Open heavy flavor measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV using the STAR Heavy Flavor Tracker

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Outline

- Motivation
- STAR experiment
    - HFT subsystem design & performance
- Heavy flavor measurements
    - D^0 R_{AA}
    - D Meson v_2
- Model comparisons
- Outlook
- Summary

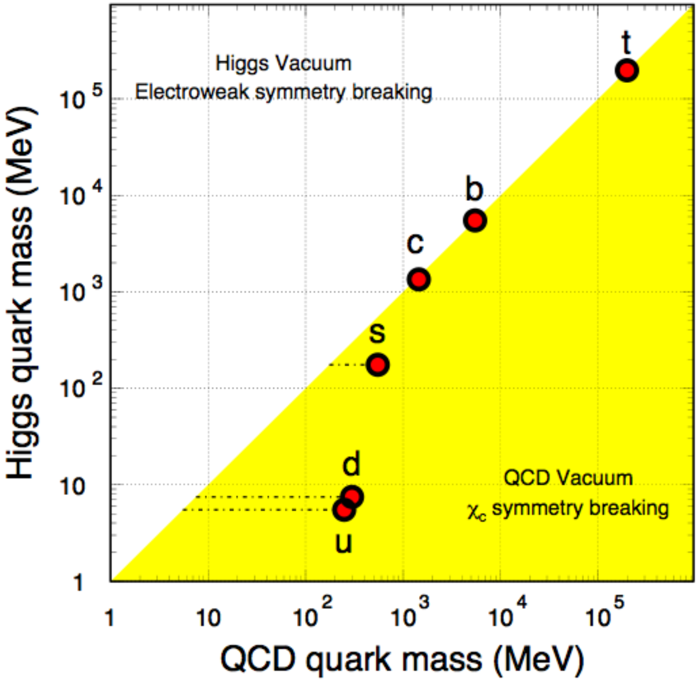
Motivation

Charm quarks:

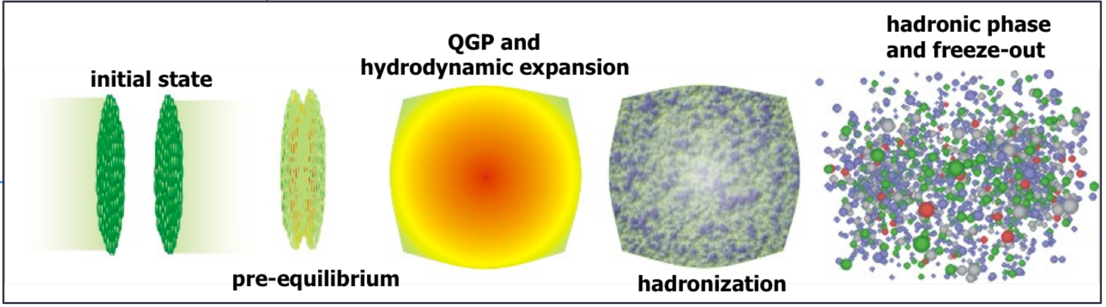
- Produced early in heavy ion collisions at RHIC, through hard scattering
- Experience the whole evolution of the system -> good probe for medium properties

Physics interest:

- High p_T: test different energy loss mechanisms: radiative vs collisional
- At low p_T: extract medium properties from motion of heavy quarks in medium (Brownian motion), e.g. diffusion coefficient

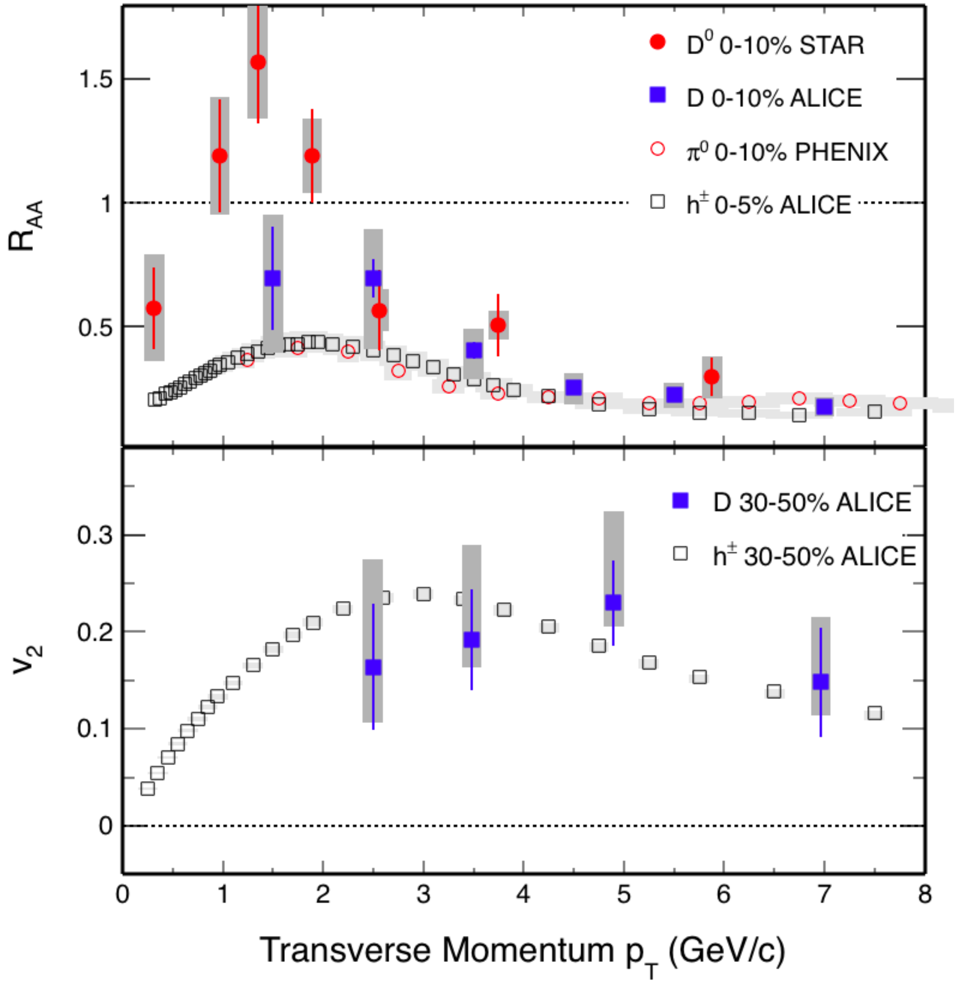


X. Zhu, *et al*, Phys. Lett. **B647**, 366(2007).



Recent developments and understanding

- RHIC and LHC: *D*-meson R_{AA} suppression at high p_T : strong charm-medium interactions
- D^0 v_2 LHC results are compatible with light flavor v_2, charm thermalized?
- v_2 and R_{AA} can be used simultaneously to constrain models
- What is occurring at low p_T at RHIC?
- Low p_T v_2 is especially sensitive to the partonic medium: scattering strength, transport properties



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

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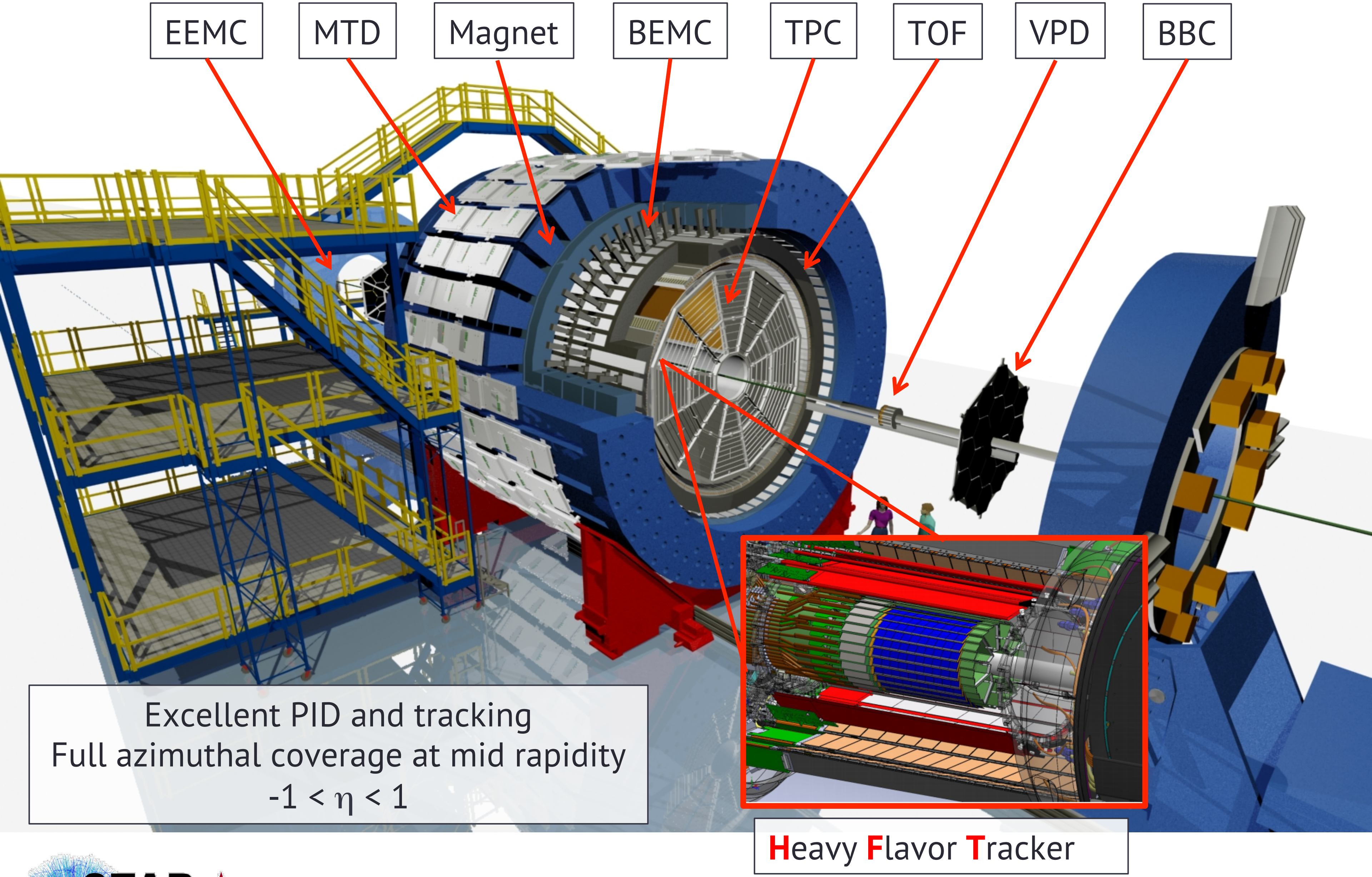
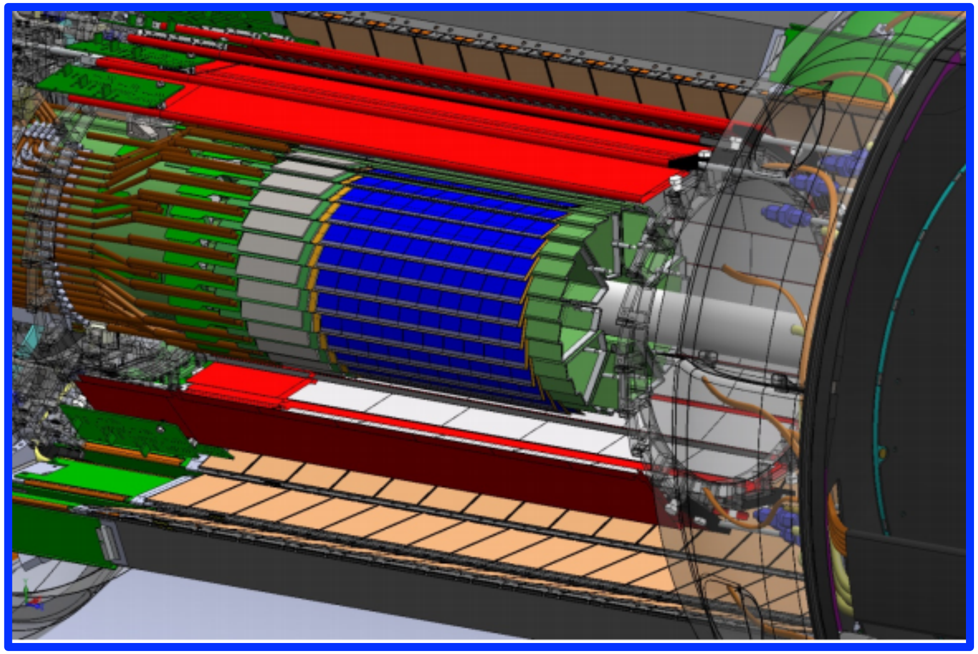
STAR experiment



Excellent PID and tracking
Full azimuthal coverage at mid rapidity
$-1 < \eta < 1$

STAR Heavy Flavor Tracker (HFT)

