Rencontres de Moriond QCD, March 23 – 30, 2019, La Thuile, Italy

Open Heavy Flavor from STAR

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University of Illinois at Chicago

Outline

- **Introduction**
- **Measurement results**
  - Parton energy loss - D^0 and B R_{AA}
  - Hadronization - D_s/D^0, Λ_c/D^0
  - Collectivity - D^0 v_n
- **Summary and outlook**

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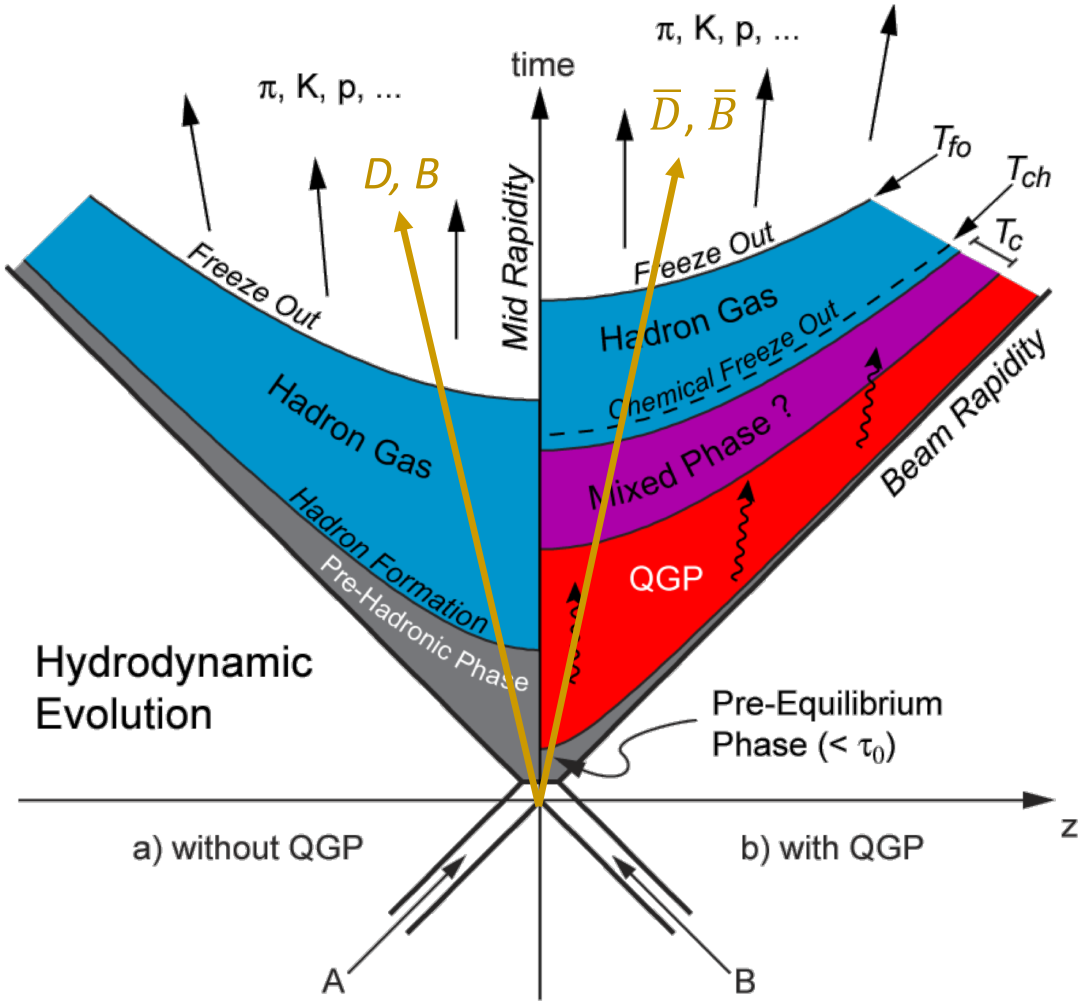
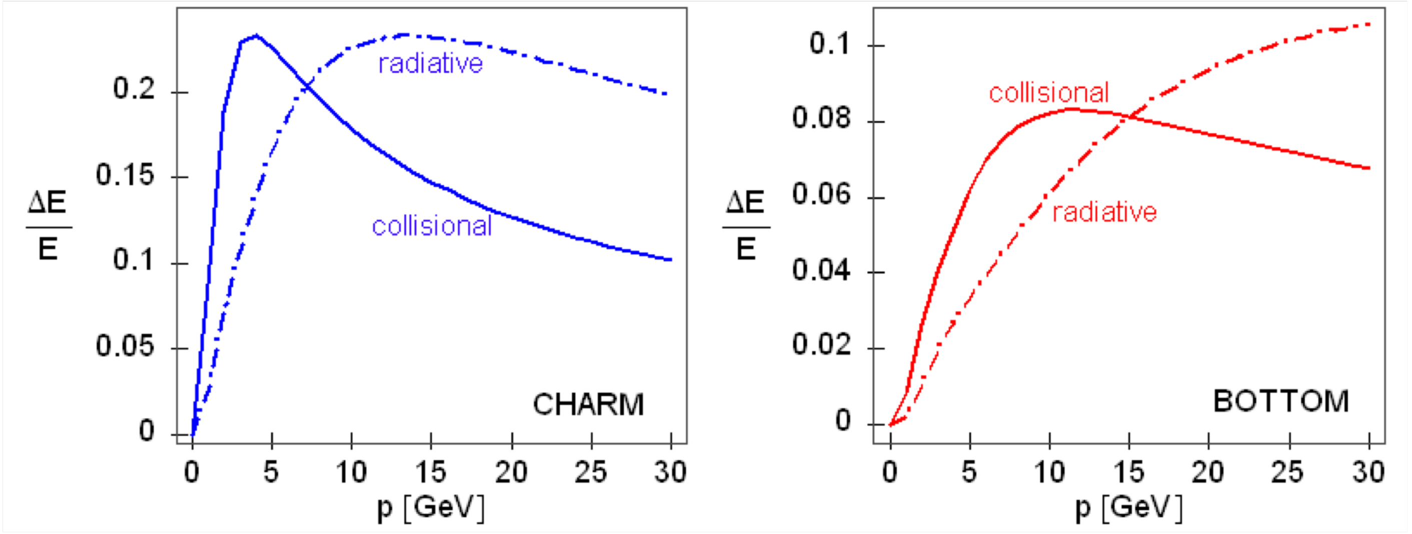
Why Studying Heavy Quarks in Heavy-Ion Collisions



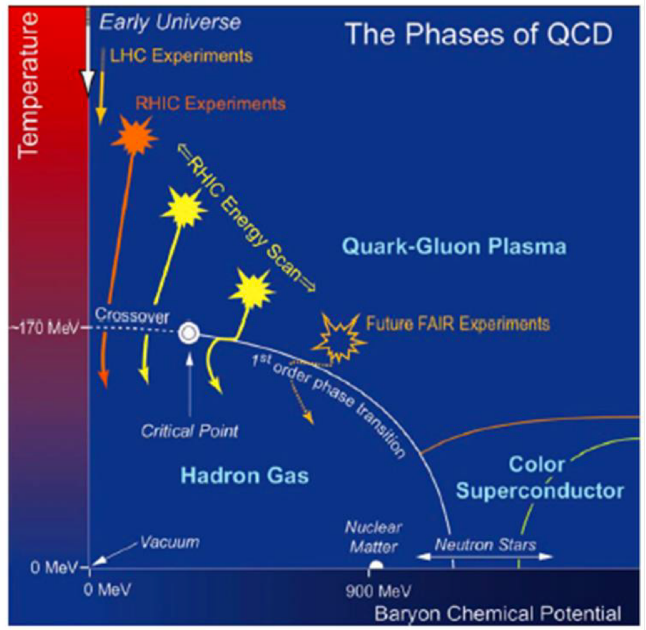
- Produced in the early stage in A+A collisions, experience the entire medium evolution
- A useful handle (m_b vs. m_c) to study parton-medium interaction: $\Delta E_b < \Delta E_c < \Delta E_q$
- Allow first principle QCD calculations
  - inputs to phenomenological models
  - comparison to models tuned to data

M. Djordjevic, PRC74 (2006) 064907

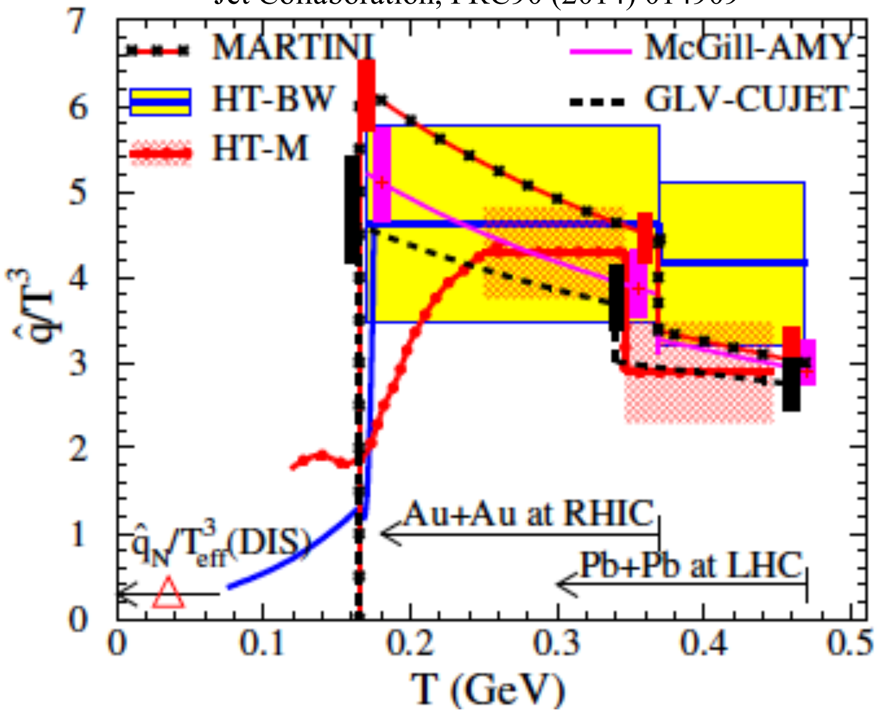


Relativistic Heavy Ion Collider

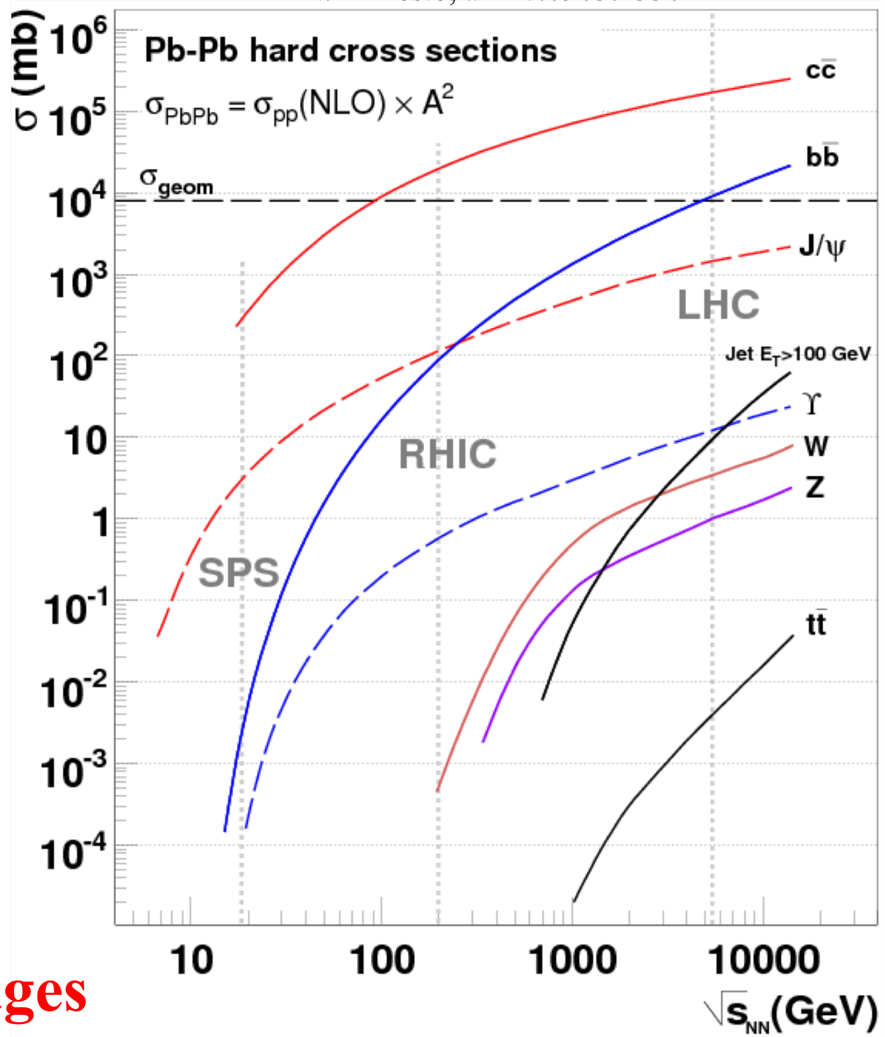
2007 NSAC Long Range Plan



Jet Collaboration, PRC90 (2014) 014909

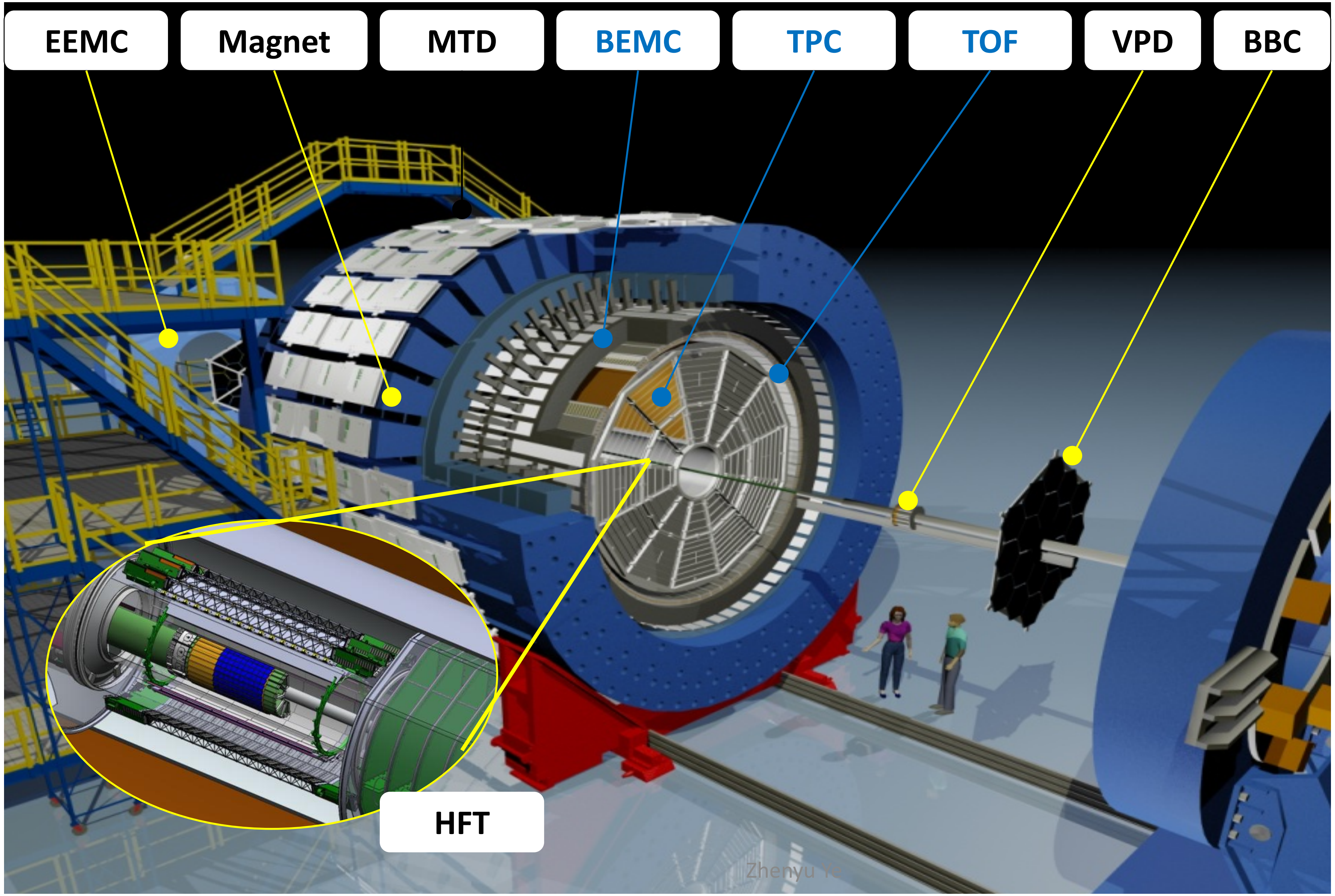


N. Armesto, arXiv:0903.1330



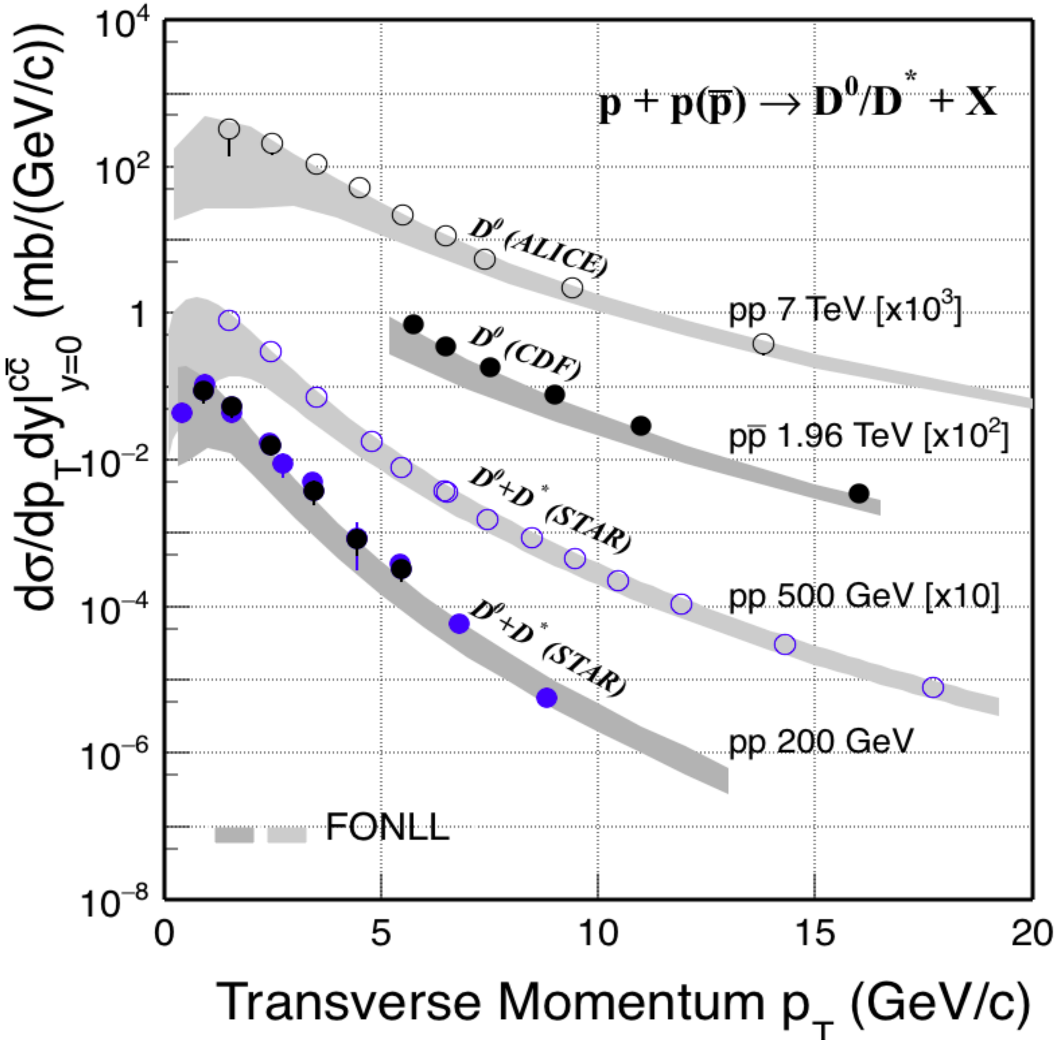
- **Measurements at RHIC and LHC are complementary**
  - temperature dependence of transport properties
  - different physics process contributions
- **Experimentally more challenging but also have advantages**
  - less gluon-splitting contribution
  - less combinatorial $Q\bar{Q}$ background for HF correlation studies

