Measurements of electron production from heavy flavor decays in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR

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Heavy Quarks: unique probes of the QGP

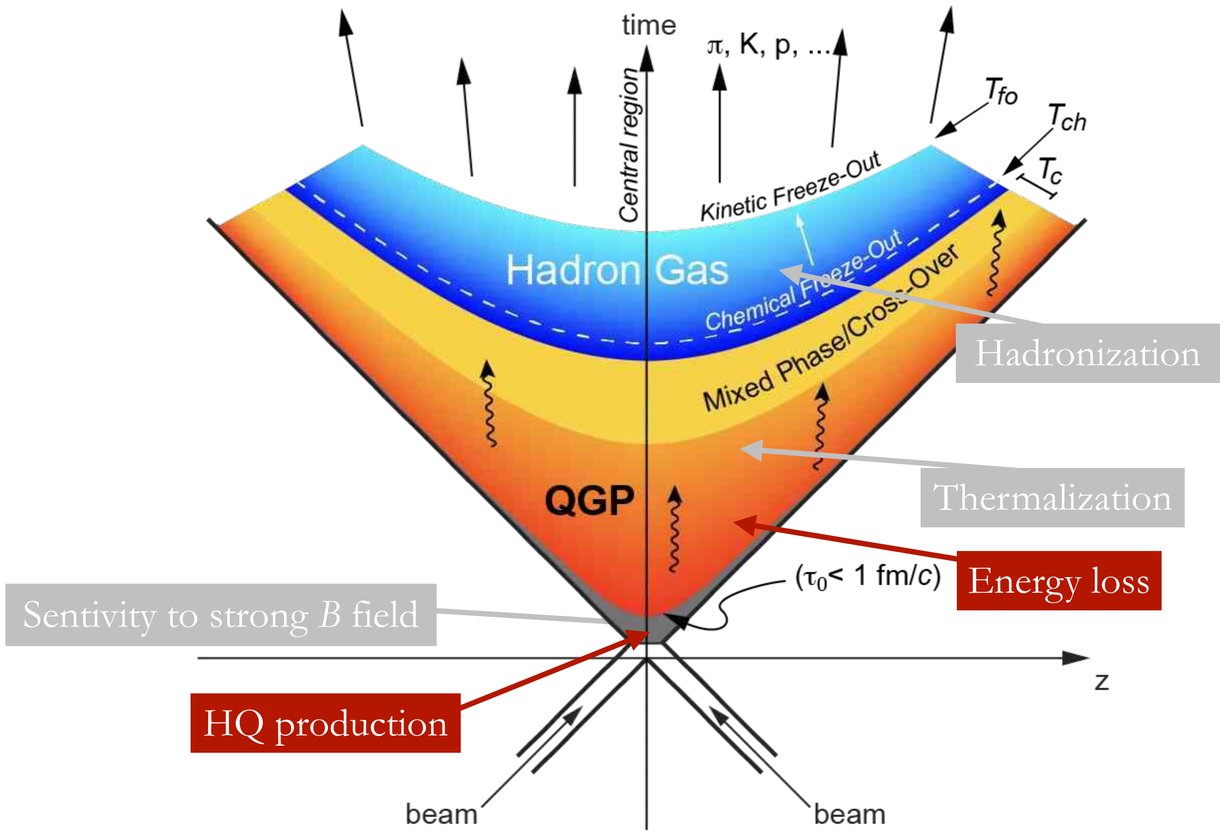
- Heavy flavours (*c* and *b*) are mainly produced in initial hard-scattering processes because of their large masses
- Undergo elastic (collisional) and inelastic (radiational) energy losses → sensitive to transport properties of QGP

➡Energy loss mechanisms: expected to loss less energy in QGP compared to light quarks

- Mass effects: $M_{u,d,s} < M_c < M_b \rightleftarrows \Delta E_b < \Delta E_c < \Delta E_{u,d,s}$

➡pp collisions:

- Test pQCD calculations
- Reference for measurements in heavy-ion collisions



Non-Photonic Electrons (NPE)

- Produced from semi-leptonic decays of open heavy flavor hadrons
- A good proxy to measure heavy flavor quark production

$m_Q >> \Lambda_{QCD}$
$m_Q >> T_{QGP}$
m_c~1.2-1.5 GeV/c^2
m_b~4.5 GeV/c^2

Outline

$\sqrt{s}$ = 200 GeV p+p collisions

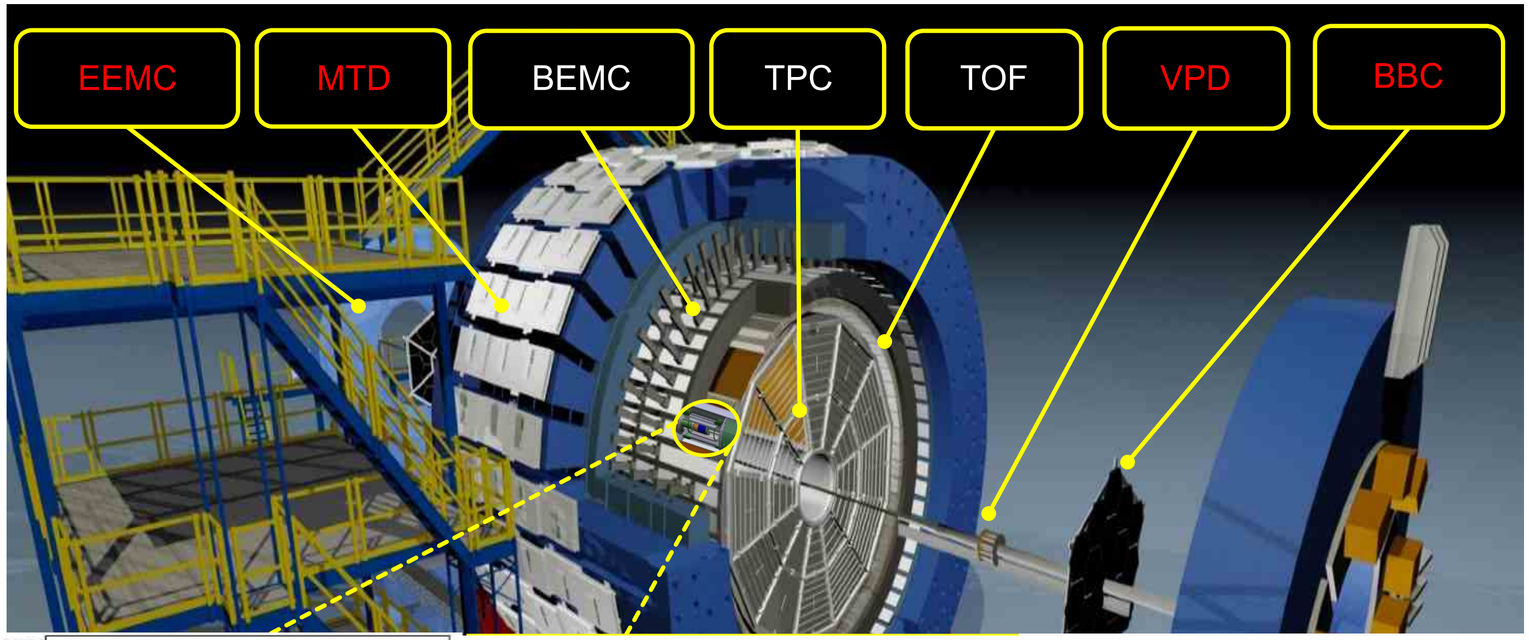
- Bottom- and charm-decayed electron fractions

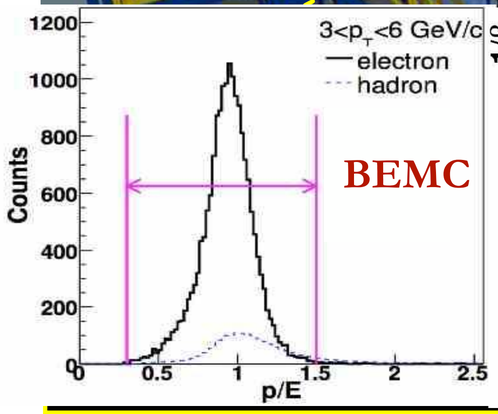
$\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions

