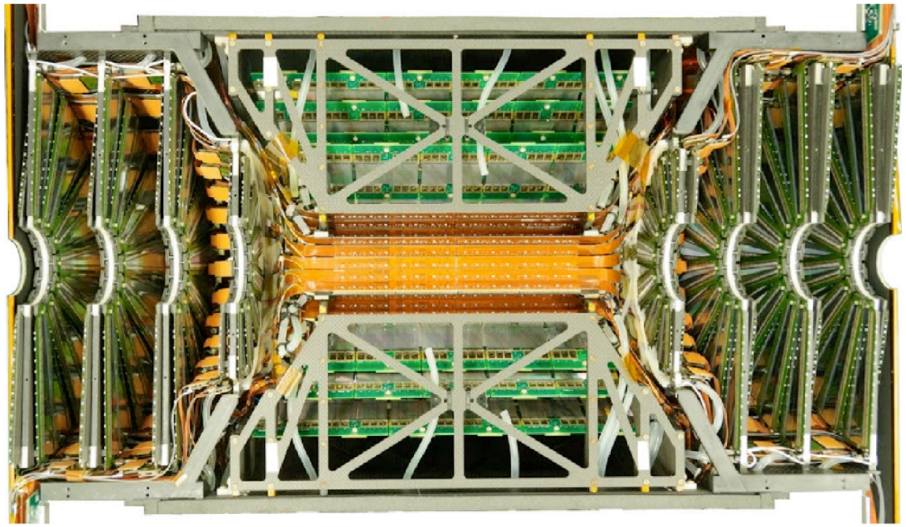
Open heavy flavor at RHIC

Michael R. Lomnitz
(Lawrence Berkeley National Laboratory)
RHIC – AGS Heavy Flavor workshop

HFT @ STAR

(F)VTX @ PHENIX



Tuesday, June 20th, 2017

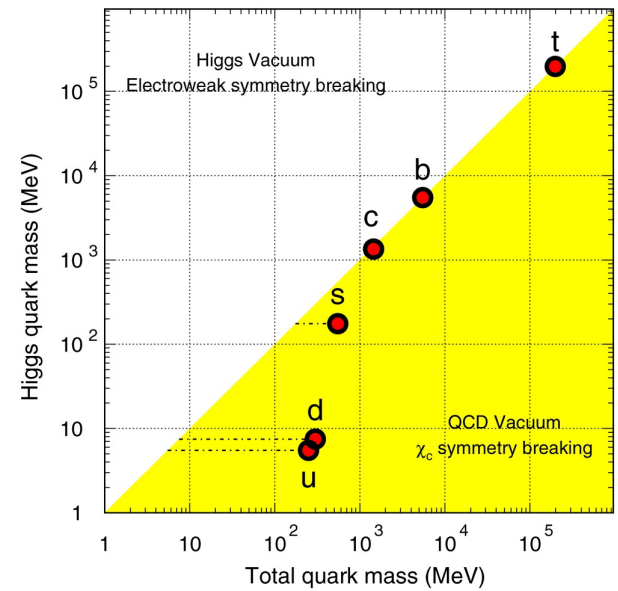
Outline

- Motivation
- Current state of affairs
- Open charm
- Open bottom
- Summary
- Future prospects

Motivation

- Heavy quark masses are mostly unchanged by chiral symmetry restoration.
  - Higgs mass: electro-weak symmetry breaking (**current** or **naked** quark mass).
  - QCD mass: chiral symmetry breaking (**constituent** or **dynamical** quark mass).
- Produced early in the collision in hard scattering processes → experience whole evolution of the QGP.

X. Zhu, *et al*, Phys. Lett. **B647**, 366(2007).



Motivation

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  - Higgs mass: electro-weak symmetry breaking (**current** or **naked** quark mass).
  - QCD mass: chiral symmetry breaking (**constituent** or **dynamical** quark mass).
- Produced early in the collision in hard scattering processes → experience whole evolution of the QGP.
- Heavy quark diffusion: study properties of the underlying fluid
  - Brownian motion approach
  - Measure charm quark flow

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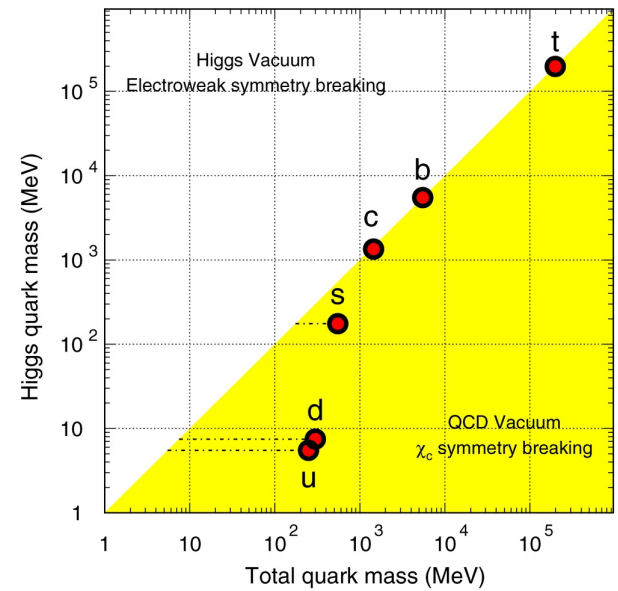
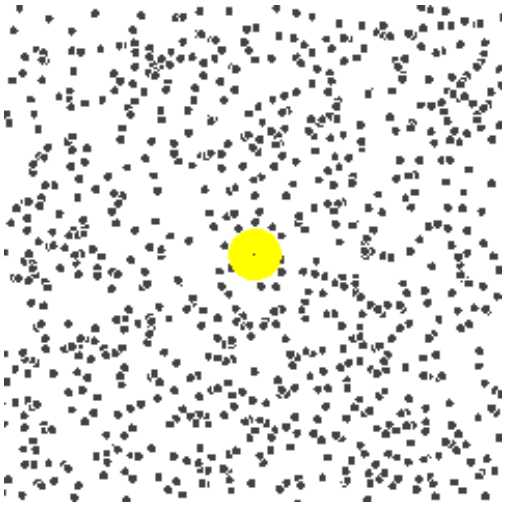




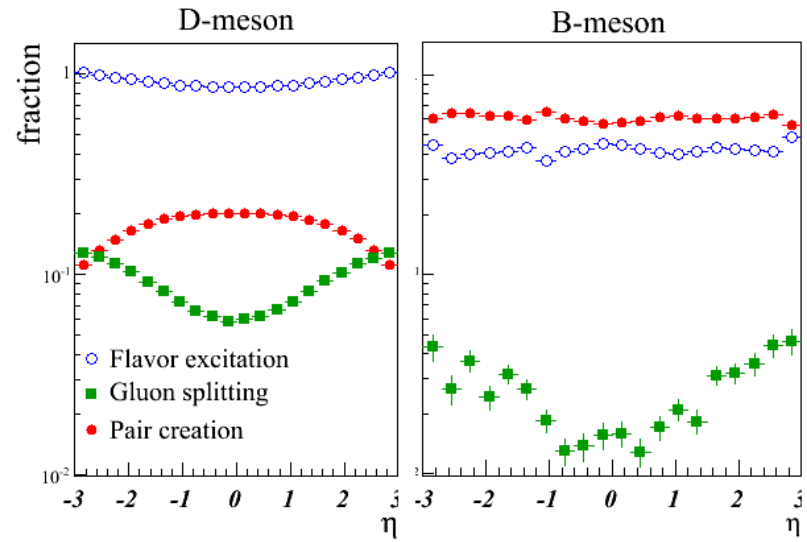
Motivation

- Total heavy quark production cross-section is only affected by initial state effect on gluons
  - Production at RHIC energies is not dominated by gluon splitting (unlike LHC)
- D vs. B can probe different production mechanisms: pair creation vs. flavor excitation
- Theoretical prediction for ΔE in medium:

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \ ?$$

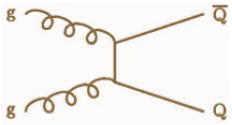
- Precise measurements of c and b quarks energy loss are crucial for understanding of parton interactions with the medium

