A 3D Track Fit with Multiple Scattering for the Mu3e Experiment

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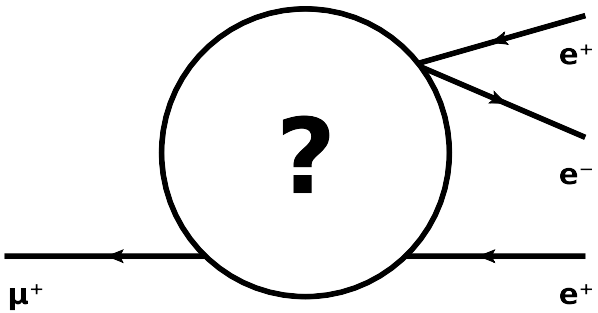
Connecting The Dots, Berkeley, 2015-02-10

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

The Mu3e Experiment

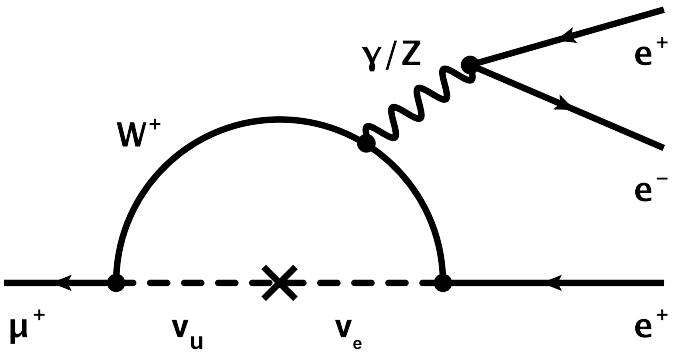


- Precision experiment
- Search for $\mu^+ \rightarrow e^+e^-e^+$

In this talk

- Experimental concept
- Track fitting in different regimes
- Triplet fit for Mu3e
- Performance comparisons

$\mu \rightarrow$ eee in the Standard Model



Features

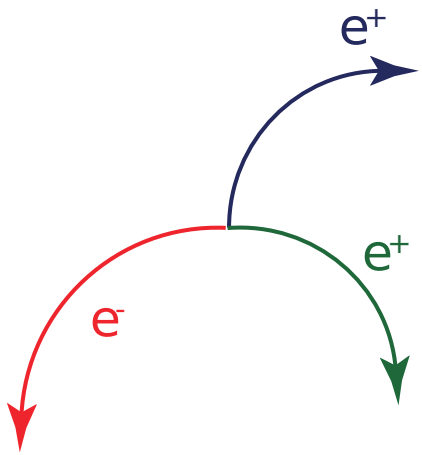
- Charged lepton flavor violating
- Expected BR($\mu \rightarrow$ eee) $\ll 10^{-50}$
- Current limit from Sindrum
  BR($\mu \rightarrow$ eee) $< 1 \cdot 10^{-12}$ @90 % CL
  `Nucl.Phys. B299(1) 1988 (1-6)`
- Our Sensitivity: 1 in 10^{16} decays

