Characterizing the sQGP with the STAR Heavy Flavor Tracker

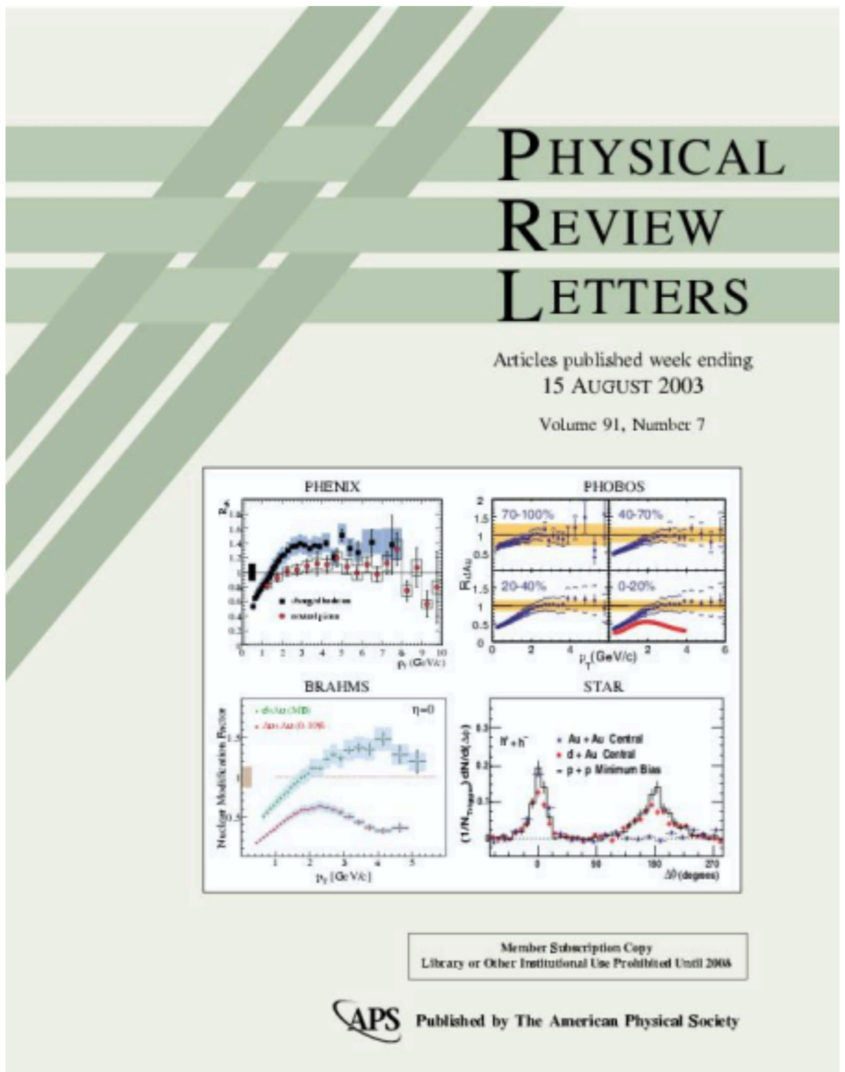
Dedicated to Retirement Celebration for

Flemming Videbaek

Xin Dong
(Lawrence Berkeley National Laboratory)

RHIC Discovery of the Strongly-Coupled QGP (sQGP)

2003 PRL Cover Page



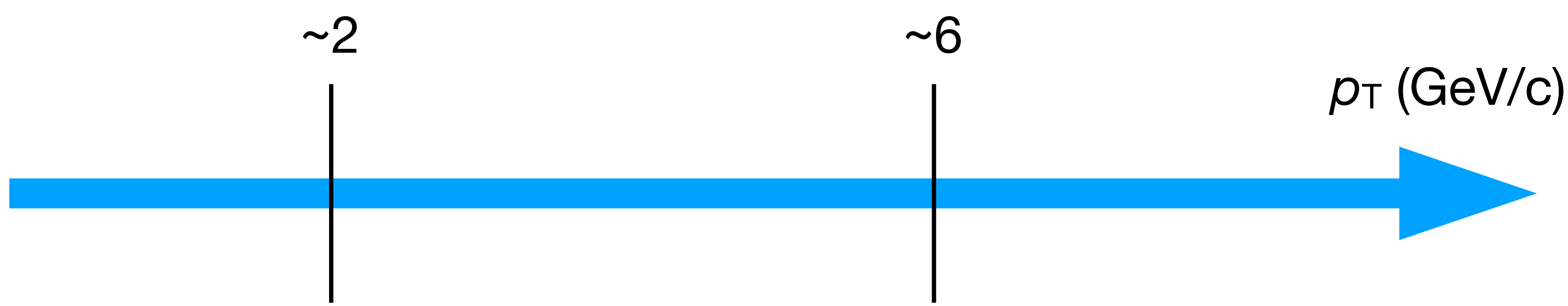
2005 RHIC White Papers

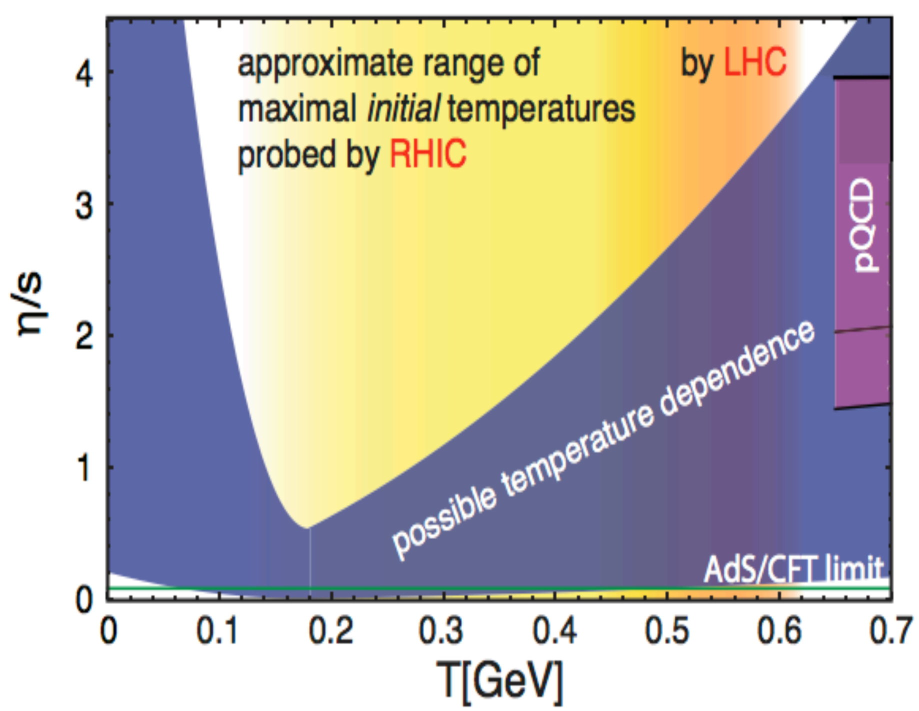
STAR:
Experimental and Theoretical Challenges in the Search for the Quark Gluon Plasma: The STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions

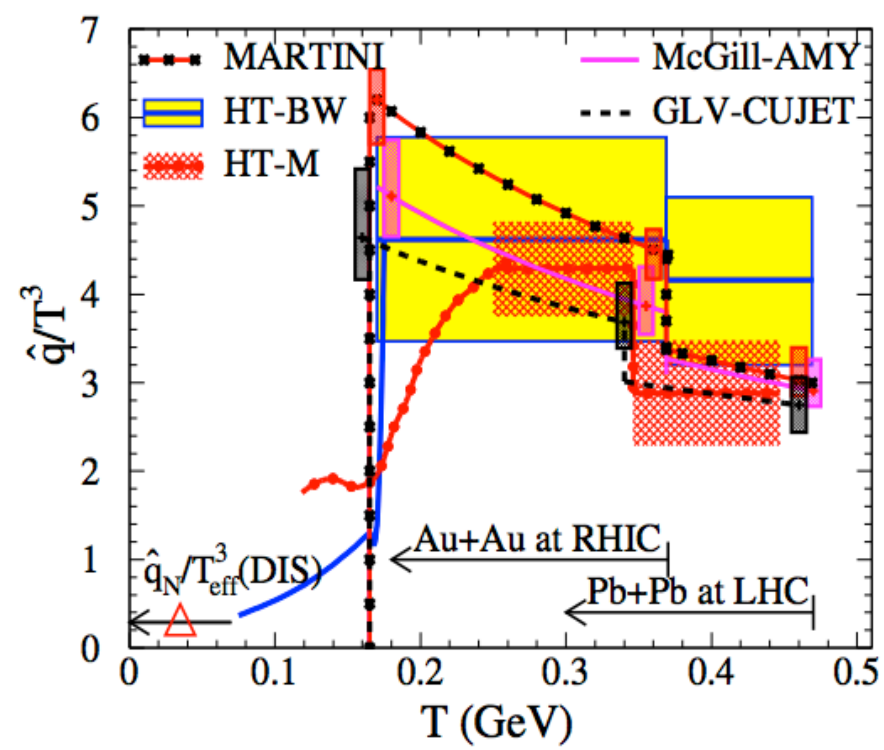
Nucl. Phys. A 757 (2005) 102

- **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







Hot QCD white paper - arXiv: 1502.02730

JET Coll., PRC 90 (2015) 014909

?

strongly coupled

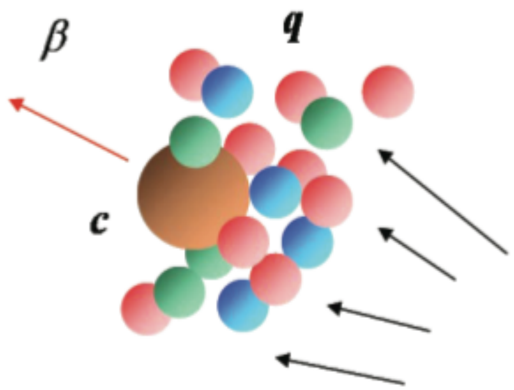
hydrodynamics

weakly coupled

pQCD

What is the microscopic picture of "perfect fluid"?

Heavy Flavor Quark Transport in sQGP



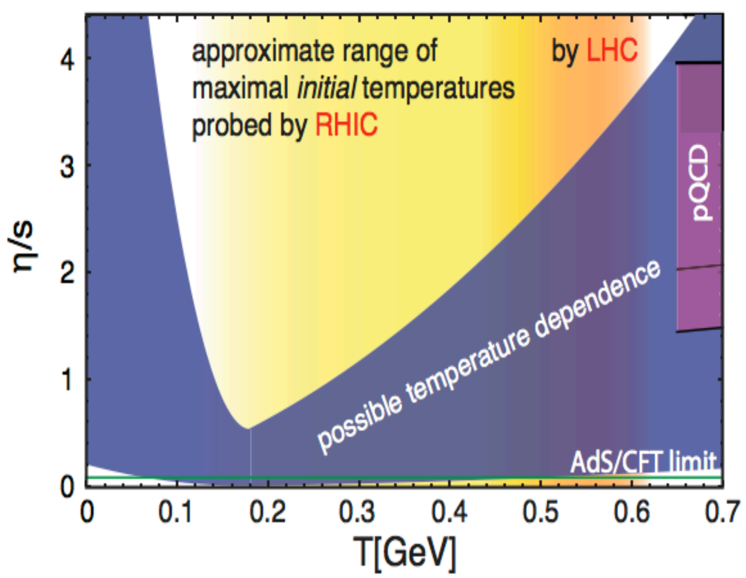
Femtoscopic “Brownian” motion

Langevin stochastic simulation

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

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

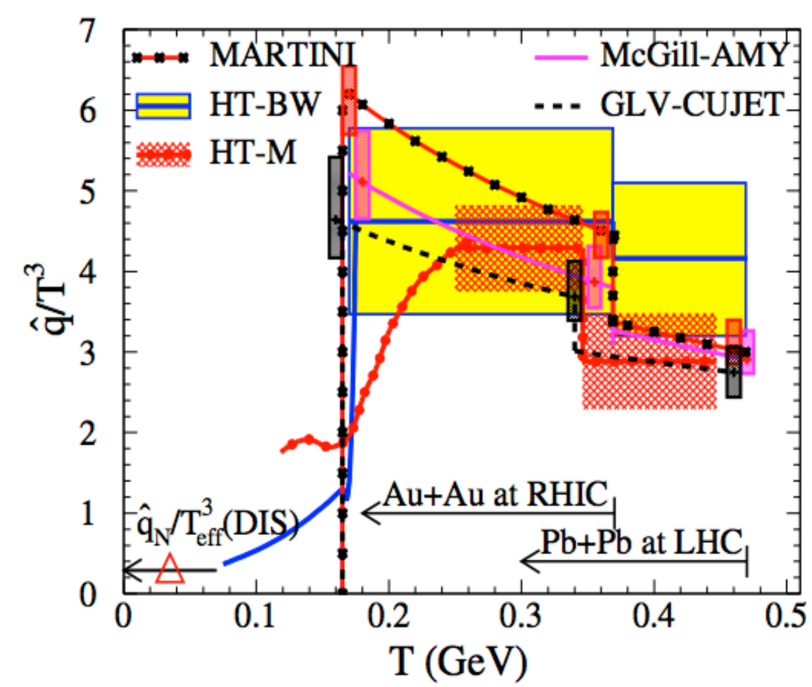
$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



$$D_s(2\pi T) \sim \eta/s$$

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096



$$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4D_pE_p}{p} \qquad 2\pi T D_S = \frac{8\pi T^3}{\hat{q}(p\to 0)}$$

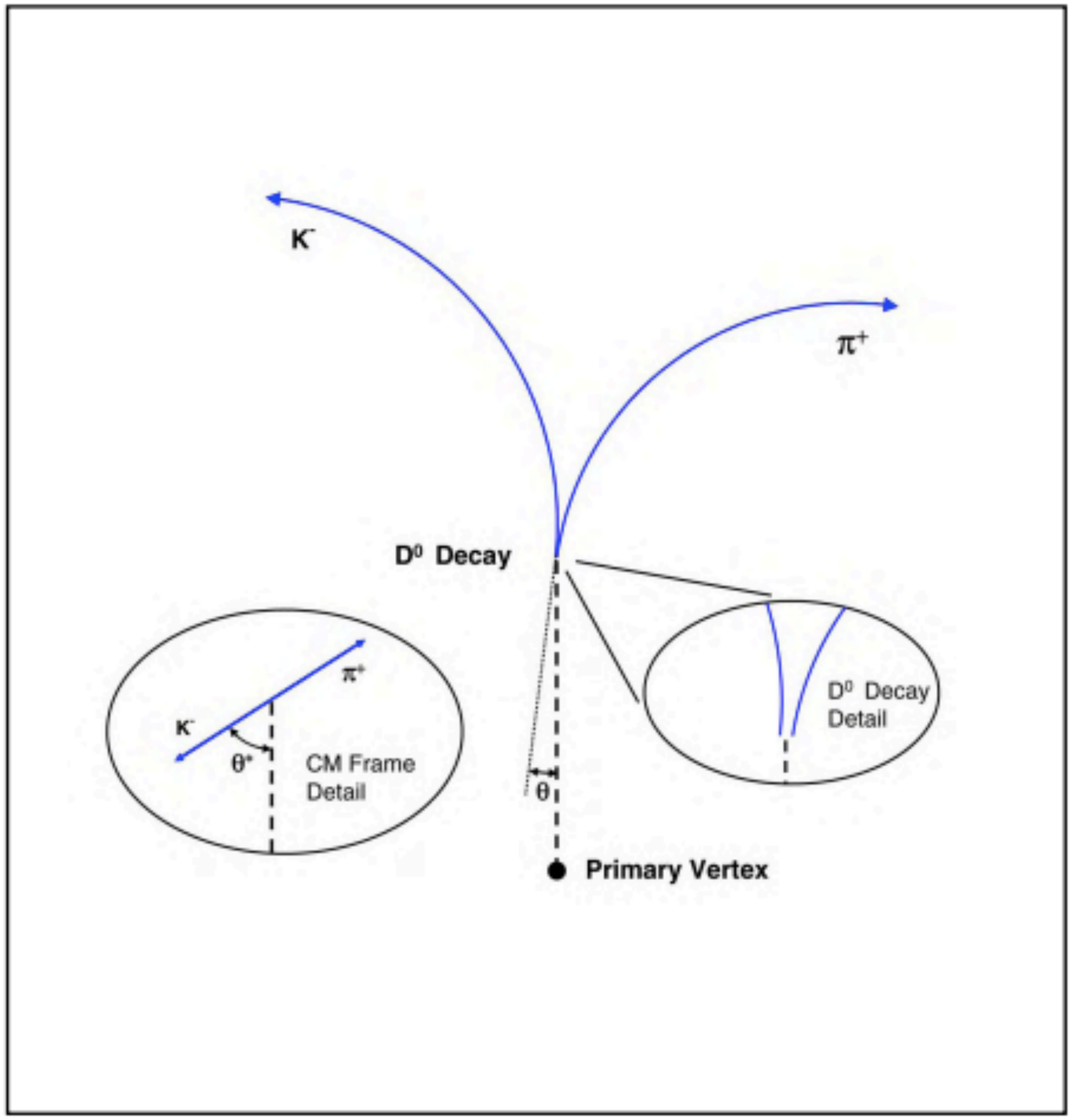
collisional vs. radiative energy loss

Heavy quark transport – to probe QGP with comprehensive p_T coverage

- unique insights to both perturbative and non-perturbative regimes

STAR Heavy Flavor Tracker Proposal

A Heavy Flavor Tracker for STAR



C. Chasman, D. Beavis, R. Debbe, J.H. Lee, M.J. Levine, F. Videbaek, Z. Xu
Brookhaven National Laboratory, Upton, NY 11973

S. Kleinfelder, S. Li
University of California, Irvine, CA 92697

R. Cendejas, H. Huang, S. Sakai, C. Whitten
University of California, Los Angeles, CA 90095

J. Joseph, D. Keane, S. Margetis, V. Rykov, W.M. Zhang
Kent State University, Kent, OH 43210

M. Bystersky, J. Kapitan, V. Kushpil, M. Sumbera
Nuclear Physics Institute AS CR, 250 68 Rez/Prague, Czech Republic

J. Baudot, C. Hu-Guo, A. Shabetai, M. Szelezniak, M. Winter
Institut Pluridisciplinaire Hubert Curien, Strasbourg, France

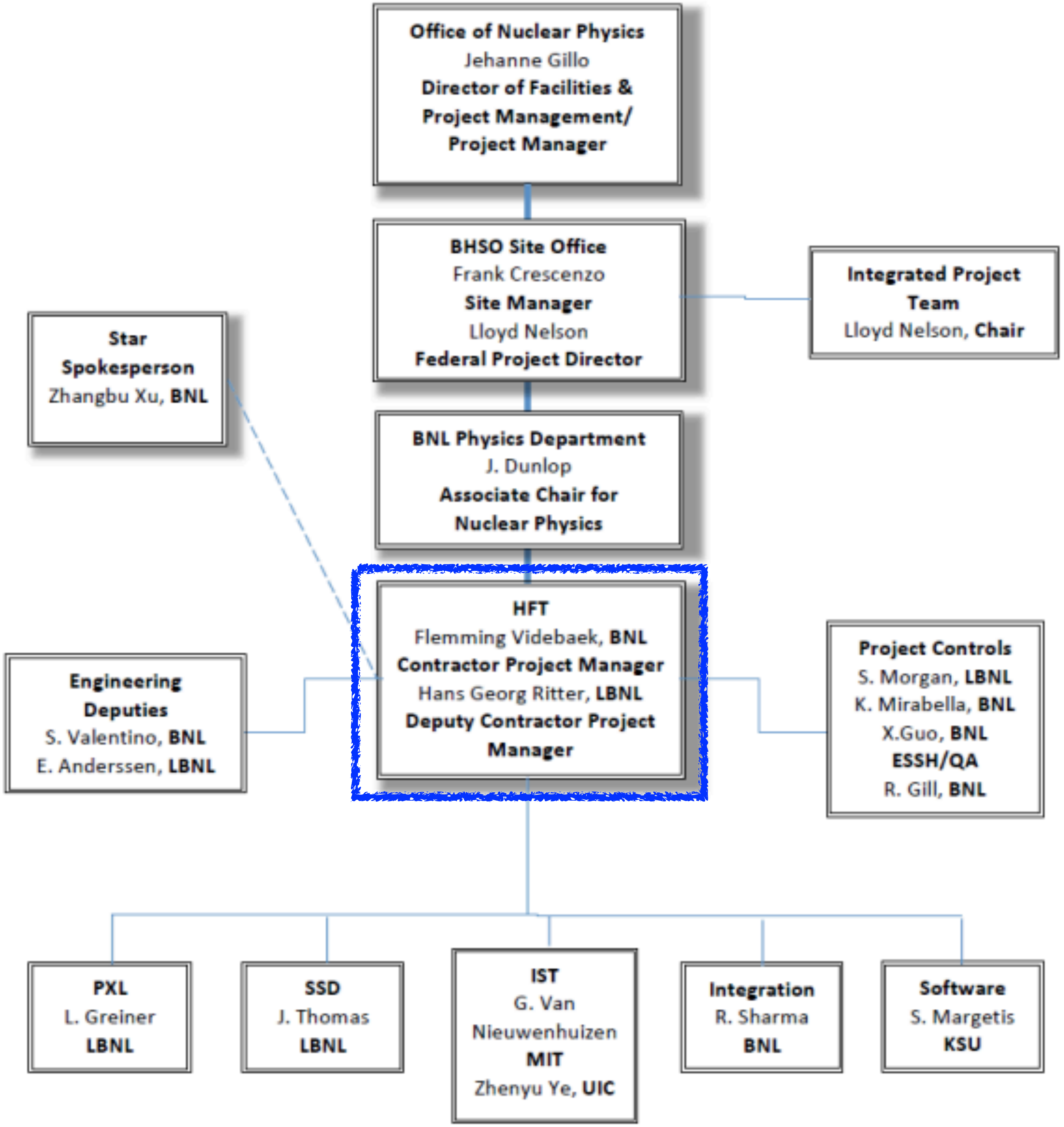
J. Kelsey, R. Milner, M. Plesko, R. Redwine, F. Simon, B. Surrow,
G. Van Nieuwenhuizen
Laboratory for Nuclear Science
Massachusetts Institute of Technology, Cambridge, MA 02139

E. Anderssen, X. Dong, L. Greiner, H.S. Matis, S. Morgan, H.G. Ritter, A. Rose,
E. Sichtermann, R.P. Singh, T. Stezelberger, X. Sun, J.H. Thomas, V. Tram, C. Vu,
H.H. Wieman, N. Xu
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

