Open Heavy Flavor Measurements at STAR

Heavy Flavor Workshop in Heavy Energy Collisions,
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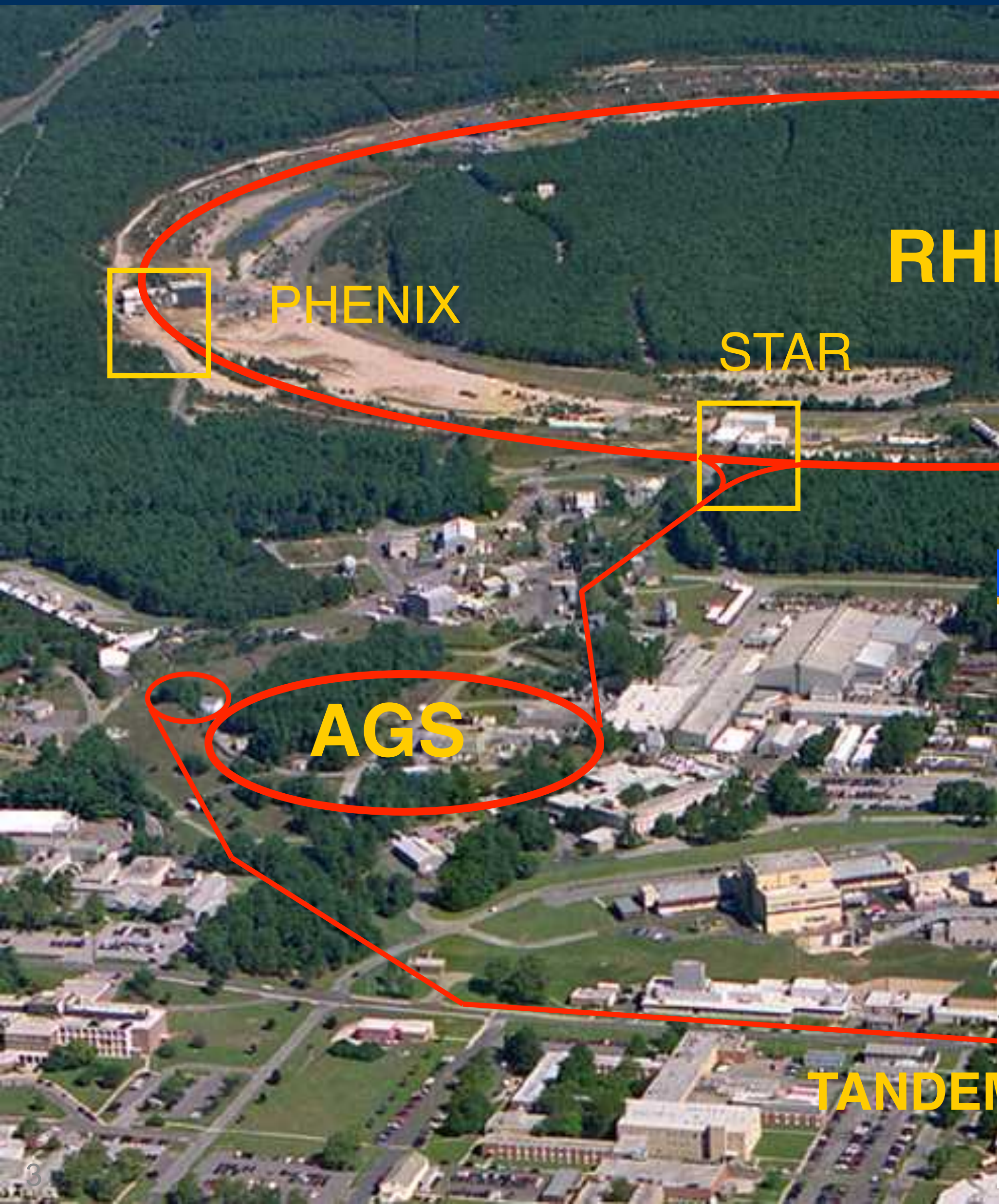
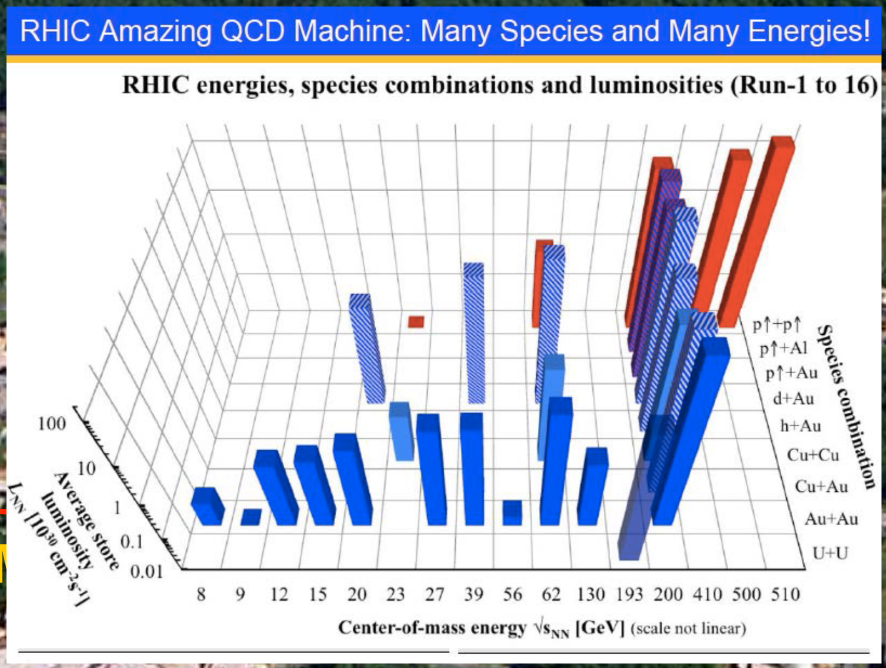
Outline

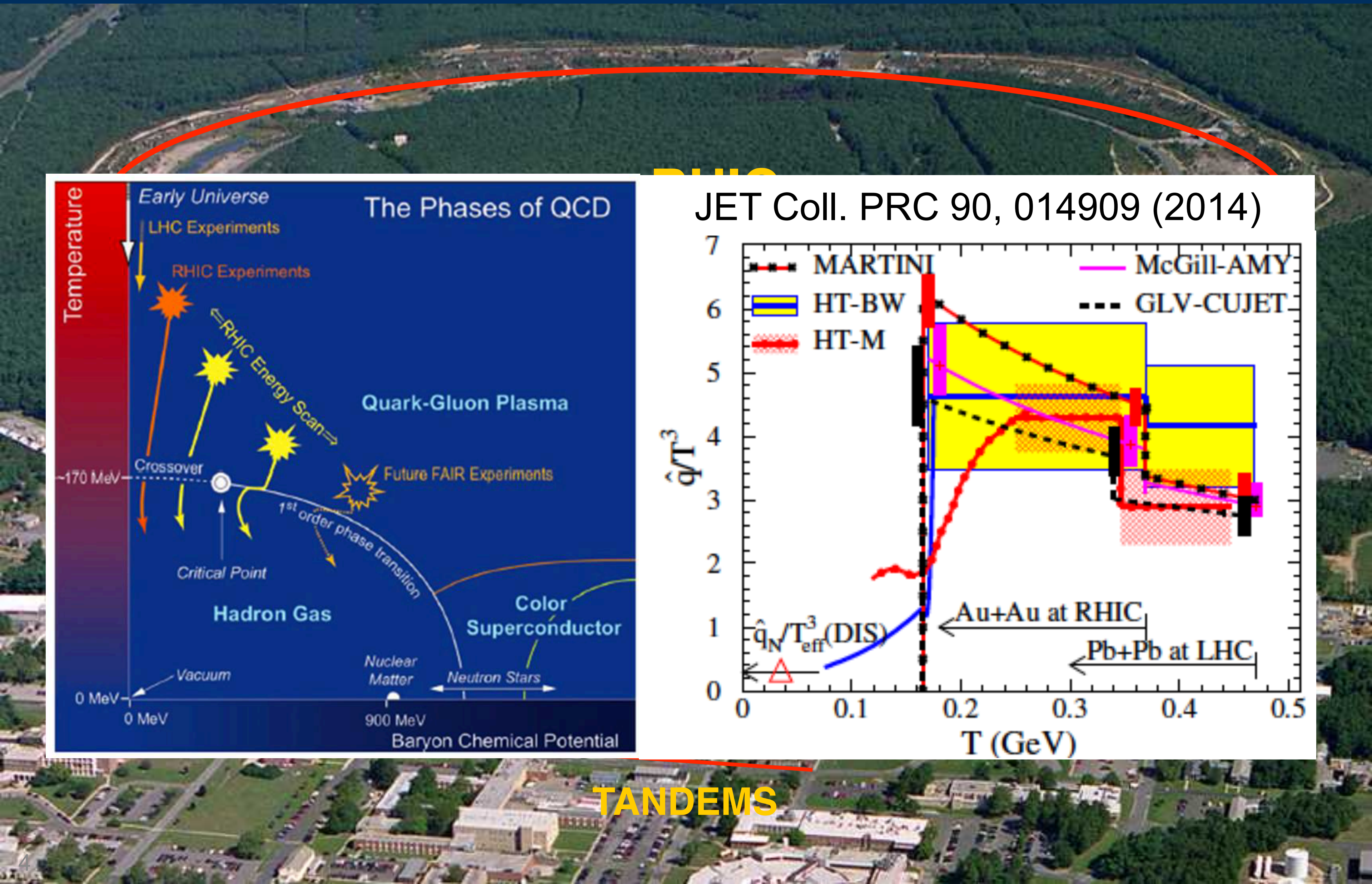
- **Introduction**
- **Open Heavy flavor at STAR**
  - **p+p collisions – test pQCD**
    - D^0 and D^* cross-sections
    - Electrons from charm and bottom decay
  - **A+A collisions – QGP properties**
    - D^0 R_{AA} – charm quark energy loss
    - D^0 flow – charm quark collectivity
    - D_s/D^0 and Λ_c/D^0 – charm quark hadronization
    - B-decay daughter R_{AA} – bottom quark energy loss
- **Summary and outlook**