Importance

- Observable rate only from
  New Physics

Signal and Backgrounds

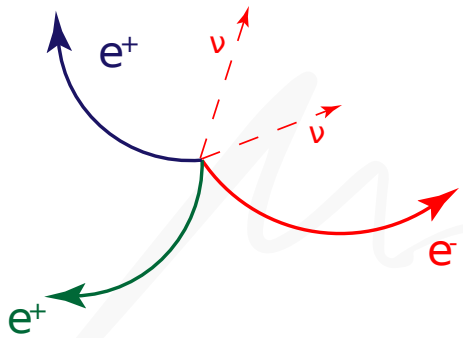
Signal



- Common vertex
- $\sum \vec{p}_i = 0$
- $p < 53\,\text{MeV}$

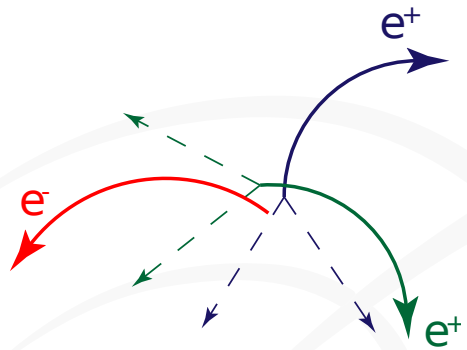
Backgrounds

Internal Conversion



- Common vertex
- $\sum \vec{p}_i \neq 0$
- In-time

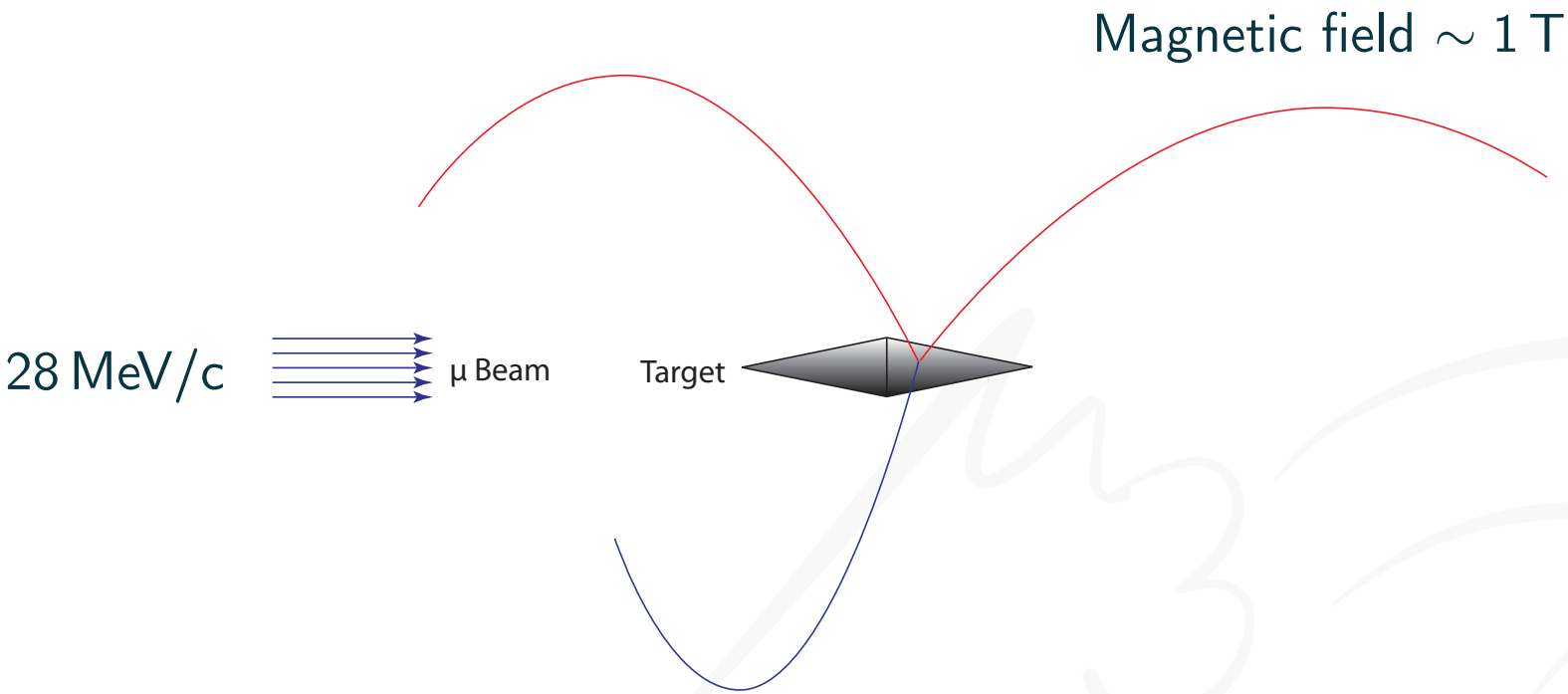
Accidental



- No common vertex
- Out-of-time

Requires $\sigma_p < 0.3\,\text{MeV}$
$\sigma_t < 1\,\text{ns}$

Detector Concept



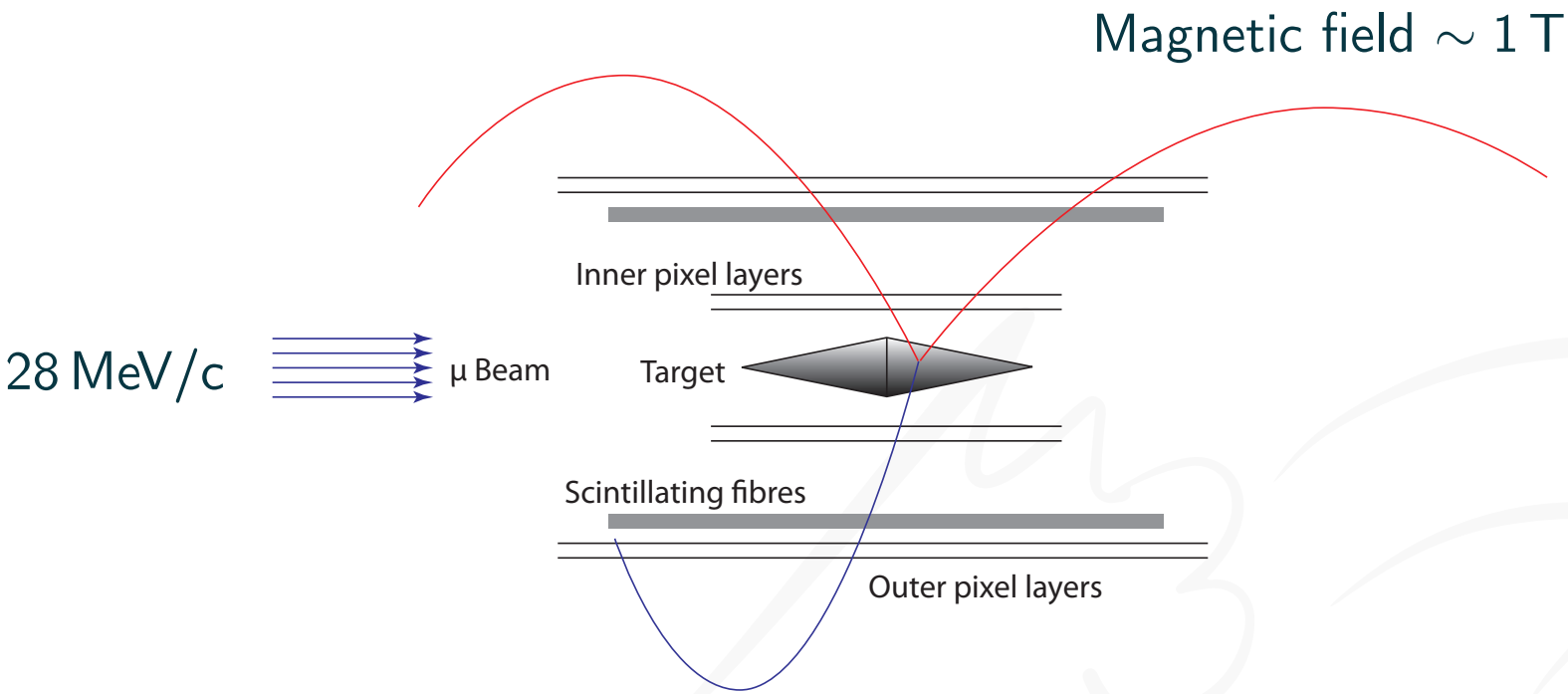
Environment

- $> 10^9$ μ^+ decays/s (continous)
- Electrons p $<$ 53 MeV/c

Pixel Tracker

- Monolithic active pixels
- 50 µm silicon, 80 µm pixel size
- Continous readout

Detector Concept



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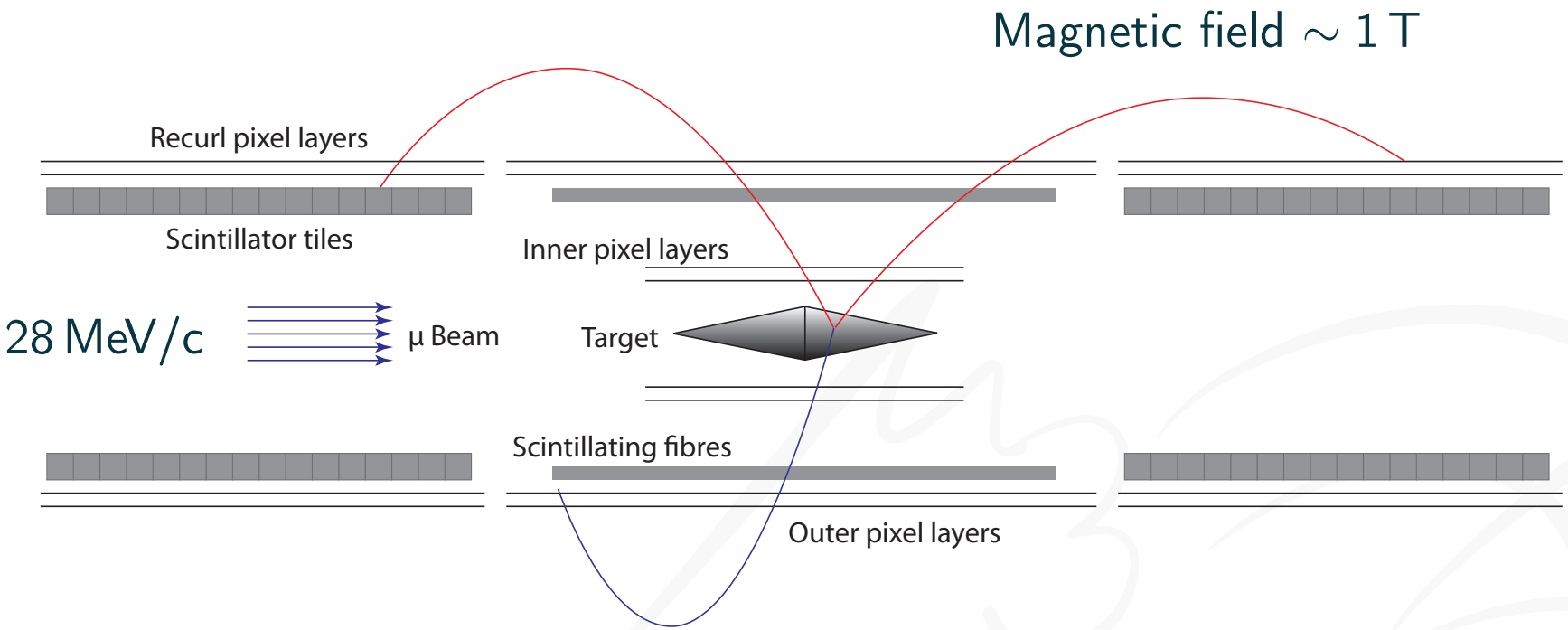

Environment

- $> 10^9$ μ^+ decays/s (continous)
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Pixel Tracker

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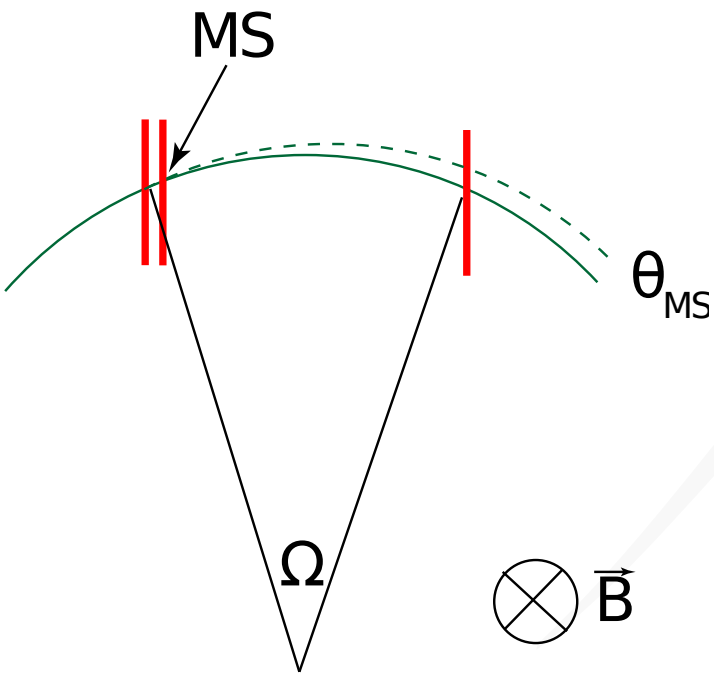
Multiple Scattering



$$\theta_{MS} \sim \frac{1}{p}\sqrt{x/X_0}$$

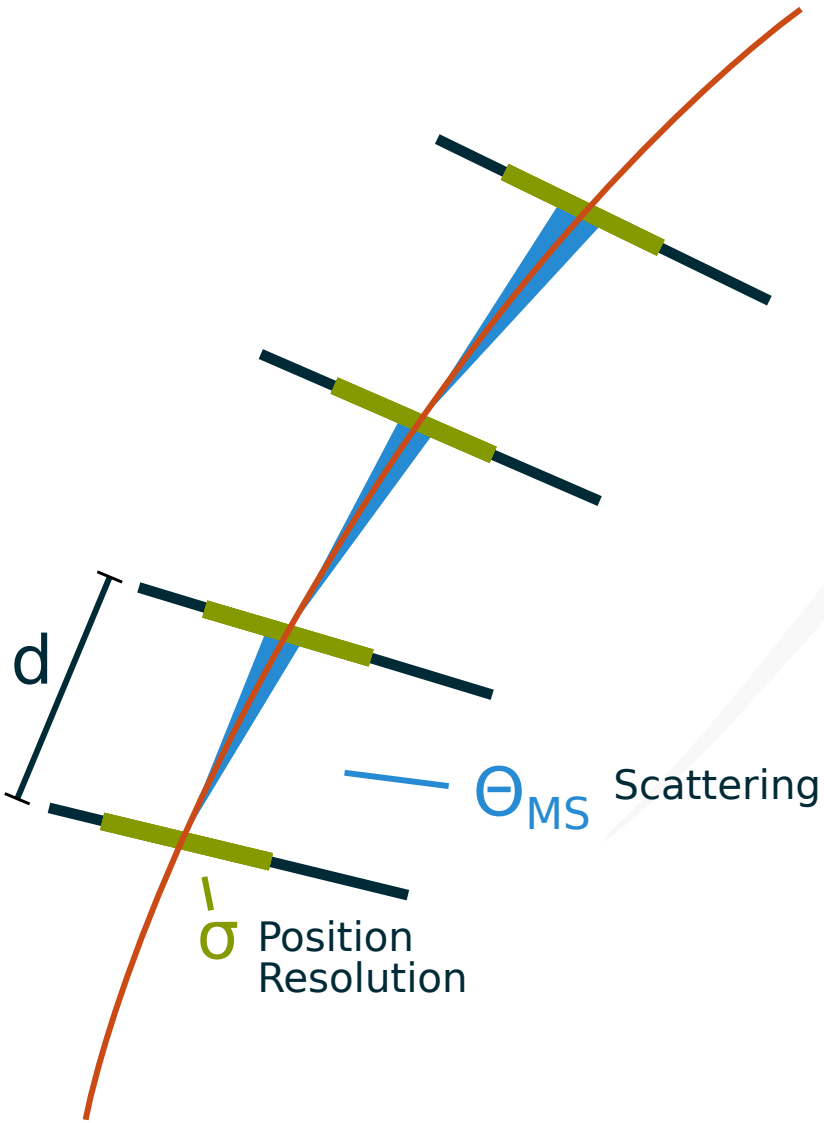
Mu3e Example

- $p = 35\,\mathrm{MeV/c}$
- $50\,\mu\mathrm{m}$ Si
- $\Omega R = 5\,\mathrm{cm}$

$\rightarrow$ $\Delta y \approx 320\,\mu\mathrm{m}$

$\rightarrow$ Scattering dominates

Tracking Models



Scattering scale factor:

$$\frac{d \cdot \theta_{MS}}{\sigma} \ll 1$$

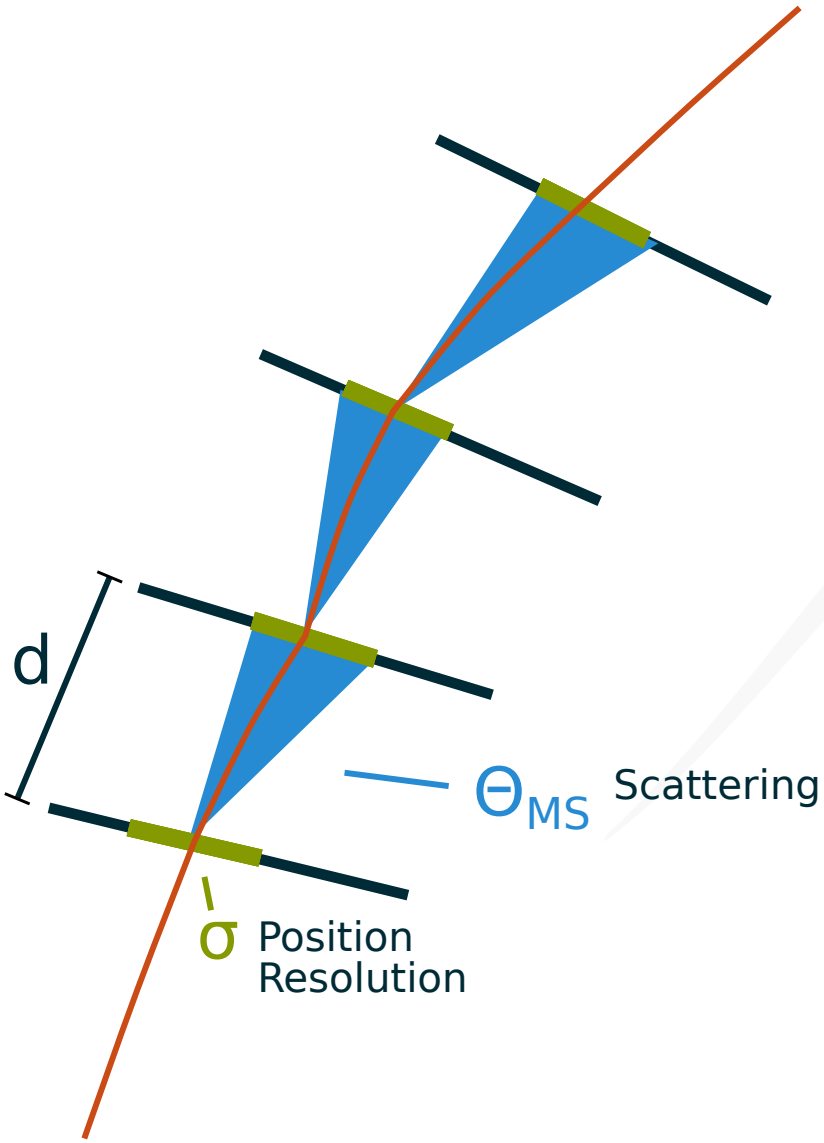
Dominated by hit resolution

Reconstruction

- Helix fit
  1. Circle fit in xy-plane

     e.g. Karimaeki 1991
  2. Straight line in sz-space
- 2.5D fit, global parameters

Tracking Models (cont'd)