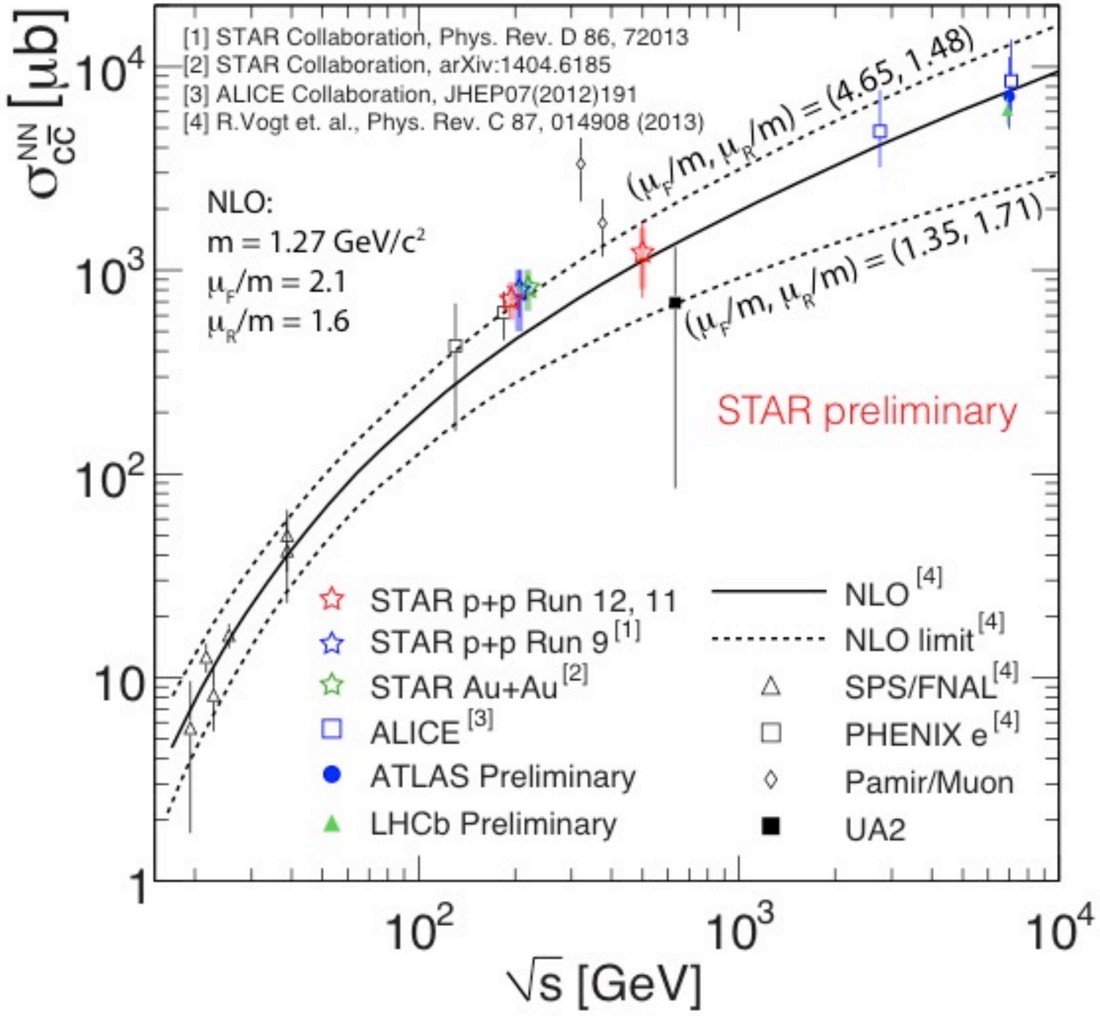
The STAR Experiment



- **Tracking and PID (full 2π)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5$
  ZDC: $6.3 < |\eta|$
- **On-going/future upgrades**
  EPD (2018): $2.1 < |\eta| < 5.1$
  iTPC (2019): $|\eta| < 1.5$
  eTOF (2019): $-1.6 < \eta < -1$
  FCS (2021+): $2.5 < \eta < 4$
  FTS (2021+): $2.5 < \eta < 4$

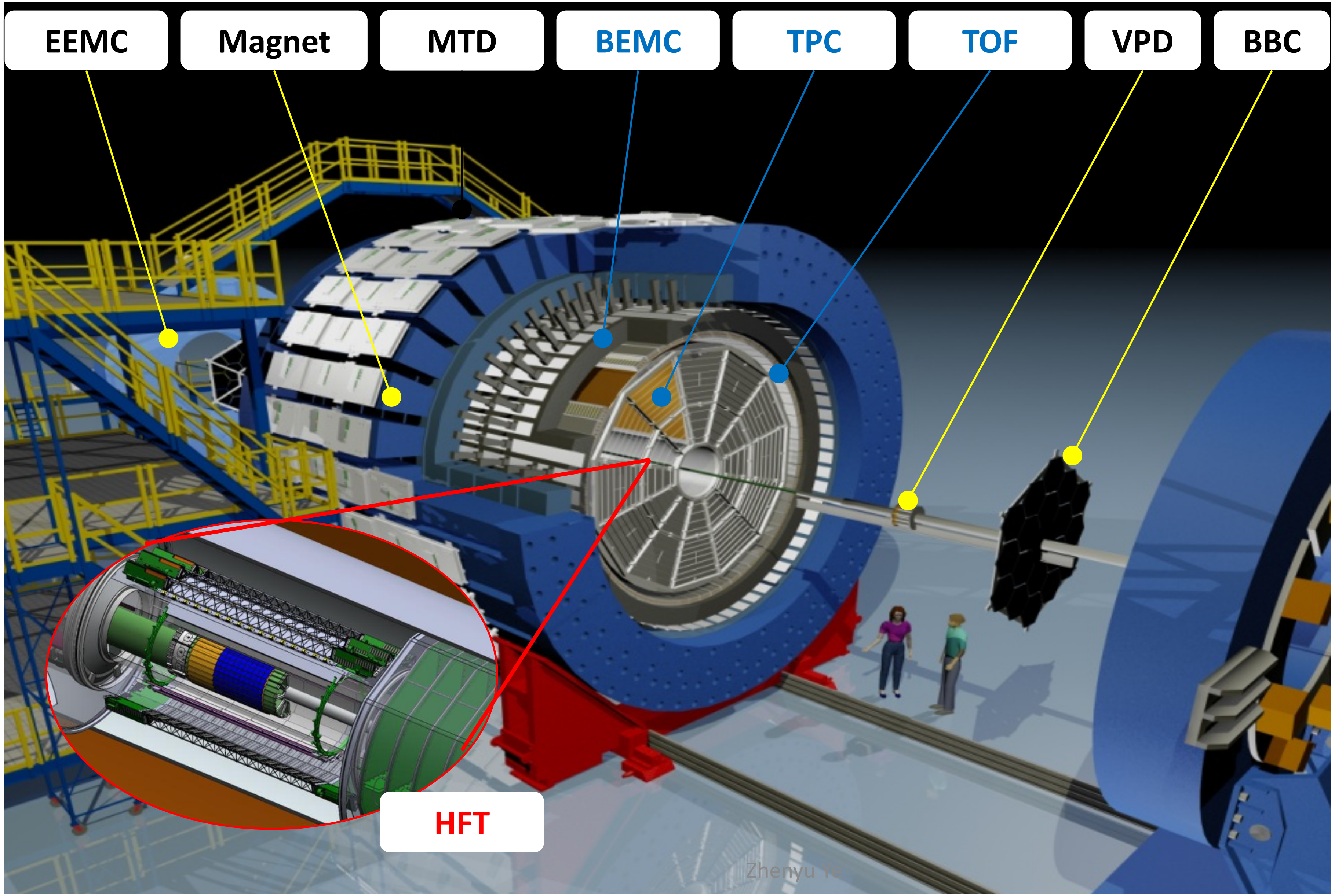
Open Charm Production in p+p Collisions





- Open charm (D^0, D*) in p+p are consistent with FONLL calculations within large theoretical uncertainties. Data are at upper boundary of FONLL calculations

The STAR Experiment



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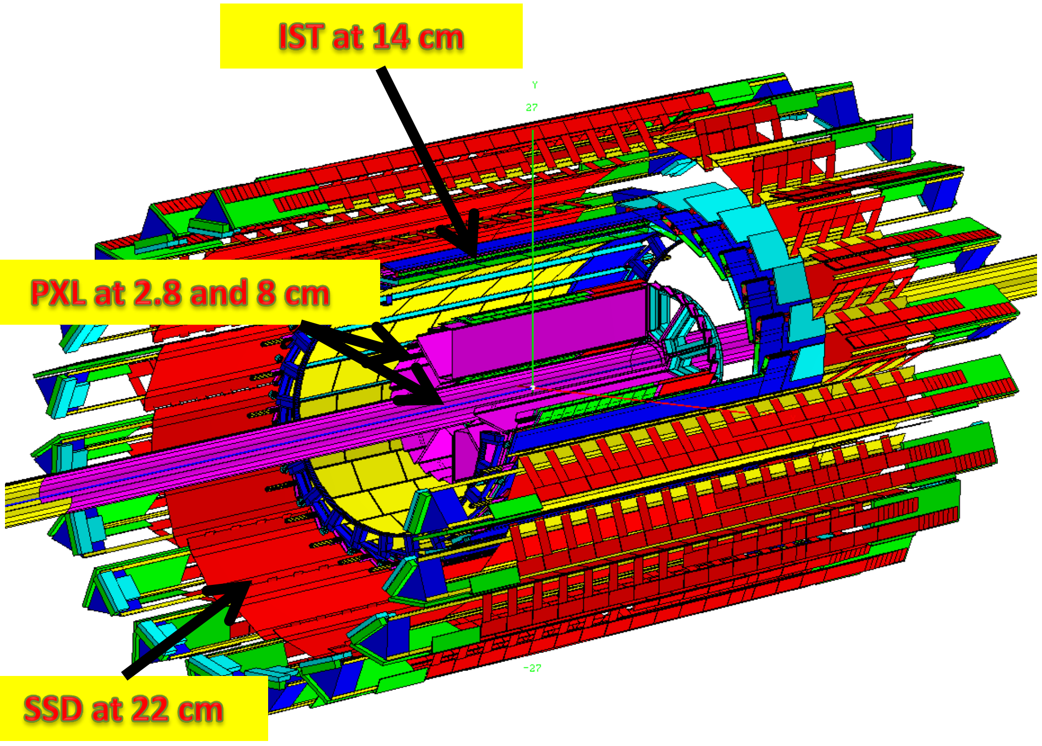
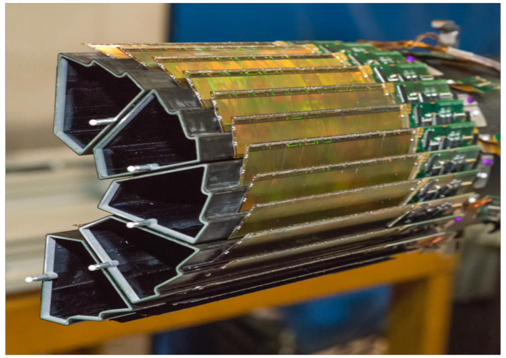
The STAR Heavy Flavor Tracker (2014-2016)

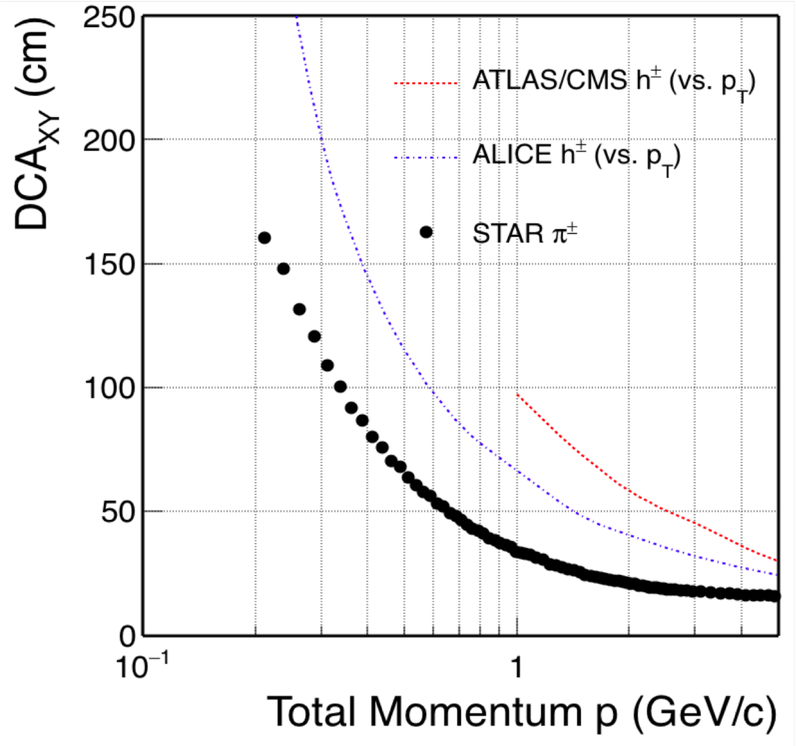


Silicon Strip Detector (SSD)
- one layer of double-sided silicon strip sensors

Intermediate Silicon Tracker (IST)
- one layer of single-sided double-metal silicon pad sensors

PiXeL detector (PXL)
- two layers of thin MAPS with ~360M 20x20 micron^2 pixels
- 1st application of MAPS technology in collider experiment





	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
pixel det. type	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	MAPS
pixel size (μm)	50x425	50x400	100x150	200x200	50x425	20x20
L1 radius (cm)	3.9	5.1	4.4	N/A	2.5	2.8
L1 thickness	1%X_0	1%X_0	1%X_0	1%X_0	1%X_0	0.4%X_0

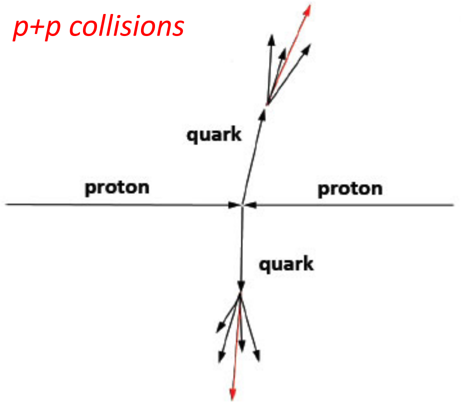
Experimental Observables

- Nuclear modification factors: R_{AA}

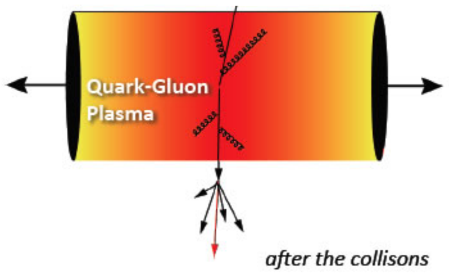
$$R_{AA} = \frac{dN_{AA}/dy}{N_{binary} \cdot dN_{pp}/dy} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

p+p collisions



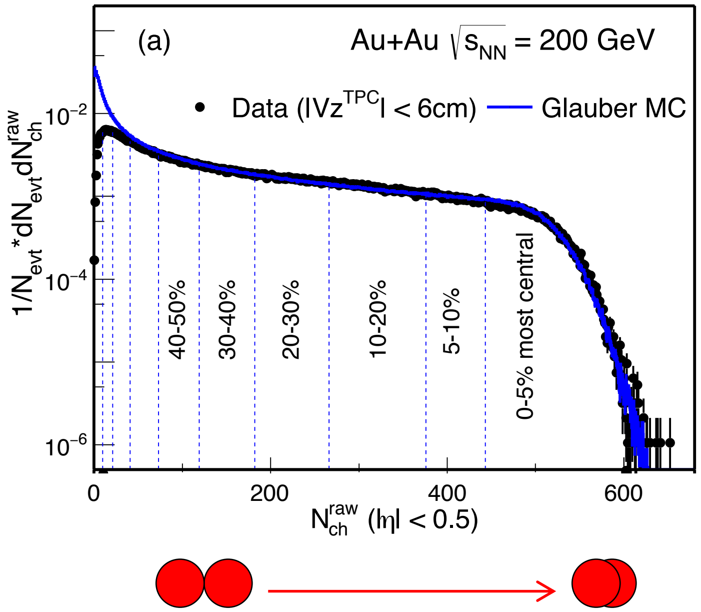
Au+Au collisions



p+Au collisions

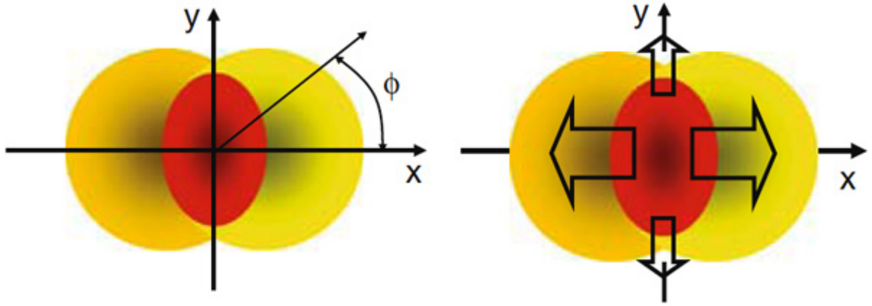
Cold Nuclear Matter effects: nuclear PDF …

STAR, arXiv:1812.10224

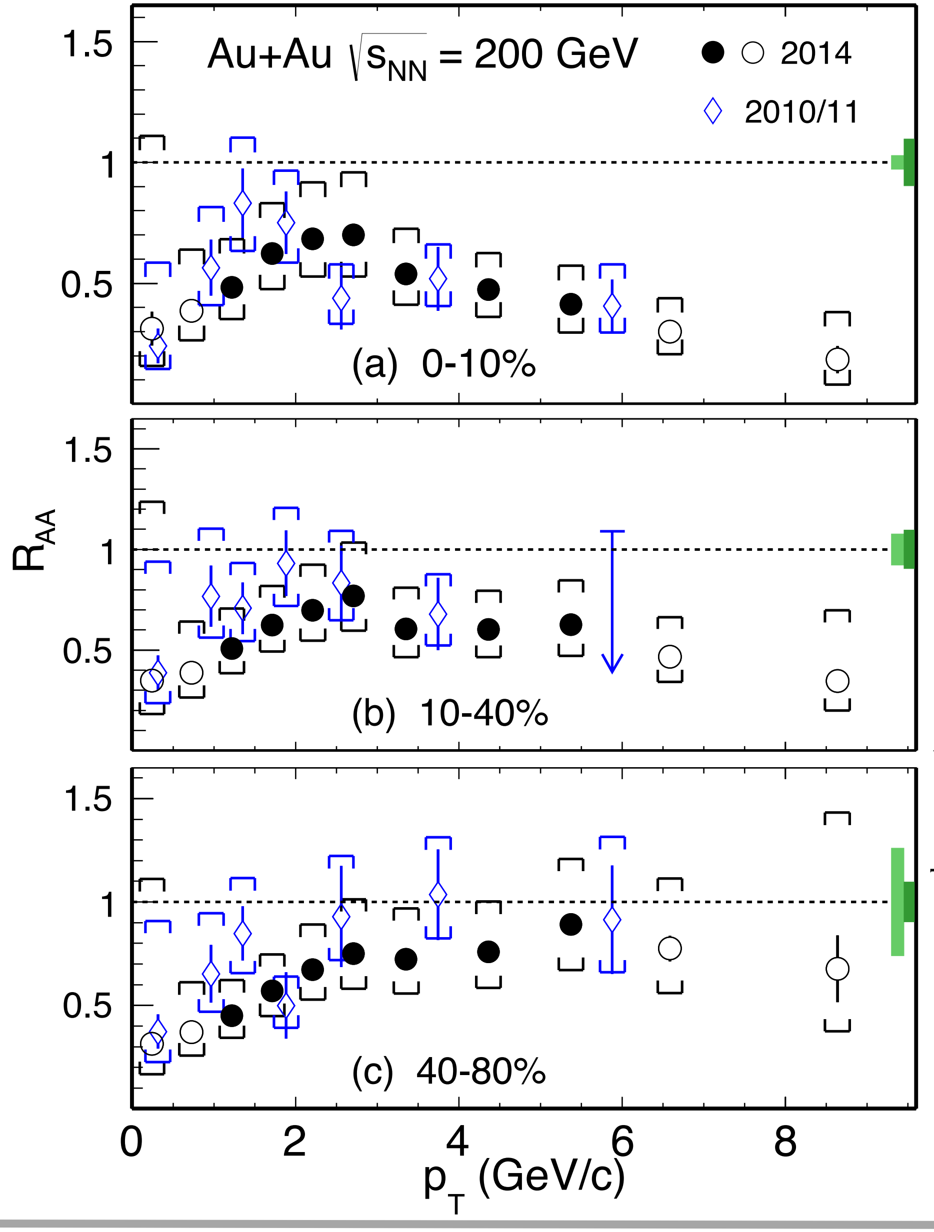


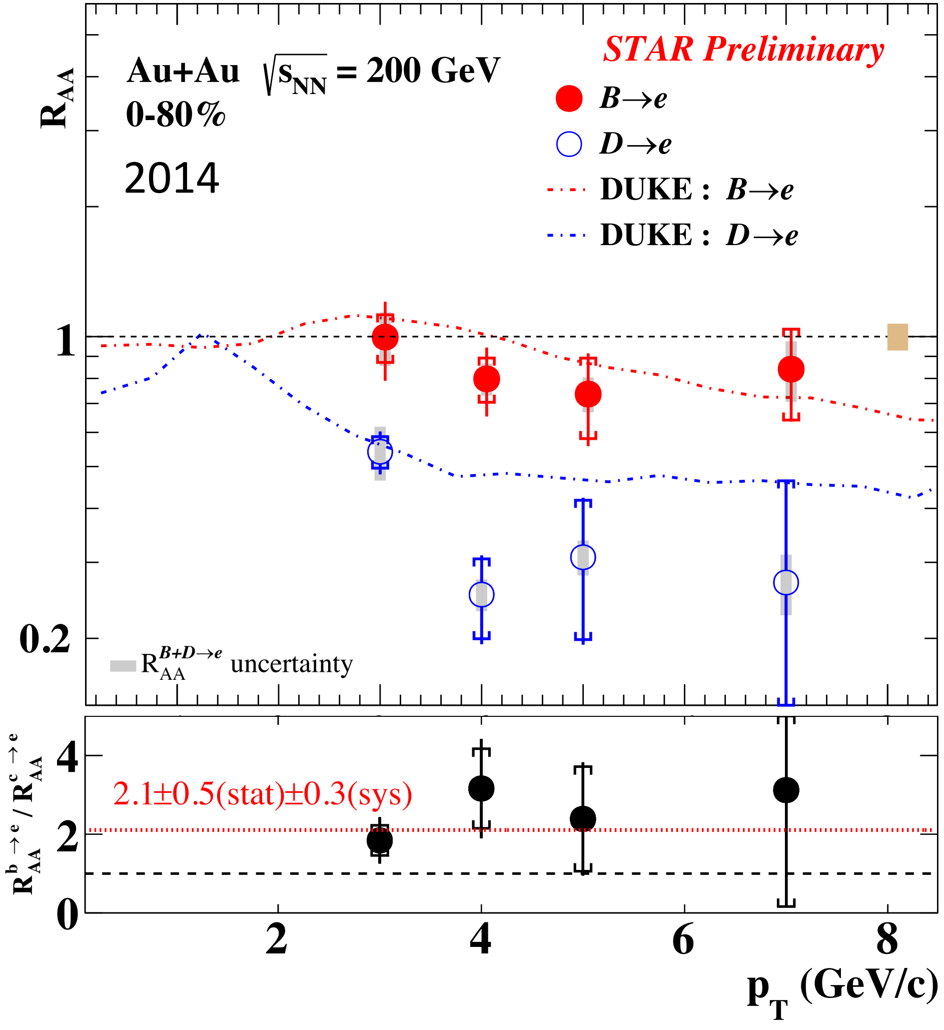
- Azimuthal anisotropy: v_n

$$\frac{dN}{d\phi} = N_0\left[1 + \sum_n 2v_n \cos n\phi\right]$$



Open Charm and Bottom Production in Au+Au Collisions





STAR D^0: PRC 99 (2019) 034908

Duke: Y. Xu, et al. PRC 97 (2018) 014907

D^0 R_{AA}

- suppression at high p_T increases towards more central collisions:

significant ΔE_c in QGP

- suppression at low p_T w/o strong dependence on collision centrality:

cold nuclear matter effects?

