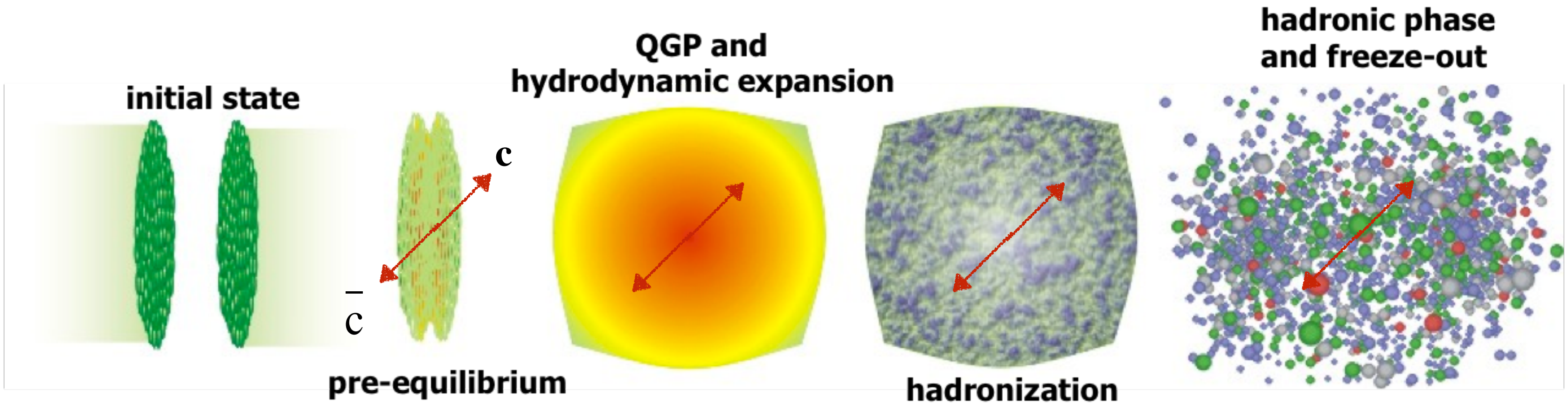
Centrality dependence of D^0 elliptic and triangular flow in Au+Au at $\sqrt{s_{NN}} = 200$ GeV at STAR

Liang He
Purdue University
For the STAR Collaboration

D^0 v_2 paper has been submitted - arXiv:1701.06060

Why heavy flavor?



Heavy flavor quarks

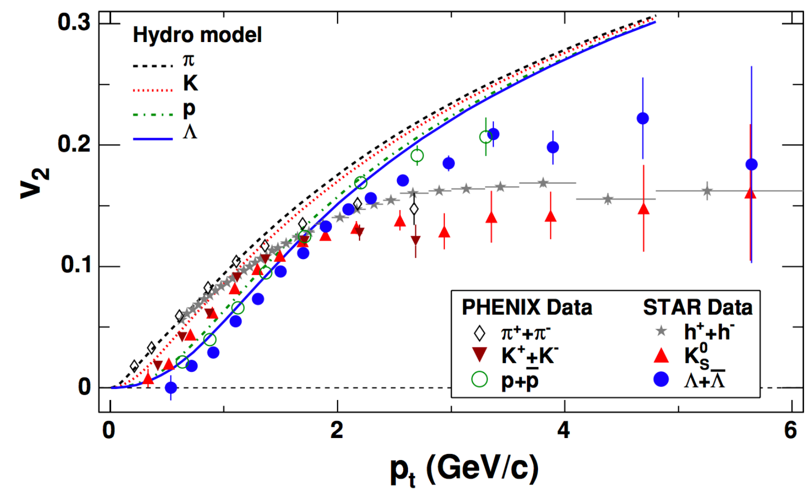
- Produced early: experience the entire evolution of the Quark-Gluon Plasma (QGP)
- Harder to thermalize: probe the dynamics of the QGP
- Brownian motion approach: heavy quark spatial diffusion coefficient in the QGP, e.g. $2\pi TD_s$

R. Rapp and H. van Hees, (2008), arXiv: 0803.0901 [hep-ph]
Müller, Berndt Phys.Scripta T158 (2013) 014004 arXiv:1309.7616 [nucl-th]

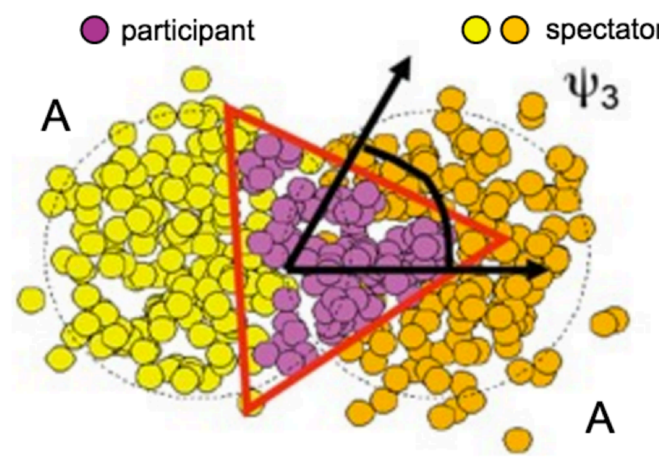
Elliptic and triangular anisotropy

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

- Light flavor v_n suggests hydrodynamic behavior of a strongly interacting matter
- Heavy quark v_n sensitive to the degree of thermalization
- Constrain heavy-quark spatial diffusion coefficient



STAR PRC72, 014904 (2005)
PHENIX PRL 91,182301 (2003)

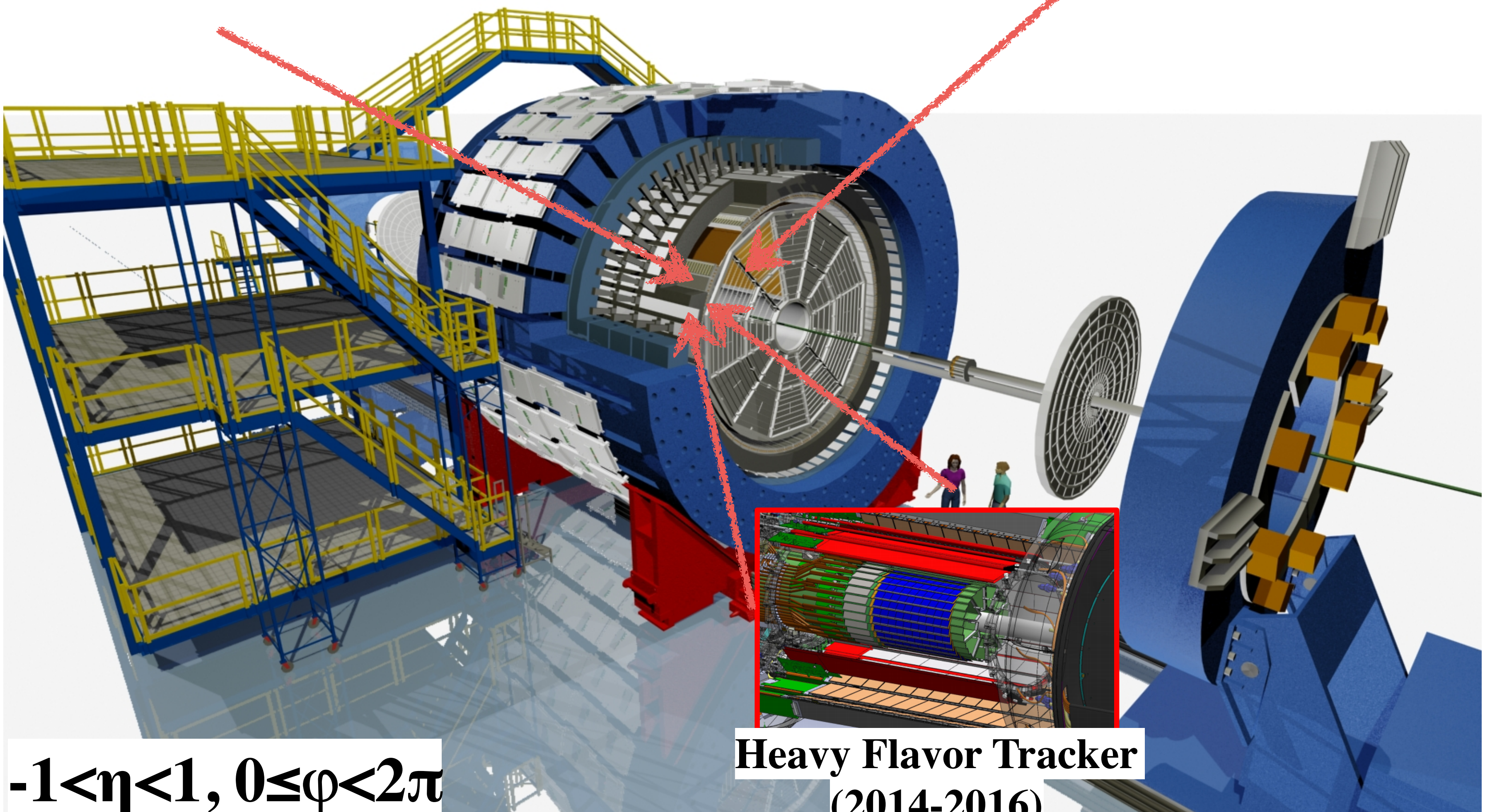


B. Alver, G. Roland, PRC81 (2010) 054905

STAR detector

Time Of Flight detector
PID (1/β)

