Nuclear modification factors, directed and elliptic flow of electrons from open heavy-flavor decays in Au+Au collisions from STAR

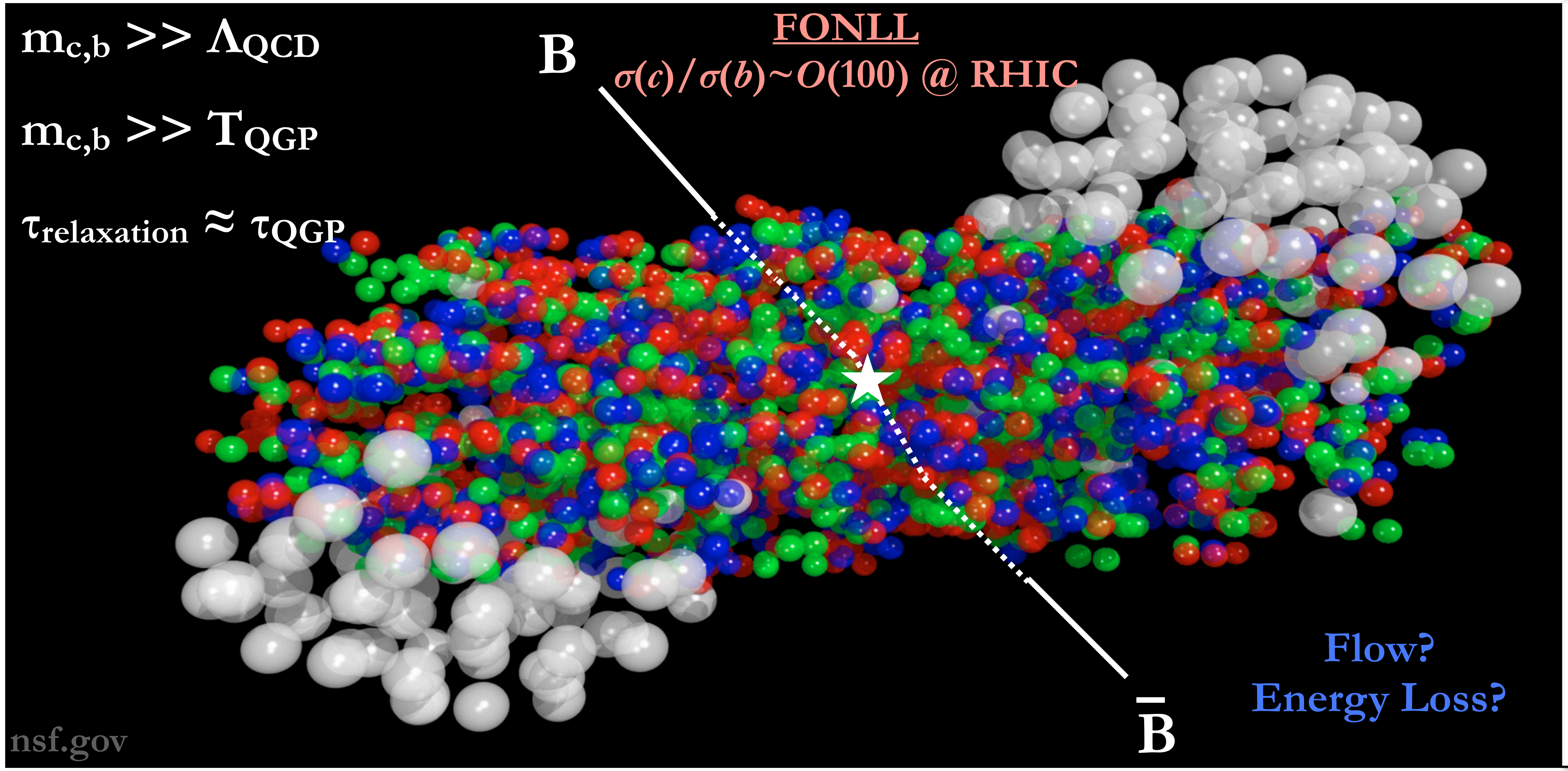
Matthew Kelsey for the STAR Collaboration
Lawrence Berkeley National Laboratory

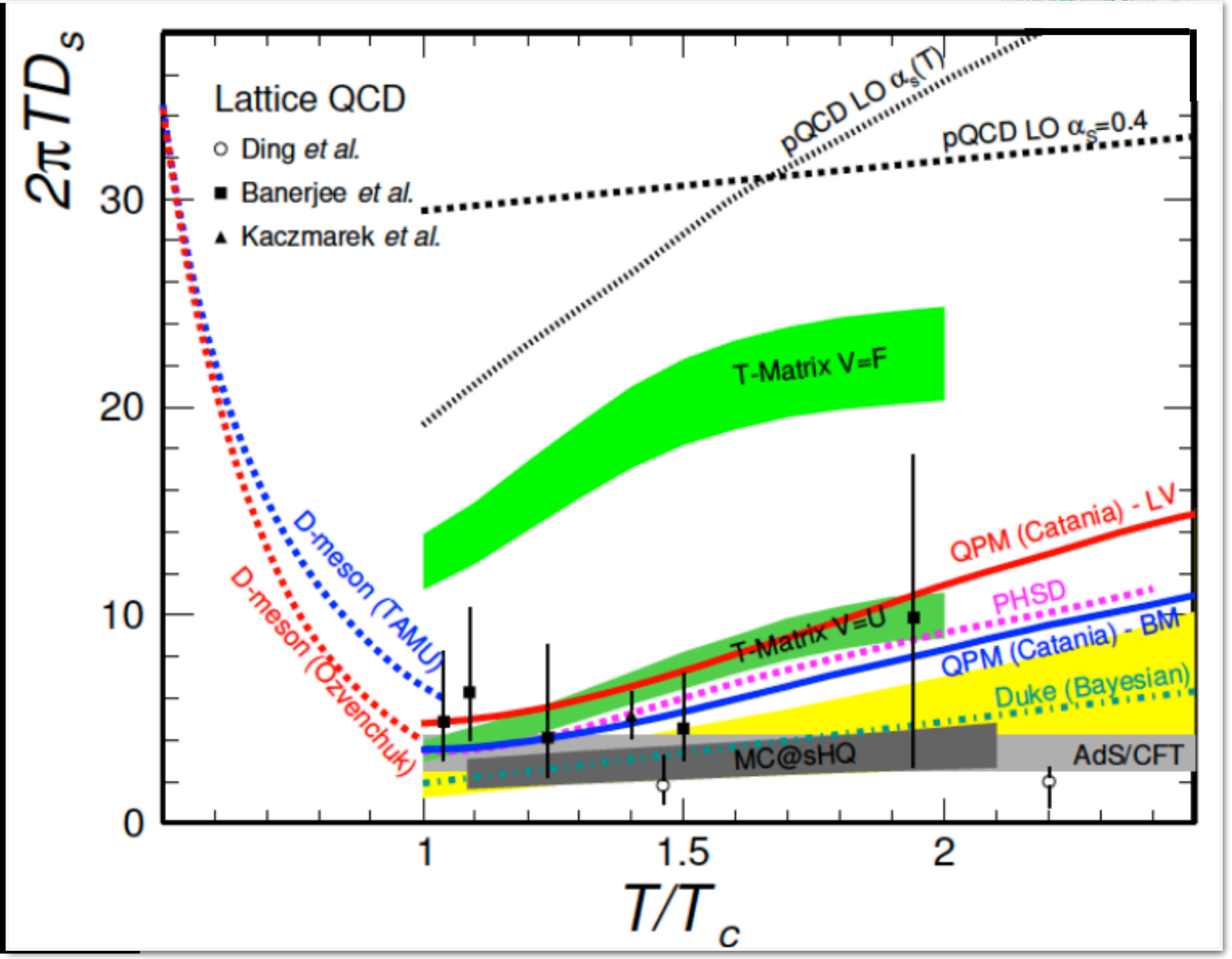
BERKELEY LAB

In part supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

STAR

Heavy-Flavor quarks in the QGP



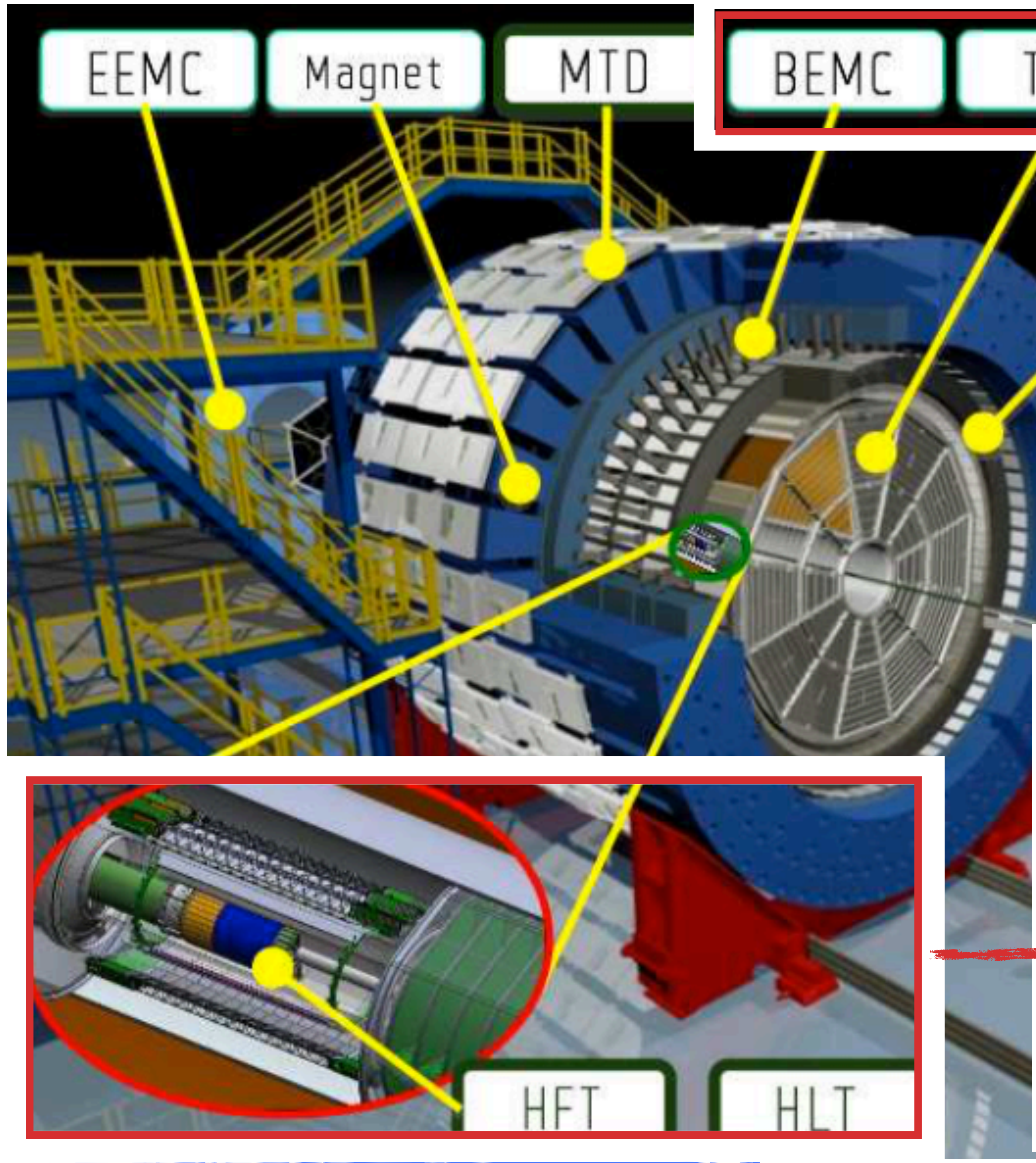


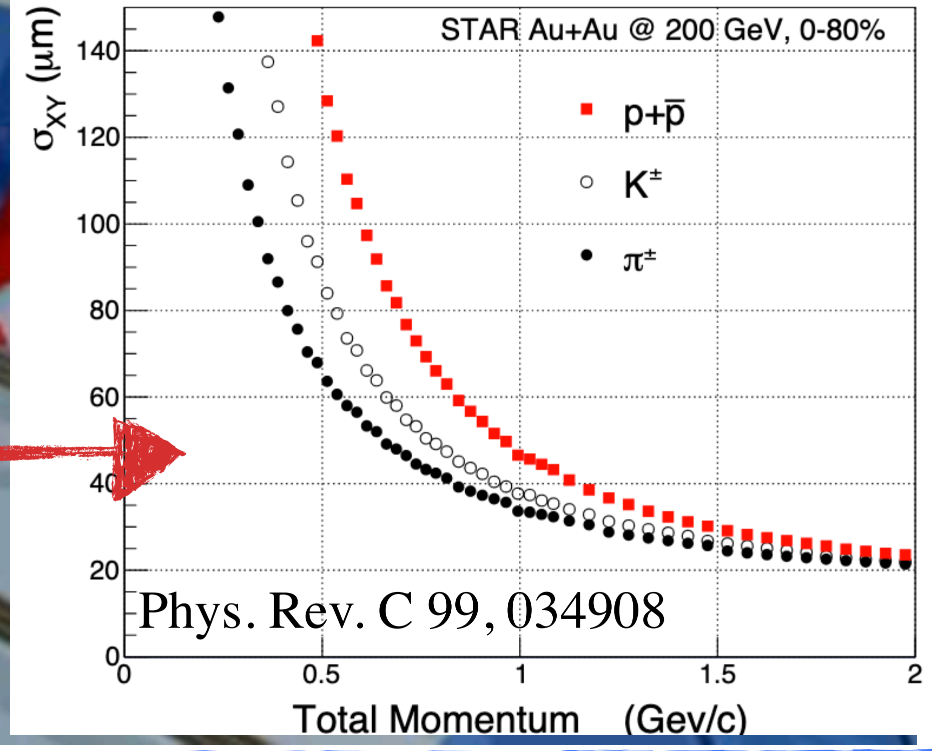
- Precise measurements of HF hadron production essential for understanding non-perturbative regime of hot QCD
- Measurements of charm R_{AA} and v_2 similar to light-hadrons in $\sqrt{s_{NN}}$ =200 GeV Au+Au collisions

➡Bottom quark ultimate HF probe of QGP at RHIC

FONLL: JHEP 1210 (2012)
Ds: j.ppnp.2018.08.001

Electrons at STAR

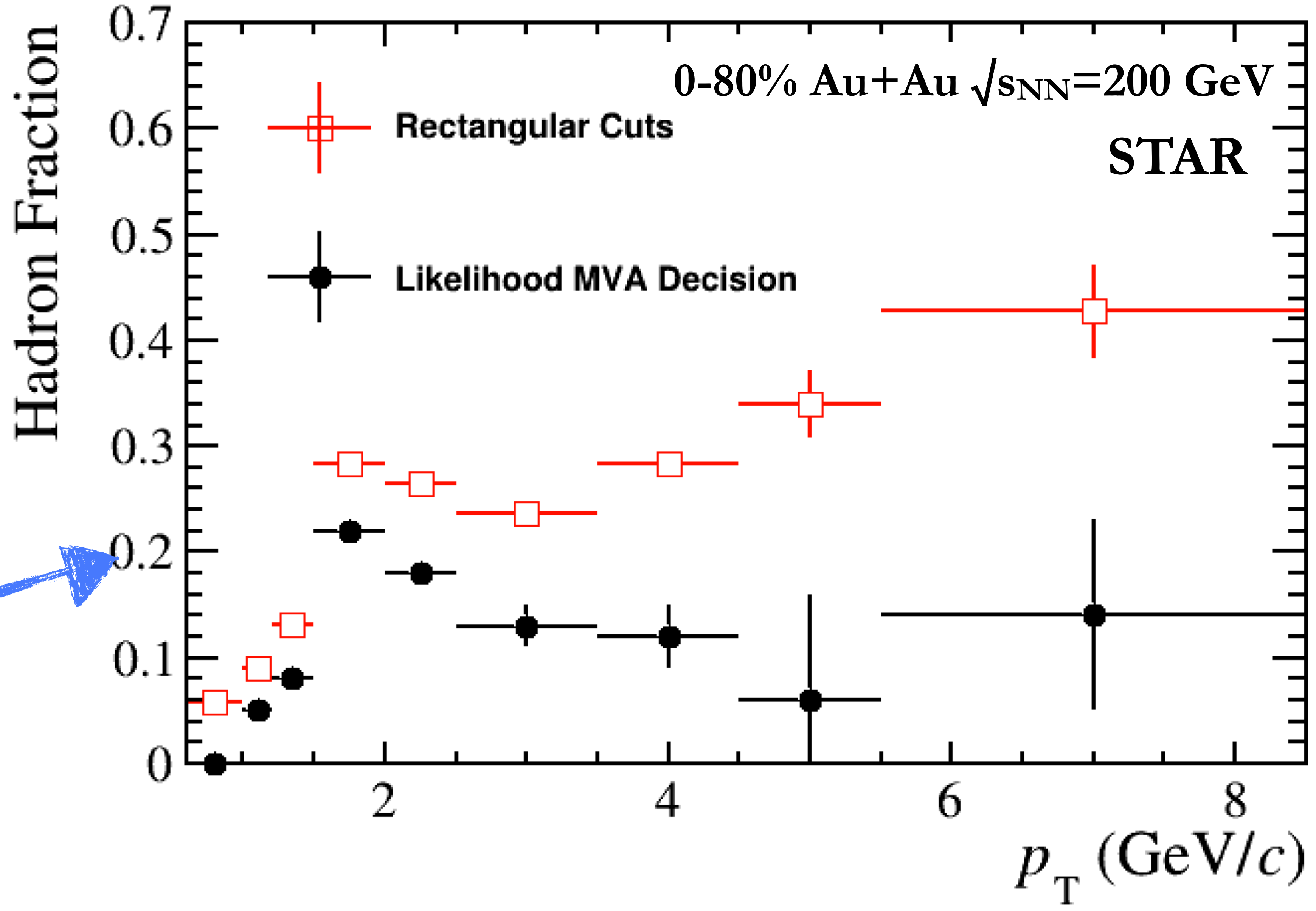




- **Time Projection Chamber** — **Tracking**
  - Full 2π azimuthal coverage at mid-rapidity
- **Heavy Flavor Tracker in 2014+2016 data**
  - First application of thin MAPS detector in collider experiment
  - Excellent pointing resolution for HF vertex and displaced daughter reconstruction

Good electron PID at mid-rapidity

- Ionization energy loss in TPC (dE/dx)
- $1/\beta$ from Time-Of-Flight detector
- Energy deposition in Barrel EM Calorimeter (p/Energy)



Outline of measurements

STAR

With HFT

- Nuclear modification factors of charm and bottom electrons in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions
- Charm electron directed flow in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions
- Charm and bottom electron elliptic flow in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions
- Inclusive HF electron elliptic flow in $\sqrt{s_{NN}}$ = 54.4 GeV Au+Au collisions

