HFT Performance & Simulation Studies

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

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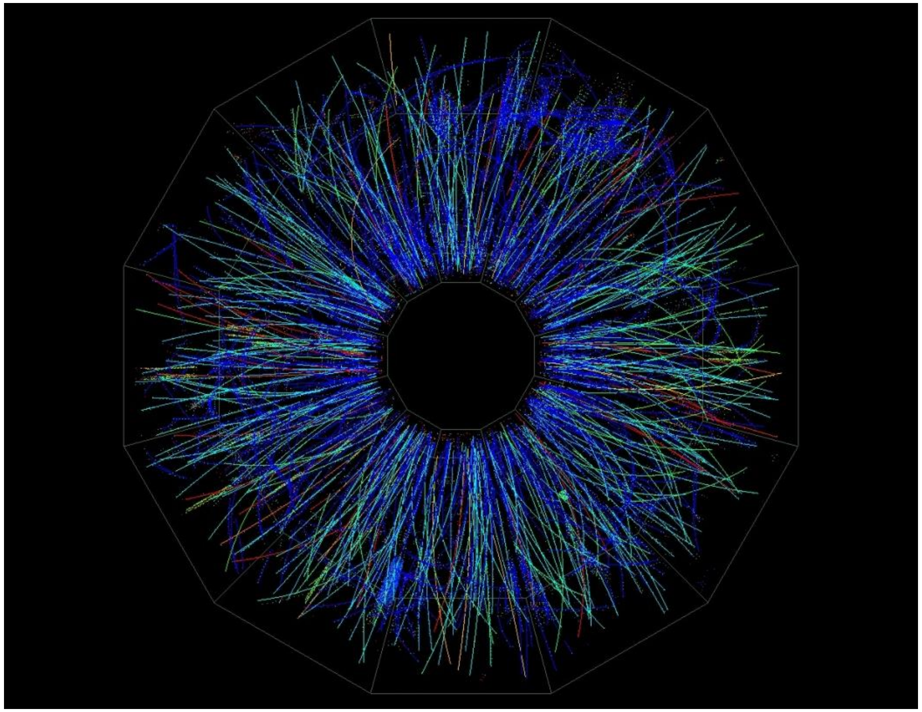
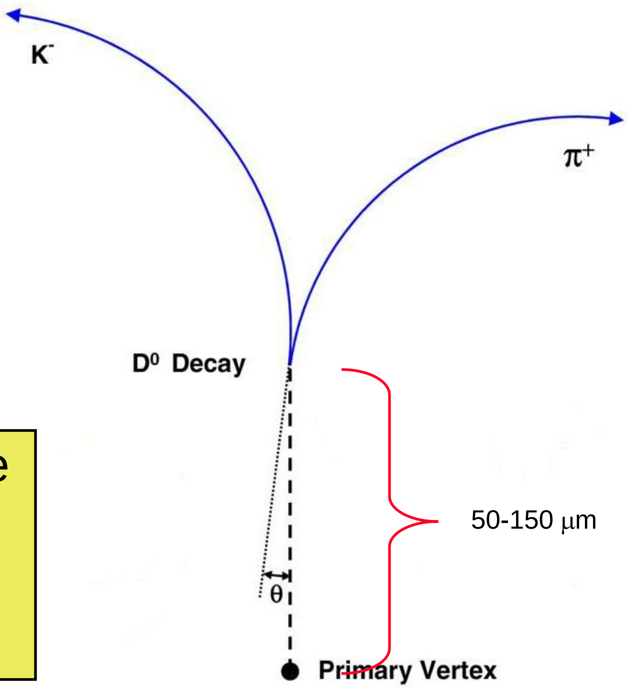
The Properties of the Open Charm Hadrons

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



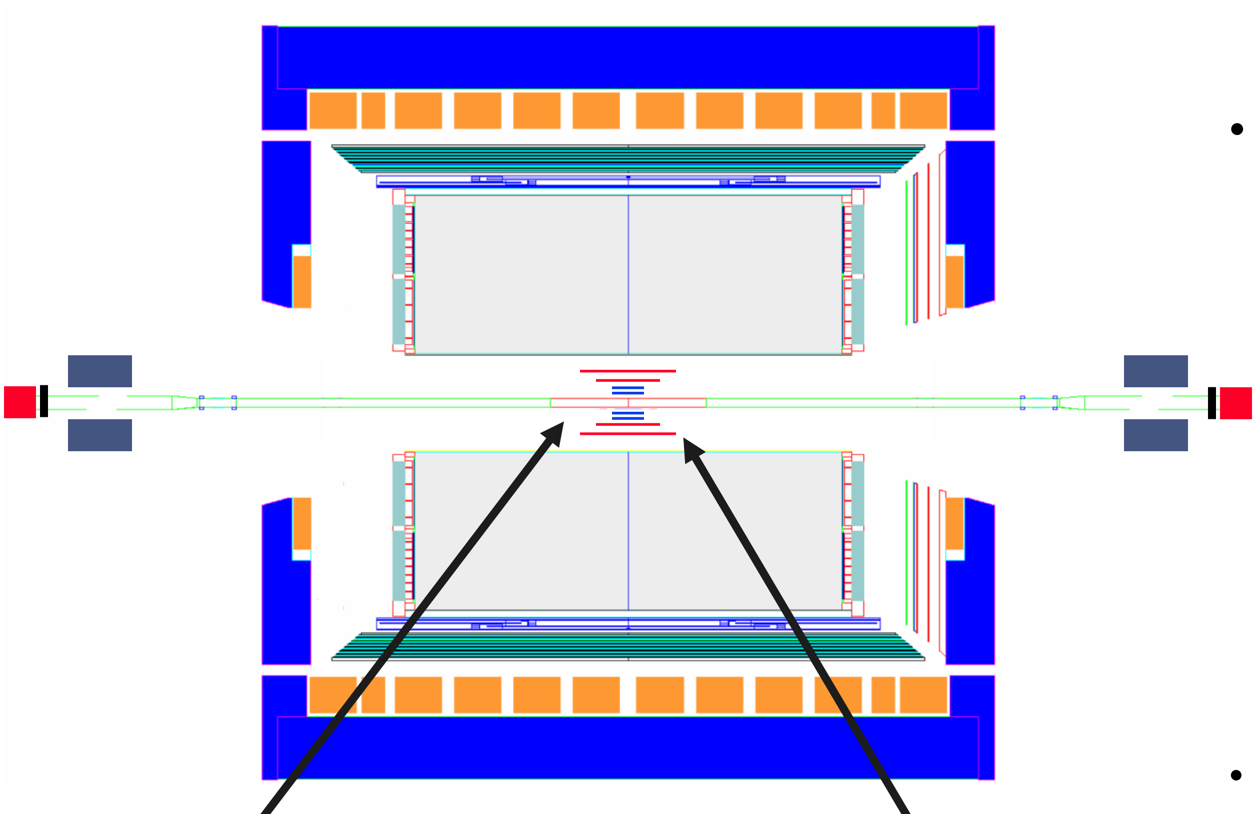
Goal: Put a high precision detector near the IP to extend the TPC tracks to small radius



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



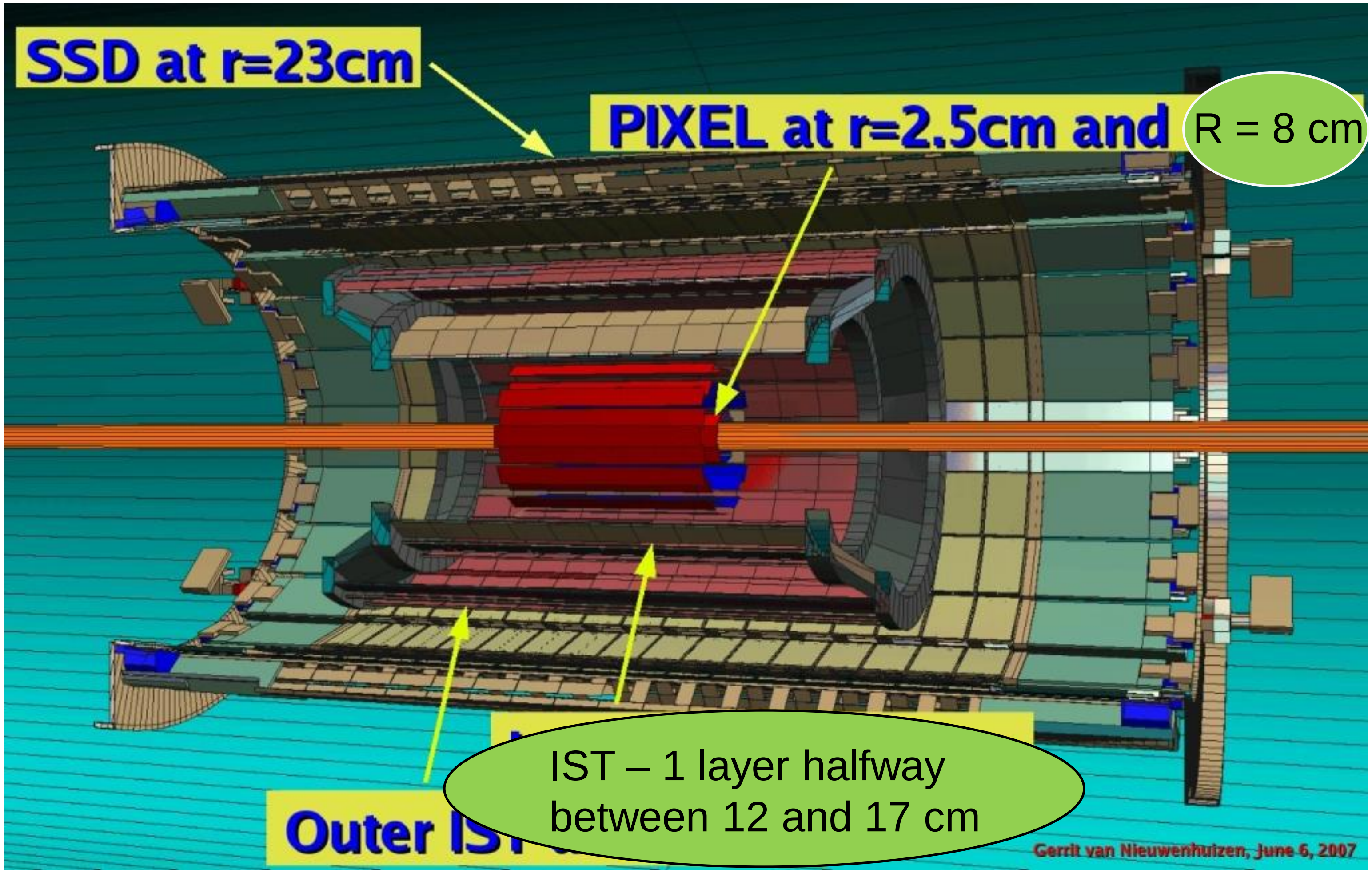
PXL: 2 layers of Si at small radii

IST: 1 or more layers of Si at intermediate radii

SSD: an existing detector at 23 cm radius

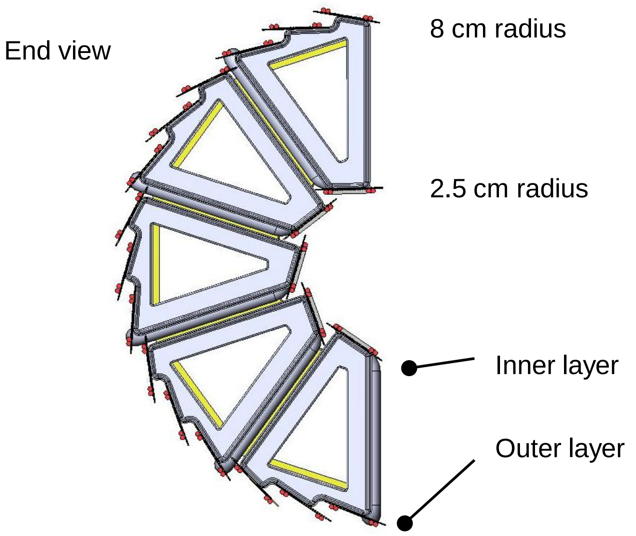
- A new detector
  - 30 μm silicon pixels to yield 10 μm space point resolution
- Direct Topological reconstruction of Charm
  - Detect charm decays with small cτ, including $D^0 \rightarrow K\ \pi$
- New physics
  - Charm collectivity and flow to test thermalization at RHIC
  - Charm Energy Loss to 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.

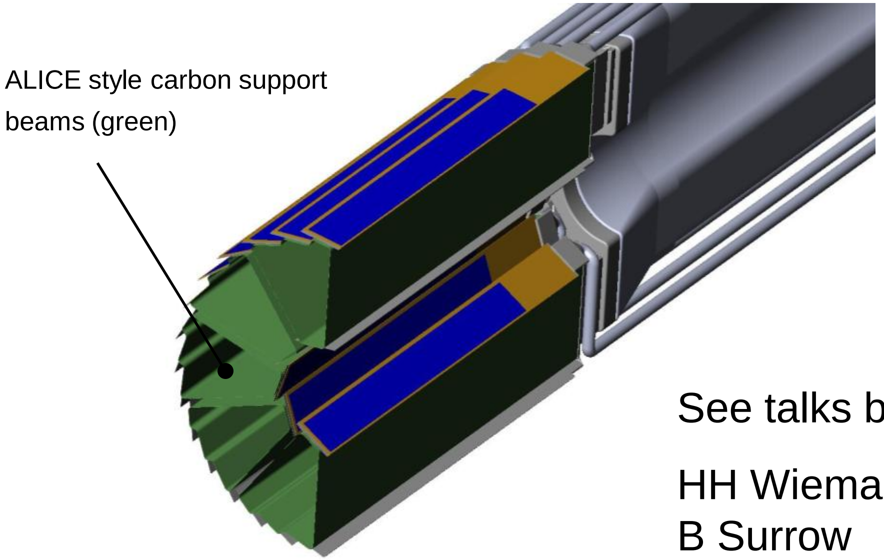
The Proposal Configuration simulated in GEANT



Engineering Design Changes since the proposal was published

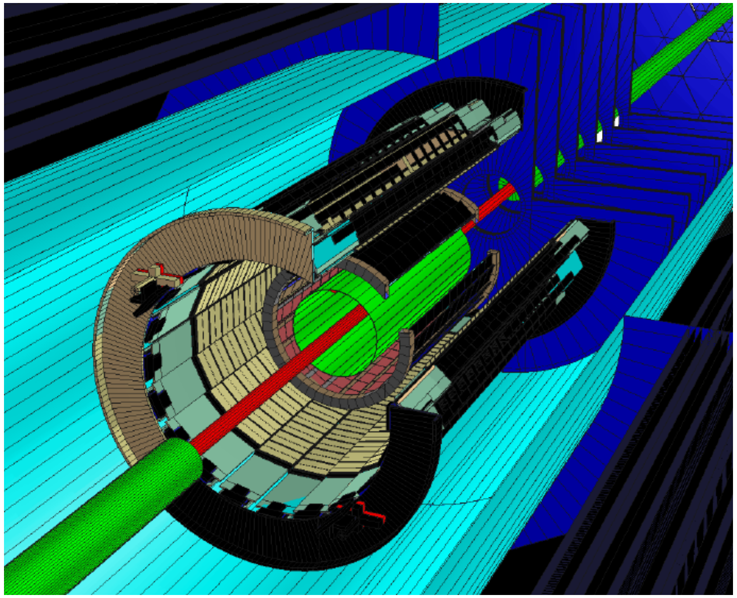
Pixel & IST – changes and progress





See talks by

HH Wieman
B Surrow



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

- Fewer channels
- Lower cost
- Extra space for PXL layers

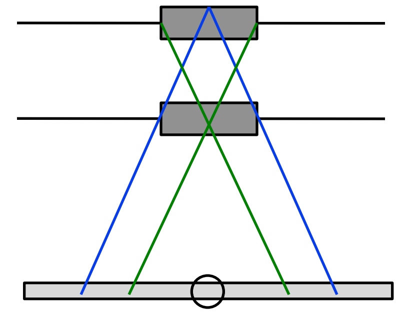
- Basic Parameters
  - Short strips (< 1 cm)
  - Wide strips (~ 500 μm)
  - Approx 150 μm x 2000 μm resolution

