Recent Open Heavy Flavor Measurements at RHIC

-- Hot medium effect

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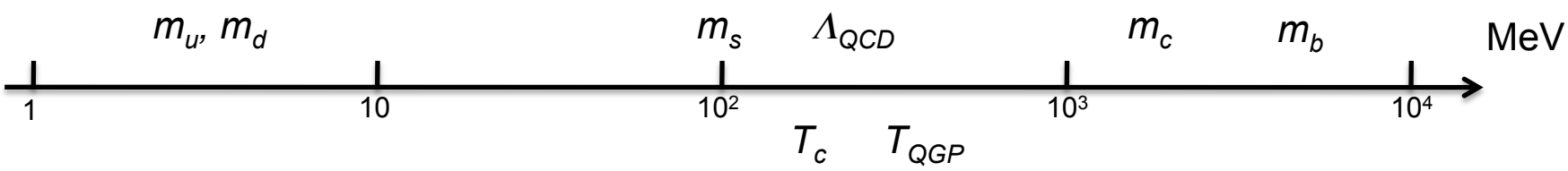
Outline

- Introductions
- Open charm hadron measurements
- Open bottom hadron measurements
- Summary

Why are heavy quarks important?

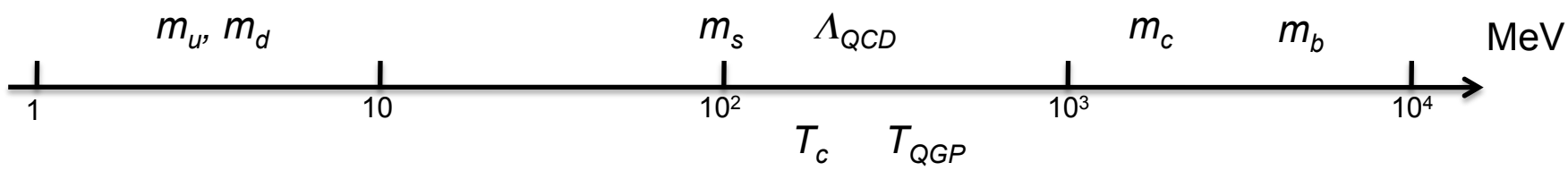


- Produced early in the history of heavy-ion collisions.

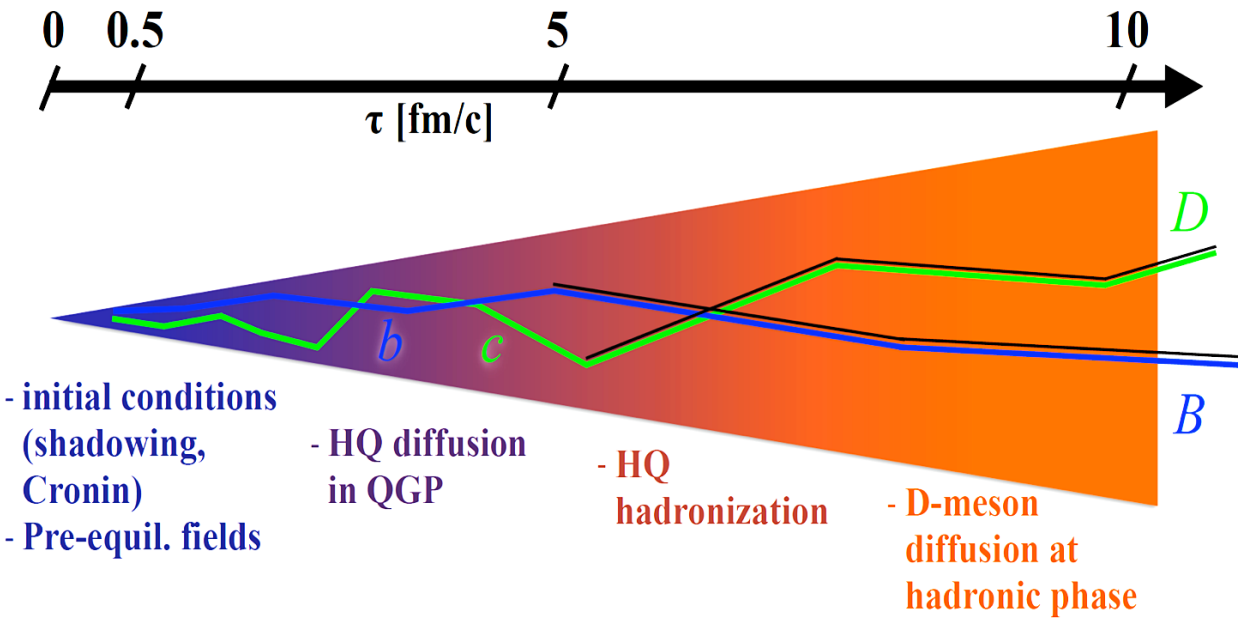
Han dynasty (~ B.C. 100)

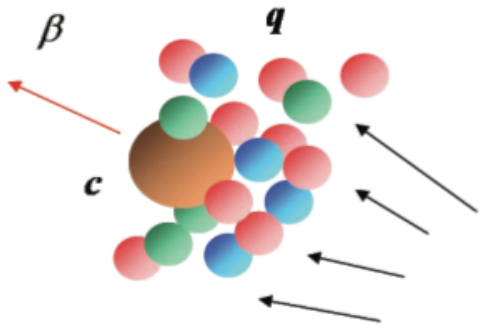
Today

Why are heavy quarks important?



- Produced early in the history of heavy-ion collisions.
- Experience most of the stages of the system evolution.
- Charm hadronization in hot medium.





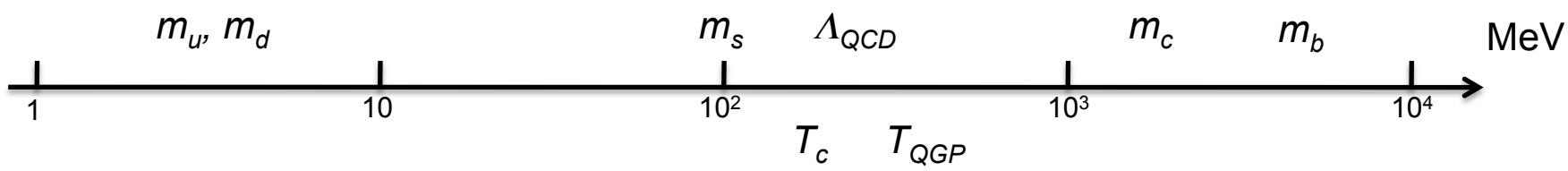
"***Brownian***" motion

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

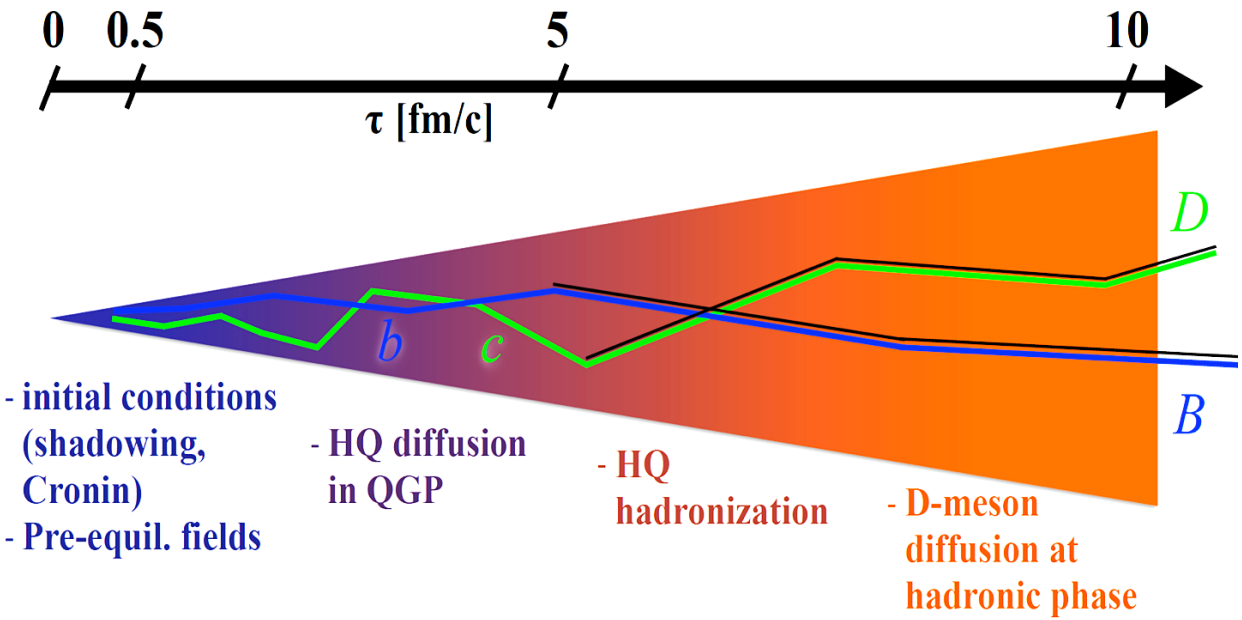
drag → η_D; fluctuations → $\xi^i(t)$

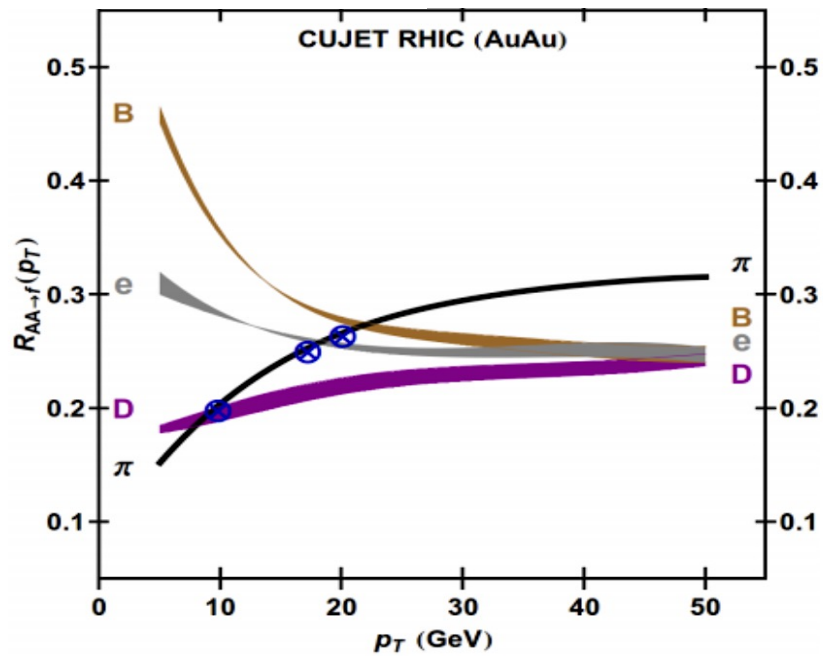
→ Diffusion coefficient D_{HQ}

Why are heavy quarks important?