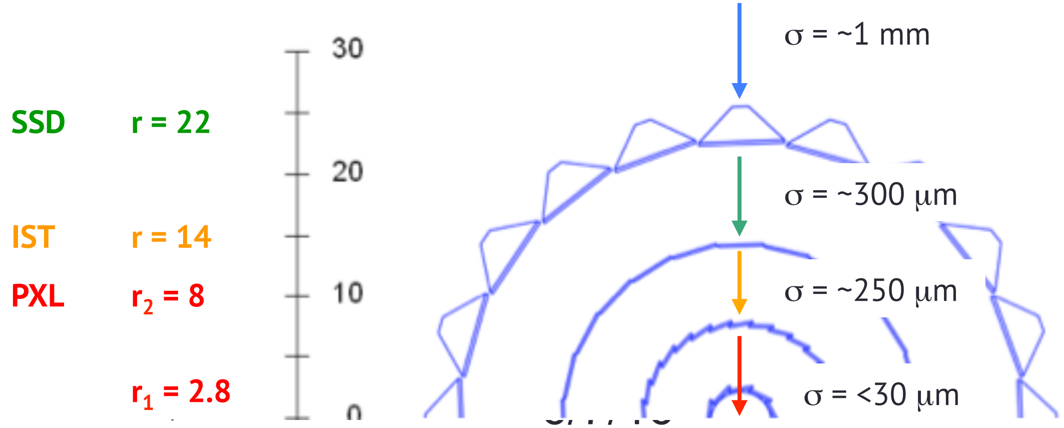


TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

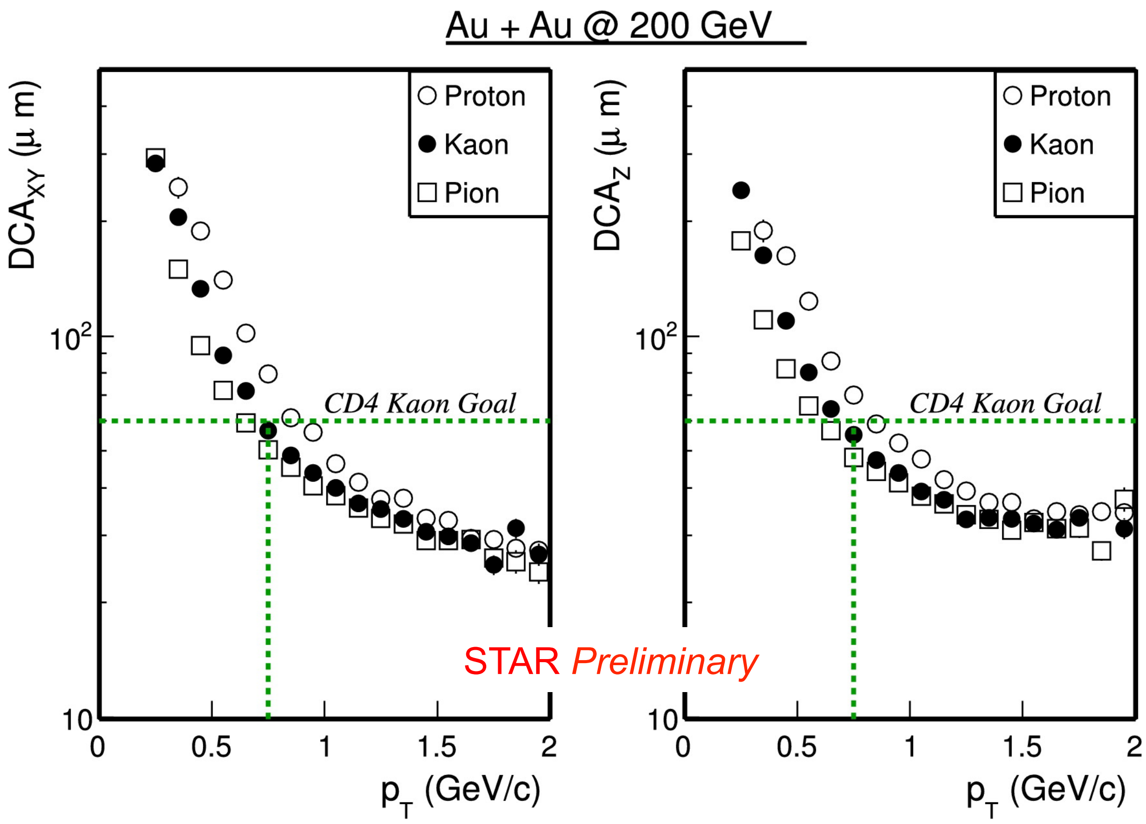
- SSD – Silicon Strip Detector
- IST – Intermediate Silicon Tracker
- PXL – Pixel Detector

Tracking inwards with gradually improved resolution:



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

HFT Performance vs design goals



- Kaon track pointing resolution exceeds the requirement <55 μm at 750 MeV/c
- Pointing resolution in the region with Al-cables ~ 45 μm

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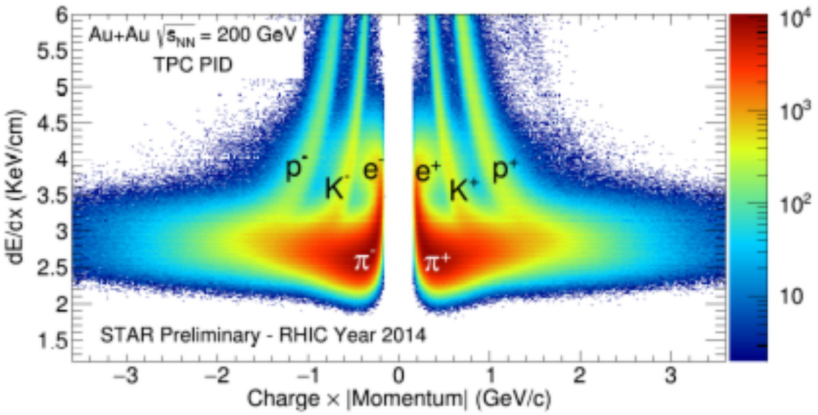
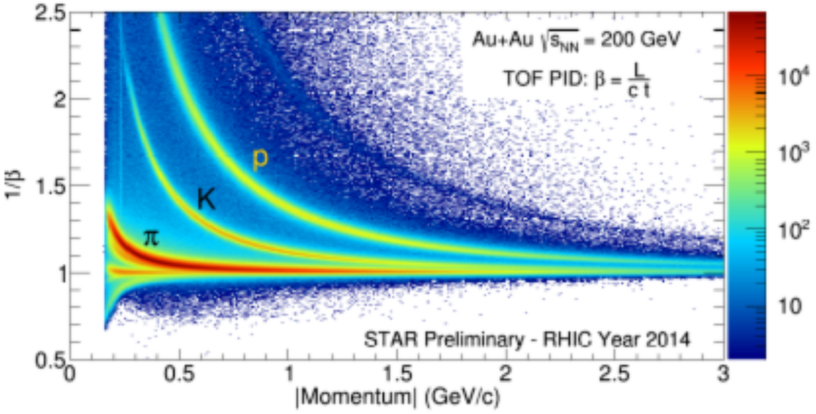
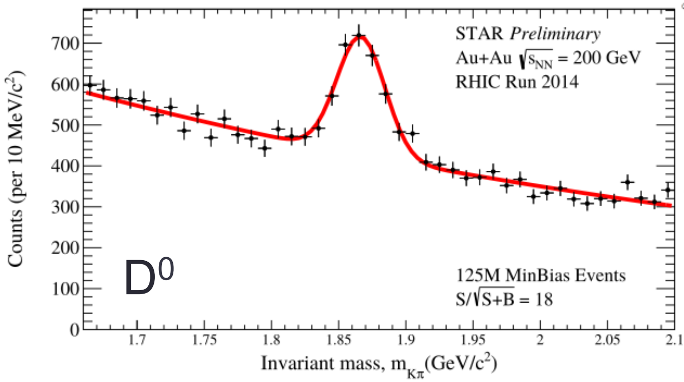
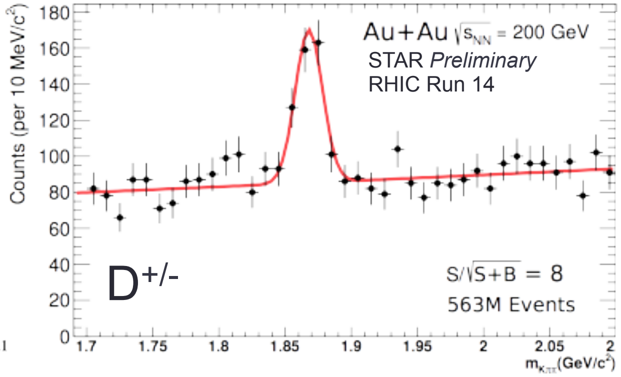
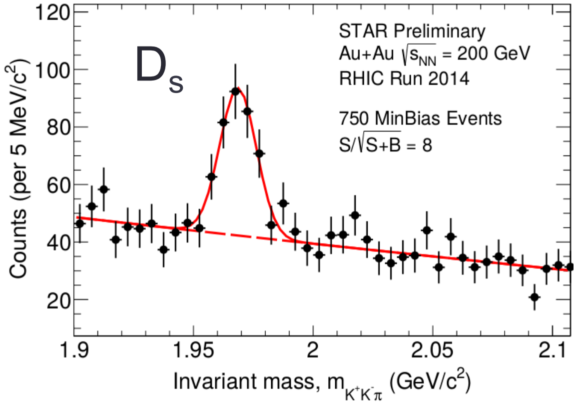
Particle Identification









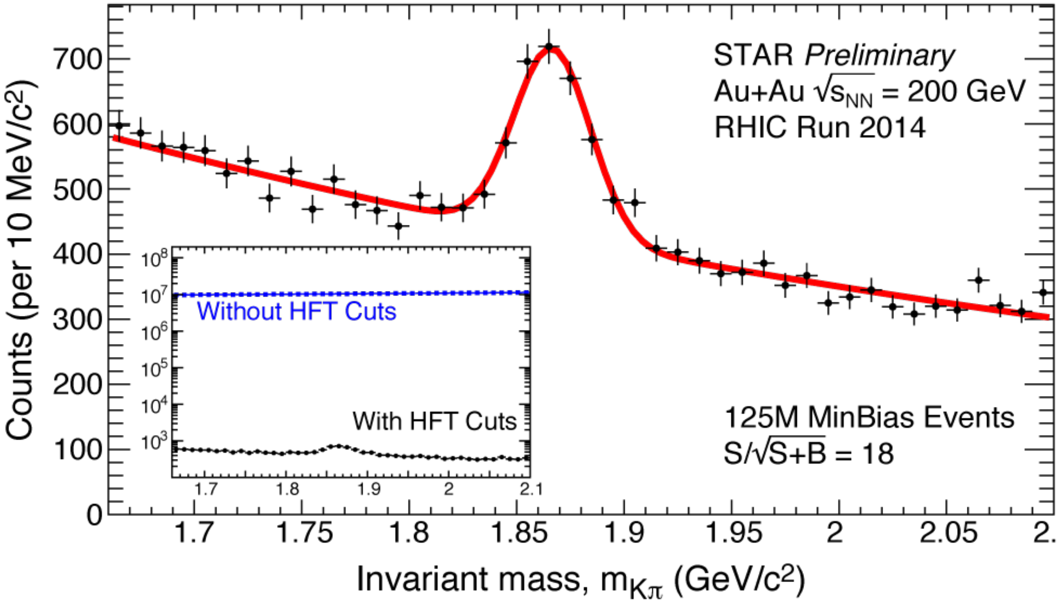


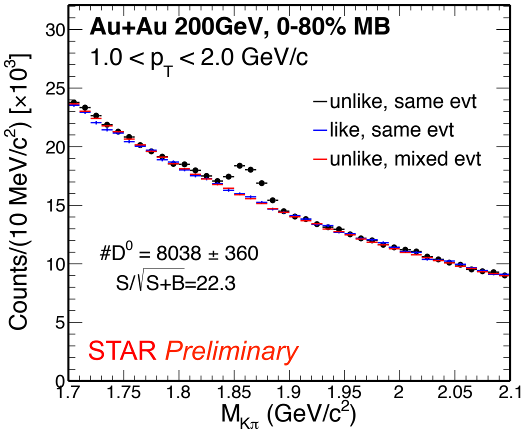
- Excellent long-lived hadron and electron identification
- Secondary vertex reconstruction with HFT → Full kinematic reconstruction of charmed hadron

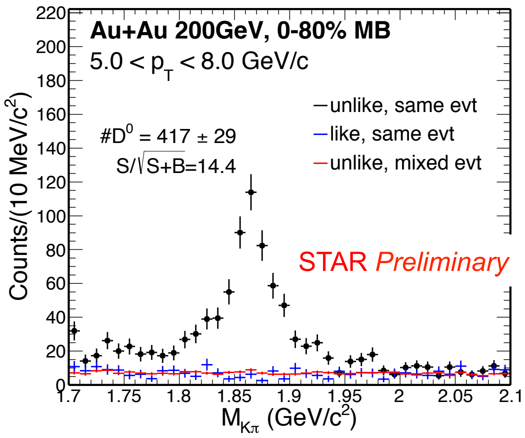
Topological reconstruction with HFT

- Greatly reduced combinatorial background (4 orders of magnitude)
- Highly improved S/B

	w/o HFT	w HFT
	2010 + 2011	2014
# events(MB) analyzed	1.1 B	780 M
significance per billion events	13	51