NPE @ 200 GeV with HFT

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

NPE @ 200 GeV with HFT

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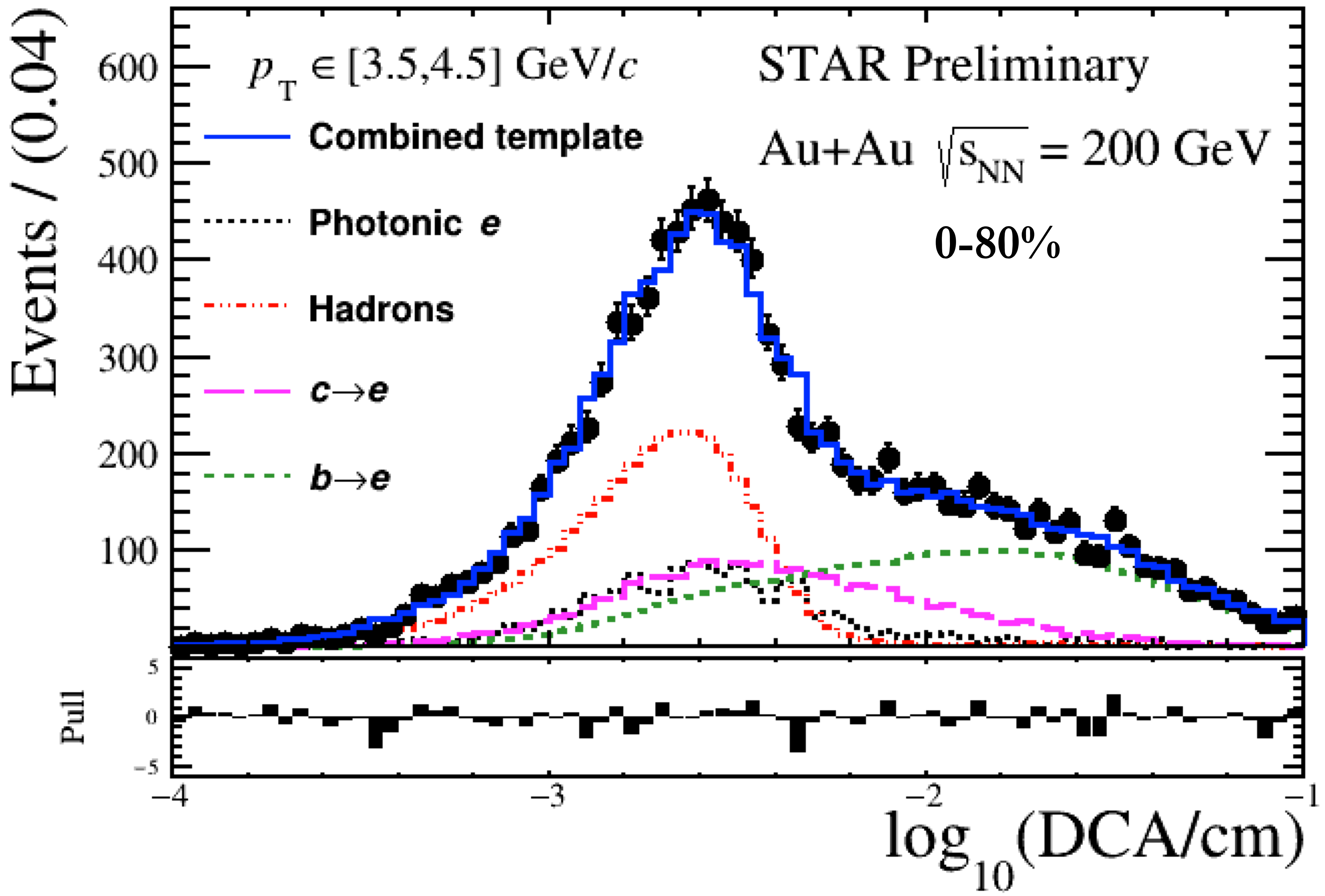
Extraction of *b*- and *c*-decayed electrons with template fit to log of 3D Distance of Closest Approach

- **Larger $c\tau$ of *b*-hadrons w.r.t. *c*-hadrons**
  - $\langle DCA(b \to e) \rangle > \langle DCA(c \to e) \rangle$
- **Large separation from backgrounds (hadrons and photonic electrons)**



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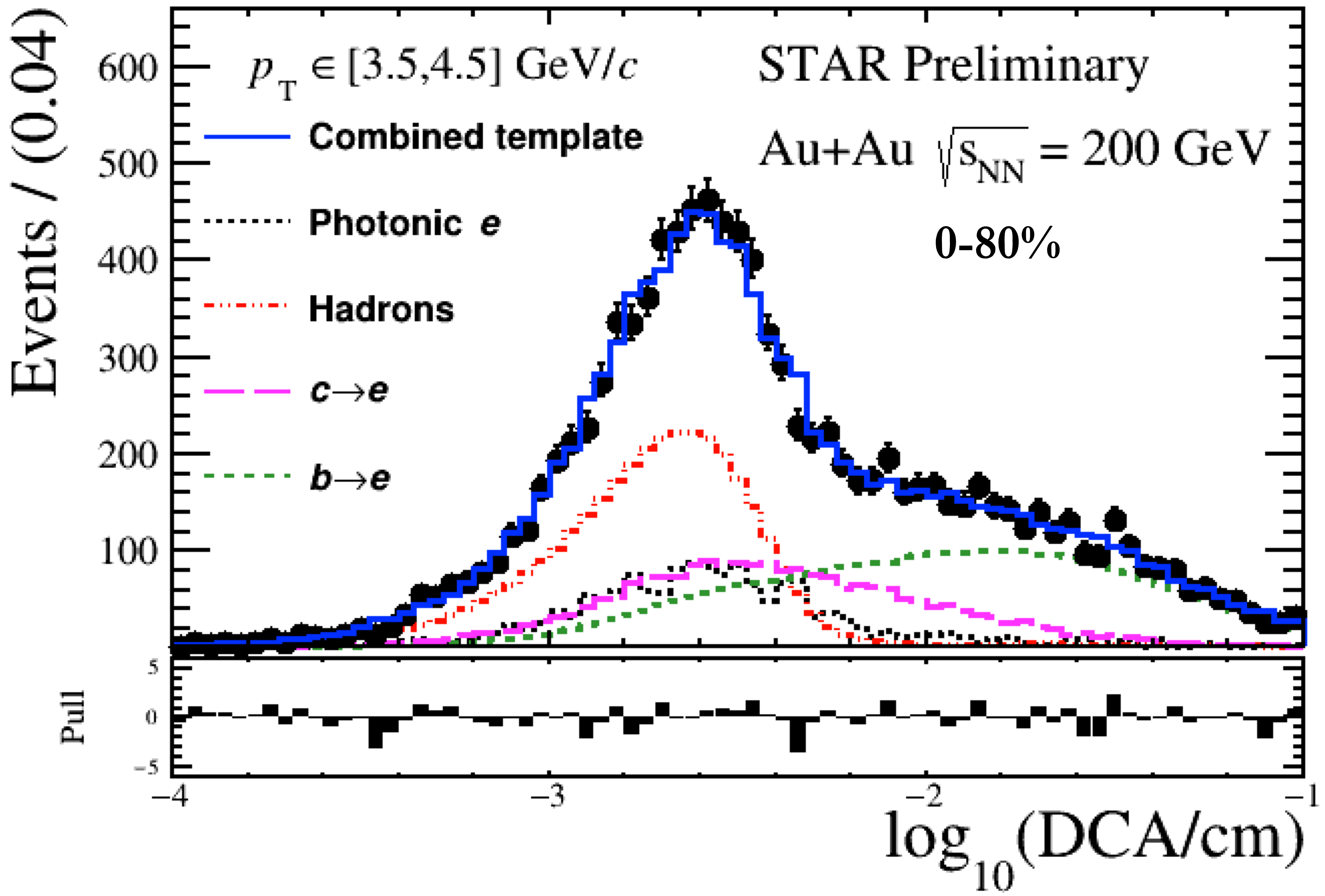
See Yingjie Zhou's poster (HF32) for details!

Hadron background reduced with Likelihood MVA PID

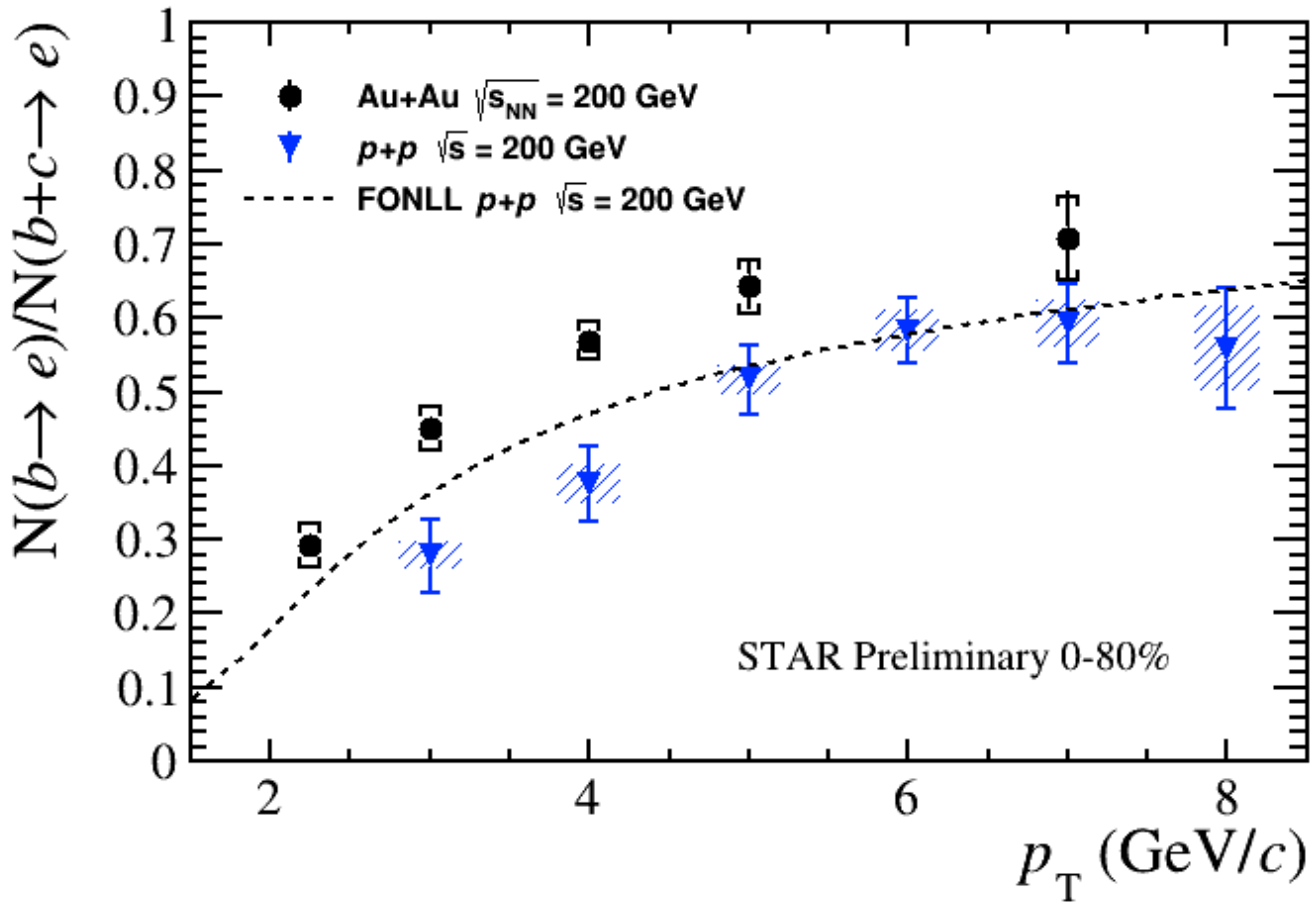
Photonic electron background rejection with single electron isolation cuts

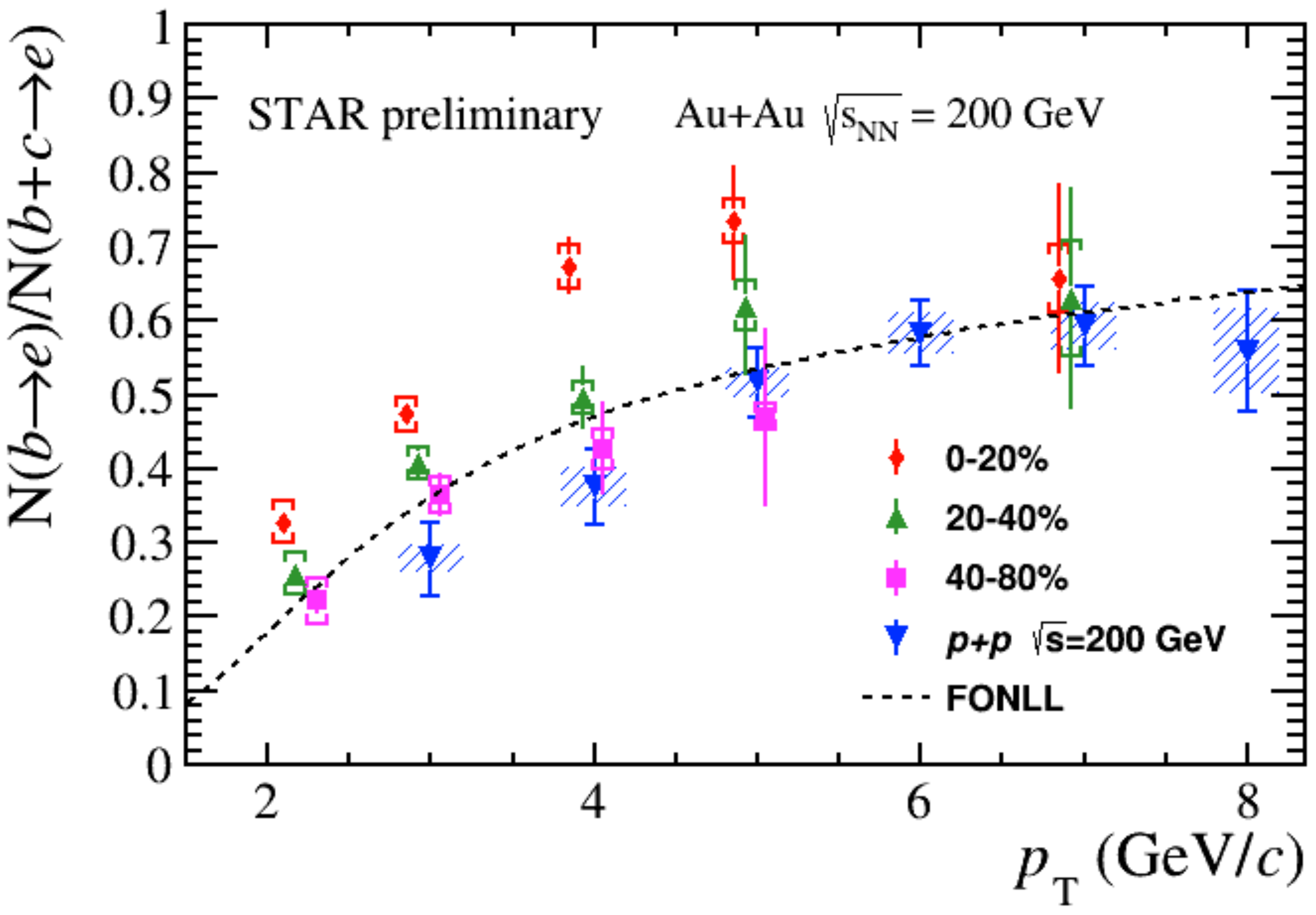
- **Large separation from backgrounds (hadrons and photonic electrons)**



Bottom Electron Fraction

See Yingjie Zhou's poster (HF32) for details!





Au+Au points shifted from bin centers

- **Bottom fraction in MB Au+Au enhanced compared to p+p measurement and FONLL prediction**
  - p+p from combined STAR 2006 published and 2012 preliminary data
- **Bottom fraction significantly enhanced in central collisions**
  - Bottom fraction in peripheral collisions consistent with p+p data

FONLL: JHEP 1210 (2012) 137
STAR 2006 pp: Phys. Rev. Lett. 105, 202301

Nuclear Modification Factors

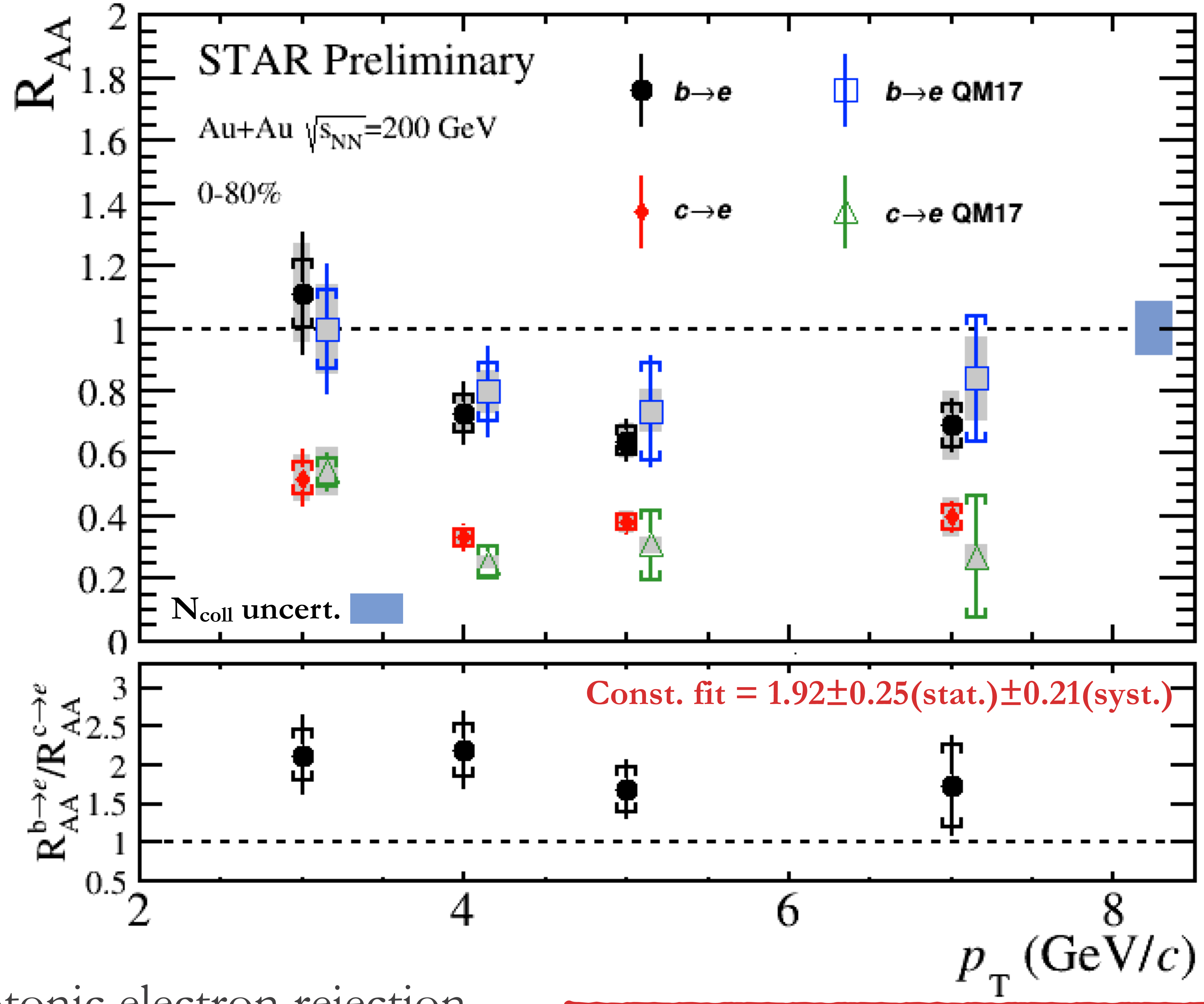
See Yingjie Zhou's poster (HF32) for details!

Bottom electron fraction translated to *b,c→e* R_{AA} with preliminary STAR inclusive NPE R_{AA}

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

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

- **Increased precision from QM2017 preliminary**
  - Increased statistics with 2014+2016 data
  - Reduced backgrounds from MVA PID and photonic electron rejection
  - Increased sensitivity to HF electrons with log(DCA) fit



QM17 points shifted from bin center

Shaded gray boxes show inclusive NPE R_{AA} uncertainty

$R_{AA}(b\rightarrow e) > R_{AA}(c\rightarrow e)$ significant at ~3σ

Nuclear Modification Factors

See Yingjie Zhou's poster (HF32) for details!

