Charm and Bottom quark energy loss and flow measurements in Au+Au collisions by the PHENIX experiment

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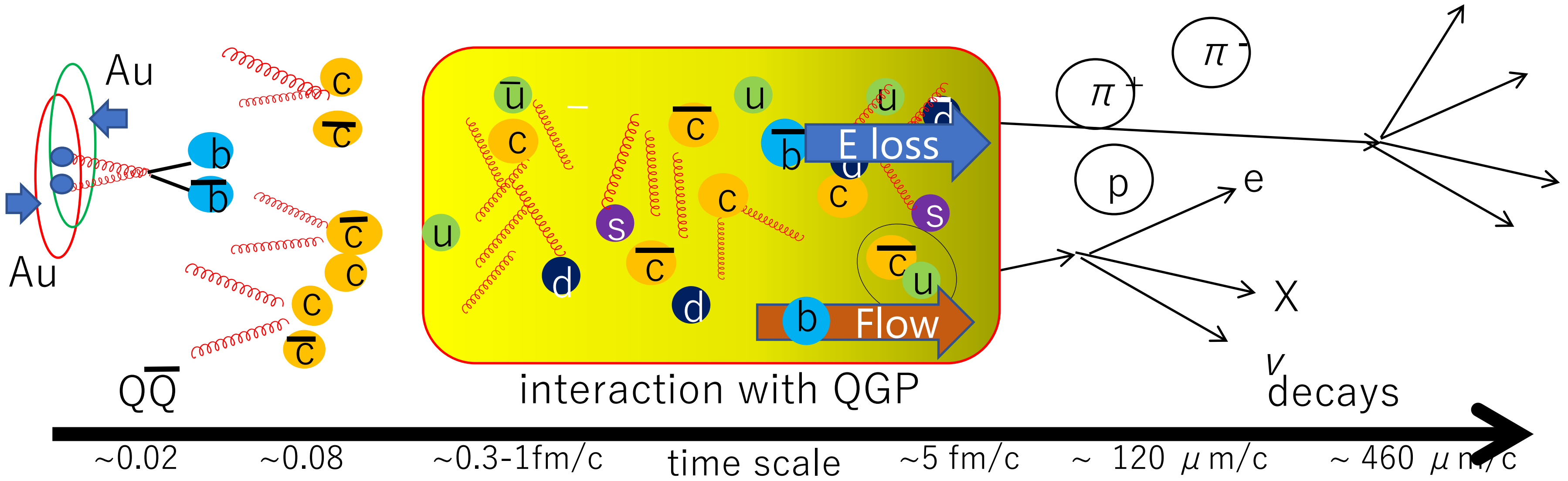
Why heavy flavor, bottom & charm ?

- Mainly created at early stage of the collision
  - Production can be calculated by pQCD
- Passing through QGP
  - Suffer energy loss and flow effects – p_T and angular distributions can be modified in QGP

M_c~1.3GeV, M_b~4.5GeV >> T_{QGP} ~400MeV, Λ_{QCD} ~200MeV

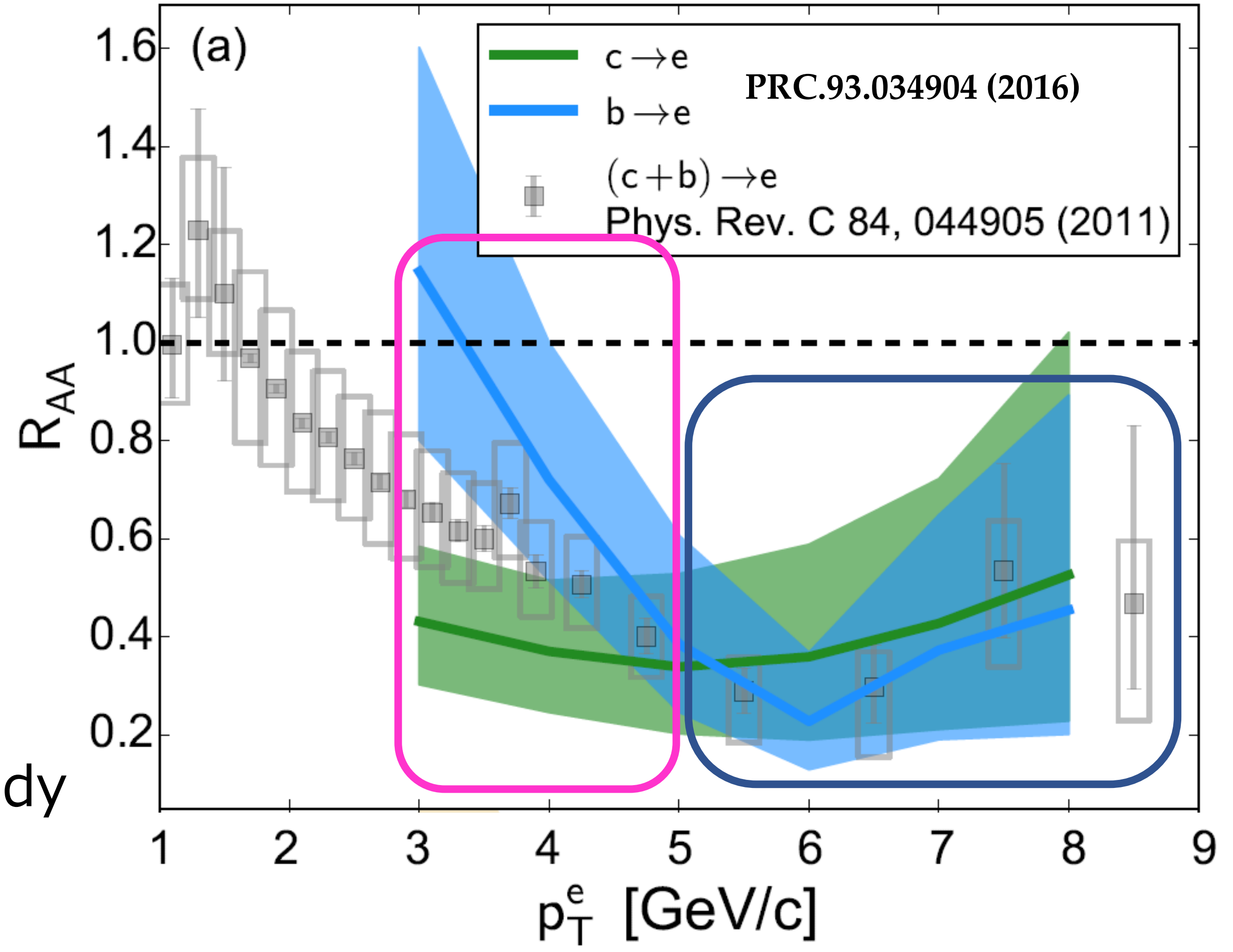


Modification of Heavy flavor is good tool to study property of QGP

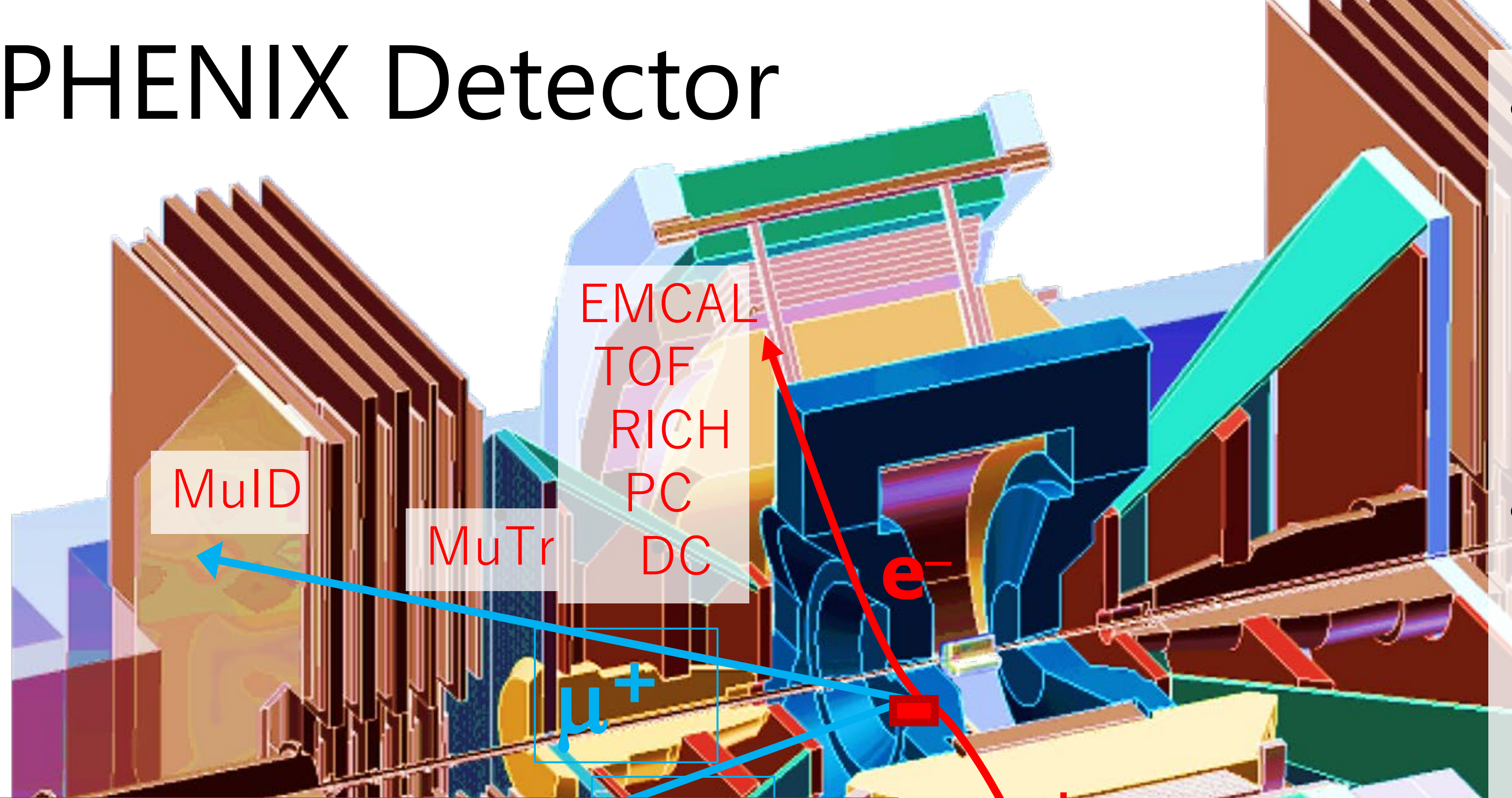
Heavy flavor suppression in HI Collisions

- PHENIX observed in electron measurements
  - $R_{AA}(b) \sim R_{AA}(c) < 1$ at high 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 important @ low p_T
- To understand the suppressions of bottom and charm, need systematic study
  - Centrality dependence
  - Azimuthal anisotropy

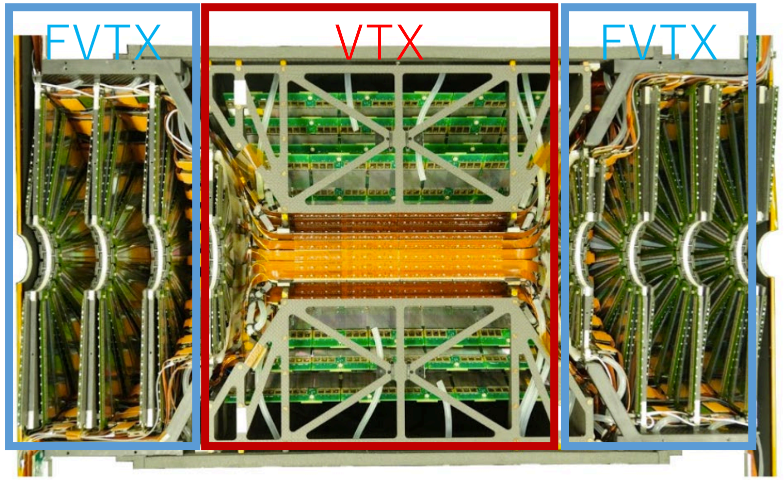
$$R_{AA} = \frac{Yield(Au+Au)}{Ncoll * Yield(p+p)}$$



