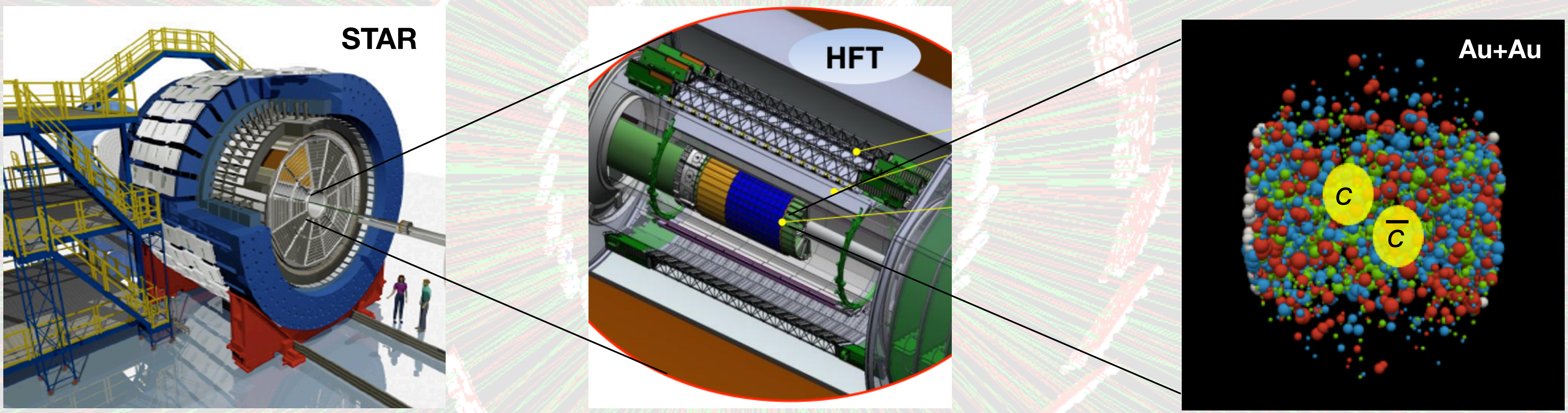
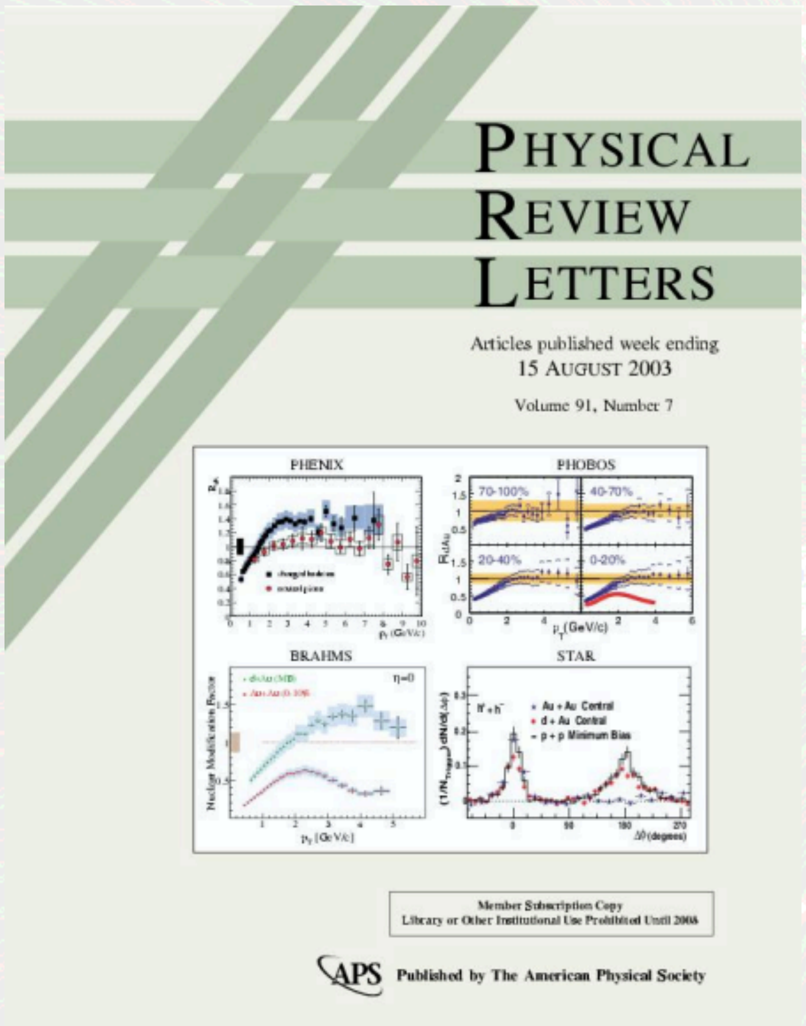
STAR's Contributions to Heavy Flavor Physics



Xin Dong
(Lawrence Berkeley National Laboratory)

RHIC Discovery of the Strongly-Coupled QGP (sQGP)

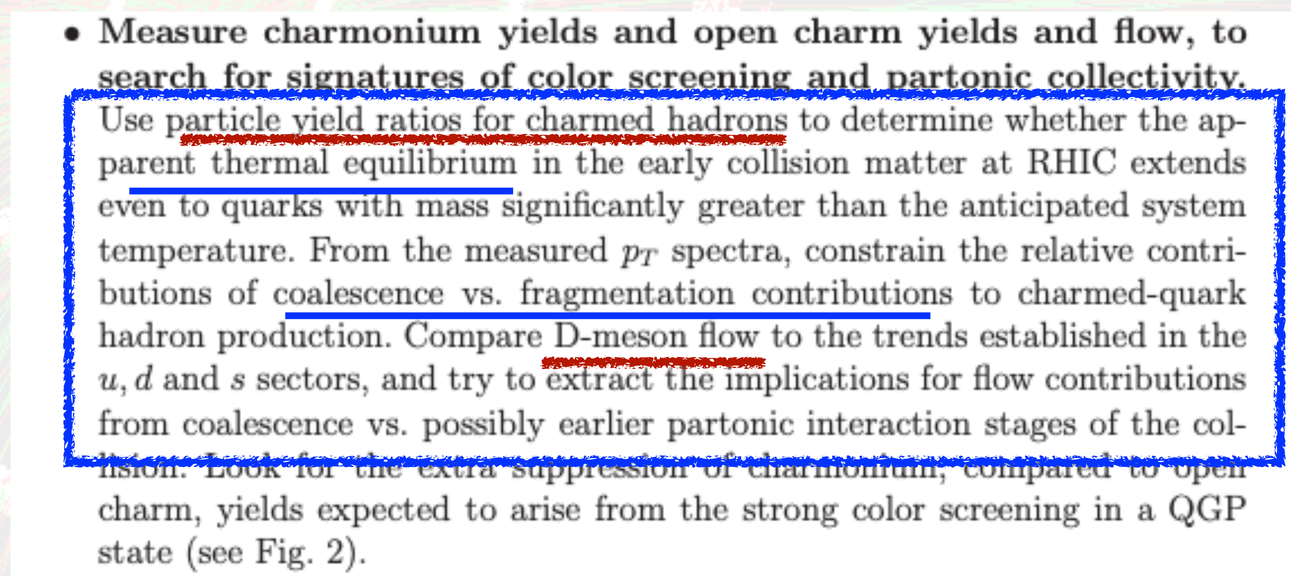
2003 PRL Cover Page



2005 RHIC White Papers

STAR:
Experimental and Theoretical Challenges in the Search for the Quark Gluon Plasma: The STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions

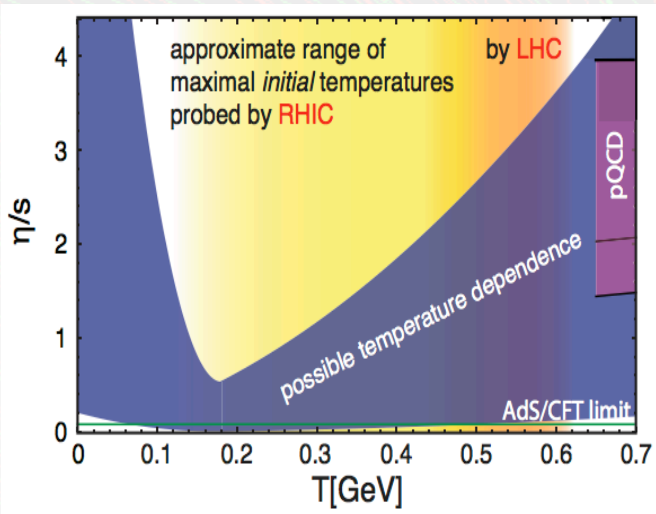
Nucl. Phys. A 757 (2005) 102



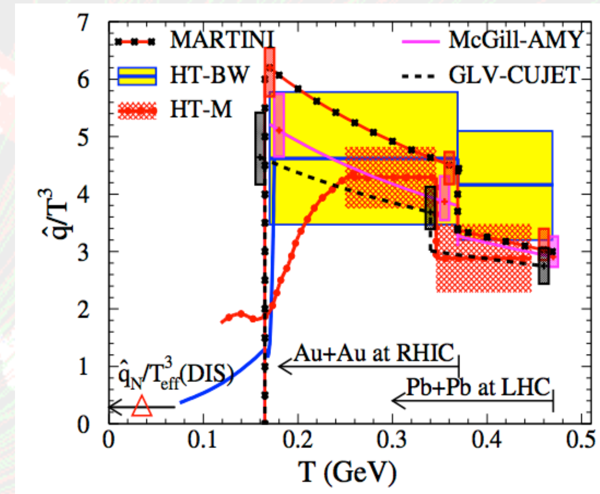
- **Measure charmonium yields and open charm yields and flow, to search for signatures of color screening and partonic collectivity.** Use particle yield ratios for charmed hadrons to determine whether the apparent thermal equilibrium in the early collision matter at RHIC extends even to quarks with mass significantly greater than the anticipated system temperature. From the measured p_T spectra, constrain the relative contributions of coalescence vs. fragmentation contributions to charmed-quark hadron production. Compare D-meson flow to the trends established in the u, d and s sectors, and try to extract the implications for flow contributions from coalescence vs. possibly earlier partonic interaction stages of the collision. Look for the extra suppression of charmonium, compared to open charm, yields expected to arise from the strong color screening in a QGP state (see Fig. 2).

sQGP Emergent Properties

~2 ~6 p_T (GeV/c)



?



What is the microscopic picture of "perfect fluid"?

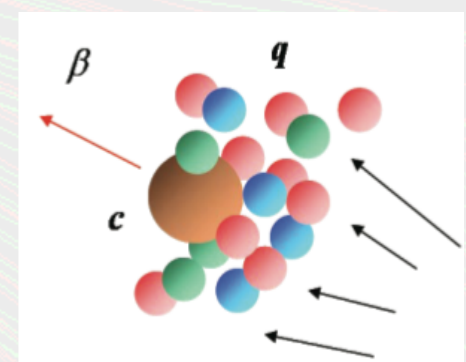
<u>Heavy Quarks in sQGP: Femtoscopic "Brownian" motion</u>

Langevin stochastic simulation

$M_Q >> T,\ \ M_Q >> gT$

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



Heavy quark transport – to probe QGP with comprehensive p_T coverage

- unique insights to both perturbative and non-perturbative regimes

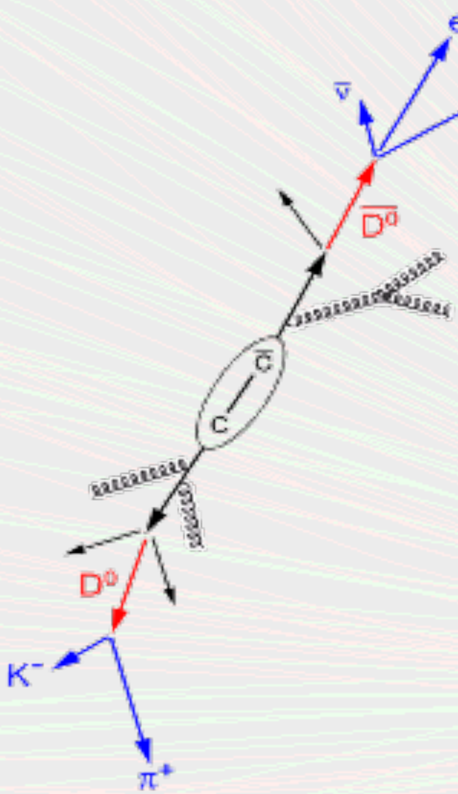
Early Measurements of Heavy Flavors

1) Decay electrons/muons:

- pros: large branching ratios; cons: bkgd, mixture of c-/b- decays

2) Hadronic decay channels

- pros: full kinematics; cons: huge bkgd w/o vertexing, small B.R.