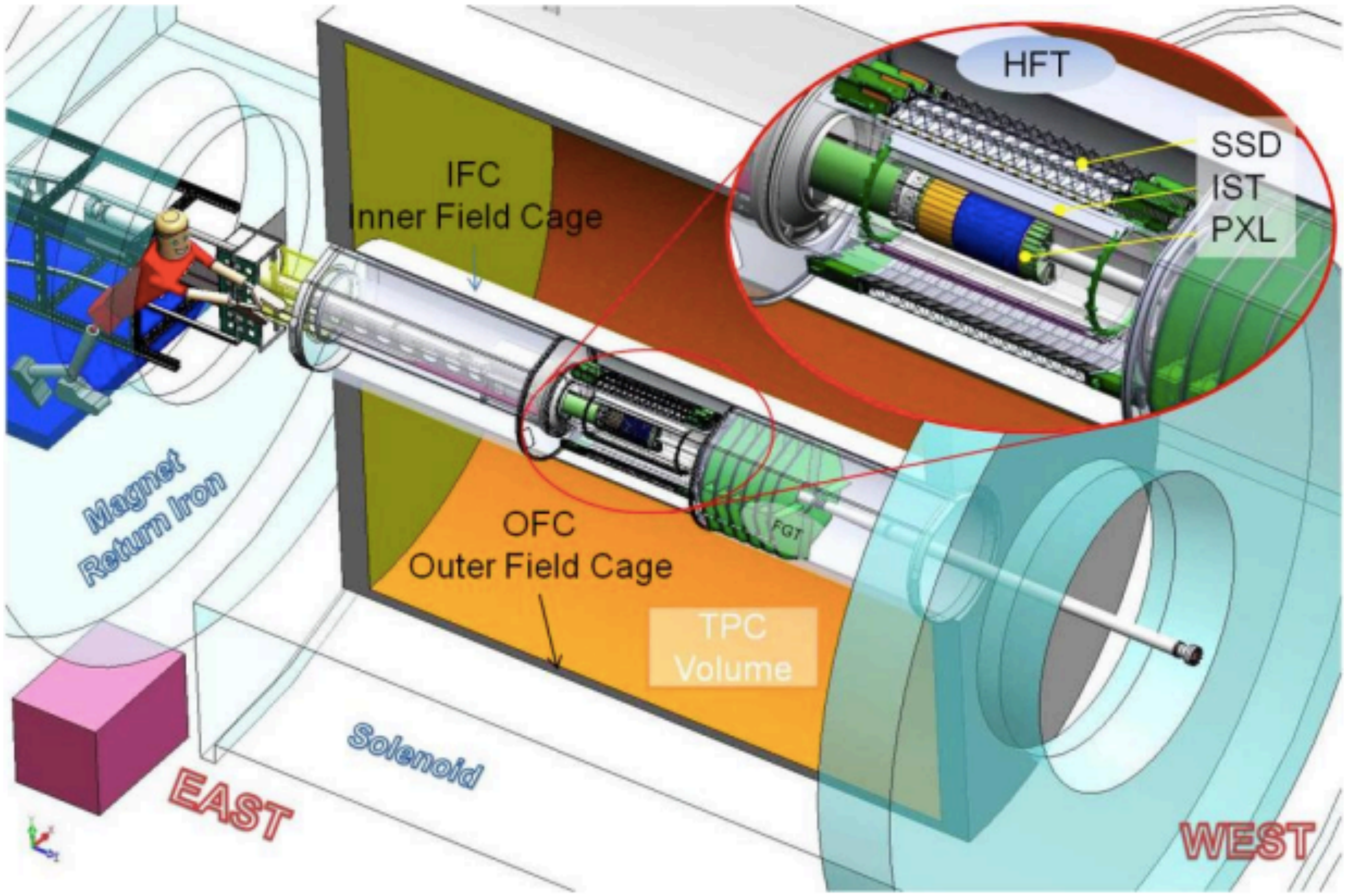
A. Hirsch, B. Srivastava, F. Wang, W. Xie
Purdue University, West Lafayette, IN 47907

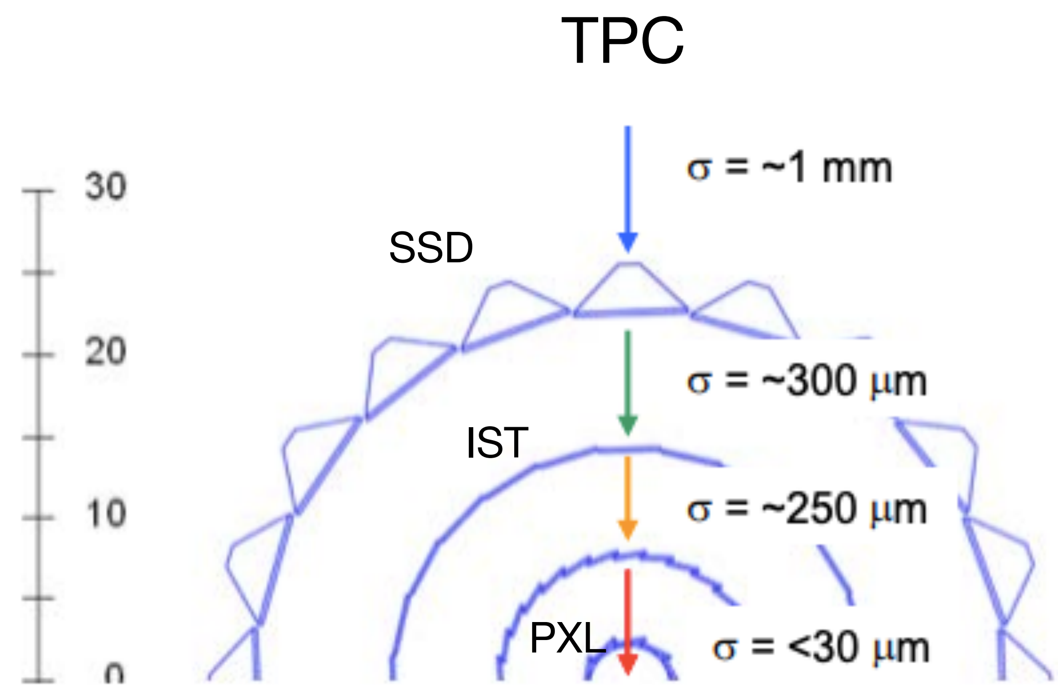
H. Bichsel
University of Washington, Seattle, WA 98195

HFT Project


Office of Nuclear Physics
Jehanne Gillo
Director of Facilities & Project Management/ Project Manager
BHSO Site Office
Frank Crescenzo
Site Manager
Lloyd Nelson
Federal Project Director
Integrated Project Team
Lloyd Nelson, Chair
Star Spokesperson
Zhangbu Xu, BNL
BNL Physics Department
J. Dunlop
Associate Chair for Nuclear Physics
HFT
Flemming Videbaek, BNL
Contractor Project Manager
Hans Georg Ritter, LBNL
Deputy Contractor Project Manager
Engineering Deputies
S. Valentino, BNL
E. Anderssen, LBNL
Project Controls
S. Morgan, LBNL
K. Mirabella, BNL
X.Guo, BNL
ESSH/QA
R. Gill, BNL
PXL
L. Greiner
LBNL
SSD
J. Thomas
LBNL
IST
G. Van Nieuwenhuizen
MIT
Zhenyu Ye, UIC
Integration
R. Sharma
BNL
Software
S. Margetis
KSU

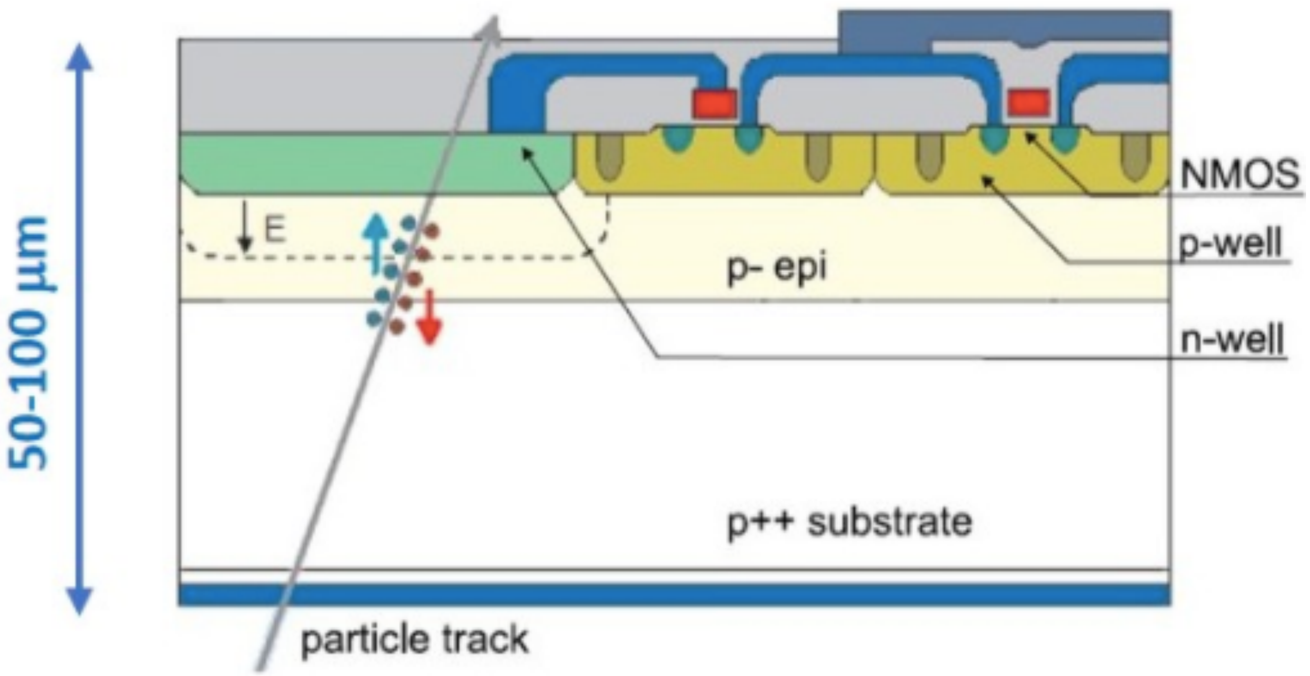
STAR Heavy Flavor Tracker (HFT)



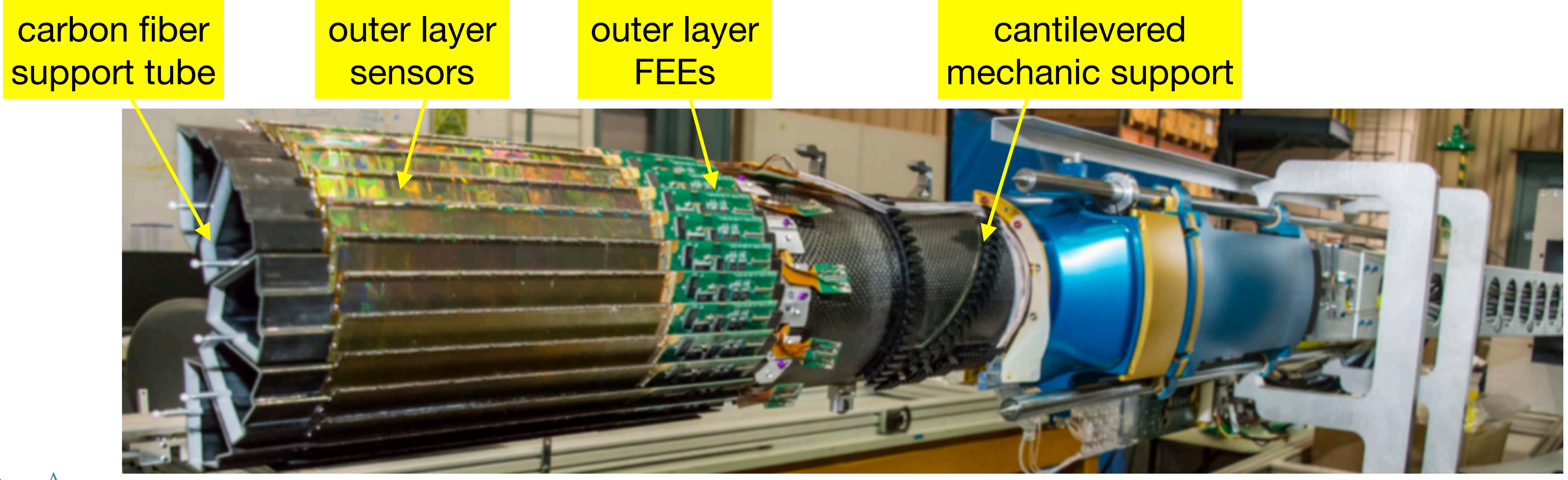


Detector	Radius (cm)	Pitch Size R/φ - Z (μm - μm)	Thickness
Silicon **S**trip **D**etector	22	95 / 40000	1% X_0
Intermediate **S**ilicon **T**racker	14	600 / 6000	1.3%X_0
PiXeL	8	**20.7 / 20.7**	0.5%X_0
	2.8	**20.7 / 20.7**	**0.4%X_0** *

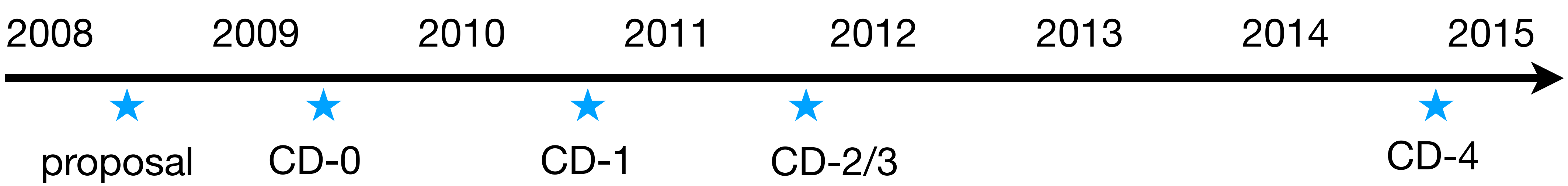
Pixel Detector for HFT



- 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)
  - ✦ radiation hard / fast replacement (~8h)
  - ✦ moderate integration time (186μs)



Managing the HFT Project



- HFT project completed under budget and ahead of schedule
- All Key-Performance-Parameters requirements for CD-4 met

Documentation

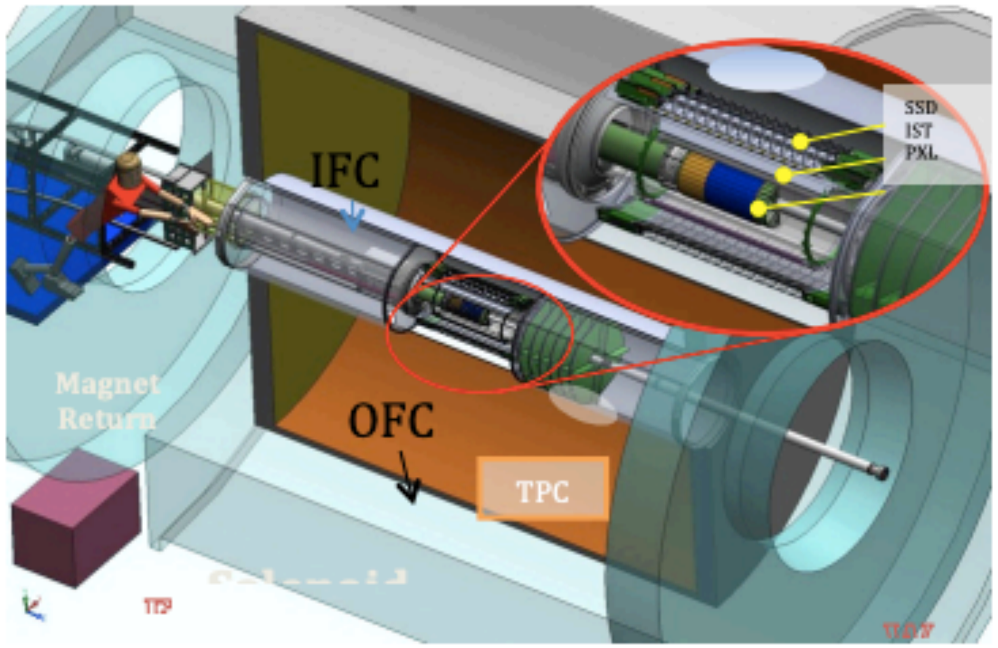
- Monthly Reports
- OPA mini review September 24 2013
- HFT Review July 12 , 2013
- CD0
- HFT 2014 Commisioning and Physics Run
- HFT BNL review Feb 15 2013
- HFT Management , including f2f meeting schedules
- HFT Related Publications
- HFT Sub-system IST
- HFT Sub-system Integration
- HFT Sub-system PXL
- HFT Sub-system SSD
- HFT annual OPA Review 2012
- HFT software meetings (overview)
- OPA CD-4 Close-out review July 31, 2014
- OPA mini-review October 2012
- post CD-4 documents
- HFT Internal reviews
- CD2-3 review
- CD1 documents final
- CD0 - dummy

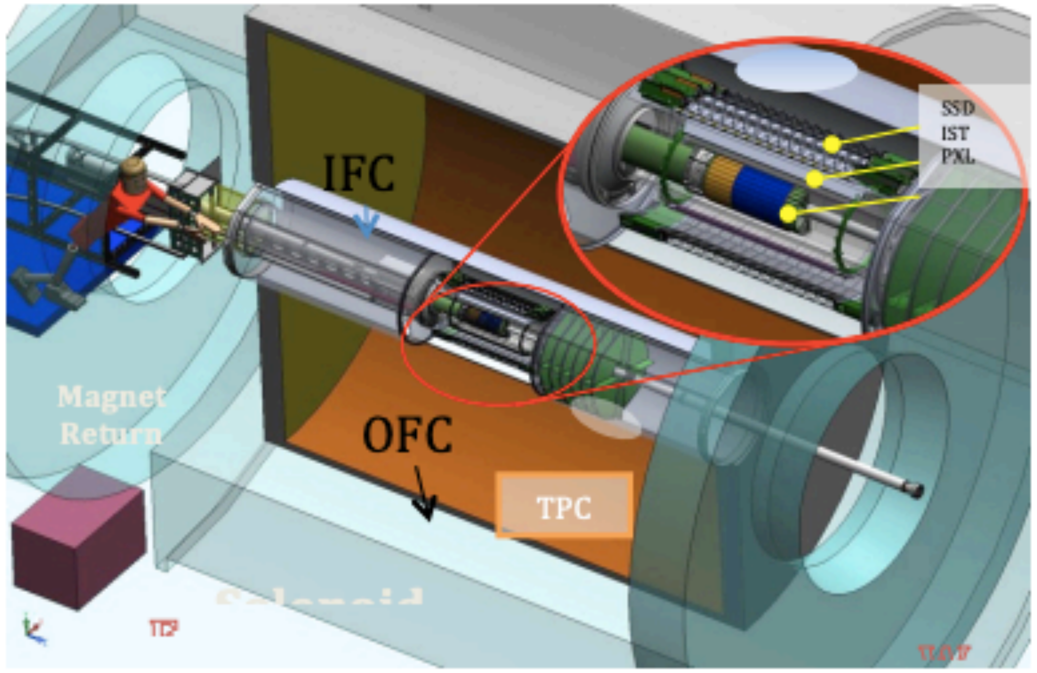
2014 Monthly reports

- September 2014 report
- August 2014 report
- July 2014 report
- June 2014 report
- May 2014 report
- April 2014 report
- March 2014 report additional information on PXL status pdf
- February 2014 report
- January 2014 report

2013 Monthly Reports

- December 2013 report
- November 2013 report
- October 2013 report
- September 2013 report
- August 2013 report
- July 2013 report
- June 2013 report
- May 2013 report
- April 2013 report
- March 2013 report





BEAM COMMISSIONING PLAN

February 2014
Version 1.9 May 2014

Performing Organization Location: Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York 11973-5000

Contract Period of Performance: FY2010-FY2015

Transition To Operations Plan

October 27, 2014
Updated April 30, 2015

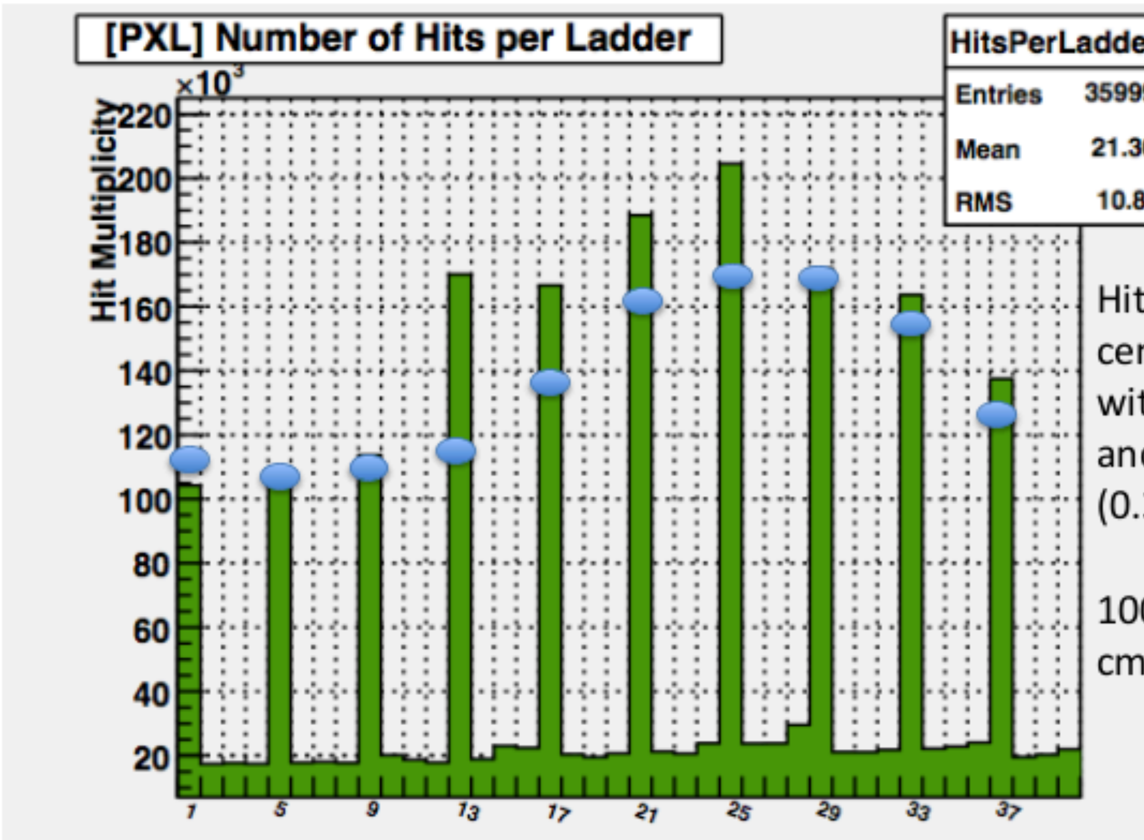
Performing Organization Location: Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York 11973-5000

Contract Period of Performance: FY2010-FY2015

BROOKHAVEN NATIONAL LABORATORY

BERKELEY LAB

Hit densities; online vs. estimate



Flemming, HFT meeting 2014

Hit density for central AuAu with rPXL=2.9 and offsets of (0.32,-0.15)

100<-> 10 hits cm**2

- Lead efforts of commissioning
- Coordinate all subsystems, online/offline QAs
- Close watch of operations and real-time calibration

HFT Online Monitoring

This page will be updated every 10 minutes, the last update was on Mon Jul 4 14:27:15 2016

Runs : **5490**

Host : **onl11** User : **GuannanXie**

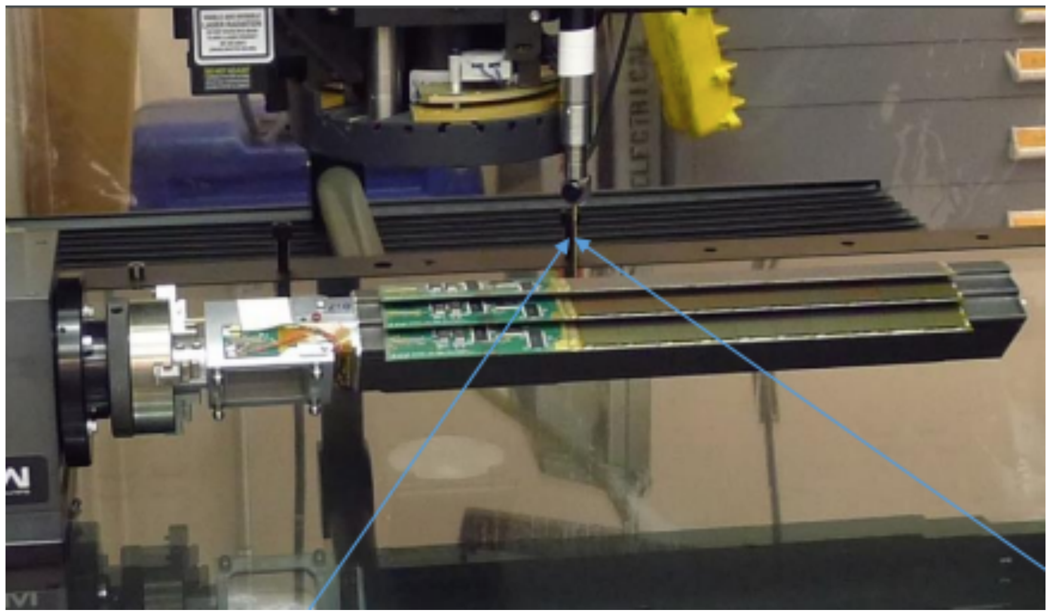
PXL status(physics+cosmic) inner:All runs Latest 50 runs outer:All runs Latest 50 runs

