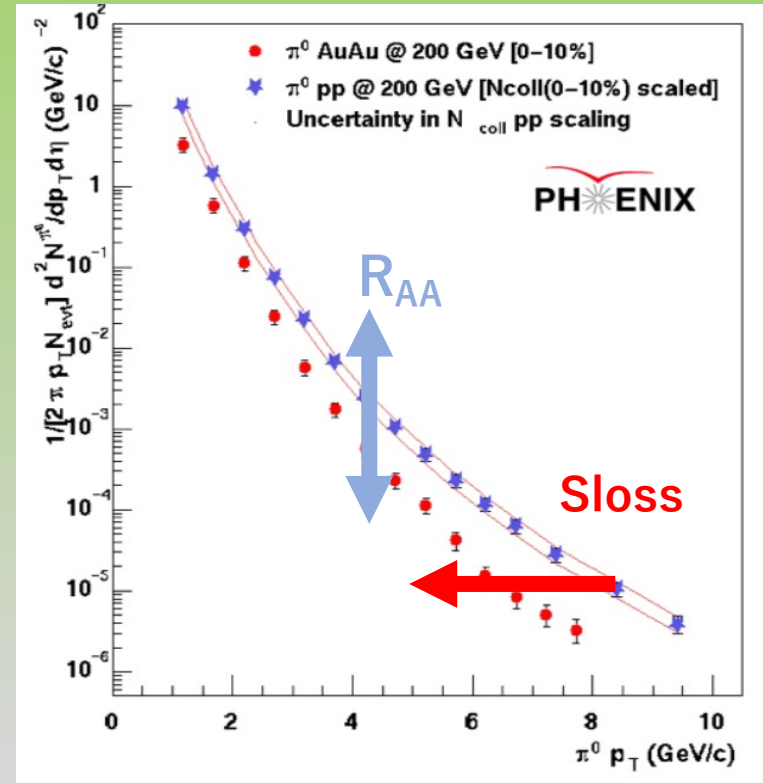
(2) Charged hadron energy loss

Previous results: Fractional momentum loss (S_{loss})

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

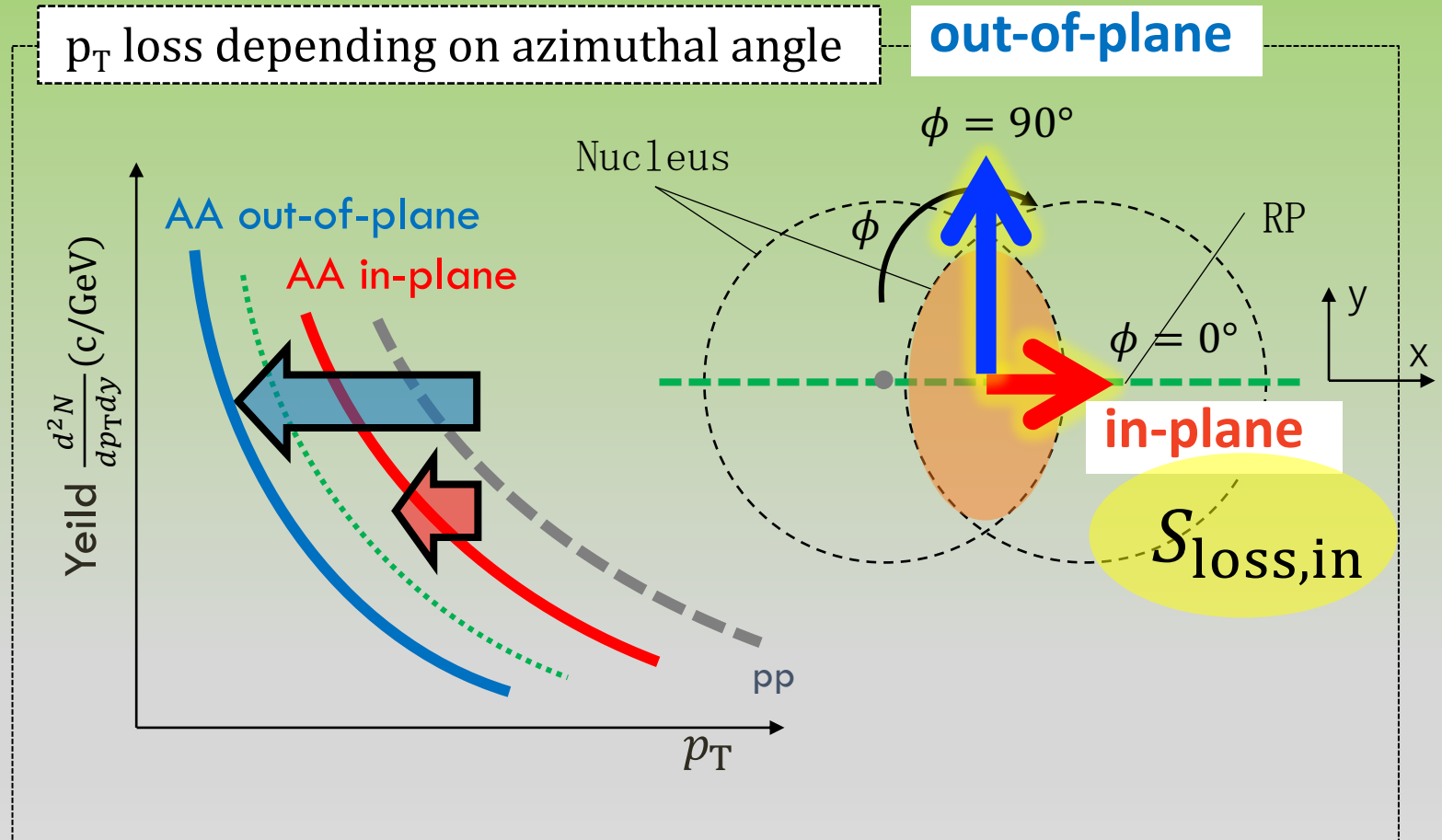
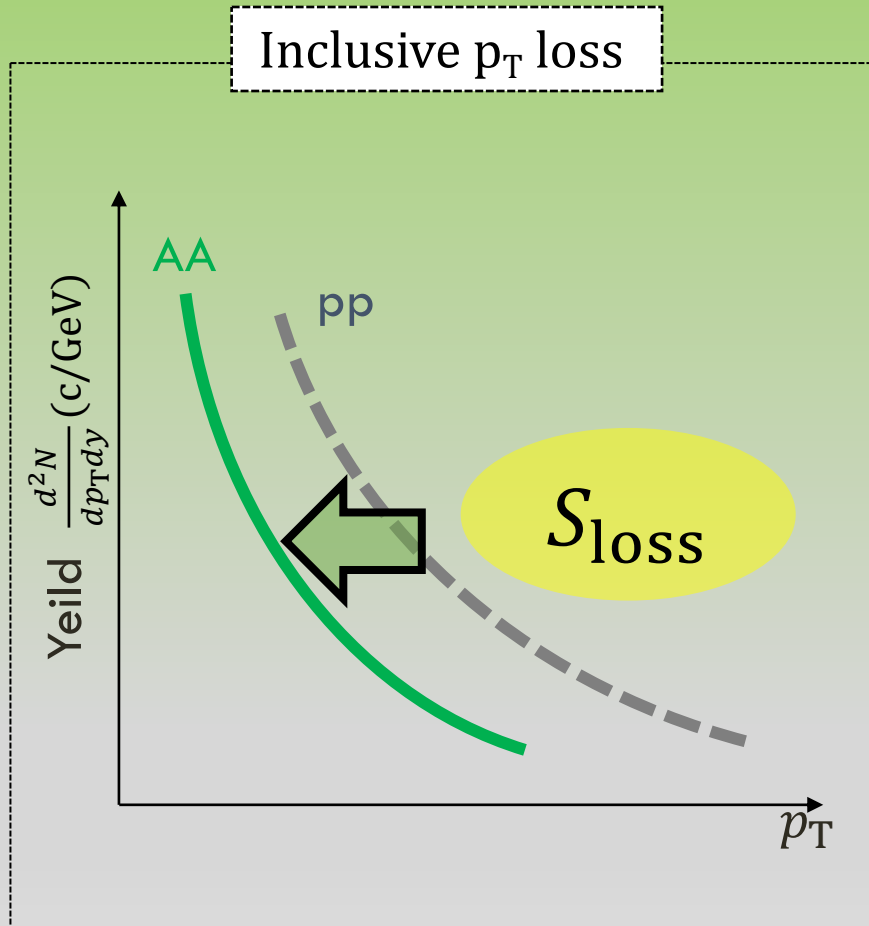
Phys. Rev. C 93.024911 (2016)

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 caused by more central collisions.
- S_{loss} depends on L_ϵ , an effective radius of the collision.

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



Analysis procedure

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

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

in-plane ($\phi = 0^\circ$)

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

out-of-plane ($\phi = 90^\circ$)

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

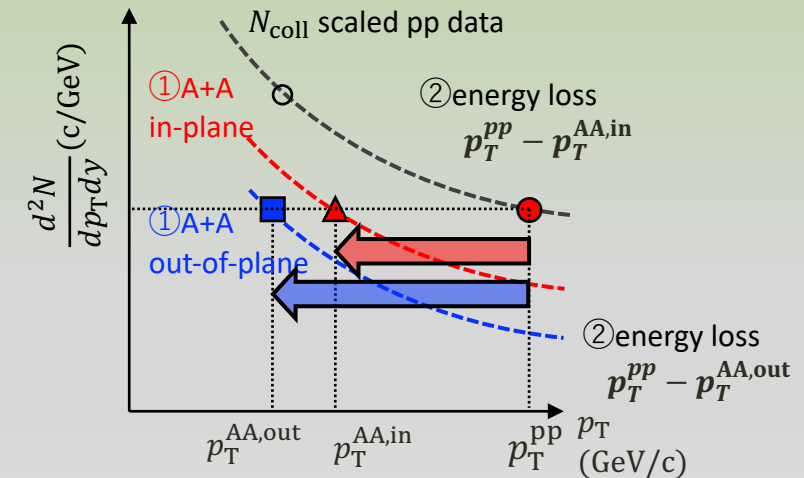
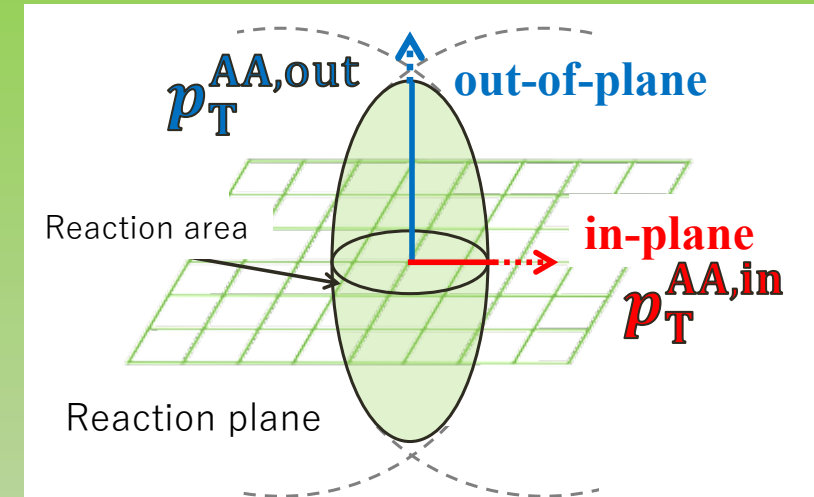
- ② The fractional momentum loss, $S_{\text{loss,in}}$ ($S_{\text{loss,out}}$), of in-plane (out-of-plane) using N_{coll} scaled pp data and in-plane spectra (out-of-plane spectra) in A+A collision

- 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:

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

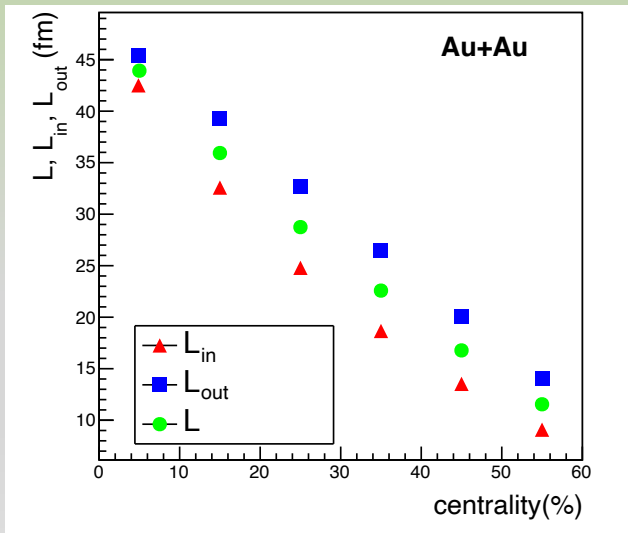


Parameters

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: $L = \frac{\overline{L_{in} + L_{out}}}{2}$



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

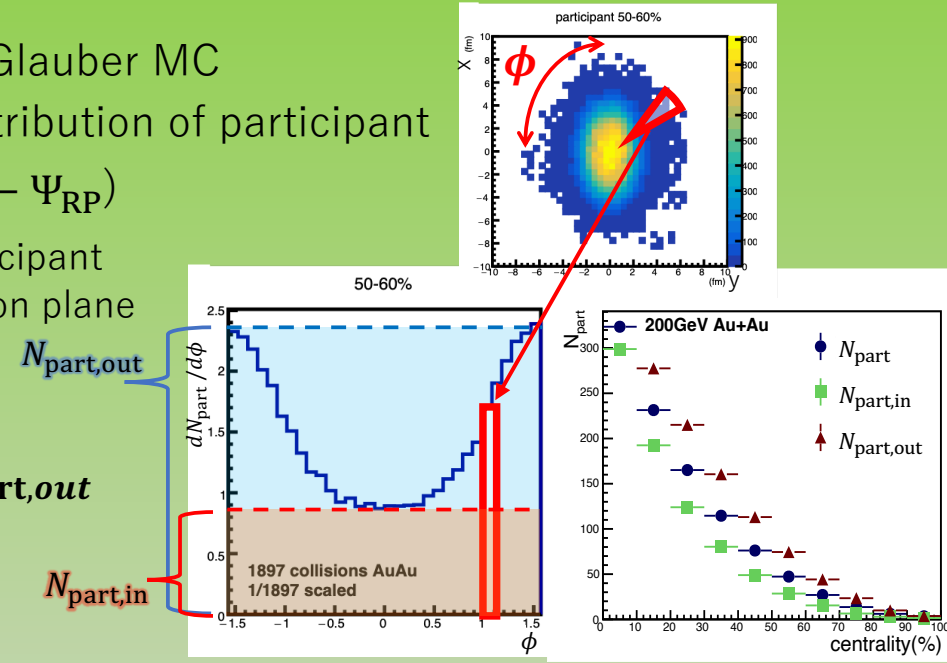
- Calculate the azimuthal distribution of participant

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

ϕ_{part} : azimuthal angle of participant

Ψ_{RP} : azimuthal angle of reaction plane

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



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

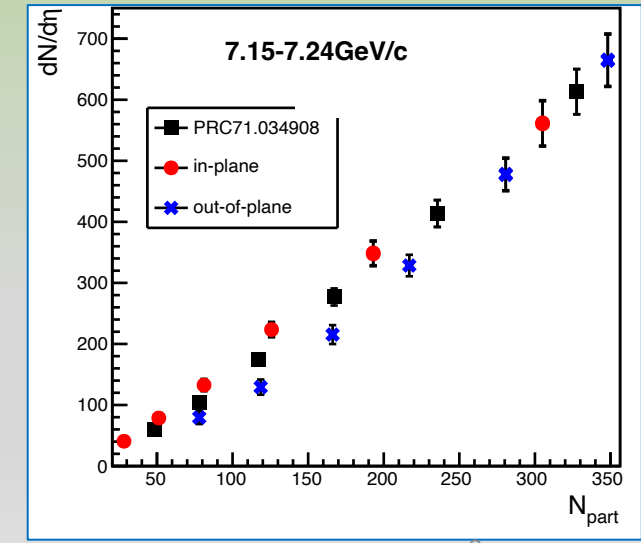
- Calculate $dN_{ch}/d\eta$ of in-plane and out-of-plane

- in-plane ($\phi = 0^\circ$)