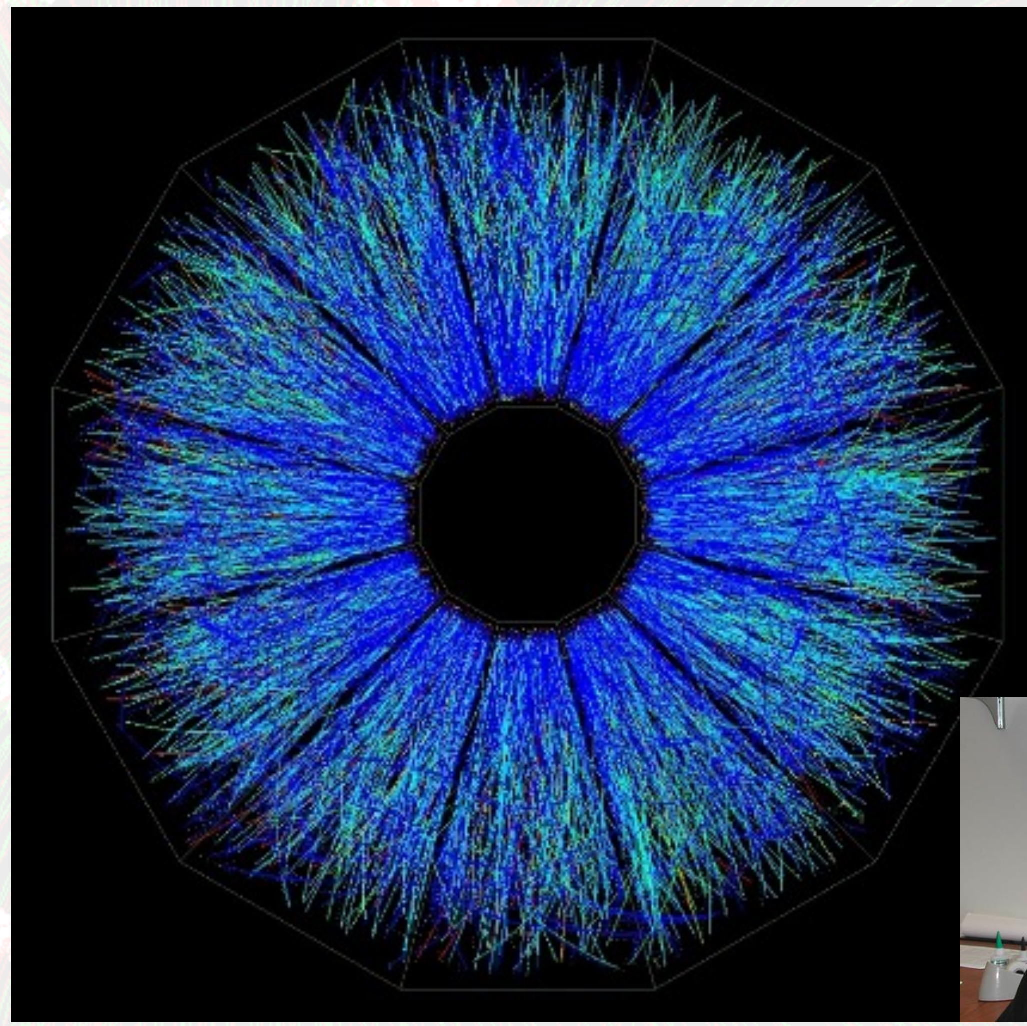


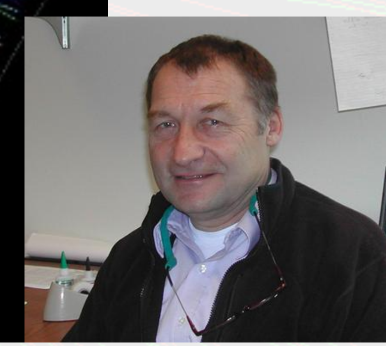
$c\tau(D^0) \sim 120\ \mu m$

$c\tau(\Lambda_c) \sim 60\ \mu m$

$BR(c \rightarrow e) \sim 10\,\%$

$BR(D^0 \rightarrow K\pi) \sim 3.8\,\%$

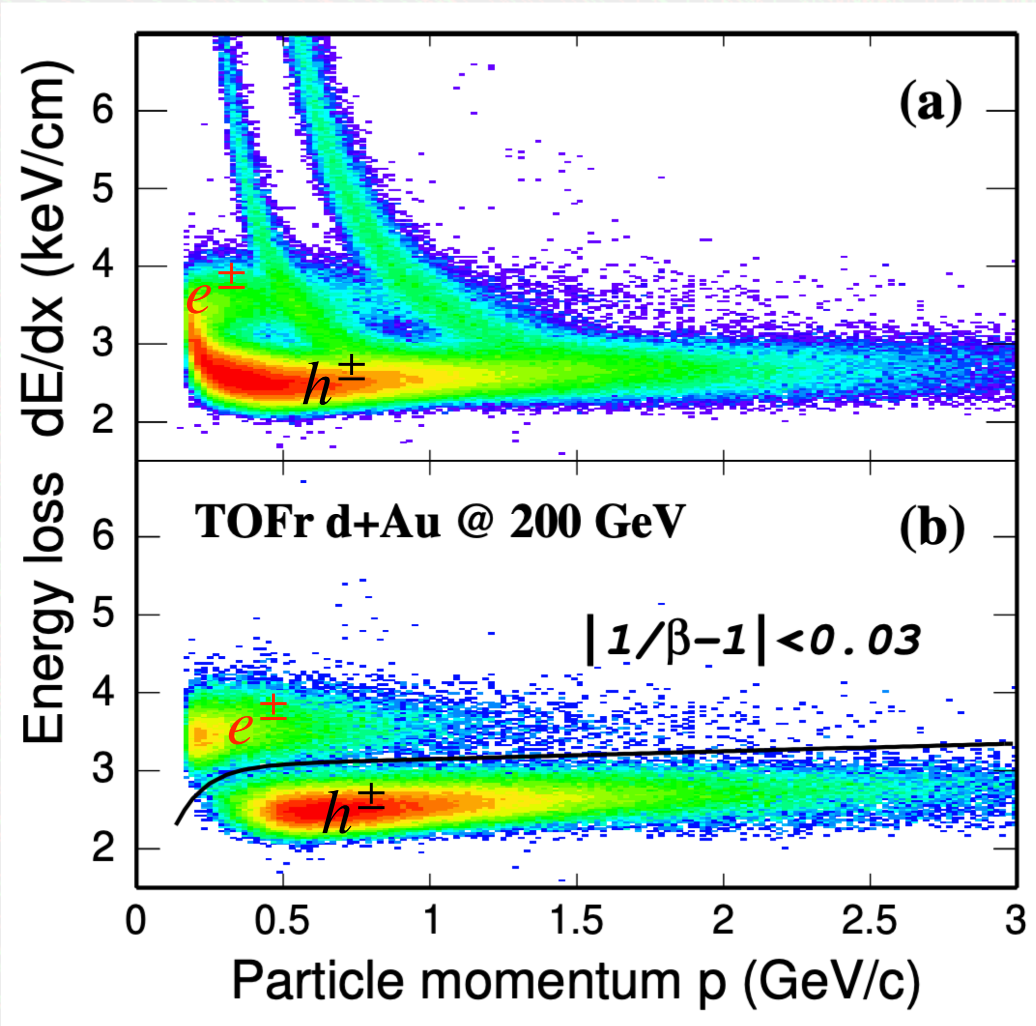




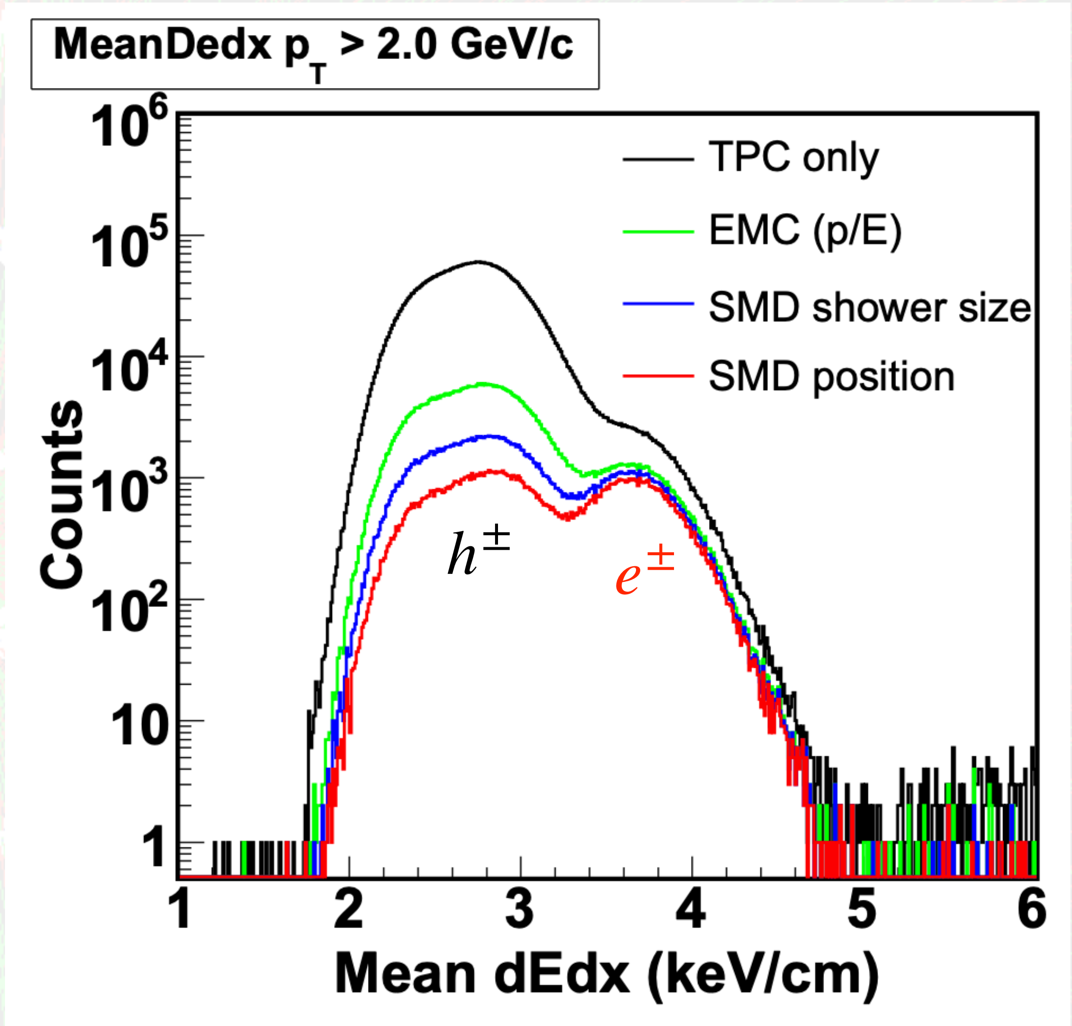
STAR TPC is designed to measure thousands of charged particles coming from heavy ion collisions, and has been in operation for 25 years flawlessly!

TPC dEdx (+ others) for Electron Identification

dE/dx + TOF



dE/dx + BEMC/BSMD



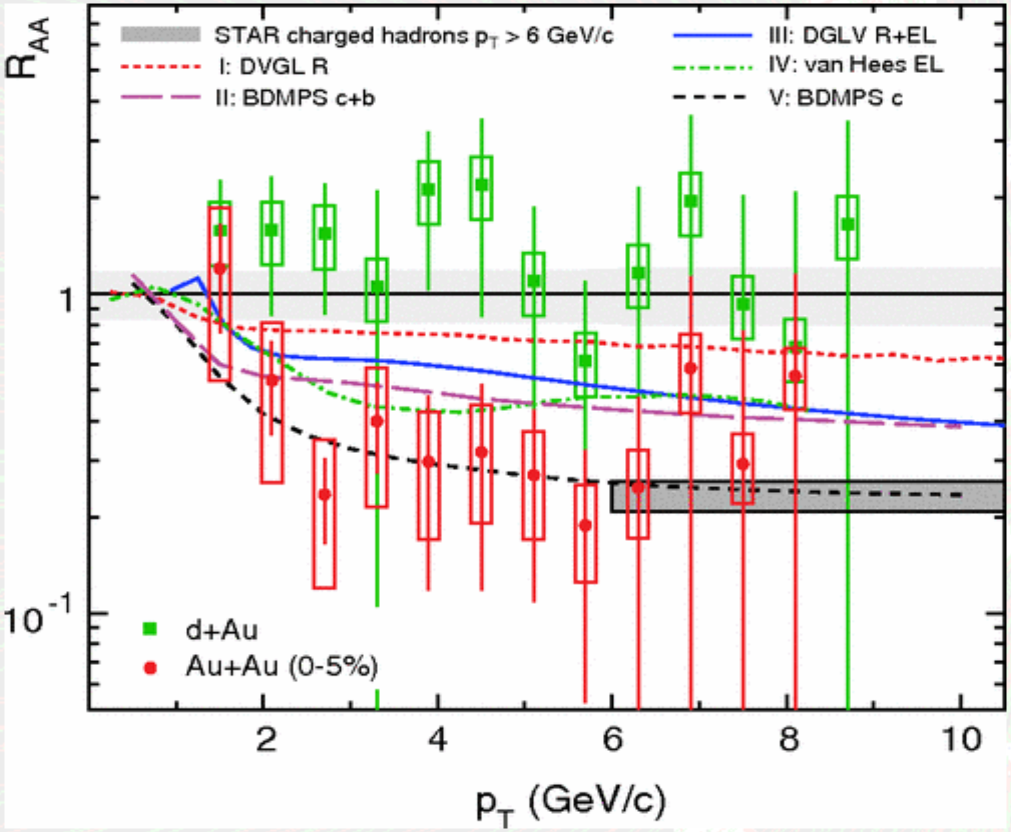
6-7% dE/dx resolution allowing separation of electrons from hadrons

