STAR HFT and D^0 v_2 measurement

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Combining QM slides from Giacomo Contin and Michael Lomnitz
Work from many people

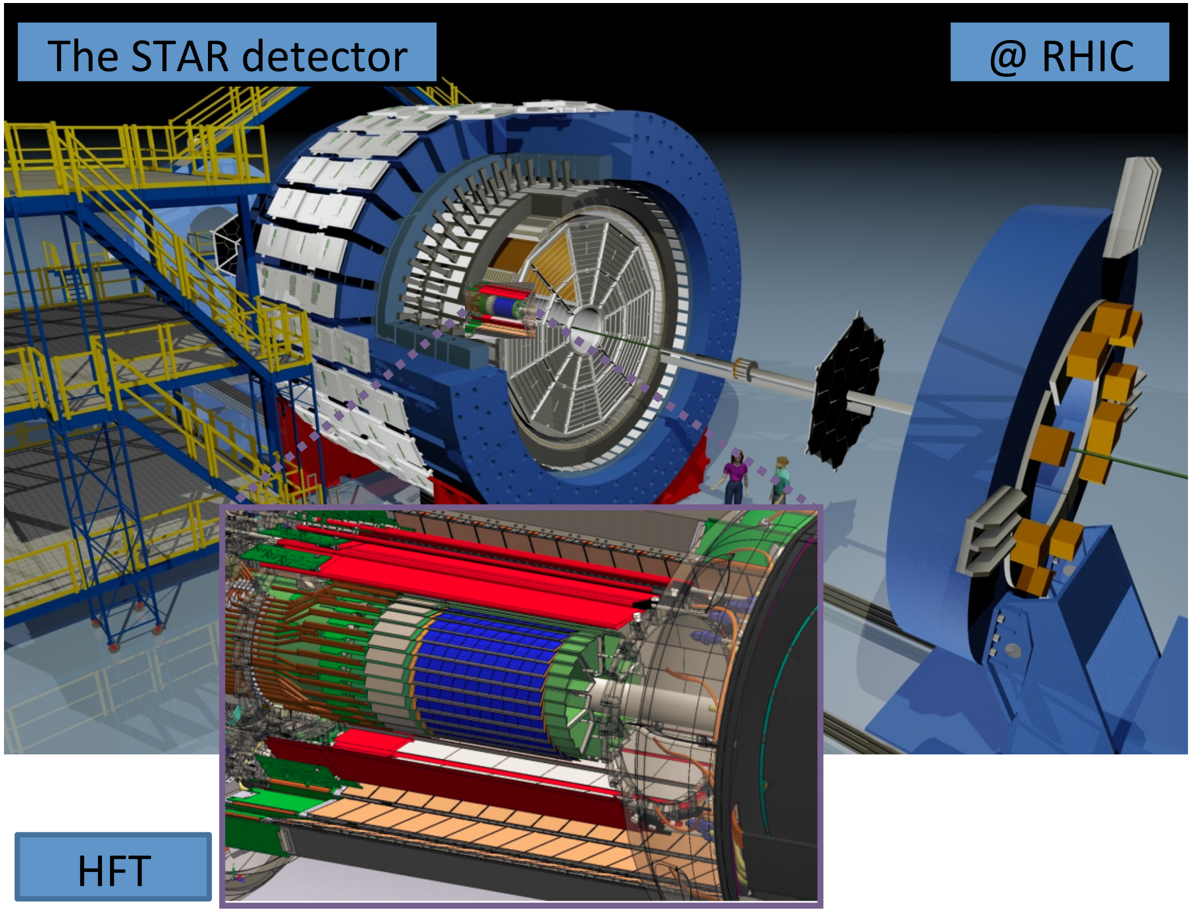
Outline – Heavy Flavor Tracker (HFT)

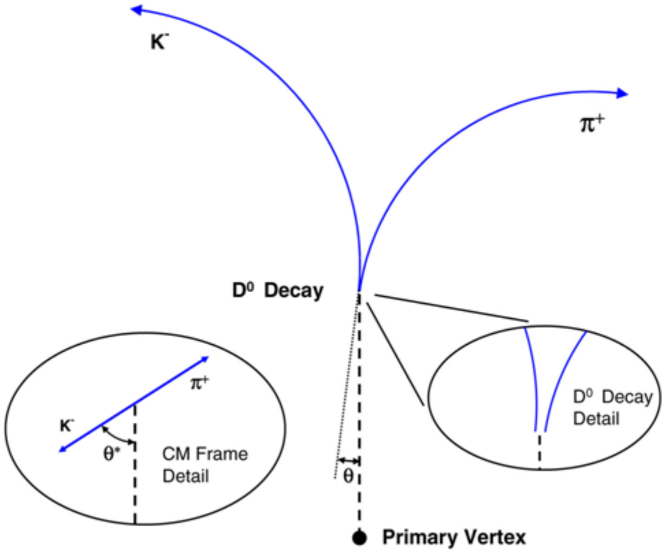
- Physics motivations
- The MAPS-based PXL detector
- HFT status and performance
- Future “HFT+” Upgrade plan
- Conclusions

STAR HFT Physics Motivation

Extend the measurement capabilities in the *heavy flavor* domain, good probe to QGP:

- Direct topological reconstruction of charm hadrons (small $c\tau$ decays, e.g. $D^0 \rightarrow K\ \pi$)

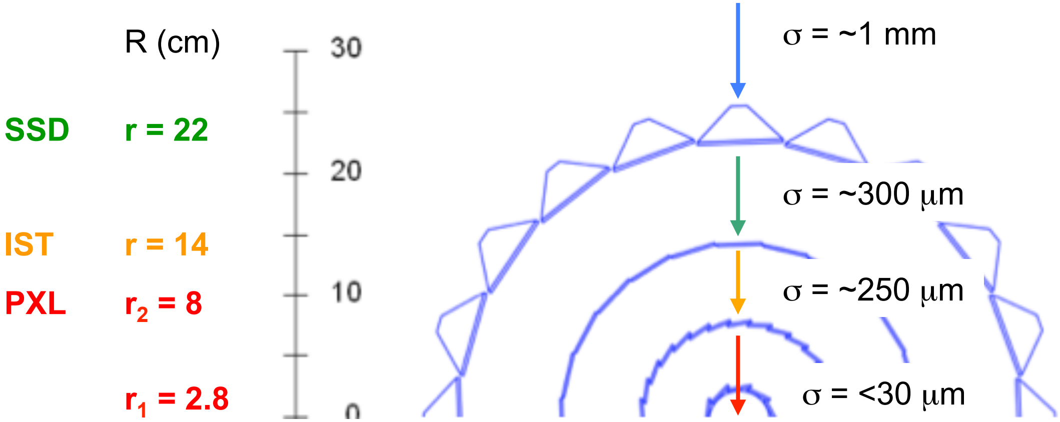




Method: Resolve displaced vertices (~120 μm)

HFT Subsystems

Tracking inwards with gradually improved resolution:



R (cm)

SSD **r = 22**

IST **r = 14**

PXL **r_2 = 8**

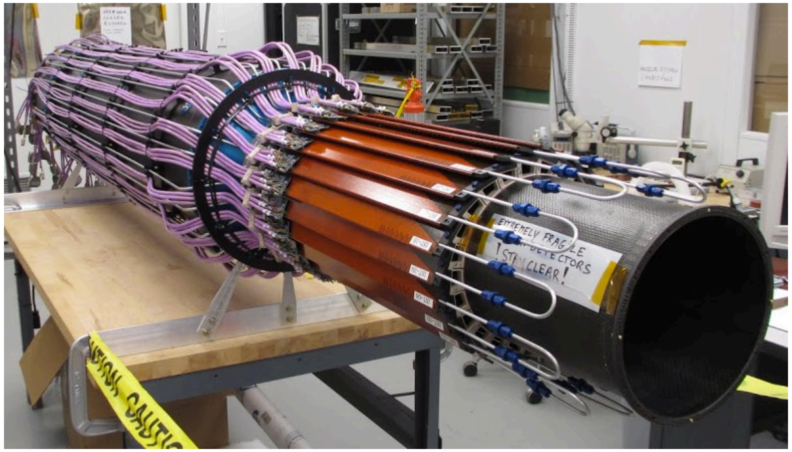
r_1 = 2.8

σ = ~1 mm

σ = ~300 μm

σ = ~250 μm

σ = <30 μm



Silicon Strip Detector (SSD)

- Double sided silicon strip modules with 95 μm pitch
- Existing detector with new faster electronics

Intermediate Silicon Tracker (IST)

- Single sided double-metal silicon pad with 600 μm x 6 mm pitch

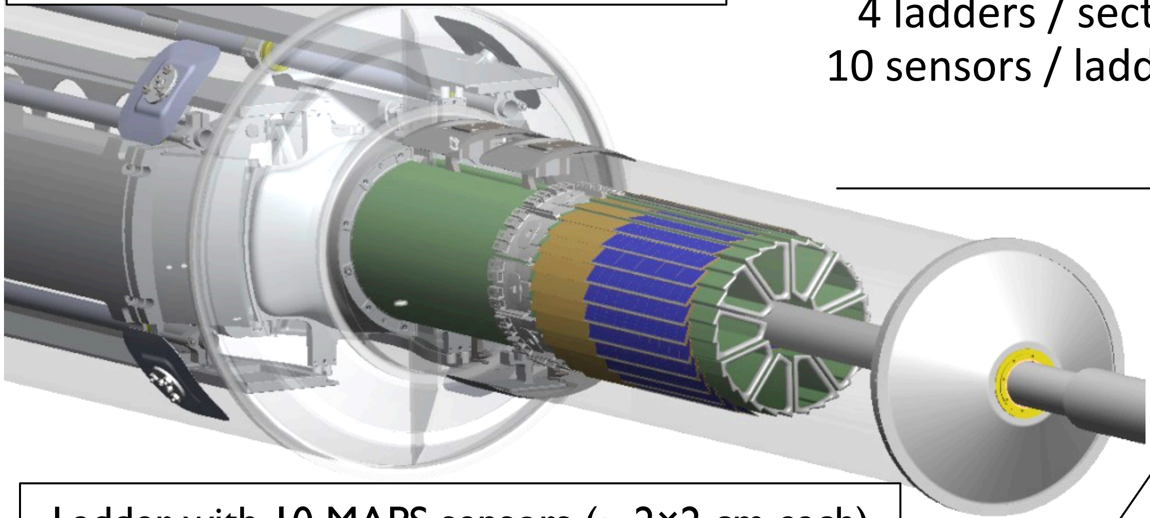
PiXeL detector (PXL)

- *Monolithic Active Pixel Sensor* technology
- 20.7 μm pitch pixels

First MAPS-based vertex detector at a collider experiment

PXL System Overview

Cantilevered mechanical support with kinematic mounts (insertion side)



10 sectors total
5 sectors / half
4 ladders / sector
10 sensors / ladder

carbon fiber sector tubes (~ 200 μm thick)

Ladder with 10 MAPS sensors (~ 2×2 cm each)

PXL insertion

- Novel insertion approach
  - Inserted along rails and locked into a kinematic mount inside the support structure
  - Capability to fully replace PXL within 12 hour

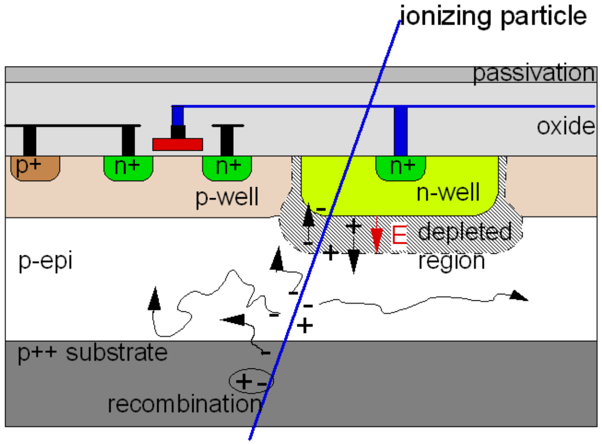
PXL Sensor

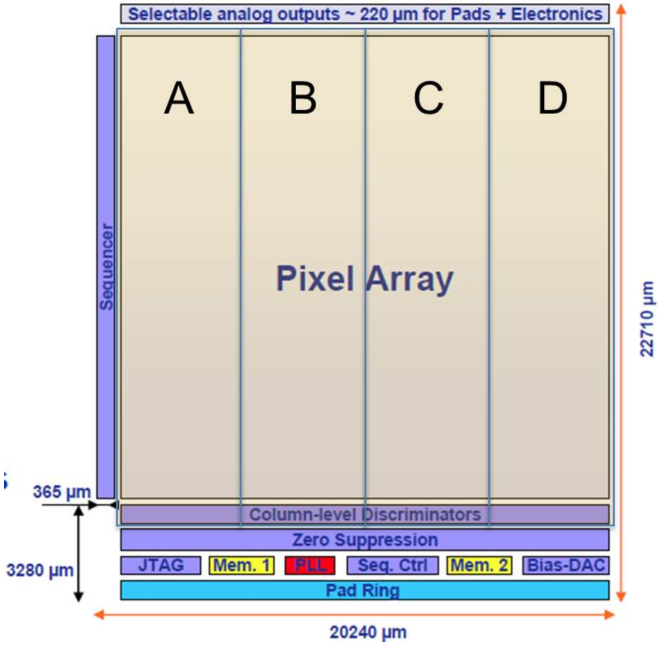
Monolithic Active Pixel Sensor technology

Ultimate-2: third generation sensor developed for the PXL detector by the PICSEL group of IPHC, Strasbourg

