Measurements of **open charm** and **bottom** hadron production in **Au+Au** collisions with the **STAR** experiment

Opportunities and Challenges with Jets at LHC and beyond,
Wuhan, June 11, 2018

Kunsu OH for the STAR collaboration
Central China Normal University

Outline

- Introduction
- STAR experiment
- Open ***charm*** production in 200 GeV Au+Au collisions
  - $\boldsymbol{\Lambda_c}$, $\boldsymbol{D^0}$, $\boldsymbol{D^\pm}$, $\boldsymbol{D^*}$, **and** $\boldsymbol{D_s}$
- Open ***bottom*** production in 200 GeV Au+Au collisions
  - **Non-prompt** ***J/ψ***, ***D****[0]* and
    c**/*****b*** **separation in non-photonic electron (*****NPE*****)**
- Summary and outlook

Introduction

★**Heavy Flavor** production

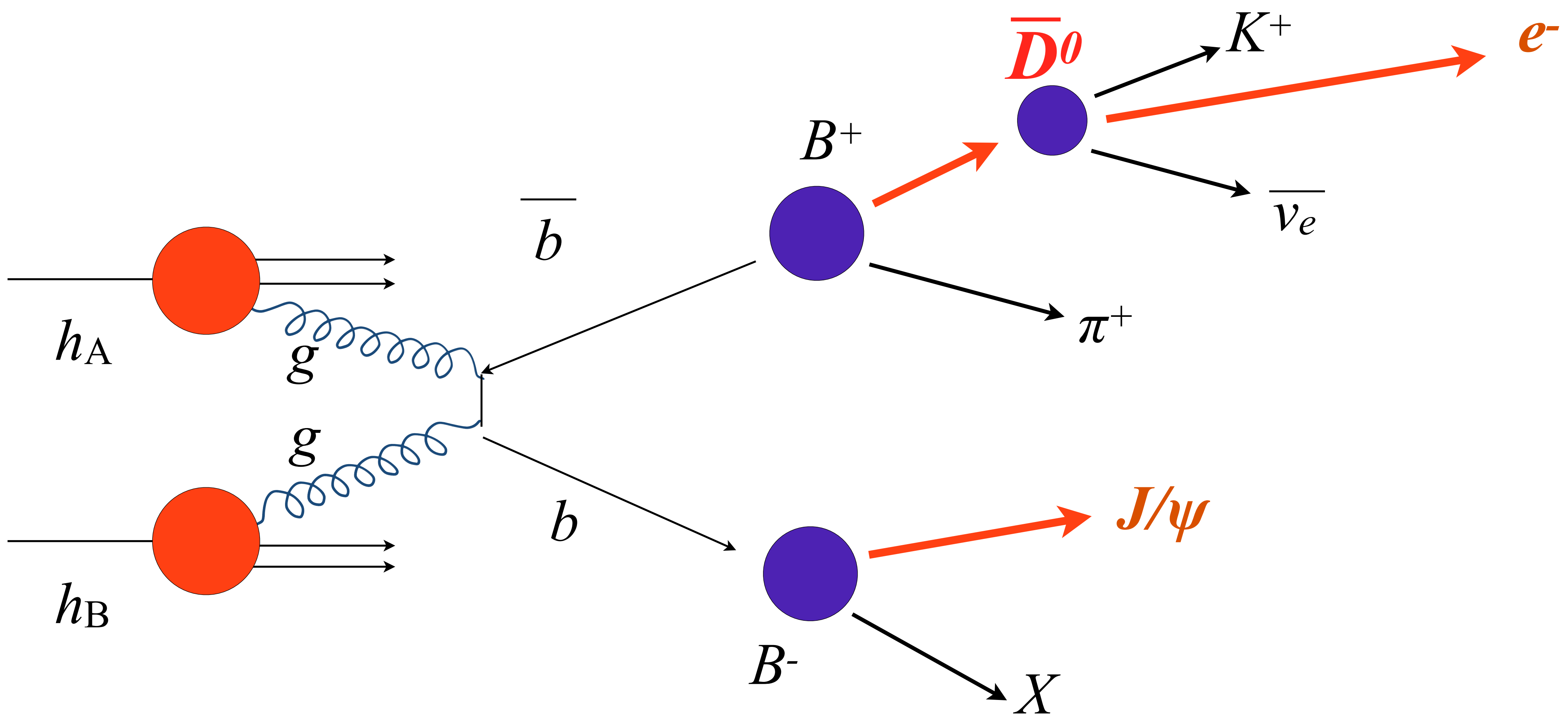
★HF quarks are primarily produced in initial hard scatterings, and interact with the **medium** (**Hot Nuclear Matter**) created in **heavy-ion collisions**.

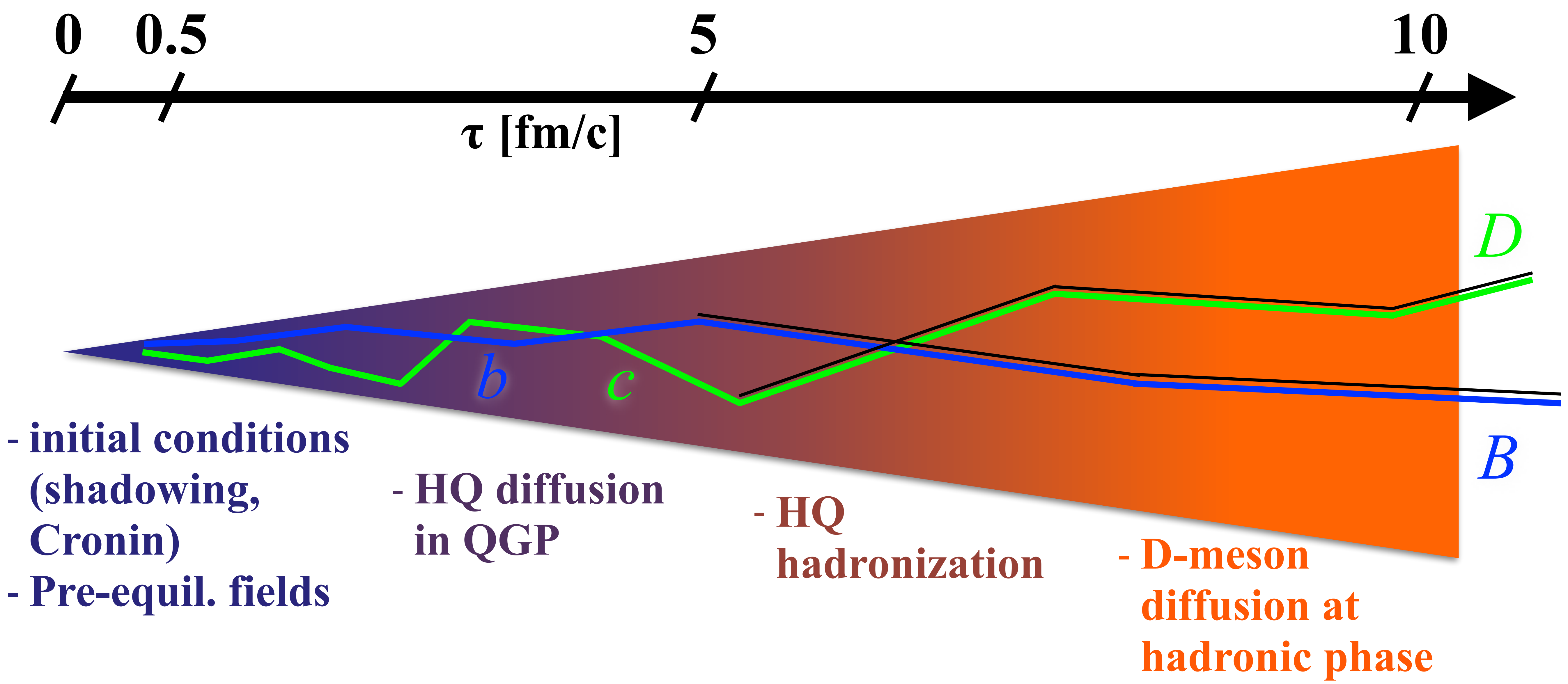
★Use HF quarks to probe the properties of the **quark gluon plasma** via studying the flavor dependence of the parton energy loss.

→ Theoretical prediction for ΔE in medium: $\Delta E_g > \Delta E_q > \boldsymbol{\Delta E_c > \Delta E_b}$

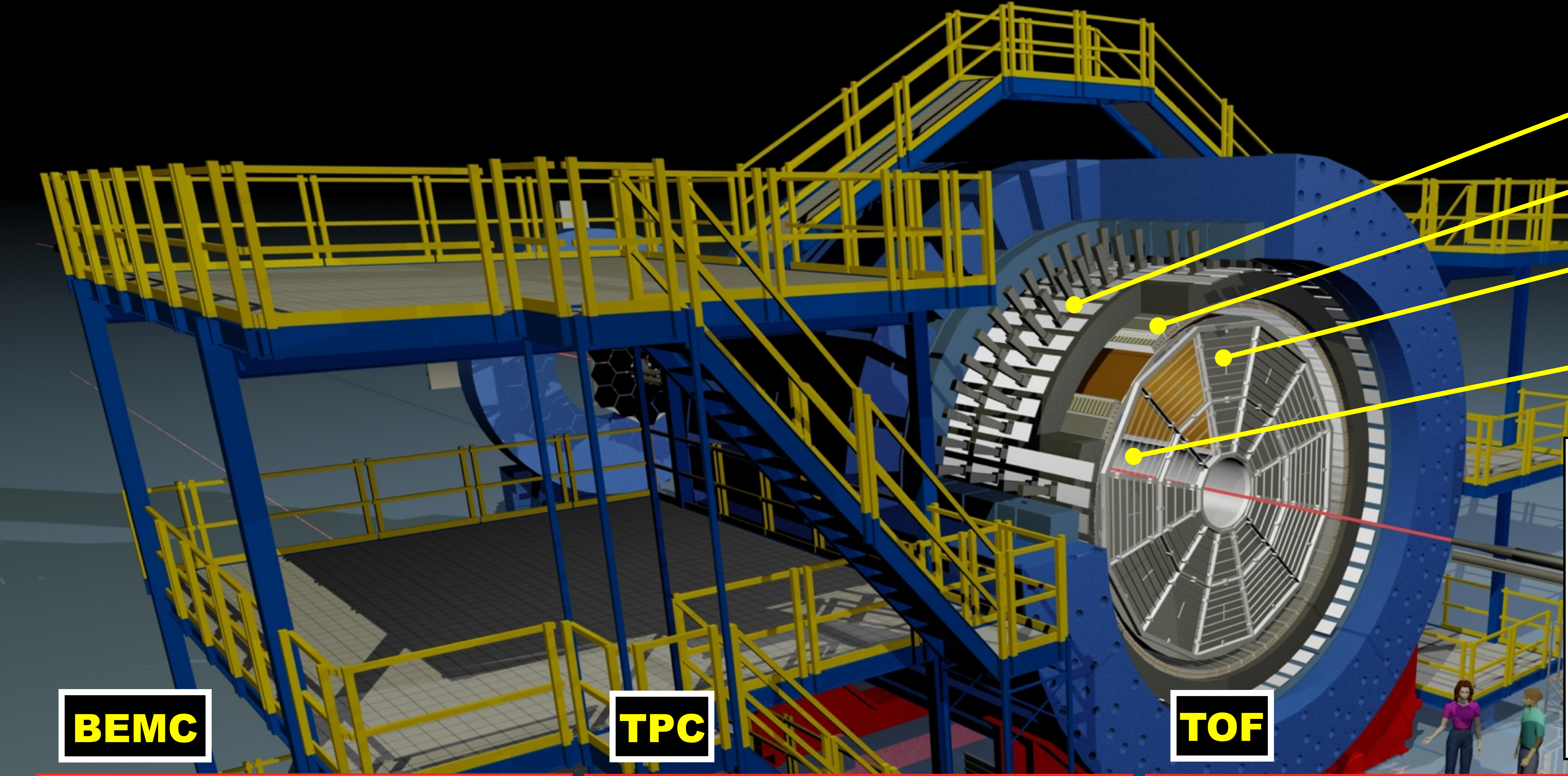
R. Baier et al., Ann. Rev. Nucl. Part. Sci. 50, 37 (2000); M. Gyulassy et al., nucl-th/0302077.

→ Precise measurements of ***c* and *b* quark energy loss separately** are crucial for understanding the parton interactions with the medium.



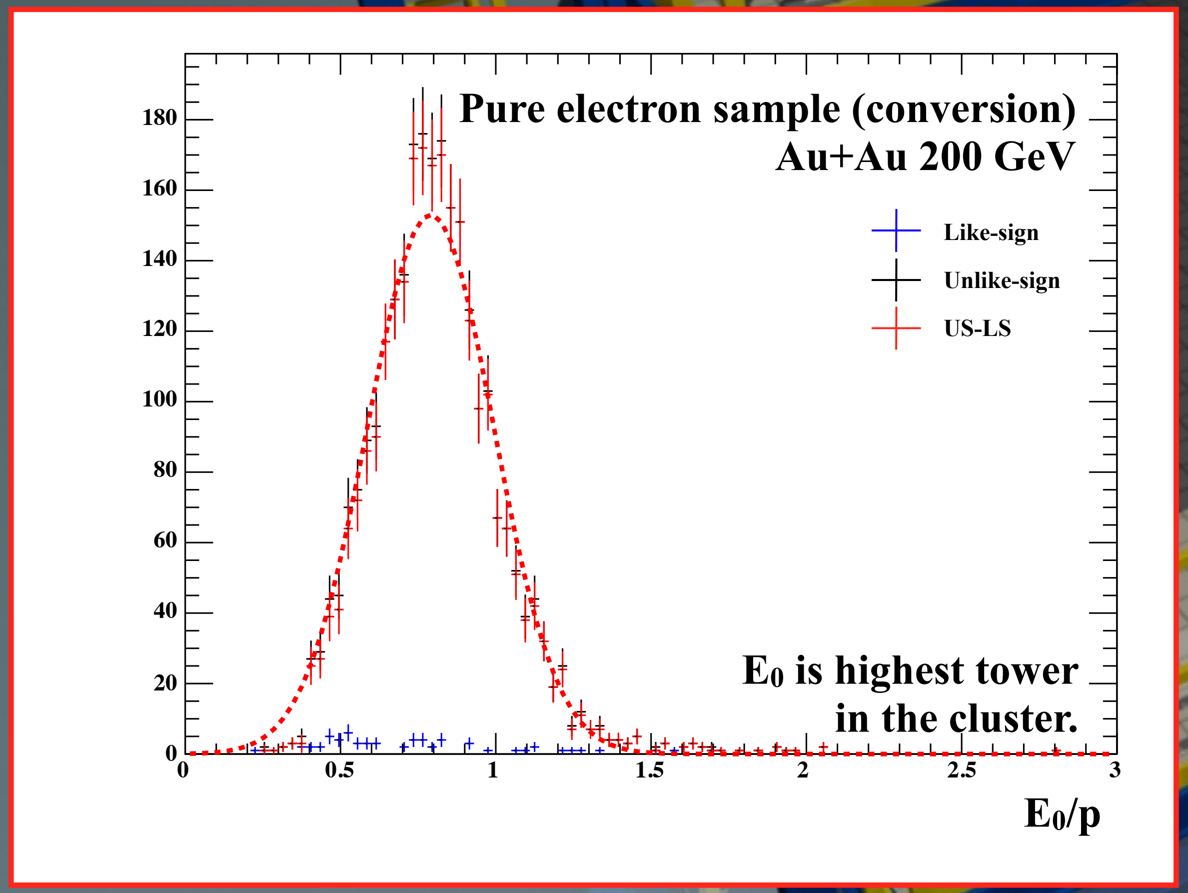


The Solenoidal Tracker At RHIC (STAR)

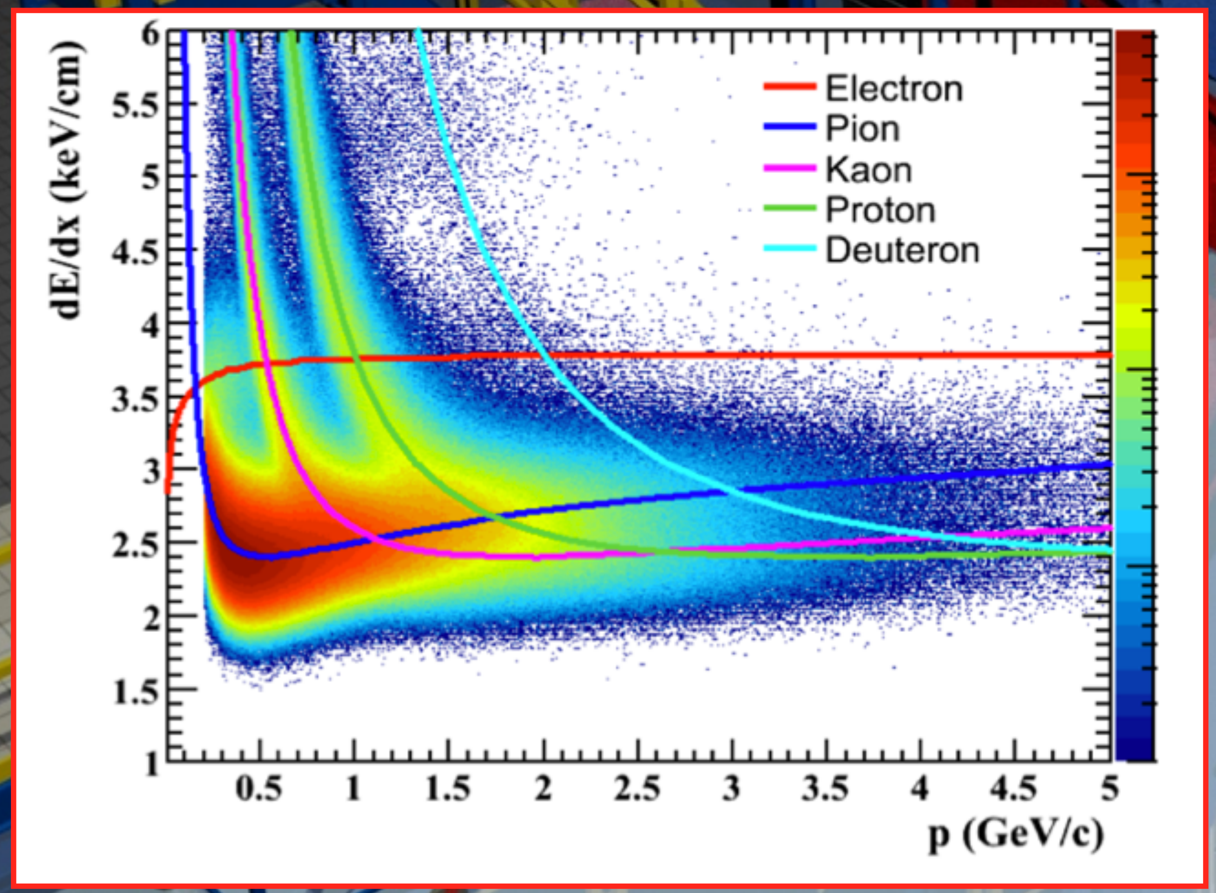


- ★ Full azimuthal coverage
- ★ $-1 < \eta < 1$ coverage
- ★ Uniform acceptance for all beam energies
- ★ Low material budget in the tracking volume
- ★ Excellent particle identification