- further suppression of hadron contamination with help of TOF and BEMC/BSMD

Achievements from Early Measurements

single electron R_{AA}

PRL 98 (2007) 192301

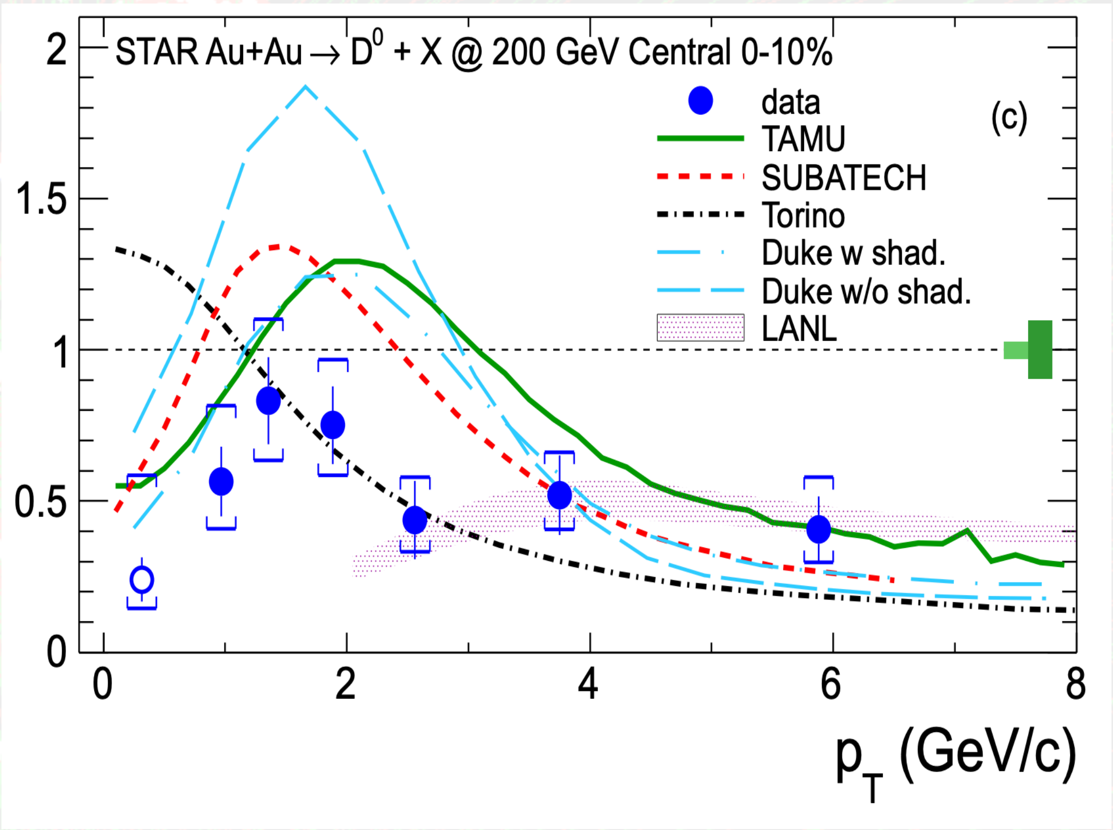


$R^e_{AA} \sim R^h_{AA}$ at high p_T

significance of **collisional energy loss**

D^0 R_{AA}

PRL 113 (2014) 142301

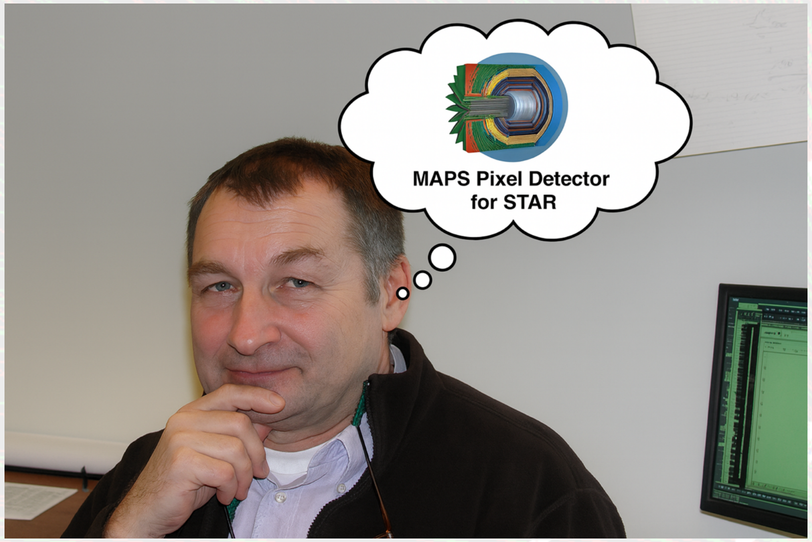


Bump structure in low p_T D^0

collective flow of *c*-quark in medium

Concept Development of Heavy Flavor Tracker

After finishing the TPC construction



CMOS based active pixel sensor technology for STAR
- idea conceived in ~1999 led by Howard Wieman

Sensor Technology	MAPS	Hybrid Pixel	CCD
Granularity	+	-	+
Material budget	+	-	+
Readout speed	+	++	-
Radiation tolerance	+	++	-

MAPS - "fast (1000+ fps) digital camera"

Early Concept

μVertex detector

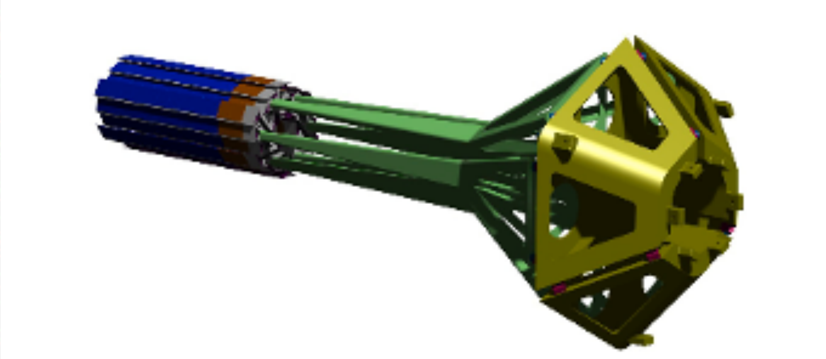
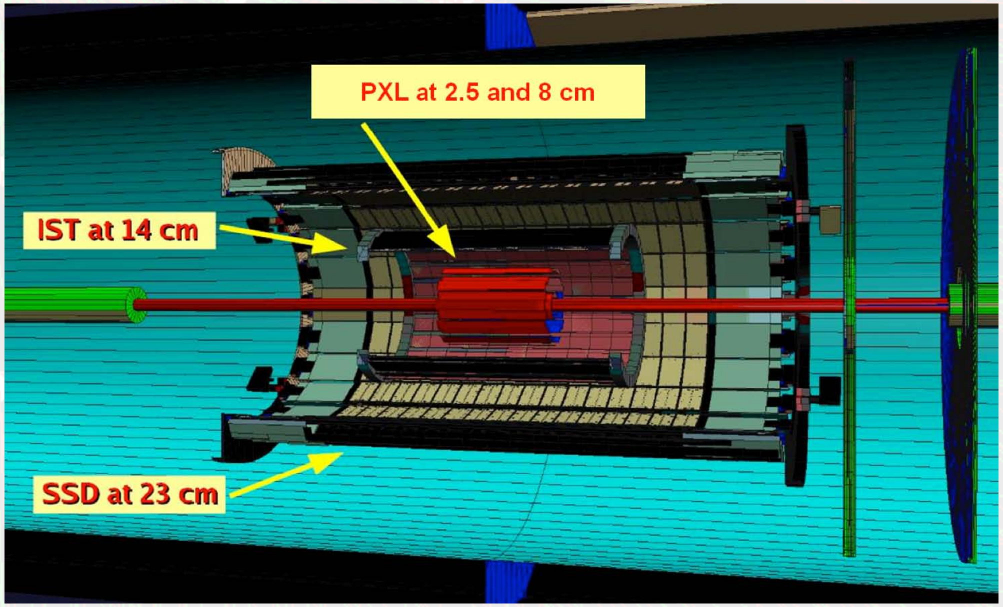


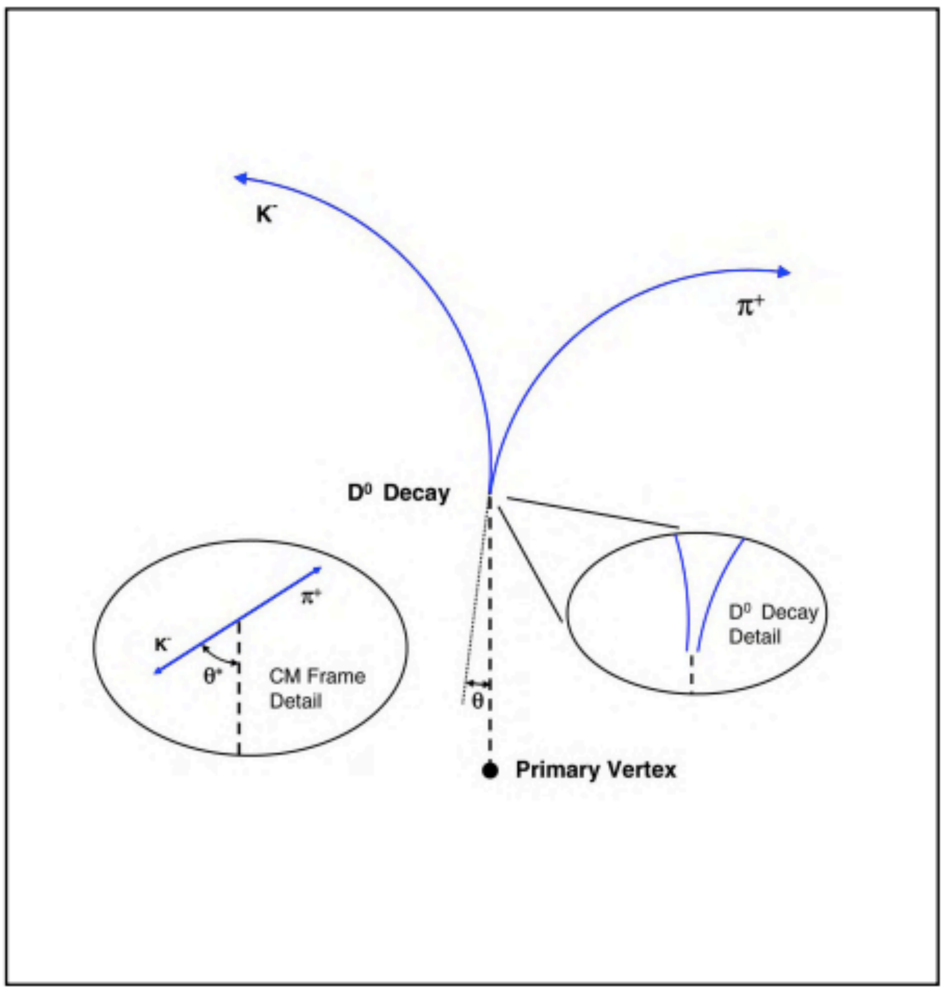
Figure 51: Detector support structure with kinematic mounts to insure repeatable detector positioning.

Heavy Flavor Tracker Proposal in 2006



STAR Heavy Flavor Tracker Proposal

A Heavy Flavor Tracker for STAR



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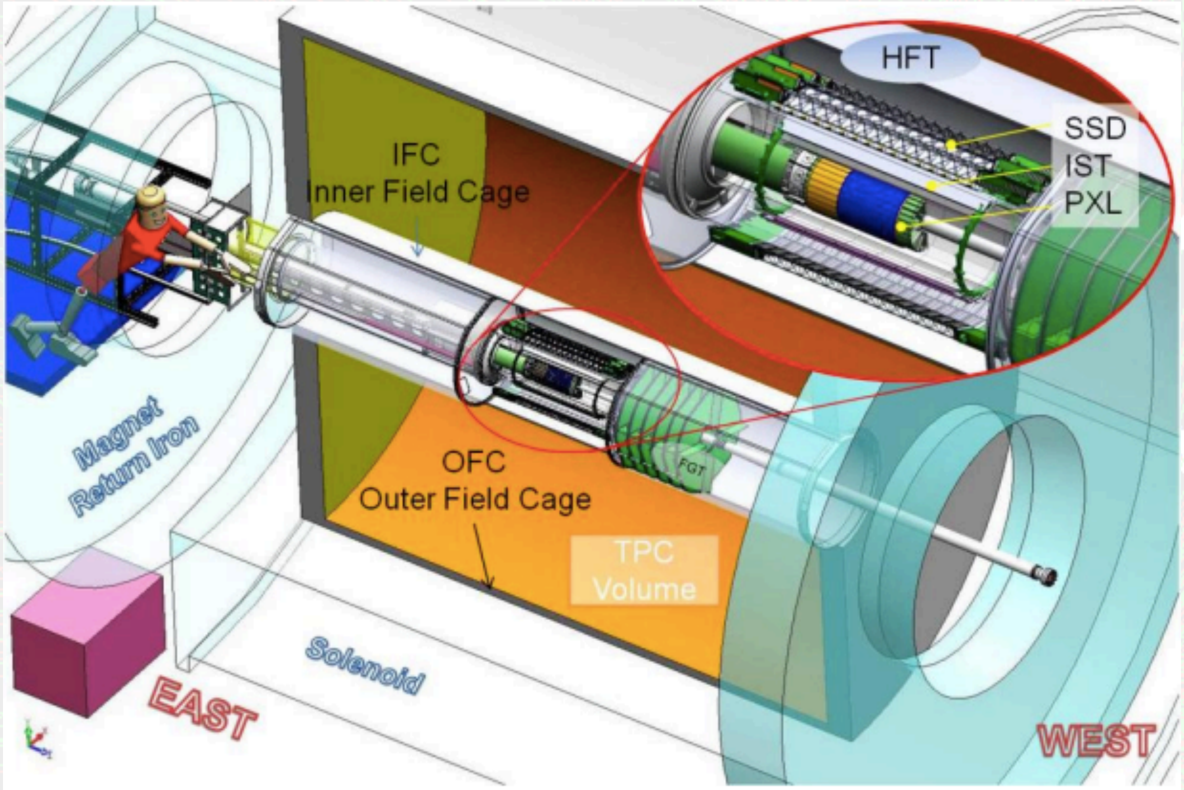
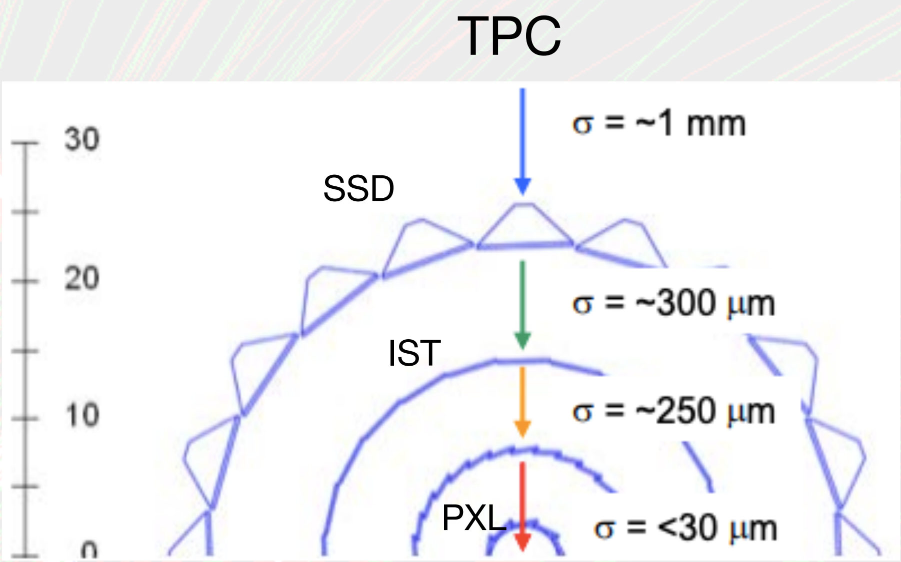
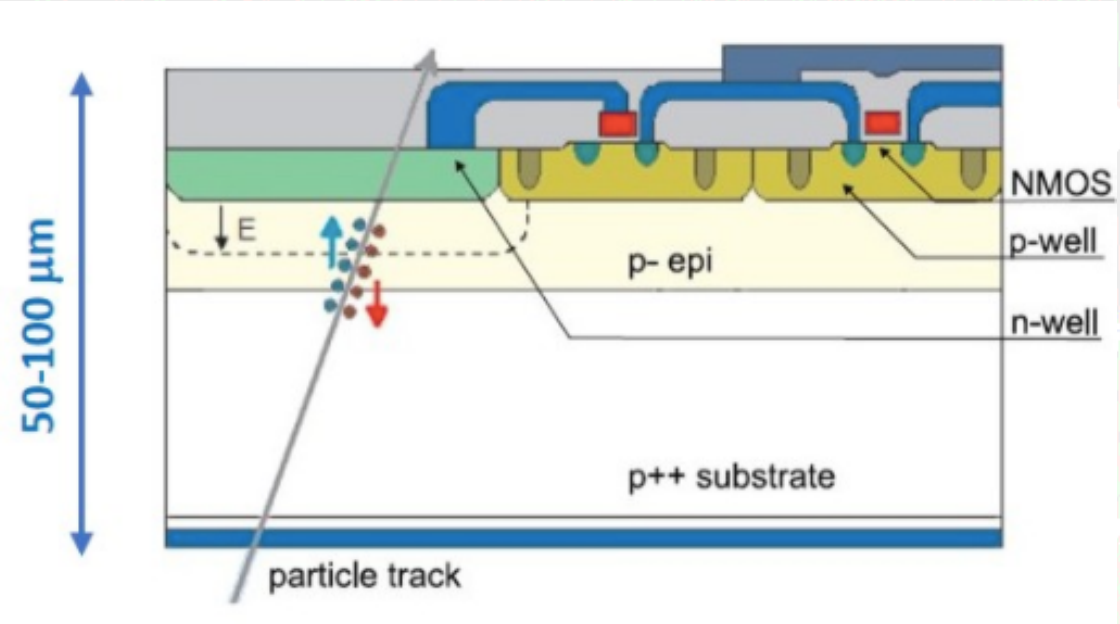
STAR Heavy Flavor Tracker (HFT)





