Track Reconstruction for Mu3e based on a Multiple Scattering Fit

14 May 2014, Workshop on Intelligent Trackers
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on behalf of the Mu3e collaboration

Outline

- The Mu3e experiment
- Multiple scattering fit
- Tracking performance
- Reconstruction on GPU

Mu3e Experiment

- Search for $\mu^+ \rightarrow e^+e^+e^-$ decay at PSI

- Current experimental status:
  - SINDRUM (PSI, 1988)
  - $Br(\mu^+ \rightarrow e^+e^+e^-) < 10^{-12}$ at 90% c.l.

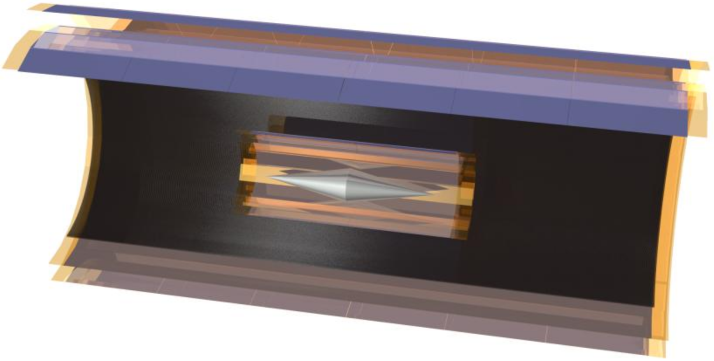
- Sensitivity goal:
  - phase I @ 10^8 μ^+/s: $Br < 10^{-15}$
  - phase II @ 10^9 μ^+/s: $Br < 10^{-16}$

- Requirements:
  - Beam: $O(10^9)$ μ^+/s
  - Good momentum and timing resolution
  - Good vertex resolution
  - Fast readout

Mu3e Collaboration:

- DPNC Geneva University
- Paul Scherrer Institute (PSI)
- Zurich University, ETH
- Heidelberg Physics Inst & KIP
- Mannheim ZITI

Experiment approved in 2013.



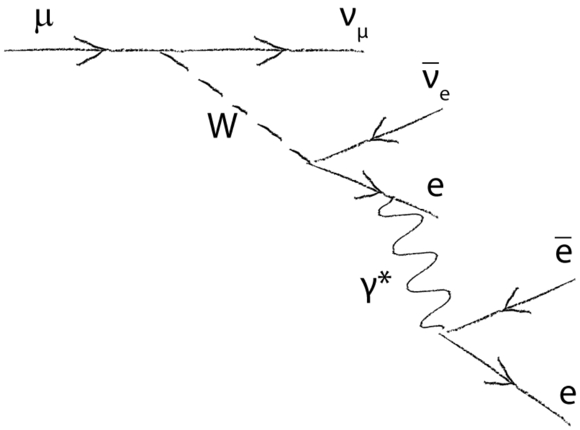
Mu3e Experiment

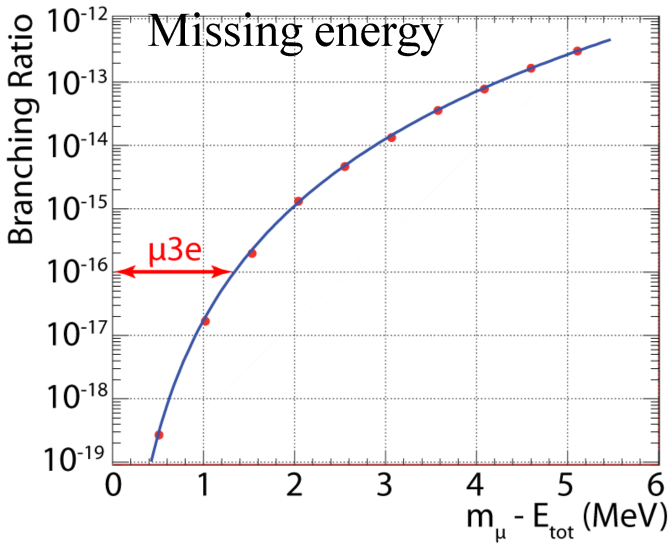
$\mu^+ \to e^+e^+e^-$:
- Muons stopped on target and decay at rest
- Maximum $e^\pm$ energy = 53 MeV
- Missing Energy = 0

Main background:
- $\mu \to e^+e^+e\nu\nu$
- photon conversion
- mis-reconstruction
- $\mu \to e\nu\nu$ + combinations

For $O(10^{-16})$ sensitivity:
- Momentum resolution: < 0.5 MeV
- Vertex resolution: 200 μm
- Low material budget
- High acceptance & efficiency