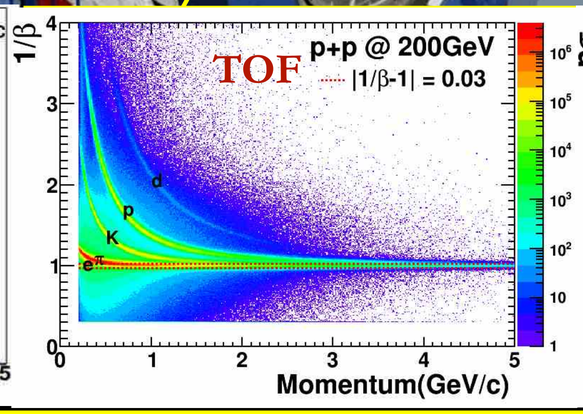
- Nuclear modification factors of charm- and bottom-decayed electrons

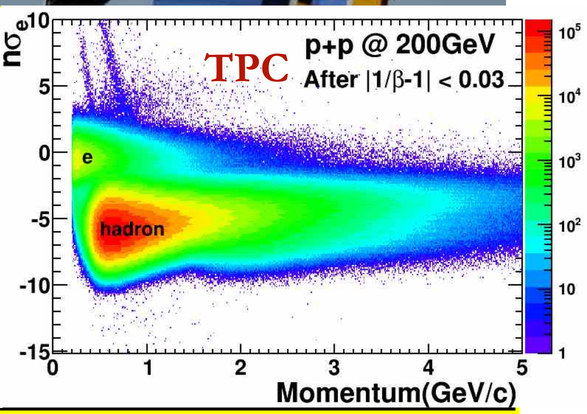
Electron measurements at STAR

•Electron identification with TPC, TOF, BEMC and HFT (in Au+Au analysis)









Barrel ElectroMagnetic Calorimeter (BEMC)
- Trigger on high p_T electrons
- PID through p/E

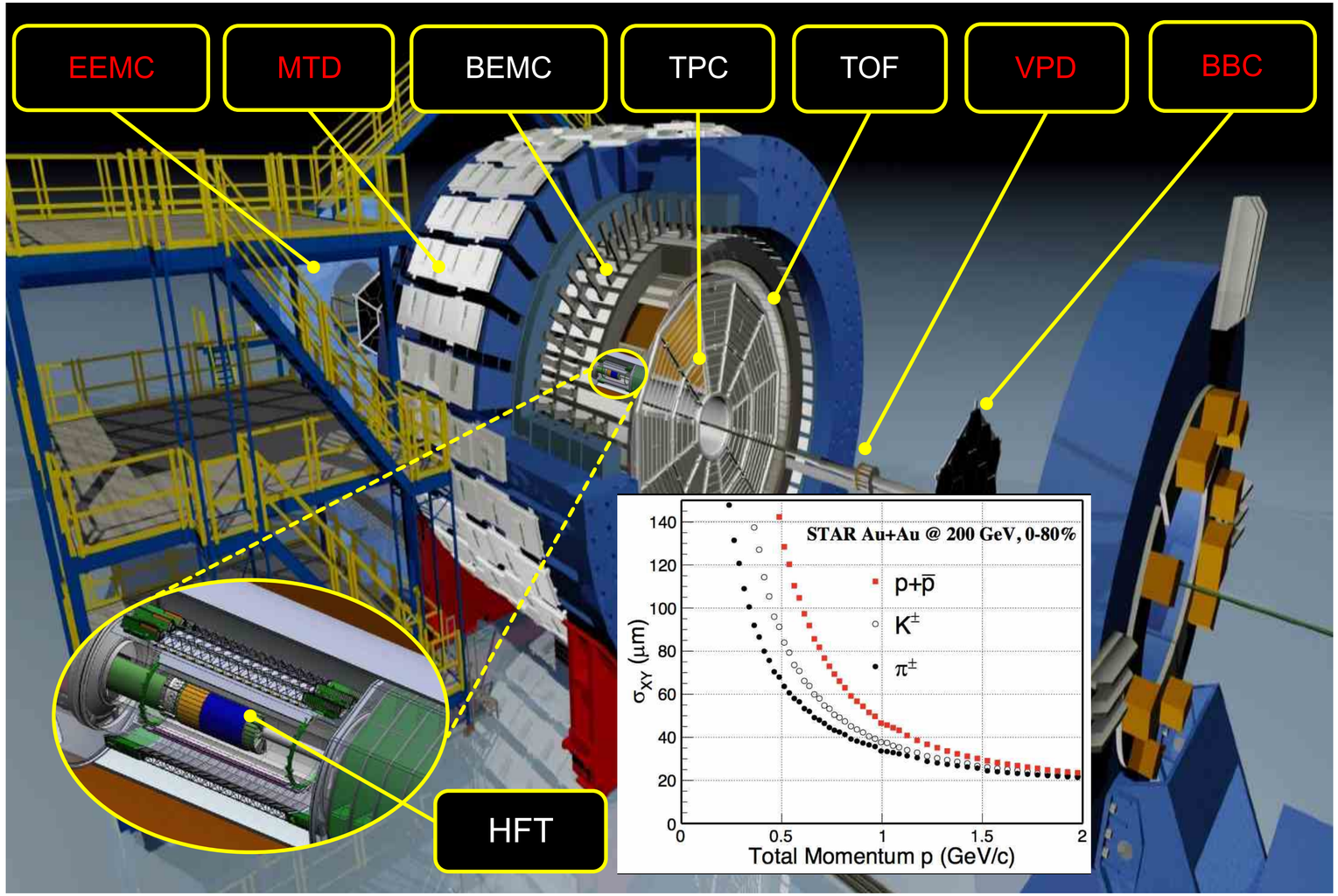
Time Of Flight (TOF)
- PID through velocity ($1/\beta$)
- Timing resolution: ~85 ps

Time Projection Chamber (TPC)
- Tracking, momentum measurement
- PID through dE/dx

$$n\sigma_e = \frac{ln(dE/dx_{measured}) - ln(dE/dx_{exp})}{R}$$

Electron measurements at STAR

•Electron identification with TPC, TOF, BEMC and HFT (in Au+Au analysis)



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Time Projection Chamber (TPC)
- Tracking, momentum measurement
- PID through dE/dx

Heavy Flavor Tracker (HFT)
- Excellent DCA resolution in both $r\varphi$ and z directions: ~30 μm at p = 1.5 GeV/c
- Allows to separate c- and b-decayed electrons

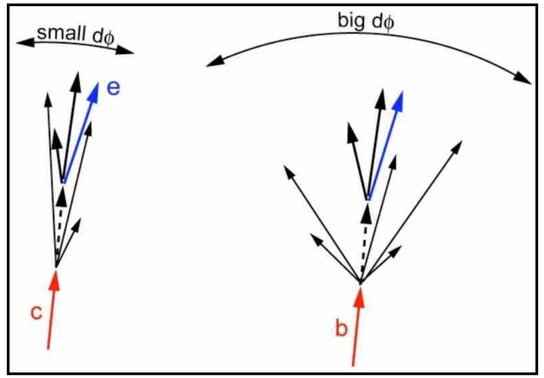
Analysis Methods

- Electron identification with TPC, TOF, BEMC and HFT (in Au+Au analysis)

- Subtract background sources of electrons
  - Photonic electrons from γ- conversions, light pseudo-scalar meson Dalitz decay (e.g. $\pi^0 \rightarrow \gamma e^+ e^-$)
  - Hadron contamination

