HFT Performance & Simulation Studies

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

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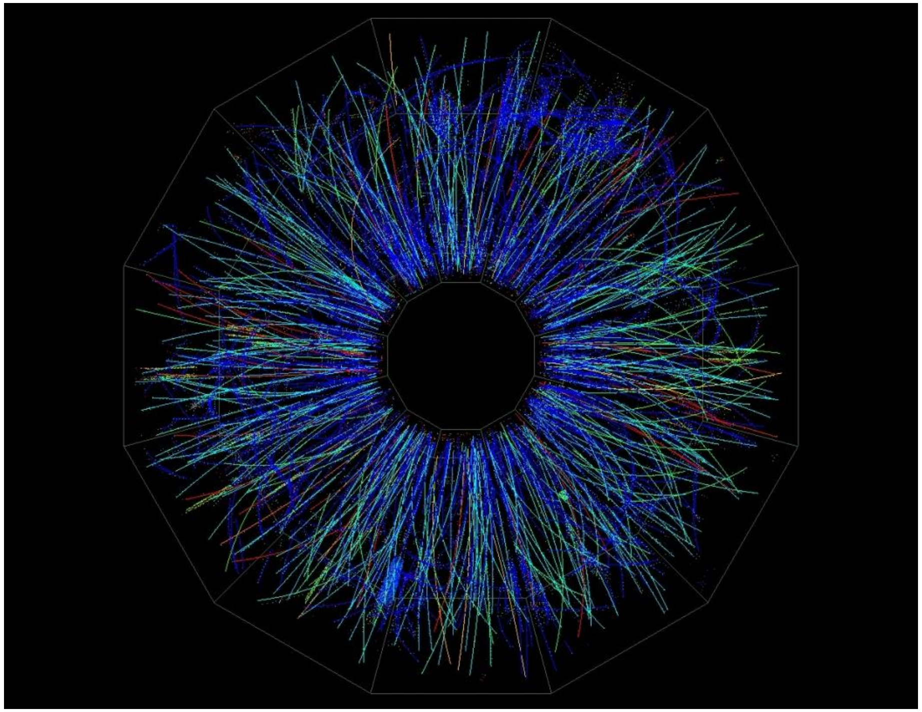
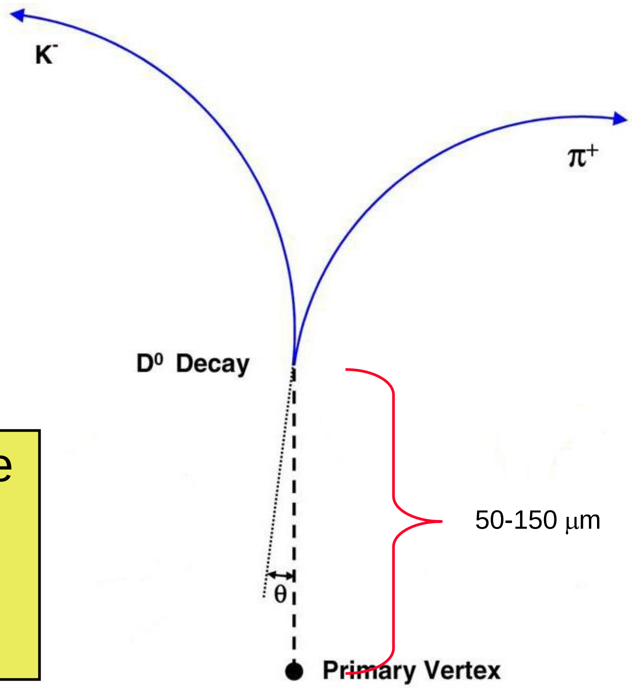
The Properties of the Open Charm Hadrons

Particle	Decay Channel	$c\tau$ (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



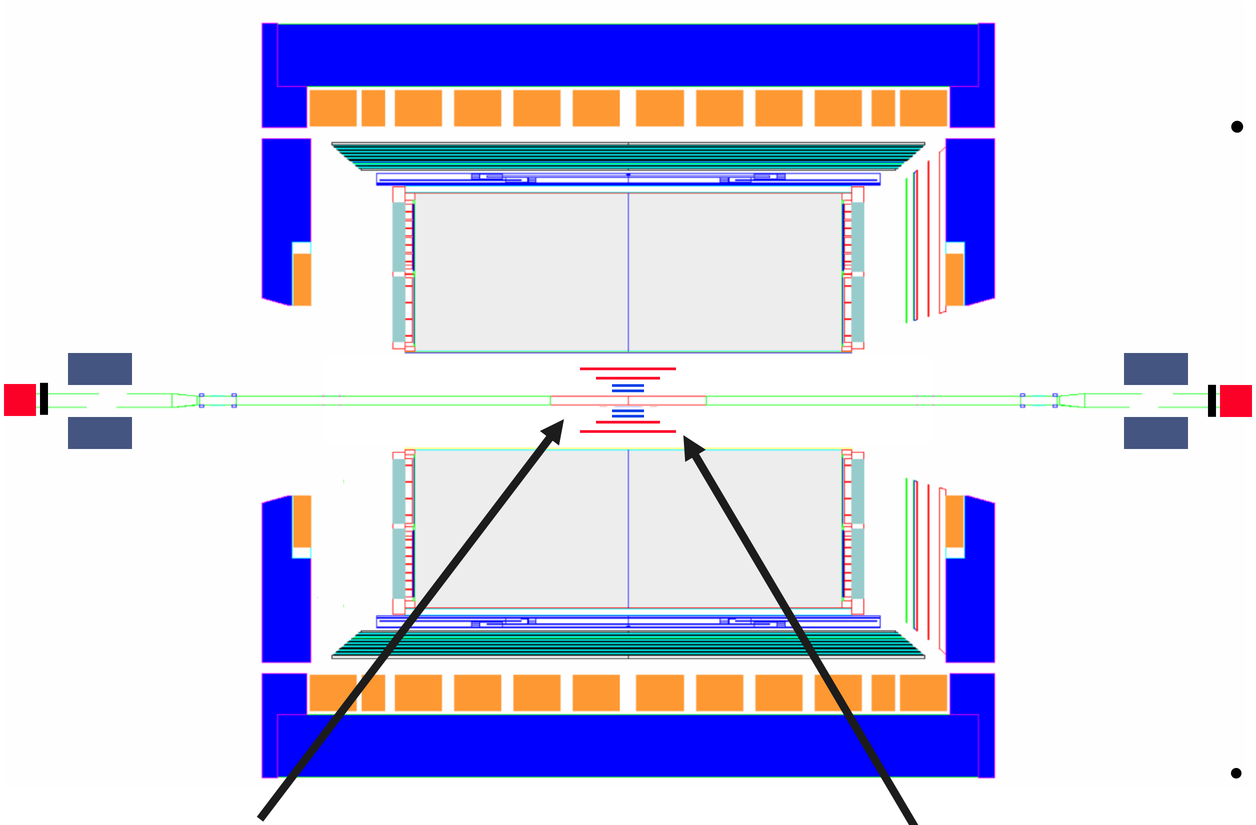
Goal: Distinguish secondary from primary vertices by putting a high precision detector near the IP to extend the TPC tracks to small radius



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



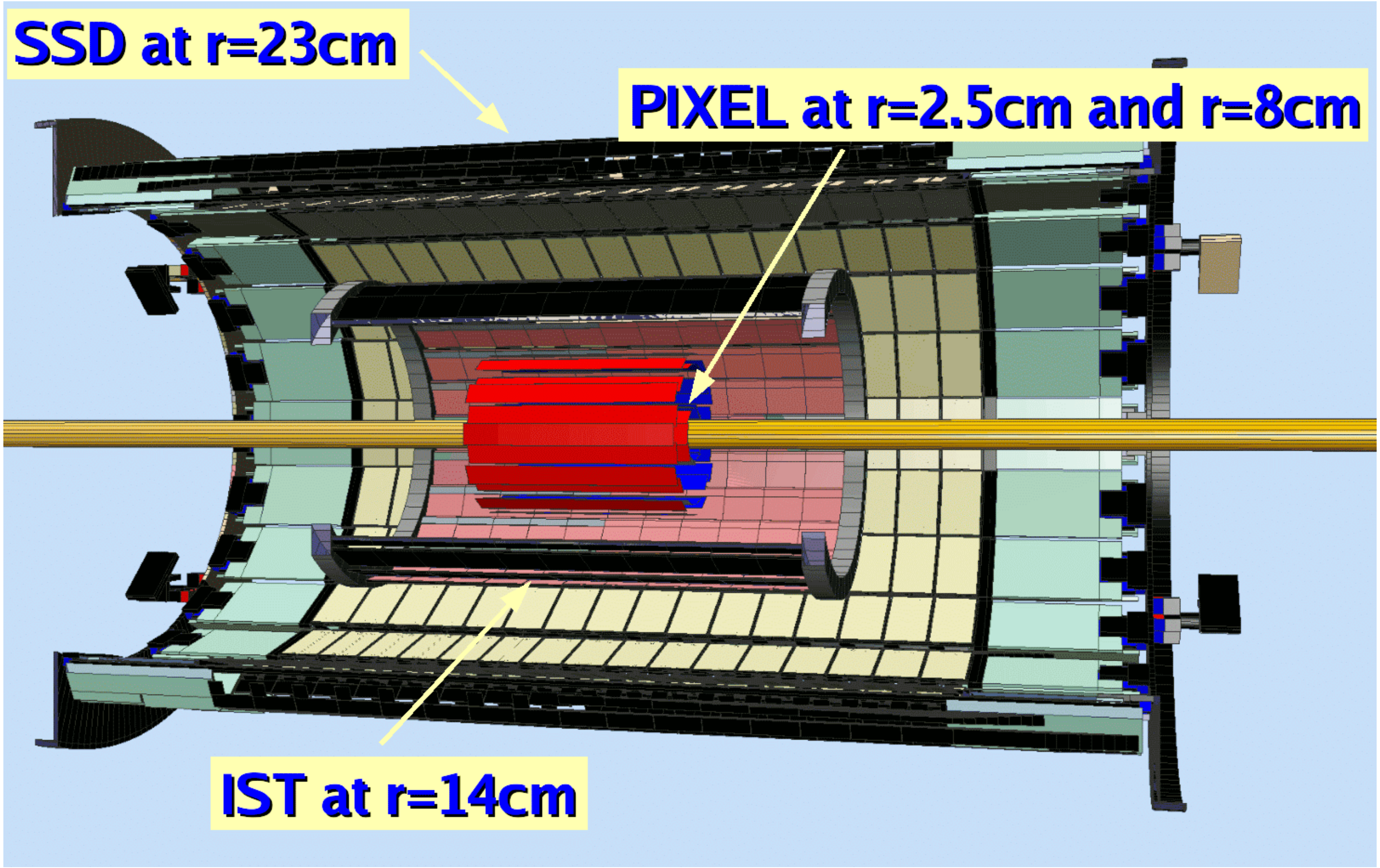
PXL: 2 layers of Si at small radii

IST: 1 layer of Si at intermediate radius

SSD: an existing detector at 23 cm radius

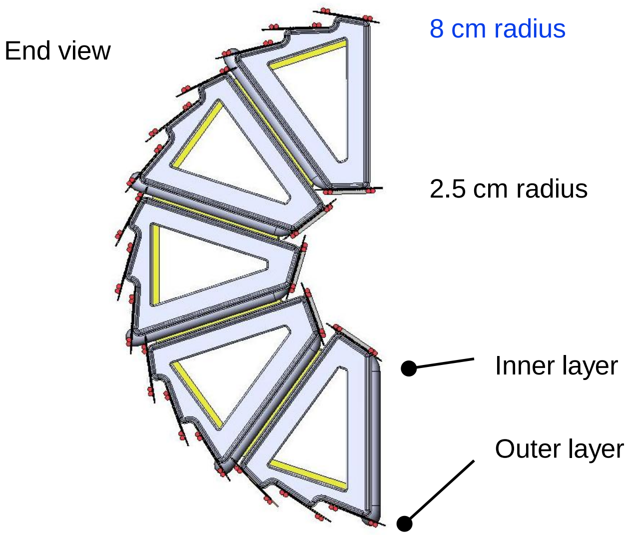
- A new detector
  - 30 μm silicon pixels to yield 10 μm space point resolution
- Direct Topological reconstruction of Charm
  - Detect charm decays with small cτ, including $D^0 \to K\ \pi$
- New physics
  - Charm collectivity and flow to test thermalization at RHIC
  - Charm Energy Loss to test pQCD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