- High resistivity p-epi layer
- S/N ~ 30
- MIP Signal ~ 1000 e^-

- 928 rows * 960 columns = ~1M pixel
- Rolling-shutter readout
  - connects row by row to end-of-column discriminators
  - 185.6 μs integration time
  - ~170 mW/cm^2 power dissipation





Position Resolution

- *Ultimate-2* sensor geometry
  - pixel size: 20.7 μm X 20.7 μm
  - 3-pixel av. cluster size ~3.7 μm resolution on center-of-mass
- Position stability
  - Vibration at air cooling full flow: ~5 μm RMS
- **Global hit resolution: Δx ~ 6.2 μm**

Δx ~ 6.2 μm

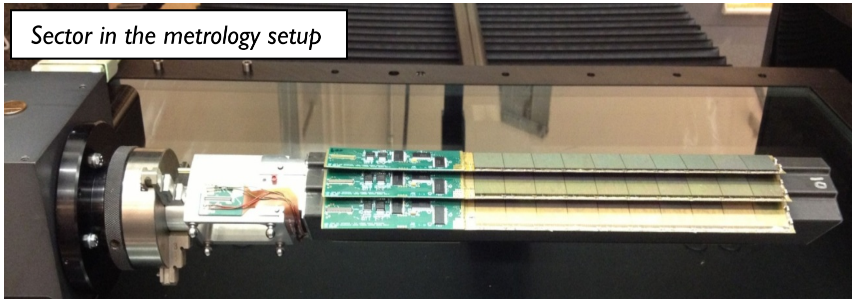
r_1 = 2.8 cm

r_2 = 8 cm

$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

HFT DCA pointing resolution:

(10 ⊕ 24/p) μm

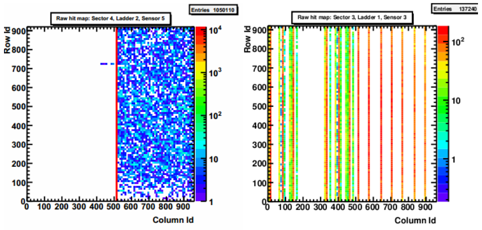


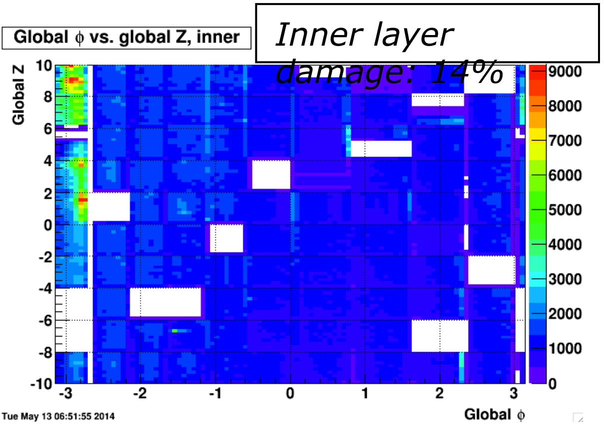
- Metrology survey
  - 3D pixel positions fully mapped and related to kinematic mounts
- Alignment
  - Using 0 field cosmic

- Thinned Sensor 50 μm
- Carbon fiber supports
- Air cooling
- **Total material budget on inner layer: 0.388% X_0**
  - (0.492% X_0 for the Cu conductor version)

Lessons learned: Latch-up damage on PXL

- Unexpected damage seen on 15 ladders in the STAR radiation environment in 2014 Run first 2 weeks
  - Digital power current increase
  - Sensor data corruption →
  - Hotspots in sensor digital section
  - Related to latch-up events





Inner layer damage: 14%

- Latch-up tests at *BASE facility* (LBL) to measure latch-up cross-section and reproduce damage
  - 50 μm & 700 μm thick, low and high resistivity sensors; PXL ladders
  - Irradiation with heavy-ions and protons

- Results and observations
  - Current limited latch-up states observed (typically ~300 mA)
  - Damage reproduced only with HI on PXL 50 μm thinned sensors

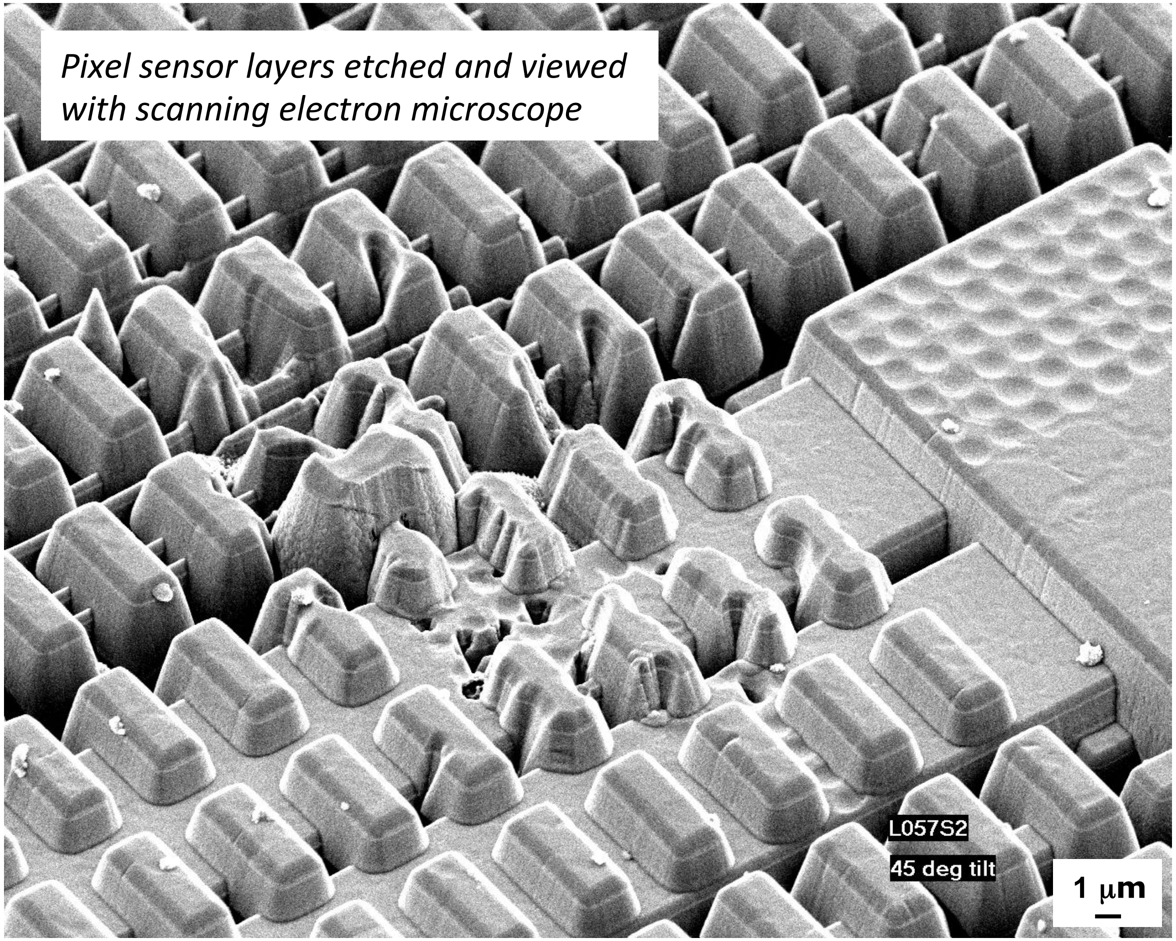
- Safe operations envelope implemented
  - Latch-up protection at 80 mA above operating current
  - Periodic detector reset

Latch-up phenomenon:

- Self feeding short circuit caused by single event upset
- Can only be stopped by removing the power

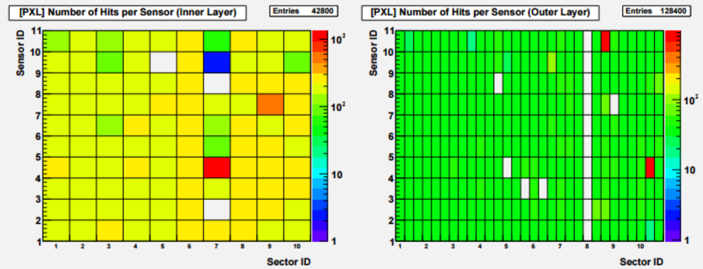
Latch-up damage: Sensor Deconstruction

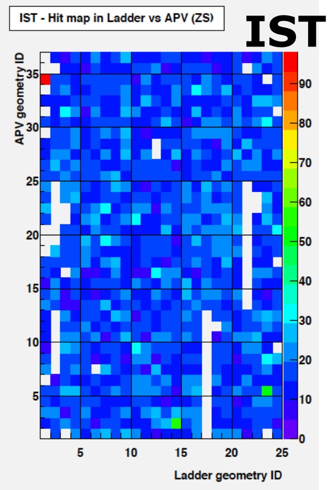
- Deconstructing damaged sensor through a plasma etching technique
- The metal layer appears to be melted

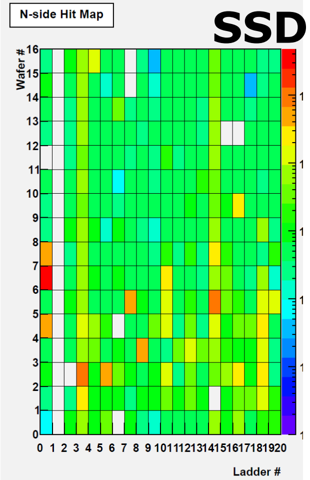

Pixel sensor layers etched and viewed with scanning electron microscope

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 sensors + 1 outer ladder off)
  - IST
    - 95% channels operational, stable
  - SSD
    - 80% channels operational (one ladder off)

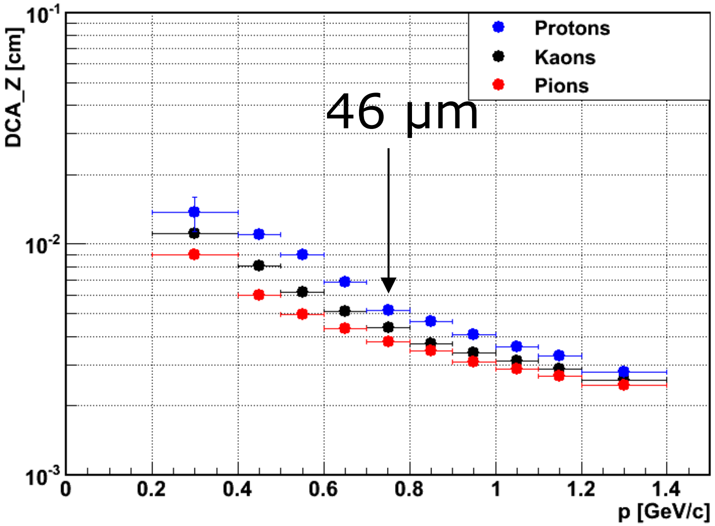




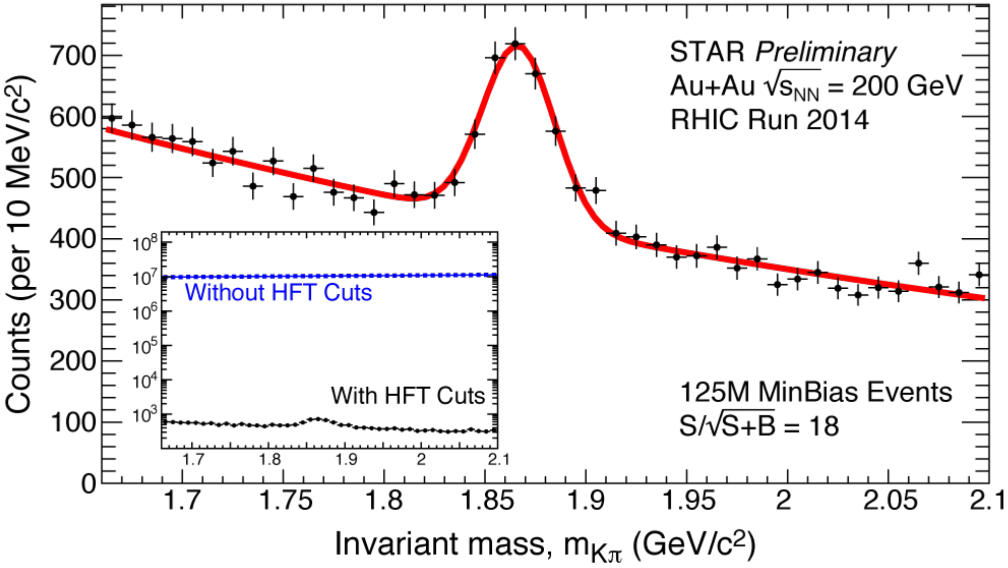


HFT Performance in 2014 Run

- DCA pointing resolution
  - Design requirement exceeded: 46 µm for 750 MeV/c Kaons for the **2 sectors** equipped **with aluminum cables on inner layer**
  - ~ 30 µm for p > 1 GeV/c
    - From 2015: all sectors equipped with aluminum cables on the inner layer


