Summary of GEANT3 Pixel Simulations for Strawman Pixel detector

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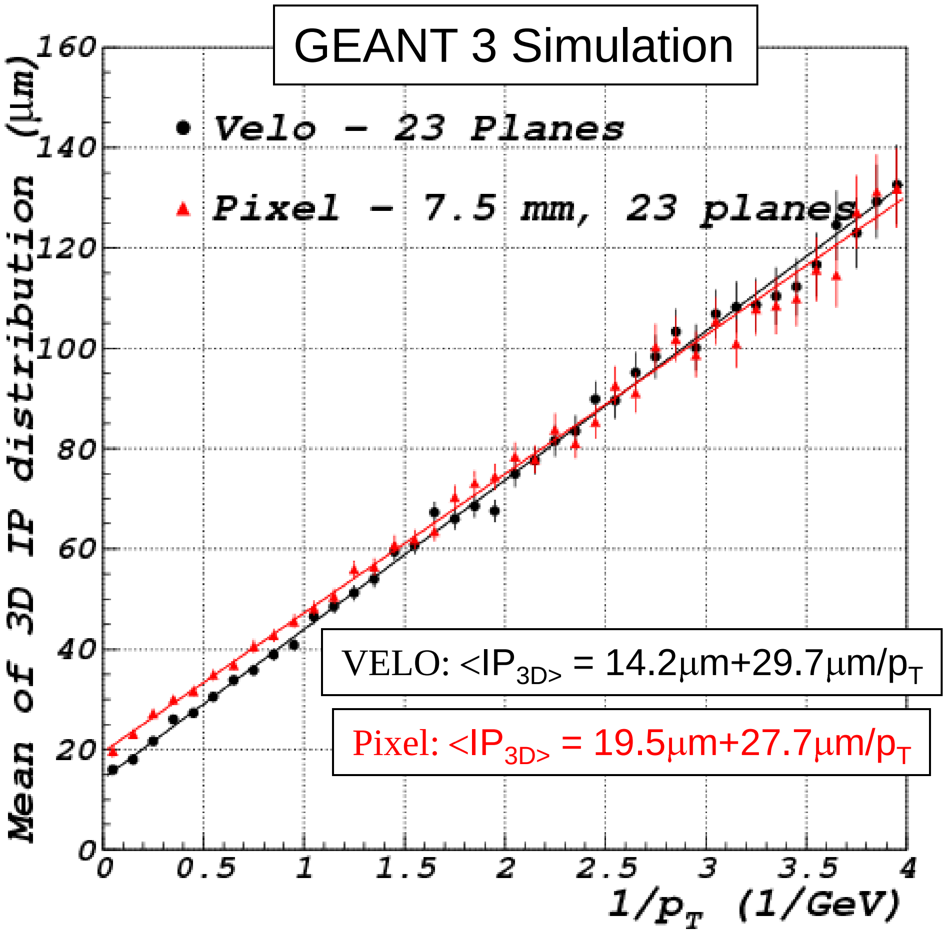
VELO Upgrade Meeting, April 28, 2010

Introduction

- GEANT3 simulation is being used to understand the sensitivity to various design parameters of the pixel detector.
  - IP resolution
    - Relate to this are vertex resolution & proper time resolution
  - Acceptance for selected B decays
- (Too) many variation possible
  - I will show you just the most important ones.
  - Several more in the backup slides

“Default” Resolution

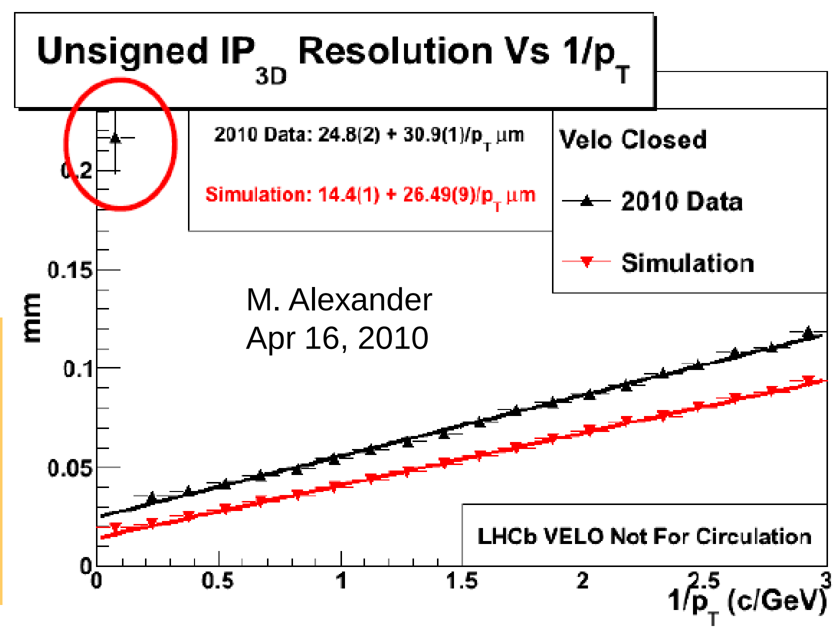


VELO

- tuned RF foil to full LHCb sim.
- resolutions from LHCb sim

Pixel

- 23 stations, as in VELO
- first pixel at 7.5 mm
- 0.5 mm guard ring
- 1% per station
- Outer edge at 34.5 mm (X and Y)
- RF foil X 0.5
- 150 μm thick resol’n function
- 1 mm overlap btwn L&R halves



- Slope in reasonable agreement with data (29.7 (G3) vs 30.9 (2010 data)). Material well-simulated.
- Intercept in 2010 data (25 μm) vs sim (14.4 μm).

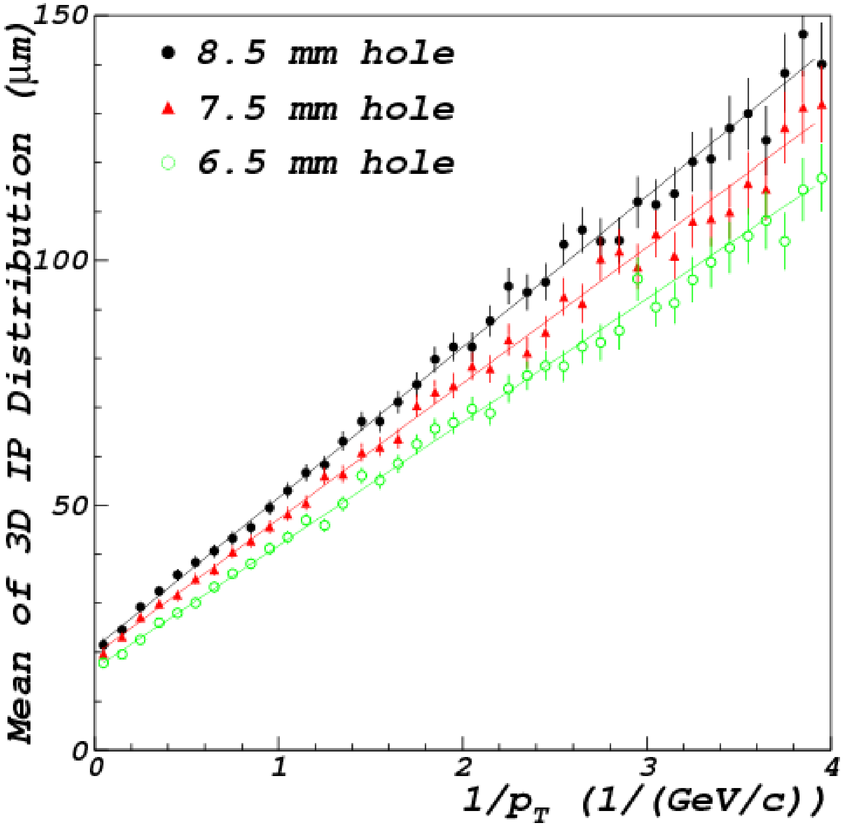
I get 14.2 um, but no vertex error. Vertex errors in 2010 data still too large, but ~20μm. If subtract 20μm in quadrature: $\sigma \sim \sqrt{25^2-20^2} \sim 15$ μm (close to 14.2 um)

Hole Size

- Resolution
- Acceptance

Resolution vs Hole Size

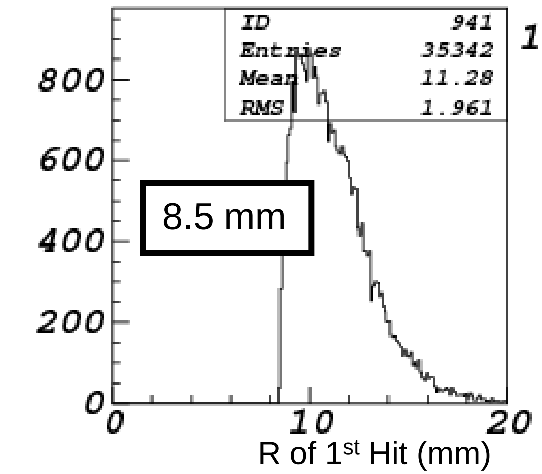
Position of first active pixel

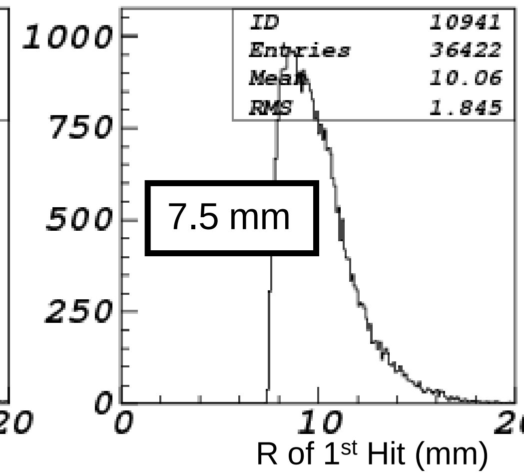


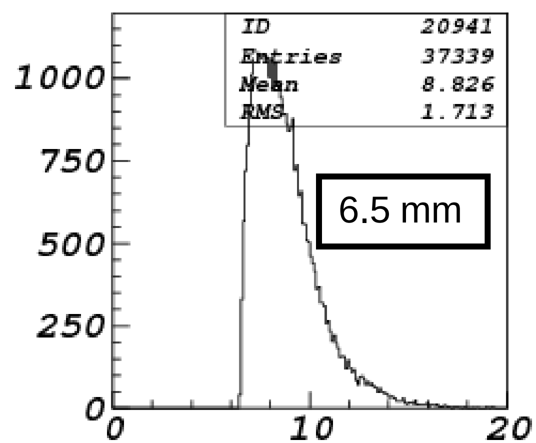
8.5 mm: $\langle IP_{3D} \rangle = 20.8\mu m + 30.8\mu m/p_T$

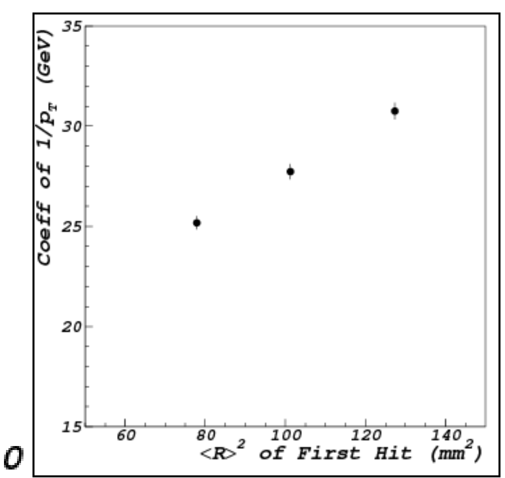
7.5 mm: $\langle IP_{3D} \rangle = 19.5\mu m + 27.7\mu m/p_T$

6.5 mm: $\langle IP_{3D} \rangle = 16.6\mu m + 25.2\mu m/p_T$









Clearly gain by getting to smaller radius by $\sim\langle R_1\rangle^2$

Acceptance

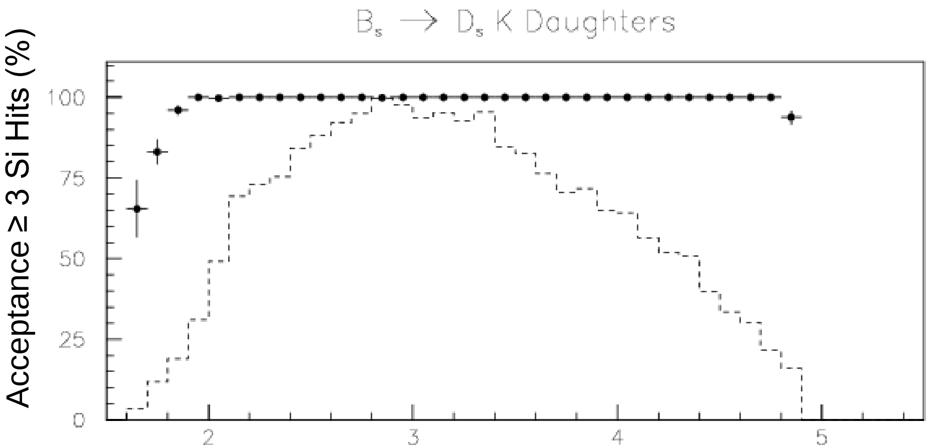
Using $B_s \rightarrow D_s(KK\pi)K$

Acceptance measured relative to tracks that have:

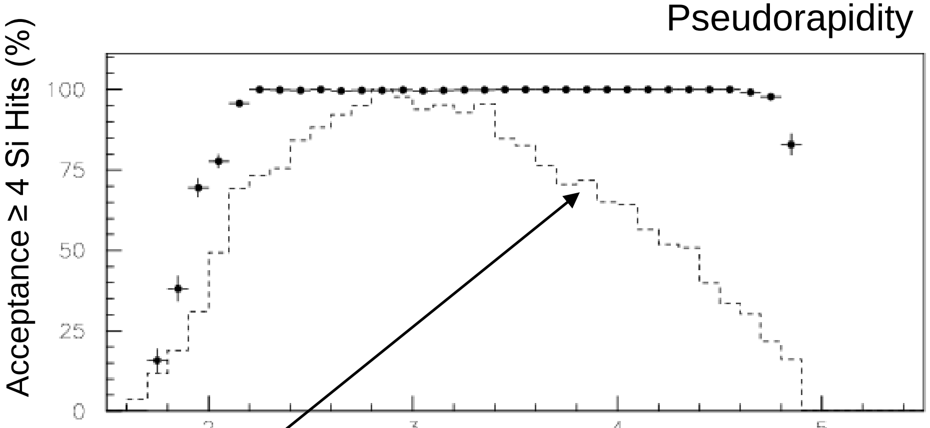
- Hit all 3 T-stations
- $|\theta_x| < 350$ mrad
- $|\theta_y| < 250$ mrad
- $|\theta| > 15$ mrad

Acceptance for $B_s \rightarrow D_s K$

Si Coverage: 7.5 mm < |X|, |Y| < 34.5 mm

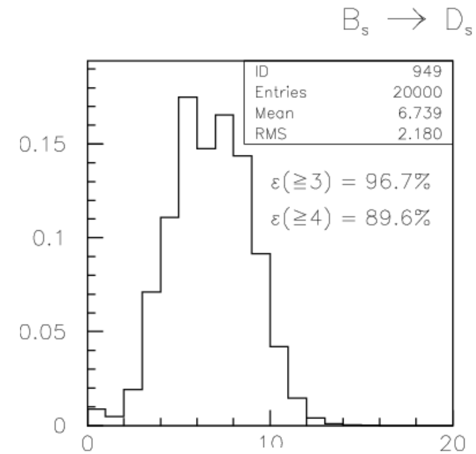


Pseudorapidity

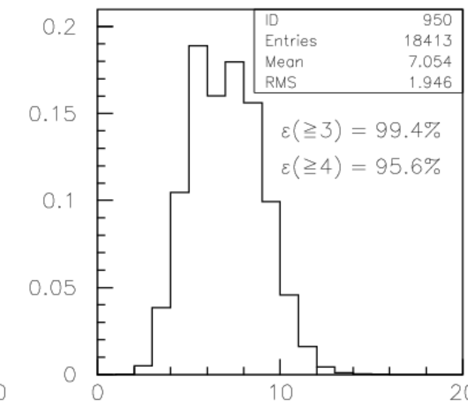


Pseudorapidity

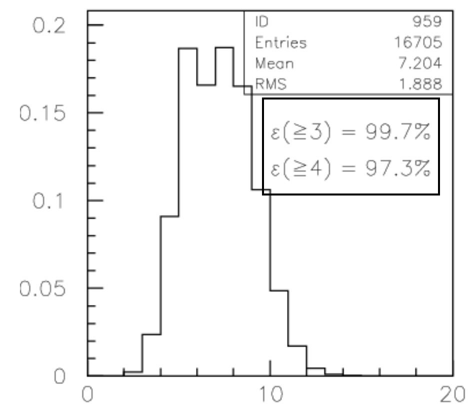
pseudorapidity spectrum



#Si hits, all tracks



#Si hits, θ cut, no T hits req.