Bottom electron fraction translated to $b,c \rightarrow e$ R_{AA} with preliminary STAR inclusive NPE R_{AA}

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

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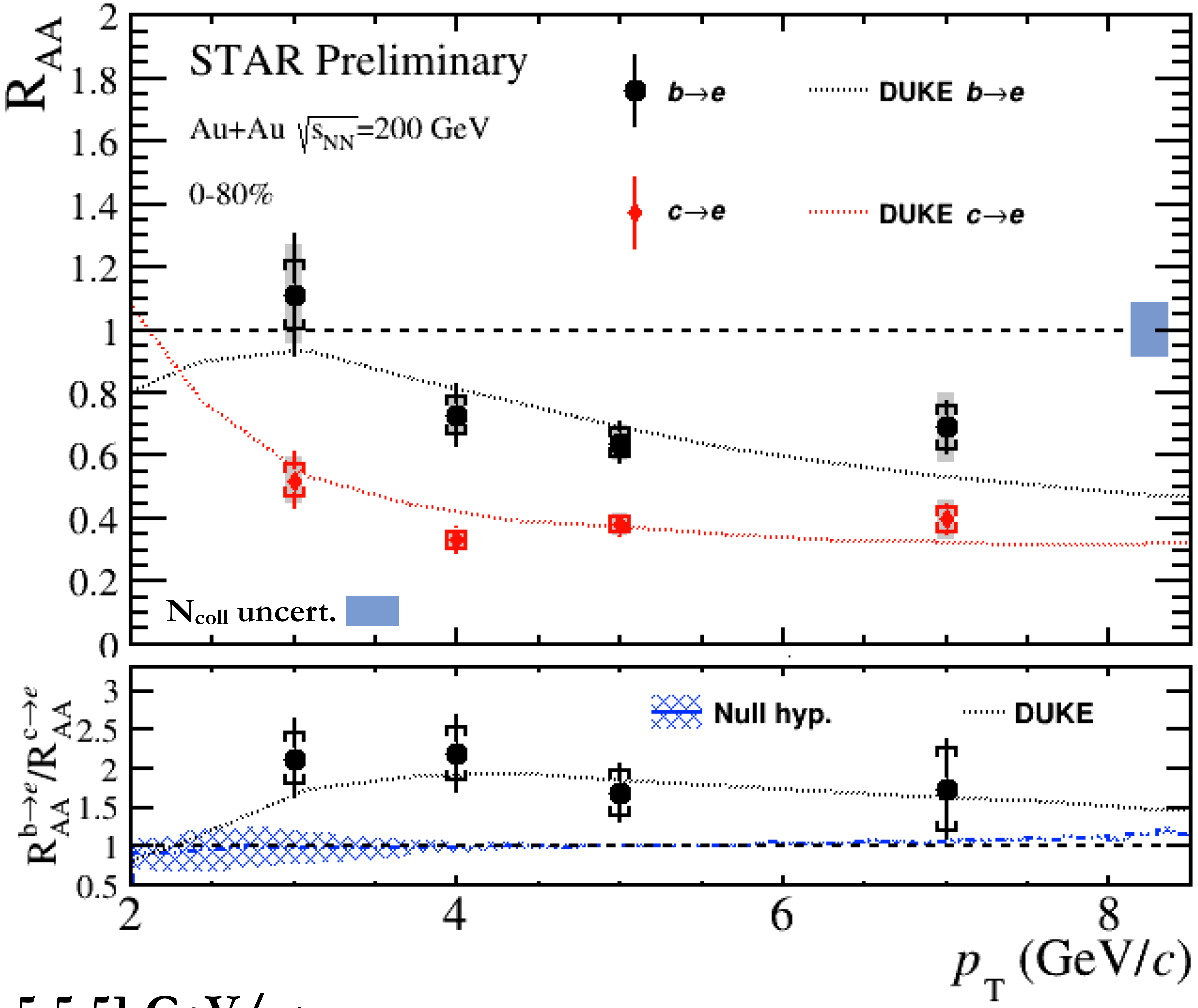


Shaded gray boxes show inclusive NPE R_{AA} uncertainty

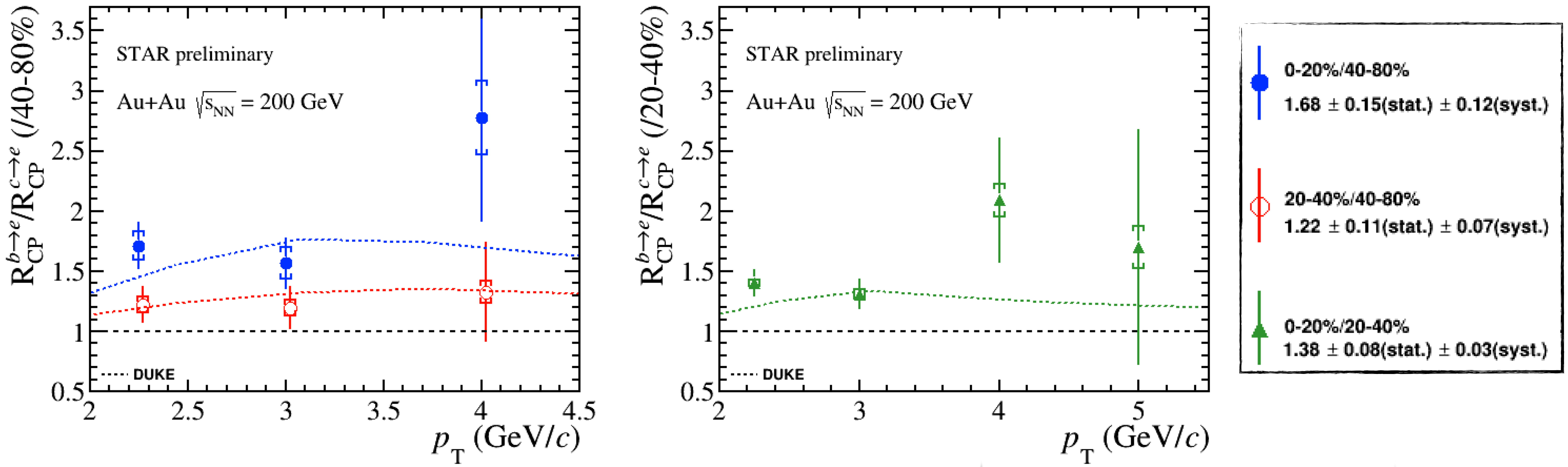
- **Data consistent with DUKE Langevin model prediction (consistent with ΔE(*b*)<ΔE(*c*))**
- **Null hypothesis [R_{AA}(B)=R_{AA}(D)] for $p_T(e) \in [2.5,5.5]$ GeV/*c*:**
  - χ^2/ndof = 8.6/2, p-value = .014

DUKE: Phys. Rev. C 92, 024907
Private Communication

Double Ratio of R_{CP}

See Yingjie Zhou's poster (HF32) for details!

Red points shifted from bin center



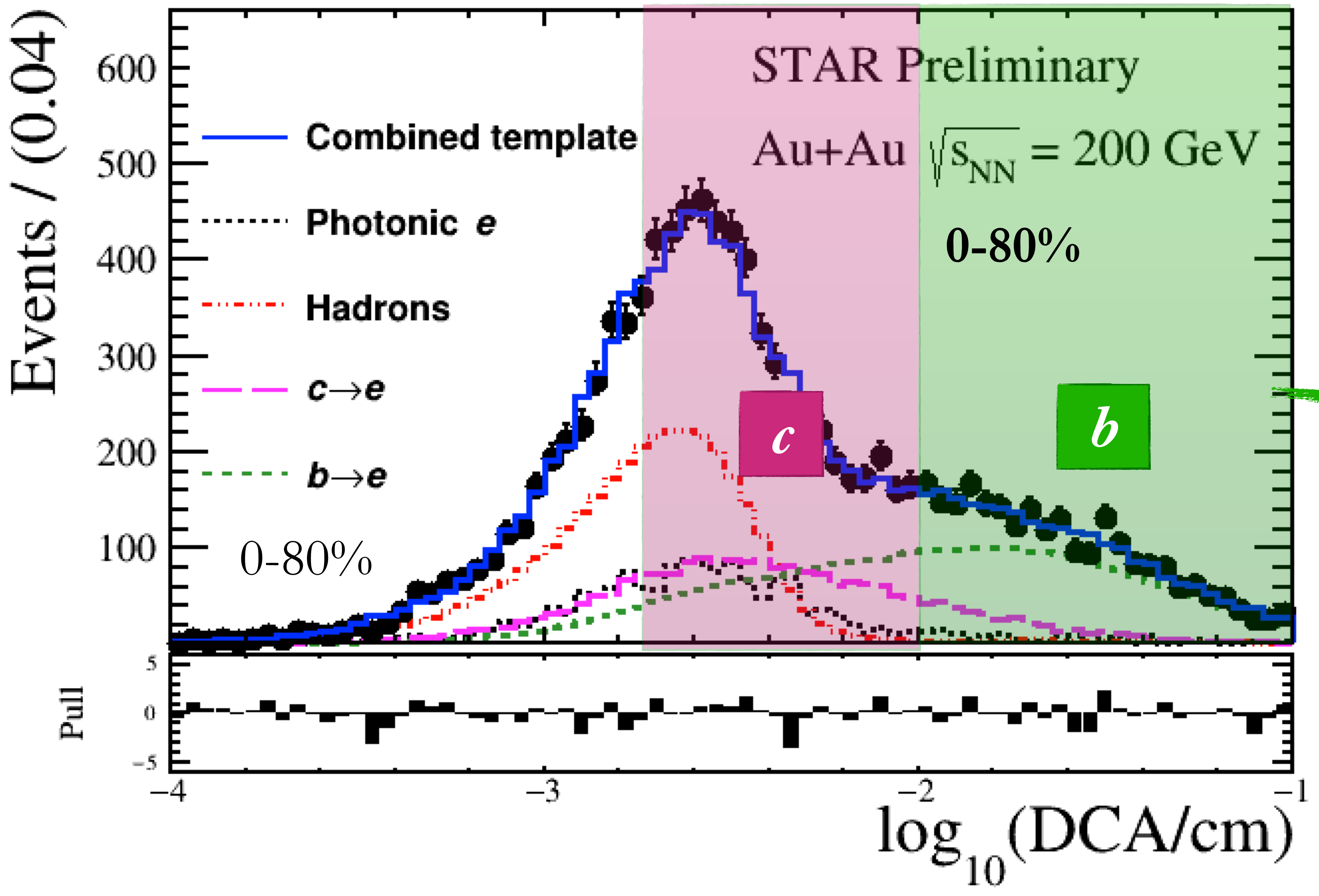
- **Calculated from centrality dependent bottom fraction**
- **Large cancelation of correlated systematic uncertainties**

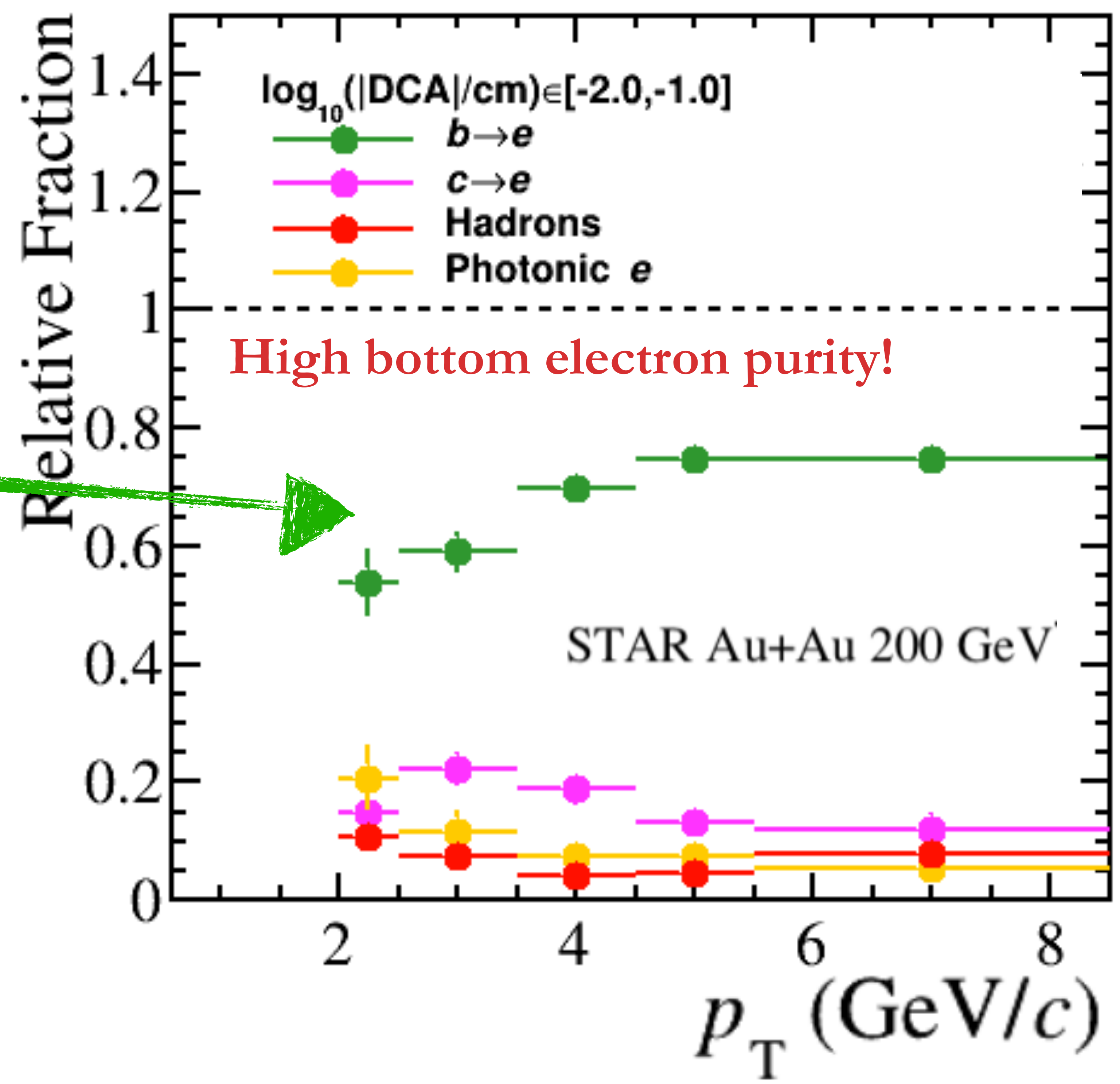
$$\frac{R_{CP}^{b\to e}}{R_{CP}^{c\to e}} = \frac{f_b^{central}}{1 - f_b^{central}} \frac{1 - f_b^{peripheral}}{f_b^{peripheral}}$$

➡ **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%)**

DUKE: Phys. Rev. C 92, 024907
Private Communication

Anisotropic Flow Strategy

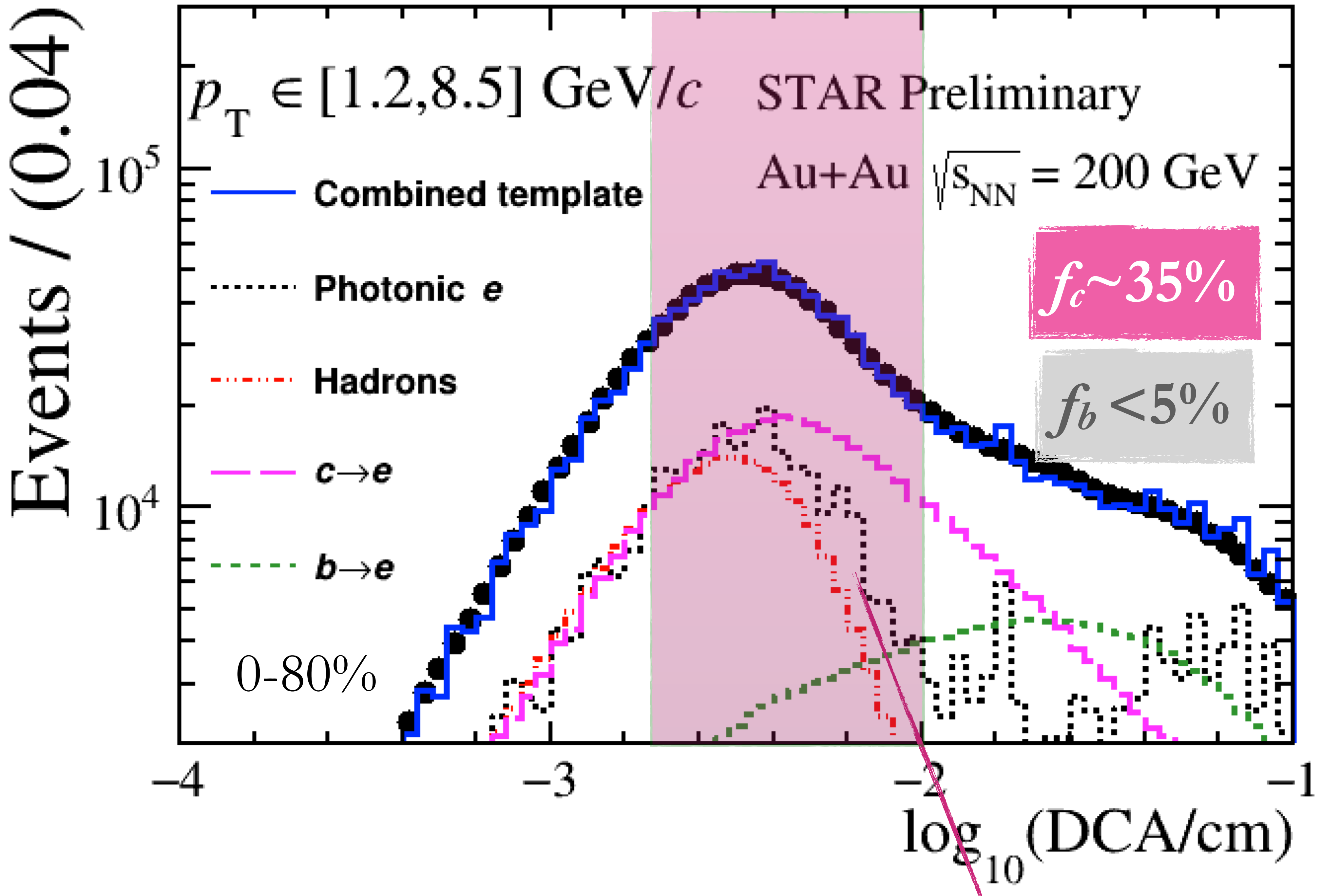




- **HFT enables study of v_1 and v_2 in log(DCA) regions rich with charm and bottom electrons and with little backgrounds**
- **Observed flow corrected for flow from background**

