MUSE

H2020-MSCA-RISE-2015 – Grant Agreement N° 690835

Simulation/Software Status.

Barry King (Univ. of Liverpool)

MUSE Mid-Term Meeting
Frascati, 11 May 2017

Outline

g-2

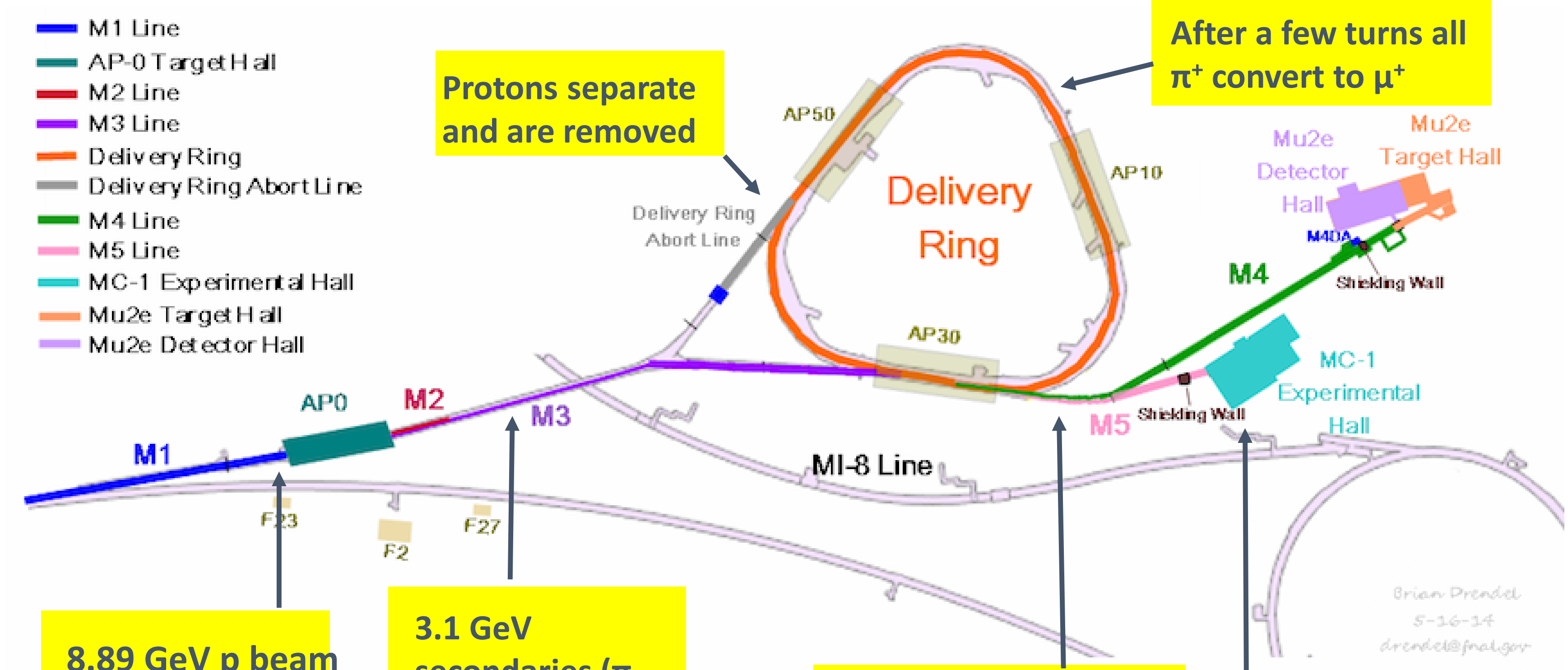
1. Simulation of beam delivery.
2. Simulation of the g-2 ring.
3. Tracker Software.
4. Calorimeter Software.

mu2e

1. Examples of software in use.

Just a flavour of the enormous amount of studies taking place.
Impossible to do justice to the huge amount of work.

Muon Campus Simulation.



Protons separate and are removed

After a few turns all π^+ convert to μ^+

8.89 GeV p beam impacts the target

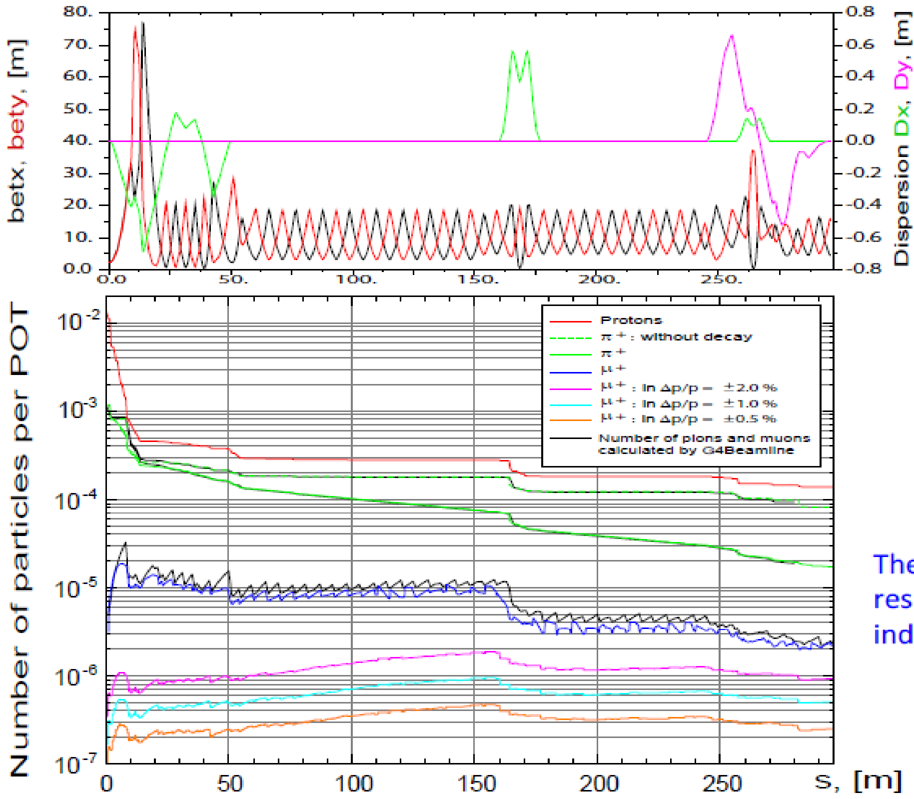
3.1 GeV secondaries (π, μ, p) travel along M2 & M3

μ^+ are extracted from the ring and transferred into the storage ring via M4, M5

μ^+ enter the g-2 storage ring

Simulation of the M2M3 Beamline.

Population of protons, pions and muons along M2M3 beamline



From 10^9 protons on target

There is good agreement between the results from Bmad and from an independent model in G4Beamline.

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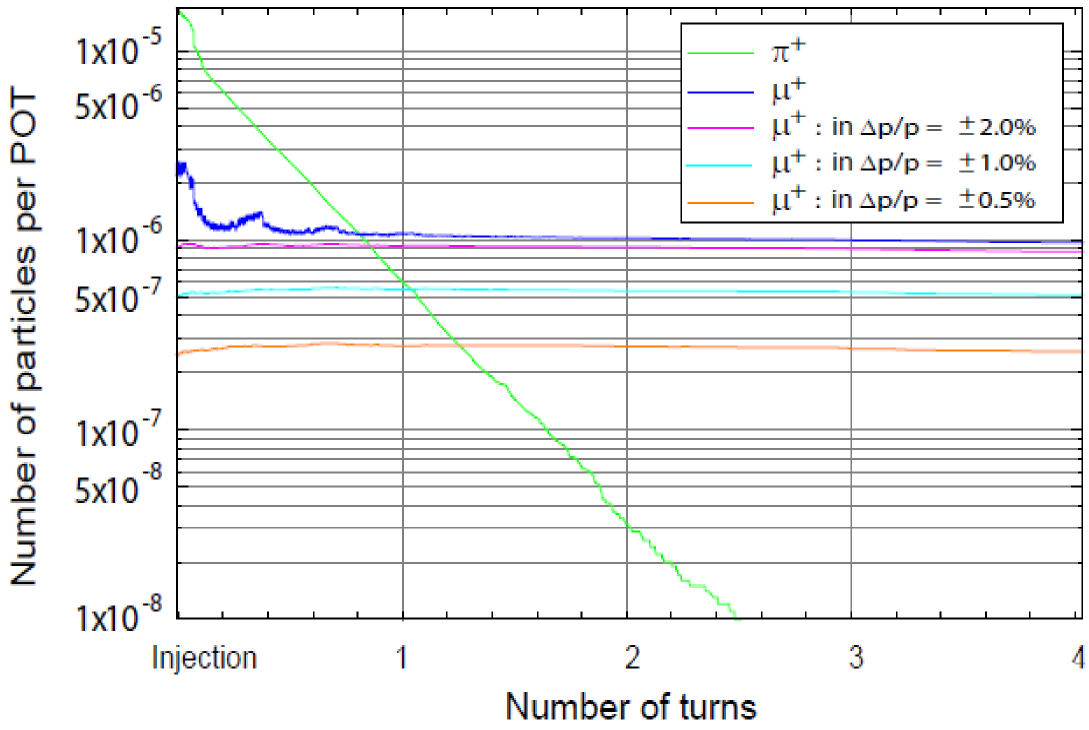
Simulation of the Delivery Ring.

Population of pions and muons in the delivery ring



Approximately half of the muons injected into the delivery ring are lost in the first turn.

The population of muons does not decrease significantly on subsequent turns.