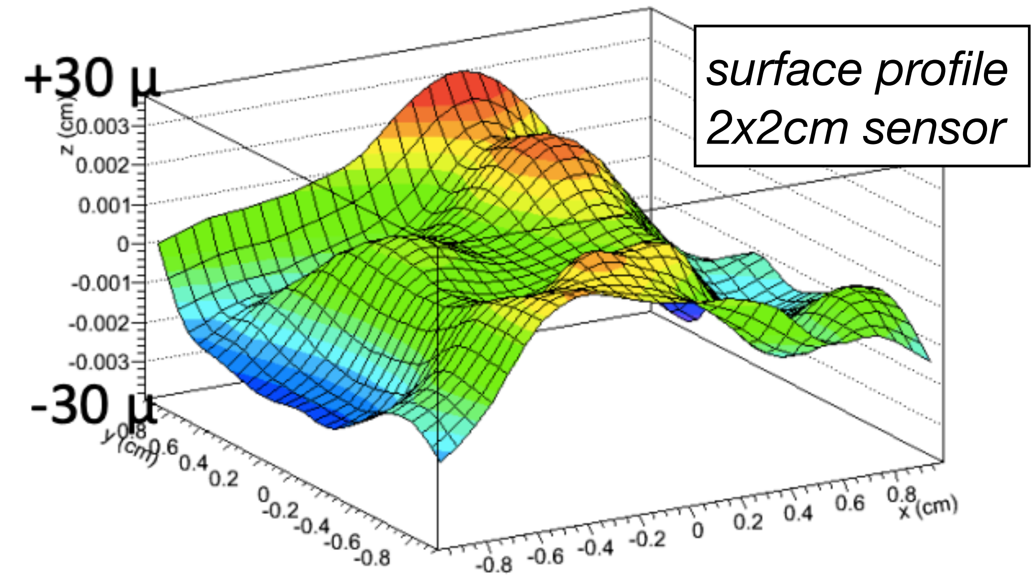
hot columns/rows

	GlbSetup	PXL QA Plots	IST QA Plots	SSD QA Plots	Events (VPDMB-5-p-sst)
All					2576328514
day 180					0
run 17180021	CosmicLocalClock	w/o Mask w/ Mask	pdf AdcQa	offlineQa QAClusters QAStrips	0
run 17180020	CosmicLocalClock	w/o Mask w/ Mask	pdf AdcQa	offlineQa QAClusters QAStrips	0
run 17180019	CosmicLocalClock	w/o Mask w/ Mask	pdf AdcQa	offlineQa QAClusters QAStrips	0
run 17180018	CosmicLocalClock	w/o Mask w/ Mask	pdf AdcQa		0
run 17180017	CosmicLocalClock	w/o Mask w/ Mask	pdf AdcQa	offlineQa QAClusters QAStrips	0

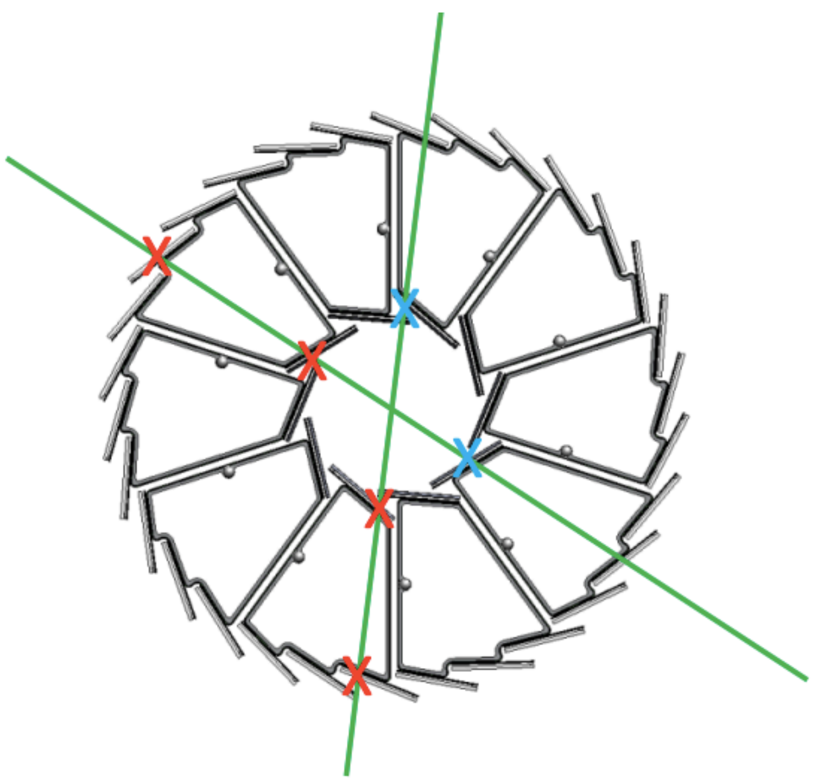
Alignment Calibration

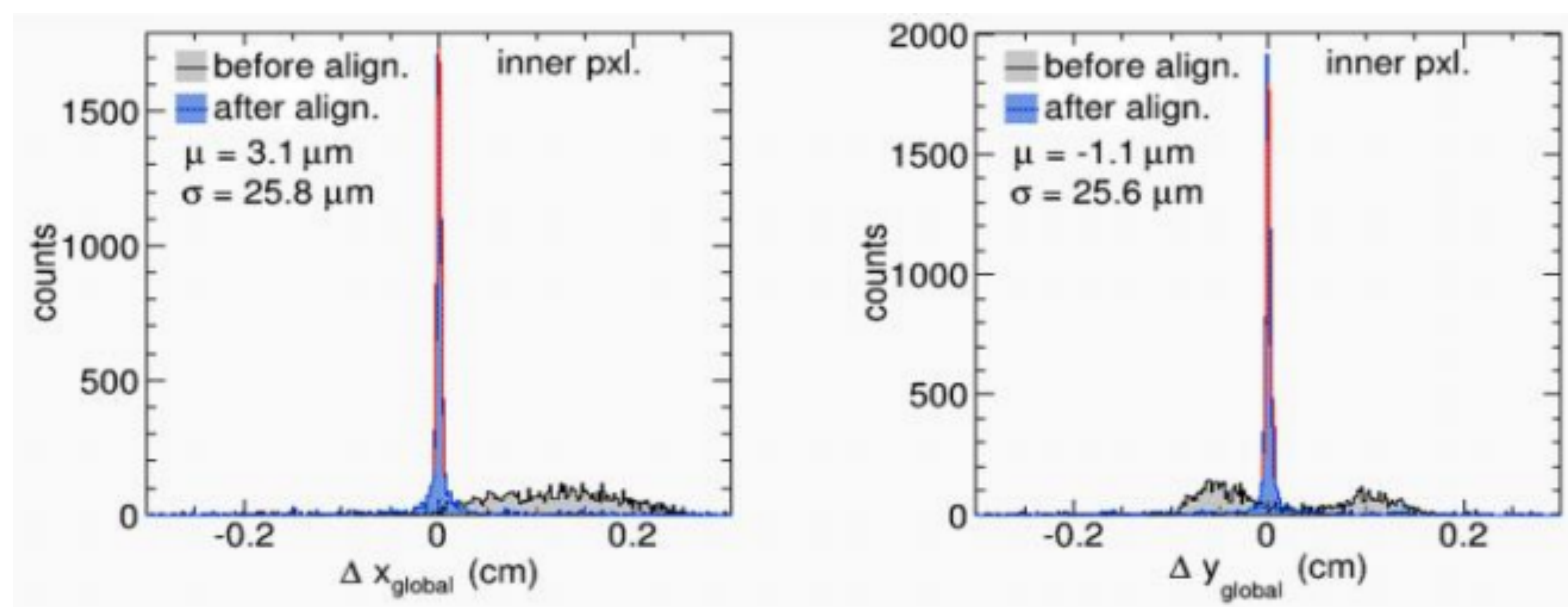
Survey measurement with CMM - individual pixel position within a sector < 10μm



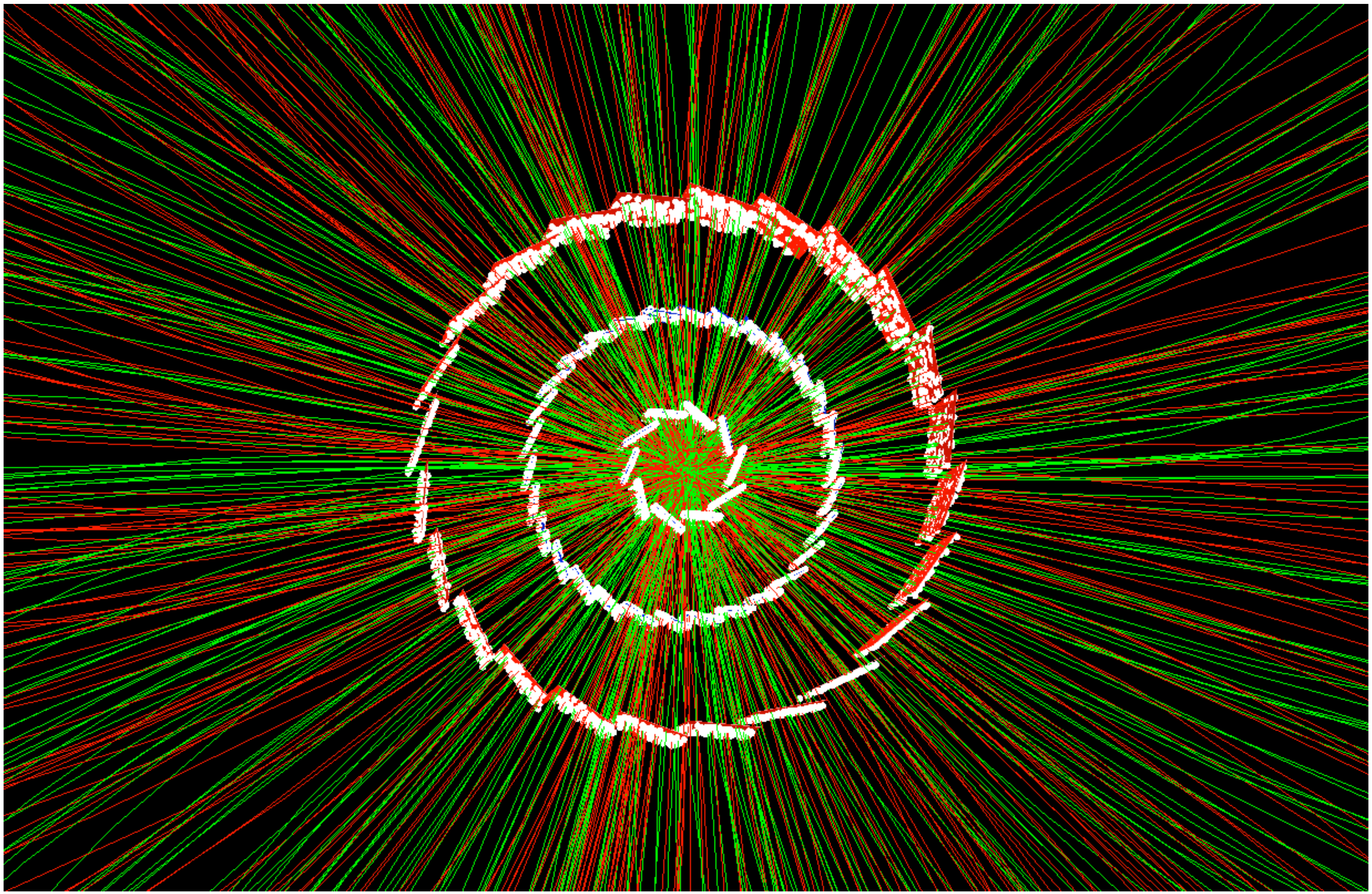


Sector-to-sector internal alignment - Zero-field cosmic ray data, residuals < 10μm



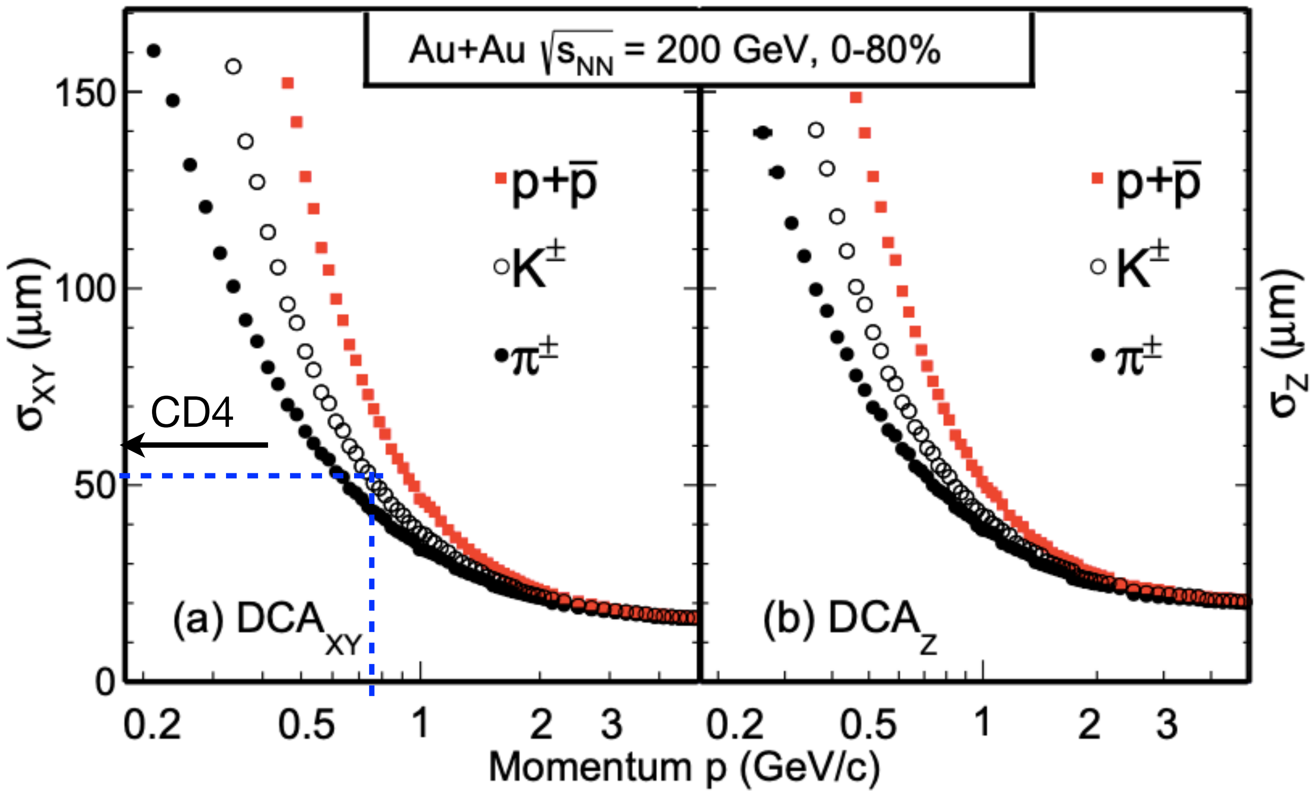


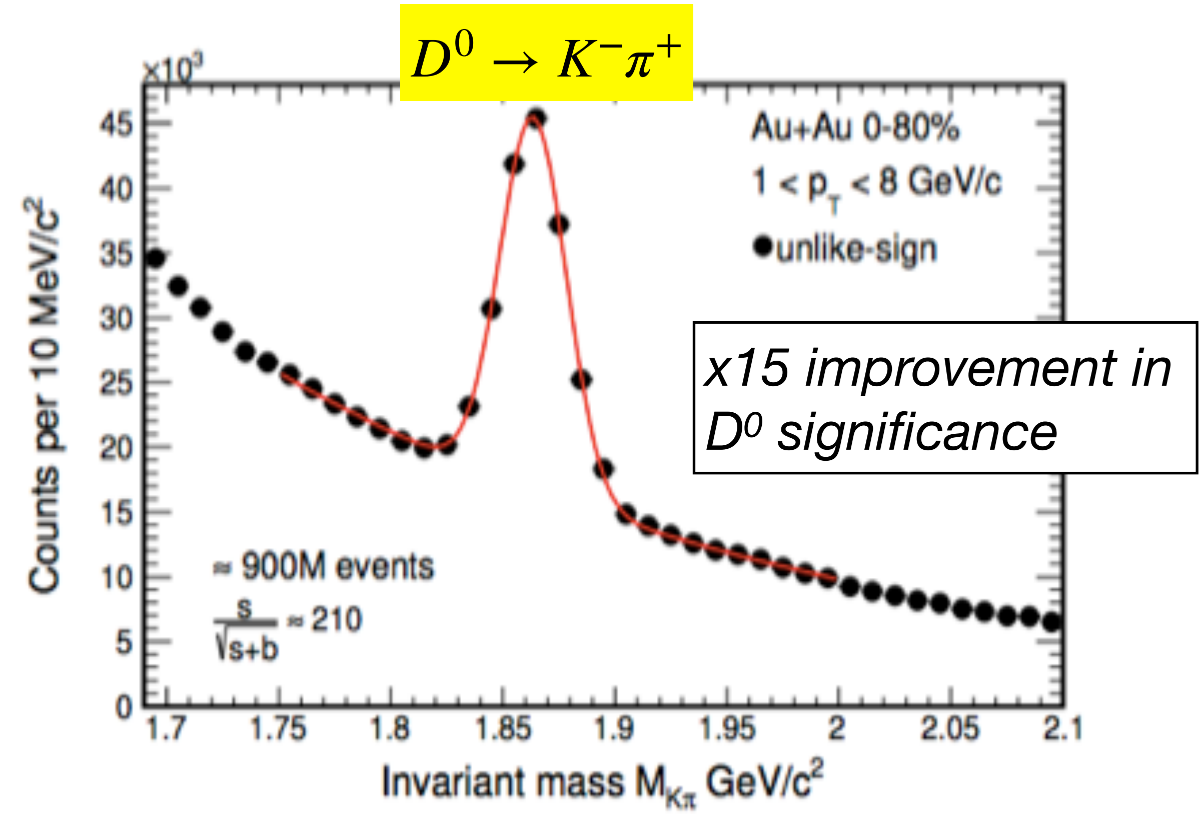
Au+Au 200 GeV event display with STAR-HFT

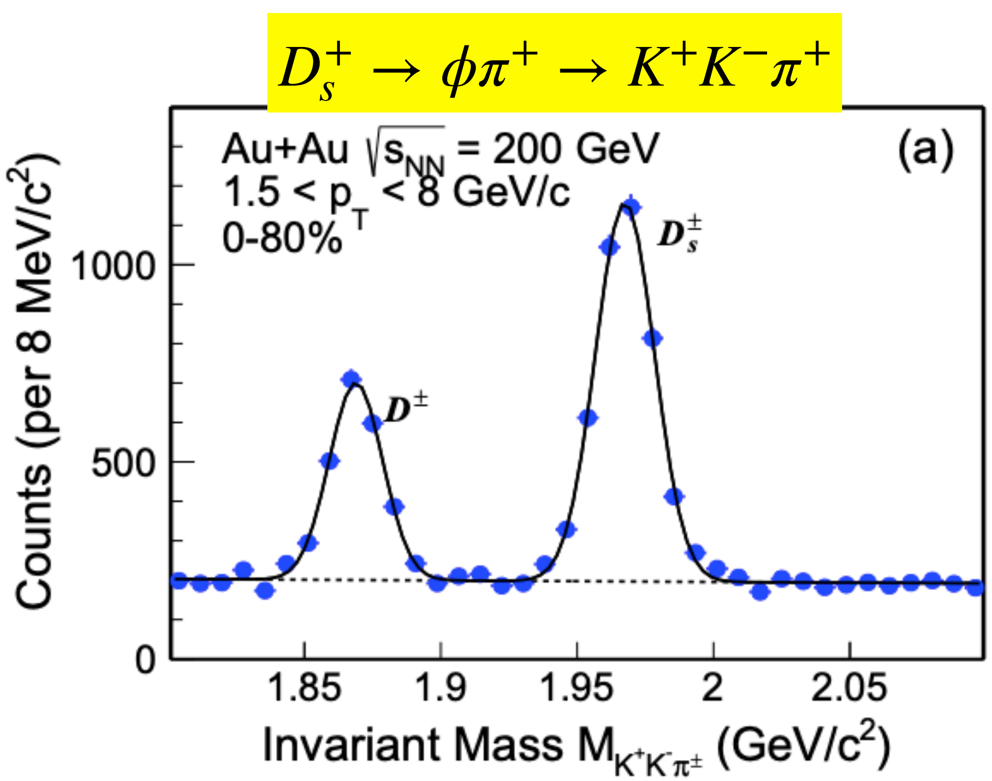


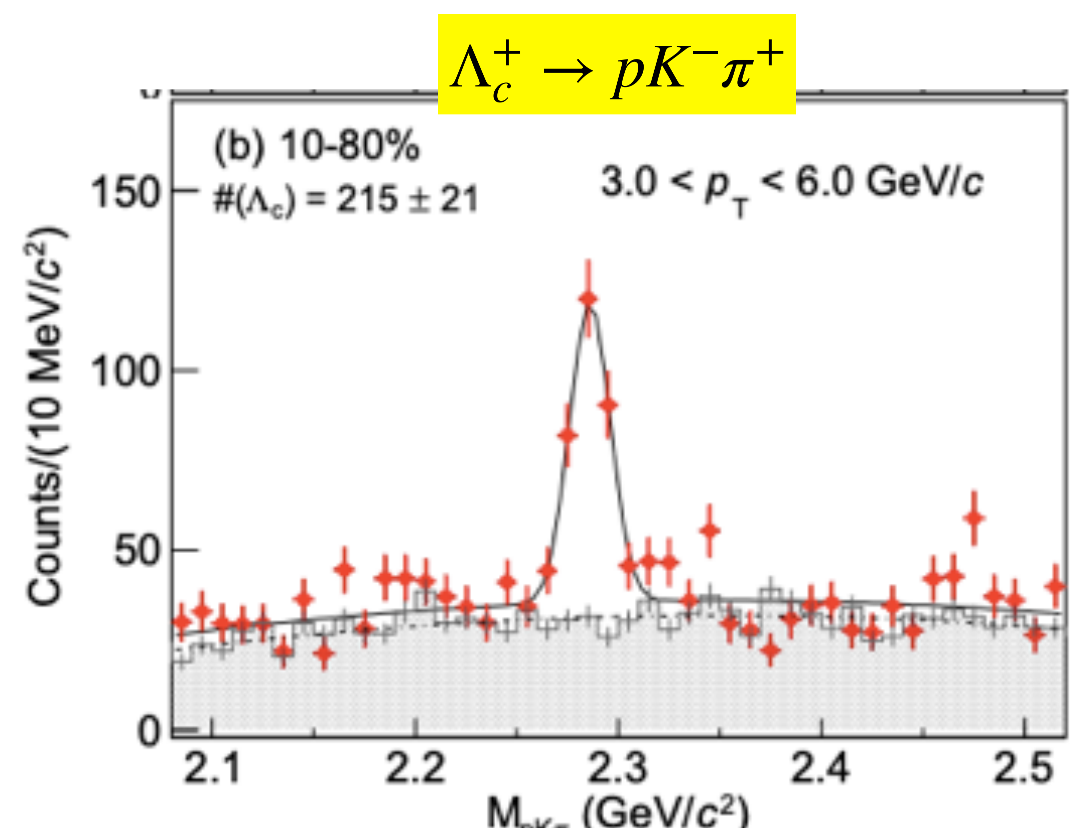
HFT Performance

STAR, PRC 99 (2019) 034908



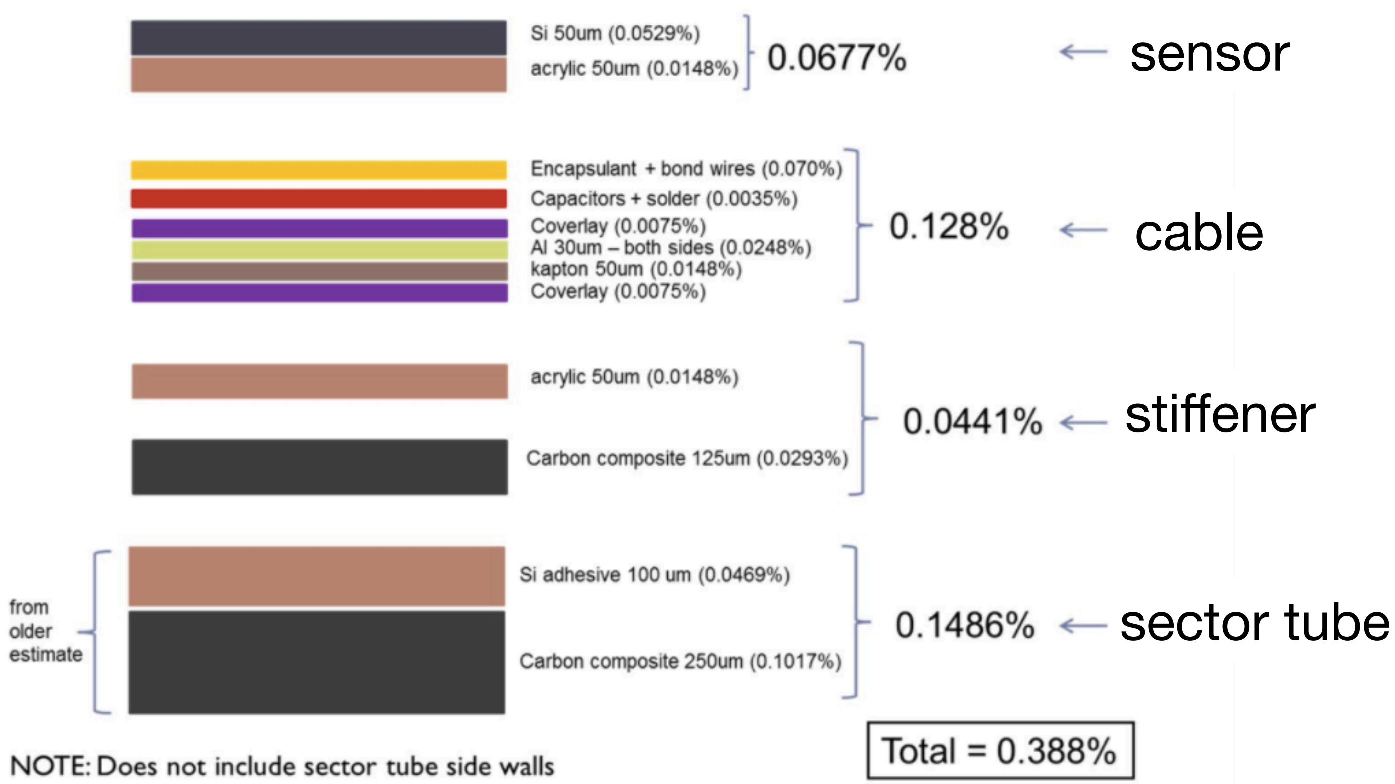






Geometry Description

Detector Material Decomposition



Sensor modifications
(prototype, production, Cu/Al-cable)

