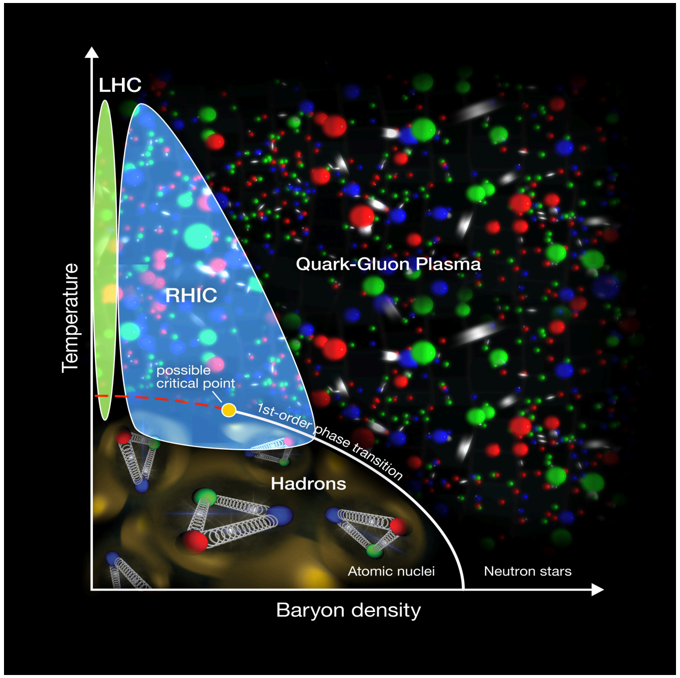
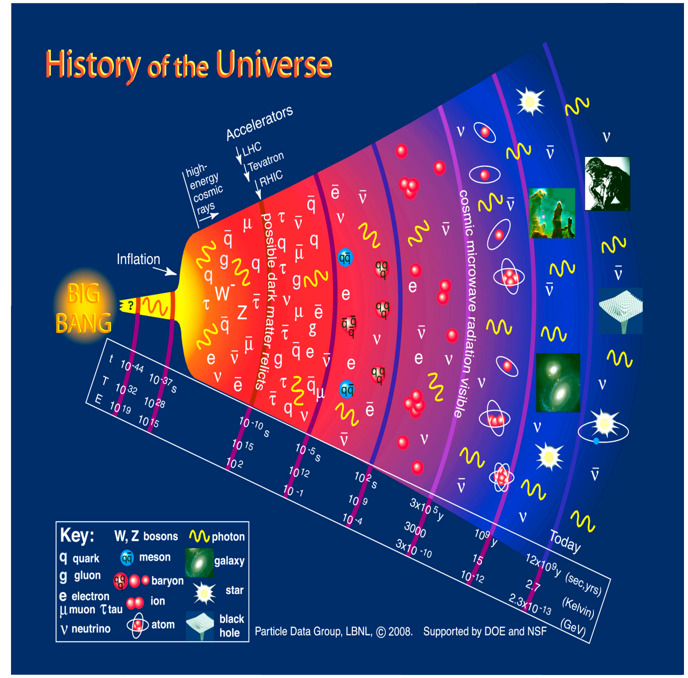
# Measurement of Open Heavy Flavor Production in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV in STAR

Guannan *XIE* (谢冠男)
Lawrence Berkeley National Laboratory

Sept. 19, 2019

# Quark-Gluon Plasma

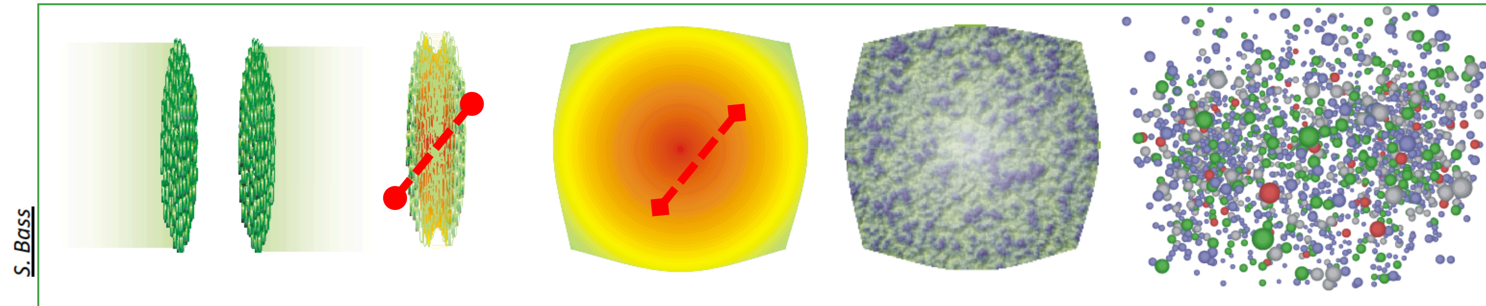



- Lattice QCD predicts a state of QCD matter at high temperature/density - quark-gluon plasma (quarks and gluons are deconfined)
- Expected to exist in early universe: t ~ $10^{-6}$s

# QGP in Laboratory

High Energy Nucleus-Nucleus Collisions



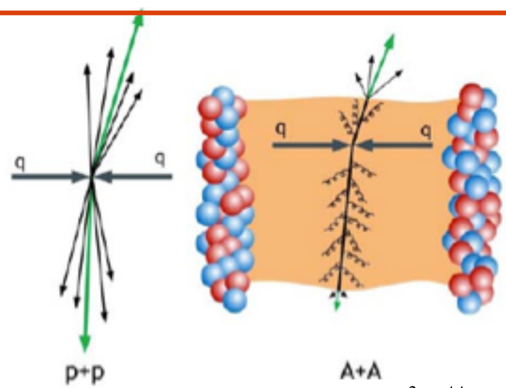

Initial conditions

Initial hard interactions

Partonic matter - QGP

Hadronization and chemical freeze-out

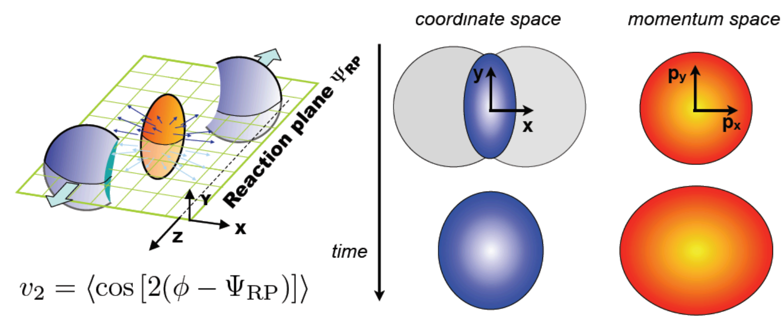
Kinetic freeze-out




$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

Nuclear modification factor ($R_{AA}$)

Characterize the medium effect

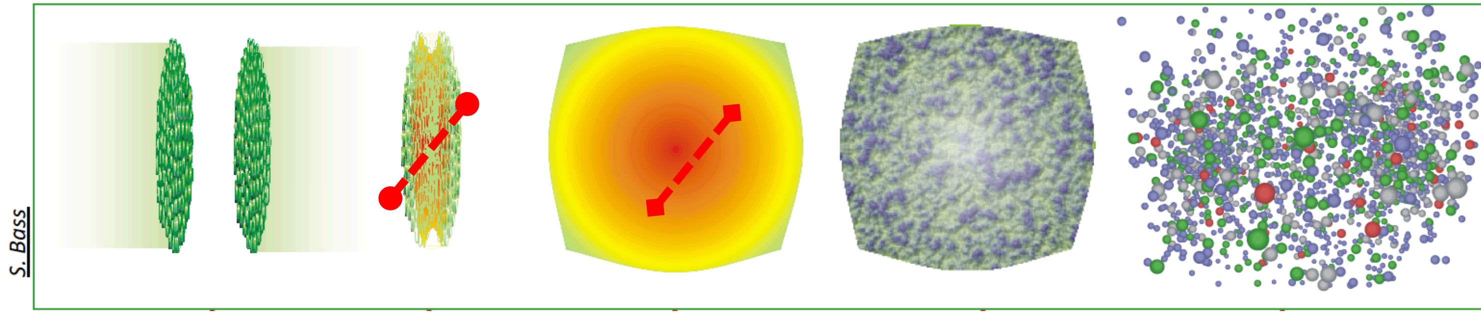



$$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle$$

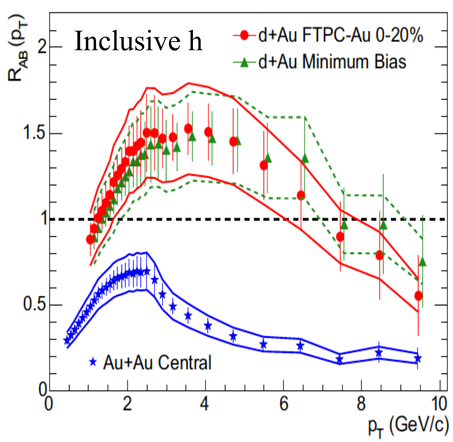
Elliptic flow ($v_2$) = 2nd Fourier coefficient

Sensitive to the early stage properties

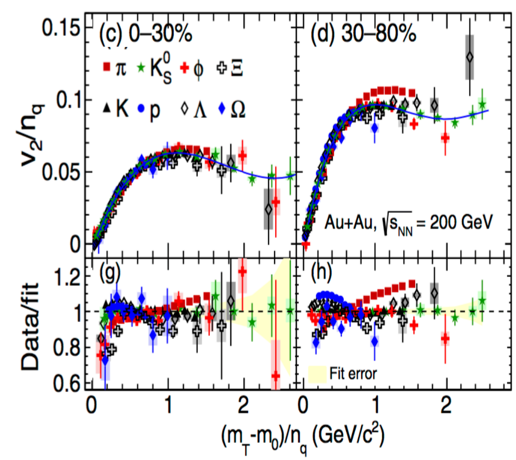
# QGP in Laboratory




Formation of strongly-coupled Quark Gluon Plasma (sQGP)!



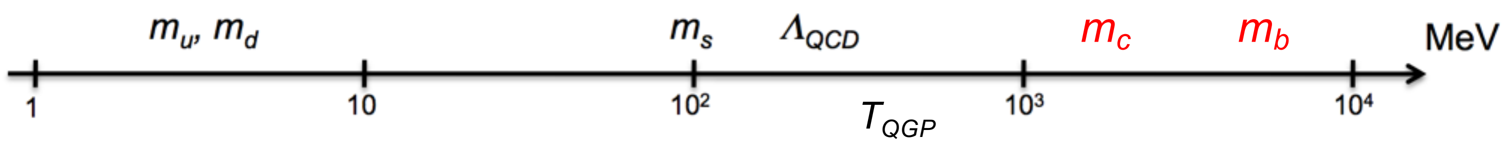

"Jet Quenching"




"Partonic Collectivity"

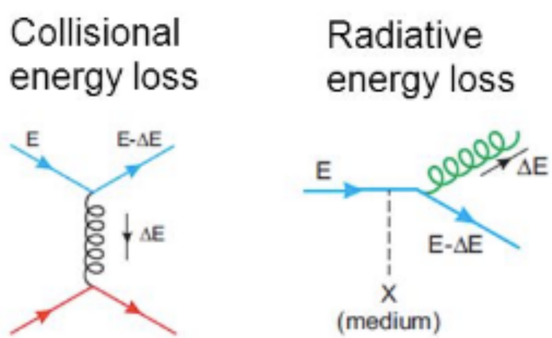
*STAR: PRL. 91 (2003) 072304*
*PRL. 99 (2007) 112301*

# Probes QGP with Heavy Quarks : Uniqueness

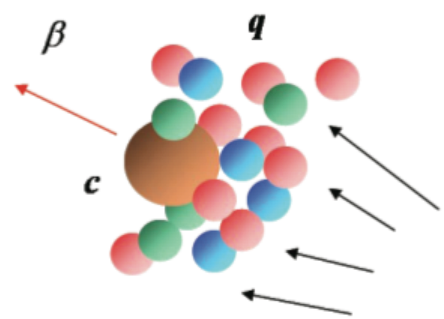



- Heavy quarks: $m_{c/b} >> \Lambda_{QCD}, T_{QGP(RHIC)}$
  - Calculable in perturbative QCD
  - Produced early in heavy-ion collisions through hard scatterings

  → good probe of medium properties




Heavy quarks
- sensitive to different energy loss mechanisms




When $M_{HQ} >> T$, $M_{HQ} >> gT$

"Brownian" motion

→ Langevin simu.

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t).$$

Drag

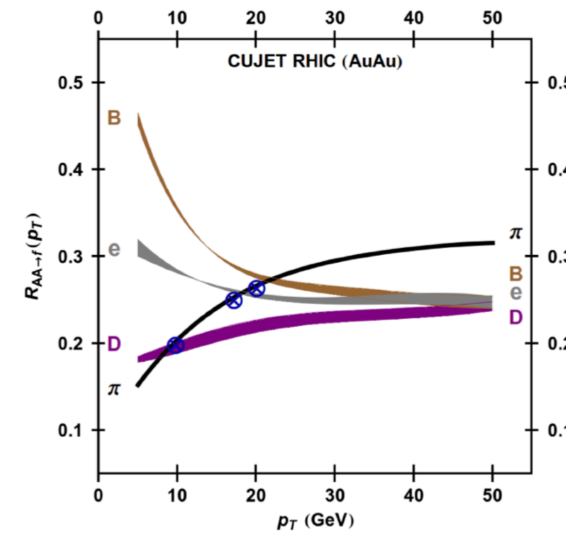
Fluctuations

Diffusion coefficient

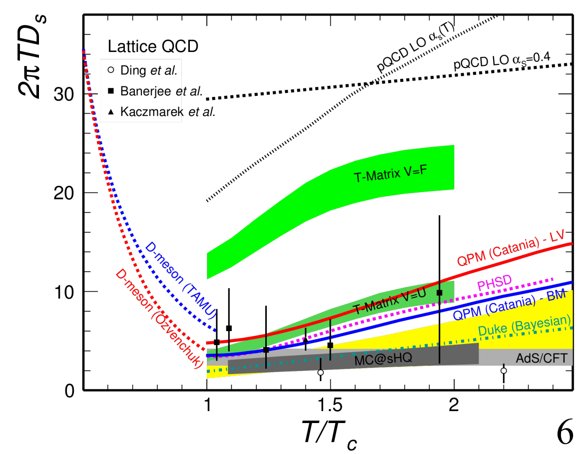
# Physics Goals and Contents

- Mass dependence of parton energy loss - $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$
- Quantify QGP transport parameter - HQ spatial diffusion coefficient, $D_s$

- In medium energy loss
  $D^0$ $R_{AA}$, $R_{CP}$
- Hadronization
  $\Lambda_c$, $D_s$
- Charm conservation
  Total charm cross-section
- Mass dependence of energy loss
  $B \rightarrow (J/\psi, D^0, e)$
- Transport coefficients
  $D^0$ $v_2$




PRL 108, 022301 (2012)




arXiv: 1502.02730

# Experimental Methods

| Hadron | Abundance | cτ (μm) |
|---|---|---|
| $D^0$ | 56% | 123 |
| $D^+$ | 24% | 312 |
| $D_s$ | 10% | 150 |
| $\Lambda_c$ | 10% | 60 |
| $B^+$ | 40% | 491 |
| $B^0$ | 40% | 456 |