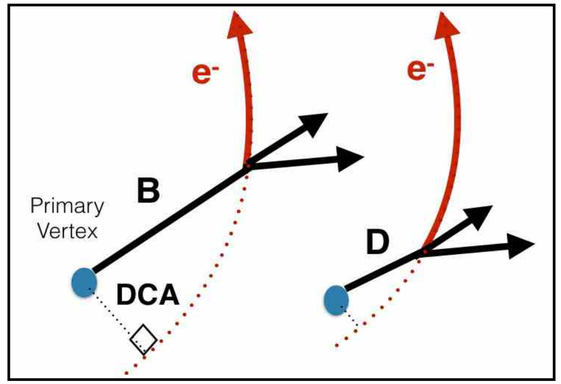
p+p analysis

- Substract non-heavy flavor background (hadrons + photonic electrons)
- Fit azimuthal correlations of electrons with charged particles to separate charm and bottom electrons



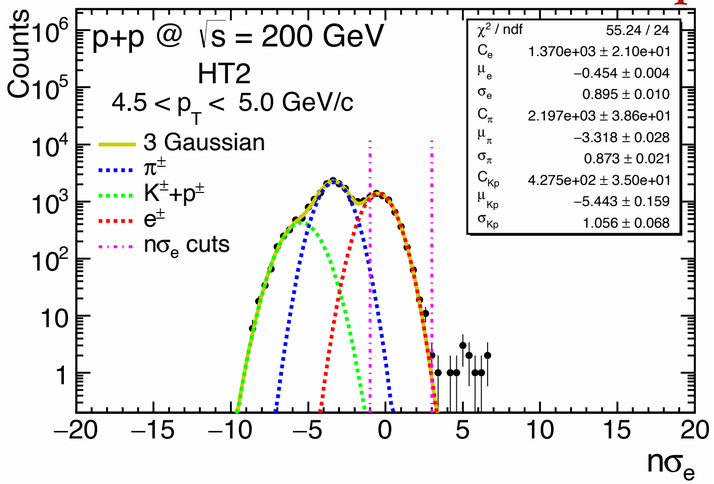
Au+Au analysis

- Fit Distance of Closest Approach (DCA) distribution with four DCA templates to separate charm, bottom, hadrons and photonic electrons



Analysis Method (p+p): Remove hadrons + photonic electrons

Fit dE/dx distribution to extract purity



$$\Delta\phi_{\mathrm{NPE-h}} = \Delta\phi_{\mathrm{Inclusive-h}} - \Delta\phi_{\mathrm{photonic-h}} - \Delta\phi_{\mathrm{hadron-h}}$$

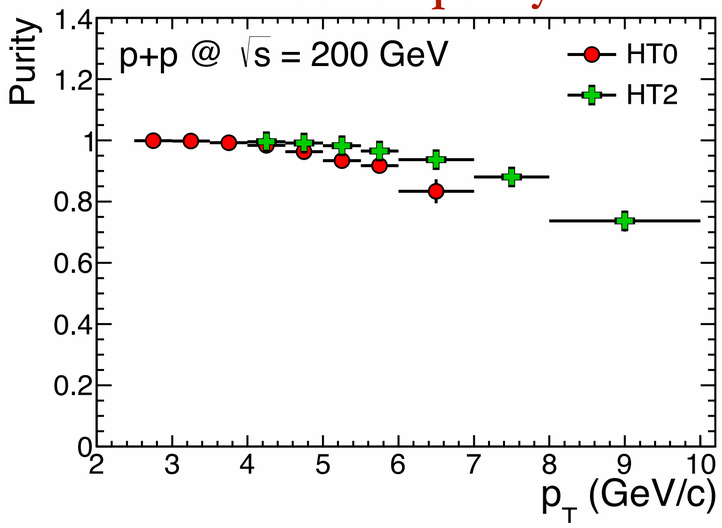
$$\Delta\phi_{\mathrm{NPE-h}} = \Delta\phi_{\mathrm{Semi\_Inc-h}} + \Delta\phi_{\mathrm{LikeSign-h}} - (1/\varepsilon_{\gamma} - 1) * \Delta\phi_{\mathrm{reco-photonic-h}} - (1 - \varepsilon_{\mathrm{purity}}) * \Delta\phi_{\mathrm{hadron-h}} * \frac{N_{inclusive}}{N_{hadron}}$$

Semi-inclusive electron: all non-paired trigger electrons after PID

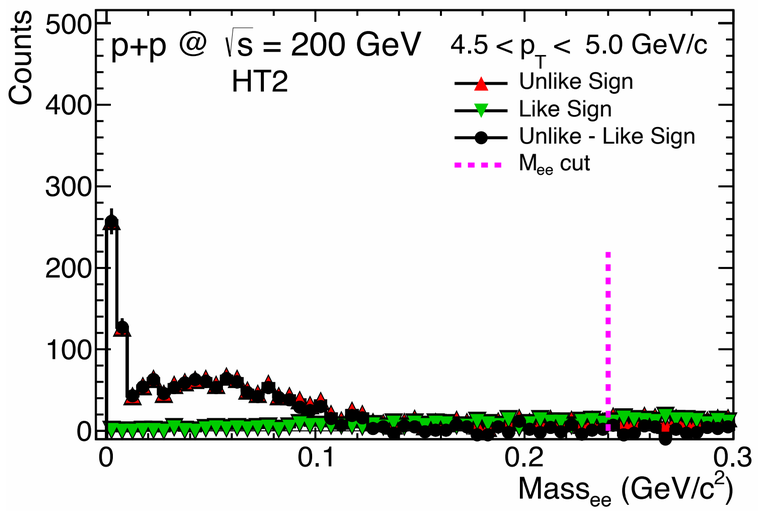
$\varepsilon_{\mathrm{purity}}$: purity of inclusive electron sample