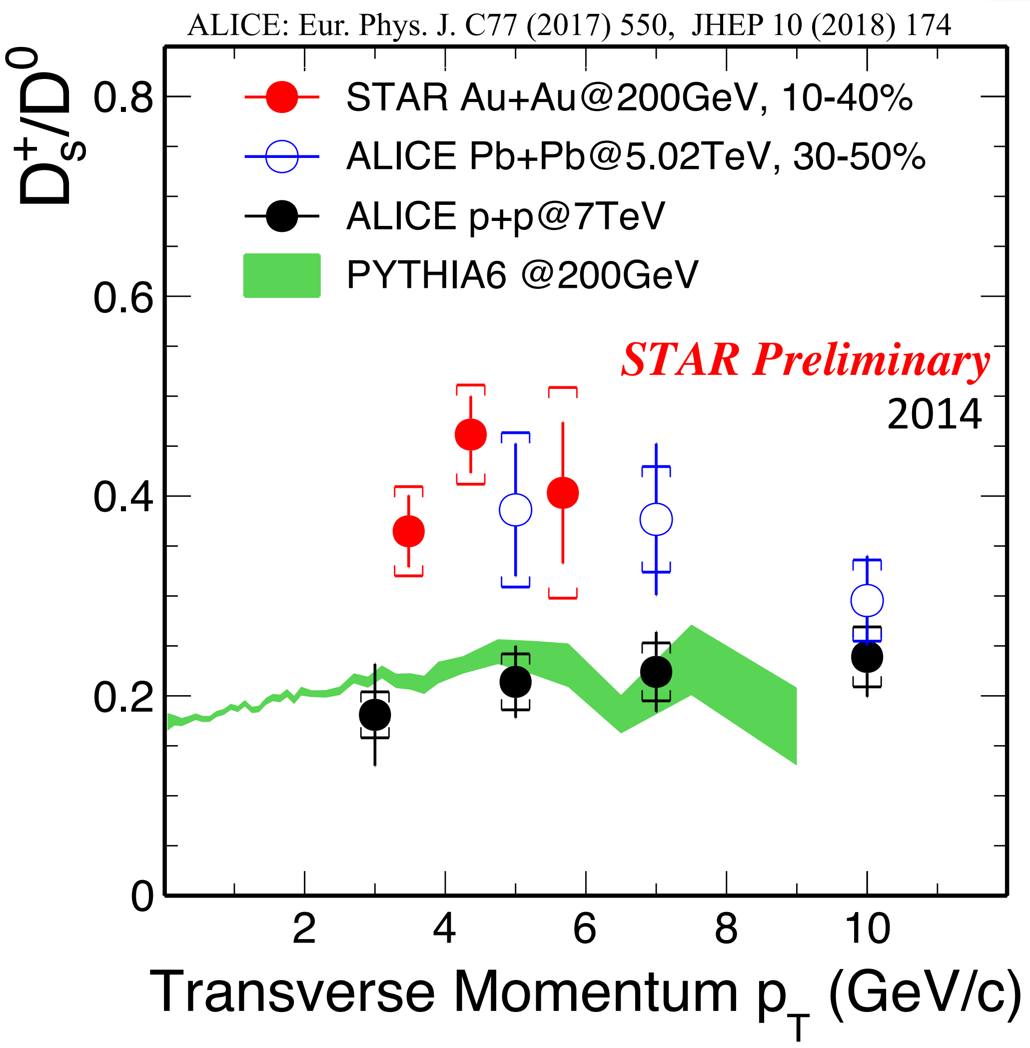
- less than unity for all p_T in 0-10% central collisions

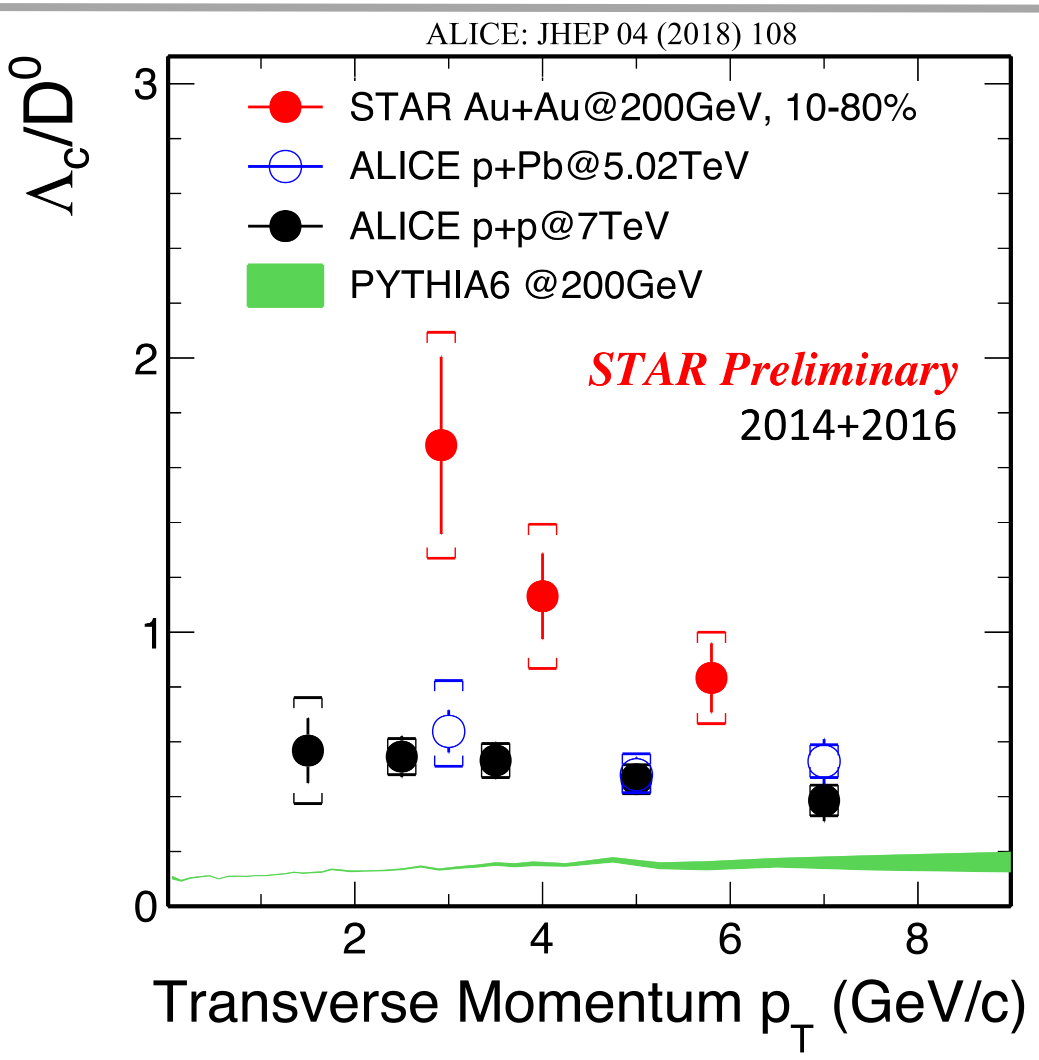
D^0 yield not scale with N_{bin}

B(->e) R_{AA}

- e^B R_{AA} > e^D R_{AA} consistent with expectation **$\Delta E_b < \Delta E_c$**

Charm Quark Hadronization in Au+Au Collisions





- D_s/D^0 and Λ_c/D^0 in Au+Au are significantly higher than p+p collisions:

charm quark hadronization through coalescence with light flavor quarks

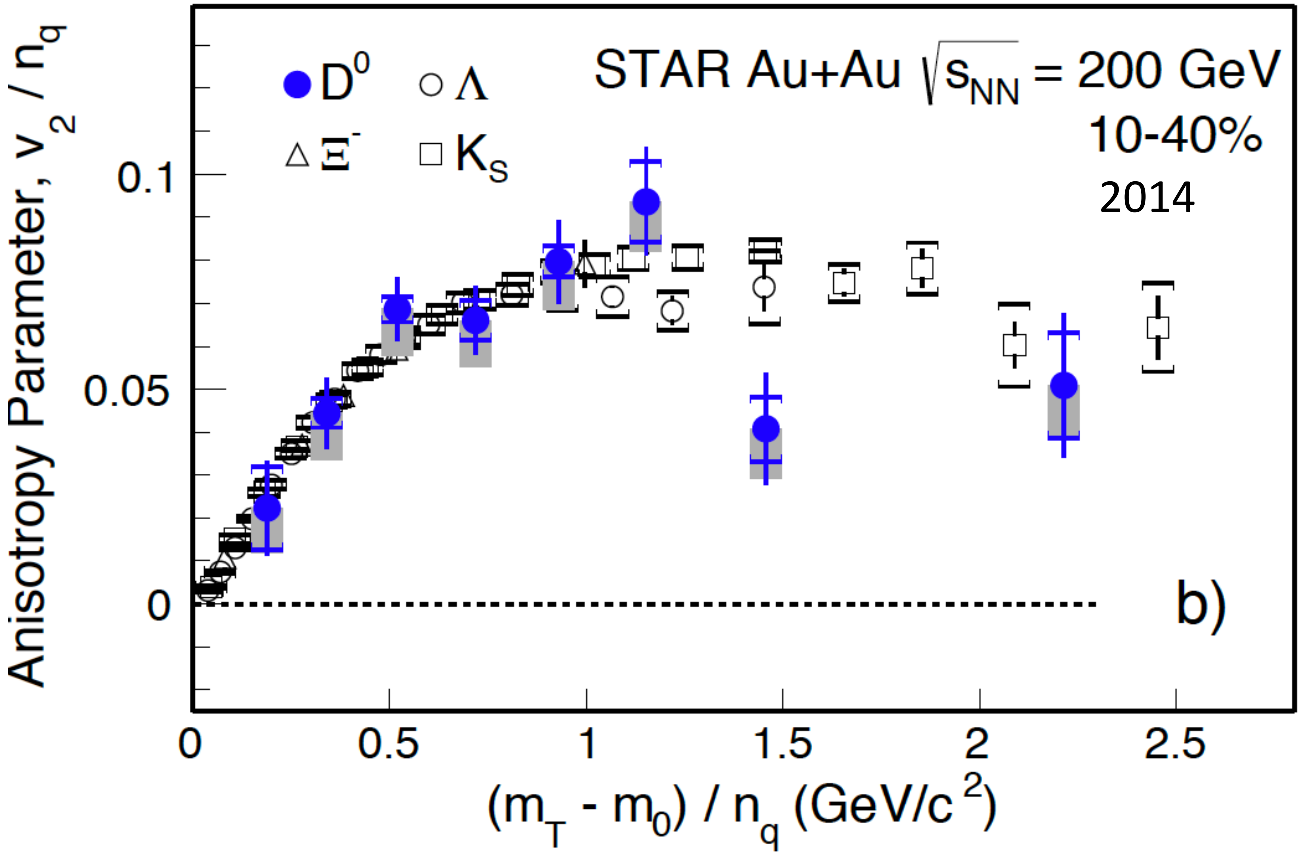
Total Charm Production Cross Section in Au+Au Collisions

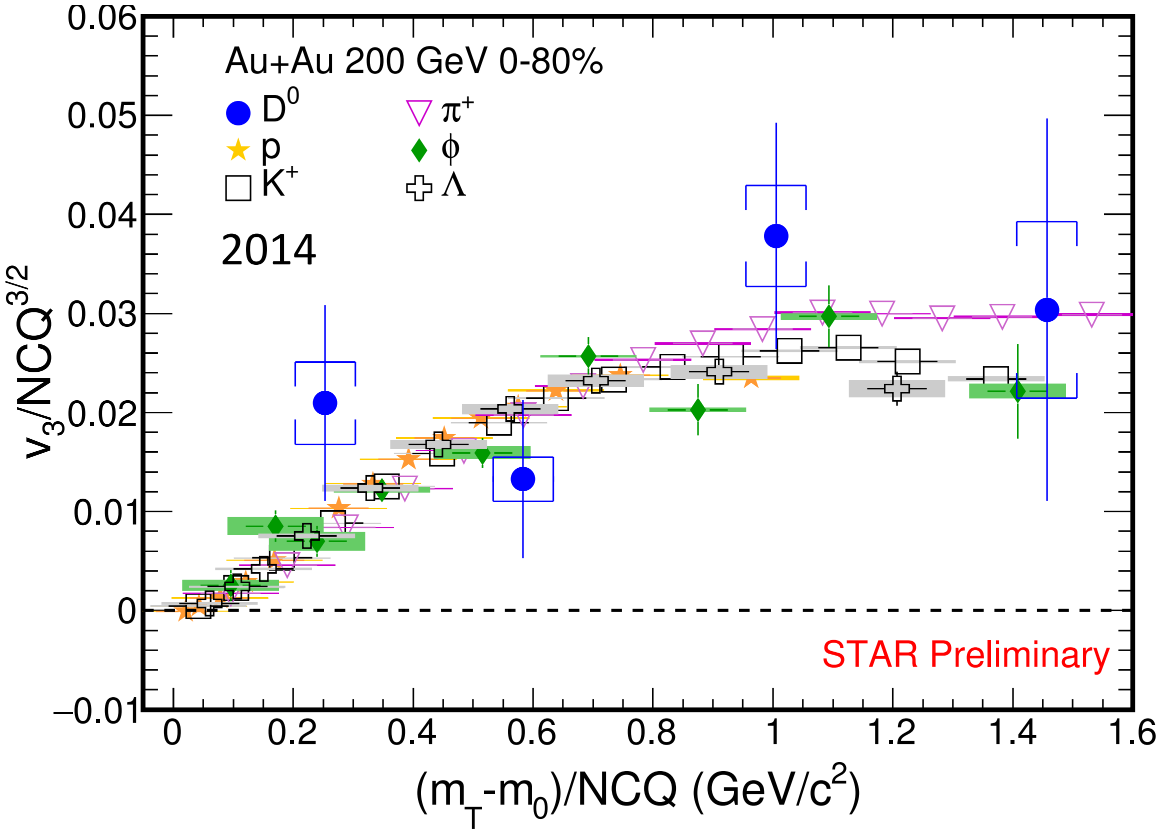
Charm Hadron		Cross Section dσ/dy (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

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

- Charm quark production cross-section per binary collision in Au+Au consistent with p+p
- Charm quark distribution among hadron species different between Au+Au and p+p

Charm Quark Collectivity in Au+Au Collisions – v_2 and v_3



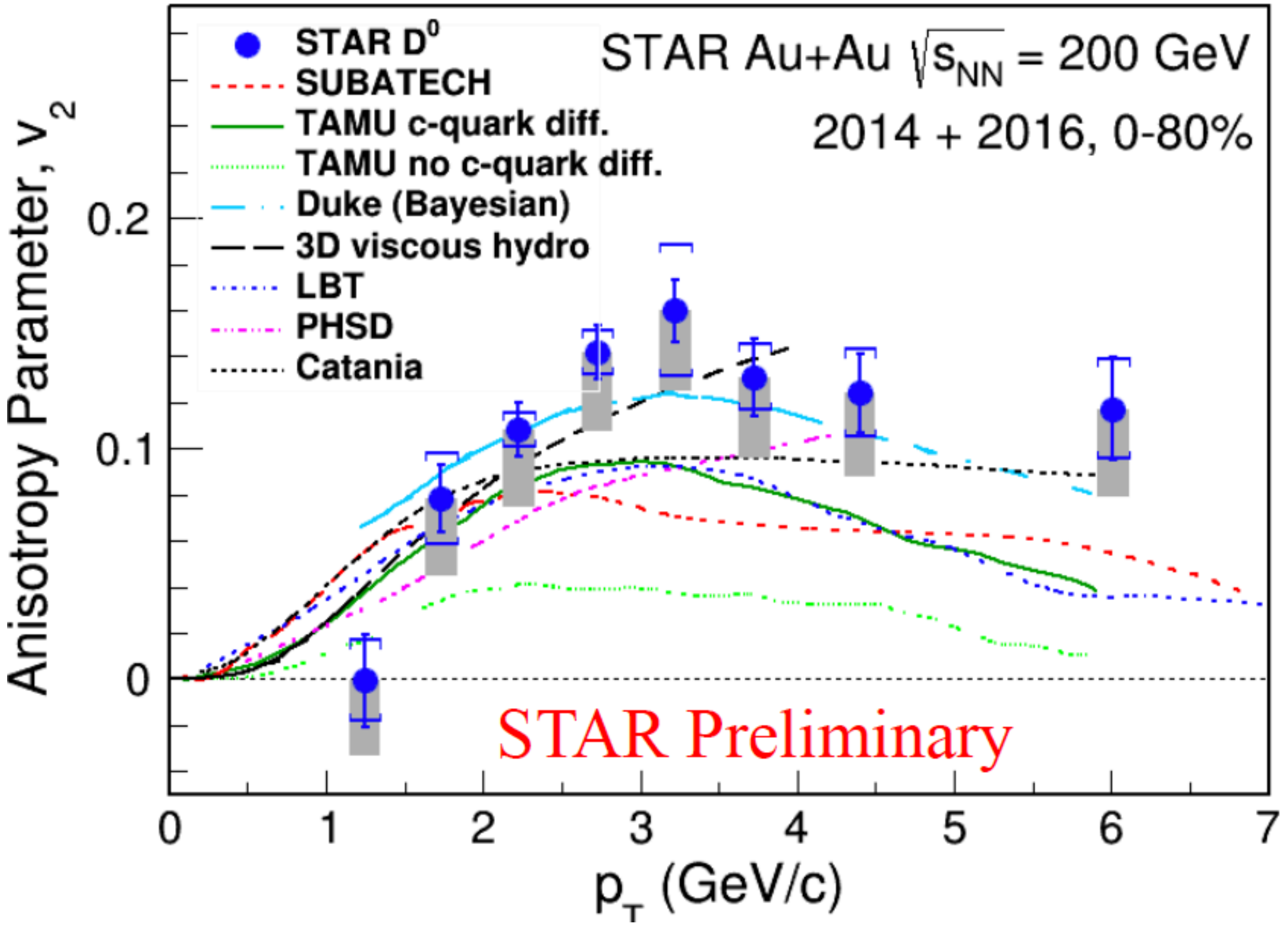


D^0 v_2: STAR, PRL 118 (2017) 212301

Λ, Ξ^-, K_s: STAR, PRC 77 (2008) 054901

- Significant D^0 meson v_2 and v_3
- D^0 meson v_2 and v_3 follow $(m_T - m_0)$ NCQ scaling as light flavor hadrons

Charm Quark Collectivity in Au+Au Collisions – v_2 and v_3

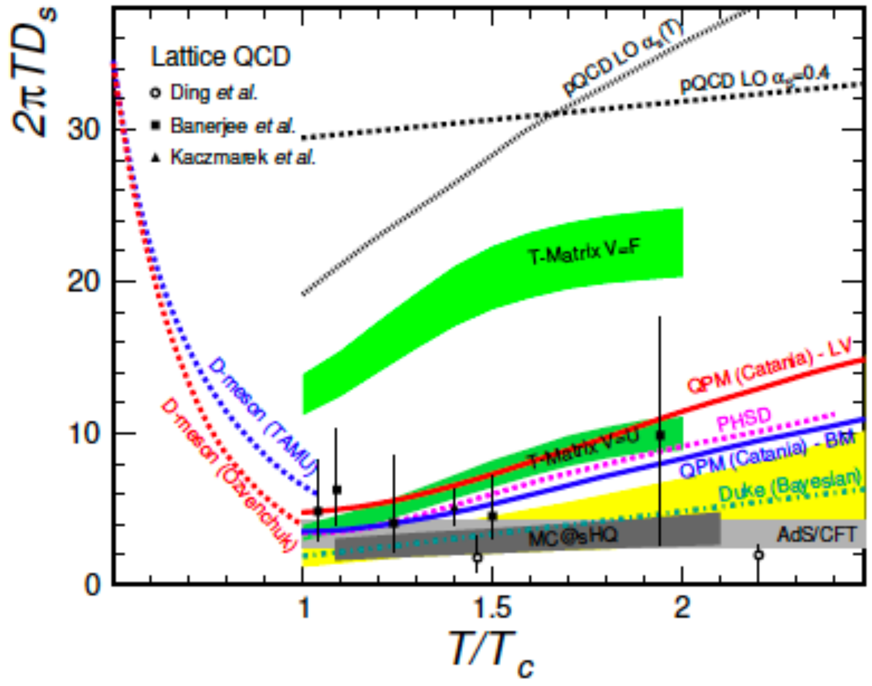


Compared Models	x2/NDF	p-value
SUBATECH [1]	17.3/8	0.026
TAMU c quark diff. [2]	12.0/8	0.15
TAMU no c quark diff. [2]	33.7/8	4.5×10^{-5}
Duke (Bayesian) [3]	8.5/8	0.39
3D viscous hydro [4]	3.7/6	0.71
LBT [5]	13.3/8	0.10
PHSD [6]	8.7/7	0.27
Catania [7]	9.7/8	0.29