#Si hits, θ cut, & 3T hits

Acceptance for this 4-body decay

All ≥3 Si hits: 99.5%

All ≥4 hits: 95.2%

Acceptance comparison: $B_s \rightarrow D_s K$

Acceptance definition:

- 3 T hits
- $|\theta_x| < 350$ mrad
- $|\theta_y| < 250$ mrad
- $|\theta| > 15$ mrad

	Acceptance per track (%)		Total 4-body acceptance (%)	
Hole Size	≥3 hits	≥4 hits	≥3 hits	≥4 hits
6.5 mm	99.8	98.0	99.8	96.4
7.5 mm	99.7	97.3	99.5	95.1
8.5 mm	99.4	96.2	98.6	91.5

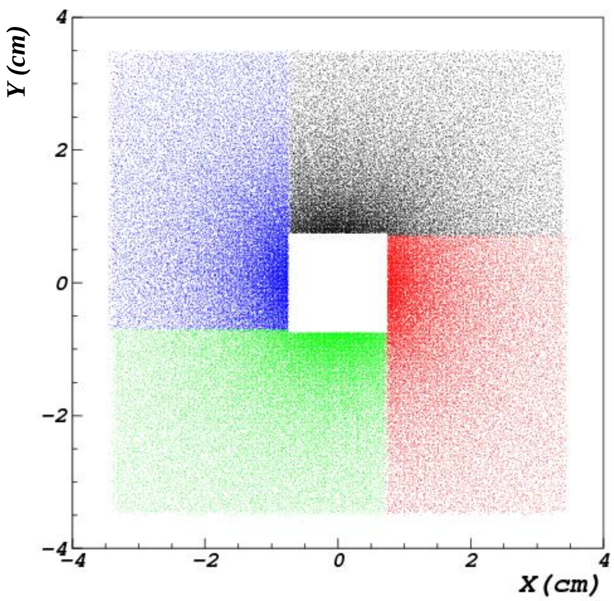
Rotated Planes

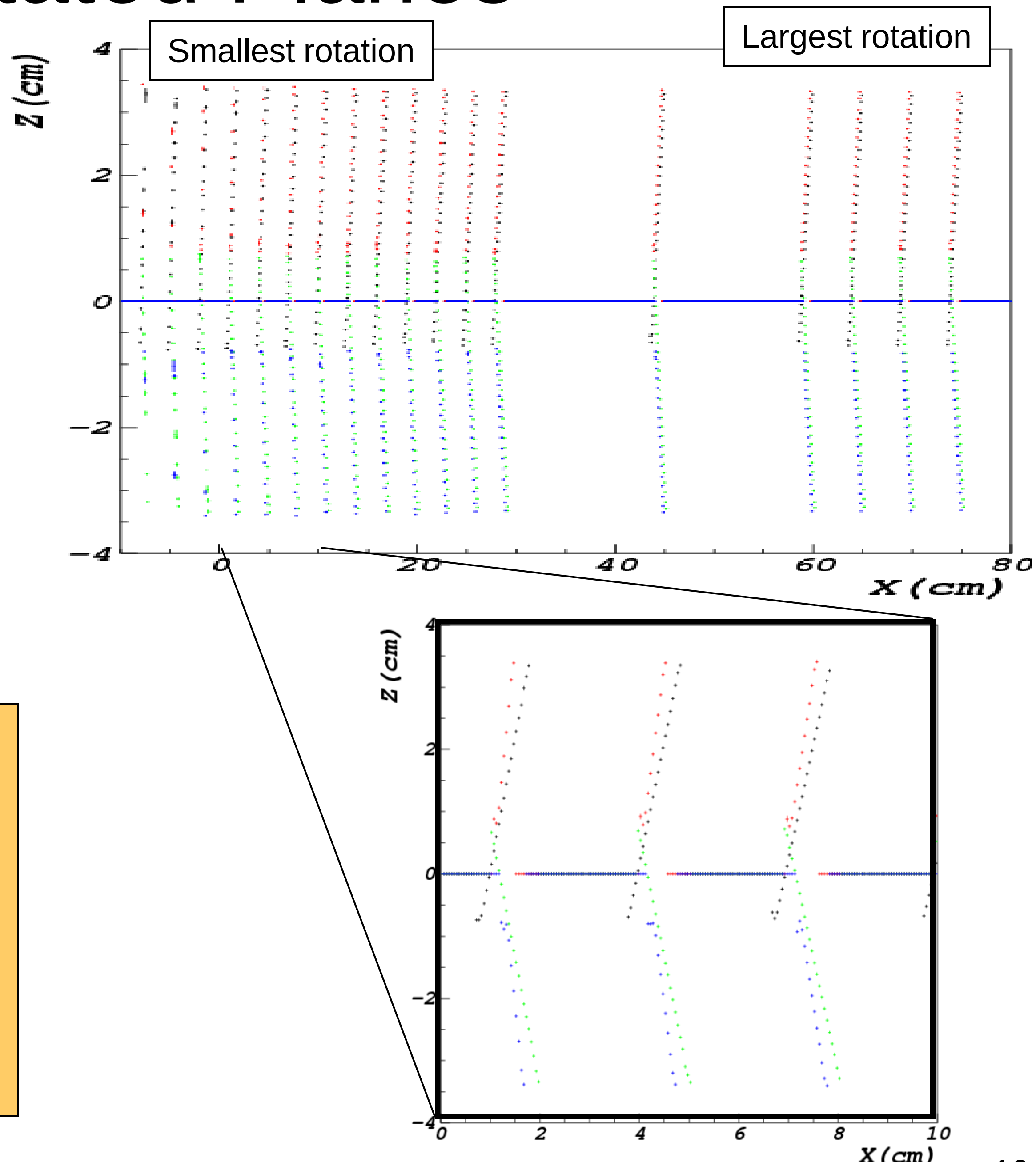
- Initial suggestions at VeloPix Kickoff meeting by Tjeerd Ketel (see presentations here)

- Pros:
  - Clearly sample resolution function closer to minimum, giving better IP resolution.
- Cons
  - Complicates mechanical design
    - Maybe not too much for just rotation around Y axis
  - Pattern recognition/trigger
    - pixel (X,Z) position will depend on X.
  - Improved IP resolution will decrease with radiation dose.
  - Lose some acceptance ~ $\cos\theta_{tilt}$
  - Slightly more material traversed (~ 1/ $\cos\theta_{tilt}$)
  - If inner region is diamond, charge sharing much less, leading to smaller gains from tilting

- Anyhow, we should have a look at the potential gains & losses.
  - Assume silicon for now
  - No attempt to include decreased hit resolution with rad. dose, although this is something we are interested in doing.

Rotated Planes





Here:
Rotate each of the 4 quadrants by 20° - <θ$_x$>, so that each quadrant of each plane has average track projected angle equal to 20°.

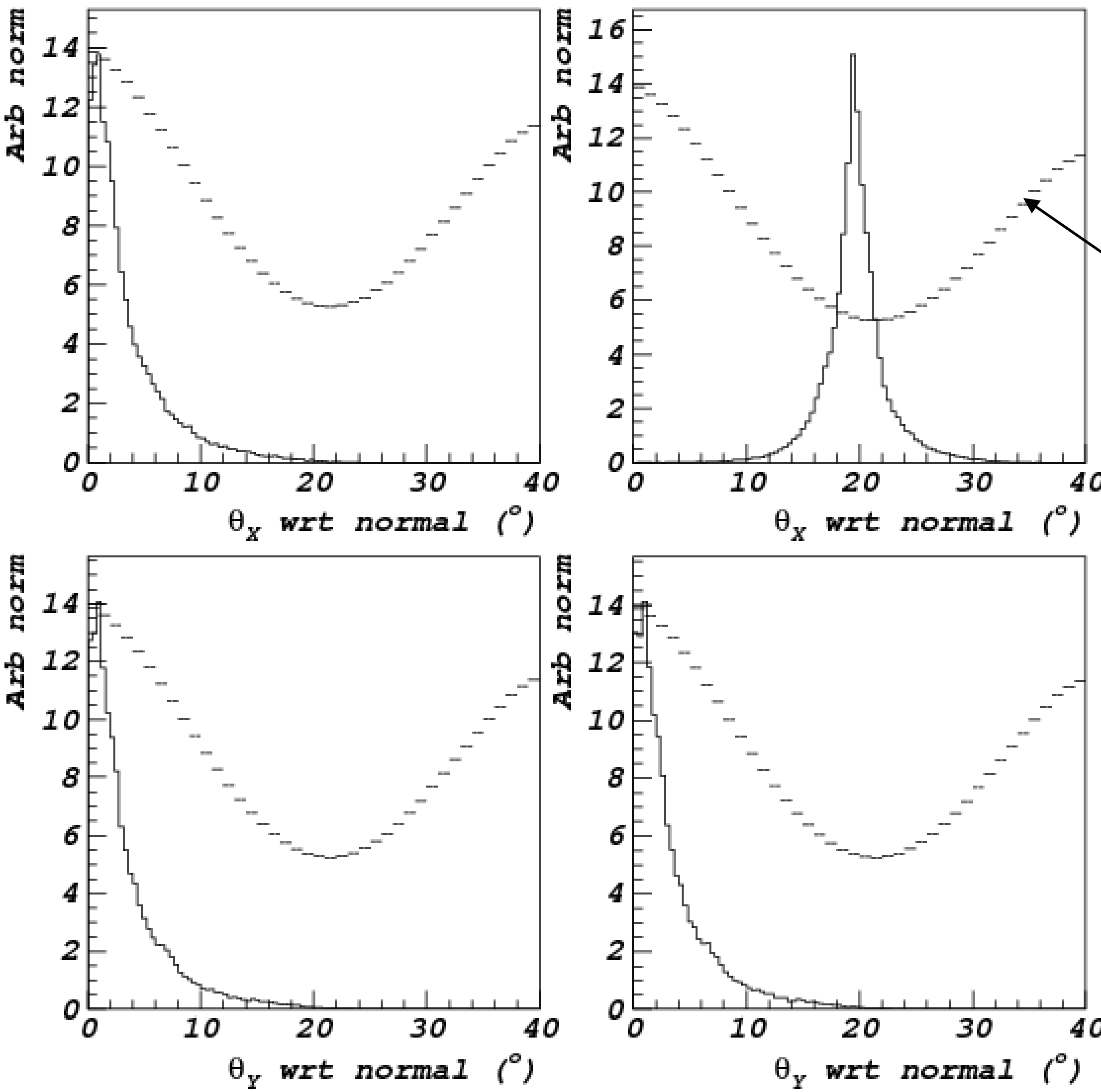
(Suggestion by Marco G.)

Angle of track with respect to sensor normal

No rotation | 'Optimized' rotation

θ_x

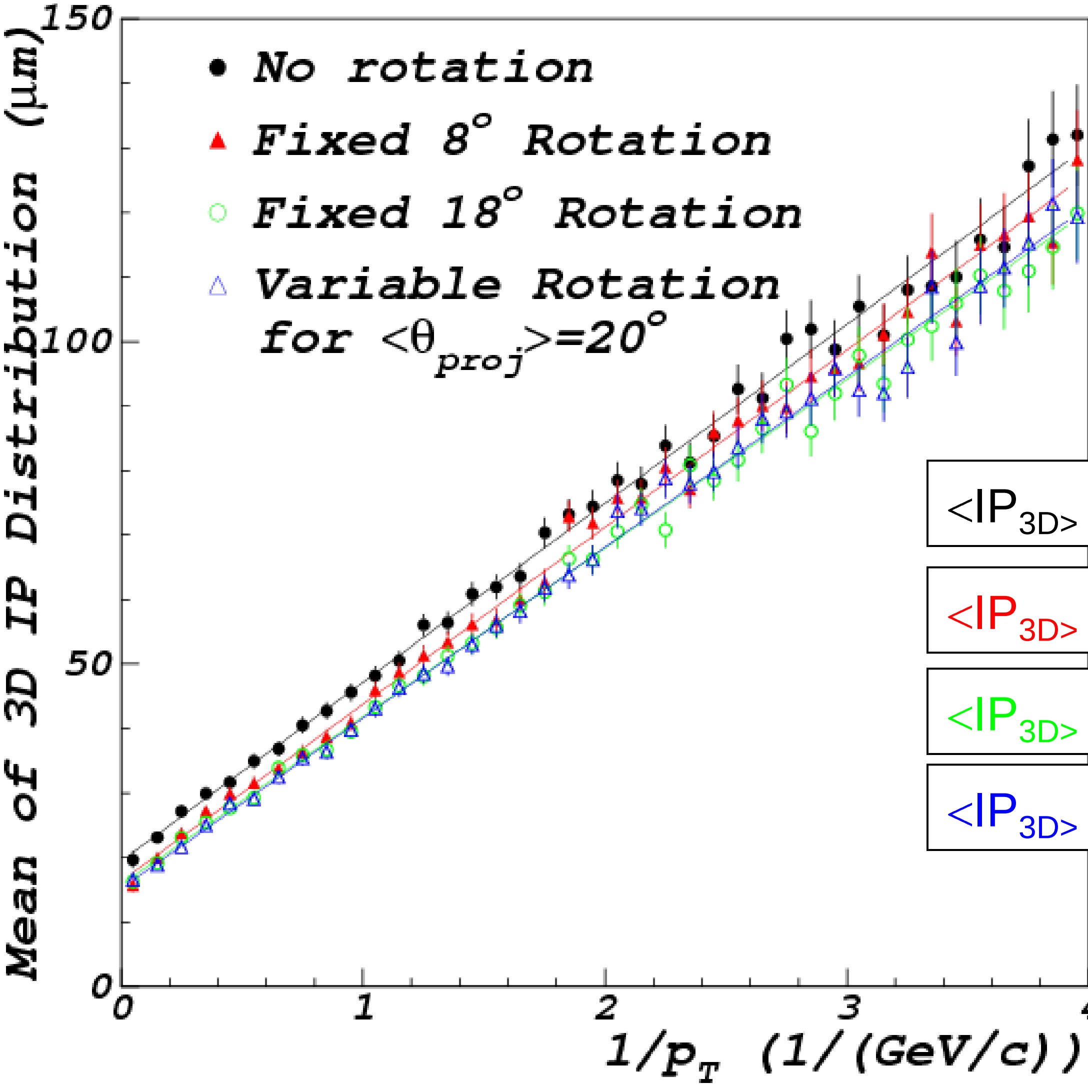
θ_y



Assumed resolution function for 150 μm thick, non-irradiated silicon.