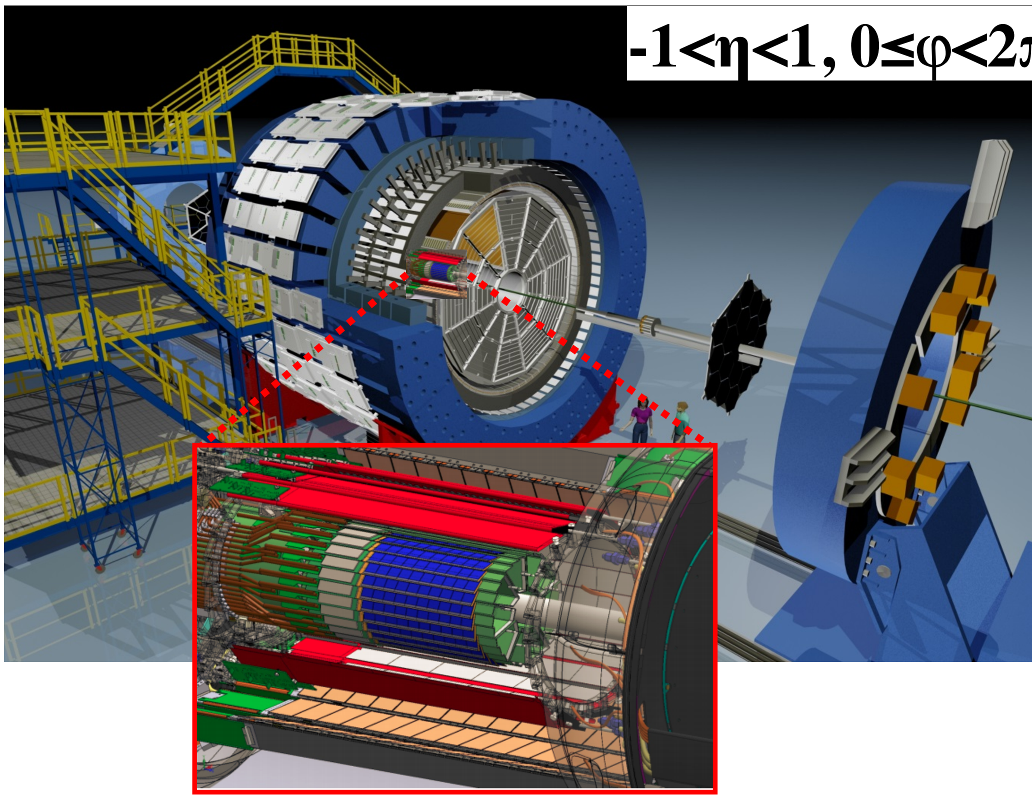
Time Projection Chamber
Tracking, dE/dx

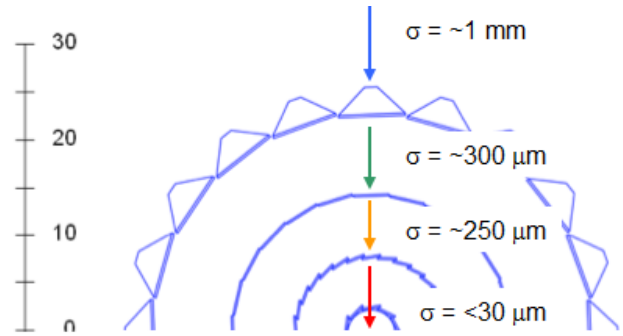


Heavy Flavor Tracker
(2014-2016)

$-1<\eta<1,\ 0\leq\varphi<2\pi$

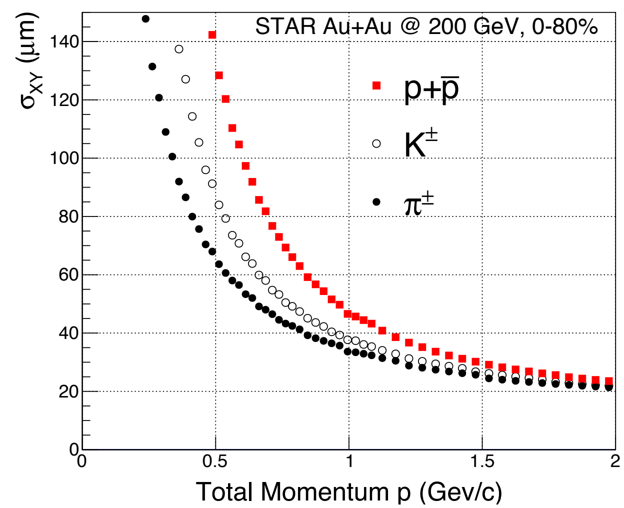
HFT (Heavy Flavor Tracker)





- SSD – Silicon Strip Detector (r~22cm)
- IST – Intermediate Silicon Tracker (r~14cm)
- PXL – Pixel Detector (r~2.8 & 8cm), 0.5%X_0 per layer (20.7 μm x 20.7 μm)

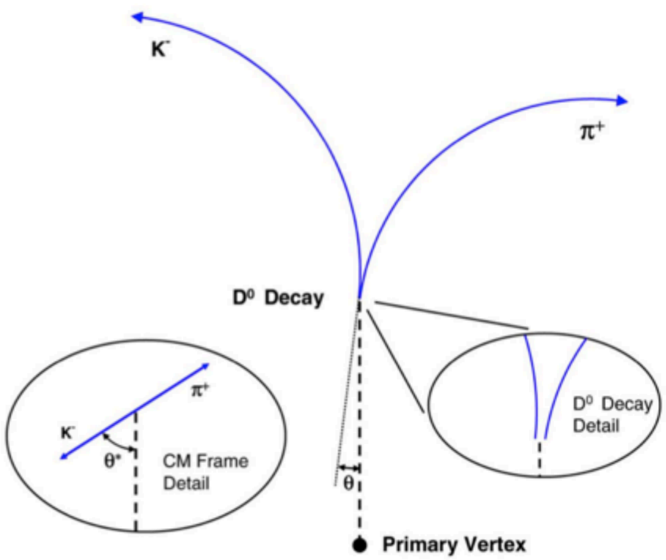
Complete topological reconstruction of charm hadrons
(e.g. D^0->Kπ, cτ~120 μm)

