The STAR Heavy Flavor Tracker

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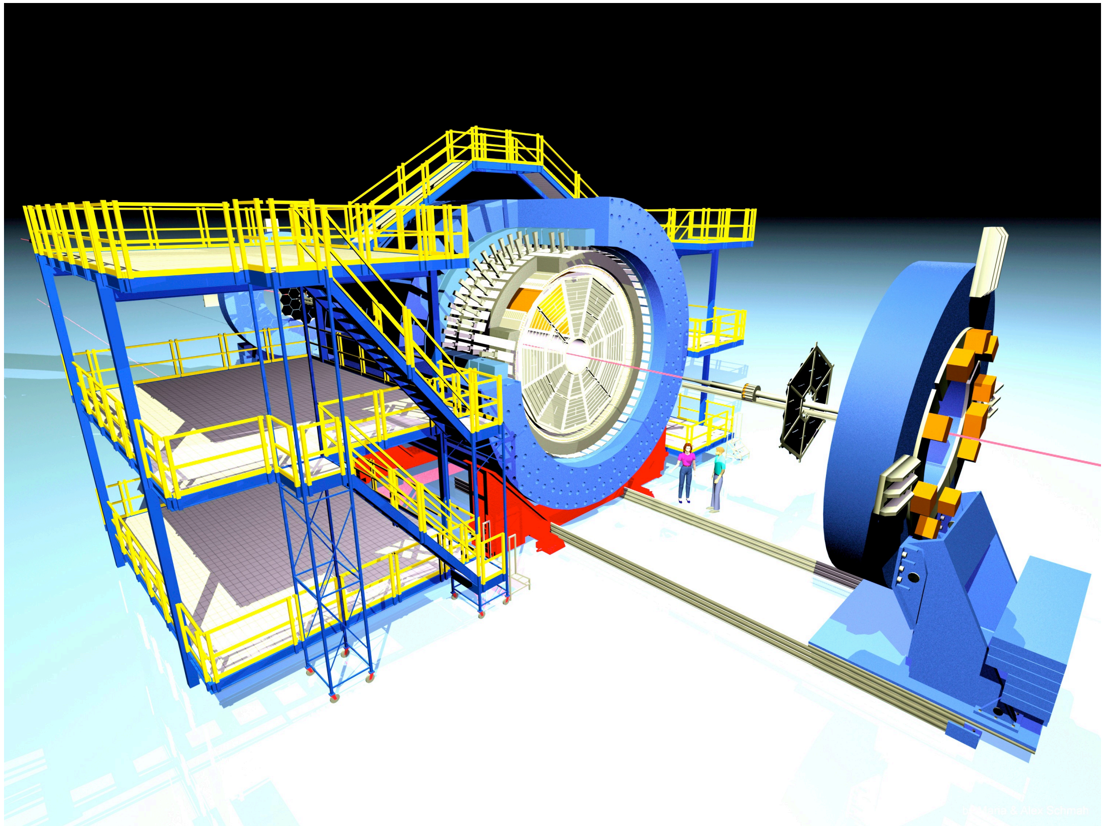
Overview

- STAR physics Program
- Requirements for HFT vertex detector
- HFT technical overview
- Collaboration and Project Status
- Examples of expected performance.

STAR detector

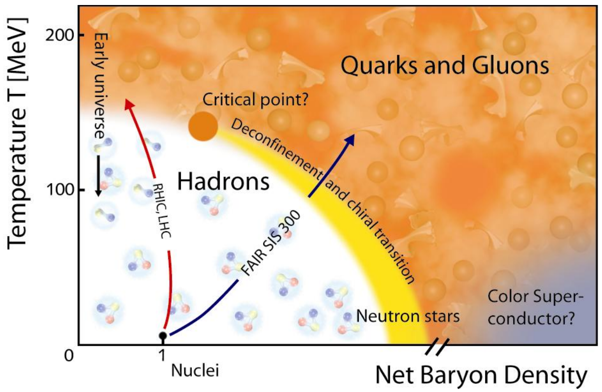
STAR is an existing detector that has operated for 11 years at RHIC

HFT is an upgrade to the inner tracking system of STAR



STAR Physics Focus

STAR HFT

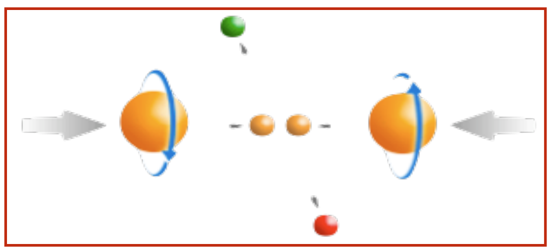


1) At 200 GeV top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

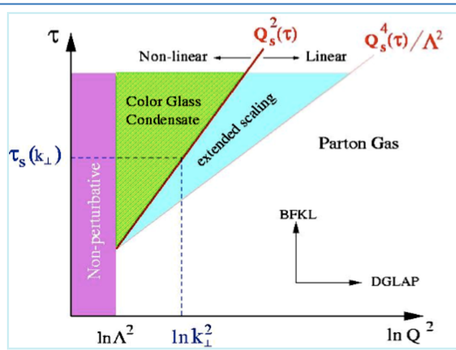
2) RHIC beam energy scan

- Search for the ***QCD critical point***
- Chiral symmetry restoration



Spin program

- Study ***proton intrinsic properties***

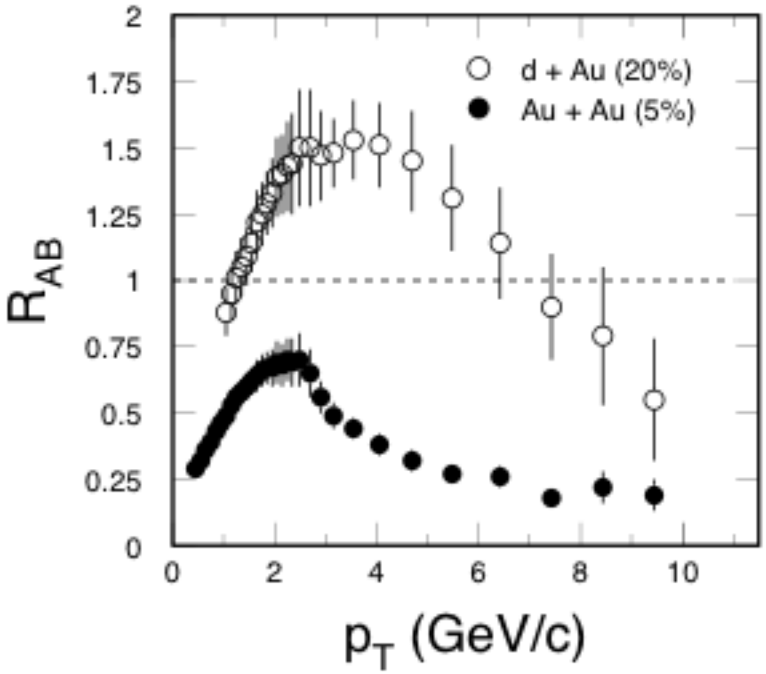


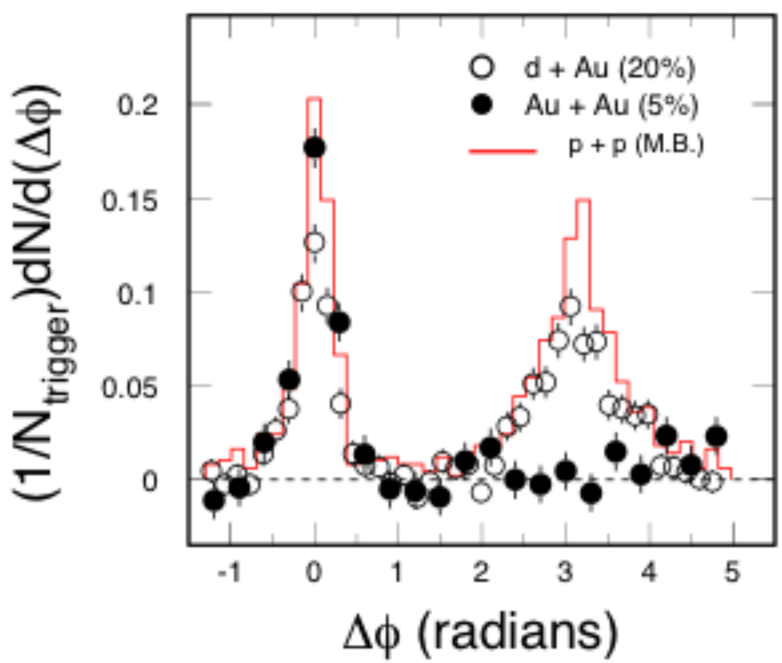
Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***

Partonic Energy Loss at RHIC

STAR: Nucl. Phys. ***A757***, 102(2005).





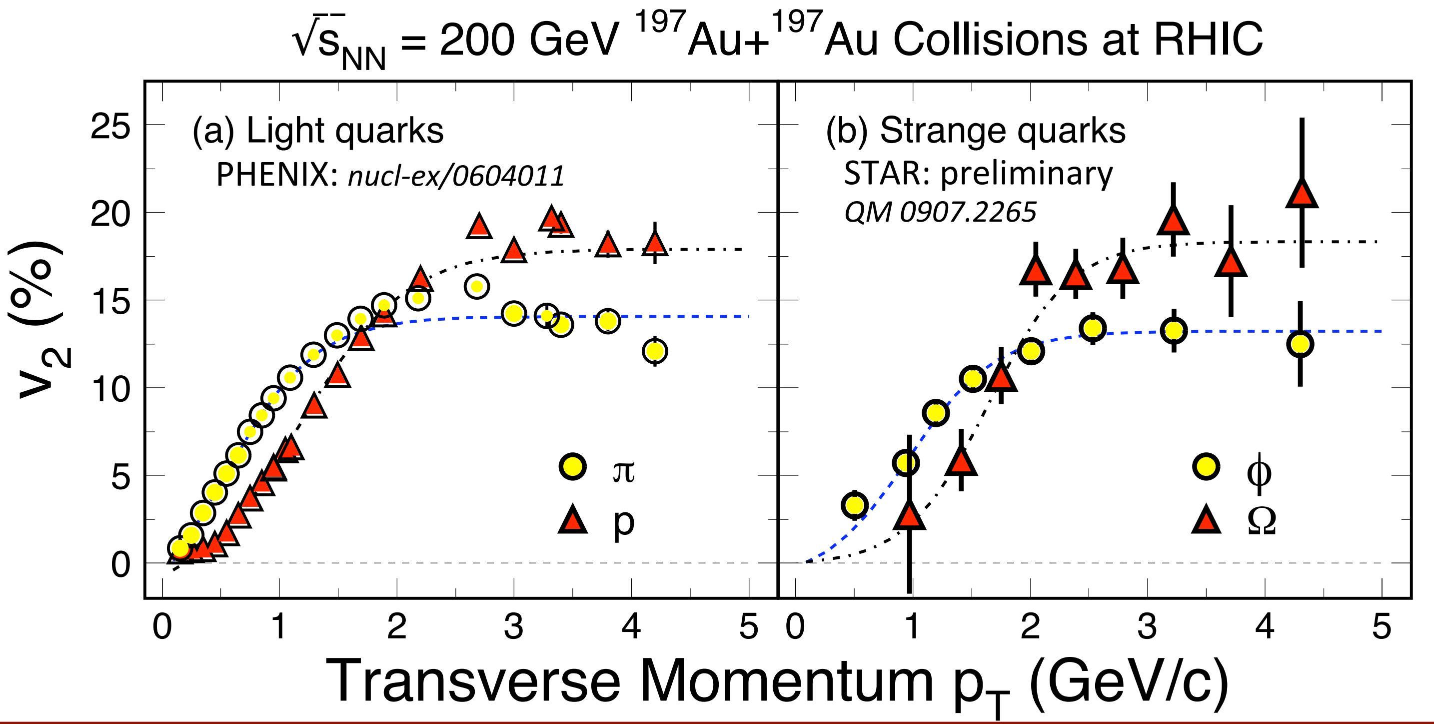
Central Au+Au collisions: light quark hadrons and the away-side jet in back-to-back 'jets' are suppressed. Different for p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Explore pQCD in hot/dense medium: heavy, early production c,b

R_{AA}(c,b) measurements are needed!

Partonic Collectivity at RHIC



QM09: arXiv 0907.2265

Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks ordering***

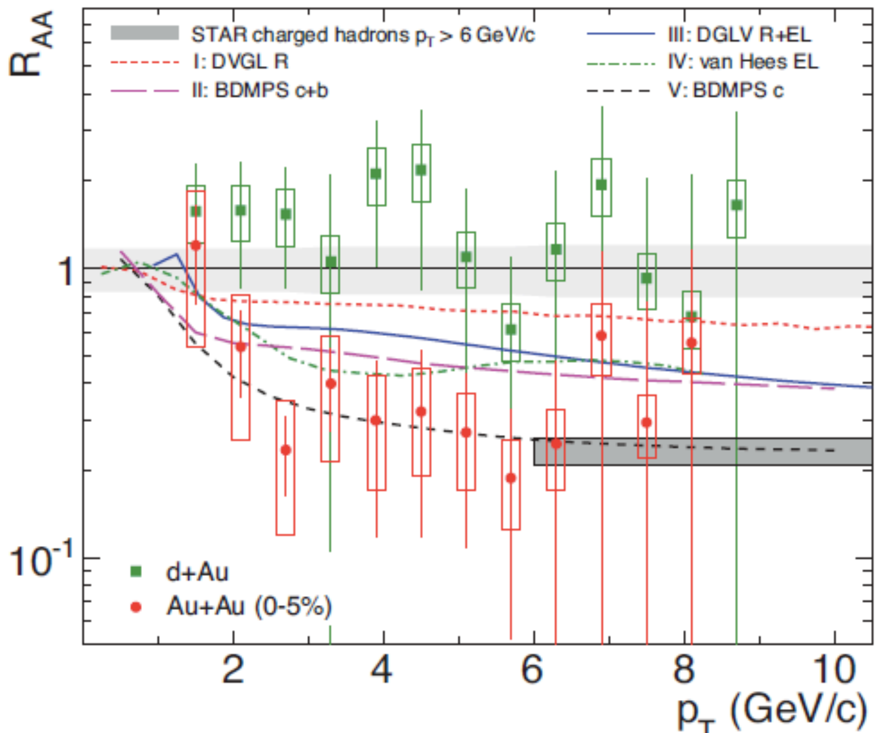
=> Collectivity developed at partonic stage!

=> De-confinement in Au+Au collisions at RHIC!

How about the heavy flavor quarks at RHIC?

Heavy Quark Energy Loss

STAR: Phys. Rev. Lett, **98**, 192301(2007).