NB: Binary resolution is ~16 μm

IP Resolution Comparison



$\langle IP_{3D} \rangle = 19.5\mu m + 27.7\mu m/p_T$

$\langle IP_{3D} \rangle = 16.3\mu m + 27.5\mu m/p_T$ -17%

$\langle IP_{3D} \rangle = 15.8\mu m + 26.1\mu m/p_T$ -19%

$\langle IP_{3D} \rangle = 15.2\mu m + 26.5\mu m/p_T$ -22%

Most of improvement can be gained for a small fixed rotation

Acceptance comparison with different rotation angles

	Acceptance per track (%)		Total 4-body acceptance (%)	
	≥3 hits	≥4 hits	≥3 hits	≥4 hits
No rotation	99.7	97.3	99.5	95.1
8^o fixed rotation	99.6	97.0	99.3	94.3
18^o fixed rotation	99.2	95.8	98.6	90.9

#Planes/Spacing

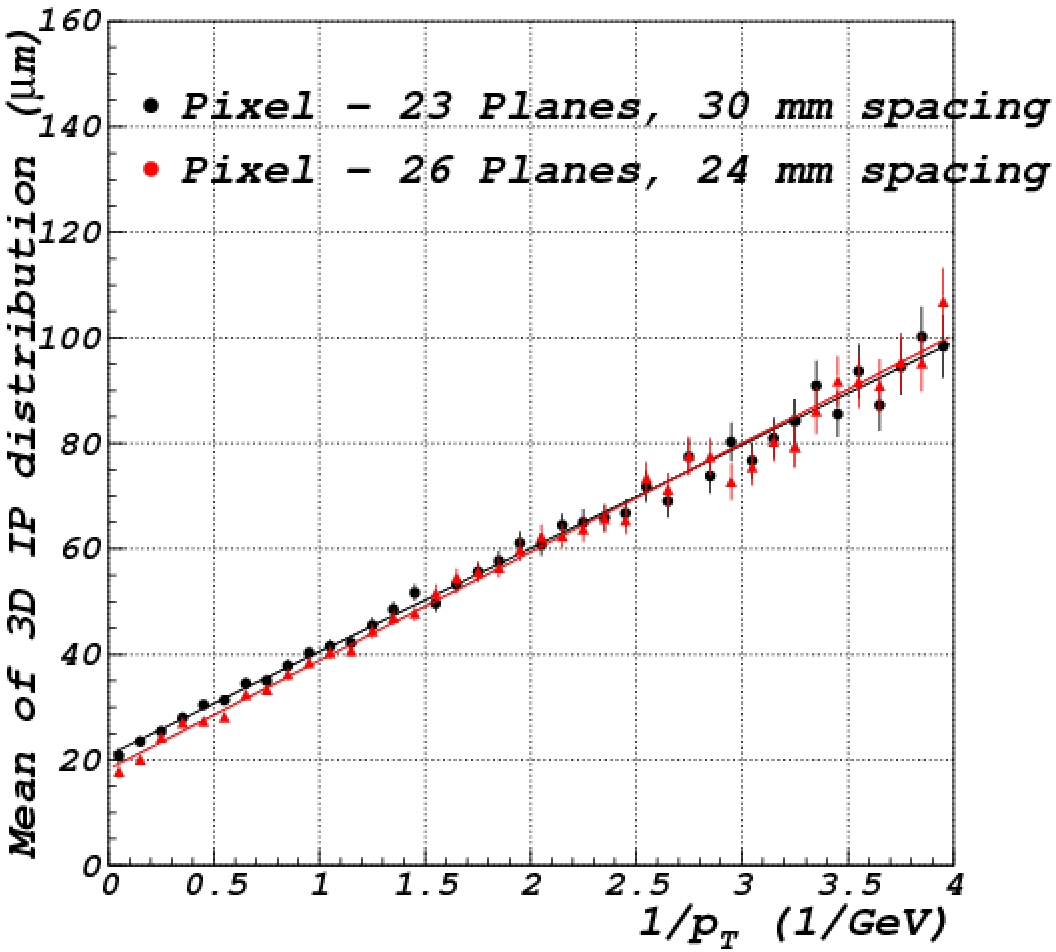
- More closely packed planes means more hits and smaller R of 1st hit. I looked at this in the past (25 mm spacing), and it was slightly better, but concern over the tight spacing..

- Worth another look as we start trying to converge!

- Marco G. sent along a suggested layout.
  - 30 mm spacing → 24 mm spacing, near IP

- No idea how to convincingly model the RF foil for this layout, so I remove it in both the 23 and 26 plane comparisons on next few slides.

Closer spaced planes 30 mm → 24 mm near IP (23 planes → 26 planes)



$\langle IP_{3D} \rangle = 20.9\ \mu m + 19.6 \mu m/p_T$

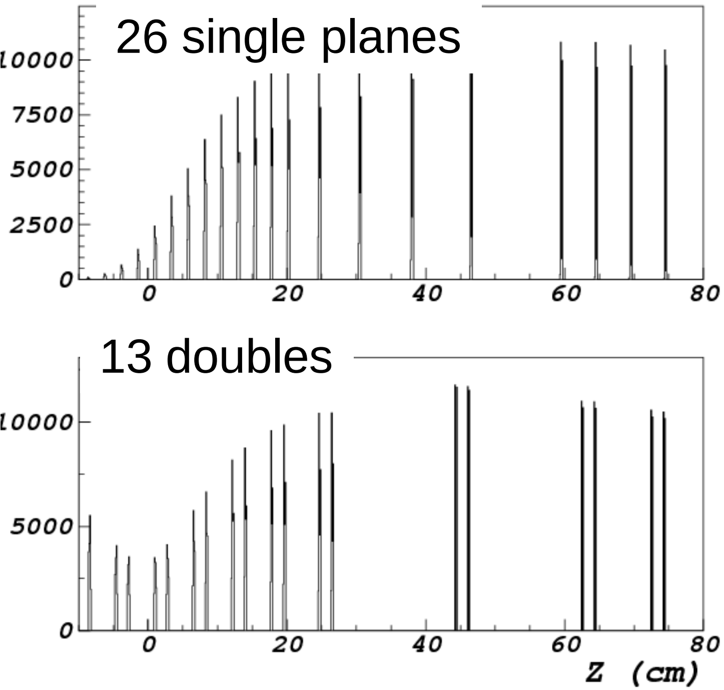
$\langle IP_{3D} \rangle = 18.3 \mu m + 20.6 \mu m/p_T$

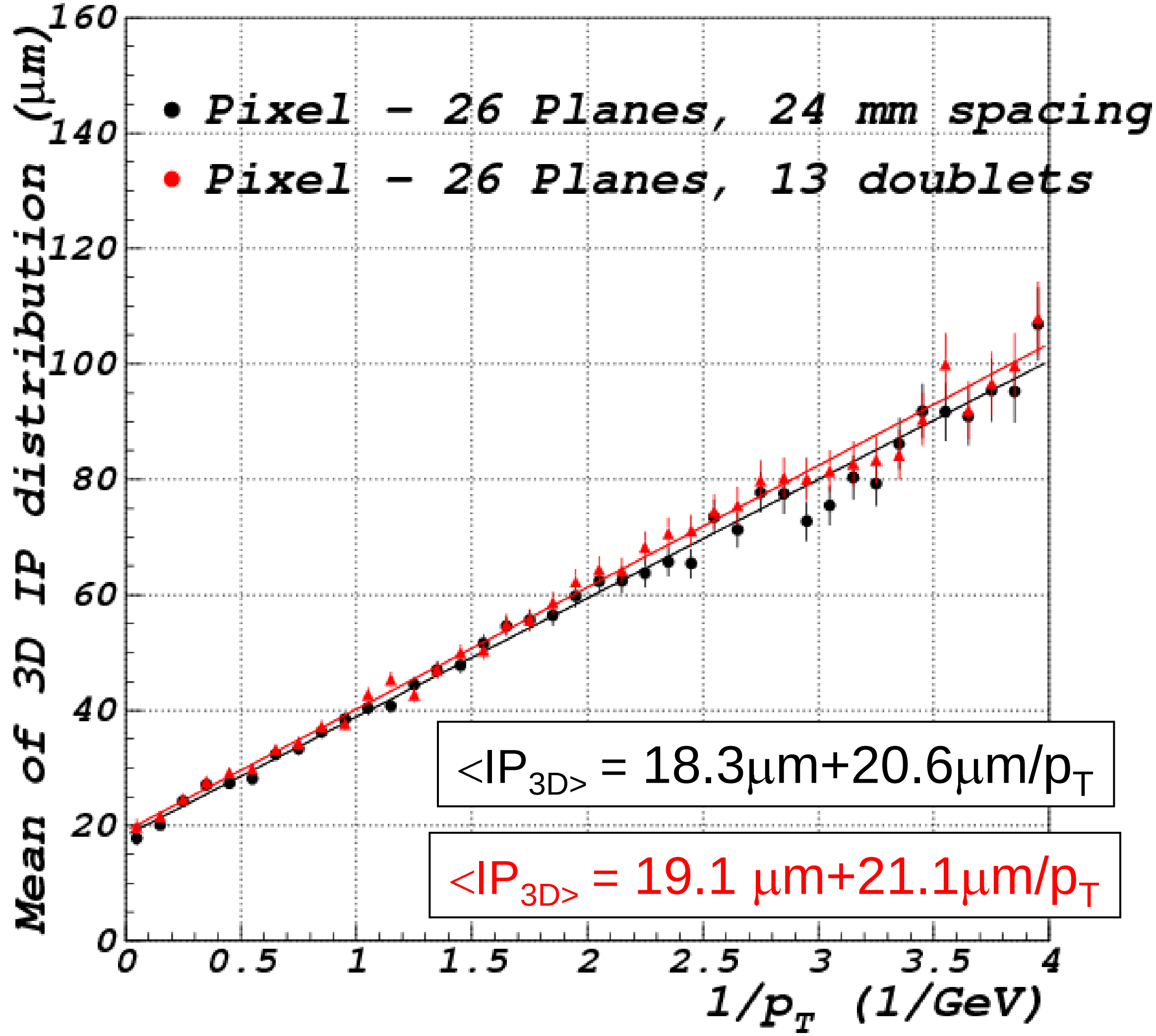
As one would expect, better resolution as $1/p_T \rightarrow 0$ since R of 1st hit smaller.

Slightly larger slope due to more material.

26 planes a bit better:
NB: But, RF foil large contribution, so hard to conclude just from this.

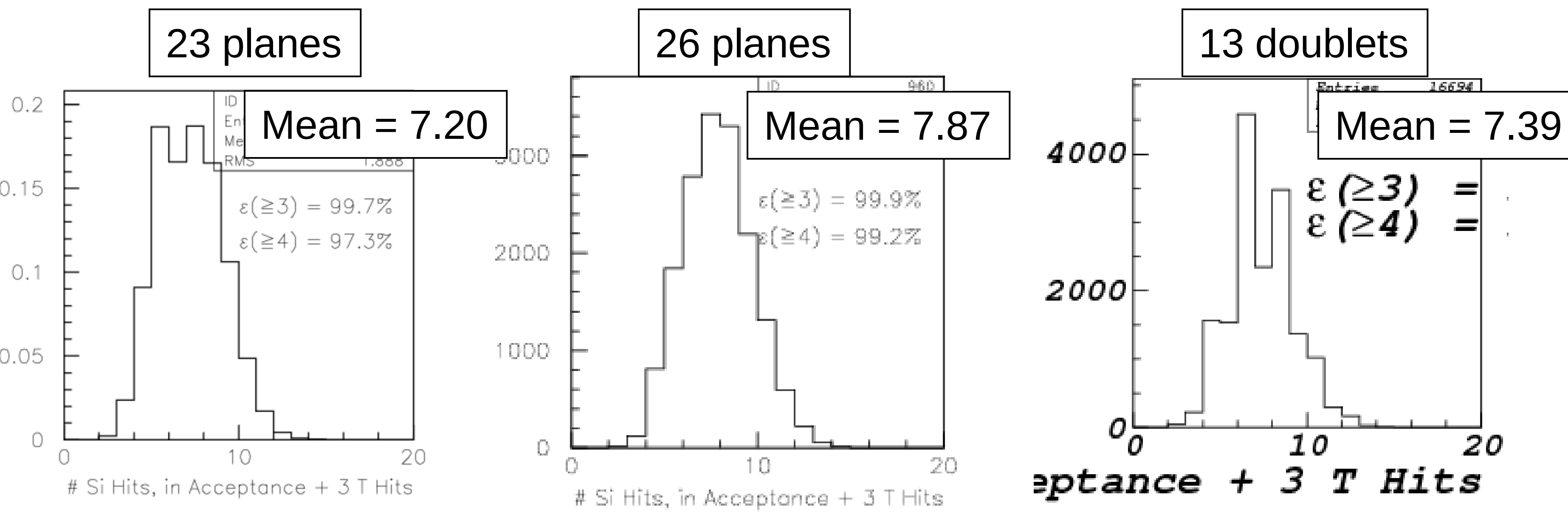
26 Single Planes vs 13 Doublets





Acceptance in $B_s \rightarrow D_s K$
23 pl, 26 pl, 13 doublets

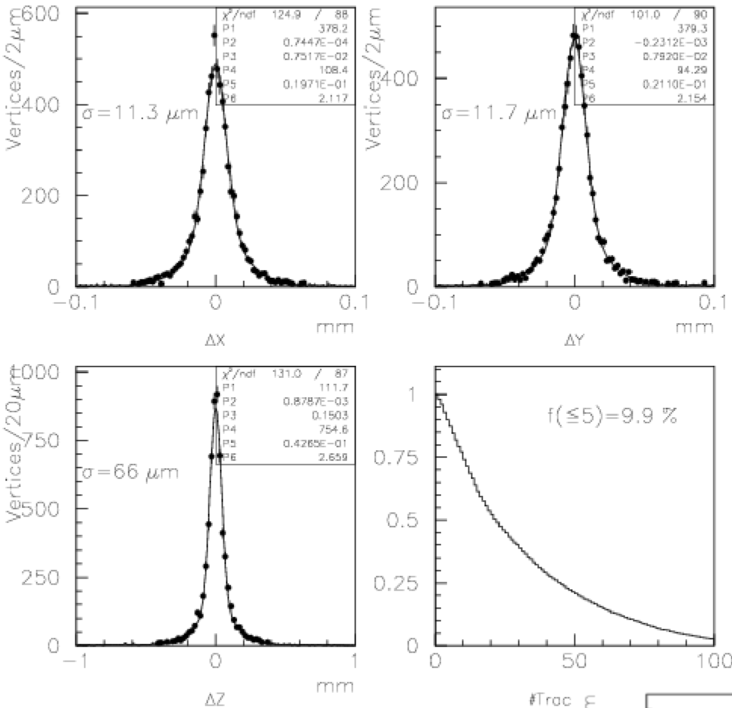
	Acceptance per track (%)		Total 4-body acceptance (%)	
	≥3 hits	≥4 hits	≥3 hits	≥4 hits
23 planes	99.7	97.3	99.5	95.1
26 planes	99.9	99.1	99.8	98.3
13 doublets	99.7	98.3	99.3	96.6



