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Measurements of electrons from heavy-flavor hadron decays in 27, 54.4, and 200 GeV Au+Au collisions in STAR

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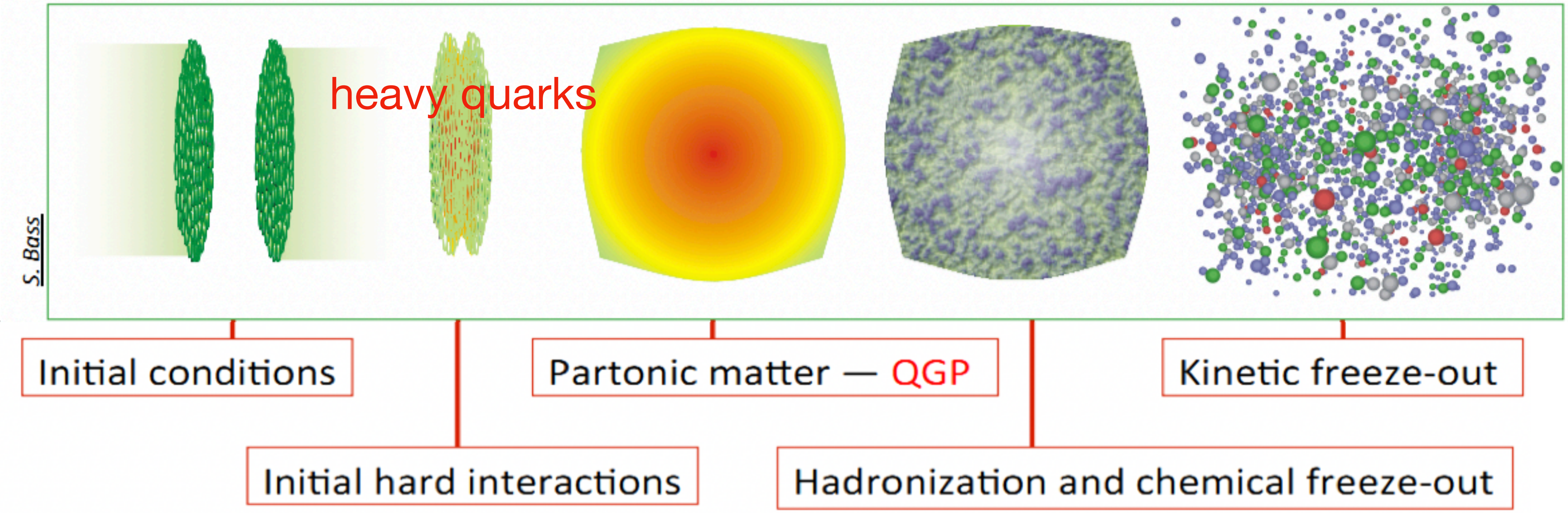
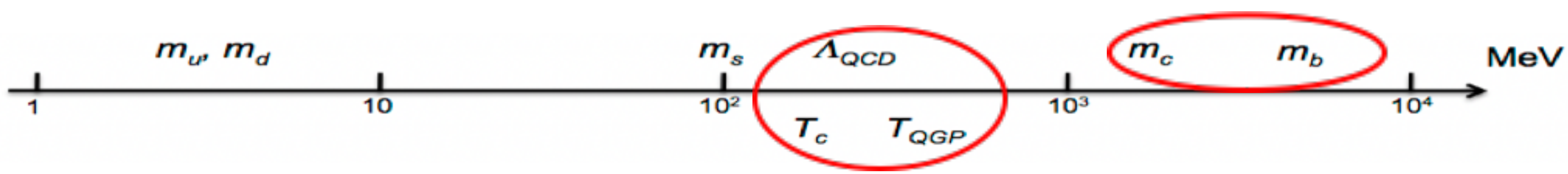
Outline

- Why heavy flavor?
- STAR experiment
- Measurements
  - Nuclear modification factors of charm and bottom electrons in 200 GeV Au+Au collisions
  - Inclusive heavy flavor electron elliptic flow in 27 and 54.4 GeV Au+Au collisions
- Summary

Why heavy flavor?

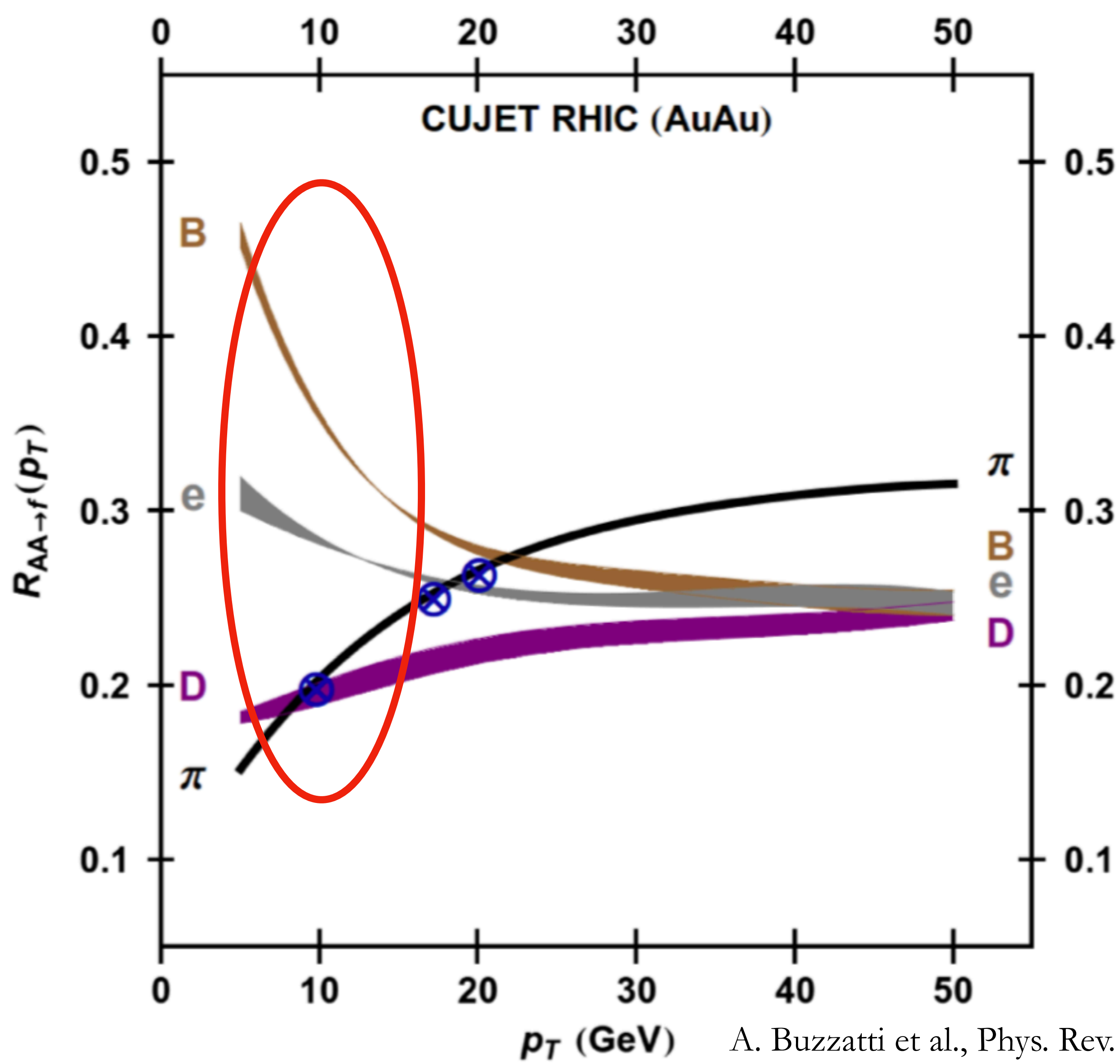




- $m_{c,b} >> T_{QGP}$; dominantly produced in hard scattering at the early stage
  - Experience all stages of QGP evolution: carry information of interaction with the medium.
  - An excellent probe to study the properties of the QGP.

Energy loss of heavy quarks

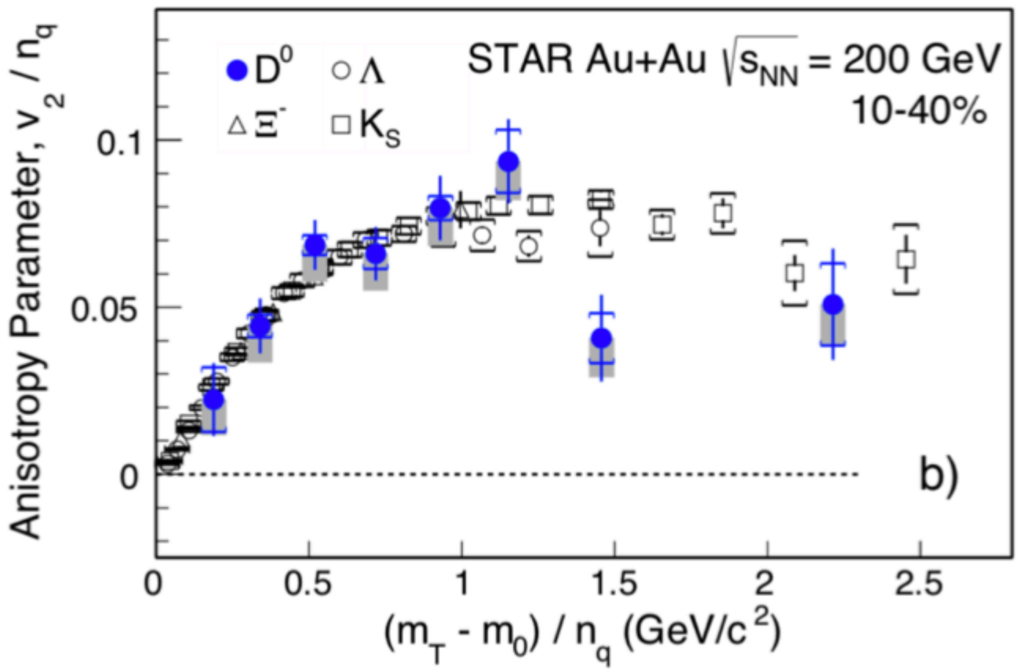
- Theoretical prediction for ΔE in medium: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$.
- Precise measurements of c and b quark energy losses separately are crucial to test the mass hierarchy of the parton energy loss.



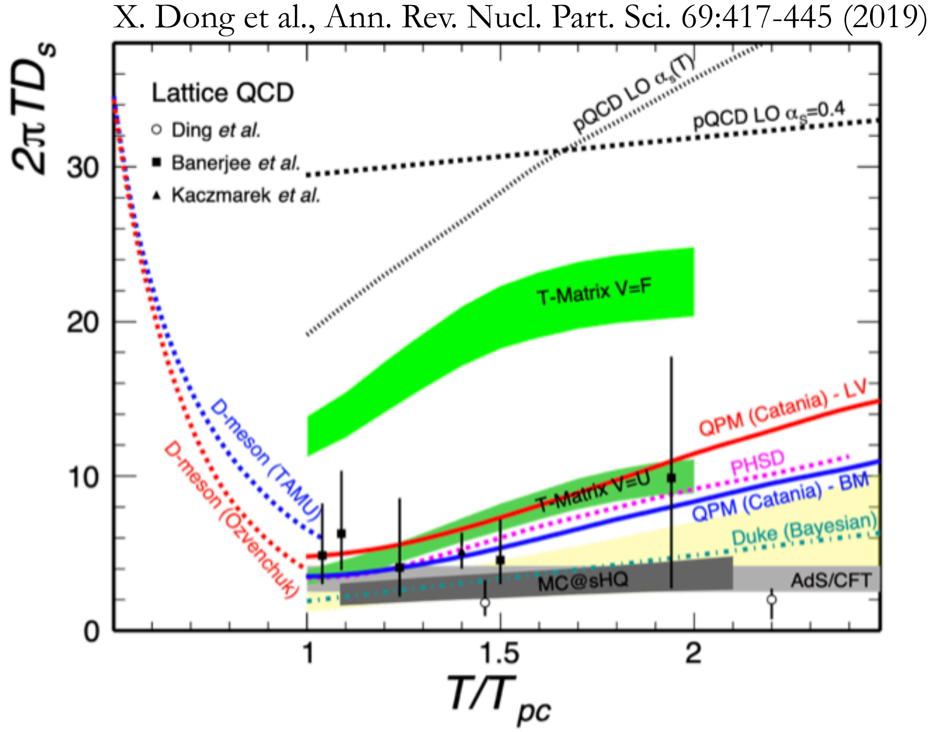
A. Buzzatti et al., Phys. Rev. Lett. 108, 022301 (2012)