1) Non-photonic electrons decayed from - charm and beauty hadrons

2) At $p_T \geq 6$ GeV/c,

R_{AA}(n.p.e.) ~ $R_{AA}(h^{\pm})$!

contradicts to naïve pQCD predictions

Surprising results -
- challenge our understanding of the energy loss mechanism
- force us to Re-think about the collisional energy loss
- **Requires direct measurements of c- and b-hadrons.**

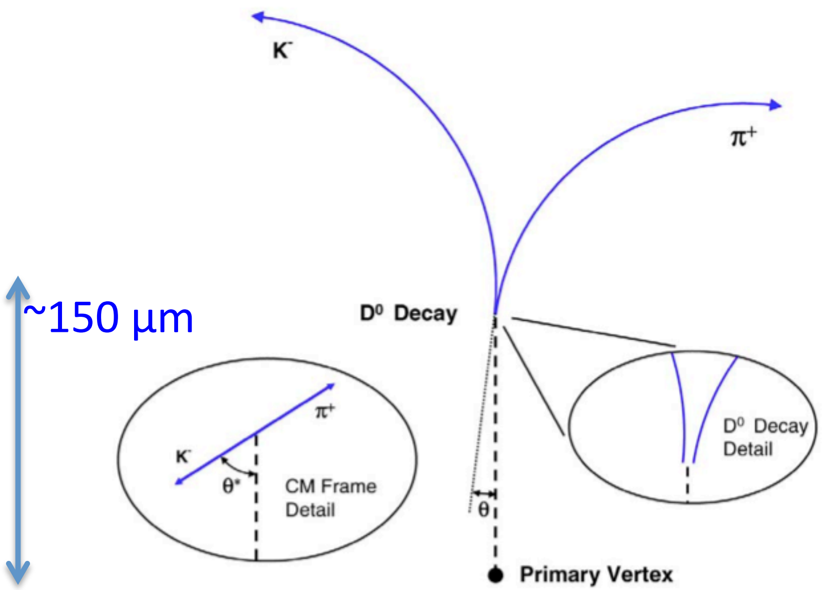
Requirement for the HFT

	Measurements	Requirements
Heavy Ion	heavy-quark hadron v_2 - the heavy-quark collectivity	- Low material budget for high reconstruction efficiency - p_T coverage ≥ 0.5 GeV/c - Mid-rapidity - High counting rate
	heavy-quark hadron R_{AA} - the heavy-quark energy loss	- High p_T coverage ~ 10 GeV/c
p+p	energy and spin dependence of the heavy-quark production	- p_T coverage ≥ 0.5 GeV/c
	gluon distribution with heavy quarks	- Wide rapidity and p_T coverage

Thin and large acceptance

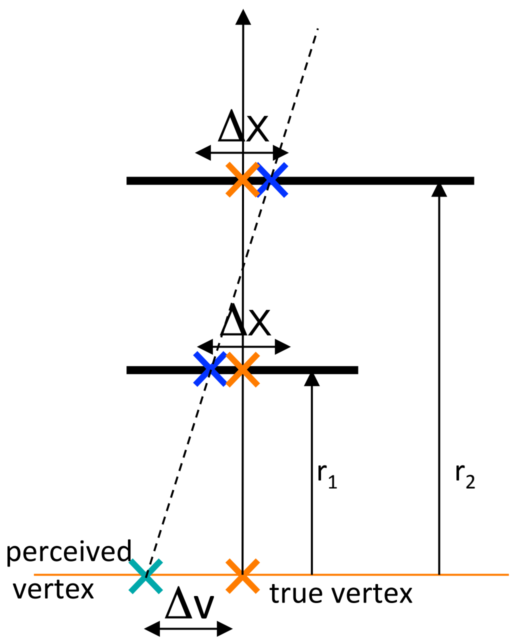
Properties of heavy quark mesons

particle	Daughters	Cτ (μm)	Mass (GeV)
D^0	$K^-\pi^+$ (3.8%)	123	1.8646
$D^\pm$	$K^-\pi^+\pi^+$ (9.2%)	312	1.8694
D_s	$K^+K^-\pi^+$ (4.4%) $\pi^+\pi^+\pi^-$ (1.0%)	147	1.9683
Λ_c	$p K^-\pi^+$ (5.0%)	59.9	2.2849



Determine DCA of pair vertex relative to event vertex with high resolution (~45μm)

Thinness Criteria



$$\sigma^2 = \frac{\sigma_1^2\, r_2^2 + \sigma_2^2\, r_1^2}{(r_2 - r_1)^2} + \frac{\theta_{mcs}^2\, r_1^2}{\sin^2(\theta)}$$

from detector position Error, res.

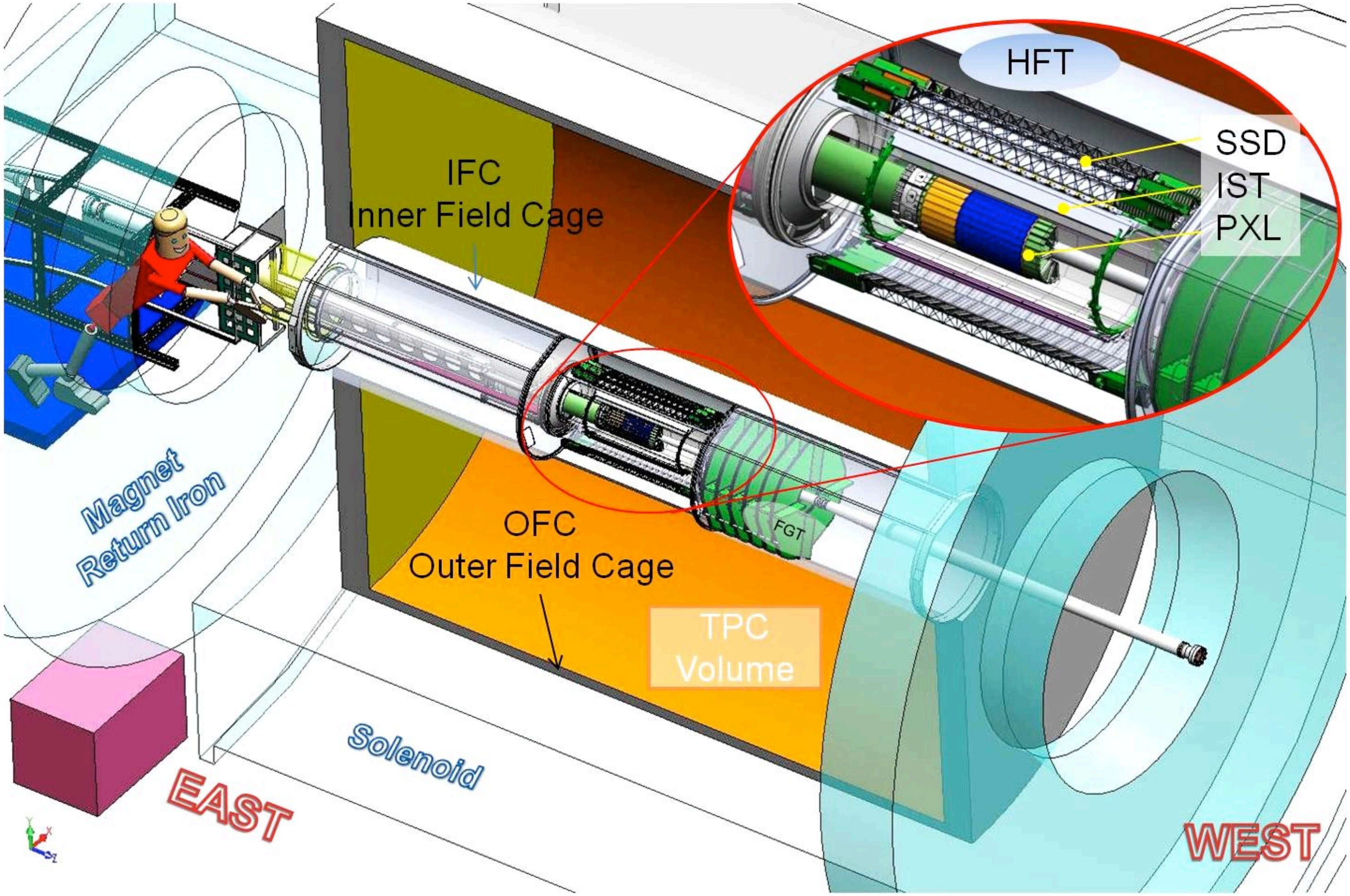
From Coulomb scattering

$$\sigma = 13\mu m \oplus \frac{22\ GeV}{p \cdot c}\mu m$$

This requires good and stable positioning and Intrinsic resolution.

Courtesy Howard W.

HFT Technical Overview

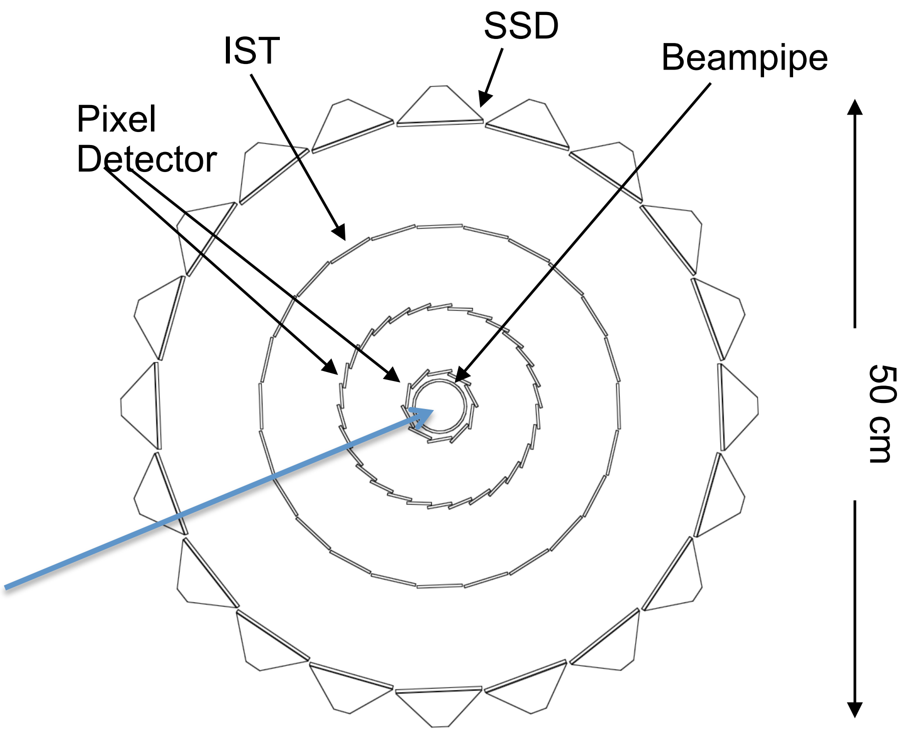


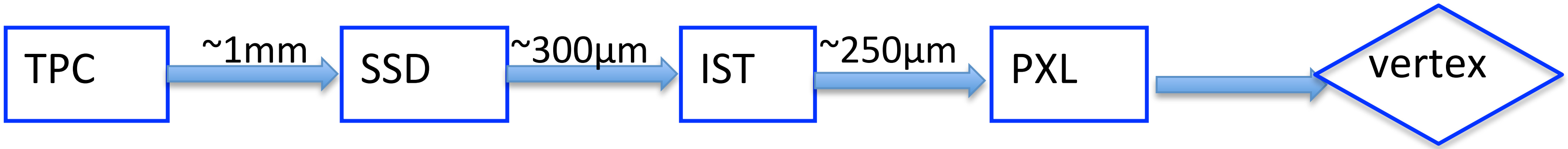
Cross section View

Outside-in tracking with graded resolution determines the requirements for the detector subsystems.

Important consideration for overall system integration.

The limited TPC pointing resolution establish the need for intermediate Si-layers.





Event Characteristics

- Particle densities per event
- Event, Pile-up QED electrons
- RHIC luminosity 200 GeV Au 50 10^{26} $cm^{-2}s^{-1}$

	PIXEL-1 Inner Layer	PIXEL-2 Outer Layer
Radius	2.5 cm	8.0 cm
Central collision hit density	17.8 cm^{-2}	1.7 cm^{-2}
Integrated MinBias collisions (pileup)	23.5 cm^{-2}	4.2 cm^{-2}
UPC electrons	19.9 cm^{-2}	0.1 cm^{-2}
Totals	**61.2 cm^{-2}**	**6.0 cm^{-2}**

Mechanical Requirements

1. Minimize multiple coulomb scattering, particularly at the inner layer
2. Locate the inner layer as close to the interaction region as possible
3. Allow rapid detector replacement
4. Provide complete spatial mapping of the PXL from the beginning

- Rapid detector replacement, is motivated by the recognition of difficulties encountered in previous experiments with unexpected detector failures. Also motivated by the need to replace detectors that may be radiation damaged by operating so close to the beam.
- The fourth goal, complete spatial mapping, is important to achieve physics results in a timely fashion. Know at installation, where each pixel is located with respect to each other to within 20 microns and to maintain the positions while installed in STAR.

Radiation Levels

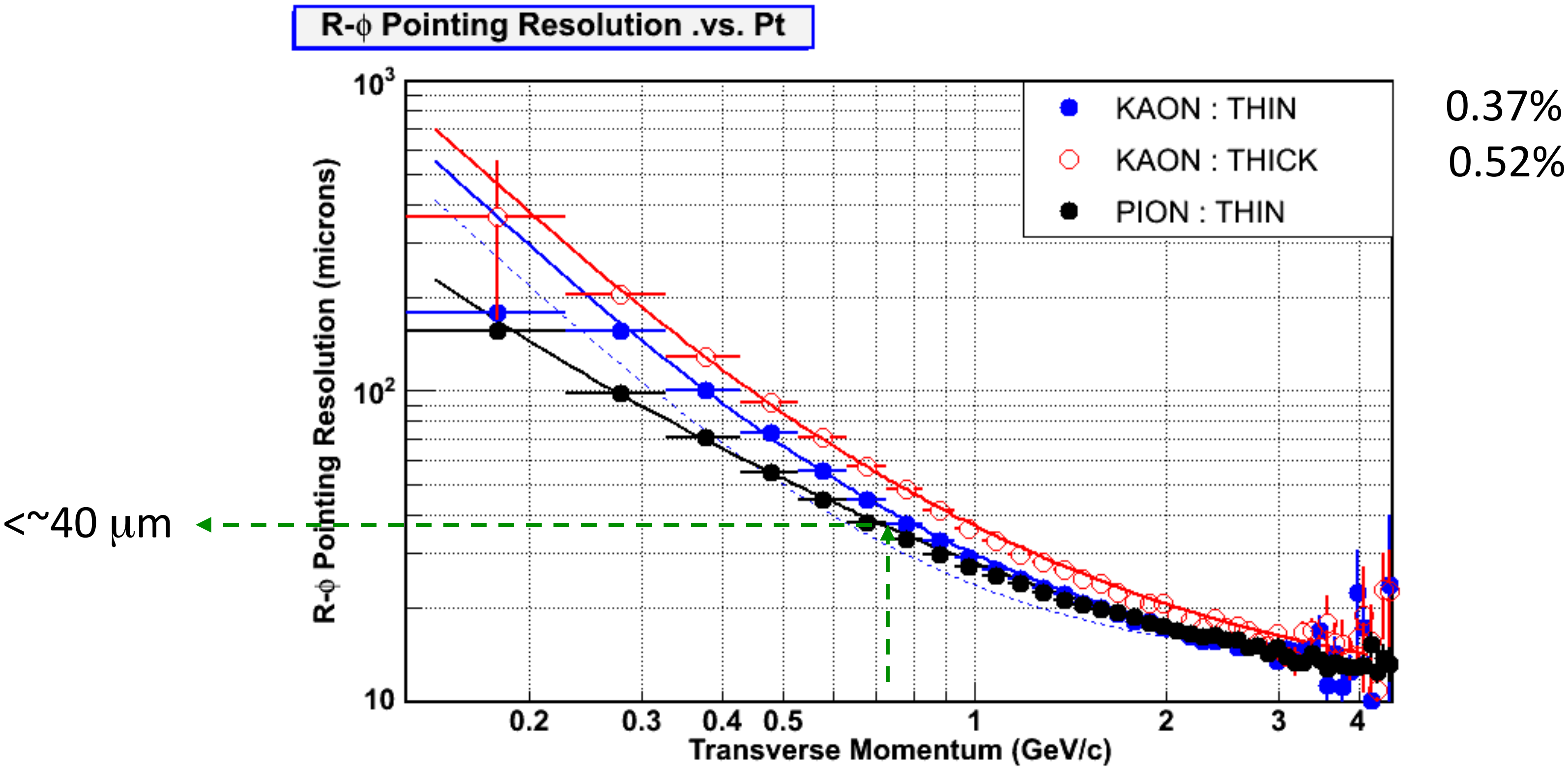
- **Radiation field in krad in the center of STAR extrapolated to RHIC II luminosities for different radial positions for 12 weeks of run time for the radii of PXL layer 1, the IST, and the SSD.**

		Radius [cm]	200 GeV	200 GeV	500 GeV	500 GeV
			Au+Au Max	Au+Au Min	p+p Max	p+p Min
	Physics	2.5	28	5.3	133	29
	Physics+UPC	2.5	60	11	---	--
PXL	**Total**	**2.5**	**88**	**17**	**267**	**58**
	Physics	14	1	0.2	4	1
IST	**Total**	**14**	**2**	**0.3**	**9**	**2**
	Physics	22	0.4	0.1	2	0.4
SSD	**Total**	**22**	**1**	**0.1**	**3**	**1**

PXL Sensor requirements

- Thin with X < 0.4% x0 per layer
- Fine segmentation σ < 20 micron
- Radiation tolerant < 300kRad per year
- Low noise, high efficiency
- Readout speed of ~1 kHz (match TPC)
- < 200 μsec sampling time.

