STAR Heavy Flavor Tracker (HFT) Detector

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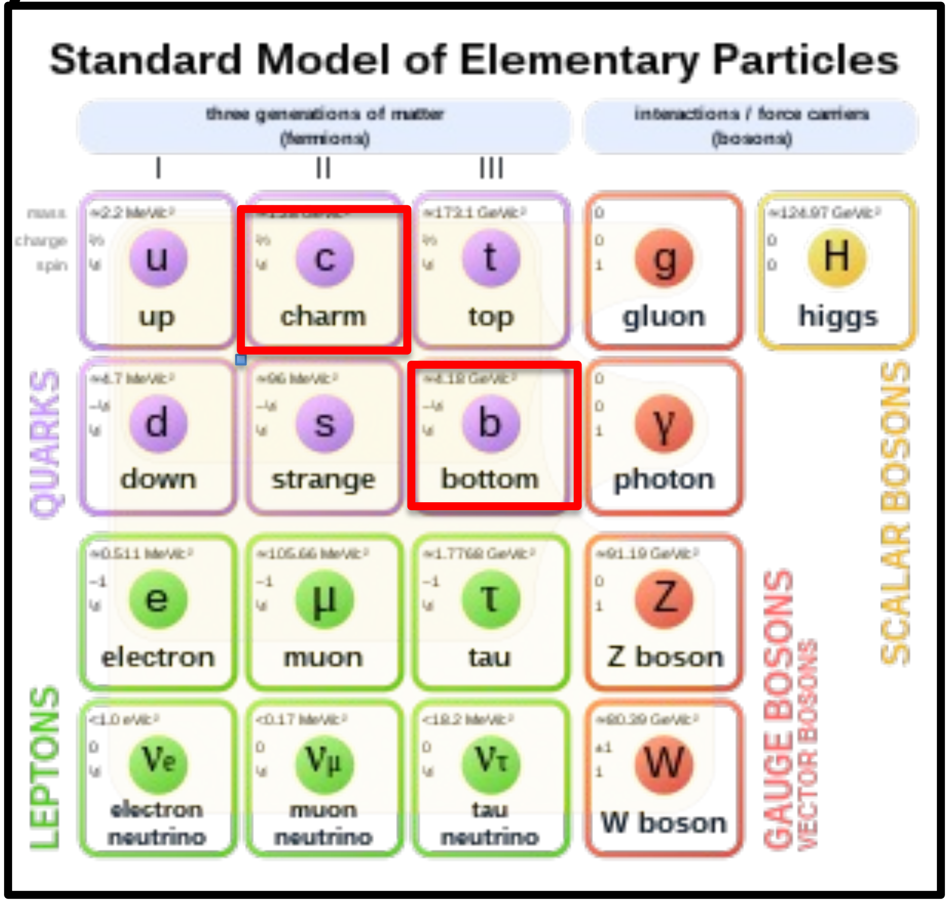
Heavy Flavor

- Heavy quarks at RHIC
- Charm M~1280 MeV
- Bottom/beauty M~ 4180MeV

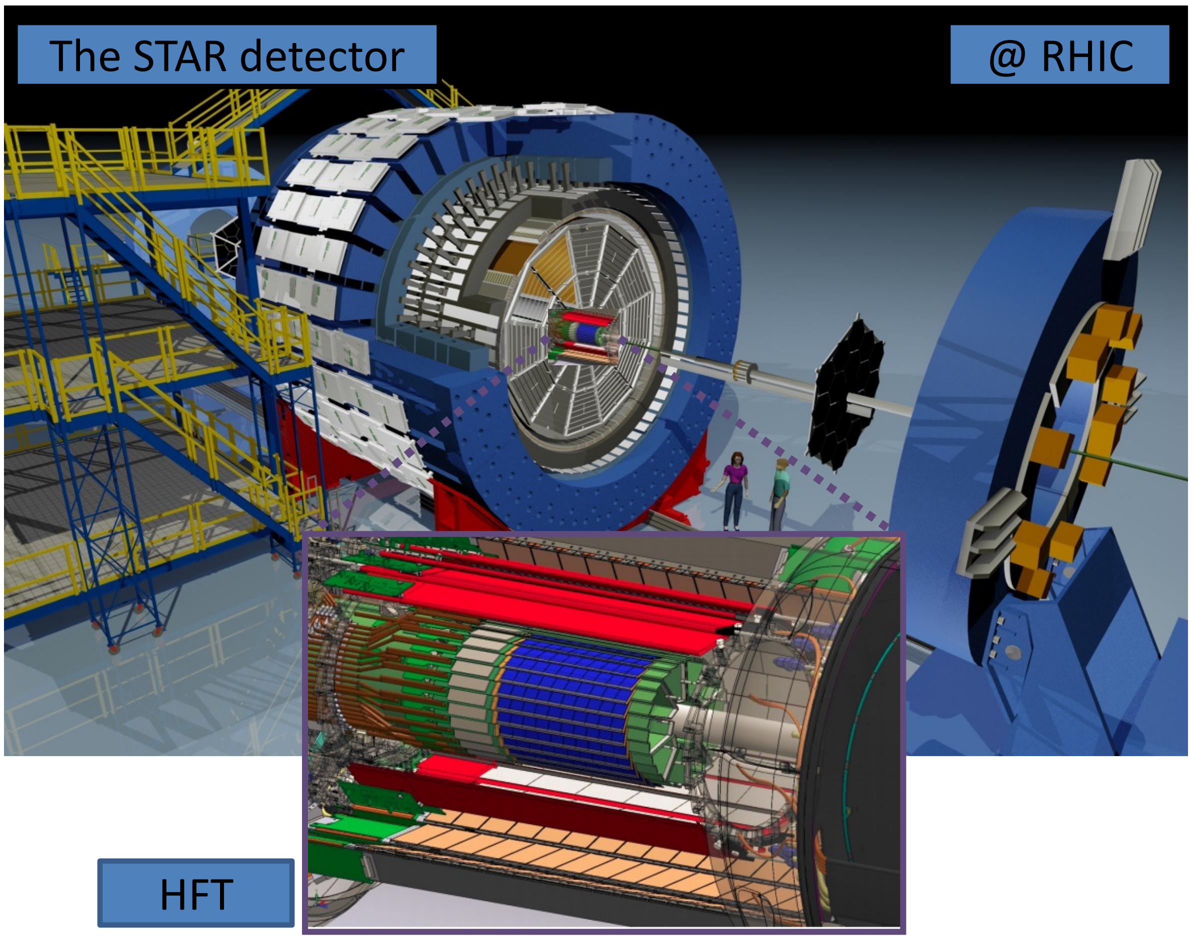
- Heavy quarks usually created in pairs c,c-bar b,b-bar
- Forms mesons, baryons that decays rather quickly with few mm.



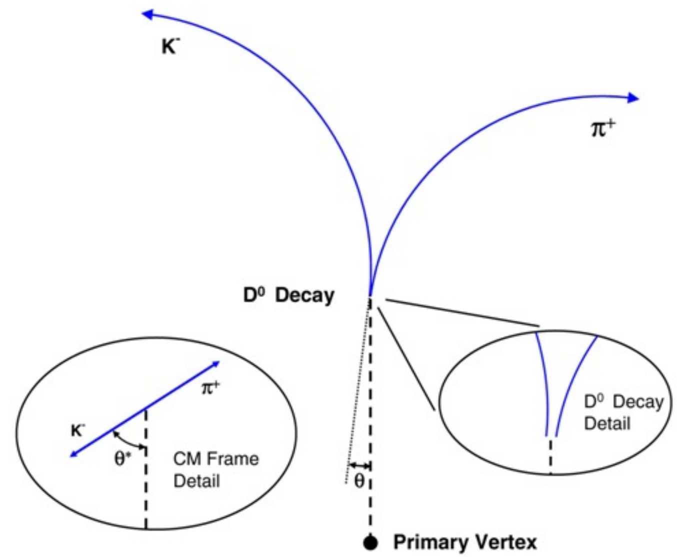
STAR HFT Physics Motivation

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

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



HFT



Method: Resolve displaced vertices (~120 μm)

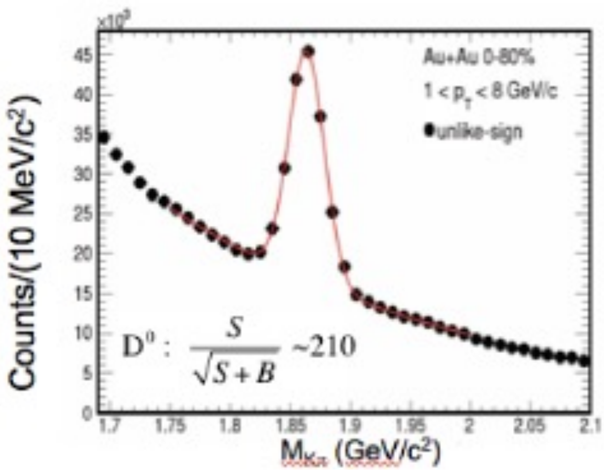
200 GeV Au+Au collisions @ RHIC

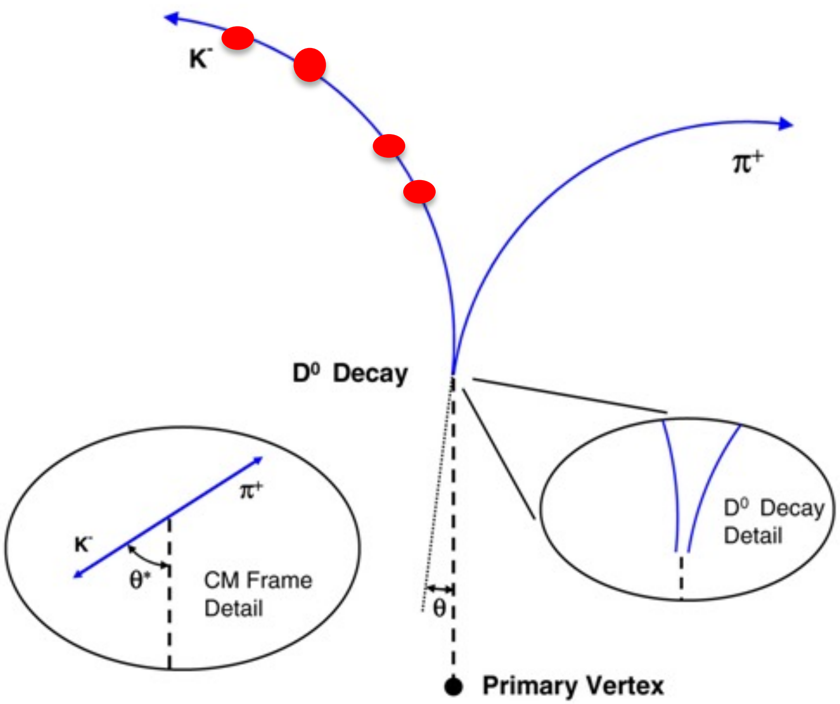
- $dN_{ch}/d\eta$ ~ 700 in central events

How are measurements done?

- Measure points on the tracks
- Determine momentum by fitting to a circle (helix)
- Project to primary vertex,
- Determine decay point and angles.

- From the momenta and masses of decay products calculate mass of decaying meson





HFT was installed into STAR

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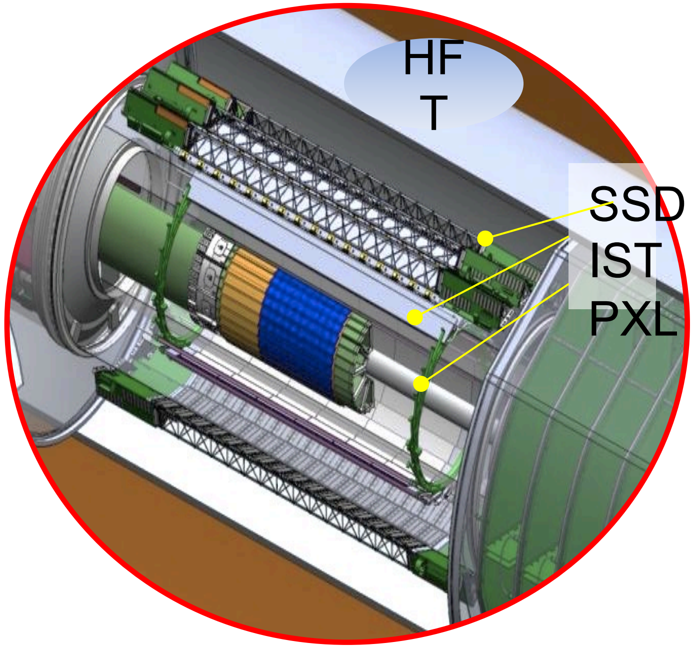


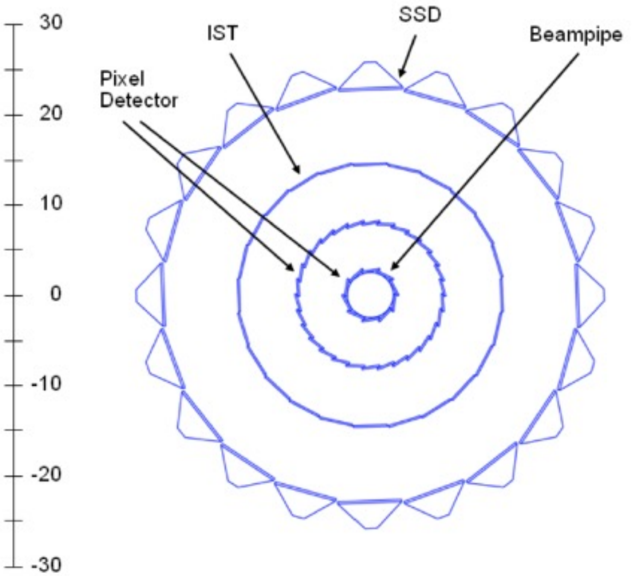
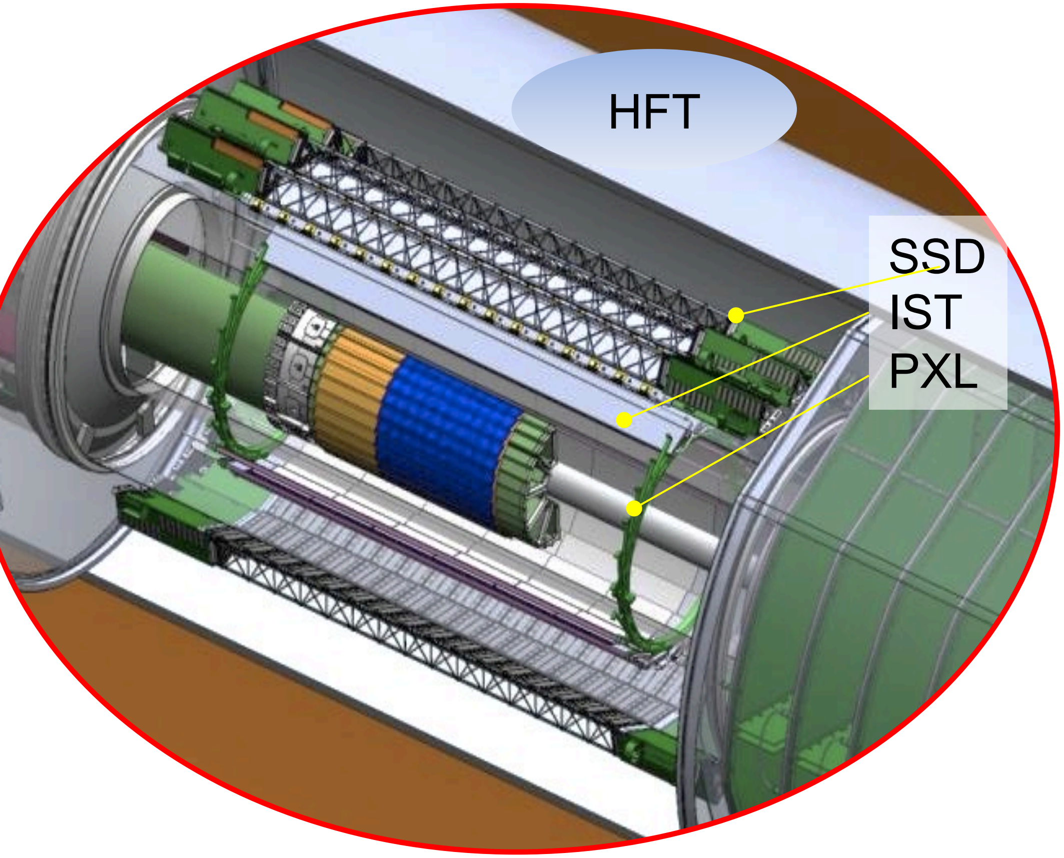


Figure 2.8 A schematic view of the Silicon detectors that surround the beam pipe.