Detector	Radius (cm)	Pitch Size R/φ - Z (μm - μm)	Thickness
Silicon **S**trip **D**etector	22	95 / 40000	1% X_0
Intermediate **S**ilicon **T**racker	14	600 / 6000	1.3%X_0
Pi**X**e**L**	8	**20.7 / 20.7**	0.5%X_0
	2.8	**20.7 / 20.7**	**0.4%X_0 ***

Monolithic Active Pixel Sensor (MAPS) Silicon Detector



- First application of Monolithic Active Pixel Sensor (MAPS) at a collider experiment
  - ✦ fine pitch size (20.7 x 20.7 μm^2)
  - ✦ thin detector design (0.4% X_0)
  - ✦ carbon fiber support, air cooling (170 mW/cm^2)
  - ✦ moderate integration time (186μs)
  - ✦ radiation hard / fast replacement (~8h)

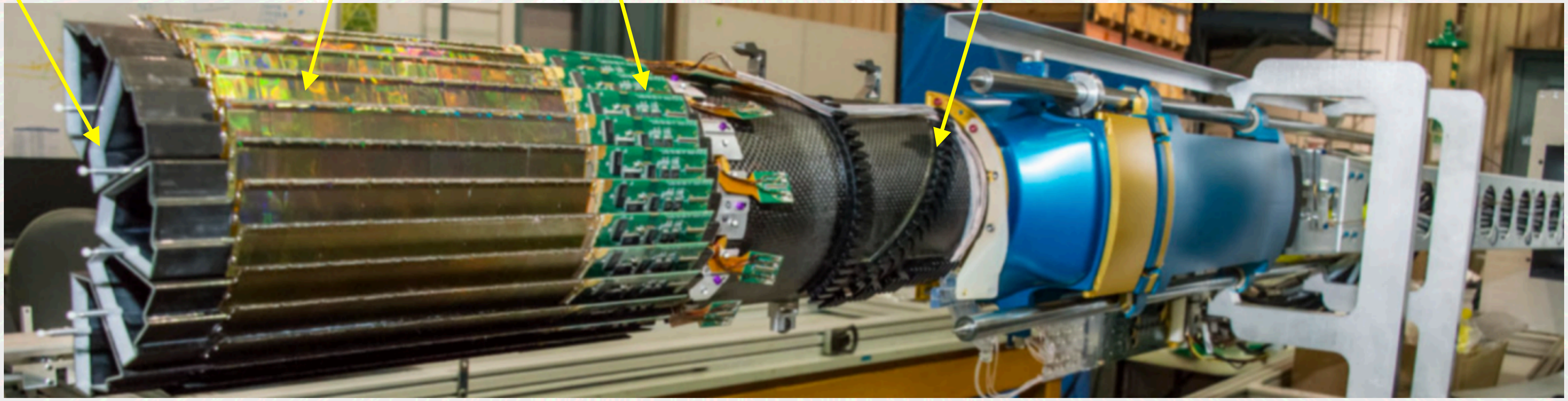
G. Contin et al, NIMA 907 (2018) 60

carbon fiber support tube

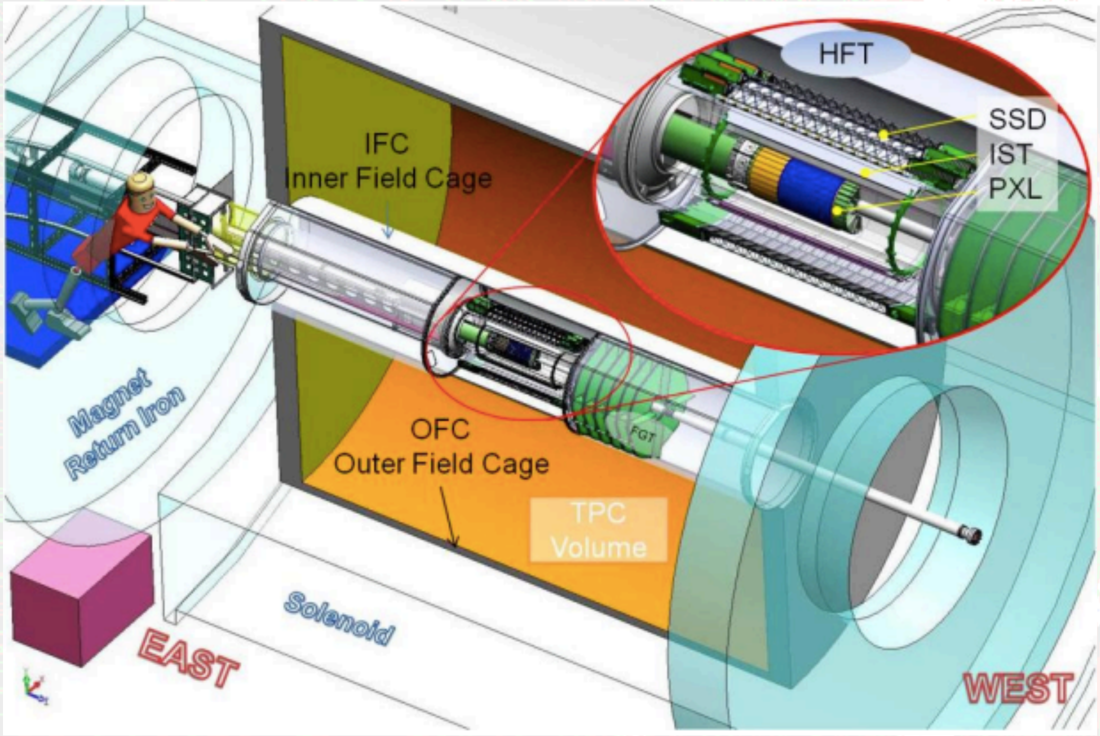
outer layer sensors

outer layer FEEs

cantilevered mechanic support



Fast Installation/Retraction



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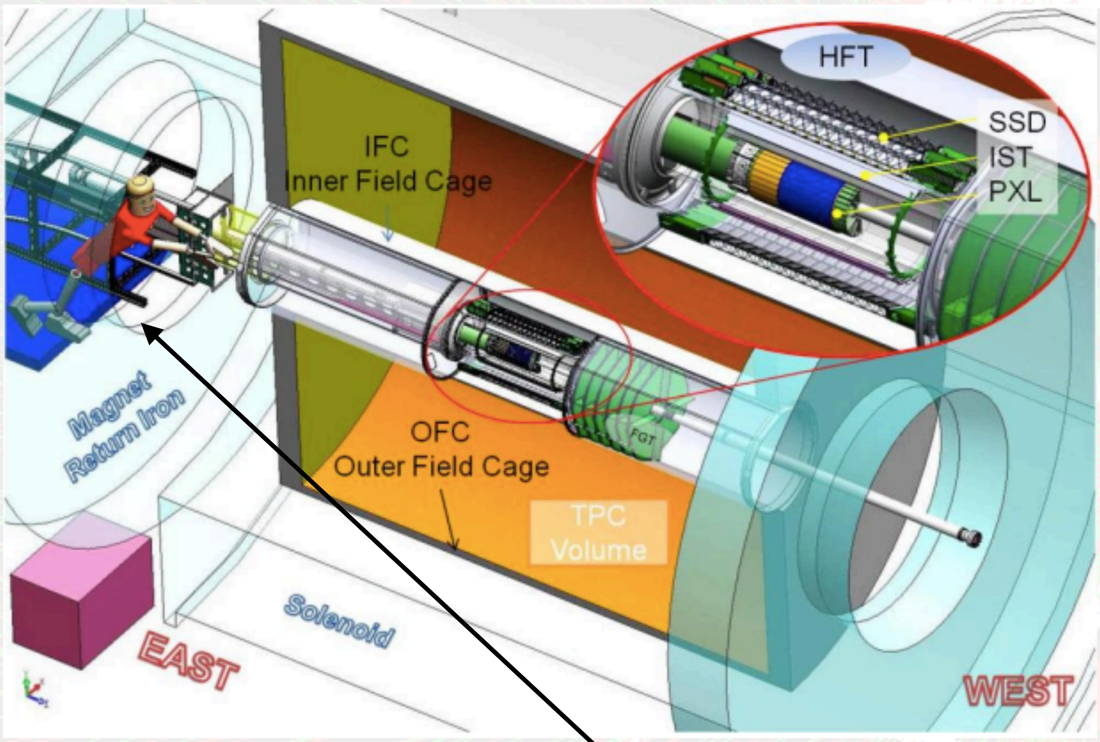
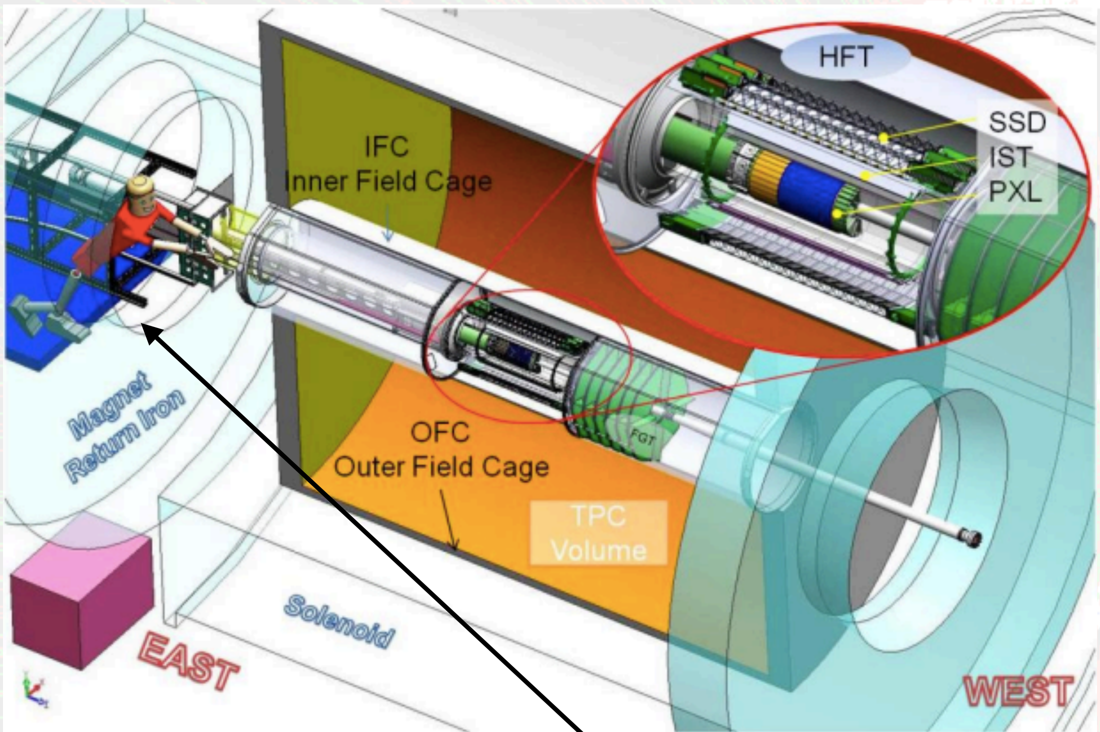