Elliptic flow (v_2) of heavy quarks

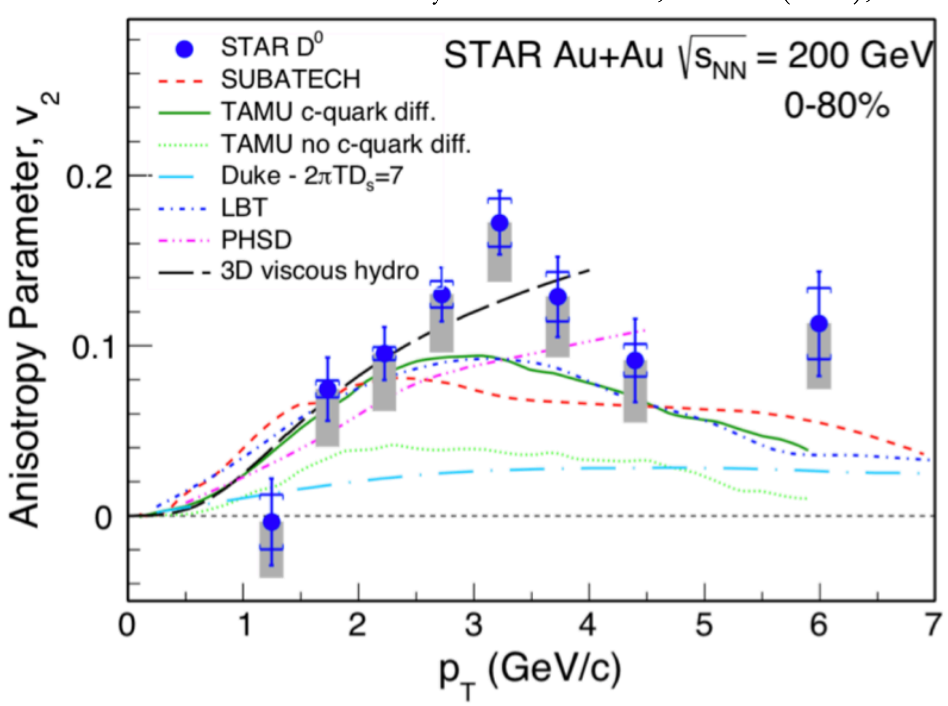
- D^0 meson v_2 follows light hadron trend in 200 GeV Au+Au collisions.
  - Charm quarks attain thermal equilibrium in the QGP?
- Model calculations with T-dependent charm quark $2\pi TD_s$ can qualitatively reproduce D^0 v_2
- What's charm quarks flow at lower energies?



X. Dong et al., Ann. Rev. Nucl. Part. Sci. 69:417-445 (2019)



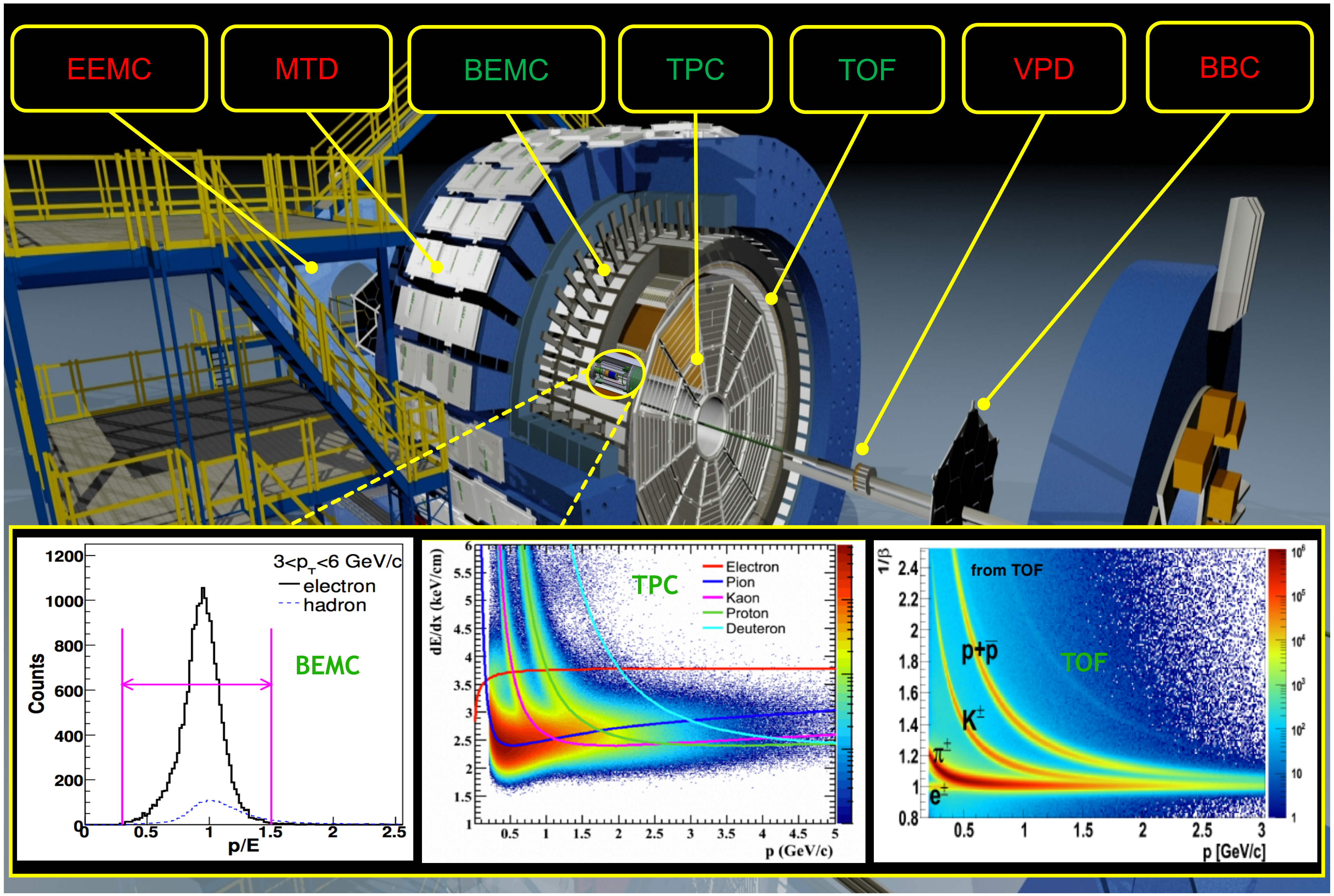
Phys. Rev. Lett. 118, 212301 (2017), STAR Collaboration



Electrons from heavy-flavor hadron decays (HFe) are a good proxy to measure heavy flavor quarks.

STAR detector

- $|\eta|<1$ and full azimuthal coverage



Time Projection Chamber (TPC)

- Momentum determination
- PID through dE/dx

Time of Flight (TOF)

- PID through the $1/\beta$
- Timing resolution:~85 ps

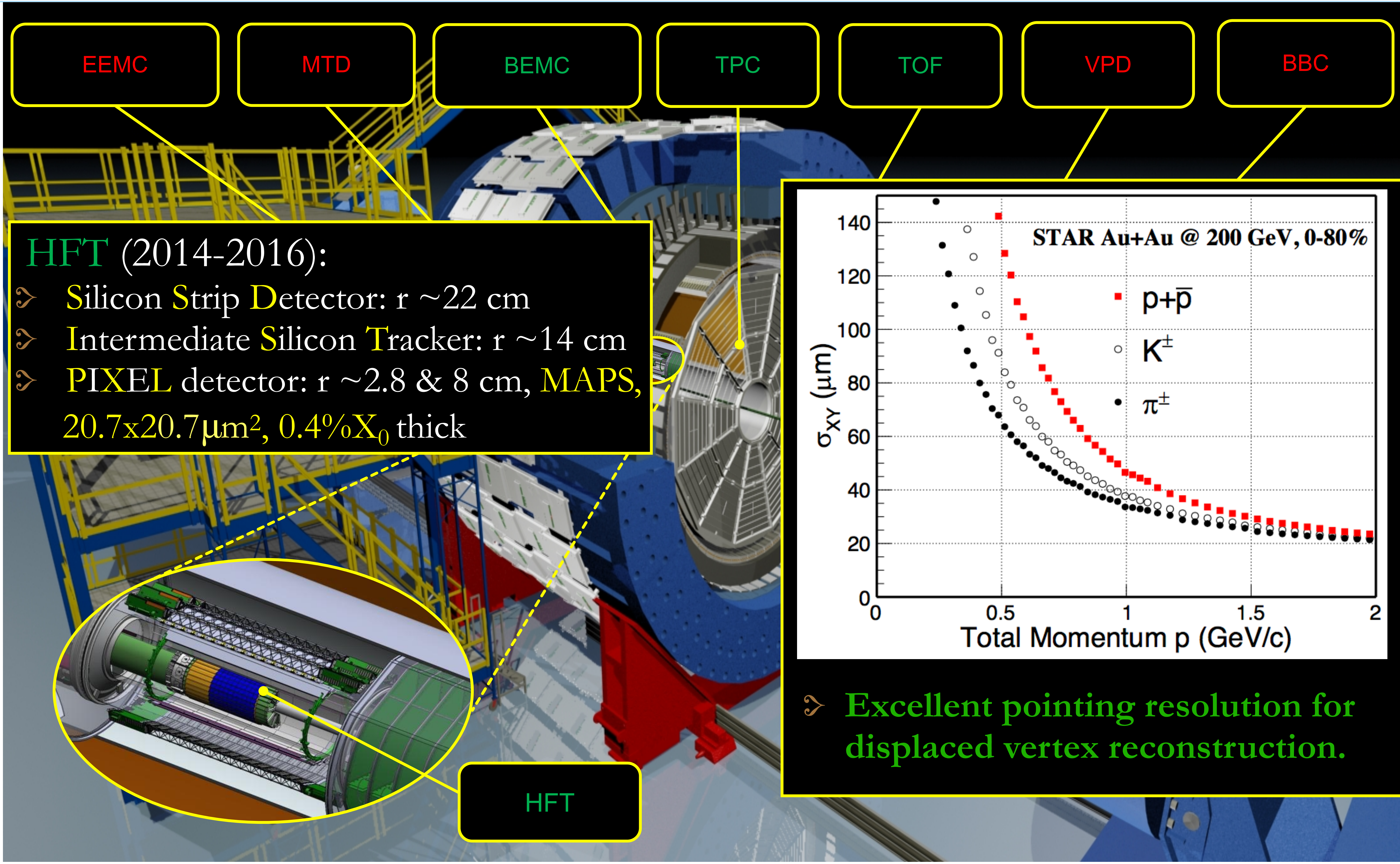
Barrel Electromagnetic Calorimeter (BEMC)

- PID through p/E
- Triggering on high-p_T electrons

Heavy Flavor Tracker (HFT)

- Excellent pointing resolution for displaced vertices

STAR detector



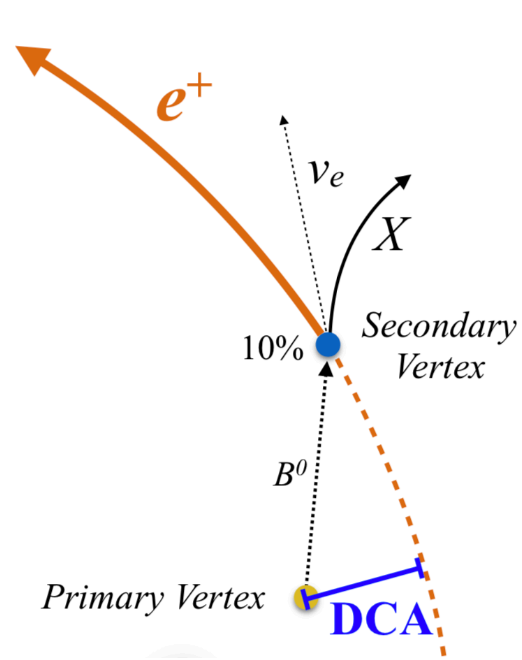
HFT (2014-2016):

- Silicon Strip Detector: r ~22 cm
- Intermediate Silicon Tracker: r ~14 cm
- PIXEL detector: r ~2.8 & 8 cm, MAPS, 20.7x20.7μm², 0.4%X_0 thick