Heavy Flavor Tracker (HFT)



Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Radiation length
SSD	22	20 / 740	1% X_0
IST	14	170 / 1800	<1.5 %X_0
PIXEL	8	12/ 12	~0.4 %X_0
	2.5	12 / 12	~0.4% X_0

PIXEL

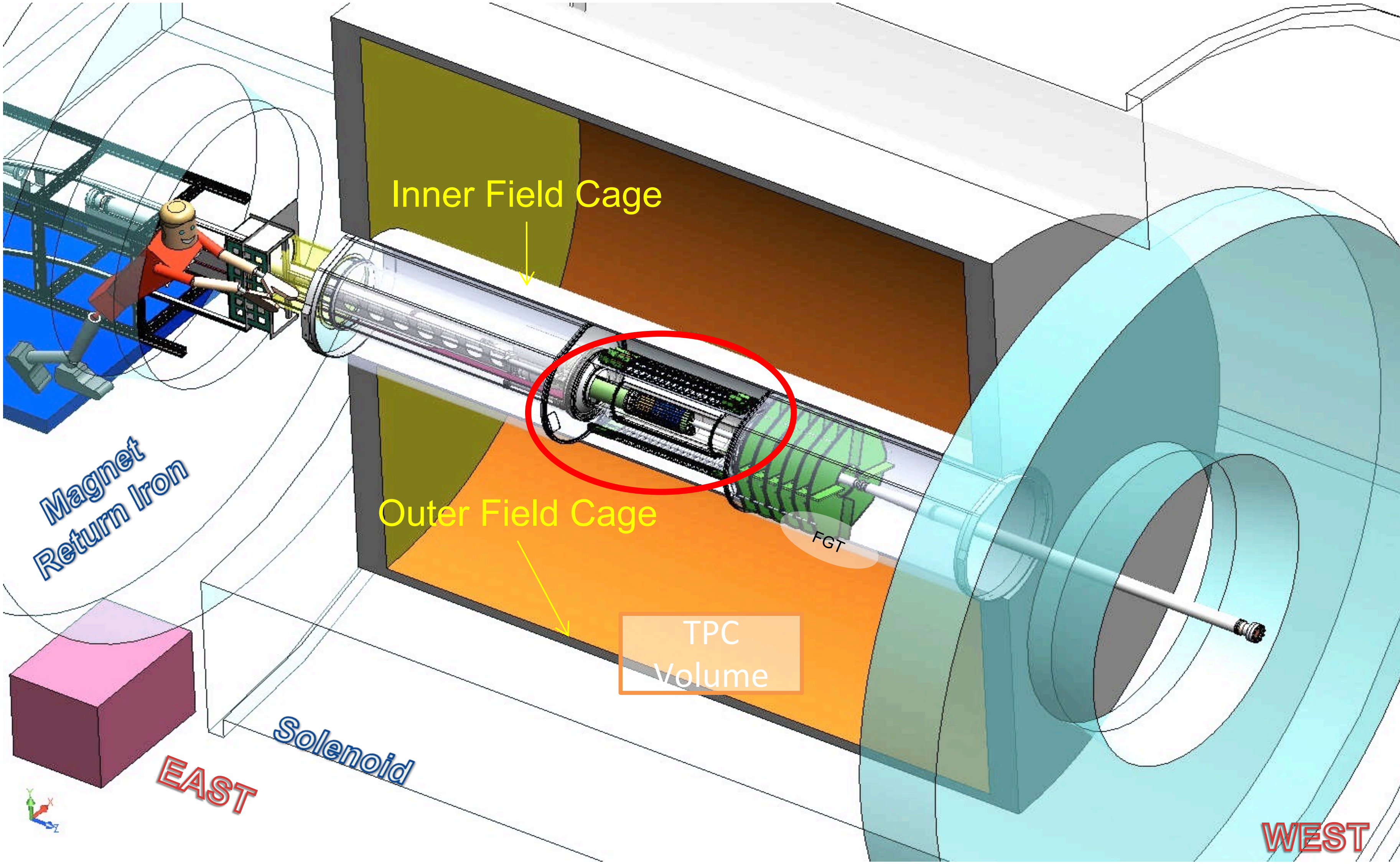
- two layers
- 18.4x18.4 μm pixel pitch
- 10 sectors, delivering ultimate Pointing resolution that allows for direct topological identification of charm.
- Monolithic active pixel sensors (MAPS) technology

SSD

- Existing single layer detector, double side strips (electronic upgrade)

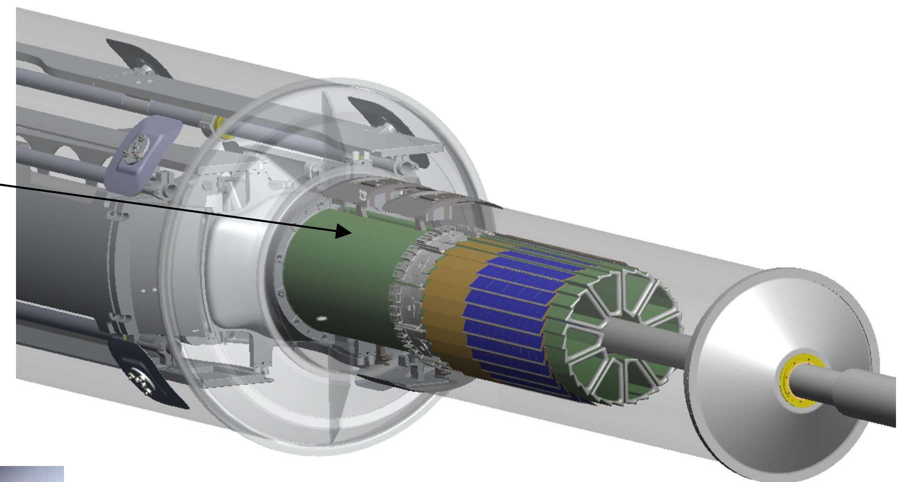
IST One layer of silicon strips along the beam direction (r-ϕ) , guiding tracks from the SSD to PIXEL detector.

Heavy Flavor Tracker (HFT)

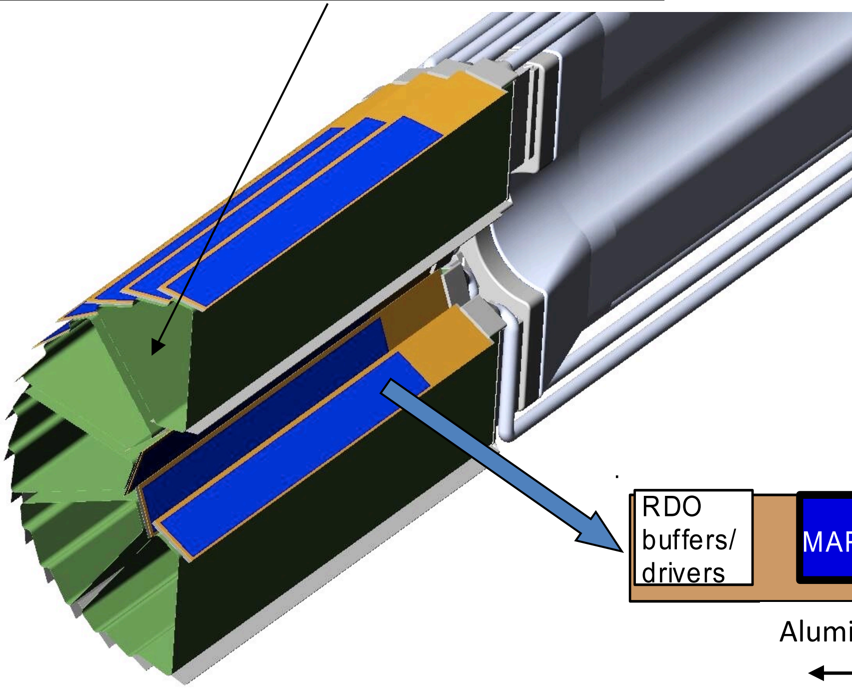


PXL Detector Mechanical Design

Mechanical support with kinematic mounts (insertion side)

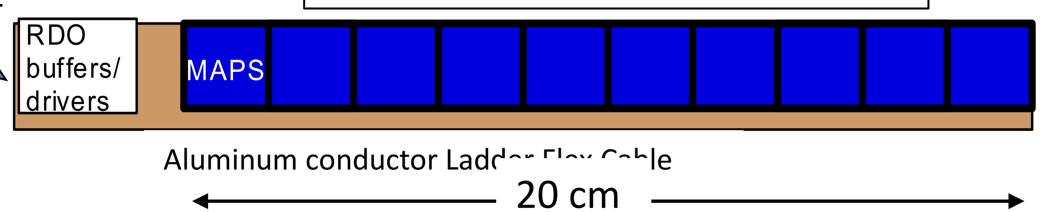


carbon fibre sector tubes (~ 200µm thick)



Insertion from one side
2 layers
5 sectors / half (10 sectors total)
4 ladders / sector

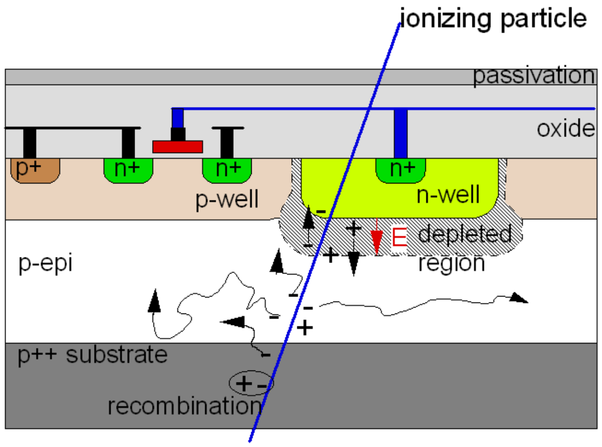
Ladder with 10 MAPS sensors (~ 2×2 cm each)



PXL Sensor

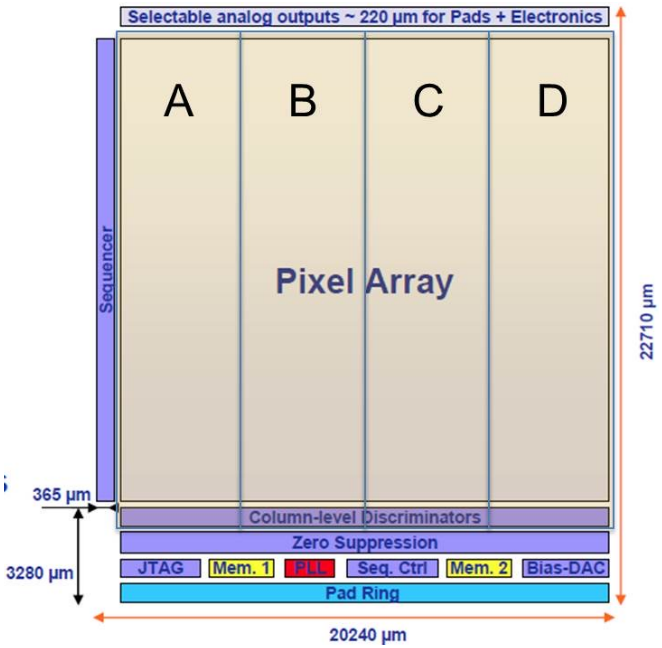
Monolithic Active Pixel Sensor technology

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



- High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness
    - 20 to 90 kRad / year - $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
- 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
- Configurable via JTAG
- 2 LVDS data outputs @ 160 MHz



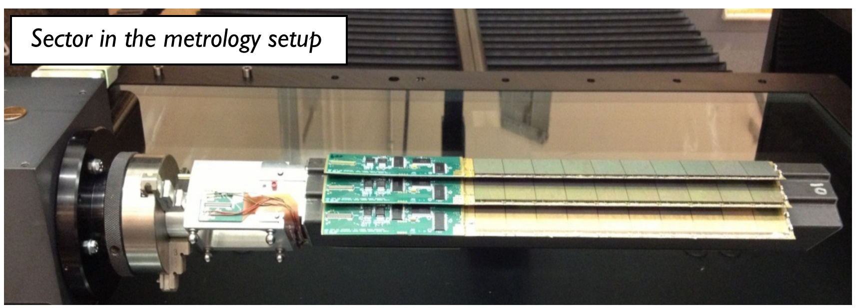
PXL Hit Position Resolution

- *Ultimate-2* sensor geometry
  - pixel size: 20.7 μm X 20.7 μm ~6 μm geometrical resolution
  - 3-pixel av. cluster size ~3.7 μm resolution on center-of-mass
- Position stability
  - Vibration at air cooling full flow: ~5 μm RMS
  - *Stable displacement at full air flow: ~30 μm*
  - *Stable displacement at power on: ~5 μm*
- **Global hit resolution: Δx ~ 6.2 μm**

Δx ~ 6.2 μm
r_1 = 2.8 cm
r_2 = 8 cm

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

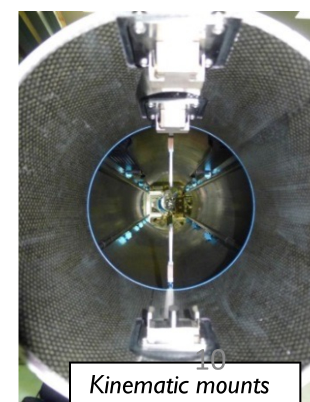
HFT DCA pointing resolution:
(10 ⊕ 24/p) μm

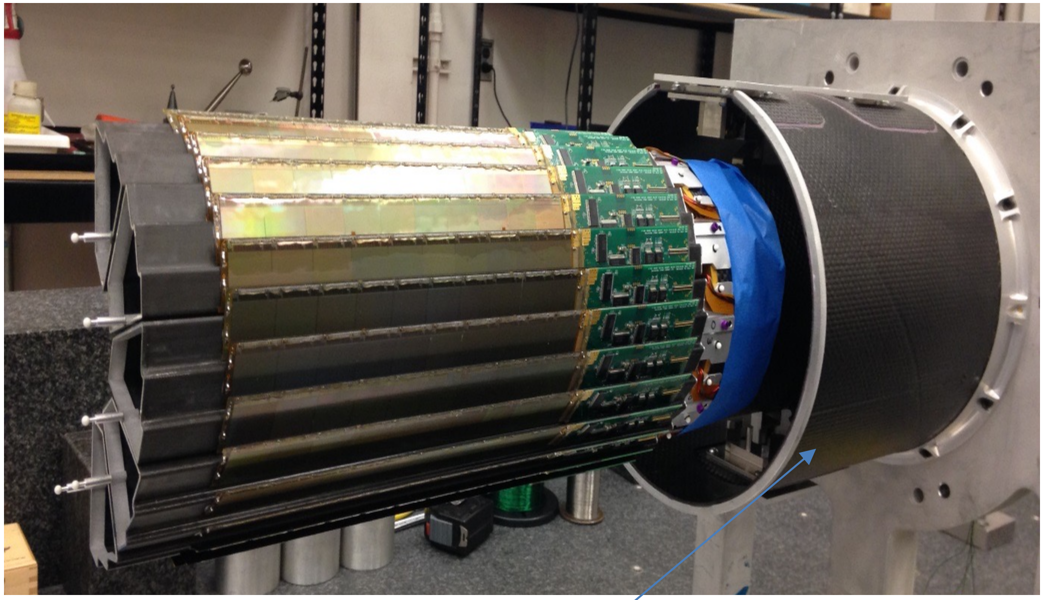

Sector in the metrology setup

- Metrology survey
  - 3D pixel positions fully mapped and related to kinematic mounts