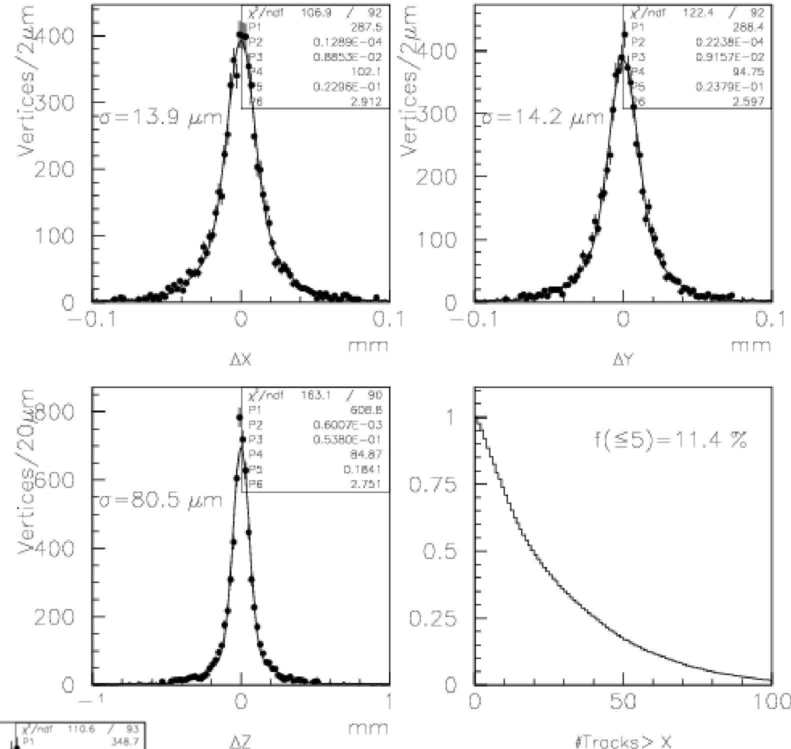
Vertex Resolution & #Tracks in PV

- Look at minbias events – 2e32
  - Run with 6.5 mm, 7.5 mm and 8.5 mm hole
- Compare:
  - Vertex resolution
  - #PV with ≤ 5 tracks
- Caveat
  - No rejection of outlier tracks in vertex fit
    - Could probably improve by outlier rejection, but not worth it for this study.
  - Velo tracks, with no T hits, use Kalman errors assuming p_T=400 MeV
    - Tried more fancy games to do better, but only marginal improvement.

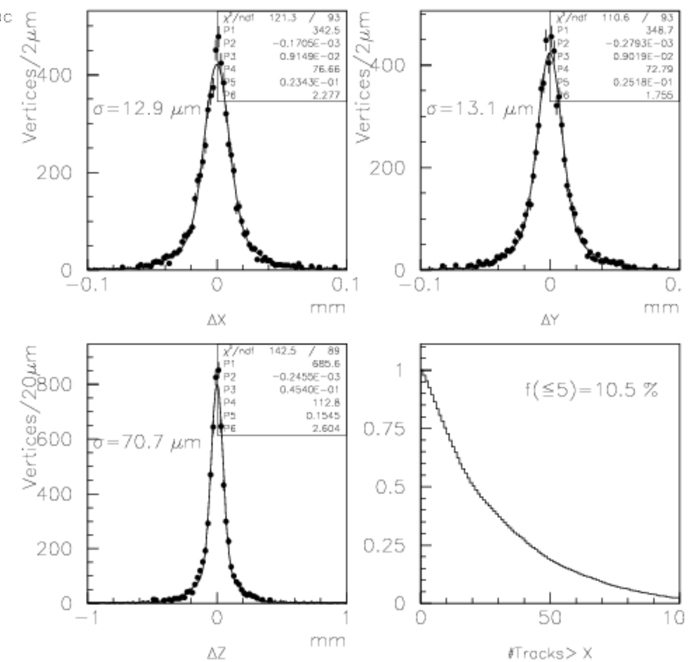
6.5 mm hole



8.5 mm hole

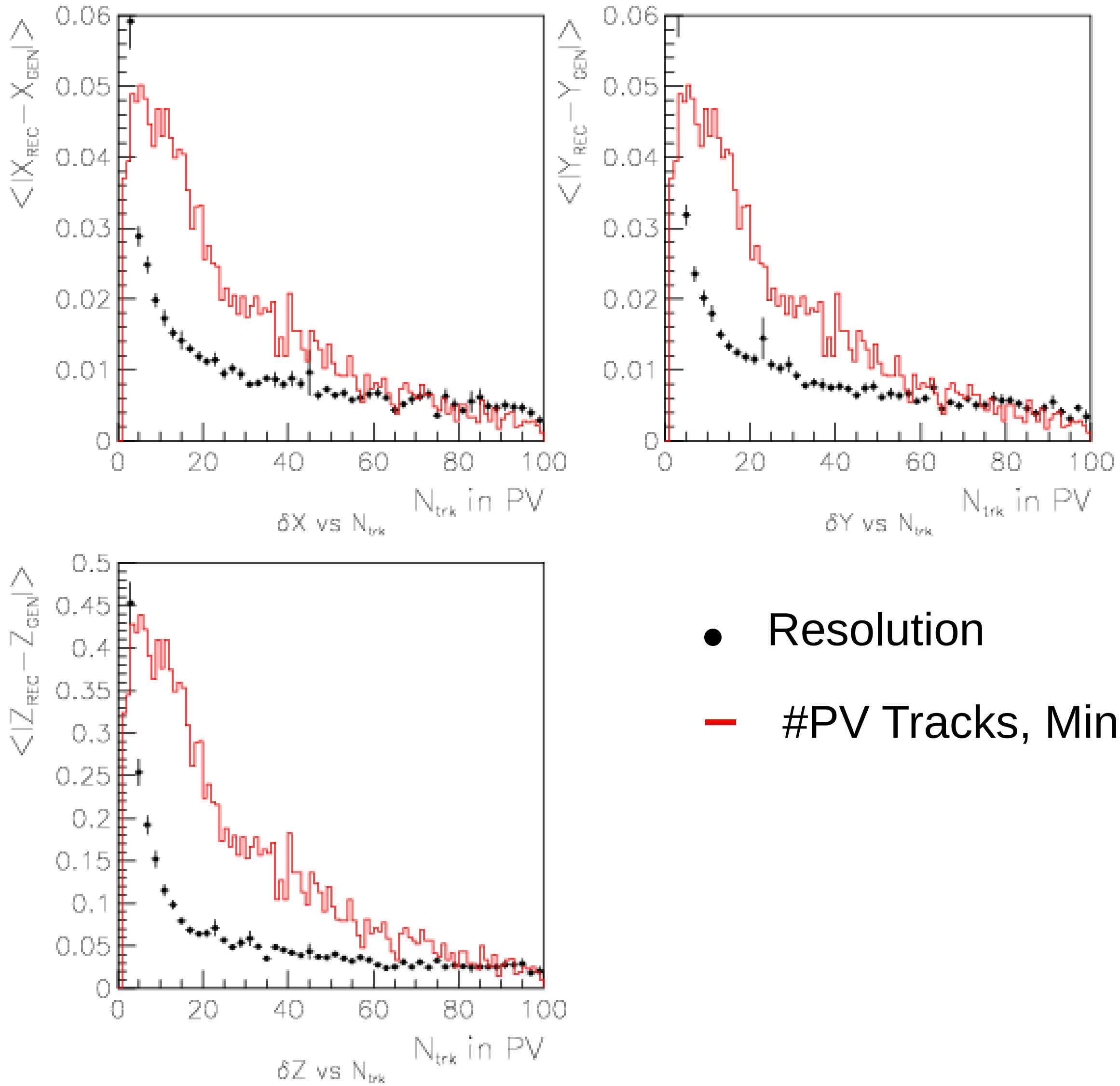


7.5 mm hole



Numbers in the same ball park as standard LHCb Velo simulation

‘Resolution’ vs #Tracks in PV



- Resolution
- #PV Tracks, Minbias, 2e32

Summary

- This is only a small sampling of the many sensitivity tests done. Other targeted, well-motivated scenarios could be tried.
  - See backups.

- All tests though follow your expectation
  - Minimize material before 2^{nd} measurement (RF foil dominates)
  - Minimize R of 1^{st} Hit
  - Minimize material overall
  - Tilting planes improves resolution (at least at t=0), small acceptance loss for fixed wafer size.

- 26 planes better than 23, at least with respect to acceptance. High p_T resolution also slightly better, but need to know if significant difference in RF foil x/X_0.

- Module doublets also give comparable IP resolutions and acceptance to single planes.

Backups

Z positions used

23 station geometry - 30 mm spacing (Z positions in cm)

-30.75 -22.75 -16.75 -13.75 -10.75 -7.75 -4.75 -1.75 1.25 4.25 7.25 10.25
13.25 16.25 19.25 22.25 25.25 28.25 44.25 59.25 64.25 69.25 74.25

26 stations – 24 mm spacing geometry (Z positions, in cm)

-30.75 -22.75 -15.9 -13.5 -11.1 -8.7 -6.3 -3.9 -1.5 0.90
3.3 5.7 8.1 10.5 12.9 15.3 17.7 20.1 24.6 30.4
37.9 46.4 59.4 64.4 69.4 74.4

26 stations – 13 doublets geometry (Z positions, in cm)

-30.75 -28.95 -22.75 -20.95 -15.9 -14.1 -10.3 -8.5 -4.7 -2.9 0.9 2.7 6.5 8.3
12.1 13.9 17.7 19.5 24.6 26.4 44.25 46.05 62.45 64.25 72.45 74.25

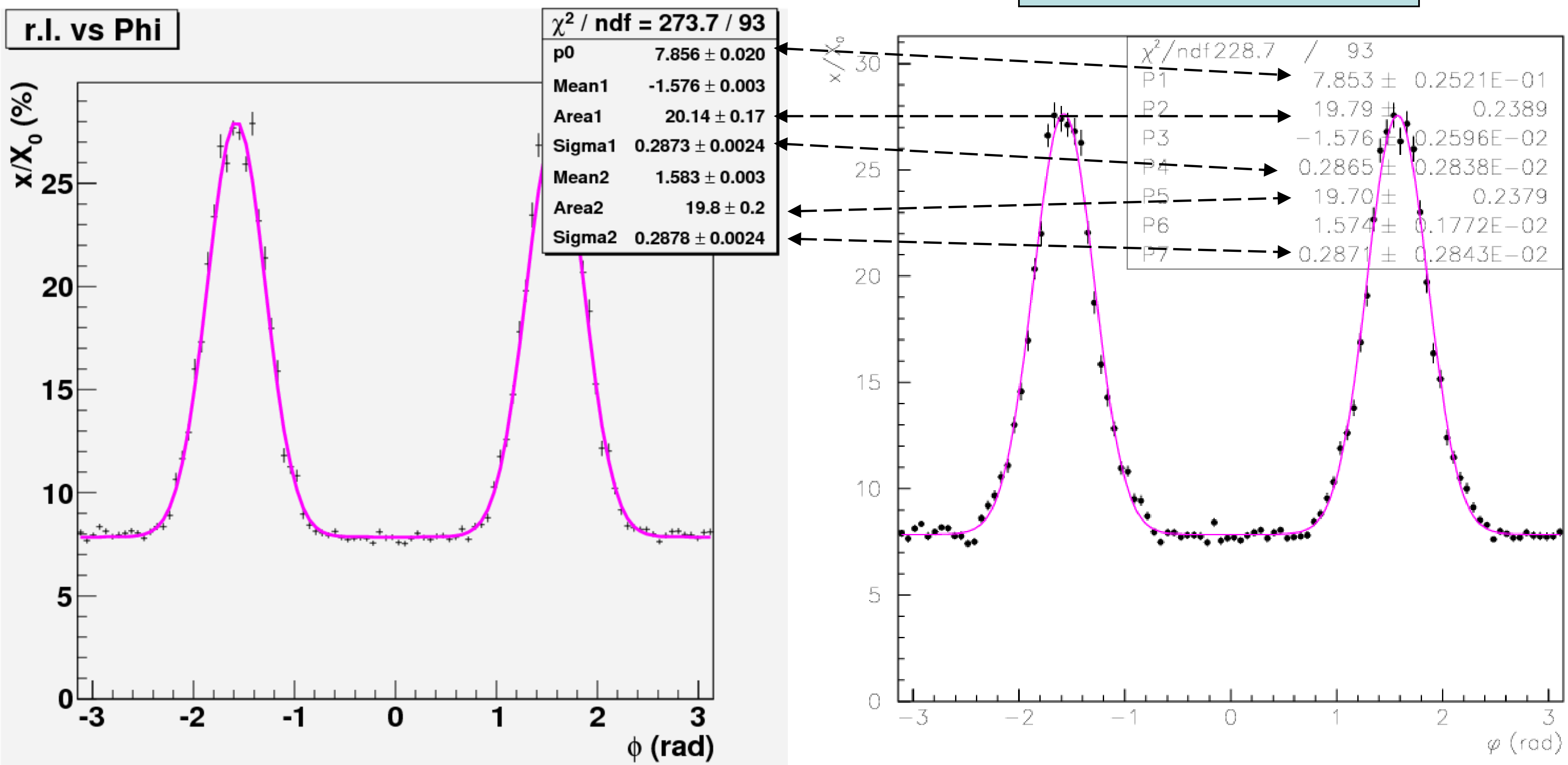
Negative X modules shifted in Z by 2 mm downstream.