$\mu^+ \to e^+e^+e^-\nu\nu$



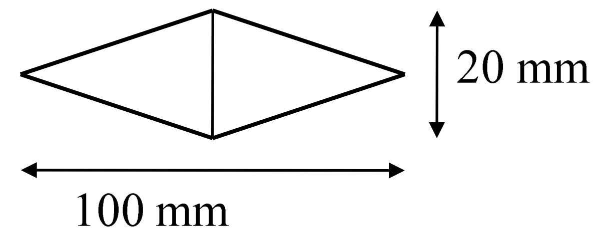


Phys.Rev.D79(2009)073004
R.M.Djilkibaev, R.V.Konoplich

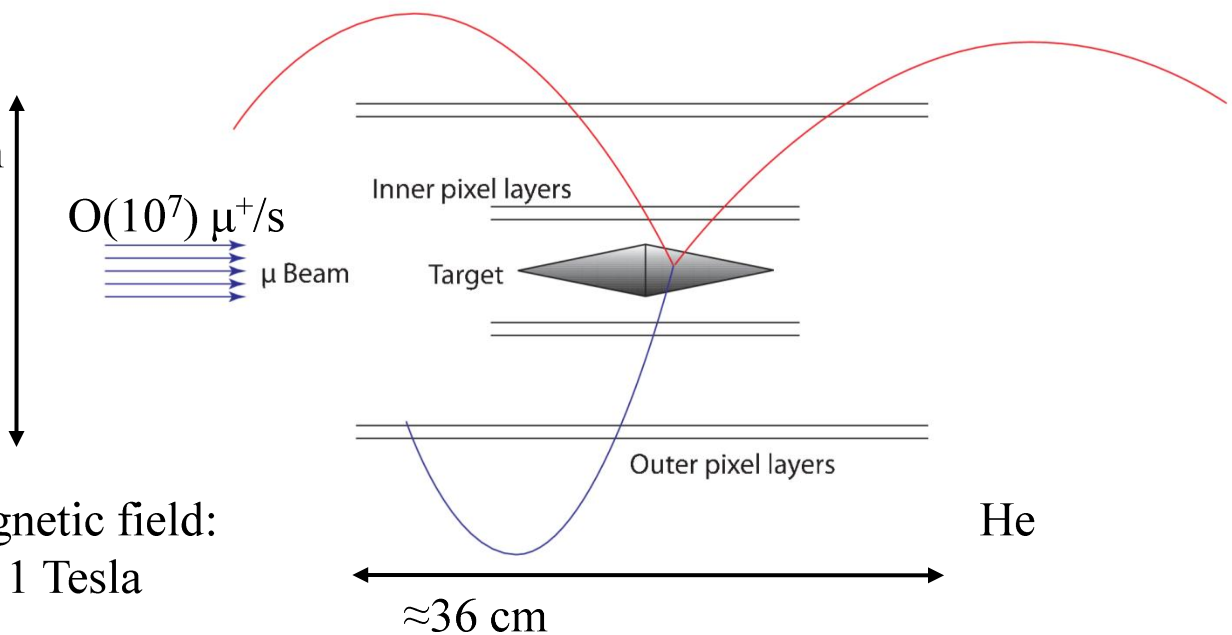
Detector design: phase Ia

Minimum configuration
- Target
- Si-pixel detectors (inner & outer layers).
  - pixel size: 80x80 μm^2
  - Efficiency: > 99 %
- Sensitivity: $O(10^{-14})$

Hollow double cone target.



≈16 cm



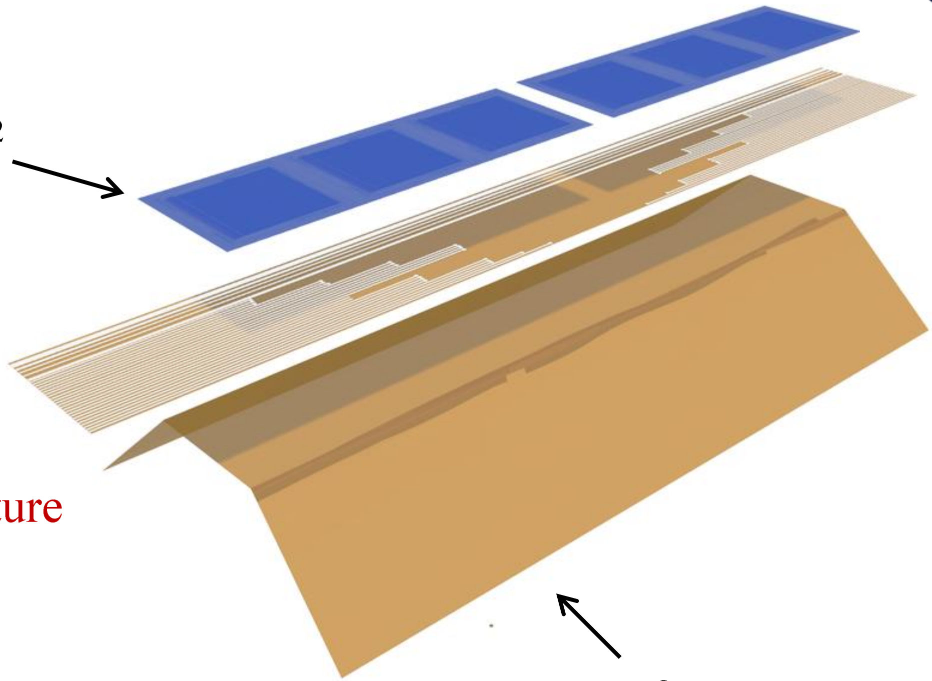
Magnetic field:
B = 1 Tesla

Si-pixel layer detector

HV-MAPS:
- Thinned to 50 μm
- Sensor size: 1x2 or 2x2 cm^2

Kapton flex print:
- 25 μm kapton
- 12.5 μm Alu traces

- Self supporting, ultra-light structure
- Material: $O(10^{-3} X_0)$

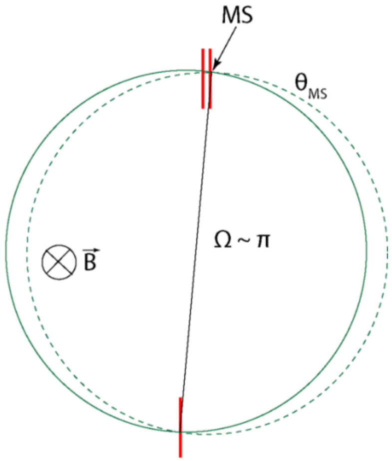


Kapton frame:
- 25 μm foil
- Self supporting

Prototype of inner two layers

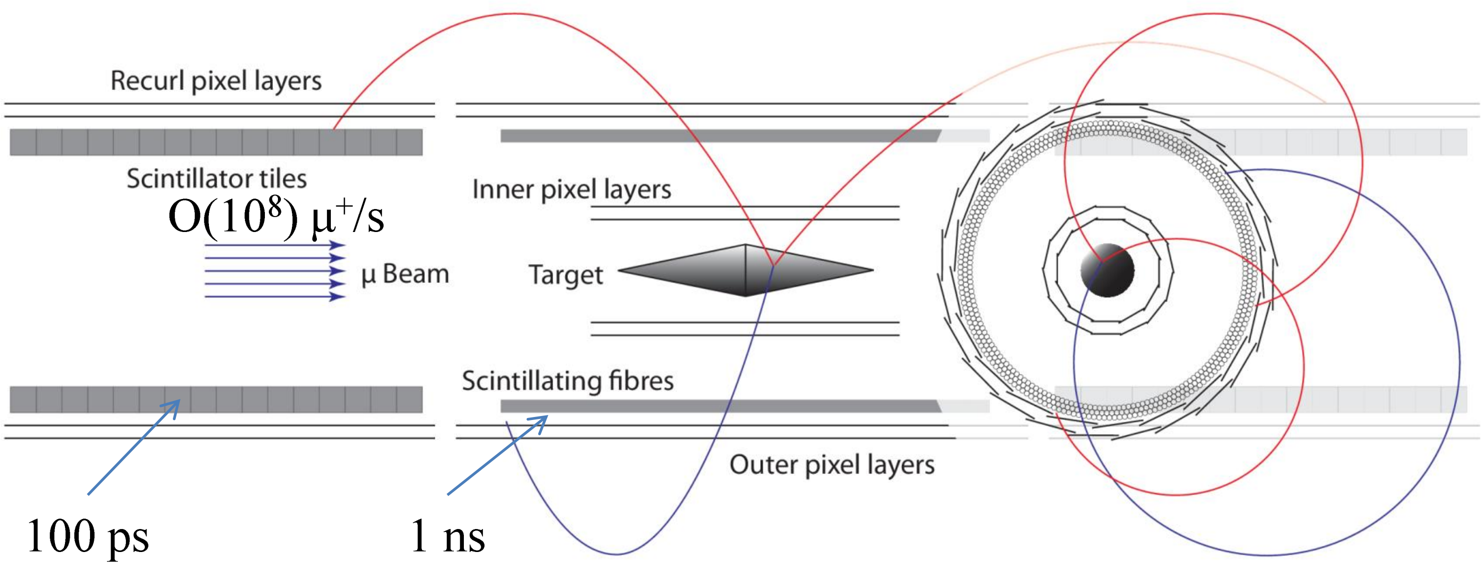
Detector design: phase Ib

- Recurl stations (double layers)
  - Increase acceptance
  - Much better (x5-x10) momentum resolution (~0.2 MeV)
- Fiber & tile detectors
- Sensitivity: $O(10^{-15})$