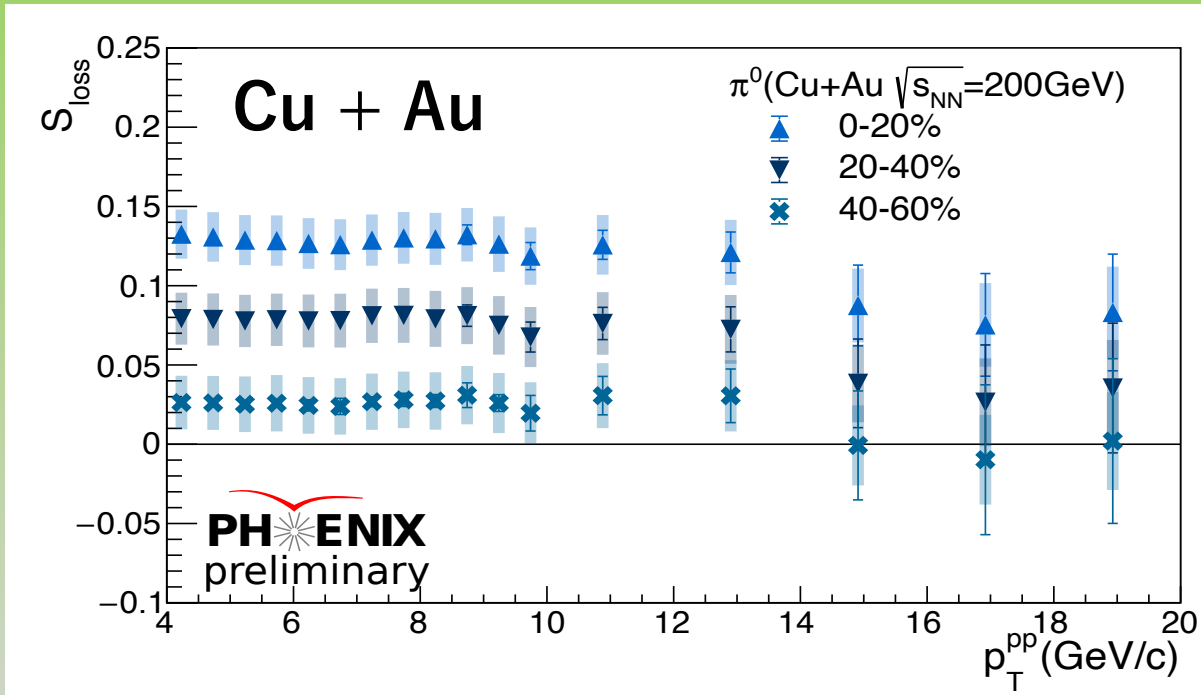
$$\left. \frac{dN_{ch}}{d\eta} \right|_{in} = \left. \frac{dN_{ch}}{d\eta} \right| \times (1 + 2v_2)$$

- out-of-plane ($\phi = 90^\circ$)

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

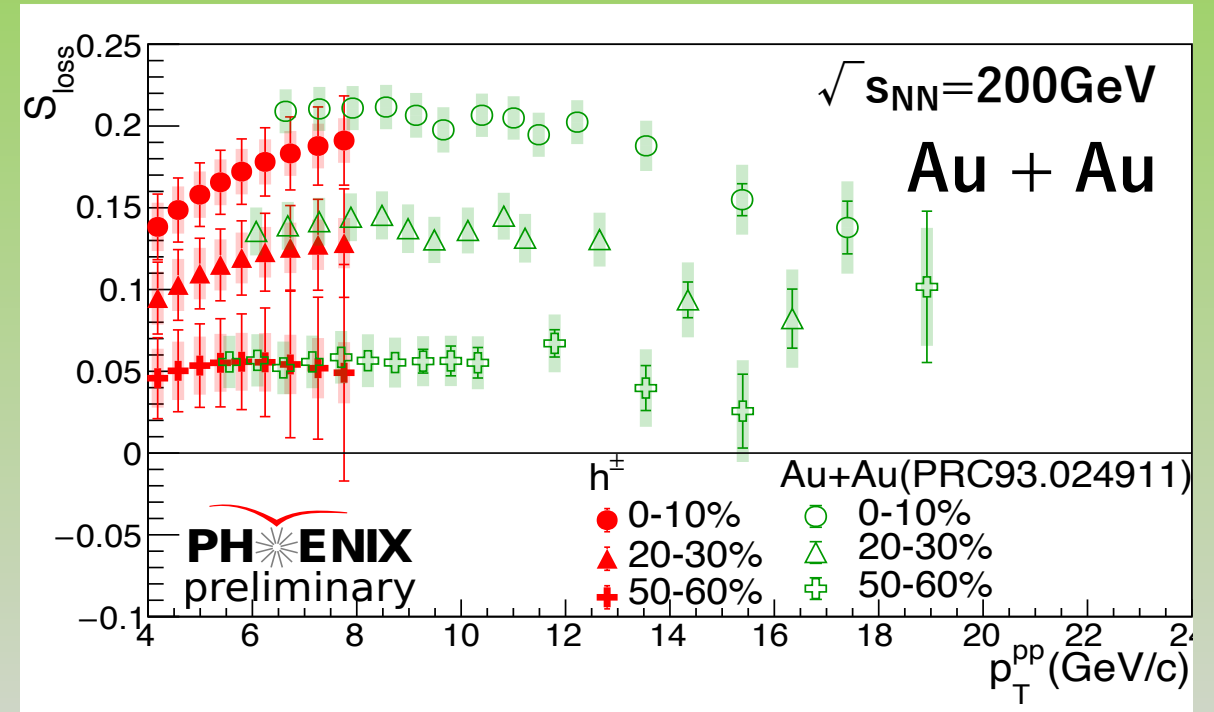


Result : S_{loss} vs. p_T



Collision size and density difference

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

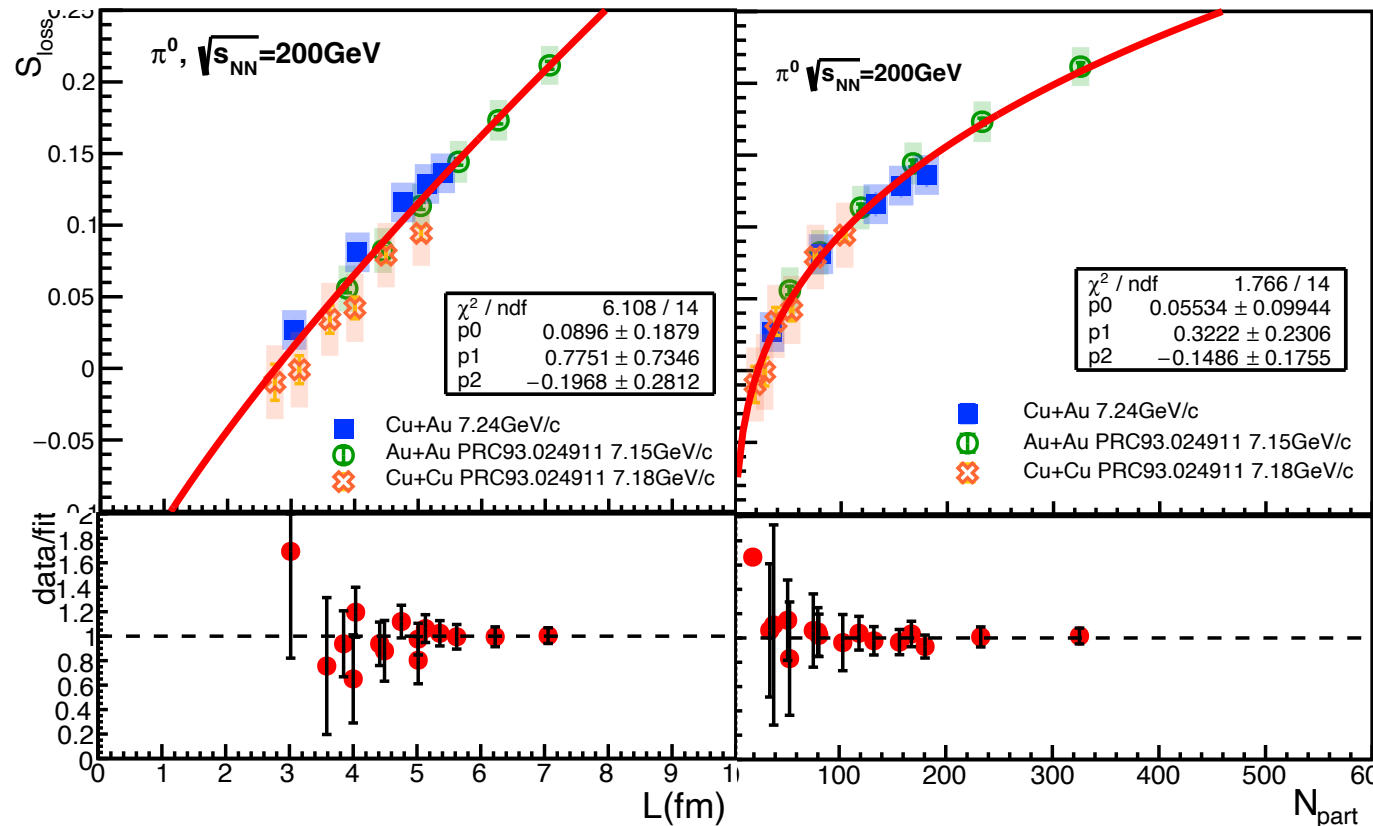


Particle species difference

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

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

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



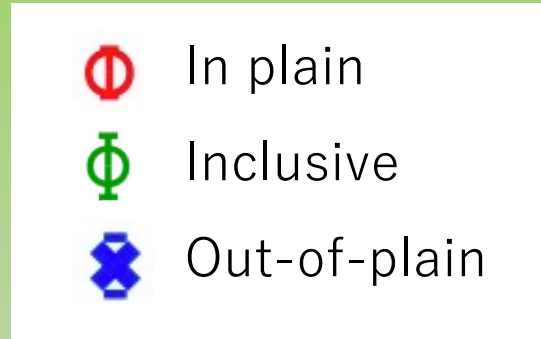
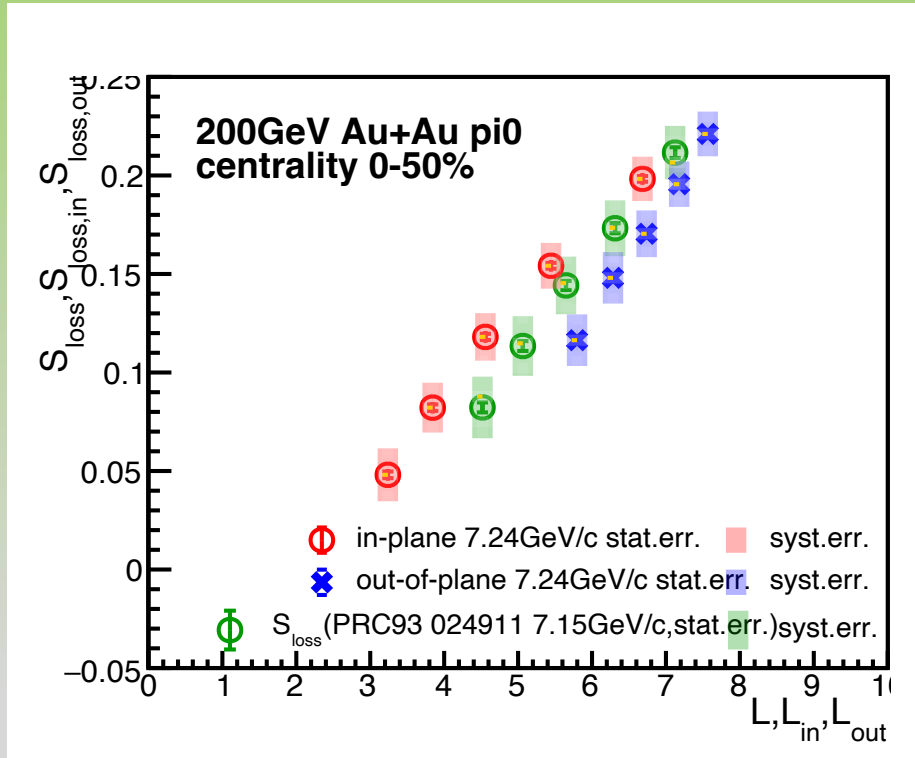
Different collision size and density

- 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} , $S_{\text{loss,in}}$, $S_{\text{loss,out}}$ vs. L

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

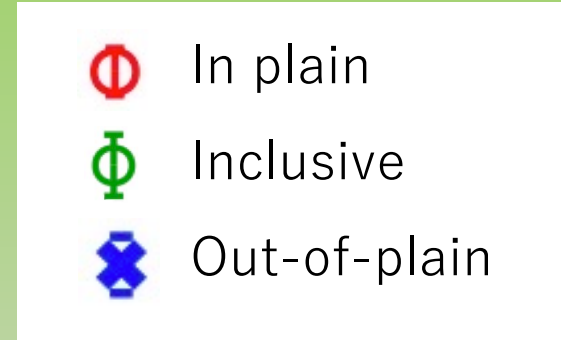
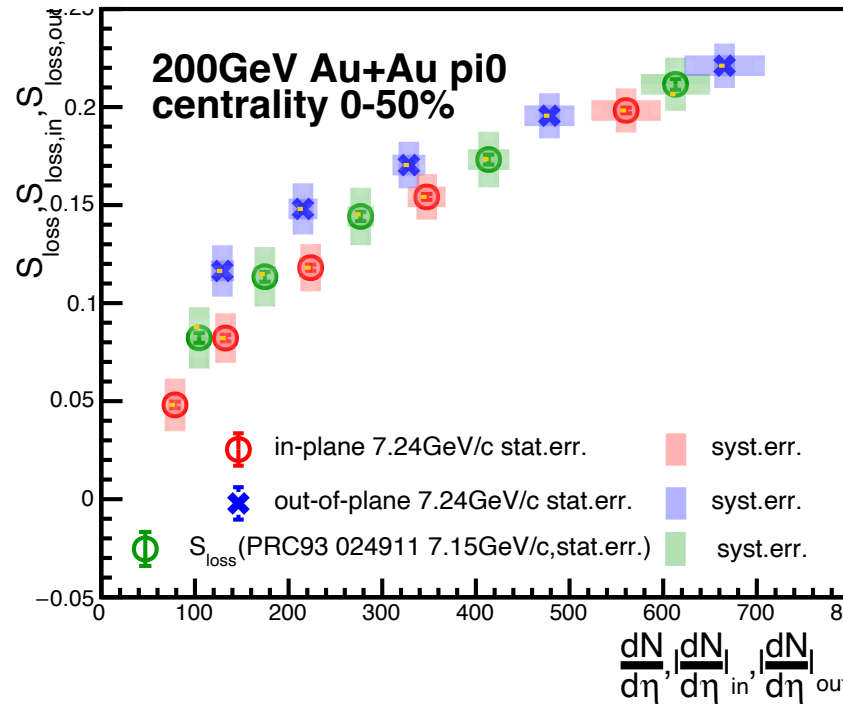
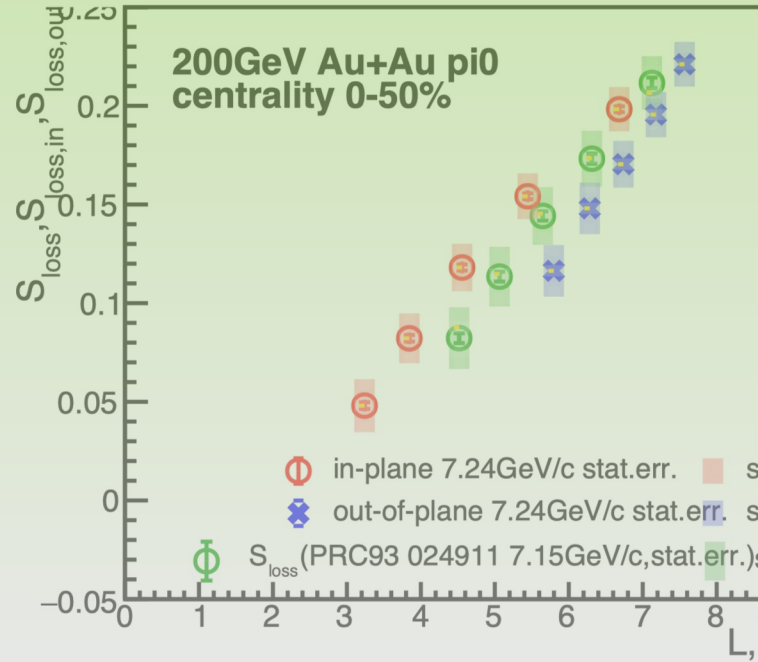


S_{loss} of in-plane and out-of-plane
 - have similar tendency.
 - but, doesn't follow the same curve
 as a function of L .

All three have different curves.

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

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

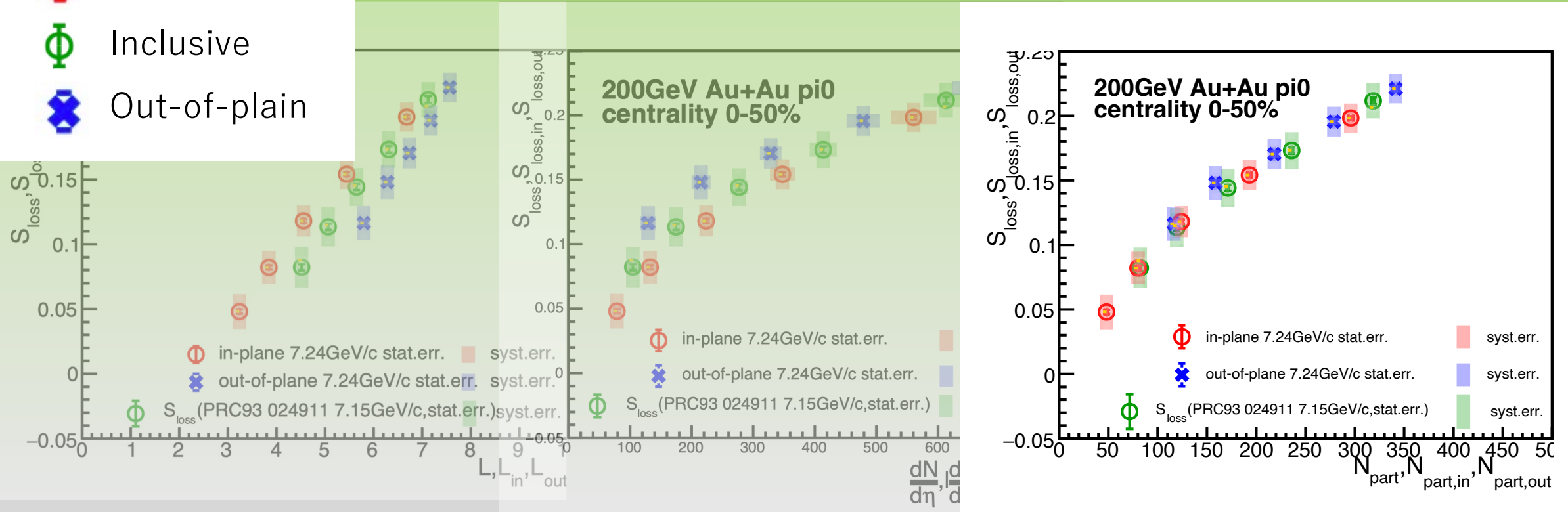


Same as L , these three S_{loss} have similar trend but doesn't follow the same curve as a function of $dN_{\text{ch}}/d\eta$.