Howard Wieman

Fast Installation/Retraction

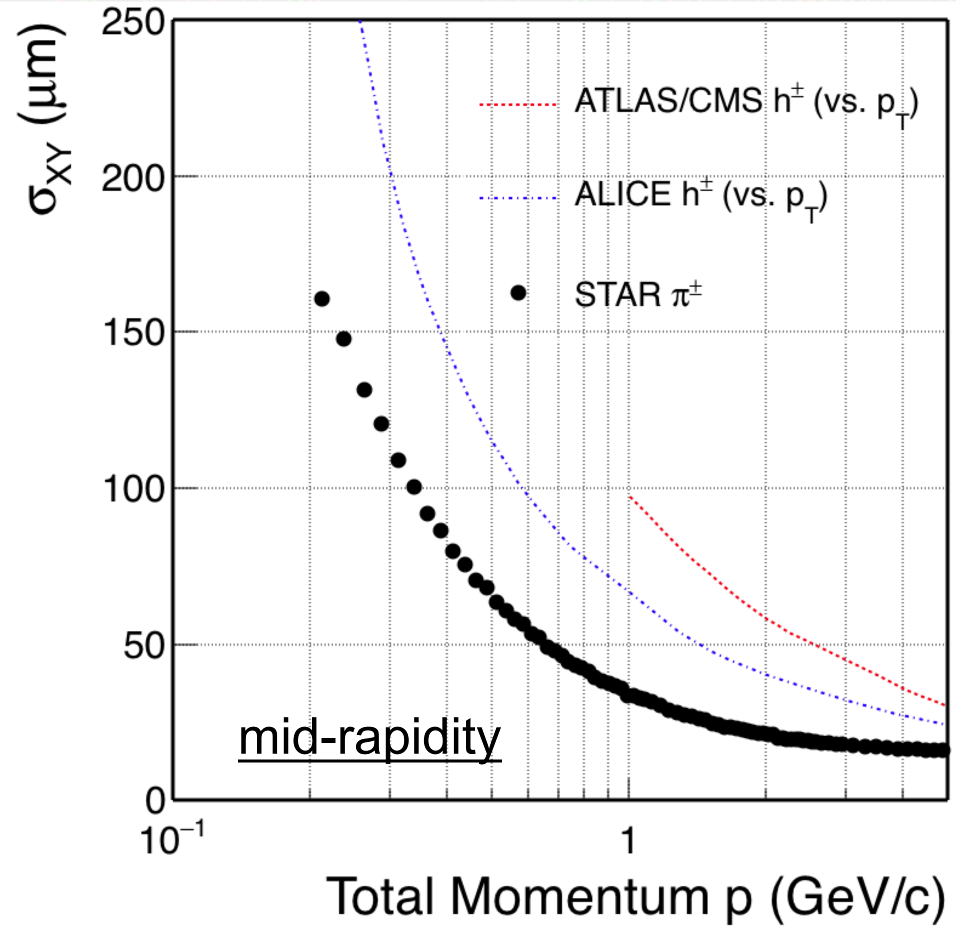


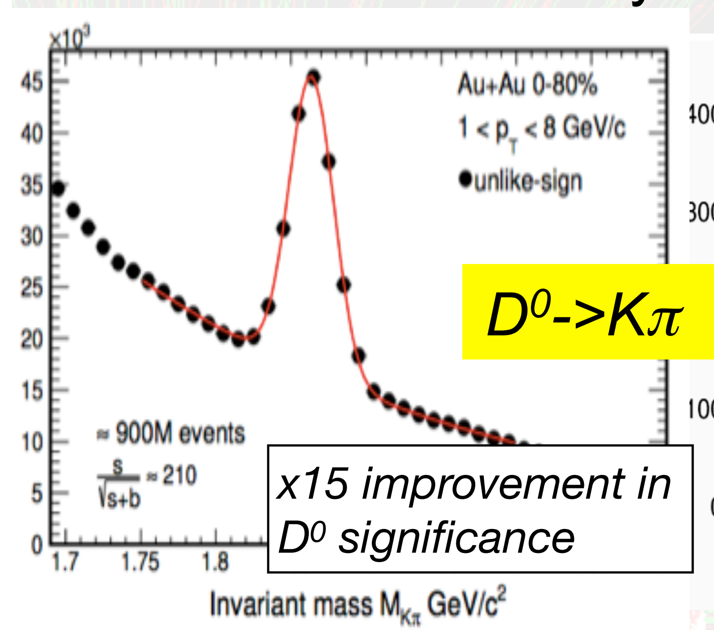
Howard Wieman

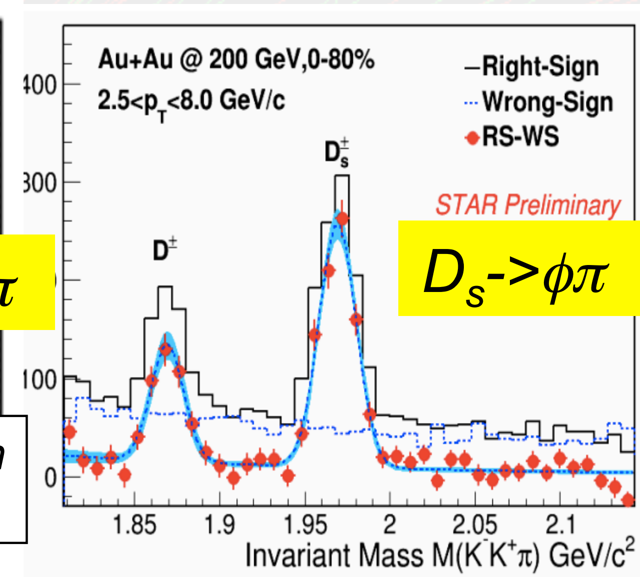

10 cm
Au+Au @ 200 GeV

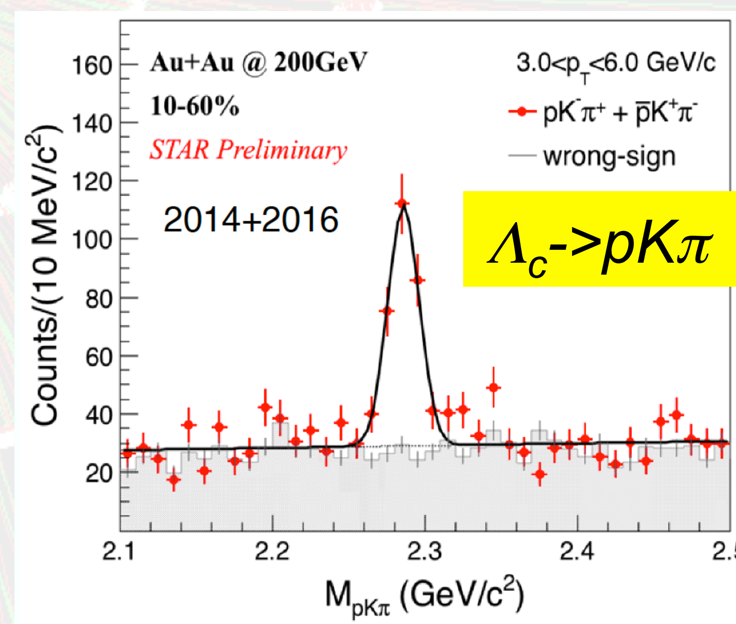
HFT Detector Performance

Exclusive reconstruction of HF hadrons in heavy-ion collisions





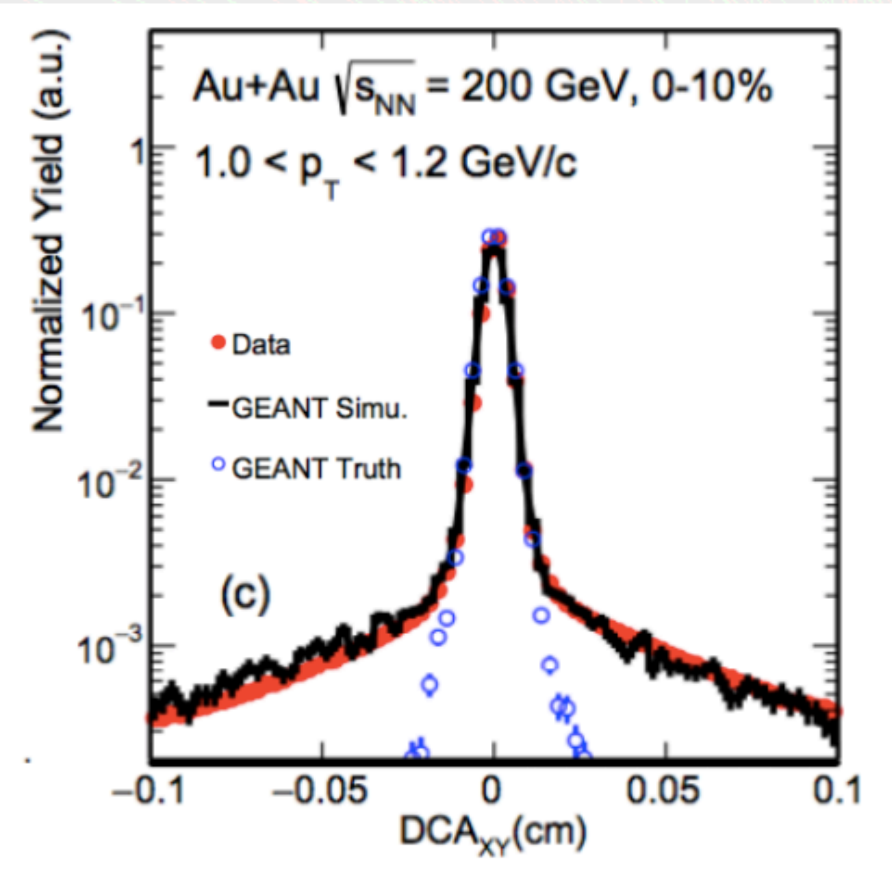




STAR	30 μm @ 1 GeV/c (p)
ALICE	70 μm @ 1 GeV/c (p_T)
ATLAS/CMS	100 μm @ 1 GeV/c (p_T)

Simulation and Embedding

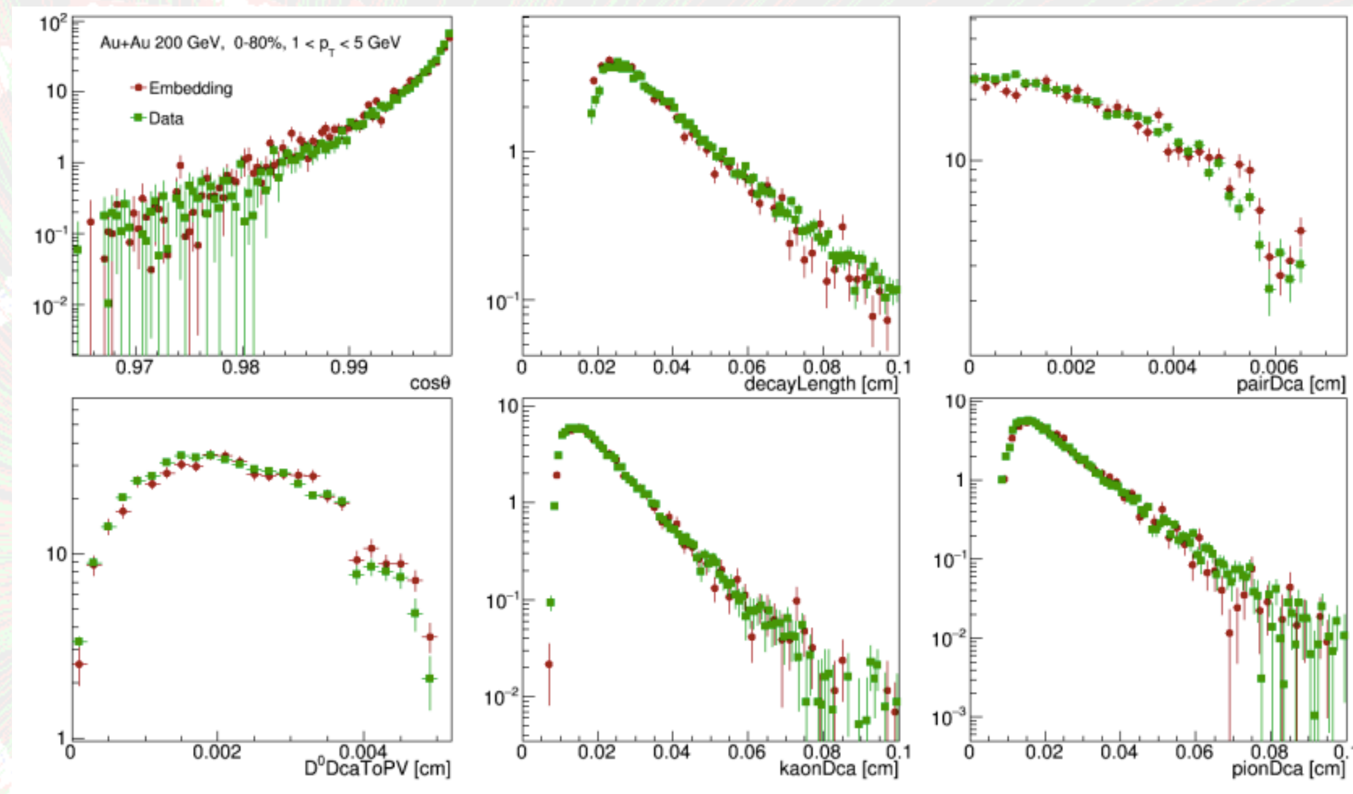
Full Hijing + Pileup Simu.