Scintillating fiber tracker:
- Time resolution: 1 ns

Tile detector:
- Time resolution: 100 ps

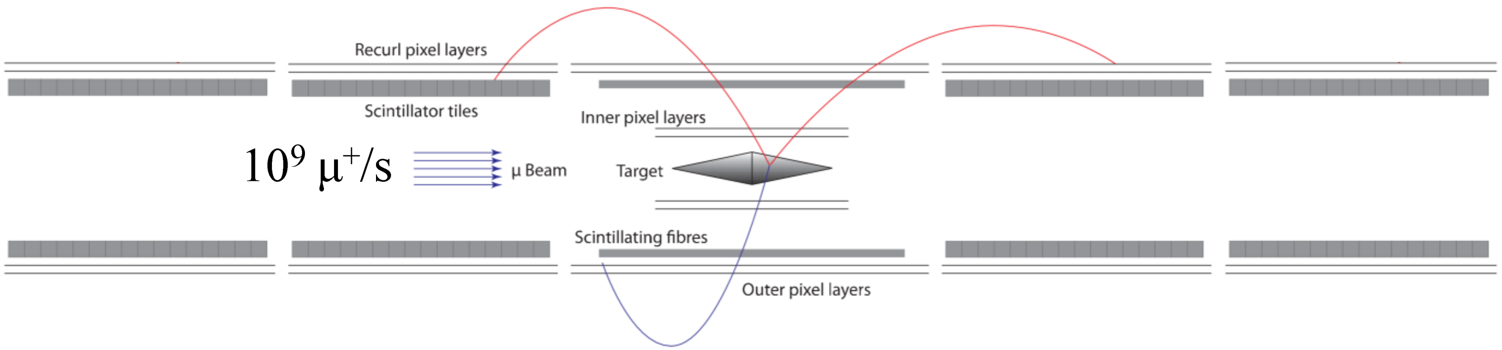


Detector design: phase II

- Additional recurl stations on both sides
- High track acceptance: ~90%
- New beam line: 10^9 μ^+/s
- Sensitivity: $O(10^{-16})$

Tracker:

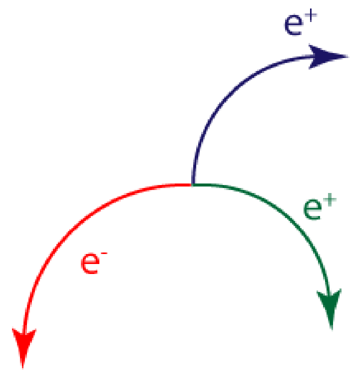
- 300M pixels
- Readout at 20 MHz (50 ns frame)
- Total data rate: O(1) Tbit/s



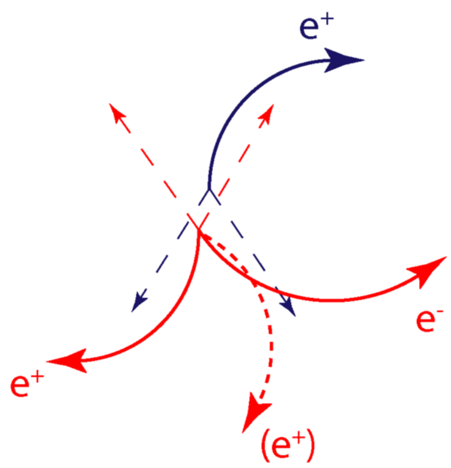
Track reconstruction & Event filtering

Triggerless system:
- Very high data rate: 1 Tbit/s
- Online data reduction required

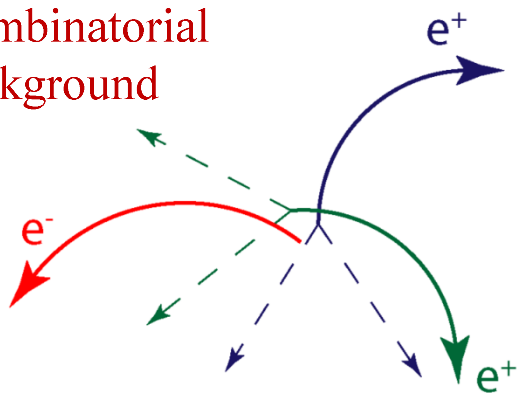
Online reconstruction & filtering:
- Reduce rate by factor 1000
- Perform “full” reconstruction & vertex fit
- Strong requirements on the tracking performance



Mu3e signal:
- 3 tracks
- common vertex
- Missing Energy ≈ 0



Combinatorial background

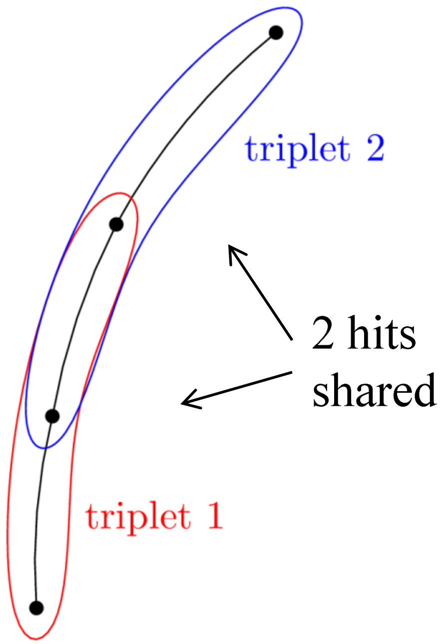


Multiple Scattering fit

- Kalman filter and broken line fits are relatively slow:
  - Both require matrix inversion

- At Mu3e e^+/e^- have low momenta (< 53 MeV)
  - Multiple Scattering (MS) dominates resolution