Scattering scale factor:

$$\frac{d \cdot \theta_{MS}}{\sigma} \approx 1$$

Reconstruction

- Kalman filter

  e.g. Fruewirth 1987

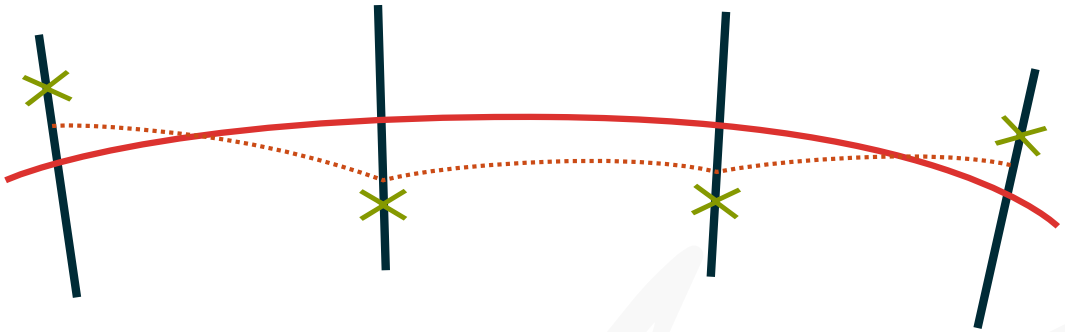
- General Broken Lines

  Blobel,Kleinwort 2011

- 3D fit

Tracking Models / General Broken Lines

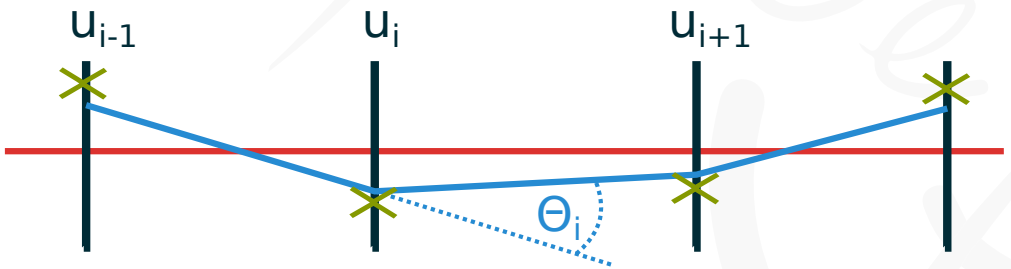
Global Trajectory (3D)



reference trajectory

linearize around reference

Local Trajectory (2D)

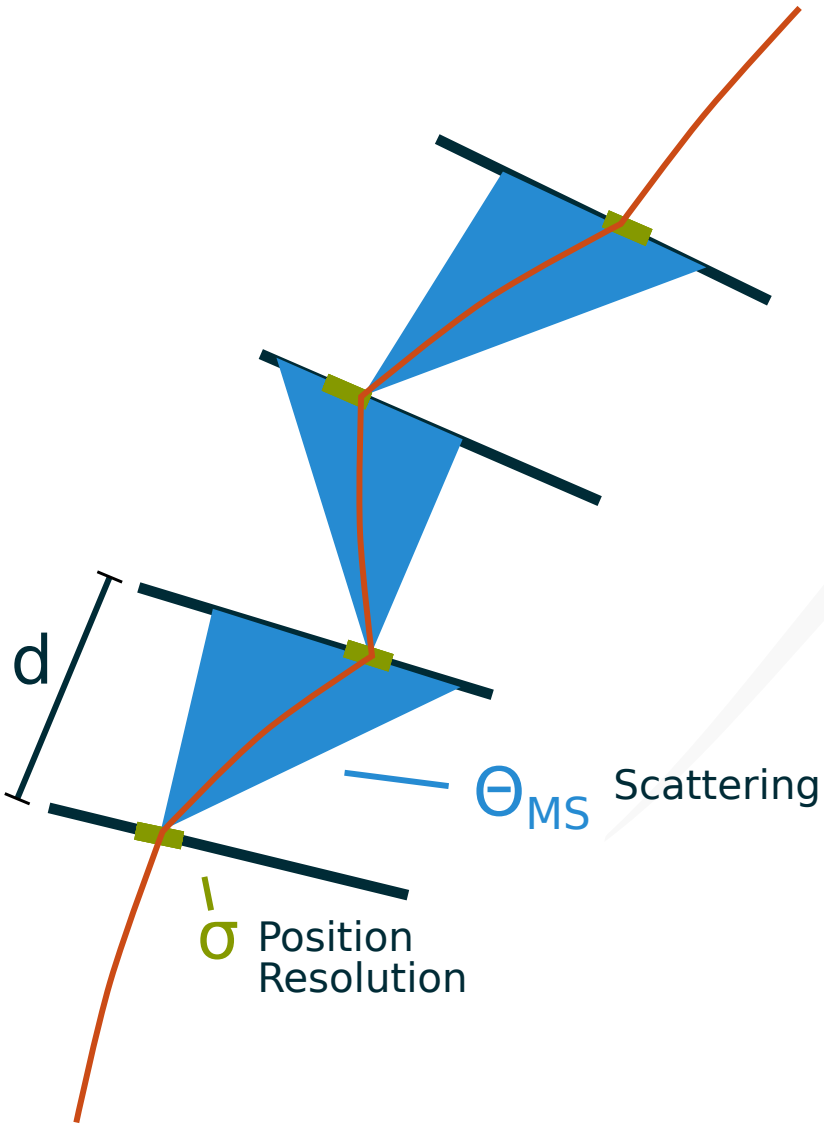


reference trajectory

Minimize u_i and θ_i

see Kleinwort 2012

Tracking Models (cont'd)



Scattering scale factor:

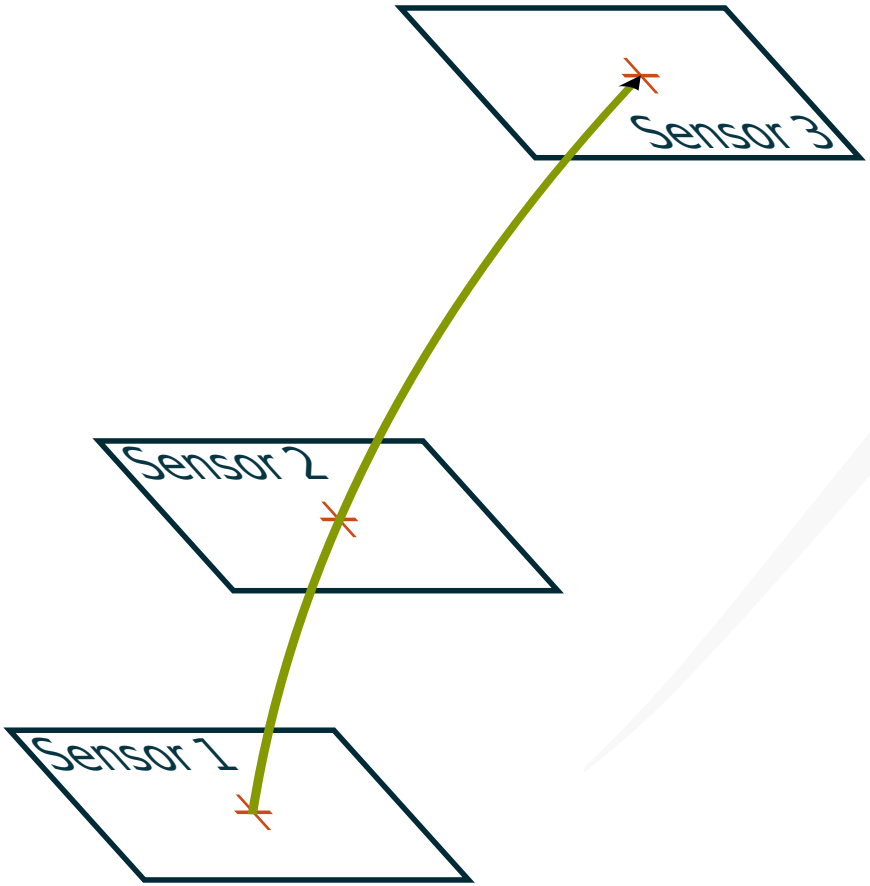
$$\frac{d \cdot \theta_{MS}}{\sigma} \gg 1$$

Dominated by scattering

Reconstruction

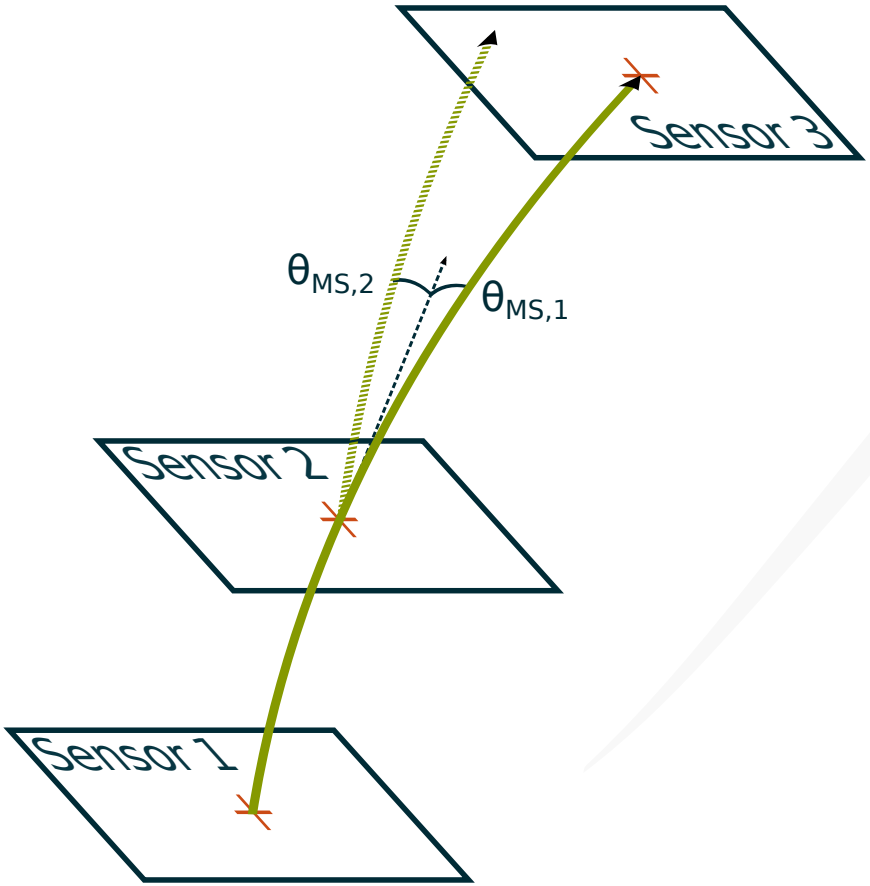
- Kalman filter
- General Broken Lines
- Anything else?

