3D-Triplet Tracking for LHC and Future High Rate Experiments

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Workshop on Intelligent Trackers

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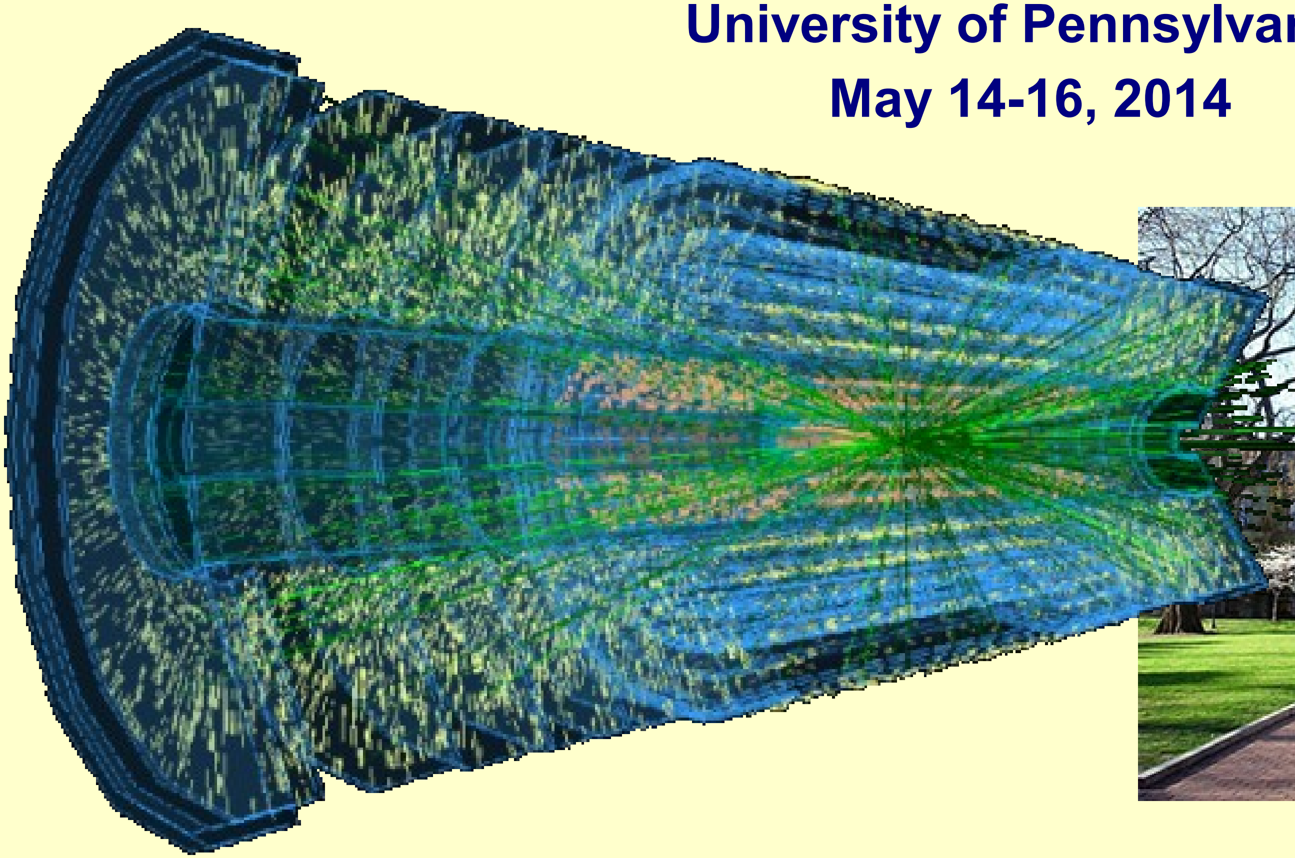


Overview

- 3D-tracking and multiple scattering
- Motivation for triplet layer designs
- General design studies:
  - track resolution
  - track linking
- Triplets and track triggers
- Conclusions

Motivation for 3D Triplet Tracking

- High-Lumi-LHC (>2025) or Future Circular Hadron Colliders (>2035-2040):

  ~ 150 Pileup Events (L=5 · 10^{34}) → **O(3000) tracks @25ns**

- **Physics benefit** depends crucially on the performance of detectors
  - **high precision** (offline)
  - **fast selectivity** (online filtering / trigger)

- The **combinatorial problem** is main problem for fast track reconstruction

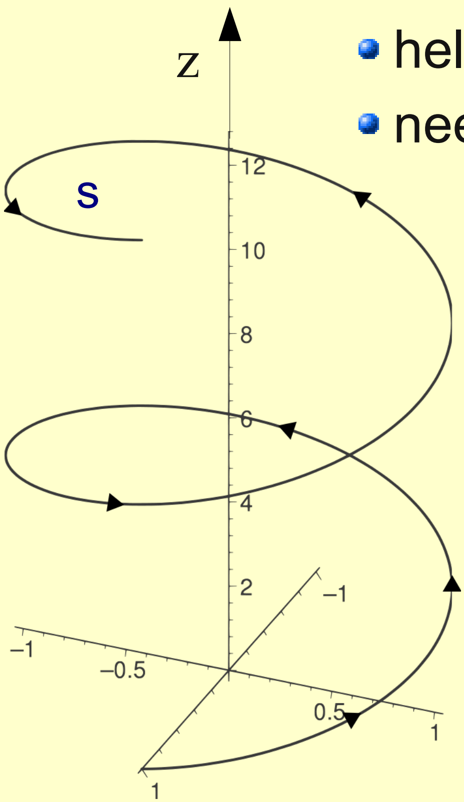
  → can be tackled by:
  - **fast algorithms**
  - **optimised tracker designs**

- Opportunities with new detector technologies (CMOS sensors)
  - build a **full pixel tracker**?
  - potential and possibilities exploiting **3D tracking?**

Three Dimensional (3D) Tracking

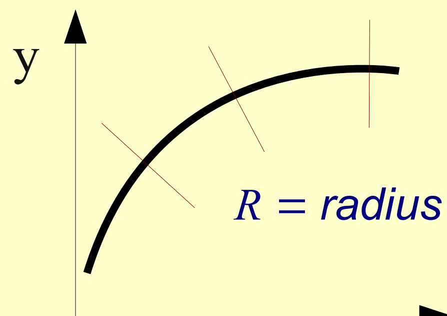
Free particle in homogenious solenoidal magnetic field

- helix decribed by 6 parameters +1 (end point)
- need to know **three** 3D space points to provide enough parameters!

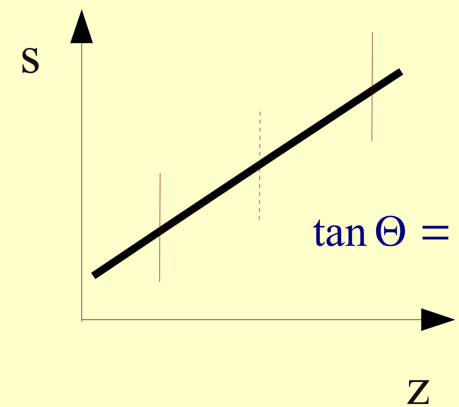


$R_{3D} \sin\Theta = R$

for symmetry reasons "2.5D tracking" is sufficient:



$\tan\Phi_0 = \left.\frac{dy}{dx}\right|_0$



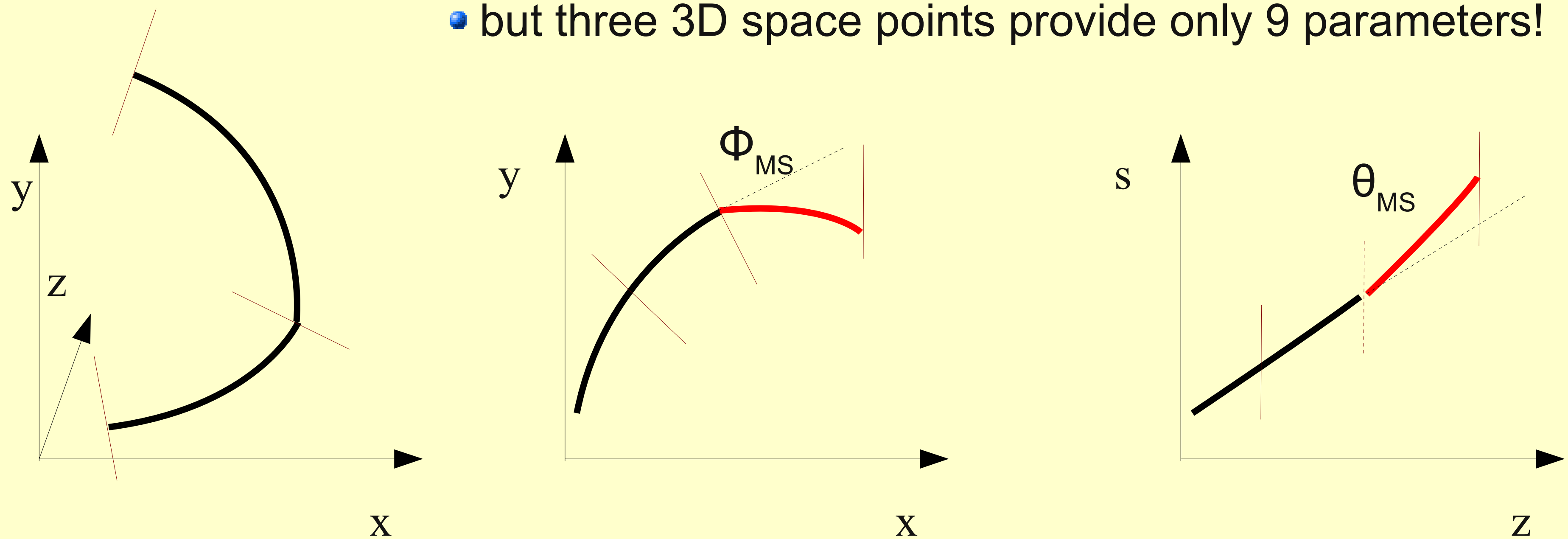
Problem: position measurement interferes with particle trajectory (**multiple scattering**)

Three Dimensional (3D) Tracking

Multiple Scattering:

3D view:

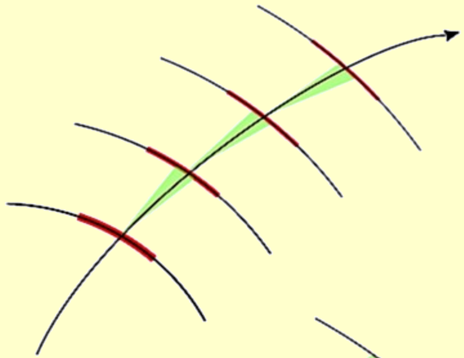
- two helix segments described by 10 parameters (assuming energy conservation)
- but three 3D space points provide only 9 parameters!



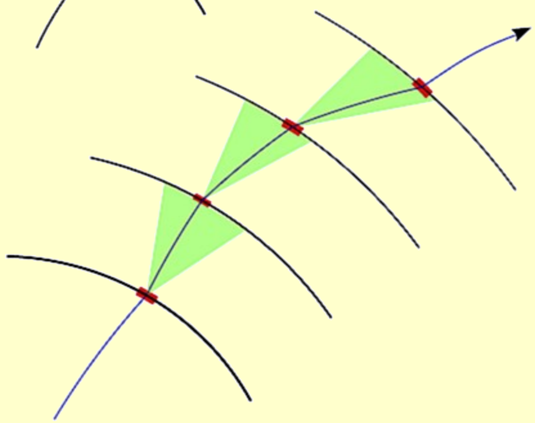
need external constraints → scattering theory!

fitting is required!

Three Dimensional (3D) Tracking



- Hit uncertainties (@high momentum)



- Multiple scattering uncertainties (@low momentum)

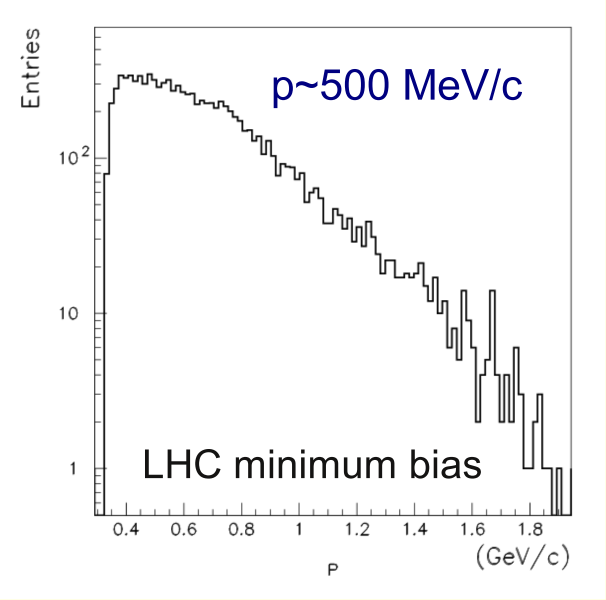
Standard implementations for track fitting:

- Kalman-Filter
- 3D Broken Line Fit

→ both time consuming (matrix inversion, iterative, complex, ...)

