STAR Heavy Flavor Tracker (HFT) and HFT+ Upgrade Plan

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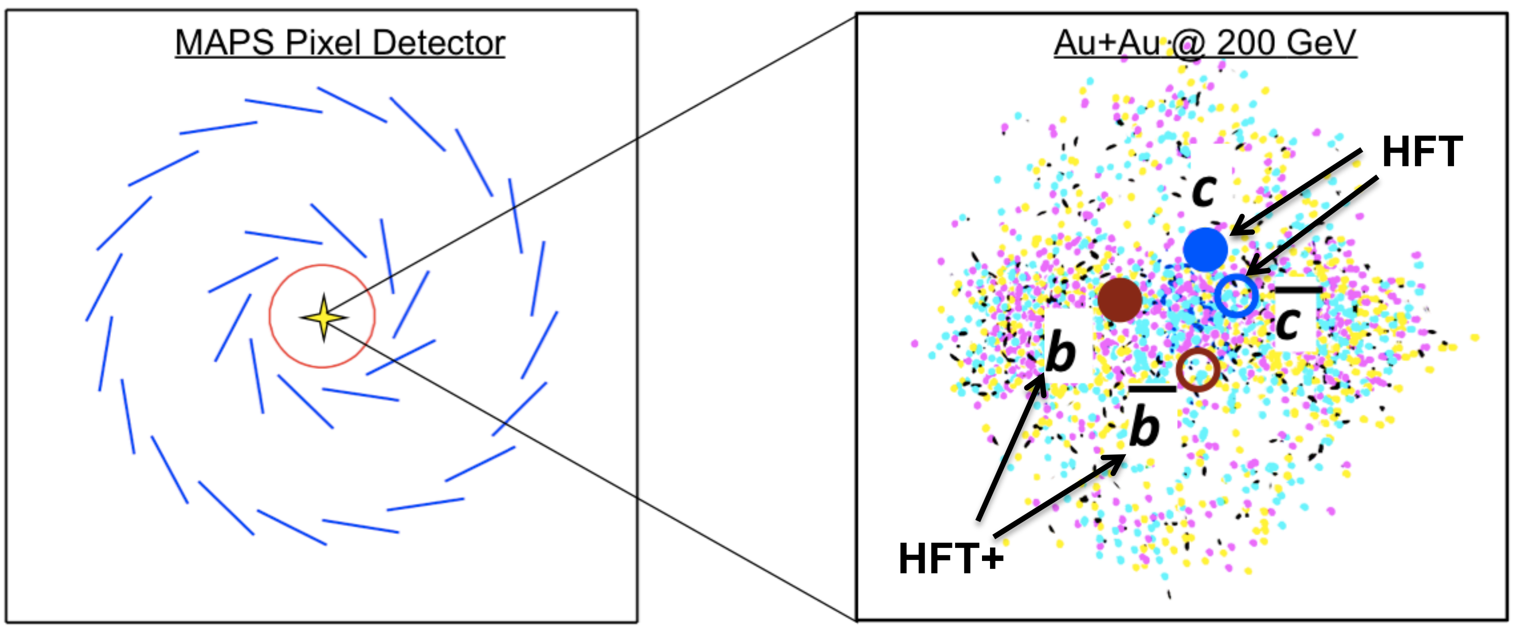
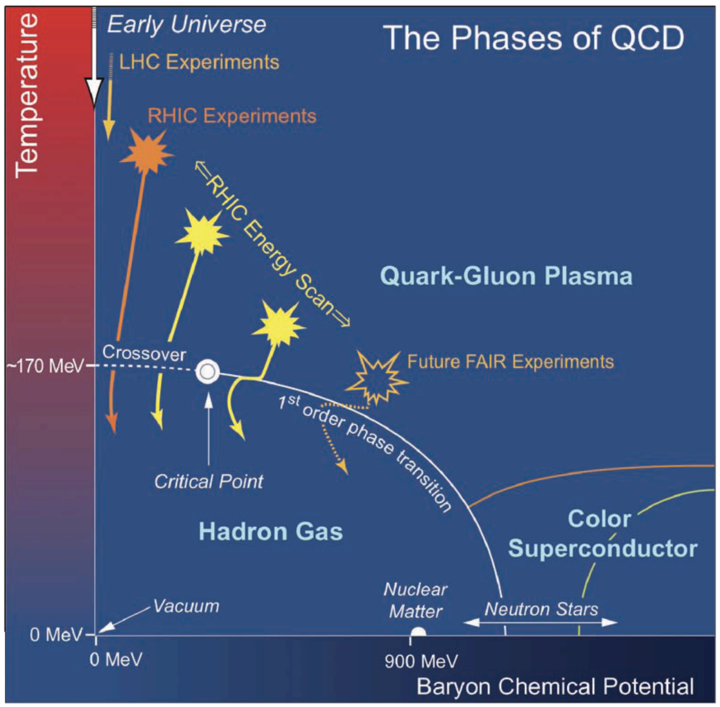
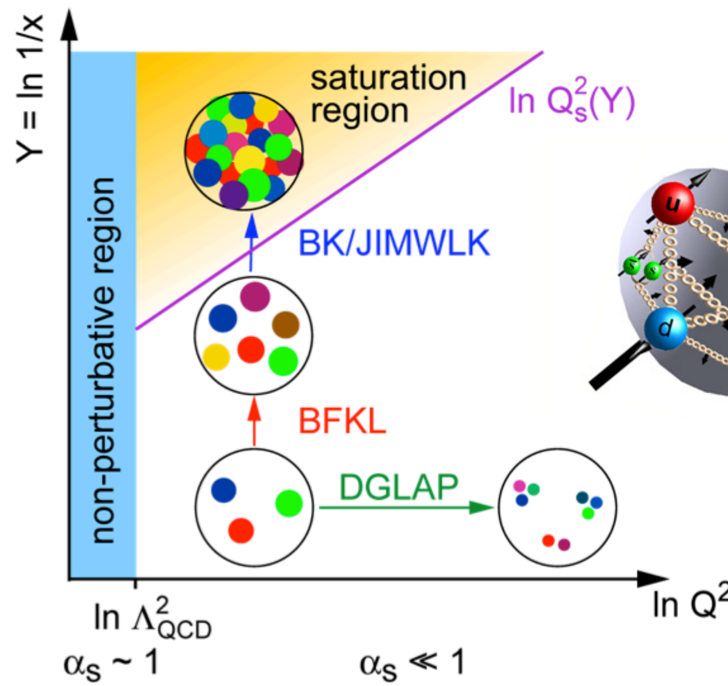


STAR Physics Program

Hot QCD



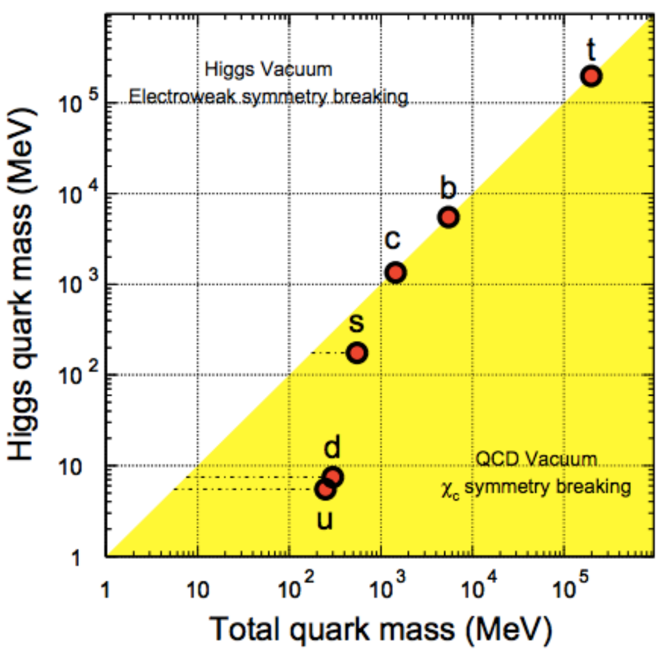
Cold QCD



Study QCD Emergent Properties

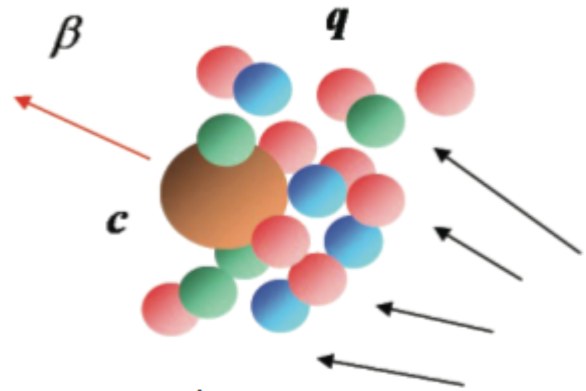
Heavy Quarks for Measuring sQGP Properties

Heavy quarks are conserved



X. Zhu et al, PLB 647(2007)366

Heavy quarks are tractable



$$\frac{\mathrm{d}p^i}{\mathrm{d}t} = -\eta_D p^i + \xi^i(t),$$

drag

fluctuations

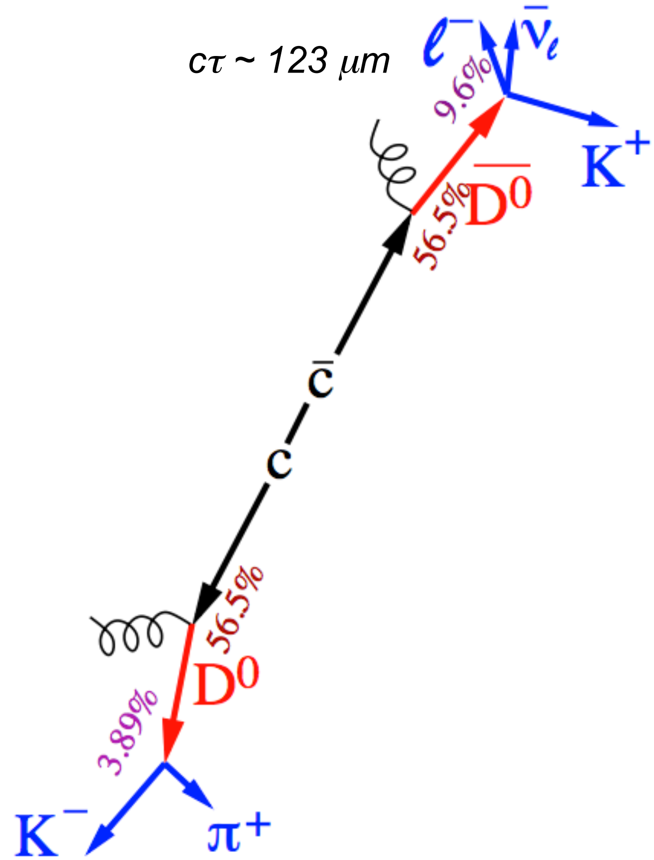
Diffusion coefficient D_{HQ}

- ➢ Heavy quarks created at early stage of HIC, and sensitive to the partonic re-scatterings
- ➢ Heavy quark collectivity/flow – more sensitive to thermalization and medium transport properties