**Direct** - Secondary vertex reconstruction

$eg.\ D^0 \to K\pi, B \to J/\psi K$

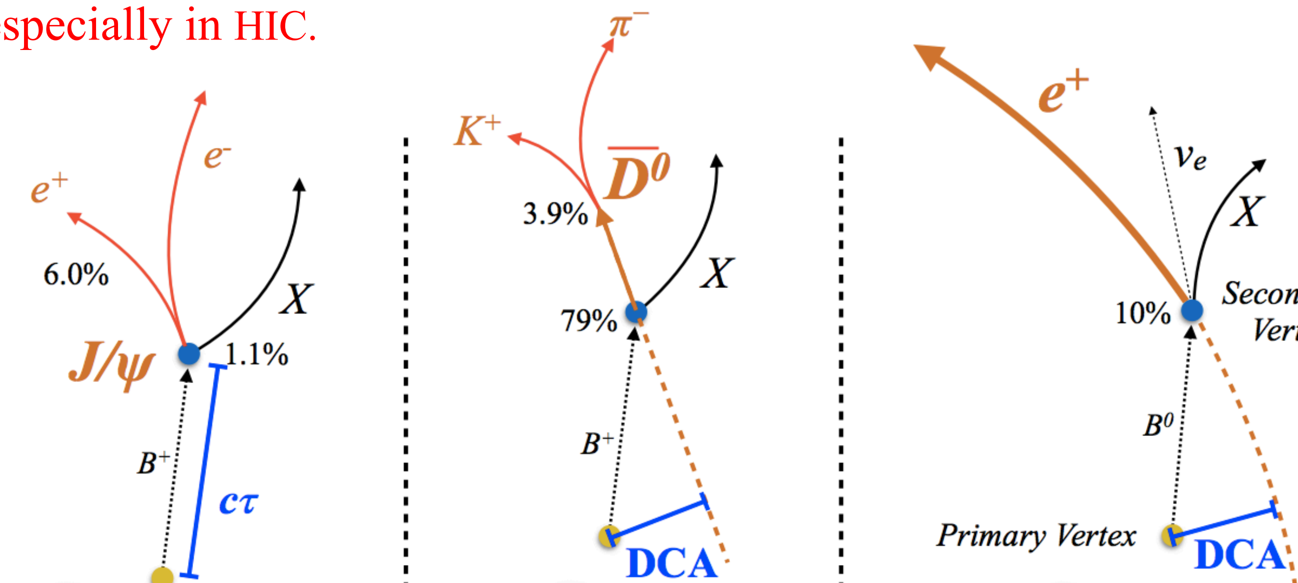
- full charmed hadron kinematics
- hard to trigger, smaller branching ratios

**Indirect** - Inclusive impact parameter method

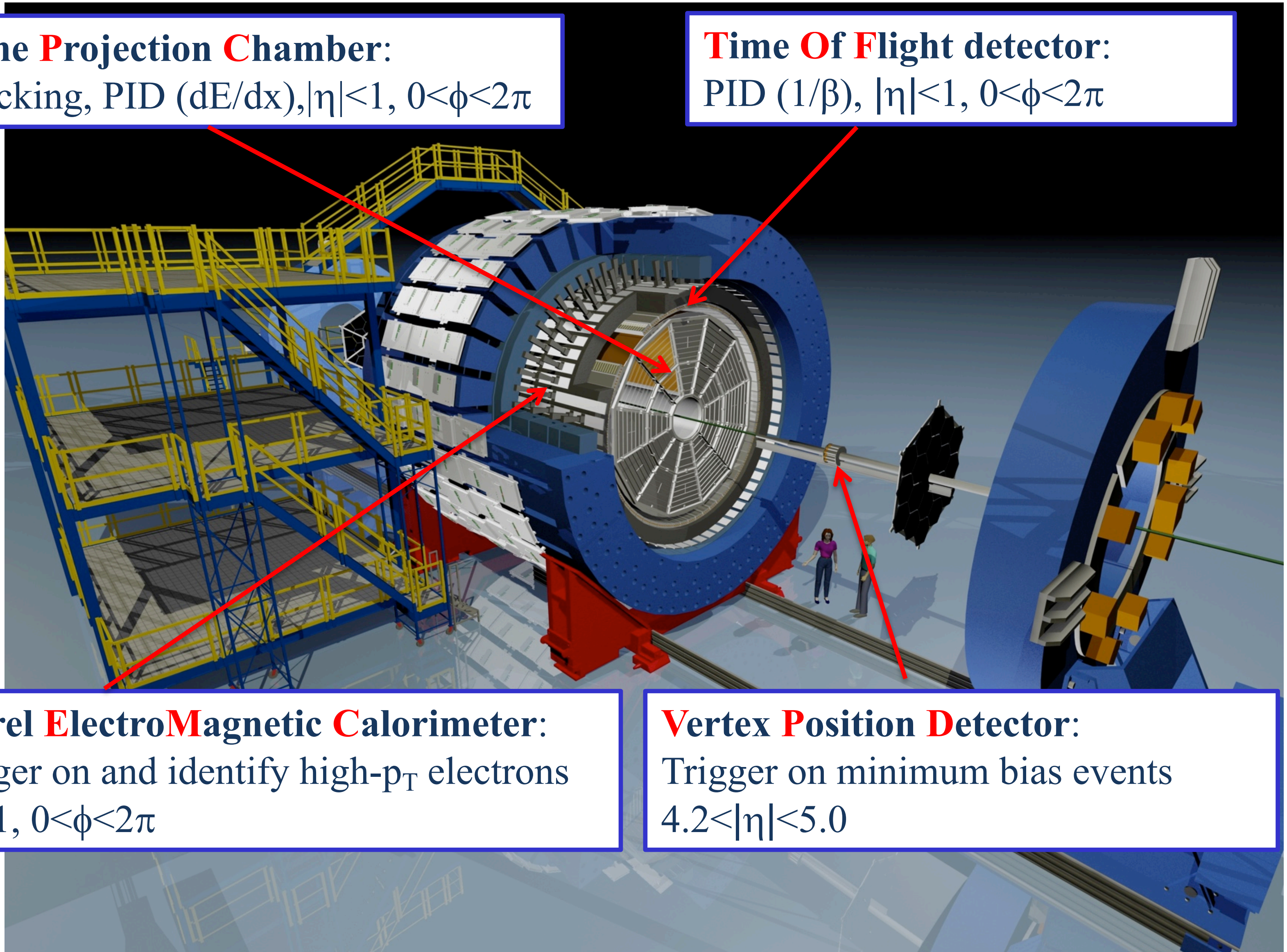
eg. $D/B \to e, B \to D, B \to J/\psi$

- easy to trigger, high statistics
- background sources, kinematic smeared

Precision silicon vertex tracker is crucial, especially in HIC.



# STAR Detector



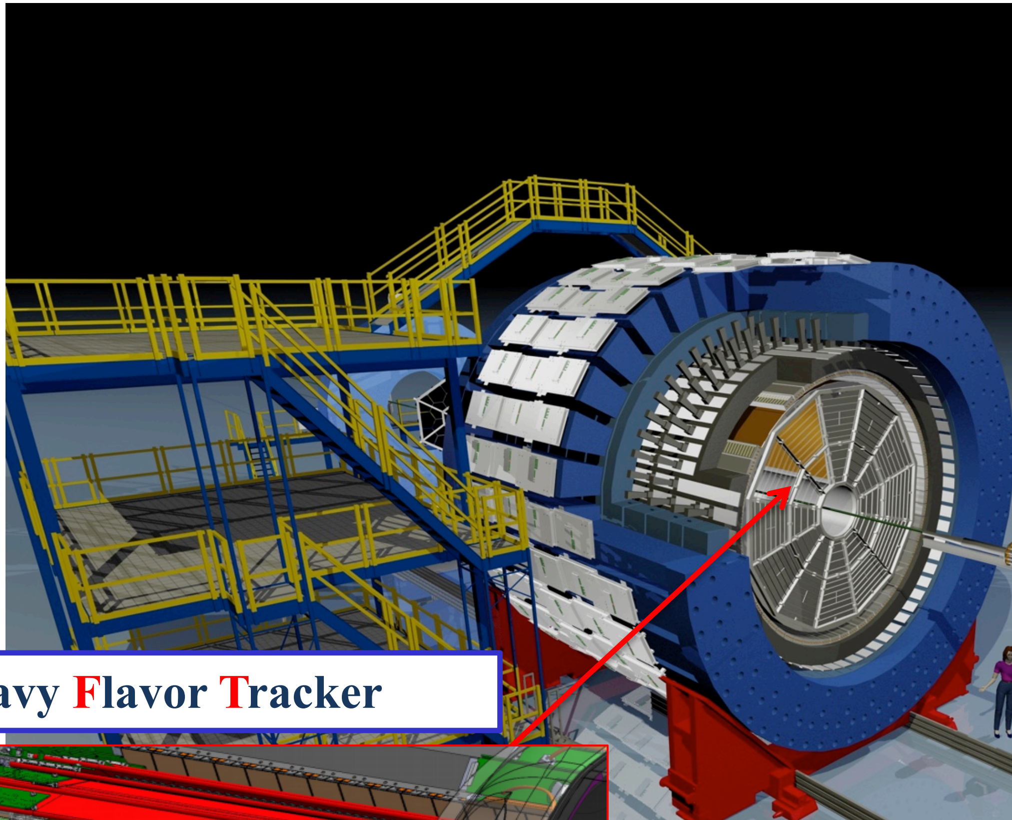
**Time Projection Chamber**:
Tracking, PID (dE/dx),$|\eta|<1$, $0<\phi<2\pi$

**Time Of Flight detector**:
PID ($1/\beta$), $|\eta|<1$, $0<\phi<2\pi$

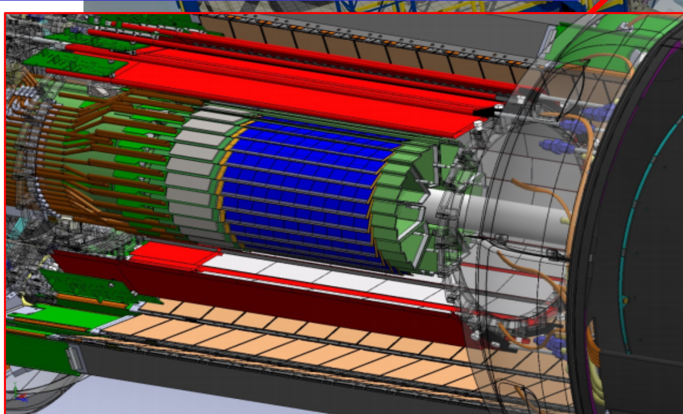
**Barrel ElectroMagnetic Calorimeter**:
Trigger on and identify high-$p_T$ electrons
$|\eta|<1$, $0<\phi<2\pi$

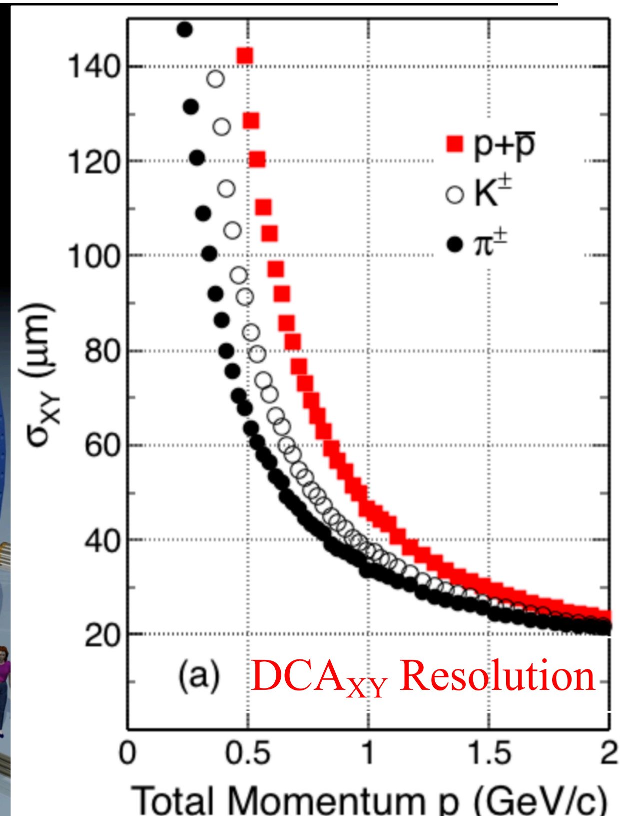
**Vertex Position Detector**:
Trigger on minimum bias events
$4.2<|\eta|<5.0$

# Heavy Flavor Tracker



**Heavy Flavor Tracker**





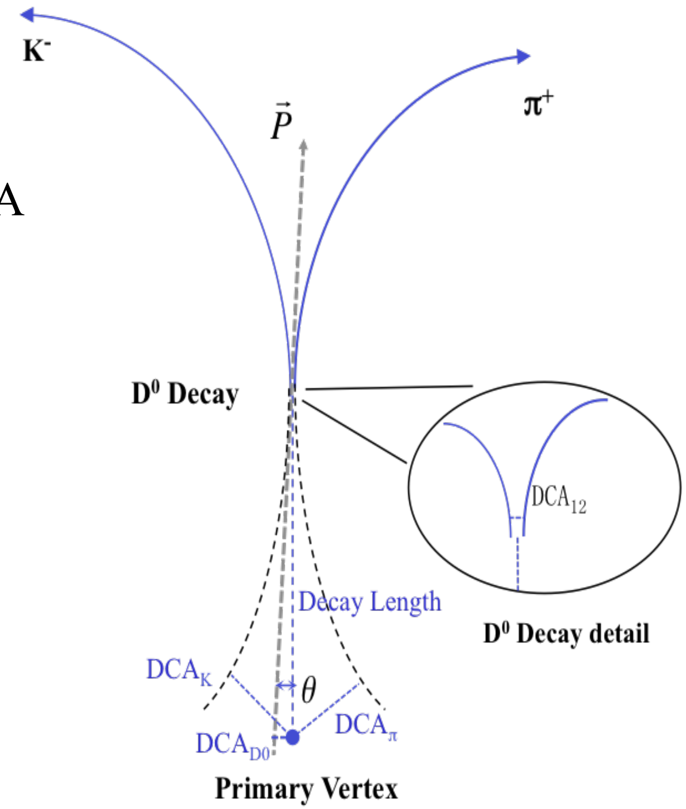

*Phys. Rev. C 99, (2019) 034908*

**HFT:** (2014-2016)

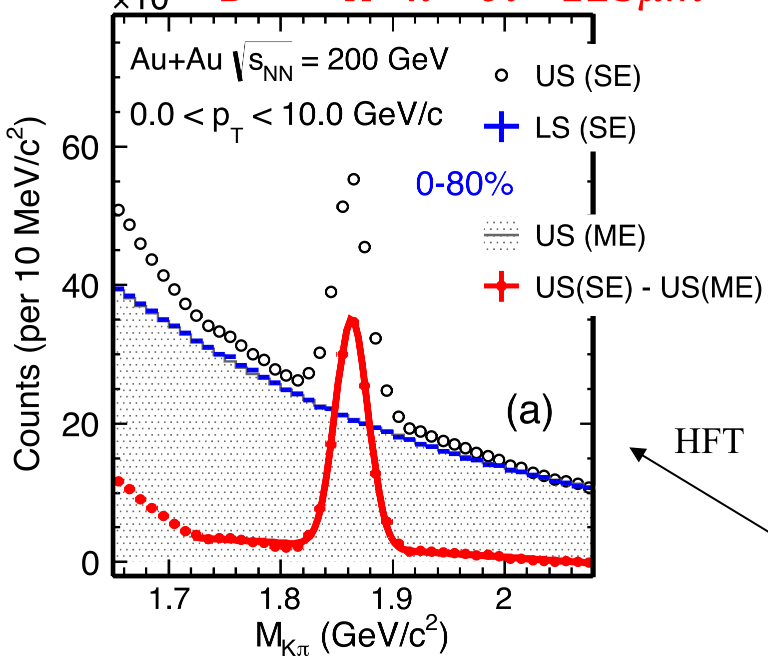
- PIXEL detector: r ~2.8 & 8 cm, MAPS, 20.7x20.7 μm$^2$, 0.5%$X_0$ (2014) 0.4%$X_0$ (2016) , air-cooled
- Intermediate Silicon Tracker: r ~14 cm
- Silicon Strip Detector: r ~22 cm