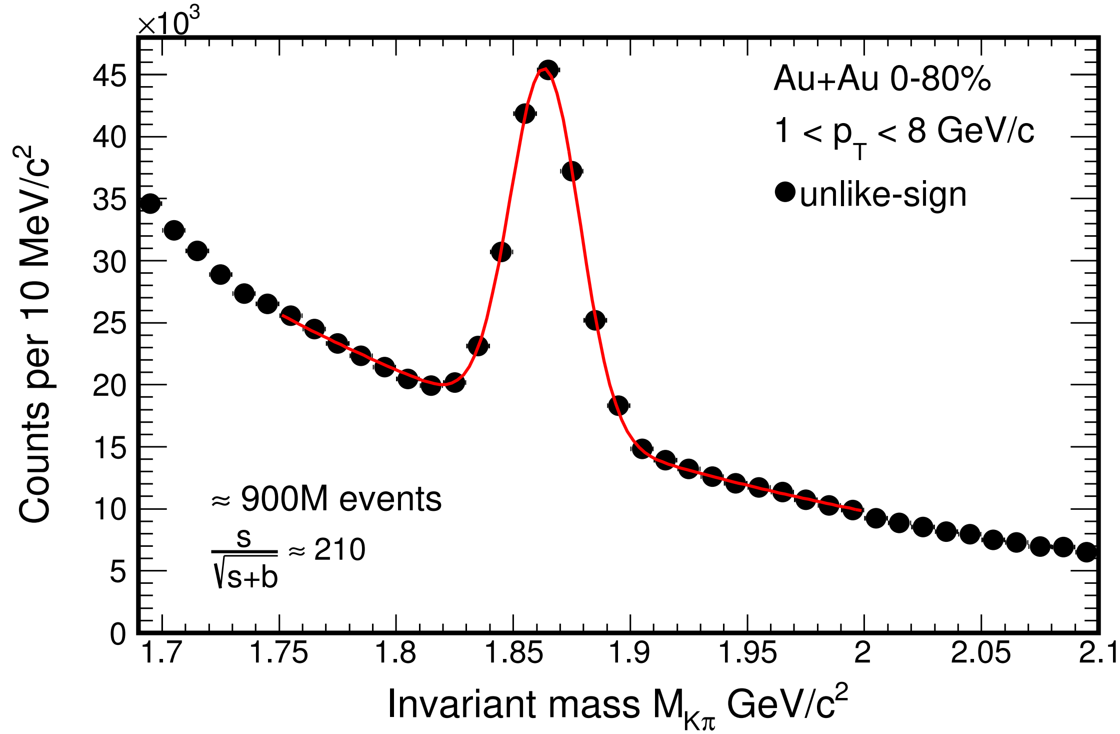


D^0 reconstruction

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

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





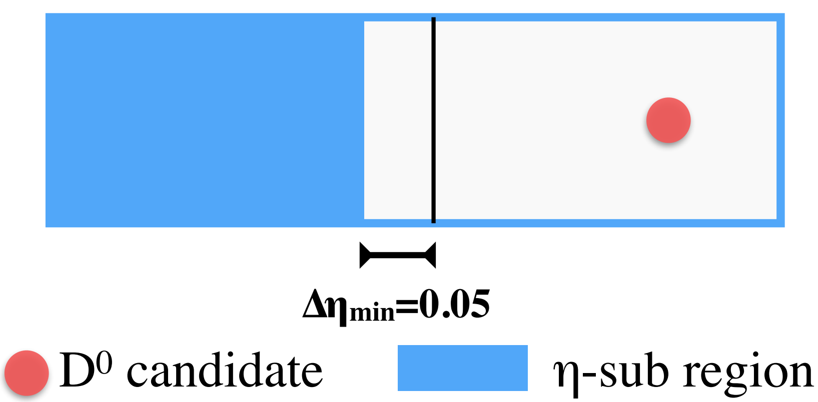
Topological cuts optimized using TMVA (Toolkit for Multivariate Analysis)

	w/o HFT	w/ HFT
	2010+2011	2014
#events(MB) analyzed	1.1 billion	~900 million
sig. per billion events	13*	220

**L. Adamczyk et al. (STAR), PRL113 142301*

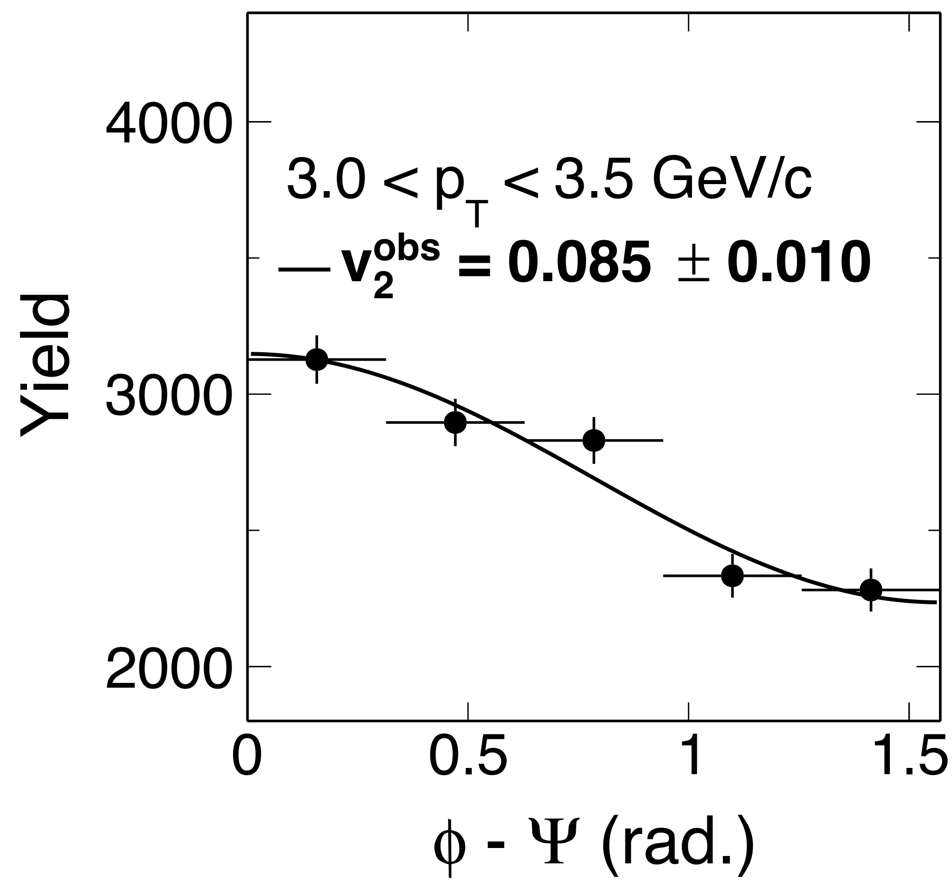
Event plane method

- Event plane (EP) reconstructed using TPC tracks with acceptance non-uniformity corrected
- Tracks in η-sub region are used to reconstruct EP to suppress non-flow effects



$$v_n\{EP\} = v_n^{obs}\{EP\} \times \left\langle \frac{1}{\text{EP Resolution}} \right\rangle$$

A.M. Poskanzer and S.A. Voloshin. PRC 58 (1998) 1671



Two-particle correlation method

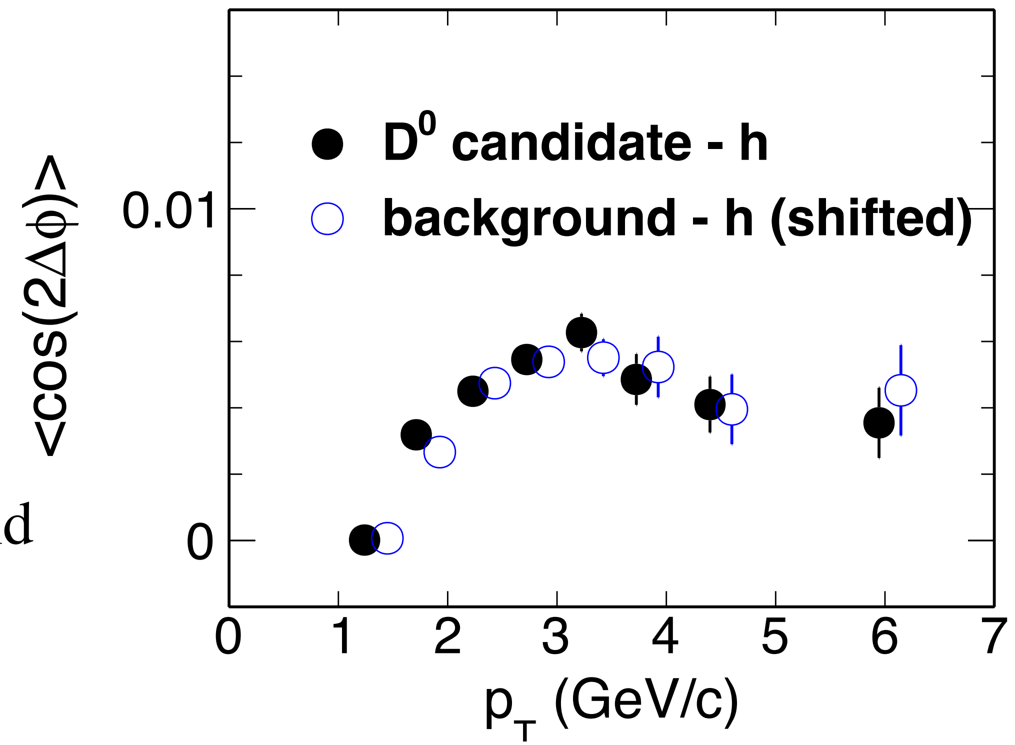
- $V_2^{D\cdot h} = \langle \cos(2\varphi_D - 2\varphi_h) \rangle = v_2^D \cdot v_2^h$

  $V_2^{h\cdot h} = \langle \cos(2\varphi_{h1} - 2\varphi_{h2}) \rangle = (v_2^h)^2$

