HFT Performance & Simulation Studies

A marriage of Intuition, Hand Calculations, and Detailed Geant Simulations

Jim Thomas
Lawrence Berkeley National Laboratory

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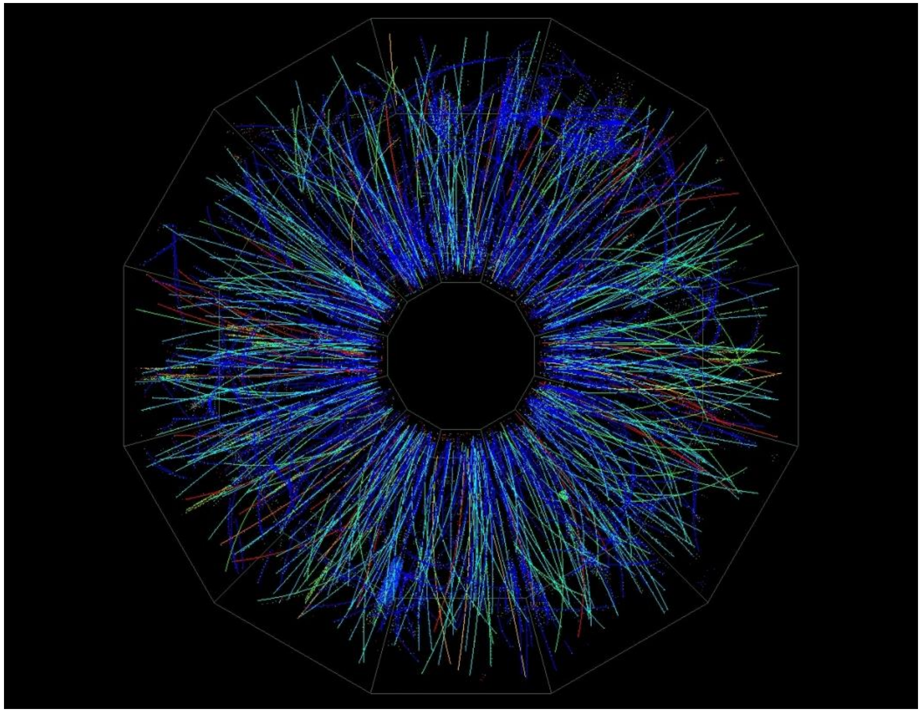
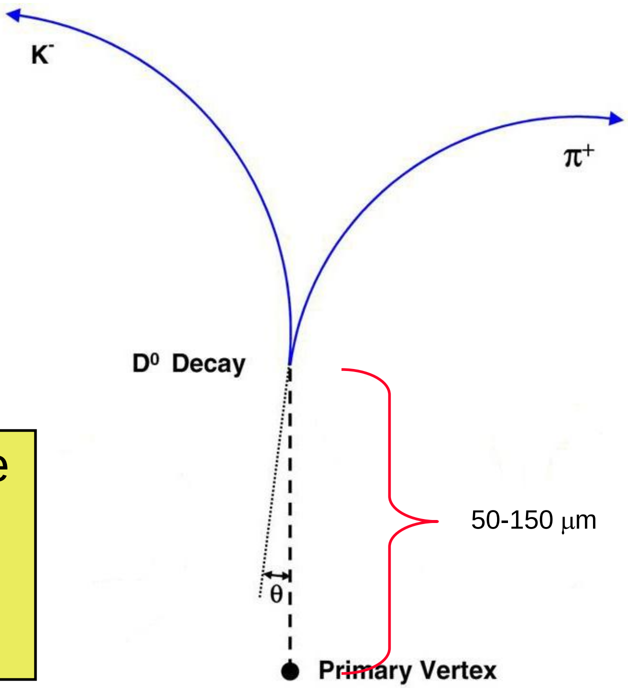
The Properties of the Open Charm Hadrons

Particle	Decay Channel	cτ (μm)	Mass (GeV/c^2)
D^0	$K^- \pi^+$ (3.8%)	123	1.8645
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312	1.8694
D_s^+	$K^+ K^- \pi^+$ (5.2%) $\pi^+ \pi^+ \pi^-$ (1.2%)	150	1.9683
Λ_c^+	$p K^- \pi^+$ (5.0%)	59.9	2.2865

Direct Topological Identification of Open Charm



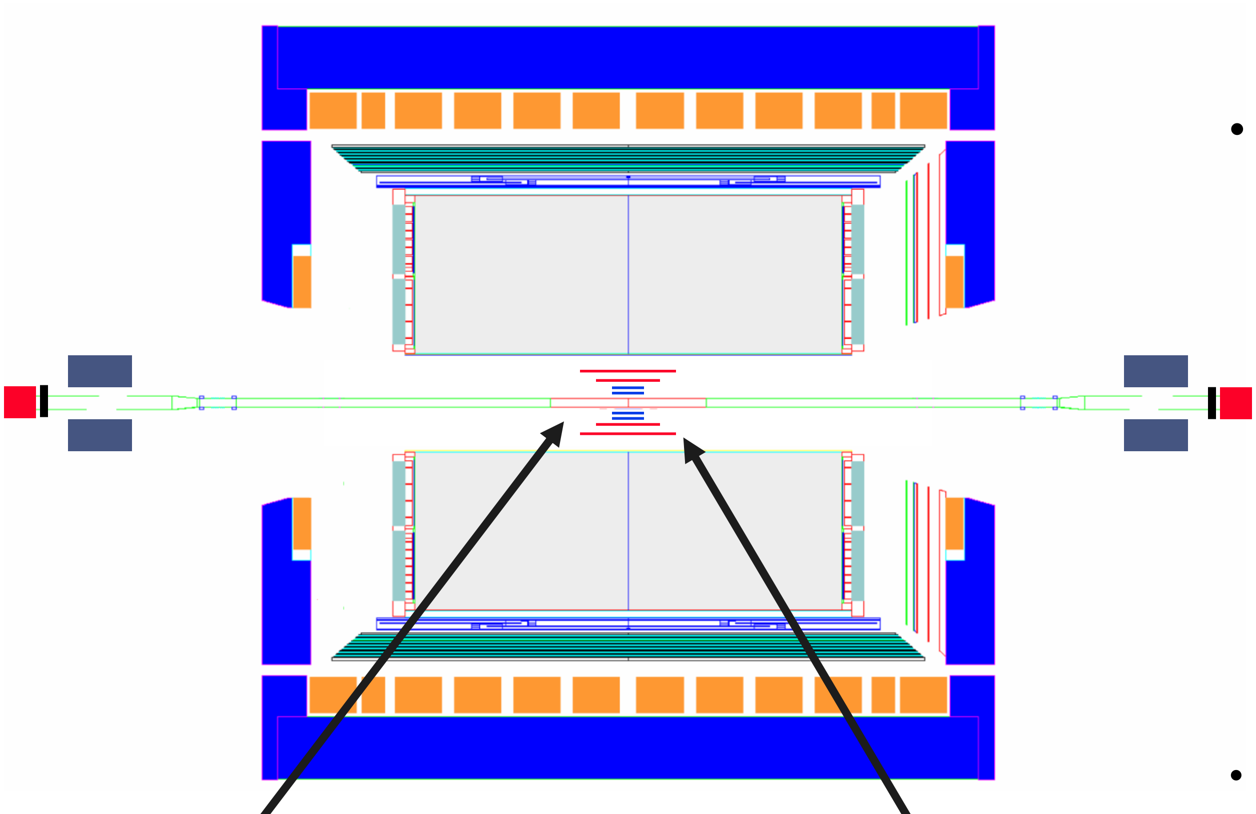
Goal: Put a high precision detector near the IP to extend the TPC tracks to small radius



The STAR Inner Tracking Upgrades will identify the daughters in the decay and do a direct topological reconstruction of the open charm hadrons.

No ambiguities between charm and beauty.

The Heavy Flavor Tracker = PXL + IST + SSD



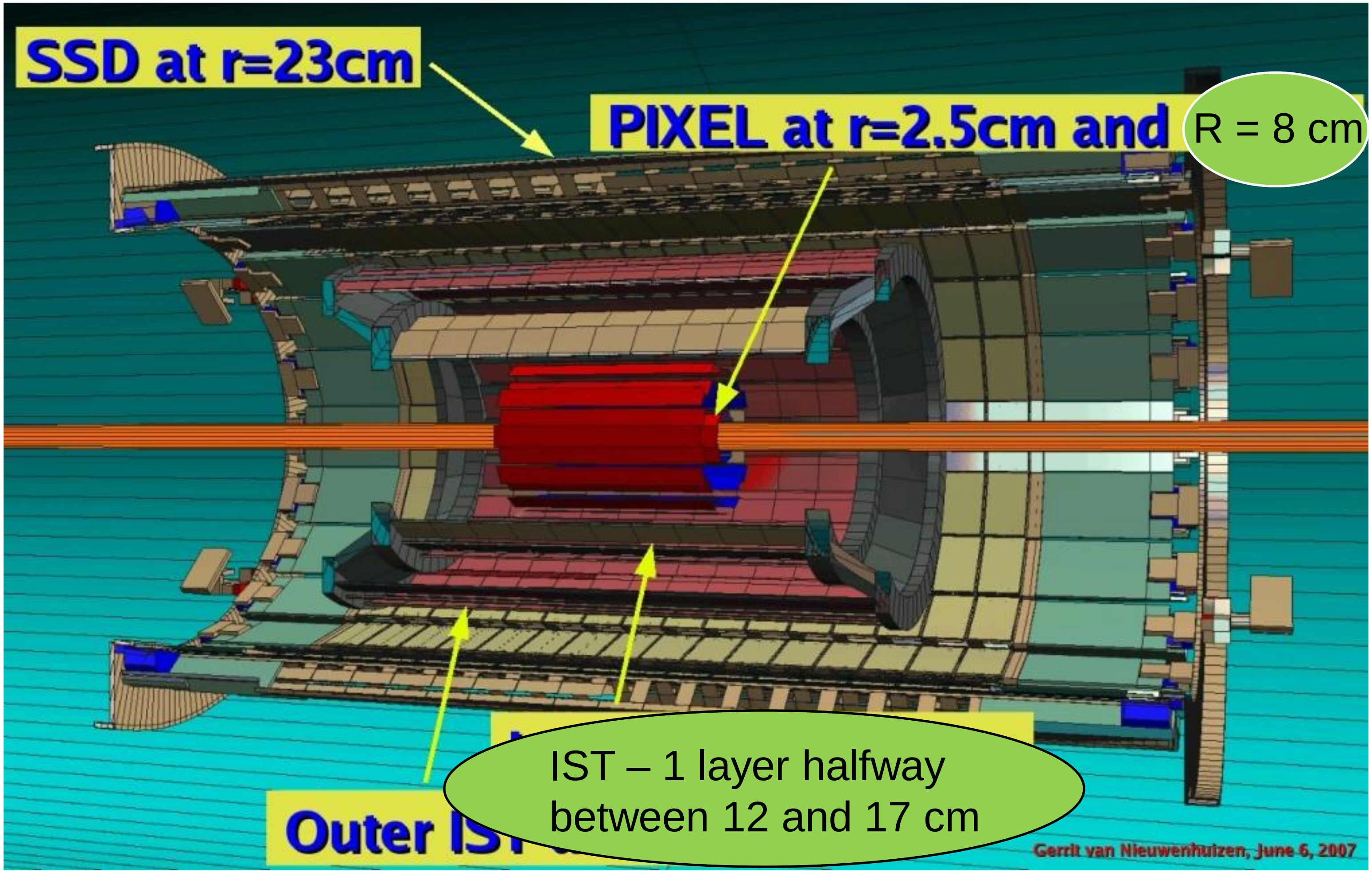
PXL: 2 layers of Si at small radii

IST: 1 or more layers of Si at intermediate radii

SSD: an existing detector at 23 cm radius

- **A new detector**
  - 30 μm silicon pixels to yield 10 μm space point resolution
- **Direct Topological reconstruction of Charm**
  - Detect charm decays with small cτ, including $D^0 \rightarrow K\ \pi$
- **New physics**
  - Charm collectivity and flow to test thermalization at RHIC
  - Charm Energy Loss to test pQCD in a hot and dense medium at RHIC
- **SSD … is part of the plan**
- **A scientific proposal has been submitted. The technical design is evolving but converging rapidly to final form.**