$$v_2(obs.) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$

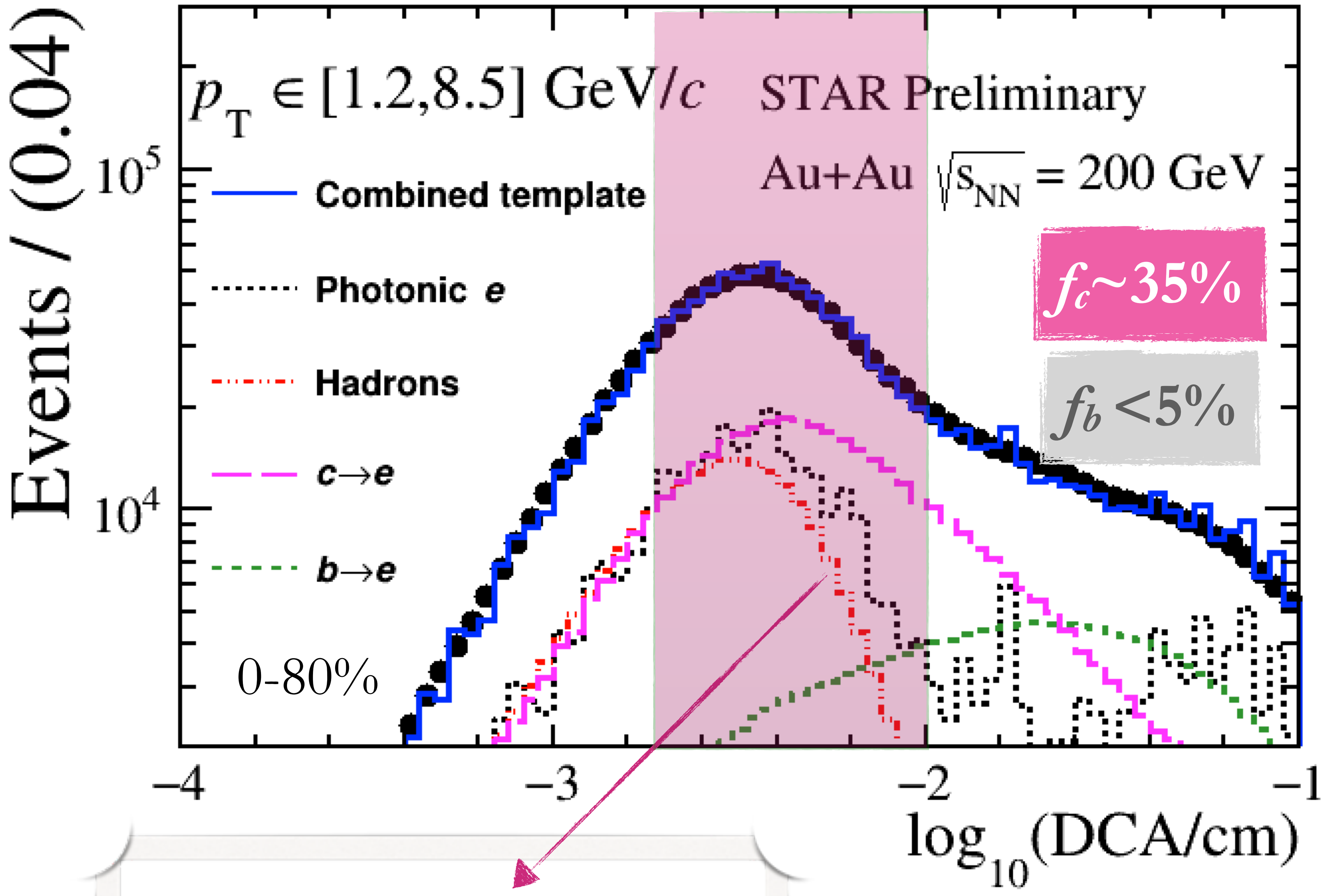
Charm→e Directed Flow



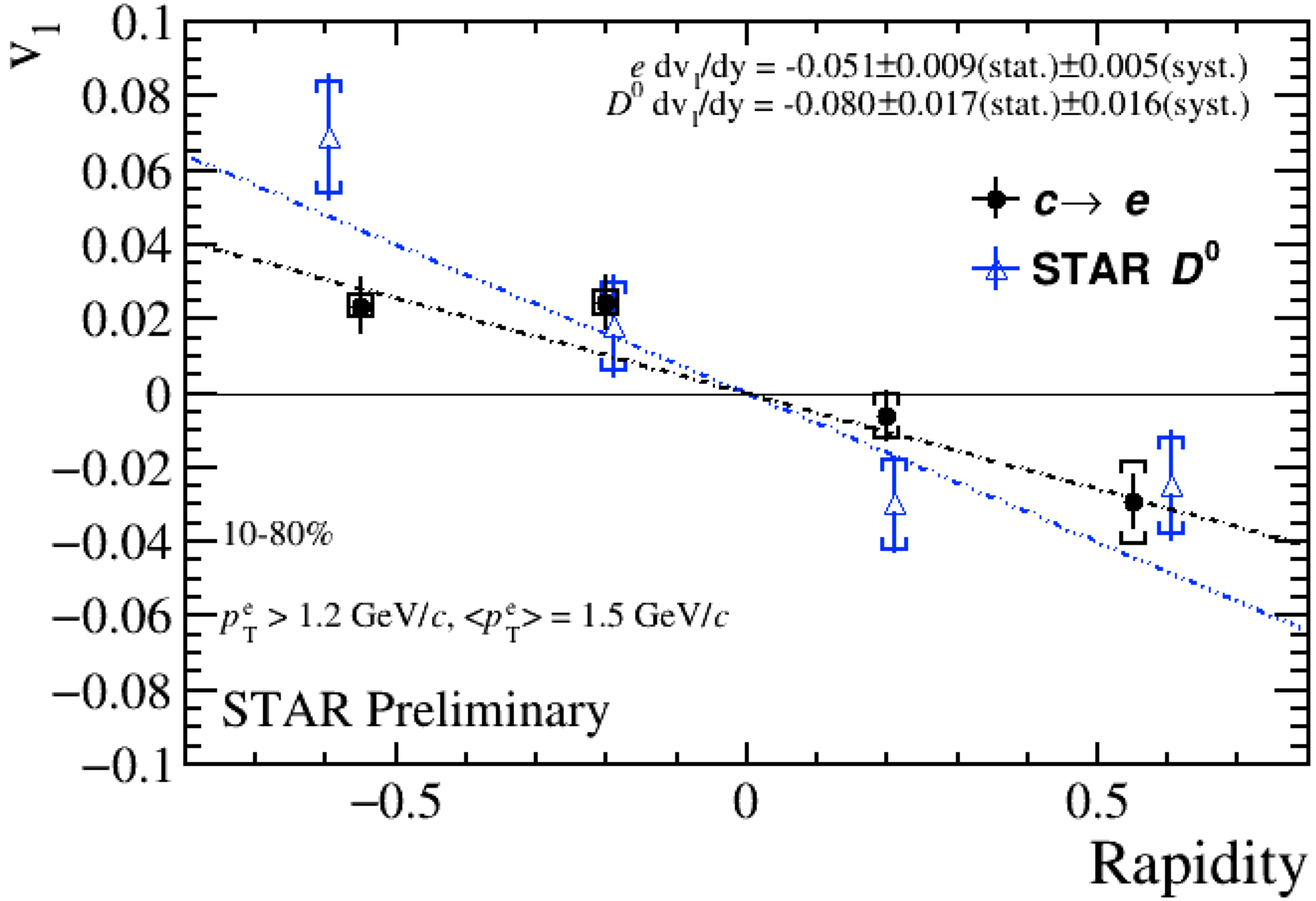
Background $\langle p_T \rangle$~1.5 GeV/c
⇒v_1(hadron)~0

$$v_1(obs.) = f_c v_1^c$$

Charm→e Directed Flow



$$v_1(obs.) = f_c v_1^c$$

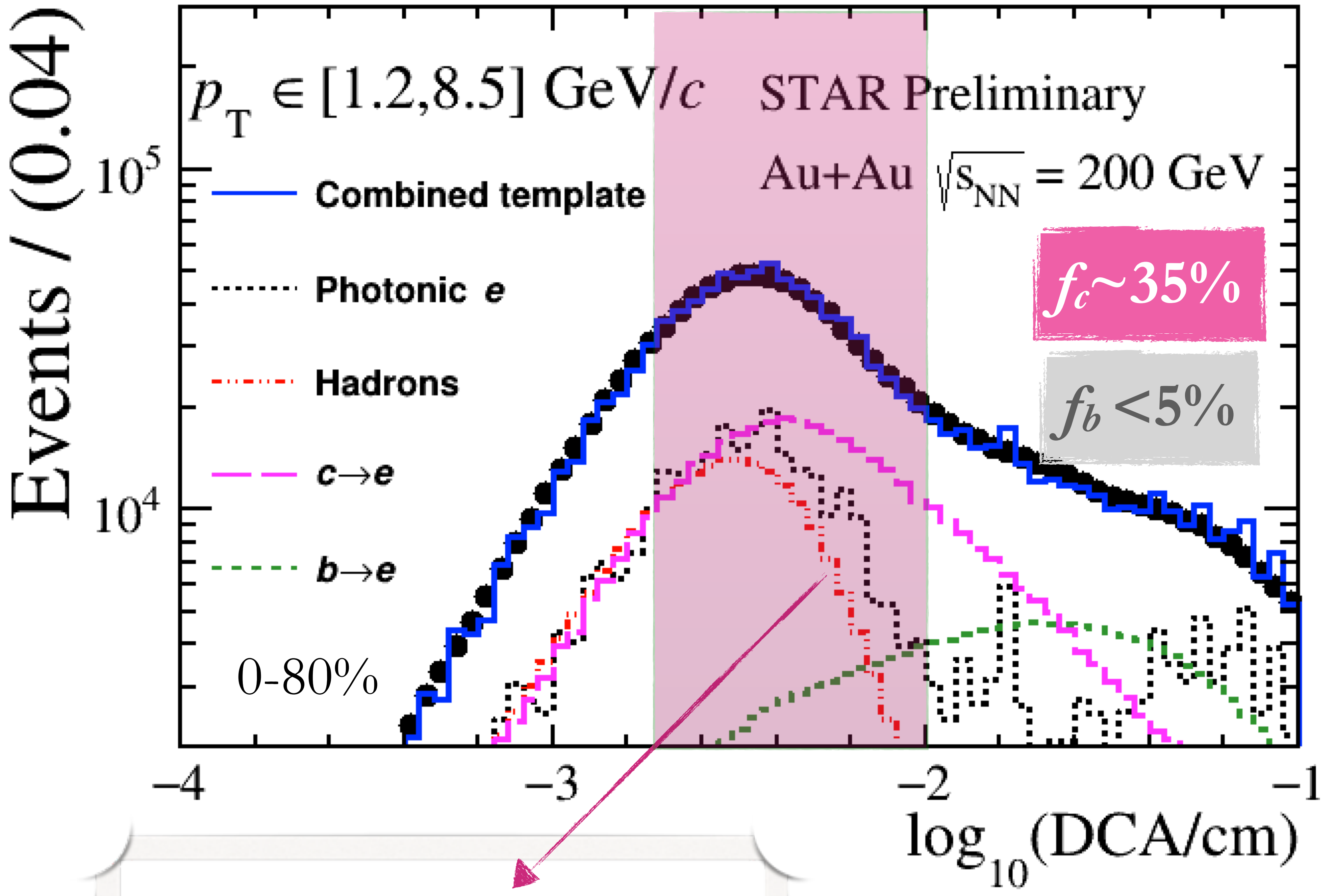


D^0 points shifted from bin center

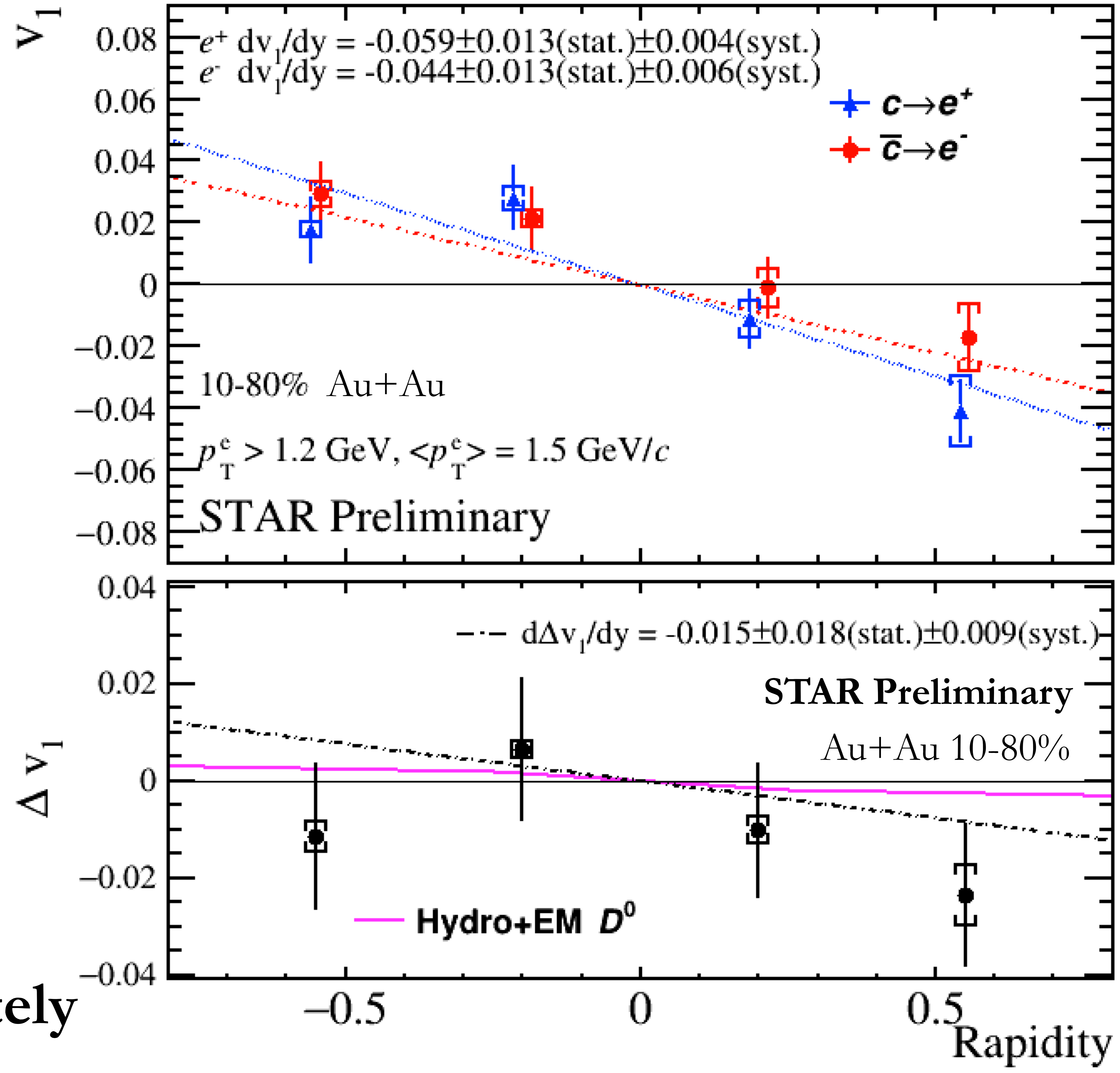
- **Charm-decayed electron dv_1/dy non-zero ~5σ level**
  - ⟨$p_T(D)$⟩ = 2.5 GeV/c for electron p_T >1.2 GeV/c
  - Magnitude consistent with STAR D^0 measurement (⟨$p_T(D^0)$⟩ = 2.2 GeV/c)

D^0 v_1: Phys. Rev. Lett. 123, 162301

Charm→e Directed Flow



$$v_1(obs.) = f_c v_1^c$$

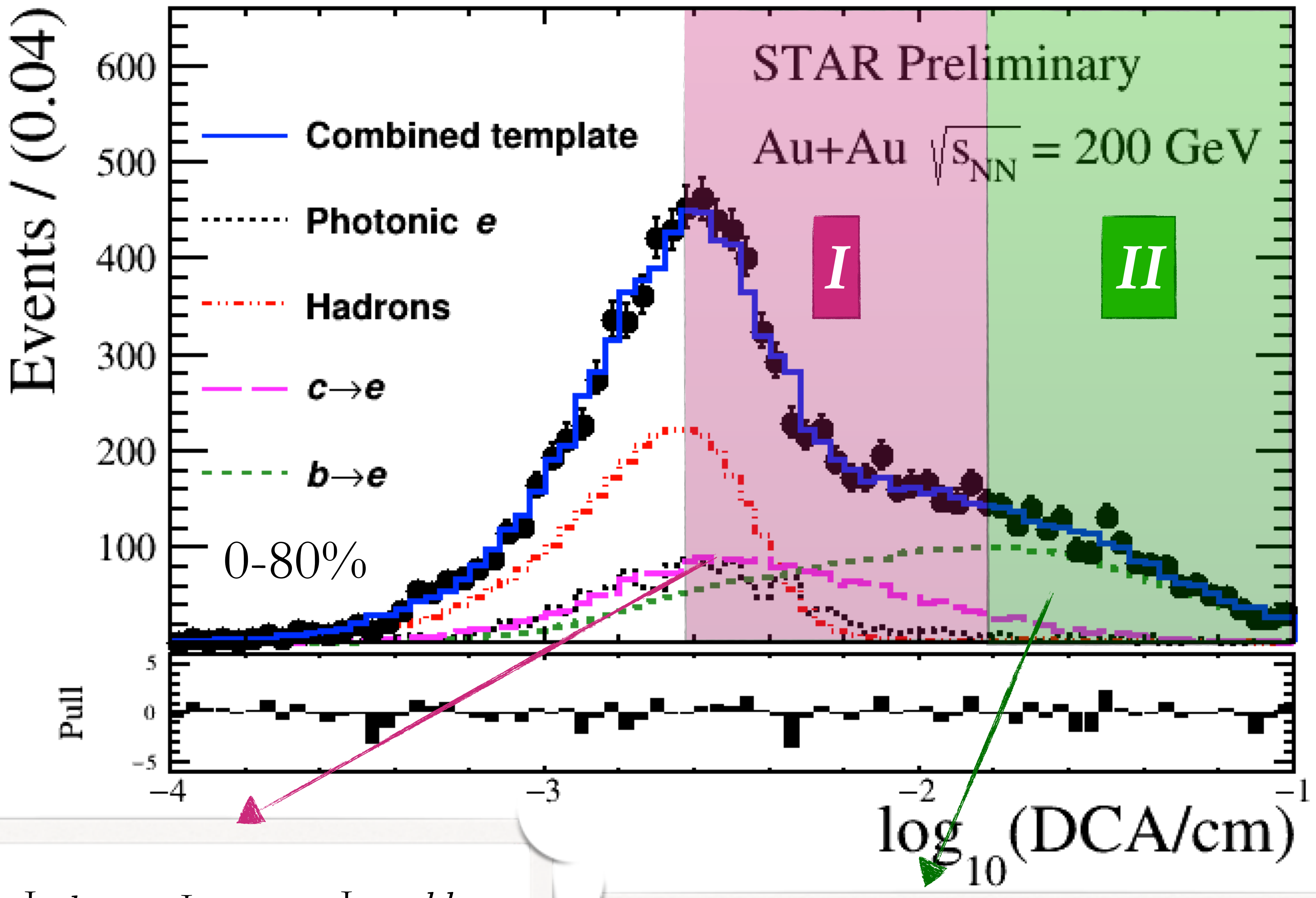


e± points shifted from bin center

- **Initial EM field predicted to alter $c/\bar{c}$ v1 oppositely**
- **Electron charge tags parent hadron flavor allowing $c/\bar{c}$ v1 probe**
  - $e^+(c)$ - $e^-(\bar{c})$ v1 difference at <1σ

D^0 v1: Phys. Rev. Lett. 123, 162301
Hydro+EM: arXiv:1804.04893

Charm→e Elliptic Flow

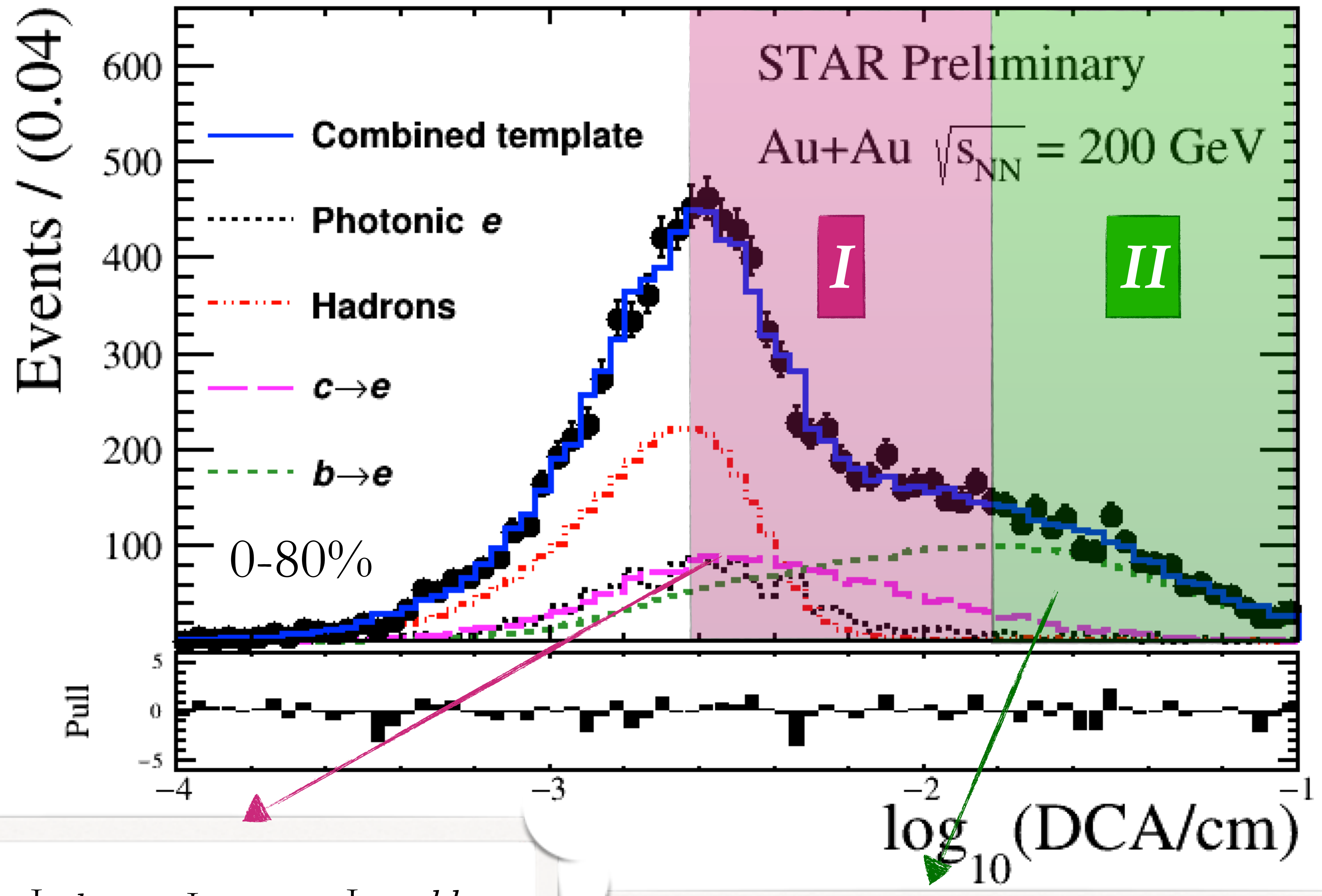


$$v_2^{\mathrm{I}}(obs.) = f_b^{\mathrm{I}} v_2^b + f_c^{\mathrm{I}} v_2^c + f_{bkg}^{\mathrm{I}} v_2^{bkg}$$

$$v_2^{\mathrm{II}}(obs.) = f_b^{\mathrm{II}} v_2^b + f_c^{\mathrm{II}} v_2^c + f_{bkg}^{\mathrm{II}} v_2^{bkg}$$