Relativistic Heavy Ion Collider

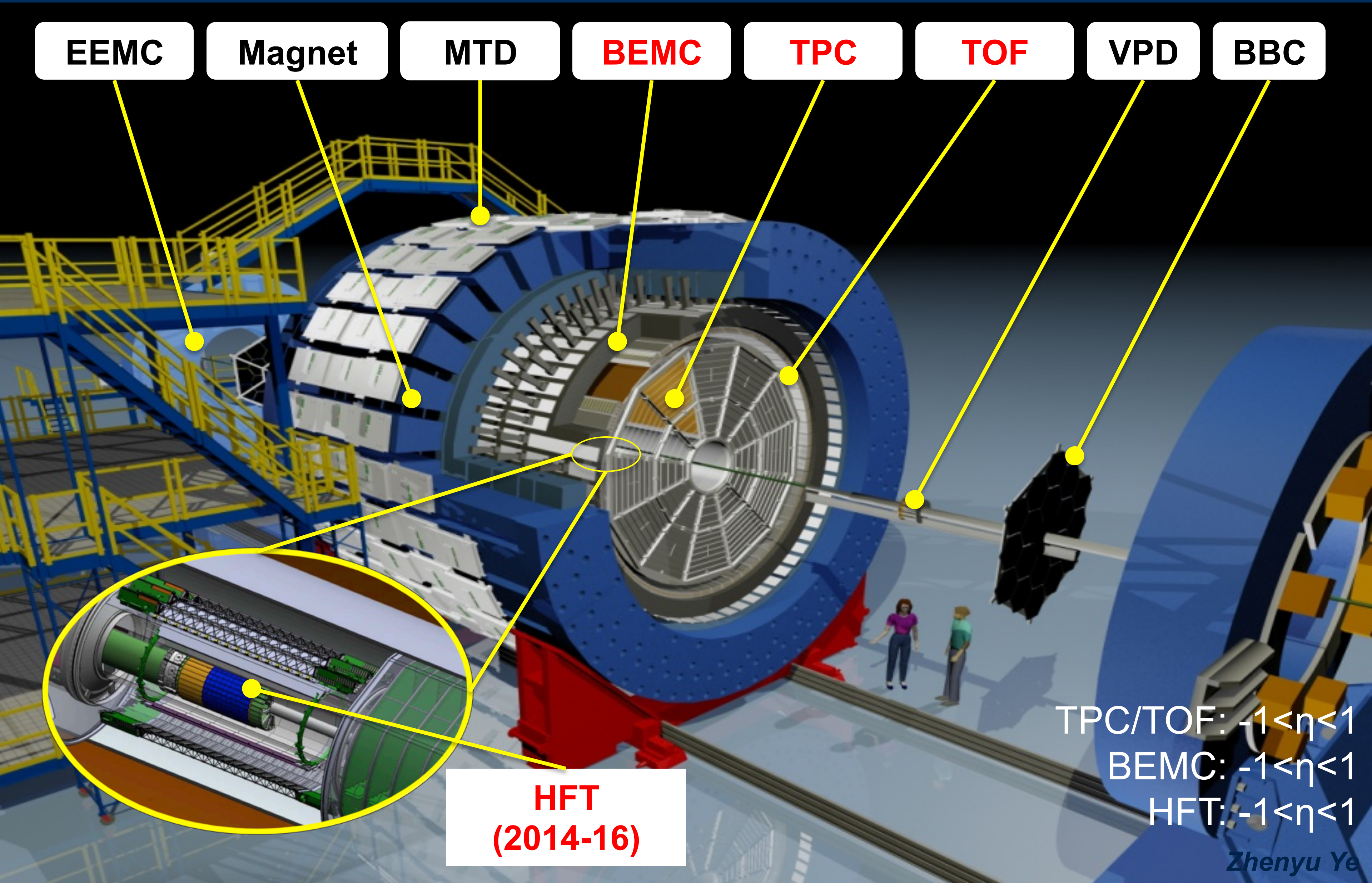




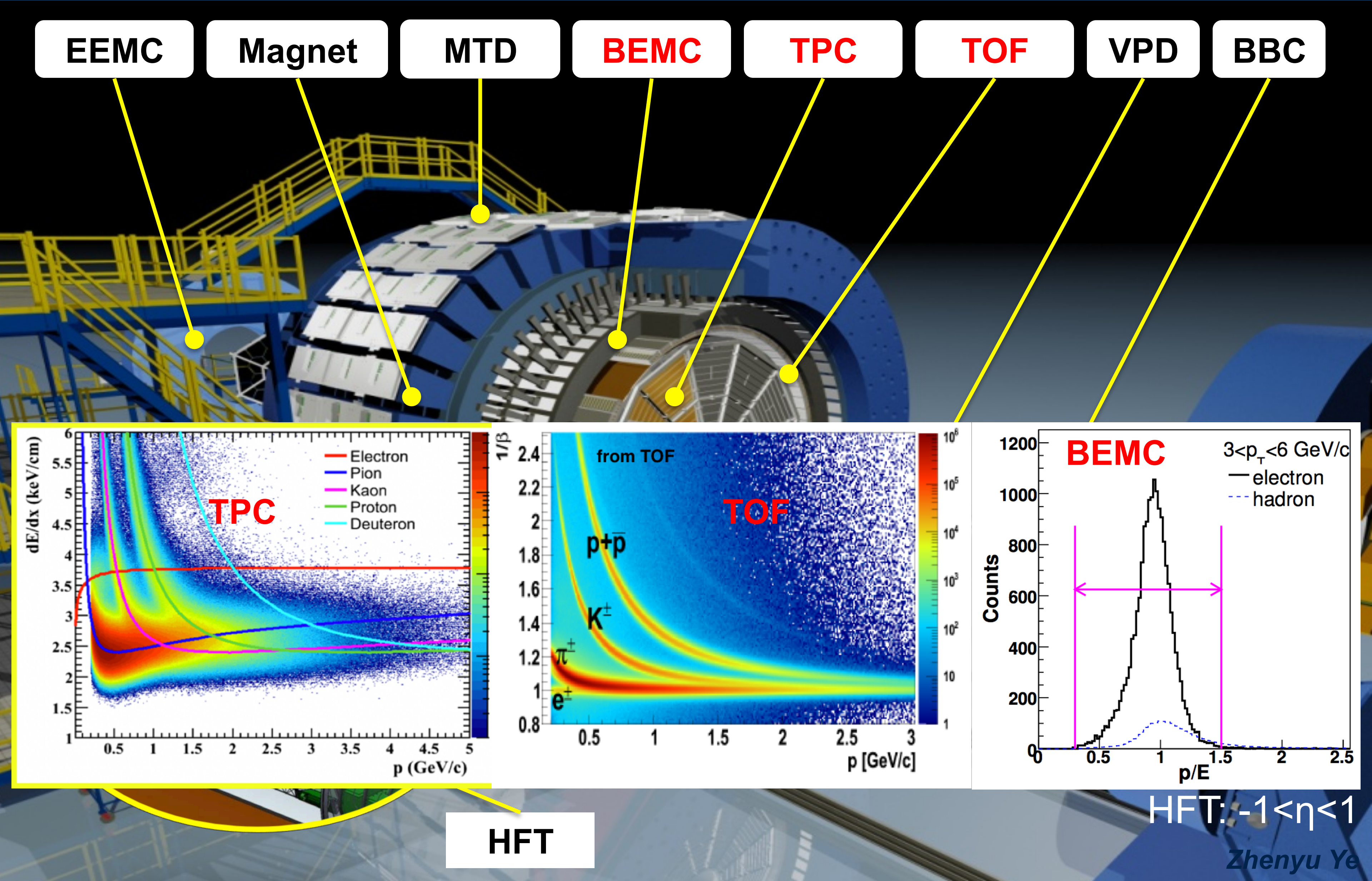
Relativistic Heavy Ion Collider



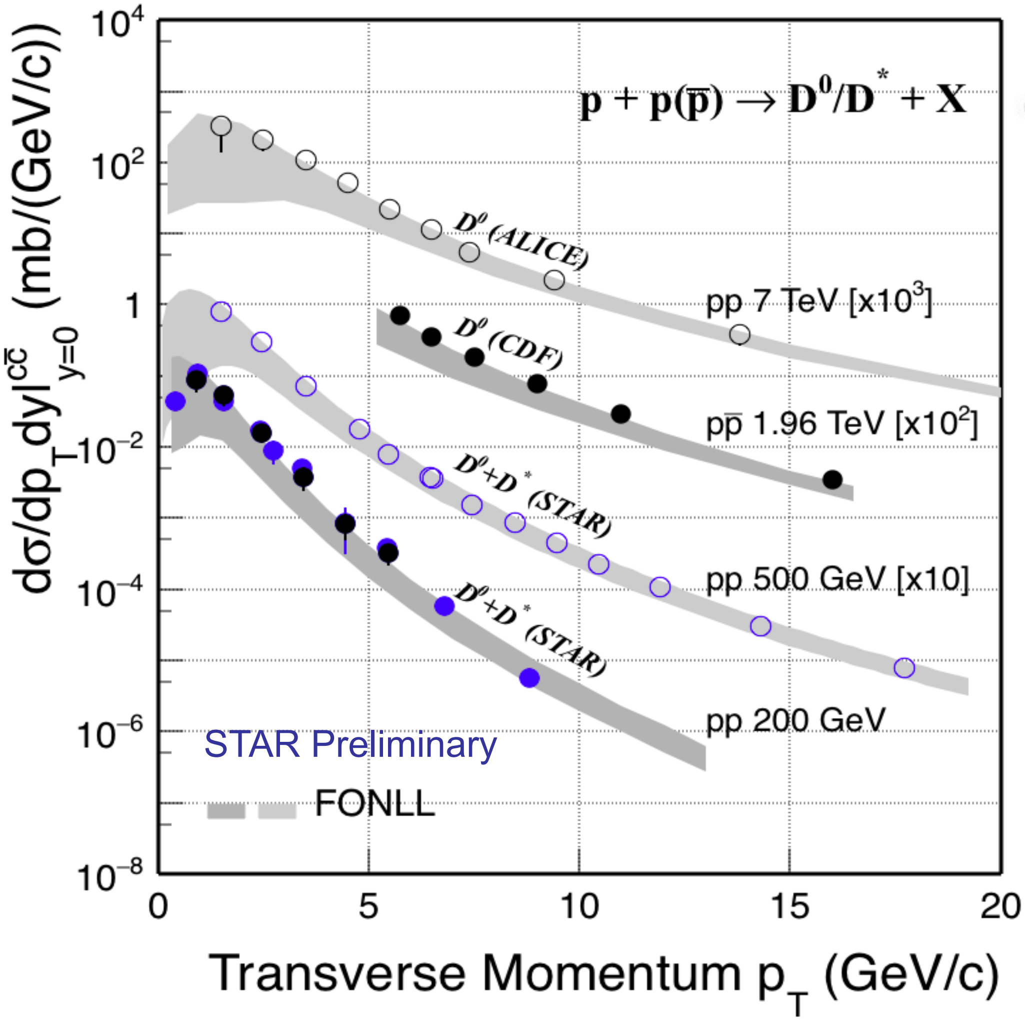
STAR Experiment at RHIC

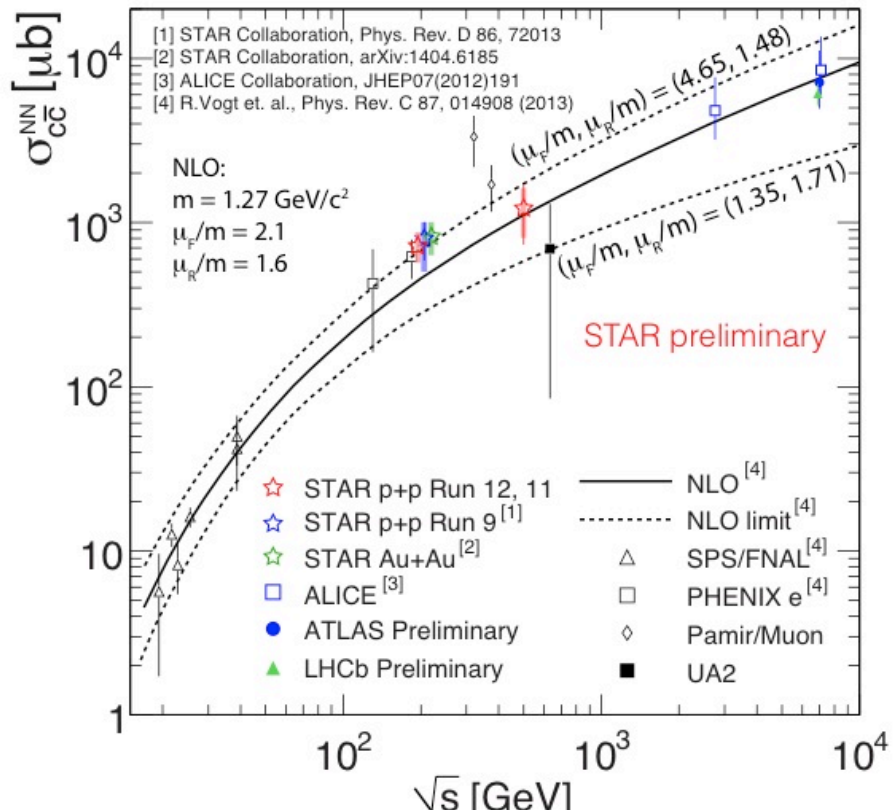


STAR Experiment at RHIC



Open Heavy Flavor in p+p





STAR, PRD **86** (2012) 072013
CDF, PRL **91** (2003) 241804
ALICE, JHEP **01** (2012) 128, EPJC **77** (2017) 550
FONLL: PRC **87** (2013) 014908

- Open heavy flavor production cross-sections in p+p collisions can be described by pQCD calculations but with large theoretical uncertainty

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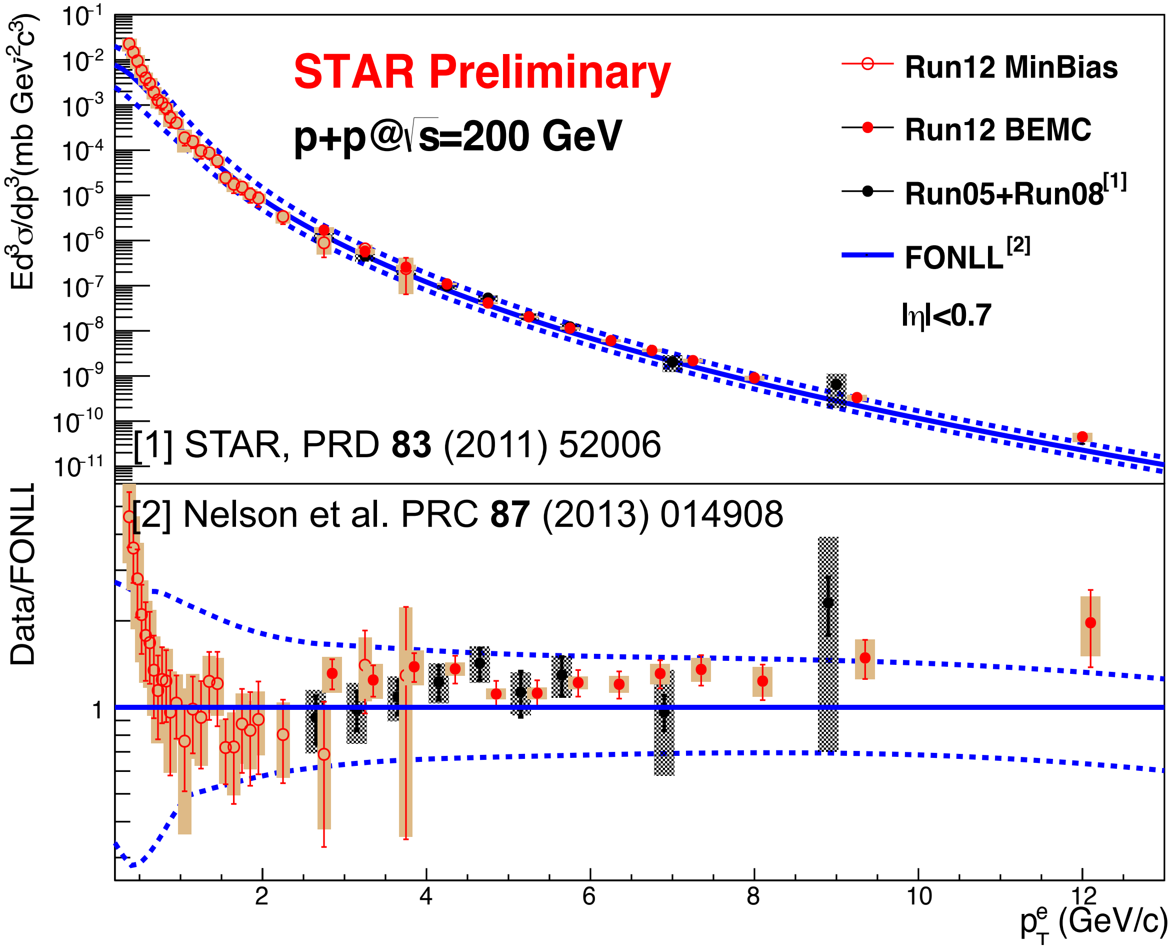
Open Heavy Flavor in p+p



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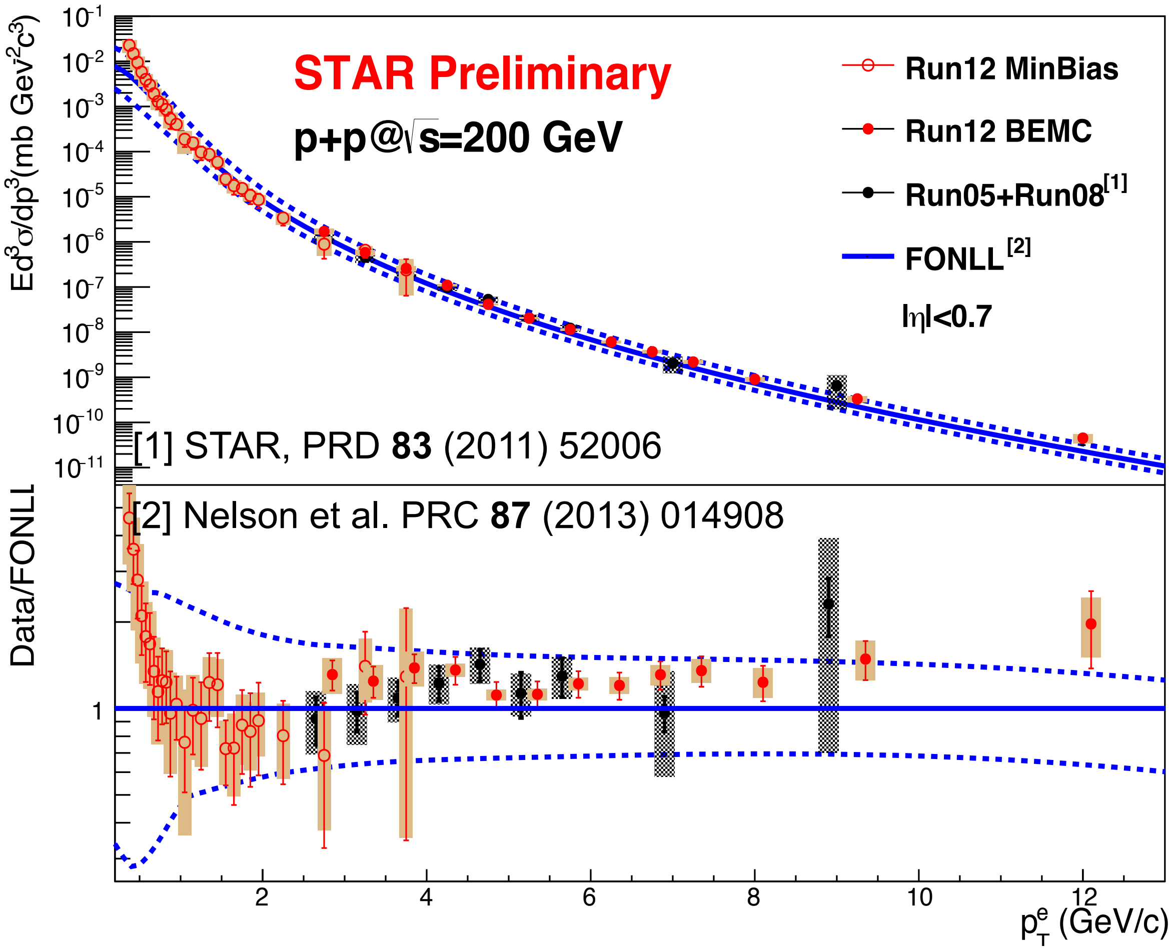
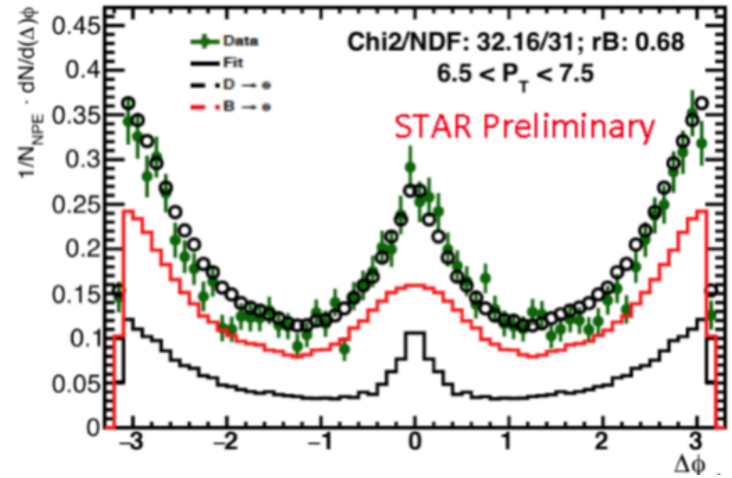
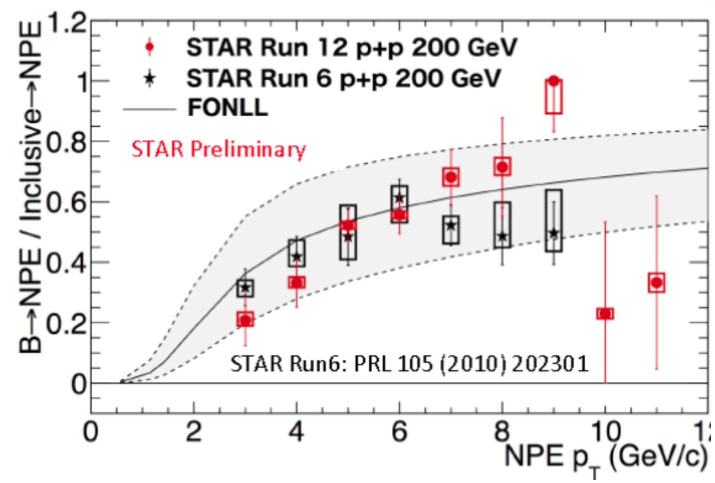
Open Heavy Flavor in p+p