Multiple Scattering @ Low Momentum

- Modern solid state tracking detectors allow for (almost) infinite precision → small pixel size
  - hit resolution becomes negligible at **low momentum** where **most particles** are!



- Fast and precise reconstruction of low momentum tracks is important for good detector performance:
  - pile up
  - track isolation
  - particle flow concept → improves jets, MET, ...

→ neglect hit uncertainties and consider **multiple scattering** only (for the moment)

Simple Multiple Scattering Fit

→ neglect hit uncertainties

Track fit model:

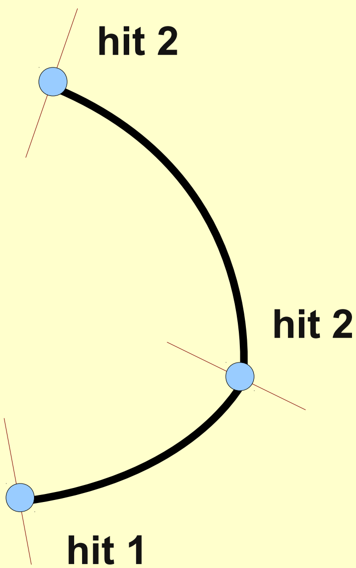
$$\chi^2(R_{3\mathrm{D}}) = \frac{\Theta_{MS}(R_{3\mathrm{D}})^2}{\sigma_\theta^2} + \frac{\Phi_{MS}(R_{3\mathrm{D}})^2}{\sigma_\phi^2}$$

→ χ^2 minimisation

Calculation:

$$R_{3\mathrm{D}} = -\frac{\kappa\,\tilde{\Phi}_{\mathrm{C}} + \beta\,\tilde{\Theta}_{\mathrm{C}}}{\kappa^2 + \beta^2}$$

constants calculable from the three hit positions



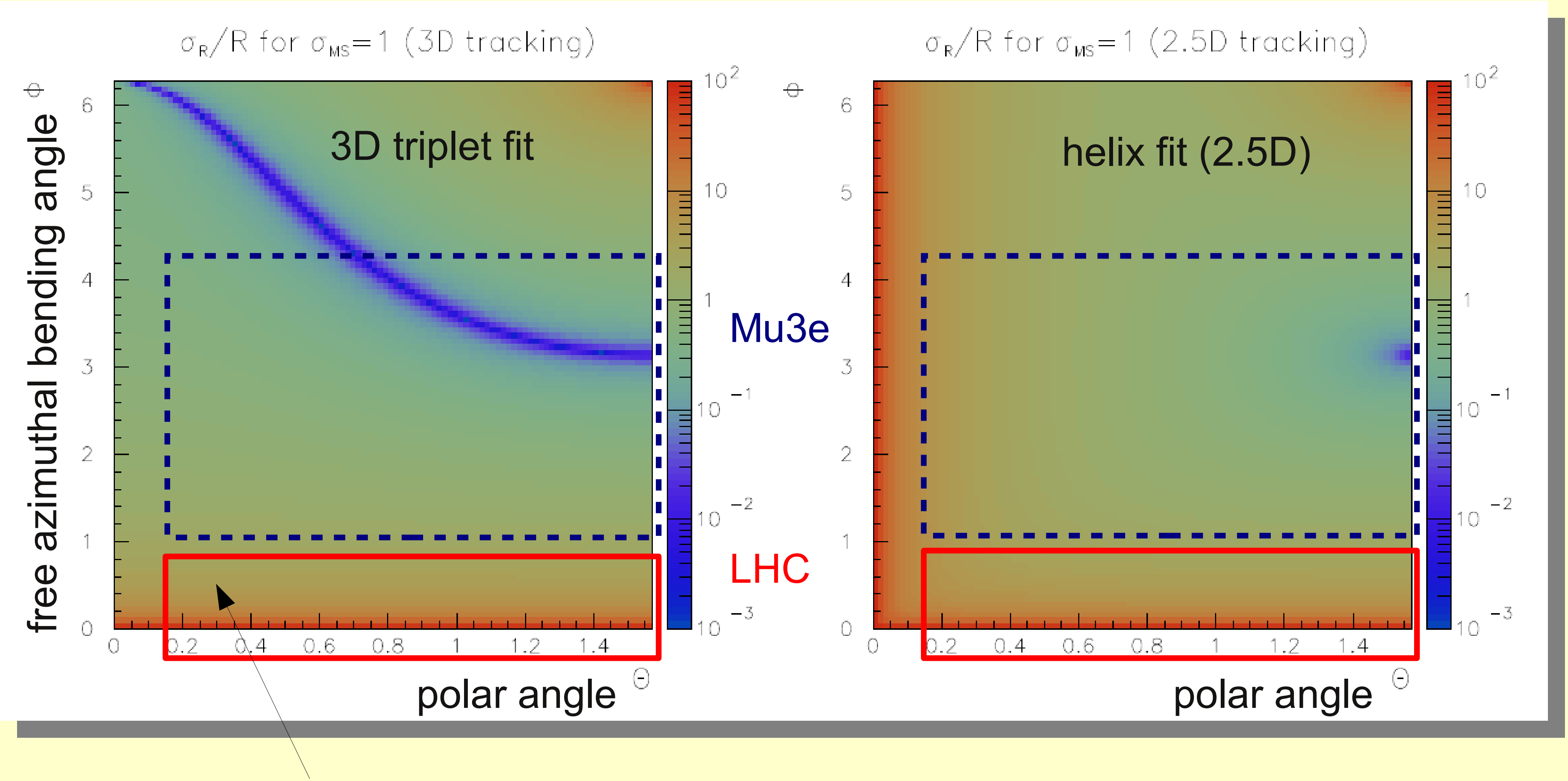
FAST!

used in Mu3e experiment (filter farm)

→ presentation by Alex Kozlinskiy

Feature of 3D Triplet-Fit

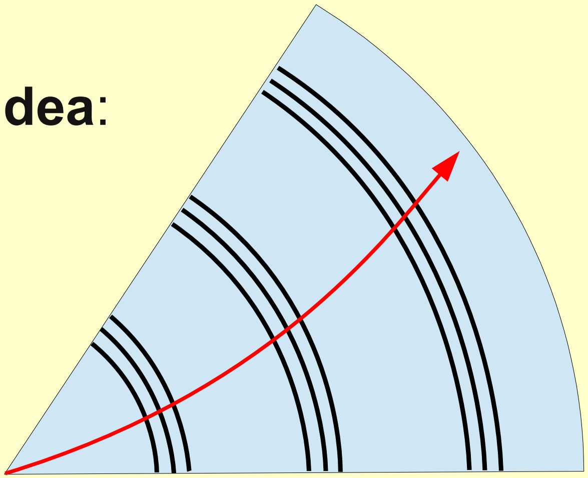
Track Resolution from multiple scattering



only slightly improved performance at low polar angles

Tracking with Triplets

Idea:



Possible advantages:

- standalone tracking in triplet layers possible
- no beamline constraint needed (helps to suppress BG)
- little combinatorics
- one triplet layer might be sufficient for triggering?

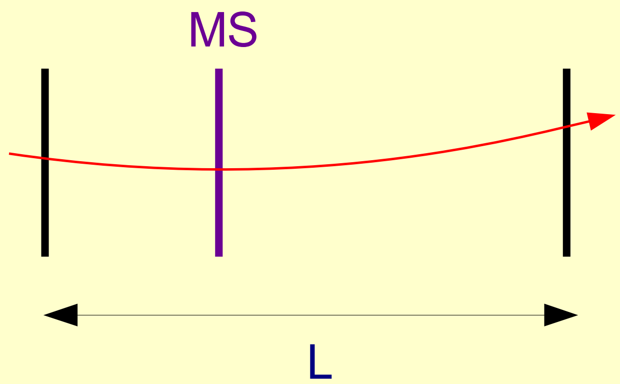
How does it compare with other (more standard) design options in terms of

- **track resolution?**
- **high momentum behaviour**?

→ study and compare different geometries

Optimal Geometry

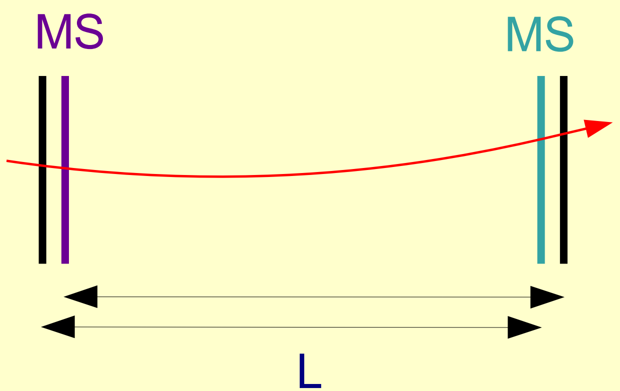
Basics:



$$\frac{\sigma(p)}{p} = \frac{2b}{B\,L}$$

independent of position of scattering layer!

Optimal geometry:



L large!

$$\frac{\sigma(p)}{p} = \frac{\sqrt{2}\,b}{B\,L}$$

two independent measurements

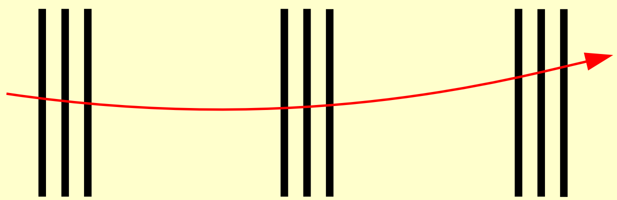
However, such a geometry cannot be used for high track multiplicity environments!

Tracker Geometry & Resolution

multiple scattering only: $$\frac{\sigma(p)}{p} = w_{geom} \frac{2b}{B\,L}$$

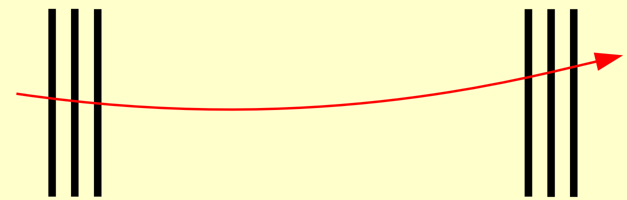
b = scattering parameter (layer material)

Triplet 9



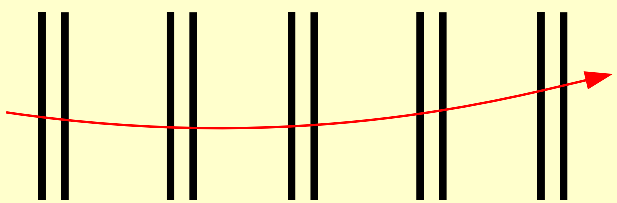
$w_{geom} = 0.96$

Triplet 6



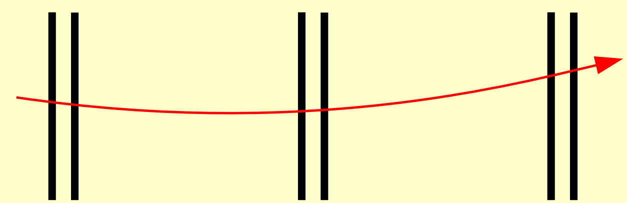
$w_{geom} = 0.71$

Vector 10



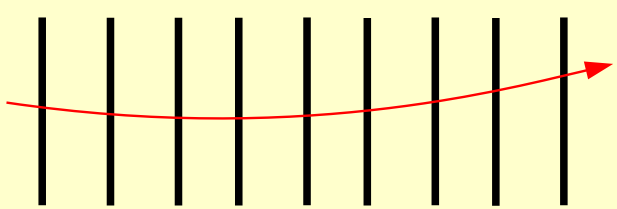
$w_{geom} = 1.38$

Vector 6



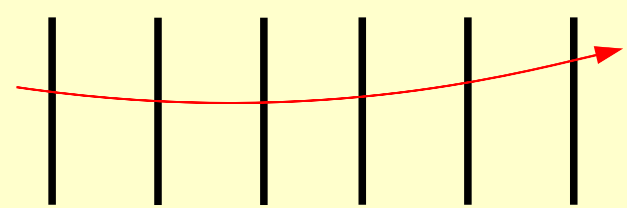
$w_{geom} = 0.99$

Equi 9

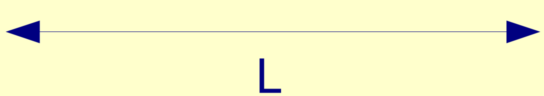


$w_{geom} = 1.51$

Equi 6



$w_{geom} = 1.25$



(assuming infinitesimal small distances in pairs and triplets)