Pointing resolution in r-ϕ

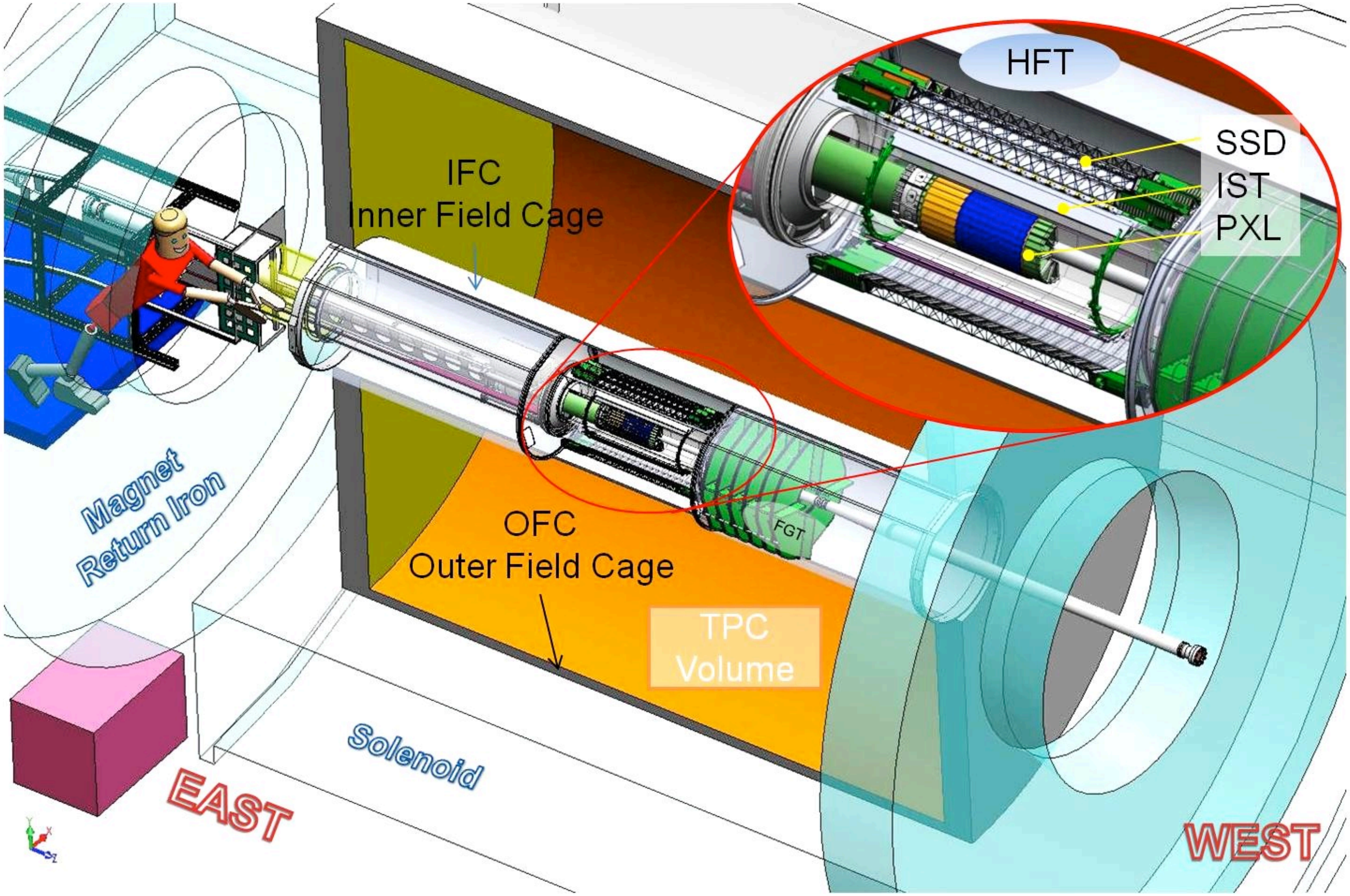


Points : full GEANT simulation : detector geometry+ STAR tracking

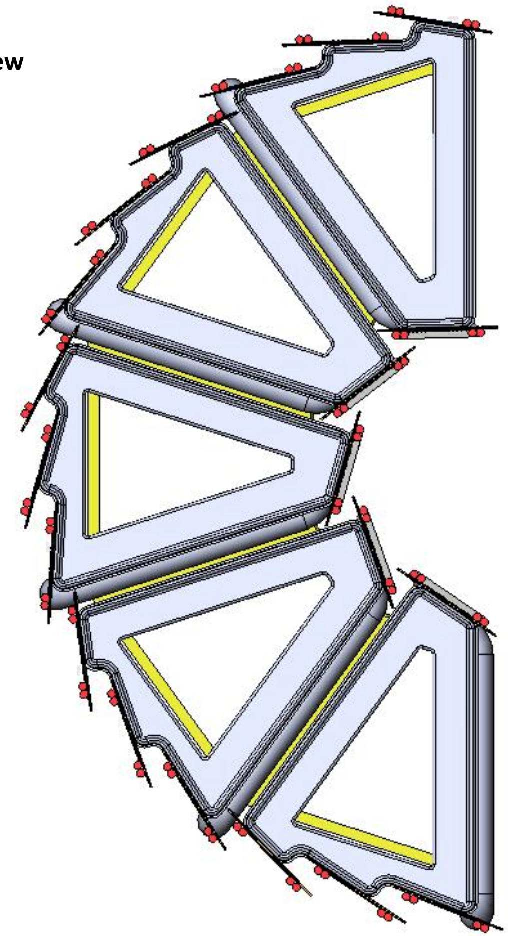
Line : hand calculation : MCS + hit resolution

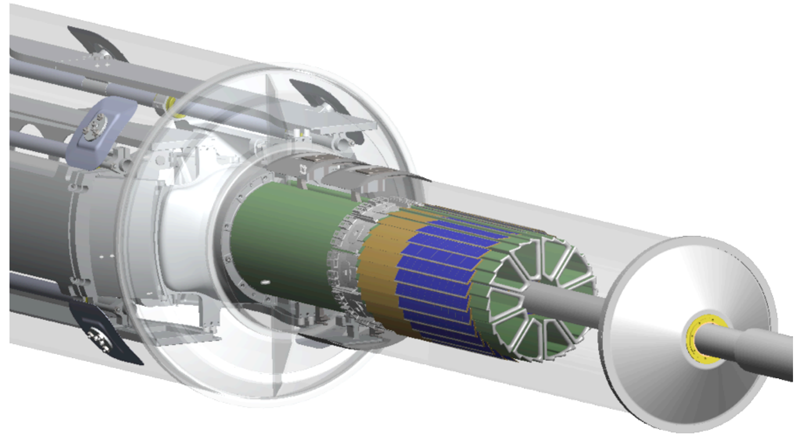
➔Pointing resolution is crucial to distinguish/measure displaced vertex

HFT Technical Overview



Pixel Detector (PXL)





Mechanical support with kinematic mounts (insertion side)

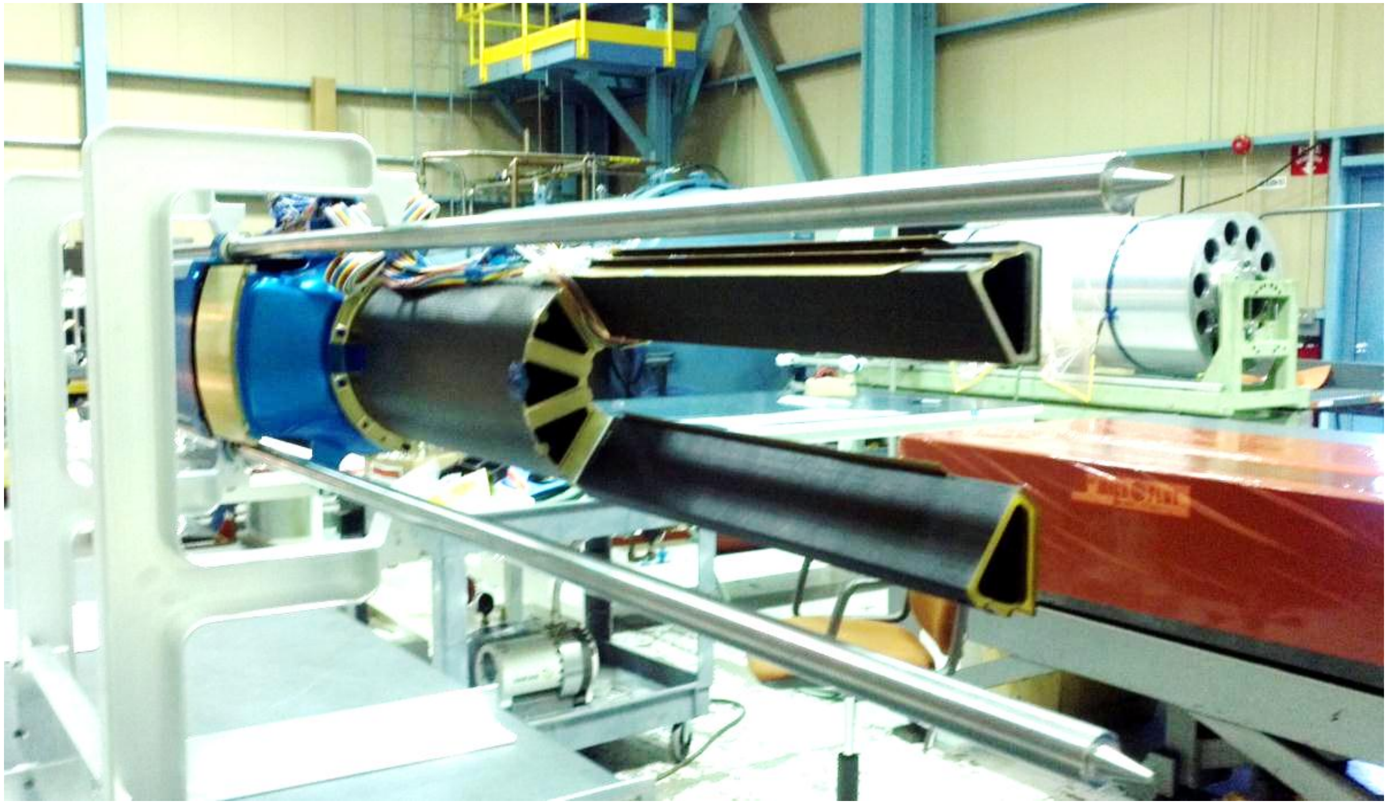
carbon fiber sector tubes (~ 200μm thick)

Insertion from one side

- 2 layers
- 5 sectors / half
- 4 ladders/sector

Details in talks by H.Wieman, L.Greiner and M.Szelezniak during this meeting.

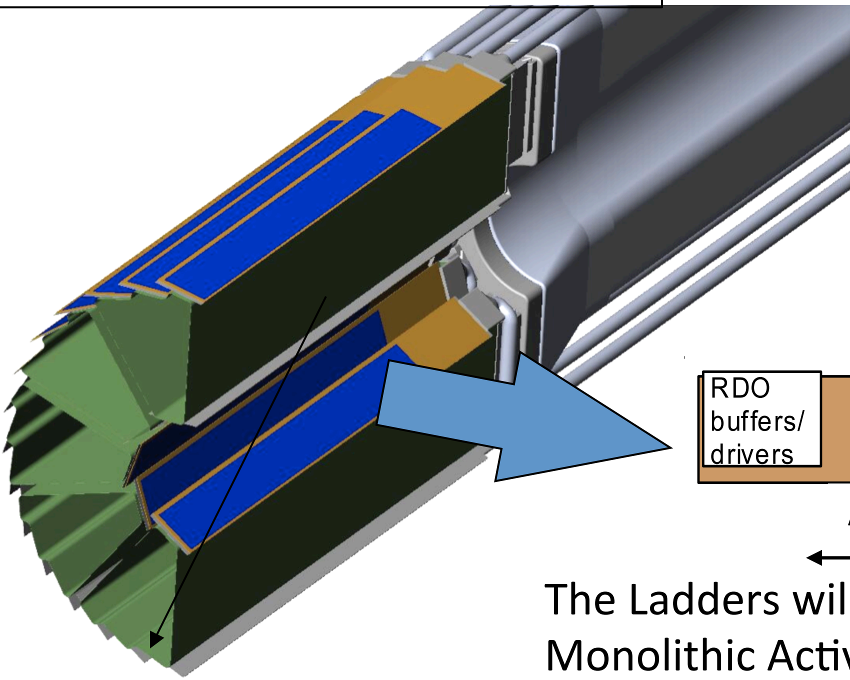
Test Setup



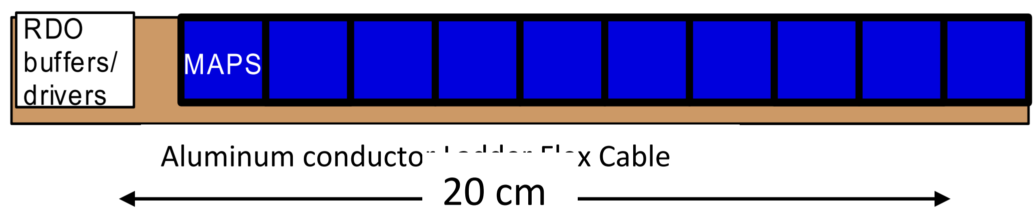
Two sector only shown in sector holder.

PXL Detector Design

carbon fibre sector tubes (~ 200µm thick)



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



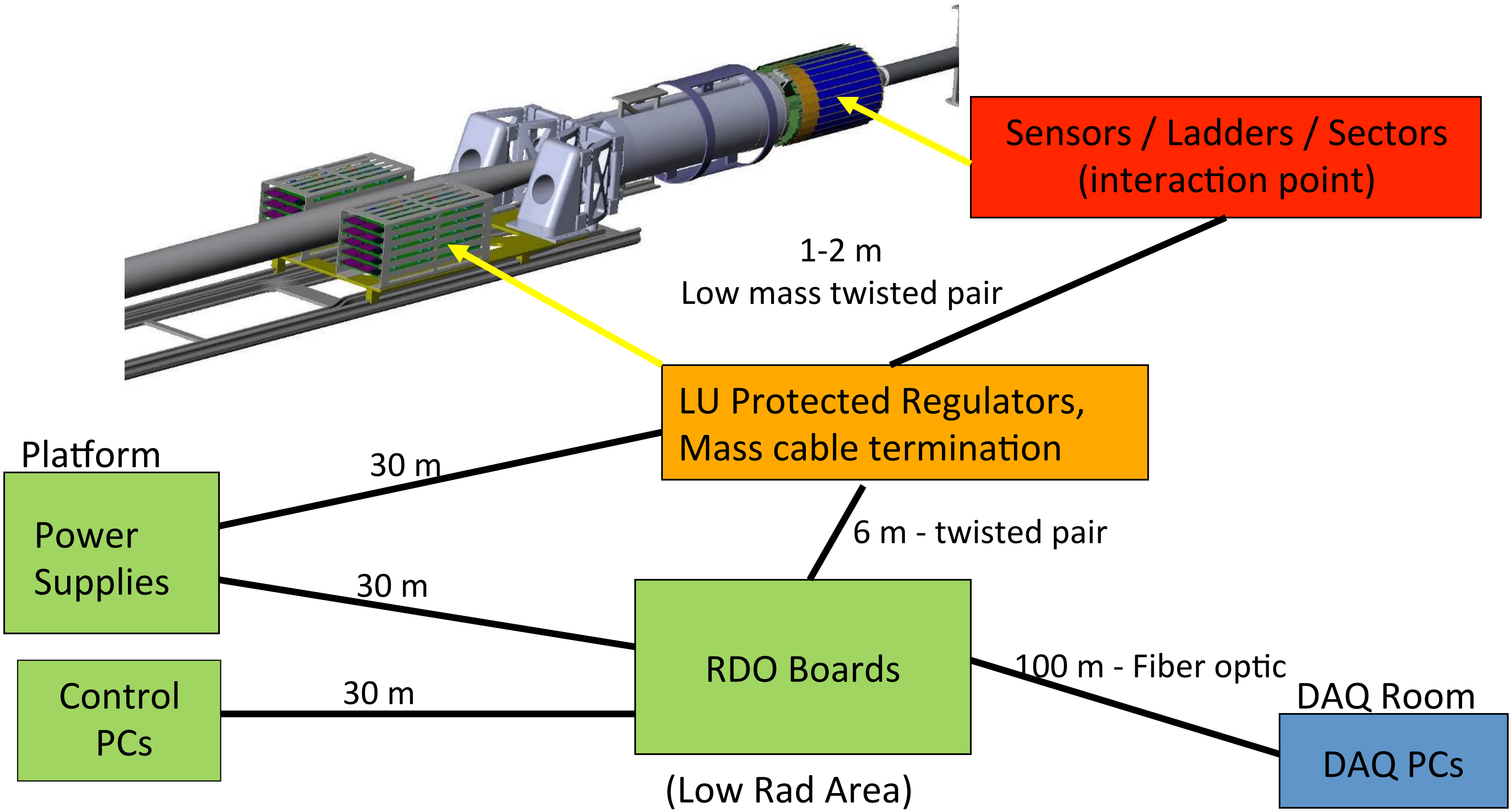
The Ladders will be instrumented with Monolithic Active Pixel Sensors thinned down to 50 micron Si
The IPHC designed sensor will use a 400 ohm*cm epitaxial layer as the default configuration.