- Open heavy flavor production cross-sections in p+p collisions can be described by pQCD calculations but with large theoretical uncertainty

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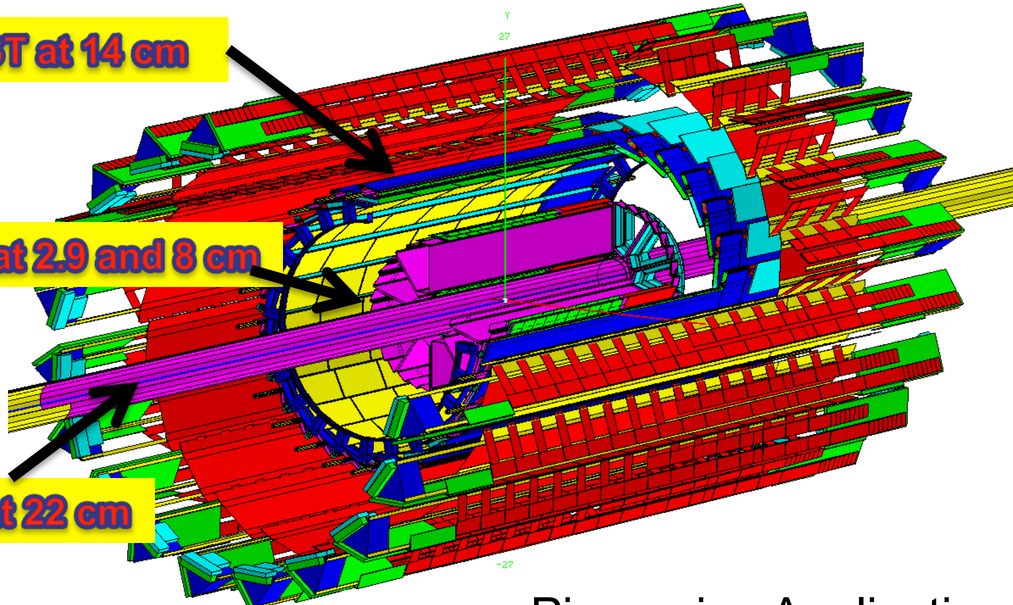
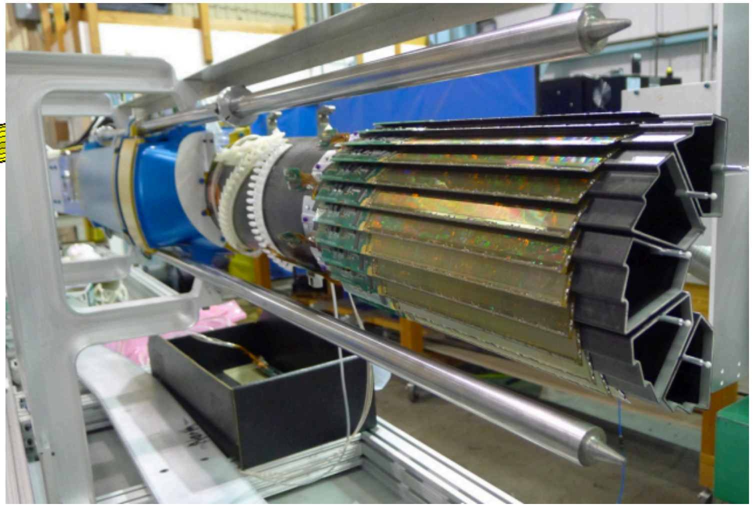
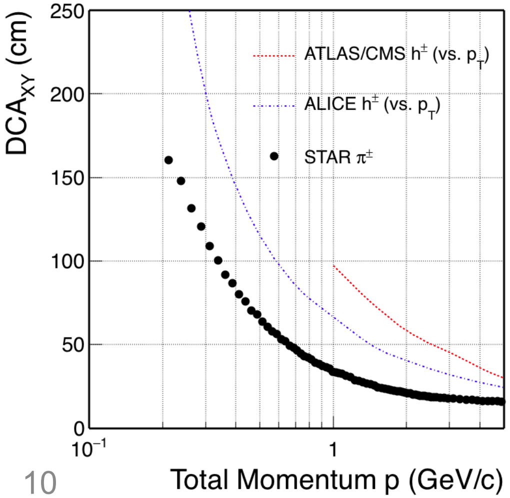
STAR Heavy Flavor Tracker



Half of STAR PXL



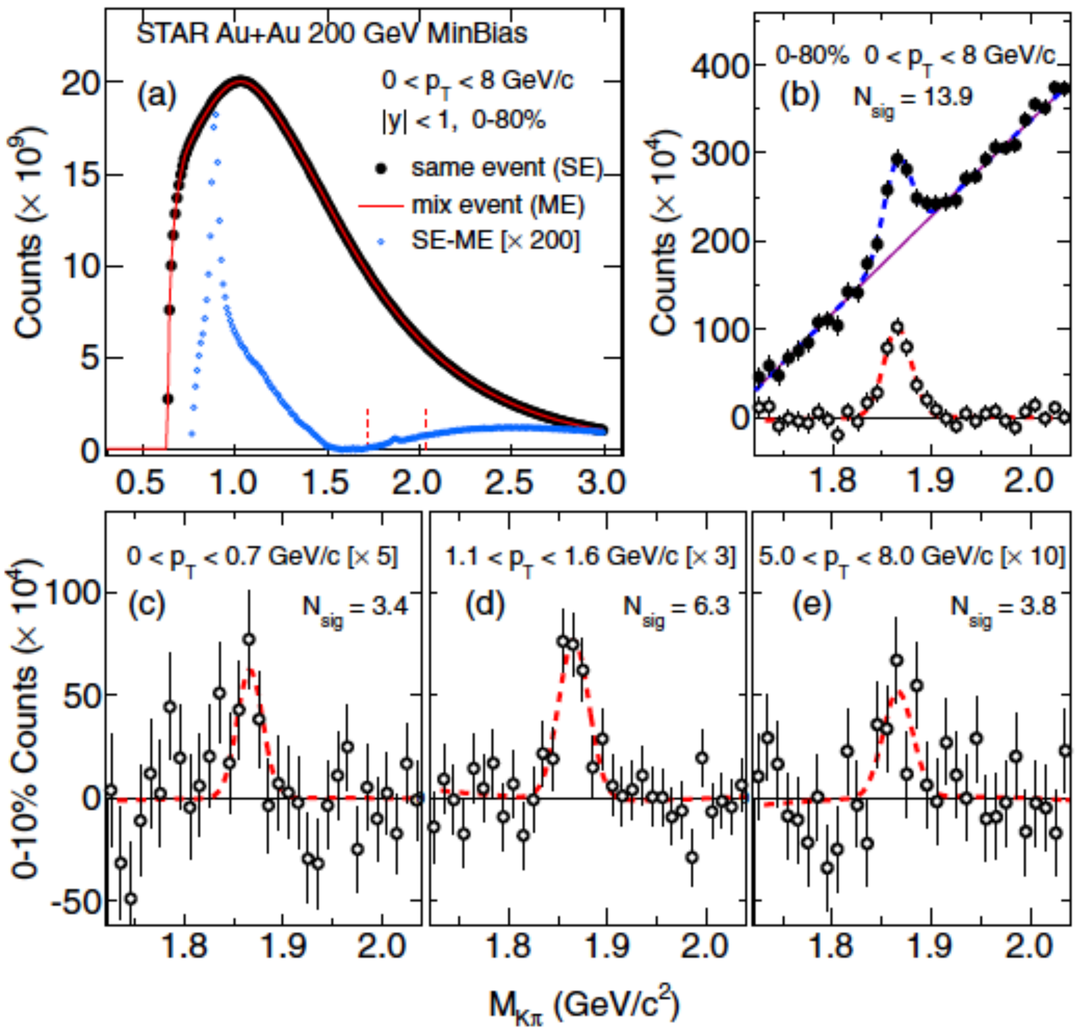


Pioneering Application of MAPS at colliders by STAR

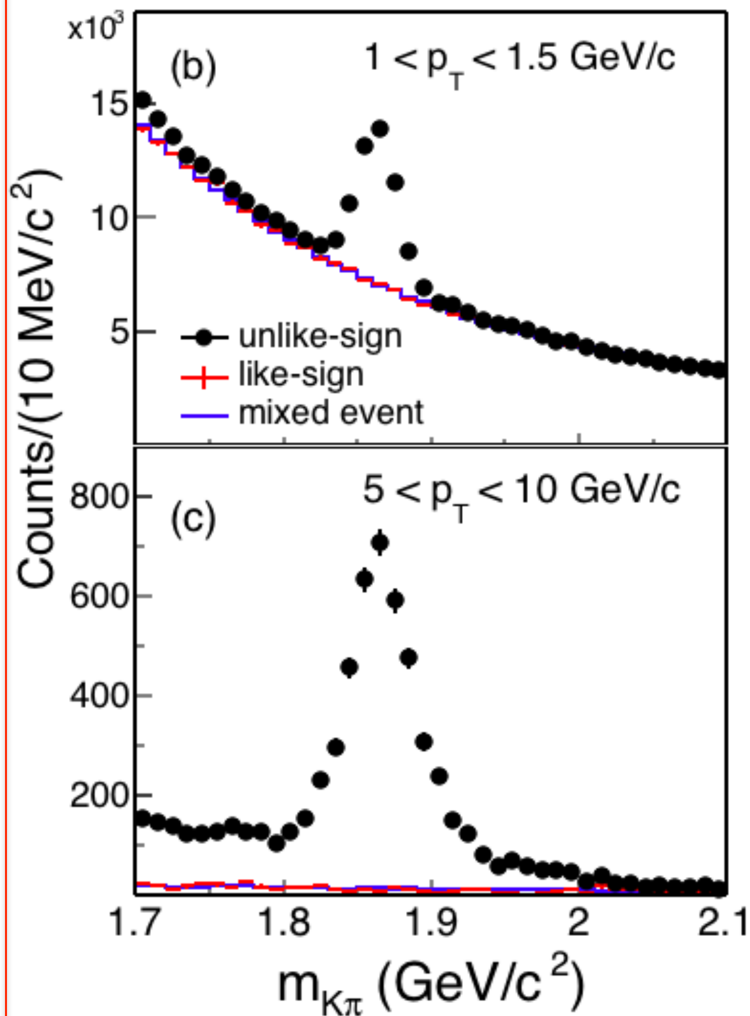
	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Technology	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	MAPS
Pixel size (μm)	50x425	50x400	100x150	200x200	50x425	20x20
Radius of 1st layer	3.9 cm	5.1 cm	4.4 cm	N/A	2.5 cm	2.8 cm
Thickness of 1st layer	1% X_0	~1% X_0	~1% X_0	~1% X_0	1% X_0	0.4% X_0