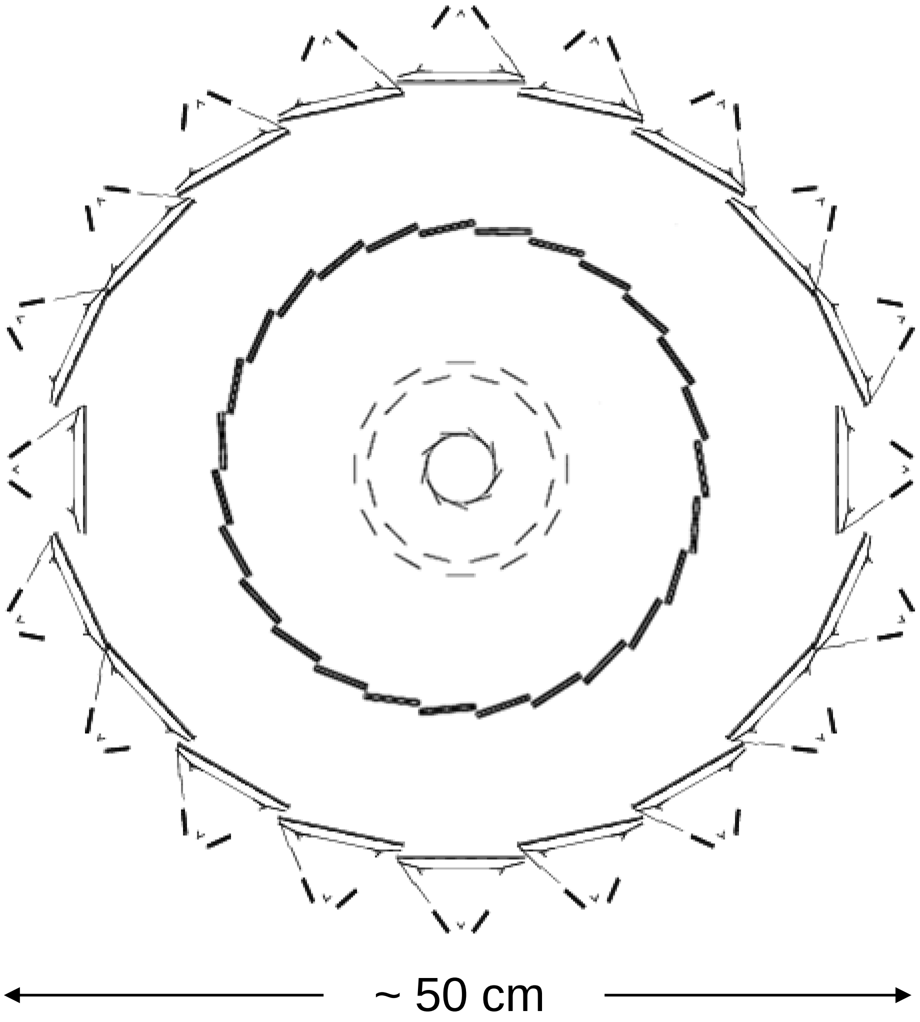
The Proposal Configuration simulated in GEANT



Engineering Design Changes since the proposal was published

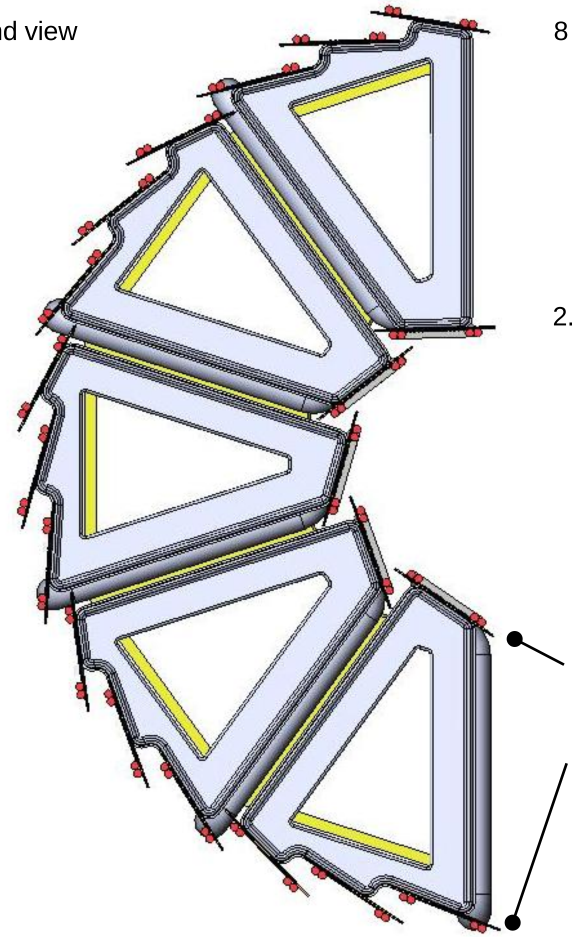
Overview & Goals for Si Detectors Inside the TPC

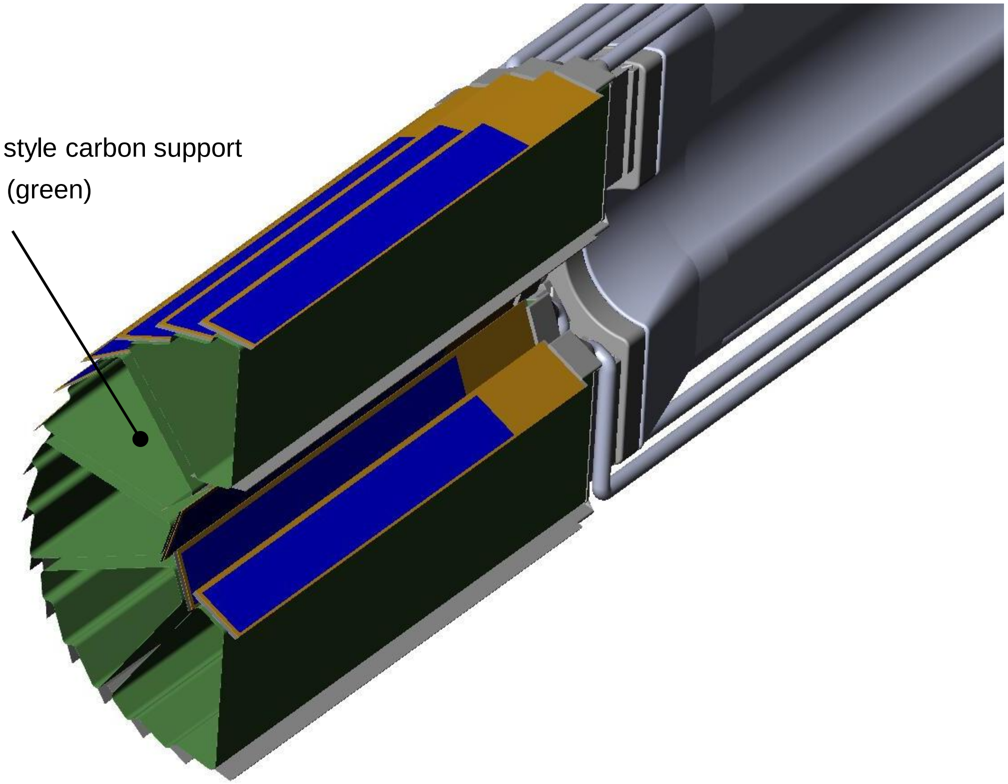
- Goal: graded resolution and high efficiency from the outside → in
- TPC – SSD – IST – PXL
- TPC pointing resolution at the SSD is ~ 1 mm
- SSD pointing at the IST is ~ 400 μm (200 x 800)
- IST pointing at PXL 2 is ~ 400 μm (200 x 800)
- PXL 2 pointing at PXL1 is ~ 125 μm (90 x 175)
- PXL1 pointing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



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

Pixel support structure – changes and progress

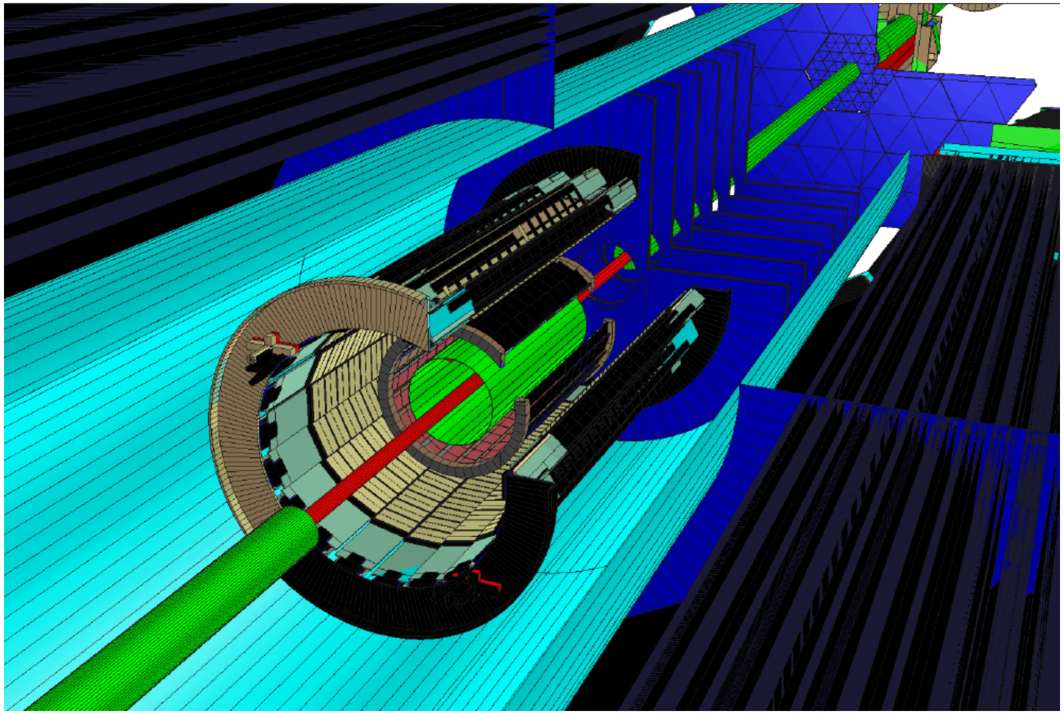




See talk by HH Wieman

The proposed changes have been verified with hand calculations and are scheduled to be put thru a full system test with GEANT/ITTF simulations. The GEANT simulations are approximately two generations behind the latest design: FOL