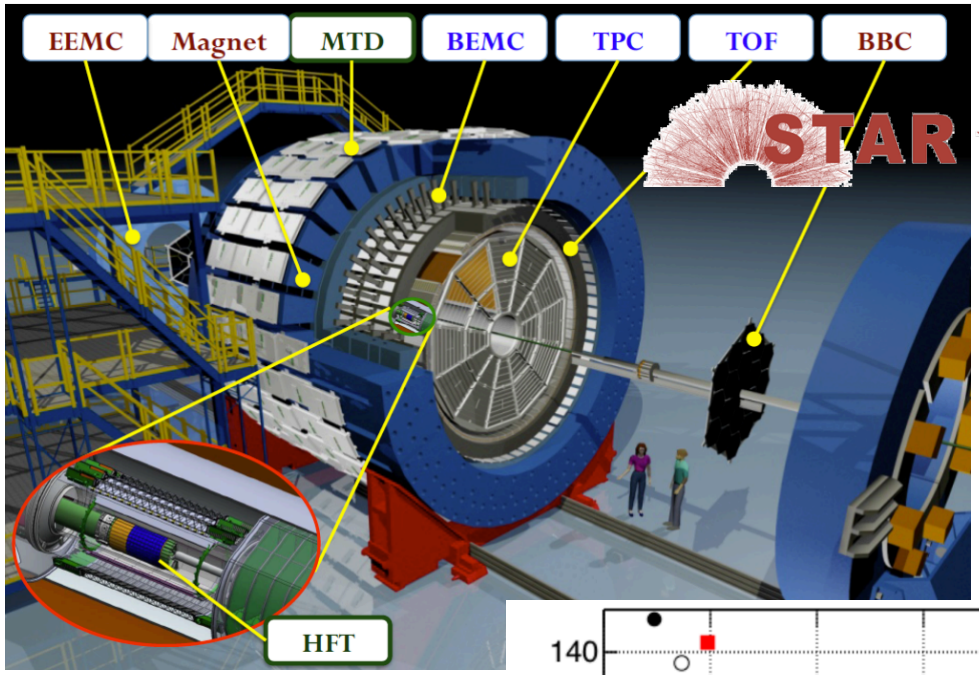
- Produced early in the history of heavy-ion collisions.
- Experience most of the stages of the system evolution.
- Charm hadronization in hot medium.
- Theory prediction: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$.

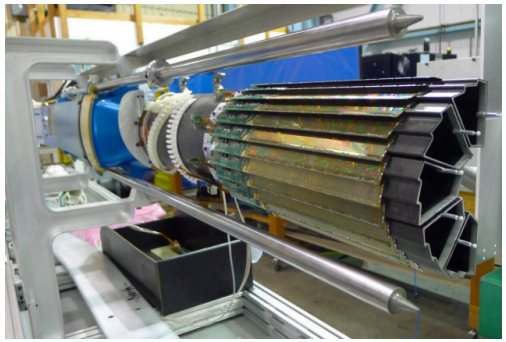


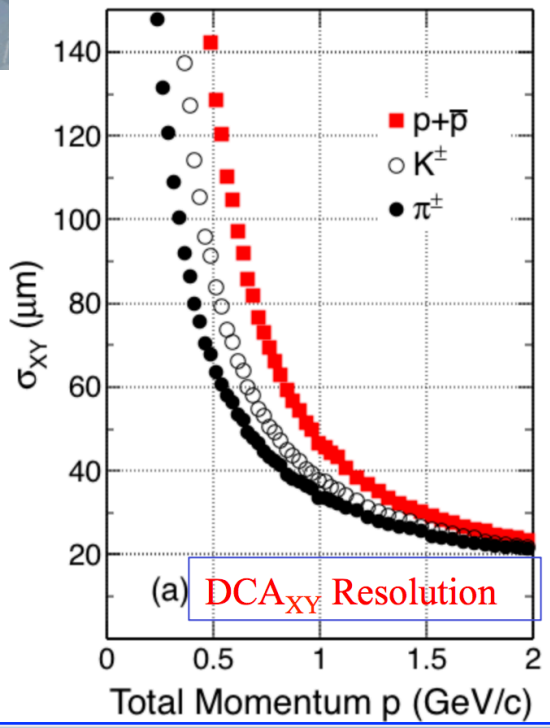


PRL 108 (2012) 022301

RHIC detectors to measure HQ





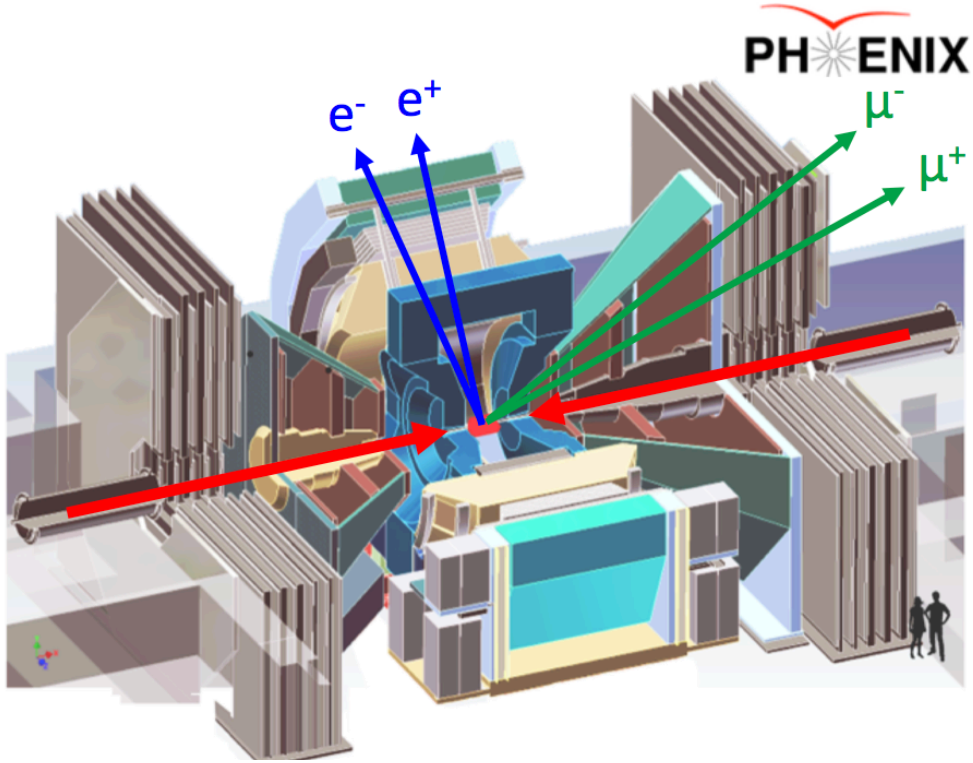


Large acceptance:

$|\eta| < 1,\ 0 < \phi < 2\pi$

Heavy Flavor Tracker

– track pointing resolution ~50 μm @ p_T ~0.8 GeV/c



[Mid-rapidity]

electrons at Central arm (with RICH and EMCal)

$\phi = \pi,\ |\eta| = 0.35$

[Forward-rapidity]

