Measurements of Open Heavy Flavor with the STAR Experiment

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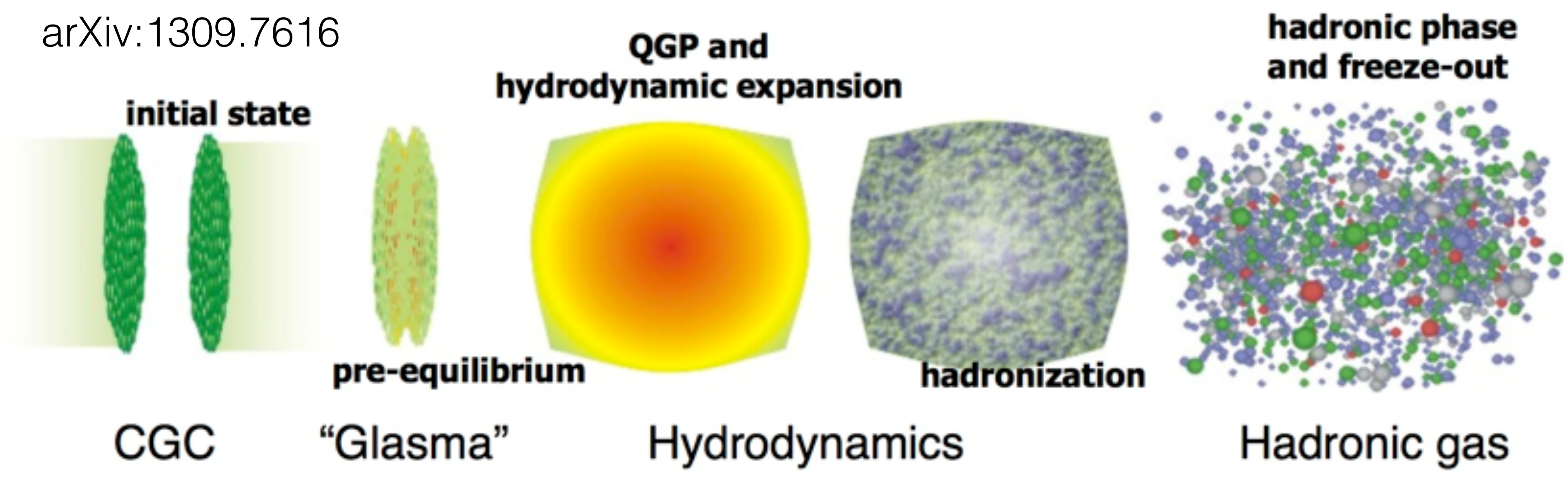
Outline

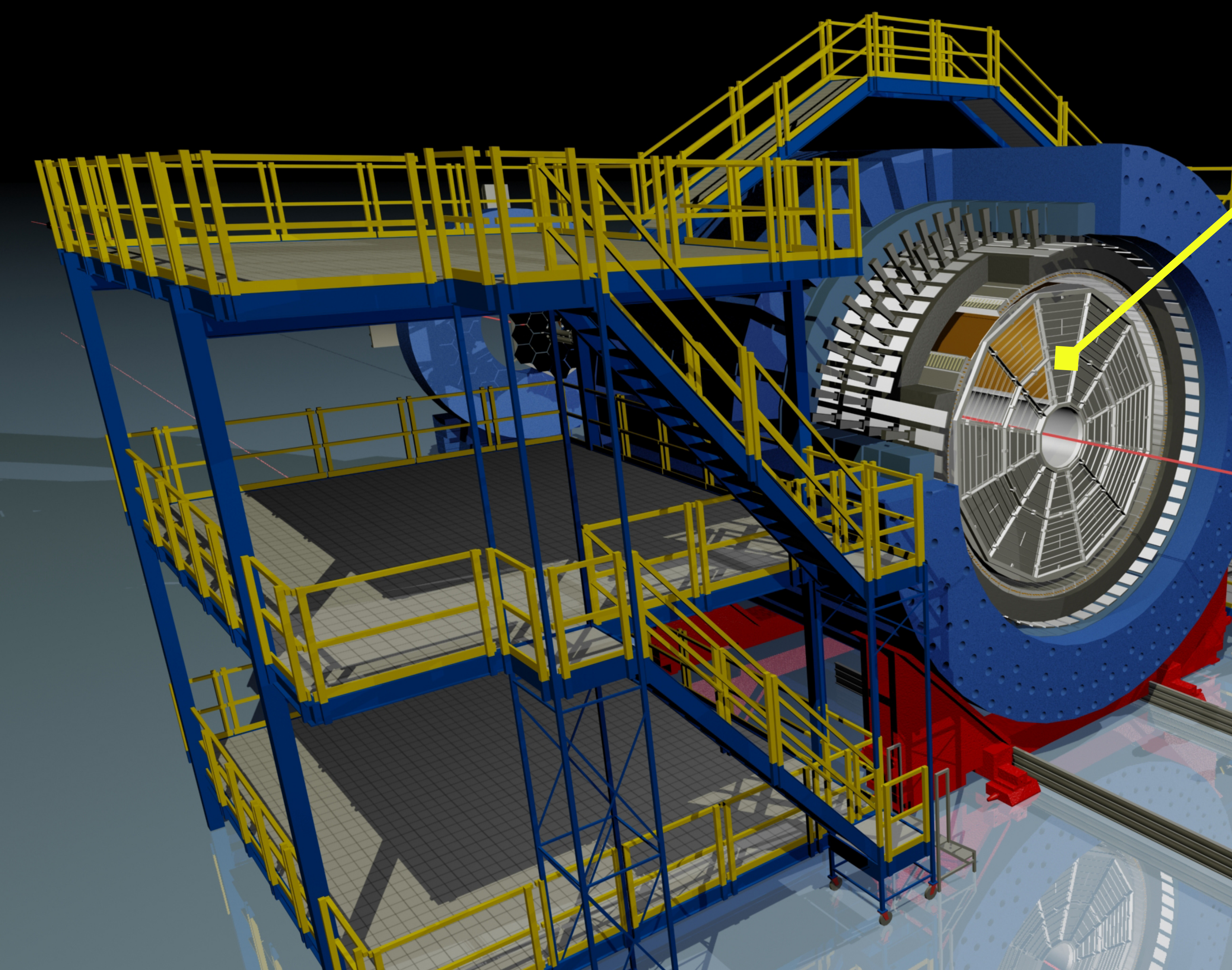
- Why Heavy Flavor?
- The STAR Detector
- Separating Bottom and Charm
  - Non-photonic electrons
  - Non-prompt D^0
  - Non-prompt J/Ψ
- D_s and Λ_c Production Measurements
- D^0 Flow Measurements
- Summary and Outlook

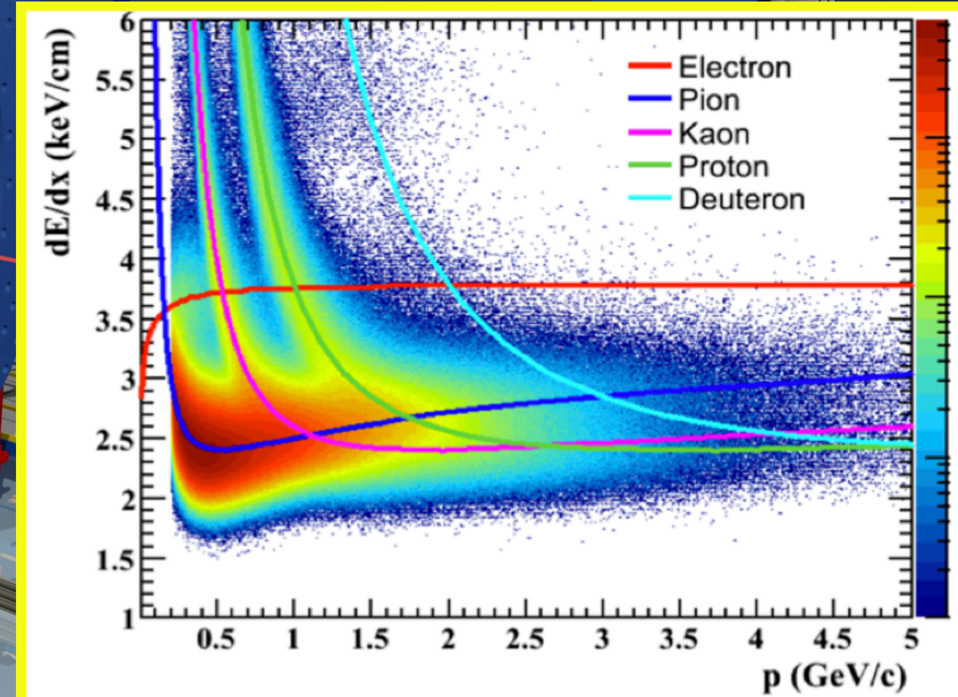
Why Heavy Flavor?



- Large mass - predominantly produced in initial hard parton scatterings.
- Long lifetime - experience full evolution of medium produced in heavy-ion collisions.
- Mass hierarchy:
  - Comparison of QGP-quark interaction for light flavor, charm and bottom may allow detailed study of collisional and radiative energy losses within medium.
  - Thermalization in medium is mass dependent. Are charm and bottom thermalized?

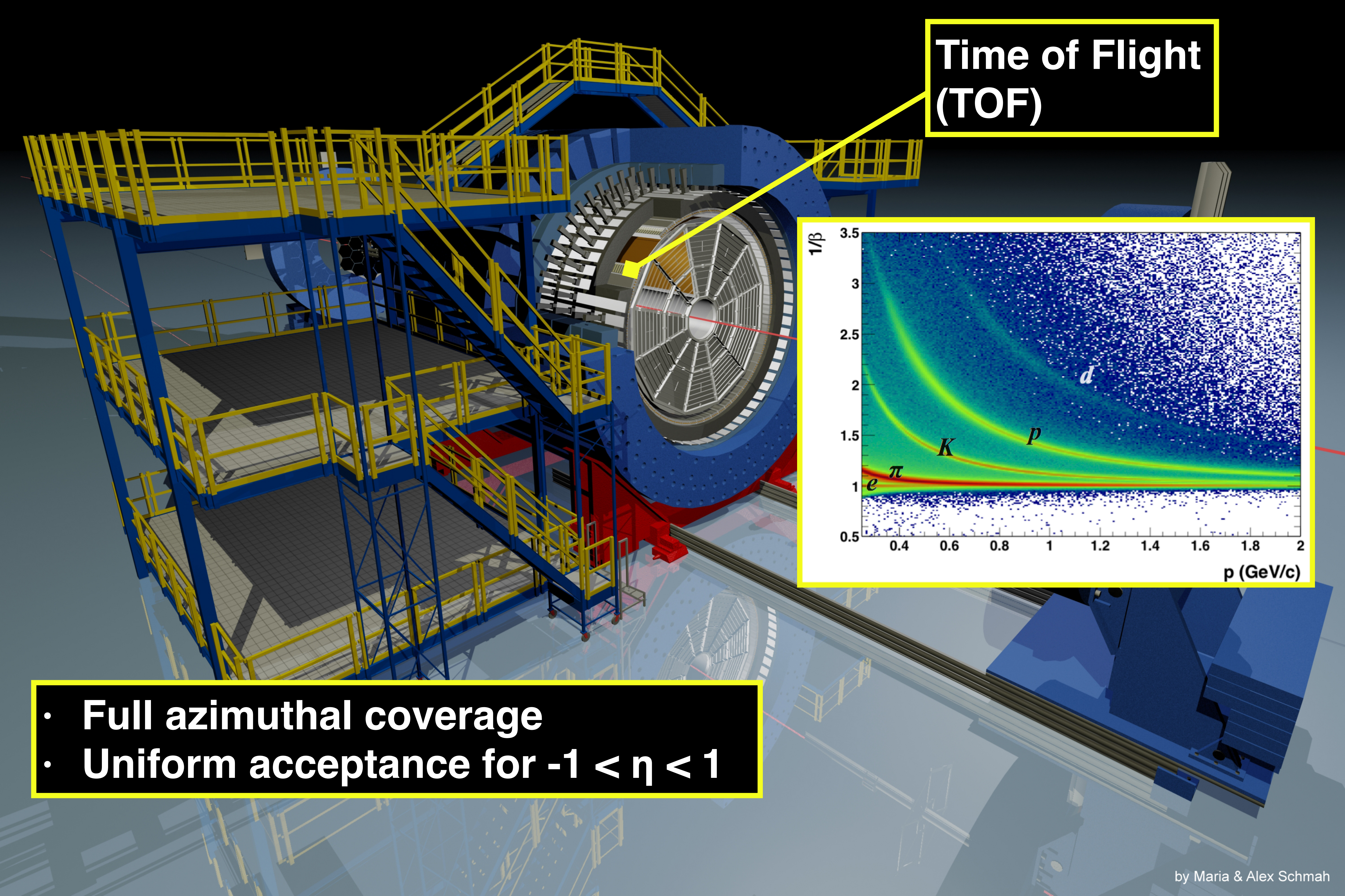
STAR Detector





- Full azimuthal coverage
- Uniform acceptance for $-1 < \eta < 1$

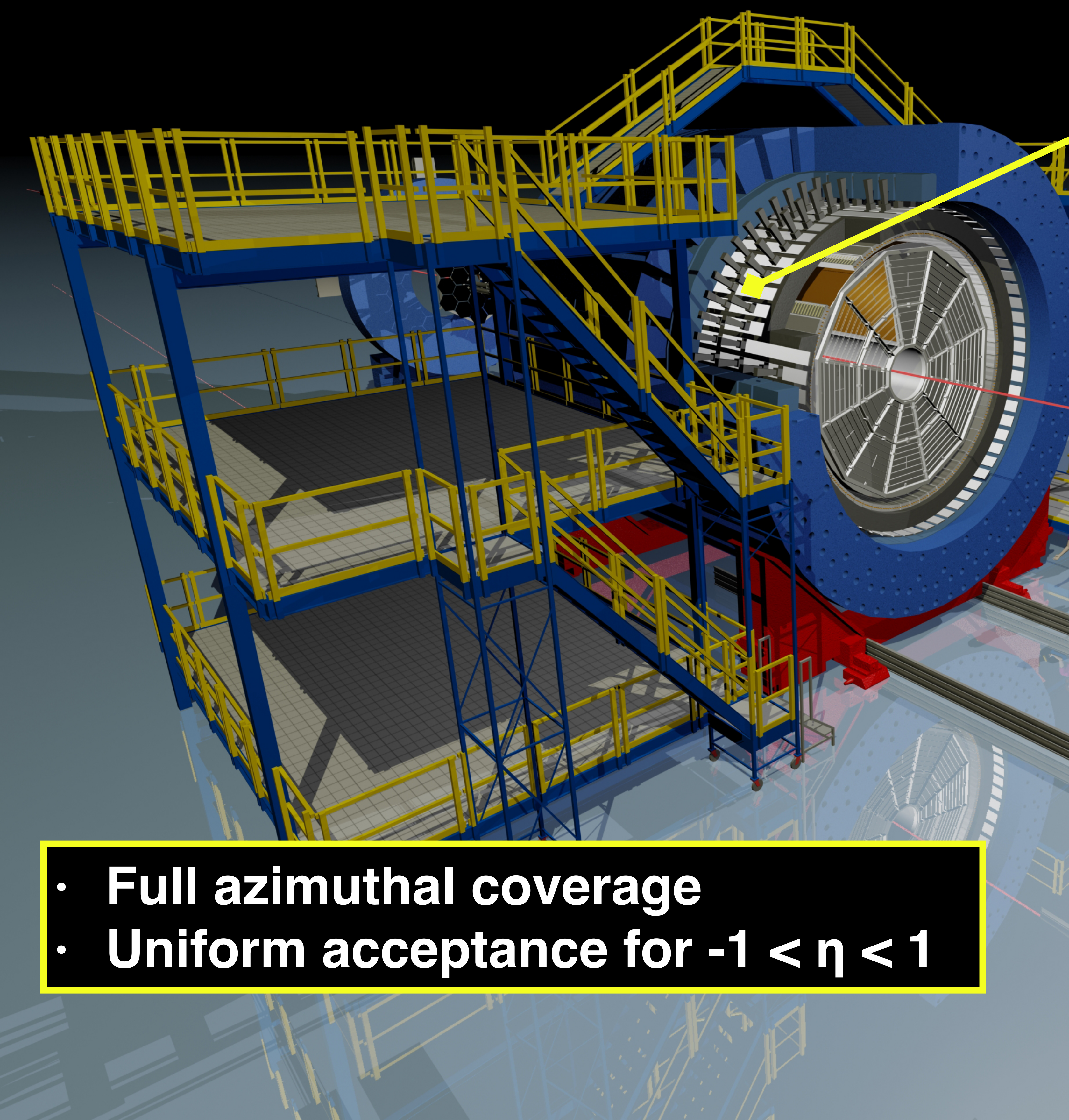
STAR Detector

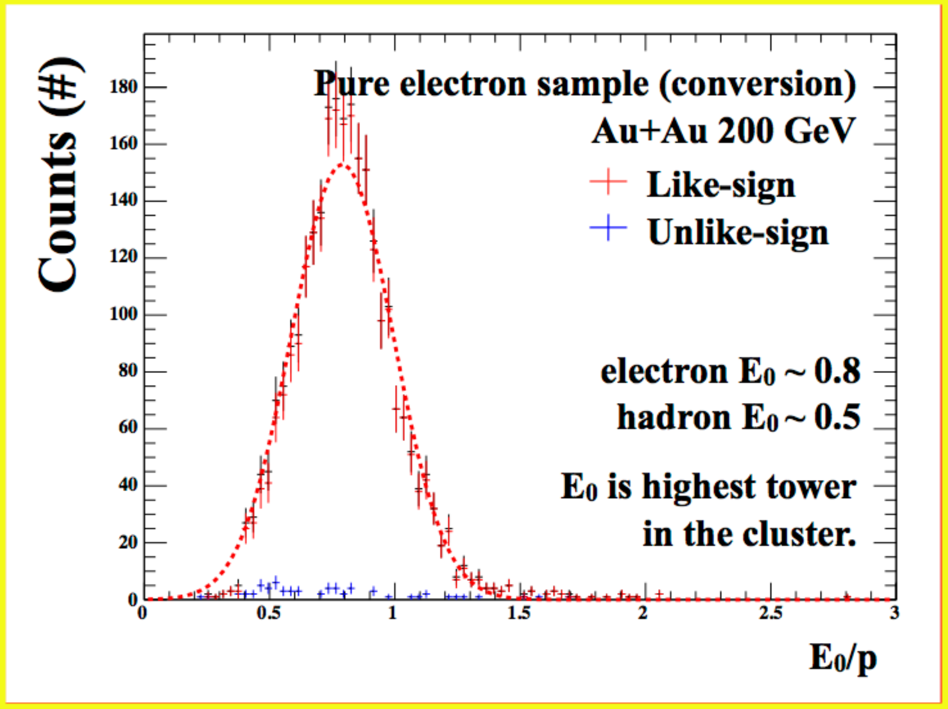


- Full azimuthal coverage
- Uniform acceptance for $-1 < \eta < 1$

by Maria & Alex Schmah

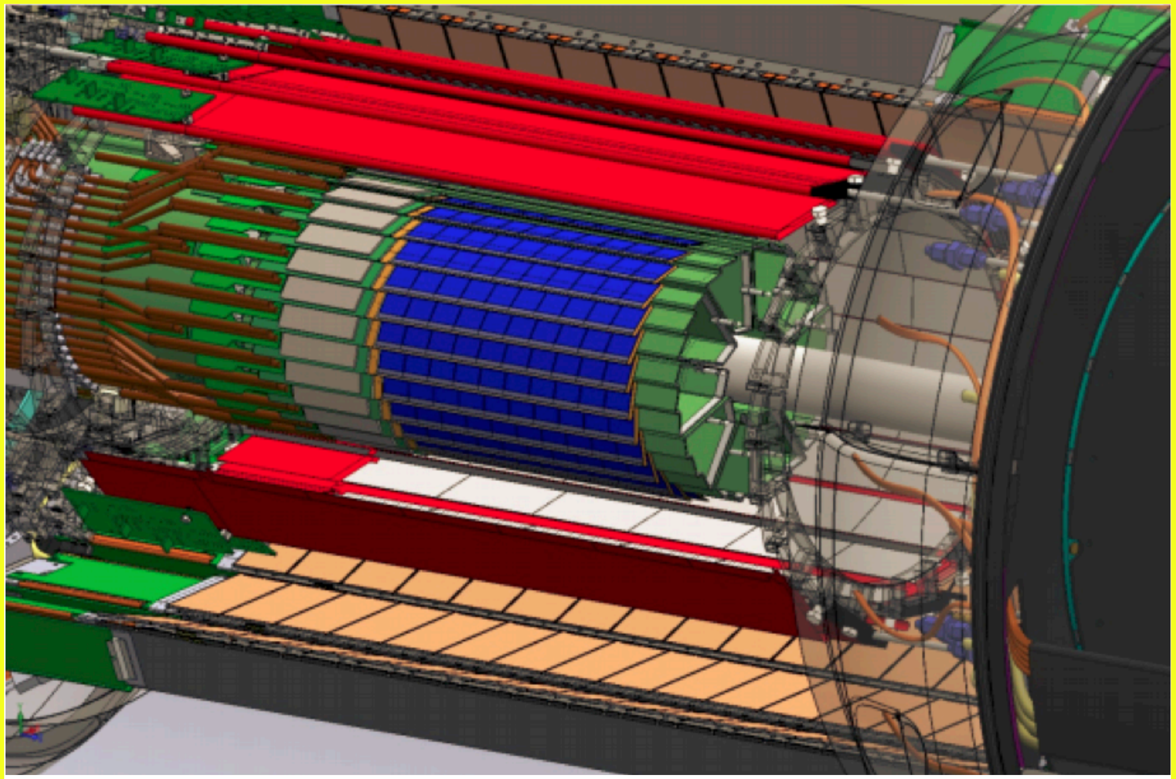
STAR Detector

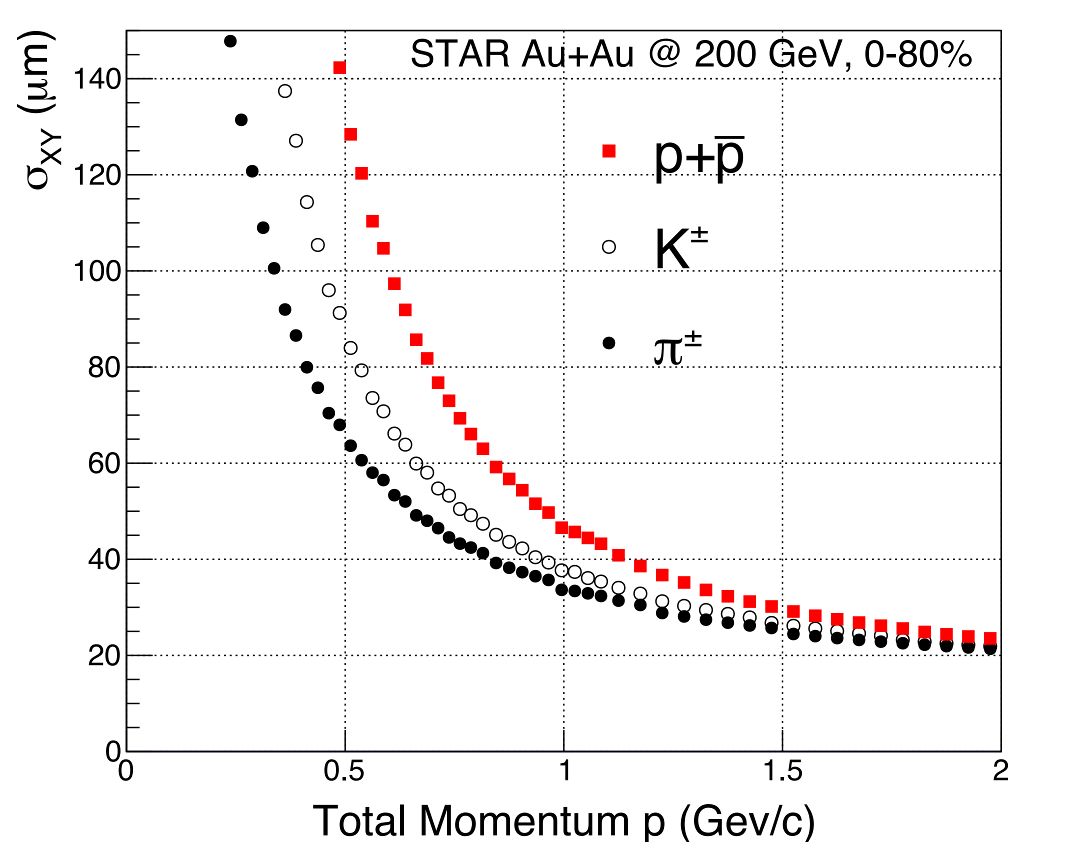




- Full azimuthal coverage
- Uniform acceptance for $-1 < \eta < 1$

STAR Detector





PXL: 2 layers of silicon pixel (MAPS)