Tracking Resolution Study

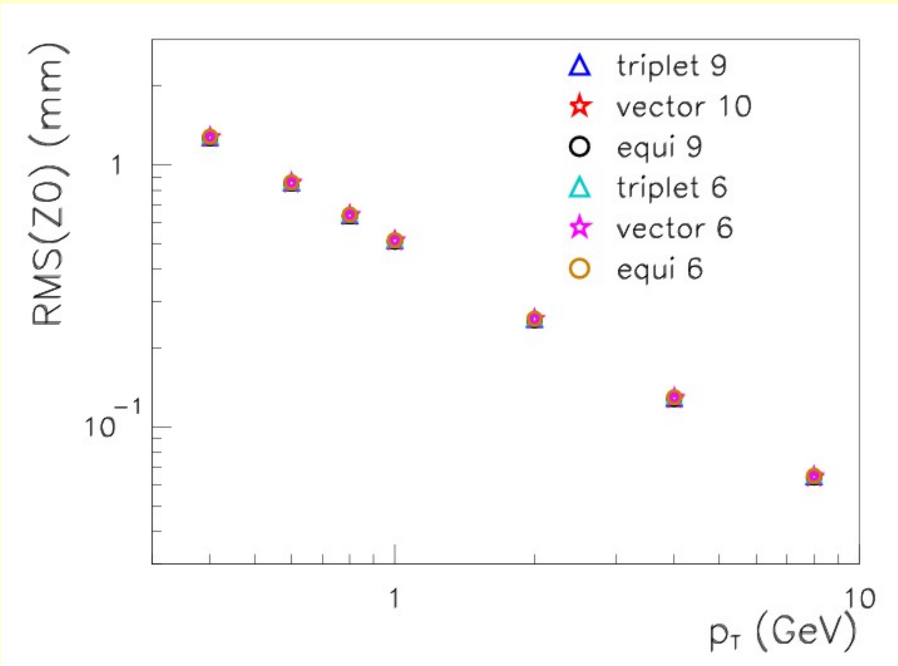
Basic simulation parameters:

- All pixel (perfect hit information)
- instrumentation: R = 20 - 100 cm
- distance between stacked layers Δ = 10 mm
- magnetic field: B = 2T
- layer thickness: $X = 0.01\ X_0$
- energy loss: 0
- only barrel type of detector with cylindrical symmetry

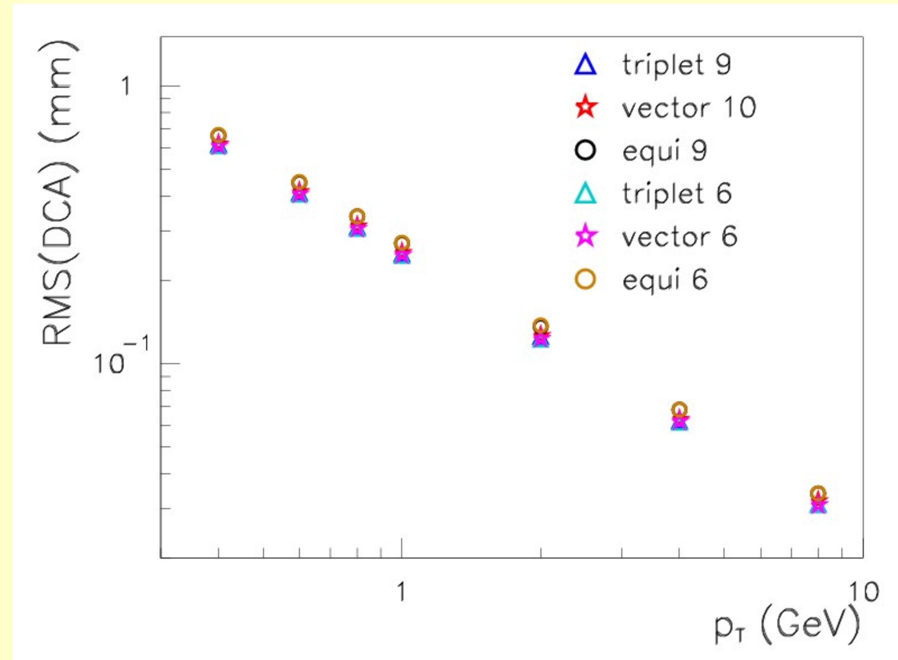
Multiple scattering simulated using Highland formula (PDG)

Results for Multiple Scattering (Only)

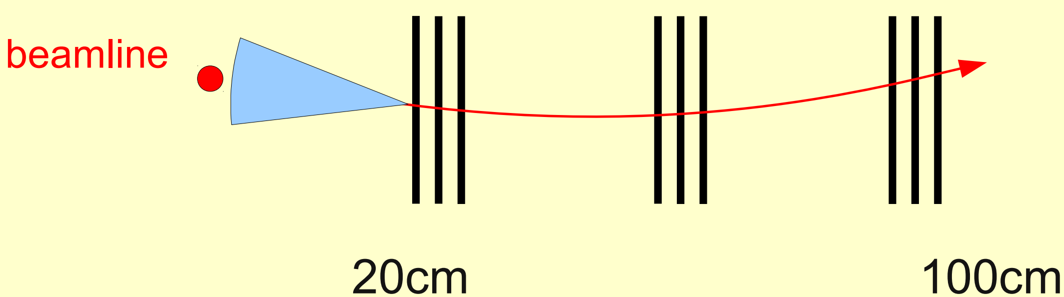
Z0 (at beamline)



Distance of Closest Approach to beamline

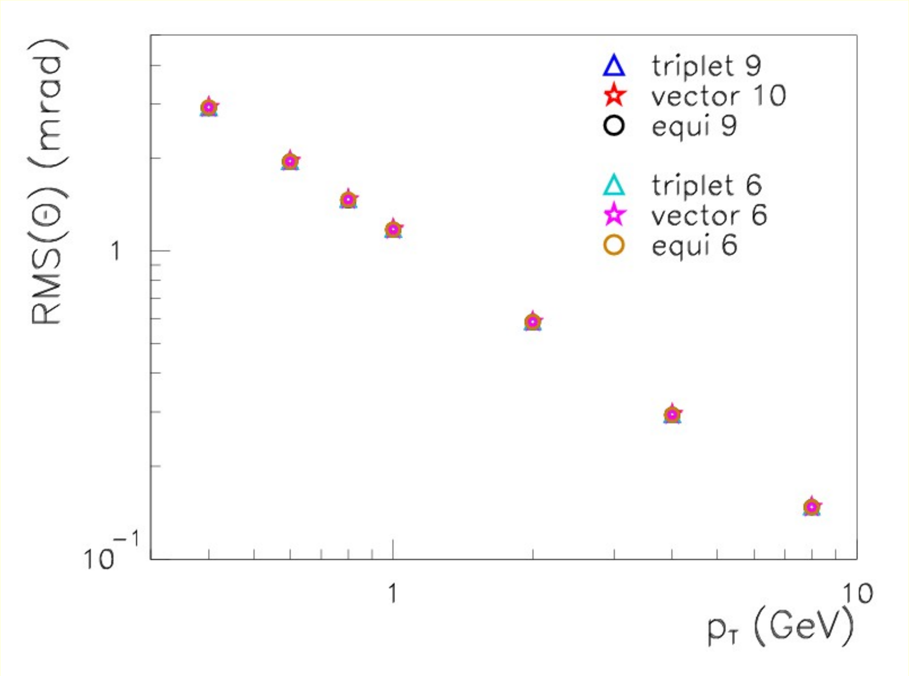


uncertainty mostly determined by scattering at innerst layer

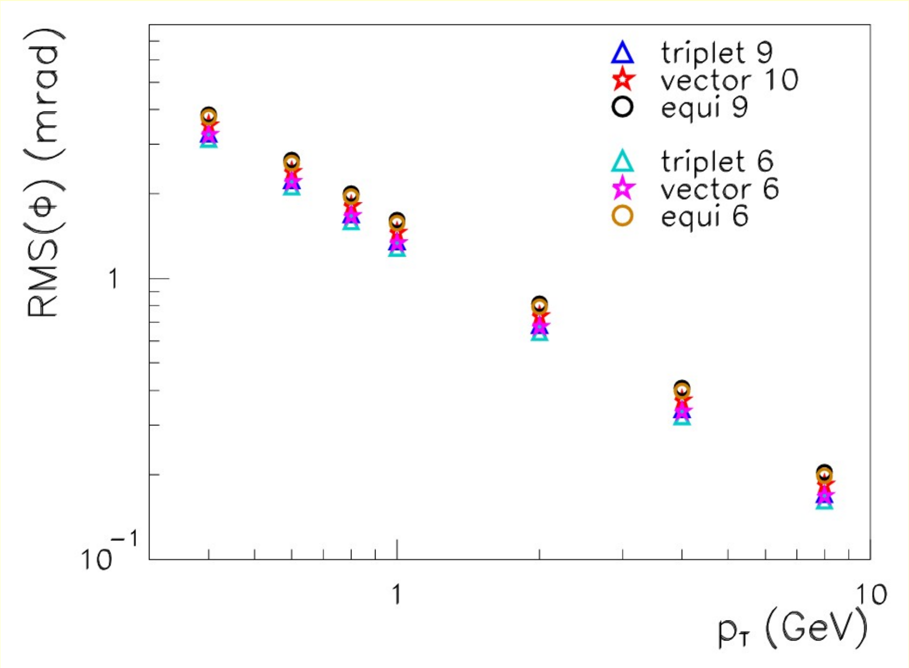


Results for Multiple Scattering (Only)