muons at Muon arm

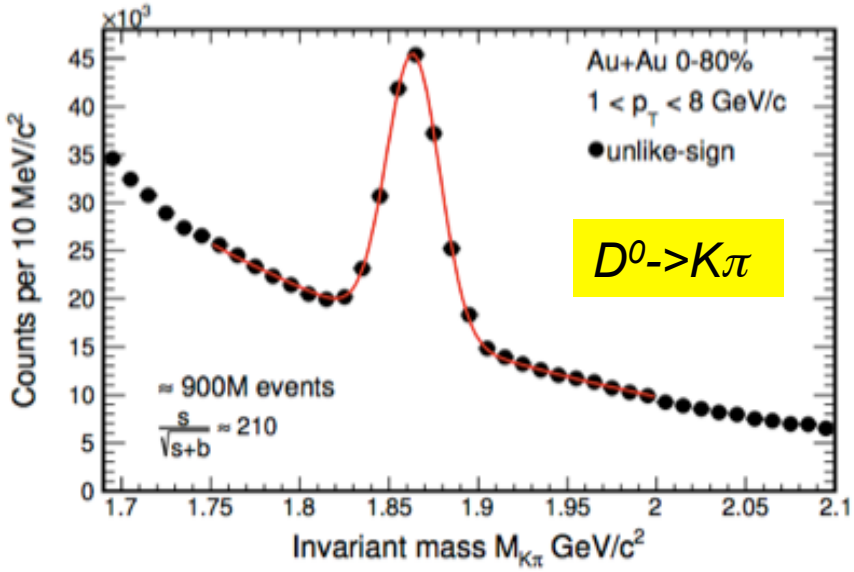
absorber: 7.2 X_{int}

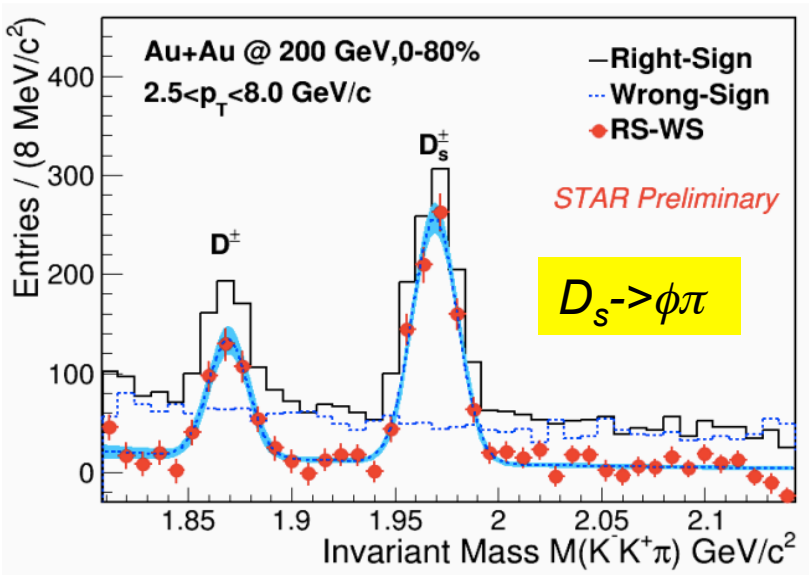
$\phi = 2\pi,\ 1.2 < |\eta| < 2.2$

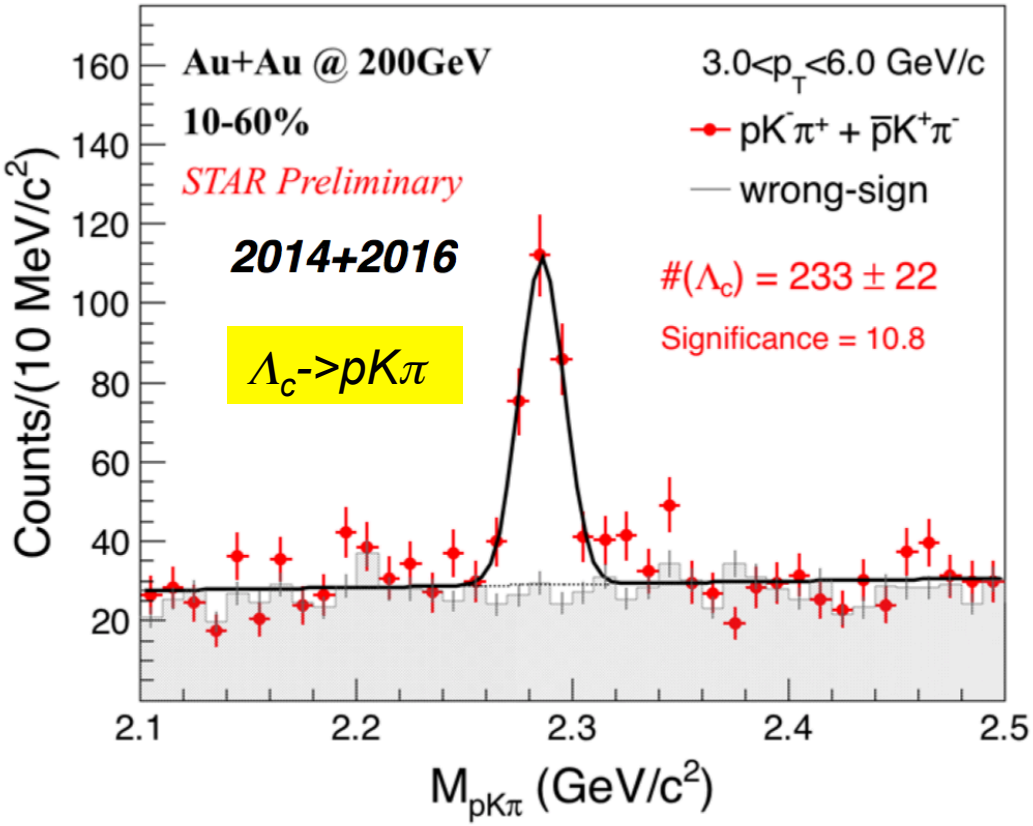
Open charm

Open charm hadron signals

Exclusive reconstruction of OHF hadrons with STAR HFT

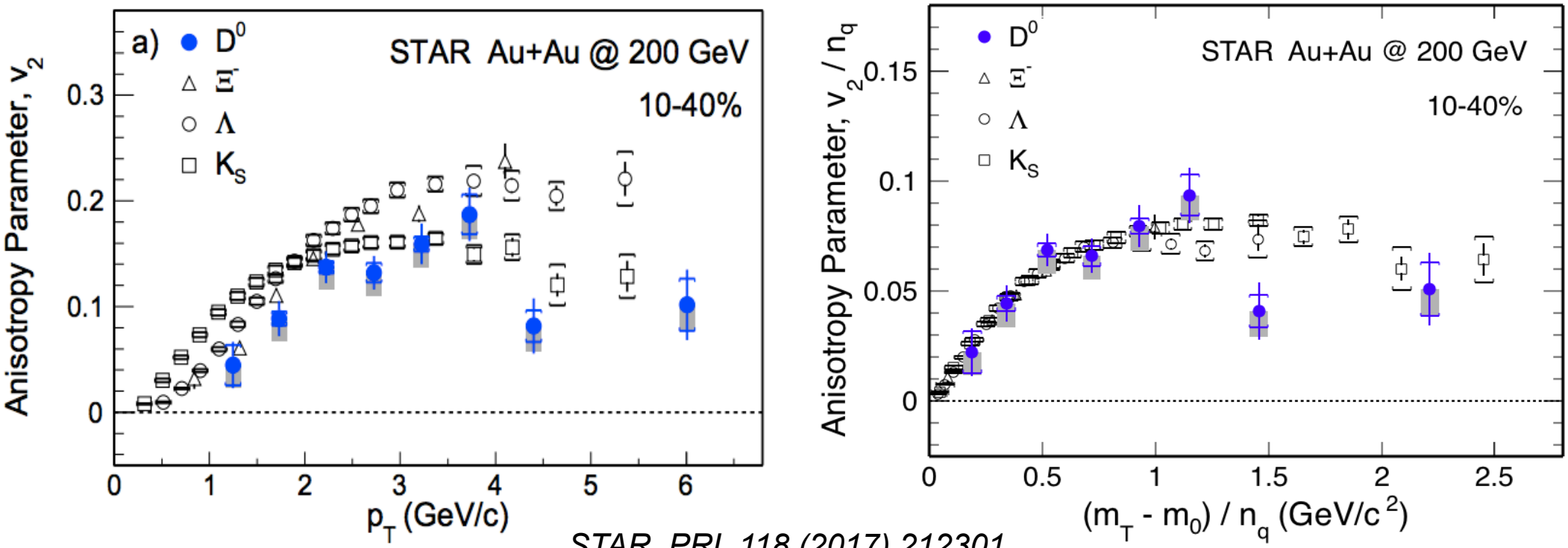






Hadron	Abundance (fragmentation)	cτ (μm)
D^0	61%	123
D^+	24%	312
D_s	8%	150
Λ_c	6%	60

Open charm hadron v_2 at RHIC

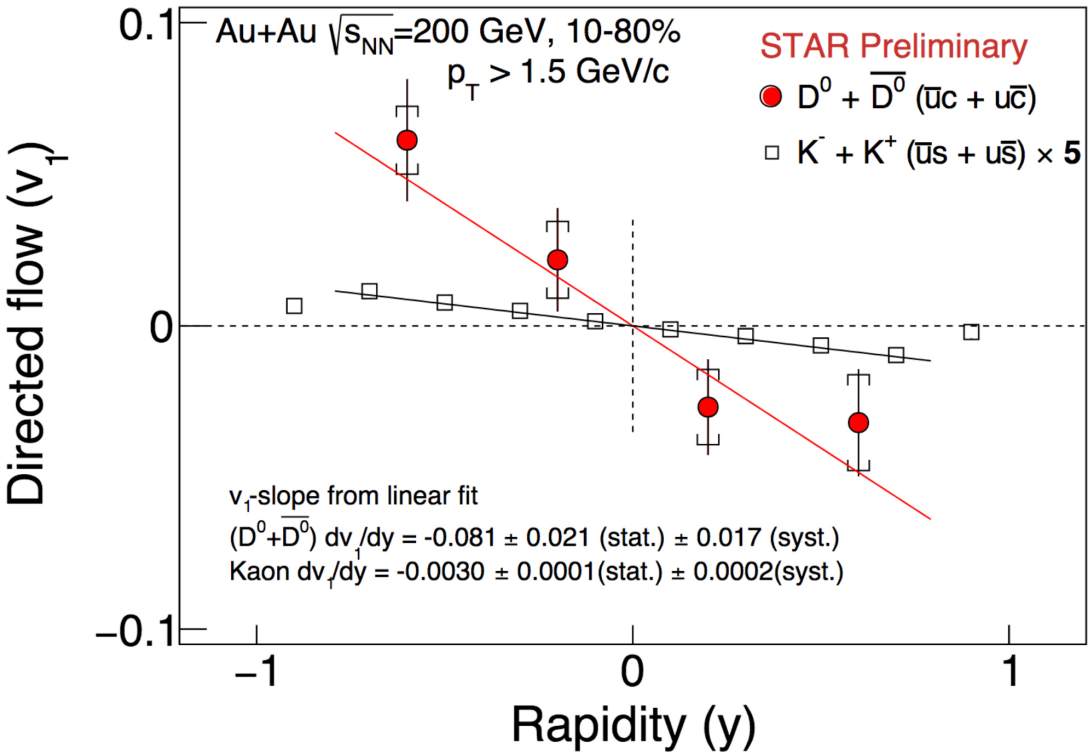


STAR, PRL 118 (2017) 212301

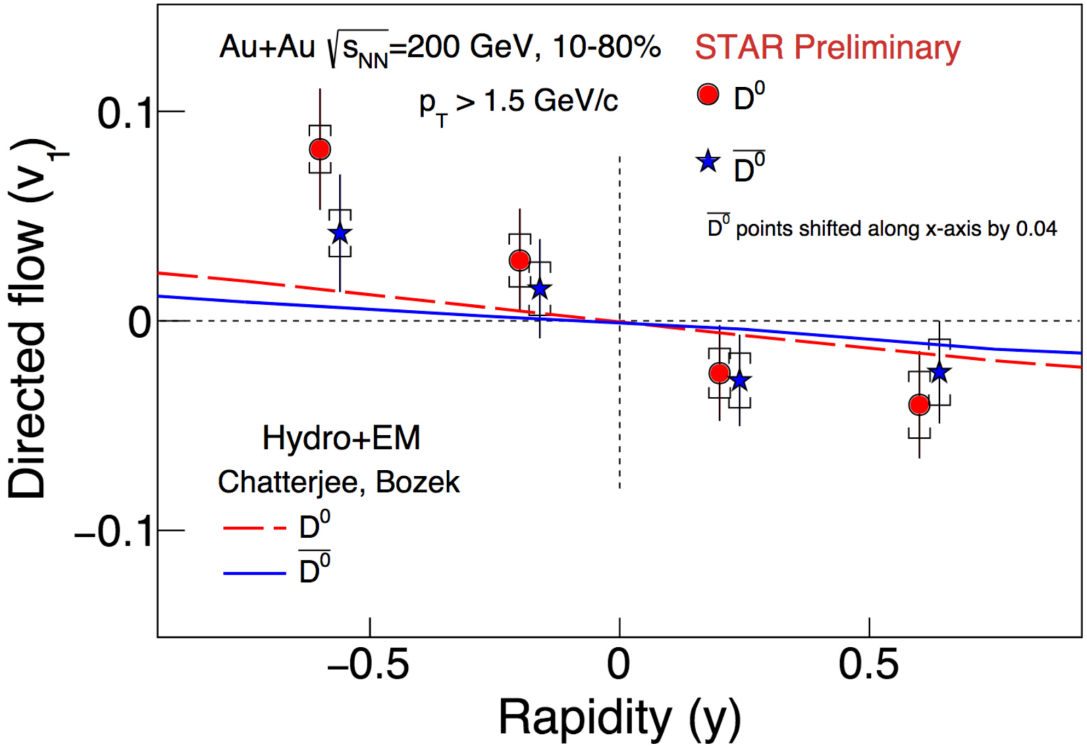
- Mass ordering at p_T < 2 GeV/c (hydrodynamic behavior)
- v_2(D) follows the (m_T-m_0) NCQ scaling as light hadrons below 1 GeV/c^2

Evidence of charm quarks following the medium collectivity
- suggest charm quarks may have achieved thermalization

Open charm hadron v_1 at RHIC



L. He, HP18

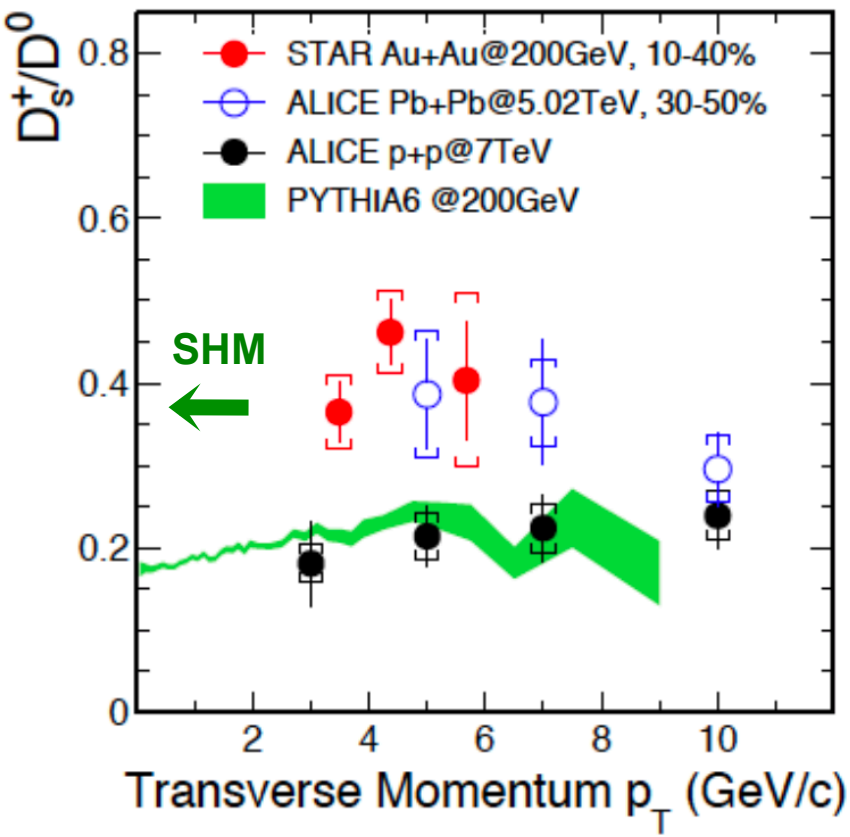


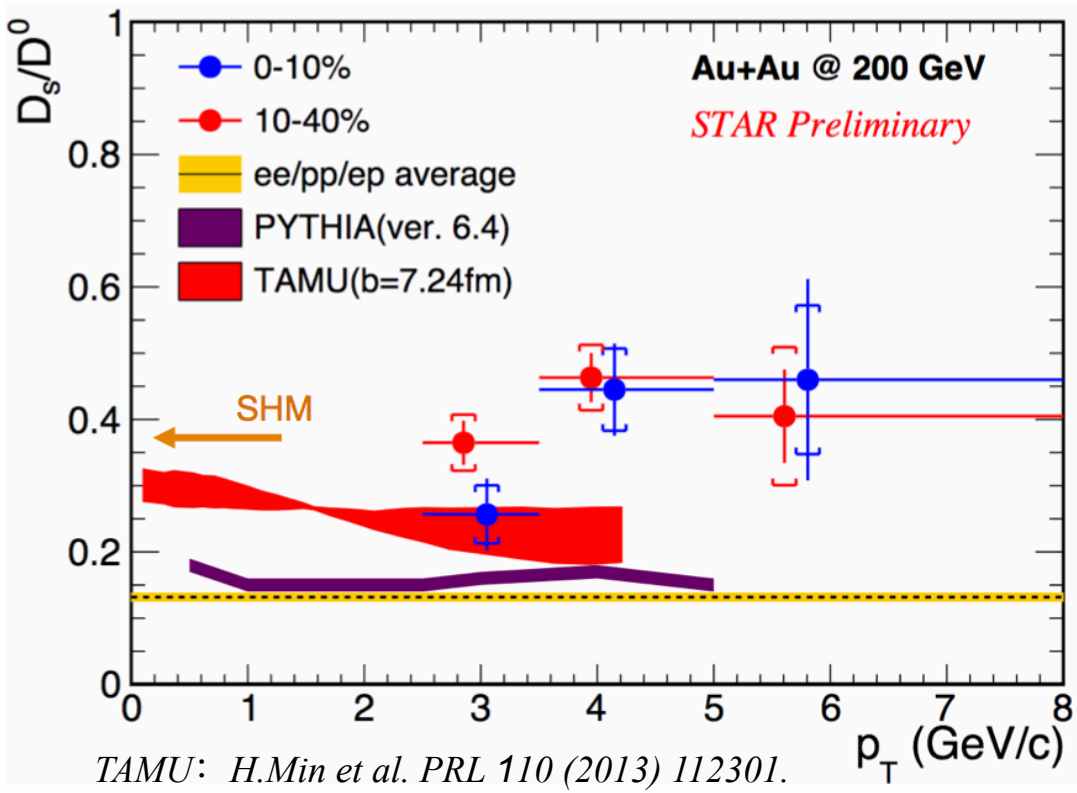
Hydro+EM: Chatterjee, Bozek: PRL 120, 192301 (2018).