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

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

- ⊖ In plain
- ⊖ Inclusive
- ⊗ Out-of-plane

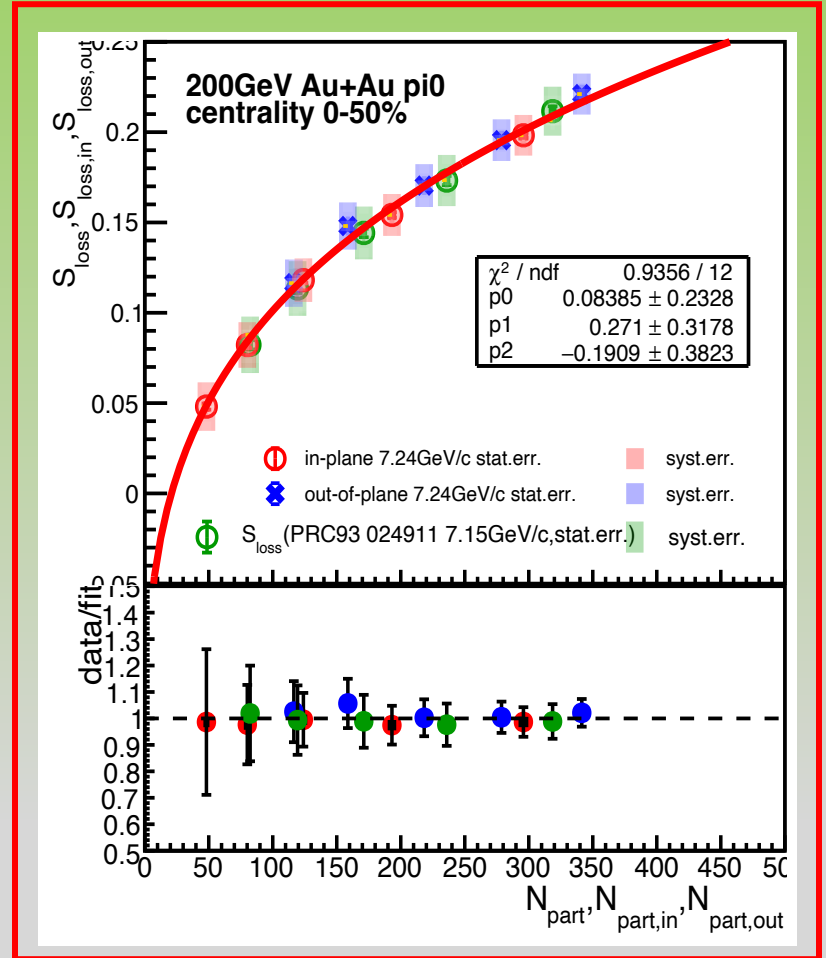
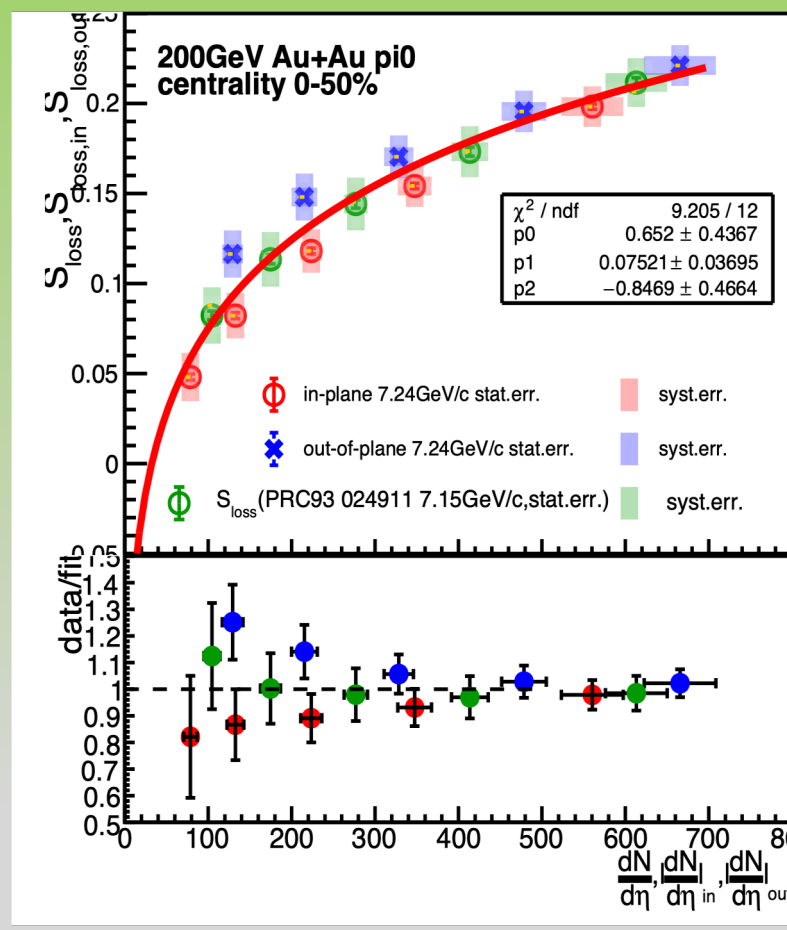
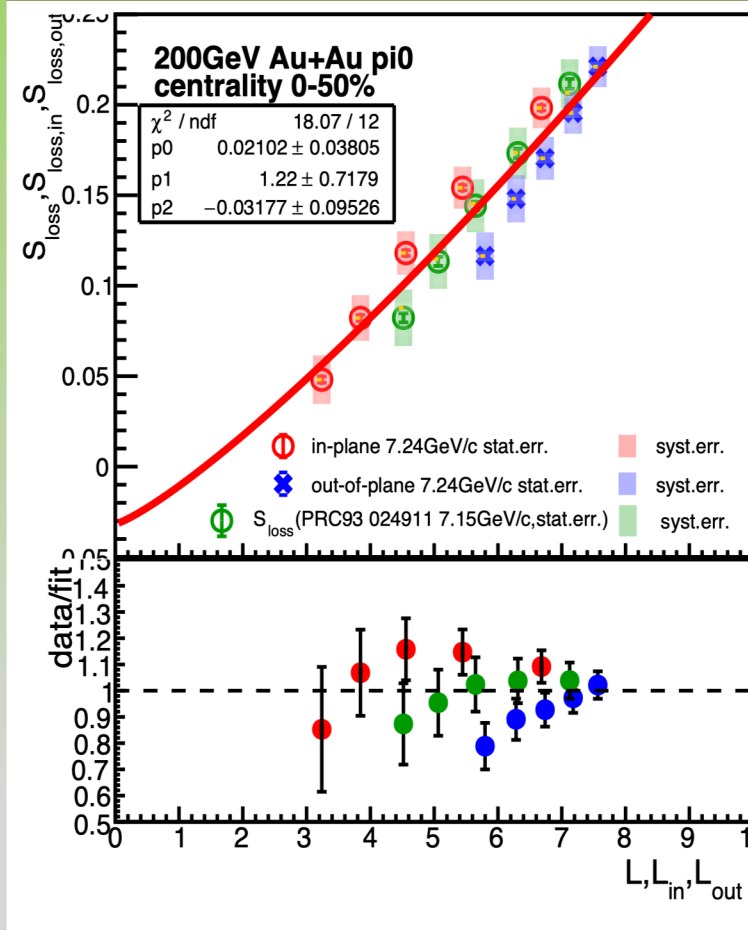


- $S_{\text{loss}}, S_{\text{loss,in}}, S_{\text{loss,out}}$ follow a curve most as a functions of N_{part} .

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

Fitting function
 $f(x) = p_0 * x^{p_1} + p_2$

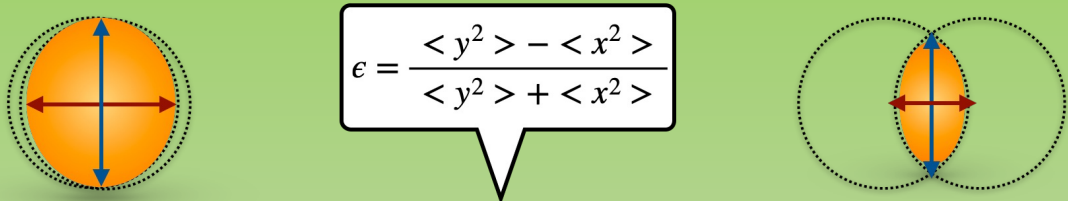
*Similar results for the measured p_T regions (4-10GeV/c)



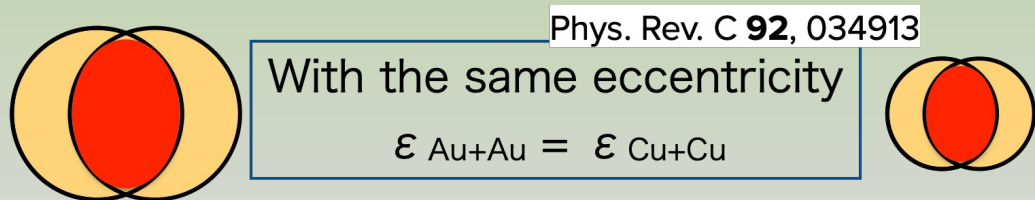
- $S_{\text{loss}}, S_{\text{loss,in}}, S_{\text{loss,out}}$ draw a curve as a functions of N_{part} better than L and $dN/d\eta$.
 → indicates the importance of initial number of particles dependence.

(3) New event classification

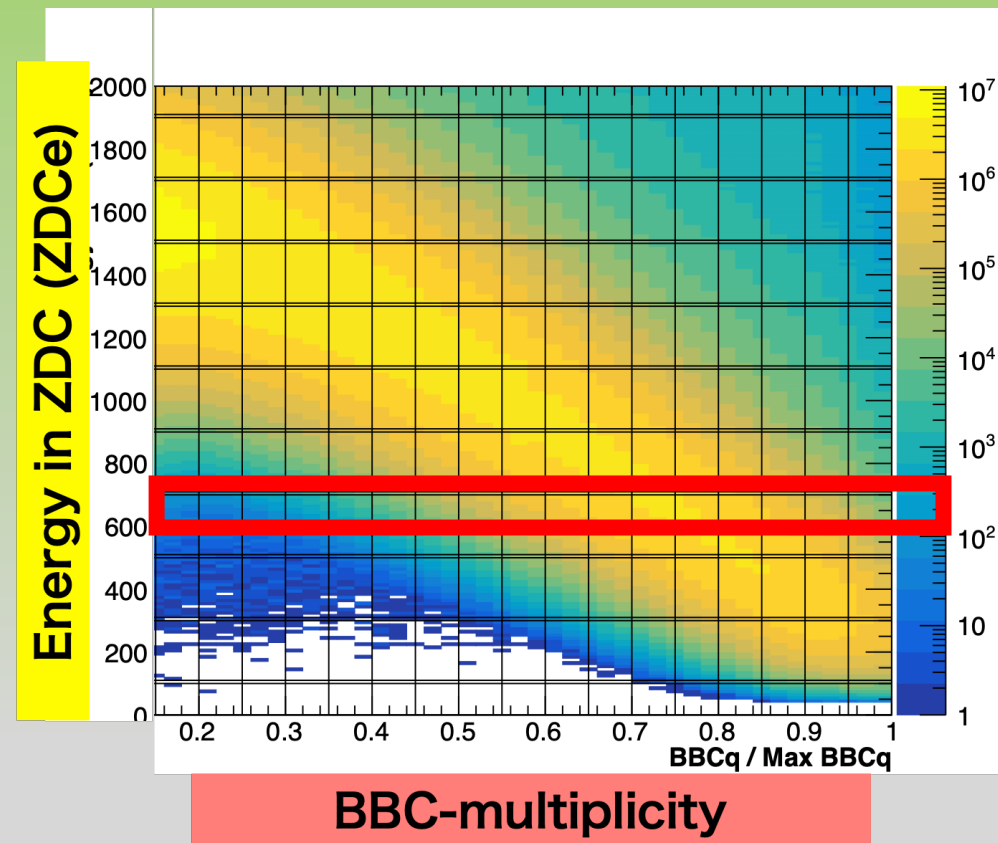
Use multiplicity and spectator info separately.



Small ← eccentricity → Large
 High ← multiplicity (dN/dη) → Low
 Large ← N_{part} → Small
 Small ← v₂ → Large



High ← multiplicity (dN/dη) → Low
 Large ← N_{part} → Small
 Large ← v₂ → Small



v_2 at different ZDCe event categorization

For the details see R. Takahama's Talk @Lake Louise Winter Institute 2023

With fixed eccentricity and N_{part} , measure v_2 as a function of multiplicity.

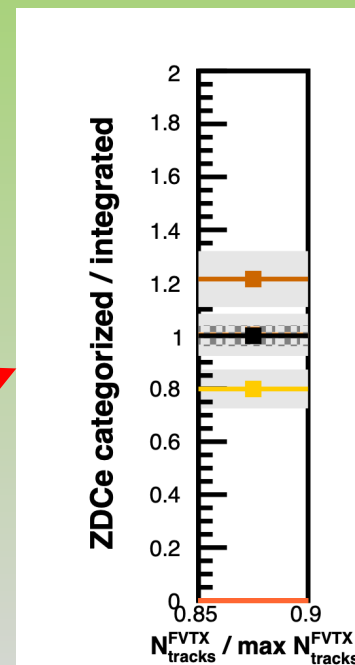
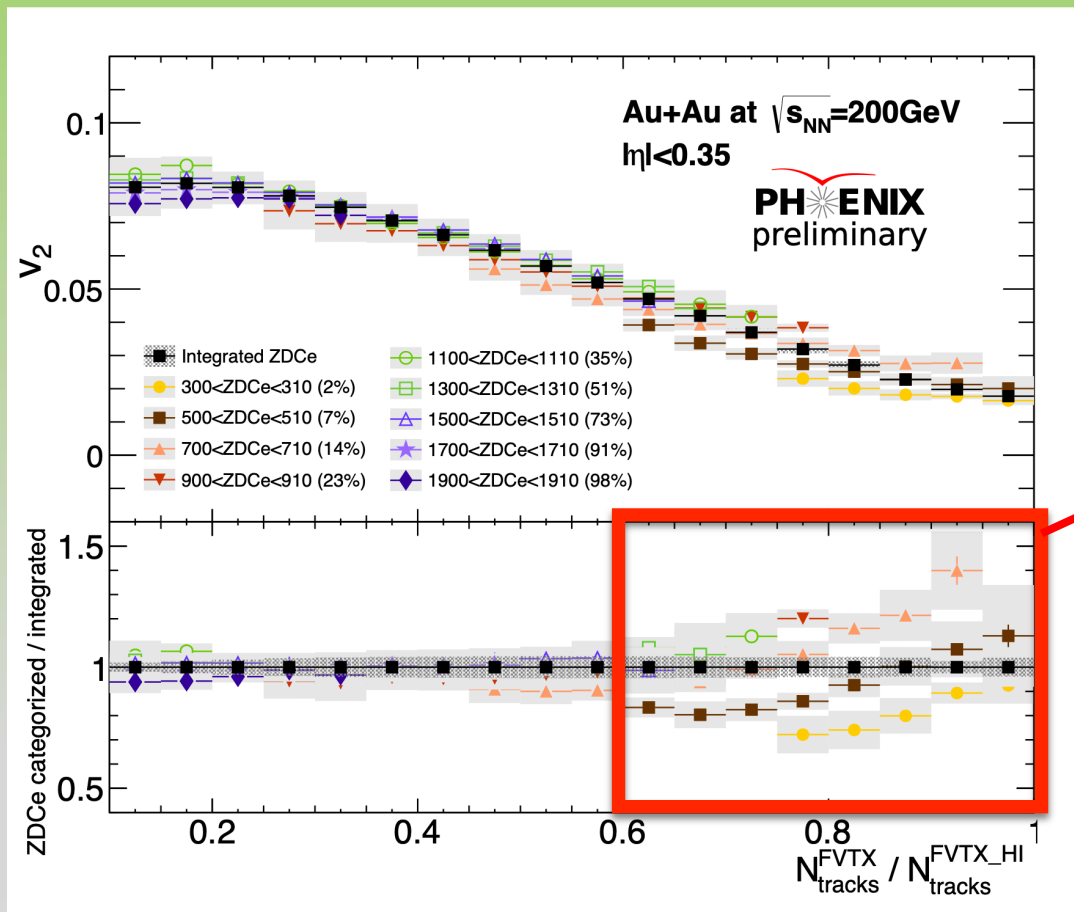
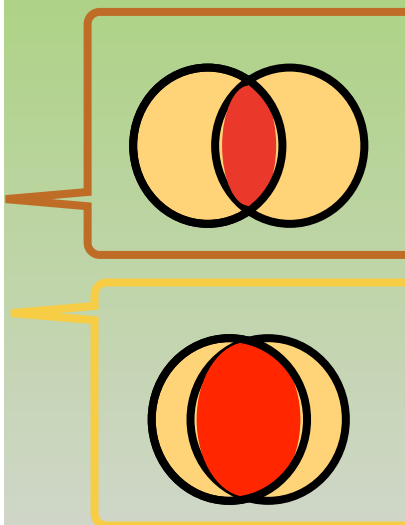


Image of the initial geometry



These v_2 seem to reflect initial geometry differences, but they have the same multiplicity.
 $\rightarrow N_{part}$ is different but $dN/d\eta$ is same.