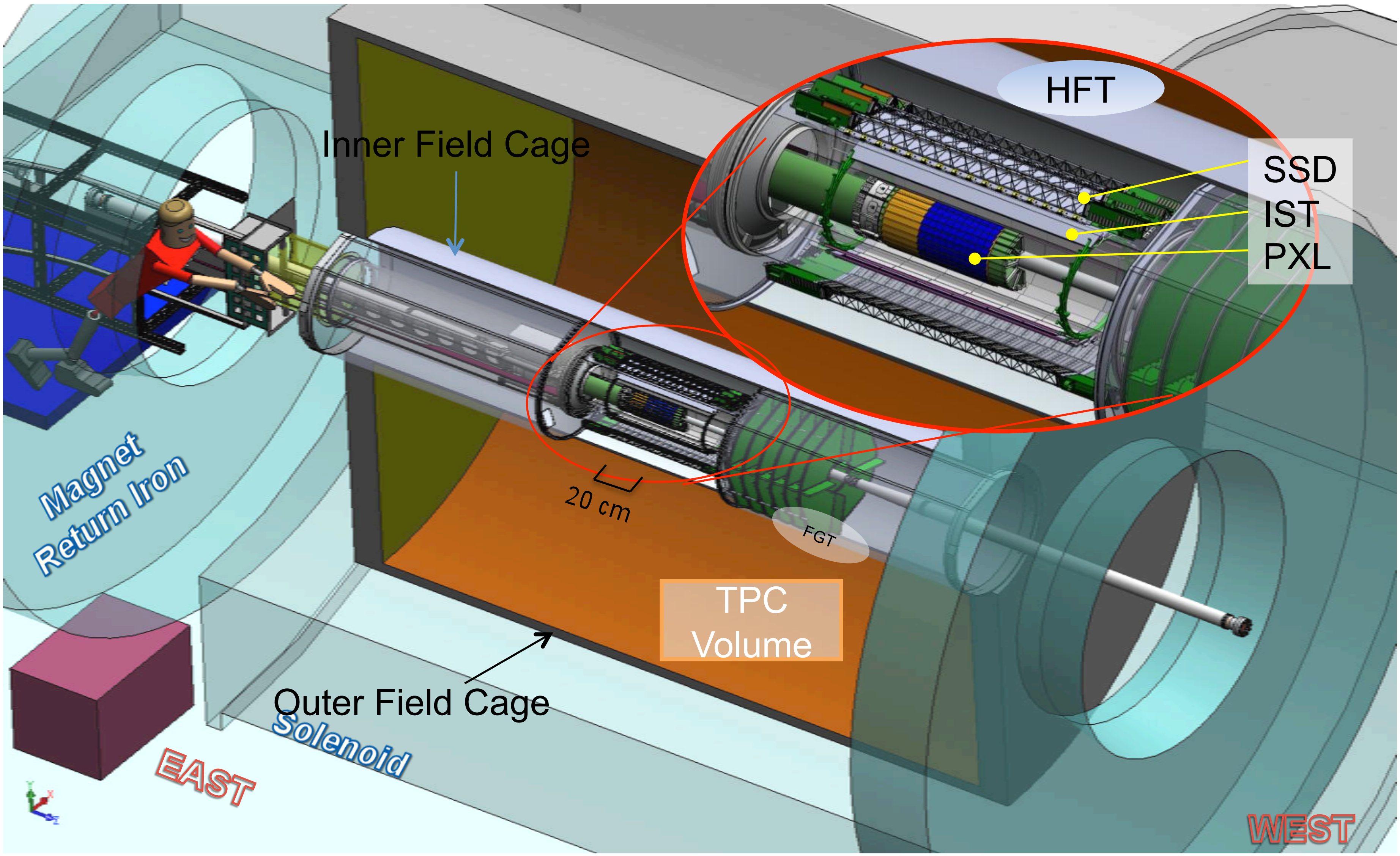
Experimental Challenges

Direct - through exclusive hadronic channels
- full charmed hadron kinematics
- hard to trigger
- smaller branching ratios
- need precision vertex detector to reduce combinatorial background
  - *$dN_{ch}/d\eta$ ~ 700 in central Au+Au collisions*

Hadron	Abundance	$c\tau$ (μm)
D^0	56%	123
D^+	24%	312
D_s	10%	150
Λ_c	10%	60
B^+	40%	491
B^0	40%	456



Heavy Flavor Tracker for STAR



HFT Design

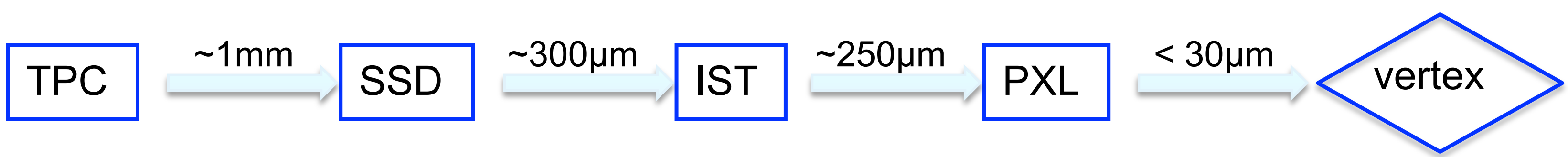
- HFT consists of 3 sub-detector systems inside the STAR Inner Field Cage

Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Thickness
SSD	22	30 / 860	1% X_0
IST	14	170 / 1800	1.32 %X_0
PIXEL	8	6.2 / 6.2	~0.52 %X_0
	2.8	6.2 / 6.2	~0.39% X_0

➢ **SSD** existing single layer detector, double side strips (electronic upgrade)

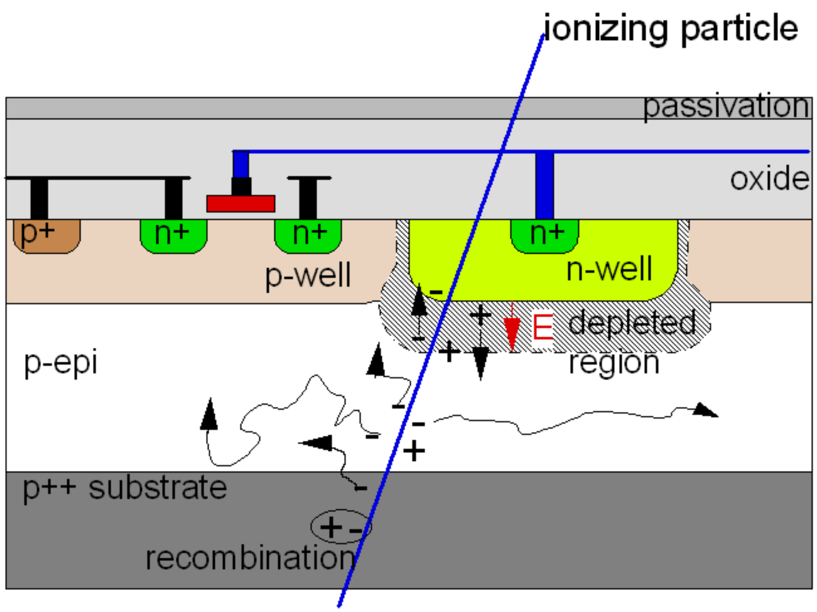
➢ **IST** one layer of silicon strips along beam direction, guiding tracks from the SSD through PIXEL detector **- proven pad technology**

➢ **PIXEL** double layers, 20.7x20.7 mm pixel pitch, 2 cm x 20 cm each ladder, 10 ladders, delivering ultimate pointing resolution. **- new active pixel technology**



Monolithic Active Pixel Sensors (MAPS) - PXL

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 Sensors	CCD
Granularity	+	-	+
Small material budget	+	-	+
Readout speed	+	++	-
Radiation tolerance	+	++	-

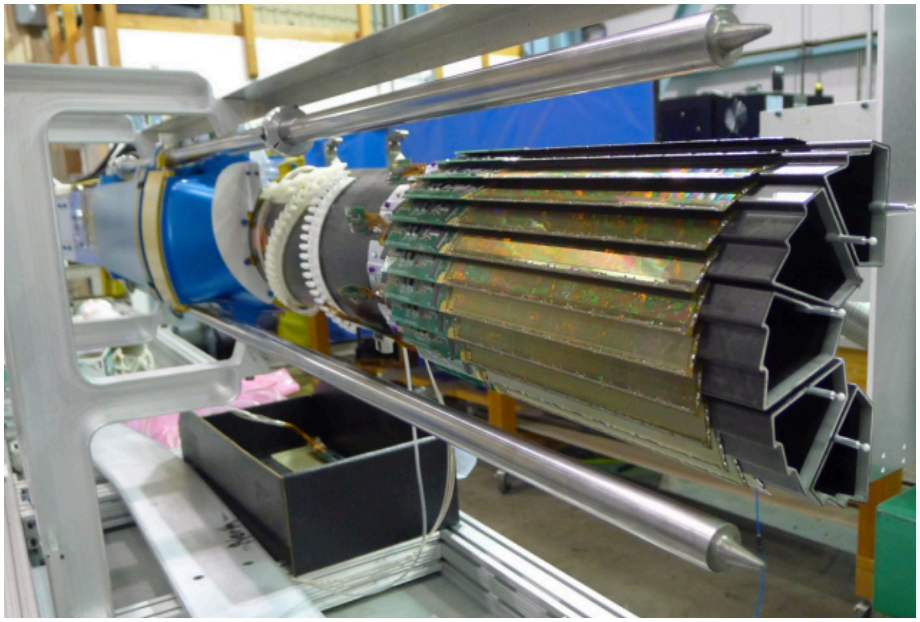
Some pixel features and specifications

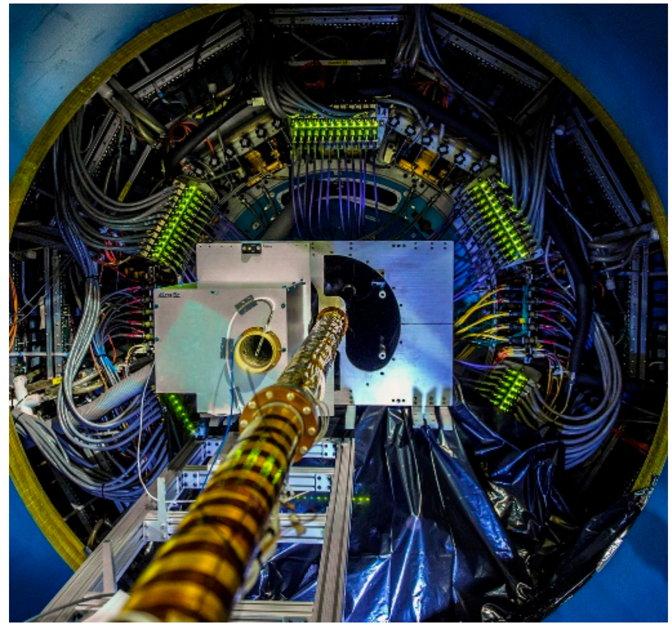
Pointing resolution	$(12 \oplus 19\text{GeV}/p\cdot c)$ μm
Layers	Layer 1 at 2.8* cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	6.2 μm rms
Position stability	8 μm (30 μm envelope)
Radiation thickness per layer	X/X_0 = 0.39% Al-cable *0.52% Cu-cable*
Number of pixels	360 M
Integration time (affects pileup)	186 μs
Radiation requirement	20-90 kRad
Rapid detector replacement	< 12 Hours