46 µm

***$D^0 \rightarrow K\, \pi$ production** in*
*$\sqrt{s_{NN}}$ **=** 200 GeV Au+Au collisions* →
(partial event sample)

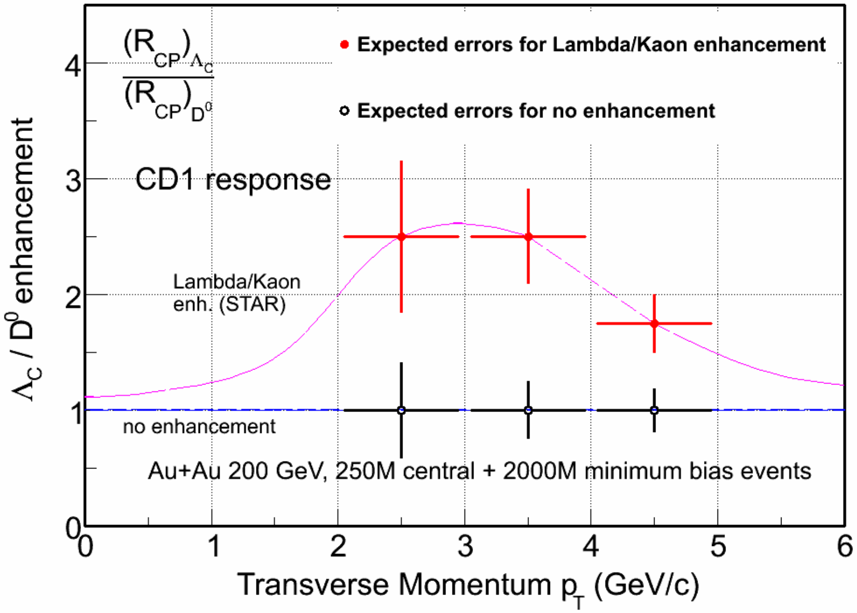


HFT goals for Au+Au data-taking in 2016

- STAR/RHIC improvements with respect to 2014 Run
  - PXL equipped with all aluminum cables on inner ladders 0.49%→0.38% X_0
  - SSD at full speed → better track matching / ghosting rate reduction
  - Increased luminosity fraction within $|V_z|$<5 cm
- RHIC beam for 2016 Run:
  - ~10 weeks Au+Au 200 GeV run
  - 2 B minimum bias events

- Physics goals:
  - Λ_c and B→J/ψ measurements
  - More differential studies on charmed hadron production

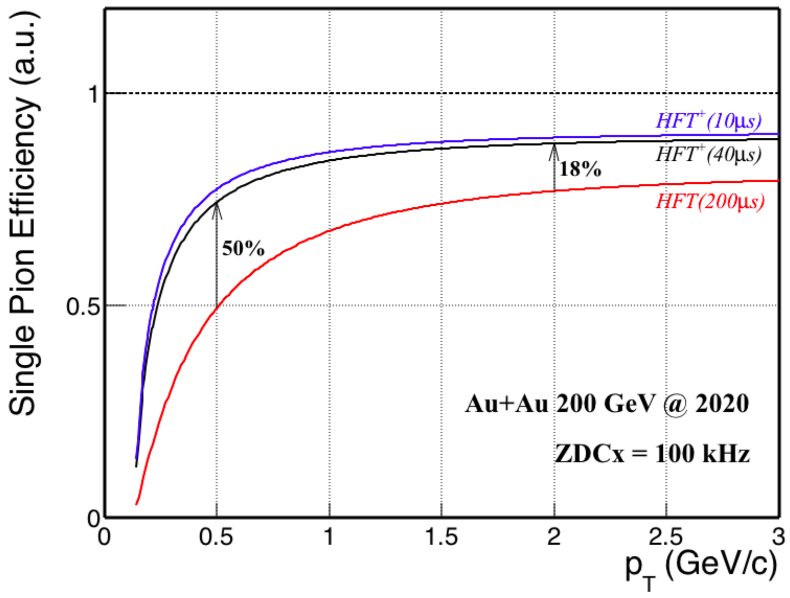
Statistical error estimations on the Λ_c/D_0 enhancement factor measurement



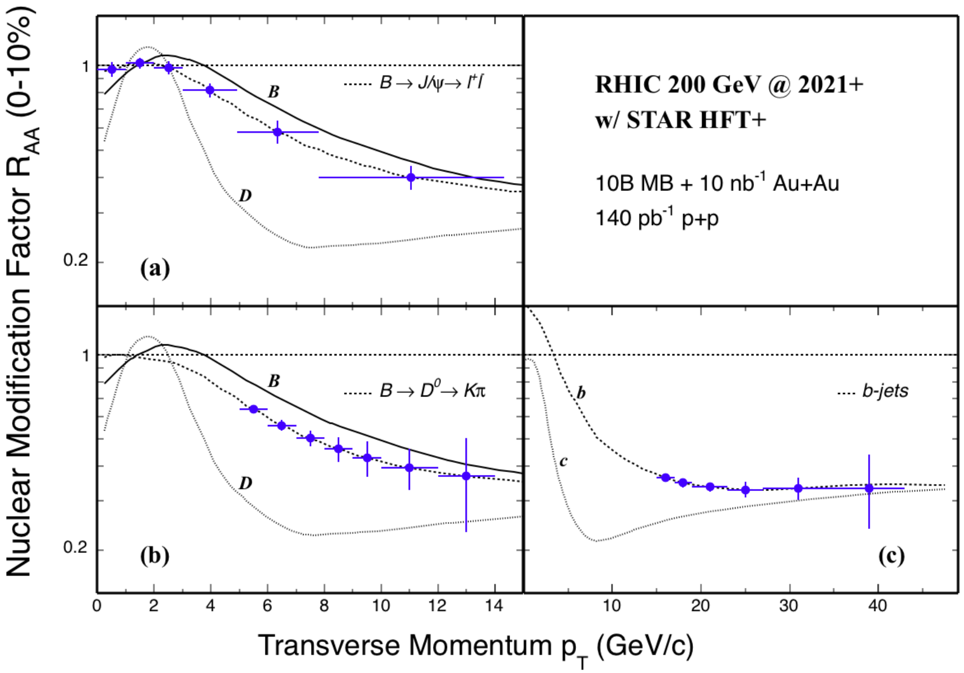
Future HFT+ Upgrade plan (2021-2022)

- Measure **bottom quark hadrons** at the RHIC energy
- **Faster** frame readout: 185.6 μs -> 40 μs or less
  - Using new MAPS sensor developed for the ALICE ITS upgrade
  - Take data in **higher luminosity** with high efficiency

Efficiency: fast vs. slow HFT



HFT+ flagship measurements



- R_{AA} for J/ψ and D^0 from *B*, and *b-jets*

Conclusions - HFT

- The STAR HFT has been successfully taking data in 2014 and 2015
- 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
- A faster HFT+ has been planned in order to measure the bottom quark hadrons at the top RHIC energy

D^0 v_2

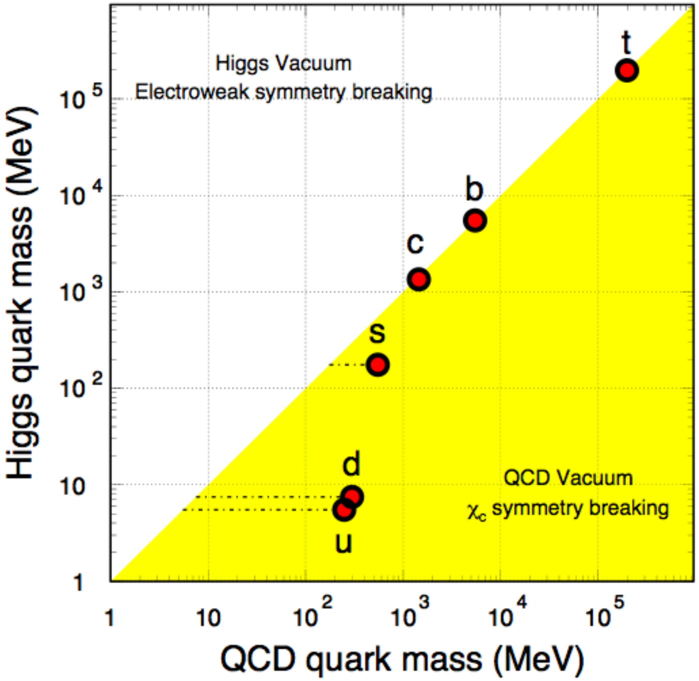
Motivation

Charm quarks:

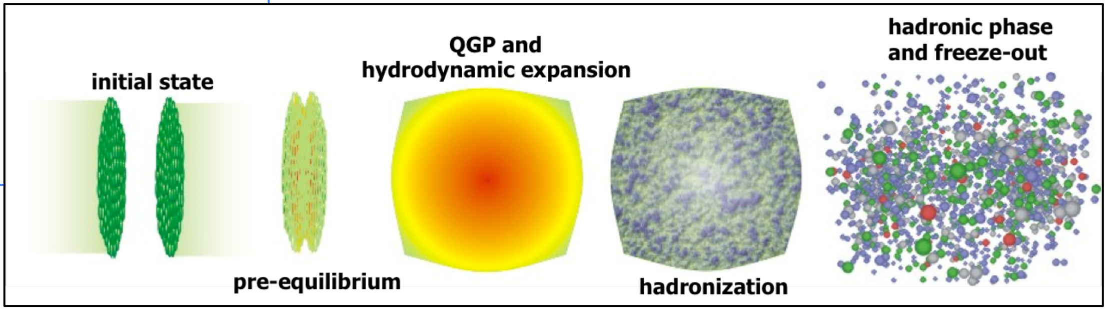
- Produced early in heavy ion collisions at RHIC, through hard scattering
- Experience the whole evolution of the system -> good probe for medium properties

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

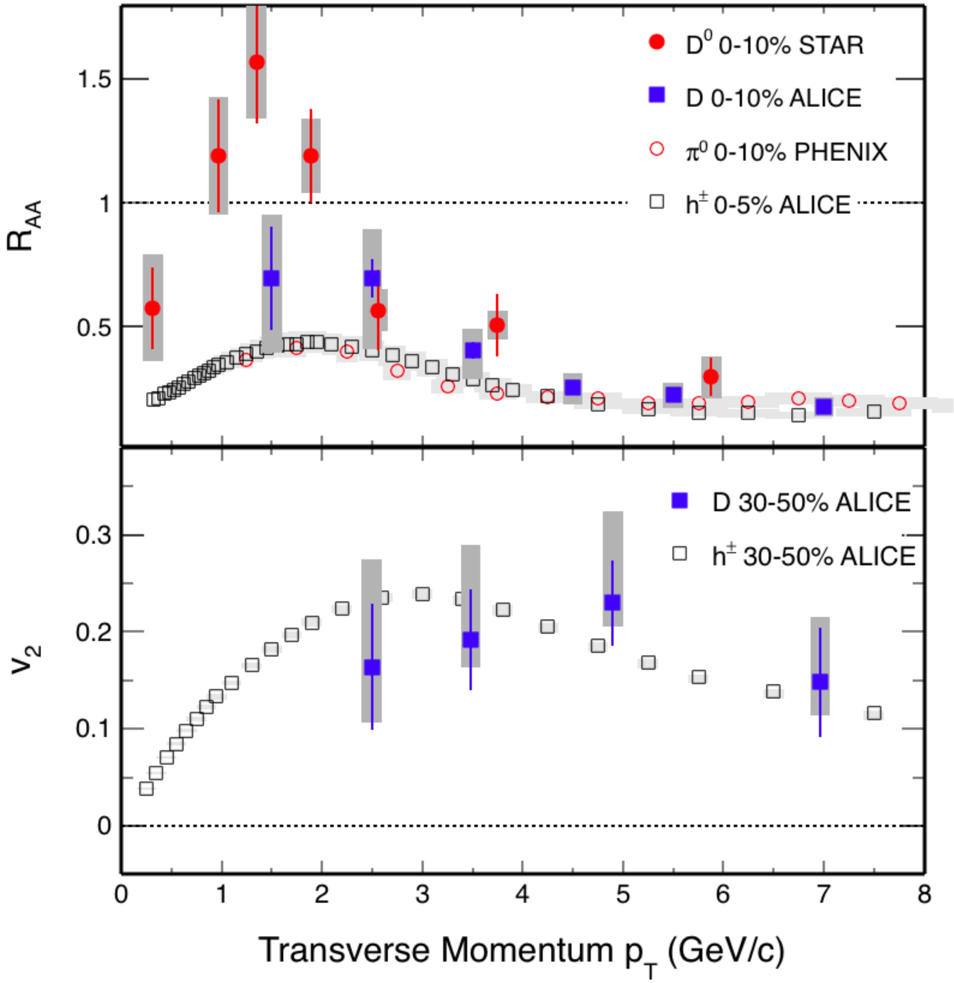
- RHIC and LHC: *D*-meson R_{AA} suppression at high p_T : strong charm-medium interactions

- 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)