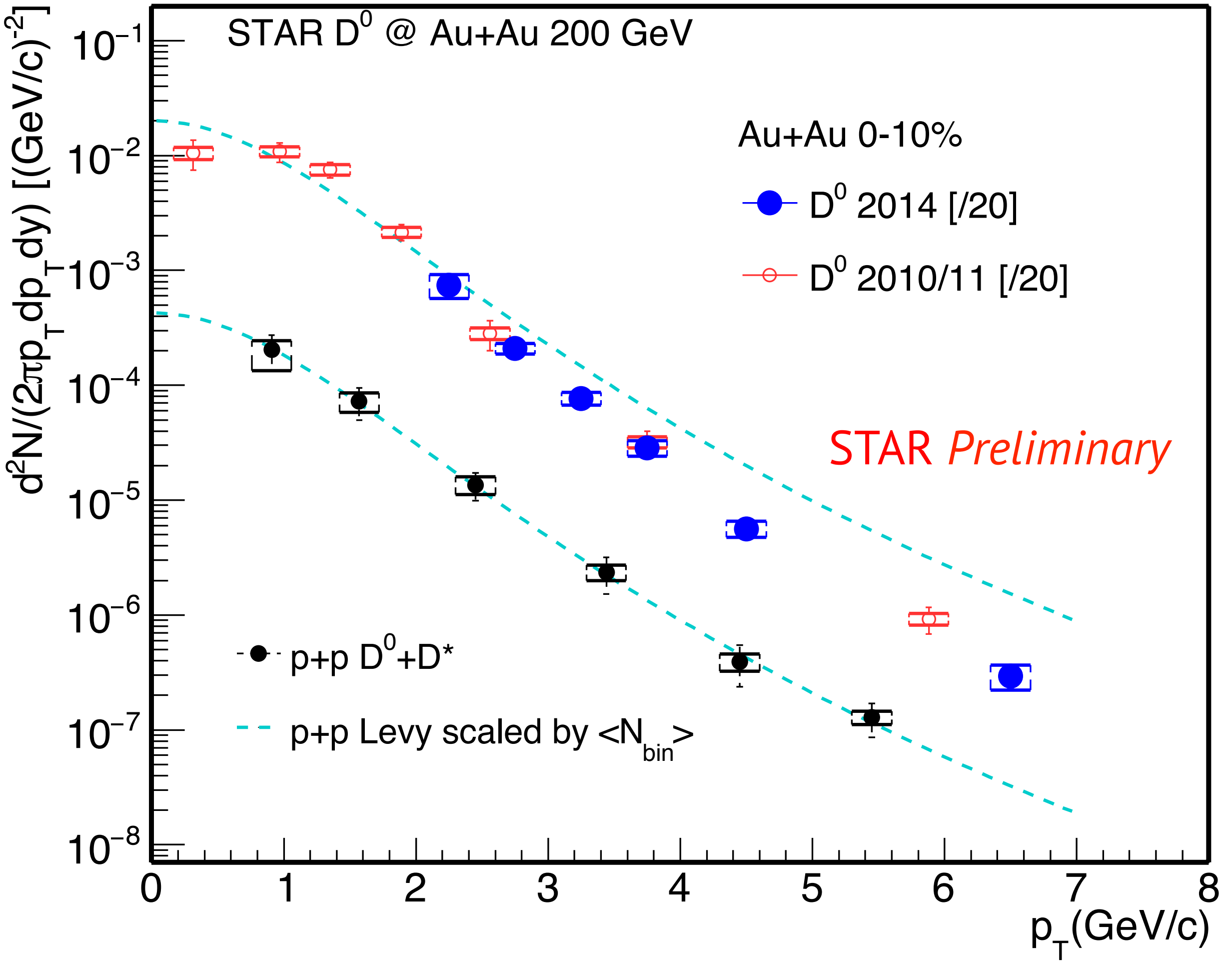






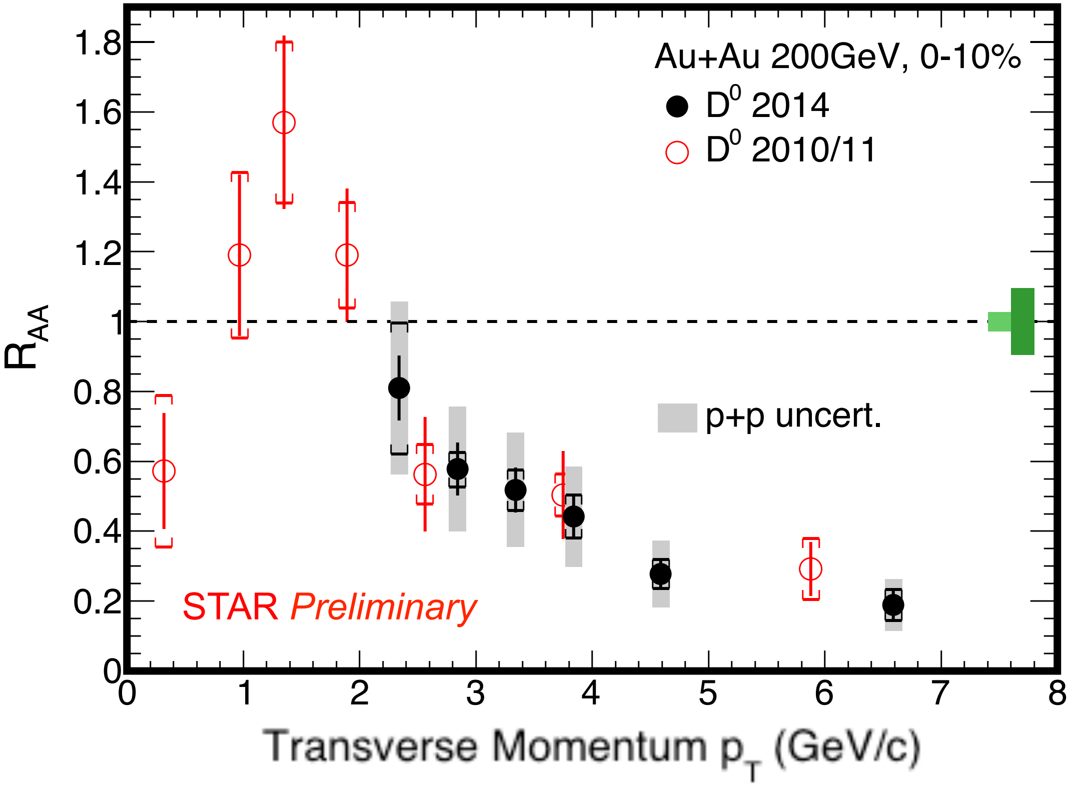
Invariant yields

STAR: PRL 113 (2014) 142301



- [High p_T] Consistent with published result, with improved statistical precision
  - Finalizing systematic uncertainties for p_T< 2 GeV/c and in peripheral collisions

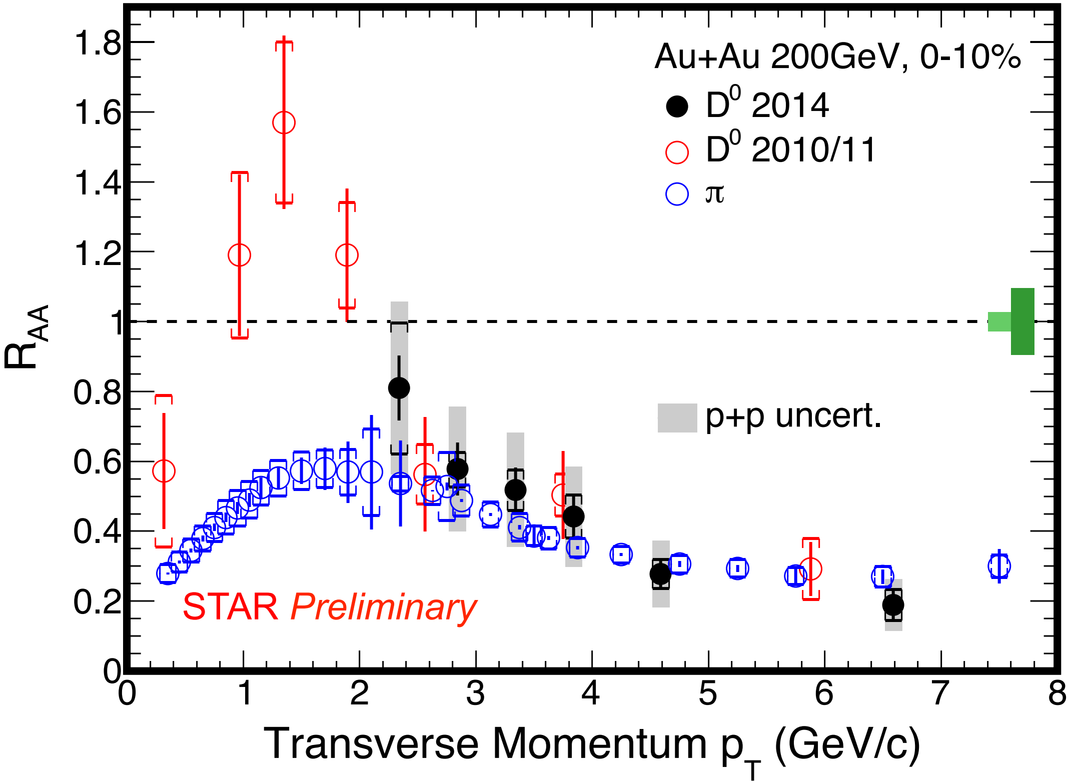
Nuclear Modification Factors



- High p_T: significant suppression in central Au+Au collisions. New results have improved precision.

