D^0 v_2 measurement at STAR

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For the STAR Collaboration

32[ND] WINTER WORKSHOP ON NUCLEAR DYNAMICS
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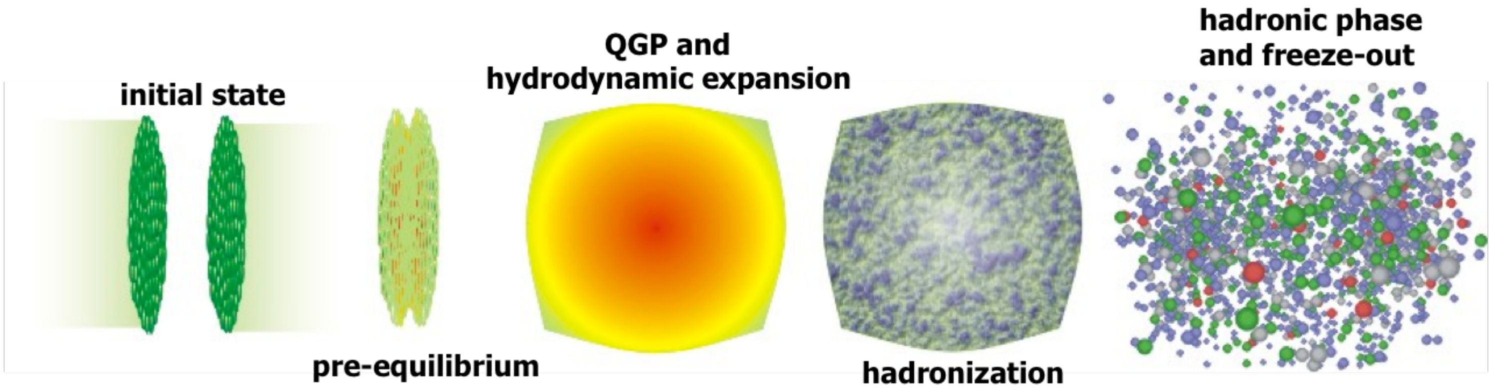
GUADELOUPE, FRANCE

Outline

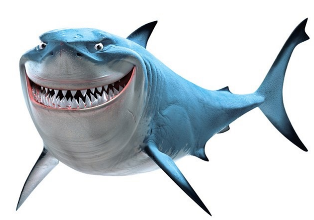
- **Motivation**
- STAR detector with HFT (Heavy Flavor Tracker)
- D^0 reconstruction
- D^0 v_2: event plane and two-particle correlation
- Discussion
- Summary and outlook

Why Charm Quark?



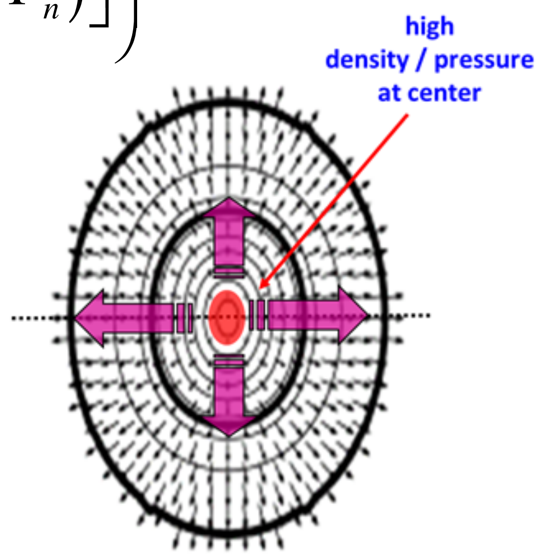
Heavy flavor quarks

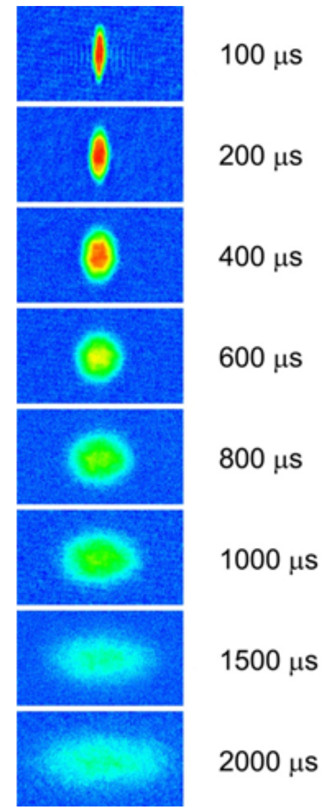
- Produced in early stage: probe properties of medium
- Thermalization is delayed by a factor of ~5-10 (m_Q/T)
- Much less gluon radiation ~$(m_q/m_c)^4$;
- Momentum transfer from thermal medium is small compared to heavy quark momentum: Brownian Motion approach;



Why Elliptic Flow (v_2)?

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi-\Psi_n\right)\right]\right)$$





Science, 298, pp. 2179-2182 (2002)
J. E. Thomas, et al.

- Elliptic flow (v_2): the second term of Fourier expansion
- V_2 in non-central heavy-ion collisions suggests hydrodynamic behavior of a strongly interacting matter.
- Charm hadron v_2 provides insights into transport properties of sQGP