PYTHIA6 hard scattering @ 200 GeV

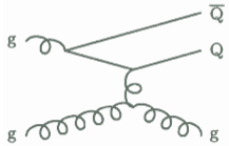


C. Luis da Silva, Parallel Session 8.4 QM17

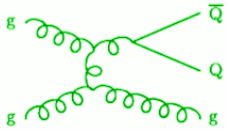
Pair creation



flavor excitation



gluon splitting

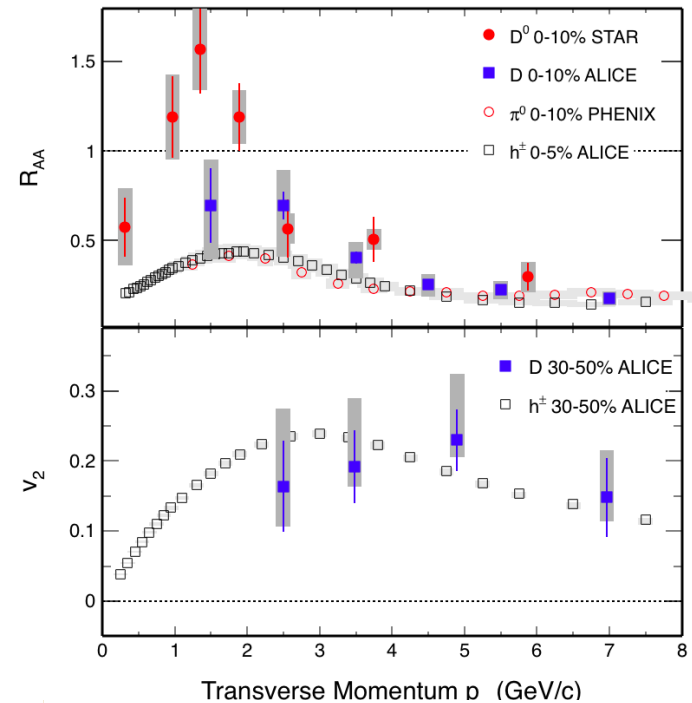


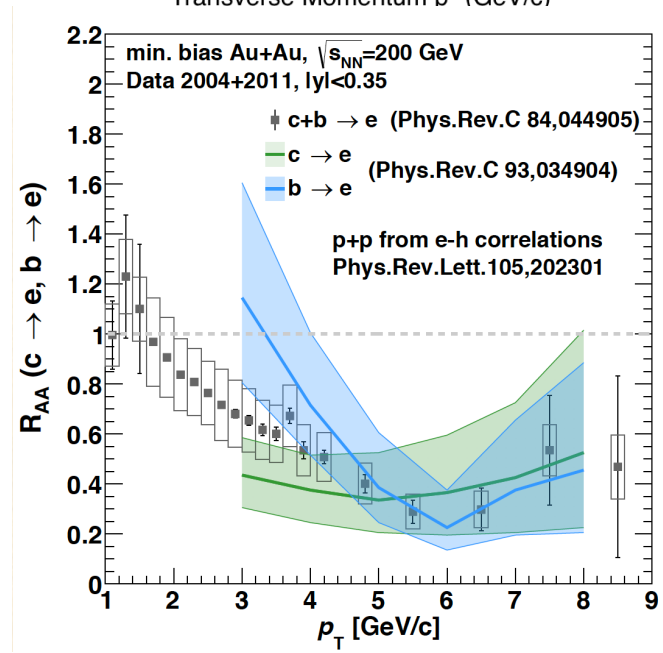
Recent developments and understanding

STAR:PRL 113 (2014) 142301
PHENIX:PRL 101 (2008) 232301
ALICE: PRL 111 (2013) 102301
arXiv:1509.06888 (2015)

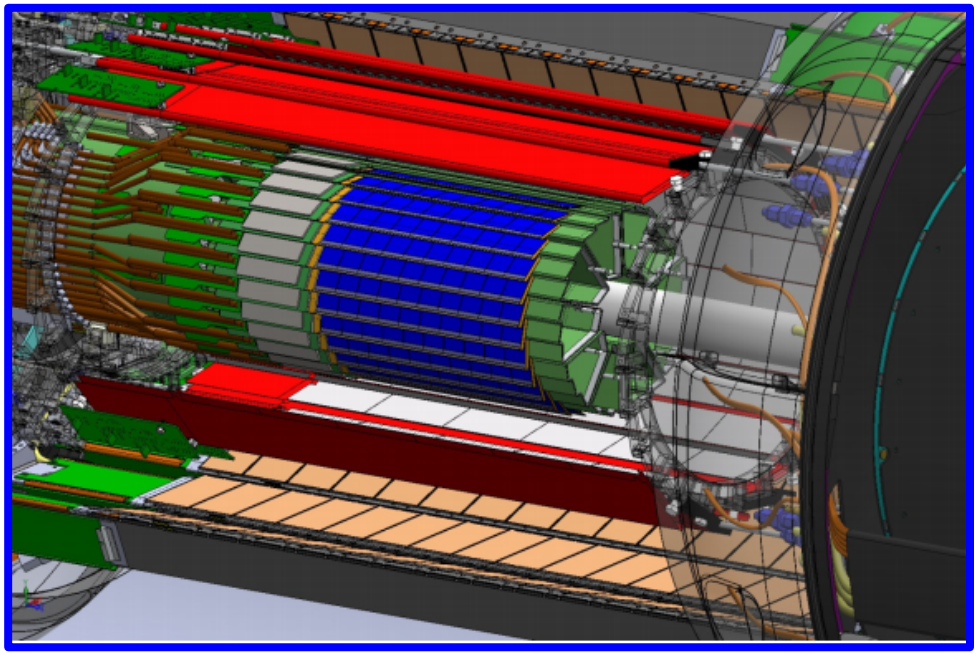
- *D*-meson R_{AA}: Significant suppression at RHIC and LHC at high p_T :

  strong charm-medium interactions
- D^0 v_2: LHC results are compatible with light flavor v_2. Are charm thermalized at LHC?
- e R_{AA}: Hint of less energy loss for b compared to c below 4 GeV/c
- What is occurring at low p_T at RHIC? v_2 is especially sensitive to the partonic medium: scattering strength, transport properties,...





STAR Heavy Flavor Tracker (HFT)

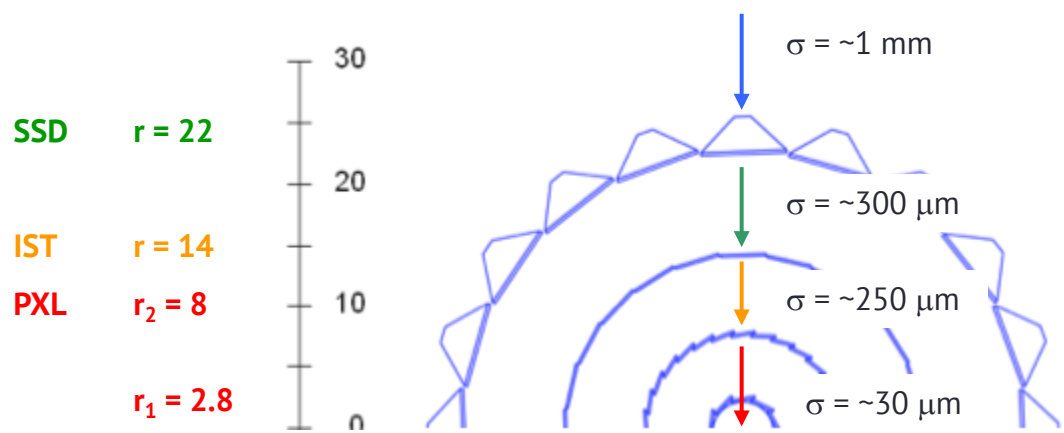


- Thinned Monolithic Active Pixel Sensor technology
- Low material budget
  - 0.52% X_0 for PXL Cu cables
  - 0.39% X_0 for PXL Al cables

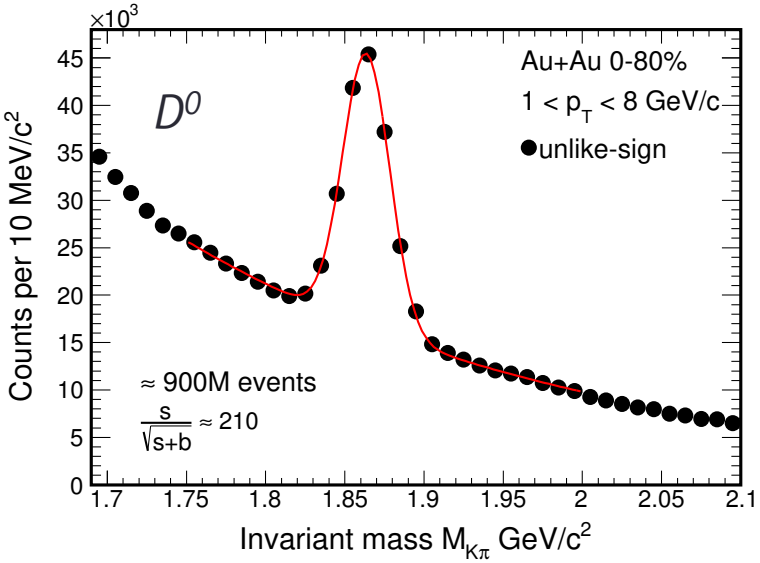
Acceptance coverage:
$-1 < \eta < 1$
$0 < \phi < 2\pi$