- **Excellent pointing resolution for displaced vertex reconstruction.**

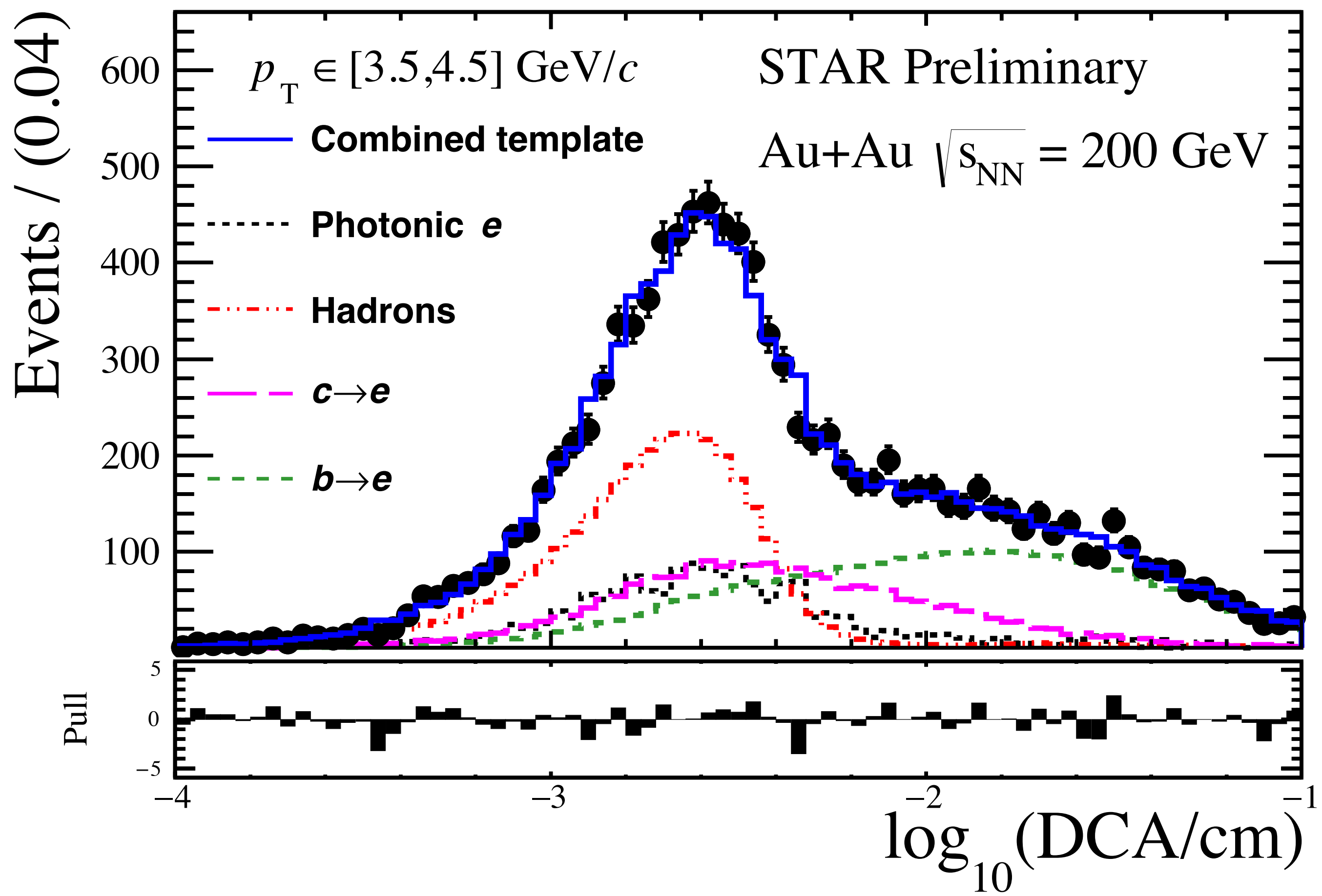
Extract b/c → e fraction

Extraction of b- and c-decayed electrons with template fit to log of 3D Distance of Closest Approach



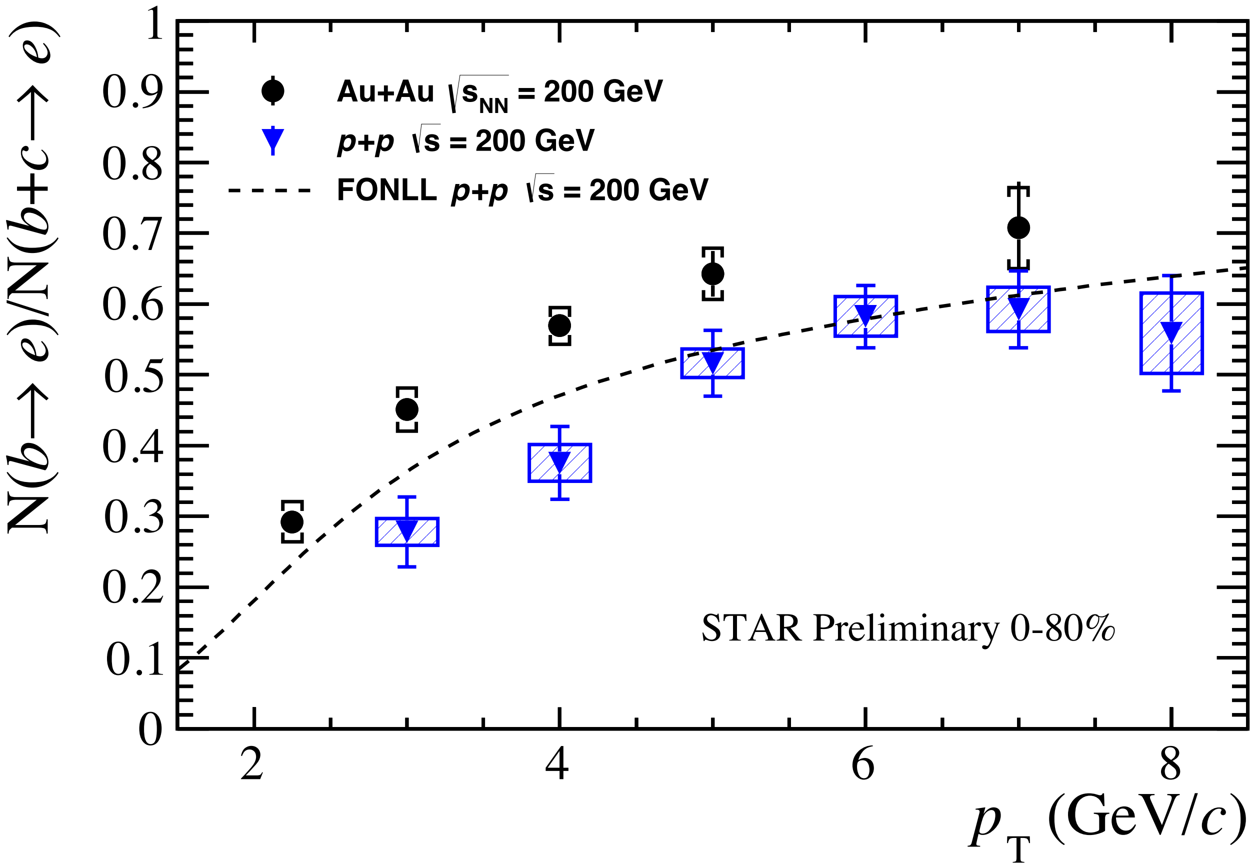
Combined 2014+2016 RHIC Runs:

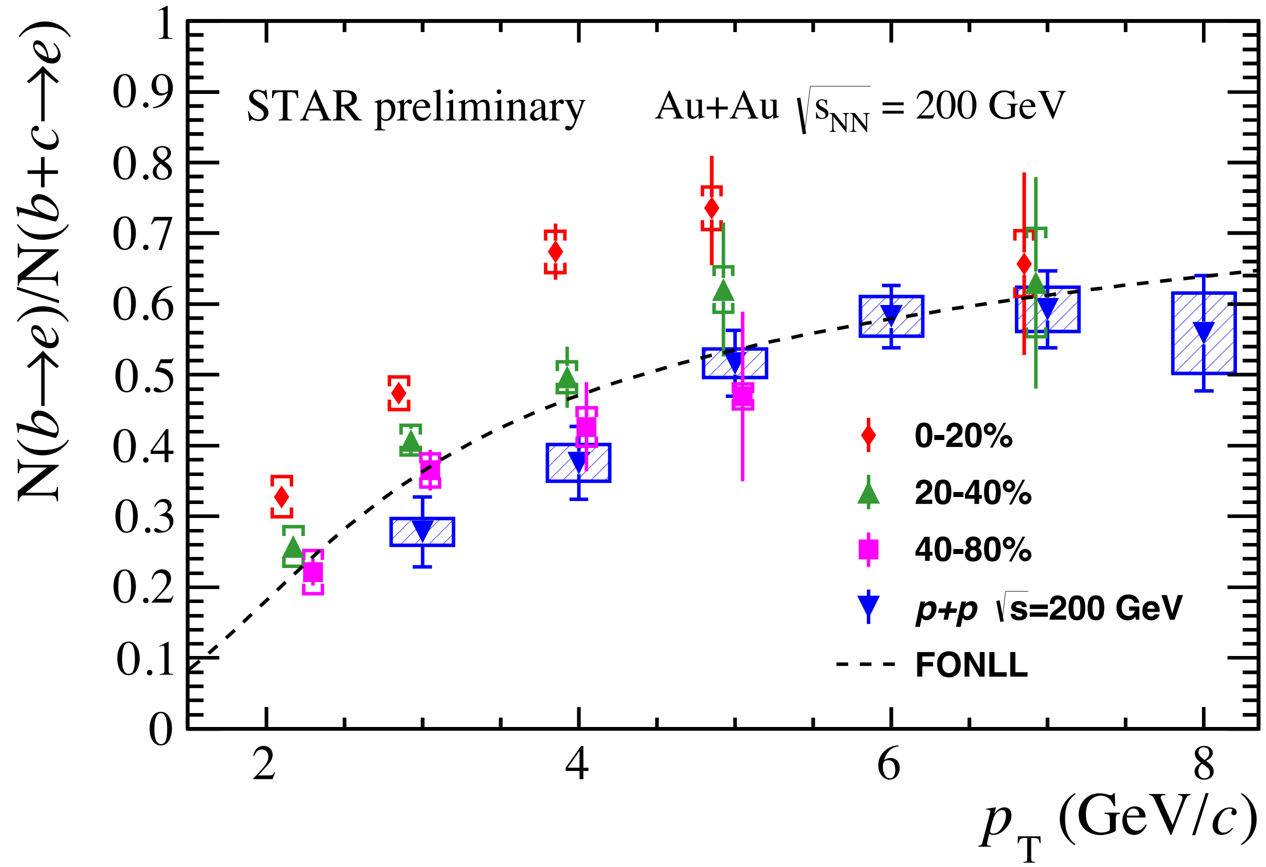
- 2014: ~0.9 B minimum bias + ~0.2 nb^{-1} BEMC triggered events
- 2016: ~1.1 B minimum bias + ~1.2 nb^{-1} BEMC triggered events



