Recent Results on Open Heavy Flavor from STAR

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(for the STAR collaboration)

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BERKELEY LAB

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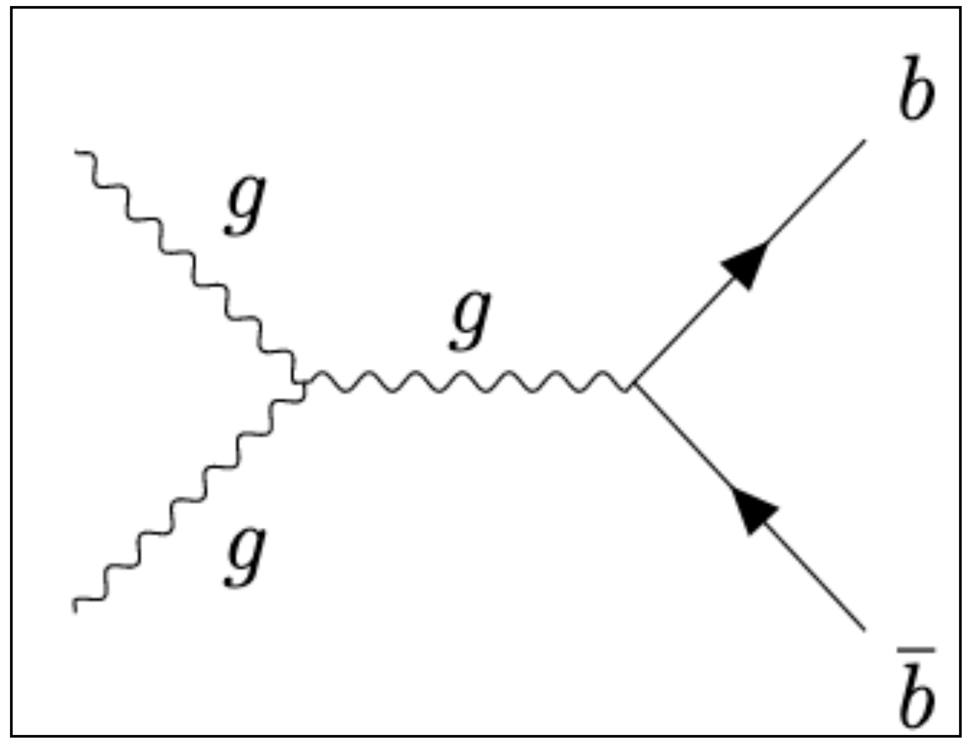
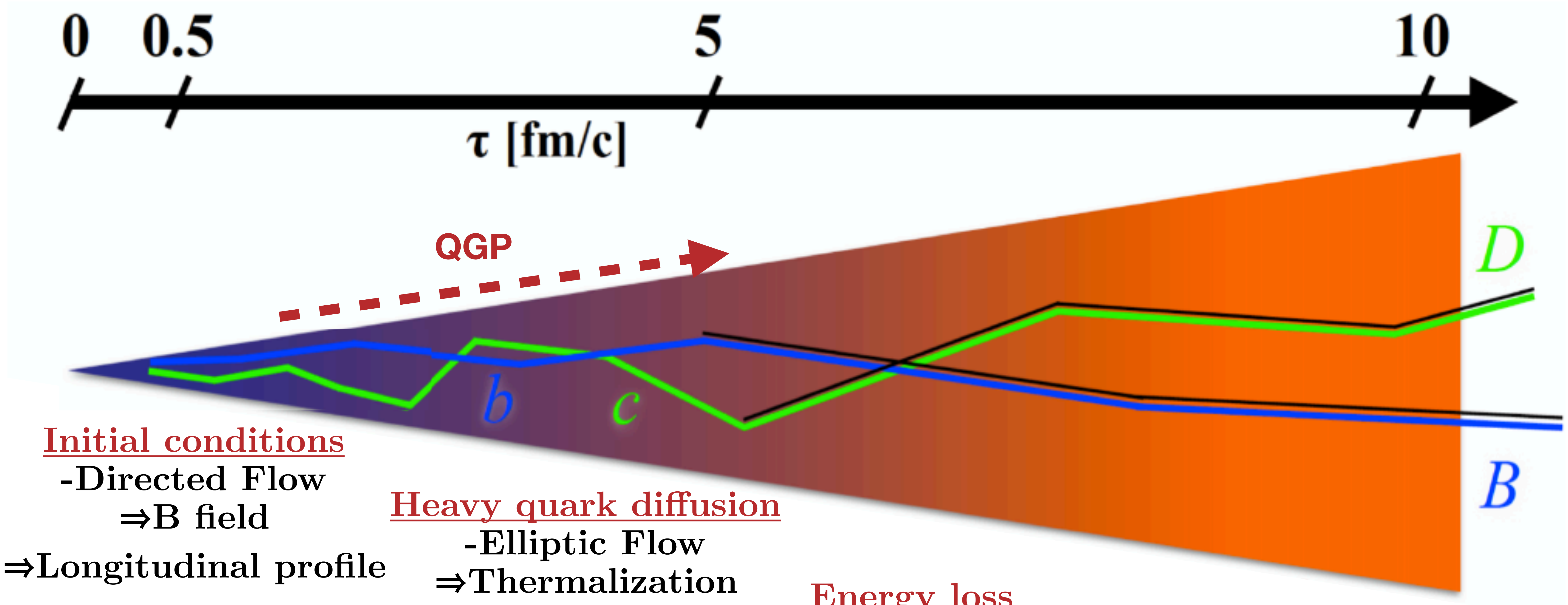
STAR

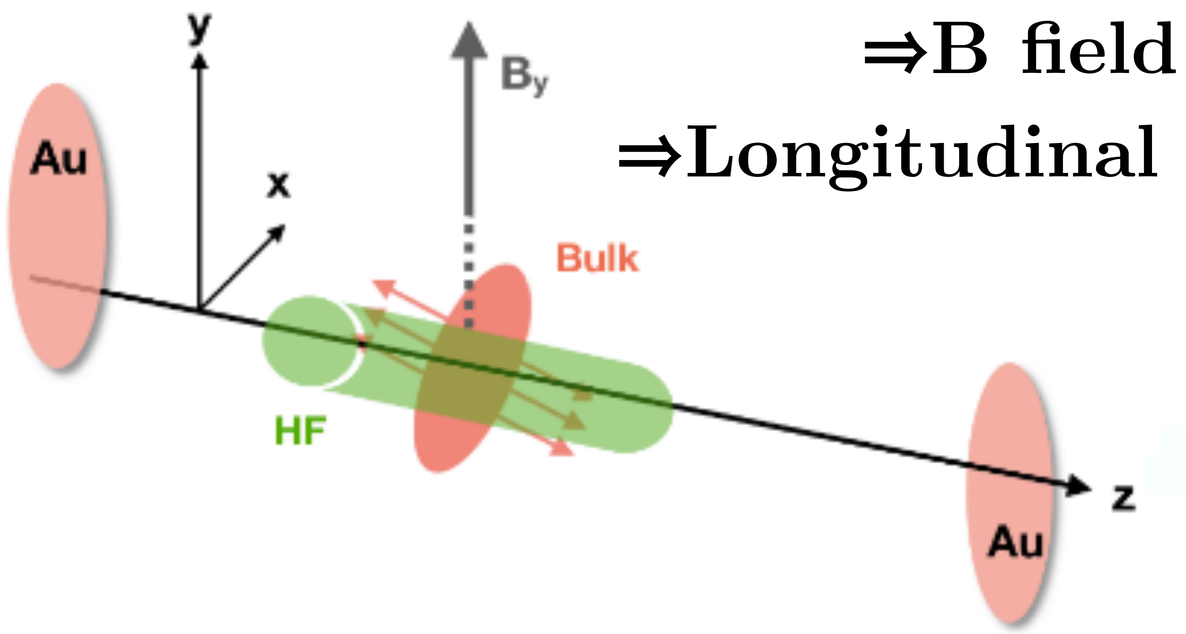
The Role of Heavy Flavor

Heavy quark production via the initial hard partonic scatterings in heavy-ion (HI) collisions $\Longrightarrow$ "External" probe of de-confined medium

<u>Elementary collisions</u>
⇒pQCD







<u>Initial conditions</u>
-Directed Flow
⇒B field
⇒Longitudinal profile

<u>Heavy quark diffusion</u>
-Elliptic Flow
⇒Thermalization
⇒$2\pi T D_s$

<u>Energy loss</u>
-$R_{AA}+R_{CP}$
⇒Collisional+radiative
⇒$\Delta E(m)$

<u>Hadronization</u>
-Λ_c+D_s production
⇒Coalescence vs. vacuum fragmentation

Outline of Measurements

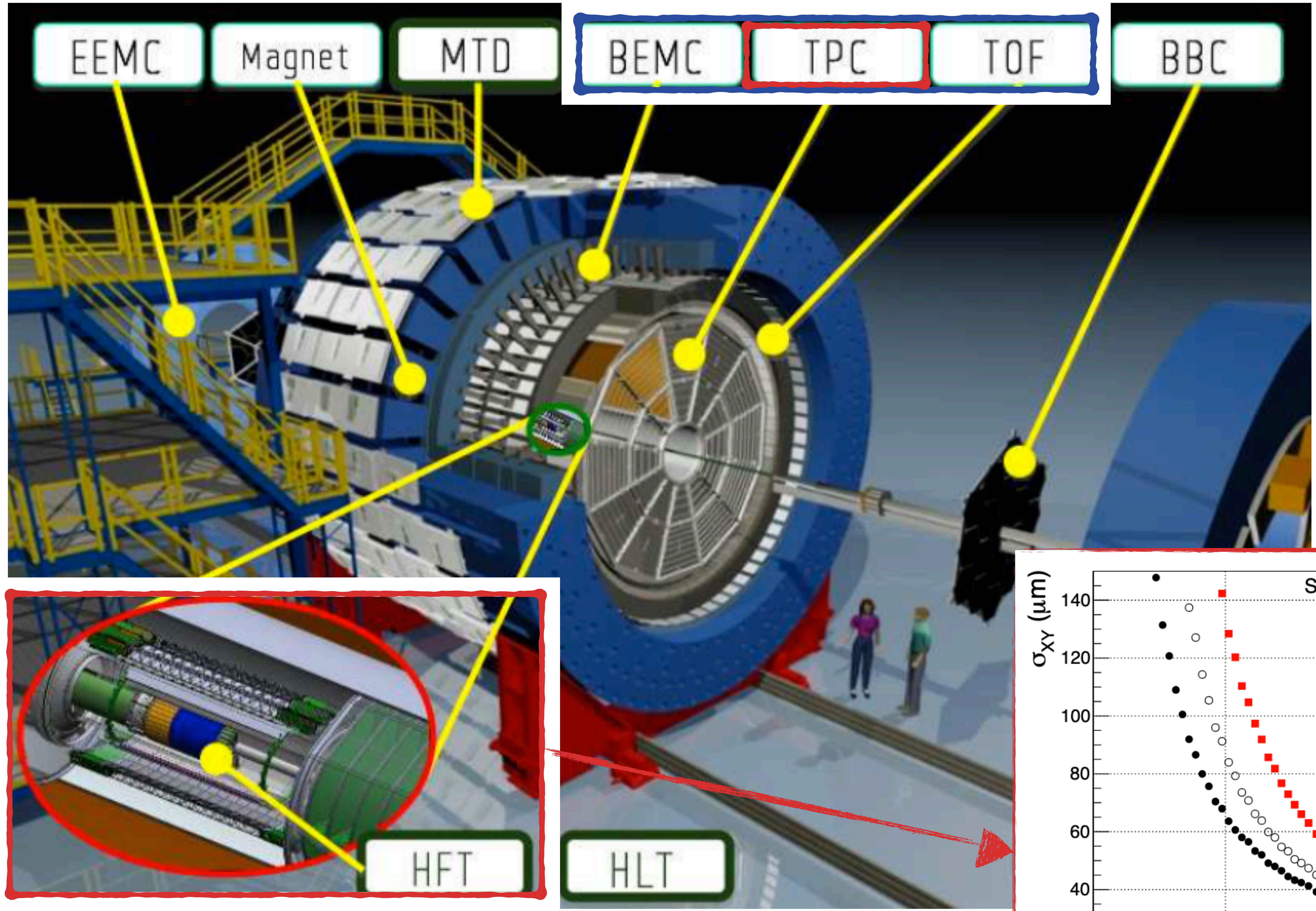
Spectra of $D^{\pm}$ and $D_s^{\pm}$ mesons in Au+Au collisions

$b/c \rightarrow e$ R_{AA} and $R_{AA/CP}$ double-ratios

Elliptic flow of non-photonics electrons in 54.4 and 27 GeV Au+Au collisions

$c \rightarrow e$ directed and $b/c \rightarrow e$ elliptic flow

The STAR Detector



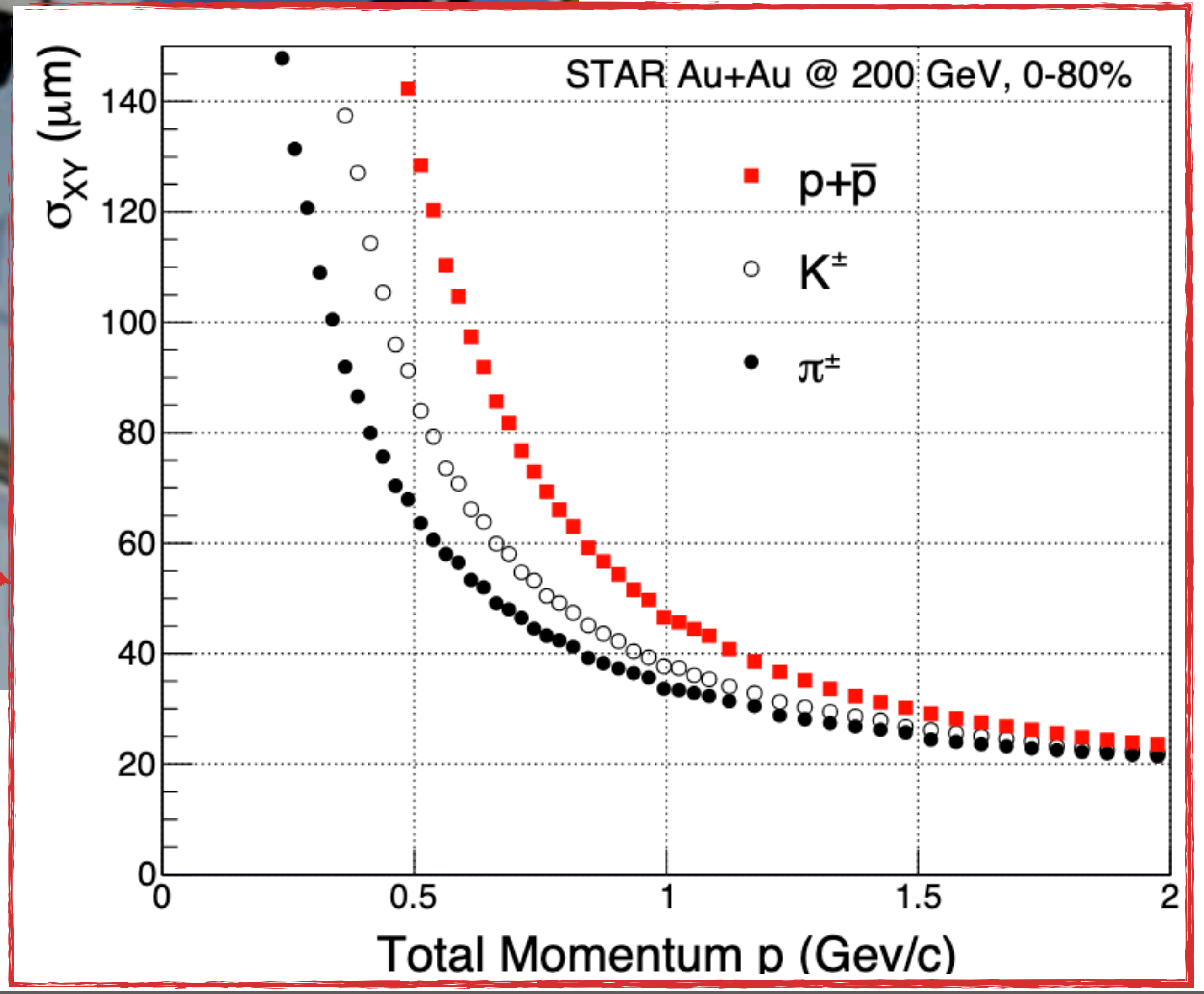
Time Projection Chamber (TPC)