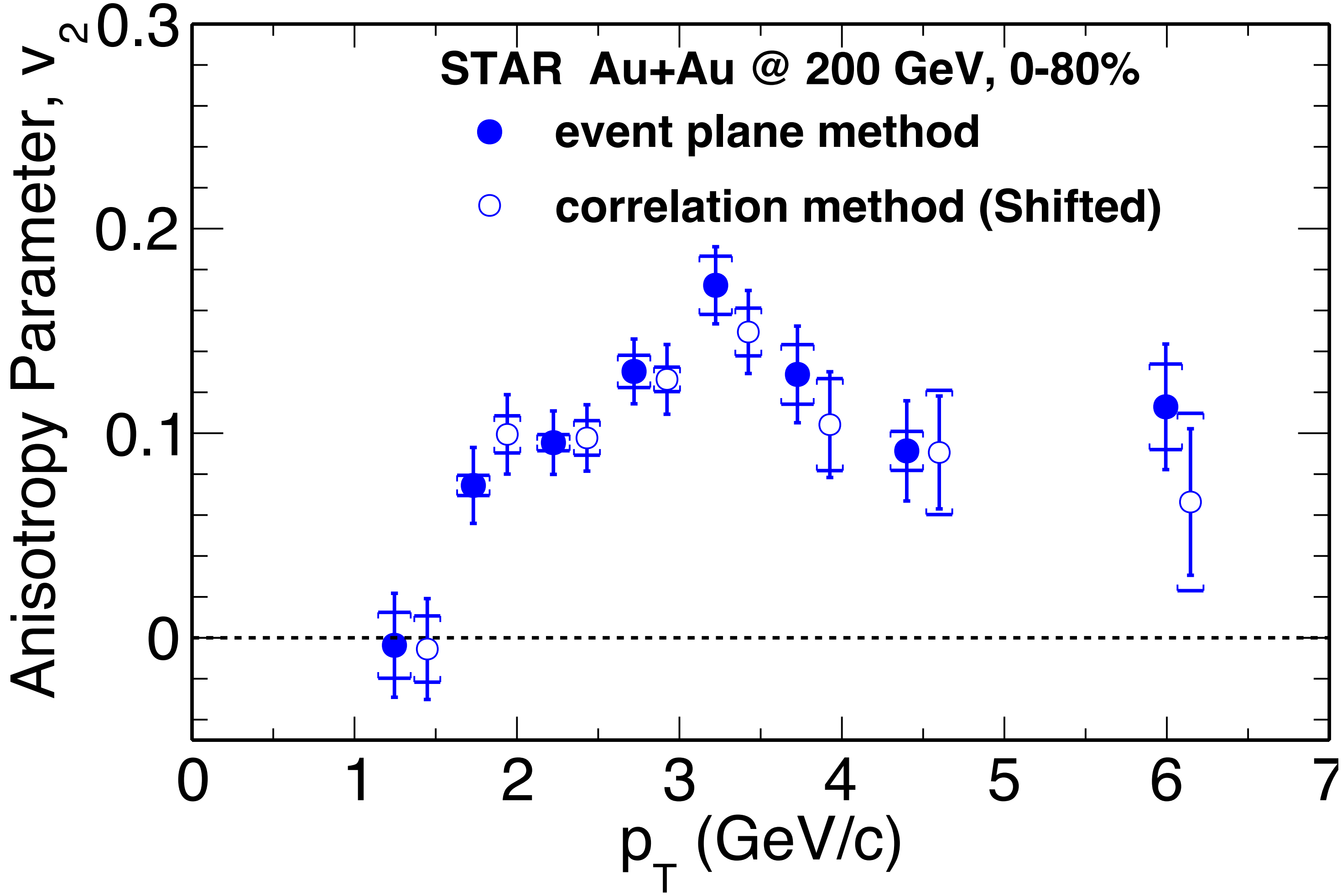
- $v_2^{signal} = \dfrac{N_{cand} \cdot v_2^{cand} - N_{bkg} \cdot v_2^{bkg}}{N_{signal}}$