A Triplet of Hits



# parameters	
+ 9	data points
- 3	start position
- 2	direction angles
- 1	curvature / radius
- 2	path lengths
+ 1	constraints

A Triplet of Hits (cont'd)

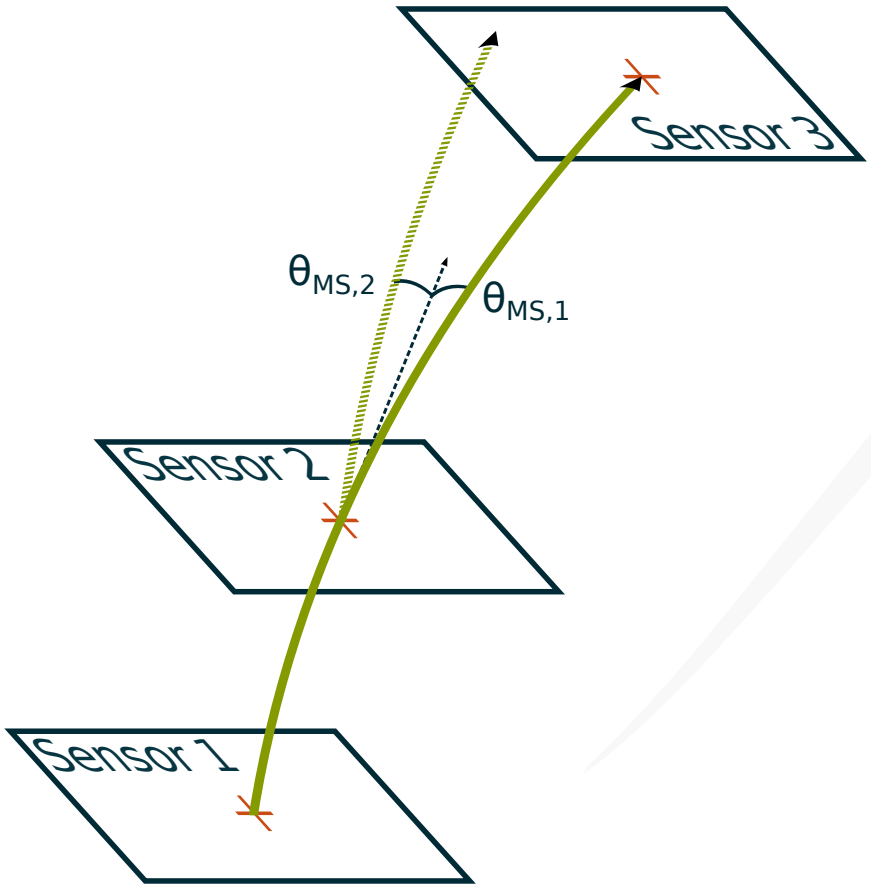


# parameters	
+ 9	data points
- 3	start position
- 2	direction angles
- 1	curvature / radius
- 2	path lengths
- 2	scattering angles
- 1	constraints

Additional constraints

- $< \theta_{MS,i} >= 0$
- $< \theta^2_{MS,i} >= PDG$
- $\Delta E \approx 0$

A Triplet of Hits (cont'd)



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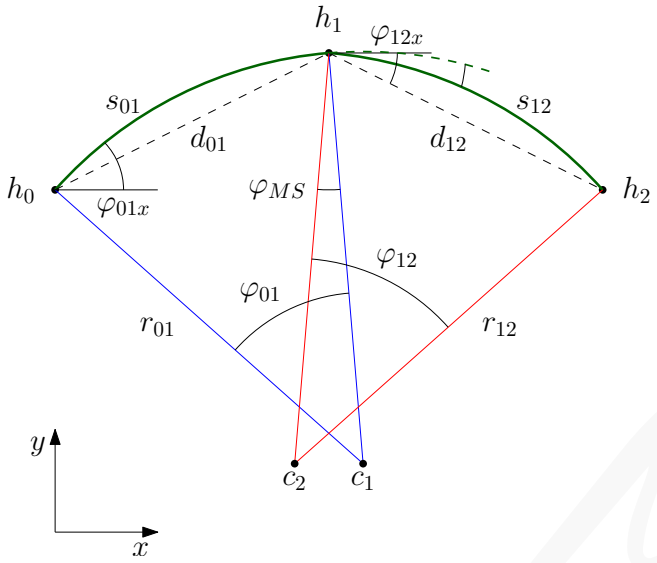
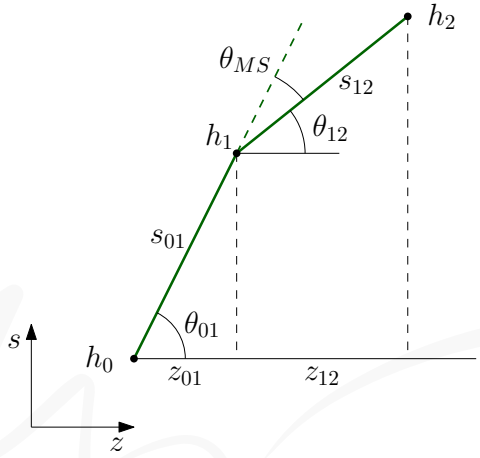
Triplet Fit





Assumptions:

- No position error
- No energy loss
- Thin scatterer at middle hit

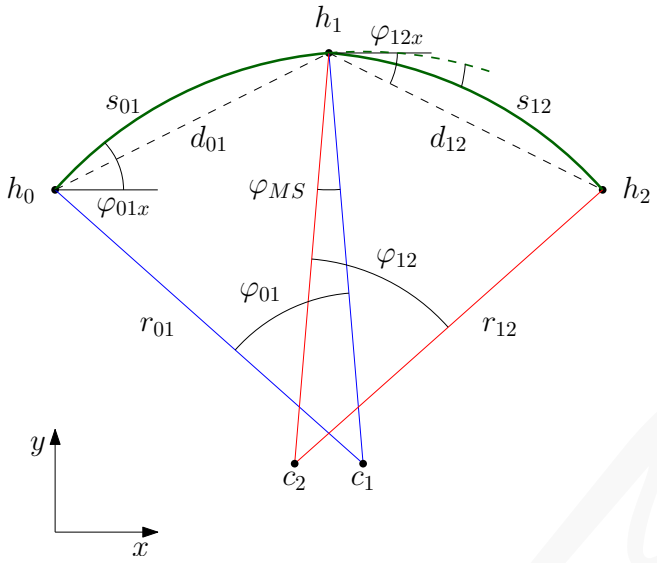
Minimize:

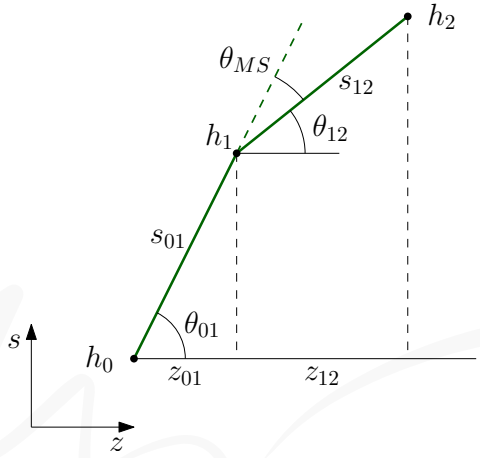
$$\chi^2_i(R_{3D}) = \frac{\varphi_{MS}(R_{3D})^2}{\sigma^2_\varphi} + \frac{\theta_{MS}(R_{3D})^2}{\sigma^2_\theta}$$

Problem: highly non-linear

Solution: linearize around circle.

Triplet Fit





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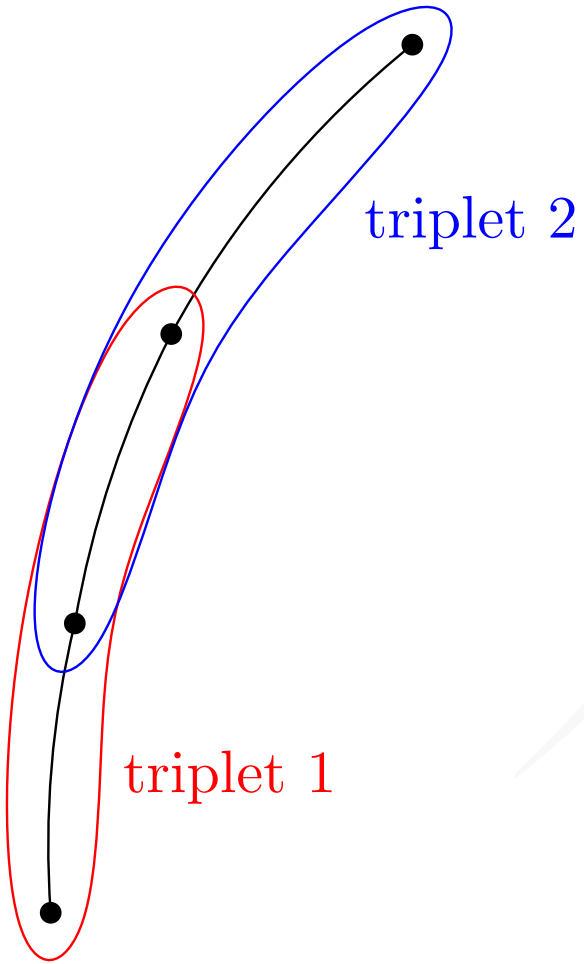
$$\chi_i^2(R_{3D}) = \frac{\varphi_{MS}(R_{3D})^2}{\sigma_\varphi^2} + \frac{\theta_{MS}(R_{3D})^2}{\sigma_\theta^2}$$

Problem: highly non-linear

Solution: linearize around circle.