Sensor Specification

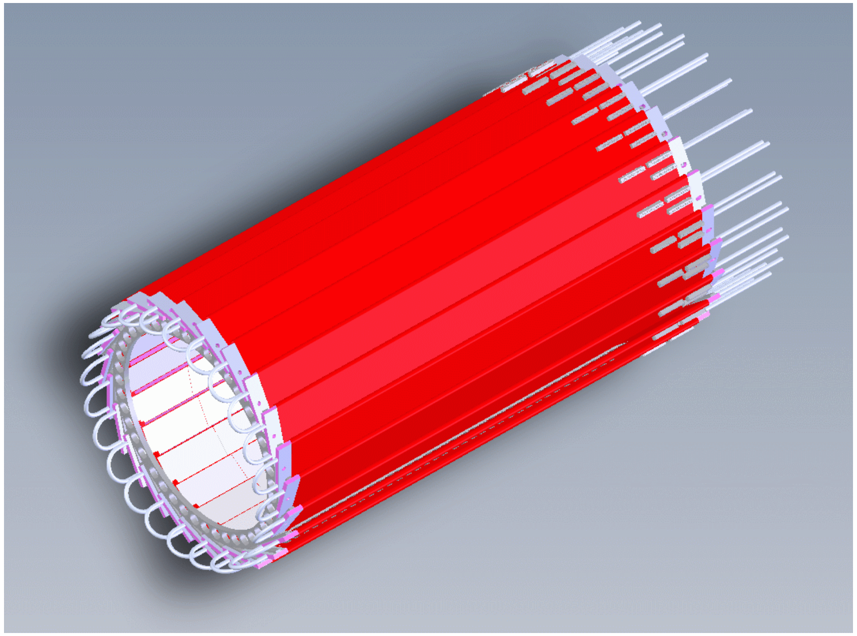
	Phase -1	Ultimate
Pixel Size	30 μm × 30 μm	20.7 μm × 20.7 μm
Array size	640 × 640	928 × 960
Active area	~ 2 × 2 cm	~ 2 × 2 cm
Frame integration time	640 μs	100 – 200 μs
S/N	>12	>12
Readout time / sensor	640 μs	100 – 200 μs
Outputs / sensor	4	2
Operating mode	Column parallel readout with all pixels read out serially.	Column parallel readout with integrated serial data sparsification.
Output type	Digital binary pixel based on threshold crossing.	Digital addresses of hit pixels with row run length encoding and zero suppression. Frame boundary marker is also included.

- Phase-1 will be used in upcoming beam tests at CERN
- The first prototype final sensors (ultimate) have been received and are being tested and characterized of these prototypes.

RDO System Design – Physical Layout



Intermediate Silicon Tracker (IST)

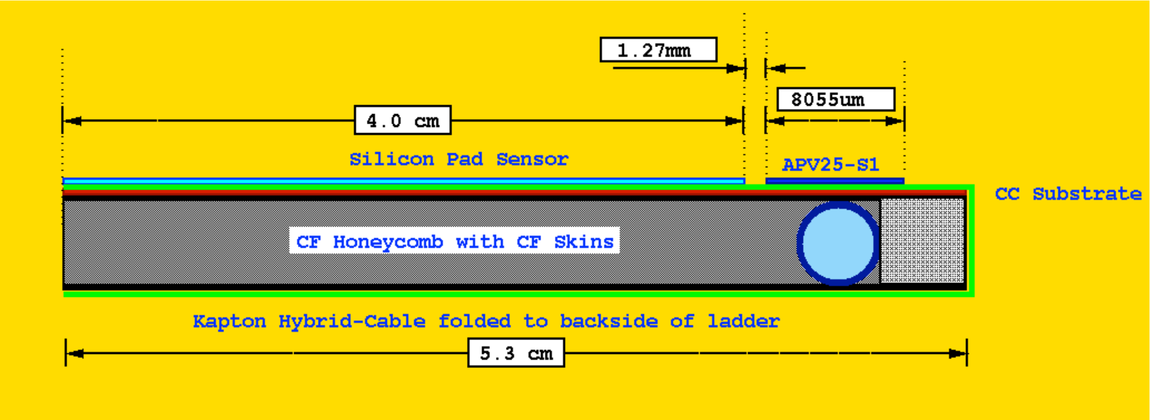


24 ladders 50 cm long at 14 cm radius

- Intermediate tracking layer with good r-phi resolution 250μm
- Conventional Si pad detector using CMS APV chip for ladders
- Readout system copy of just completed FGT detector system

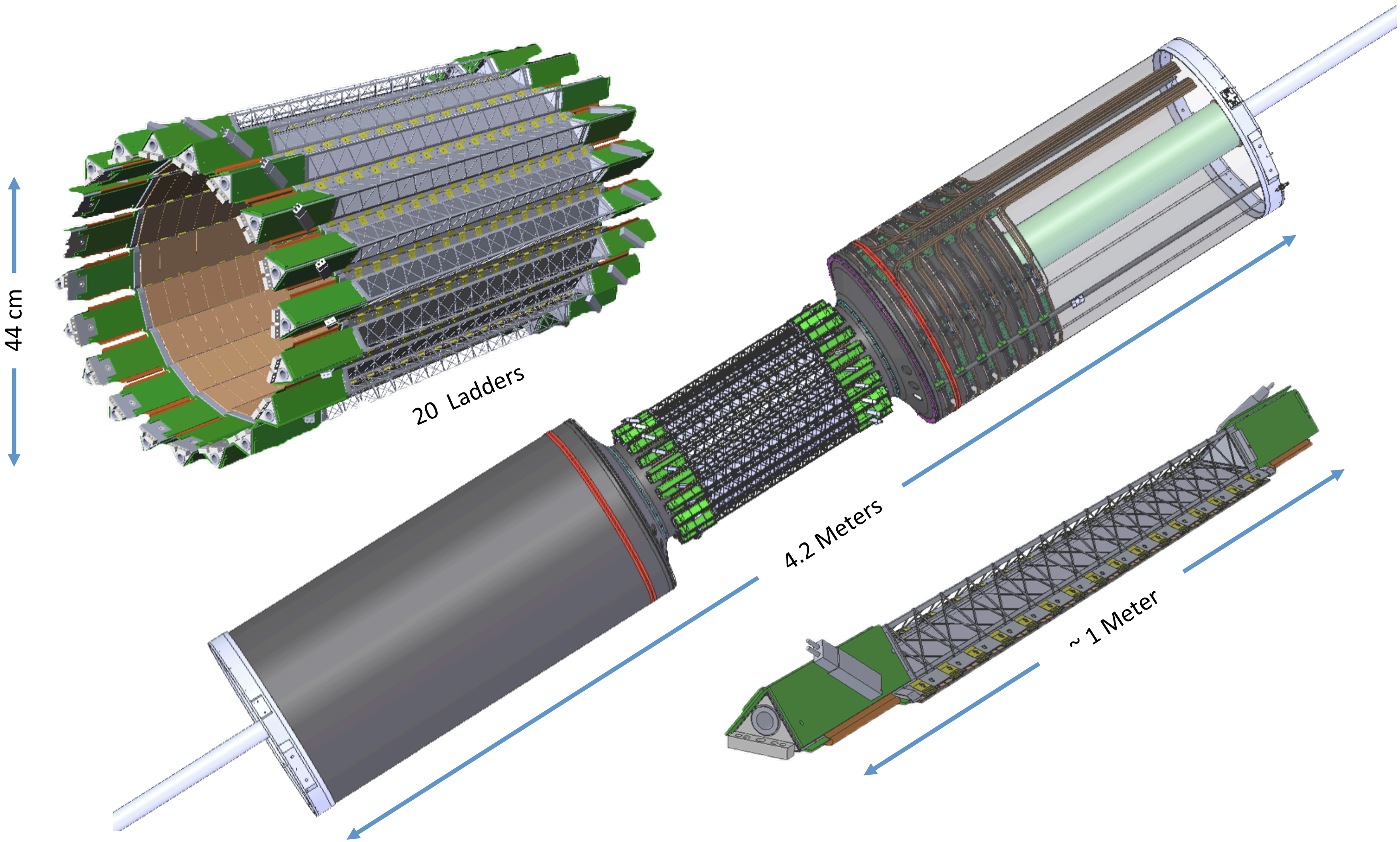
IST Characteristics

Radius	14 cm
Length	50 cm
ϕ-Coverage	2π
$\|\eta\|$-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



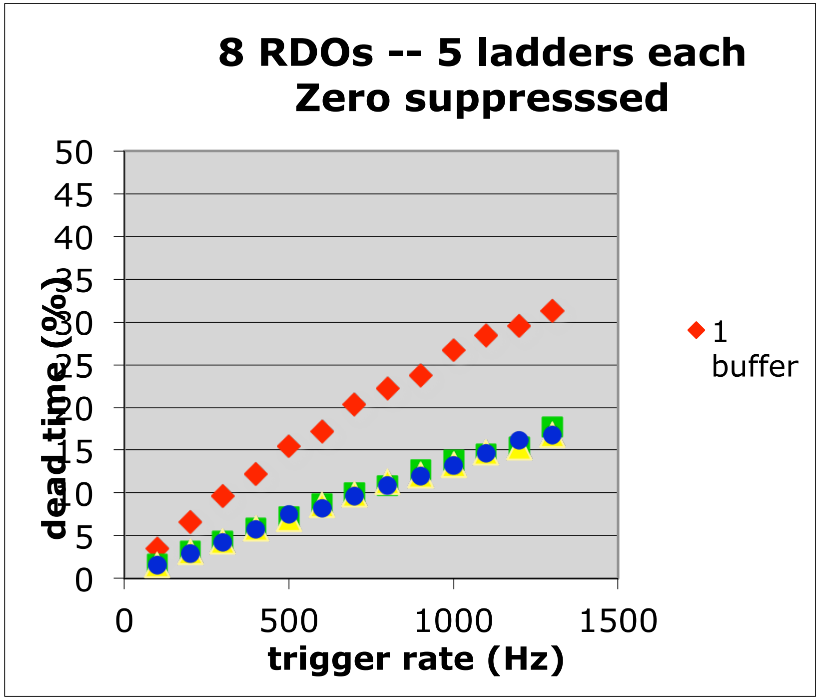
- Liquid cooling
- Carbon Fiber ladder
- APD chips flex hybrid cable
- <1.5% Xo
- Fast detector

Silicon Strip Detector (SSD)



SSD

- Instrument 20 of the existing SSD ladders with new readout electronics compatible with STAR TPC readout
- SSD to be installed on the Outer Support Cylinder at 20 cm
- Provide cabling and cooling compatible with the IDS structure and FGT
- Upgraded cooling system



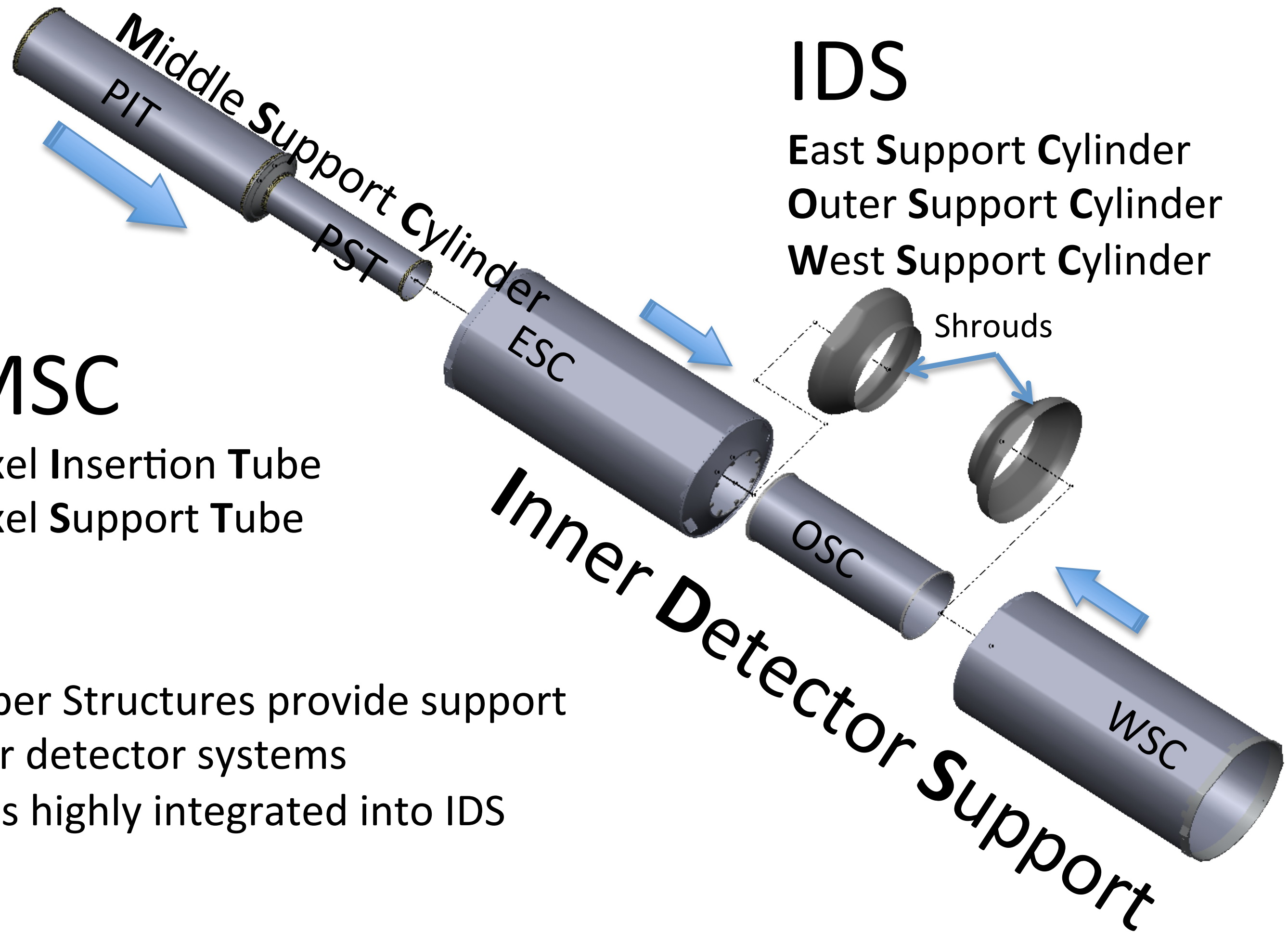
Inner Detector Support (IDS)

MSC

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

IDS

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



Carbon Fiber Structures provide support
For 3 inner detector systems
All systems highly integrated into IDS

Carbon Fiber Cylinders

Outer supports will be installed for the upcoming run at RHIC

Project History

- 2003 and later - R&D
- 2005 - The Inner vertex tracking upgrade identified as a critical component soon after the start of RHIC and developed into proposal and R&D projects within STAR. Reviewed by BNL Detector Advisory Committee and included in the RHIC detector upgrade mid-term plan
- 2007 – Reviewed by BNL Technical Advisory Committee
- 2008 – pre-CD-0 review
- 2009 – CD-0 approval
  – pre-CD-1 review
- 2010 – CD-1 approval – received initial funding for design and prototyping.
- 2011 – CD2/3 review July 13-14.

Project Status

- Scheduled to received final approval and funding following successful CD2/3 review
- Goal to complete fabrication and assembly in two years for first data taking in beginning of 2014
- A PXL prototype with iltimate sensors and Cu cable with 3 sectors instrumented is planned for data taking in STAR in early 2013
- Total cost ~17.5 M$.