IST – changes and progress



- **One IST layer at 14 cm**
- **Good performance**
- **Assumes a working SSD**

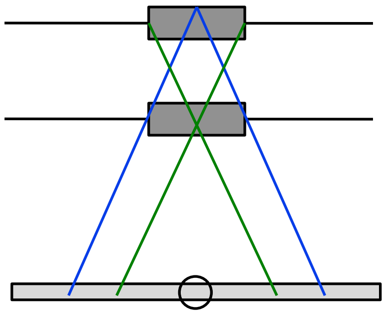
- **Fewer channels**
- **Lower cost**
- **Provides extra space for PXL layers**

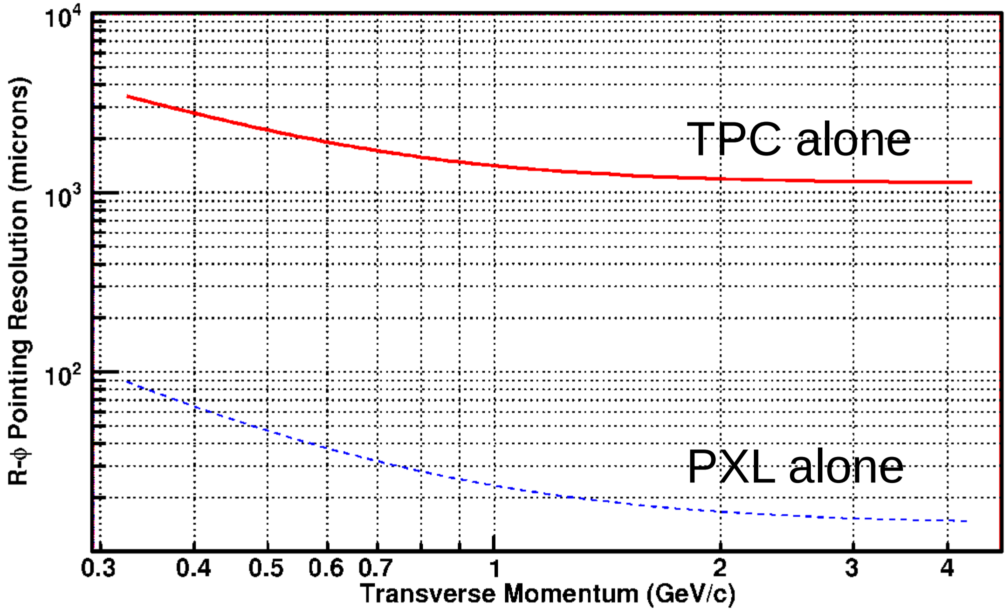
- **Basic Parameters**
  - **Short strips (< 1 cm)**
  - **Wide strips (~ 500 μm)**
  - **Approximately 150 μm x 2000 μm resolution**

See talk by
B Surrow

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**



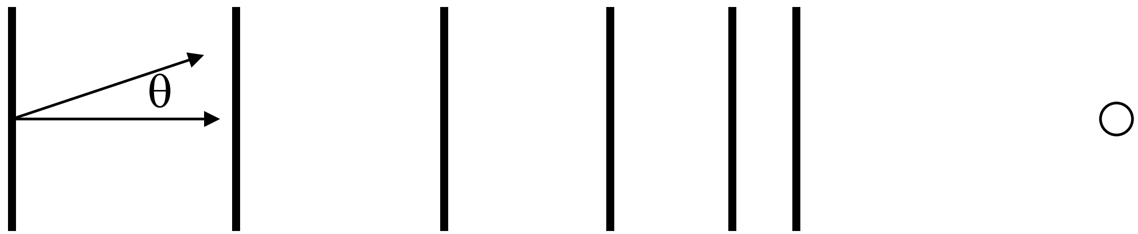


$$\sigma^2 = \frac{\sigma_1^2\, r_2^2 + \sigma_2^2\, r_1^2}{(r_2 - r_1)^2} + \frac{\theta_{mcs}^2\, r_1^2}{\sin^2(\theta)}$$

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

- **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 …**

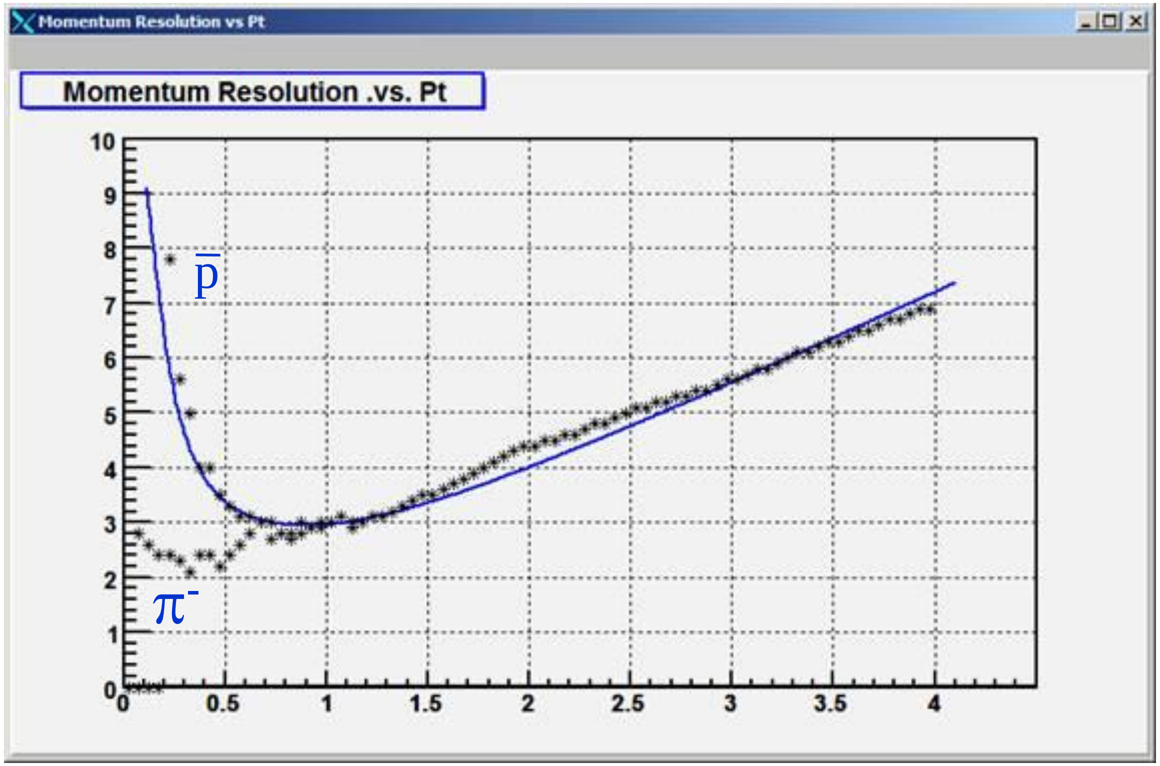
Calculating the Performance of the Detector



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

- **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.**

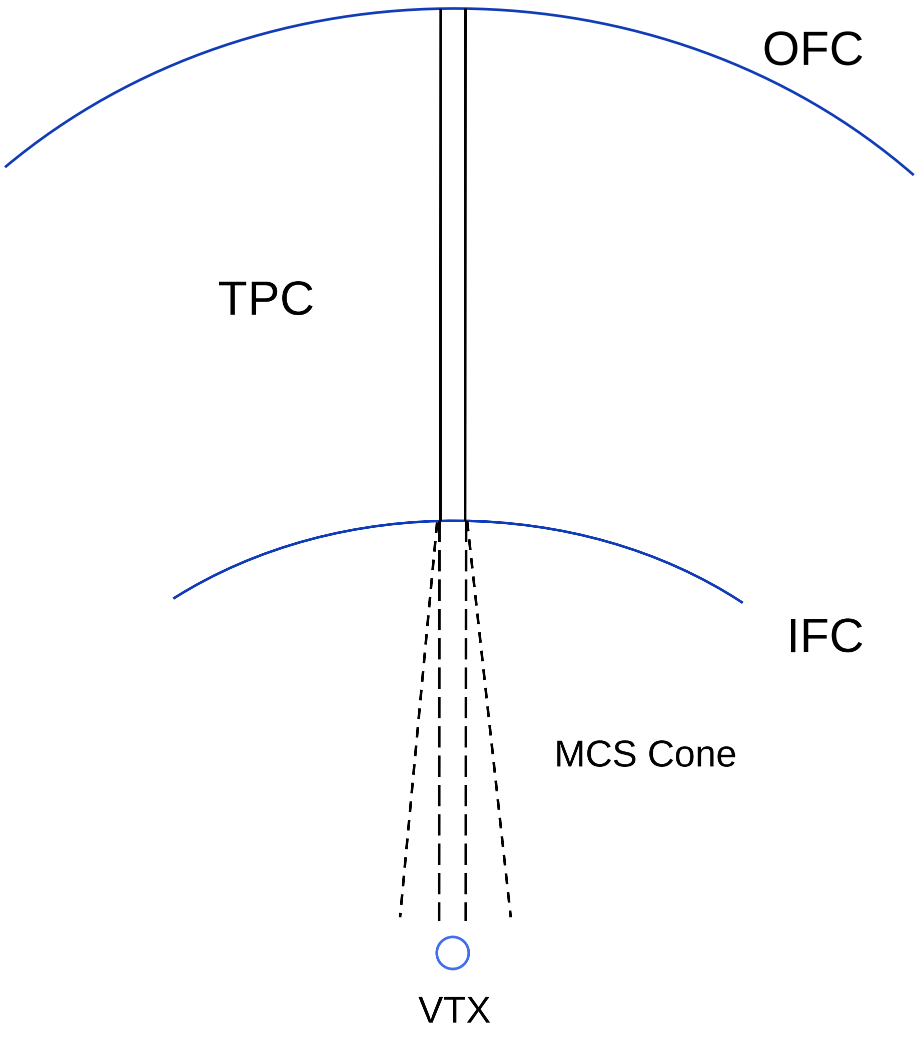
Hand Calculations – p_T resolution, a basic test