ε_{γ}: photonic electron reco. efficiency

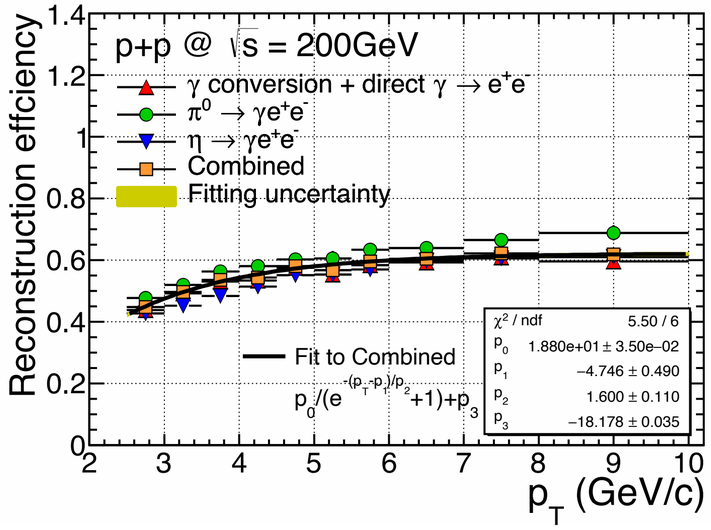
Electron purity



Photonic electron reconstruction

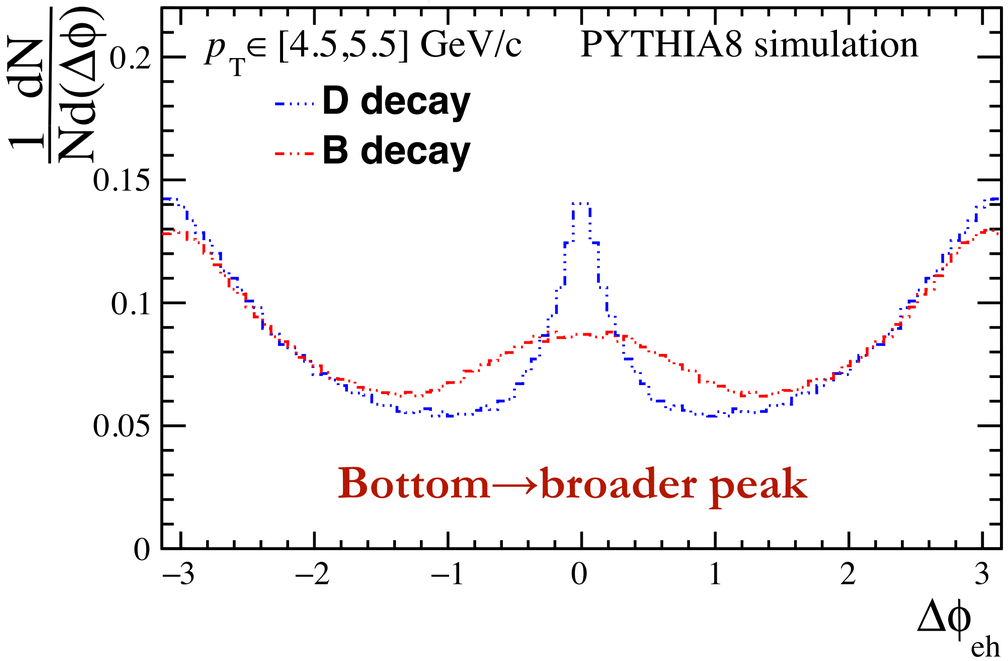


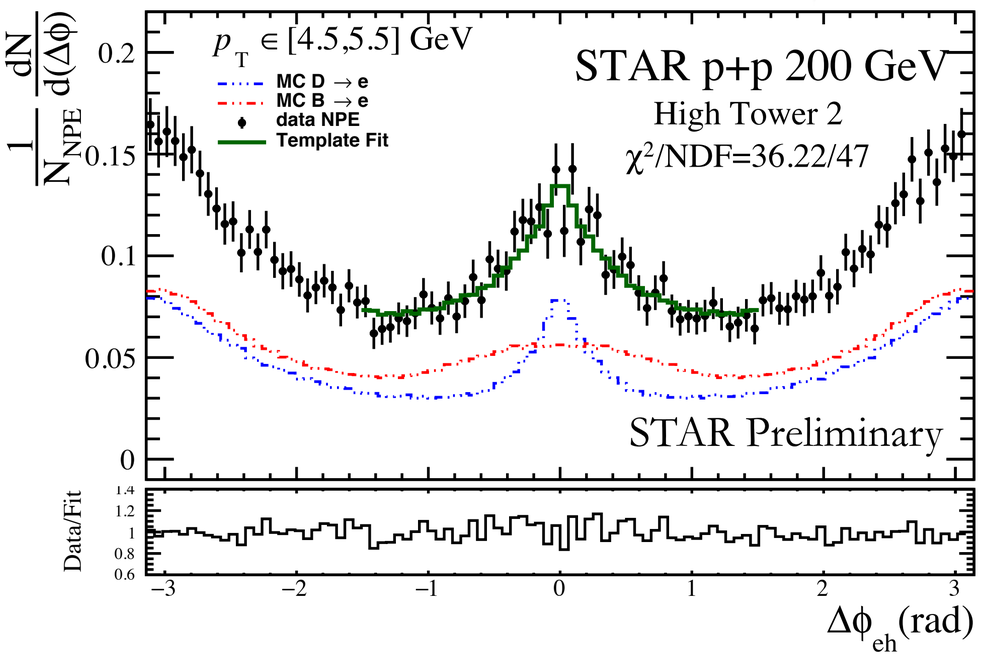
Photonic electron reconstruction efficiency



Analysis Method (p+p): Fit azimuthal correlations

$$\Delta\phi_{\mathrm{NPE-h}} = \Delta\phi_{\mathrm{Semi\_Inc-h}} + \Delta\phi_{\mathrm{LikeSign-h}} - (1/\varepsilon_{\gamma} - 1) * \Delta\phi_{\mathrm{reco-photonic-h}} - (1 - \varepsilon_{\mathrm{purity}}) * \Delta\phi_{\mathrm{hadron-h}} * \frac{N_{inclusive}}{N_{hadron}}$$





Fit NPE-h correlations from data with separated correlation templates of *c*-/*b*-decayed electrons from Monte Carlo:

- ➡**PYTHIA 8.1 combined with STAR-HF-Tune Version 1.1 to generate *e*(D)-h and *e*(B)-h correlations**
- ➡**Fit the near-side peak with B→*e* and D→*e* templates from the simulation**
  - **Fit function:** $(r_B$ * **PYTHIA(B)** + $(1 - r_B)$ * **PYTHIA(D))** * *Norm*
  - r_B **is B contribution,** *Norm* **is a free parameter**

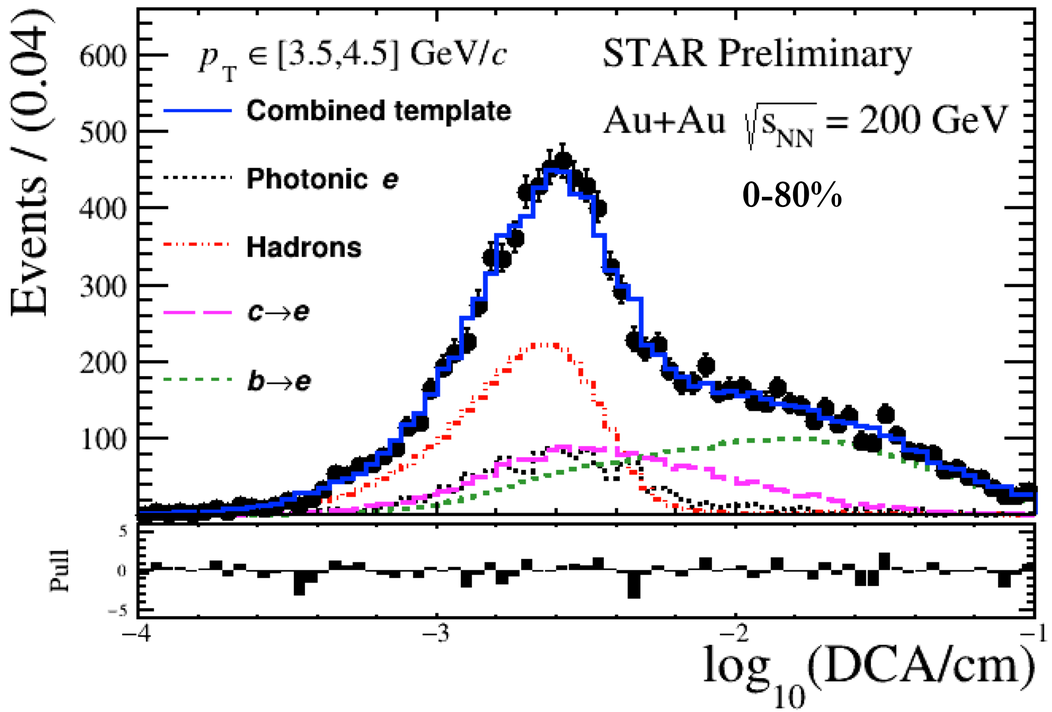
Analysis Method (Au+Au): Fit DCA templates

- Separation of *b*- and *c*-decayed electrons with template fit to log of 3D DCA

