The STAR Heavy Flavor Tracker

An Introduction and Brief Review of the Physics Goals at Mid-rapidity plus comments on tracking in a high multiplicity environment

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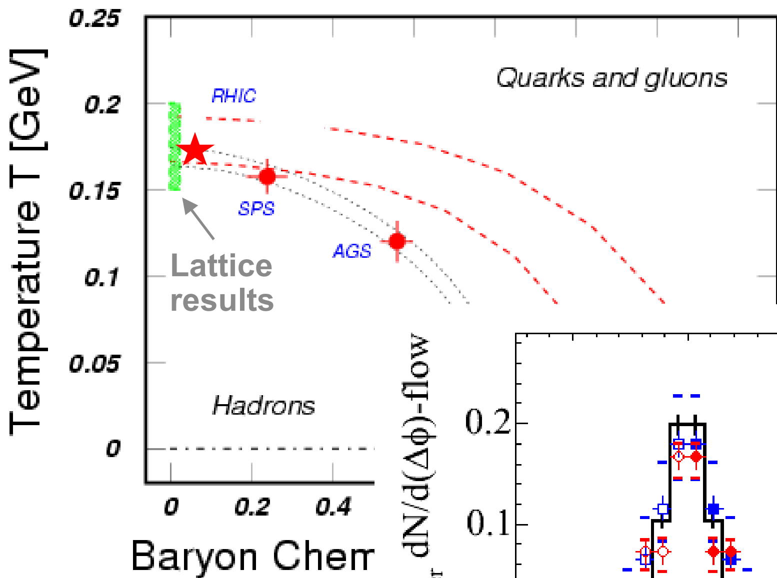
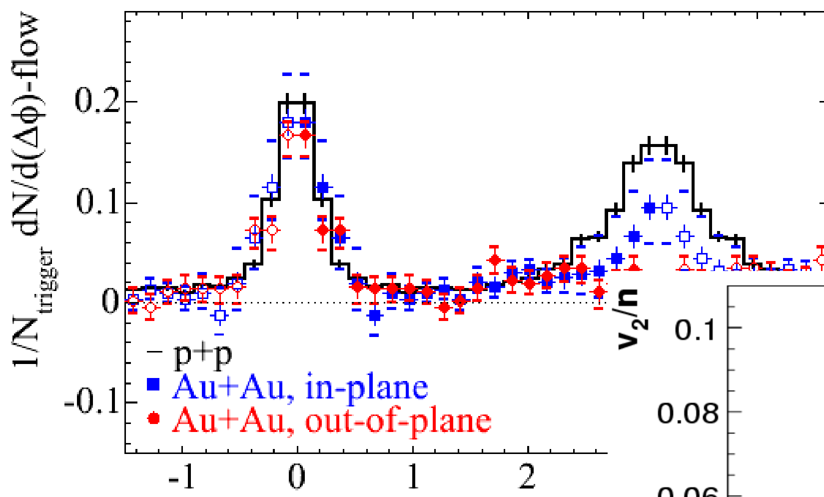
May 29th, 2011

The Light Quark Program at RHIC is Compelling





Its hot

Spectra

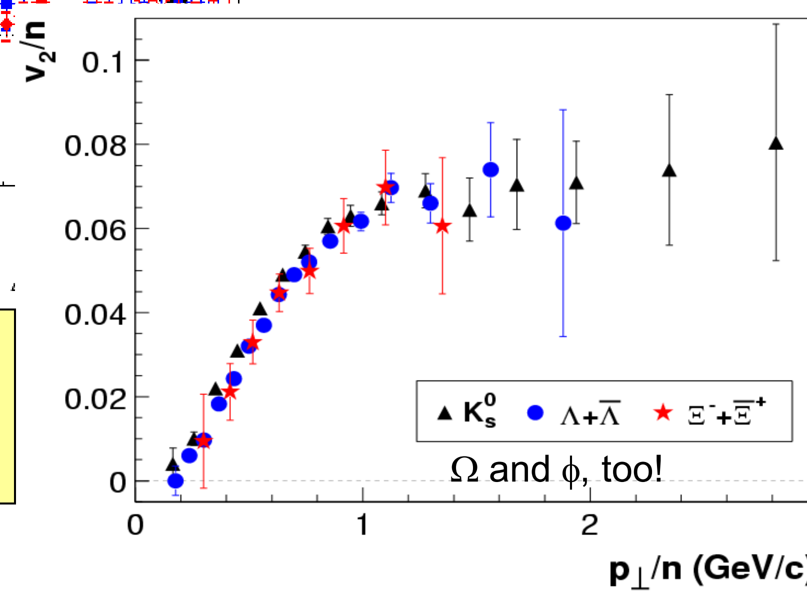
Its dense

Jets & R_{cp}

and it flows

at the partonic scale

V_n



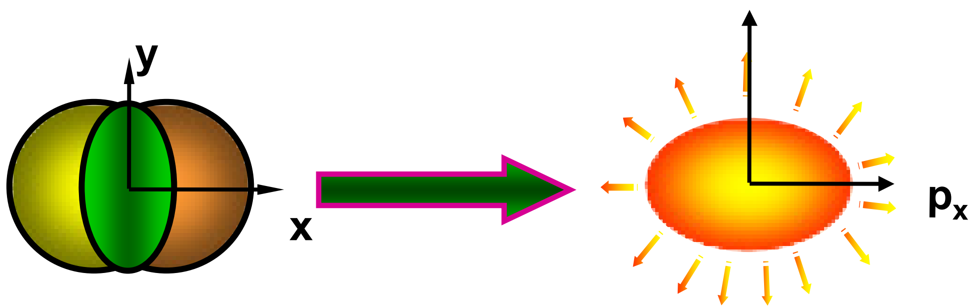
The evidence for a low viscosity, strongly interacting QGP is overwhelming, especially after QM 2011 (v_3, v_n wow …!!)

Flow: Probing Thermalization of the Medium

Semiperipheral collisions

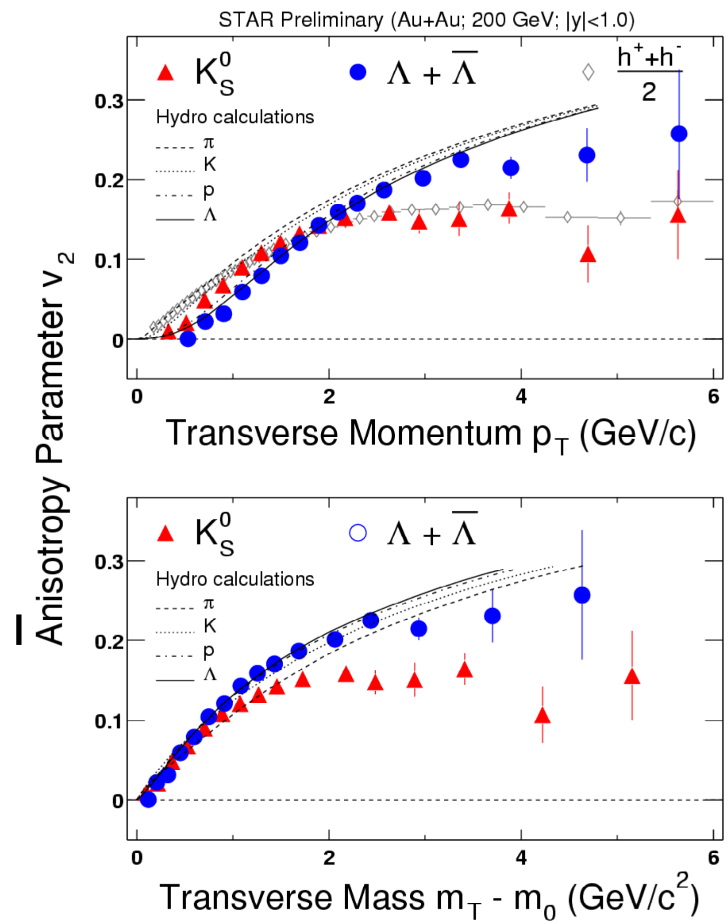
Coordinate space: initial asymmetry

Momentum space: final asymmetry



$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

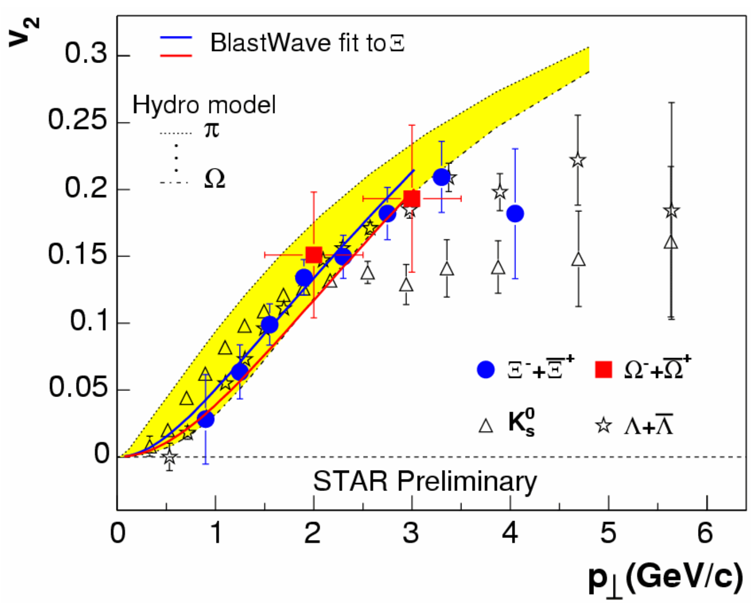
Signals early equilibration ($t_{eq} \leq$ 0.6 fm/c)

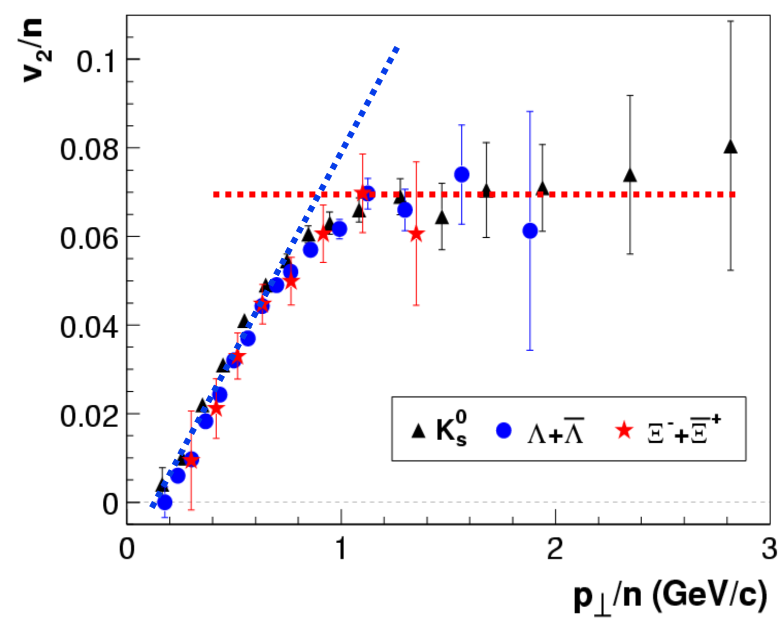


Flow: Constituent Quark Number Scaling

In the recombination regime, meson and baryon v_2 can be obtained from the quark v_2 :

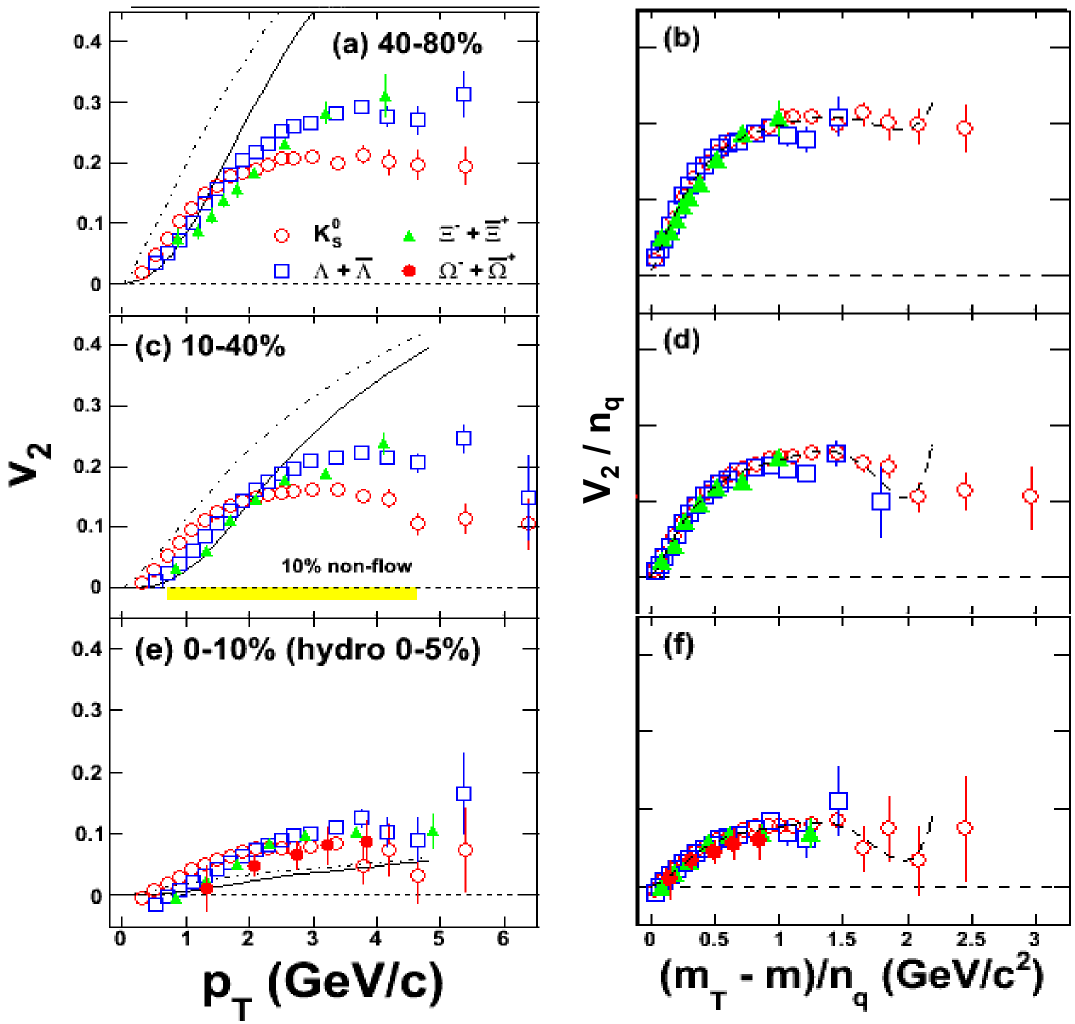
$$v_2^M(p_t) = 2v_2^q\left(\frac{p_t}{2}\right) \qquad v_2^B(p_t) = 3v_2^q\left(\frac{p_t}{3}\right)$$