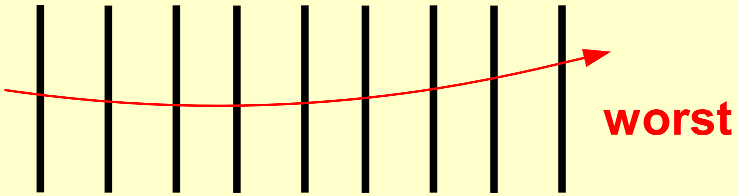
Polar angle at beamline



Azimuthal angle at beamline

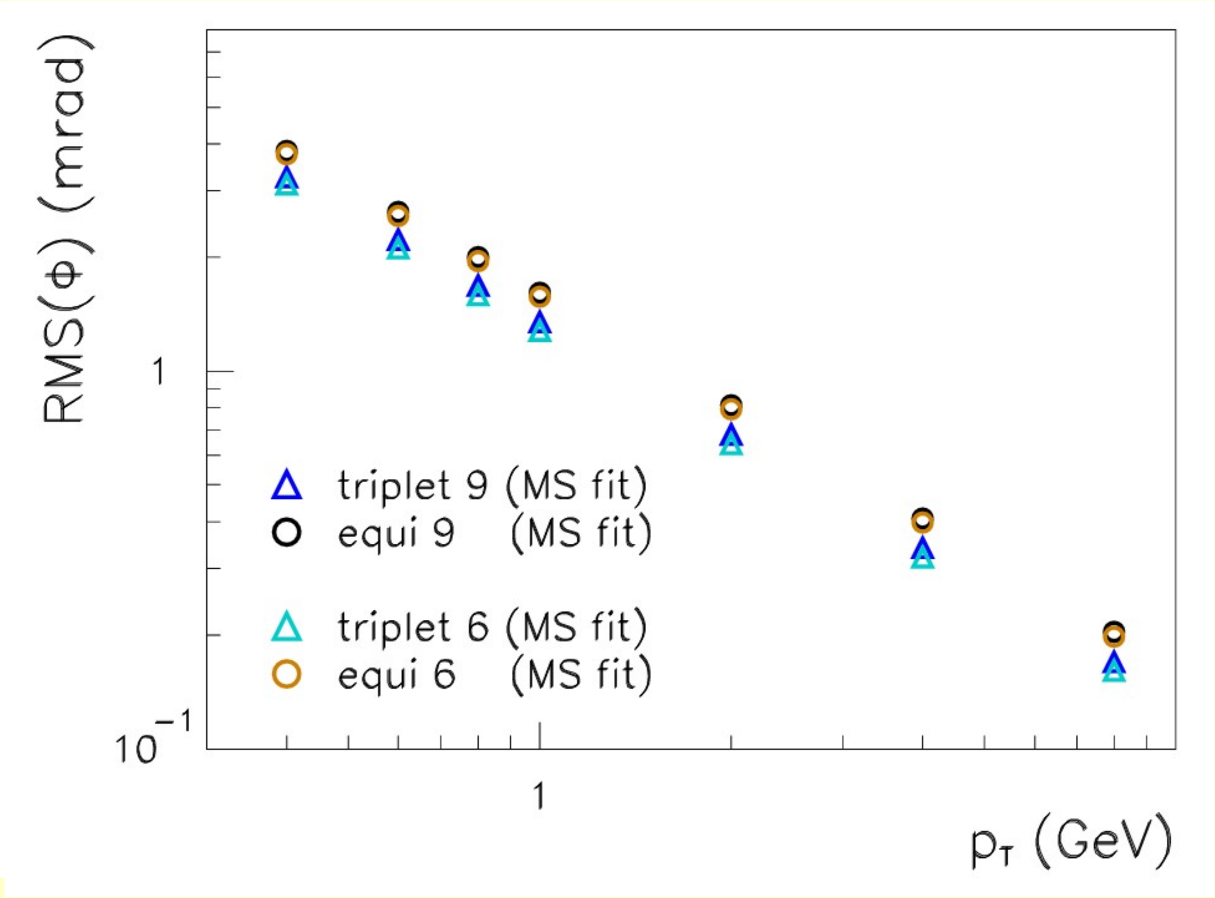


geometries with large bending distances improve measurement precision for Φ



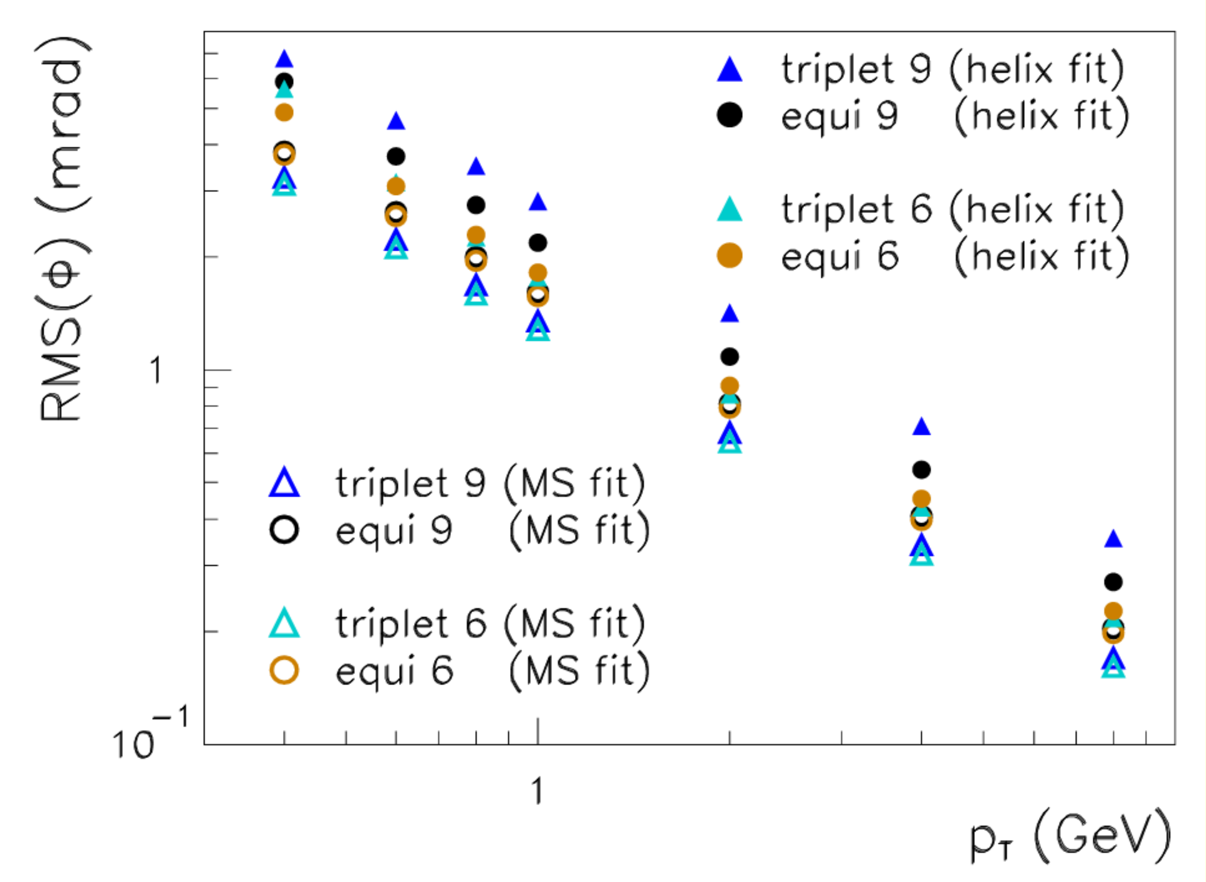
Comparison: MS with Helix Fit

Azimuthal angle at beamline



Comparison: MS with Helix Fit

Azimuthal angle at beamline



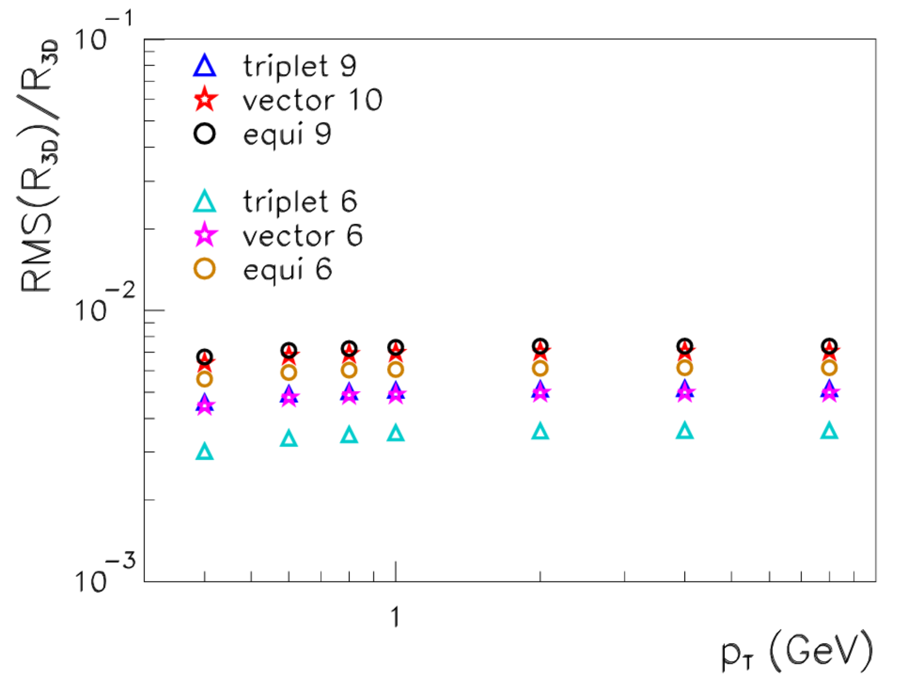
<u>In general:</u>
MS-fit about 2 times better than helix fix!

- small differences for **regular** designs
- large differences for **irregular** designs