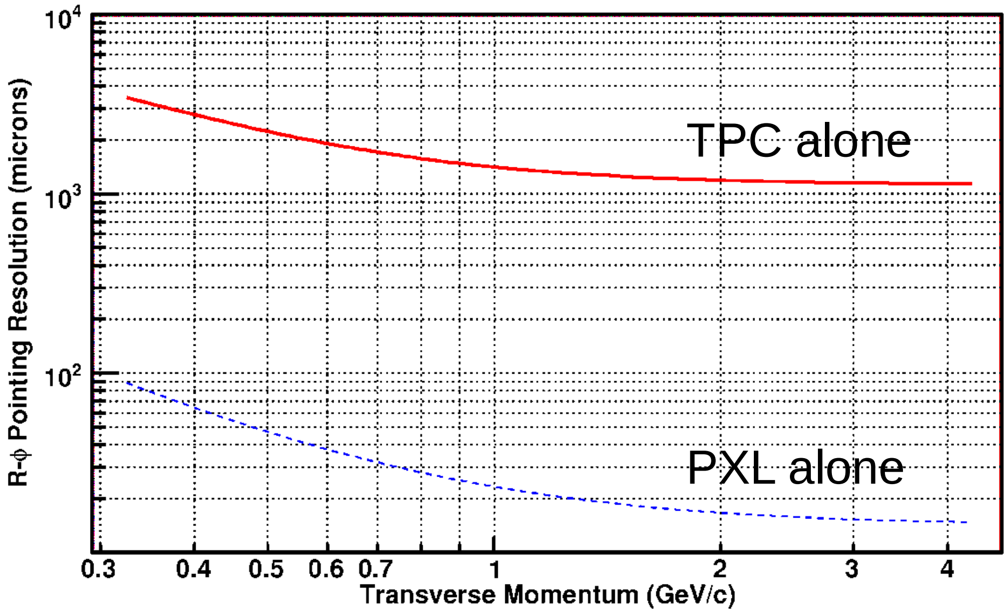
The proposed changes have been verified with hand calculations and are scheduled to be put thru a full system test with GEANT/ITTF simulations.

The GEANT simulations are approximately two generations behind the latest design: FOL

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**



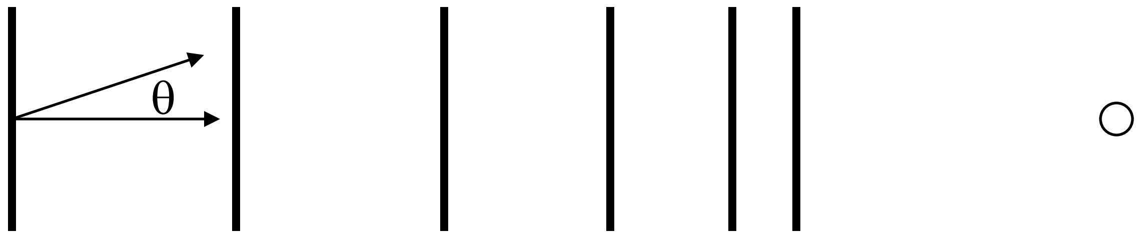


$$\sigma^2 = \frac{\sigma_1^2\, r_2^2 + \sigma_2^2\, r_1^2}{(r_2 - r_1)^2} + \frac{\theta_{mcs}^2\, r_1^2}{\sin^2(\theta)}$$

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

- **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

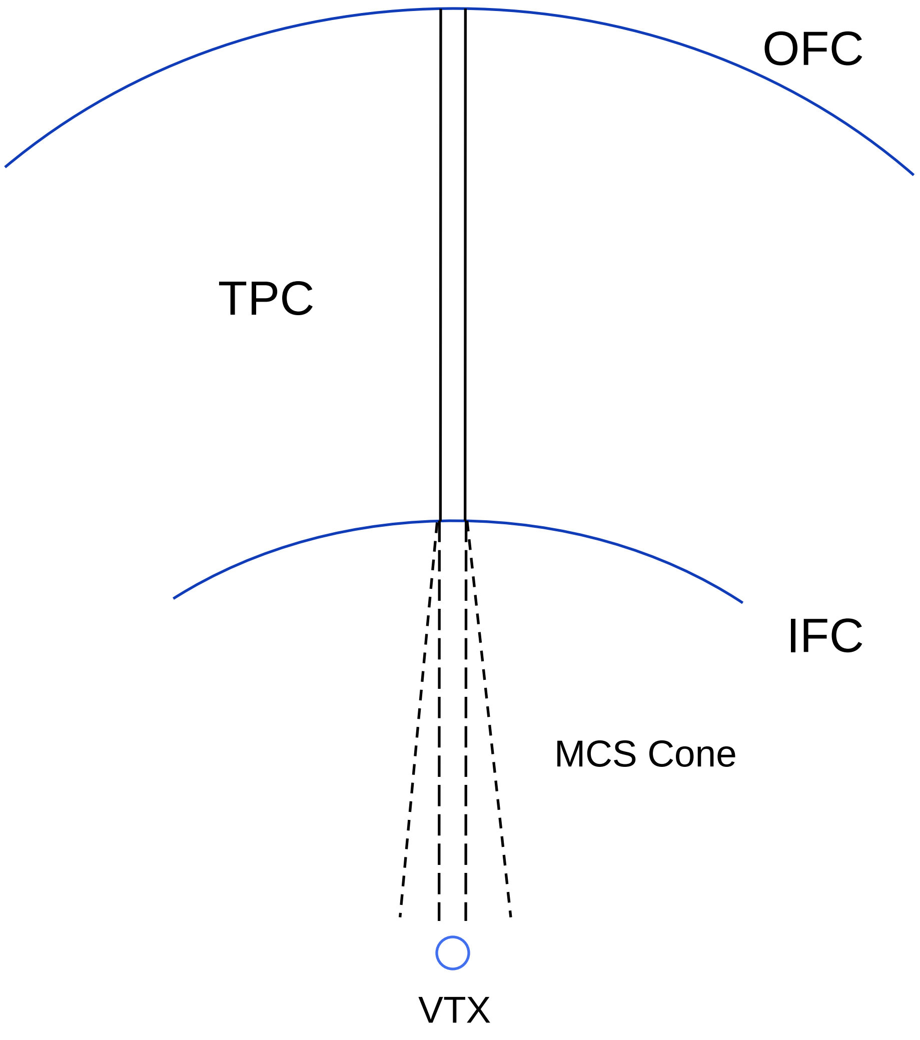


$$[MCS][D][M][MCS][D][M][MCS] \quad \bullet \quad \bullet \quad \bullet$$

- **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.**

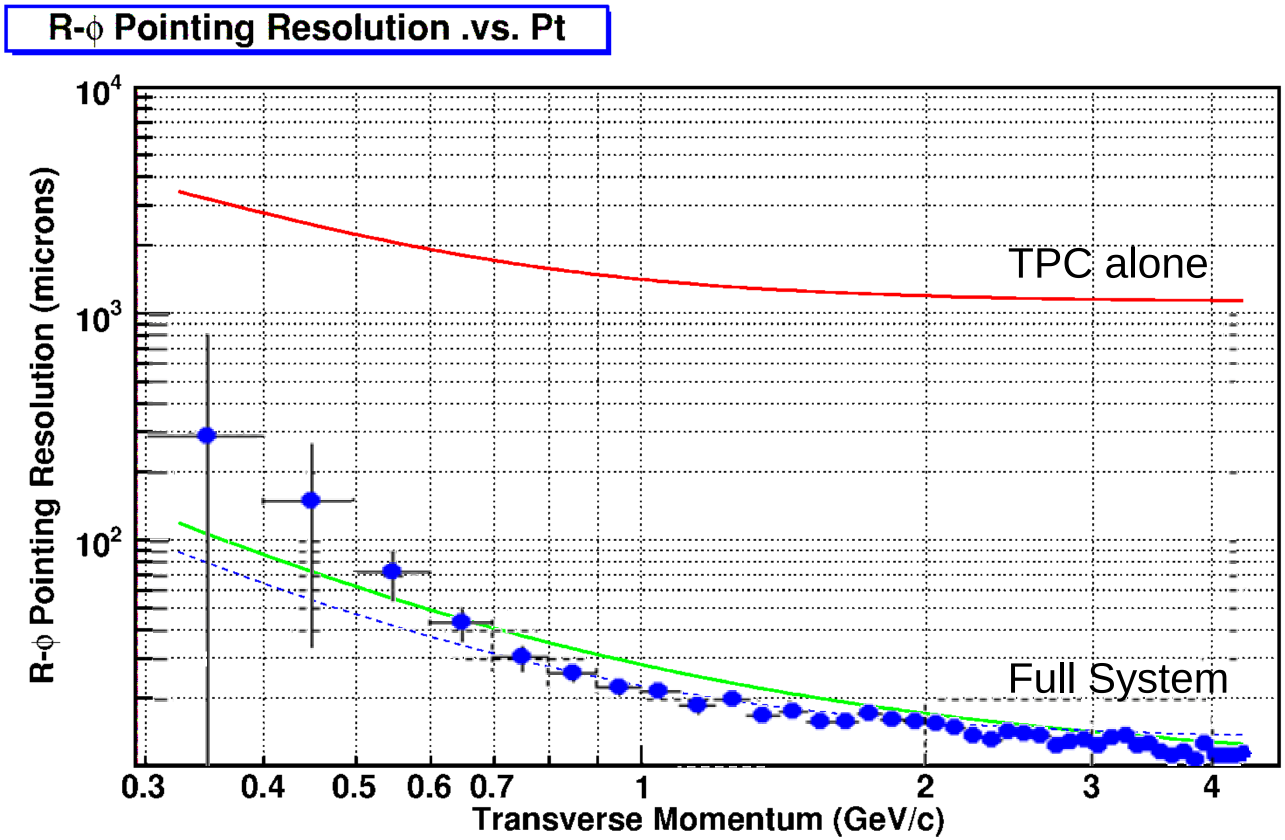
Getting a Boost from the TPC

- **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



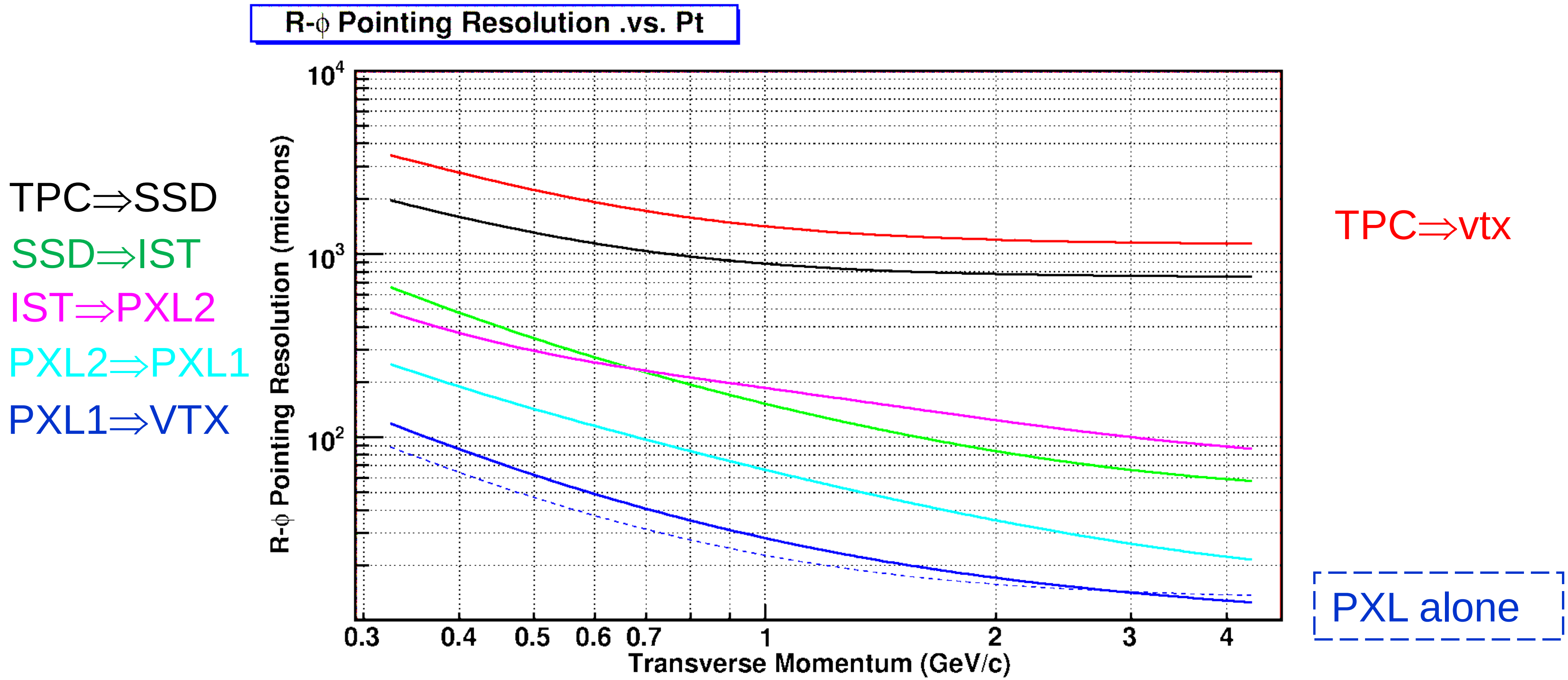
- - - - PXL stand alone configuration

—— 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

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

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

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 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

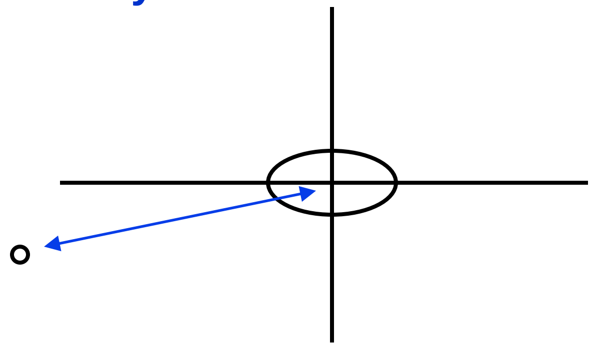
P(bad association) ≈ $2\pi\, \sigma_x\, \sigma_y\, \rho$