PHENIX Detector



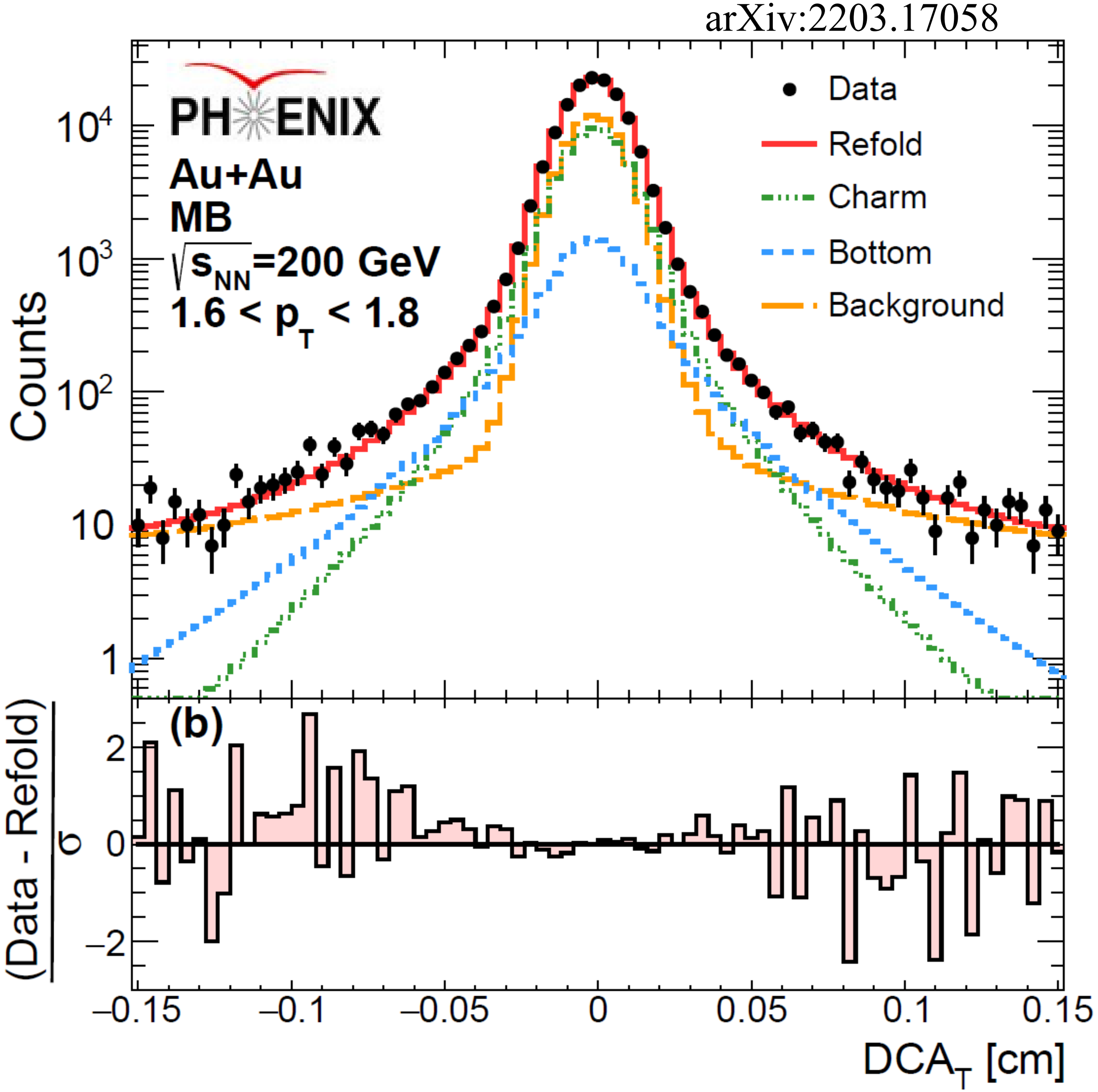
VTX & FVTX



- Central Arms
  - $|y|<0.35$, $\phi\sim2\cdot\pi/2$
  - Electrons, γ, hadrons
    - DC, PC, RICH, EMCAL,TOF
- Muon Arms
  - $1.2\sim|y|<2.2$, $\phi\sim2\cdot\pi/2$
  - Muons, Hadrons
- VTX-FVTX
  - Precise tracking for HF-ID

PHENIX completed the data taking 2016
The data production completed
Analyses are going

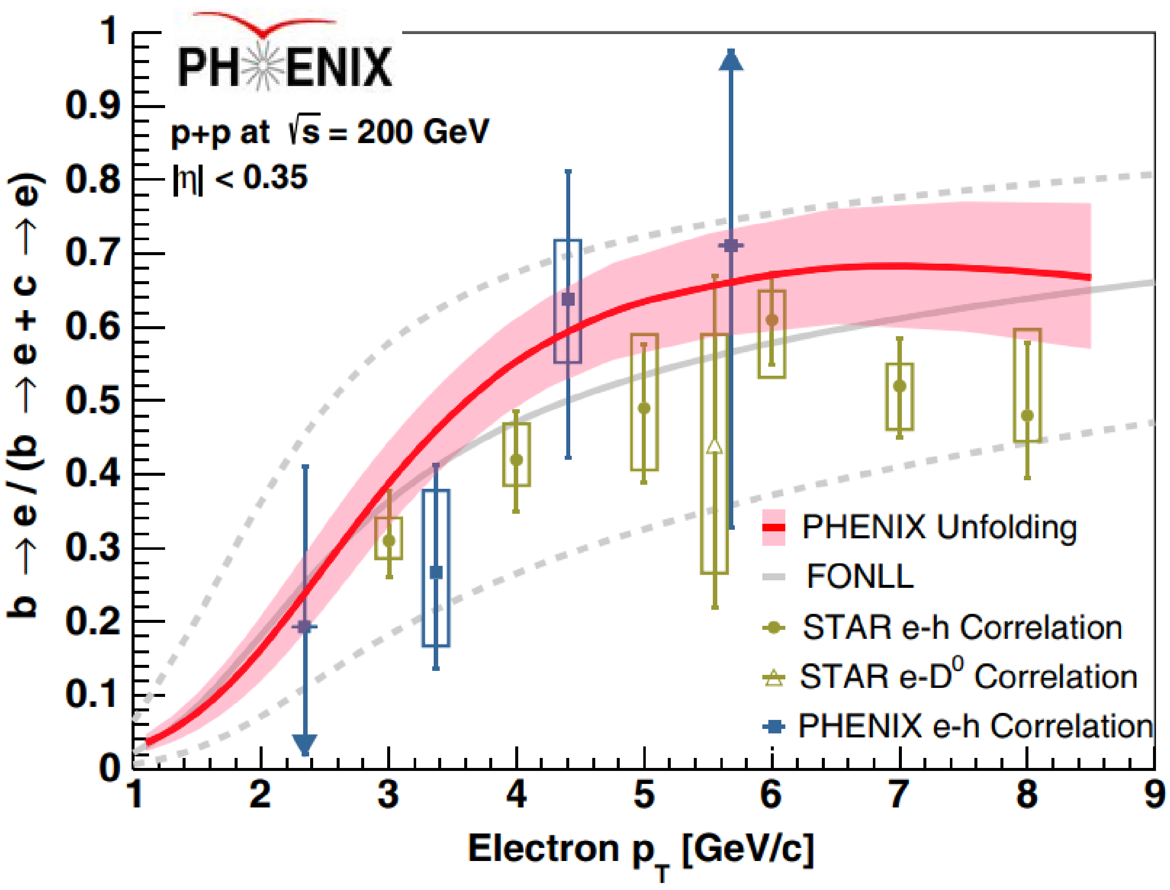
Bottom and charm separation



- 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

p+p baseline : Bottom Electron Fraction

PRD **99**, 092003 (2019)