Improvement with HFT

2010/2011 w/o HFT: PRL 113 (2014) 142301



2014 w HFT: PRL 118 (2017) 212301



The following results are mostly based on 2014 Au+Au HFT data

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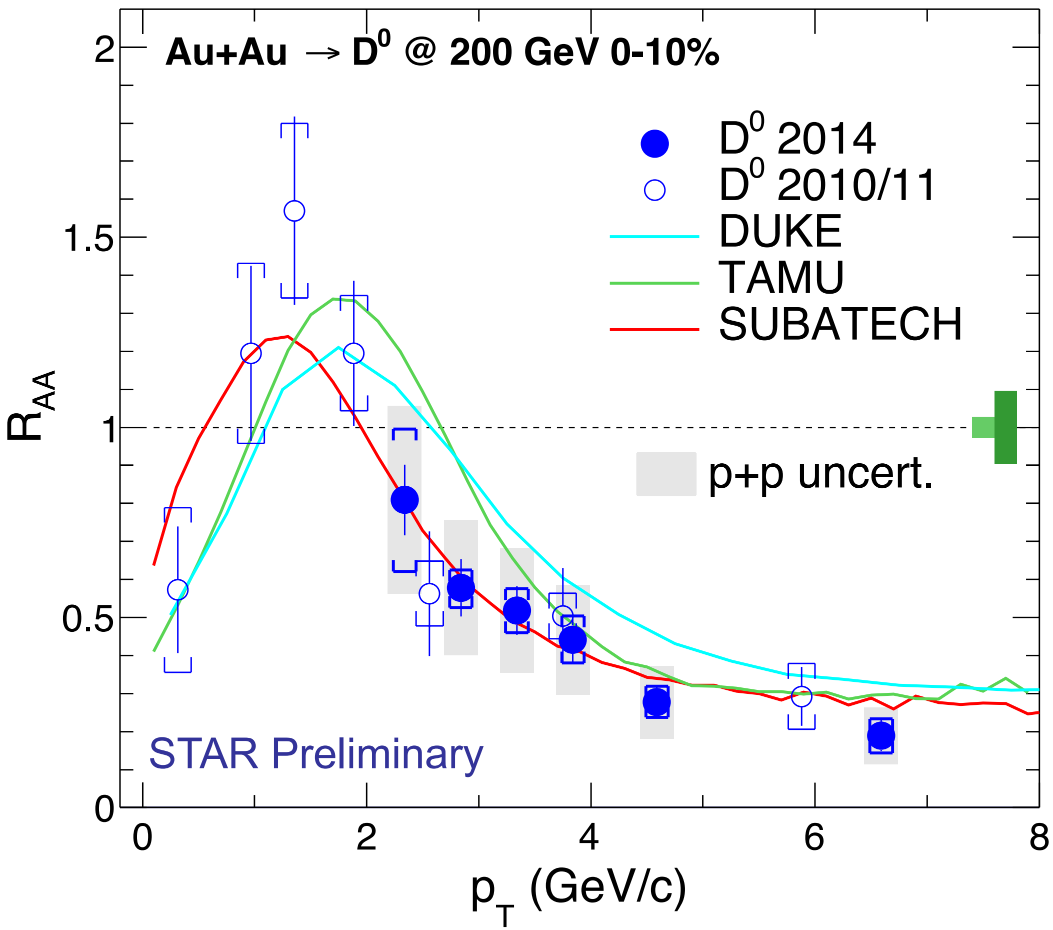
D^0 R_{AA} – Charm Quark Energy Loss



- High p_T: significant suppression in central Au+Au collisions
- New Au+Au HFT results have improved statistical and systematic precision
- p+p precision to be improved using 2015 data

STAR 2010/11: PRL 113 (2014) 142301

- Significant suppression for D^0 production at high p_T in central 200 GeV Au+Au collisions. Results at low p_T, other centrality and p/d+Au soon

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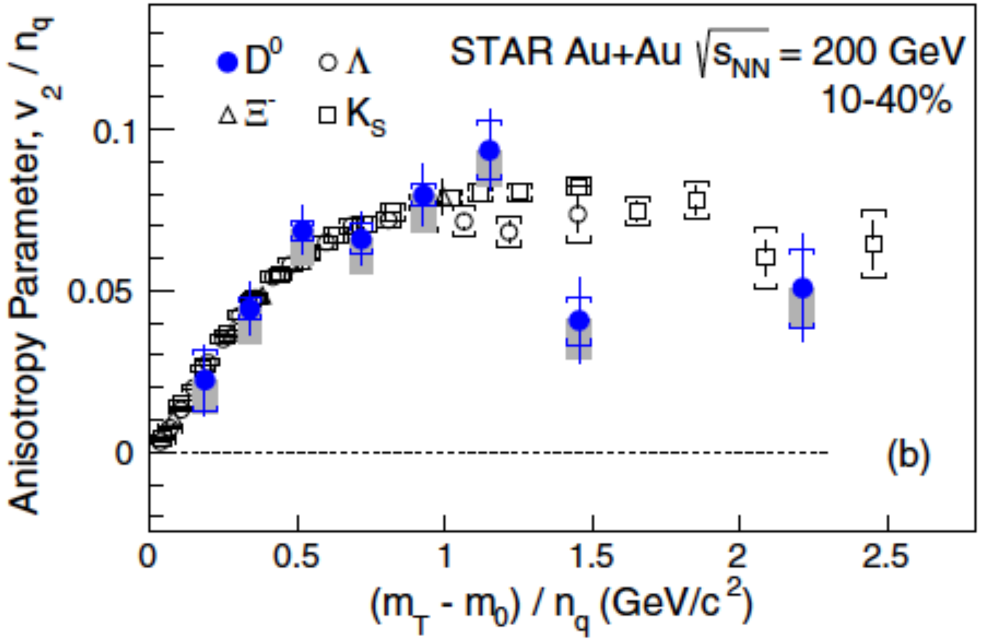
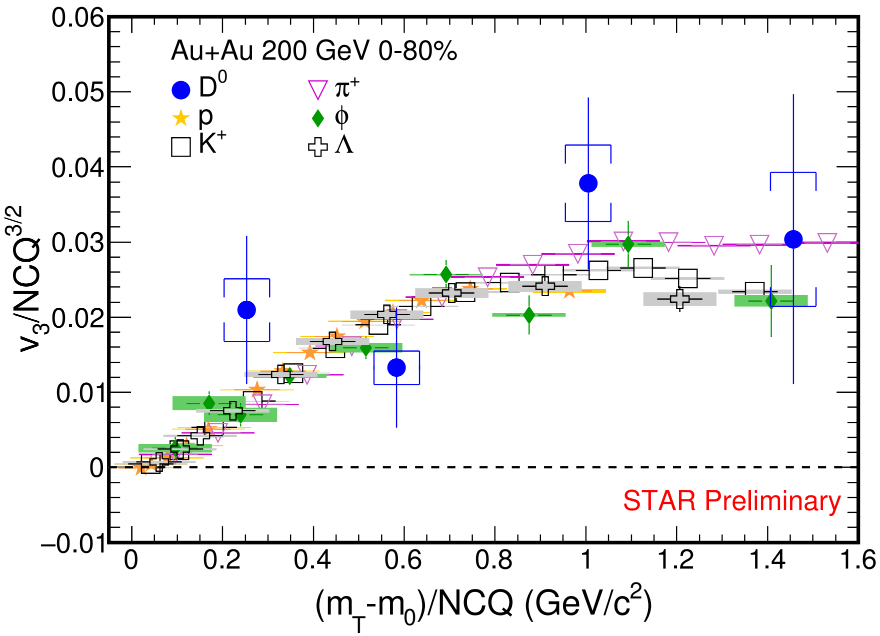
D^0 v_2 and v_3 – Charm Quark Collectivity





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 meson v_2 and v_3 follow the same NCQ scaling as light hadrons

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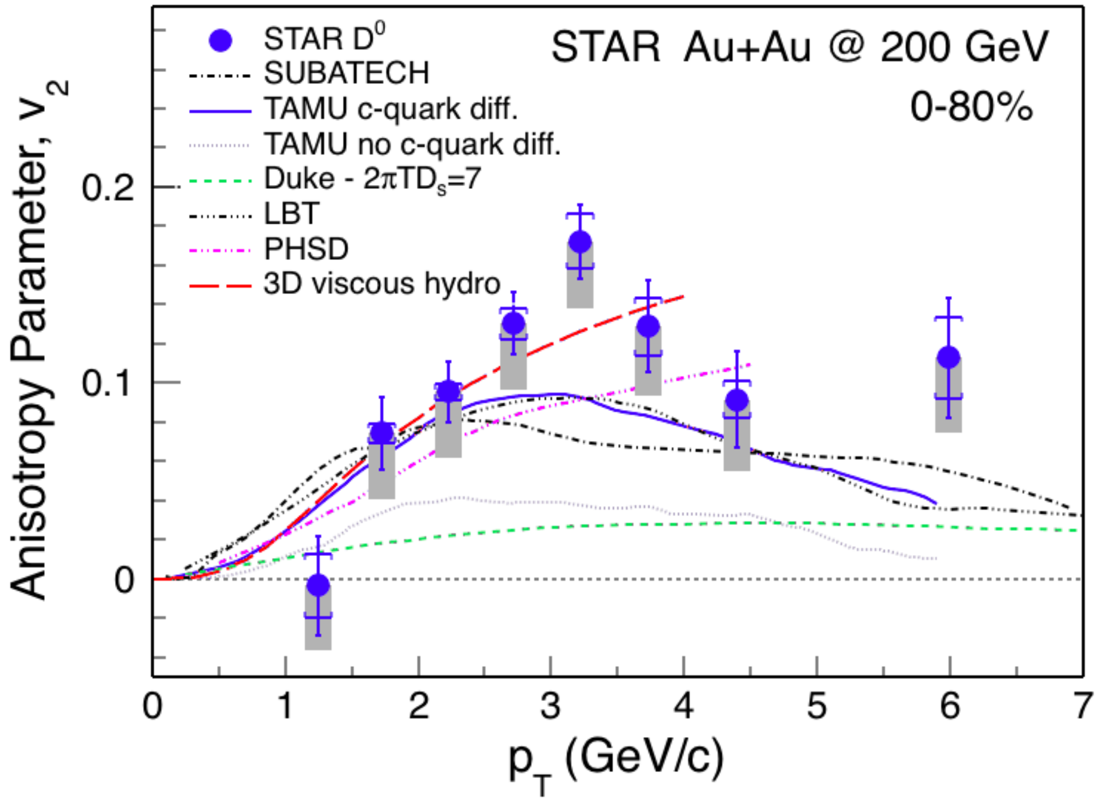
D^0 v_2 and v_3 – Charm Quark Collectivity



- Data rule out
  - TAMU no c-quark diffusion
  - Duke $2\pi TD_s=7$
- Data described by
  - SUBTECH
  - TAMU c-quark diffusion
  - LBT
  - PHSD
  - 3D viscous hydro.

STAR: PRL 118 (2017) 212301

- Charm quarks flow, and may have reached a local equilibrium with the medium

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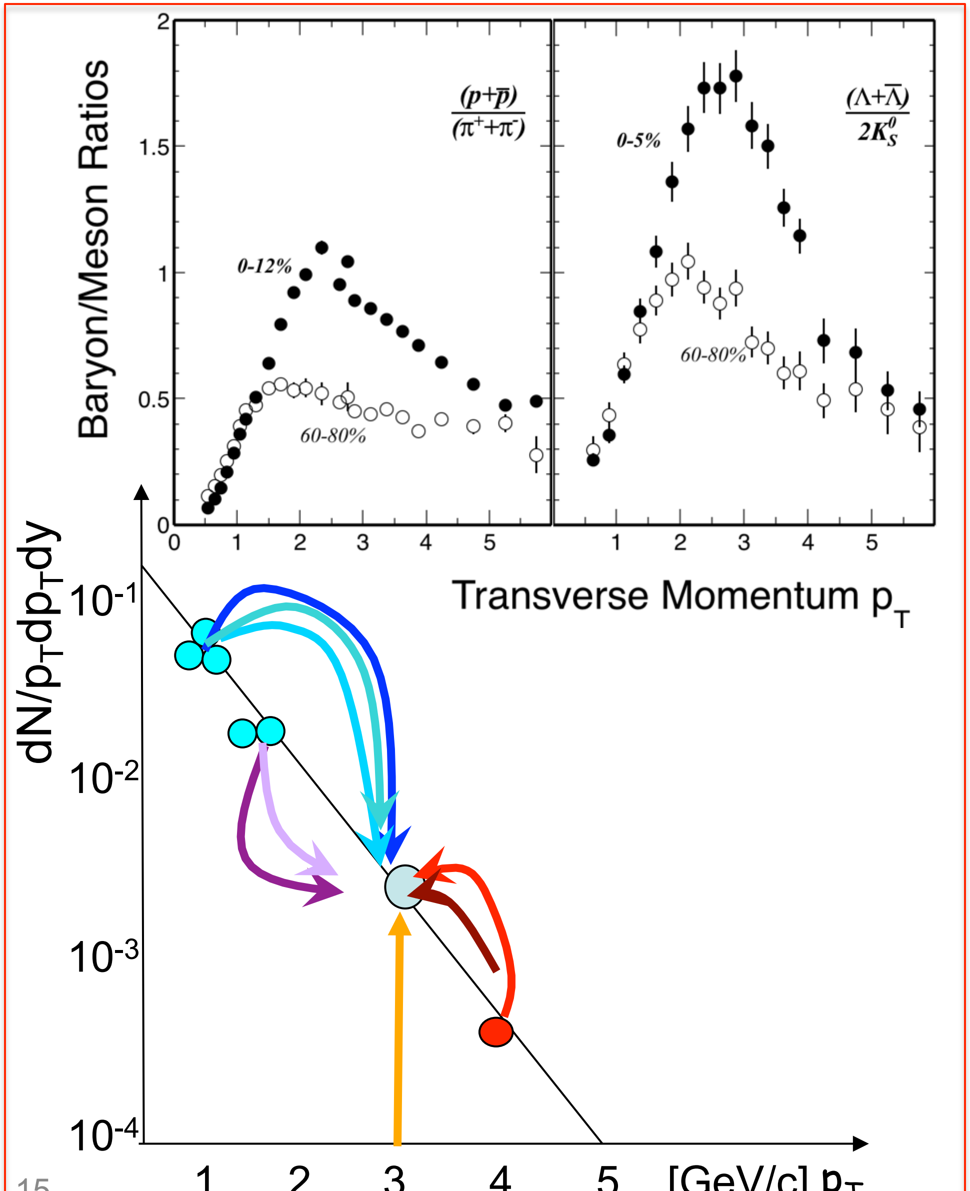
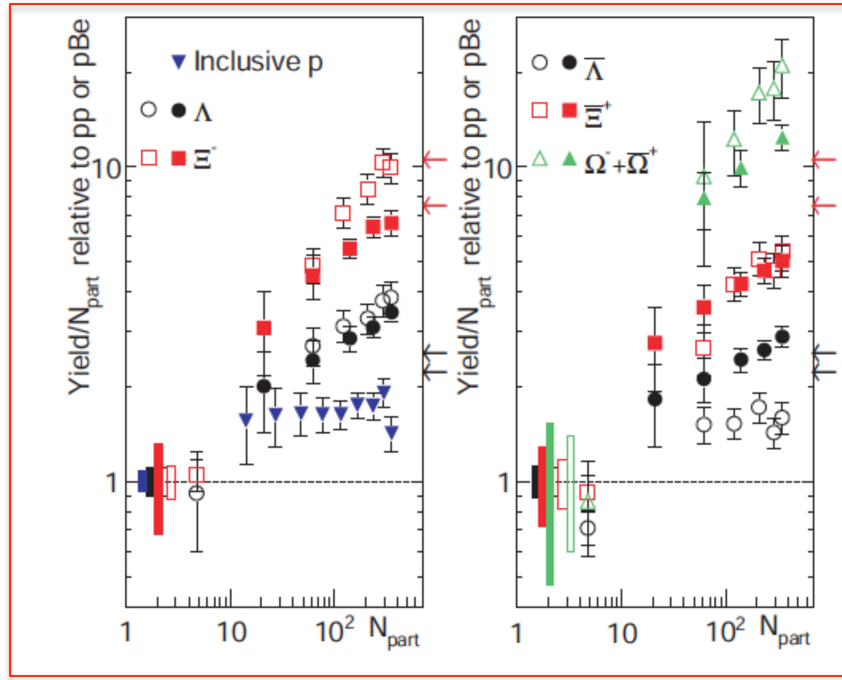
Charm Quark Hadronization





- Baryon-to-meson ratio enhancement at intermediate p_T due to hadronization through coalescence
- Strangeness enhancement due to high production rate gg-> ss in QGP
- Will we see the same enhancements in heavy flavor sectors?