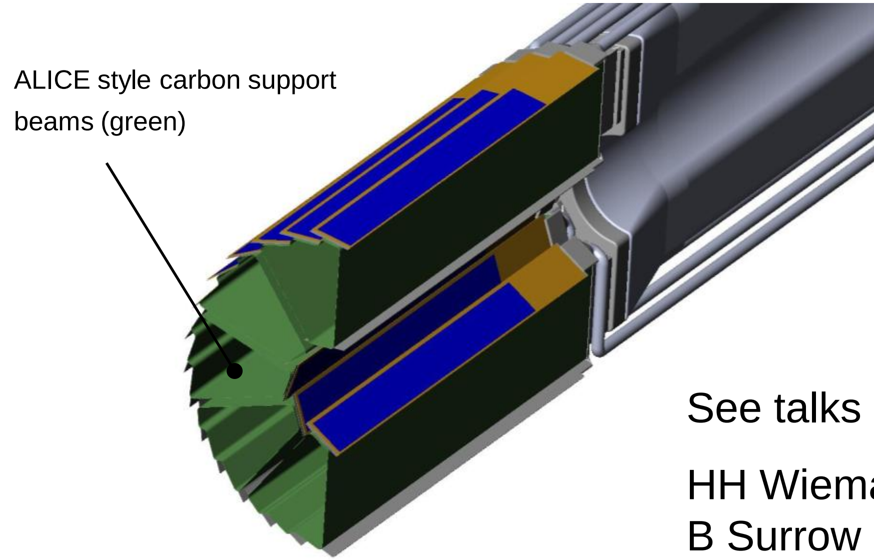
Optimized HFT Configuration



The HFT configuration described in the Addendum

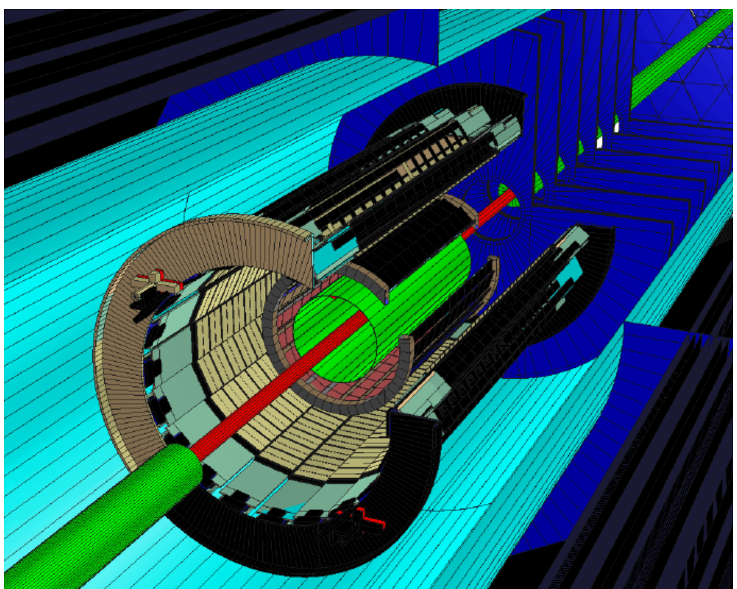
Pixel & IST – optimizations and progress





See talks by

HH Wieman
B Surrow

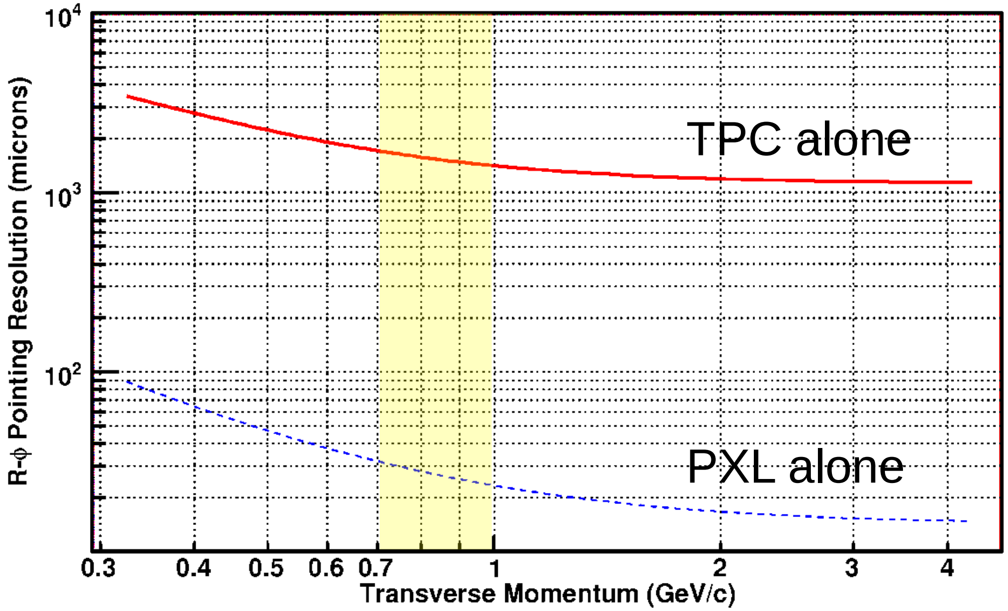


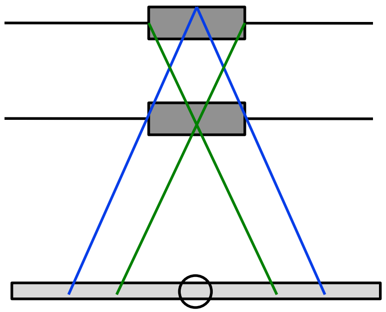
- One IST layer at 14 cm
- Good performance
- Utilizes the existing SSD
- Fewer channels
- Lower cost
- Extra space for PXL layers
- Basic Parameters
  - Short strips (< 1 cm)
  - Wide strips (~ 500 μm)
  - Approx 150 μm x 2000 μm resolution

The proposed changes and optimizations have been verified with hand calculations and are scheduled to be put thru a full system test with GEANT/ITTF simulations.

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**



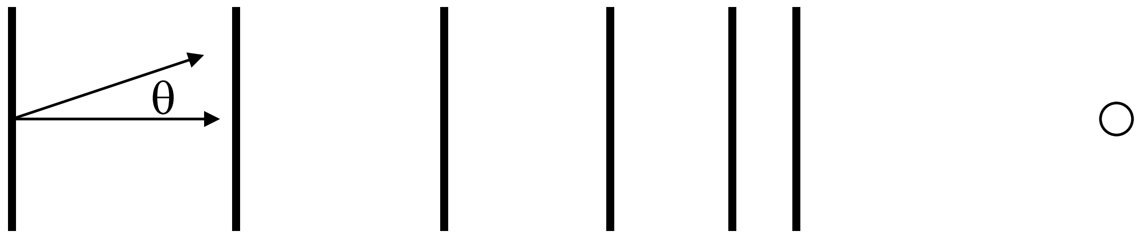


$$\sigma^2 = \frac{\sigma_1^2 r_2^2 + \sigma_2^2 r_1^2}{(r_2 - r_1)^2} + \frac{\theta_{mcs}^2 r_1^2}{\sin^2(\theta)}$$

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

- **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 = 123 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

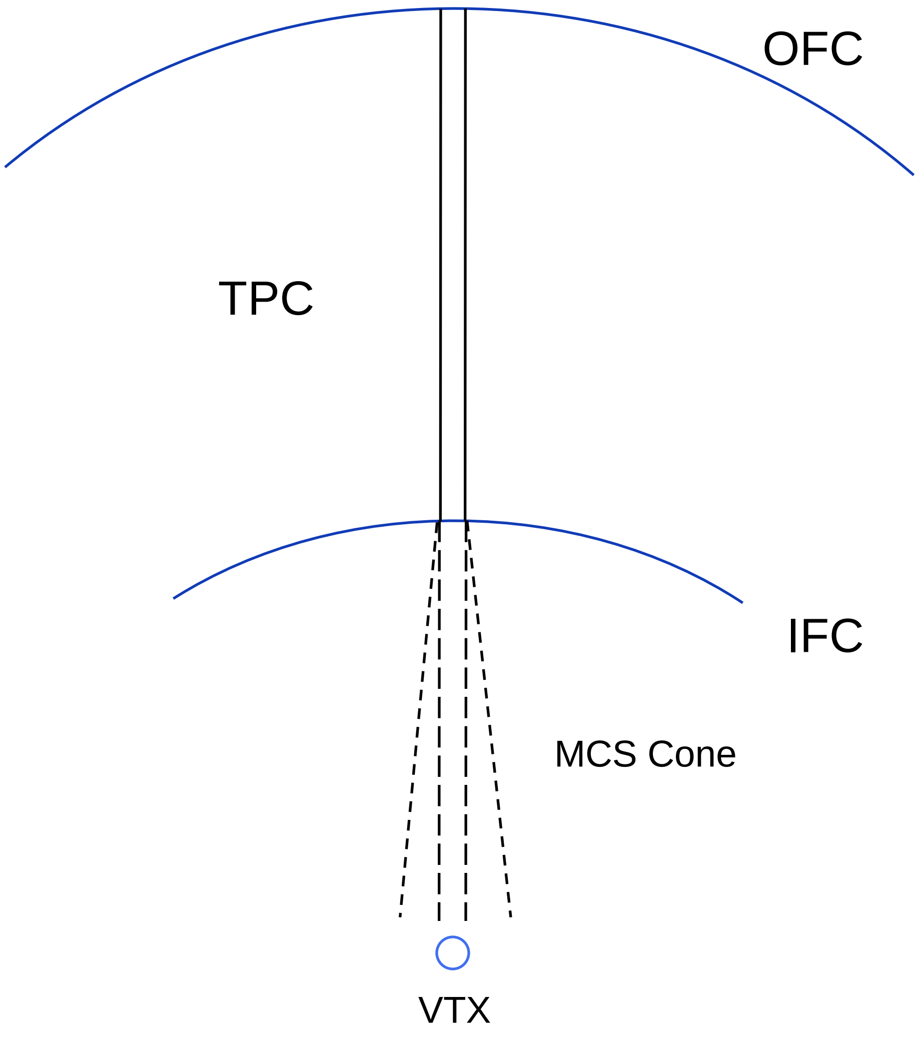


$$[MCS][D][M][MCS][D][M][MCS] \quad \bullet \quad \bullet \quad \bullet$$

- **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**
- **ITTF tracking software 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.**