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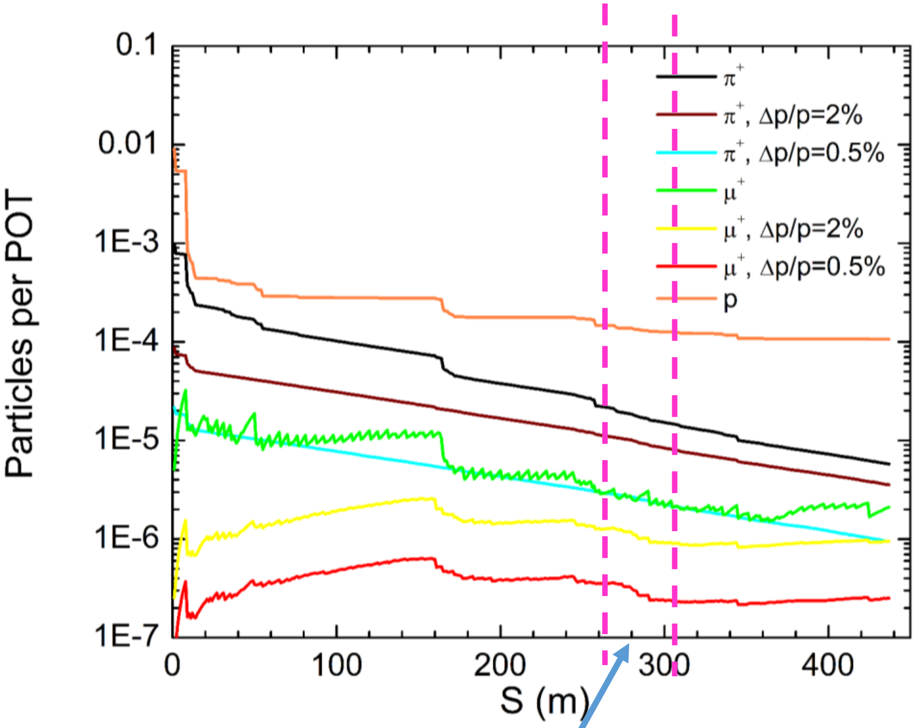
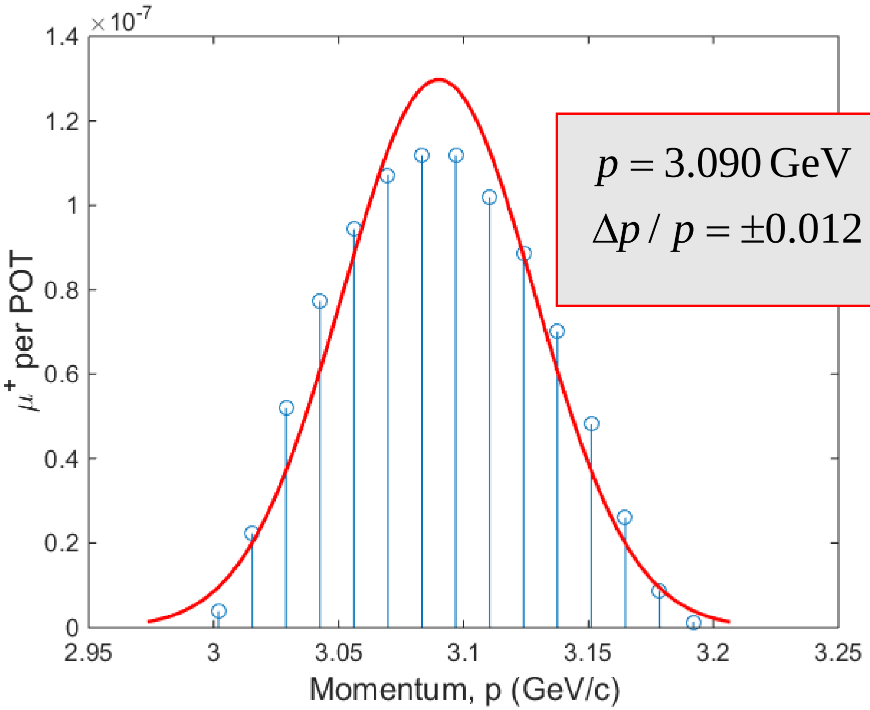
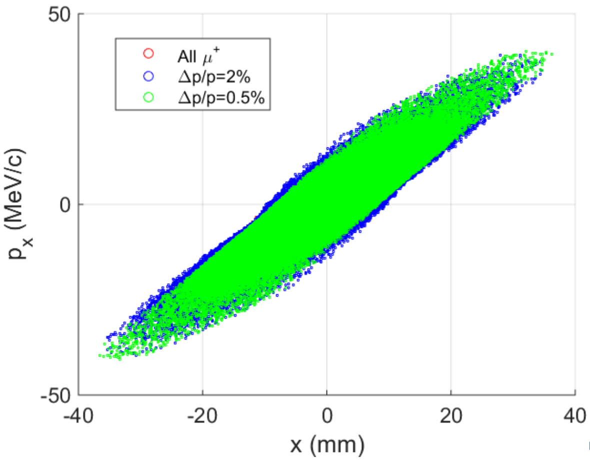
Muon distribution at end of M5.





For commissioning run the delivery ring simulation can be omitted.



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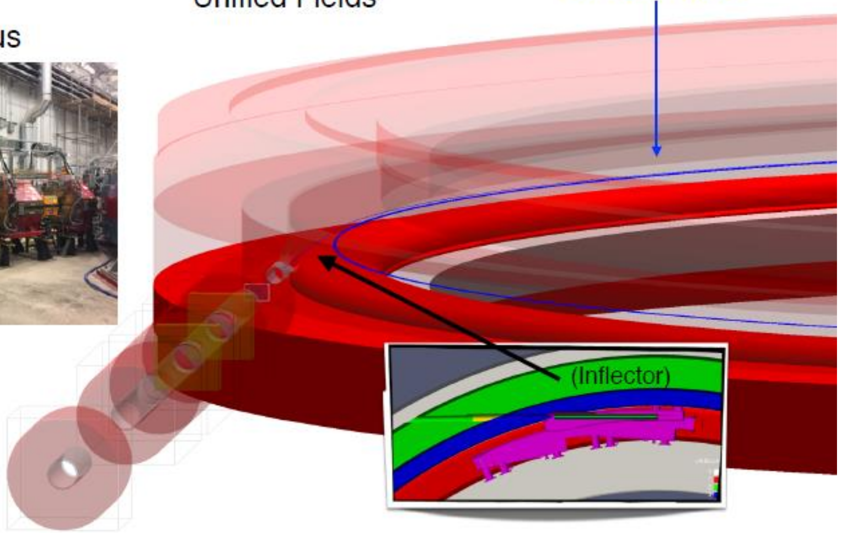
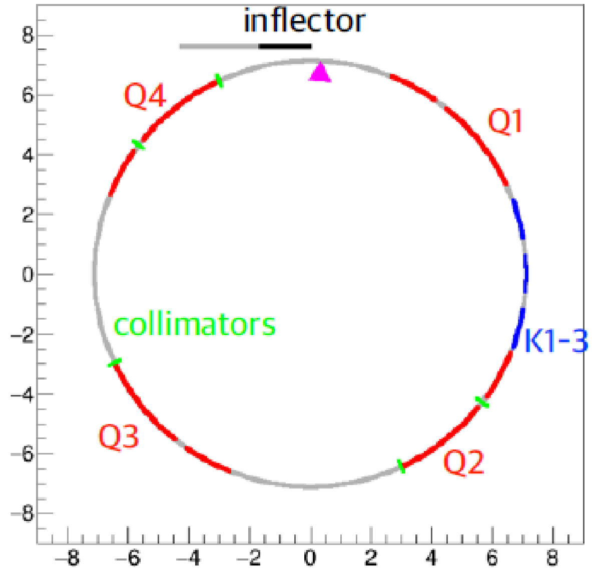
Beam Dynamics.

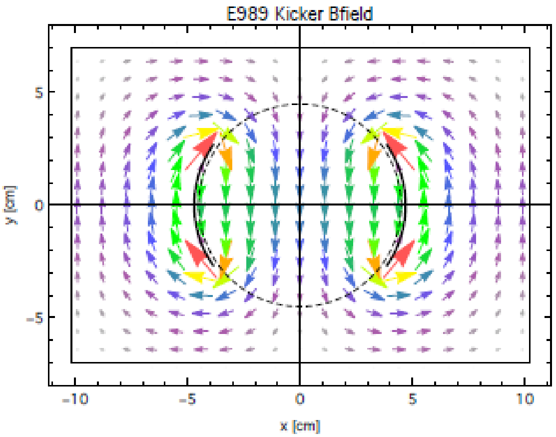
Final Focus

“Unified Fields”





Kicker B-field applied (logically) to G4Volumes



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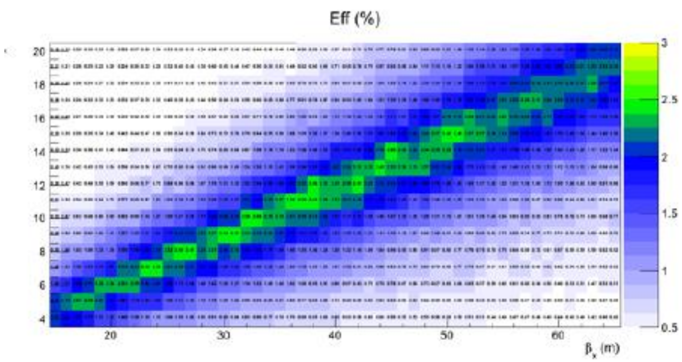
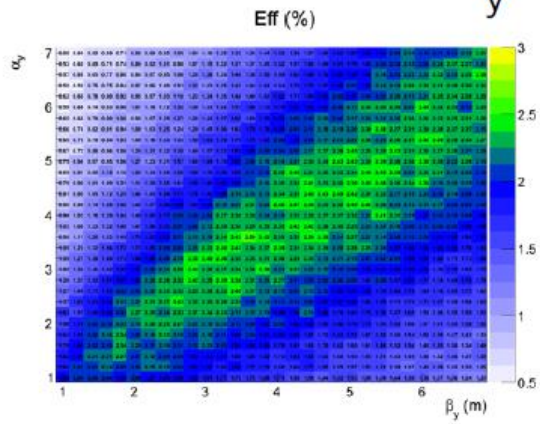
Muon Capture Studies.

x



y

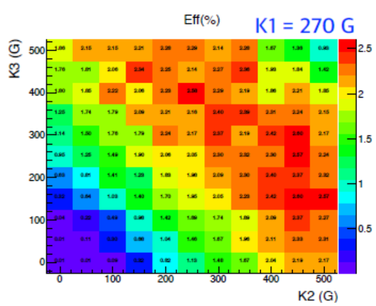


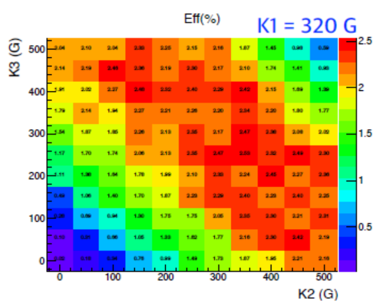
target value : β_x=33, α_x=10

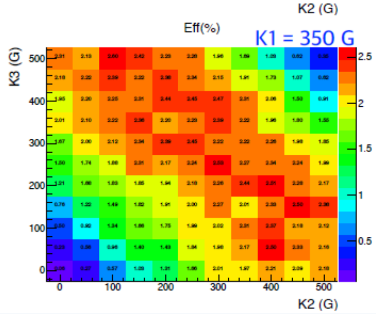
target value : β_y=3, α_y=3

Muon capture by inflector tuning.
Best efficiency ~2%

Muon capture by the kicker strength







Nominal values in our simulation
K1,K2,K3 = (320, 300, 250)

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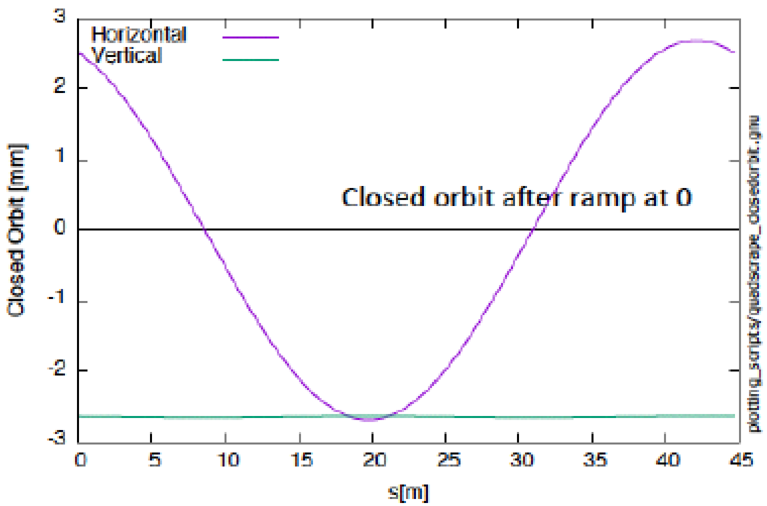
Muon capture studies by kicker adjustments.
Best efficiency ~2%

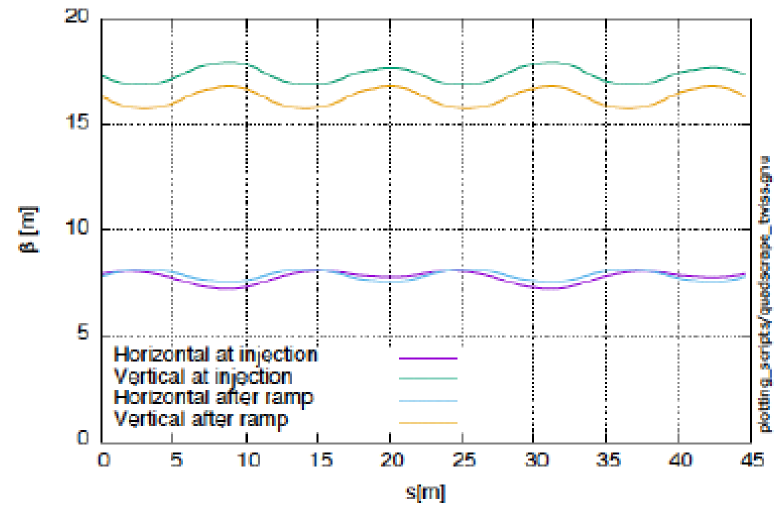
Studies of quadrupole tuning.

