Measurements of open charm hadrons in Au+Au collisions at the STAR experiment

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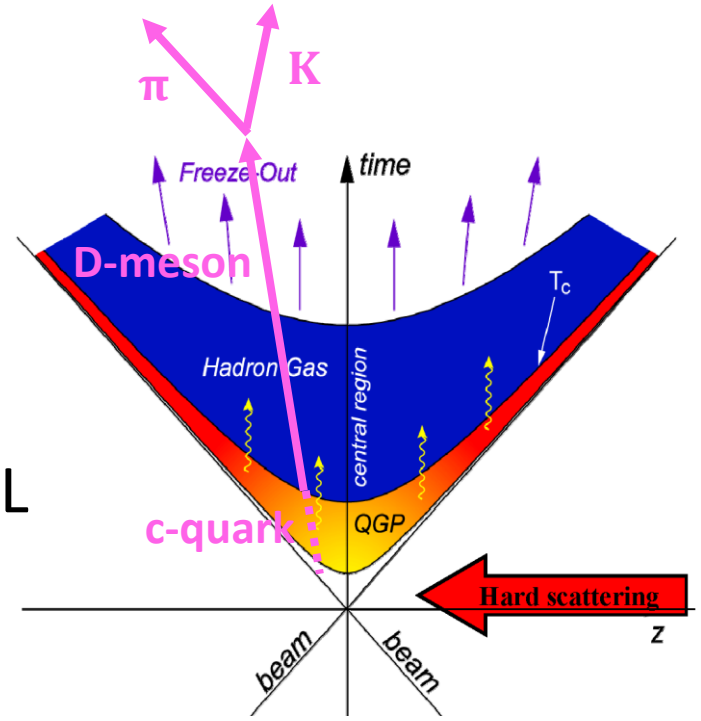
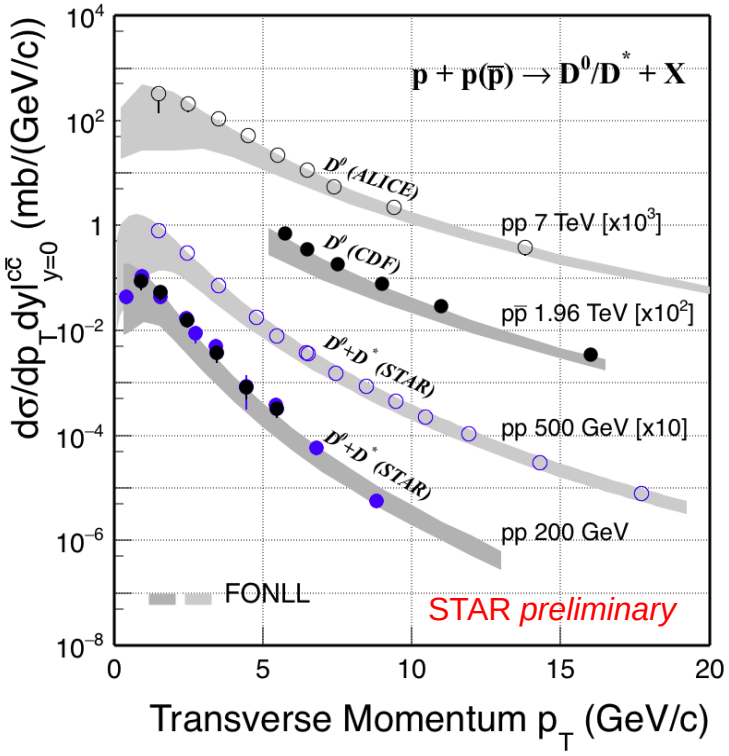
Studying QGP with open charm hadrons – D^0, $D^{\pm}$, D_s , Λ_c

- $m_c \gg T_{QGP}, \Lambda_{QCD}$
- Produced in hard scatterings during early stages of heavy-ion collisions
- Production cross-section in p+p collisions described well by FONLL
- Excellent probe for energy loss mechanisms in the QGP
  - Precise measurements of D^0 R_{AA} and v_2
- New measurements of D_s, Λ_c production bring more insights into charm quark hadronization





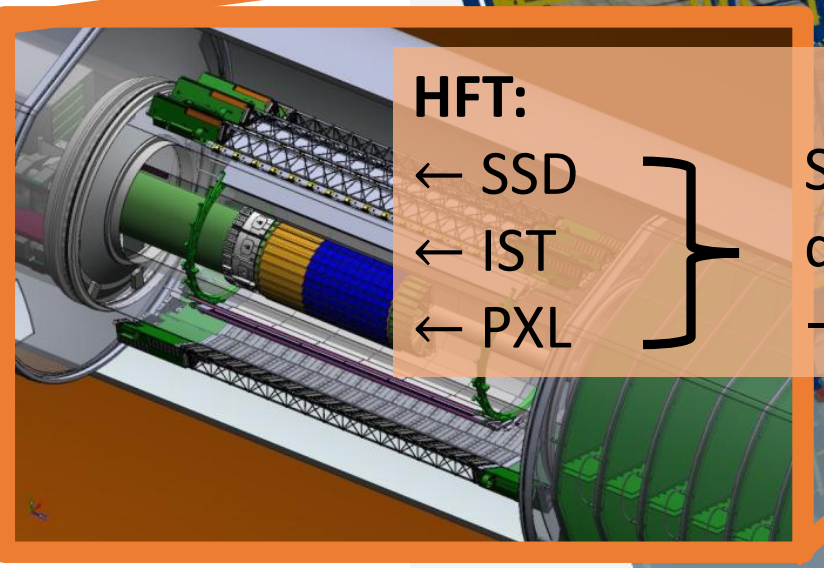
[STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520; CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128; FONLL: PRL 95 (2005) 122001]

STAR detector at RHIC

2π acceptance in azimuth

TOF:
$1/\beta$(PID)
$-1 < \eta < 1$ $\rightarrow$

TPC: Tracking
dE/dx (PID)
$\leftarrow$ $-1 < \eta < 1$

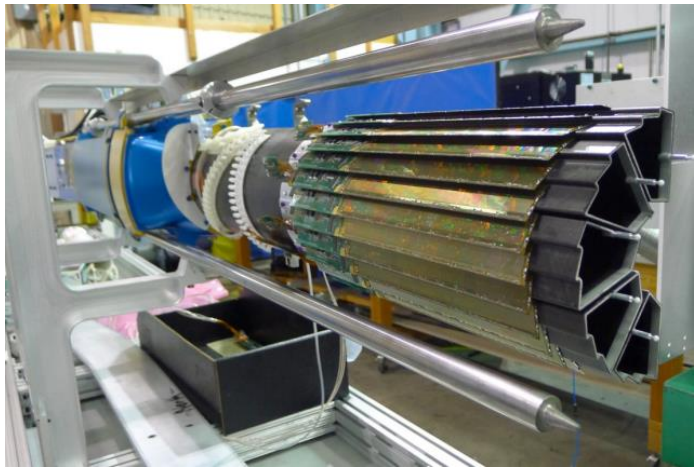


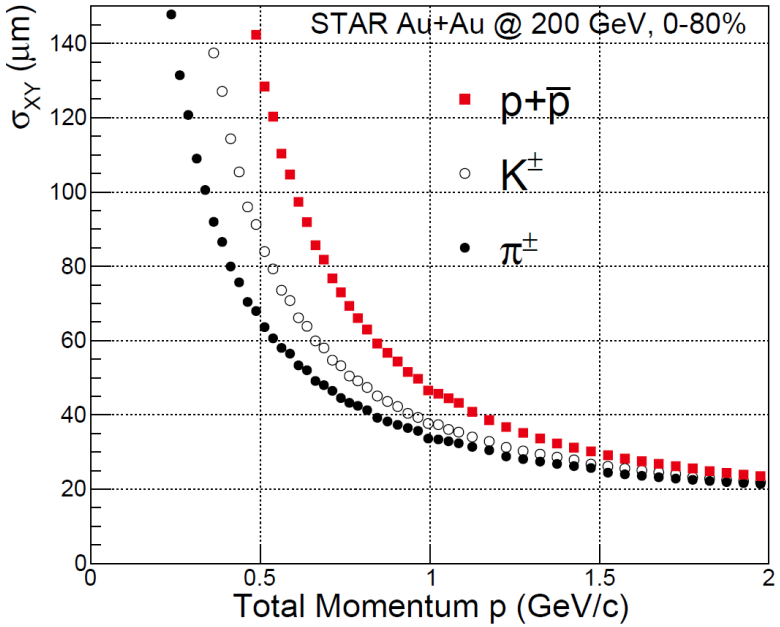
HFT:
$\leftarrow$ SSD
$\leftarrow$ IST
$\leftarrow$ PXL