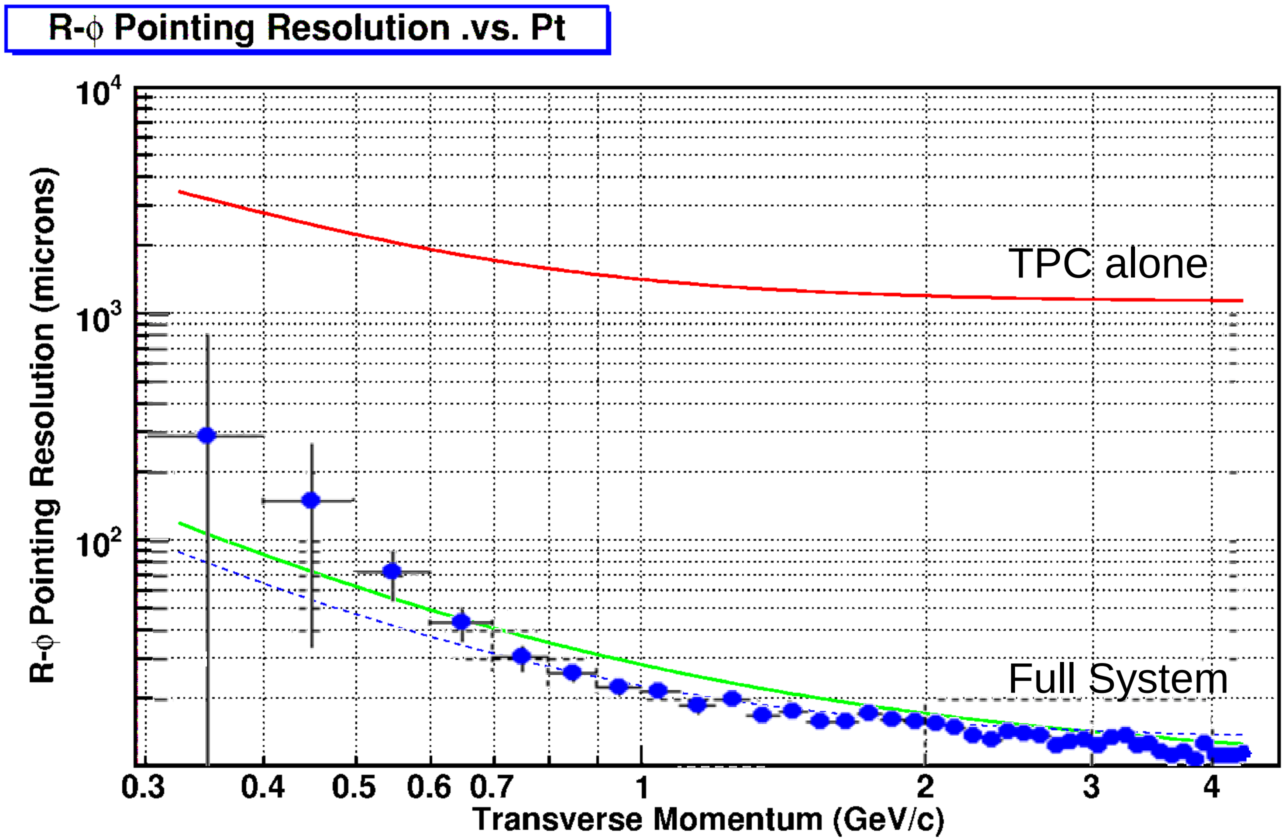
Getting a Boost from the TPC

- **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



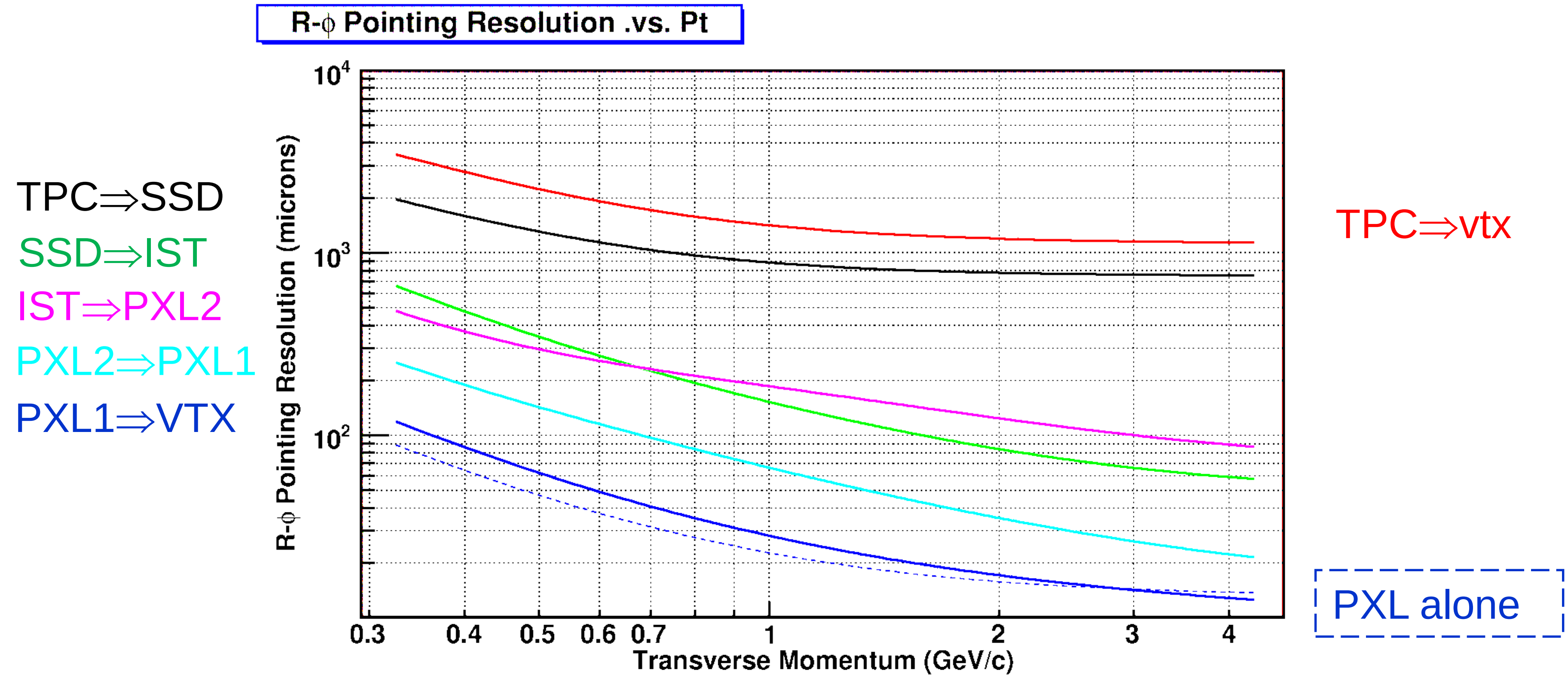
- - - - PXL stand alone configuration

—— Paper Proposal configuration

● ● ● GEANT & ITTF

—— 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 spatial 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

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

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

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 Formulas	HIJING thru GEANT
PXL 1	2.5 cm	17.8 cm^{-2}	19.0 cm^{-2}
PXL 2	8.0 cm	1.7 cm^{-2}	1.8 cm^{-2}
IST	14.0 cm	0.57 cm^{-2}	0.66 cm^{-2}
SSD	23.0 cm	0.21 cm^{-2}	0.23 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

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

An area

A density, depends on τ and pileup

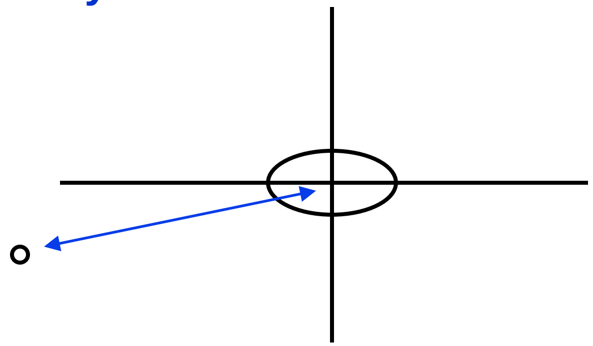
P(bad association) $\approx 2\pi\, \sigma_x\, \sigma_y\, \rho$

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 (cm^{-2})**
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

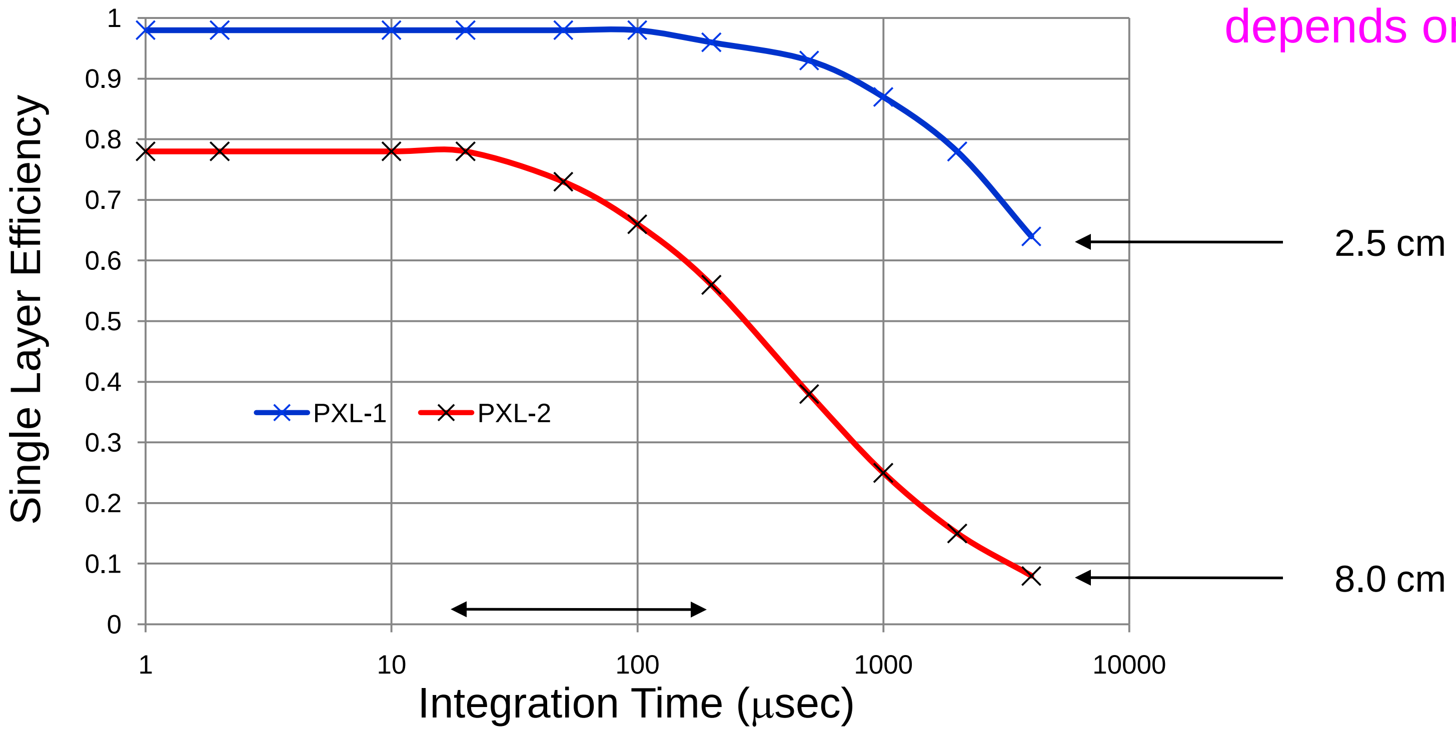
This is surprising: The hard work gets done at 8 cm!

The performance of the TPC pointing at the PXL

- **The performance of the TPC acting alone to point at the PXL detector depends on the integration time of the PXL chips**

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

depends on τ

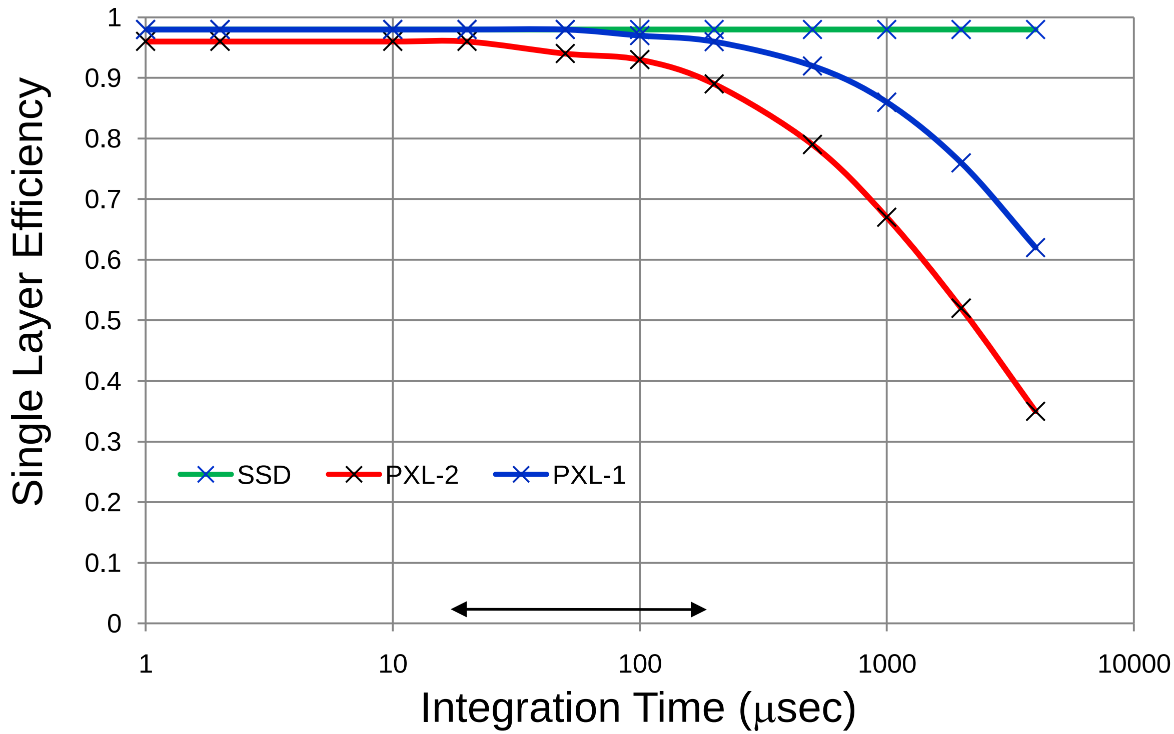


The purpose of intermediate tracking layers is to make 55% go up to ~100%

The performance of the TPC + SSD + PXL

- **The performance of the TPC + HFT 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 $S = 2\pi\,\sigma_x\,\sigma_y\,\rho$**

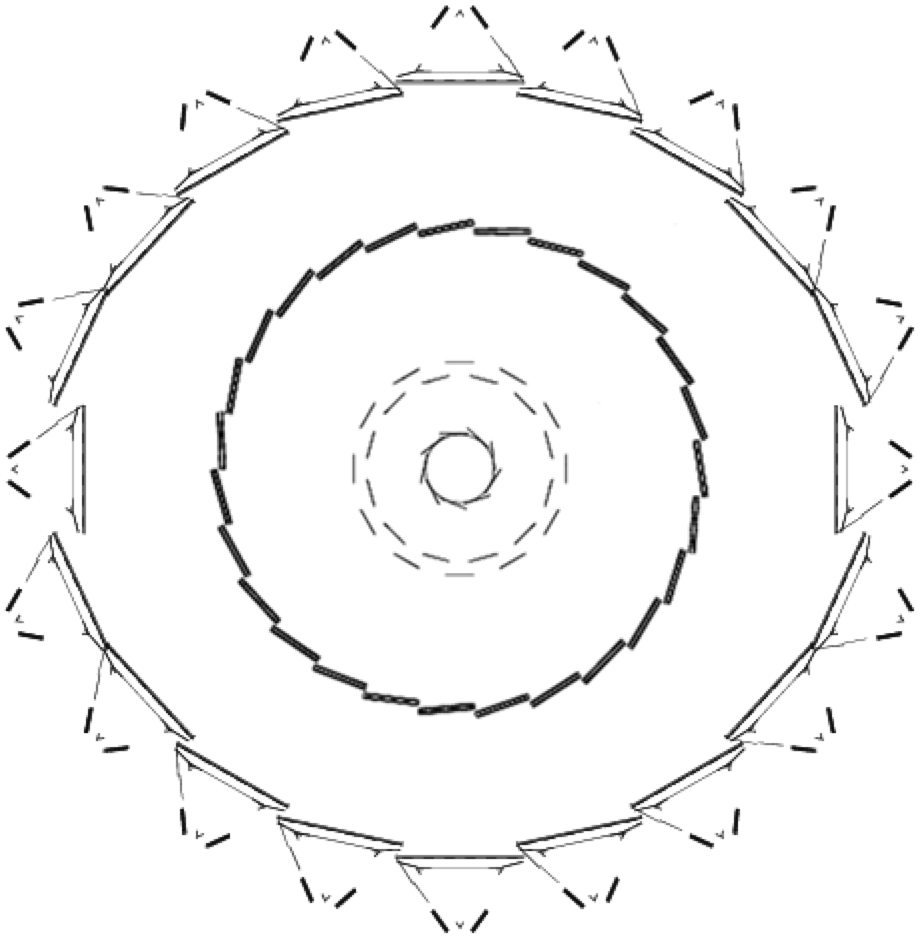


Note that systematic errors are not included in the hand calculations nor in the GEANT Simulations