- **Low material budget, 0.5% * X_0 (2014)**
- **Excellent resolution**
  - **Pitch 20.7 μm x 20.7 μm**
- **2.8 cm and 8 cm from beam**

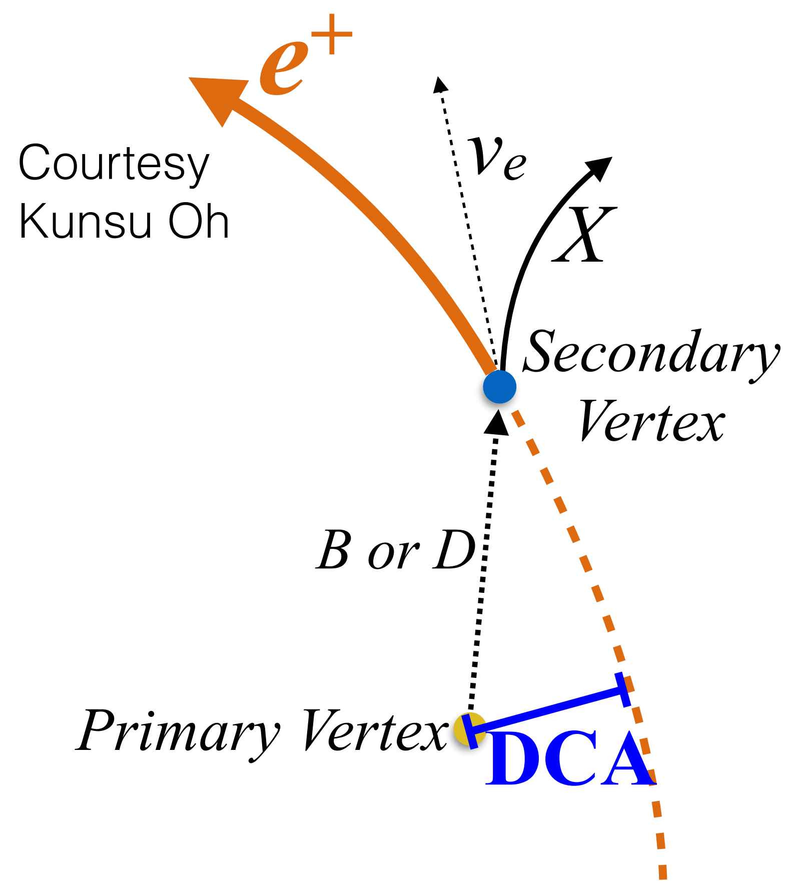
IST & SSD: Silicon pad/strip detectors

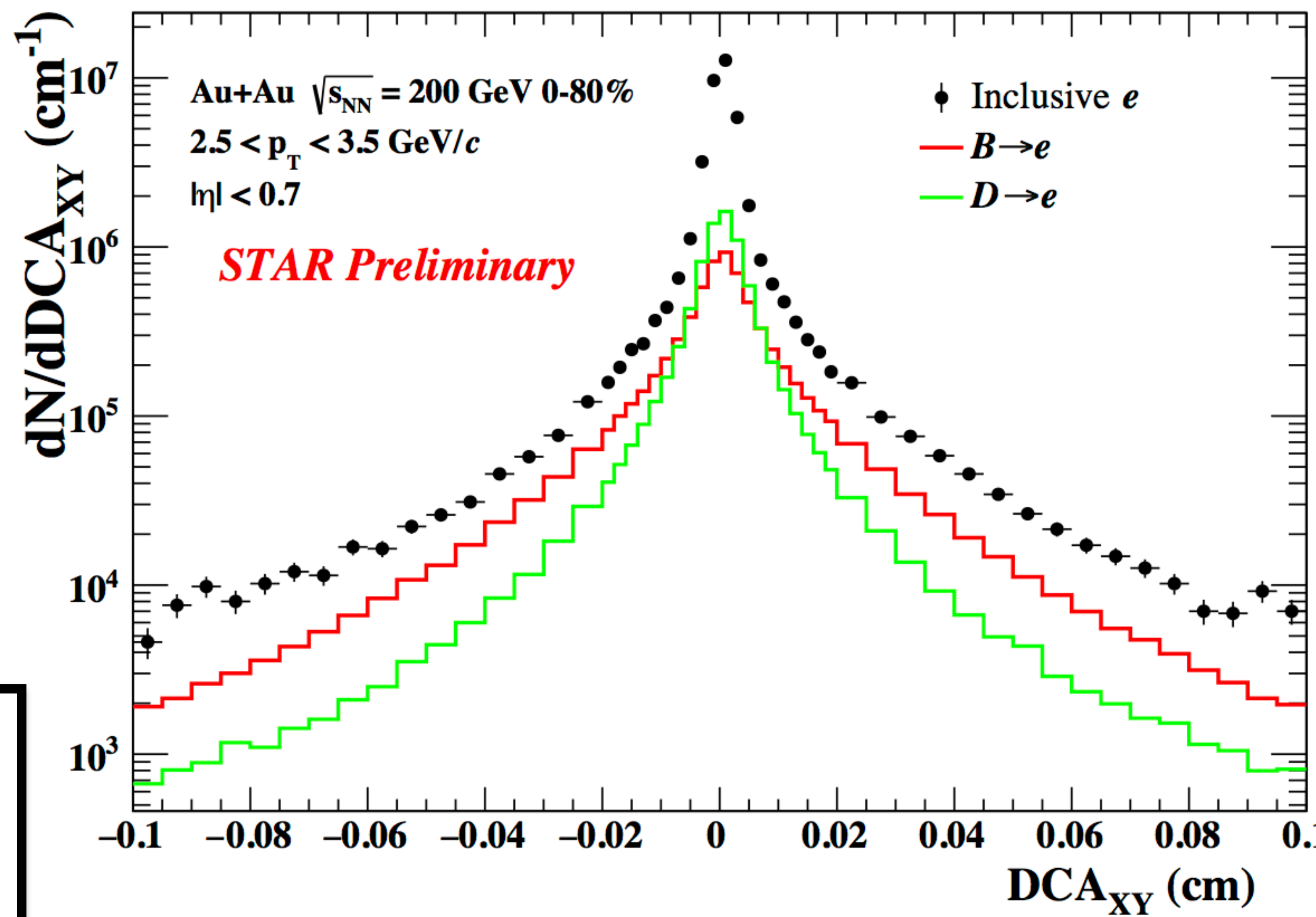
- **Fast signals to remove pileup**
- **14 cm and 22 cm from beam**

In use: 2014 - 2016 (R.I.P.)

by Maria & Alex Schmah

b/c→e in Au+Au 200 GeV



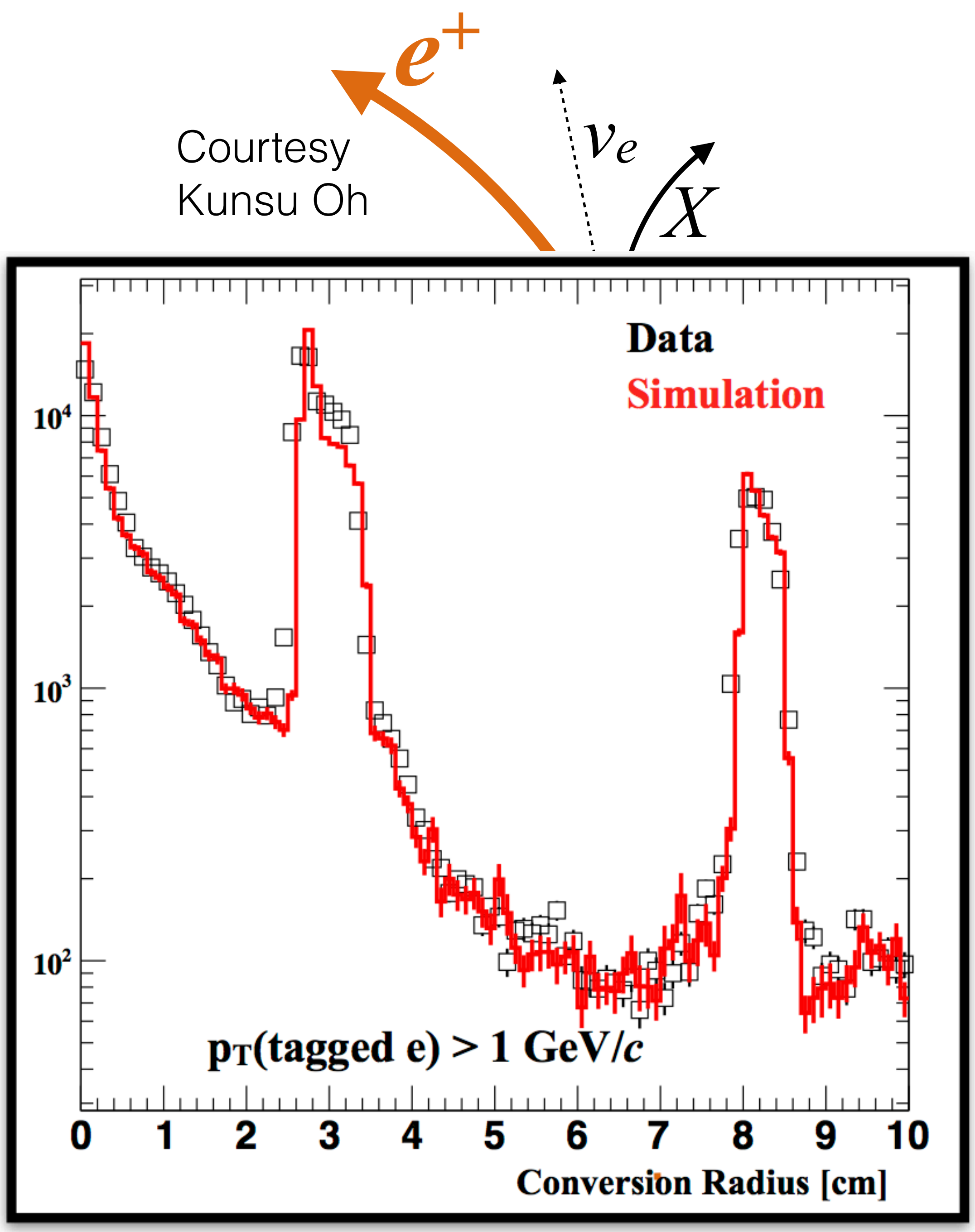


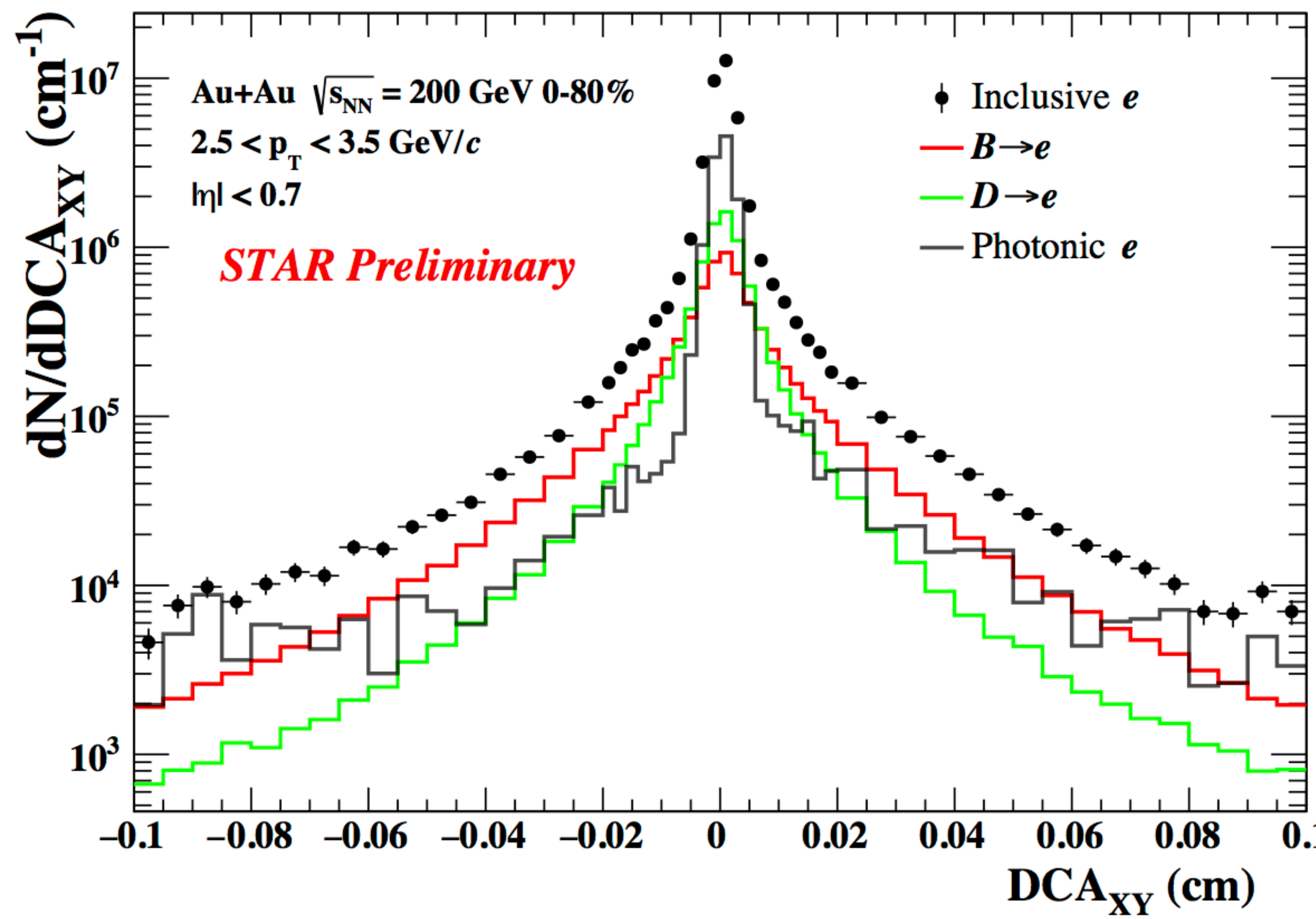
$c\tau(D^0)$ ~ 123 μm; $c\tau(B^0)$ ~ 459 μm

$c\tau(D^\pm)$ ~ 312 μm; $c\tau(B^\pm)$ ~ 491 μm

The improved track pointing resolution with the HFT allows use of DCA to separate individual contributions to inclusive electrons.

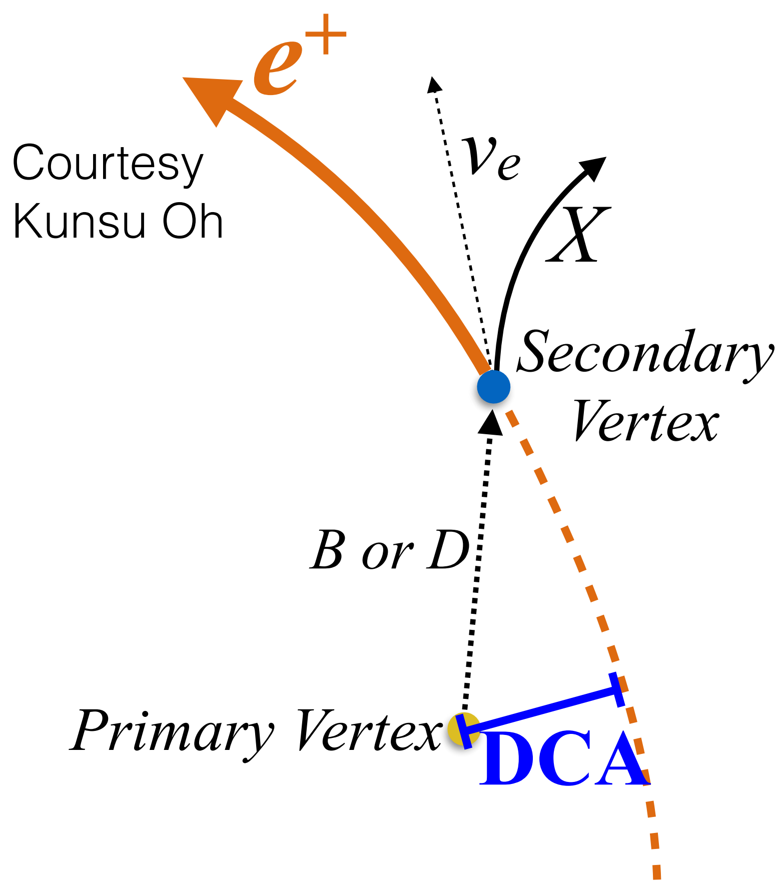
b/c→e in Au+Au 200 GeV





Photonic electrons from Dalitz decays and gamma conversions.

b/c→e in Au+Au 200 GeV



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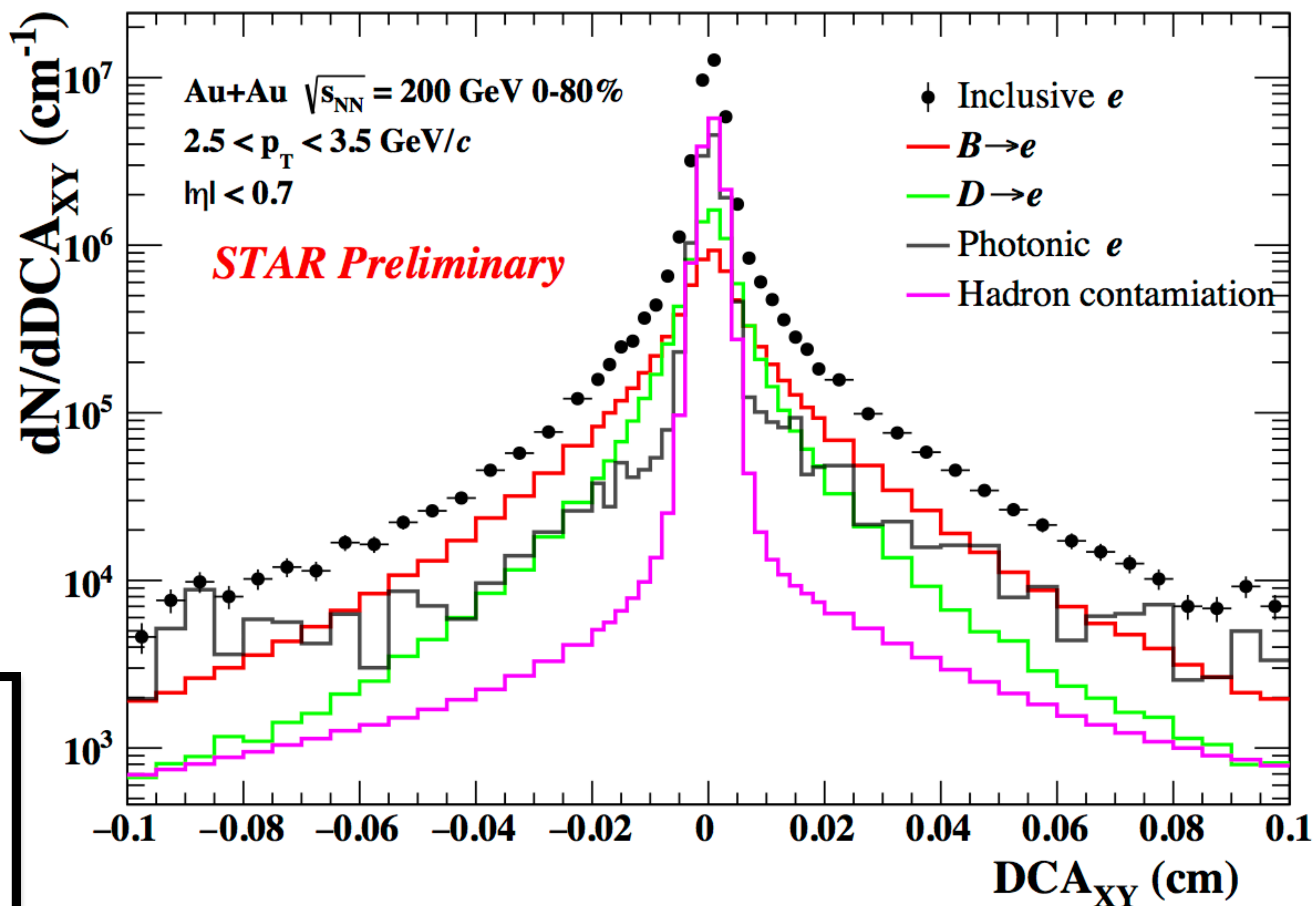
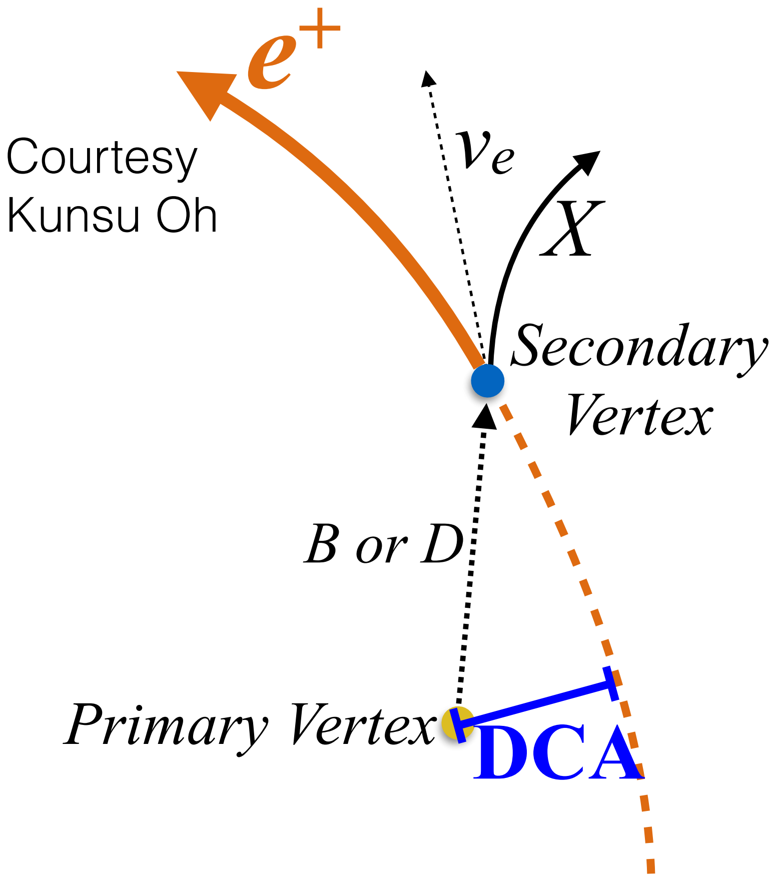
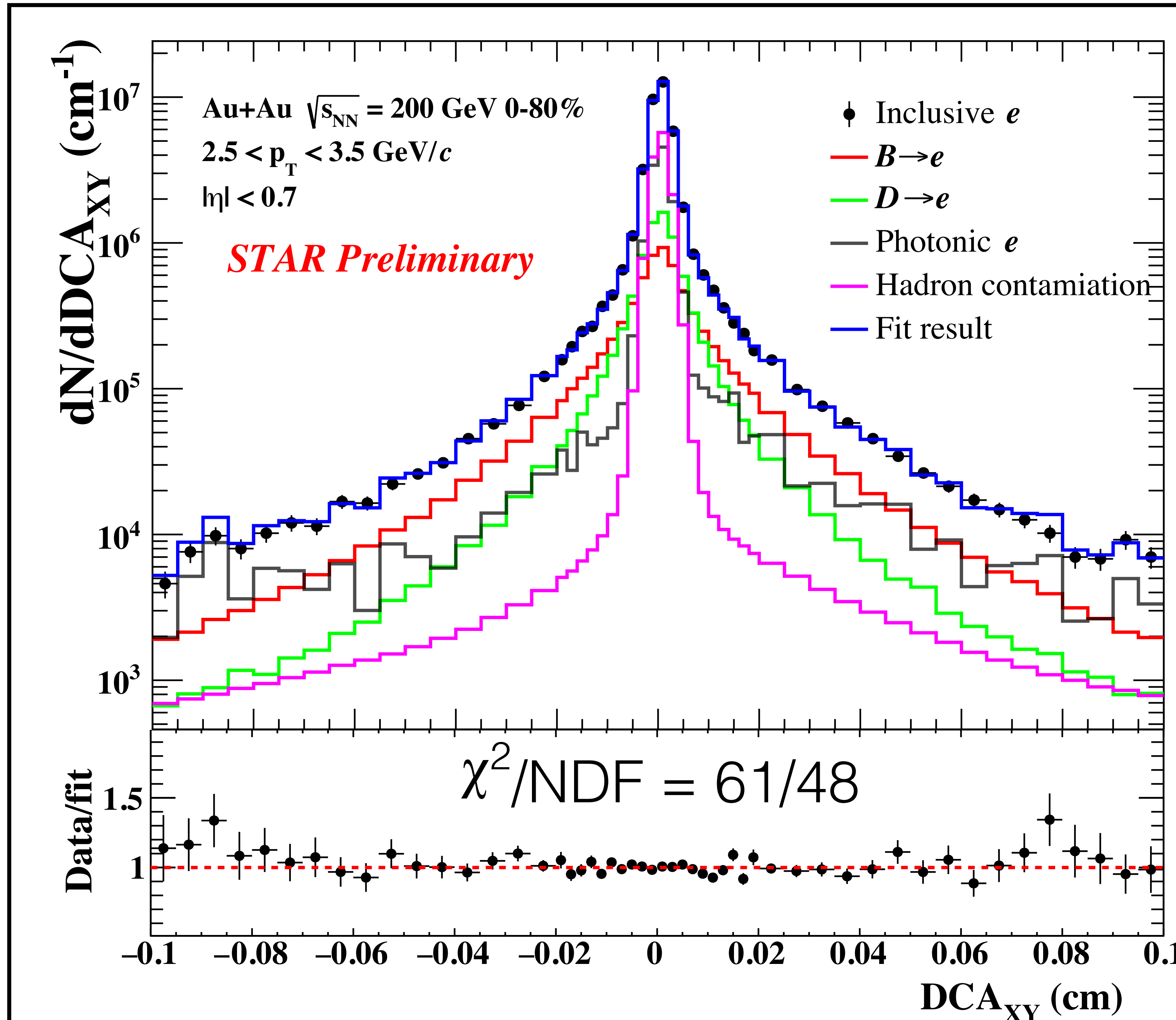