Summary

(1) No clear R_{AA} difference have been seen (yet?) between π^0 hadrons and hf hadrons. Need more study.

(2) 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 $dN/d\eta$. The initial particle density has important role.

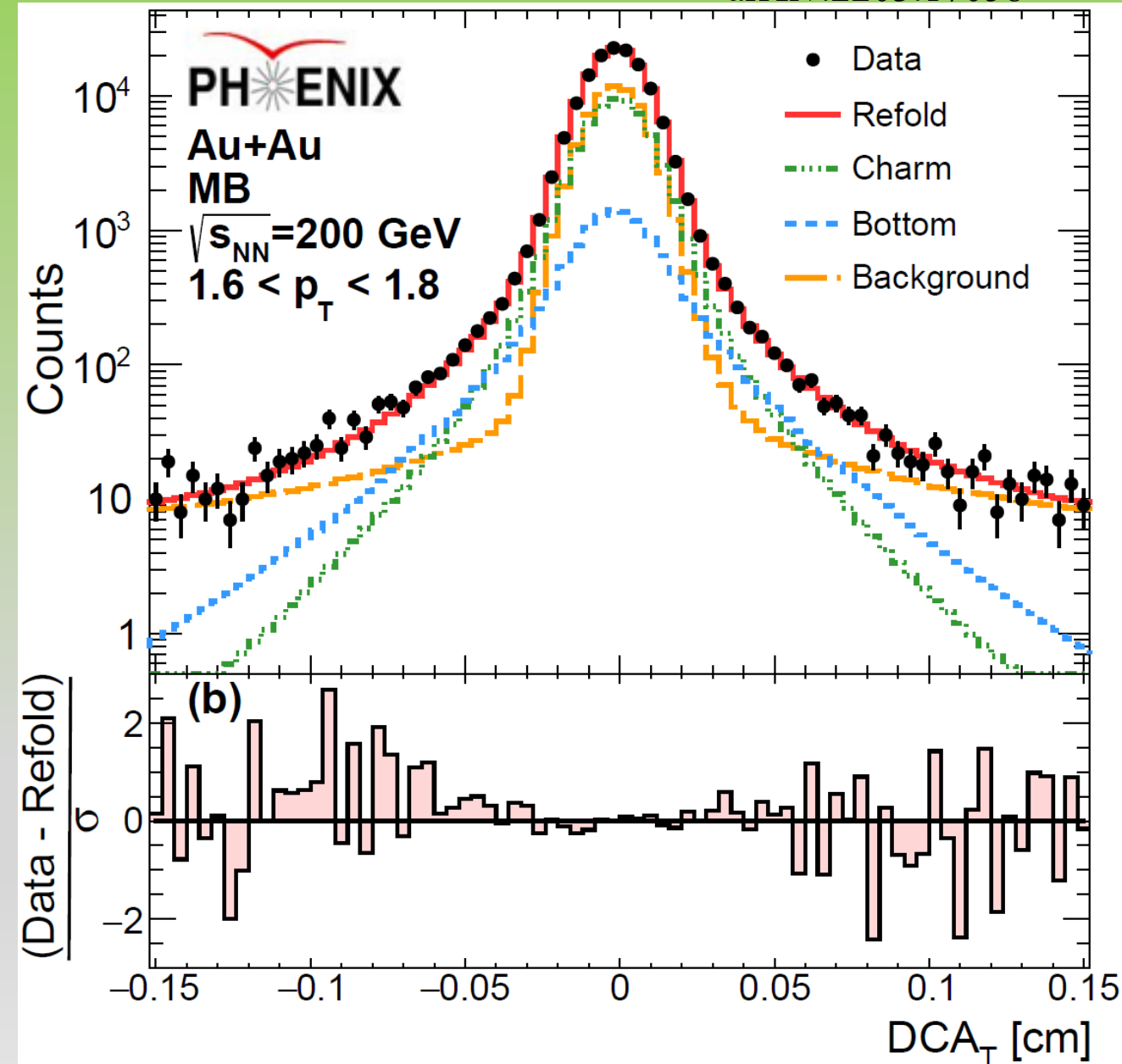
(3) New event classification can provide the results with more finely classified events.

N_{part} and multiplicity as different variables.

Back Up

Bottom and charm separation

arXiv:2203.17058

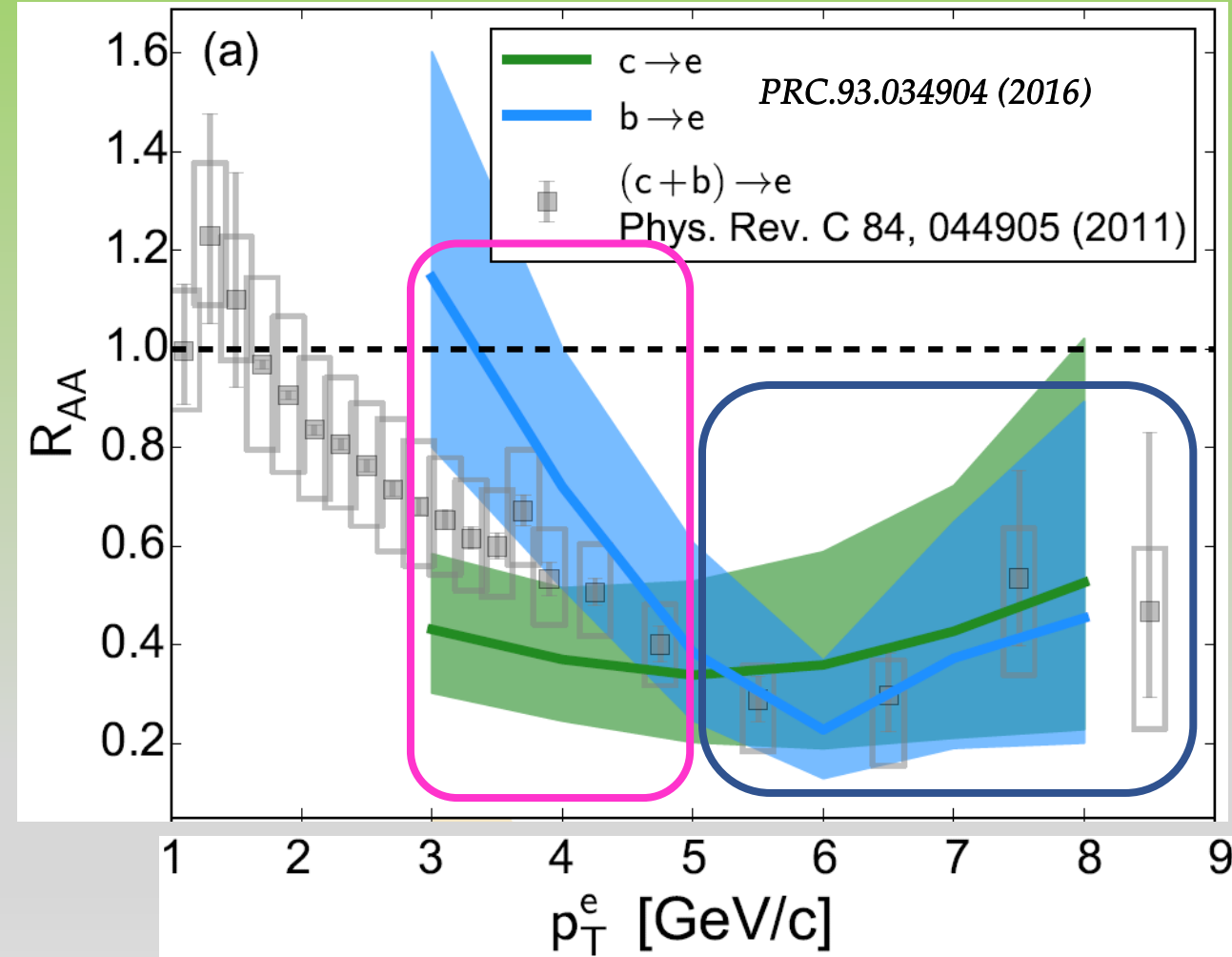


- Au+Au 200 GeV in 2014
 - 17 B events = 3 times larger than 2011
- Electrons from charm and bottom hadron decays
- Charm and bottom separation using the distance-of-closest-approach (DCA) and p_T distribution
- Bayesian unfolding method:
 - Separates charm and bottom contribution in electrons
 - Extract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

Findings2 : HF Mass dependence of suppression

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

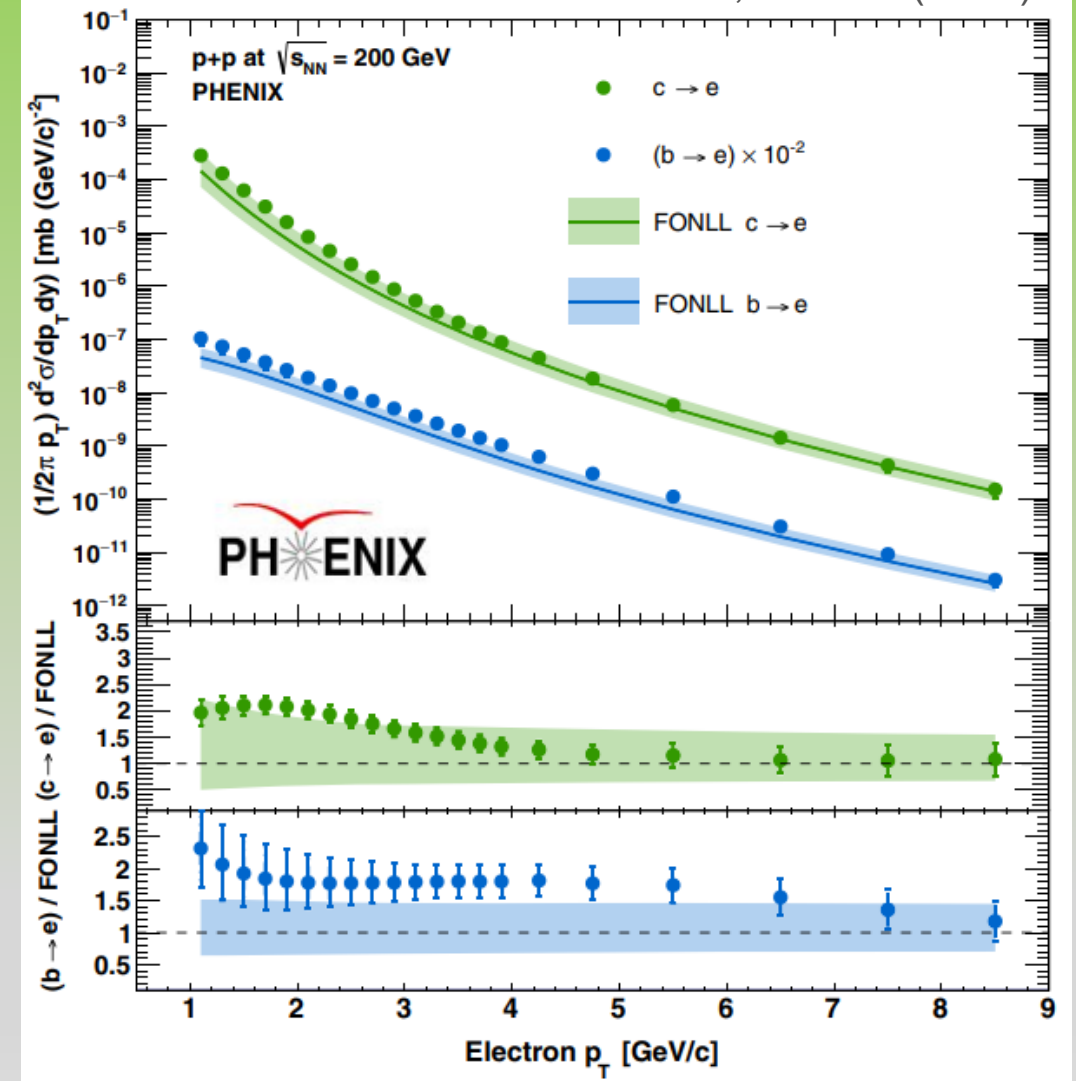
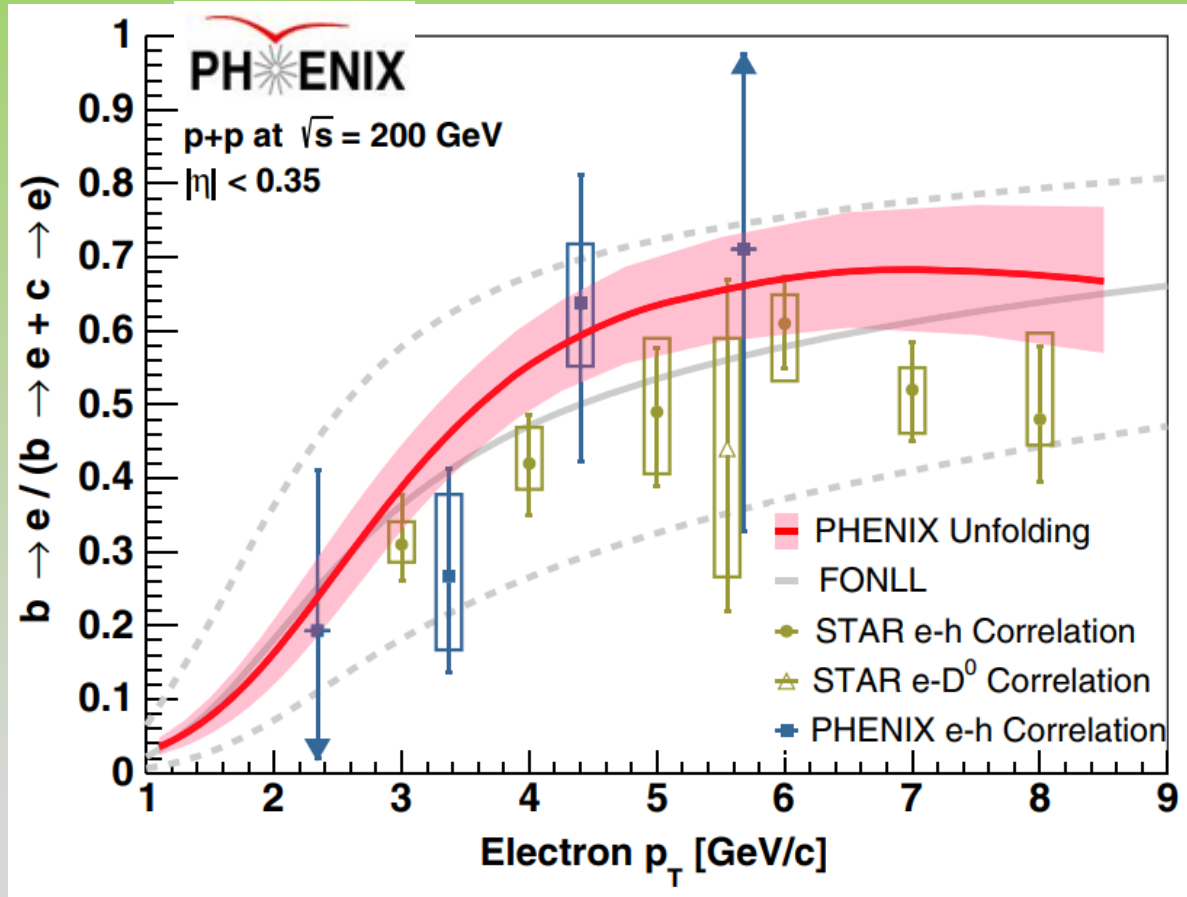
- Both are suppressed at high p_T
 - $R_{AA}(b) \sim R_{AA}(c) < 1$ at high p_T
- B is less suppressed at low p_T
 - $R_{AA}(b) > R_{AA}(c)$ at low p_T
- Consistent with the expected mass ordering
 - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Radiative loss @ high p_T
- Coll. & Rad. 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)