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

The performance of the TPC + SSD + IST + PXL

- **Goal: graded resolution and high efficiency from the outside → in**
- **TPC – SSD – IST – PXL**
- **TPC pointing resolution at the SSD ~ 1 mm** **ε = 0.98**
- **SSD pointing at the IST is ~ 400 μm** **ε = 0.98**
- **IST pointing at PXL 2 is ~ 400 μm** **ε = 0.93**
- **PXL 2 pointing at PXL1 is ~ 125 μm** **ε = 0.94**
- **PXL1 pointing at the VTX is ~ 40 μm**

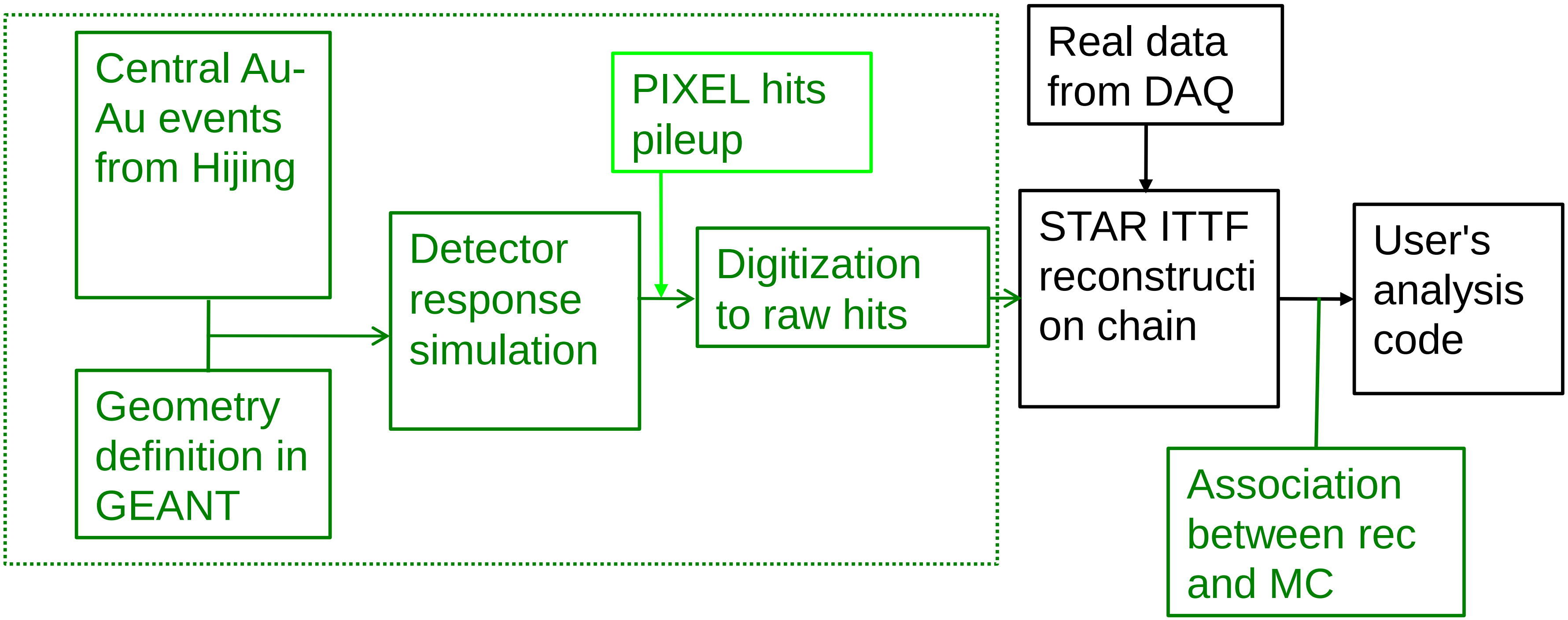


~ 50 cm

Raw HFT Tracking Efficiency: 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 Tot = 0.55

Monte Carlo Simulation Strategy & Updates



<u>D^0 Measurements:</u> dN/dy per NN collision ~ 0.004 (STAR)
we take half of this as our estimate of the rate

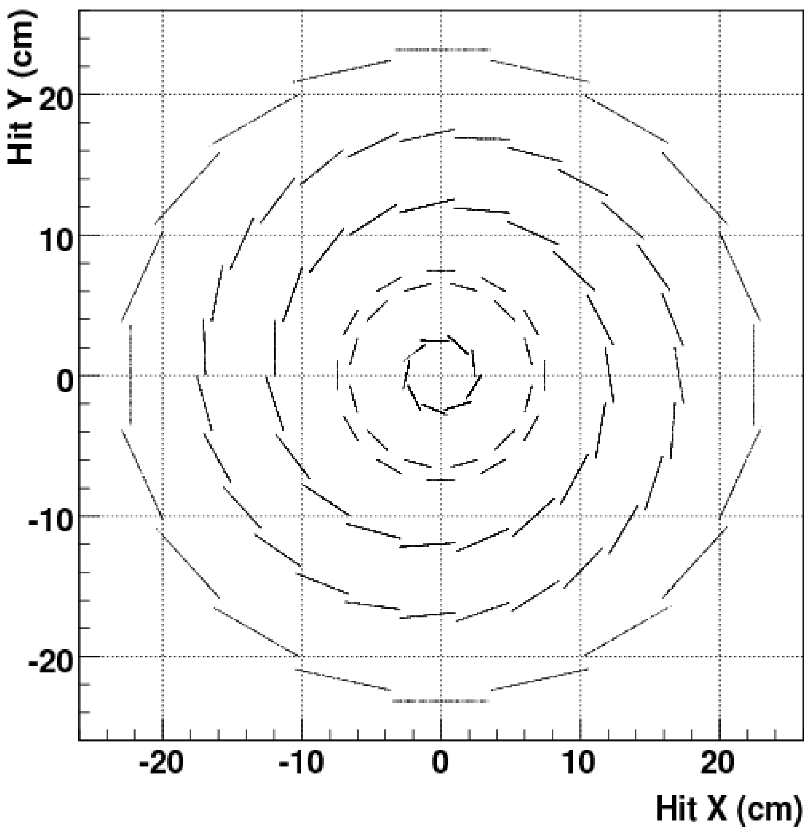
<u># Hits selection in PIXEL:</u> MC hits and Rec hits can be > 2
we include these tracks

<u>D^0 Background:</u> K from D decays and π from other decays -- important at high p_T. $D^0 \to K^- + X$ (53%)

<u>PID with TOF</u>: Assume perfect K/π at $p_T < 1.5$ GeV/c, no PID for K/π beyond that. Background also includes PID contamination.

Geometry definition in MC and event sample

Hit position in silicon layers from MC

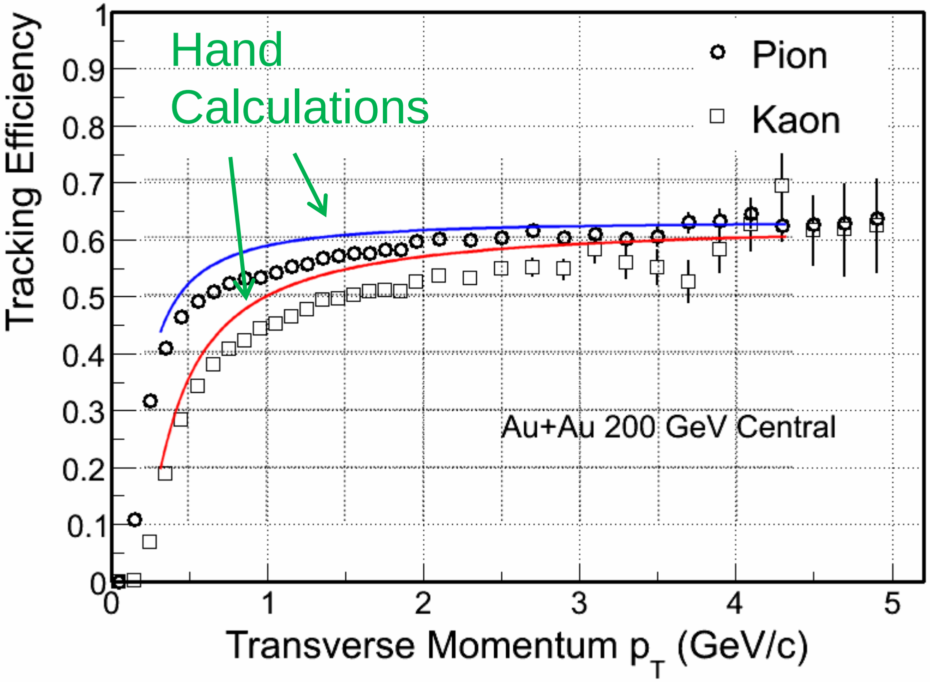


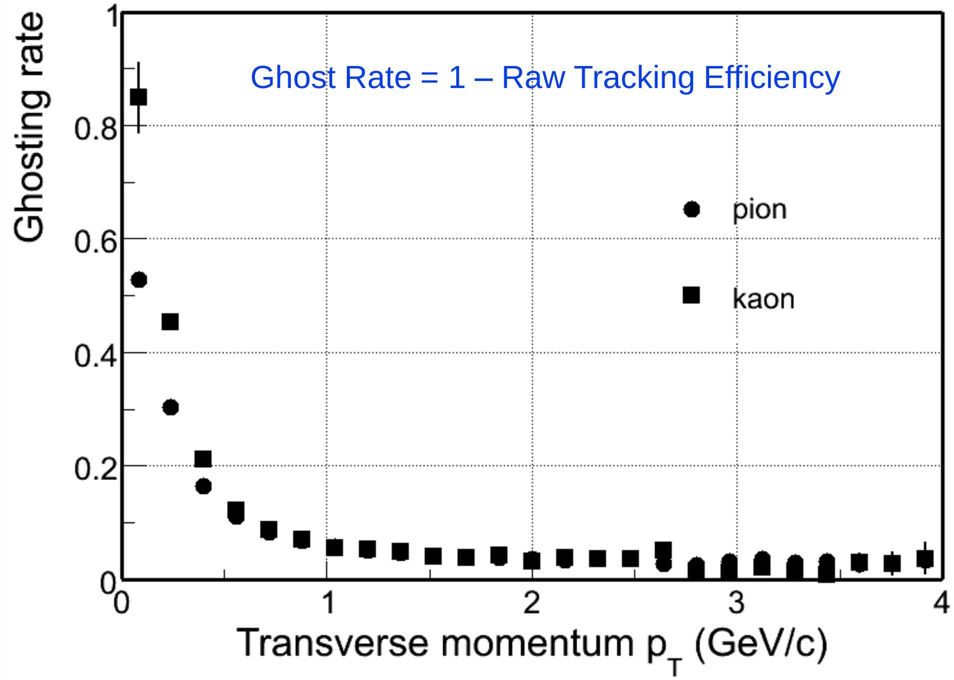
Segment sizes and resolutions

	R (cm)	Dimension ($r\phi \times z$) ($\mu m \times \mu m$)	Tracking $\sigma_{r\phi} \times \sigma_z$ ($\mu m \times \mu m$)
SSD	23	95×42000	30×699
IST2-B	17	60×40000	17×11000
IST2-A	17	40000×60	11000×17
IST1	12	60×20000	17×5500
PIXEL2	7	30×30	9x9
PIXEL1	2.5	30×30	9x9

Central (b = 0-3 fm) Au-Au Hijing + 10 D^0 per event (flat p_T, eta)
|Vertex_z| < 5 cm $D^0 \rightarrow K^- + \pi^+$ BR=100%