- Provide strong constraint on model calculations
- Charm quarks gain collectivity, and may have reached a local equilibrium with the medium

Summary and Outlook

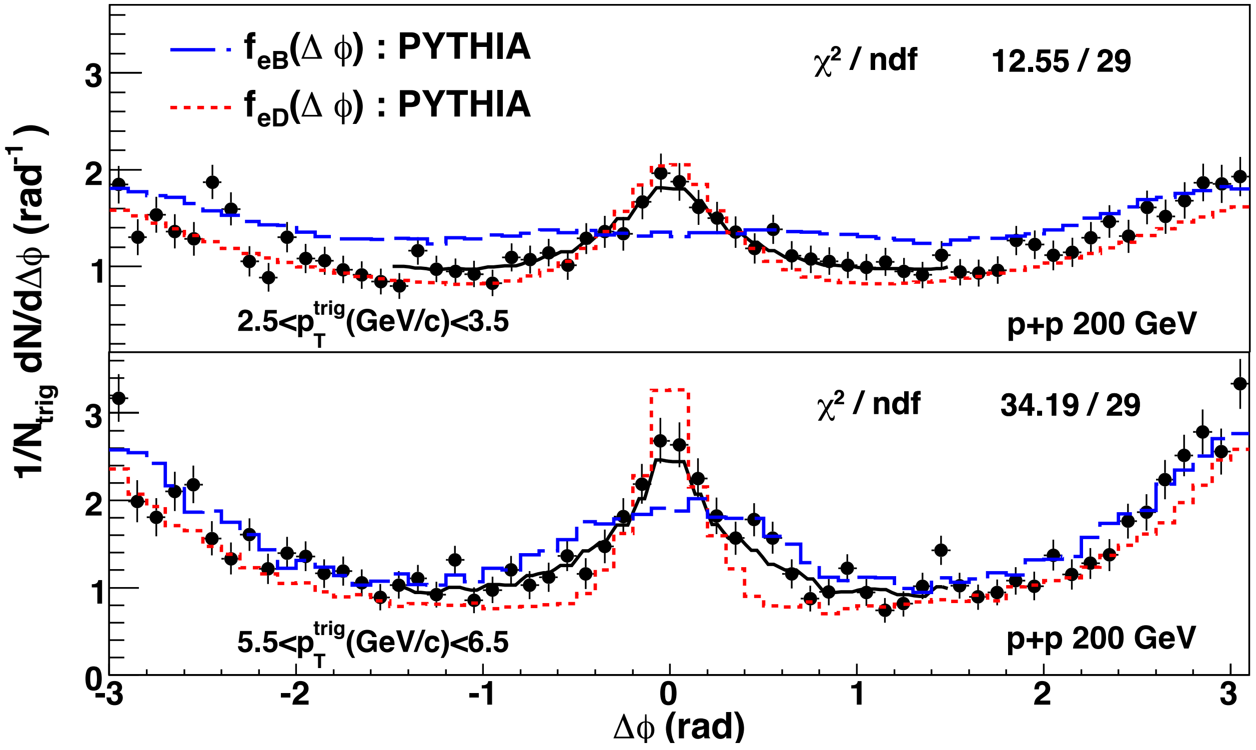
- **Extensive studies of open charm production with the Heavy Flavor Tracker at STAR**
  - charm quark energy loss: D^0 R_{AA}
  - charm quark collectivity: D^0 v_n
  - charm quark hadronization: D_s/D^0, Λ_c/D^0
  - not covered: D^+ R_{AA}, D_s v_2, D^*/D^0, $\overline{D^0}/D^0$, e^{HF} R_{AA} and v_2, D-h correlations
- **First look into open bottom production**
  - mass hierarchy of energy loss $\Delta E_b < \Delta E_c$: e^B R_{AA} > e^D R_{AA}
  - not covered: non-prompt J/psi and non-prompt D^0 R_{AA}

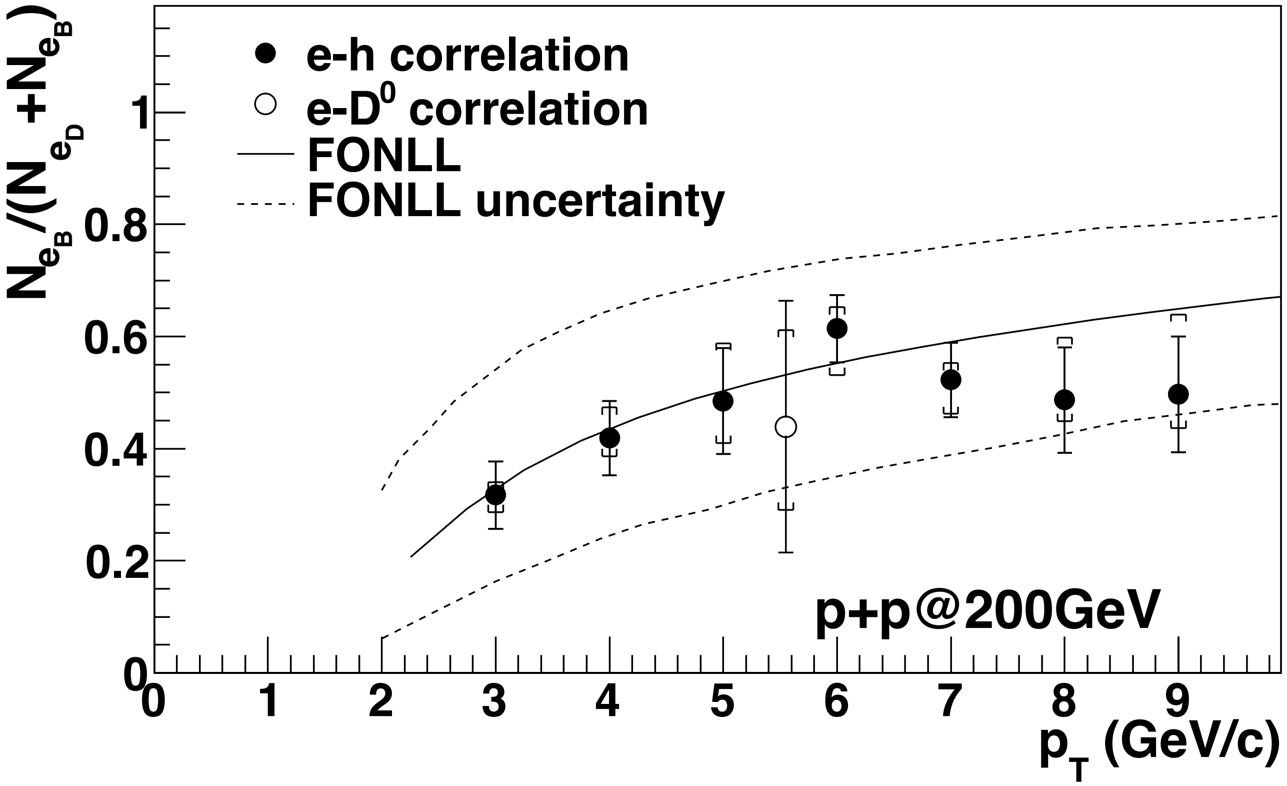


- **Ongoing data analyses for**
  - 2015 p+p: improved p+p reference
  - 2015 p+Au, 2016 d+Au: Cold Nuclear Matter effects
  - 2016 Au+Au : improved B->e

  Stay tuned!

Open Bottom Production in p+p Collisions



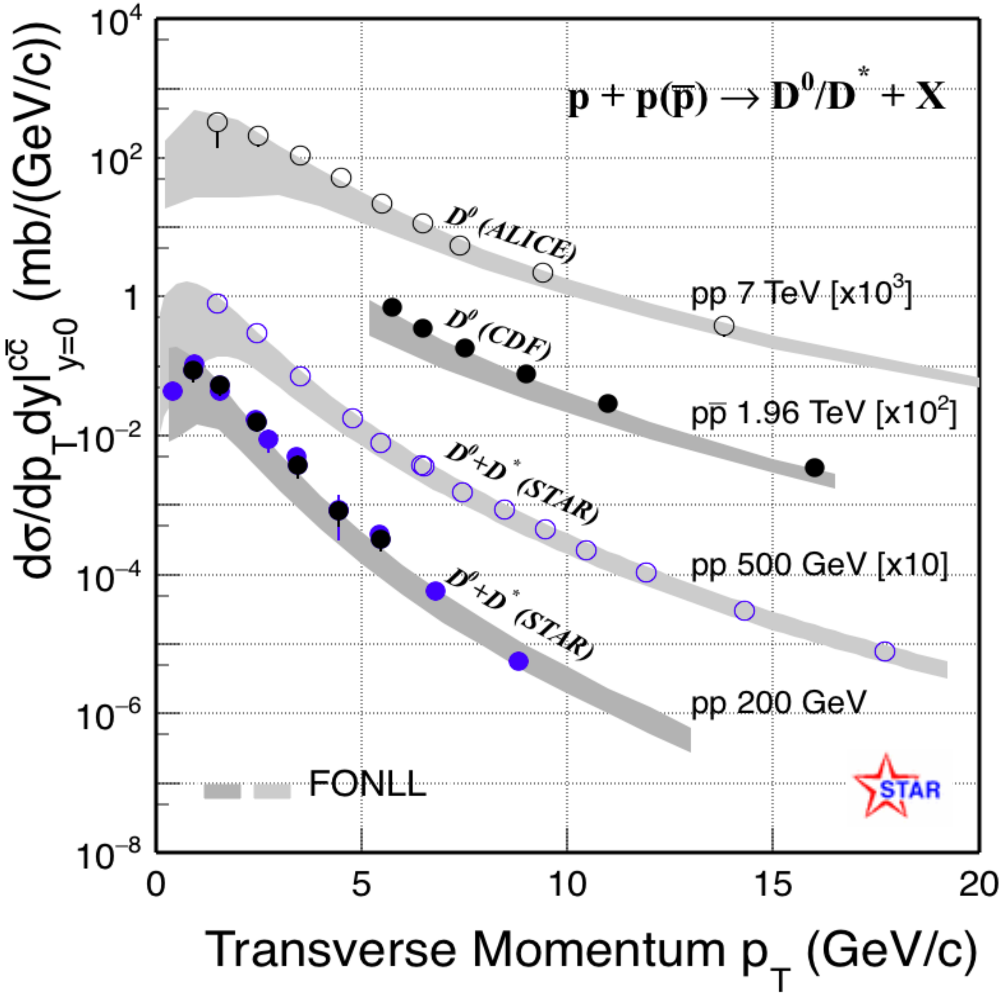


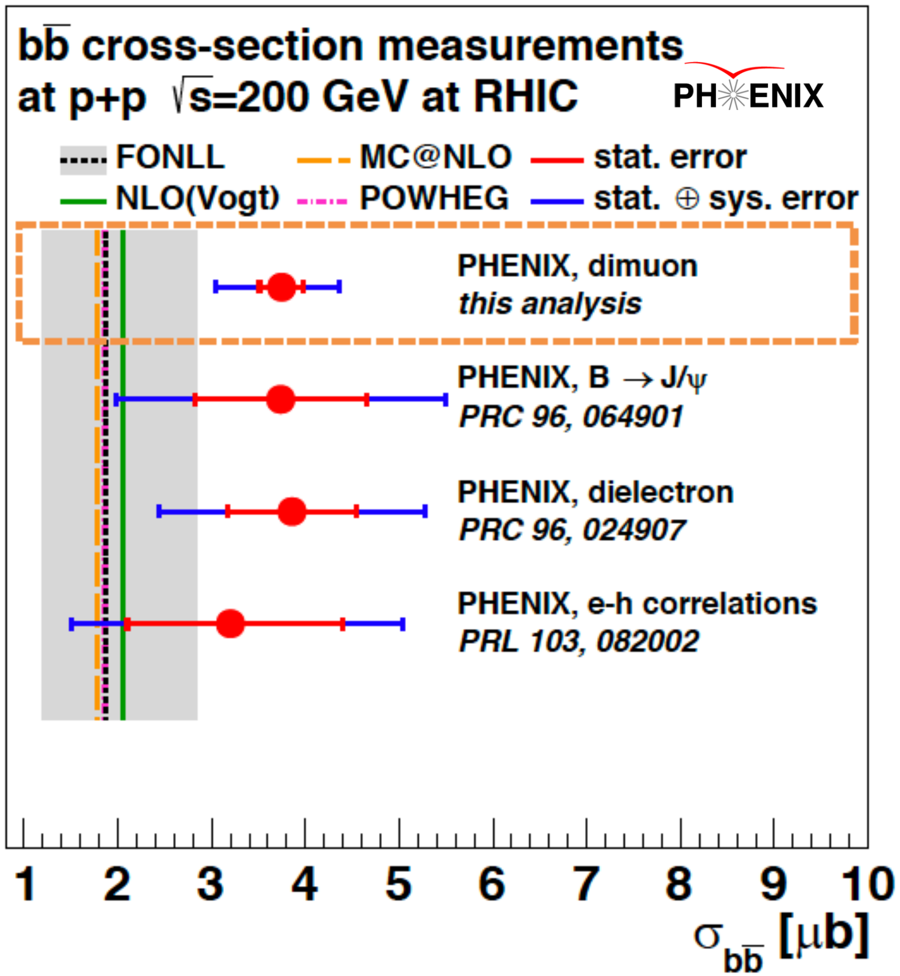
STAR, PRL 105 (2010) 202301

FONLL: M. Cacciari, et al. PRL 95 (2005) 122001

- Fraction of B-decayed electrons described by FONLL calculations within large theoretical uncertainties. Data are close to the center of FONLL calculations

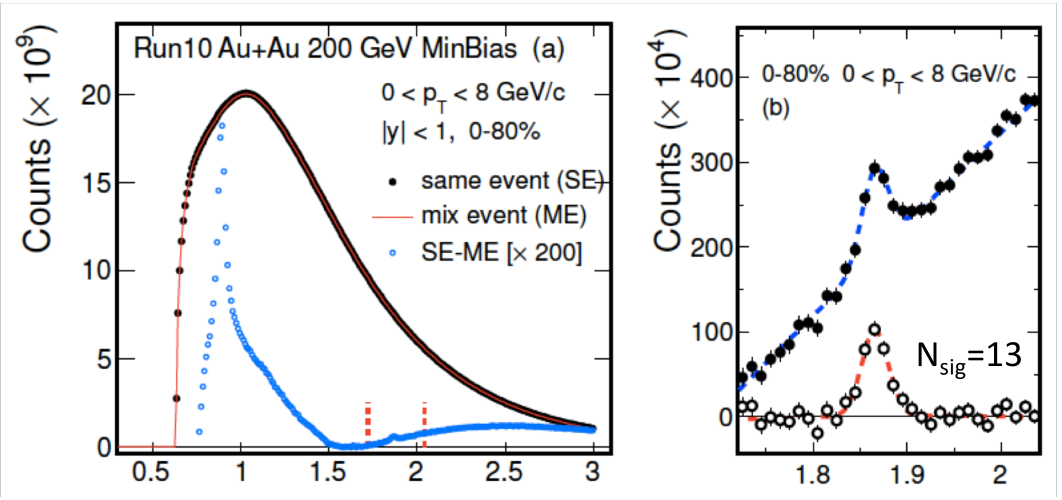
Open Heavy Flavor Production in p+p Collisions

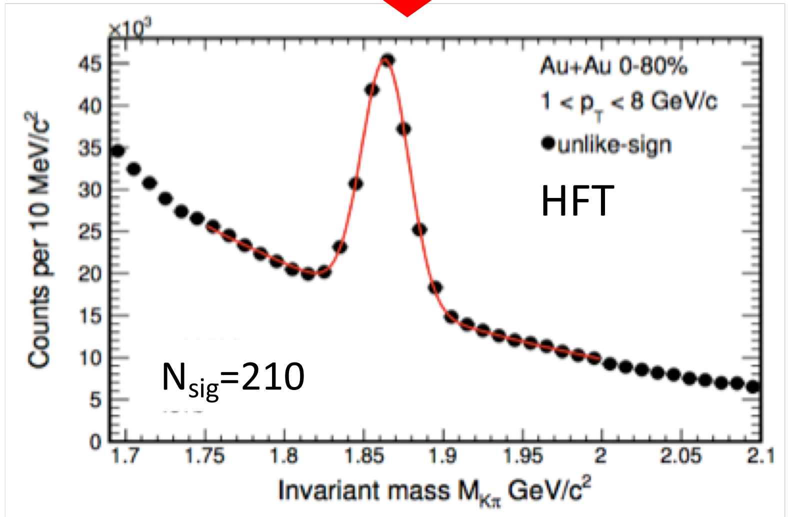


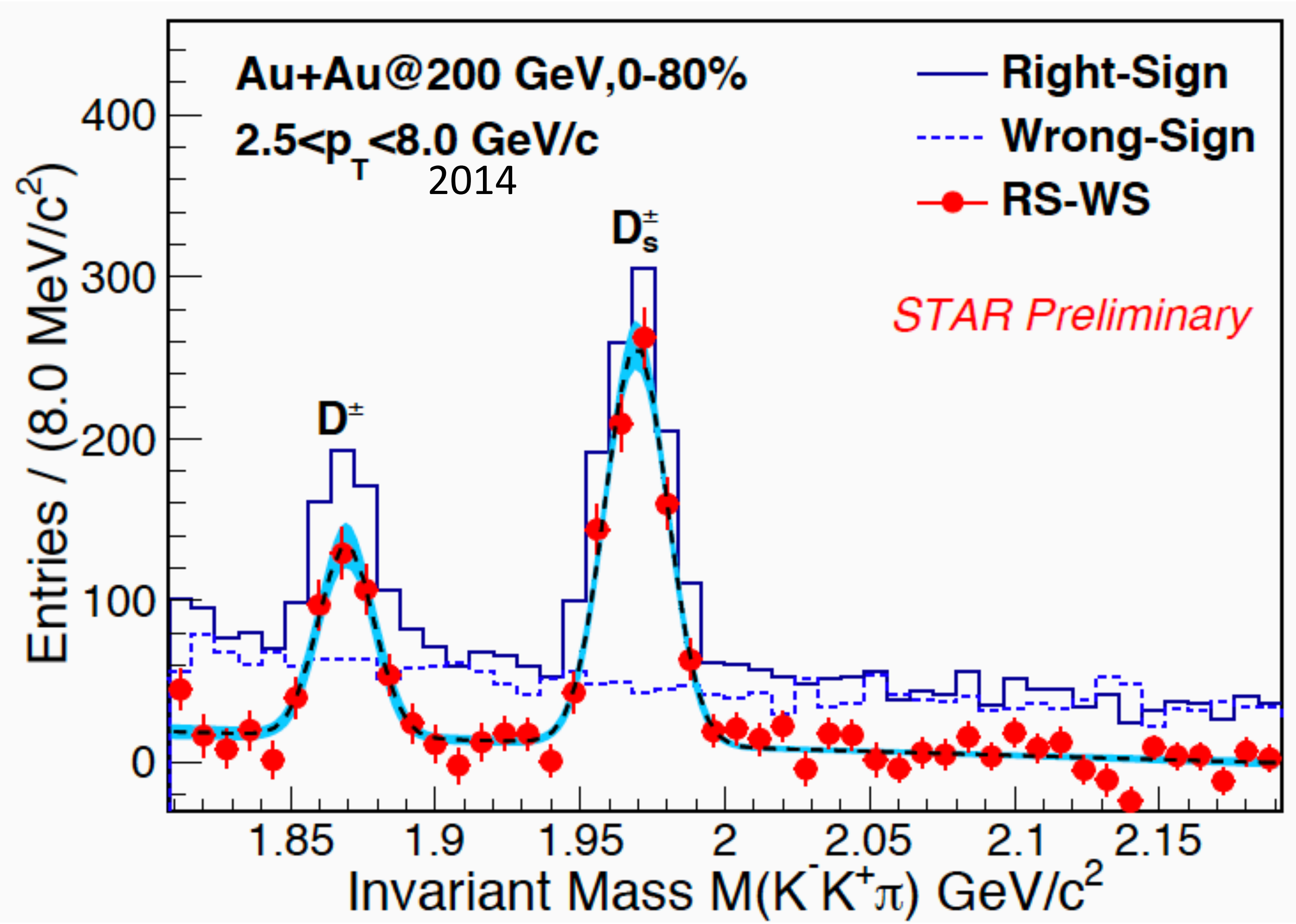


- Open charm (D^0, D*) and bottom (B-decayed e/μ, J/ψ) measured at RHIC
- Data described by pQCD within large theoretical uncertainty

Open Charm Signals in Au+Au Collisions







- HFT significantly improves D^0 S/N, and enables the first $D^{*\pm}$, $D^{\pm}$, D_s, Λ_c studies at RHIC