PRC 99 (2019) 034908

Embedding into Real Data

D⁰ topo variables

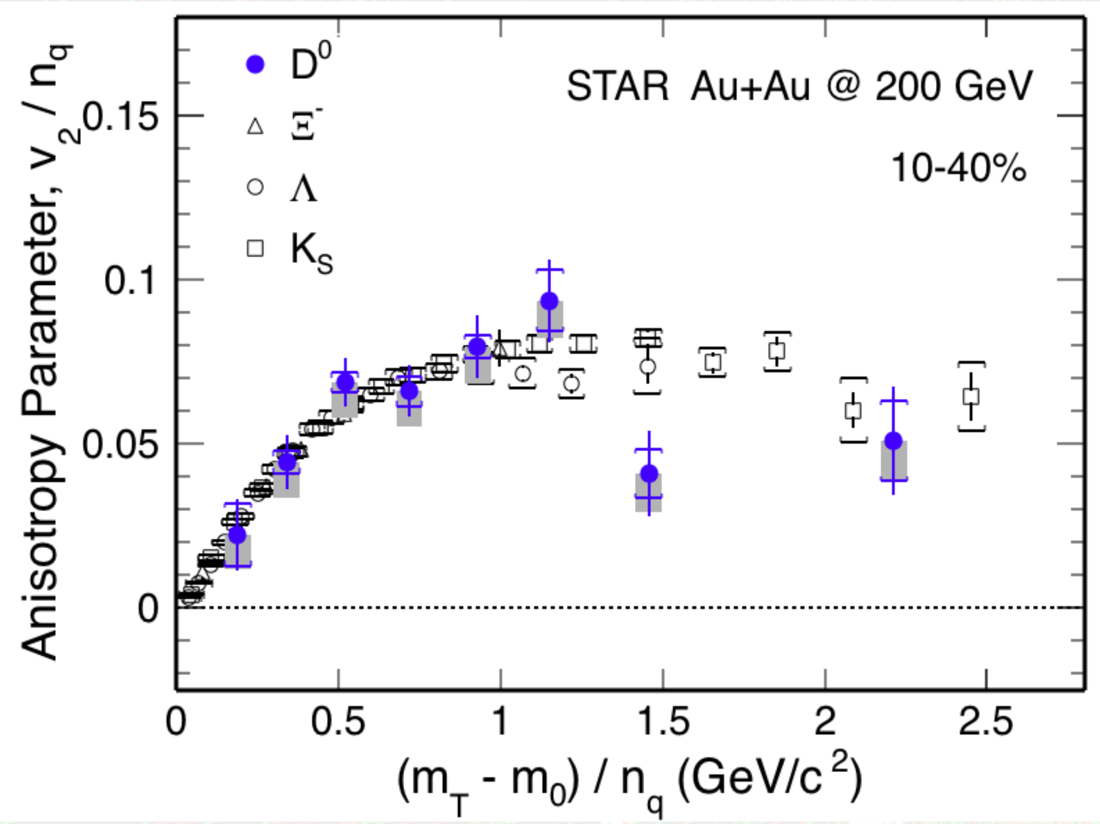


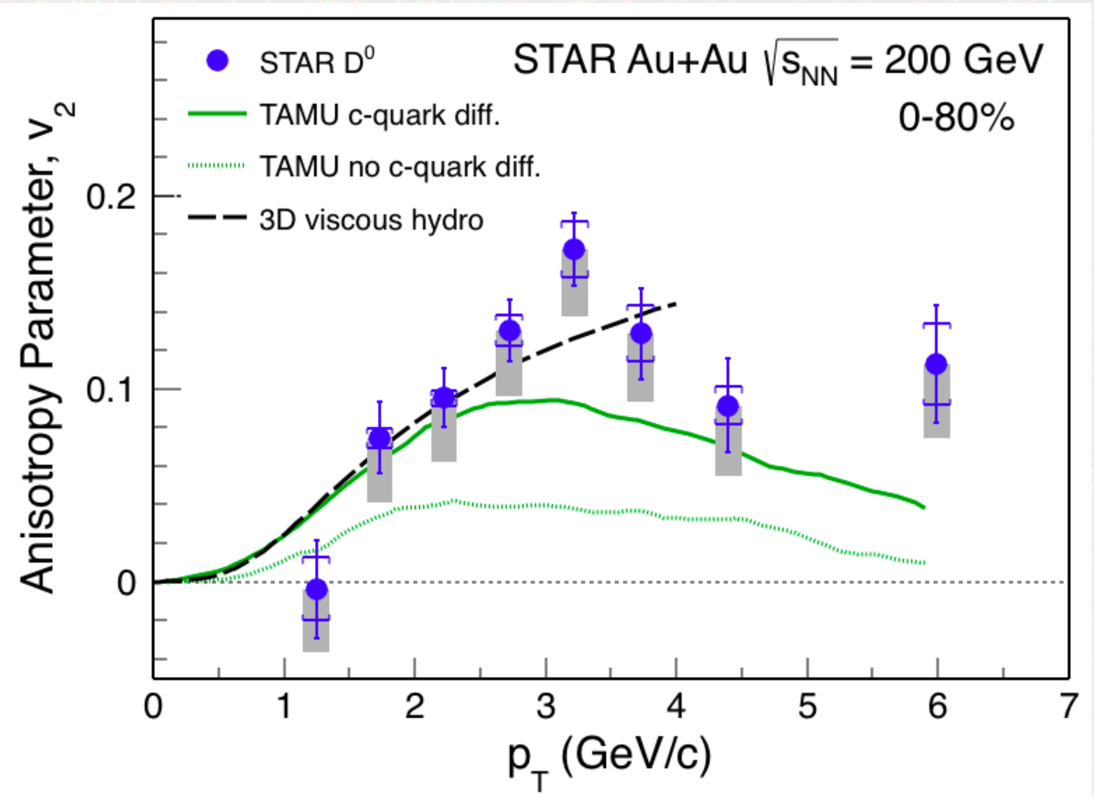
J. Webb et al., CHEP 2019

Very good description of HFT performance (DCA, matching ratio, D^0 topo variables) with both full simulation and embedding production!

D^0 Meson v_2 in A+A Collisions

PRL 118 (2017) 212301

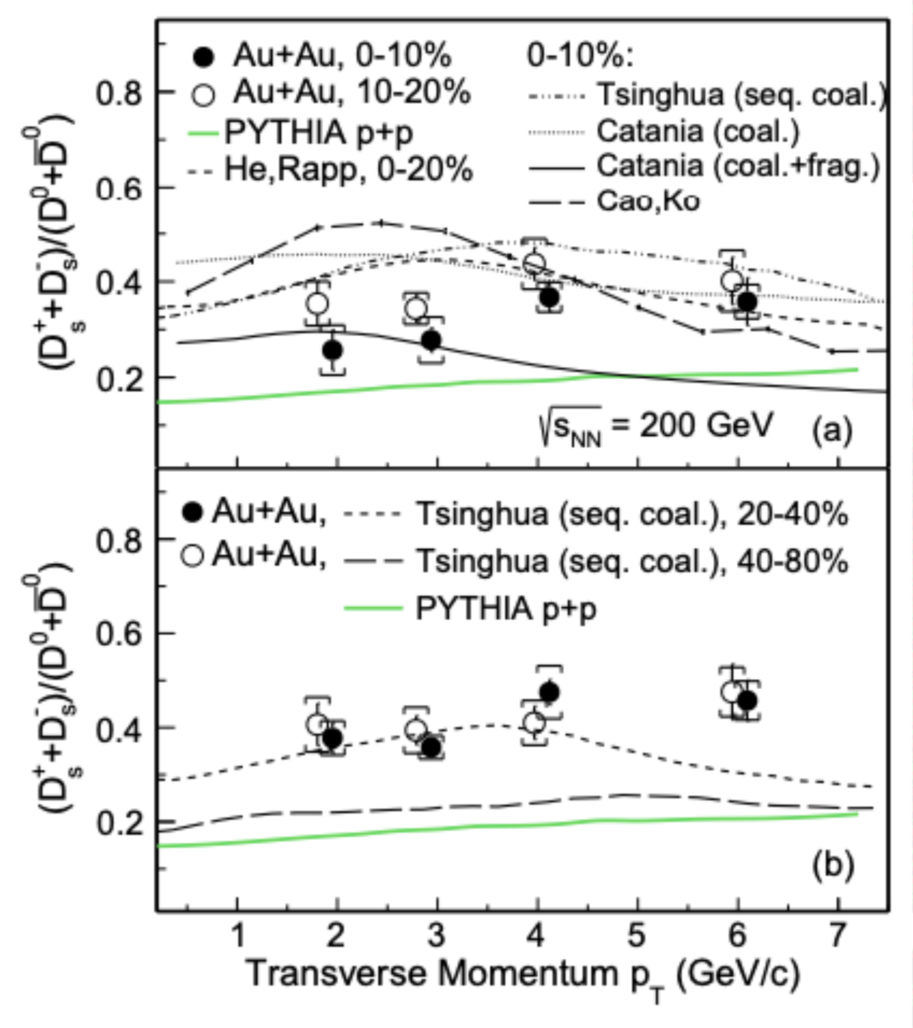




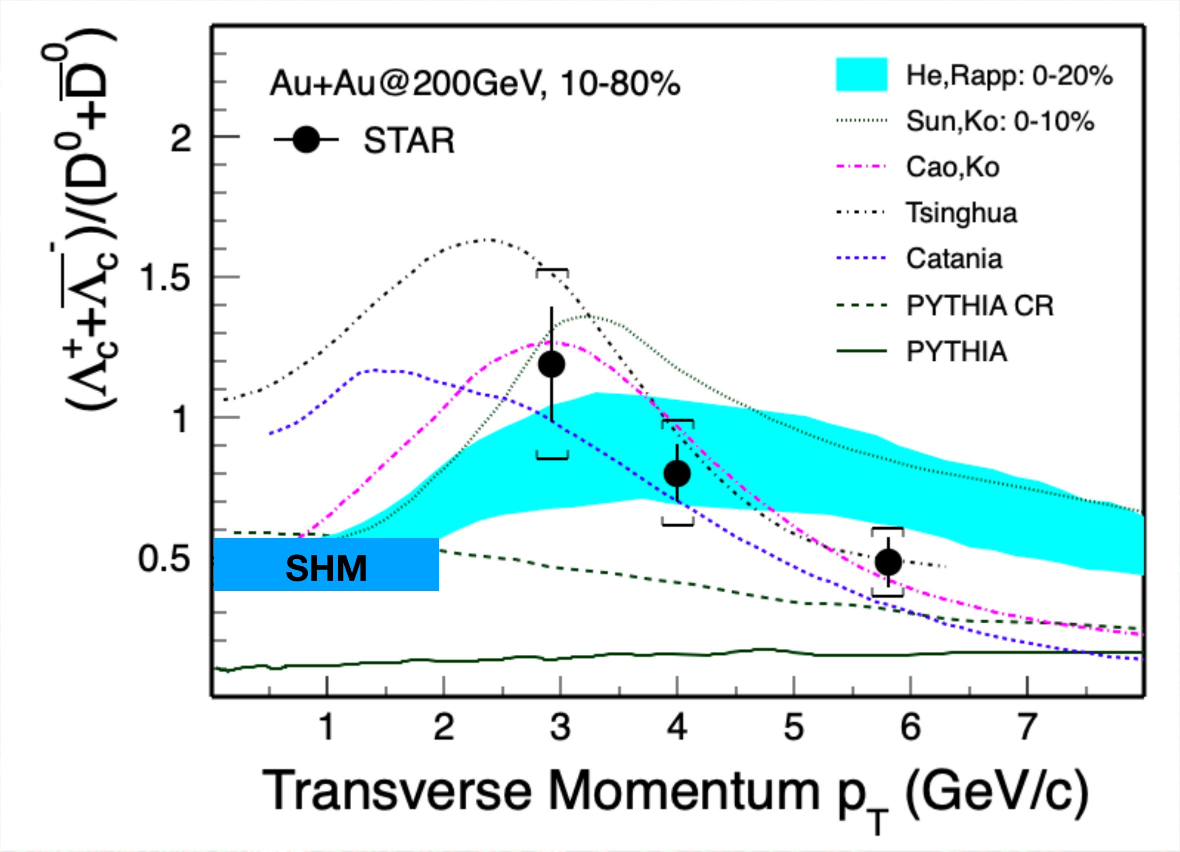
- v_2(D) follows the $(m_T\text{-}m_0)/n_q$ scaling as light hadrons

  Evidence of charm quarks reaching local thermal equilibrium!
- Large D^0 v_2 ordinates from charm quark diffusion in QGP
- 3D viscous hydro consistent with D^0 v_2 data up to 4 GeV/c

D_s^+/D^0 and Λ_c^+/D^0 Enhancement in Heavy Ion Collisions



PRL 127 (2021) 092301

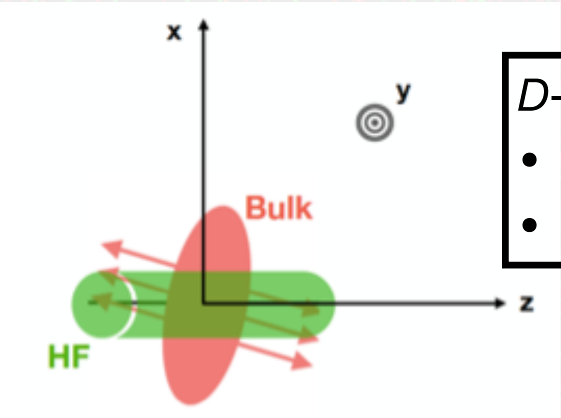


PRL 124 (2020) 172301

- D_s^+/D^0 and Λ_c/D significantly higher than fragmentation baseline
- Models with coalescence hadronization + strangeness enhancement qualitatively reproduce the data

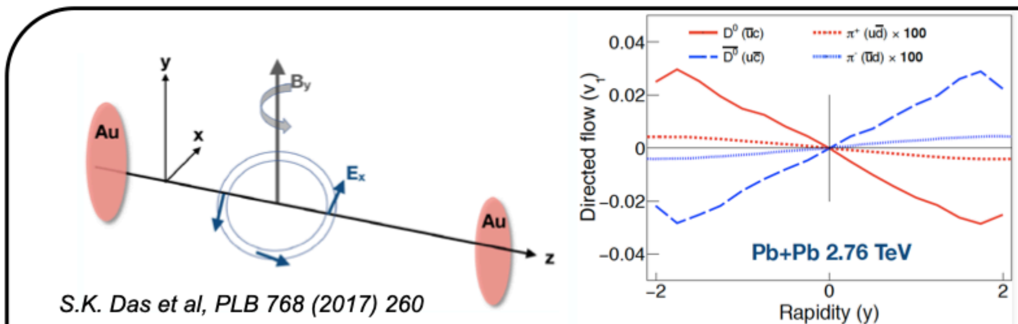
$D/\overline{D}$ v₁ - sQGP Properties and Initial *B*-field

S. Chatterjee & P. Bozek, PRL 120 (2018) 192301



D-meson v_1 sensitive to
- geometry tilt of QGP source
- HQ diffusion coefficient $D_s(T)$