Tuning of Material

VELO – $B_s \rightarrow \phi\phi$ daughters used here for both

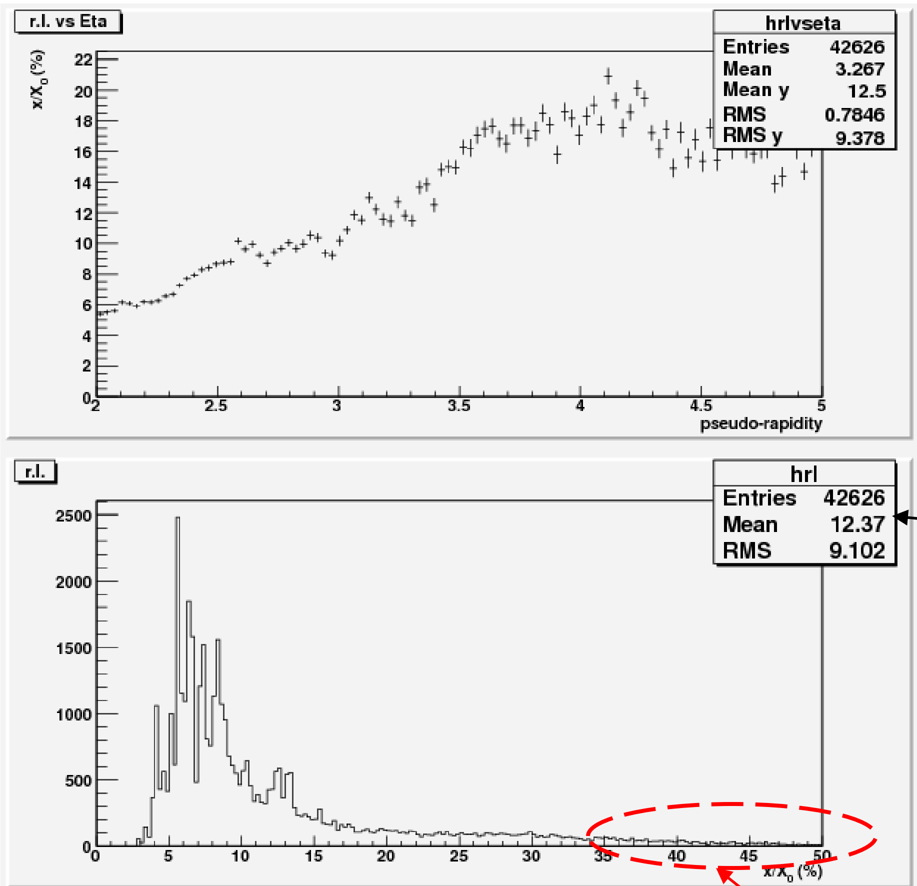
Full LHCb Simulation

GEANT3 Simulation

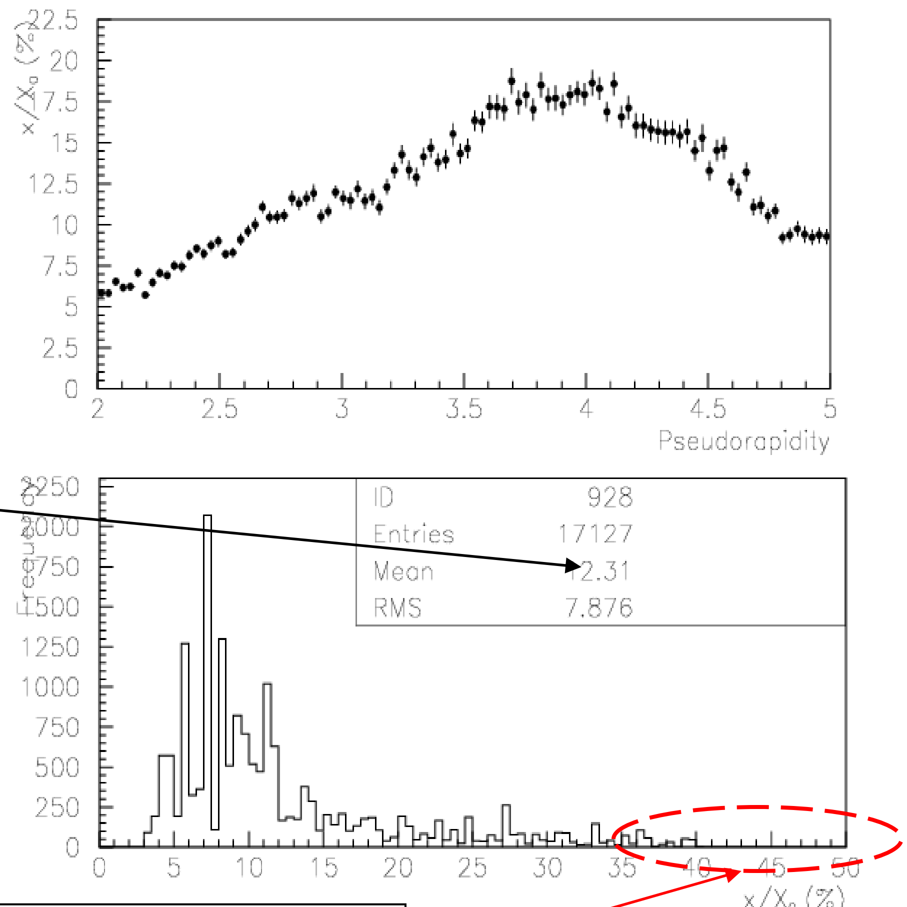


x/X_0 vs Pseudorapidity, Total

Full LHCb Simulation



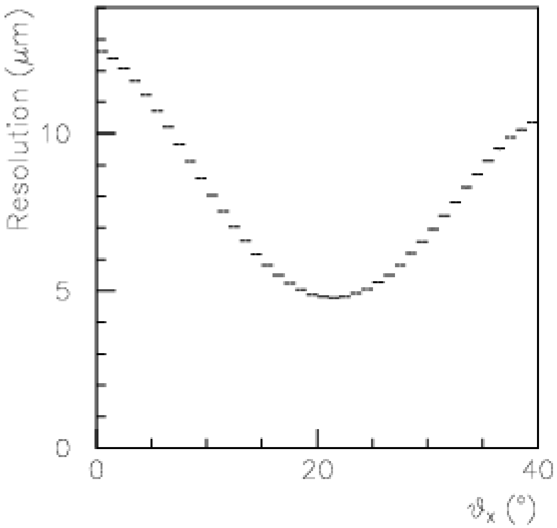
GEANT3 Simulation

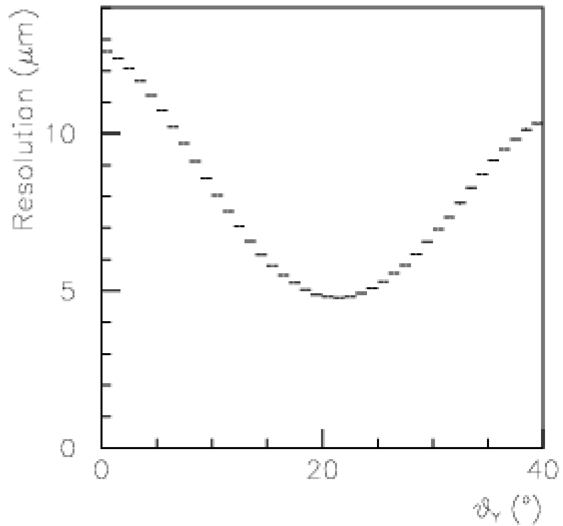


Hard to get the very loooong tail without a more detailed model.

New resolution function

150 μm silicon thickness

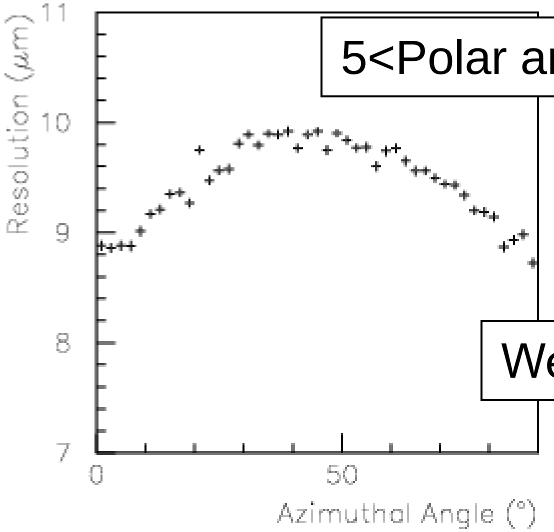




Best resolution at ~20º ~ 350 mrad!

Edge of acceptance

NB: Binary is ~ 16 μm



5<Polar angle <7º

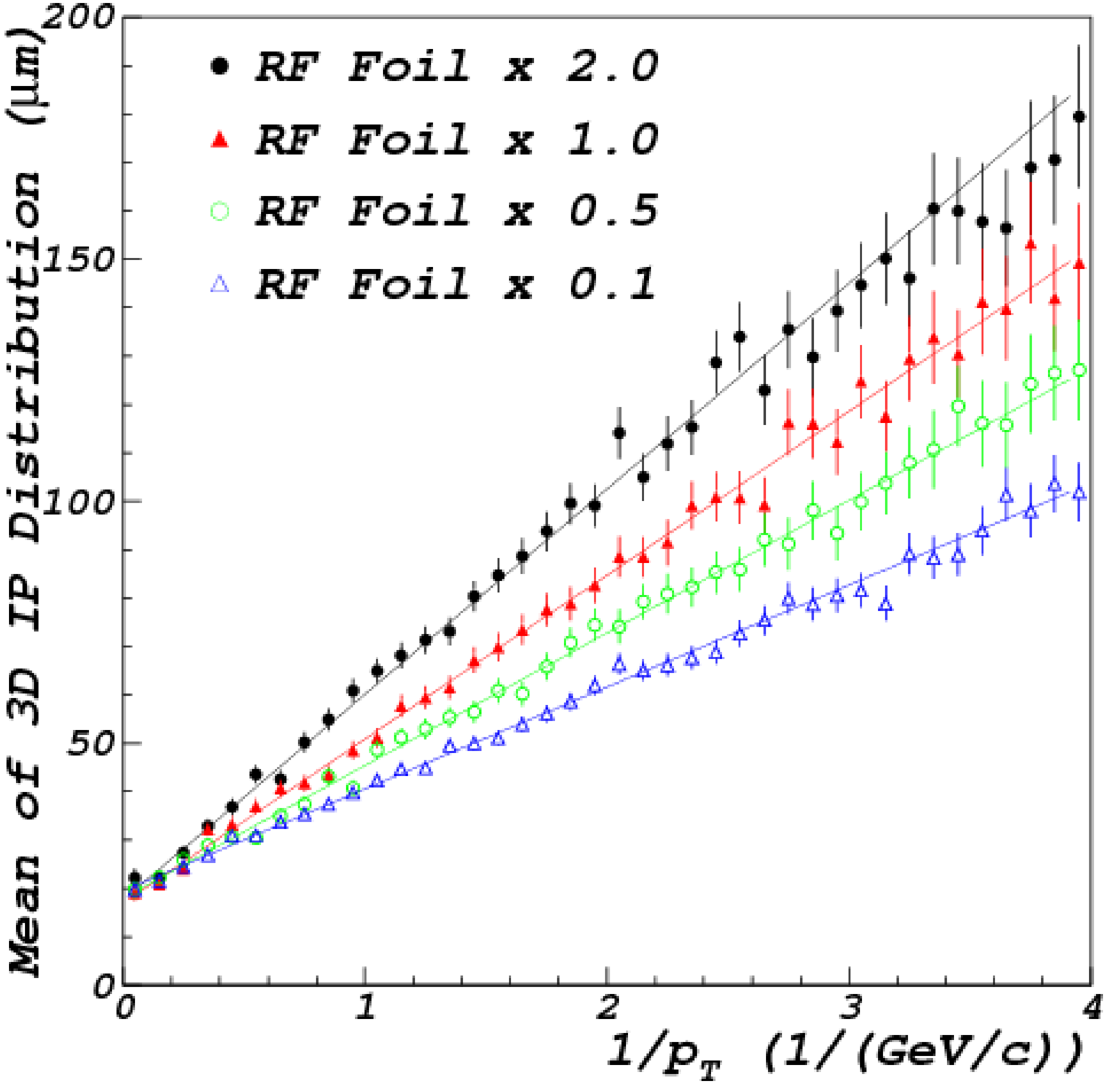
We expect this…

Based on Marcin's Boole implementation

Pixel – RF Foil x/X_0 dependence

$B_s \rightarrow \phi\phi$, all stable tracks in event.

Module x/X_0 fixed at 1%



$\langle IP_{3D} \rangle = 17.7\mu m + 42.4\mu m/p_T$

$\langle IP_{3D} \rangle = 17.0\mu m + 33.9\mu m/p_T$

$\langle IP_{3D} \rangle = 18.0\mu m + 27.4\mu m/p_T$

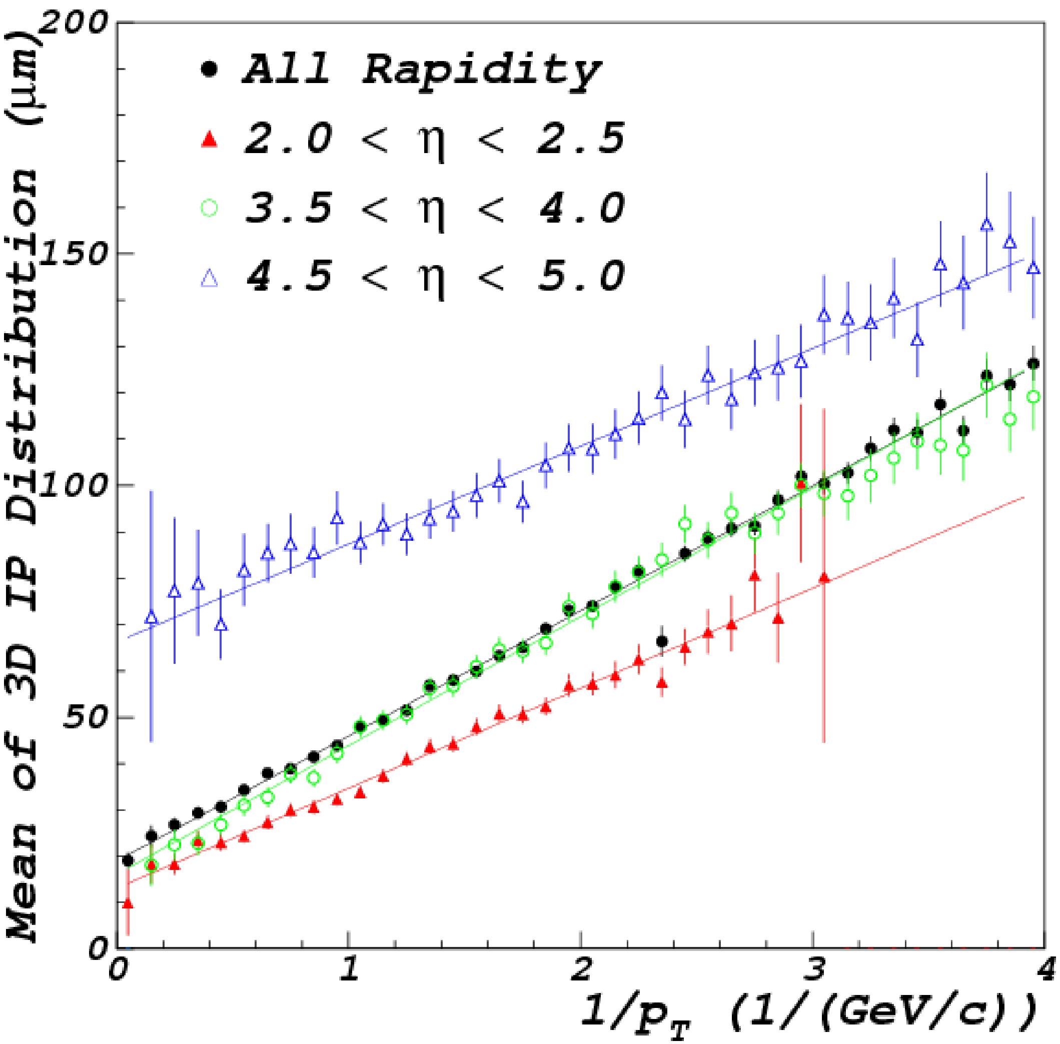
$\langle IP_{3D} \rangle = 19.5\mu m + 21.1\mu m/p_T$