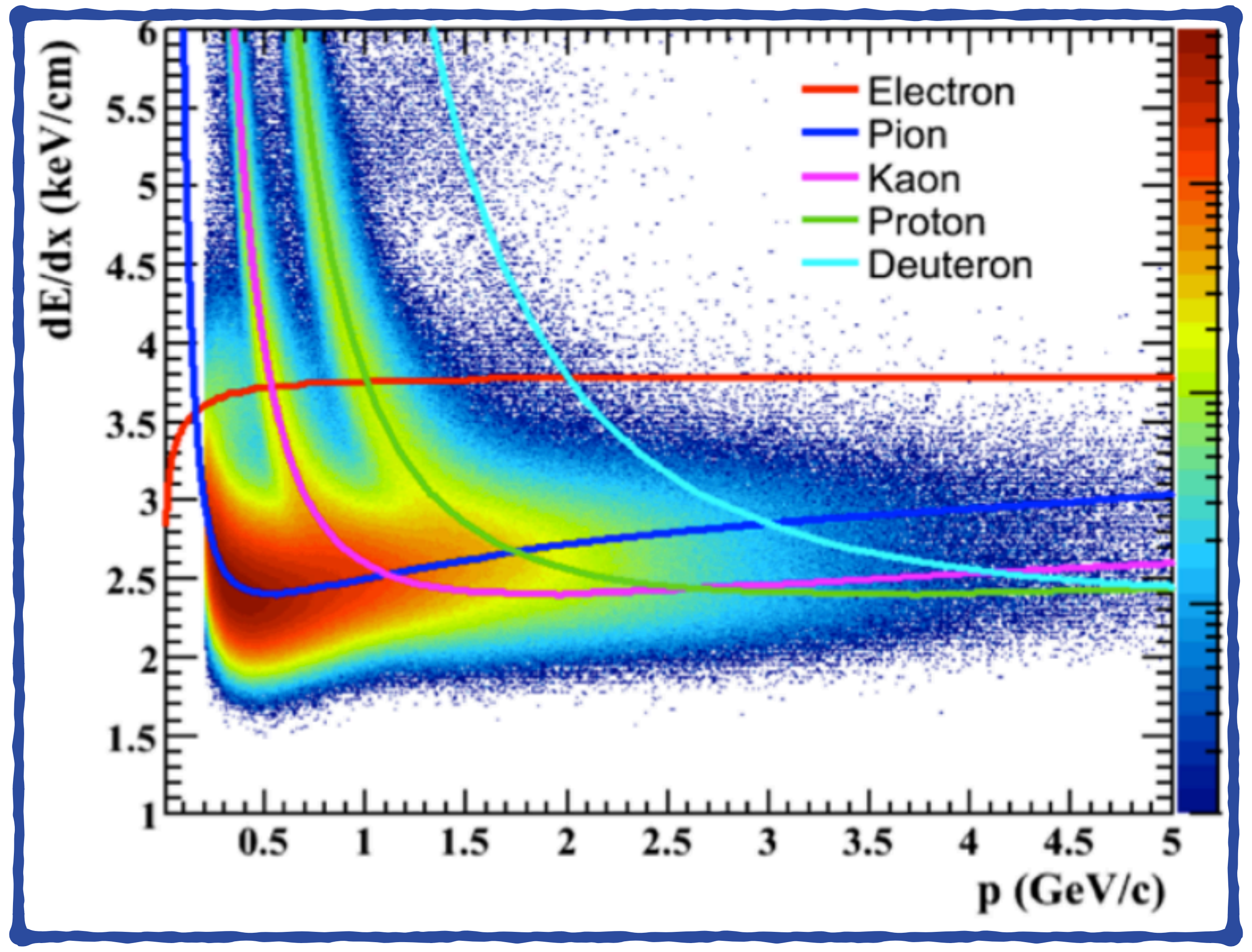
- Full 2π azimuthal coverage at mid-rapidity

Heavy Flavor Tracker (HFT)

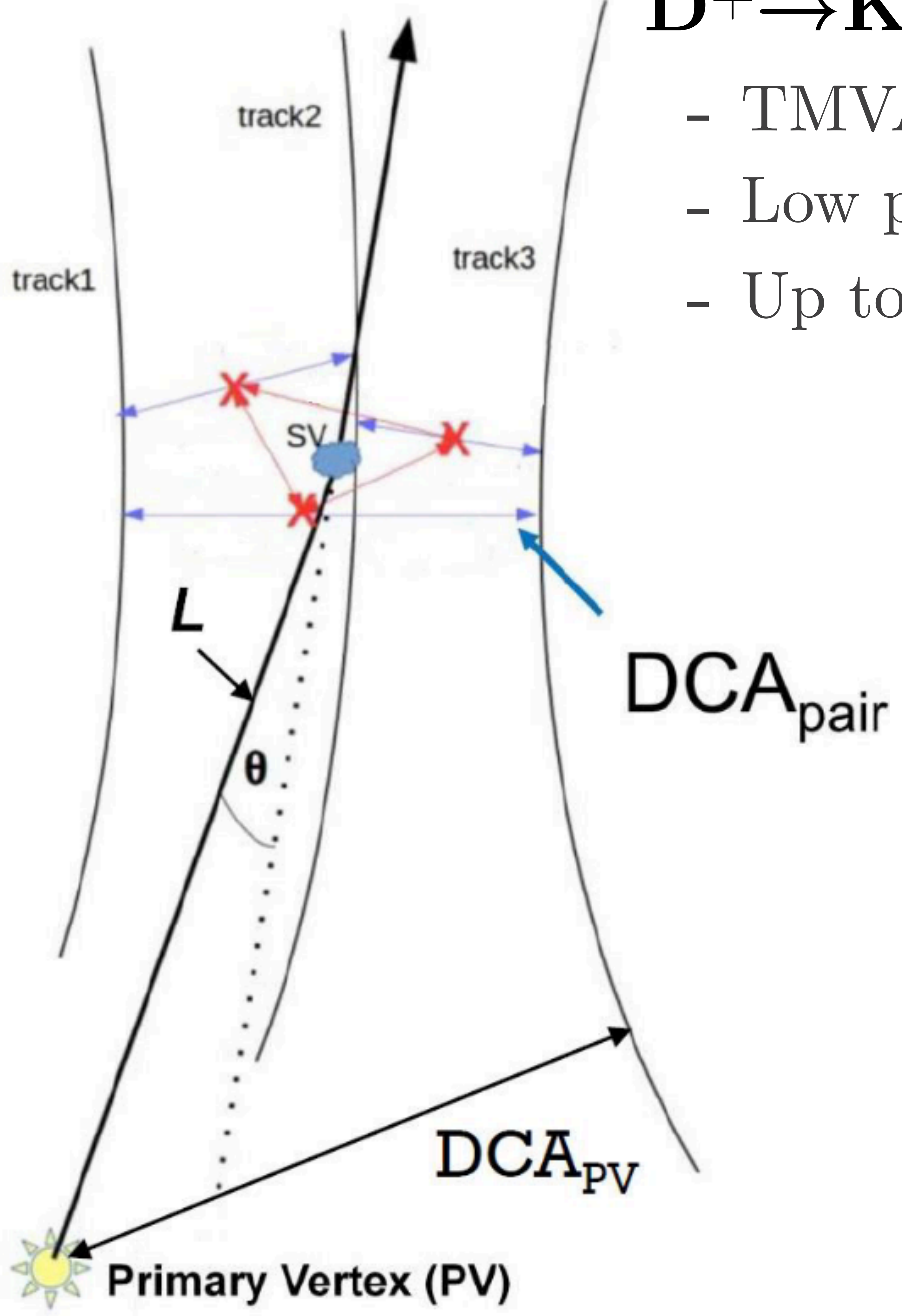
- First application of thin MAPS detector in collider experiment (2014+2016)
- Excellent pointing resolution for secondary vertex and displaced daughter reconstruction

PID achieved with TPC, Time-of-Flight (TOF), and Barrel Electromagnetic Calorimeter (BEMC)



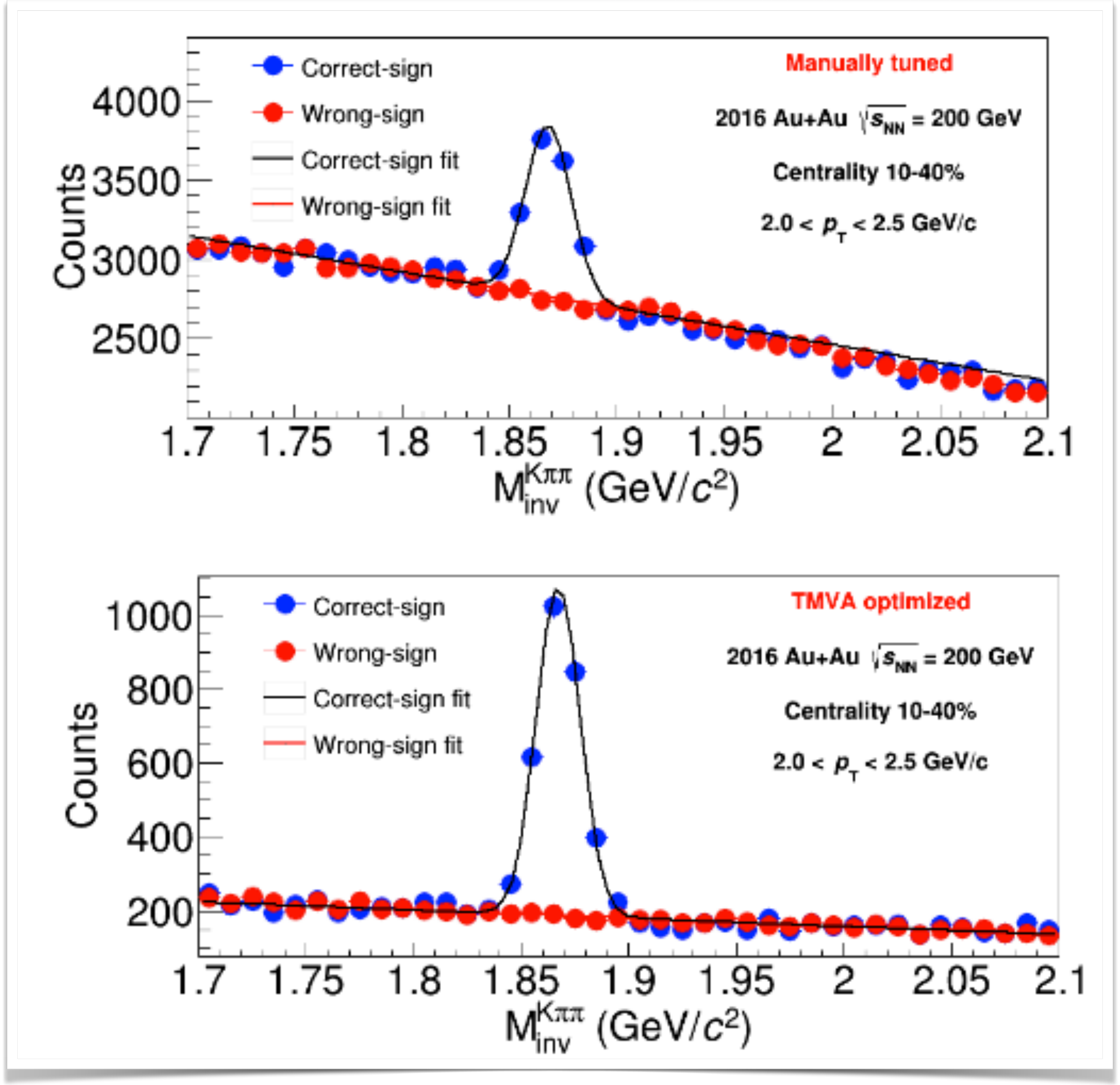


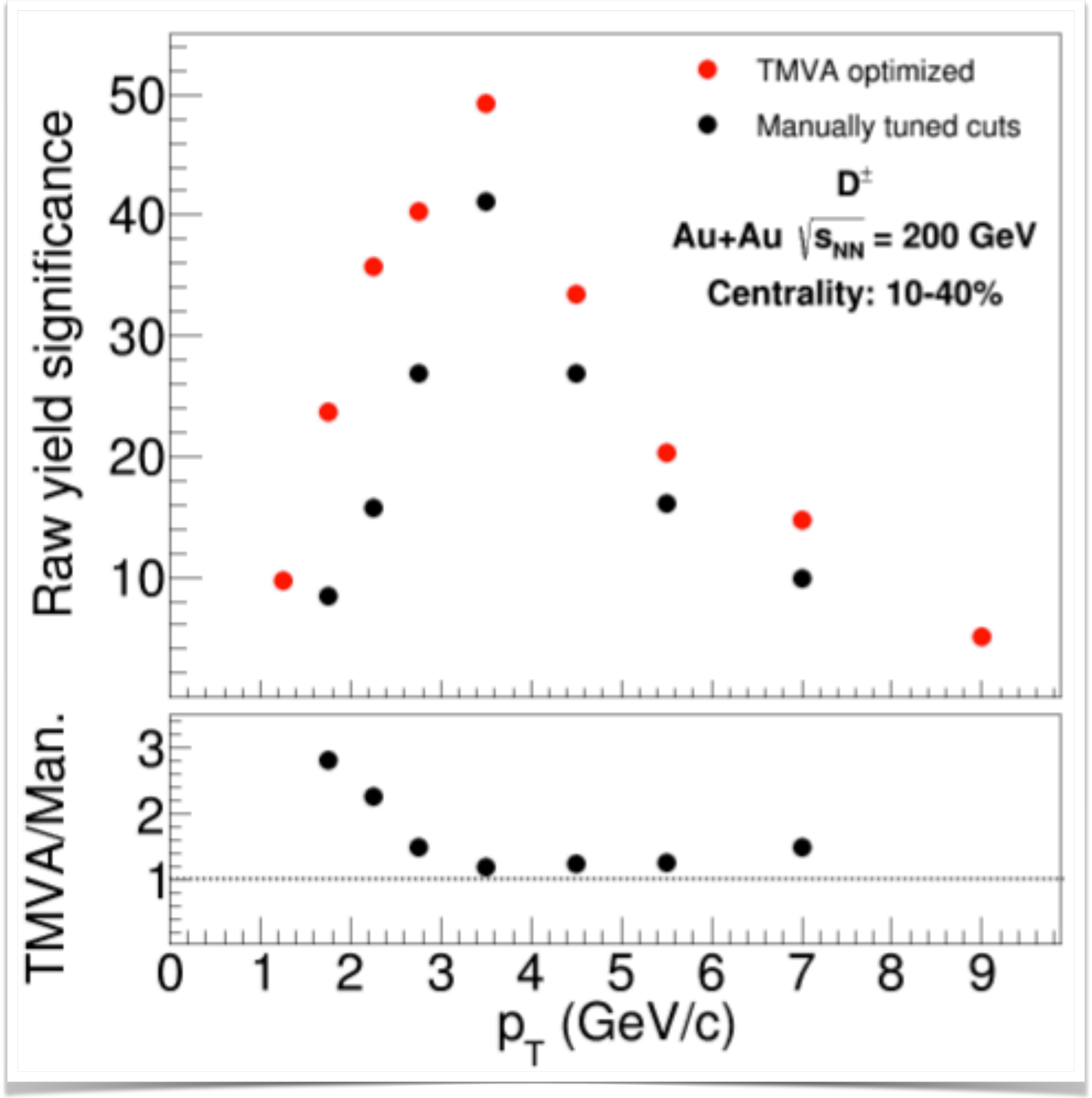
$D^{\pm}$ Production in $\sqrt{s_{NN}} = 200$ GeV Au+Au



$D^+ \to K^+\pi^+\pi^-$ reconstructed topologically using HF decay vertex

- TMVA optimized selection
- Low p_T reach extended to 1 GeV/c
- Up to 3x improvement in signal significance at low p_T