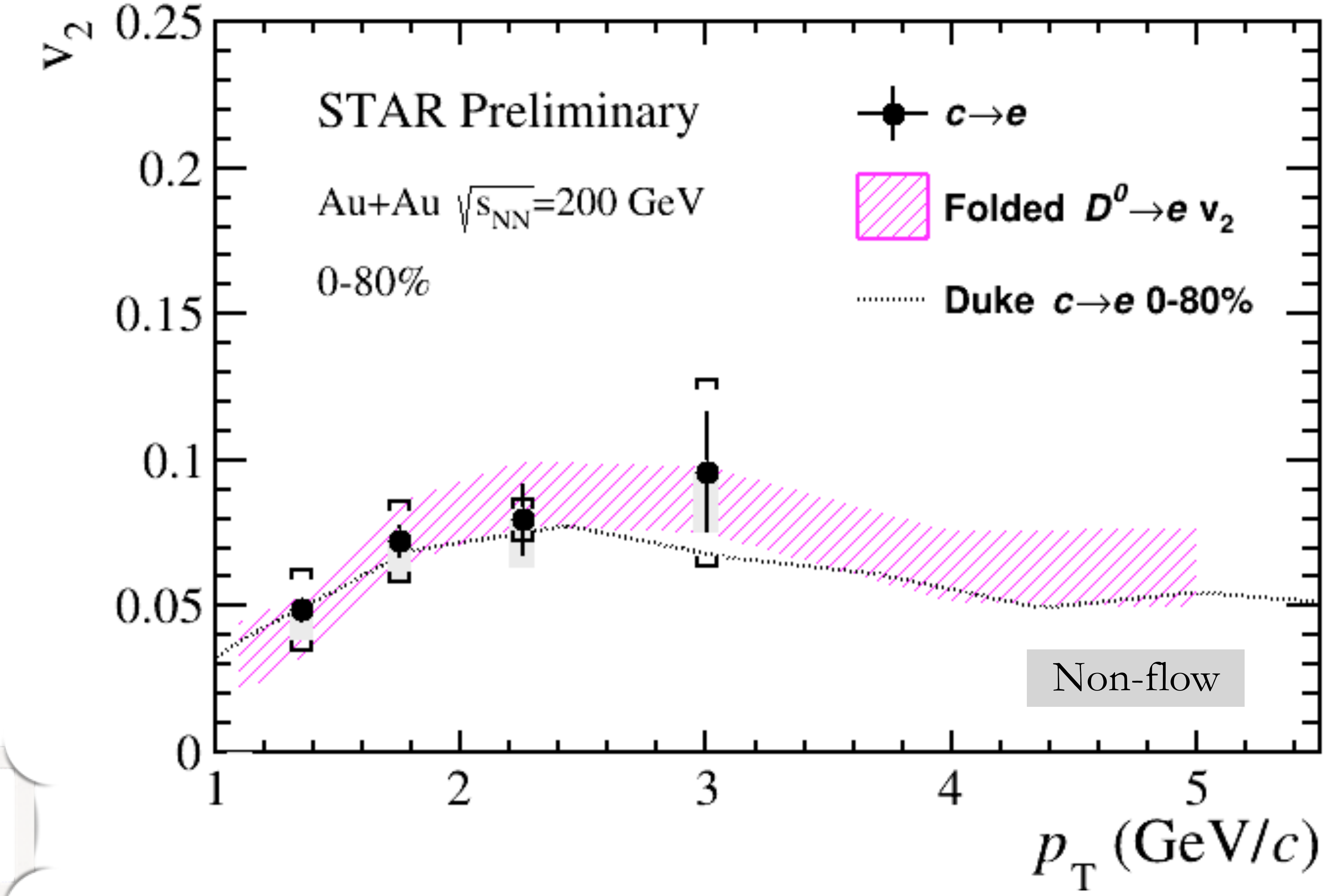
- **Second order event plane measured with TPC tracks using η-sub event method**
- **Simultaneous fit to two log(DCA) regions; solve for v_2(c→e)**

Charm→e Elliptic Flow



$$v_2^{\mathrm{I}}(obs.) = f_b^{\mathrm{I}} v_2^b + f_c^{\mathrm{I}} v_2^c + f_{bkg}^{\mathrm{I}} v_2^{bkg}$$

$$v_2^{\mathrm{II}}(obs.) = f_b^{\mathrm{II}} v_2^b + f_c^{\mathrm{II}} v_2^c + f_{bkg}^{\mathrm{II}} v_2^{bkg}$$

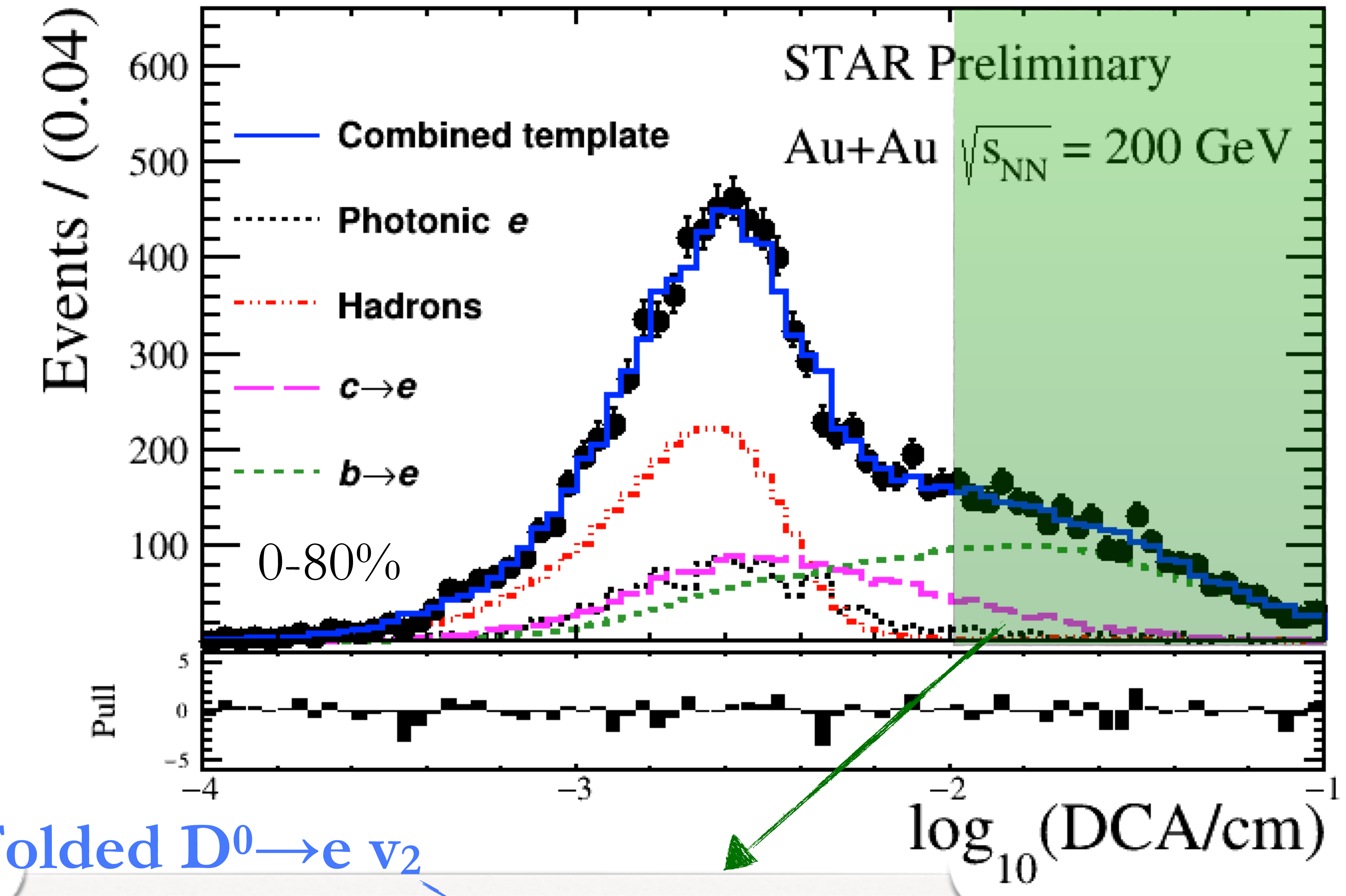


- **Non-flow estimated with two-particle (e-h) correlations in PYTHIA**
- **Measured D^0 v_2 folded to decayed electron with simulated semileptonic decays in EvtGen**

➡**Charm electron v_2 consistent with folded D^0 v_2 and DUKE model**

D^0 v_2: Phys. Rev. Lett. 118, 212301
DUKE: Phys. Rev. C 92, 024907
Private Communication

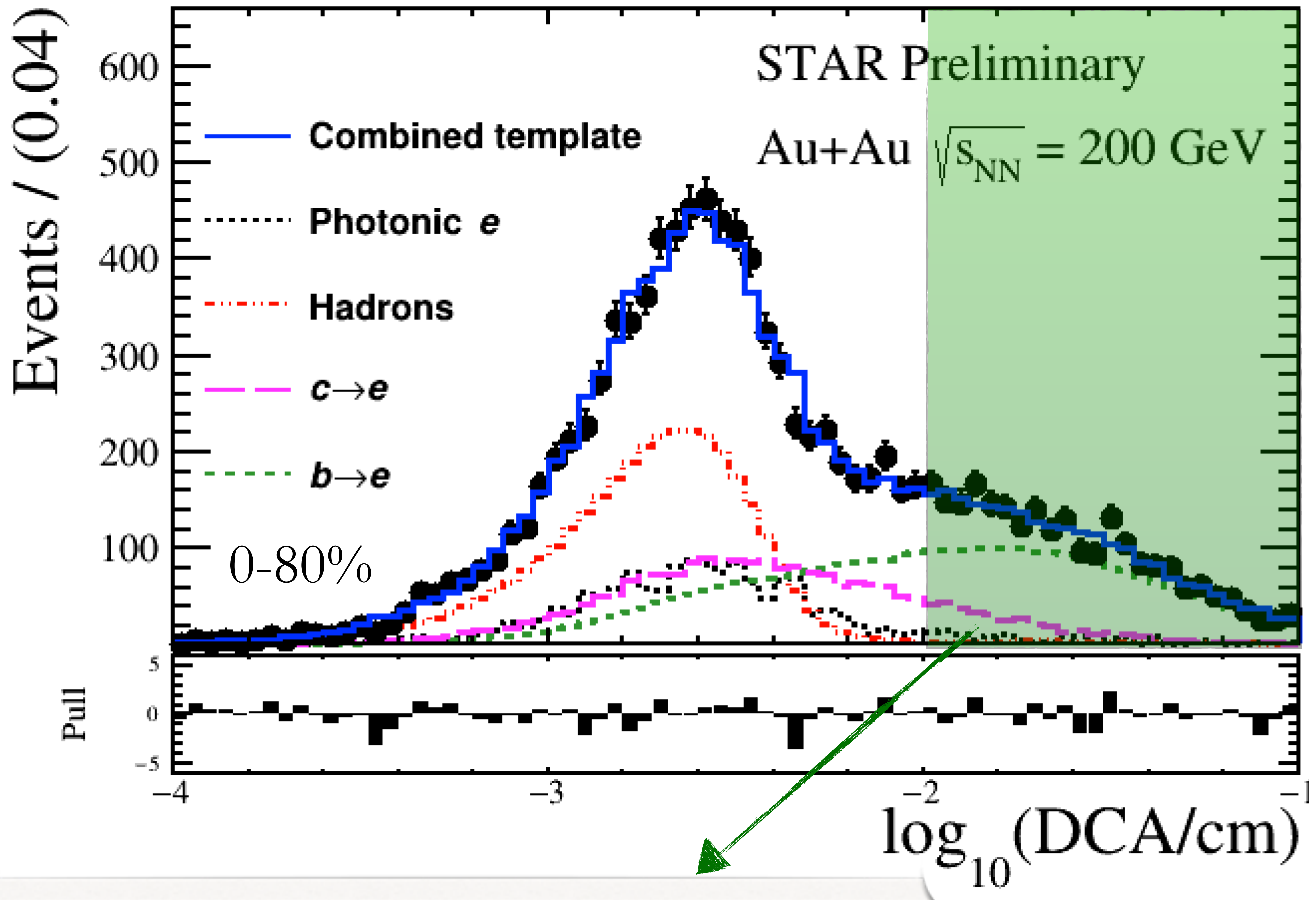
Bottom→e Elliptic Flow



Folded $D^0 \to e$ v_2

$$v_2(obs.) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$

Bottom→e Elliptic Flow



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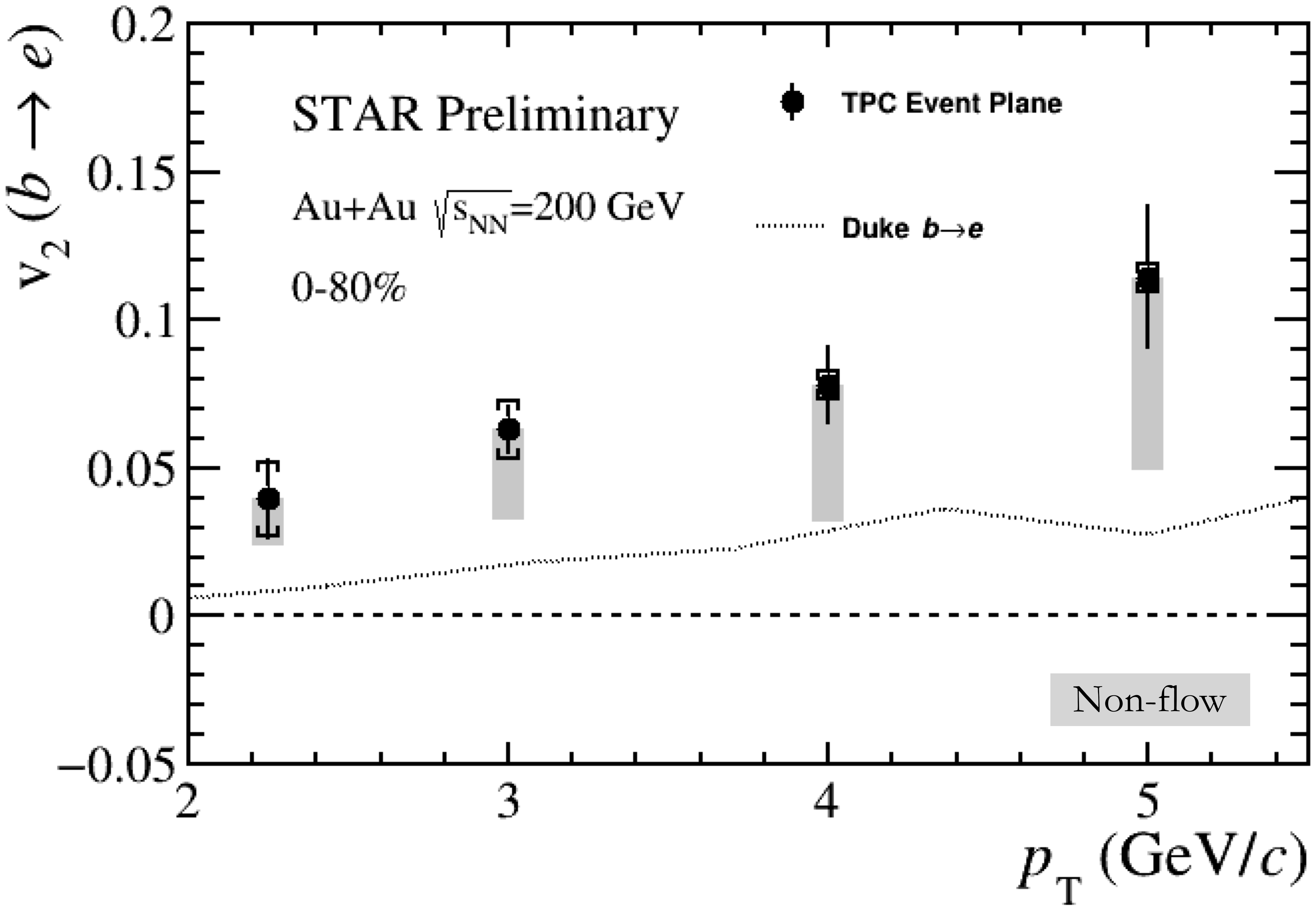
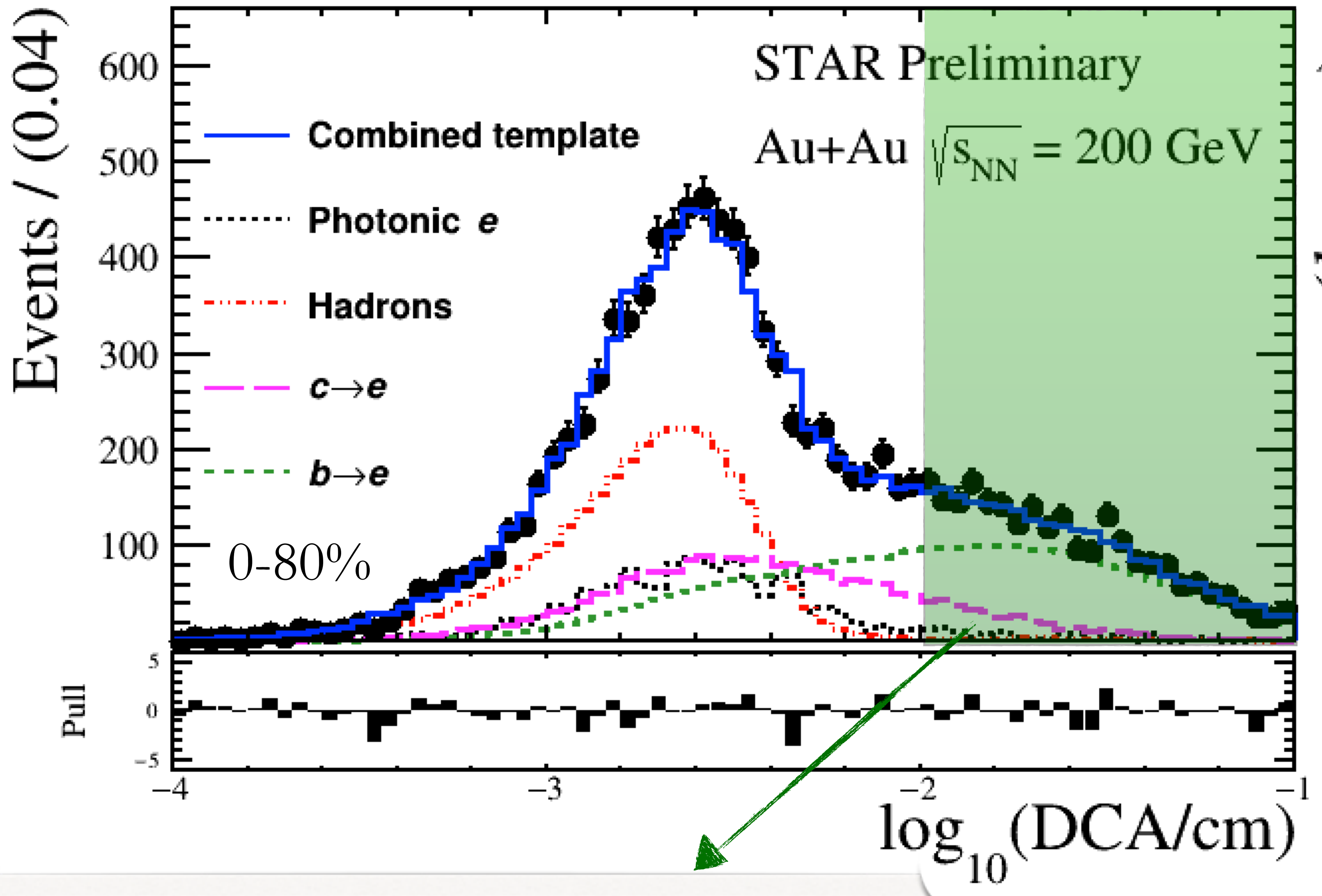