Single Track Efficiencies & Ghosting





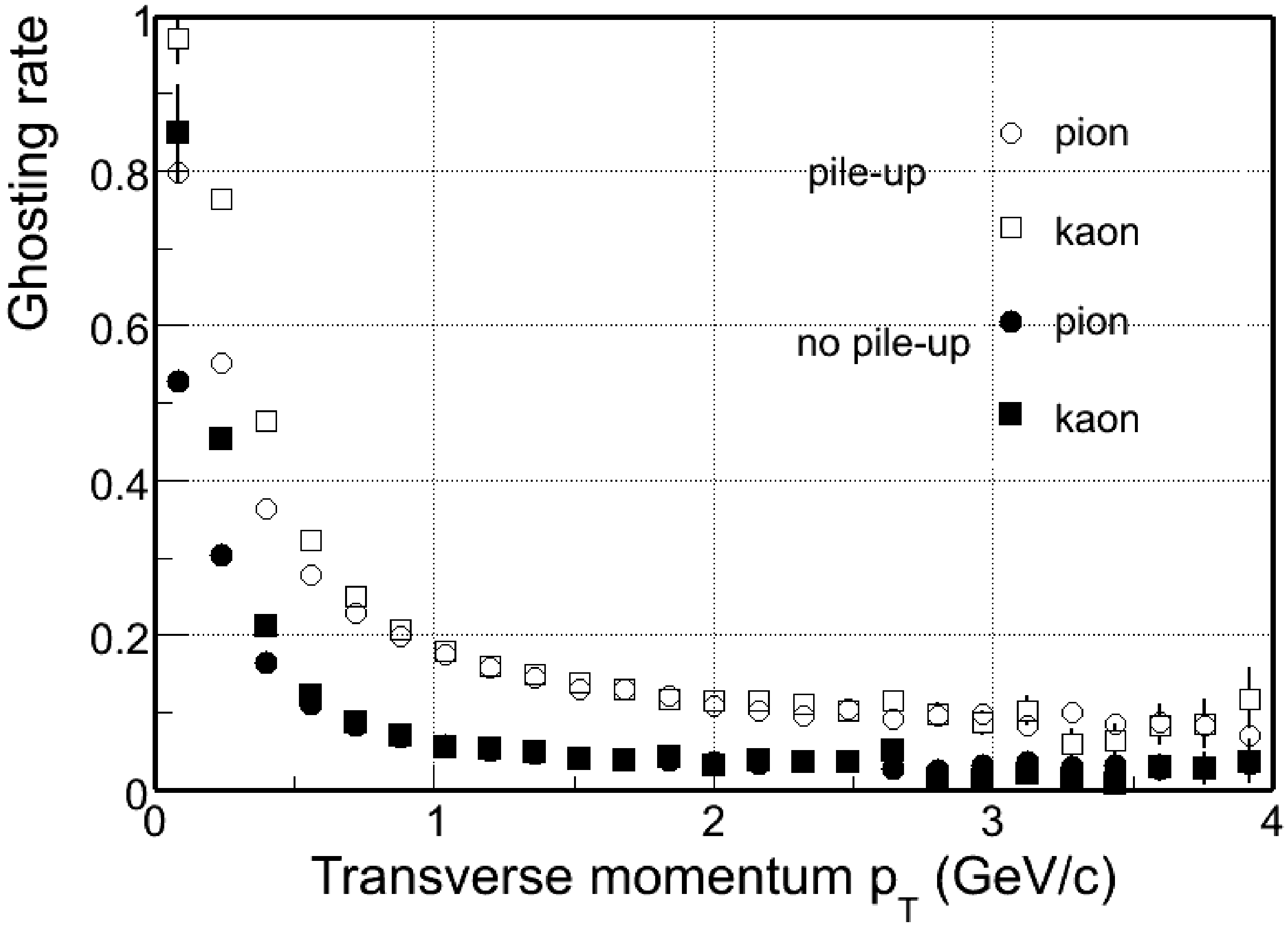
Au + Au central collisions @ 200 GeV

- TPC tracking efficiency ~80-85%
- Ghosting =

$$\frac{\text{\# of tracks with 2 PIXEL hits \& either of 2 PIXEL hits is a wrong hit}}{\text{\# of track with 2 PIXEL hits}}$$

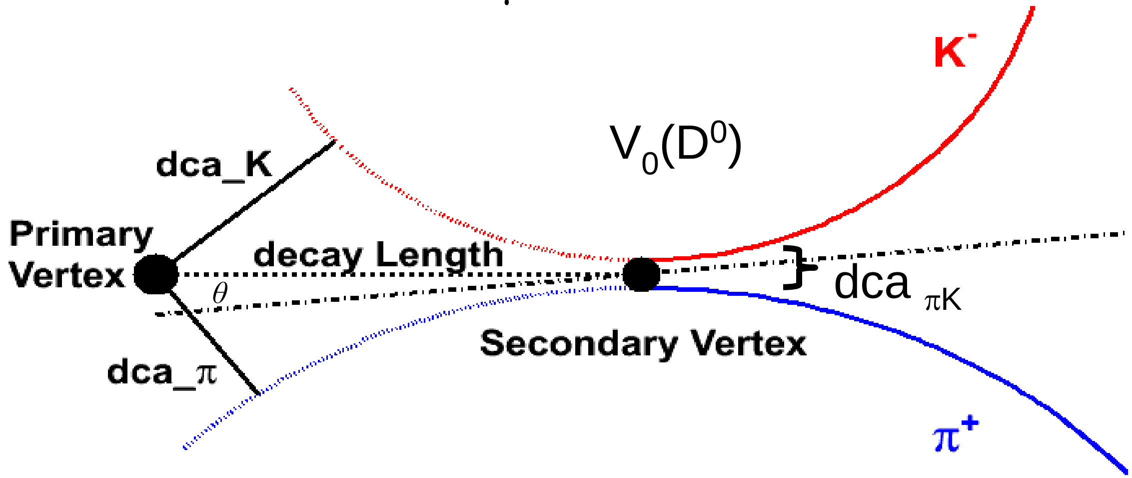
Ghosting increases as pileup increases

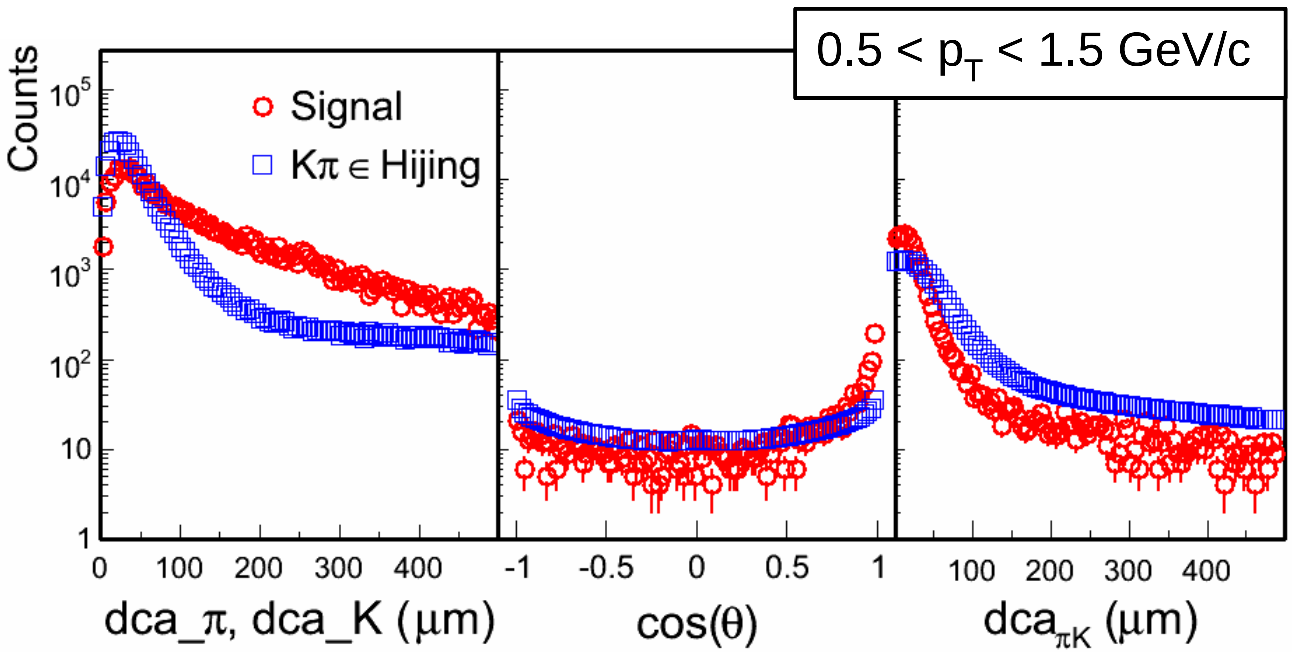
Pile-up level: 1x RHIC II luminosity



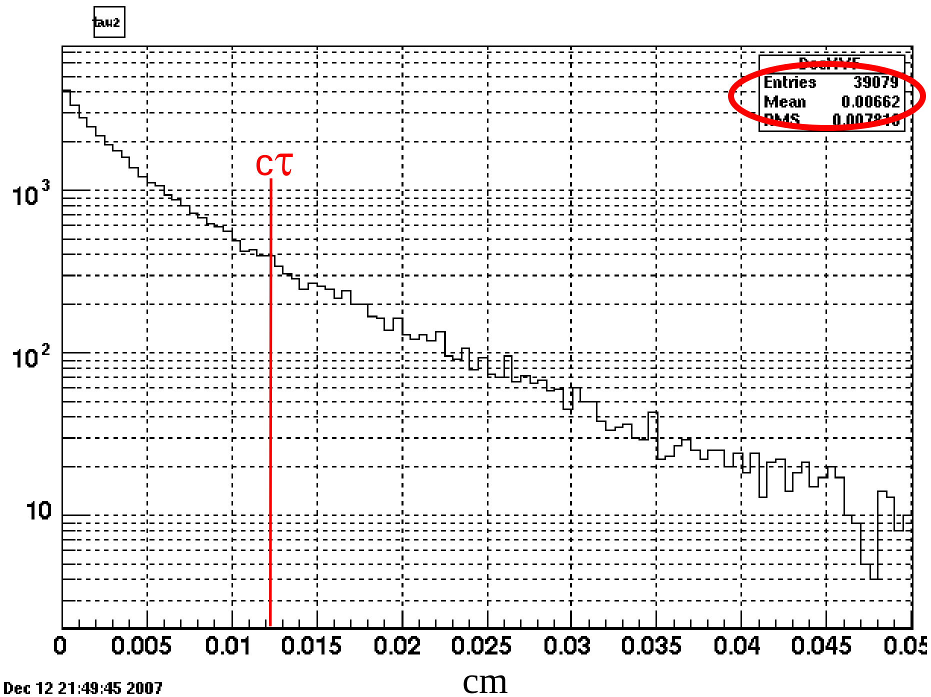
D^0 reconstruction

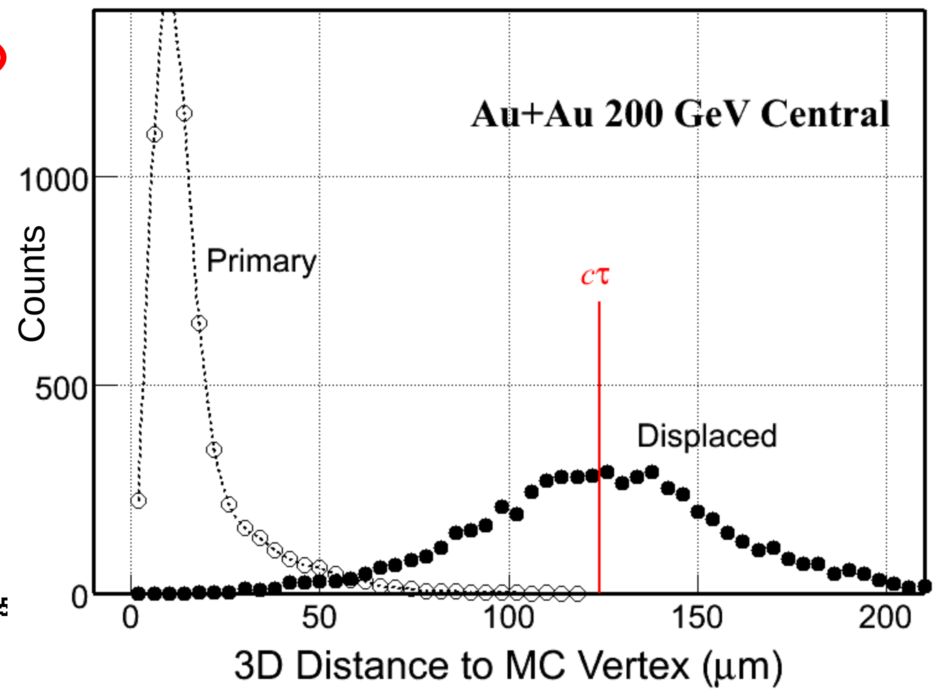
$M_{D0} = 1.8645 \text{ GeV}/c^2$ $\quad c\tau = 123 \ \mu m$