Hadron contamination is primarily from pions misidentified as electron candidates.

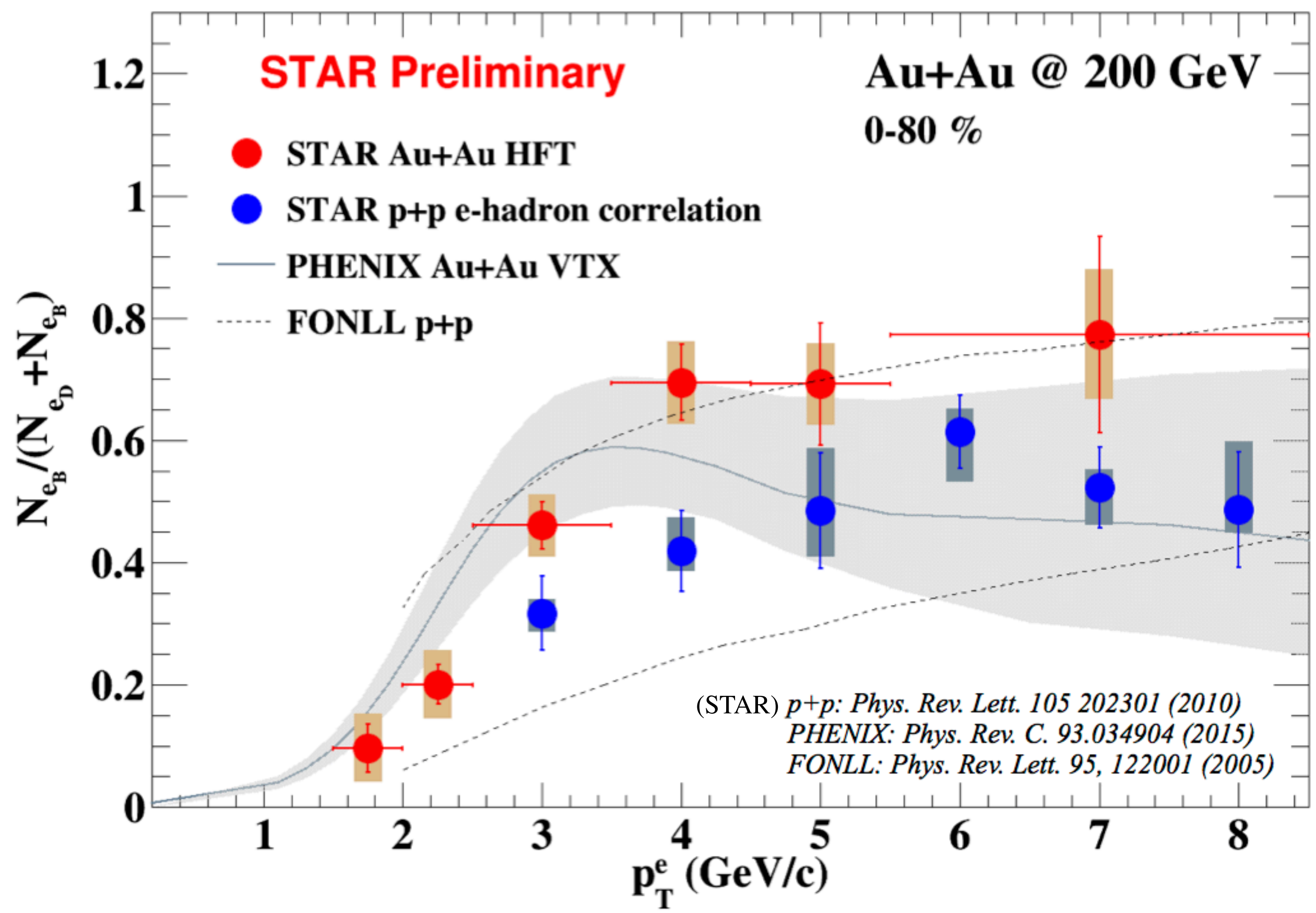
b/c→e in Au+Au 200 GeV

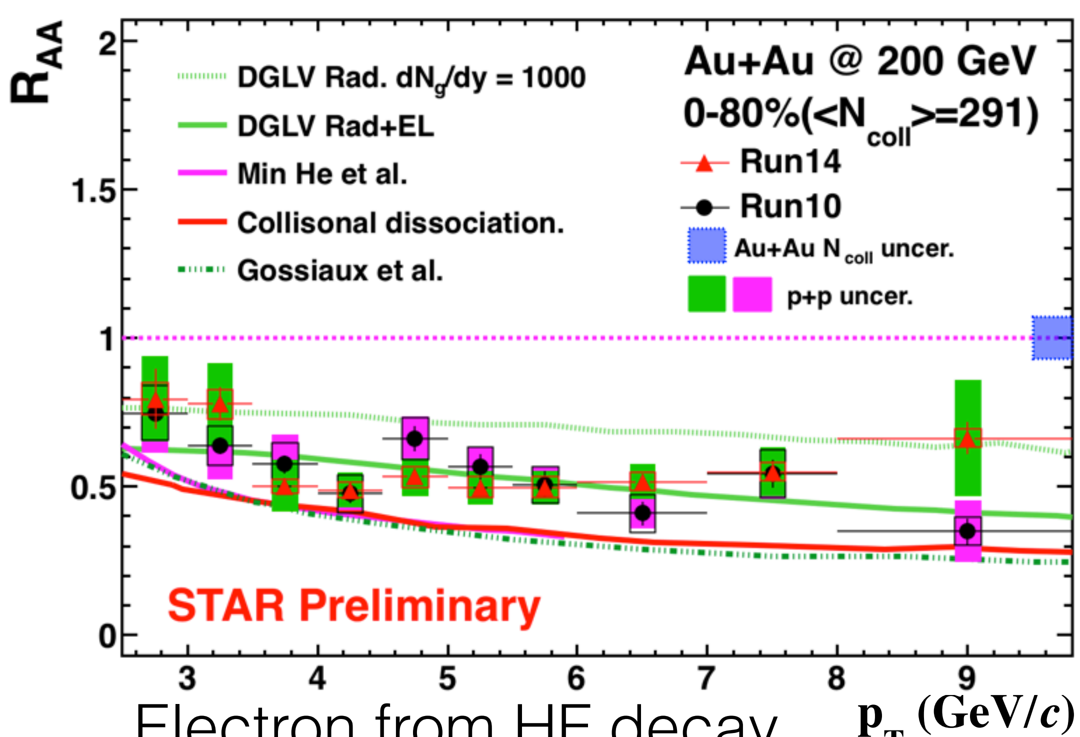




These inputs, along with floating contribution parameters, are used to fit the data.

b/c→e in Au+Au 200 GeV





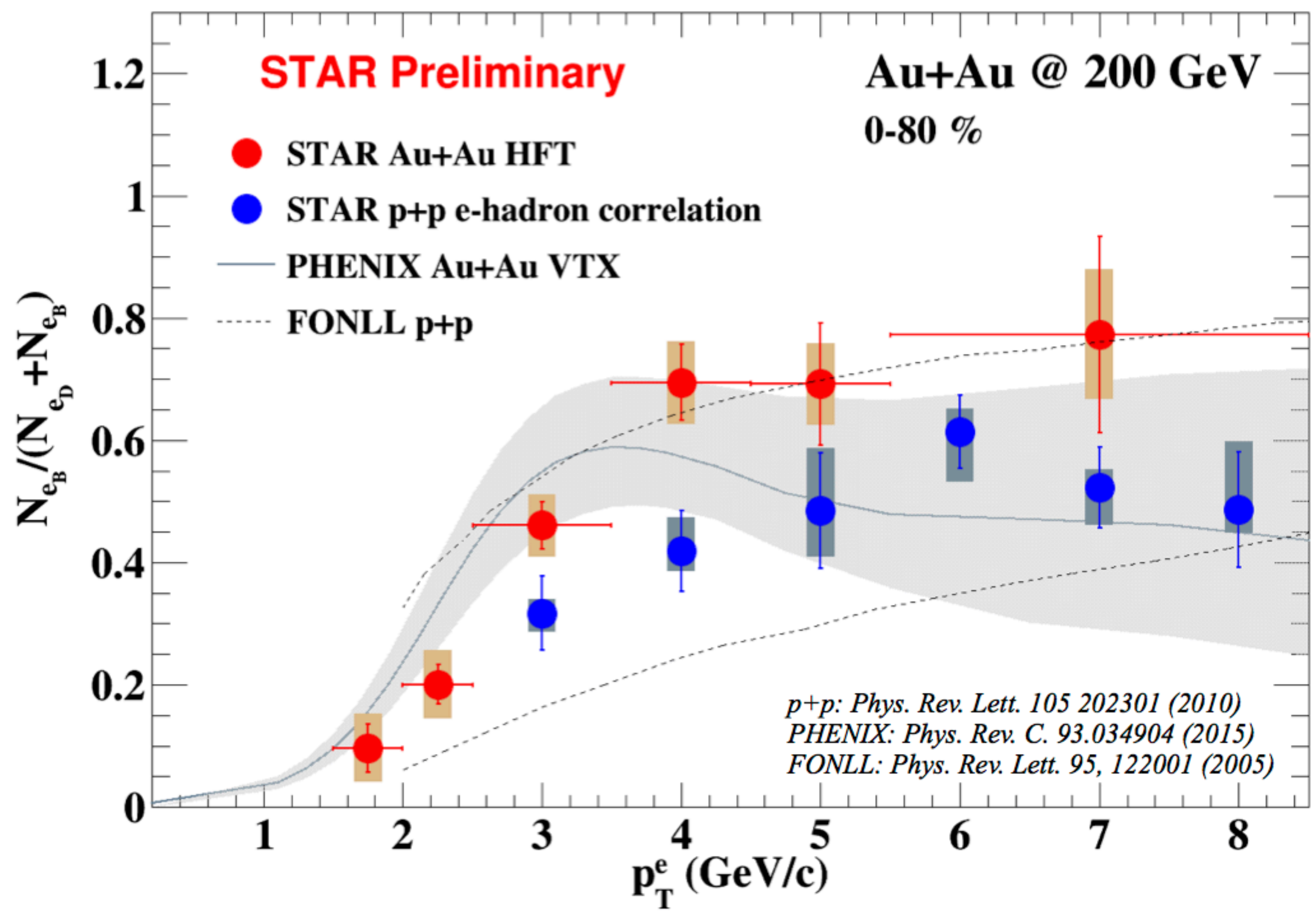
Electron from HF decay

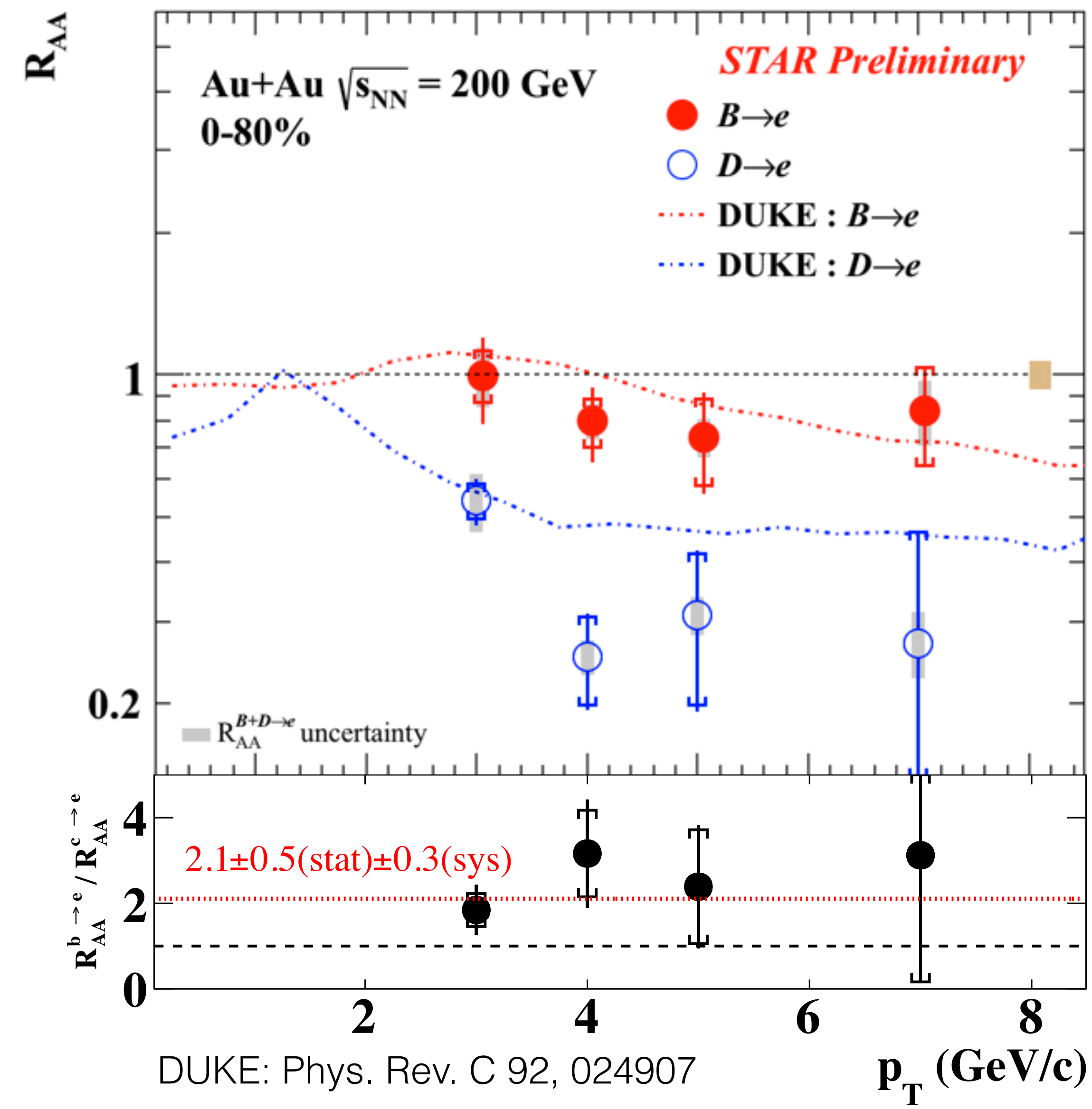
- b→e ratio shows enhancement relative to p+p measurement at STAR.

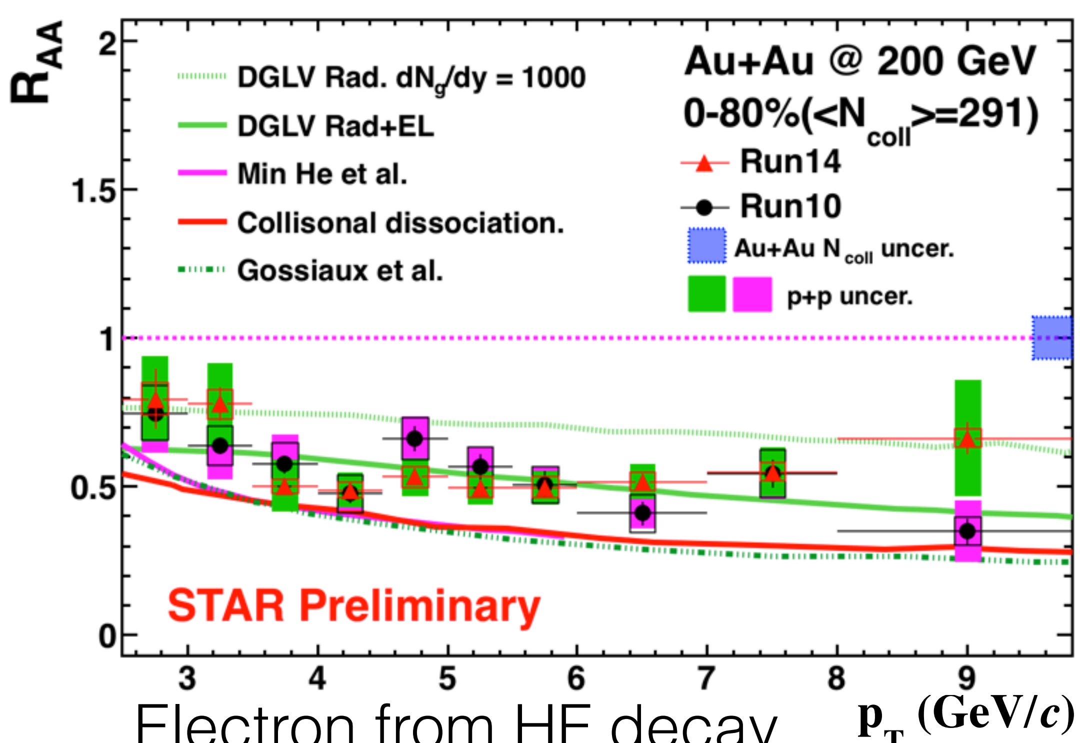
$$R_{AA}^{B\rightarrow e} = \frac{f_{Au+Au}^{B\rightarrow e}(data)}{f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc.\ e}(data)$$