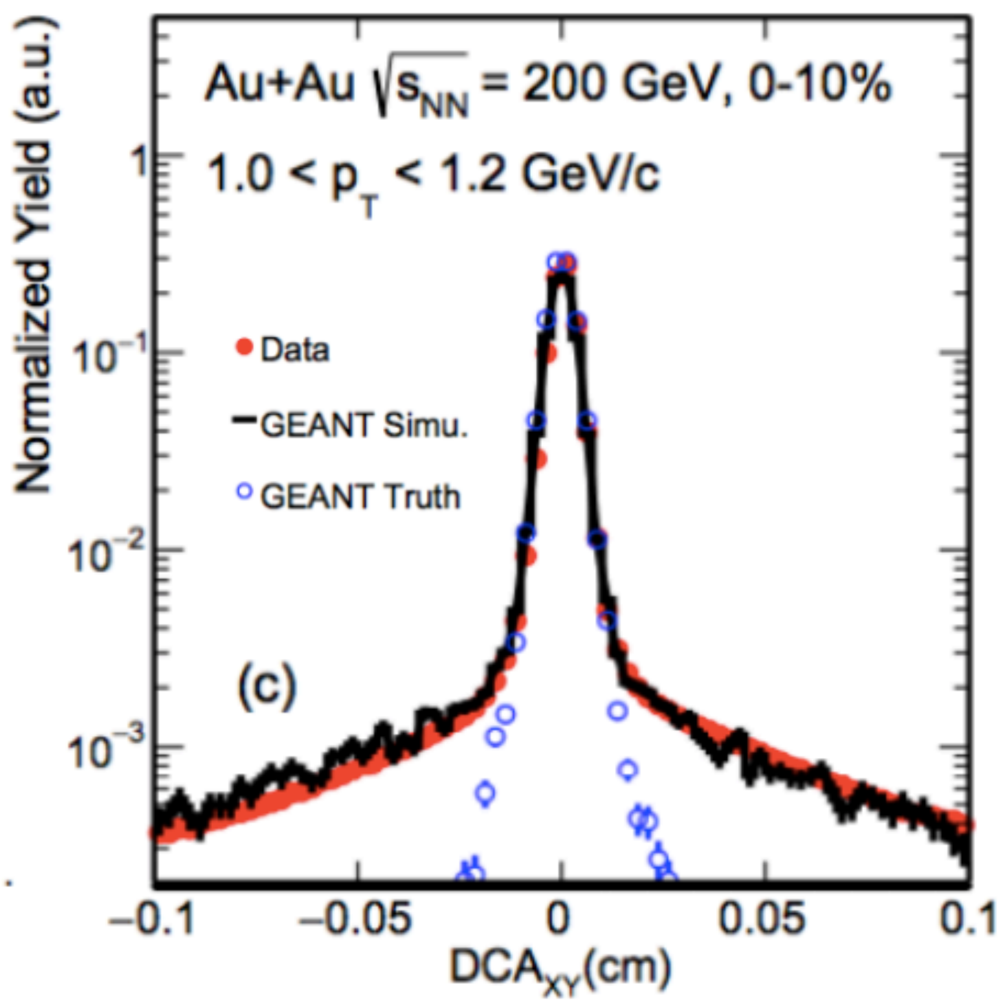
Active/inactive material in simu./tracking
(in/out HFT acceptance)

Geometry file in STAR software

```

<Document file="StarVMC/Geometry/PixlGeo/PixlGeo6a.xml">
   <Module name="PixlGeo6b" comment="Pixel Detector Geometry  ">

   <Author  name="JBouchet,FVidebaek" />
   <Created date="11/07 2013" />

<!-- global idea of implementation : all the elements of a single sector are defined according a translation SolidWorks to TGeo (F. Videbaek)
 once the sector is assembled, it is placed in a TUBS with opening
 angles slightly larger (by 2 deg.) than the real geometry  then we duplicate x10 this volume
This is derived forom pixlgeo5.xml, but with the modified tube geometry for y2013
-->
```

Simulation and Embedding

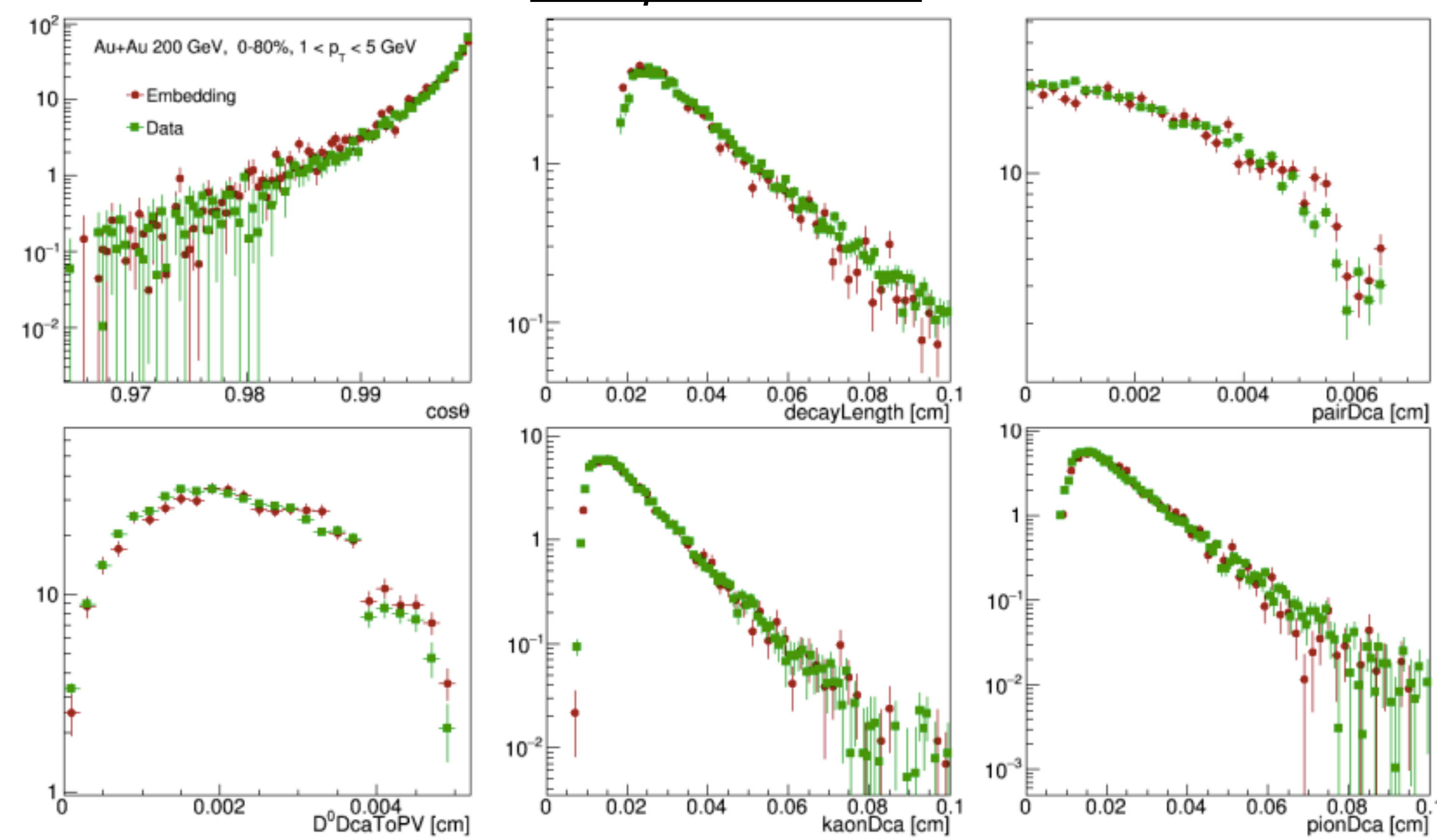
Full Hijing + Pileup Simu.



STAR, PRC 99 (2019) 034908

Embedding into Real Data

<u>*D^0 topo variables*</u>

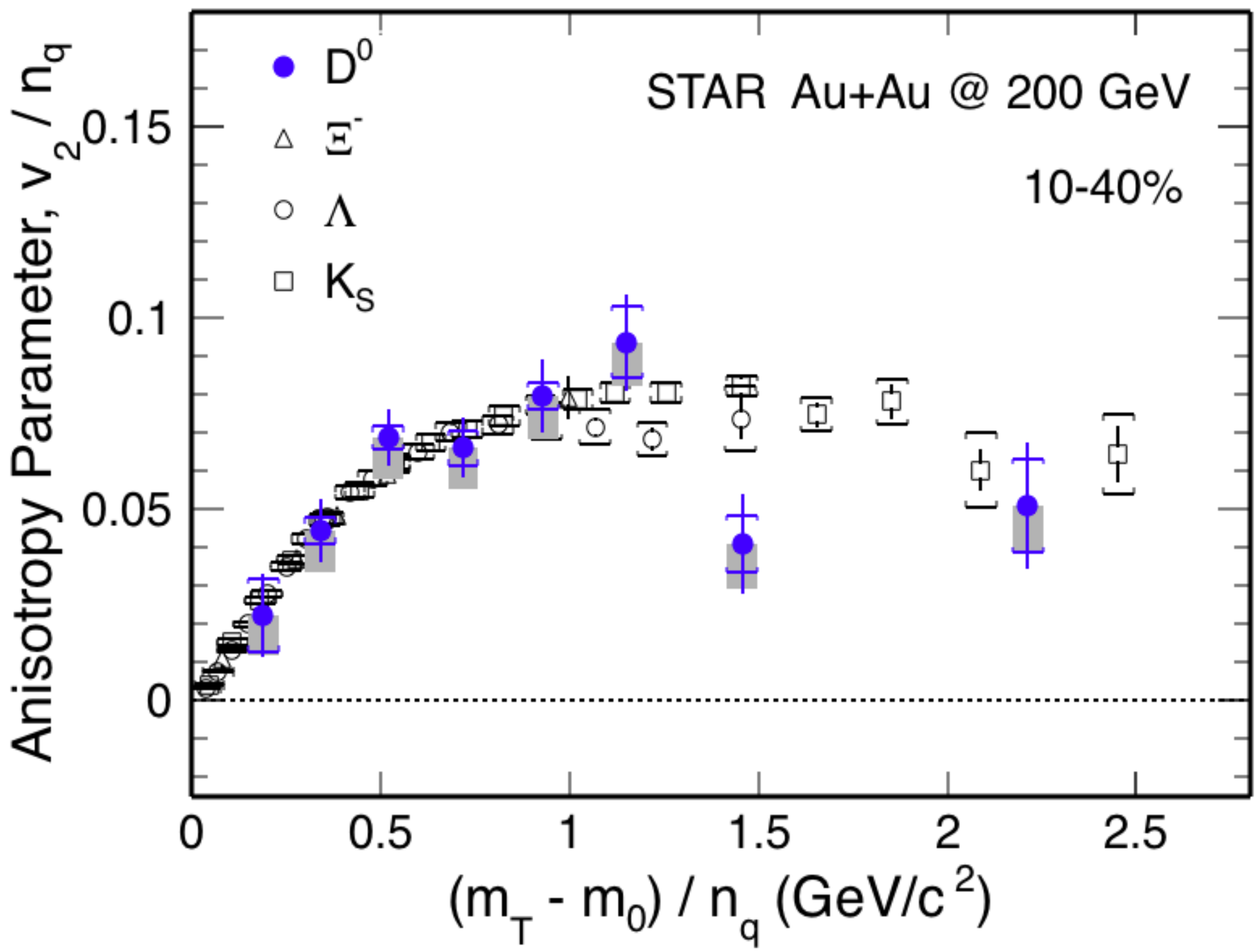


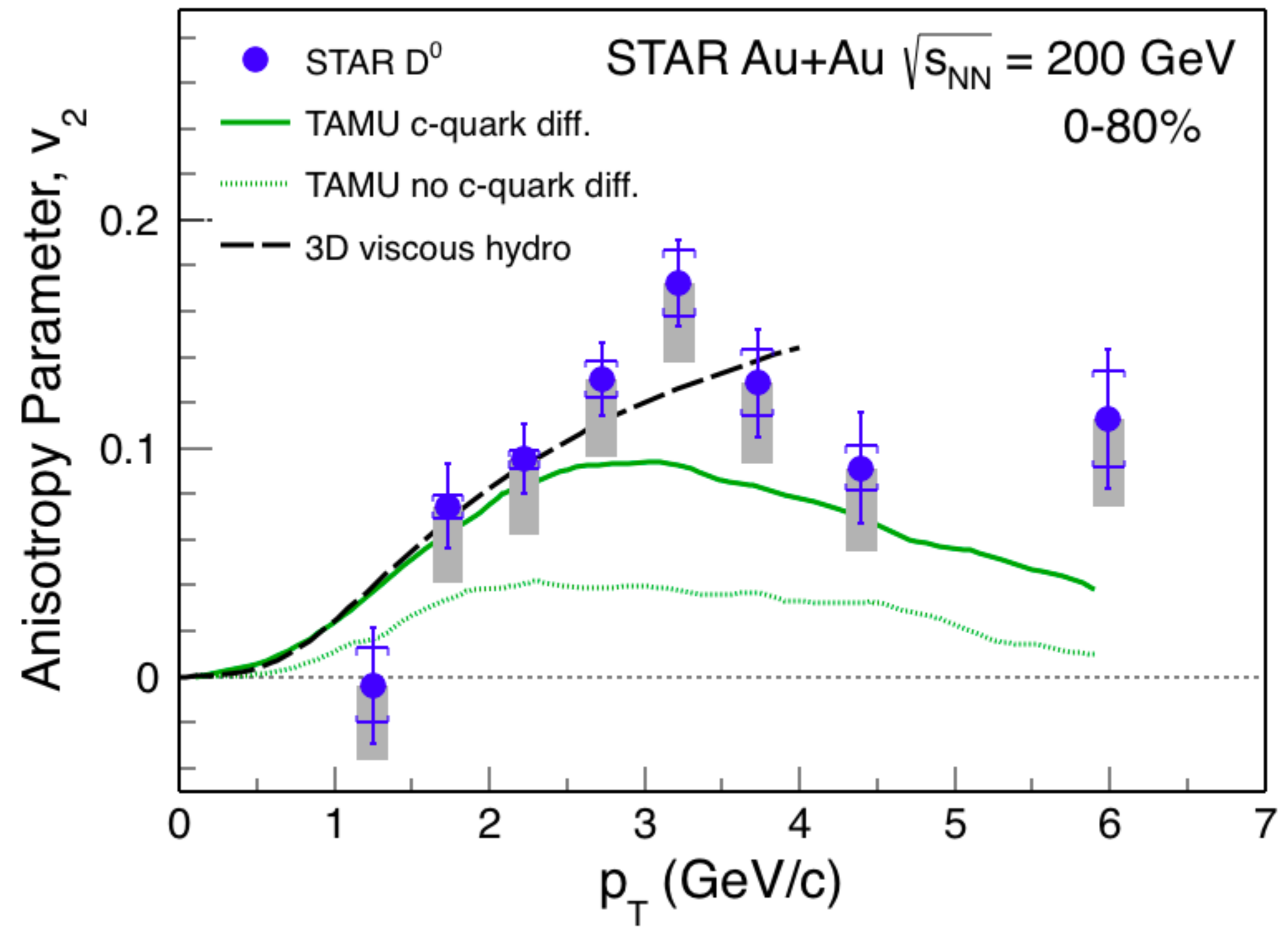
J. Webb et al., CHEP 2019

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

D^0 Meson v_2 in A+A Collisions

STAR, PRL 118 (2017) 212301



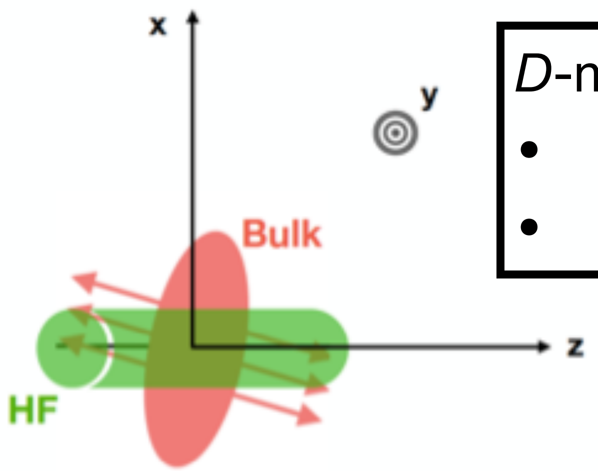


- v_2(D) follows the $(m_T\text{-}m_0)/n_q$ scaling as light hadrons

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

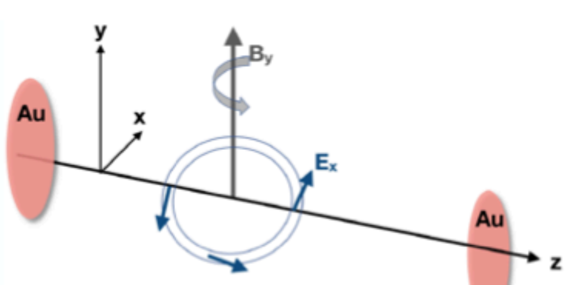
$D/\bar{D}$ v_1 - sQGP Properties and Initial *B*-field

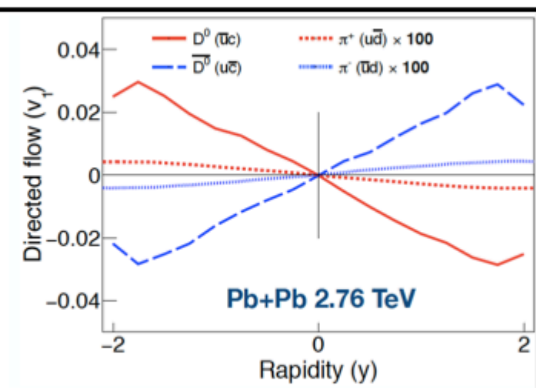
S. Chatterjee & P. Bozek, PRL 120 (2018) 192301