Closed orbit, tunes, and β at injection and after ramp

Quad voltage at injection

	Top	Bottom	Inner	Outer
Q1	32	22.7	-32	-32
Q2	32	22.7	-22.7	-32
Q3	32	22.7	-32	-32
Q4	32	22.7	-32	-22.7





	Tunes at Injection	Tunes after ramp
Q_x	0.9137	0.9039
Q_y	0.4090	0.4403

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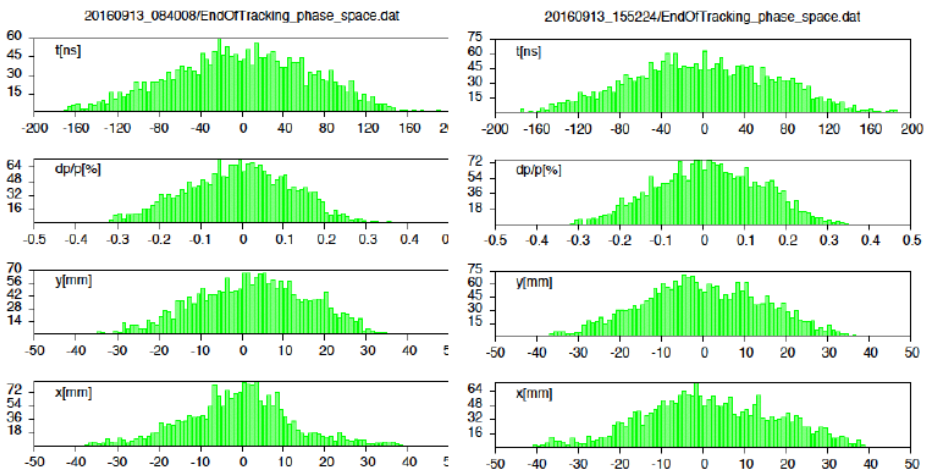
Beam Properties after 300 turns.

Muon distributions after 300 turns



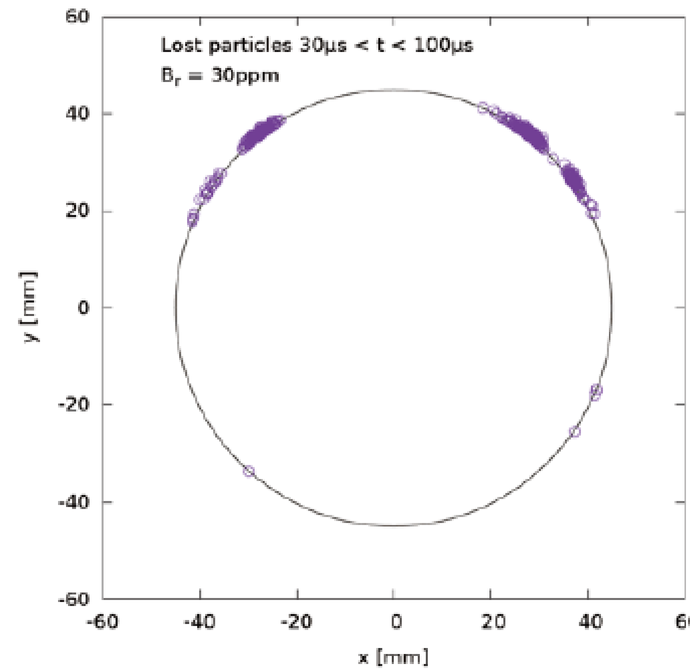
With scraping

2153/70000 (3.1%) stored

Without scraping

2357/70000 (3.4%) stored

Hit distribution of "lost" muons with B_{radial} = 30 ppm



Researchers funded by MUSE contributed and have become experts at running the ring simulation code.
Importantly they added the possibility to simulate muons with a non-zero Electric Dipole Moment.
Crucial for the EDM analysis.

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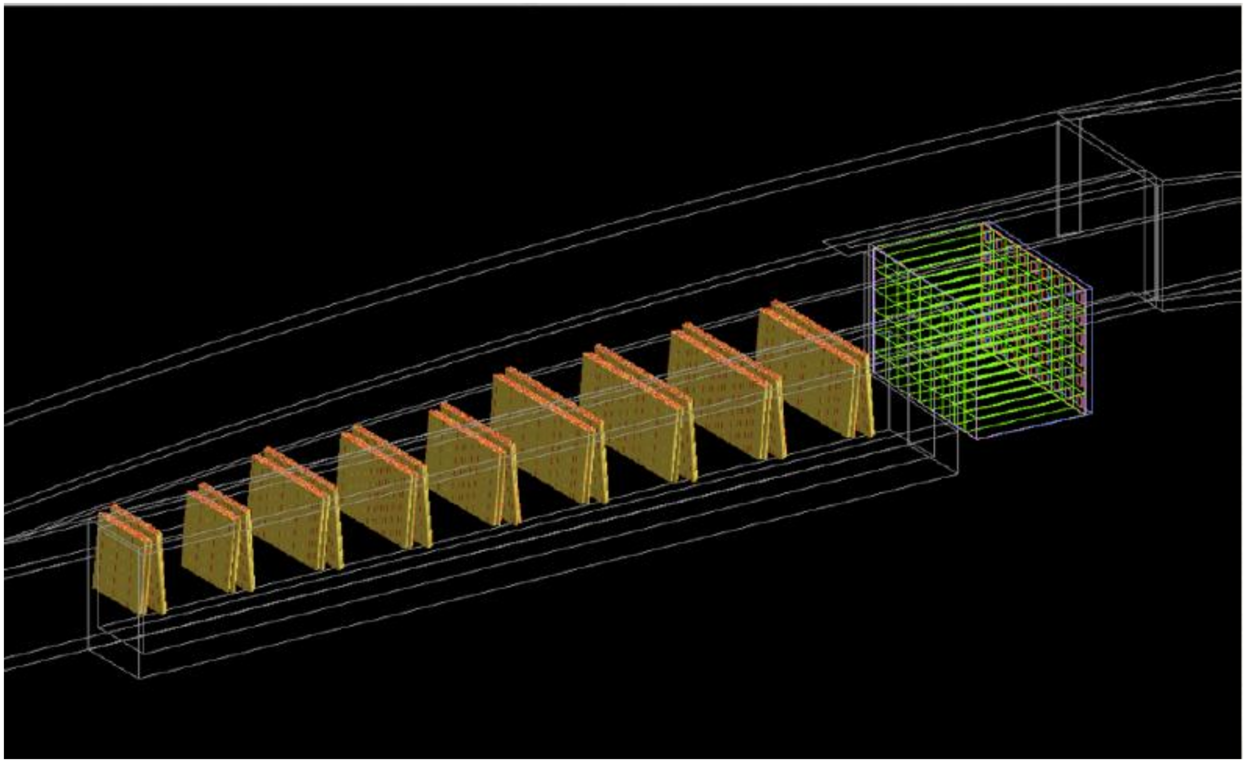
Simulation of Tracker and Calo.

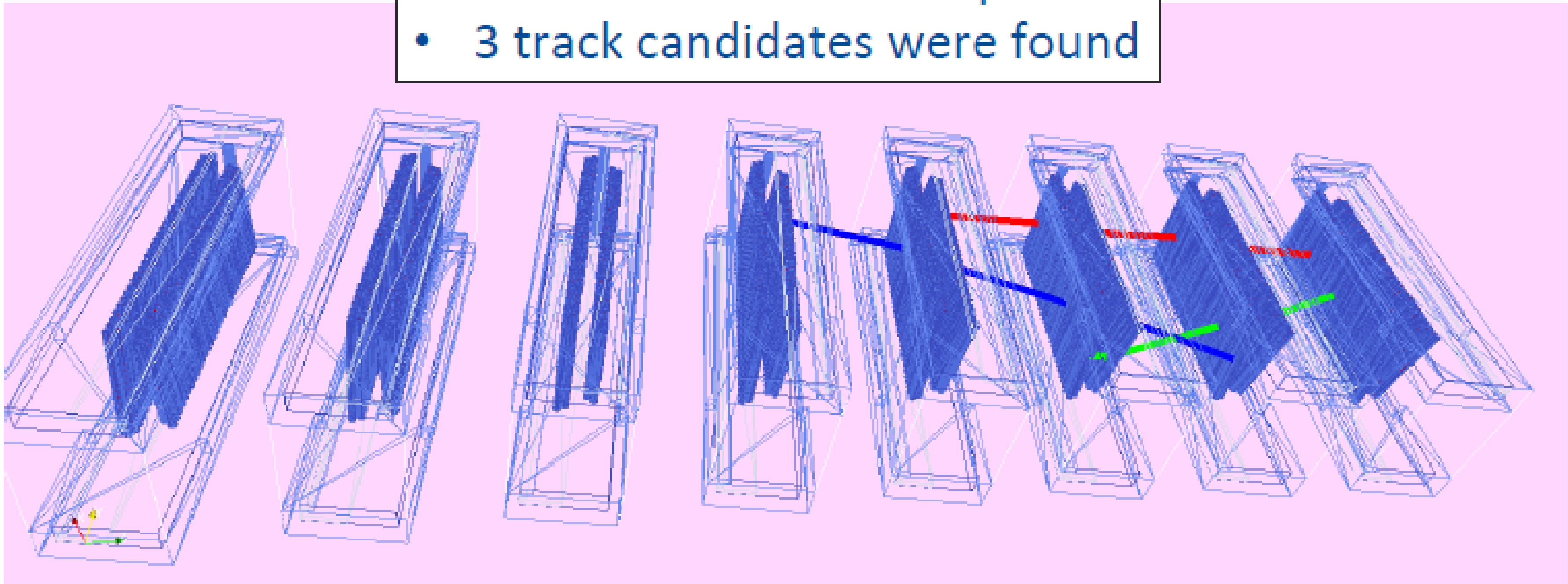


Positrons from muon decays are tracked and the response of the 3 trackers and 24 calorimeters modelled.

Tracker Simulation Example.