- **TPC acting alone … showing measured momentum resolution for anti-protons and pions compared to hand calculations using Billoir's implementation of a Kalman Filter.**
- **Data from STARs first run at 130 GeV, B = 0.25 T**
  - **M. Anderson et al., NIM A499 (2003) 659-678.**

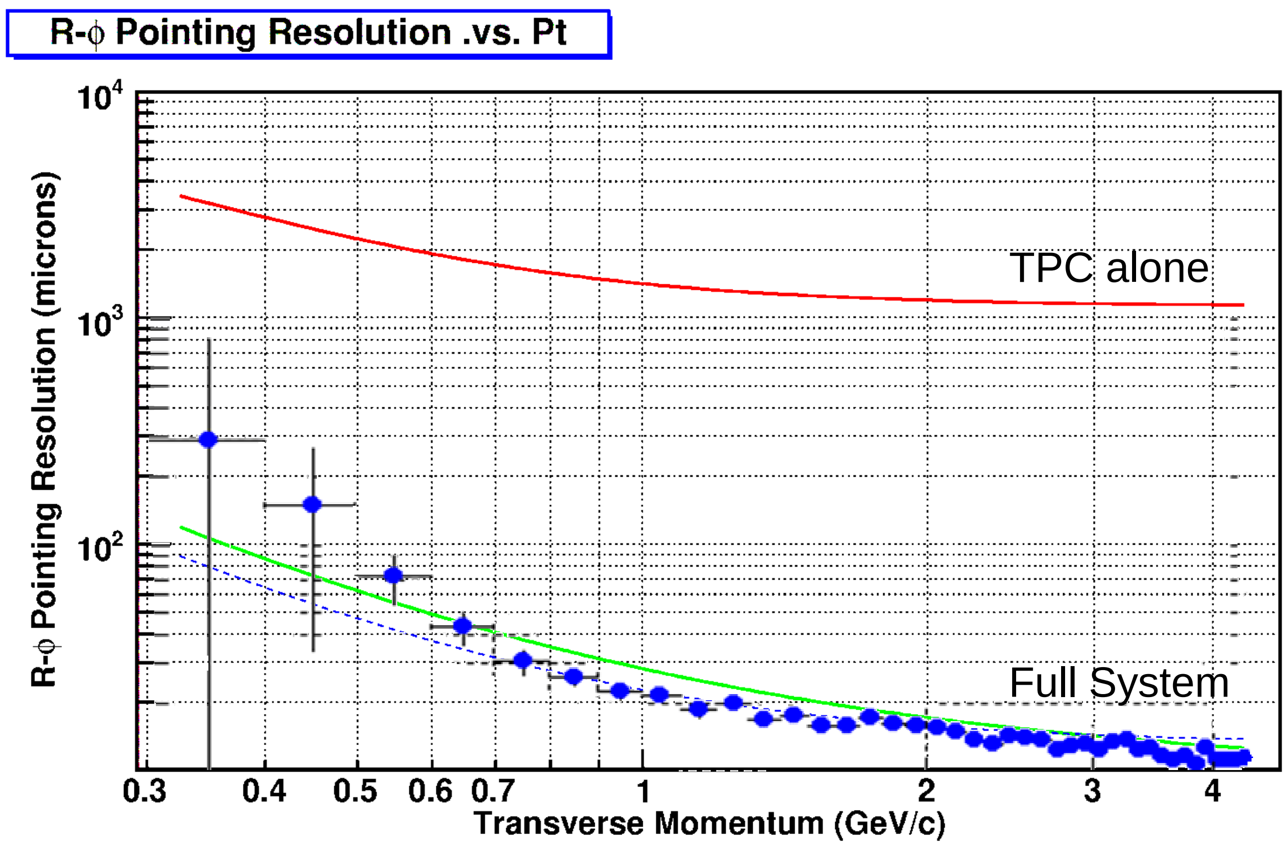
Getting a Boost from the TPC

- **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

Hand Calculations .vs. GEANT & ITTF



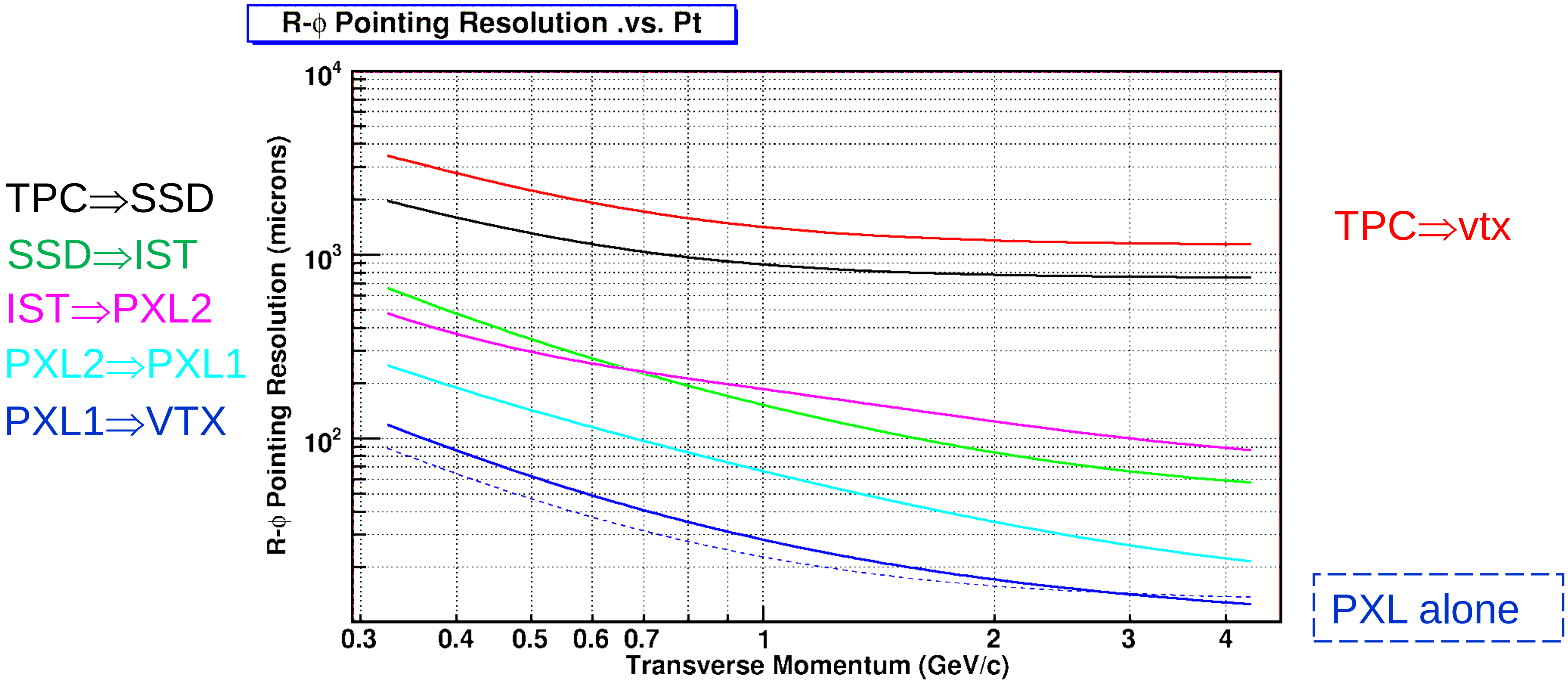
- - - - PXL stand alone configuration

—— Paper Proposal configuration

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

—— Updated configuration … no significant changes in pointing at VTX

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 x 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

STAR

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

Spencer was right

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

STAR

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

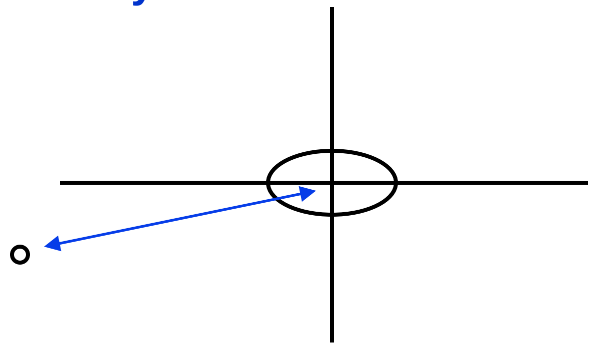
P(bad association) $\approx 2\pi \, \sigma_x \, \sigma_y \, \rho$

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**

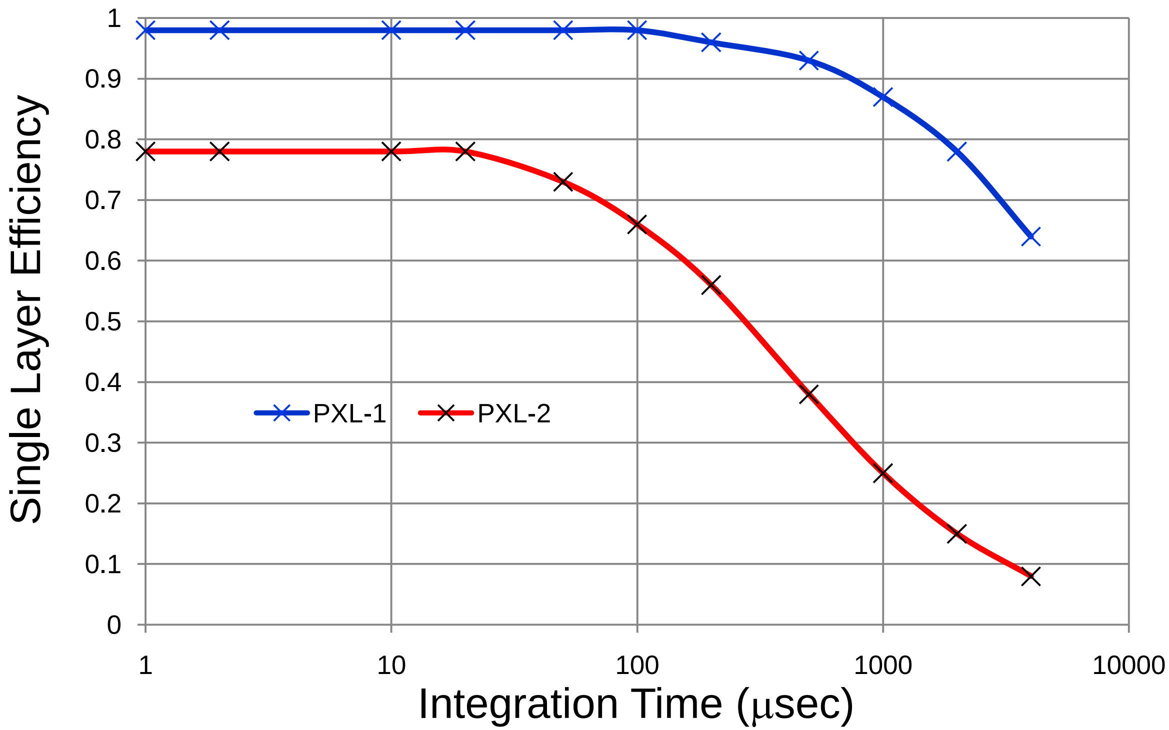
- **The probability of a good hit association on the first pass**
  - **55% on PXL2** The purpose of the intermediate tracking layers is to make 55% go up to ~100%
  - **95% on PXL1** All values quoted for mid-rapidity Kaons at 750 MeV/c