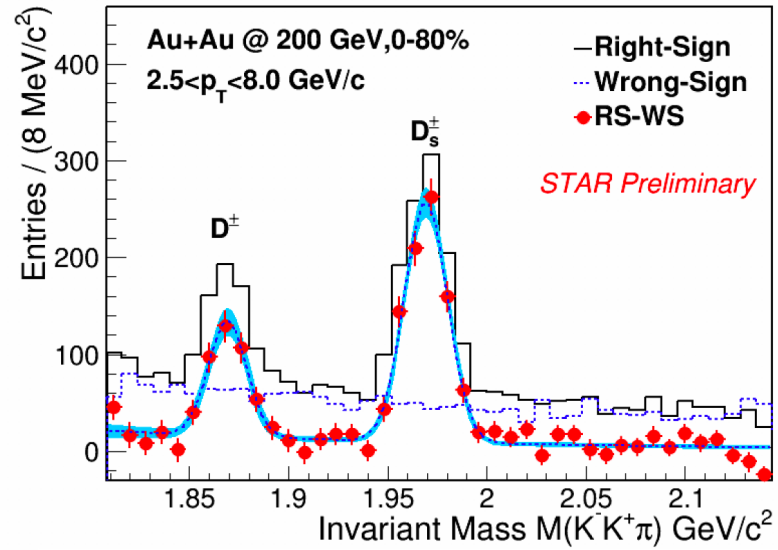
Tracking inwards with gradually improved resolution:

- SSD – Silicon Strip Detector
- IST – Intermediate Silicon Tracker
- PXL – Pixel Detector



Charm hadron reconstruction at RHIC



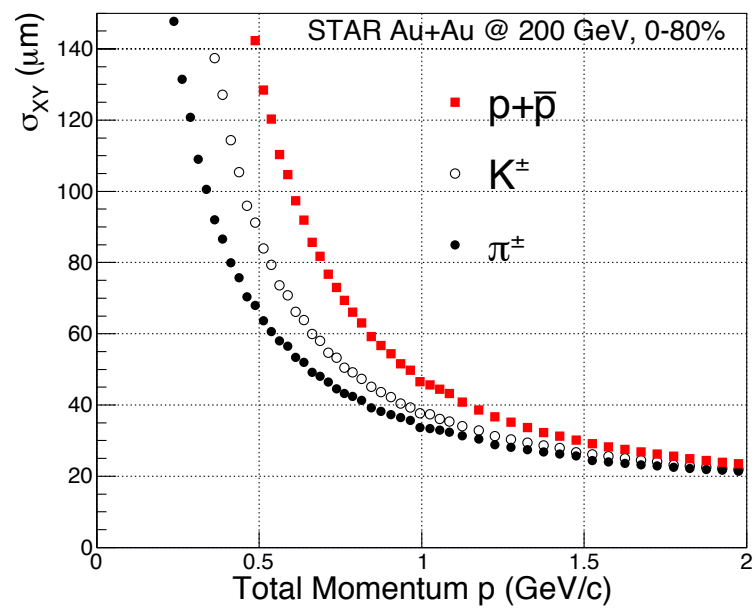


- Exclusive reconstruction of heavy flavor hadrons using the HFT:

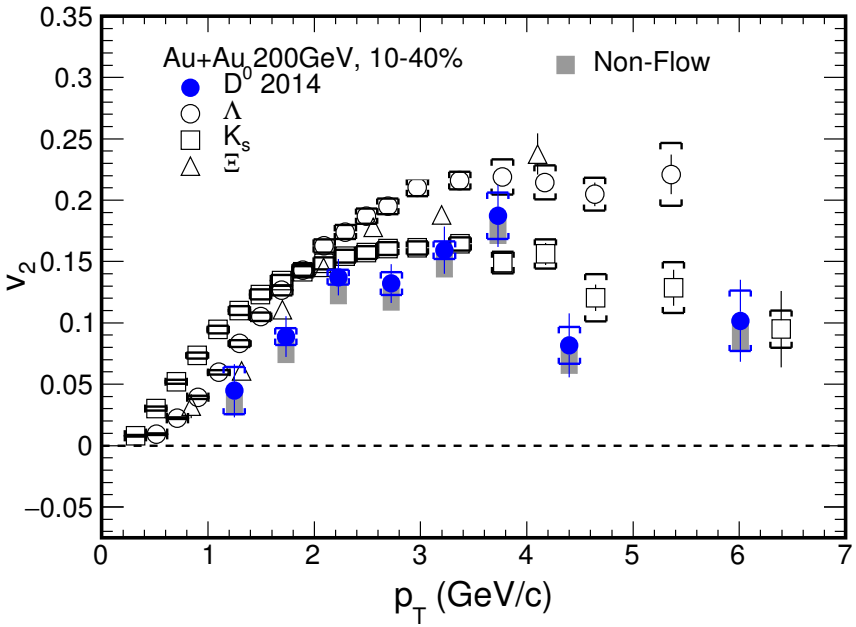
  30μm pointing resolution @ 1.5 GeV

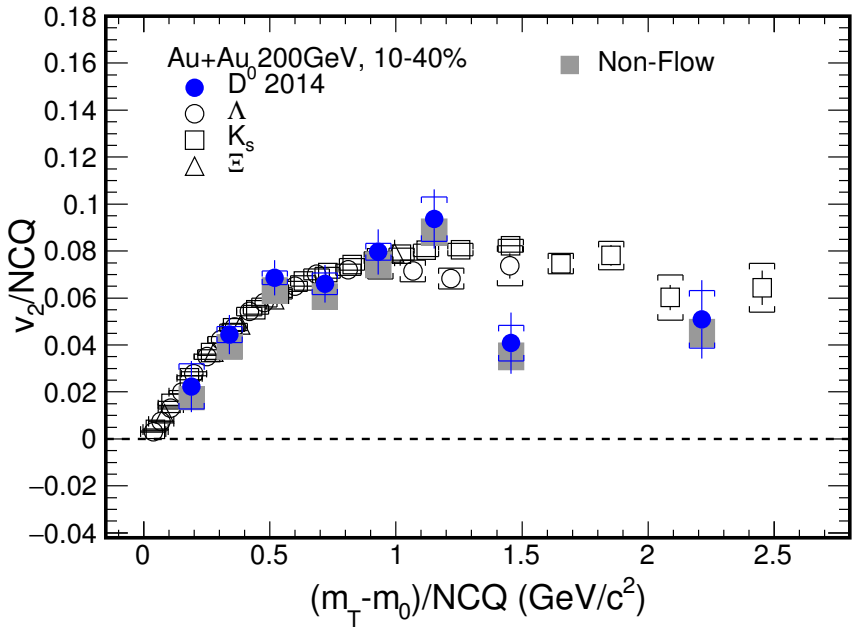
- HFT: 1st succesful MAPS vertex detector:

next generation planned/proposed for ALICE and sPHENIX



Charm flow





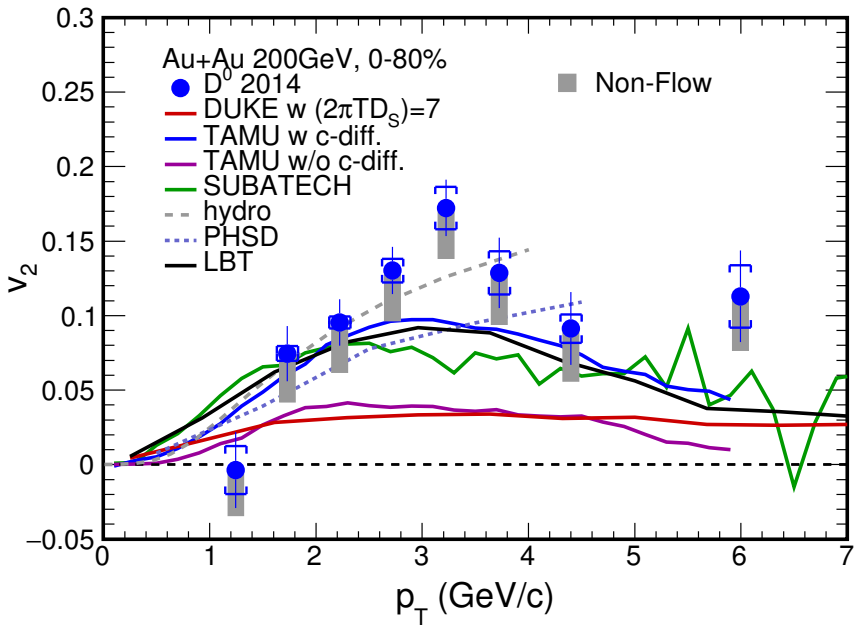
- Mass ordering for p_T < 2 GeV/c suggesting hydrodynamic behavior
- $v_2(D)$ follows the m_T-m_0 scaling as observed for the light species