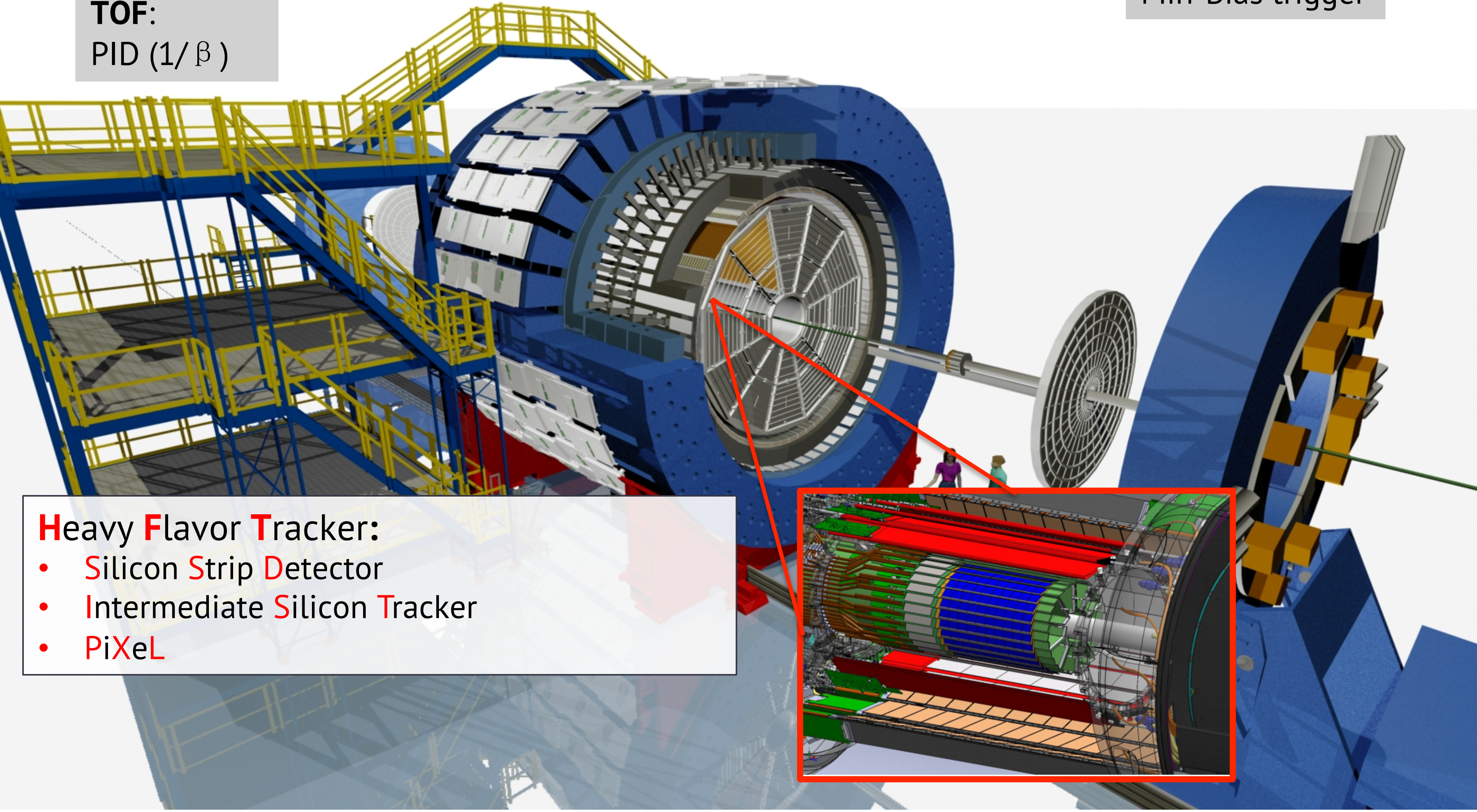
STAR experiment

TPC:
Tracking,
PID (dE/dx)

TOF:
PID (1/β)

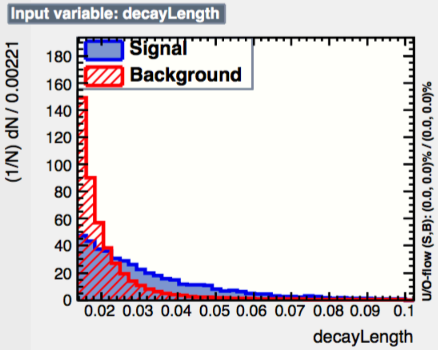
-1< η <1, 0≤φ<2π

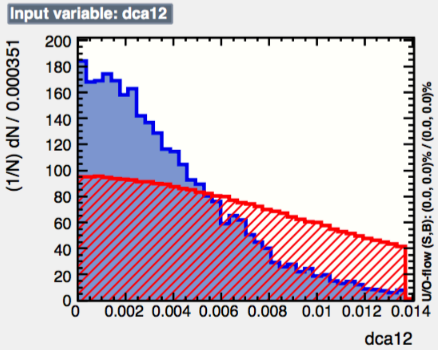
VPD:
Min-Bias trigger

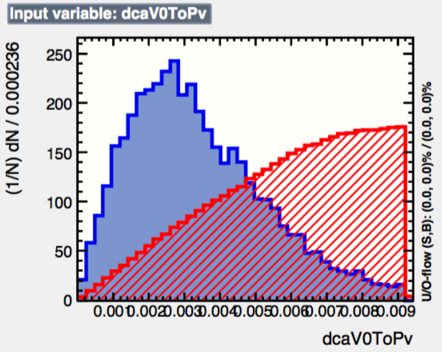


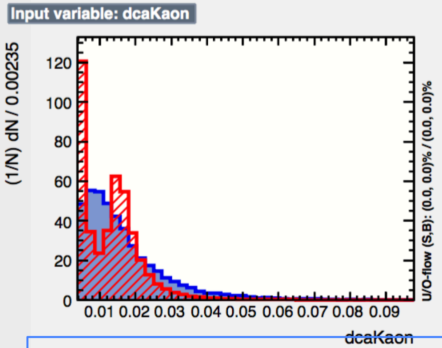
Heavy Flavor Tracker:
- Silicon Strip Detector
- Intermediate Silicon Tracker
- PiXeL

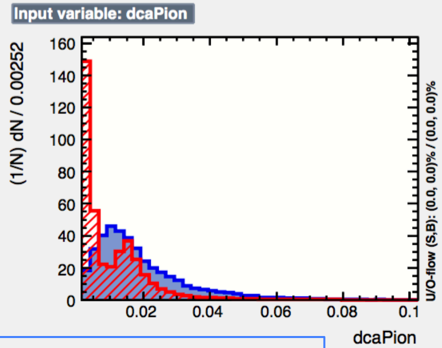
D^0 reconstruction

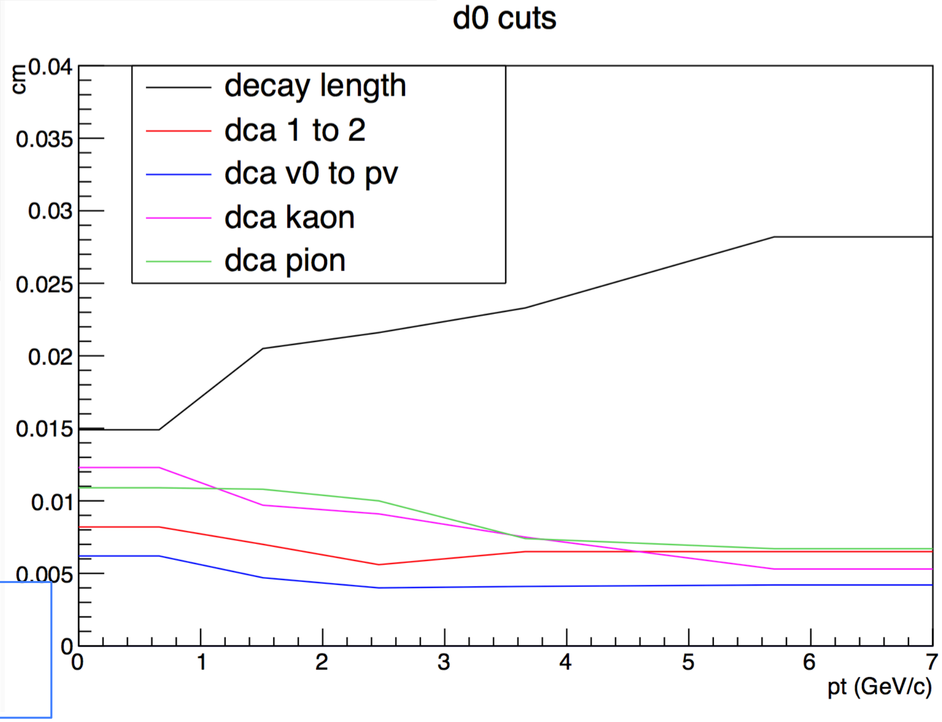












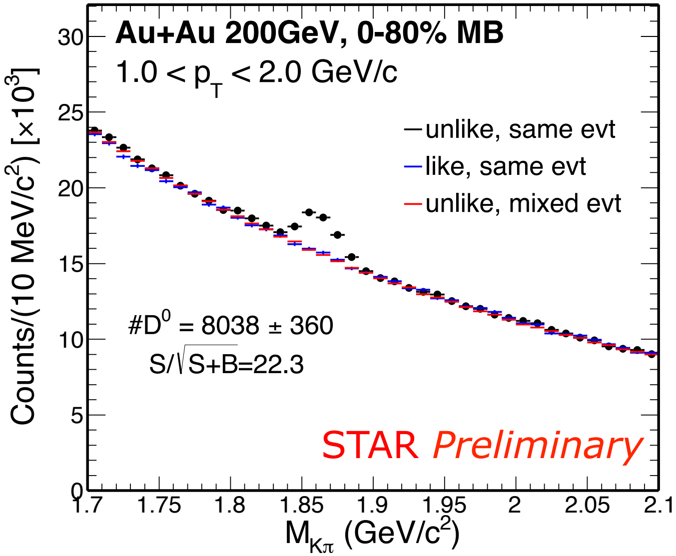
- Direct topological reconstruction through channel:

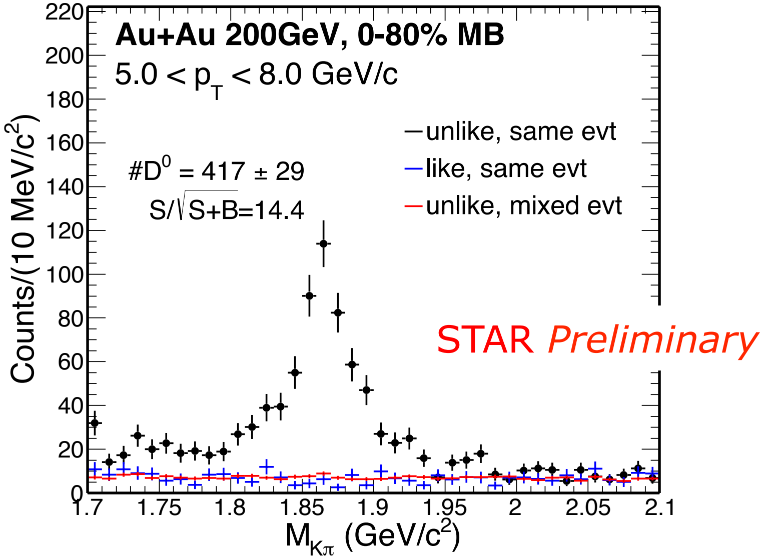
$$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$$

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

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

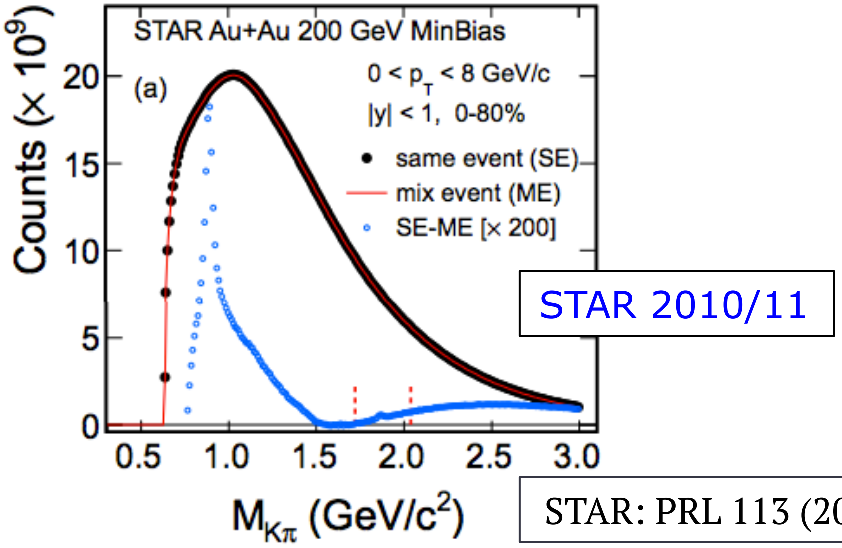
D^0 reconstruction





- 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
sig per billion events	13	51



STAR 2010/11

STAR: PRL 113 (2014) 142301

v_2: Event plane method

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

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

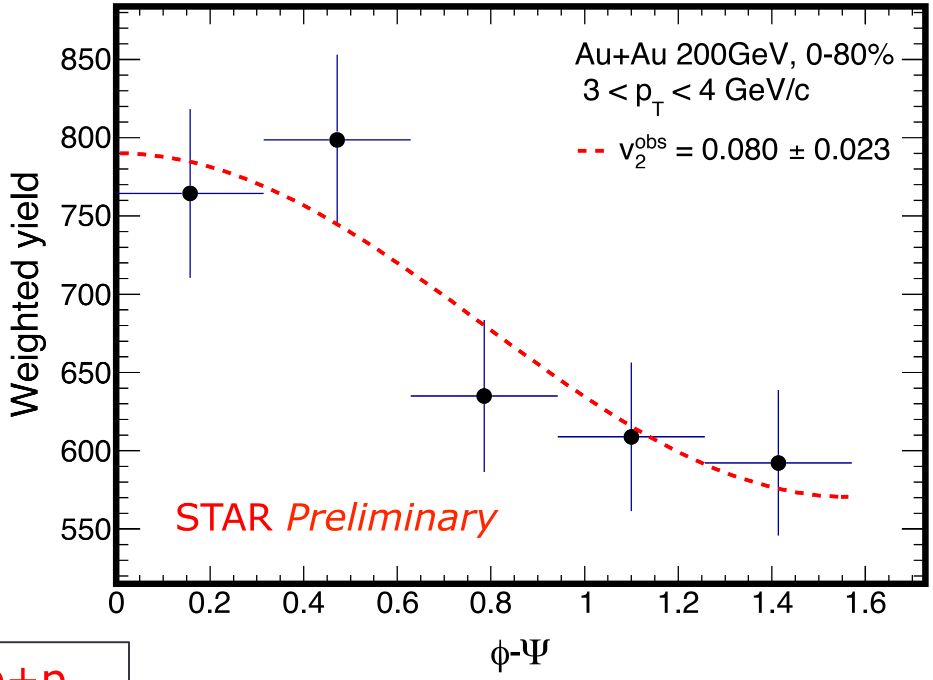
- Δη gap of ~0.15 used in event plane reconstruction