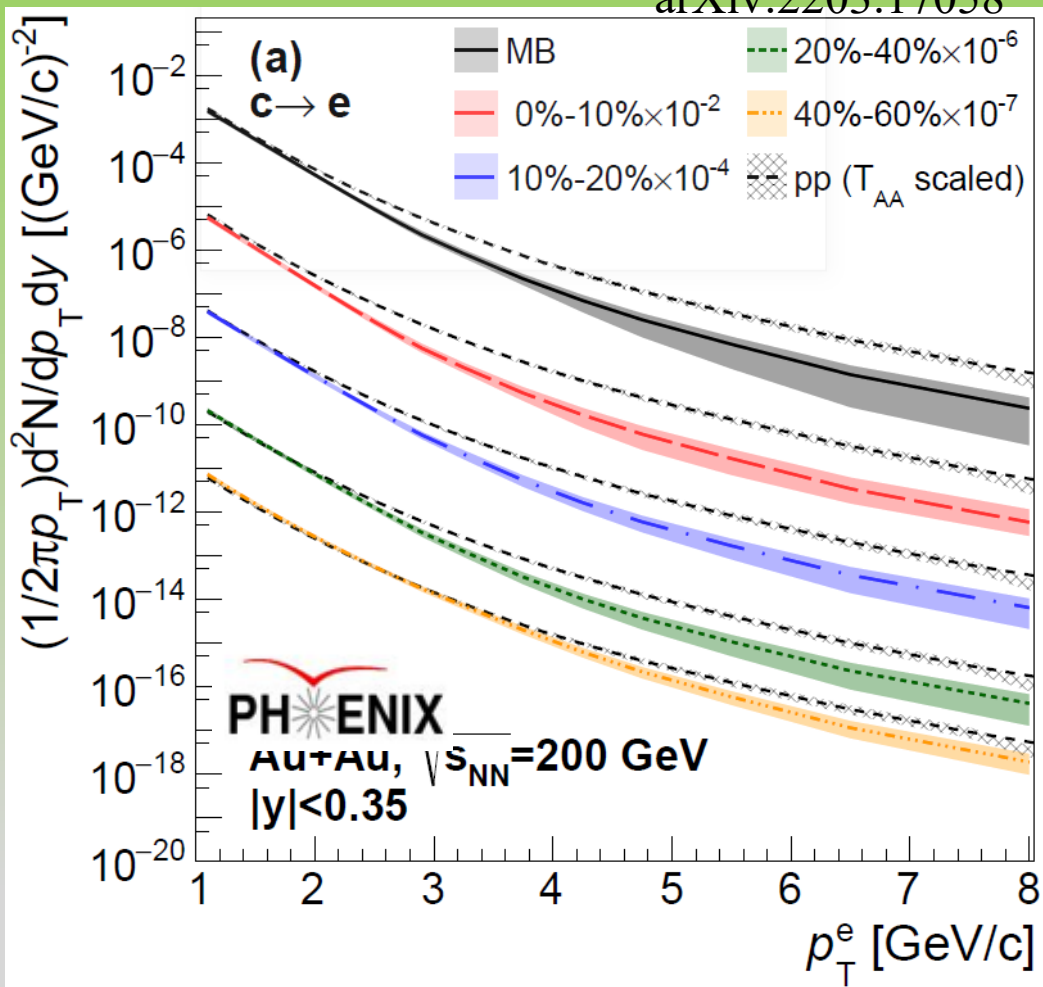
PRD 99, 092003 (2019)



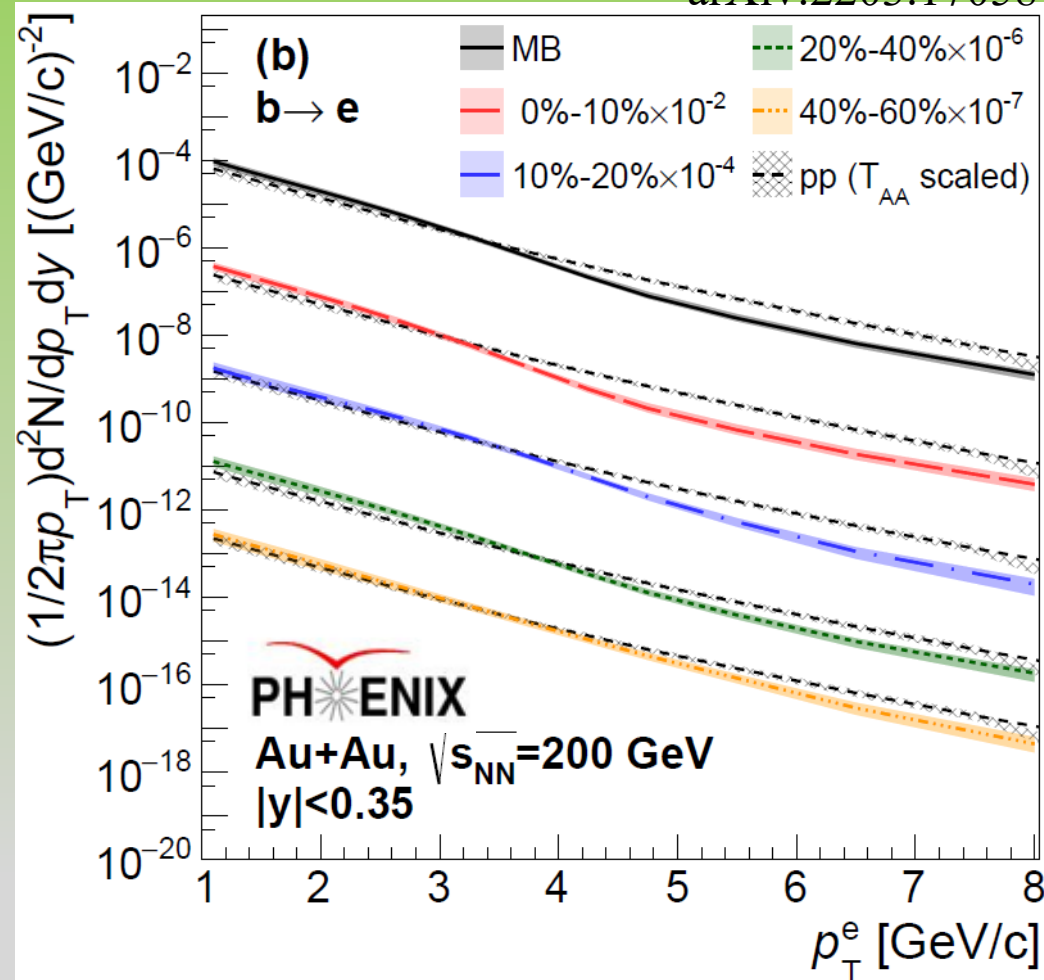
- New p + p baseline of bottoms and charms available w/ $p_T = 1 \sim 8$ GeV/c

Charm and Bottom Electron yields in Au+Au

arXiv:2203.17058

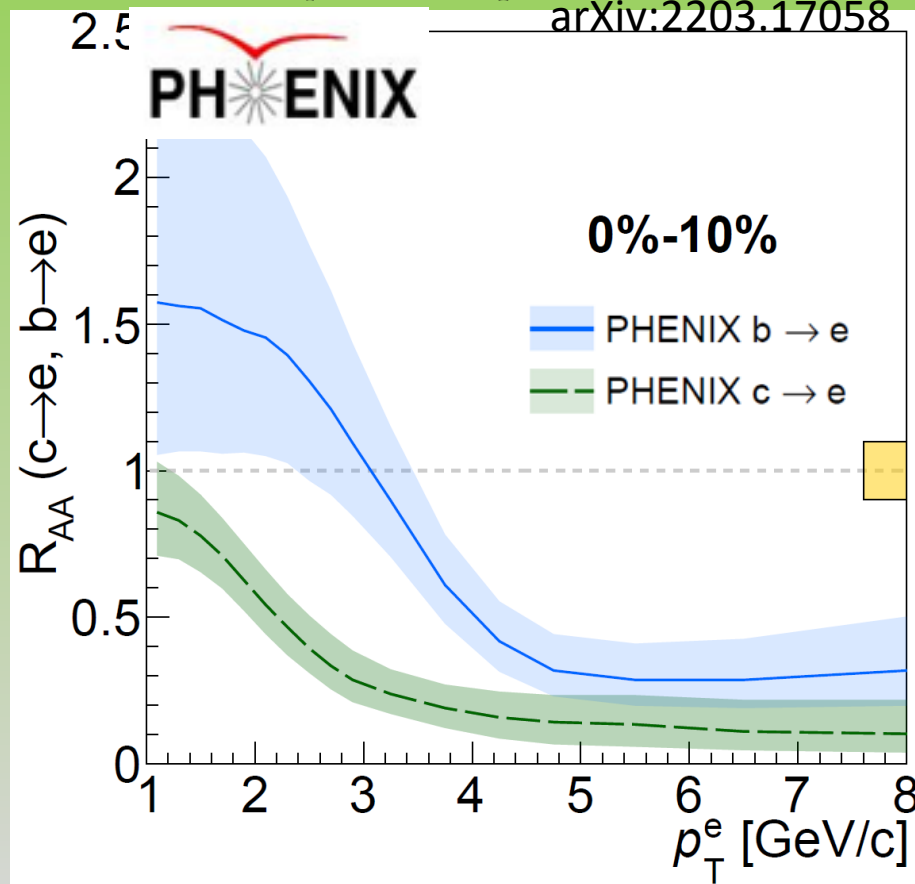


arXiv:2203.17058

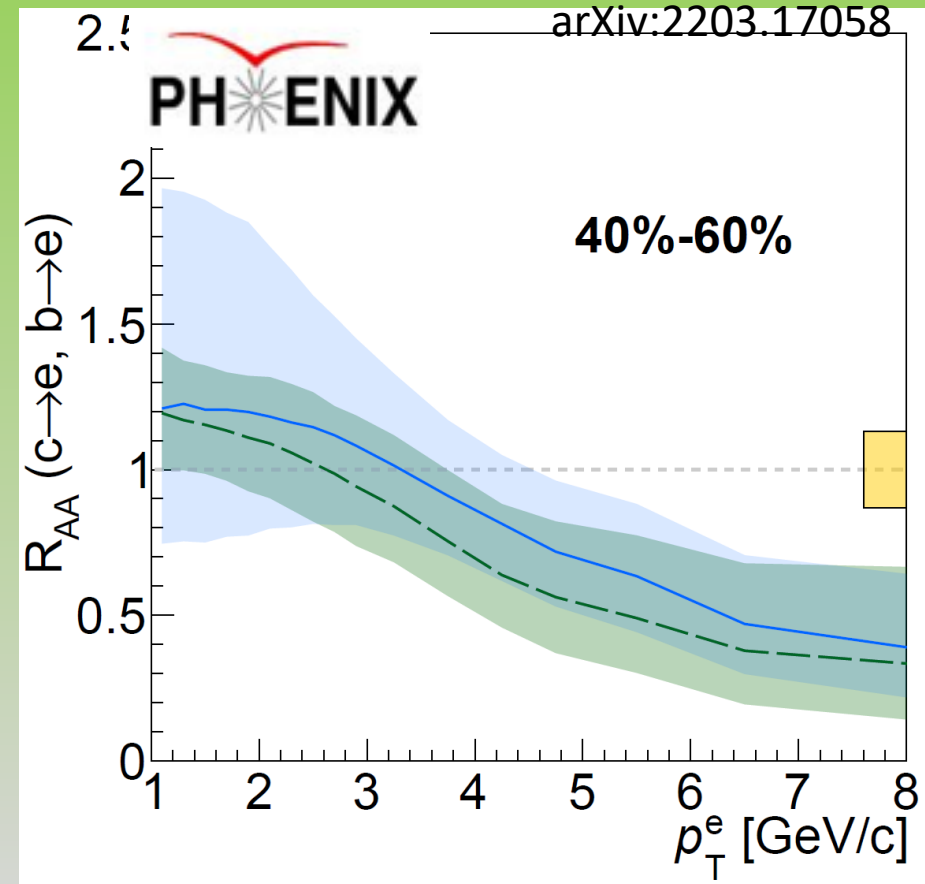


- Yields in Au+Au are measured in MB, 0-10, 10-20, 20-40, 40-60%
- Show the difference from p+p scaled by T_{AA} at high p_T

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



c and b are different and suppressed.

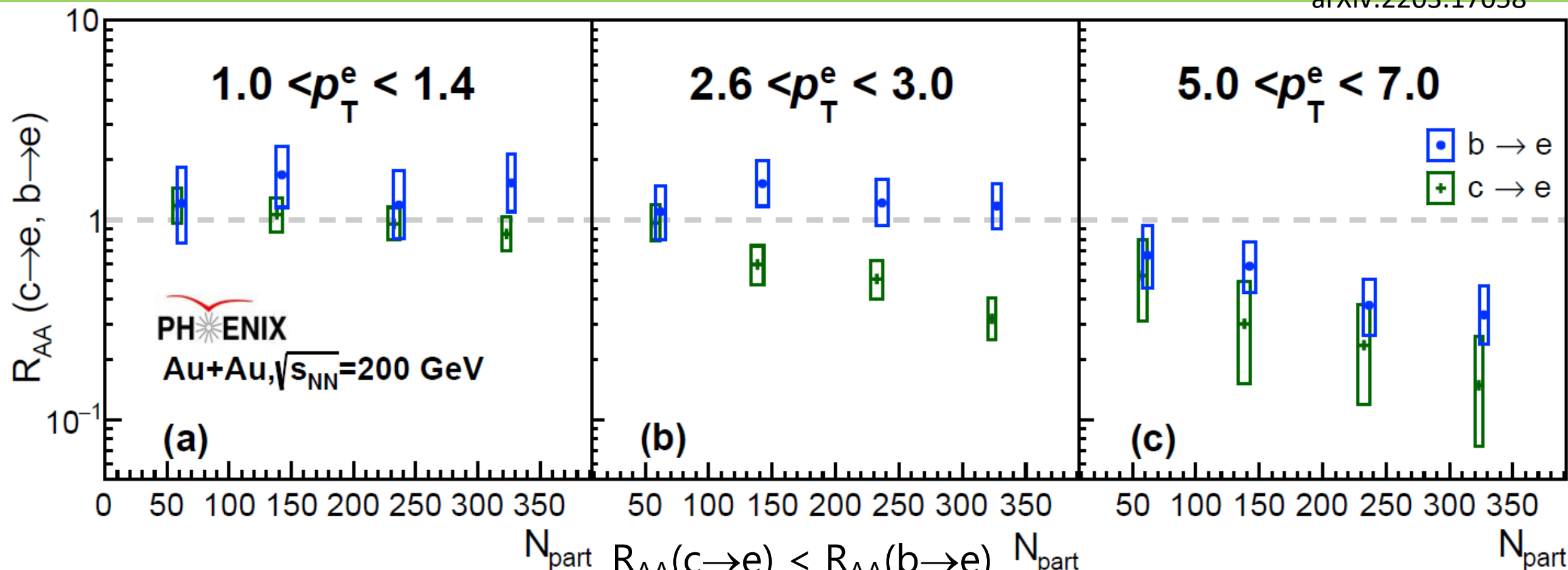


c and b are similar and less suppressed.

Centrality dependence of the energy loss is seen as expected.

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

arXiv:2203.17058



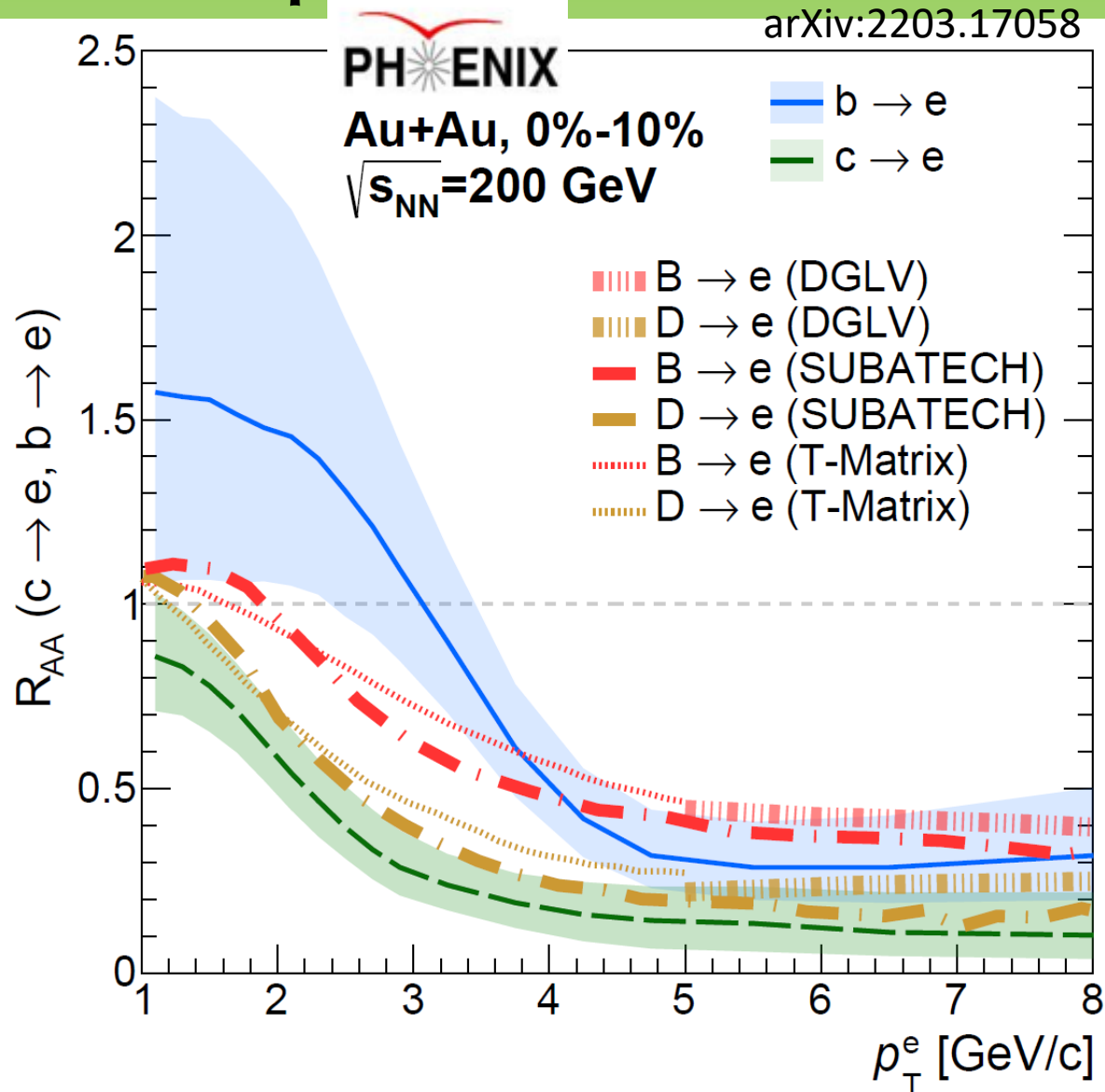
$R_{AA}(c \rightarrow e) \sim R_{AA}(b \rightarrow e) \sim 1$