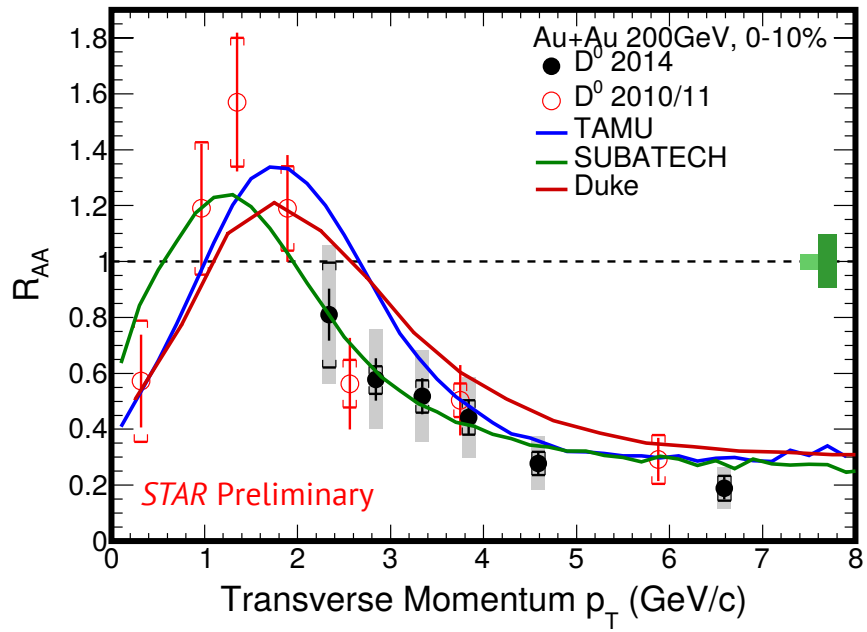
Evidence that charm is flowing with the medium!

- Indicative of local thermal equilibrium

STAR: PRL**118**, 212301

Theory comparison

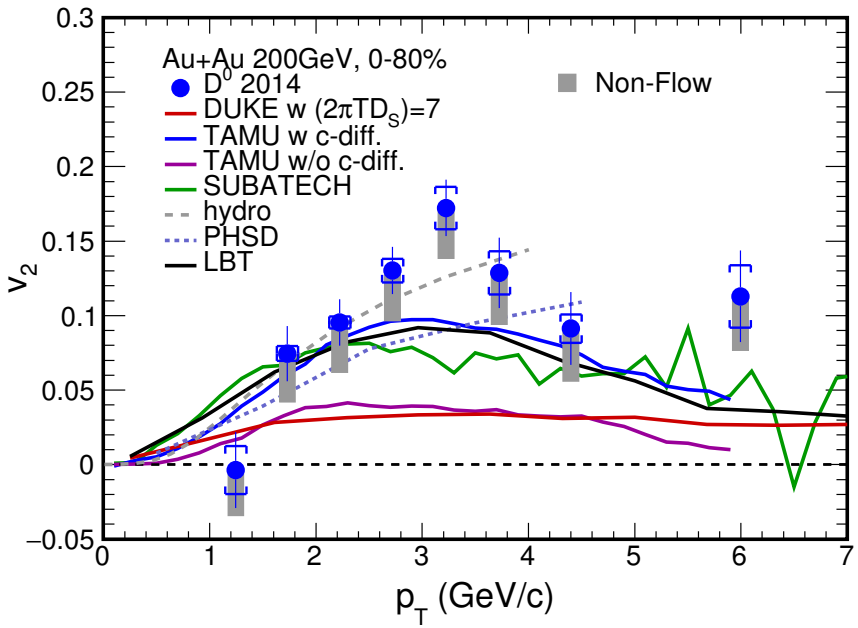


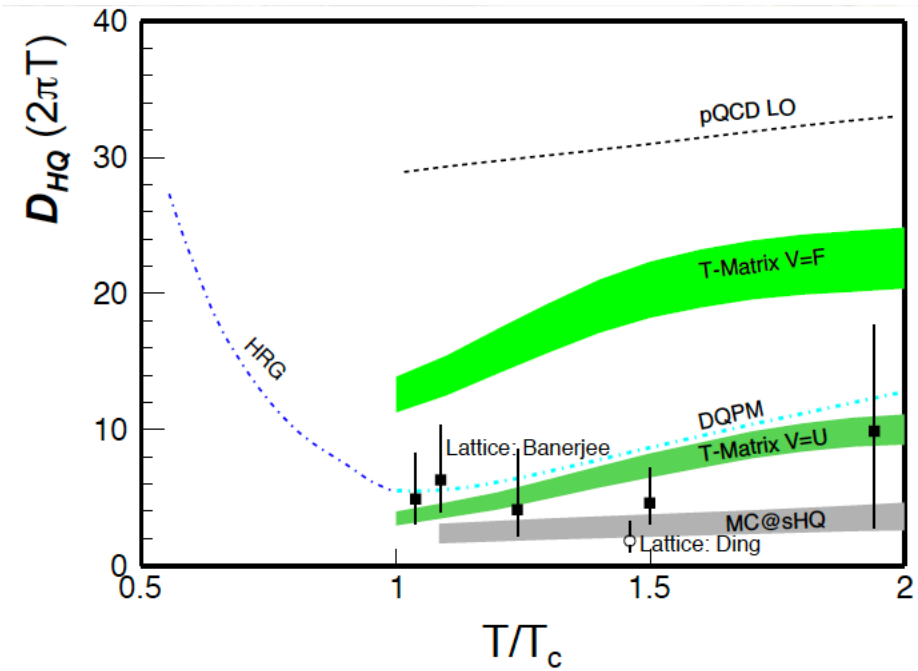


- Series of models can simultaneously describe the D^0 v_2 and R_{AA} at RHIC
- 3D viscous hydro can describe the D^0 v_2 at $p_T < 4$ GeV/c: suggests charm quarks have reached local thermal equilibrium
- Data impose stringent constraints on model calculations

STAR: PRL**118**, 212301

Theory comparison

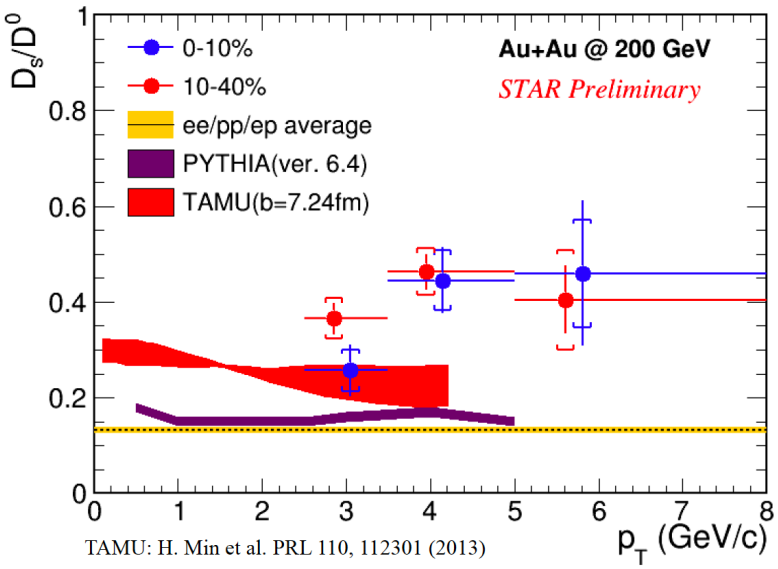


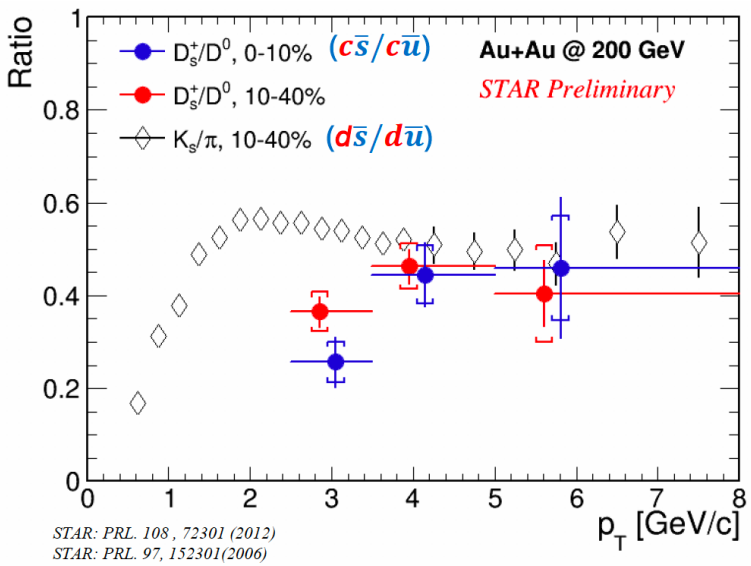


	$2\pi TD_{HQ}$	χ^2/N.D.F.	p value
SUBATECH	2-4	15.2/8	0.06
TAMU c diff.	5-12	10.0/8	0.26
TAMU no c diff.	…	29.5/8	2×10^{-4}
Duke	7	35.7/8	2×10^{-5}
LBT	3-6	11.1/8	0.19
PHSD	5-12	8.7/7	0.28
3D viscous hydro	…	3.6/6	0.73