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

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

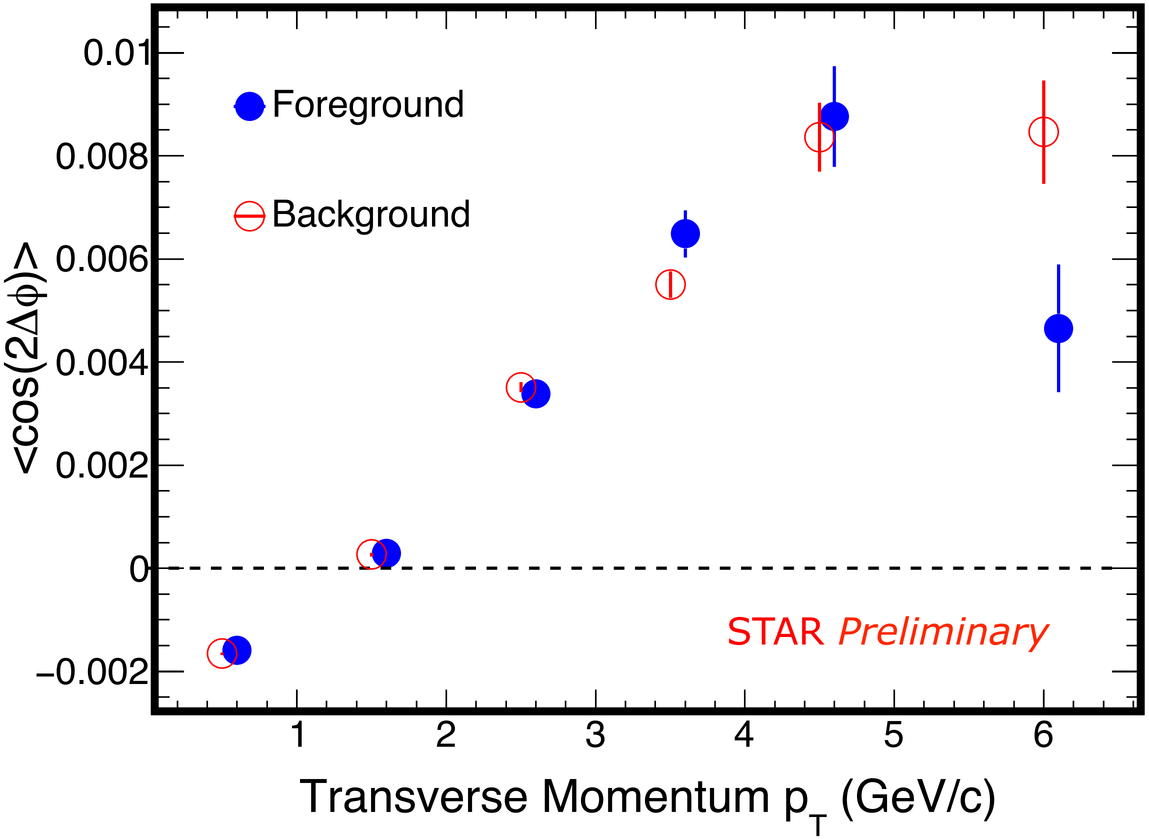
v_2: Two particle correlation

- 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

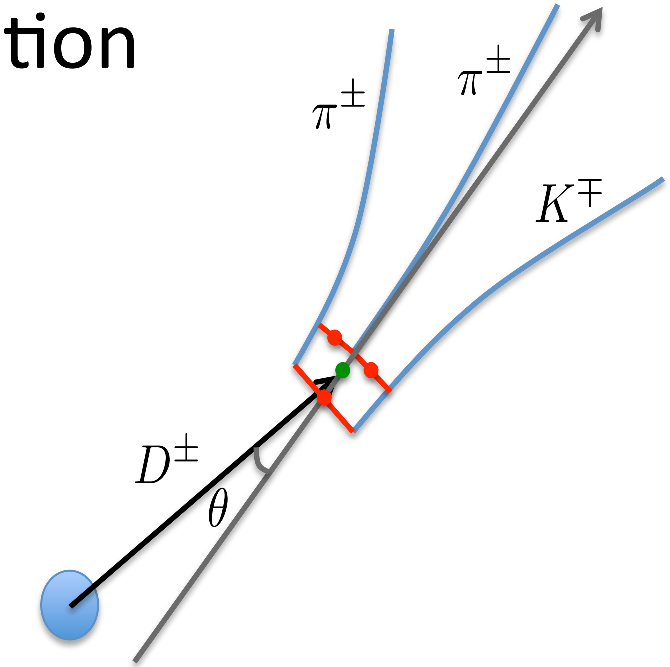
$D^{+/-}$ reconstruction

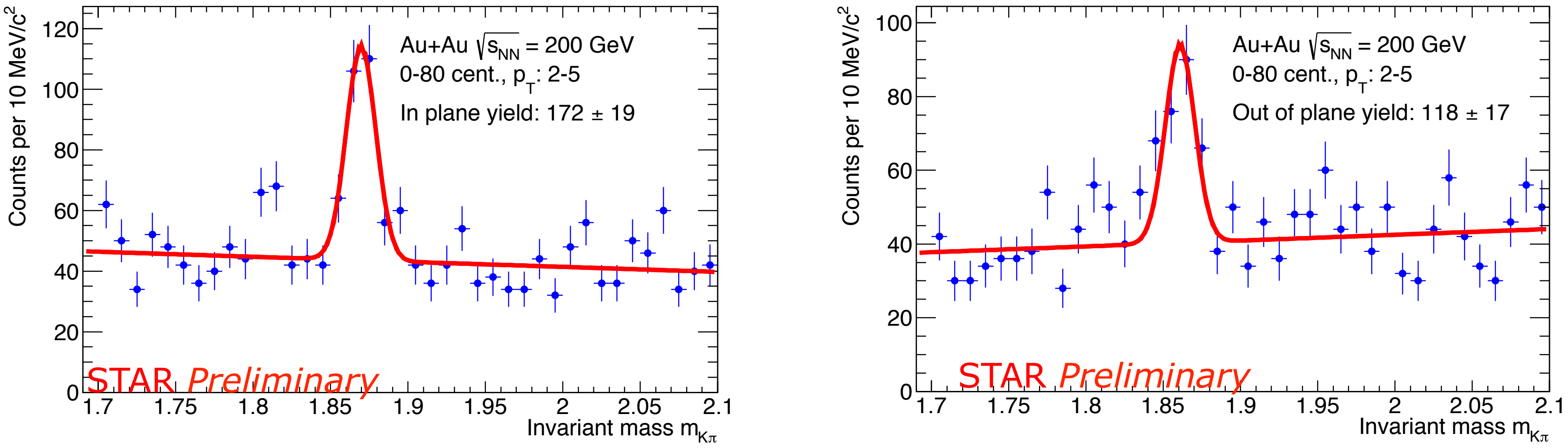
- Direct topological reconstruction through channel:

$$D^{\pm} \to K^{\mp} 2\pi^{\pm}$$

$$\text{B.R. } 9.1\% \quad c\tau \sim 300\ \mu m$$

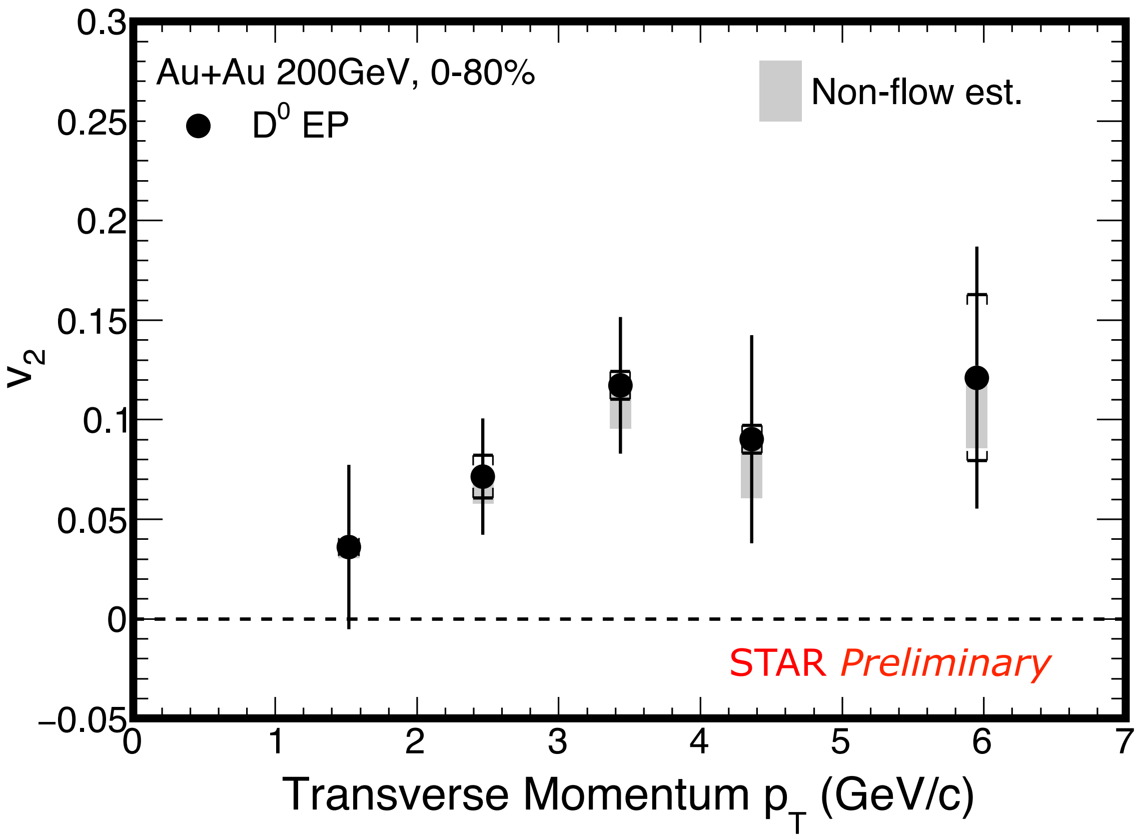
- Yield in plane and out of plane obtained following event plane method