critical and difficult

more than a factor of 3 better than hybrid vertex detectors

HFT Commission and Operation in STAR

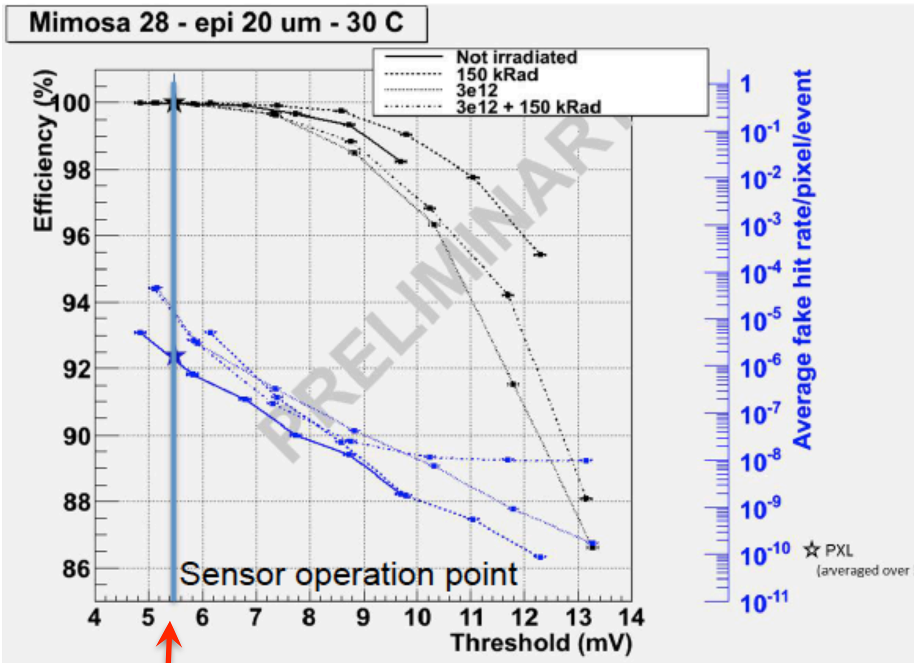


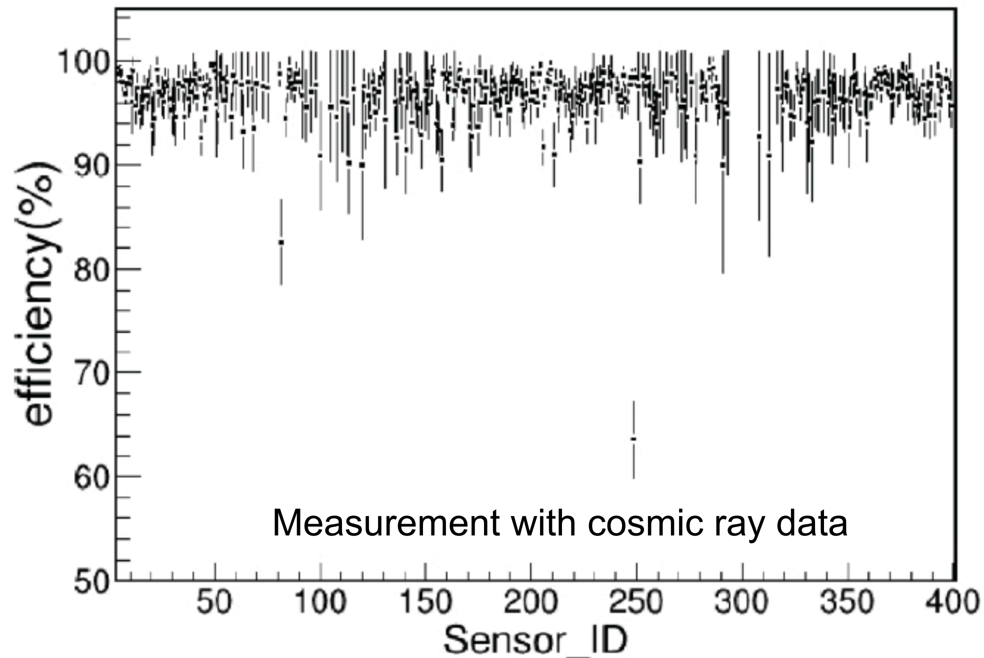


2013 May	– PXL prototype engineering run with 3 sectors (out of 10 in total)
2013 Sept	– IST, SSD fully installed into STAR
2014 Jan	– PXL fully installed into STAR (within 12 hours)
2014 Jan-Feb	– cosmic runs for detector commissioning, data for alignment calibration
2014 March	– Commissioning in Au+Au 200 GeV collisions. Physics mode since then
2014 Sept	– HFT project closeout. Project finished on time and under budget

STAR HFT – first application of MAPS pixel detector at a collider

Detector Hit Efficiency and Noise

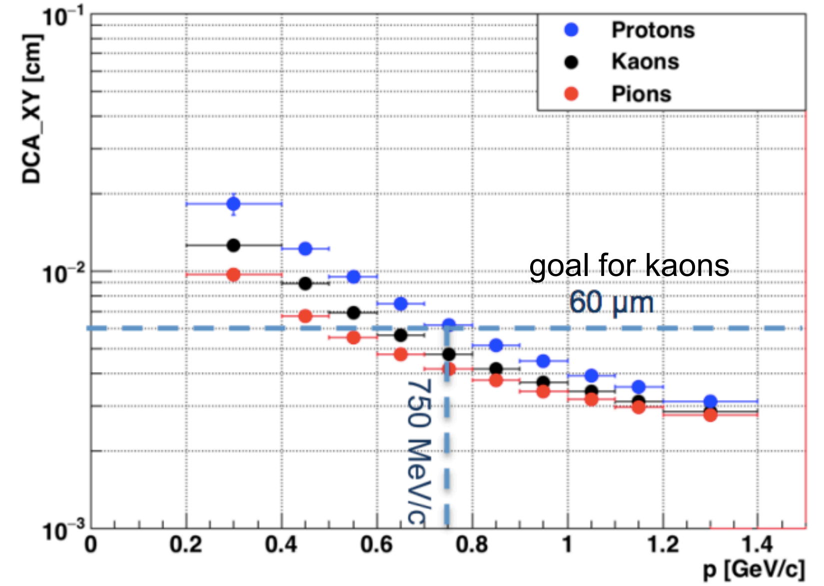


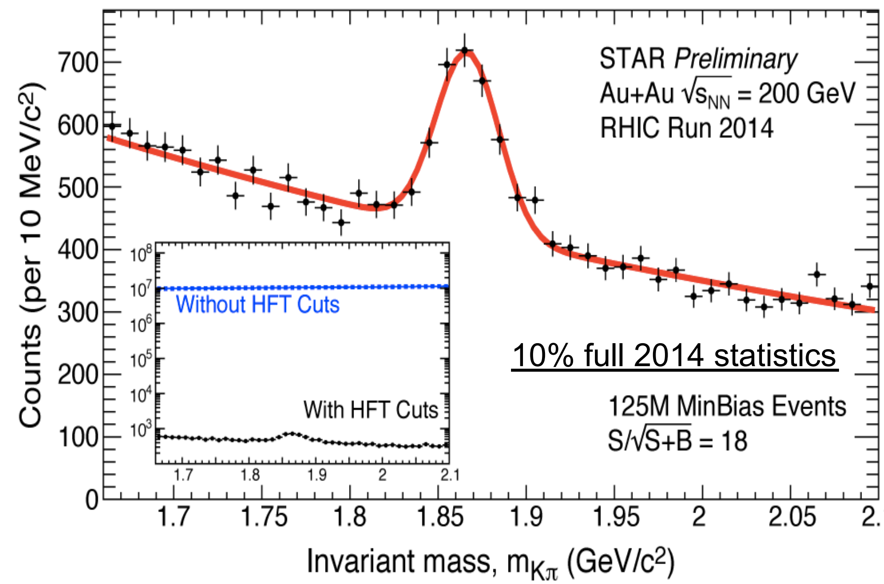


Operating point: noise rate ~ 2 x 10^{-6} with >99% efficiency
Goal: > 98% at 10^{-4} noise rate

Efficiency measured with cosmic ray data - ~ 97.2% average efficiency over all sensors

Pointing Resolution and D^0 from Au+Au Collisions



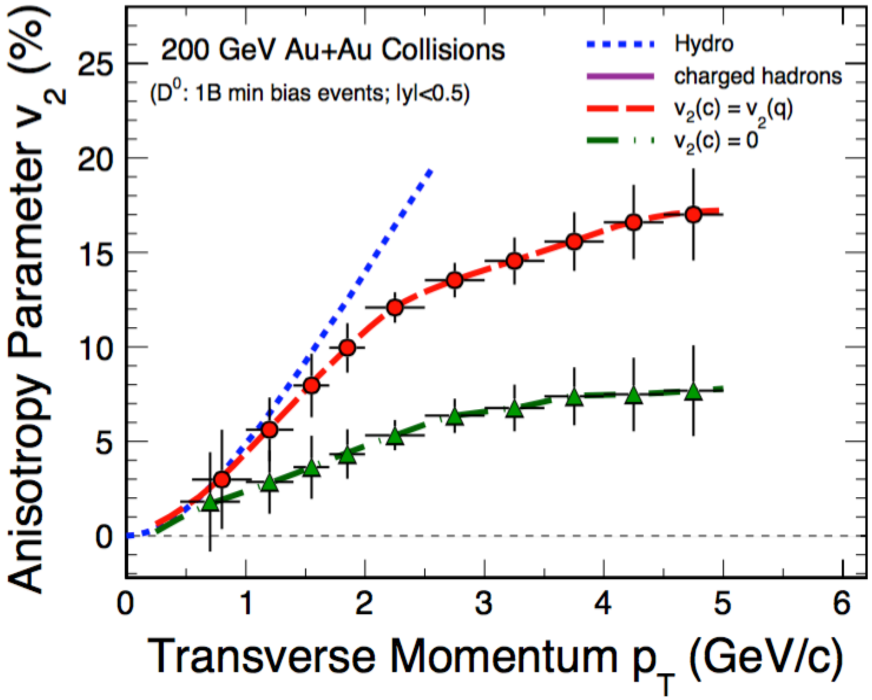


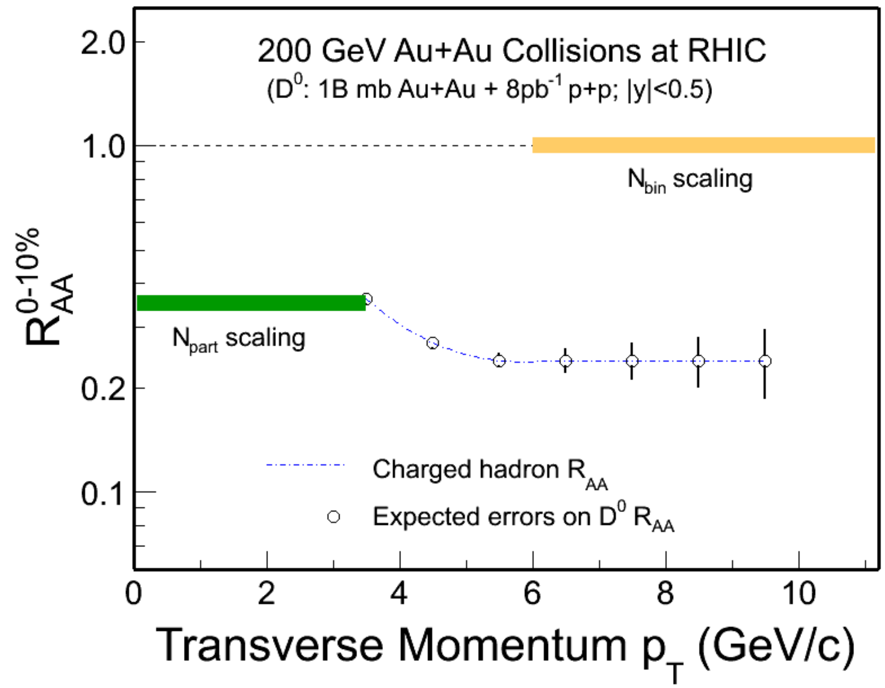
Physics datasets collected with STAR-HFT

	Beam Species	Data sets	Physics goals
2014	Au+Au 200 GeV	1.2B minbias	D-meson v_2, R_{cp}
2015 Al-cable	p+p 200 GeV	1.1B minbias, 12 pb^{-1}	D-meson R_{AA} baseline
	p+Au 200 GeV	0.5B minbias, 42 nb^{-1}	D-meson R_{pA}
2016* Al-cable	Au+Au 200 GeV	2B minbias, 1 nb^{-1}	Λ_c, bottom, D-meson v_2, R_{AA}
	Au+Au 62.4 GeV	1B minbias	$\sqrt{s}$ dependent D-meson v_2, R_{cp}

* 2016 requests accommodated by the STAR Beam-Use-Request

Physics Goals with HFT





Assuming D^0 v_2 distribution from quark coalescence.