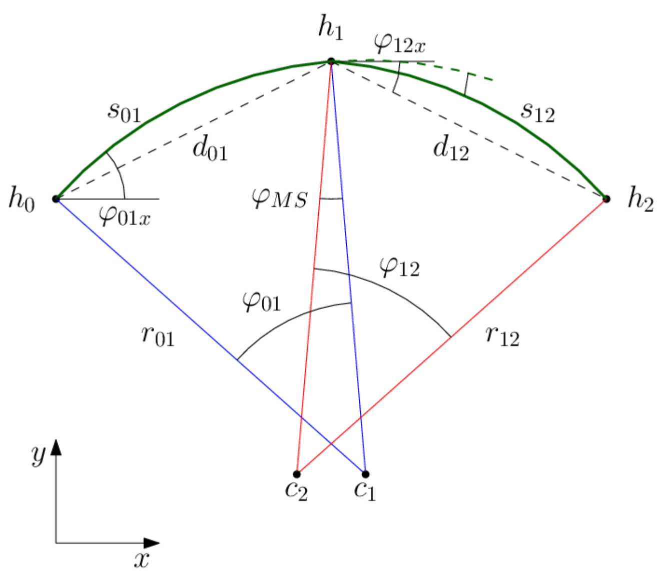
Multiple scattering fit:
- Assume zero measurement uncertainties
- Describe tracks as a sequence of hit triplets:
  - MS takes place in middle hit of each triplet
  - Track parameters are calculated by taking a weighted mean over all triplets

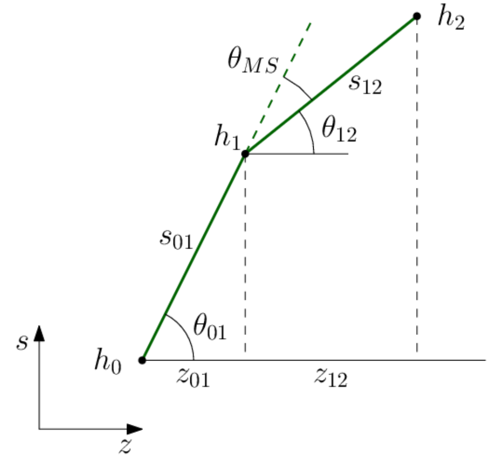


Multiple Scattering fit

- Each triplet is described by 10 parameters
  - three 3D points (fixed)
  - momentum (3D curvature)
  - 2 helical trajectories (h_0h_1 and h_1h_2)
    - Same 3D radius (energy conservation)

- Two strategies to solve triplet equations:
  - numerical
  - linearization around circle solution





2 helixes:

$\varphi_{01,12}(R_{3D})$

$\theta_{01,12}(R_{3D})$

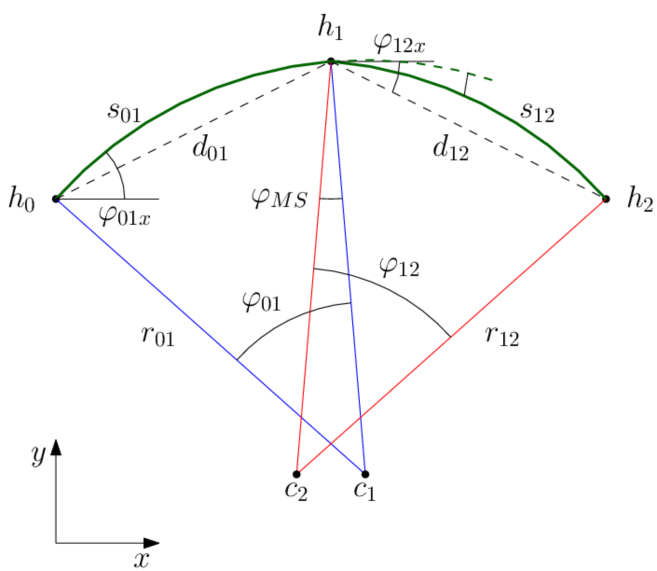
MS angles:

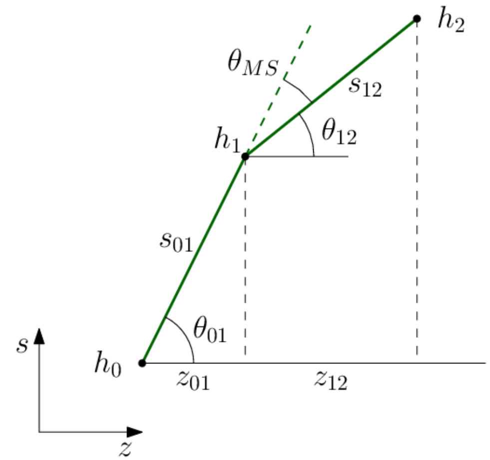
$\varphi_{MS}(R_{3D})$

$\theta_{MS}(R_{3D})$

Multiple Scattering fit

- Minimize $\chi^2 = \dfrac{\varphi^2_{MS}(R_{3D})}{\sigma^2_{MS}} + \dfrac{\theta^2_{MS}(R_{3D})}{\sigma^2_{MS}}$
- MS angles are small:
  - use linearization around circle solution
  - very simple equations
  - $R_{3D} = -\dfrac{\dfrac{d\theta_{MS}}{dR_{3D}}\theta_{MS,0} + \dfrac{d\varphi_{MS}}{dR_{3D}}\varphi_{MS,0}}{\left(\dfrac{d\theta_{MS}}{dR_{3D}}\right)^2 + \left(\dfrac{d\varphi_{MS}}{dR_{3D}}\right)^2}$
  - Note: all parameters (including derivatives) are easily calculated from position of 3 hits.





2 helixes:
$\varphi_{01,12}(R_{3D})$
$\theta_{01,12}(R_{3D})$

MS angles:
$\varphi_{MS}(R_{3D})$
$\theta_{MS}(R_{3D})$

Track reconstruction

- Fully reconstructed tracks:
  - triplets & 4-hit tracks – seeds.
  - recurls: 6- and 8-hit tracks

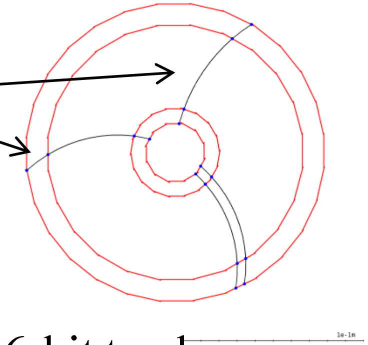
- Finding first triplet (first 3 layers) is most expensive operation:
  - No beam line constraint due to extended target
  - $O(n^3)$, n – number of hits in layer