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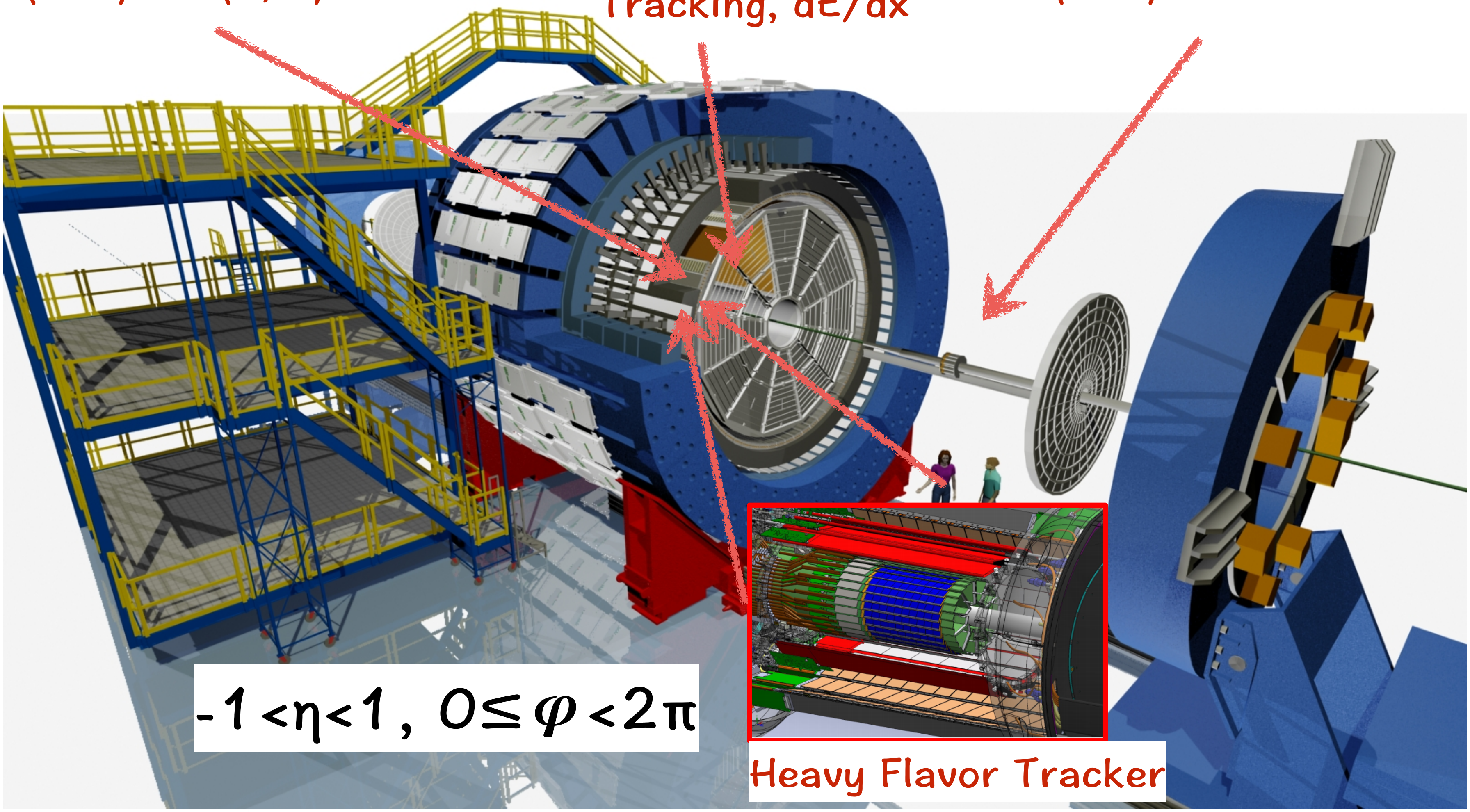
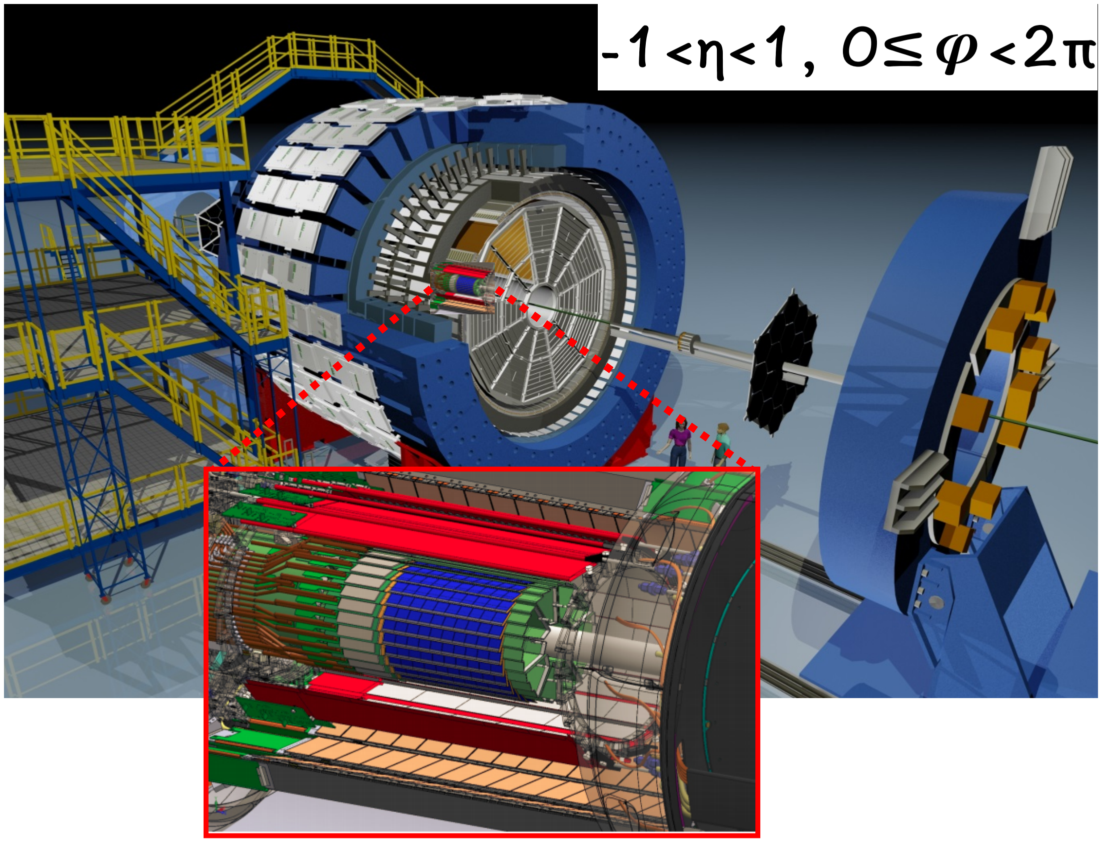
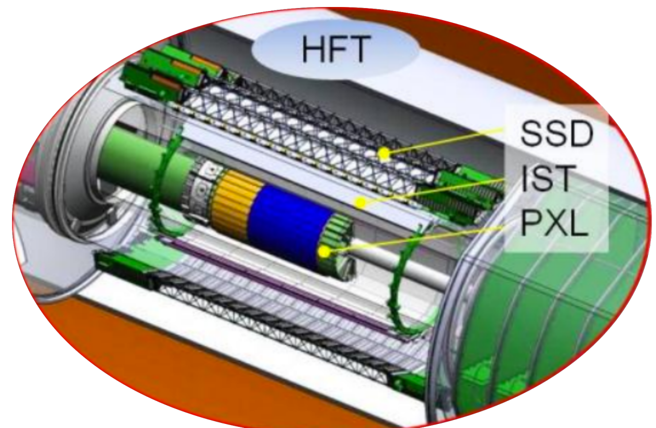
STAR Detector



HFT (**H**eavy **F**lavor **T**racker)



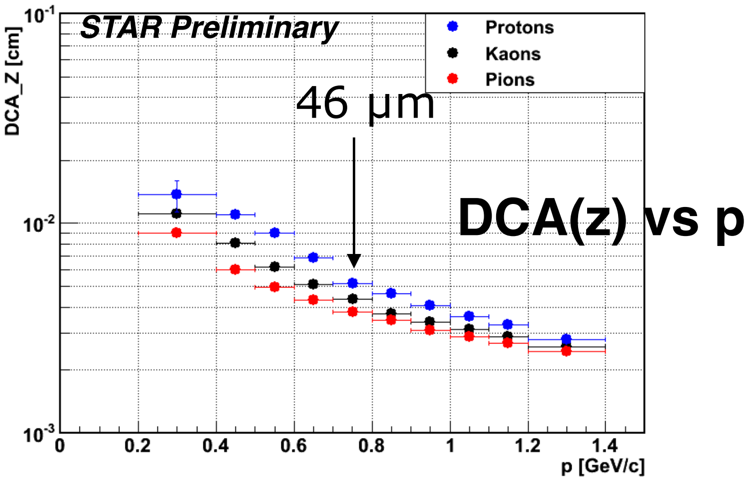
- SSD – Silicon Strip Detector (r~22cm)
- IST – Intermediate Silicon Tracker (r~14cm)
- PXL – Pixel Detector (r~2.8 & 8cm)

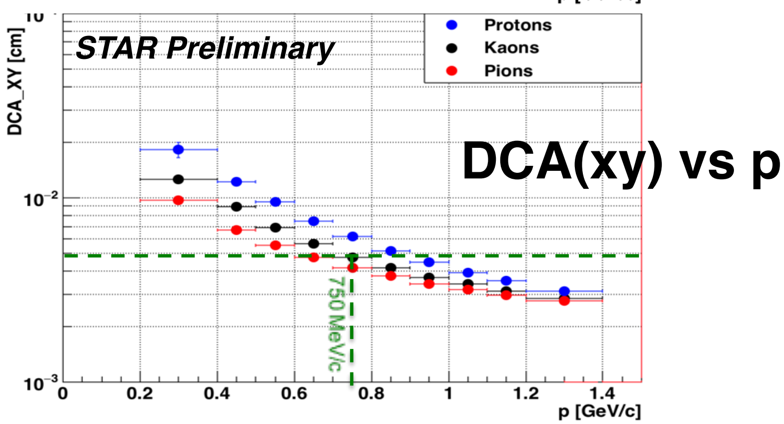


Direct topological reconstruction of charm hadrons (e.g. $D^0 \to K\pi$, $c\tau$~120 μm)