- Sensitive to initial tilt of fireball and viscous drag on charm quarks from QGP.
- Initial EM field predicts difference between D^0 and anti-D^0 v_1.

- Larger v_1-slope observed than for light flavor hadrons.
- In agreement with Hydro + EM model predictions.

Strangeness enhancement in charm sector



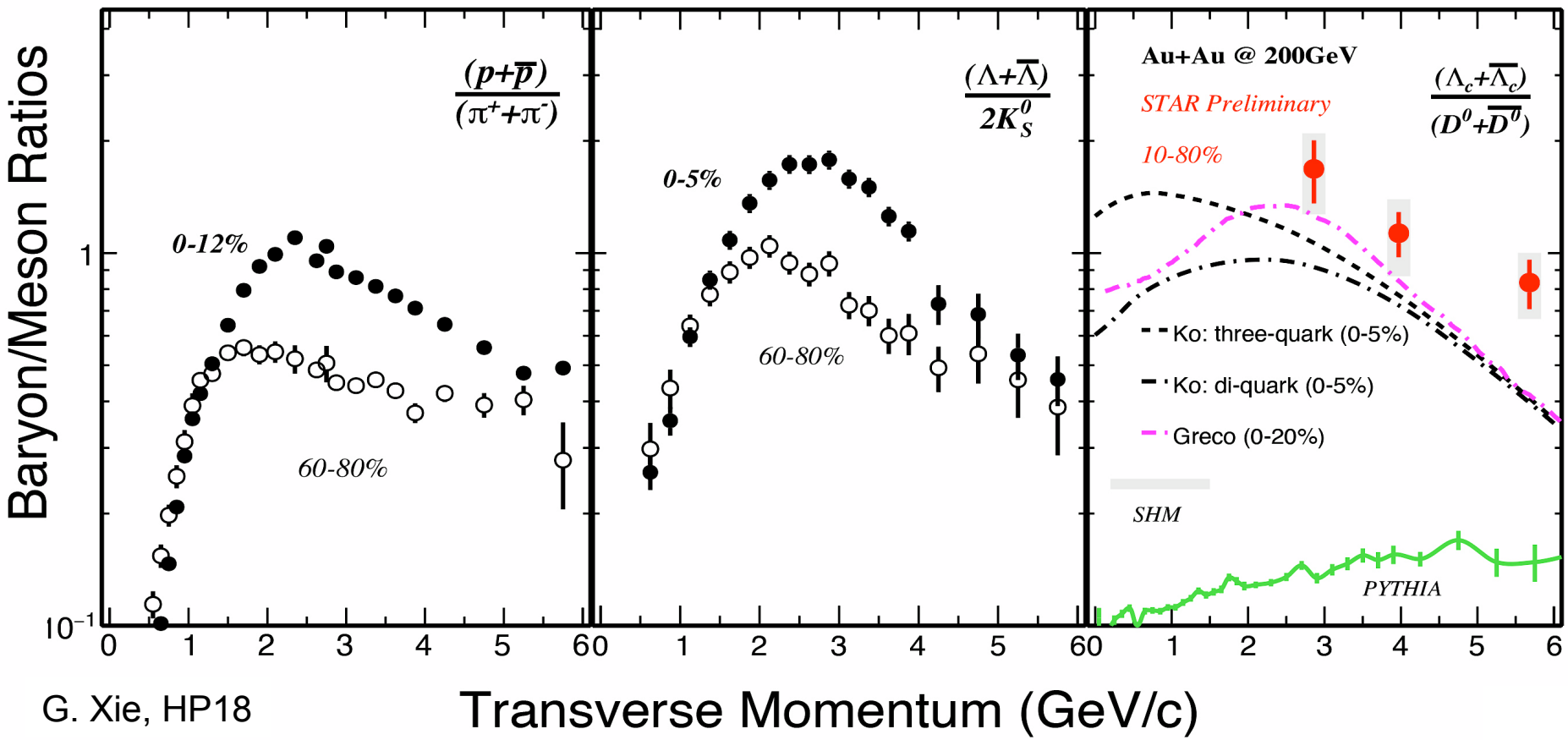


TAMU: H.Min et al. PRL 110 (2013) 112301.
SHM: A. Andronic et al. PLB 571 (2003) 36.

Significant D_s/D^0 enhancement in mid-central Au+Au and Pb+Pb collisions w.r.t fragmentation baseline or p+p measurement

- Charm coalescence hadronization
- Strangeness enhancement
- SHM predicts D_s/D^0 ratio ~ 0.35-0.40 (central)

Baryon over meson ratio in charm sector

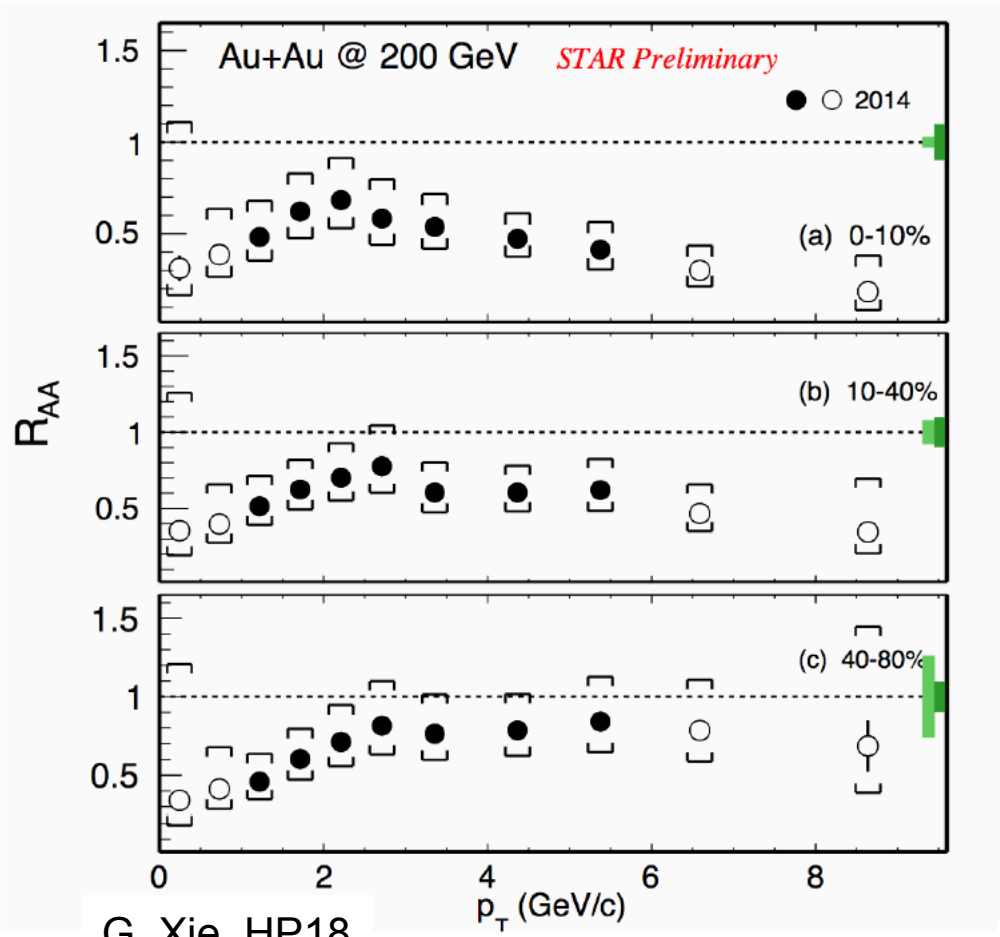


G. Xie, HP18

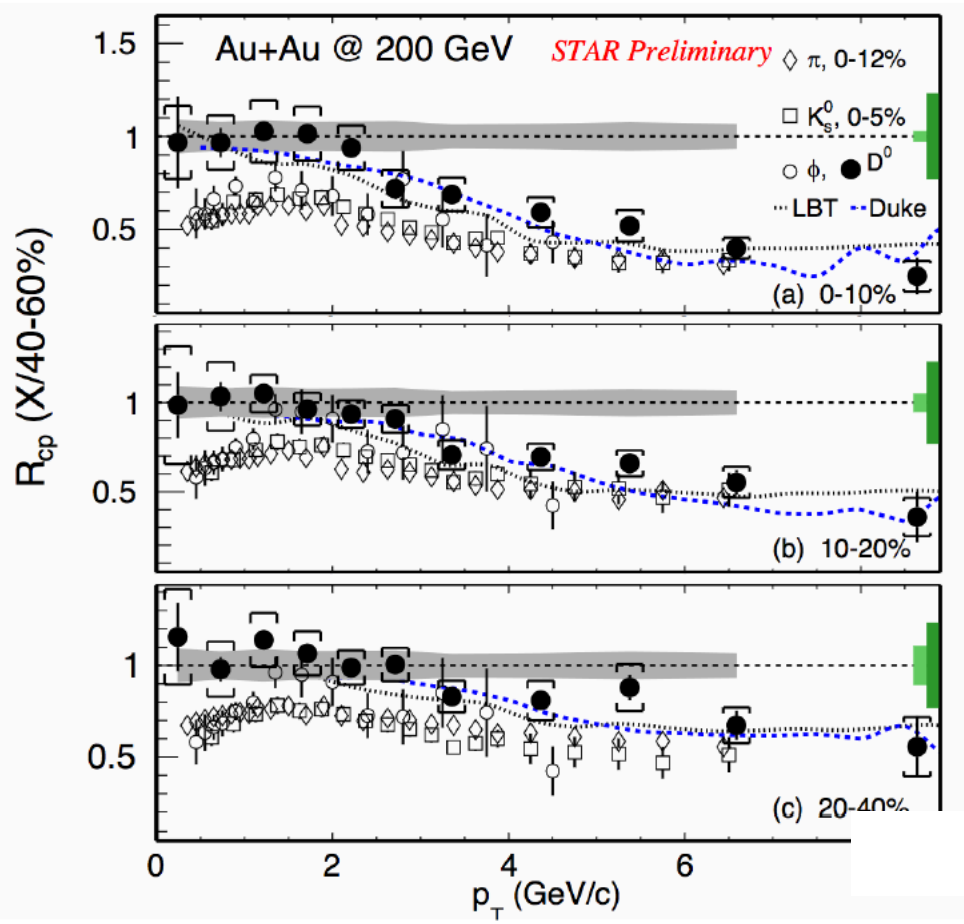
Ko model : PRC 79 (2009) 044905; Greco model : EPJC 78 (2018) 348)

- Significant enhancement in Λ_c/D^0 compared to PYTHIA/fragmentation baseline.
- The Λ_c/D^0 ratio is compatible with light flavor baryon-to-meson ratios.
- Consistent with coalescence + thermalized charm quarks, higher at high p_T.