  Background estimated from side-band

- Same $\Delta\eta$ gap as used in EP method

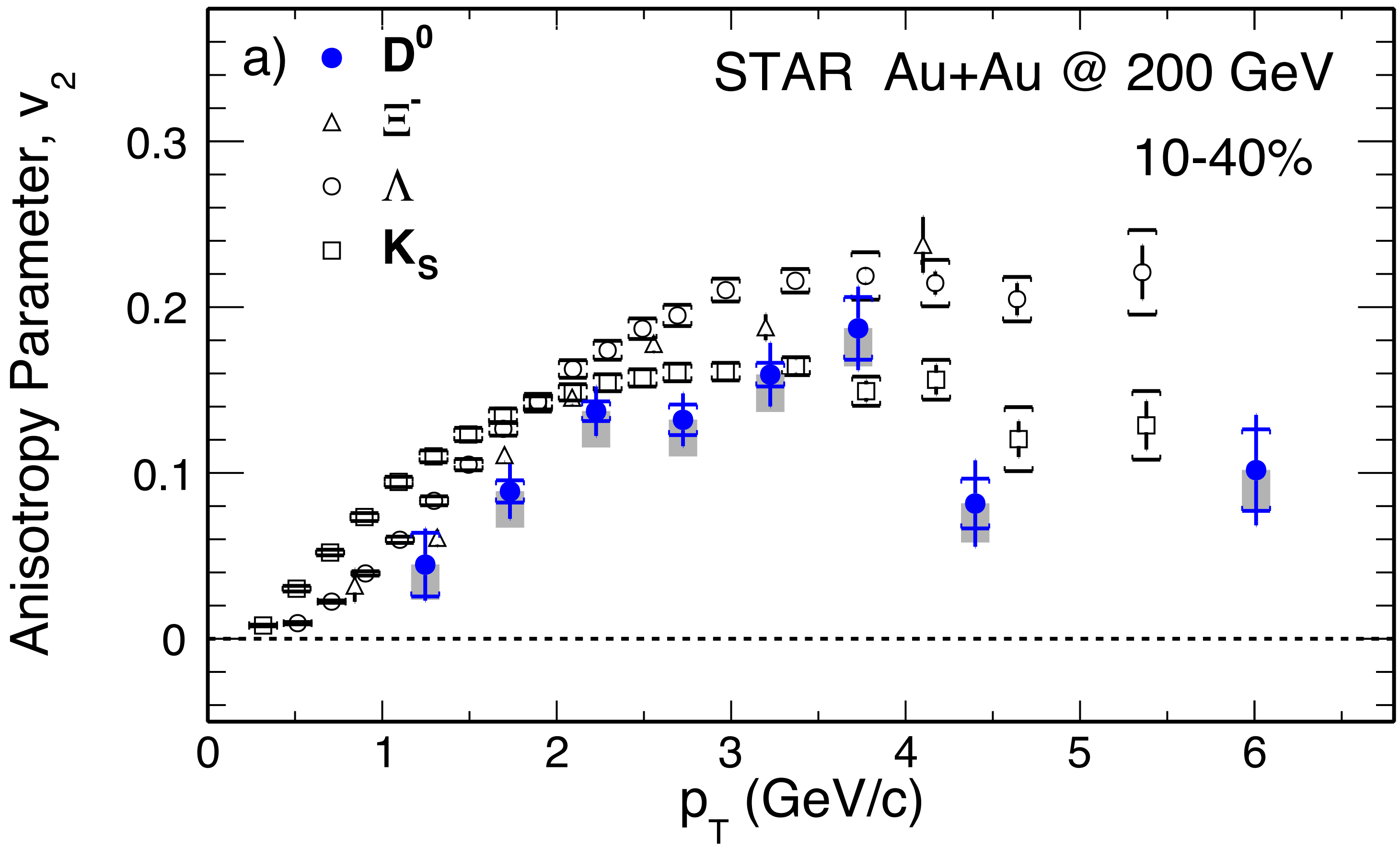


D^0 v_2 from two methods



- Good agreement

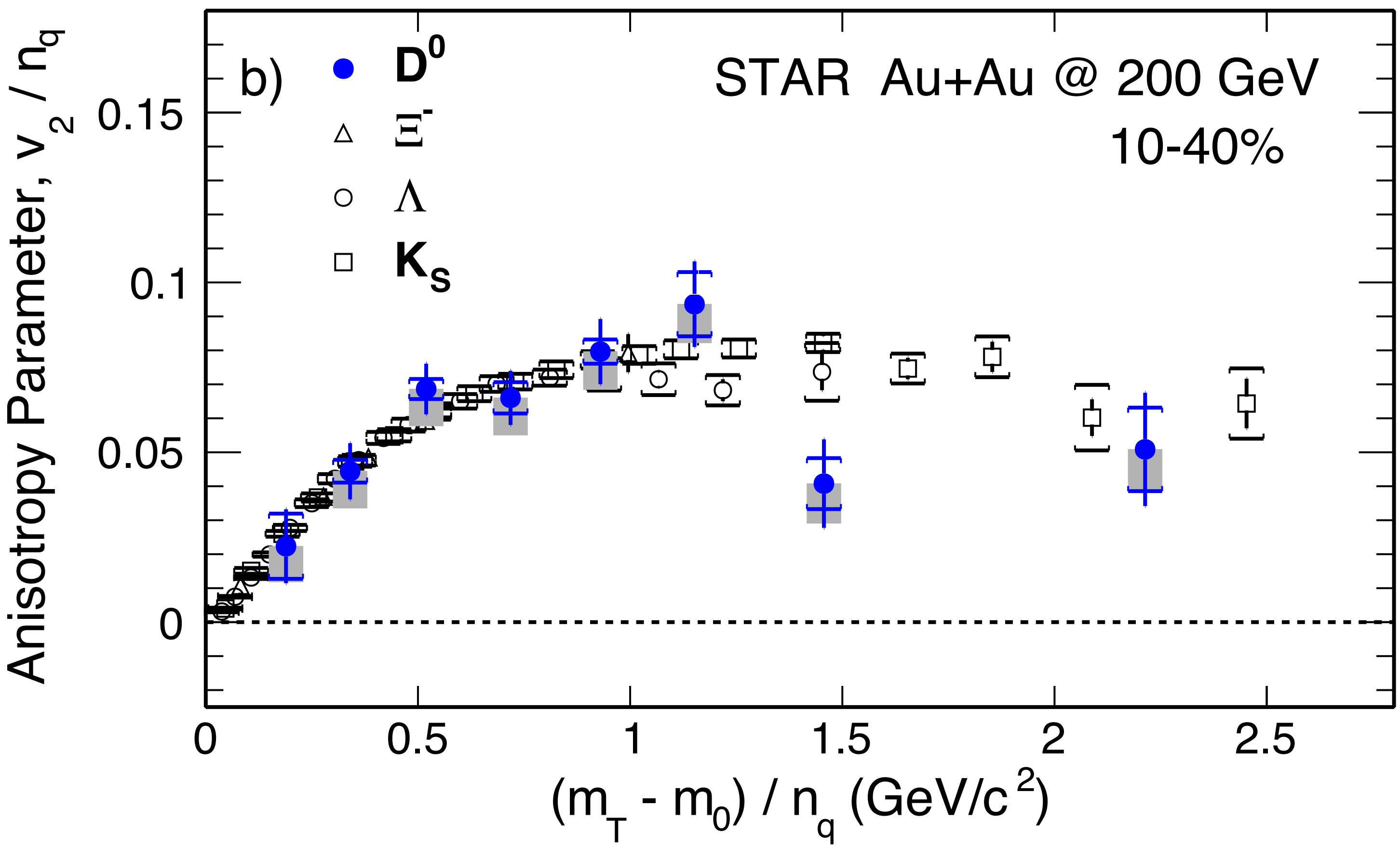
D^0 v_2 compared to light hadrons



Non-flow is estimated from D^0-hadron correlation in p+p collisions

- Clear mass ordering for $p_T < 2$ GeV/c
- D^0 follows other light mesons for $p_T > 2$ GeV/c

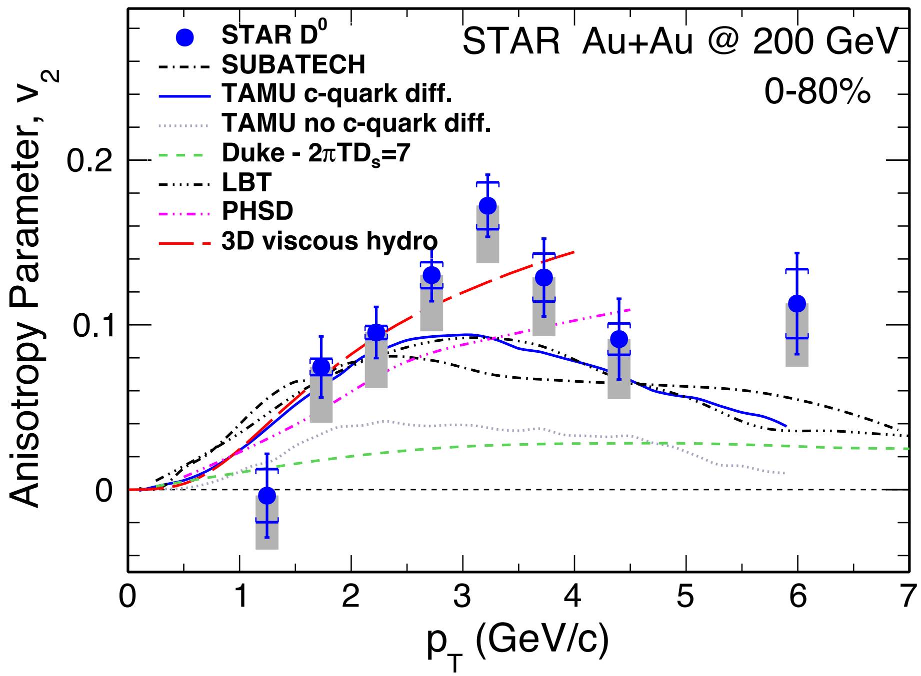
NCQ scaling



$^*m_T = \sqrt{p_T^2 + m_0^2}$

- D^0 v_2 follows NCQ scaling
- Suggest that charm quarks flow with the QGP

D^0 v_2 compared to models

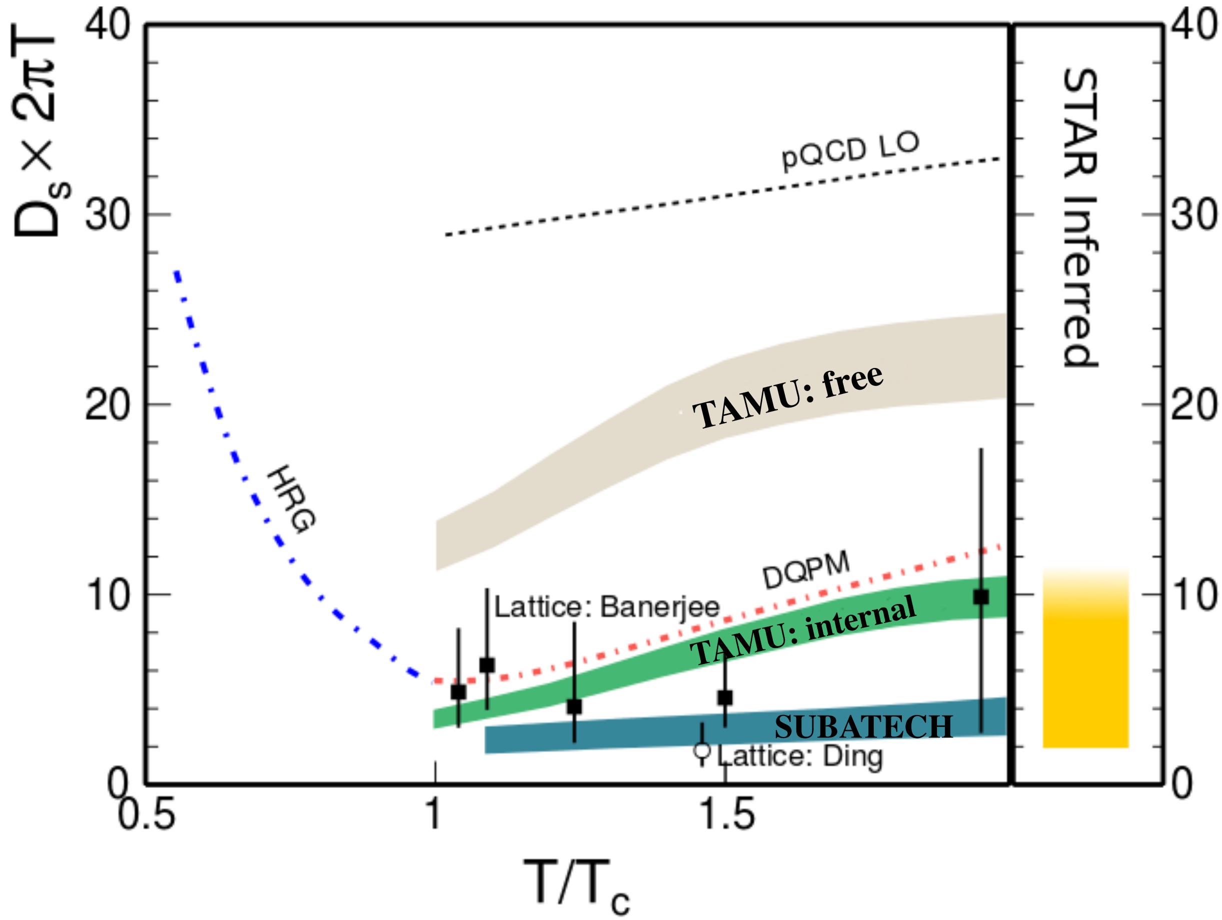


Different models:

- **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, PRC86, 014903 (2012)*
- **Duke: free constant D_s, fit to LHC high p_T R_{AA}**
  - *S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)*
- **hydro: A 3D viscous hydrodynamic model**
  - *L.-G. Pang, Y. Hatta, X.-N. Wang, and B.-W. Xiao,PRD91, 074027 (2015)*
- **PHSD: Parton-Hadron-String Dynamics, a transport model**
  - *H. Berrehrah et al. PRC90 (2014) 051901*
- **LBT: A Linearized Boltzmann Transport model**
  - *S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)*