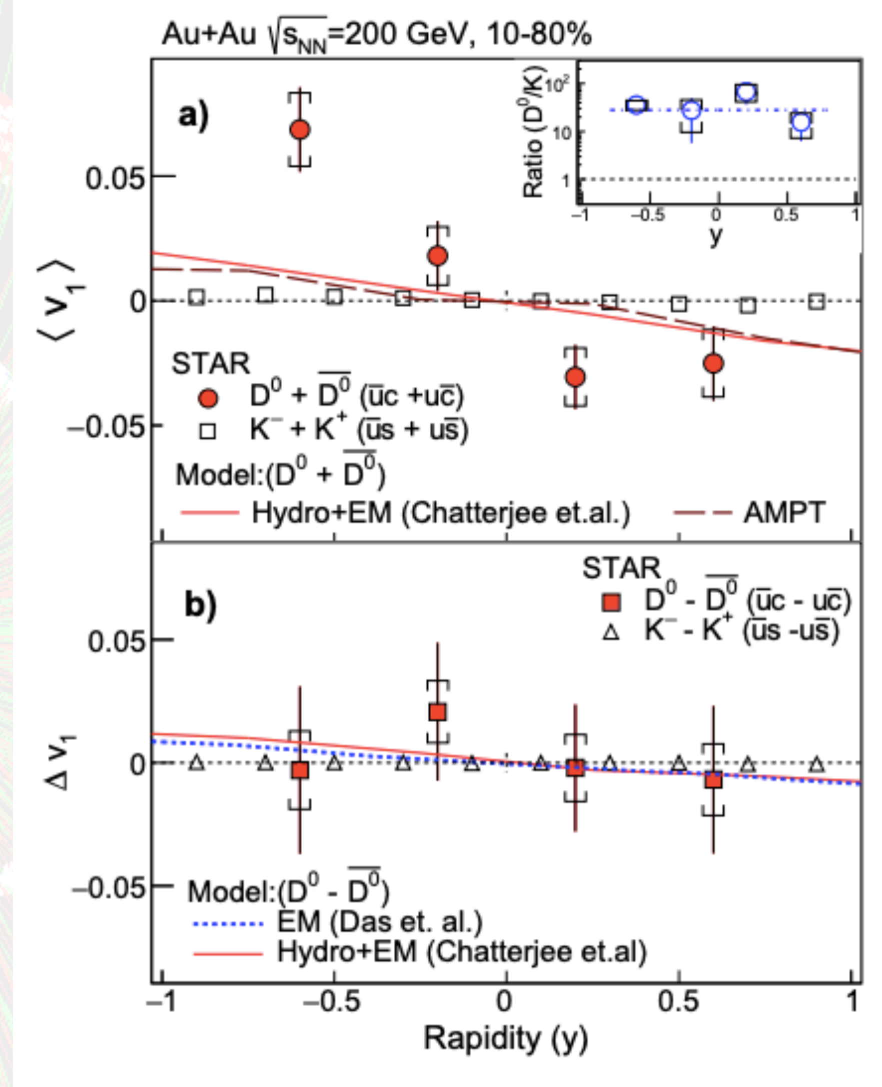
$D/\overline{D}$ v_1 difference sensitive to
- initial magnetic field



S.K. Das et al, PLB 768 (2017) 260

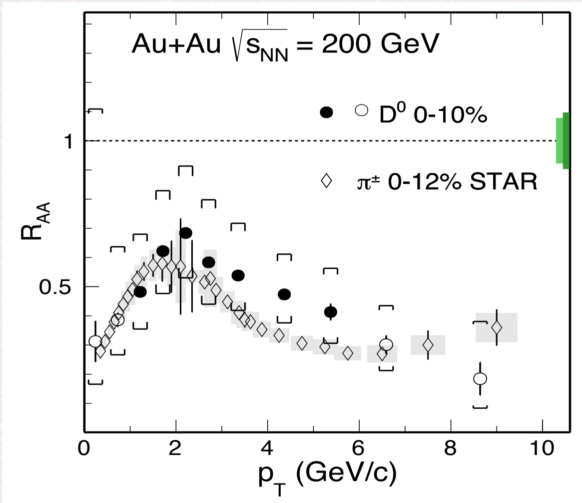
Strong B field in HIC -> v_1(D) = − v_1(Dbar), $v_1(h^+)-v_1(h^-)$~0

PRL 123 (2019) 162301



- $v_1(D) \gg v_1(h)$
  - *T*-dependence of diffusion coefficient
- $\Delta v_1(D)$: need more precise measurements

Mass Hierarchy of Parton Energy Loss

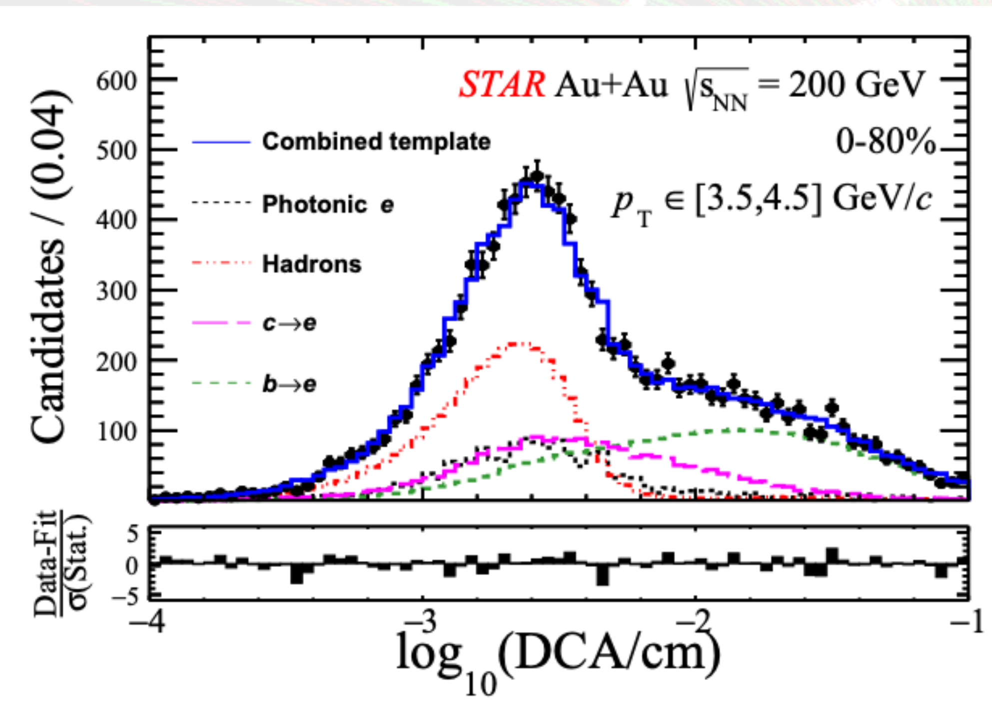


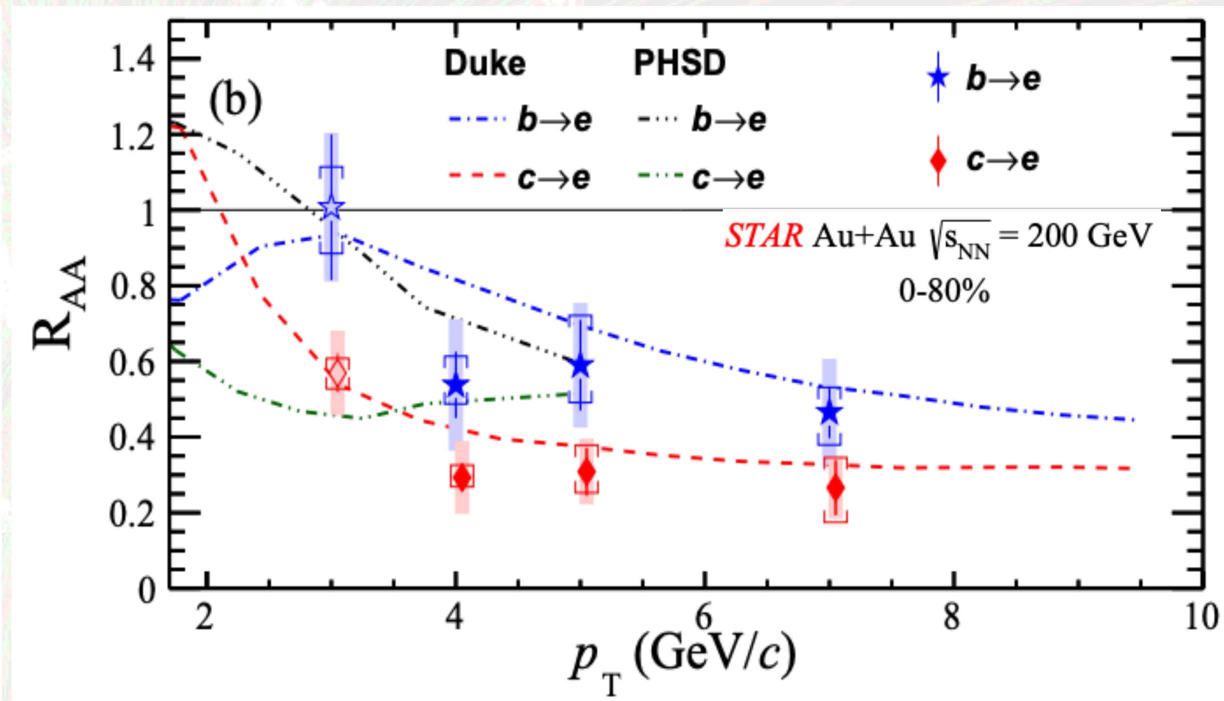
- Energy loss models predict:

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

- Data: $R_{AA}(D) \sim R_{AA}(\pi)$ at 6 GeV/c ! Go for open bottom!