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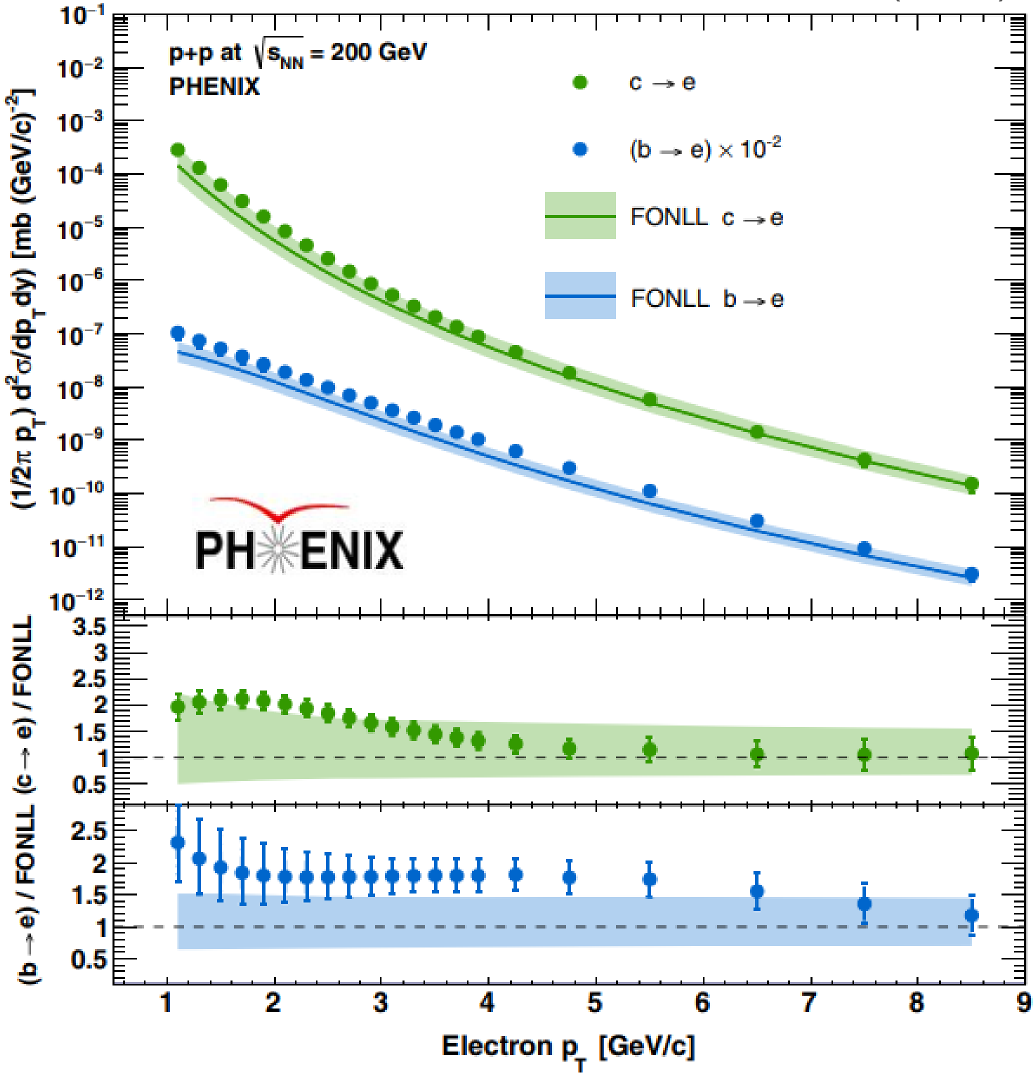
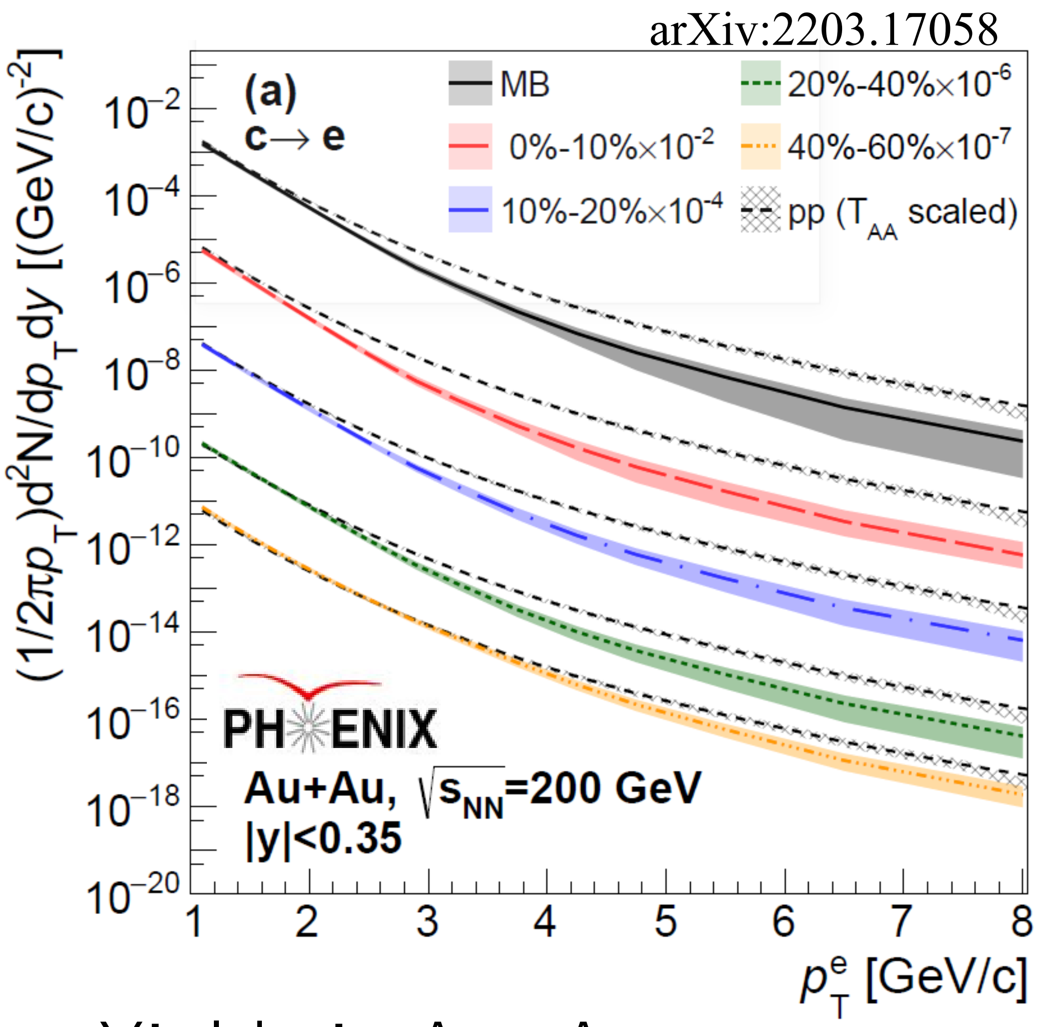
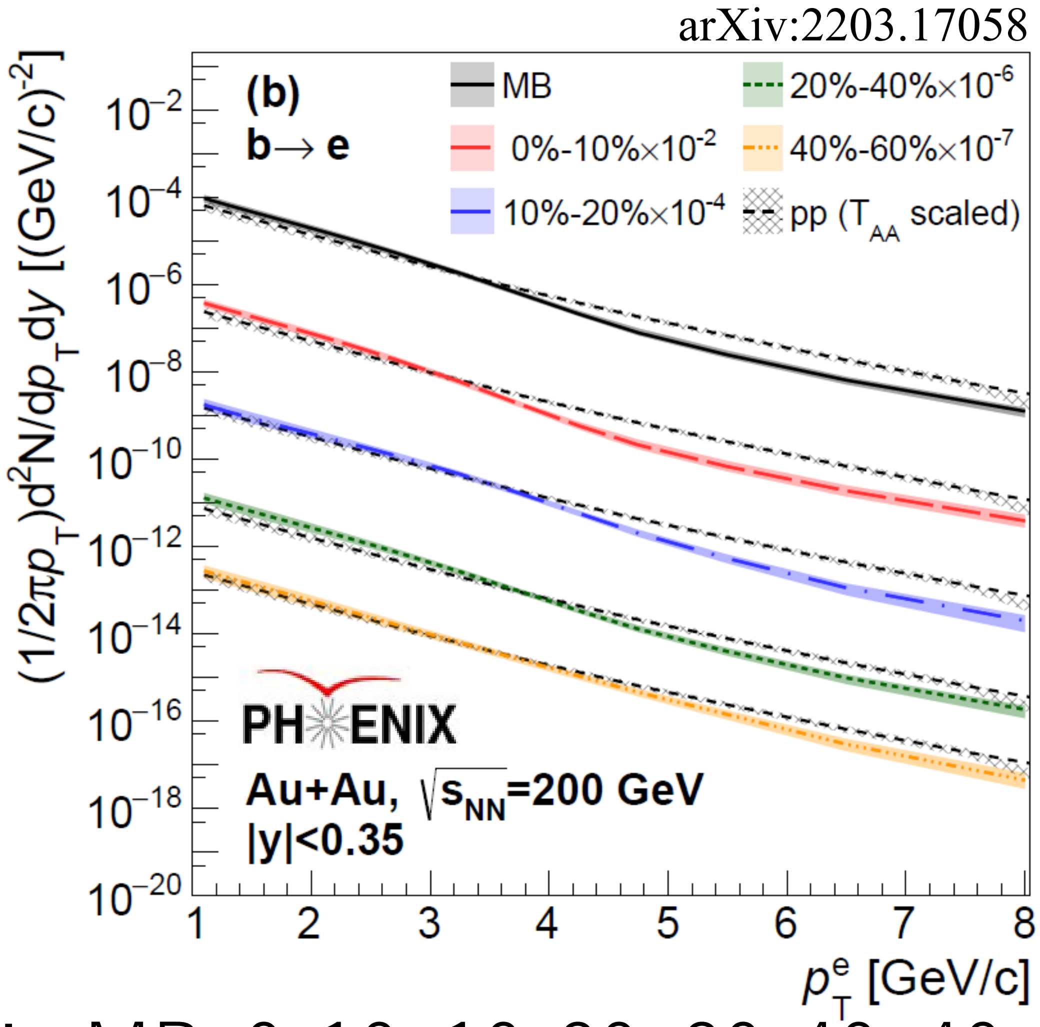


- New p + p baseline of bottoms and charms available w/ p_T = 1~8 GeV/c

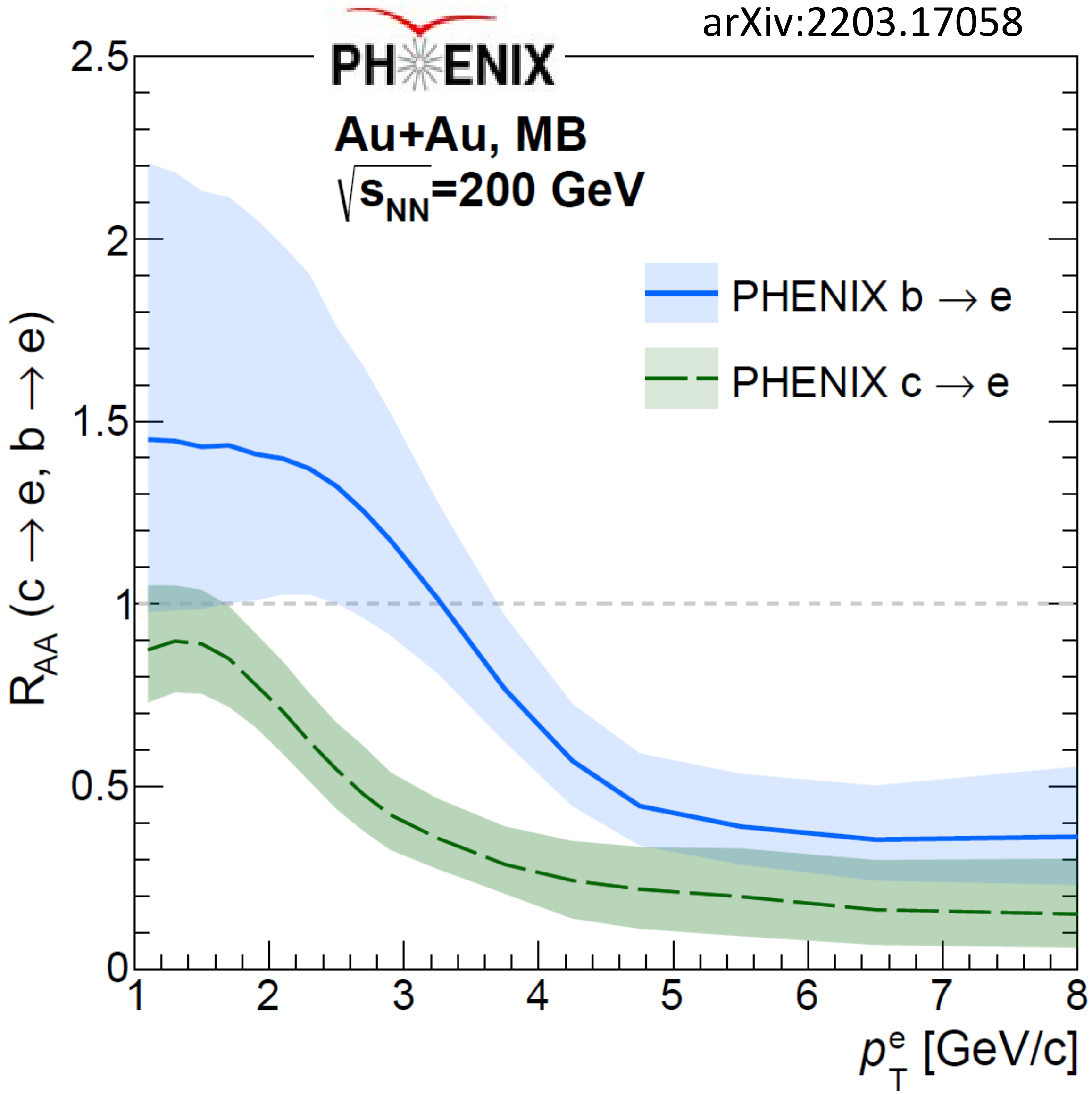
Charm and Bottom Electron yields in Au+Au





- Yields in Au+Au are measured in MB, 0-10, 10-20, 20-40, 40-60%
- compared with p+p scaled by T_{AA}

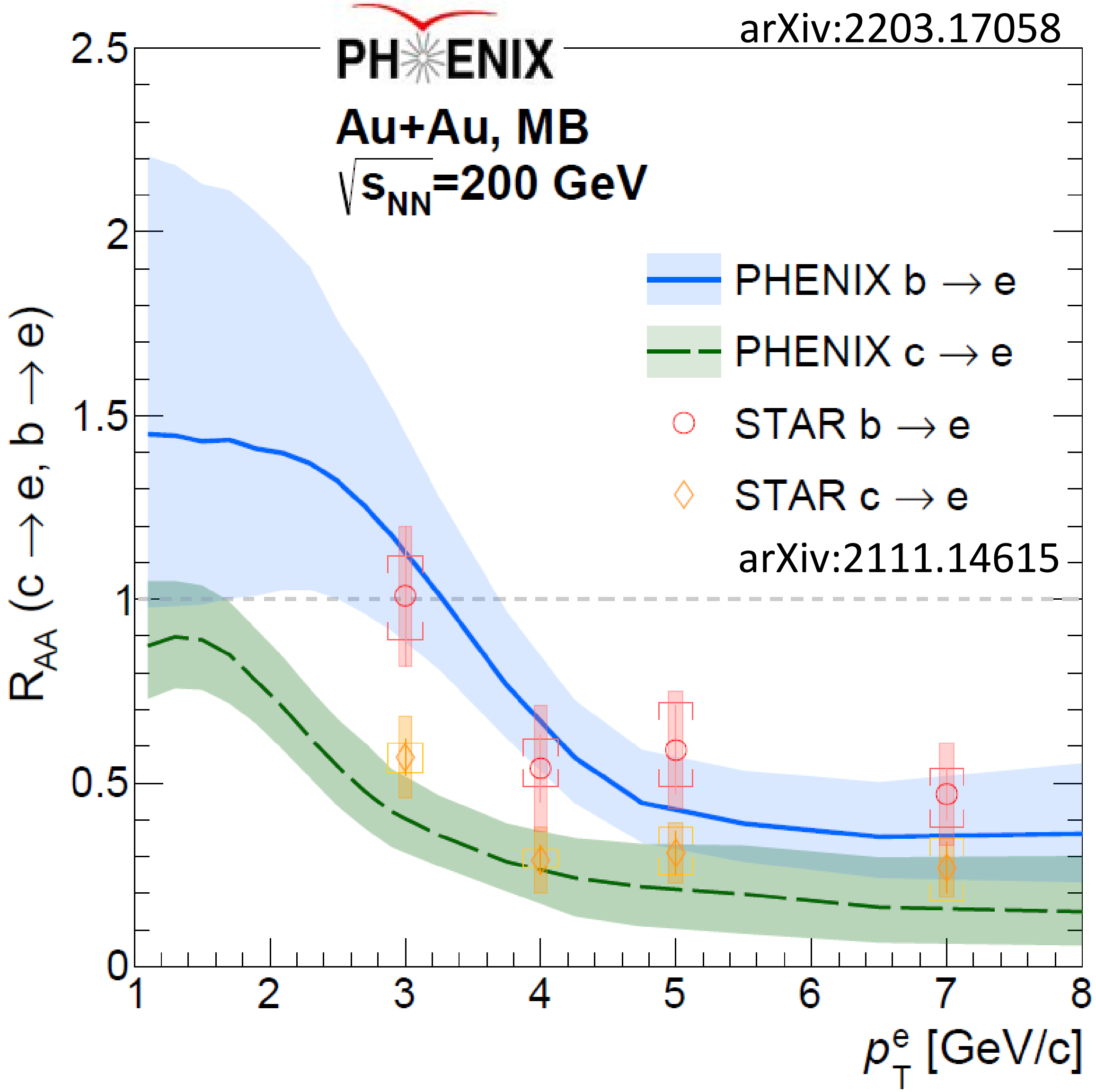
$R_{AA}(b \to e)$ & $R_{AA}(c \to e)$ in Au+Au 200GeV