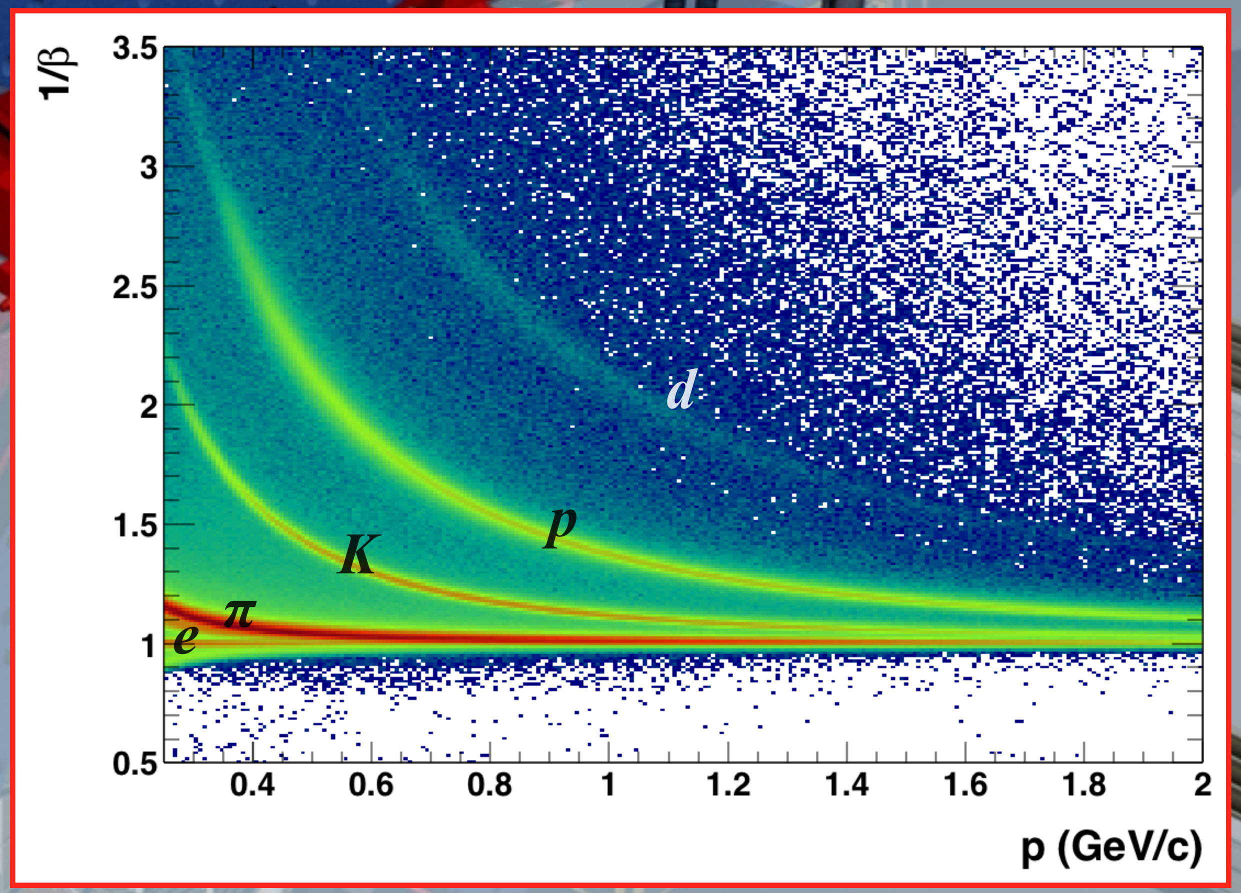
BEMC



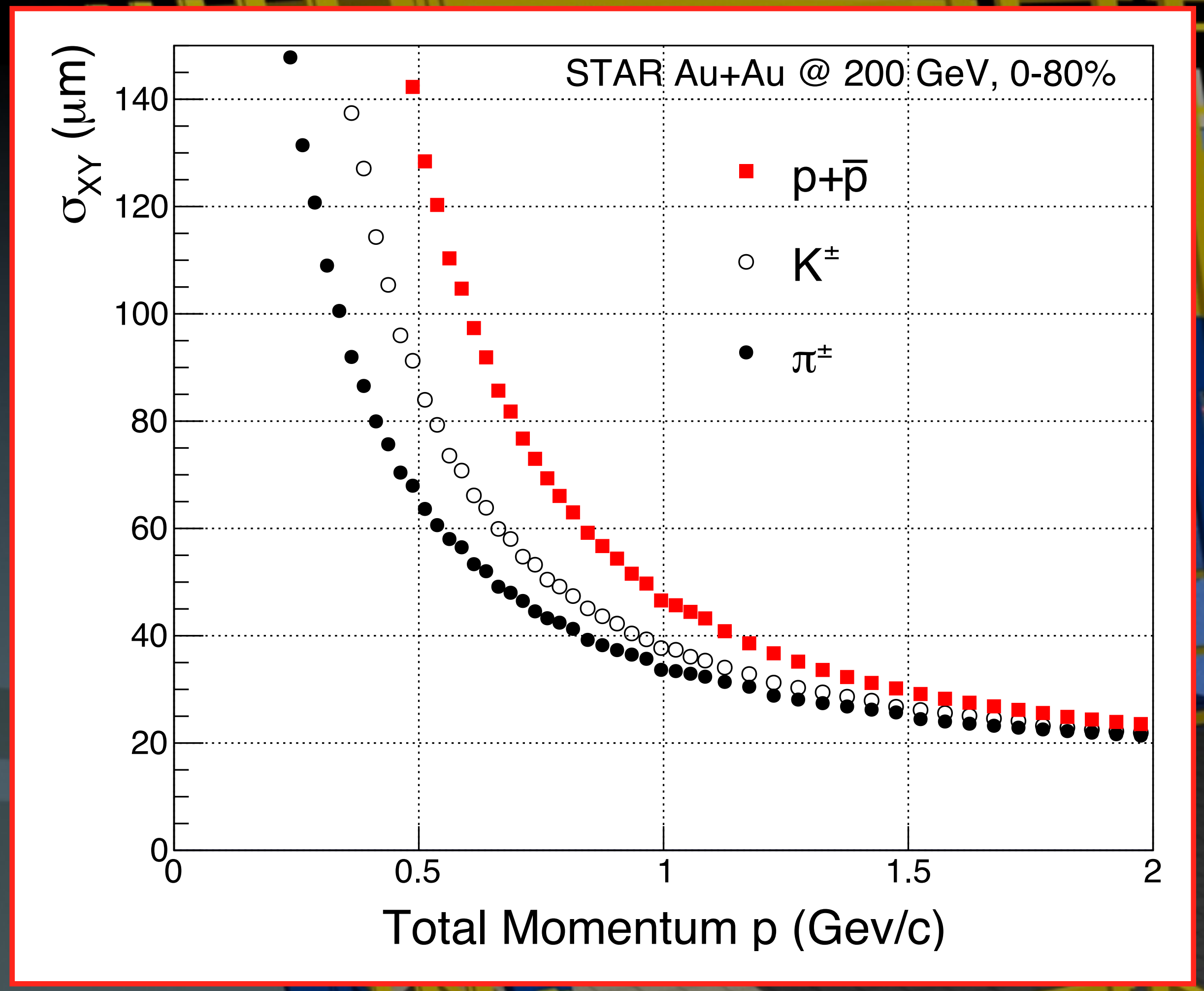
TPC

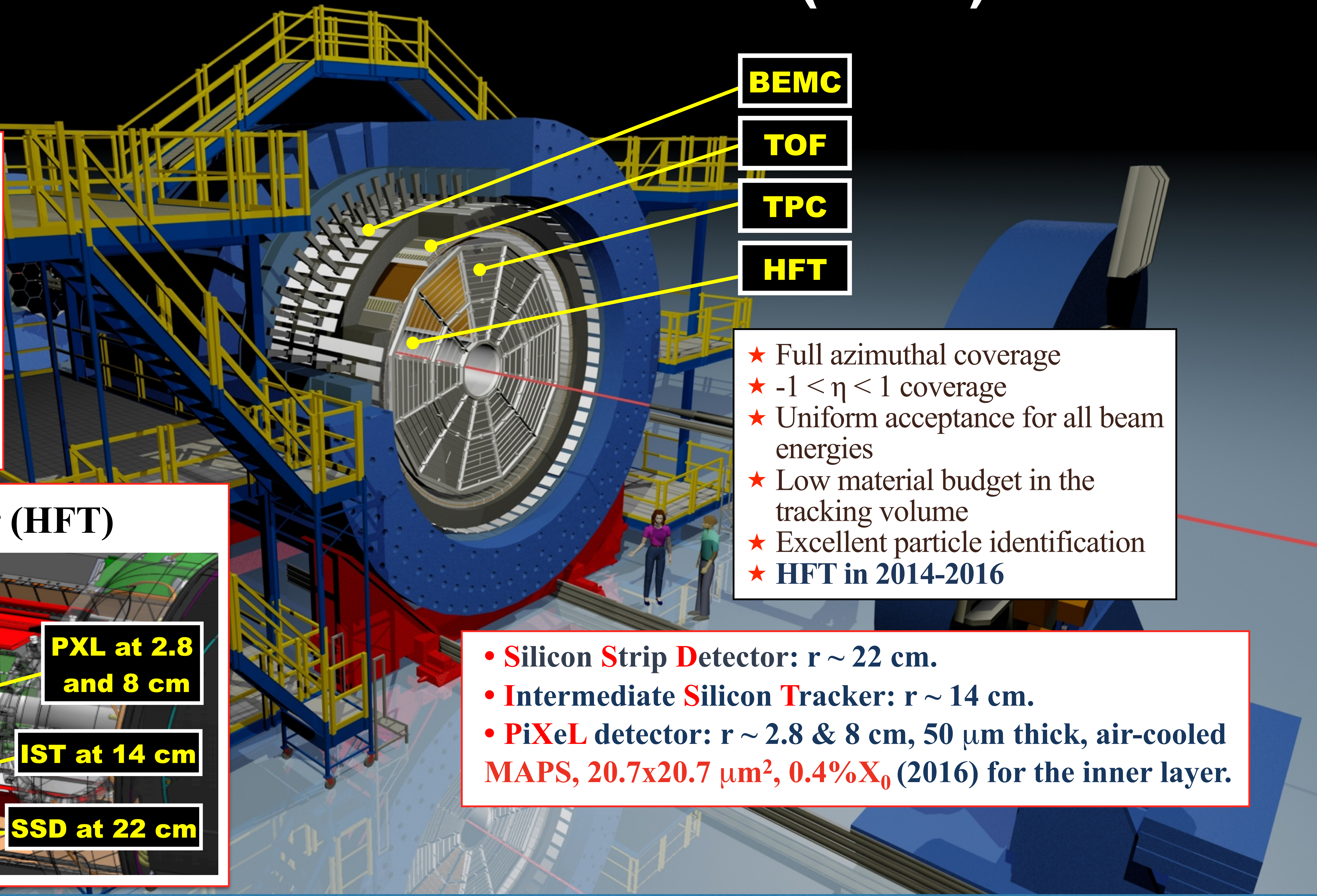


TOF



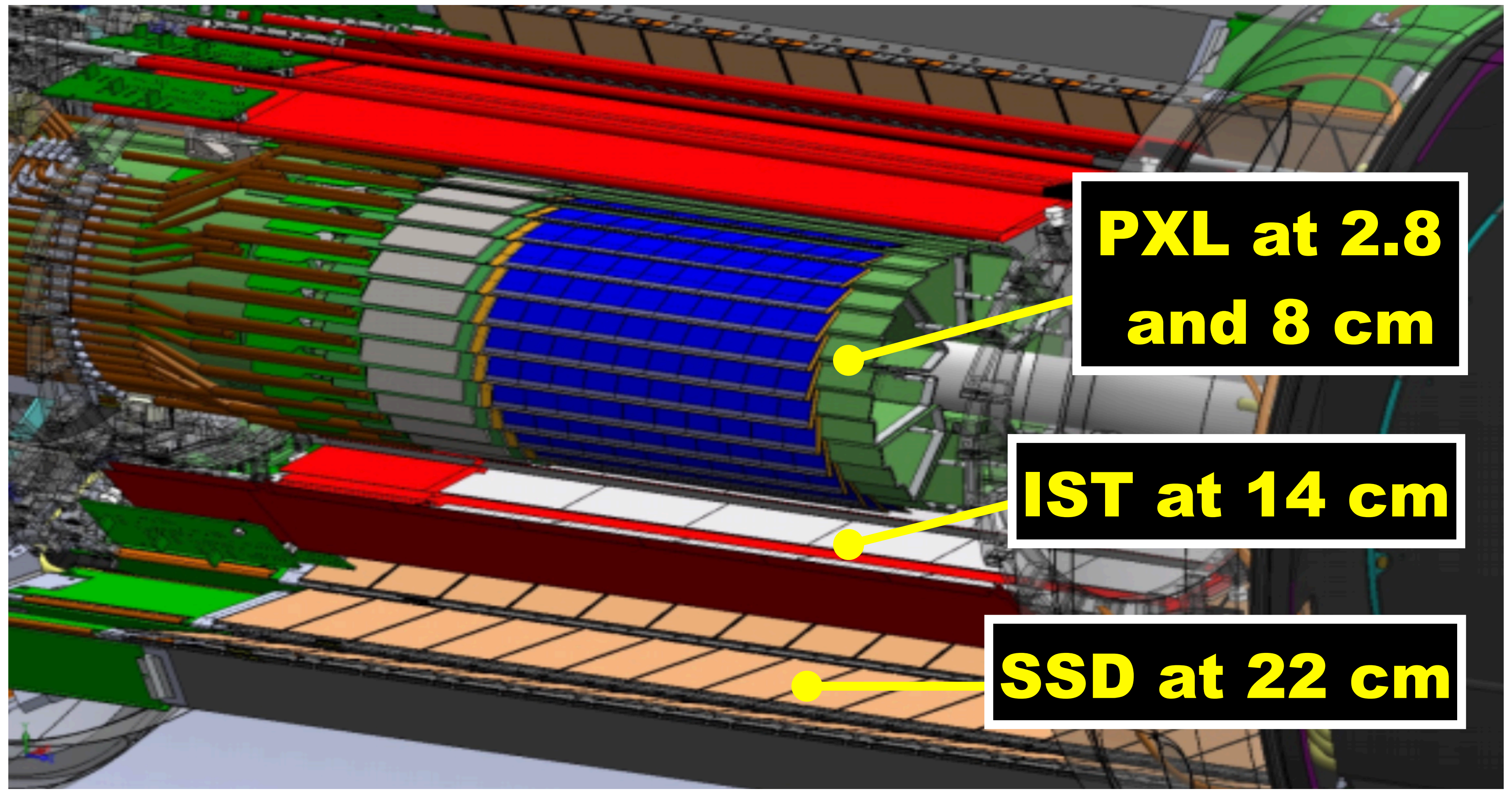
The Solenoidal Tracker At RHIC (STAR)





- ★ Full azimuthal coverage
- ★ $-1 < \eta < 1$ coverage
- ★ Uniform acceptance for all beam energies
- ★ Low material budget in the tracking volume
- ★ Excellent particle identification
- ★ HFT in 2014-2016

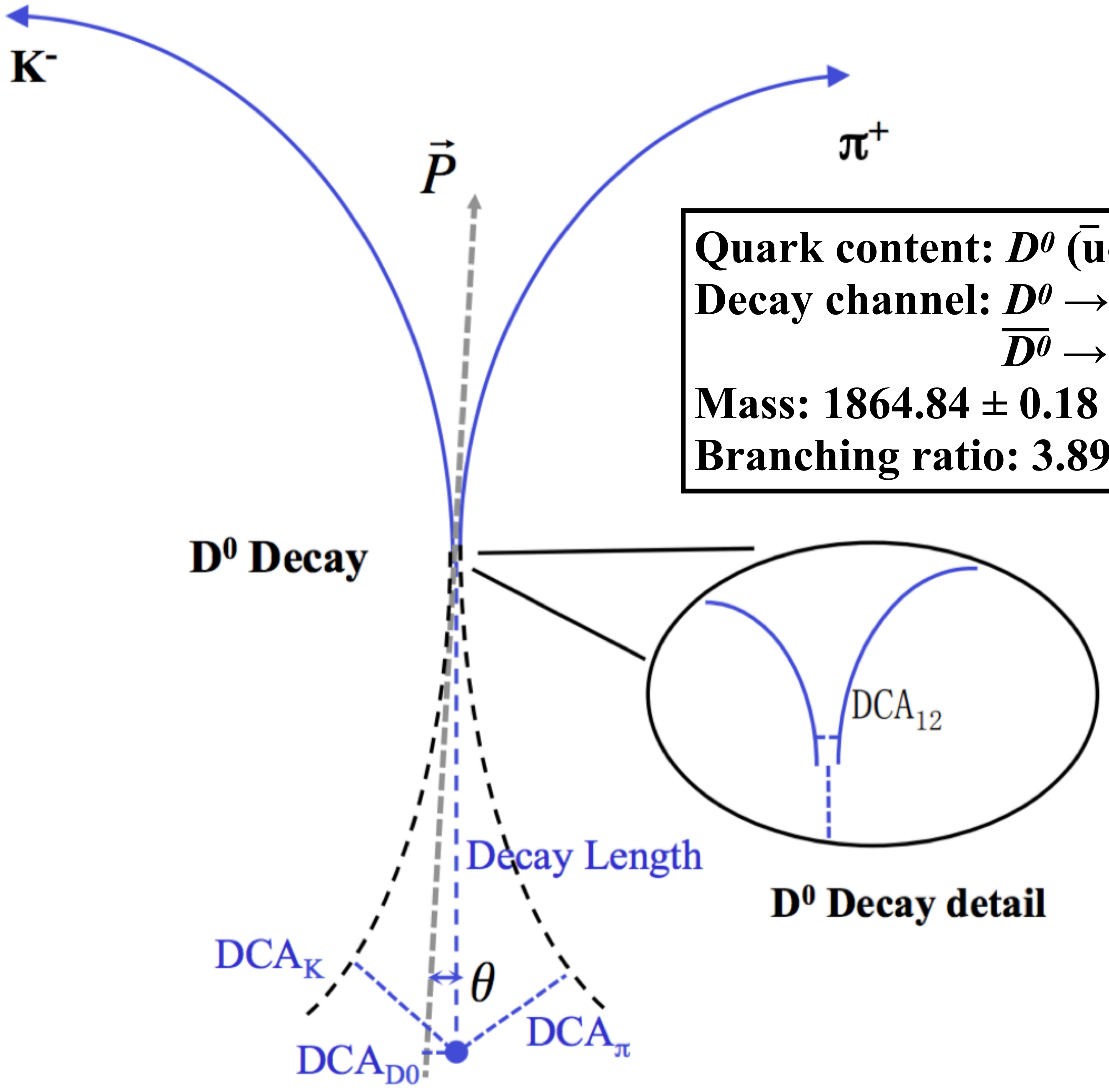
Heavy Flavor Tracker (HFT)



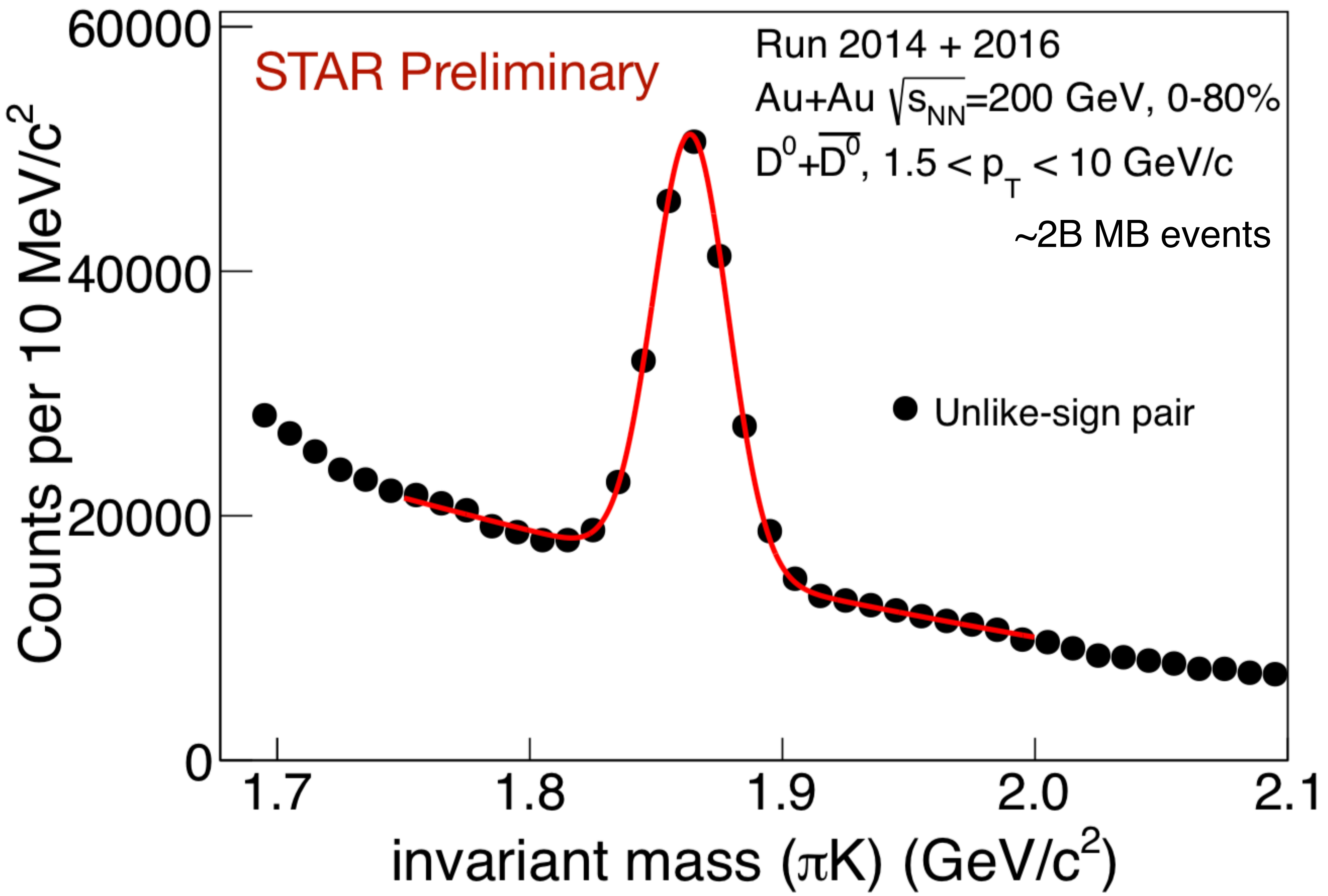
- Silicon Strip Detector: r ~ 22 cm.
- Intermediate Silicon Tracker: r ~ 14 cm.
- PiXeL detector: r ~ 2.8 & 8 cm, 50 μm thick, air-cooled MAPS, 20.7x20.7 μm², 0.4%X_0 (2016) for the inner layer.

D^0 reconstruction with HFT

D⁰ decay topology:

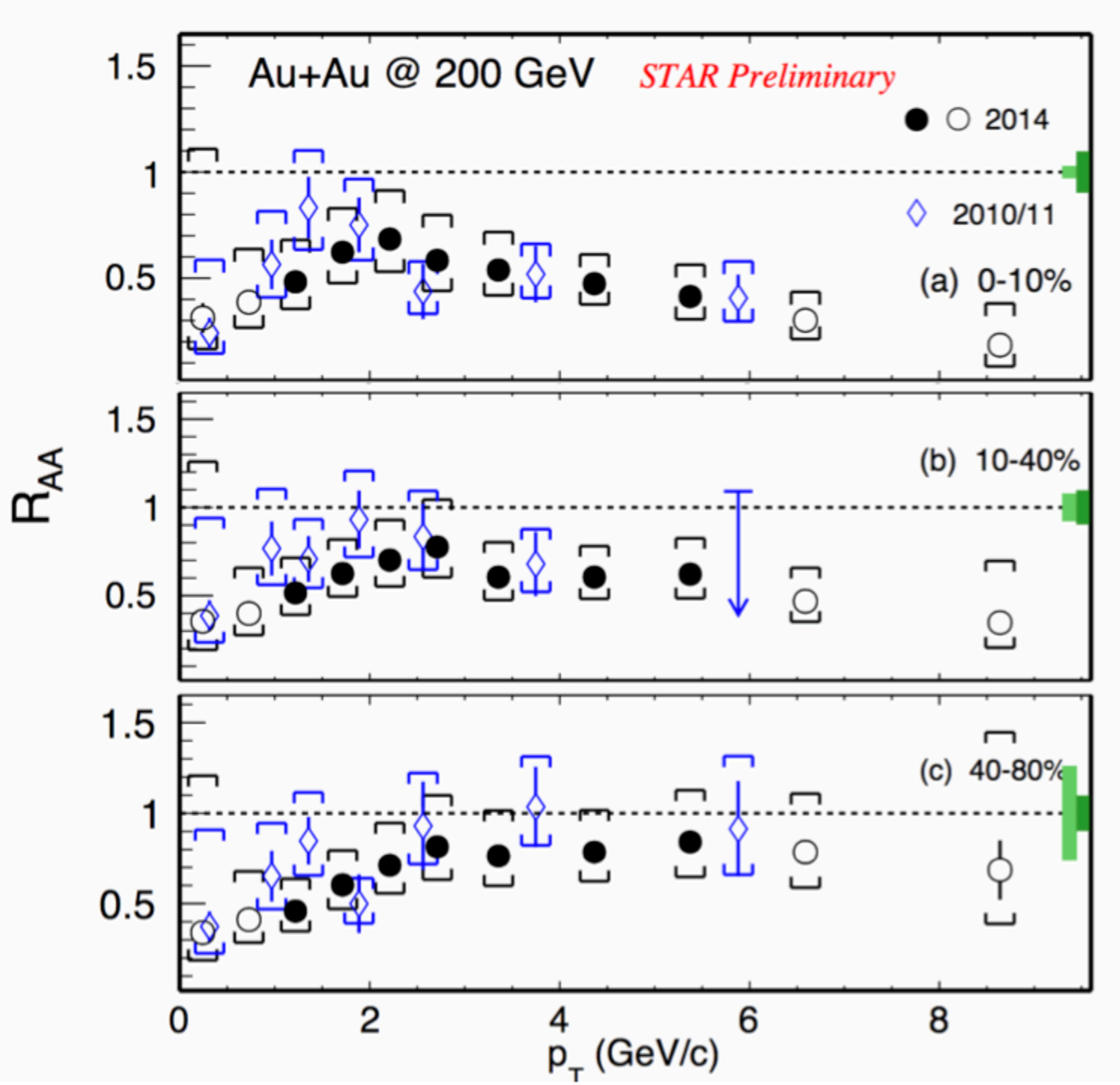


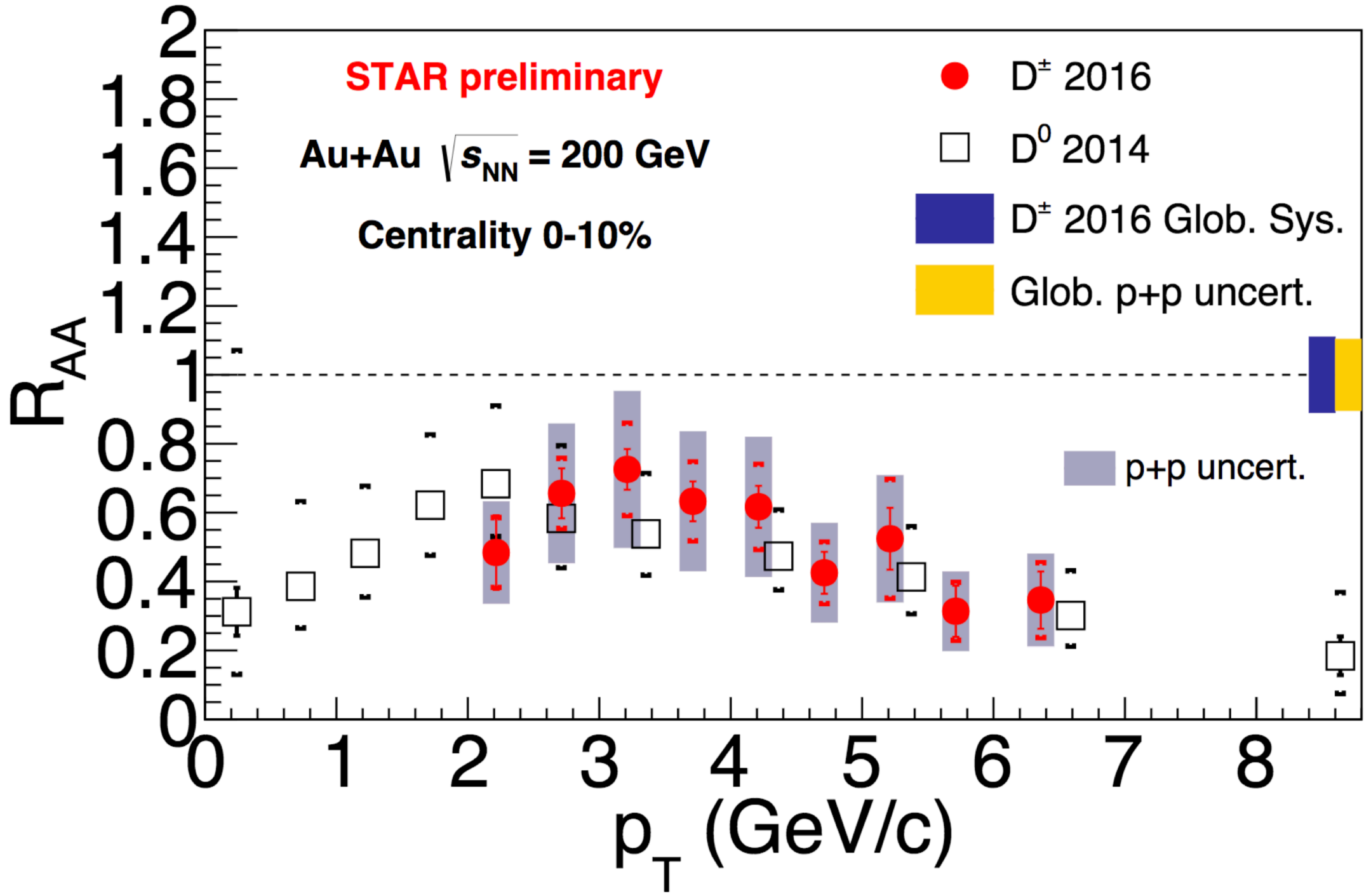
Quark content: D^0 ($\bar{u}c$), $\overline{D^0}$ ($u\bar{c}$),
Decay channel: $D^0 \rightarrow K^-\pi^+$
$\overline{D^0} \rightarrow K^+\pi^-$ ($c\tau \sim 120$ μm)
Mass: 1864.84 ± 0.18 MeV/c^2
Branching ratio: 3.89 %



- Data with HFT from 2014 and 2016 runs

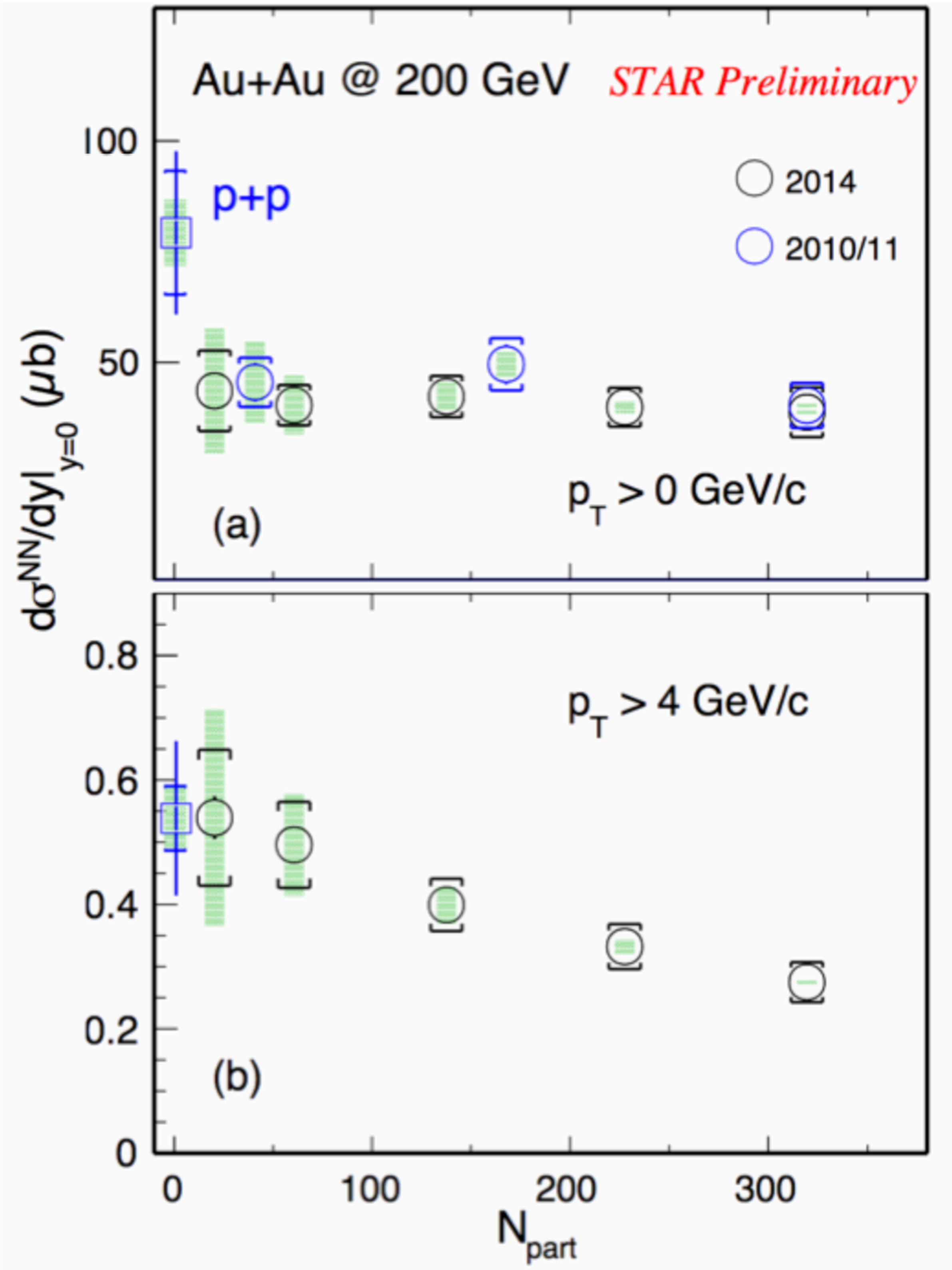
D^0 and $D^{\pm}$ R_{AA} vs. p_T

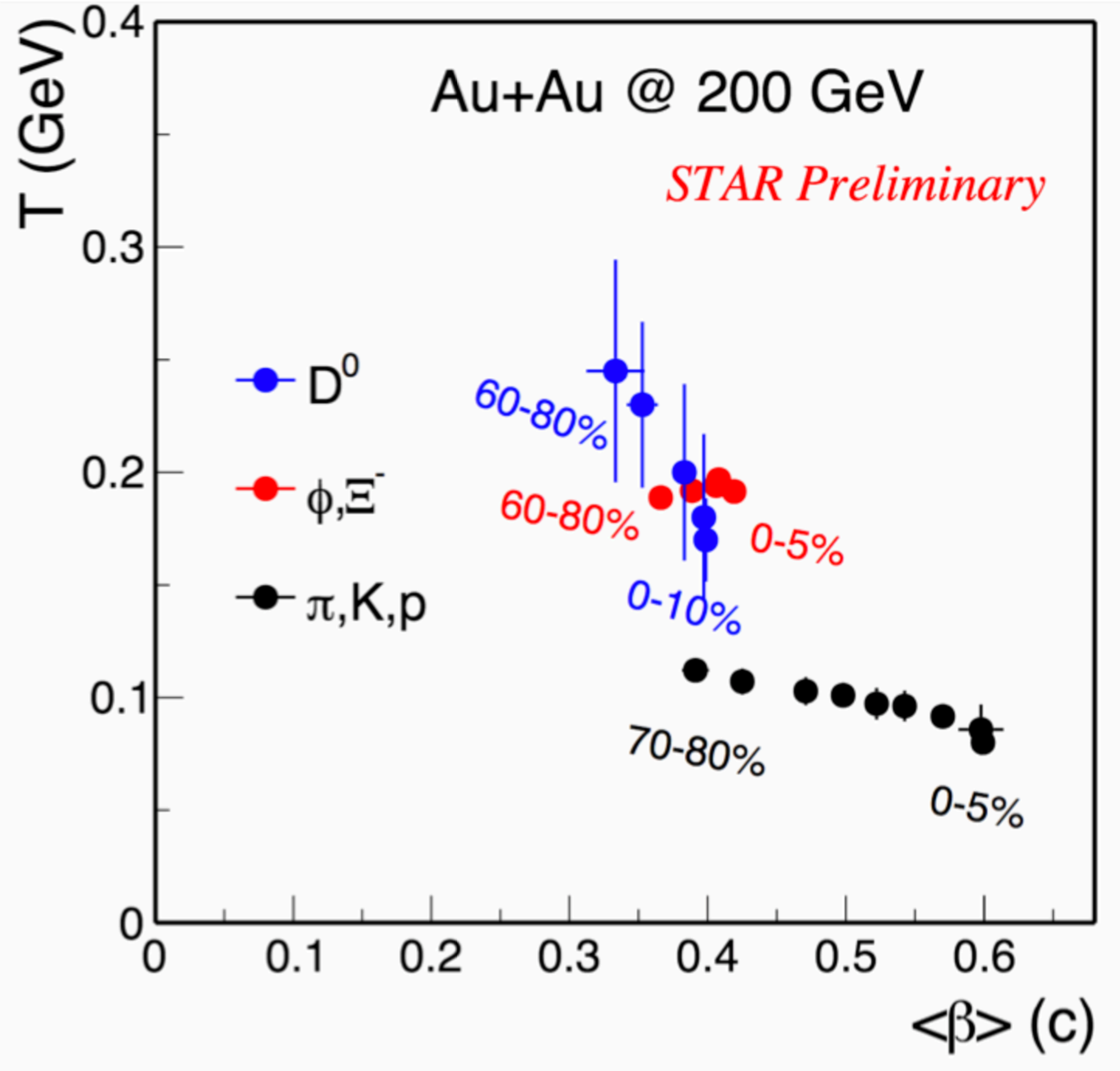




- New D^0 and $D^{\pm}$ measurements.
- The $\boldsymbol{D^0}$ **R_{AA}** is less than 1 in Au+Au collisions.
  → Strong **suppression at high p_T** in **central** collisions.
  → Centrality independent suppressions at low p_T
- The $\boldsymbol{D^{\pm}}$ **R_{AA}** is consistent with $\boldsymbol{D^0}$ results within uncertainties.

D^0 cross-section and freeze-out parameters

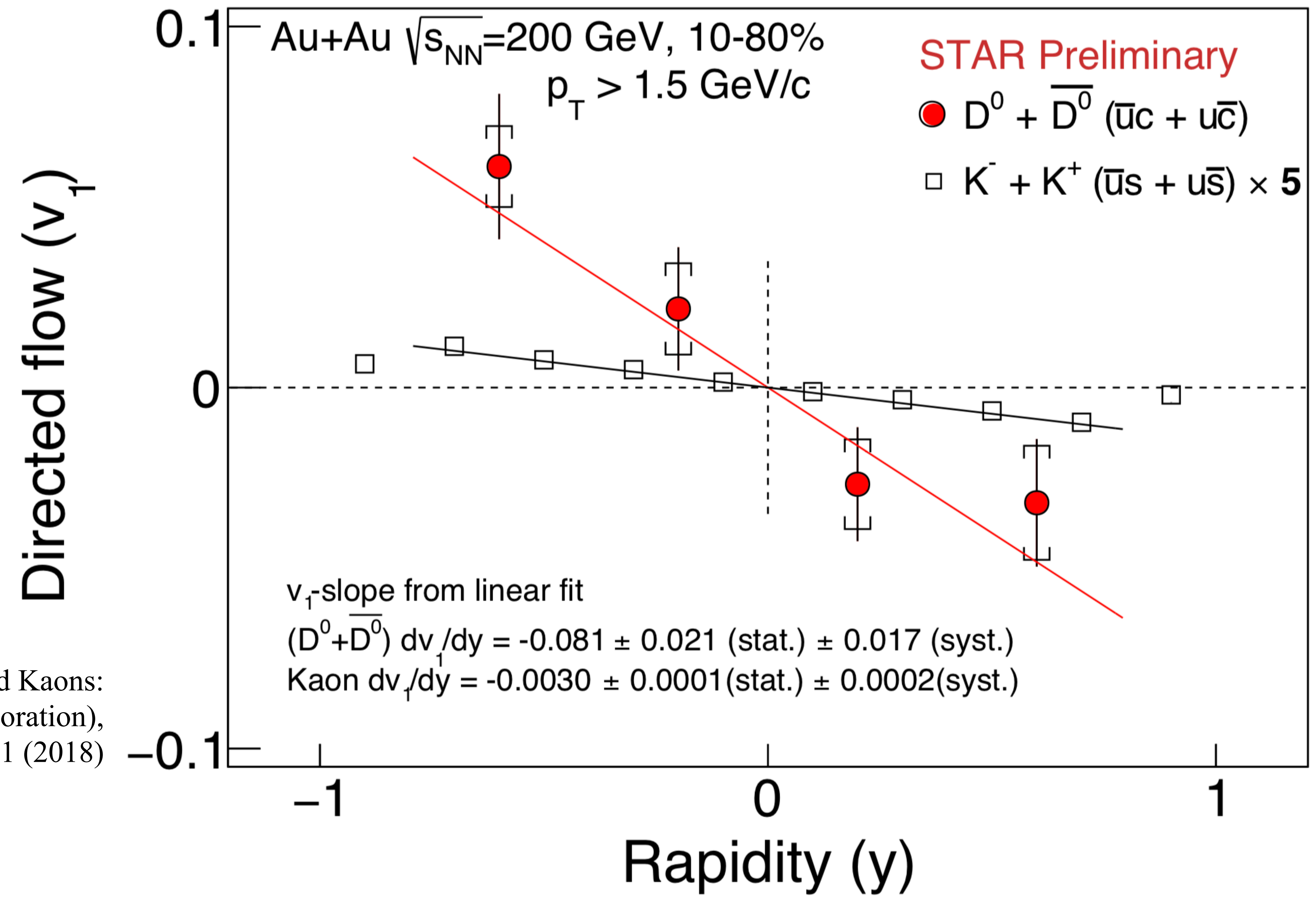




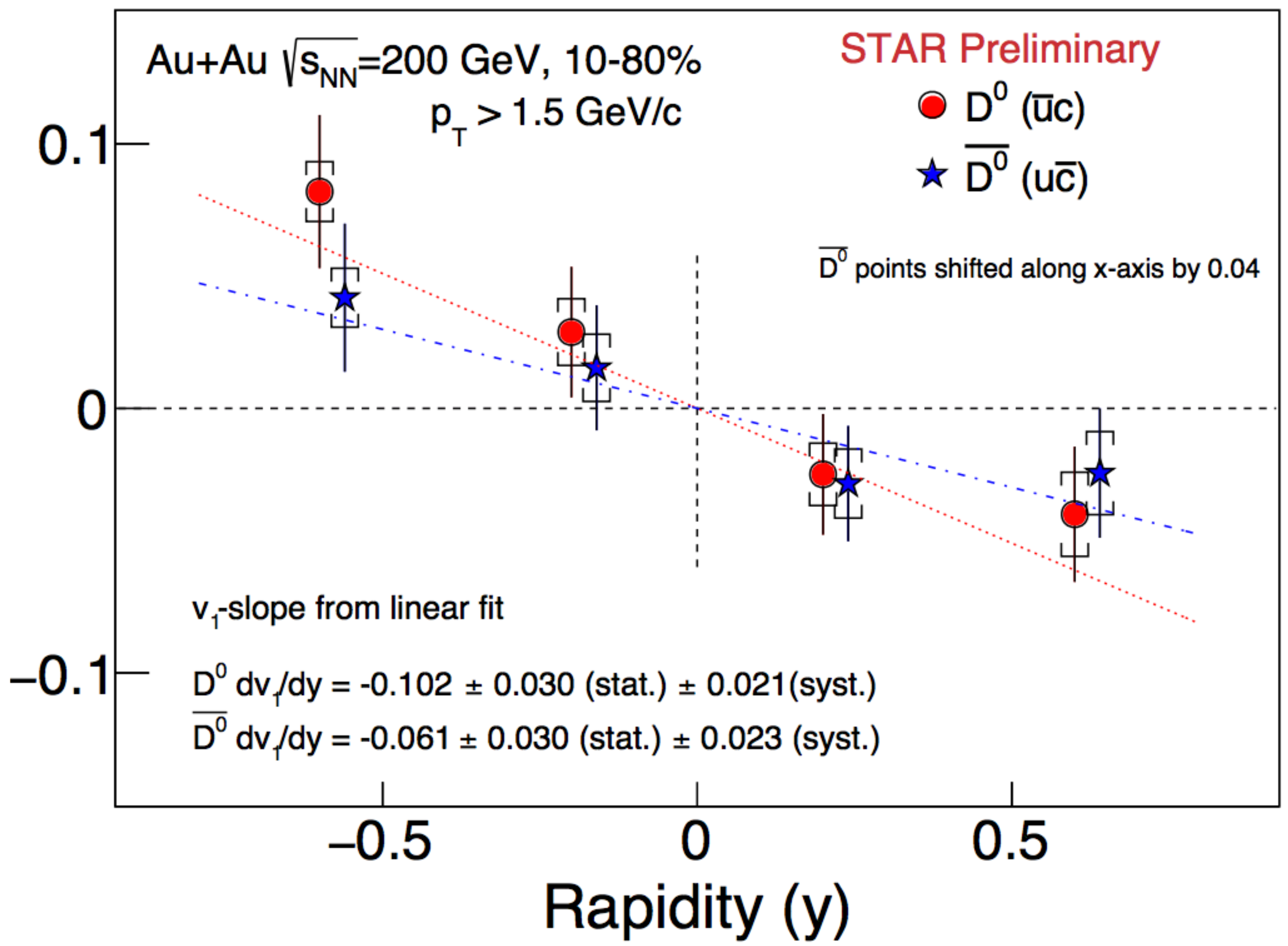
Phys. Rev. C 79 (2009) 64903
Phys. Rev. Lett. 97 (2006) 152301

- **p_T > 0** GeV/*c*: *D^0* cross-section is smaller in Au+Au than that in p+p with **no strong centrality** dependence.
- **p_T > 4** GeV/*c*: *D^0* cross-section **decreases** rapidly towards central collisions → **energy loss**
- (Tsallis) Blast Wave fits for p_T < 5 GeV/*c*: **smaller <β> and larger T than LF → freeze out earlier?**

D^0 v_1 vs. rapidity



Charged Kaons:
L Adamczyk et. al. (STAR Collaboration),
Phys Rev. Lett. 120, 62301 (2018)



★ First evidence of **non-zero directed flow** for charm hadrons at mid-rapidity.

★ **Charm v_1 > light flavor v_1** (D^0 vs. $K^{\pm}$)

Chatterjee, Bojek: Phys Rev Lett 120, 192301 (2018), 1804.04893v1

→ (**Hydro**) Qualitatively explained by charm quarks dragged by a tilted source in a hydrodynamic model

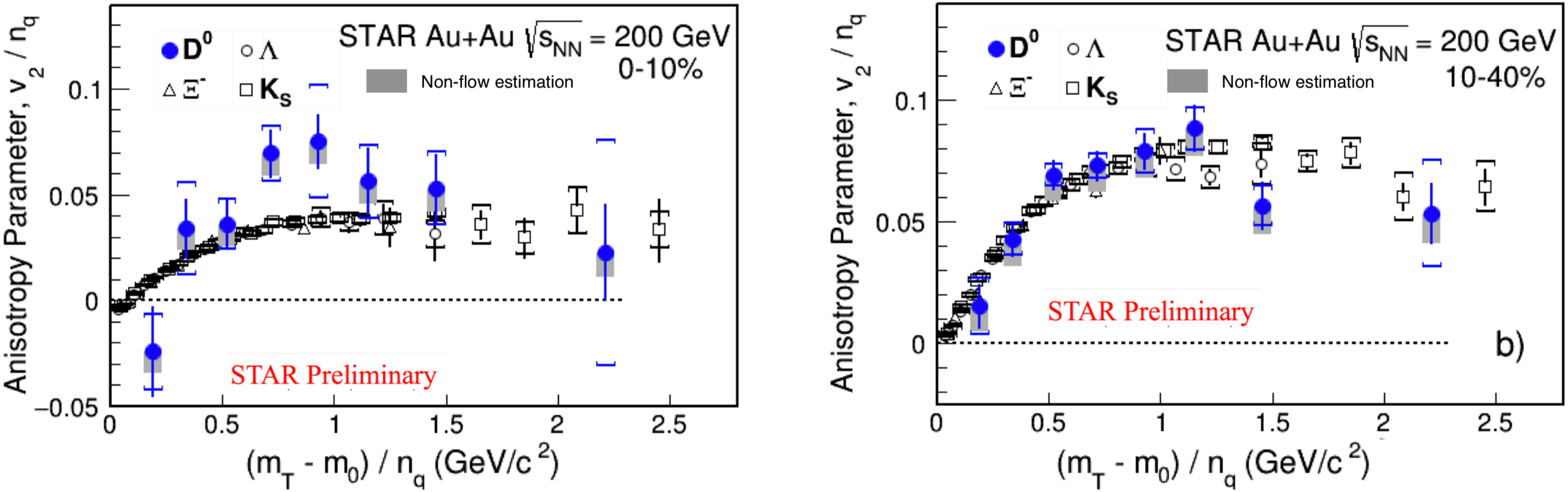
★ Both $\boldsymbol{D^0}$ and $\boldsymbol{\overline{D^0}}$ v_1 show a **negative slope**

→ Predicted splitting of v_1 due to **strong initial EM field** Das et. al., Phys Lett B 768, 260 (2017)

→ Current precision is not sufficient to draw conclusions about difference between D^0 and anti-D^0 v_1.