Example:

- Generated 100 muons per fill
- 3 track candidates were found



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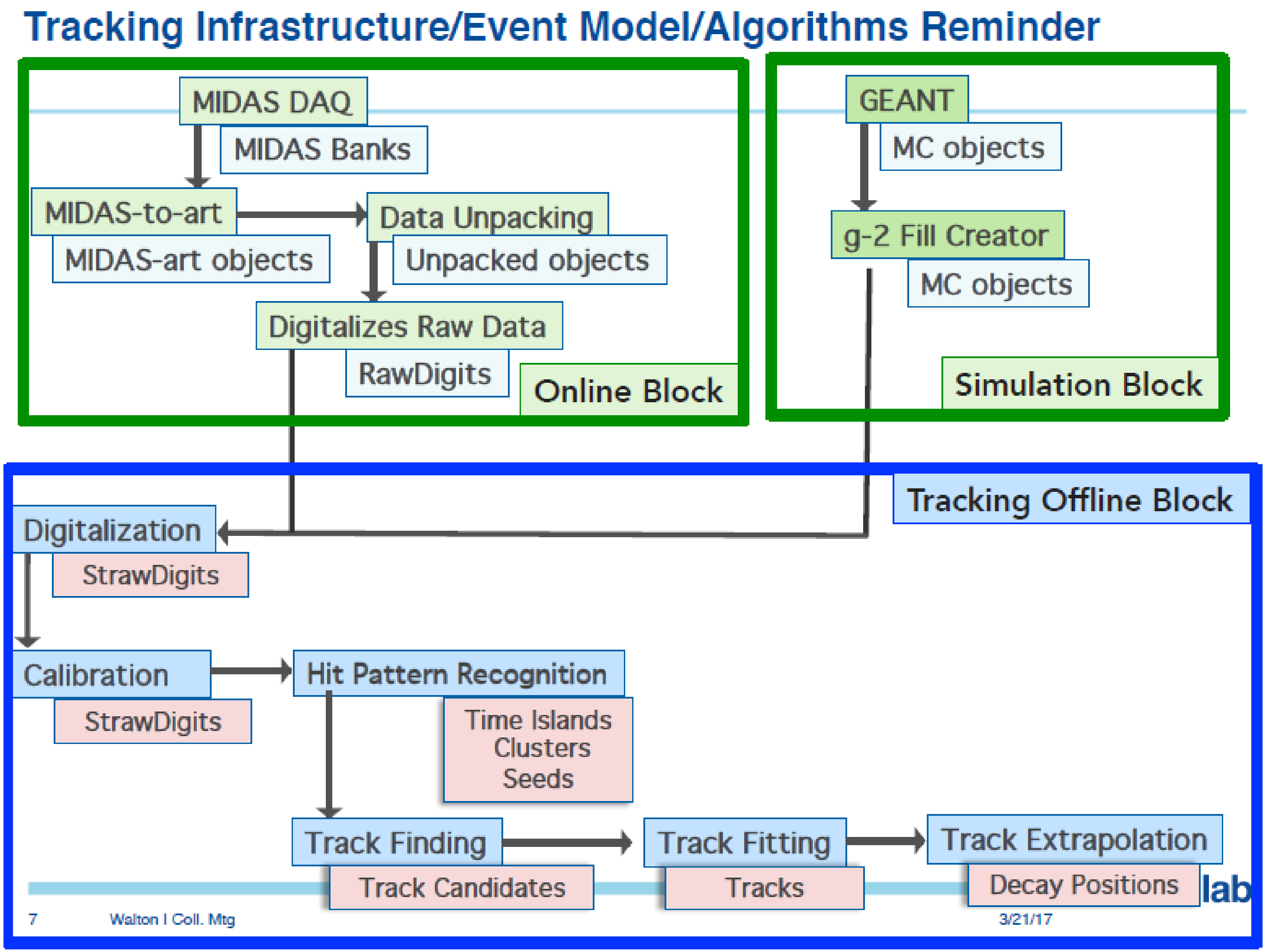
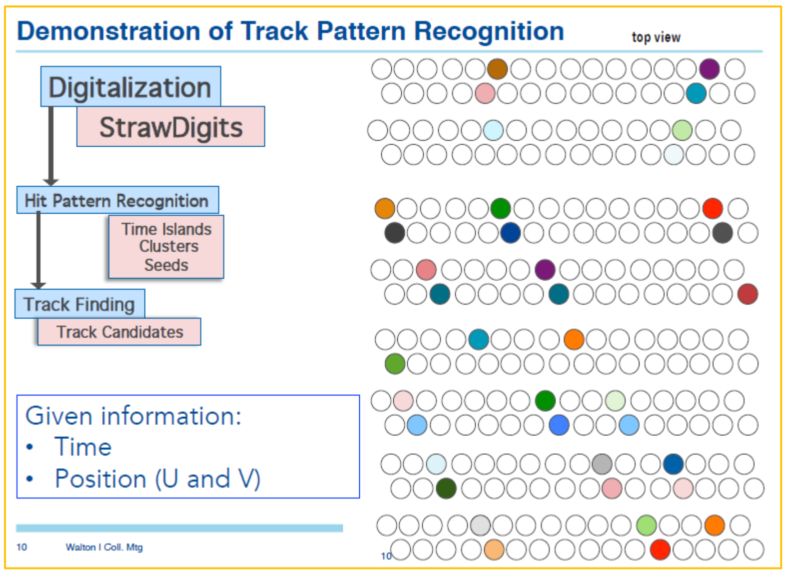
Tracker Software.

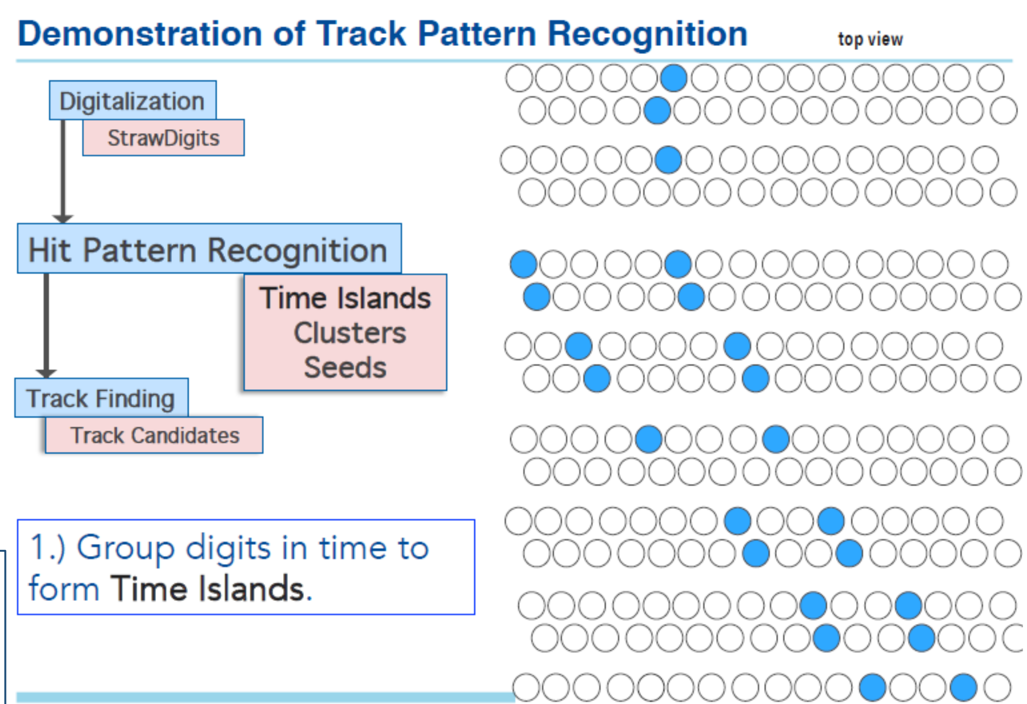


Track Finding.

Distribution of tracker hits before "time island" grouping.



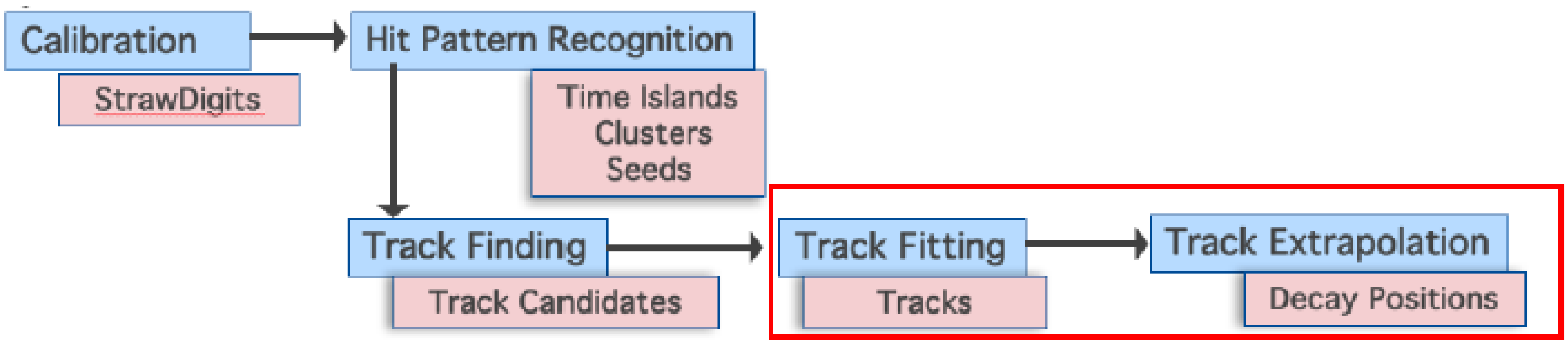
Distribution of tracker hits after "time island" grouping.



After "time island" grouping stage there is usually just one track in the Straw Tracker.

Track Fitting.

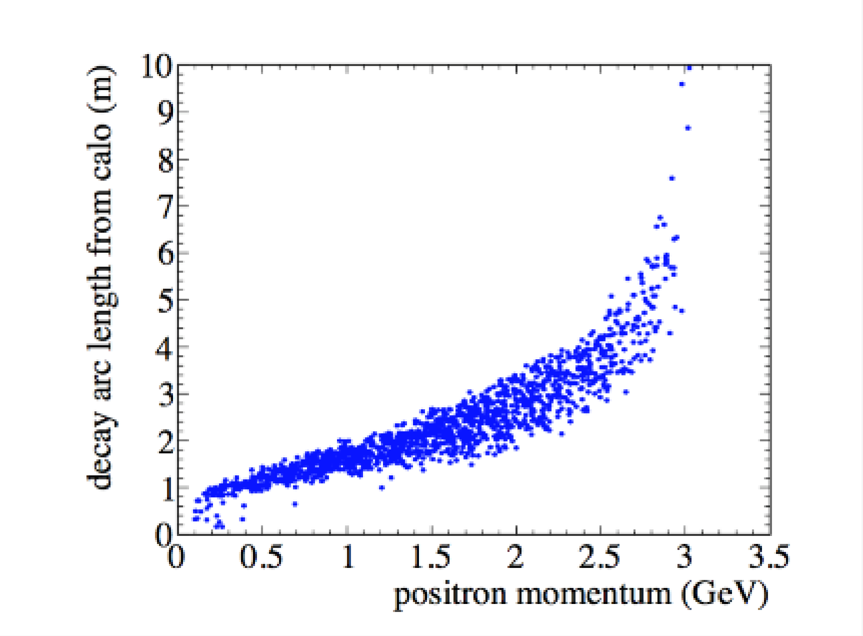
Reconstruction flow



- Take in "Track Candidates" which are provided by Tammy's finding code
- Fit them with Geane track fitting code, and provide "Track States" and "Tracks" to extrapolation code

Track Fitting.