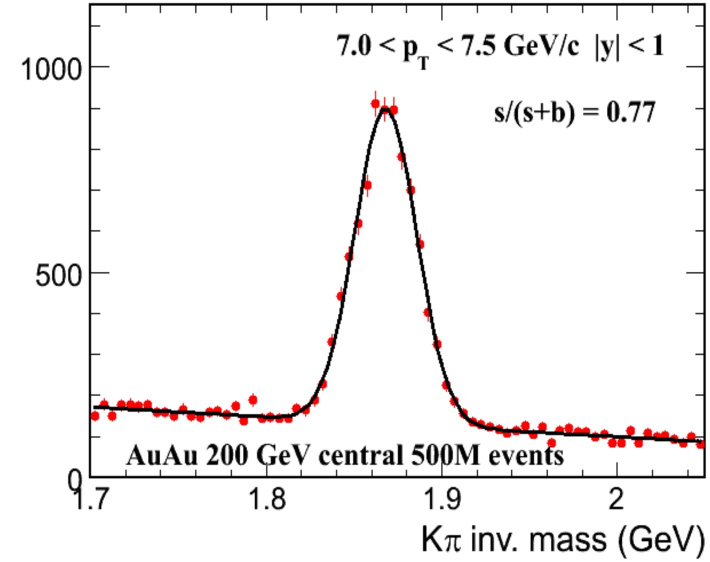
Collaboration and Responsibilities

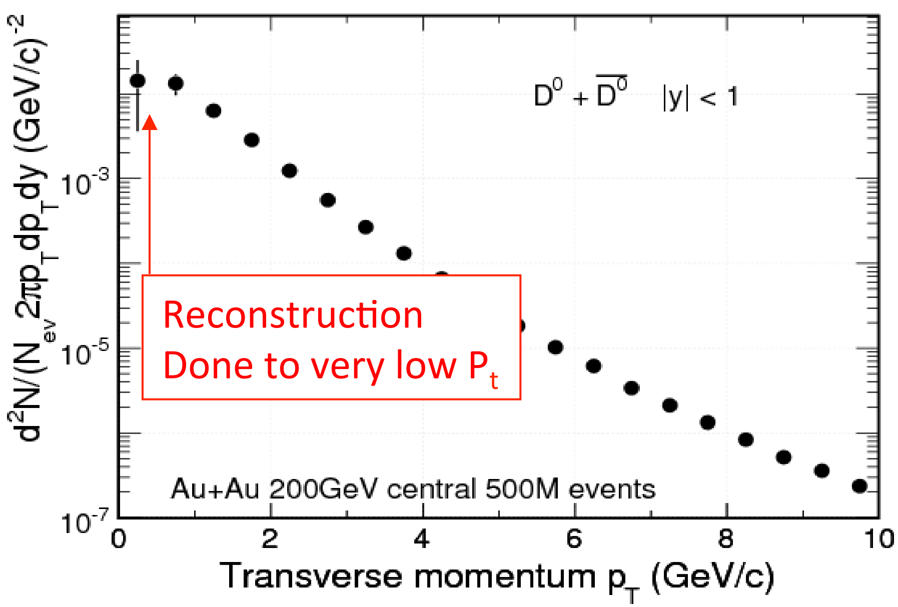
- BNL
  - Project management, integration, safety, SSD electronic upgrade
- LBNL
  - PXL detector, PXL readout, Global support, SSD, integration, management,
- MIT
  - IST detector
- IPHC
  - Sensor development
- SUBATECH
  - Engineering for SSD readout
- UT-A
  - PXL readout, PXL telescope beam test
- Kent State, UCLA, Purdue, NPI, CTU, USTC, LBNL, BNL
  - Software development as part of calibration, offline needs.
- STAR collaboration

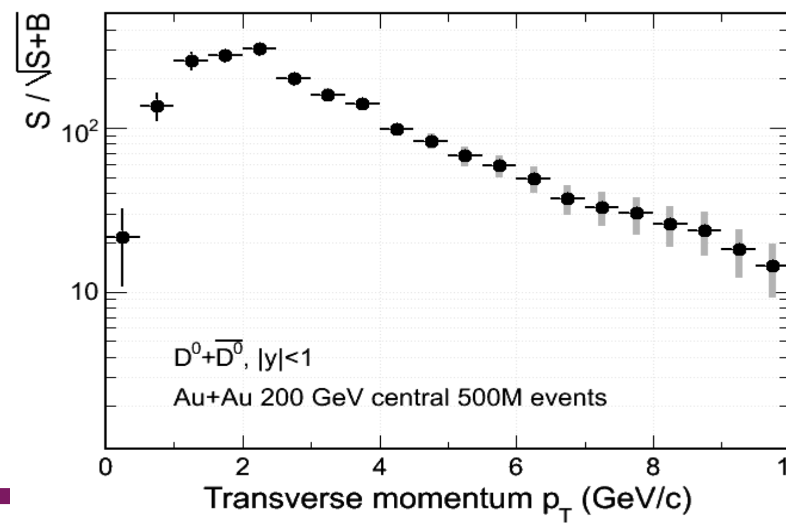
PHYSICS PERFORMANCE

1.Performance example on the $D^0 \rightarrow K\pi$

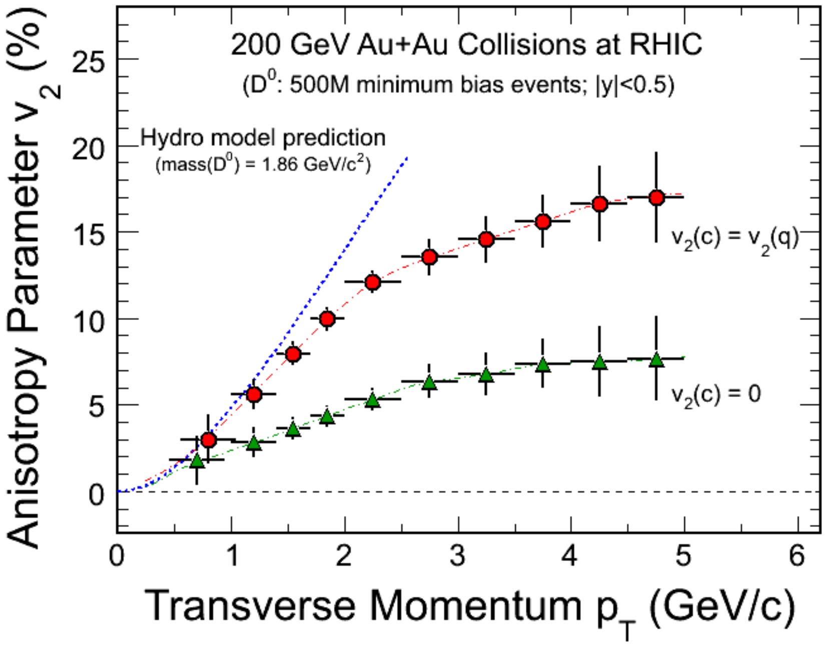
- Simulation of Au+Au@200GeV Hijing events with STAR tracking software including pixel pileup (RHIC-II luminosity) extrapolated to 500 M events.
- Identification done via topological cuts and PID using Time Of Flight

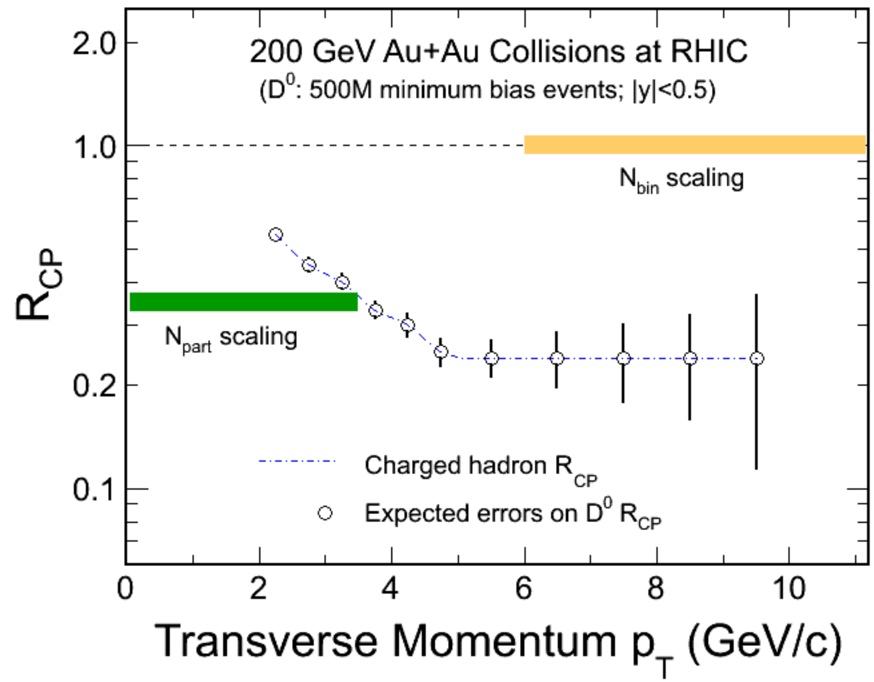






2. Physics projections

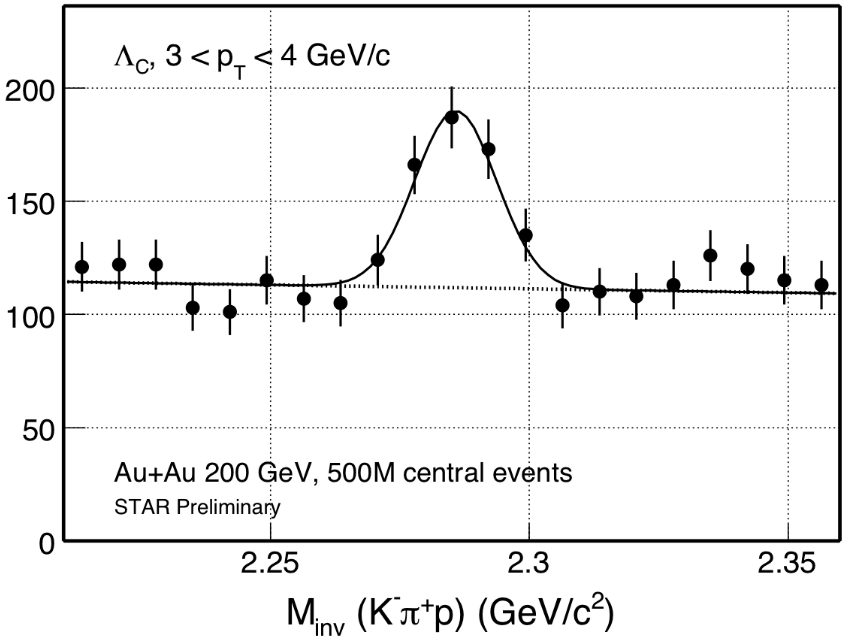


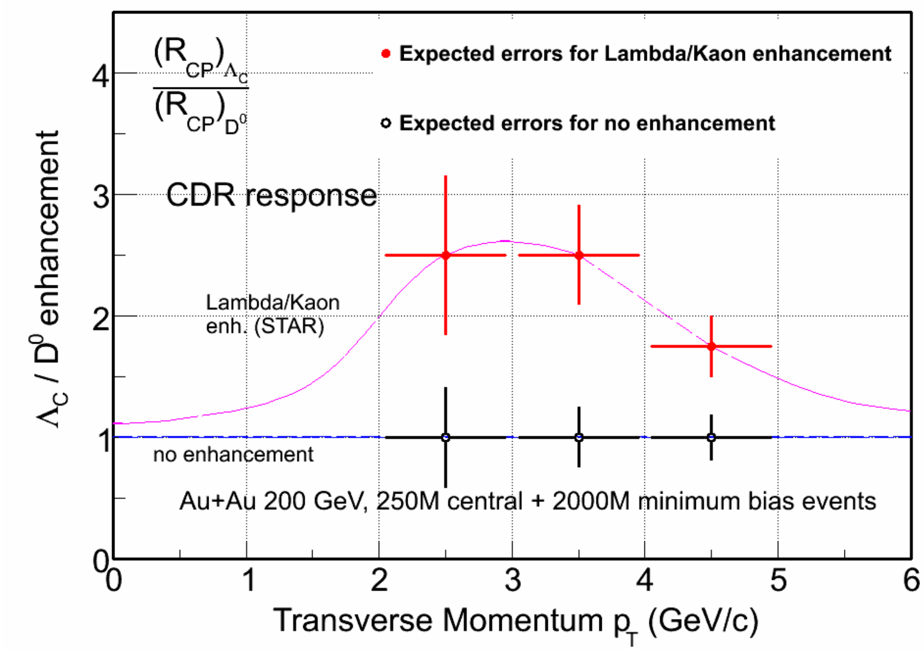


- Can disentangle/discriminate models where charm quarks flow or not.

3. Baryon to meson ratio via Λ_c reconstruction

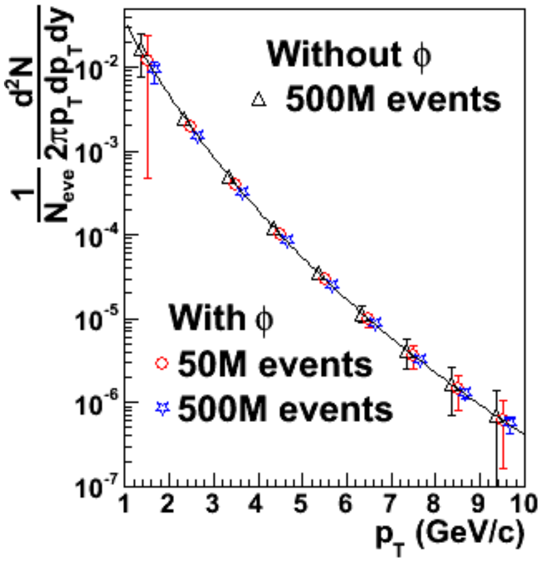
J. Kapitan, *Eur. Phys. J. C* **62** (2009) 217-221

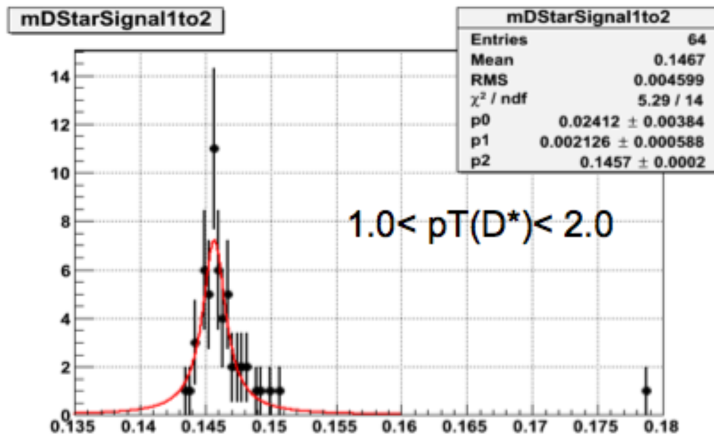


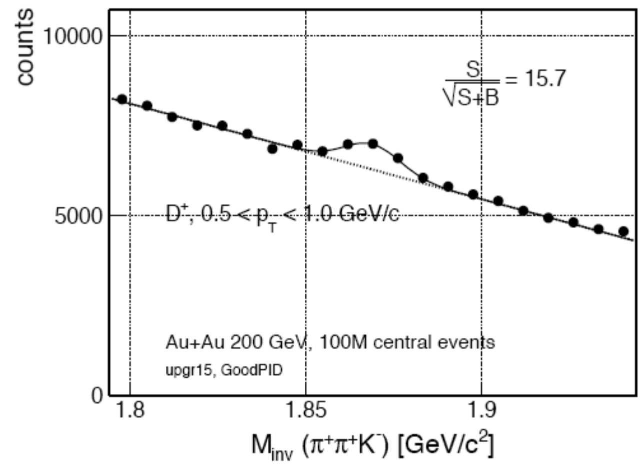


- Lowest mass charm baryon ; ratio of $\Lambda_c(\rightarrow pK\pi)$ to D^0
- Test in the heavy quark sector the baryon to meson ratio.
- Quark coalescence model.