1 billion Au+Au m.b. events at 200 GeV.

- Charm v_2

Thermalization of light-quarks!
Drag/diffusion coefficients!

Assuming D^0 R_{AA} as charged hadron

1 billion Au+Au m.b. events at 200 GeV + $8pb^{-1}$ sampled L in p+p 200 GeV

- Charm R_{AA} ⇨

Energy loss mechanism!
Interaction with QCD matter!

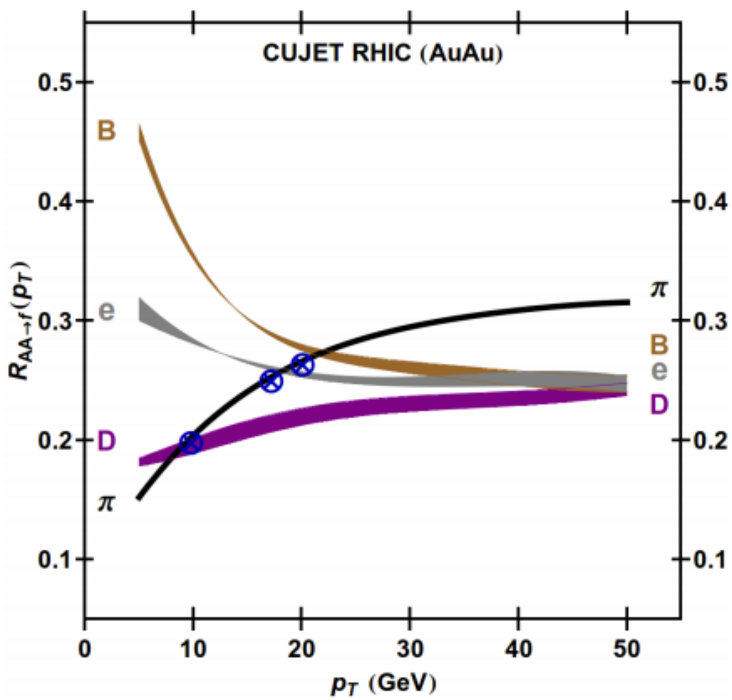
HF-II Program at 2020+ for Bottom Production

<u>Open bottom</u> production over a wide range of momentum

Flavor dependence of parton energy loss – medium properties at small scale

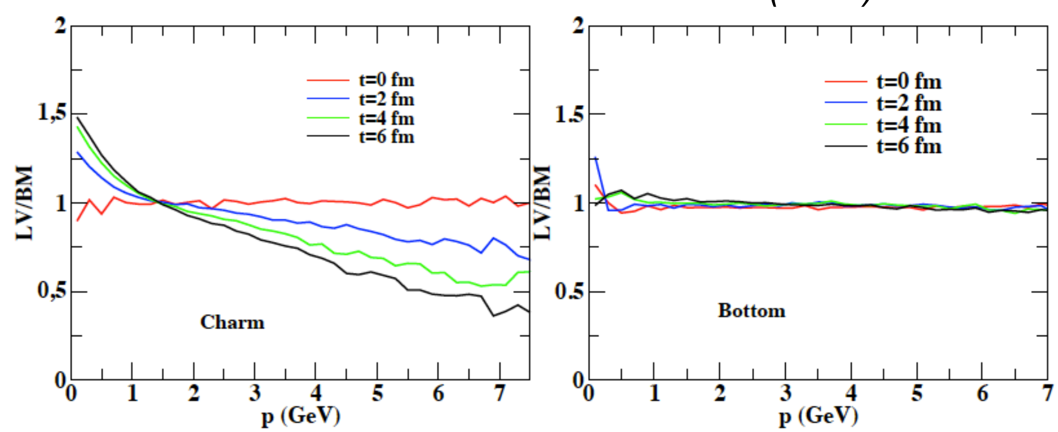
Cleanest probe to quantify medium transport properties – e.g. $\boldsymbol{D_{HQ}}$
- medium properties at large scale

Total bottom yield
- verify CNM for precision interpretation of Upsilon suppression



PRL 108 (2012) 022301

PRC 90 (2014) 044901



Is charm heavy enough?
Sizable correction to the Langevin approach for charm
- may limit the precision in determining $\boldsymbol{D_{HQ}}$

HFT+ Upgrade for Bottom Production Measurements

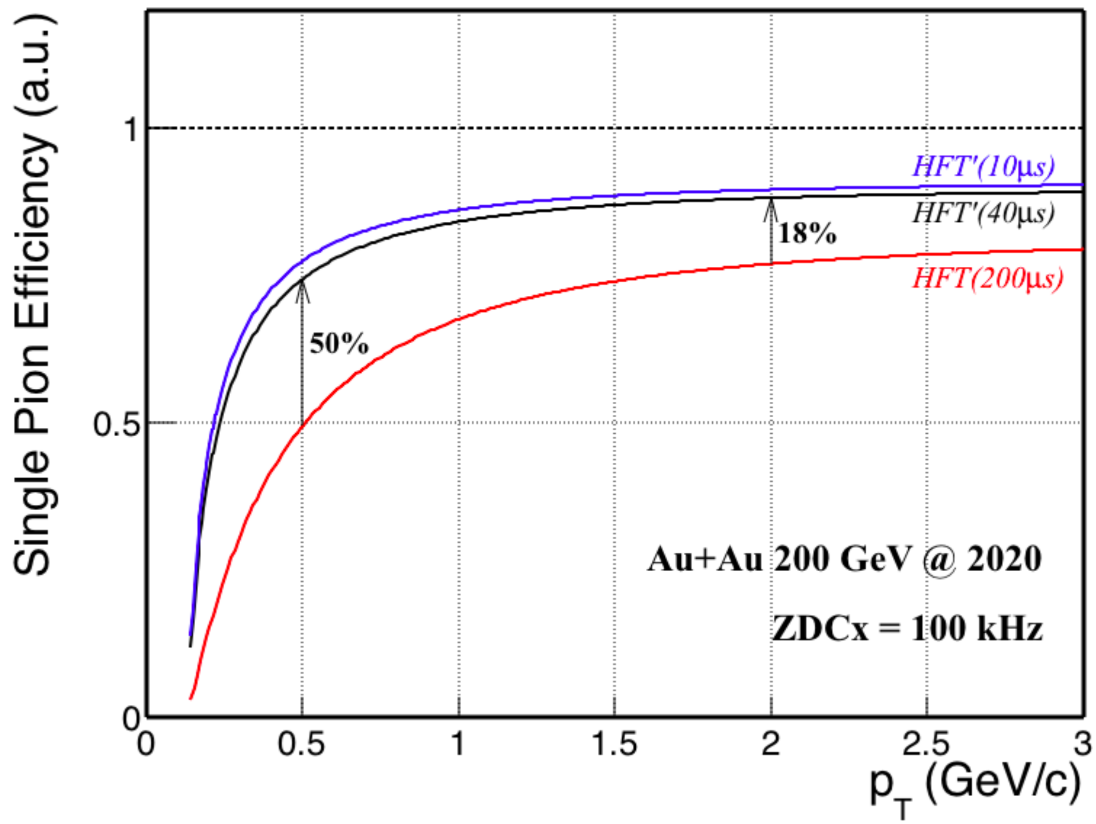
Next generation fast MAPS sensors – integration time reduced from 186μs to <20μs

R&D projects under development for ALICE ITS upgrade

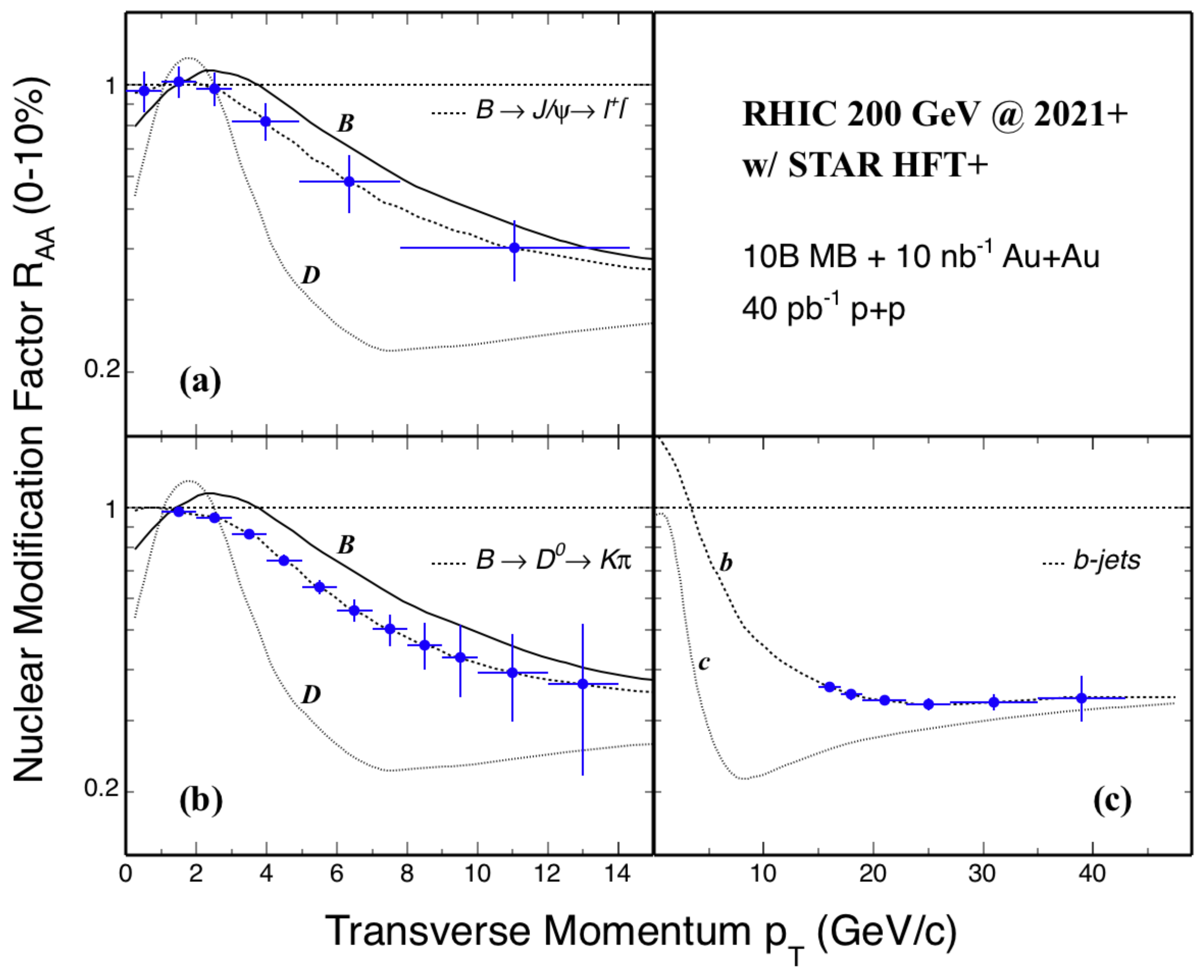
Detector capable of being operated at high luminosity with good efficiency

CAD projected L at 2020+ is 100x10^{26} cm^{-2}s^{-1}(ZDCx rate ~ 100kHz)

Preserve high detection efficiency in high luminosity environment



Physics Projection with STAR-HFT+



Curves – average of calculations from TAMU, Duke and CUJET

HFT+: aimed for precision open bottom measurements at RHIC
- flavor dependent energy loss
- cleaner extraction of medium transport properties D_{HQ}

Summary

STAR Heavy Flavor Tracker (HFT)