arXiv:2203.17058

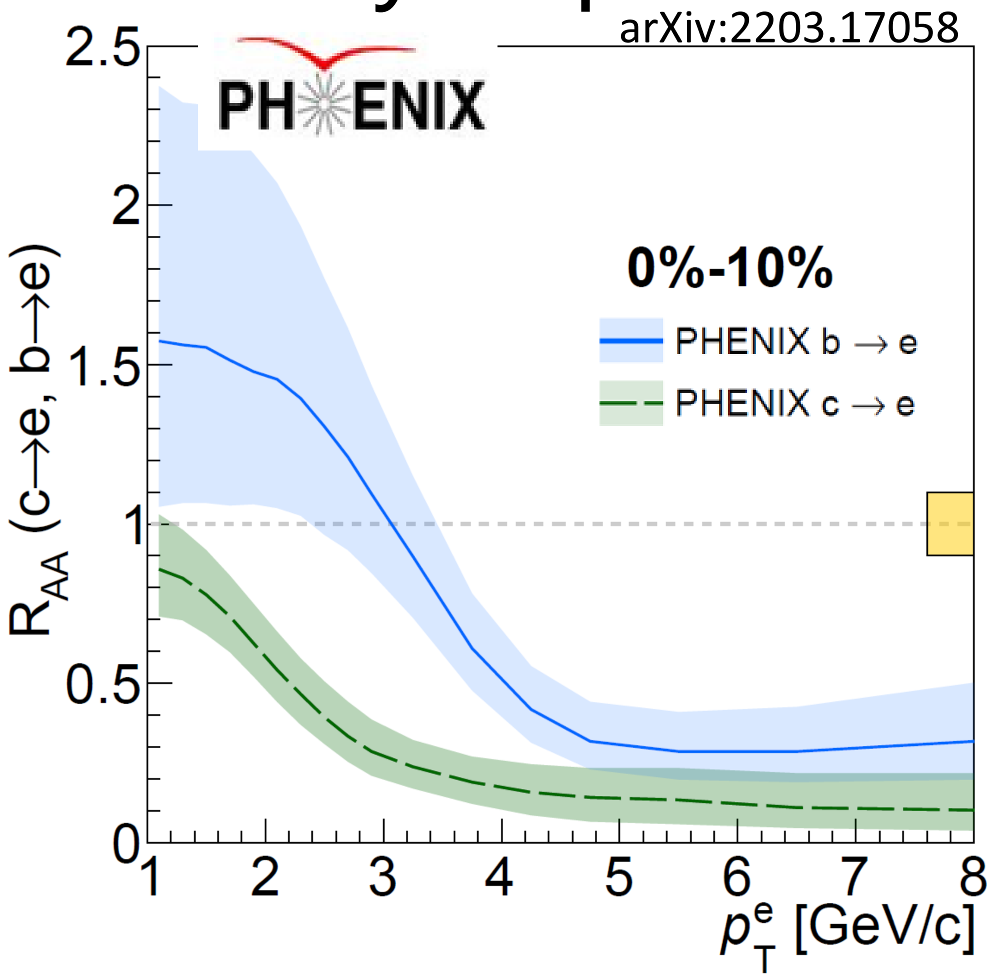
- Nuclear modification factor R_{AA}
  - Broad p_T range : 1 – 8 GeV/c
  - Small uncertainty with new p+p baseline
- Low p_T : R_{AA}(b->e) ~ R_{AA}(c->e) = 1
- Mid p_T : R_{AA}(b->e) > R_{AA}(c->e)
- High p_T: R_{AA}(b->e) ~ R_{AA}(c->e) < 1
- Bottom suppression is different from charm
  - A clear p_T dependence

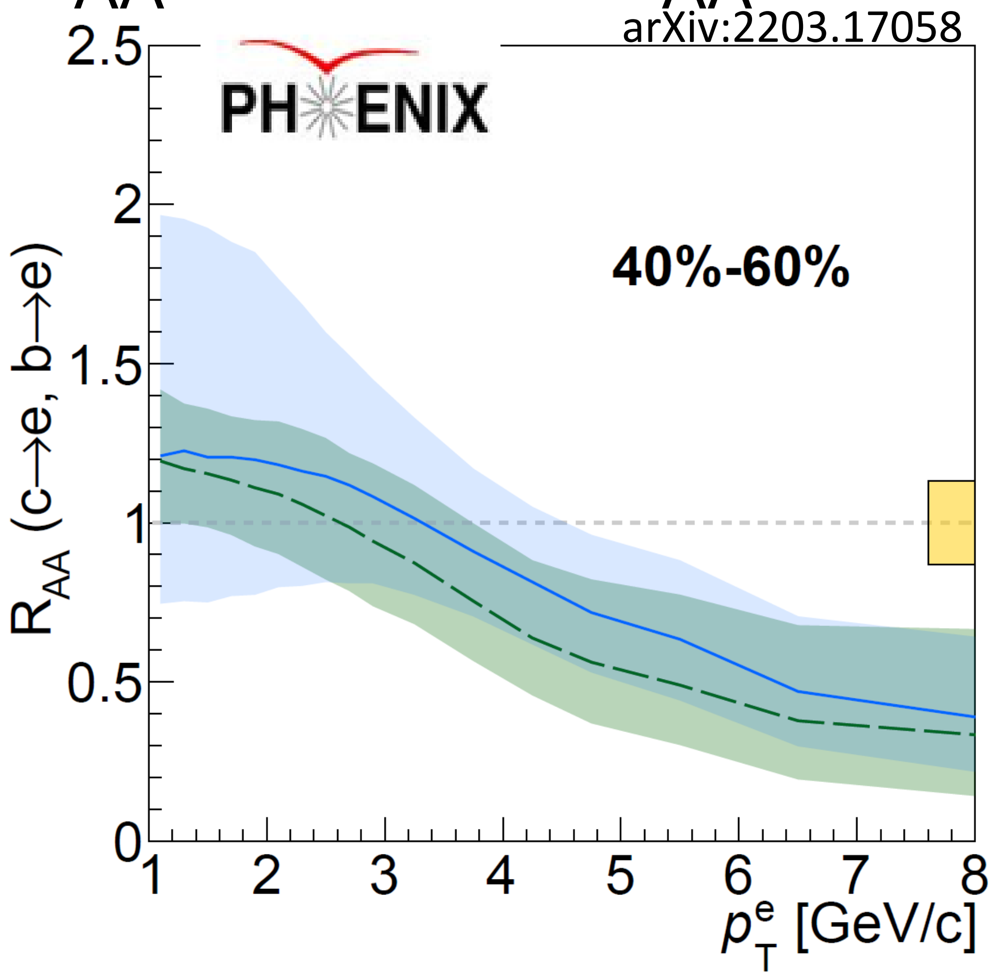
R_{AA}(b→e) & R_{AA}(c→e) comparison with STAR 0-80%



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

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



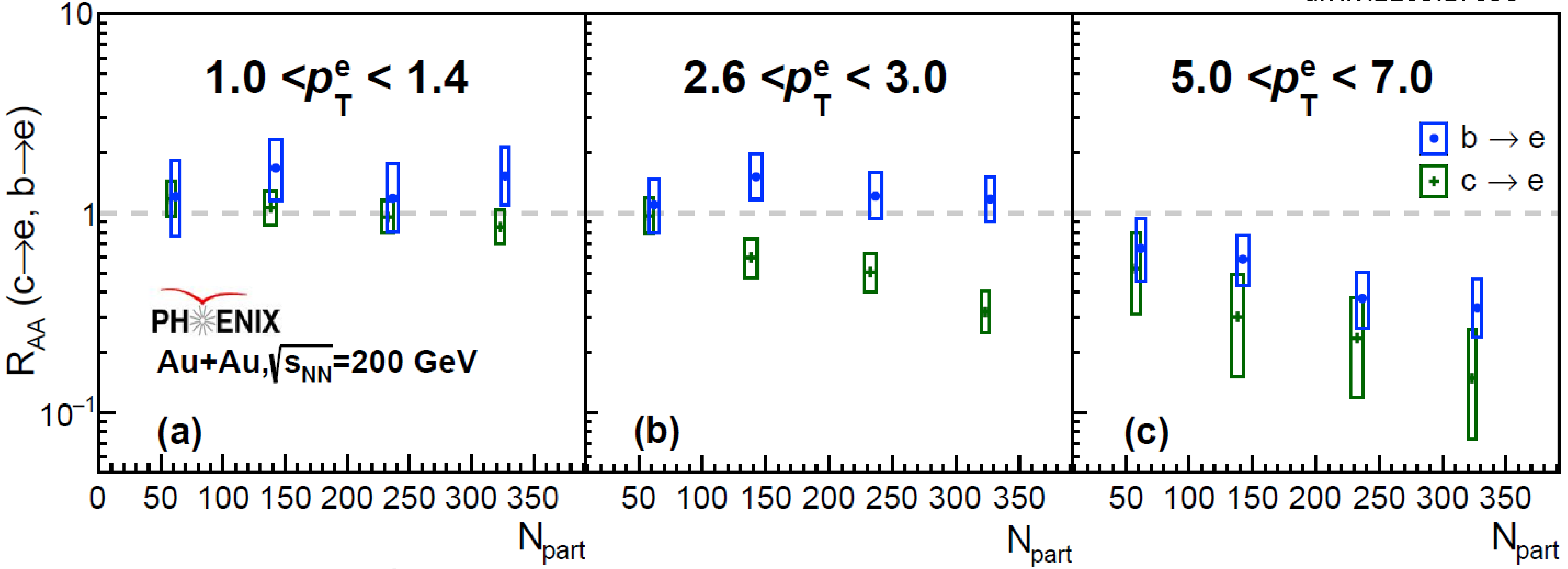


- In 0-10%, bottom and charm suppression are clearly seen
- In 40-60%, bottom and charm are similar and less suppressed