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 = $2\pi\,\sigma_x\,\sigma_y\,\rho$**



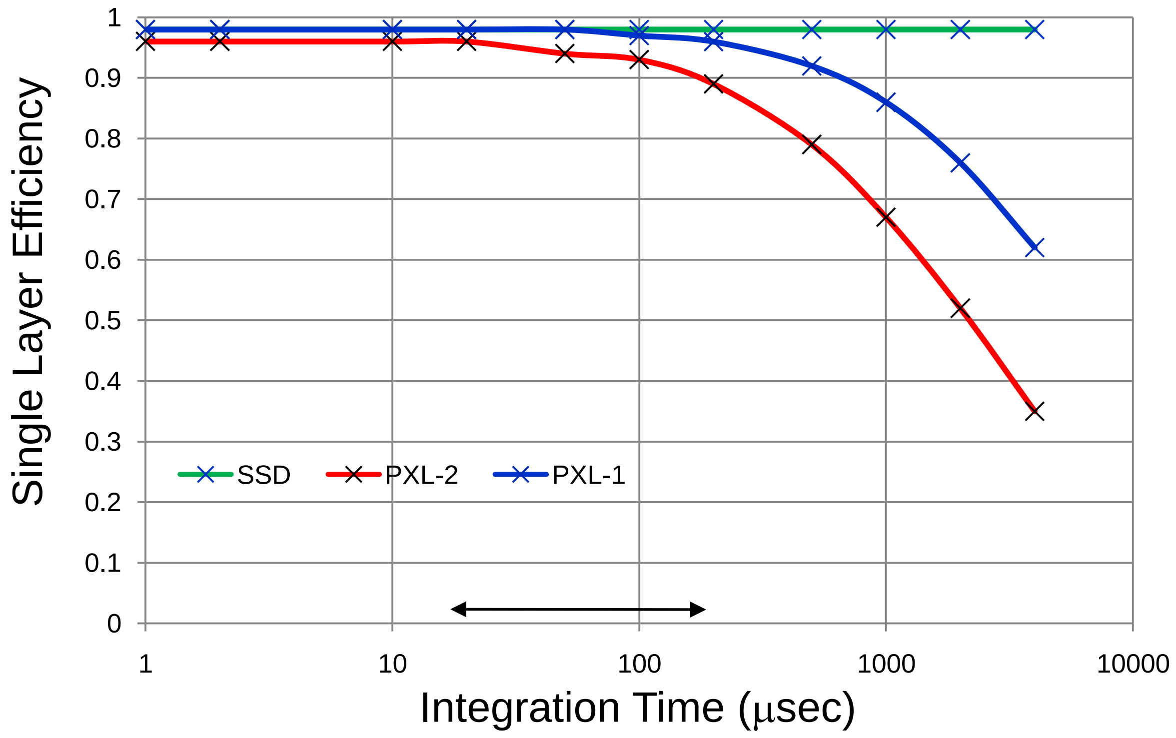
Note that the hard work gets done at PXL layer 2. This is a surprise.

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**

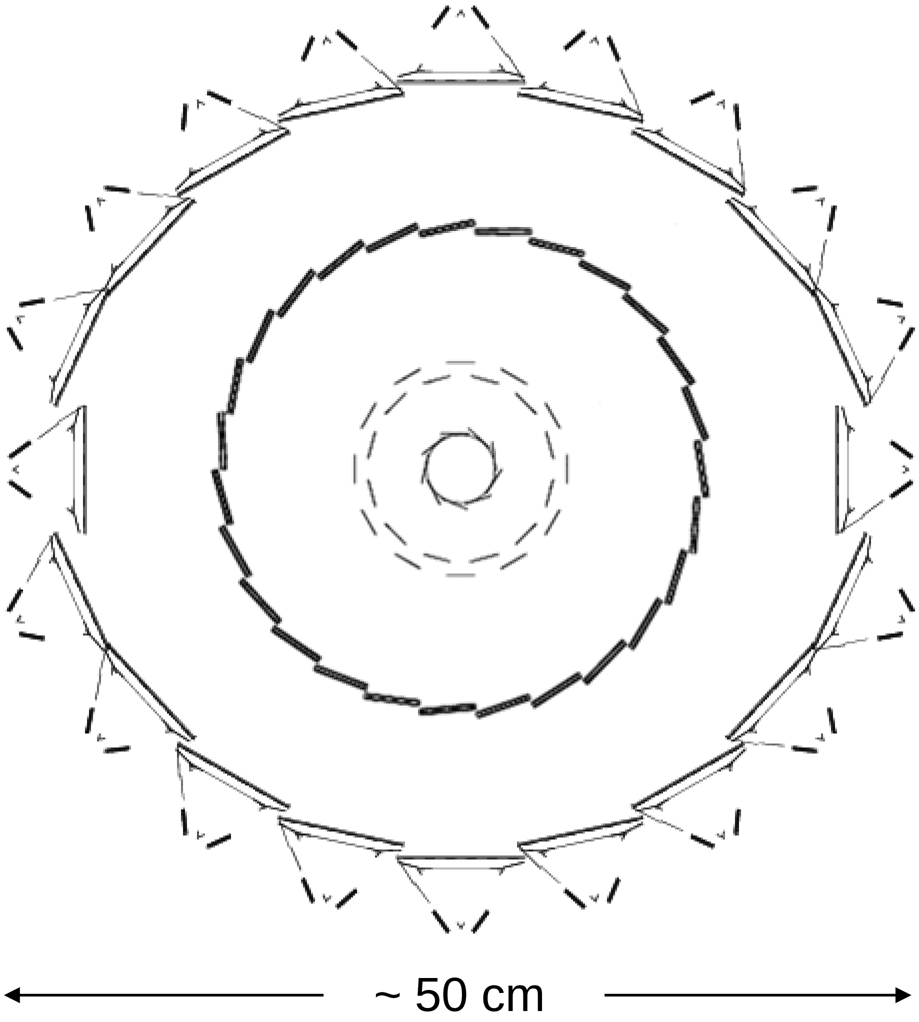
P(good association) = 1 / (1+S) **where $S = 2\pi \sigma_x \sigma_y \rho$**



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

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 $\varepsilon = 0.98$
- IST pointing at PXL 2 is ~ 400 μm $\varepsilon = 0.98$
- PXL 2 pointing at PXL1 is ~ 125 μm $\varepsilon = 0.93$
- PXL1 pointing at the VTX is ~ 40 μm $\varepsilon = 0.94$



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

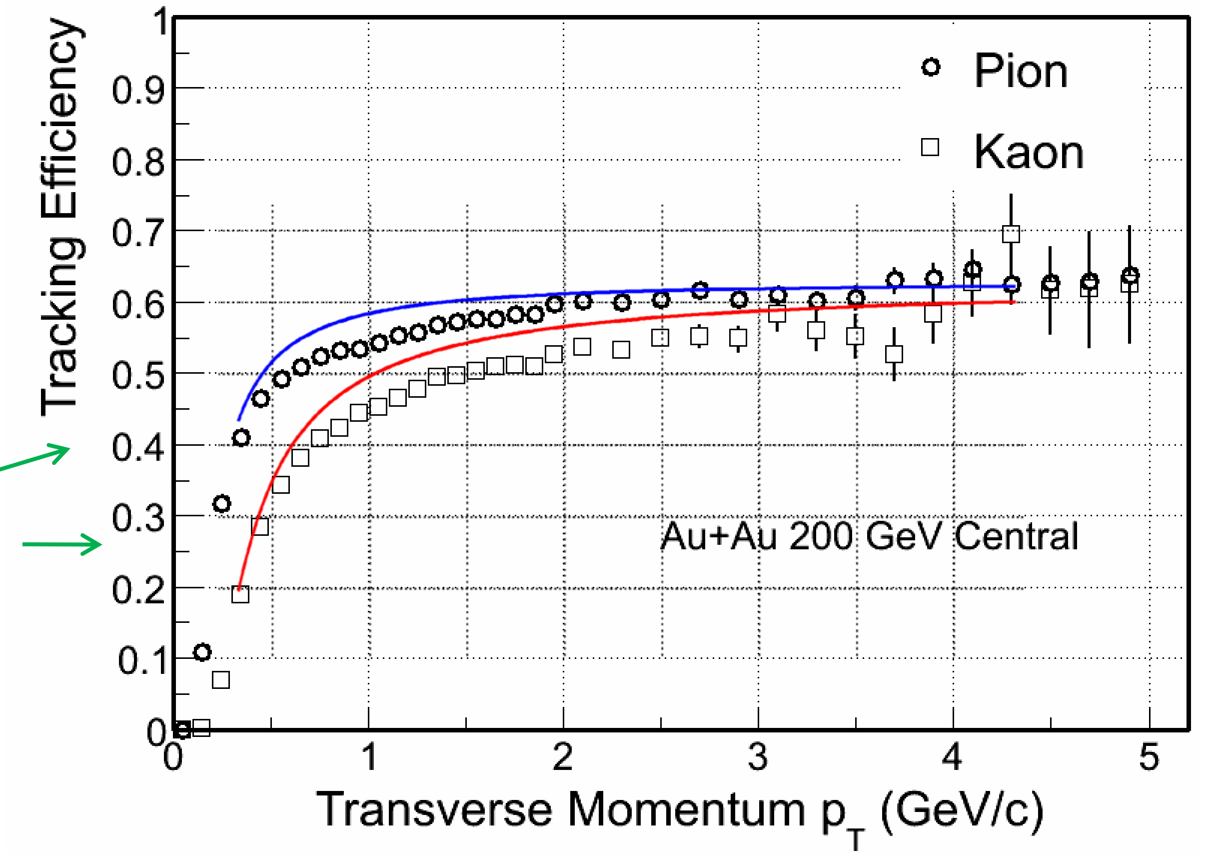
A Quick Note About Absolute Efficiencies