- **Physics goal 1**: measure the muon beam profile at multiple locations around the ring, as a function of time throughout the muon fill
- **Physics goal 2:** reduce several important systematic uncertainties associated with the g-2 measurement
- **Physics goal 3**: identify any tilt in the muon precession plane away from vertical – indicative of muon EDM



Track Fitting.

Reduction of systematic errors associated with the trackers

Uncertainty	E821 value	E989 goal	Role of tracking
Magnetic field seen by muons	0.03 ppm	0.01 ppm	Measure beam profile on a fill by fill basis ensuring proper muon beam alignment
Beam dynamics corrections	0.05 ppm	0.03 ppm	Measure beam oscillation parameters as a function of time in the fill
Pileup correction	0.08 ppm	0.04 ppm	Isolate time windows with more than one positron hitting the calorimeter to verify calorimeter based pileup correction
Calorimeter gain stability	0.12 ppm	0.02 ppm	Measure positron momentum with better resolution than the calorimeter to verify calorimeter based gain measurement
Precession plane tilt	4.4 μRad	0.4 μRad	Measure up-down asymmetry in positron decay angle

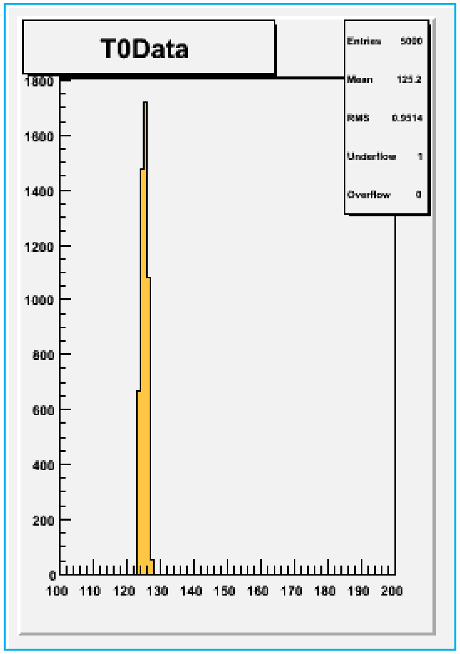
Goal 1

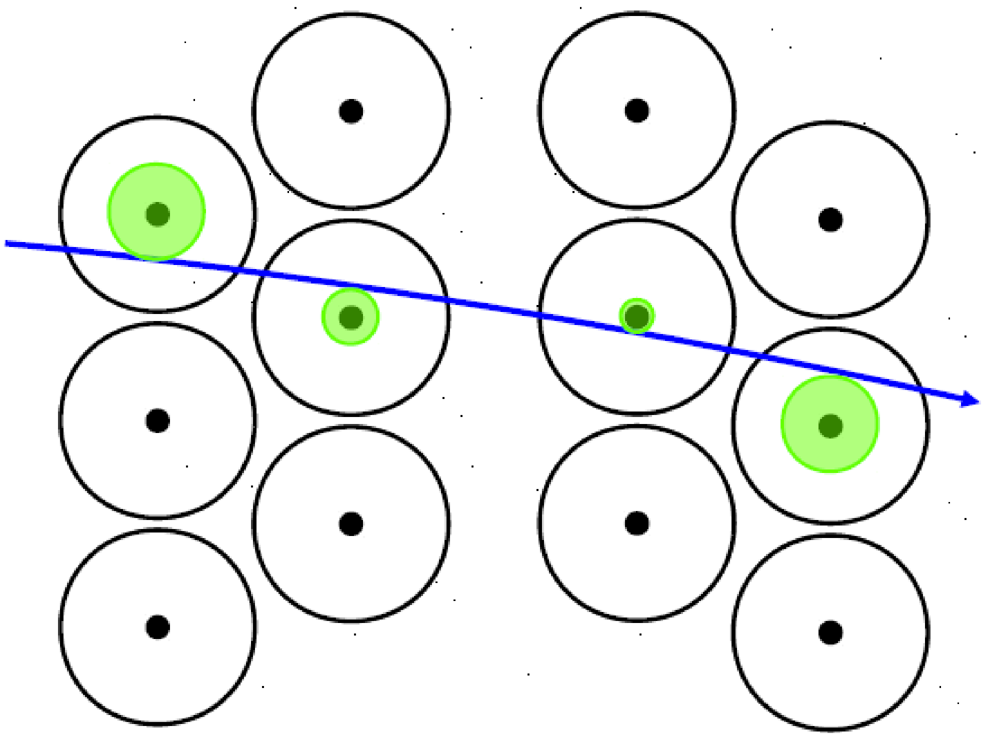
Goal 2

Goal 3

Track Fitting.

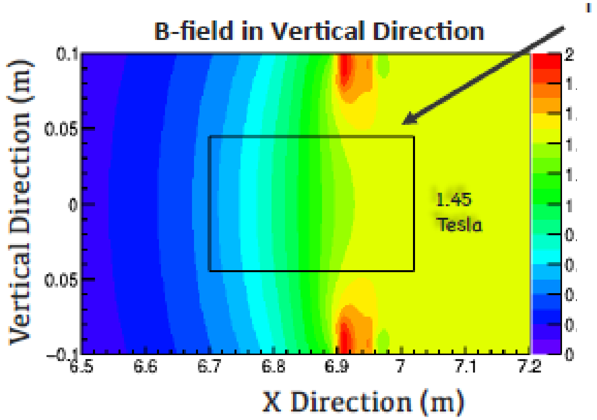
Use hit times and t0 estimate to get drift circles.



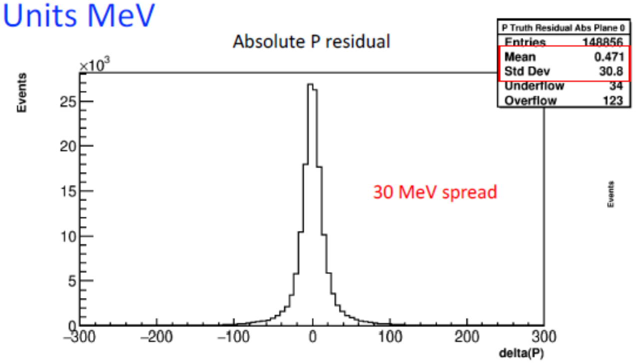


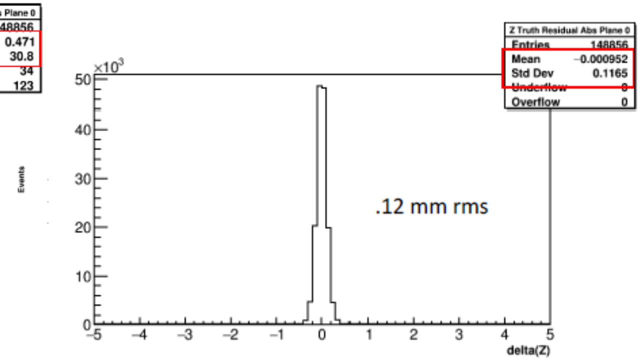
Kalman filter.

Major challenge is the varying magnetic field in the tracker region. Doesn't just vary vertically, but has a varying radial component.



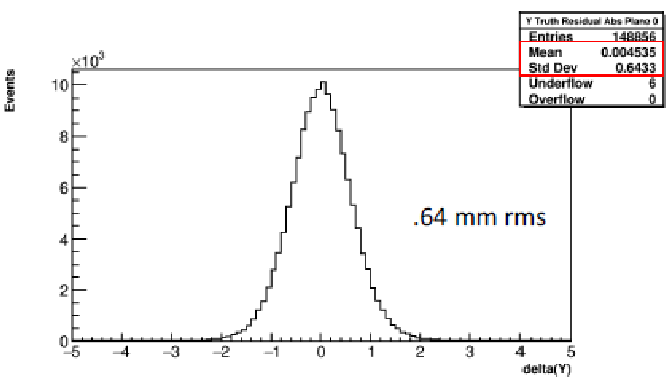
Units MeV



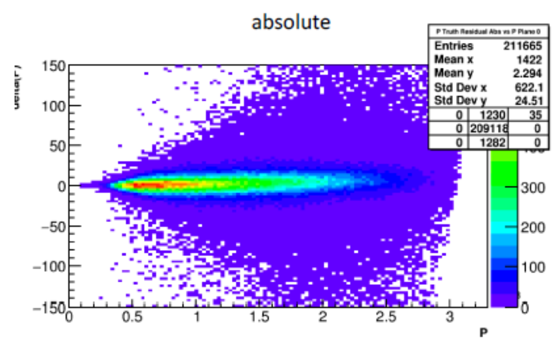


Horizontal position

Units mm



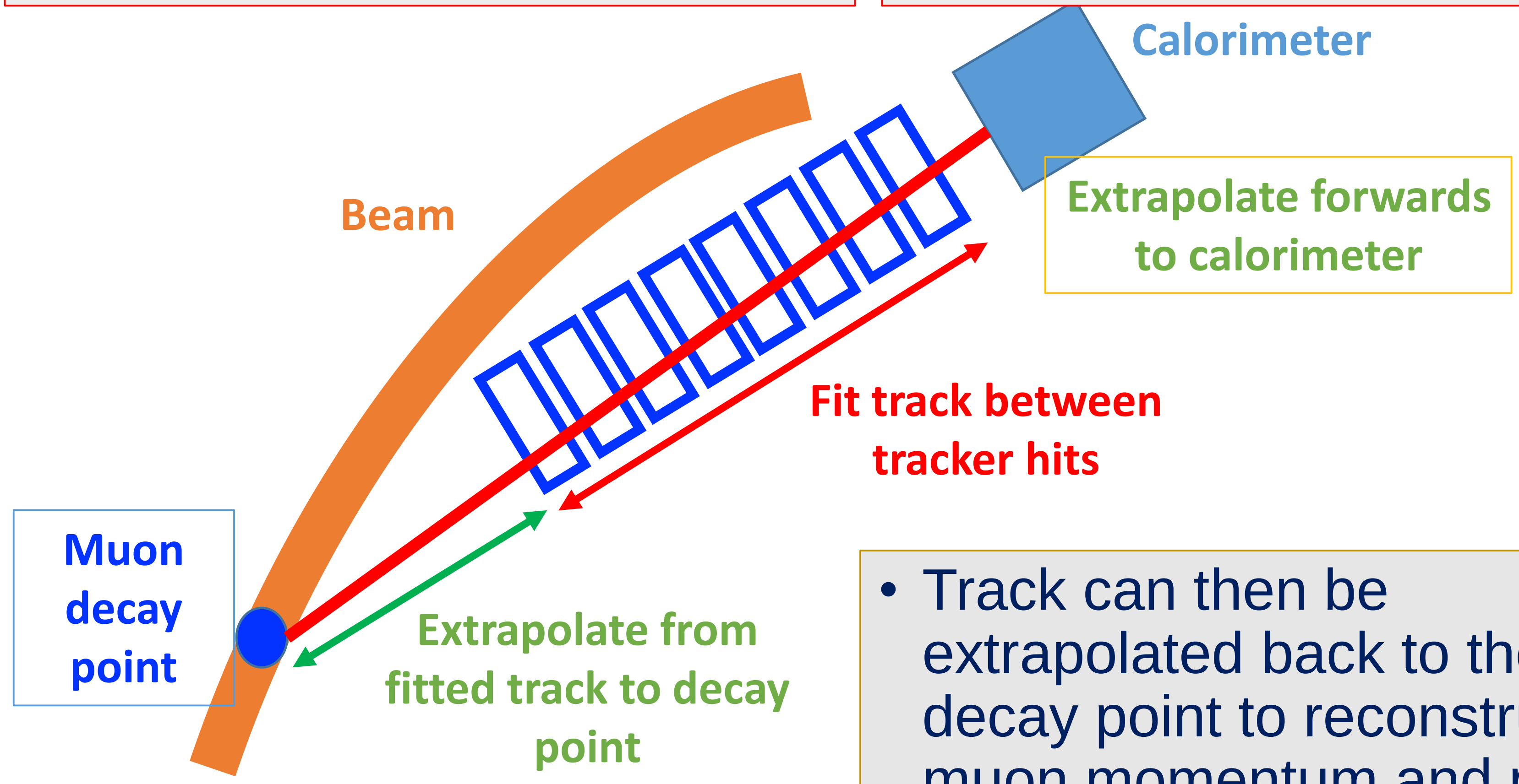
Vertical position



Determination of muon decay point.