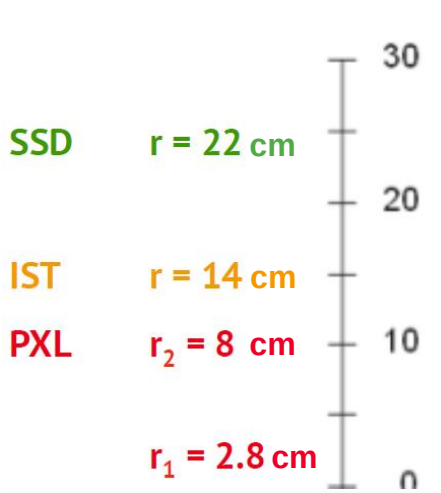
Silicon vertex detector
$-1 < \eta < 1$

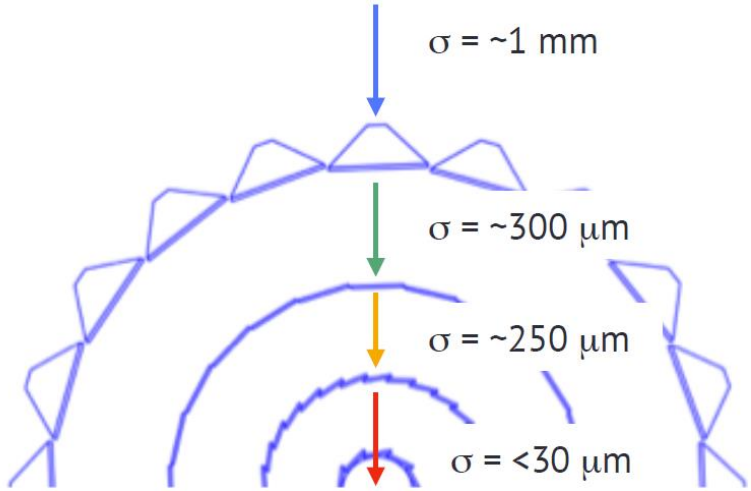
STAR Heavy Flavor Tracker

- The Pixel detector: First MAPS technology in a collider experiment
- Pointing resolution: ~20 μm at high p_T (exceeds the requirement of 55 μm for 750 MeV/c kaons)
- Radiation length: 0.4 % X_0 for the 1st layer of pixel
- Recorded ~3×10^9 good Au+Au events in 2014 and 2016





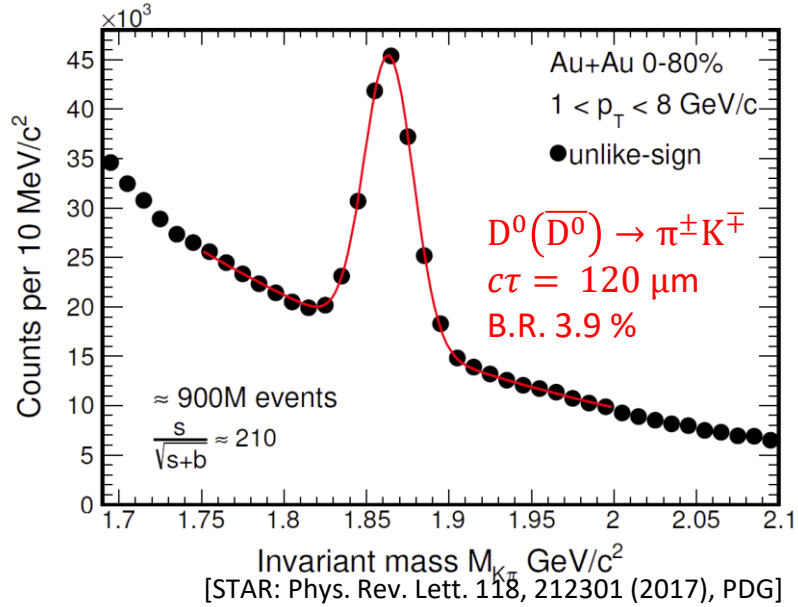




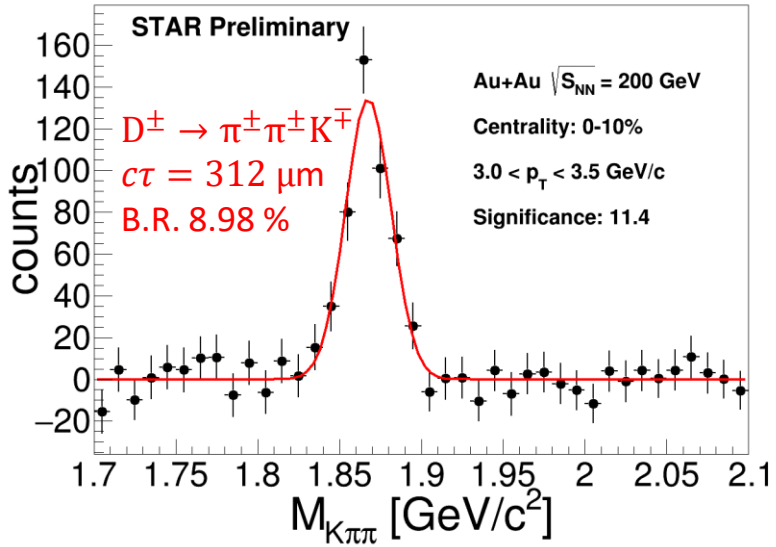
[STAR: PRL 118 (2017) 212301]

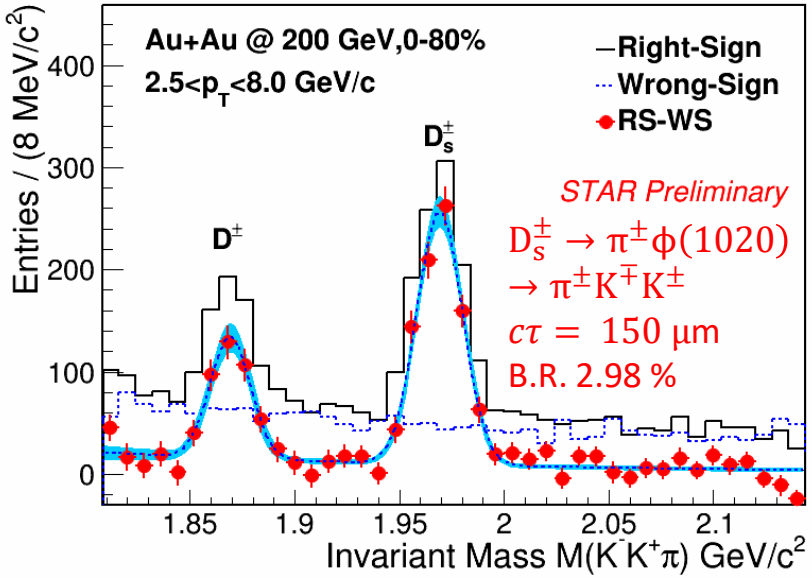
Topological reconstruction with the HFT

- HFT used for reconstruction of secondary vertices with high precision
- Usage of TMVA for cut optimization
- Combinatorial background greatly suppressed
  - In 2010+2011, D^0 significance was $s/\sqrt{s+b} \sim 13.9$ with 1.2 B events
  - In 2014, D^0 significance with HFT is $s/\sqrt{s+b} \sim 210$ with 900 M events



[STAR: Phys. Rev. Lett. 118, 212301 (2017), PDG]