Aiming for reducing RF foil material in half

Resolution in different rapidity ranges

Minimum Bias Events

- RF Foil x/X_0 scale factor fixed at 0.5
- Module x/X_0 fixed at 1%



$\langle IP_{3D} \rangle = 66.2\mu m + 21.2\mu m/p_T$

$\langle IP_{3D} \rangle = 19.0\mu m + 27.0\mu m/p_T$

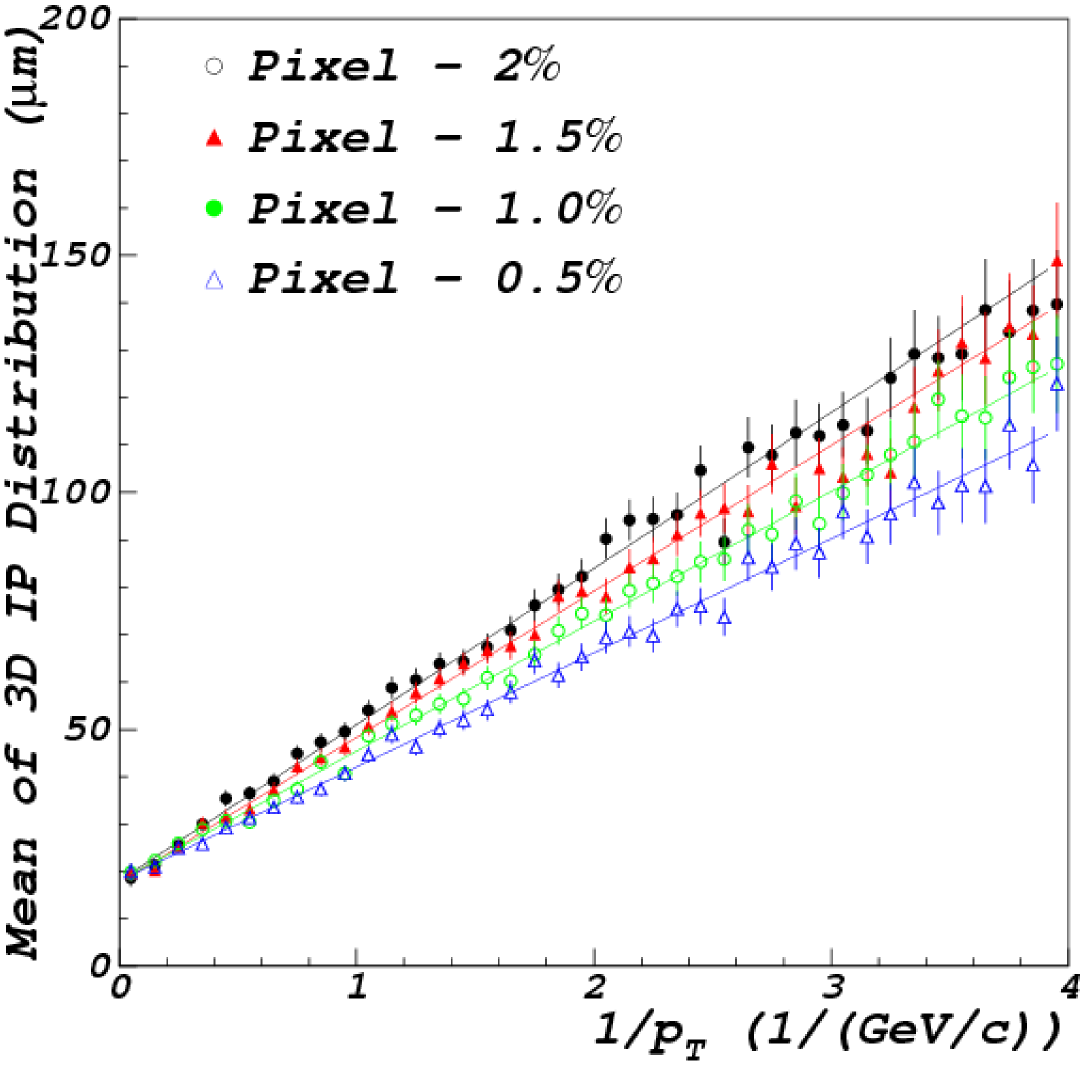
$\langle IP_{3D} \rangle = 16.1\mu m + 27.8\mu m/p_T$

$\langle IP_{3D} \rangle = 13.1\mu m + 21.6\mu m/p_T$

Dependence on Pixel module x/X_0

$B_s \rightarrow \phi\phi$, all stable tracks in event.

RF Foil x/X_0 scale factor fixed at 0.5



$<IP_{3D}> = 18.1\mu m + 32.9\mu m/p_T$

$<IP_{3D}> = 17.5\mu m + 30.8\mu m/p_T$

$<IP_{3D}> = 18.0\mu m + 27.4\mu m/p_T$

$<IP_{3D}> = 18.0\mu m + 24.1\mu m/p_T$

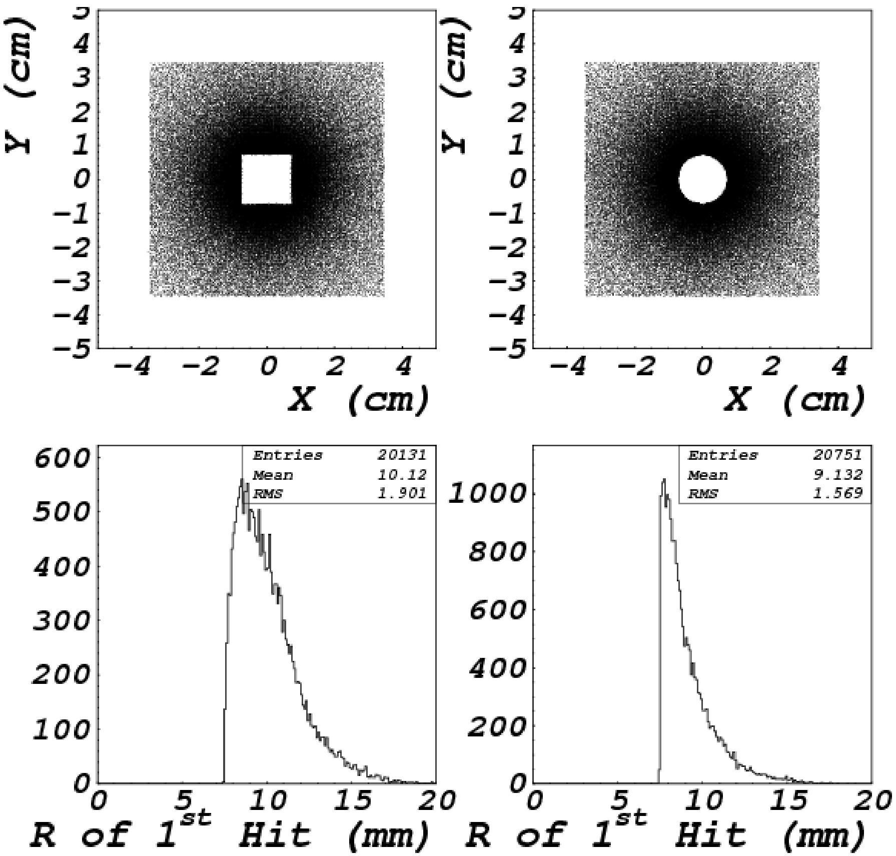
Hole Geometry – Square vs Round

$B_s \rightarrow \phi\phi$, all stable tracks in event.

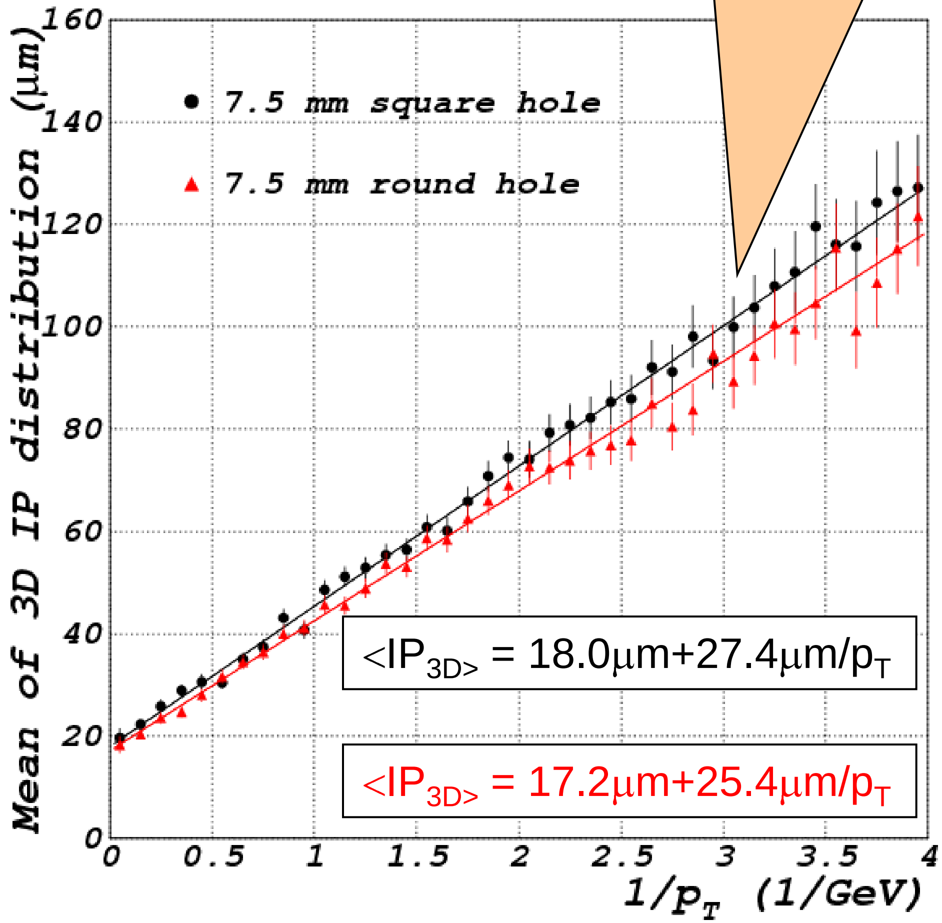
- RF Foil x/X_0 scale factor fixed at 0.5
- Pixel Module fixed at 1%

7.5 mm square hole

7.5 mm round hole

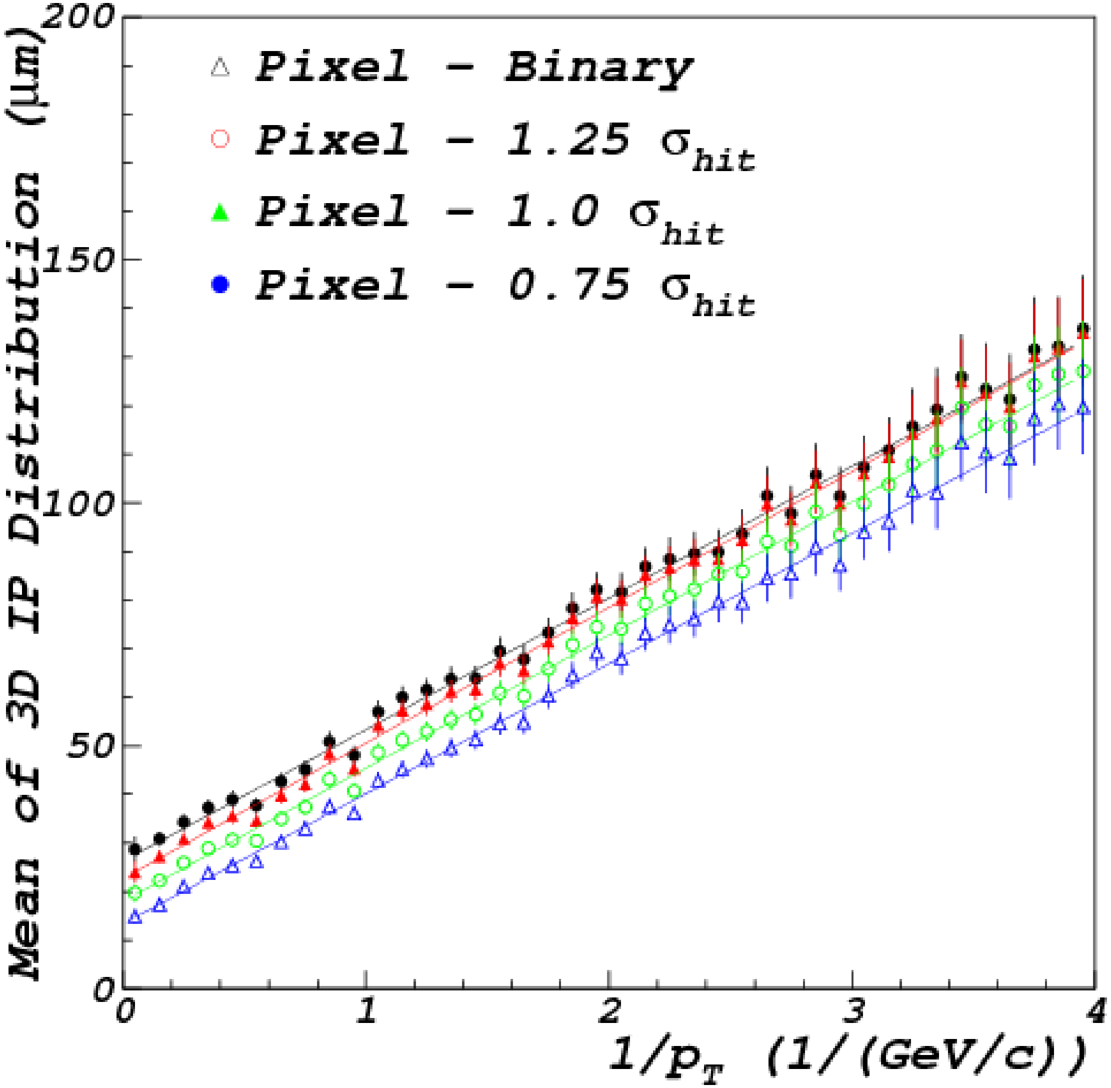


Eq 4.1 in Velo TDR suggests σ_{ip} scales as r_1^2 → 23% worse resolution for square hole over round hole … looks more like it scales ~ r_1^1



Dependence on Hit Resolution

$B_s \rightarrow \phi\phi$, all stable tracks in event.