STAR: PRL**118**, 212301

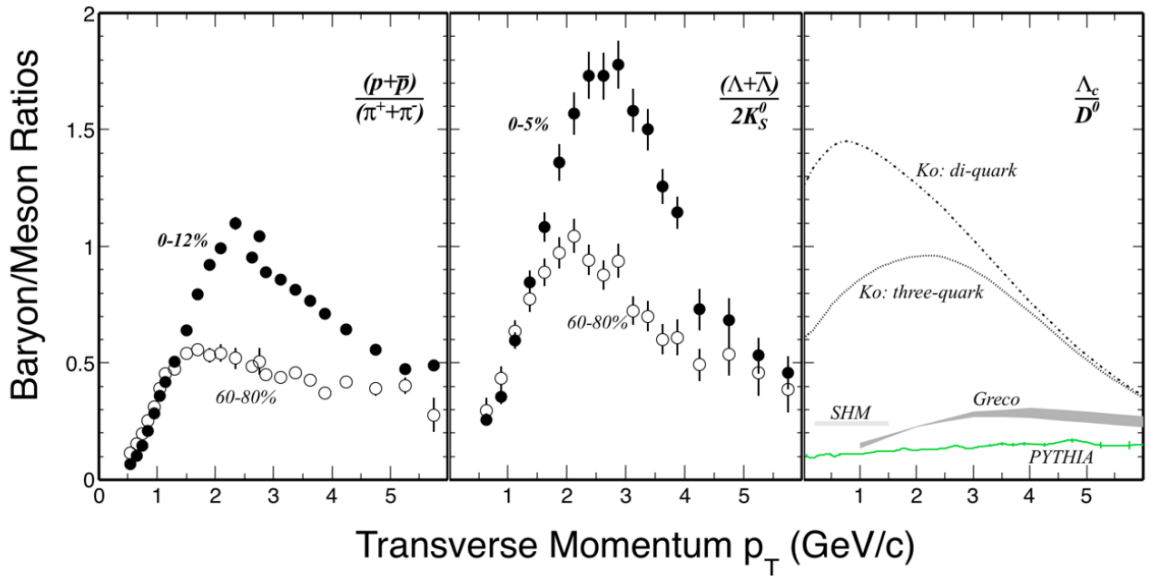
D_s and strangeness enhancement





- D_s/D^0 ratio is significantly larger than fragmentation baseline:
  - ee/ep/pp average 0.132 *M. Lisovyi, et. al. EPJ C 76, 397(2016)*
- Ratio is larger than model predictions (10-40%)
- Comparable enhancement in central and semi-central events
- Similar enhancement as observed for light species for p_T > 3.5 GeV/c; smaller enhancement in 2.5-3.5 GeV/c

Motivation : Λ_c



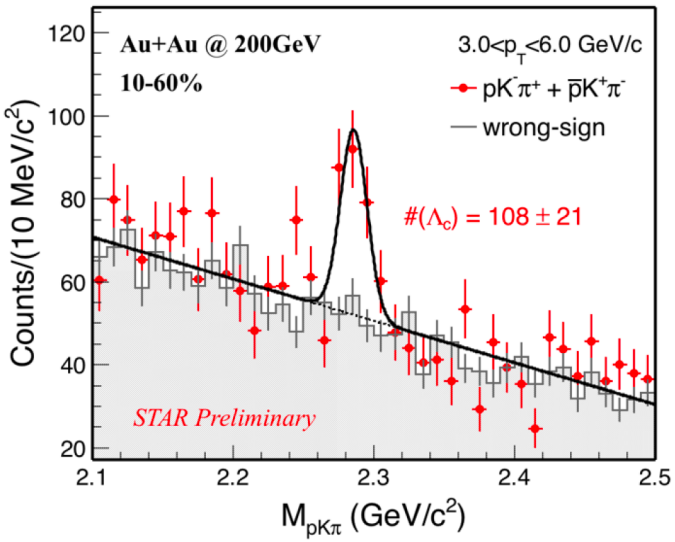
Ko: PRC**79**,044905
Greco: PRD**90**,054018

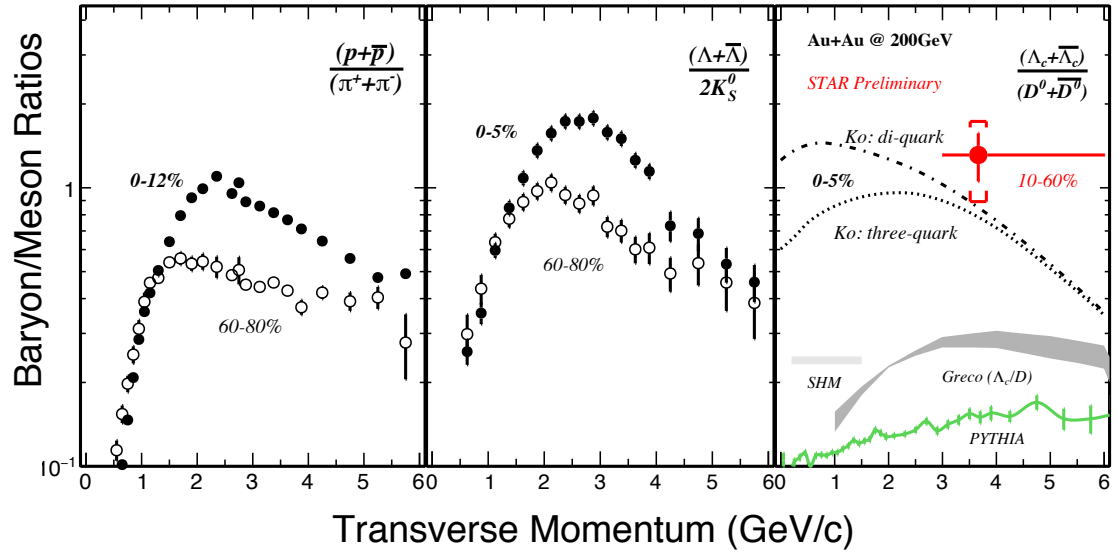
- Significant enhancement in baryon-to-meson ratio observed in central A+A collisions for light hadrons:

  Coalescence mechanism well describes the observation

- Enhancement in Λ_c/D^0 depends on degree of charm quark thermalization and whether charm quarks participate in coalescence hadronization

Λ_c reconstruction in Heavy Ion Collisions



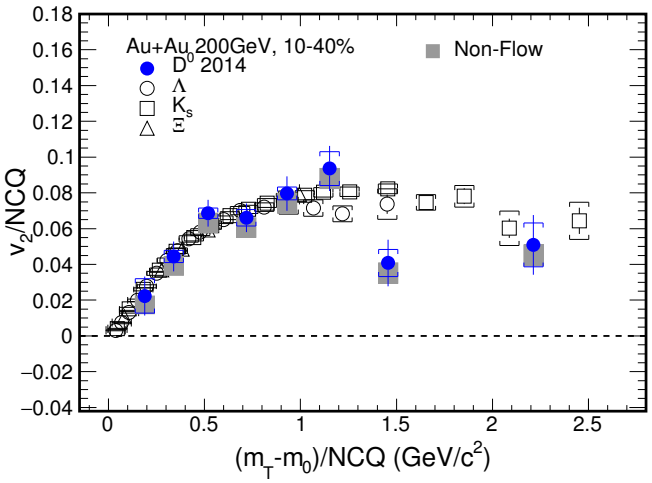


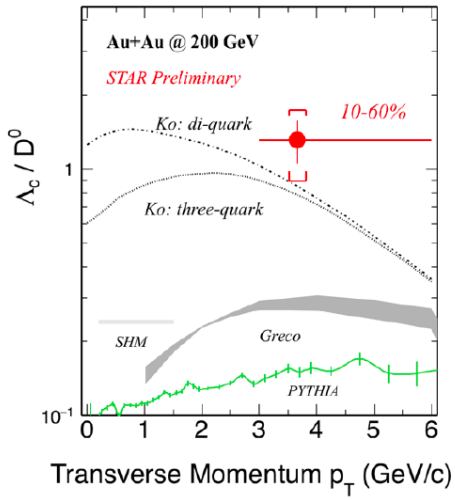
Ko: PRC**79**,044905
Greco: PRD**90**,054018

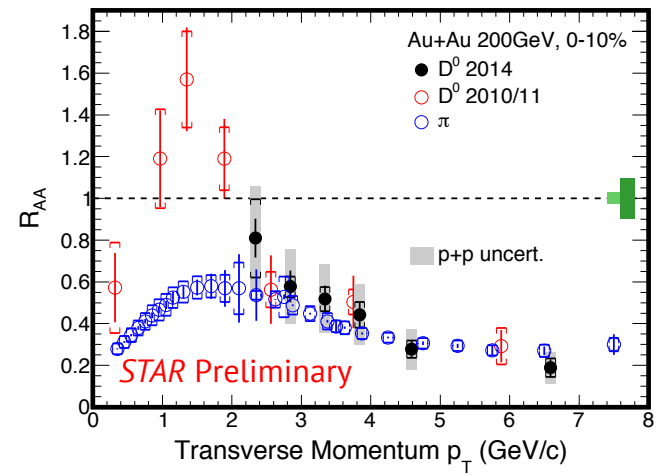
- First ever measurement of Λ_c in heavy ion collisions with the HFT

  Λ_c --> pKπ , cτ ~ 60 μm , B.R. = 6.5%
- Significant enhancement in the Λ_c/D^0 ratio compared to PYTHIA baseline
- Λ_c/D^0 ratio is compatible with light flavor baryon/meson ratios.
- Consistent with coalescence + thermalized charm (Ko model).