- **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 ~80% 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 0.8 = 0.65** **In this example Total = 0.55**

Absolute efficiencies will be shown in all Geant/ITTF generated spectra

Single Track Efficiencies – Hand Calc .vs. ITTF

Hand
Calculations



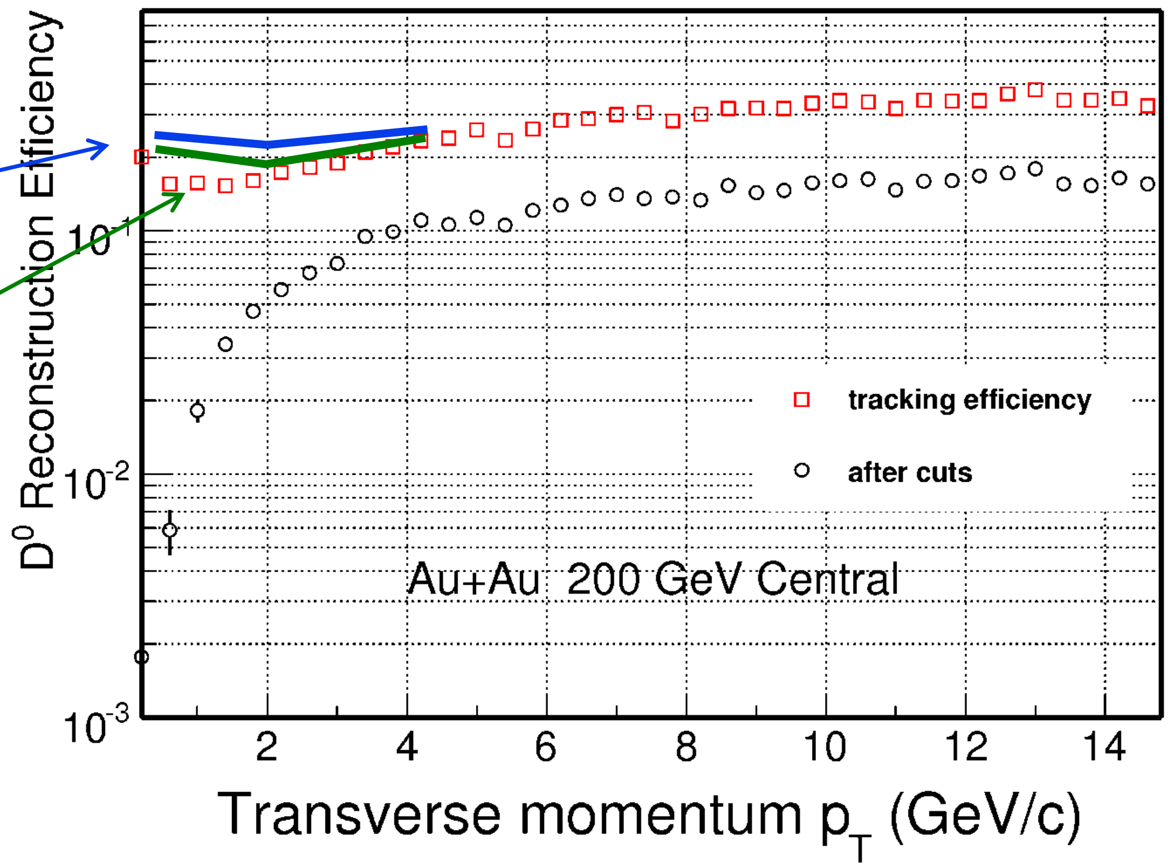
Hand calculations assume the acceptance is flat in p_T and assume a single track at $\eta = 0.5$

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

Hand Calculations

Pythia from Single Particle



Geant/ITTF

See Talk by Xin Dong

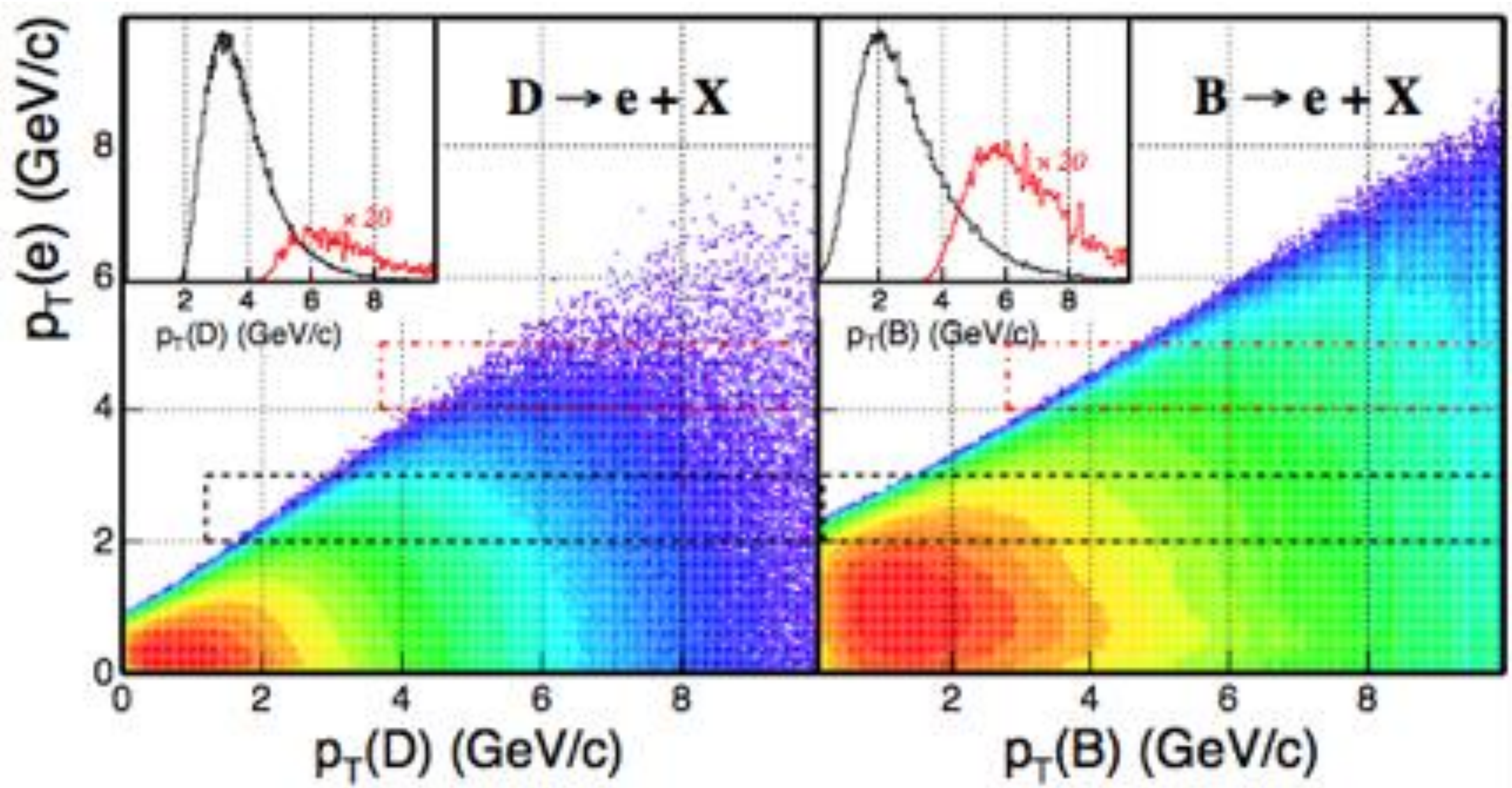
- The blue line shows the D^0 efficiency predicted by the hand calculations
  - Single track efficiencies for the kaon and pion are integrated over the Lorentz kinematics of the daughter particles to predict the D^0 efficiency
- Hand Calculation give guidance … but more complex questions should be answered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

Conclusion: A Robust Design

- The HFT is thin, unique, innovative and robust
- The design has been tested extensively with hand calculations and the full set of GEANT/ITTF simulations
  - I have shown you what can be learned from hand calculations
  - with the most up-to-date design parameters
- For a richer simulation story, including background, p_T dependent acceptance, and physics spectra
  - see the talk by Xin Dong
  - for the latest results from the paper proposal configuration
- For examples of the unique & innovative hardware
  - see the talks by H.H. Wieman and B. Surrow

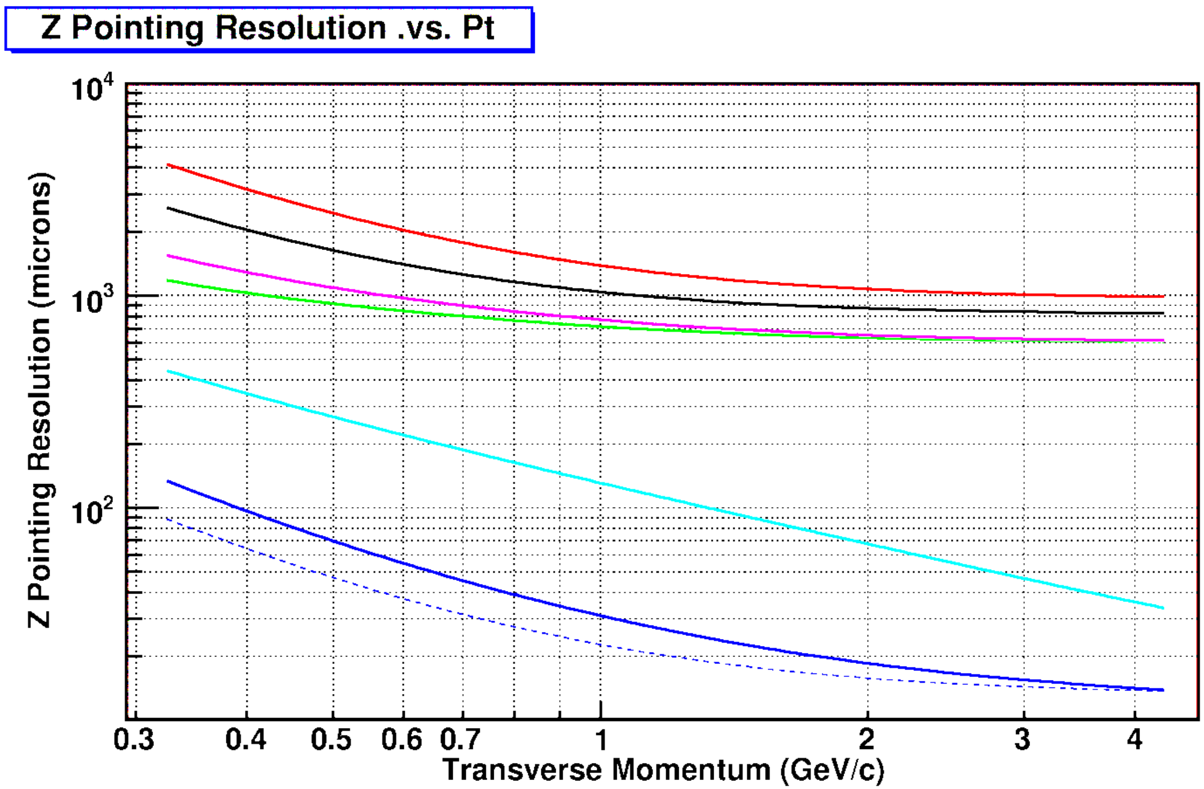
There is a rich physics program that can be addressed with the HFT in STAR