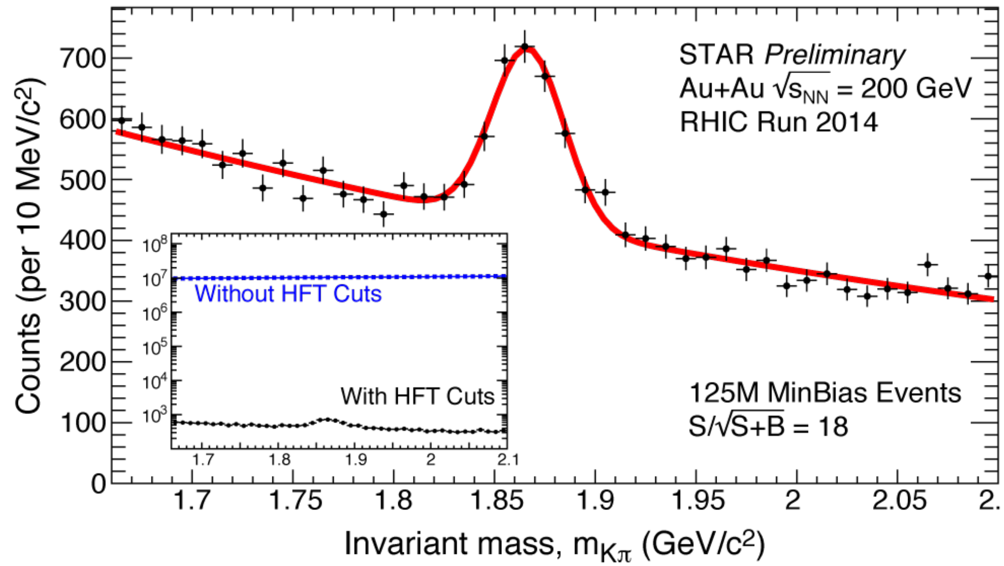
HFT Performance

DCA resolution





- Good DCA (Distance of Closest Approach) resolution
- <30μm for high p_T tracks



Kπ invariance mass spectrum with and w/o HFT

- Clear D^0 signal
- Background rejection by 4 orders of magnitude

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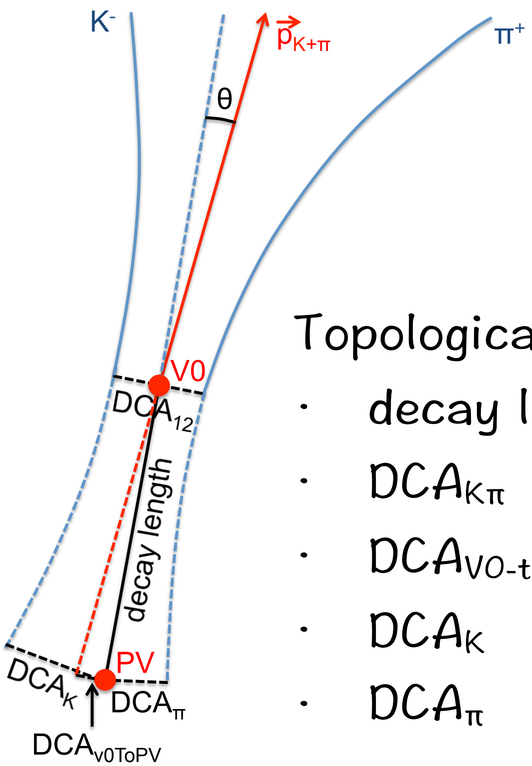
Topological Reconstruction

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

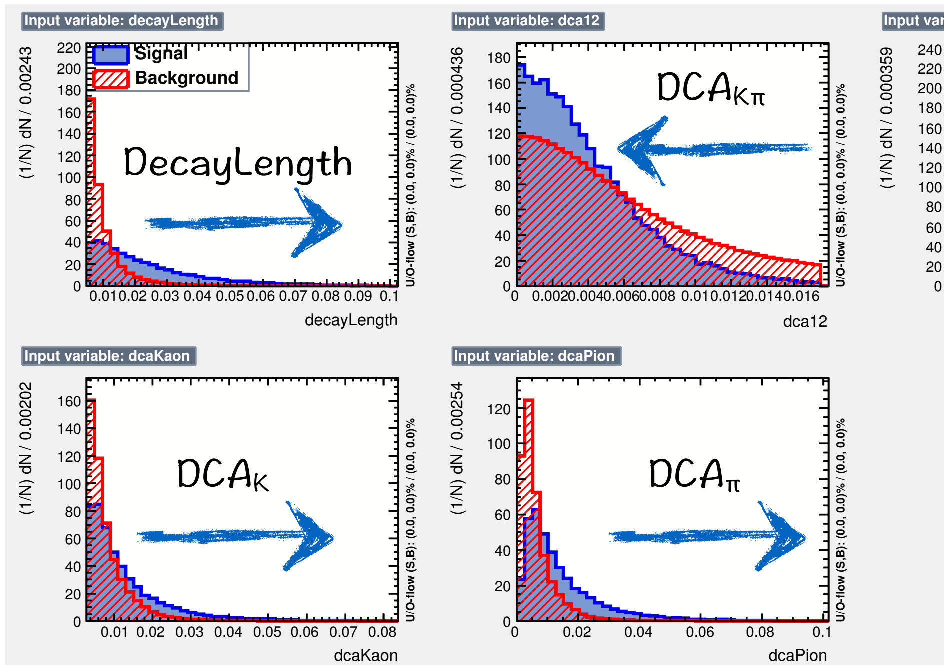
B.R. 3.9% $c\tau \sim 120\ \mu m$



Topological cuts:

- decay length
- $DCA_{K\pi}$
- $DCA_{V0\text{-to-}PV}$
- DCA_K
- DCA_π

DCA : Distance of Closest Approach



TMVA (Toolkit for Multivariate Analysis)

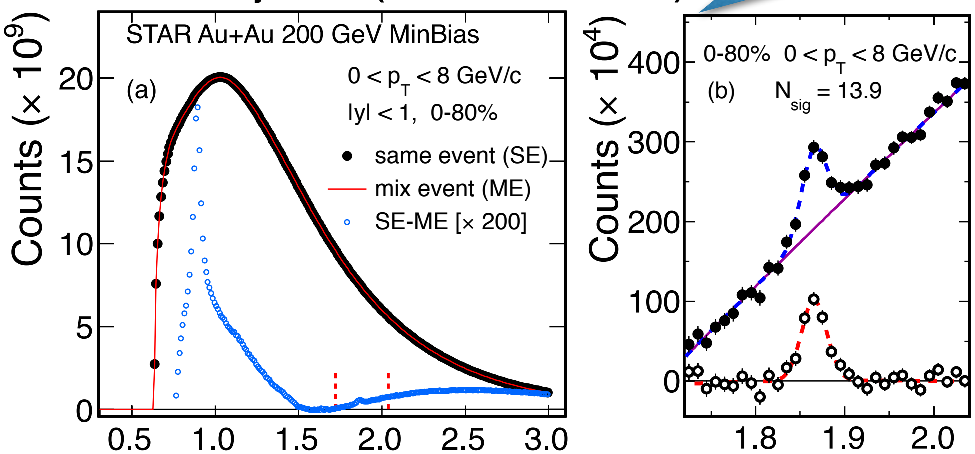
- Signal
- Background

Improvement with HFT

Significance greatly enhanced compared to previous STAR result (2010+2011)