✓Hadron shape: from data, constrained by purity

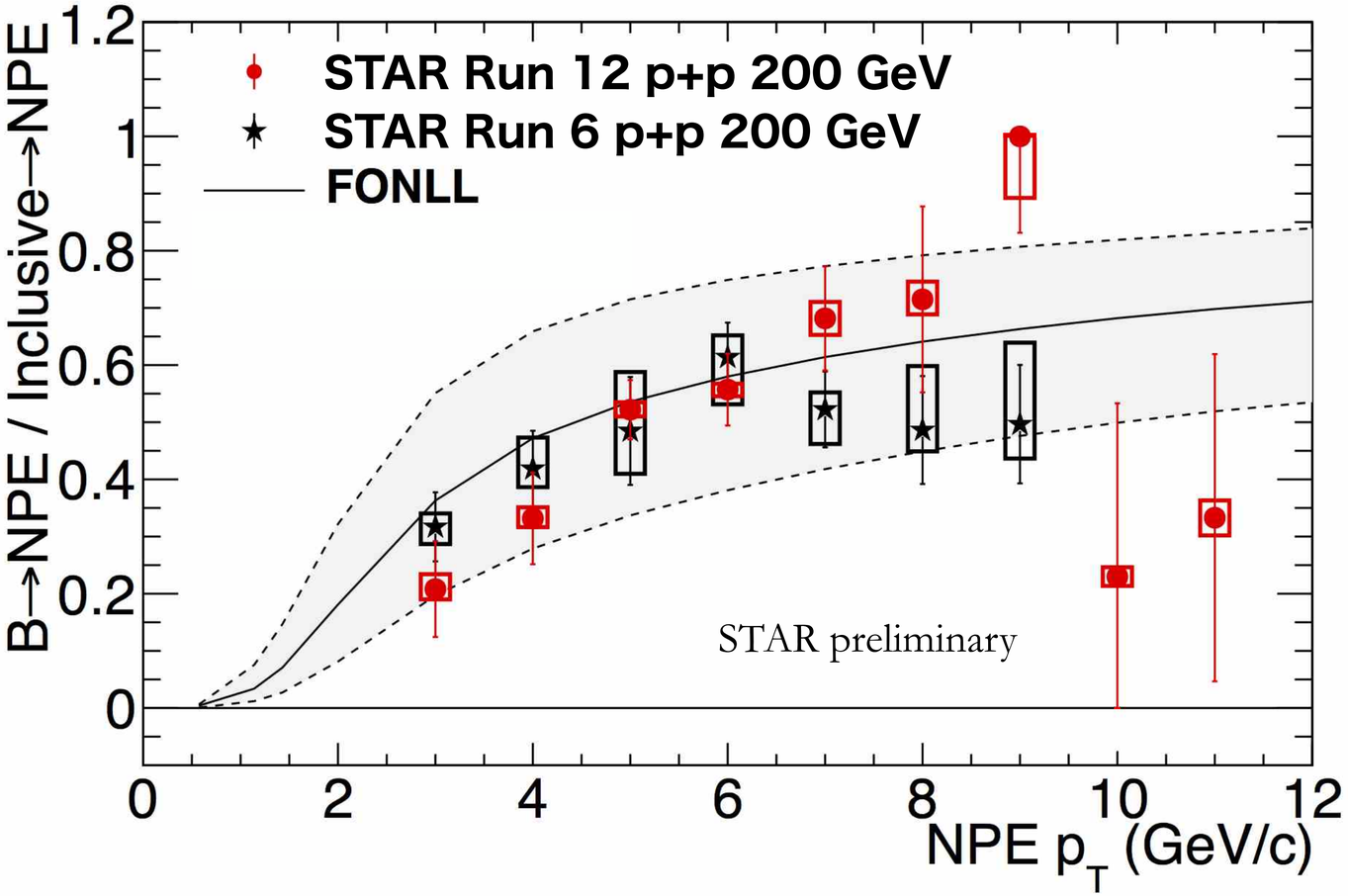
✓Photonic electron shape: from simulation, constrained by photonic electron fraction

✓HF→*e* shape: determined from simulating all ground state $B^{\pm}$, B^{0}, B_s, Λ_b and $D^{\pm}$, D^{0}, D_s, Λ_c semi-leptonic decays



b-hadrons $c\tau$ ~ 500 μm
c-hadrons $c\tau$ ~ 60-300 μm
Larger $c\tau$ of *b*-hadrons w.r.t. *c*-hadrons
$\langle DCA(b \to e) \rangle > \langle DCA(c \to e) \rangle$