EPJC 82 (2022) 1150



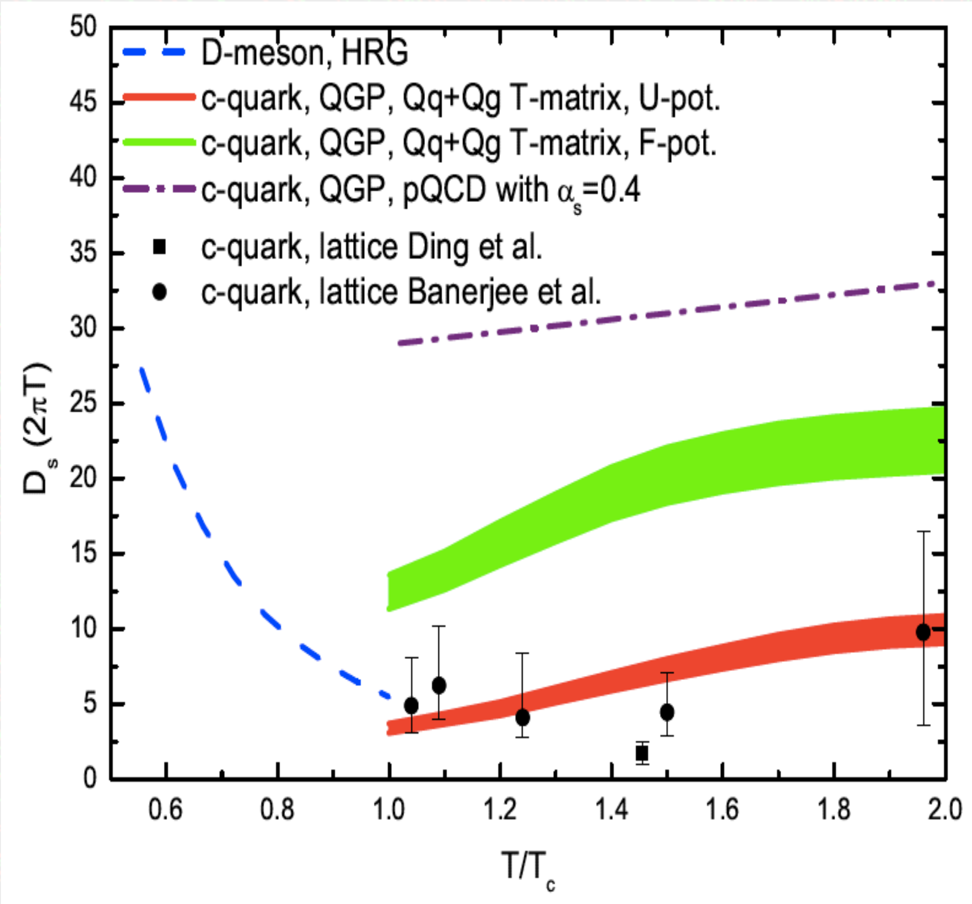


- $R_{AA}(e_b) > R_{AA}(e_c)$ at $p_T > 3$ GeV/c

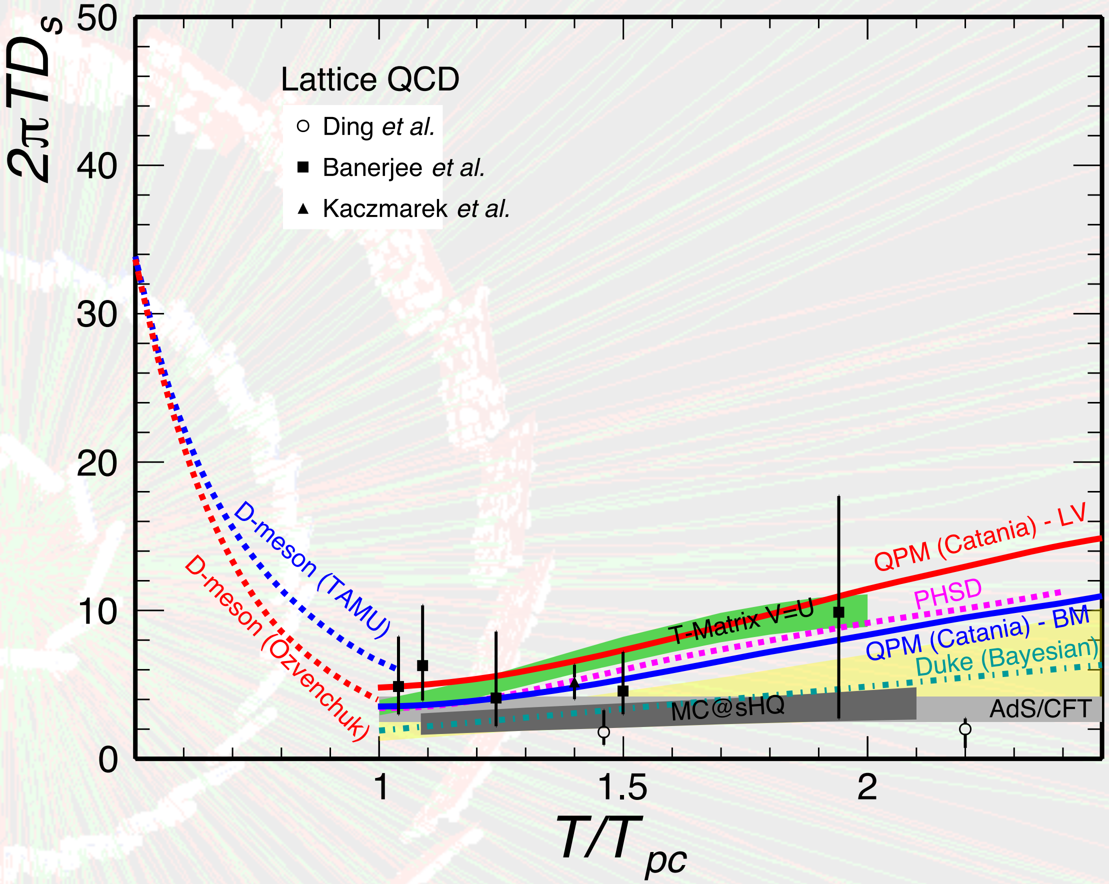
- mass hierarchy of parton energy loss

Charm Quark Diffusion Coefficient

2015



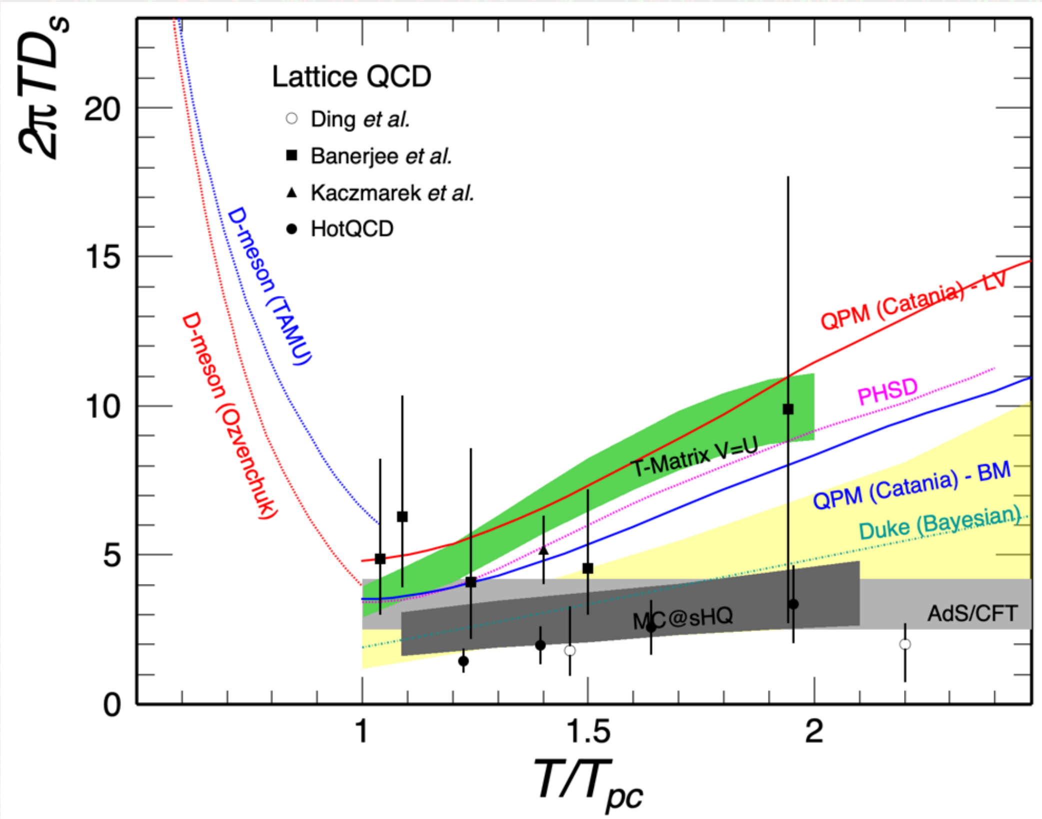
2019

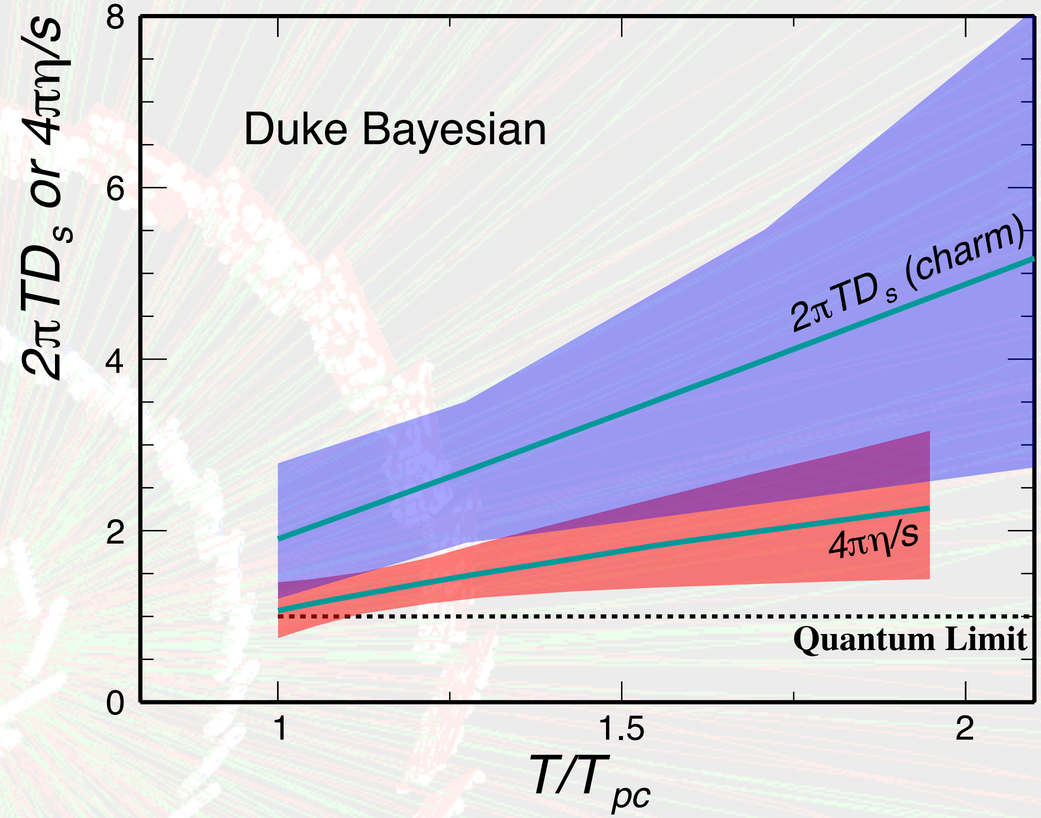


- Charm quark $2\pi TD_s$ **~ 2-5** at near T_c
    - consistent with lattice QCD calculations

Microscopic Picture of "Perfect Fluid"

$2\pi TD_s$: Y. Xu et al, PRC 97 (2018) 014907
η/s: J. Bernhard et al, Nature Physics 115 (2019) 1113





- $2\pi TD_s$ **~ 2-5** at near T_c
- Scattering width $\Gamma \sim 3/D_s \sim$ 1 GeV
  - no light quasi-particles

$$\frac{2\pi TD_s}{4\pi\eta/s} = \begin{cases} 5/2 & \text{pQCD} \\ 1 & \text{AdS/CFT} \end{cases}$$

Temperature dependence - transition from strongly coupled fluid to weakly coupled pQCD region

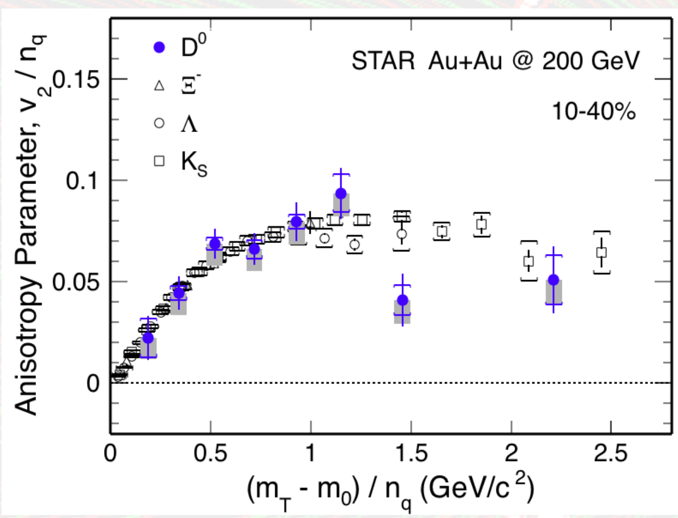
STAR's Contributions to HF and Beyond

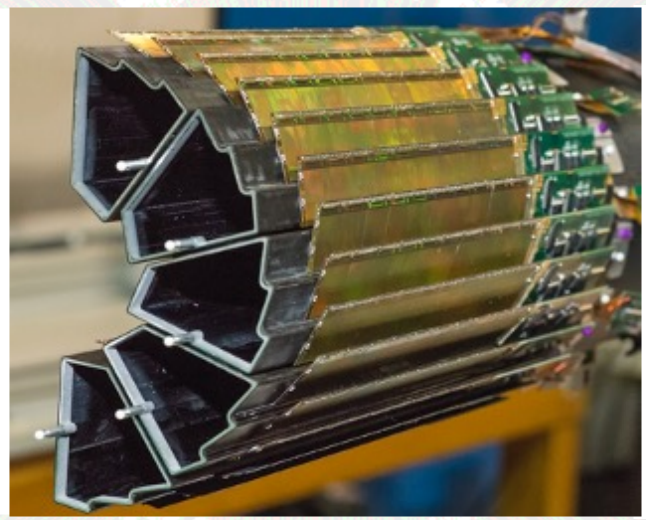
To Heavy Flavor Physics

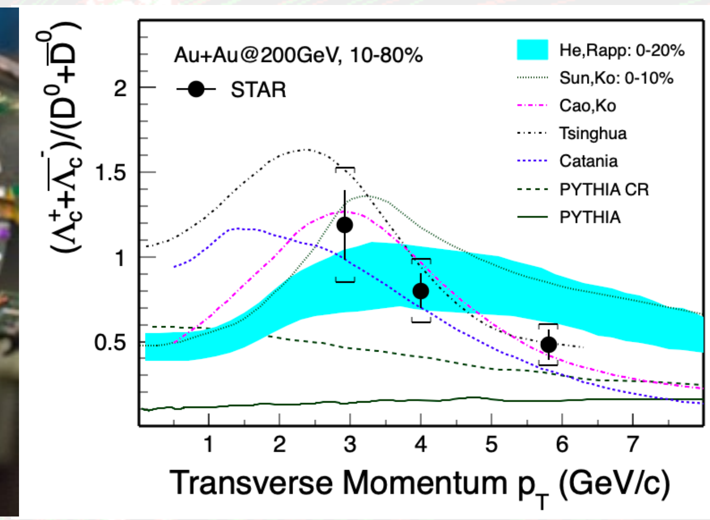
1) Revealed collisional energy loss mechanism

2) Demonstrated charm quark collectivity through diffusion

3) Illustrated coalescence hadronization





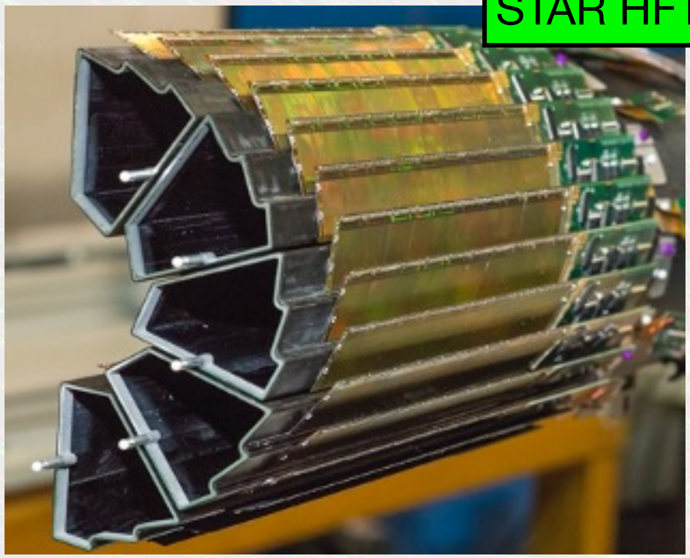


More profoundly:

STAR pioneered the use of MAPS silicon detectors in collider experiments. New generations of MAPS silicon detectors are now widely deployed or planned across numerous experiments for vertexing, tracking and beyond!

Generations of MAPS-based Silicon Detectors

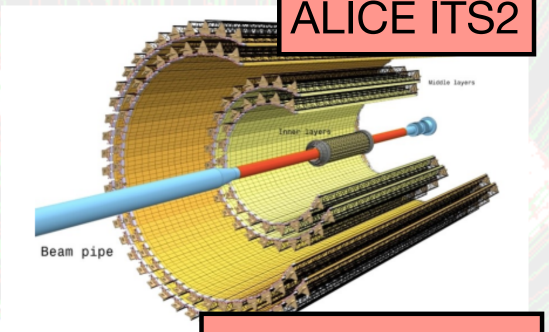
STAR HFT



First application in collider experiment!

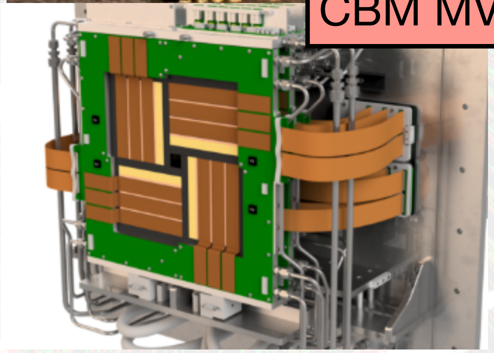
Faster

ALICE ITS2



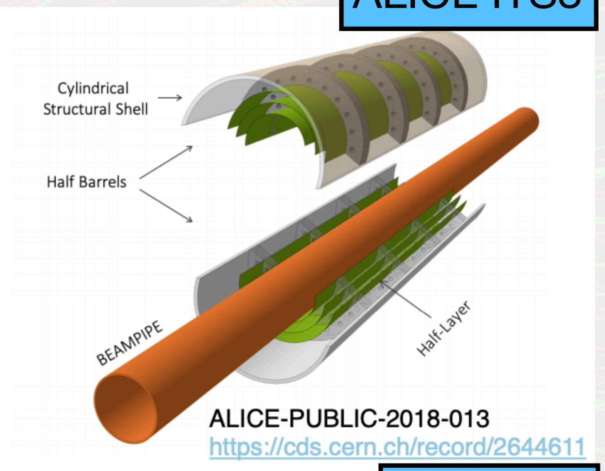
sPHENIX MVTX

CBM MVD



Thinner

ALICE ITS3



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