Scaling as a Function of $(m_T - m_0)$

STAR Preliminary work by Yan Lu



Yuting Bai, QM 2006 for the STAR Collaboration

- The light quark sector scales beautifully with v_2/n_q .vs. $(m_T - m_0)/n_q$
  - Note that $p_T < 1$ GeV always did scale !
- The strange quark sector also scales with $<v^2>$ and the scaling holds at all centralities
- Even the ϕ meson

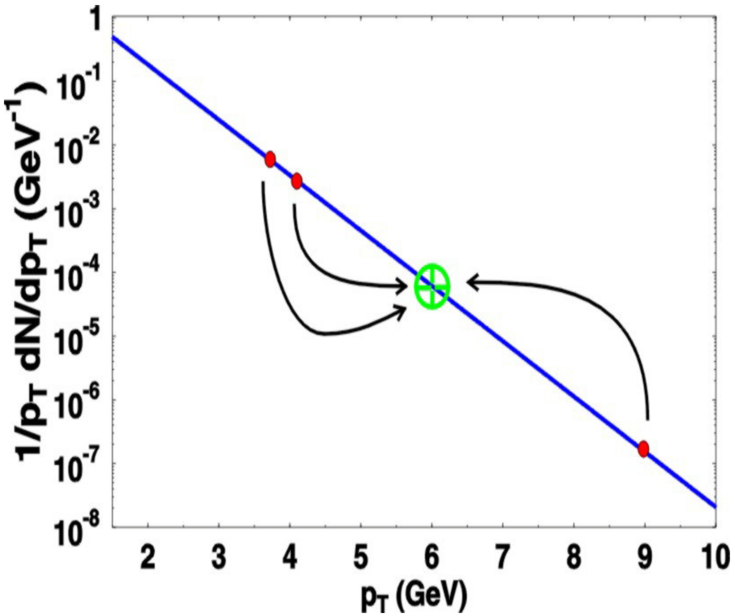
Does it work in the Charm Sector?

A strong test of the theory

Baryons vs. mesons

- Coalescence and fragmentation conspire at intermediate p_T to give constituent quark number scaling and Baryon-Meson differences.

- Coalescence and fragmentation of charm quarks is different than for light quarks … so it is a strong test of the theory



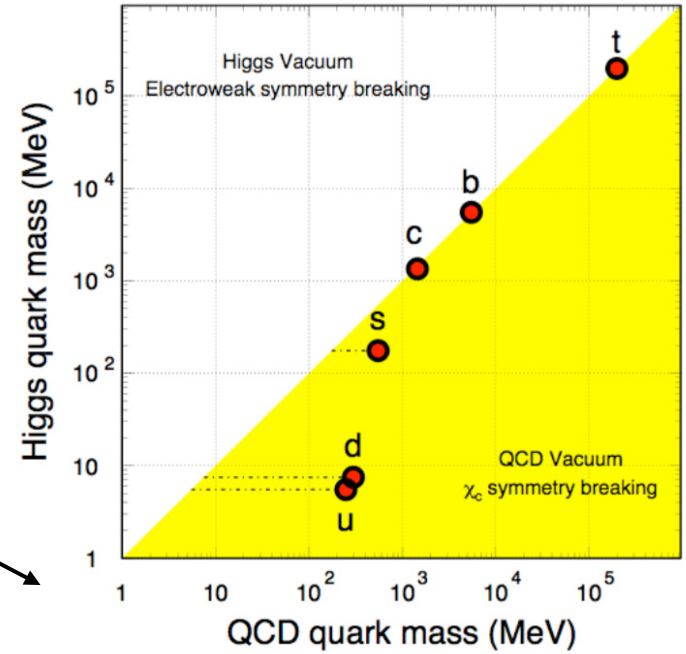
- Coalescence of light quarks implies deconfinement and thermalization prior to hadronization
- How do baryons and mesons behave in the Charm sector?
- The Λ_c will be a fascinating test … and we might be able to do it with the HFT via Λ_c / D

"Heavy Flavor" is the next frontier at RHIC

- **A low viscosity, sQGP is the universally accepted hypothesis**
- **The next step in confirming this hypothesis is the proof of thermalization of the light quarks in RHIC collisions**
- **The key element in proving this assertion is to observe the flow of charm … because charm and beauty are unique in their mass structure**

Current quark: a bare quark whose mass is due to electroweak symmetry breaking

Constituent quark: a bare quark that has been dressed by fluctuations in the QCD sea

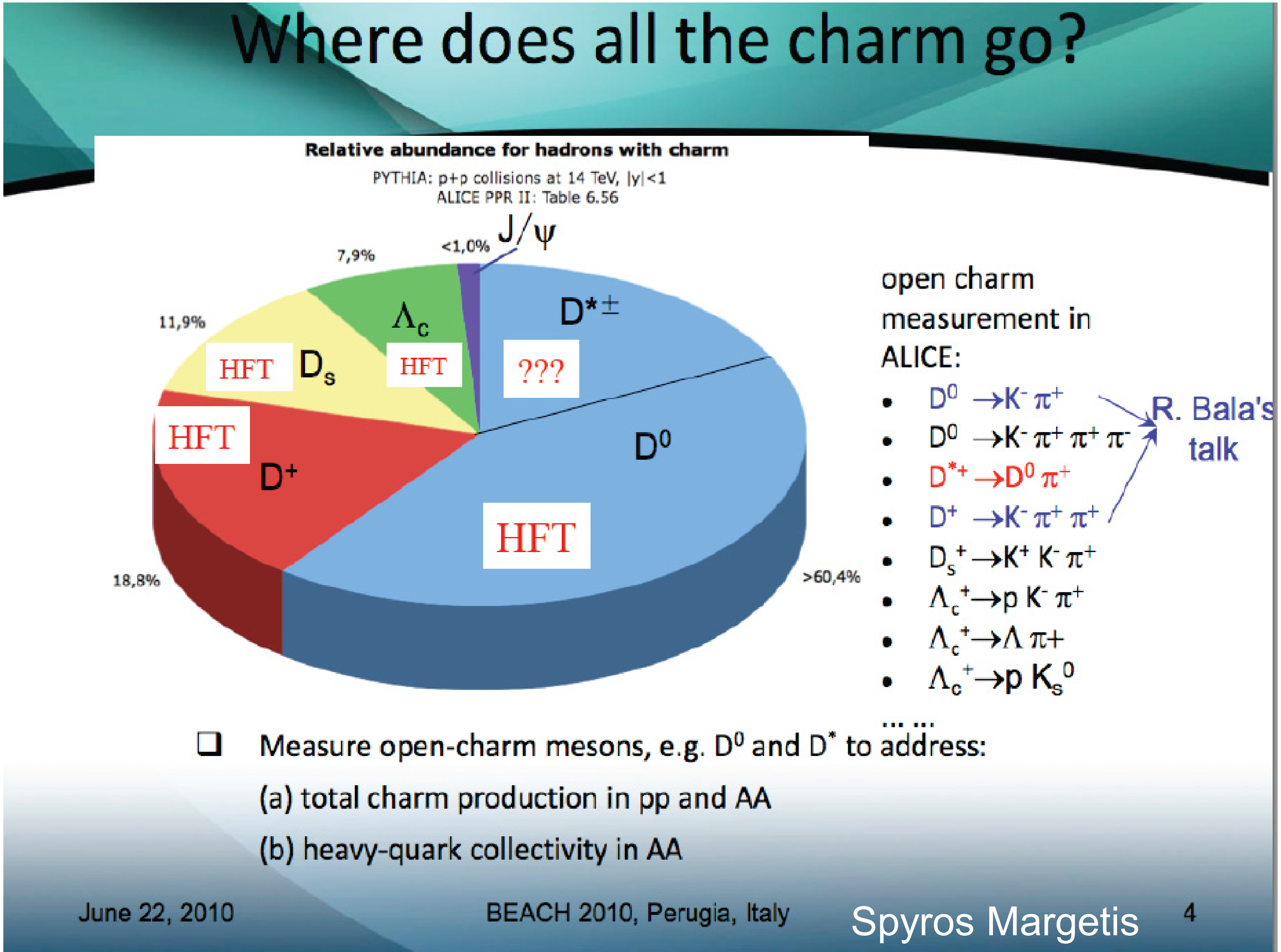


- **If heavy quarks flow**
  - **frequent interactions among all quarks**
  - **light quarks (u,d,s) likely to be thermalized**

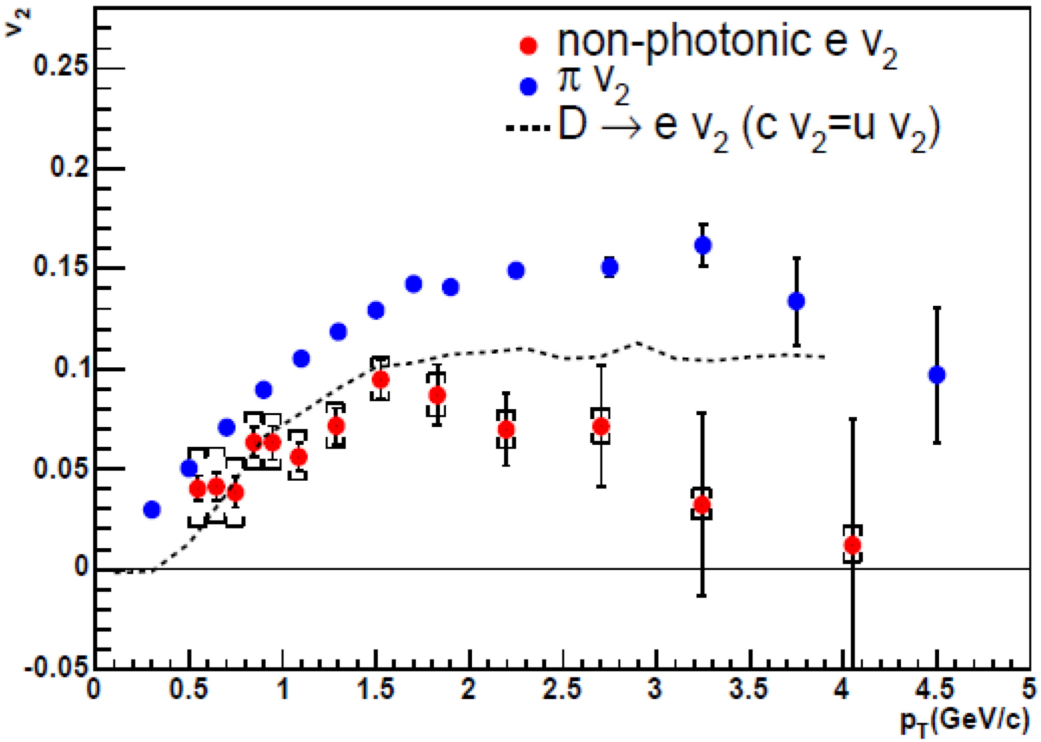
Opening the Heavy Flavor Sector

- When RHIC turned on … Strange quarks were "heavy and exotic"
  - We built a Si vertex tracker to locate strange mesons and baryons
  - This turned out to be too easy to do with the TPC, alone
    - Kaons, Lambdas, Omegas, Phi and even the Cascade
    - Cross sections, Flow, R_{aa} and more
- Now we want to re-define "heavy and exotic" and go after the Charm quark
  - Some success already with non-photonic electrons (leptonic and semi-leptonic decays)
  - Topological reconstruction of open Charm is better. Requires a new high resolution Si detector.
- Of course, at the LHC the definition of "heavy and exotic" is quite different. The yield of charmed mesons is greatly enhanced and so they are not exotic. B decays may be "rare and exotic" for ALICE … but maybe not. $\sqrt{s}$ can do magical things ….
  - Note that some success with Upsilon's at RHIC. Upsilon suppression reported by STAR at QM 2011 using non-photonic electrons.

The Question for STAR



Hints of Elliptic Flow with Charm



Shingo Sakai, QM 2006 for the PHENIX Collaboration

Better if we can do direct topological identification of Charm

- **D → e +X**

  Single electron spectra from PHENIX show hints of elliptic flow

  Is it charm or beauty?