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

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

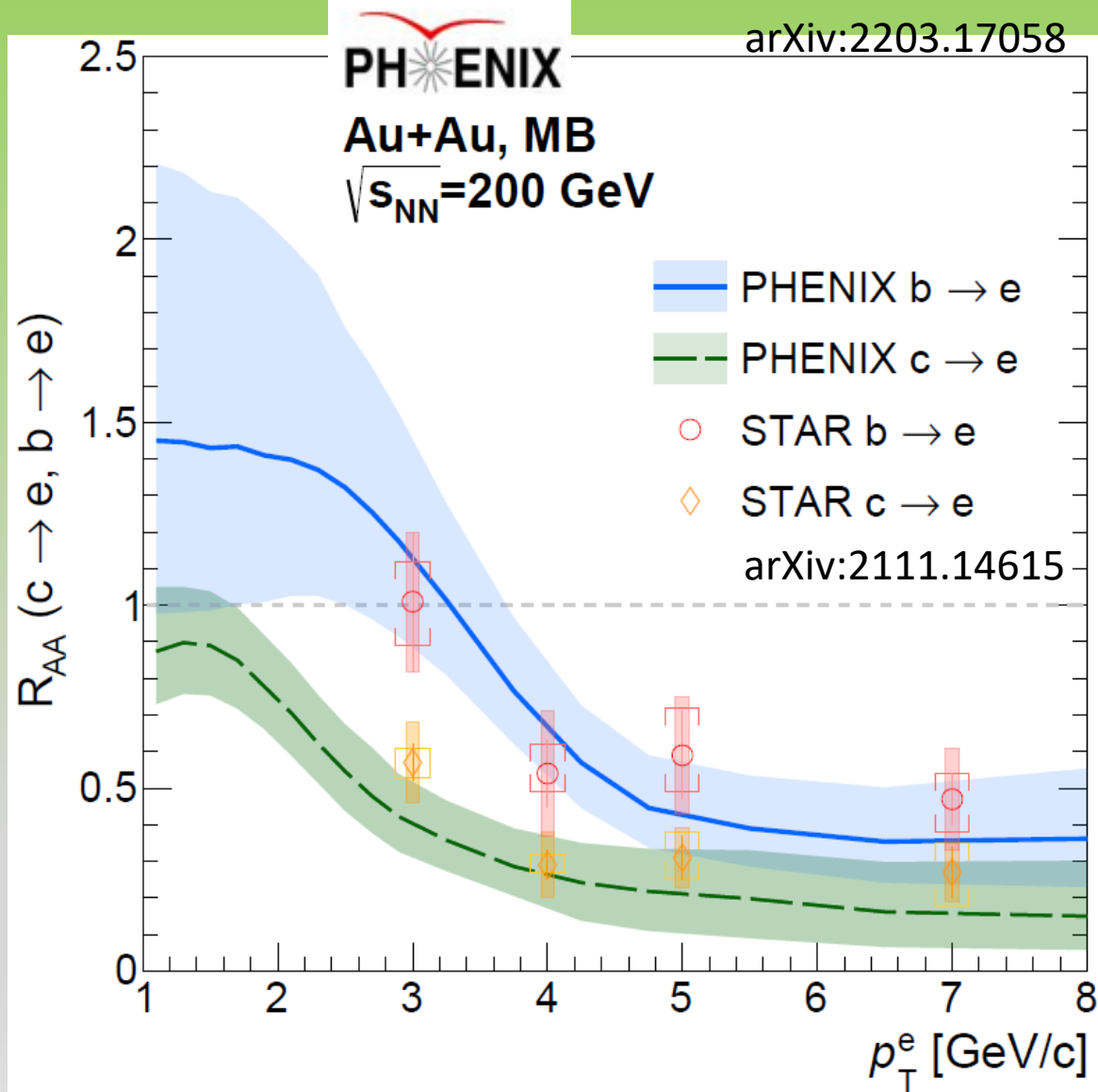
Centrality and p_T dependence are observed

Comparison with Models



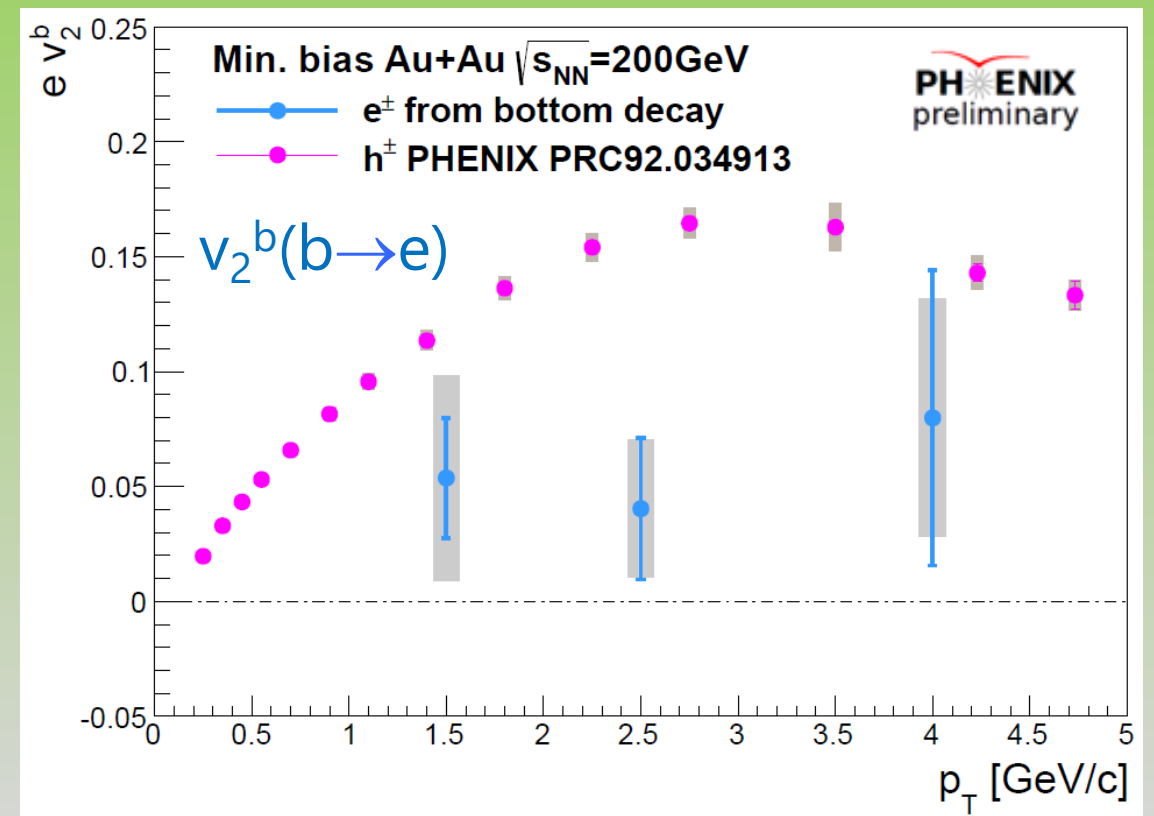
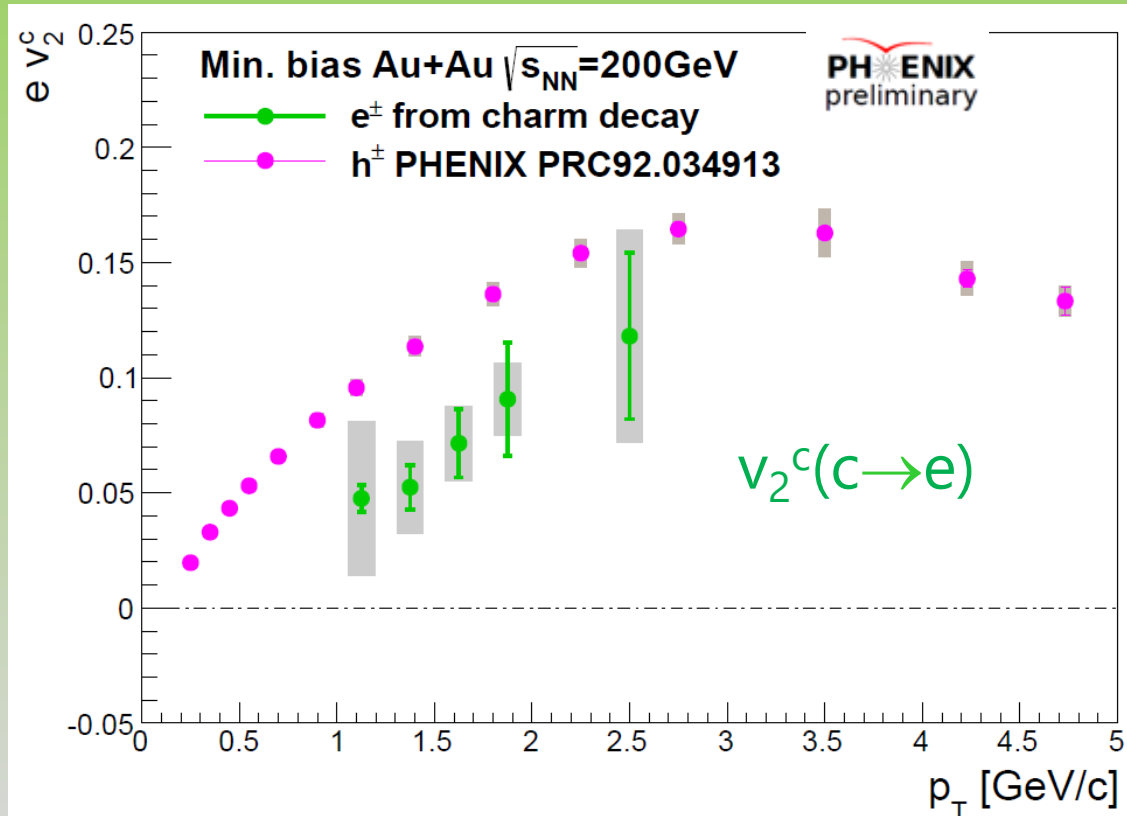
- 3 models
 - DGLV (Phys. Rev. C 90 034910)
 - E-loss + plasma w/ static potentials
 - SUBATECH (Phys. Rev. C 78 014904)
 - : E-loss + running coupling
 - T-Matrix + diffusion ($2\pi TD=4$) (Phys. Rev. Lett. 100 192301)
 - Strongly coupled QGP
- E-loss models agree with data at high p_T
- At low p_T
 - **b models underestimates the data**
 - **c models slightly higher than data**

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

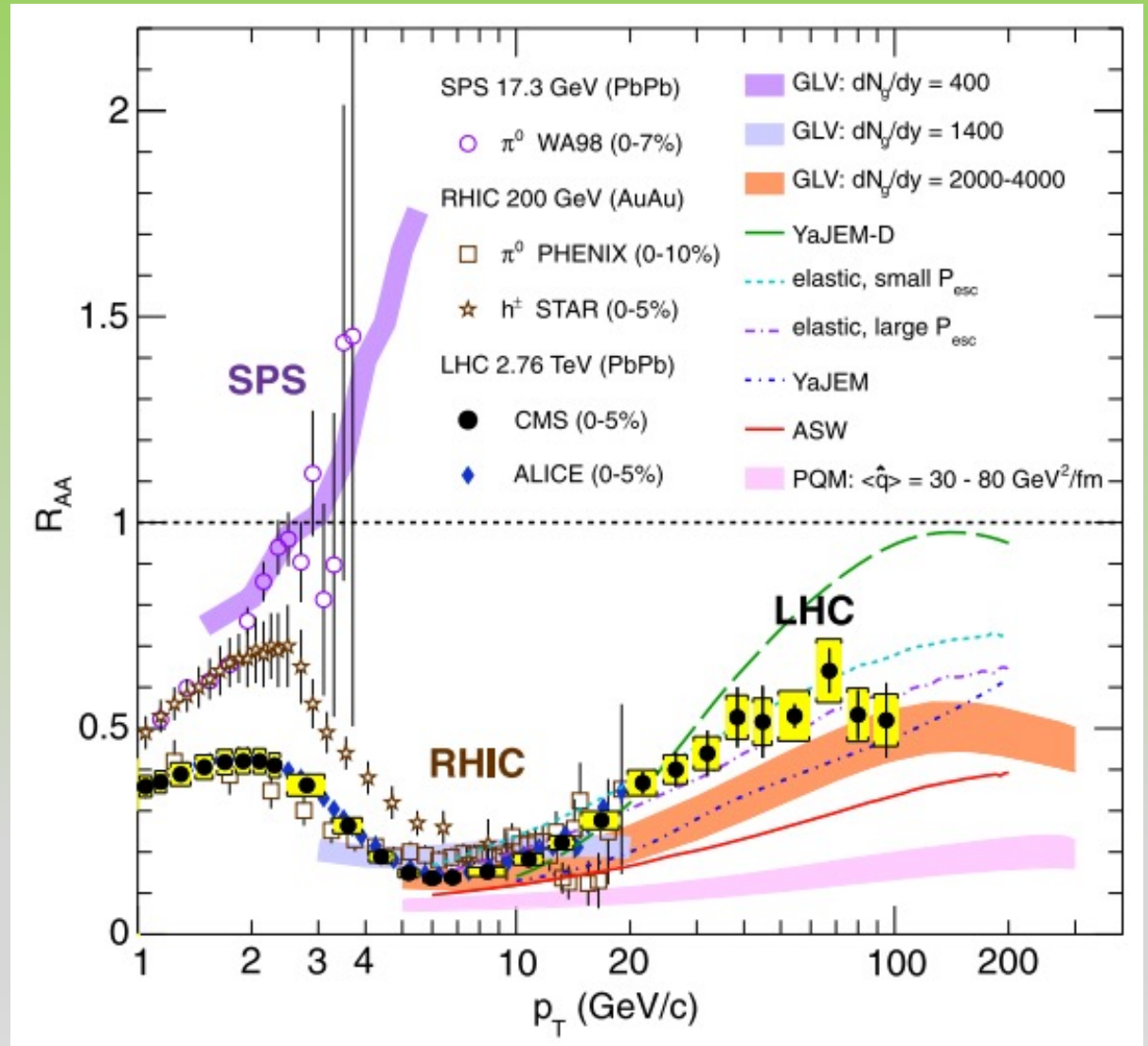


- PHENIX MB and STAR 0-80% are in good agreement within uncertainties

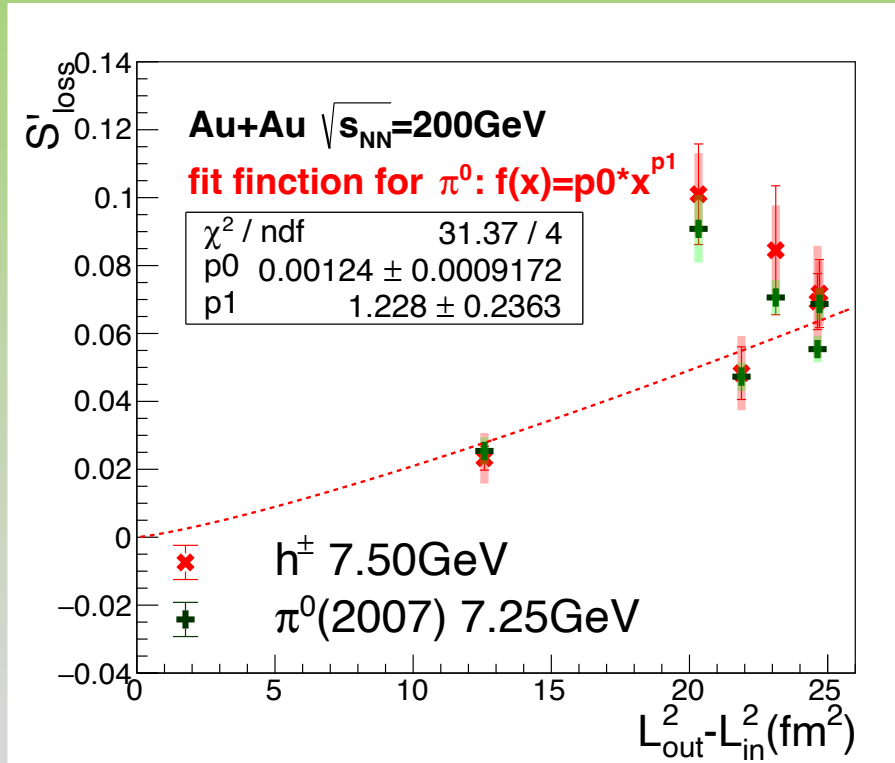
$v_2^c(c \rightarrow e)$ and $v_2^b(b \rightarrow e)$ in Au+Au 200GeV