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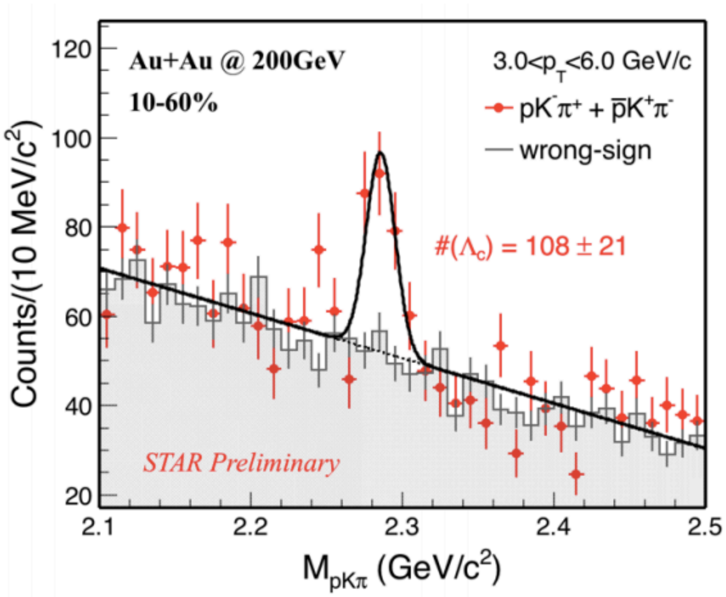
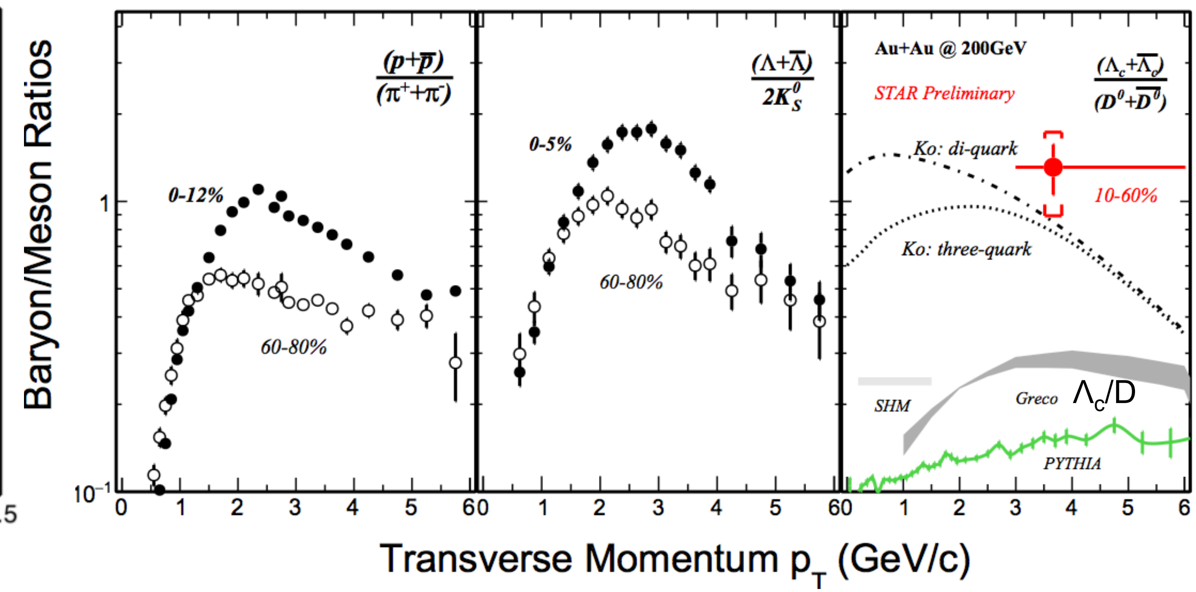
Λ_c/D^0 - Charm Quark Hadronization

First measurement of charmed baryon in heavy-ion collisions





Ko: PRL 100 222301 (2008), PRC 79 (2009) 044905
Greco: PRD 90 054018 (2014)

The Λ_c/D^0 ratio in Au+Au collisions is significantly larger than that in p+p − charm quark hadronization in heavy-ion collisions through coalescence

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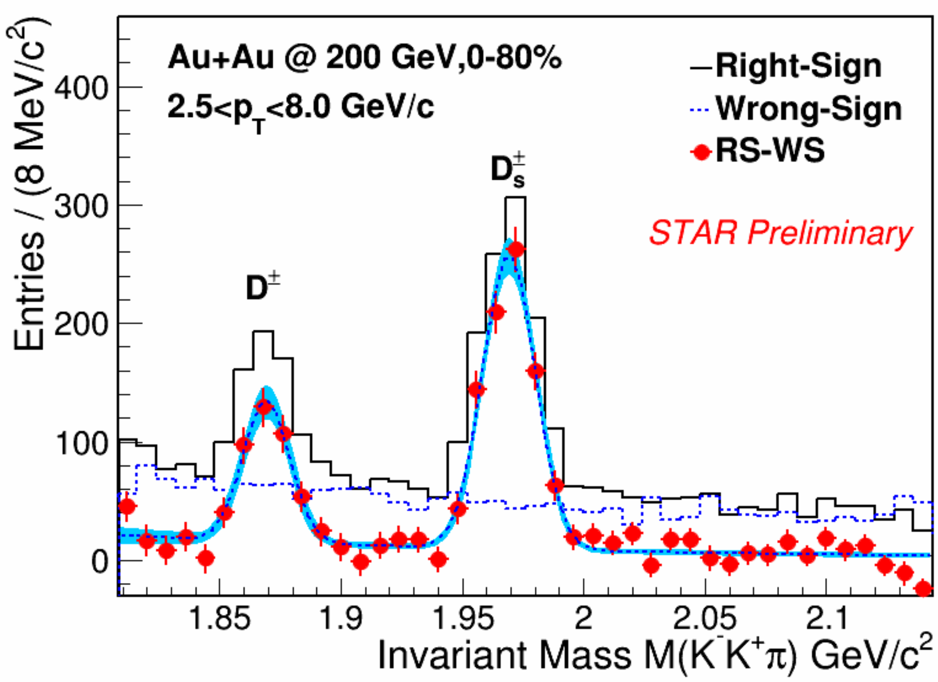
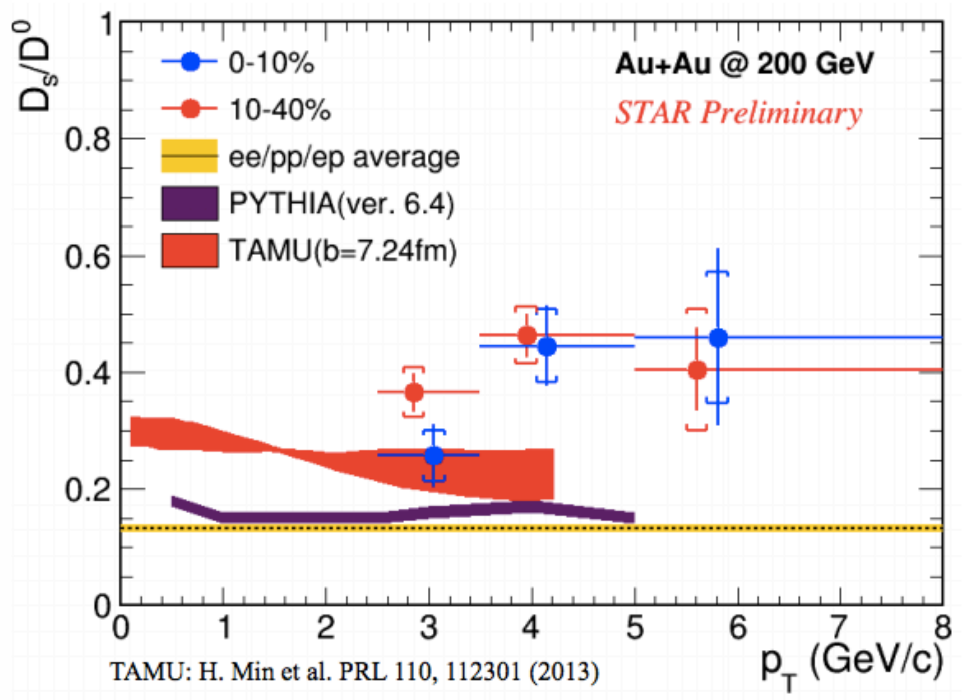
D_s/D^0 – Charm Quark Hadronization





The D_s/D^0 ratio in 200 GeV Au+Au collisions significantly larger than in p+p – charm quark hadronization in heavy-ion collisions through coalescence

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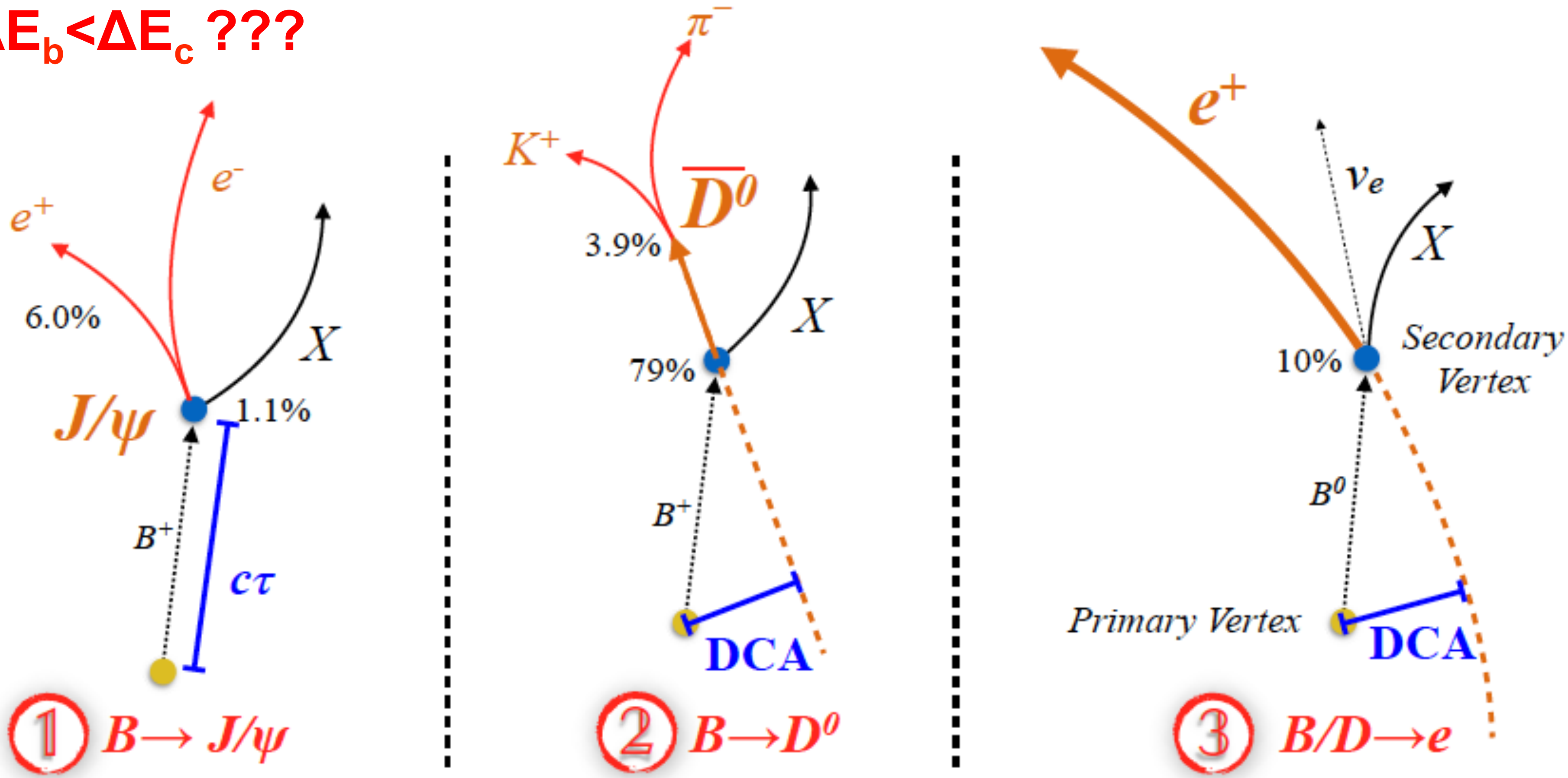
Bottom R_{AA} at RHIC

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



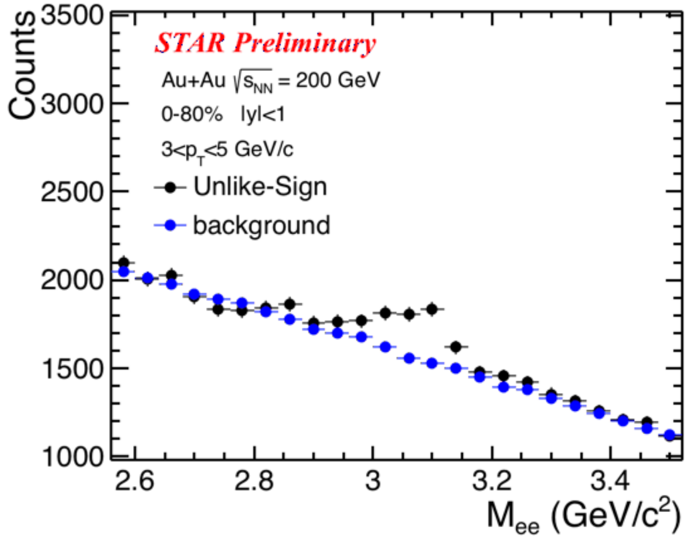
- We have measured 3 different decay channels of **B hadrons** enabled by the **HFT**.