Triplet Fit (cont'd)



1. Define overlapping triplets

$$\chi^2(\bar{R}_{3D}) = \sum \chi_i^2$$

2a. Minimize χ^2 globally

$$\bar{R}_{3D} = \arg\min_x \chi^2(x)$$

2b. Equivalent: minimize each triplet

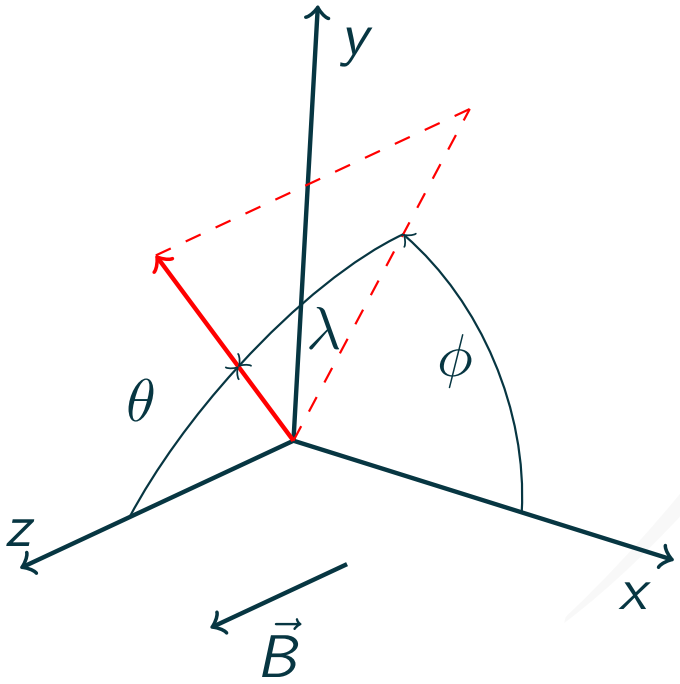
$$\bar{R}_{3D} = \frac{\sum w_i R_{3D,i}}{\sum w_i}$$

Compared Track Fits

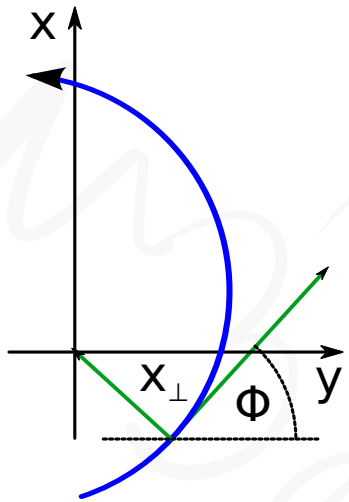
	What is considered?	
	Positions	Scattering
Helix	✓	✗
Triplet	✗	✓
GeneralBrokenLines	✓	✓

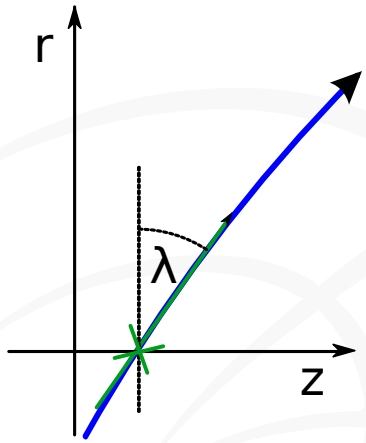
Coordinates and Track Parameters

Coordinate System



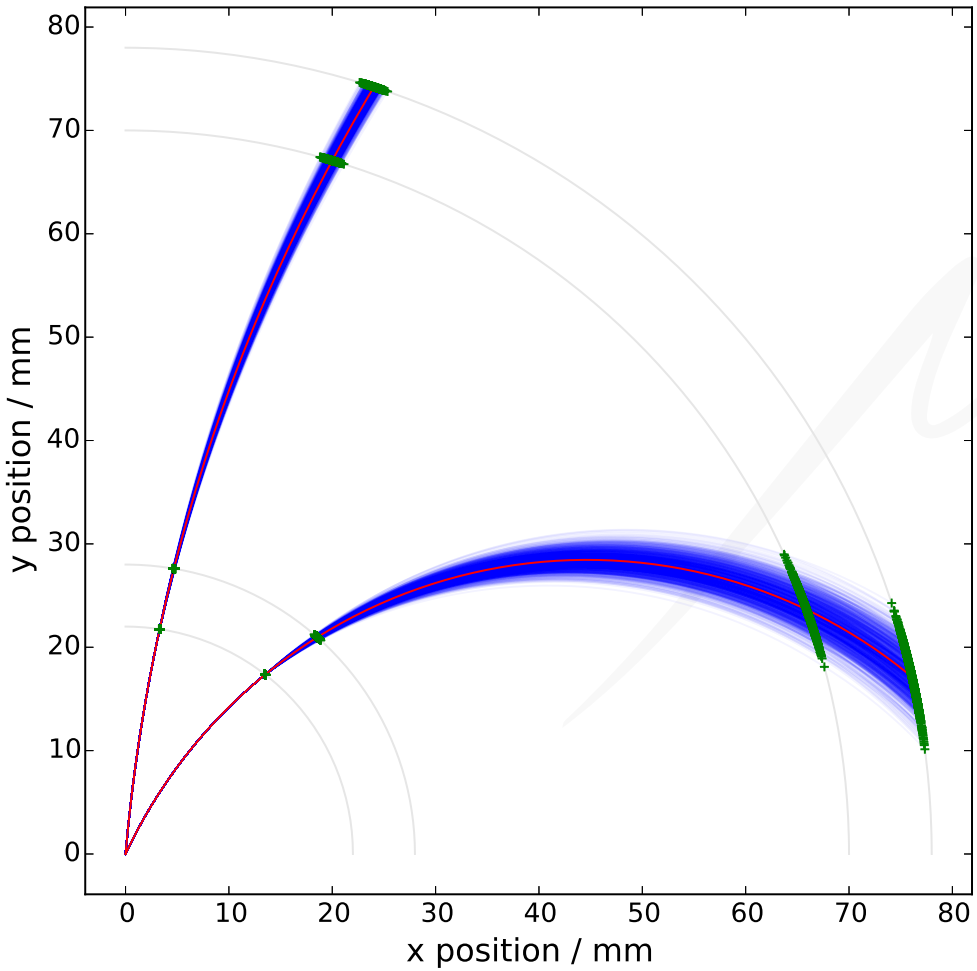
Track Parameters





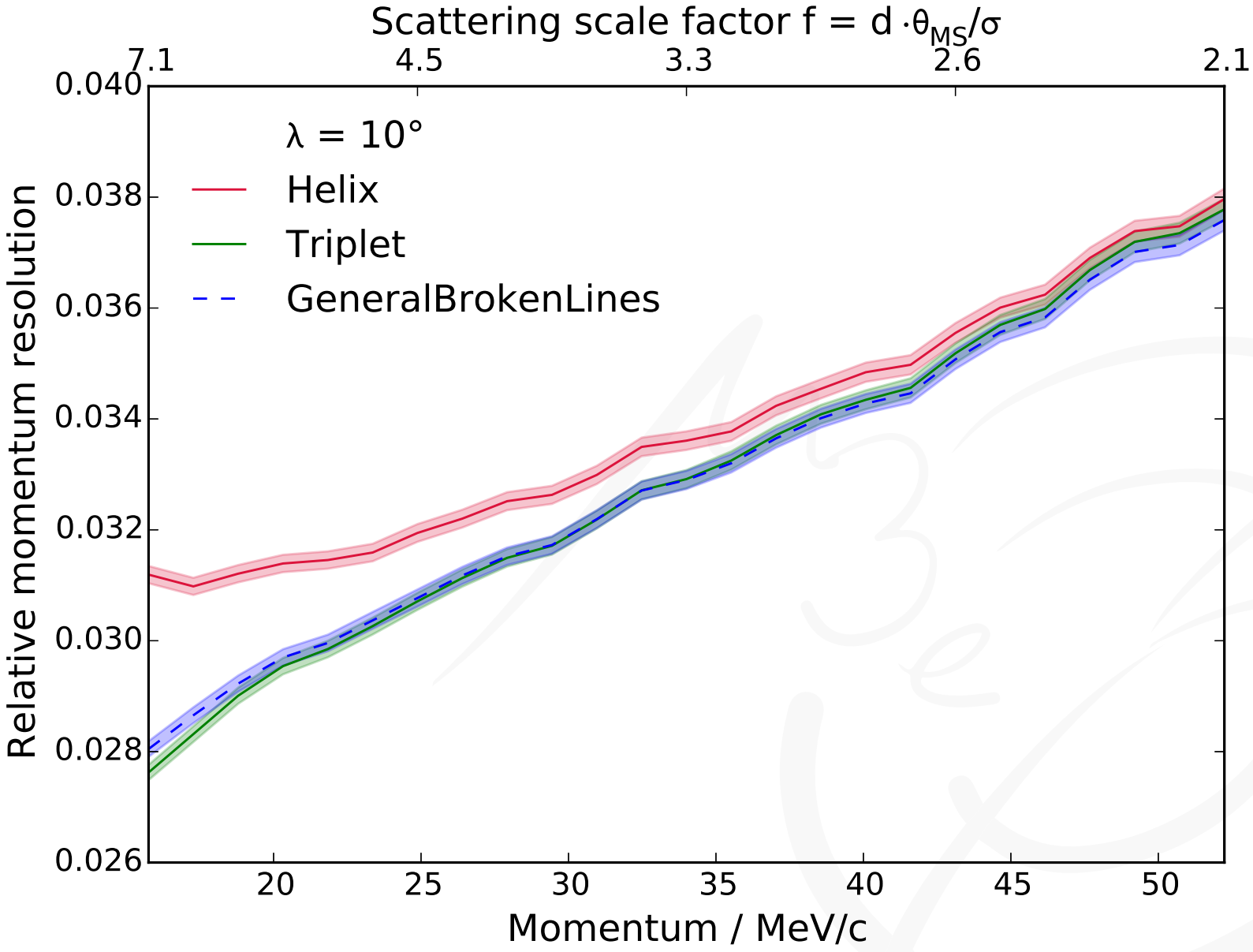
All parameters defined at inner-most layer