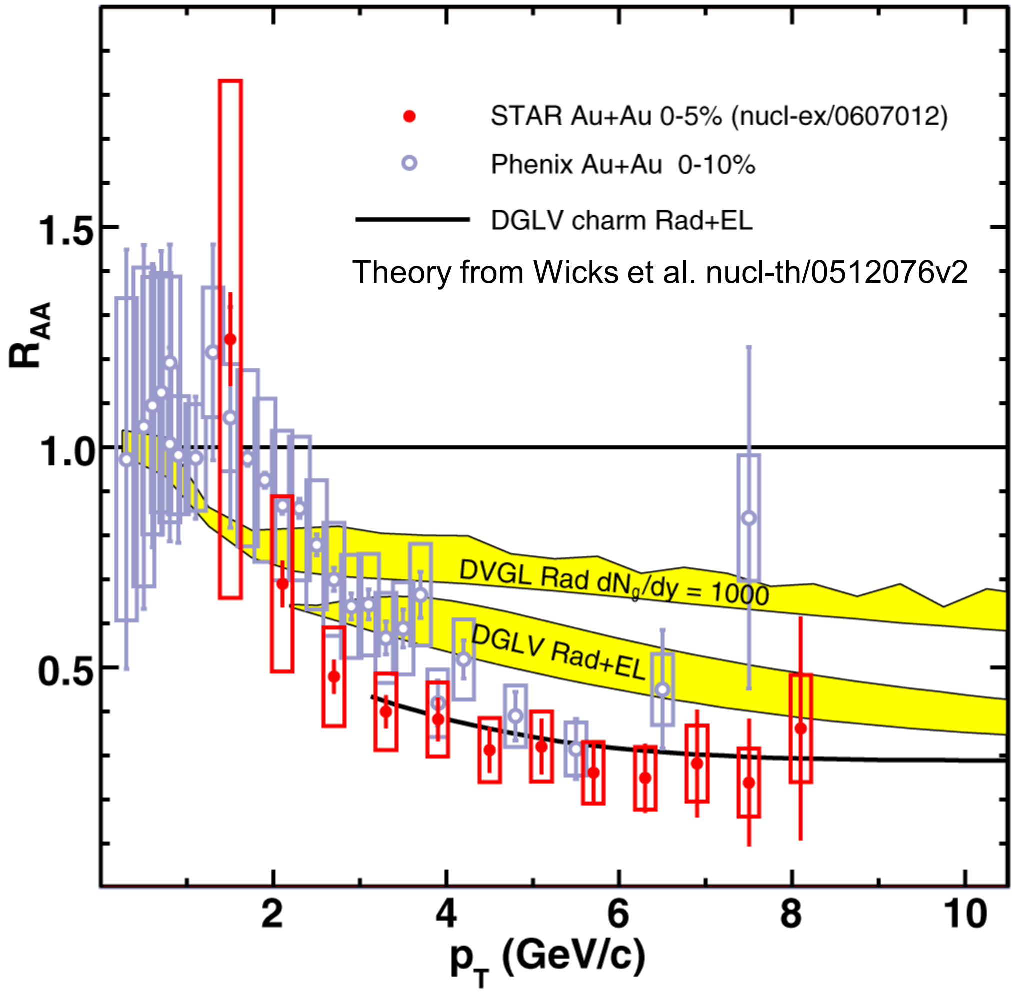
- **The HFT will cut out large photonic backgrounds:**

  $\gamma \rightarrow e^+e^-$

  and reduce other large stat. and systematic uncertainties

- **STAR can make this measurement with 50 M Au+Au events in the HFT**
- **Smoking gun for thermalization at RHIC!**

Heavy Flavor Energy Loss … R_{AA} for Charm



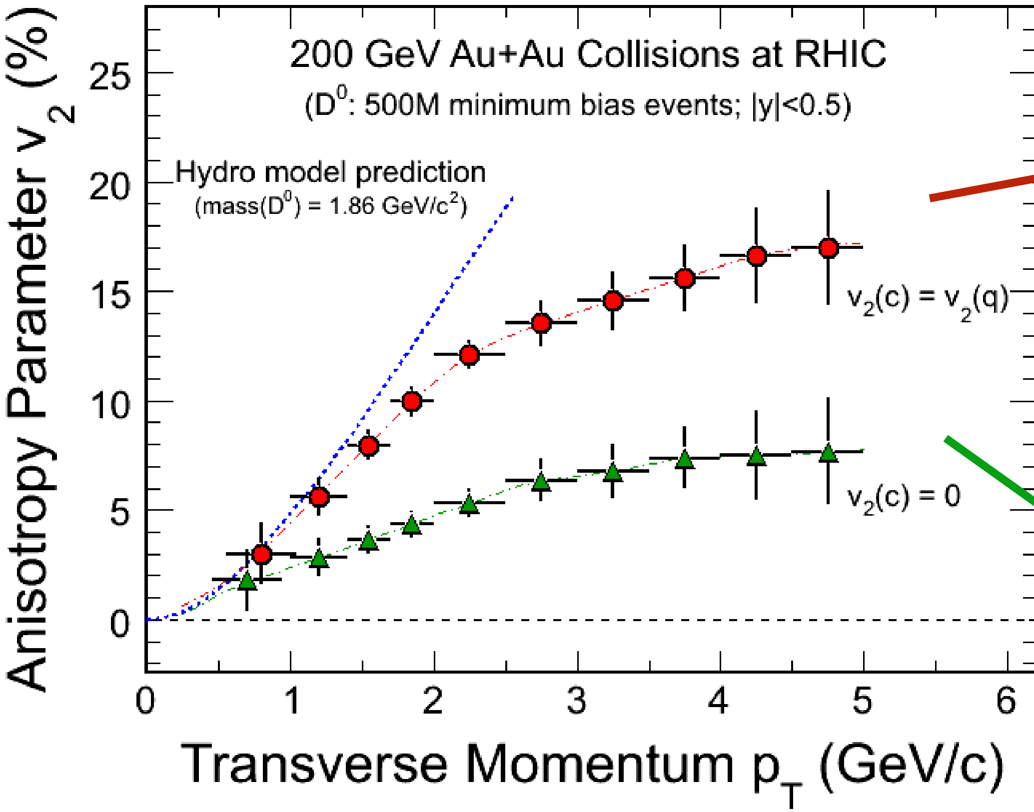
Where is the contribution from Beauty?

- **Heavy Flavor energy loss is an unsolved problem**
  - **Gluon density ~ 1000 expected from light quark data**
  - **Better agreement with the addition of inelastic E loss**
  - **Good agreement only if they ignore Beauty …**
- **Beauty dominates single electron spectra above 5 GeV**
- **We can separate the Charm and Beauty by the direct topological identification of Charm**

The HFT – Signature Physics Measurements

Charmed Hadron v_2

using 200 GeV Au+Au minimum bias collisions (500M events)



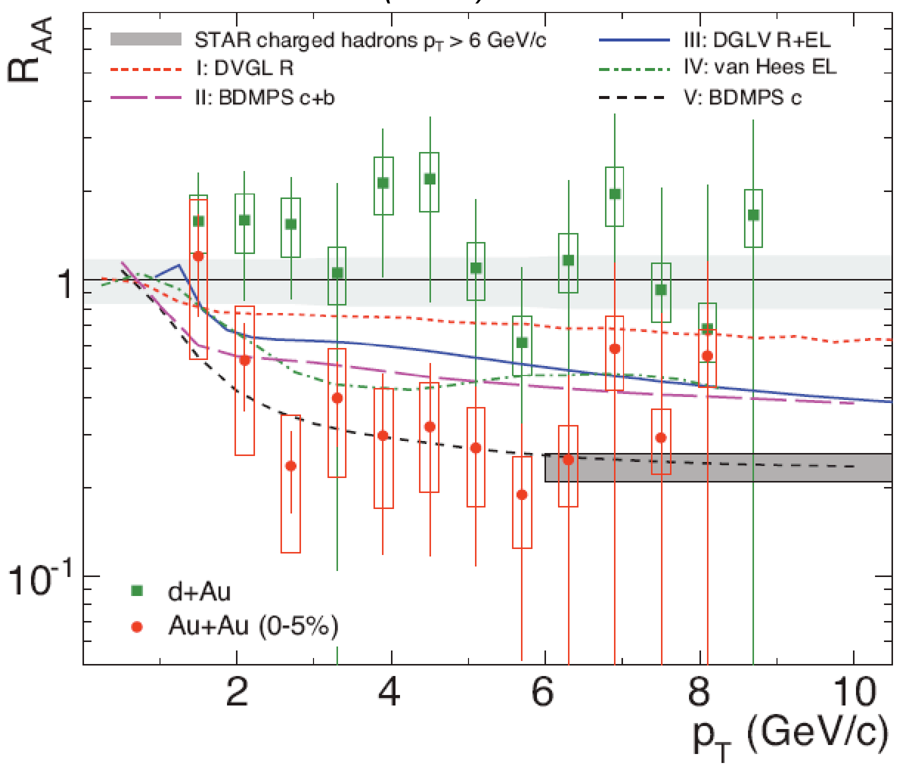
Charm-quark flow
→ Thermalization of light-quarks

Charm-quark does not flow
→ Drag coefficients

DOE milestone for 2016: "Measure production rates, high pT spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the QGP."

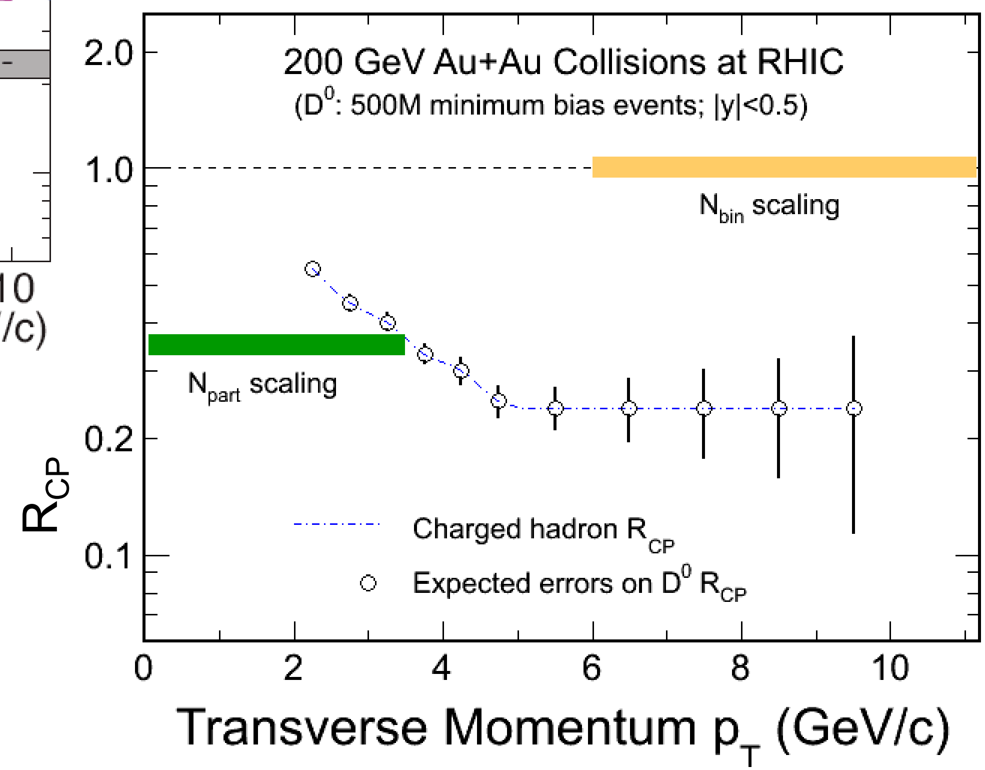
The HFT – Heavy Quark Energy Loss

STAR PRL 98 (2007) 192301 and Erratum

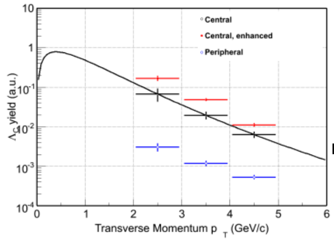


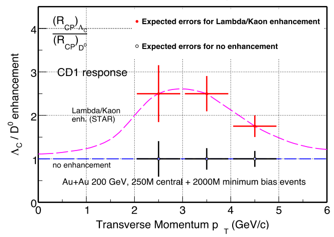
- Non-photonic electrons decayed from charm **and** beauty hadrons
- At $p_T \geq 6$ GeV/c, R_{AA}(n.p.e.) ~ $R_{AA}(h^{\pm})$
- A surprising result

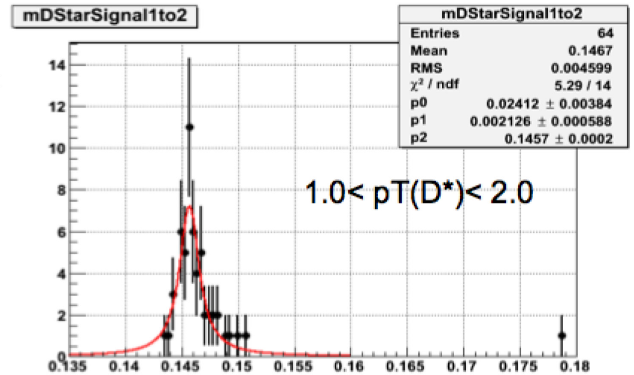
- **Here is what we can do with the HFT using topological ID of open charm**



HFT Charm







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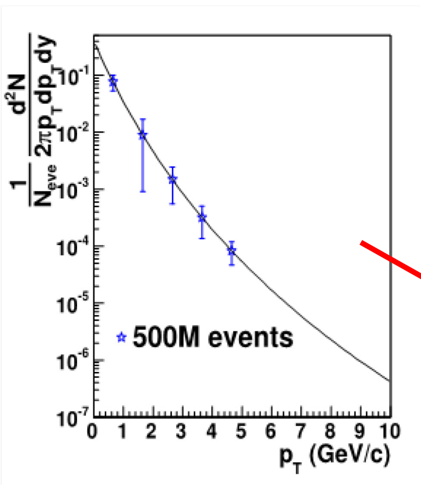
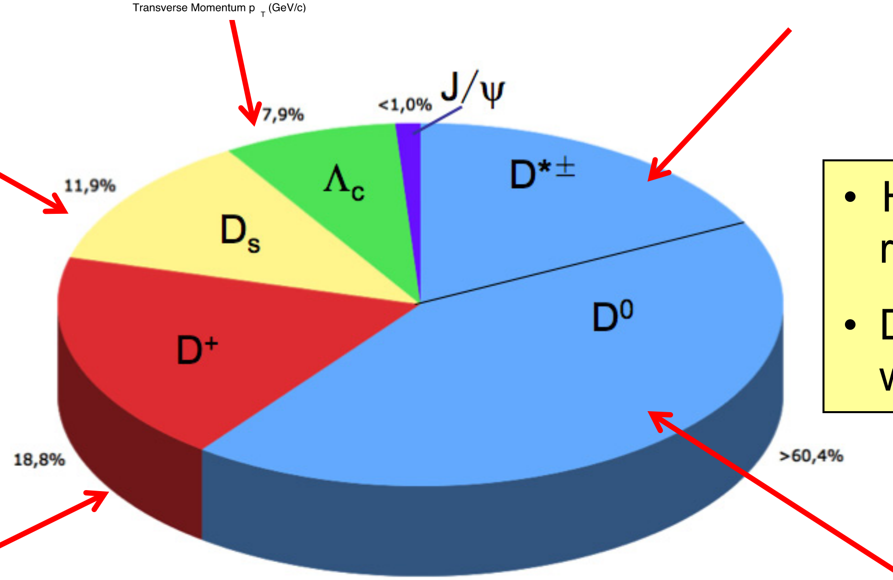
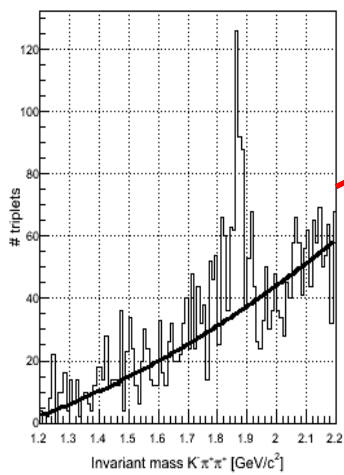
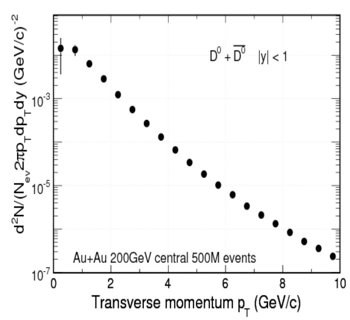
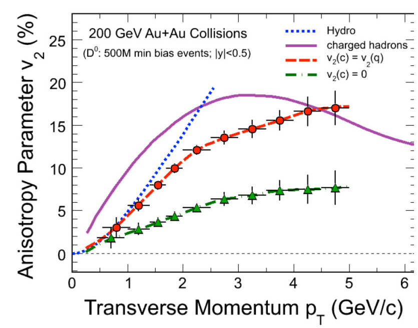