- Track can be fitted between the reconstructed hit points using e.g. Kalman Filter

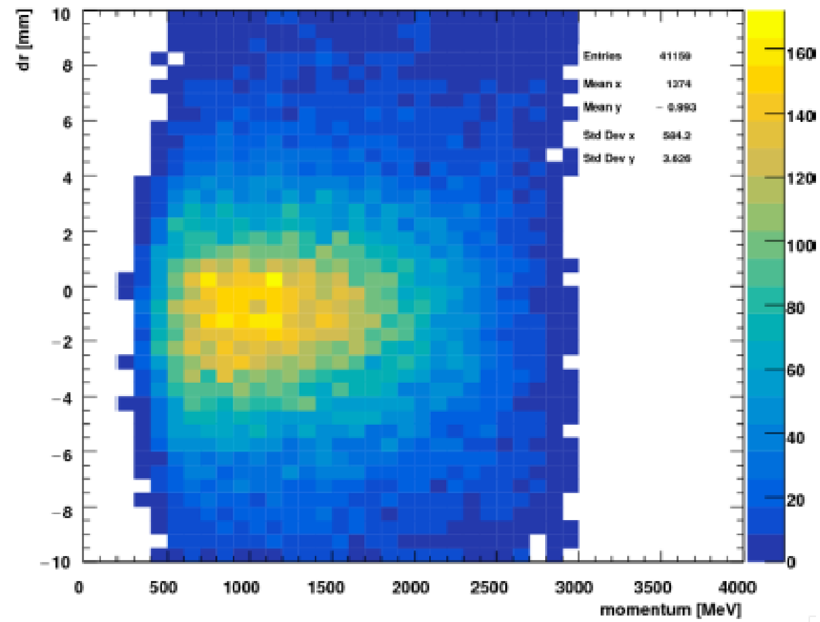
Obtain best estimate of track parameters at first module position (1/p, x, y, dx/dz , dy/dz)

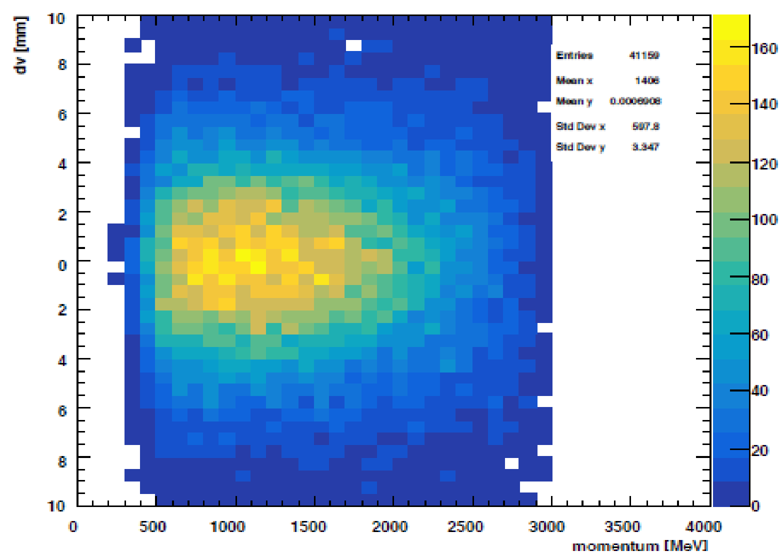


- Track can then be extrapolated back to the muon decay point to reconstruct the muon momentum and position

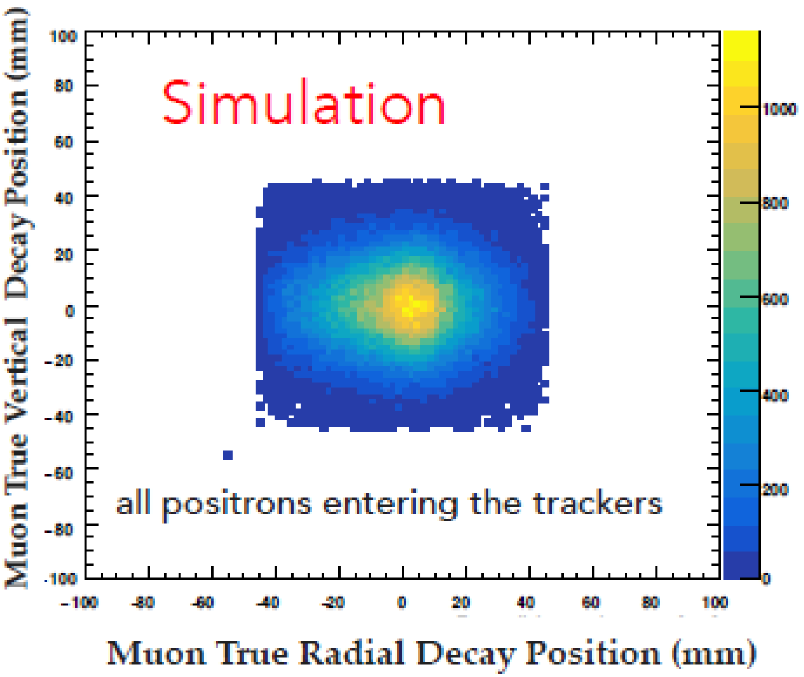
Determination of muon decay point.

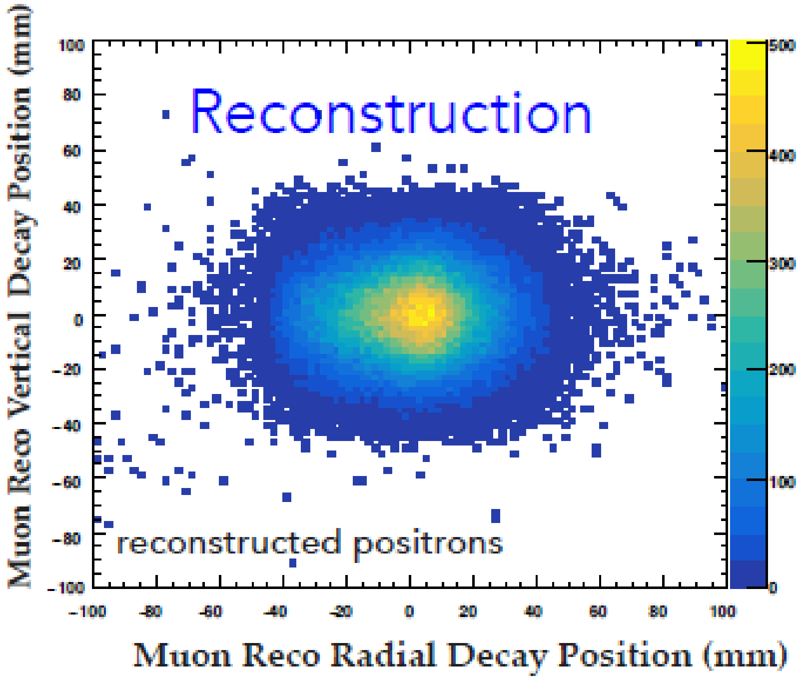
- Using Runge-Kutta track extrapolation algorithm.
- Lookup the magnetic field at each step, and predict the position and momentum of the particle at the next step
- Stop extrapolating when the track momentum is tangential to the magic radius



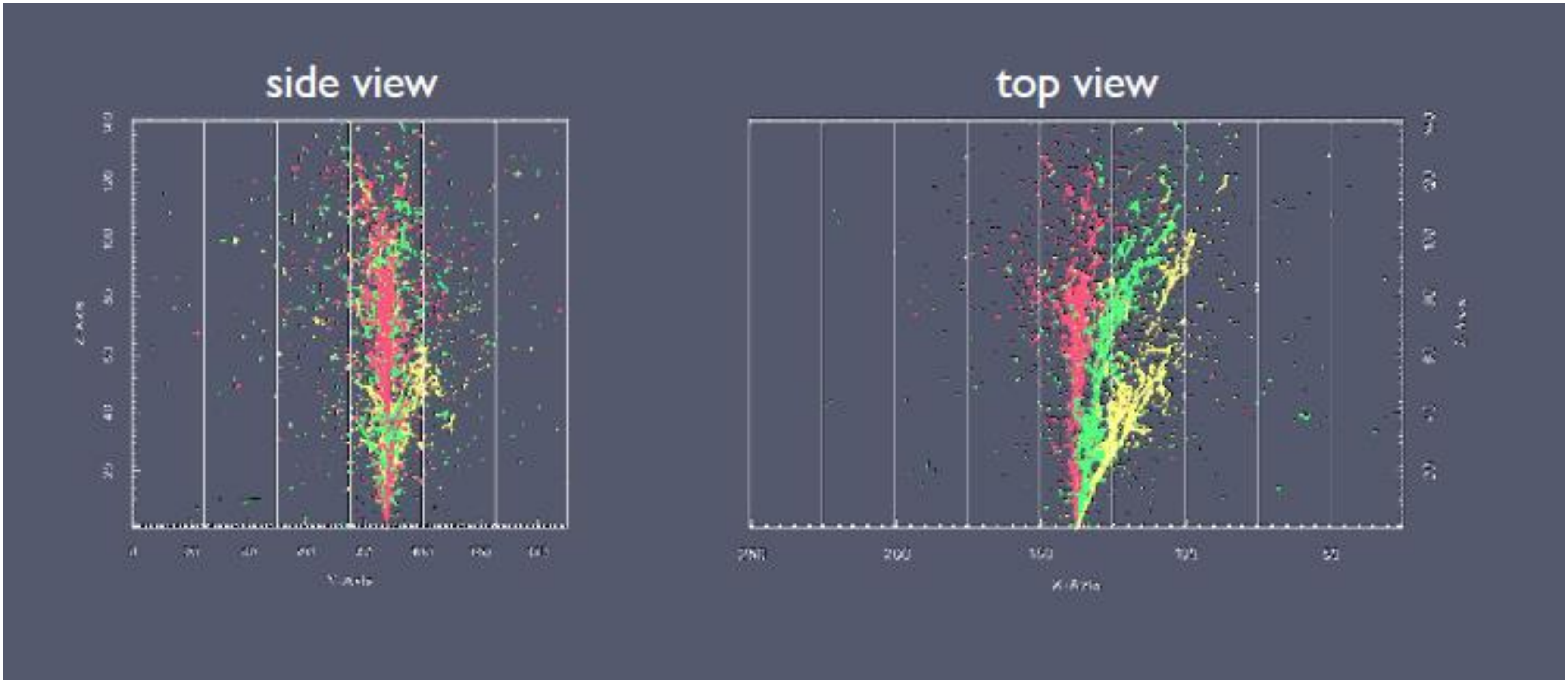


Determination of muon decay point.