→ **Triplet geometry with MS-fit provides best resolution**

Relative Momentum Resolution

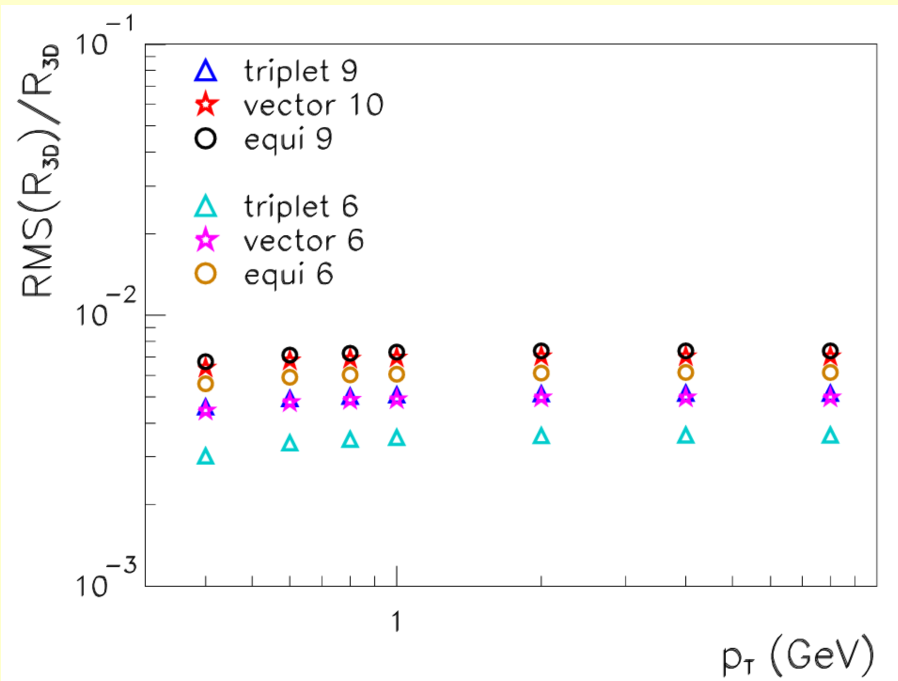
multiple scattering only



- constant up to very high p_T

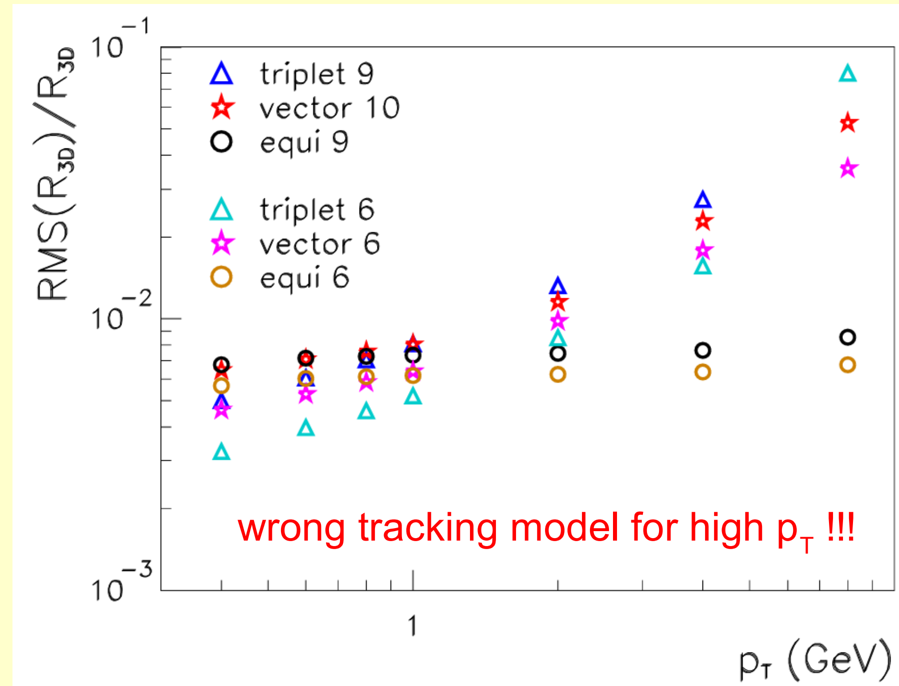
Relative Momentum Resolution

multiple scattering only



- constant up to very high p_T

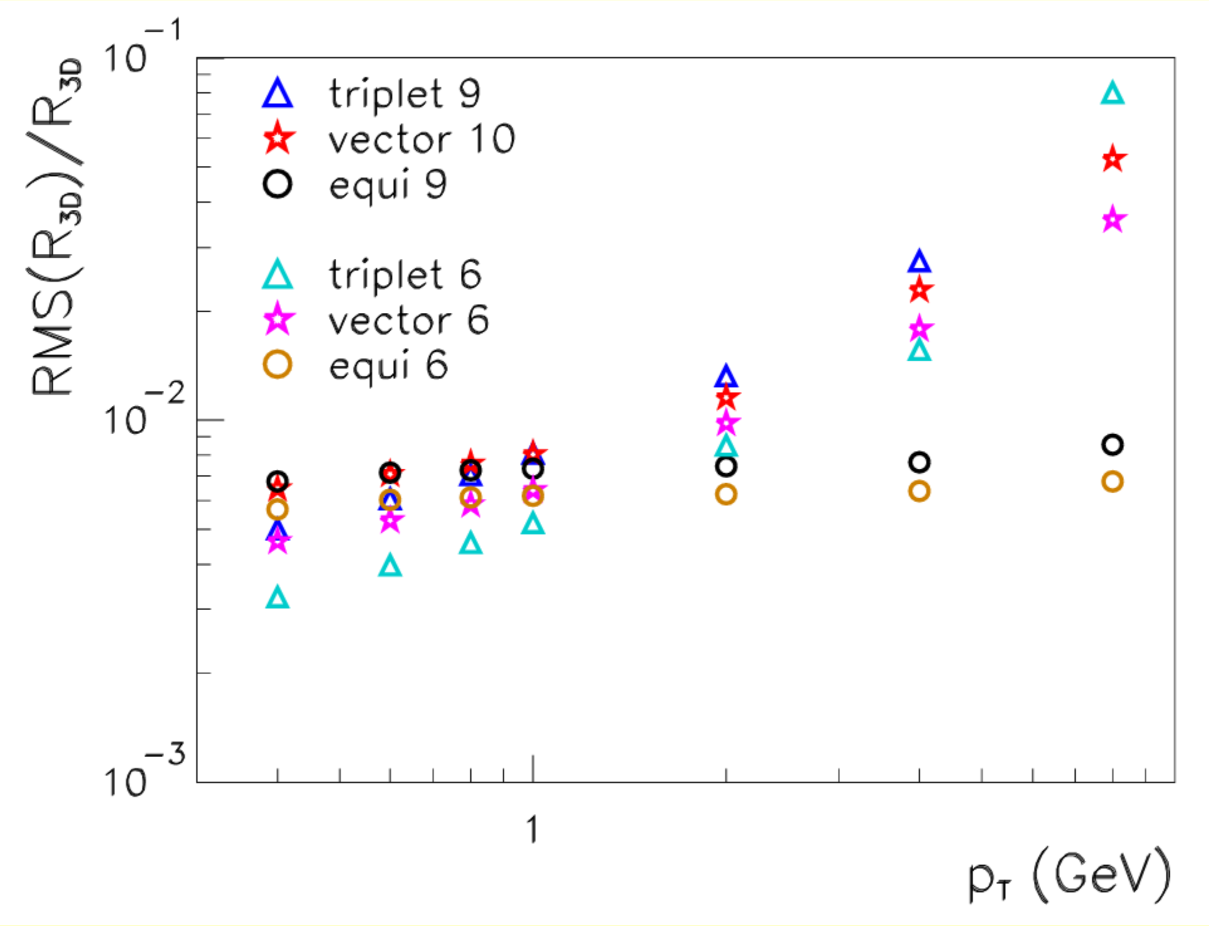
finite pixel size*: 40 µm x 40 µm



- finite pixel size destroys good momentum resolution at high p_T (as expected)
- regular geometry more robust

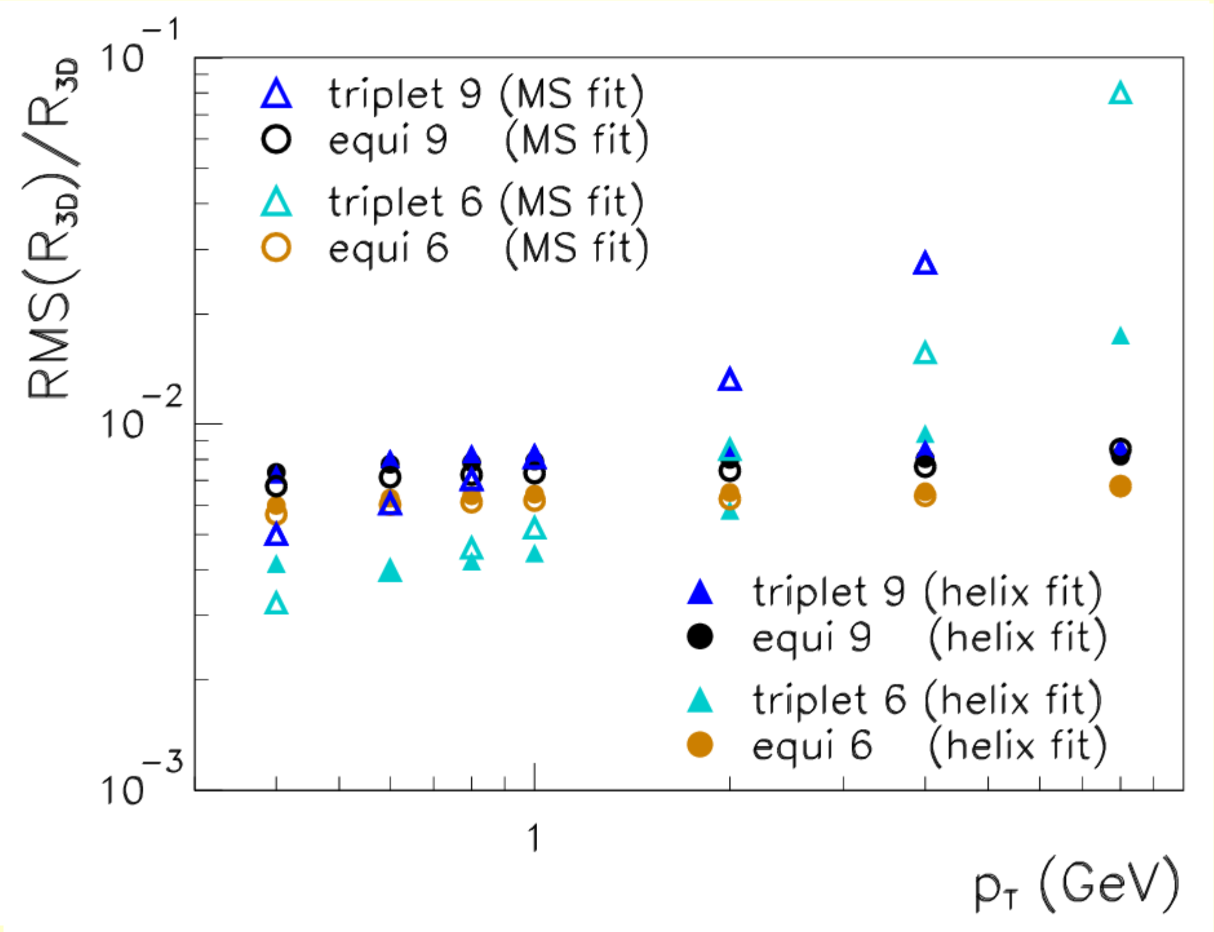
* 40x40 µm² motivated by Mu3e (80x80 µm²)