Charm redistributes and energy loss in HI

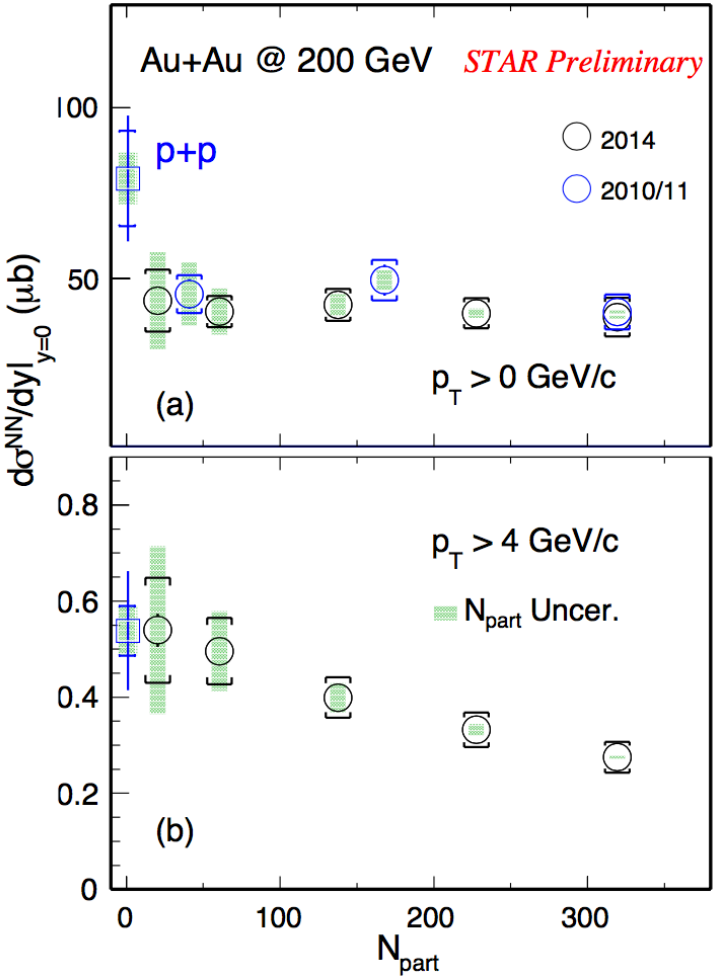


G. Xie, HP18



- R_{AA} shows suppression at low p_T may due to charm redistributions in medium.
- Both R_{AA} and R_{CP} show significant suppression at high p_T in central collisions.
- Transport models with charm quark energy loss can describe the data.

D^0 and total charm cross sections



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
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

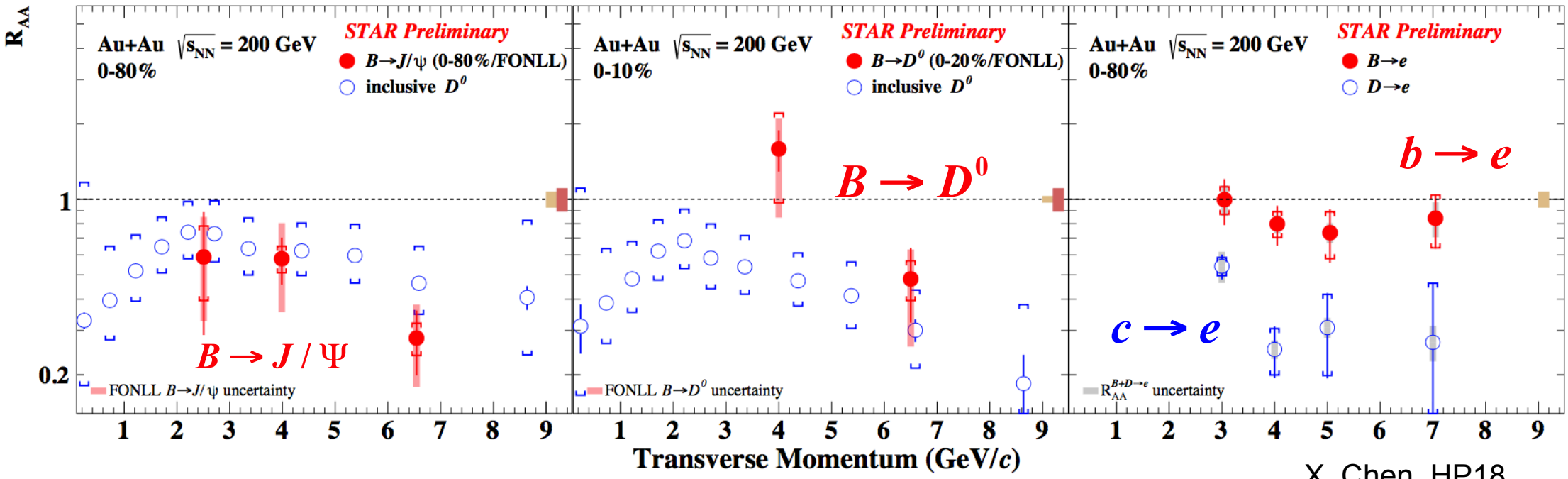
*** derived using Λ_c^+ / D^0 ratio in 10-80%**

X. Chen, G. Xie

- p_T integrated D^0 cross section is nearly independent with centrality and smaller than in p+p collisions. But for p_T > 4 GeV/c, it decreases towards central collisions.
- Total charm cross section in Au+Au collisions is consistent with p+p value within uncertainties, but redistributed among different charm hadron species.

Open bottom

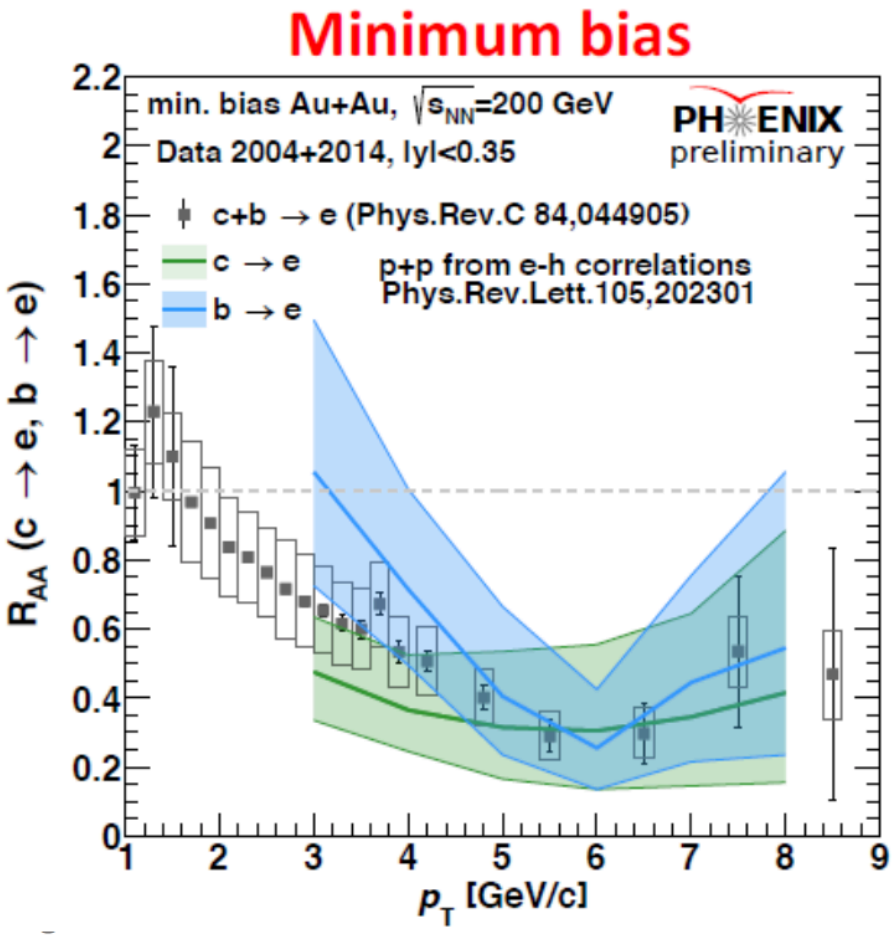
Bottom measurement at STAR

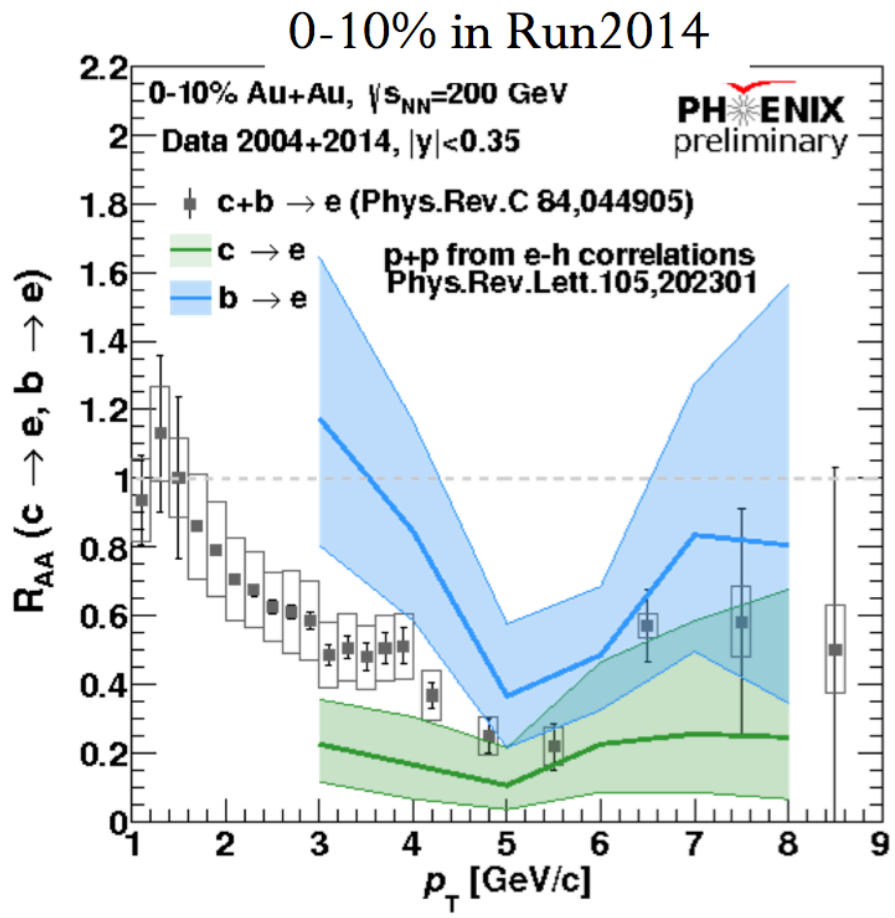


X. Chen, HP18

- Strong suppression for B->J/Ψ and B->D^0 at high p_T => Bottom interacts with QGP?
- Less suppression for B->e than D->e (~2σ), consistent with $\Delta E_c > \Delta E_b$.
- A factor of ~1.5 more MB and ~5 more HT Au+Au events recorded in 2016 for D^0 and electron decay channels.