NCQ-scaling for D^0 v_2

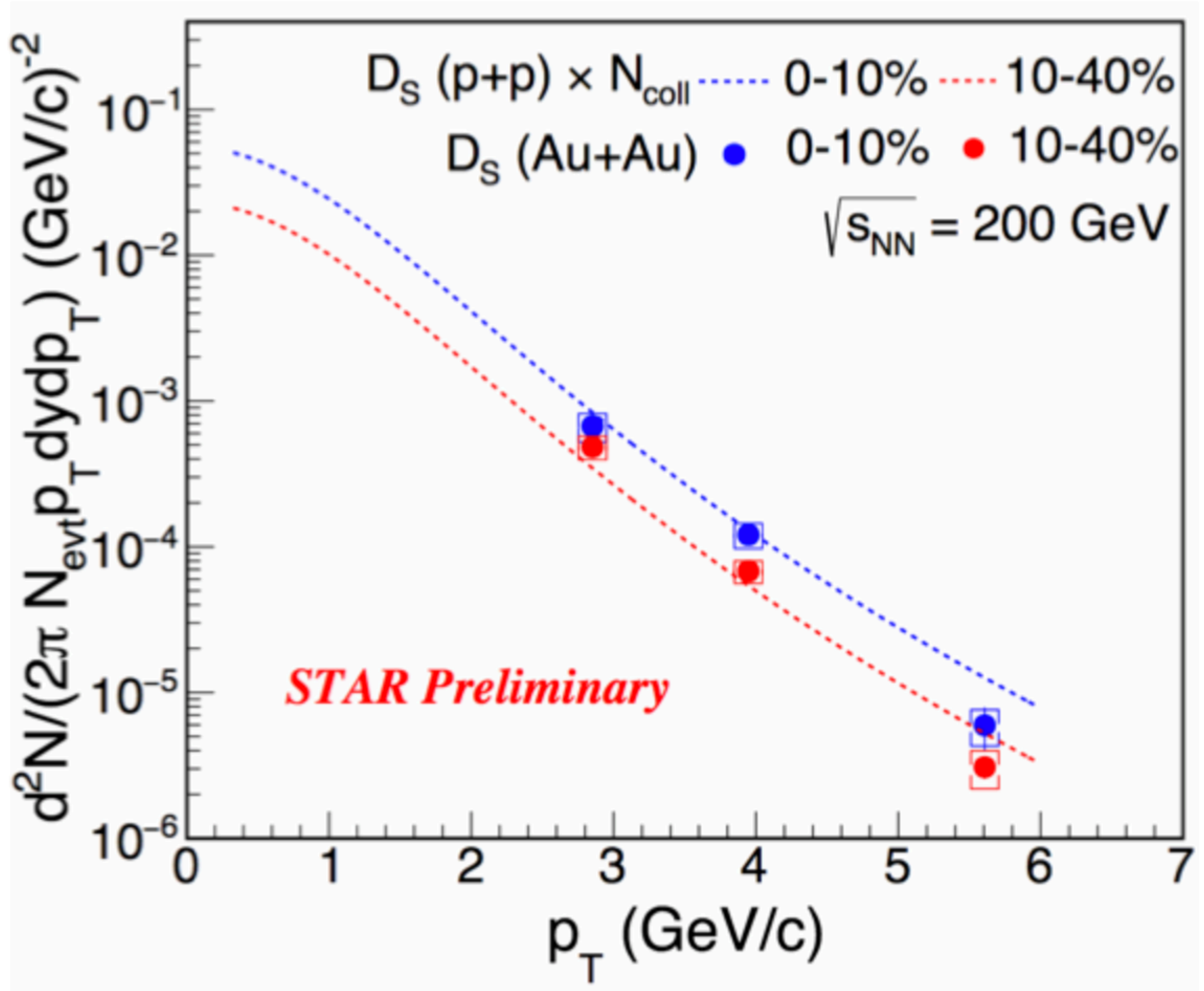
L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 118, 212301 (2017)

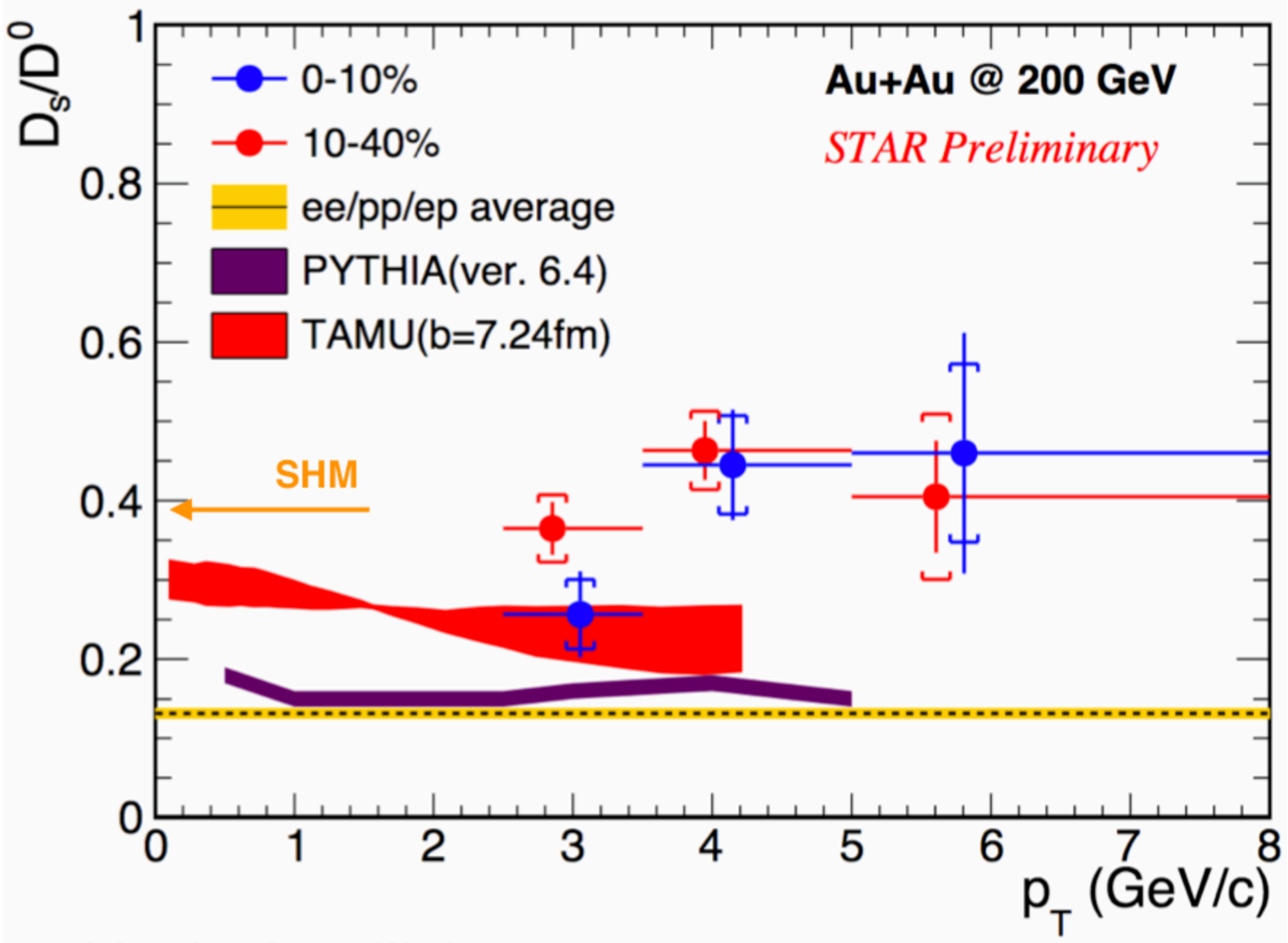


★Improved precision of D^0 v_2 results with combined 2014 and 2016 data
→ D^0 v_2 measurement extended to 0-10% centrality with event plane method

★NCQ-scaled D^0 v_2 is consistent with light flavors.
→ Charm quarks **acquire** collectivity at RHIC

D_s enhancement

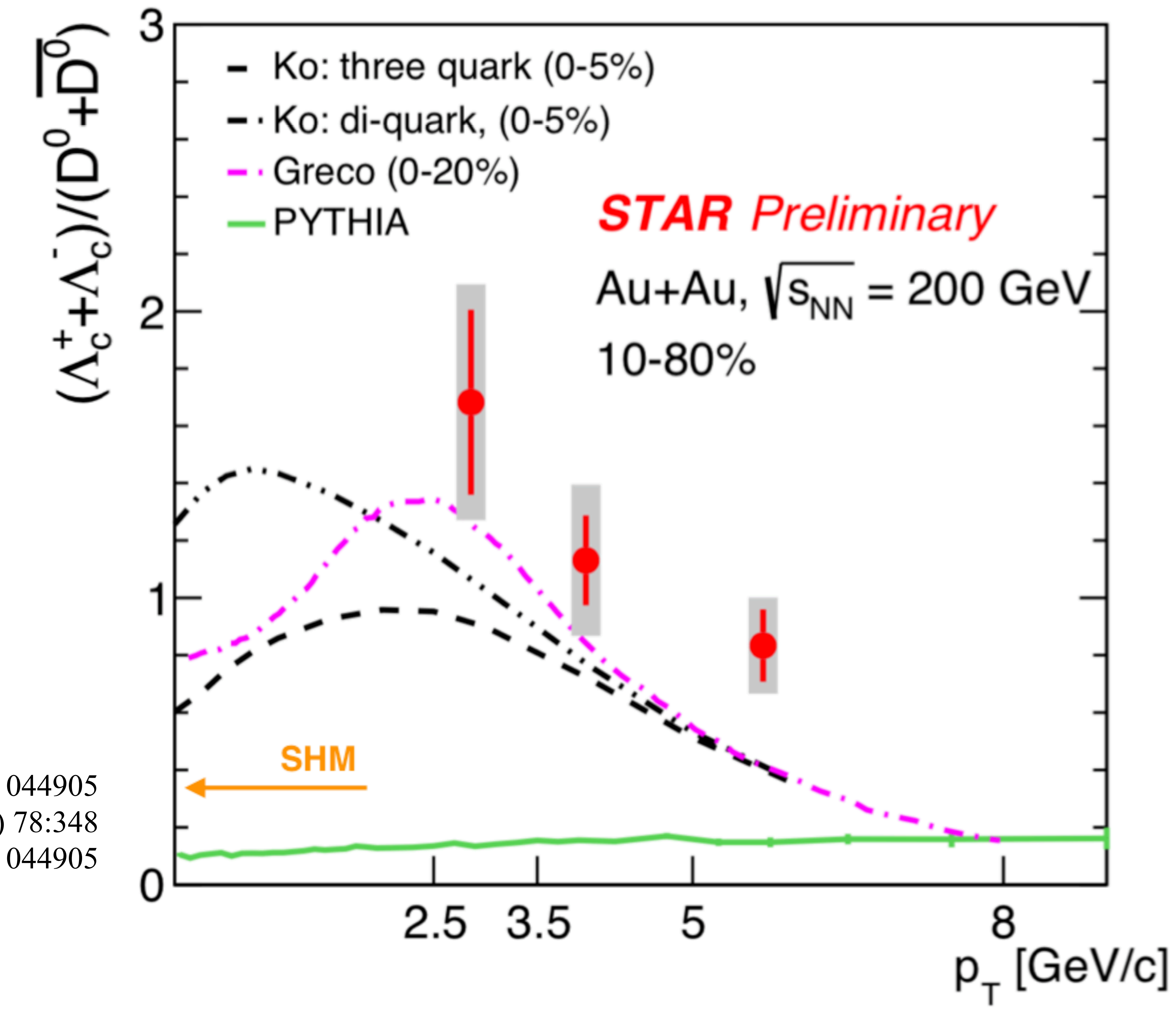




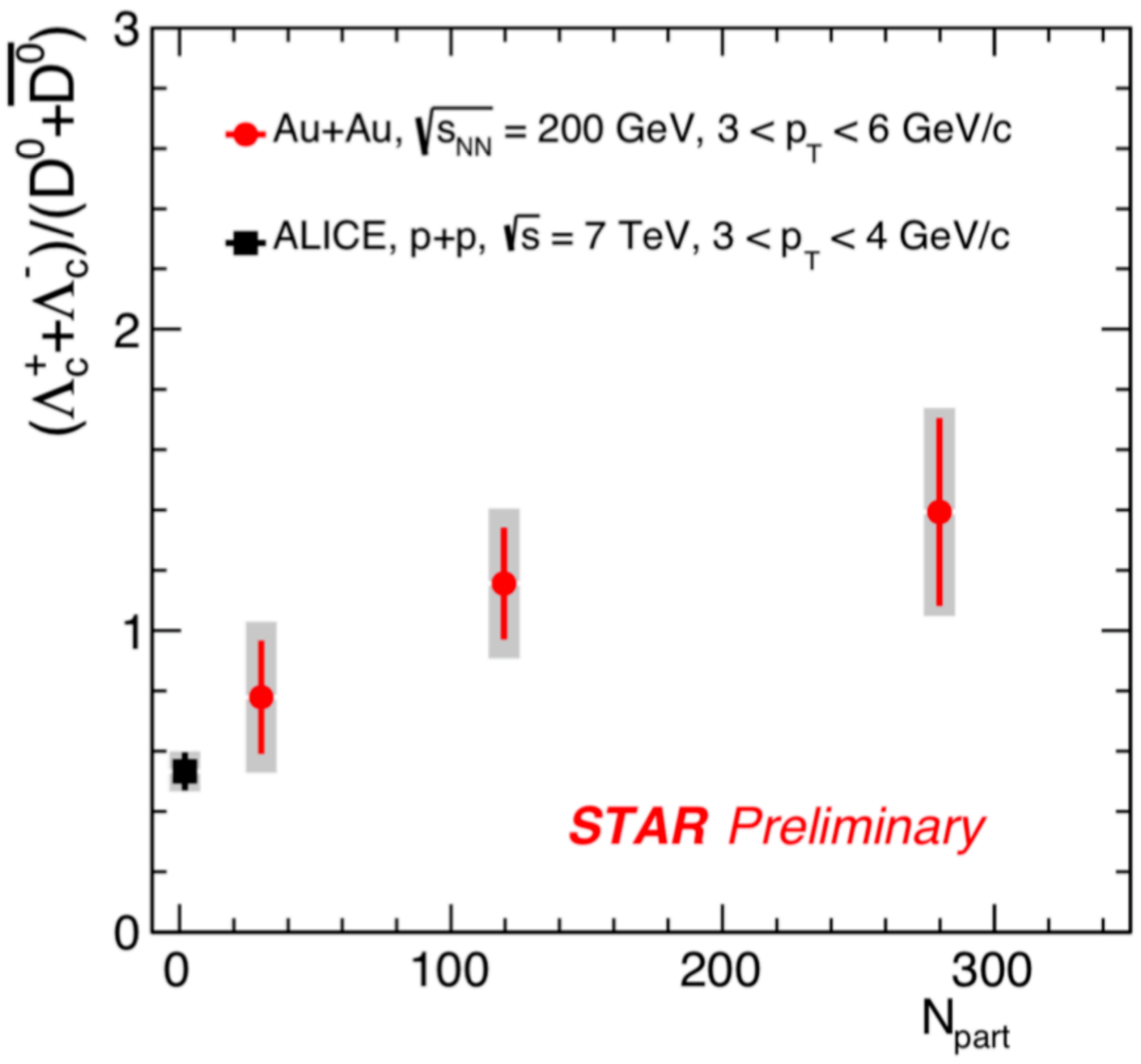
ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, 397 (2016)
TAMU: H. Min et al. PRL 110, 112301 (2013)
SHM: A. Andronic et al., PLB 571 (2003) 36

- **Enhancements** in D_s/D^0 ratio are observed in 200 GeV Au+Au collisions compared to elementary collisions and PYTHIA prediction.
- No evidence of centrality dependence within uncertainties.
- The enhancement is larger than the TAMU calculations.
- Strangeness enhancement and **coalescence hadronization**

Λ_c/D^0 ratio vs. p_T and centrality



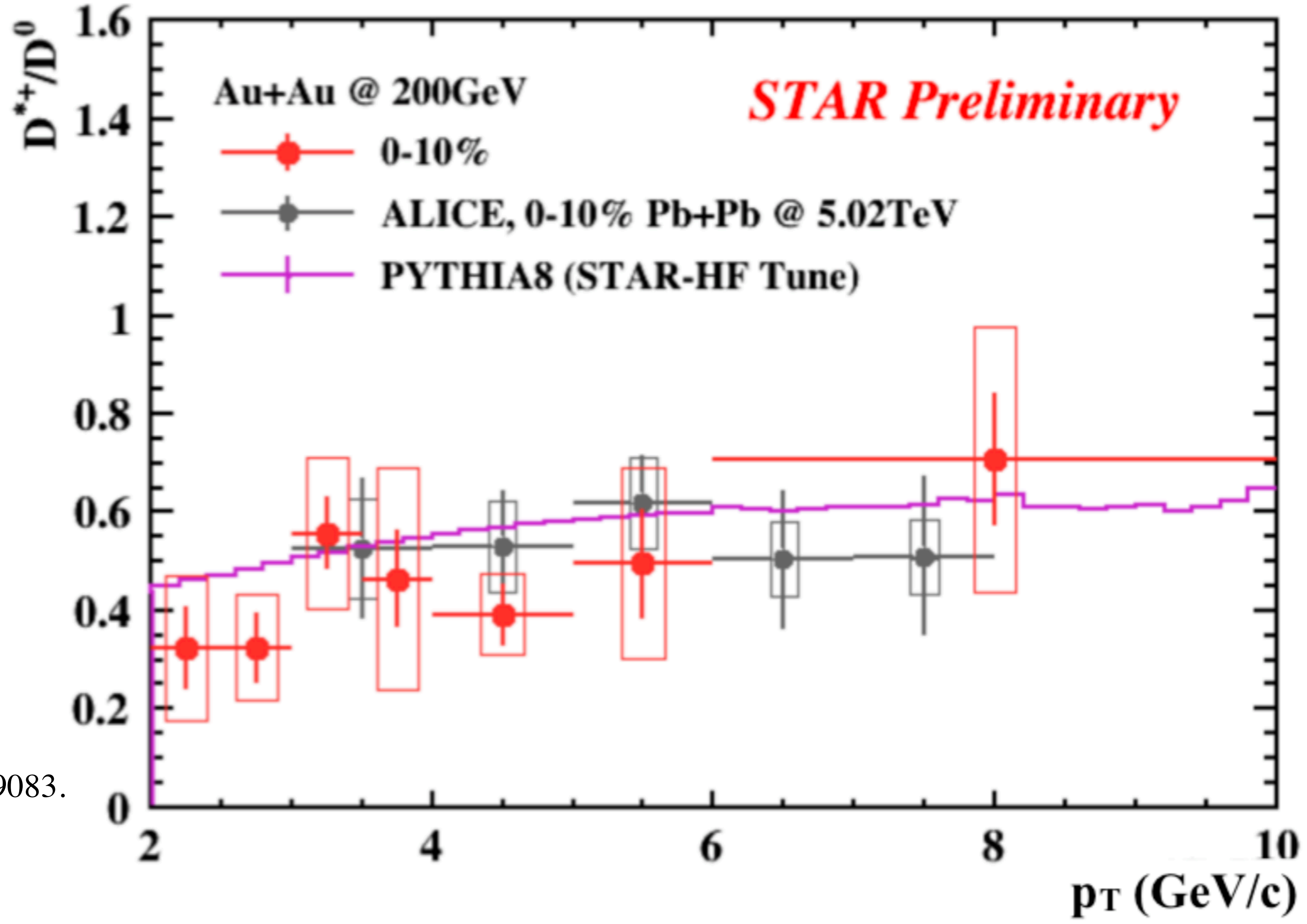
Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905



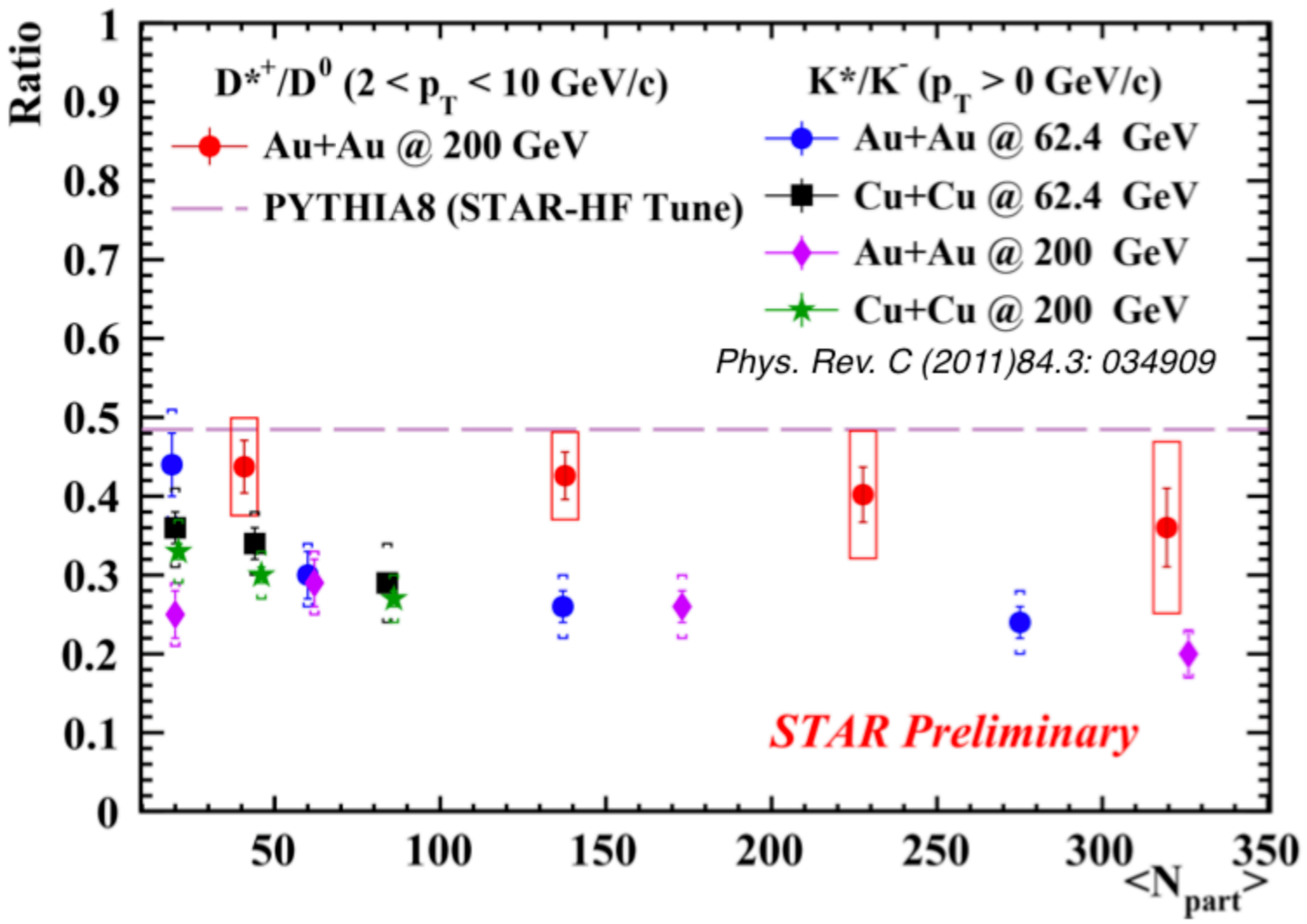
ALICE: arXiv:1712.09581

- New measurements for Λ_c as functions of p_T and centrality (N_{part}).
  - 2014+2016 data: Boosted Decision Trees tuning
- **Strong enhancement** - increasing towards **low p_T** and **central collisions**
- **Coalescence hadronization?** The coalescence model predictions are closer to data than PYTHIA, but the measured enhancement is larger than the model calculations, particularly at higher p_T.