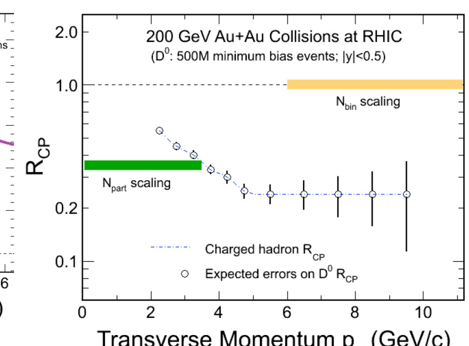


- Hermetic/Full topological reconstruction of Charm
- Detailed flow, R_{AA} studies with identified charm





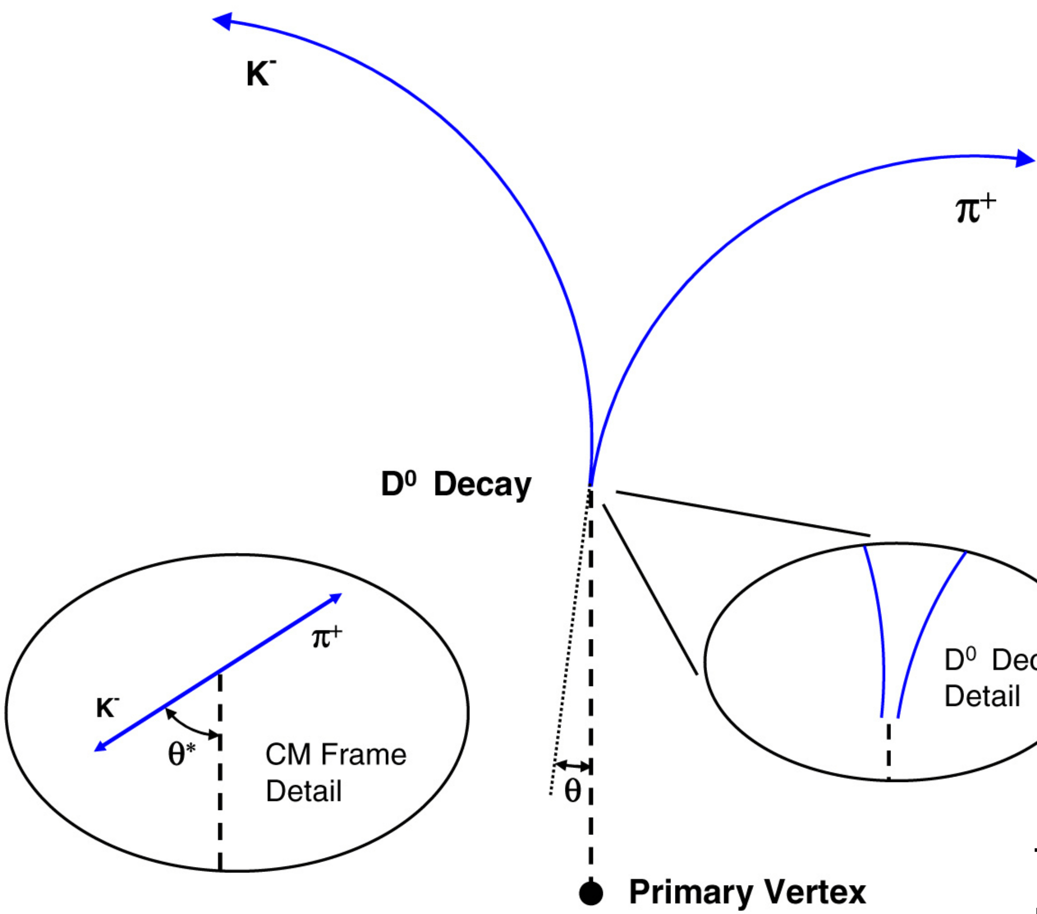




A Rich Physics Program

- **There is a rich physics program when all of the STAR physics detectors are working together**
  - **Flow in the Charm sector**
  - **dE/dx in the Charm sector**
  - **Recombination and R_{AA} in the Charm sector**
  - **Vector Mesons**
  - **Charm Angular Correlations**
  - **non-photonic electrons**
  - **…**

The HFT: The Challenge



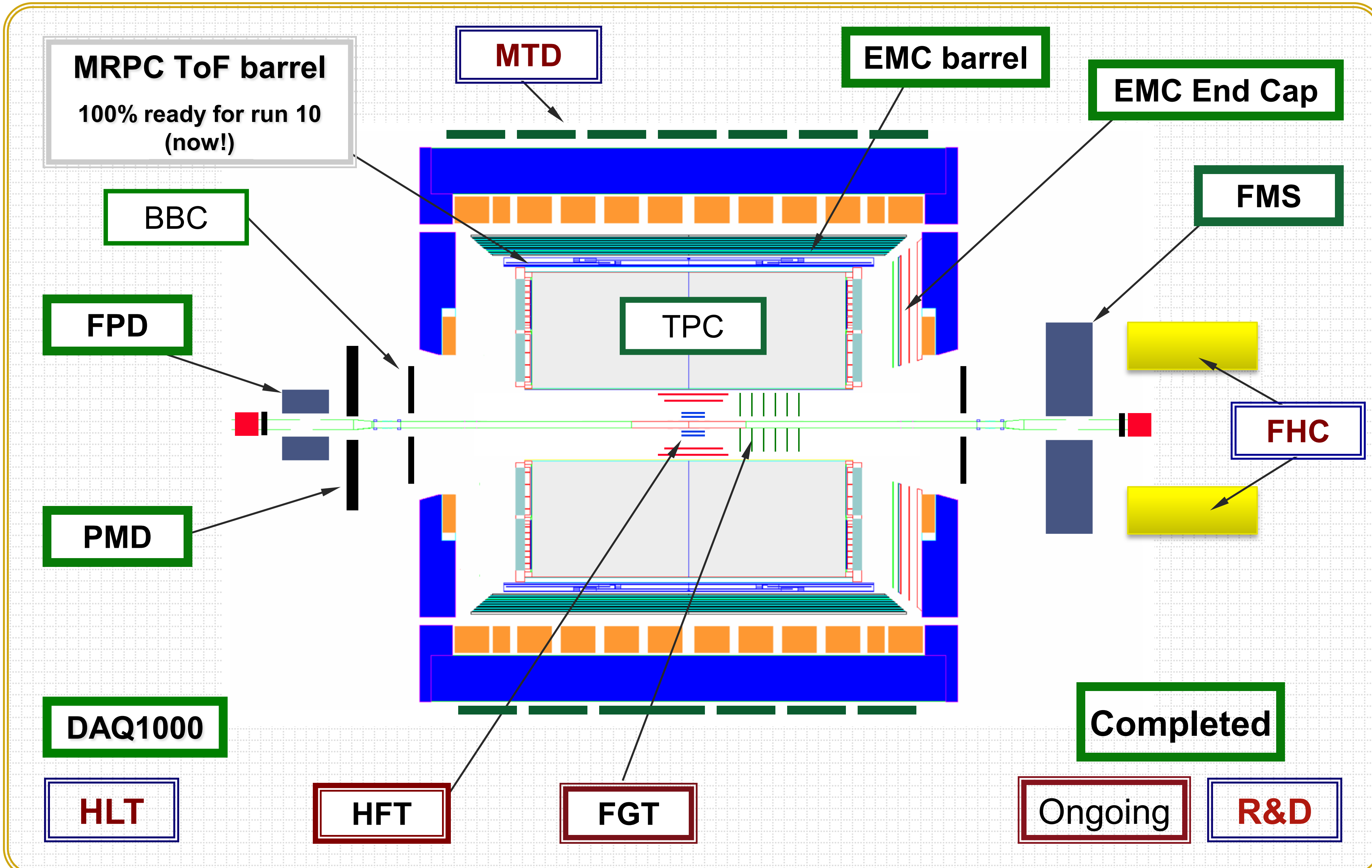
- **Primary Challenges**
  - **Neutral particle decay**
  - **Proper lifetime, cτ, 123 μm**
  - **Find a common vertex away from the primary vertex**
  - **Identify daughters, measure p_T, and reconstruct the invariant mass**

The STAR HFT has the capability to reconstruct the displaced vertex of

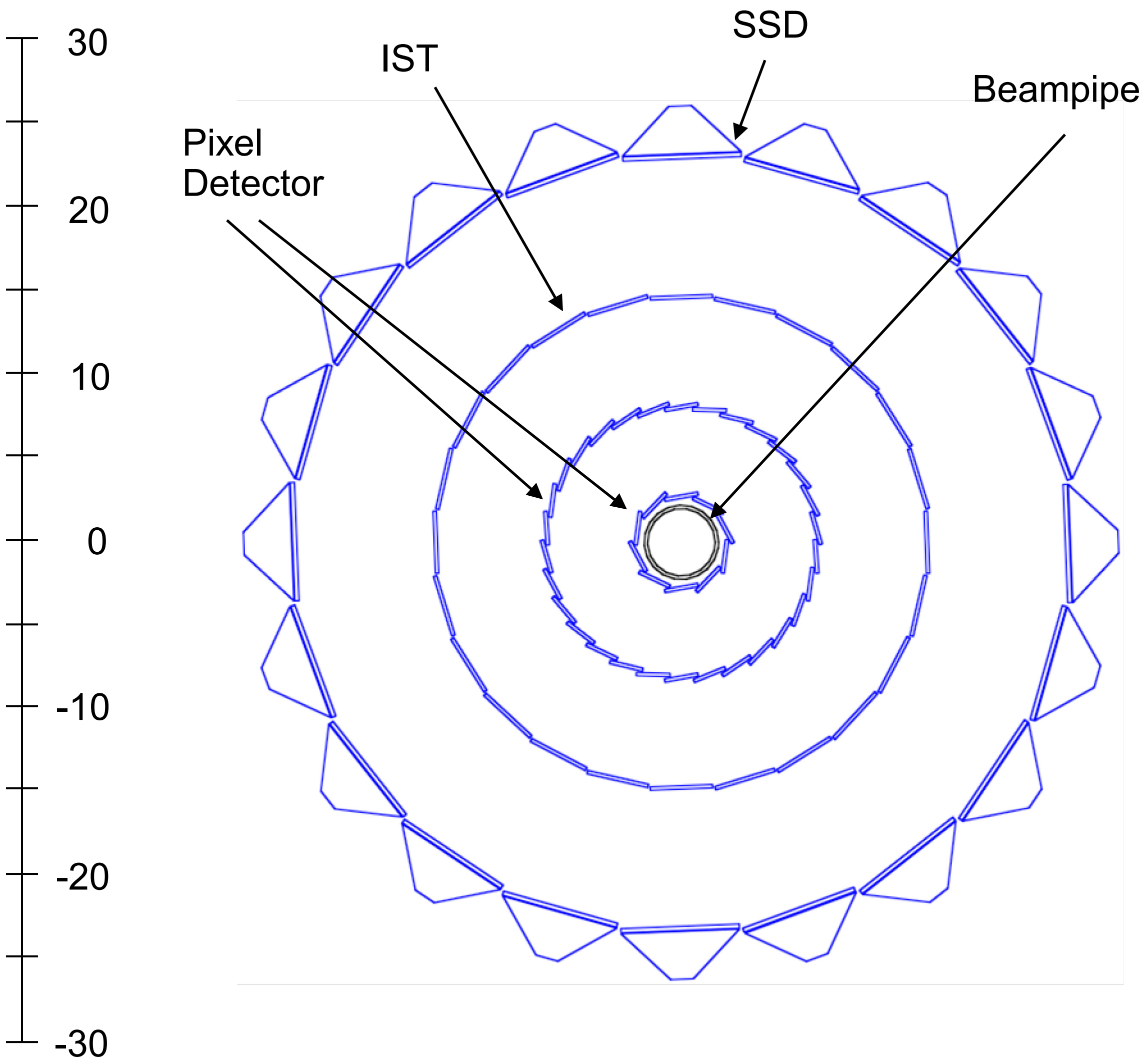
D^0 → Kπ (B.R 3.8%, cτ = 123 μm)
Λ_c → πKp (B. R. 5.0%, cτ = 59.9 μm)
and more …