- 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 insertion


Kinematic mounts

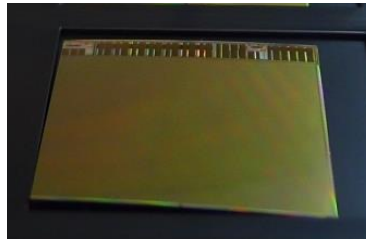


duplicate, truncated PXL support tube with kinematic mounts

- After assembling sectors in a half shell sector tooling balls measured with touch probe relative to kinematic mount coordinate frame
- Since the shells are supported the same way in the CMM and in the STAR installation the relative pixel position mapping is not disturbed

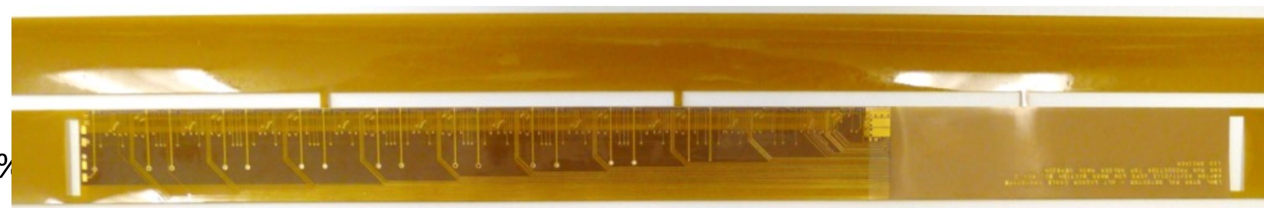
PXL Material Budget

- Thinned Sensor
  - 50 μm
  - 0.068% X_0



- Curved sensor
- 40-60% yield after thinning, dicing and probe testing

- Flex Cable
  - Aluminum-Kapton
  - two 32 μm-thick Al layers
  - 0.128% X_0
    - *Copper* version → 0.232%



- Carbon fiber supports
  - 125 μm stiffener
  - 250 μm sector tube
  - 0.193% X_0

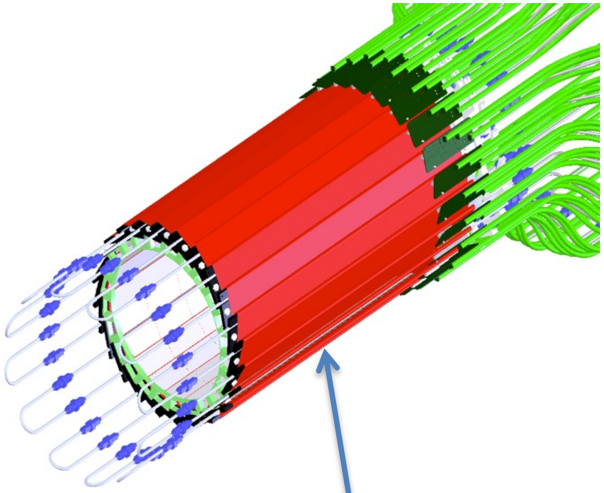
- Cooling
  - Air cooling: negligible contribution

- **Total material budget on inner layer: 0.388% X_0**

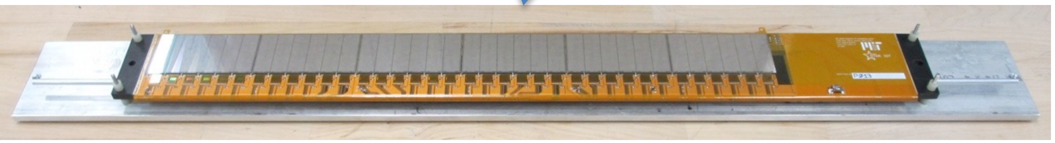
(0.492% X_0 for the Cu conductor version)

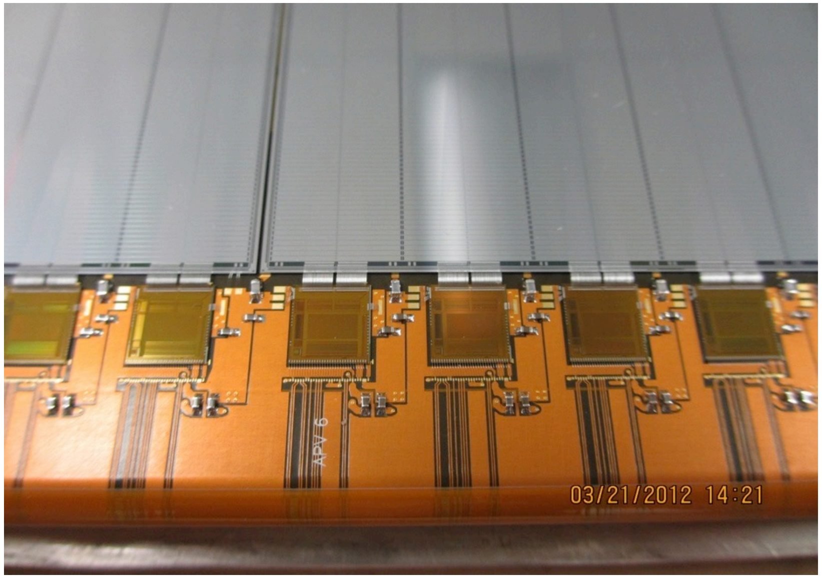
HFT DCA pointing resolution:
(10 ⊕ 24/p) μm

Intermediate Si Tracker



24 ladders, liquid cooling

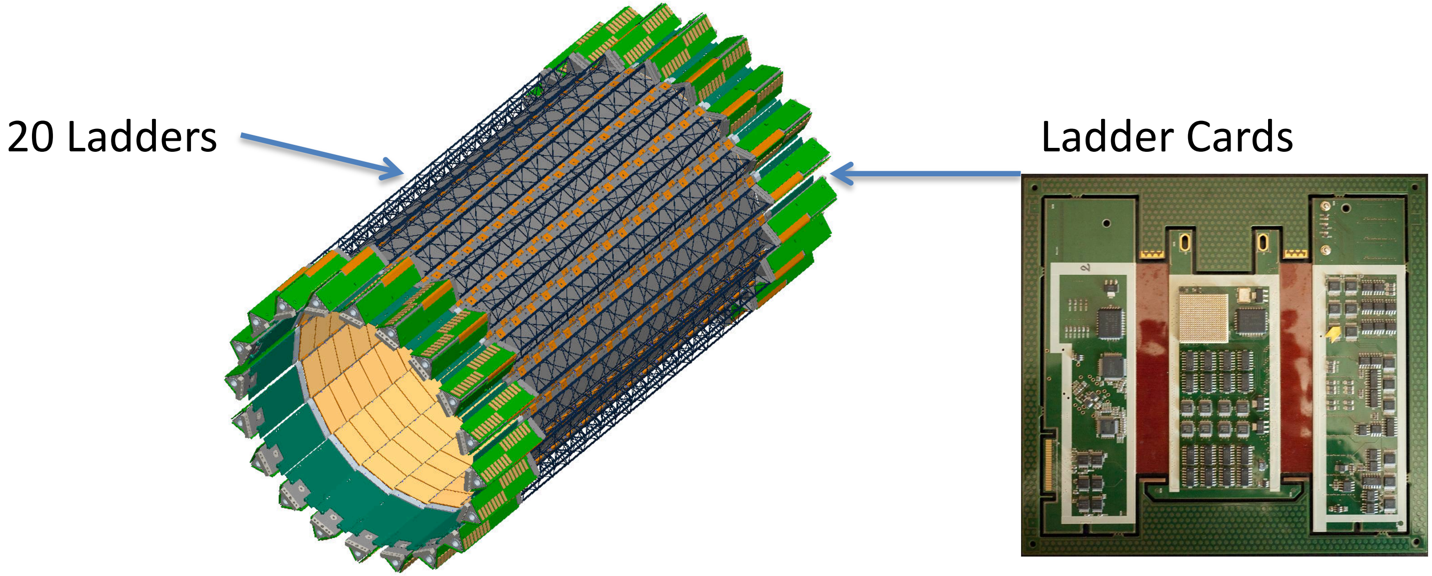




Details of wire bonding

Prototype Ladder
S:N > 20:1
>99.9% live and functioning channels

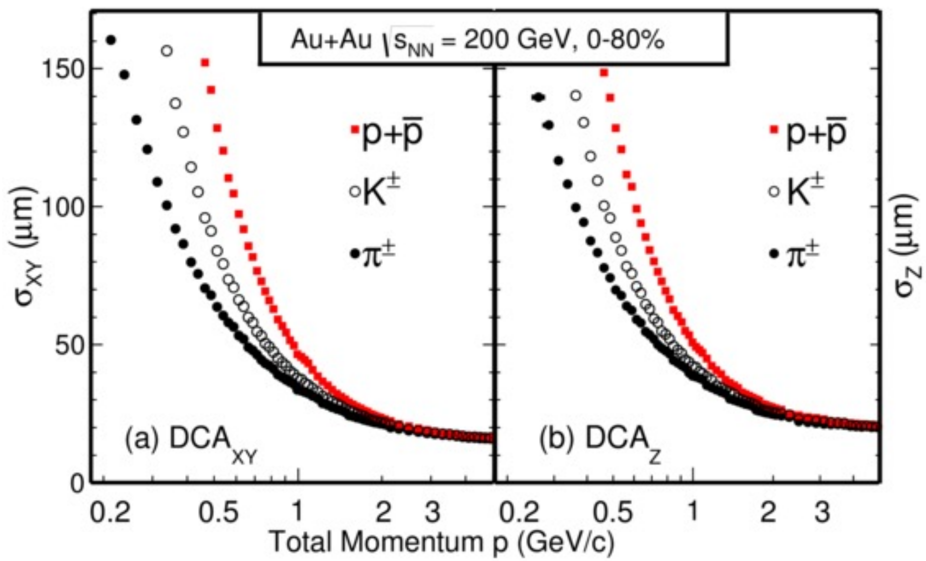
Silicon Strip Detector (SSD)

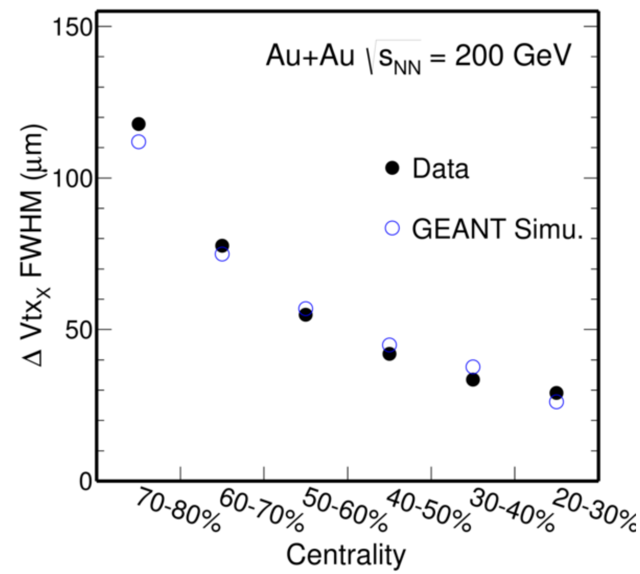


- The ladders and Si-sensors was from existing detector
- Upgrade readout system with new ladder cards on detector, RDO cards, and cooling system

HFT performance

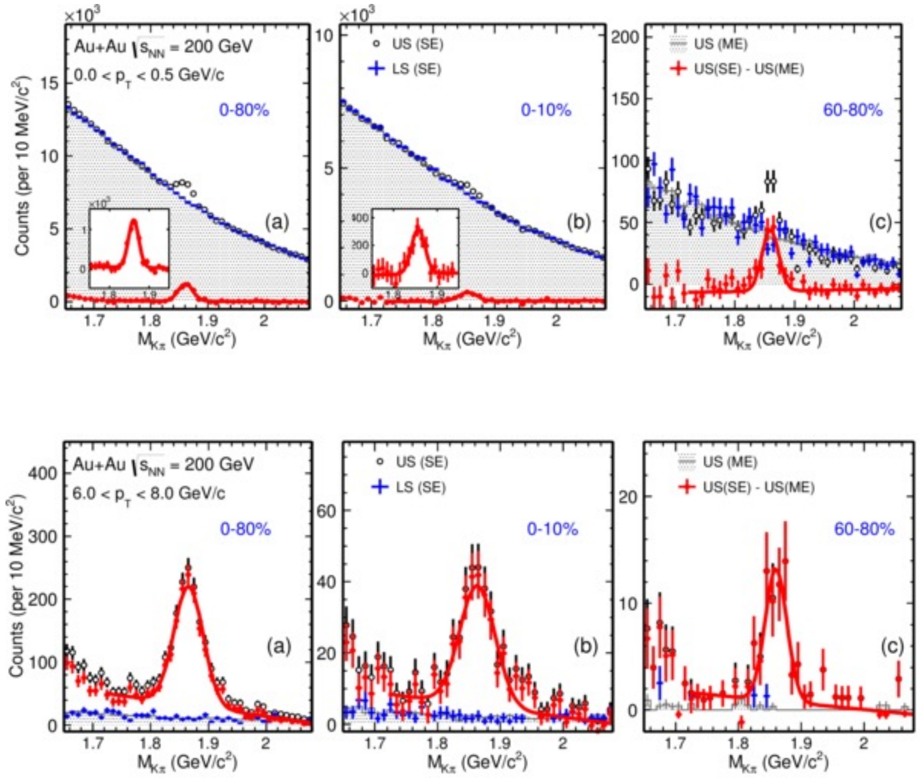
- Pointing resolution was determined in Au+Au collisions at 200 GeV in transverse plane and longitudinal. Measurements are in agreement with expectations.
- Important also to take into account the vertex resolution vs. centrality, particular for the most peripheral collisions





D^0 spectra

- We have achieved very good significance for D^0
- Low p_T is difficult due to the pileup and miss matched hit points



Timeline

- R&D 2003- LBL with IHPC, Strasbourg for MAPS sensors
- 2008 Project start ; 2010-2014 construction
- 2013 Commissioning run
- 2014-16 Physics
  - 14: AuAu
  - 15: pp
  - 16: AuAu dAu
- 2017 Removed from STAR and in storage

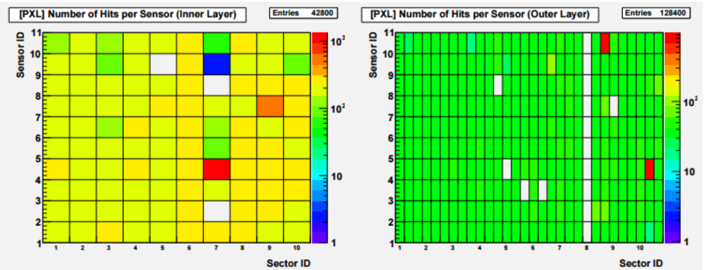
More questions?