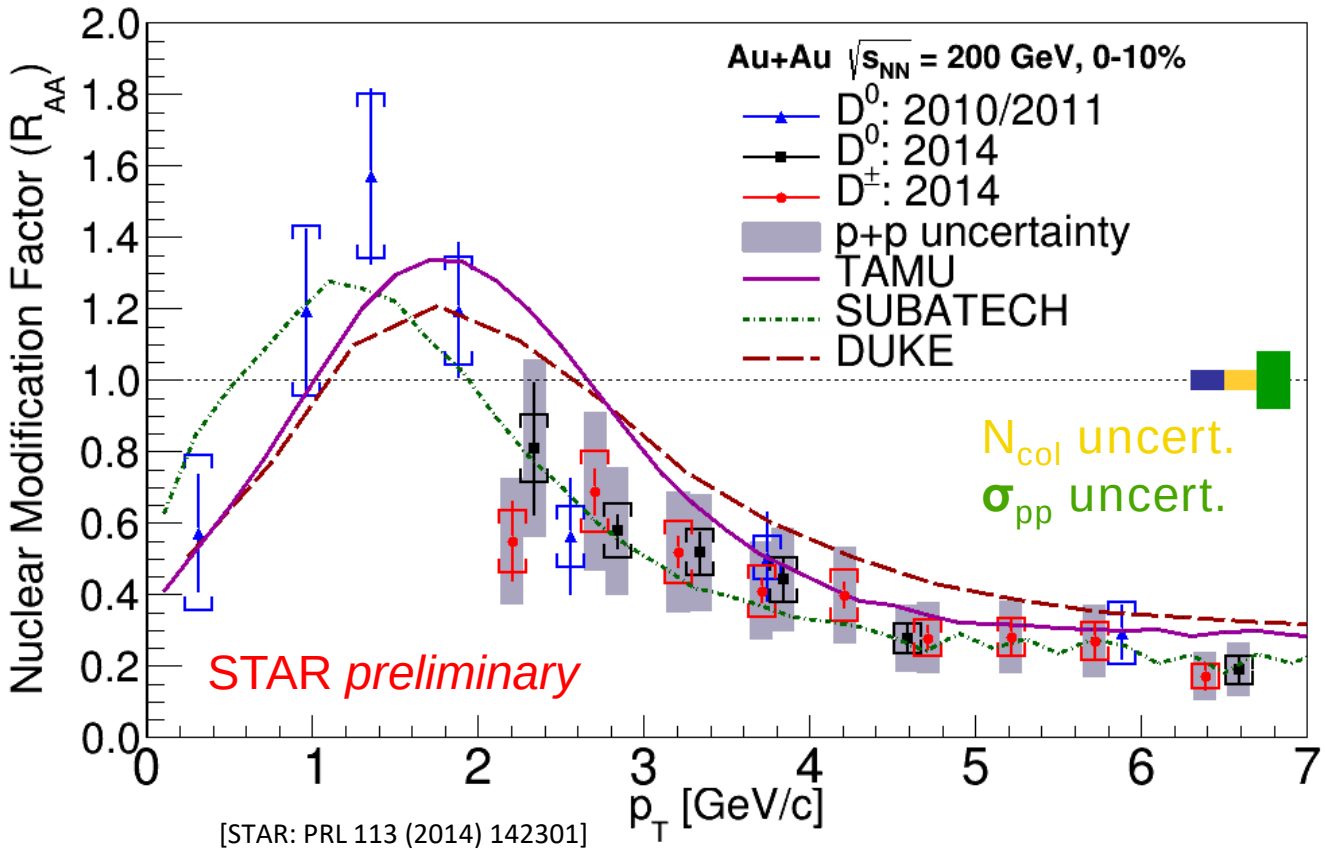




Nuclear modification factor R_{AA} of D^0 and $D^{\pm}$

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

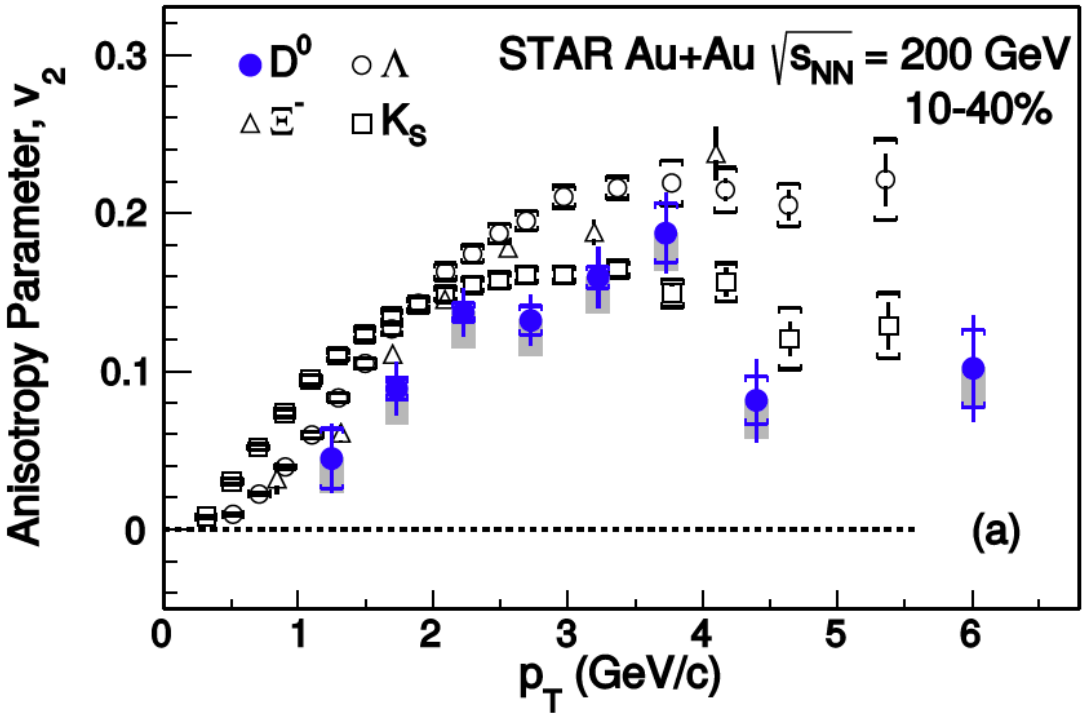
- Improved precision with the HFT
- Results from D^0 and $D^{\pm}$ are consistent
- Yield at $p_T > 2.5$ GeV/c suppressed
- Models with strong charm-medium interactions describe the data



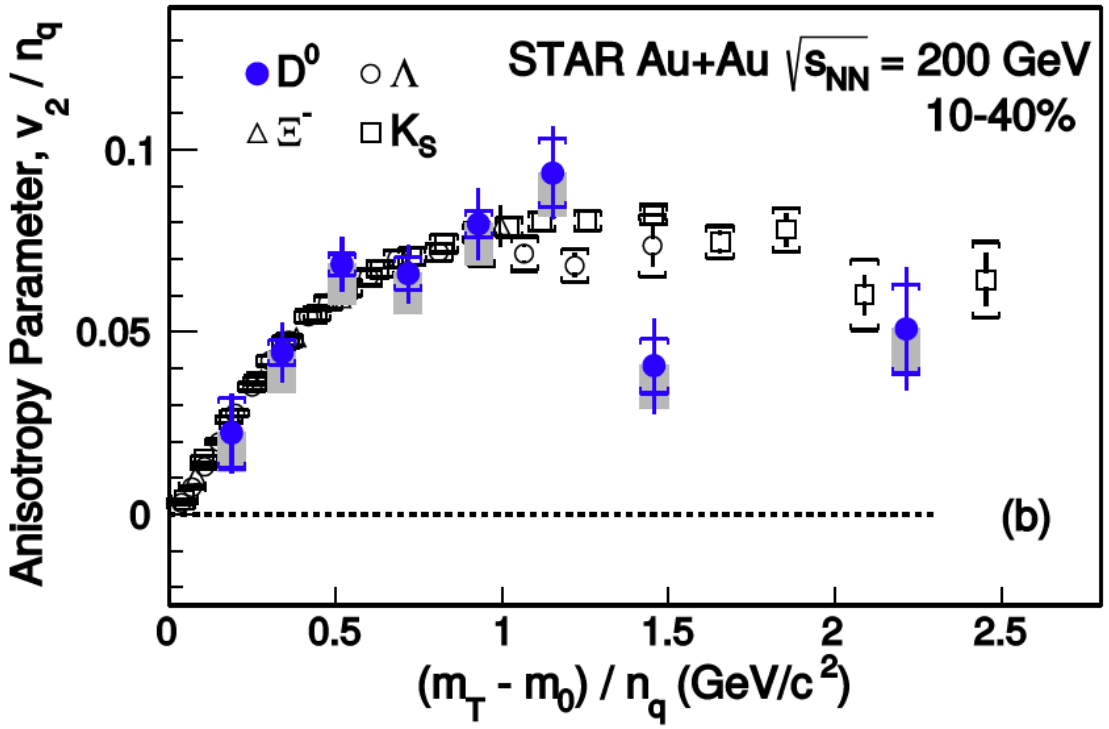
[STAR: PRL 113 (2014) 142301]
[Theory:
TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.;
SUBATECH: PRC 91(2015) 054902 & private comm.;
Duke: PRC 92(2015) 024907 & private comm.]

D^0 azimuthal anisotropy v_2

- Significantly above zero for p_T > 1.5 GeV/c



- D^0 v_2 exhibits same NCQ scaling as light hadrons

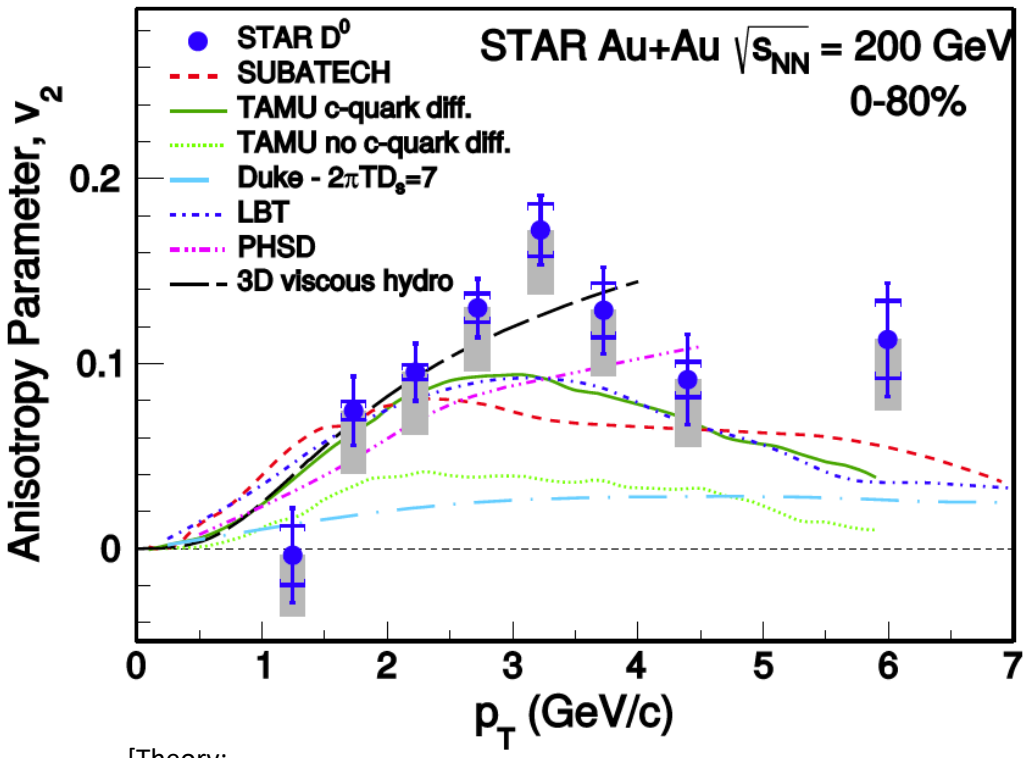


[STAR: PRC 77 (2008) 54901, PRL 116 (2016) 62301, PRL 118 (2017) 212301]