# Example of $D^0$ Reconstruction

- Direct reconstruction secondary vertex
- Topological variables optimized by TMVA
- A factor of >15 improvement in terms of significance compare to tpc results

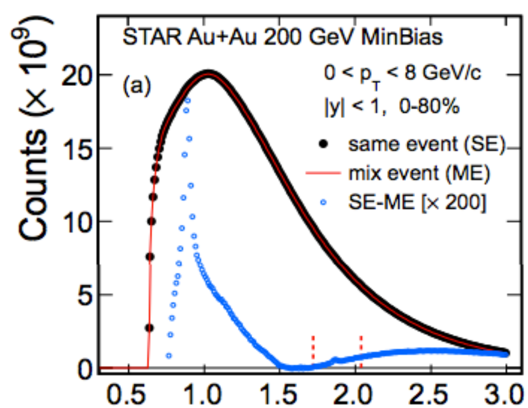



$D^0 \to K^-\pi^+ \; c\tau \sim 123\mu m$




HFT

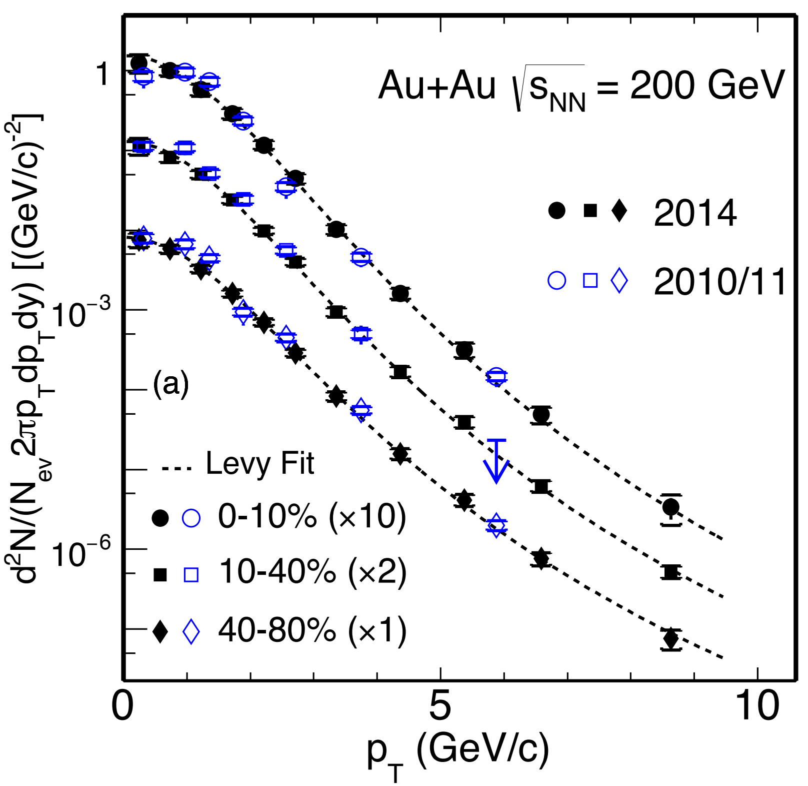
TPC

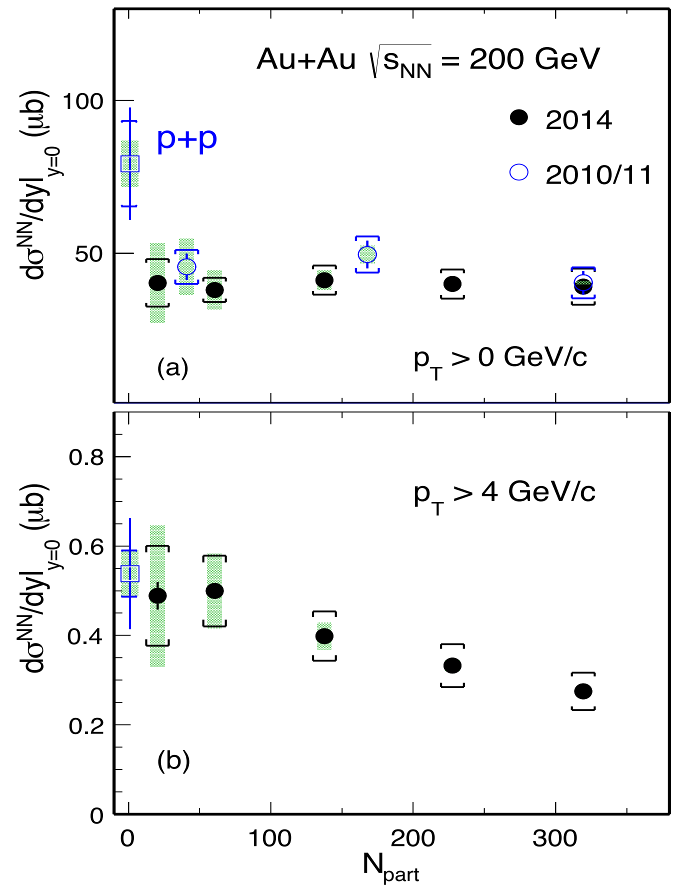



PRL 113 (2014) 142301

# $D^0$ $p_T$ Spectra

- $D^0$ measurement was much improved with the help of HFT
- $p_T$-integrated $D^0$ cross-section is nearly independent of centrality, and smaller than in p+p collisions. However, for $p_T$ > 4 GeV/c it increases towards peripheral collisions.

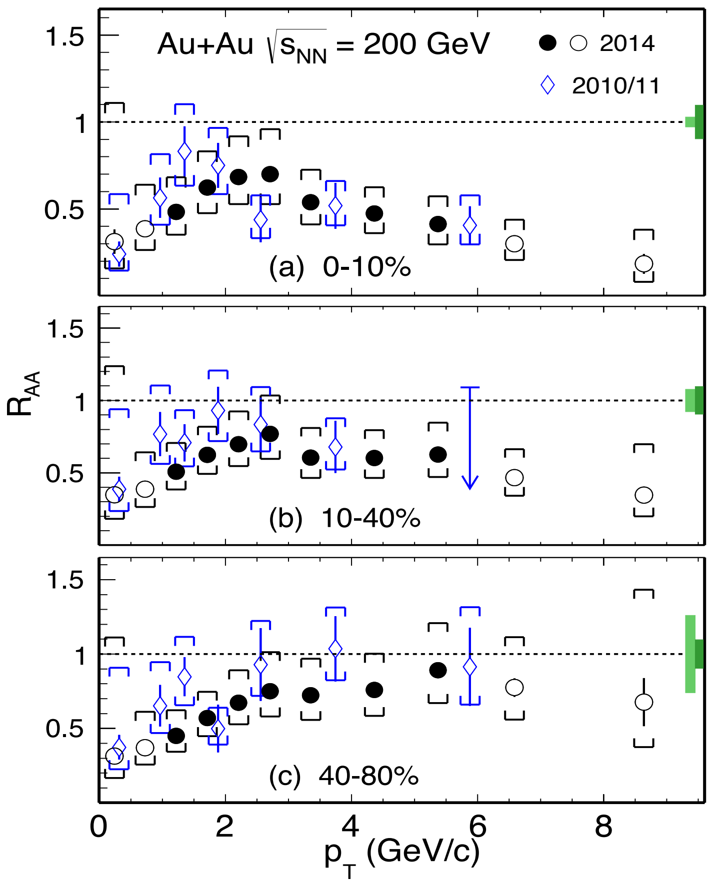


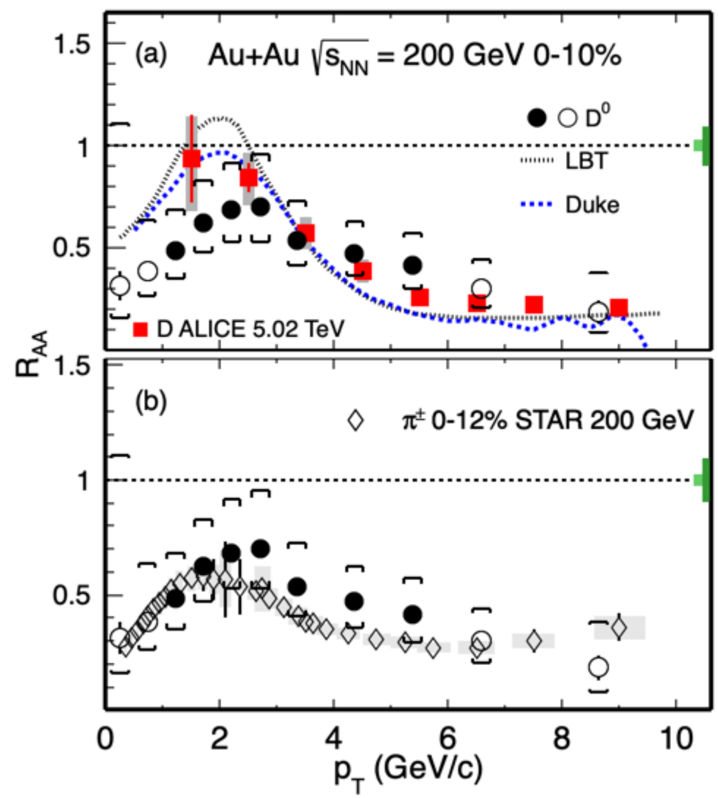




*Phys. Rev. C 99, (2019) 034908*
*Phys. Rev. Lett. 121, (2018) 229901*
*Phys. Rev. D 86, (2012 ) 072013 .*

# $D^0$ $R_{AA}$

- $R_{AA} < 1$ in the 0-10% centrality interval for all $p_T$
- Suppression at high $p_T$ increases towards more central collisions
- Similar suppression trend as D-mesons at LHC and high-$p_T$ pions at RHIC

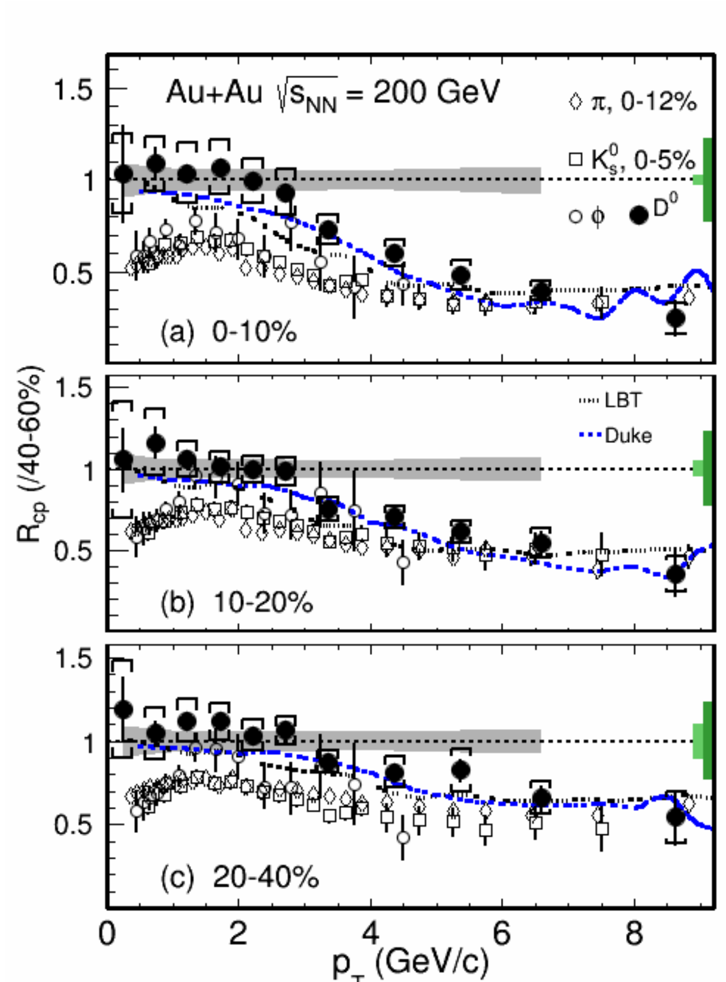


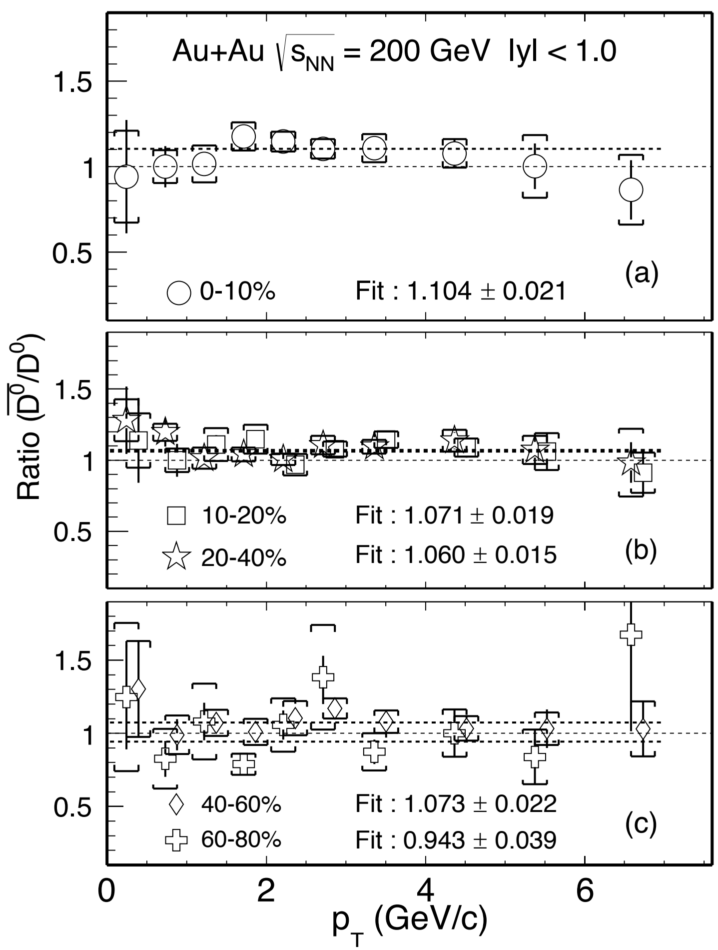




STAR: Phys. Lett. B 655 (2007) 104, Phys. Rev. C 99, (2019) 034908
ALICE: JHEP 1810 (2018) 174,
LBT: Phys. Rev. C 94 (2016) 014909 +private comm.
DUKE: PRC 92 (2015) 024907+private comm.