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

b/c→e in Au+Au 200 GeV



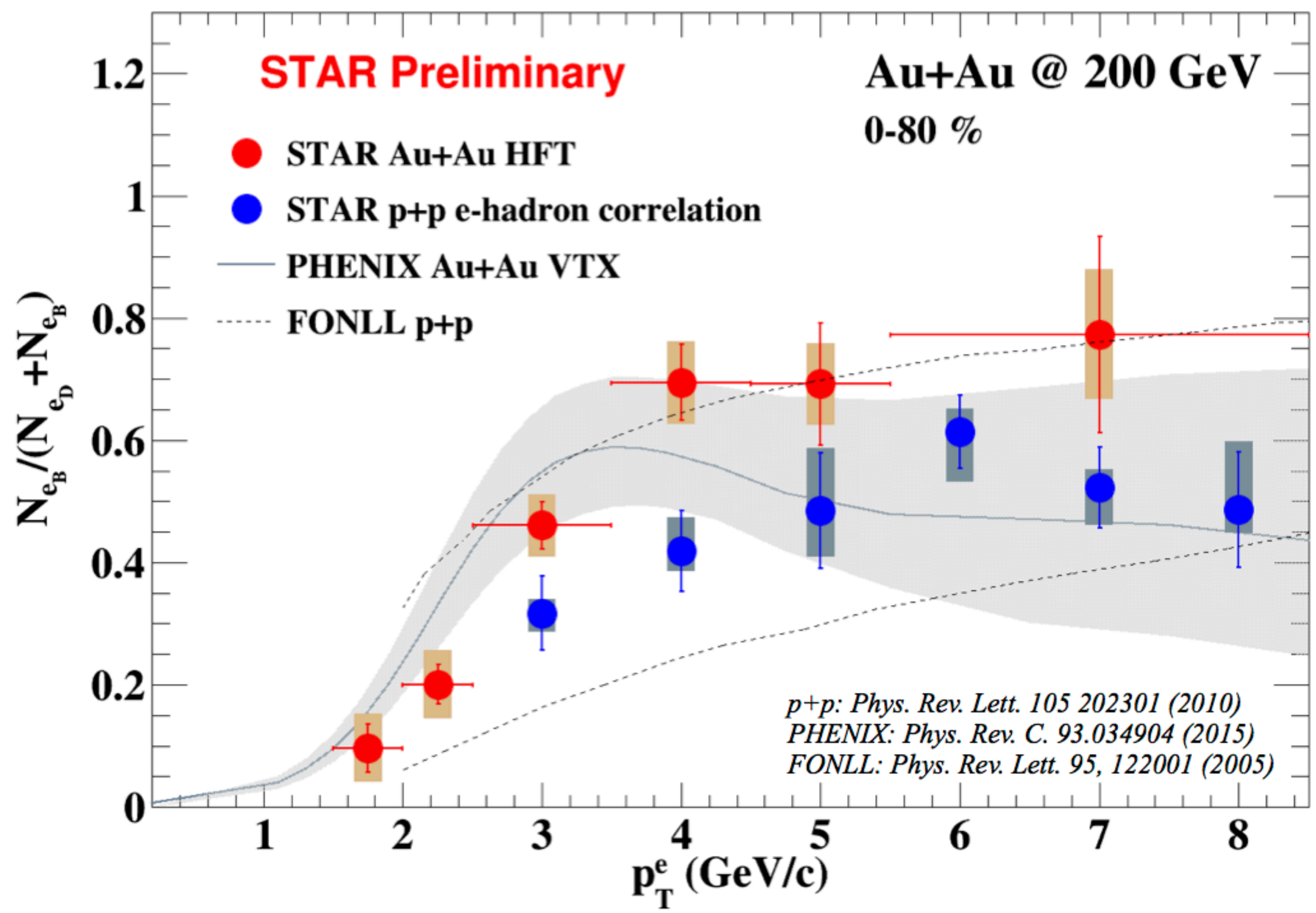


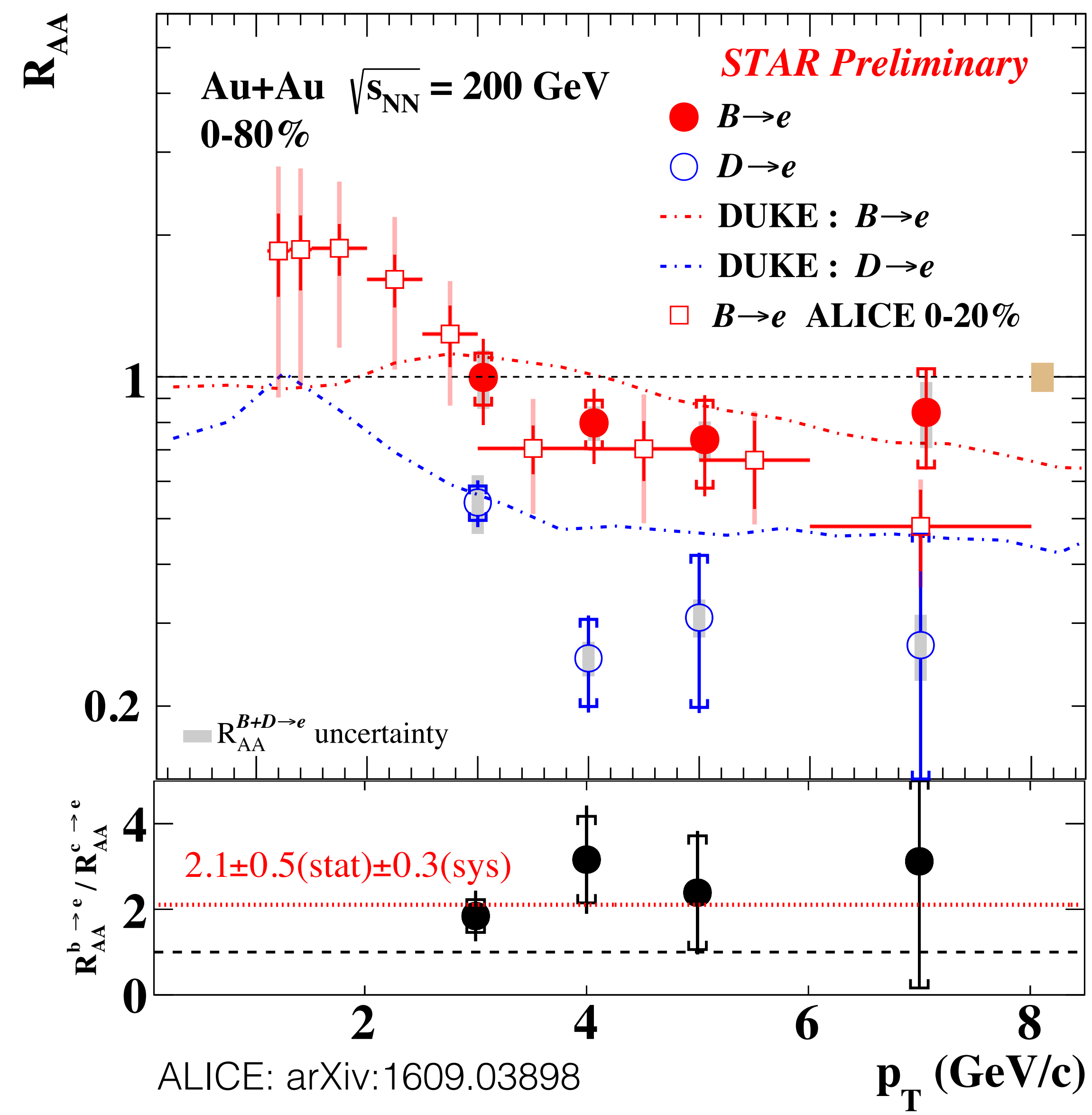


Electron from HF decay

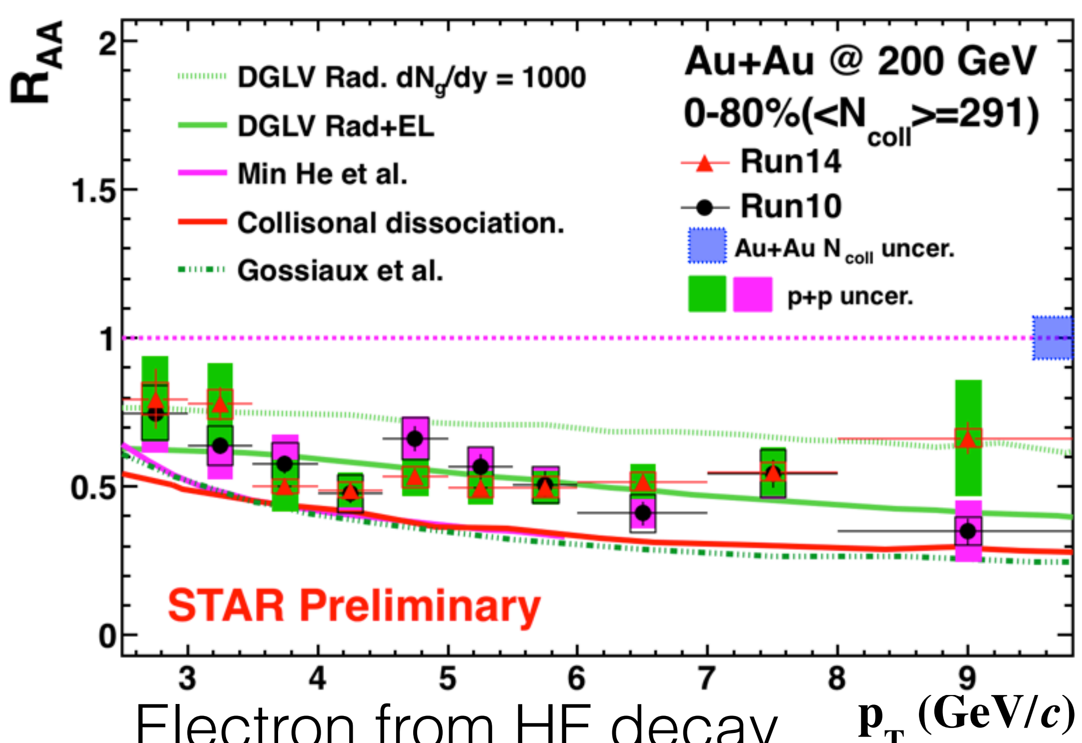
- Consistent with mass hierarchy of energy loss ($\Delta E_c > \Delta E_b$)

b/c→e in Au+Au 200 GeV





ALICE: arXiv:1609.03898

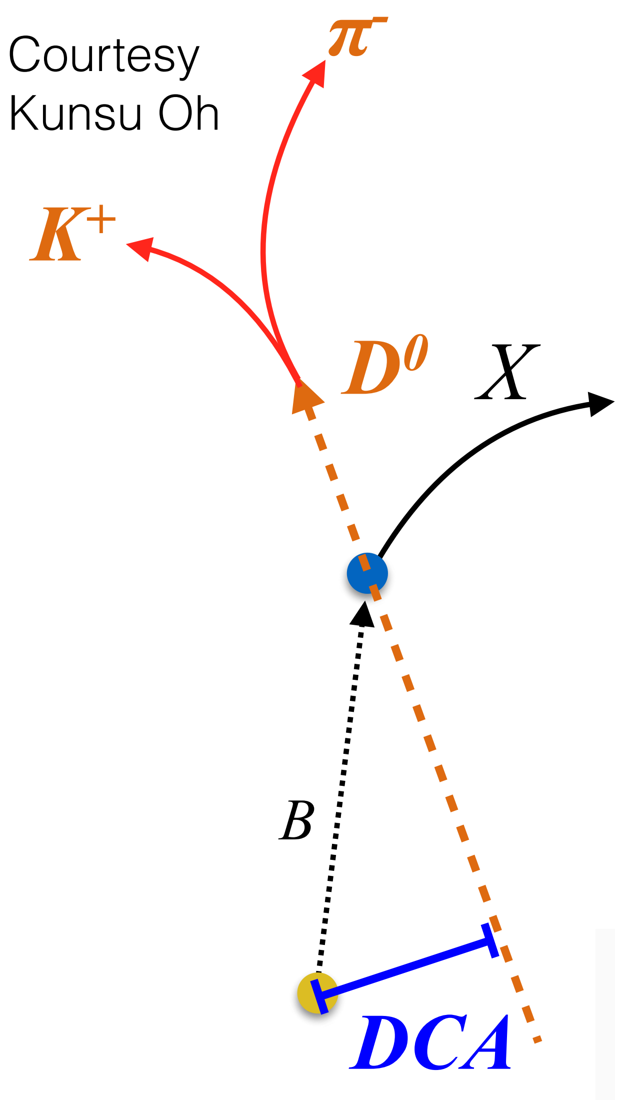


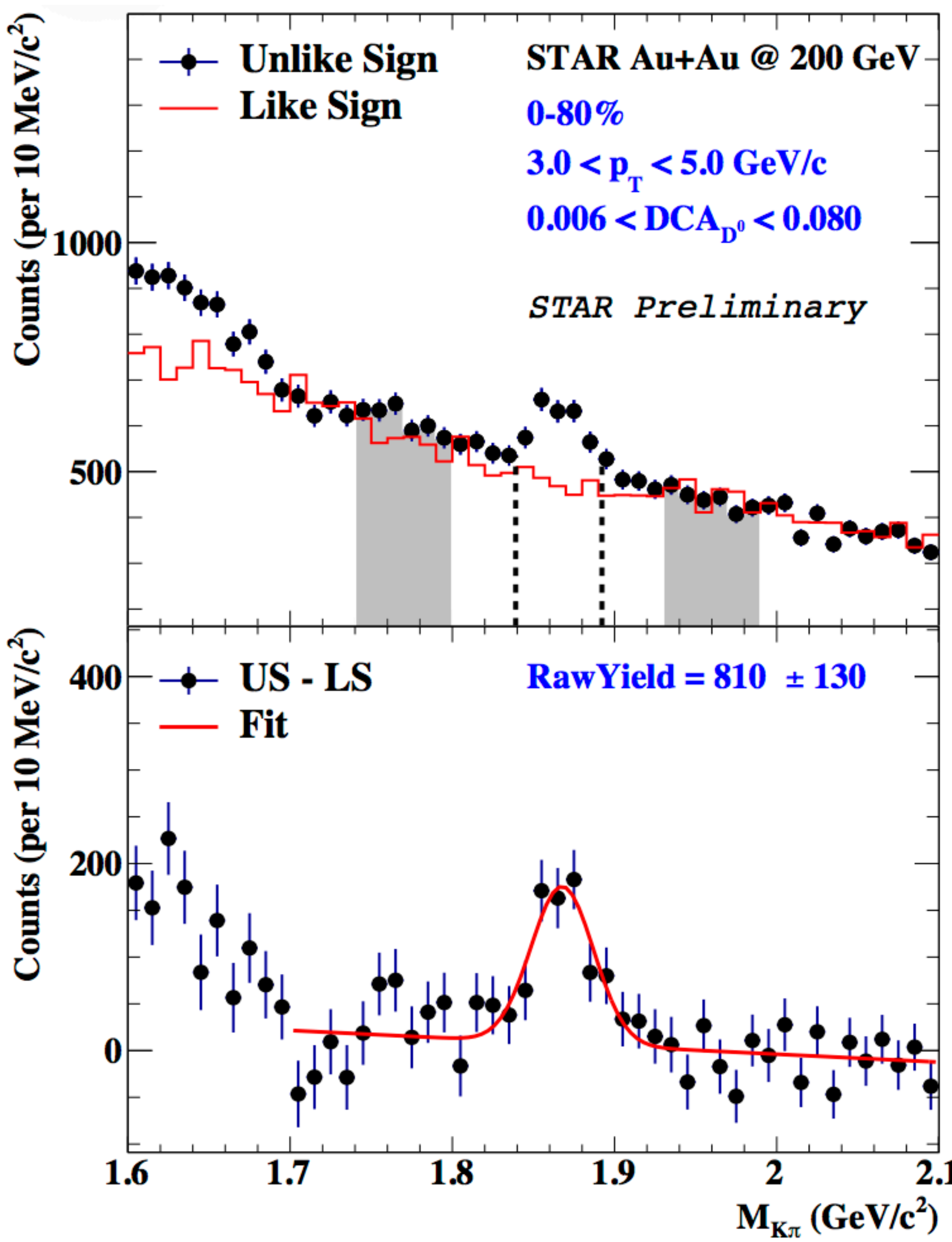
Electron from HF decay

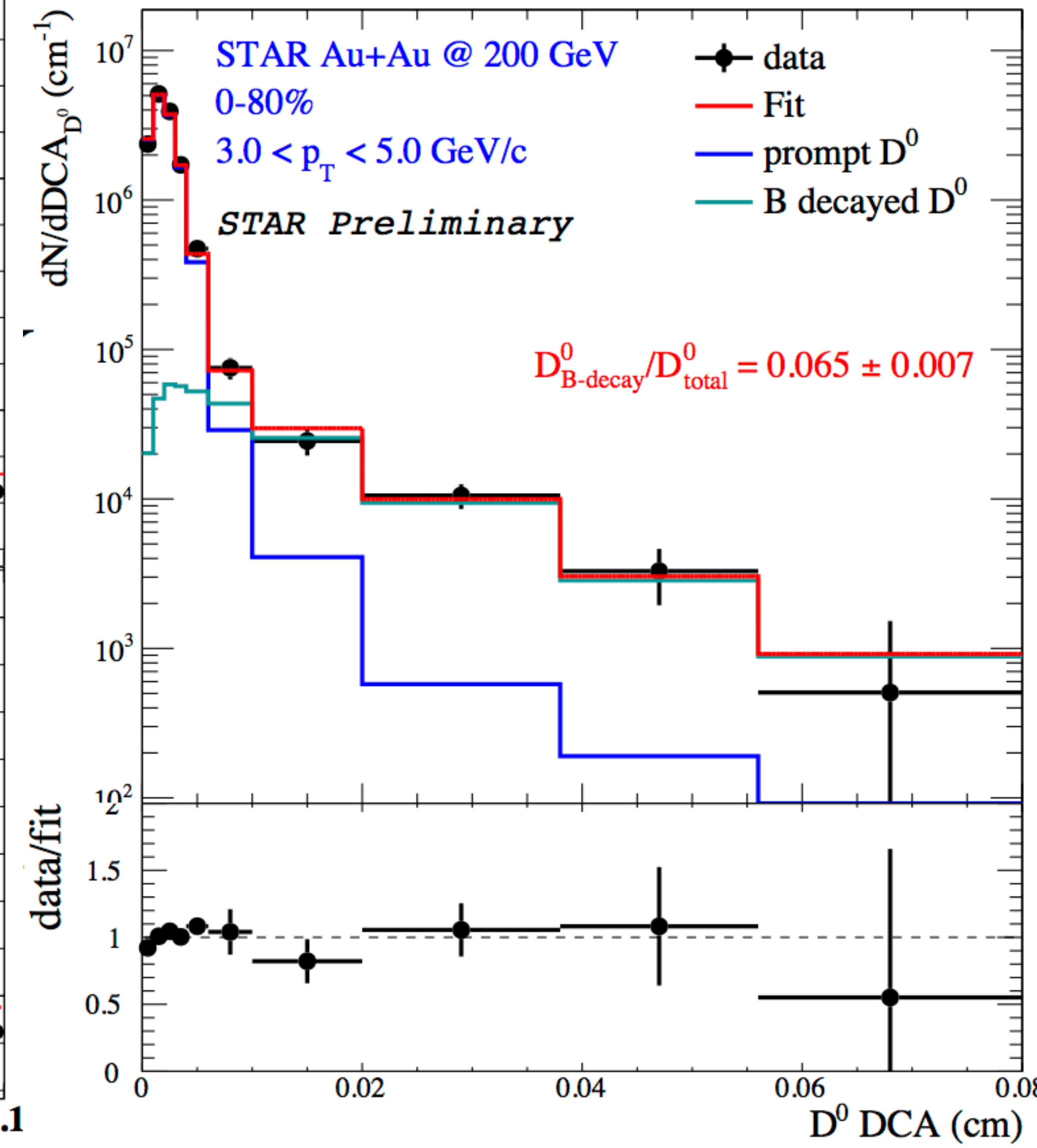
- Competitive precision compared to ALICE measurements in the same p_T ranges.

Non-prompt D^0 Production

Courtesy Kunsu Oh

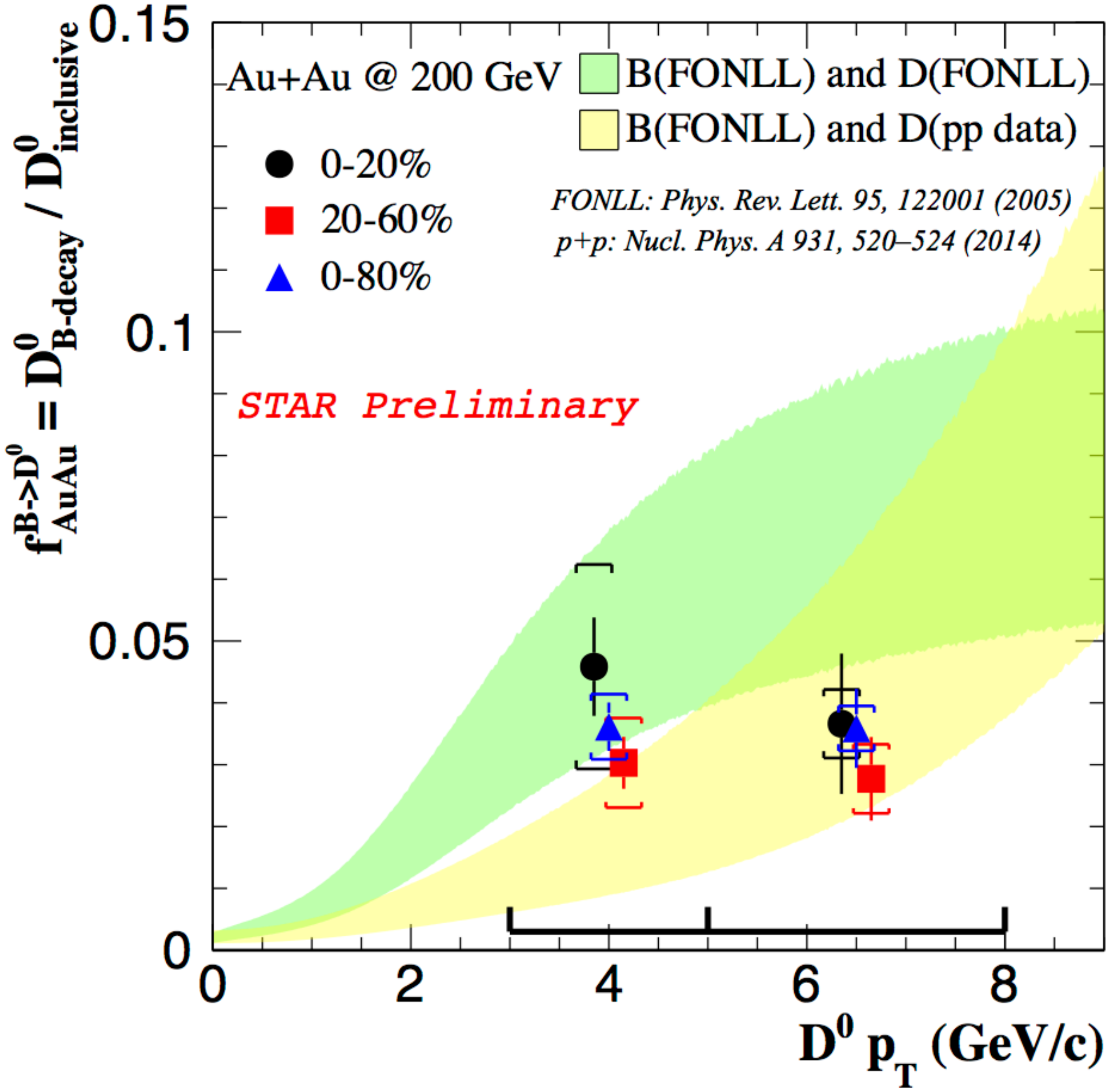


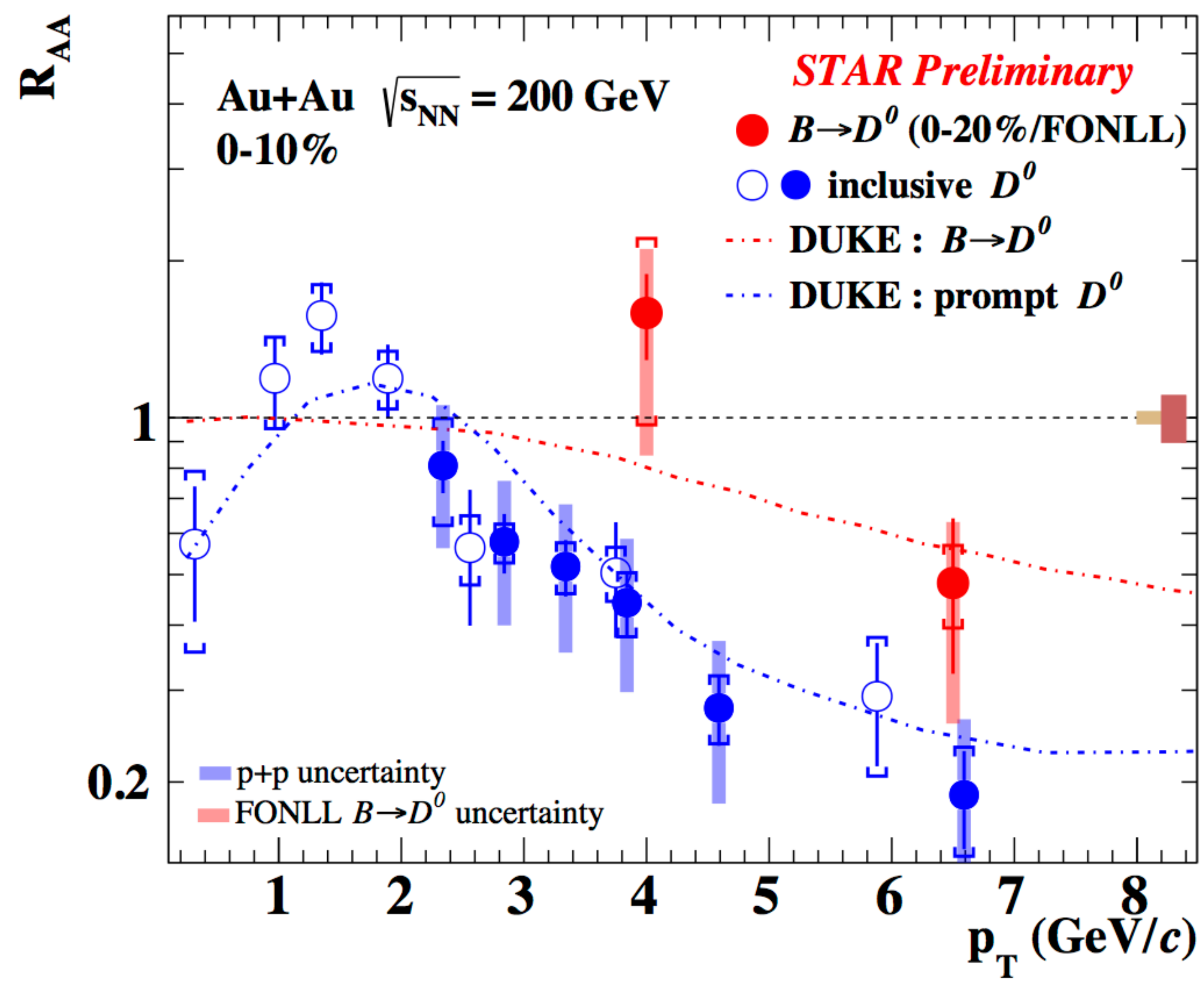




- HFT significantly reduces background.
- Use DCA fitting to find $B \rightarrow D^0$ from secondary vertex.