- Charm quarks flow with the medium

$$\frac{dN}{d\phi} = N_0\left(1 + \sum_n 2v_n \cos[n(\varphi - \psi_n)]\right)$$

Comparison of v_2 to theoretical predictions

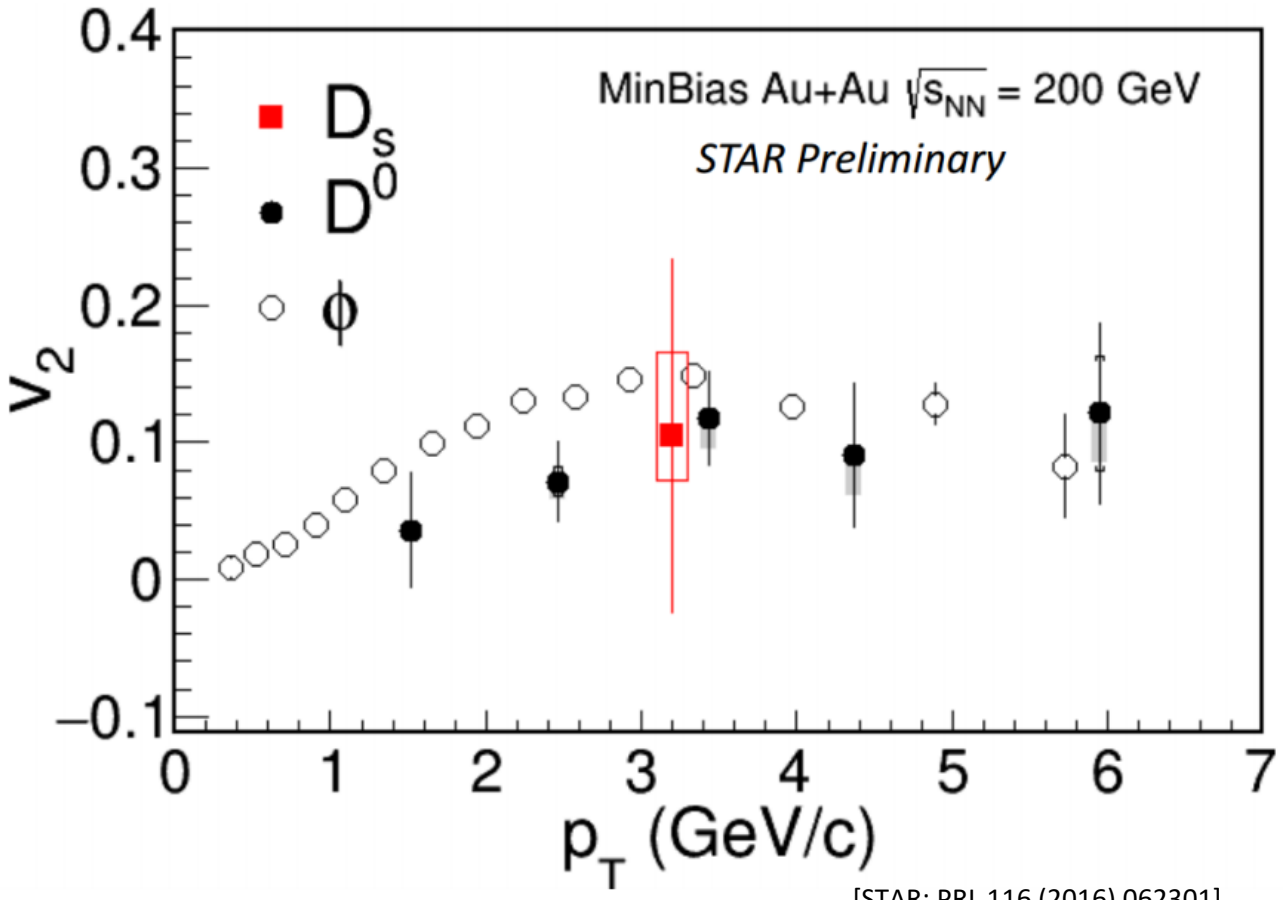


[Theory:
TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.;
SUBATECH: PRC 91(2015) 054902 & private comm.;
Duke: PRC 92(2015) 024907 & private comm.;
PHSD: PRC 90, 051901 (2014), PRC 92, 014910 (2015);
LBT: Phys. Rev. C 94, 014909 (2016);
3D viscous hydro: PRC 86, 024911 (2012), PRD 91, 074027 (2015) & private comm.]
[STAR: PRL 118, 212301 (2017)]

- 3D viscous hydro, tuned to light hadrons
- D_s spatial diffusion coefficient
- Duke: Langevin simulation with transport properties tuned to LHC data
  - $(2\pi T)D_s = 7$
- Linearized Boltzmann Transport
  - Jet transport model extended to heavy quarks
  - $(2\pi T)D_s = 3-6$
- Parton-Hadron-String Dynamics : Effective potential of c-quarks:
  - $(2\pi T)D_s = 5-12$
- TAMU: non-perturbative T-matrix approach:
  - $(2\pi T)D_s = 5-12$
- SUBATECH: pQCD + hard thermal loops for resummation:
  - $(2\pi T)D_s = 2-4$
- Together: $(2\pi T)D_s = \sim 2-12$