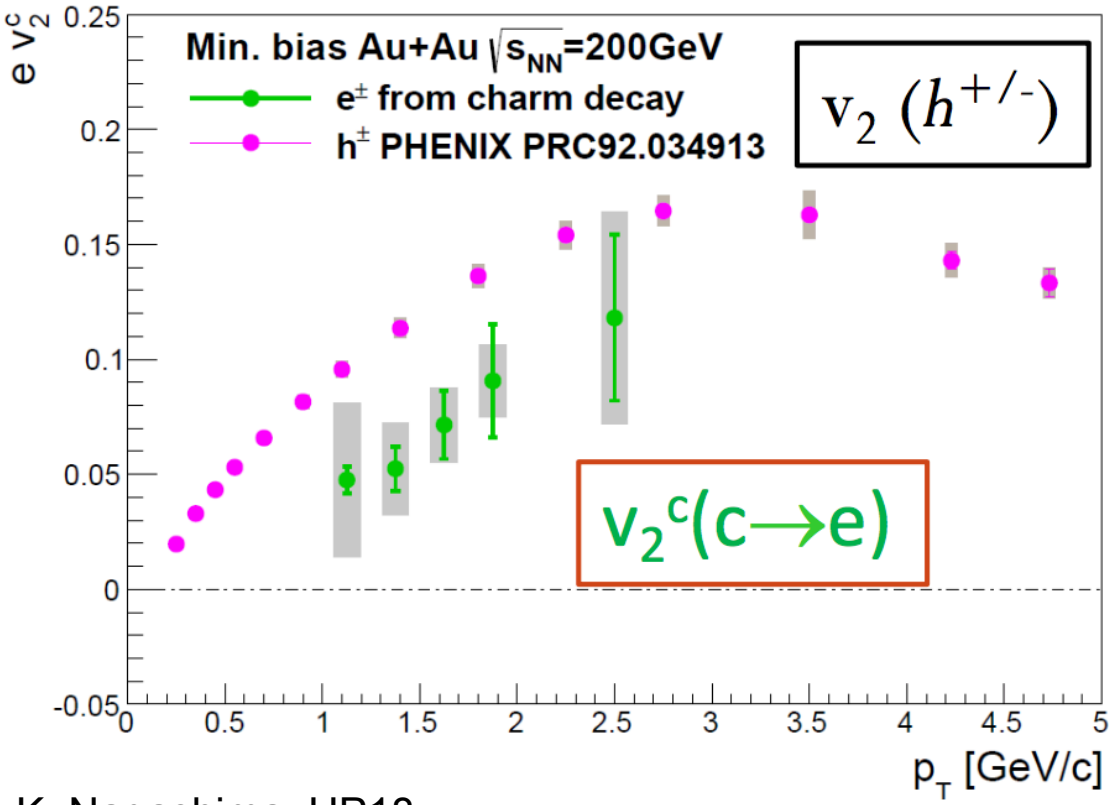
Bottom measurement at PHENIX

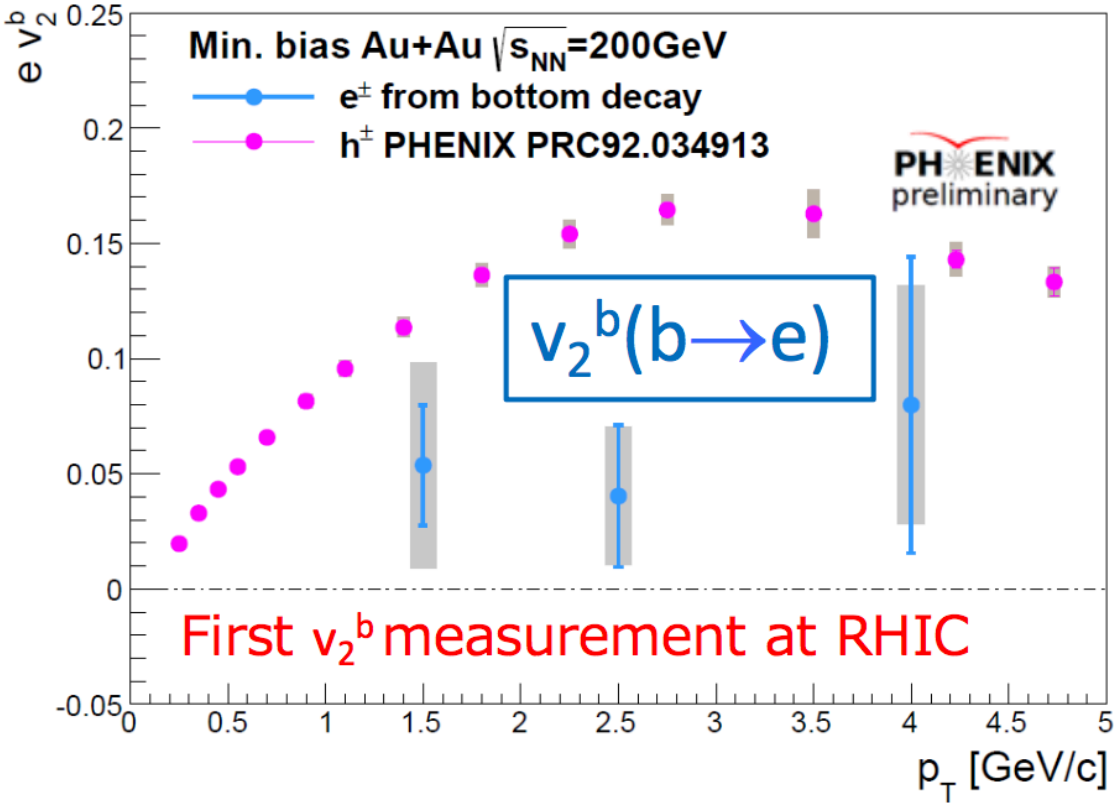




- Electron from charm quarks are more suppressed.
- Common trend in minimum bias and central collisions.
- Will be improved with new p+p baseline.

Bottom measurement at PHENIX

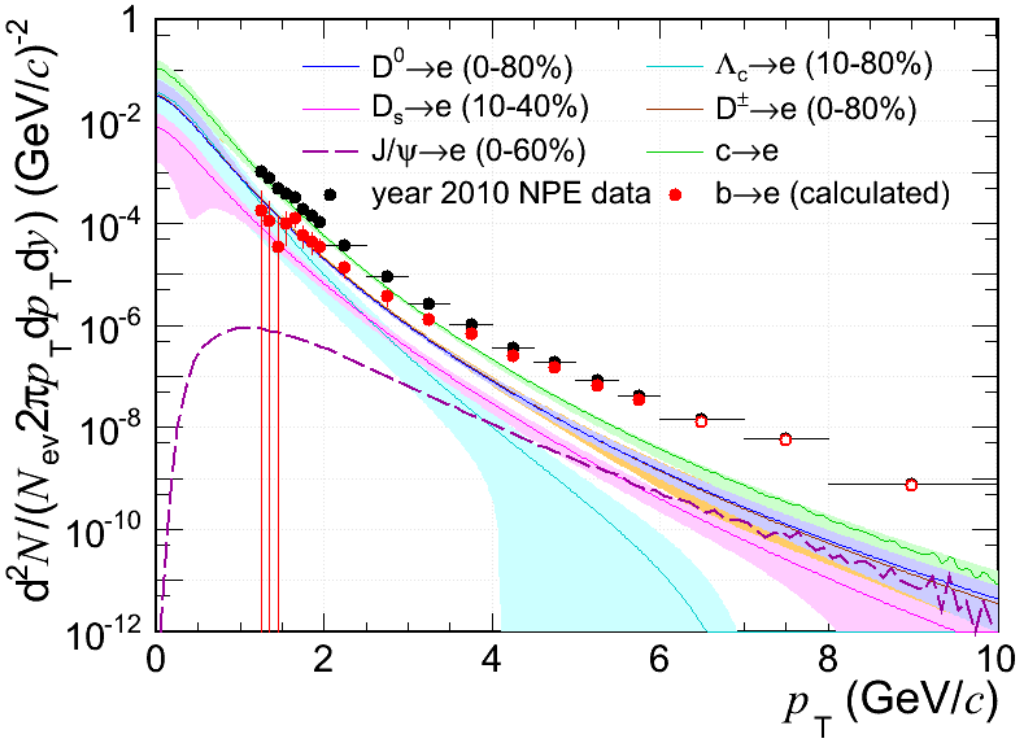


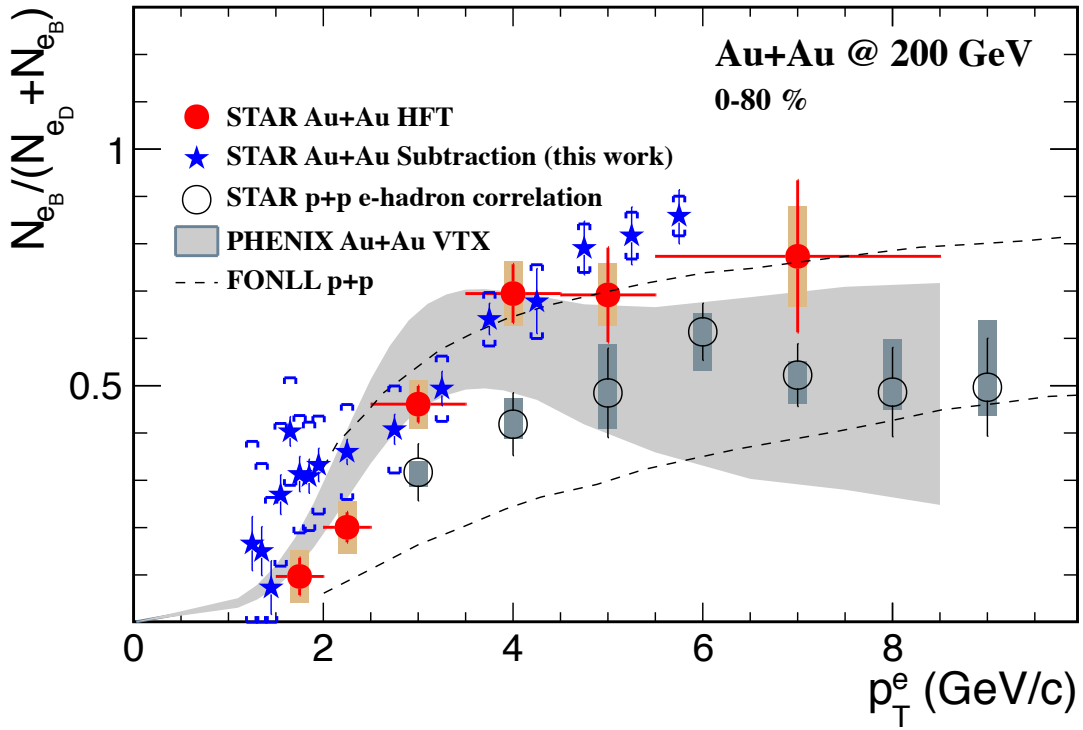


K. Nagashima, HP18

- Flows of electron from charms and bottoms in Au+Au are separated.
- Charm flows less than light-flavor hadrons, hydro mass ordering.
- Hint of bottom flow at RHIC with large uncertainties.