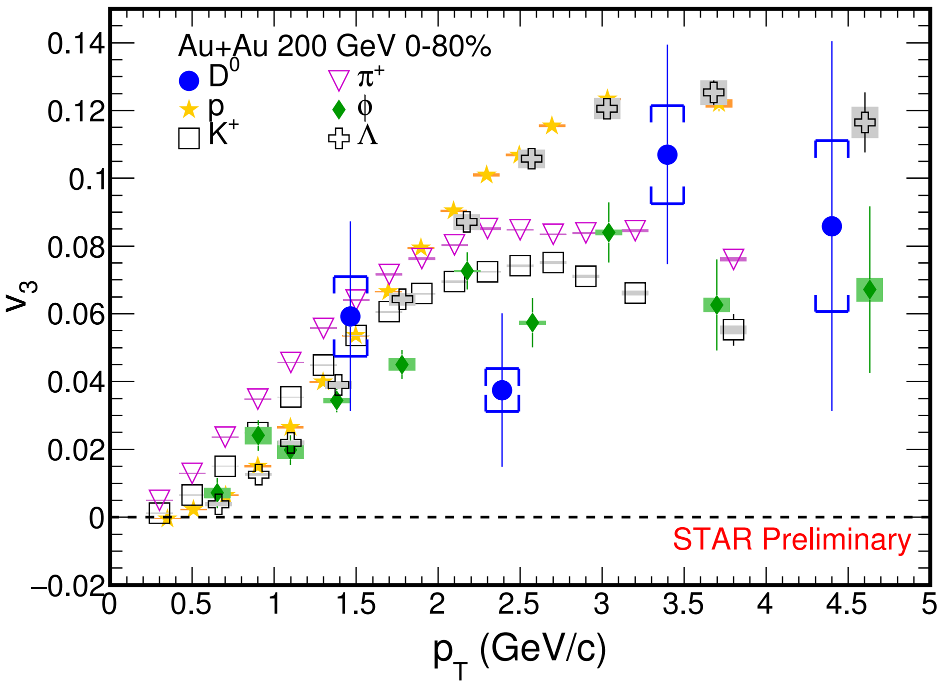
compare with	$2\pi TD_s$	χ2/n.d.f.	*p*-value
3D viscous hydro	-	3.6 / 6	0.73
LBT	3-6	11.1 / 8	0.19
PHSD	5-12	8.7 / 7	0.28
TAMU c quark diff.	2-12	10.0 / 8	0.26
SUBATECH	2-4	15.2 / 8	0.06
TAMU no c quark diff.	-	29.5 / 8	2 x 10-4
DUKE	7	37.5 / 8	2 x 10-5

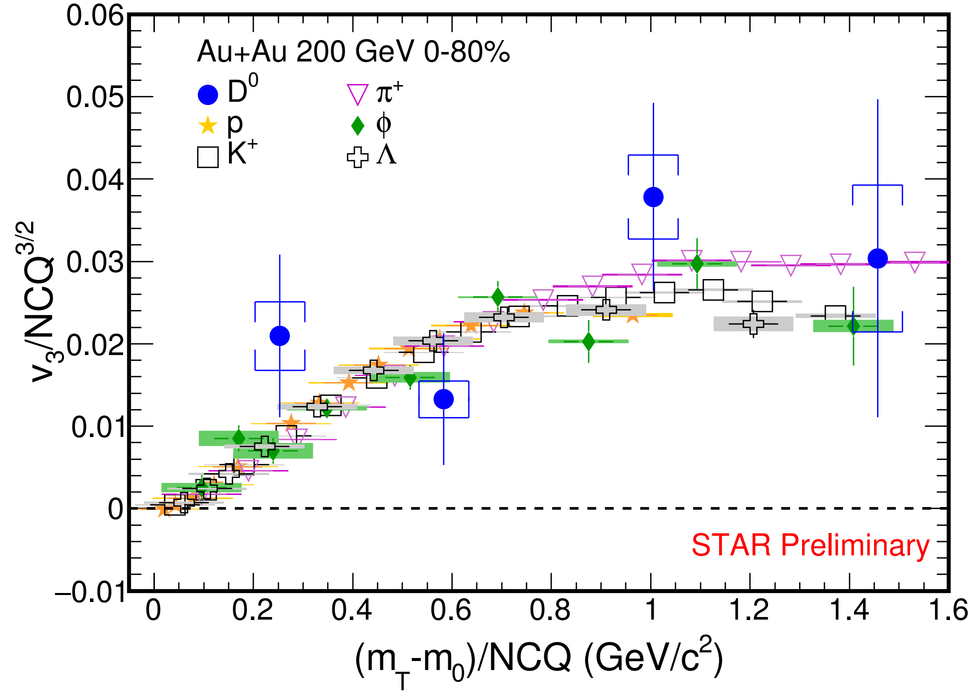
Temperature dependence of $2\pi TD_s$ in models



- Dynamic models describe data well
  - with diffusion coefficient $2\pi TD_s$ of ~2-5 at T_c
  - a temperature dependent range of ~2-12 at T_c to $2T_c$

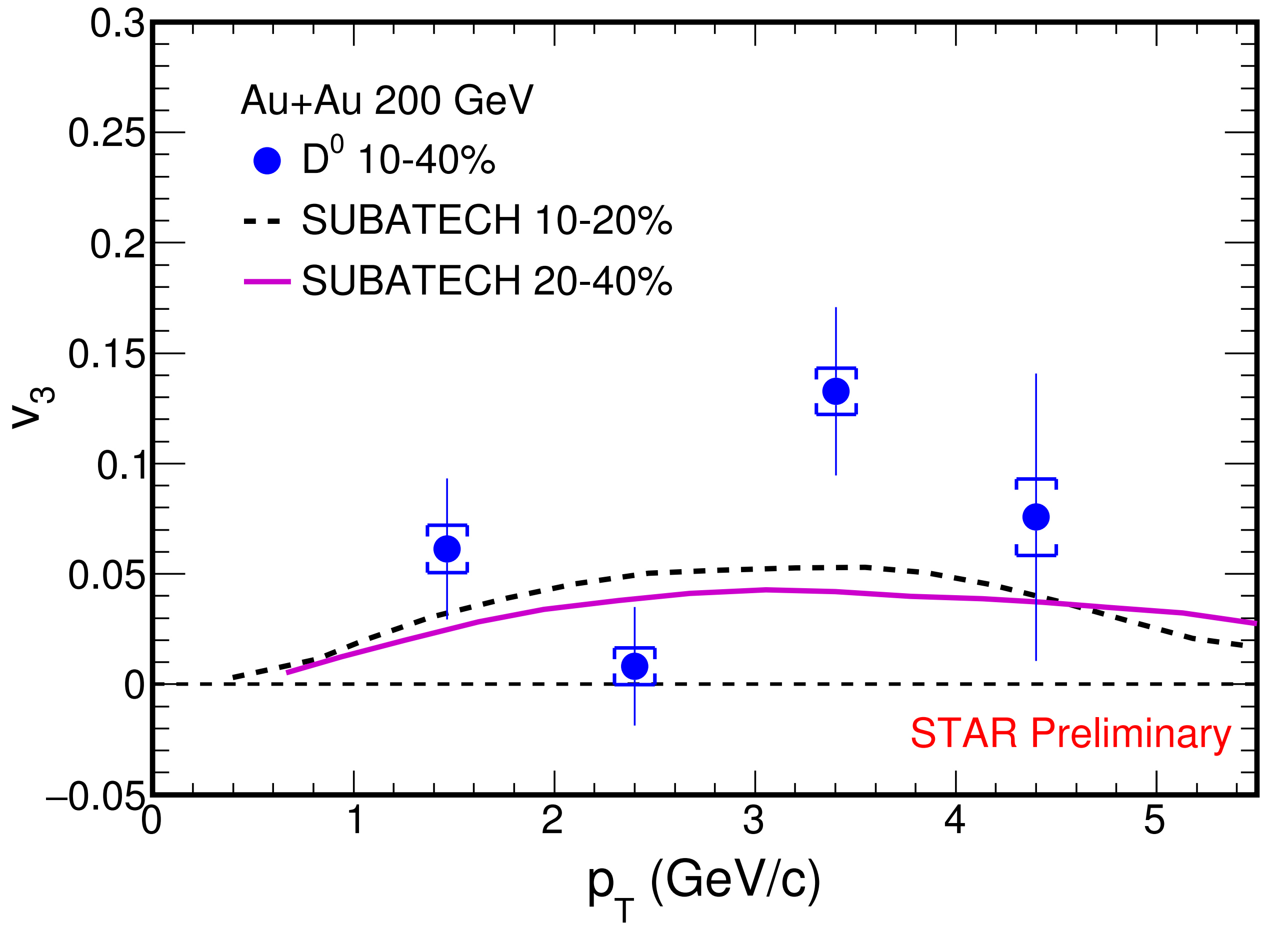
D^0 v_3





- First measurement of D^0 v_3 at RHIC
- D^0 v_3 is non-zero (χ^2/n.d.f. = 17.5/4)
- D^0 v_3 consistent with NCQ scaling within large error bars