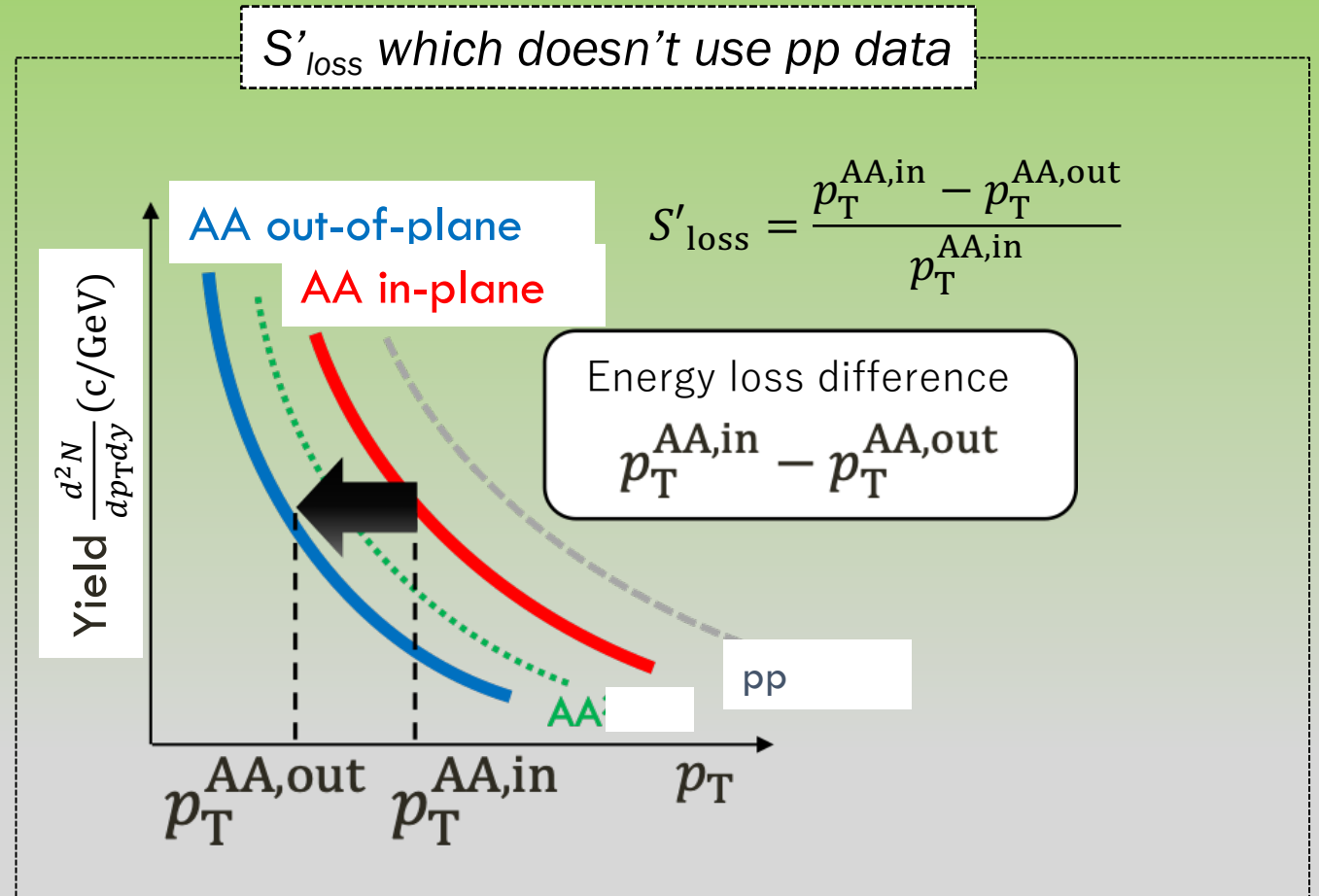
- $v_2(c \rightarrow e)$ is positive with ~ 3.5 sigma
- $v_2(b \rightarrow e)$ indicates positive with 1.1 sigma
- Mass ordering is seen --> consistent with energy loss expectation.



S'_{loss} without pp collisions



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

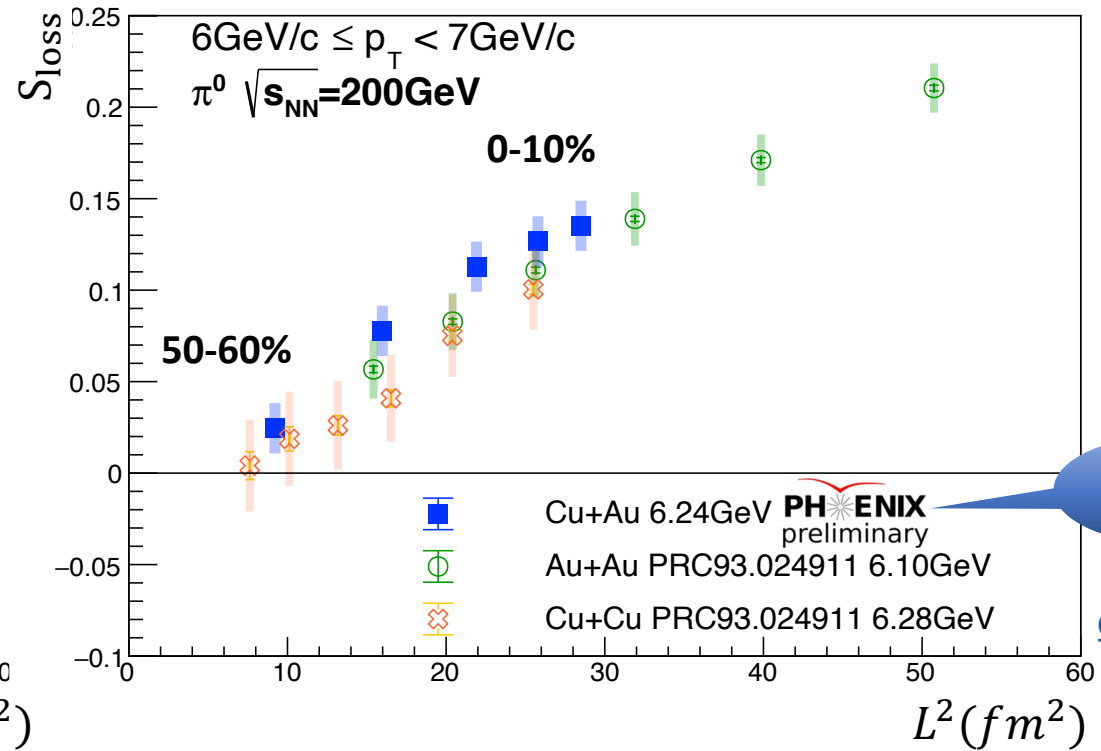
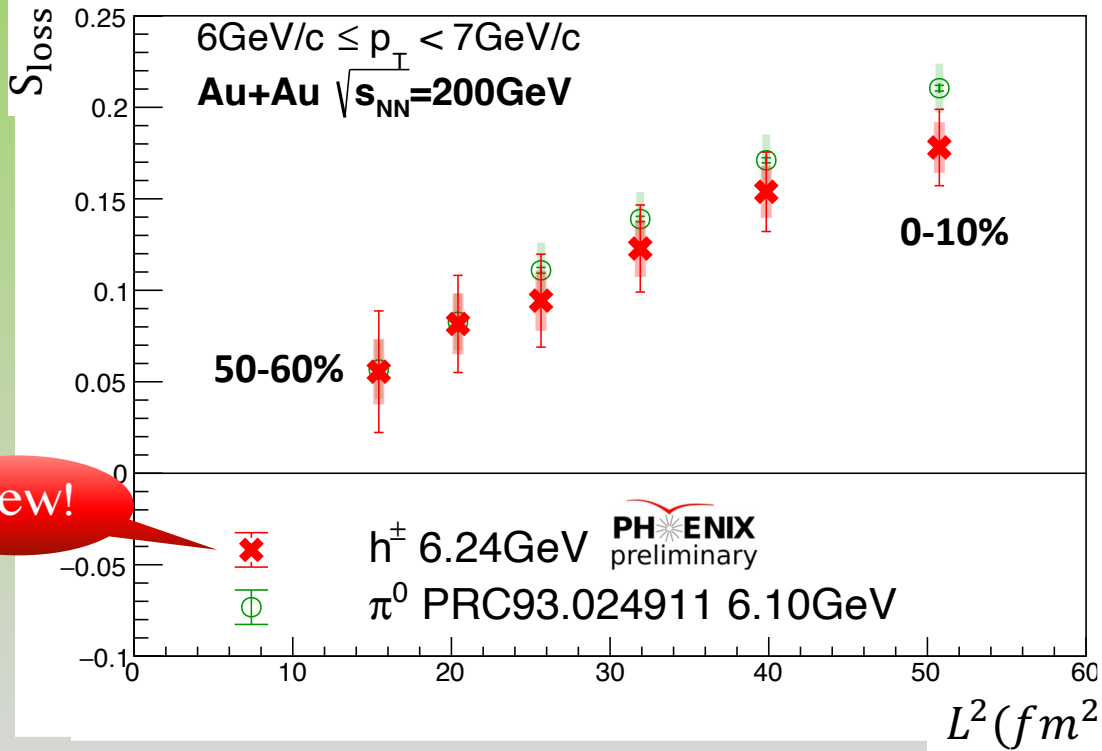


S_{loss} vs. L^2 (h^\pm (Au+Au), π^0 (Cu+Au))

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

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

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

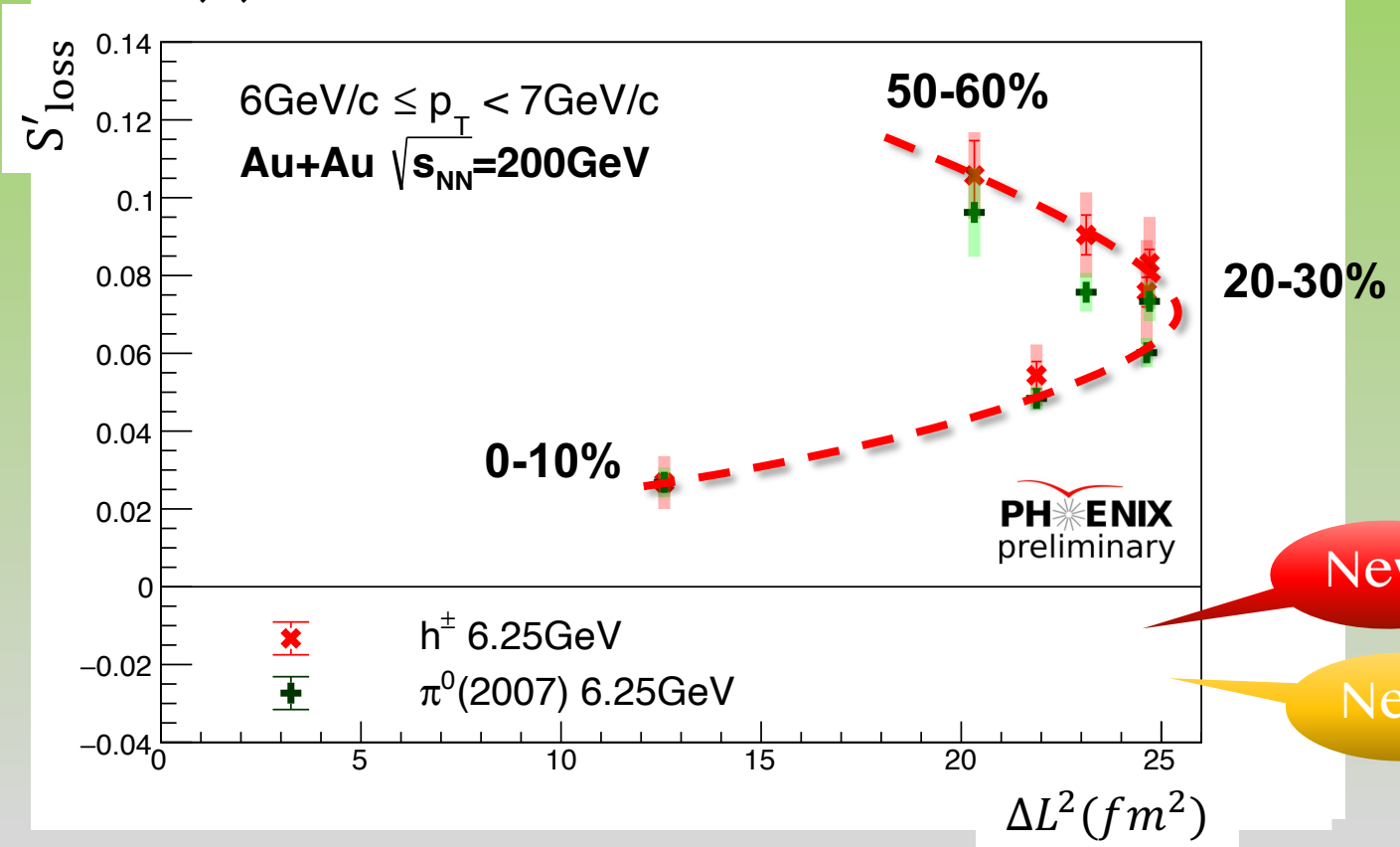


- S_{loss} is proportional to L^2 for both h^\pm s and π^0 s, and it is common in Au+Au, Cu+Cu, and Cu+Au.
- It implies the gluon radiation loss is dominant.

S'_{loss} VS. $\Delta L^2 (= L^2_{out} - L^2_{in})$ (h^\pm, π^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.

New!

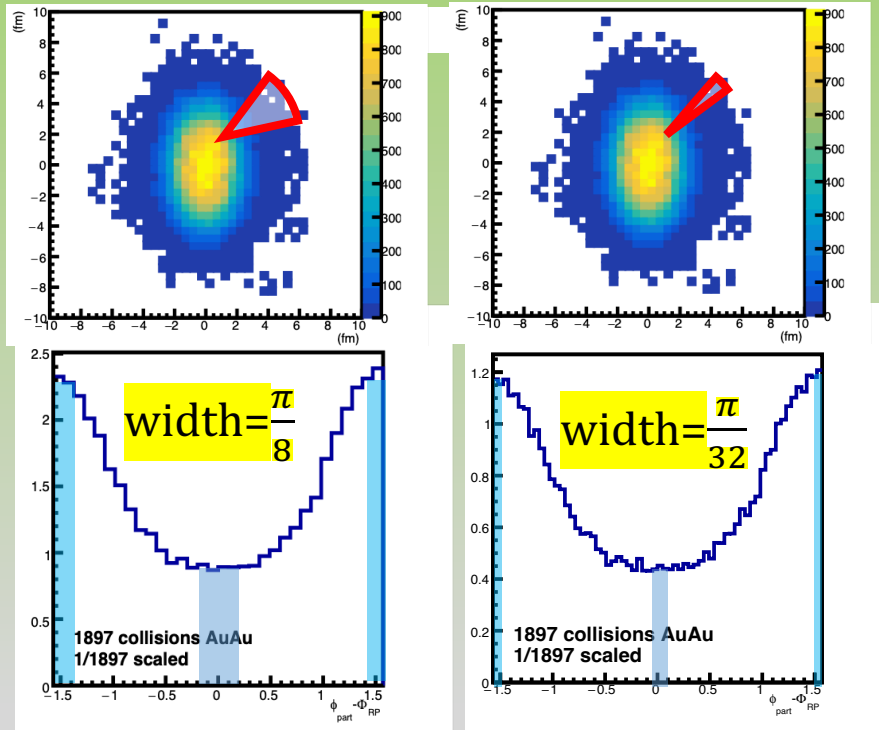
New!