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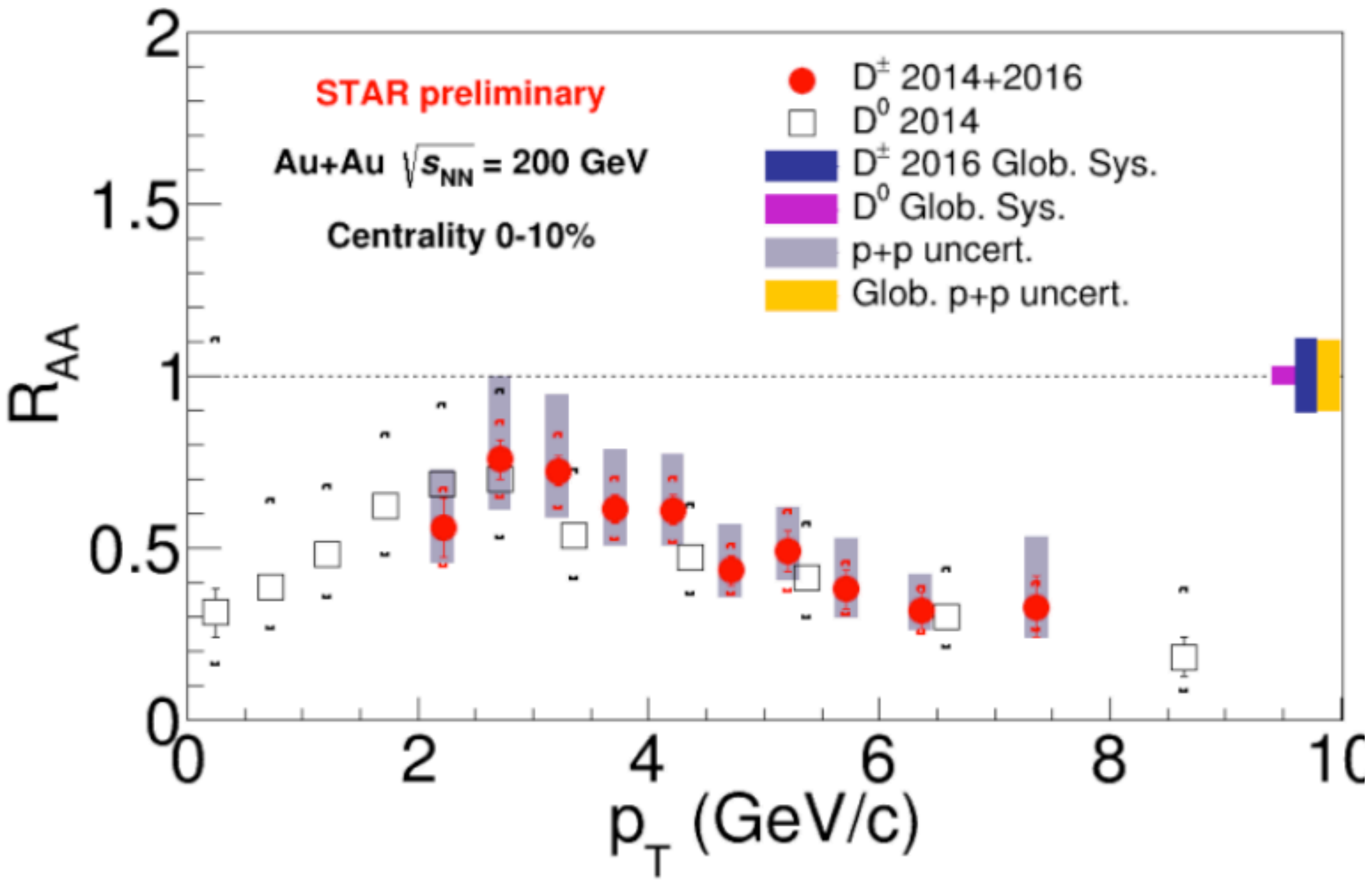
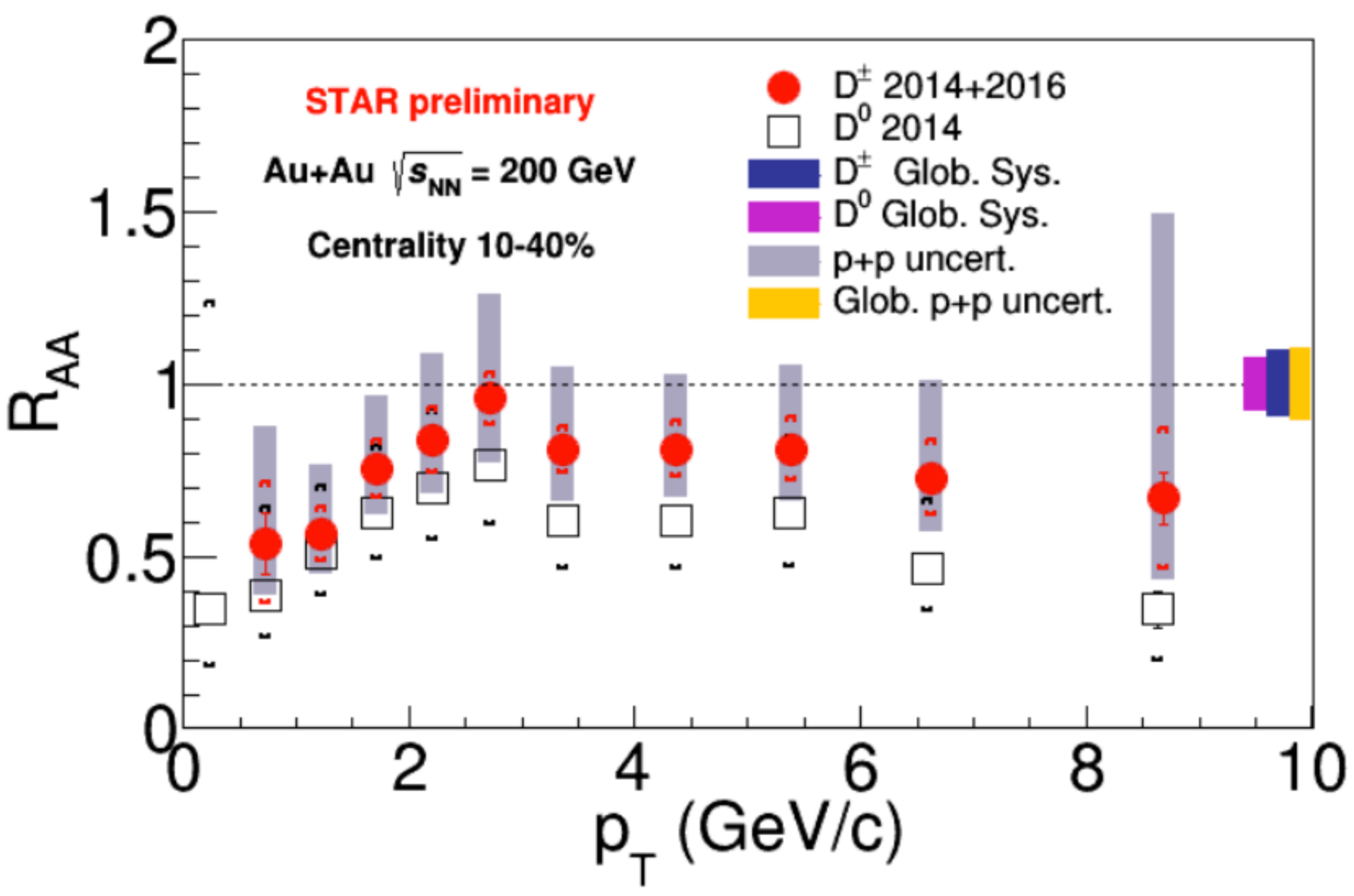
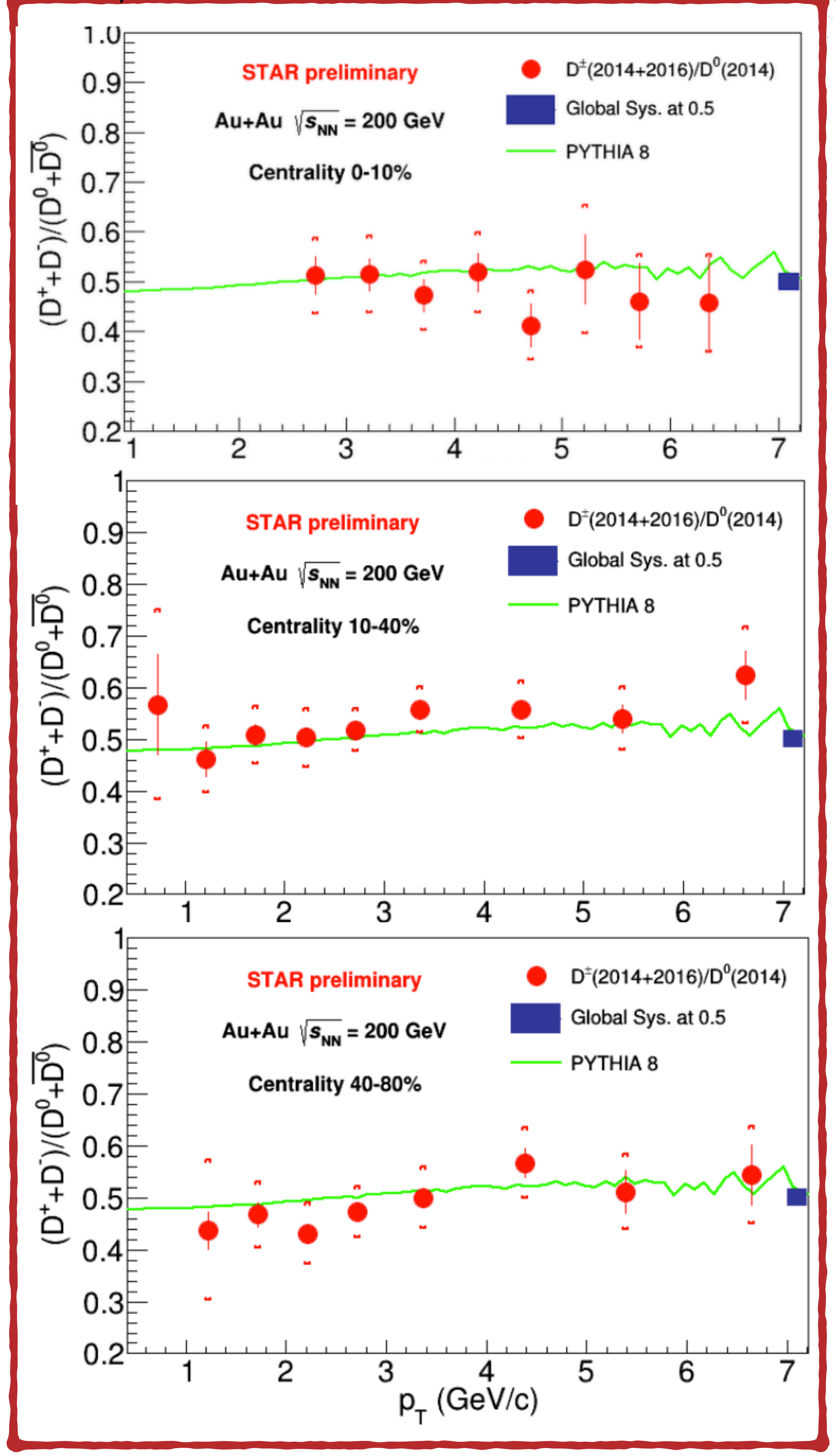




D^+/D^0 Ratios

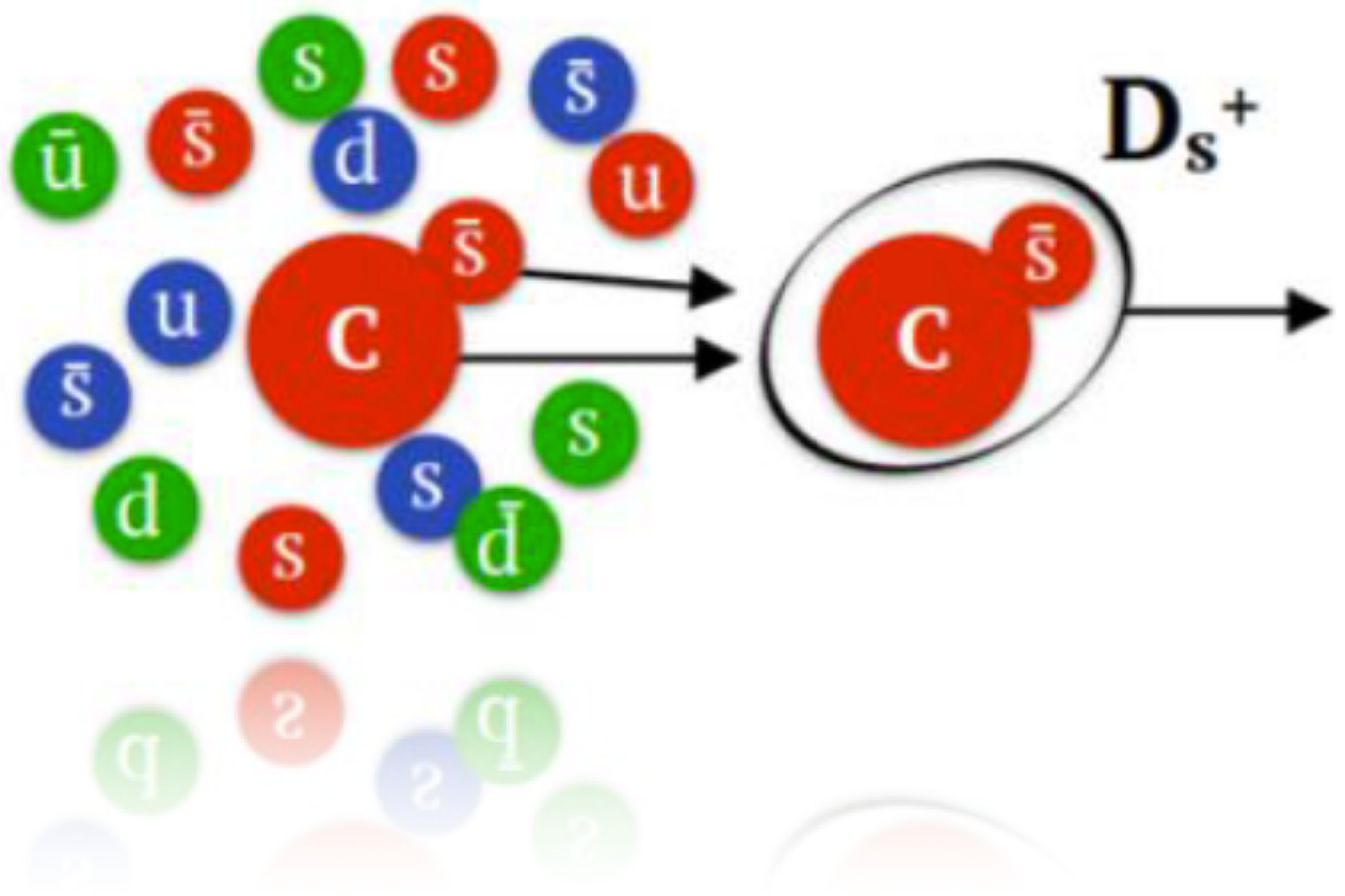


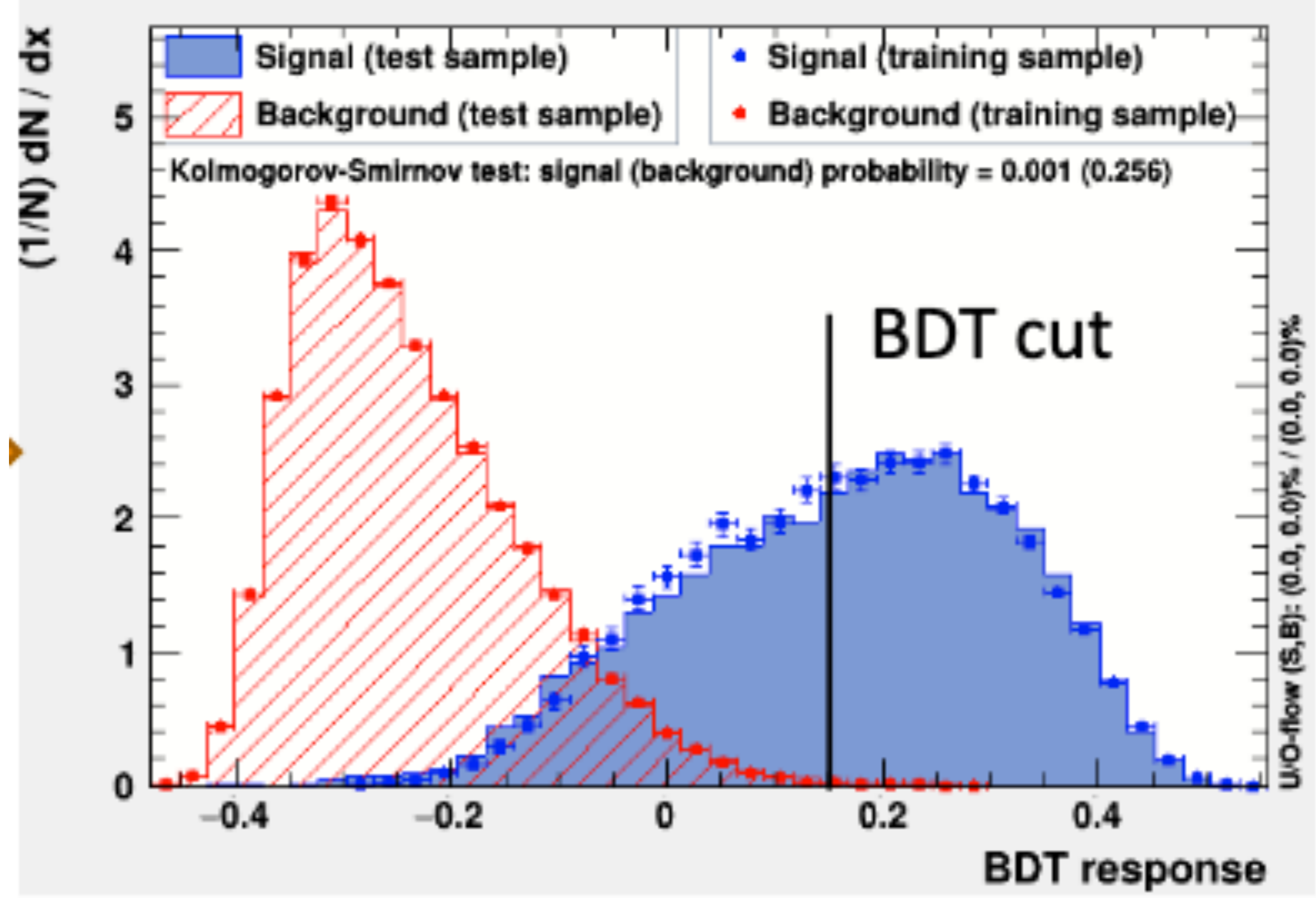
Measured D^+ R_{AA} comparable to D^0 within uncertainties

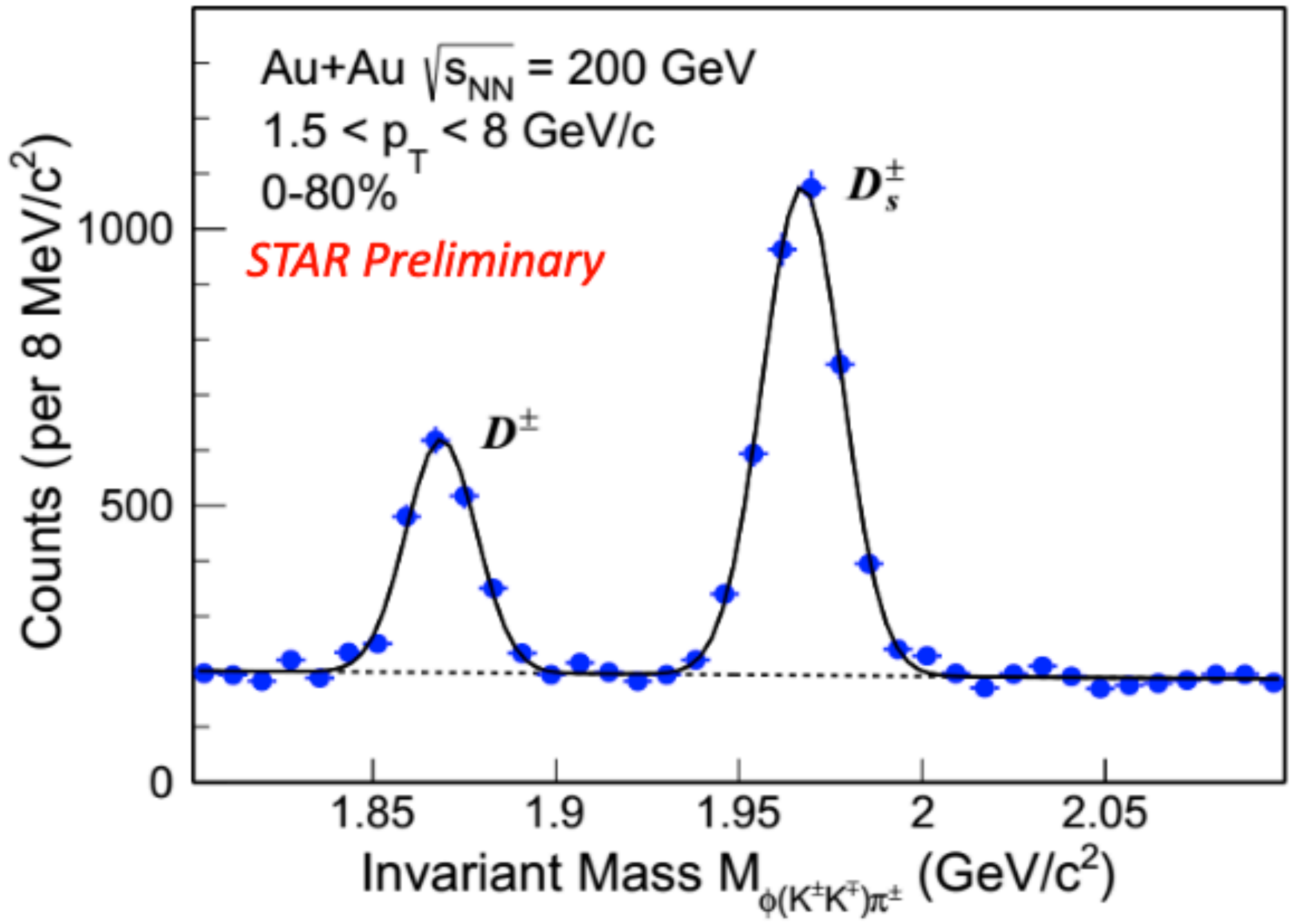
- Significant suppression in central Au+Au at high p_T