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

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

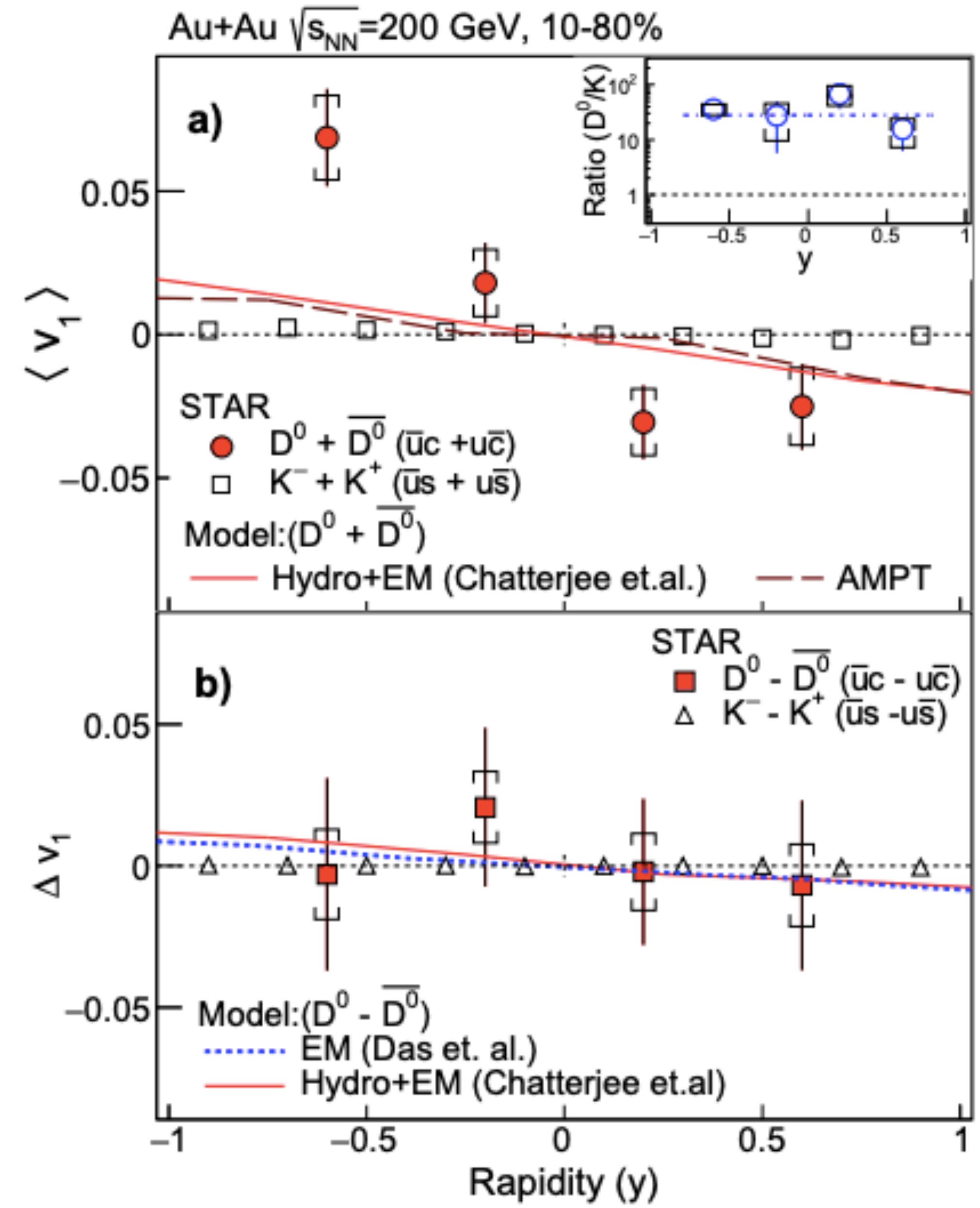




S.K. Das et al, PLB 768 (2017) 260

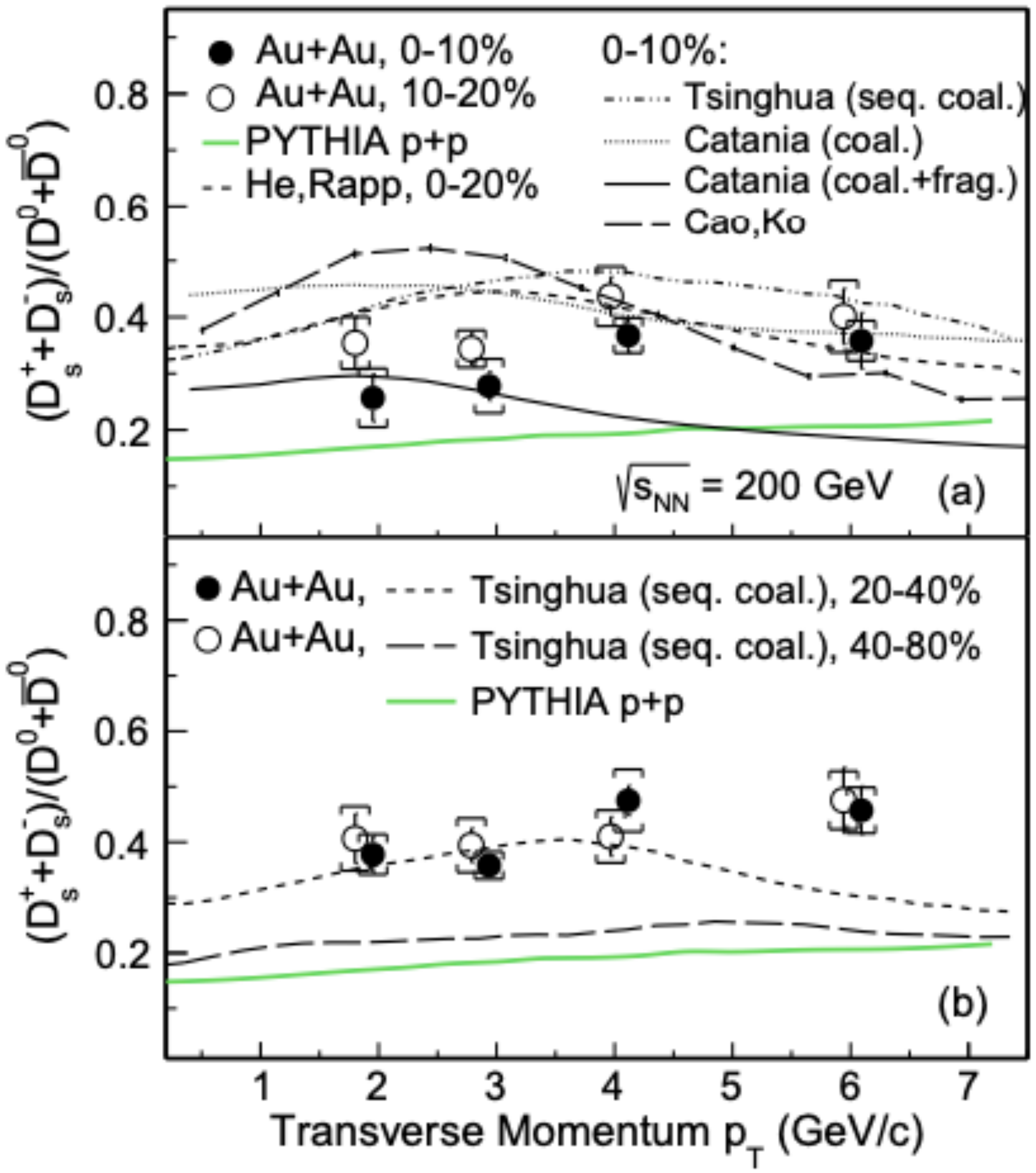
Strong B field in HIC -> **v_1(D) = − v_1(Dbar), $v_1(h^+)$-$v_1(h^-)$~0**

STAR, PRL 123 (2019) 162301

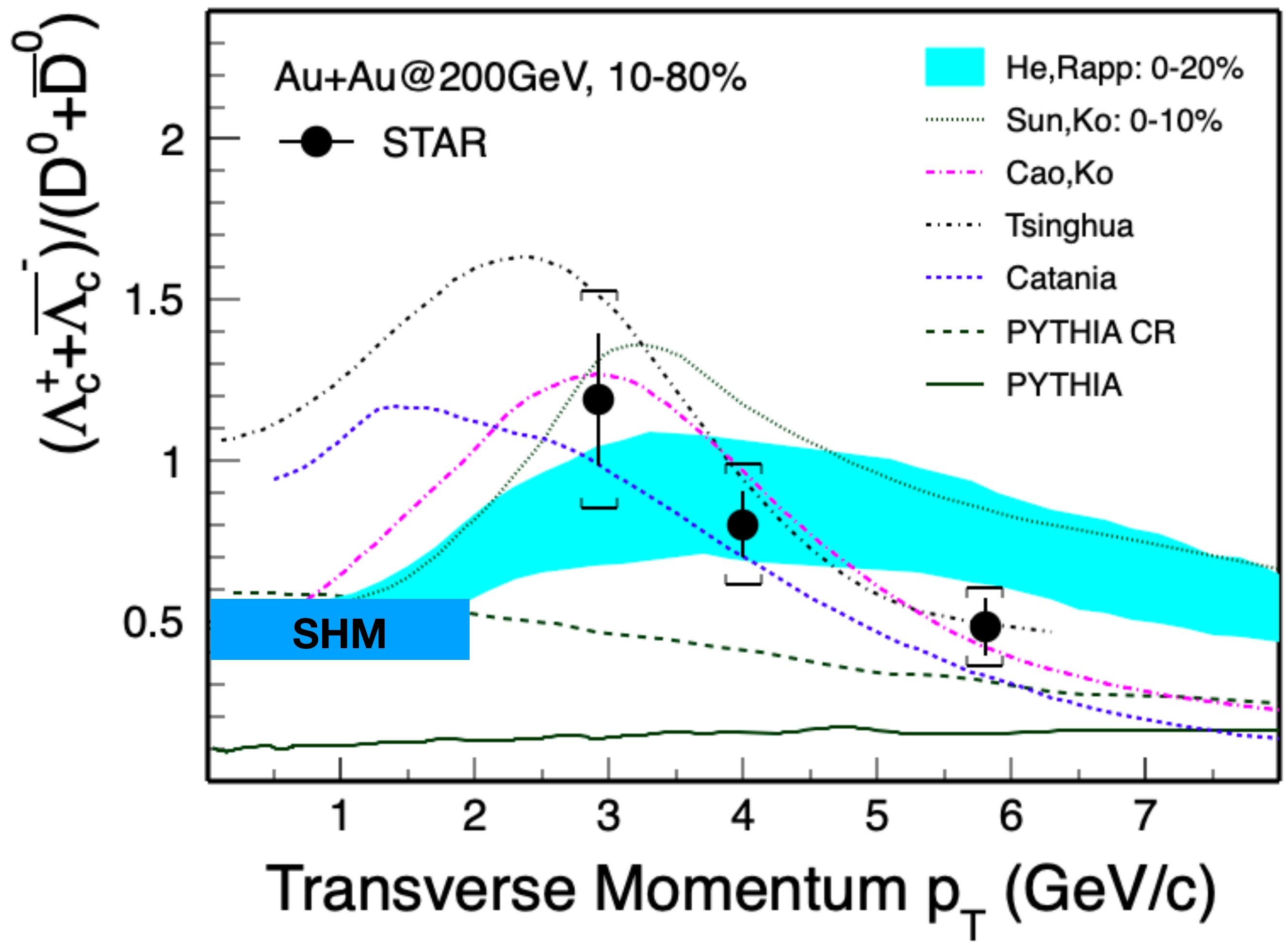


- $v_1(D) \gg v_1(h)$
  - *T*-dependence of diffusion coefficient
- $\Delta v_1(D)$: need more precise measurements

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



STAR, PRL 127 (2021) 092301

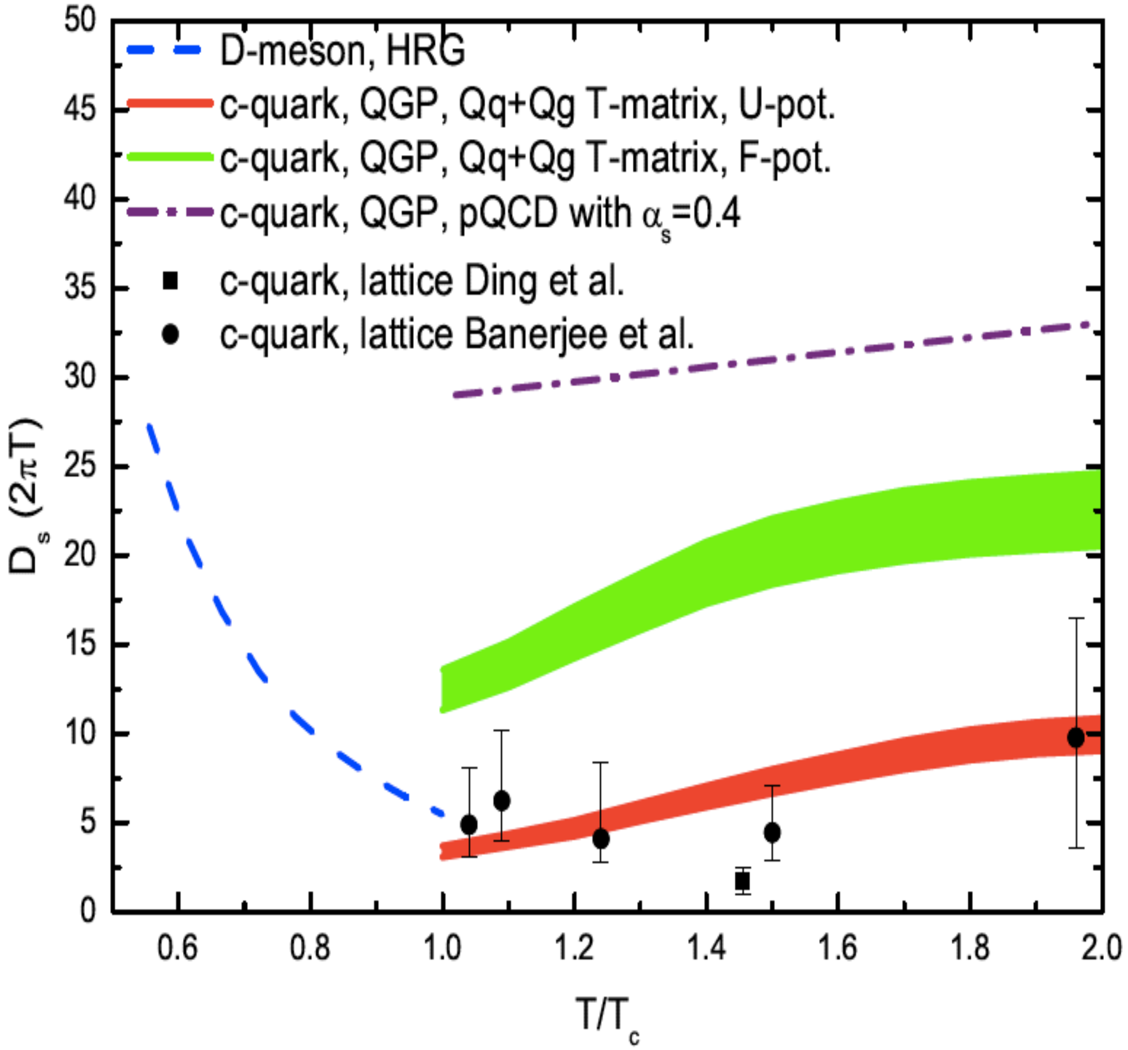


STAR, PRL 124 (2020) 172301

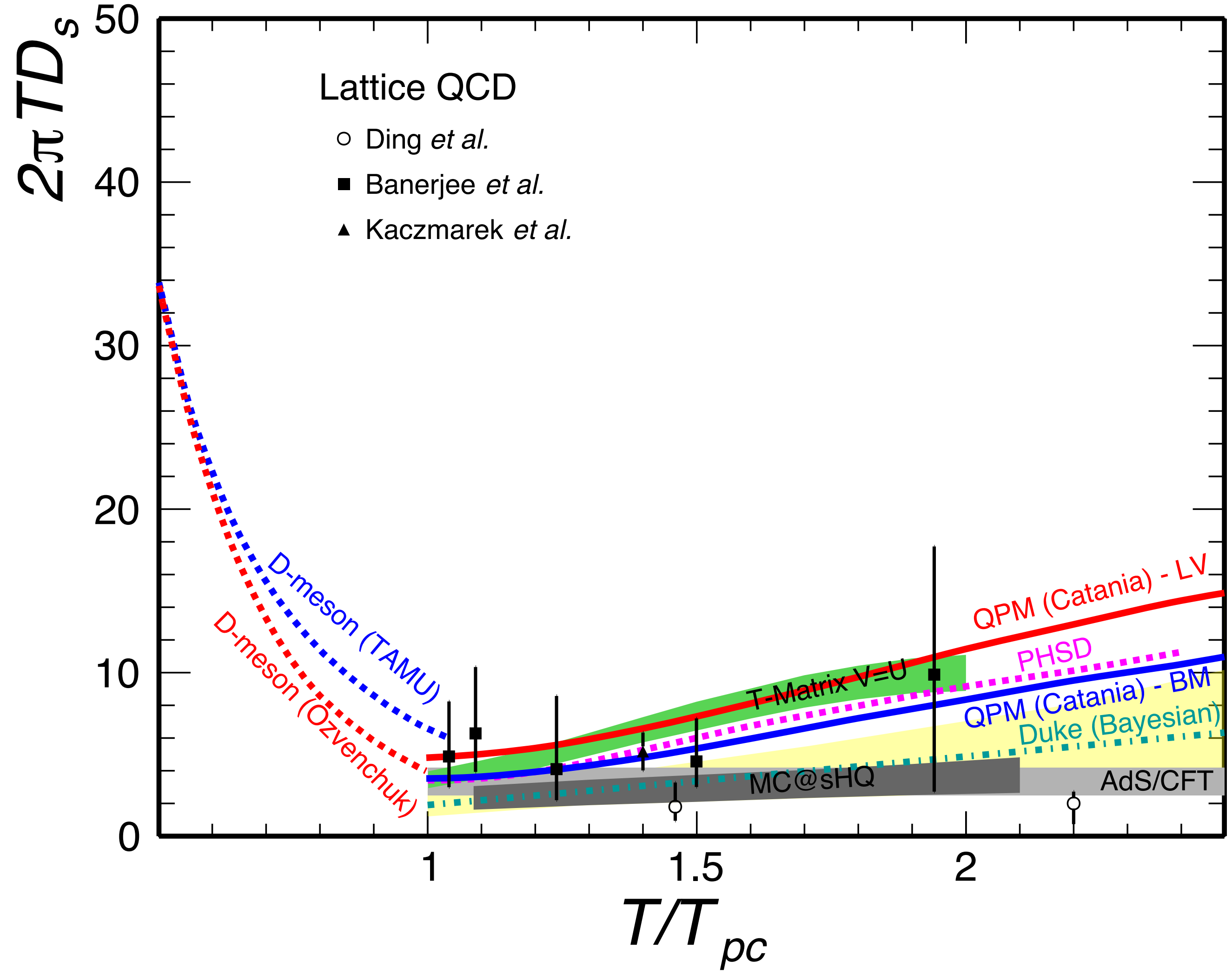
- D_s^+/D^0 and Λ_c/D significantly higher than fragmentation baseline
- Models with coalescence hadronization + strangeness enhancement qualitatively reproduce the data

Charm Spatial Diffusion Coefficient

2015



2019

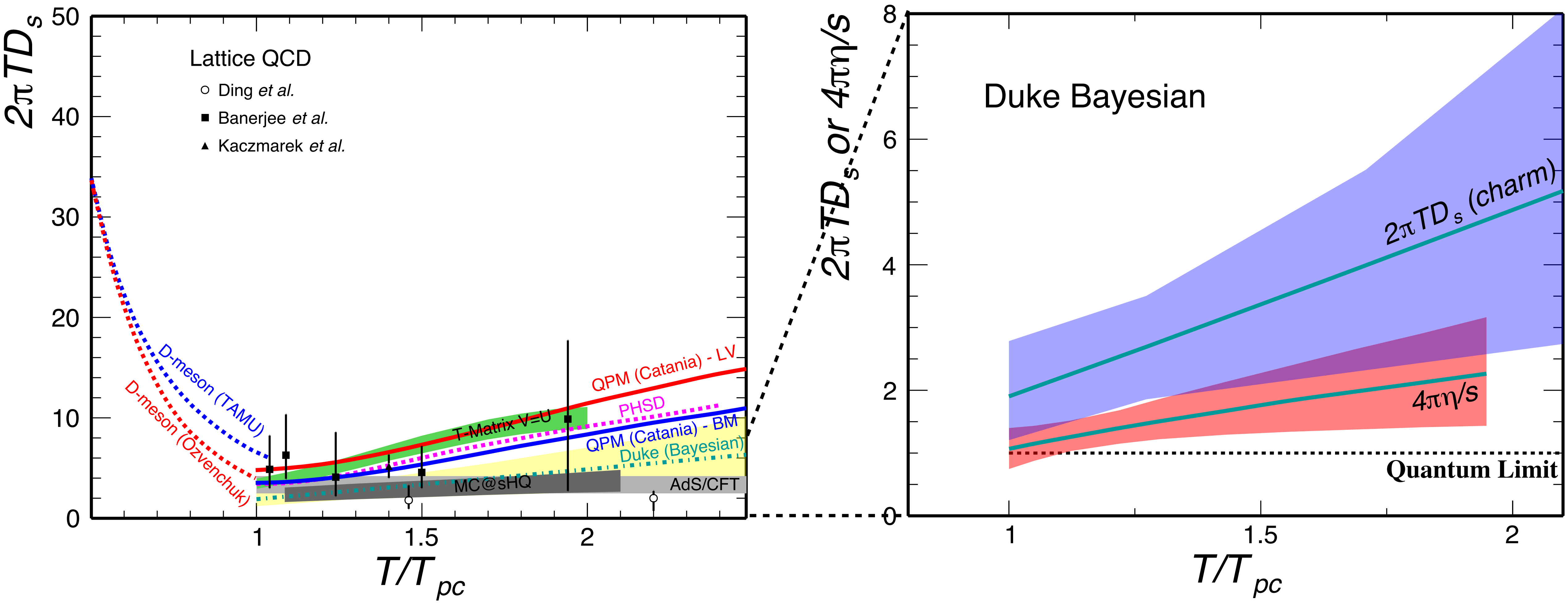


- Charm quark $2\pi TD_s$ **~ 2-5** at near T_c
  - consistent with quenched lattice calculations

momentum/temperature dependence? charm vs. bottom universality?

→ ***Next generation fast/thin MAPS + high lumi./stat. data at RHIC and LHC***

sQGP Transport Parameters



$2\pi TD_s$: *Y. Xu et al, PRC 97 (2018) 014907*

η/s: *J. Bernhard et al, Nature Physics 115 (2019) 1113*

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

momentum/temperature dependence? charm vs. bottom universality?

→ *Next generation fast/thin MAPS + high lumi./stat. data at RHIC and LHC*

Training Next Generation

STAR, PRL 127 (2021) 092301

University of Science and Technology of China

A dissertation for doctor's degree

Measurements of $D_s^{\pm}$ production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the STAR experiment

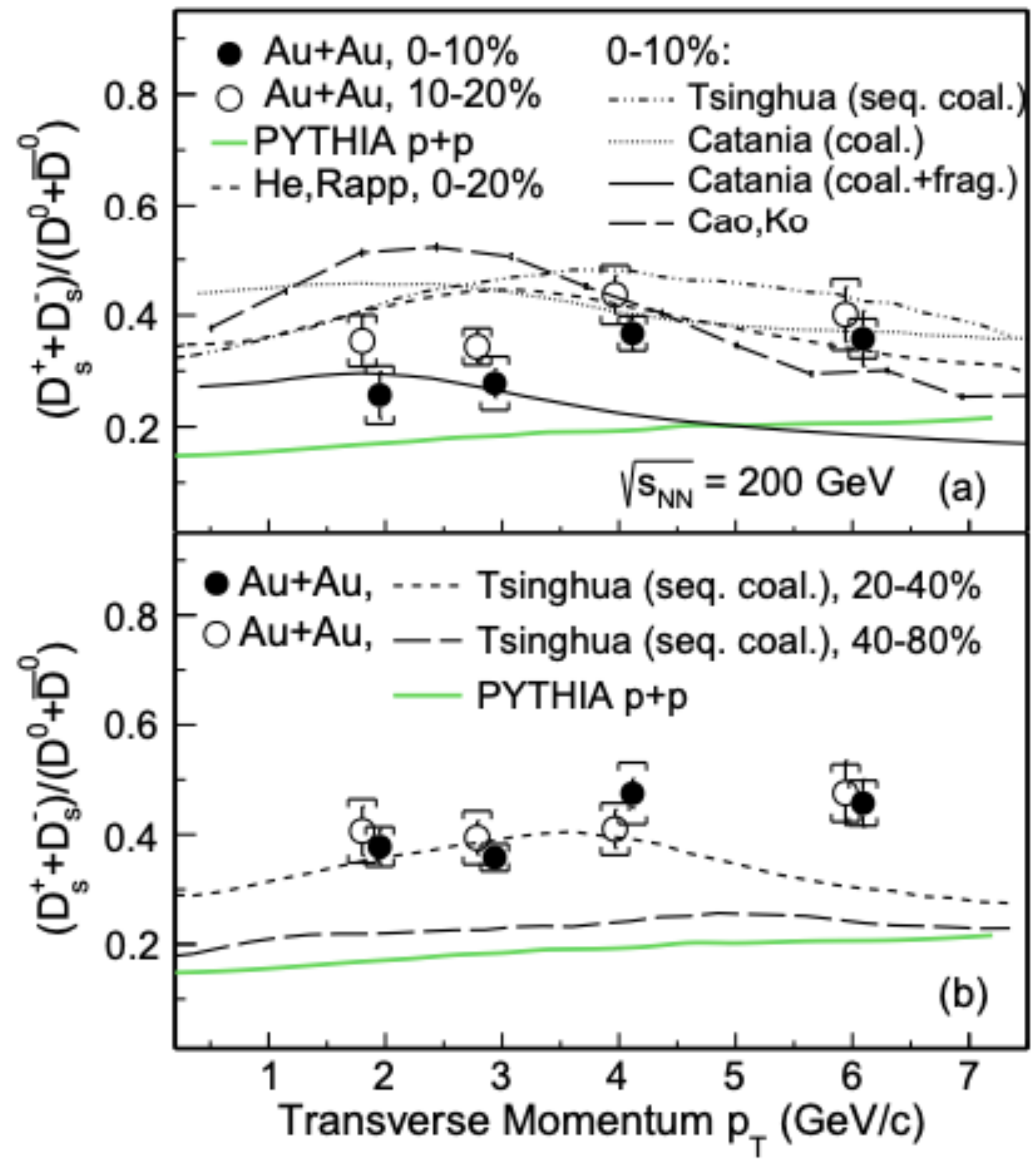
Author : Long Zhou

Speciality : Particle Physics and Nuclear Physics

Supervisor : Prof. Chen Li

Prof. Yifei Zhang, Prof. Flemming Videbaek

Finished Time : Mar, 2017



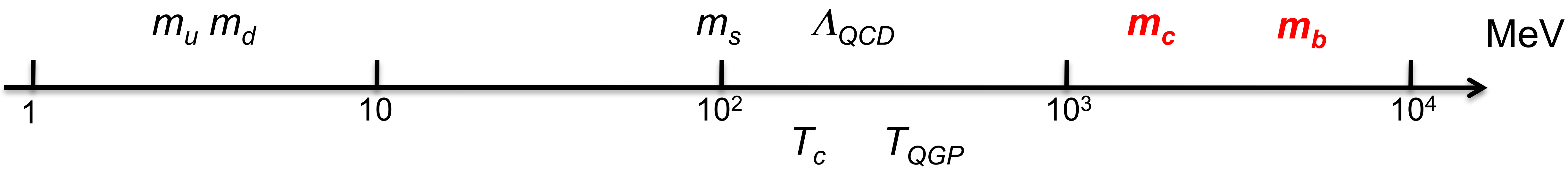
***11** PhDs graduated on HFT measurements*

Thank you, Flemming!