Mu3e Geometry

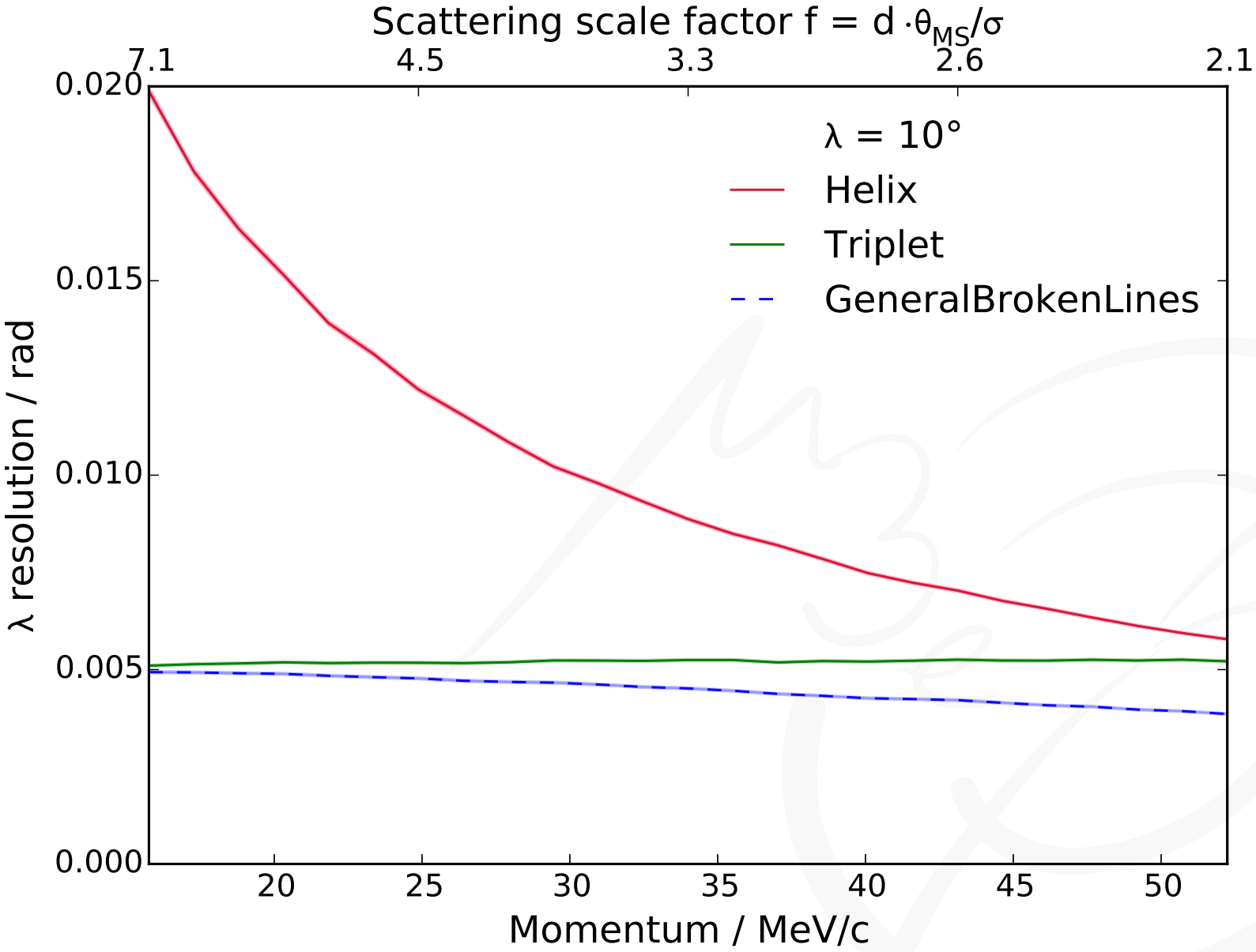


- 4 layers
- B = 1 T
- $x/X_0 = 1\,‰$
- $\sigma = 23\,\mu m$
- p = 15–53 MeV

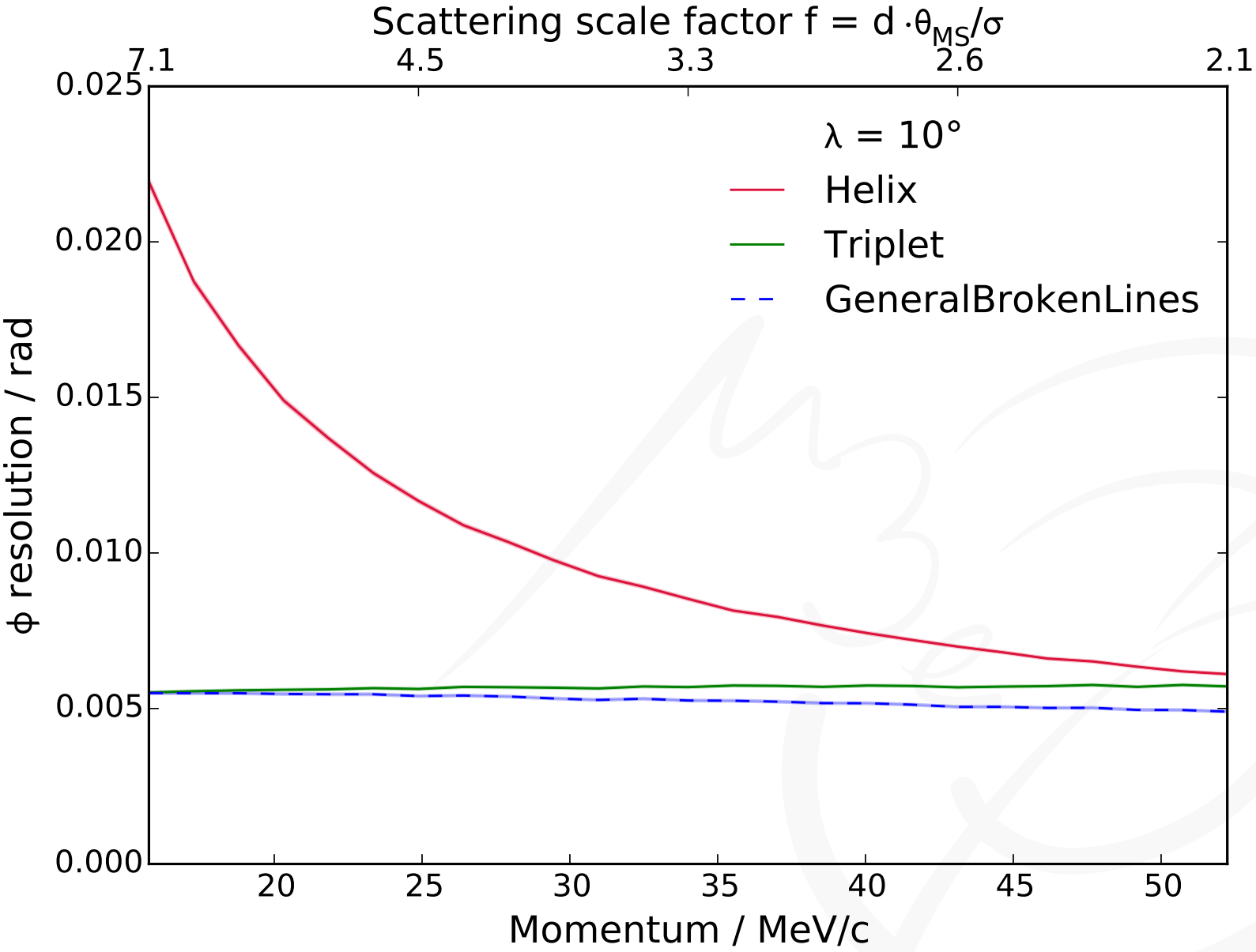
Momentum Resolution



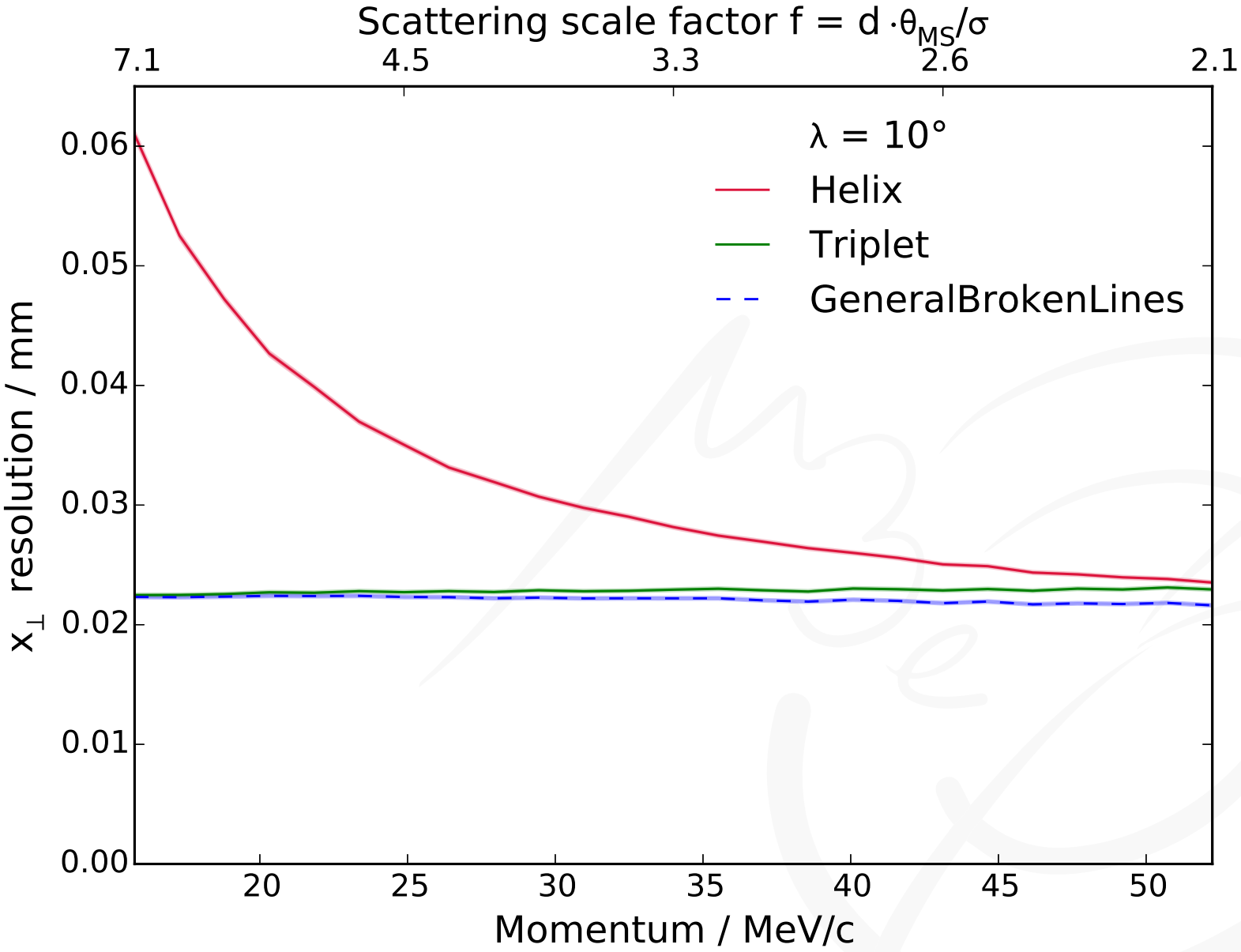
Dip Angle λ Resolution



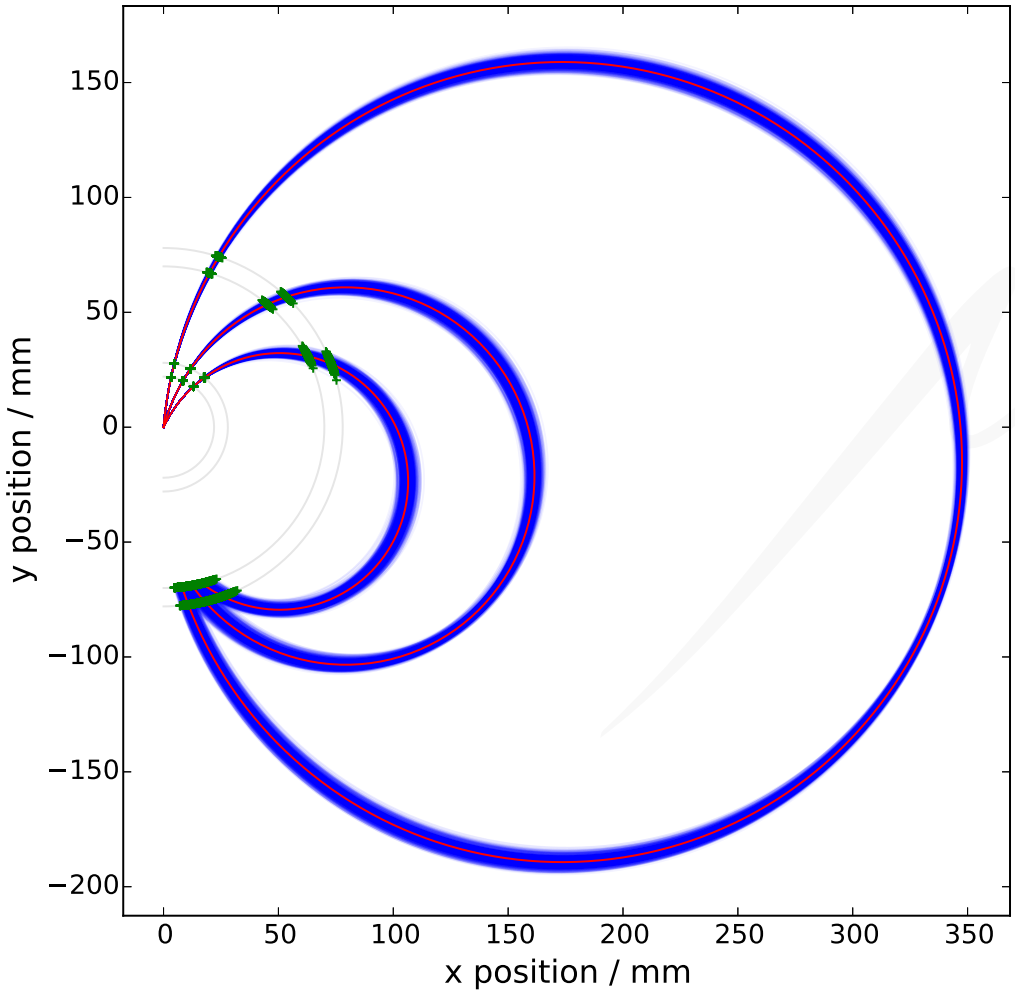