D^*/D^0 ratio vs. p_T and centrality



ALICE Collaboration. arXiv:1804.09083.



- New ***D**** measurement in 200 GeV Au+Au collisions.
  - Feed-down contribution to D^0 yields ($D^{*+} \rightarrow D^0 X$ (~100%), PDG)

R.Rapp et.al Phys. Rev. C (2018)97, 034918

  - Hot medium effects: possibly **shorter lifetime** and **rescattering**

STAR, Phys. Rev. C (2011)84, 034909

- The D^*/D^0 ratio is consistent with ALICE measurement and PYTHIA calculation.
  → No strong system or collision energy dependence.
- The D^*/D^0 ratio of integrated yields within $2 < p_T < 10$ GeV/c shows no strong centrality dependence.

Charm measurements at STAR

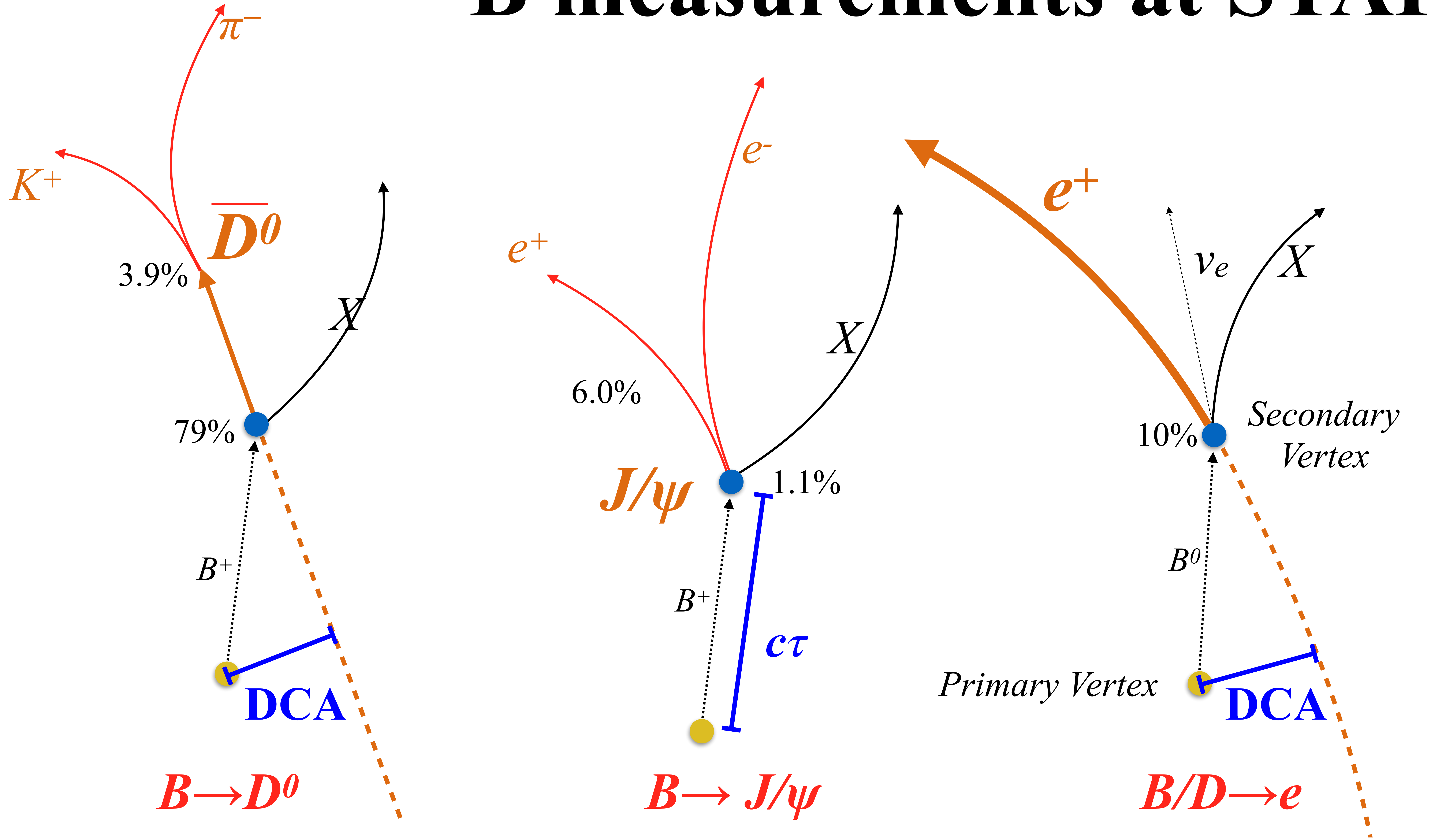
Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+/D^0 ratio in 10-80%**

The total charm cross consistent with p+p

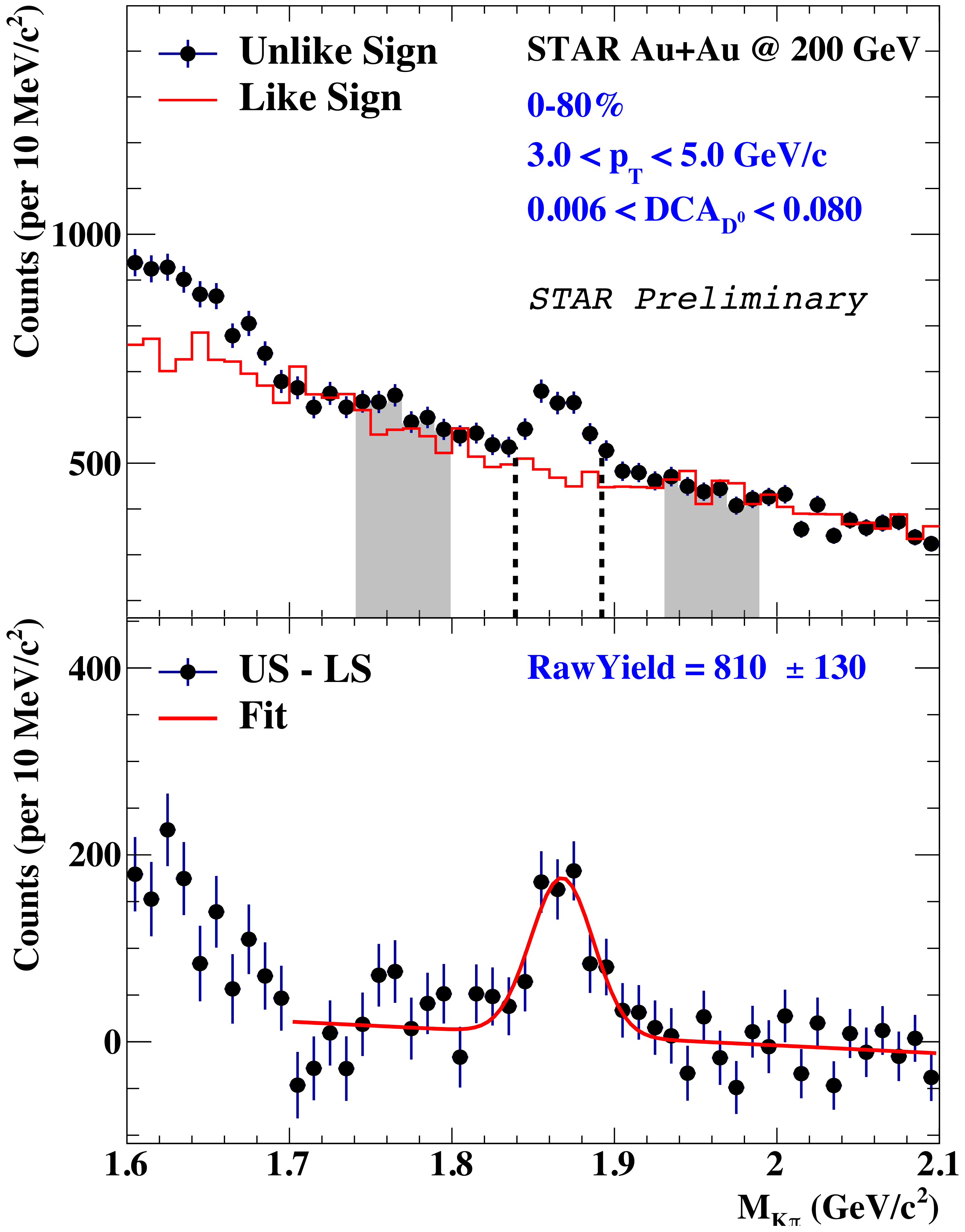
- **Extensive measurements of charm production in 200 GeV Au+Au collisions**
    - Λ_c - **Strong enhancement** in low p_T and central collisions
    - D^0 - Precise measurements of $\mathbf{R_{AA}}$, and **directed and elliptic flow** → Strong suppression at high p_T and significant v_1 and v_2 signals
    - $D^{\pm}$ - Similar trends with D^0 in R_{AA}
    - D_s - Strangeness enhancement and **coalescence hadronization** in open charm production
    - D^* - New measurement of D^*/D^0 ratio

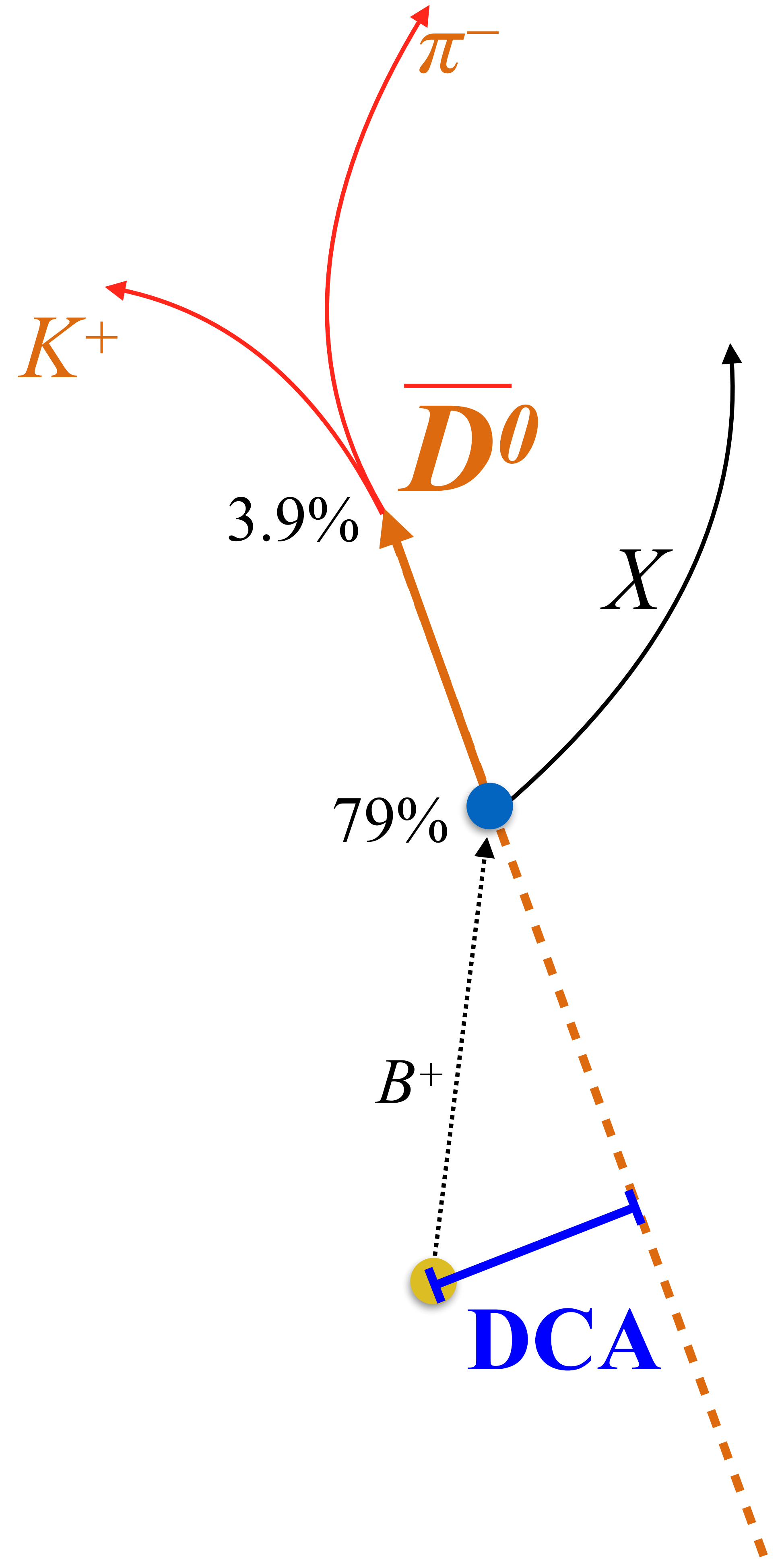
B measurements at STAR

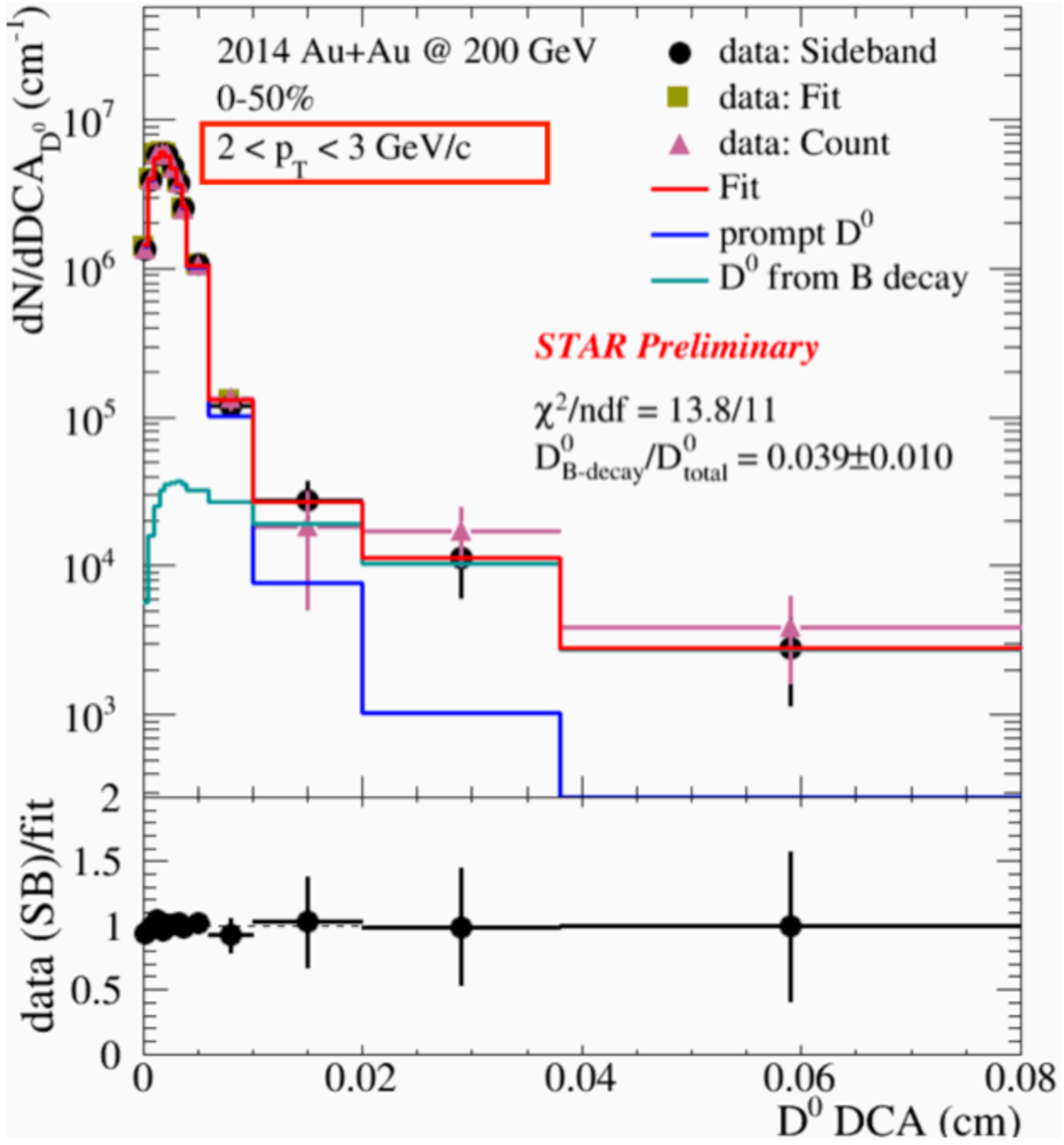


- Measurements of 3 different decay channels of open bottom hadrons enabled by the HFT.
  → $B \to D^0$ in 0-20% centrality (2014)
  → $B \to J/\psi$ in 0-80% centrality (2014 + 2016)
  → $D \to e$ and $B \to e$ in 0-80% centrality (2014)

$B \to D^0$ in 200 GeV Au+Au collisions



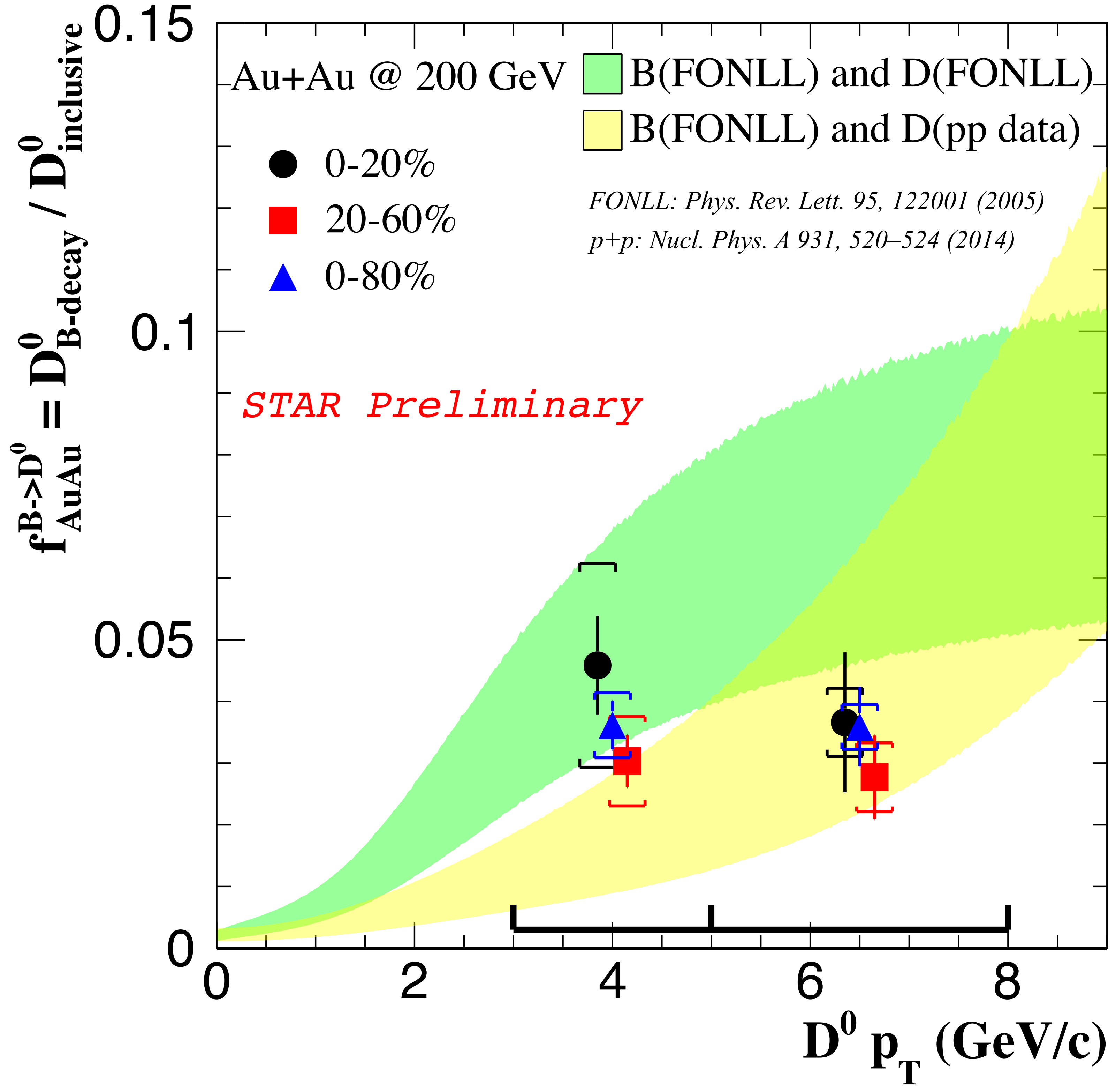


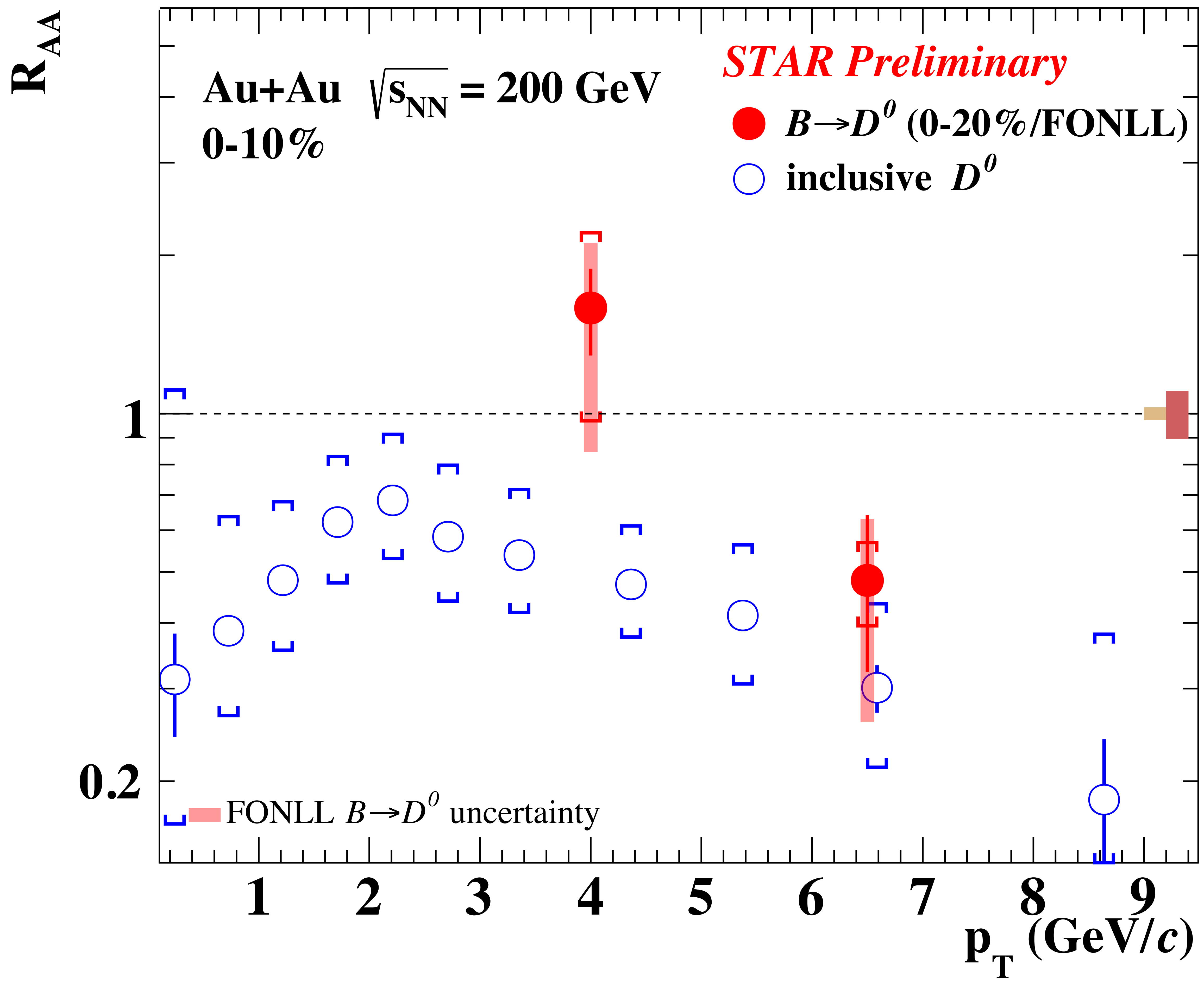


- Background is extracted from side-bands.
- D^0 DCA distribution is fitted with non-prompt and prompt D^0 templates.