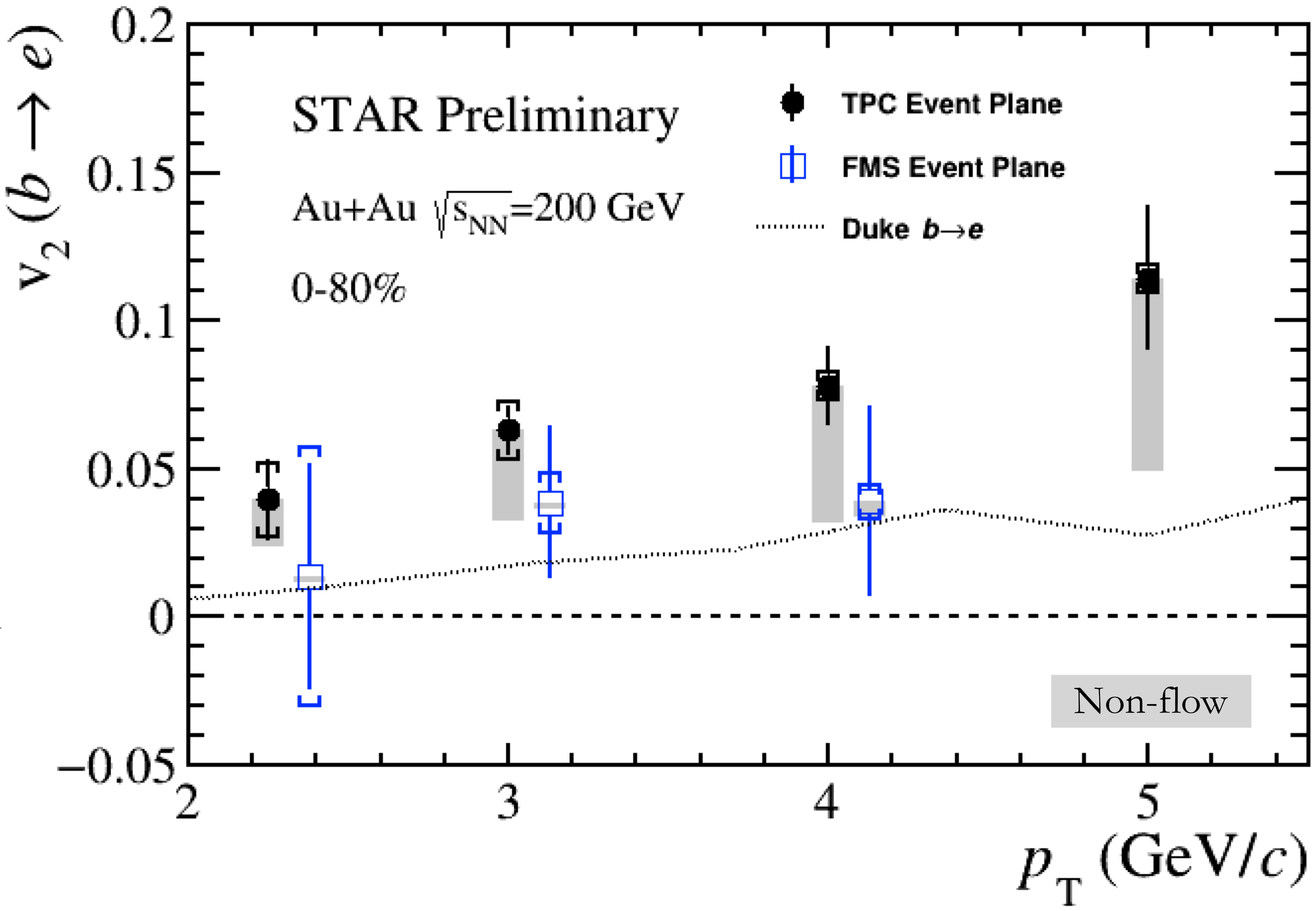
- **Non-flow estimated from two particle correlations (e-h) in PYTHIA**
- **Data qualitatively consistent with Duke model considering non-flow**

DUKE: Phys. Rev. C 92, 024907
Private Communication

Bottom→e Elliptic Flow



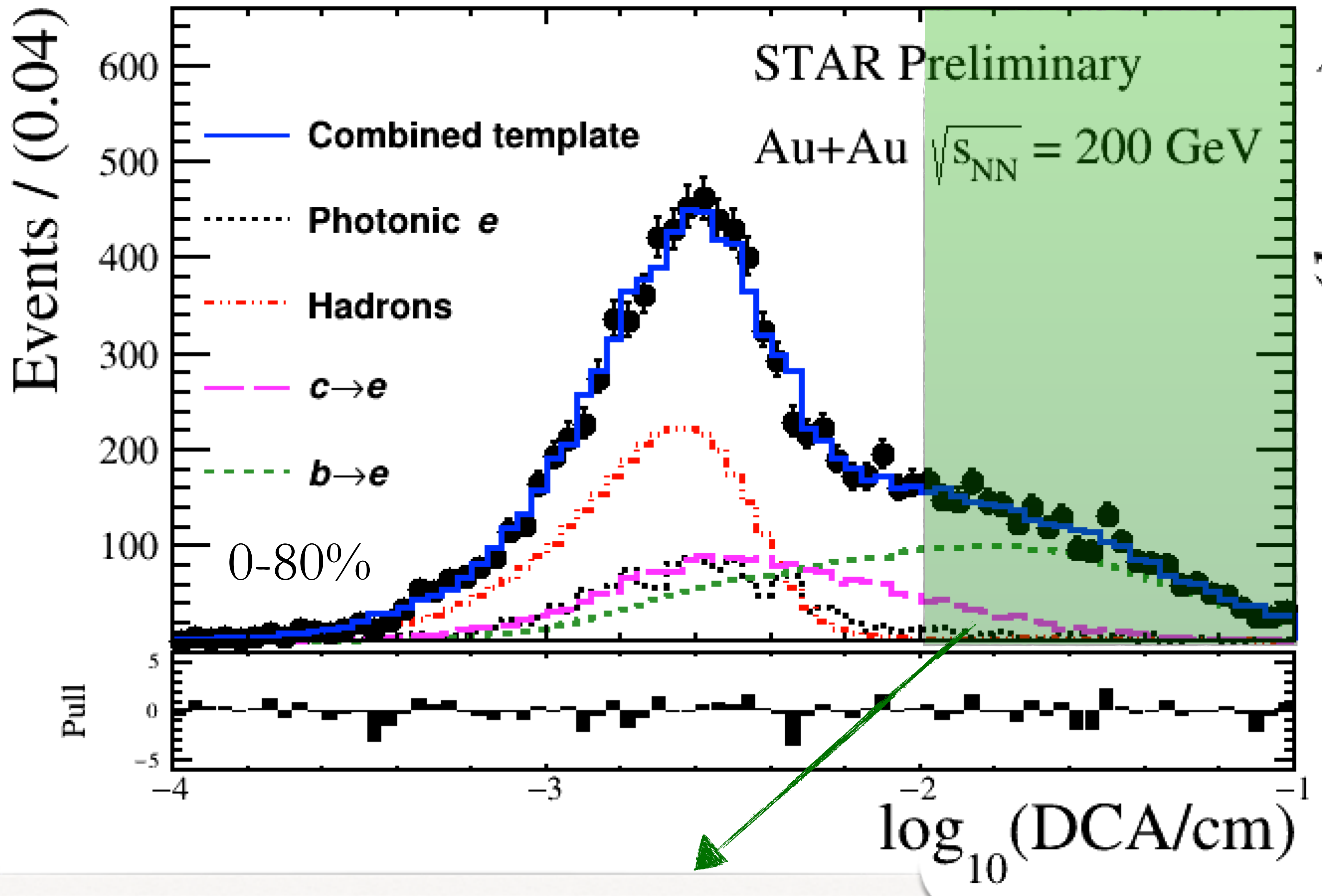
$$v_2(obs.) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$



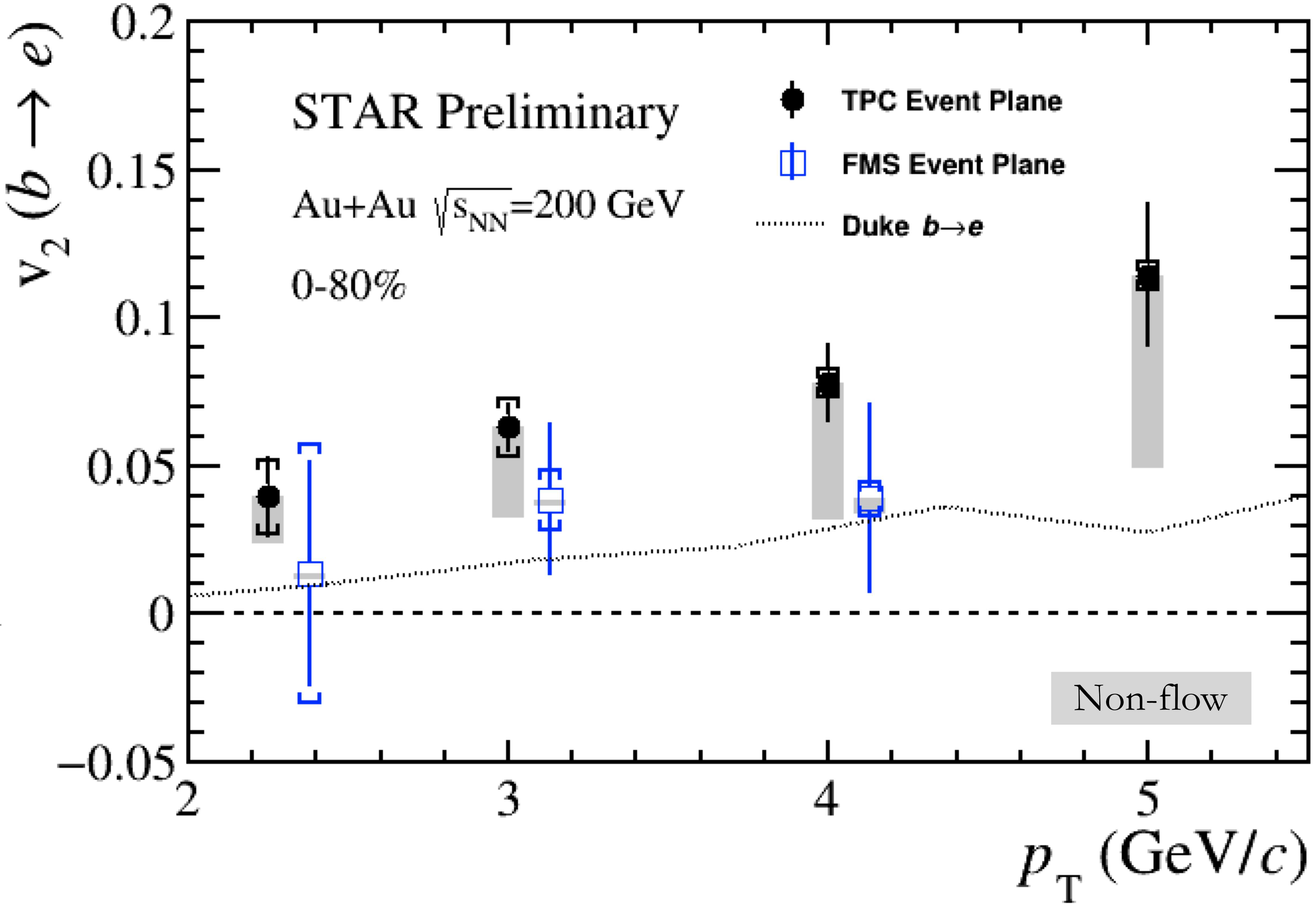
- **Forward Meson Spectrometer (2.5<η<4) as EP detector reducing non-flow to <0.5%**
  - ~1/4 sample size w.r.t. total minimum bias
- **FMS EP data consistent within uncertainties with TPC EP measurement**

DUKE: Phys. Rev. C 92, 024907
Private Communication

Bottom→e Elliptic Flow



$$v_2(obs.) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$

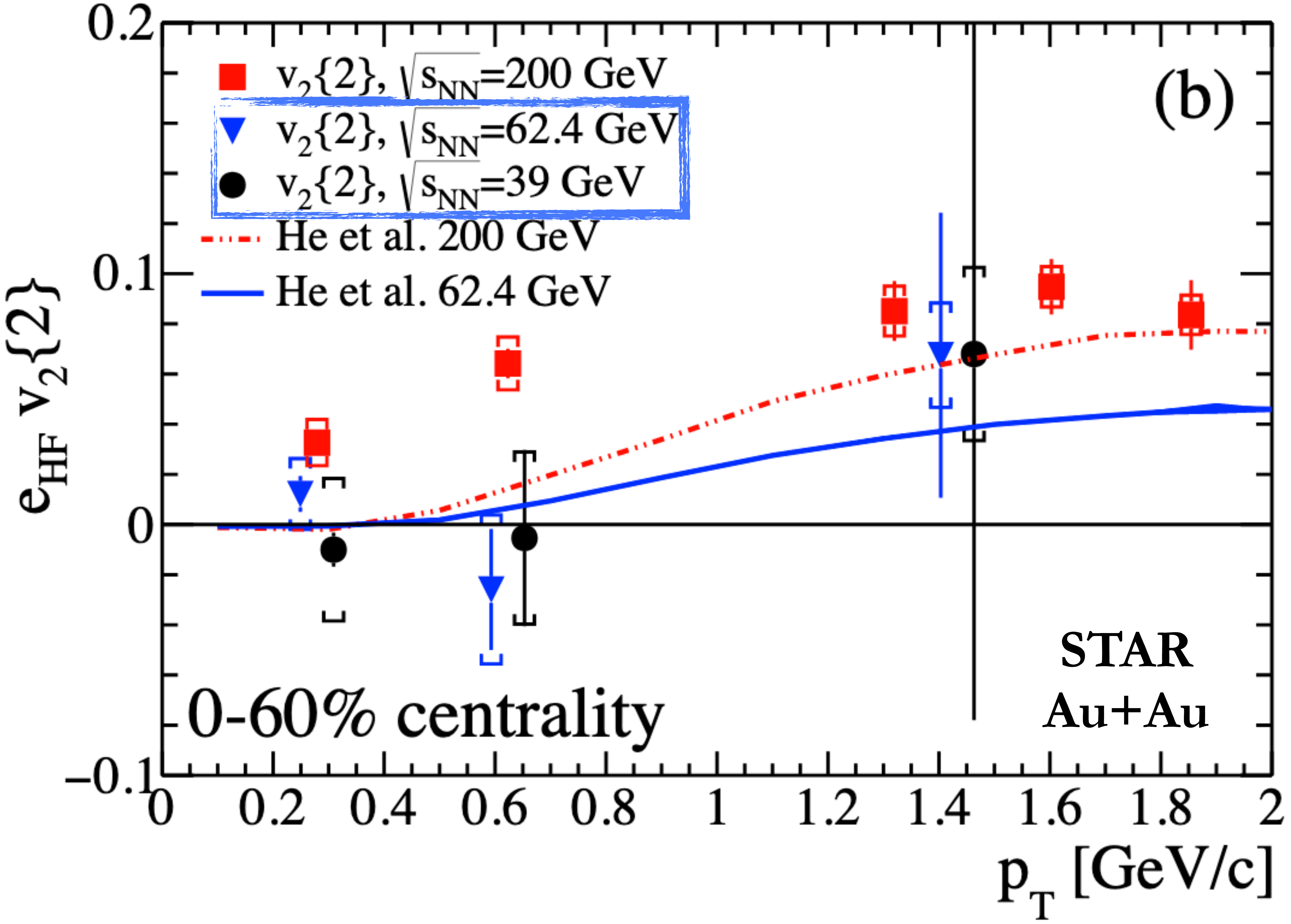


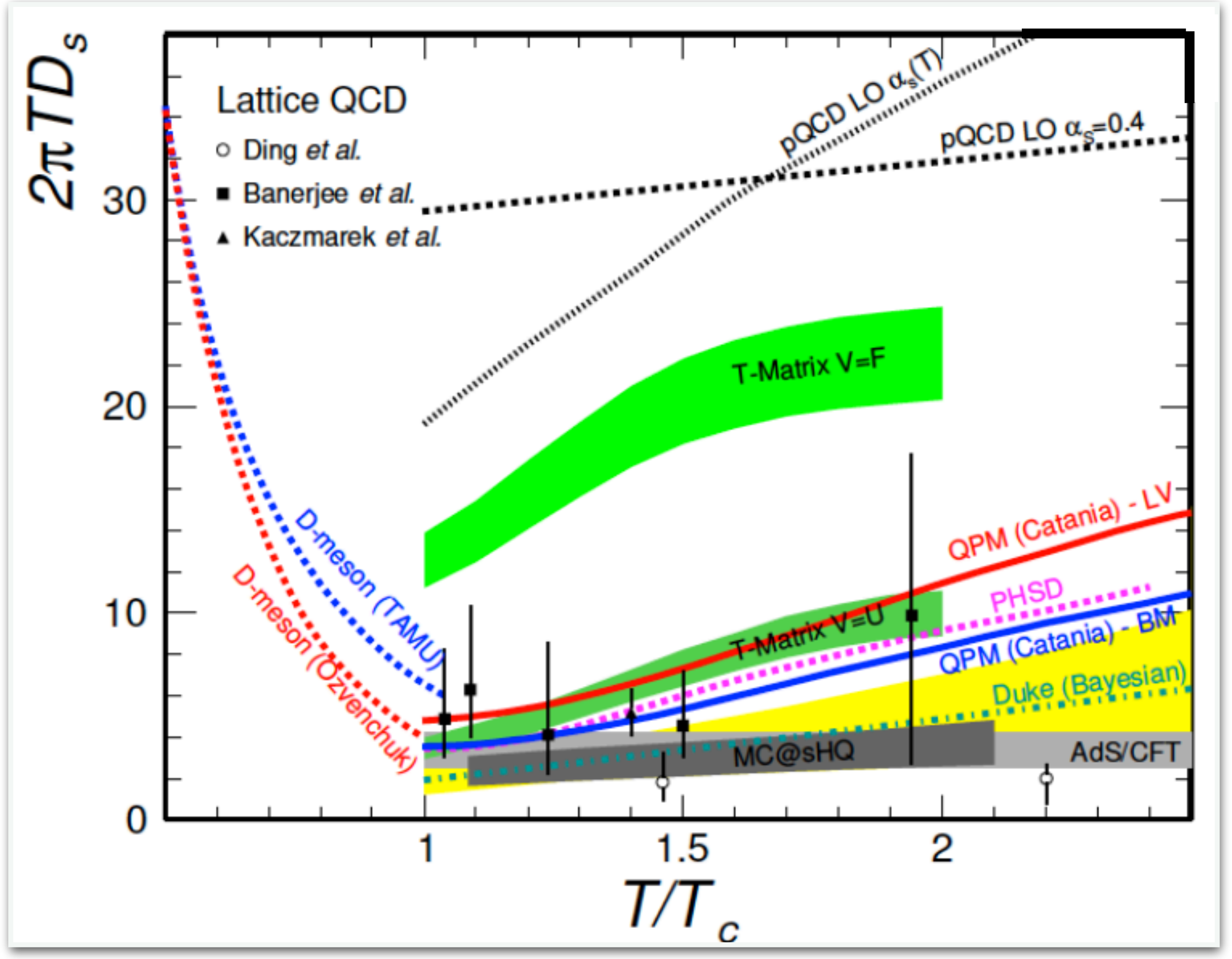
- **TPC EP measurement null hypothesis with full non-flow subtraction:**
  - χ^2/ndof = 17.1/3, p-value = .00067 (**~3.4σ**)