Topological Reconstruction of Open Charm

The STAR Detector

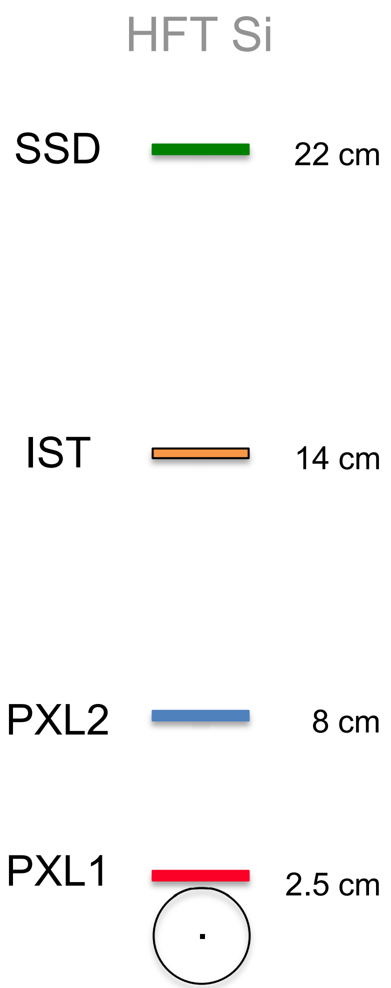


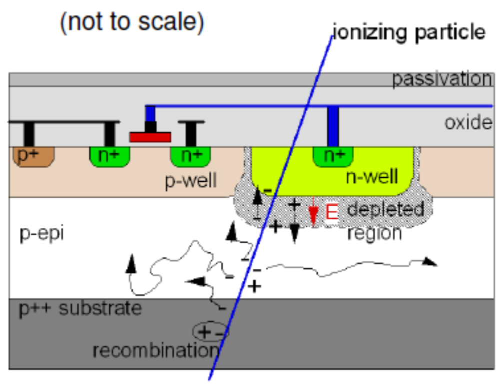
The HFT – The configuration



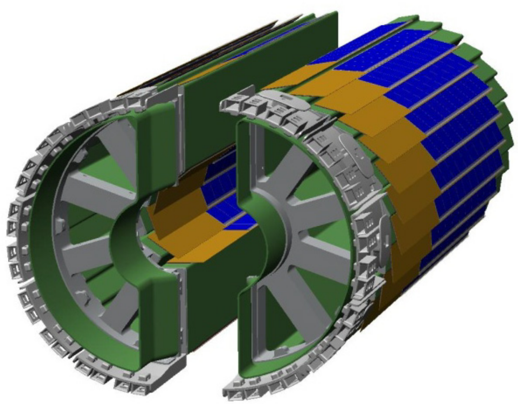
- The HFT puts 4 layers of Silicon around the vertex
- Provides 8 μm space point resolution @ 2.5 cm
- 30 μm vertex resolution @ 1 GeV, 10 μm @ 5 GeV
- Works at high rate (~ 800 Hz – 1K)
- Does topological reconstruction of open charm
- Will be ready for the 2014 run

The HFT – Pixel Technology





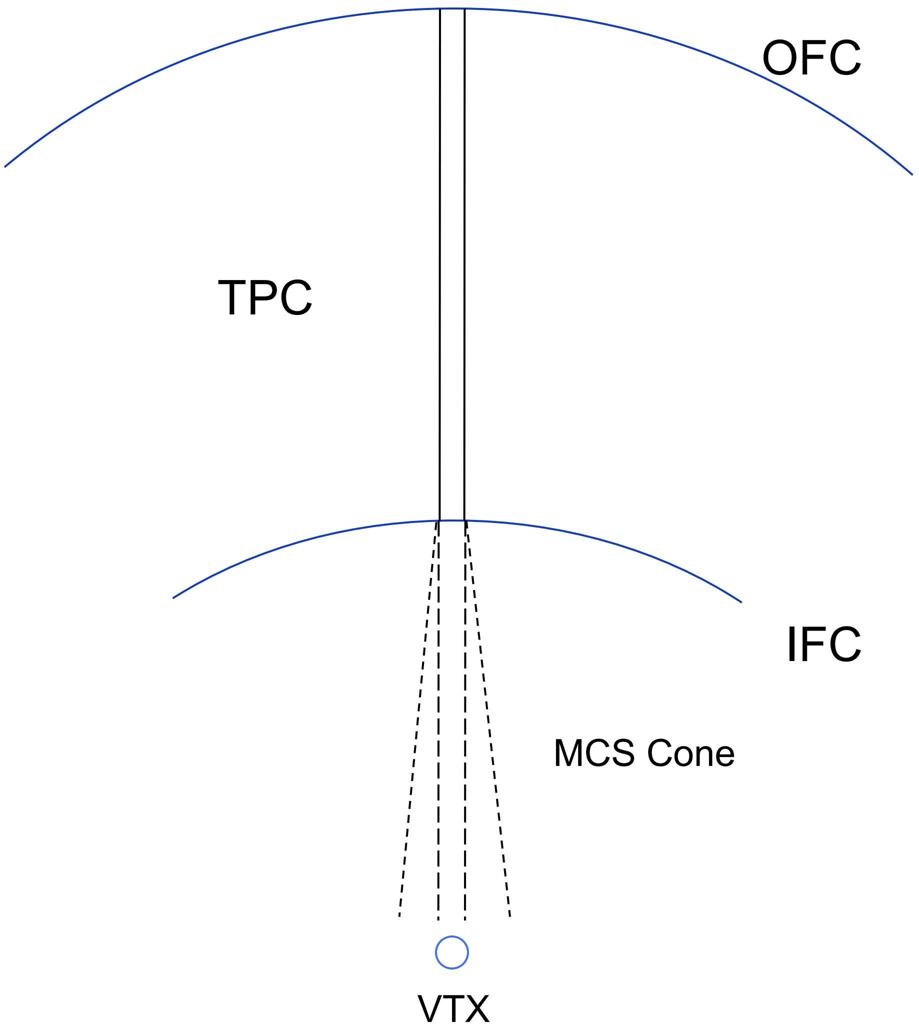
Now using high resistivity Si which allows for a biased depletion region (previously relied upon diffusion to collect the charge)



- **Unique Features**
  - **20.7 x 20.7 μm pixels**
  - **100-200 μsec integration time**
  - **436 M pixels**
  - **0.37% X/X_0 per layer**
  - **Install and Replace in 8 hours**
- **News**
  - **Change in process: now using HighResistivity Si**
  - **Better signal to noise and higher radiation tolerance >300 kRad**
  - **Don't have to replace the detector every year**

Tracking: Getting a Boost from the TPC

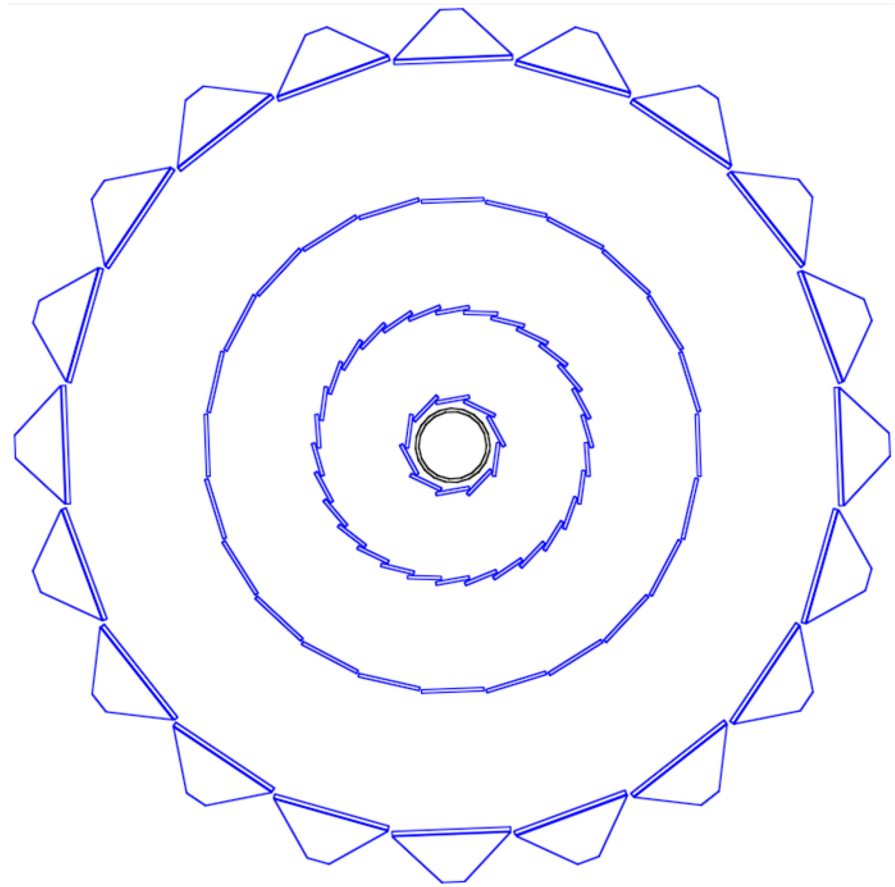
- **The TPC provides good but not excellent resolution at the vertex and at other intermediate radii**
  - ~ 1 mm
- **The TPC provides an excellent angular constraint on the path of a predicted track segment**
  - This is very powerful.
  - It gives a parallel beam with the addition of MCS from the IFC
- **The best thing we can do is to put a pin-hole in front of the parallel beam track from the TPC**
  - This is the goal for the Si trackers: SSD, IST, and PXL
- **The SSD and IST do not need extreme resolution. Instead, the goal is to maintain the parallel beam and not let it spread out**
  - MCS limited
  - The PXL does the rest of the work



The Gift of the TPC

Overview & Goals for Si Detectors Inside the TPC

- Goal: graded resolution and high efficiency from the outside → in
- TPC – SSD – IST – PXL
- TPC pointing resolution at the SSD is ~ 1 mm
- SSD pointing at the IST is ~ 400 μm (200 x 800)
- IST pointing at PXL 2 is ~ 400 μm (200 x 800)
- PXL 2 pointing at PXL1 is ~ 125 μm (90 x 175)
- PXL1 pointing at the VTX is ~ 40 μm (Kaon at 750 MeV)

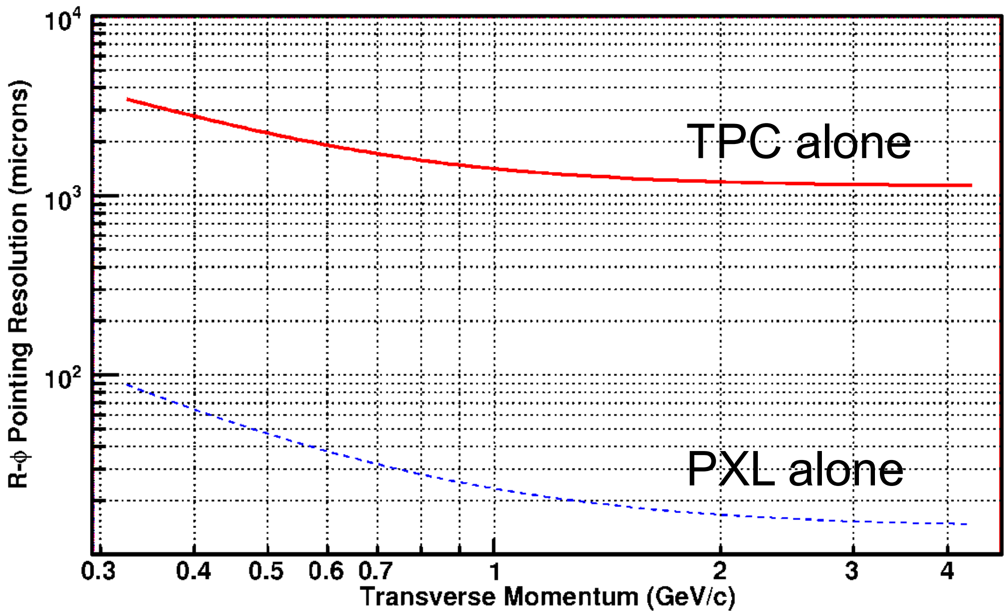


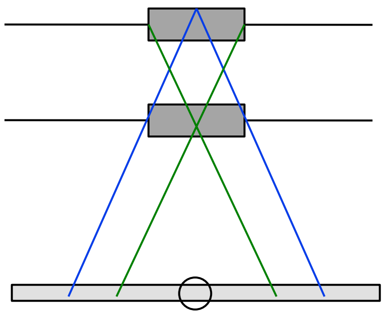
~ 50 cm

The challenge is to find tracks in a high density environment with <u>high</u> <u>efficiency</u> because a D^0 needs single track ε^2

The Simplest 'Simulation' – basic performance check

- **Study the last two layers of the system with basic telescope equations with MCS**
  - **PXL 1 and PXL 2 alone (no beam pipe)**
  - **Give them 9 μm resolution**