# $D^0$ $R_{CP}$ and $\overline{D^0}/D^0$ Ratio

- Significant suppression at high $p_T$ .
- Reasonable agreement with theoretical calculations
- $\overline{D^0}/D^0$ ratio is larger than 1, possibly due to finite baryon density




*Phys. Rev. C 99, (2019) 034908*

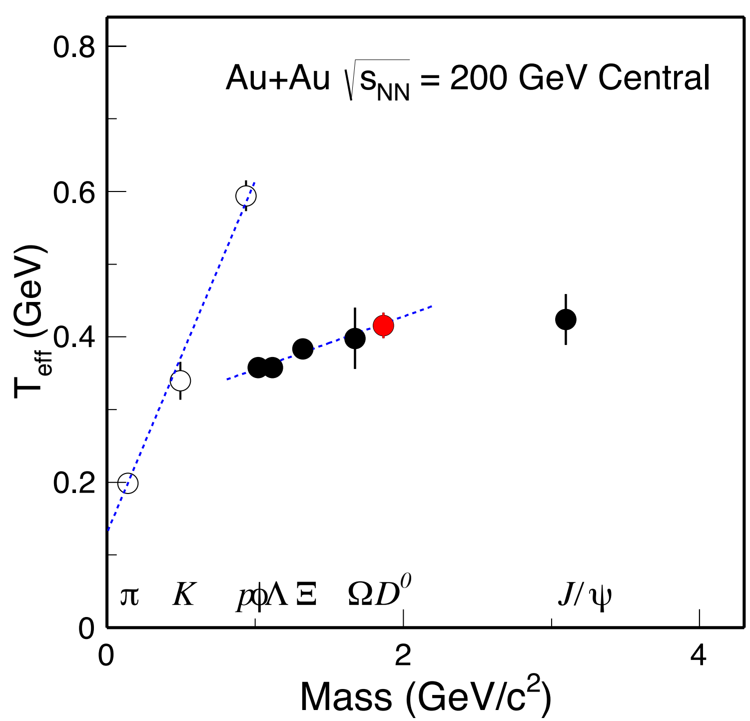
# $D^0$ Radial Flow

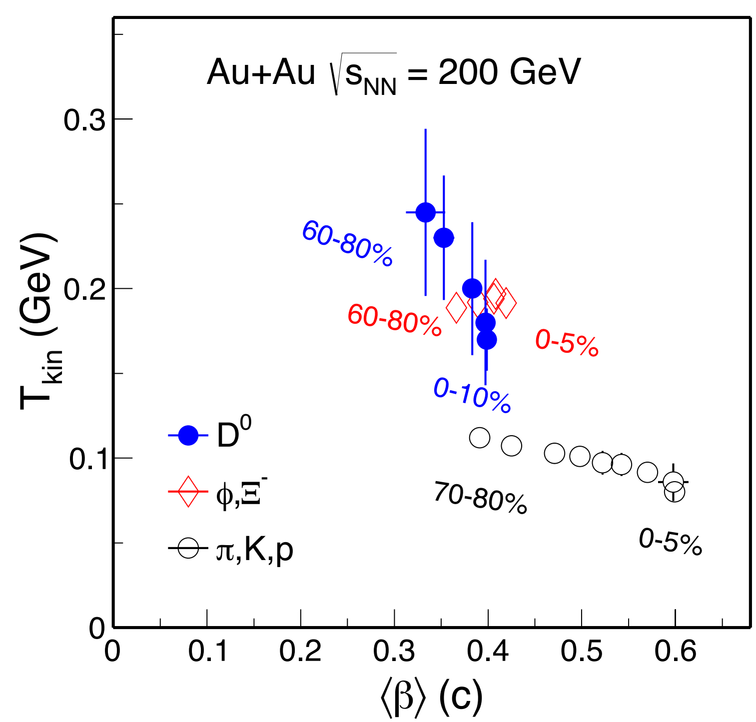
- Exponential fit to the $m_T$ spectra : collective behavior, $T_{eff}$ slope parameter follows the same trend as multi-strange hadrons
- Blast Wave fits ($p_T$ < 5 GeV/c) :

$T_{kin}(\boldsymbol{D^0}) \sim T_{kin}(\phi,\Xi) > T_{kin}(\pi,K,p)$ and $\beta(\boldsymbol{D^0}) \sim \beta(\phi,\Xi) < \beta(\pi,K,p)$

→ suggests earlier freeze-out of $\boldsymbol{D^0}$ compared to light-flavor hadrons.

$T_{eff} = T_{fo} + m_0 \langle\beta_T\rangle^2$



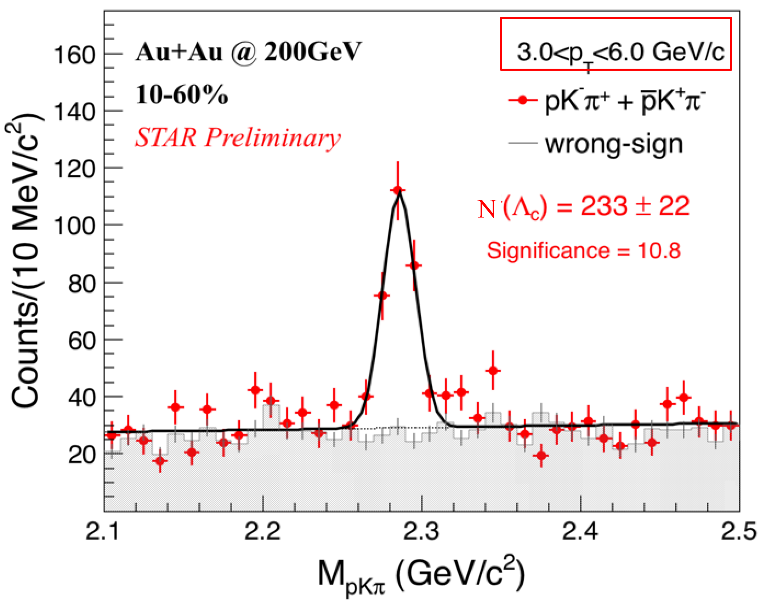




*Phys. Rev. C 99, (2019) 034908*

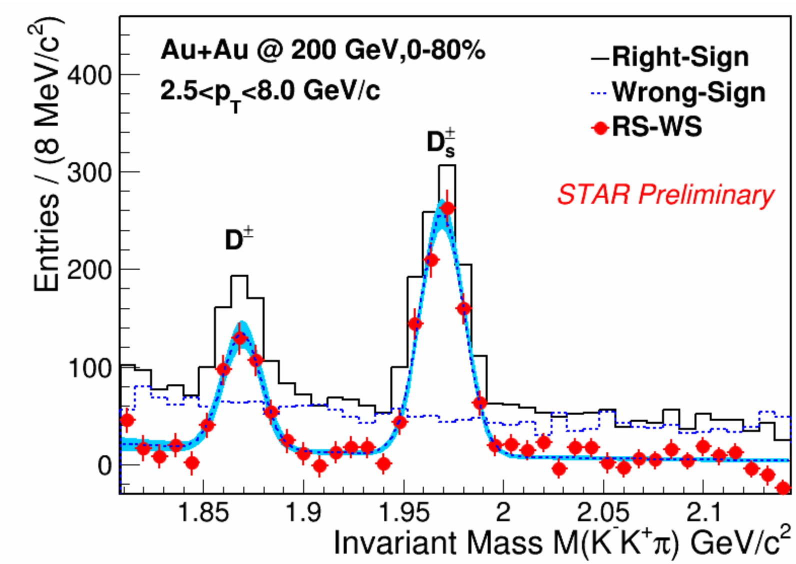
# Heavy Quark Hadronization : $\Lambda_c$ and $D_s$

- Exclusive reconstruction of charmed hadrons in HIC from STAR: $\Lambda_c^+$, $D_s^+$, $D^{\pm}$, $D^{\pm*}$, $D^0$
- More challenge for three body reconstruction and short life-time particles
- $\Lambda_c^+$ Reconstructed first time in A+A collisions

$\Lambda_c^+ \rightarrow p^+K^-\pi^+ \quad c\tau \sim 60\mu m$

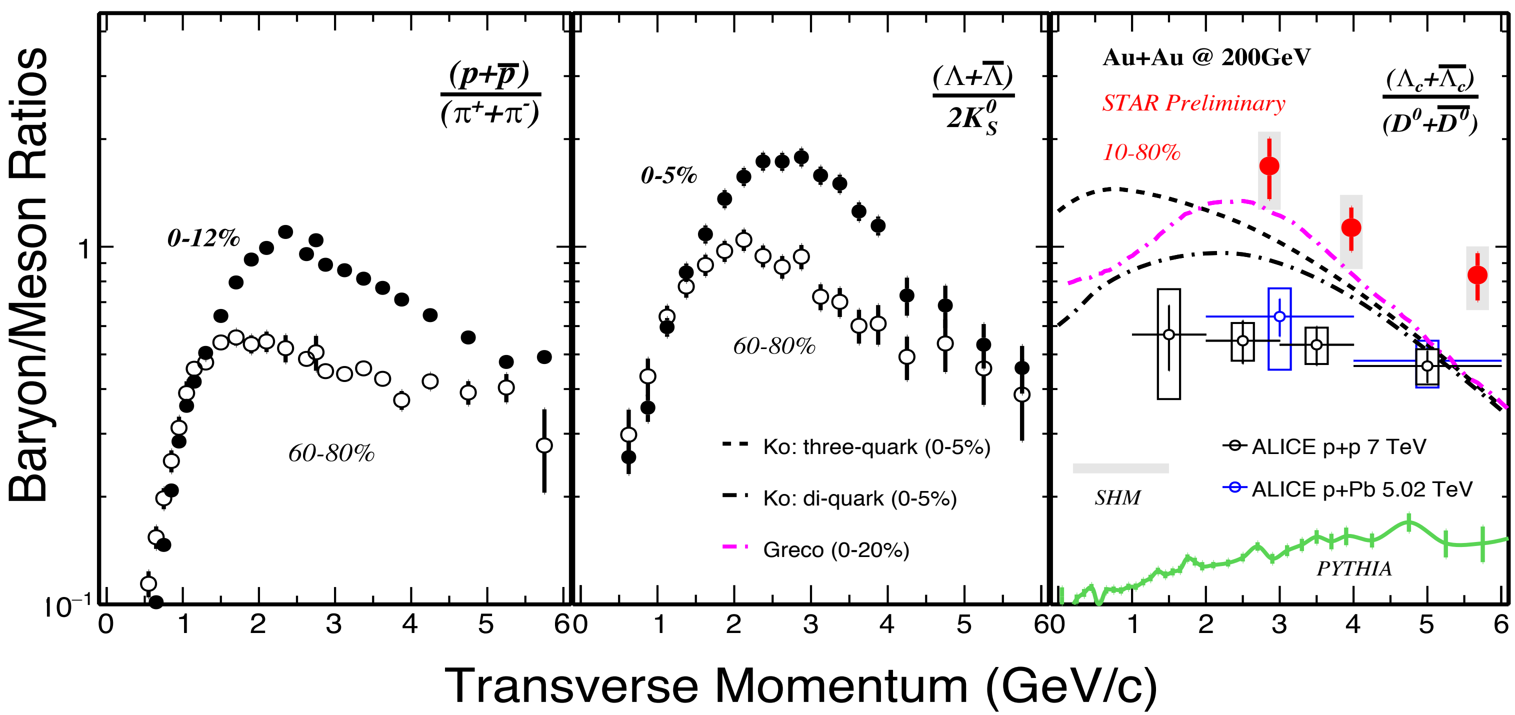



$D_s^+ \rightarrow \phi\,\pi^+ \rightarrow K^+K^-\pi^+ \quad c\tau \sim 151\mu m$



# $\Lambda_c/D^0$ : $p_T$ Dependence

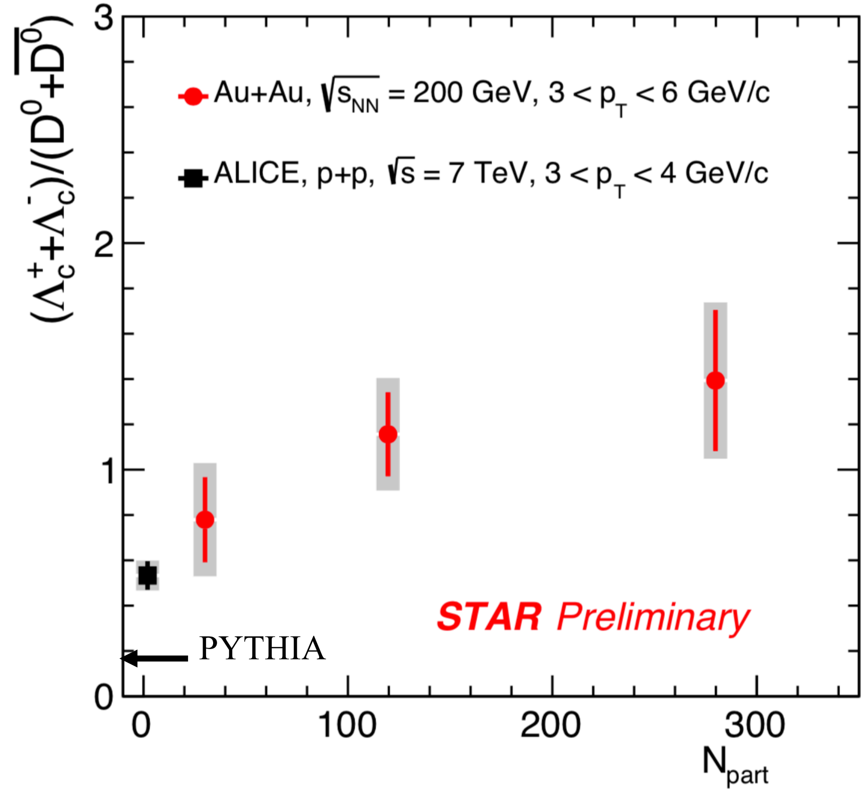
- Significant enhancement of $\Lambda_c/D^0$ compared to PYTHIA/fragmentation baseline and p+p, p+Pb at LHC
- The $\Lambda_c/D^0$ ratio is comparable with light flavor baryon-to-meson ratios
- Consistent with charm quark hadronization via coalescence
  -- higher than model predictions, particularly at higher $p_T$




Ko: PRC 79 (2009) 044905 Greco: Eur.Phys.J.C (2018) 78:348
SHM: PRC 79 (2009) 044905 ALICE: JHEP 04 (2018) 108

# $\Lambda_c/D^0$ : Centrality Dependence

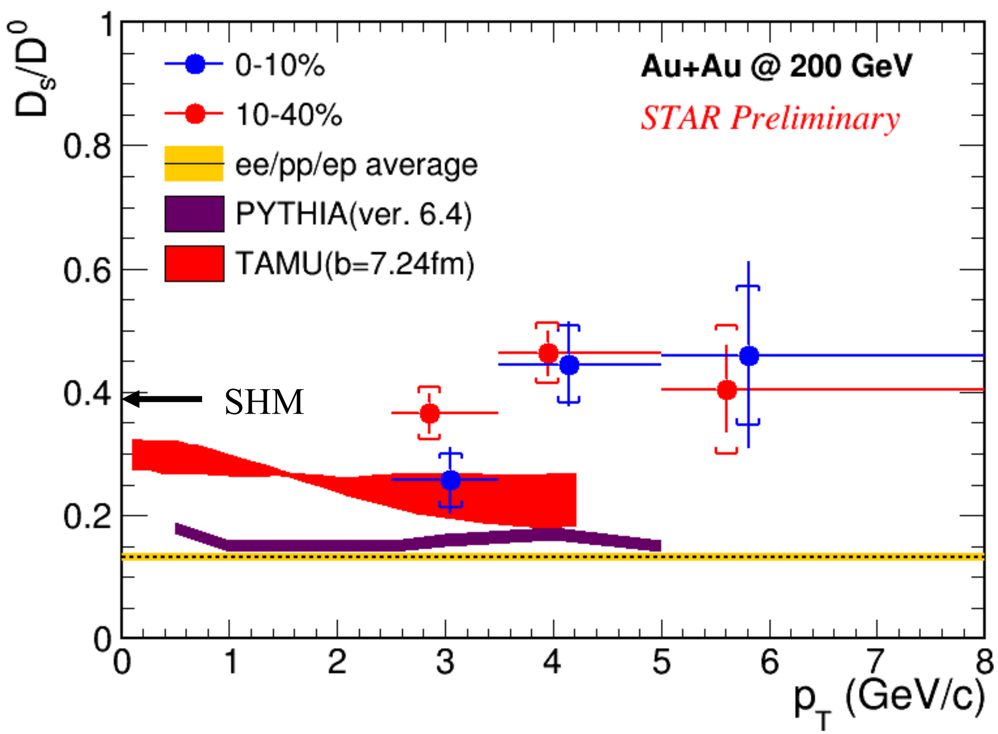
- Trends of $\Lambda_c/D^0$ ratio increases from peripheral to central collisions
- Ratio for peripheral Au+Au comparable with p+p value at 7 TeV