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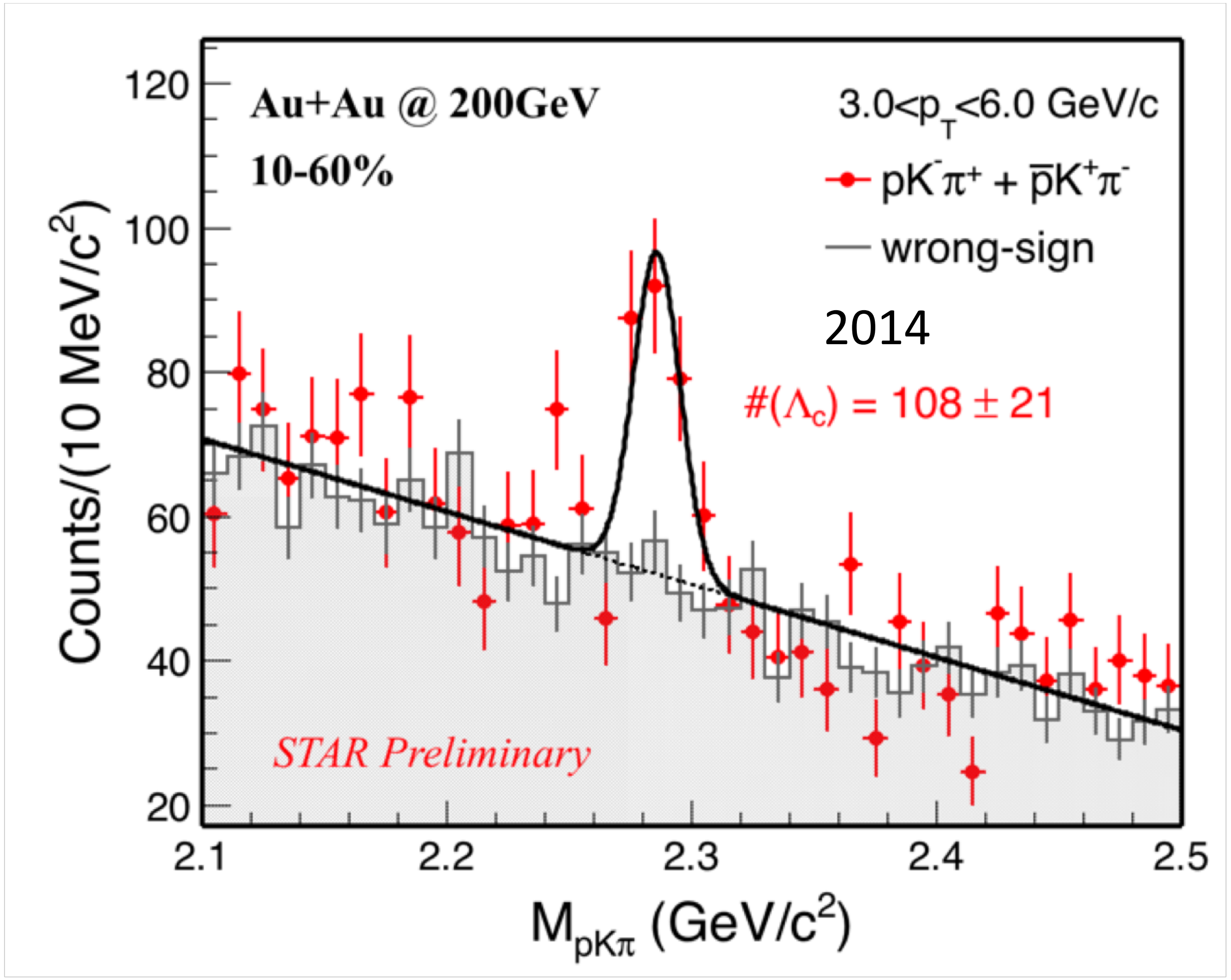

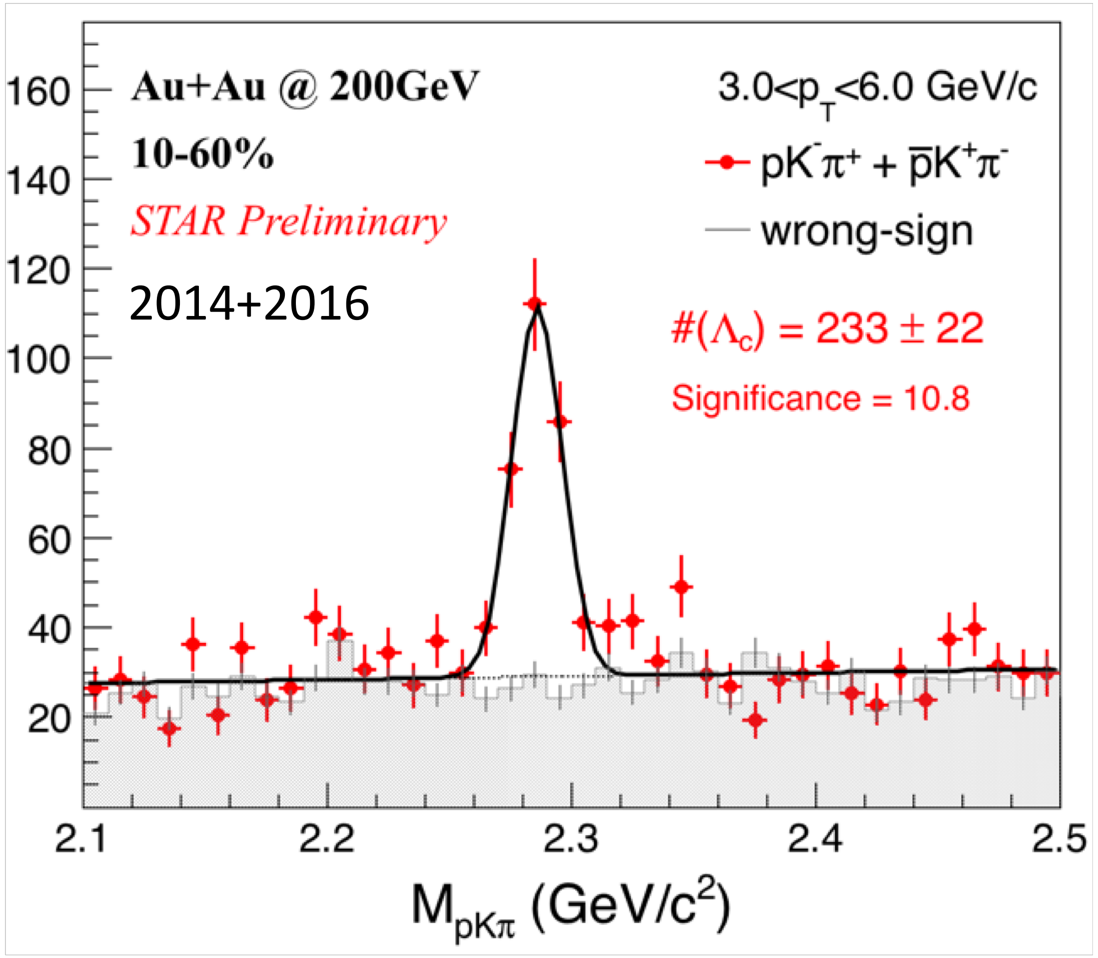

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- Further improvement from multivariant data analysis technique

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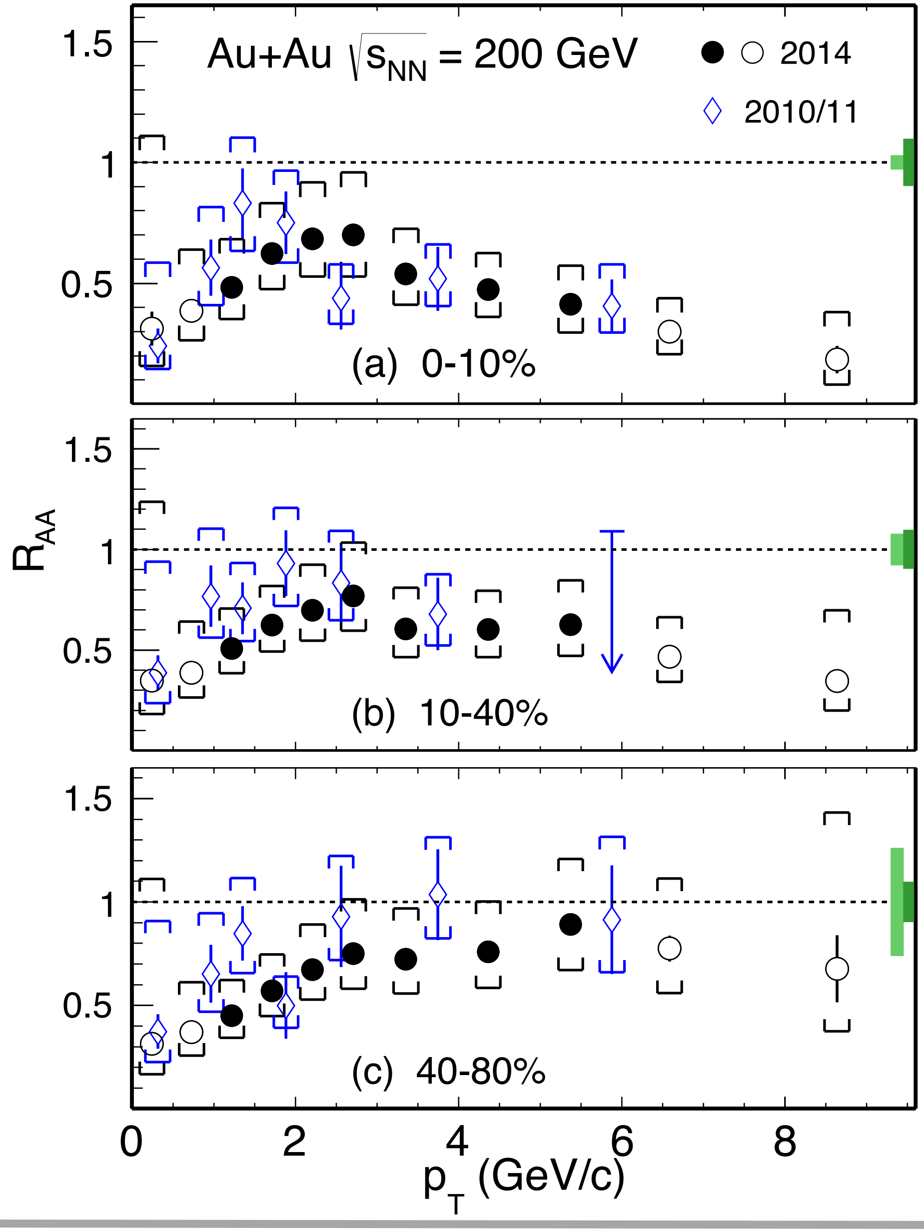
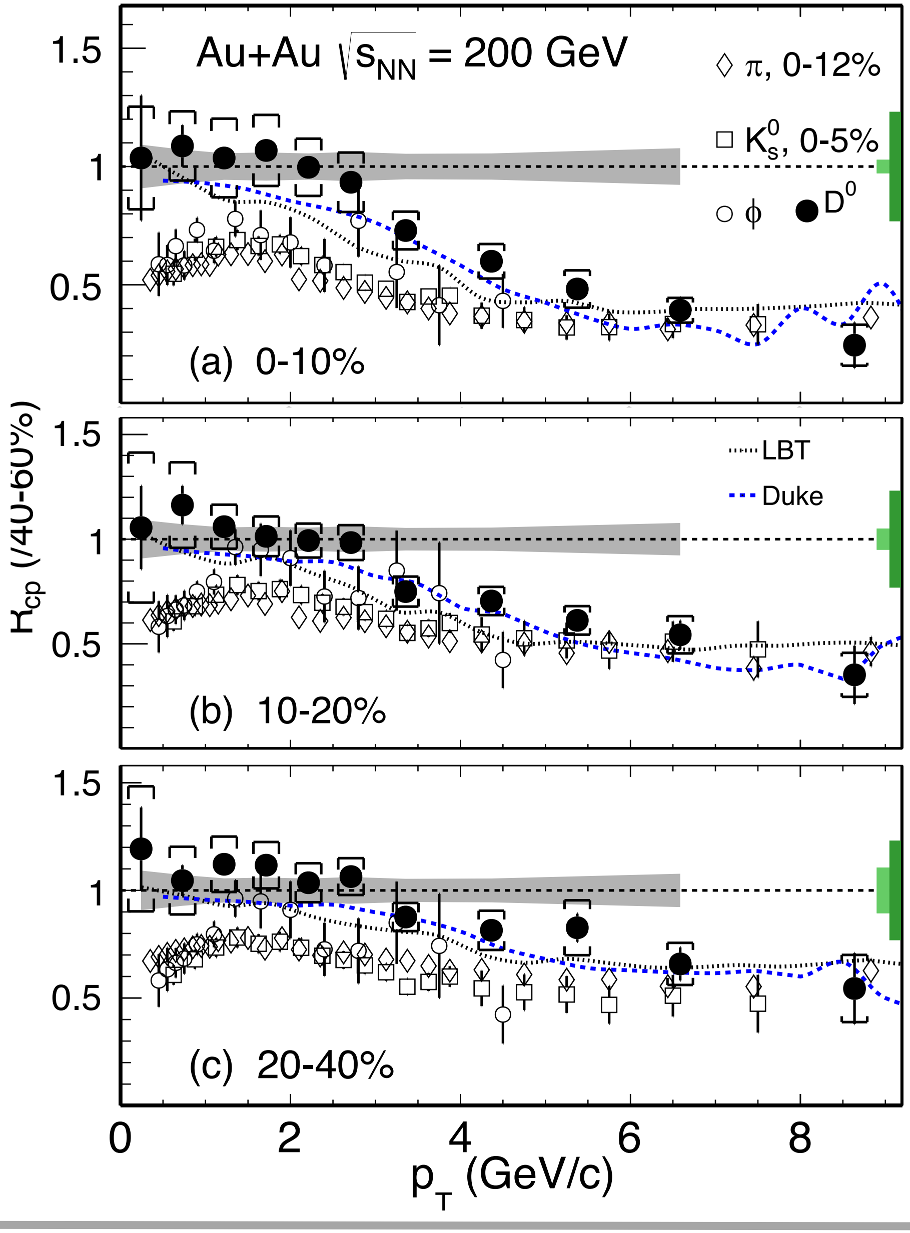




D^0 R_{AA}

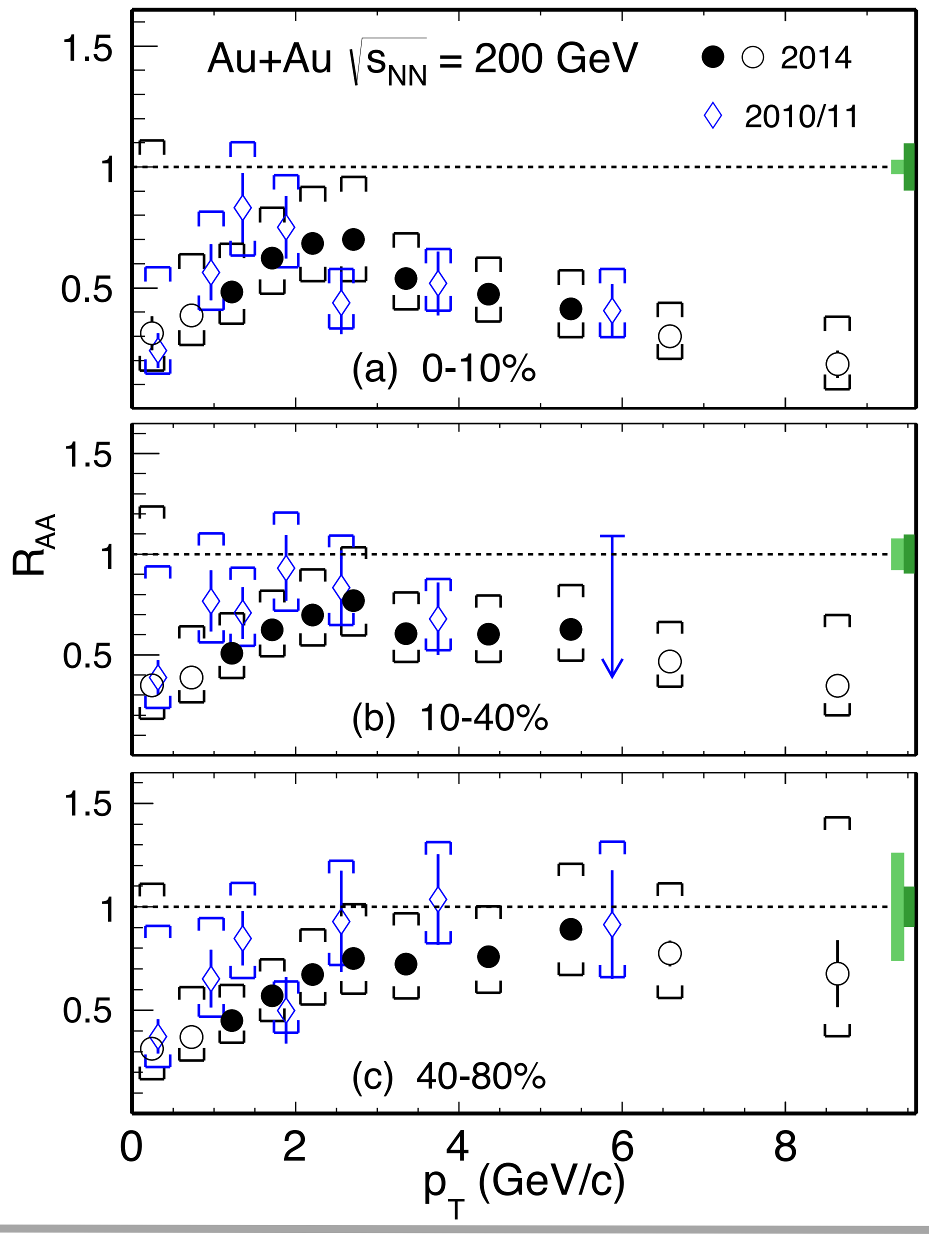
- less than unity for all p_T in 0-10% central collisions
- suppression at low p_T w/o strong centrality dependence
- suppression at high p_T increases towards more central collisions

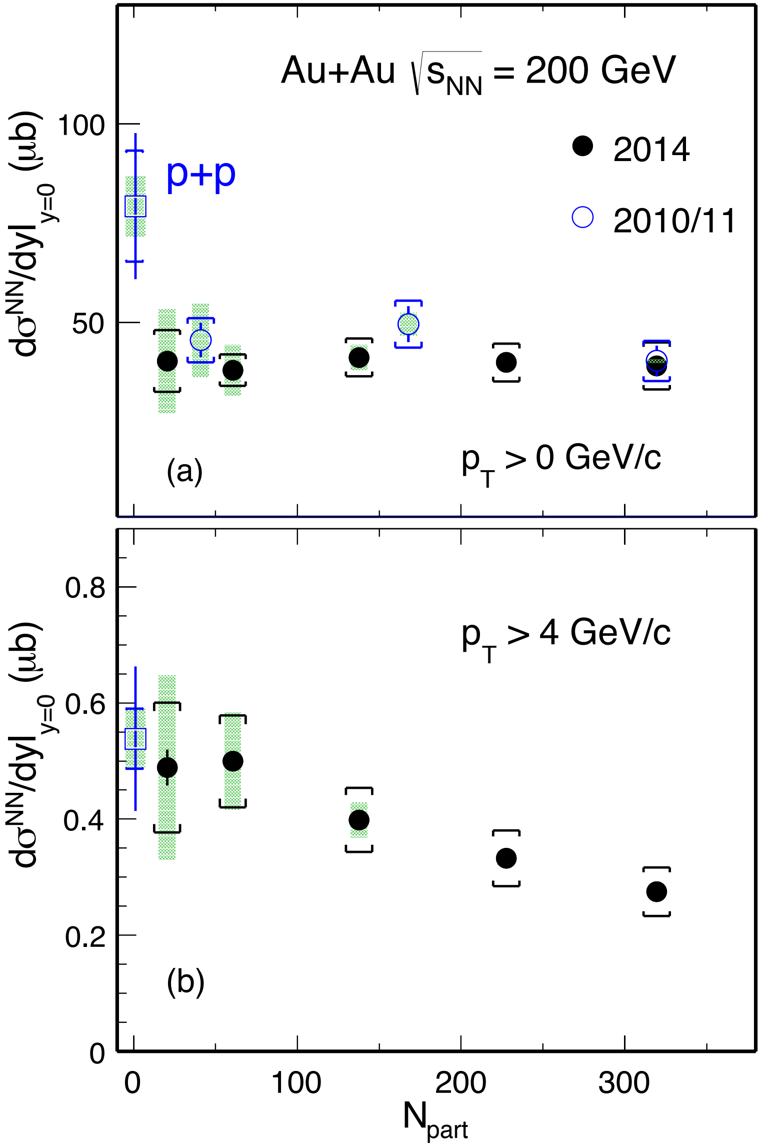
D^0 R_{CP}

- confirm the centrality dependence of R_{AA}
- compatible to light flavor hadrons at high p_T, higher at low/intermediate p_T
- described well by LBT and Duke (Bayesian) models

STAR: arXiv:1812.10224 , submitted to PRC
LBT: S. Cao, et al. PRC 94 (2016) 014909
Duke: Y. Xu, et al. PRC 97 (2018) 014907

Open Charm Production in Au+Au Collisions





D^0 R_{AA}

- less than unity for all p_T in 0-10% central collisions
- suppression at low p_T w/o strong centrality dependence
- suppression at high p_T increases towards more central collisions