4. Other Charmed hadrons







particle	Daughters(BR)	$c\tau$ [μm]	Mass [GeV/c^2]
D^0	$K\pi$(3.9%)	123	1.864
$D^{+/-}$	$K\pi\pi$ (9.2%)	311	1.869
D_s	$KK\pi$ (5.5%)	149	1.968
D^{*+}	$D^0\,\pi$ (67.7%)	X	2.01
Λ_c	$pK\pi$(5.0%)	60	2.28

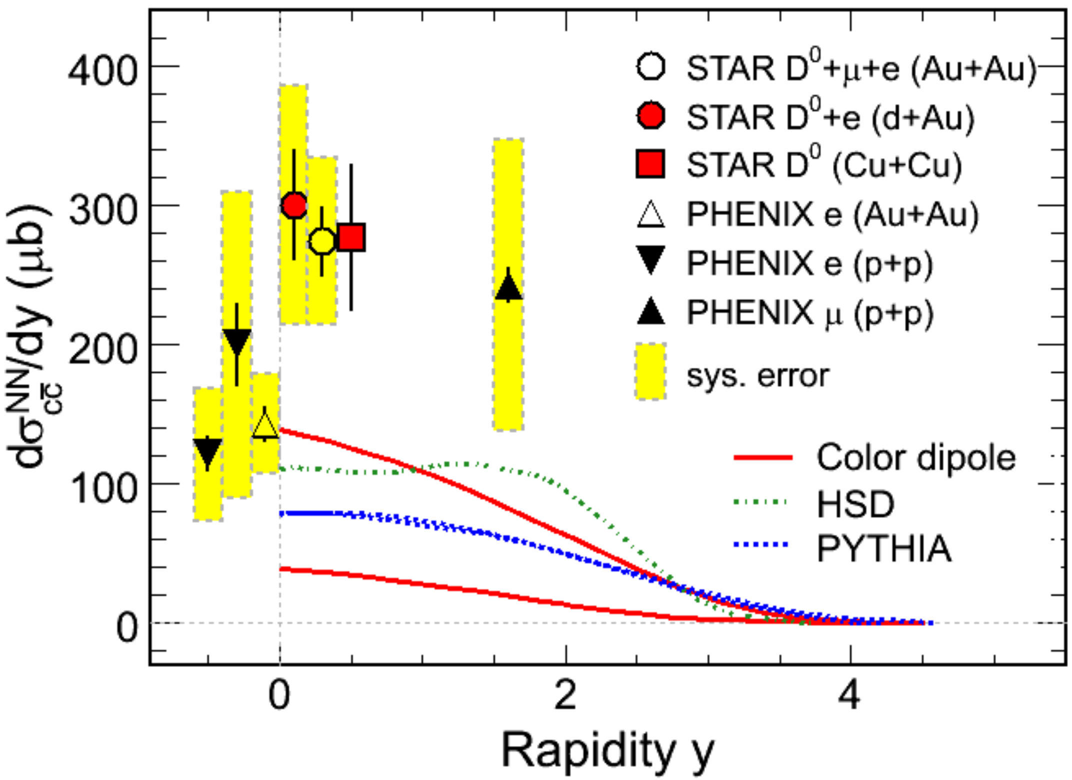
Projected Run Plan

- **1**) First run with HFT: 200 GeV Au+Au
  ⇨ v_2 and R_{CP} with 1,000M M.B. collisions
  2) Second run with HFT: 200 GeV p+p
  ⇨ R_{AA}
  3) Third run with HFT: 200 GeV Au+Au
  ⇨ Centrality dependence of v_2 and R_{AA}
  ⇨ Charm background for di-electron measurements
  ⇨ Λ_C baryon with sufficient statistics

Summary

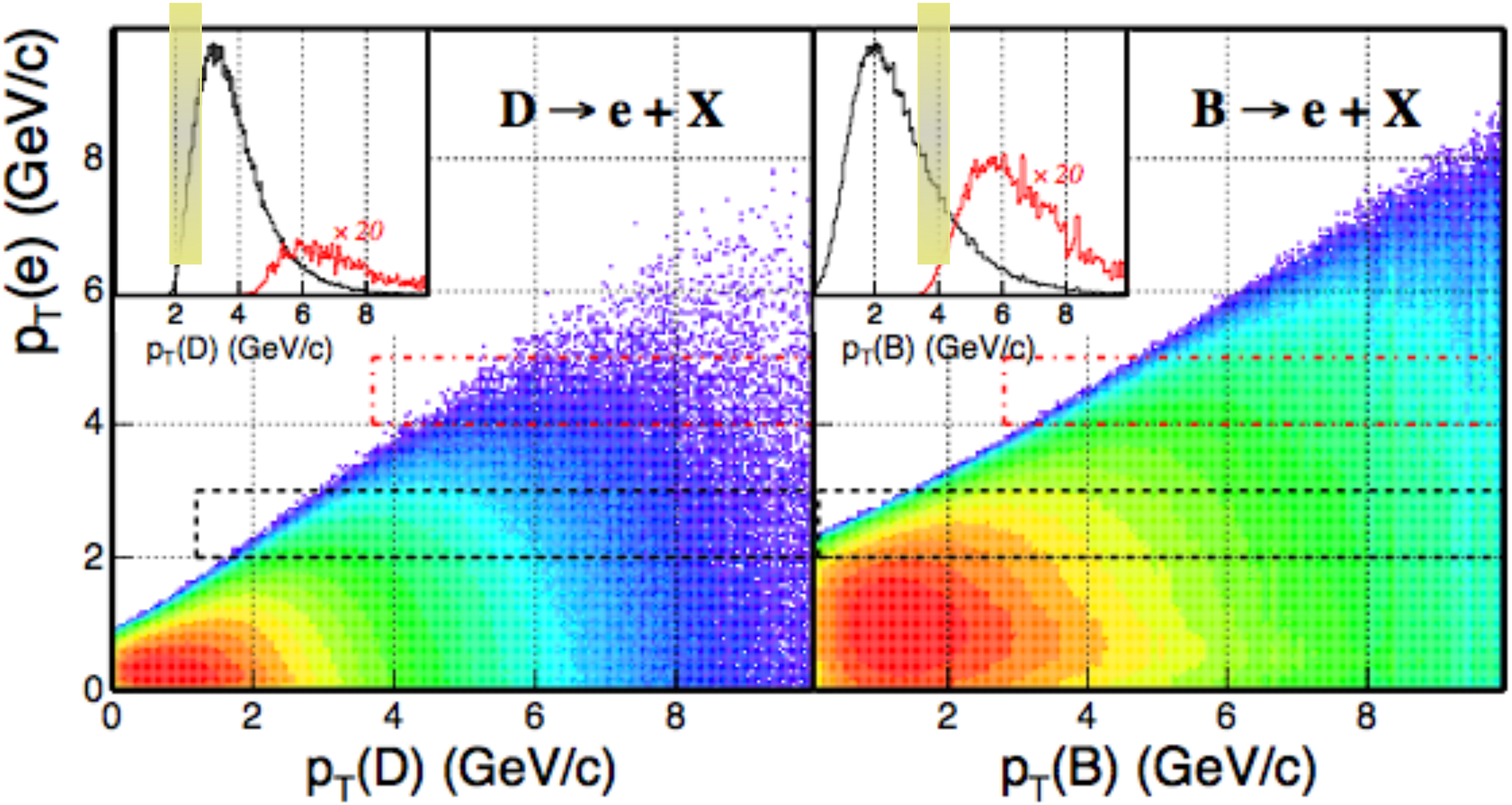
- The STAR HFT upgrade with the ultra-thin PXL vertex well underway for the future program with heavy quarks at RHIC.
- Extensive prototyping nearly complete.
- Thinned MAPS and air cooling key to very small radiation length budget.
- Novel rapid insertion mechanism allows for dealing effectively with failures and radiation damage to MAPS.

Charm Cross Sections at RHIC



1) Large systematic uncertainties in the measurements
2) Direct topologically reconstructed measurements for c- and b-hadrons are needed ⇨ **HFT *Upgrade***

Decay *e* p_T vs. B- and C-hadron p_T

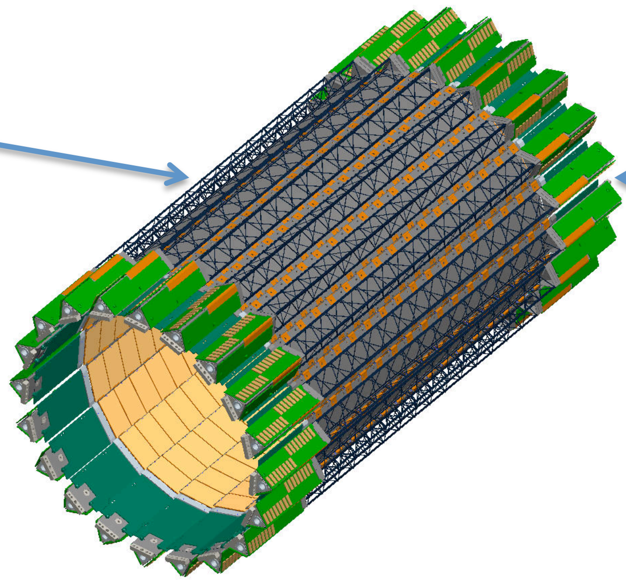


Key: ***Directly reconstructed heavy quark hadrons!***

Pythia calculation   Xin Dong, USTC October 2005

Bits per address	20
Integration time	200 μs
Luminosity	8 x 10^{27}
Hits per frame on inner sensors (r=2.5cm)	246
Hits per frame on outer sensors (r=8.0cm)	24
Sensors inner ladders	100
Sensors outer ladders	300
Average pixels per cluster	2.5
Average trigger rate	1 kHz

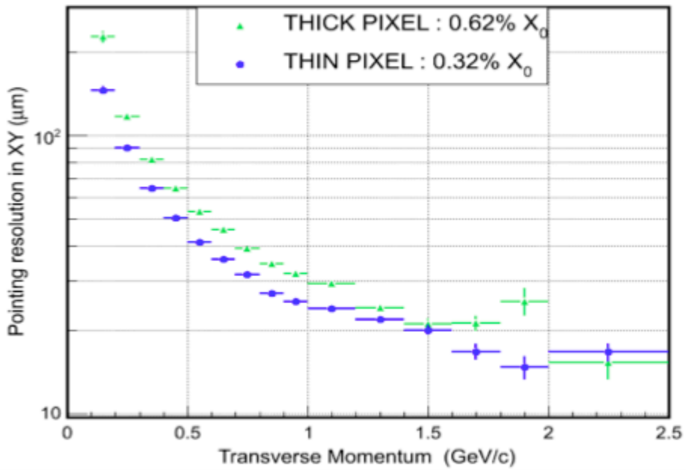
Silicon Strip Detector (SSD)

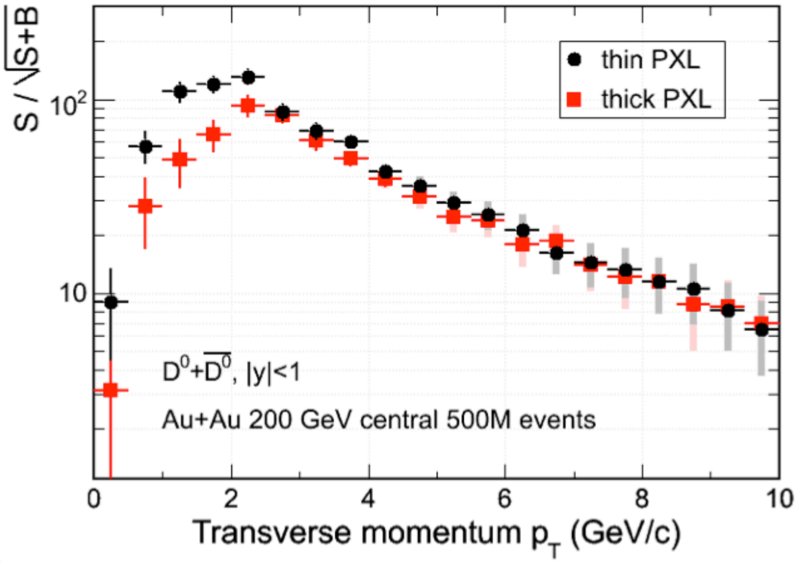


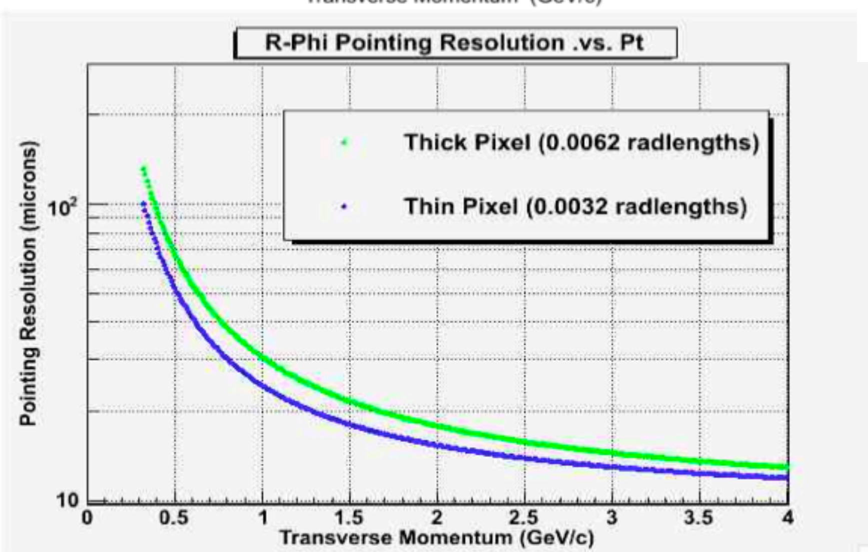
- The ladders and Si-sensors are from existing detector
- Upgrade readout system with new ladder cards on detector, RDO cards, and cooling system

Why thickness is important

STAR HFT



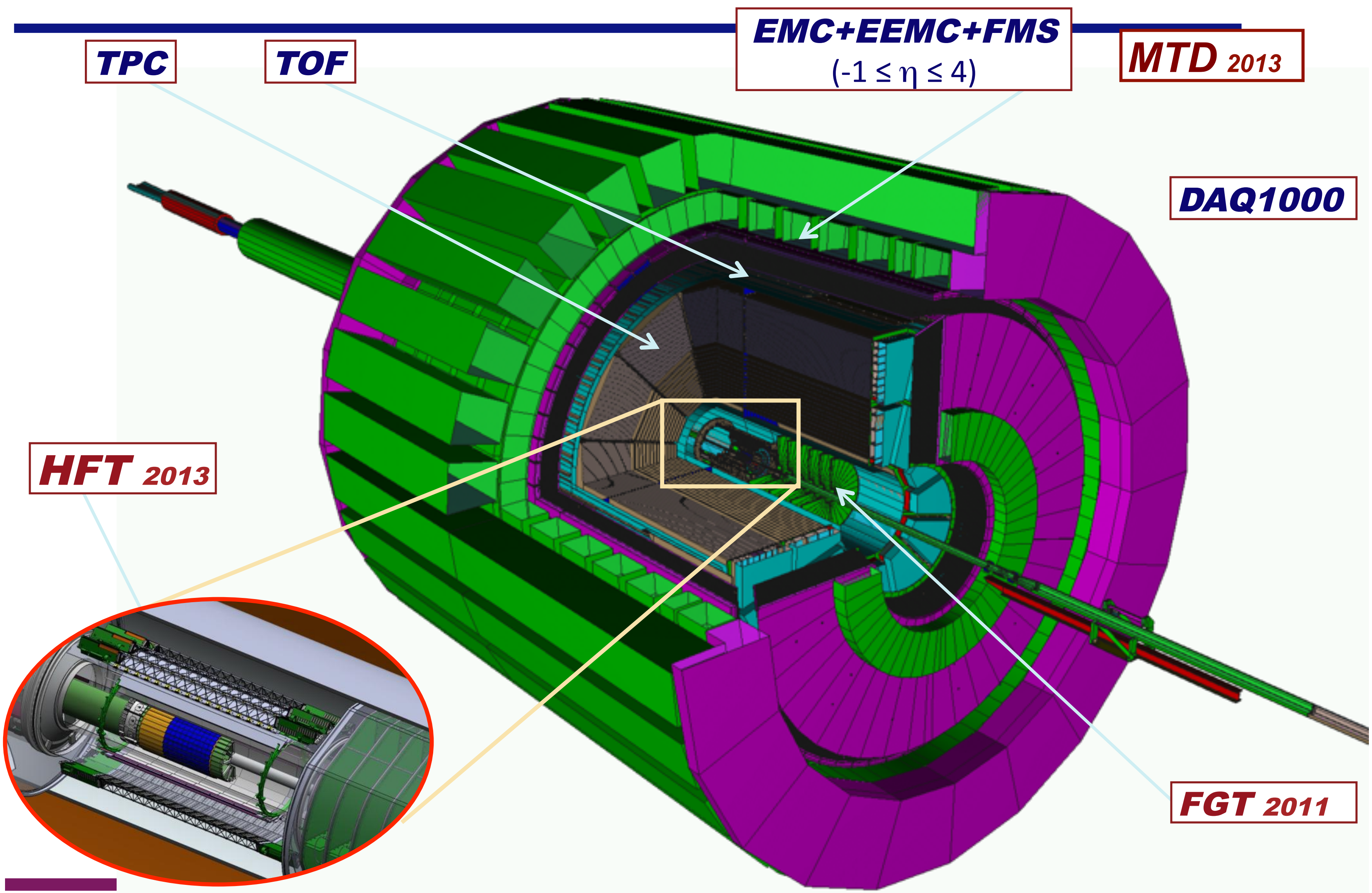




- Left : single track DCA for thin layer (.32%X_0) and thick layer.
- Right : consequences of the layer' s thickness on the D^0 significance.