Momentum Resolution with Pixel Errors

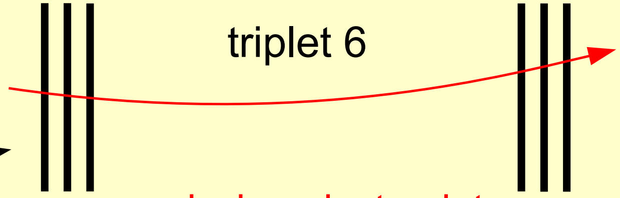


Momentum Resolution with Pixel Errors

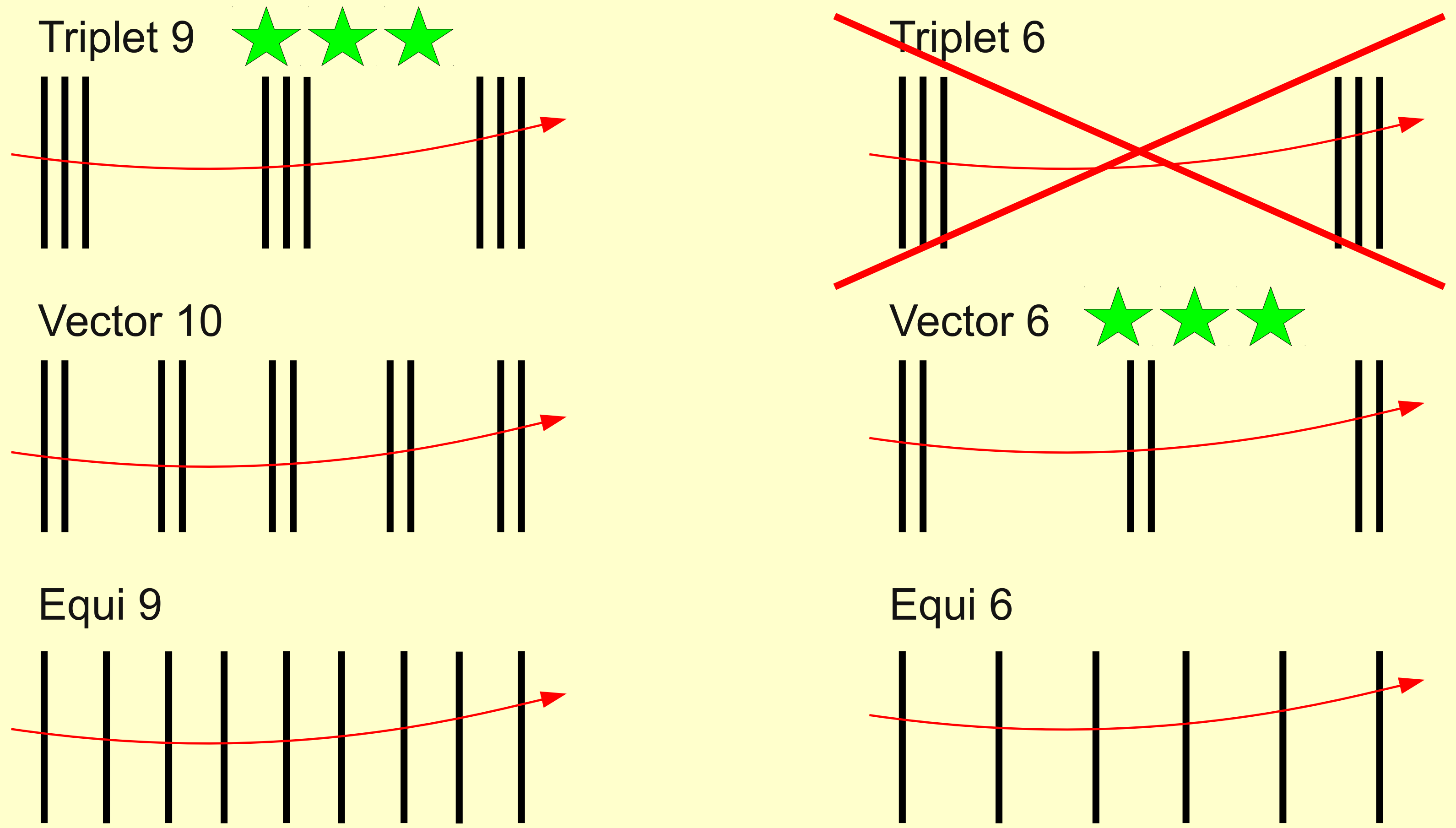
REDO PLOT



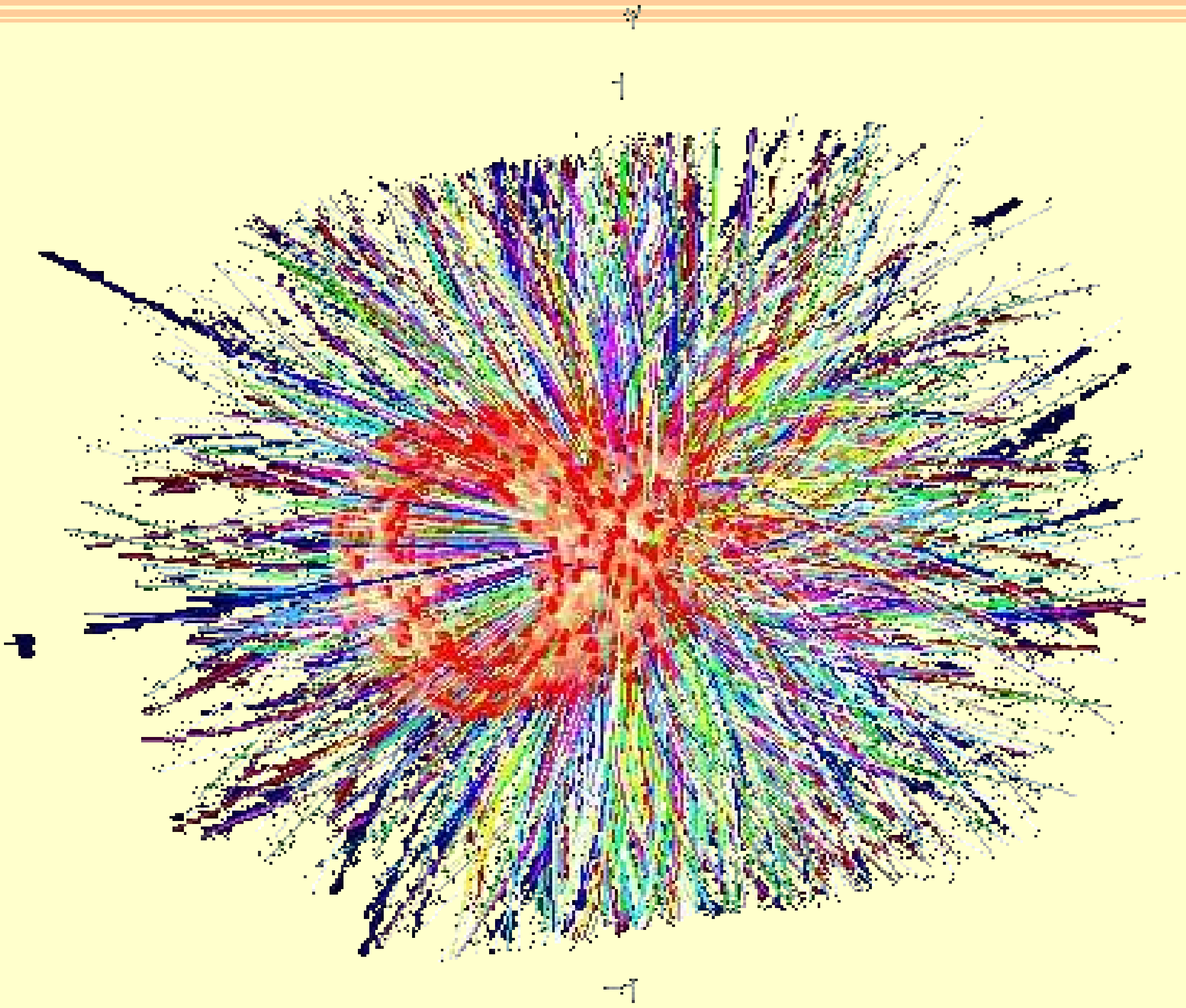
- Loss of resolution recovered with “right” fitting model
- Triplet designs beneficial at small p_T (as expected)
- No “revovery” possible for “triplet 6” design



Summary of Resolution Studies



Track Reconstruction +Linking

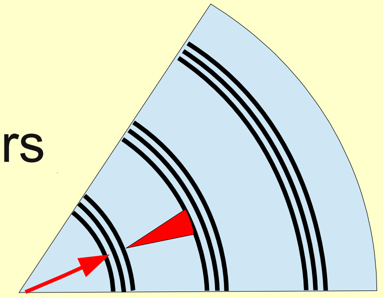


… and the combinatorial problem

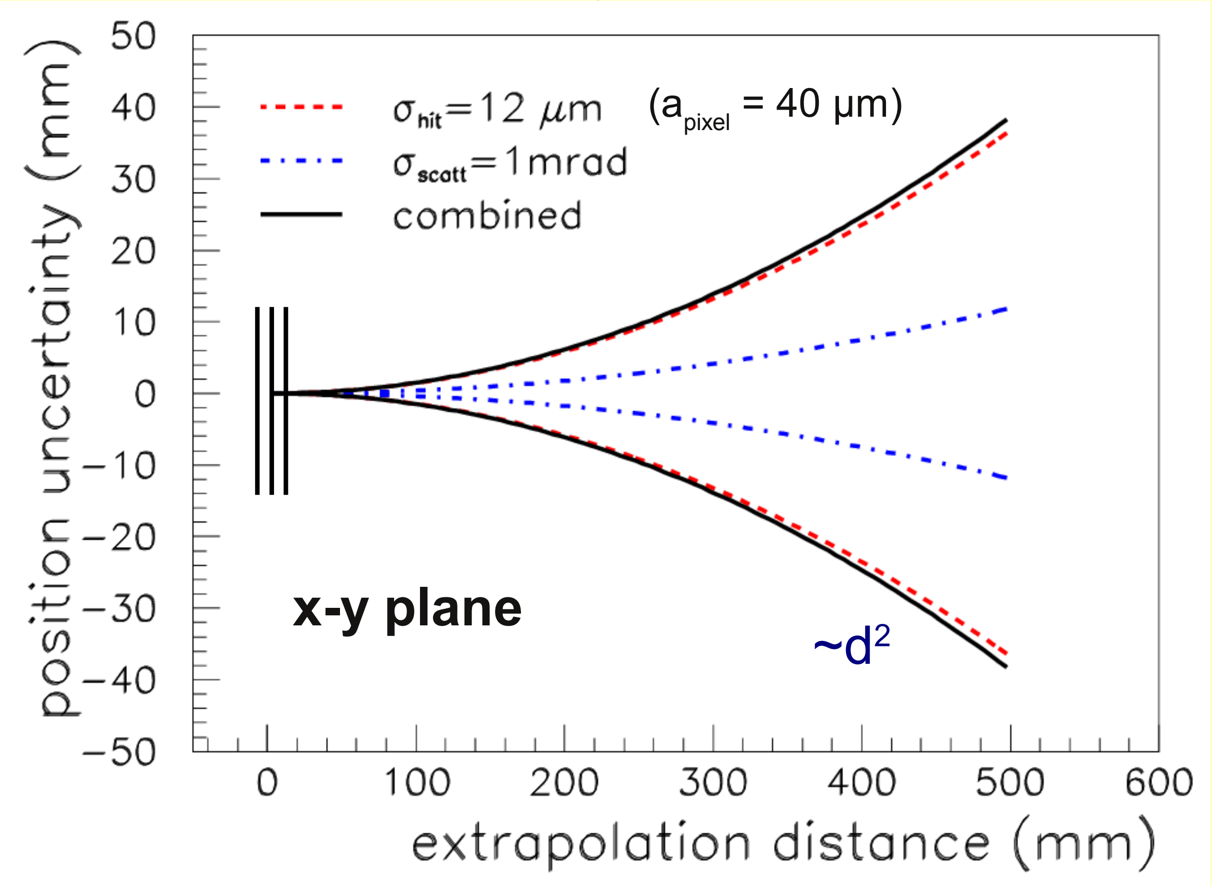
Extrapolation of Track Uncertainties

Track uncertainties determine the combinatorial problem in track linking!

A) hit errors
B) scattering errors



Extrapolation uncertainty for triplets: Δ = 10 mm



uncertainty ~25 mm at d=40cm

Remark:
reduced uncertainty if momentum known!

Extrapolation of Track Uncertainties

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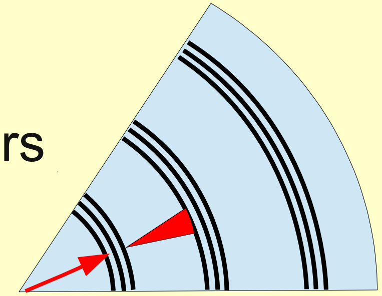

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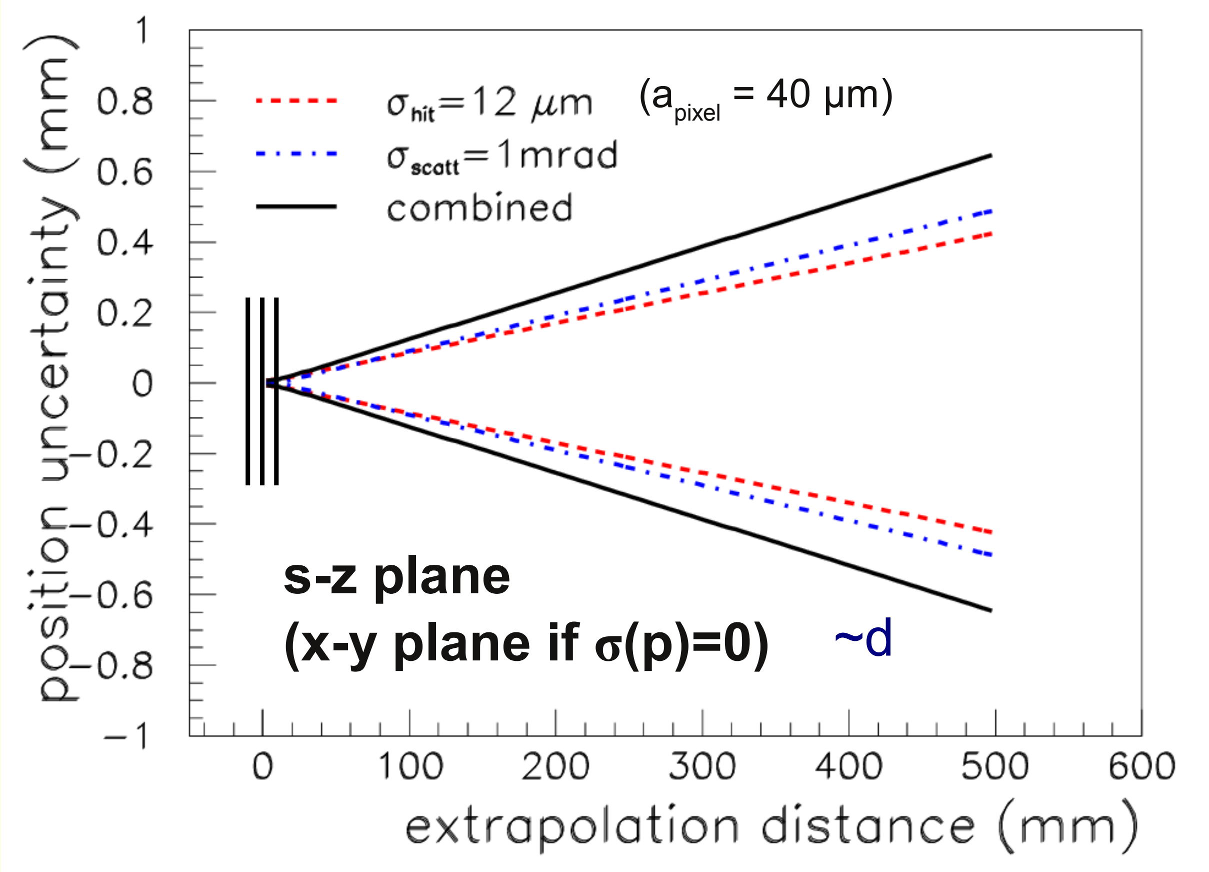

uncertainty ~600 μm at d=40cm

Extrapolation of Track Uncertainties

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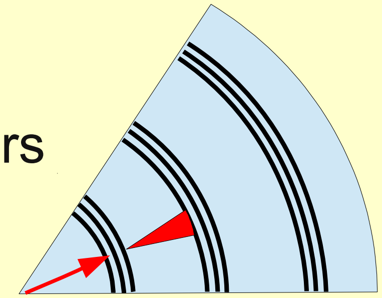
A) hit errors
B) scattering errors