- Signal (b/c→e):
  - EventGen+ data driven simulation (D^0, $D^{\pm}$, D_S, Λ_c and B^0, $B^{\pm}$, B_S, Λ_b)
  - Larger c_τ of b-hadrons w.r.t. c-hadrons ⟨DCA(b→e)⟩ > ⟨DCA(c→e)⟩
- Background:
  - Hadrons: from data, constrained by purity
  - Photonic electron: from simulation, constrained by photonic electron fraction

b/c → e fraction

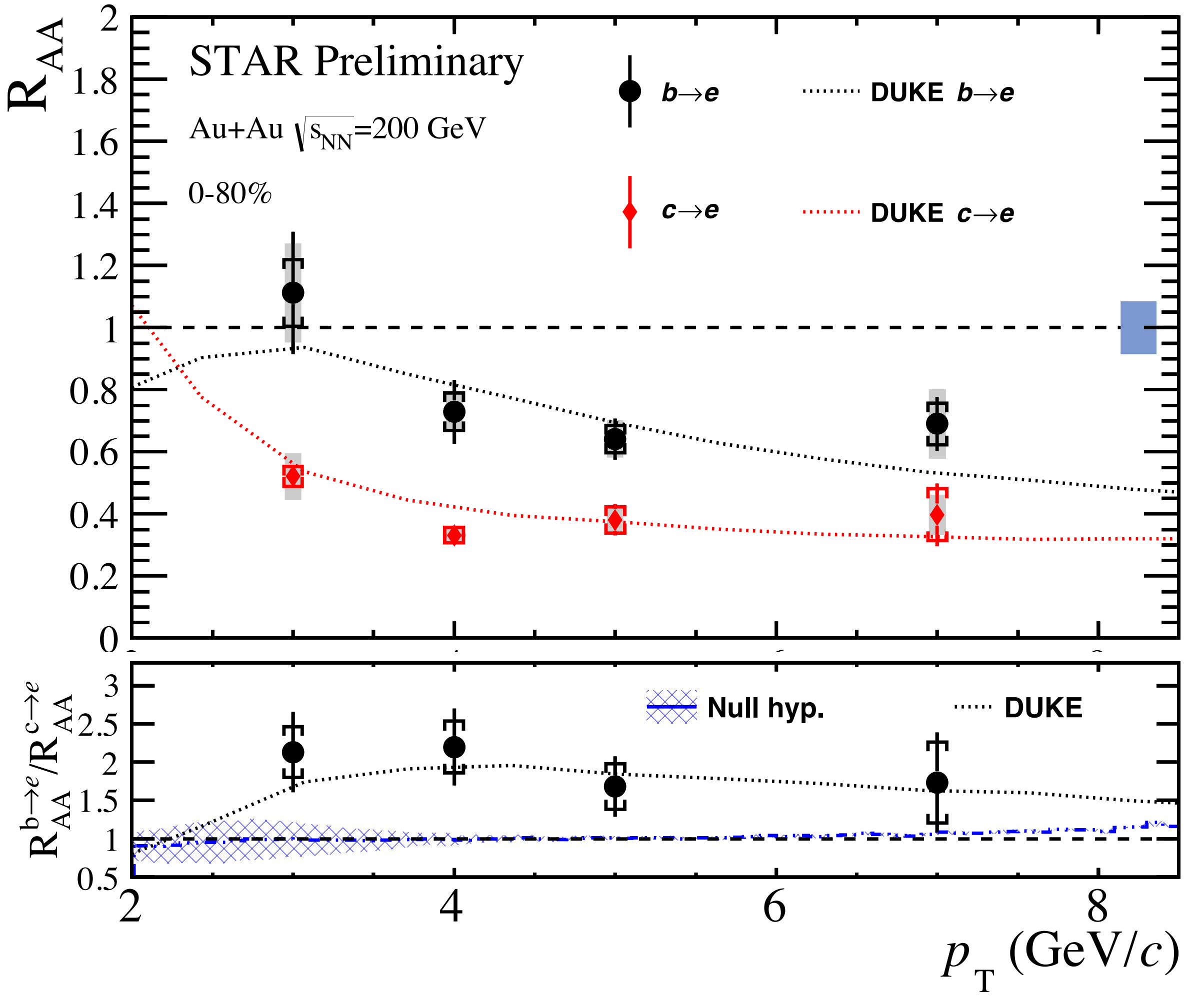




- Enhancement of the bottom fraction is observed in 0-80% Au+Au collisions compared to that in p+p collisions and FONLL prediction.
- Bottom fraction significantly enhanced in central Au+Au collisions at 200 GeV and consistent with p+p and FONLL in peripheral collisions.

b/c → e R_{AA}

DUKE: S. Cao et al., Phys. Rev. C 92, 024907 Private Communication



- Bottom electron fraction used to calculate b, c→e R_{AA} with preliminary STAR inclusive HFe R_{AA}

$$R_{AA}^{b\to e} = \frac{f_{Au+Au}^{b\to e}}{f_{p+p}^{b\to e}} R_{AA}^{HFe}$$

$$R_{AA}^{c\to e} = \frac{f_{Au+Au}^{c\to e}}{f_{p+p}^{c\to e}} R_{AA}^{HFe}$$

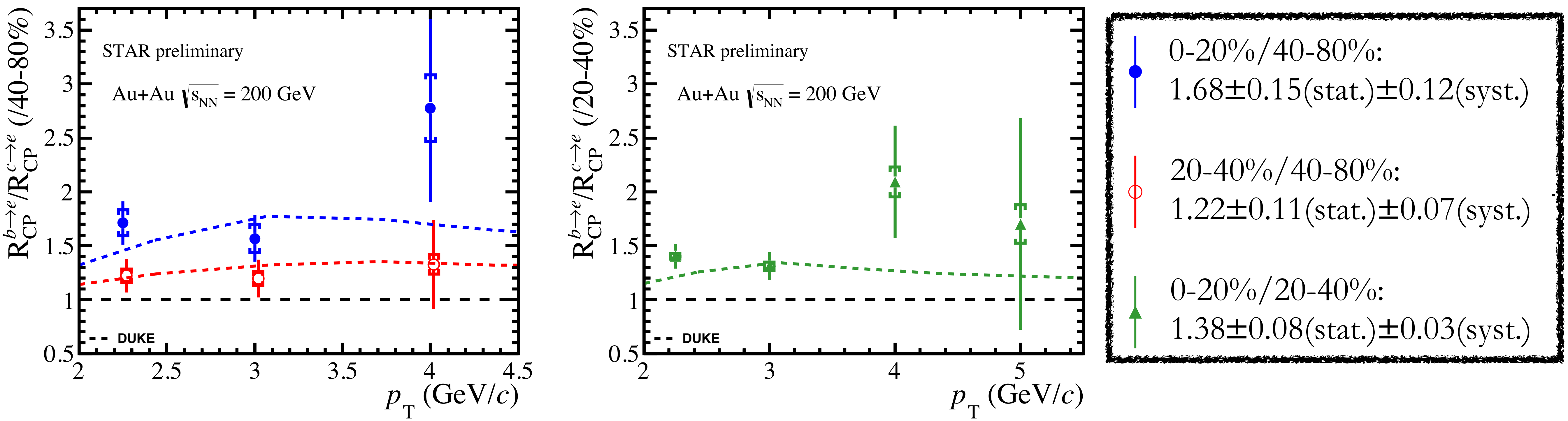
- R_{AA} (c→e) < R_{AA} (b→e) (~3σ at 3 - 7 GeV/c).
- Consistent with mass hierarchy of parton energy loss ($\Delta E_c > \Delta E_b$) .
- Consistent with the DUKE model prediction.
- Null hypothesis [R_{AA}(B)= R_{AA}(D)] for p_T (e) ∈ [2.5,5.5]GeV/c:
  - χ^2/ndof = 8.6/2, p-value = .014

Double ratio of R_{CP}

- Calculated from centrality dependent bottom fraction.
- Large cancelation of correlated systematic uncertainties.

$$\frac{R_{CP}^{b\to e}}{R_{CP}^{c\to e}} = \frac{f_b^{central}}{1-f_b^{central}} \frac{1-f_b^{peripheral}}{f_b^{peripheral}}$$

Red points shifted from bin center



➢ Constant fit to double ratio >1, significant at 3.5σ and 4.4σ for R_{CP}(0-20%/40-80%) and R_{CP}(0-20%/20-40%).

Extract HFe v_2

$$N^{HF} v_2^{HF} = N^{Inc} v_2^{Inc} - N^{pho} v_2^{pho} - \sum_h f_h \cdot N^{Inc} v_2^h$$

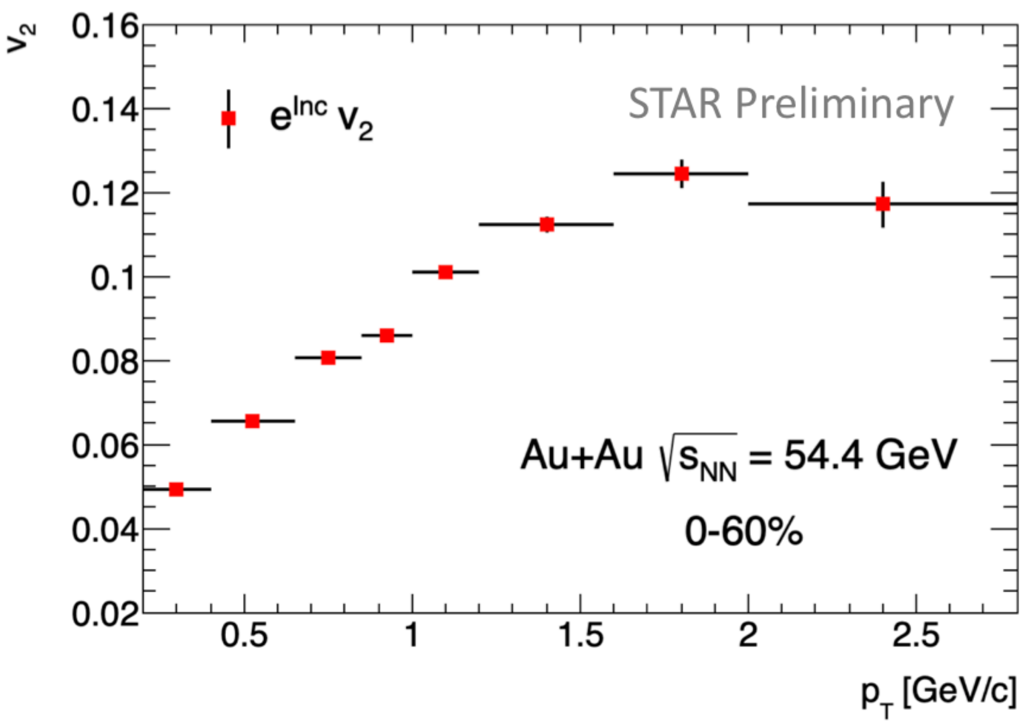
Large data samples of 27 and 54.4 GeV Au+Au collisions collected in 2017-2018

- 10×more statistics compared to 39 and 62.4 GeV taken in 2010
- Significantly improve the precision

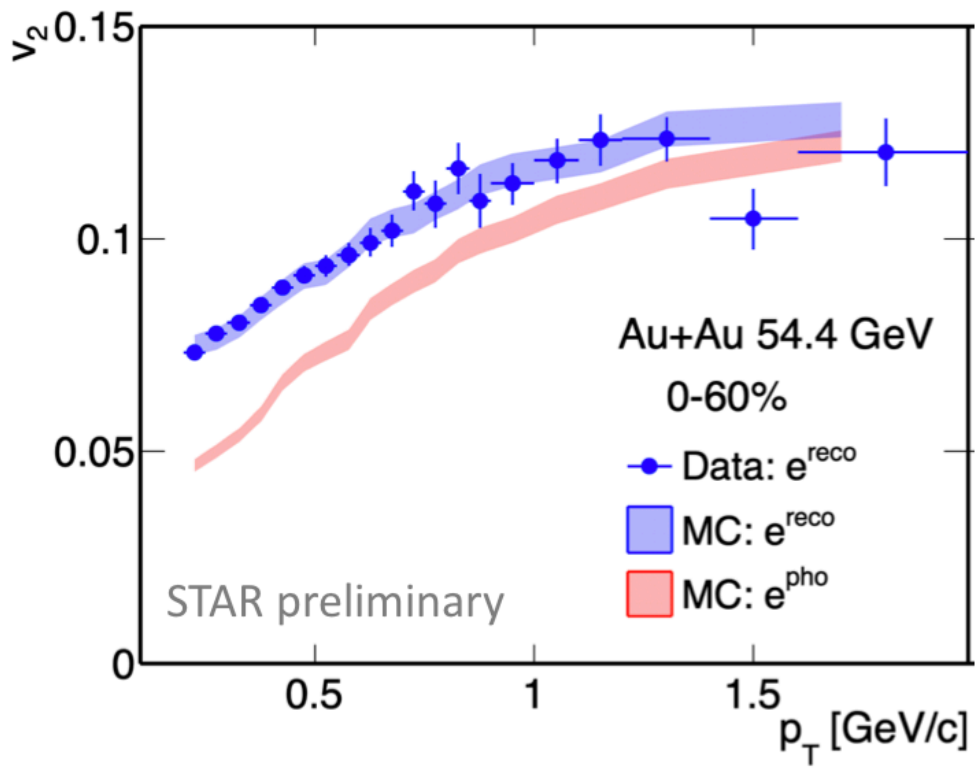
Phys. Rev. C 88, 014902 (2013), STAR Collaboration

- v_2^h from STAR published result.