Centrality dependence clearly seen

Charm and Bottom R_{AA} vs Npart

arXiv:2203.17058



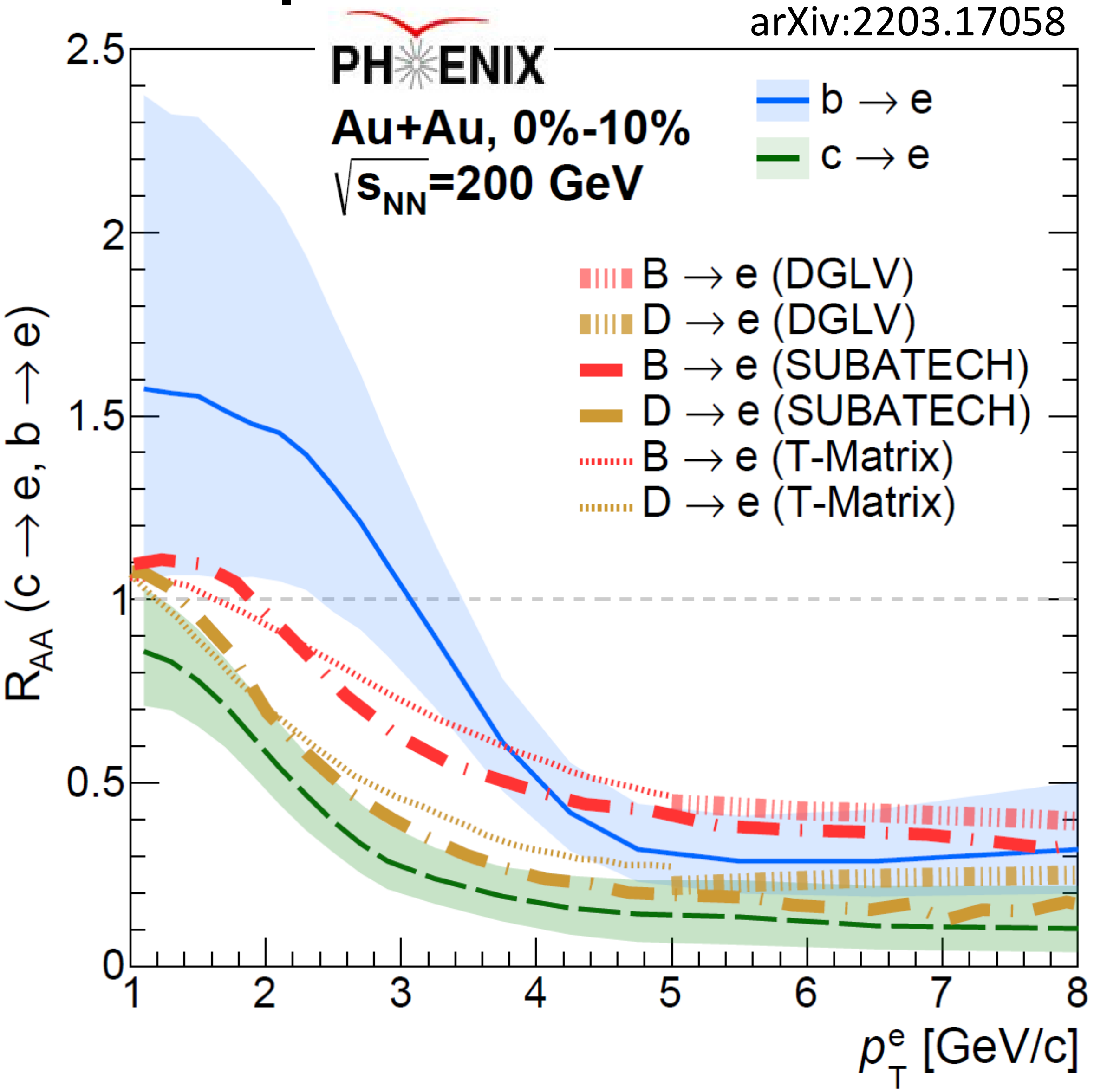
R_{AA}(c→e) ~ R_{AA}(b→e) ~ 1

R_{AA}(c→e) < R_{AA}(b→e)
R_{AA}(b→e) ~ 1

R_{AA}(c→e) ~ R_{AA}(b→e) < 1

Clear centrality and p_T dependence observed

Comparison with Models

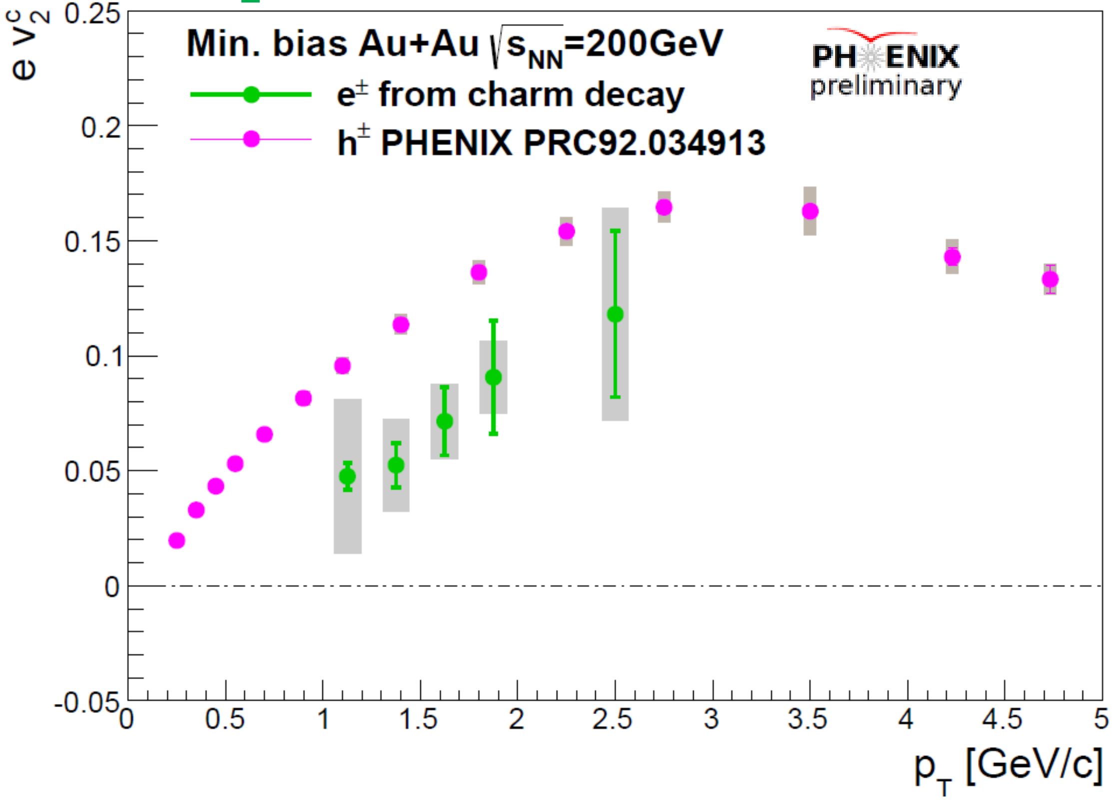


- Compared with 3 models
  - DGLV (Phys. Rev. C 90 034910)
    - E-loss + plasma w/ static potentials
  - SUBATECH (Phys. Rev. C 78 014904)
    - : E-loss + running coupling
  - T-Matrix + diffusion (2πTD=4) (Phys. Rev. Lett. 100 192301)
    - Strongly coupled QGP

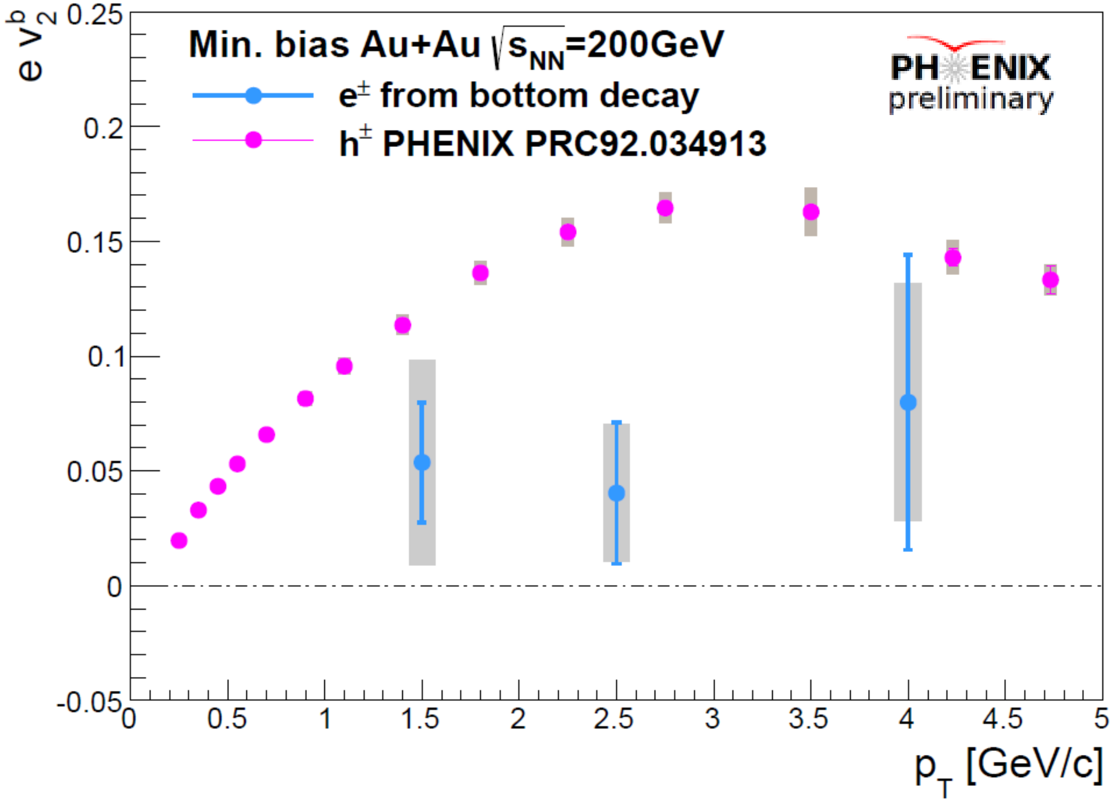
- Models qualitatively consistent with data
  - Mass dependent energy loss agree with the mass dependent suppression
  - Bottom models underestimates the data
  - Charm models slightly higher than data

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

$v_2^c(c \to e)$



$v_2^b(b \to e)$



- $c \to e\ v_2$ is positive with ~3.5 sigma
- A hint of positive $b \to e\ v_2$ with 1.1 sigma

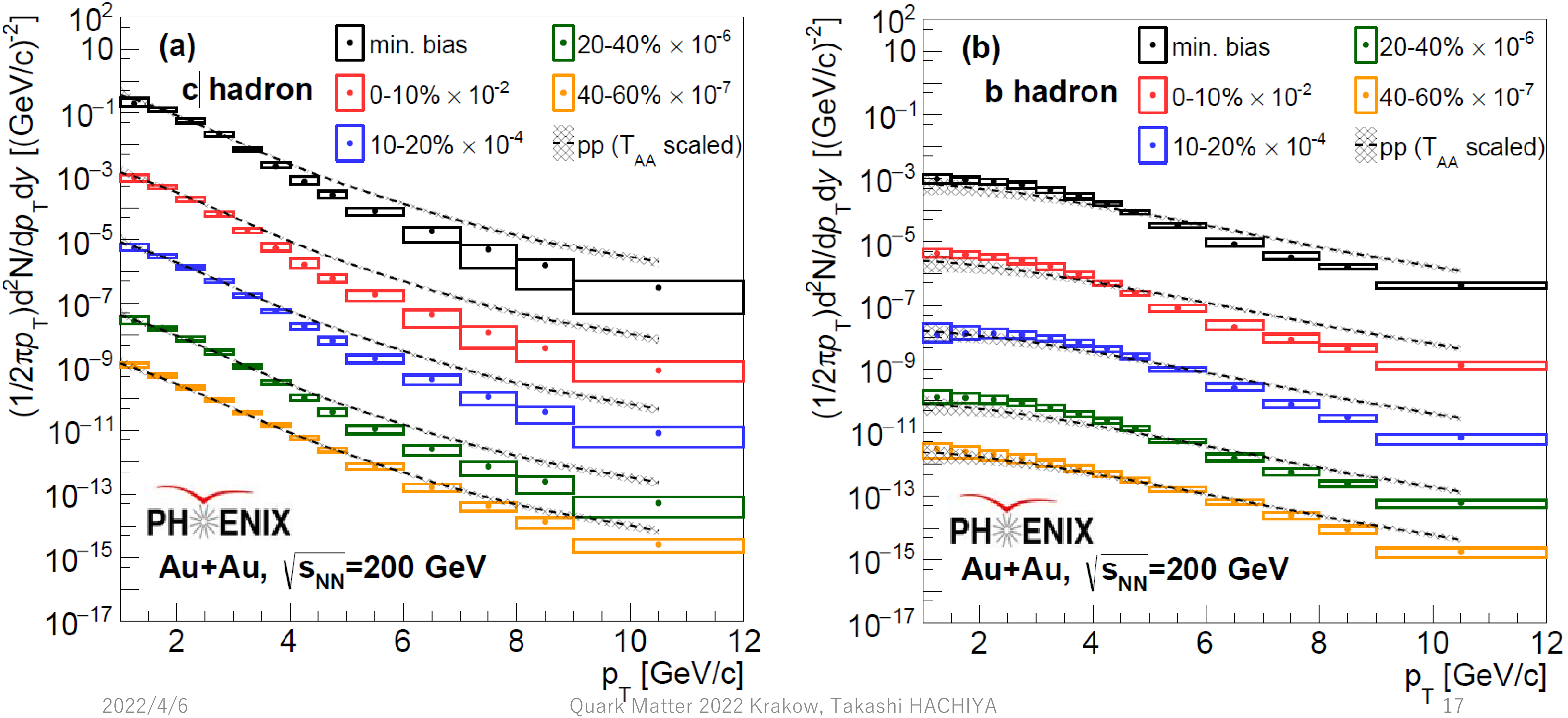
- Final v_2 result with improved yield unfolding coming soon