HFT Status in 2014 - 2016 Run

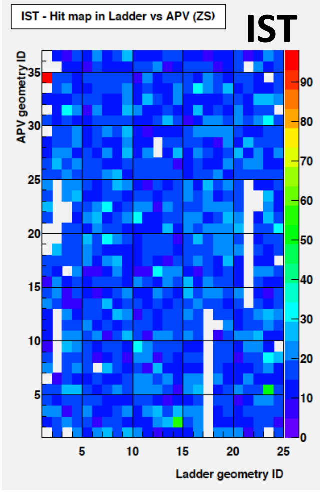
- Typical trigger rate of ~0.8kHz with dead time <5%
- Limit interaction rate due to 186microsec pileup

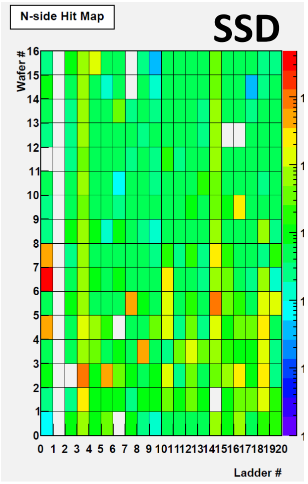
- Sub-detector active fraction
  - PXL
    - > 99% operational at the delivery
    - 2015 Run ended with 5% dead sensors damaged sensors + 1 outer ladder off)
  - IST
    - 95% channels operational, stable
  - SSD
    - 80% channels operational (one ladder off)

PXL1



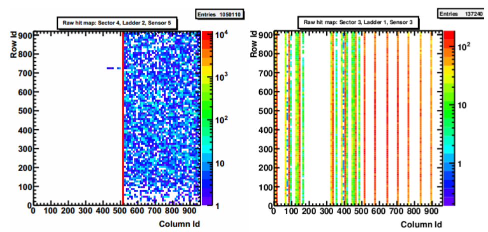
PXL2



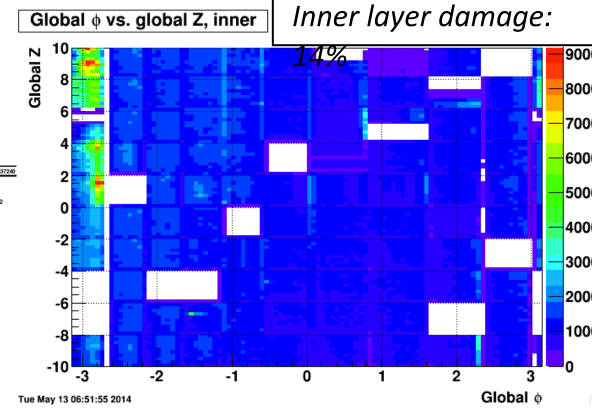


Lessons learned: Latch-up damage on PXL

- 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

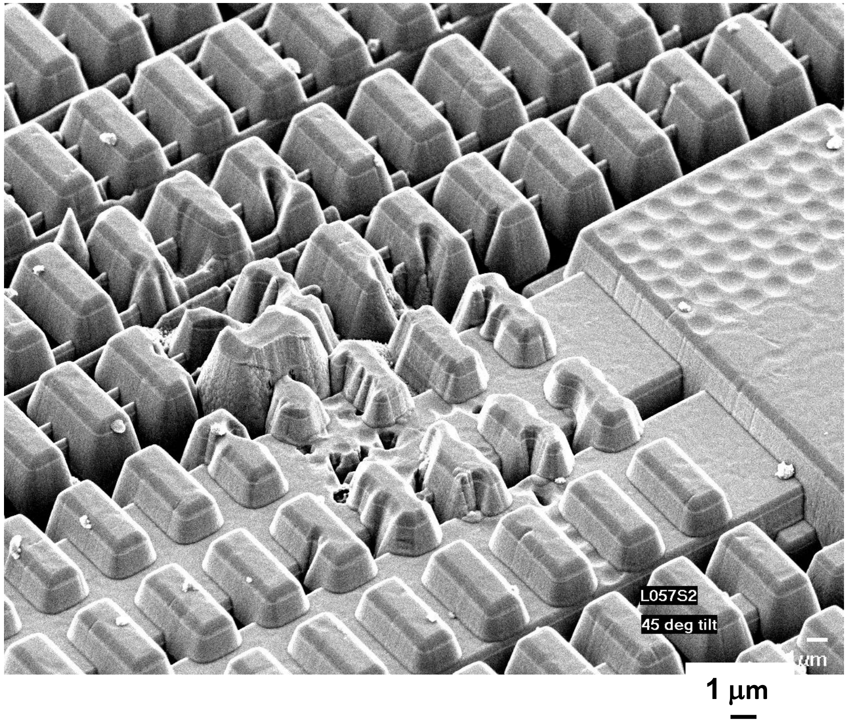
Info on PXL detector mechanics and construction

- NIM Article
  - arXiv 1710.02176
  - NIM A97(2018) 60
- Howard Wieman
  - HFT PXL mechanics
  - Forum on Tracking Detector Mechanics
  - 30 June-2 July 2014 at DESY, Hamburg
  - https://indico.cern.ch/event/287285/contributions/1640694/attachments/534386/736809/PXL_mechanics.pdf

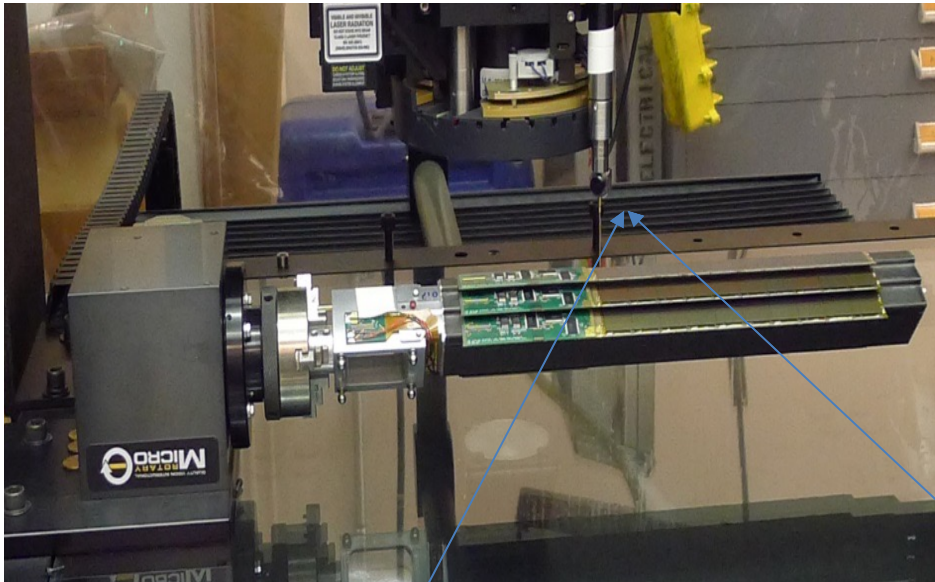
Latch-up damage: Sensor Deconstruction

- 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



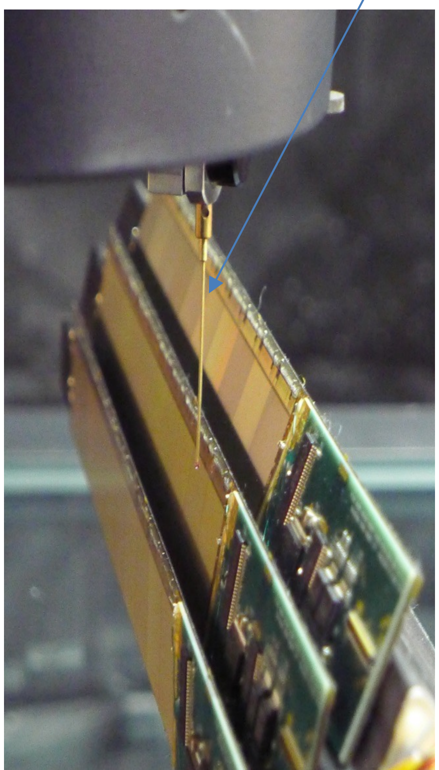
Spatial mapping of the pixels

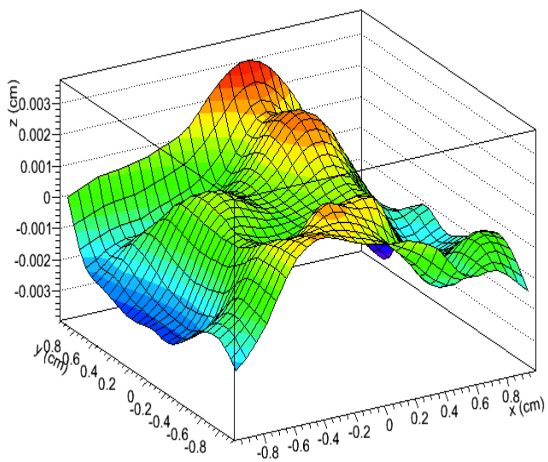


Pixel locations determined with CMM equipment to within 10 μm prior to installation in STAR

Programmed CMM Measurement method#:

- All pixels located on a sector with respect to 3 sector tooling balls
  - 2 Lithography points on the chips measured with optical head
  - Chip surface profile measured with 11 x 11 point pattern using a Feather Probe*. Using a touch probe permits picking up over hung surfaces

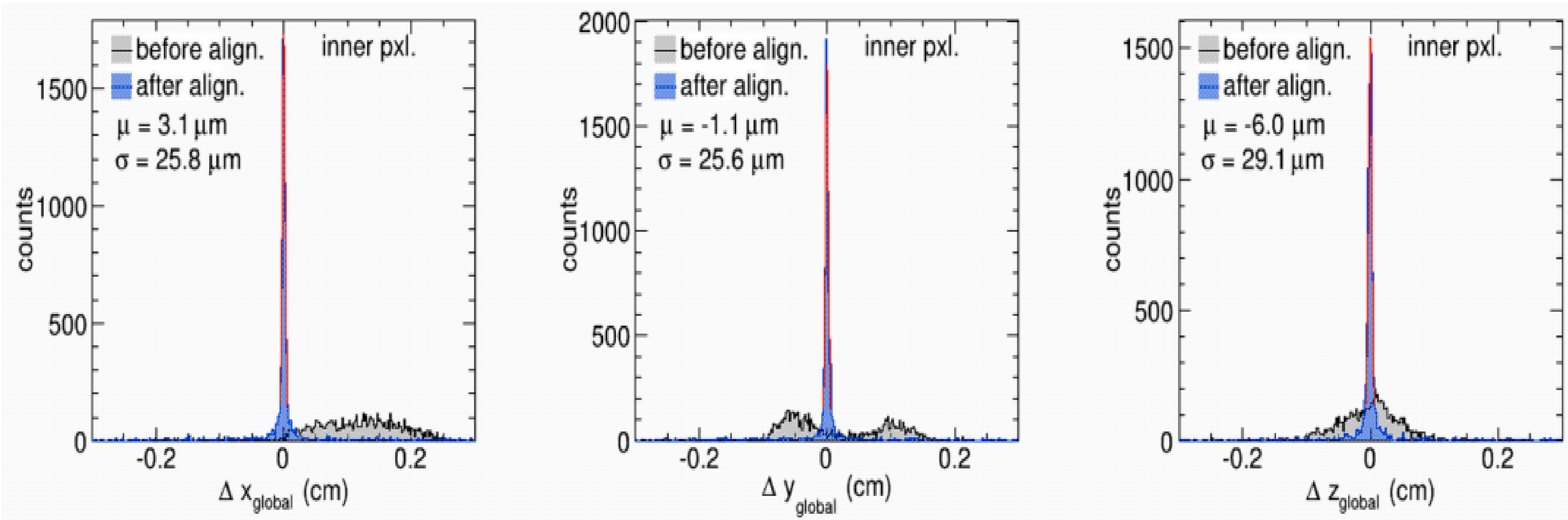


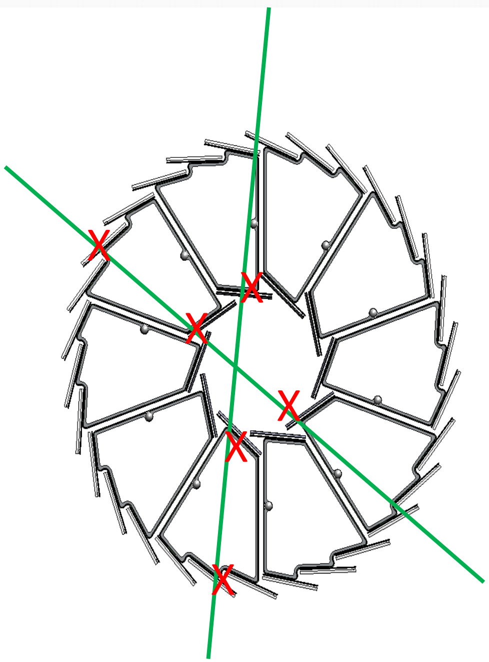


Full sector measurement takes ~ 8 hours

PXL sensor surface profile from survey:
± 30 μm > PXL hit error,
and the chip to chip surface deviation along the ladder surface is still larger,
but all of this is then corrected with the spatial map
Parametriuzed by 5*5 spline fct

Final operating pointing performance in STAR



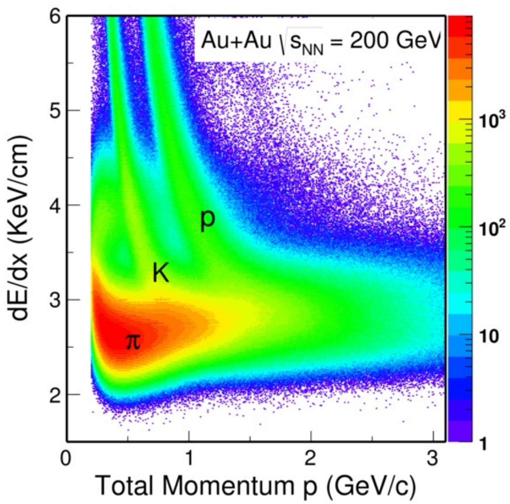


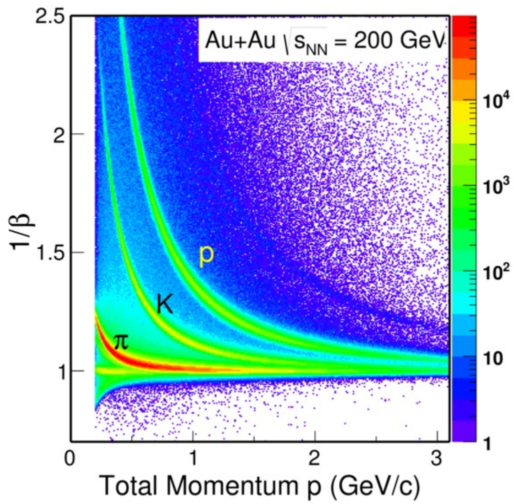
Cosmic ray result
Excellent half to half pointing, sub 30 μm
But after half to half alignment which was required to correct poor reproducibility of kinematic mount seating

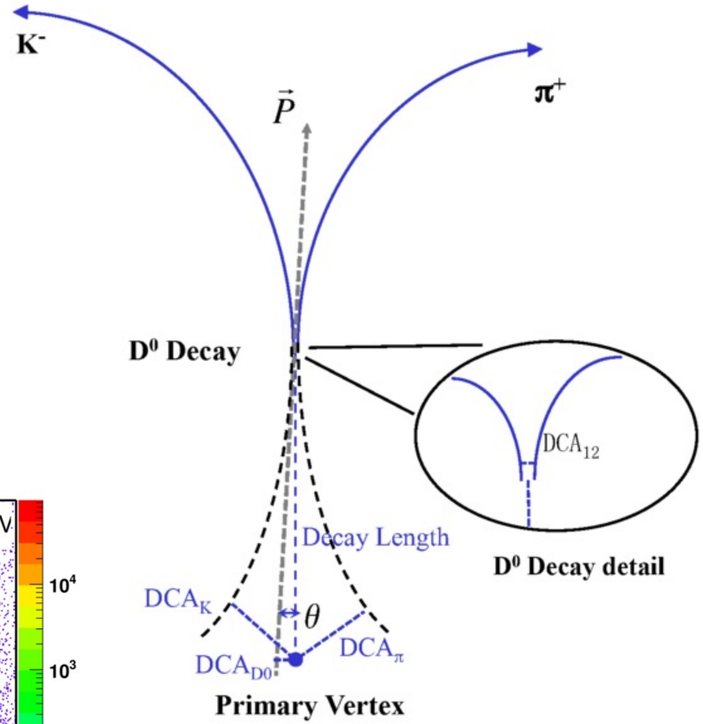
Check alignment with very low luminosity AuAu also