- Triplets & 4-hit tracks used online

- Long tracks are used for offline analysis:
  - Strong constraint on 3D radius
  - $\sigma_p \approx 0.2$ MeV

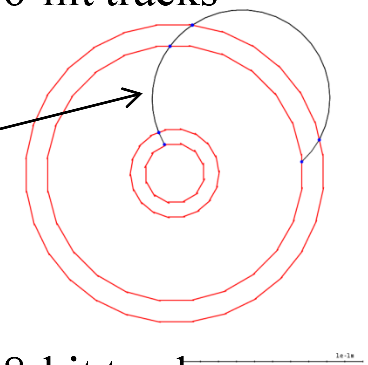
4-hit tracks

seeds



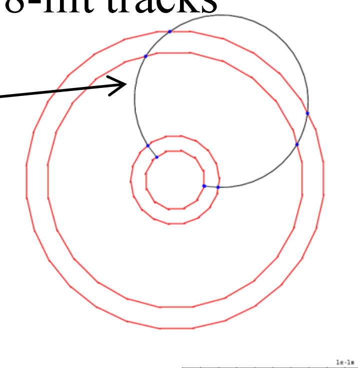
6-hit tracks

4-hit tracks extended to 6-hit tracks



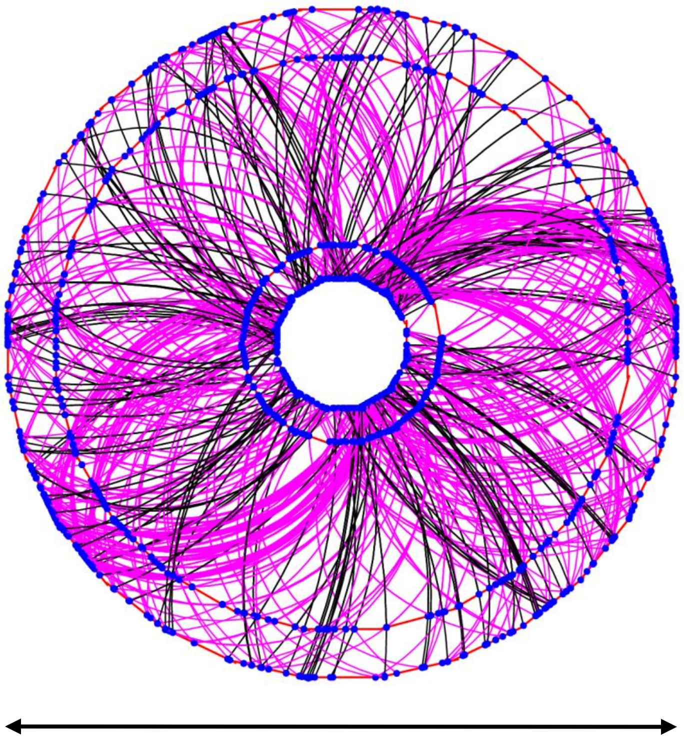
8-hit tracks

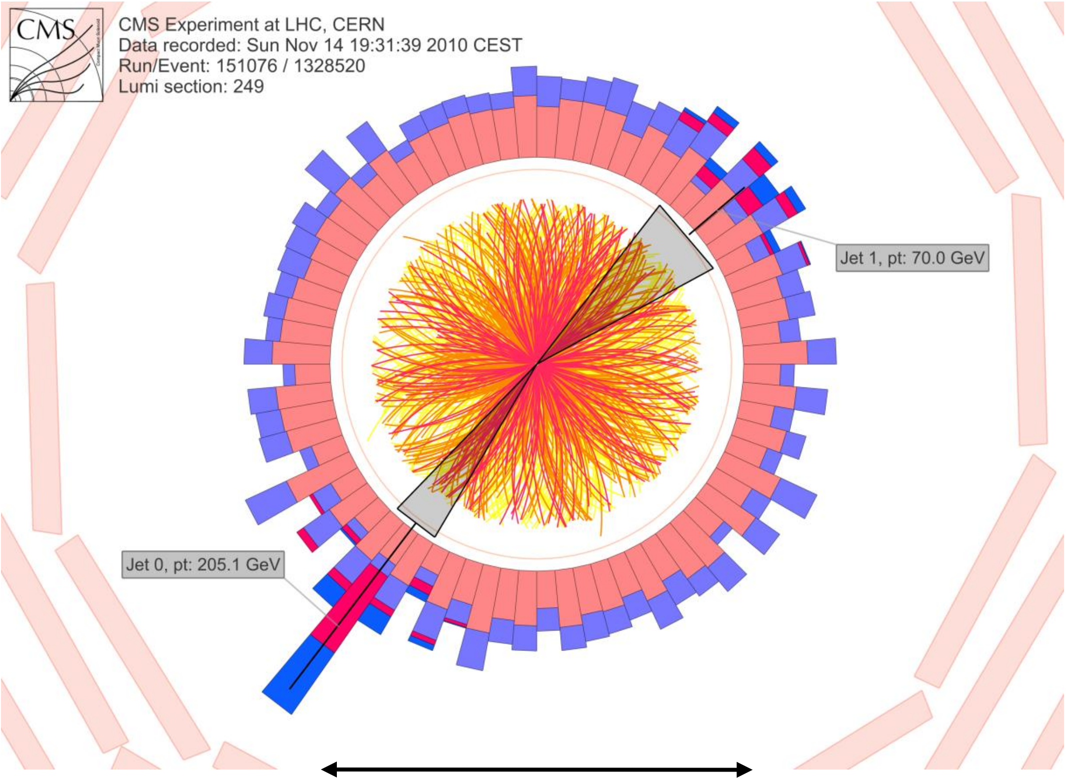
8-hit tracks from pair of 4-hit tracks



Reconstruction performance

Mu3e: reconstructed 4-hit tracks





≈16 cm
Readout in frames of 50 ns
E ~ 10-50 MeV

≈2.5 m
Collision every 25 ns
E ~ 200 GeV

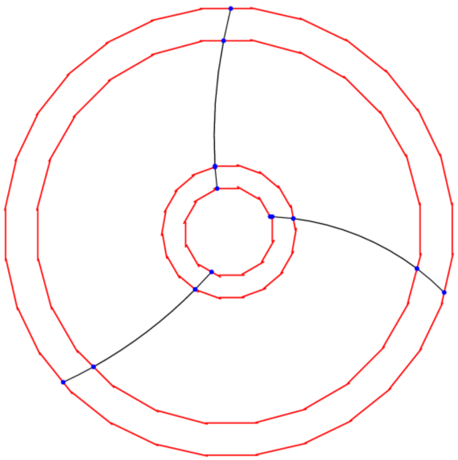
Performance

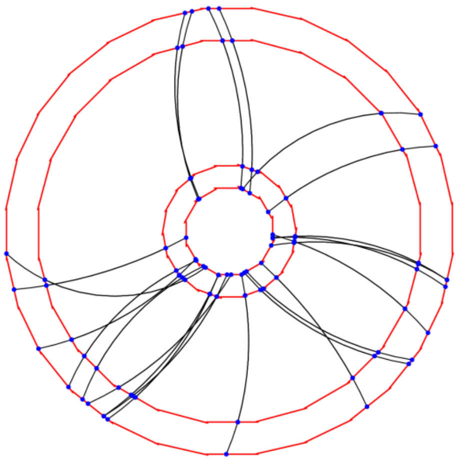
Monte Carlo study:
- Final detector geometry
- Geant4 full detector simulation
- Track reconstruction with Multiple Scattering fit
- Different beam intensities