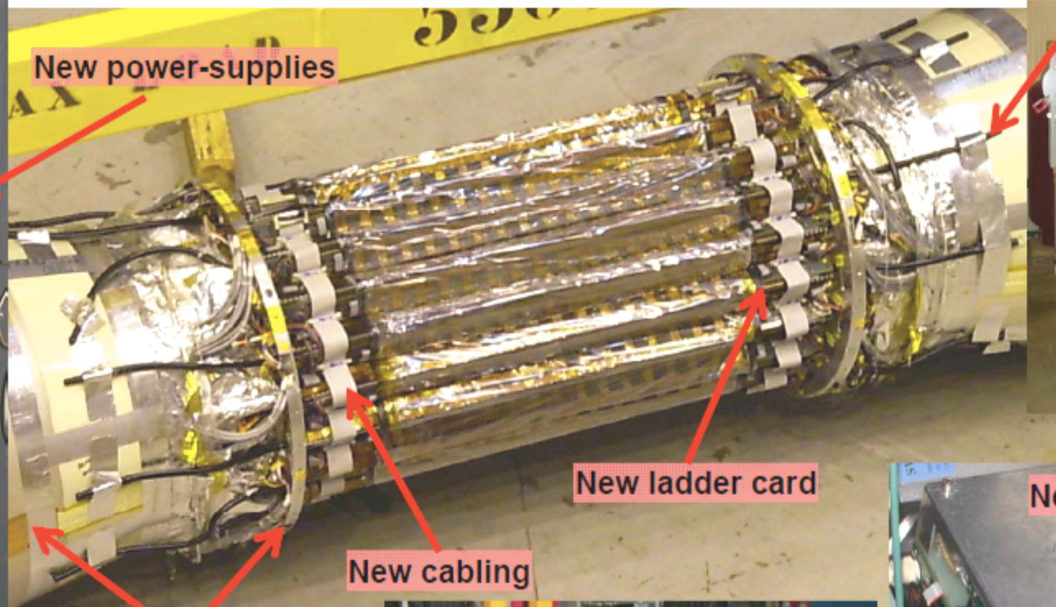
Graded Resolution from the Outside - In		Resolution (σ)
TPC pointing at the SSD	(22 cm radius)	~ 1 mm
SSD pointing at IST	(14 cm radius)	~ 400 μm
IST pointing at PXL-2	(8 cm radius)	~ 400 μm
PXL-2 pointing at PXL-1	(2.5 cm radius)	~ 125 μm
PXL-1 pointing at the vertex		~ 40 μm

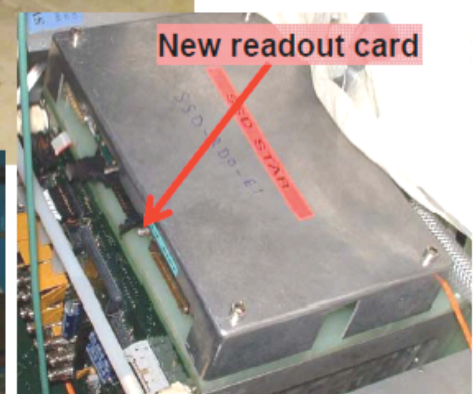
STAR Detectors *Fast* and *Full* azimuthal particle identification



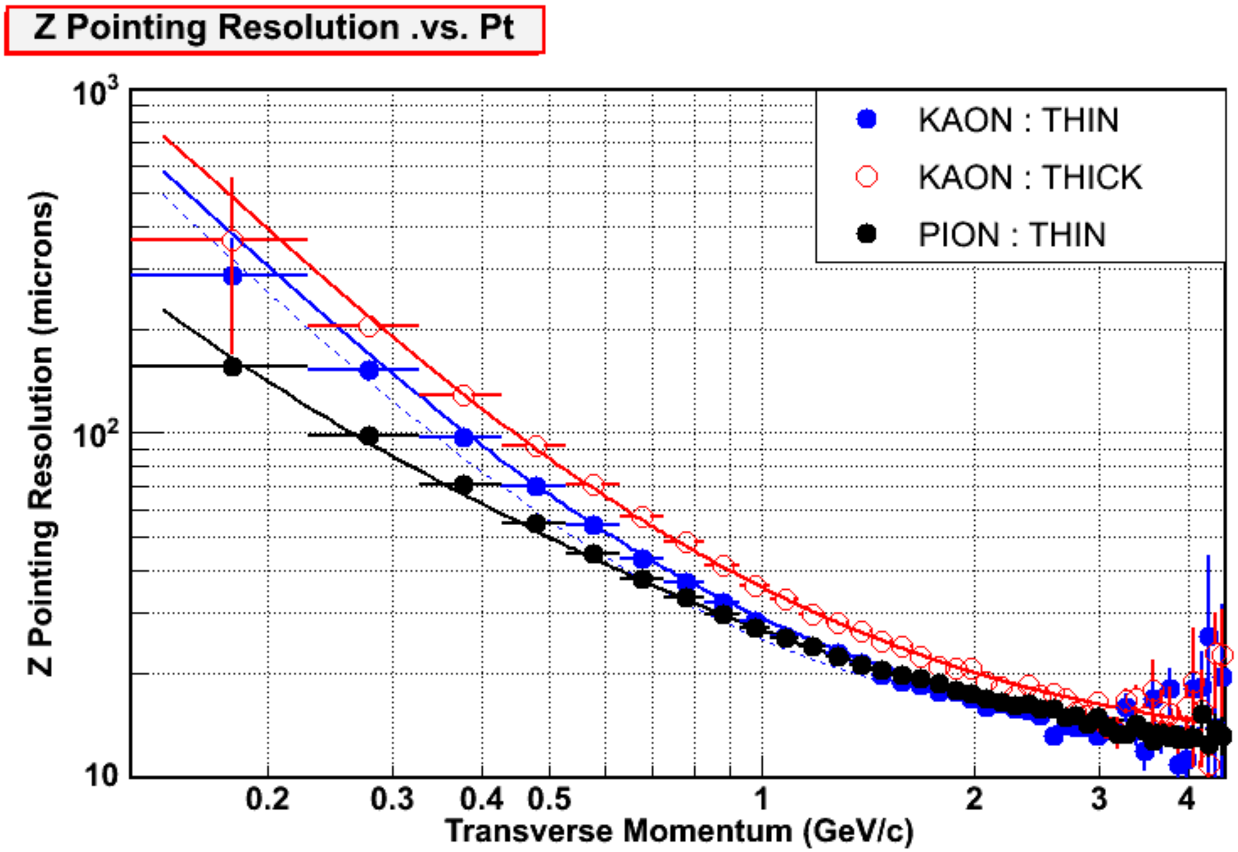
Modifications Needed for the SSD Upgrade

- Use existing SSD silicon sensors
- Upgrade readout from 200 Hz to 1 kHz
- Improve reliability of sub-systems





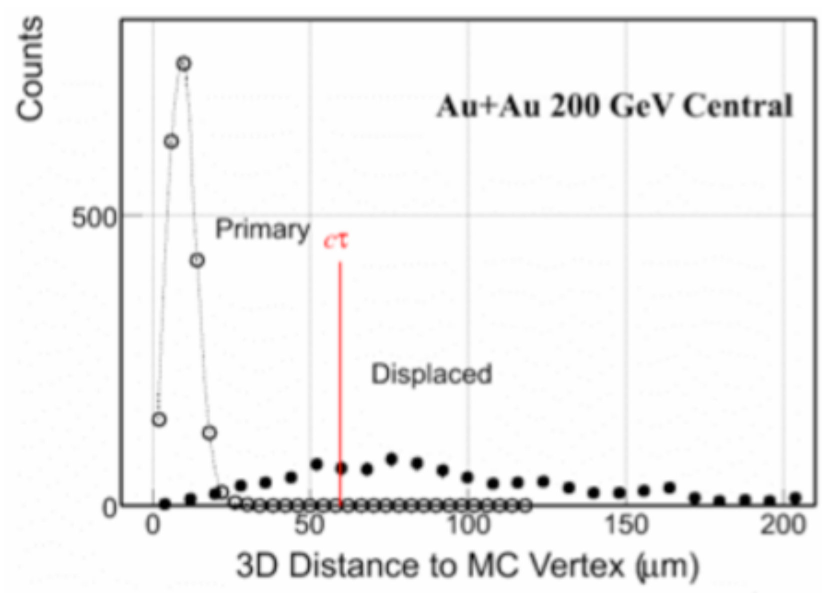
Pointing resolution in Z

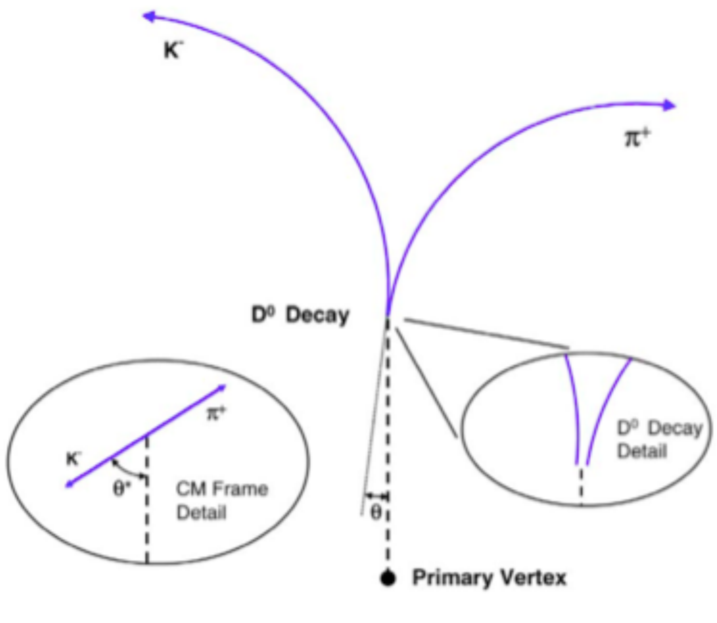


Points : full GEANT simulation : detector geometry+ STAR tracking

Line : hand calculation : MCS + hit resolution

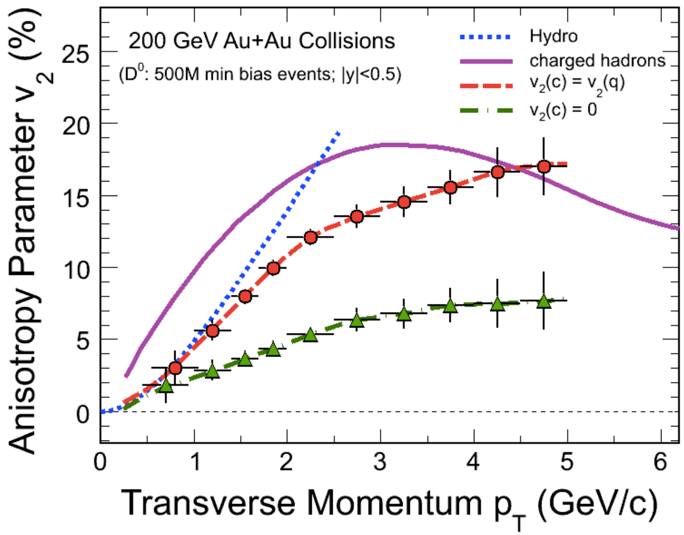
Displaced vertex

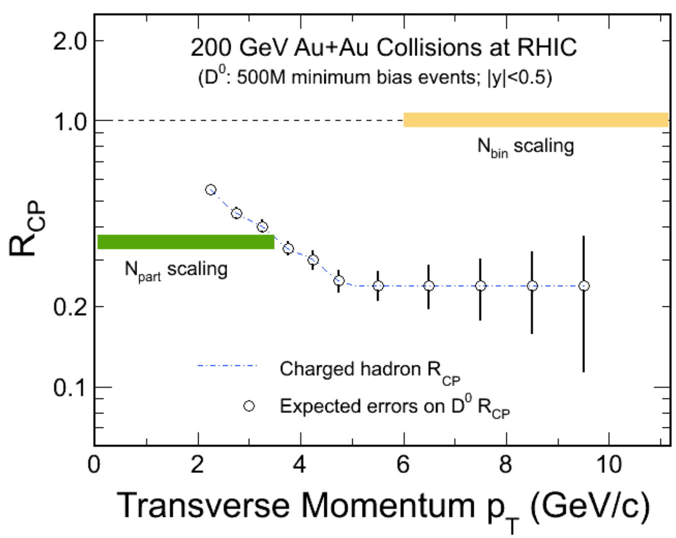


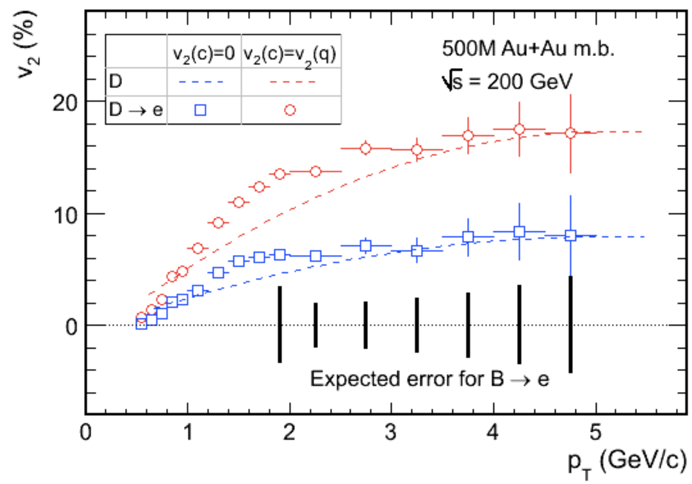


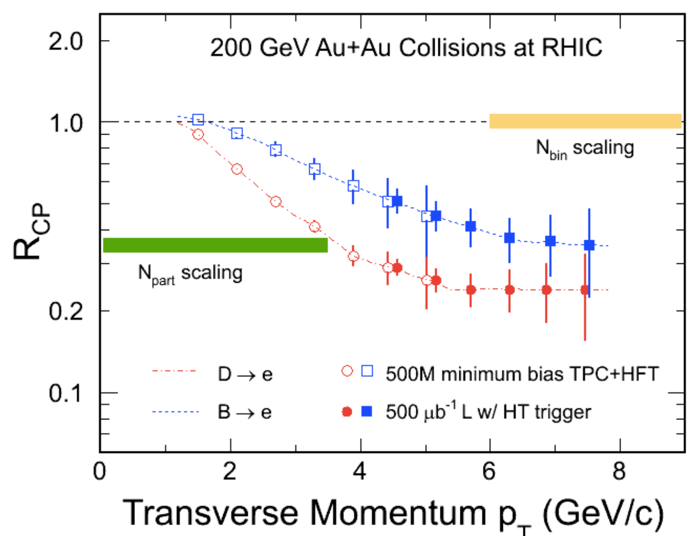
- Good pointing resolution allows to separate primary event vertex from secondary vertex (Fig. left : mean decay vertex of Λ_c)
- Strategy for charmed particle reconstruction : use of topological cuts to remove combinatorial background (Fig. right : decay of D^0)