D^0 reconstruction

- Use topological variables
- Use particle ID

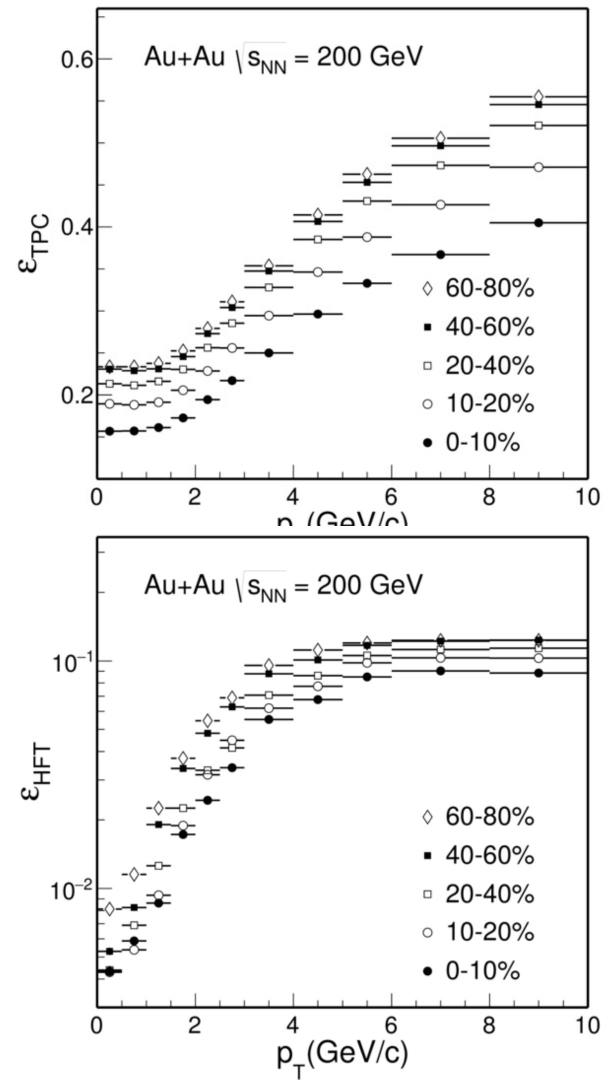




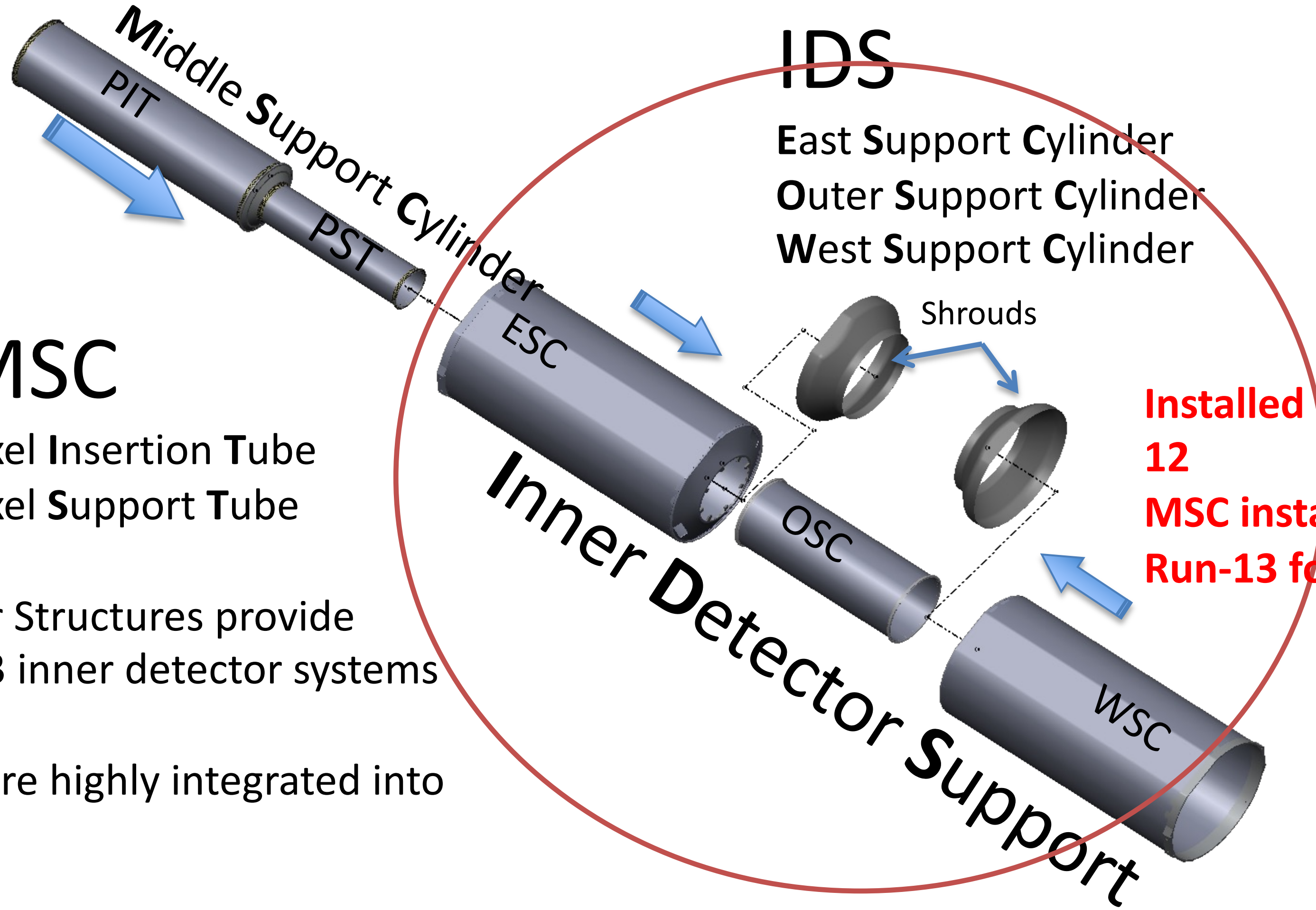


Some words on efficiency

- We have applied two methods to evaluate efficiencies
- Fast simulation data driven to replicate multi dimensional basic observables
- Geant embedding with displaced geometries
- Methods agrees well



Inner Detector Support (IDS)



IDS

East **S**upport **C**ylinder
Outer **S**upport **C**ylinder
West **S**upport **C**ylinder

Installed for Run-12
MSC installed for Run-13 for PXL

MSC

Pixel **I**nsertion **T**ube
Pixel **S**upport **T**ube

Carbon Fiber Structures provide support for 3 inner detector systems and FGT.
All systems are highly integrated into IDS.

Physics of the Heavy Flavor Tracker at STAR

- Direct HF hadron measurements (p+p and Au+Au)

  (1) Heavy-quark cross sections: $D^{0\pm*}$, D_S, Λ_C , B, …

  (2) Both spectra (R_{AA}, R_{CP}) and v_2 in a wide p_T region: 0.5 - 10 GeV/c

  (3) Charm hadron correlation functions, heavy flavor jets

  (4) Full spectrum of the heavy quark hadron decay electrons
- Physics

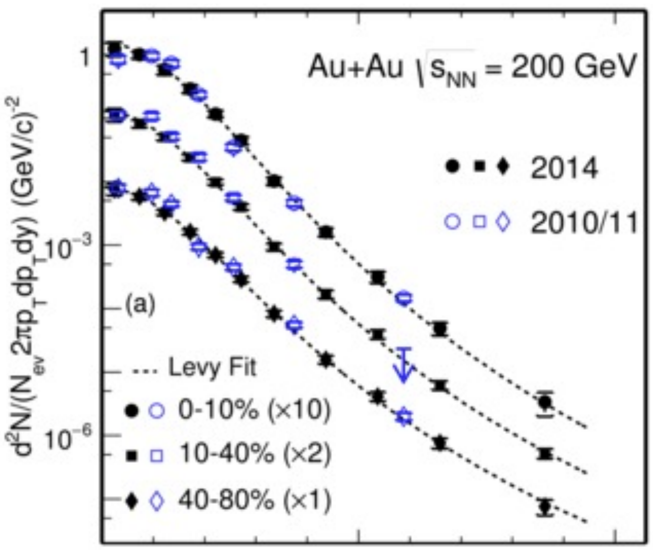
  (1) Measure heavy-quark hadron v_2, heavy-quark collectivity, to study the medium properties e.g. light-quark thermalization

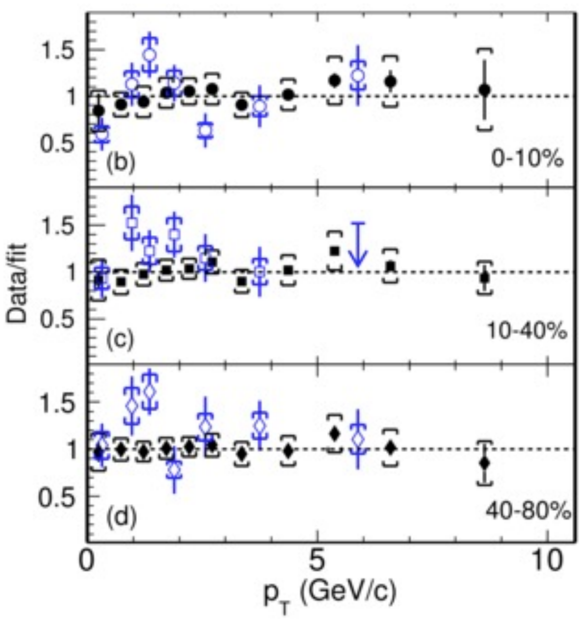
  (2) Measure heavy-quark energy loss to study pQCD in hot/dense medium e.g. energy loss mechanism

  (3) Analyze hadro-chemistry including heavy flavors

D^0 spectra

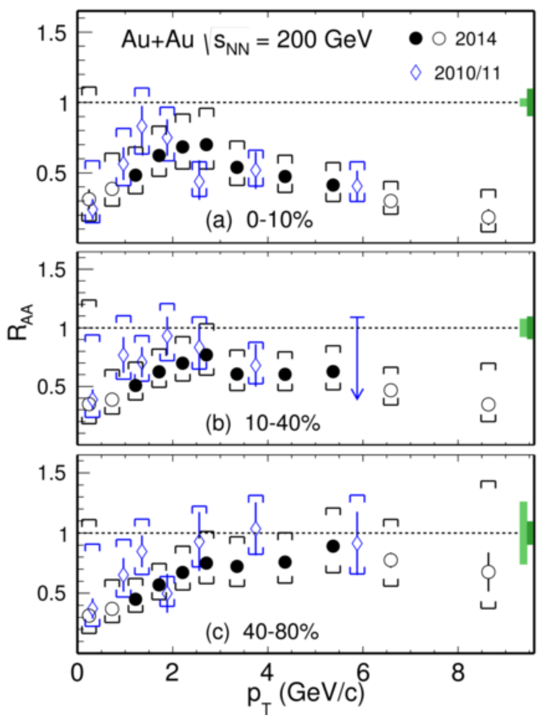
- Precise measurements extends to low p_T and non-central collisions. Data from 2014
- Results consistent with 2010/11 TPC only analysis
- Data from submitted paper: arXiv 1812.10224

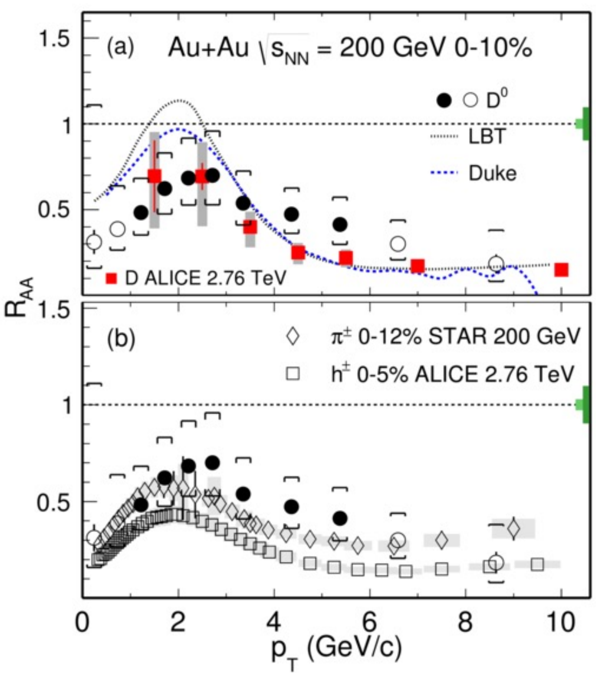




D^0 R_{AA}

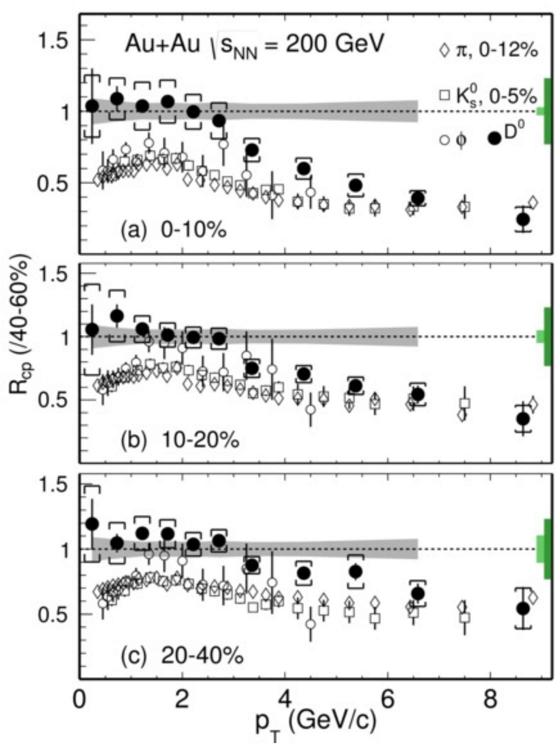
- $R_{AA} < 1$ for 0-10% for all p_T
- Suppression at high p_T increases for more central collisions
- Same trends as at LHC and for light mesons

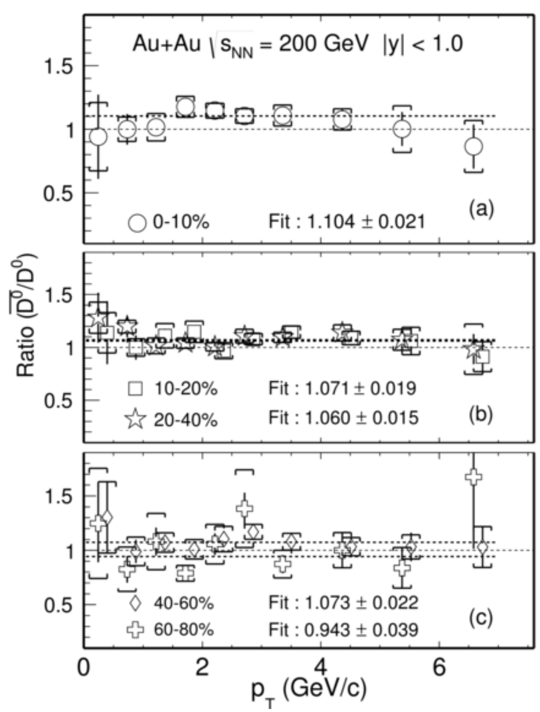




D^0 R_{CP}

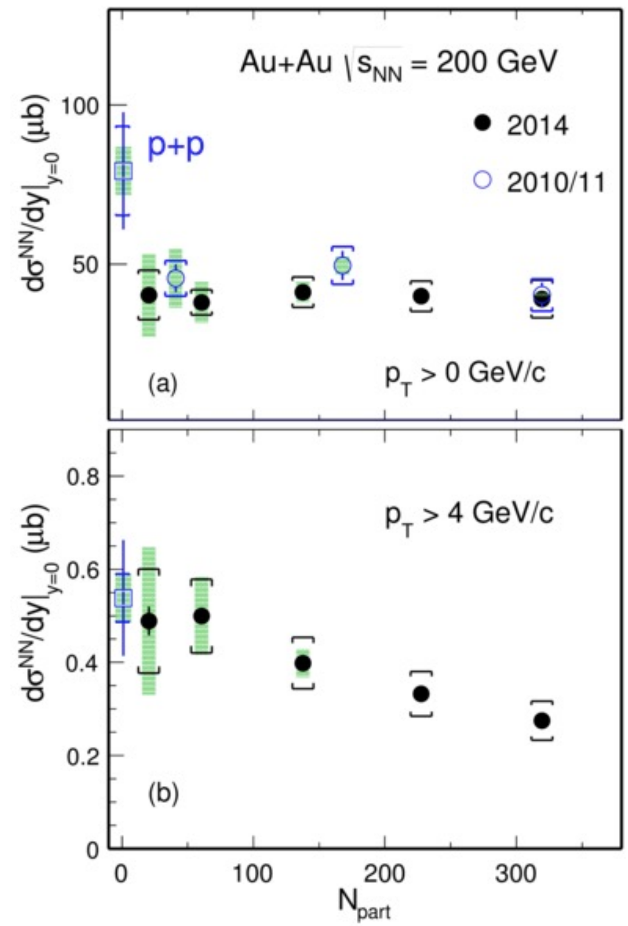
- Significant suppression at high p_T
- Matches theoretical calculations
- D^0-bar/D^0 slightly greater than one
  - Possible due to slight baryon asymmetry at RHIC