Non-prompt D^0 Production

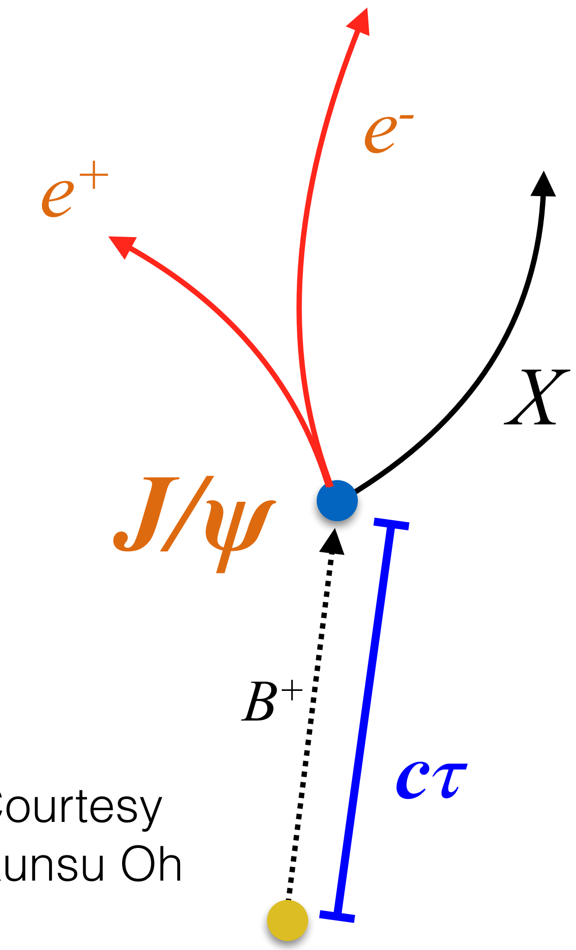




$$R_{AA}^{B\to D^0} = \frac{1}{\langle N_{coll}\rangle} \frac{f^{B\to D^0}_{Au+Au} \times dN^{incl.\ D^0}_{Au+Au}/dp_T}{dN^{B\to D^0}_{FONLL}/dp_T}$$

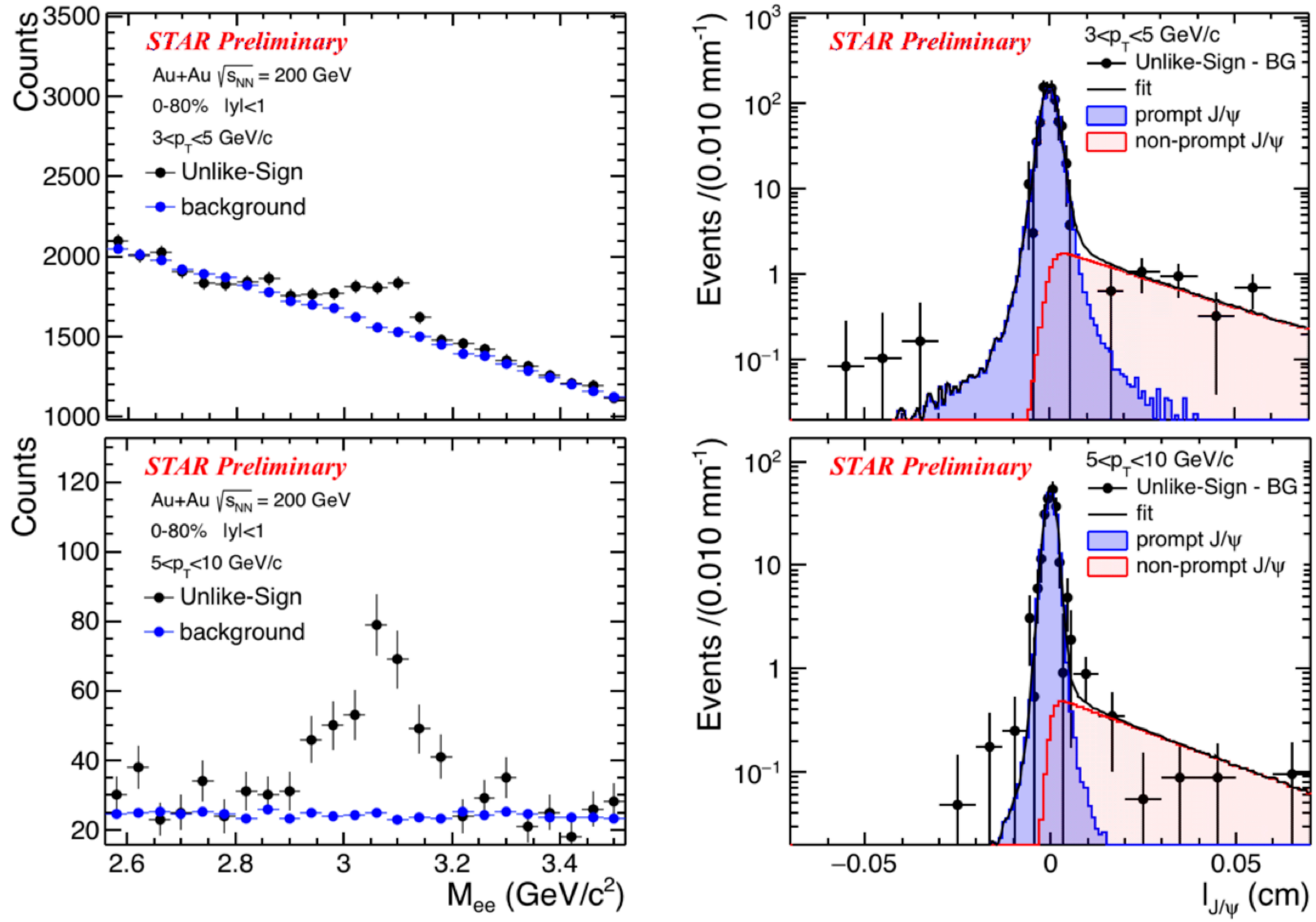
- No observed centrality dependence for the non-prompt D^0 fraction.
- Hint that non-prompt D^0 sees less suppression than inclusive D^0.

Non-prompt J/Ψ Production



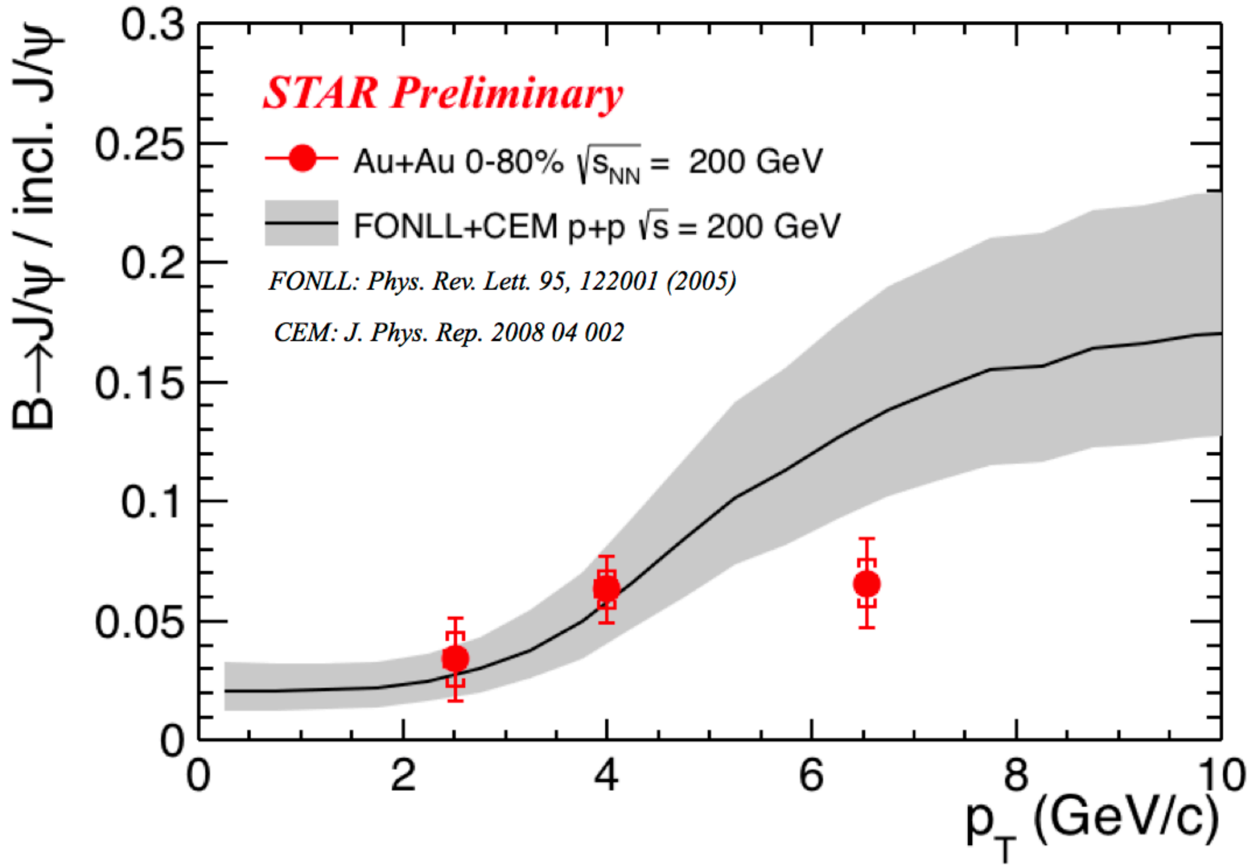
Courtesy
Kunsu Oh

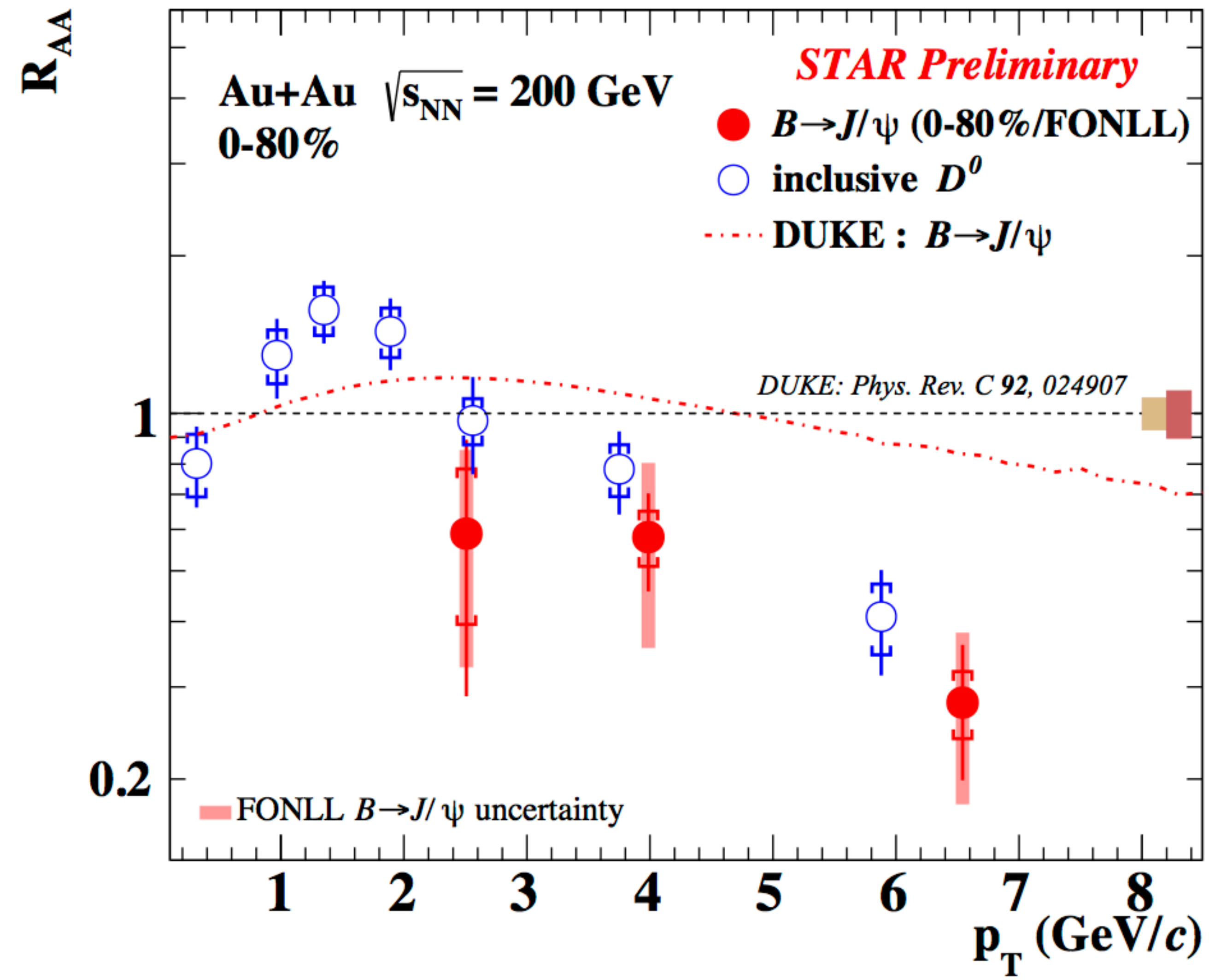
$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|\vec{p}|/c}\cdot M_{J/\psi}$$



- Extract the J/Ψ signal then calculate the pseudo proper decay length.
- Template based fitting to $l_{J/\psi}$ distribution is used to separate the contributions.

Non-prompt J/Ψ Production



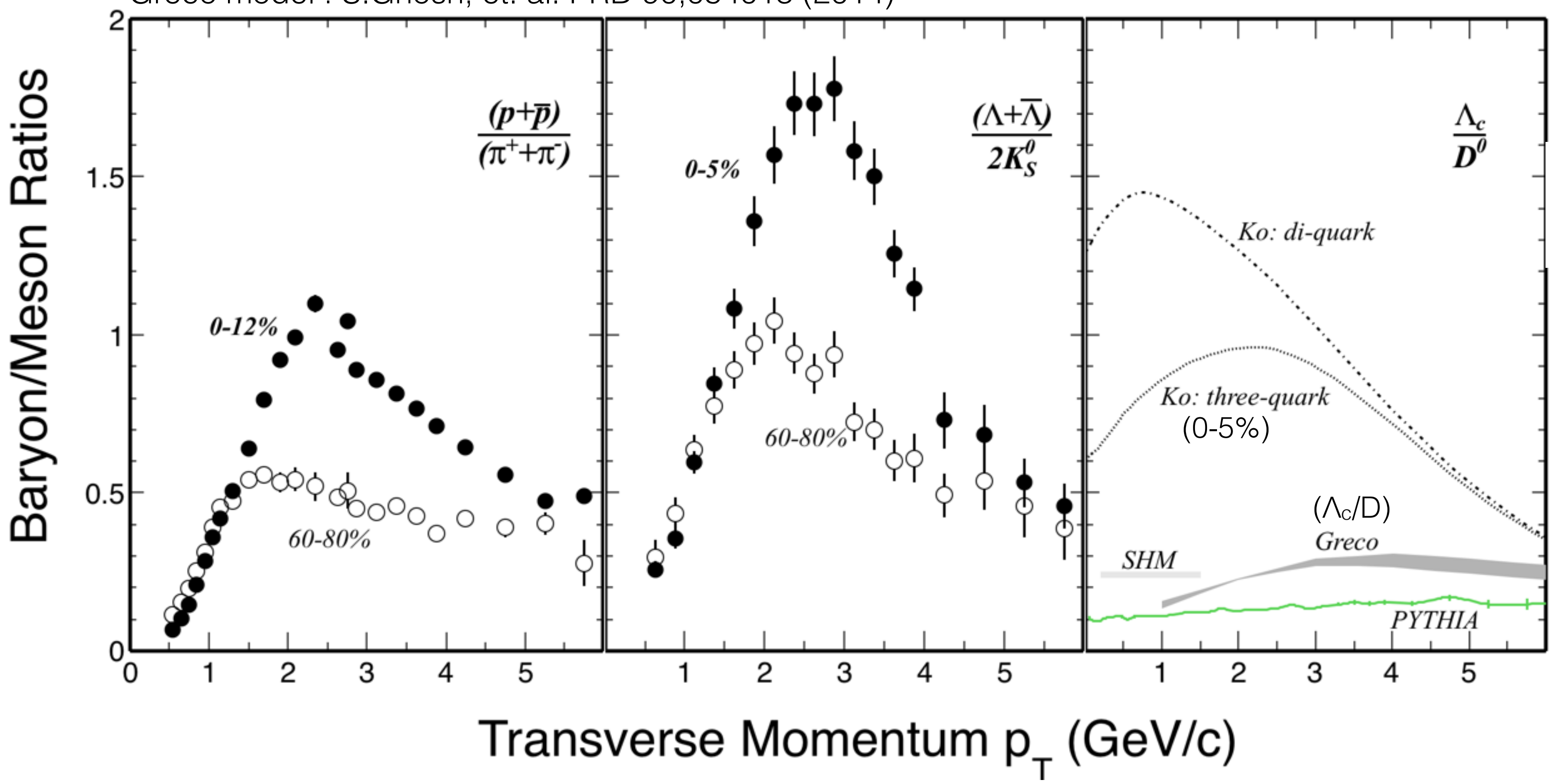


$$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(data)}{f_{p+p}^{B\to J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data)$$

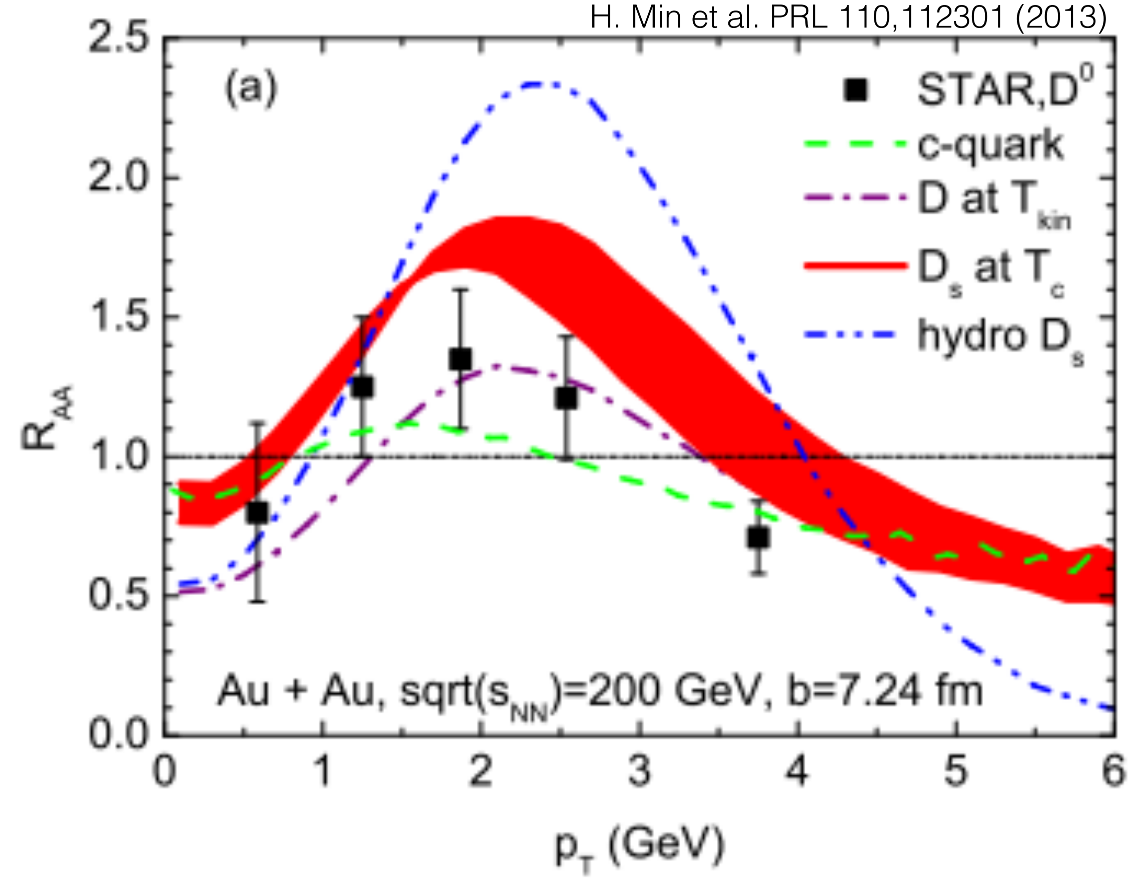
- Observe strong suppression of B→J/Ψ at high p_T. Similar trend for R_{AA} as D^0.