ALICE: JHEP 04 (2018) 108

# $D_s/D^0$ Enhancement

- Strong $D_s/D^0$ enhancement observed in central A+A collisions w.r.t fragmentation baseline
  - Strangeness enhancement and coalescence hadronization
- Enhancement is larger than p+p, PYTHIA predictions

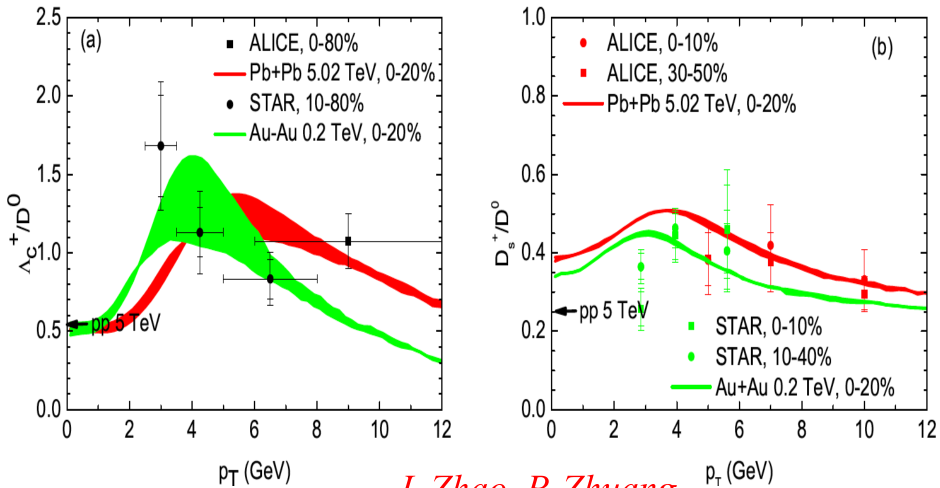



*ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, (2016) 397*
*TAMU: H. Min et al. PRL 110, (2013) 112301*
*SHM: A. Andronic et al., PLB 571 (2003) 36*

# Recent Model Predictions

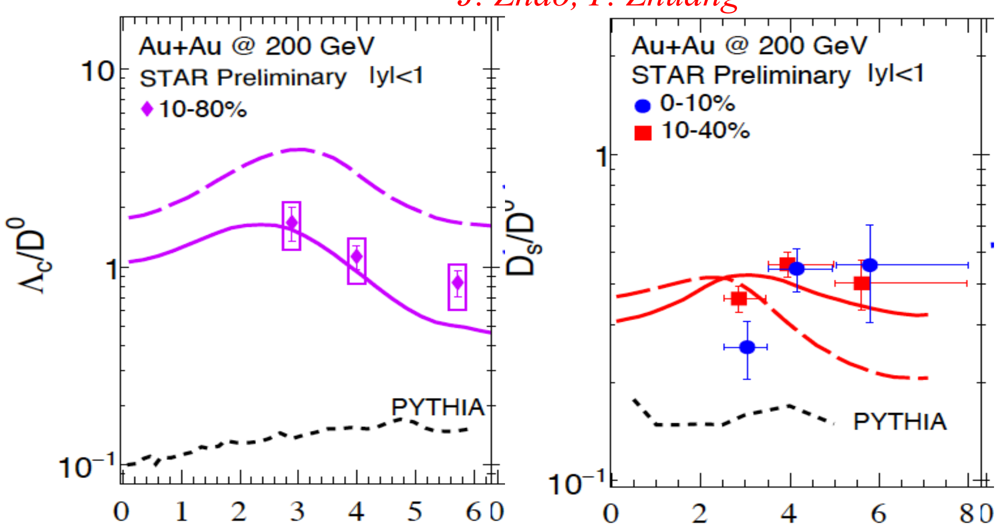
- Recent model predictions developed fast

*M.He, R. Rapp*

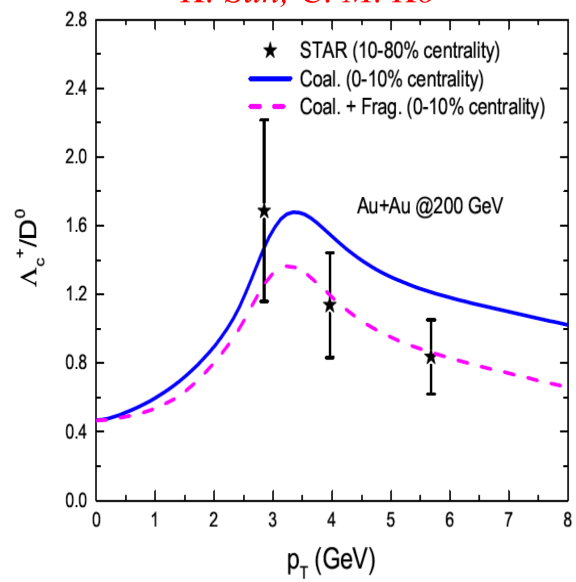



*M. He and R. Rapp arXiv:1905.09216*
*K. Sun, C. M. Ko, etc. arXiv:1905.09774*
*J. Zhao, P. Zhuang, etc  arXiv:1805.10858*

*J. Zhao, P. Zhuang*




*K. Sun, C. M. Ko*



# Total Charm Cross-section

- Total charm cross-section is extracted from the various charm hadron measurements

-- $D^0$ yields are measured down to zero $p_T$

-- For $D^{+/-}$ and $D_s$, Levy function fits to measured spectra are used for extrapolation.

-- For $\Lambda_c$, fits of three models to data are used and differences are included in systematics

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

*** derived using $\Lambda_c^+ / D^0$ ratio in 10-80%**

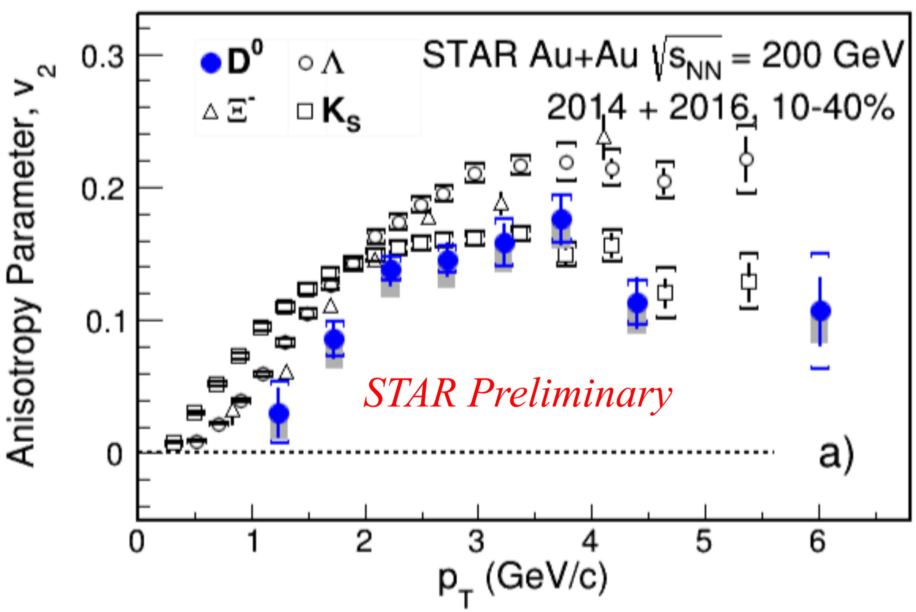
- Total charm cross-section per nucleon-nucleon collision is consistent with p+p value within uncertainties, but redistributed among different charm hadron species

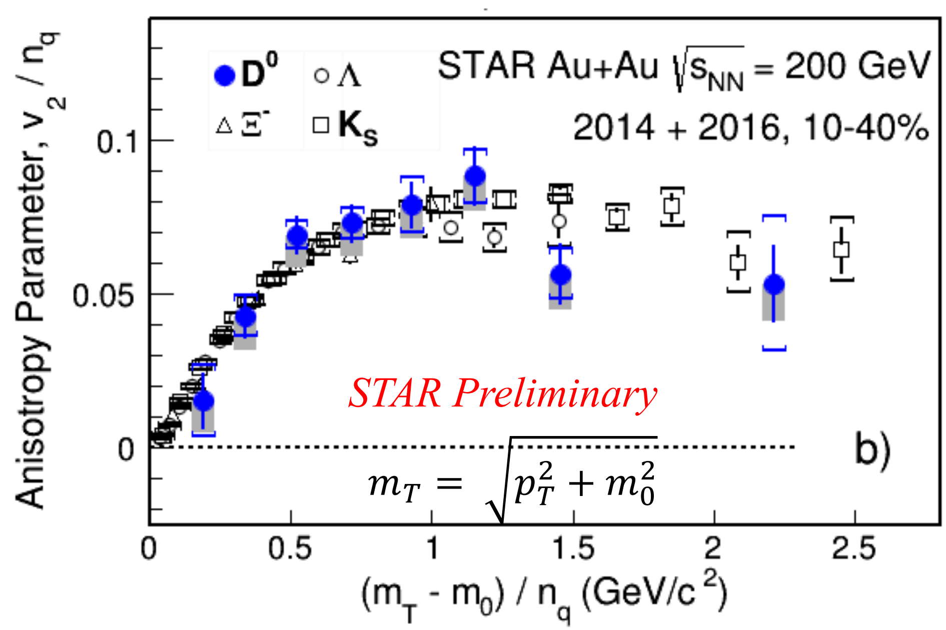
# $D^0$ Elliptic Flow

- Mass ordering at $p_T < 2$ GeV/c (hydrodynamic behavior)
- $v_2(\boldsymbol{D^0})$ follows the $(m_T - m_0)$ NCQ scaling as light flavor hadrons below 1 GeV/$c^2$
  → Evidence of charm quarks flowing with the medium

2014 +2016 Dataset

*2014 data, Phys. Rev. Lett. 118, (2017) 212301*

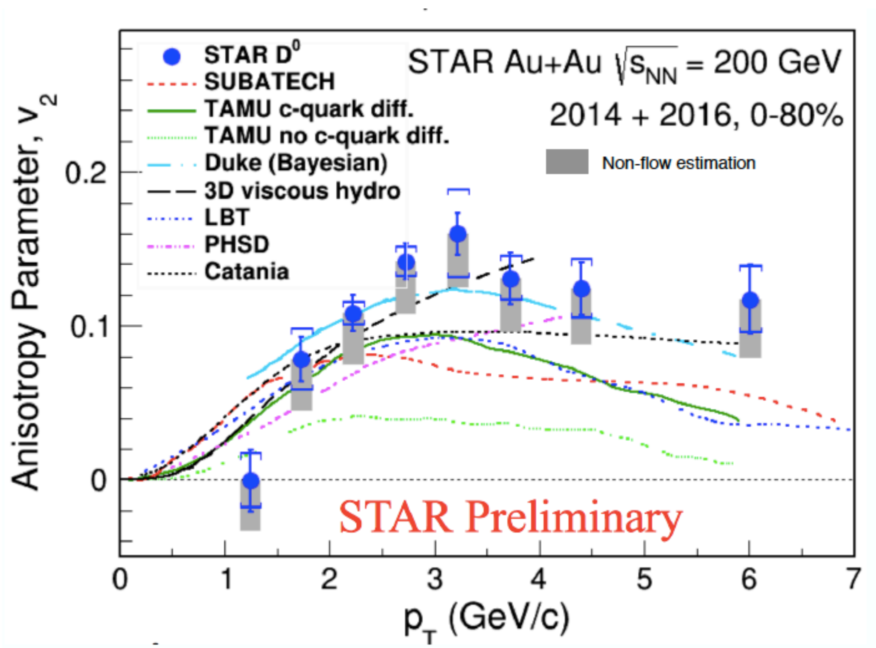


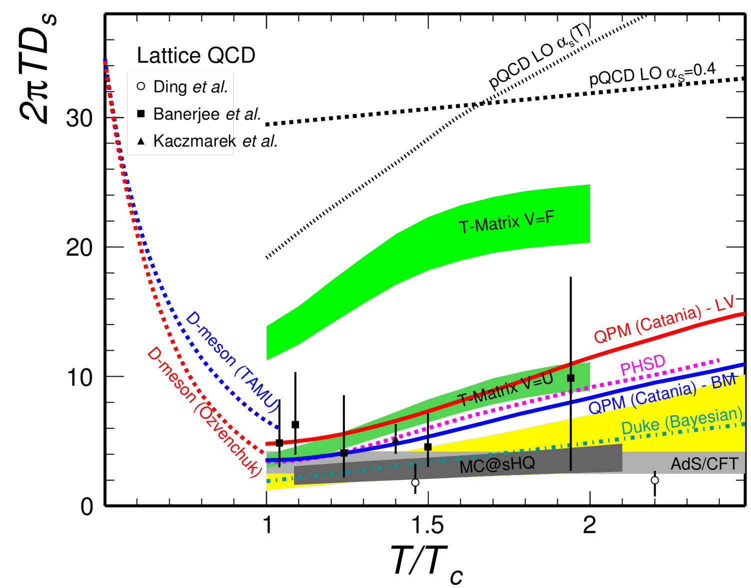



# $D^0$ Elliptic Flow

- High precision of $v_2$ data offers stringent constraints to model calculations. Transport models with charm quark diffusion in the medium can describe the data
- Sensitivity to charm diffusion coefficient $2\pi TD_s$ and its temperature dependence. Models describe $D^0$ $v_2$ well with $2\pi TD_s$ in the range of 2 – 5 around $T_c$

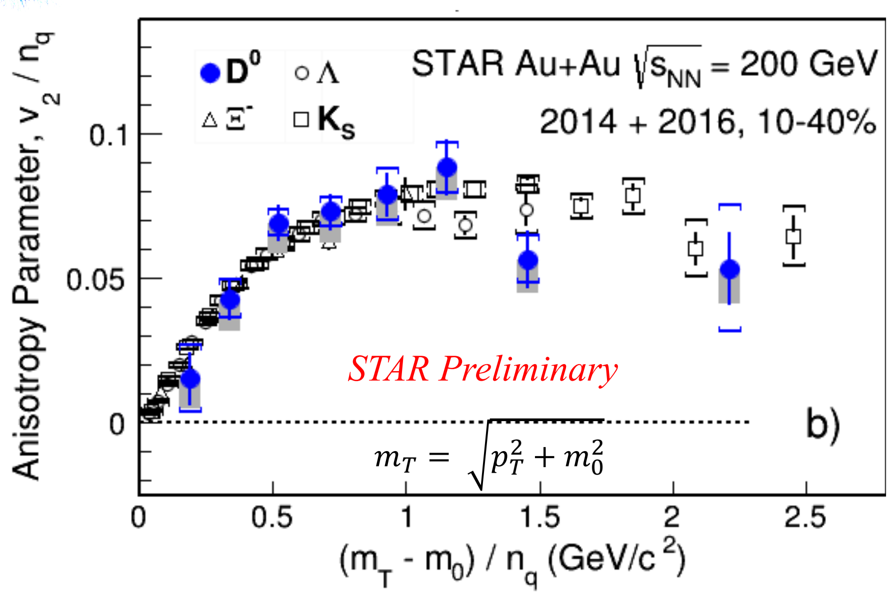
2014+2016 Dataset

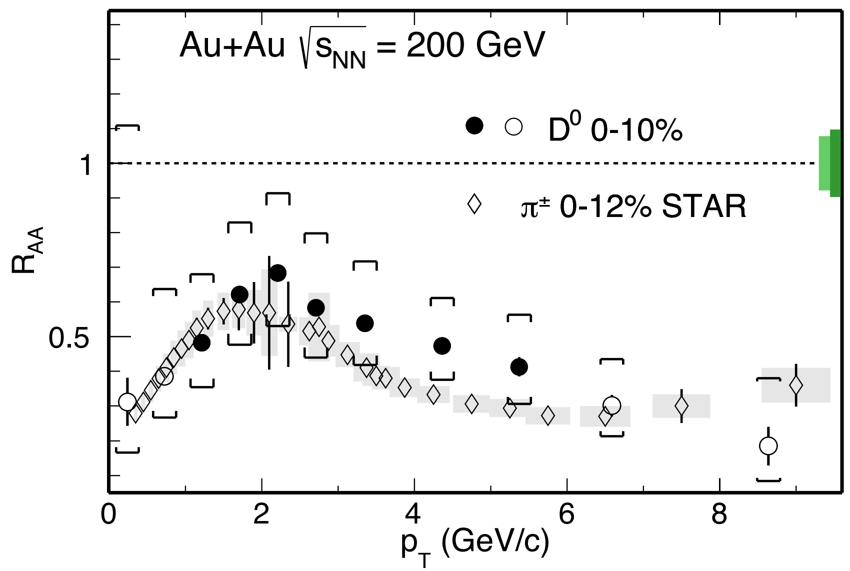



X. Dong and V. Greco, Progress in Particle and Nuclear Physics, 104 (2019) 97
[1] SUBATECH: Phys Rev C 90, 054909 (2014), Phys Rev C 92, (2015) 014910 [2] TAMU: Phys Rev C 86, (2012) 014903 Phys Rev Lett 110, (2013) 112301 [3] Duke: Phys Rev C 92, (2015) 024907 [4] 3D viscous hydro: Phys Rev C 86, (2012) 024911 [5] LBT: Phys Rev C 94, (2016) 014909 [6] PHSD: Phys ReV 90, (2014) 051901 , Phys ReV 90, (2014) 051901 [7] Catania: Phys ReV 96, (2017) 044905