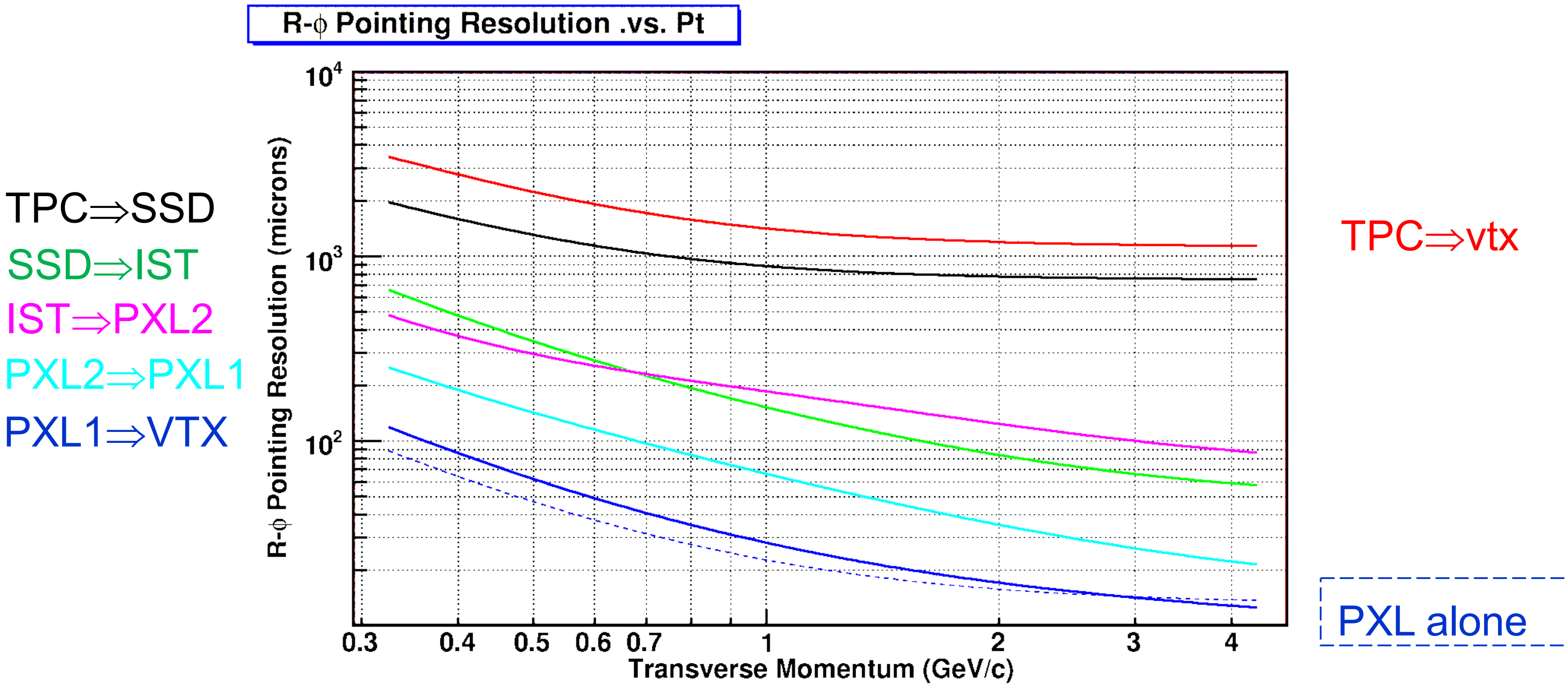


$$\sigma^2 = \frac{\sigma_1^2 \, r_2^2 + \sigma_2^2 \, r_1^2}{(r_2 - r_1)^2} + \frac{\theta_{mcs}^2 \, r_1^2}{\sin^2(\theta)}$$

$$\theta_{mcs} = \frac{13.6\,(MeV/c)}{\beta \;\; p} \sqrt{\frac{x}{X_0}}$$

- **In the critical region for Kaons from D^0 decay, 750 MeV to 1 GeV, the PXL single track pointing resolution is predicted to be 20-30 μm … which is sufficient to pick out a D^0 with cτ = 125 μm**
- **The system (and especially the PXL detector) is operating at the MCS limit**
- **In principle, the full detector can be analyzed 2 layers at a time …**

Graded Resolution from the Outside ⇒ In



- **A PXL detector requires external tracking to be a success**
  - **The TPC and intermediate tracking provide graded resolution from the outside-in**
- **The intermediate layers form the elements of a 'hit finder'**
  - **The spectral resolution is provided by the PXL layers**
- **The next step is to ensure that the hit finding can be done efficiently *at every layer* in a high hit density environment**

Central Collisions: Density of hits on the Detectors

STAR

$$\frac{dN}{dz} = \frac{dN}{d\eta} \times \frac{d\eta}{dz} \qquad \text{where} \qquad \frac{d\eta}{dz}(r,z) = \frac{1}{\sqrt{r^2+z^2}}$$

$$\frac{dN}{dA}(Central) = \frac{dN}{dz} \times \frac{1}{2\pi r} = \frac{700}{2\pi r^2} = 17.8\ cm^{-2}$$

Au+Au Luminosity (RHIC-II)	$80 \times 10^{26}\ cm^{-2}s^{-1}$
dn/dη (Central)	700
dn/dη (MinBias)	170
MinBias cross section	10 barns
MinBias collision rate (RHIC-II)	80 kHz
Interaction diamond size, σ	15 cm
Integration time for Pixel Chips	200 μsec

Slightly conservative numbers

100,000 pixels cm^{-2}

	Radius	Simple Formula $\lvert\eta\rvert = 0$	$\lvert\eta\rvert < 0.2$	$\lvert\eta\rvert < 1.0$
PXL 1	2.5 cm	$17.8\ cm^{-2}$	$19.0\ cm^{-2}$	$15.0\ cm^{-2}$
PXL 2	8.0 cm	$1.7\ cm^{-2}$	$1.8\ cm^{-2}$	$1.5\ cm^{-2}$
IST	14.0 cm	$0.57\ cm^{-2}$	$0.66\ cm^{-2}$	$0.52\ cm^{-2}$
SSD	23.0 cm	$0.21\ cm^{-2}$	$0.23\ cm^{-2}$	$0.19\ cm^{-2}$

The density of hits is not large compared to the number of pixels on each layer.
The challenge, instead, is for tracking to find the good hits in this dense environment.

MinBias Pileup – The PXL Layers Integrate over Time

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Integrate over time and interaction diamond

$$\frac{dN}{dA}(MinBias, z, r, \sigma) = \frac{dN}{d\eta} \times \frac{1}{2\pi r} \times ZDC \times \tau \times \int_{-a}^{a} \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-z_0^2}{2\sigma^2}} \frac{d\eta}{d(z - z_0)} dz_0$$

200 µsec

$$\frac{dN}{dA}(MinBias, z, r, \sigma) = \frac{2720}{2\pi r} \times \int_{-a}^{a} \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-z_0^2}{2\sigma^2}} \frac{1}{\sqrt{r^2 + (z - z_0)^2}} dz_0$$

	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}**

Pileup is the bigger challenge

Not insignificant

A full study of the integrated hit loading on the PIXEL detector includes the associated pileup due to minBias Au-Au collisions and the integration time of the detector.

Efficiency Calculations in a high hit density environment

The probability of associating the right hit with the right track on the first pass through the reconstruction code is:

P(good association) $= 1 / (1+S)$

where $S = 2\pi\, \sigma_x\, \sigma_y\, \rho$

P(bad association) $=$ (1 – Efficiency) $= S / (1 + S)$

and when S is small

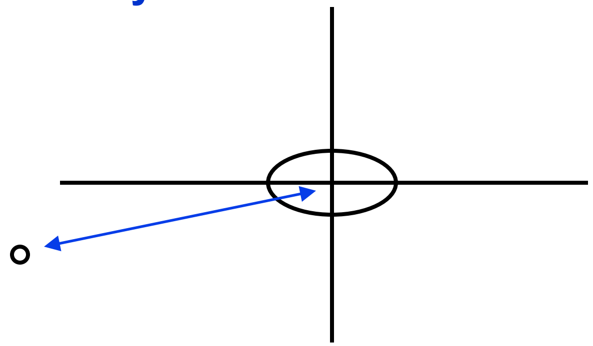
P(bad association) $\approx 2\pi\, \sigma_x\, \sigma_y\, \rho$

σ_x is the convolution of the detector resolution and the projected track error in the 'x' direction, and ρ is the density of hits.

The largest errors dominates the sum

$$\sigma_x = \sqrt{(\sigma^2_{xp} + \sigma^2_{xd})}$$

$$\sigma_y = \sqrt{(\sigma^2_{yp} + \sigma^2_{yd})}$$



Asymmetric pointing resolutions are very inefficient … try to avoid it

TPC Pointing at the PXL Detector

- **The TPC pointing resolution on the outer surface of the PXL Detector is greater than 1 mm …** **but lets calculate what the TPC can do alone**
  - **Assume the new radial location at 8.0 cm for PXL-2, with 9 μm detector resolution in each pixel layer and a 200 μsec detector**

Radius	**PointResOn (R-φ)**	**PointResOn (Z)**	**Hit Density**
8.0 cm	1.4 mm	1.5 mm	6.0
2.5 cm	90 μm	110 μm	61.5

  - **Notice that the pointing resolution on PXL-1 is very good even though the TPC pointing resolution on PXL-2 is not so good**

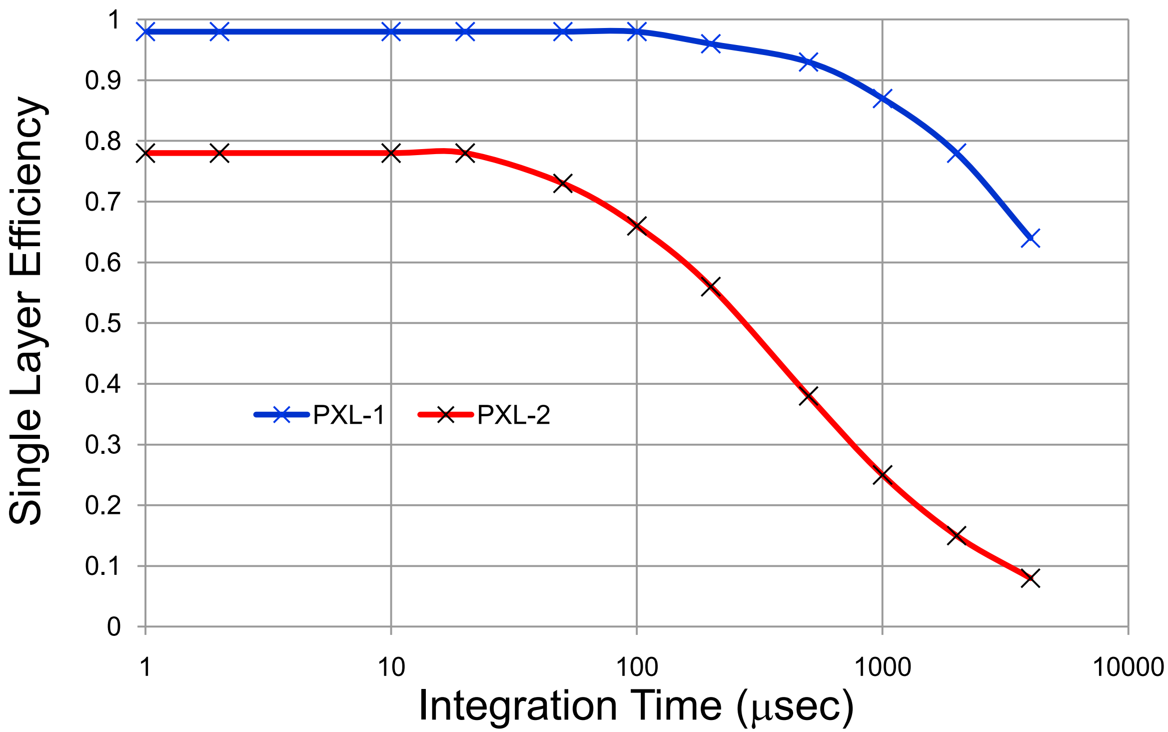
- **The probability of a good hit association on the first pass**
  - **55% on PXL2** The purpose of the intermediate tracking layers is to make 55% go up to ~100%
  - **95% on PXL1** All values quoted for mid-rapidity Kaons at 750 MeV/c

This is a surprise: The hard work gets done at 8 cm!

The performance of the TPC acting alone

- **The performance of the TPC acting alone depends on the integration time of the PXL chip**

P(good association) = 1 / (1+S) **where $S = 2\pi\, \sigma_x\, \sigma_y\, \rho$**



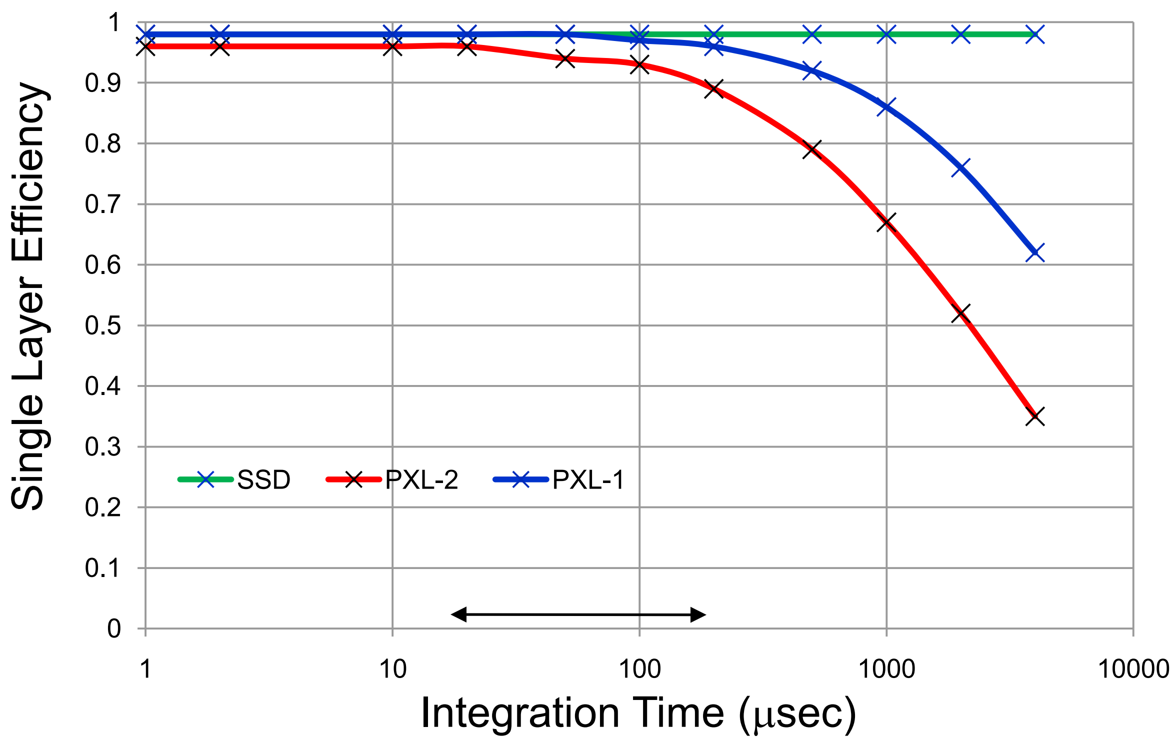
Note that the hard work gets done at PXL layer 2. This is a surprise.