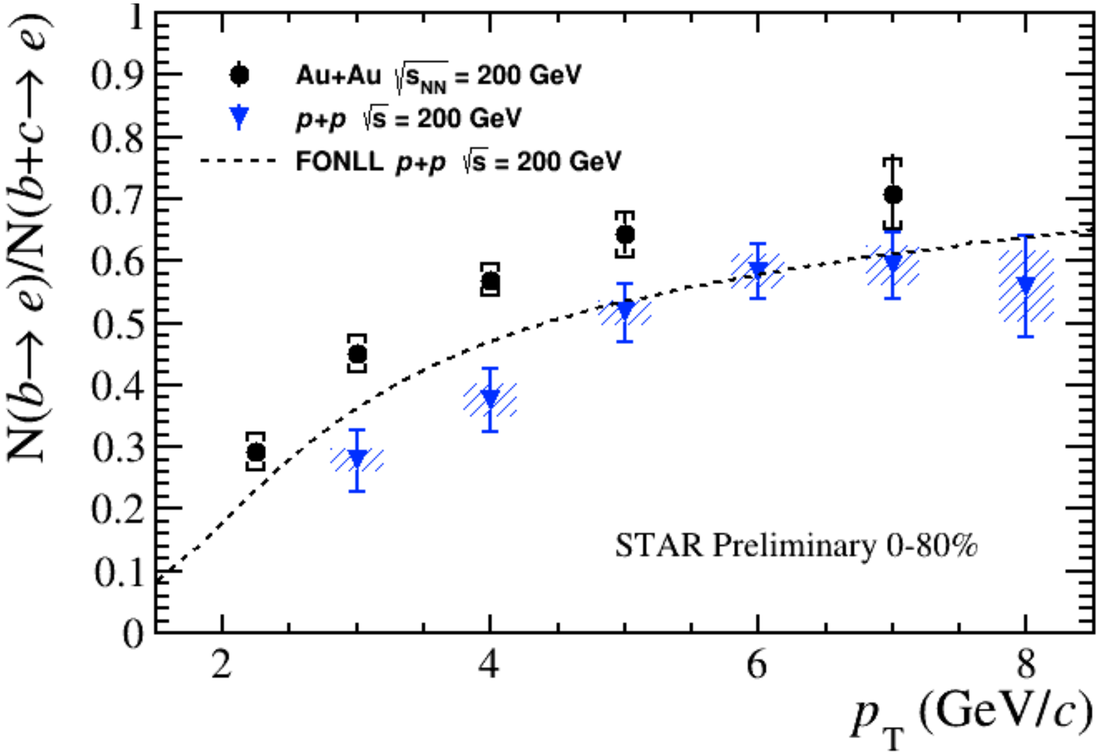
Bottom→e fraction in p+p collisions

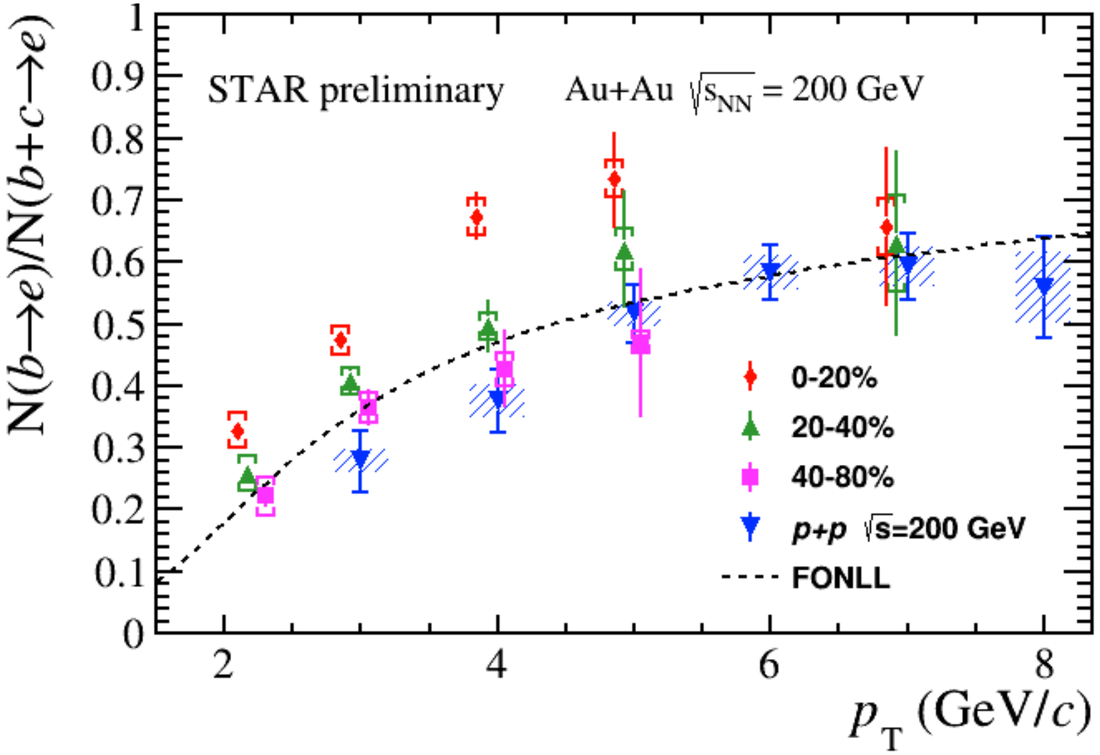


- **Bottom electron fraction:**
  Increase with p_T, and surpassing $c \rightarrow e$ contribution for p_T>5 GeV/c
  FONLL calculation consistent with data

FONLL: JHEP 1210 (2012) 137
STAR 2006 pp: PRL 105 (2010) 202301

Bottom→e fraction in Au+Au collisions





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 and consistent with p+p in peripheral collisions**

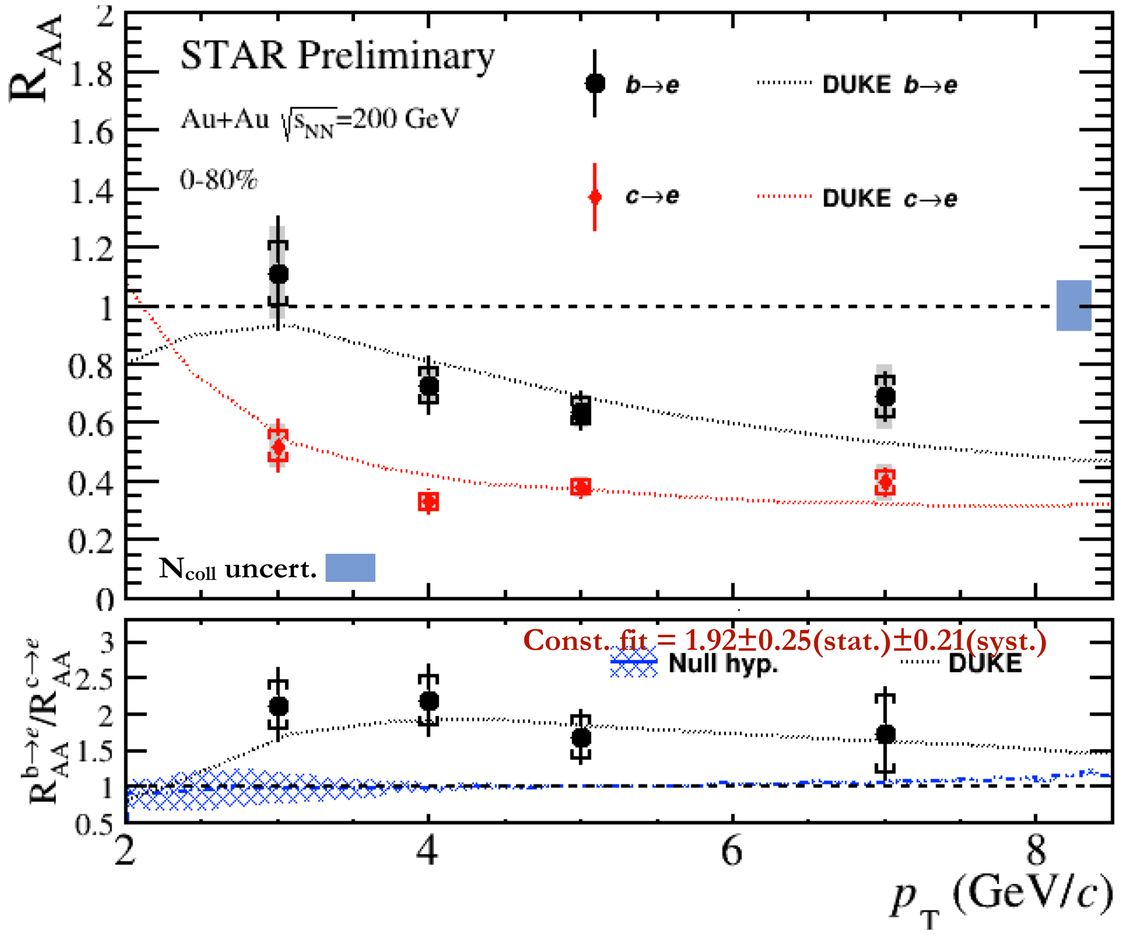
FONLL: JHEP 1210 (2012) 137
STAR 2006 pp: PRL 105 (2010) 202301

Bottom→e R_{AA}

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

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

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



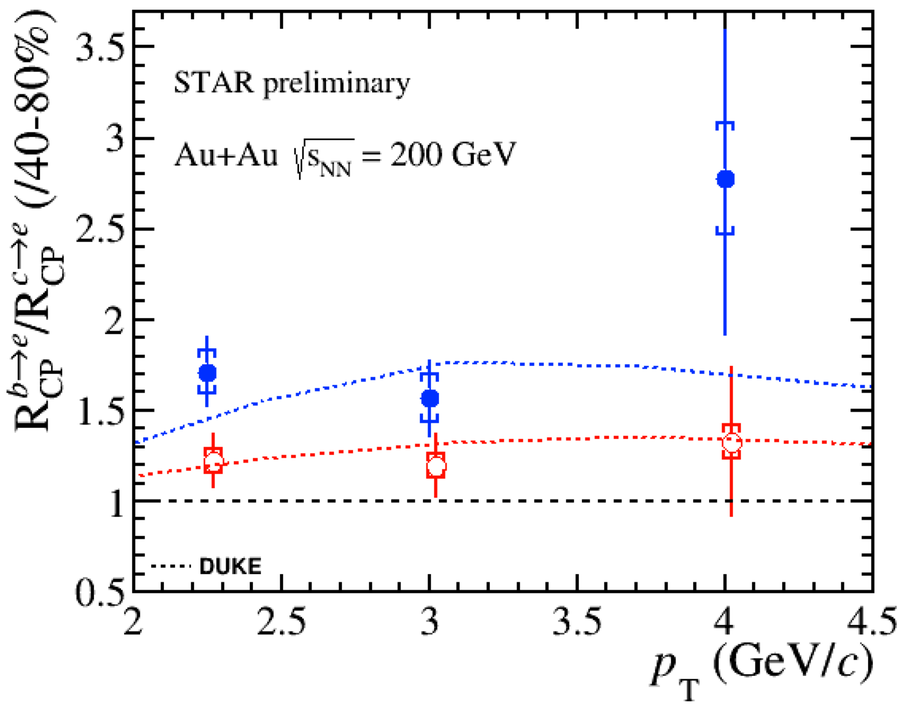
Shaded gray boxes show inclusive NPE R_{AA} uncertainty