D^0 p_T-integrated yield

- independent of centrality
- less than p+p yield

D^0 p_T>4 GeV/c yield

- decrease towards central

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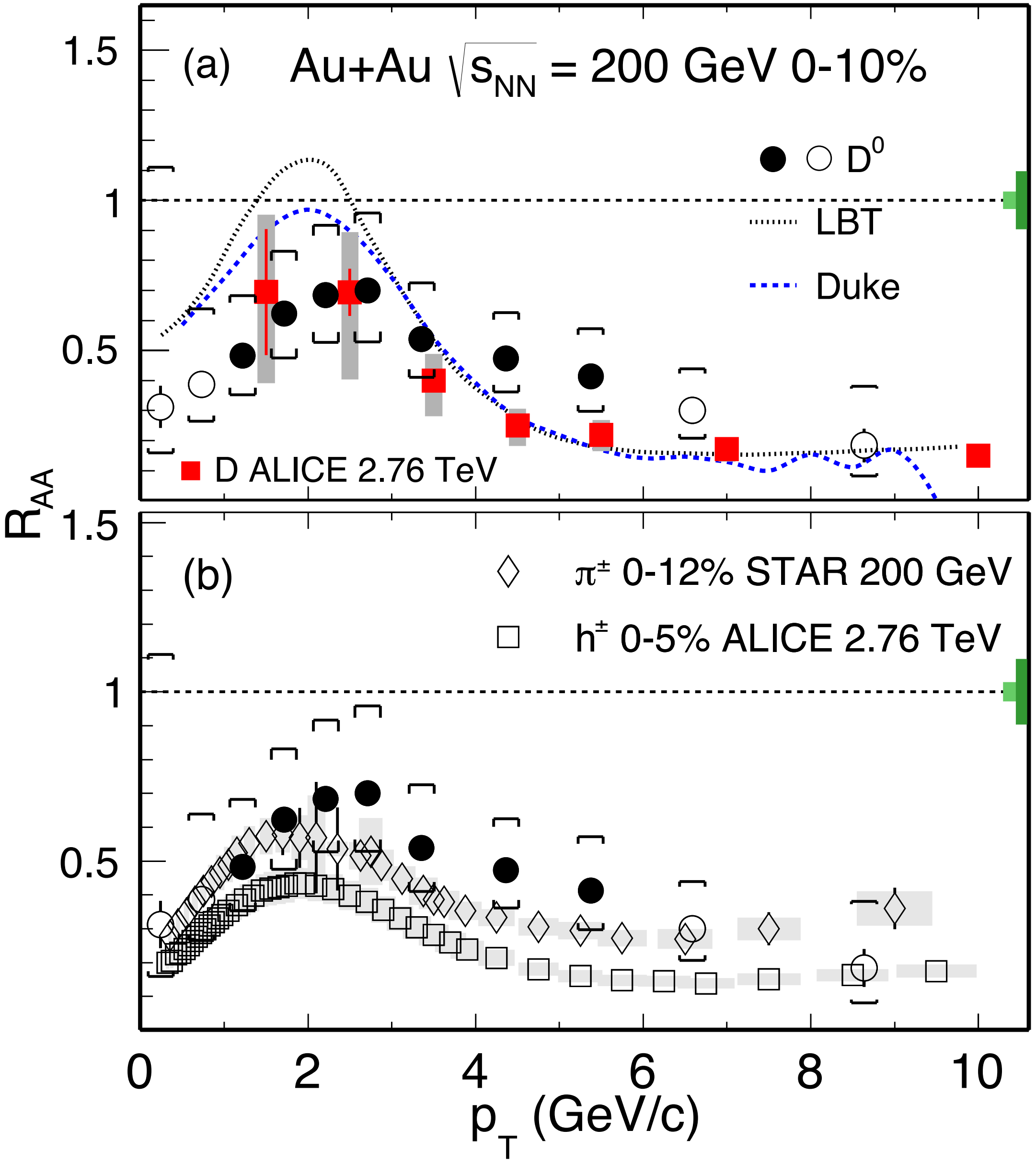
Open Charm Production in Au+Au Collisions



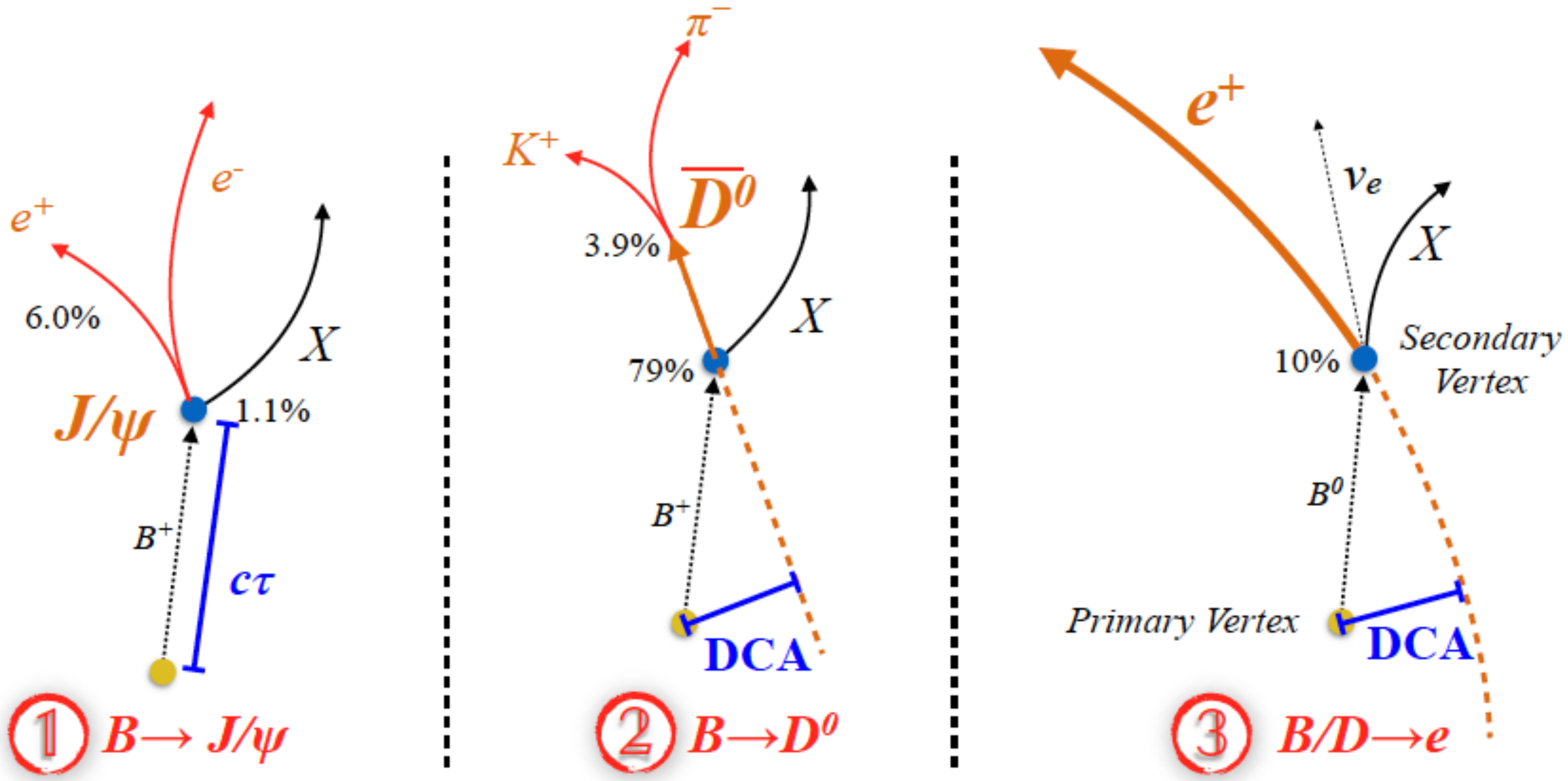
D^0 R_{AA} in 0-10%

- compatible to LHC results
- compatible to light flavor hadrons at high p_T, but higher at intermediate p_T
- exhibits a bump structure consistent with expectation of radial flow
- qualitatively described by LBT and Duke (Bayesian) models

STAR: arXiv:1812.10224 , submitted to PRC
LBT: S. Cao, et al. PRC 94 (2016) 014909
Duke: Y. Xu, et al. PRC 97 (2018) 014907

Open Bottom Signals in Au+Au Collisions

$\Delta E_b < \Delta E_c$???



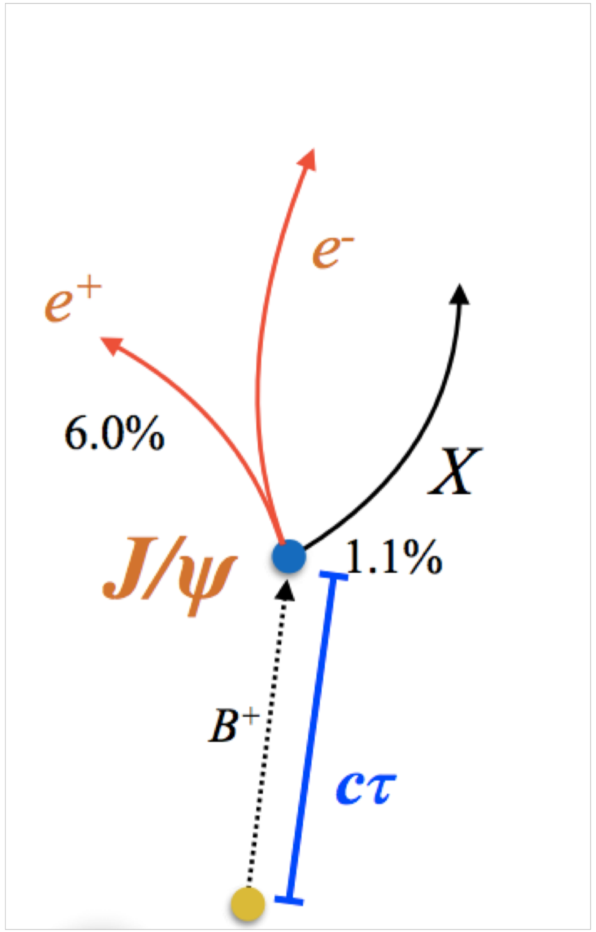
- We have measured 3 different decay channels of **B hadrons** enabled by the **HFT**.

  1 → ~900M MB (2014) + ~1.2 nb^{-1} HT events (2014 + 2016)

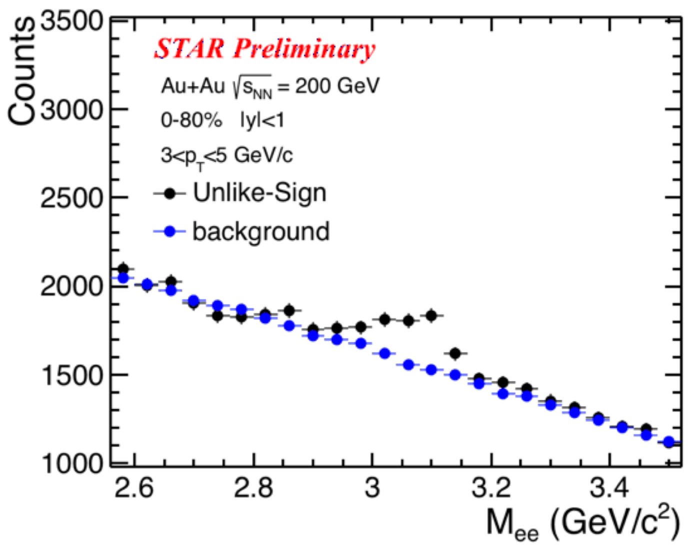
  2 → ~900M MB (2014)

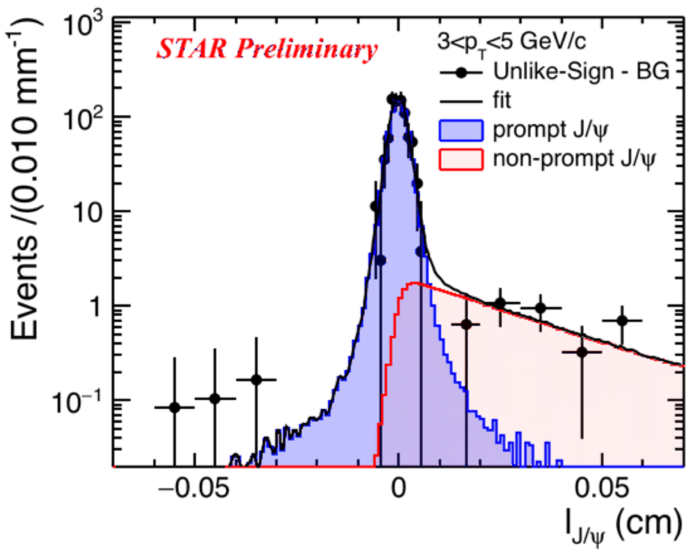
  3 → ~900M MB (2014) + ~0.2 nb^{-1} HT events (2014)

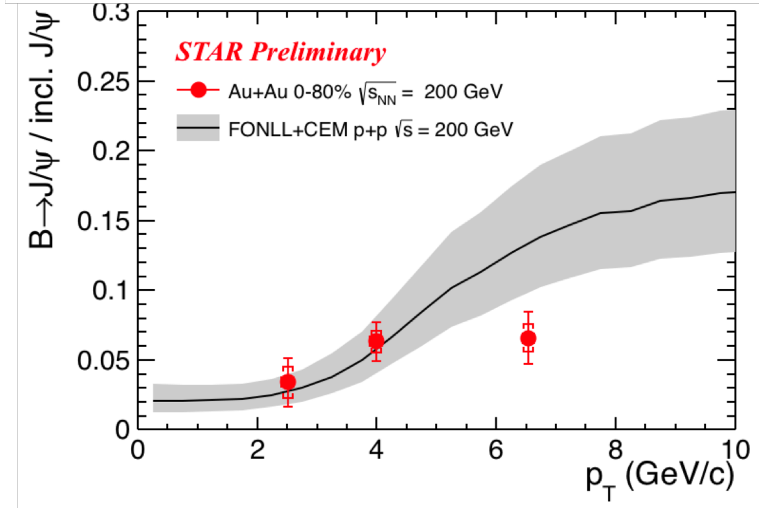
Open Bottom Production in Au+Au Collisions

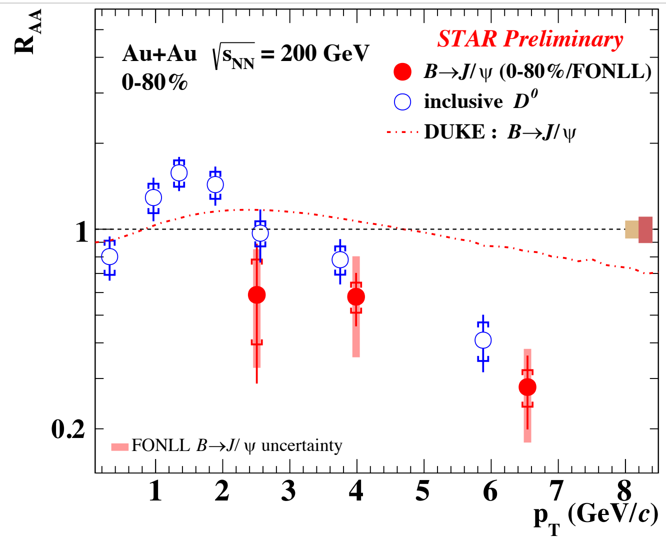


$$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(data)}{f_{p+p}^{B\to J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data)$$

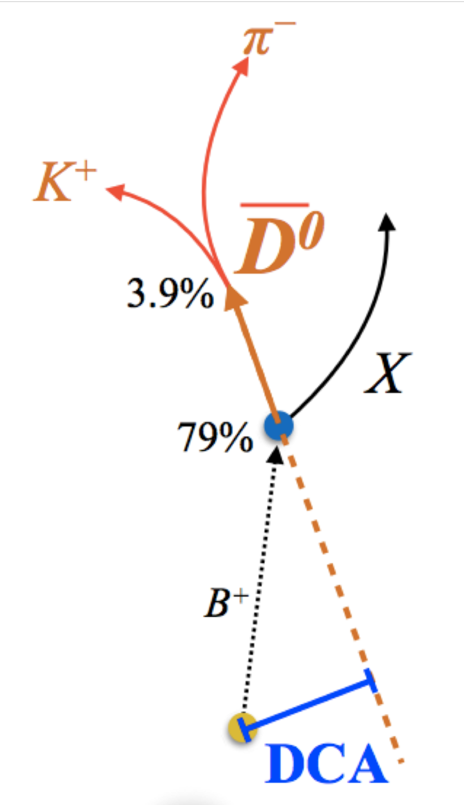




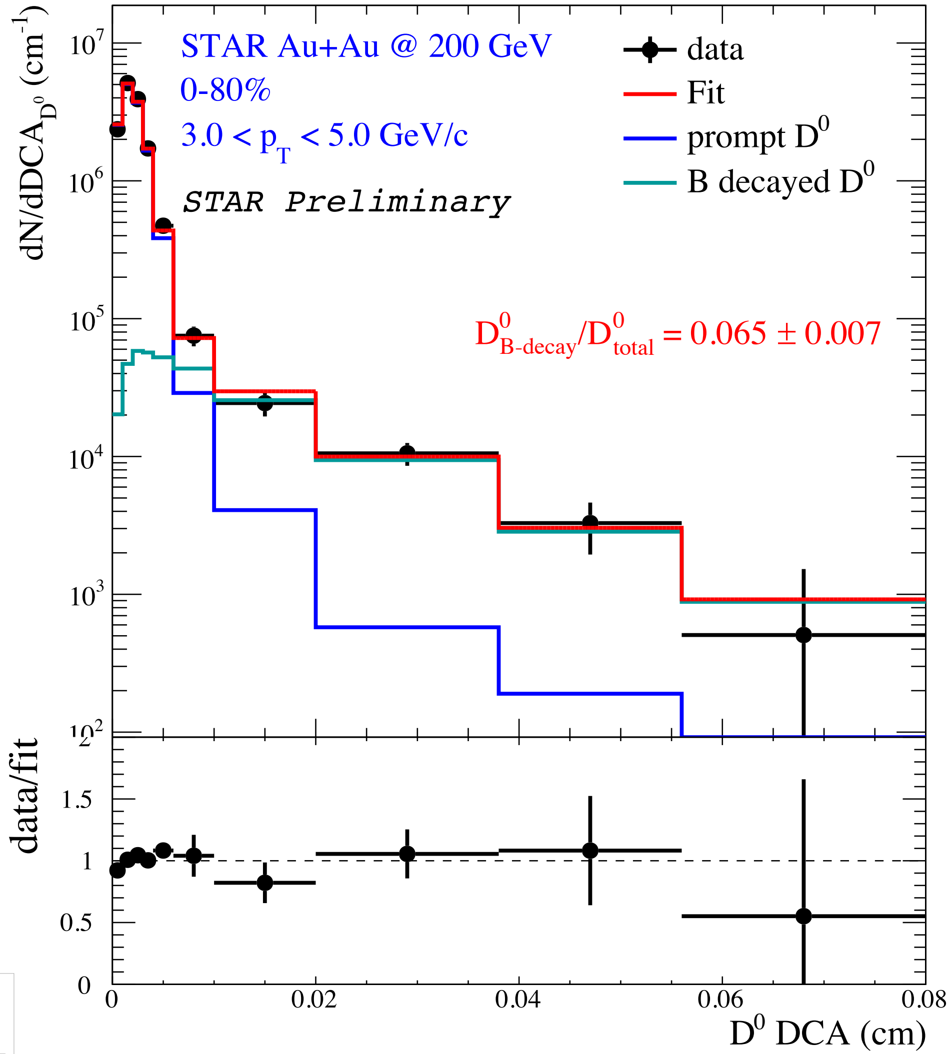


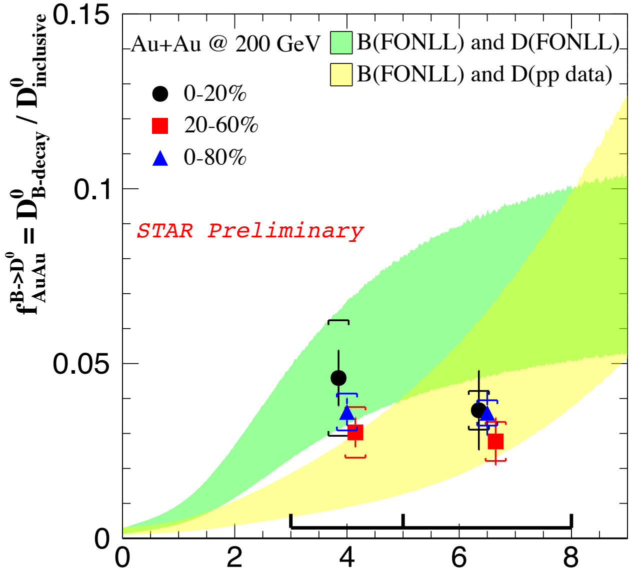


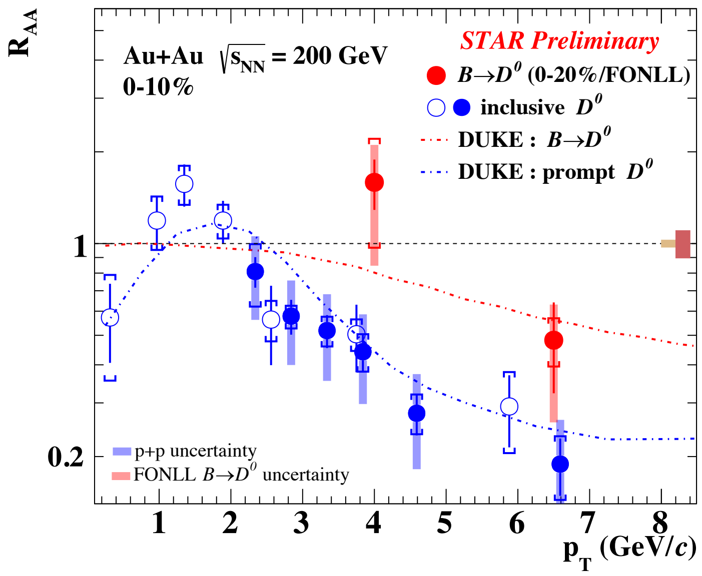
Open Bottom Production in Au+Au Collisions