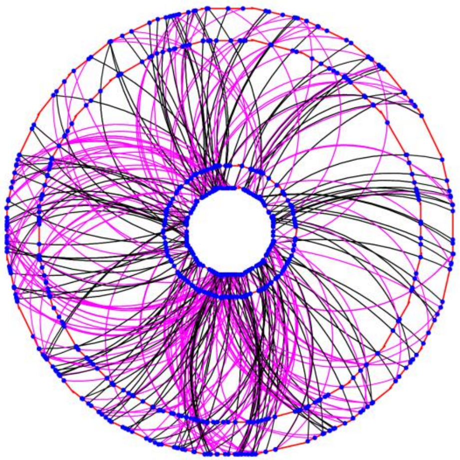
Ia: beam 10^7 μ^+/s:
- 3 track candidates/frame
- fake candidates ~ 5%

Ib: beam 10^8 μ^+/s:
- 30 candidates/frame
- fake candidates ~ 5%

II: Beam $2 \cdot 10^9$ μ^+/s:
- 300 track candidates/frame
- ~50% fake candidates





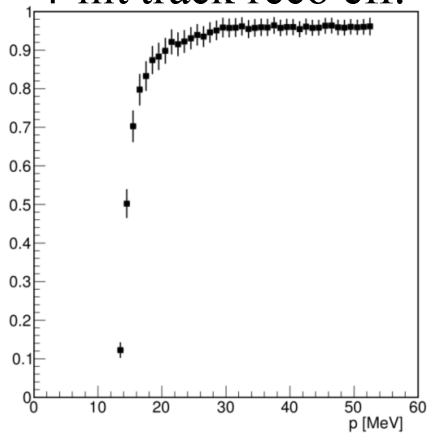


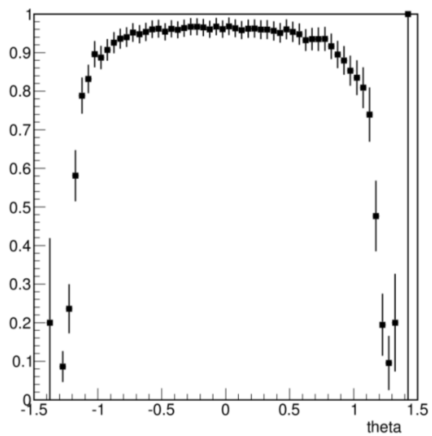
Performance

Good reconstruction efficiency:
- 90-95% for 4-hit and 6-hit tracks
- Defined by χ^2 cuts

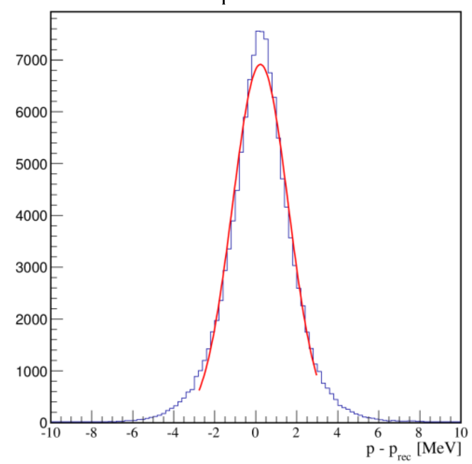
Momentum resolution:
- 1.5 MeV for triplets (layers 1,2,3)
- 0.2 MeV for 6-hit tracks (recurlers)

4-hit track reco eff.

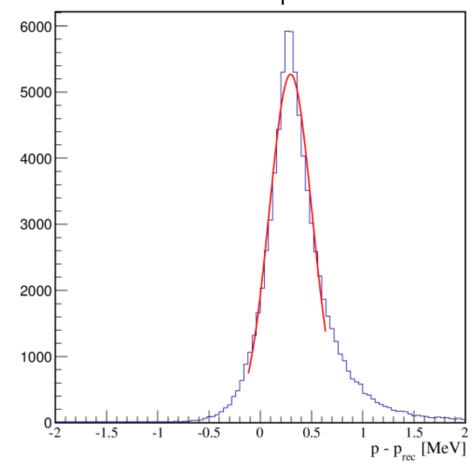




Triplets: $\sigma_p \approx 1.5$ MeV

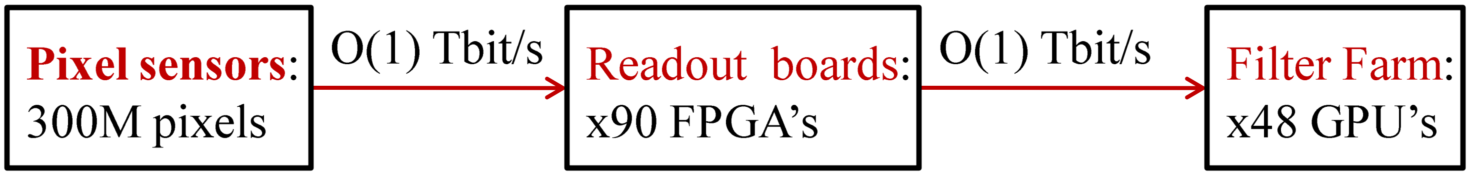


6-hit tracks: $\sigma_p \approx 0.2$ MeV



Note: no correction for energy loss

GPU event filter farm



Readout (FPGA):

- Directly copy data (DMA) to GPU
- High parallelism but limited memory
- Sort/group hits (time, geometry)
- Simple pre-selections

Filter Farm (GPU):

- Find 3 triplets/4-hit tracks & Fit vertex
    - Process all combinations of hits from first 3 layers
- For each frame give decision (write/drop)
- Main limitations:
    - Slow memory access
    - Total bandwidth

GPU reconstruction/performance

- First implementation of GPU reconstruction
- Result: ~10G triplet combinations per second