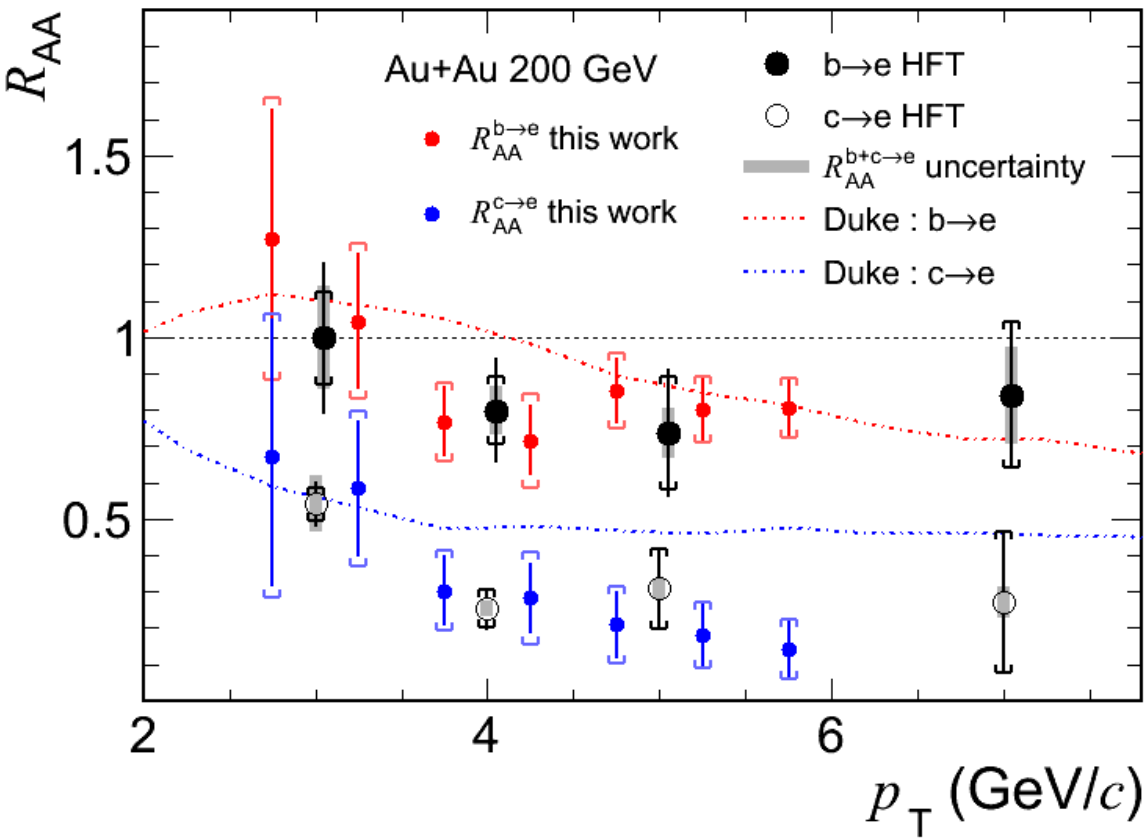
Data driven method to extract B->e





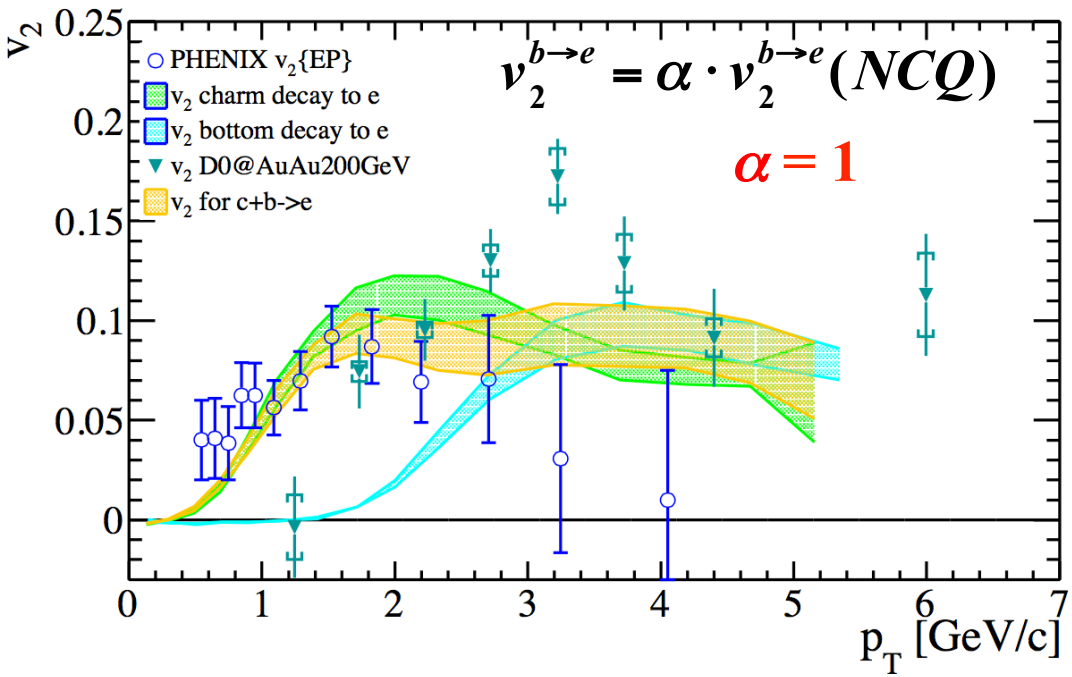
- Extracted B->e with good statistical errors based on published data.
- Systematic errors dominated (reducible with precision charm measurement).
- Subtraction method is comparable with template fit method within uncertainties.
- Consistent with FONLL calculation.

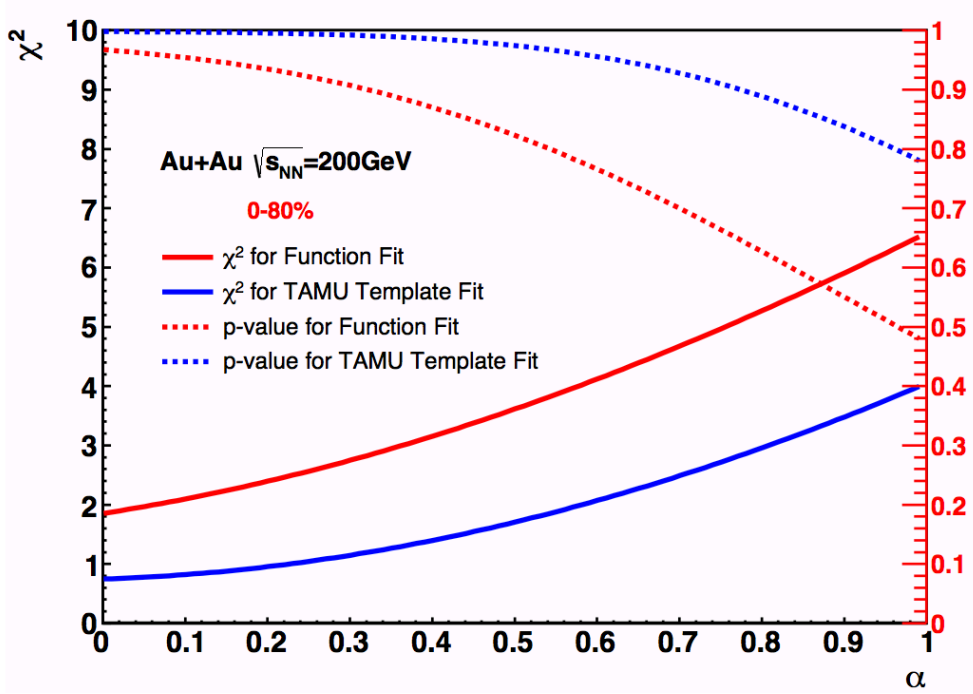
Data driven method to extract B->e



- R_{AA} of electron from charms and bottoms are separated.
- Subtraction method is comparable with template fit method.
- Consistent with model calculations.
- Will be improved with latest data.

Bottom v_2

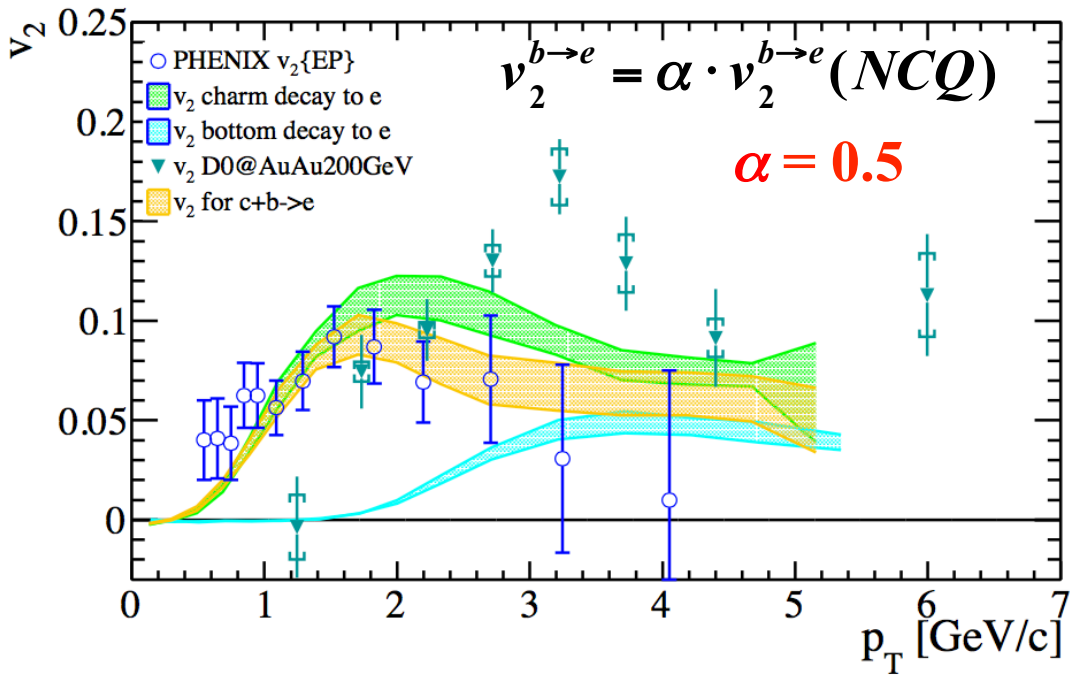


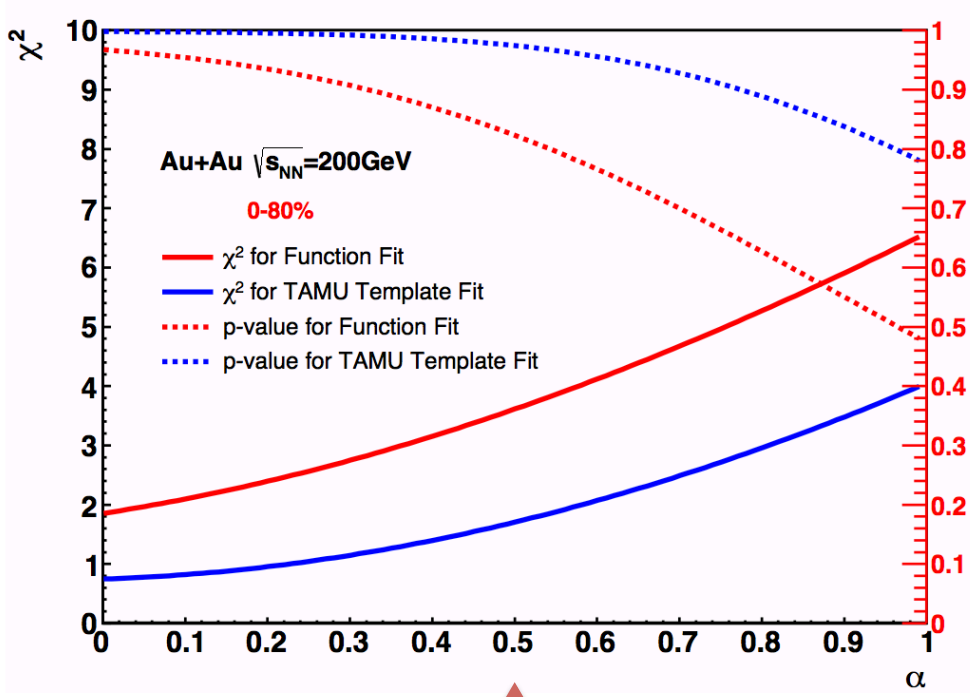


$\alpha = 1$

- Extract bottom v_2 using data driving method.
- Assuming v_2 of electron from bottoms follows NCQ scaling (shape) * α.
- The c+b->e yellow band fits to PHENIX inclusive HF electron data.