A long, happy and healthy retirement!

Backup

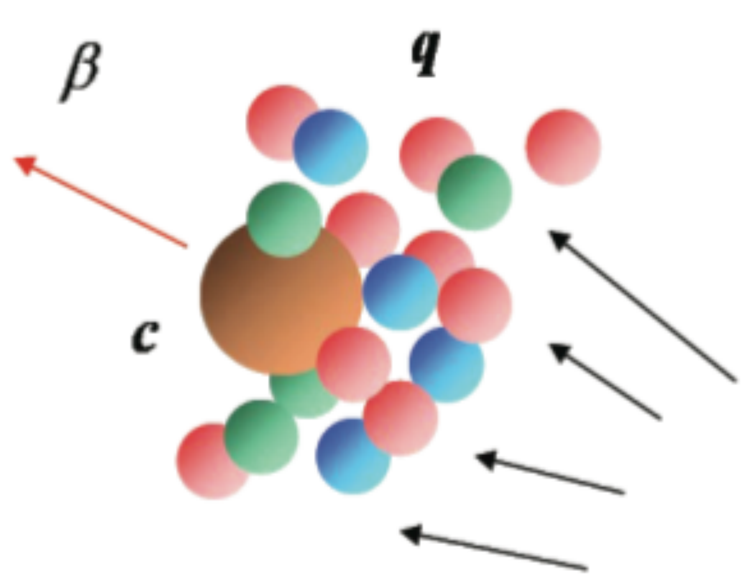
Uniqueness of Heavy Flavor Quarks



$m_{c,b} >> \Lambda_{QCD}$ *amenable to perturbative QCD*

$m_{c,b} >> T_{QGP}$ *predominately created from initial hard scatterings*

“Brownian” motion



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

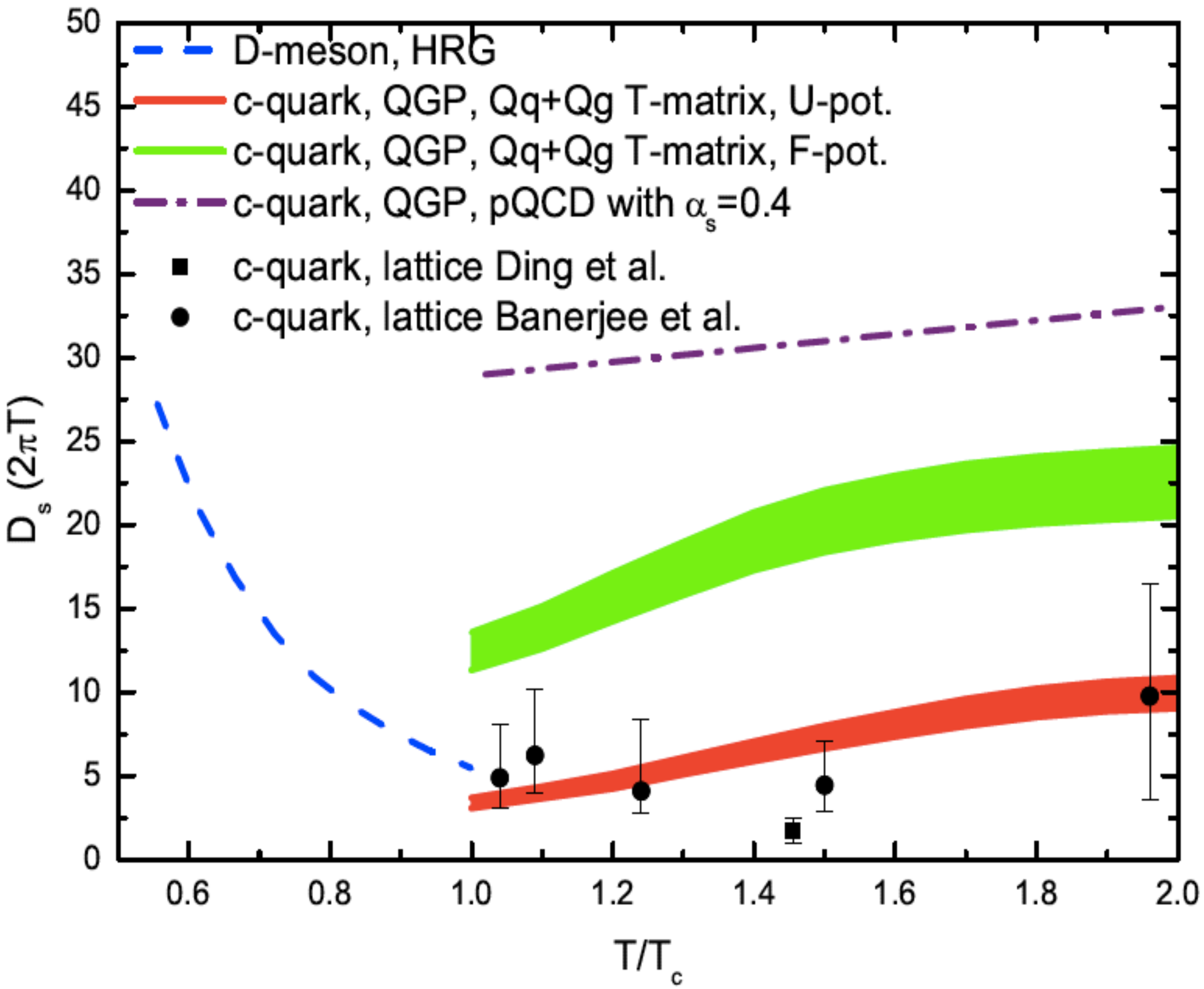
Diffusion Equation

$$\frac{\partial \rho}{\partial t} = D\frac{\partial^2 \rho}{\partial x^2} \qquad \langle x^2(t)\rangle - \langle x^2(0)\rangle \sim Dt$$

***D* or *D*$_s$** - spacial diffusion coefficient

- used to reveal medium substructures
- e.g. $D = \frac{RT}{N_A 6\pi\eta a} = \frac{k_B T}{6\pi\eta a}$

Heavy Quark Diffusion Coefficient



HotQCD white paper - arXiv: 1502.02730

2015

- $2\pi T D_s$ ~ up to 30 @ T_c

To determine HQ diffusion coefficient

Precision measurement of D^0 production (R_{AA} and v_2), particularly at low p_T

$$D^0 \rightarrow K^-\pi^+ \qquad c\tau \sim 123\mu m$$

$$\Lambda_c^+ \rightarrow pK^-\pi^+ \qquad c\tau \sim 60\mu m$$

Big Challenge

Combinatorial background in heavy-ion collisions

Silicon pixel detector to separate secondary decay vertex!

Instrumentation

	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	$1\%X_0$	$\sim 1\%X_0$	$\sim 1\%X_0$	$\sim 1\%X_0$	$1\%X_0$	**$0.4\%X_0$**

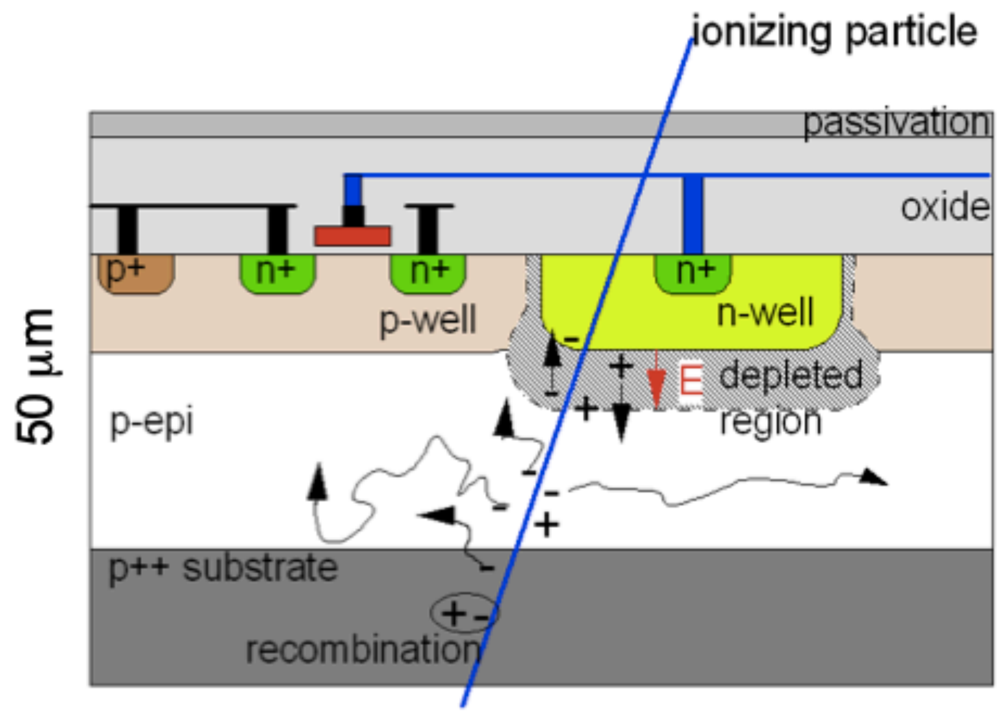
STAR Pixel - first application of **MAPS** technology in collider experiments
Monolithic Active Pixel Sensor

Next generation MAPS sensor deployed for ALICE-ITS2, sPHENIX-MVTX upgrades

MAPS-based pixel detector planned for CBM, EIC tracker etc.

Monolithic Active Pixel Sensor (MAPS)

MAPS pixel cross-section (not to scale)



Properties:

- Standard commercial CMOS technology
- Sensor and signal processing are integrated in the same silicon wafer
- Signal is created in the low-doped epitaxial layer (typically ~10-15 μm) → MIP signal is limited to <1000 electrons
- Charge collection is mainly through thermal diffusion (~100 ns), reflective boundaries at p-well and substrate

MAPS and competition	MAPS	Hybrid Pixel	CCD
Granularity	+	-	+
Small material budget	+	-	+
Readout speed	+	++	-
Radiation tolerance	+	++	-

MAPS - particularly chosen for measuring HF hadron decays in heavy ion collisions

Project Timeline and Completion Summary

Level	Milestone	Baseline Date	Actual/Forecast Date
1	CD-0 Approve Mission Need	Q2, FY09	2/18/09 (A)
1	CD-1 Approve Alternative Selection and Cost Range	Q4, FY10	8/31/10 (A)
1	CD-2 Approve Performance Baseline	Q4, FY11	10/11/11(A)
1	CD-3 Approve Start of Fabrication	Q4, FY11	10/11/11(A)
1	CD-4 Approve Project Completion	Q4, FY15	9/25/14 (F)

Summary

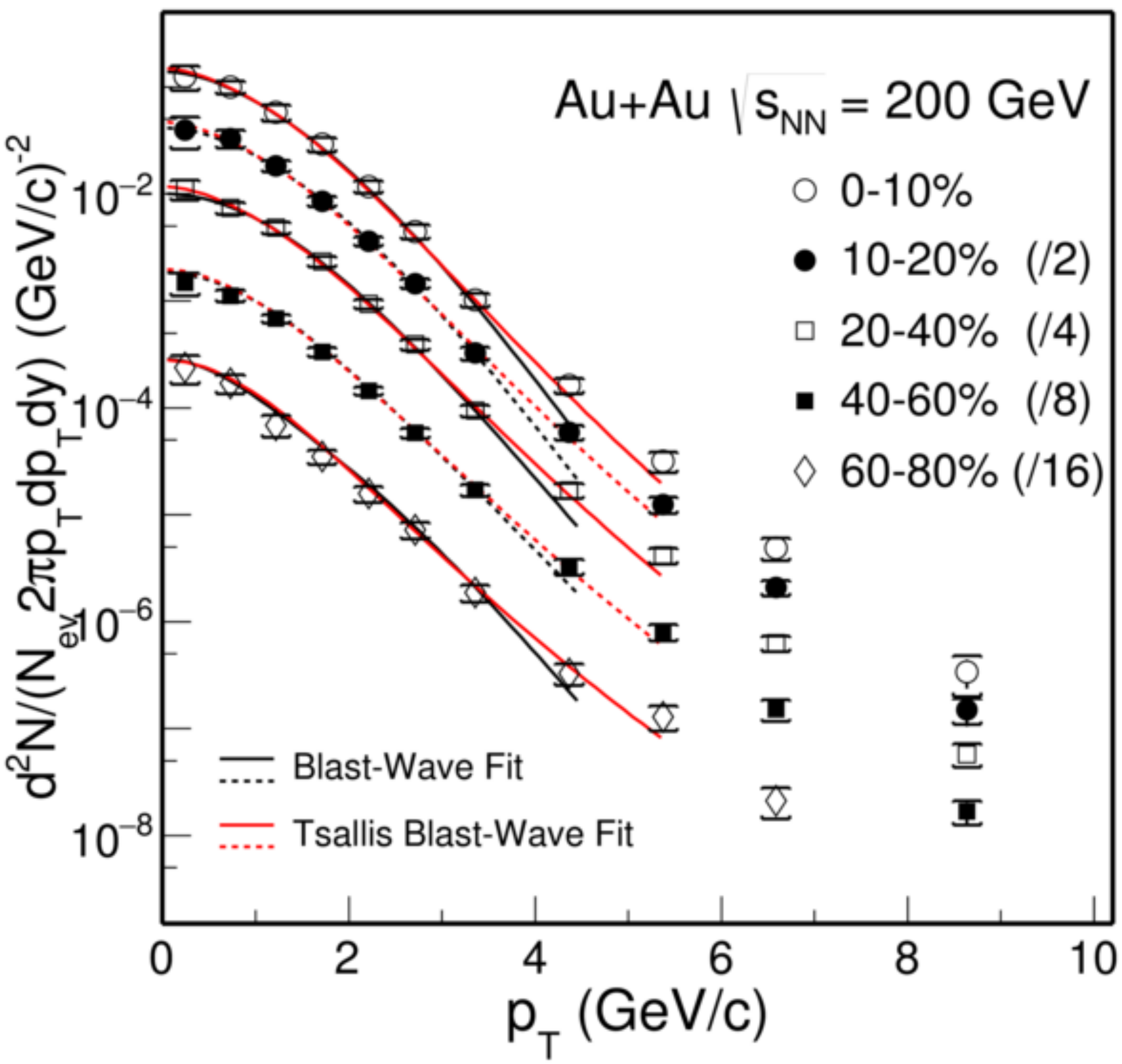
STAR HFT

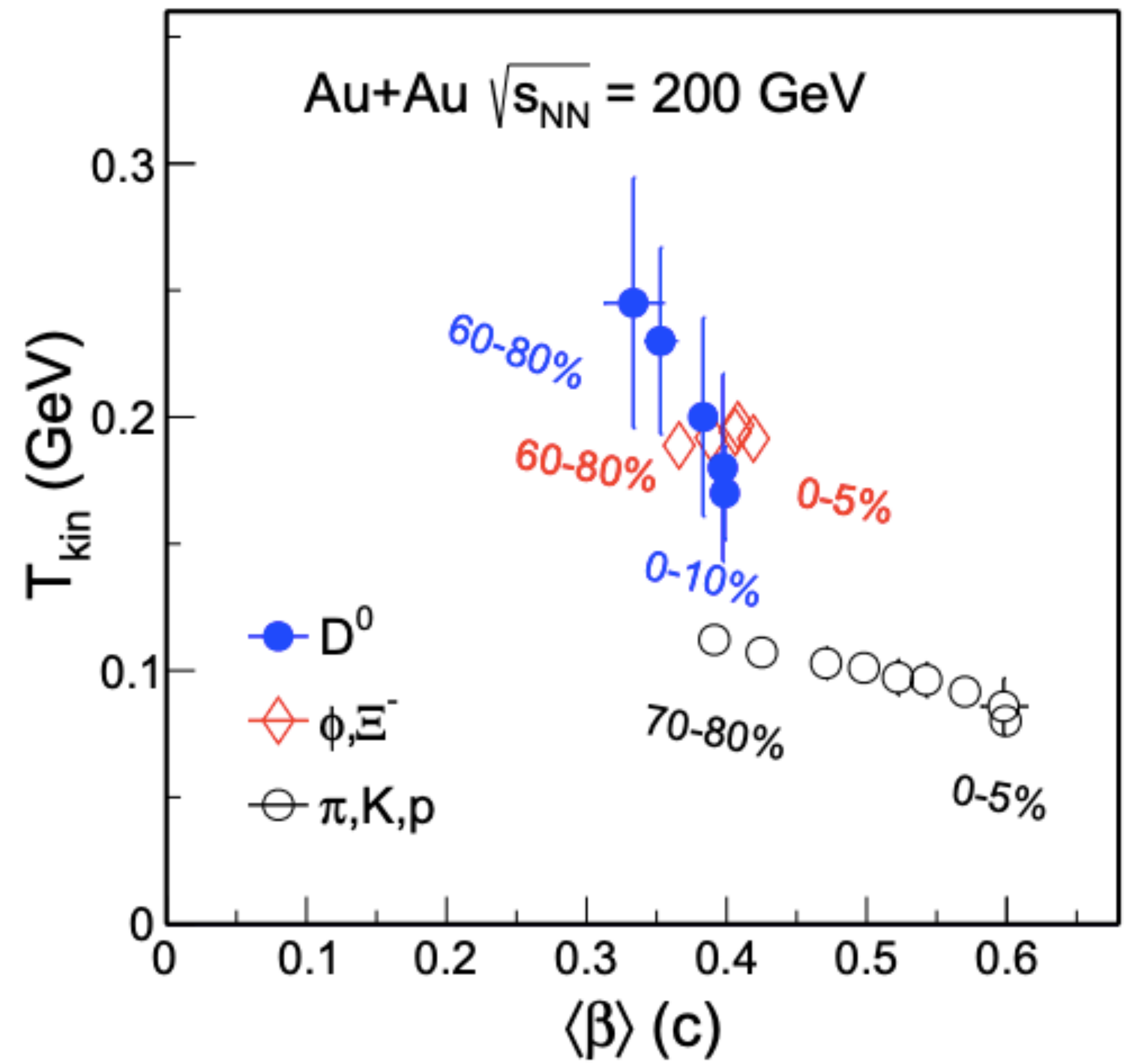
- The HFT project systems were installed ahead of the RHIC run-14
- With PXL and IST included in the run STAR collected 1.2B minimum bias events. This met the STAR physics goals for HFT in run-14.
- The SSD system also completed commissioning and took 172M physics events
- The first PXL detector will be refurbished and be ready for future years running, as per design of the replaceable inner tracking system
- Project will complete significantly under budget (~M$ 2) and ahead of schedule
- The HFT system has met the KPP requirements for CD-4

BROOKHAVEN NATIONAL LABORATORY 7/31/14 *Project Closeout Review* Office of Science U.S. DEPARTMENT OF ENERGY 24