Λ_c and D_s Motivation

STAR arXiv:nucl-ex/0601042
Ko model : Y. Oh, et.al. PRC 79,044905 (2009)
Greco model : S.Ghosh, et. al. PRD 90,054018 (2014)

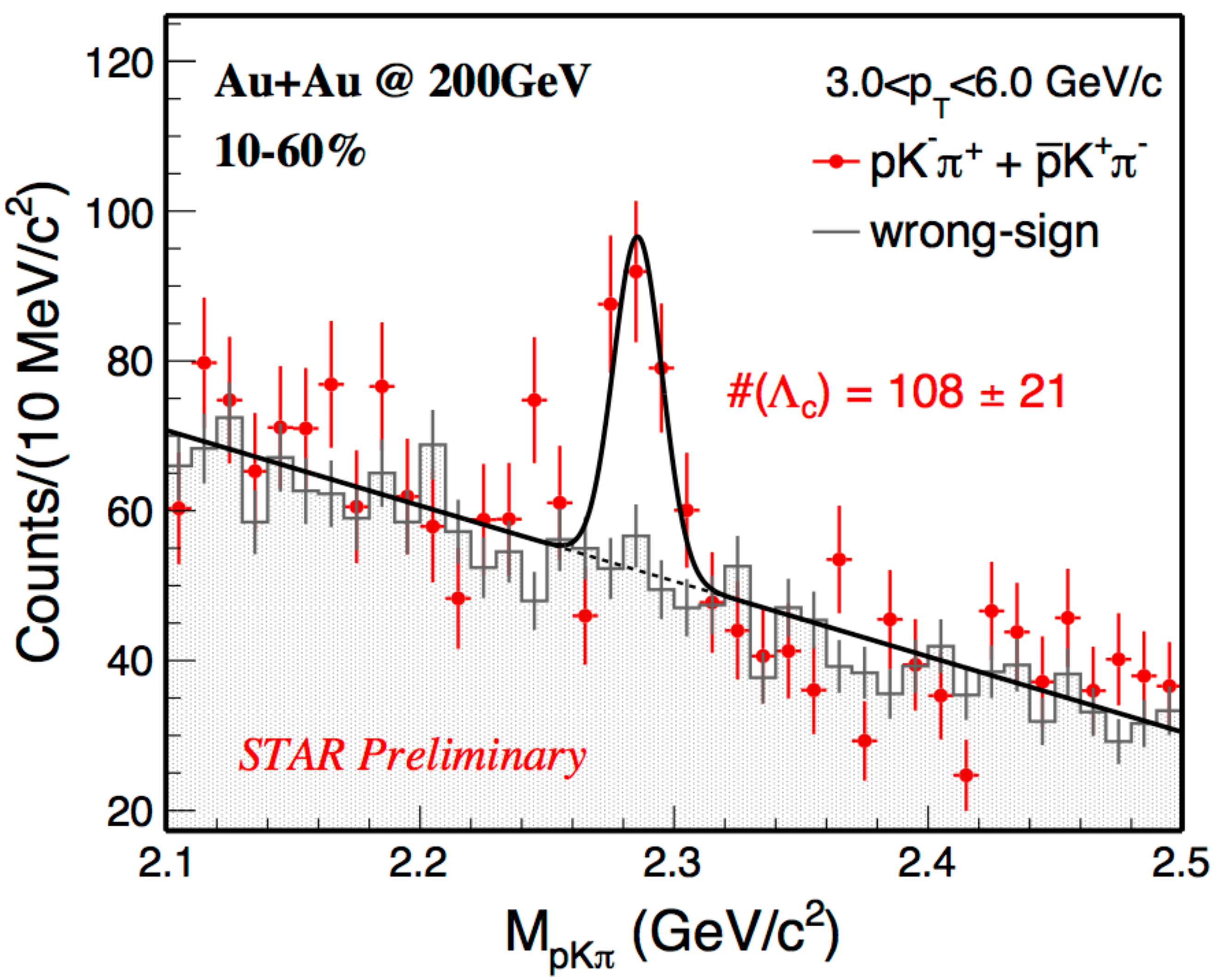


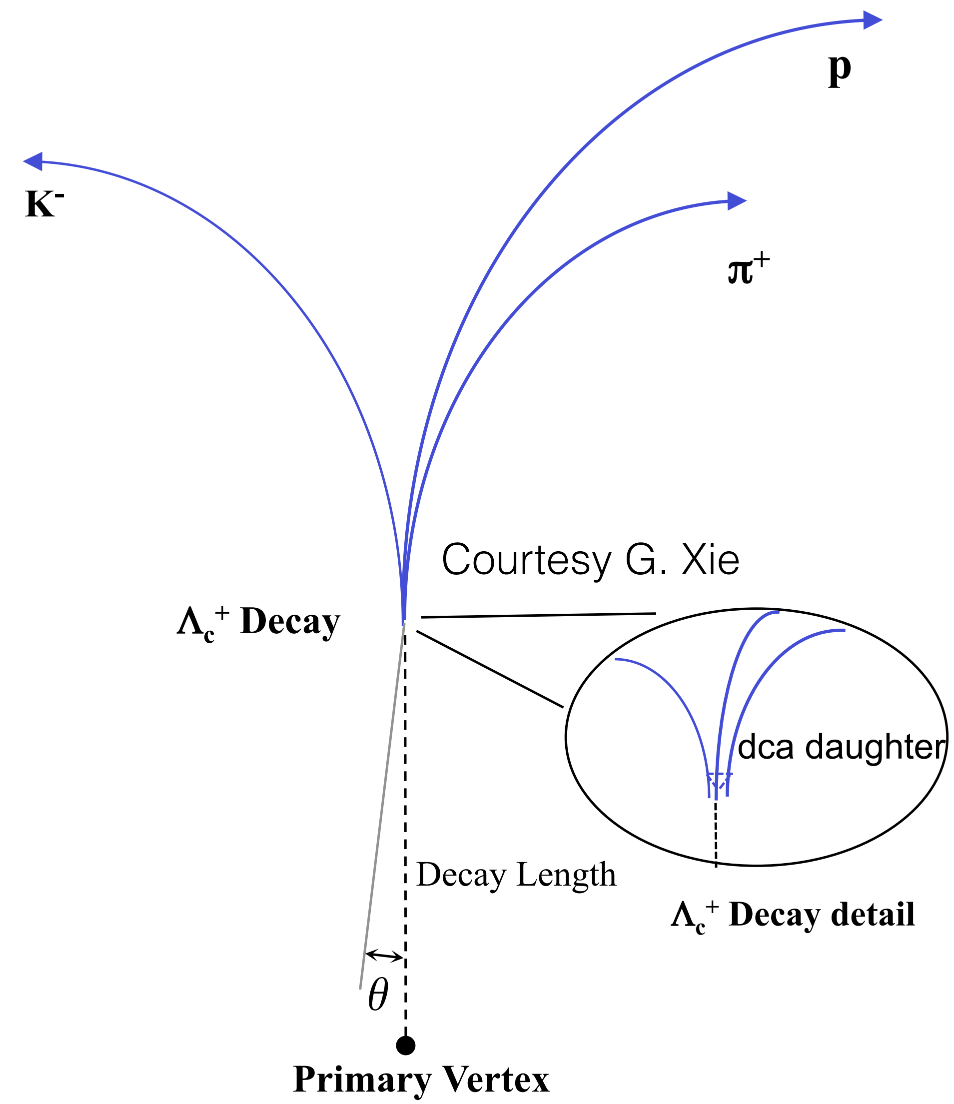
(STAR) Y. F. Zhang, J. Phys. G38, 124142 (2011)
H. Min et al. PRL 110,112301 (2013)



- Baryon-to-meson ratio and strangeness enhancement observed for light flavors. Attributed to coalescence.
- Coalescence hadronization models predict enhancement of D_s and Λ_c in Au+Au collisions compared to p+p collisions.
- Can help constrain total charm yield.

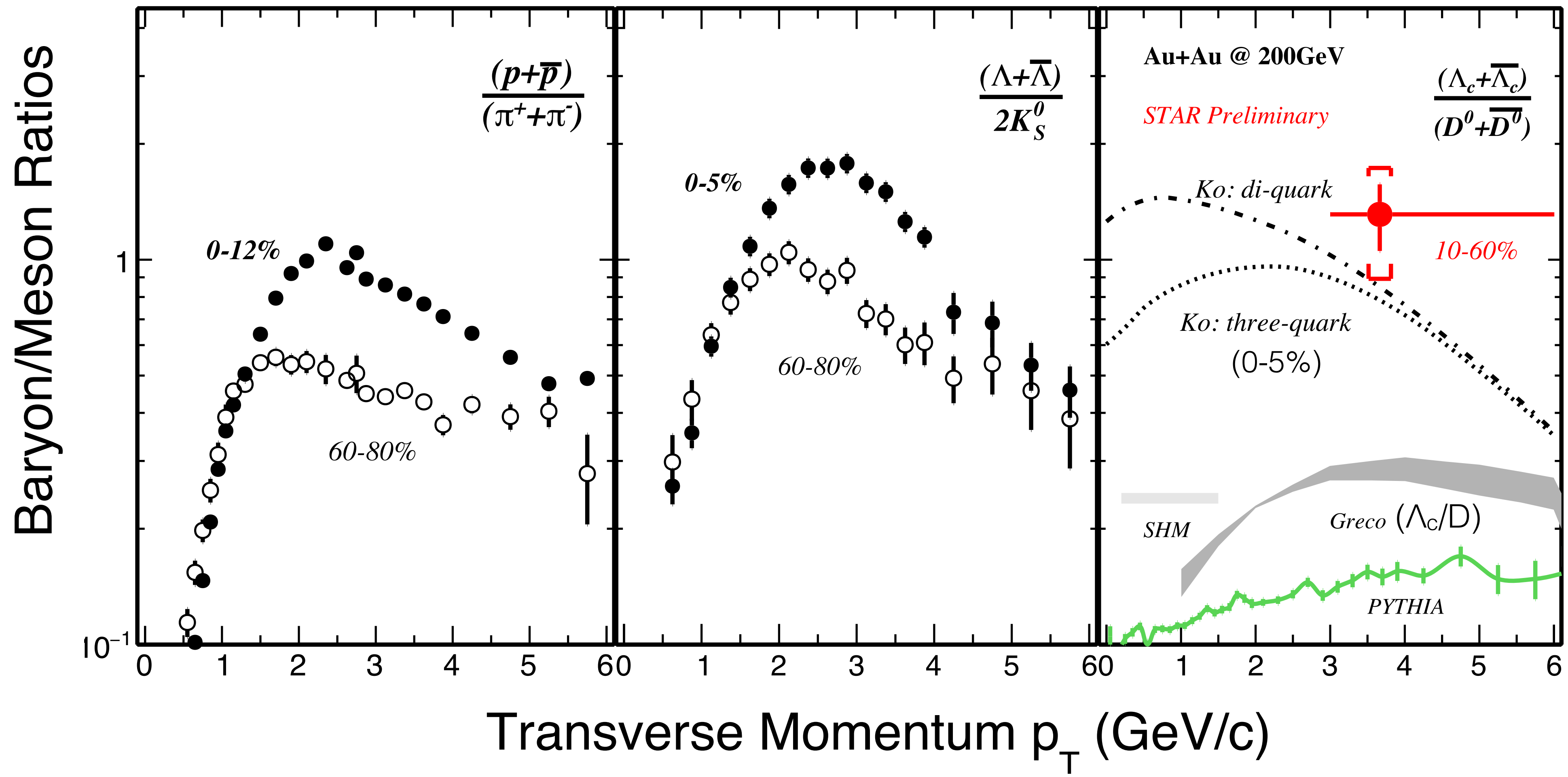
Λ_c Production





- First measurement of Λ_c in heavy-ion collisions.
- Measured in $\Lambda_c^+ \rightarrow pK^-\pi^+$ channel (BR ~ 6.35%).

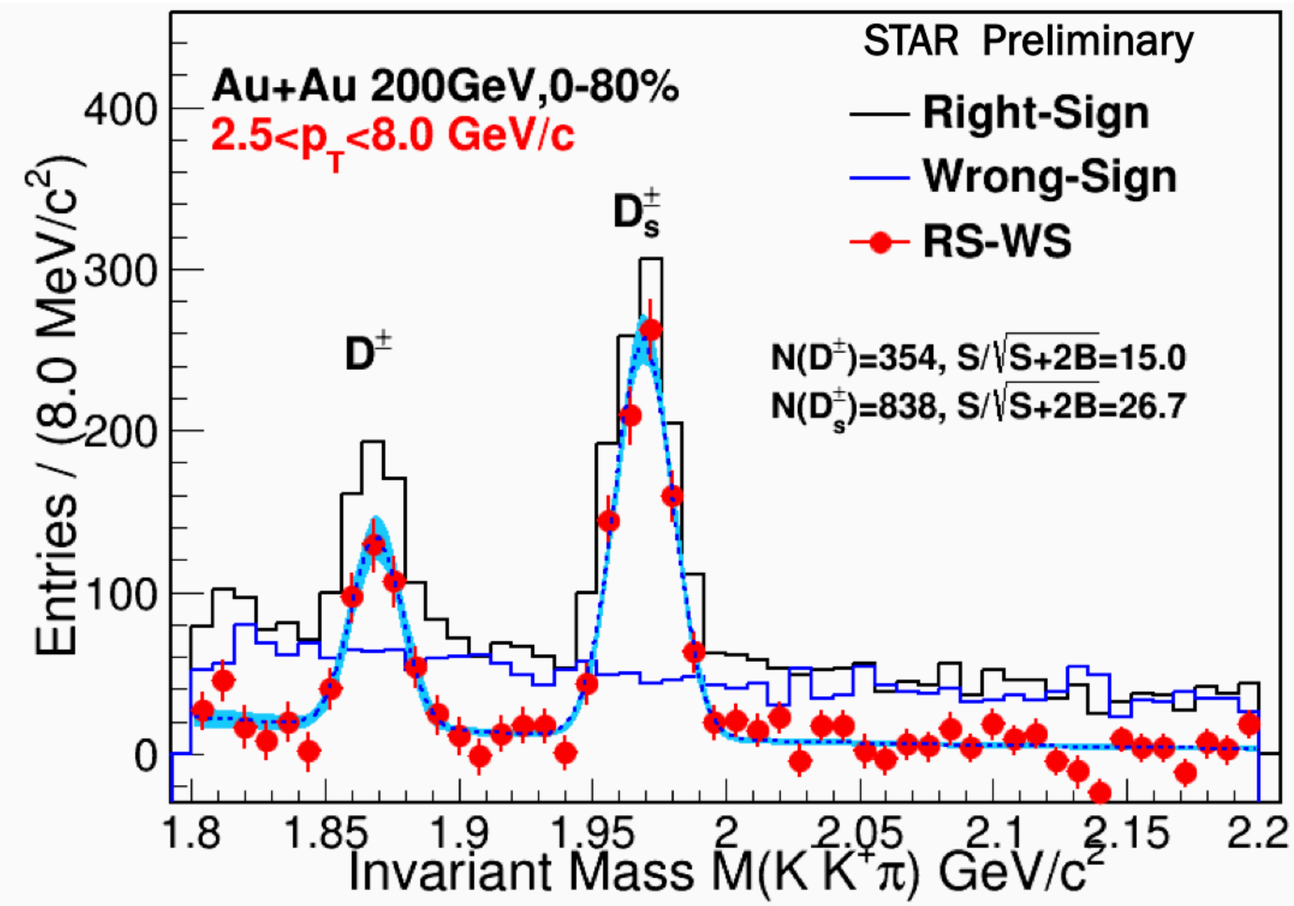
Λ_C Production

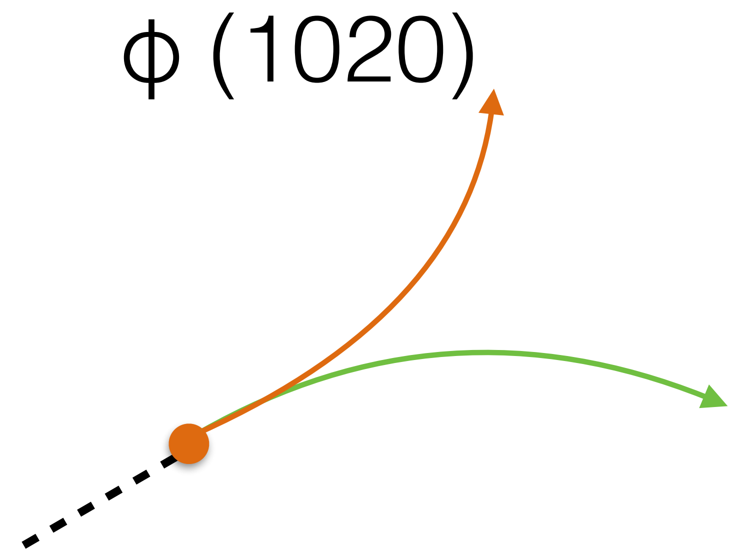


[1] S. Ghosh et al.,PRD 90 054018 (2014).
[2] Y. Oh et al.,PRC 79 044905 (2009).
[3] S. Lee et al.,PRL 100 222301 (2008).

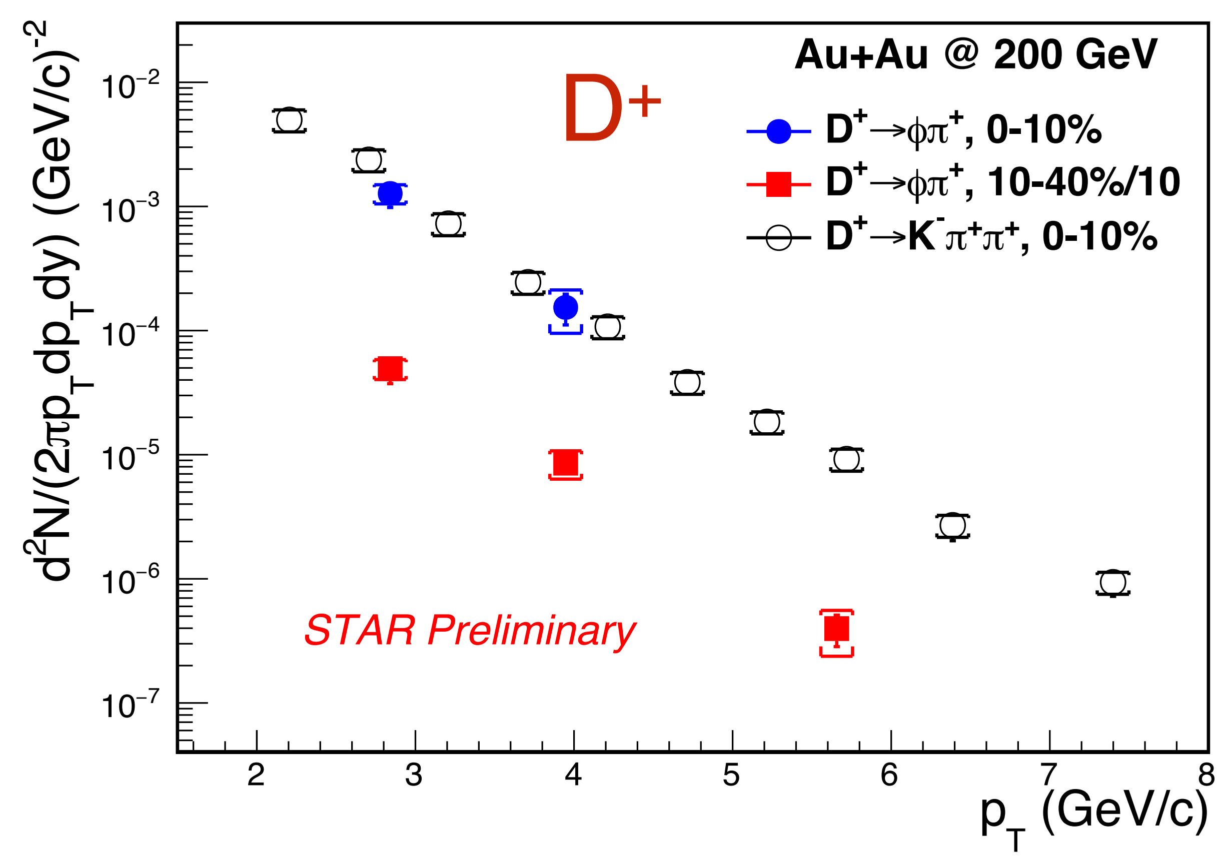
- Observed an enhancement of Λ_C/D^0 ratio relative to PYTHIA prediction.
    - Λ_C/D^0 = 1.3 ± 0.3 (stat) ± 0.4 (sys)
- Model including coalescence and thermalized charm quark is consistent with the data.
- Magnitude of the enhancement is similar to observations for light hadrons.