D_s azimuthal anisotropy v_2

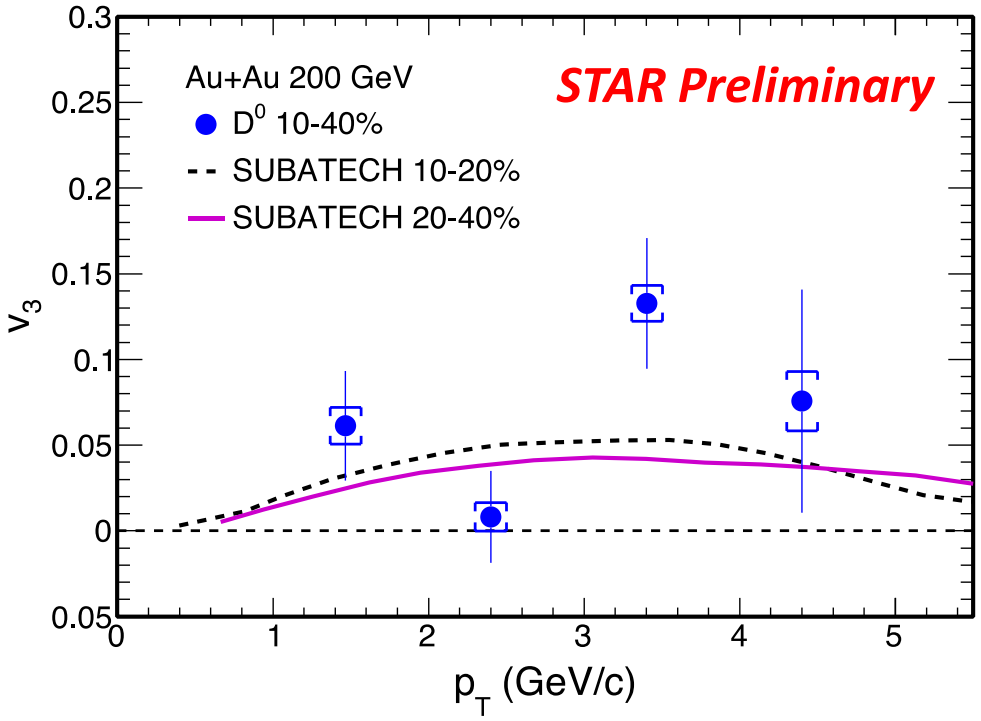
- First measurement of D_s v_2 at RHIC



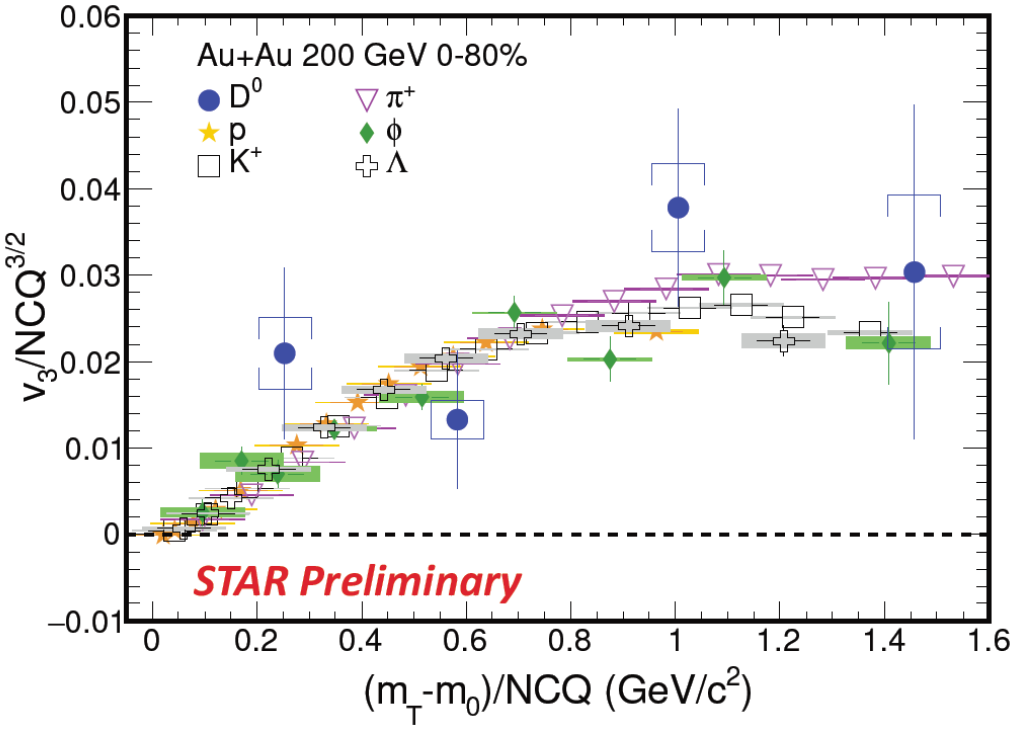
[STAR: PRL 116 (2016) 062301]

D^0 triangular flow v_3

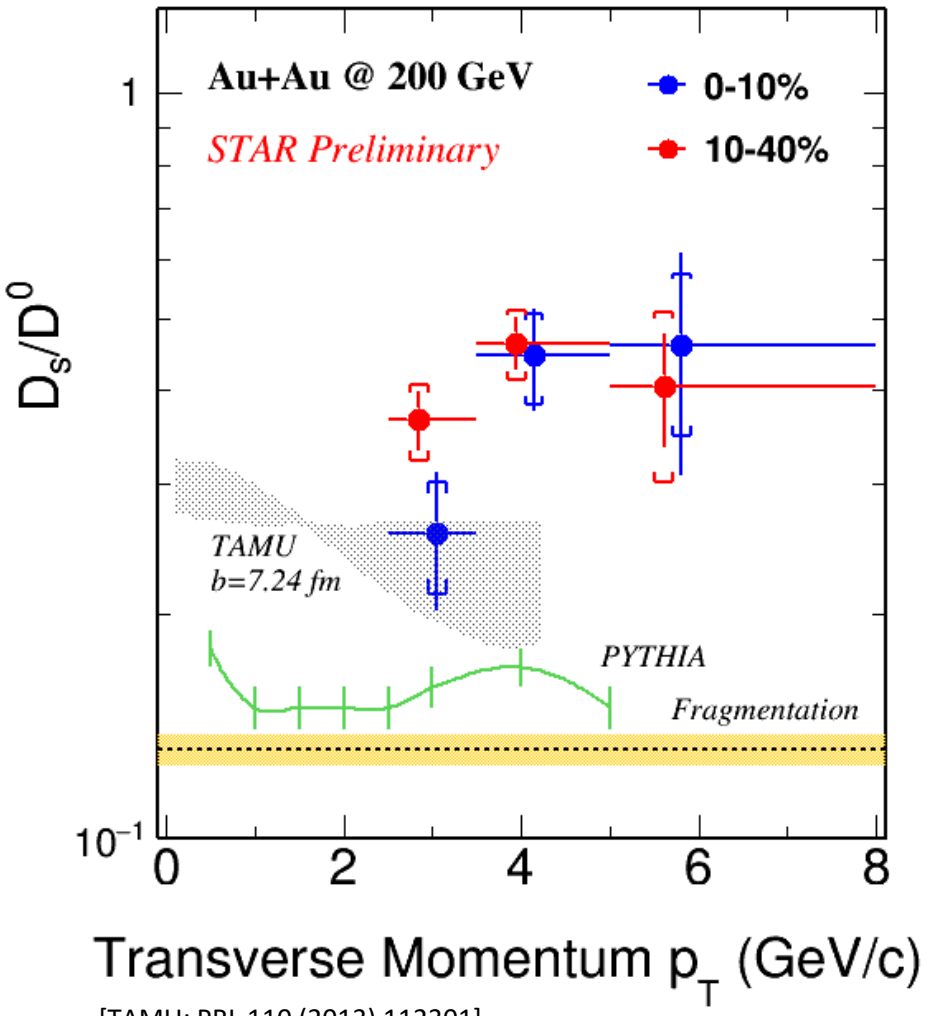
- First measurement of D^0 v_3 at RHIC
- SUBATECH model describes the data
- Data are consistent with NCQ scaling



[SUBATECH: PRC 91 (2015) 014904]



D_s/D^0 yield ratio



[TAMU: PRL 110 (2013) 112301]

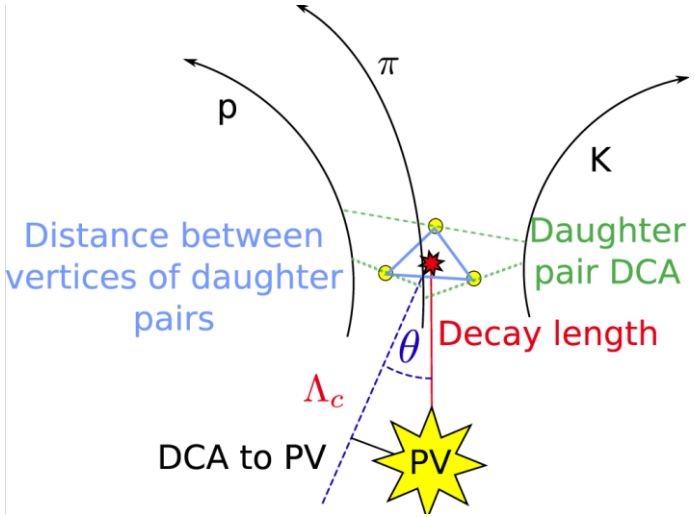
- Observed strong enhancement of the D_s/D^0 ratio, compared to:
  - Fragmentation ratio measured at HERA
  - PYTHIA version 6.4

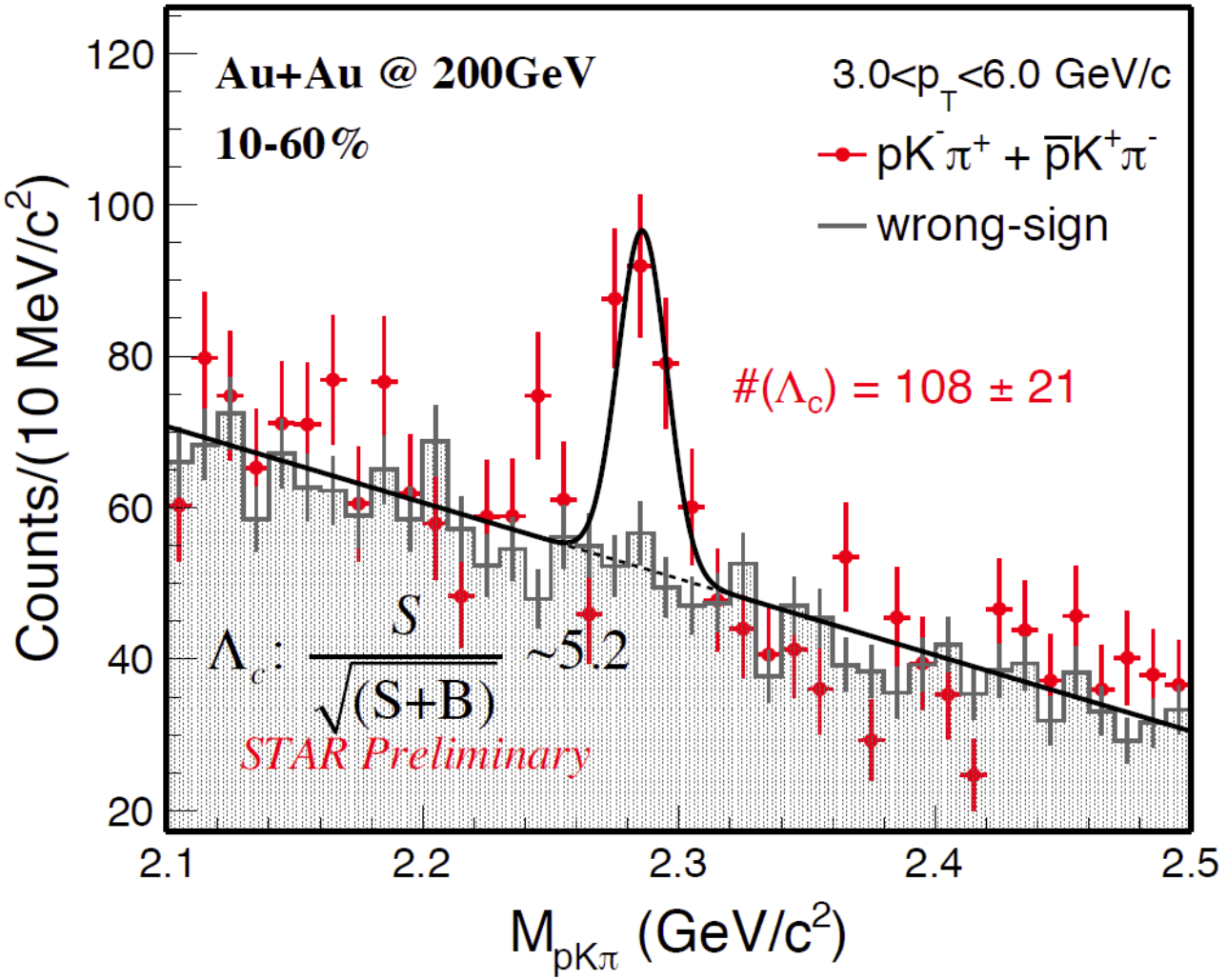
[H1 Collaboration, Eur.Phys.J.C38(2005)447]
[ZEUS Collaboration, Eur.Phys.J.C44(2005)351]