STAR: PRL 113 (2014) 142301

D^0 vs. π

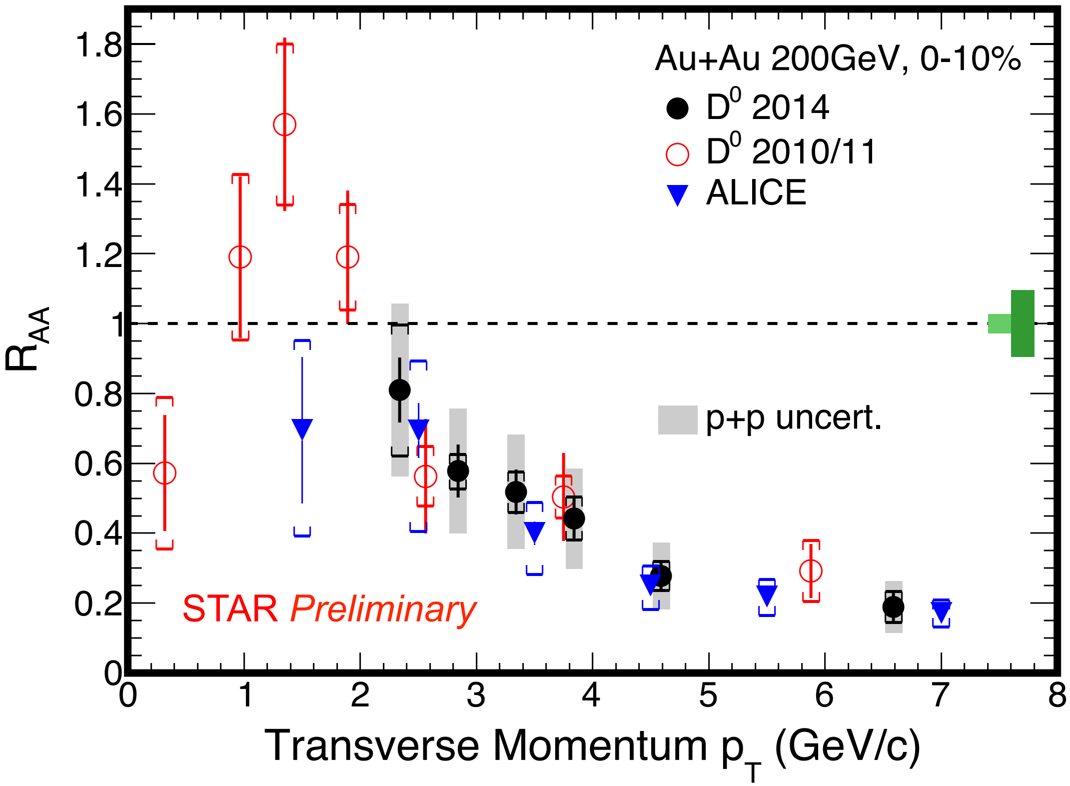


- $R_{AA}(D) \sim R_{AA}(p)$ at p_T>4 GeV/c

Similar suppression for light partons and charm quarks at high p_T

STAR: PRL 113 (2014) 142301
PLB 655 (2007) 104

RHIC vs. LHC

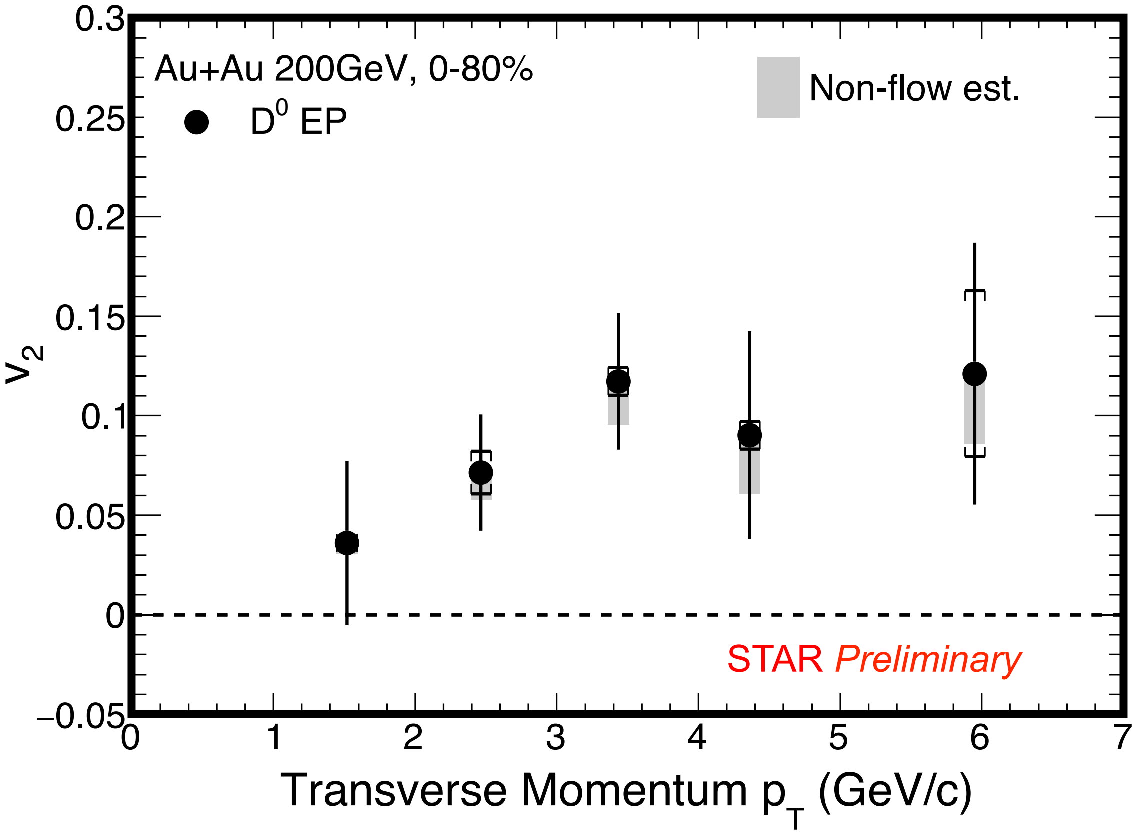


- R_{AA}@ RHIC ~ R_{AA}@LHC

strong charm-medium interaction at RHIC and LHC

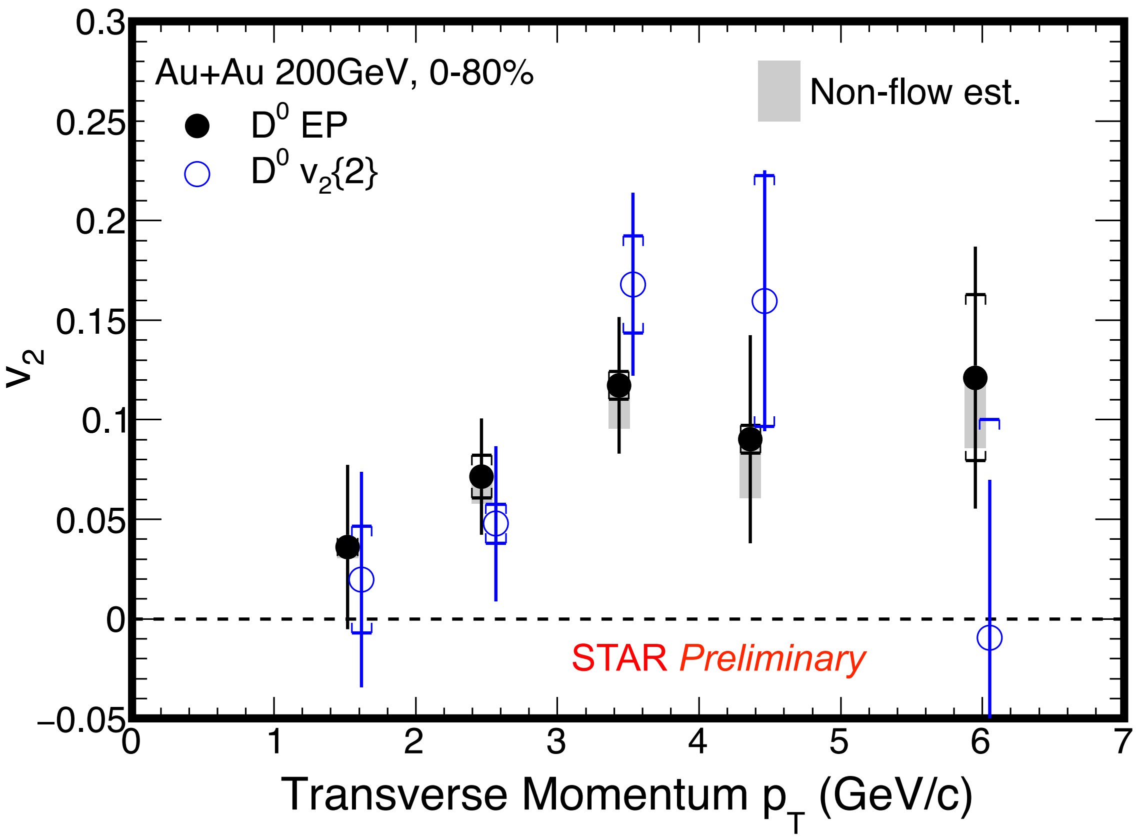
STAR: PRL 113 (2014) 142301
ALICE: arXiv: 1509.06888

D Meson v_2



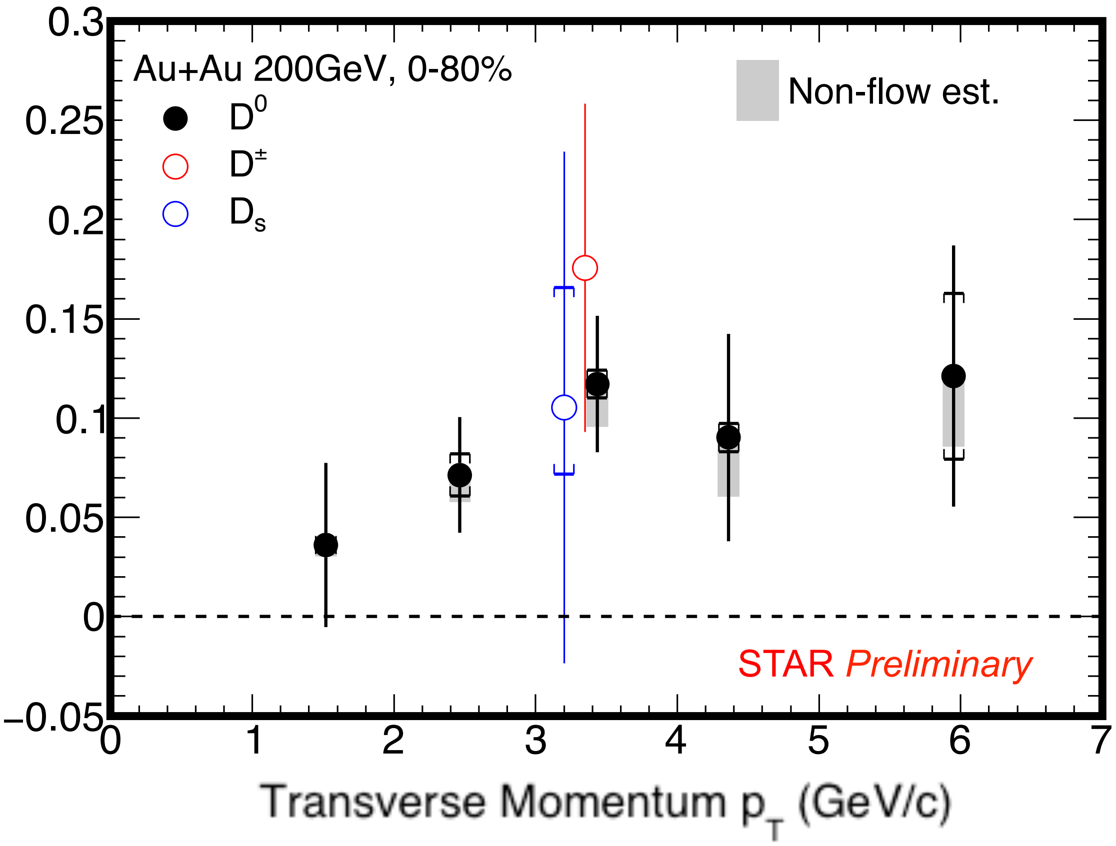
- *D^0* azimuthal anisotropy significantly different from zero for $p_T > 2$ GeV/c
  (χ^2/n.d.f. = 17.5/4)
- B->D feed down is negligible at RHIC energies (<5% relative contribution)

D Meson v_2



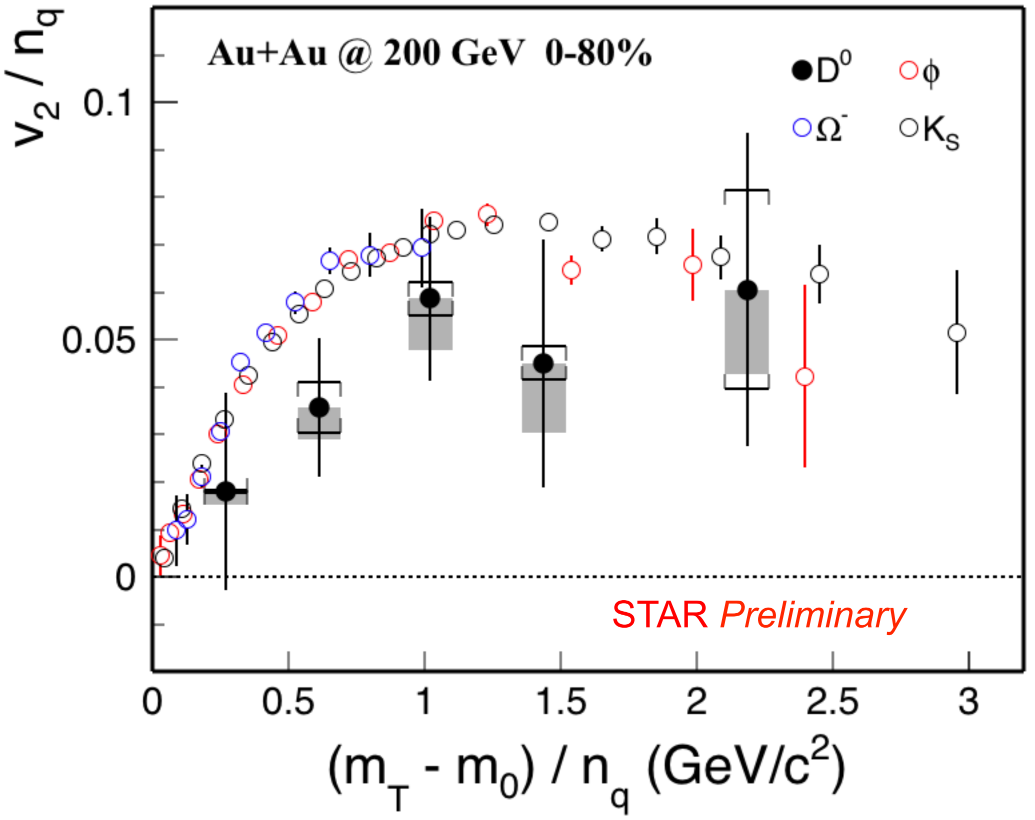
- Good agreement between EP and 2 PC methods within systematics

D Meson v_2



- $D^{+/-}$ v_2 compatible with D^0 albeit within large error bars
- First measurement of D_s v_2 in heavy-ion experiment, limited statistics

Mass effect



- Systematically below results obtained for light hadrons
  - Need better statistics for a firm conclusion

Suggests something beyond hydro

STAR:PRC 77 (2008) 54901

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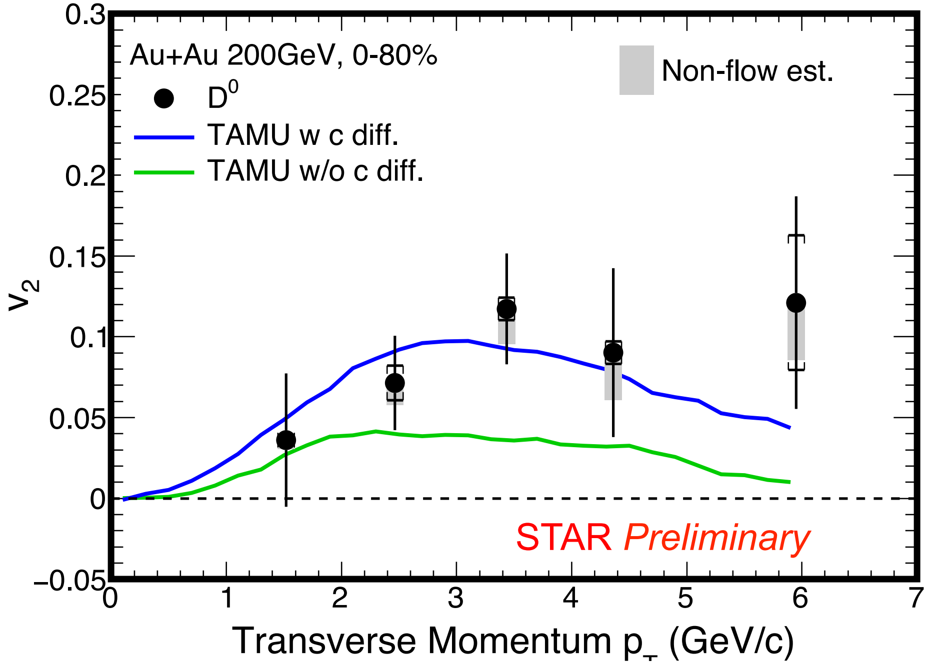
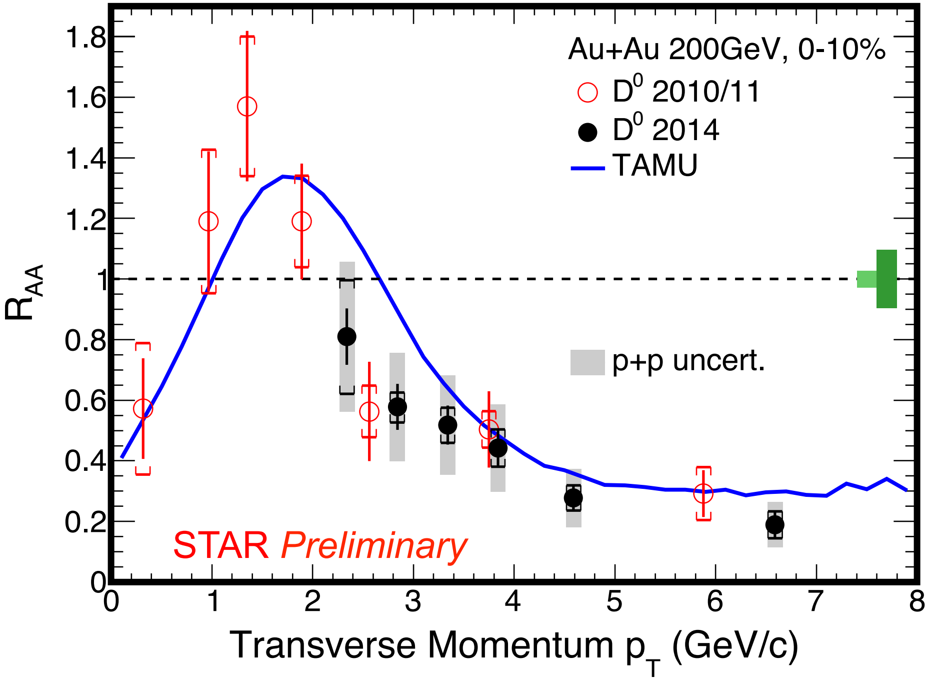
Model comparison: TAMU

- Full T-matrix treatment, non-perturbative model with internal energy potential
- Diffusion coefficient extracted from calculation $2\pi T \times D = 2\text{-}10$
- Good agreement with D^0 meson v_2 at low p_T, data favor model including c quark diffusion in the medium
  (w/ c diff. χ^2/n.d.f. = 1.8/5)
  (w/o c diff. χ^2/n.d.f. = 7.4/5)
  - χ^2 tests done to v_2