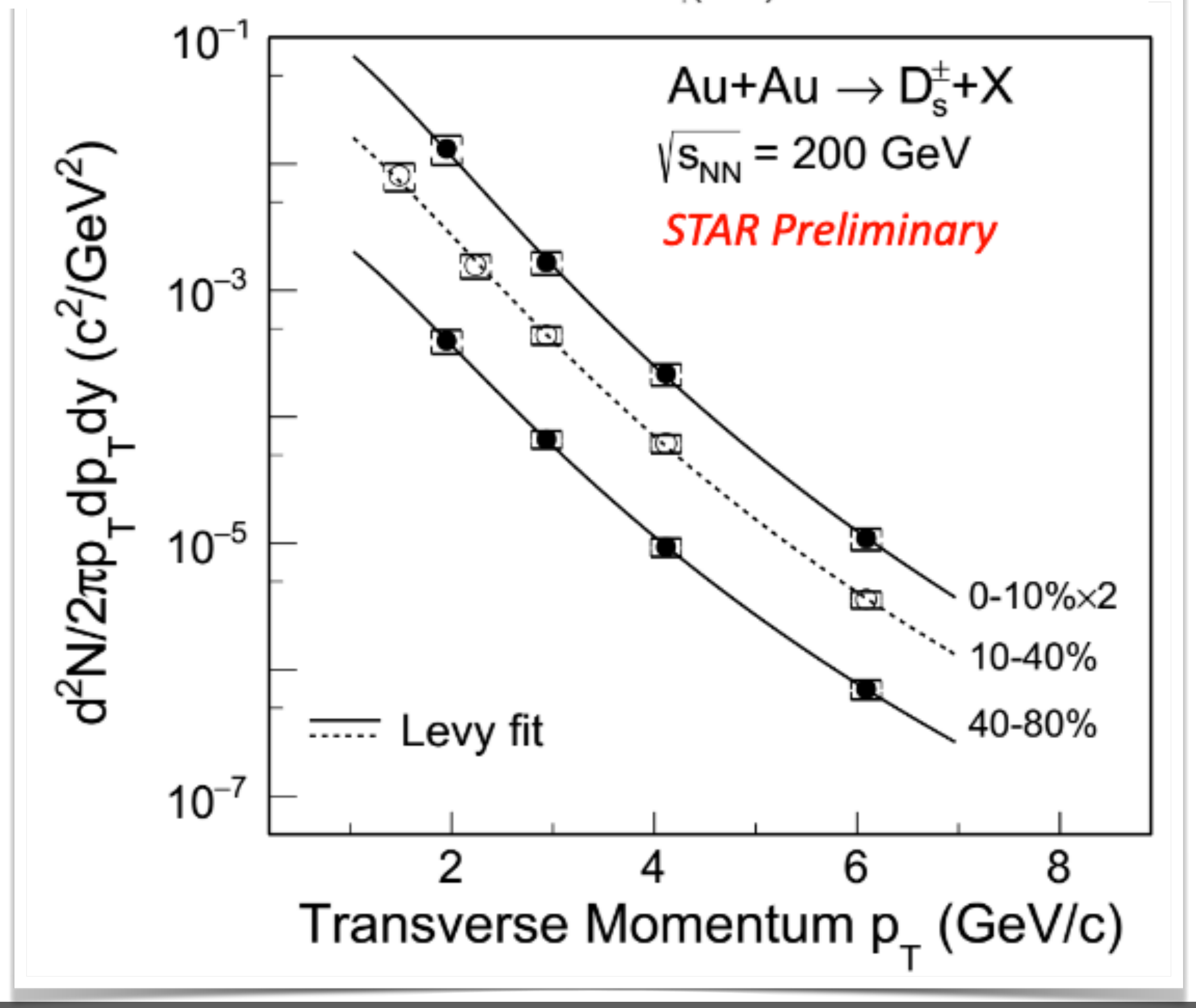
Measured D^+/D^0 yield ratio are consistent with PYTHIA 8 predictions across all collision centralities

$D_s^{\pm}$ Production in $\sqrt{s_{NN}} = 200$ GeV Au+Au









Good probe of strangeness enhancement + coalescence hadronization

Boosted decision tree optimized to select $D_s^+ \rightarrow \varphi(K^+K^-)\pi^+$ decays

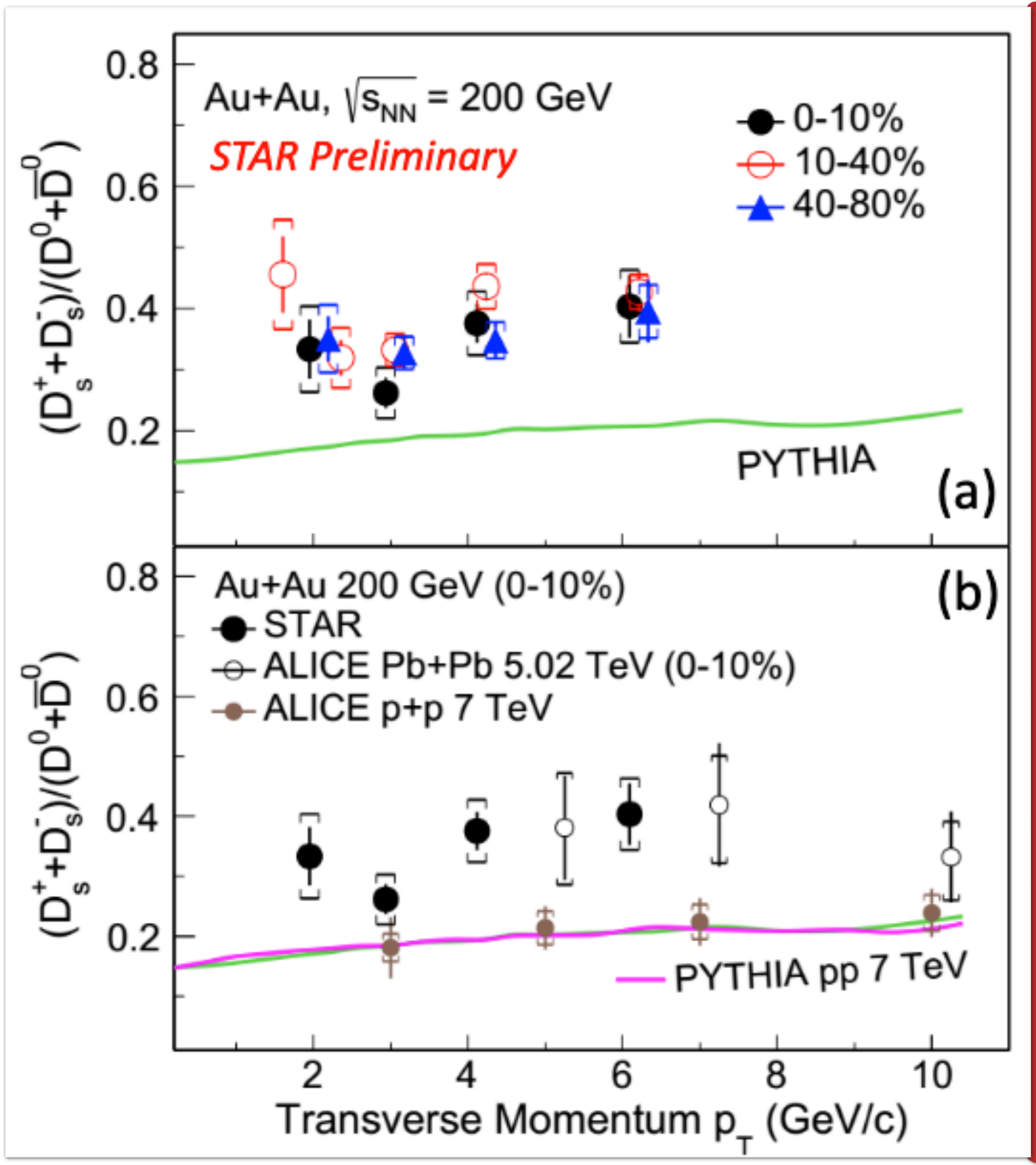
- Improved signal significance by 30% compared to traditional cut-based approach
- Measured down to $p_T = 1$ GeV/c

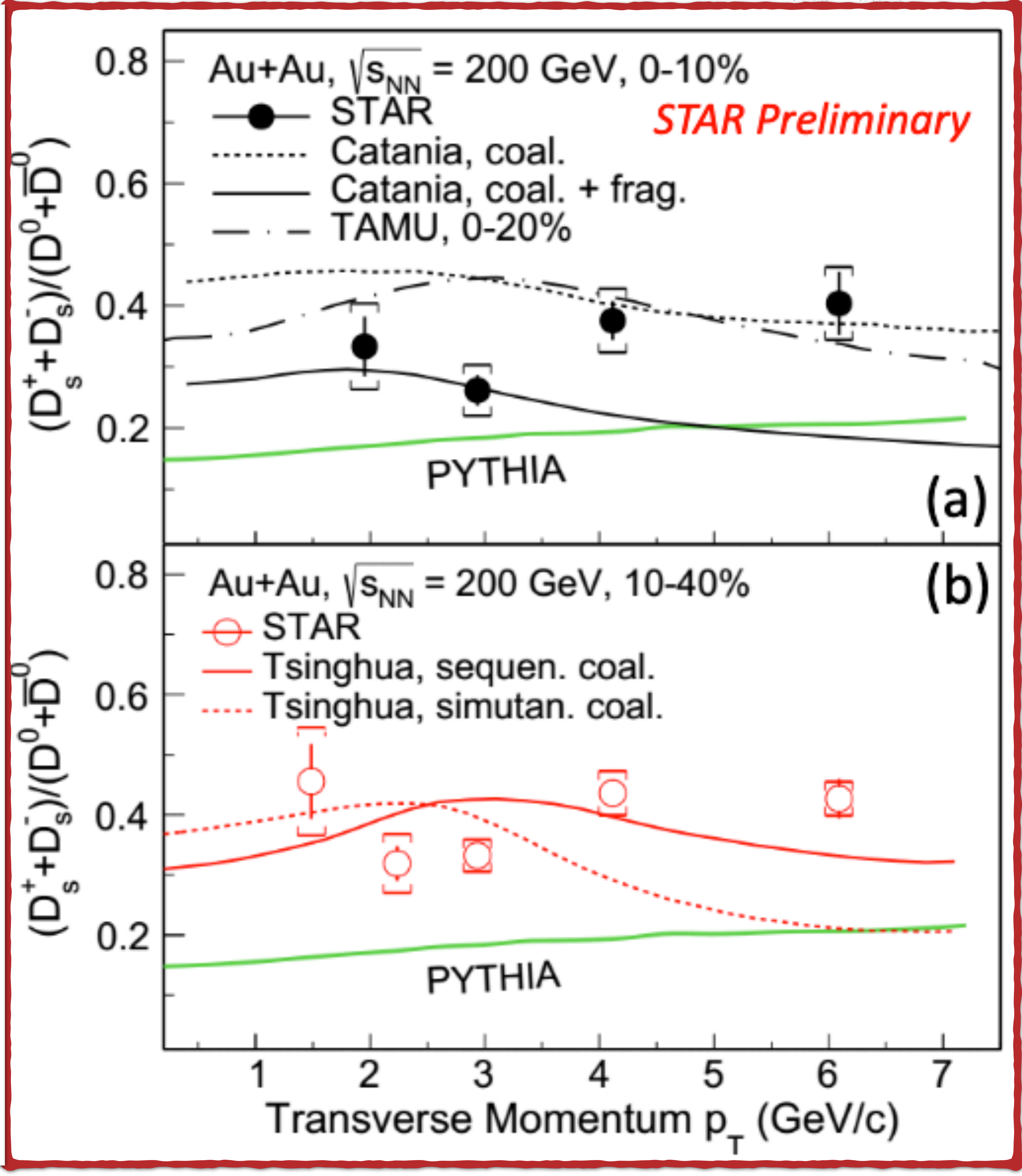
$D_s^{\pm}$ Production in $\sqrt{s_{NN}} = 200$ GeV Au+Au

Significant enhancement in D_s^+/D^0 ratio compared to PYTHIA 6

- No strong centrality dependence
- Comparable to ALICE Pb+Pb data @ $\sqrt{s_{NN}} = 5.02$ TeV
- Larger ratio than ALICE p+p @ $\sqrt{s} = 7$ TeV

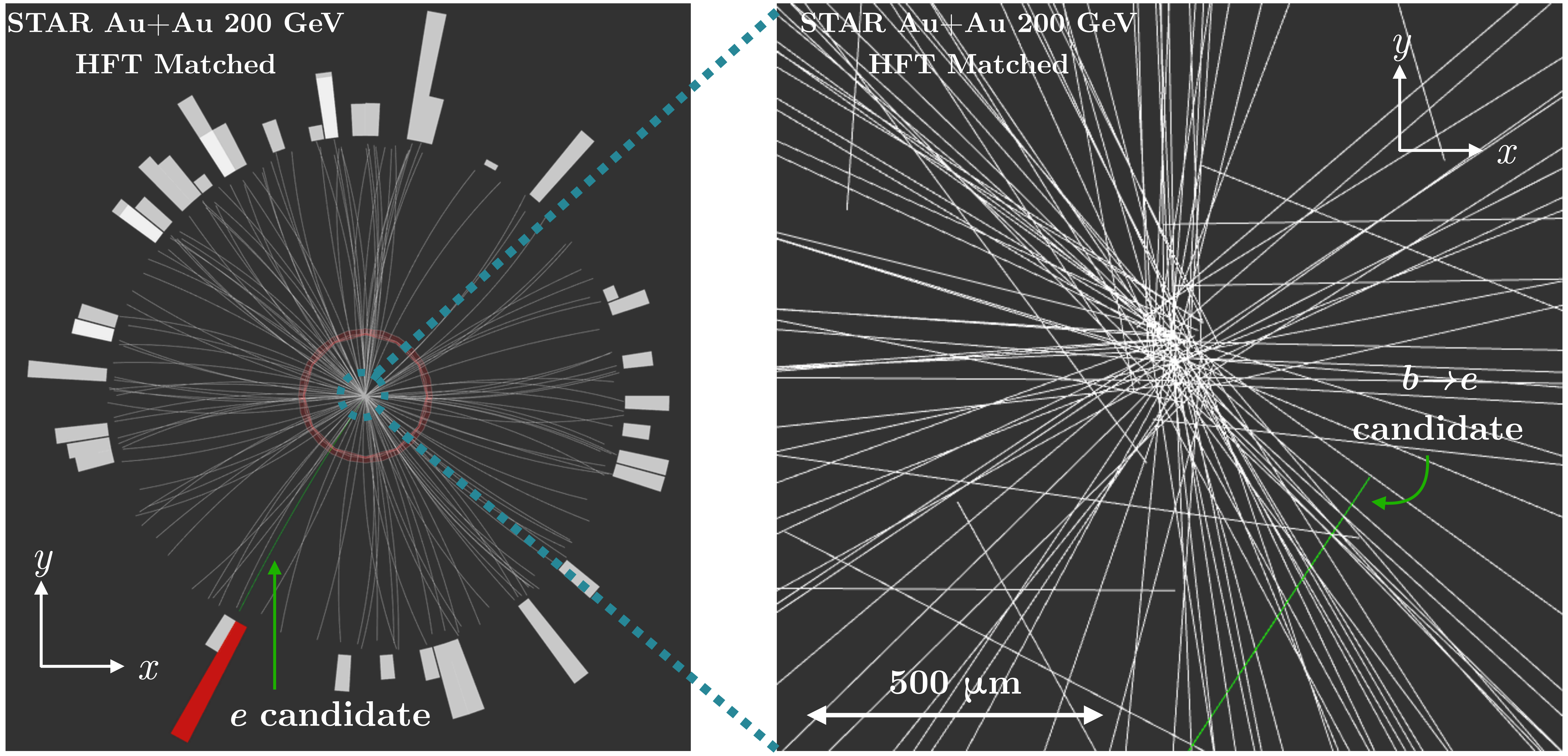
Models including coalescence hadronization also show enhancement