- v_2^{Inc} from data using event plane $\eta - sub$ method: $v_2 = <\dfrac{cos2(\phi - \Psi_2)}{R}>$

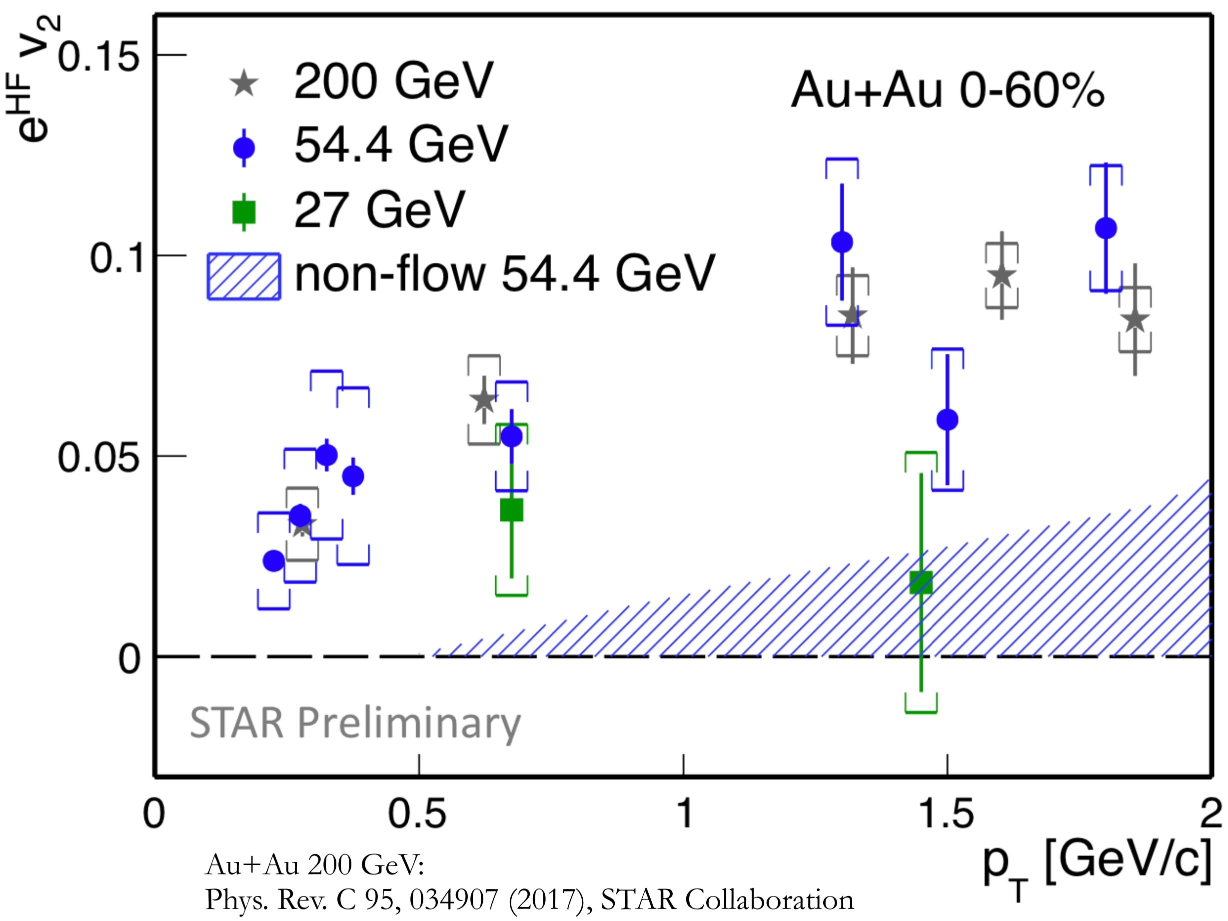


- v_2^{pho} from simulation using event plane method with parent particle p_T and ϕ weight: $1 + 2v_2 cos2(\phi - \Phi_2)$
  - ϕ weight is set according to the v_2 of parent particle from data.



HFe v_2

- HFe v_2 in 27 and 54.4 GeV Au+Au collisions

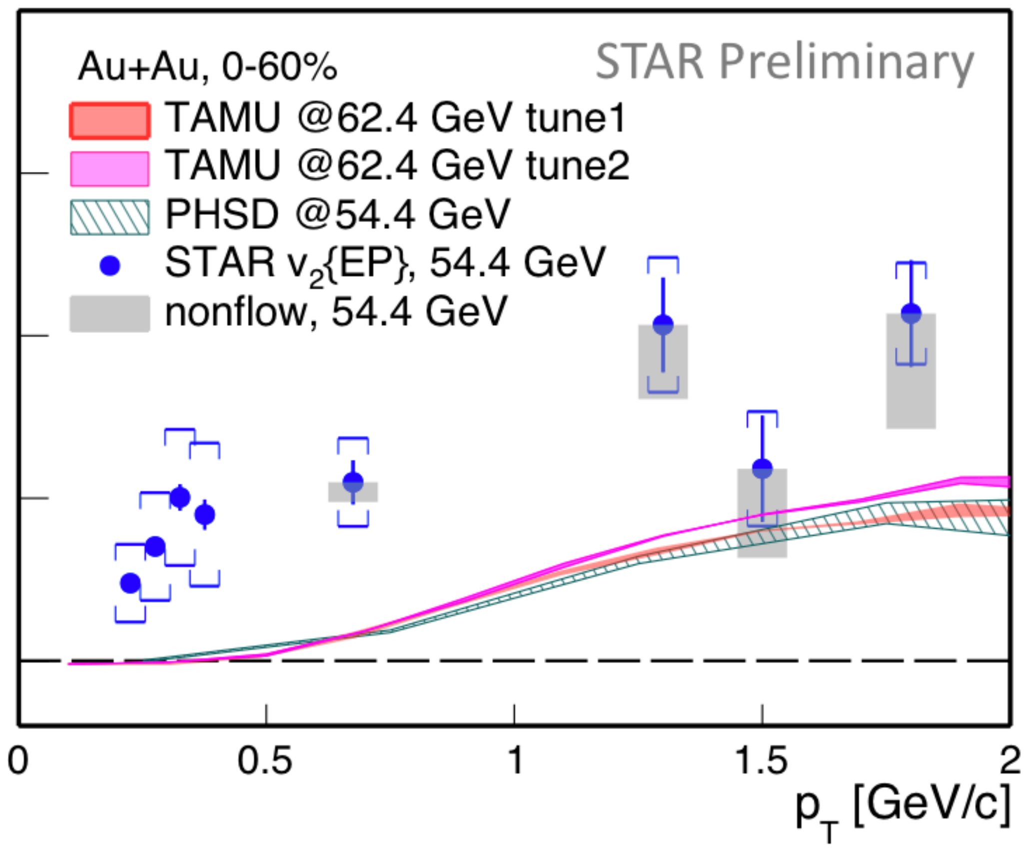


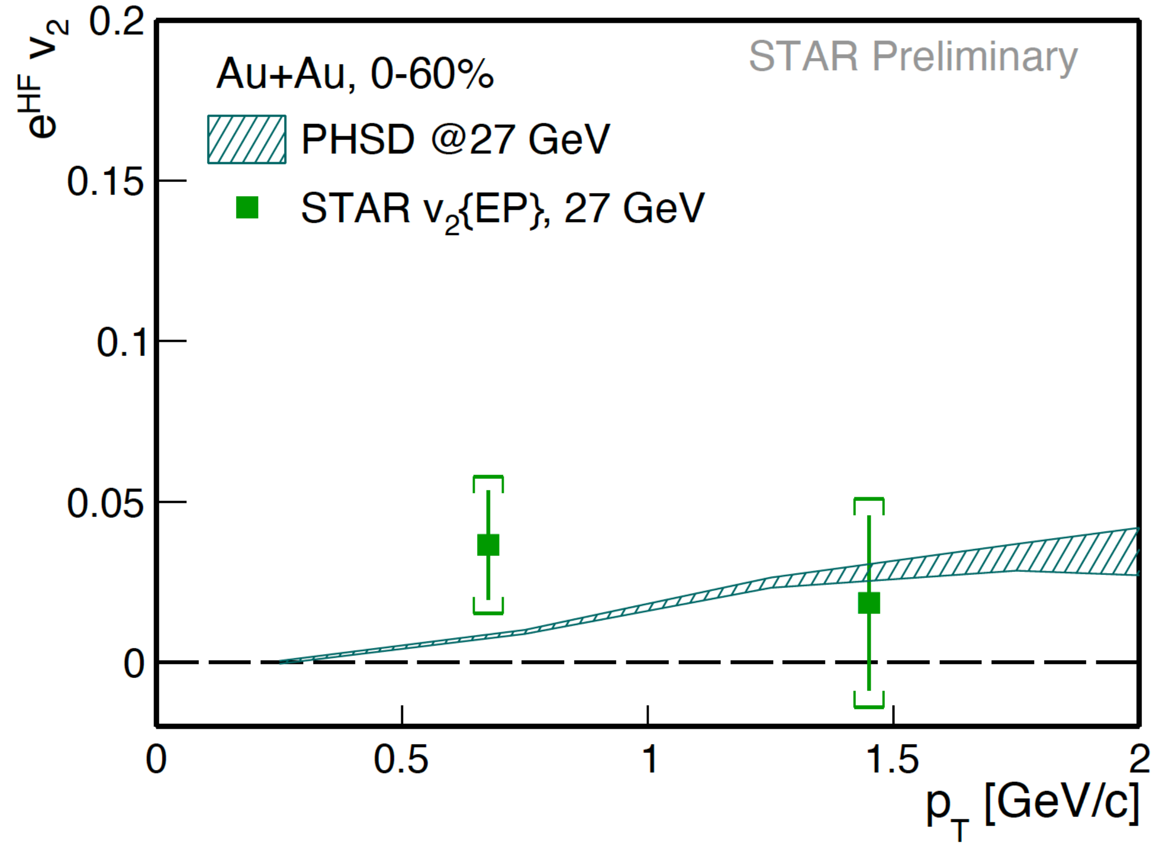
Au+Au 200 GeV:
Phys. Rev. C 95, 034907 (2017), STAR Collaboration

- HFe in 54.4 GeV Au+Au collisions have non-zero v_2, comparable to that at 200 GeV.
  - Charm quark interacts strongly with the medium at 54.4 GeV
- Hint of lower HFe v_2 in 27 GeV Au+Au collisions than those at 54.4 and 200 GeV.

HFe v_2: compare to models

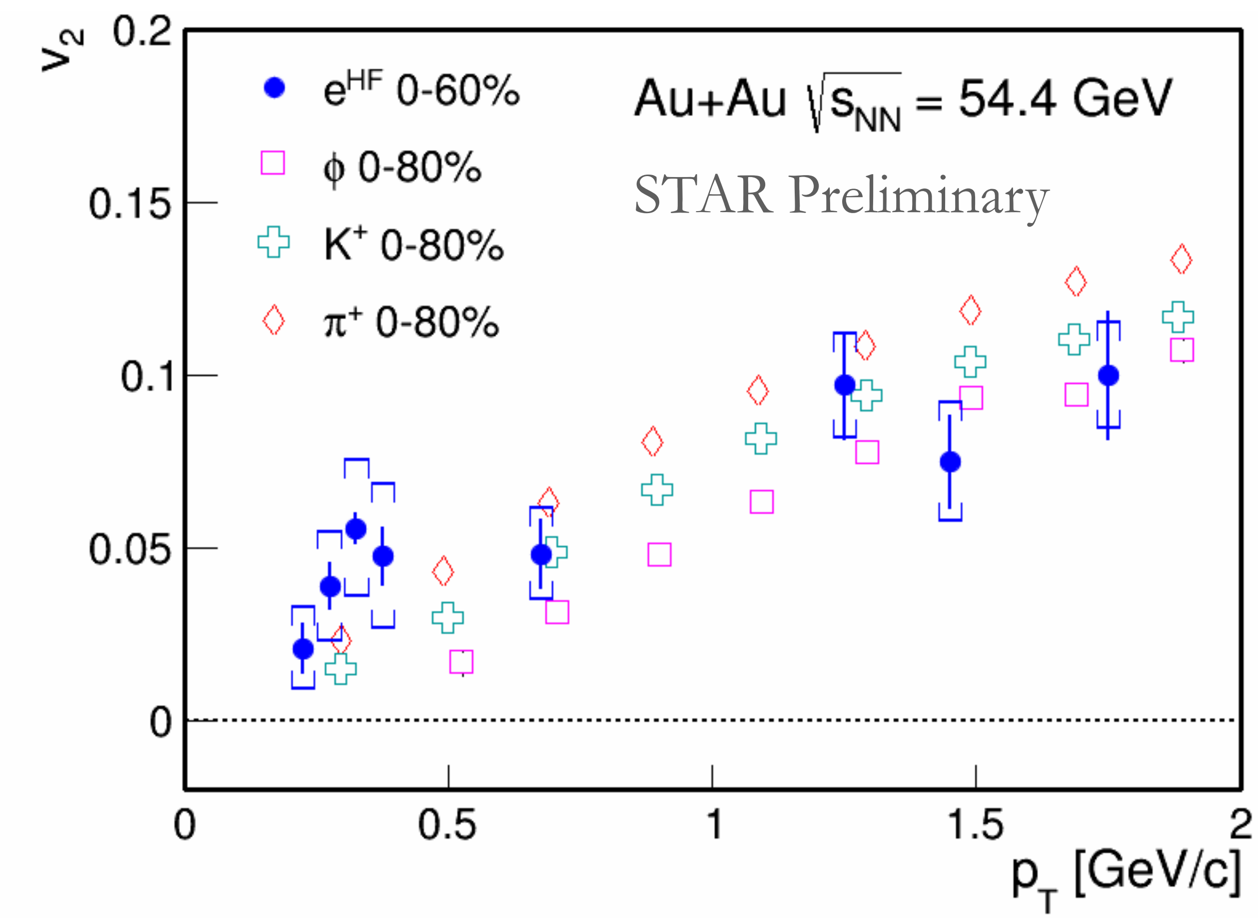
M. He et al., PRC 91,024904 (2015)
T. Song et al., PRC 92, 014910 (2015)
T. Song et al., PRC 96, 014905 (2017)