# Summary - Charm



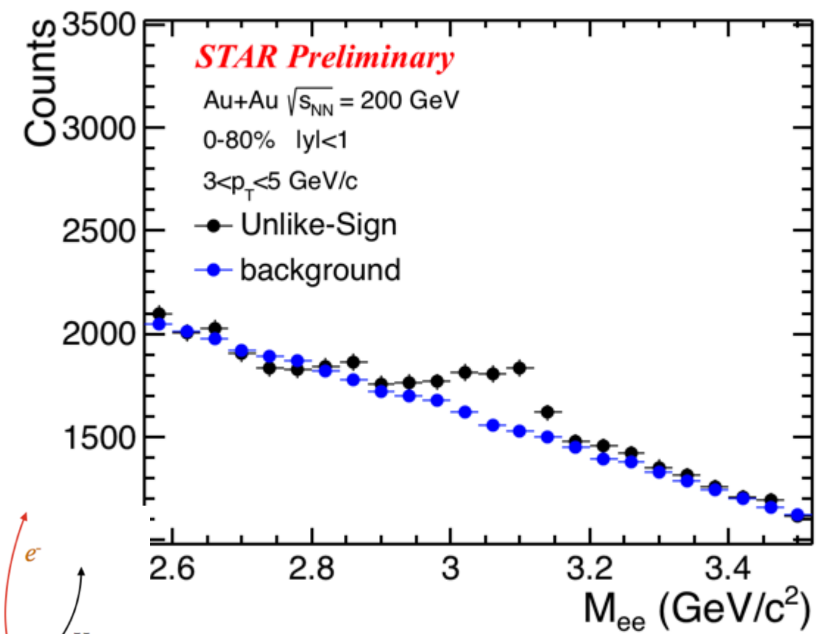



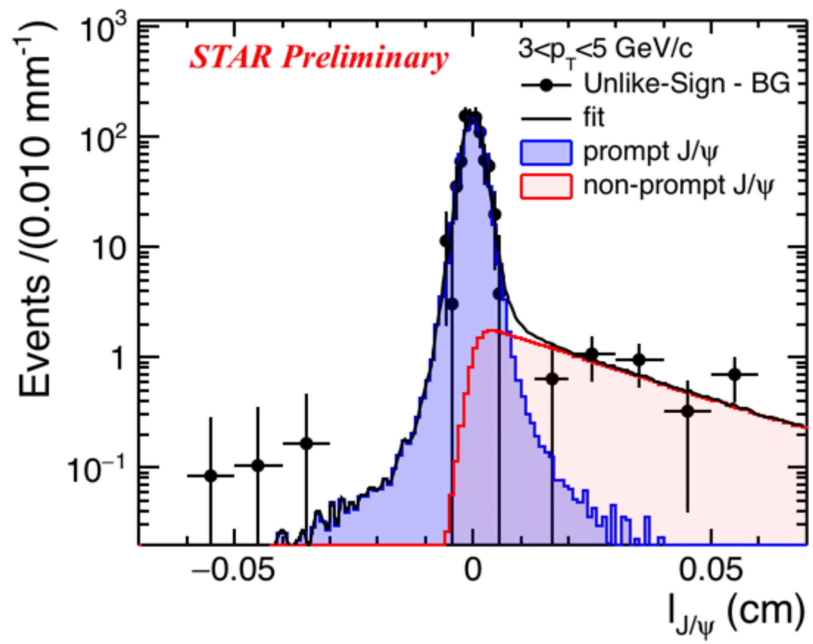

- Open heavy flavor (charm)
  - $v_2(D) \sim v_2(h)$ vs. $m_T$ → charm quark flow like light quarks
  - $R_{AA}(D) \sim R_{AA}(h)$ ($p_T > 5$ GeV) → charm quark lose significant energy
  - $D_s/D^0 and\ \Lambda_c^+/D^0$ enhancement → coalescence hadronization

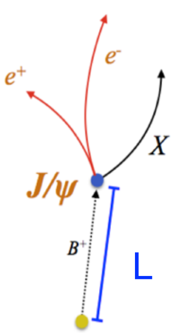
Charm quark strongly coupled with QGP.

# B → $J/\psi$

- Background is estimated using event mixing method
- Template fitting the reconstructed (prompt + non-prompt) signals
- Extract non-prompt fraction from pseudo-proper decay length ($l_{J/\psi}$)



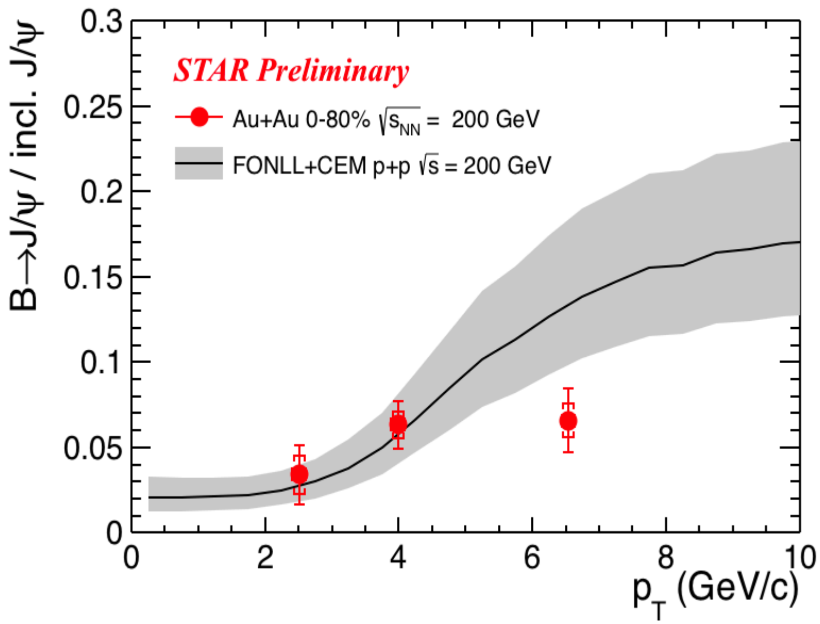



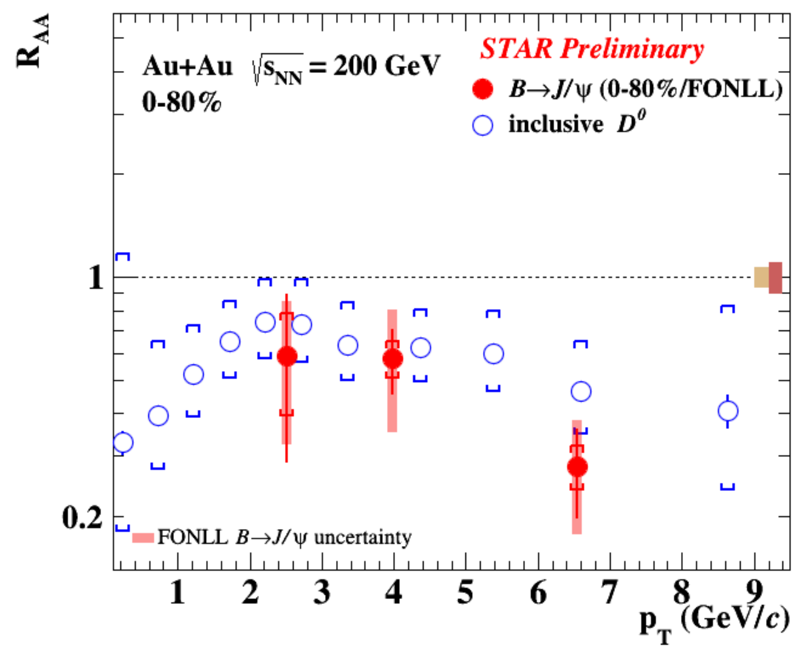




$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|\vec{p}|/c}\cdot M_{J/\psi}$$

# B → $J/\psi$

- Extract $B \to J/\psi$ $R_{AA}$ from non-prompt fraction
- Strong suppression is observed for non-prompt $J/\psi$ at high $p_T$ and is similar to that of $D^0$ mesons.

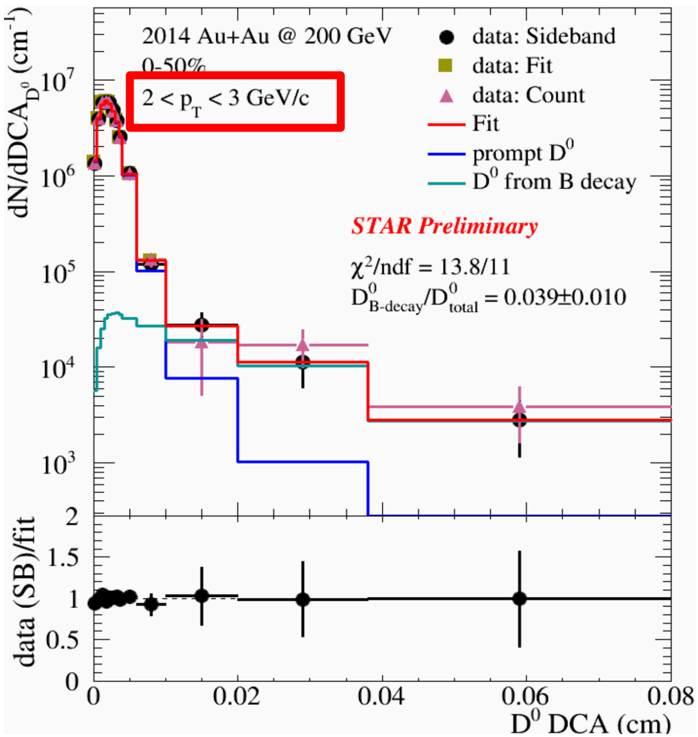


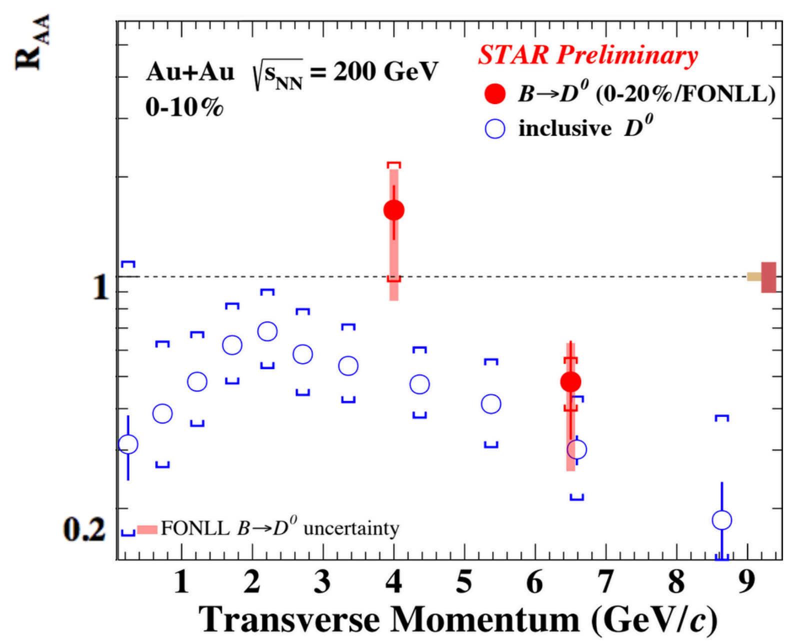




$$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(data)}{f_{p+p}^{B\to J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data)$$

# $B \rightarrow D^0$

- Extract non-prompt fraction and $R_{AA}$ from $D^0$ DCA distribution
- Strong suppression of non-prompt $D^0$ at $p_T$ range 5-8 GeV/c
- Hint of less suppression for $B \rightarrow D^0$ at $p_T$ range 3-5 GeV/c.

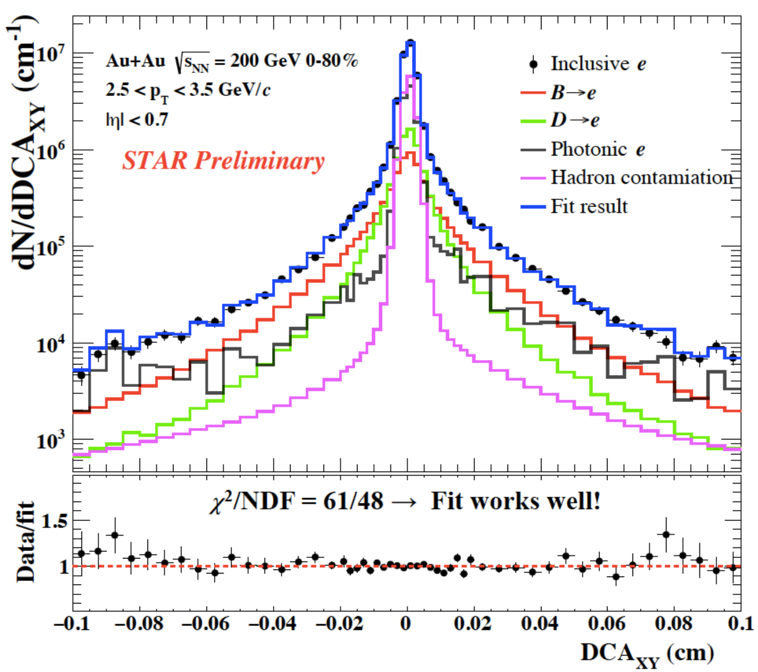


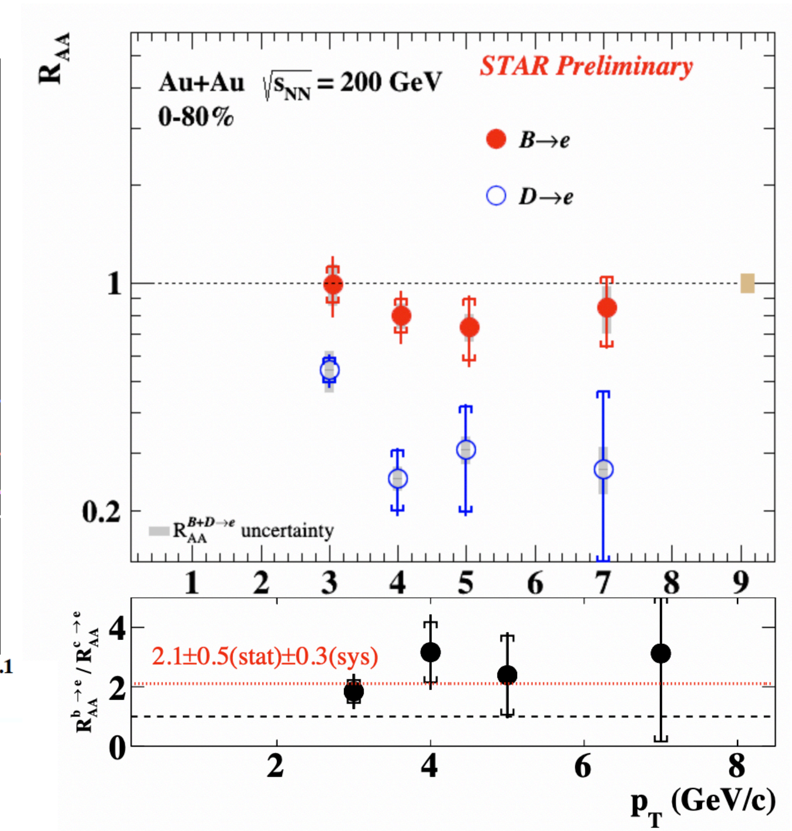




$$R_{AA}^{B\rightarrow D^0} = \frac{1}{<N_{coll}>} \frac{f_{Au+Au}^{B\rightarrow D^0} \times dN_{Au+Au}^{incl.\ D^0}/dp_T}{dN_{FONLL}^{B\rightarrow D^0}/dp_T}$$