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**

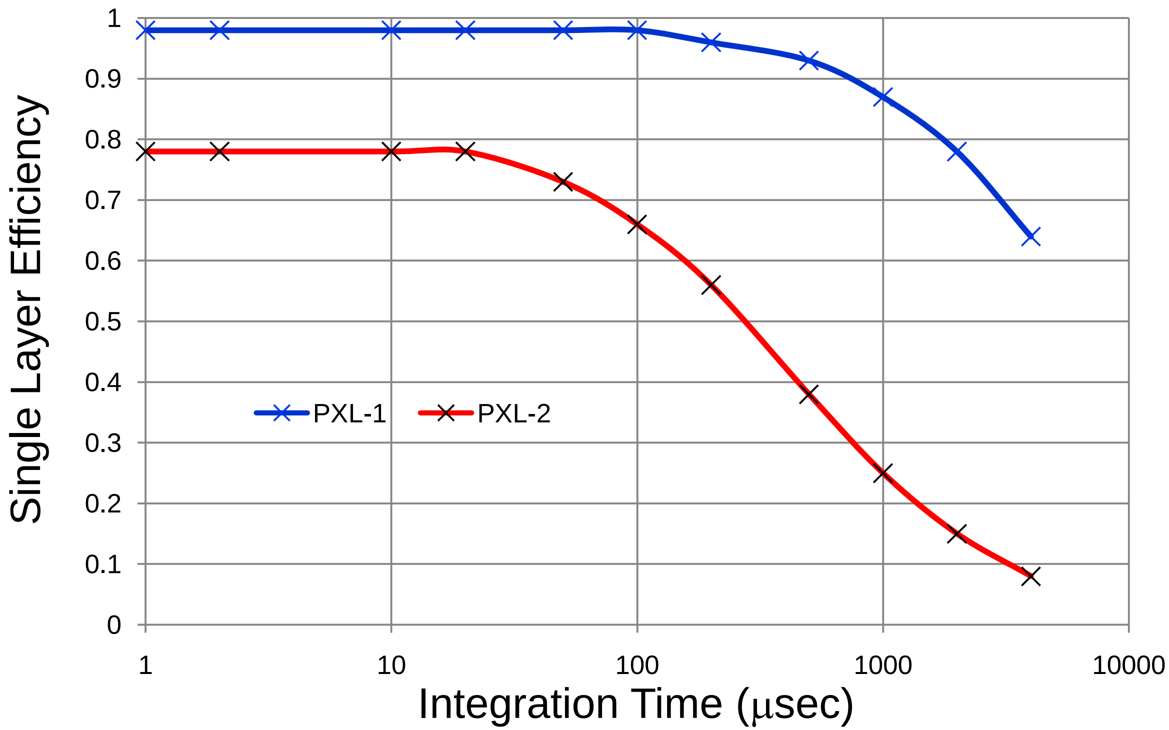
- **The probability of a good hit association on the first pass**
  - **55% on PXL2** The purpose of the intermediate tracking layers is to make 55% go up to ~100%
  - **95% on PXL1** All values quoted for mid-rapidity Kaons at 750 MeV/c

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



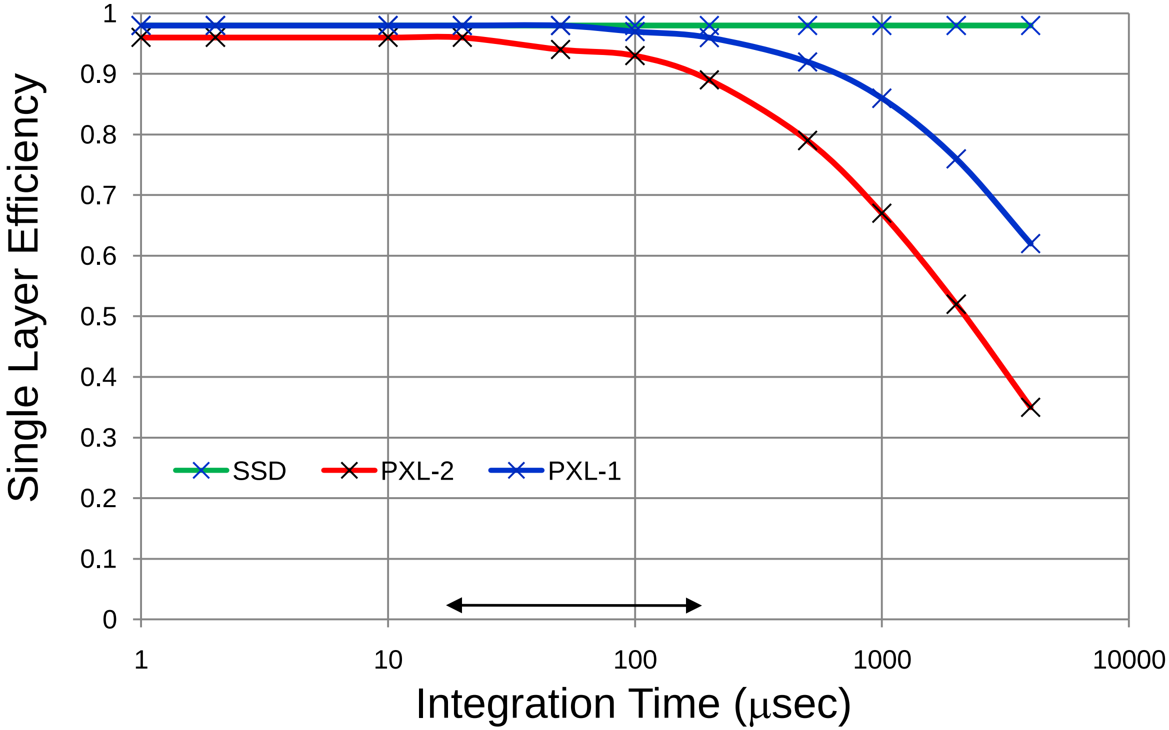
Note that the hard work gets done at PXL layer 2. This is a surprise.

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**

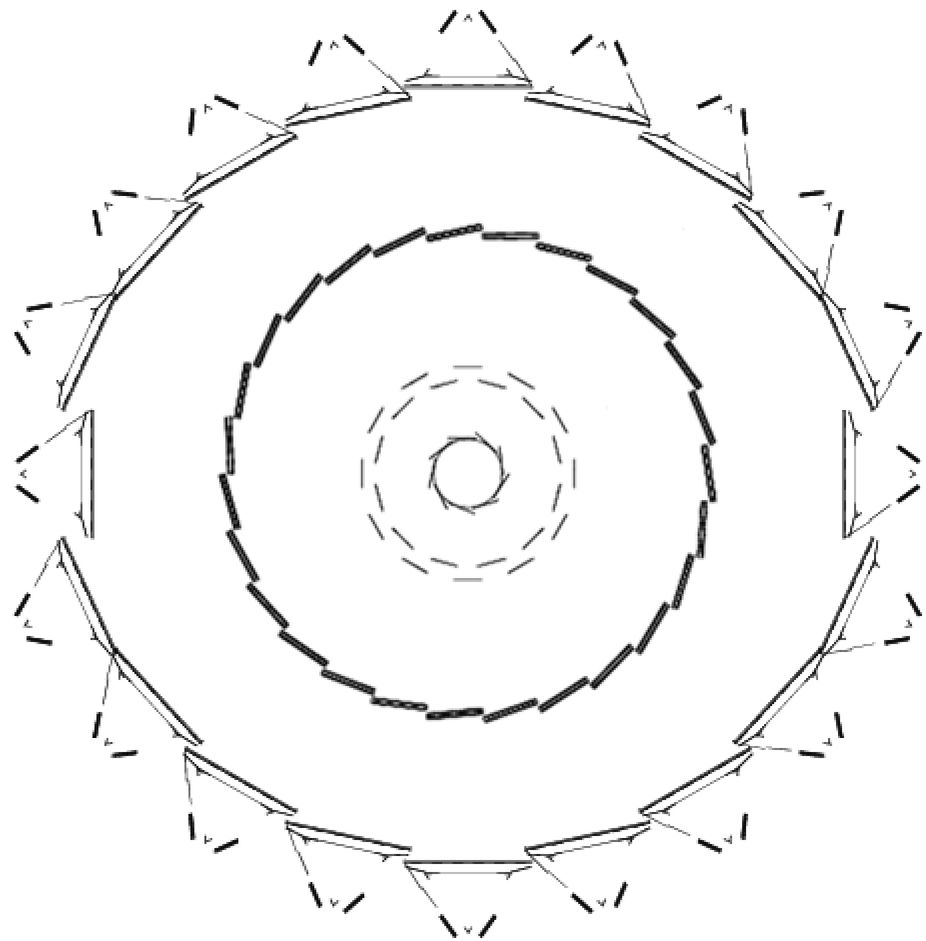
P(good association) = 1 / (1+S) **where S = $2\pi\ \sigma_x\ \sigma_y\ \rho$**



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

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

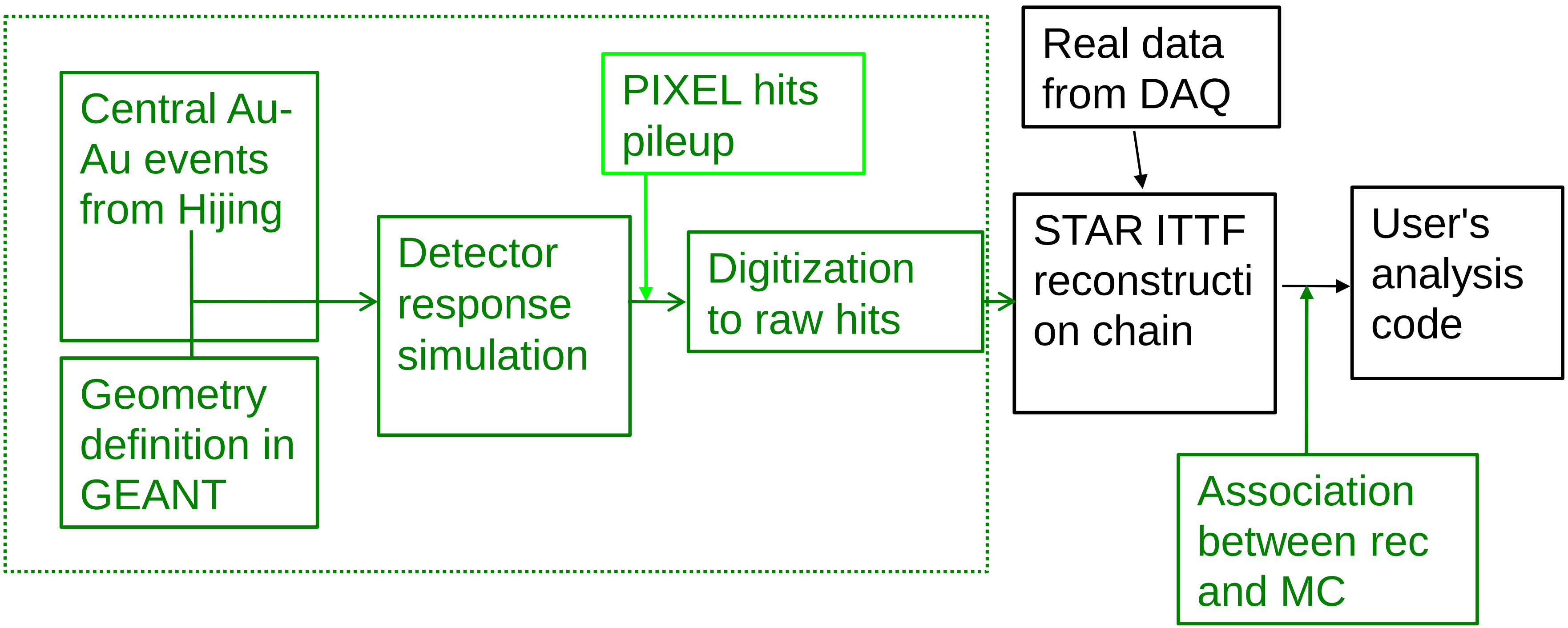


~ 50 cm

Raw HFT 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

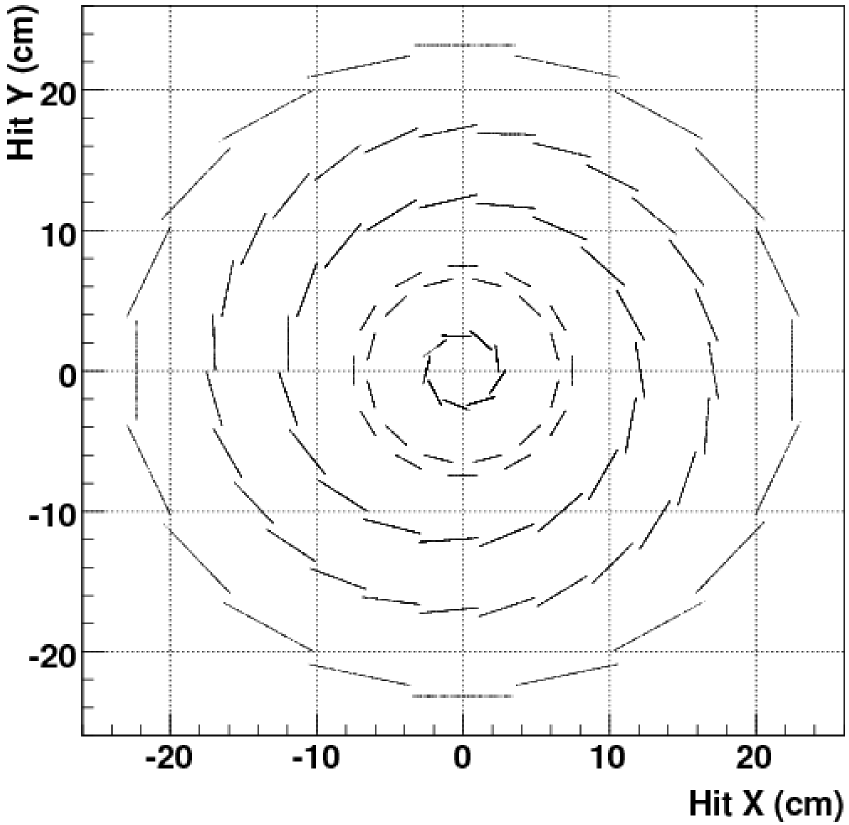
<u># Hits selection in PIXEL:</u> MC hits and Rec hits can be > 2
we include these tracks

<u>D^0 Background:</u> K from D and π from other decays -- important at high p_T
$D^0 \rightarrow K^- + X$ (53%), as well as kaon from other charm hadrons