Backup Slides



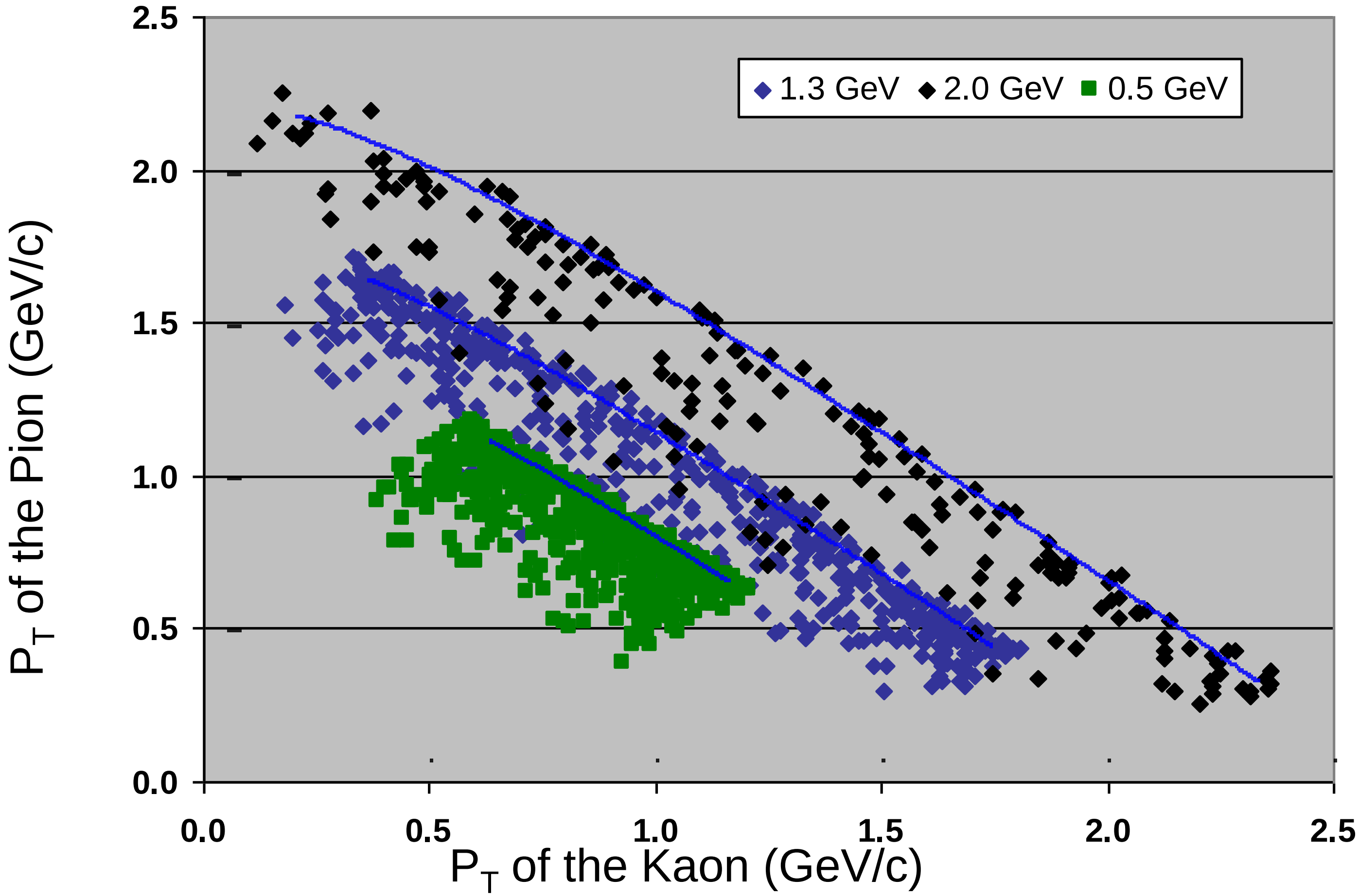
- p_T **distributions of electrons from semi-leptonic decay of heavy flavor mesons (left D-mesons, right B-mesons) as a function of parent** p_T**. The inserted plots represent the projections to the corresponding heavy flavor distributions. The widths of the electron** p_T **windows are indicated by dashed boxes.**

Graded Resolution from the Outside ⇒ In



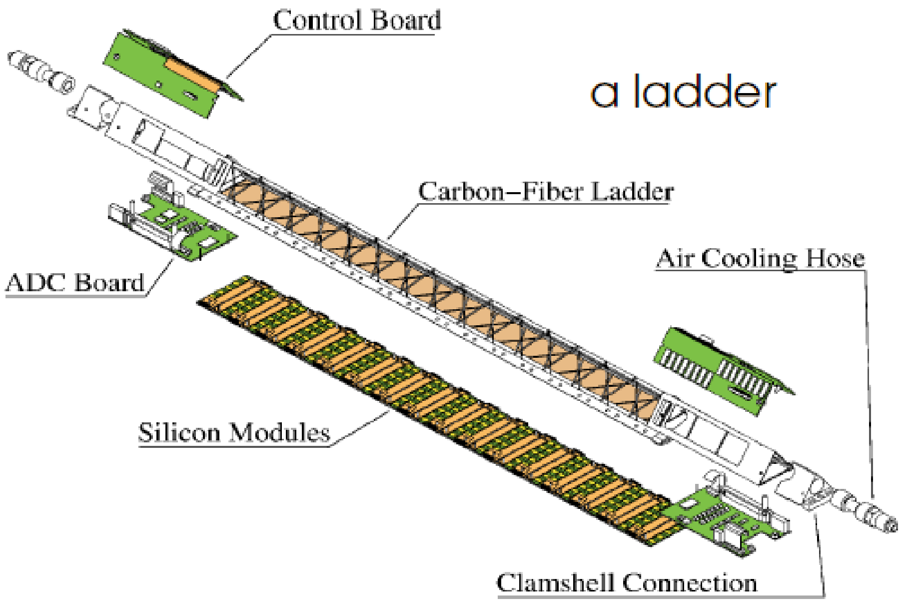
- **Hand Calculations showing graded resolution in the Z direction**
- **Red – TPC pointing at VTX, Black – TPC pointing at SSD**
- **Green – SSD pointing at IST, Magenta – IST pointing at PXL 2**
- **Cyan – PXL 2 pointing at PXL 1, Blue – PXL1 pointing at VTX**

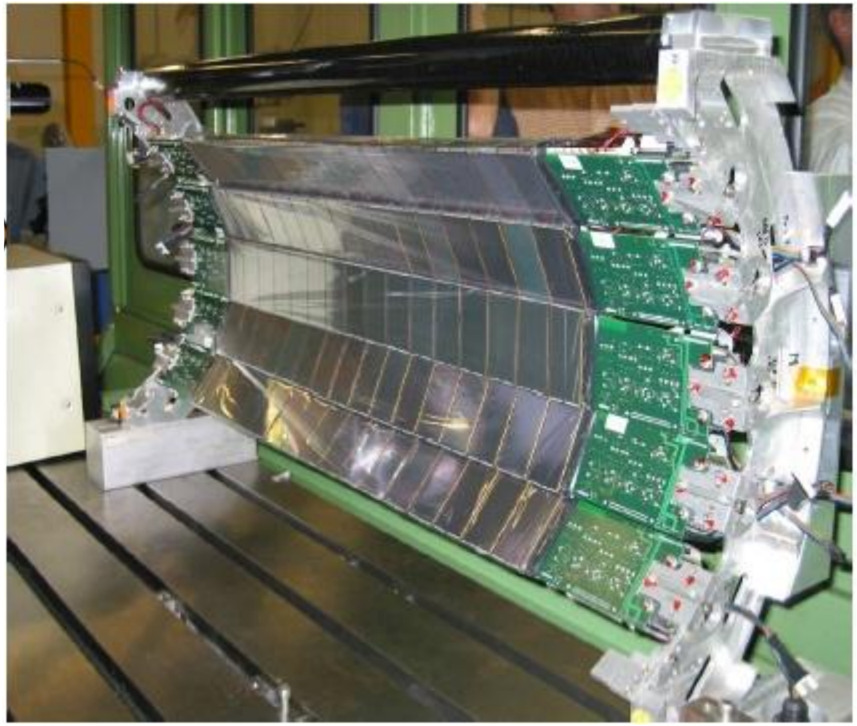
D^0 Decay Kinematics



- **D^0's thrown by Pythia for p-p collisions**
- **D^0 p_T shown by different color dots (e.g. Blue = 1.3 GeV D^0s)**

Keep the SSD, it is a beautiful detector!