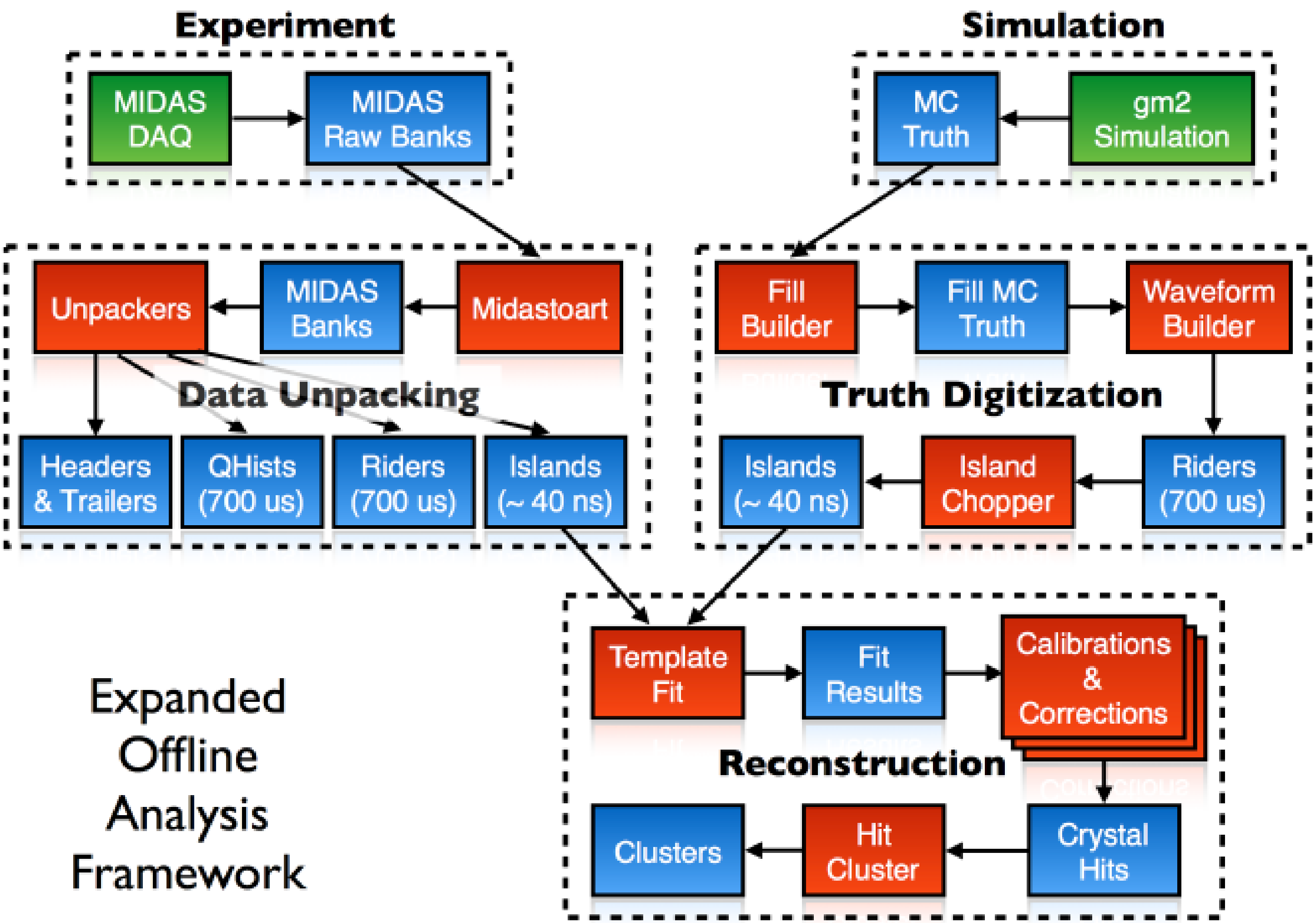




Calorimeter Showers.



Overview of g-2 framework (calo)

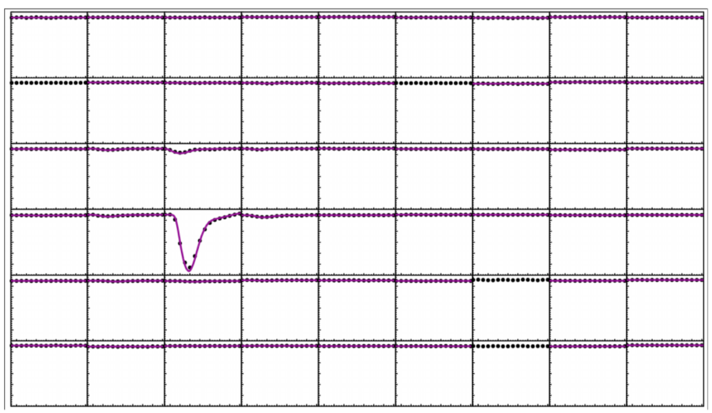


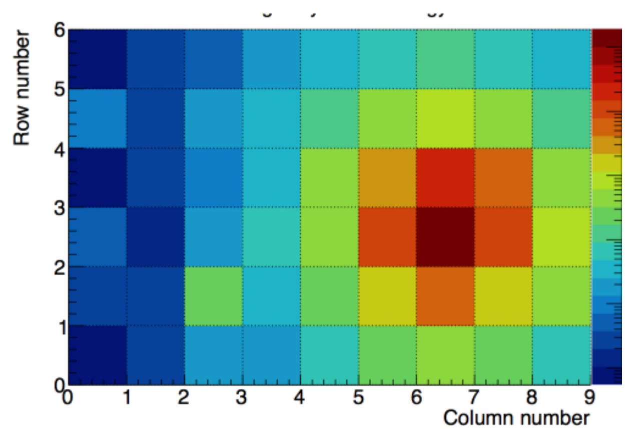
Expanded Offline Analysis Framework

Calo software overview.

- Transform digitized detector waveforms into reconstructed decay events
  - pulse finding: pulse island -> pulse area [ADC counts] & time
  - calibration: pulse area -> pulse photoelectrons
  - clustering: pulse collection -> decay event energy, time, position

e+ impact





(E,t)

Calo software overview.

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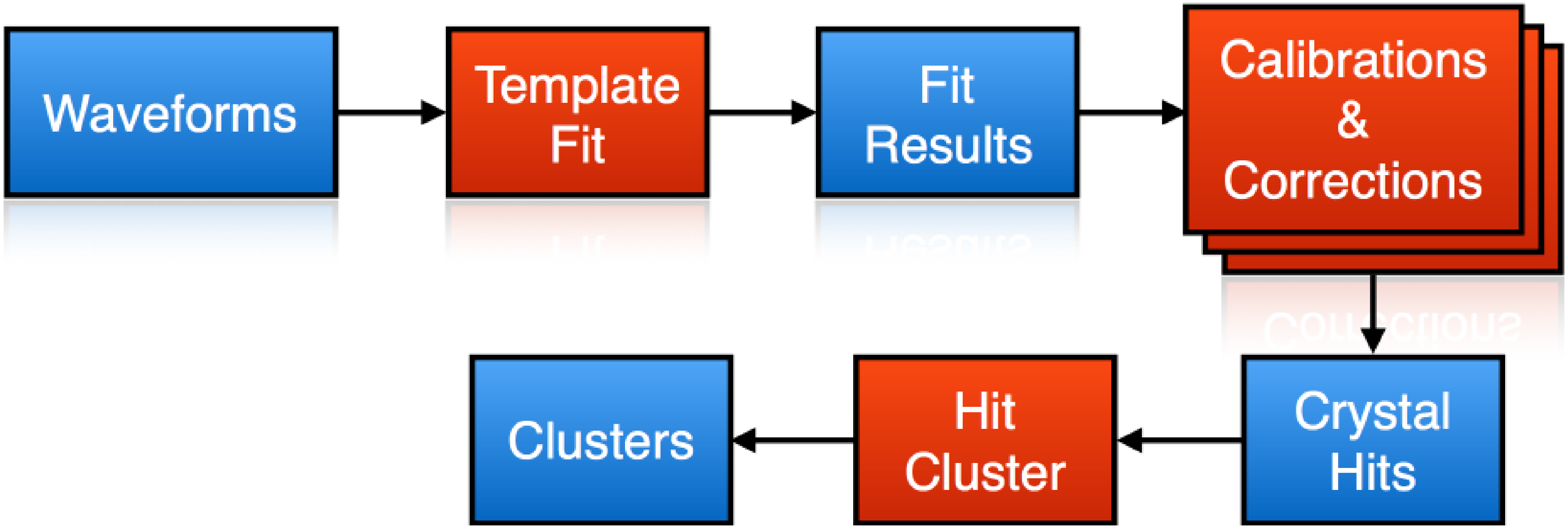
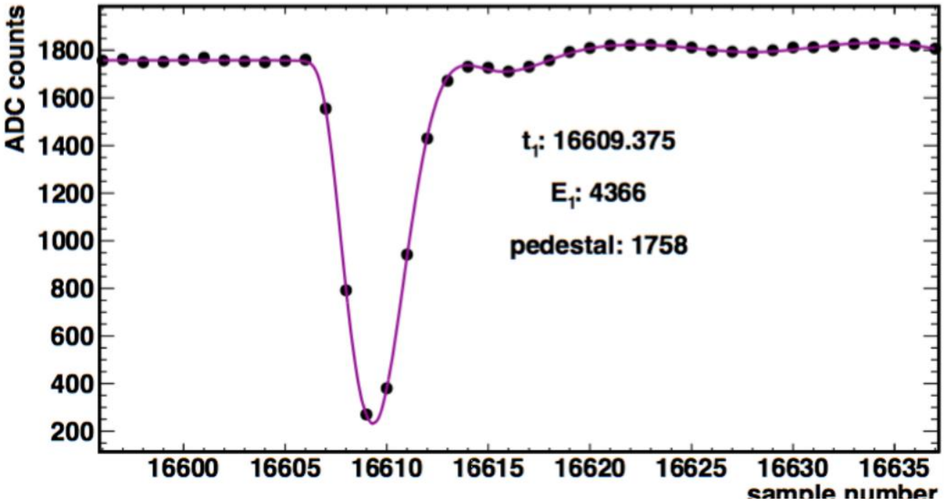


Calo software overview.



template fitting

baseline pulse finding algorithm is **template fitting**
a **template** is an empirical pulse shape extracted from data

- using template to fit pulse islands for time, energy, pedestal
- fitting additional pulses as needed, 2*nPulses + 1 parameters

Calo software overview.

clustering

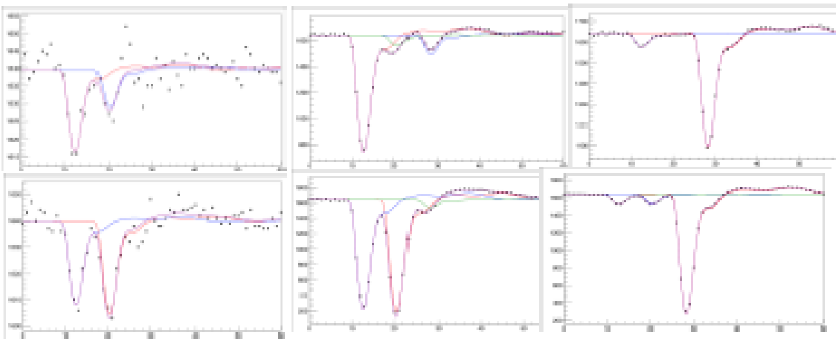
- clustering algorithm takes a collection of calibrated crystal hits and outputs an arbitrary number of reconstructed decay positron parameters, called "clusters"