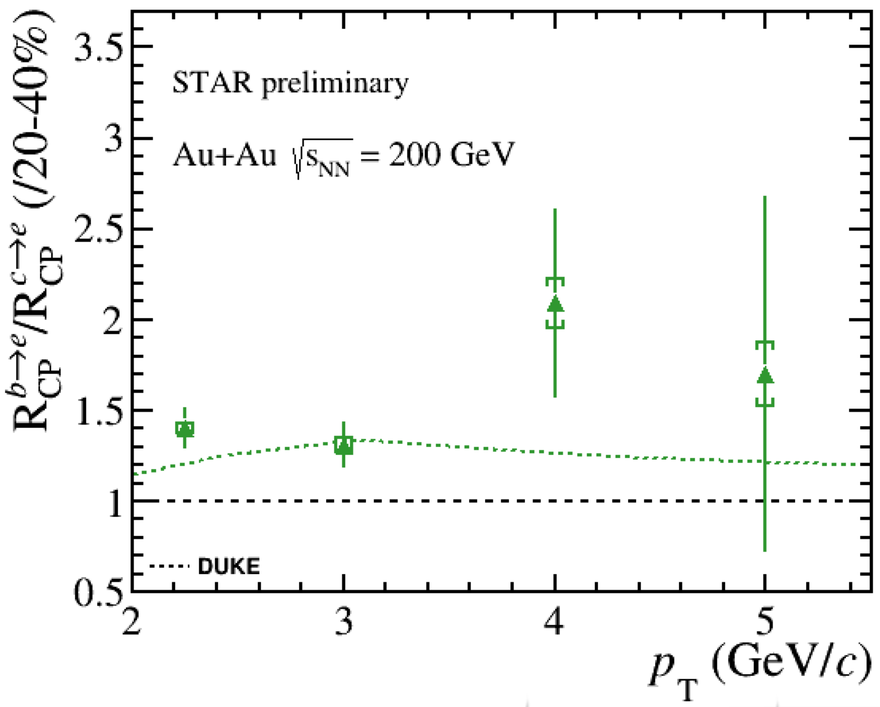
- $R_{AA}(b\to e) > R_{AA}(c\to e)$ significant at ~3σ
- DUKE Langevin model calculation consistent with data (consistent with $\Delta E(b)<\Delta E(c)$)
- Null hypothesis [R_{AA}(B)=R_{AA}(D)] for $p_T(e) \in$ [2.5, 5.5] GeV/c
  - χ^2/ndof = 8.6/2, p-value = .014

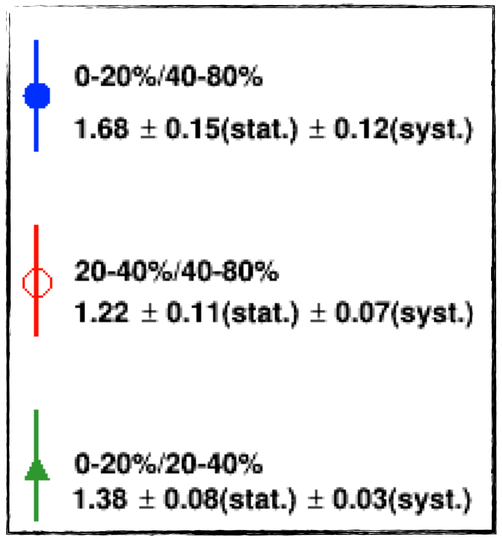
DUKE: PRC 92 (2015) 024907
Private Communication

Double Ratio of R_{CP}

Red points shifted from bin center







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

- Calculated from centrality dependent bottom fraction
- Large cancelation of correlated systematic uncertainties
  - ➡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: PRC 92 (2015) 024907
Private Communication

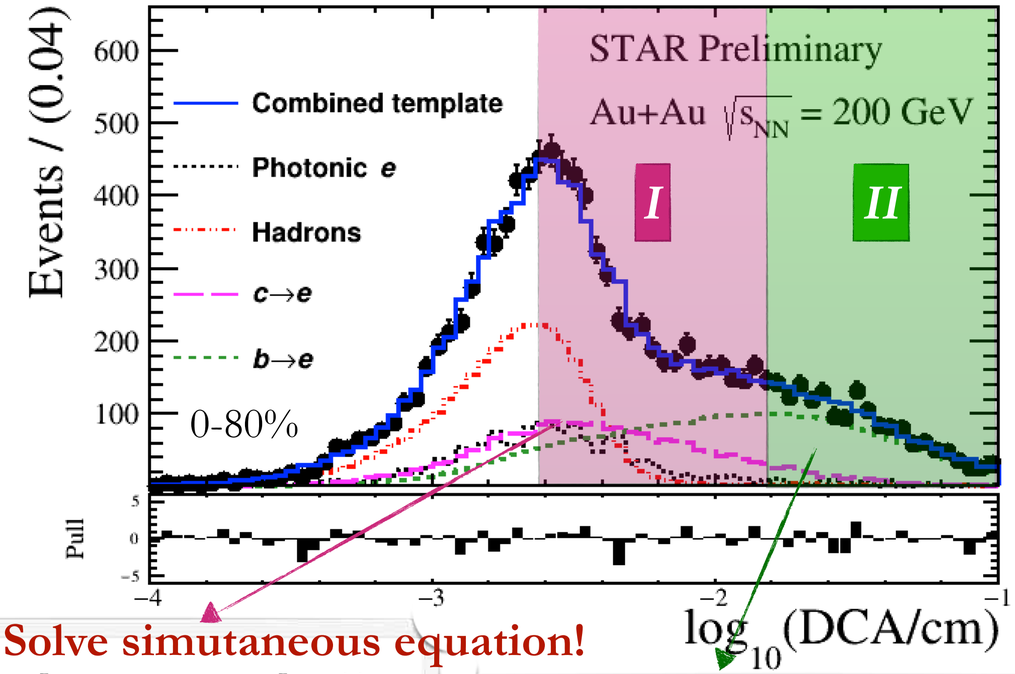
Summary

- **p+p collisions**
  - ➡**Charm and bottom-decayed electron fractions described by pQCD calculation**

- **Au+Au collisions**
  - ➡**Measured $b \rightarrow e$ suppression less than $c \rightarrow e$ with $\geq 3\sigma$ significance (R_{AA}(B)>R_{AA}(D))**
    - ✓**Consistent with the predicted quark-mass dependent energy loss ($\Delta E(b) < \Delta E(c)$)**

Backup slides follow

Charm→e Elliptic Flow in Au+Au collisions

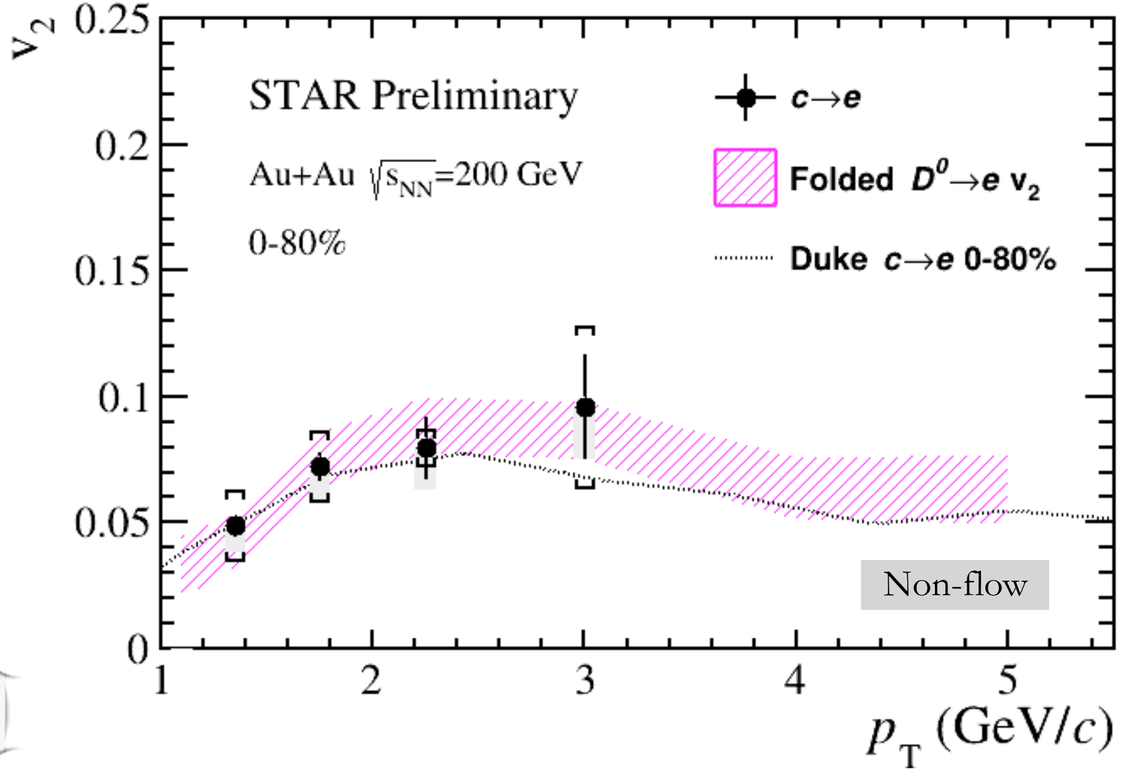


Solve simutaneous equation!