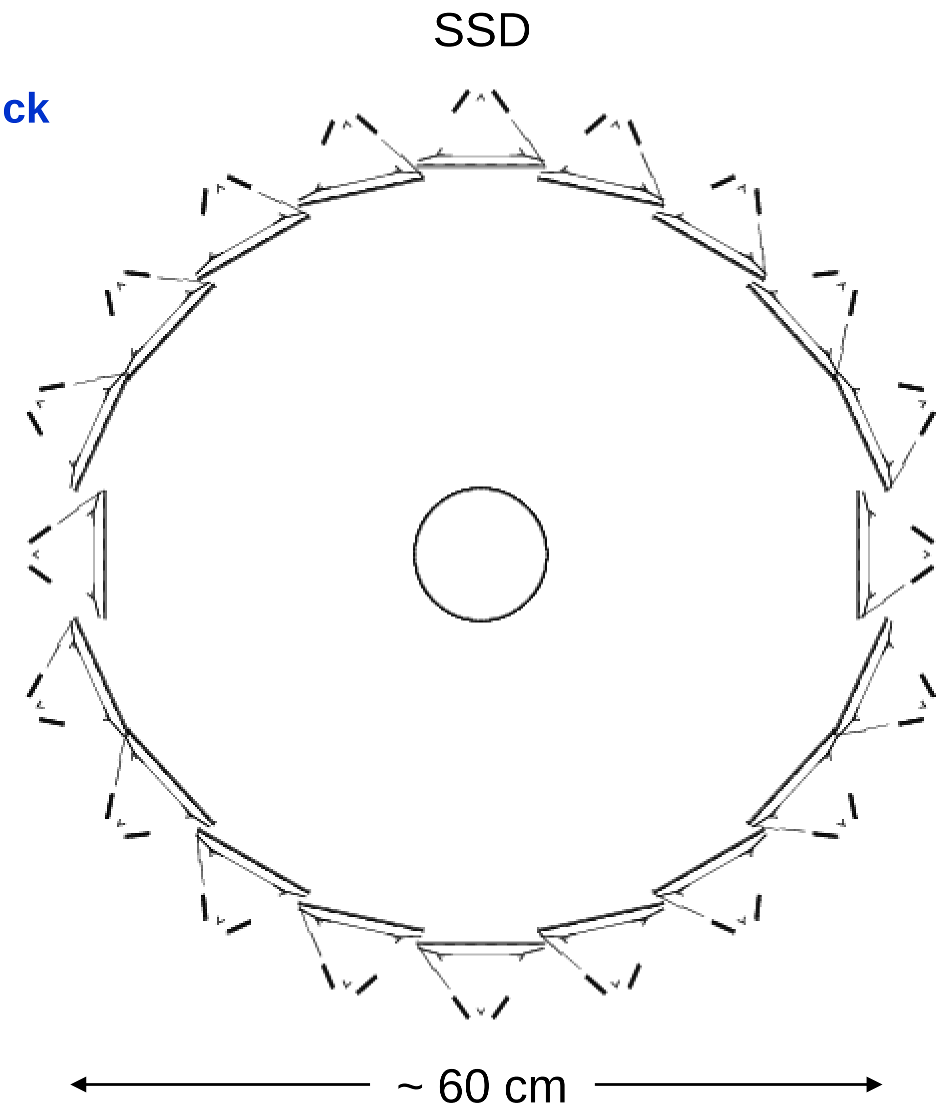




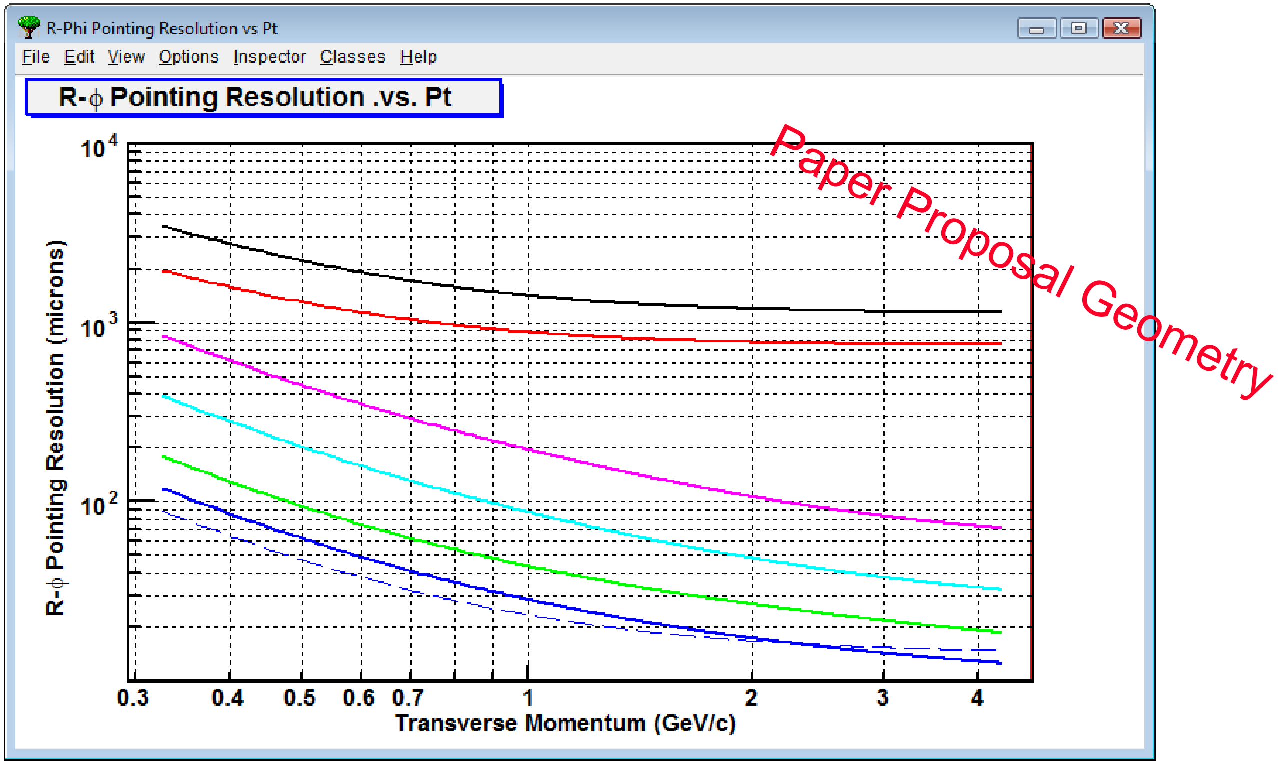
- **The SSD is thin**
  - **1% - double sided Si**
- **The SSD lies at an ideal radius**
  - **23 cm - midway between IP and IFC**
- **The SSD has excellent resolution**
  - **(rumor says better than design)**
- **The SSD is too large to be replaced**
  - **The money is better spent, elsewhere**

SSD Parameters

- Double sided Si wafers 300 μm thick with 95 μm x 4.2 cm strips
- Crossed at 35 mrad – effectively 30 μm x 900 μm
- One layer at 23 cm radius
- 20 ladders, 67 cm long
- air cooled
- $|\eta| < 1.2$
- 1 % radiation length @ $\eta = 0$



PXL Detectors working with External Tracking

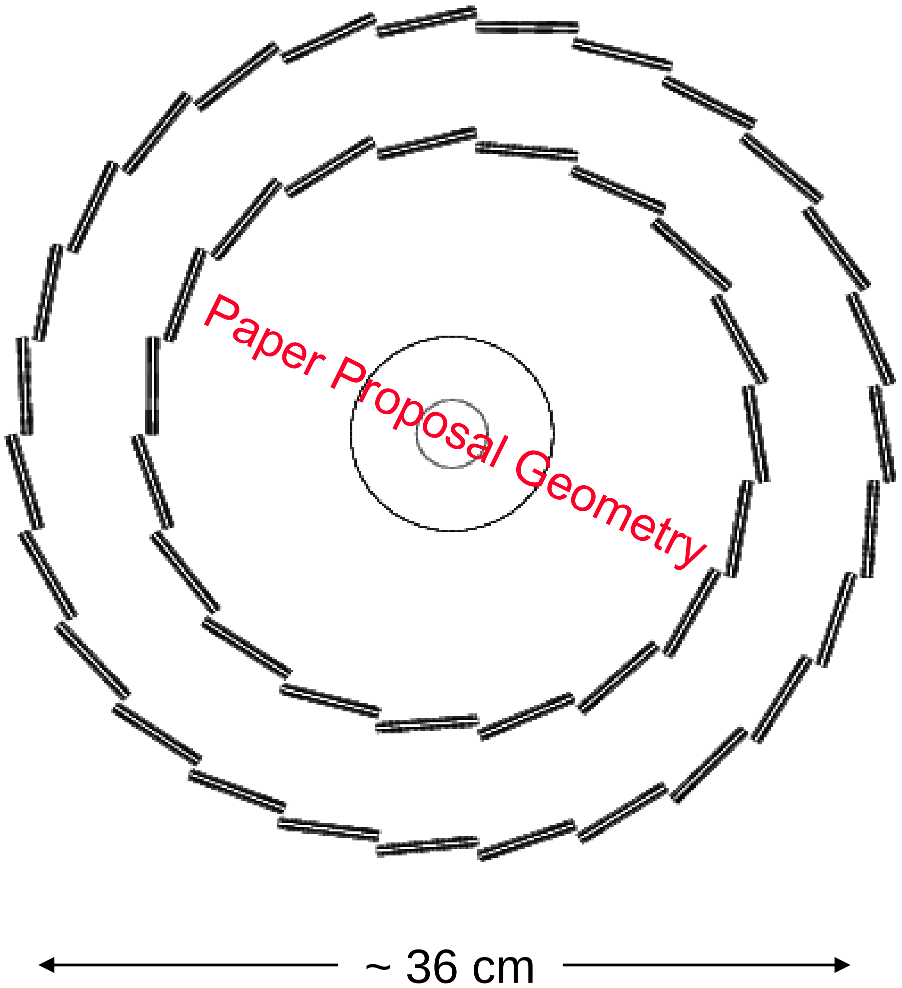


- **A PXL detector requires external tracking to be a success**
- **The TPC and intermediate tracking provide graded resolution from the outside-in**
- **The intermediate layers form the elements of a 'hit finder'**
  - **The spectral resolution is provided by the PXL layers**

IST Parameters in the Proposal Configuration

- Singled sided Si wafers 300 μm thick
  - 60 μm x 4.0 cm strips on IST2
  - 60 μm x 2.0 cm strips on IST1
- Two layers at 17 & 12 cm radius
  - 27 ladders, 52 cm long
  - 19 ladders, 40 cm long
- air cooled
- $|\eta| < 1.2$
- 1.5 % per layer @ $\eta = 0$

Total number of strips/channels	692,480
Number of barrels	2
Number of ladders	46
Outer barrel (27 ladders)	r = 17 cm
Inner barrel (19 ladders)	r = 12 cm
Detector module active area	4 cm × 4 cm
Thickness (outer)	1.5 % X_0
Thickness (inner)	0.75 % X_0
Strip dimension (outer)	60 μm × 4 cm
Orientation of strips (outer)	best resolution in z and r-ϕ
Strip dimension (inner)	60 μm × 2 cm
Orientation of strips (inner)	best resolution in r-ϕ
Resolution of one strip	17 μm
Pseudo-rapidity coverage	± 1.2 units



PXL Parameters in the Proposal Configuration

- Active Pixel Sensors,
  - thinned to 50 μm thickness
  - 30 μm x 30 μm pixels
- Two layers at 7 & 2.5 cm radius
  - 24 ladders, 19.2 cm long
  - 9 ladders, 19.2 cm long
- air cooled
- $|\eta| < 1.2$
- 0.28 % radiation length @ $\eta = 0$

Number of pixels	135,168,000
Pixel dimension	30 μm × 30 μm
Resolution of one pixel	9 μm
Detector chip active area	19.2 mm × 19.2 mm
Detector chip pixel array	640 × 640
Number of ladders	33
Ladder active area	192 mm × 19.2 mm
Number of barrels	2
Outer barrel (24 ladders)	r = 7.0 cm
Inner barrel (9 ladders)	r = 2.5 cm
Frame read time	0.2 msec
Pseudo-rapidity coverage	± 1.2 units
Thickness: Si on ladder (w/Al cable)	0.28 % X_0
Beam pipe thickness	0.5 mm or 0.14 % X_0