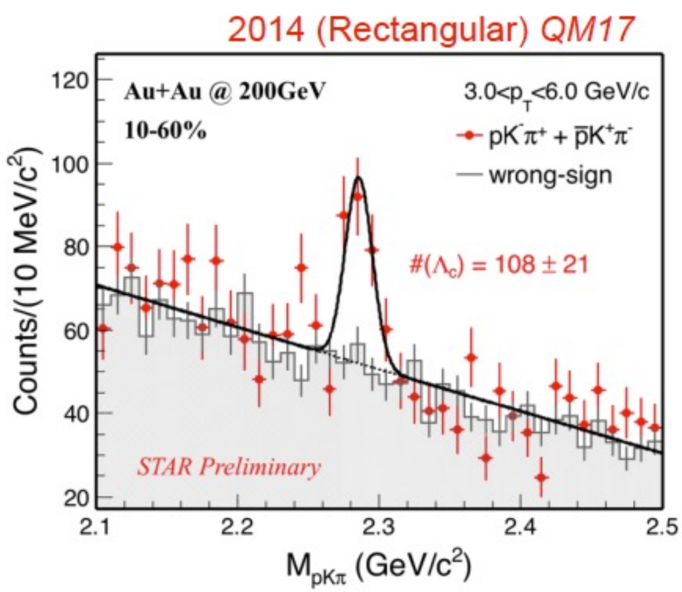
D^0 cross section

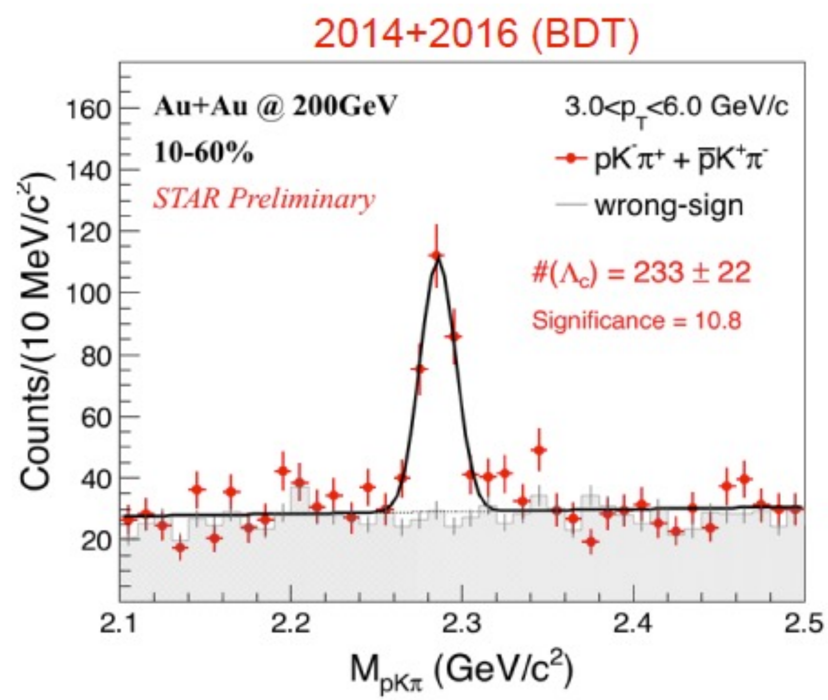
- Total D^0 cross section is nearly independent of centrality, and smaller than in *p+p*. For p_T > 4 GeV/c it decreases with centrality



Λ_c reconstruction

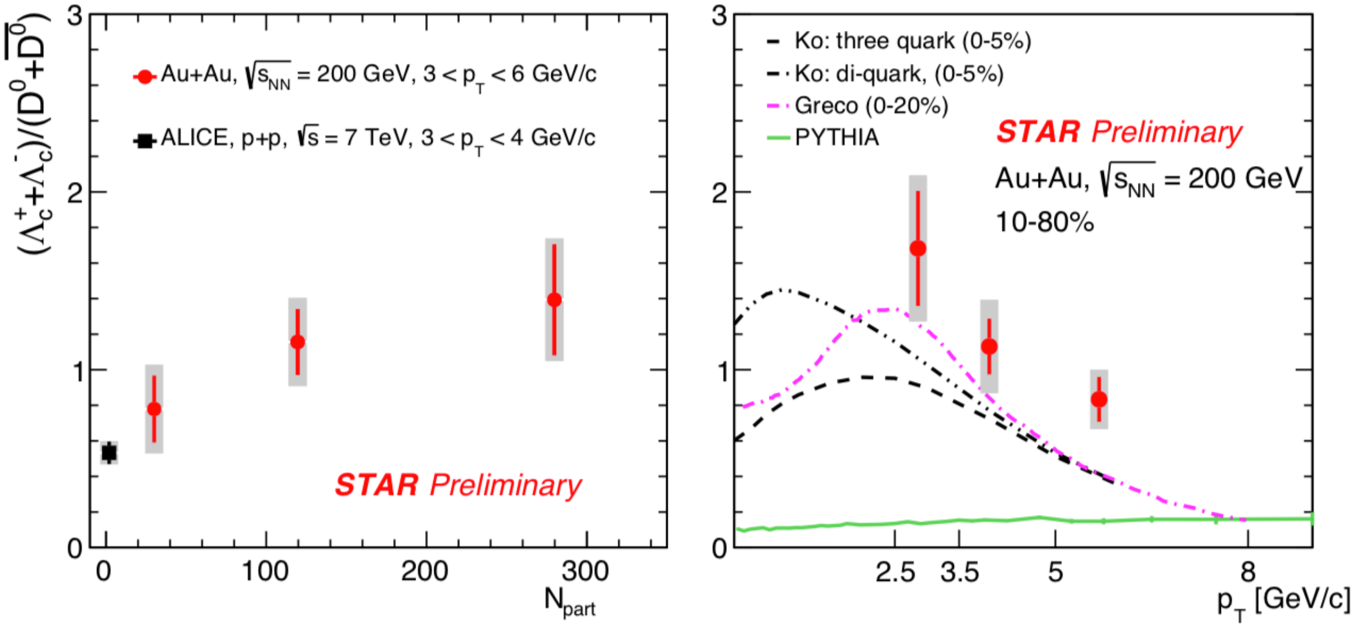
- More than 50% improvement in signal significance with TMVA methods
- Includes 2016 dataset





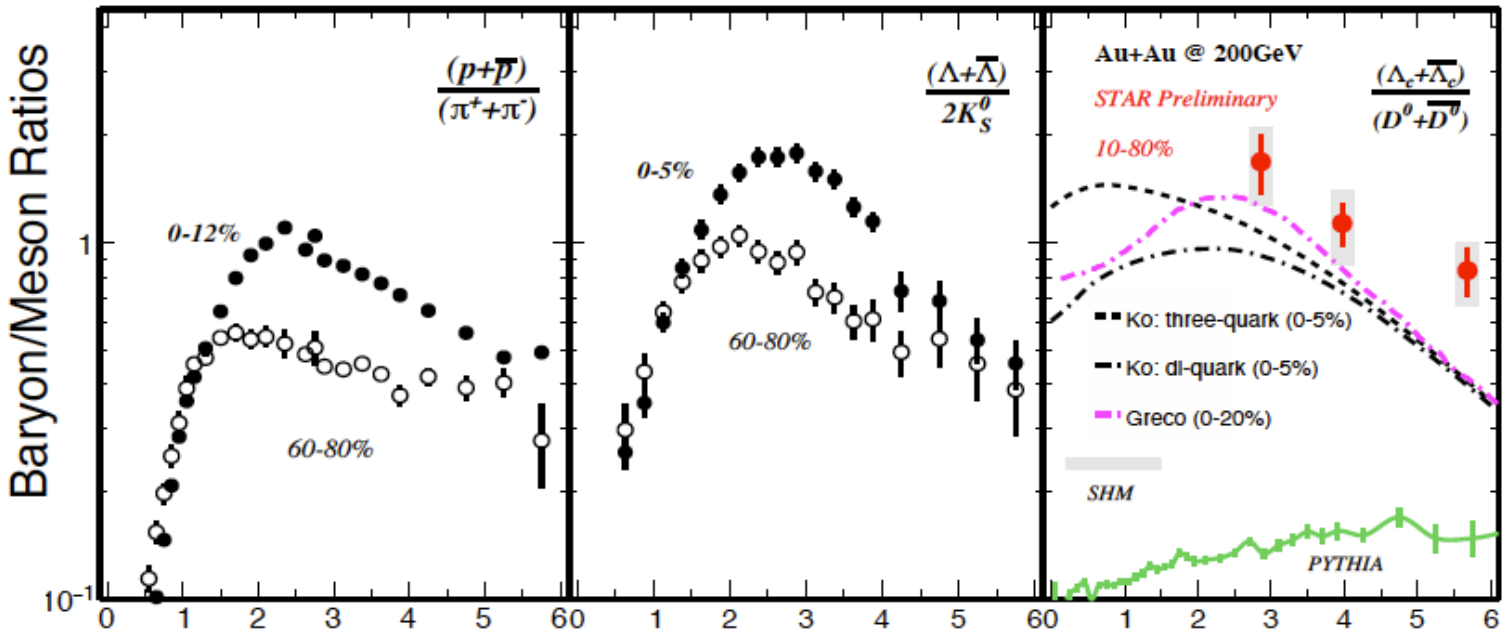
Λ_c/D^0 centrality dependence

- Λ_c enhancement increases towards more central Au+Au collisions
- Large contribution to total charm cross sections in HI



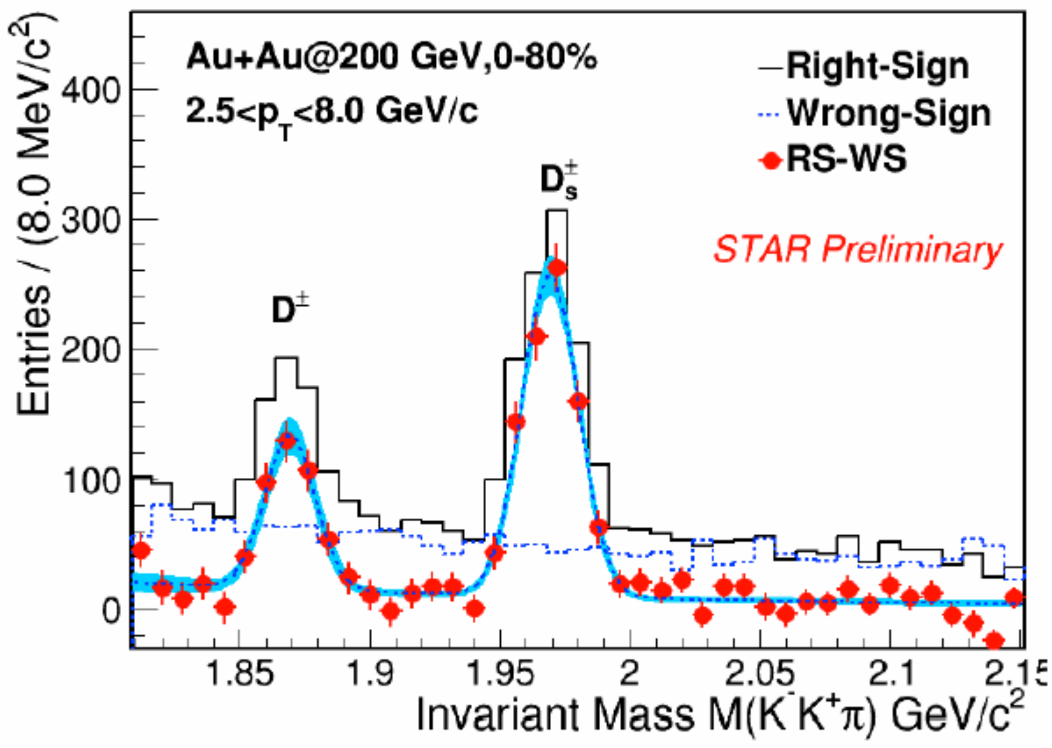
Λ_c/D^0 p_T dependence

- Significant enhancement of Λ_c/D^0 compared to p+p.
- Comparable with light flavor B-to-M ratios
- Consistent with charm quark hadronization via coalescence



Strange Charmed quarks

- Reconstruct $D_s^{\pm}$ via $D_s^{\pm} \rightarrow \phi(1020) + \pi^{\pm} \rightarrow K^+K^-\pi^{\pm}$ decay channel
- Reconstruct $D^{\pm}$ via $D^{\pm} \rightarrow \phi(1020) + \pi^{\pm} \rightarrow K^+K^-\pi^{\pm}$ decay channel



Total charm cross section

- D^0 yields measured down to p_T=0 GeV/c
- For D^{+-}, D_s Levy fits to measured spectra for extrapolation
- For Λ_c three model fits to data are used and included in systematics

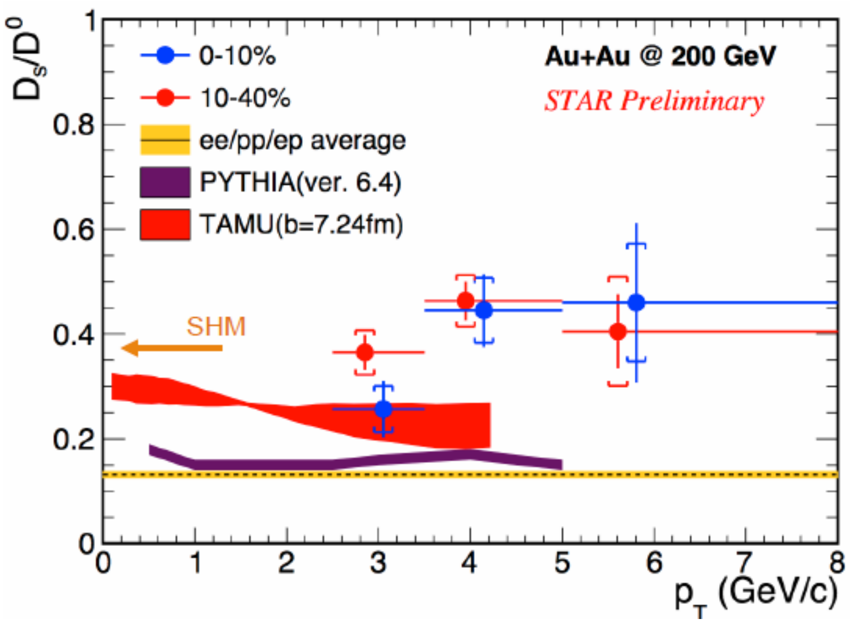
Charm Hadron		Cross Section dσ/dy (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

Total charm cross section is consistent with p+p values
Redistributed on meson and baryons

D_s, D^0 enhancement

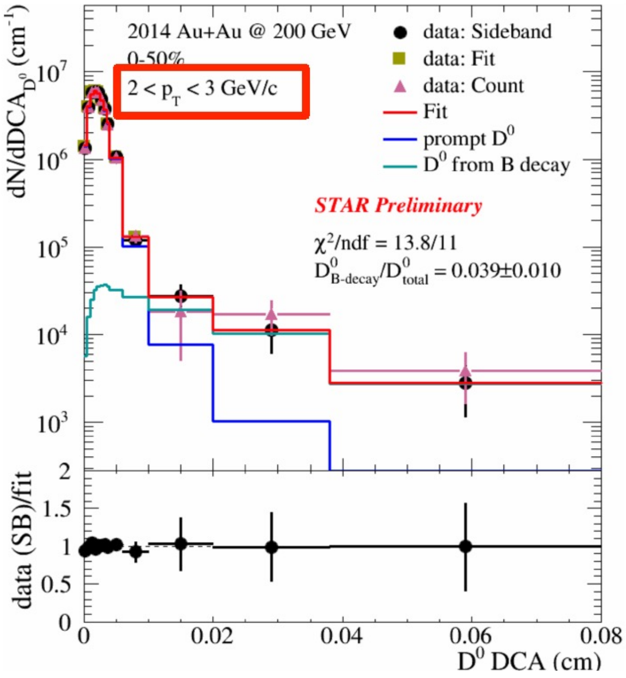
- Strong enhancement of D_s/D^0 observed in central A+A w.r.t fragmentation baseline
- ->Strangeness enhancement and coalescence
- Enhancement larger than model, particular at high p_T