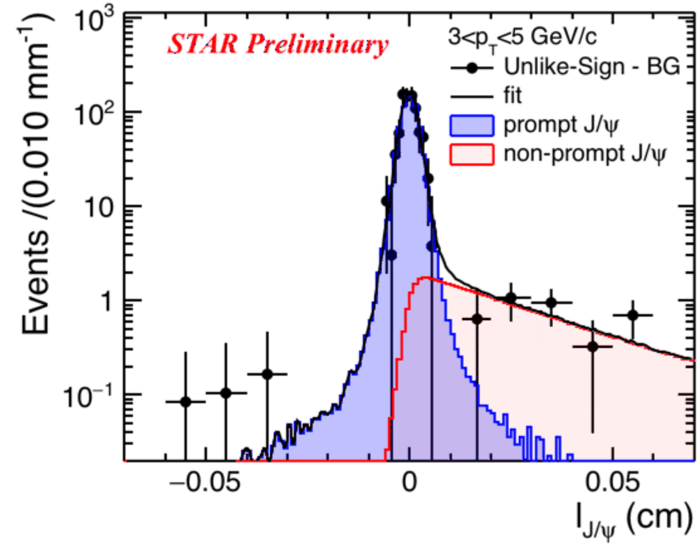
  1 → ~900M MB (2014) + ~1.2 nb^{-1} HT events (2014 + 2016)

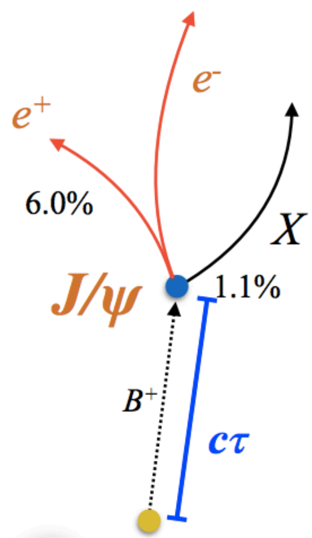
  2 → ~900M MB (2014)

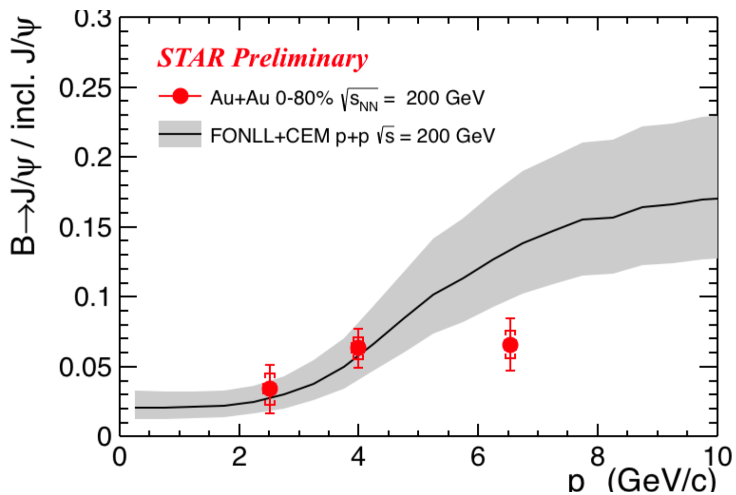
  3 → ~900M MB (2014) + ~0.2 nb^{-1} HT events (2014)

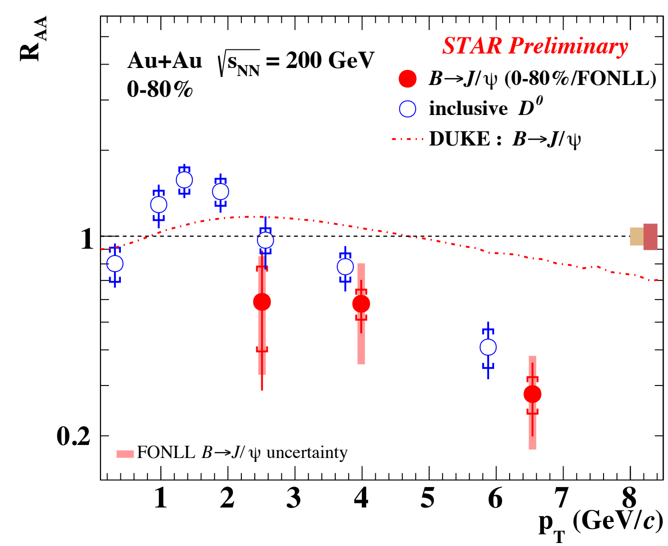
B->J/Ψ R_{AA} – Bottom Energy Loss











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

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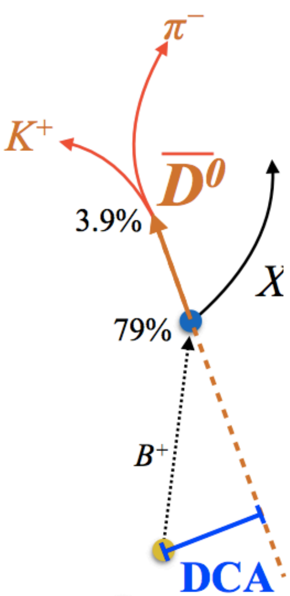
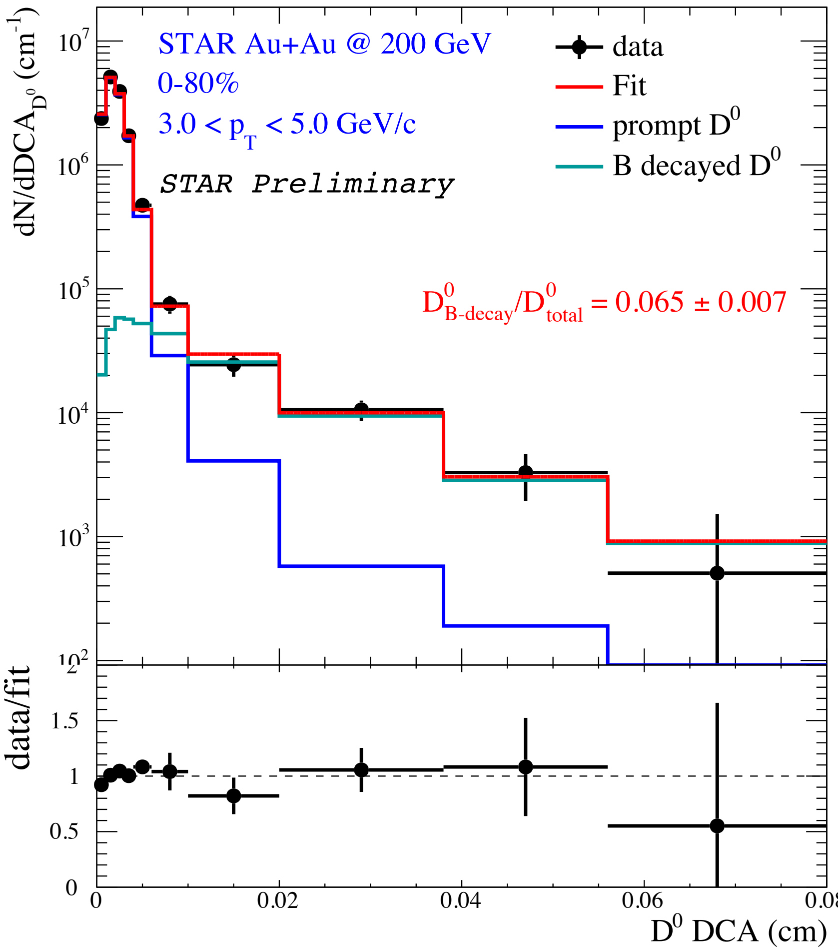
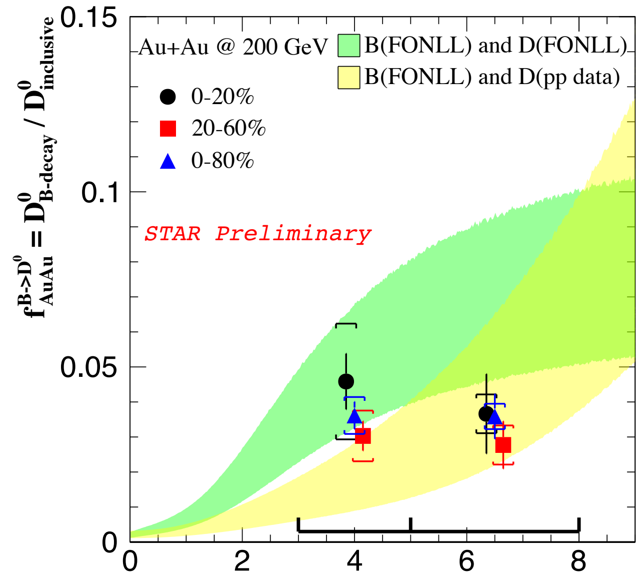
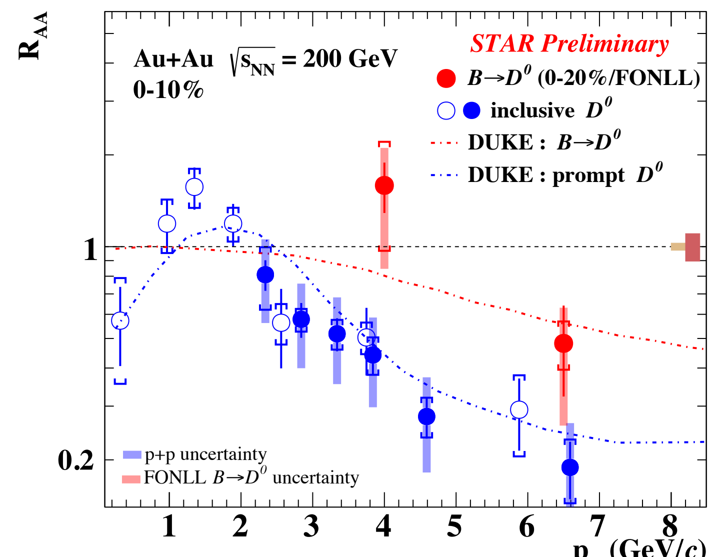
B->D^0 R_{AA} – Bottom Energy Loss









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

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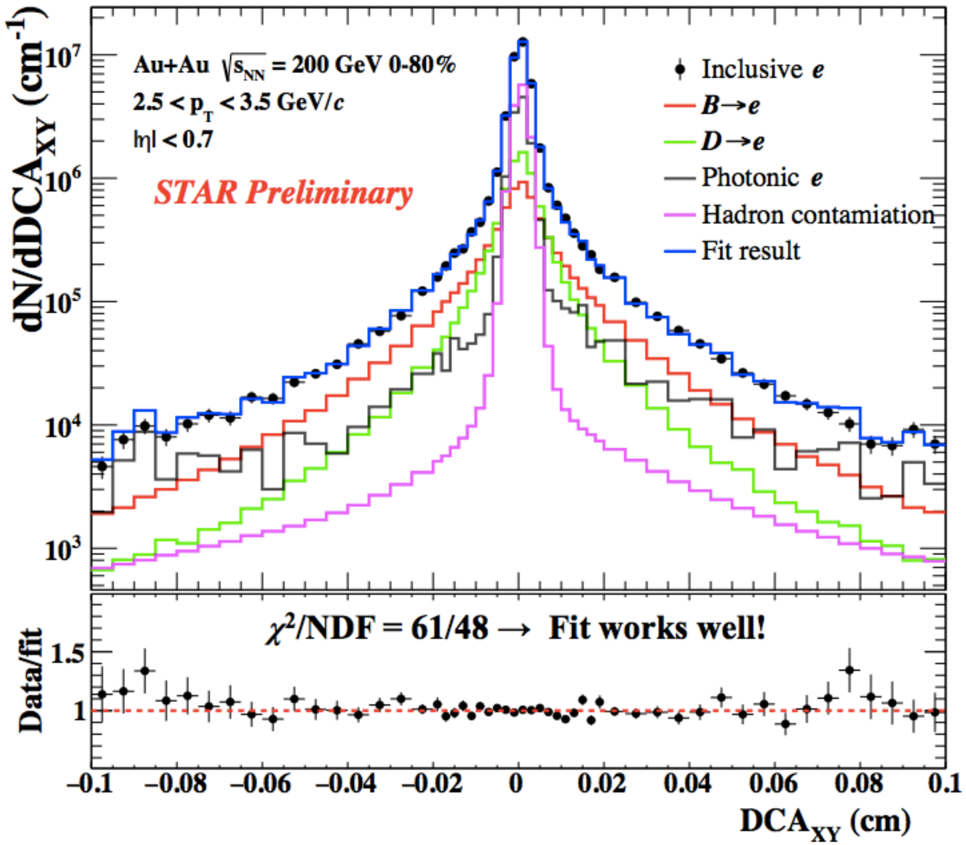
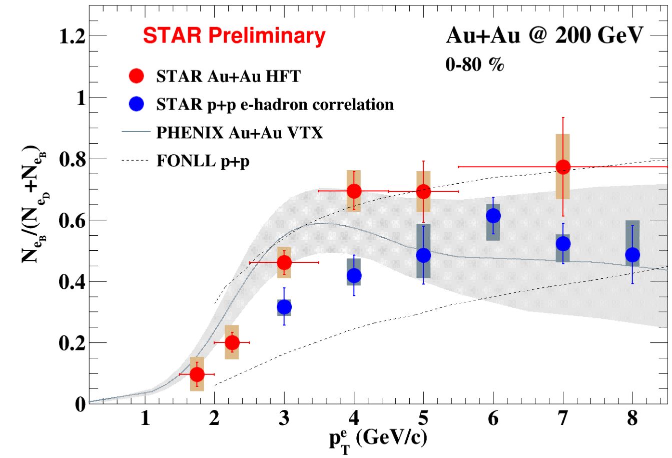
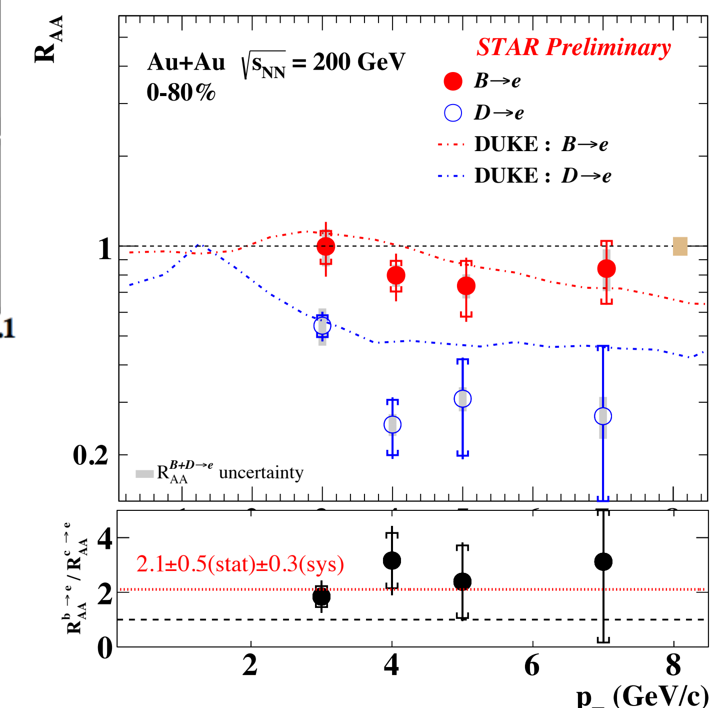
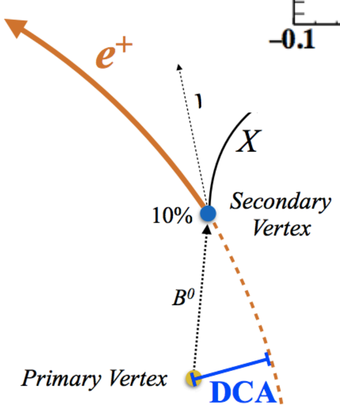
B->e R_{AA} – Bottom Energy Loss