Summary

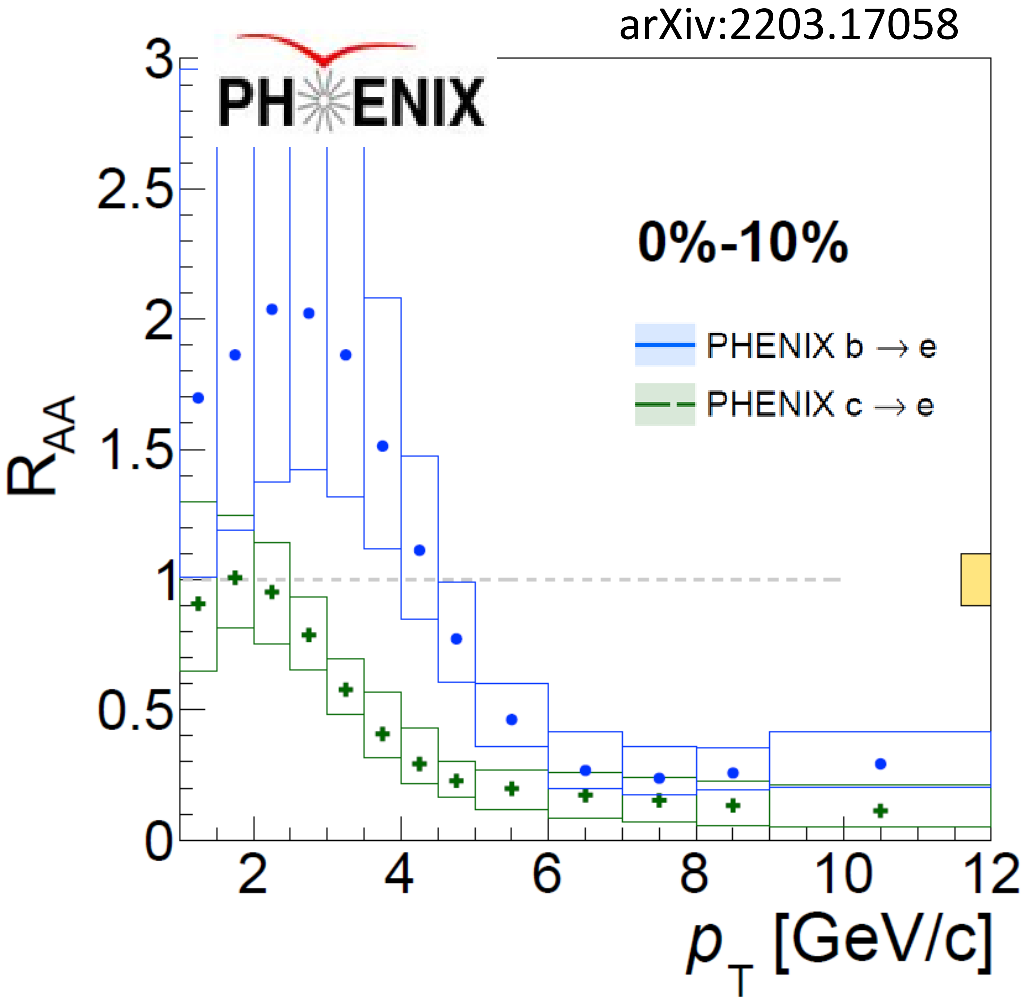
- PHENIX measures charm and bottom R_{AA} and v_2 in MB and 0-10, 10-20, 20-40, 40-60% central Au+Au collisions
- Clear p_T and centrality dependence
  - $R_{AA}(b \rightarrow e)$ and $R_{AA}(c \rightarrow e)$ ~ 1 at low p_T
  - $R_{AA}(b \rightarrow e) > R_{AA}(c \rightarrow e)$ at mid p_T
  - $R_{AA}(b \rightarrow e) \sim R_{AA}(c \rightarrow e) < 1$ at high p_T
  - Consistent with the models with mass dependent energy loss
- Charm and Bottom v_2
  - Positive charm $v_2^c(c \rightarrow e)$
  - A hint of positive bottom $v_2^b(b \rightarrow e)$
- Outlook
  - Au+Au in 2016 data will be added
  - New bottom and charm results in Au+Au and small systems are coming soon

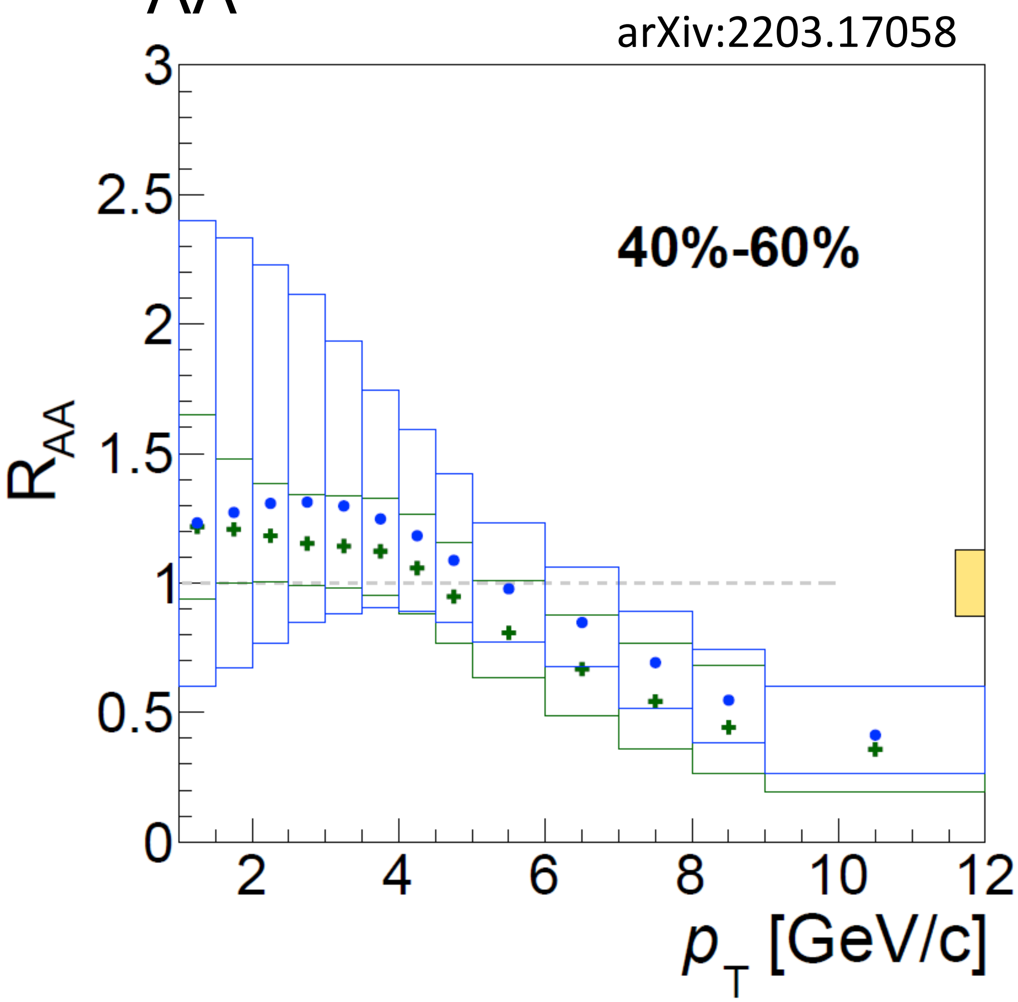
backup

Charm and Bottom Hadron yields in Au+Au



Charm and Bottom hadron R_{AA}

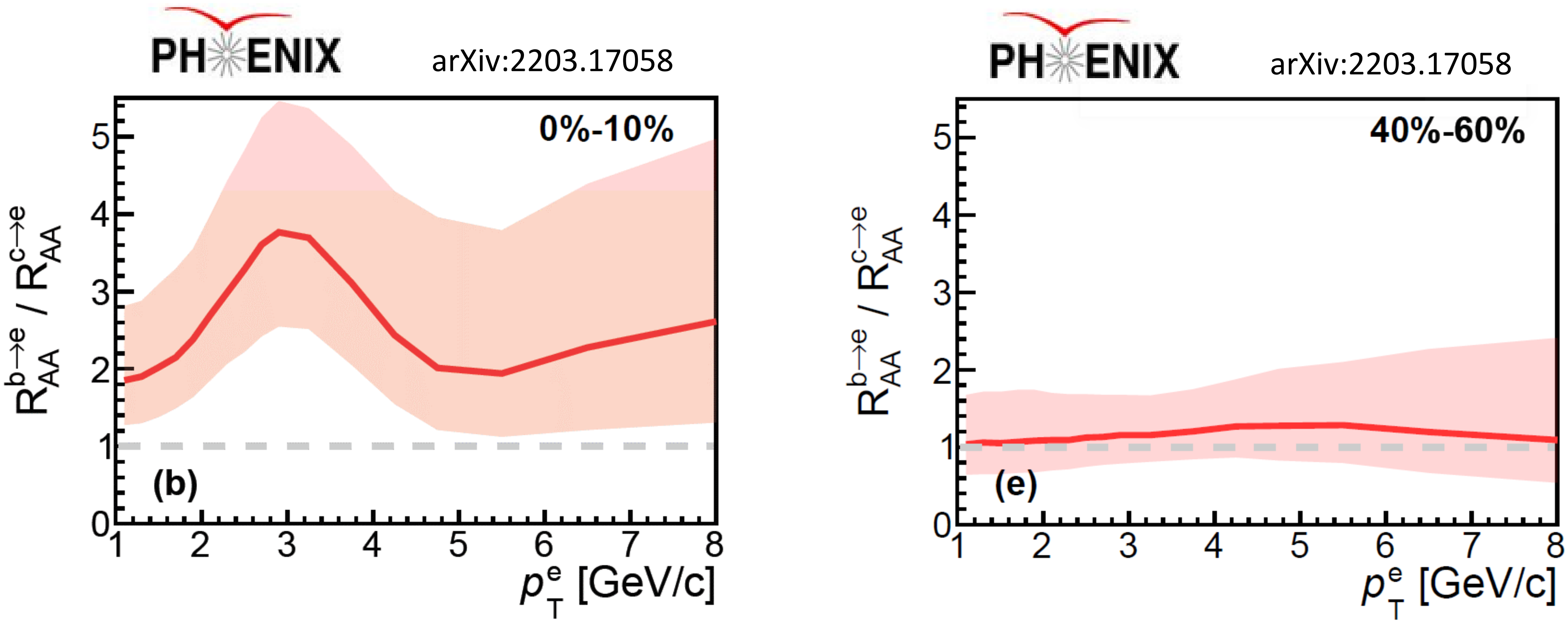




- Charm and Bottom hadron R_{AA} for whole rapidity to account for the decay kinematics
- Different suppression in 0-10% but similar in 40-60%