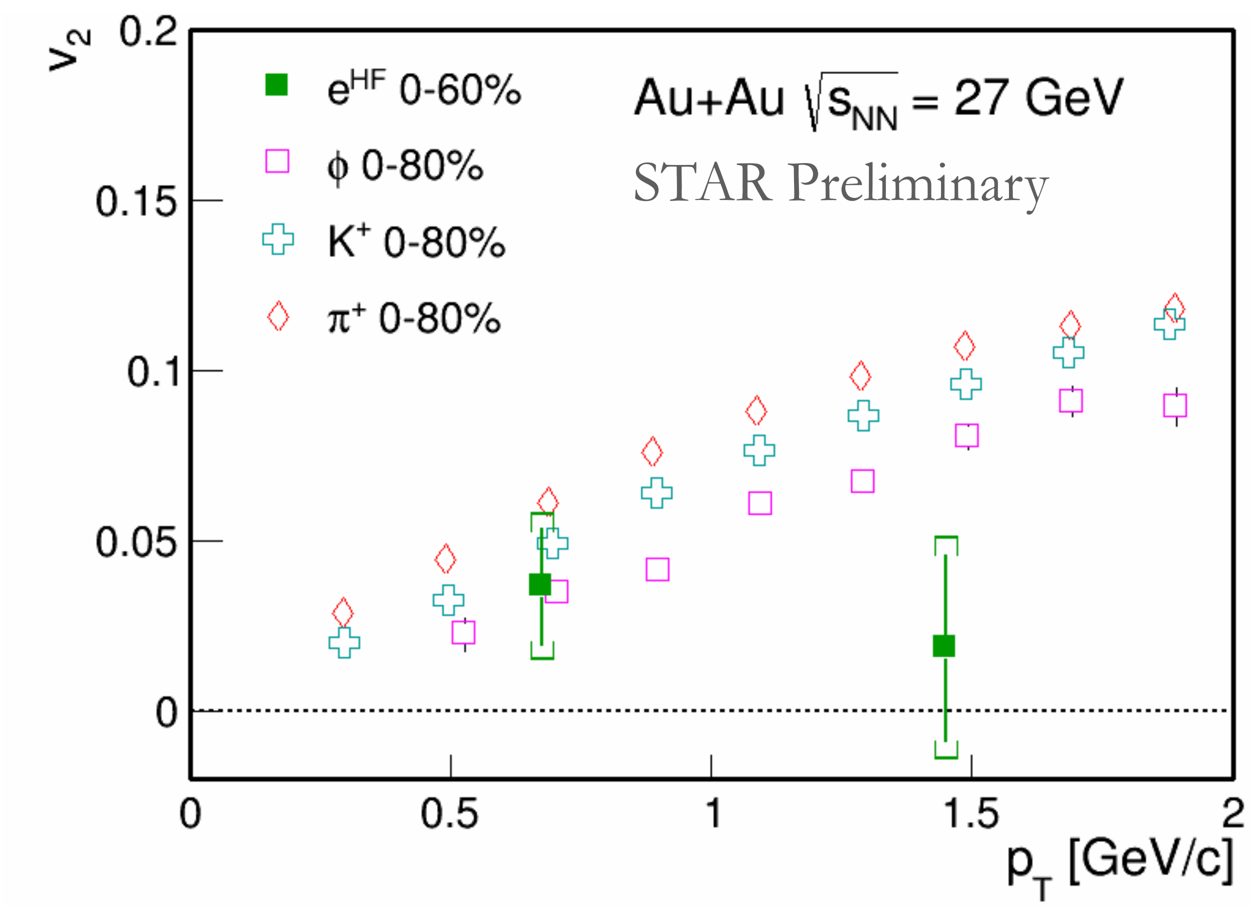




- At low p_T : TAMU and PHSD calculations are lower than v_2 at 54.4 GeV.
- At high p_T : data and model calculations are comparable considering the upper limit of estimated non-flow contribution and uncertainties.
- PHSD calculation is comparable to data with large uncertainties at 27 GeV.

v_2: HFe and identified particles





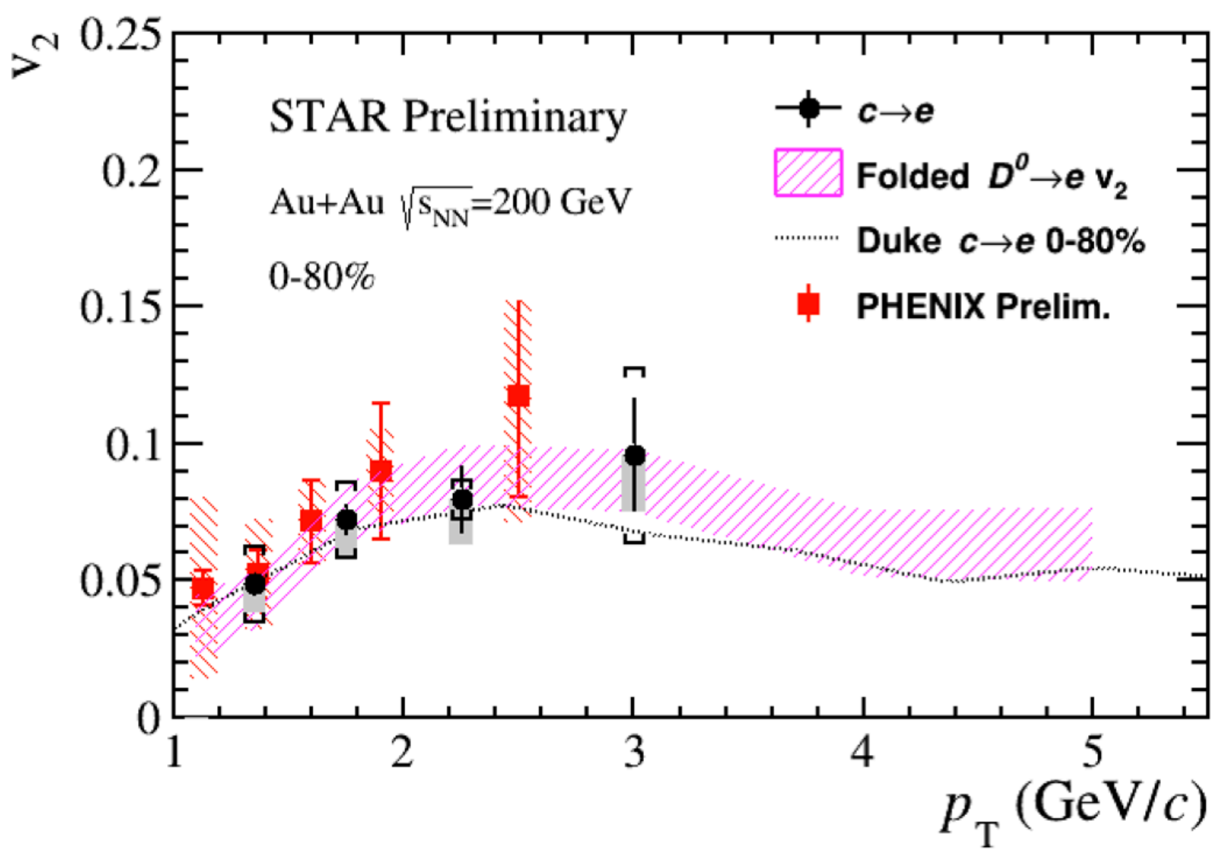
- HFe v_2 is comparable to those of light flavor mesons at 54.4 GeV.
- Hint of HFe v_2 at p_T >1 GeV/c lower than those of light flavor mesons at 27 GeV.

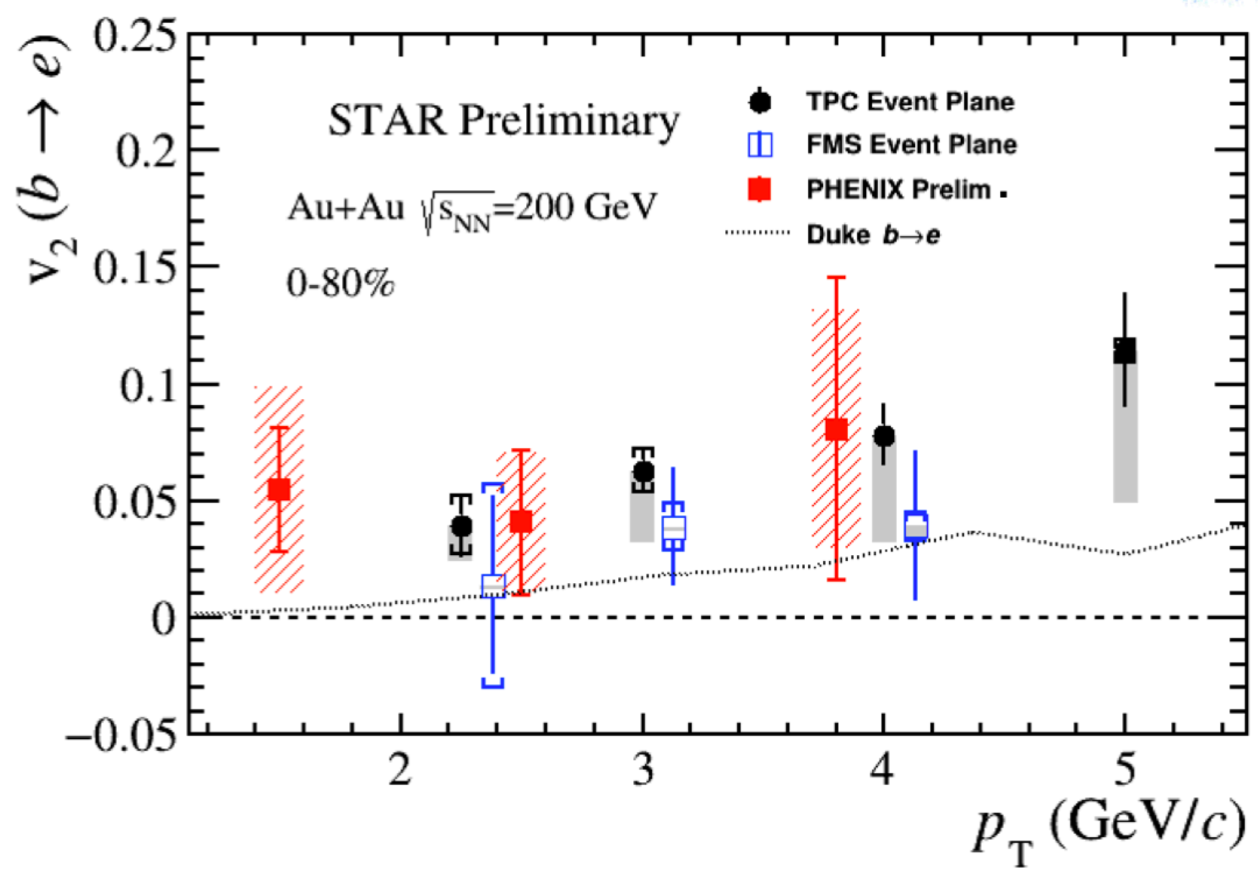
Summary

- b/c → e R_{AA}/R_{CP} in 200 GeV Au+Au collisions
  - Less suppression for b → e than c → e (with >= 3σ significance): consistent with the mass hierarchy of parton energy loss.
  - Consistent with the DUKE model prediction.
- HFe v_2 in 54.4 and 27 GeV Au+Au collisions
  - HFe v_2 in 54.4 GeV Au+Au collisions is comparable to that in 200 GeV, while a hint of smaller HFe v_2 in 27 GeV Au+Au collisions.
  - Model calculations are systematically lower than measured HFe v_2 at low p_T and comparable to data considering non-flow contribution and uncertainties at high p_T in 54.4 GeV Au+Au collisions.
  - HFe v_2 in 54.4 GeV Au+Au collisions is comparable to those of light flavor mesons.