<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



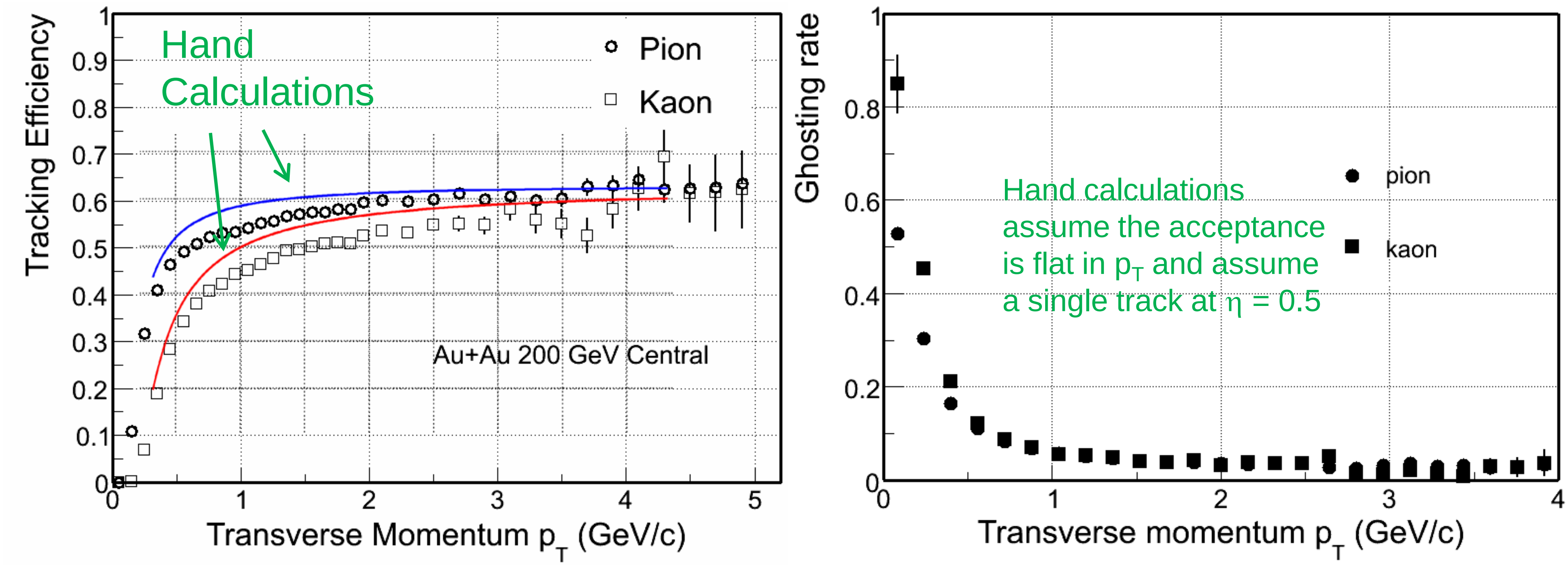
Segment sizes and resolutions

	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	77×77 *
PIXEL1	2.5	30×30	77×77 *

* larger errors for tracking to ensure efficiency
track helix then refit with ultimate errors on PIXEL hits

Central (b = 0-3 fm) Au-Au Hijing + 10 D^0 per event (flat p_T, eta)
|Vertex_z| < 15 cm $D^0 \rightarrow K^- + \pi^+$ BR=100%