# B/D → e

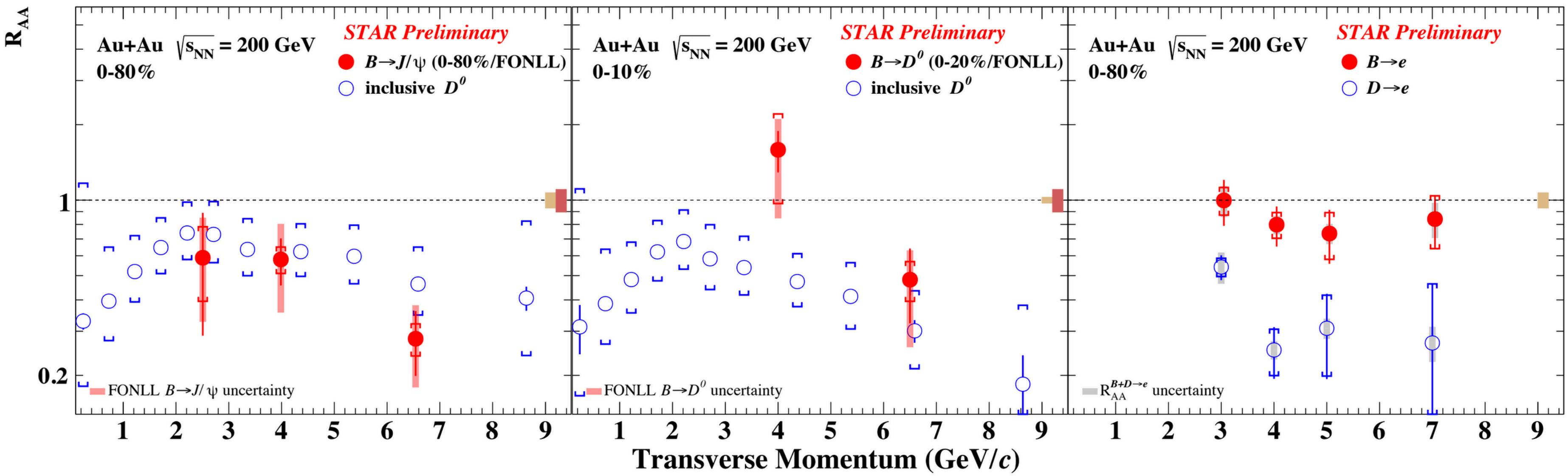
- Impact parameter method to separate c/b→electrons
- Indication of less suppression for $B \rightarrow e$ than $D \rightarrow e$ (~2 $\sigma$): consistent with $\Delta E_c > \Delta E_b$ .




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

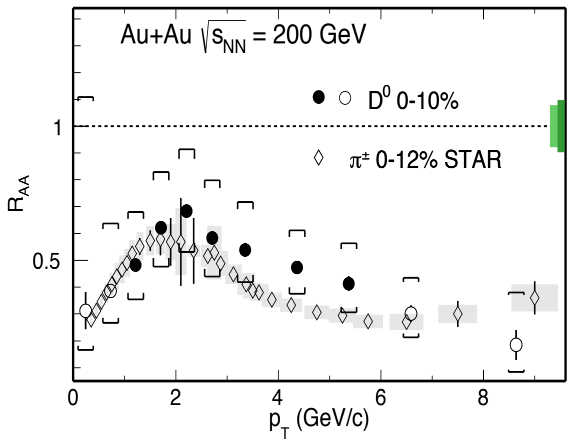
# Summary - Bottom

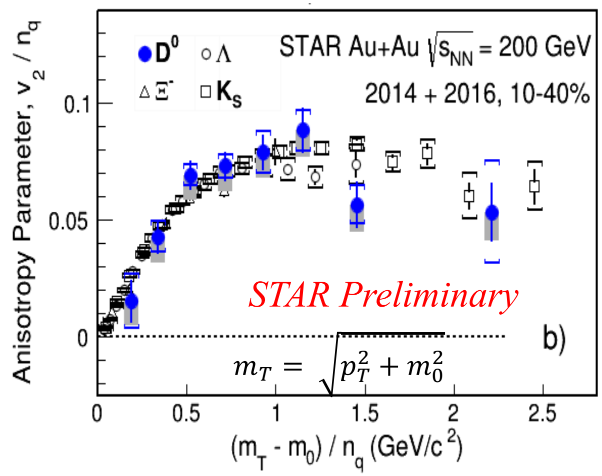


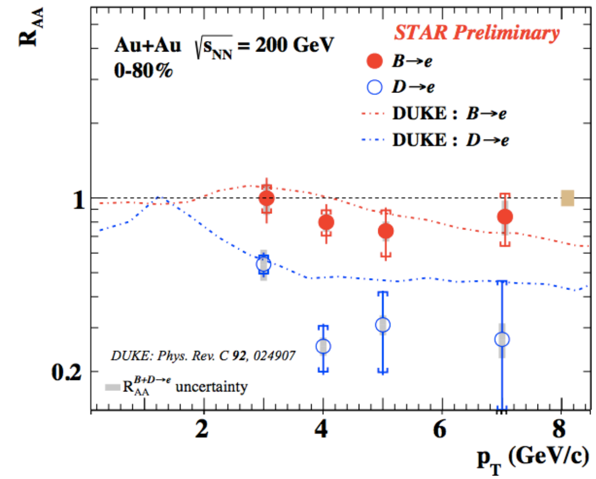

- Open heavy flavor (bottom)
  - Strong suppression for B → J/ψ and B → $D^0$ at high $p_T$
  - Indication of less suppression for B → e than D → e (~2$\sigma$): consistent with $\Delta E_c > \Delta E_b$

Evidence of less energy loss of bottom in the QGP.

# Outlook and Future




Improved p+p reference, p/d+Au for cold nuclear matter effect

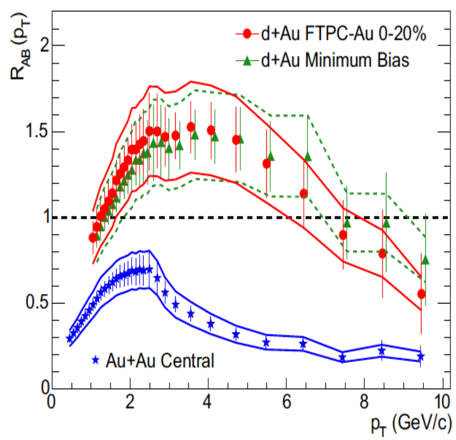
Bottom :

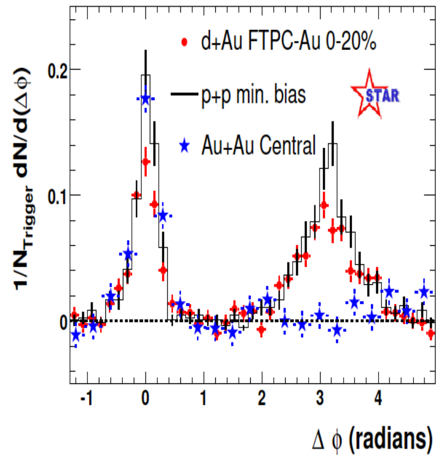
- Precision low $p_T$ bottom measurements ($R_{AA}$, $v_2$)
  - precision determination of HQ diffusion coefficient
  - systematic investigate mass dependence of parton energy loss

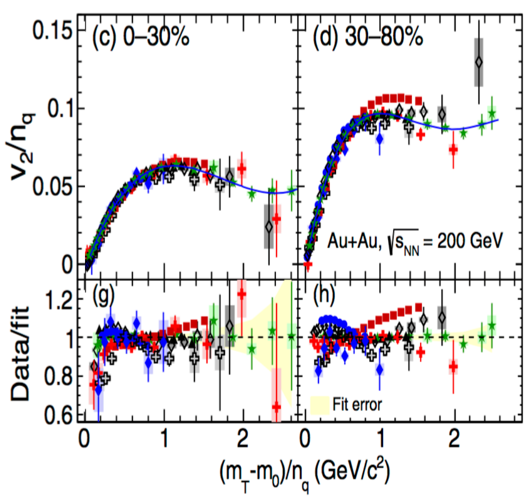
Guannan Xie

# Back up

# Light Flavor Behavior



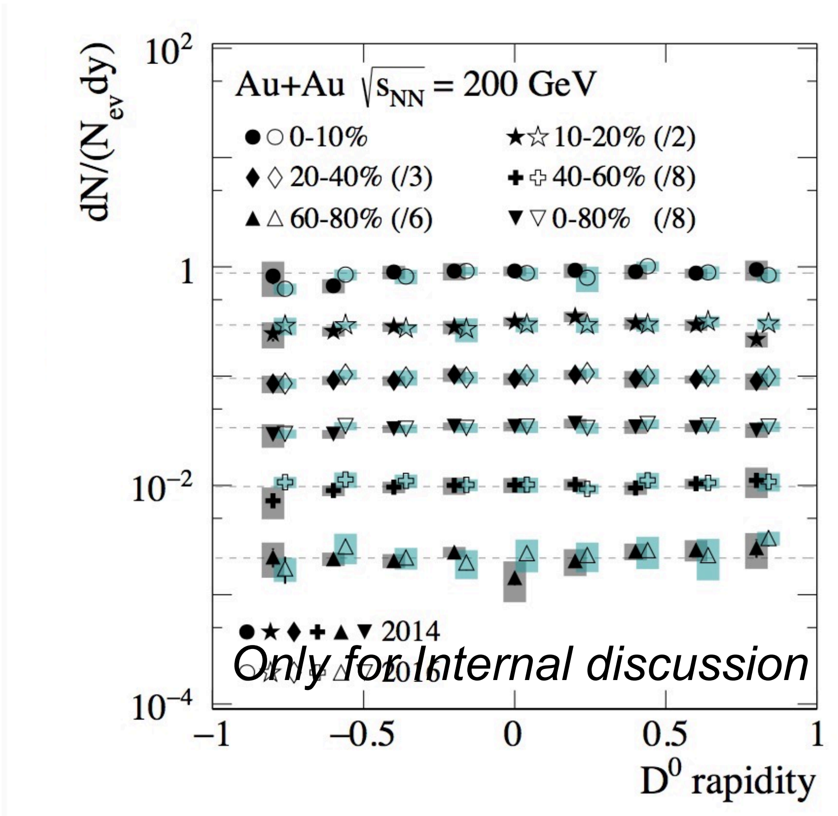

High $p_T$:
Light quark e-loss, Jet quenching
Low $p_T$:
Hydrodynamics works
Multi-strange hadrons flow
Intermediate $p_T$:
Number of Constituent Quark scaling flow s~u,d

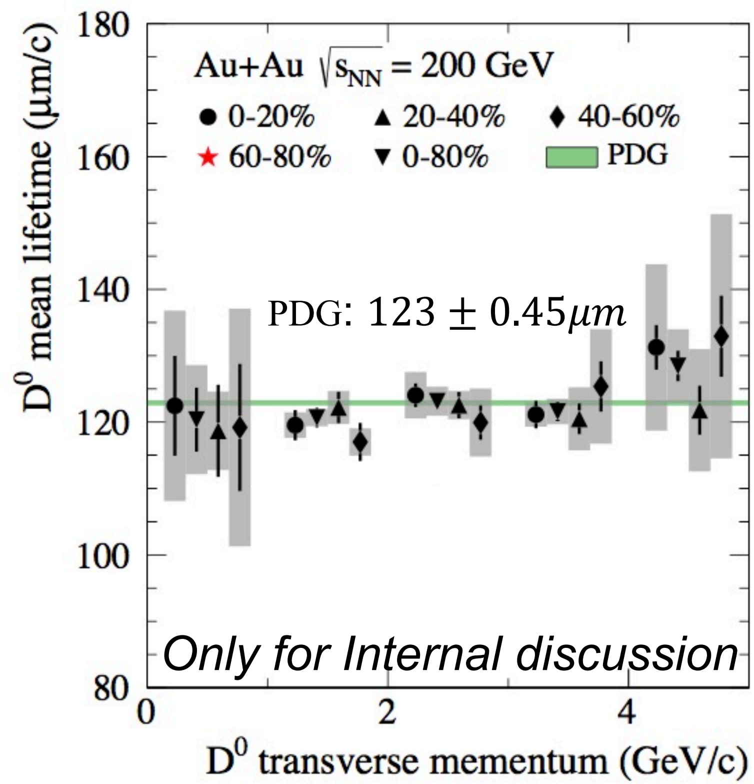
Large partonic collective flow observed.
u,d,s quarks strongly interact with Hot/dense medium.
What about heavy quarks?
Is the medium hot/dense enough to modify heavy quarks at RHIC energy? And LHC energy?

# More differential $D^0$ measurement

Ref.