Azimuthal Angle ϕ Resolution



Local Offset $x_\perp$ Resolution

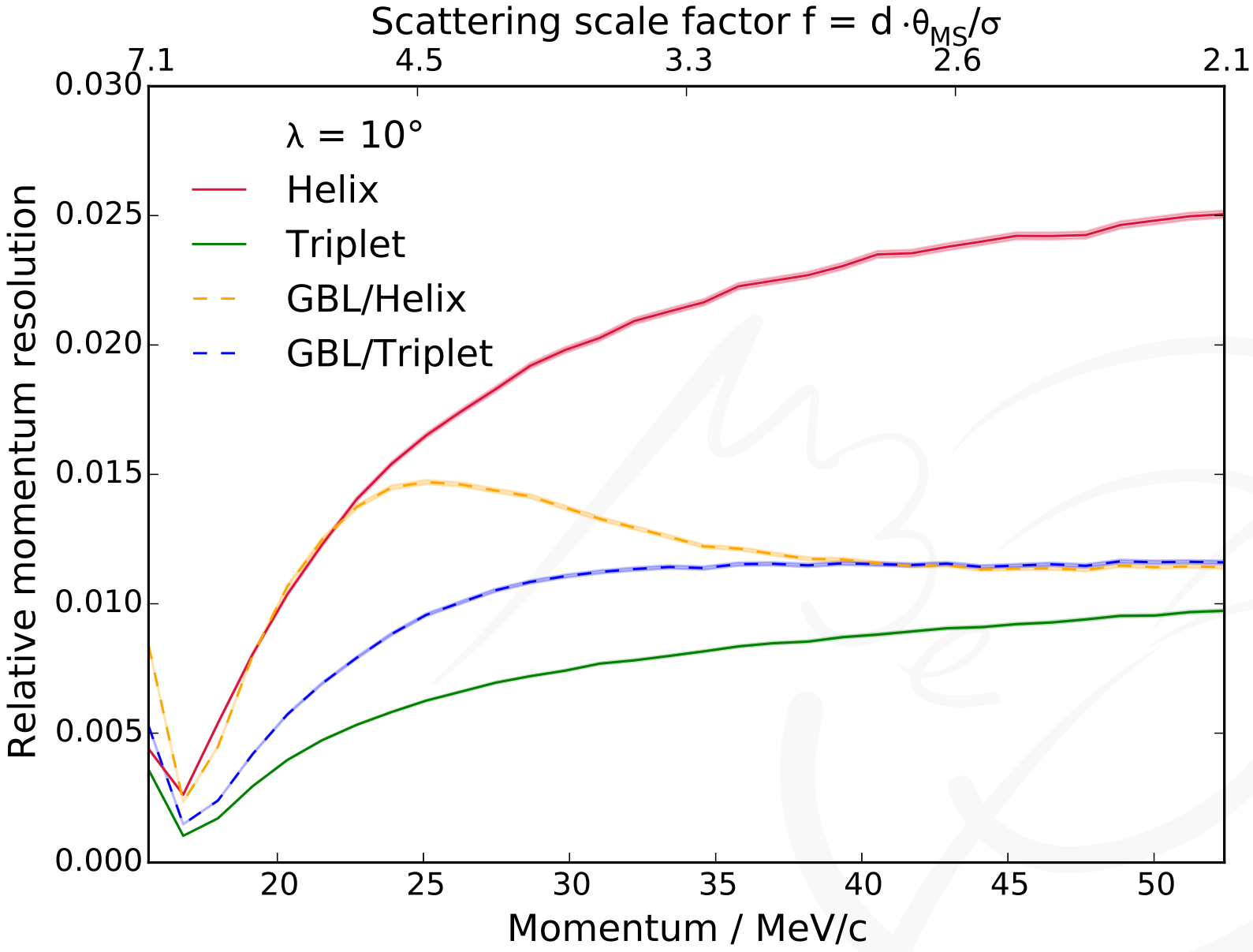


Mu3e Geometry with Recurlers

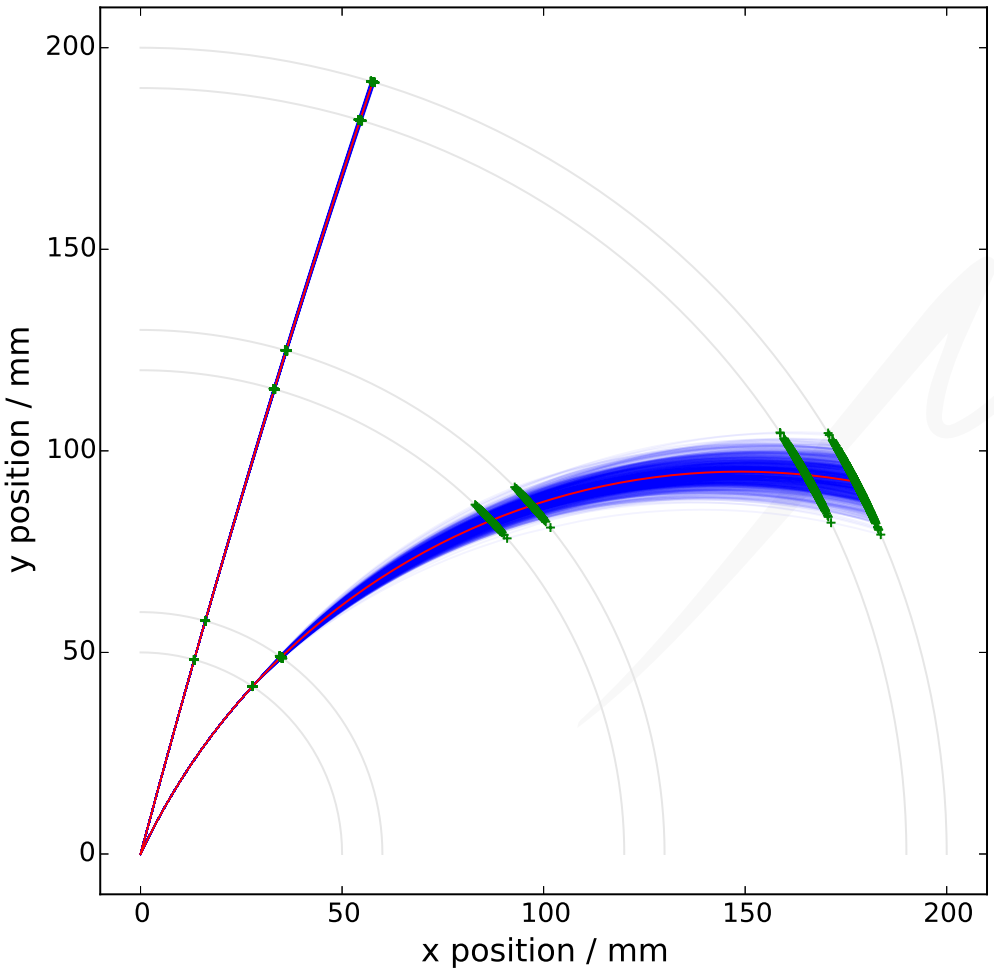


- 4 layers, but > 4 hits
- $B = 1\,T$
- $x/X_0 = 1\,‰$
- $\sigma = 23\,\mu m$
- $p = 15$–$53\,MeV$