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

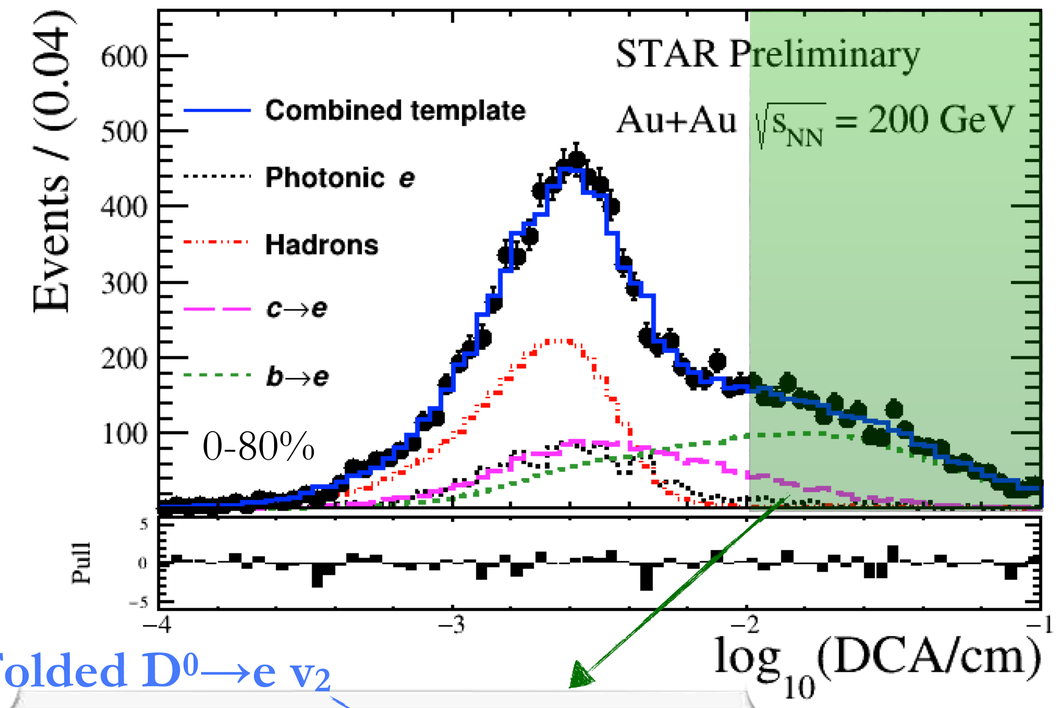
$$v_2^{\mathrm{II}}(obs.) = f_b^{\mathrm{II}} v_2^b + f_c^{\mathrm{II}} v_2^c + f_{bkg}^{\mathrm{II}} v_2^{bkg}$$

Divide DCA region to charm rich and bottom rich



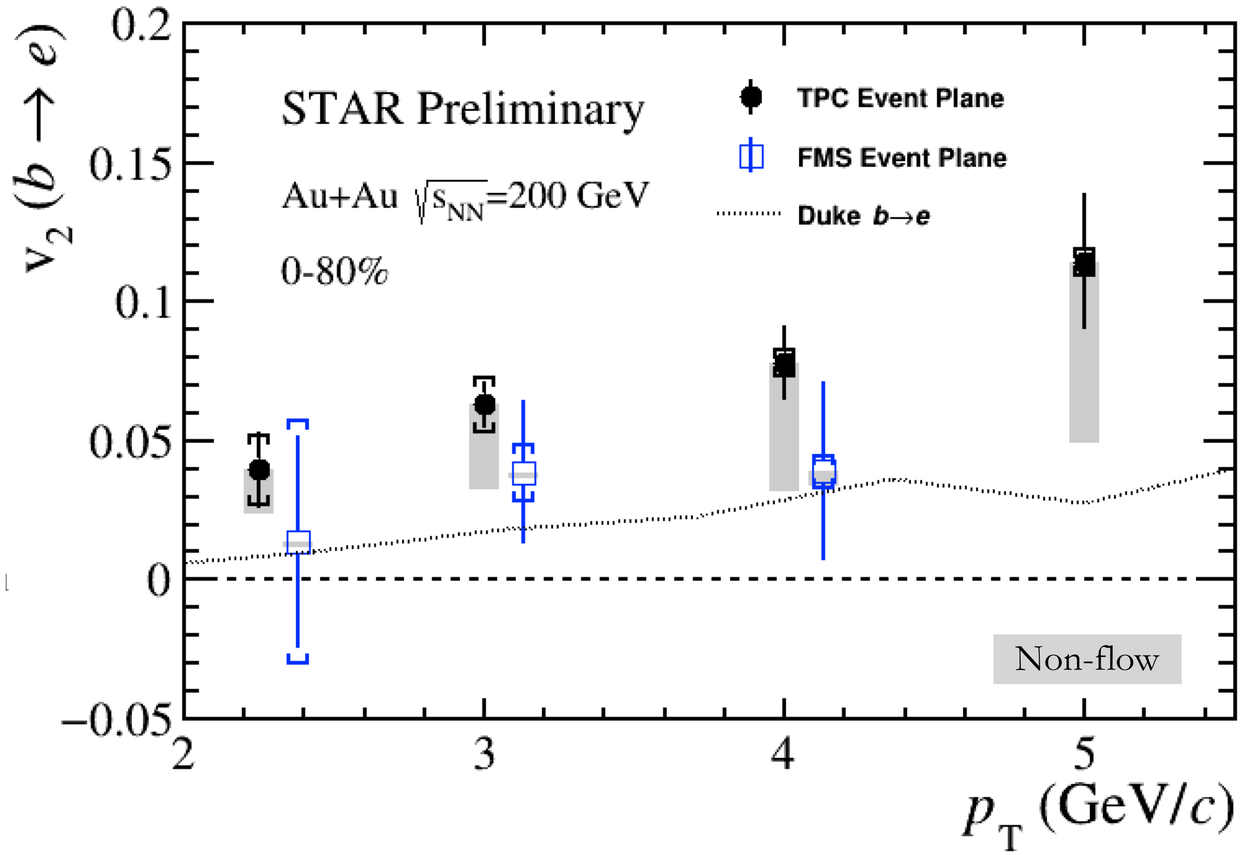
- **Second order event plane measured with TPC tracks($|\eta|$<1) using η-sub event method**
- **Charm electron v_2 is consistent with folded D^0 v_2 and DUKE model(charm quarks largely thermalize in QGP until hadronization)**
  - **➡Measured D^0 v_2 folded to decayed electron with simulated semileptonic decays in EvtGen**

Bottom→e Elliptic Flow in Au+Au collisions



Folded $D^0 \rightarrow e$ v_2

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



- Data qualitatively is consistent with Duke model considering non-flow
- TPC EP measurement null hypothesis with full non-flow subtraction:
  - FMS(2.5<η<4.0) EP data is consistent within uncertainties with TPC(|η|<1) EP measurement
  - χ^2/ndof = 17.1/3, p-value = .00067 (~3.4σ)

➡Hint of non-zero bottom→e v_2!