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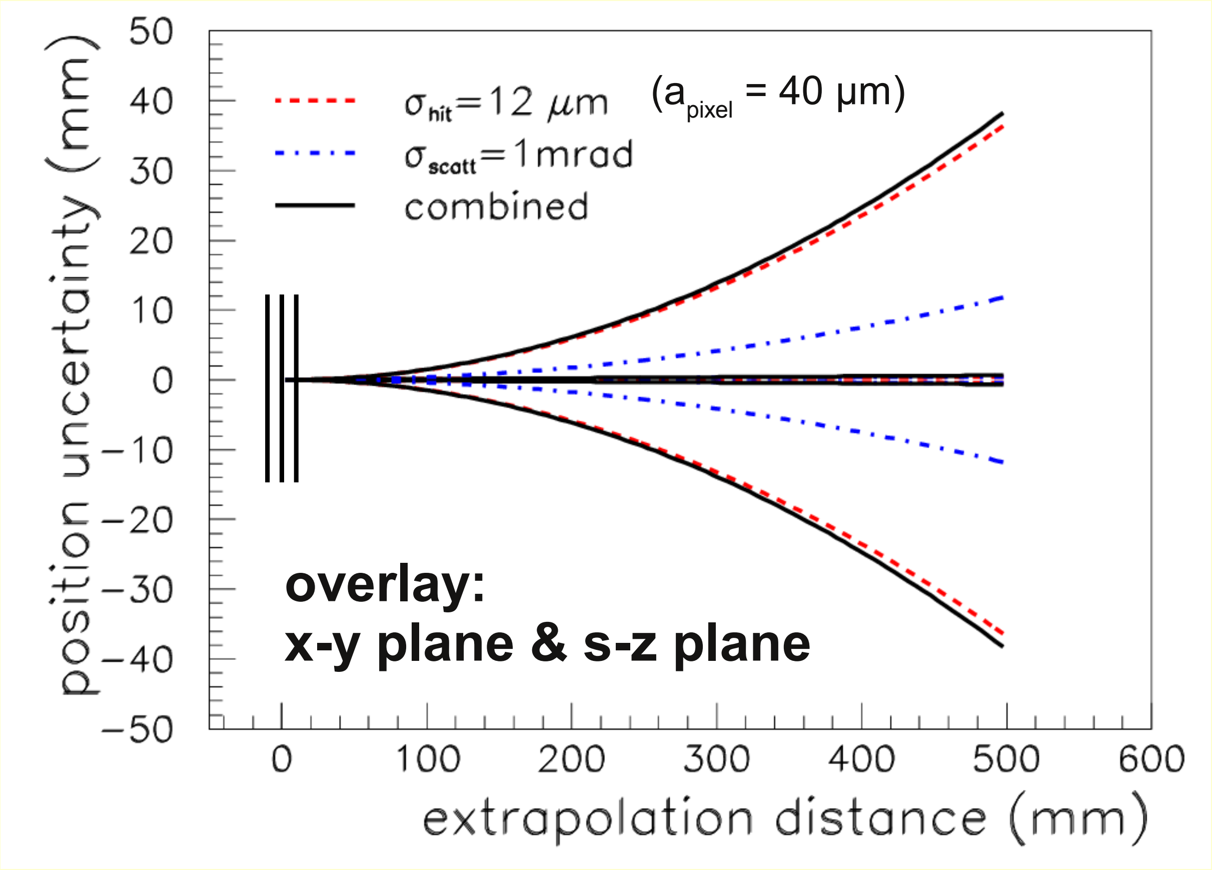
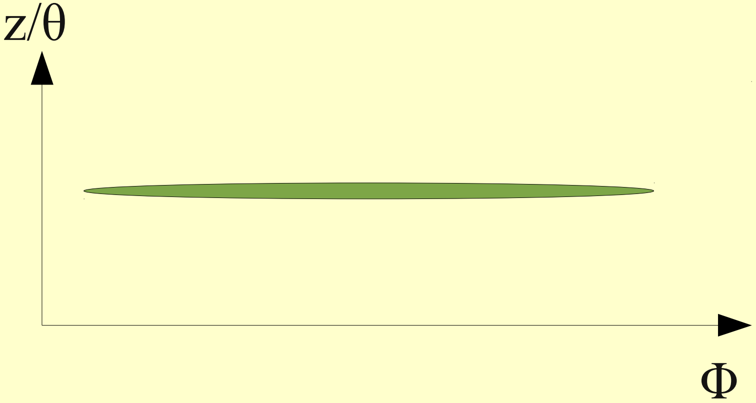


position uncertainty envelop



very precise in longitudinal direction!
→ fine z-segmentation
→ pixel detectors

General Design Linking Study

Methodology

- Generation of minimum bias events
- track multiplicity 250 - 64000 per event for $|\eta|<1.5$
- Simulation: scattering and hit errors
- Single hit efficiency 100%
- Hits required in all planes
- Linking based on track fit (chi2-cut based on MS&hit error)
  → 99.5% track finding efficiency

linking speed depends also on linking strategy

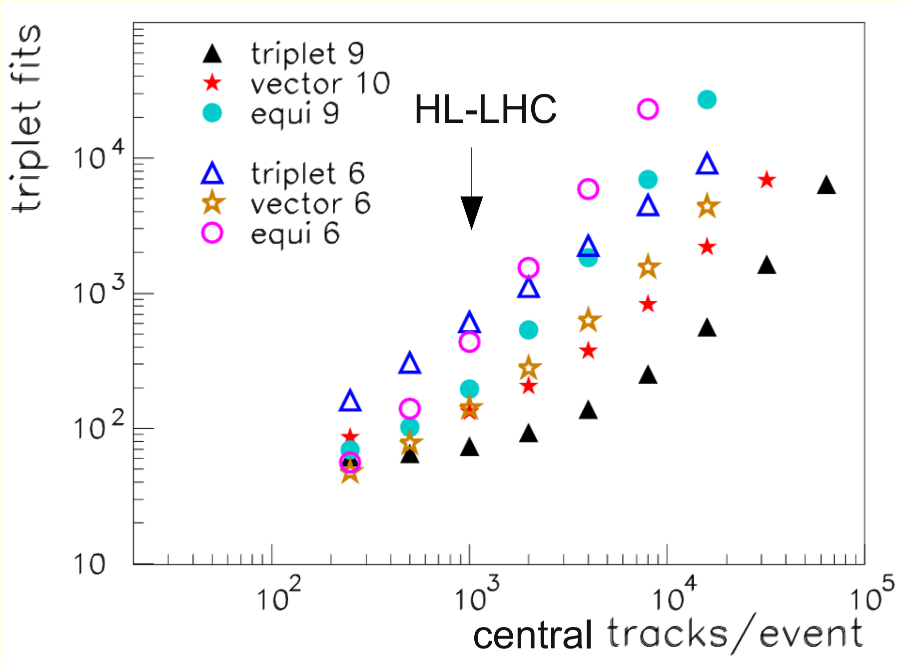
- **strategy A: inside out**
- strategy B: vector tracking (first form pairs)
- strategy C: triplet tracking (first form triplets)

Figures of merit:

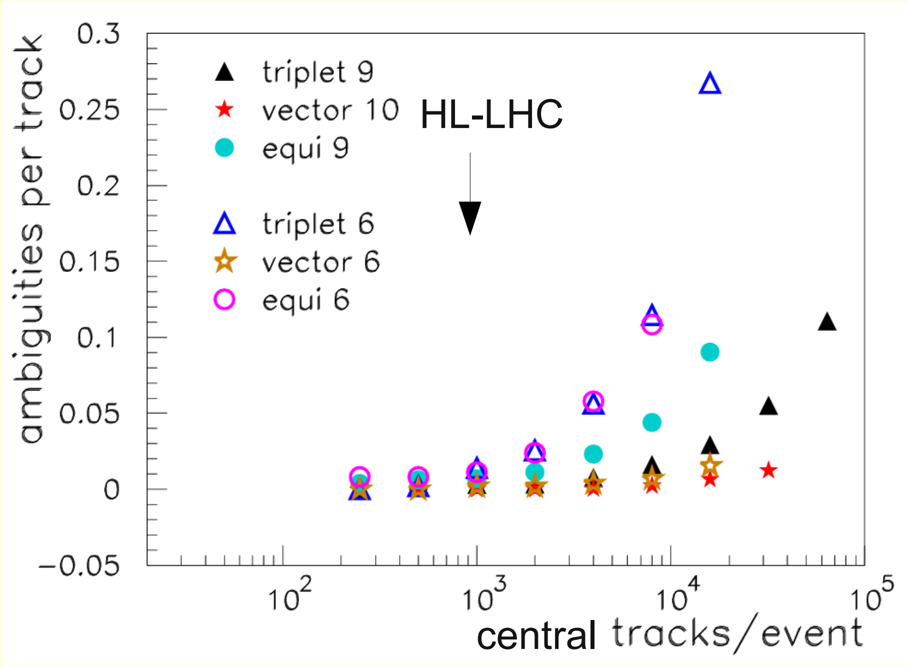
- number of triplet fits → **speed performance**
- hit ambiguities (fake track) rate → **physics performance**

Track Linking Results

number of (triplet) fits for linking



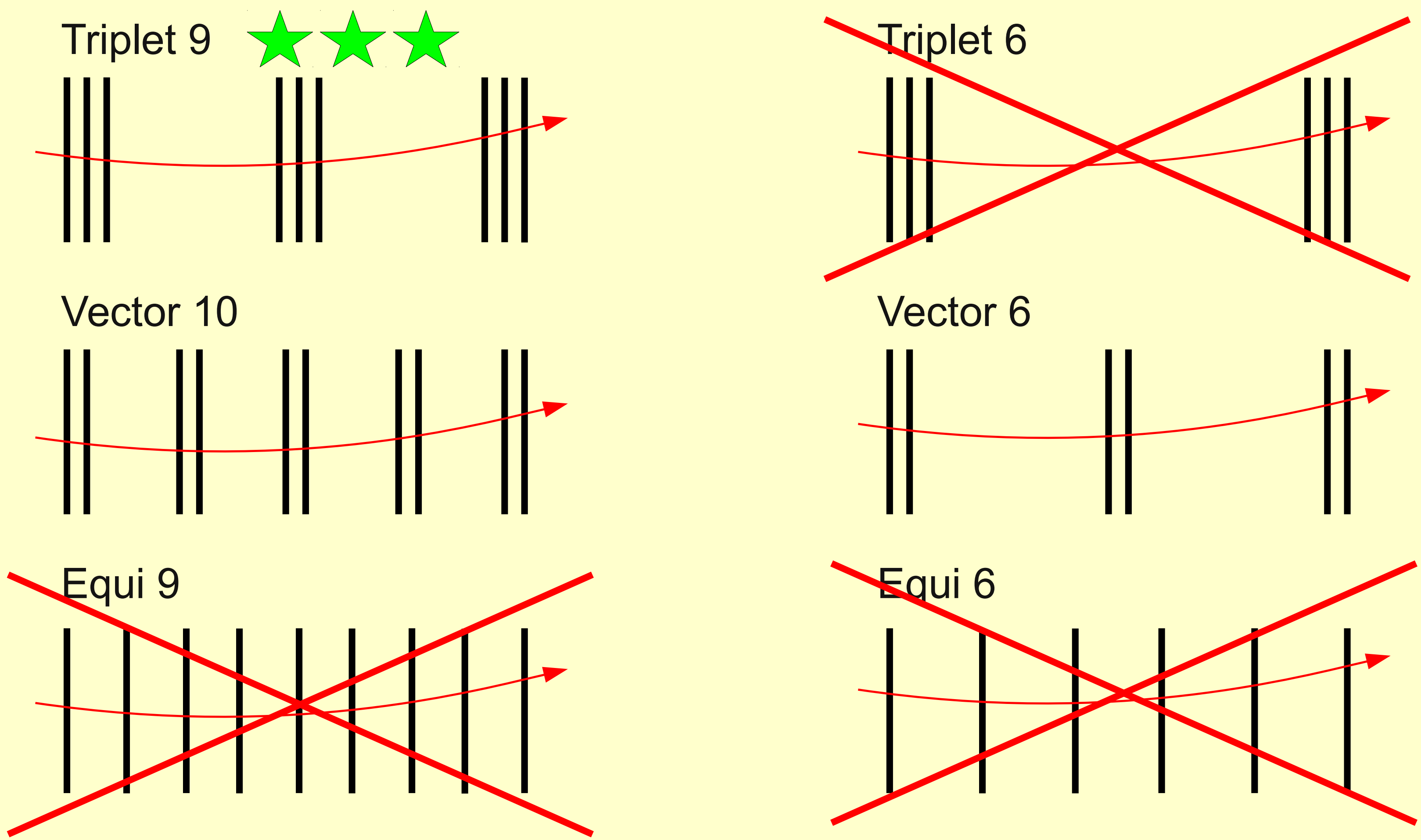
ambiguous tracks (fake candidates)



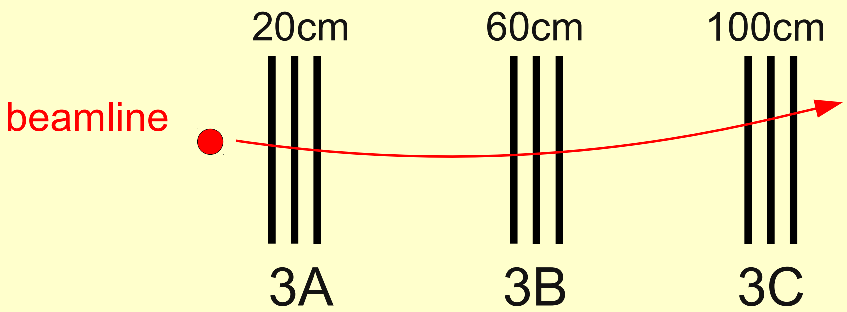
Best peformance achieved for:

- triplet 9 → smallest number of fits
- vector 6,10 → least ambiguities

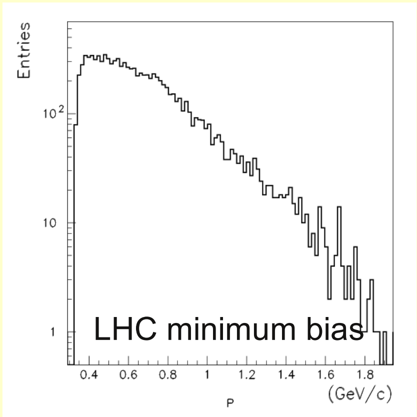
Summary of Linking Studies



Triplets for Track Triggers



stacking Δ=10mm



- Independent track reconstruction (local) in triplets
- Goal: **reject low momentum tracks**