2010+2011

STAR: PRL 113 (2014) 142301
L. Adamczyk et al. (STAR Collaboration)

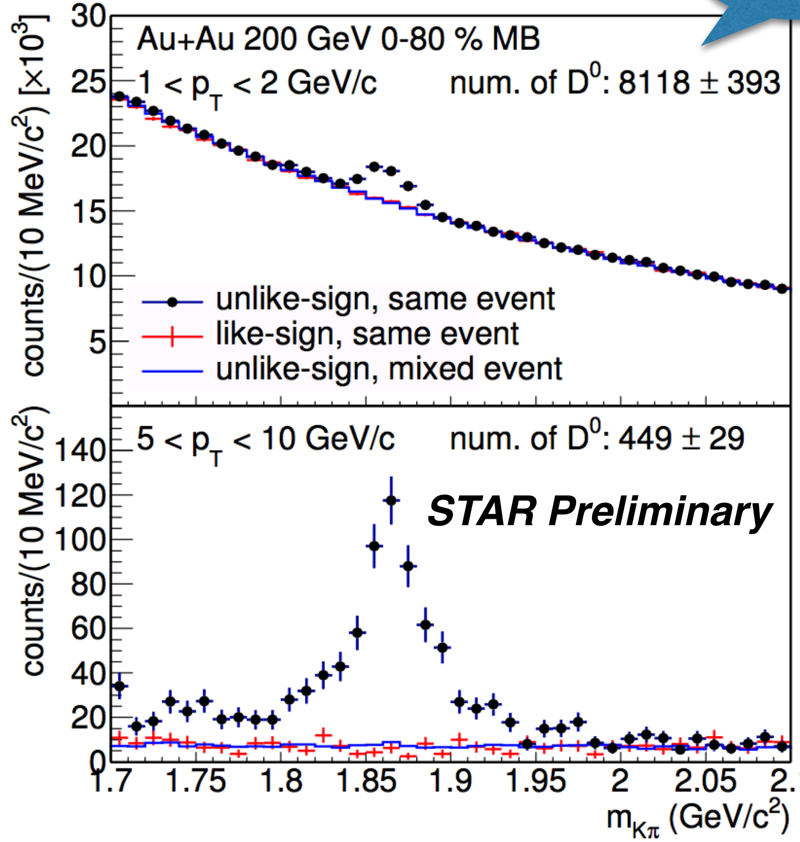


D^0 reconstruction at STAR in 2010+2011

- Solid circle : SameEvent-MixEvent
- Open circle: residual background subtracted

	w/o HFT	w HFT
	2010+2011	2014
#events(MB) analyzed	1.1 billion	780 million
sig. per billion events	13	51

2014



D^0 reconstruction at STAR in 2014

- Good significance from low to high p_T range

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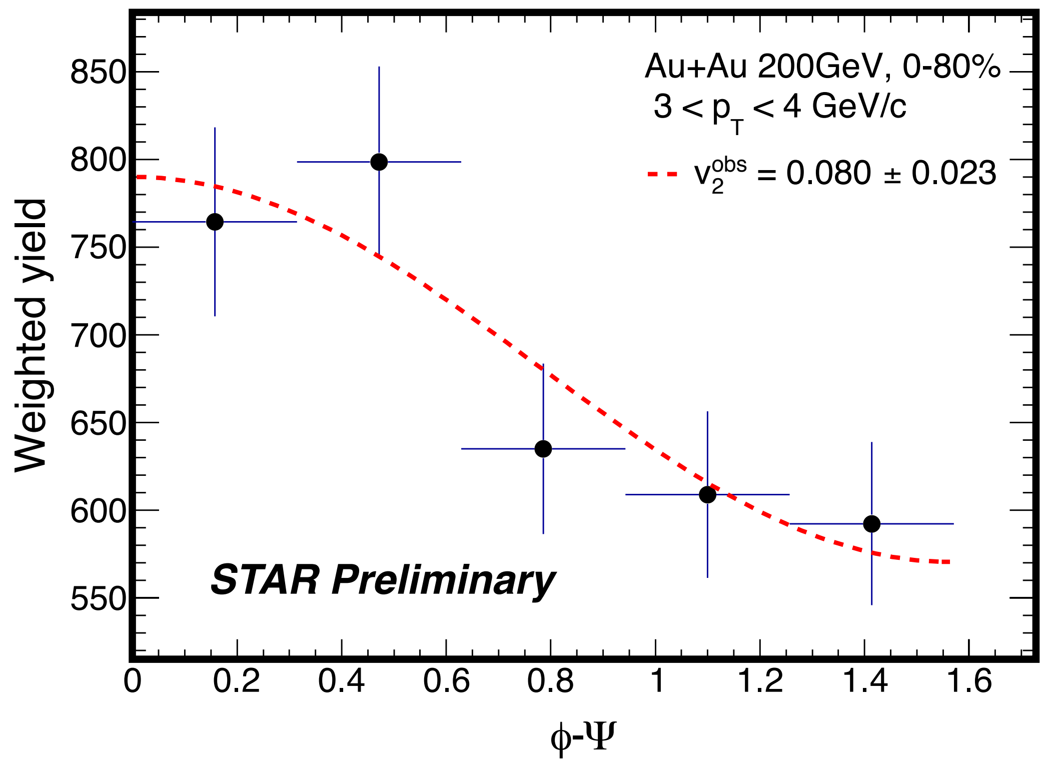
Event Plane Method

- Event plane v_2

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

- Fit with $N(1+2v_2^{obs}\cos(2(\phi-\Psi))$

- $\Delta\eta$~0.15 between D^0 and event plane is required to suppress the non-flow effect



Two-particle Correlation

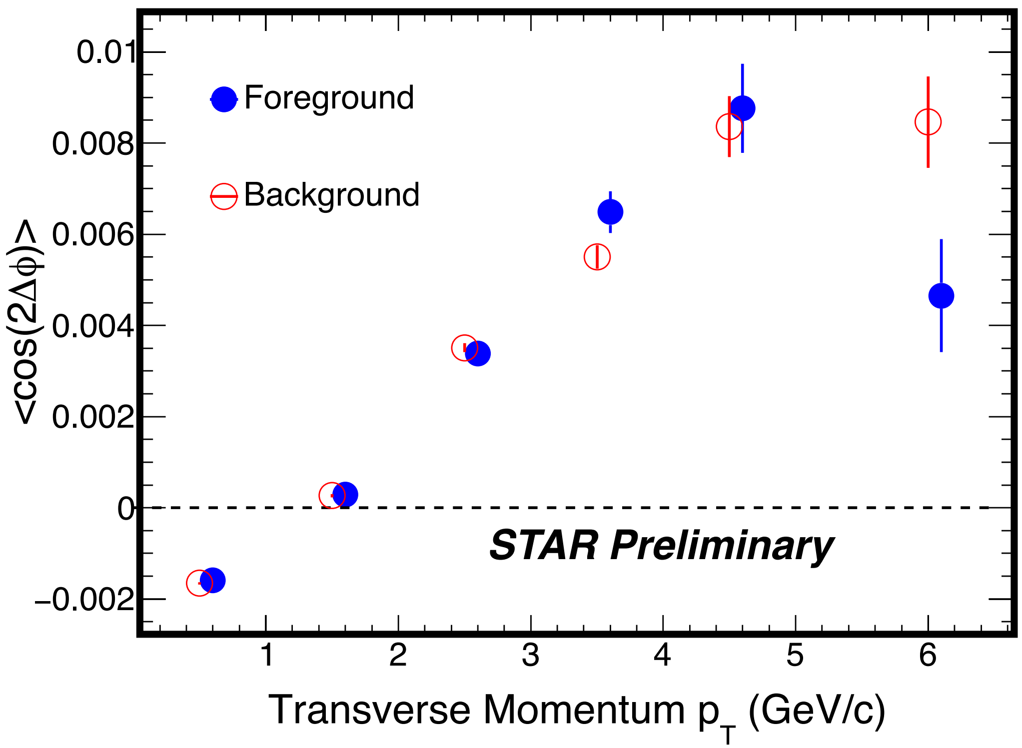
- Correlation v2

$$v_2^{D\bullet h} = < \cos(2\varphi_D - 2\varphi_h) >$$
$$\approx < \cos(2\varphi_D - 2\psi_{PP}) > \bullet < \cos(2\varphi_{hadron} - 2\psi_{PP}) >$$
$$= v_2^D \bullet v_2^h$$
$$< \cos(2\varphi_{h1} - 2\varphi_{h2}) > = (v_2^h)^2$$