Physics Goals for HFT

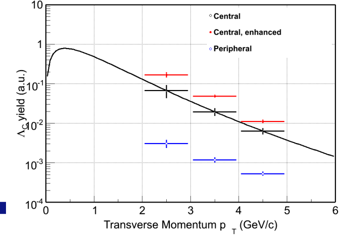


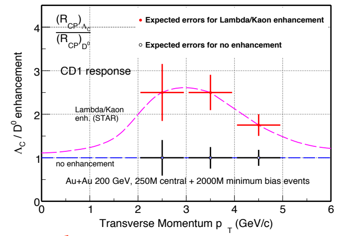


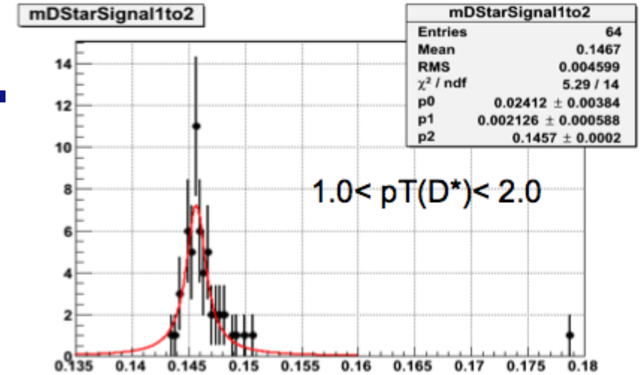


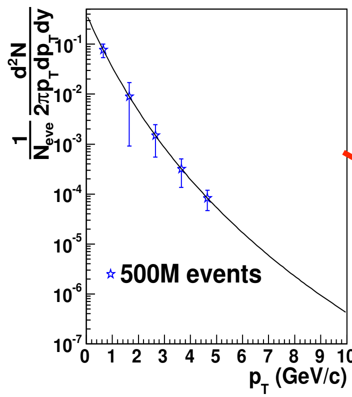


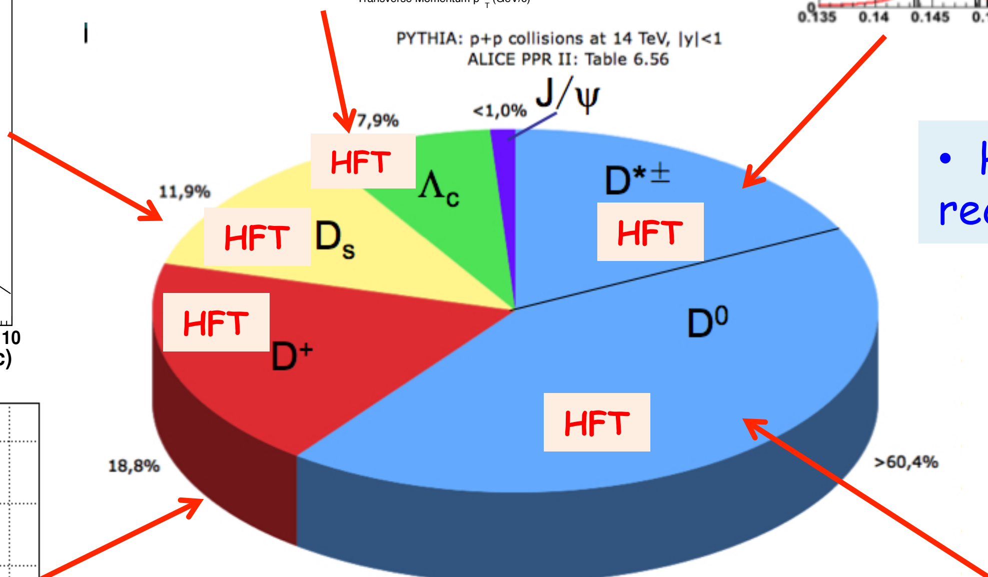
HFT
Charm Capabilities



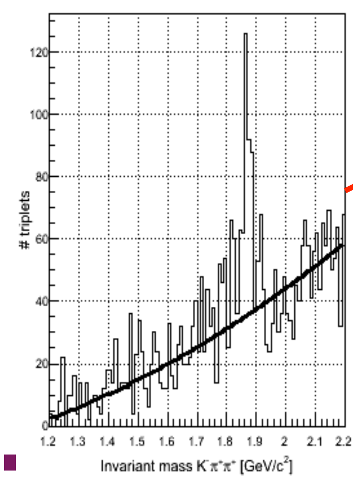


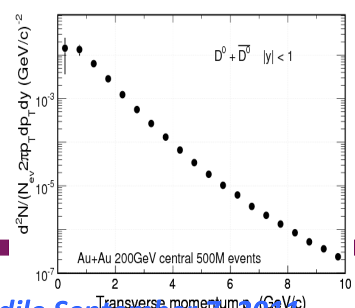


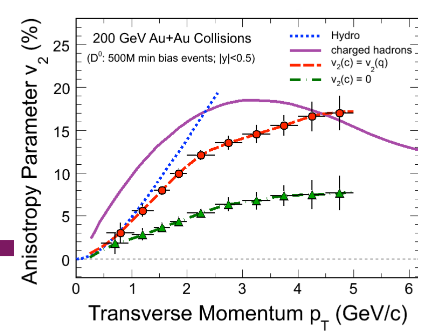


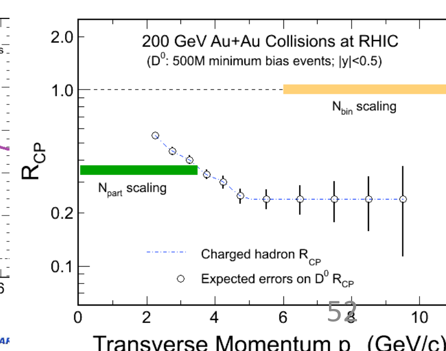


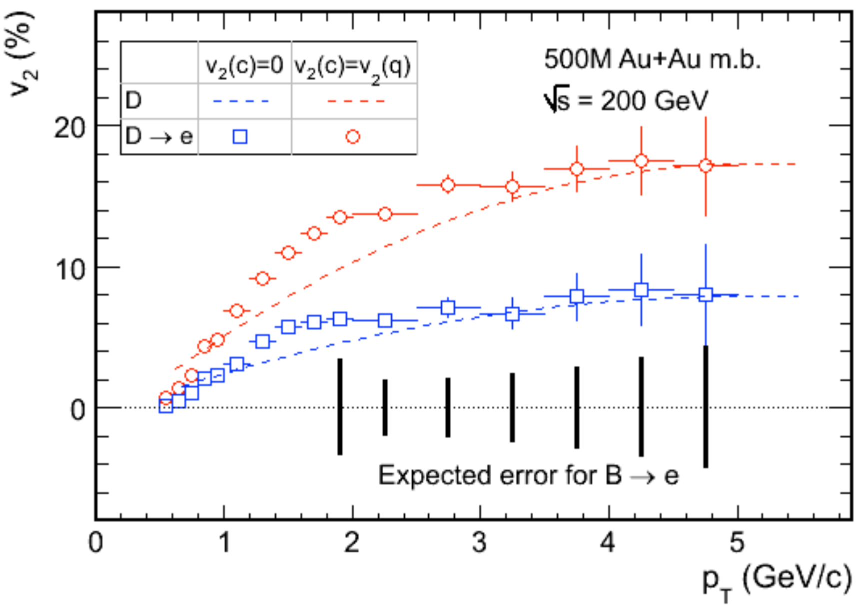
- Hermetic/Full topological reconstruction of Charm



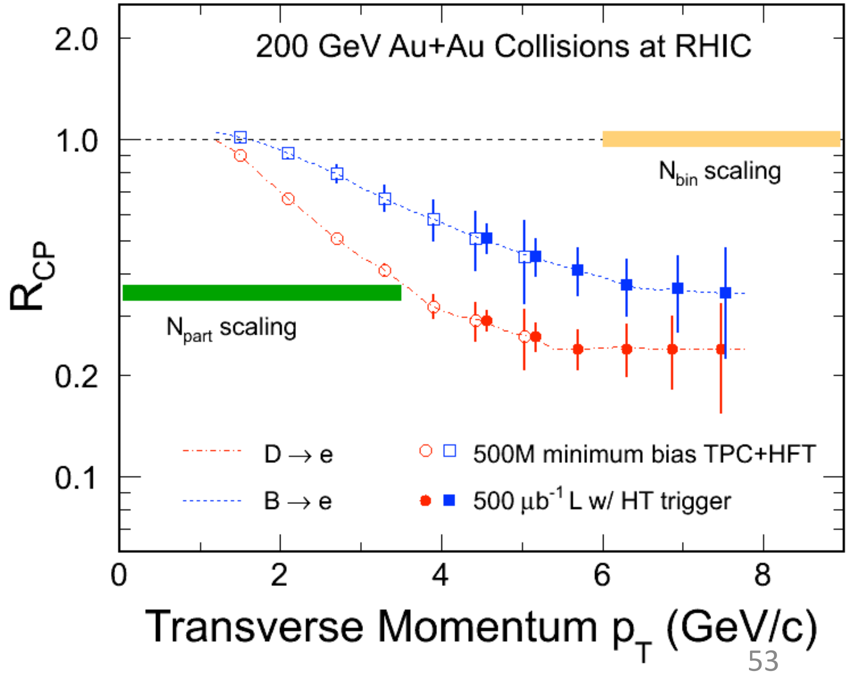






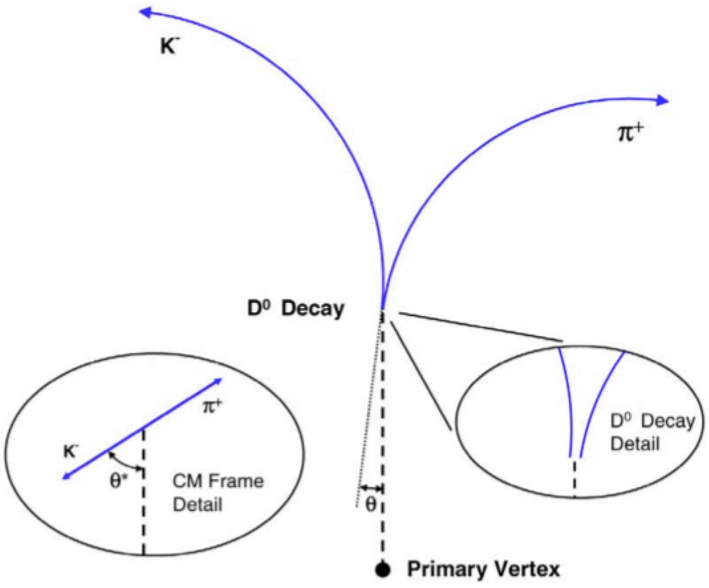


- Bottom electrons via subtraction method
- Bottom trigger capabilities of MTD in progress
  - Exclusive bottom reconstruction

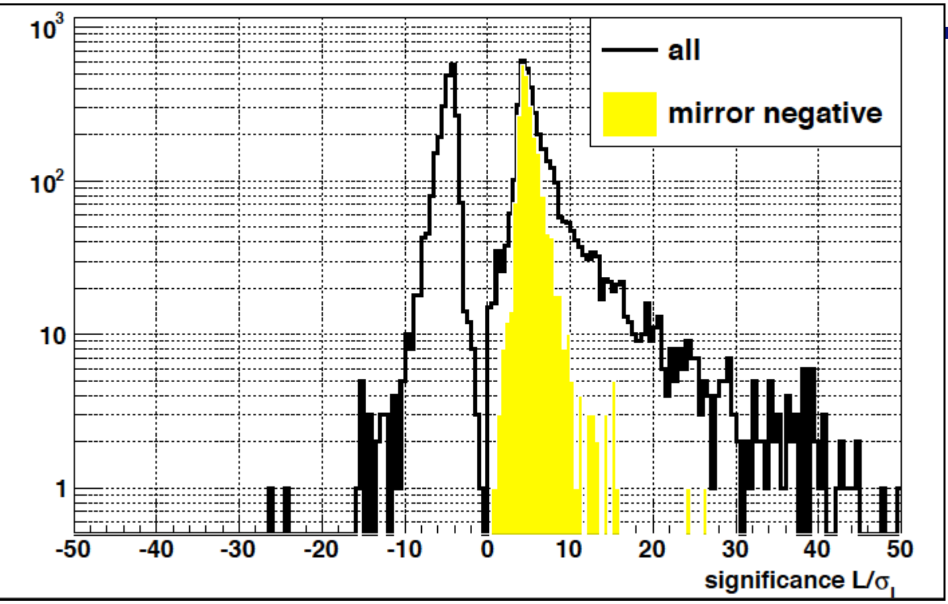


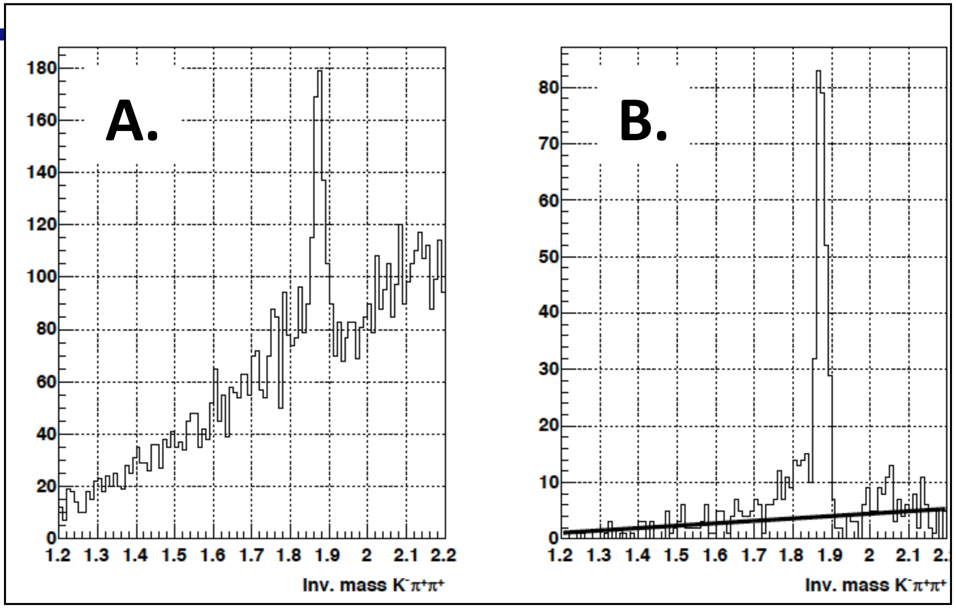
Properties of D and B mesons

Particles	cτ (μm)	Mass (GeV/c^2)	q(c,b) → X FR	X → e BR
D^0	123	1.865	0.54	0.0671
D^+	312	1.869	0.21	0.172
B^0	459	5.279	0.40	0.104
B^+	491	5.279	0.40	0.109



Update on D$^+$ measurement





- Left : decay length significance = decay length /error
  - Real decays have >0 significance, background have < 0 decay length (i.e the secondary vertex is reconstructed before the primary vertex).
- Right :
  - **A.** : invariant mass Kππ before a cut on the decay length significance . A cut based on the daughters to the secondary vertex < **40 μm** removes a lot of background.
  - **B.** invariant mass Kππ after a cut on the decay length significance.
  - → Improvement of the signal/noise ratio.

Physics of the Heavy Flavor Tracker at STAR

1) 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

2) Physics

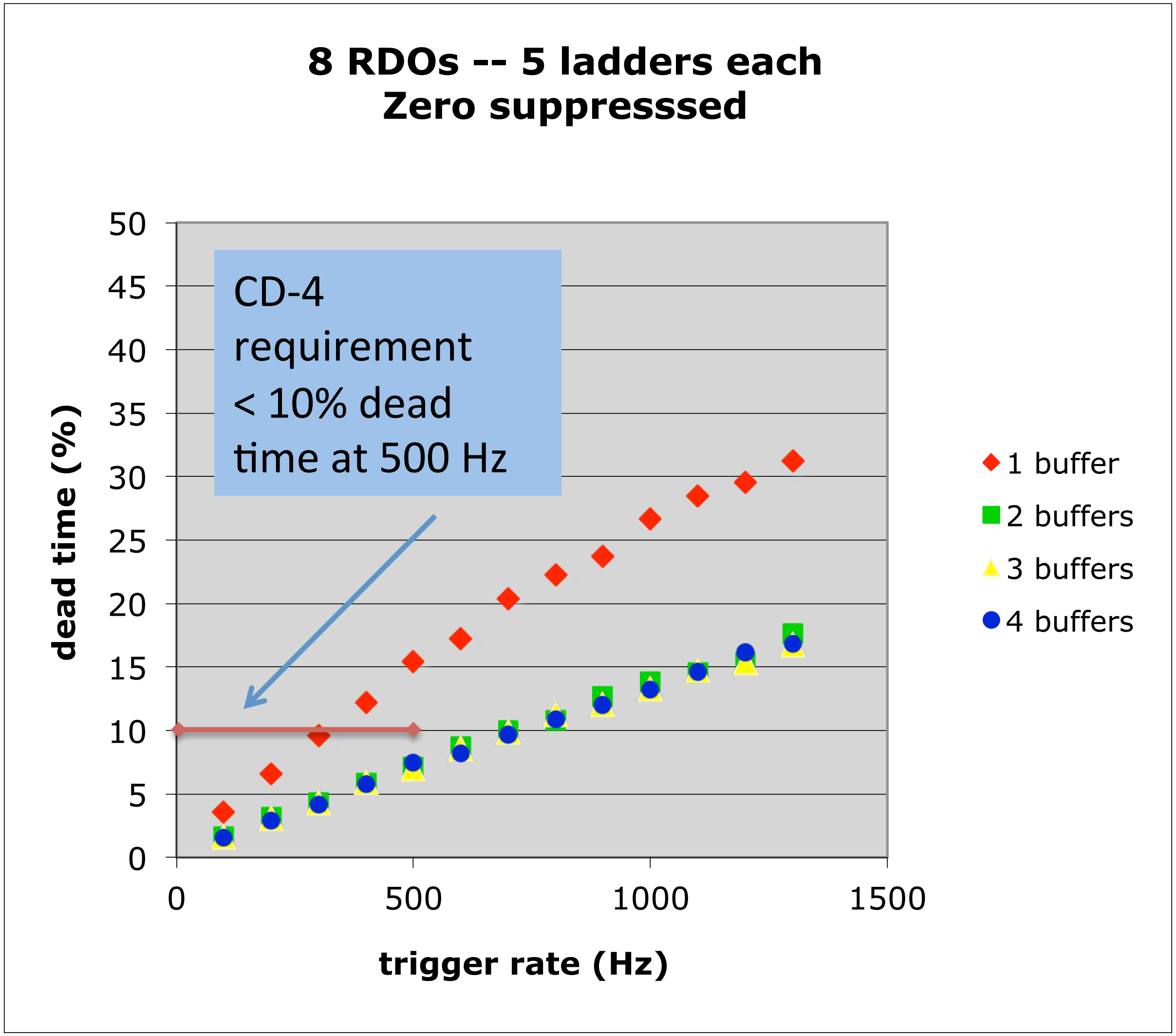
(1) Measure heavy-quark hadron v_2, heavy-quark collectivity, to study the medium properties ***e.g. light-quark thermalization***

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

(3) Measure di-leptons to study the ***direct radiation*** from the hot/dense medium

(4) Analyze ***hadro-chemistry including heavy flavors***

SSD Requirements on Dead time



- Dead-time as a function of random trigger rate
  - Simulated performance with 3% occupancy
- The SSD will have 4 buffers as part of the firmware
- Multiple buffers hide the downstream DAQ from the dead-time of the system for randomly arriving triggers