D_s and $D^{\pm}$ Production



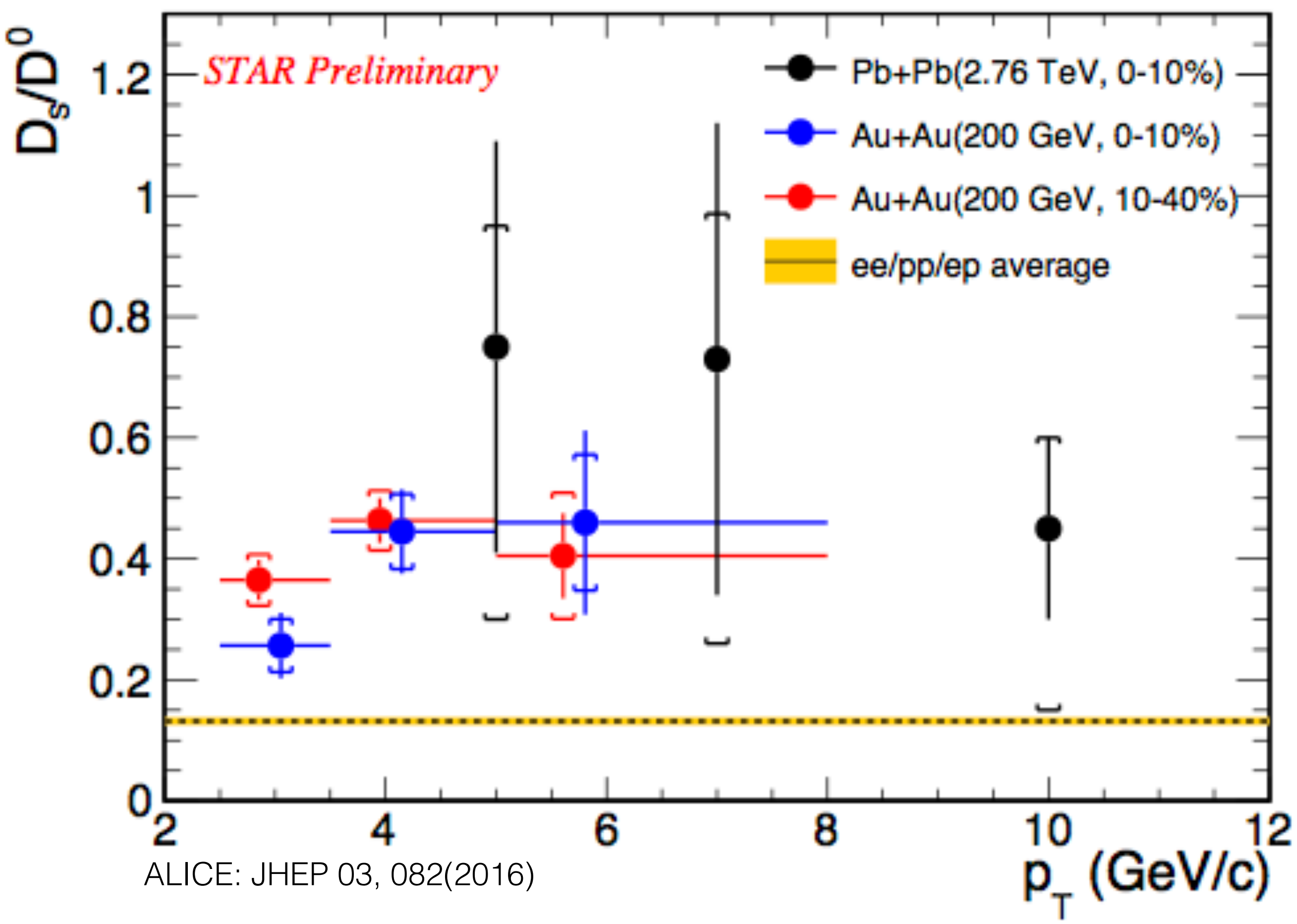


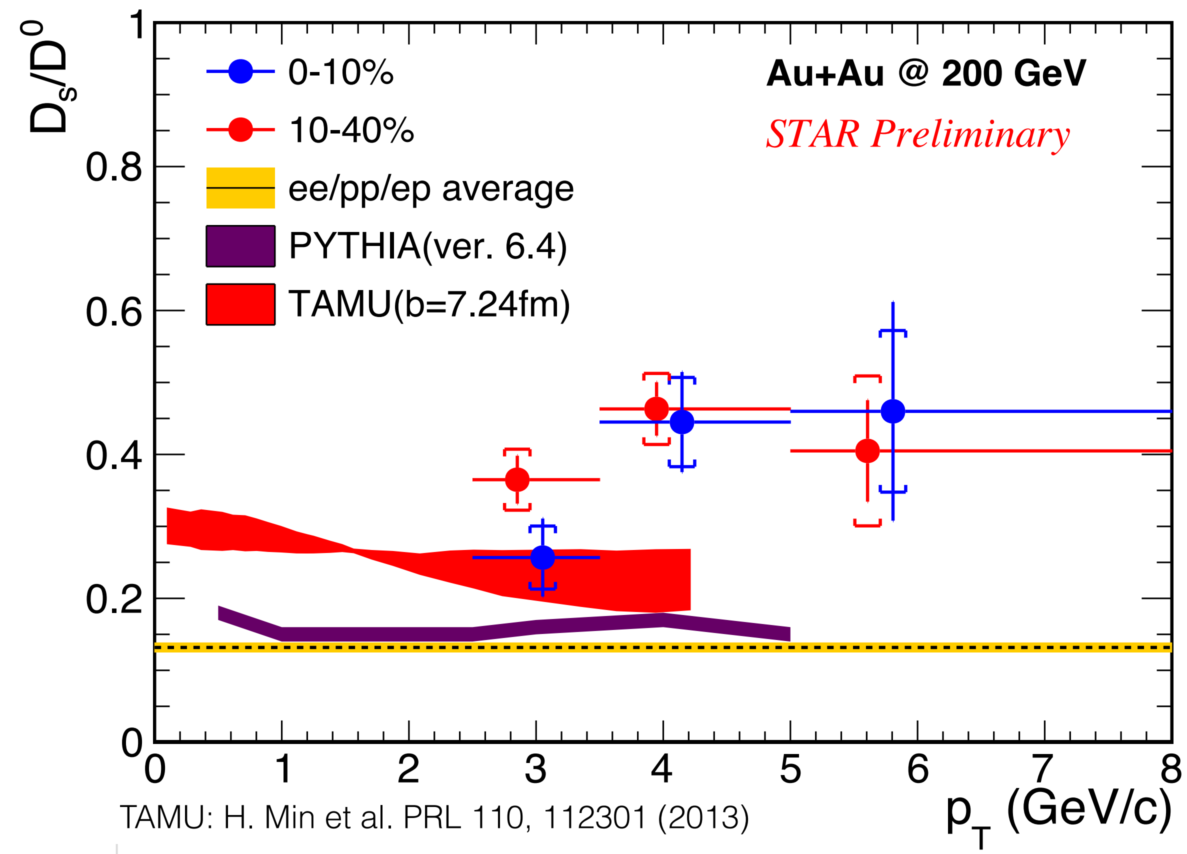
$$D_s \to \phi + \pi^+ \to K^+ K^- \pi^+$$

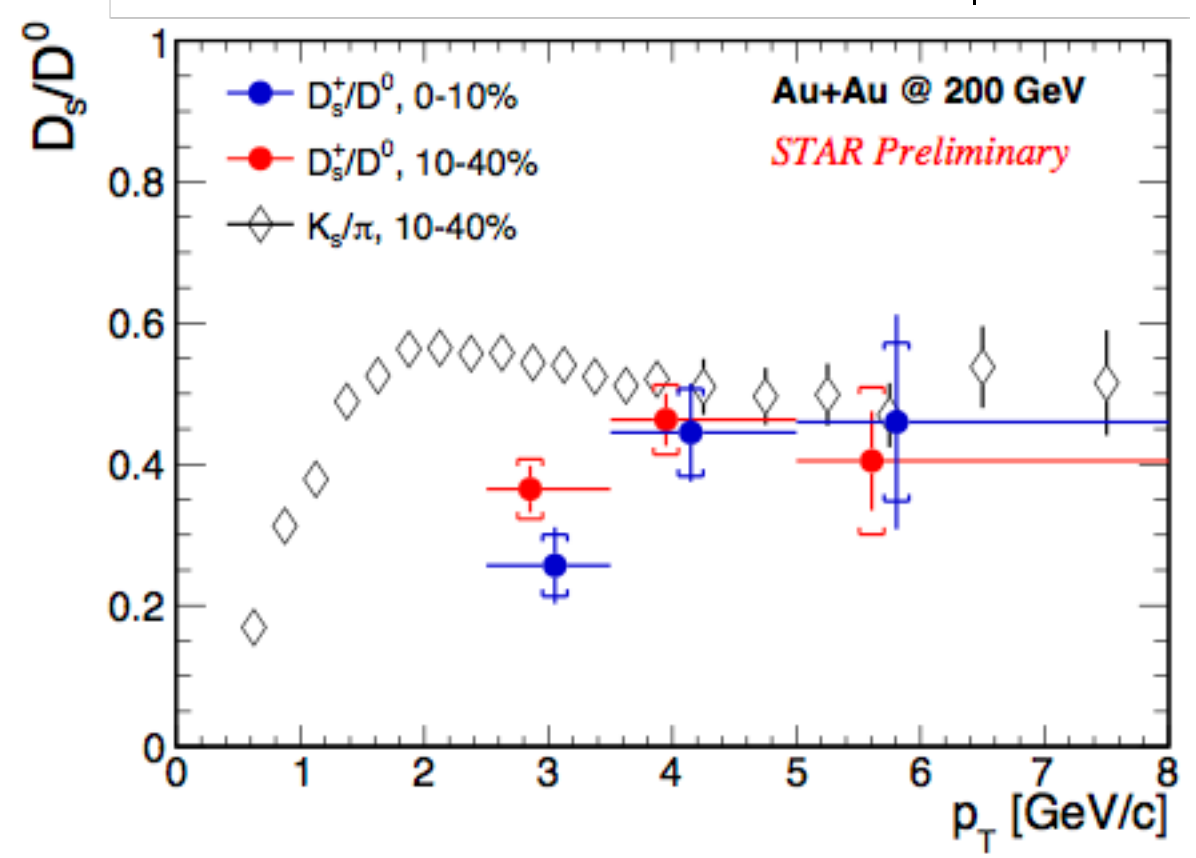


- $D_s^{\pm}$ and $D^{\pm}$ (BR = 0.27%) are reconstructed via [ϕ(1020) + π] decay channel.
- $D^{\pm}$ also reconstructed in $K\pi\pi$ channel (BR = 9.46%). Agreement between channels.

D_s/D^0

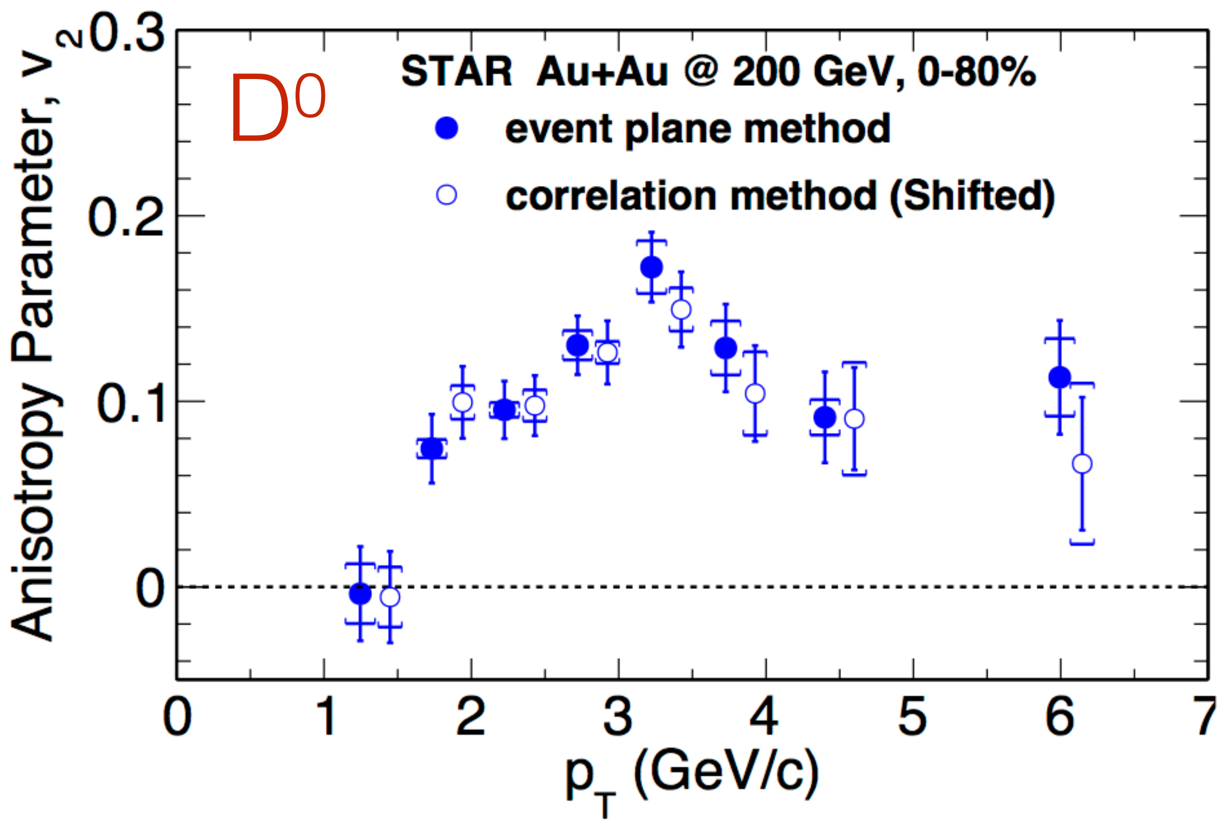


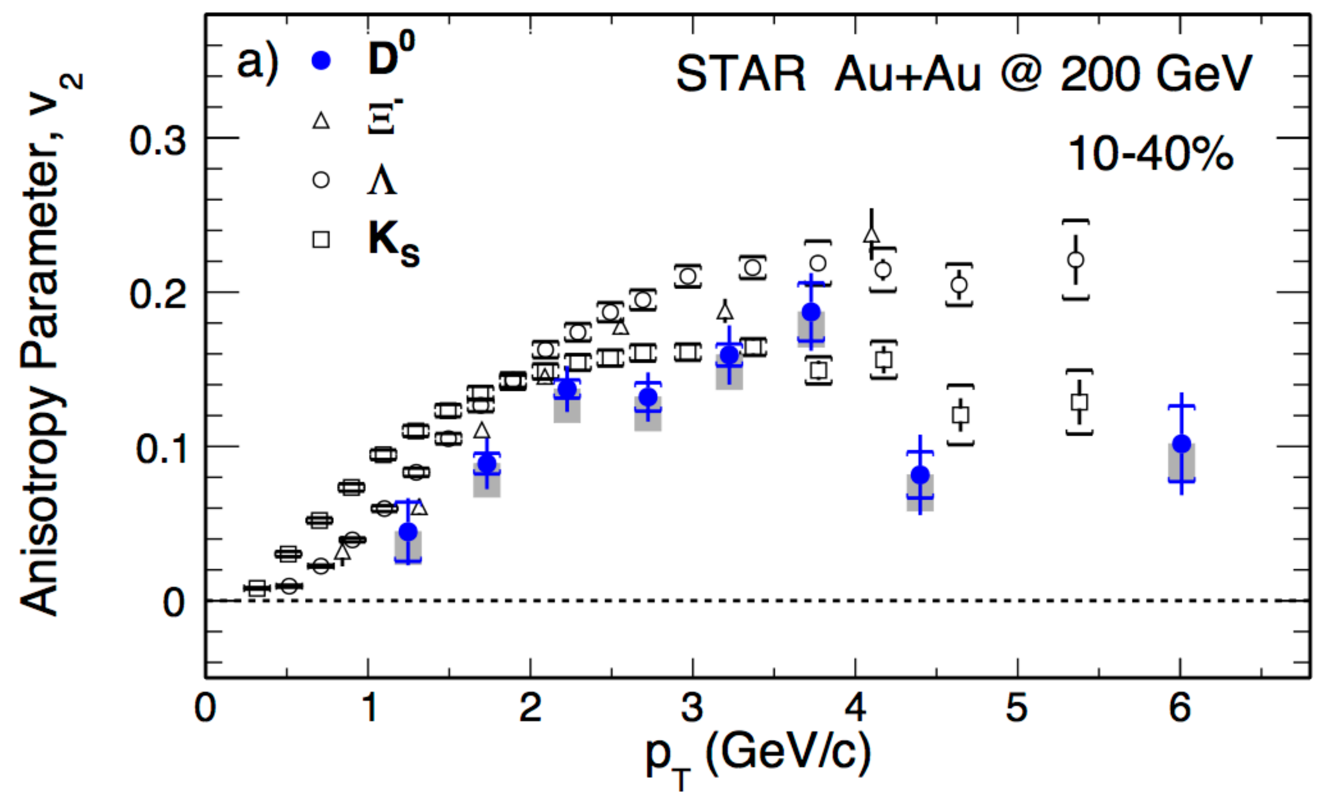




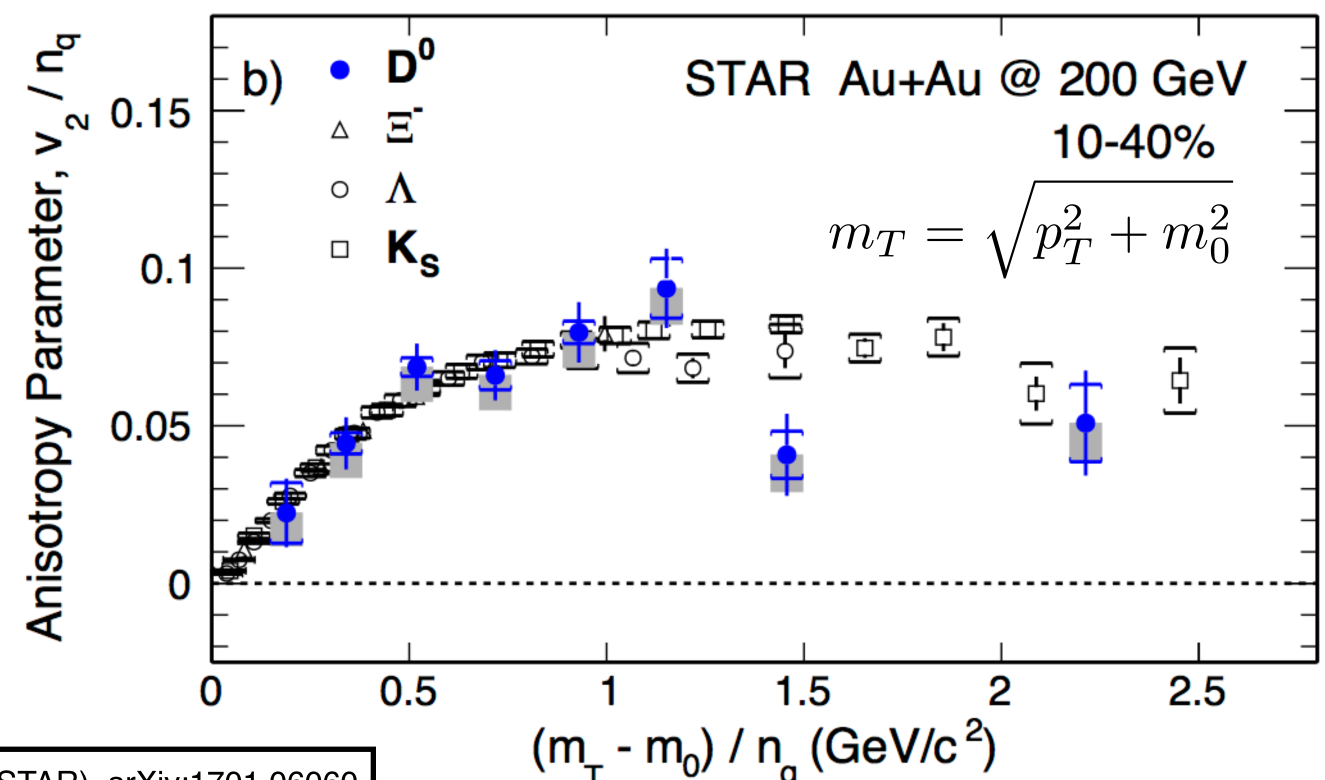
- No strong centrality dependence to the enhancement.
- D_s/D^0 shows enhancement compared to PYTHIA and TAMU model.
- Same magnitude as K/π ratio above 3.5 GeV/c, but disagreement at low p_T.

D^0 Flow (v_2)



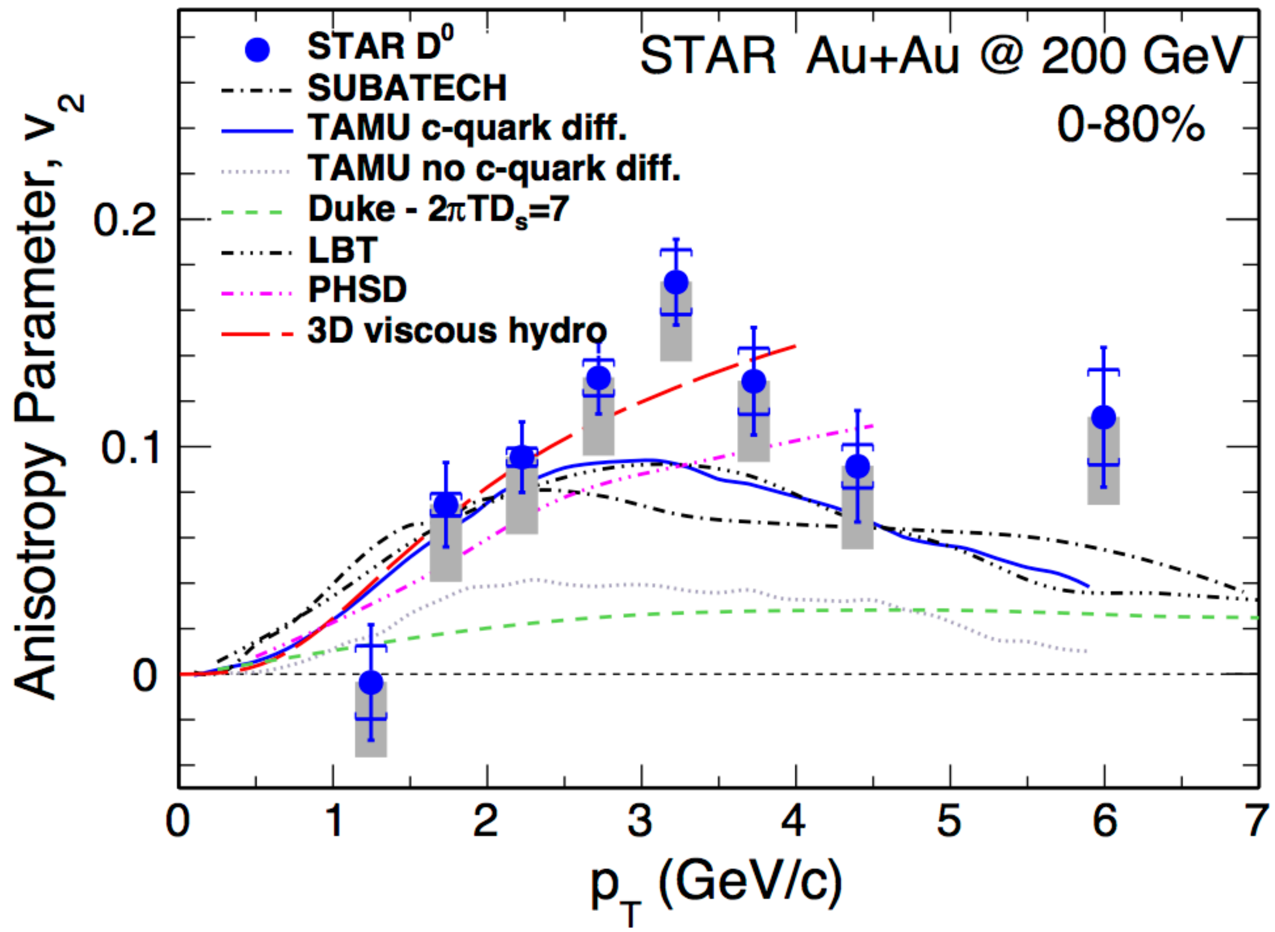


- Multiple methods for determining v_2 agree.
- D^0 follows with mass ordering at $p_T < 2$ GeV/c
- D^0 follows NCQ scaling, suggesting that charm quarks may be just as thermalized as light flavors.