Theory: arXiv:1506.03981 (2015) & private comm.
STAR: PRL 113 (2014) 142301

* See talk by R. Rapp, Plenary II



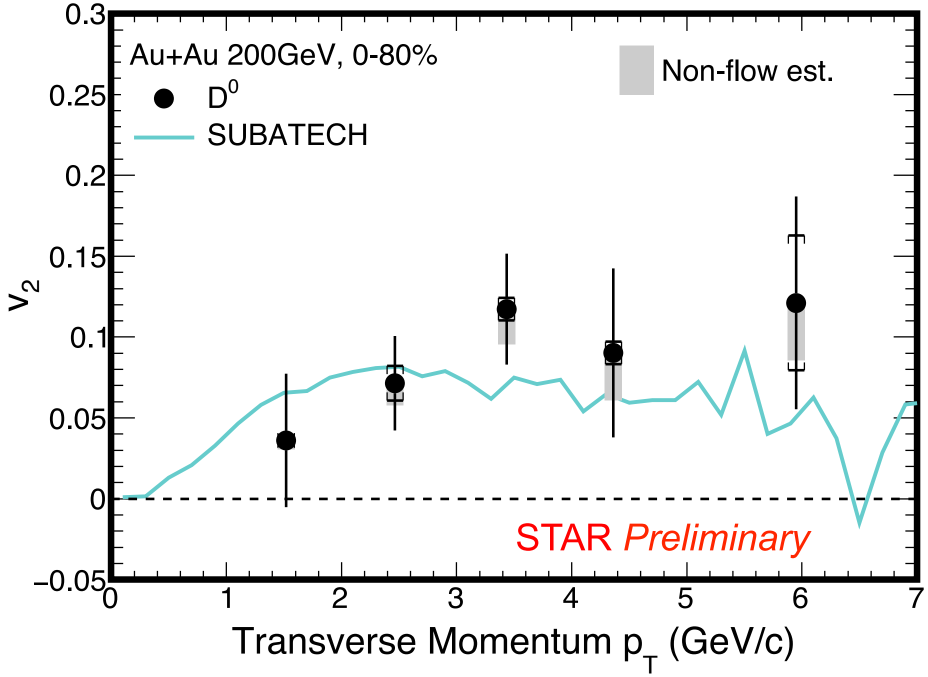


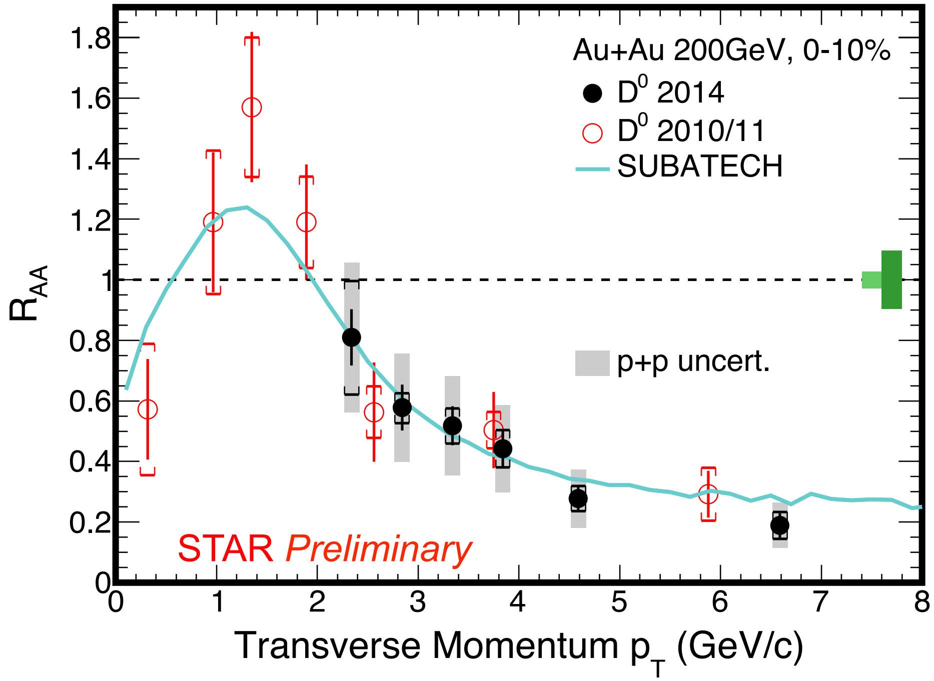
Model comparison: SUBATECH

- pQCD+HTL calculation with latest EPOS3 initial conditions
- Diffusion coefficient extracted from calculations $2\pi T \times D \sim 2\text{-}4$
- Good agreement between model and experiment for both v_2 and R_{AA} in entire p_T range
  (χ^2/n.d.f. = 2.8/5)
  - *χ^2 tests done to v_2*

Theory: arXiv:1506.03981 (2015) & private comm.
STAR: PRL 113 (2014) 142301

* See talk by PB Gossiaux, HF Workshop



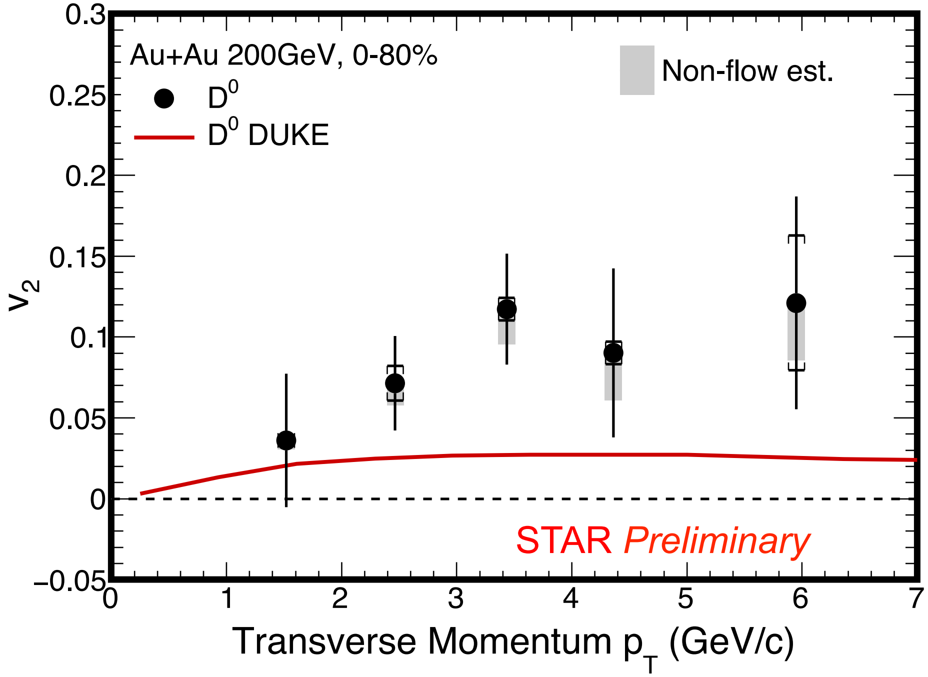


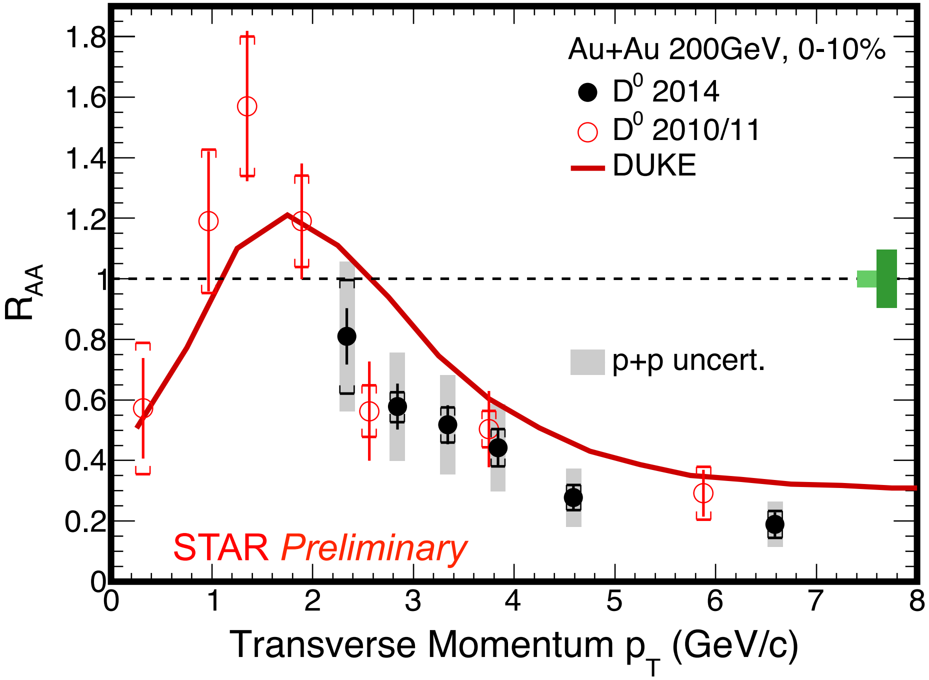
Model comparison: Duke

- Diffusion coefficient is a free parameter, fixed by fitting to R_{AA} at high p_T
- Input value for diffusion coefficient $2\pi T \times D = 7$ fixed to fit LHC results
- Model with $2\pi T \times D = 7$ doesn't describe the magnitude of v_2 in experimental data

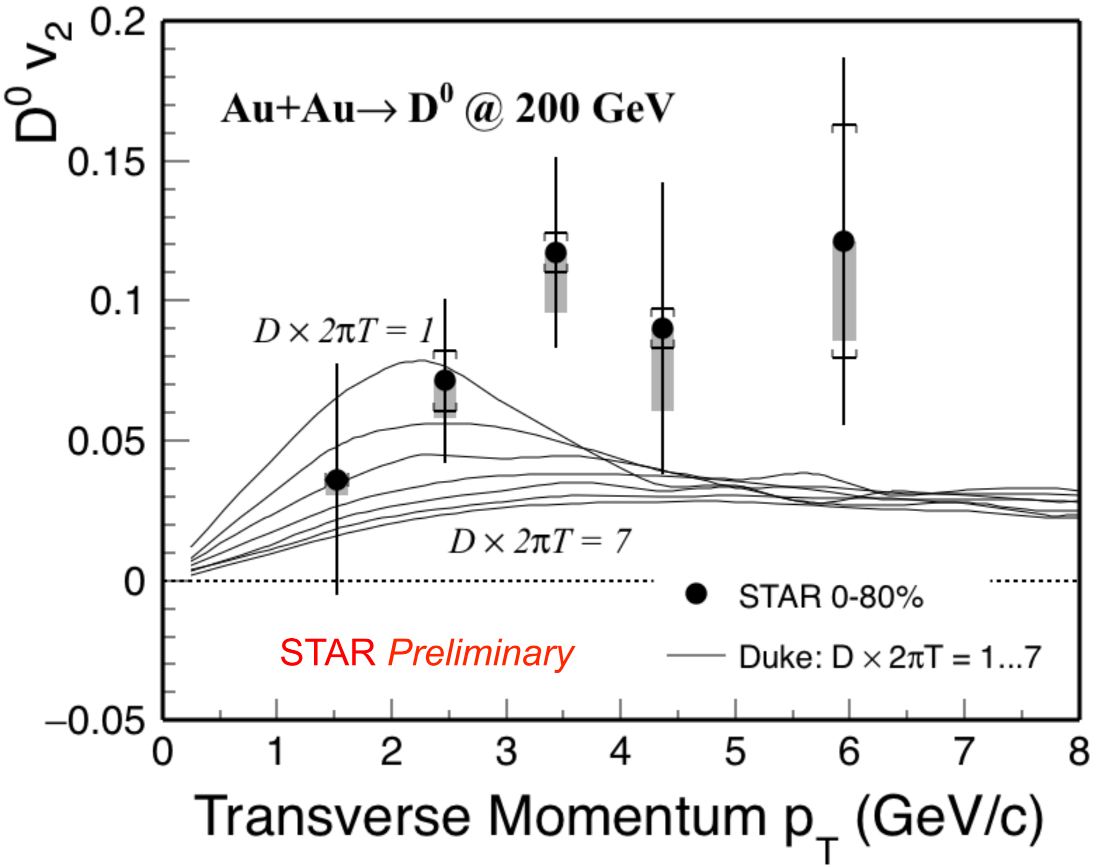
Theory: arXiv:1505.01413 & private comm.
STAR: PRL 113 (2014) 142301

* See talk by S. Cao, HF Workshop





Charm diffusion coefficient

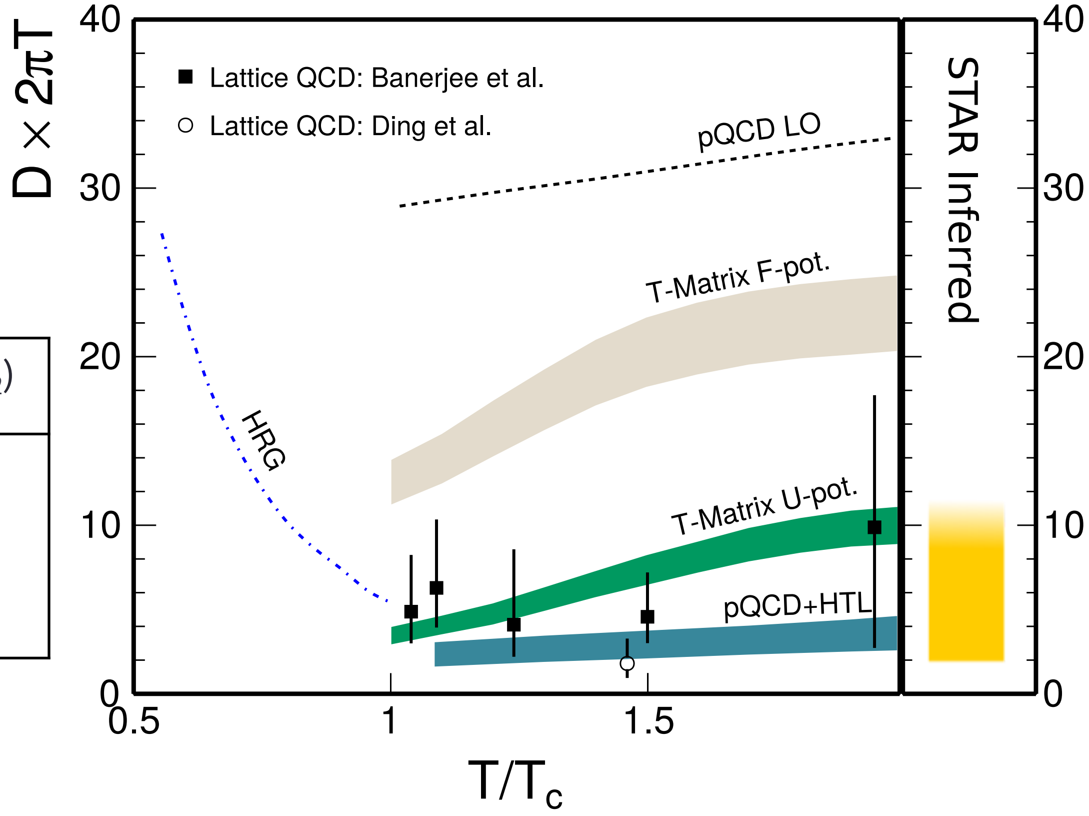


- Scan different values of the diffusion coefficient to find best agreement to data
- Best agreement for diffusion coefficient $2\pi T \times D = \sim 1 - 3$
- This model seems to underestimate the data for $p_T > 3$ GeV/c

Theory: arXiv:1505.01413 & private comm.