- Background Extraction using side-band

$$N_{cand} = N_{signal} + N_{bkg} \Rightarrow \frac{dN_{cand}}{d\varphi} = \frac{dN_{signal}}{d\varphi} + \frac{dN_{bkg}}{d\varphi}$$
$$N_{cand}[1 + 2v_2^{cand}\cos(2\varphi)] =$$
$$N_{signal}[1 + 2v_2^{signal}\cos(2\varphi)] + N_{bkg}[1 + 2v_2^{bkg}\cos(2\varphi)]$$

$$v_2^{signal} = \frac{N_{cand} \bullet v_2^{cand} - N_{bkg} \bullet v_2^{bkg}}{N_{signal}}$$



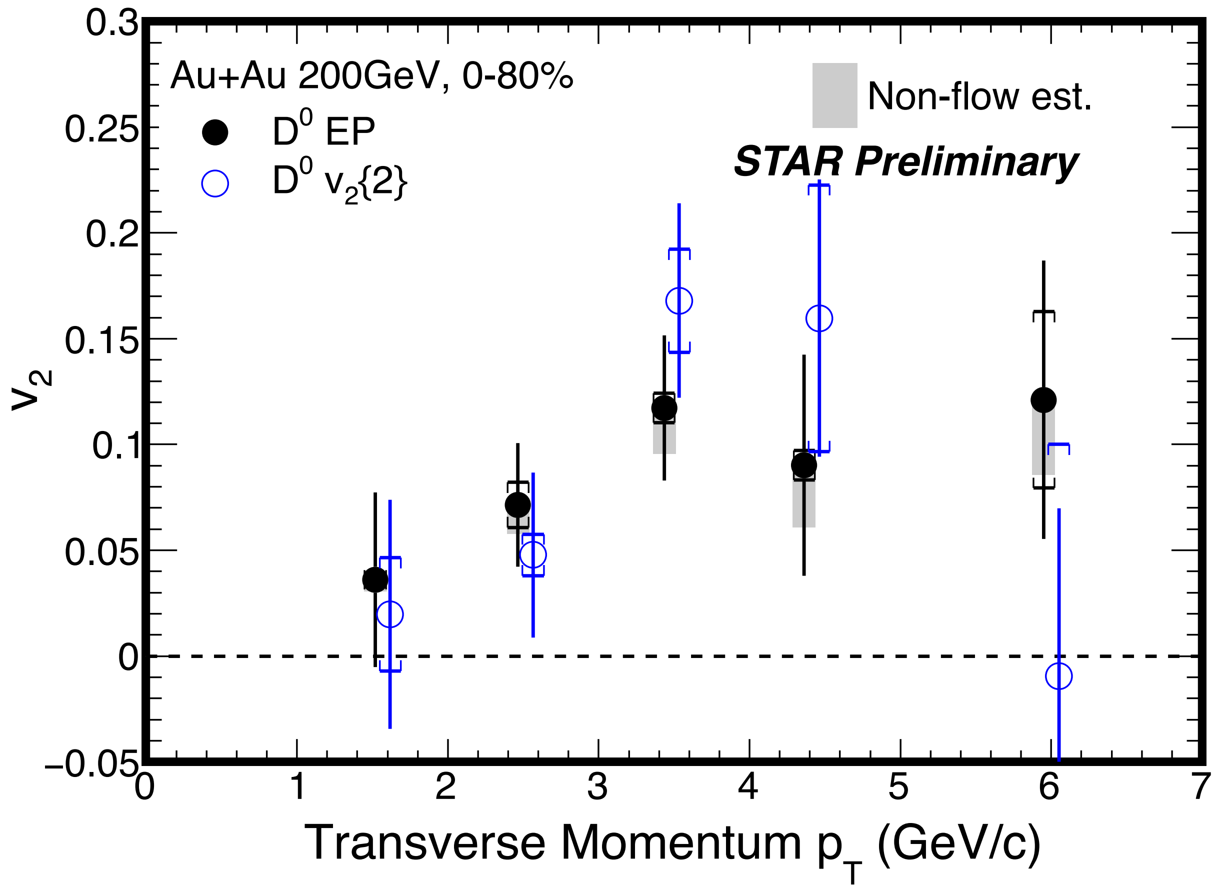
Systematic Uncertainty

- Event Plane Method:
  - Background uncertainty: fitting range and side bands
- Two-particle Correlation Method:
  - Yield fitting function
  - Background uncertainty: like-sign and unlike-sign, side bands

p_T (GeV/c)	1.51	2.46	3.43	4.36	5.95
Event plane method	0.0017	0.0131	0.0077	0.0057	0.0343
Two-particle correlation	0.0268	0.0098	0.0243	0.0629	0.1095

Systematic uncertainty for D^0 v_2 in different pT bins

Result



Non-flow contribution is estimated using $D^{*\pm}$-hadron correlation in p+p collisions at 200GeV

- D^0 v_2 is above zero for p_T>2GeV/c (χ^2/n.d.f.=17.5/4)
- B->D feed down is very small at RHIC energies (<5% relative contribution)