	Low beam intensity (phase Ib, 10^8 μ^+/s)	High intensity (phase II, $2 \cdot 10^9$ μ^+/s)
Number of hits per layer	50-100	200-500
Number of combinations per 50 ns frame	100K-1M	10M-100M
Single GPU reconstruction performance [frames/s]	50K	500
Filter Farm (48 GPU units) [frames/s]	2.5M	25K

- Current limitation: internal memory throughput
- Room for improvement:
  - Memory access pattern
  - FPGA pre-processing, associative memory
  - Expect another factor 10 improvement
  - But still factor 100 missing for phase II (work in progress)

Summary

Mu3e experiment:
- Search for LFV with 10^{16} muons (Br fraction at 10^{-16})
- HV-MAPS based silicon tracker
    - ~300M pixels
    - High precision & efficiency
    - Large data rates

Triplet fit for track fitting in MS dominated environment
- Fast: O(1M) fits/s on CPU
- Algorithm easily portable to GPU
- Simple GPU implementation x100 faster than CPU

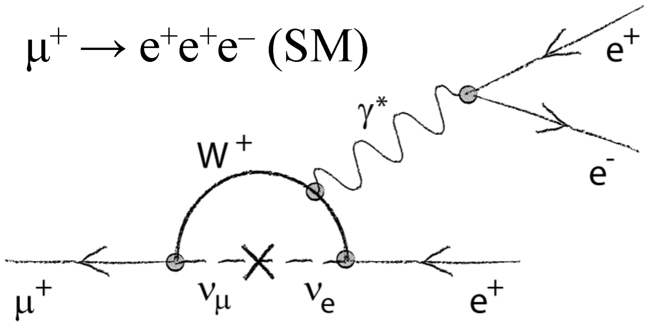
Work ongoing:
- Optimization of detector design
- Detector R&D (pixels, fibers, tiles)
- Optimization of GPU reconstruction
- Implementation of vertex fit on GPU

Backup

Lepton Flavor Violation

- There is no LFV in SM:
  - Neutrino mixing
  - Br ratio suppressed by 10^{50}
- Can be enhanced in SUSY, GUT, EDIM, extended Higgs models, etc.
- Current experimental status:
  - SINDRUM (PSI, 1988):
  - $Br(\mu^+ \rightarrow e^+e^+e^-) < 10^{-12}$
- Search for $\mu\rightarrow 3e$:
  - Test of current models where LFV is expected
  - Complementary to other searched ($\mu\rightarrow e\gamma$, etc.)
- To set limit at the level of $O(10^{-15})$:
  - Need at least 10^{16} muon decays

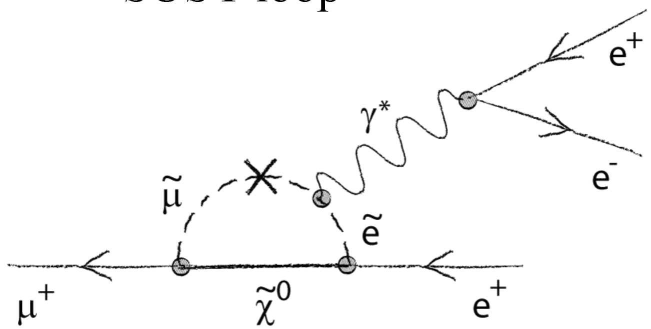
$\mu^+ \rightarrow e^+e^+e^-$ (SM)



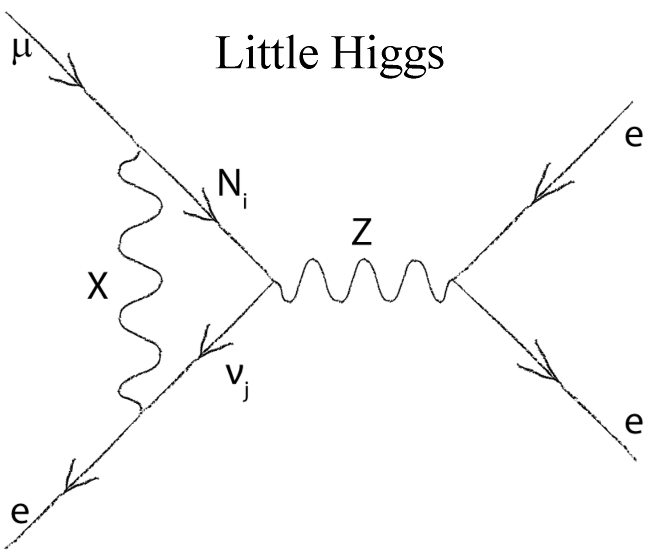
Lepton Flavor Violation

Other models:
- SUSY and other BSM models
- GUT models (leptoquarks)
- Extended Higgs models
- Extra dimensions
- New heavy bosons
- Many other models

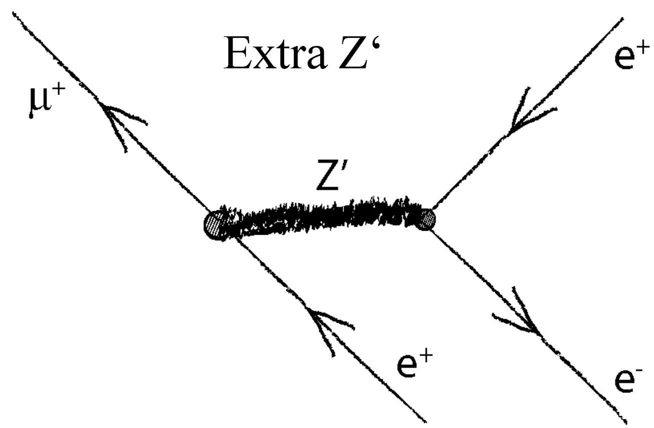
SUSY loop



Little Higgs



Extra Z'



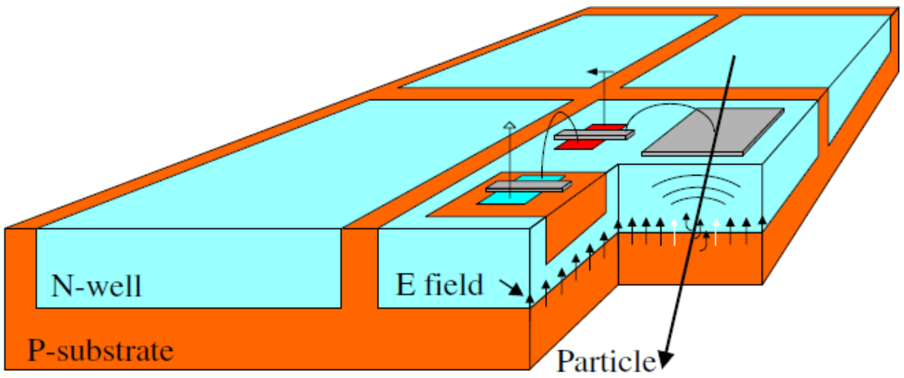
HV-MAPS

High Voltage Monolithic Active Pixel Sensor:

- HV CMOS technology
- N-well in p-substrate

- Reverse bias ≈60V
- Charge collection via drift
- Fast: < 1 ns charge collection
- Thinned down to 50 μm

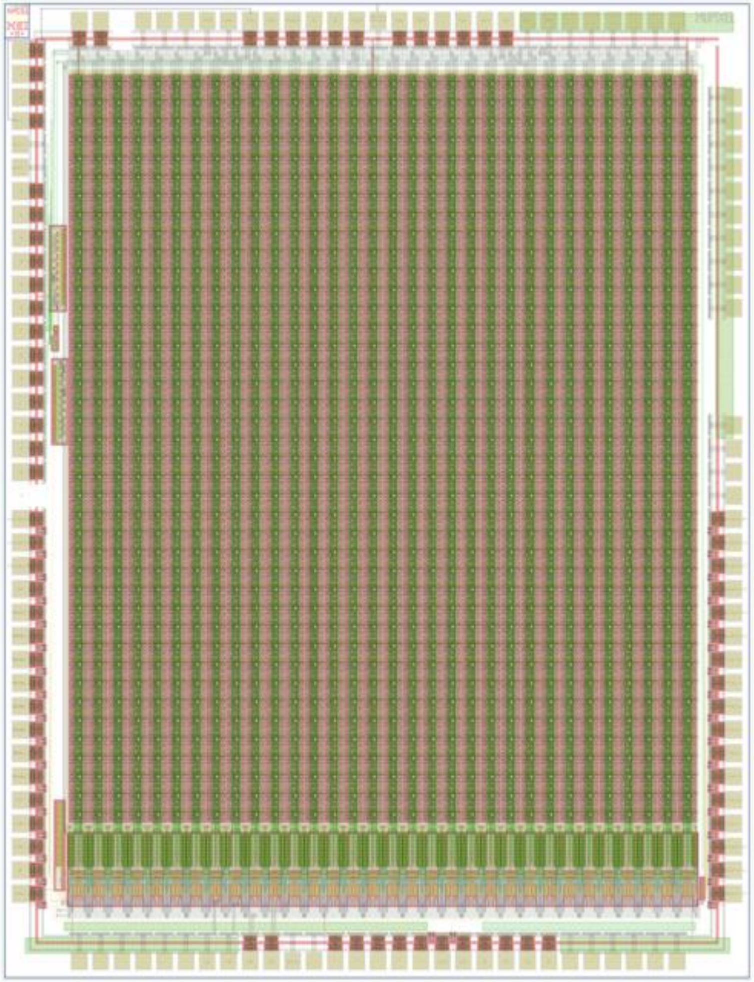
- Integrated readout electronics



MuPix chip prototype

MuPix4:
- 180 nm HV-CMOS
- Matrix:
  - 40x32 pixels
  - pixel size: 98x80 μm^2

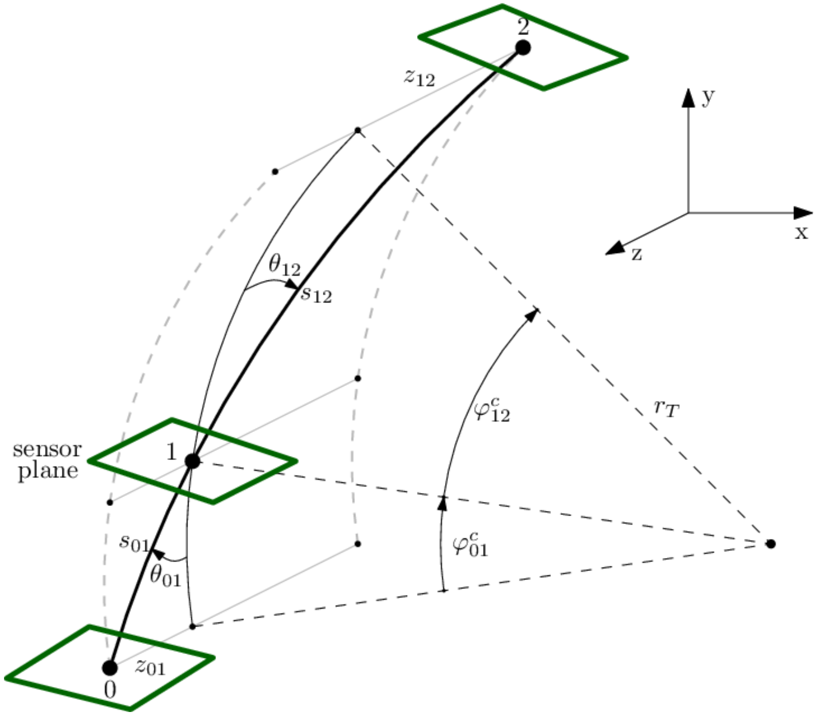
MuPix6:
- Matrix:
  - 40x32 pixels
  - pixel size: 103x80 μm^2



Triplet fit

First step:

- Start with circle solution in XY-plane (hit triplet 012)
  - transverse radius: r_T
  - $r_T = r_{T01} = r_{T12}$
- r_T, z_{01}, z_{12}:
  - path lengths in 3D: s_{01} & s_{12}
  - 3D radii:
    - $r_{01} = r_{T01} / \cos(\theta_{01})$
  - helix angles: θ_{01} & θ_{12}
    - MS angle $\theta_{MS} = \theta_{12} - \theta_{01}$
- Note:
  - MS angle $\varphi_{MS} = 0$
  - No energy conservation
    - $r_{01} \mathrel{!}= r_{12}$



Triplet fit

Second step:

- Solving $r_T \cdot \sin(\varphi_{01}/2) = d_{01}/2$:
  - $d\varphi_{01} = \alpha_{01} \cdot dr_{01}$ & $d\varphi_{12} = \alpha_{01} \cdot dr_{01}$
  - $d\theta_{01} = \beta_{01} \cdot dr_{01}$ & $d\theta_{01} = \beta_{01} \cdot dr_{01}$
  - $2 \cdot \varphi_{MS} = \alpha_{12} \cdot (r - r_{12}) + \alpha_{01} \cdot (r - r_{01})$
- Fit:
  - vary **r** => changes r_{T01}, r_{T12}, etc.
  - minimize $\chi^2 = (\varphi^2_{MS}(r) + \theta^2_{MS}(r)) / \sigma^2_{MS}$