Single Track Efficiencies & Ghosting



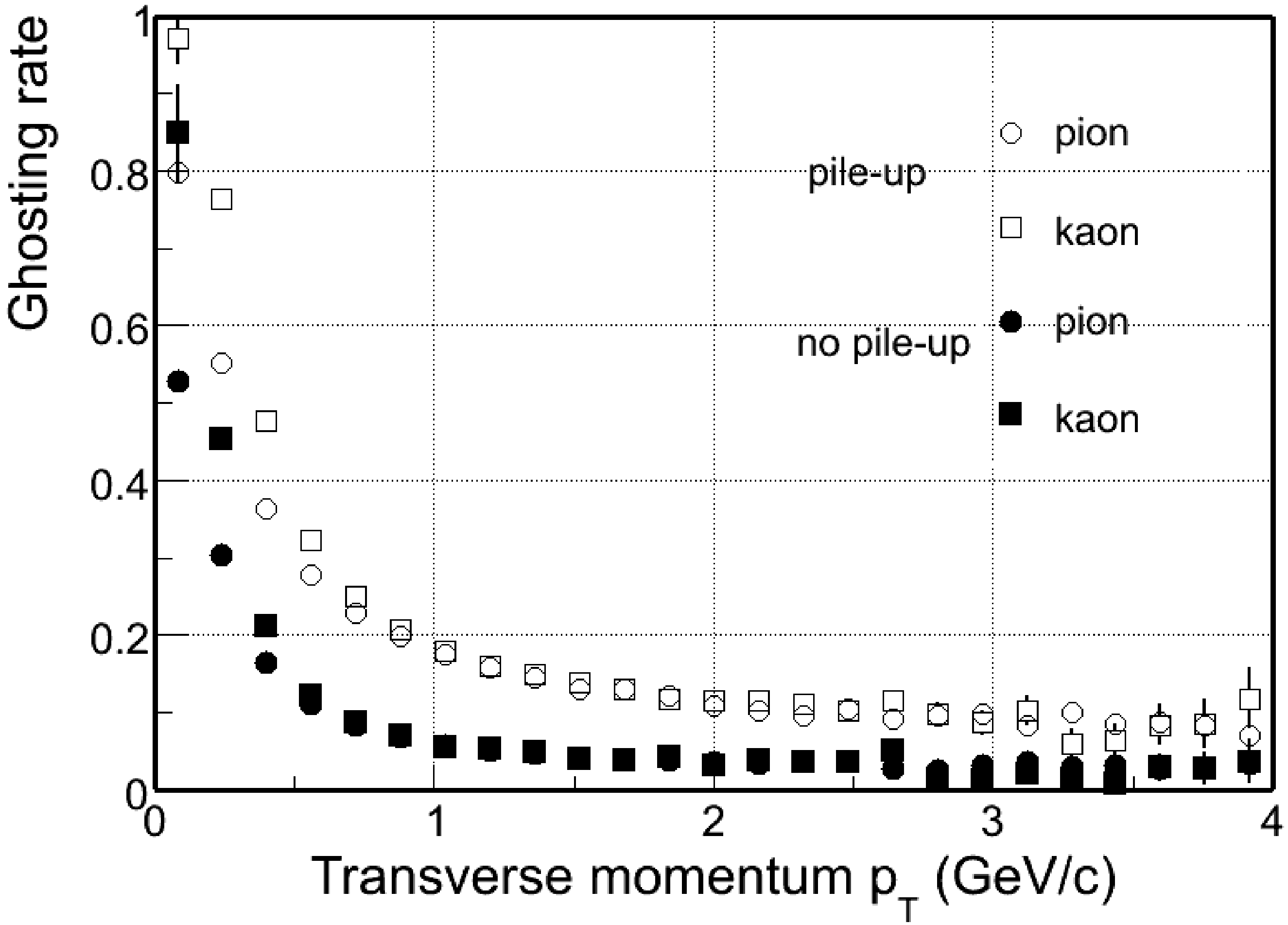
Au + Au central collisions @ 200 GeV

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

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

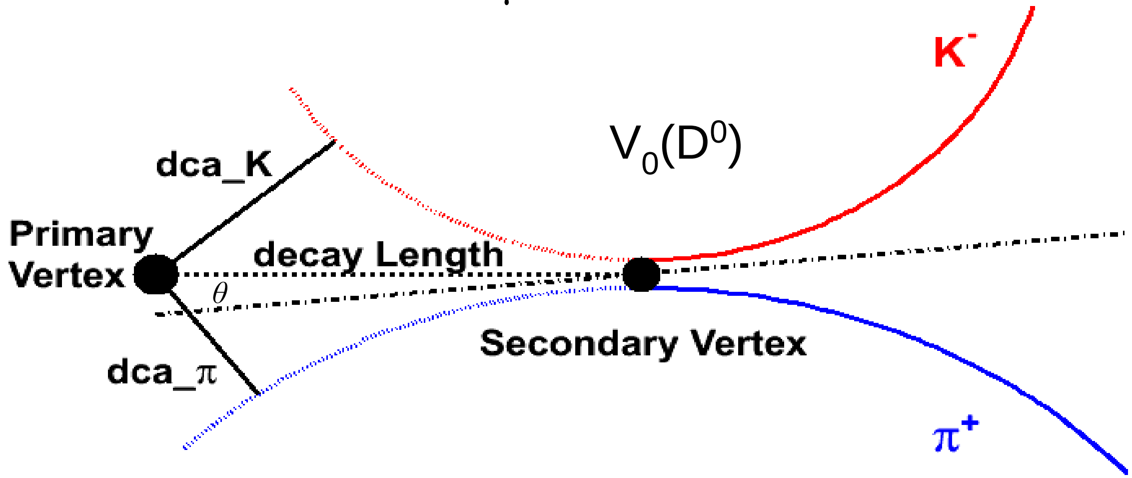
Ghosting increases as pileup increases

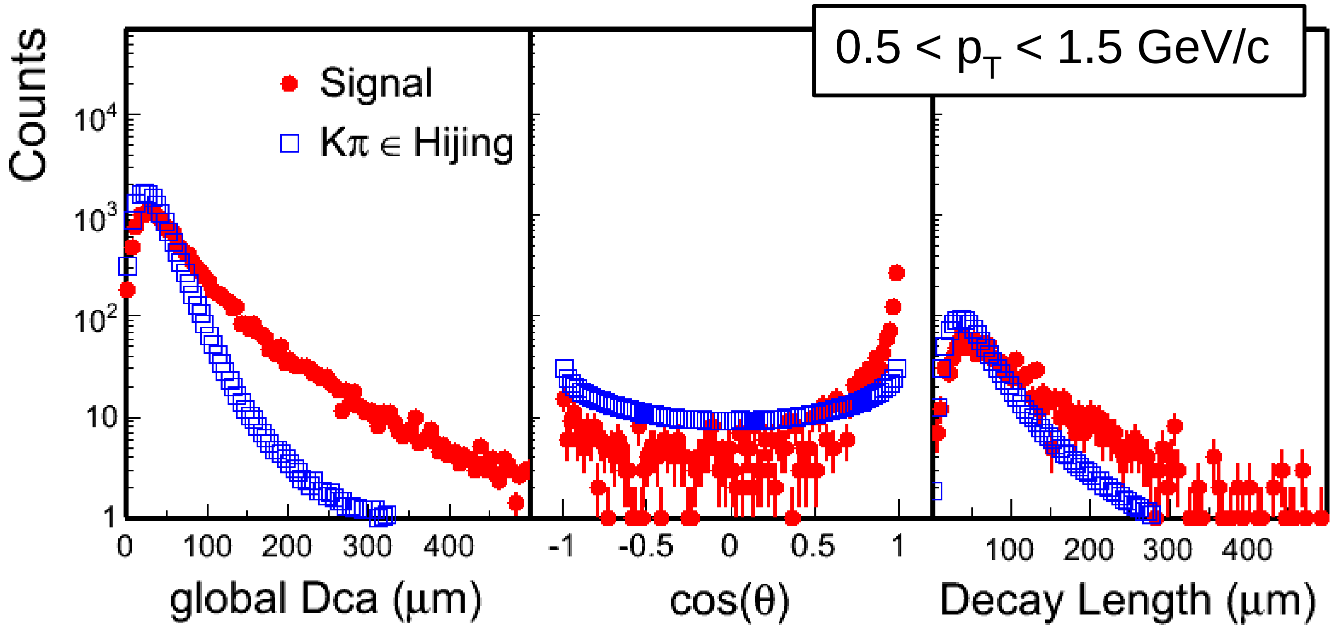
Pile-up level: 1x RHIC II luminosity



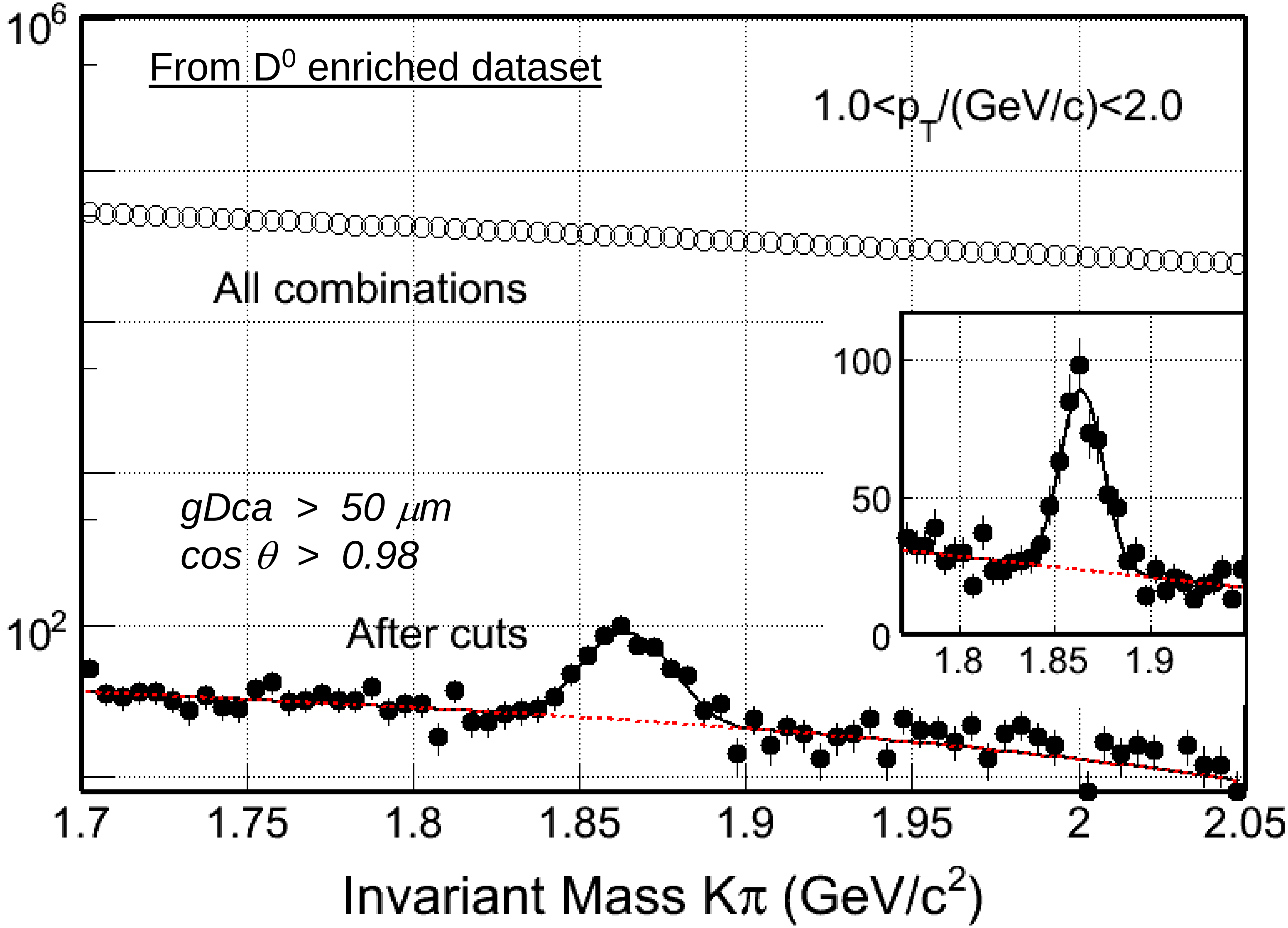
D^0 reconstruction

M_{D0} = 1.8645 GeV/c^2 $c\tau$ = 123 μm

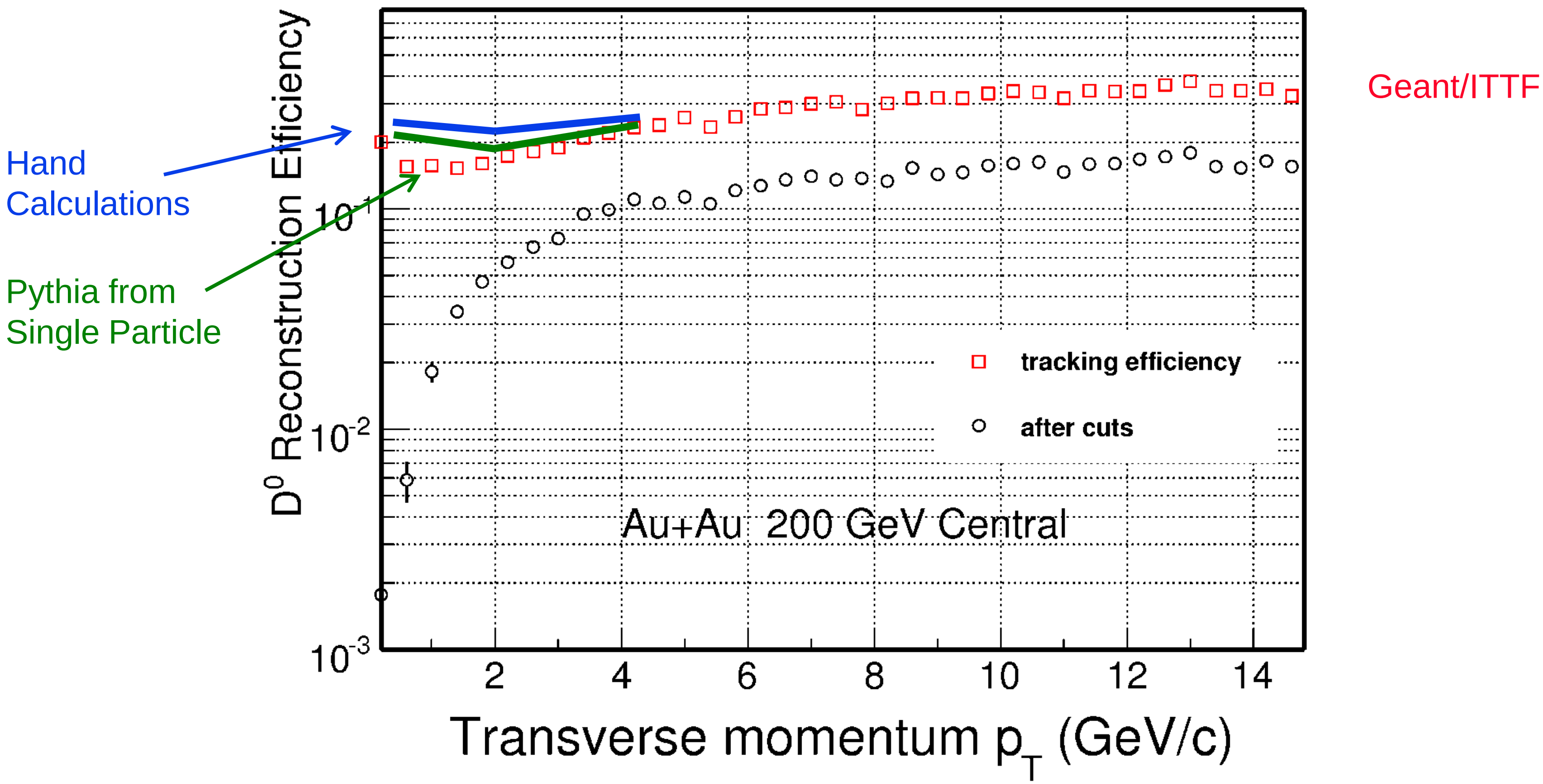




D^0 invariant mass plot from MC sample

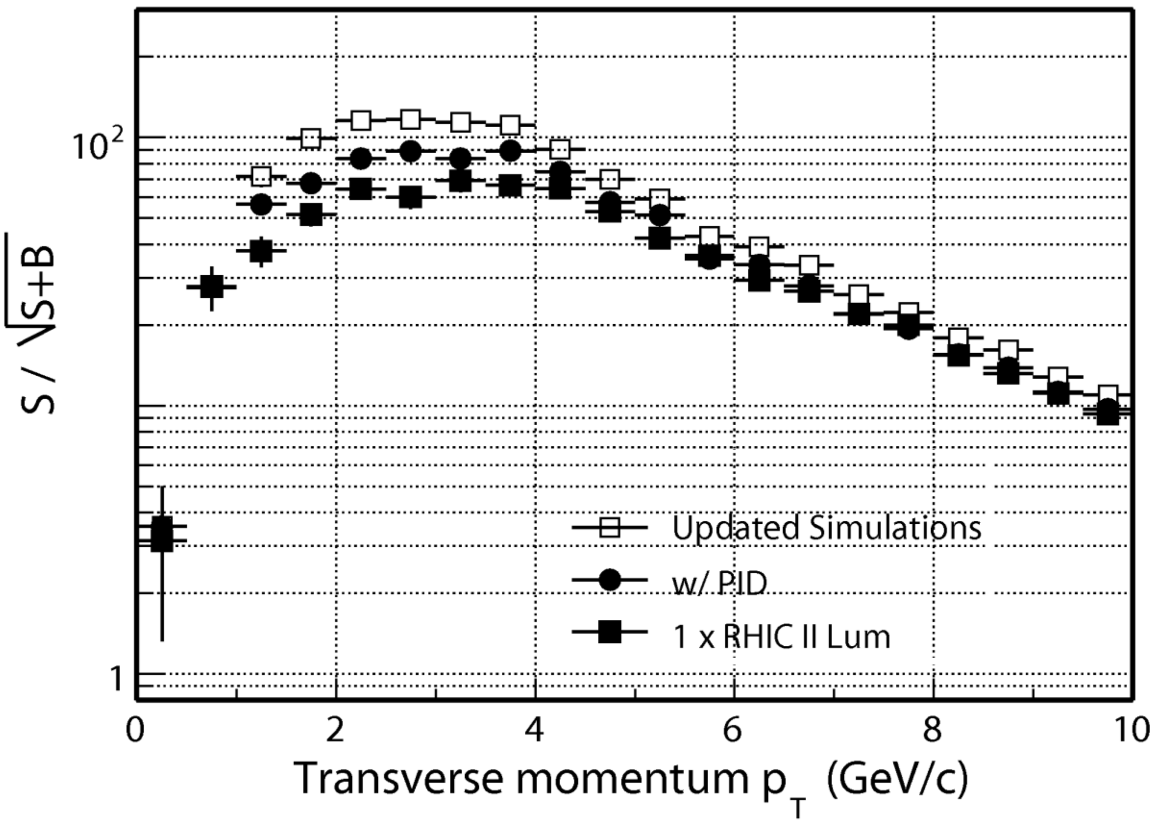


D^0 Reconstruction Efficiency



- **The green line shows the D^0 efficiencies predicted by the Geant/ITTF single particle efficiencies**
- **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**

Improved understanding of signal / background

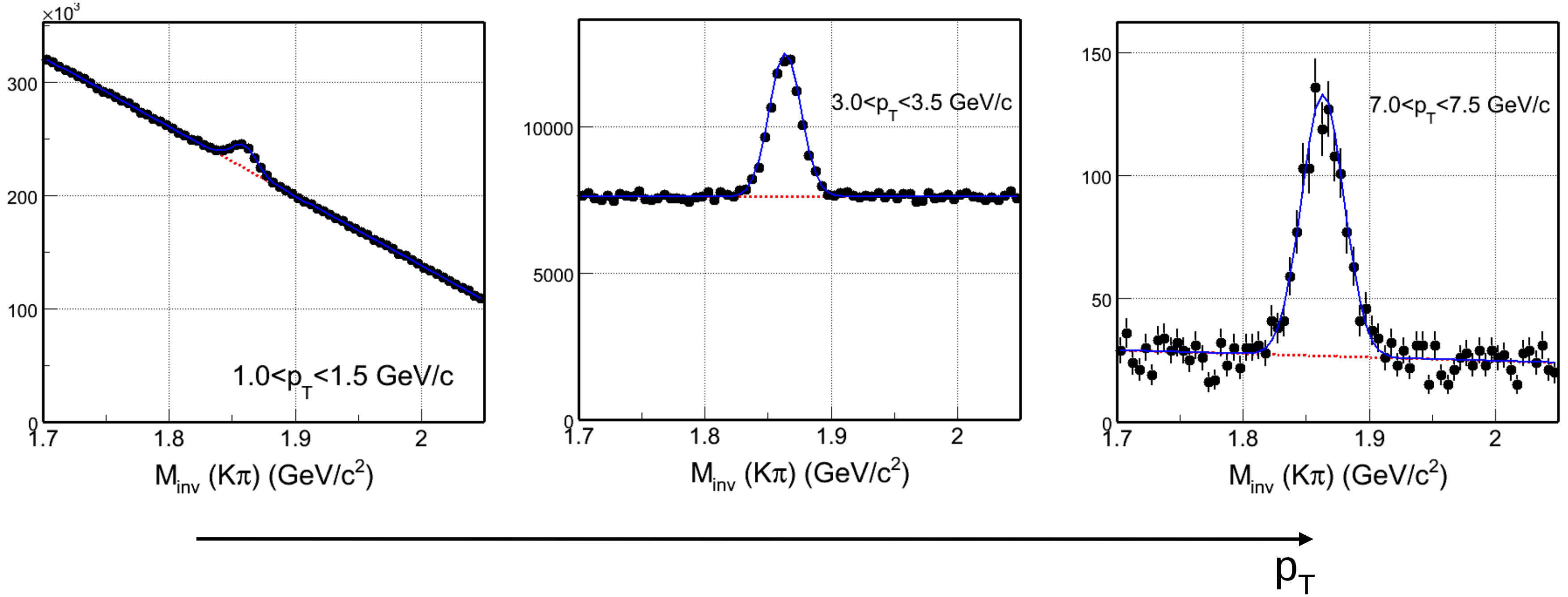


100 M Au+Au central
@ 200 GeV

$|\eta| < 1$, D^0+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

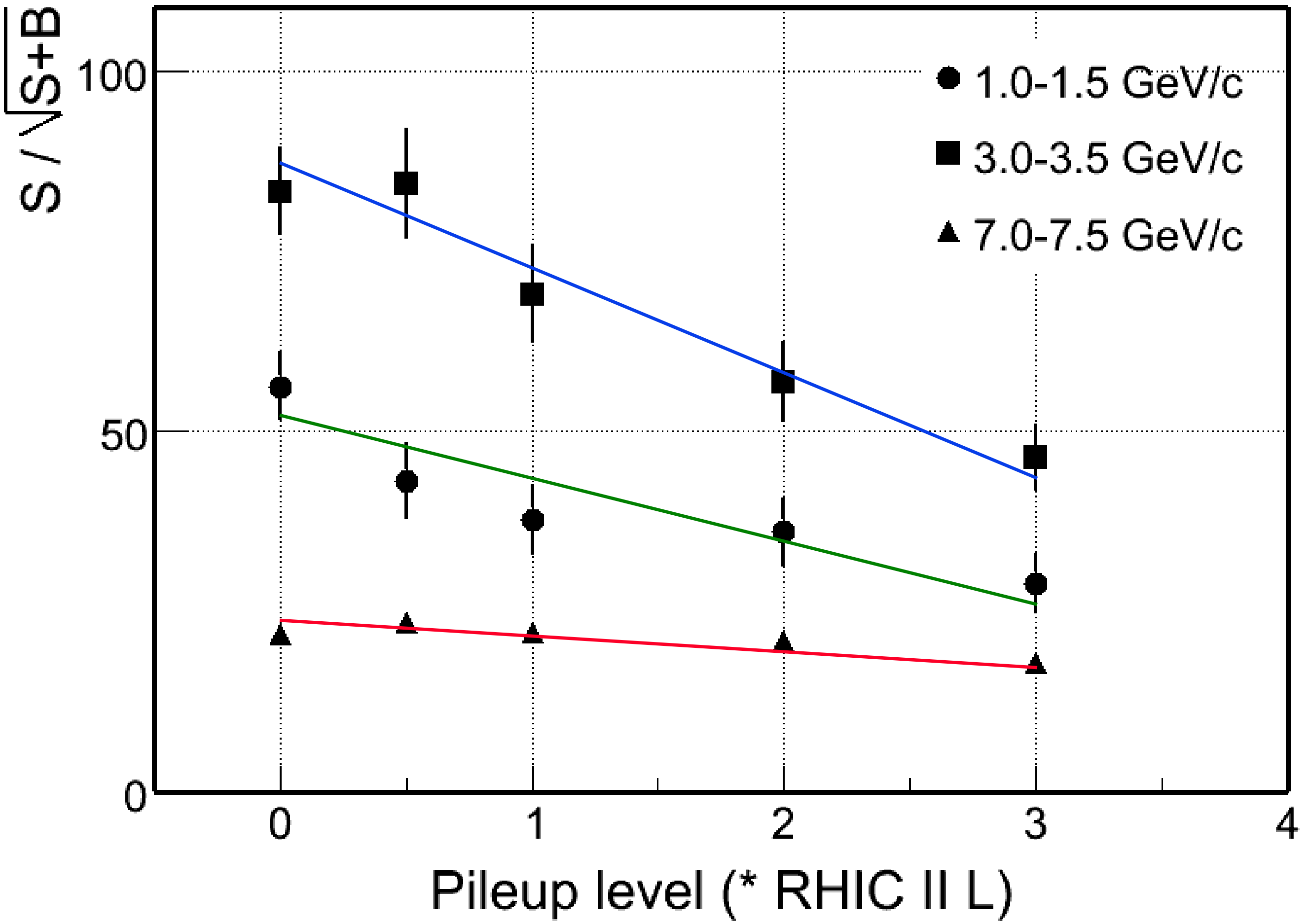
D^0 expected invariant mass distributions



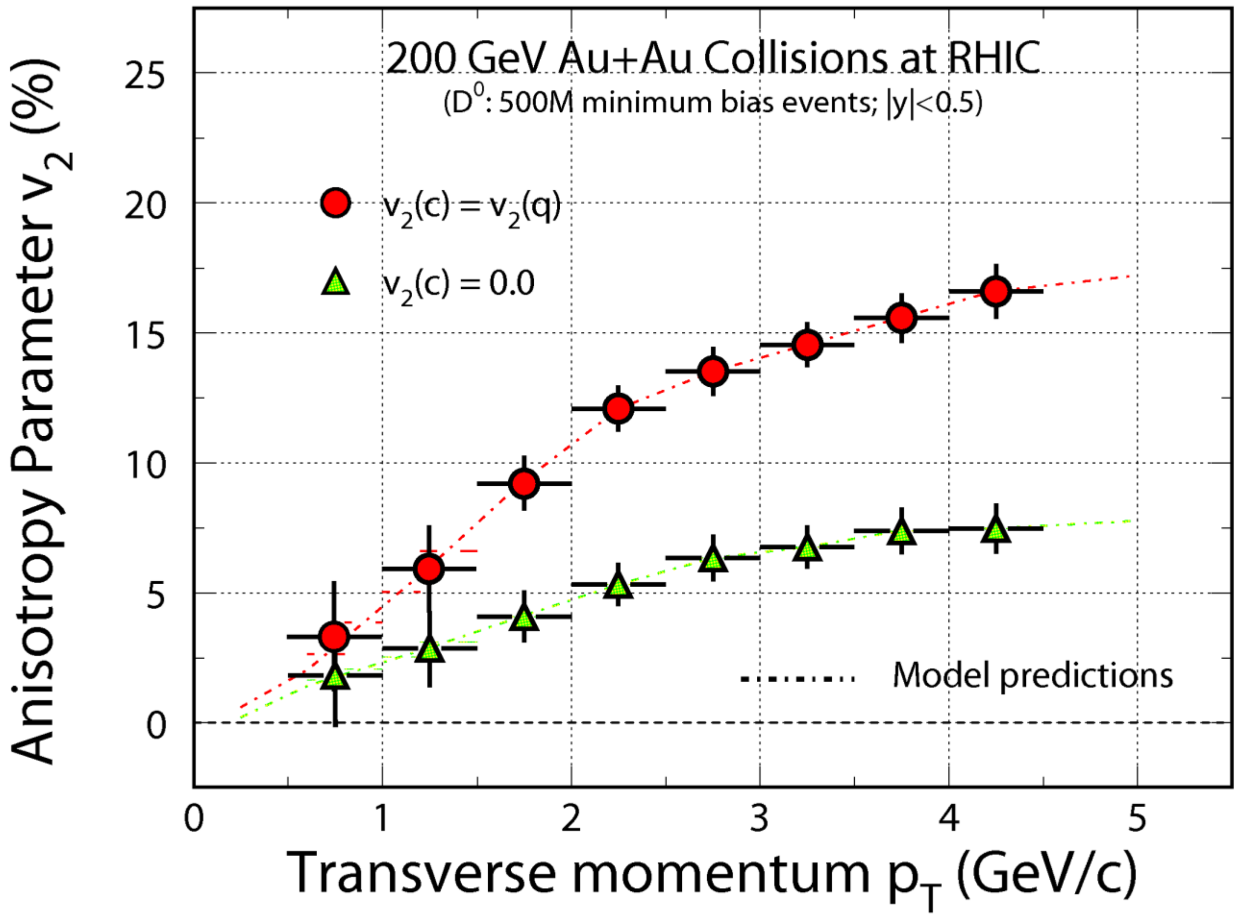
For 100 M Au+Au central collisions at 1x RHIC II luminosity