RF Foil x/X_0 scale factor fixed at 0.5
Module fixed at 1%

$\langle IP_{3D} \rangle$ = 26.2μm+27.1μm/p_T

$\langle IP_{3D} \rangle$ = 22.7μm+27.9μm/p_T

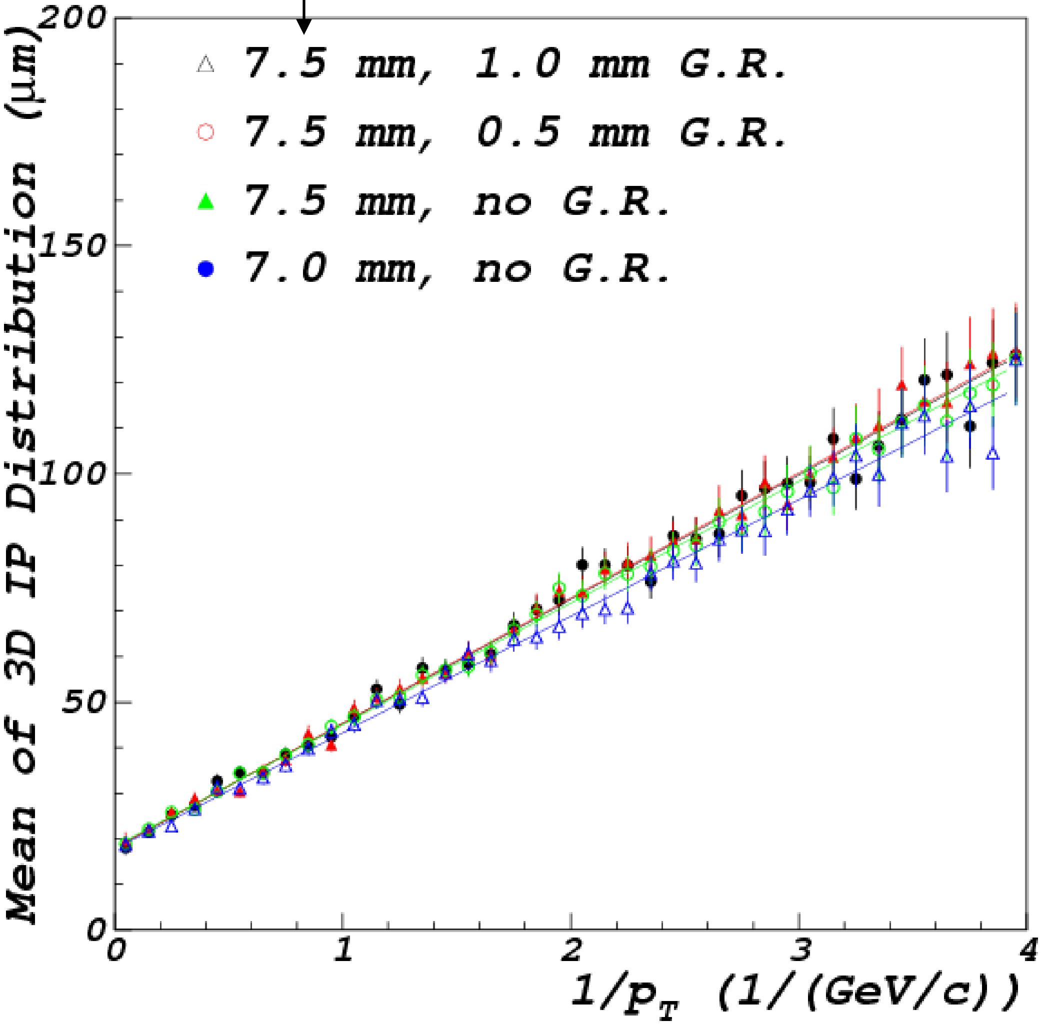
$\langle IP_{3D} \rangle$ = 18.0μm+27.4μm/p_T

$\langle IP_{3D} \rangle$ = 13.4μm+26.8μm/p_T

Dependence on Guard ring

$B_s \rightarrow \phi\phi$, all stable tracks in event.

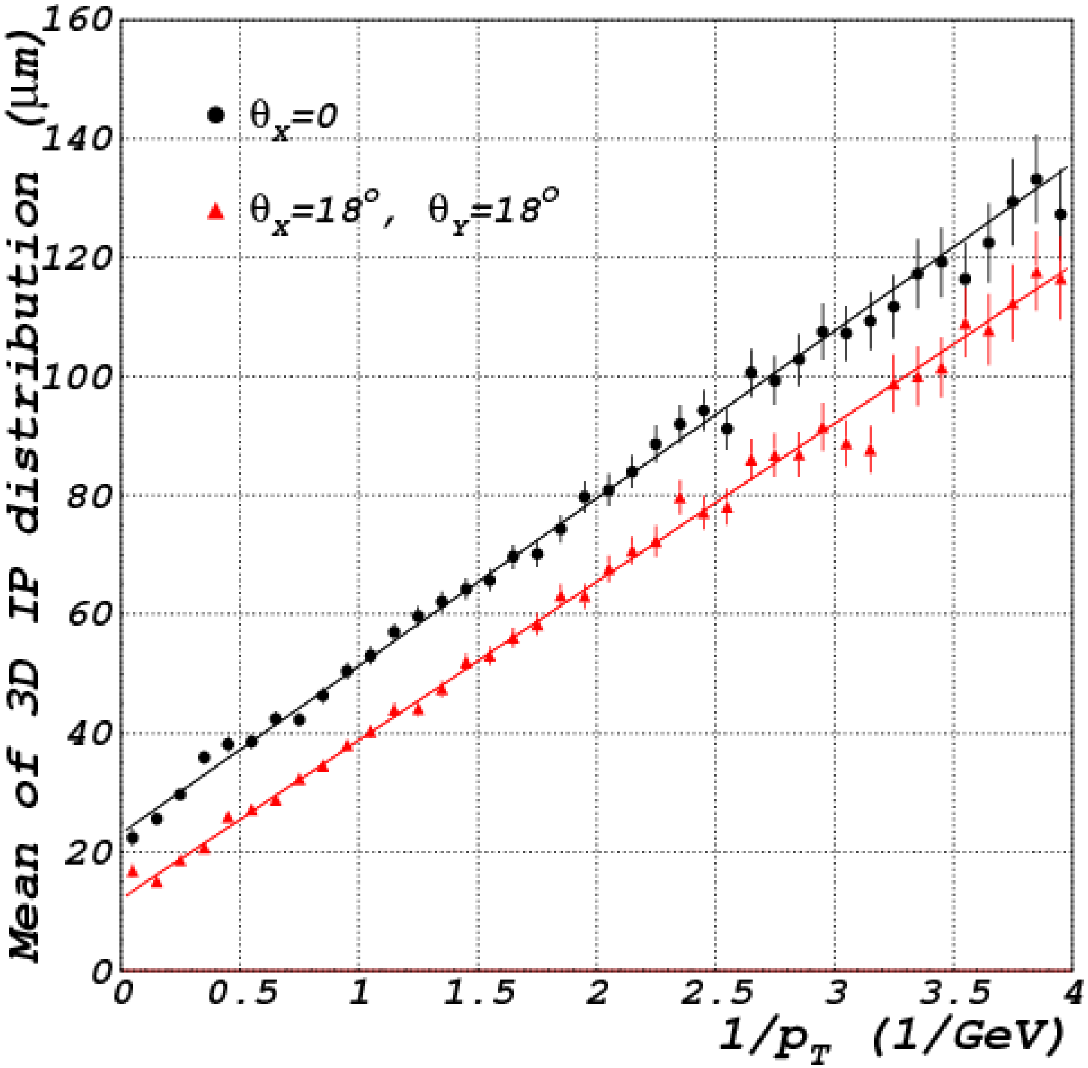
First active pixel



- RF Foil x/X_0 scale factor fixed at 0.5
- Module fixed at 1%

- Minimal effect of guard ring.
- Material before first point dominated by RF foil

Resolution comparison (Rotation around X&Y axis)



$<IP_{3D}> = 22.6\mu m + 28.3\mu m/p_T$

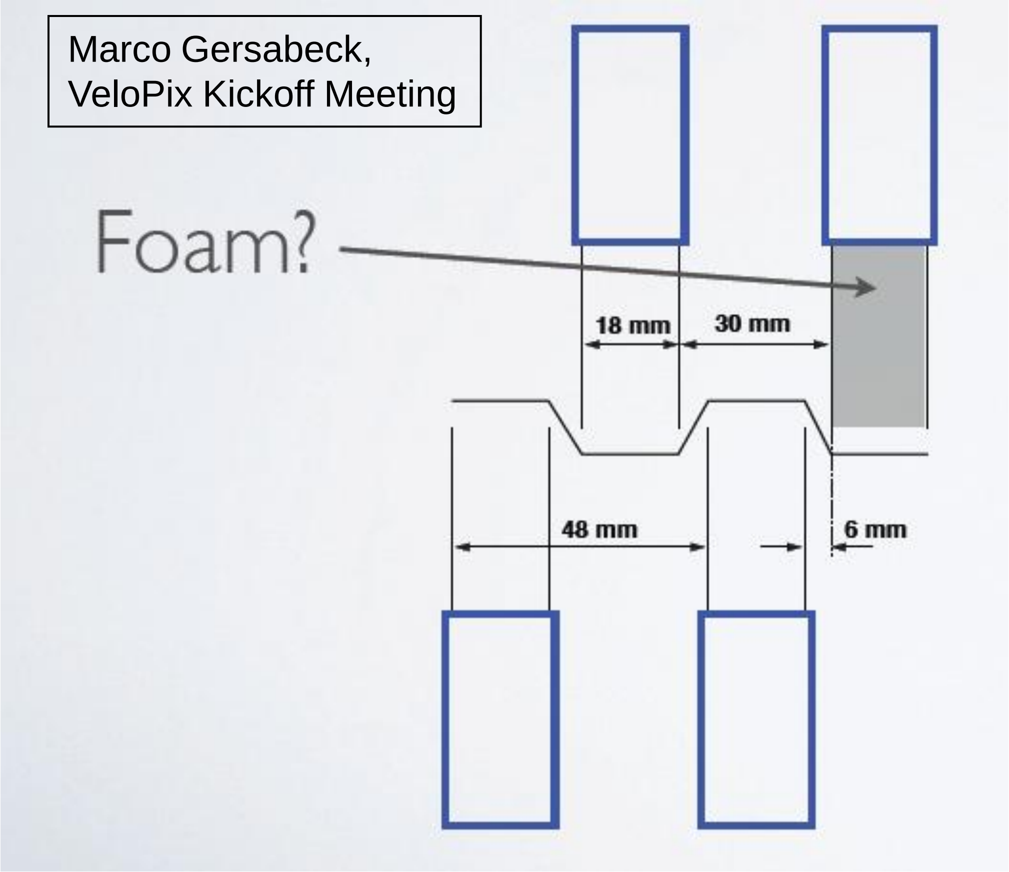
$<IP_{3D}> = 11.7\mu m + 26.9\mu m/p_T$

NB: Hit resolution scale factor was 1.25 for this plot, higher than the 1.1 used in the body of this talk.

This is why the intercept is larger.

Single Planes (Singlets) vs Plane Pairs (Doublets)

Pixel Module Doublets



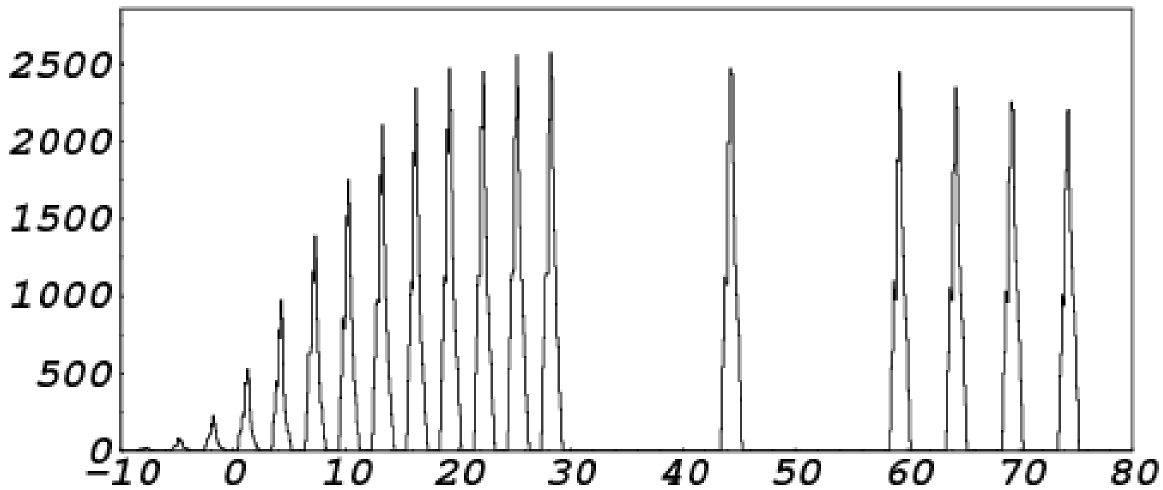
- ❑ Build module doublets
- ❑ More rigid?
- ❑ Fewer folds → less material traversed?

- ❑ Maintain Z length of VELO

- ❑ Different foil than current VELO.

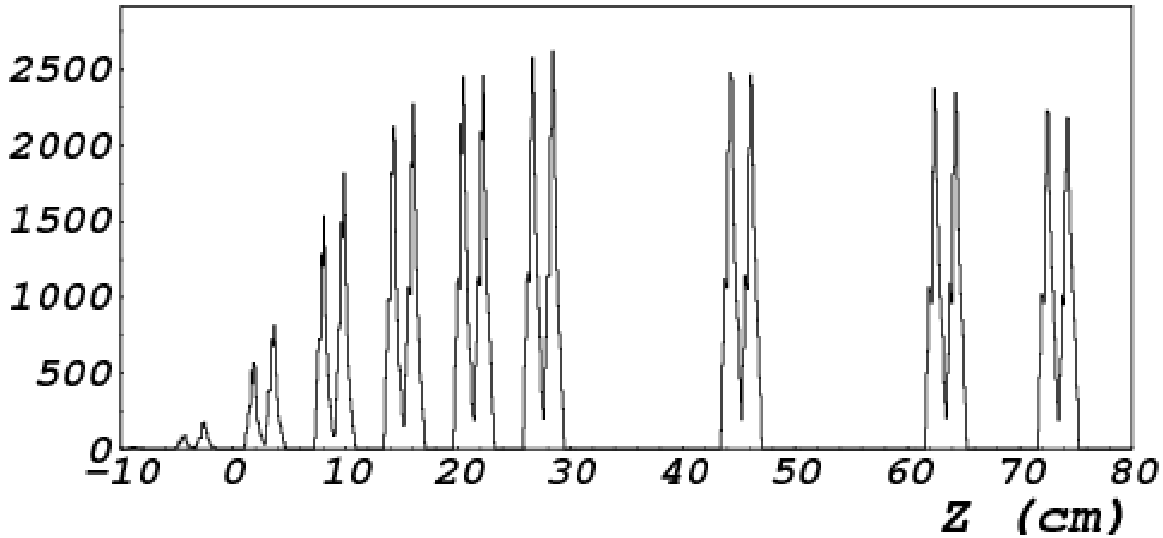
❑To compare, remove RF foil from both "standard" 30 mm spacing design, and this one.