L. Adamczyk et al. (STAR), arXiv:1701.06060

D^0 Flow (v_2)

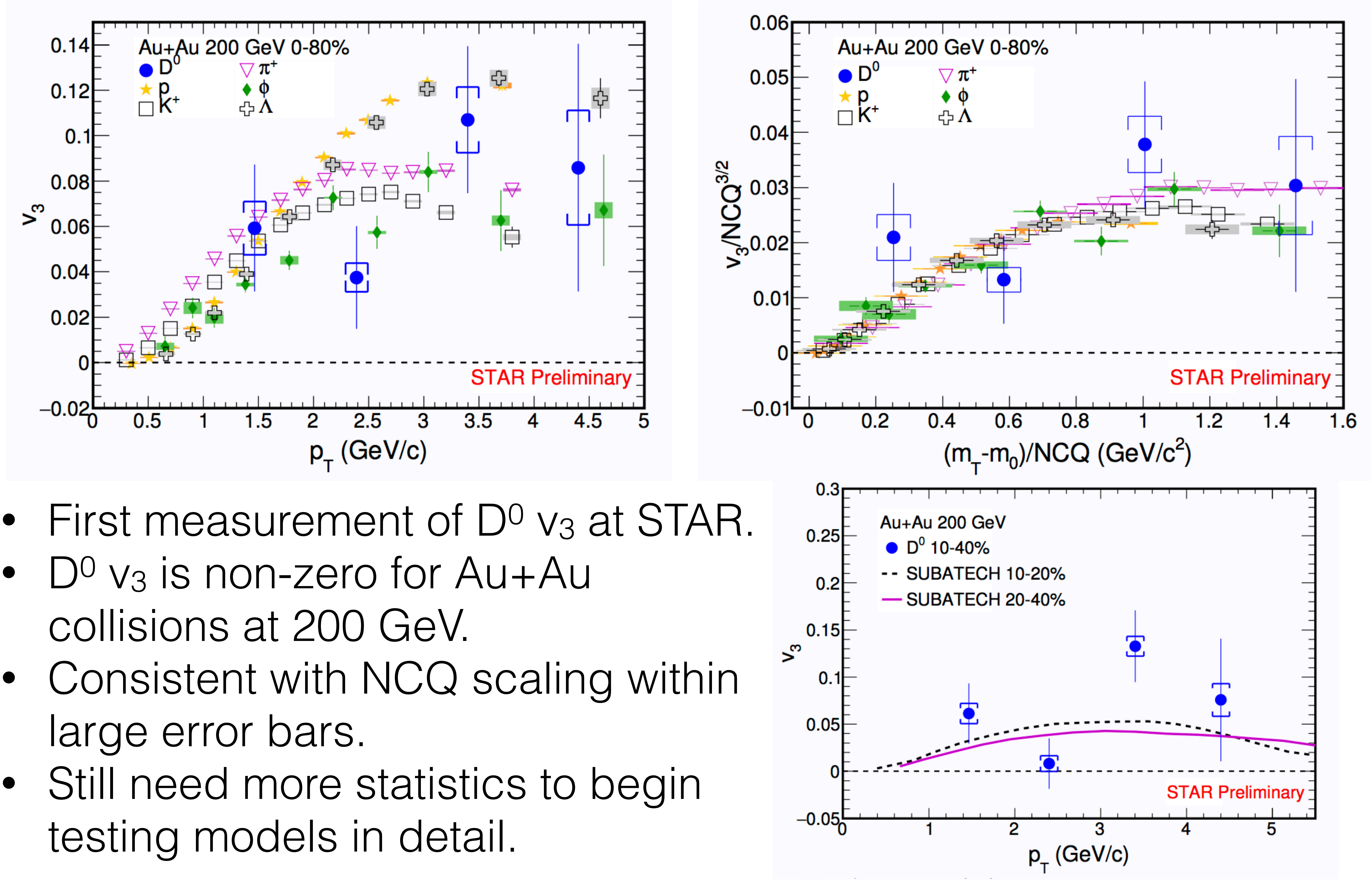


Different models:

- **SUBATECH: pQCD + hard thermal loop**
  - *P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, Strangeness in quark matter*
- **TAMU: T-matrix, non-perturbative model with internal energy potential**
  - *M. He, R. J. Fries, and R. Rapp, PRC86, 014903 (2012)*
- **Duke: free constant D_s, fit to LHC high p_T R_{AA}**
  - *S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)*
- **hydro: A 3D viscous hydrodynamic model**
  - *L.-G. Pang, Y. Hatta, X.-N. Wang, and B.-W. Xiao, PRD91, 074027 (2015)*
- **PHSD: Parton-Hadron-String Dynamics, a transport model**
  - *H. Berrehrah et al. PRC90 (2014) 051901*
- **LBT: A Linearized Boltzmann Transport model**
  - *S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)*

compare with	$2\pi TD_s$	$\chi2$/n.d.f.	*p*-value
3D viscous hydro	-	3.6 / 6	0.73
LBT	3-6	11.1 / 8	0.19
PHSD	5-12	8.7 / 7	0.28
TAMU c quark diff.	2-12	10.0 / 8	0.26
SUBATECH	2-4	15.2 / 8	0.06
TAMU no c quark diff.	-	29.5 / 8	2×10^{-4}
DUKE	7	37.5 / 8	2×10^{-5}

D^0 v_3



- First measurement of D^0 v_3 at STAR.
- D^0 v_3 is non-zero for Au+Au collisions at 200 GeV.
- Consistent with NCQ scaling within large error bars.
- Still need more statistics to begin testing models in detail.

Summary

- Separate measurements of B→e and D→e R_{AA} is consistent with **mass hierarchy in energy loss($\Delta E_c > \Delta E_b$).**
- See strong suppression of B→J/Ψ and B→D^0 in high p_T region.
- Observe significant enhancement in Λ_c/D^0 and D_s/D^0 ratios with respect to PYTHIA predictions. The Λ_c/D^0 ratio is consistent with models that include **coalescence hadronization** and charm quark thermalization.
- D^0 v_2 measurements are consistent with models including charm quark flow.
  - 3D viscous hydrodynamic model describes data **suggesting charm quarks have achieved thermal equilibrium.**
  - Dynamic models describe data well with a diffusion coefficient $2\pi TD_s$ of ~2-5 at T_c, and a temperature dependent range of ~2-12 within $2T_c$.

Outlook

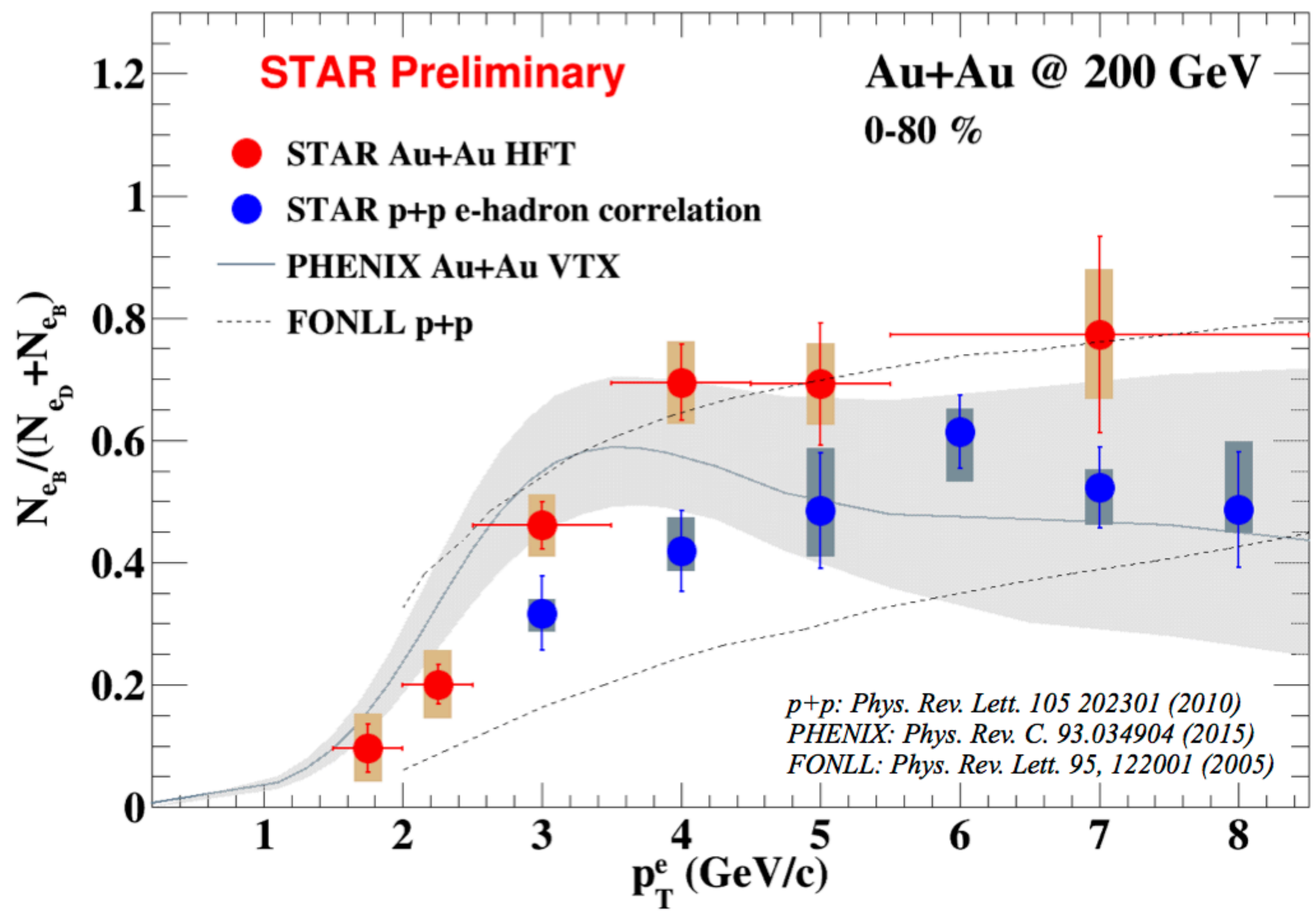
Already on disk at STAR:

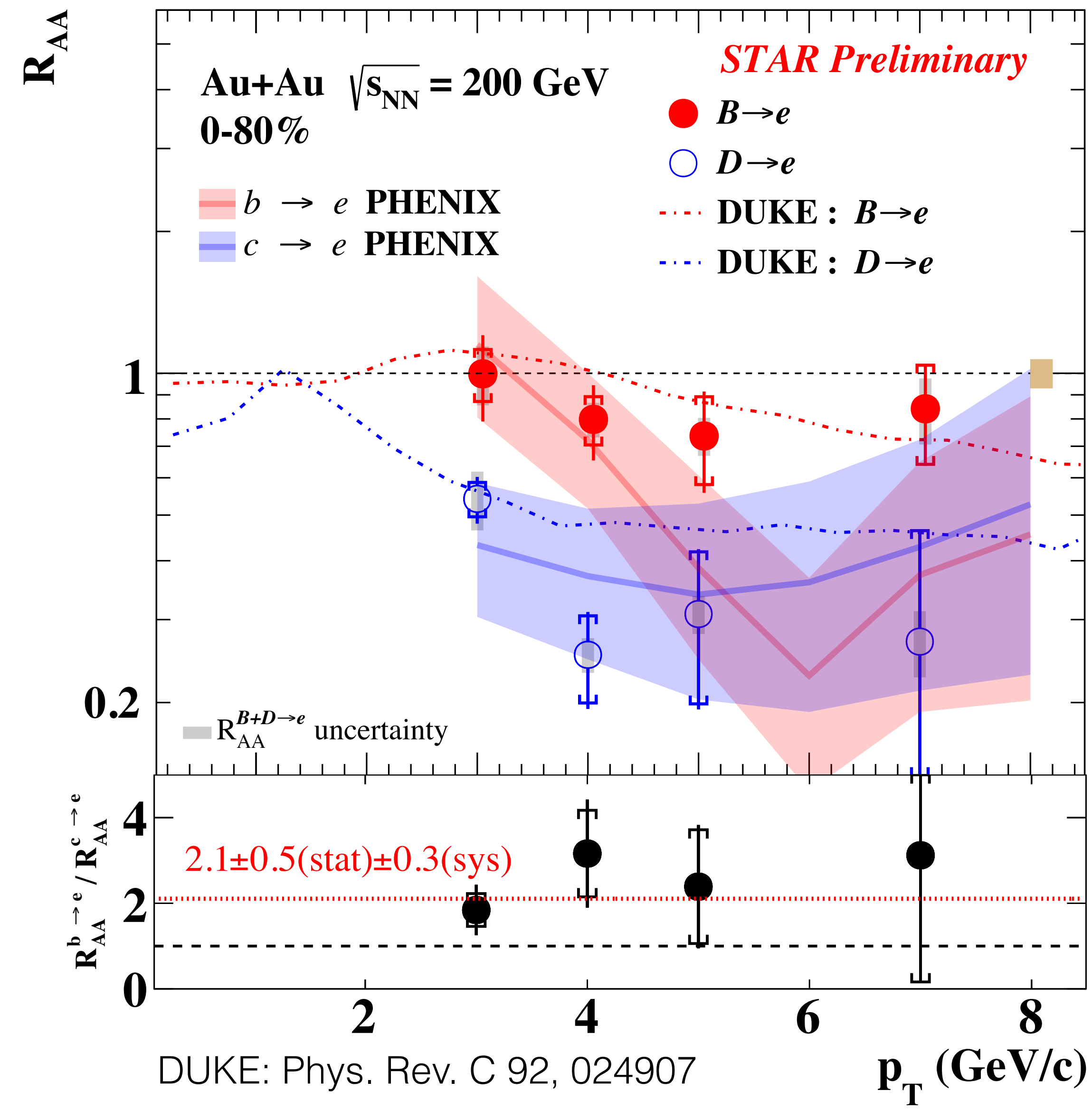
- High statistics p+p data at $\sqrt{s}$ = 200 GeV to improve the baseline for heavy flavor production measurements.
- High statistics p+Au data at $\sqrt{s}$ = 200 GeV to investigate CNM effects on heavy flavor production.
- Another large Au+Au dataset at $\sqrt{s_{NN}}$ = 200 GeV.

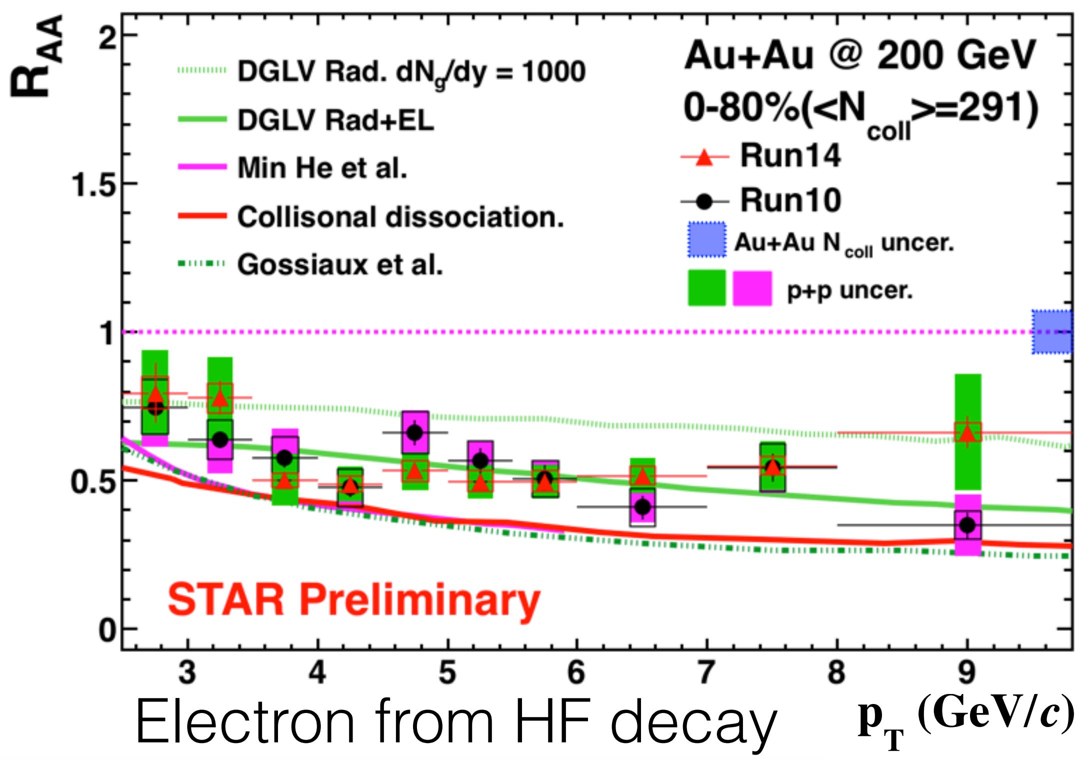
The next few years at STAR will be filled with exciting heavy flavor results!

Backup

b/c→e in Au+Au 200 GeV



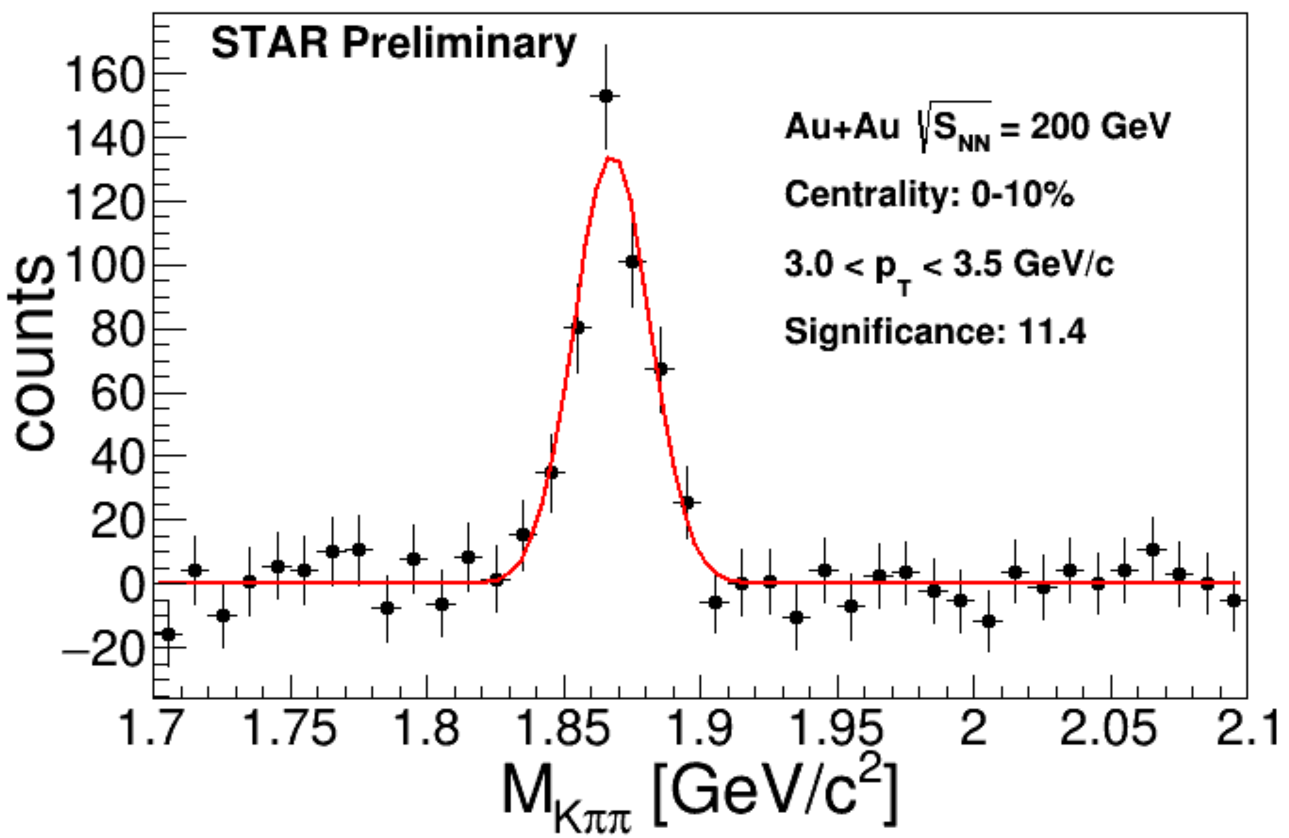


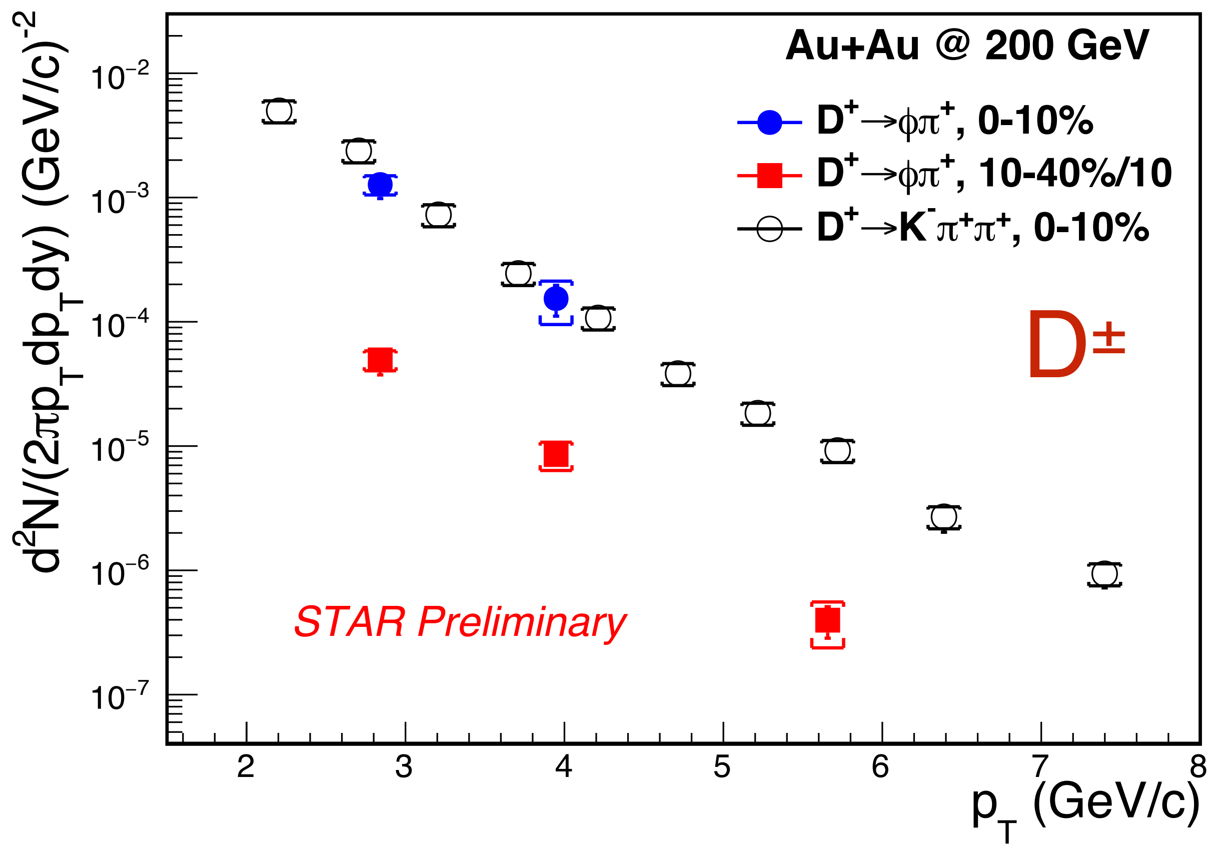


- Generally agree with PHENIX results, though within large errors bars from PHENIX at high p_T.

D_s and $D^{\pm}$ Production

$$D^+ \to K^- \pi^+ \pi^+$$





See strong suppression at high p_T, consistent with suppression seen in D^0. Indicates substantial energy loss for charm quarks in QGP.