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







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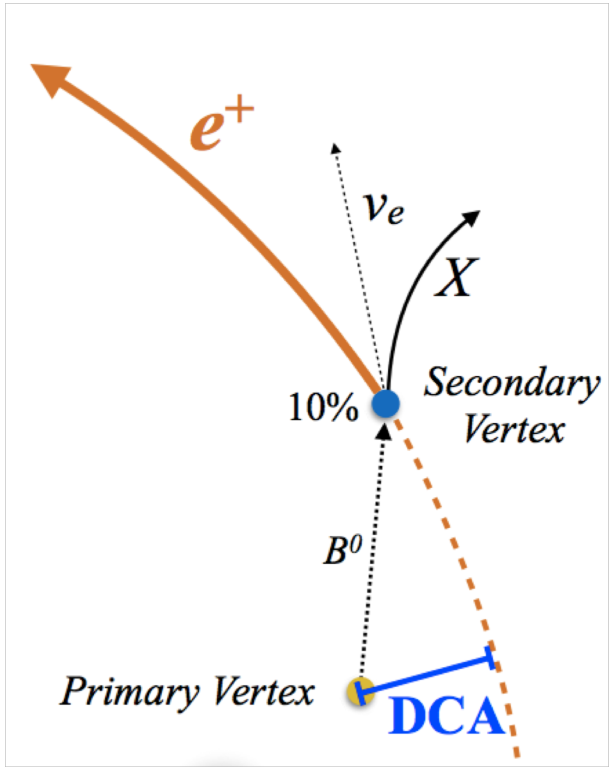
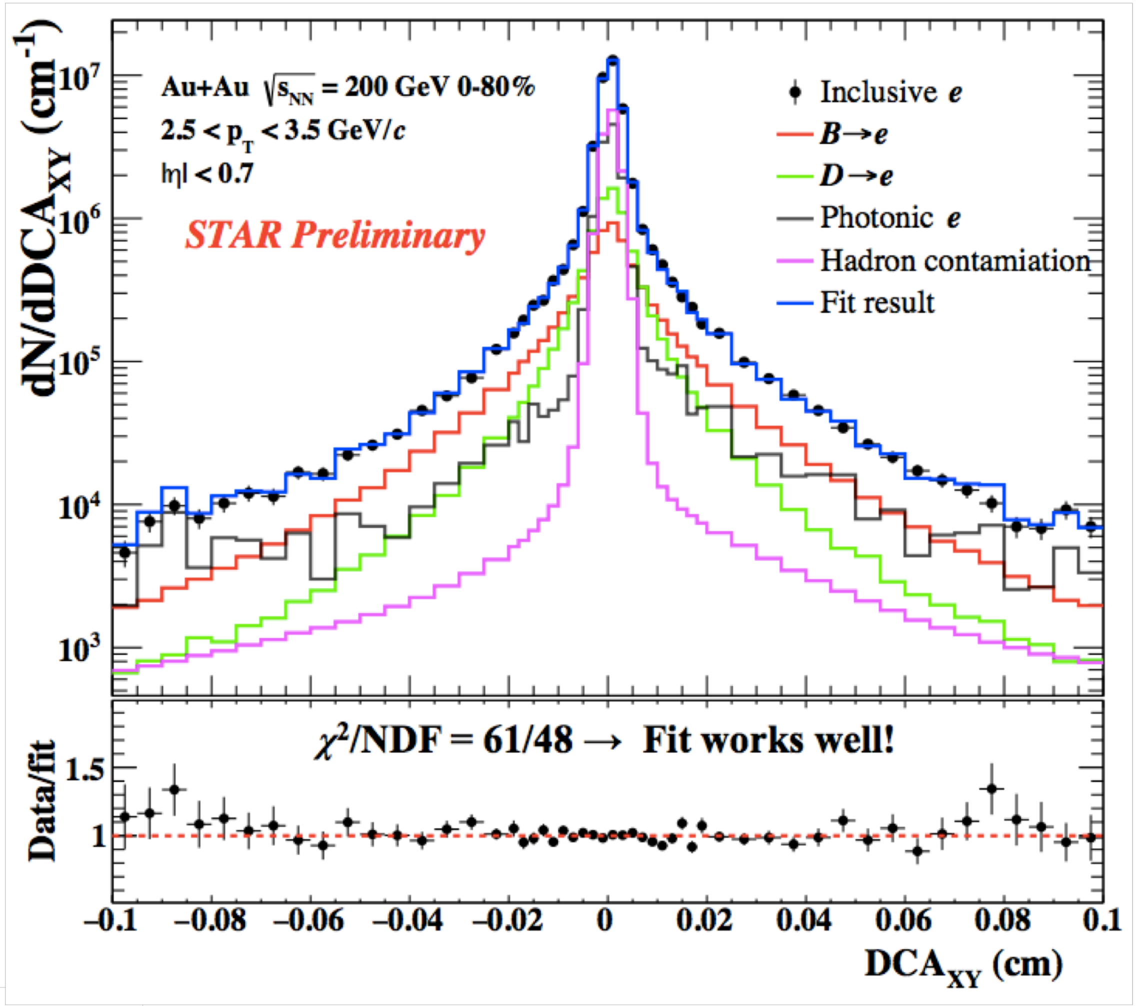
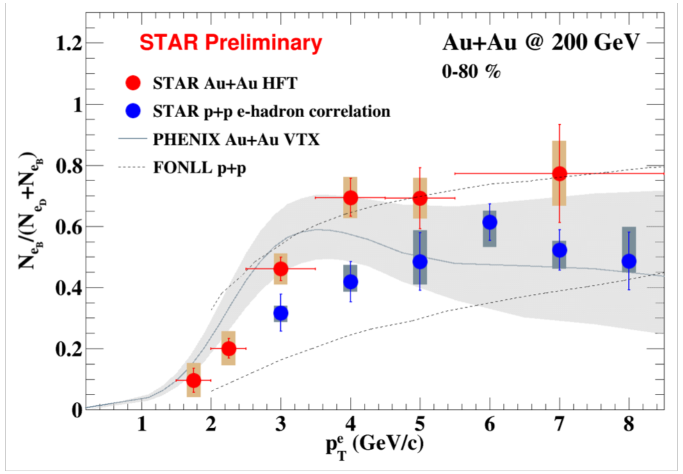
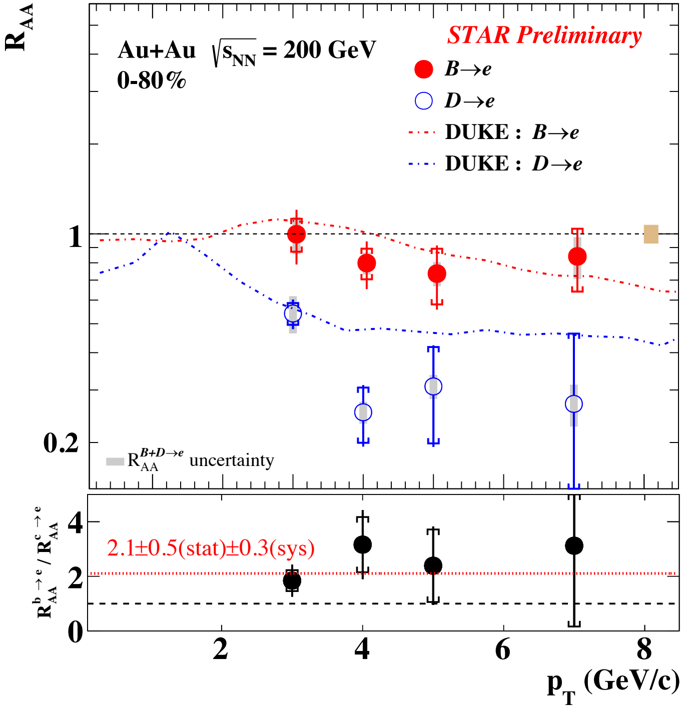


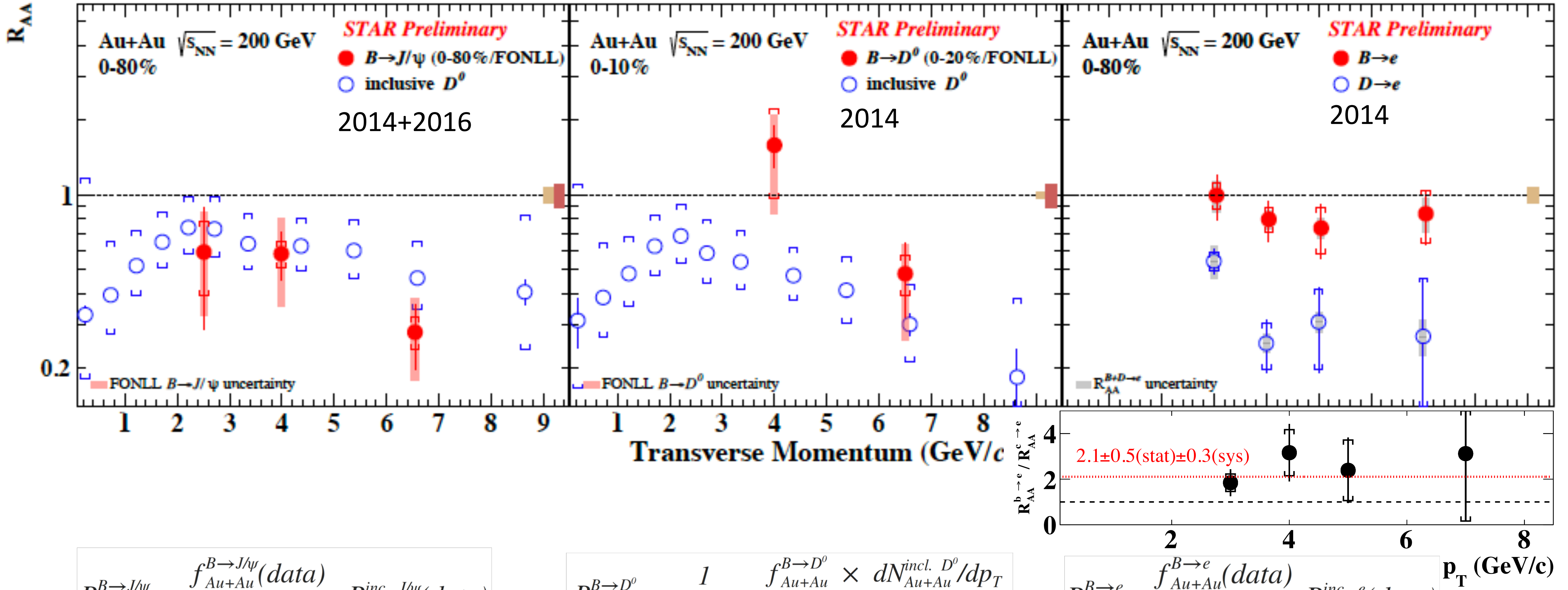






$$R_{AA}^{B\rightarrow e} = \frac{f_{Au+Au}^{B\rightarrow e}(data)}{f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc.\ e}(data)$$

Bottom Quark Energy Loss in Au+Au Collisions



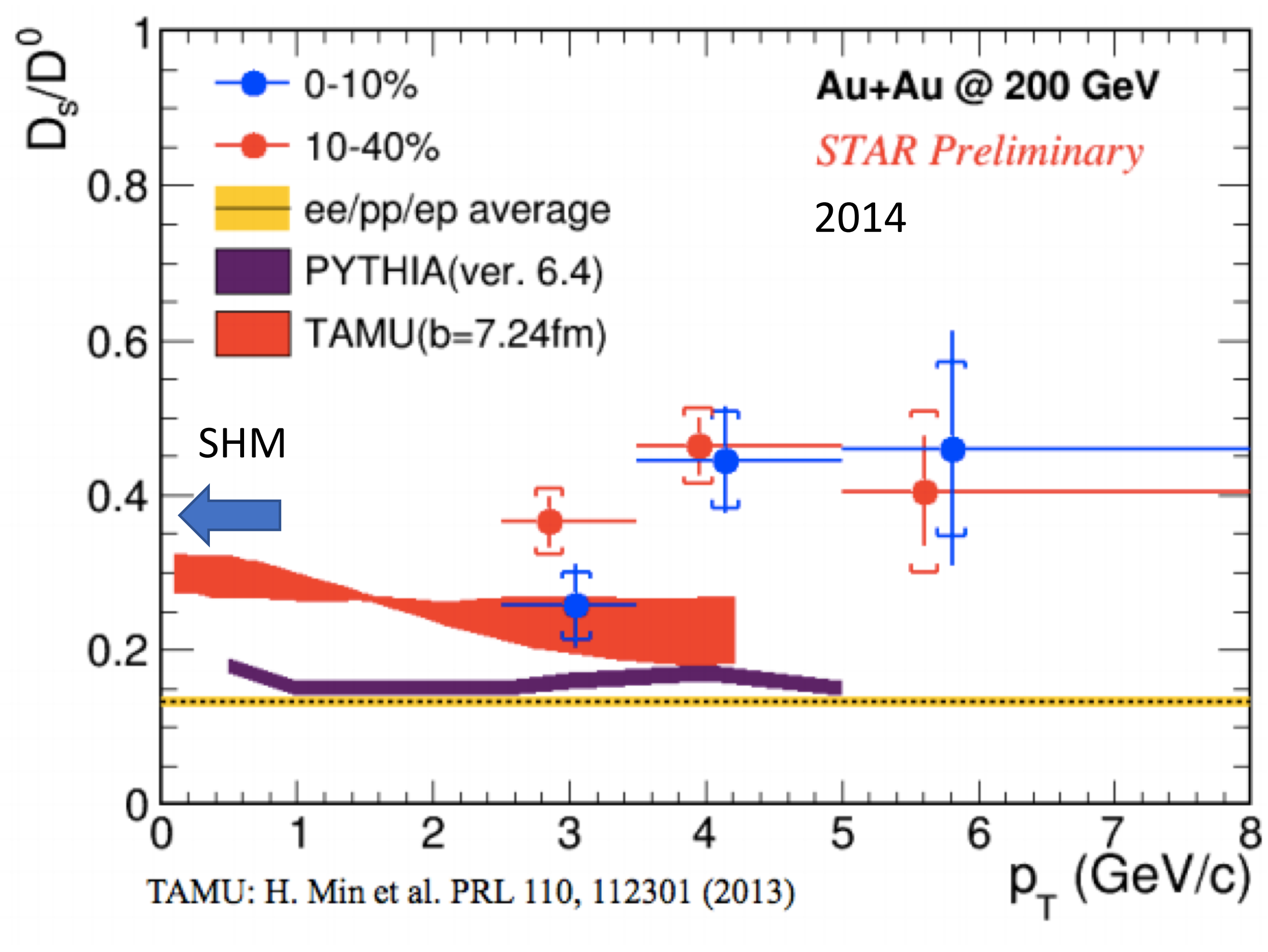
$$R_{AA}^{B\to J/\psi}=\frac{f_{Au+Au}^{B\to J/\psi}(data)}{f_{p+p}^{B\to J/\psi}(theory)}R_{AA}^{inc.\ J/\psi}(data)$$

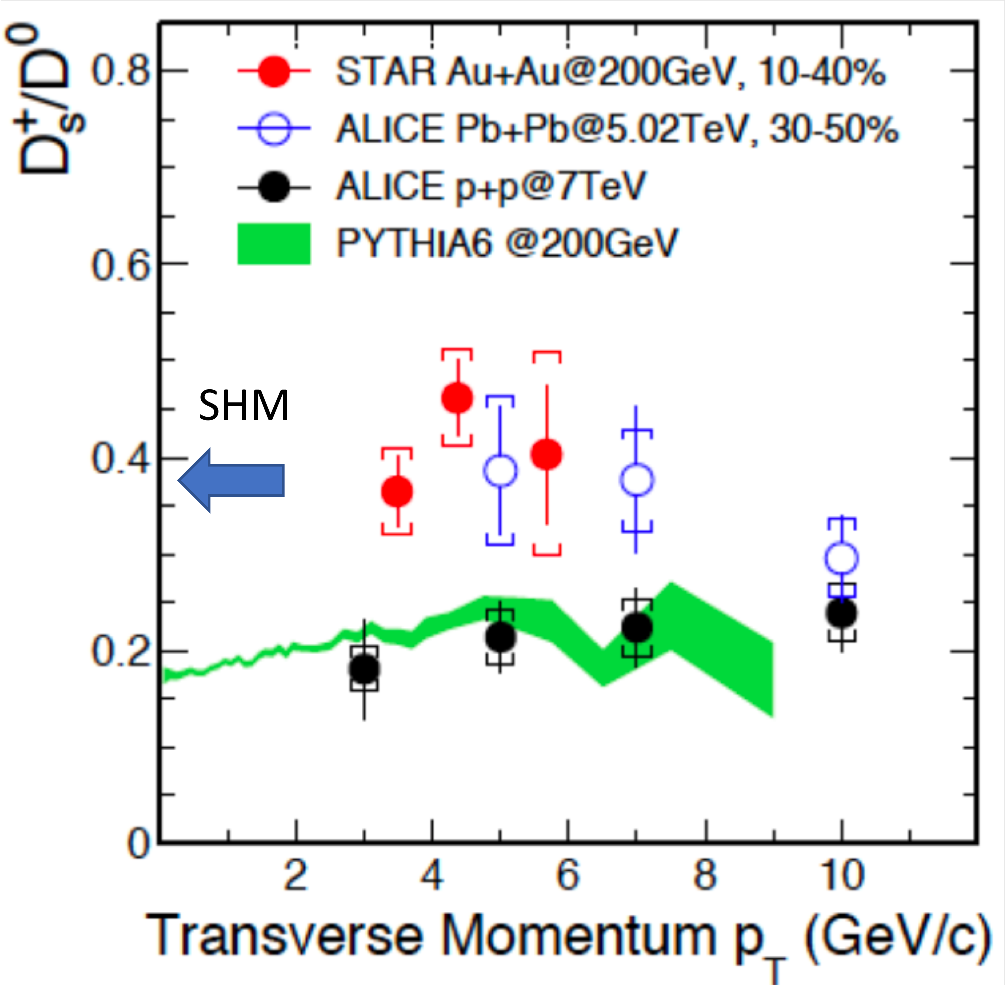
$$R_{AA}^{B\to D^0}=\frac{1}{\langle N_{coll}\rangle}\frac{f_{Au+Au}^{B\to D^0}\times dN_{Au+Au}^{incl.\ D^0}/dp_T}{dN_{FONLL}^{B\to D^0}/dp_T}$$

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

- Suppression of B-decayed J/ψ and D^0 at high p_T
- e^B R_{AA} > e^D R_{AA} consistent with expectation $\Delta E_b < \Delta E_c$

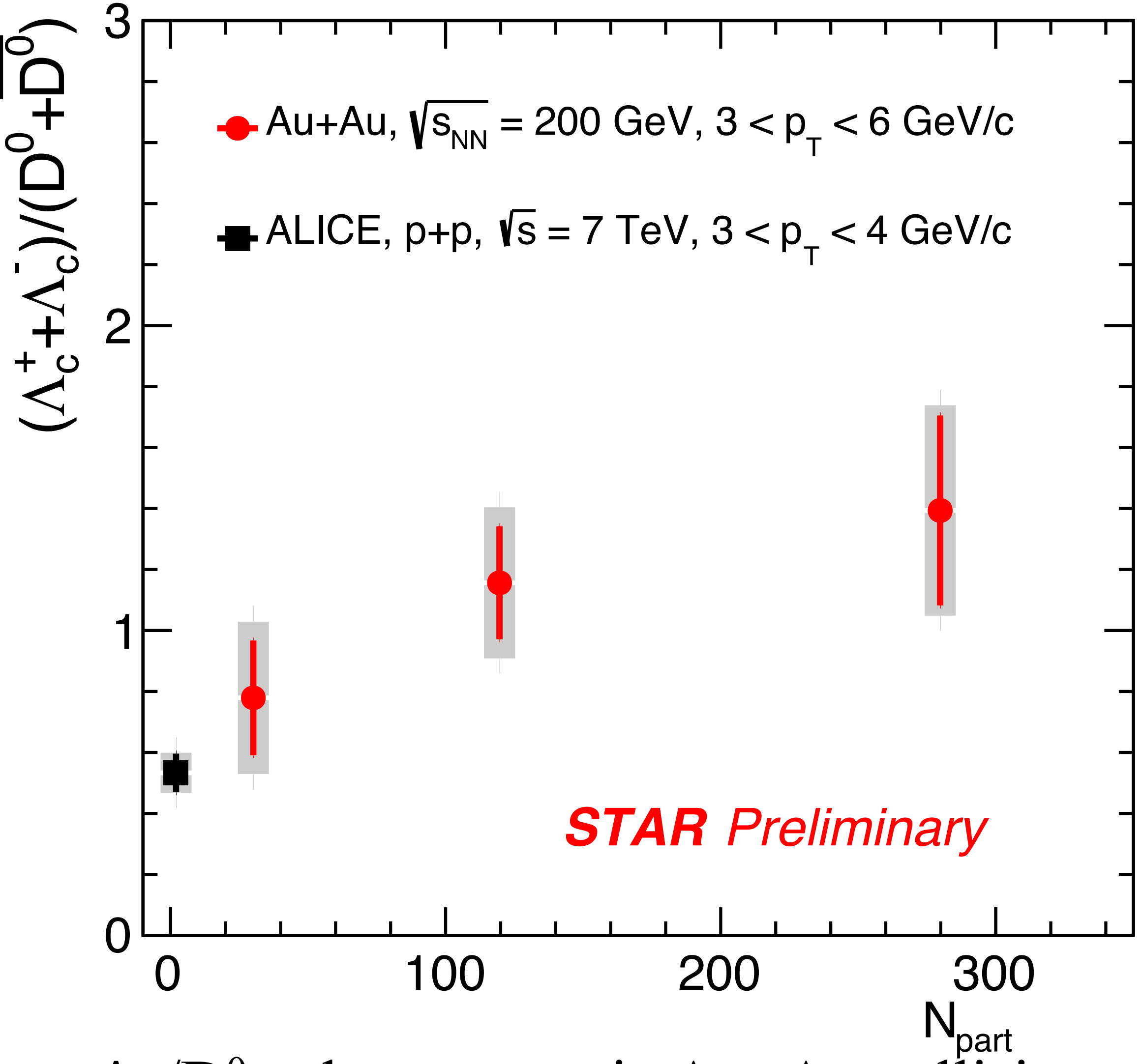
Charm Hadronization in Au+Au Collisions - D_s/D^0