D^0 v_3 compared to model



- Need more statistics
- More details see poster by M. Lomnitz (**B18**)

Summary and outlook

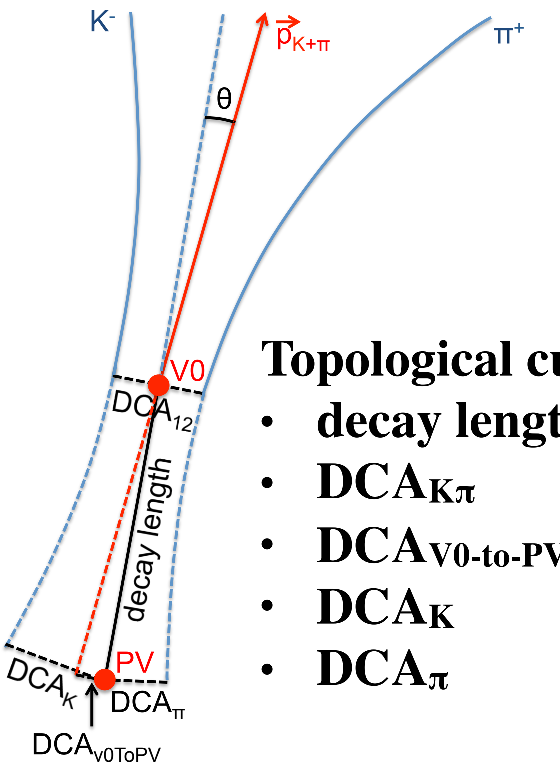
- Large non-zero D^0 v_2 and v_3: strong collective behavior
- Charm v_n follows NCQ scaling as light hadron v_n
  - suggests that charm quarks have gained significant flow through interactions with the QGP
- Models consistent with D^0 v_2
  - 3D viscous hydrodynamic model describes data below 4 GeV/c: suggesting charm quarks have achieved thermal equilibrium
  - Dynamic models describe data well with diffusion coefficient $2\pi TD_s$ of ~2-5 at T_c, and a temperature dependent range of ~2-12 within $2T_c$
- More data are coming: two billion events recorded in 2016

Backups

Topological cuts

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

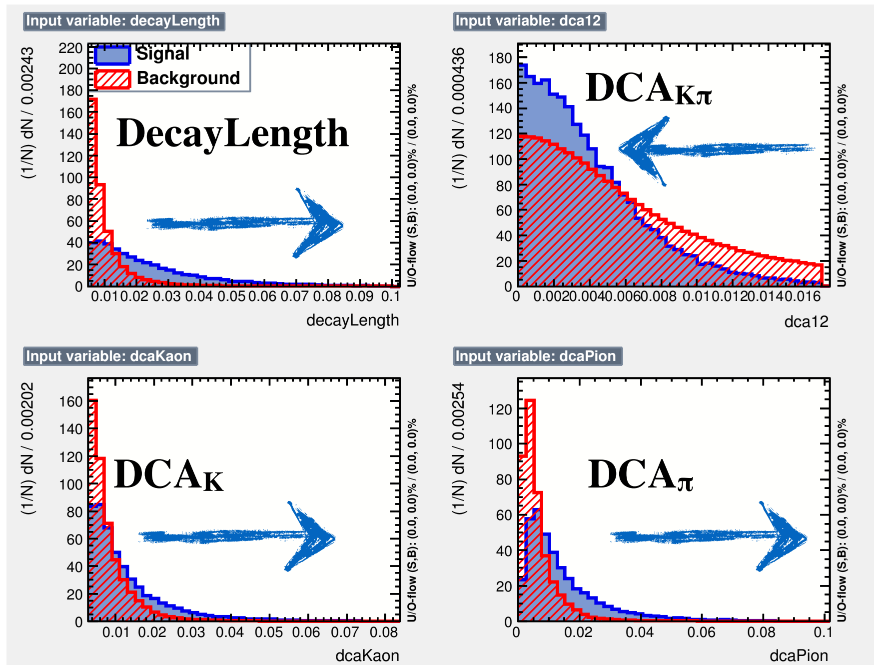
B.R. 3.9% $c\tau \sim 120\ \mu m$



Topological cuts:

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

DCA : Distance of Closest Approach



TMVA (Toolkit for Multivariate Analysis)

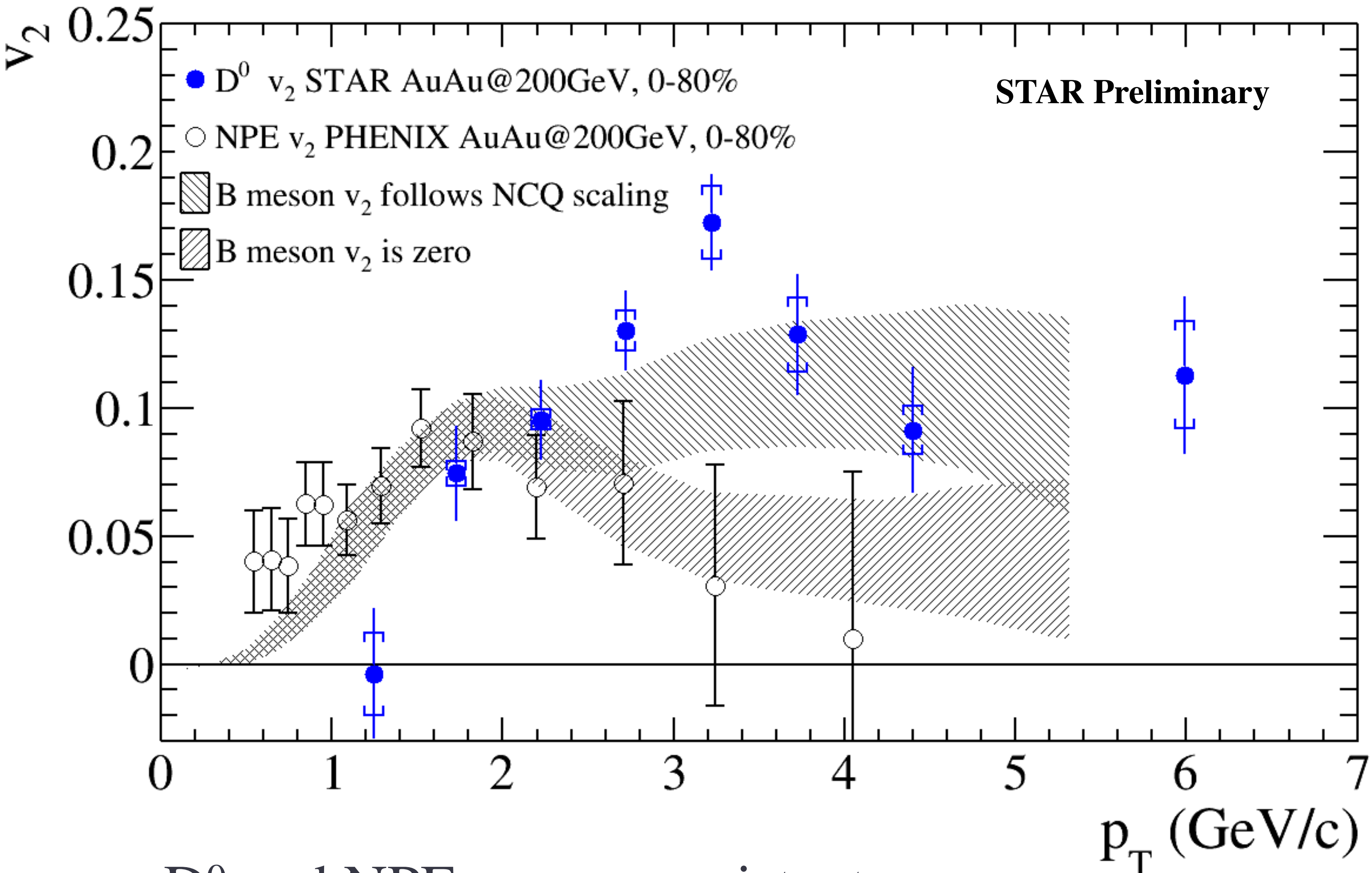
- **Signal**
- **Background**

Non-flow effect

- $$v_2^{non-flow} = \frac{\left\langle \sum_i \cos\left(2\left(\phi_{D^0} - \phi_i\right)\right)\right\rangle}{M\left\langle v_2 \right\rangle}$$
- $\cos(2(\phi_{D^0}-\phi_i))$: D^0-hadron from p+p collisions
  - $p_T > 3$ GeV/c: deduced from D^*-hadron correlations using STAR 2012 data
  - $p_T < 3$ GeV/c: PYTHIA simulation
- M, $\langle v_2 \rangle$: multiplicity and average hadron v_2 in Au+Au collisions
- Same $\Delta\eta$ gap is applied in estimating D^0-hadron correlation and hadron v_2