Momentum Resolution

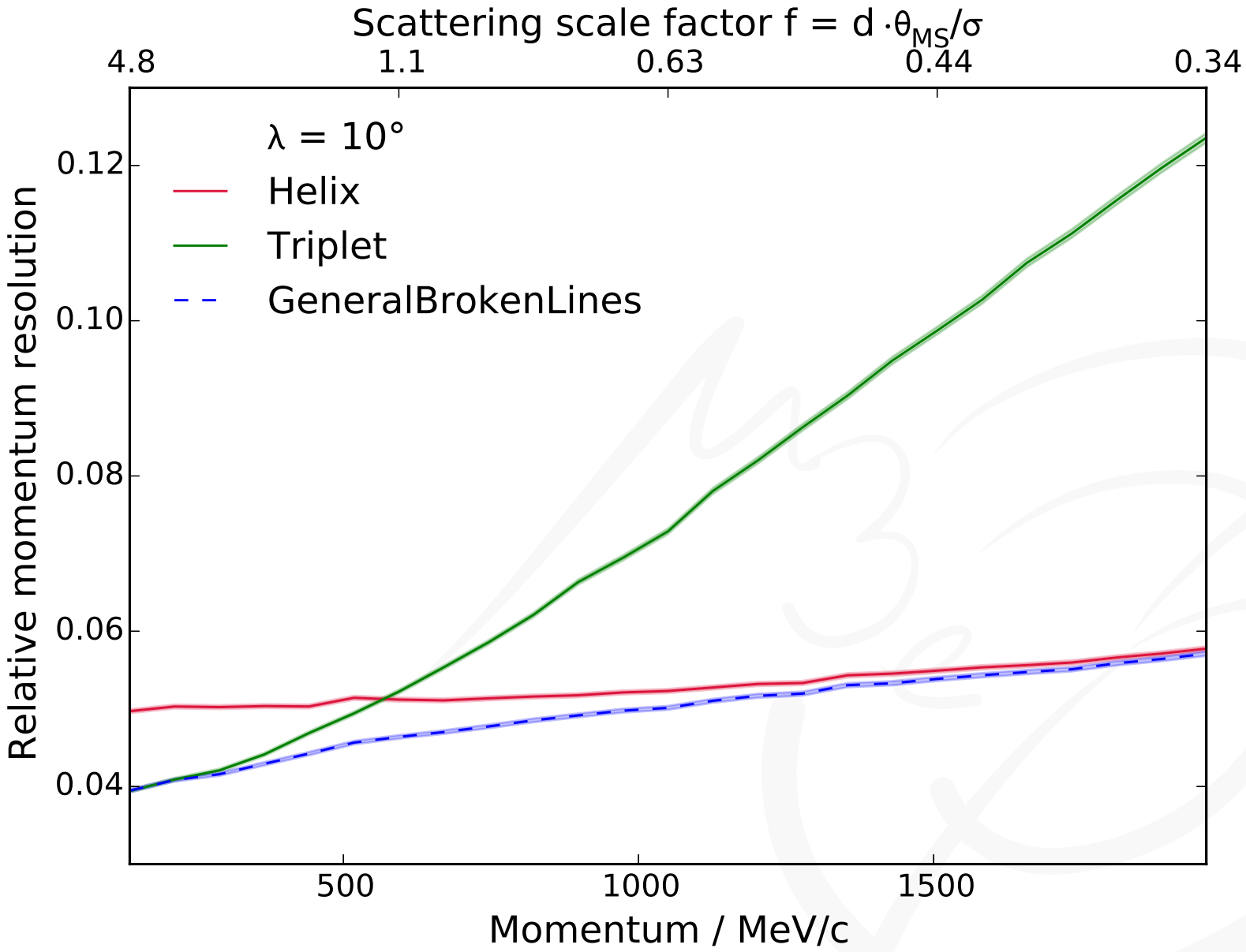


LHC-like Geometry

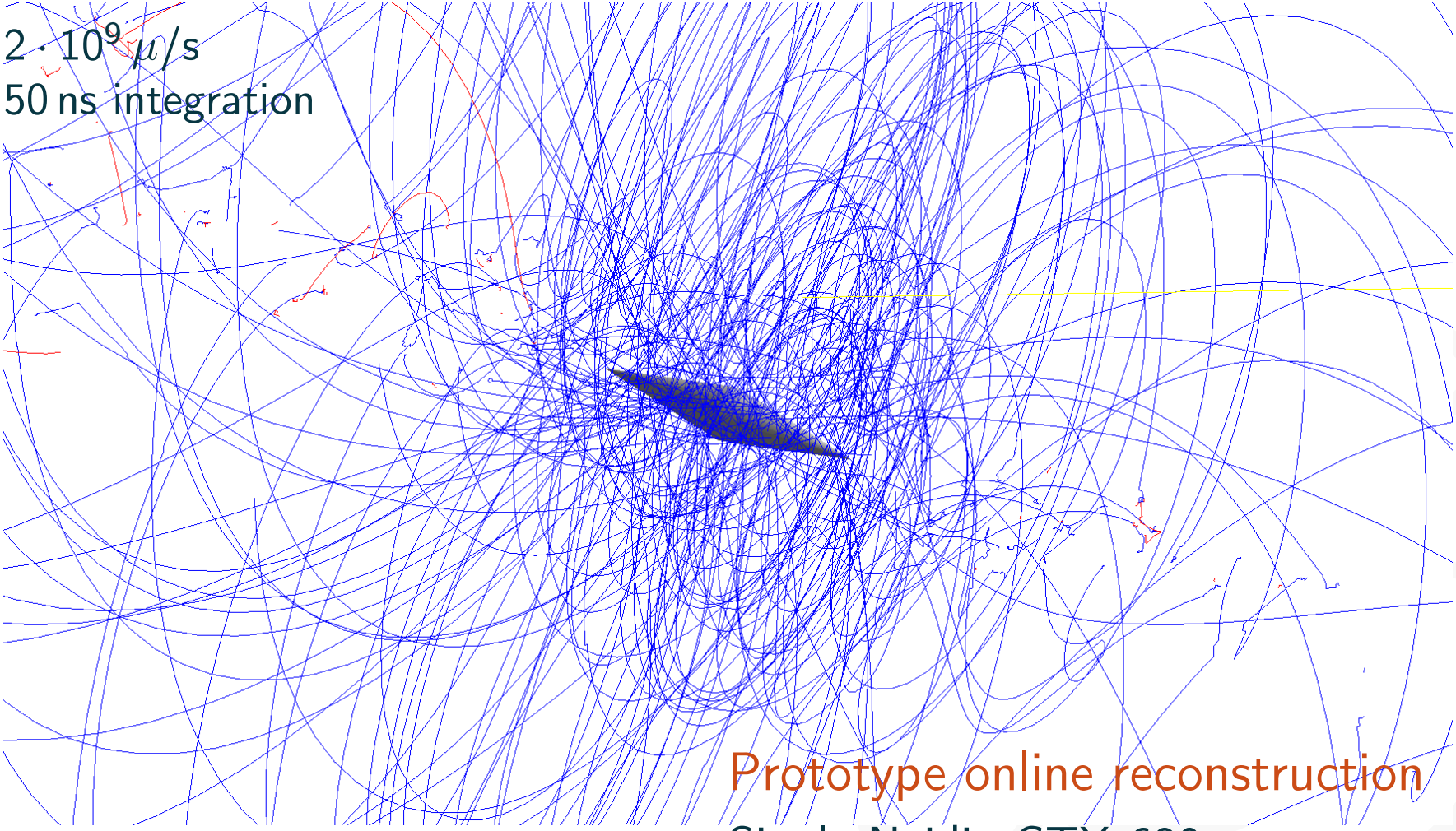


- 6 layers
- $B = 2\,T$
- $x/X_0 = 2\,\%$
- $\sigma = 25\,\mu m$
- $p = 100$–$2000\,MeV$

Momentum Resolution



Speed



Prototype online reconstruction

Single Nvidia GTX 680

$> 10^9$ Triplets/s

Summary and Outlook

Mu3e triplet fit

- 3D fit w/ scattering
- Fast, non-iterative
- Works for us

Applications

- Low momentum, dominating scattering
- Fast online reconstruction
- Reference for refit

Next?

- Full paper coming soon

http://www.psi.ch/mu3e

Backup

The Mu3e Collaboration

University Geneva

Heidelberg University

Karlsruhe Institute of Technolo

Mainz University

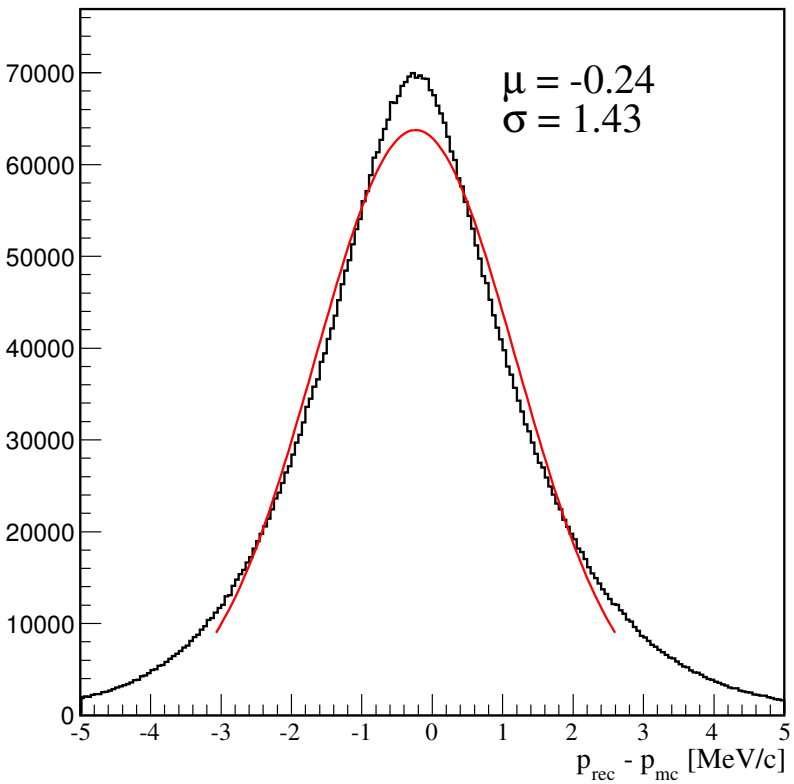
Paul Scherrer Institute

ETH Zürich

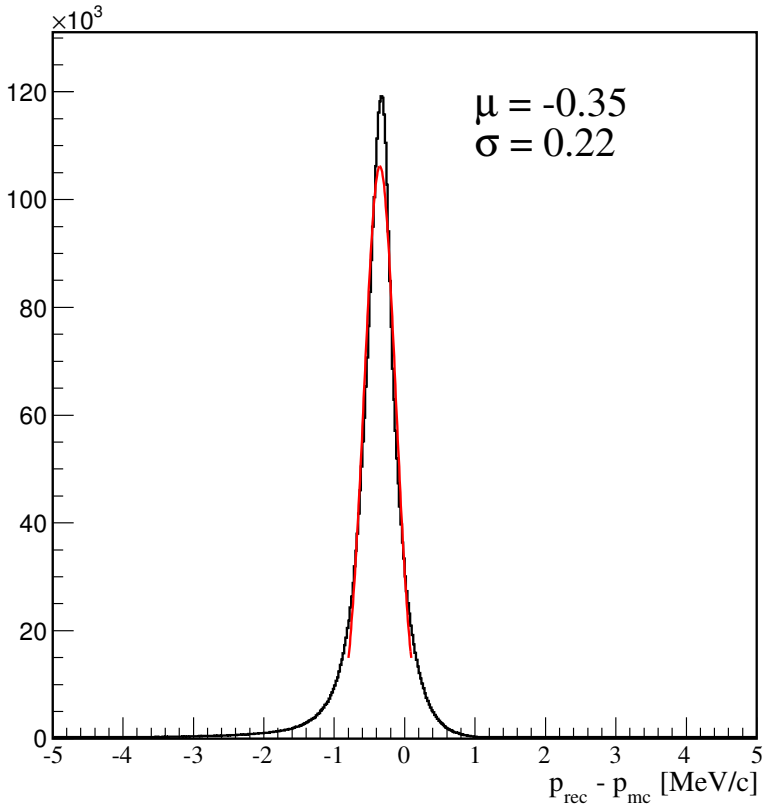
University Zürich

Performance Full Mu3e Simulation

4 Hits



6 Hits (Recurler)



Geant4 simulation w/ complete detector

No energy loss correction