➡**Observation of non-zero bottom electron v_2!**

DUKE: Phys. Rev. C 92, 024907
Private Communication

Energy dependence of HF v_2





- **Probe of temperature dependence of diffusion coefficient**
- **Previous HF v_2 measurements in 62.4 and 39 GeV Au+Au collisions inconclusive with limited statistics**

Dataset at 54.4 GeV allows more precise measurement at lower energy

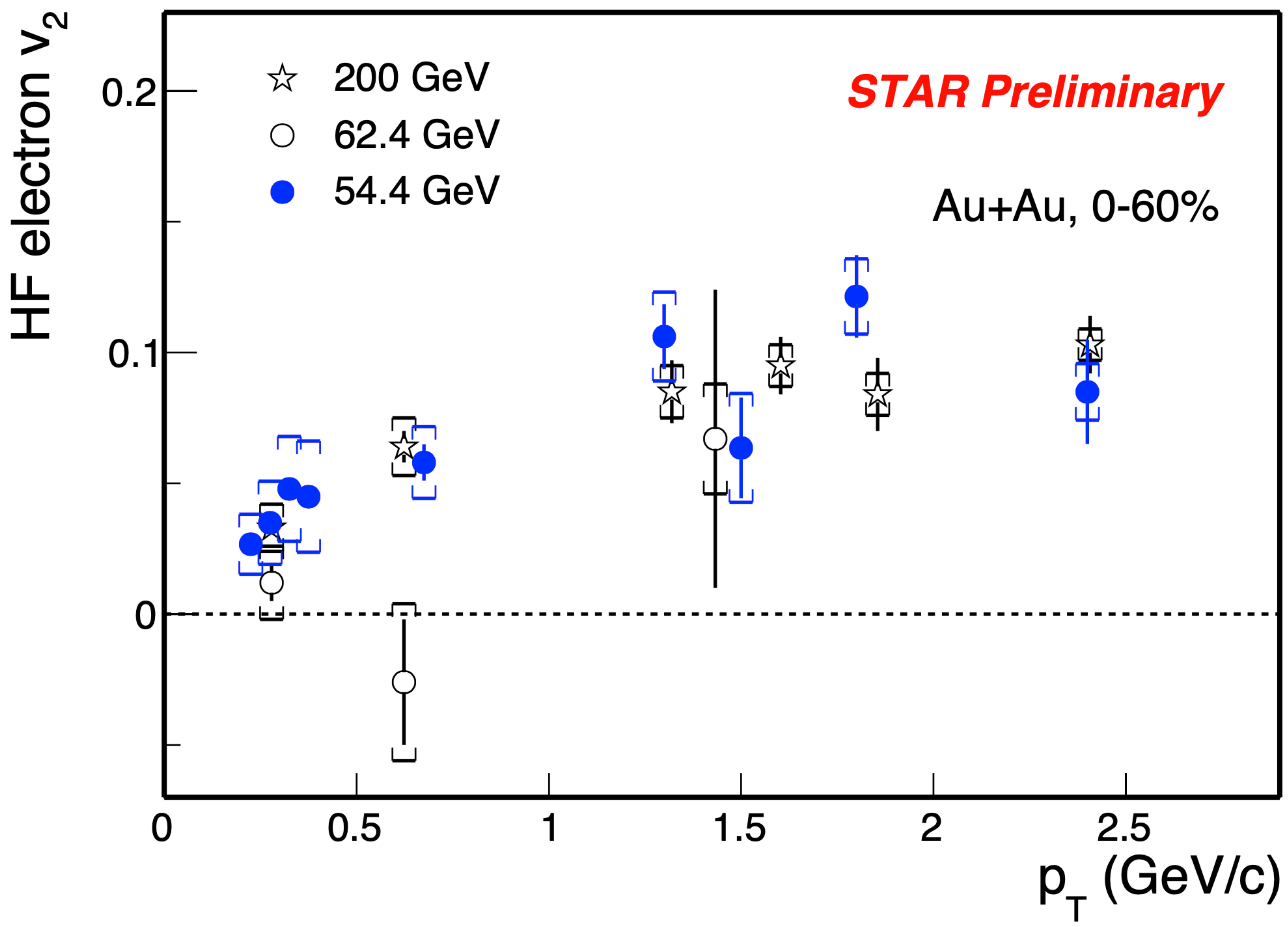
➡15x increase in statistics compared to 62.4 GeV!

NPE v_2: Phys. Rev. C 95, 034907
Ds: j.ppnp.2018.08.001

Inclusive NPE v_2 @ 54.4 GeV

- Significant non-zero values of NPE v_2 in 54.4 GeV Au+Au collisions
- Similar magnitude as NPE v_2 @ 200 GeV

➡HF(c) quarks interact strongly with the medium in 54.4 GeV Au+Au collisions



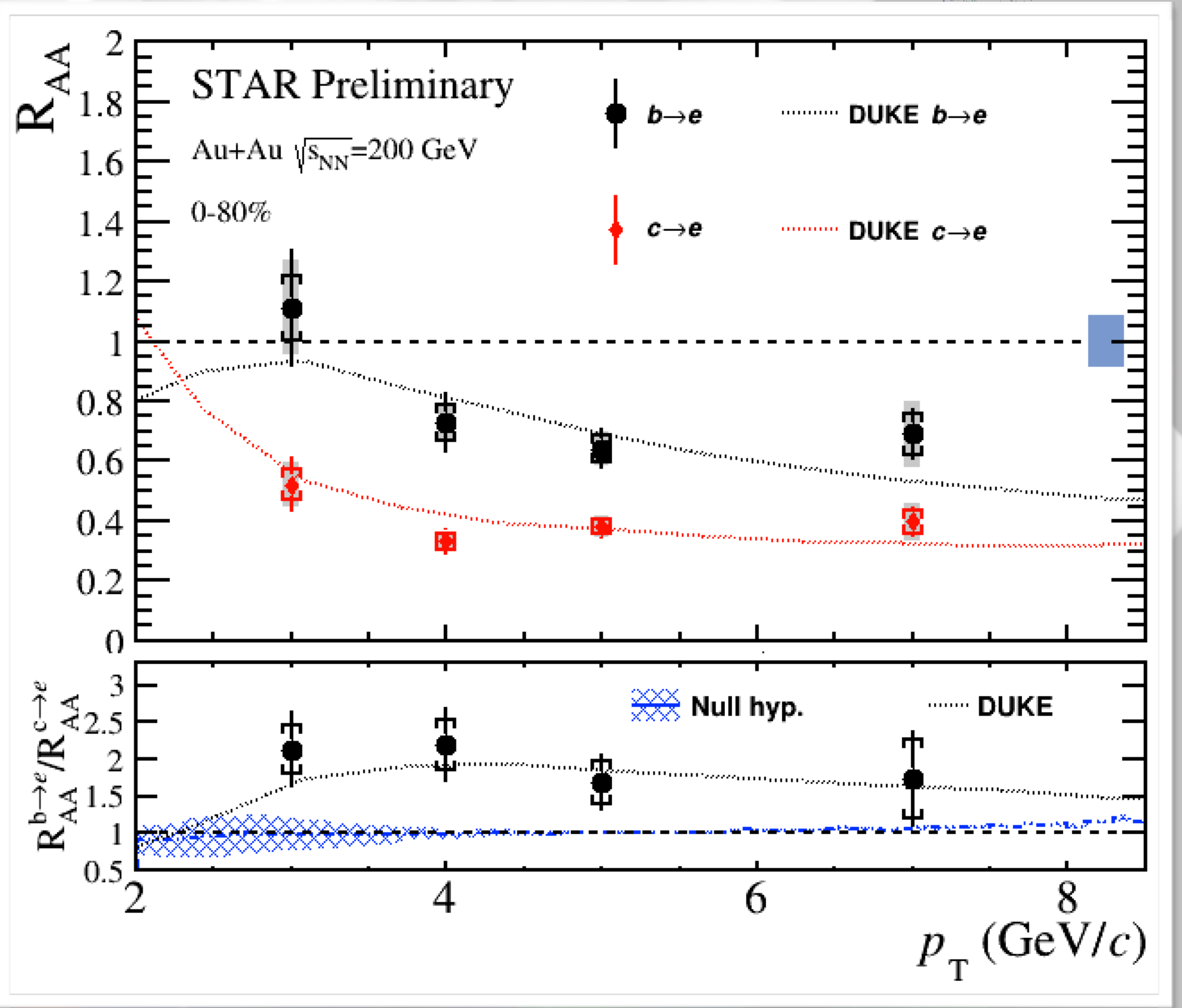
See Yuanjing Ji's poster (HF29) for details!

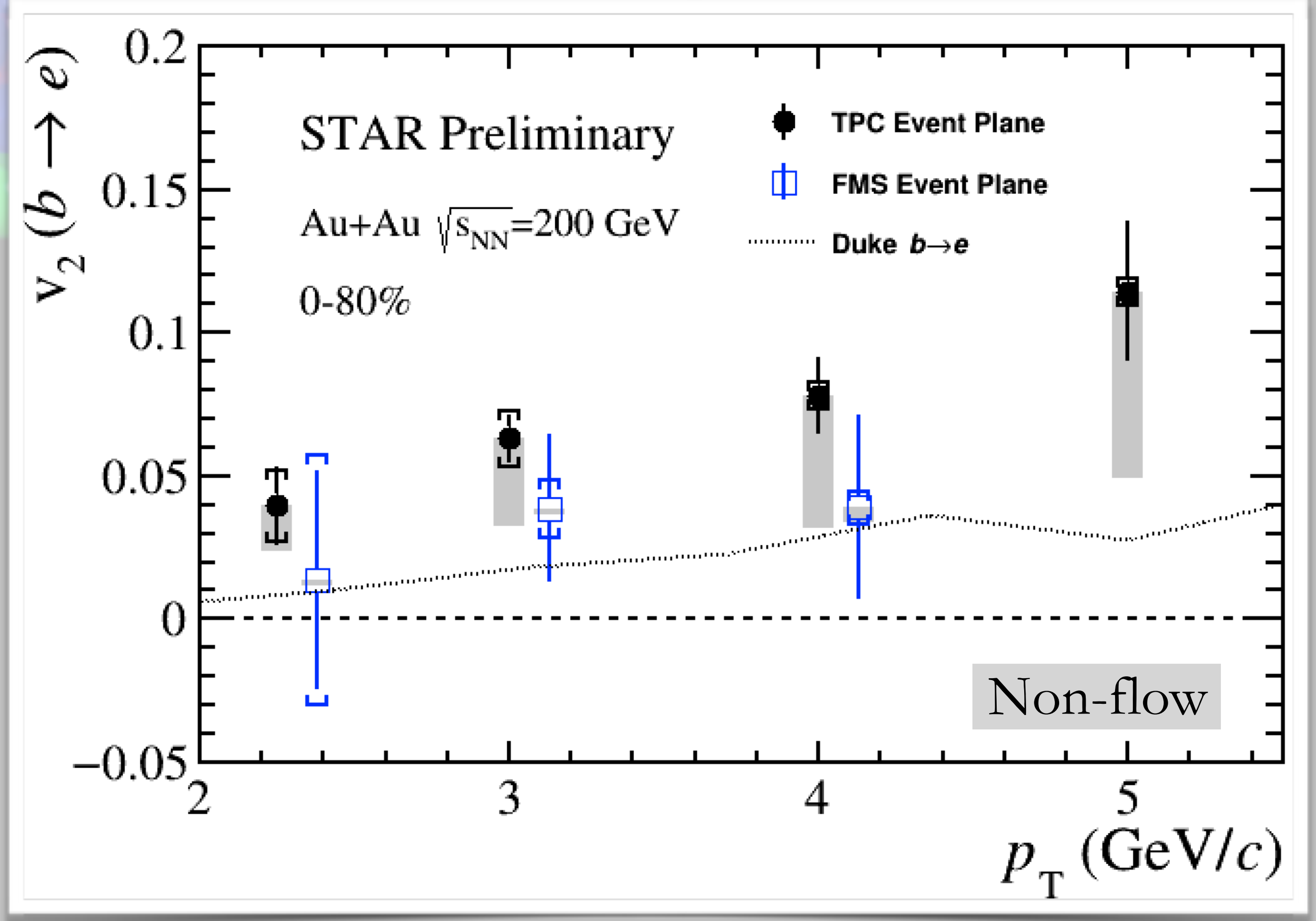
Summary

➡ Measured $b \rightarrow e$ suppression less than $c \rightarrow e$ with $\geq 3\sigma$ significance (consistent with $\Delta E(b) < \Delta E(c)$)!

➡ First observation of non-zero bottom electron v_2 significant at 3.4σ!

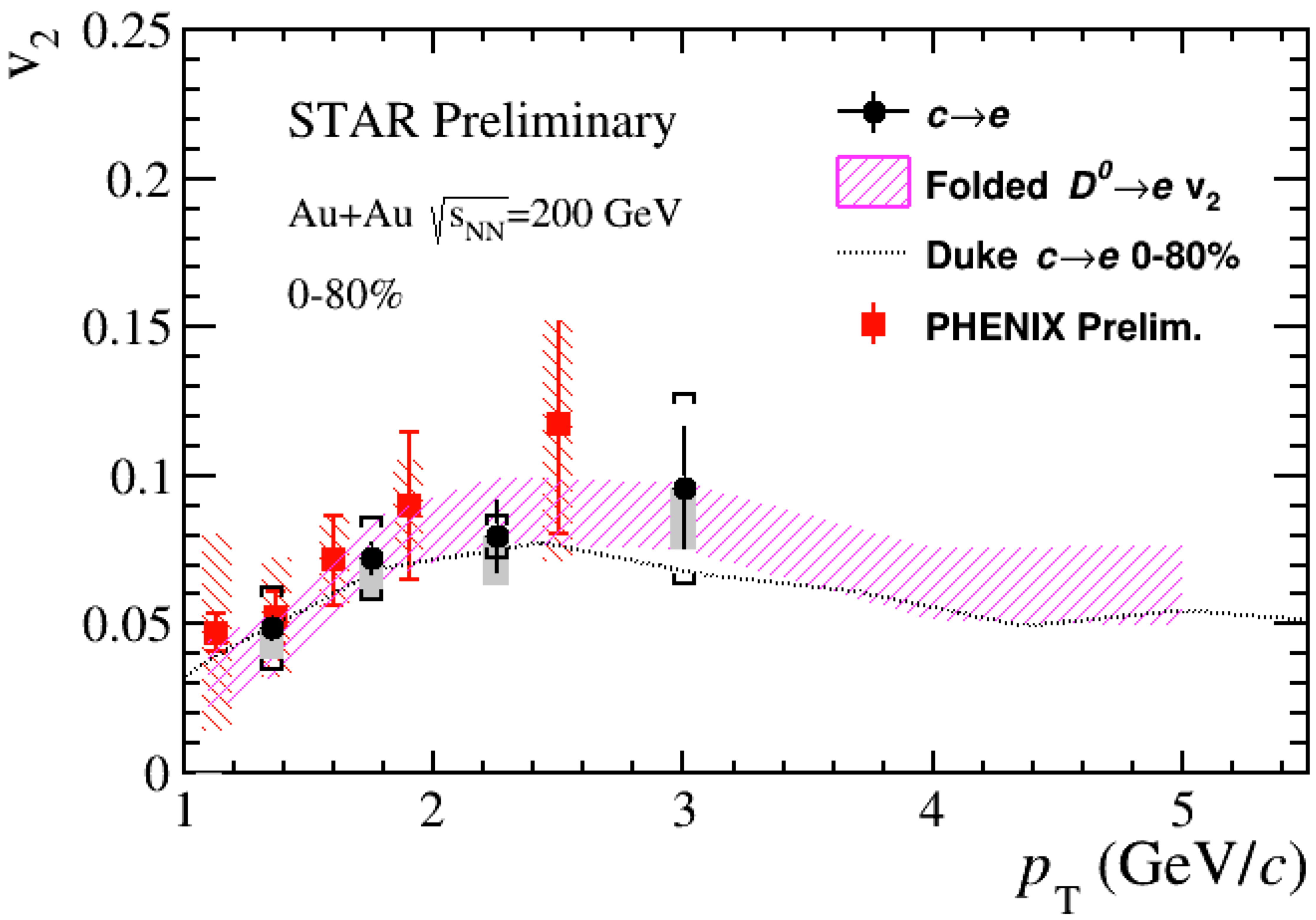
- **Anisotropic flow for charm-decayed electrons**
  - dv_1/dy at ~5σ; consistent with D^0 measurement
  - v_2 consistent with measured D^0 v_2
- **Significant NPE v_2 in Au+Au collisions @ $\sqrt{s_{NN}}$ = 54.4 GeV**
  - Consistent with NPE v_2 @ $\sqrt{s_{NN}}$ = 200 GeV