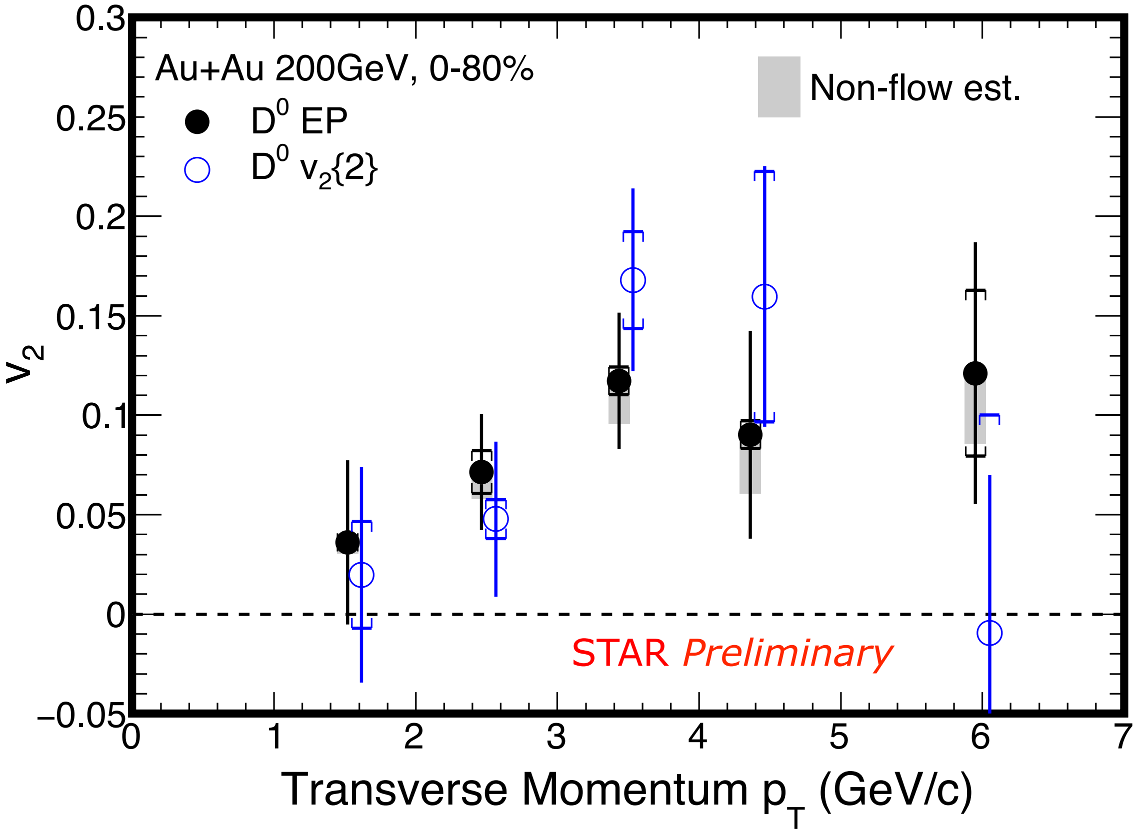
$D^{+/-}$ yield in and out of plane

D Meson v_2



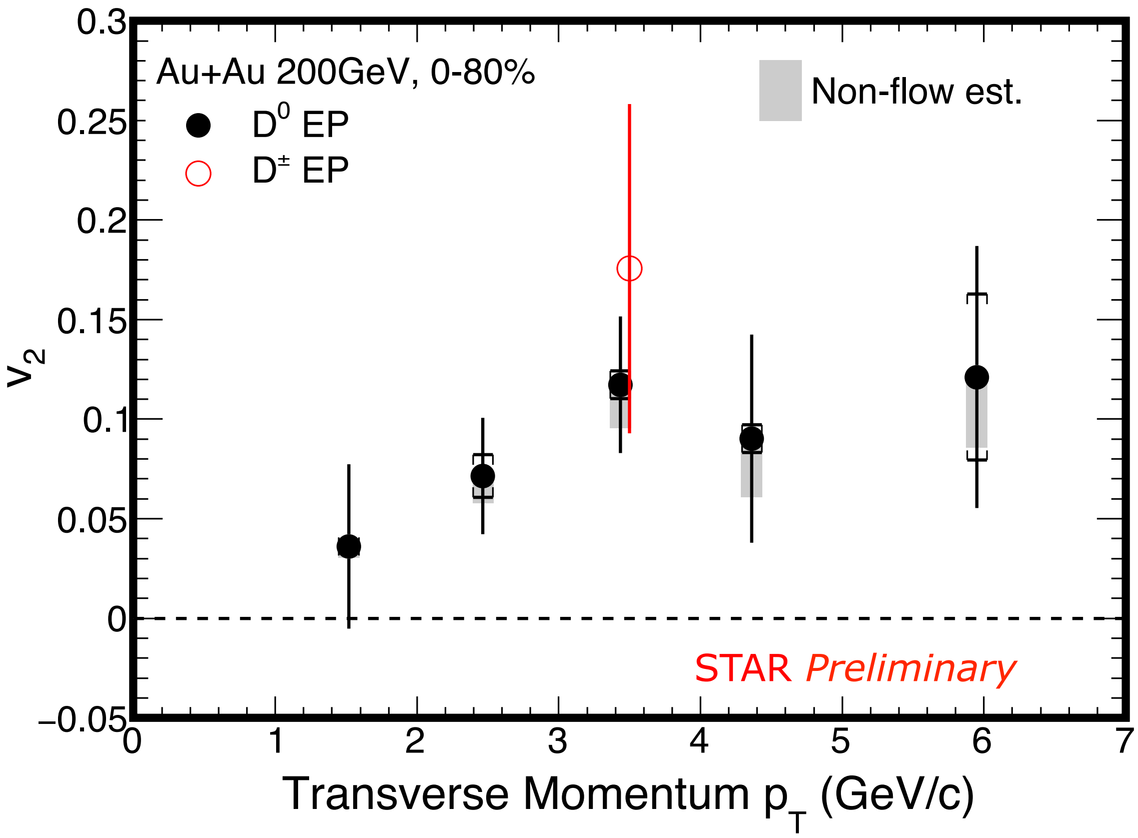
- *D^0* azimuthal anisotropy significantly different from zero for p_T > 2 GeV/c
  (χ^2/n.d.f. = 17.5/4)
- B->D feed down is negligible at RHIC energies (<5% relative contribution)

D Meson v_2



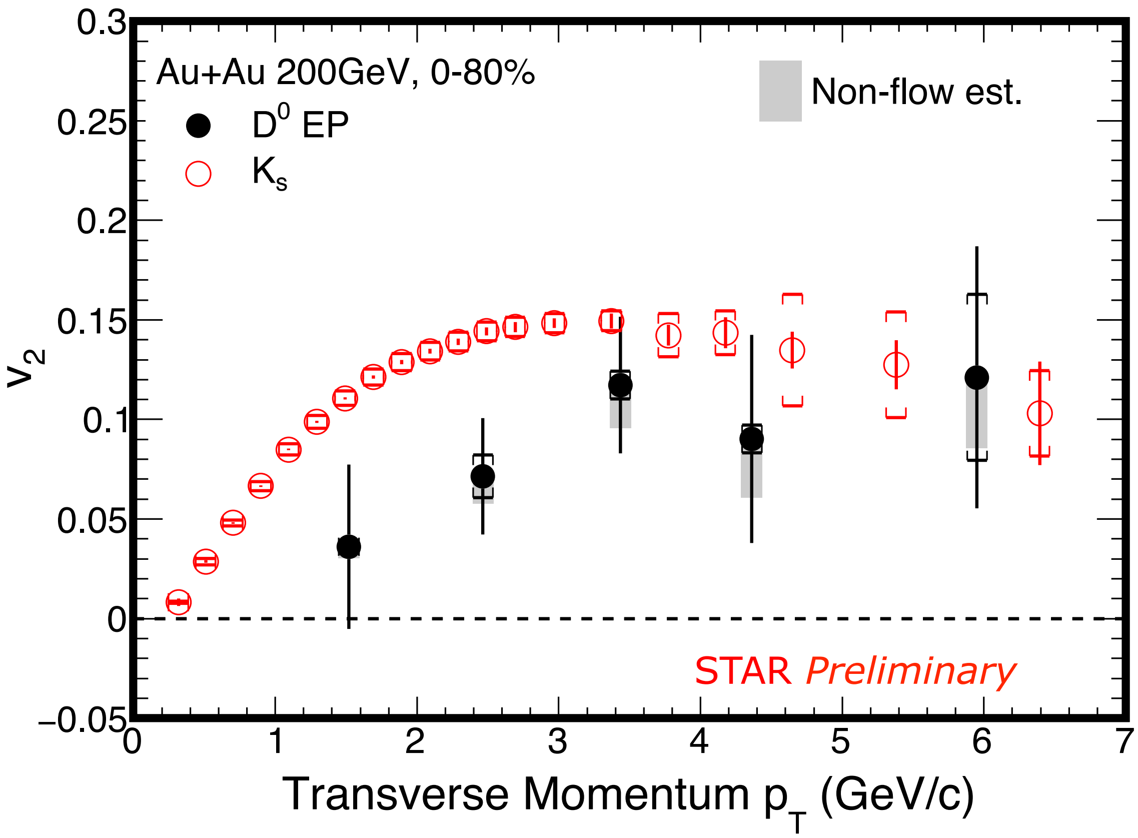
- Good agreement between EP and 2 PC methods within systematics

D Meson v_2



- *D*$^{+/-}$ v_2 compatible with *D*^{0} albeit within large error bars

Comparison to experiment



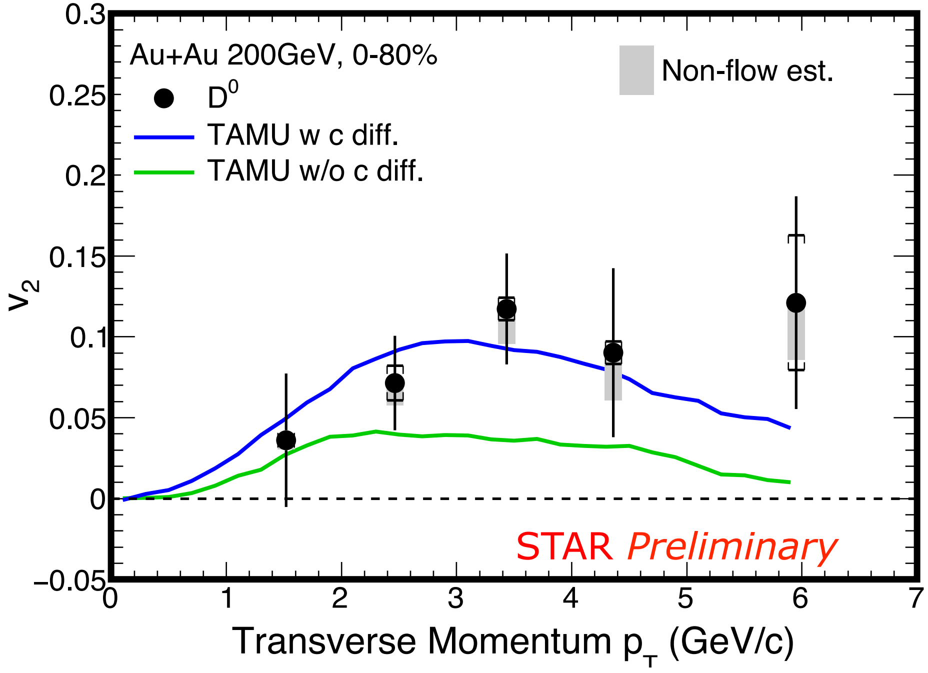
- D^0 v_2 is below light hadrons for $1 < p_T < 4$ GeV/c
    - (χ^2/n.d.f. = 9.6/3)

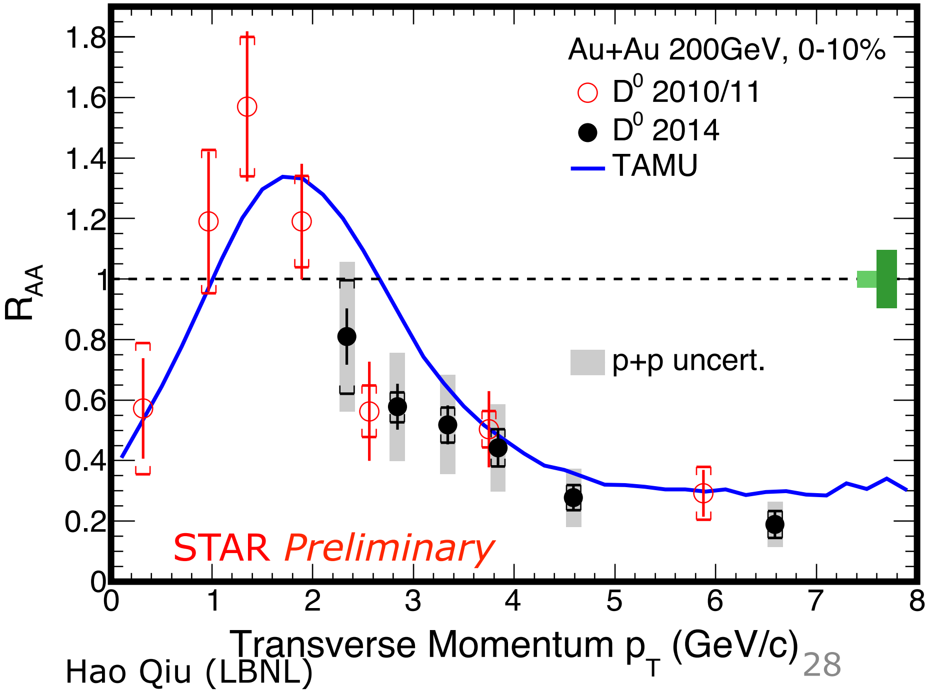
STAR:PRC 77 (2008) 54901

Model comparison: 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)
  - *χ^2 tests done to v_2*

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

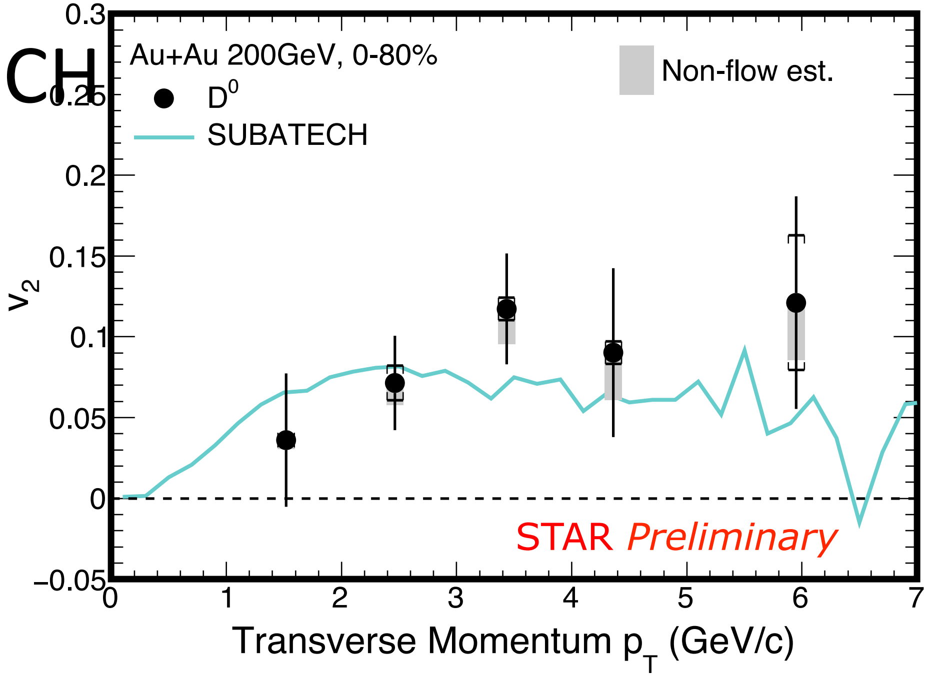


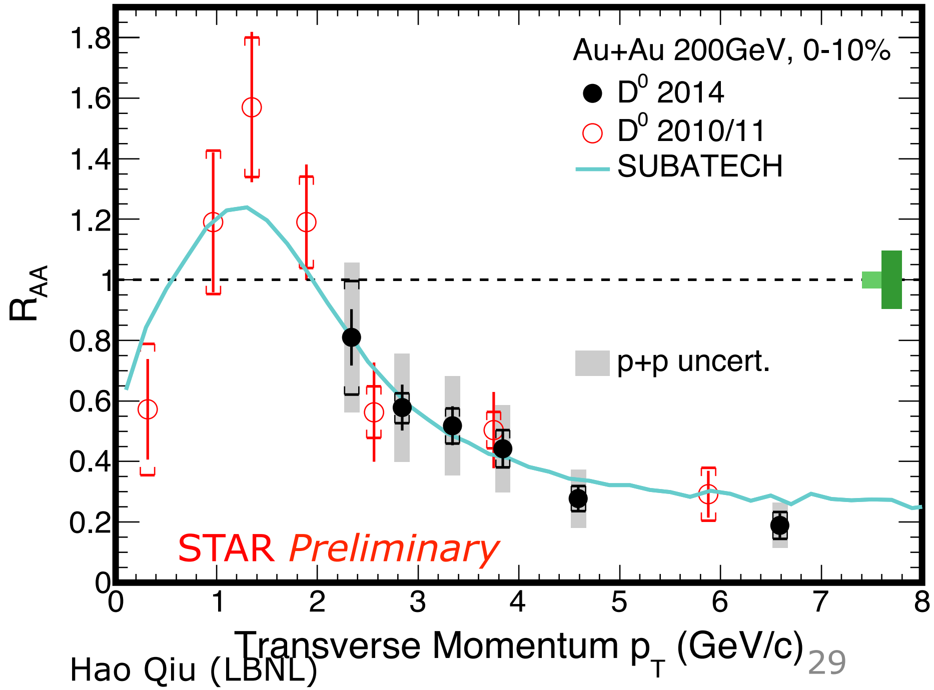


Model comparison: SUBATECH

- 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
  ($\chi^2/\text{n.d.f.} = 2.8/5$)
  - *χ^2 tests done to v_2*