- Enhancement in 10–40 % centrality is stronger than the TAMU model calculation with charm quark coalescence

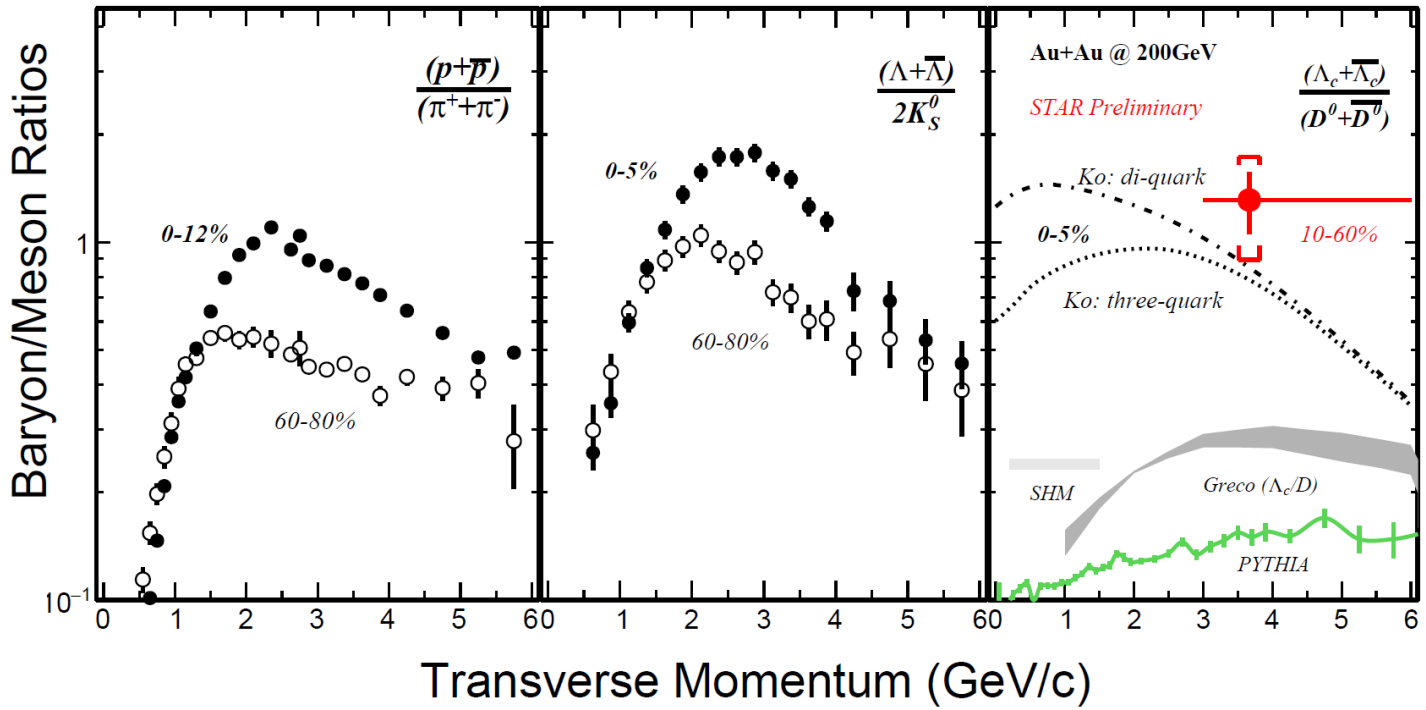
Λ_c baryon

- $\Lambda_c^{\pm} \rightarrow p^{\pm}K^{\mp}\pi^{\pm}$ BR = 5 %
- $c\tau \sim 60\ \mu m$
- First measurement of charmed baryons in high-energy heavy-ion collisions





Λ_c/D^0 yield ratio



[STAR: PRL 108 (2012) 072301]
[Theory:
SHM: PRC 79 (2009) 044905;
Greco: PRD 90 (2014) 054018;
Ko: PRL 100 (2008) 222301]

- Clear enhancement observed compared to PYTHIA
- Compatible with baryon-to-meson ratios of light hadrons
- Ko model describes the data for both di-quark + 1 quark, and three-quark coalescence scenarios
- The Greco model is calculated using all D meson species (D^0, $D^{\pm}$, and D_s)
  - May go up by a factor of 1.5 (p+p baseline) once only D^0 mesons are used
- SHM prediction is lower than the data

Summary

- Comprehensive study of charmed hadrons in Au+Au collisions at STAR

- Heavy Flavor Tracker opens a new era of precision charm quark measurements at RHIC
- First measurement of D^0 v_2, v_3, $\mathrm{D}^{\pm}$, and $\mathrm{D_s}$ at RHIC
  - The $\mathrm{D}^{\pm}$ R_{AA} is consistent with the D^0 measurement
  - D^0 v_2: NCQ scaling is observed; Charm quarks flow with the medium
  - D^0 v_3: Follows the NCQ scaling of light hadrons
  - Enhancement of the $\mathrm{D_s}/\mathrm{D}^0$ ratio – indication of charm quark coalescence hadronization from the QGP
  - Hint of non-zero $\mathrm{D_s}$ v_2
- First measurement of Λ_c baryons in heavy-ion collisions
  - Enhancement of the Λ_c/D^0 ratio – Indication of charm quark coalescence

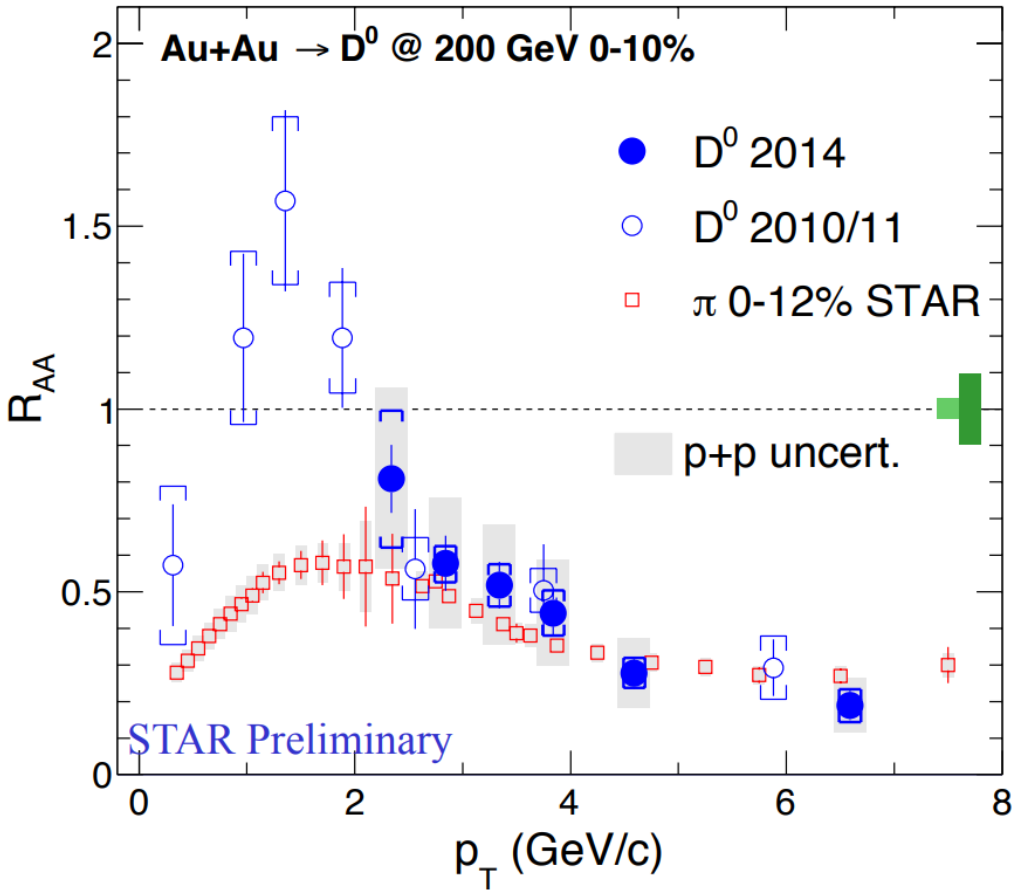
- About 2 billion more Au+Au events were recorded by STAR in 2016
- Stay tuned!