J. Adams et al. (STAR), Phys. Rev. Lett. 93, 252301 (2004)

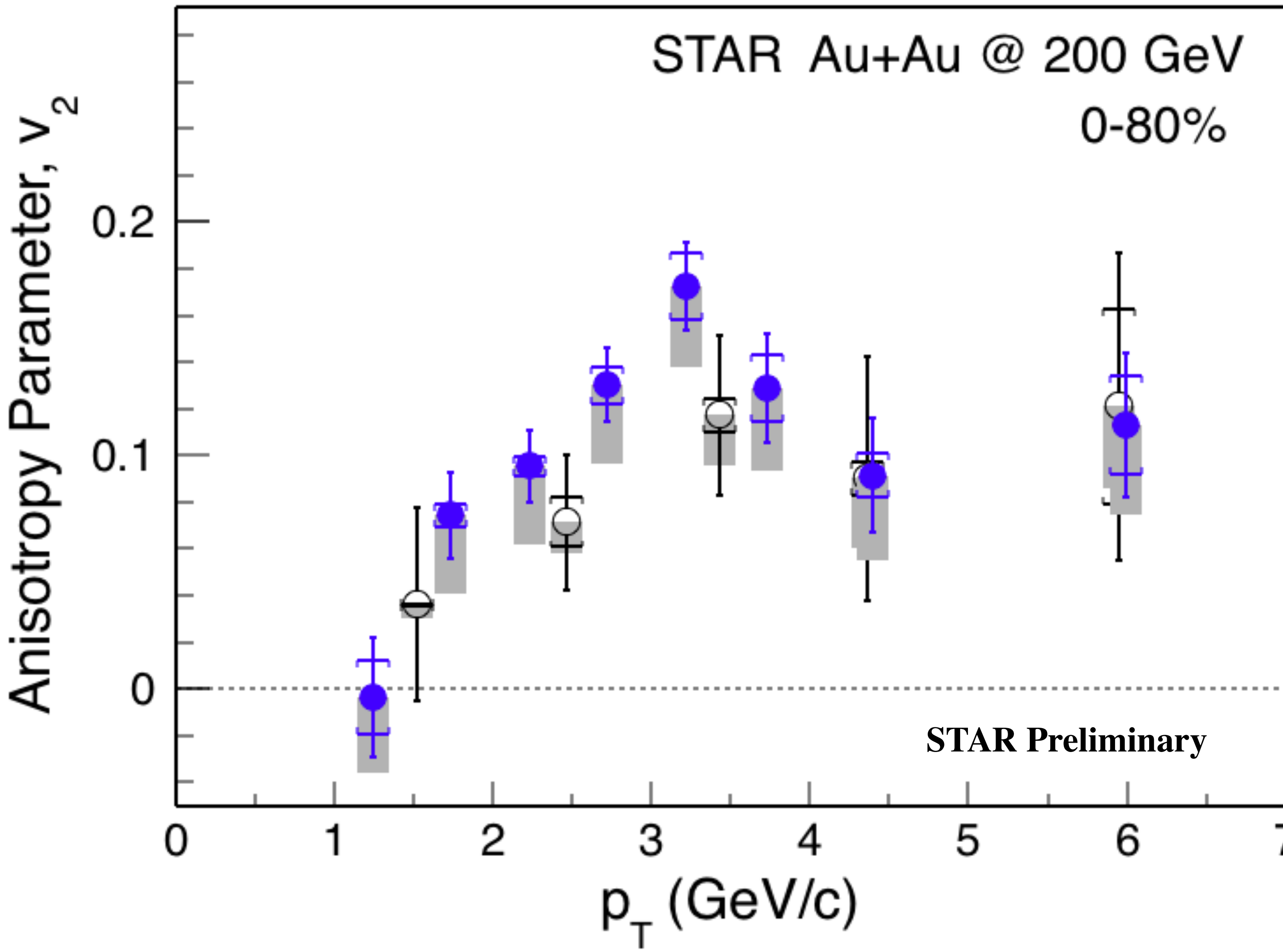
Compared to NPE



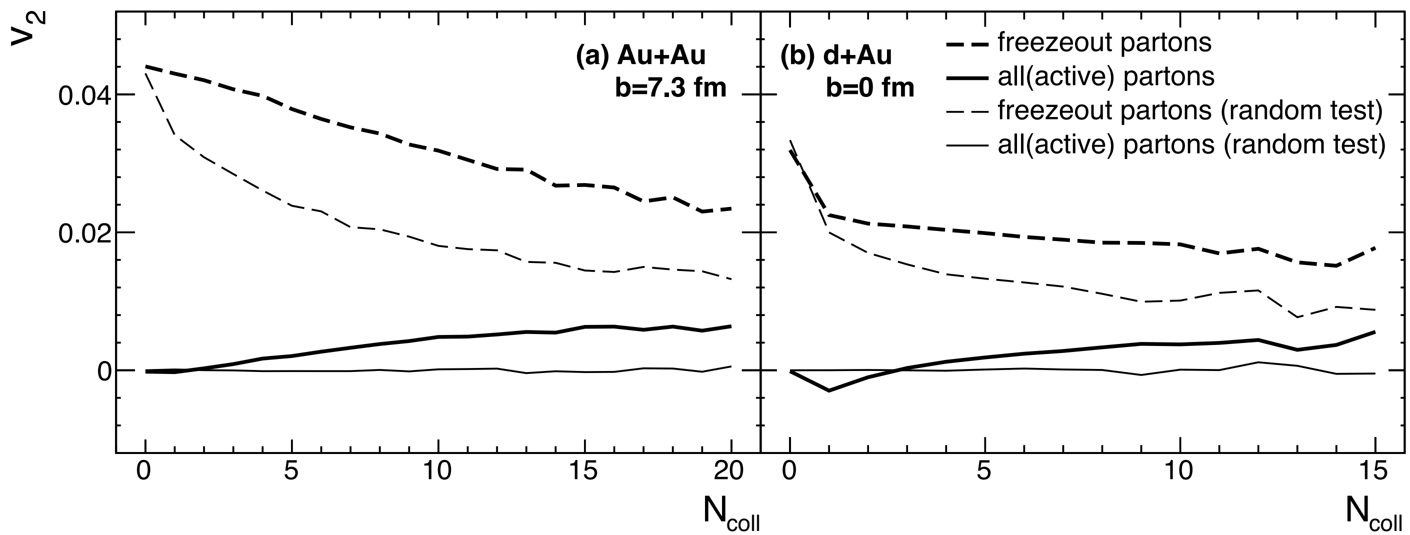
- D^0 and NPE v_2 are consistent

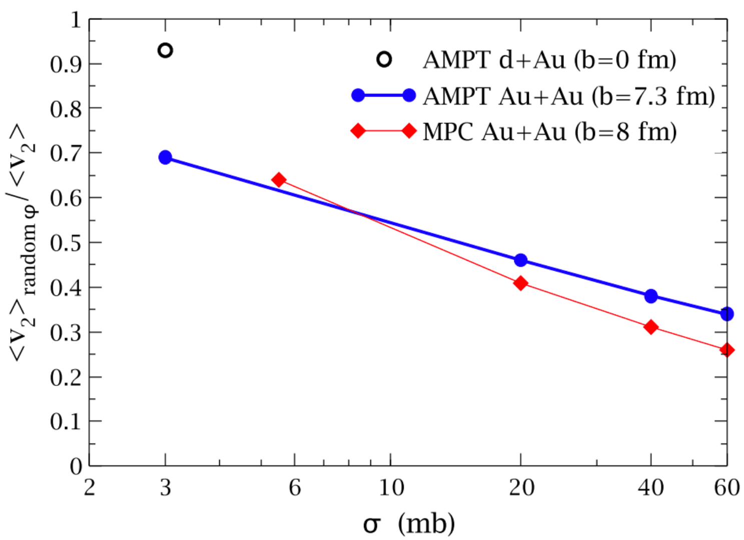
PHENIX PRC.84(2011) 044905
PHENIX PRC 93(2011) 034904

Compared to QM2014



Escape mechanism





- The escape mechanism: v_2 due to anisotropic escape probability
- ~69% of v_2 originates from escape

L. He et al, Physics Letters B (2016), pp. 506-510