Collectivity - Radial Flow

(Tsallis) Blast-Wave fits



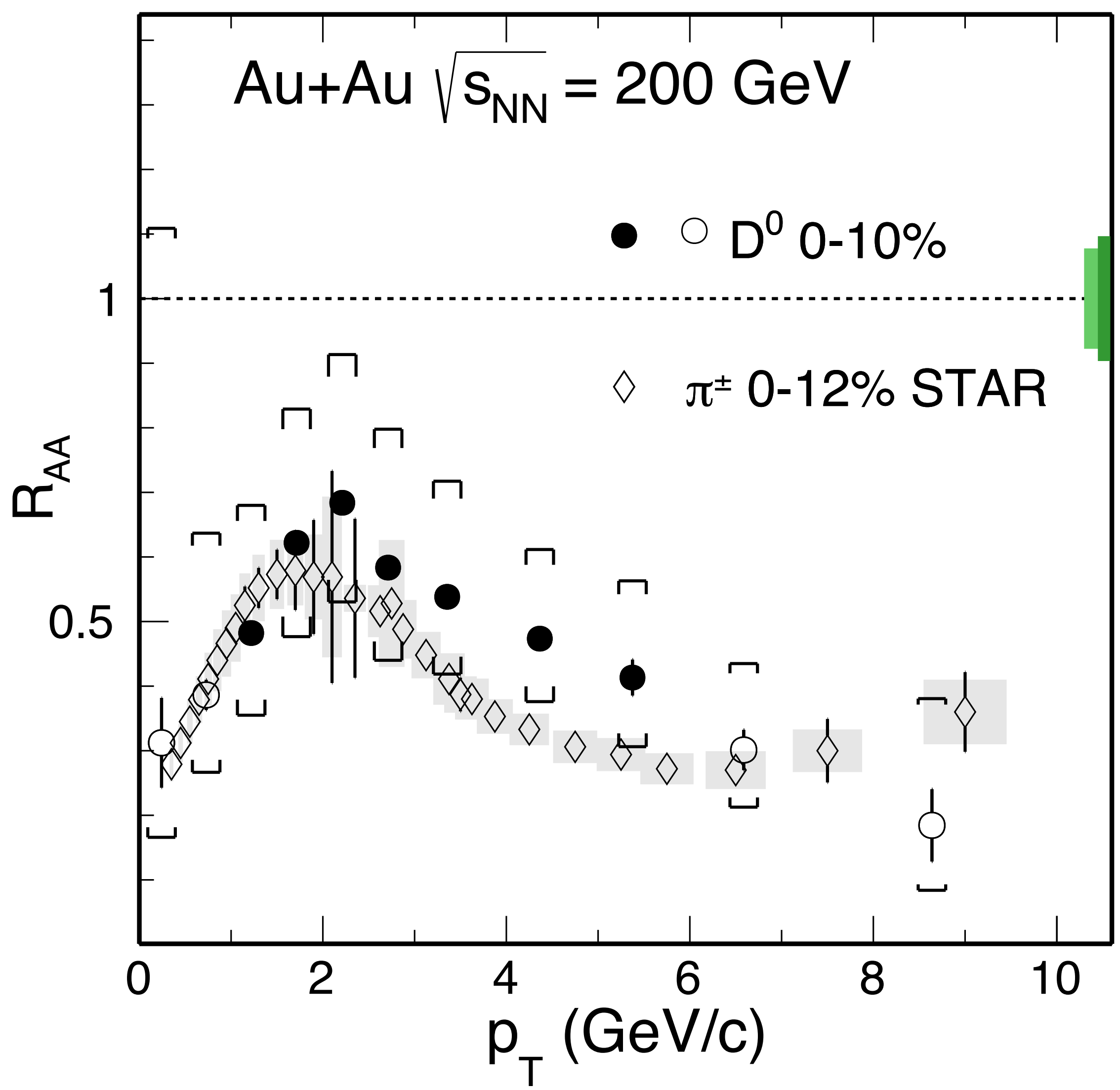


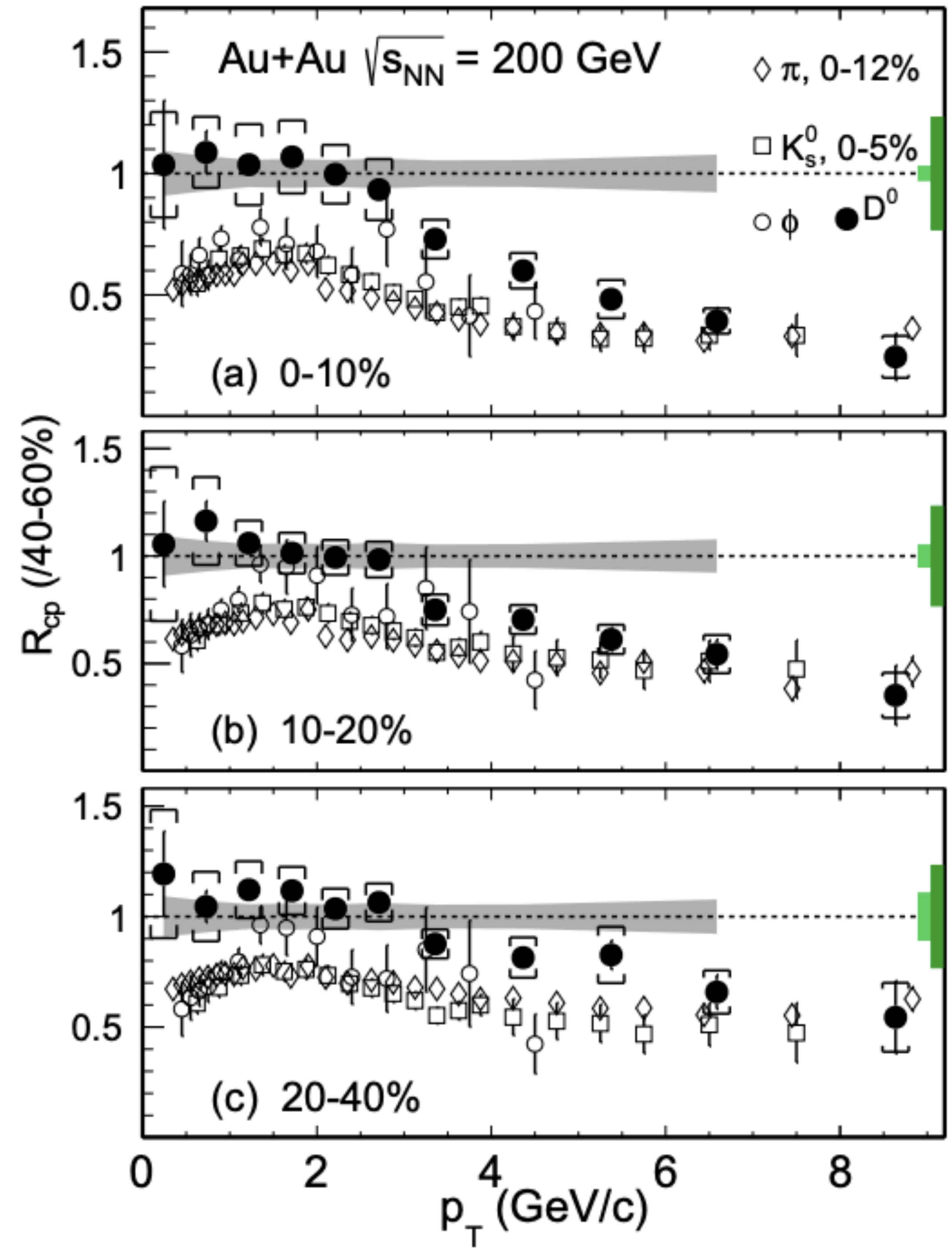
STAR, PRC 99 (2019) 034908

- Blast-wave model fit: similar to multi-strange harons, *D^0* mesons kinetically freeze out earlier than light hadrons
  - collectivity from partonic stage interactions

D^0 Meson R_{AA}/R_{CP} in A+A Collisions

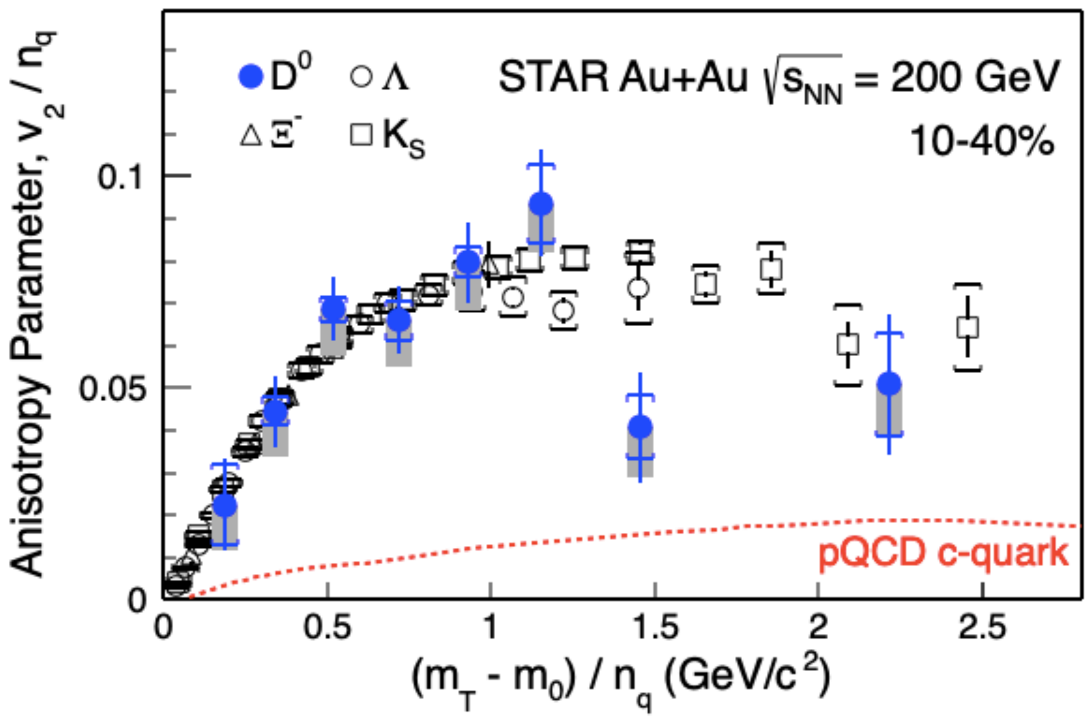
STAR, PRC 99 (2019) 034908

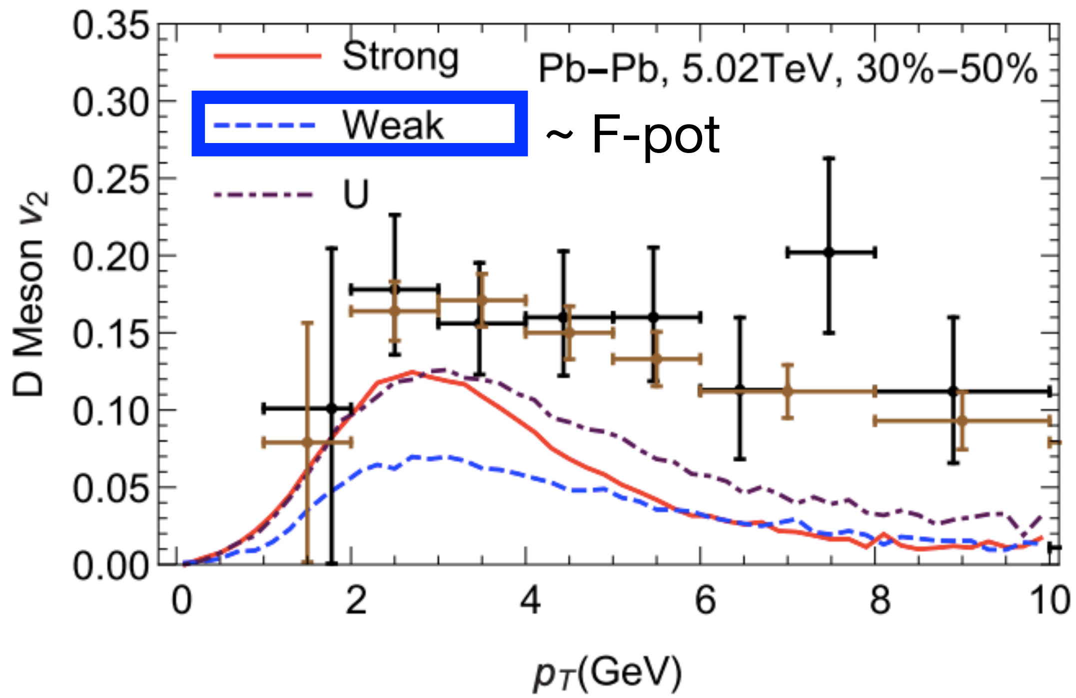




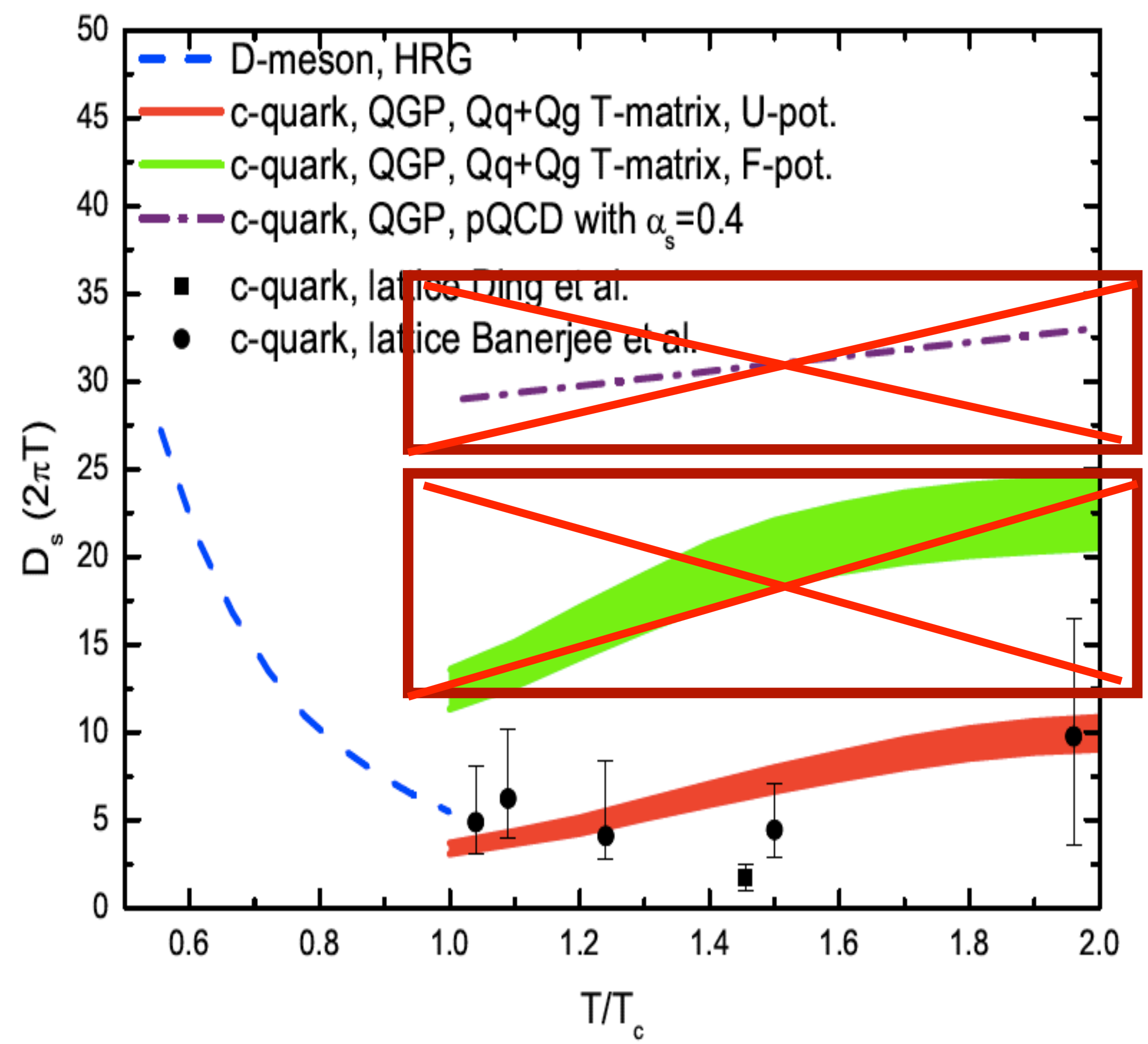
- $R_{AA}(D)$ ~ $R_{AA}(h)$ at p_T > ~4 GeV/c
  - significant charm quark energy loss in the QGP medium
  - importance of radiative and collisional energy loss

D^0 v_2 Compared with Model Calculations





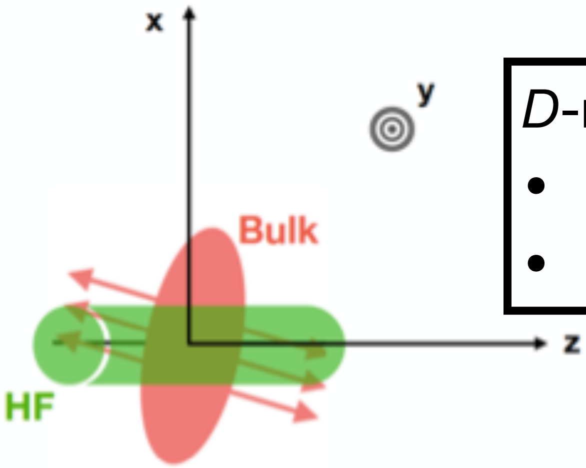
pQCD c-quark (b=7fm):
R. Rapp & H. van Hees, arXiv: 0903.1096
T-Matrix with F-pot:
S. Liu et al, PRC 99 (2019) 055201



- pQCD calculation and T-Matrix with F-pot. cannot reproduce the data
  - heavy quarkonium R_{AA} data disfavors F-pot.

D^0 v_1 - T-dependent sQGP Properties

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

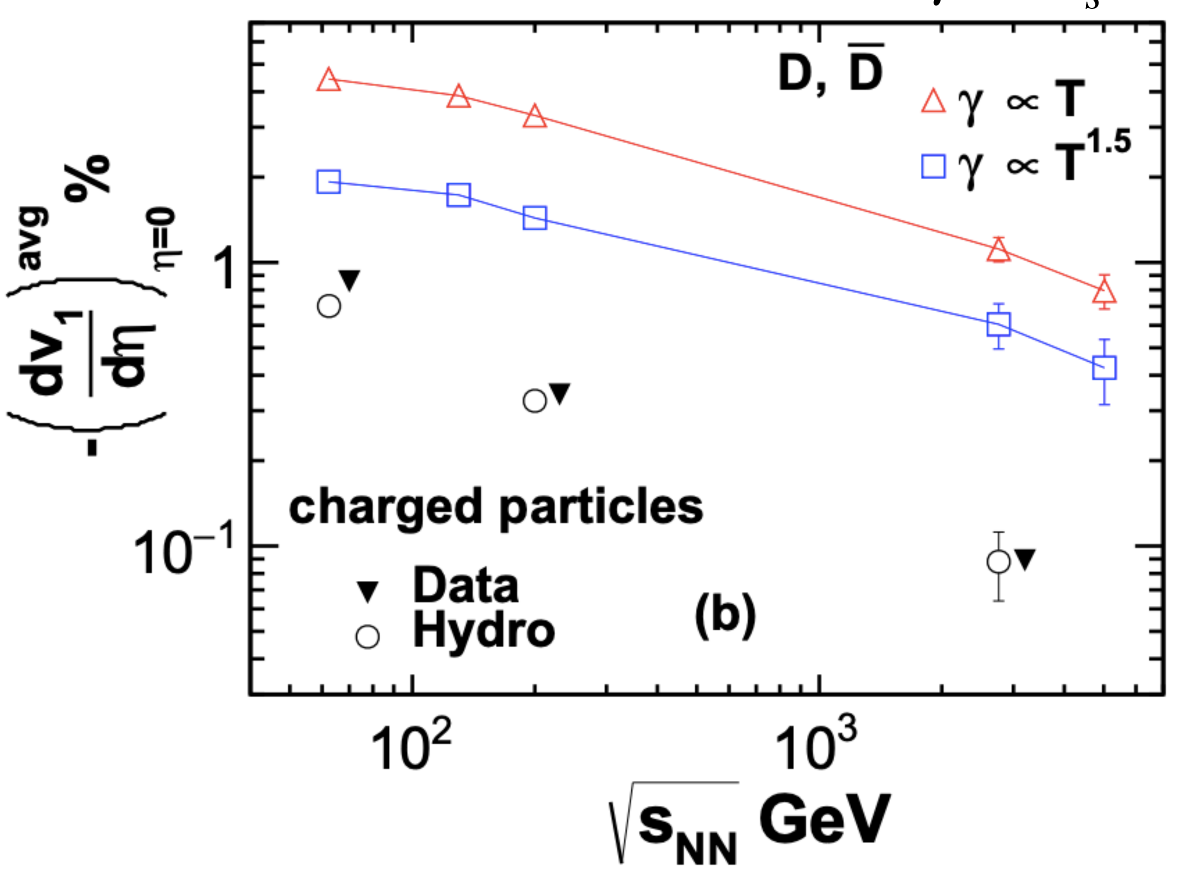


D-meson v_1 sensitive to

- geometry tilt of QGP source
- HQ diffusion coefficient $D_s(T)$

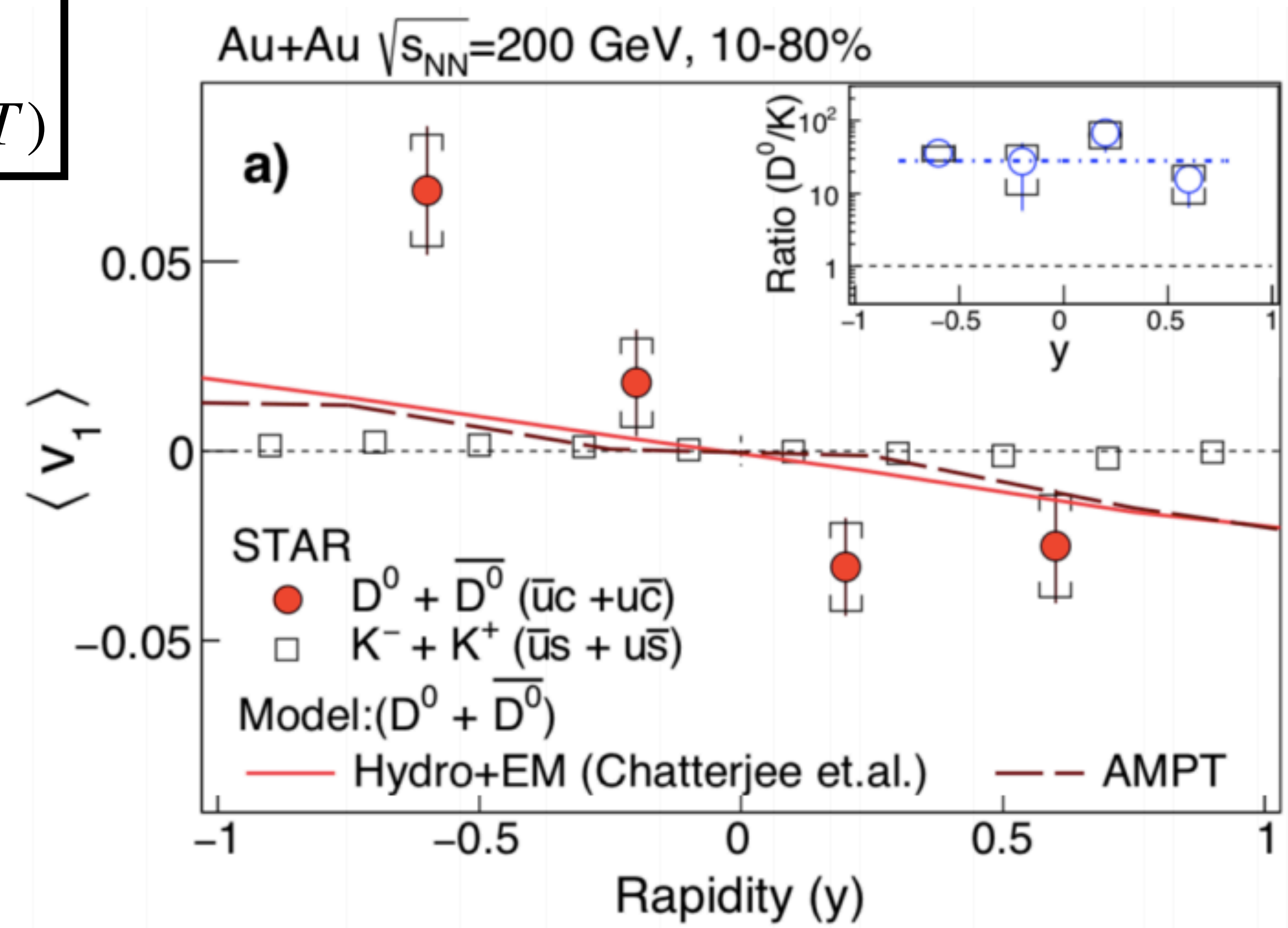
Hydro model

$\gamma = D_s/ET$



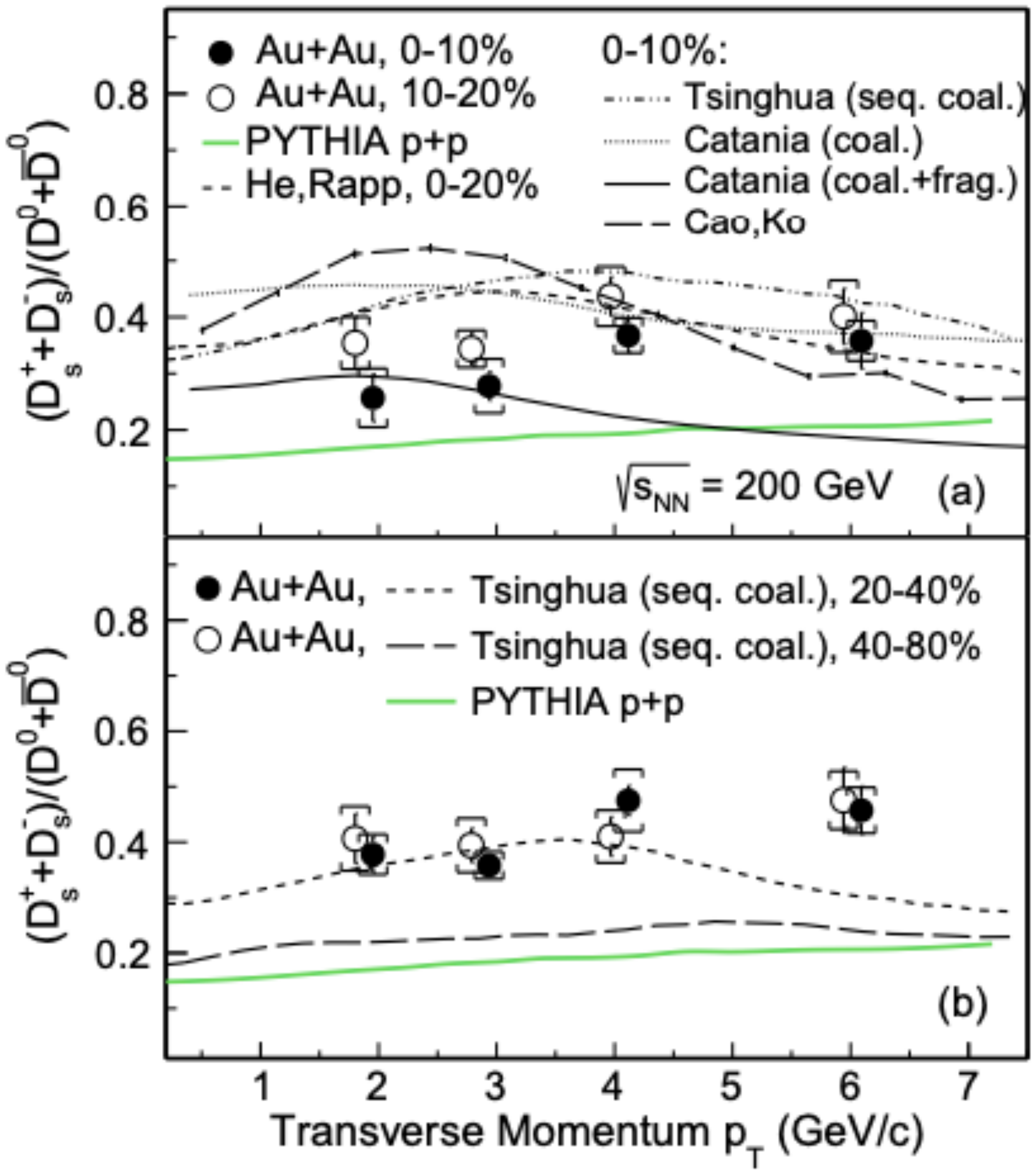
S. Chatterjee & P. Bozek, PLB 798 (2019) 134955