Plane Spacing details



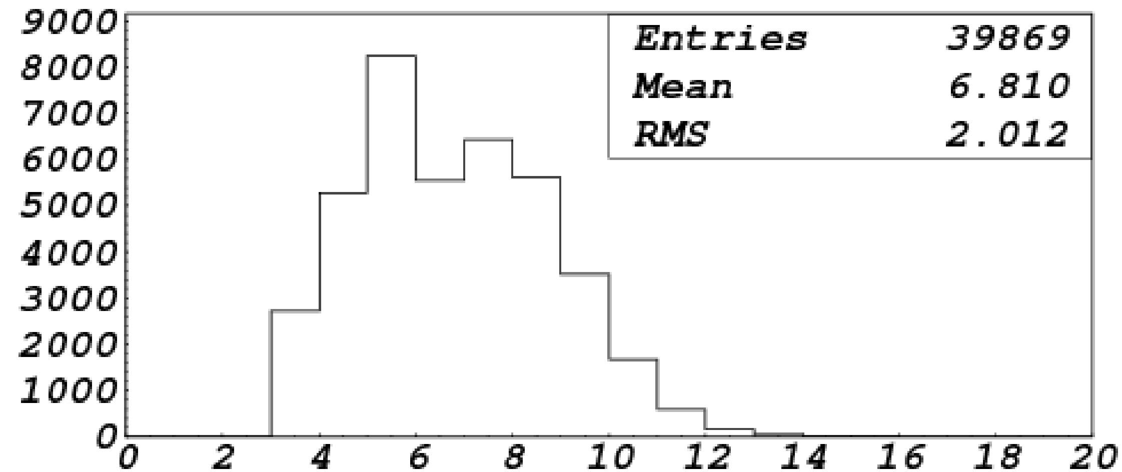
Only forward tracks here

Both have 16 planes
surrounding IP region



6.2 cm pitch near IP
1.8 cm between two in pair

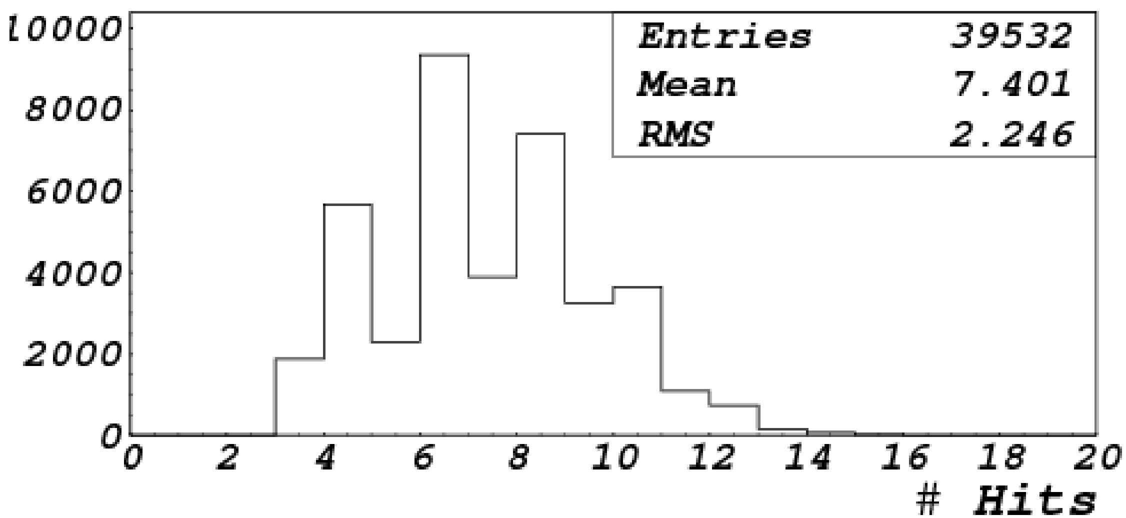
Hits Comparison



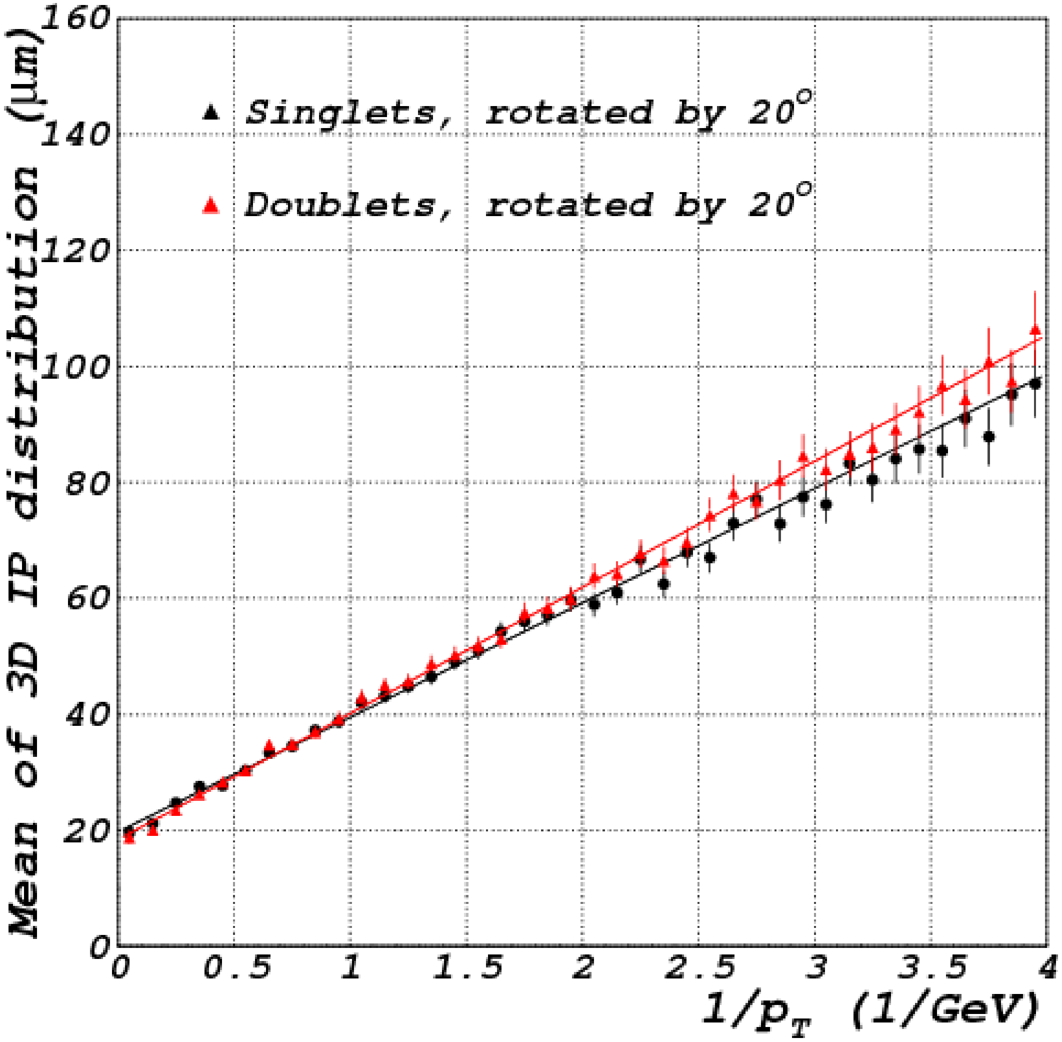
More hits on average for the doublets (6.8 → 7.4)

Slightly fewer reconstructed tracks with ≥ 3 hits for doublets

(Same tracks, same stats)



IP resolution (Only rotation around Y axis)



No RF foil in either case, since it's not clear how I should simulate it for doublet scenario.

'Apples & apples' comparison

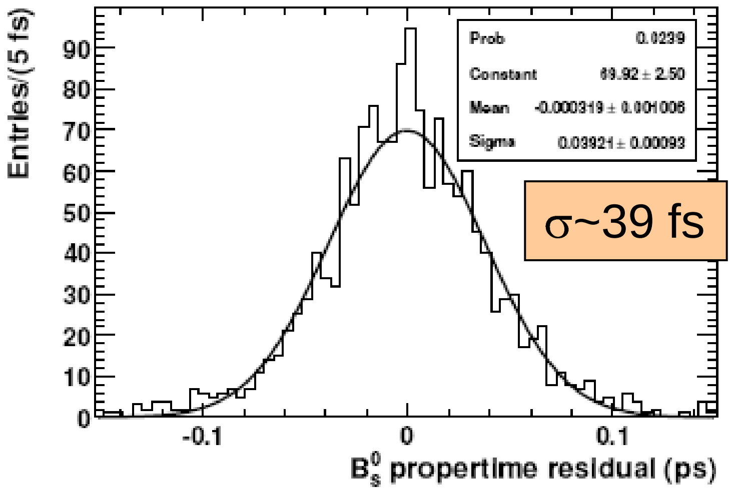
$<IP_{3D>} = 19.7\mu m + 19.7\mu m/p_T$

$<IP_{3D>} = 18.4\mu m + 21.8\mu m/p_T$

Slightly better IP resolution for doublets at high p_T, worse at low p_T (more hits, more mass)

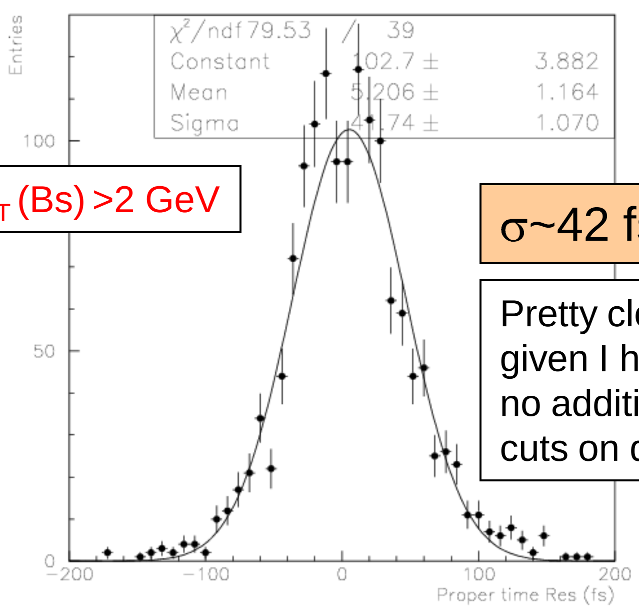
Time Resolution $B_s \rightarrow D_s K$

LHCb-PUB-2009-003



σ~39 fs

Geant3 Least squares vertex fit, VELO,

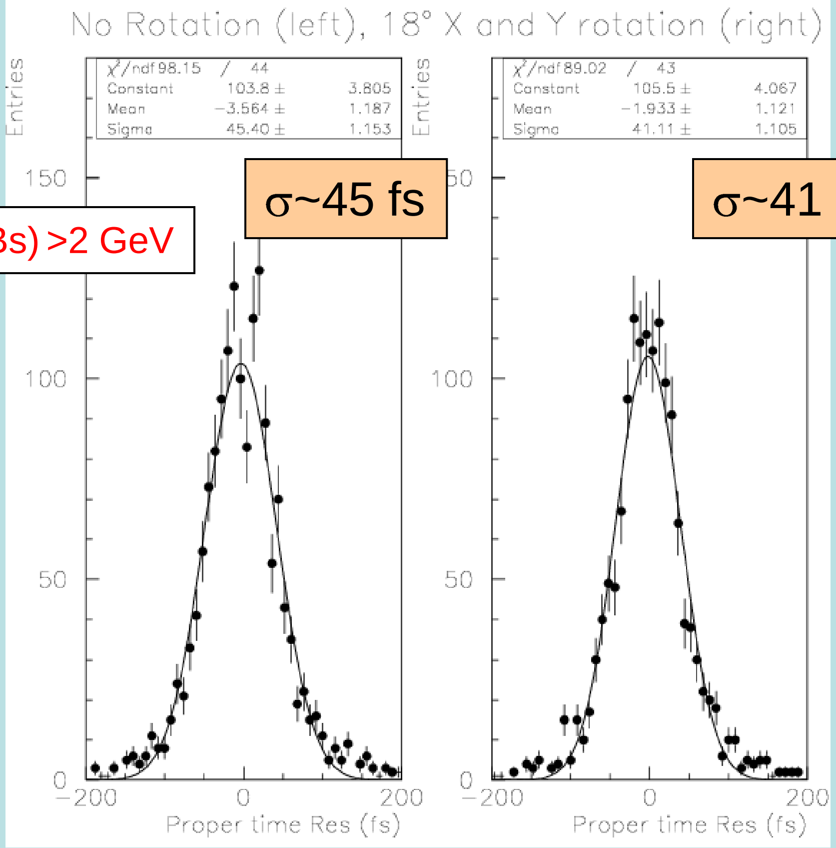


p_T (Bs) >2 GeV

σ~42 fs

Pretty close, given I have no additional cuts on daughters

Geant3, Pixels with least squares vertex fit



p_T (Bs) >2 GeV

σ~45 fs

σ~41 fs

For the Geant3, I use the Kalman track fit errors in the vertex fit, but had to include a $1/p_T$-dependent scale factor to get the IP pulls to have a width of 1.0.

~10% improved proper time resolution with rotated planes (for this decay).

Side Check

Do a linear least squares fit, no multiple scattering in error matrix, just hit resolutions.
Look at ΔX_{IP} to generated production point.

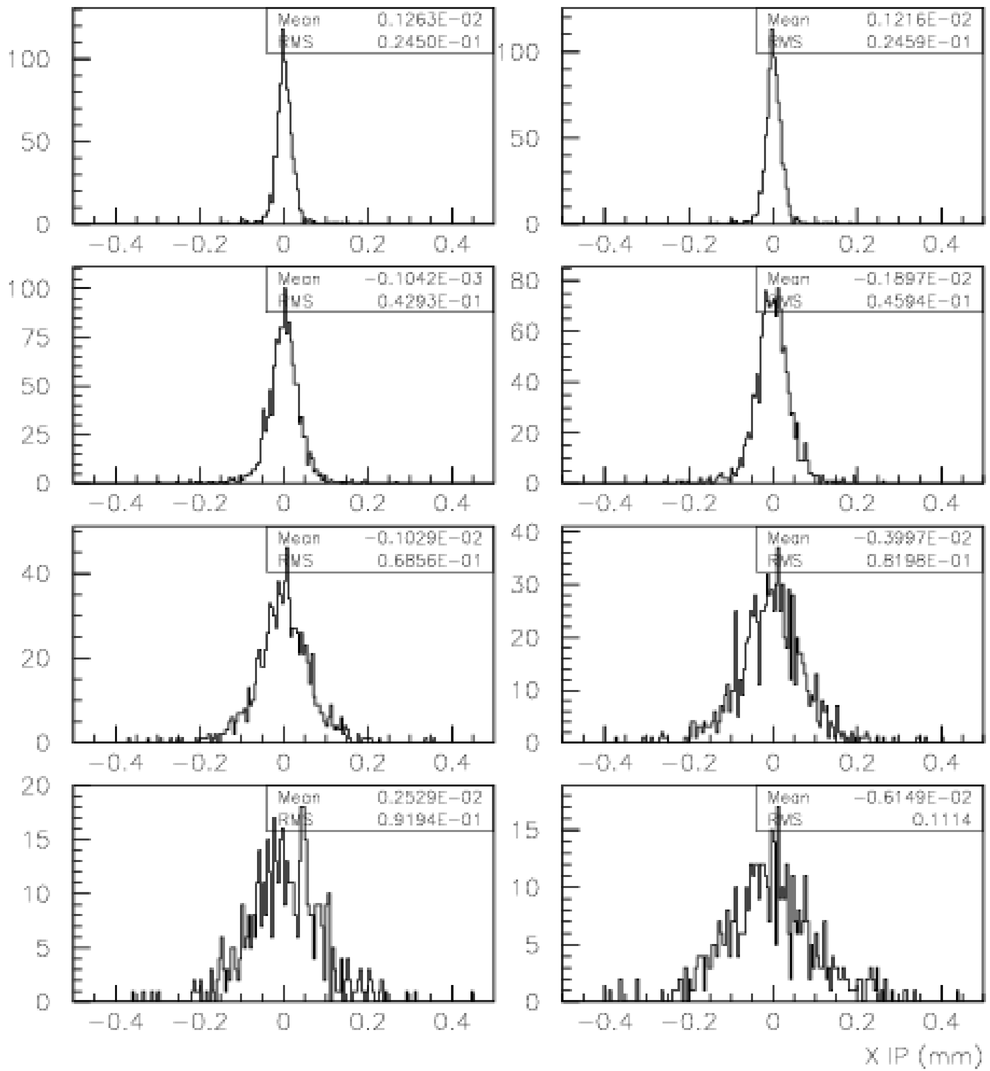
Kalman fit | Linear Fit

$\langle 1/p_T \rangle = 0.15$

$\langle 1/p_T \rangle \sim 1$

$\langle 1/p_T \rangle \sim 2$

$\langle 1/p_T \rangle \sim 3$



Compare RMS.

Nearly identical for high momentum.

Kalman better at low momentum