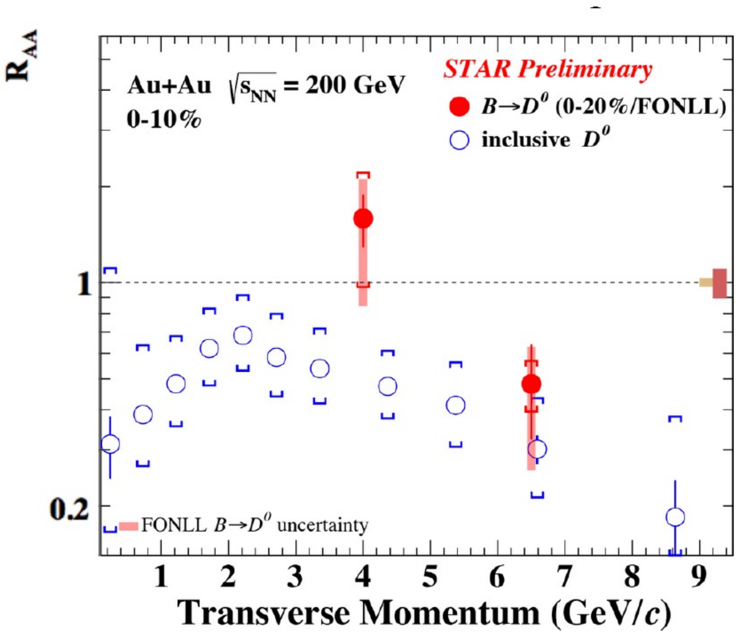


ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, 397 (2016)
TAMU: H. Min et al. PRL 110, 112301 (2013)
SHM: A. Andronic et al., PLB 571 (2003) 36

Non prompt D^0, B-decay

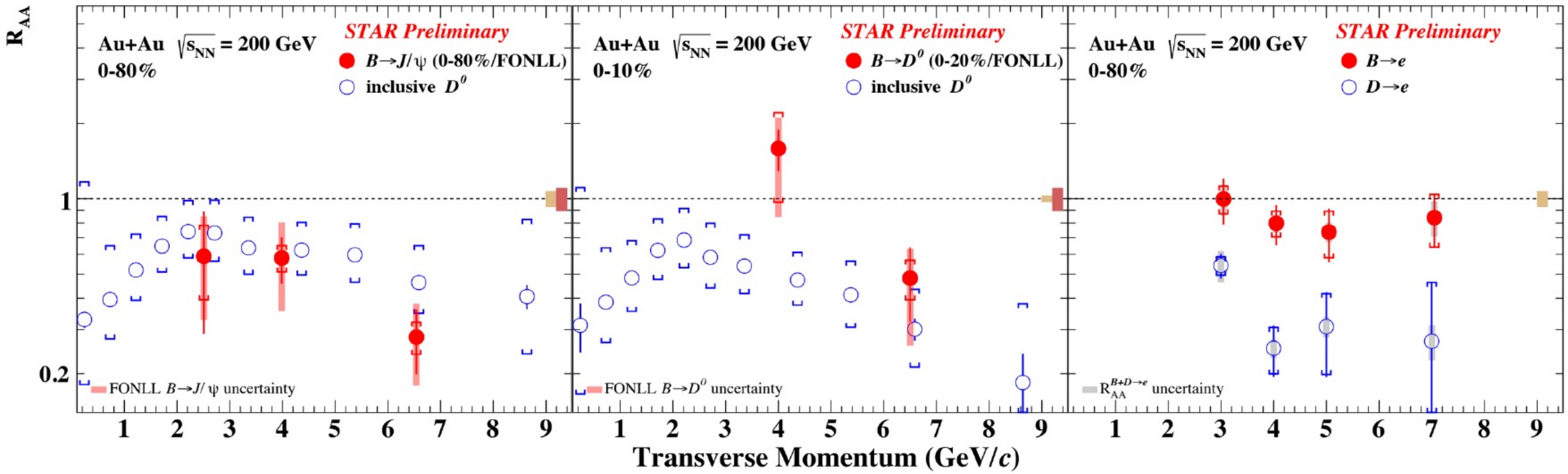
- Strong interaction of charm with the medium.
- What about bottom?
- R_{AA} of non-prompt D^0 extracted.
- Improved signal significance using BDT
- Will get results form combined data set





B study from different channels

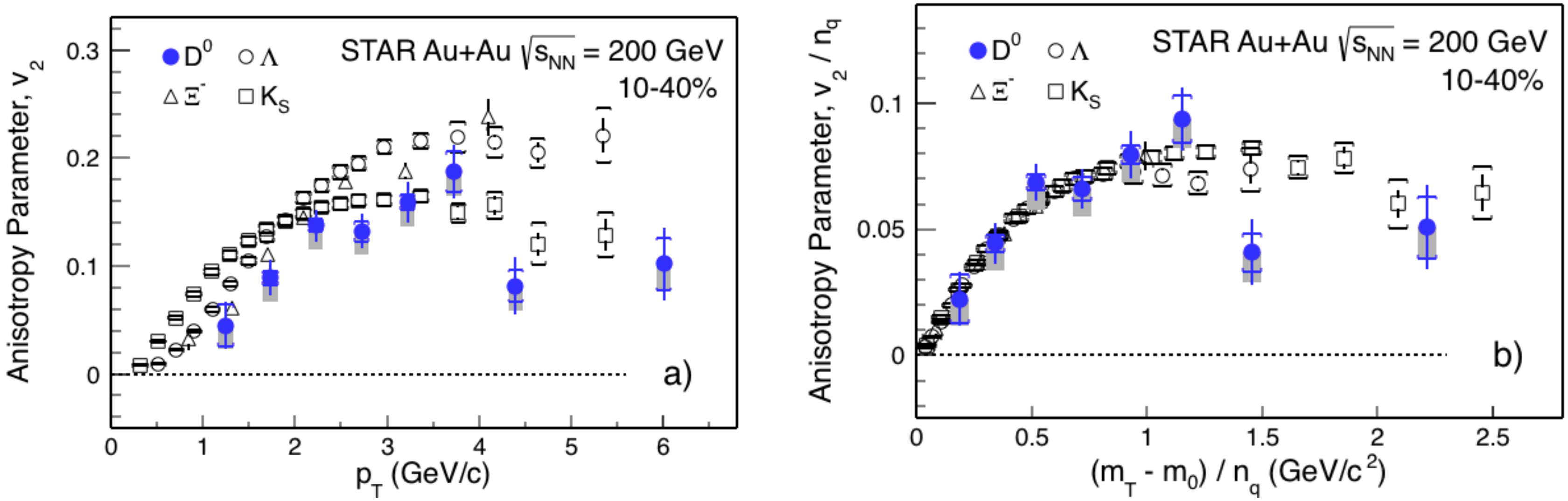
Strong suppression for $B \rightarrow J/\psi$ and D^0 at high p_T.
Indication of less suppression for $B \rightarrow e$ than $D \rightarrow e$ (~2 σ): consistent with $\Delta E_c > \Delta E_b$
Measurements with improved precision are on the way



Note: R_{AA} references (data vs. theory) are different for these comparisons.
The decay kinematics needs to be unfolded for different channels.

D^0 Elliptic Flow

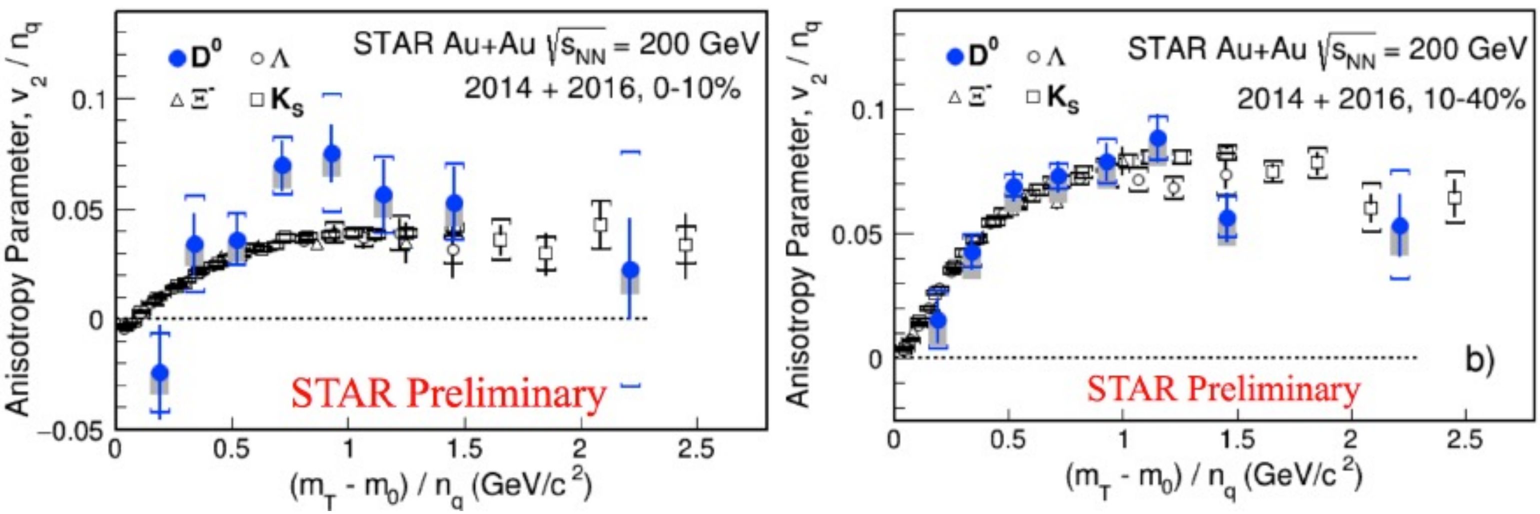
- Published D^0 v_2 from 2014 dataset
- Clear mass ordering for p_T < 2 GeV/c
- Follows NCQ scaling in mid-central (10-40%) collisions



Phys.Rev.Lett 118, 212301 (2017))

D^0 Elliptic Flow

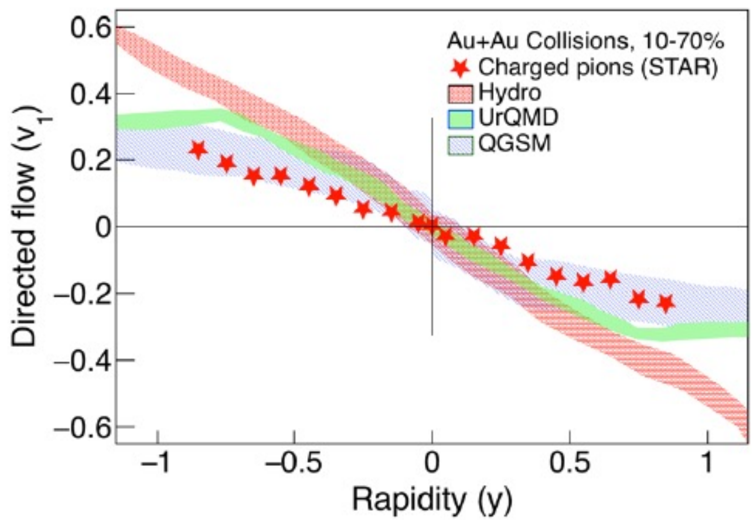
- D^0 v_2 measurements extended to 0-10% centrality with combined 2014 and 2016 data set
- Significant flow observed

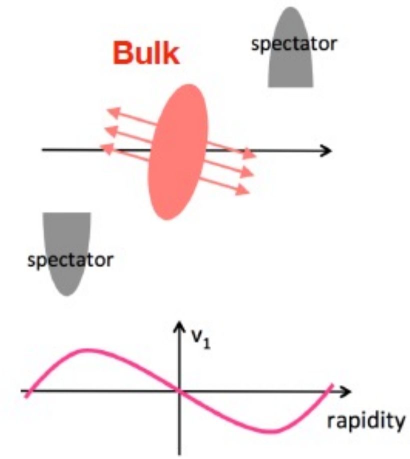


Directed flow in heavy-ion collisions

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}[1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos 2(\phi - \Psi_R) + ...]$$

Directed flow $v_1 \sim \langle\cos(\varphi - \Psi_R)\rangle$

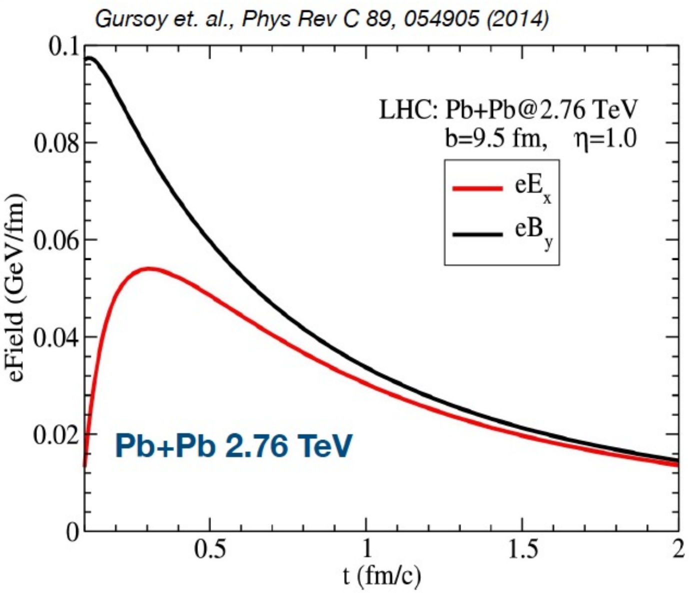


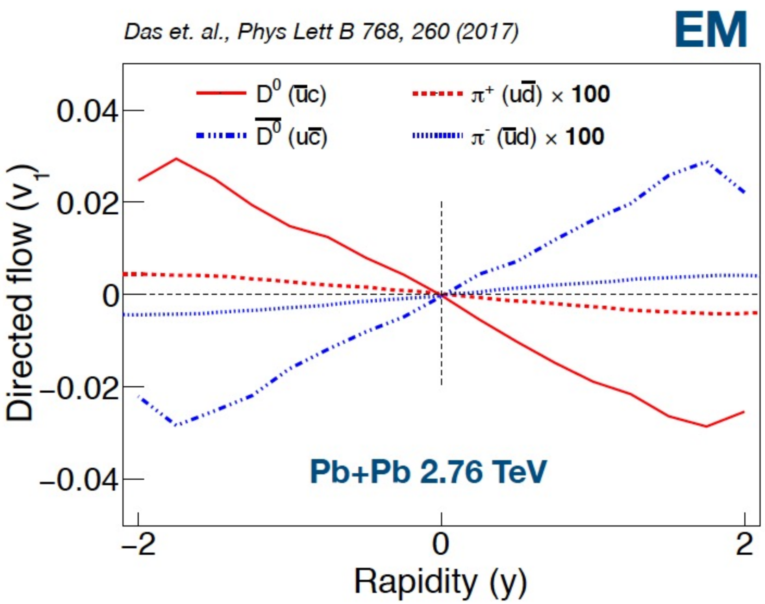


L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 108, 202301 (2012)
Hydro: P. Bozek, I. Wyskiel, Phys Rev. C. 81, 054902 (2010)
UrQMD: H. Peterson et al, Phys Rev. C. 74, 064908 (2006)
QGSM: J. Beibel et al, Phys Rev. C. 76, 024912 (2007)
Transport: R. Snellings, et al, Phys Rev. Lett. 84, 2803 (2000)