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

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

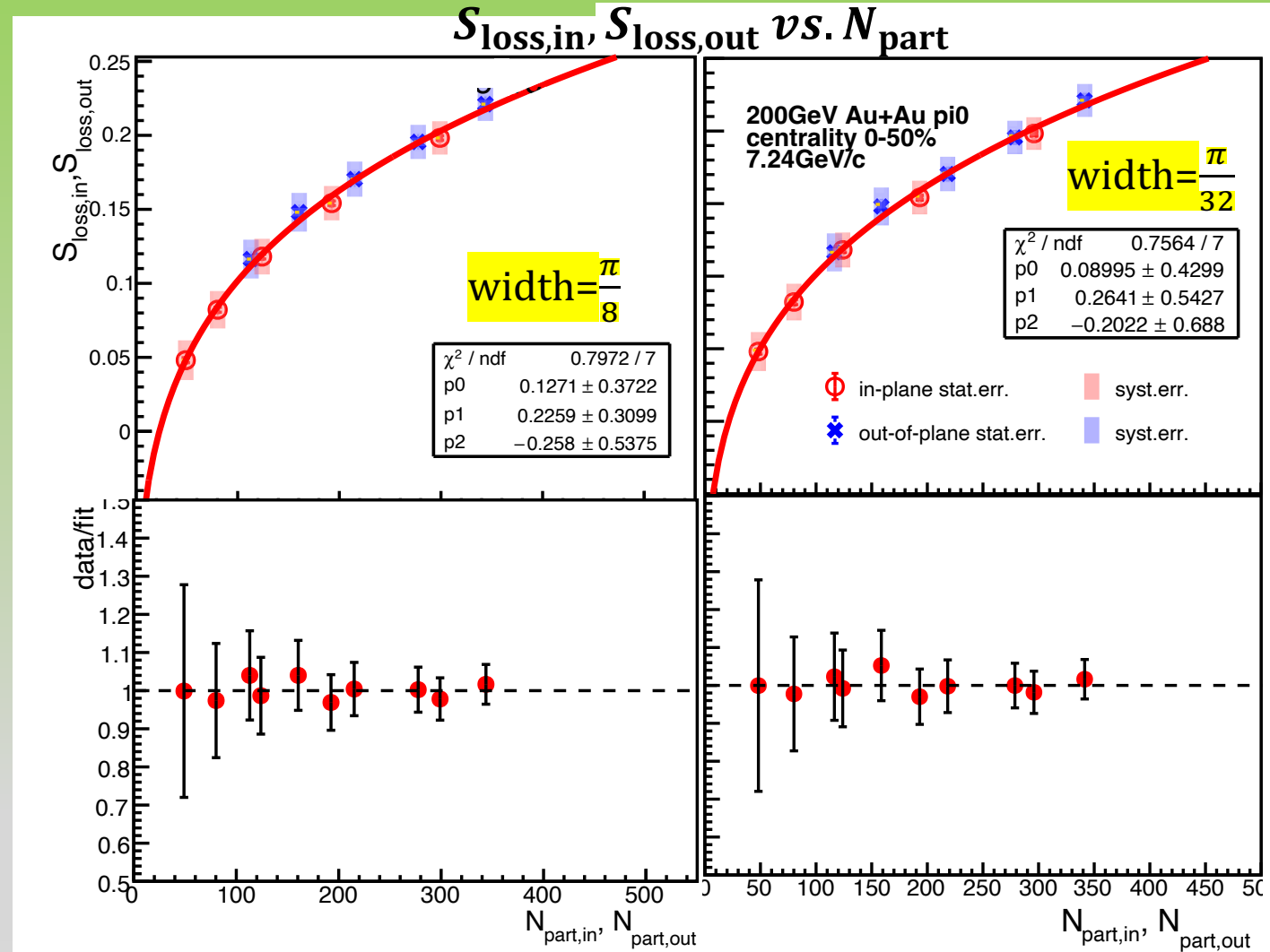
Systematic uncertainty from the calculation of $N_{\text{part,in}}N_{\text{part,out}}$

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



- No significant different of χ^2/ndf

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

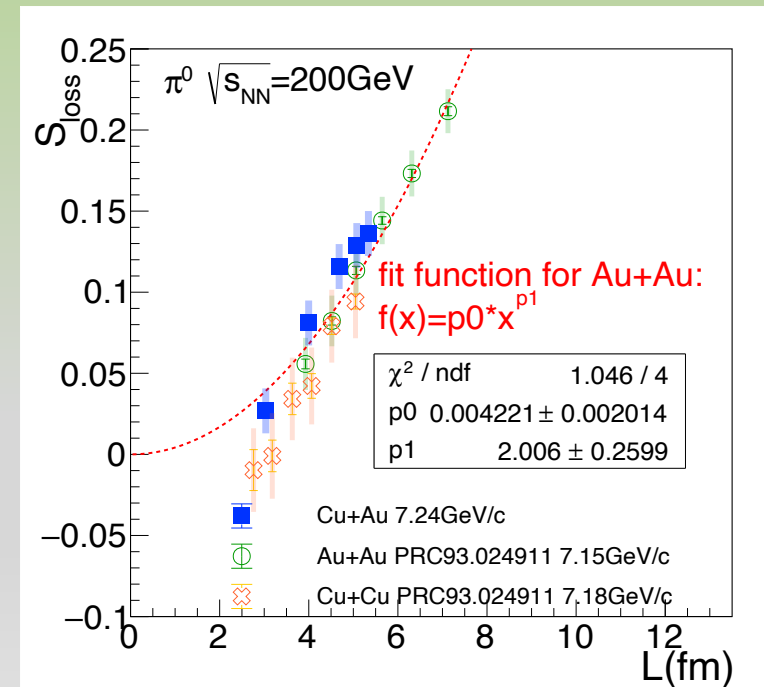
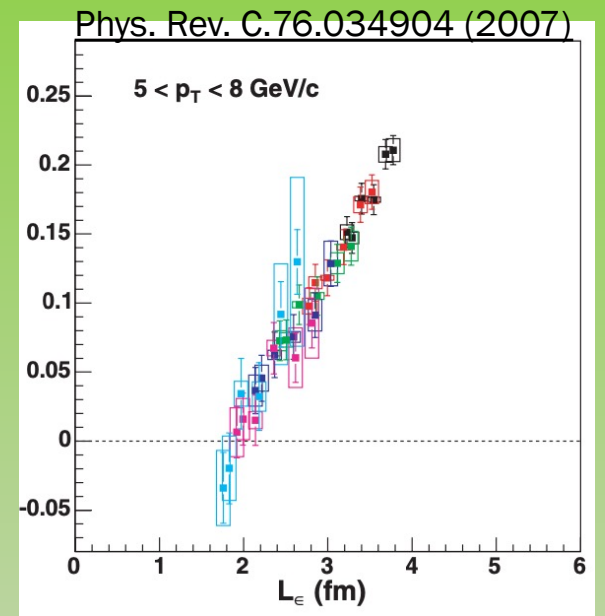


L dependences

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

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

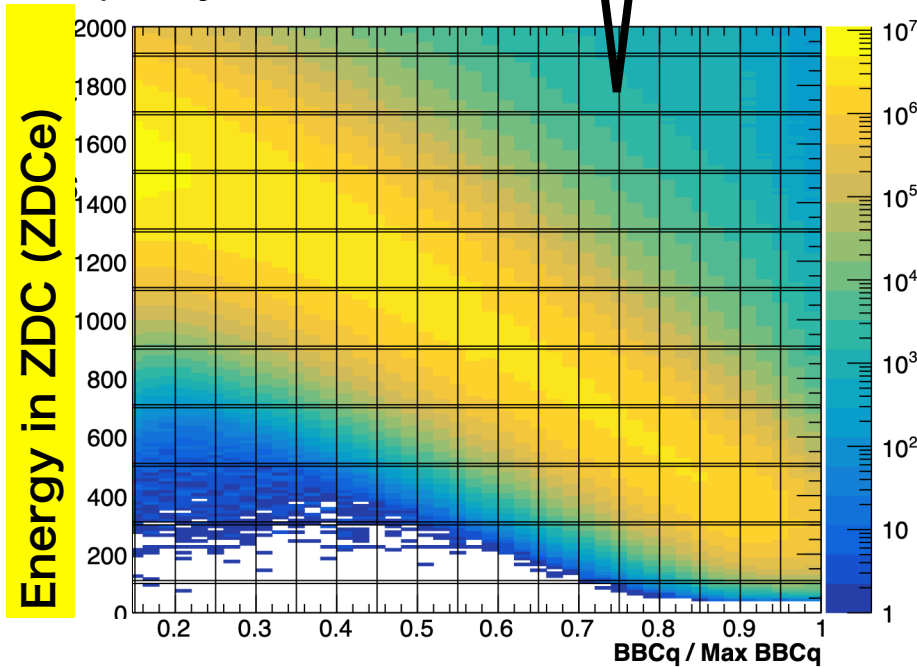
1. S_{loss} does not strongly depend on p_T , decreases as centrality increases. ([Phys. Rev. C. 93. 024911 \(2016\)](#))
2. S_{loss} increases with L_ϵ , an effective radius of the collision. ([Phys. Rev. C. 76. 034904\(2007\)](#))



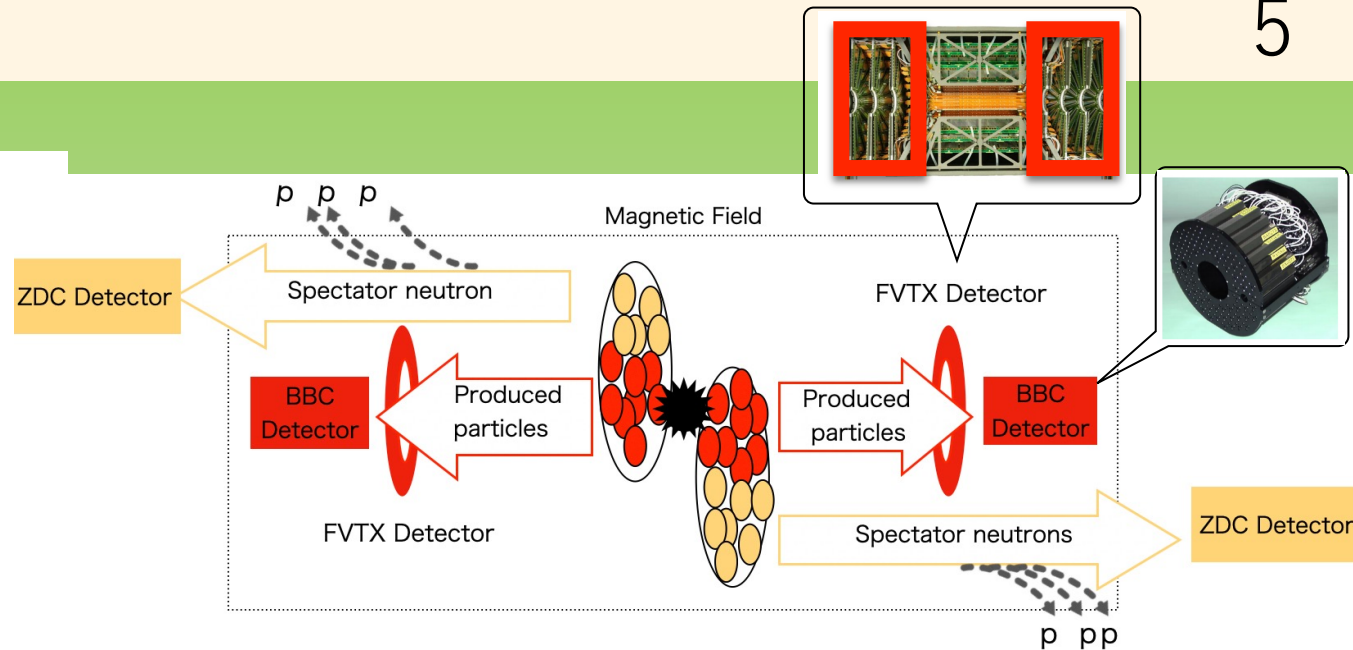
Analysis Procedure

- **Correlation of ZDC-energy and multiplicity**

The energy in ZDC(ZDCe) ($\propto N_{\text{spec}}$) has a negative correlation with multiplicity.



BBC-multiplicity

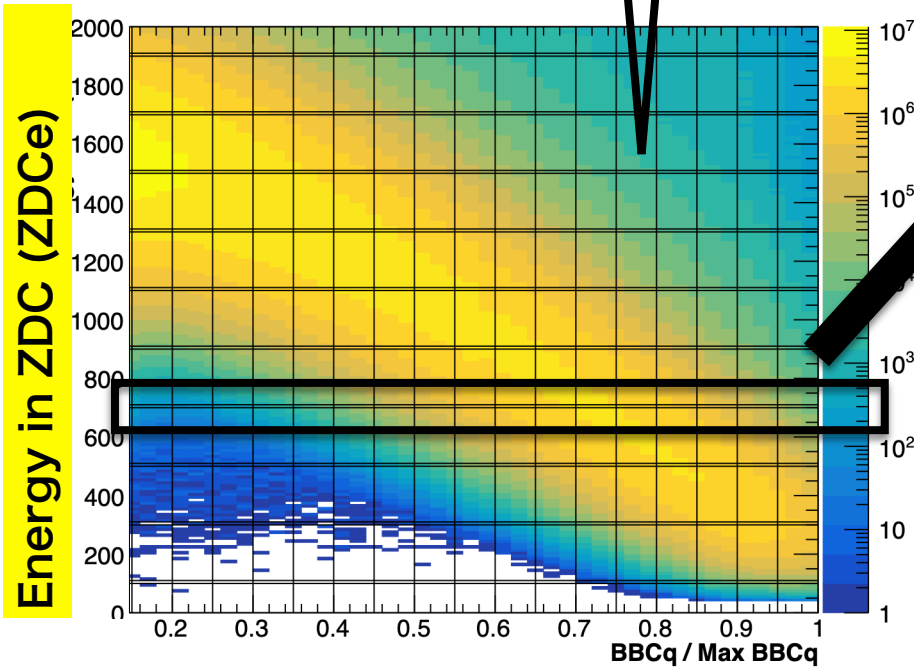


- Measurement the energy of spectator neutrons ($\propto N_{\text{spec}}$)
→ **Zero Degree Calorimeter (ZDC)**
- Measurement of the multiplicity
→ **• Beam Beam Counter (BBC)**
• Forward Silicon Vertex Tracker (FVTX)

Analysis Procedure

Correlation of ZDC-energy and multiplicity

The energy in ZDC(ZDCe)
($\propto N_{\text{spec}}$) has a negative correlation with multiplicity.



BBC-multiplicity

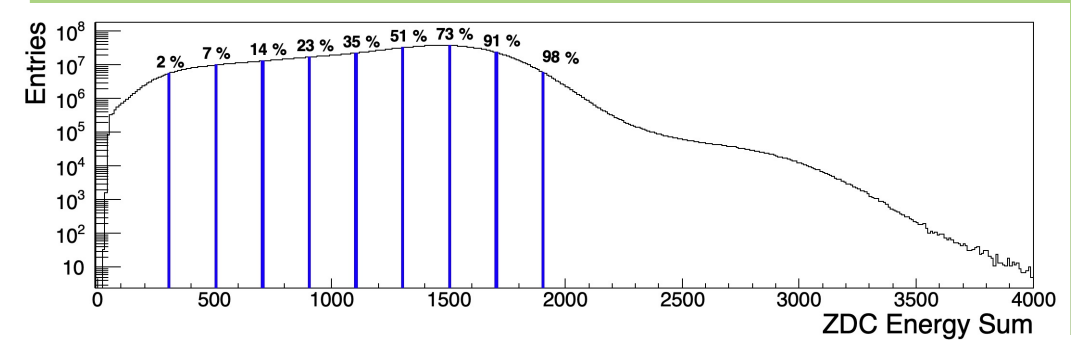
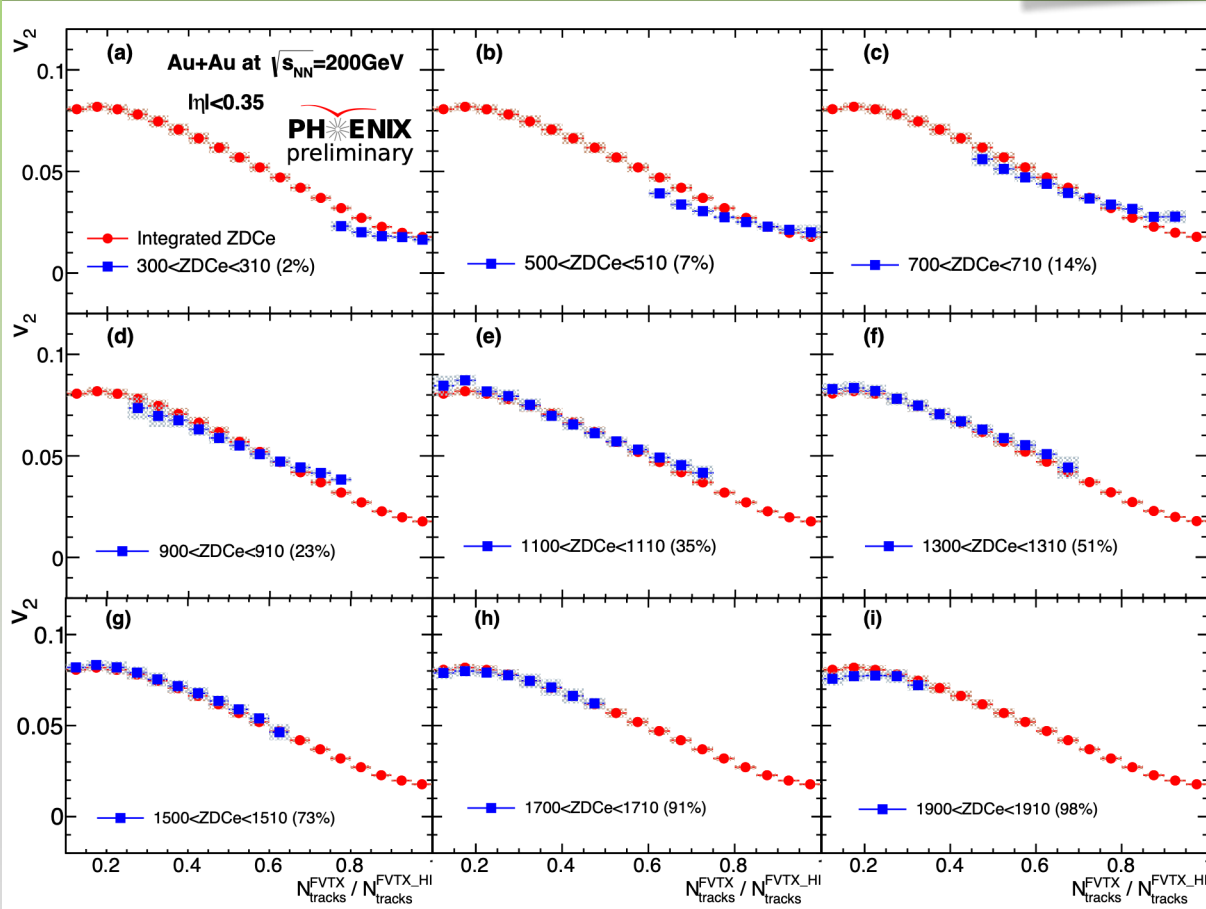
By fixing a narrow ZDC bins we studied how v_2 changes with the multiplicity.

Results: v_2 with ZDCe event categorization

v_2 as a function of FVTX-multiplicity

Red : without ZDCe event categorization (same plots in all panels)

Blue : with ZDCe event categorization



- In each panel, different ZDCe event categorization is applied.
- In all ZDCe event categorizations, the tendency is the same, that v_2 decrease as FVTX- multiplicity increase.