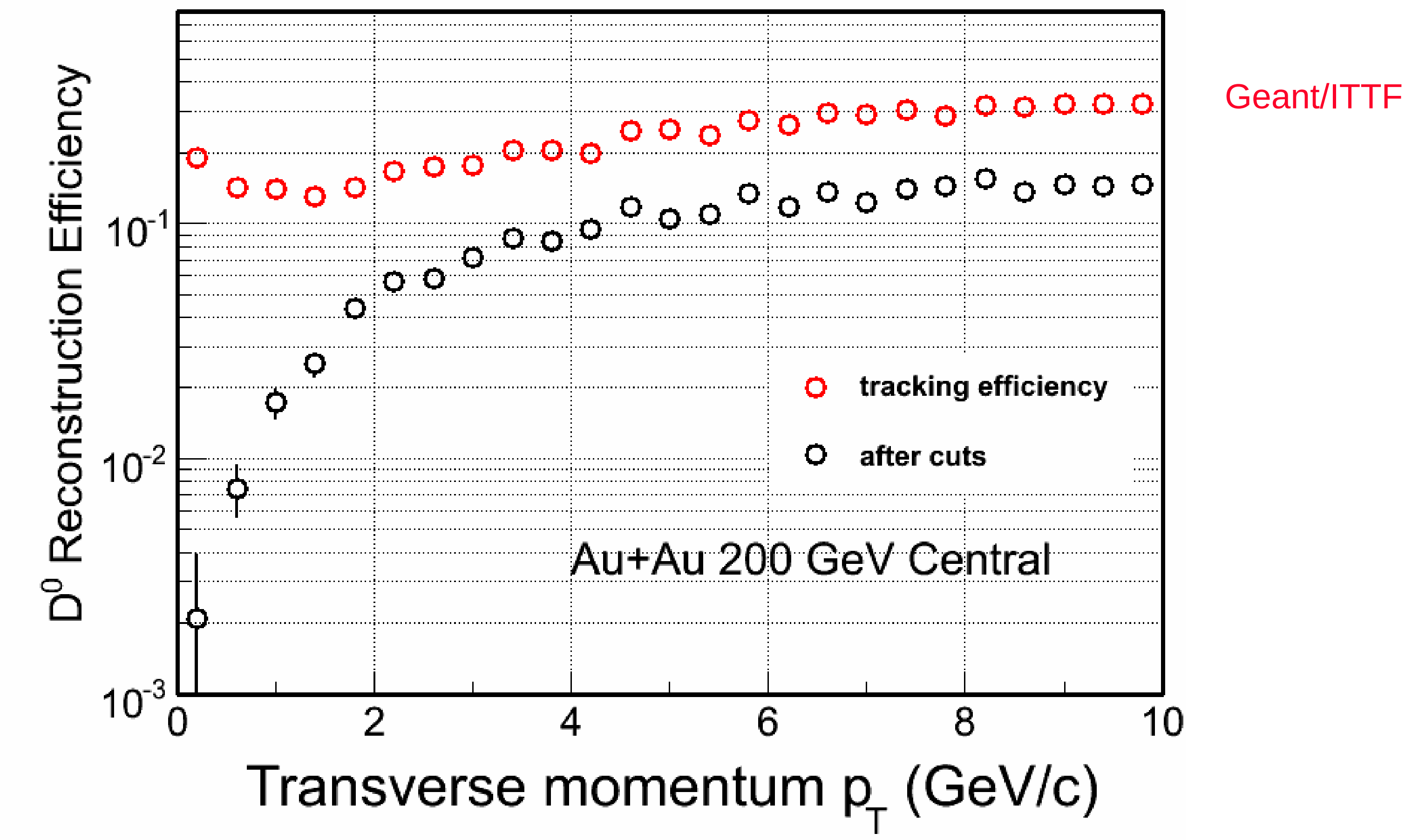
Secondary Vertex Resolution





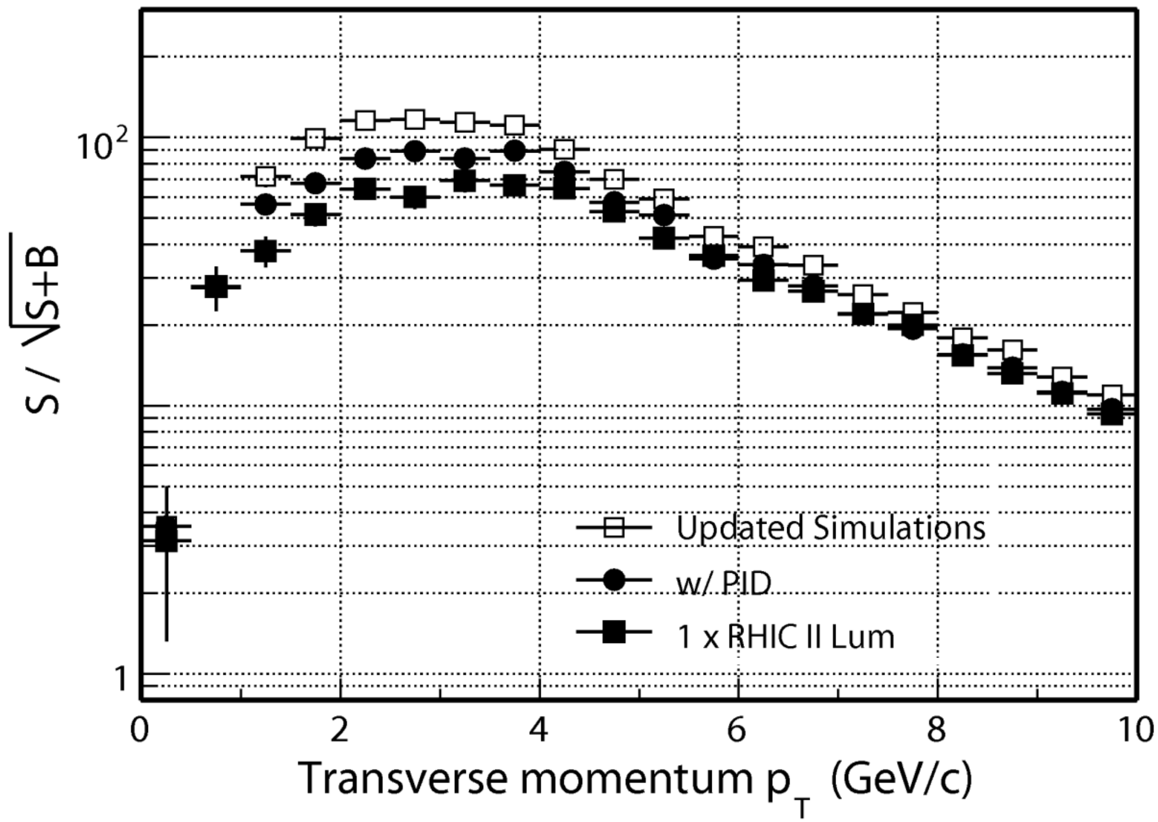
- Left figure, observed decay length (including realistic p_T weighting)
- Right figure, D^0 decay length scaled by a factor of $1/\beta\gamma$
- No beamline constraint required …
- In central AuAu collisions, the D^0 secondary vertices are clearly separated from the primary vertex

D^0 Reconstruction Efficiency



- **The predicted <u>absolute</u> efficiency of the HFT detector.**
  - **The red squares show the efficiency for finding the D^0 meson with the full set of Geant/ITTF techniques. The black circles show the efficiency AFTER cuts.**
- **The tracking efficiency is improved by 20-30% compared to the simulation in the proposal. Mostly due to improved hit selection in PXL.**

Improved understanding of signal / background

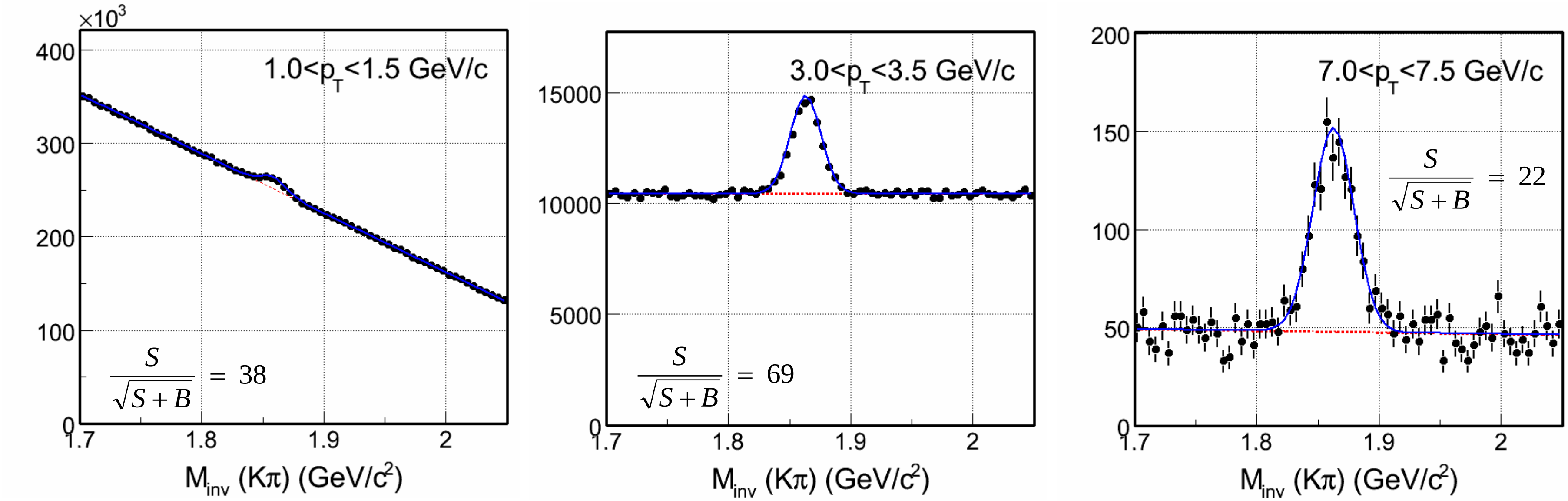


100 M Au+Au central
@ 200 GeV

$|\eta| < 1$, $D^0+\overline{D}^0$

- ➢Updated:
  - ✓ S: D^0 yield dN/dy = 2
  - ✓ Loosen the # of PIXEL hits selection
  - ✓ D^0 background in more real estimation
- ➢ Assume perfect PID at p_T<1.5 GeV and no PID at p_T>1.5 GeV/c