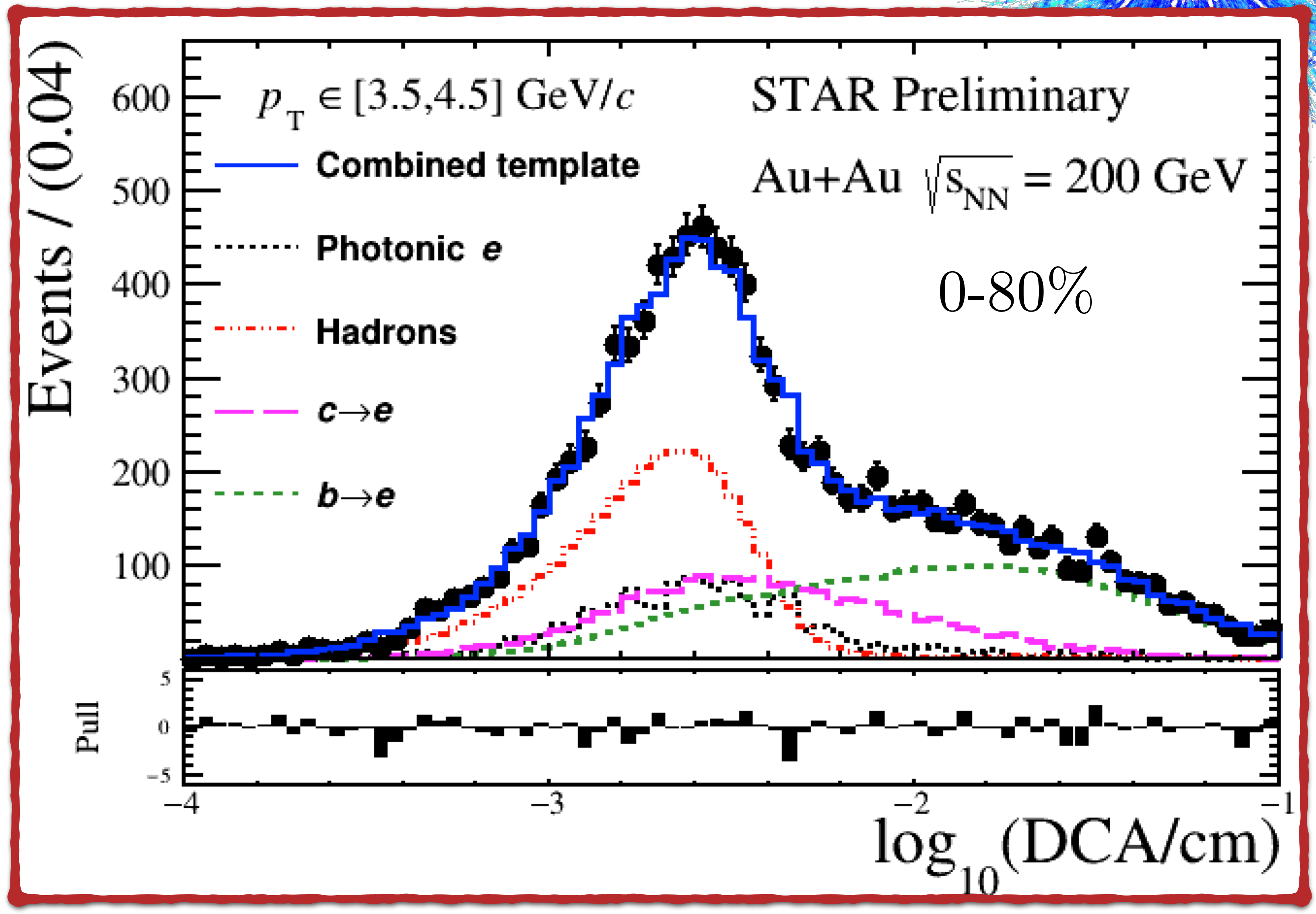




ALICE: Eur. Phys. J. C (2017) 77: 550
ALICE: J. High Energ. Phys. (2018) 2018: 174
Zhao J., Shi S., Xu N., Zhuang P. arXiv(2018):1805.10858
Plumari S., Minissale V., Das S. K., el alEur. Phys. J. C (2018) 78: 348
He M, Ralf R., In preparation (2019)

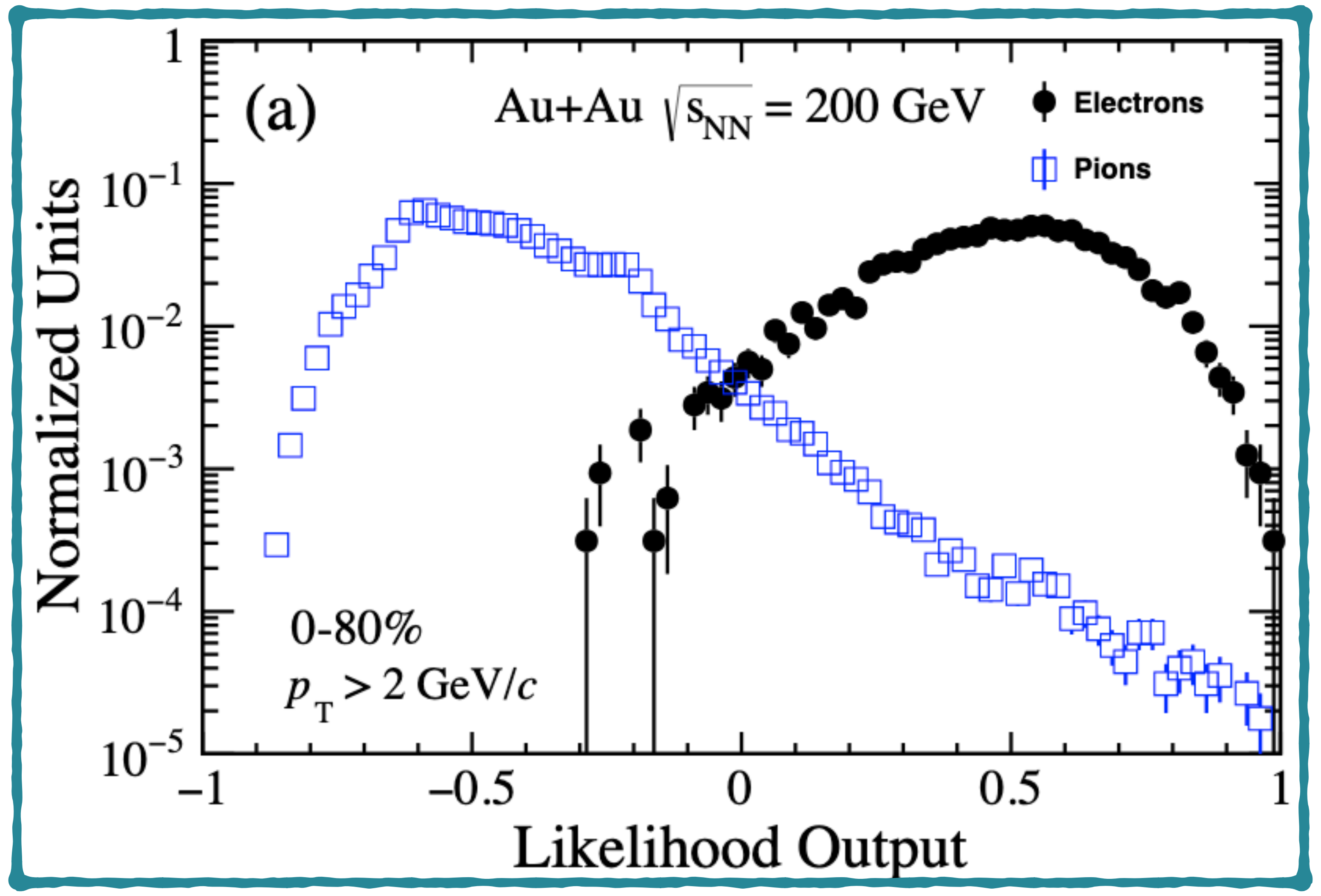
Single Electrons from Bottom Hadrons





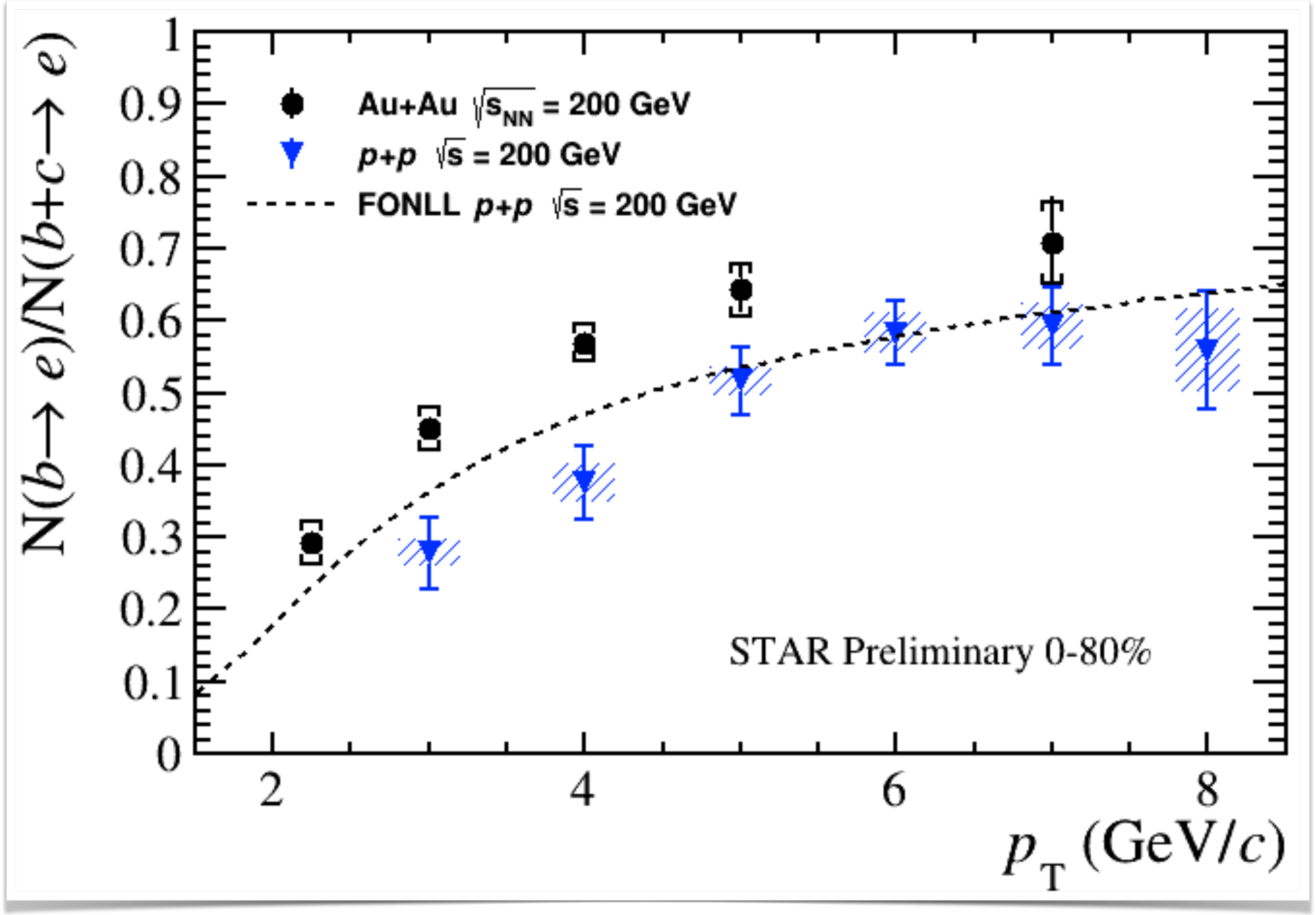
Log(3D DCA) distribution provides excellent separation between $c \to e$, $b \to e$, and BKG

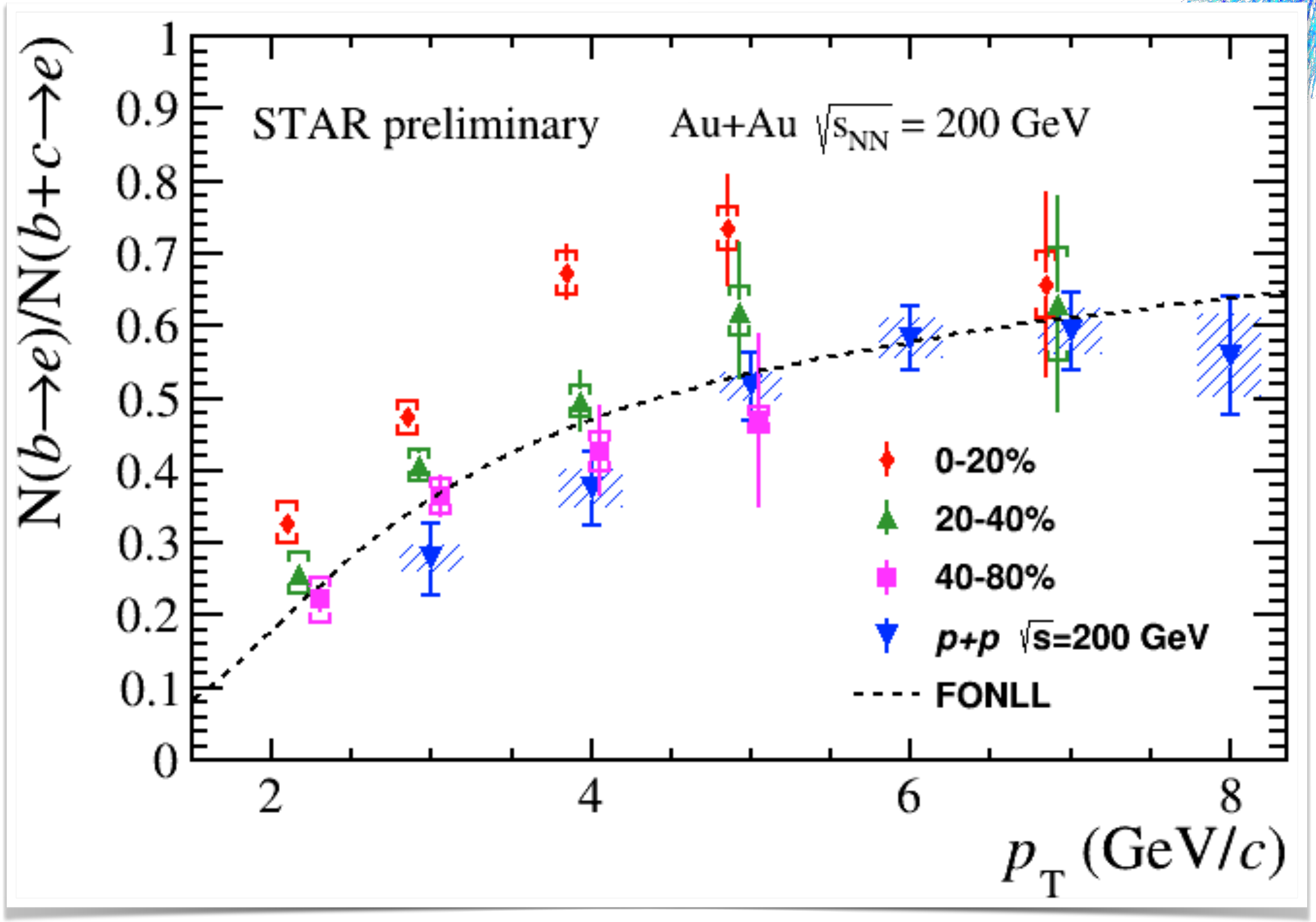
Electron PID improved with likelihood MVA classifier; Hadron contamination reduced by factor of two



Photonic electron (π^0, η, and γ) background veto; Reduction by 60%

Single Electrons from Bottom Hadrons





Fraction of $b\rightarrow e$/c+b$\rightarrow e$ significantly enhanced in central and min. bias $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions

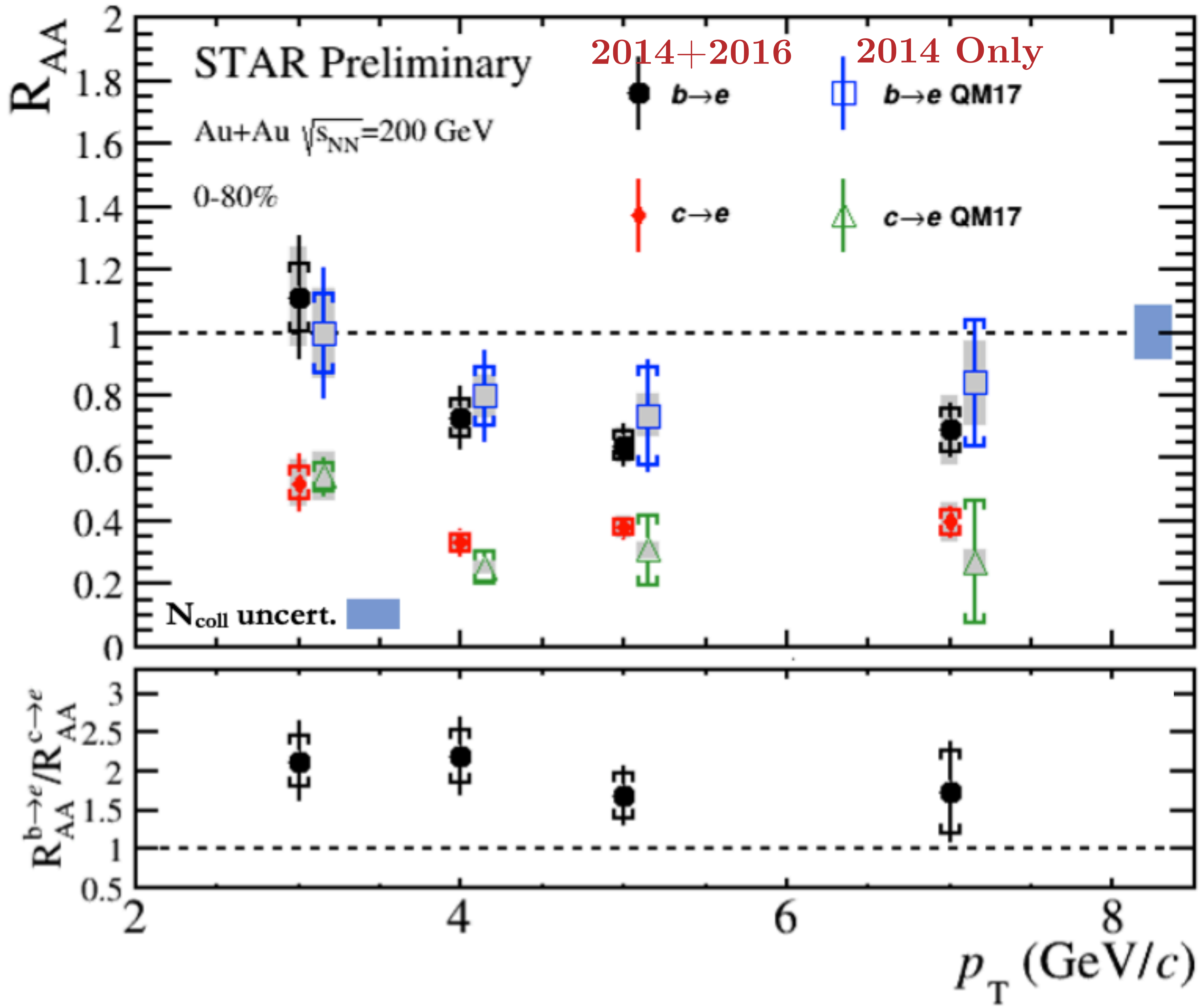
Peripheral $b\rightarrow e$/c+b$\rightarrow e$ fraction consistent with $\sqrt{s} = 200$ GeV p+p and FONLL