The purpose of intermediate tracking layers is to make 55% go up to ~100%

The performance of the TPC + SSD + IST

- **The performance of the TPC + SSD or TPC + IST acting together depends on the integration time of the PXL chip … but overall the performance is very good**

P(good association) = 1 / (1+S) **where S = $2\pi\, \sigma_x\, \sigma_y\, \rho$**



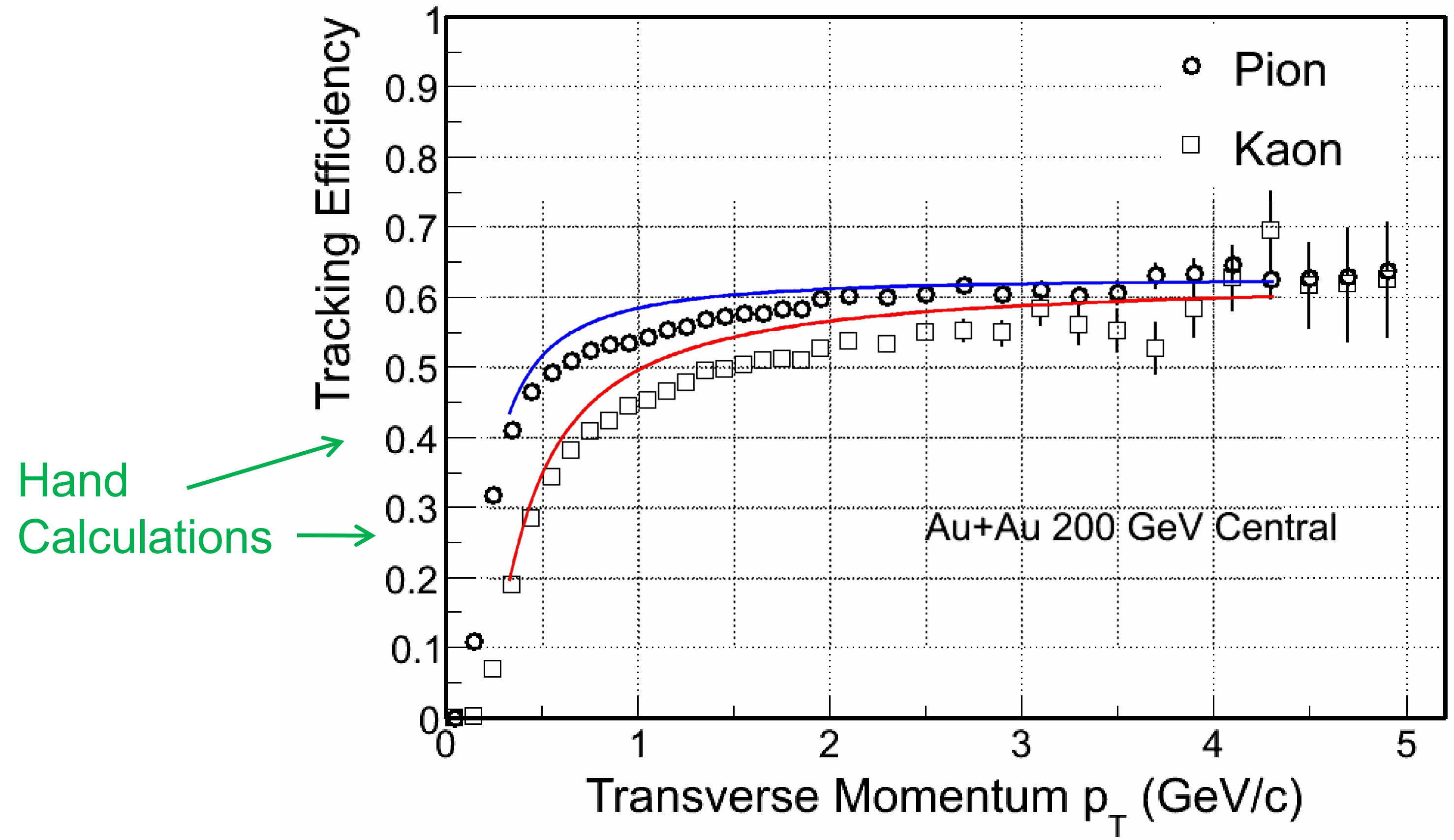
Random errors <u>only</u> included in hand calculations and in GEANT/ITTF simulations

A Quick Note About Absolute Efficiencies

- The previously quoted efficiencies do not include the geometric acceptance of the detectors
- The TPC has an approximately 90% geometric acceptance due to sector boundaries and sector gaps
  - In addition, the TPC has an additional ~90% efficiency factor at RHIC II luminosities … this is a software and tracking issue due to the large multiplicity of tracks
- The SSD has an approximately 90% geometric acceptance due to areas where the crossed strips don't achieve full coverage
- All 'new' detectors are assumed to have 100% geometric acceptance
- Efficiency from the previous slide
  - 0.98 x 0.98 x 0.93 x 0.94 = 0.84
- Geometric acceptance and TPC track finding efficiencies
  - 0.9 x 0.9 x 0.9 = 0.73

In this example Total = 0.61

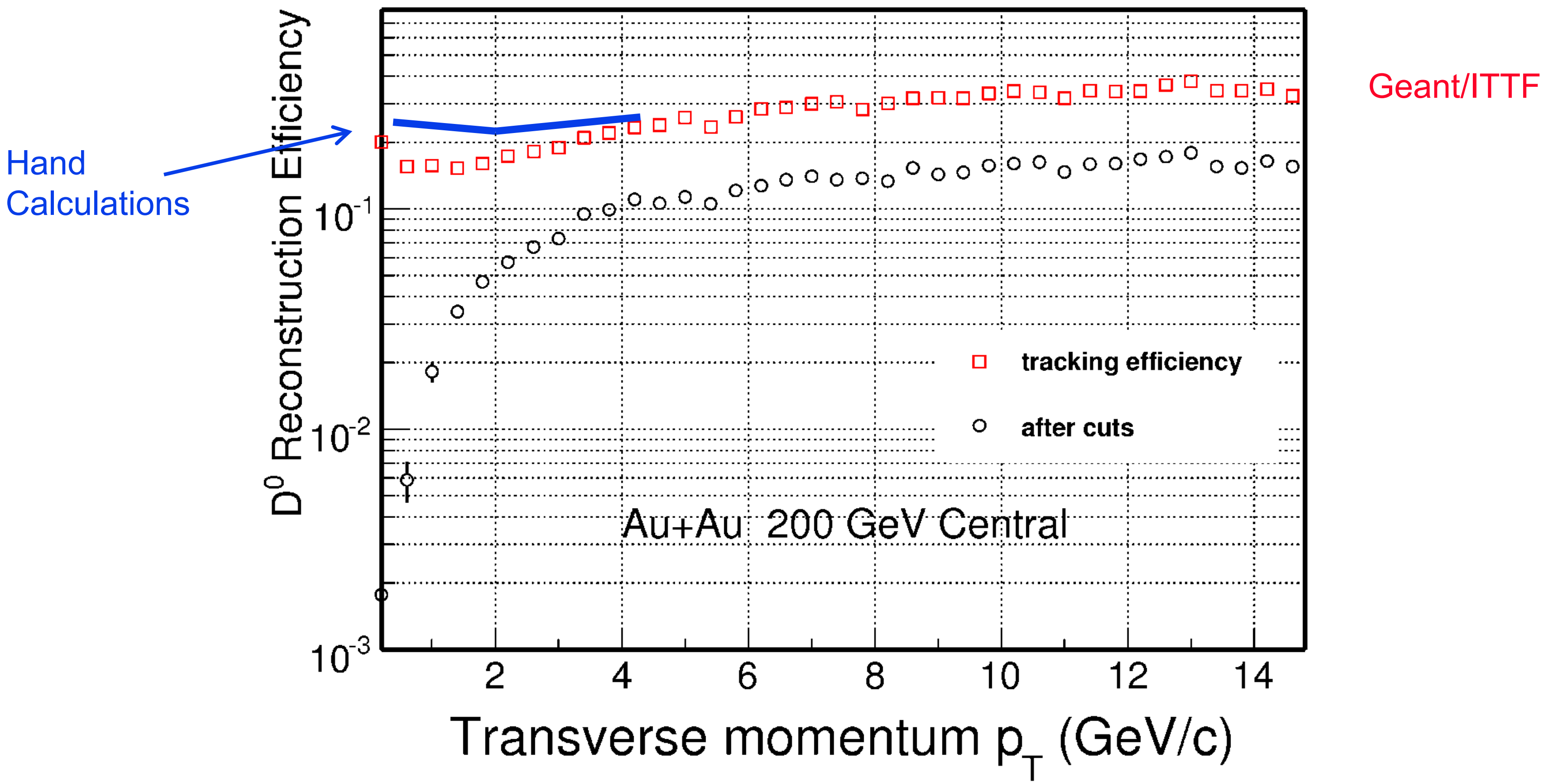
Single Track Efficiencies – Hand Calc .vs. ITTF



Hand calculations assume the acceptance is flat in p_T and assume a single track at $\eta = 0.5$

The efficiency for finding tracks in central Au+Au collisions in the STAR TPC and the HFT. Finite acceptance effects for the TPC and SSD are included in the simulations. The quoted efficiency from GEANT/ITTF is for $|\eta| < 1.0$ and for tracks coming from the primary vertex with $|v_z| < 5$ cm.

D0 Reconstruction Efficiencies Compared



- The blue line shows the D^0 efficiency predicted by the hand calculations
  - Single track efficiencies for the kaon and pion are integrated over the Lorentz kinematics of the daughter particles to predict the D^0 efficiency
- Hand Calculation give guidance … but more complex questions should be answered by the full suite of tools available to Geant/ITTF

A Robust Design

- **The HFT is thin, unique, innovative and robust**
- **The designs have been tested extensively with hand calculations and more carefully with specific examples tested with GEANT/ITTF simulations**

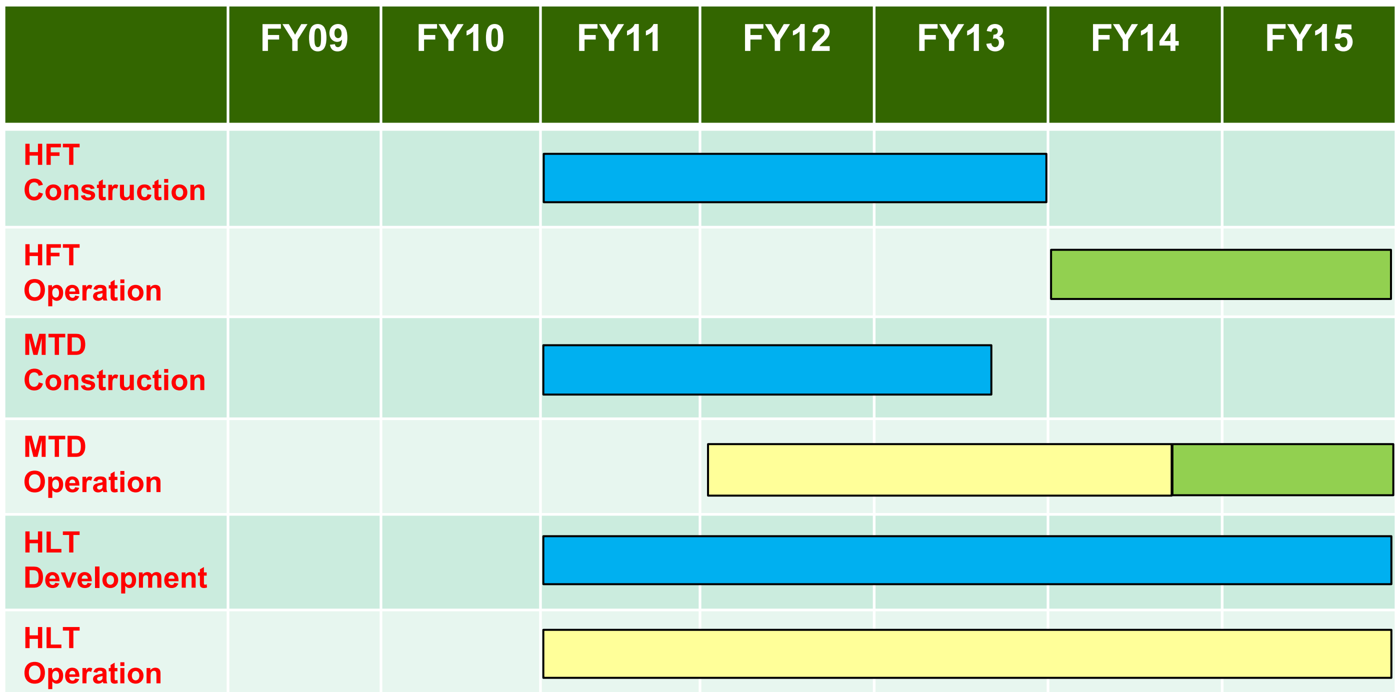
There is a rich physics program that can be addressed with the HFT in STAR

Summary

- The HFT will explore the Charm sector at RHIC
- We will do direct topological reconstruction of Charm
- Our measurements will be unique at RHIC
- The key measurements include
  - V_2
  - Energy Loss
  - Charm Spectra, R_{AA} & R_{cp}
  - Vector mesons
  - Angular Correlations
- The technology is available on an appropriate schedule