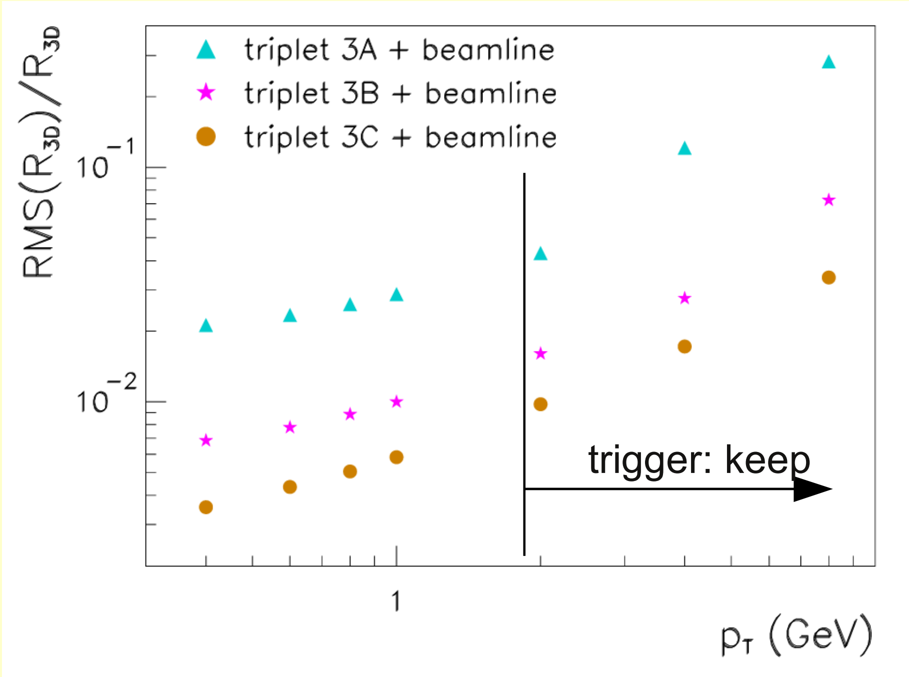
<u>Performance of inner triplet (3A)</u>

σ(DCA) = 5-8 mm (w/o additional constraints)

σ(Z0) = 5-15 mm (w/o additional constraints)

$\sigma(p)/p$ = 4% @ p_T=2 GeV

momentum resolution with beamline constraint



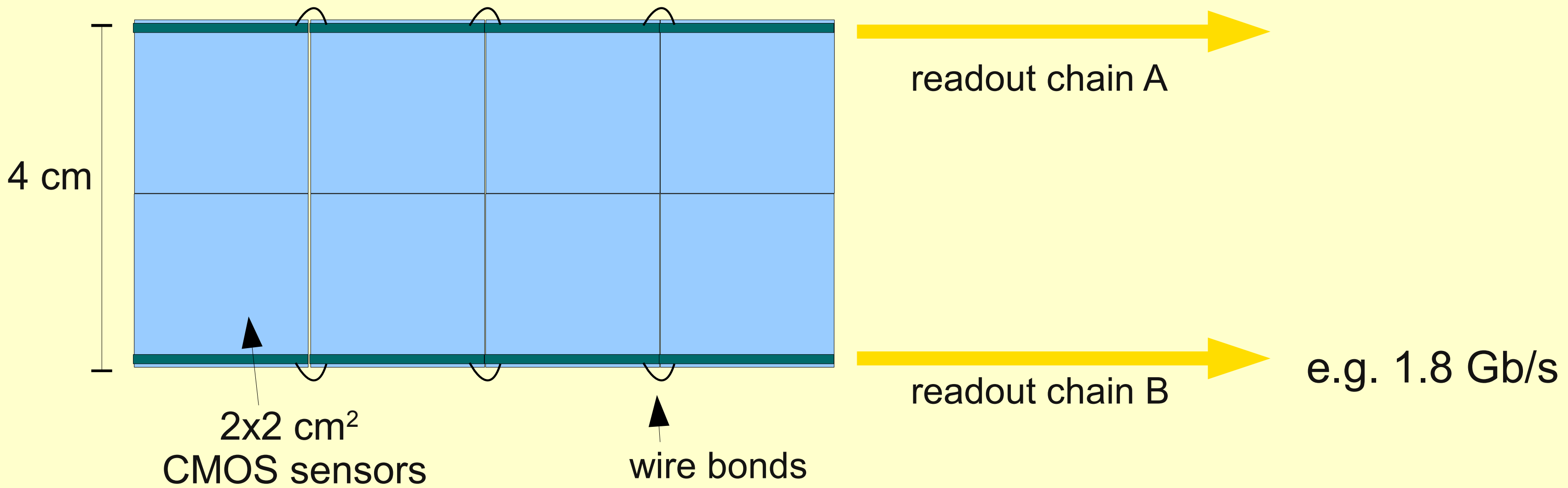
<u>Conclusion:</u>

triplets are very robust against BG from

- low momentum tracks
- → secondary (tertiary) interactions

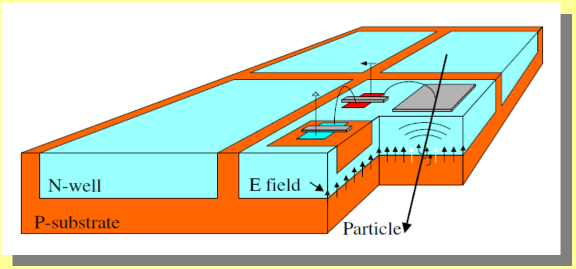
Note: precision could be further improved by increasing the layer stacking

HV-MAPS Triplets & Online Reconstruction



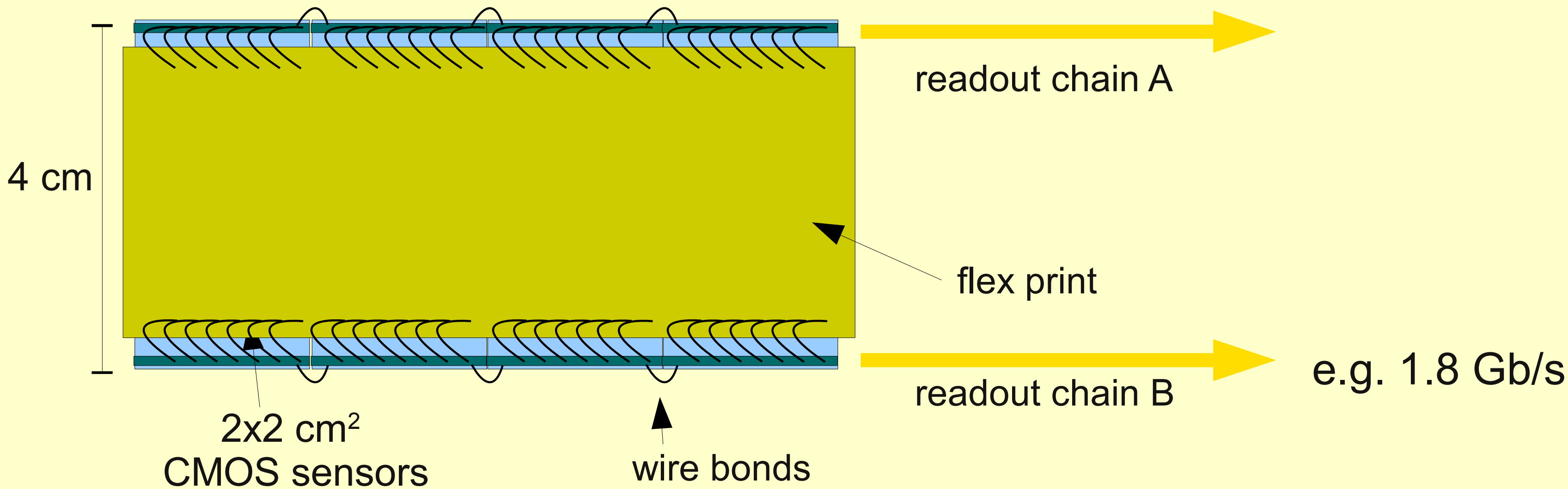
- stitched CMOS chips
- module width 4cm
- 5% readout strip at both sides
- power and control via flex prints
- wire bonding between sensors and to flex prints
- readout chain
- push hit address and timestamp

MU3e HV-CMOS developments



50μm glass on 25μm kapton

HV-MAPS Triplets & Online Reconstruction



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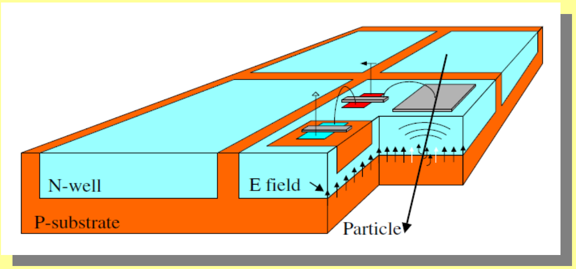

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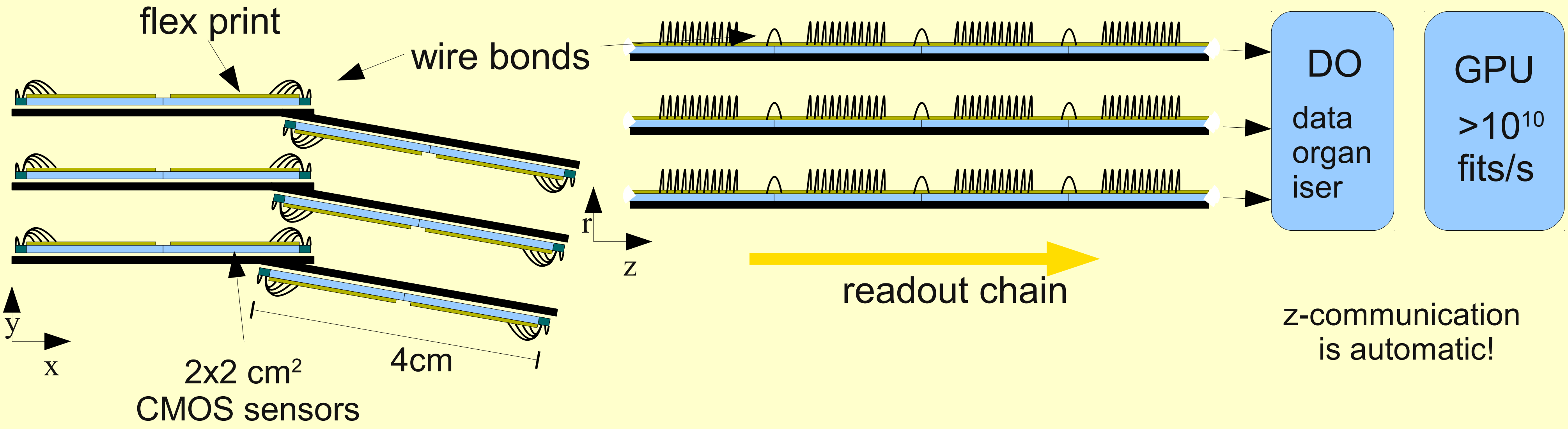
HV-MAPS Triplets & Online Reconstruction



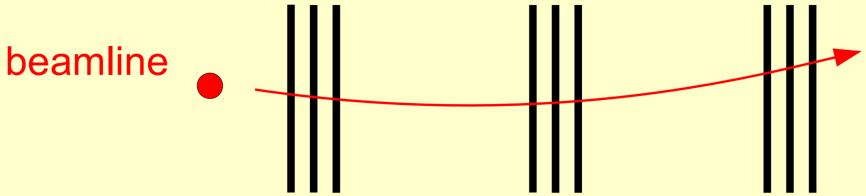
Rate Estimates for HL-LHC |η|<3

triplet radius	#ladders	data rate/ module (Gbit/s)	#hits per halfladder	#GPUs
20 cm	36	120	$1.2 \cdot 10^9$/s	72
60 cm	100	40	$0.4 \cdot 10^9$/s	200
100 cm	164	24	$0.24 \cdot 10^9$/s	328

- **GPU solution - processing all hits for every event - technically feasible**

Conclusions

- Pixel tracker with triplet layer geometry proposed for tracking in hadron colliders (LHC, …) with highest multiplicities
- Triplet of pixels provide full track information, benefitial for fast and robust track reconstruction (trigger)
- Resolution for low momentum tracks can be even improved with the three triplet design



Results obtained so far are promising and motivate more detailed studies...