$B \rightarrow D^0$ in 200 GeV Au+Au collisions

$$R_{AA}^{B\rightarrow D^0} = \frac{1}{<N_{coll}>} \frac{f_{Au+Au}^{B\rightarrow D^0} \times dN_{Au+Au}^{incl.\ D^0}/dp_T}{dN_{FONLL}^{B\rightarrow D^0}/dp_T}$$



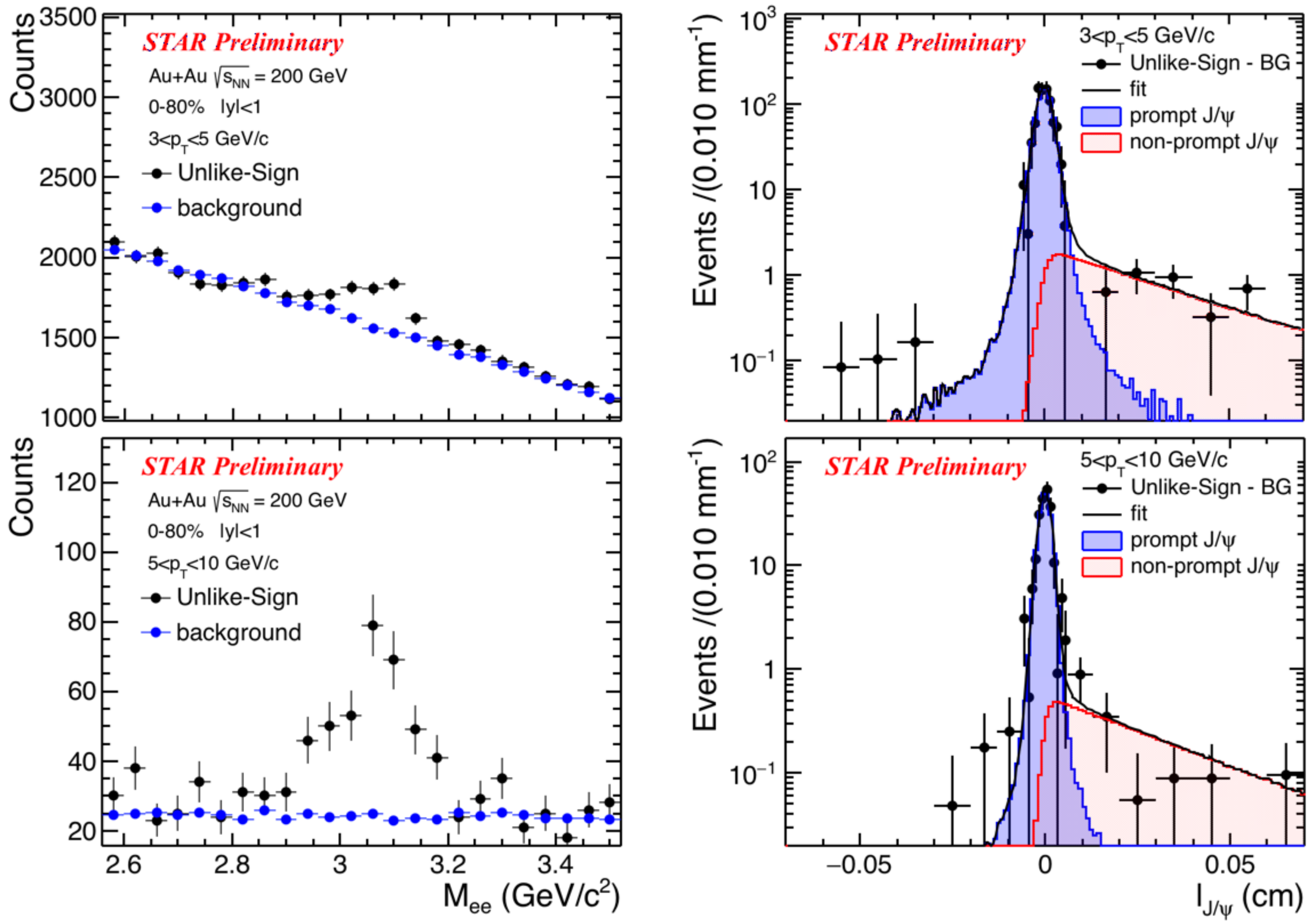


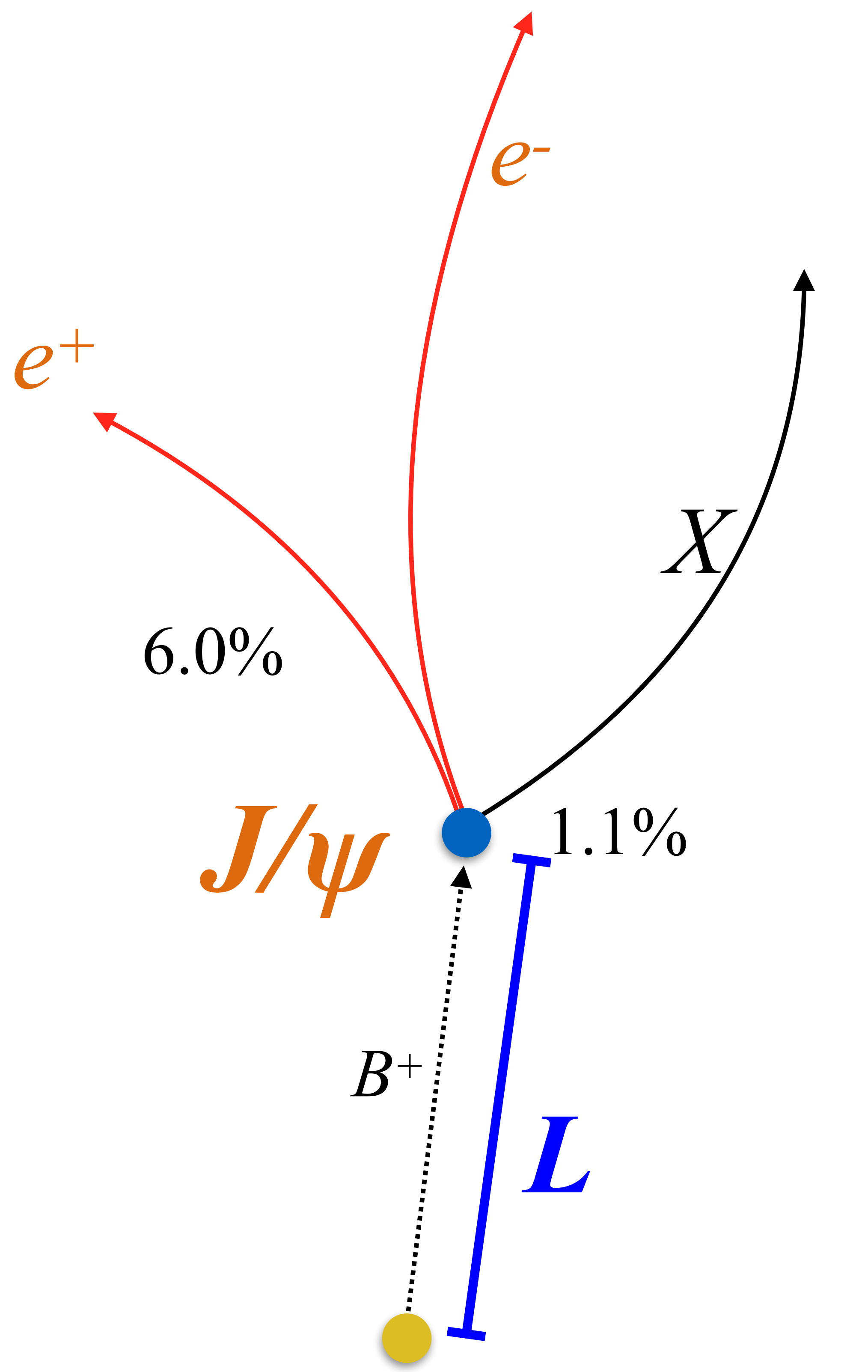
- Nuclear modification factor is calculated with non-prompt D^0 yield from FONLL prediction.

  → Strong non-prompt D^0 suppression at high p_T ($p_T > 5$ GeV/c)

  → Hint of less suppression for non-prompt than prompt D^0 at 3-8 GeV/c

$B \to J/\psi$ in 200 GeV Au+Au collisions



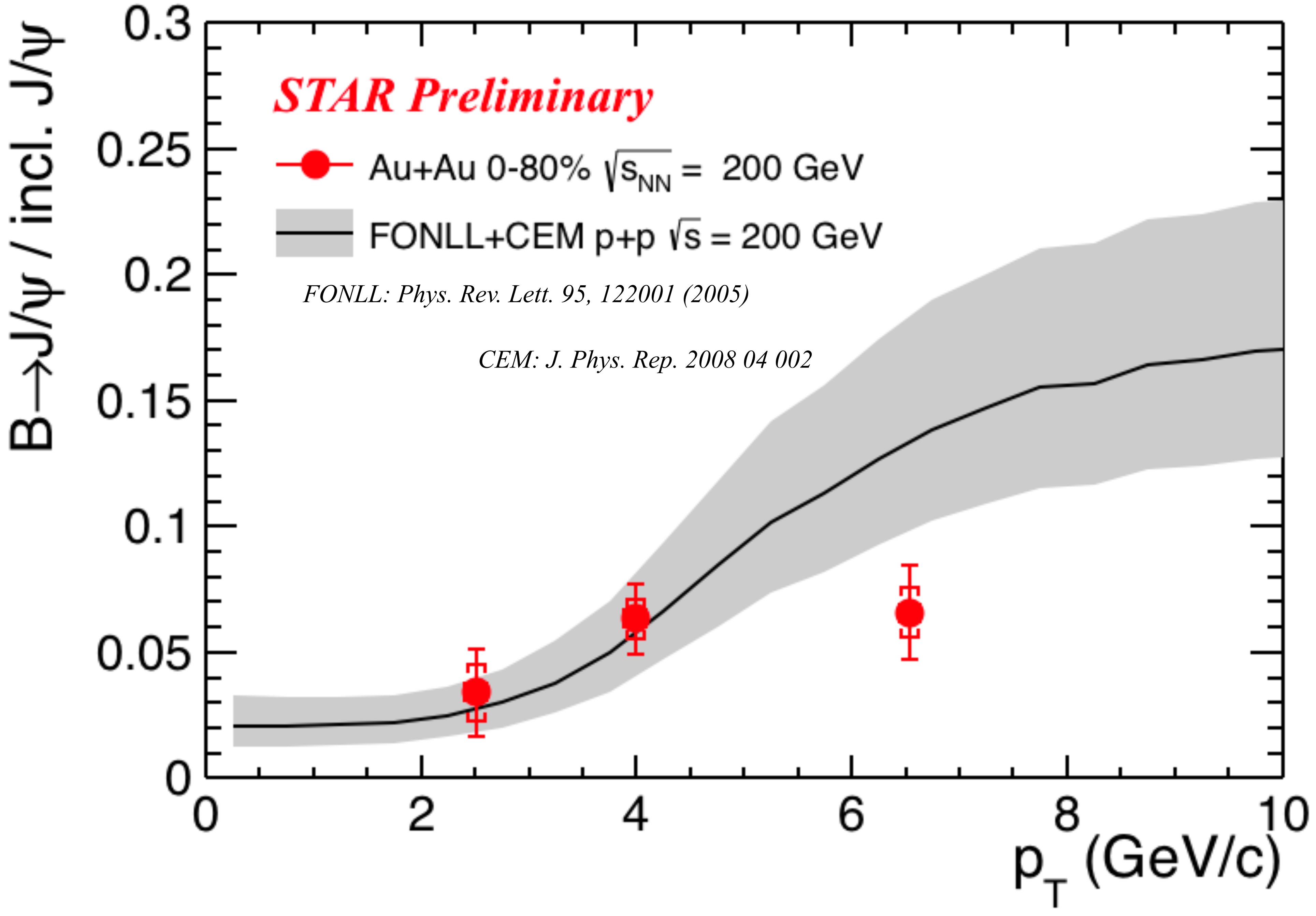


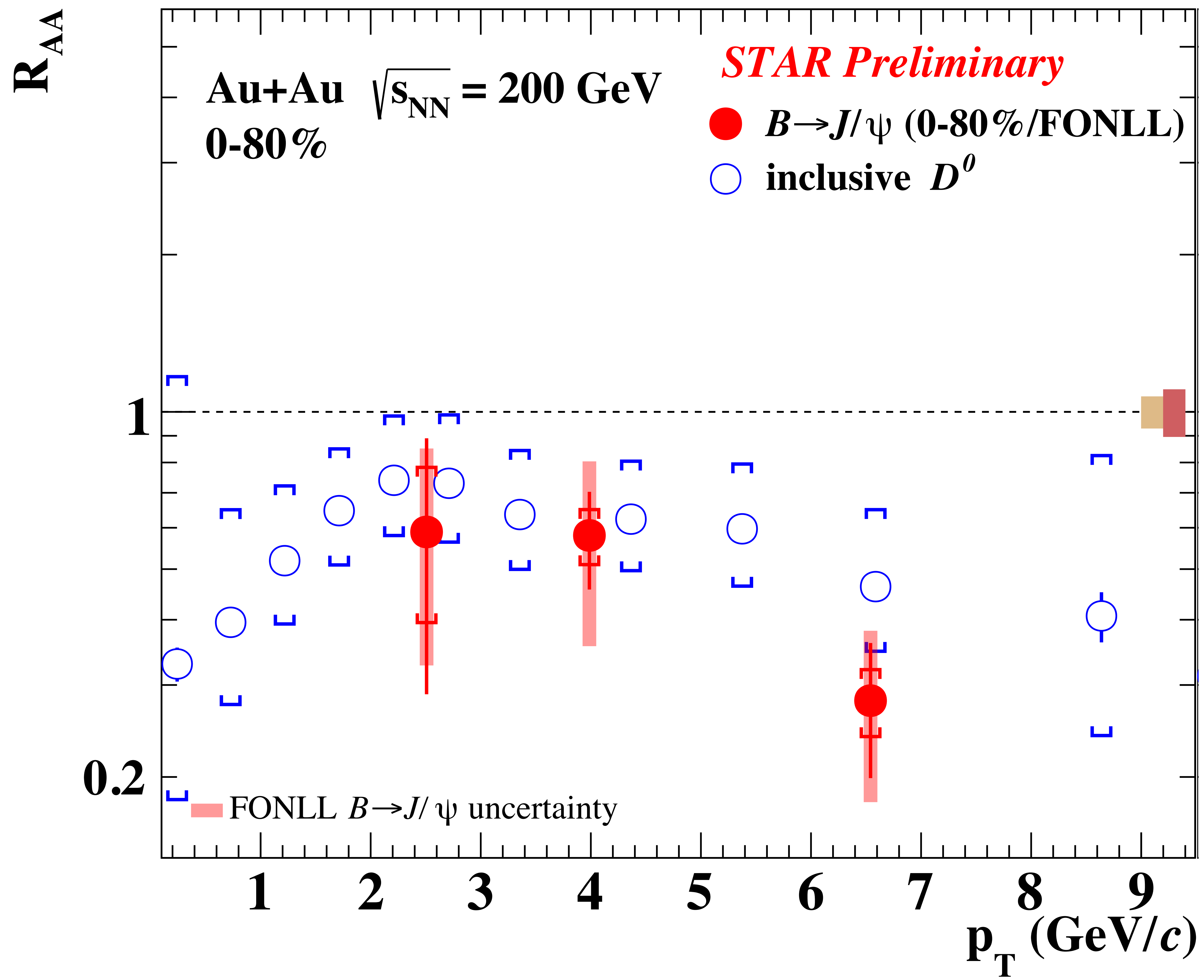
$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|p|/c} M_{J/\psi}$$

- Background is reconstructed using event mixing method.
- $l_{J/\psi}$ distribution is fitted with non-prompt and prompt J/ψ templates.

$B \rightarrow J/\psi$ in 200 GeV Au+Au collisions

$$R_{AA}^{B\rightarrow J/\psi} = \frac{f_{Au+Au}^{B\rightarrow J/\psi}(data)}{f_{p+p}^{B\rightarrow J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data)$$

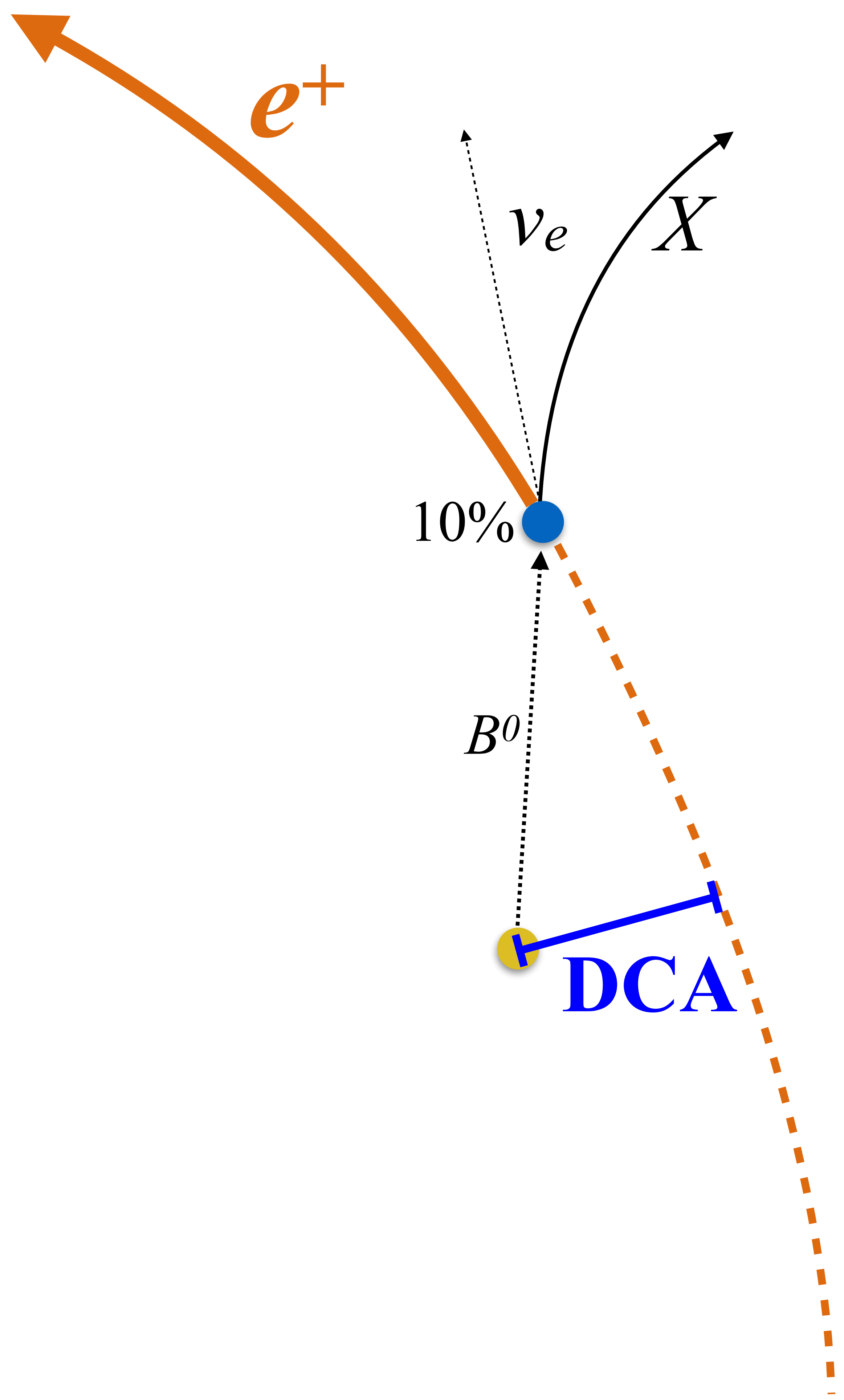


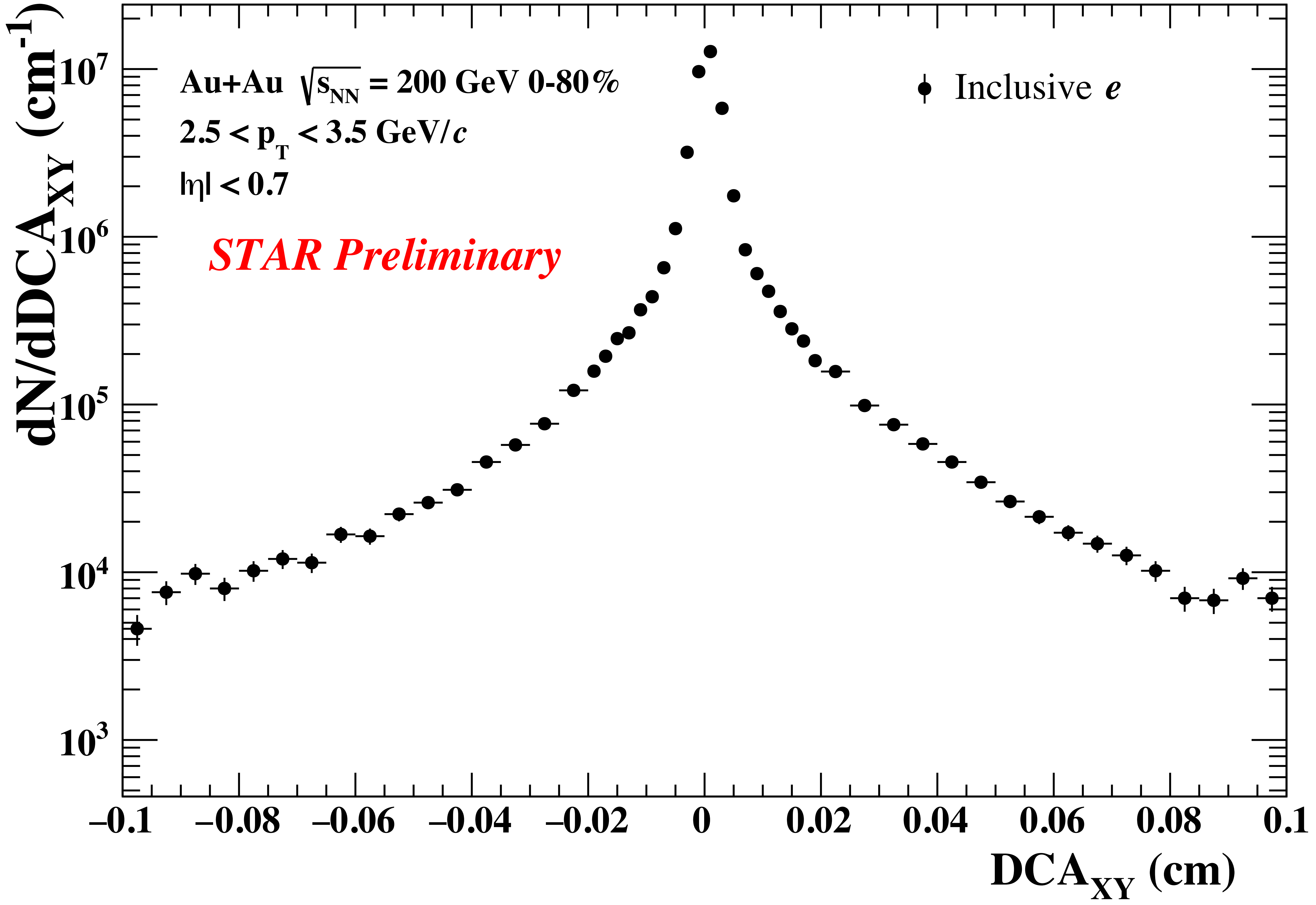


- Nuclear modification factor is calculated with non-prompt J/psi fraction **in p+p from FONLL+CEM** and **in Au+Au from this measurement**.