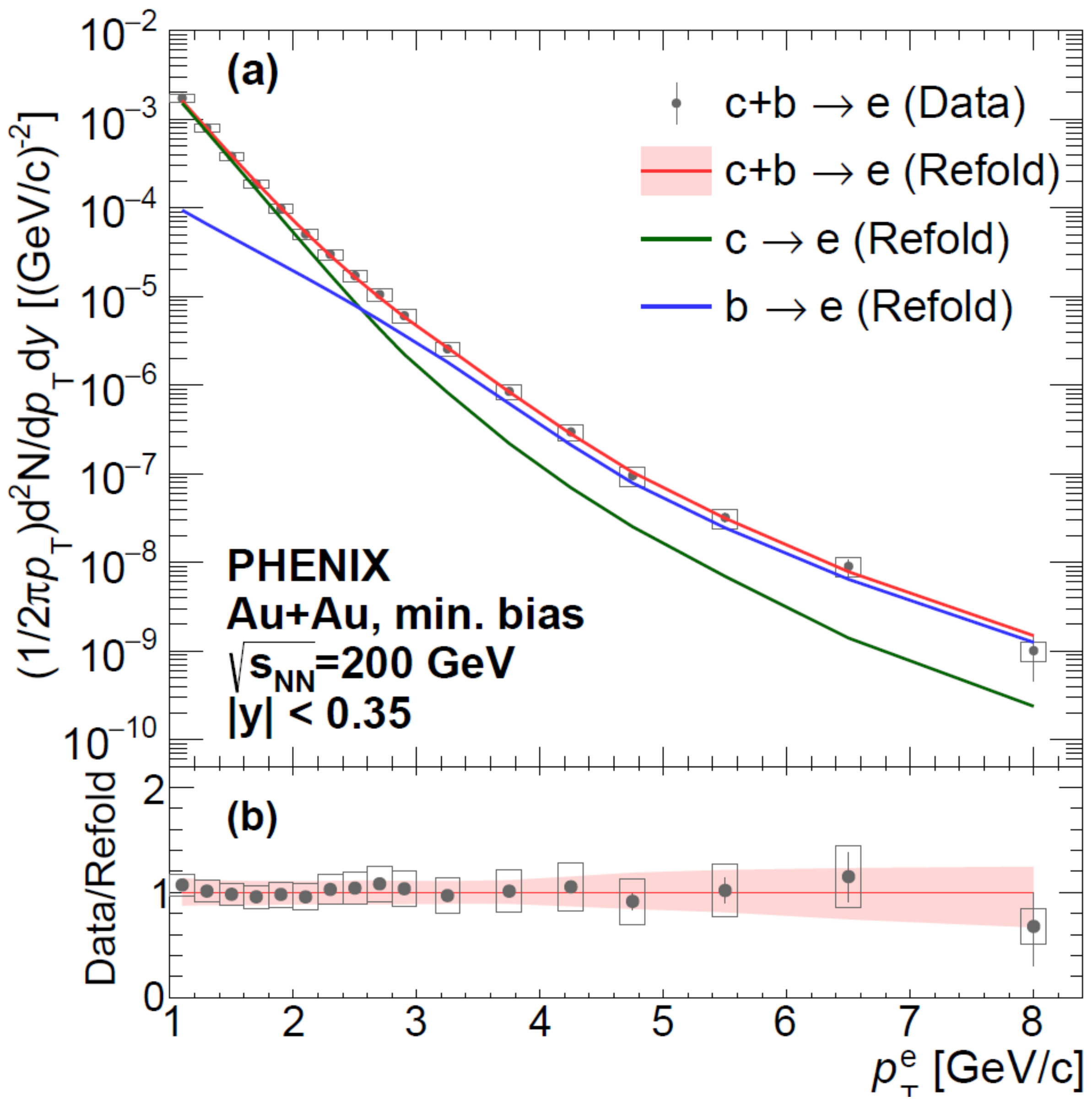
Centrality dependence clearly seen

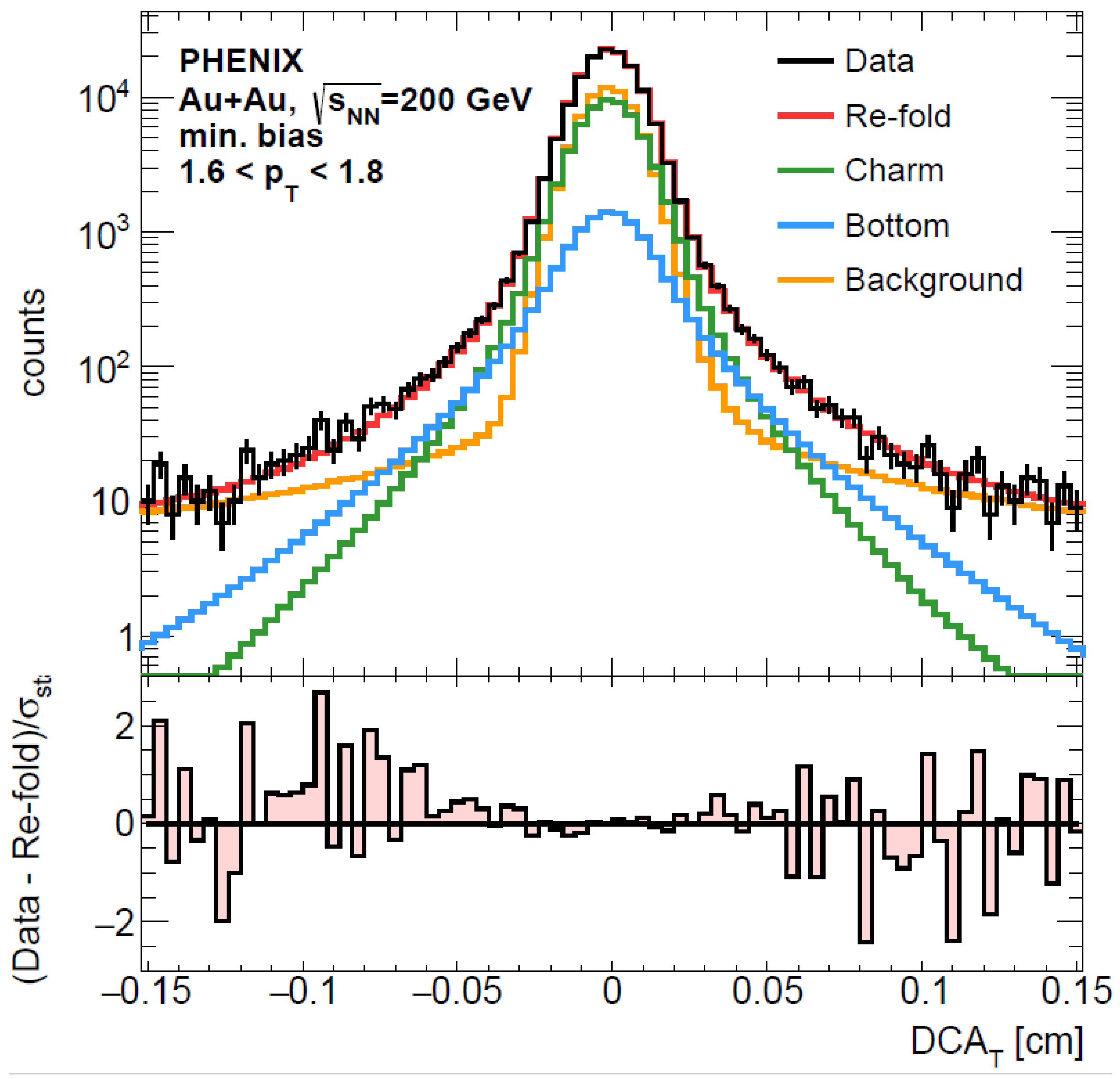
Double ratio of R_{AA}

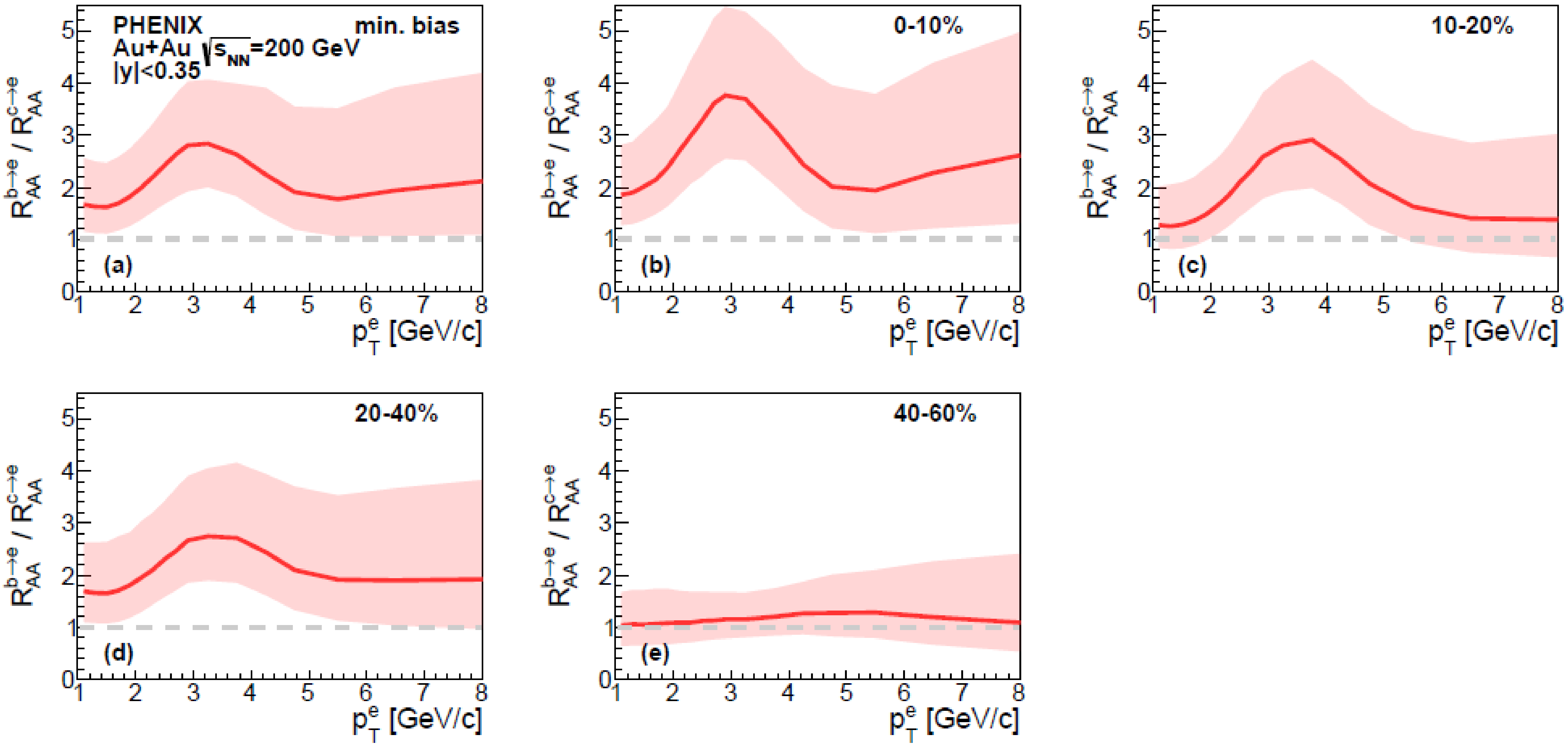


- 0-10% Bump structure at p_T ~ 3 GeV/c caused by the different suppression
- 40-60% Flat and consistent with unity

Centrality dependence clearly seen


(a)
c+b → e (Data)
c+b → e (Refold)
c → e (Refold)
b → e (Refold)
PHENIX
Au+Au, min. bias
√sNN=200 GeV
|y| < 0.35
(1/2πpT)d2N/dpTdy [(GeV/c)-2]
(b)
Data/Refold
pTe [GeV/c]