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

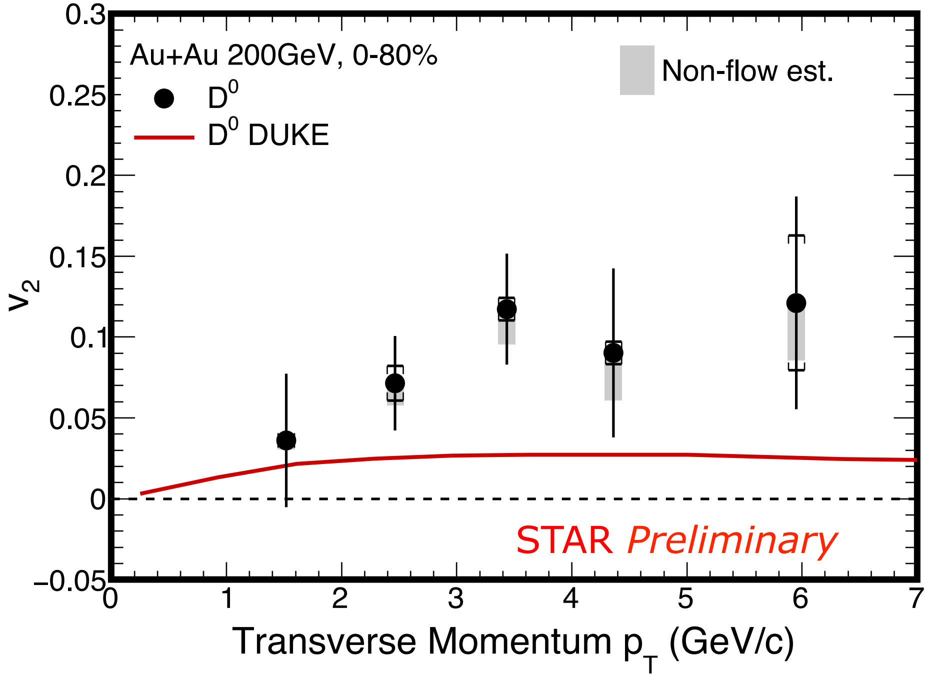


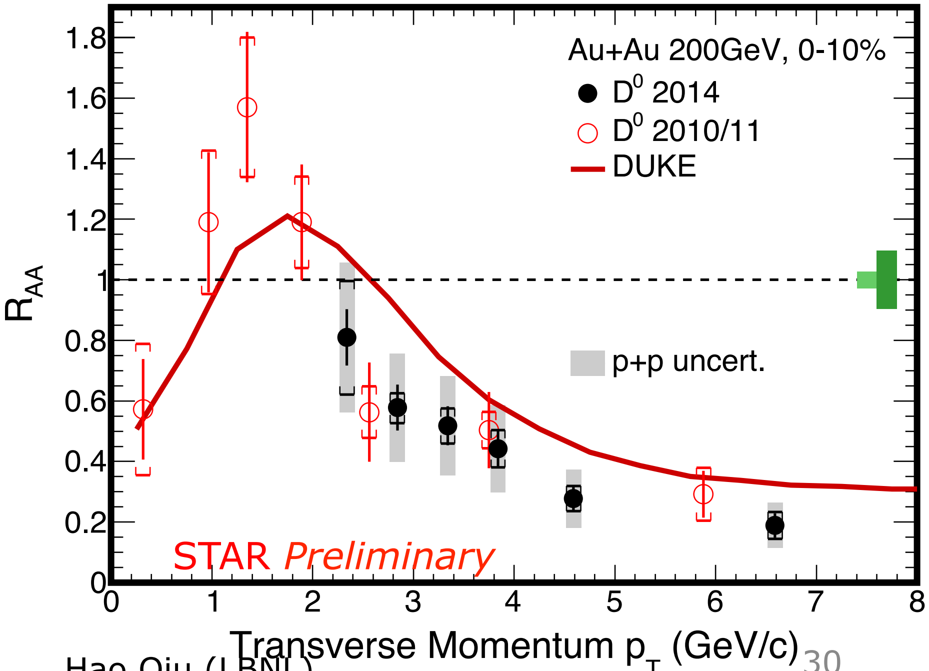


Model comparison: Duke

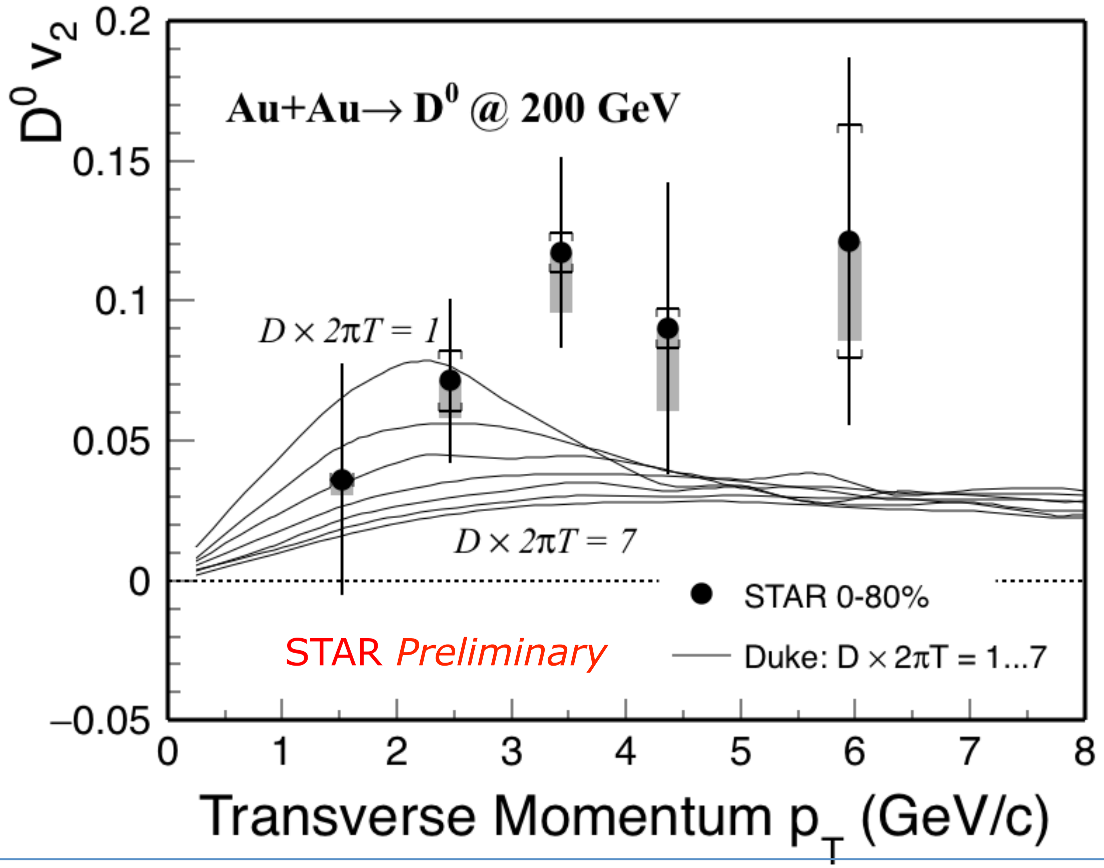
- Diffusion coefficient is a free parameter, fixed by fitting to R_{AA} at high p_T
- Input value for diffusion coefficient $2\pi T \times D = 7$ fixed to fit LHC results
- Model with $2\pi T \times D = 7$ doesn't describe the magnitude of v_2 in experimental data

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





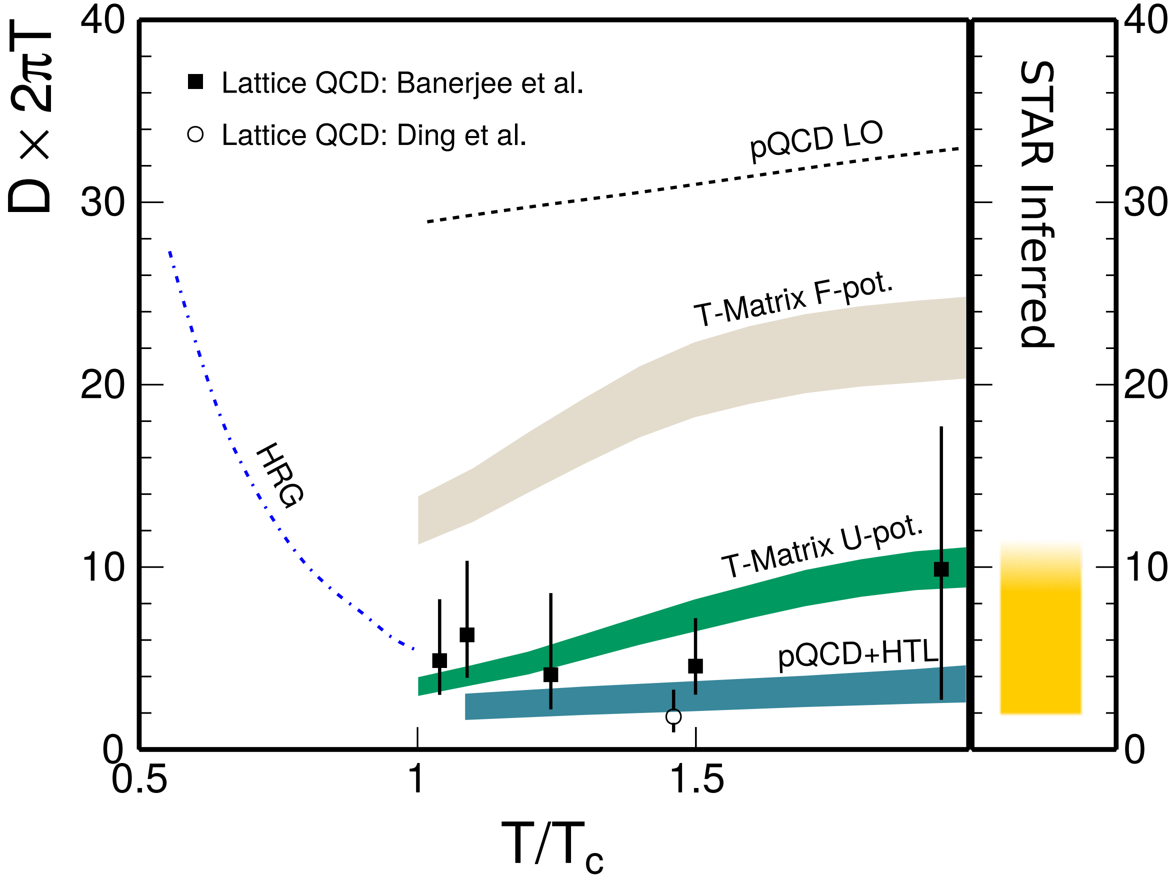
Charm diffusion coefficient



- 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.