BACK UP

Comparisons to PHENIX



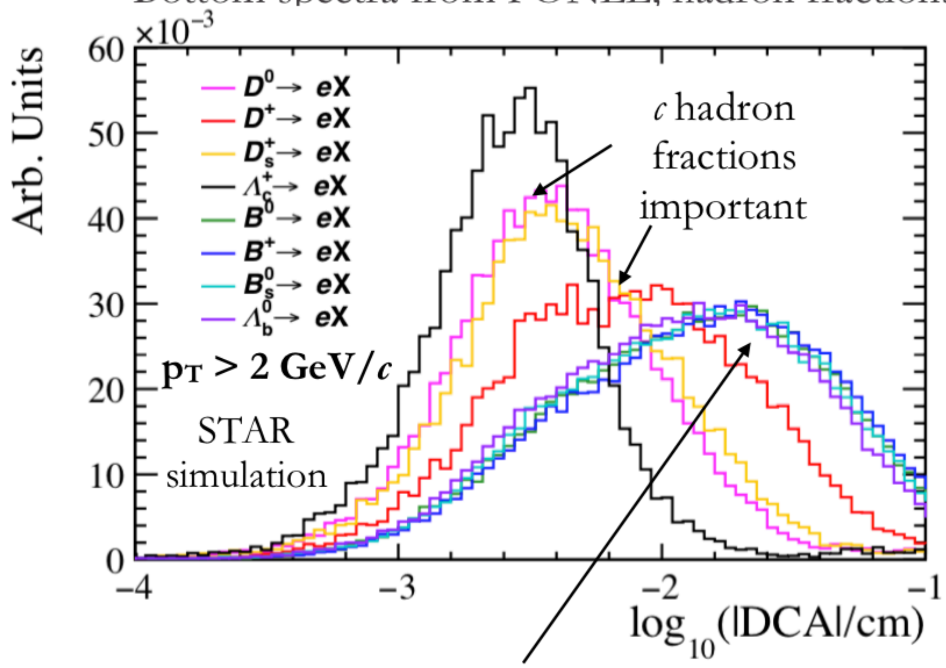


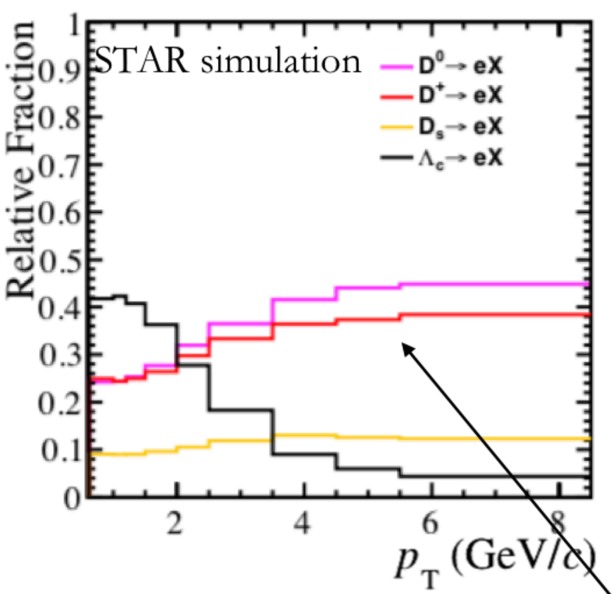
- **Preliminary PHENIX *b,c→e* from Hard Probes 2018**
- **Excellent consistency between experiments within uncertainties**

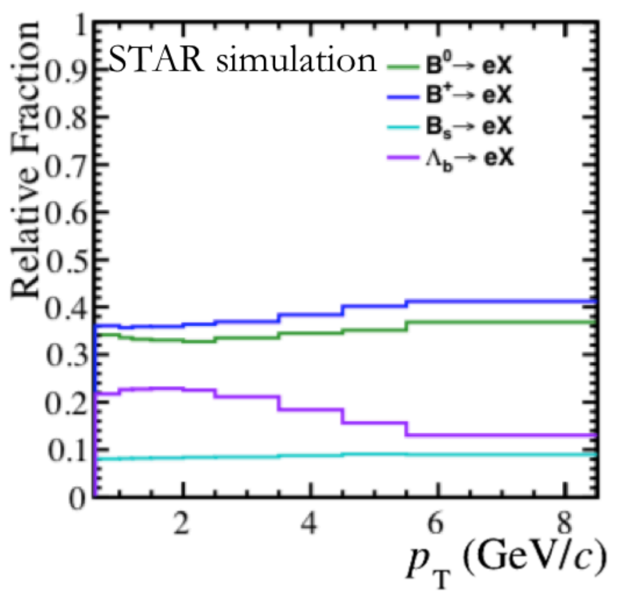
PHENIX: K. Nagashima Hard Probes 2018
DUKE: Phys. Rev. C 92, 024907
Private Communication

HF log(DCA) template model

- **HF decayed electron DCA templates from EvtGen generator corrected for efficiency and momentum/position resolution determined from data**
- **Ground state $B/D^{+/0}$, B_s/D_s, and $\Lambda_{b,c}$ hadron decays simulated with all known semileptonic decays**
  - Charm re-weighted with measured D^0 spectra and preliminary hadron fractions from STAR in Au+Au collisions @ $\sqrt{s_{NN}}$ =200 GeV
  - Λ_c corrected using Λ_c/D_0 preliminary measurement from STAR + model calculations in Au+Au collisions @ $\sqrt{s_{NN}}$ =200 GeV
  - Bottom spectra from FONLL; hadron fractions from LHCb p+p measurement







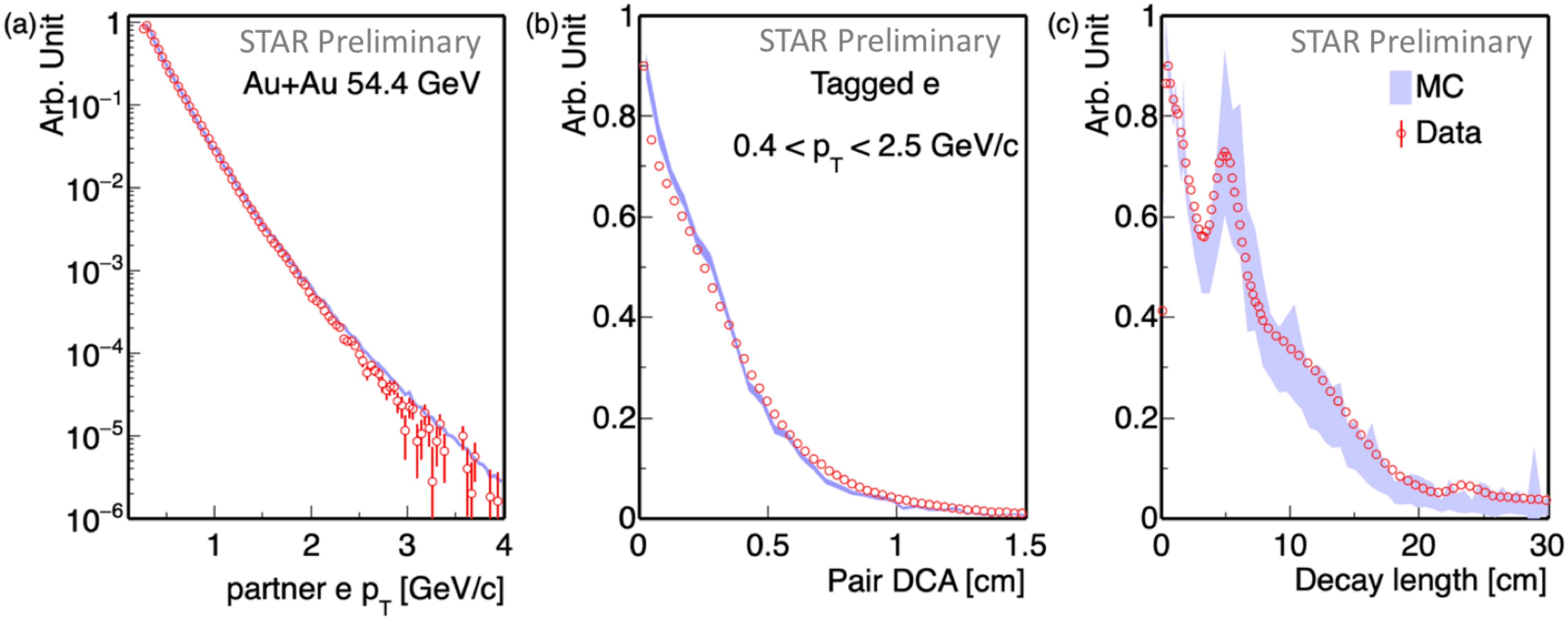
Less sensitive to b hadron fractions

Large uncertainty coming from D+/D0 ratio

LHCb: PhysRevD.100.031102
FONLL: JHEP 1210 (2012)

Reconstruction efficiency extraction

$\pi^0/\eta/\gamma$ p_T weight → Full detector simulation → Tagging electrons by reconstruction method → Reconstructed electron; Partner electron; Electron pair DCA and decay length.



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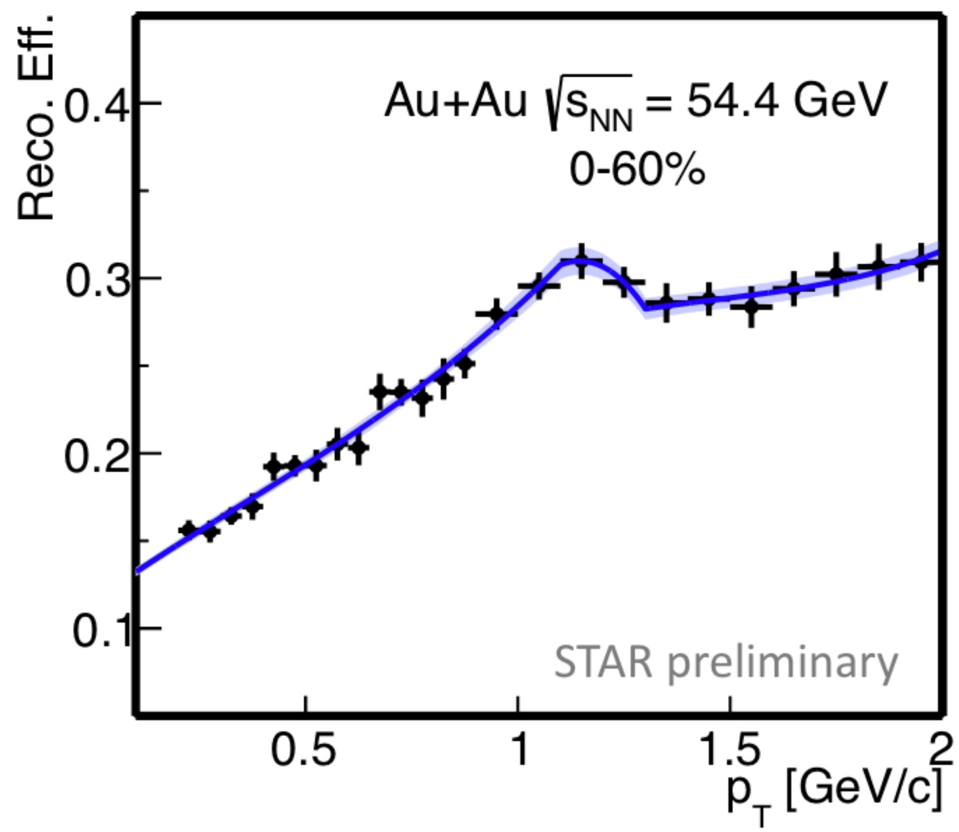
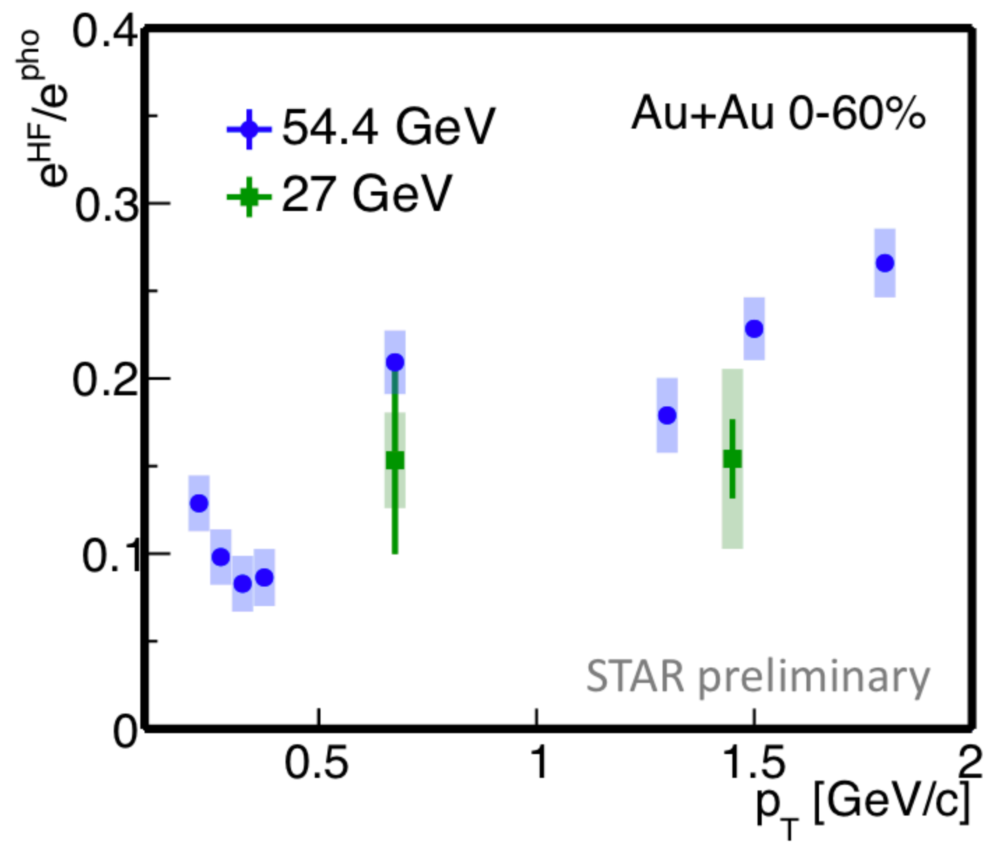