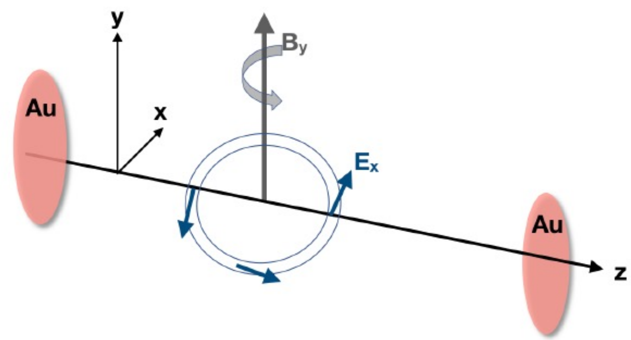
- Charged pions exhibit negative v_1 slope ("anti-flow") near mid-rapidity
- Models with hadronic physics or with baryon stopping and space momentum correlation can qualitatively explain "anti-flow" shape
- In hydro calculations with initially tilted bulk, the "anti-flow" shape is reproduced
- However, the sensitivity of the charged particle $v_1(y)$ to the tilt parameter is not very strong

Heavy quark v_1 from EM field



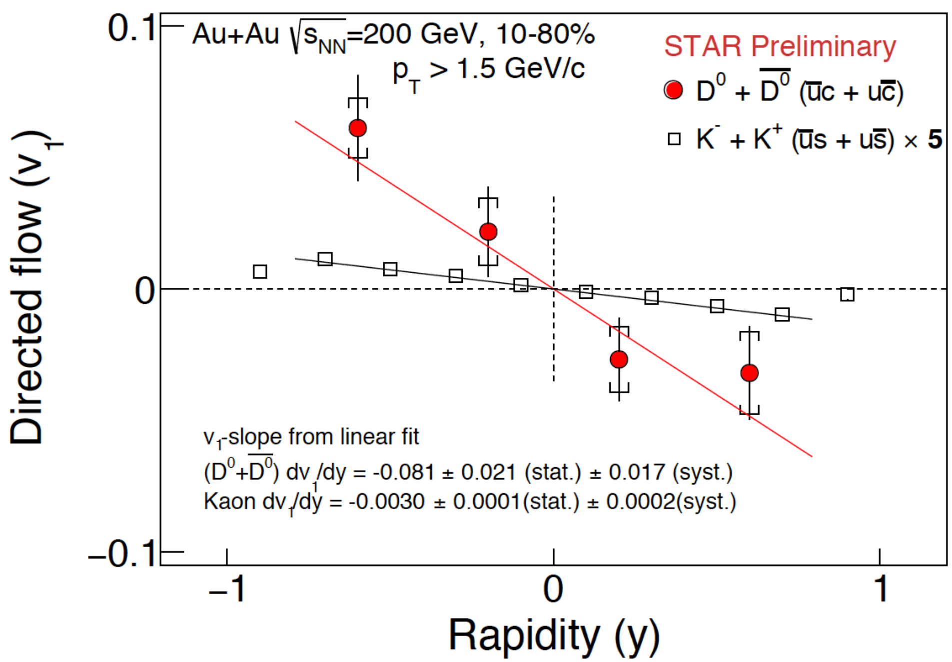


- Incoming charged particles can produce an enormously large EM field
- Due to early production of heavy quarks (τ_{CQ}~0.1 fm/c), positive and negative charm quarks can get deflected by the initial EM force
- Model calculation demonstrates that such initial EM field can induce opposite v_1 for charm and anti-charm quarks
- The magnitude of induced v_1 of charm hadrons can be order of magnitude larger than that of the light flavor hadrons



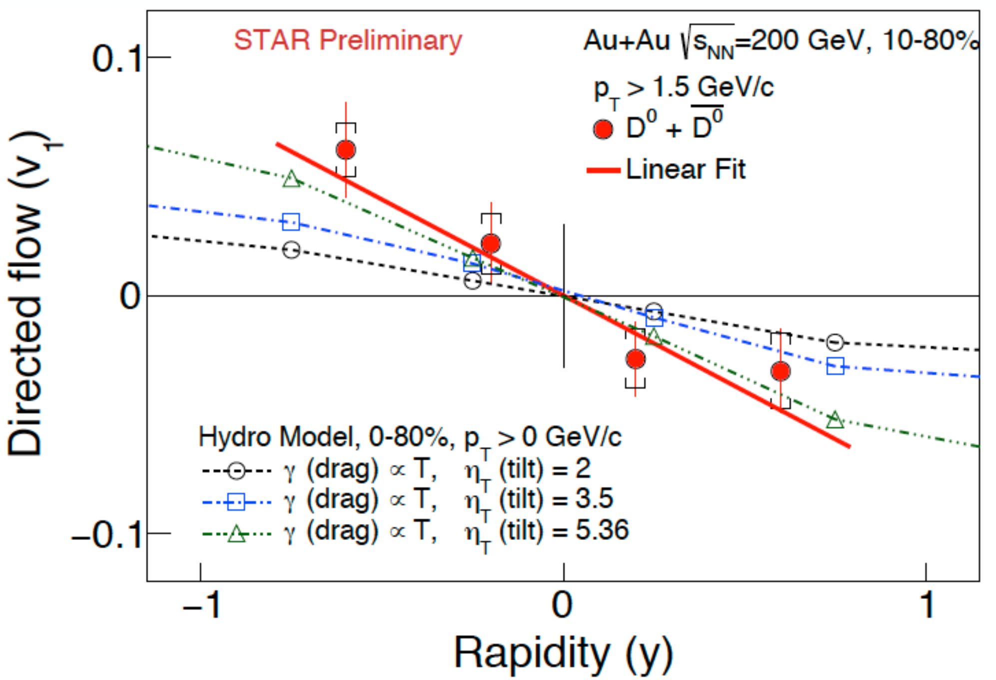
D^0 and $\overline{D}^0$ v_1 can offer insight into the early time EM fields

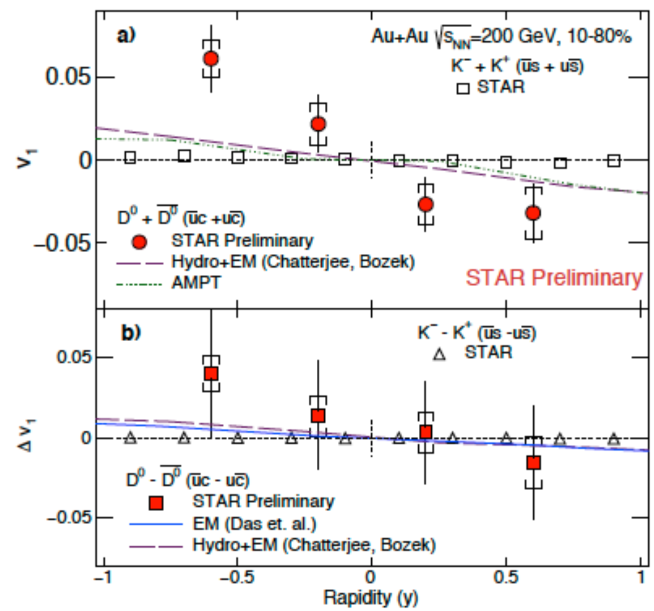
D^0 directed flow (v_1)



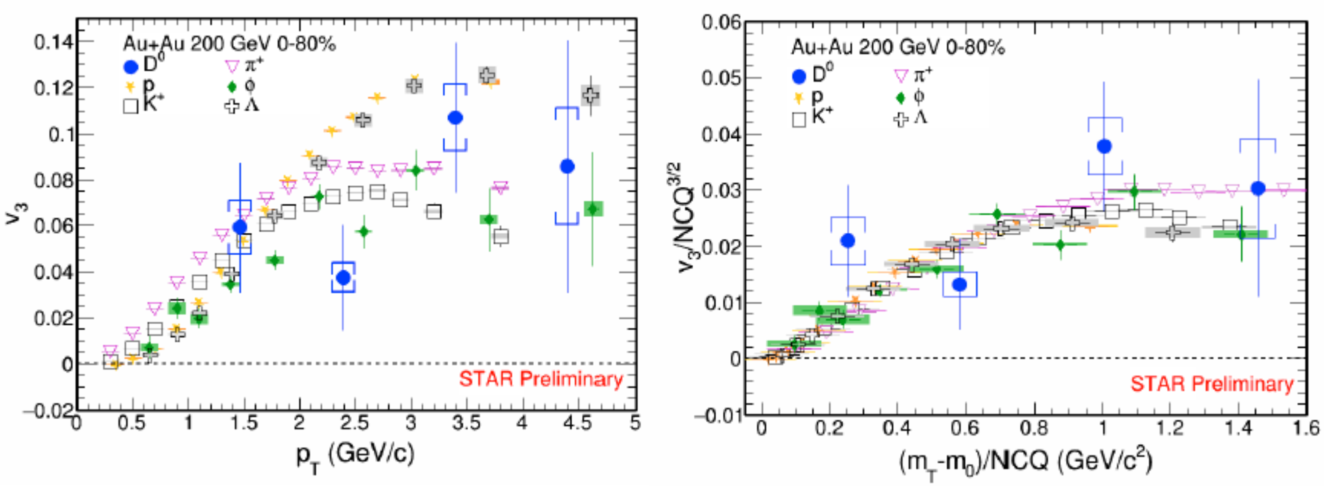
Charged Kaons:
L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)

First evidence for non-zero v1 for D's
Much larger than K+-K-
May imply effect of strong EM fields in collision system


STAR Preliminary
Au+Au $\sqrt{s_{NN}}$=200 GeV, 10-80%
p_T > 1.5 GeV/c
$D^0 + \overline{D^0}$
Linear Fit
Hydro Model, 0-80%, p_T > 0 GeV/c
γ (drag) ∝ T, η_T (tilt) = 2
γ (drag) ∝ T, η_T (tilt) = 3.5
γ (drag) ∝ T, η_T (tilt) = 5.36
Directed flow (v_1)
Rapidity (y)
0.1
0
−0.1
−1
0
1


a)
Au+Au $\sqrt{s_{NN}}$=200 GeV, 10-80%
$K^- + K^+$ ($\bar{u}s + u\bar{s}$)
STAR
$D^0 + \overline{D^0}$ ($\bar{u}c + u\bar{c}$)
STAR Preliminary
Hydro+EM (Chatterjee, Bozek)
AMPT
STAR Preliminary
v_1
0.05
0
−0.05
b)
$K^- - K^+$ ($\bar{u}s - u\bar{s}$)
STAR
$D^0 - \overline{D^0}$ ($\bar{u}c - u\bar{c}$)
STAR Preliminary
EM (Das et. al.)
Hydro+EM (Chatterjee, Bozek)
Δv_1
0.05
0
−0.05
−1
−0.5
0
0.5
1
Rapidity (y)

- First D^0 v_3 measurement at STAR
- Large non-zero D^0 v_3
  - ➔ Strong collective behavior
- Consistent with the NCQ scaling (empirical m_T scaling)
  - ➔ Charm quarks may have acquired similar flow as light quarks
- Need more statistics to draw a solid conclusion

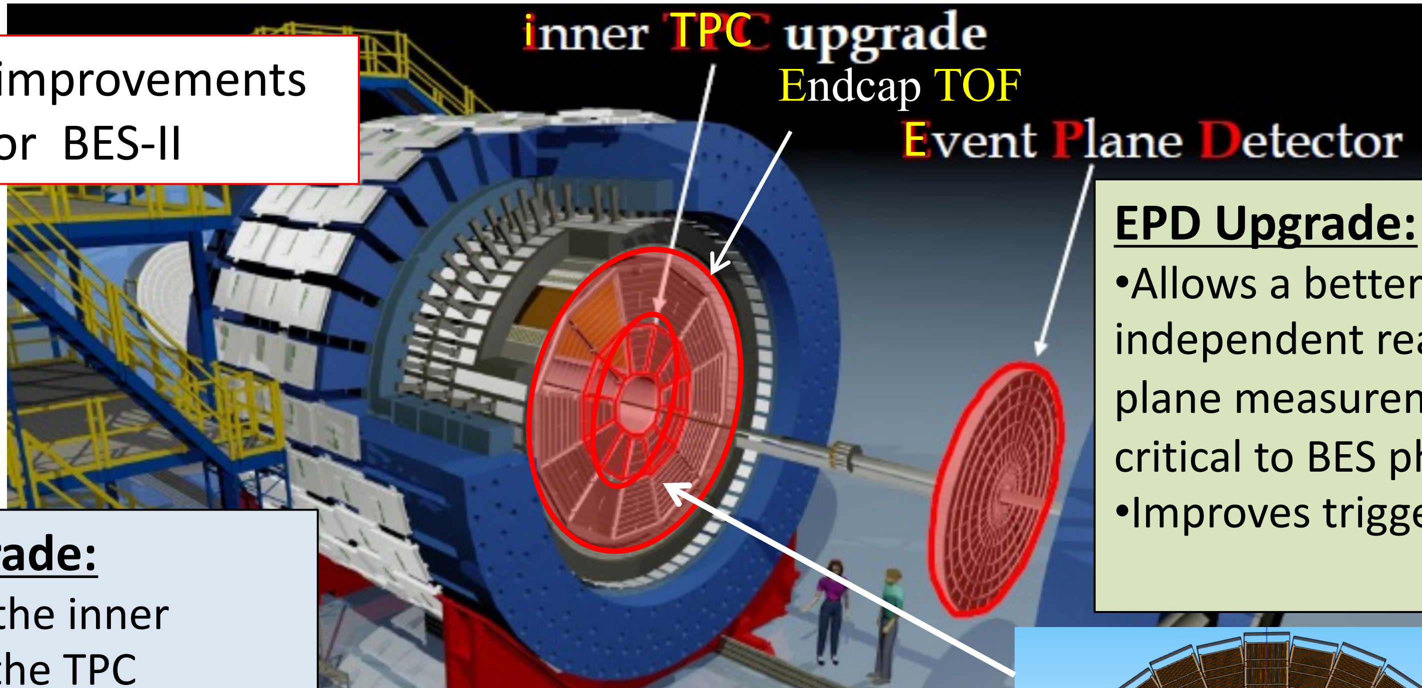


Summary

- The HFT upgrade was overall successfully and has hopefully lead the way for future high resolution vertex detectors (ALICE ITS, sPHENIX, EIC)
- Strong Modification of charm hadron spectra and hadro chemistry in AA collisions as witnessed by the different observations
  - Total charm cross section is conserved.
  - Substantial energy loss , coalescence
  - Gain significant flow & may have achieved thermal equilibrium in medium (v_2)
  - Observed non-zero directed flow
- Indication for suppression at high p_T for B->D^0 ,… measurements
- Thanks to the many STAR collaborators that has worked on HFT construction and analysis over the years

The STAR Upgrades and BES Phase II

Major improvements for BES-II



<u>EPD Upgrade:</u>

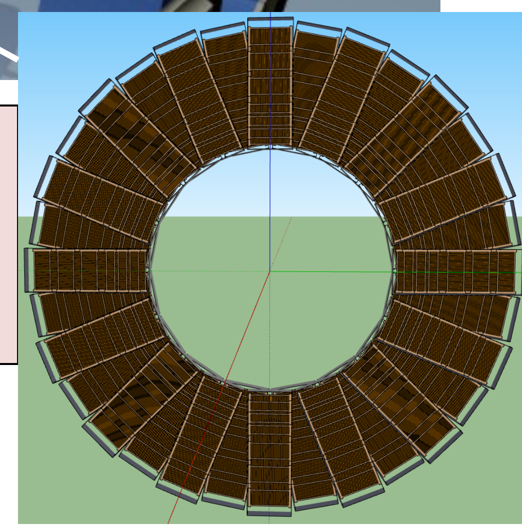
- Allows a better and independent reaction plane measurement critical to BES physics
- Improves trigger

<u>iTPC Upgrade:</u>

- Rebuilds the inner sectors of the TPC
- Continuous Spatial Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

<u>EndCap TOF Upgrade:</u>

- PID at η = 1.1 to 1.5
- Provided by CBM-FAIR Phase-0



All detectors now in place for BES II