- first application of MAPS pixel detector at a collider
- fully in operation and meet all performance goals
- physics results anticipated - precision charm measurements

STAR HFT+

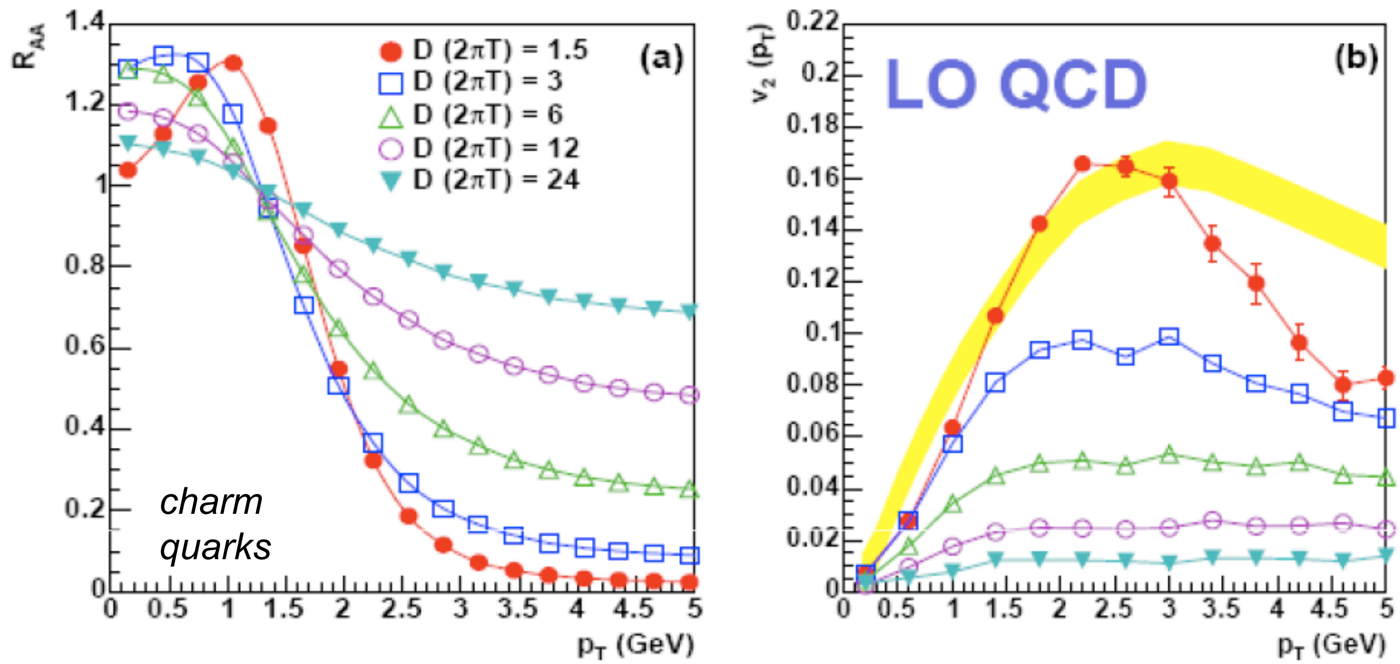
- next generation fast MAPS pixel detector
- aim for open bottom measurements at 2020+ period

	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	STAR HFT PHENIX (F)VTX Precision charm			Spin		BES-II		STAR HFT+ sPHENIX Open bottom	
LHC	LS1	Run 2 (x10 statistics)				LS2		ALICE ITS upgrade CMS/ATLAS upgrades Run 3 (x100 statistics)	

Backups

Heavy Quarks to Probe Medium Thermalization

➢ Heavy quarks created at early stage of HIC, and sensitive to the partonic re-scatterings.
➢ Heavy quark collectivity/flow to experimentally quantify medium thermalization.



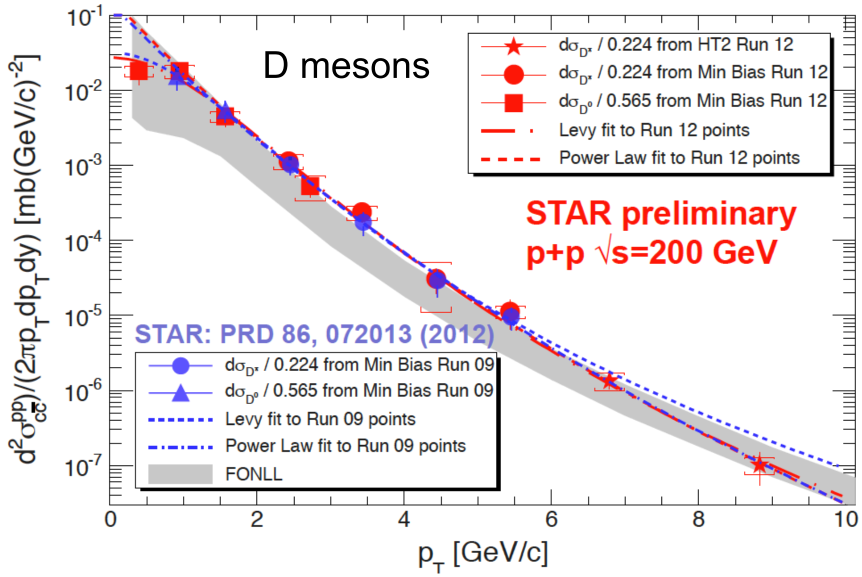
G. Moore & D. Teaney, PRC 71 (2005) 064904

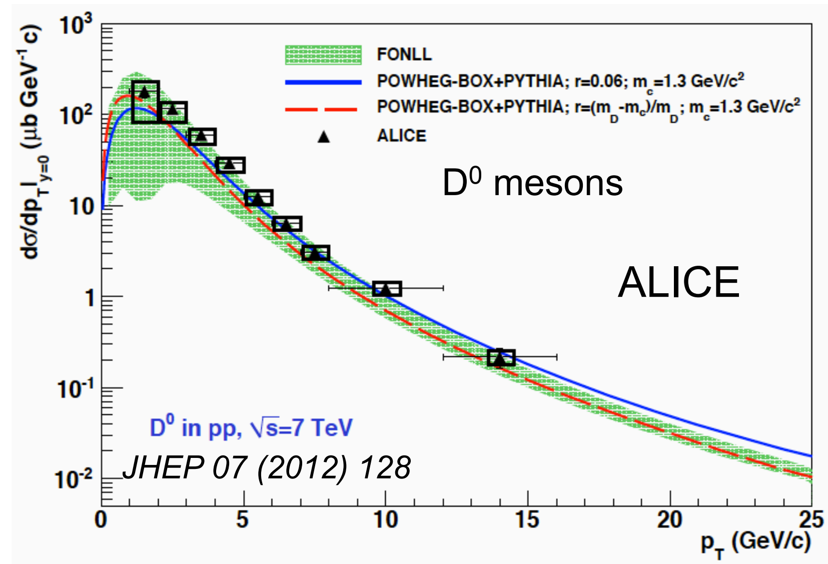
HQ propagation in QCD medium – Brownian Motion, described by Langevin Equation

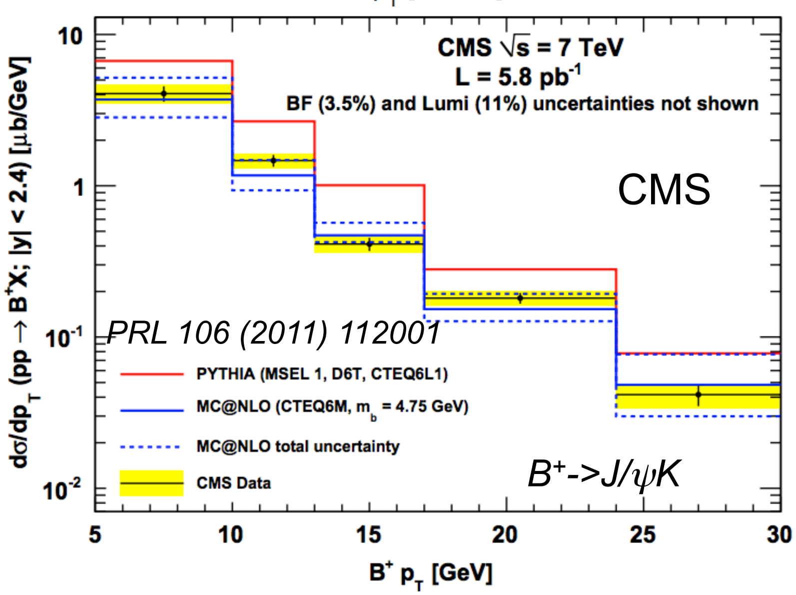
$$\frac{dp_i}{dt} = \xi_i(t) - \eta_D p_i$$

η_D / ξ – drag/diffusion coefficients related to the medium transport properties

Heavy Quark Production in p+p Collisions







Charm/bottom hadron spectra well described by pQCD calculations (FONLL, MC@NLO etc.)

- Similar for data at Tevetron, HERA etc.