FONLL: M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, JHEP 1210(2012) 137
M. Cacciari, M. L. Mangano, and P. Nason, arXiv:1507.06197

Bottom vs. Charm Energy Loss

$$R_{AA}^{b\to e} = \frac{f_b^{AA}}{f_b^{pp}} R_{AA}^{NPE}$$

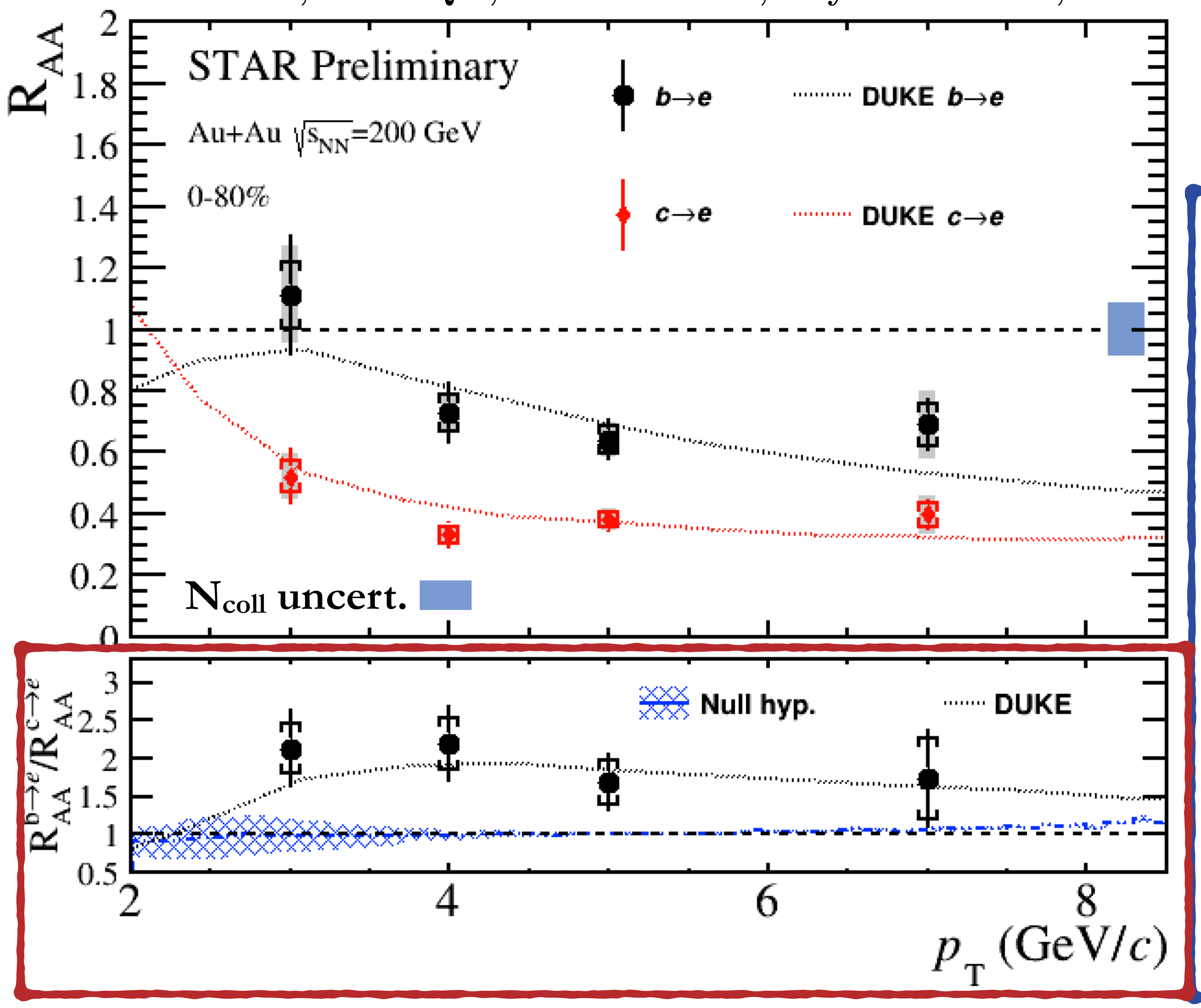
$$R_{AA}^{c\to e} = \frac{1 - f_b^{AA}}{1 - f_b^{pp}} R_{AA}^{NPE}$$



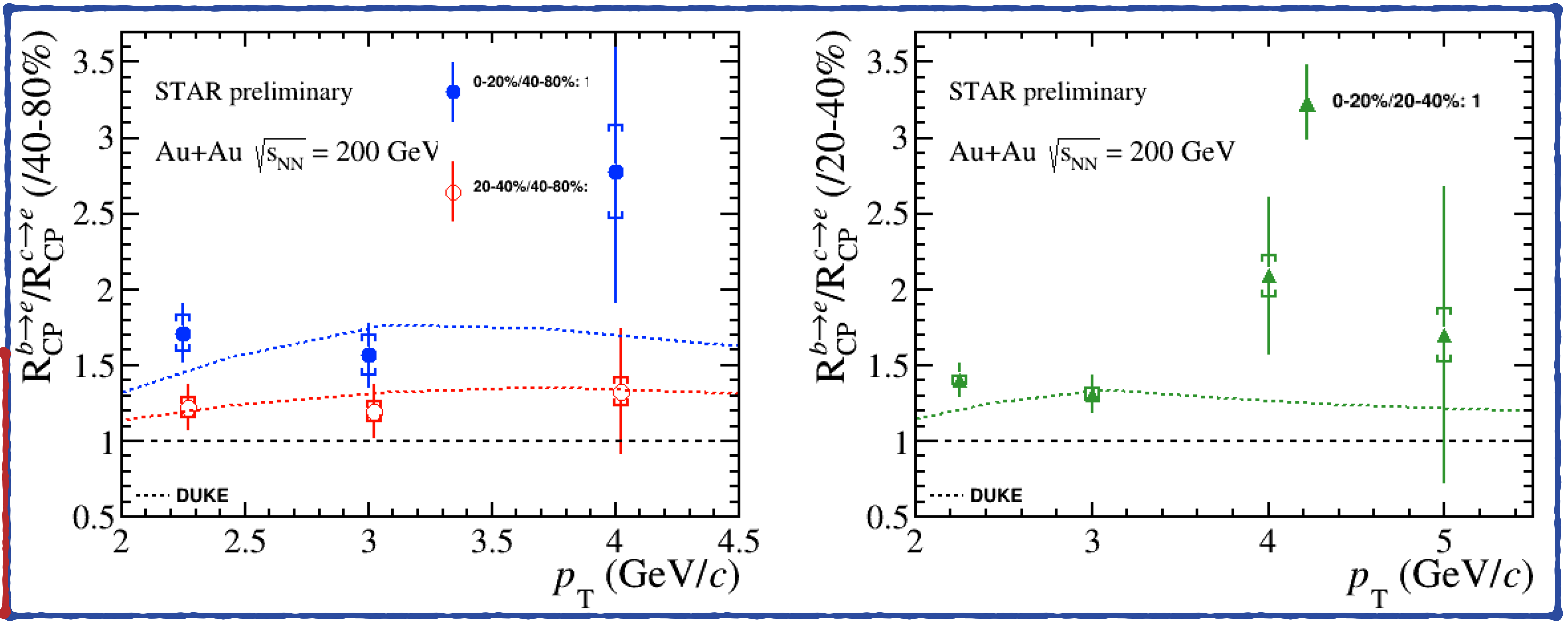
Significant improvement in experimental uncertainties since QM17!

Bottom vs. Charm Energy Loss

Duke: S. Cao, G.-Y. Qin, and S. A. Bass, Phys. Rev. C 92, 024907 (2015)



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



R_{AA} double ratios deviate from unity by 3σ; null hyp. (assumption of same R_{AA} for bottom/charm) by 2σ

- Fixed electron p_T probes roughly same charm and bottom hadron average p_T (within relative 12%)

R_{CP}[0-20%/40-80%(20-40%)] double ratios deviate from unity by 4.4(3.5)σ

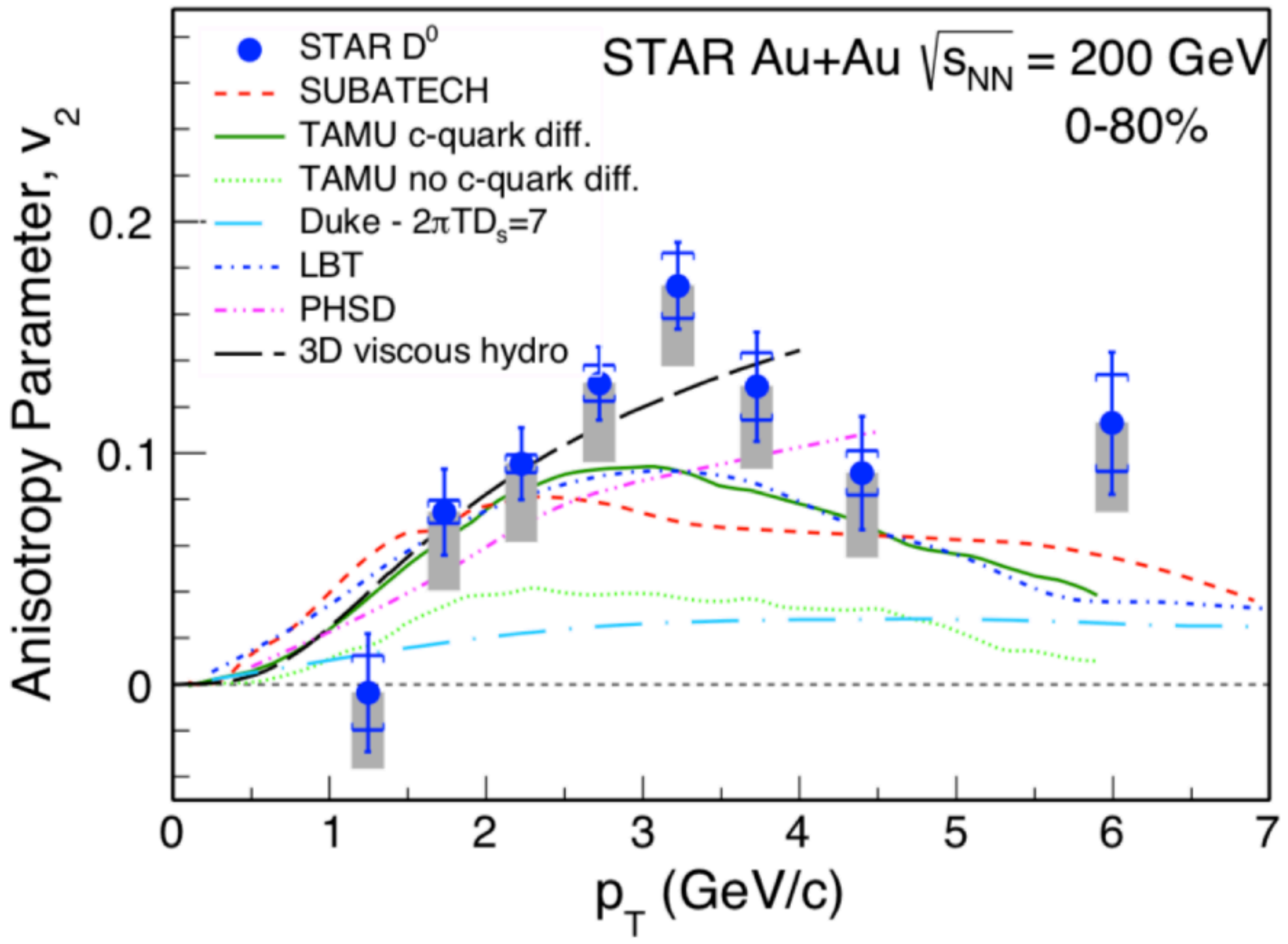
- R_{CP} null hyp. consistent with unity (not shown)

Data consistent with Duke Langevin model prediction

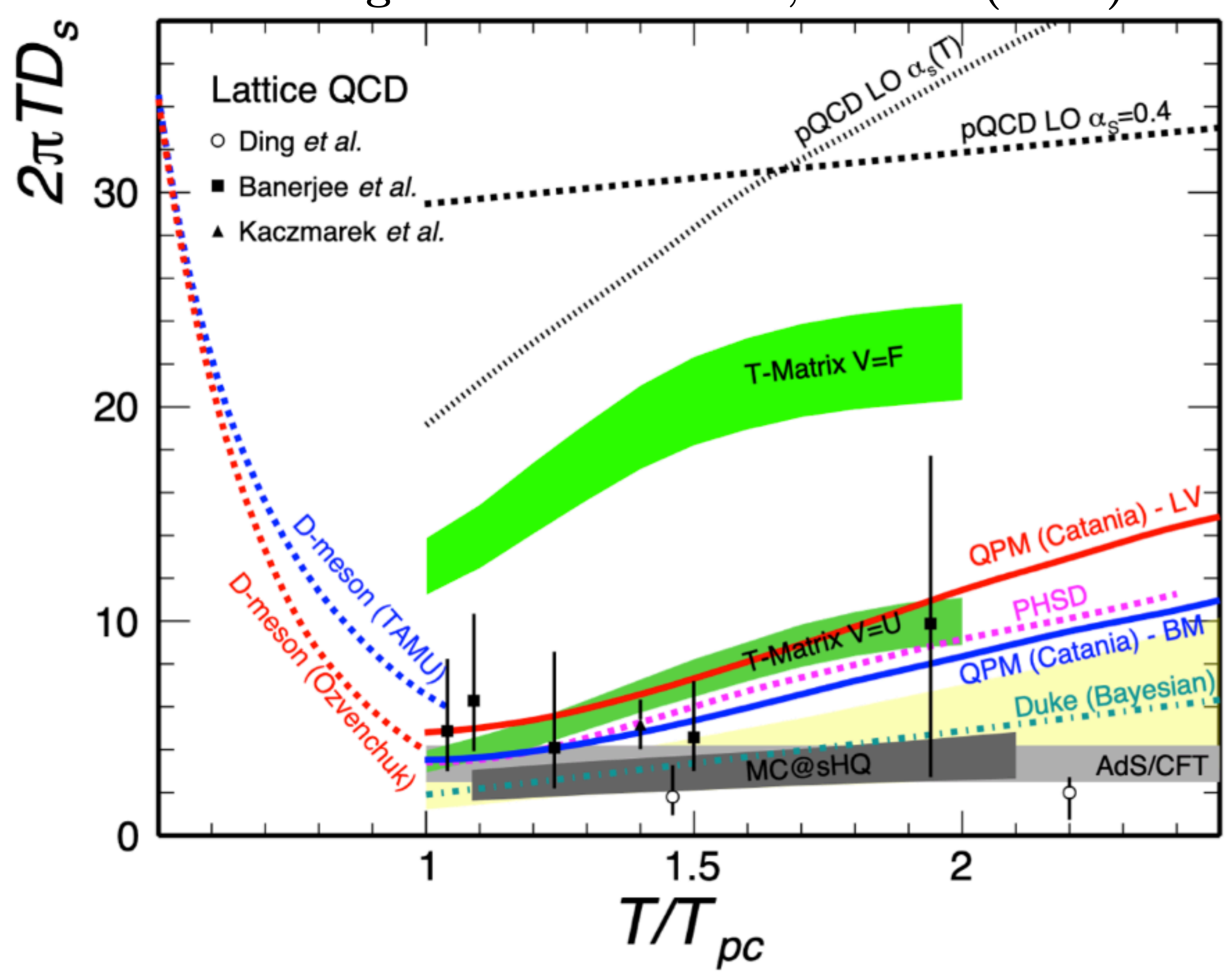
Provide a conclusive picture of c and b quark energy loss consistent with ΔE(b)<ΔE(c)