Thank you for your attention

Backup

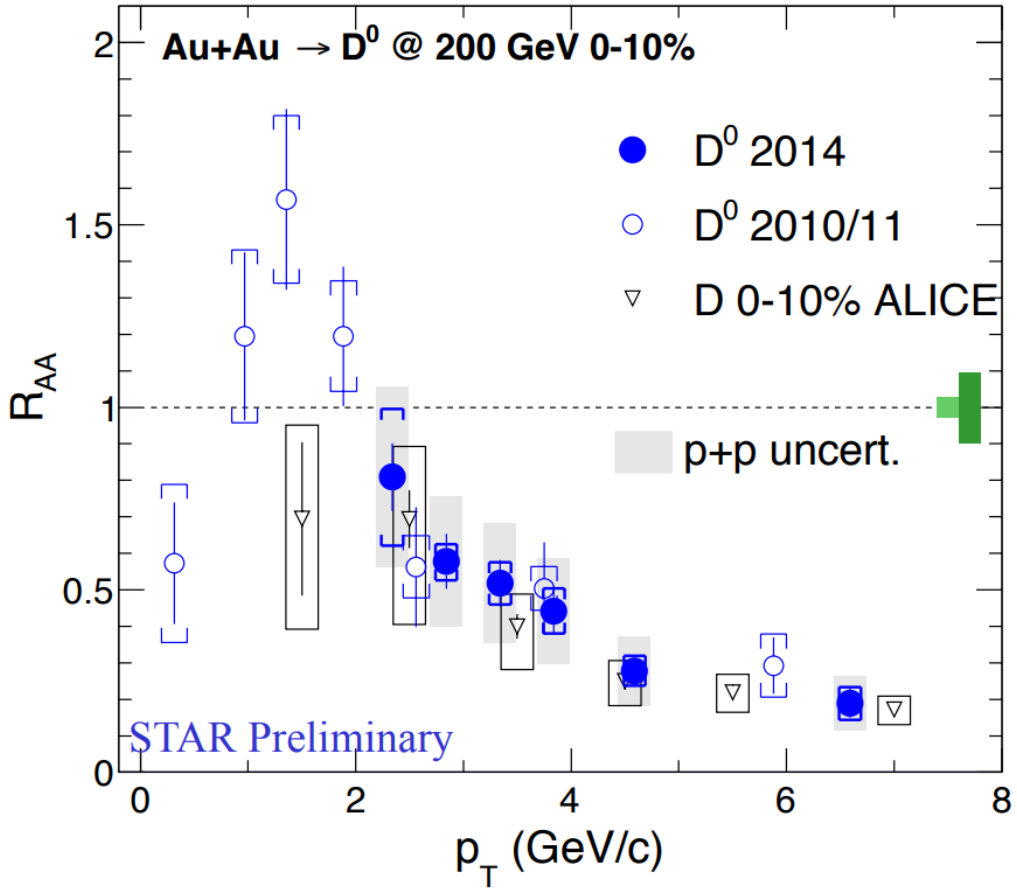
D^0 v_2

Comparison to pions



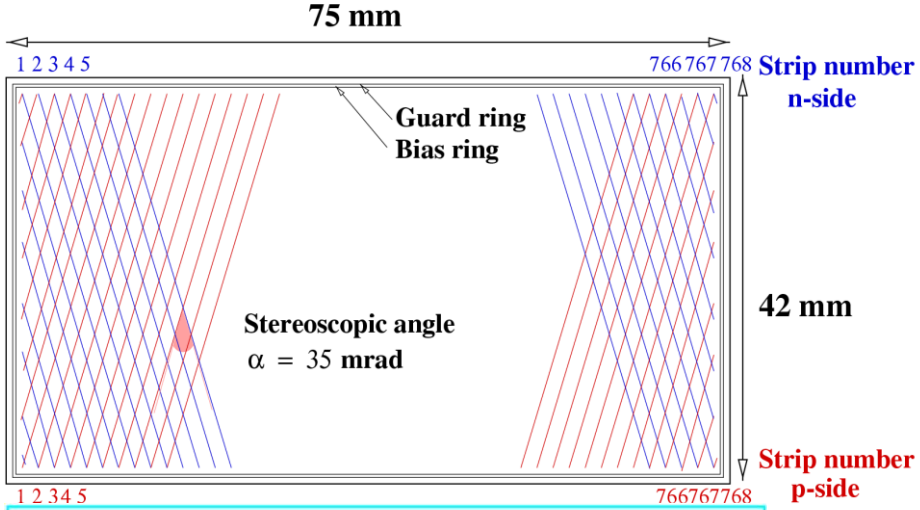
[STAR: PRL 113 (2014) 142301, PLB 655 (2007) 104]

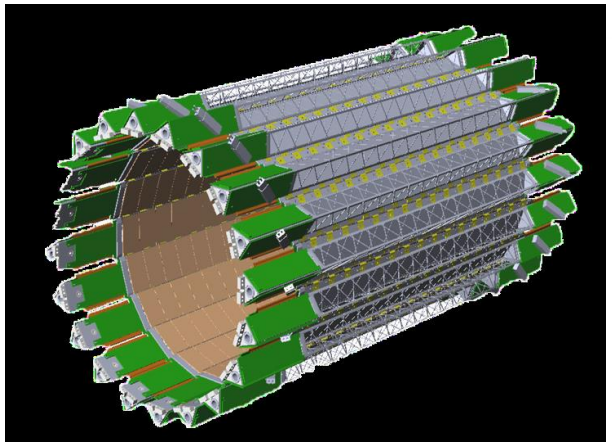
Comparison to ALICE

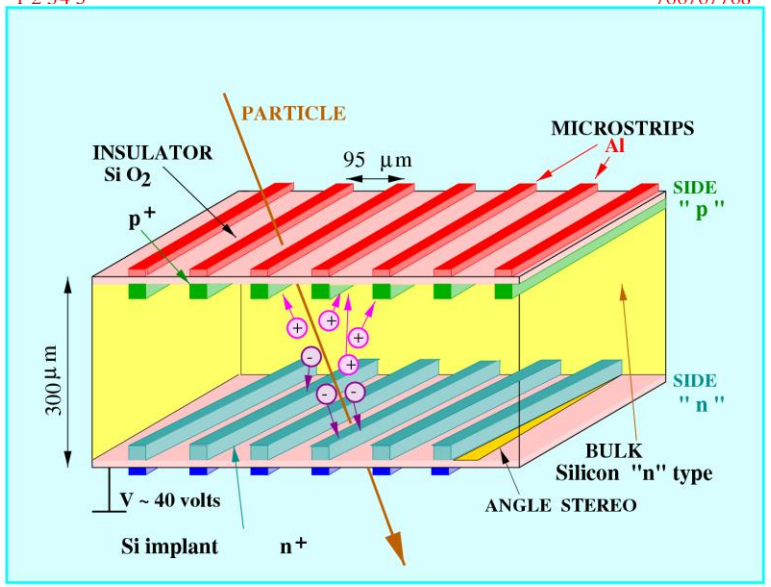


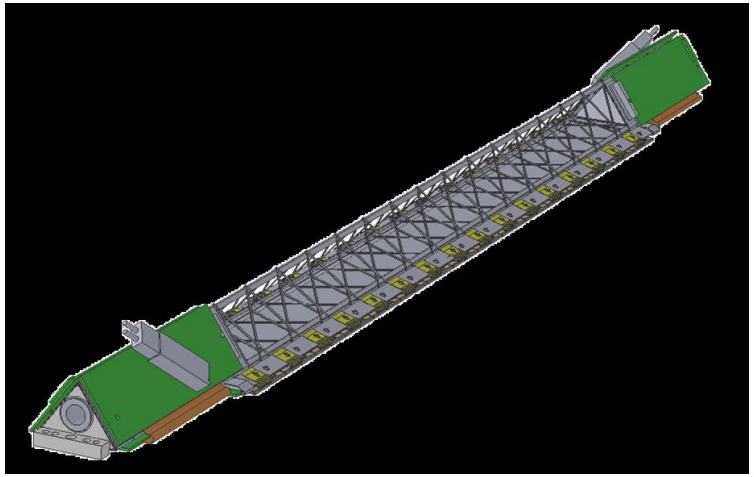
[ALICE: arXiv: 1509.06888]

Silicon Strip Detector (SSD)