Summary (part 1): charm







- Significant charm energy loss in the medium: $R_{AA}(D) \sim R_{AA}(h)$ for $p_T > 4$ GeV
- Charm quarks flow similarly as light flavor: $v_2(D) \sim v_2(h)$ vs. m_T
- Indications that charm quarks are near local thermal equilibrium
- Indications of coalescence hadronization: Λ_c/D^0 and D_s/D^0 > fragmentation baseline

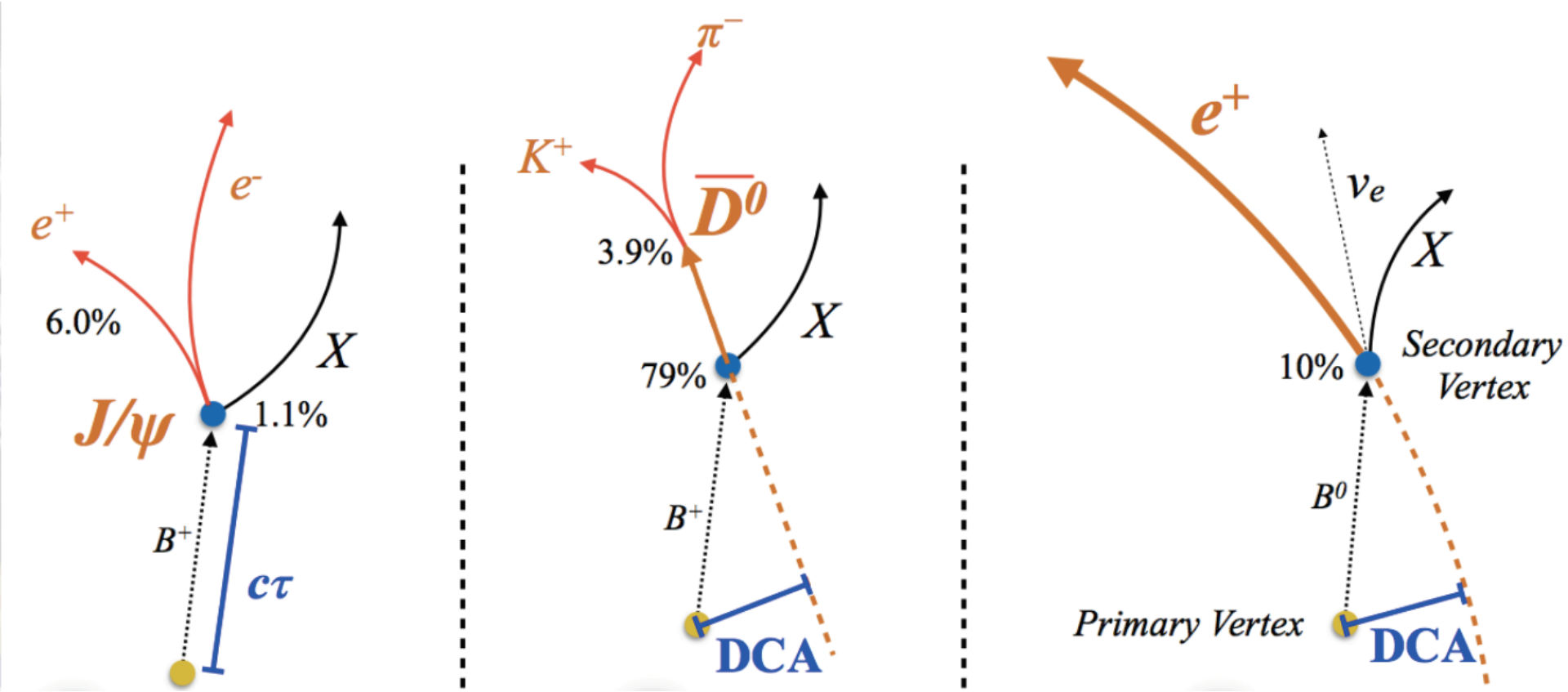
Picture is fully consistent with QGP

Experimental access to b quarks

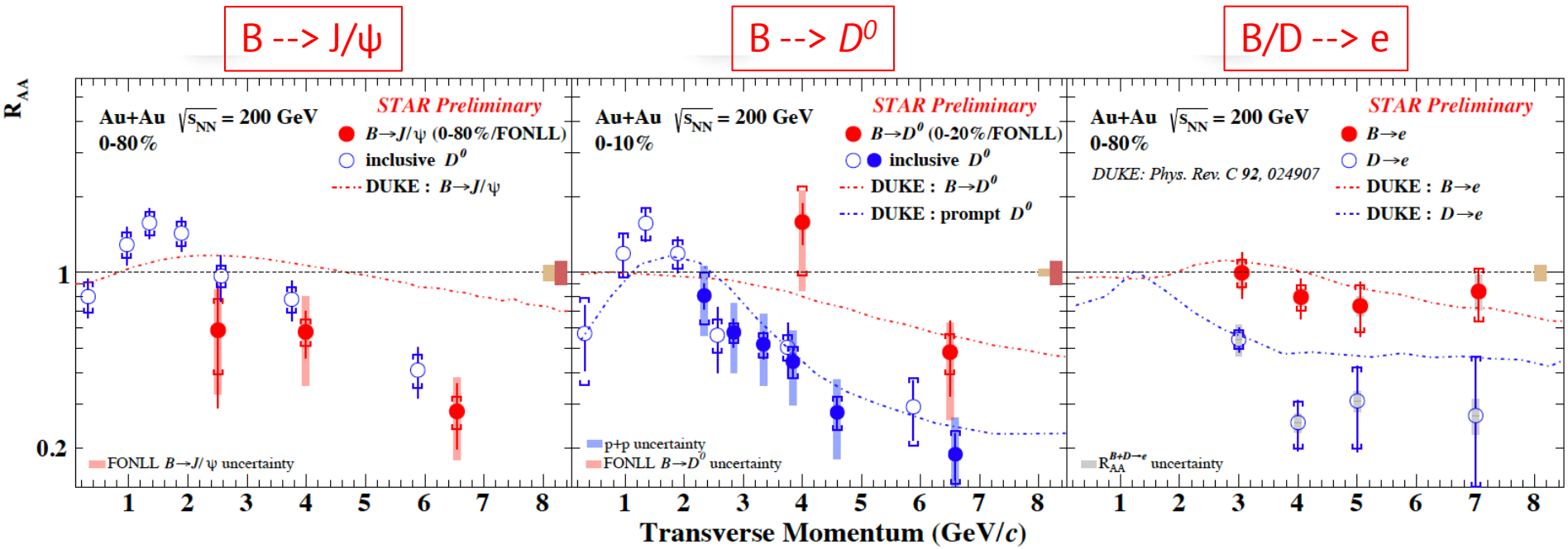
Inclusive impact parameter method

e.g. *D/B --> e* , *B --> D* , *B --> J/ψ*

High precision vertex detector is essential for flavor separation



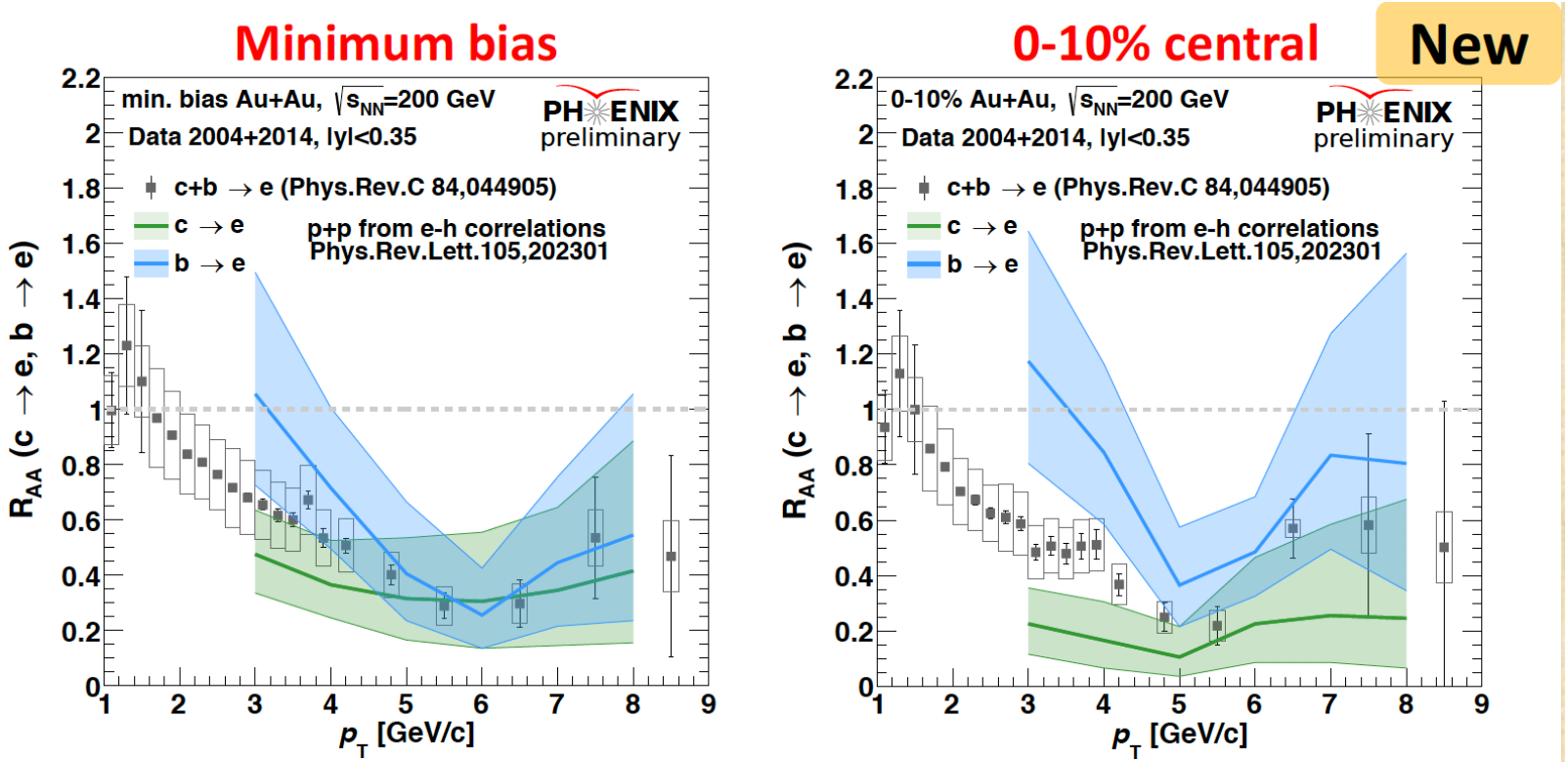