Backup Slides

Three STAR Upgrade Projects

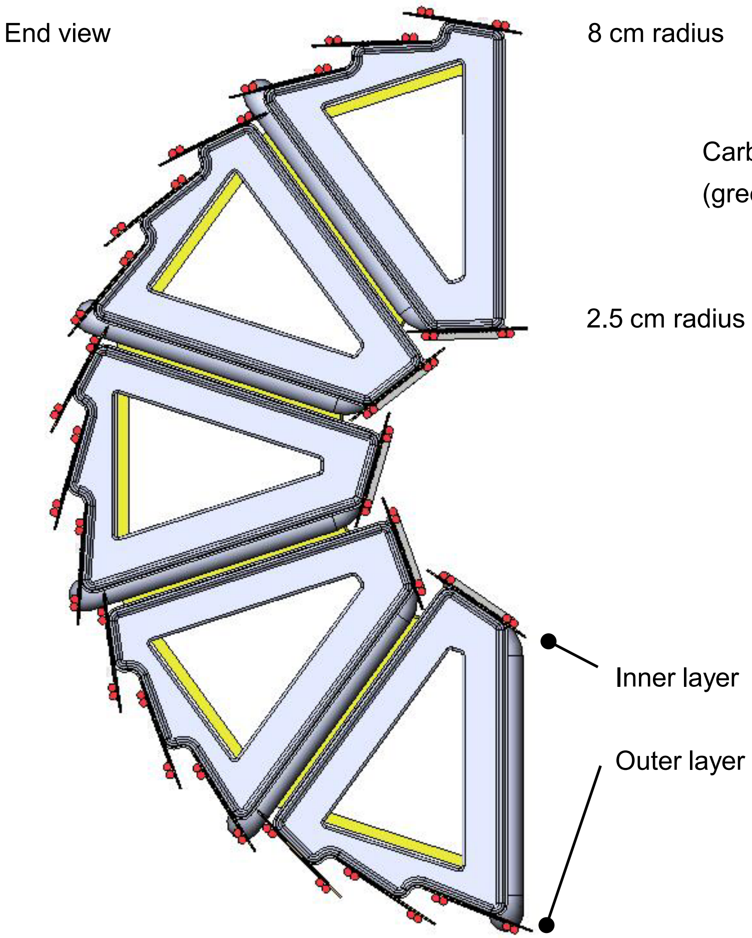


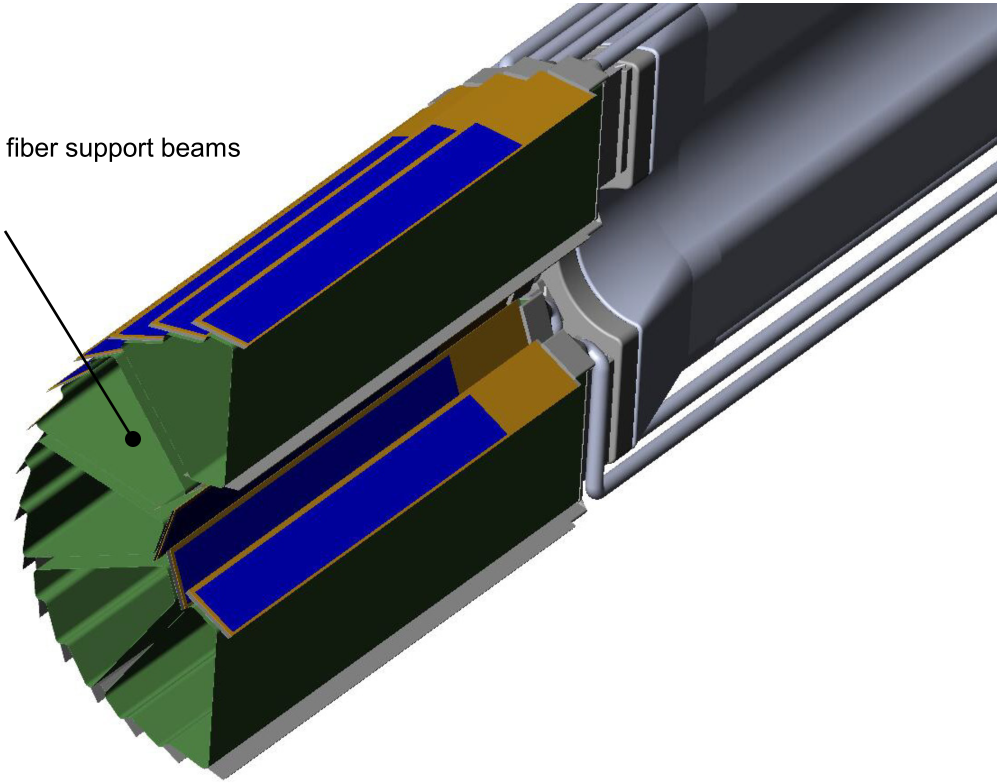
Finish HFT in time for the 2014 run

Finish MTD project by Mar, 2014 and make 80% of the full system ready for year 2014 run

HLT is seeking funds but is projected to be under development through FY15, and will be available for physics at all times

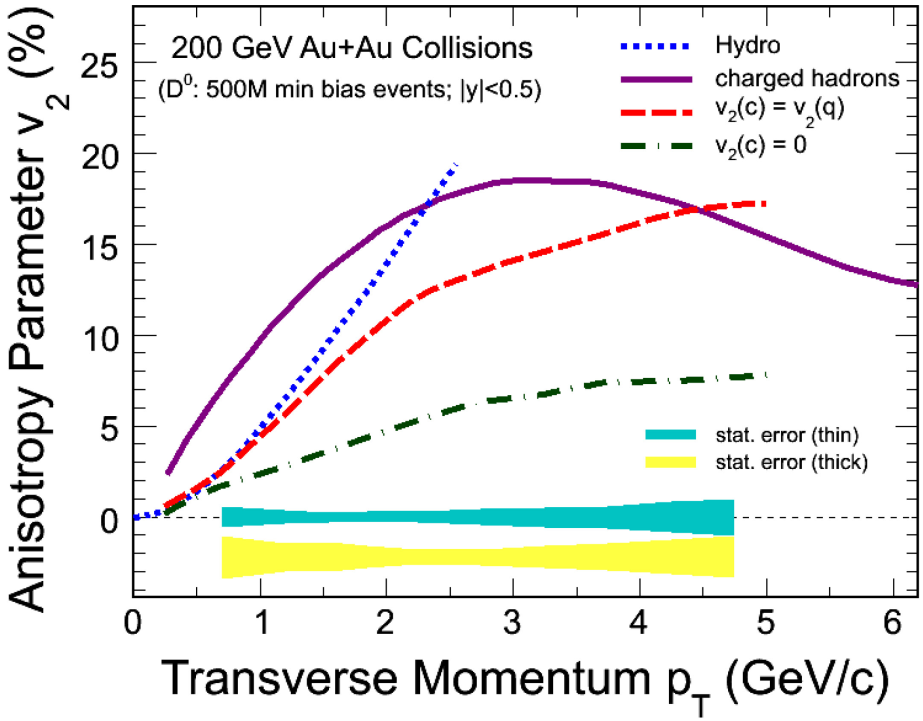
Pixel support structure near the vertex

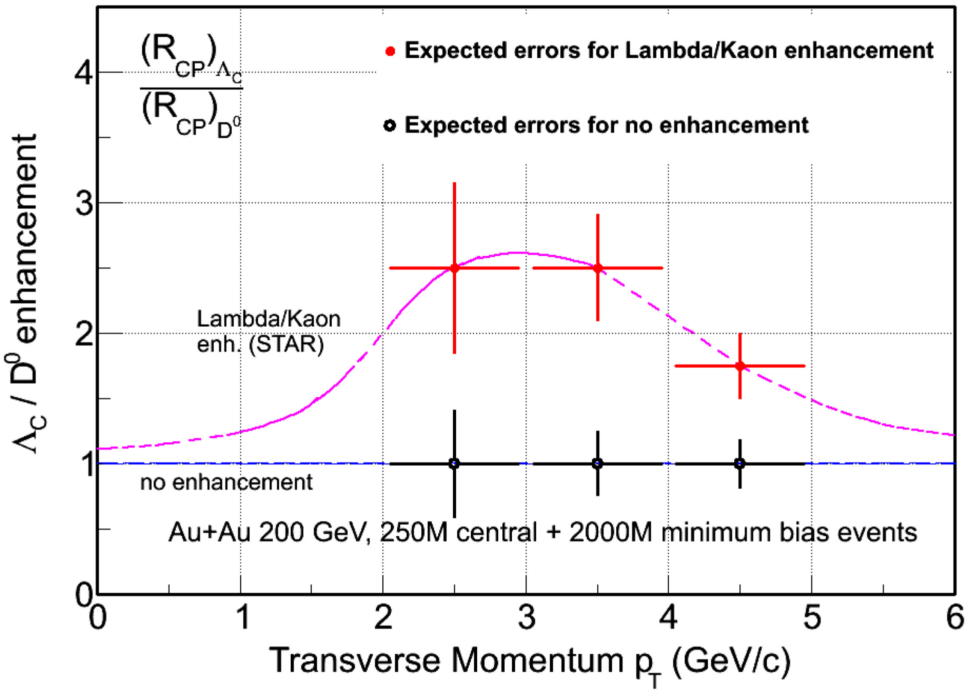




Two "D" sectors form the heart of the PXL detector. The two halves separate in order to allow for easy access, removal and repair.

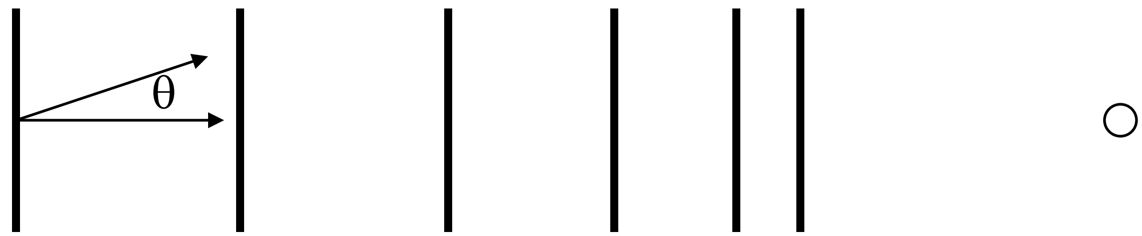
Properties of the sQGP





- Does charm flow **hydrodynamically**?
  - Heavy Flavor Tracker: unique access to low-p_T fully reconstructed charm
- Are charmed hadrons produced via **coalescence**?
  - Heavy Flavor Tracker: unique access to charm baryons
  - Would force a significant reinterpretation of non-photonic electron R_{AA}
- Muon Telescope Detector: precision measurements of J/ψ flow

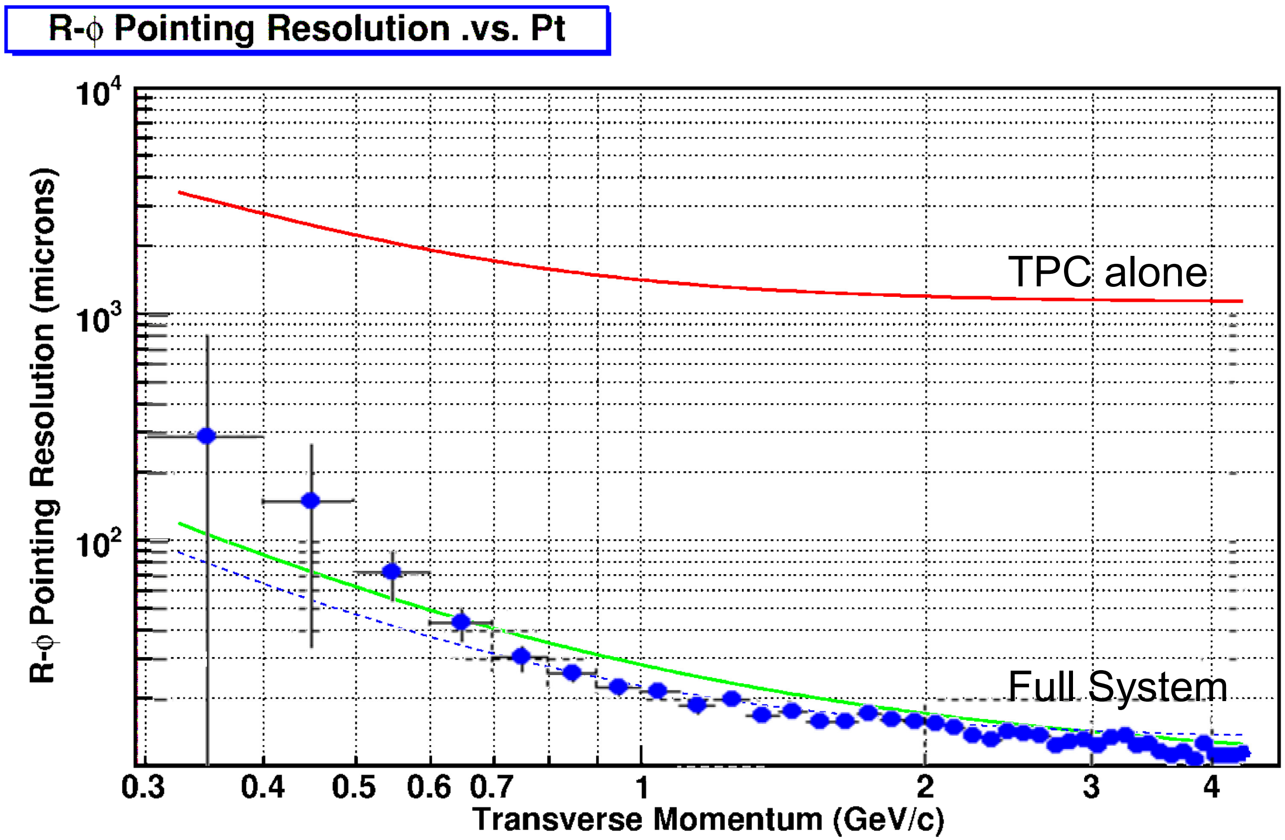
Calculating the Performance of the Detector



$$[MCS][D][M][MCS][D][M][MCS] \quad \bullet \quad \bullet \quad \bullet$$

- **Billoir invented a matrix method for evaluating the performance of a detector system including MCS and dE/dx**
  - **NIM 225 (1984) 352.**
- **The 'Information Matrices' used by Billoir are the inverse of the more commonly used covariance matrices**
  - **thus, σ's are propagated through the system**
- **The calculations can be done by 'hand' or by 'machine'** **(with chains)**
- **STAR ITTF 'machine' uses a similar method (aka a Kalman Filter)**
  - **The 'hand calculations' go outside-in**
  - **STAR Software goes outside-in and then inside-out, and averages the results, plus follows trees of candidate tracks. It is 'smart' software.**

Hand Calculations .vs. GEANT & ITTF



- - - - PXL stand alone configuration

Paper Proposal configuration

● ● ● GEANT & ITTF adjusted to have the correct weights on PXL layers

Updated configuration … no significant changes in pointing at VTX