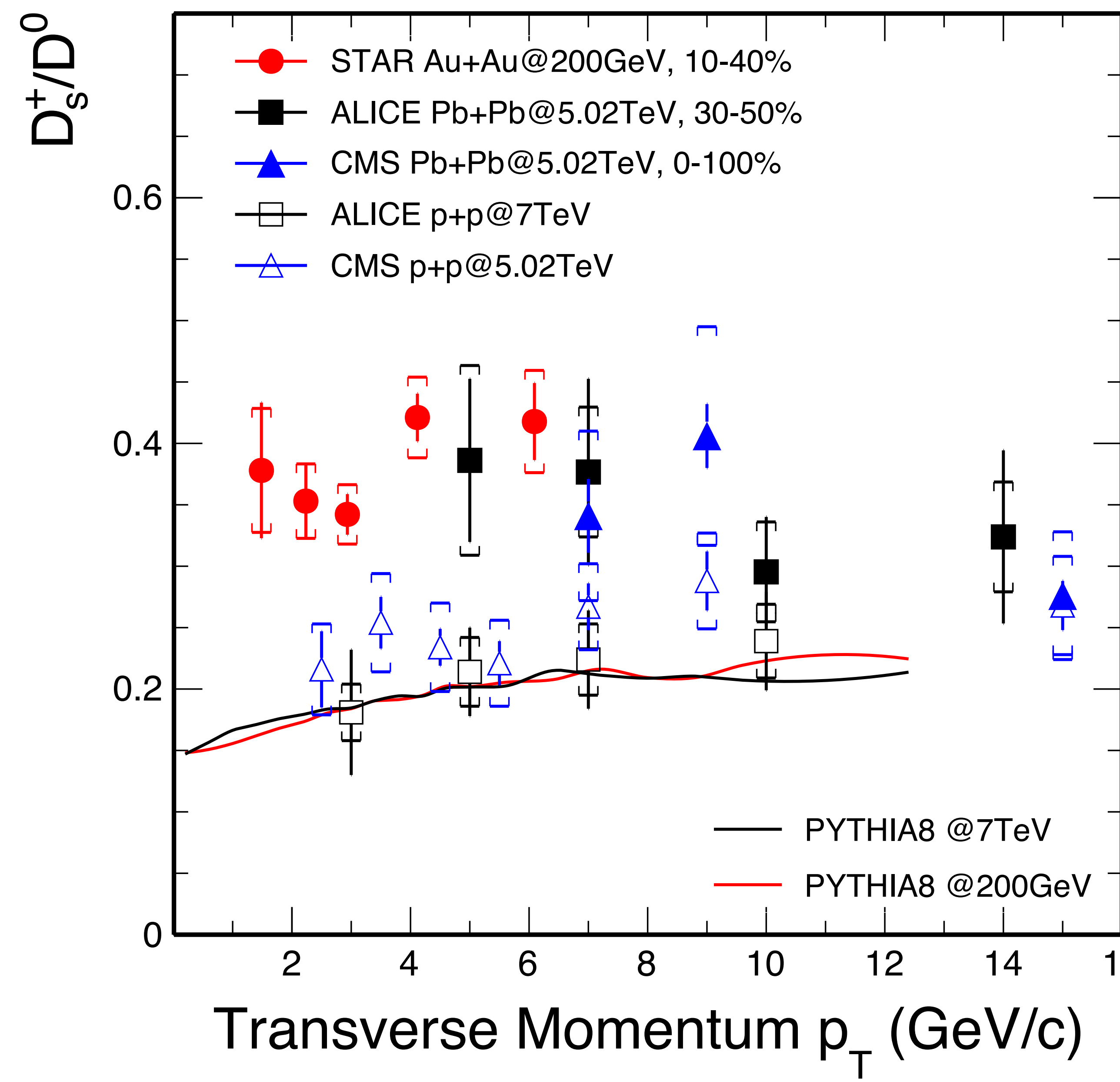
STAR, PRL 123 (2019) 162301



- $v_1(D) \gg v_1(h)$
  - Constraints on T-dependence of HQ diffusion coefficient

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

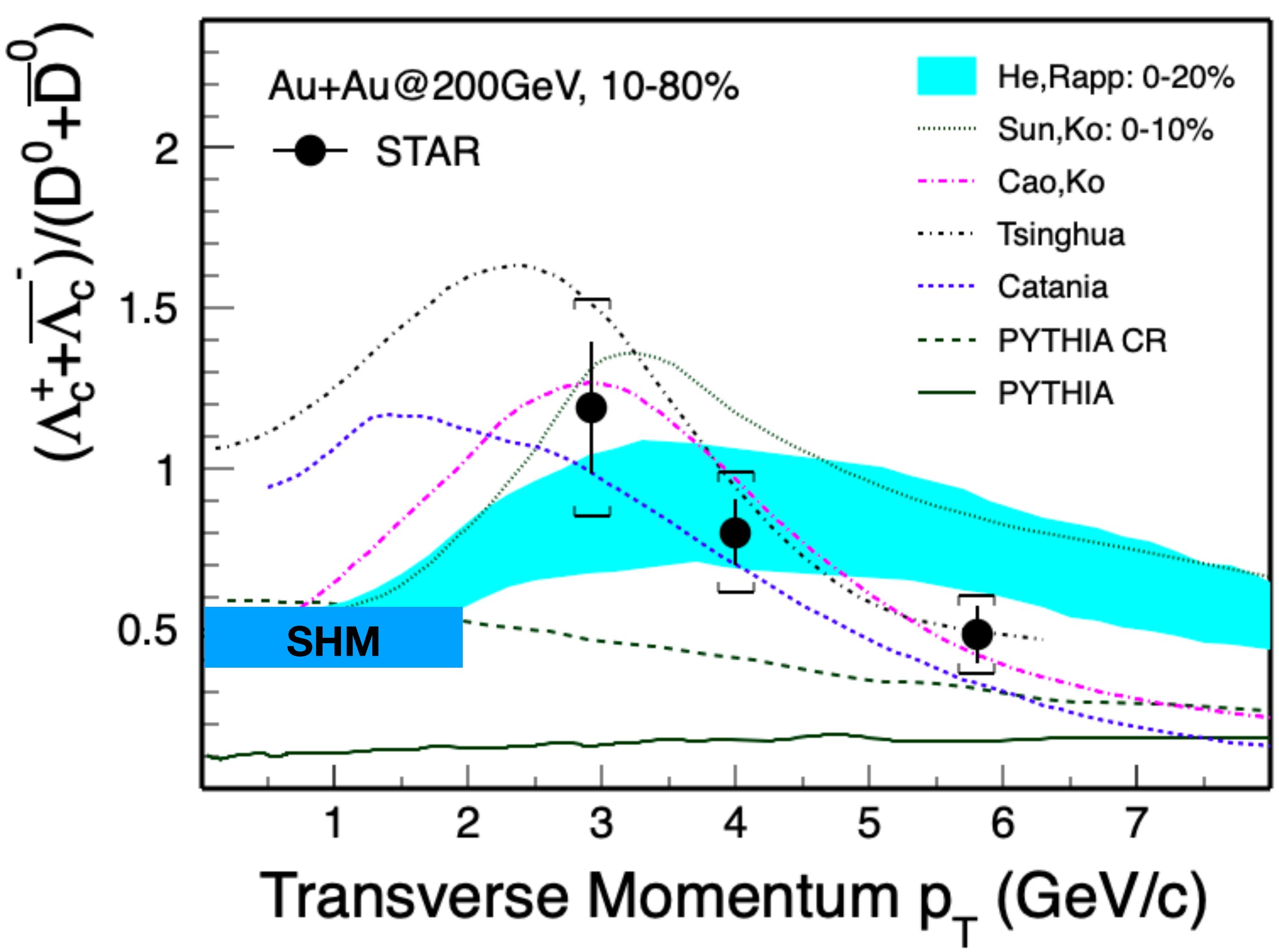


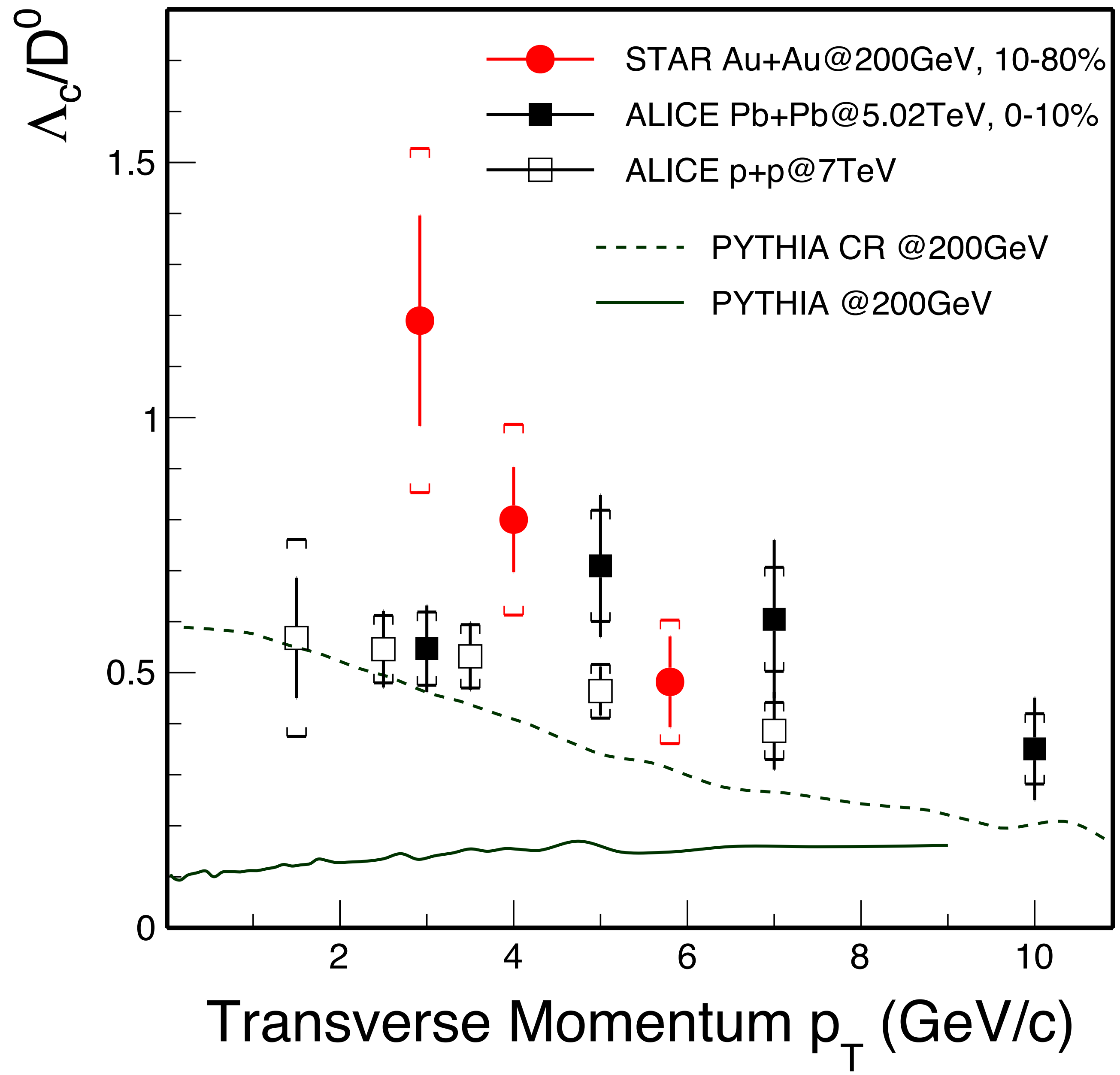


STAR, PRL 127 (2021) 092301, CMS, PAS-HIN-18-017
ALICE, JHEP 1810 (2018) 174, EPJC77 (2017) 550

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

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

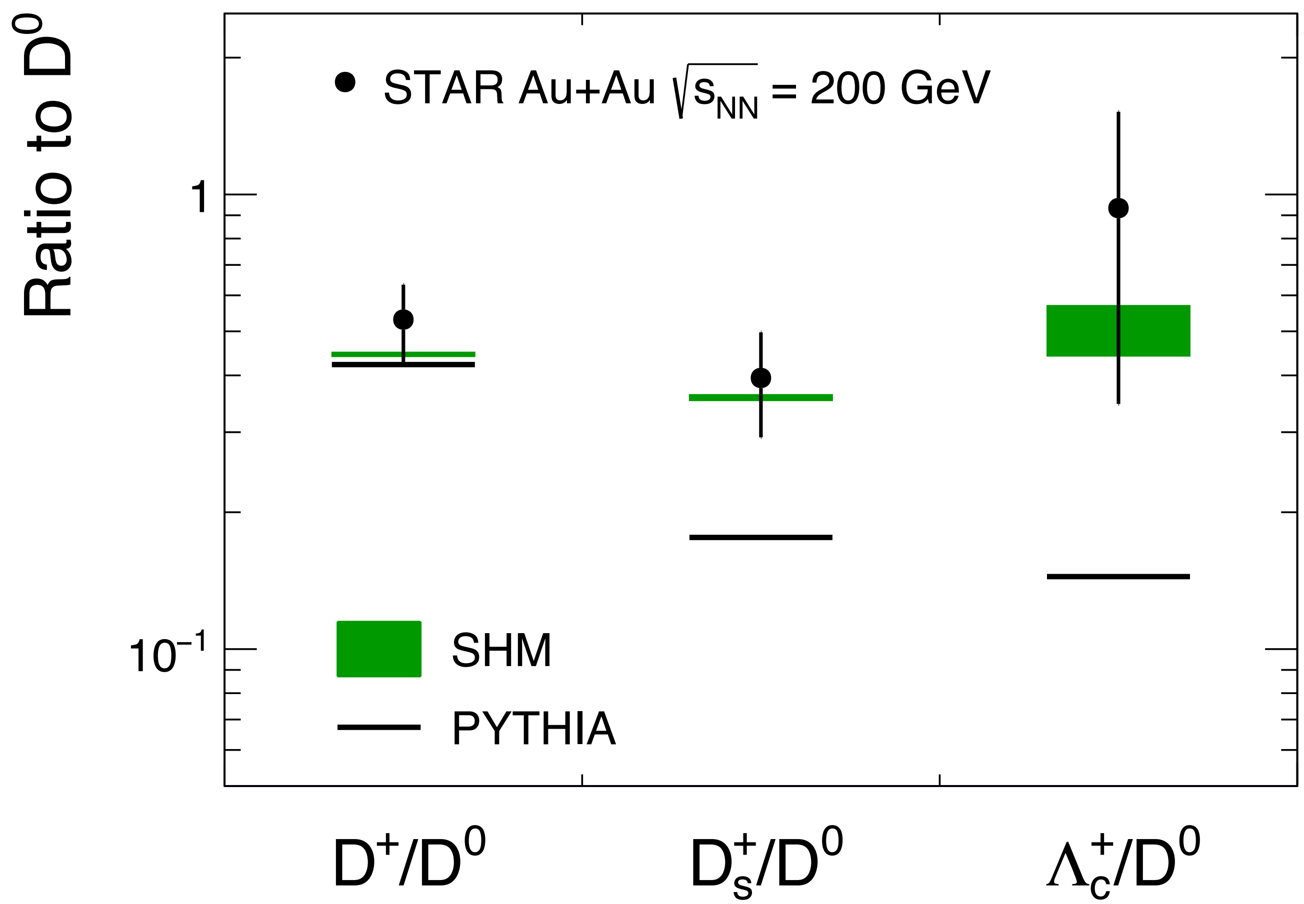




STAR, PRL 124 (2020) 172301
ALICE, JHEP 04 (2018) 108, QM19
CMS, PLB 803 (2020) 135328

- Λ_c/D ratio comparable to light/strange hadrons in A+A collisions
- Λ_c/D enhancement w.r.t the PYTHIA predictions (w/ and w/o CR)
- Coalescence models qualitatively reproduce the large Λ_c/D ratio

Charm Hadrochemistry



Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 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**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

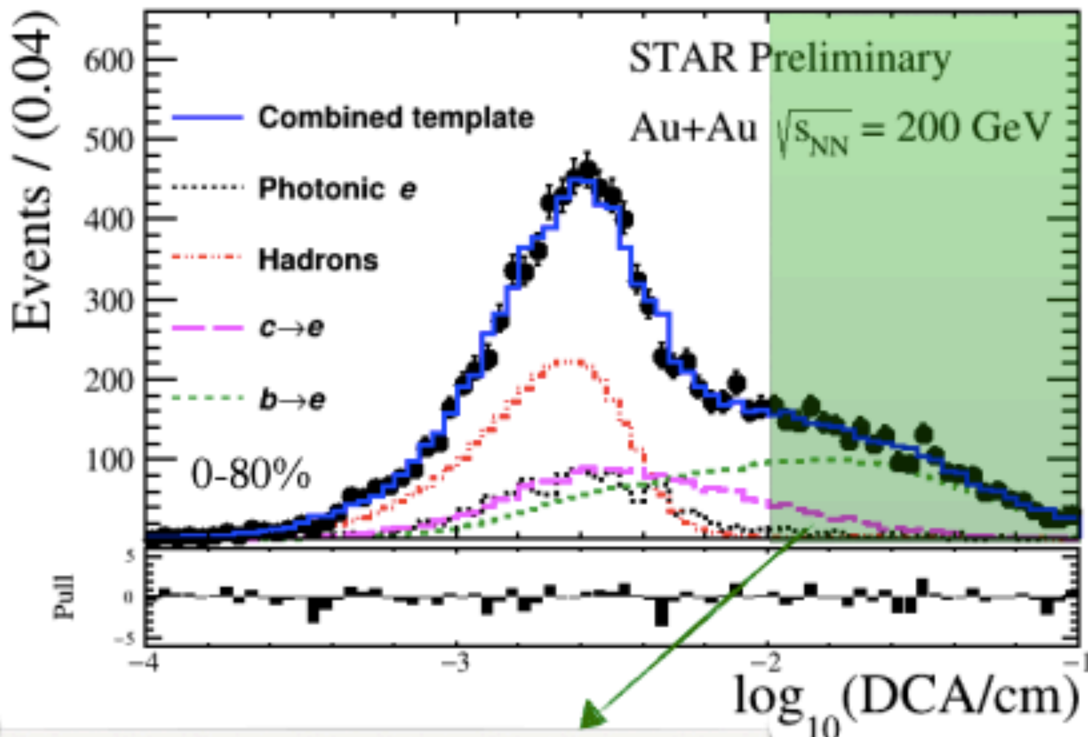
** extracted from 10-80%*

SHM: THERMUS calculations
chemical FO parameters from the fit to light/strange hadrons

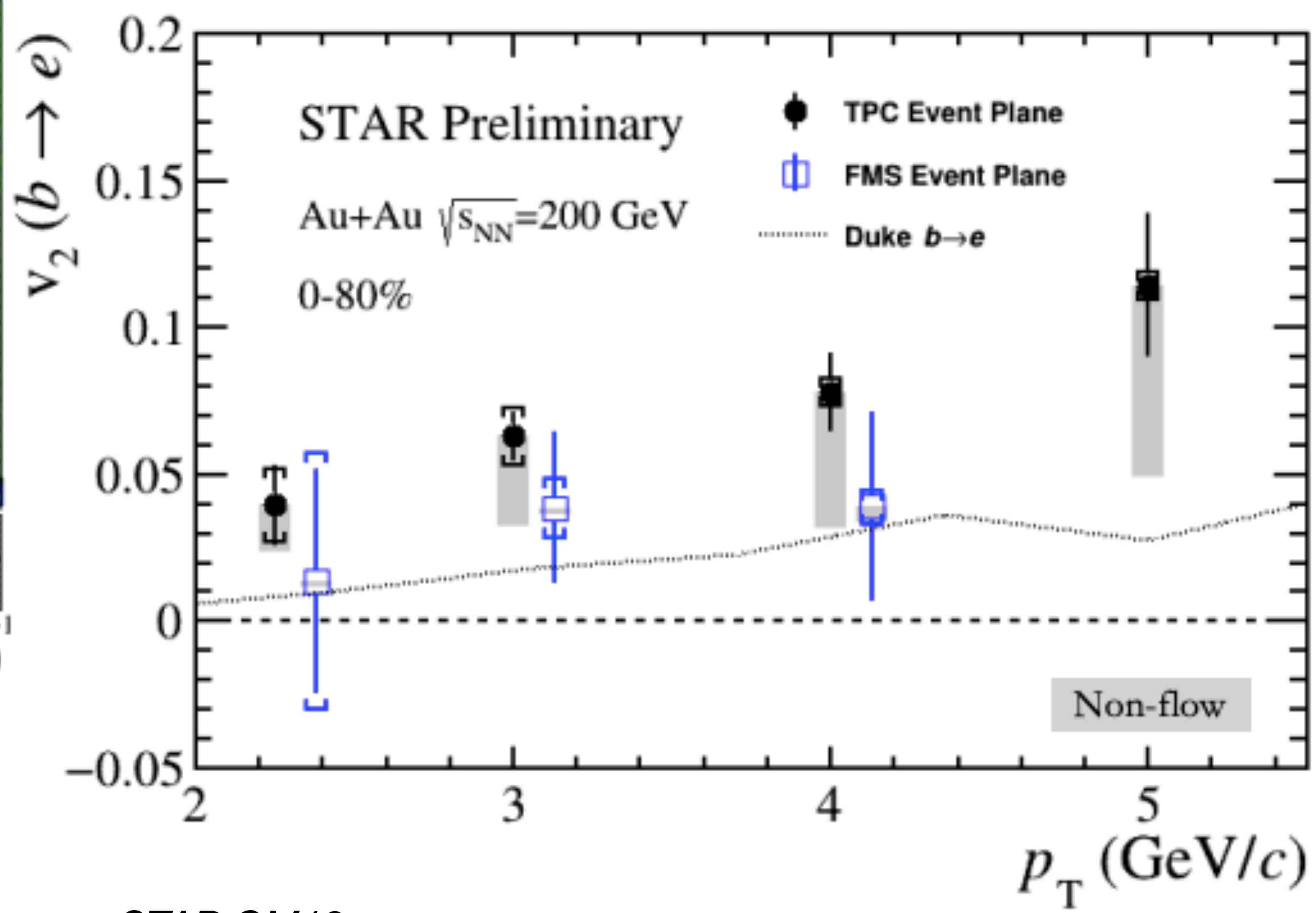
<u>at RHIC top energy</u>

- Total charm cross section follows ~ N_{bin} scaling from p+p to Au+Au
- However, charm hadrochemistry changes considerably in Au+Au collisions!

First Look at the Bottom v_2



$$v_2(obs.) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$



STAR QM19

- TPC and FMS ($2.5 < \eta < 4.0$) methods provide consistent results

  Evidence of non-zero bottom v_2 (3.4σ)

Summary of D^0 v_2 and R_{AA} at RHIC and LHC