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



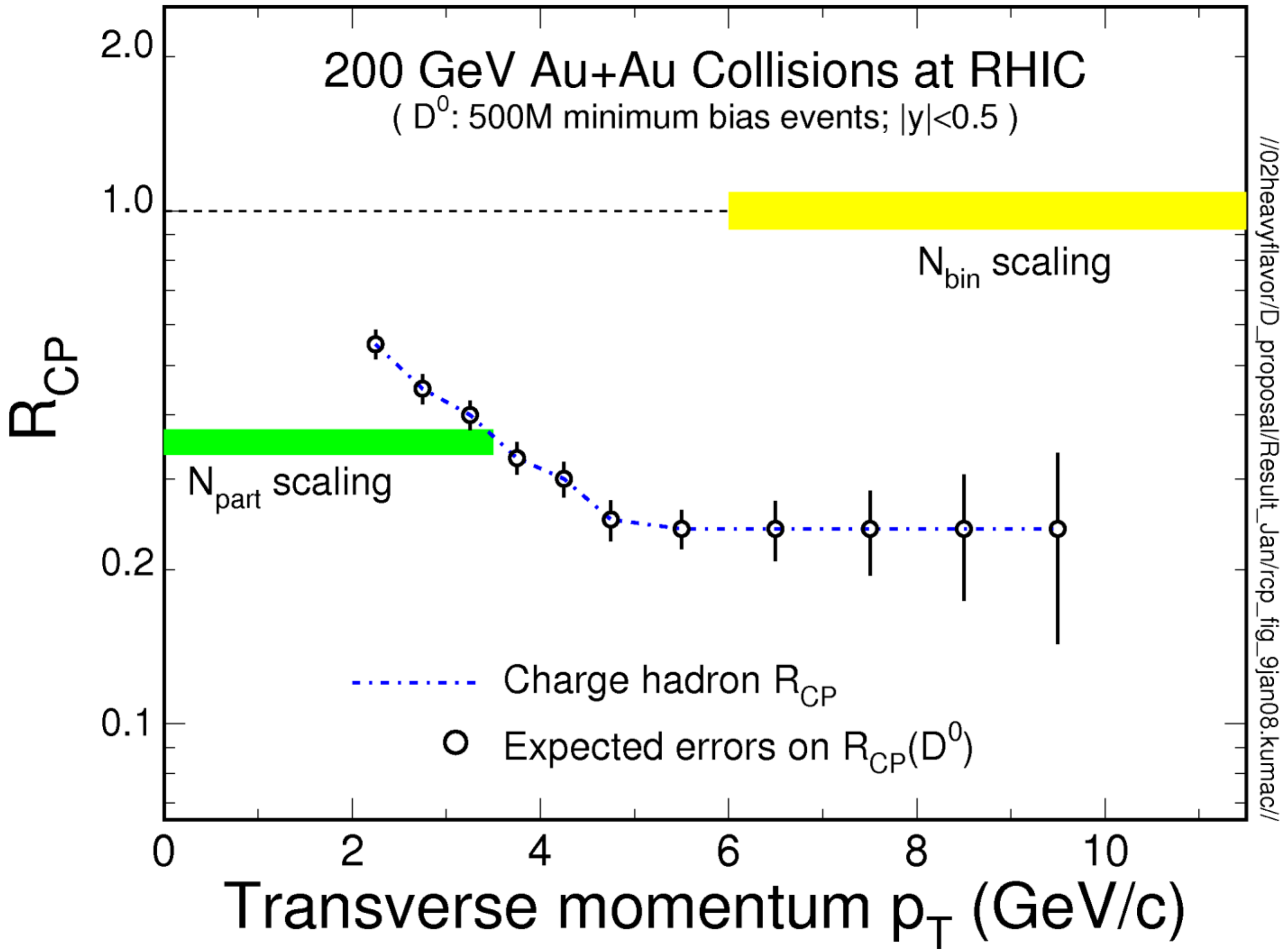
Estimate v_2 sensitivity – focus on the error bars



From central to minimum bias, assume:

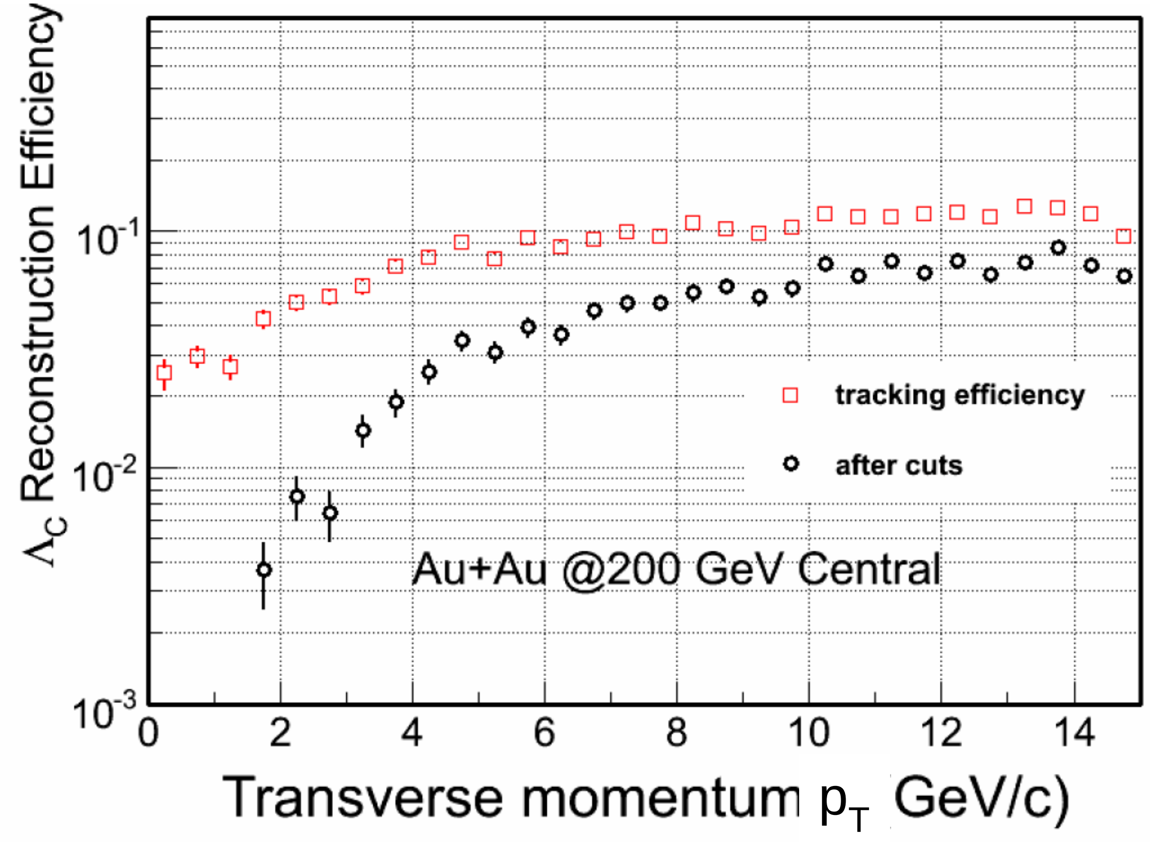
- D^0 scaled by N_{bin}
- Hijing background scaled by N_{part}

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

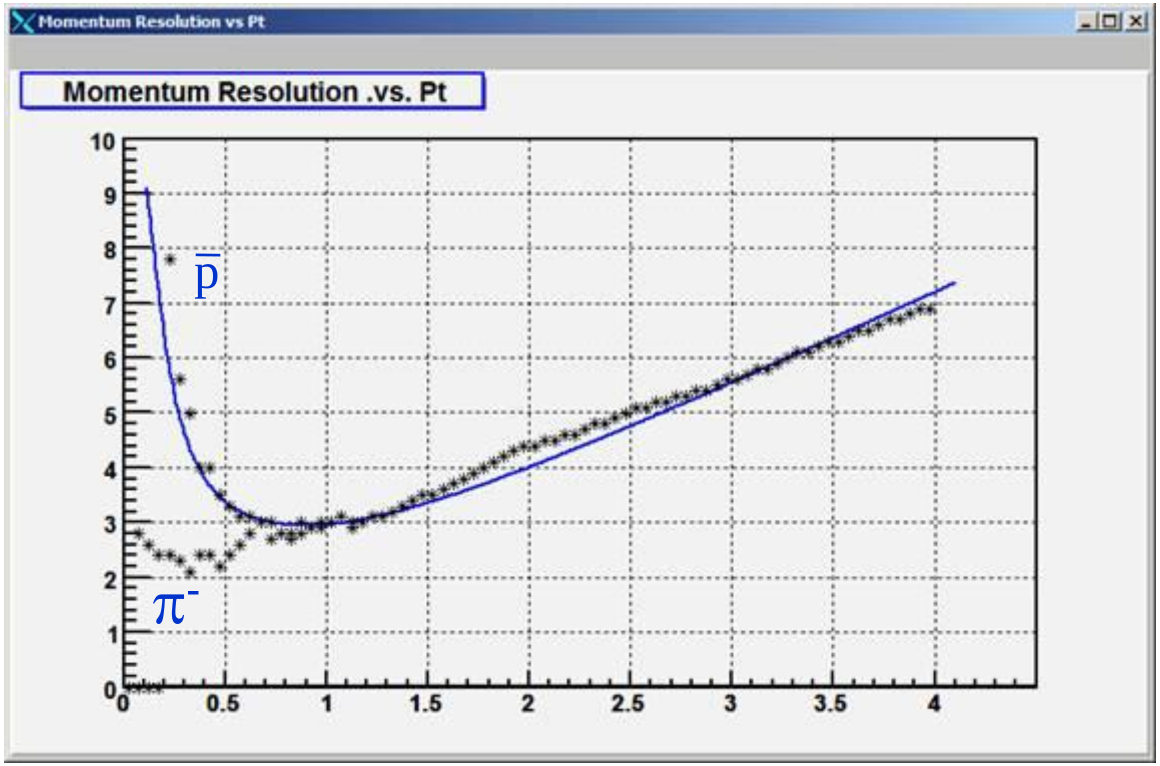


Summary: A rich physics program with the HFT

- The HFT is thin, unique, innovative and robust
- The design have been tested extensively with hand calculations and a few specific examples tested with GEANT/ITTF simulations
- Simulations
  - ✓ 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 and p+p collisions
  - ✓ 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
  - ➢ p+p 200/500 GeV simulations, pile-up effect and improved vertex finders

Deleted Slides

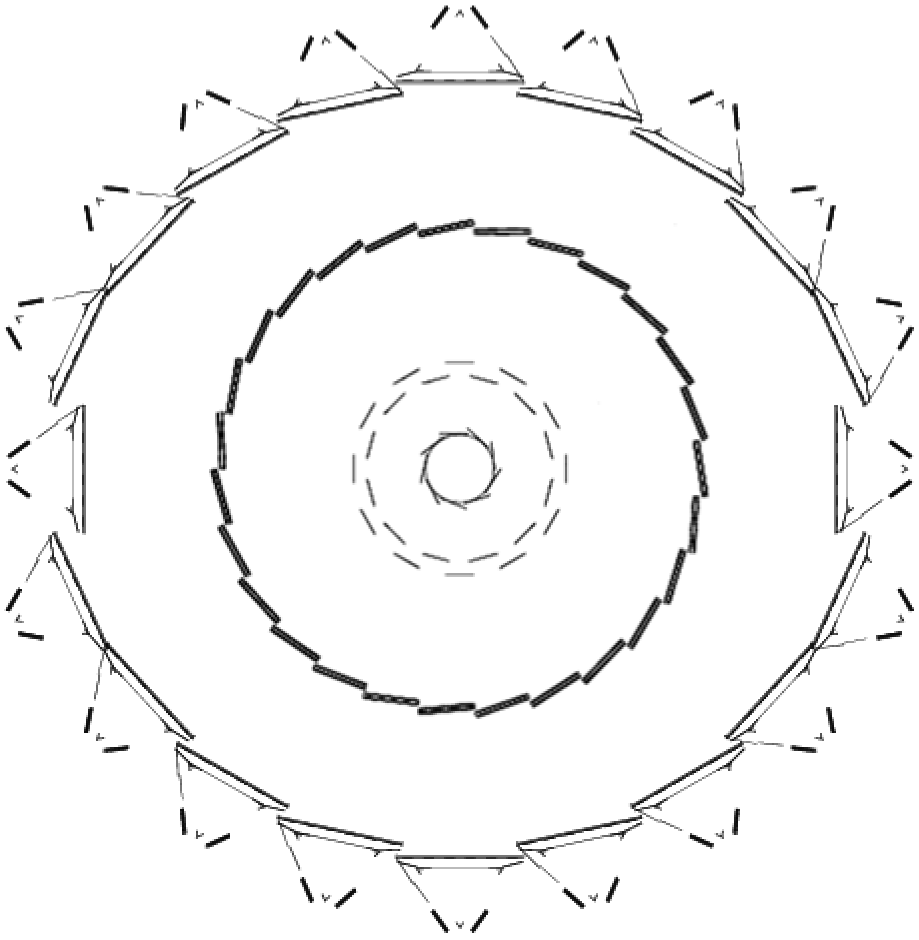
Hand Calculations – p_T resolution, a basic test



- 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.