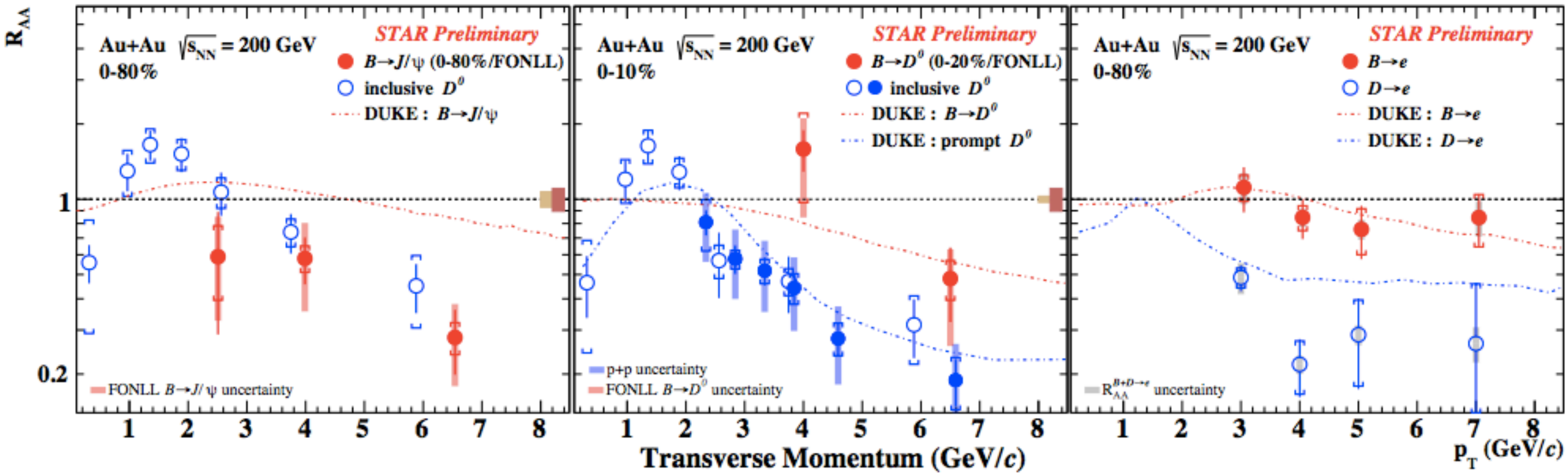






$$R_{AA}^{B\to e} = \frac{f_{Au+Au}^{B\to e}(data)}{f_{p+p}^{B\to e}(data)} R_{AA}^{inc.\ e}(data)$$

Bottom R_{AA} at RHIC



- Suppression of B-decayed J/ψ and D^0 for p_T > 5 GeV/c
  – significant ΔE_b
- $e^B R_{AA} > e^D R_{AA}$
  – consistent with expectation $\Delta E_b < \Delta E_c$

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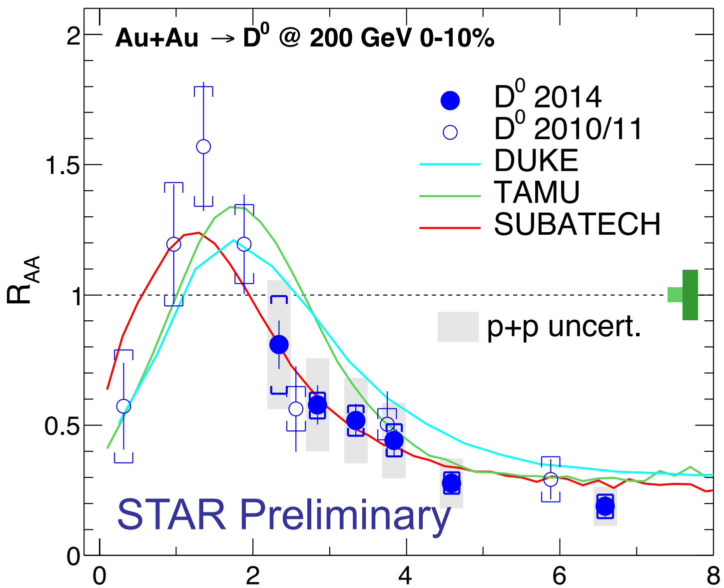
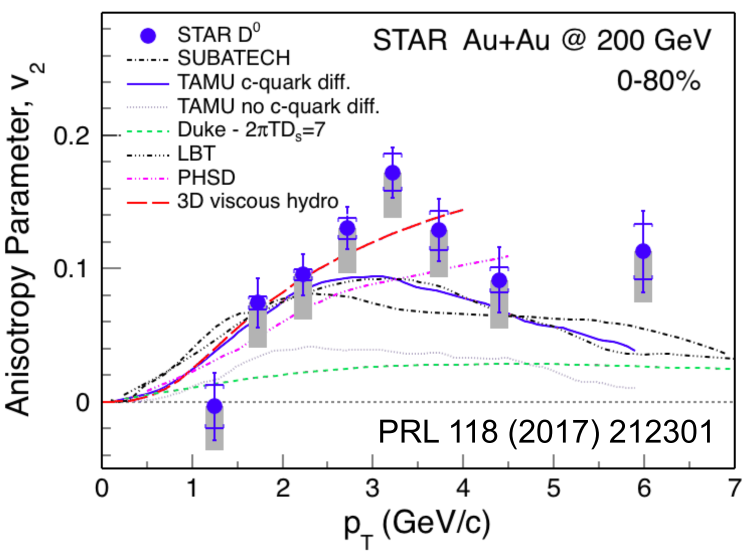
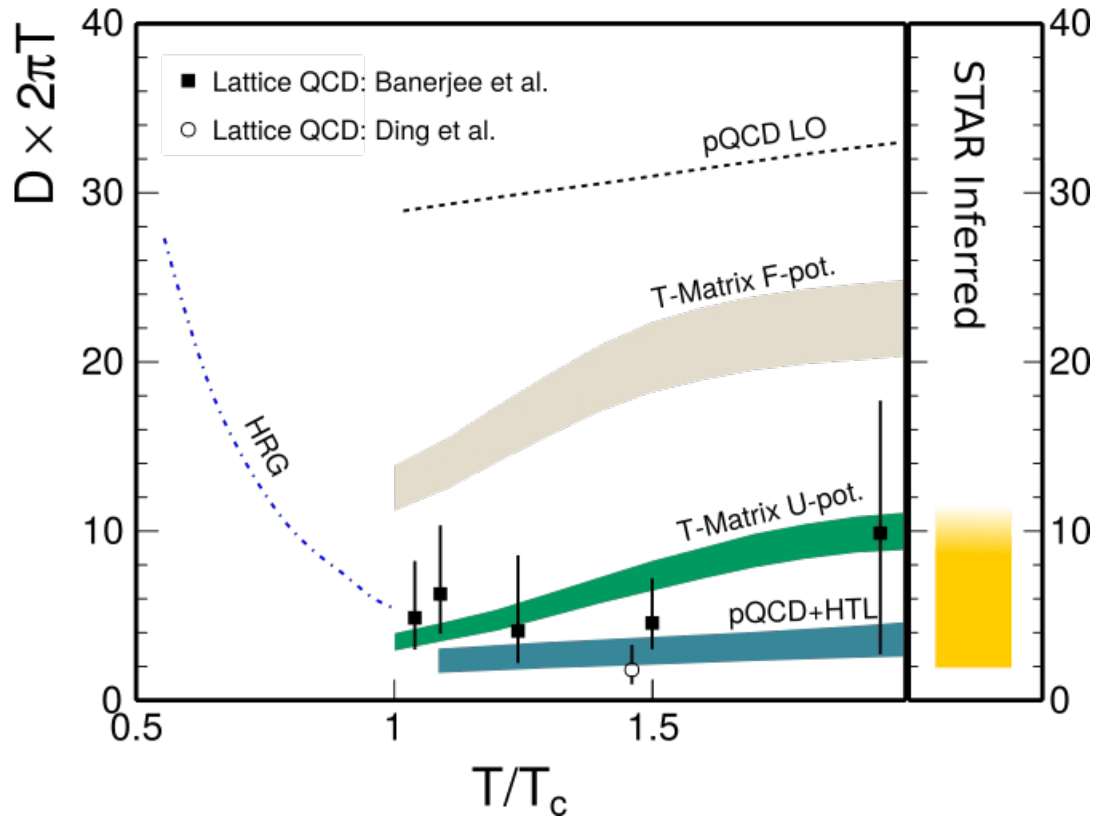
Compare with Model Calculations







Models corresponding to charm spatial diffusion coefficient of 2-12 for T_c-$2T_c$ describe D^0 R_{AA} and v_2. Lattice calculations consistent with this range.

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Summary and Outlook

- **Charm quarks strongly interact with QGP**
  - supported by D^0 flow at low p_T and suppression at high p_T
- **Charm quarks thermalize with the QGP medium**
  - supported by D^0 flow
- **Charm quarks hadronize through coalescence**
  - supported by D_s/D^0 and Λ_c/D^0 enhancements
- **Mass hierarchy of parton energy loss $\Delta E_b < \Delta E_c$**
  - Hint from B->e and D->e R_{AA}

- New results from 2015-2016 data, and on p+Au, d+Au, HF correlations ... are underway. Stay tuned!

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Backup

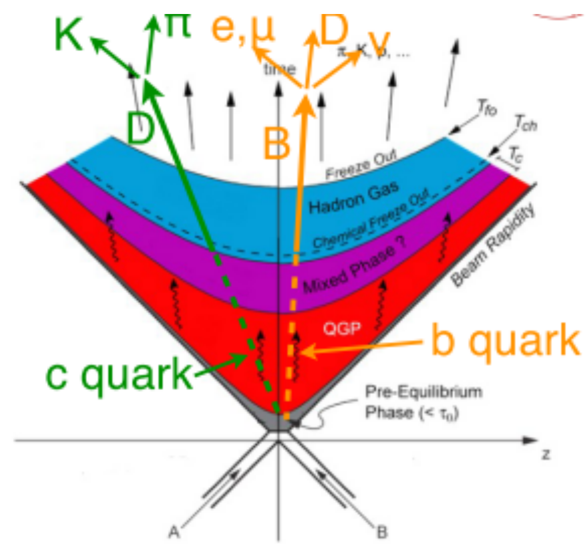
Open HF production in A+A collisions

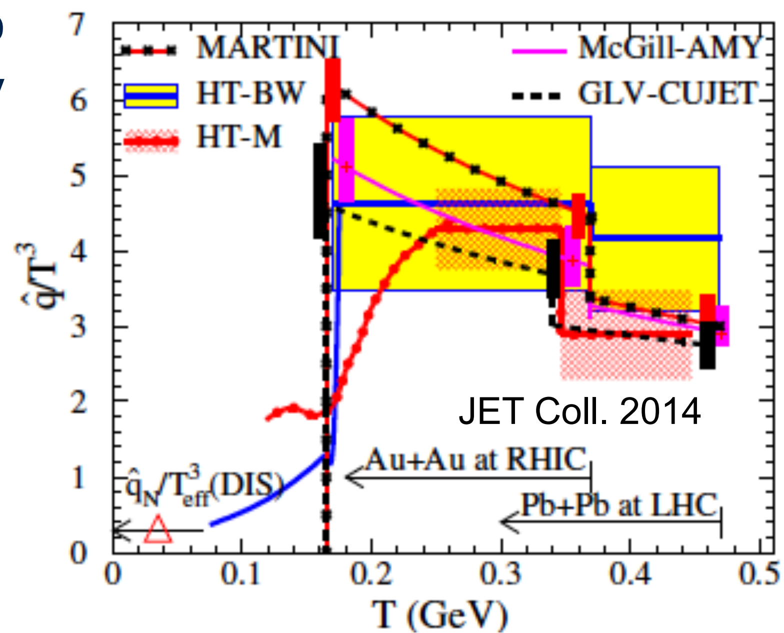
Heavy quark tomography

- produced mostly from initial hard parton scatterings at RHIC energies; exposed to the whole evolution of the QGP
- yield or mass not (significantly) altered within the QGP

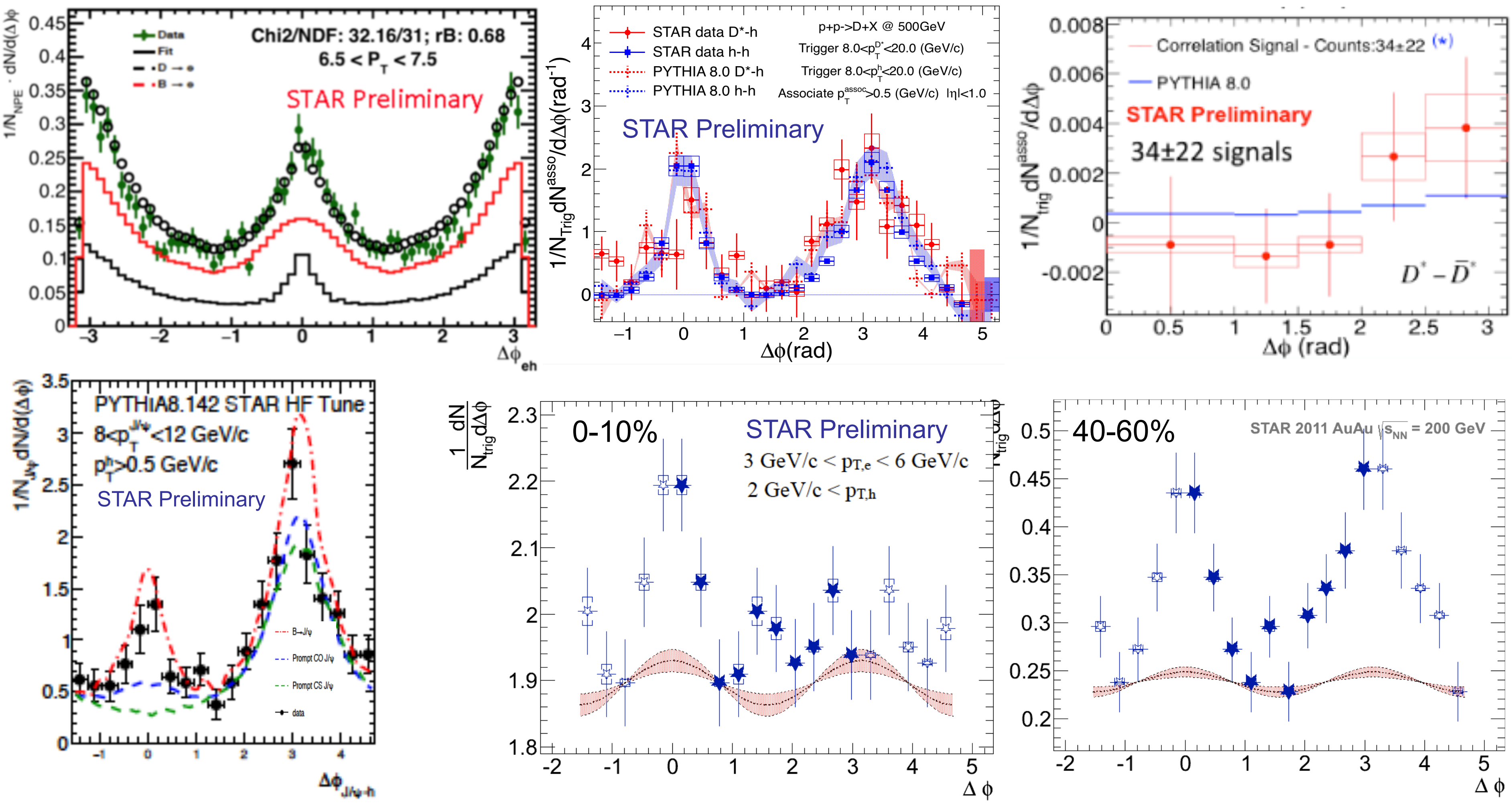
Sensitive to parton-medium interactions and medium properties

- Comparing light, charm and bottom to disentangle radiative vs collisional energy losses
- Compare different charm hadron (D^0, D_s, Λ_c) yields to study hadronization
- Extraction of p- and T-dependent parton transport coefficients needs precise charm and bottom data at both low and high p_T from RHIC and LHC