Low Energy Electron Elliptic Flow

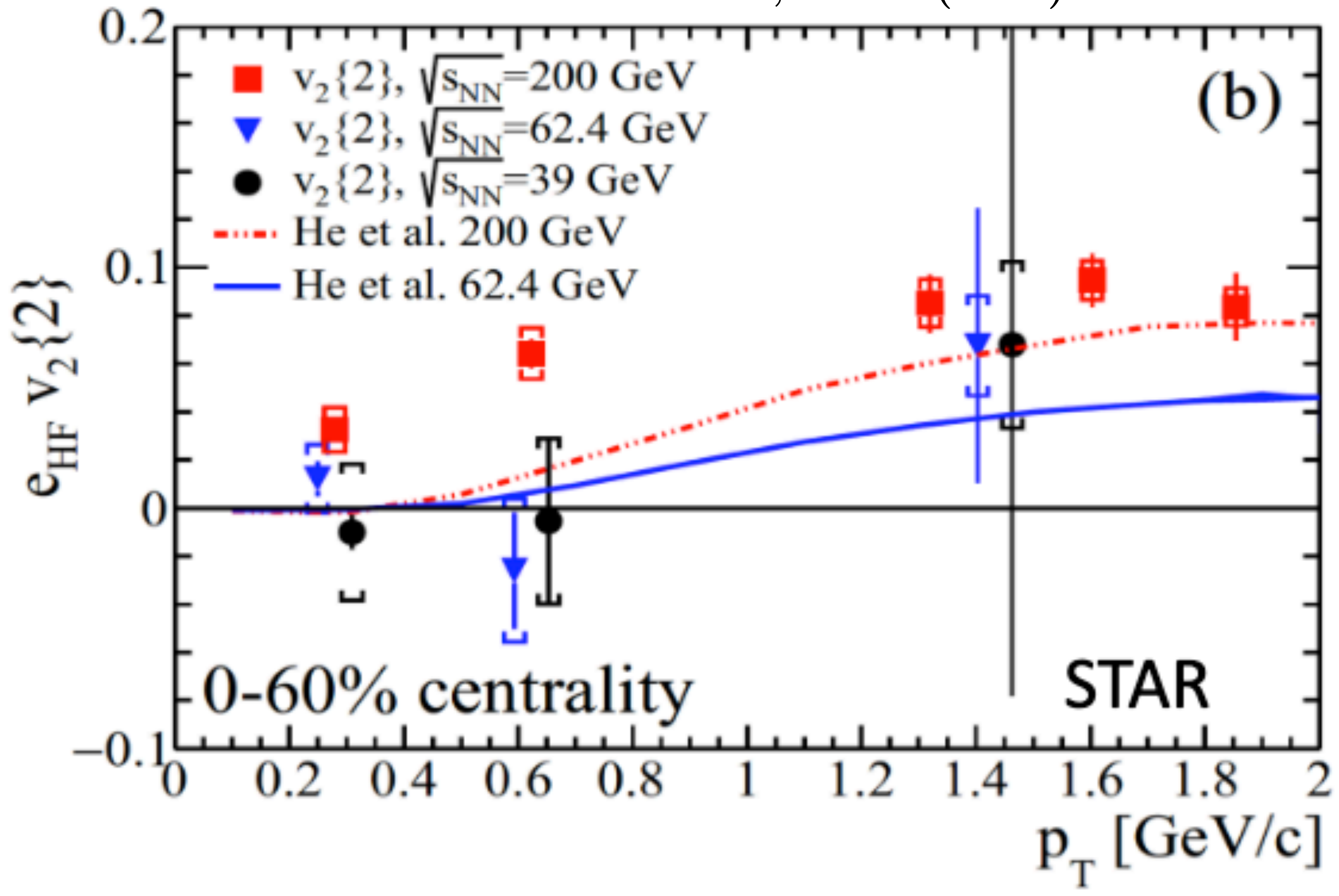
STAR PRL 118 (2017) 212301



X.Dong et al. PPNP 104, 97-141 (2019)



STAR PRC 95, 34907 (2017)

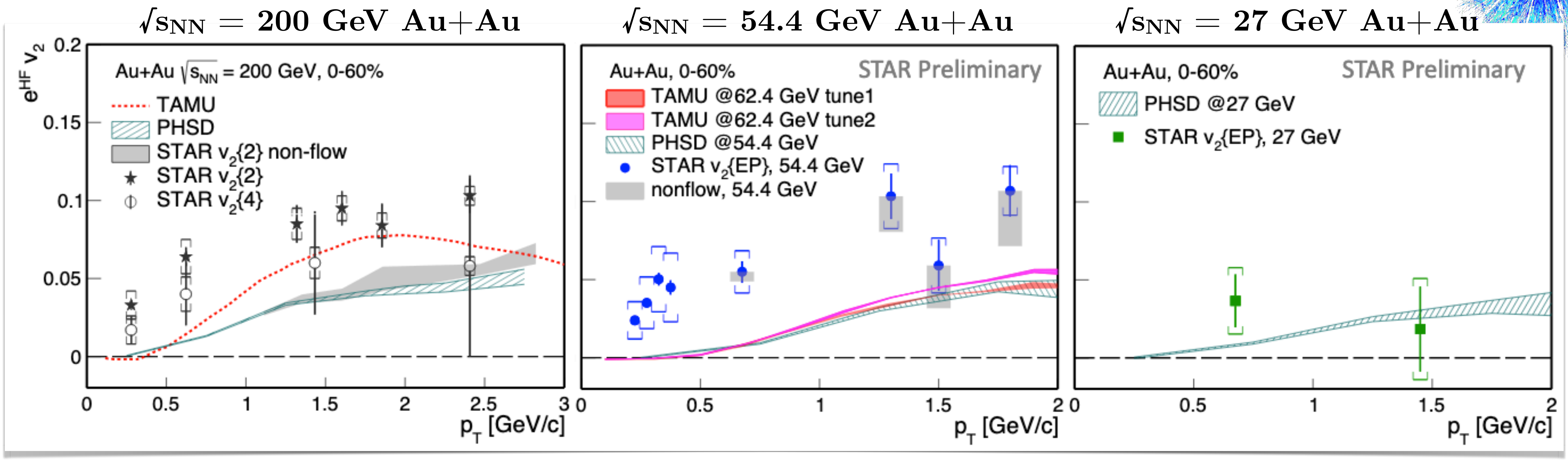


***D^0* v_2 well described by models including *c* quark diffusion**

Low energy non-photonic electron (NPE) v_2 good probe of temperature dependence

RHIC Run17+18: Au+Au collisions at $\sqrt{s_{NN}} = 54.4+27$ GeV; 10x increase in statistics compared to previous STAR low energy measurements

Low Energy Electron Elliptic Flow



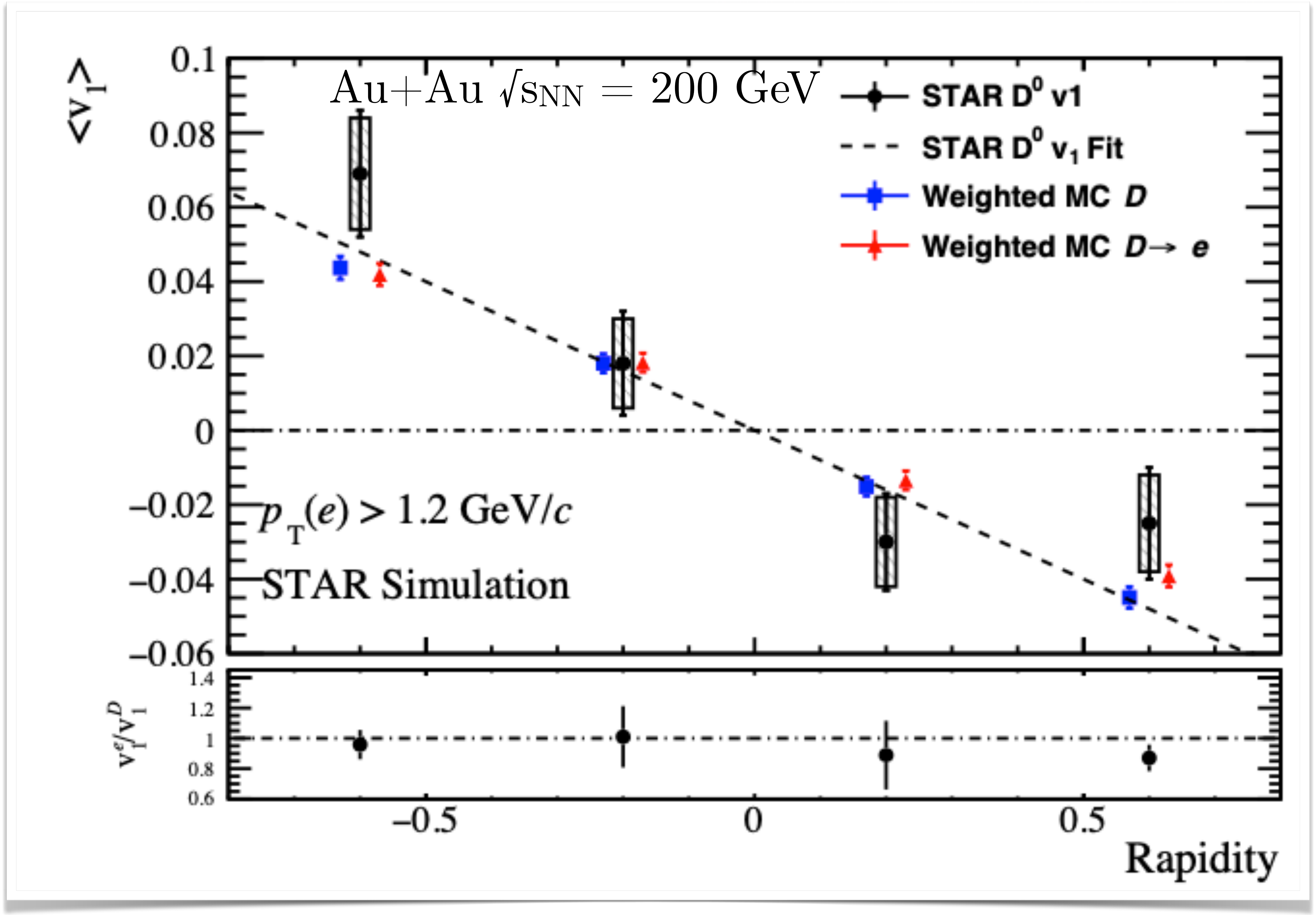
Significant NPE v_2 at 54.4 GeV; comparable to those at $\sqrt{s_{NN}} = 200$ data

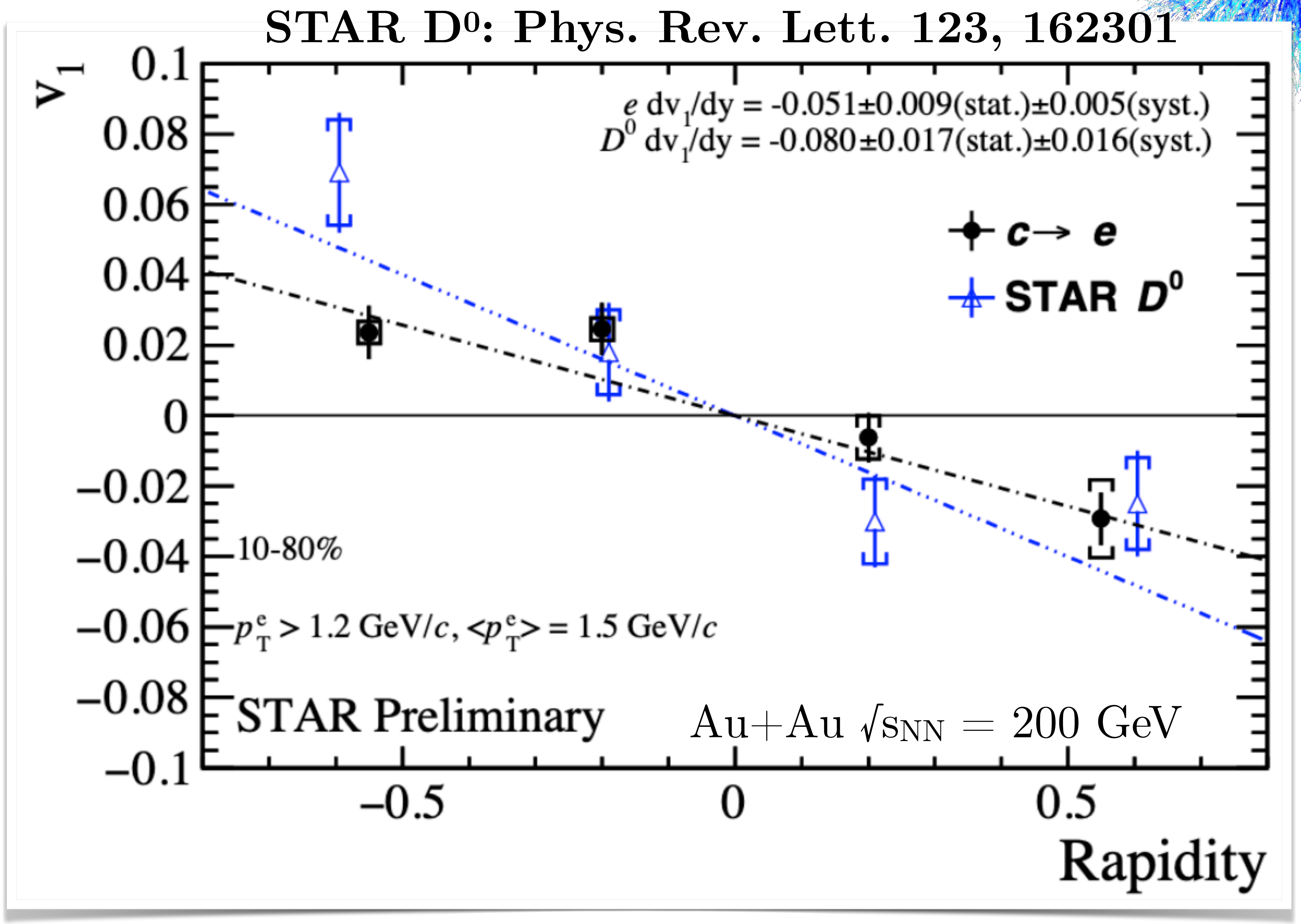
NPE v_2 at 27 GeV consistent with zero within experimental uncertainties

Above p_T=1 GeV/c model comparisons consistent considering non-flow and all uncertainties; disagreement at p_T<1 GeV/c

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

Charm Quark Directed Flow





Electrons from charm hadron semileptonic decays excellent proxy for parent hadron v_1

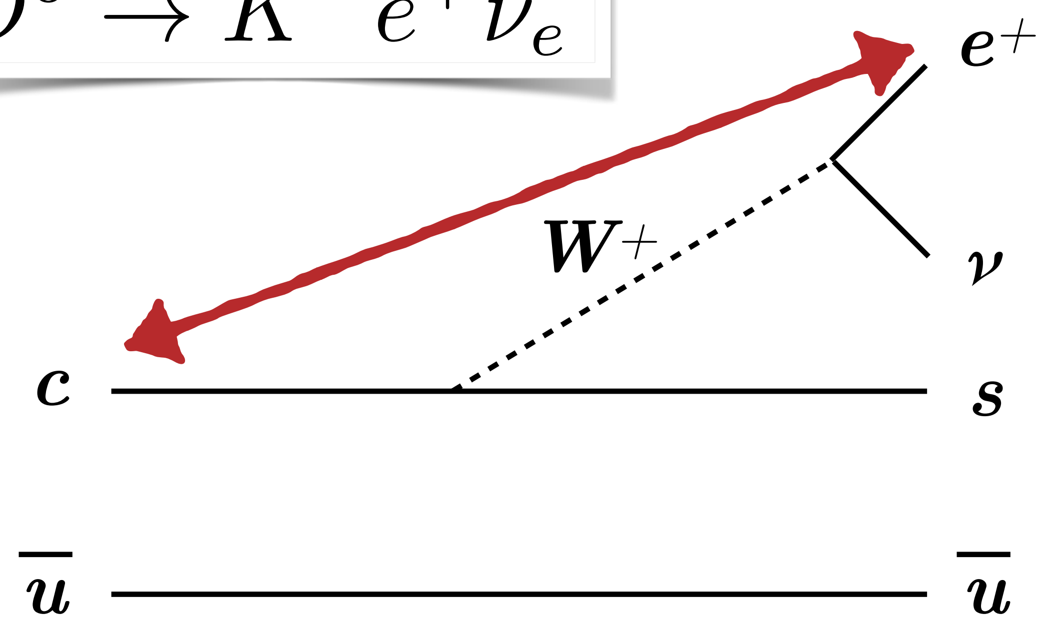
- Beneficial channel due to improved statistics; requires good single track pointing resolution to isolate signal

Average $c \to e$ v_1 comparable to measured D^0 v_1 from STAR in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions

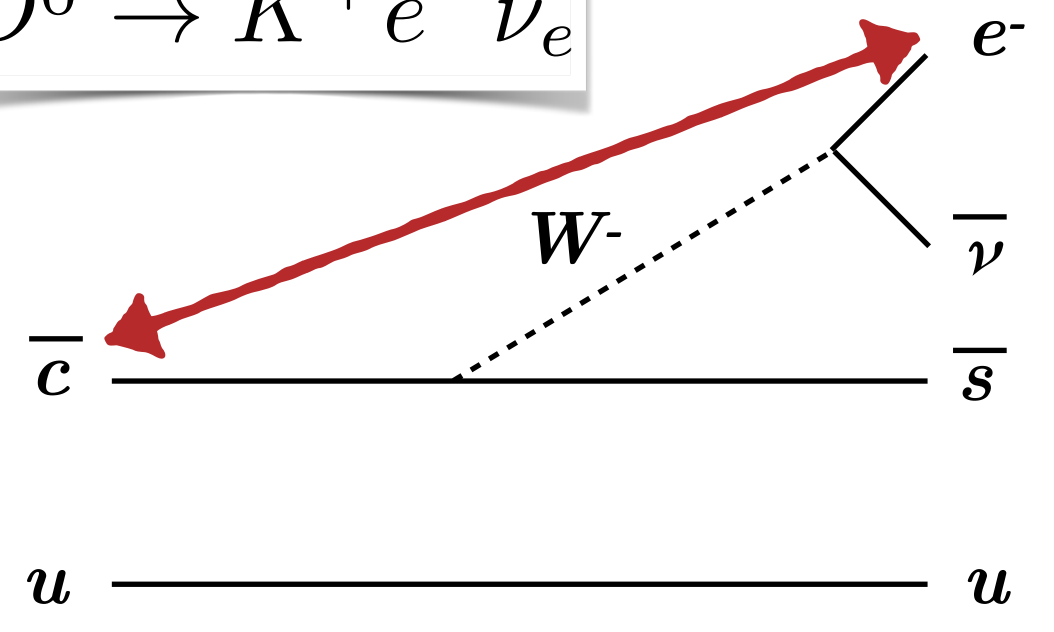
- Similar hadron p_T probed: $\langle p_T(D)\rangle = 2.5$ GeV/c in $c \to e$ vs. 2.2 GeV/c for D^0 measurement
- Improved precision offers improved constraint to initial tilt of QGP bulk