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**



~ 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

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

Motivation

Understand the HFT performance in the STAR tracking (ITTF) environment

- tracking (matching) efficiency
- ghosting hits/tracks
- pointing resolution & its impact on charm hadron secondary decay vertex
- charm hadron reconstruction efficiency & signal / background estimation
- performance under RHICII luminosity (pile-up effect on PIXELs)
- performance in small systems (p+p)

Status report

Some definitions

Pointing resolution: pointing res. of tracks from outer layers pointing to inner layers

Ghosting hit: the hit picked up in this track is not the real MC hit

Ghosting track: the track reconstructed doesn't have an associated MC track

Track efficiency: possibility of reconstructing a MC track (including geometric acceptance and track quality cut eff)

D^0 efficiency: possibility of reconstructing a MC D^0 (including acceptance and track quality cut eff for daughters and other pair quality cuts for D^0 candidates)

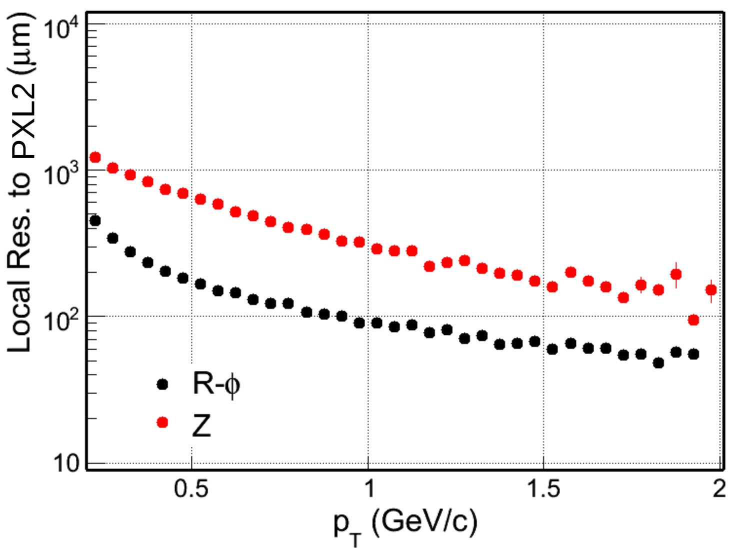
Background: not from D^0, hijing tracks.

D^0 signal: a good reconstructed D^0 with both daughters have the correct associated MC tracks (no mis-PID for daughters)

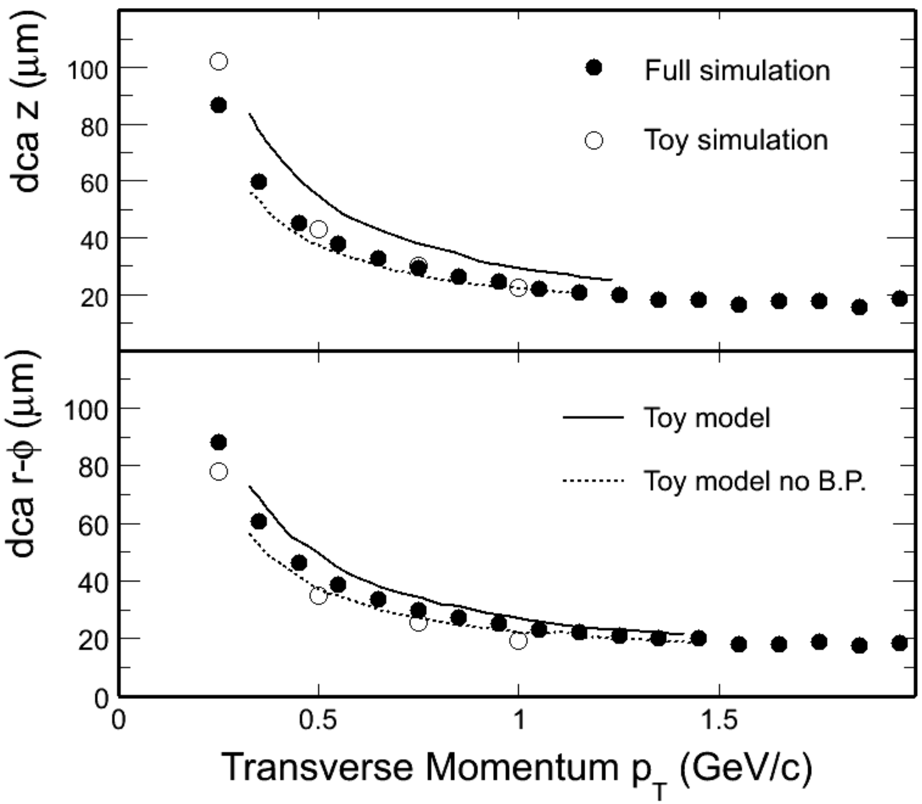
D^0 background: either of the rec. daughter is not from a MC daughter of MC D^0

Pointing Resolution

From outer layers to PIXEL 2

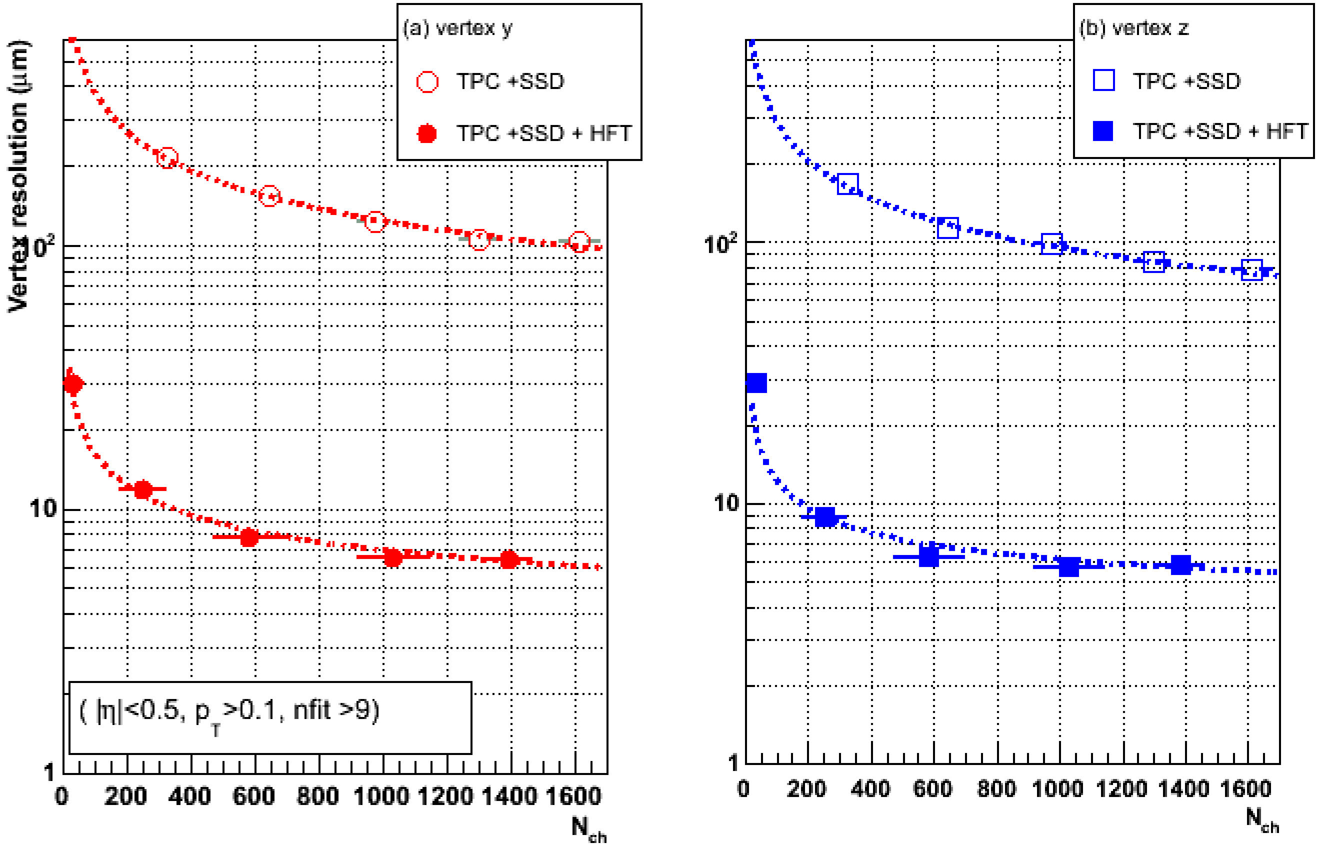


From all hits to primary vertex



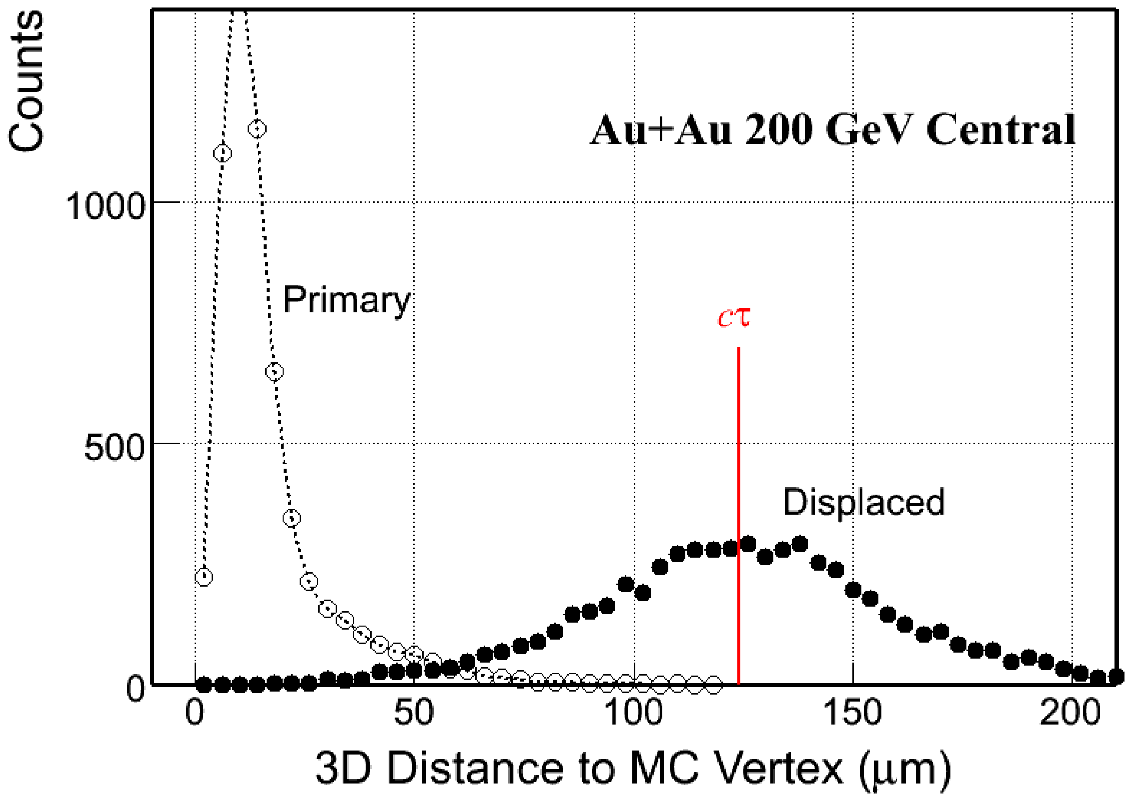
Primary vertex resolution

From Hijing minibias event sample



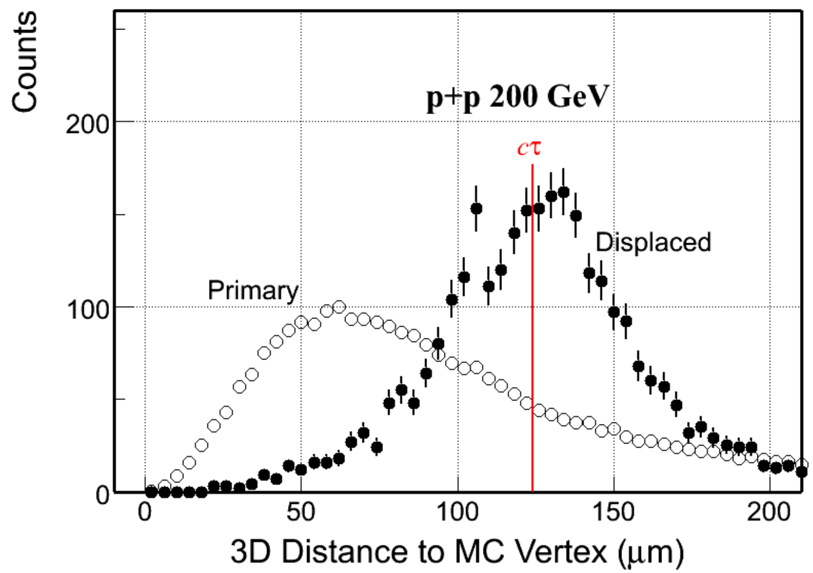
The vertex resolution nicely follows $a \oplus \frac{b}{\sqrt{N}}$

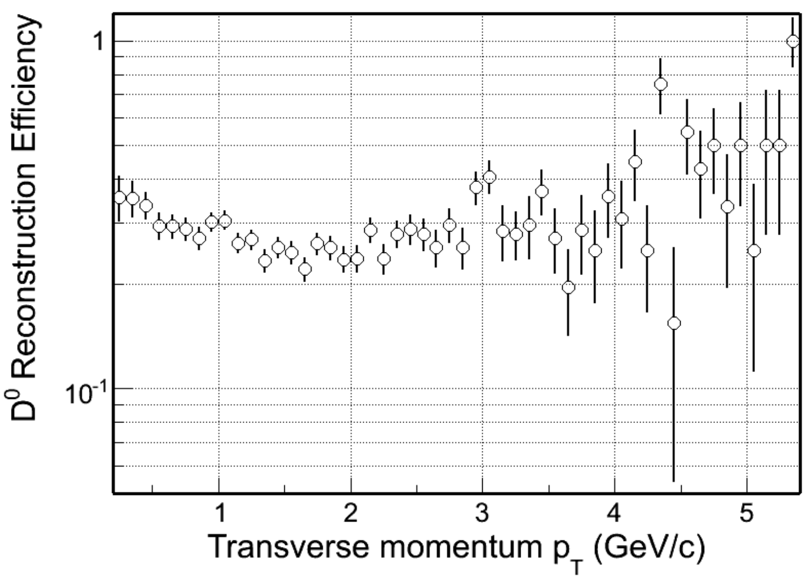
Secondary Vertex Resolution



- All D^0 were scaled by a factor of $1 / \beta\gamma$
- In central AuAu collisions, D^0 secondary vertex is clearly separated from the primary vertex