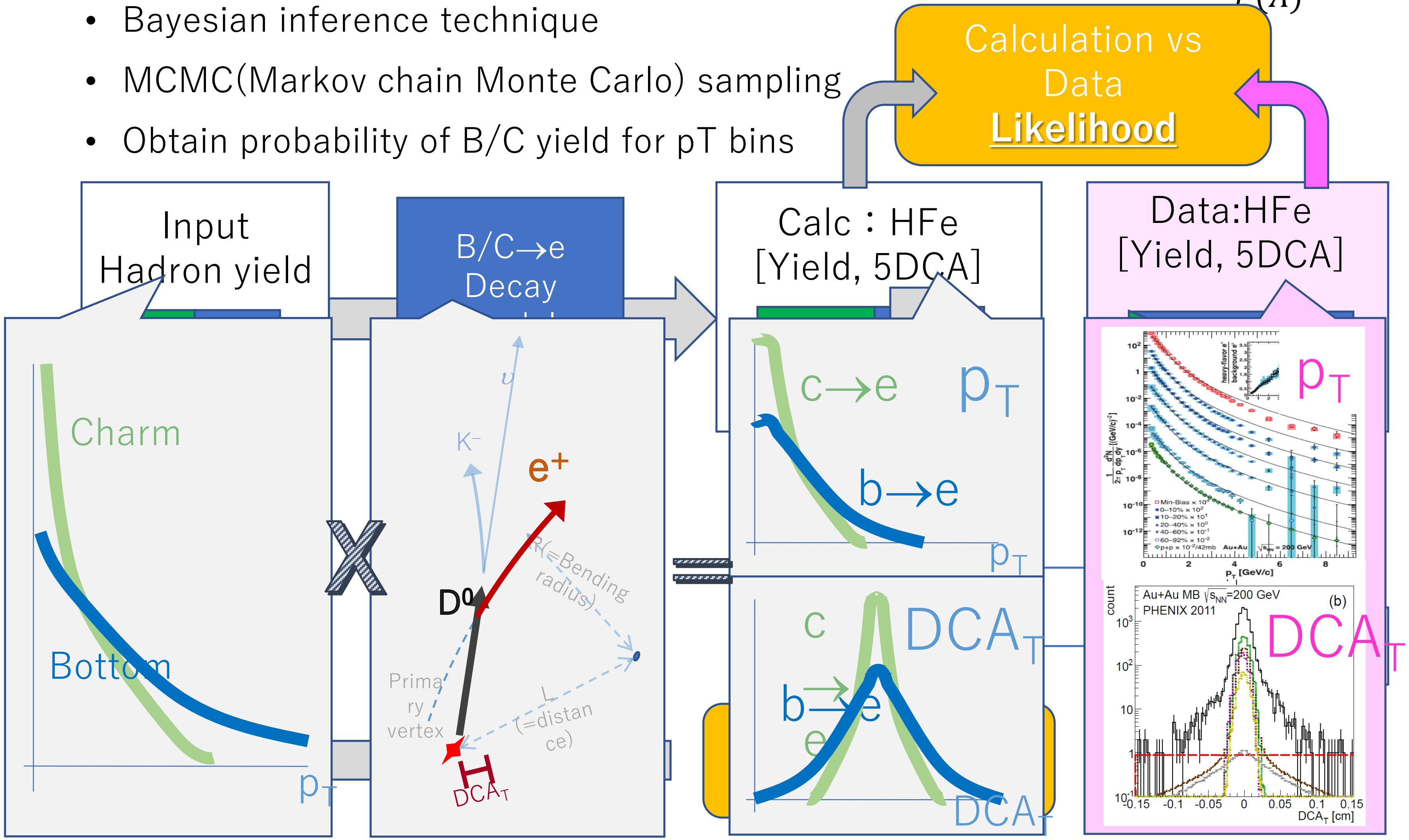

PHENIX
Au+Au, √sNN=200 GeV
min. bias
1.6 < pT < 1.8
Data
Re-fold
Charm
Bottom
Background
counts
(Data - Re-fold)/σst
DCAT [cm]

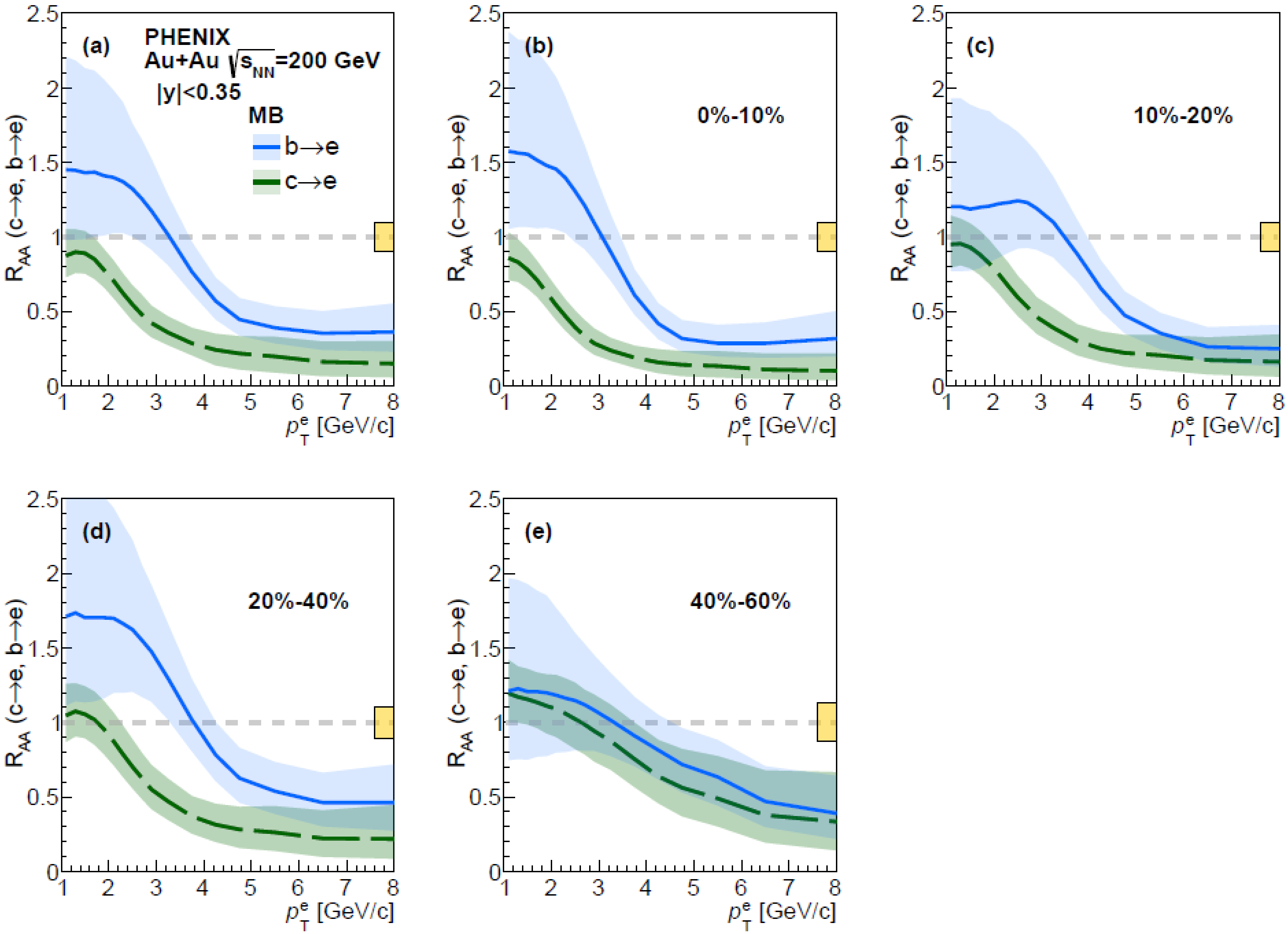

PHENIX
Au+Au $\sqrt{s_{NN}}$=200 GeV
|y|<0.35
min. bias
0-10%
10-20%
20-40%
40-60%
(a)
(b)
(c)
(d)
(e)
$R_{AA}^{b\to e} / R_{AA}^{c\to e}$
p_T^e [GeV/c]

Unfolding: Bayesian inference

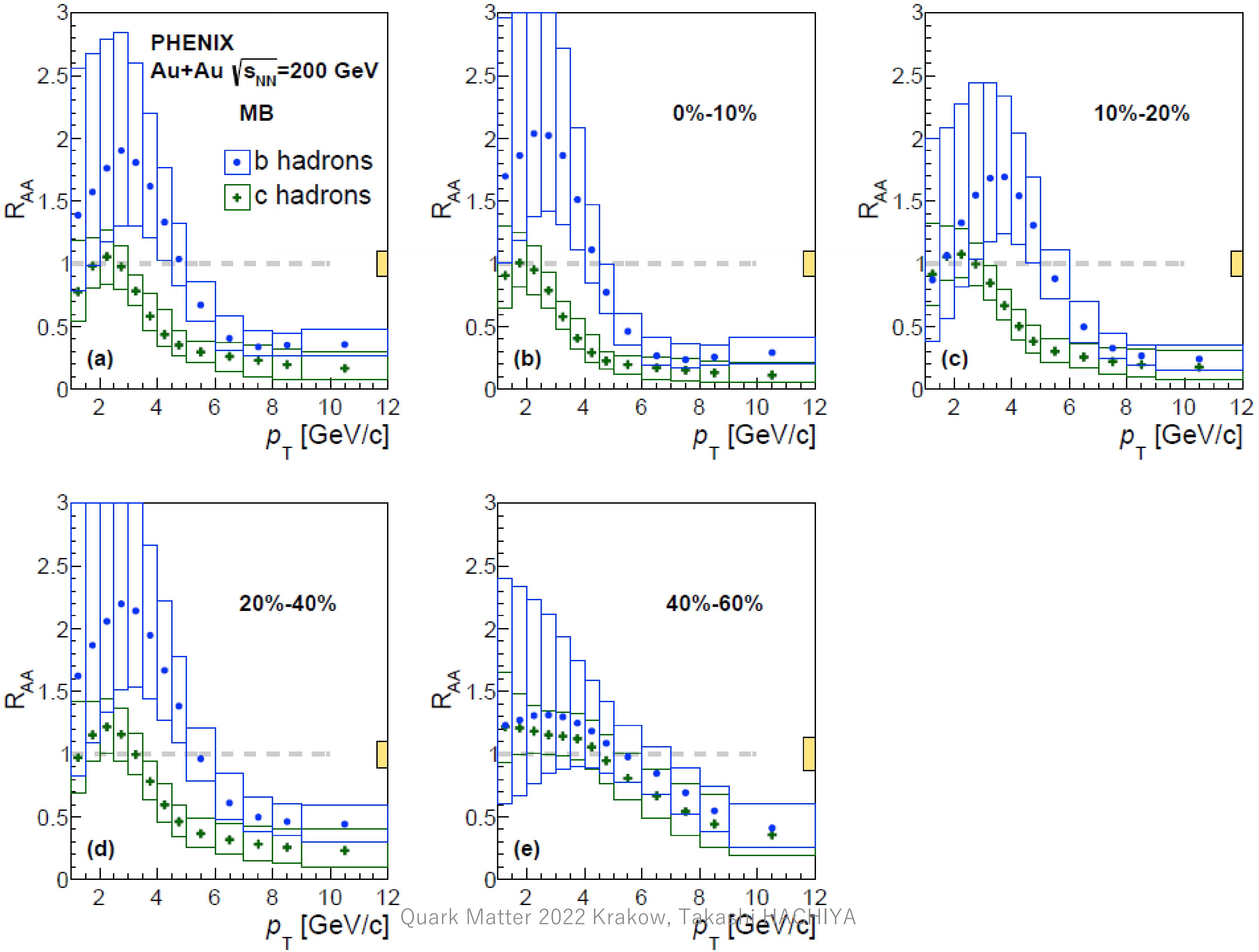
- Purpose: extract parent B/C hadron yield
  - Bayesian inference technique
  - MCMC(Markov chain Monte Carlo) sampling
  - Obtain probability of B/C yield for pT bins

$$P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$$





PHENIX
Au+Au $\sqrt{s_{NN}}$=200 GeV
|y|<0.35
MB
b→e
c→e
(a)
(b)
(c)
(d)
(e)
0%-10%
10%-20%
20%-40%
40%-60%
R_{AA} (c→e, b→e)
p_T^e [GeV/c]


PHENIX
Au+Au √s_NN=200 GeV
MB
b hadrons
c hadrons
(a)
0%-10%
(b)
10%-20%
(c)
20%-40%
(d)
40%-60%
(e)
R_AA
p_T [GeV/c]