D^0 expected invariant mass distributions

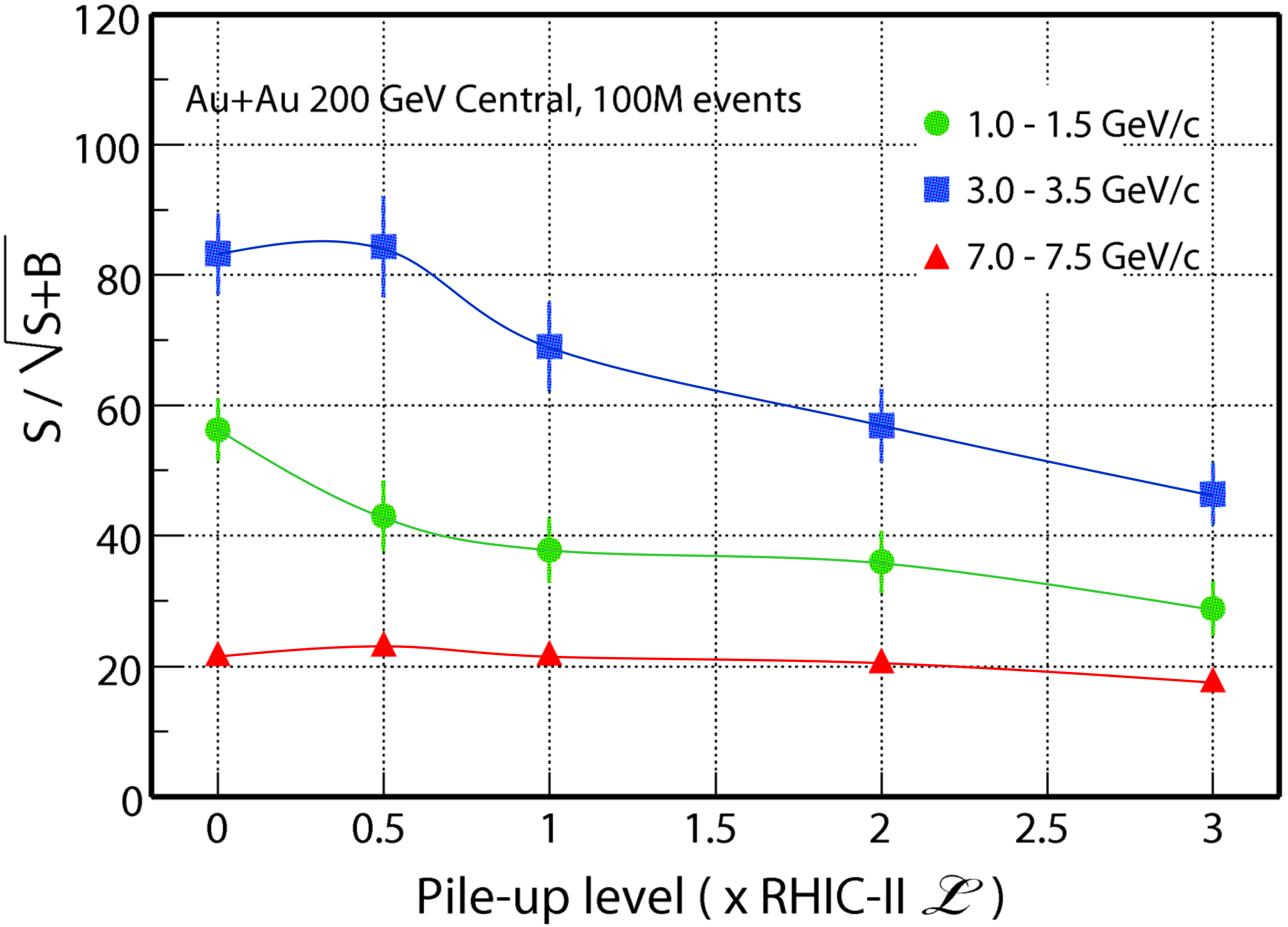


p_T

For 100 M Au+Au central collisions at 1x RHIC II luminosity

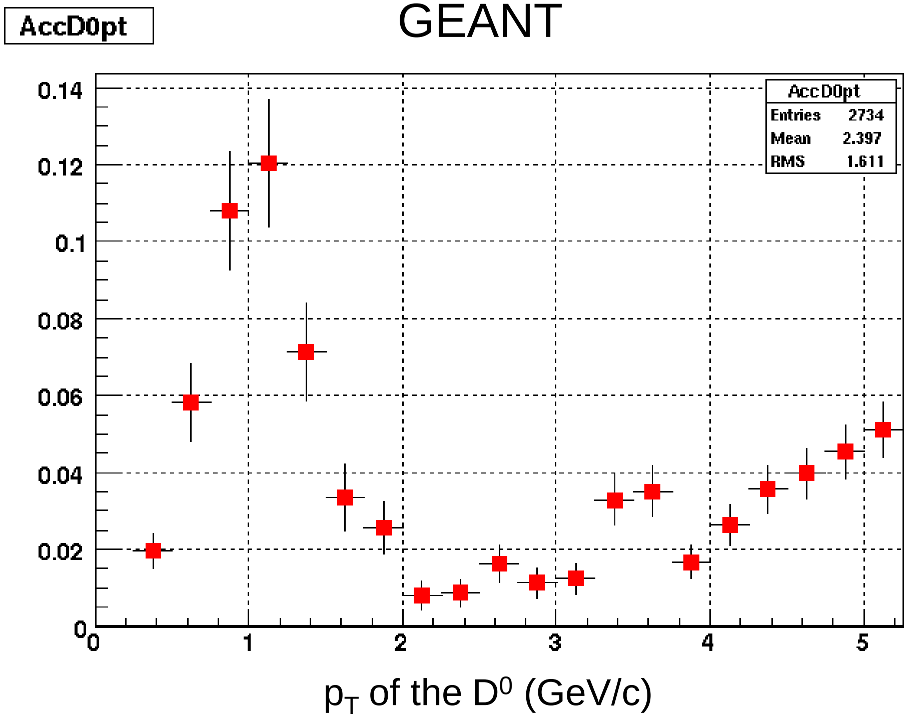
p_T distributions for (S,B) at high p_T are from power-law guess and Hijing, respectively.
D^0 Background slope at high p_T could be uncertain due to limited statistics in MC.

D^0 S,B evolution with different pileup levels

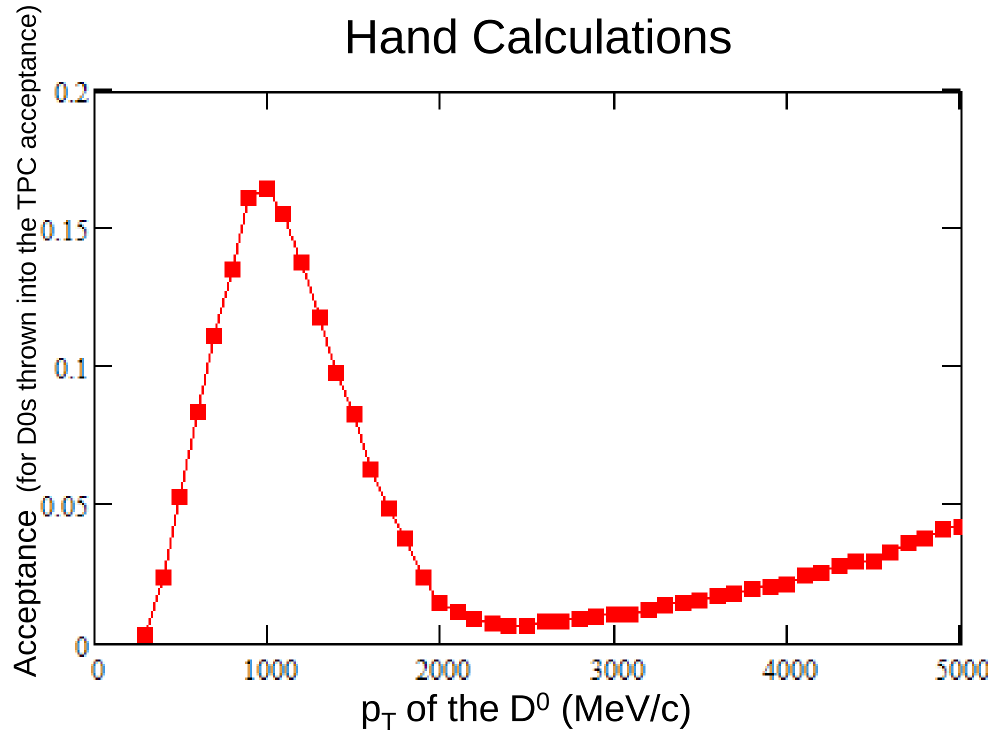


Pixel Prototype – Geant .vs. Hand Calculations

GEANT



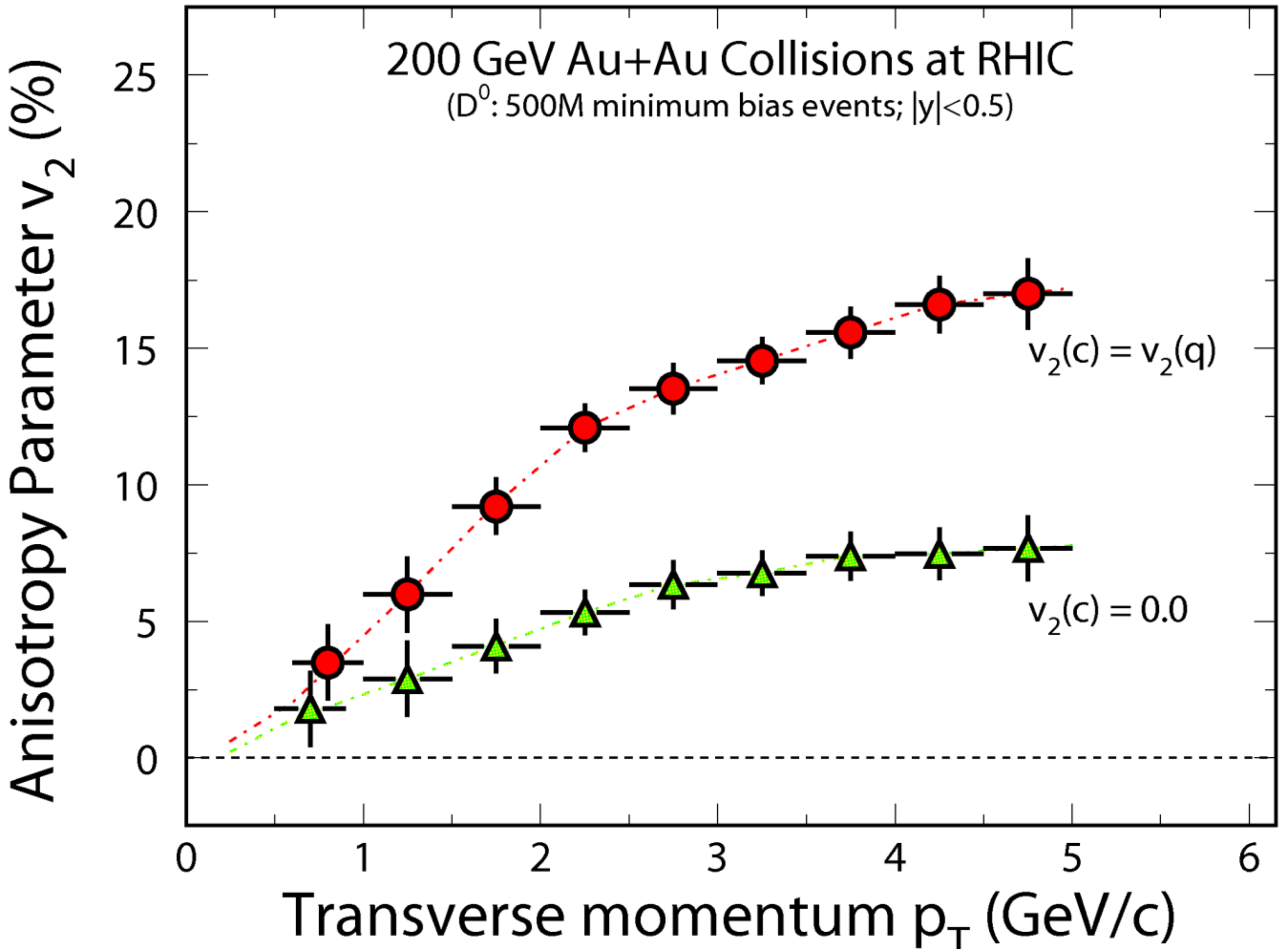
Hand Calculations



3 patches, 120 deg separation, 20 cm in z, 120 chips

- Three arm PXL prototype configuration (early deployment / engineering test)
- Good acceptance around the expected mean p_T of D^0's (i.e. ~1 GeV)
- Ideal to measure charm cross-section via direct topological reconstruction

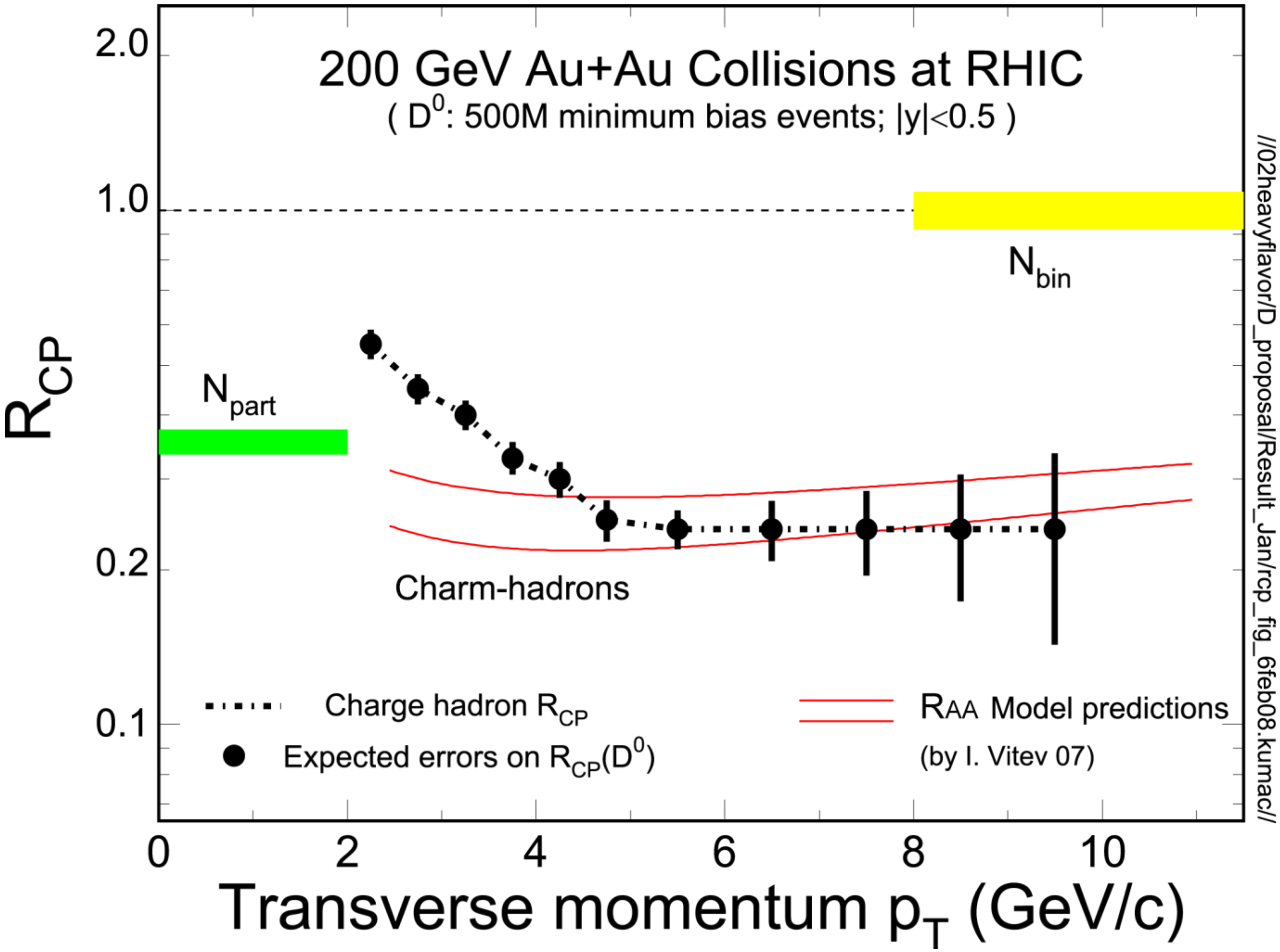
Estimate v_2 sensitivity – focus on the error bars