D^0 simulation in p+p collisions





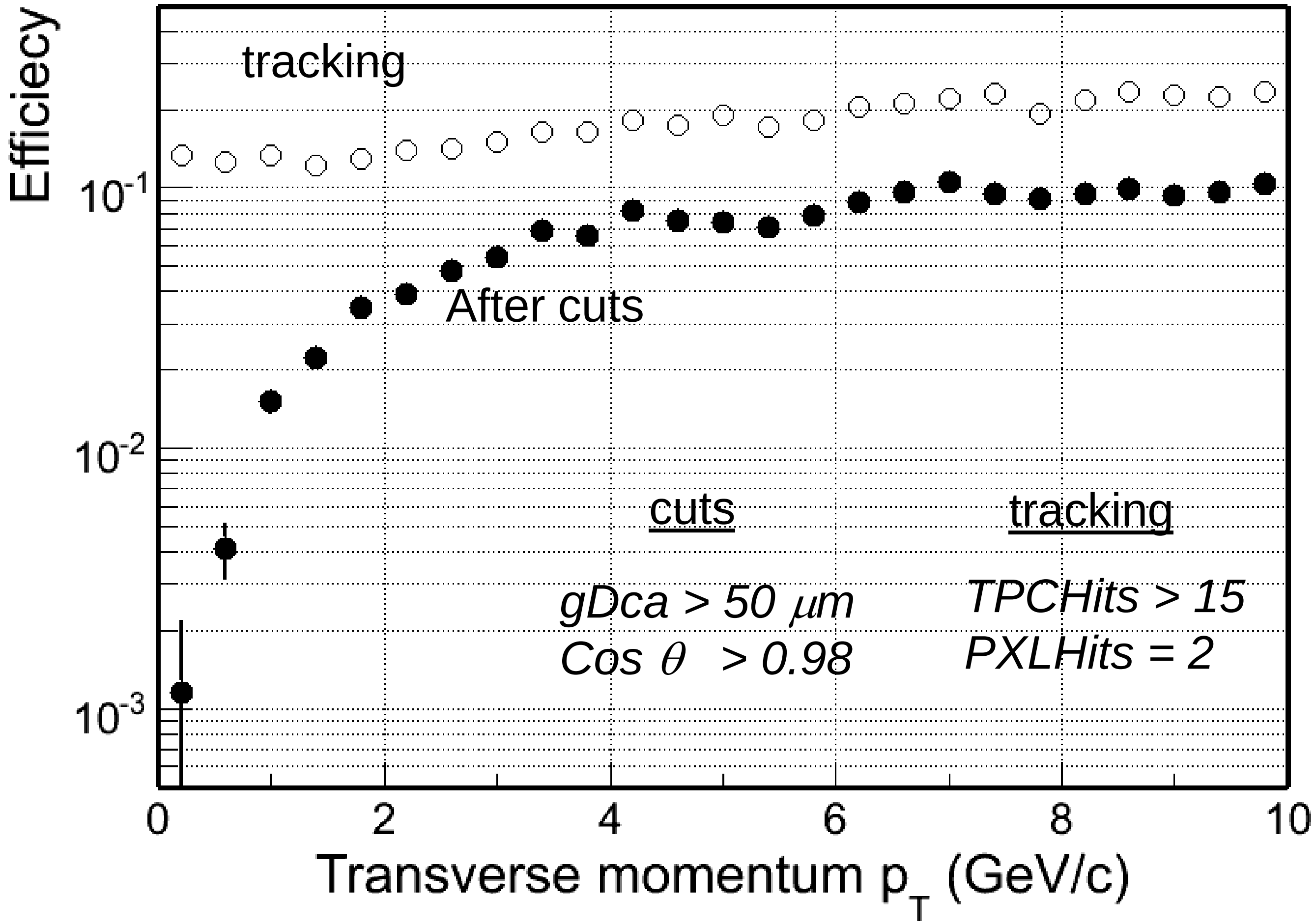
- A first estimation on the D^0 efficiency in p+p collisions
- PYTHIA charm events only + GEANT simulation, no QCD background simulation yet

Statistical error on R_{AA}

P_T (GeV/c)	Δp_T (GeV/c)	R_{AA} relative error (%)
4.5	1.0	1.0
5.5	1.0	1.8
6.5	1.0	2.8
7.5	1.0	4.3
8.5	1.0	6.4
9.5	1.0	9.3

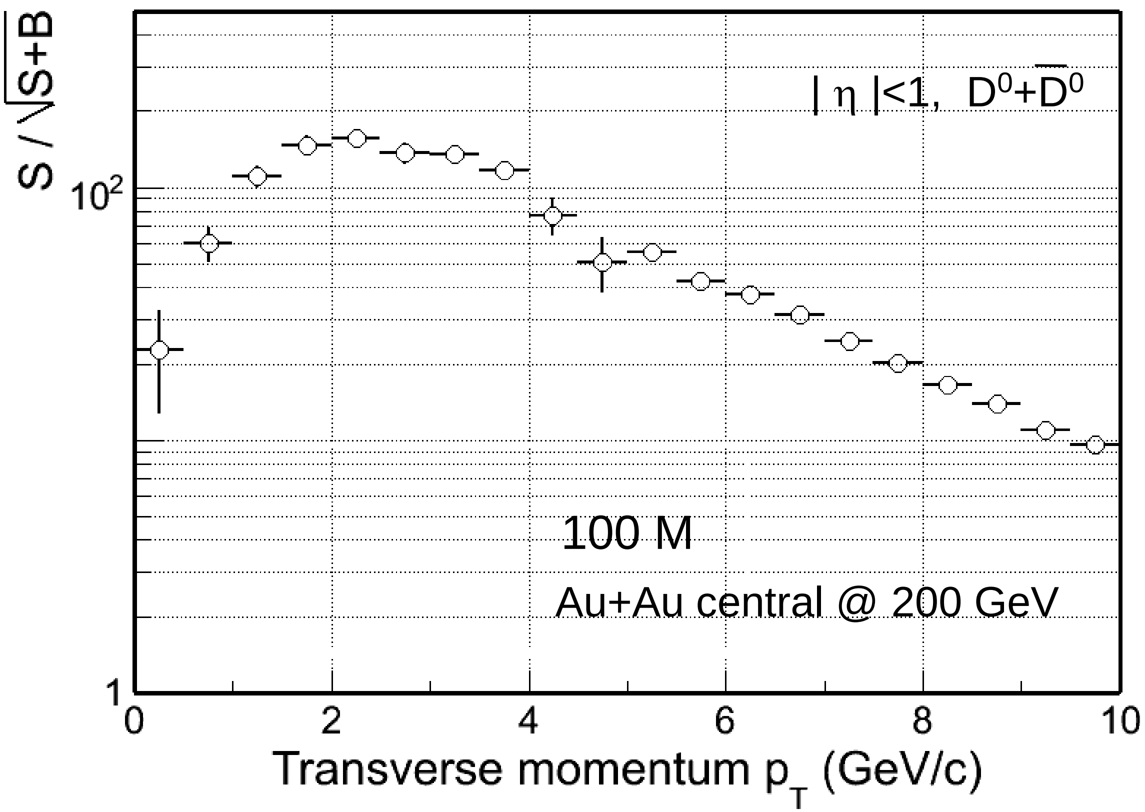
- 1.0 pb^{-1} analyzed data in $|v_z| < 15$ cm
- error in central AuAu neglected
- Background not included yet

D^0 efficiency



- Kinematic cuts may be optimized after systematic studies.

D^0 signal / background



relative error on yield in p_T spectrum

$$\sim \frac{1}{S/\sqrt{S+B}}$$

absolute error on v2

$$\sim \frac{1}{S/\sqrt{S+B}}$$

- S, B are scaled to real situation
- central, no pile-up
- Assume perfect PID

S: D^0 yield $dN / d\eta = 2$
power-law with $\langle p_T \rangle$ = 1GeV/c, n=11
B: Combinatorial background from
Hijing and D^0 decay daughters
Hijing shape for background ext.

Updates

D^0 Measurements: dN/dy per NN collision ~ 0.004 (STAR)
we take half of it as the estimation

Hits selection in PIXEL: MC hits and Rec hits can be > 2
we include those tracks

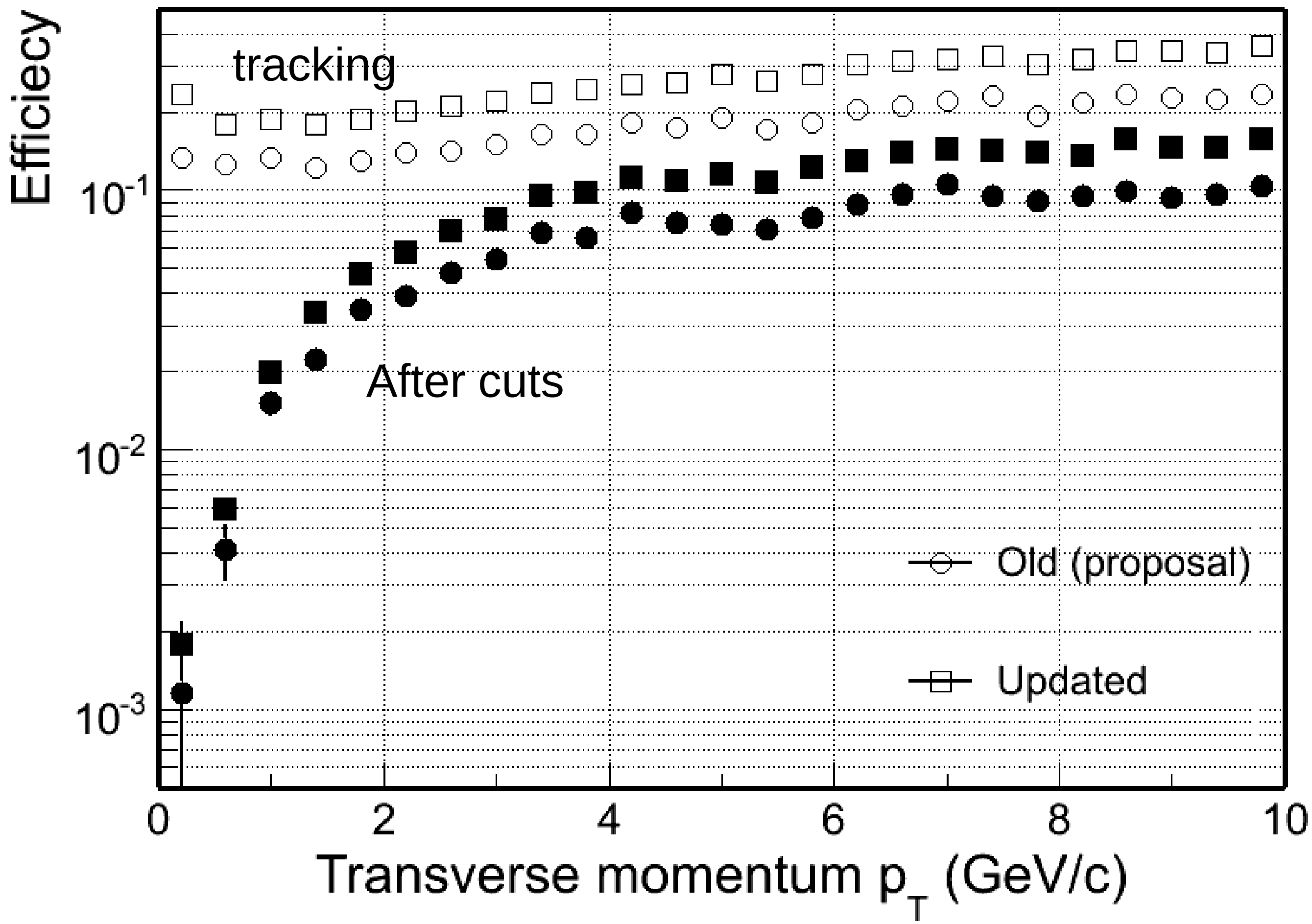
D^0 Background: K from D and pi from others -- important in high p_T
$D^0 \to K^- + X$ (53%), as well as kaon from other charm hadrons.

→ Update version

PID with TOF:

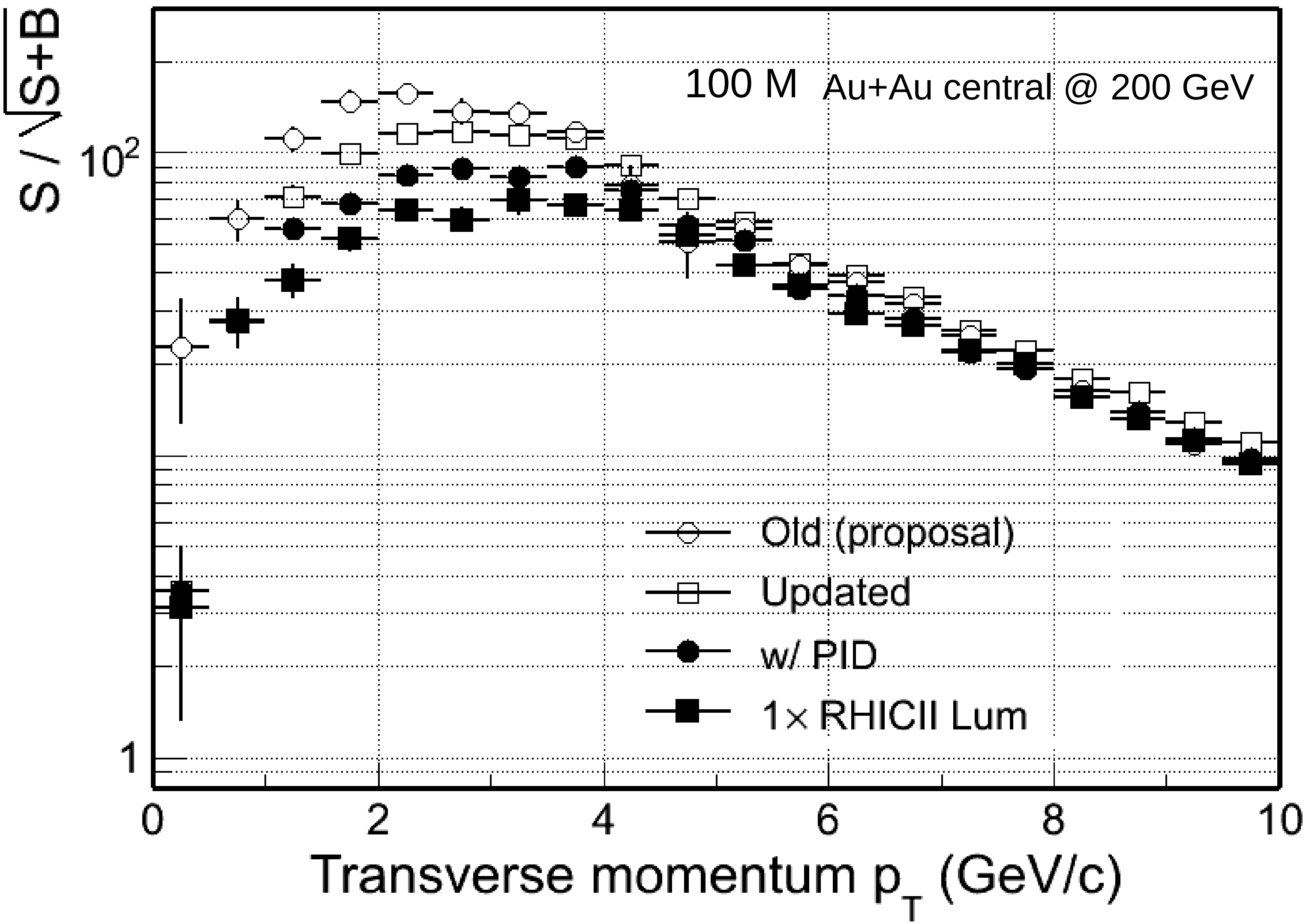
Assume perfect K/pi at p_T<1.5 GeV/c, no PID for K/pi beyond that.
Background estimation also includes PID contamination.

Improvement on Efficiency



Single track efficiency improved by ~ 20-30%
-- # of hits selection in PIXELs

D^0 signal / background @ RHIC II luminosity



Pile-up in PIXEL

Beam diamond sigma = 15 cm
minibias collision rate = 80 kHz
PIXEL chip integration time = 200 us

Pile-up hit density (cm^{-2}) (from minibias collisions)

Pile-up level	PIXEL1	PIXEL2
0.5x	21	3
1.x	43	6
2.x	86	12
3.x	129	18
AuAu central	19	2.4

Total hit density in PIXEL
= hit density from one central Au+Au event
+ hit density from pile-up events at A x RHICII luminosity level in PIXEL
+ UPC electrons

Summary

Currently we have:

✓A full Monte Carlo simulation + reconstruction chain with HFT in STAR has been set up.
✓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 and p+p collisions
✓Quantify the pile-up effect on the single track efficiency (ghosting), D0 background and signal significance.

We are working on:

- Improving our understanding of detail characteristics of tracking algorithm
  - single track efficiency / pointing resolution
  - ghosting rate at low p_T
- Optimization of D^0 reconstruction at low p_T – improving efficiency
- Systematic study on other charm hadrons
- p+p 200/500 GeV simulation, pile-up effect and incorporating vertex finders