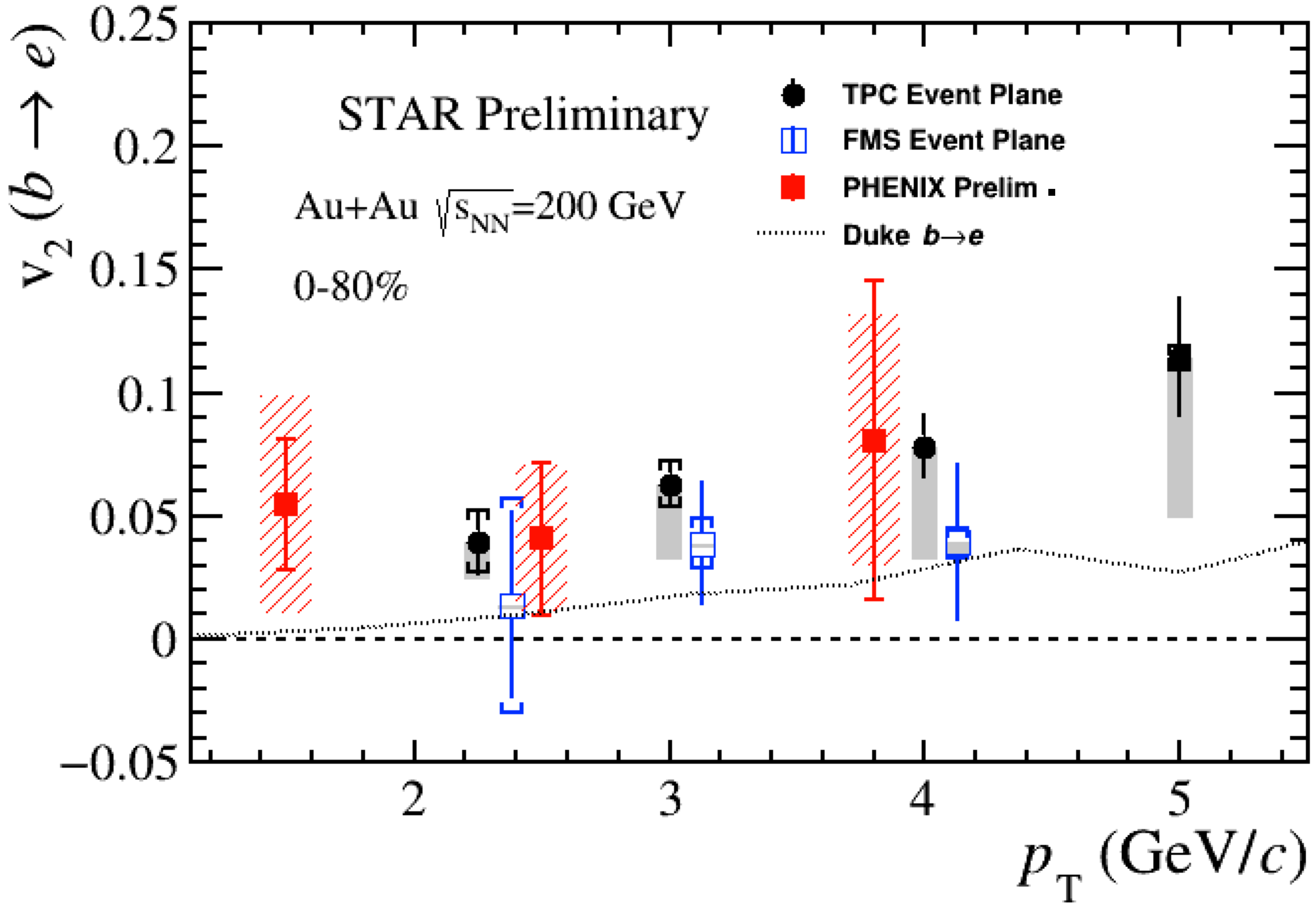




Backup slides follow

Comparisons to PHENIX



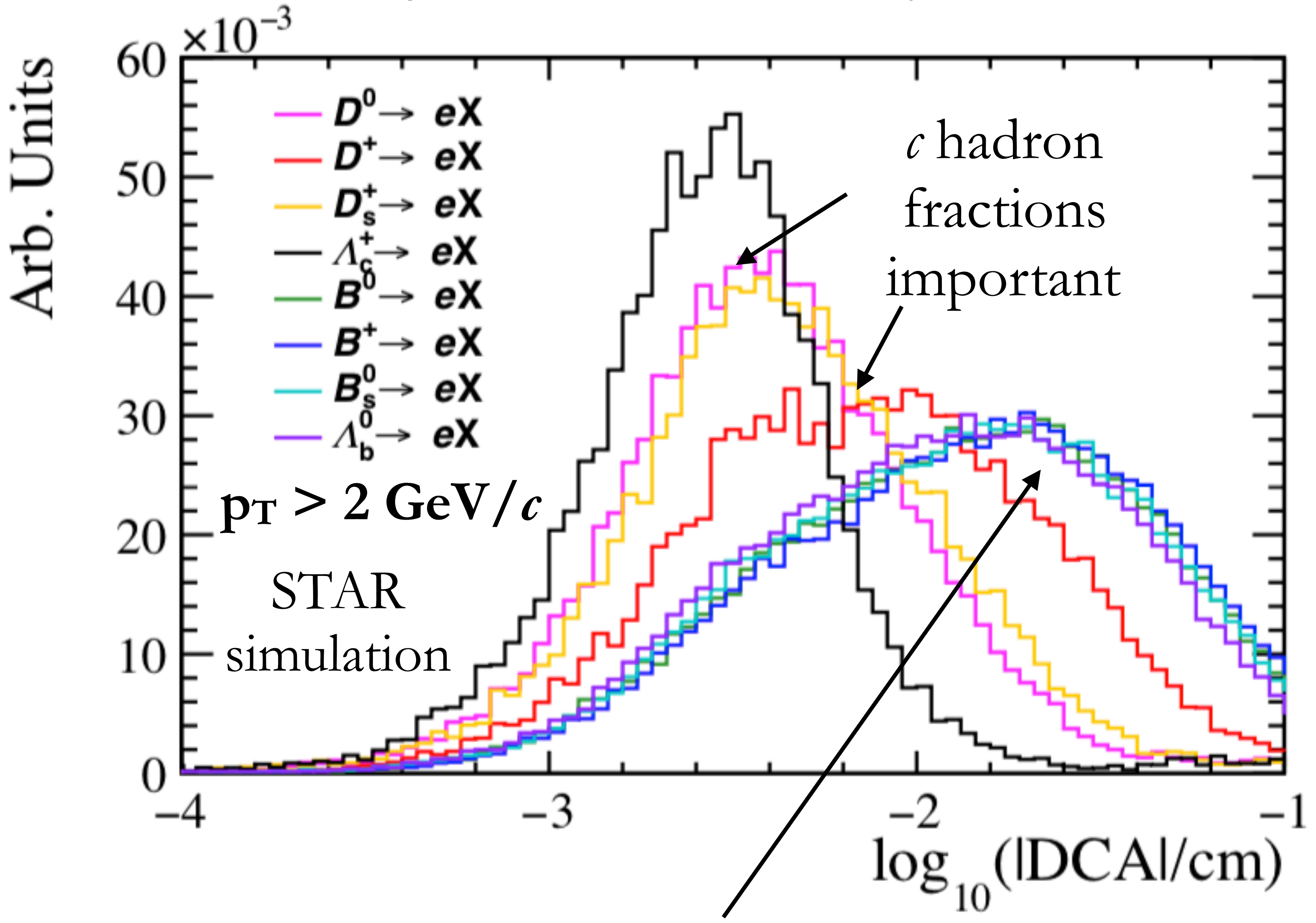


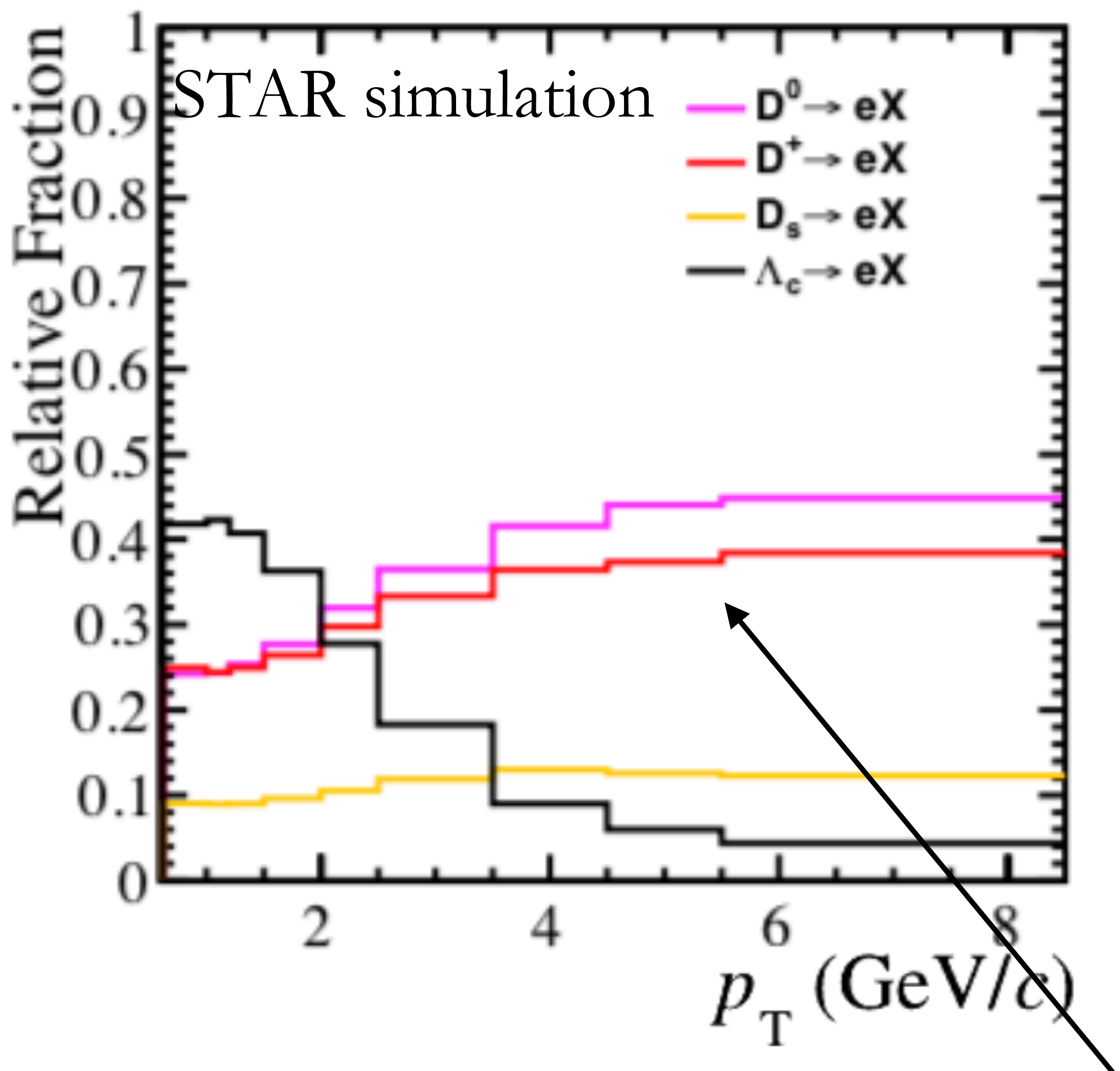
- **Preliminary PHENIX *b,c→e* from Hard Probes 2018**
- **Excellent consistency between experiments within uncertainties**

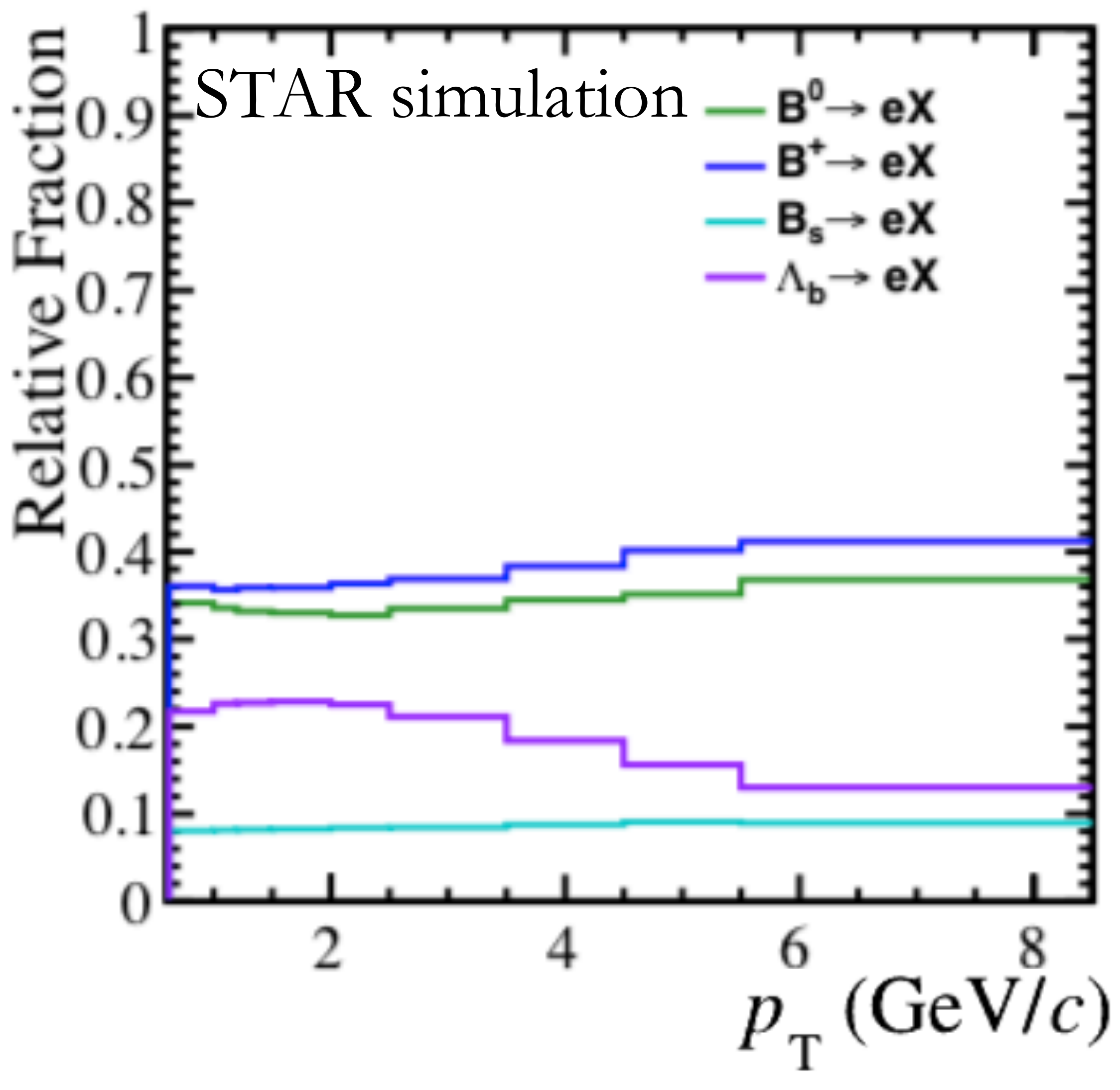
PHENIX: K. Nagashima Hard Probes 2018
DUKE: Phys. Rev. C 92, 024907
Private Communication

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





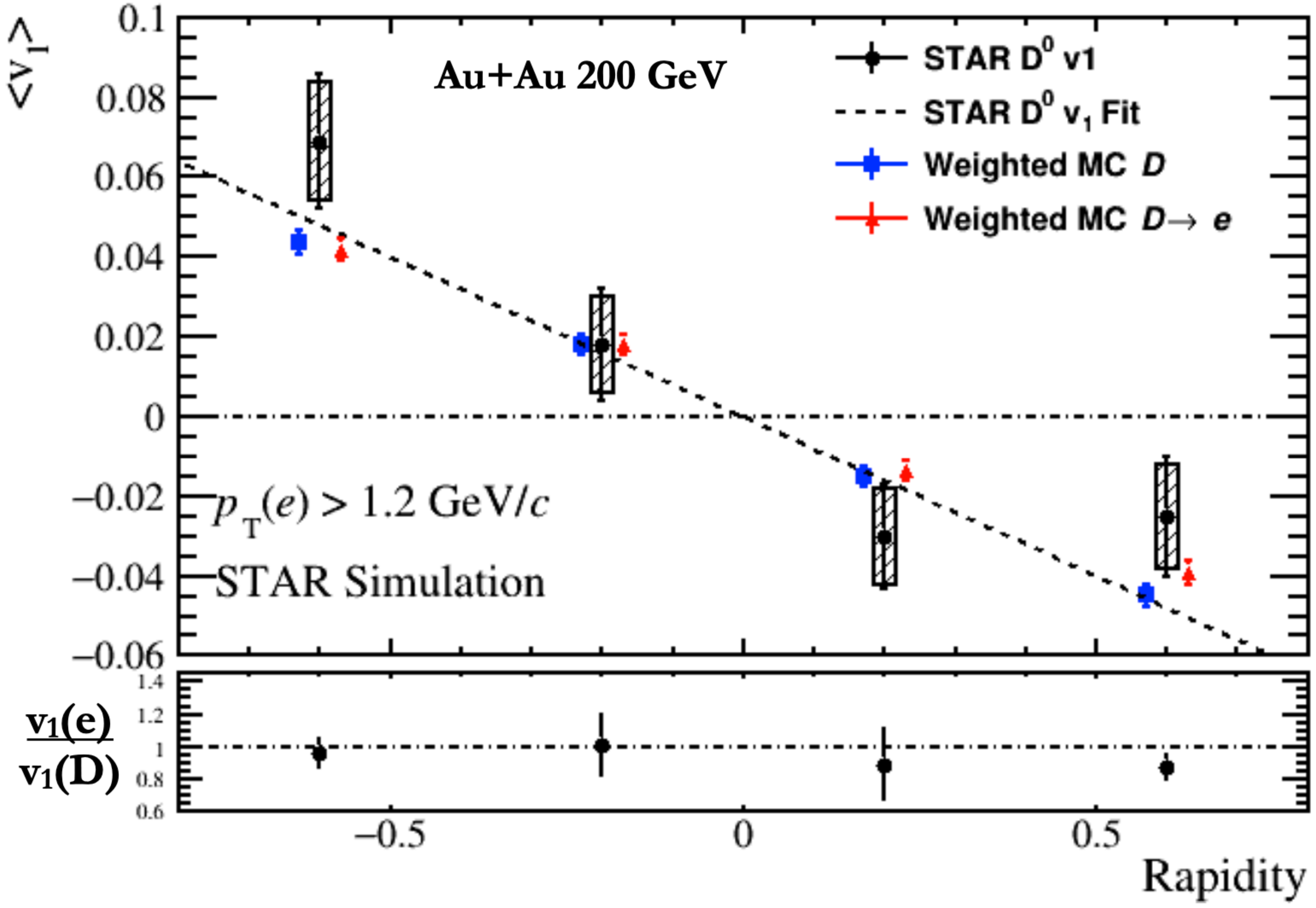


Less sensitive to *b* hadron fractions

Large uncertainty coming from D^+/D^0 ratio

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

Charm→e Directed Flow Simulation

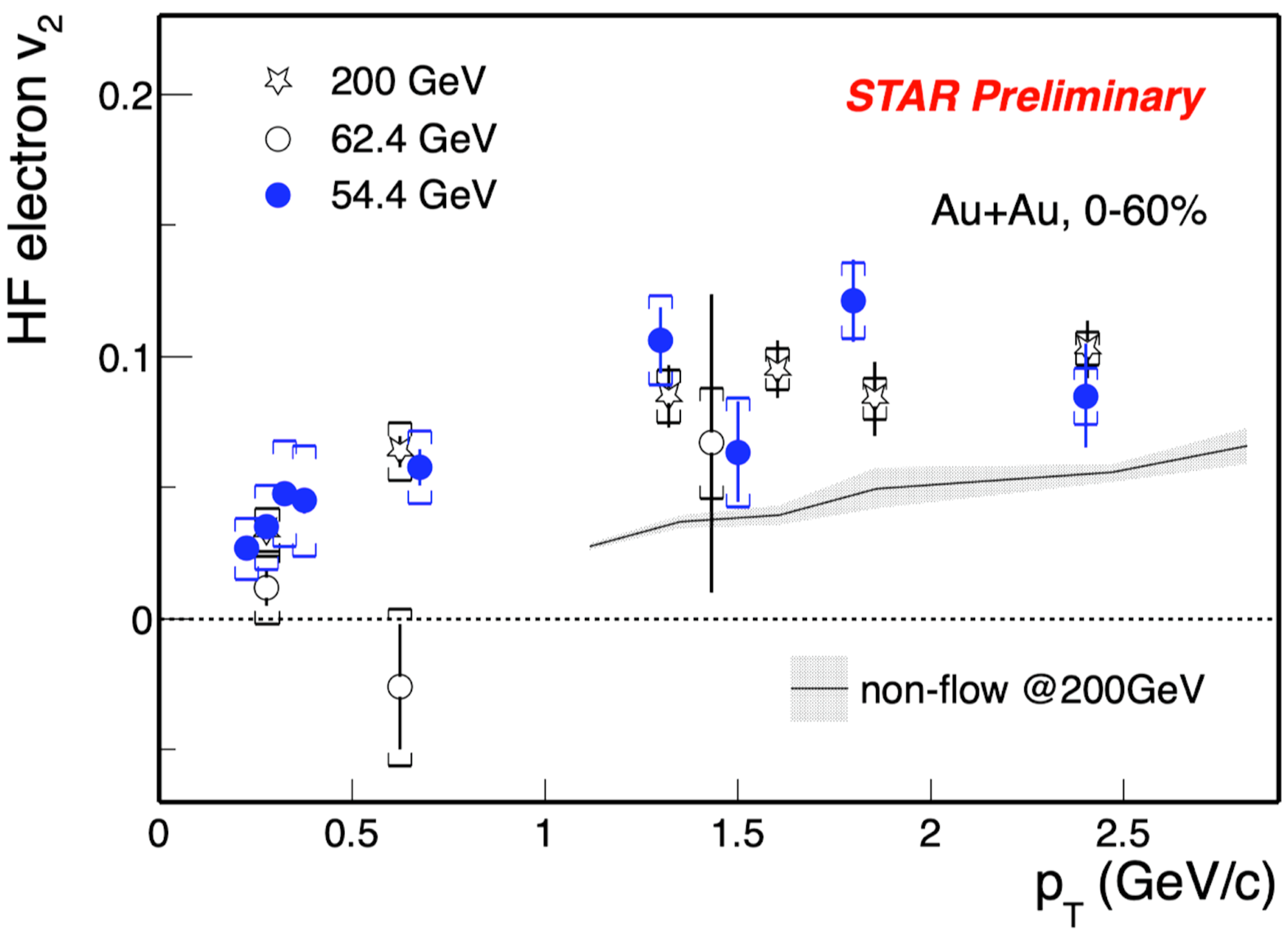


- **Measured D^0 v_1 fit folded into $D \rightarrow e$ simulation**
- **Electrons with $p_T > 1.2$ GeV/c show little loss of parent hadron v_1 due to decay**

Inclusive NPE v_2 @ 54.4 GeV

- **Significant non-zero values of NPE v_2 in 54.4 GeV Au+Au collisions**
- **Similar magnitude as NPE v_2 @ 200 GeV**

➡HF(*c*) quarks interact strongly with the medium in 54.4 GeV Au+Au collisions



See Yuanjing Ji's poster (HF29) for details!

Non-flow estimated using electron-hadron correlations in 200 GeV pp data