→ Strong non-prompt J/ψ suppression at high p_T

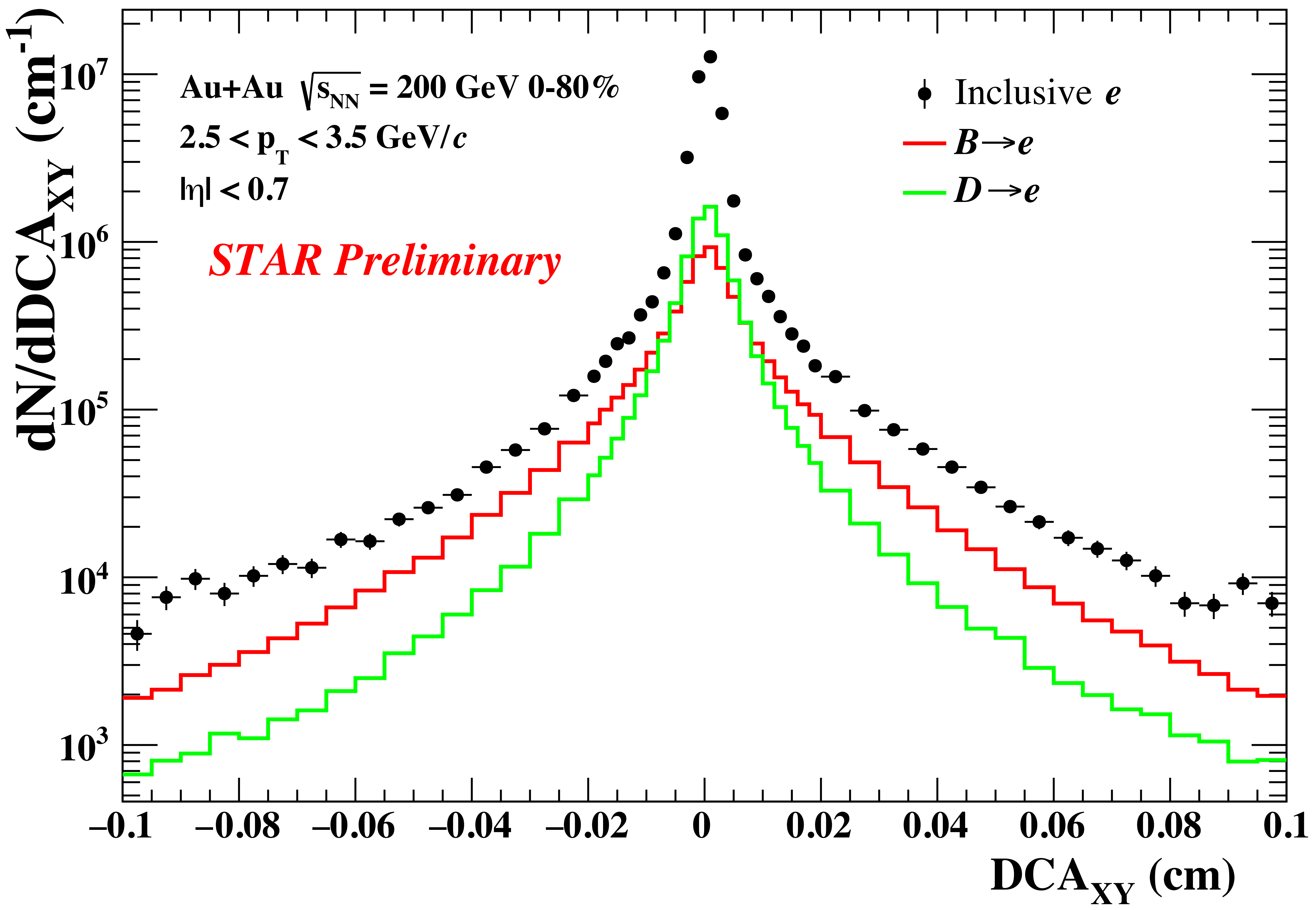
B/D→e in 200 GeV Au+Au collisions





- Inclusive single electron DCA_{XY} distribution fitted to **charm**- and **bottom**-decayed electron, **photonic** electron, and **hadron** contamination templates.

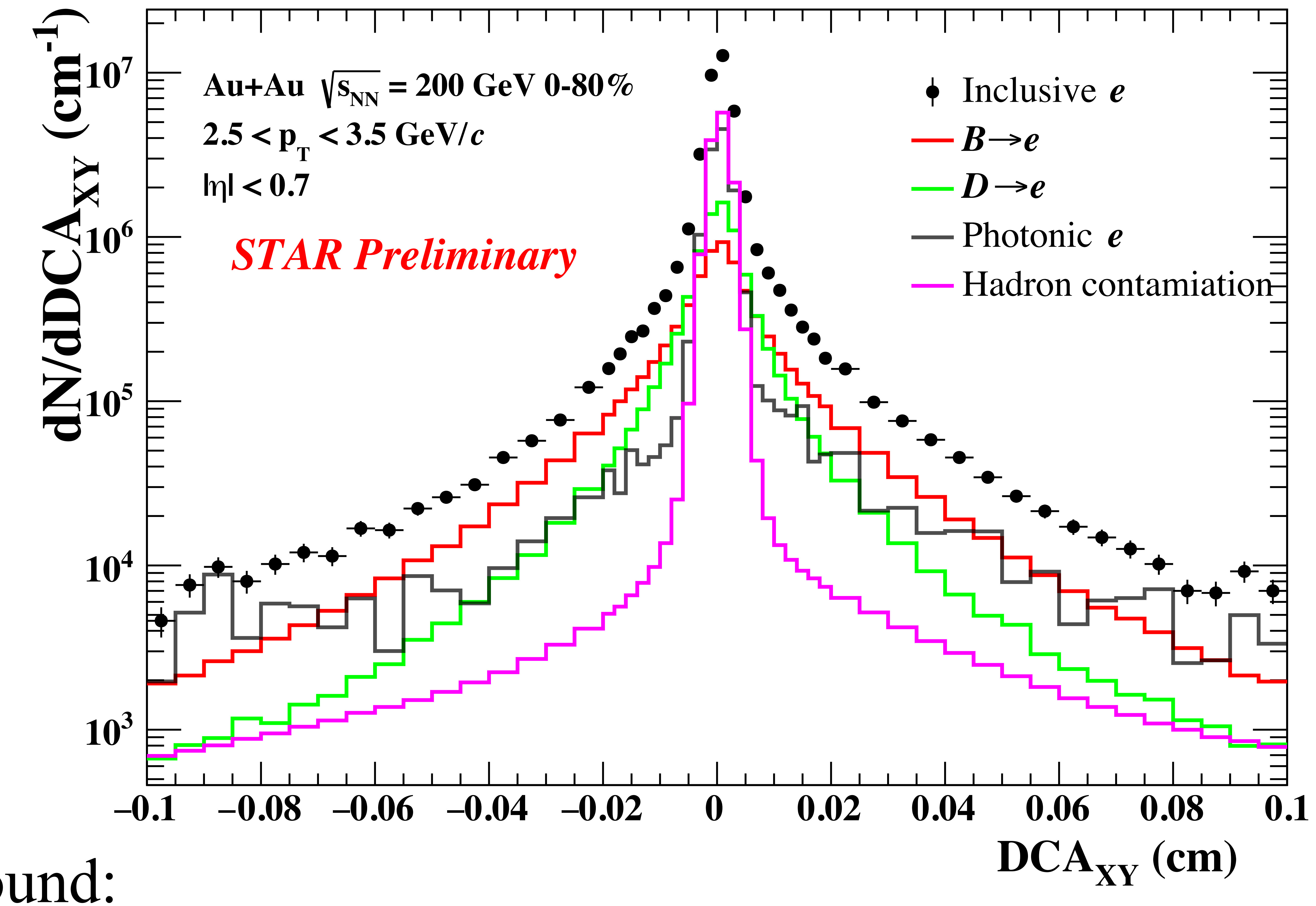
B/D→e in 200 GeV Au+Au collisions



$c\tau(D^0)$	~ 123 μm
$c\tau(D^\pm)$	~ 312 μm
$c\tau(B^0)$	~ 459 μm
$c\tau(B^\pm)$	~ 491 μm

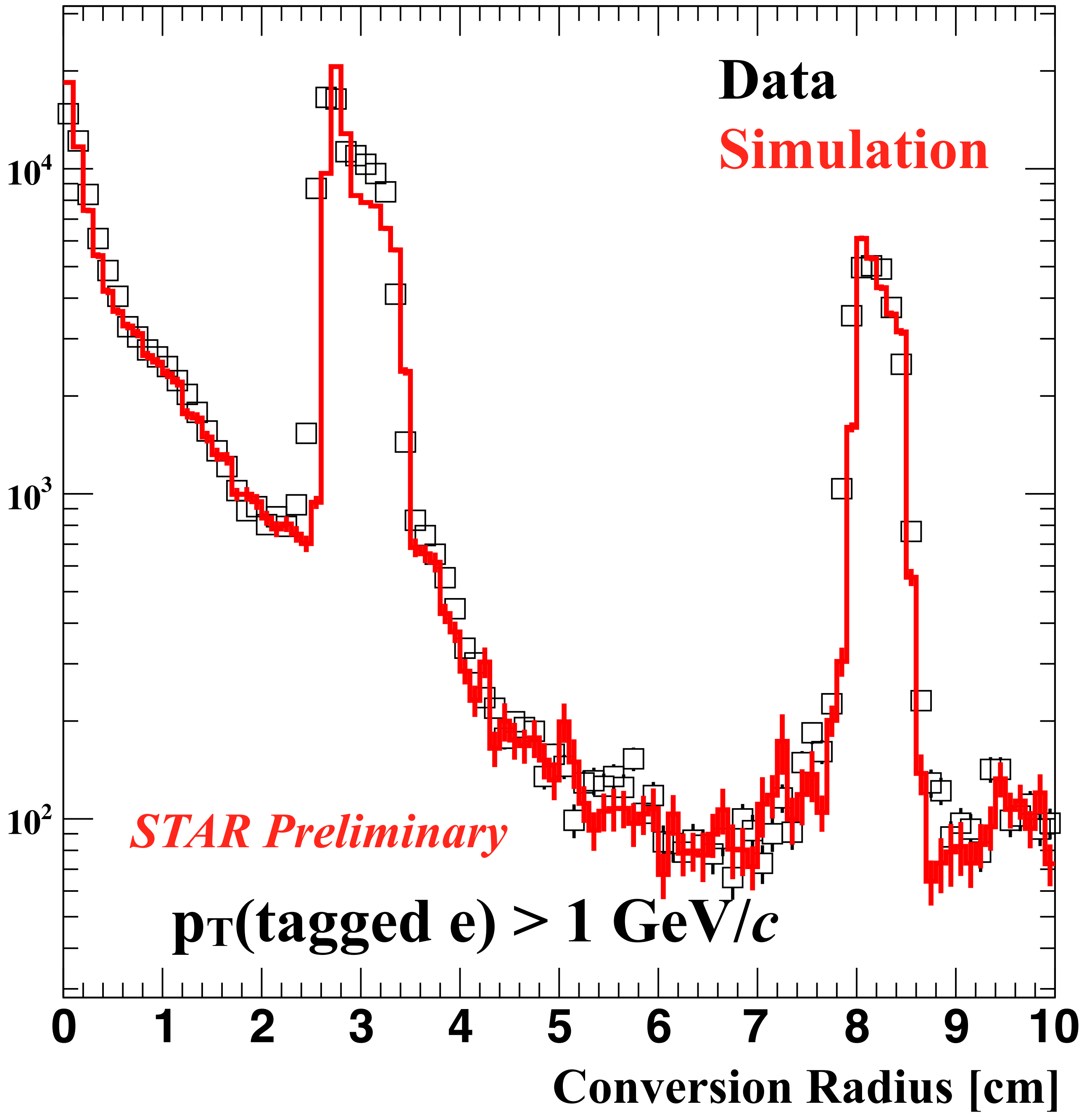
- *B* hadrons have longer life time than *D* hadrons → broader DCA_{XY} distribution for **bottom**- than **charm**-decayed electrons

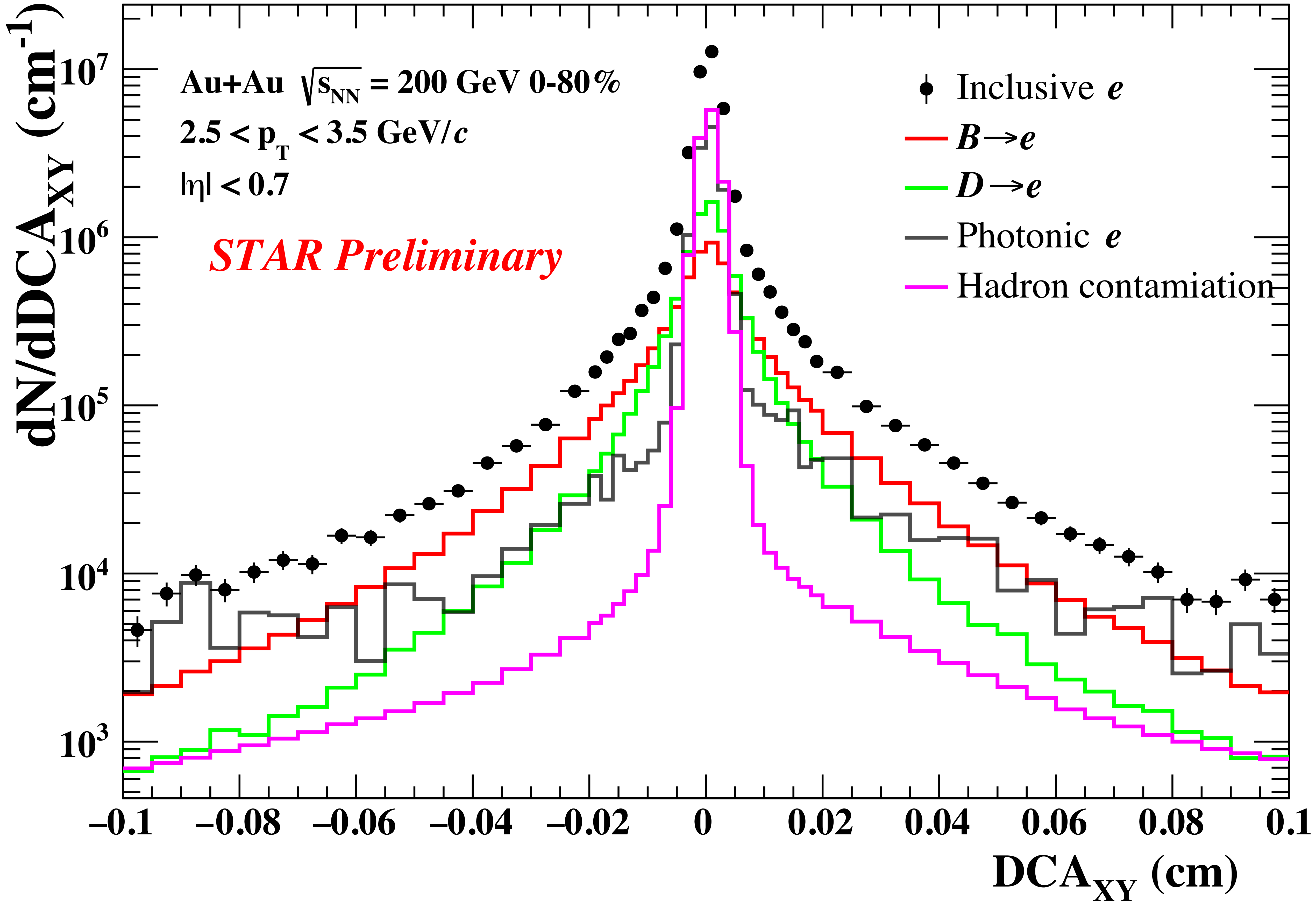
B/D→e in 200 GeV Au+Au collisions



- Background:
  - Mis-identified **hadrons** and electrons from hadron decays
  - **Photonic electron** — gamma conversion and light meson Dalitz decay