From central to minimum bias, assume:

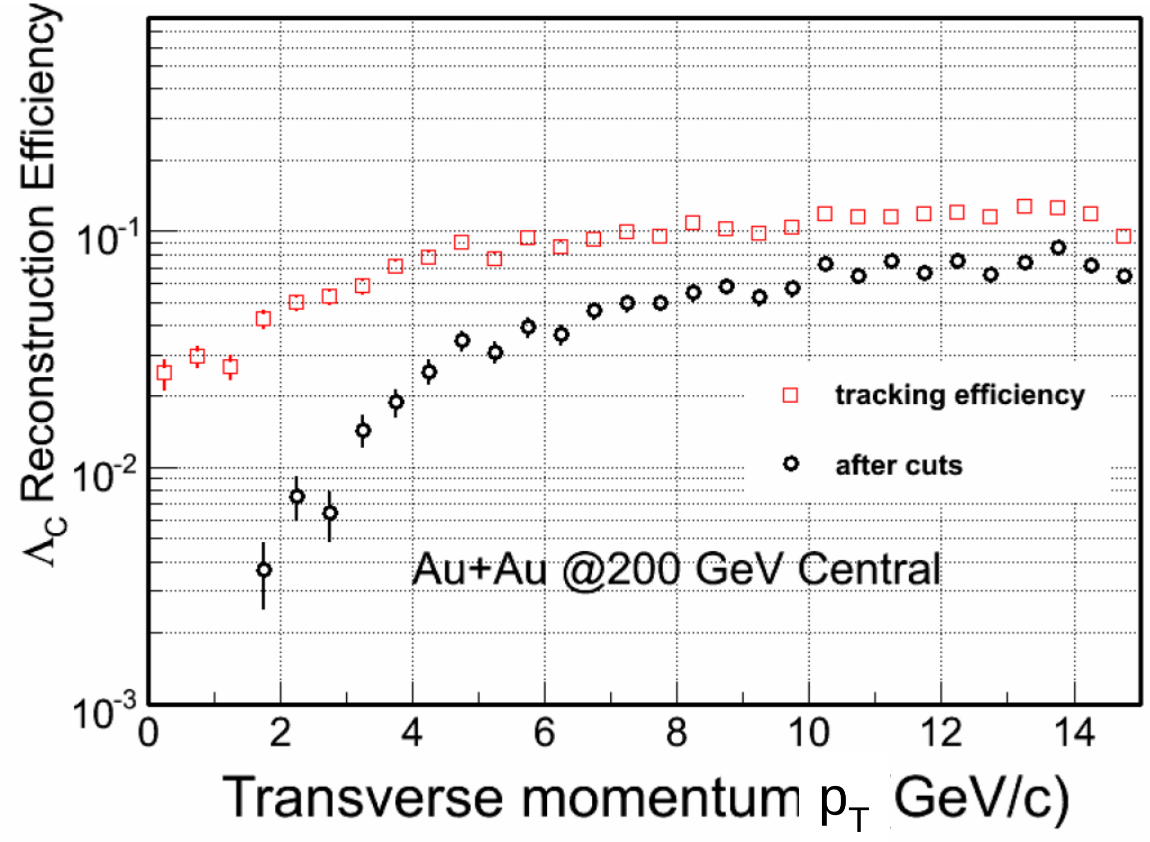
- D^0 scaled by N_{bin}
- Hijing background scaled by N_{part}

Estimate R_{cp} sensitivity: focus on the error bars



The next level of difficulty: Charm baryon - Λ_c

$\Lambda_c \rightarrow pK^- \pi^+$ M = 2.286 GeV/c^2 $c\tau$ = 60 μm

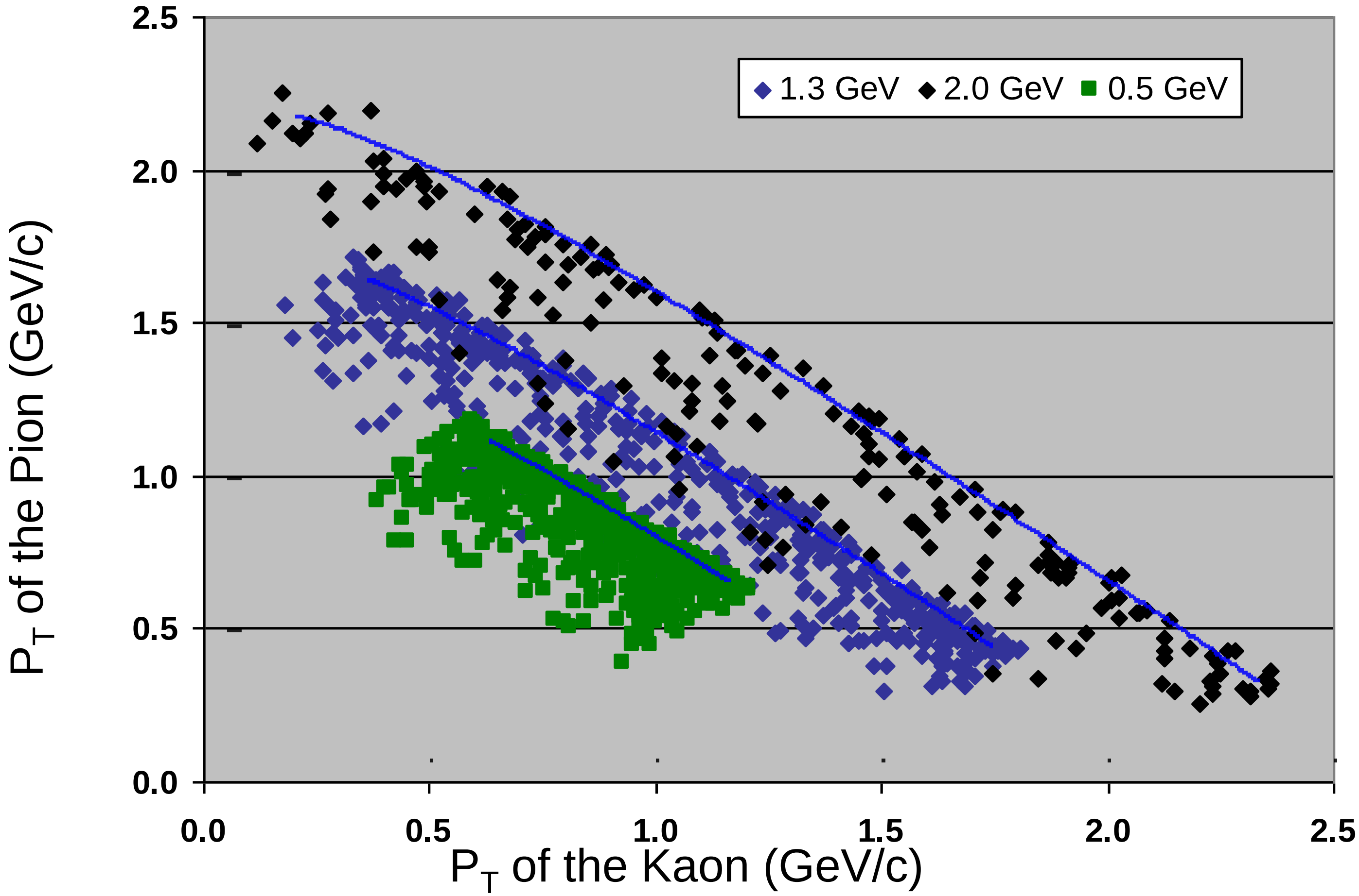


Summary: A rich physics program with the HFT

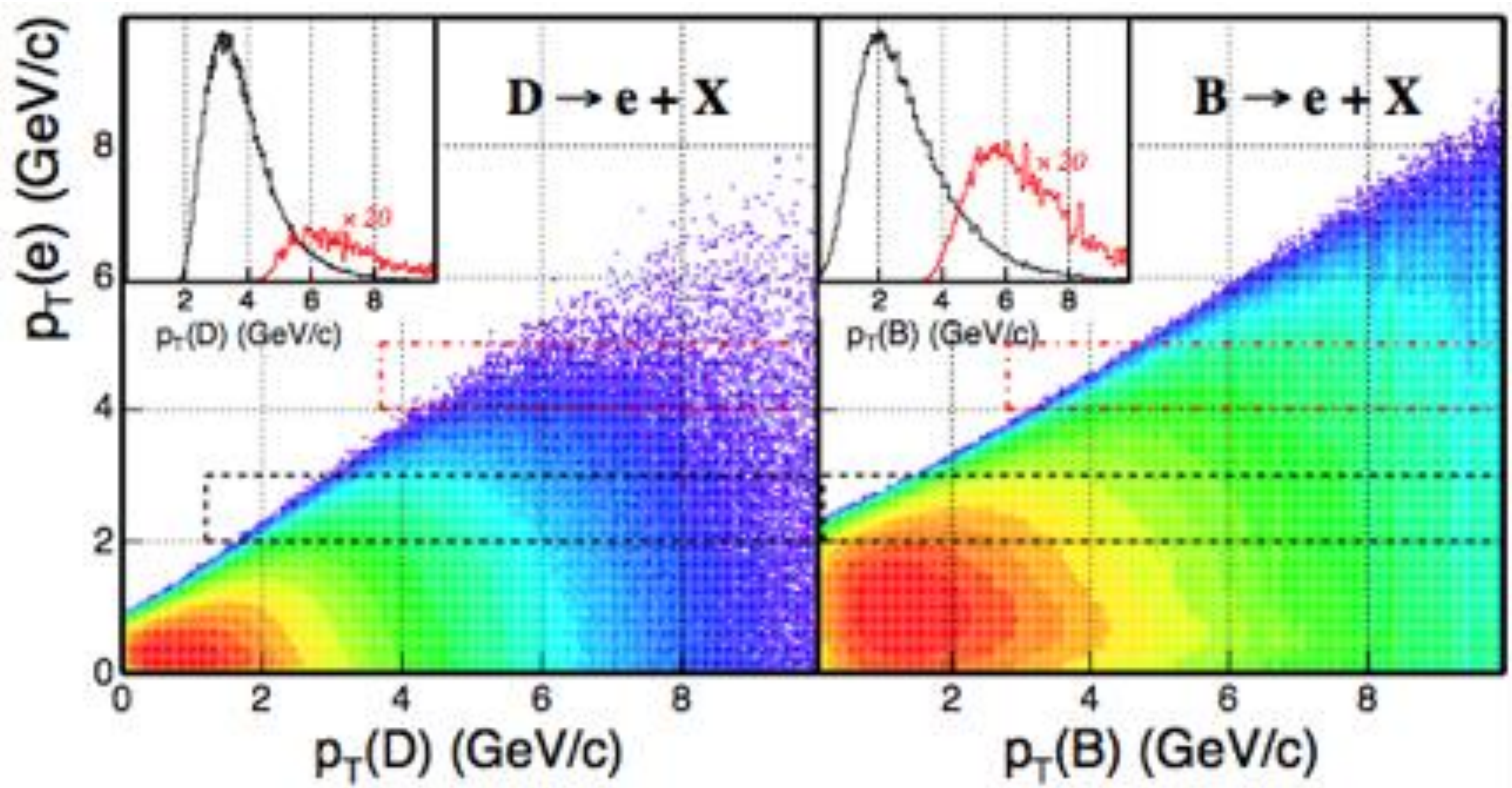
- **The HFT is thin, unique, innovative and robust**
- **The design have been tested extensively with hand calculations and a few key examples have been simulated with GEANT/ITTF software**
- **Simulations … completed tasks**
  - ✓ **A full Monte Carlo simulation + reconstruction chain with HFT in STAR**
  - ✓ **Comprehensive study on the pointing resolution and single track efficiency for the STAR system with HFT with full MC simulations.**
  - ✓ **Comprehensive study on the D^0 reconstruction in Au+Au central collisions, including realistic signal/background study.**
  - ✓ **D^0 reconstruction efficiency in Au+Au**
  - ✓ **Quantify the pile-up effect on the single track efficiency (ghosting), D^0 background and signal significance.**
- **To do**
  - ➢ **Improved understanding of single track efficiency and ghosting at low p_T**
  - ➢ **Optimization of D^0 reconstruction at low p_T – improving efficiency**
  - ➢ **Systematic study of other Charm hadrons, such as the Λ_c, and Bottom**
  - ➢ **p+p 200/500 GeV simulations, pile-up effect and improved vertex finders**

Backup Slides

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)



- 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.