B meson @ STAR



STAR measurement of B production in 200 GeV Au+Au collisions via three channels:

- Impact parameter method used to separate b and c contributions in the three channels
- Strong suppression for B --> J/ψ and D^0 at high p_T
- Indication of less suppression for B --> e compared to D --> e (~2σ): consistent with $\Delta E_c > \Delta E_b$ prediction

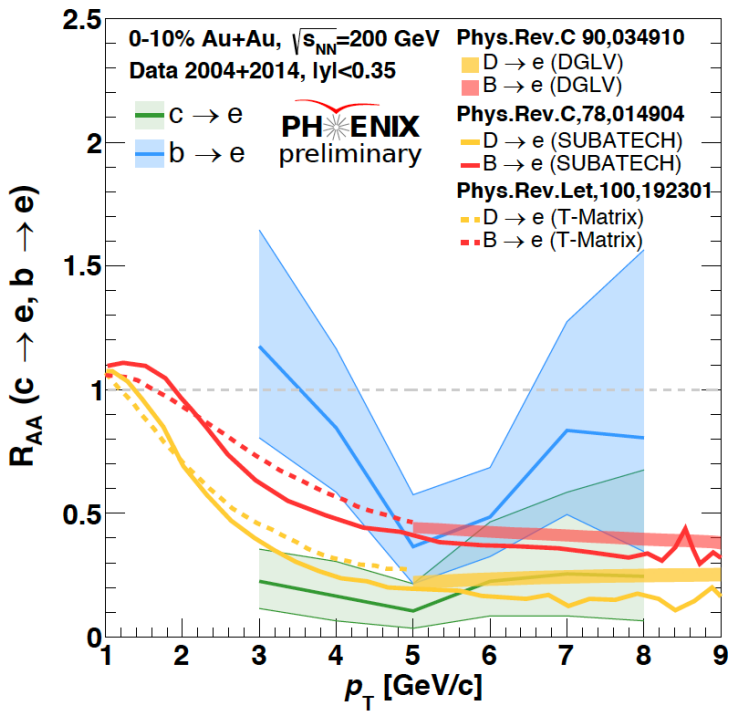
b --> e vs. c --> e @ PHENIX

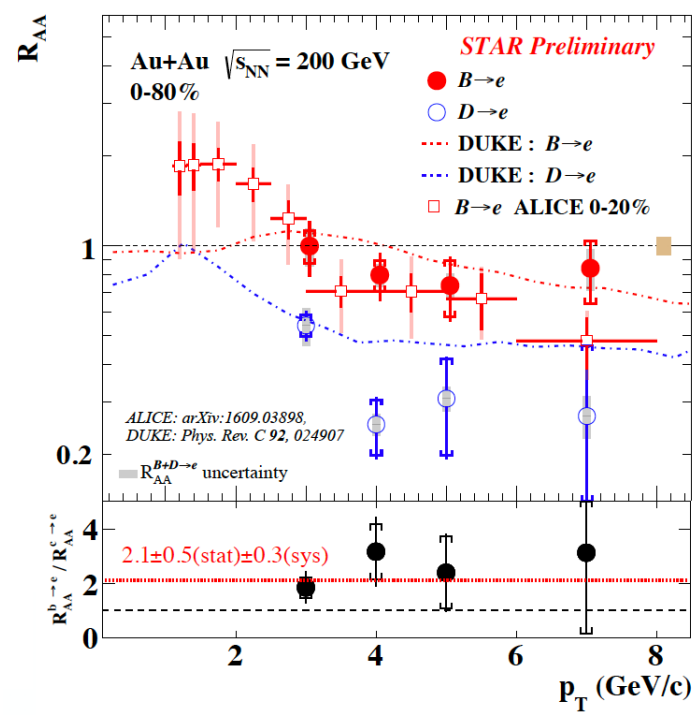


Statistical templates used to separate contributions from b and c quarks:

- Indication of less suppression for B --> e vs. D --> e
- Larger suppression for D --> e observed in 0-10% events compared to Min-Bias sample