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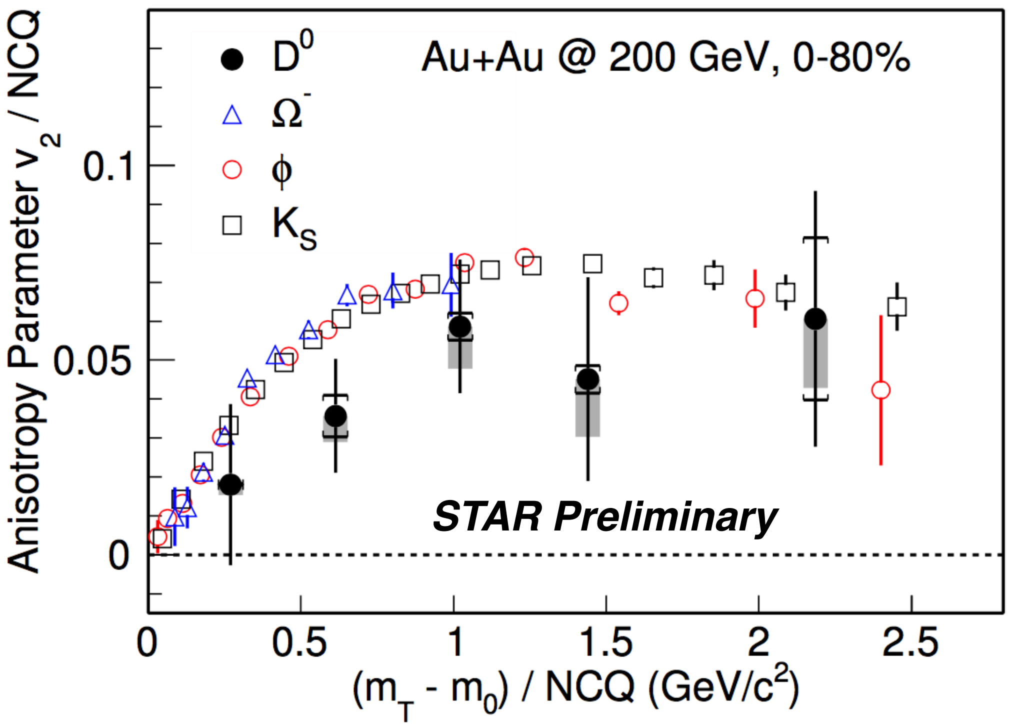
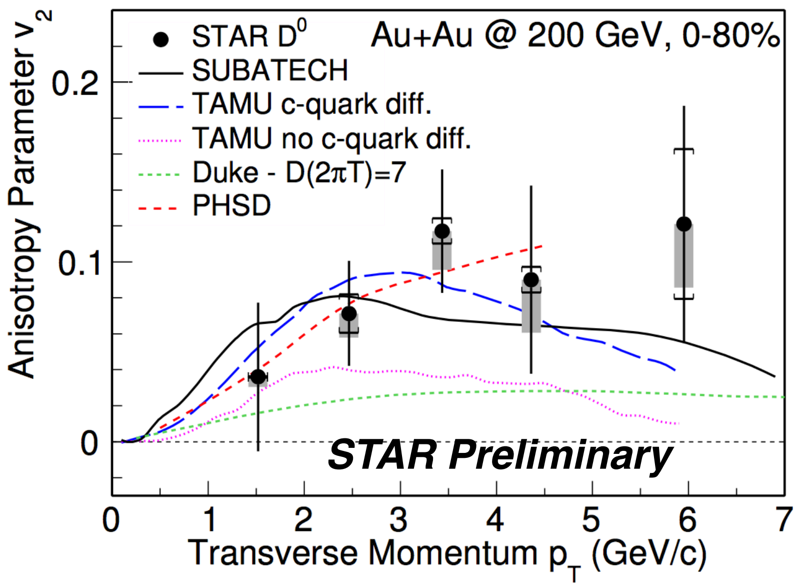
Discussion #1: Compare With Light Flavor



- Plot v_2/NCQ vs. $(m_T - m_0)$/NCQ
- An indication that v_2 of D^0 is smaller than light hadrons => **Charm is not fully thermalized with the medium.**

Discussion #2: Compare With Models



Different models:

- SUBATECH: pQCD + hard thermal loop
  - P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, Strangeness in quark matter
- TAMU: T-matrix, non-perturbative model with internal energy potential
  - M. He, R. J. Fries, and R. Rapp, Phys. Rev. C86, 014903 (2012)
- Duke: free constant D_s, fit to LHC high p_T R_{AA}
  - S. Cao, G.-Y. Qin, and S. A. Bass, Phys. Rev. C88, 044907 (2013)
- PHSD: Parton-Hadron-String Dynamics, a transport model
  - H. Berrehrah, P. B. Gossiaux, J. Aichelin, W. Cassing, J. M. Torres-Rincon, and E.Bratkovskaya, Phys. Rev. C90, 051901 (2014)

Charm quark exhibits finite collective behavior

compare with	$2\pi TD_s$ (spatial diffusion coefficient)	$\chi 2$/n.d.f.
SUBATECH	2-4	2.8 / 5
TAMU c quark diff.	2-7	2.1 / 5
TAMU no c quark diff.	-	7.4 / 5
DUKE	7	9.3 / 5
PHSD	5-12	0.46 / 4

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Outlook

Run 14:

- Results with full statistics available soon

Run 15:

- Aluminum cables for inner layer of PXL
- p+p (for R_{AA} reference) and p+A (for CNM effect) data sets with HFT

Run 16:

- Aluminum cables for inner layer of PXL
- Factor 2 -3 improvement for D^0 significance @ 1 GeV allows measuring 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
	Future	
Run 16		
	Au+Au	2 B

Summary

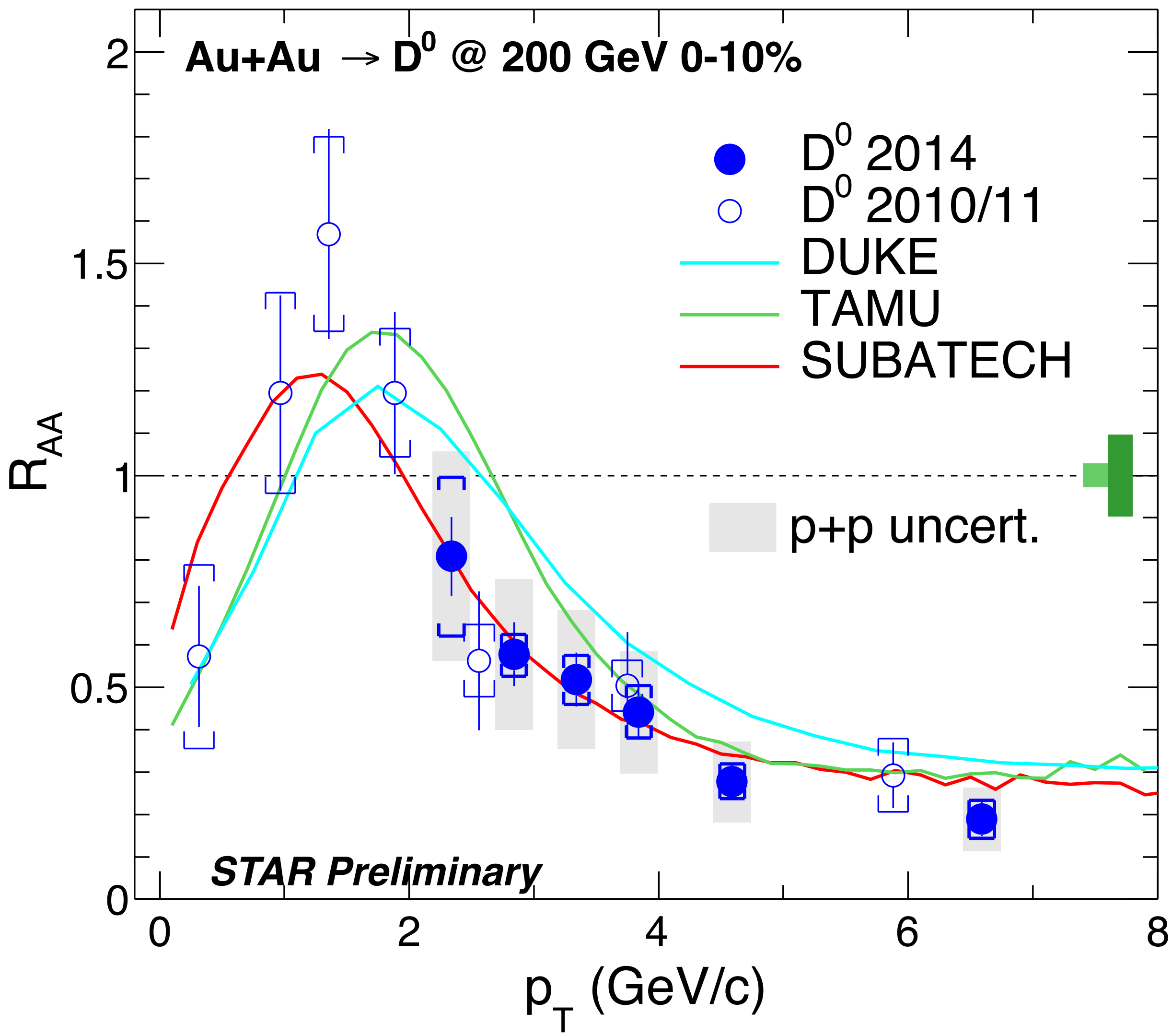
- Finite D^0 v_2 is measured within STAR using Heavy Flavor Tracker
- Comparison between measured D^0 v_2 and model calculations suggests collective behavior of charm quarks
- Smaller D^0 v_2 (than light quarks) indicates that charm quarks may not be fully thermalized
- Theoretical calculations with $2\pi TD_s$ ~2-12 can reproduce our D^0 v_2 result.