Photonic electron reconstruction efficiency



Heavy flavor electron to photonic electron ratio

Photonic electron v_2 simulation

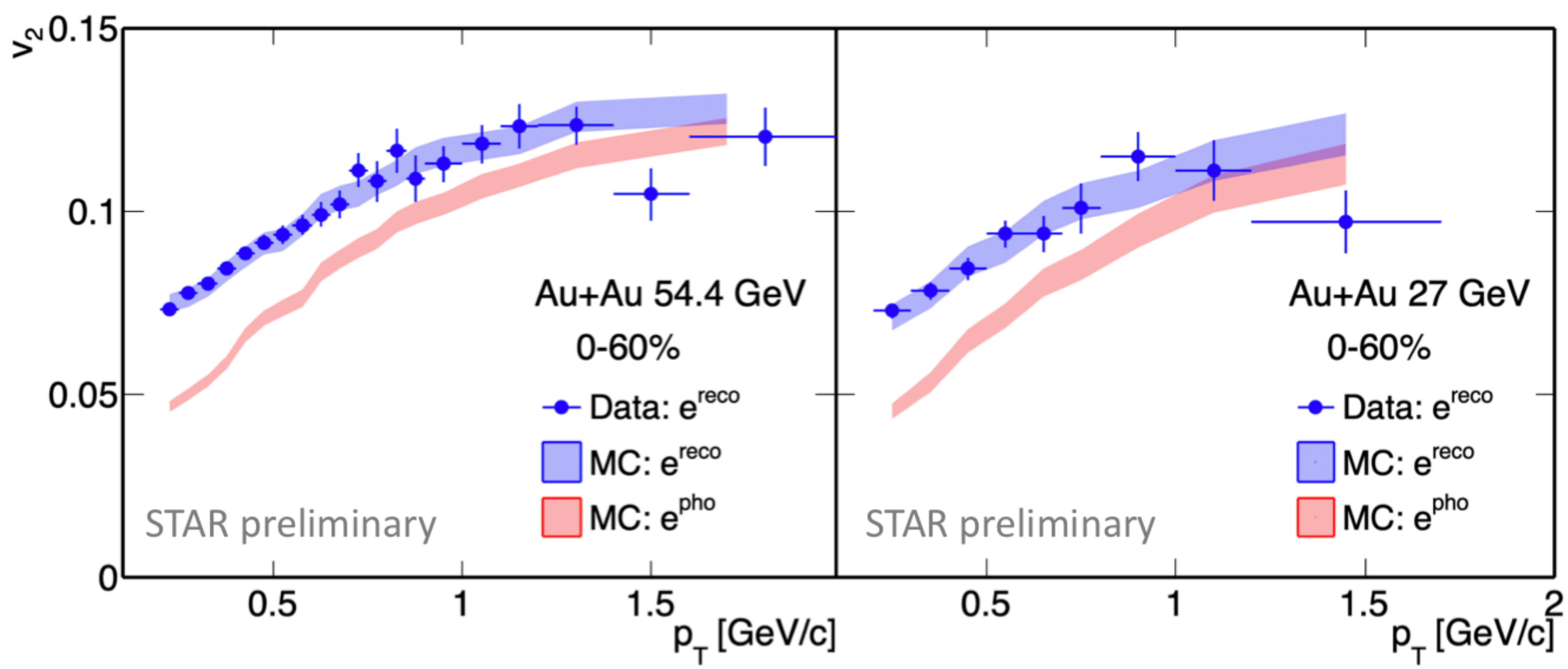
$\pi^0/\eta/\gamma$
p_T weight;
ϕ weight:
$1 + 2v_2 \cos 2(\phi - \Phi_2)$

Sample random event plane

Full detector simulation

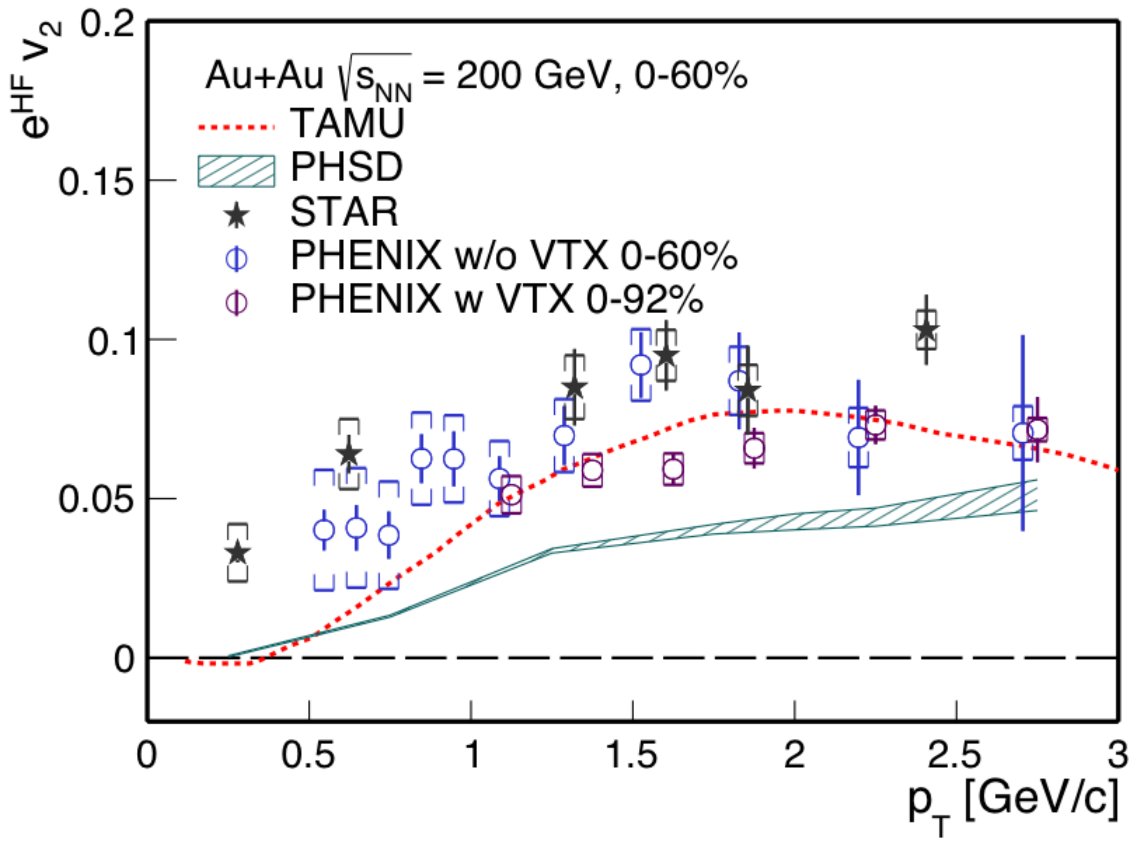
Electrons passing track quality cut → Photonic electron v_2 (Pink band)

Tagging electrons by reconstruction method → reconstructed electron v_2 (Blue band)

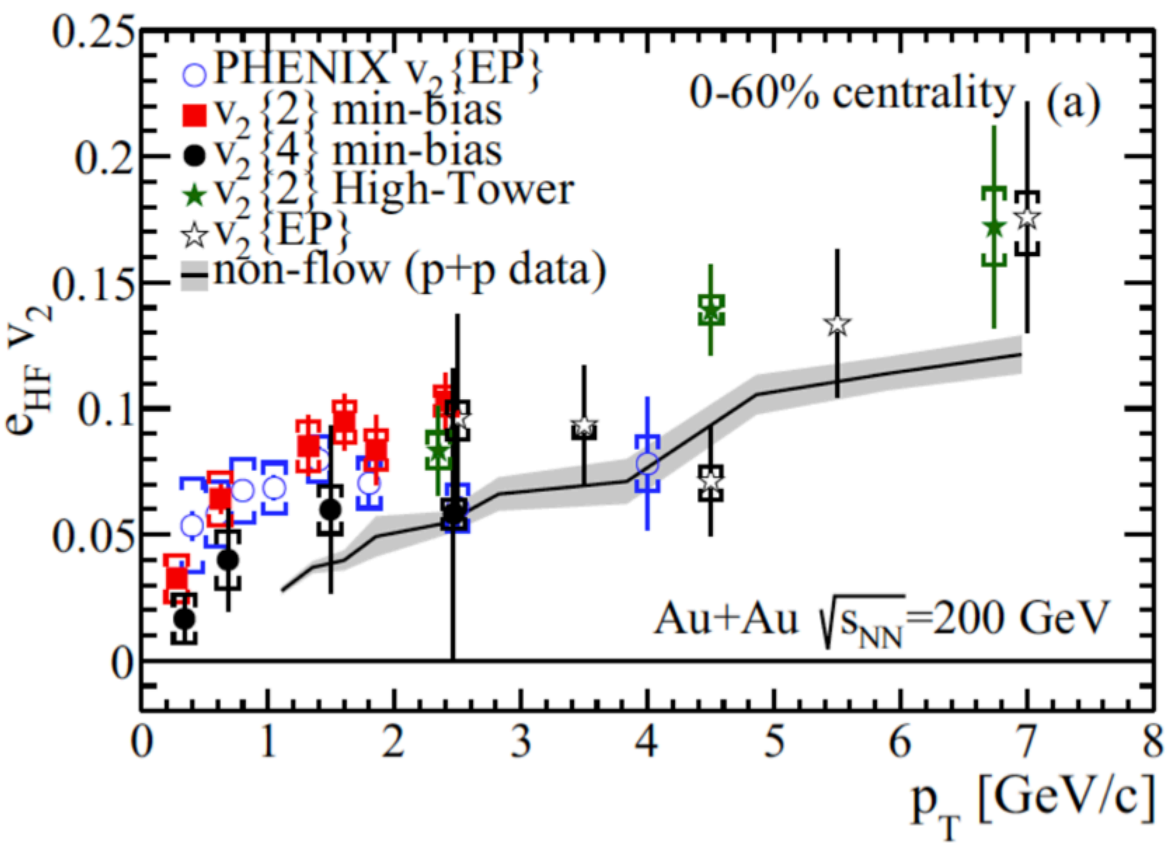


Reconstructed electron v_2 from simulation is consistent with data.

Au+Au 200 GeV NPE



M. He et al. PRC 91,024904 (2015)
T. Song et al. PRC 92, 014910 (2015)
T. Song et al. PRC 96, 014905 (2017)
PHENIX. PRL 98, 172301 (2007)
T. Hachiya, Nucl. Phys. A, 982, 663-666 (2019)



STAR. PRC 95, 34907 (2017)