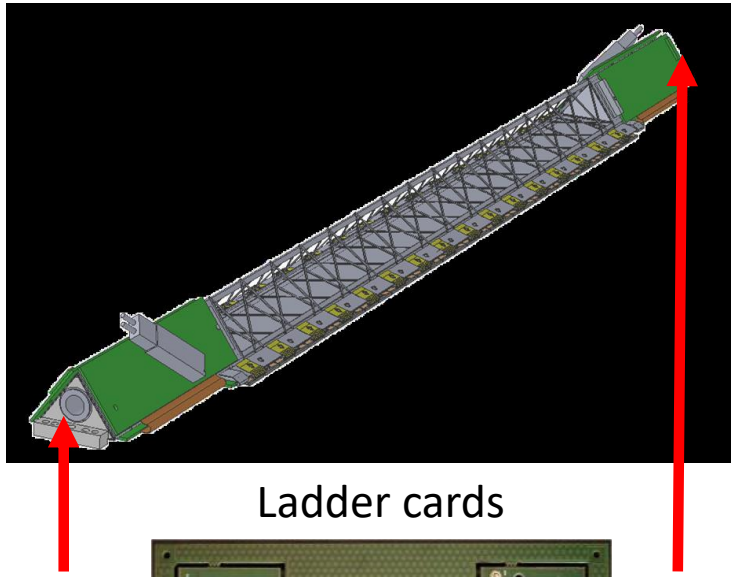




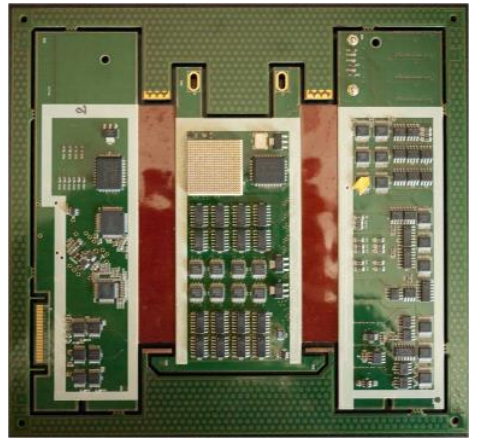
SSD radius	22 cm
SSD length	106 cm
$\|\eta\|$ coverage	< 1.2
Number of ladders	20
Number of wafers per ladder	16
Total number of wafers	320
Number of strips per wafer side	768
Number of sides per wafer	2
Total number of channels	491520
Silicon wafer size	75 × 42 mm
Silicon wafer sensitive size	73 × 40 mm
Silicon thickness	300 μm
Strip pitch	95 μm
Stereo angle	35 mrad
R-ϕ resolution	20 μm
Z resolution	740 μm

SSD readout refurbishment

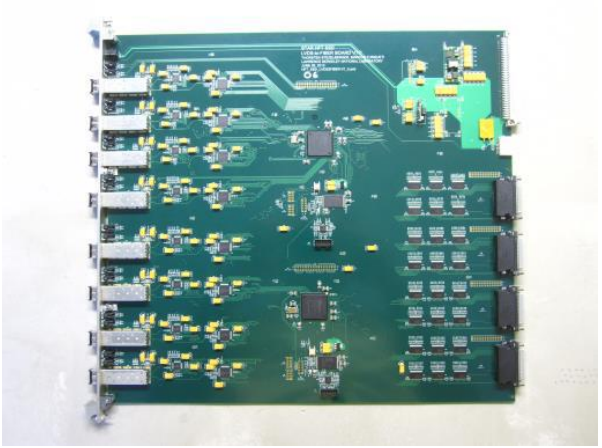
- Upgrade from 200 Hz to 1 kHz
- New
  - 40 ladder cards on detector
  - 5 RDO cards
  - 5 Fiber-to-LVDS boards



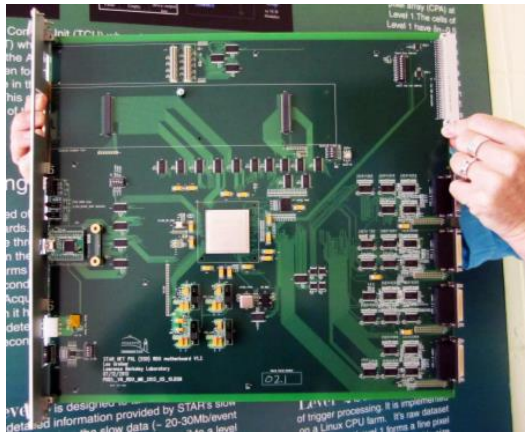
Ladder cards



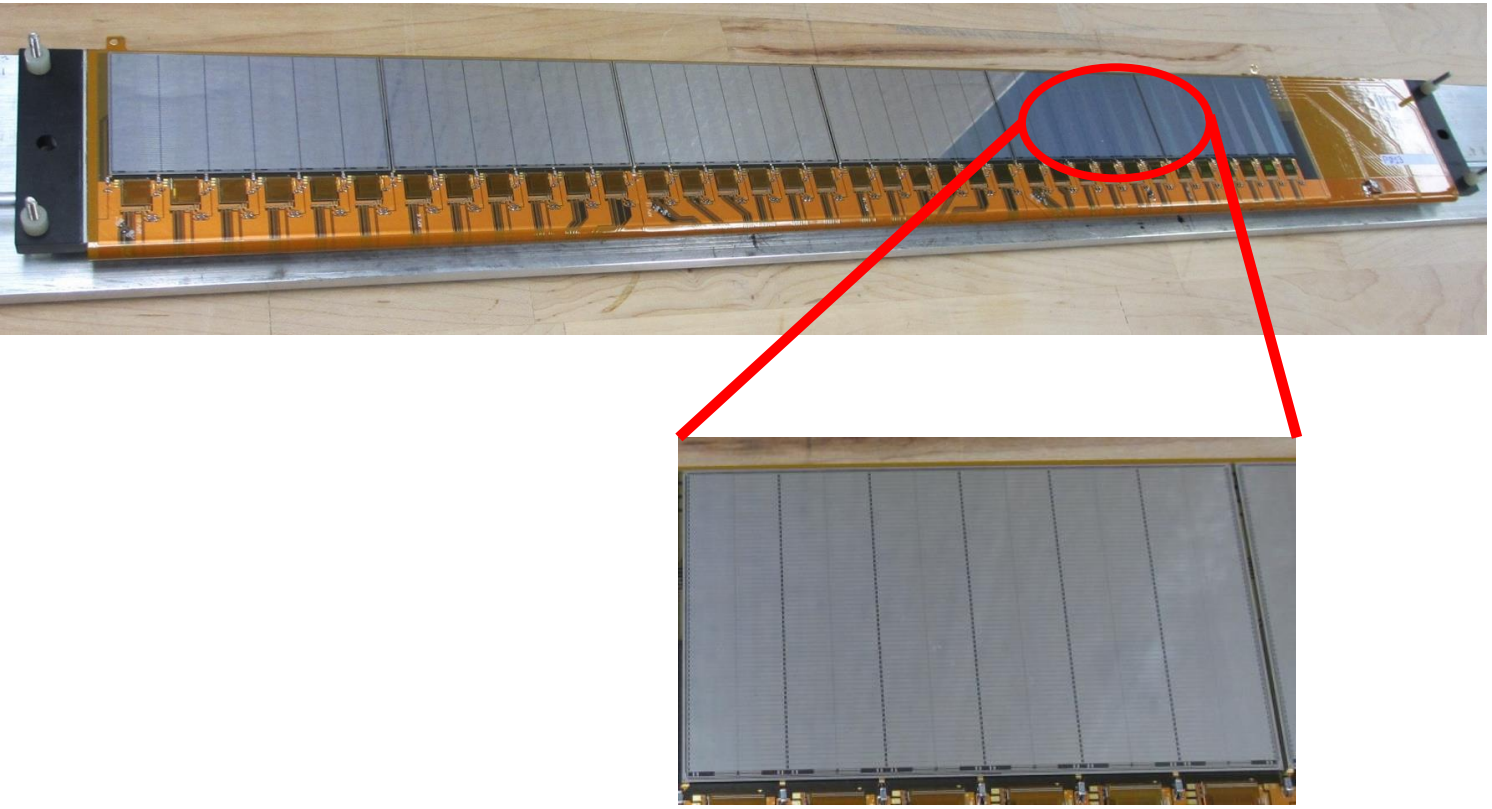
Fiber-to-LVDS



RDO board – adapted from PXL



Intermediate Silicon Tracker (IST)



Radius	14 cm
Length	50 cm
ϕ-Coverage	2π
$\lvert\eta\rvert$-Coverage	≤ 1.2
Number of ladders	24
Number of hybrids	24
Number of sensors	144
Number of readout chips	864
Number of channels	110592
R-ϕ resolution	172 μm
Z resolution	1811 μm
Z pad size	6000 μm
R-ϕ pad size	600 μm

Pixel detector (PXL)

DCA pointing resolution	$(12 \oplus 24$ GeV$/p_T c)$
Radii	Layer 1 at 2.8 cm Layer 2 at 8 cm
Pixel size	$20.7\ \mu\text{m} \times 20.7\ \mu\text{m}$
Hit resolution	$3.7\ \mu\text{m}$
Position stability	$6\ \mu\text{m}$ RMS ($20\ \mu\text{m}$ envelope)
Radiation length	Layer 1: $X/X_0 < 0.4\%$ Layer 2: $X/X_0 < 0.5\%$
Number of pixels	~ 356 M
Integration time (affects pileup)	185.6 ms
Radiation environment	20 – 90 kRad/year 2×10^{11} to 10^{12} 1 MeV n eq/cm^2
Installation time	~ 1 day