Bottom v_2





$\alpha = 0.5$

- Extract bottom v_2 using data driving method.
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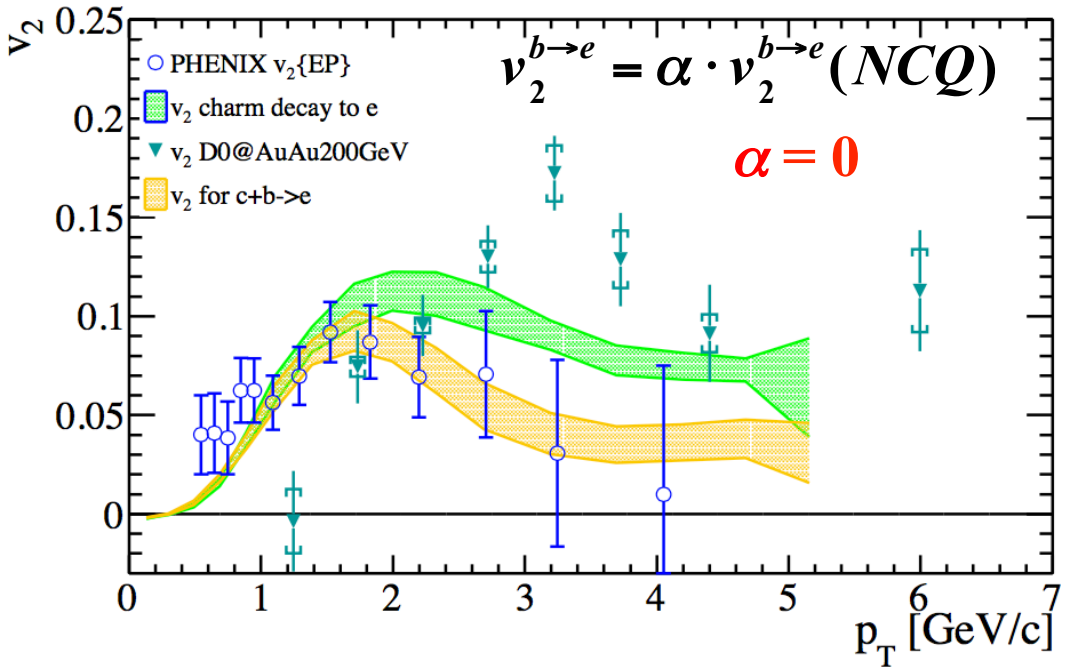
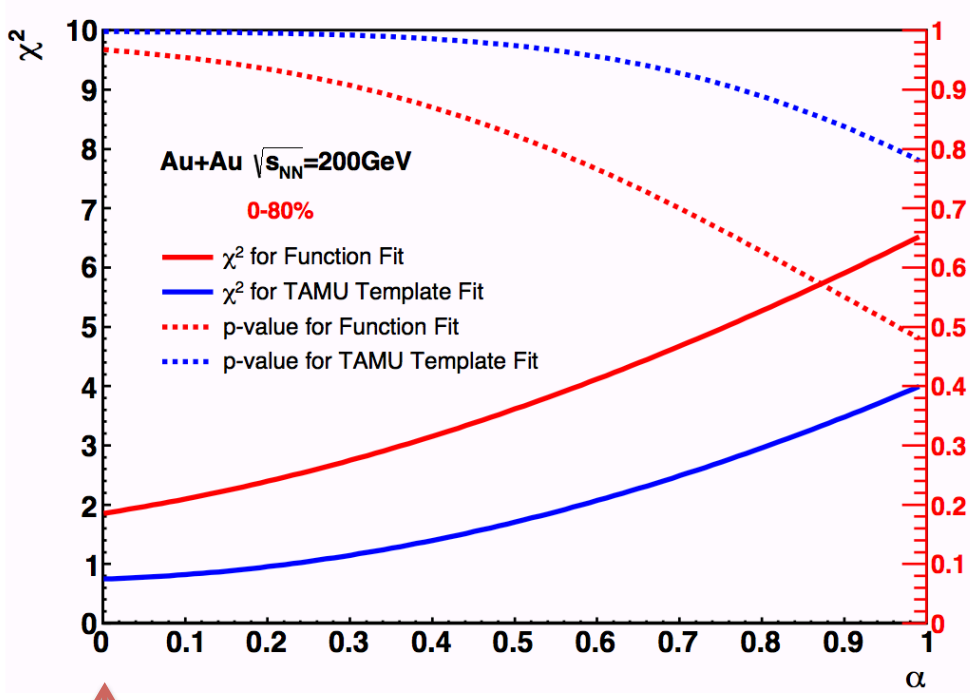
Bottom v_2

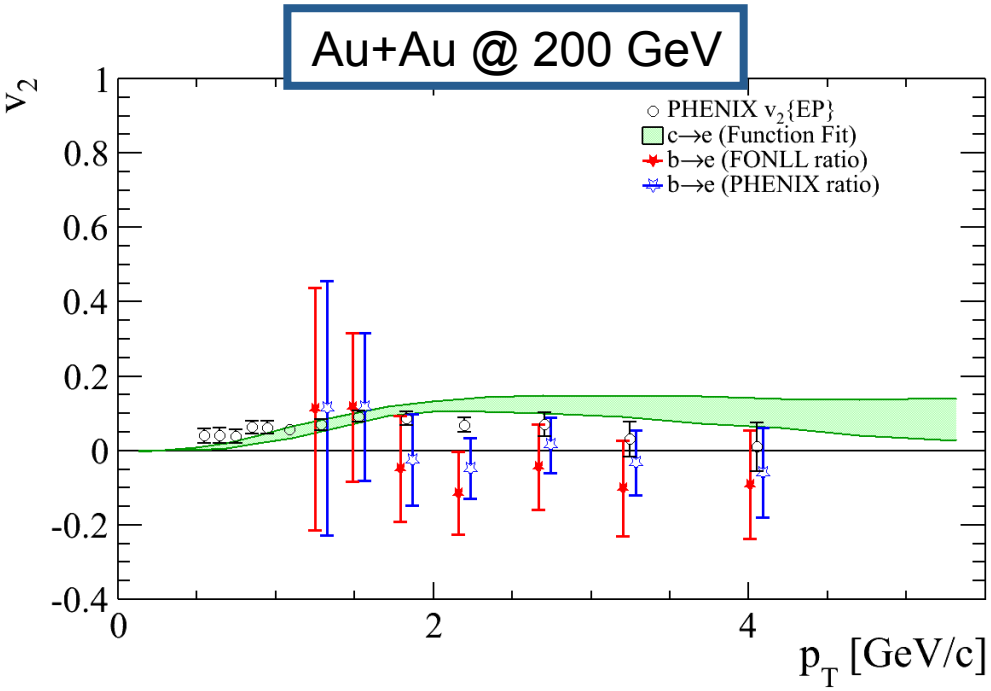


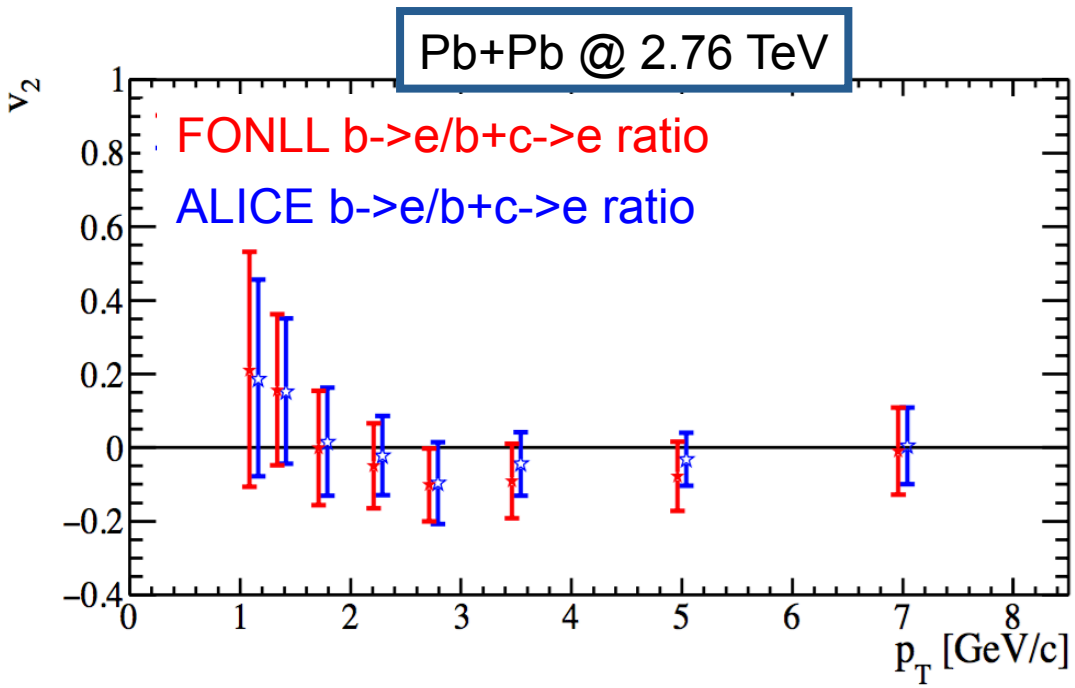


$\alpha = 0$

- Extract bottom v_2 using data driving method.
- Assuming v_2 of electron from bottoms follows NCQ scaling (shape) * α.
- The c+b->e yellow band fits to PHENIX inclusive HF electron data.
- χ^2-test method suggests small bottom v_2.

Bottom v_2





- Decomposition / χ^2-test methods give consistent results.
- Bottom v_2 is consistent with zero at both RHIC and LHC.
- Will be significantly improved by latest precise data.

Summary

- Open heavy flavor probes offer unique sensitivity to sQGP medium properties.
- Strong modification of open charm hadron spectra in A+A collisions at RHIC.
  - significant charm flow (D^0, D->e) following hydro mass ordering.
  - total charm quark cross section is consistent with that in p+p collisions but redistributed in hadronization.
  - significantly suppressed at high p_T – HQ energy loss .
  - D_s/D^0, Λ_c/D^0 enhancement => coalescence hadronization.
- Impressive progress on bottom measurement in A+A collisions at RHIC.
  - strong suppression of B->J/Ψ and B->D^0 at high p_T => bottom interacts with medium.
  - indication of less suppression for B->e than D->e, consistent with $\Delta E_c > \Delta E_b$.
  - hint of non-zero bottom v_2, needs more data to confirm.

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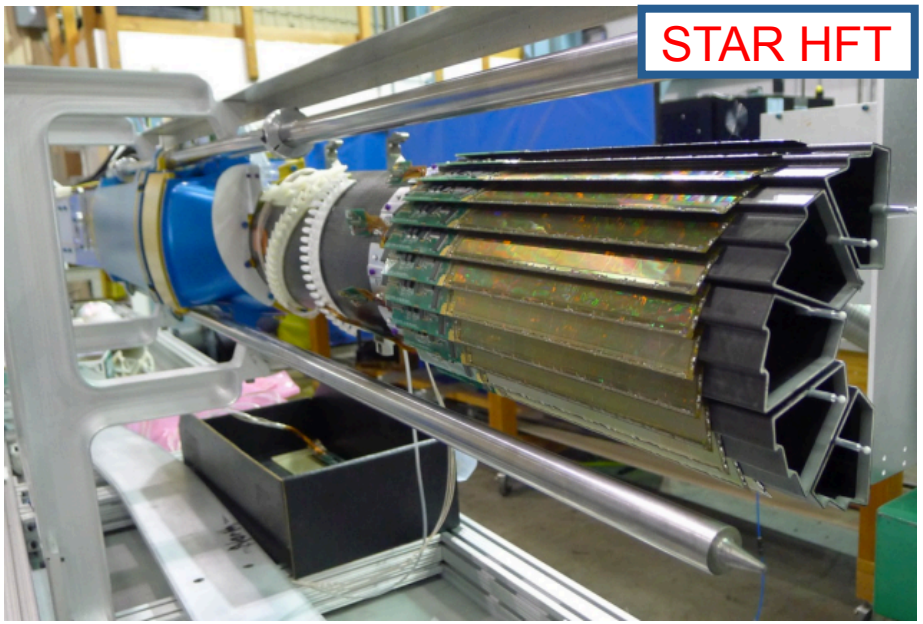
Thank you for your attention!

Backup slides

Cutting-edge technology for HF measurement

	ALICE	ATLAS	CMS	LHCb	PHENIX	**STAR**
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	$1\%X_0$	$\sim 1\%X_0$	$\sim 1\%X_0$	$\sim 1\%X_0$	$1\%X_0$	**$0.4\%X_0$**



- 2004 Starts R&D
- 2009.11 CDR
- 2011.6 TDR
- 2013.5 Engineering run with 3/10 sectors
- 2014.2 Commissioning and physics mode
- 2015 p+p and p+Au 200 GeV
- 2016 Au+Au and d+Au 200 GeV