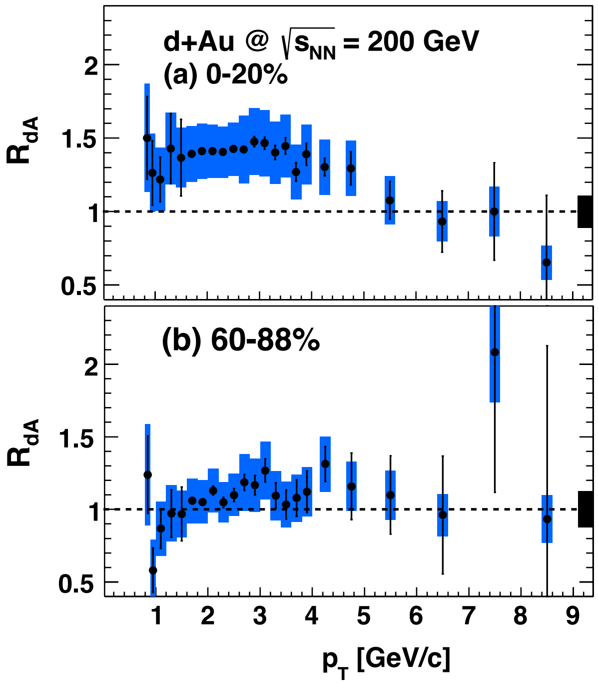


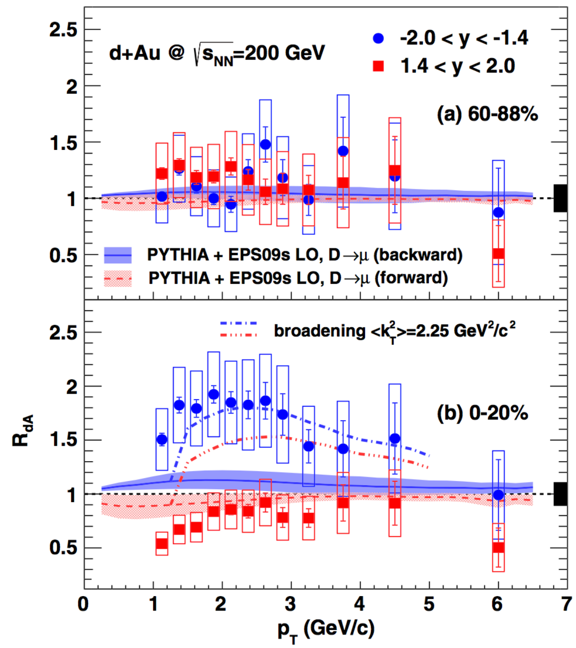
Open HF correlations

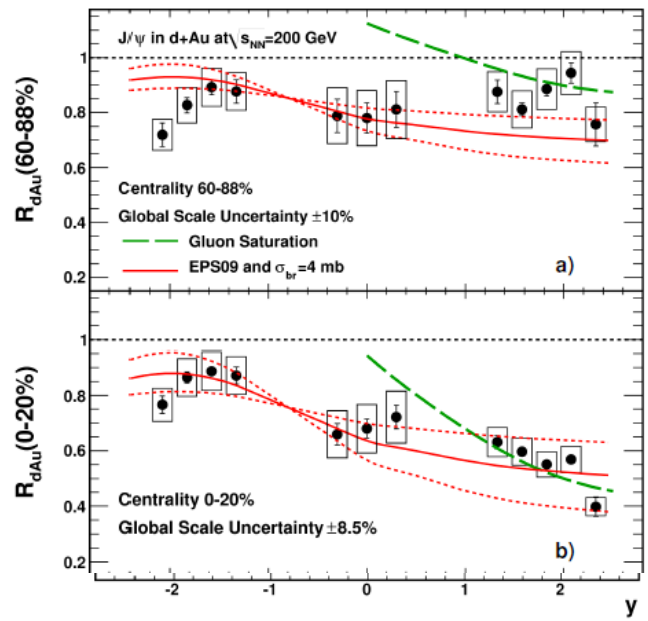


- e^{HF}/D-h in p+p described by PYTHIA8, large uncertainty for $D-\bar{D}$
- Away side suppression e^{HF}-h in 0-10% Au+Au collisions relative to 40-60%

HF in d+A collisions at RHIC







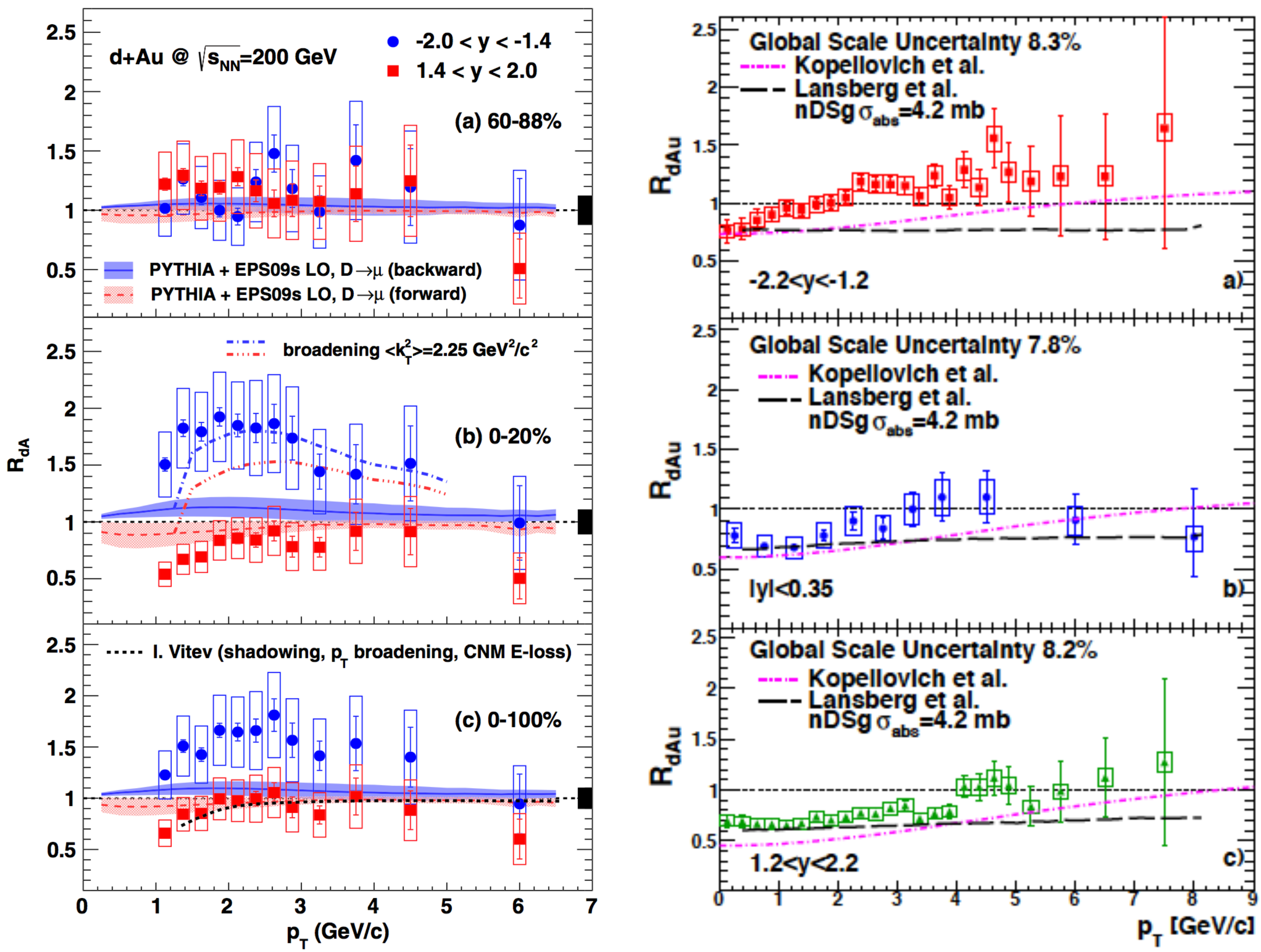
In 60-80%: open HF R_{dA}~1, J/ψ R_{dA}~0.8-0.9

In 0-20%:

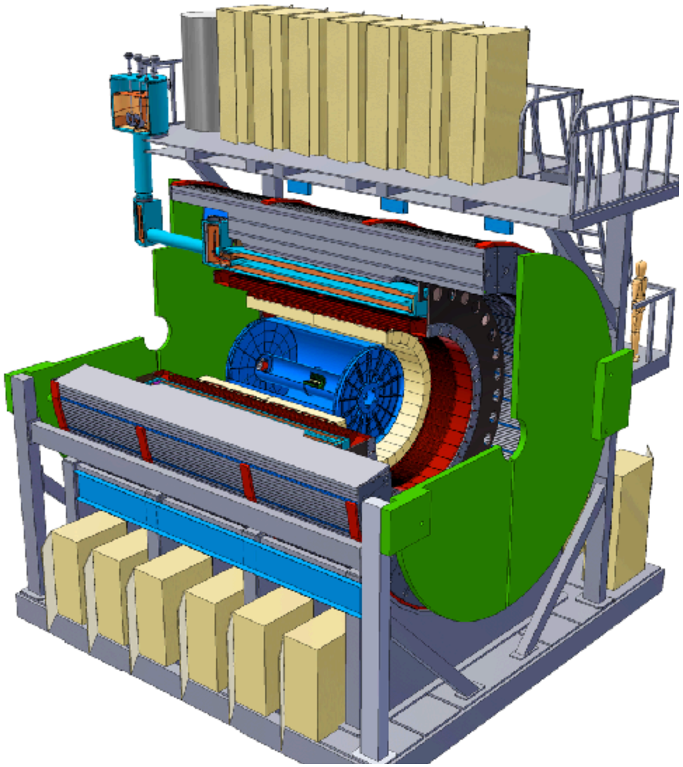
- mid-y and A-going (y<0), open HF R_{dA}>1, J/ψ R_{dA}~0.7-0.8
- d-going (y>0), open HF R_{dA}<1, J/ψ R_{dA}~0.6

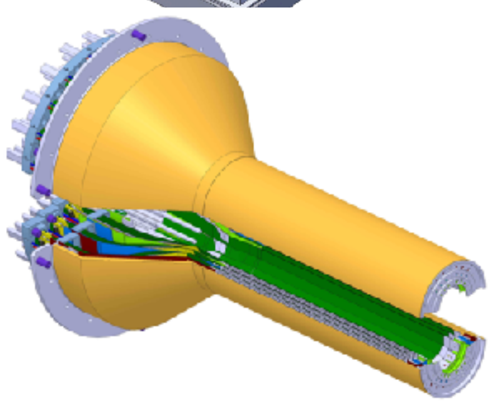
Nuclear PDF+other CNM effect for open HF, nuclear absorption for J/ψ

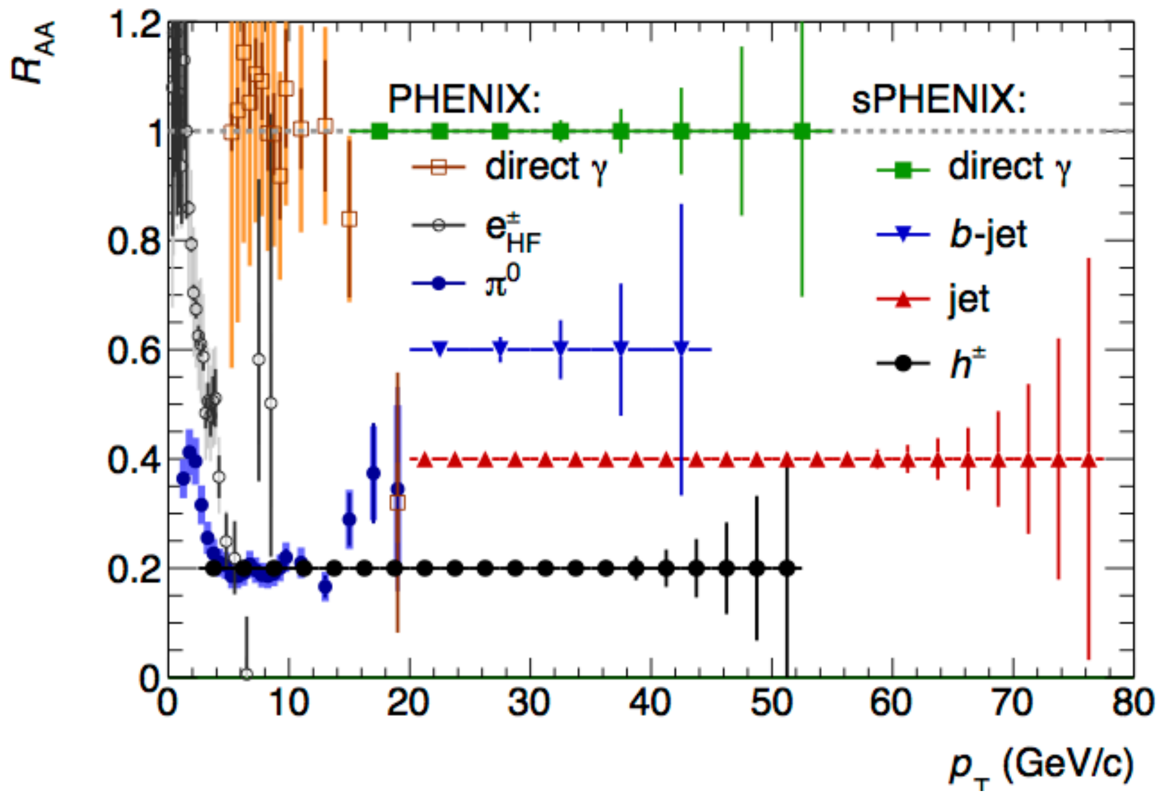
HF in d+A collisions at RHIC

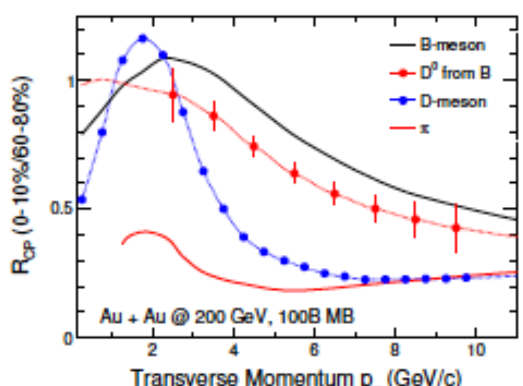


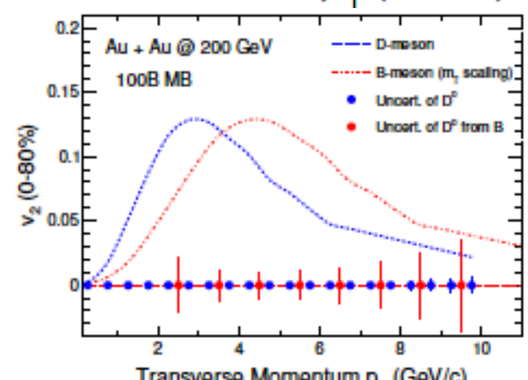
sPHENIX (2022-2026)











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