Diffusion coefficient

	Diffusion coef.	χ^2/n.d.f. (to v_2)
TAMU	2-10	1.8/5
SUBATECH	2-4	2.8/5
Duke	7	13.0/5



- Compatible with models predicting a value of diff. coefficient between 2 to ~10
- Lattice calculations, although with large uncertainties, are consistent with values inferred from data

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Outlook

- Run 14:
  - Full statistics available soon
- Run 15:
  - Full aluminum cables for inner layer of PXL
  - p+p and p+A data sets with HFT
- Run 16:
  - Full aluminum cables for inner layer of PXL
  - Factor 2 -3 improvement for D^0 significance @ 1 GeV -> centrality dependence for v_2

Year	System	Events(MB)
Run 14:		
	Au+Au	1.2 B
Run 15:		
	p+p	1 B
	p+Au	0.6 B
Run 16:		
	Au+Au	1.5 B *
	d+Au	~0.3 B

* Up to Date

Future HFT+ Upgrade plan (2021-2022)

HFT+ upgrade motivation:

- Measure **bottom quark hadrons** at the RHIC energy
- Take data in **higher luminosity** with high efficiency

HFT+ detector requirements:

- **Faster** frame readout of 40 μs or less
- **Similar or better**: pointing resolution
  - S/N ratio
  - Total power consumption
  - Radiation length

→ **ALICE ITS Upgrade**
MAPS sensor

- **Compatible** with the existing insertion mechanism, support structure, air cooling system

→ **STAR HFT**
mechanics and services

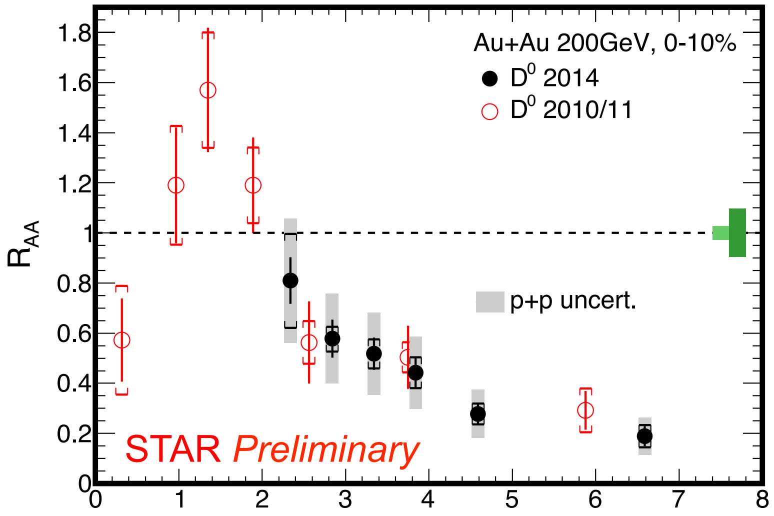
HFT+ read-out electronics requirements:

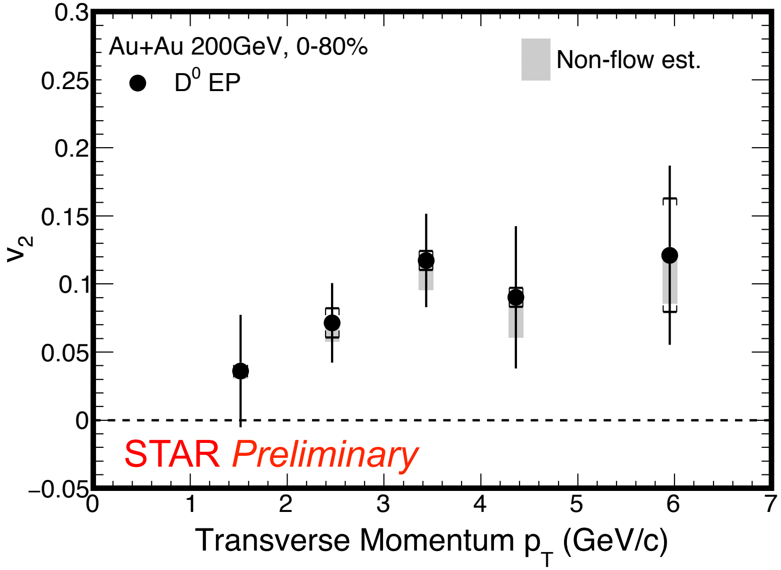
- **Compatible** with STAR DAQ system and trigger

→ **STAR + ALICE**
new development

Summary

- The STAR HFT has been successfully installed and taking data in 2014-2016
- State-of-the-art MAPS technology proved to be suitable for vertex detector application
- The HFT enabled STAR to perform a direct topological reconstruction of the charmed hadrons – factor 4 improvement in D^0 significance
- A faster HFT+ has been planned in order to measure the bottom quark hadrons at the top RHIC energy
- Presented first results of charmed meson R_{AA} and v_2 using the HFT
- D^0 is significantly suppressed for high p_T in 0-10% Au+Au collisions



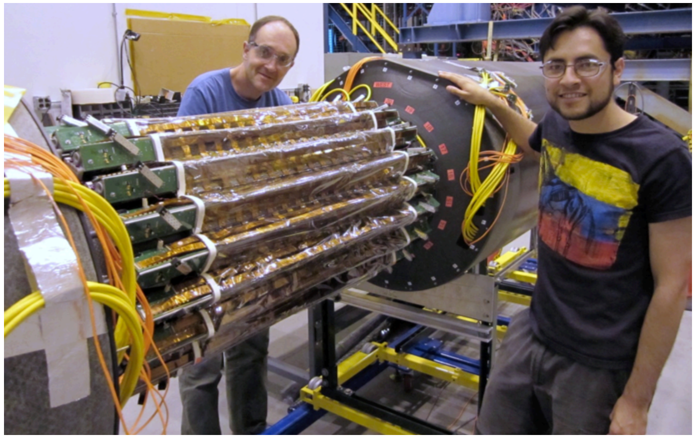


- D^0 v_2 is finite for $p_T > 2.0$ GeV/c and lower than light hadrons for $1 < p_T < 4.0$ GeV/c
- Data favor model scenario where charm quarks flow
- D^0 v_2 and R_{AA} can be described simultaneously by models and are consistent with values of 2πTxD between 2 and ~10
- Looking forward to improved baseline from 2015 and statistics in year 2016

Thank you!

Back ups

HFT Subsystems

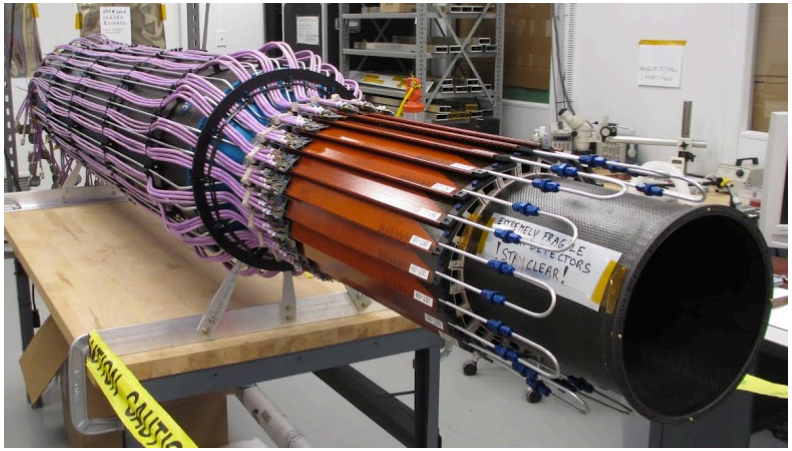


Silicon Strip Detector (SSD)

- Double sided silicon strip modules with 95 µm pitch
- Existing detector with new faster electronics
- Radius: 22 cm – Length: ~106 cm

Intermediate Silicon Tracker (IST)

- Single sided double-metal silicon pad with 600 µm x 6 mm pitch
- Radius: 14 cm – Length: ~50 cm



PiXeL detector (PXL)

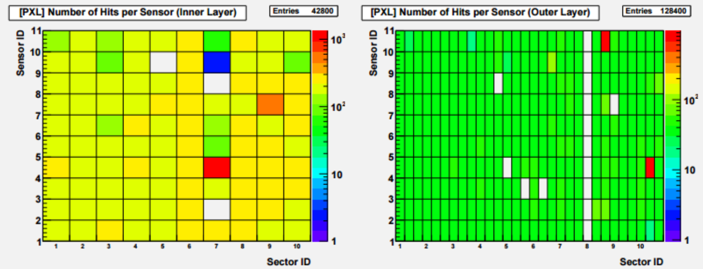
- *Monolithic Active Pixel Sensor* technology
- 20.7 µm pitch pixels
- Radius: 2.8 and 8 cm – Length: ~20 cm

First MAPS-based vertex detector at a collider experiment

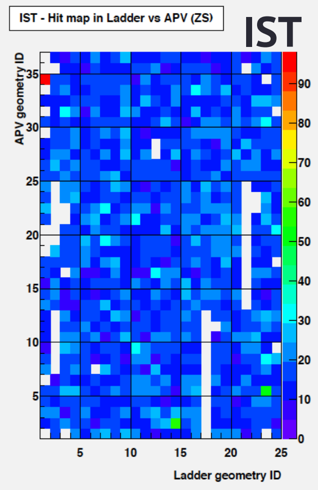
HFT Status in 2014 and 2015 Run

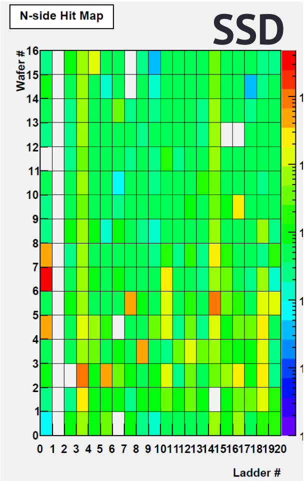
- Collected minimum bias events in HFT acceptance:
  - 2014 Run 1.2 Billion Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
  - 2015 Run: → { ~ 1 Billion p+p
    ~ 0.6 Billion p+Au } @ $\sqrt{s_{NN}}$ = 200 GeV
- Typical trigger rate of ~0.8kHz with dead time <5%
- Sub-detector active fraction
  - PXL
    - > 99% operational at the delivery
    - 2015 Run ended with 5% dead sensors
      (6 damaged sensors + 1 outer ladder off)
  - IST
    - 95% channels operational, stable
  - SSD
    - 80% channels operational (one ladder off)

PXL1



PXL2





Topological reconstruction

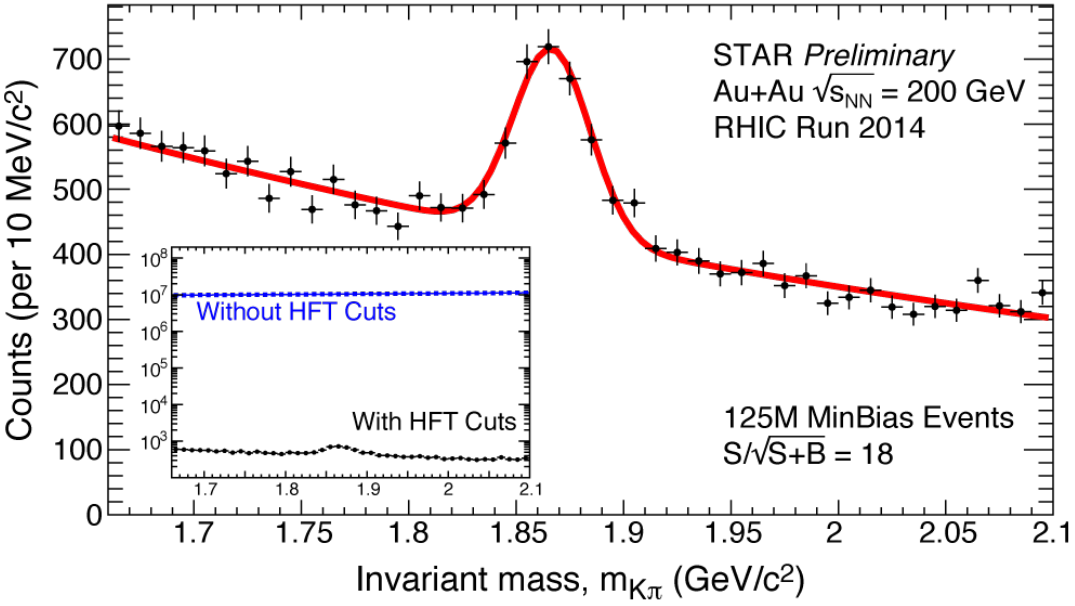
- Direct topological reconstruction through hadronic channels, for instance:

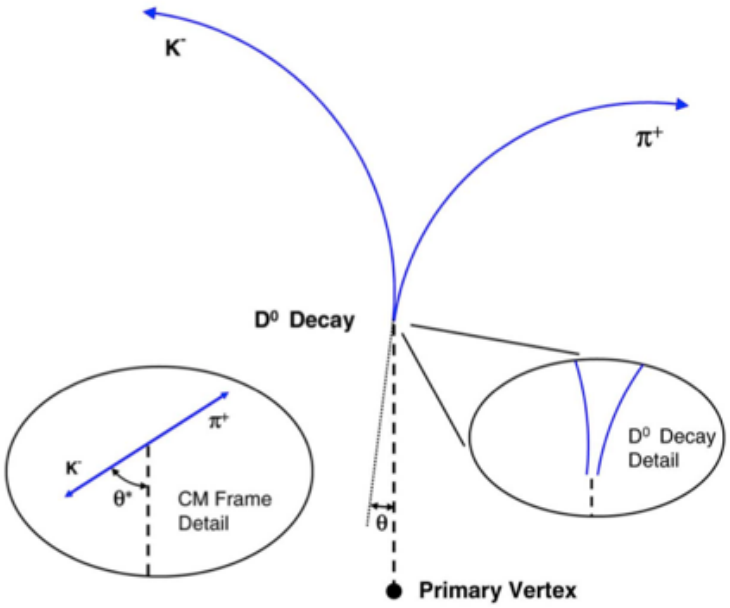
$$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$$

$$\text{B.R. } 3.9\% \quad c\tau \sim 120\ \mu m$$

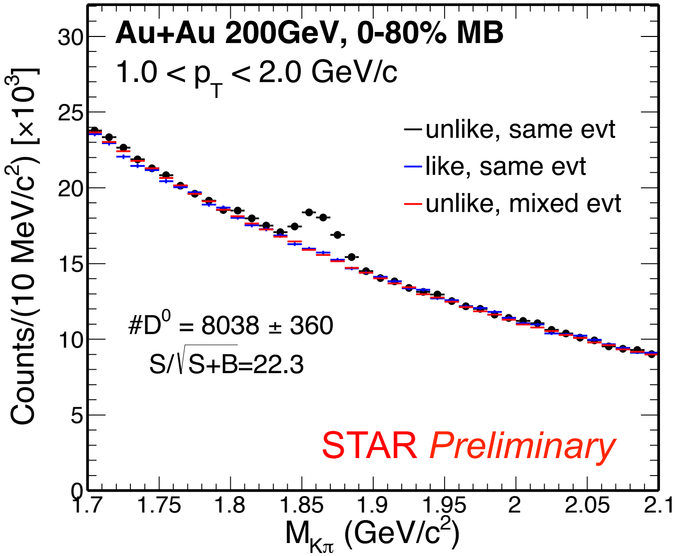
- Greatly reduced combinatorial background (4 orders of magnitude)

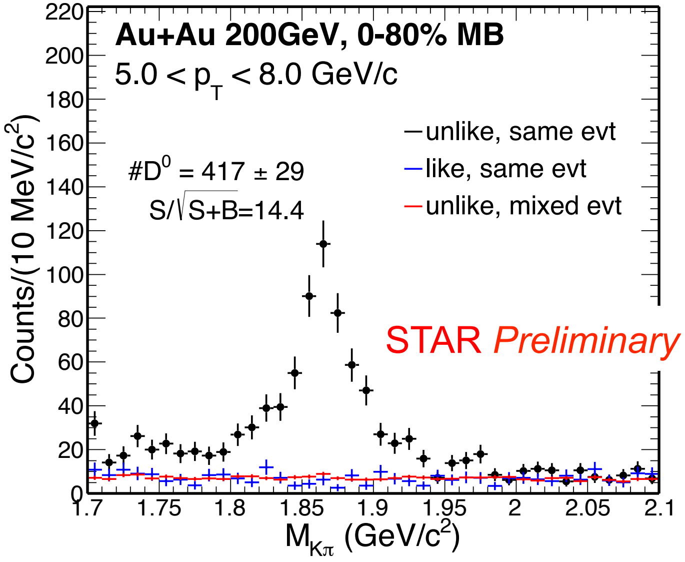
- Topological cuts optimized using TMVA (Toolkit for Multivariate Analysis)





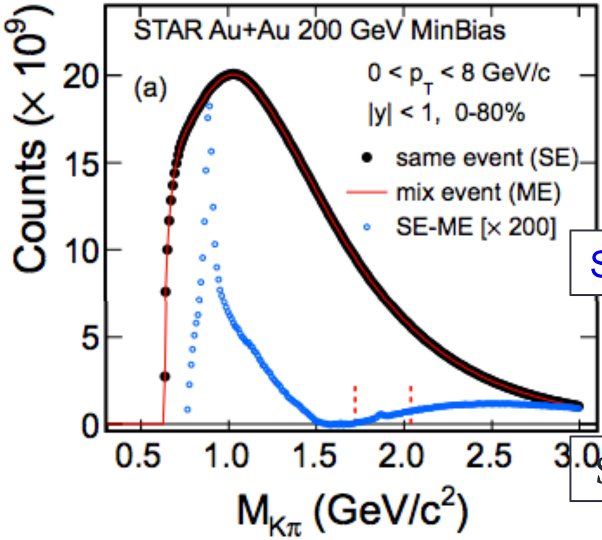
D^0 reconstruction using HFT





- Significance greatly enhanced compared to STAR previous, 2010+2011 results.

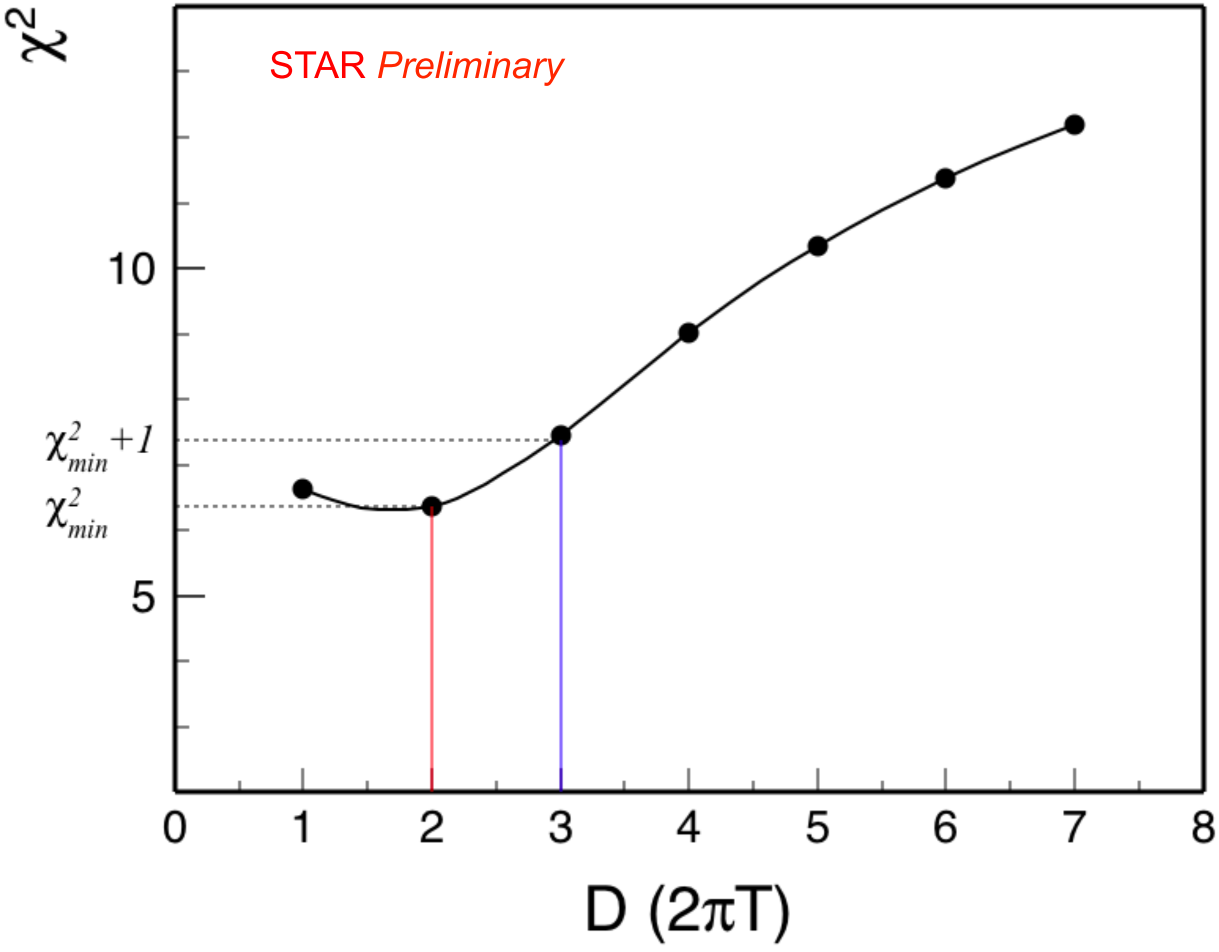
	w/o HFT	w HFT
	2010 + 2011	2014
# events(MB) analyzed	1.1 B	780 M
significance per billion events	13	51



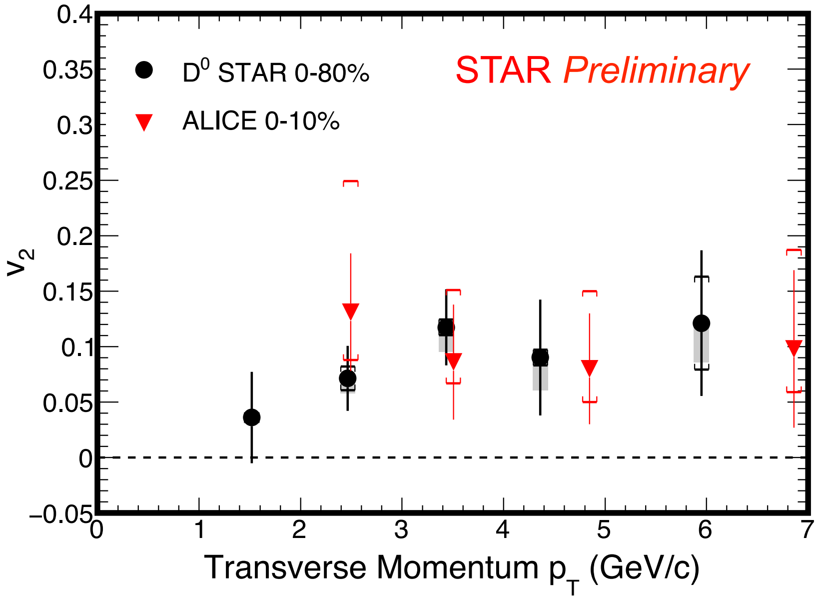
STAR 2010/11

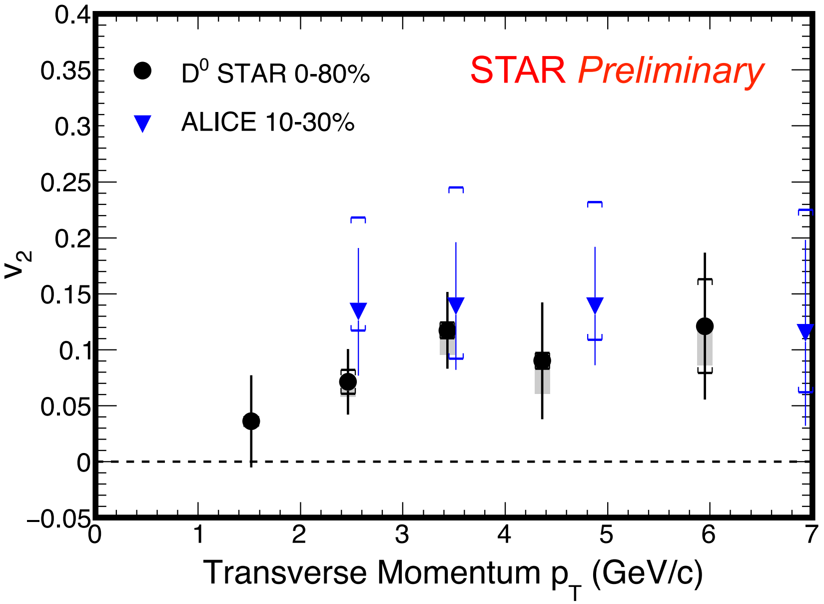
STAR: PRL 113 (2014) 142301

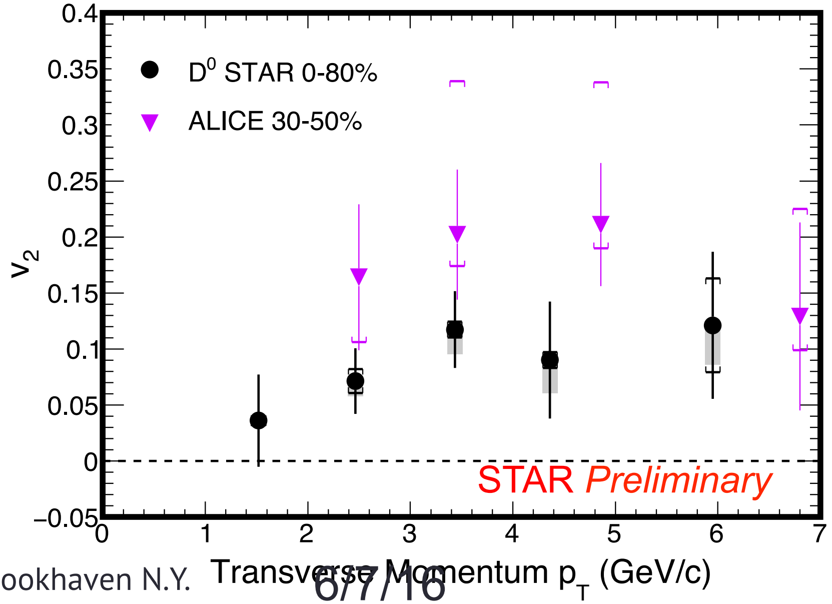
Diffusion Coefficient from DUKE



Comparison to ALICE







v_2: Event plane method

- Event plane reconstructed using charged hadrons within STAR TPC acceptance ($|\eta|<1$)
- Corrected for detector acceptance
- Yields in $\phi-\Psi$ bins corrected for event plane resolution

$$v_2 = v_2^{obs} \times \left\langle \frac{1}{\text{E.P. Resolution}} \right\rangle$$