Charm diffusion coefficient



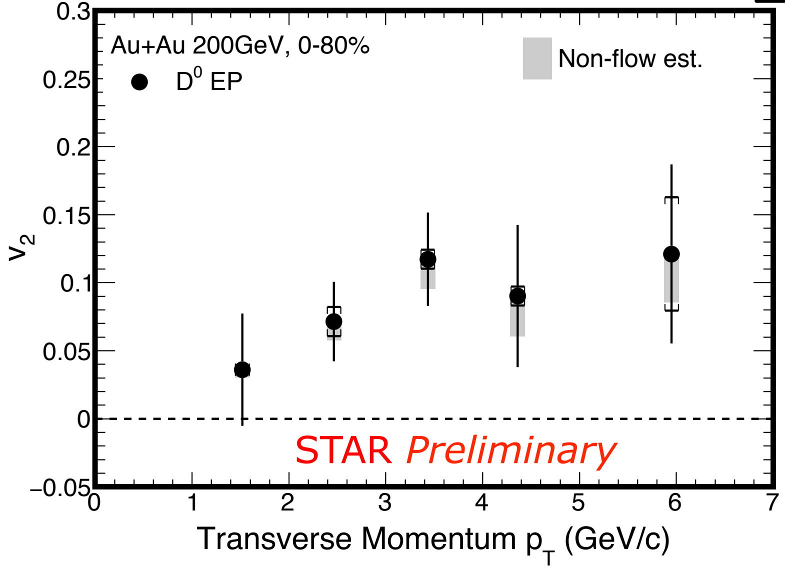
- Compatible with models predicting a value of diff. coefficient between 2 to ~10
- Lattice calculations, although with large uncertainties, are consistent with values inferred from data

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
Future		
Run 16:		
	Au+Au	2 B

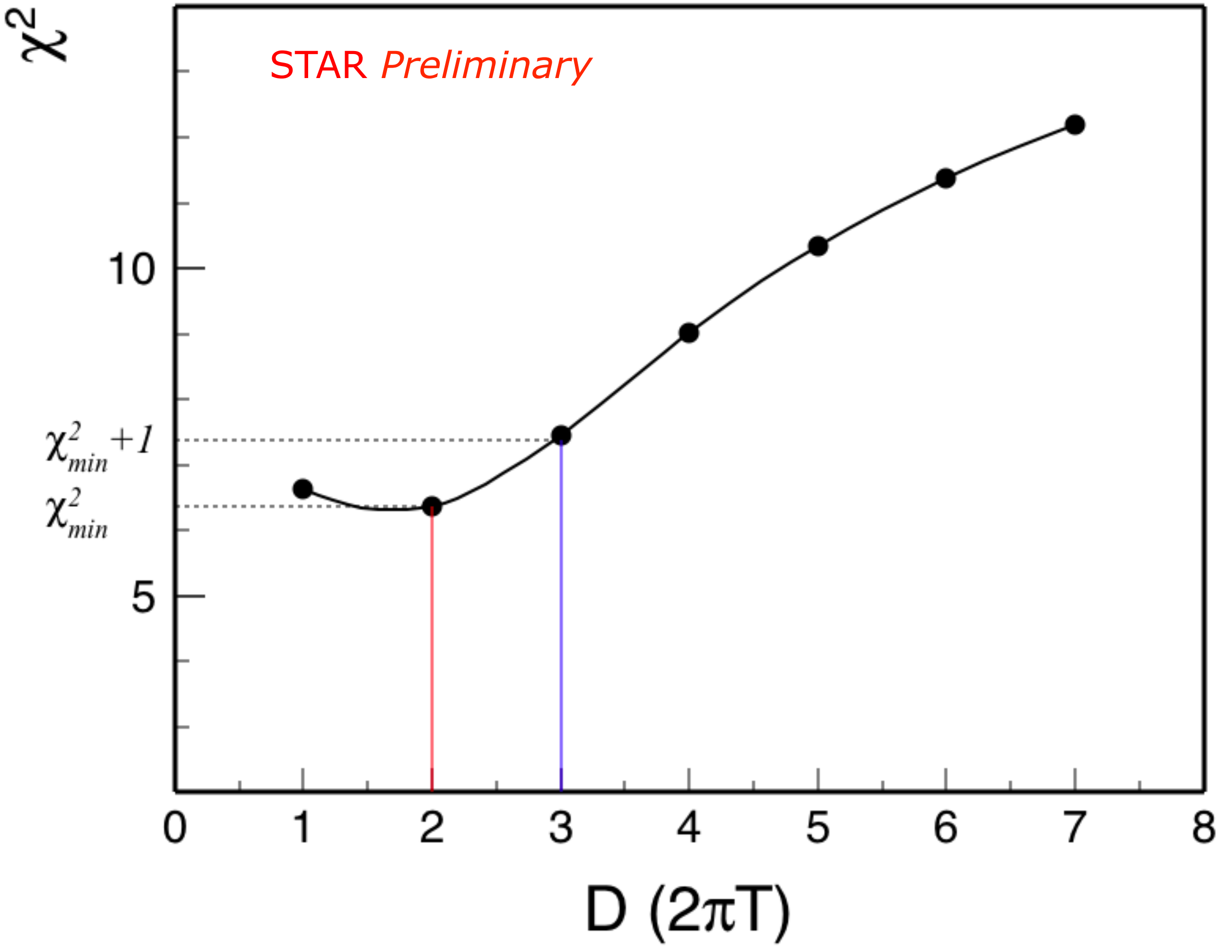
Summary – D^0 v_2



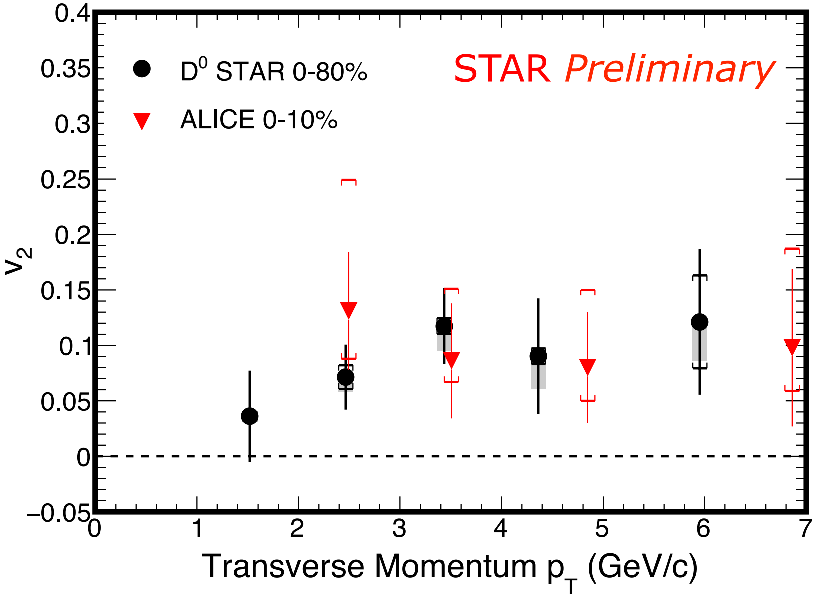
- D^0 v_2 is finite for $p_T > 2.0$ GeV/c
- D^0 v_2 lower than light hadrons for $1 < p_T < 4.0$ GeV/c
- Data favor model scenario where charm quarks flow
- D^0 v_2 and R_{AA} can be described simultaneously by models and are consistent with values of $2\pi TxD$ between 2 and ~10
- Looking forward to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

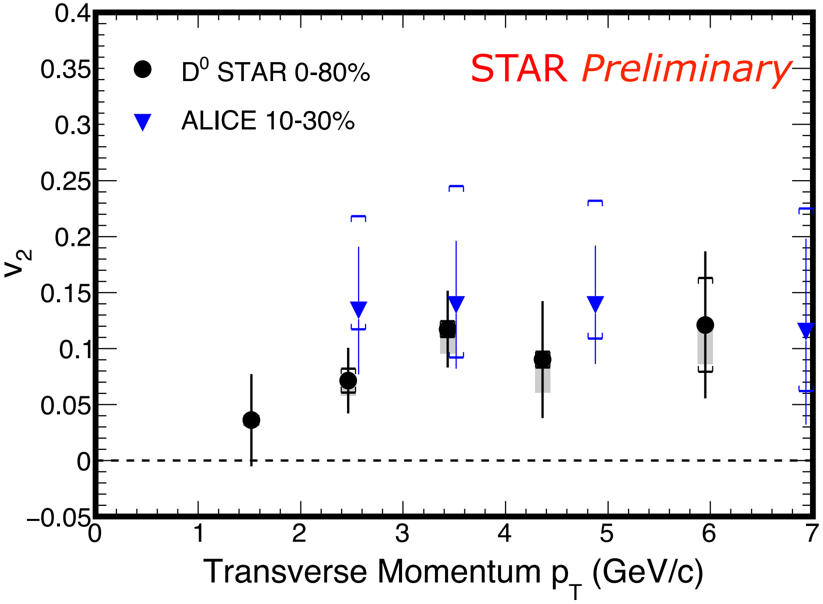
Thank you!
☺

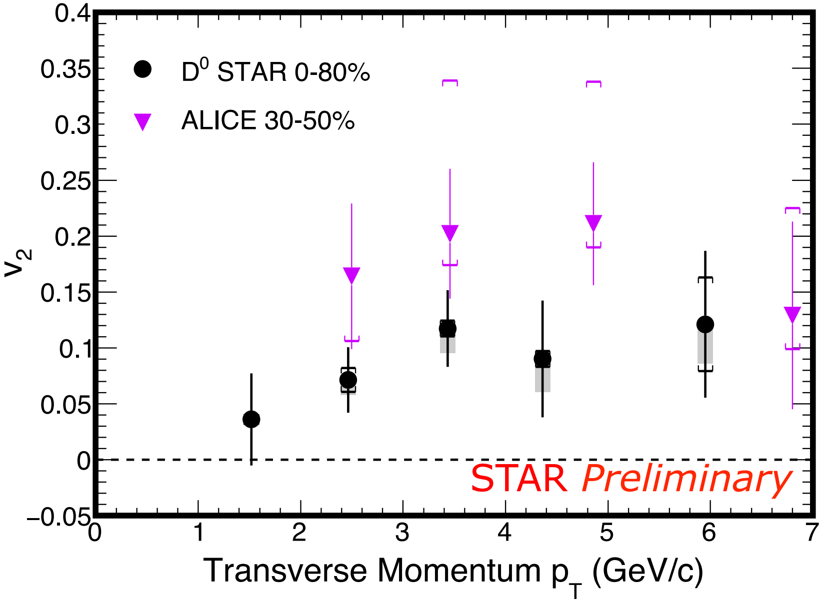
Diffusion Coefficient from DUKE



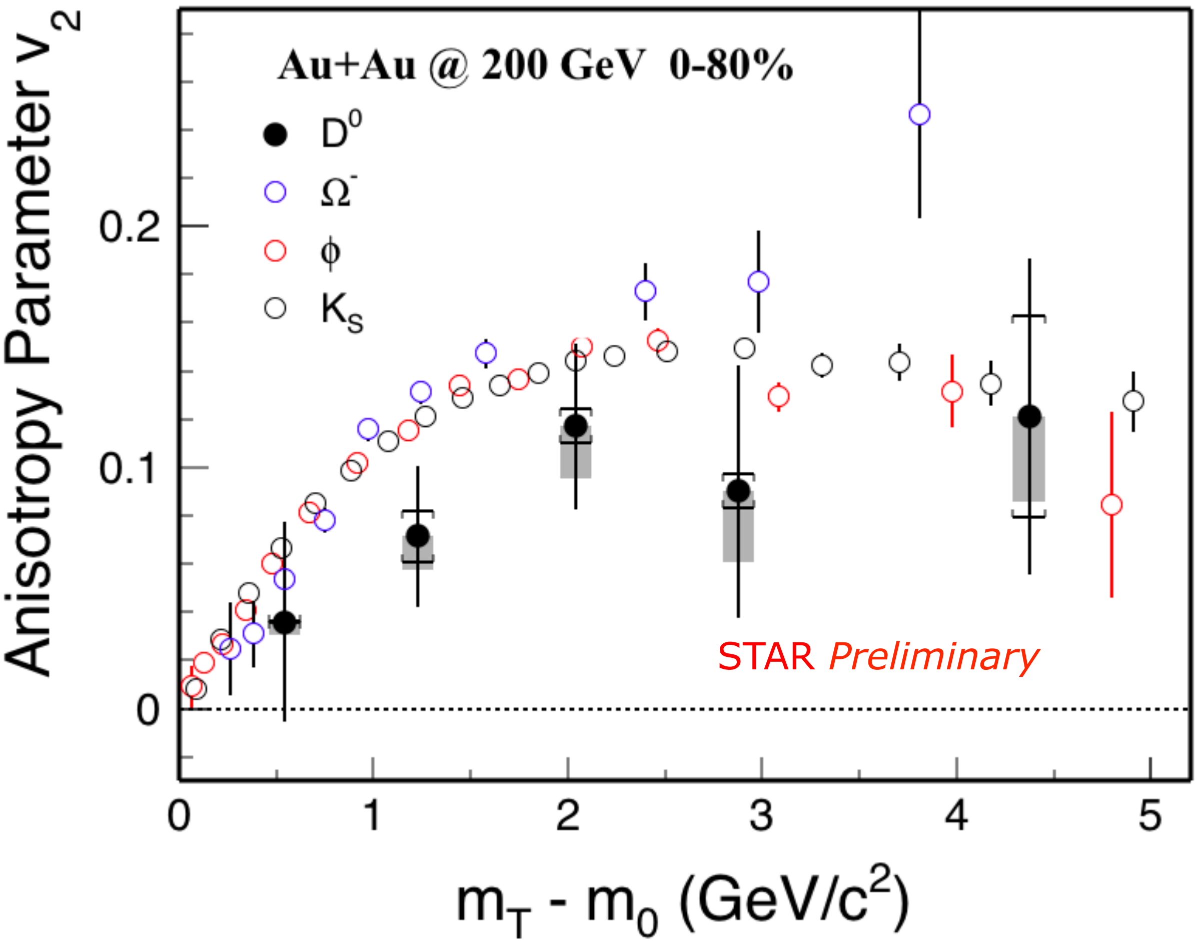
Comparison to ALICE







Mass Effect


Au+Au @ 200 GeV 0-80%
● D^0
○ Ω^-
○ ϕ
○ K_S
STAR Preliminary
Anisotropy Parameter v_2
0
0.1
0.2
m_T - m_0 (GeV/c^2)
0
1
2
3
4
5