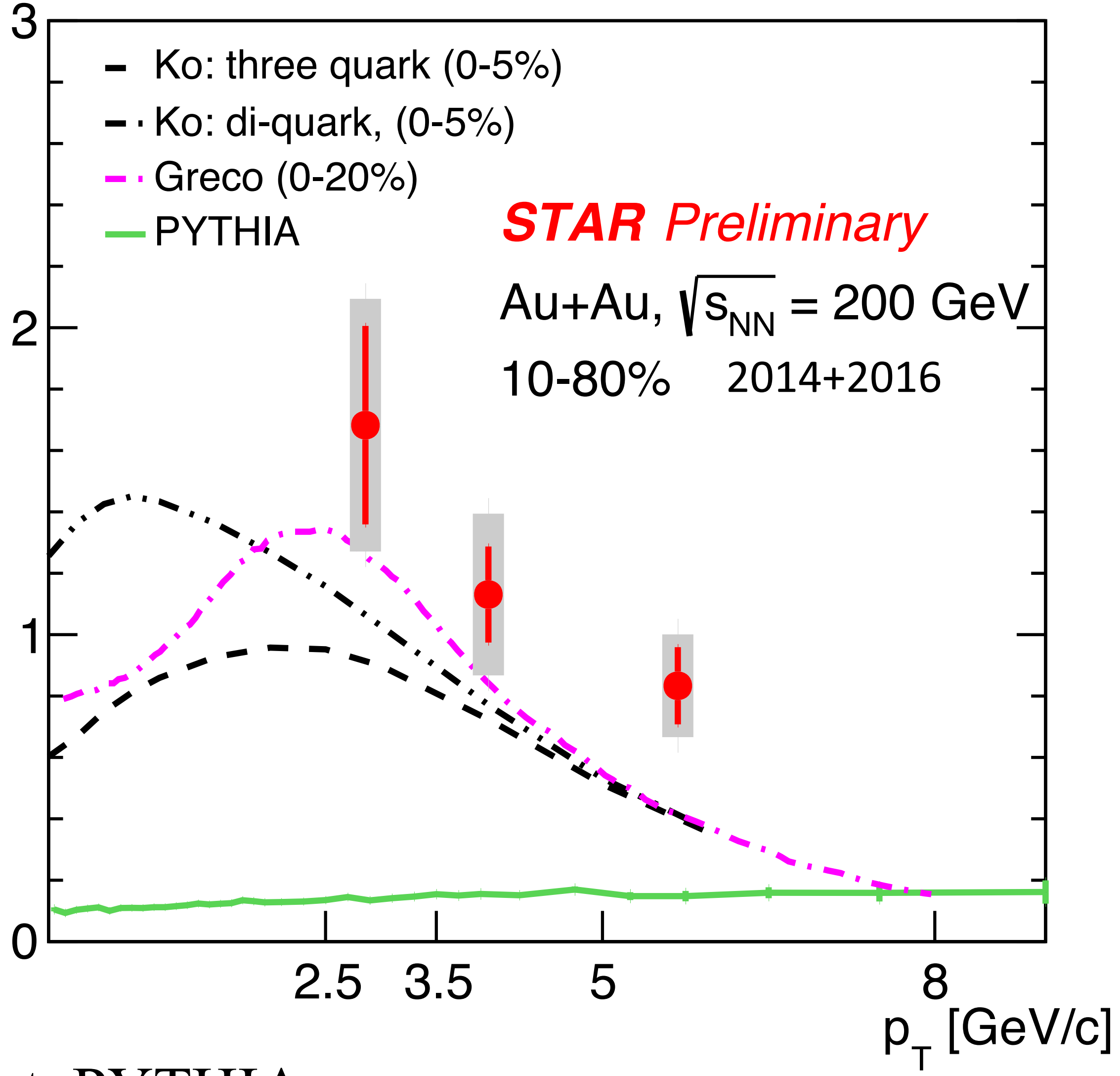




- D_s/D^0 ratio in Au+Au compatible with LHC Pb+Pb, and significantly higher than p+p
- TAMU model under-predicts data

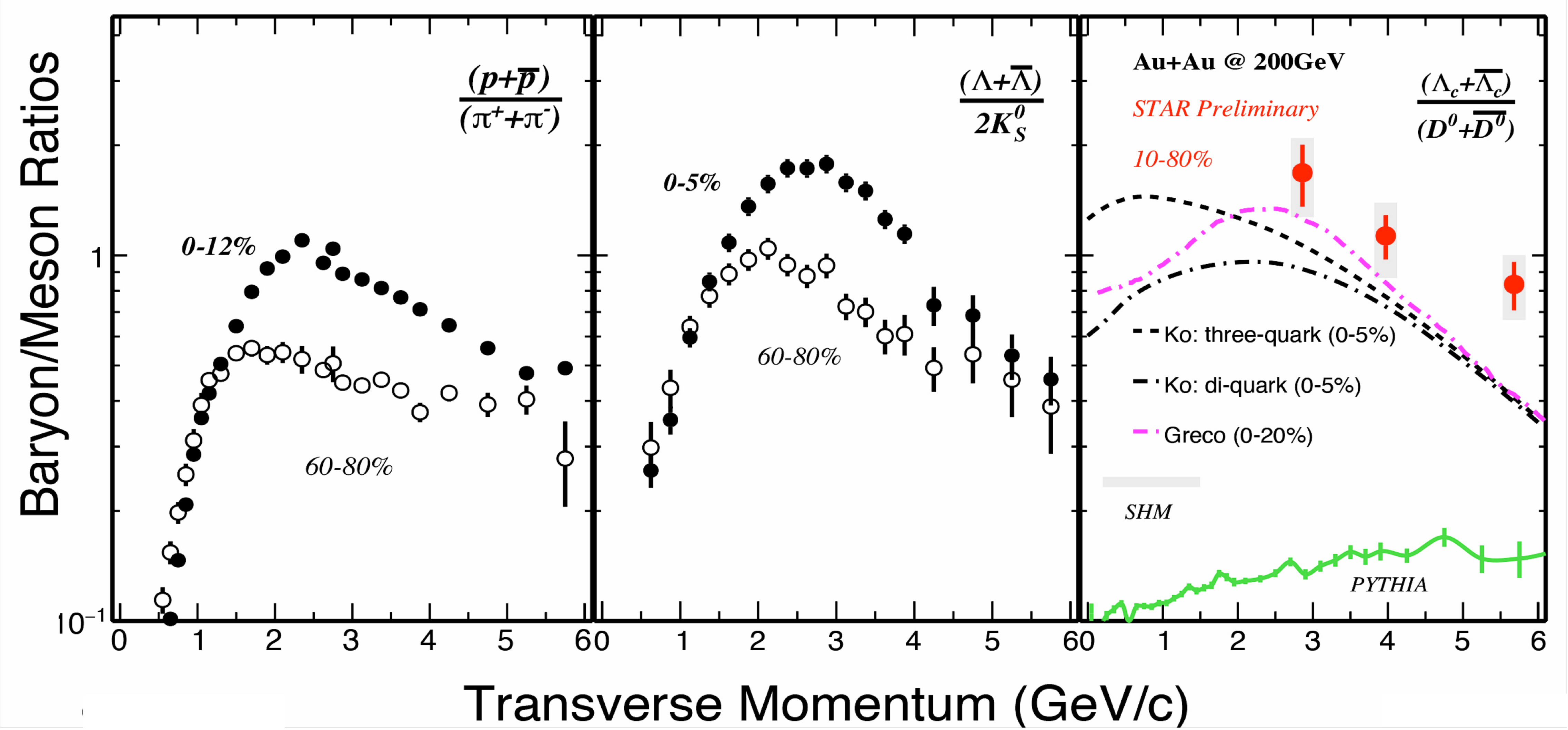
Charm Hadronization in Au+Au Collisions - Λ_c/D^0





- Λ_c/D^0 enhancement in Au+Au collisions w.r.t. PYTHIA
- Models with charm quark coalescence hadronization qualitatively describe data

Charm Hadronization in Au+Au Collisions - Λ_c/D^0



- Λ_c/D^0 enhancement in Au+Au collisions w.r.t. PYTHIA
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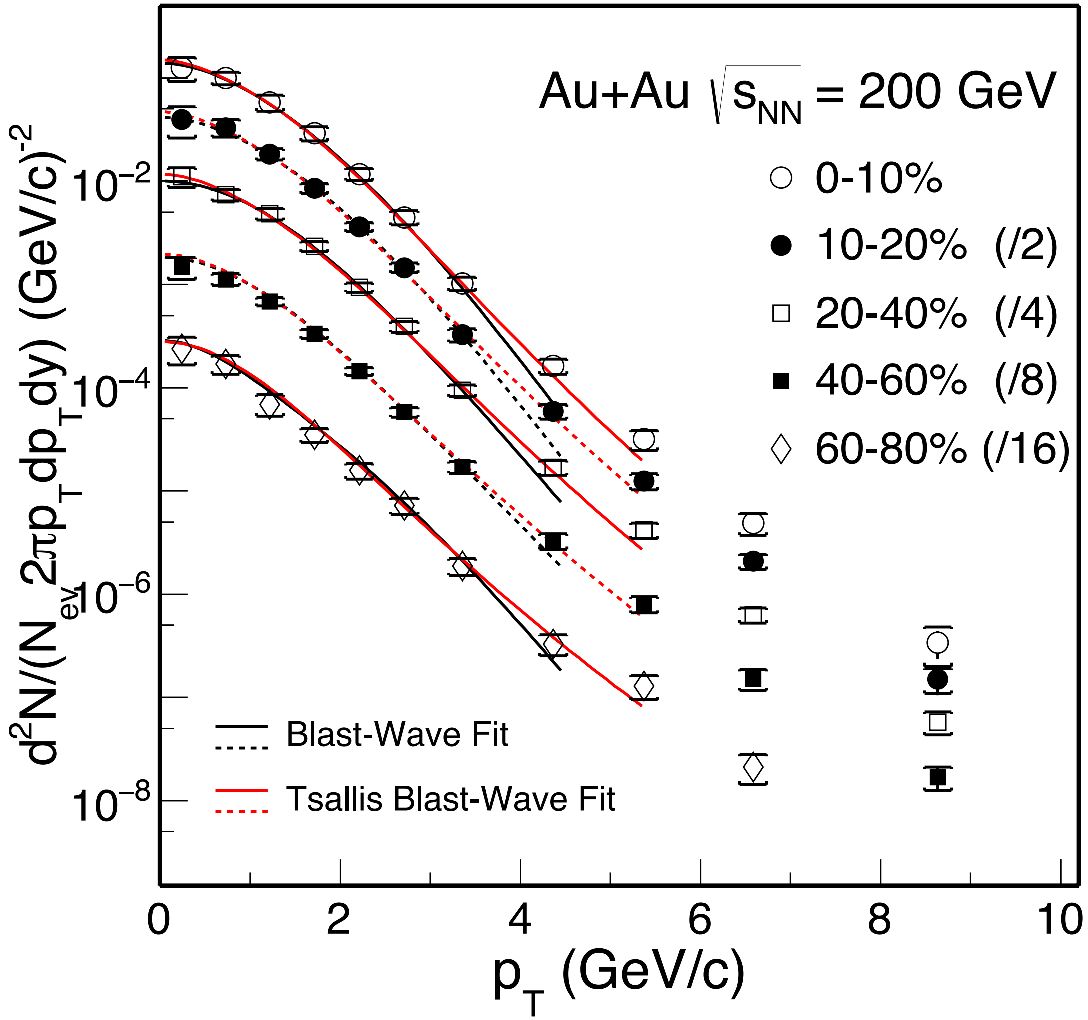
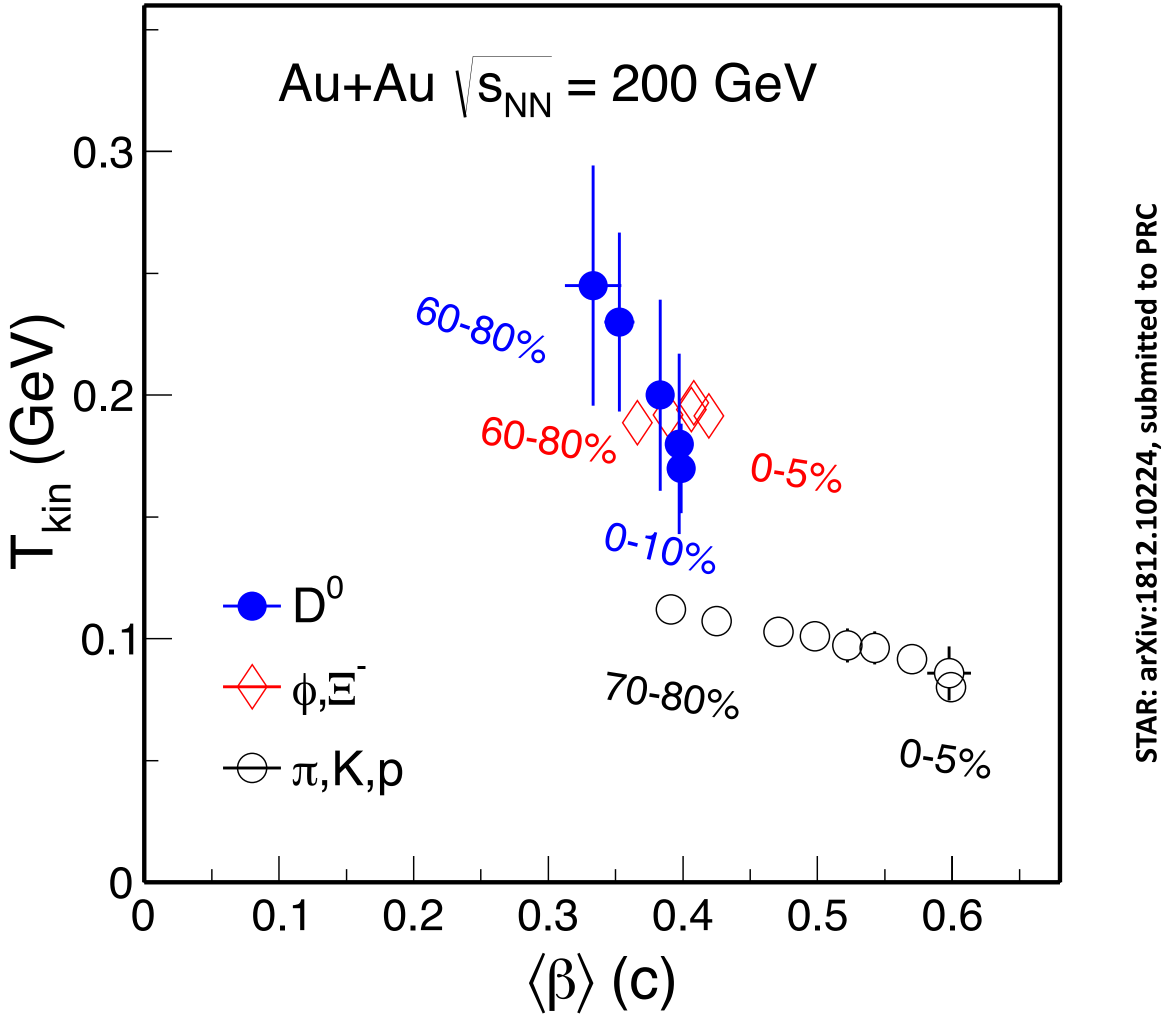
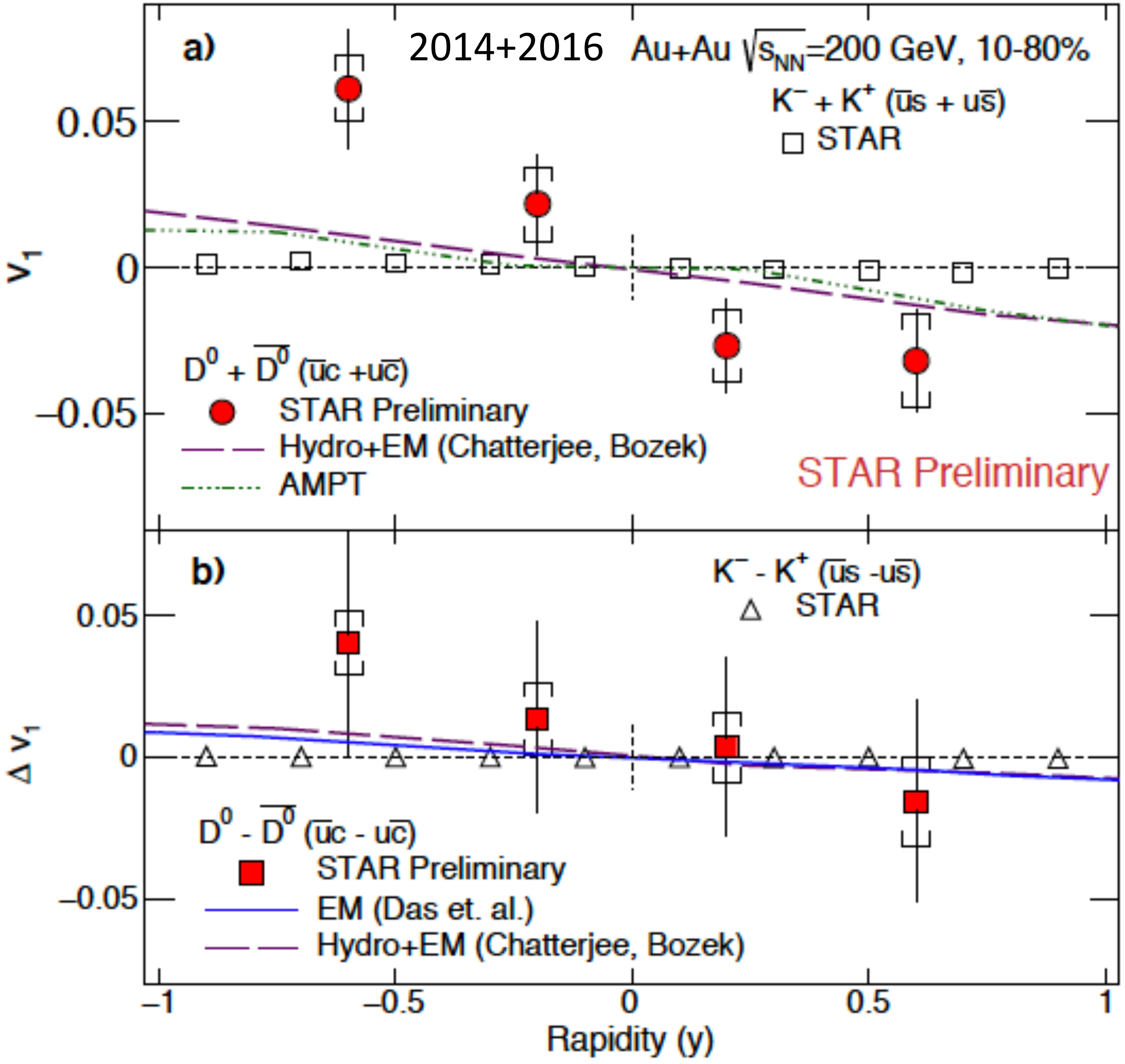
Charm Quark Collectivity in Au+Au Collisions –Radial Flow

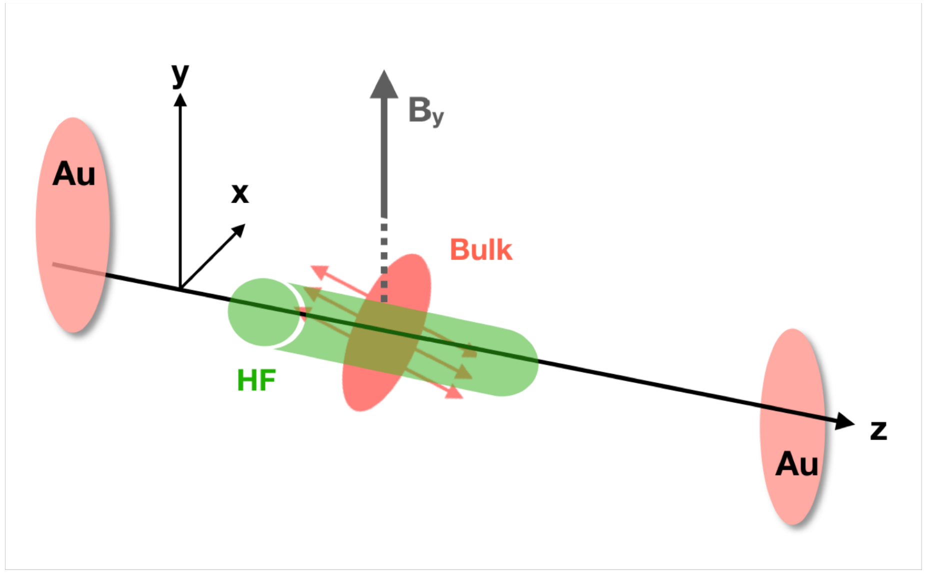




- BW fits suggest early freeze-out and smaller radial flow of D^0 than light flavor hadrons
- T_{kin} close to critical temp. T_c, suggesting D^0 radial flow mostly from partonic stage

Charm Quark Collectivity in Au+Au Collisions – v_1





- **First evidence for non-zero $D^0 v_1$:**

$$D^0 + \overline{D^0}\ dv_1/dy$$
$$= -0.081 \pm 0.021(\text{stat.}) \pm 0.017(\text{syst.})$$

probe the initial tilt of the source and EM field