Comparison to models

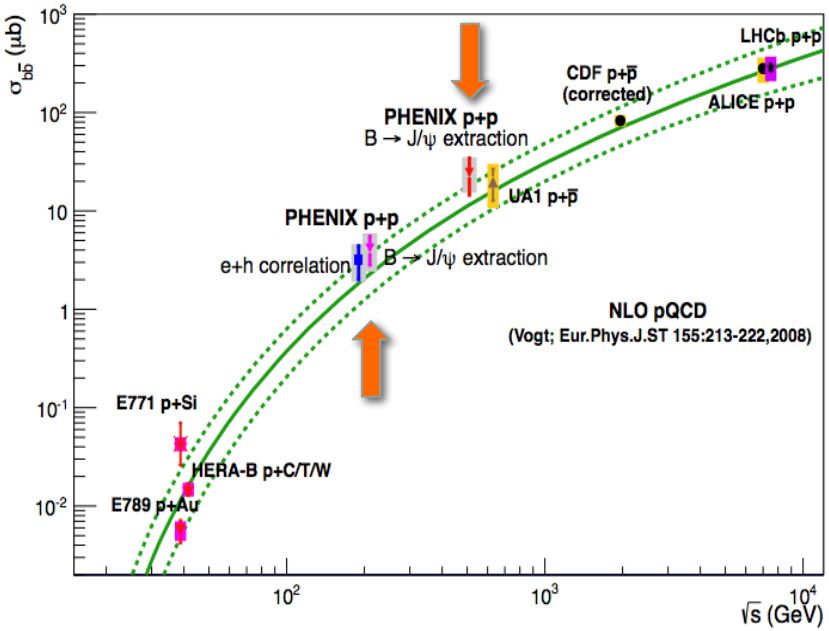


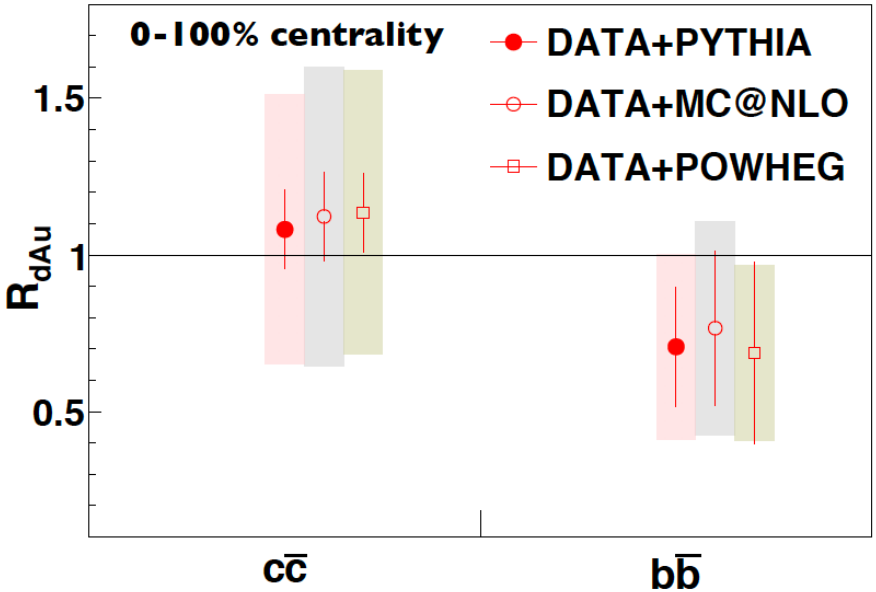


- Reasonable agreement (within uncertainties) with models including strong coupling between heavy quarks and the QGP medium (D(2πT) < 4)
- Coming soon: reduced uncertainties and broader p_T range once full datasets from 2014 and 2016 are analyzed

Cold nuclear matter effect for B meson

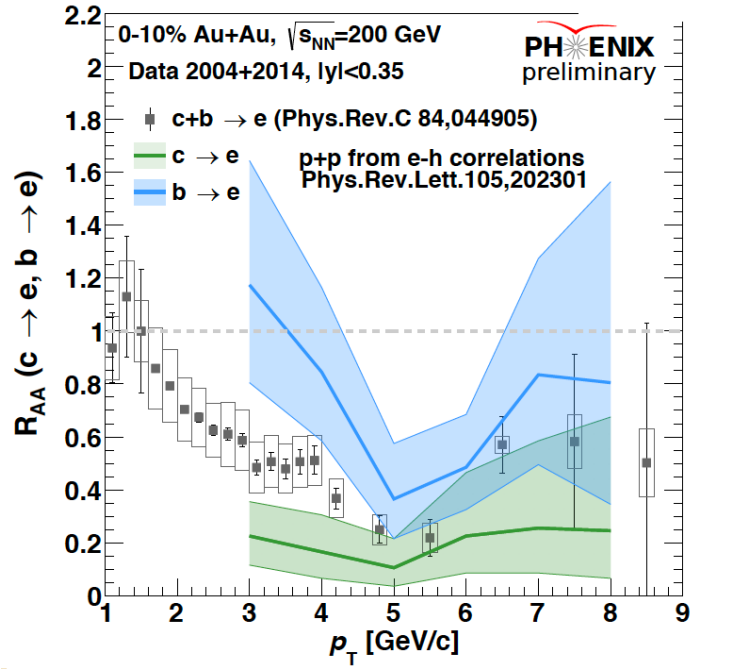
200 GeV result: arXiv 1702.01085
510 GeV result: PRD**95**,092002 (2017)

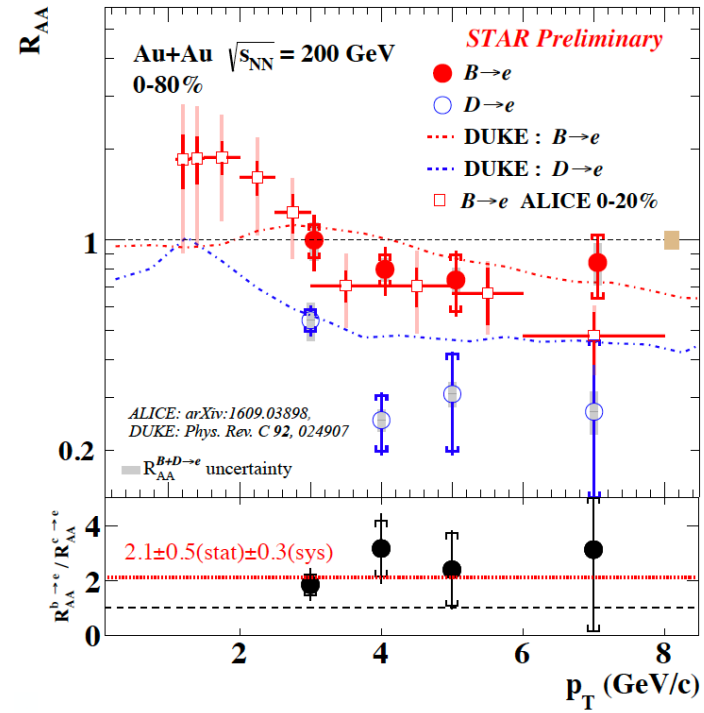




- B-meson consistent with
  - No significant suppression in d+Au collissions
    - Model independent
- PHENIX can measure most of the b cross section (mid and forward rapidities) ➔ √s dependence is well described by pQCD calculations

Summary (part 2): bottom



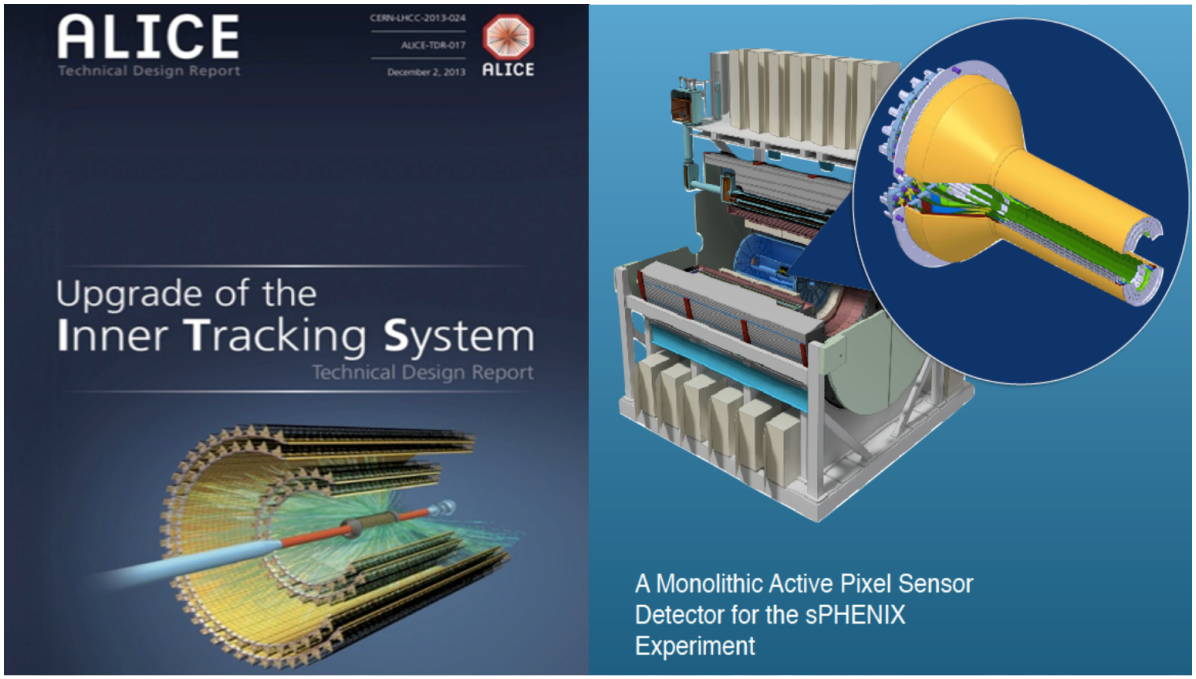


- Less R_{AA} suppression observed for B → e compared to D → e at $2 < p_T < 8$ GeV/c consistent with mass hierarchy for parton energy loss:

$$\Delta E_c > \Delta E_b$$

Future prospects

ALICE ITS **sPHENIX MVTX**



Ongoing analysis with full datasets from STAR and PHENIX
Precision open bottom (B-meson & b-jet) measurements over a broad pT range, in particular at low p_T (< 1 GeV/c):

- Detailed investigation of mass dependence of parton energy loss
- Precision measurement of heavy quark diffusion coefficient and QGP transport parameters
- Charm quark chemistry ➔ conclusive measurments