Data precision provides inputs to constrain pQCD calculations

- R.E. Nelson et al, PRC 87(2013)014908

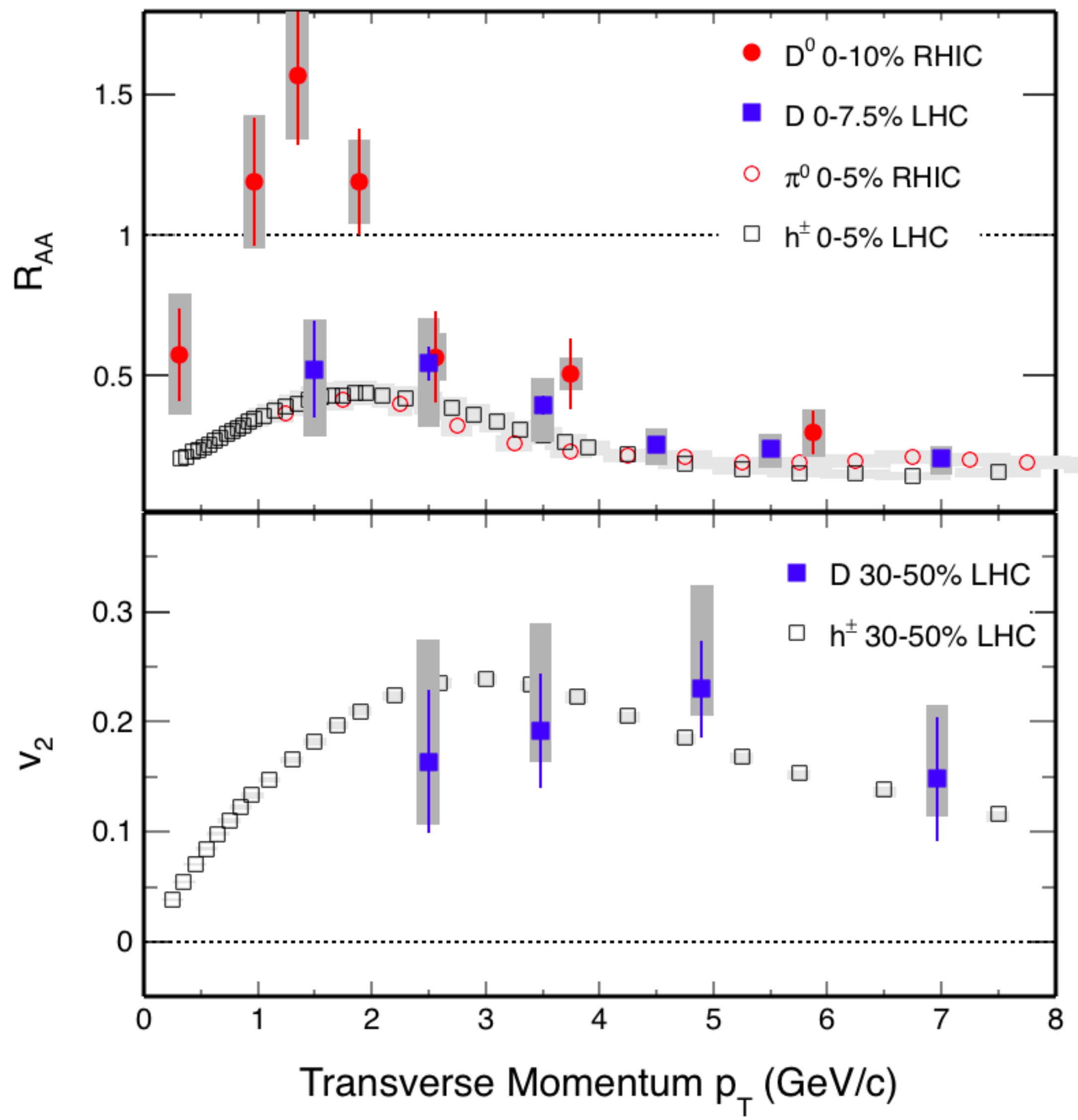
A Comparative Look on RHIC vs. LHC

Comparable suppression at high p_T

- collisional and radiative ΔE

Possibly different physics at low p_T

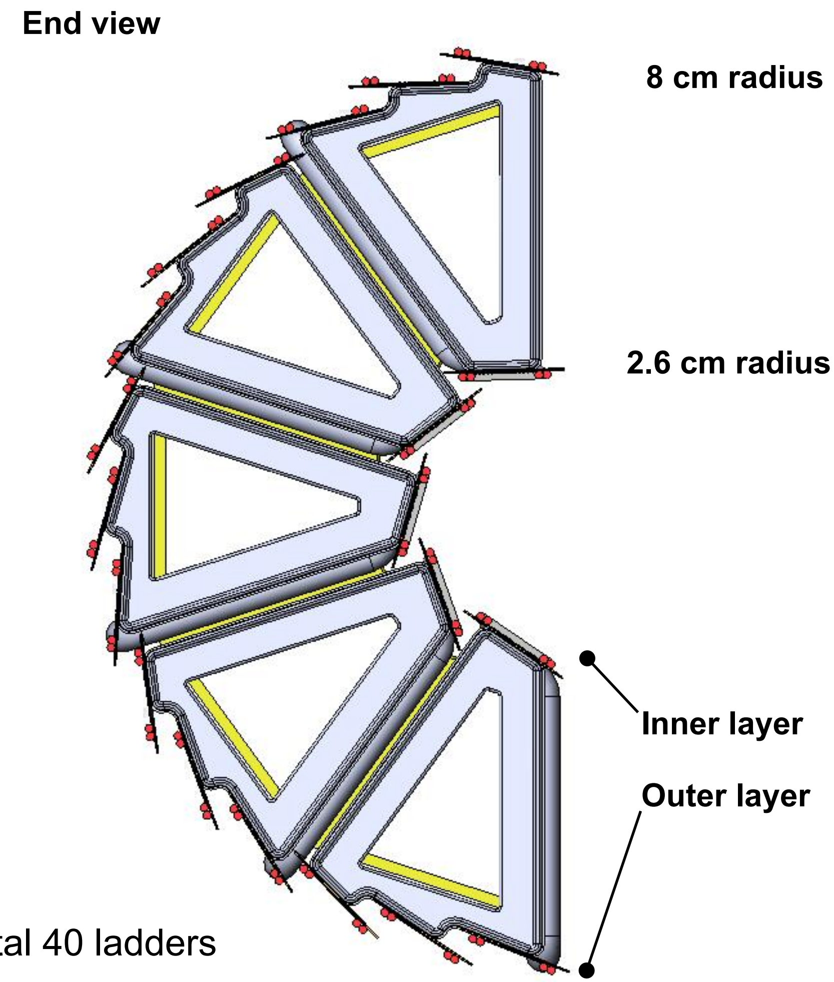
- Initial parton distributions
  x_T at 2 GeV/c ~ 10^{-2} (RHIC)
  ~ 10^{-3} (LHC)
- "Cronin" effect
- Charm quark flow

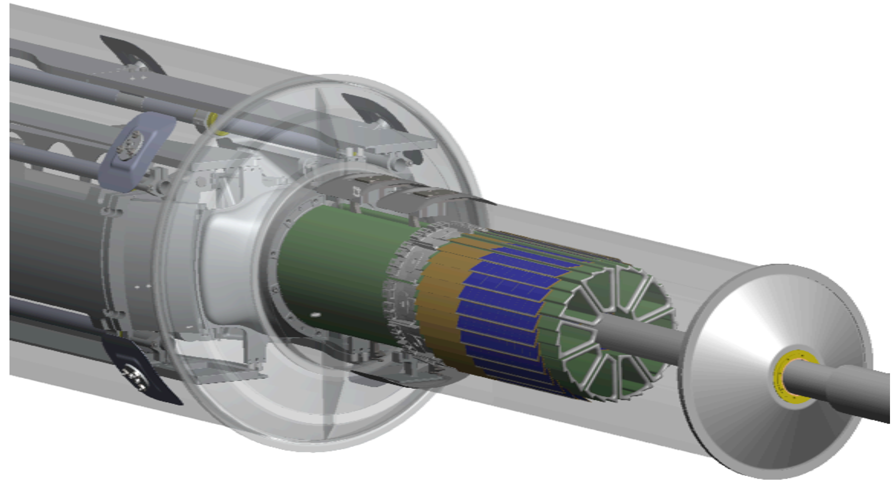


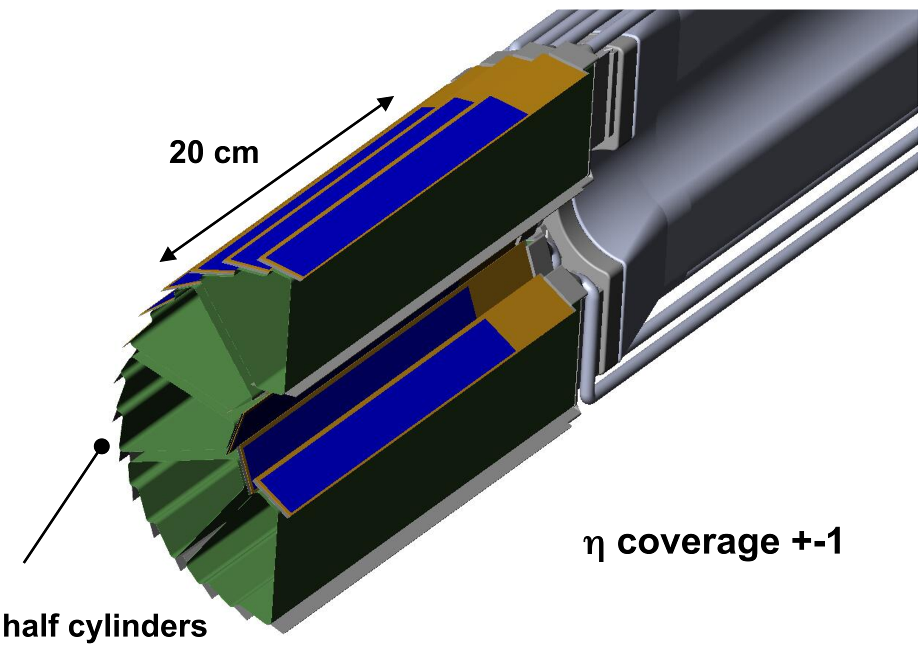
Precision charm v_2 data, particularly to low-intermediate p_T are critical for the extraction of sQGP D_{HQ}.

STAR, PRL 113(2014)142301
ALICE, PRL111 (2013) 102301, PRC 90 (2014) 034904

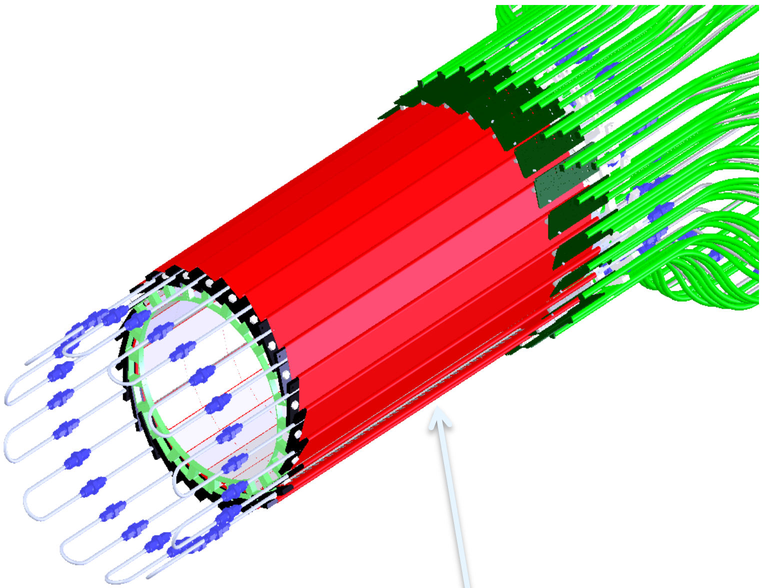
Pixel Geometry

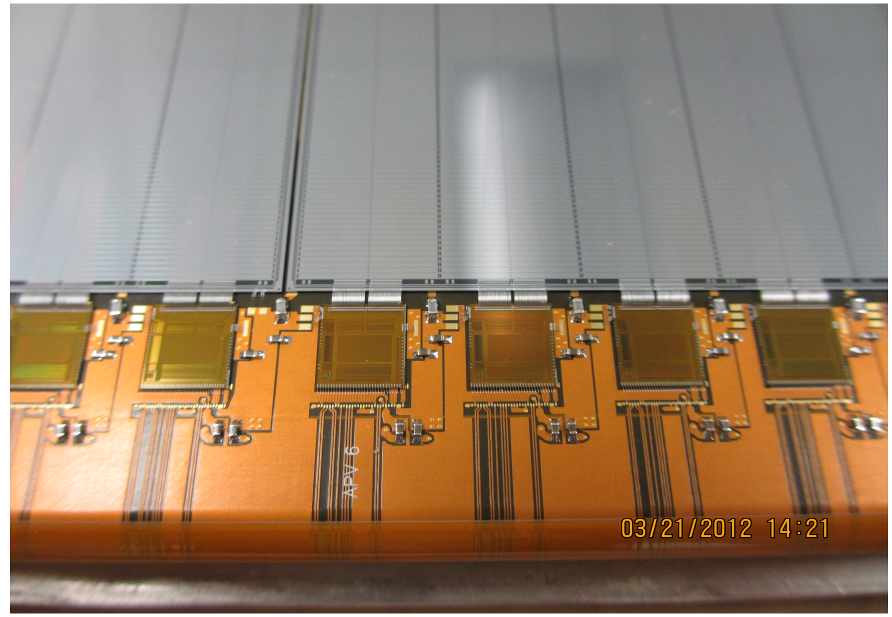




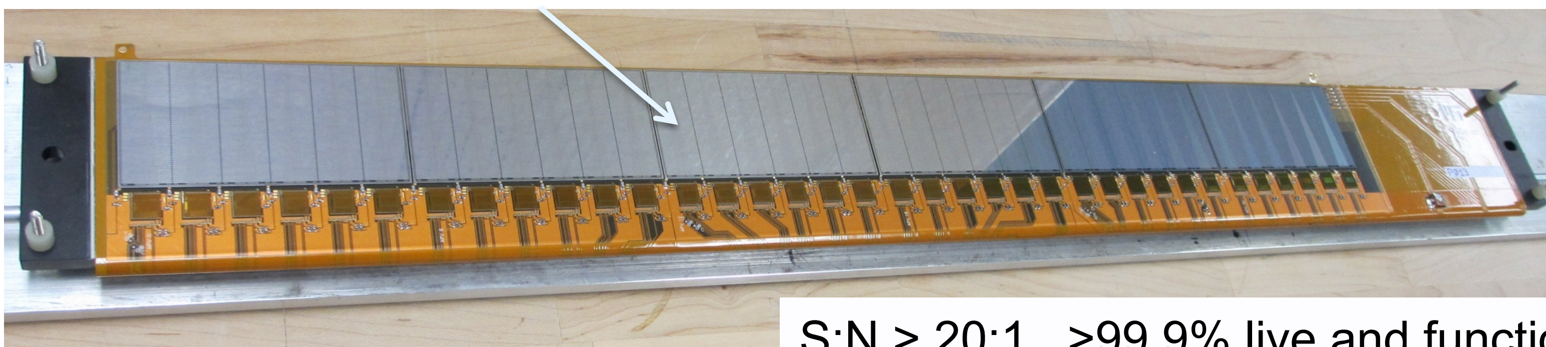


Intermediate Silicon Tracker (IST)