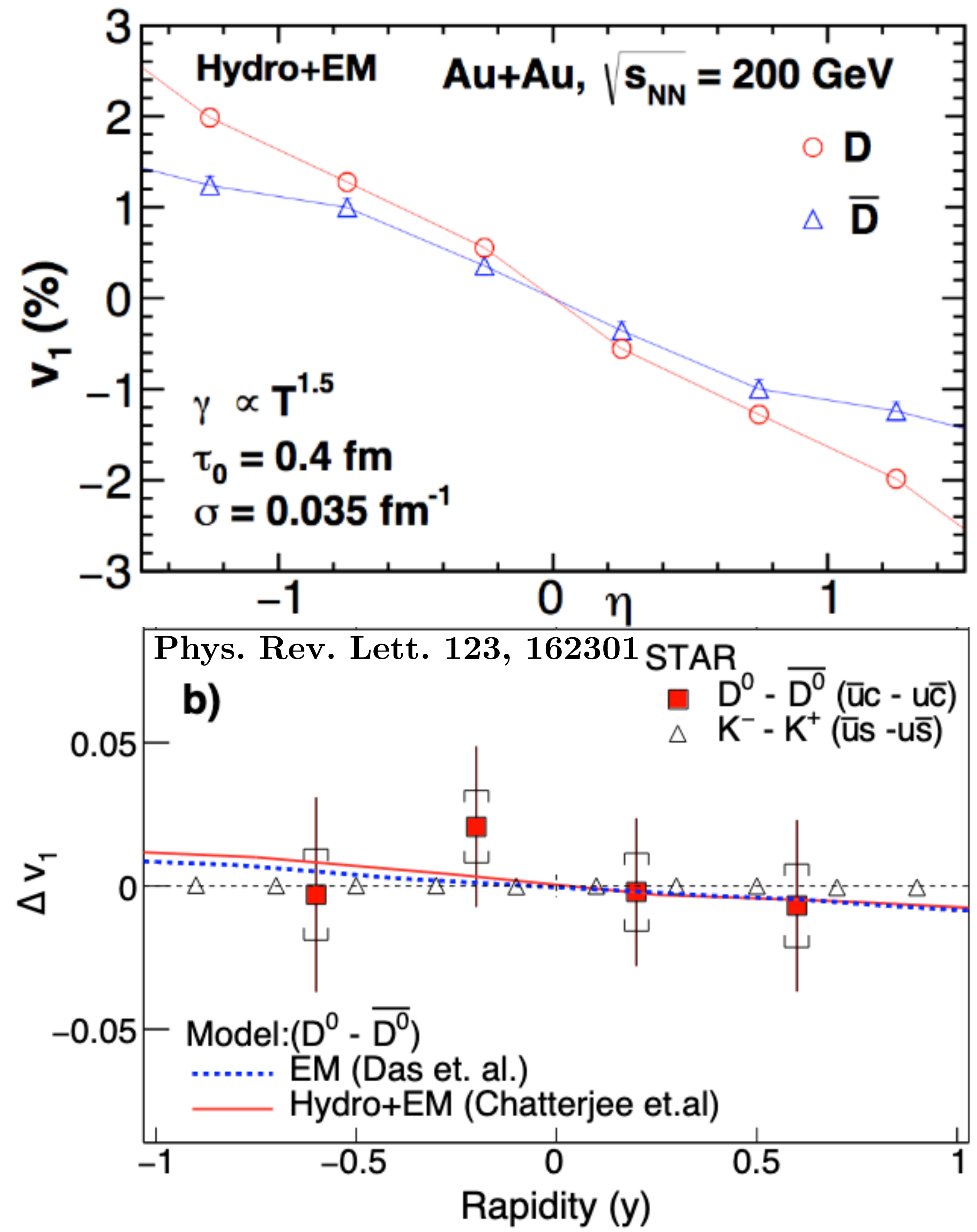
Charm Quark Directed Flow

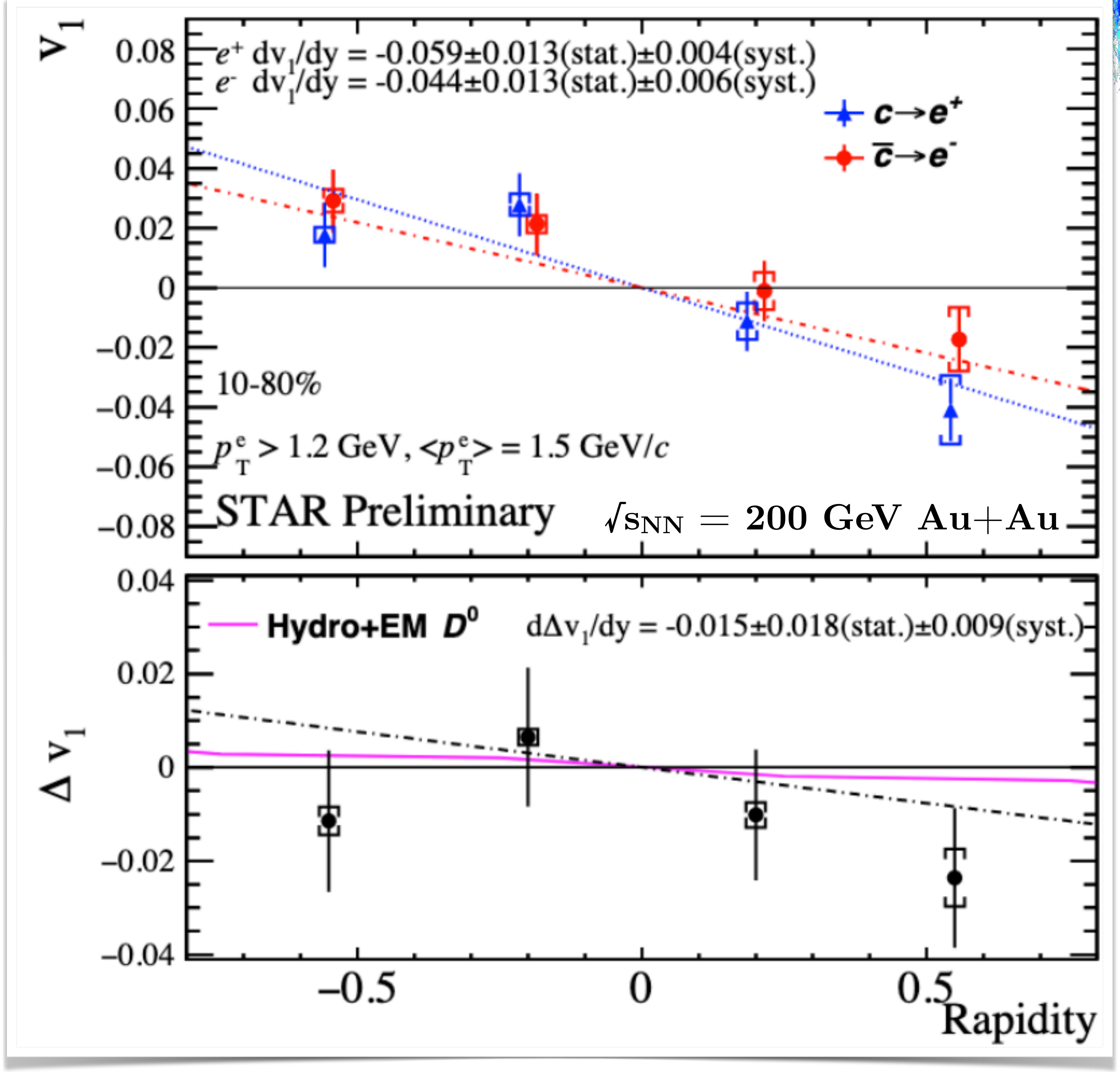
$D^0 \to K^- e^+ \nu_e$



$\bar{D}^0 \to K^+ e^- \bar{\nu}_e$







Initial EM field predicted to affect c and anti-c quarks differently

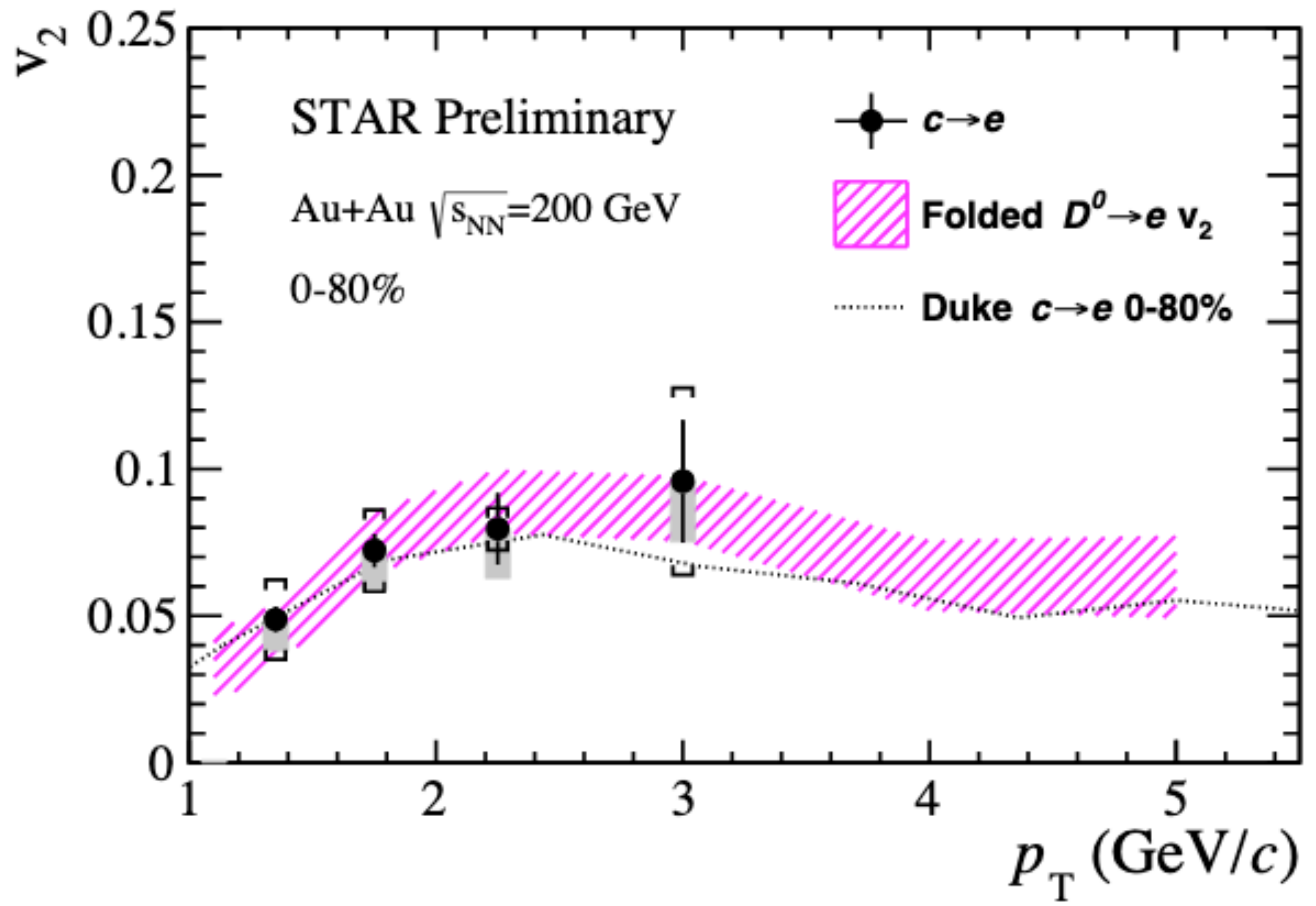
Hydo+EM: Chatterjee, Bojek: arXiv1804.04893v1
Das et. al., Phys Lett B 768, 260 (2017)

Electron charge tags initial heavy quark flavor in semileptonic decays

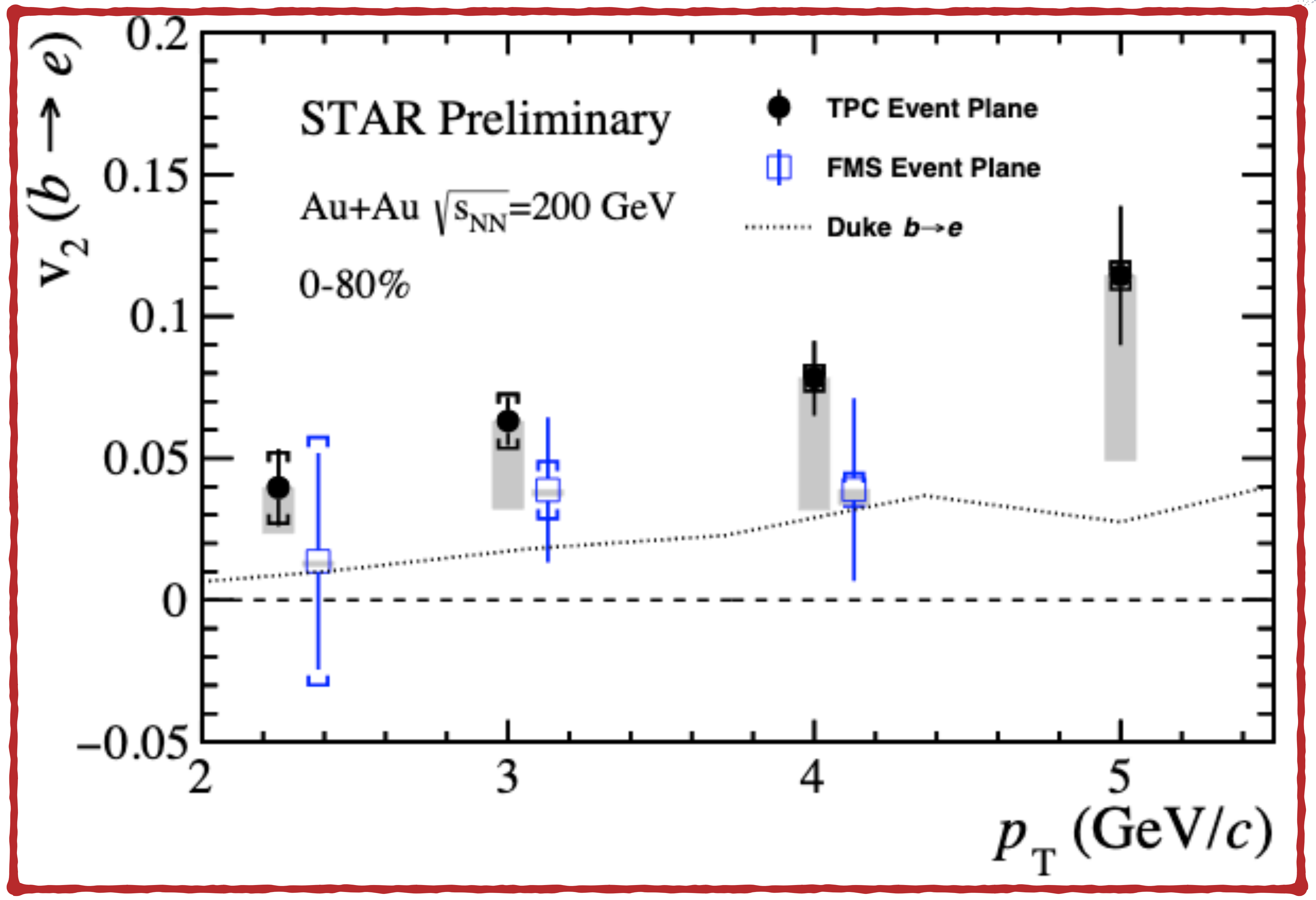
Electron v_1 difference trend same as D^0 measurement; consistent with zero at 1σ level

Bottom-decayed Electron Elliptic Flow

STAR D^0 PRL 118 (2017) 212301



Duke: S. Cao, G.-Y. Qin, and S. A. Bass, Phys. Rev. C 92, 024907 (2015)



FMS = Forward ($2.5<\eta<4$)
Meson Spectrometer

$c \rightarrow e$ v_2 consistent with STAR D^0 measurement folded to decay electron

Non-zero $b \rightarrow e$ v_2 with significance $>3\sigma$ (first significant bottom v_2 at RHIC)

Consistency with Duke model considering non-flow

Summary

- ✓ Significant suppression of D^+ in central HI collisions; Similar D^+/D^0 yield to PYTHIA 8
- ✓ Significant enhancement of $D_s{}^+/D^0$ ratios in HI collisions w.r.t. p+p
- ✓ Separation of $b/c \rightarrow e$ $\mathrm{R_{AA}}$ and significant $\mathrm{R_{AA/CP}}$ double ratios $>$ unity
- ✓ Elliptic flow of NPE: Non-zero in 54.4 GeV collisions; Consistent with zero in 27 GeV collisions
- ✓ $c \rightarrow e$ $\mathrm{v_1}$ and $\mathrm{v_2}$ consistent with previous STAR measurement
- ✓ First significant non-zero $b \rightarrow e$ $\mathrm{v_2}$ @ RHIC