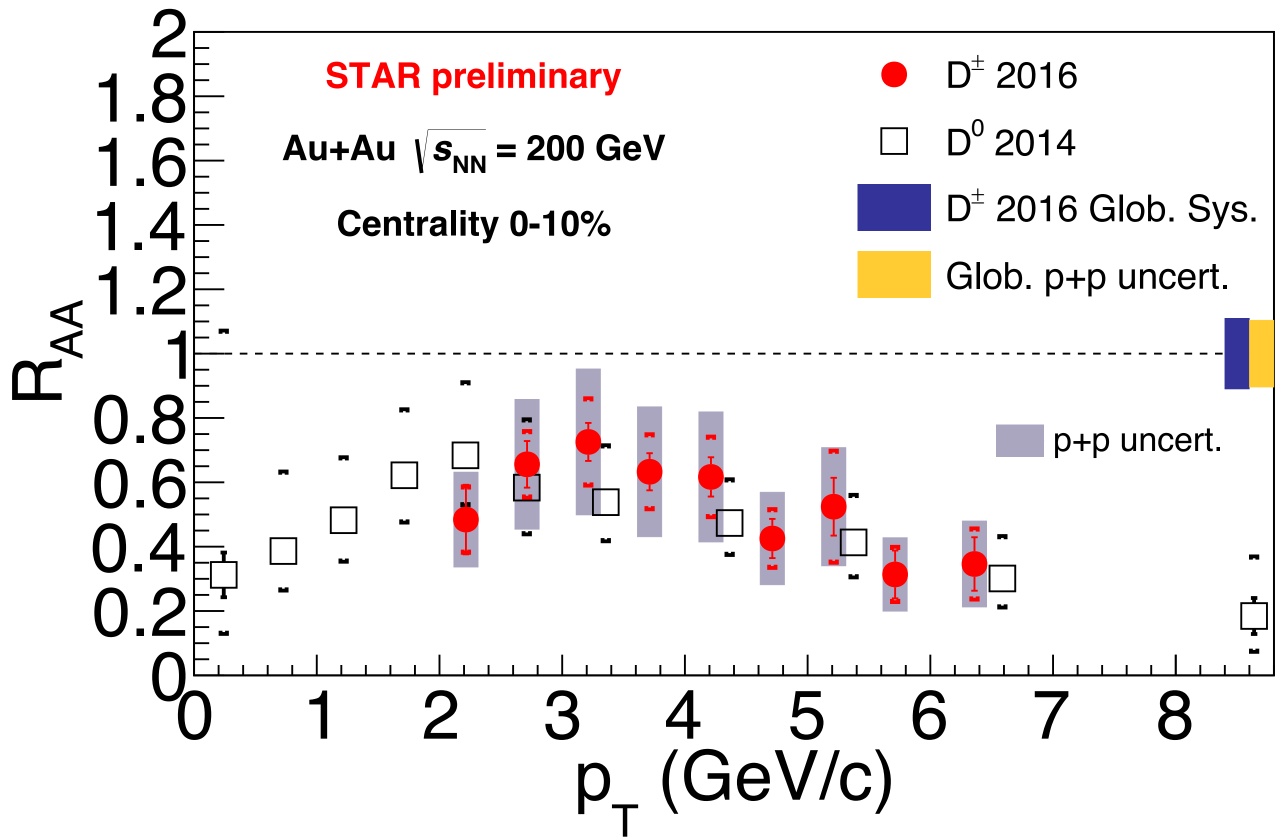
- $D^0$ lifetime cτ measurement
- $D^0$ cross-section vs rapidity measurement



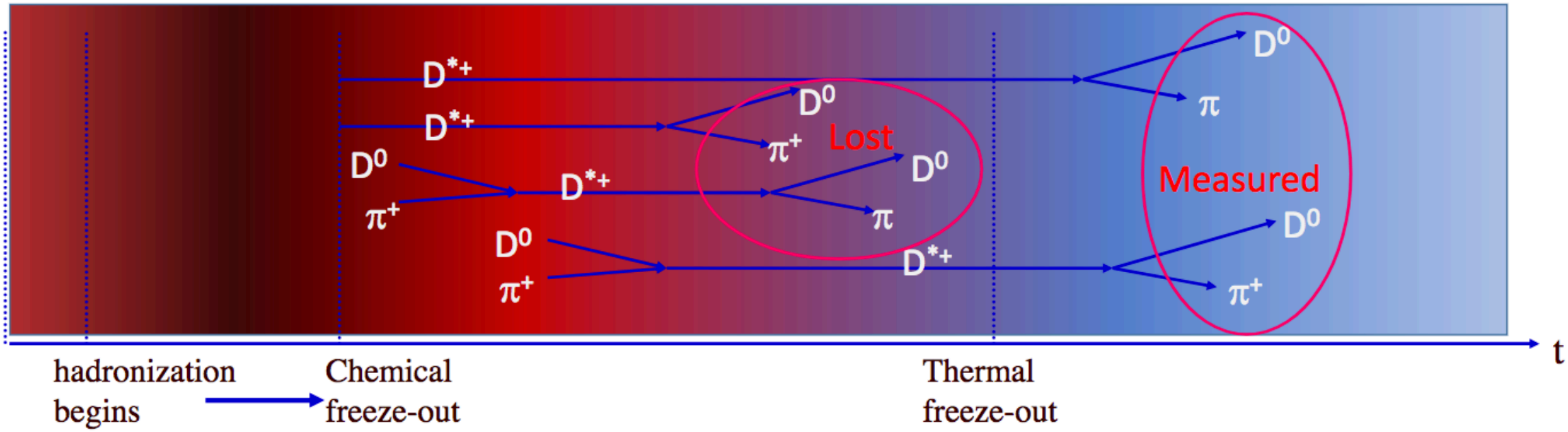
# $D^{+/-}$ $R_{AA}$

- Similar suppression for $D^0$ and $D^{+/-}$
- Spectra measurement is important for the total charm cross-section



# $D^{*+}$ Production in Au+Au Collisions

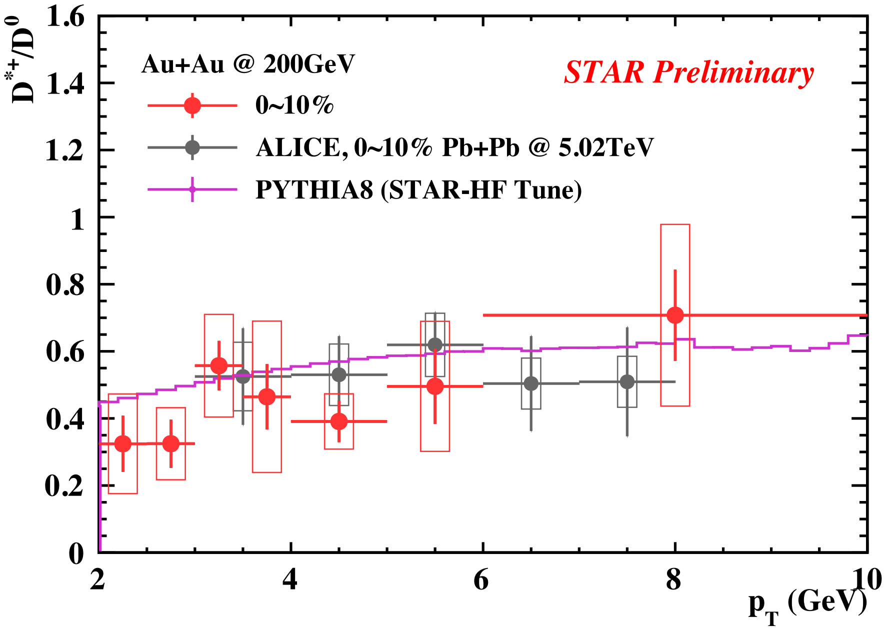
- $D^{*+}$ feeds down to $D^0$ yields $D^{*+} \rightarrow D^0 + \pi^+_{soft}$
- Possible hot medium effects :
  - $D^{*+}$ life time could become shorter in hot medium
  - Re-scattering can lead to loss of yield

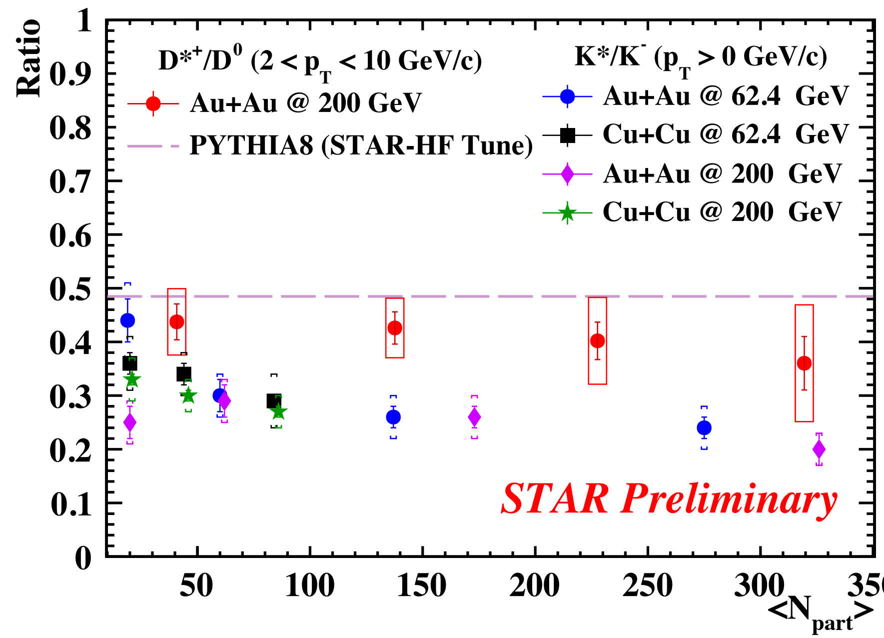



*Shuai Y. F. Liu and Ralf Rapp. Phys. Rev. C 97 (2018) 034918.*

# $D^{*+}/D^0$ Ratio in Au+Au Collisions

- $D^{*+}/D^0$ ratio in Au+Au collisions at 200 GeV is consistent with PYTHIA and with ALICE data at higher $p_T$.
- Ratio of the integrated yields shows no strong centrality dependence



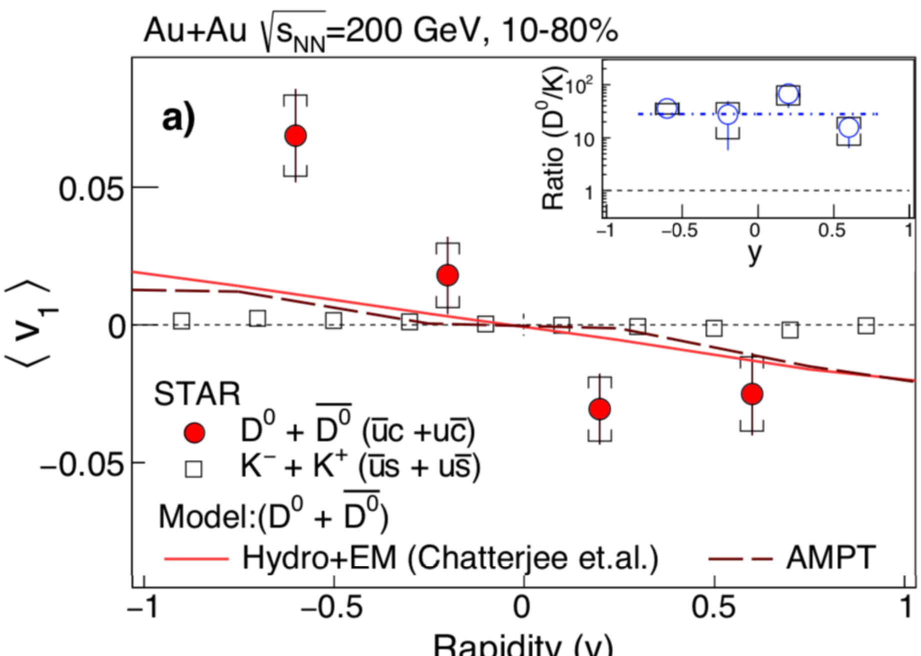




*K*/K, Phys. Rev. C (2011) 84. 034909.*
*ALICE Collaboration, arXiv:1804.09083.*

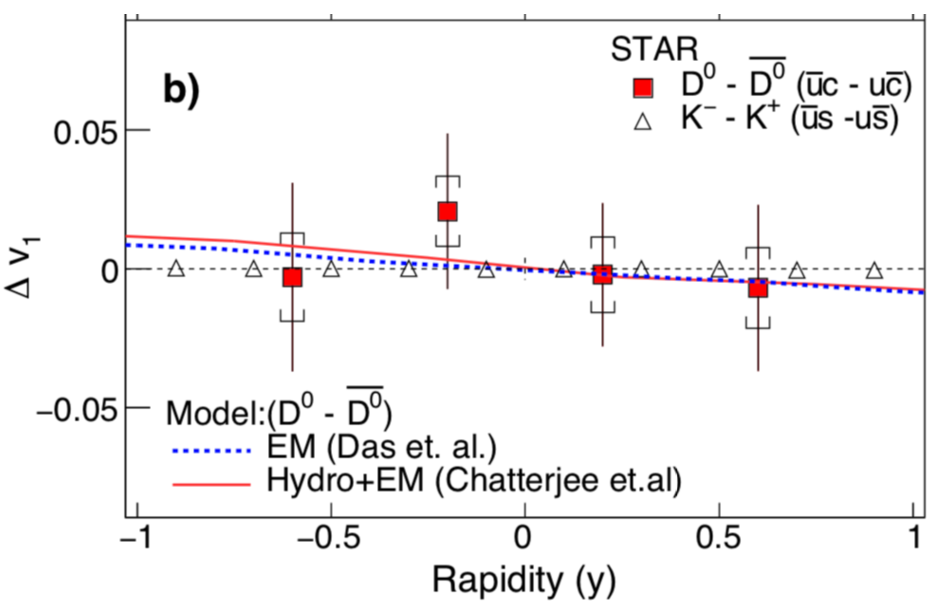
# $D^0$ Directed Flow ($v_1$)

*S.K. Das et al, PLB 768 (2017) 260*

- Charm quarks interact with bulk medium → $D^0$ $v_1$ sensitive to the initial tilt of the source (bulk) *S. Chatterjee and P. Bożek, PRL 120 (2018) 192301*
- Charm and anti-charm quarks can be deflected differently by the initial EM field → difference between $D^0$ and $\overline{D^0}$ $v_1$ sensitive to EM field
- First observation of non-zero (negative) $D^0(\overline{D^0})$ $v_1$ slope, much larger than that of kaons $D^0 + \overline{D^0}$ $dv_1/dy = -0.081 \pm 0.021(stat) \pm 0.017(sys)$
- More precise data are needed for $\Delta v_1$ $d\Delta v_1/dy = -0.041 \pm 0.041(stat) \pm 0.020(sys)$

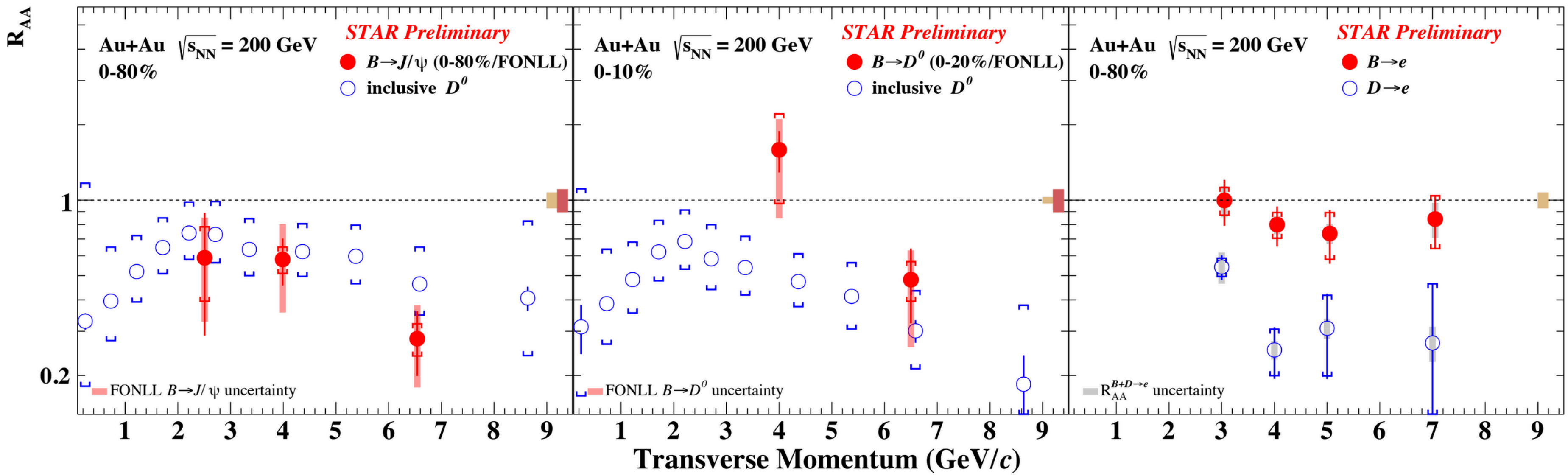



STAR, arXiv:1905.02052



# B Study from Non-prompt J/ψ & $D^0$ & e

- Strong interaction of charm with the medium. How about bottom?
- 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 $\sigma$): consistent with $\Delta E_c > \Delta E_b$. Measurements with improved precision on the way




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

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

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

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

$R_{AA}$ references (data vs. theory) are different for comparisons. The decay kinematics needs to be unfolded for different channels.

Guannan Xie