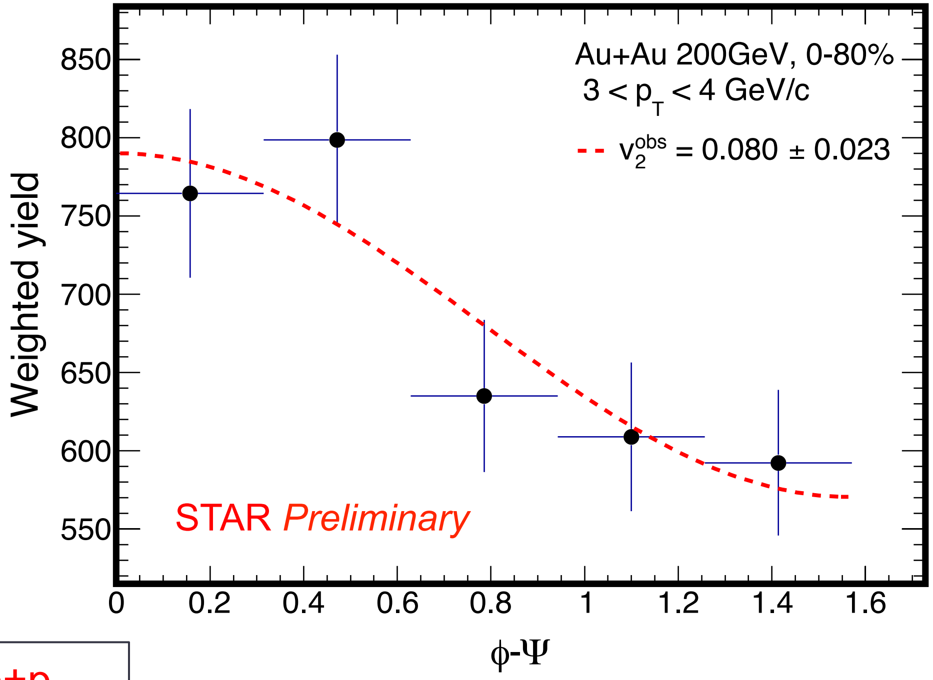
- $\Delta\eta$ gap of ~0.15 used in event plane reconstruction

$$v_2^{nonFlow} = \frac{< \sum_h \cos(2(\phi_{D^0} - \phi_h)) >}{M v_2^h}$$

p+p

Au+Au

- Non-flow estimated from measured D-h correlations in p+p 200GeV



A.M. Poskanzer, et al. PRC 58 (1998) 1671
STAR: PRL 93 (2004) 252301

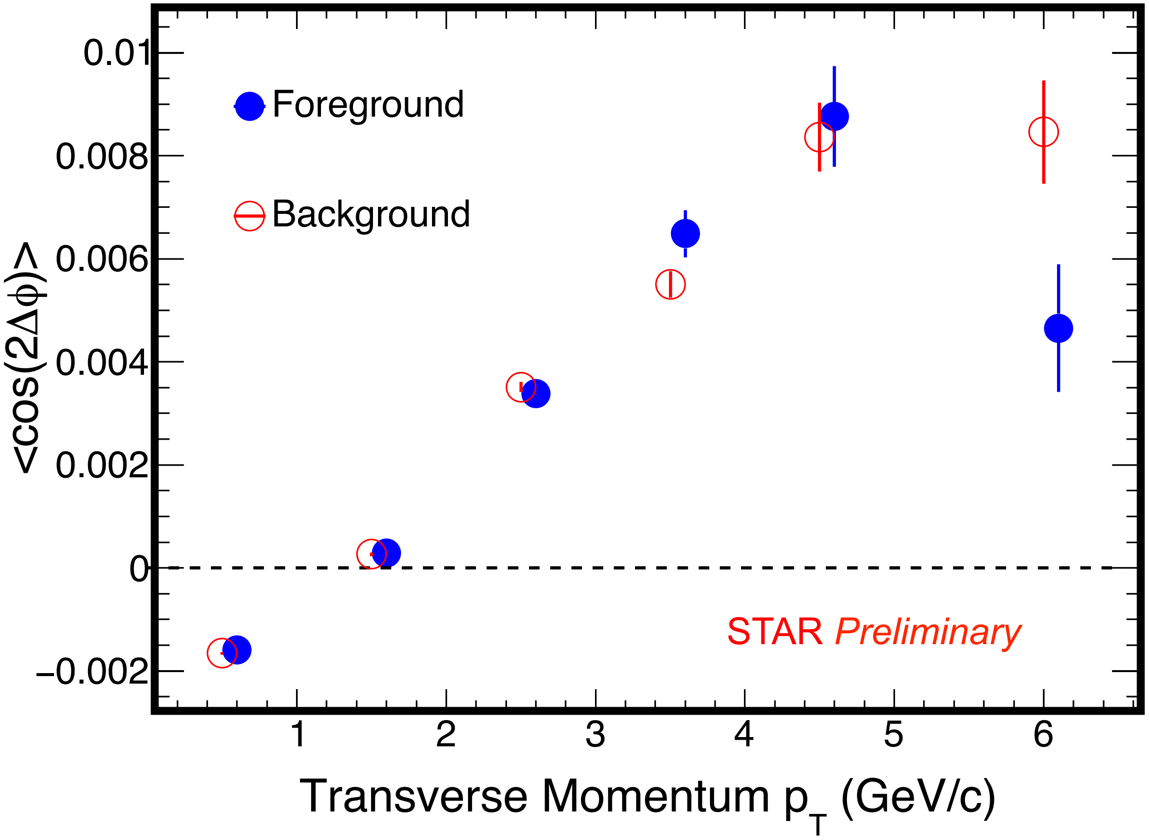
v_2: Two particle correlation

- Event by event v_2 for foreground and background

$$< \cos(2\varphi_{h1} - 2\varphi_{h2}) >= (\nu_2^h)^2$$

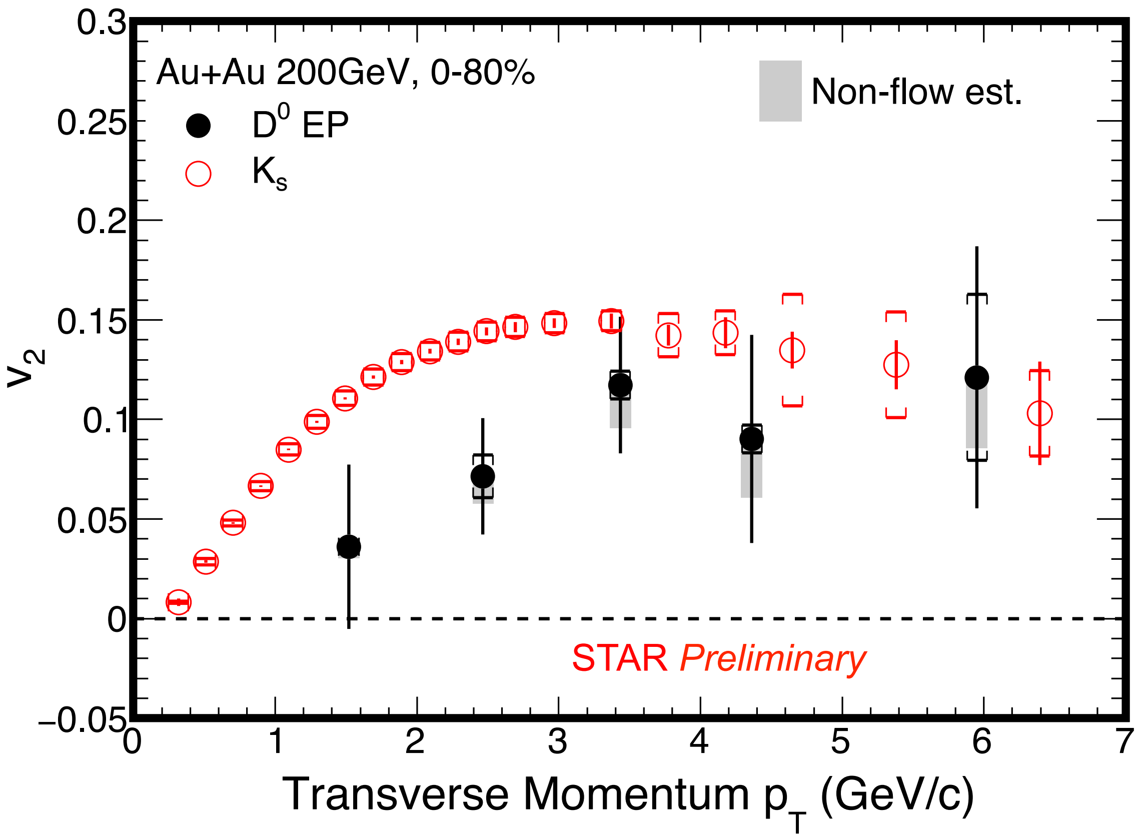
$$\nu_2^D = \frac{< \cos(2\varphi_D - 2\varphi_h) >}{\sqrt{< \cos(2\varphi_{h1} - 2\varphi_{h2}) >}}$$

- h_1 in $\eta < 0$, h_2 in $\eta > 0$
- Statistically subtract background from foreground to obtain D^0 v_2
- Corrected for detector acceptance



A.M. Poskanzer, et al. PRC 58 (1998) 1671

Comparison to experiment

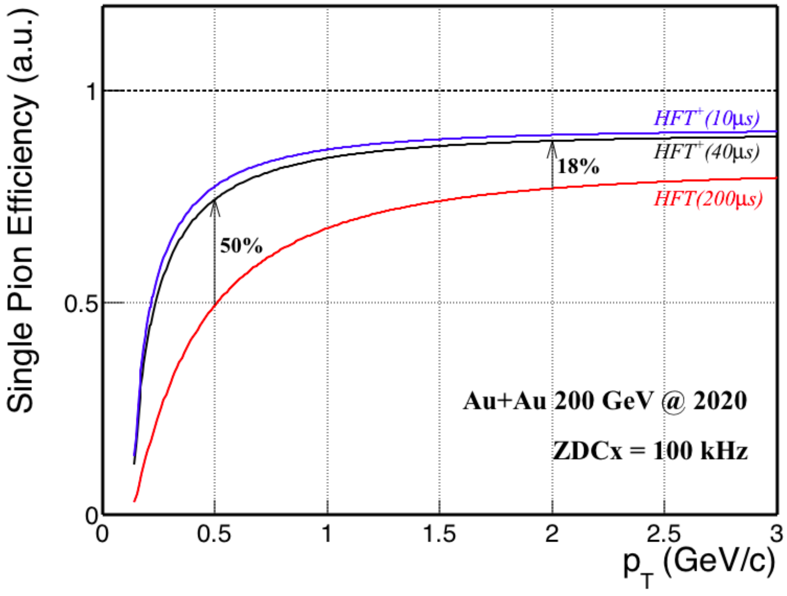


- D^0 v_2 is below light hadrons for $1 < p_T < 4$ GeV/c
  - (χ^2/n.d.f. = 9.6/3)

STAR:PRC 77 (2008) 54901

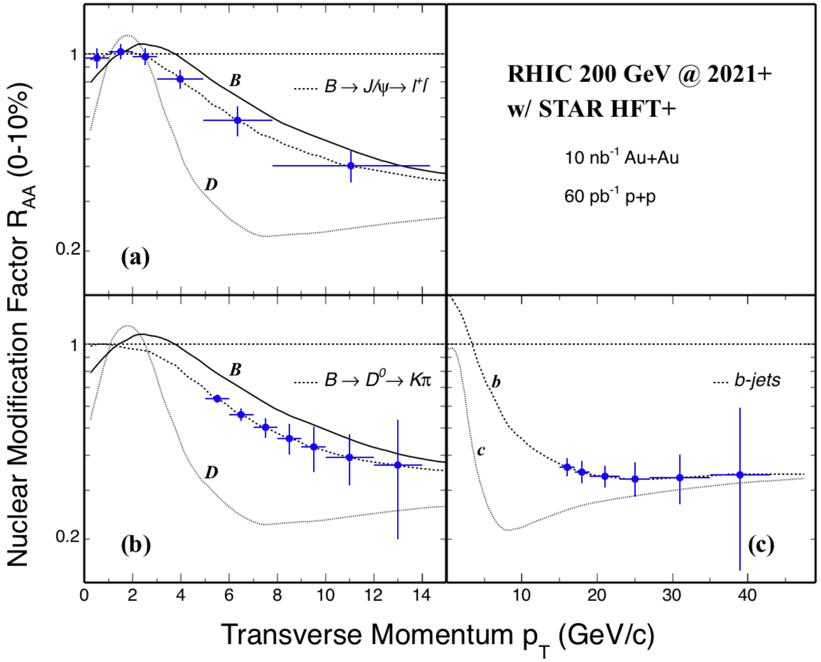
HFT+ simulation

Efficiency: fast vs. slow HFT



- HFT (~200 µs) → HFT+ (≤40 µs)

HFT+ flagship measurements



- R_{AA} for *J/ψ* and *D⁰* from *B*, and *b-jets*

- The planned HFT+ program (2021-2022) is complementary to sPHENIX at RHIC and ALICE HF program at LHC