Thank you!

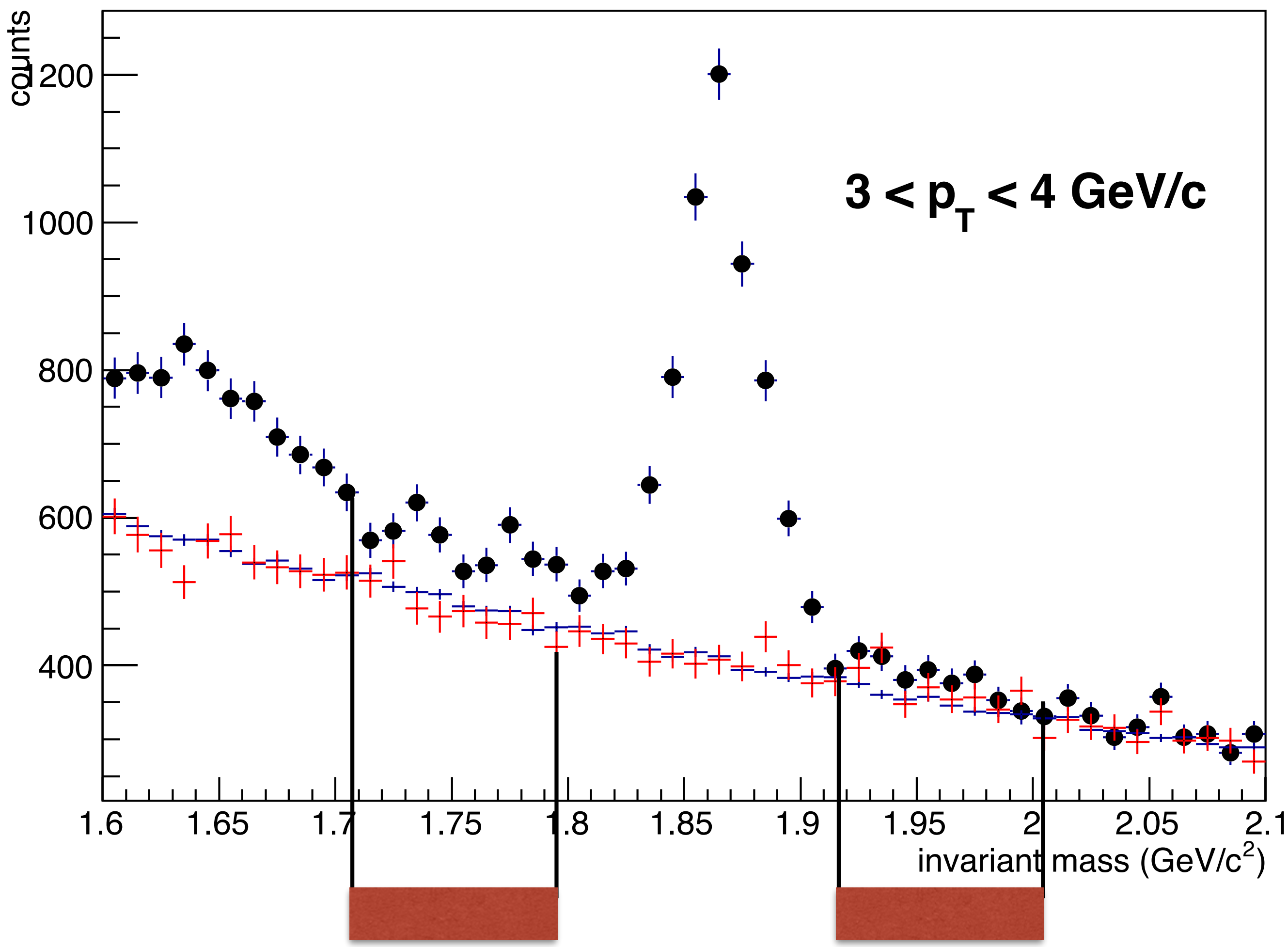
Backups

- D^0 R_{AA} compare with models
- Side-band definition
- Topological cuts
- Models details

D^0 R_{AA} Compare With Models



Side-band



Side-band: (-9σ,-4σ) &(4σ,9σ)

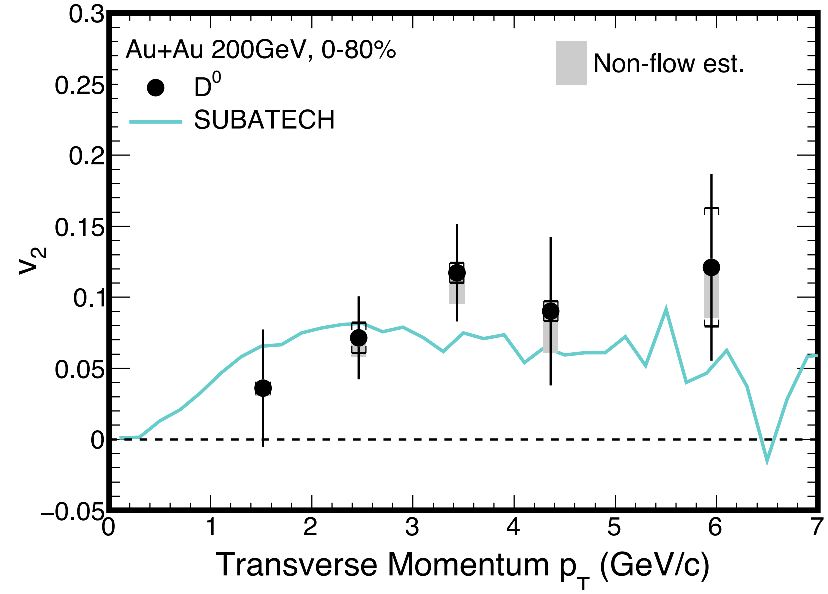
STAR

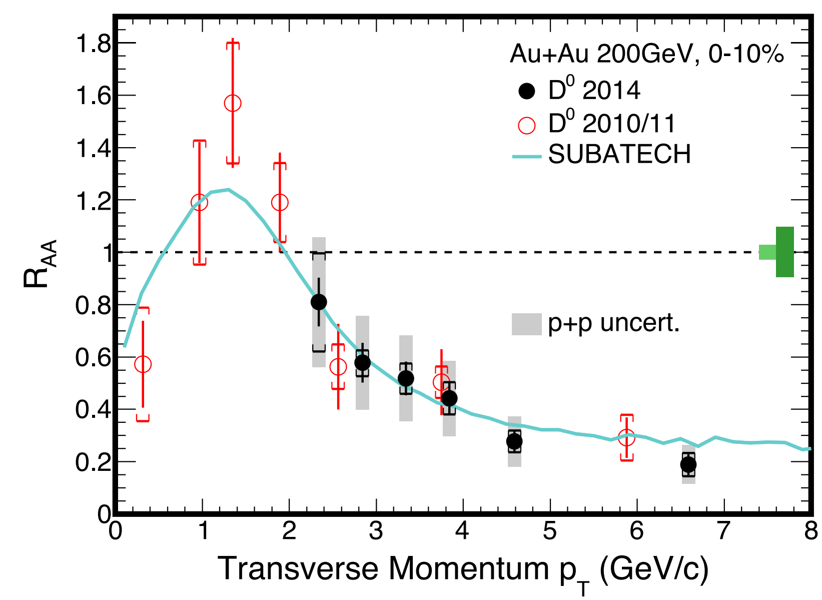
Topological cut

$D^0 p_T$ range (GeV)	(0,1)	(1,2)	(2,3)	(3,5)	(5,10)
Kaon $p_T >$ (GeV)	0.6	0.6	0.6	0.6	0.6
Pion $p_T >$ (GeV)	0.6	0.6	0.6	0.6	0.6
decay length $> (cm)$	0.0145	0.0181	0.0212	0.0247	0.0259
DCA$(K, \pi) < (cm)$	0.0084	0.0066	0.0057	0.0050	0.0060
DCA$(K, PV) < (cm)$	0.0103	0.0091	0.0095	0.0079	0.0058
DCA$(\pi, PV) < (cm)$	0.0110	0.0111	0.0086	0.0081	0.0062
DCA$(V0, PV) < (cm)$	0.0061	0.0049	0.0038	0.0038	0.0040