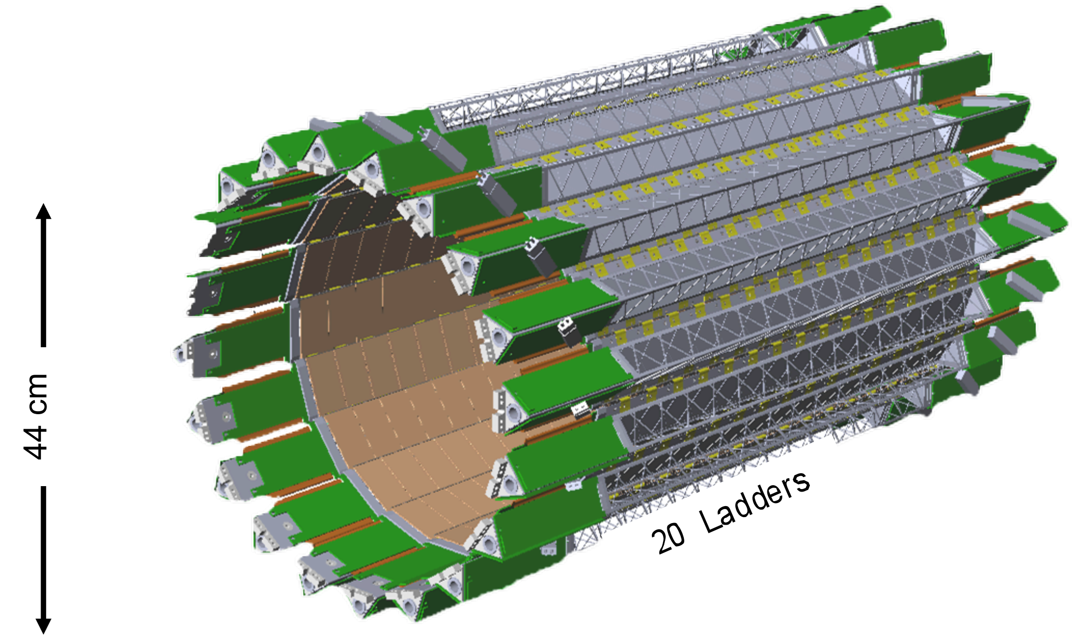


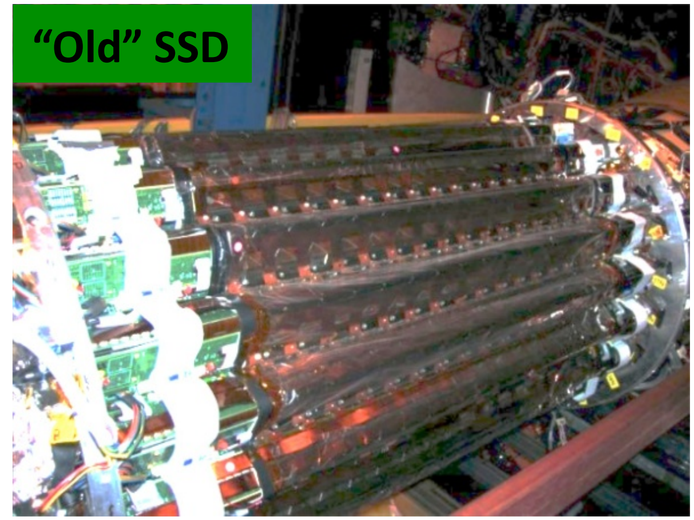
24 ladders, liquid cooling.

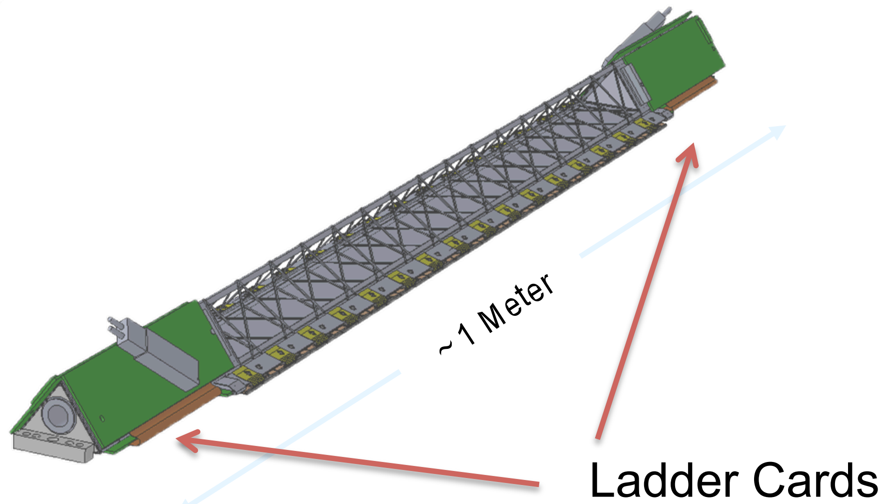


S:N > 20:1, >99.9% live and functioning channels

Silicon Strip Detector (SSD)







New/Faster Readout
"Old" Ladders, refurbished
New, direct mounting on support

Uniqueness

Uniqueness of HFT:

Fine pixel granularity provides ultimate hit resolution

Thin detector design allows precision measurements down to low p_T

State-of-art mechanical design retains detector stability

Full azimuthal acceptance allows high statistics correlation measurements

HF measurements at RHIC – not just complementary to those at LHC

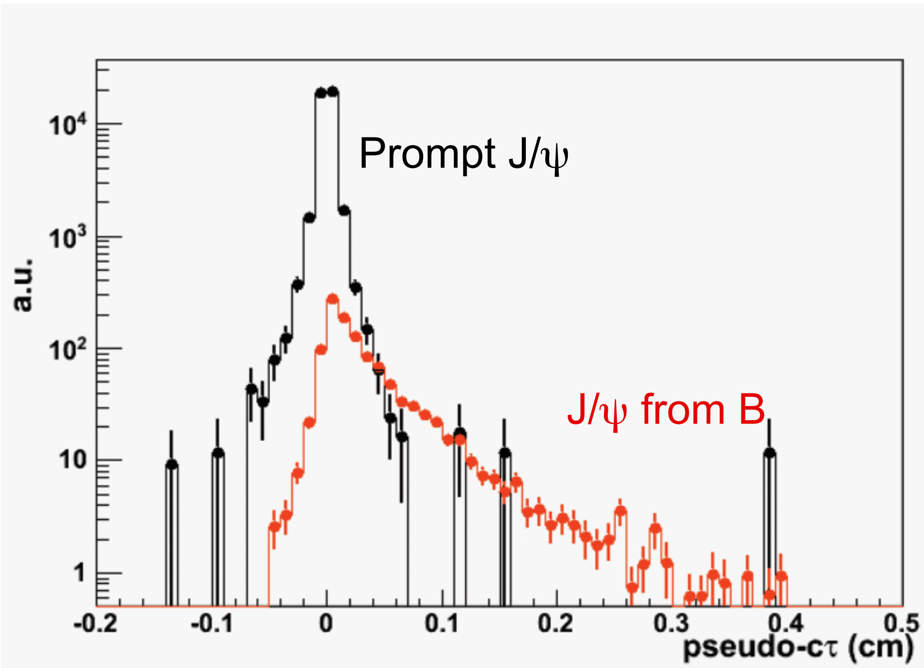
Uniqueness of HF measurements at RHIC

Heavy quarks are calibrated probes at RHIC - predominately created via initial gluon-gluon hard scatterings.

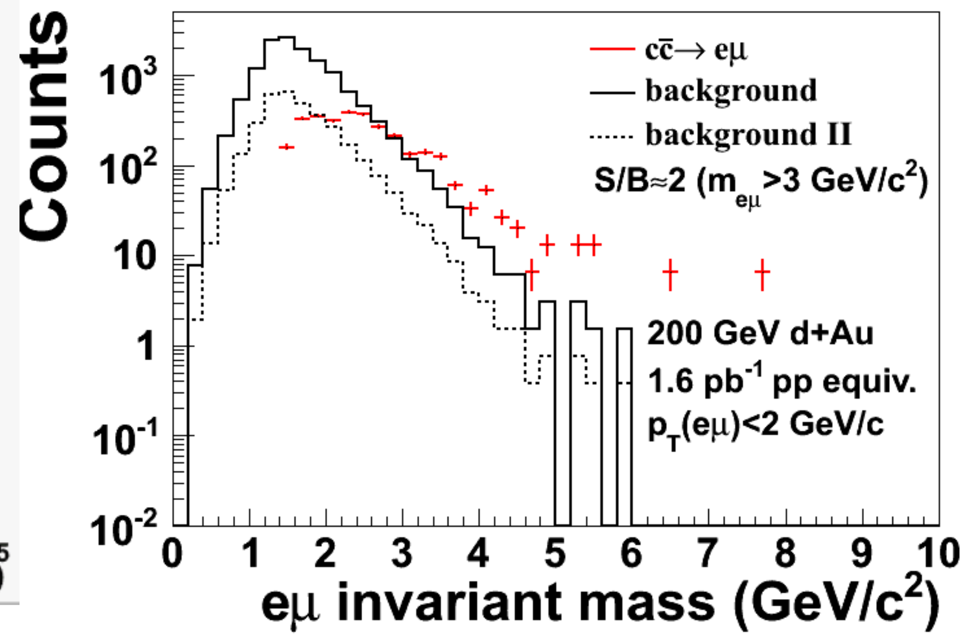
Heavy quarks are mostly created through the leading order 2->2 process at RHIC – clean physics interpretation of results, particularly correlation measurements.