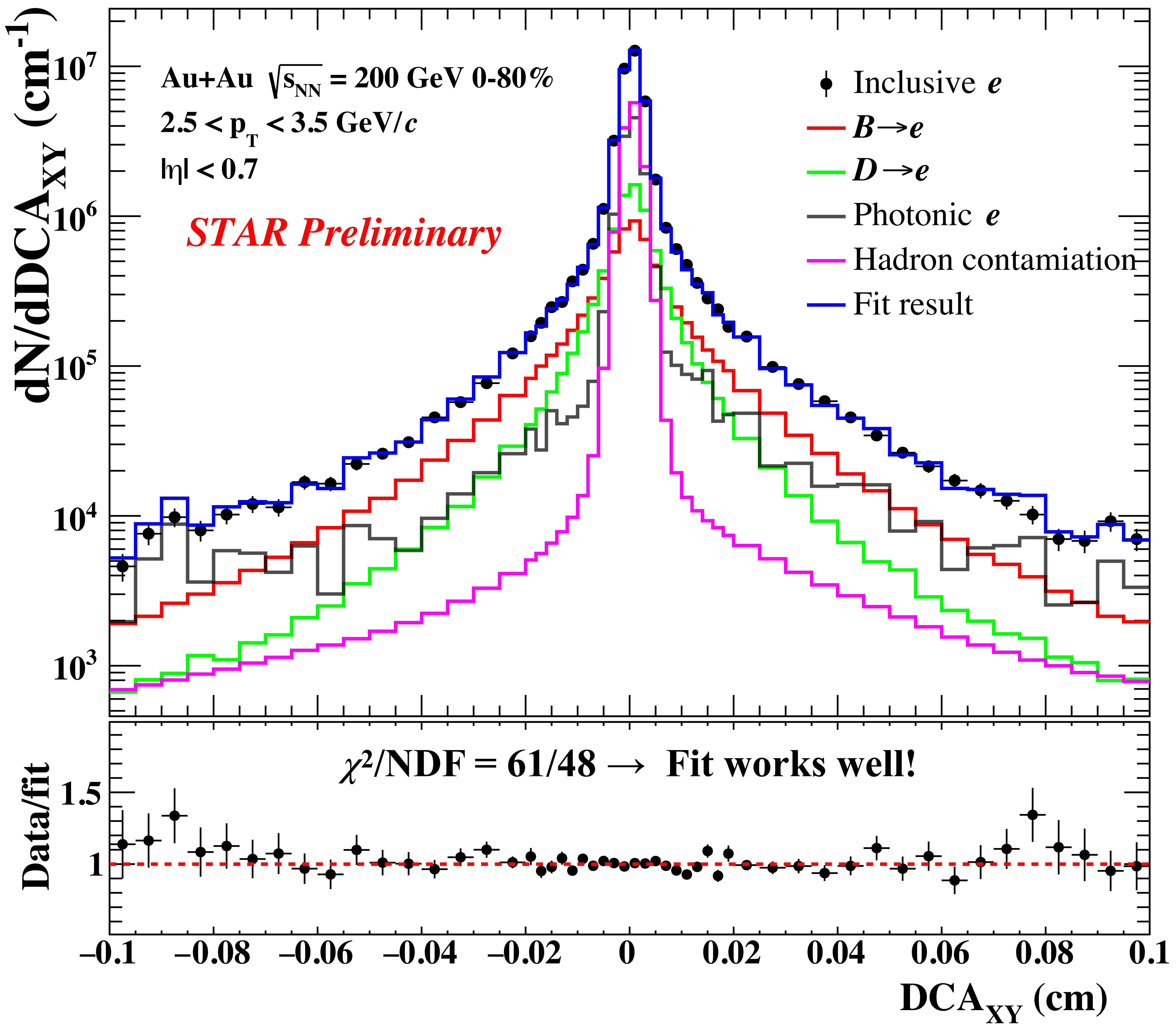
B/D→e in 200 GeV Au+Au collisions



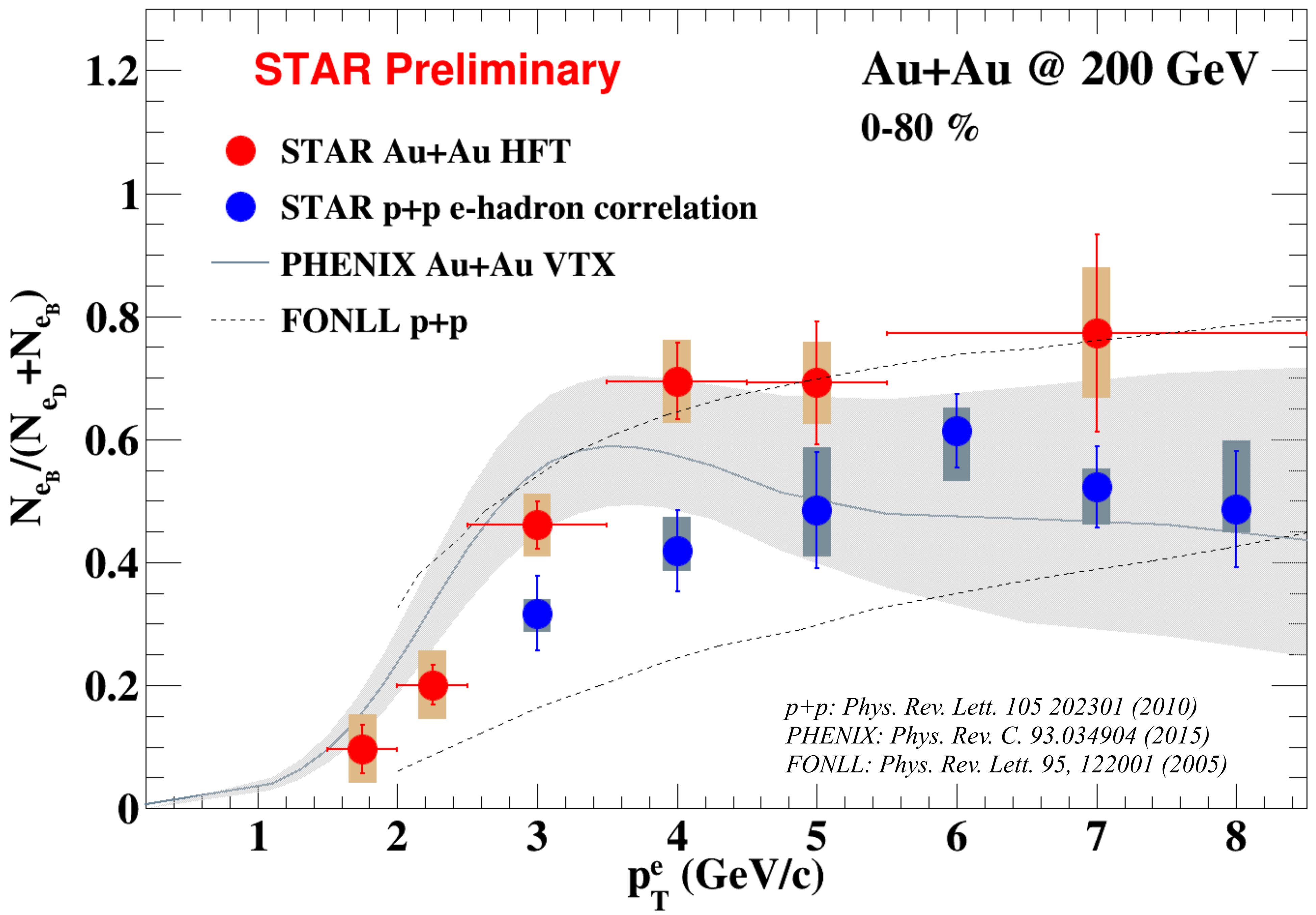


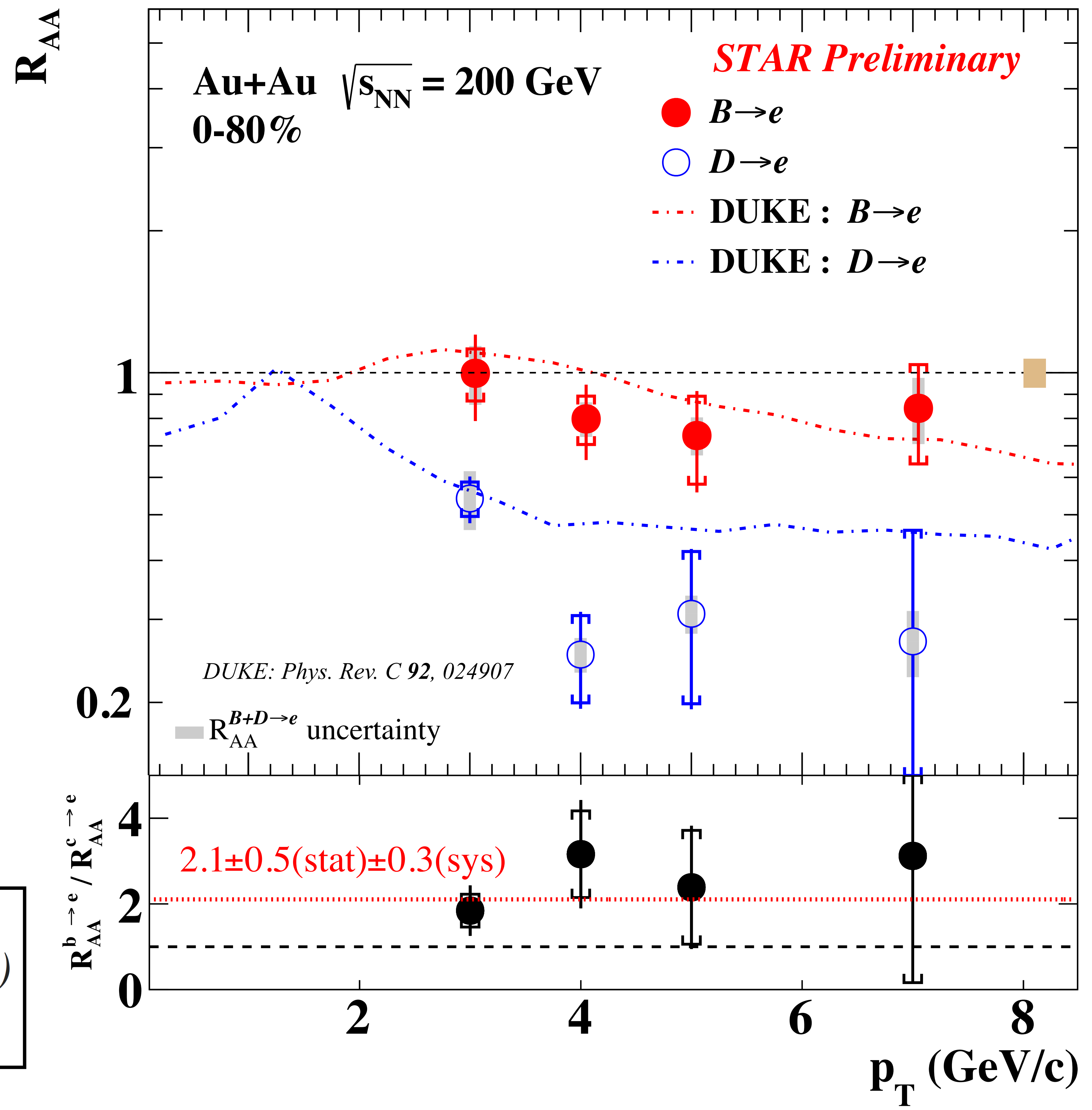
- Radius distribution of photonic electron pairs in data can be well described by detector simulation.

B/D→e in 200 GeV Au+Au collisions



B/D→e in 200 GeV Au+Au collisions

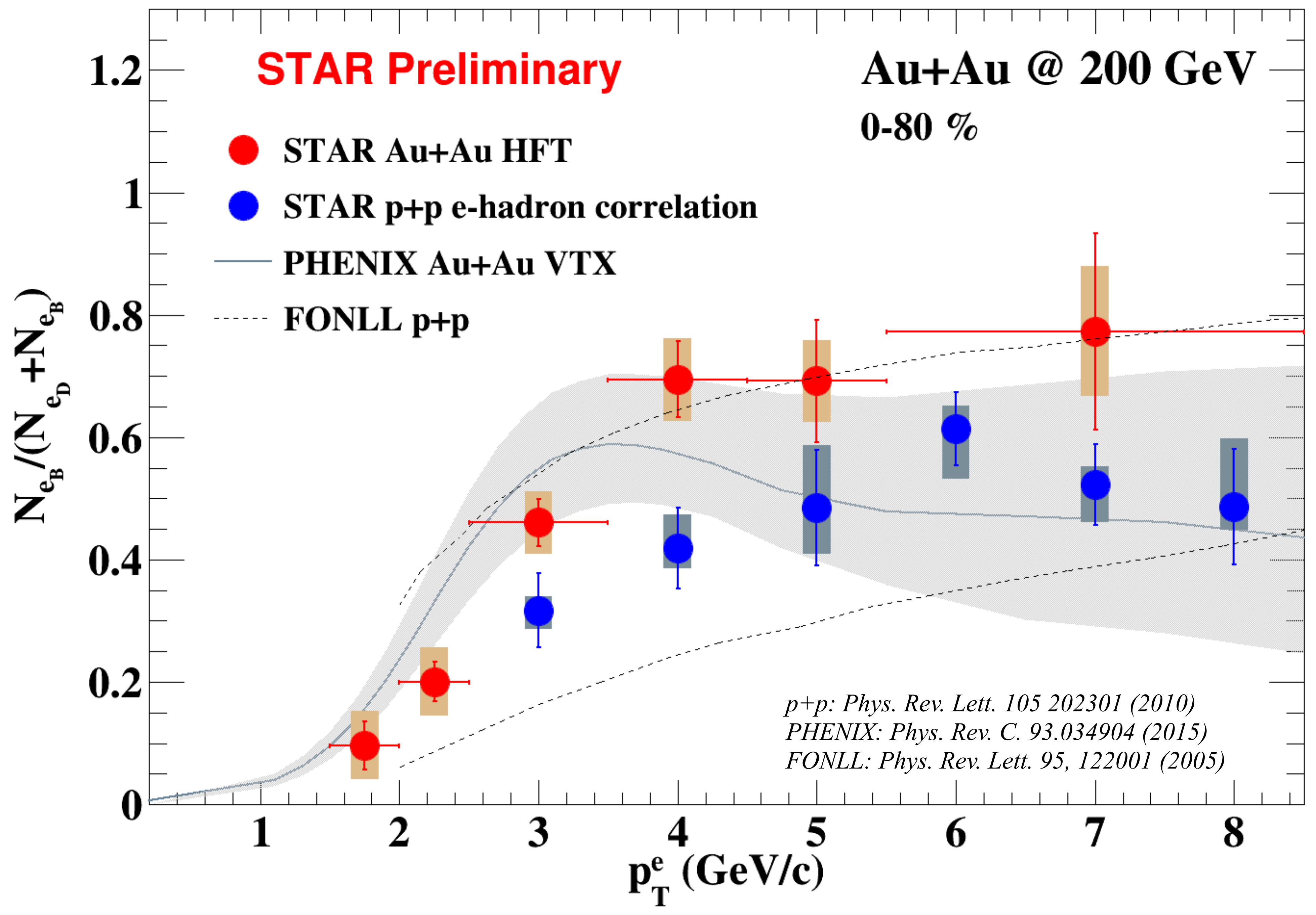


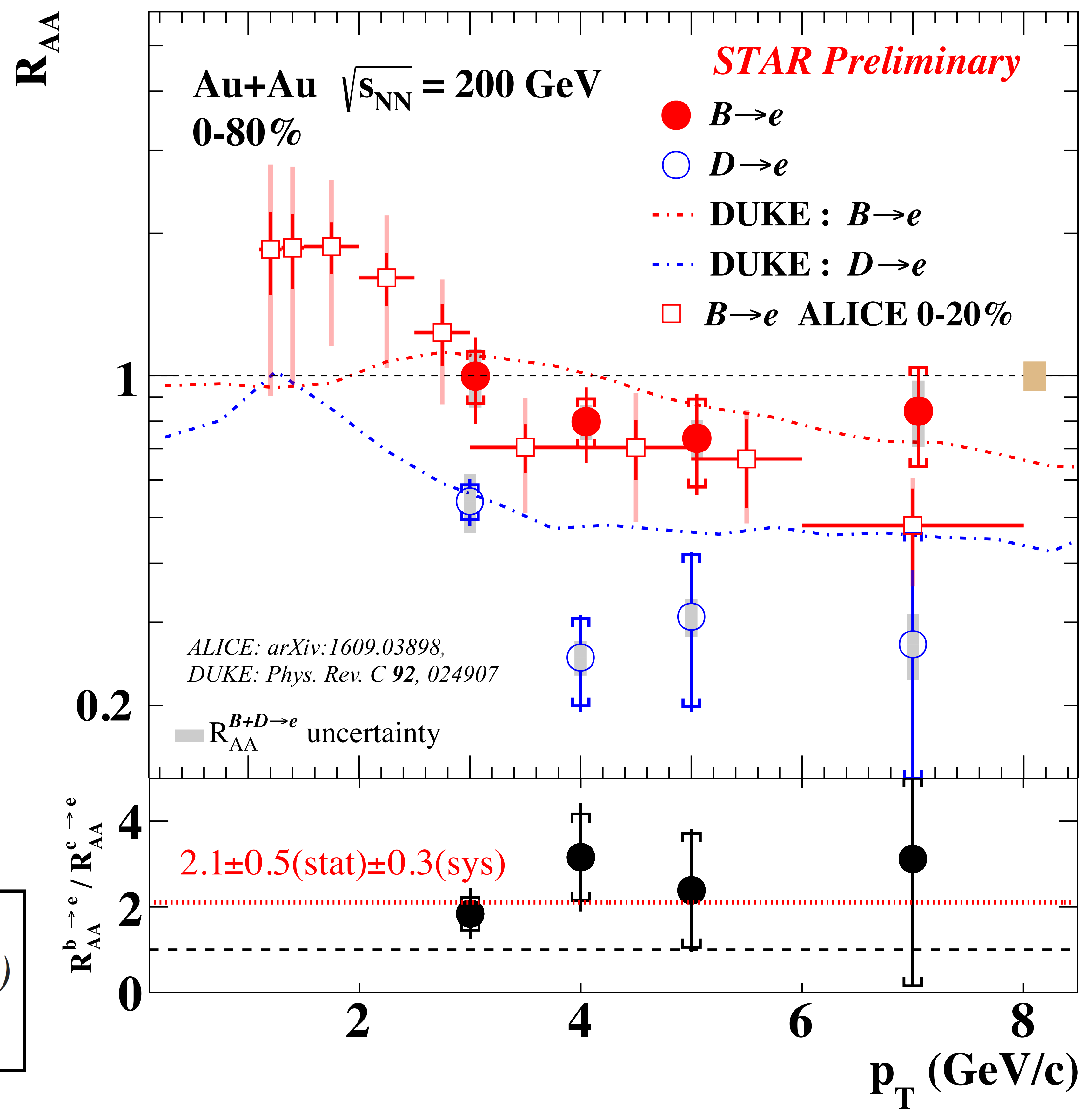


$$R_{AA}^{B\to e}=\frac{f^{B\to e}_{Au+Au}(data)}{f^{B\to e}_{p+p}(data)}R_{AA}^{inc.\ e}(data),\quad R_{AA}^{D\to e}=\frac{1-f^{B\to e}_{Au+Au}(data)}{1-f^{B\to e}_{p+p}(data)}R_{AA}^{inc.\ e}(data)$$

- Nuclear modification factor calculated with inclusive NPE R_{AA}, and bottom-decayed electron fractions measured in p+p and Au+Au.
  → R_{AA} (e_D) < R_{AA} (e_B) (~2σ at 3-8 GeV/c)
  → Consistent with mass hierarchy of parton energy loss ($\Delta E_c > \Delta E_b$)

$B/D\rightarrow e$ in 200 GeV Au+Au collisions

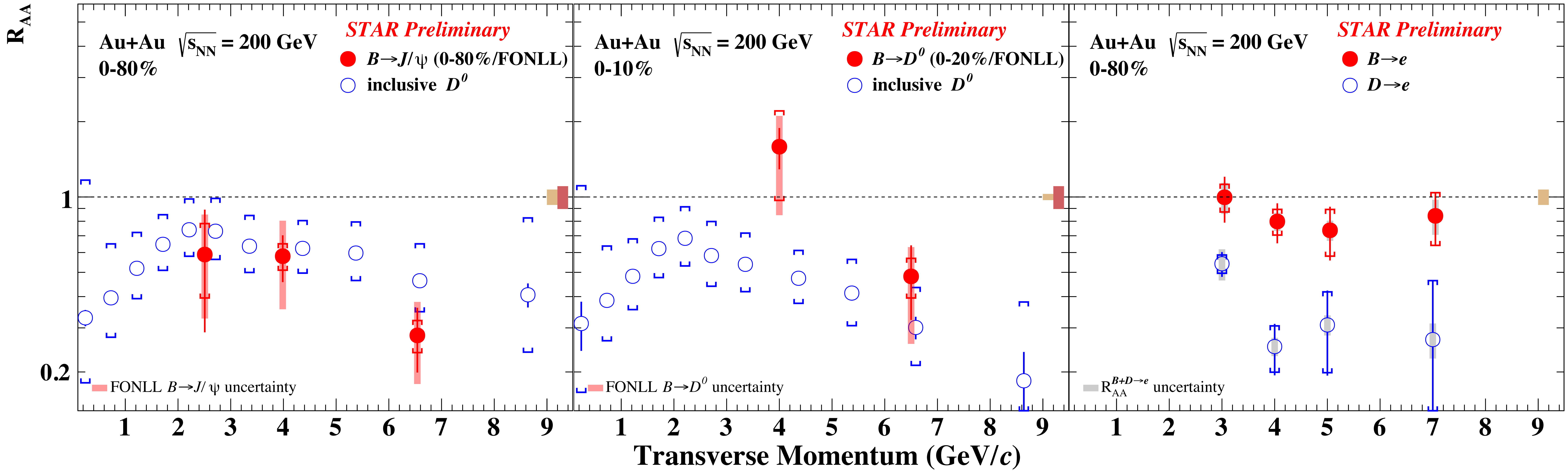




$$R_{AA}^{B\rightarrow e} = \frac{f_{Au+Au}^{B\rightarrow e}(data)}{f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc.\ e}(data),\quad R_{AA}^{D\rightarrow e} = \frac{1-f_{Au+Au}^{B\rightarrow e}(data)}{1-f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc.\ e}(data)$$

- $B\rightarrow e$ R_{AA} precision competitive to other experiments
- 5× more statistics from year 2016

Bottom measurements at STAR



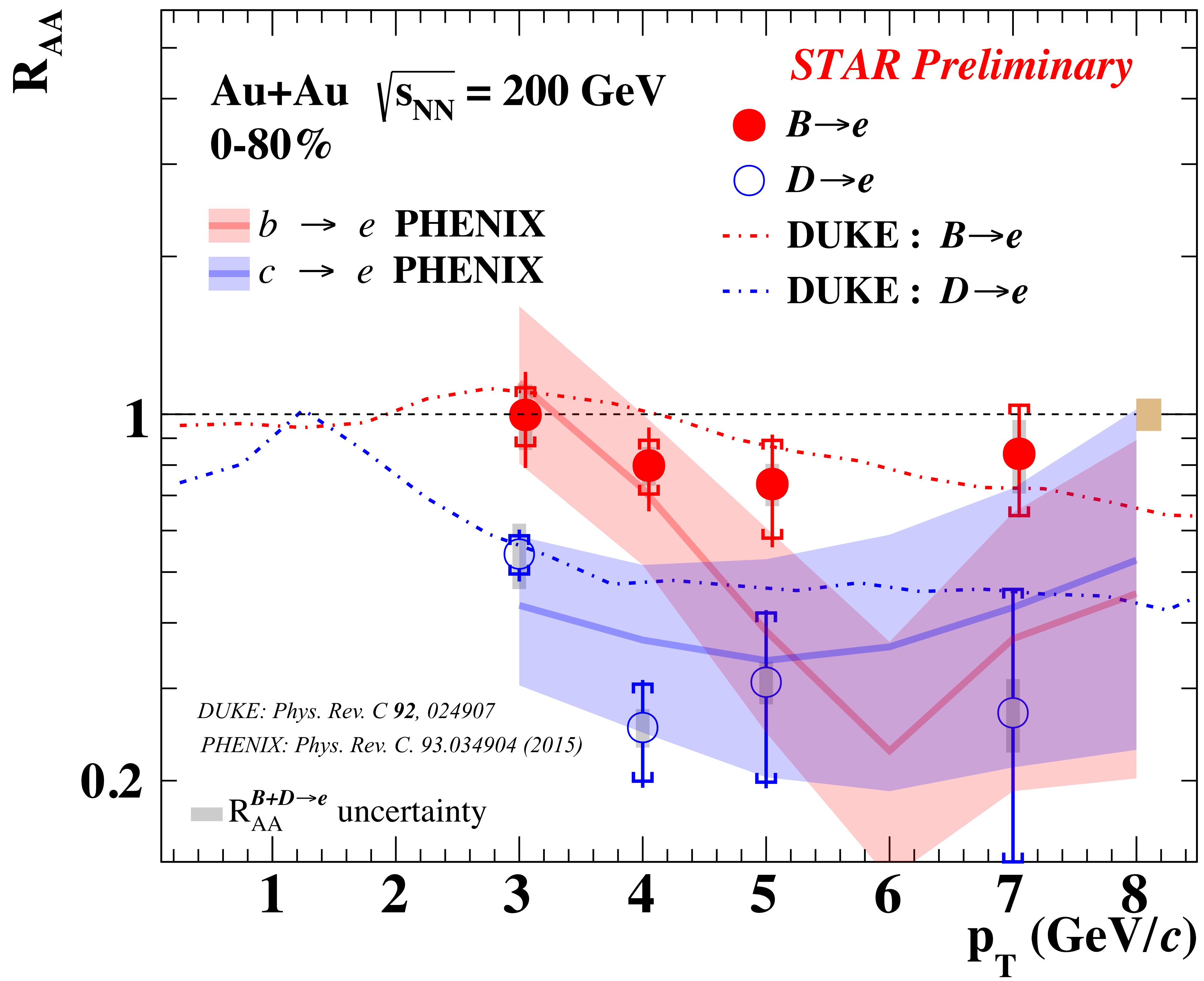
- ★ We have measured ***B* production** via J/ψ, D^0 and electron decay channels **in 200 GeV Au+Au collisions** at **STAR**.
  - ➢ Strong suppression for $B\to J/\psi$ and D^0 at high p_T.
  - ➢ Indication of less suppression for $B\to e$ than $D\to e$ (~2 σ): consistent with $\Delta E_c > \Delta E_b$
- ★ Outlook:
  - ★ ~1.6B MB events for $B\to D^0$ and 1 nb^{-1} (5× times) HT events for $B/D\to e$ from 2016

Summary

- Open charm production
  - STAR directly measures various open charm hadrons — Λ_c, D^0, $D^{\pm}$, D^*, and D_s in 200 GeV Au+Au collisions with HFT
  - Strong suppression of D^0 and $D^{\pm}$ yields at higher p_T in most central collisions → substantial energy loss
  - Strong enhancements for Λ_c/D^0 and D_s/D^0 ratios → Coalescence hadronization of deconfined charm quarks in the medium
  - First evidence of non-zero directed flow for heavy flavor→ Heavy flavor v_1 > light flavor v_1
- Open bottom production
  - Measures indirectly via multiple decay channels — $B\rightarrow J/\psi$, D^0, electrons in 200 GeV Au+Au collisions with HFT
  - Strong suppression for $B\rightarrow J/\psi$ and D^0 at high p_T.
  - Indication of less suppression for $B\rightarrow e$ than $D\rightarrow e$ (~2 σ) → consistent with $\Delta E_c > \Delta E_b$

Backup

Comparison with PHENIX



D⁰ R$_{AA}$ with 2010/2011 data