SUBATECH

- pQCD+HTL calculation with latest EPOS3 initial conditions
  - $L=(L_{QCD}+L_{HTL})+\Delta L_{HTL}$
- 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)

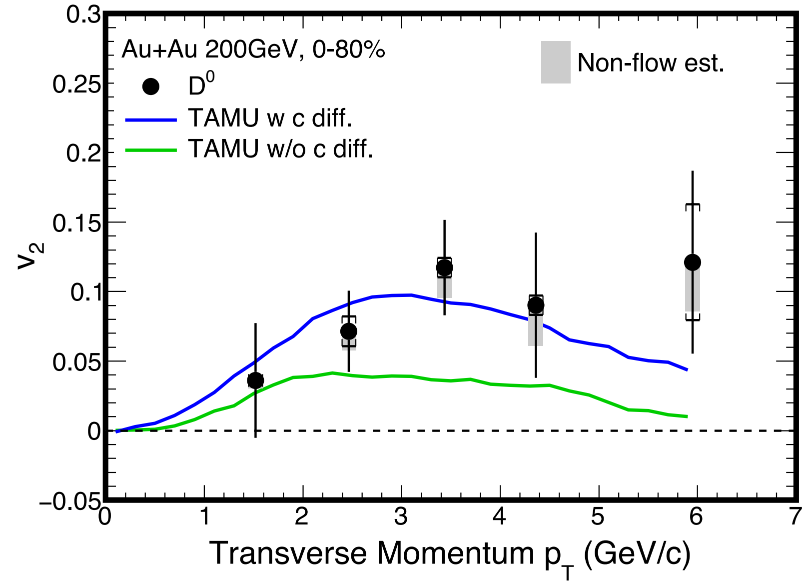


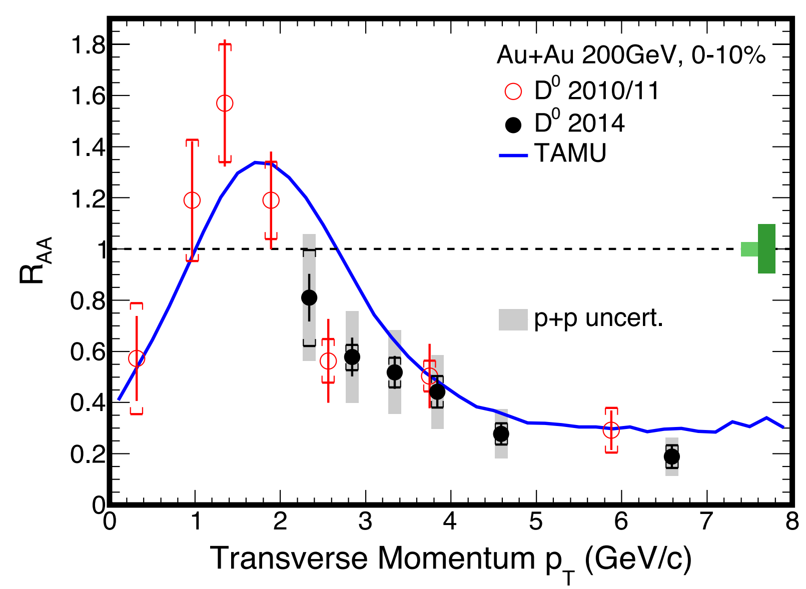


Theory: arXiv:1506.03981 (2015) & private comm.
STAR: PRL 113 (2014) 142301

TAMU

- Full T-matrix treatment, non-perturbative model with internal energy potential
- Diffusion coefficient extracted from calculation 2πT x D = 2-7
- Good agreement with D^0 meson v_2 at low p_T, data favors 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)

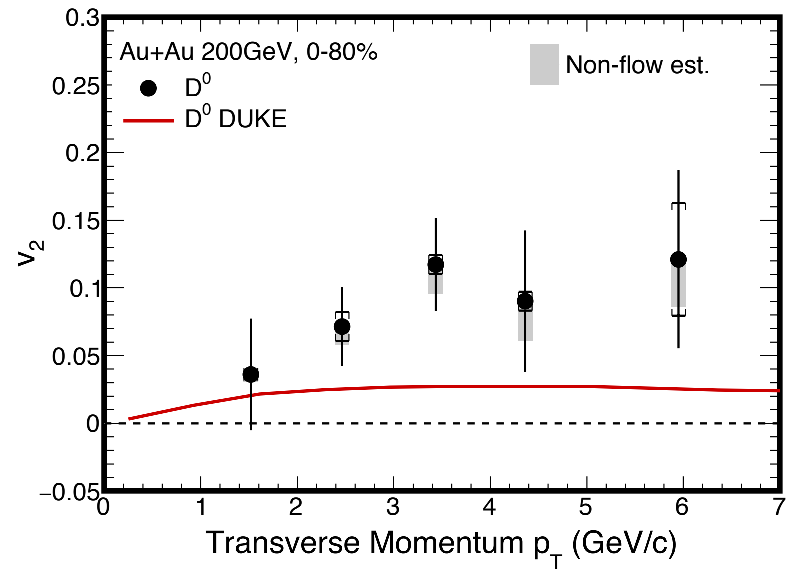


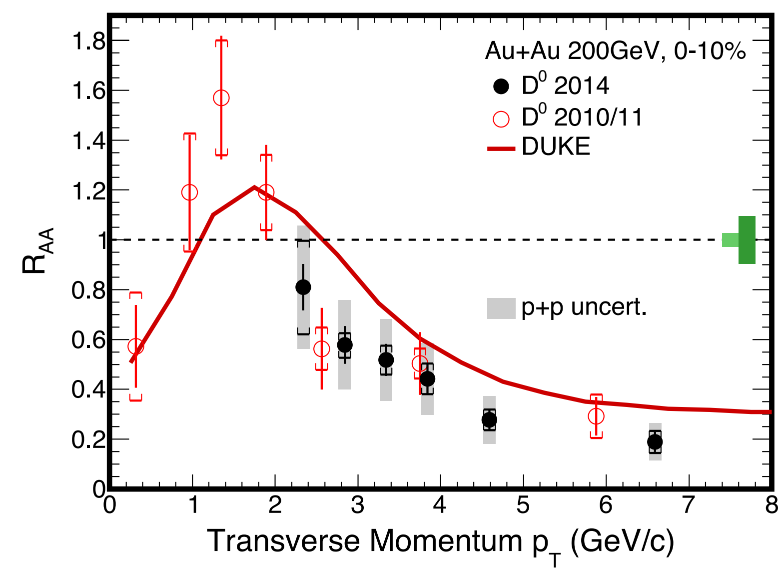


Theory: arXiv:1506.03981 (2015) & private comm.
STAR: PRL 113 (2014) 142301

DUKE Model

- 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