Unique Measurements with HFT+TPC+MTD

B ➔J/ψ + X



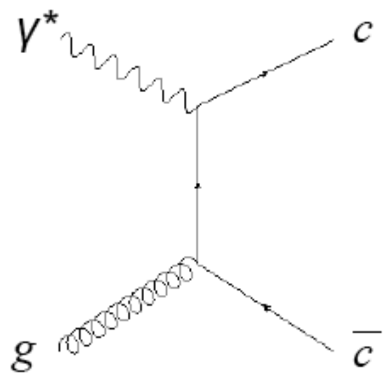
Lepton pairs from correlated charm



- HFT to separate B decay J/ψ from prompt J/ψ
- MTD to reconstruct J/ψ from di-muon decays

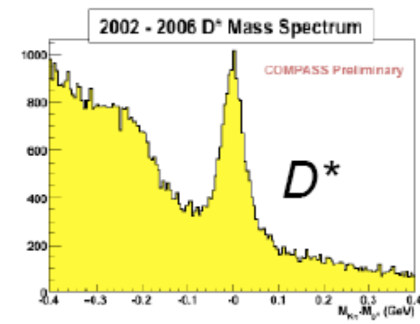
- MTD - unique measurement of e-μ correlation
- HFT+MTD – systematic measurement of e-e, e-μ, μ-μ with controlled charm contributions

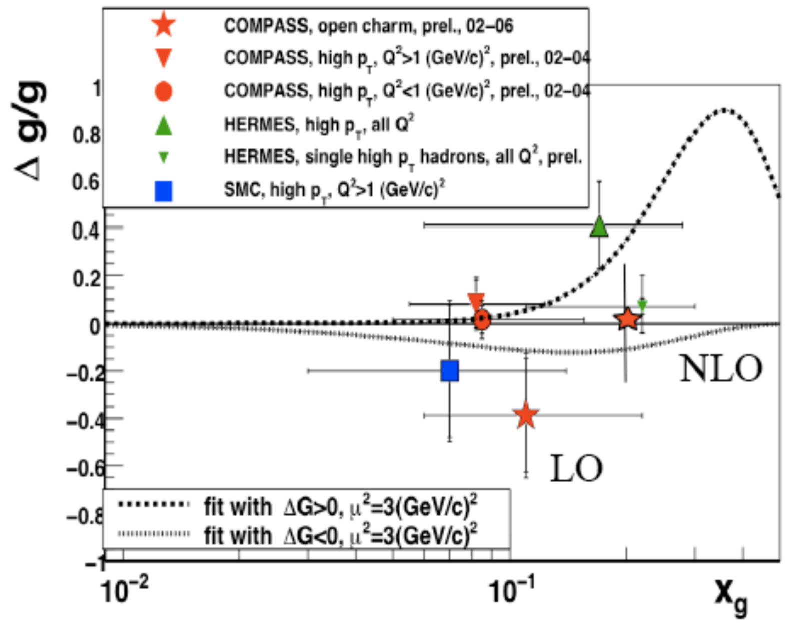
Charm to Probe Nucleon/Nucleus Structure



$e(\mu)+p(A)$

$\gamma^* + p \rightarrow D + X$



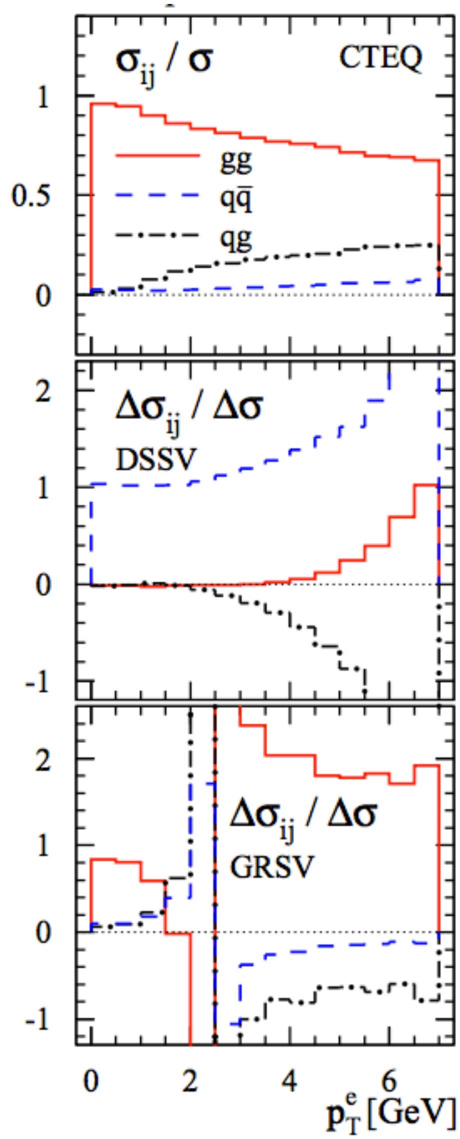


K.Kurek, Spin Workshop @LBL 2009

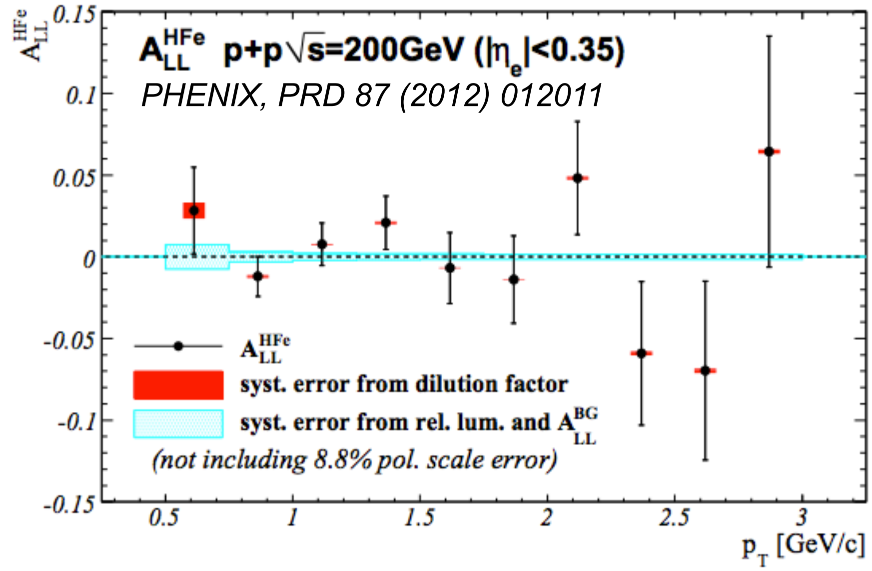
Charm production

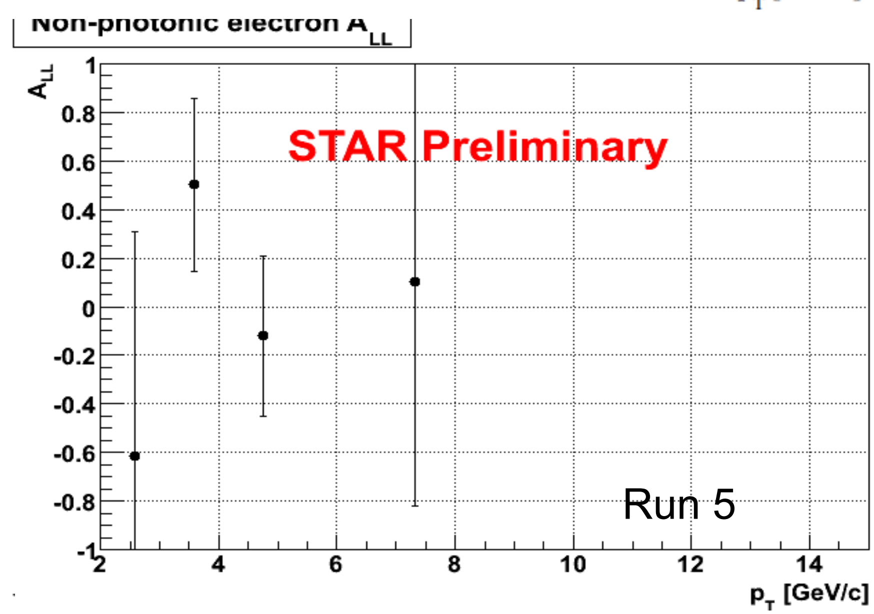
- Sensitive to gluon distribution functions.
- A sensitive probe of low x gluons and QCD at an Electron Ion Collider (201?/202?).

Heavy Flavor to Probe Gluon Spin Structure



Riedl et al, PRD 80 (2009) 114020





Heavy Flavor Probes for Broad QCD Studies

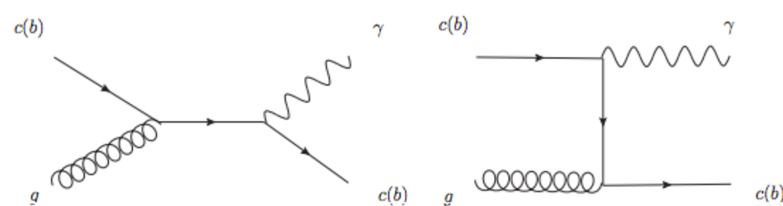
W^+ ➔ *$c + \bar{s}$*   higher decay B.R. than semi-leptonic decays

W reconstruction via full di-jets (one charm jet)

- explored by UA1

Heavy flavor jet – intrinsic HF PDF in nucleon/nucleus

$$pp \to \gamma + c(b)\text{-jet} + X.$$



- Heavy flavor jet – good probe to study the hot QCD medium properties

Key Instruments

Pixel Silicon Detector at LHC/RHIC experiments

	ATLAS	CMS	ALICE	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	MAPS
Pitch size (μm^2)	50x400	100x150	50x425	50x425	20x20
Radius of first layer (cm)	5.1	4.4	3.9	2.5	2.8
Thickness of first layer	~1%X_0	~1%X_0	1%X_0	1%X_0	0.4%X_0

* physics results from PHENIX/STAR discussed here don't include data from silicon pixel detectors

What we have learned?

A) How do energetic heavy quarks lose energy in sQGP medium?

$R_{AA}(h) \sim R_{AA}(e) \sim R_{AA}(D) < R_{AA}(J/\psi^{B})$ at high p_T

- described by pQCD calculations including collisional and radiative energy loss

- only revealed with heavy quark measurements

B) How do charm quark flow?

low-intermediate p_T:

"bump" structure in $R_{AA}(D)$ at RHIC – hint of charm flow + coalescence

$v_2(D) \sim v_2(\pi)$ at LHC – indication of large charm flow

C) Can we extract the medium transport properties (e.g. D_{HQ})?

Theory: Need to unify different models – diff. in initial cond., medium evolution etc.

Experiments: Precision data

Future Measurements:

- Precision charmed hadron data (particularly v_2) over a broad momentum range
- Open bottom production over a broad momentum range
- Heavy quark correlations

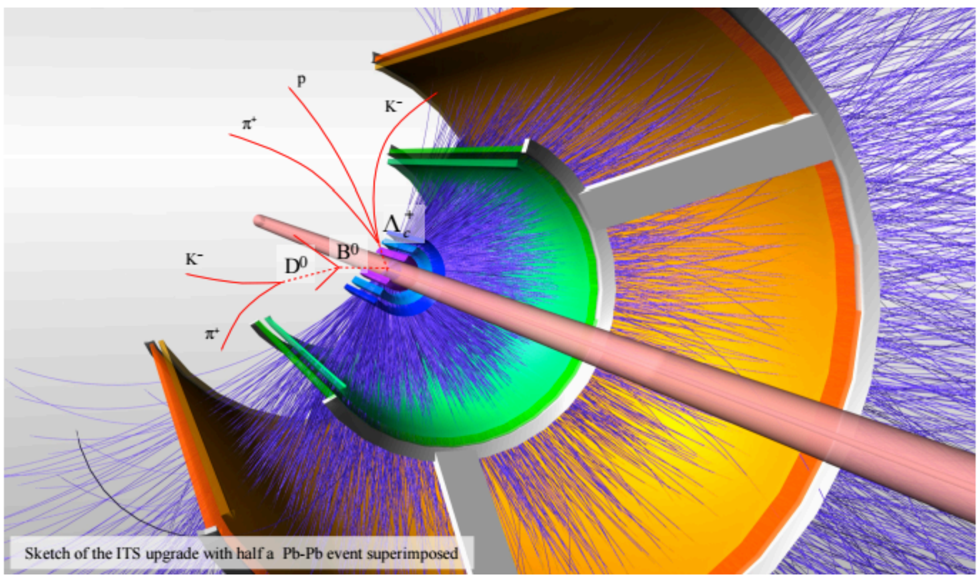
Calibration of charm/bottom total cross section
Cold nuclear matter effects

ALICE ITS-upgrade

Next generation MAPS sensors with much shorter integration time (< 20 μs)

Goals:

- precision charmed hadron (D^0, Λ_c) measurements down to low p_T
- open bottom measurements



Sketch of the ITS upgrade with half a Pb-Pb event superimposed