- basic two step clustering algorithm in place that meets baseline requirements:
  - step one: time partitioning
  - step two: spatial separation and energy partitioning
  - additionally, reports cluster position for single-positron clusters

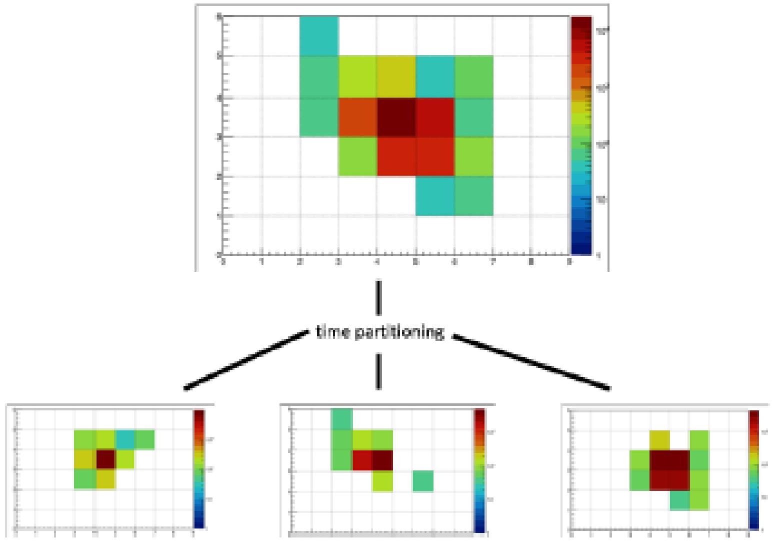
Calo software overview.

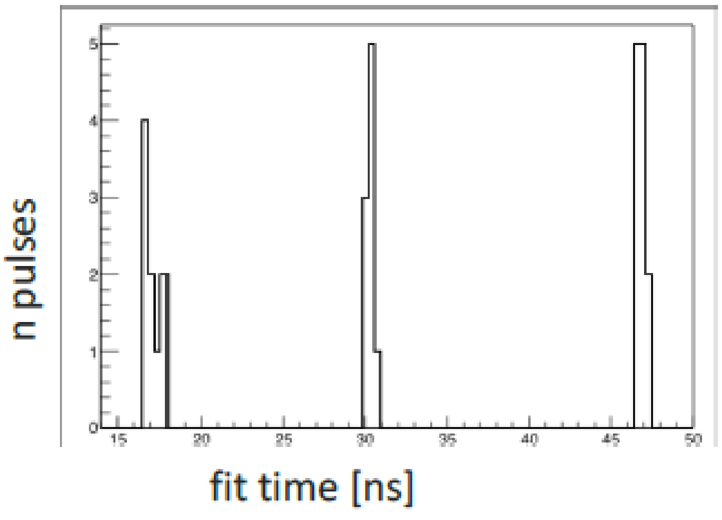
cluster time partitioning

- sort fit results from a given island by time
- group results with $\Delta T < \sim 5\ ns$



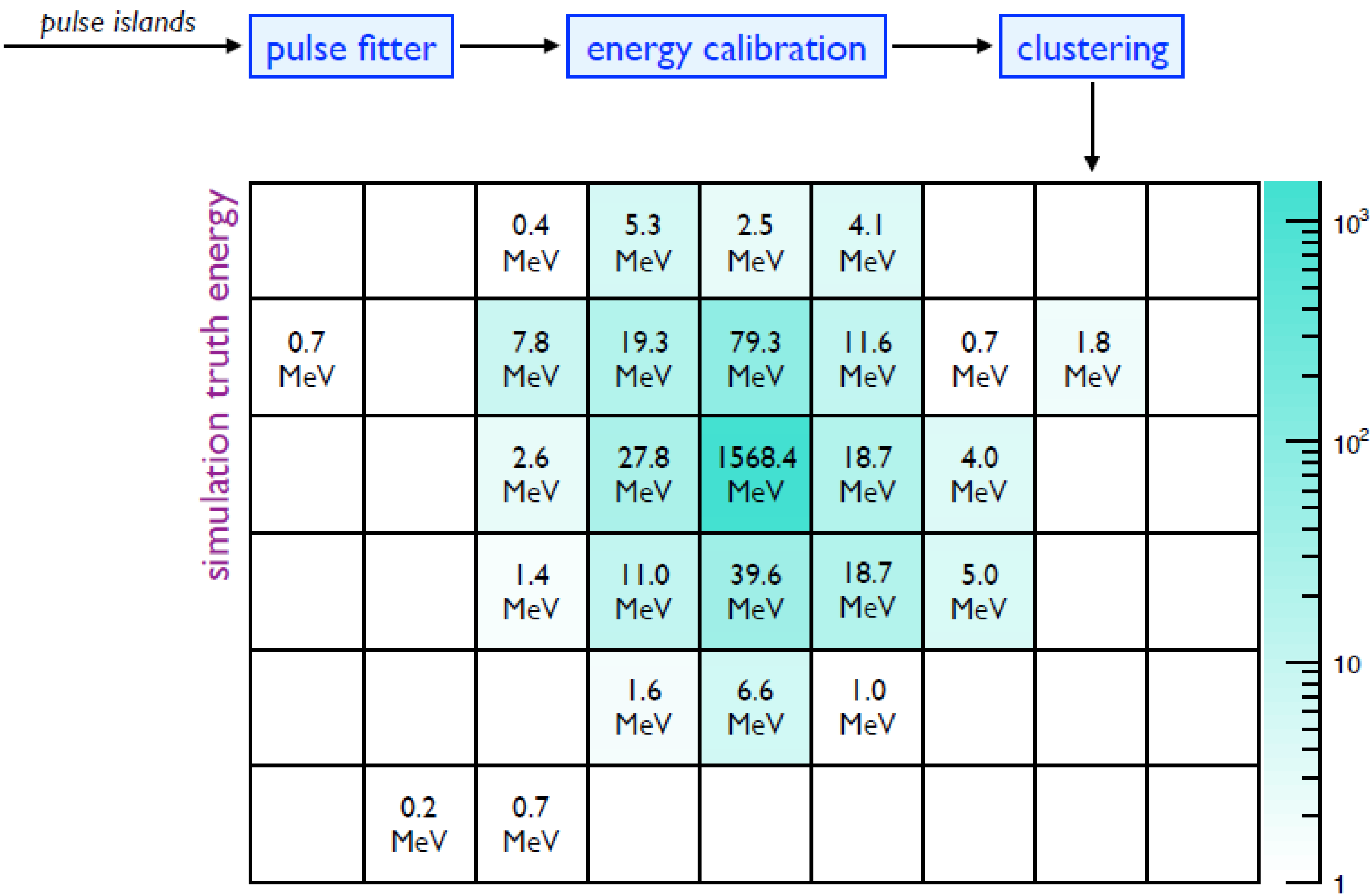
fits from a triple pileup event





Cluster position reconstruction.

calorimeter reconstruction chain



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Cluster position reconstruction.

position reconstruction

simplest technique is the energy-weighted linear combination

reconstructed position is biased towards the crystal center

shower center-of-gravity

- linear weighting
- logarithmic weighting
- square root weighting

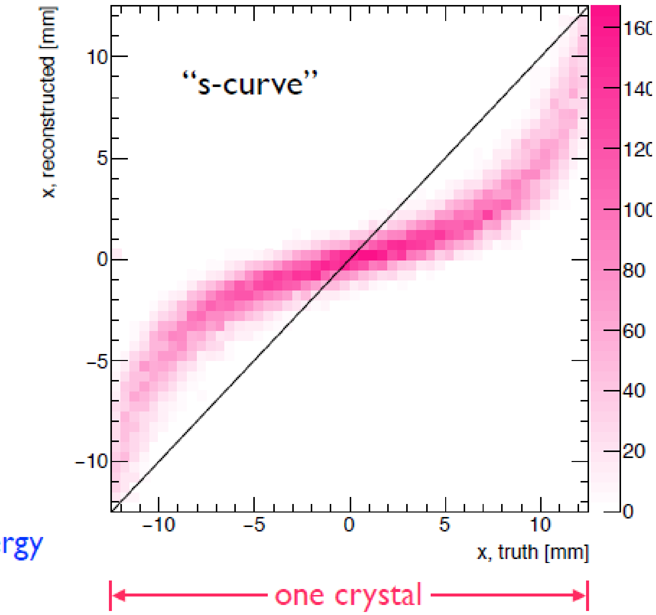
crystal center

$$x_{\mathrm{reco}} = \frac{\sum_i w_i \cdot x_i}{\sum_i w_i},$$

weights

$$w_i = E_i$$

deposited energy



two-crystal logarithmic weigh

- opposite crystals
- adjacent crystals

exponential lateral fitting

- single exponential
- double exponential

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Cluster position reconstruction.

center-of-gravity method
with logarithmic weights

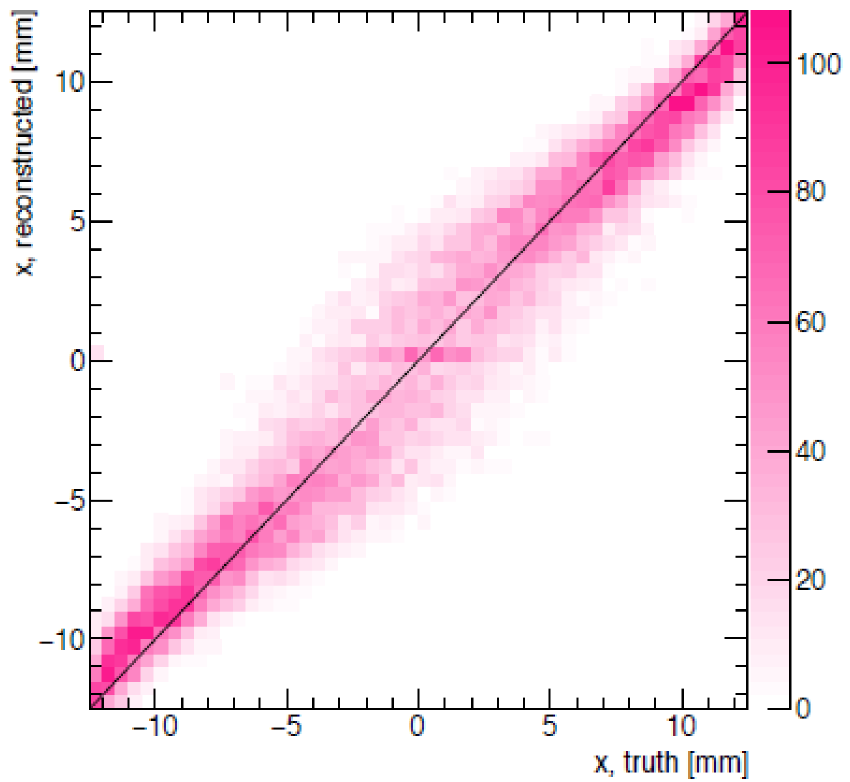
$$x_{\text{reco}} = \frac{\sum_i w_i \cdot x_i}{\sum_i w_i},$$

← crystal center (for x_i)

$$w_i \sim \log \frac{E_i}{\sum_j E_j}$$

↑ fraction of deposited energy

reconstruction results



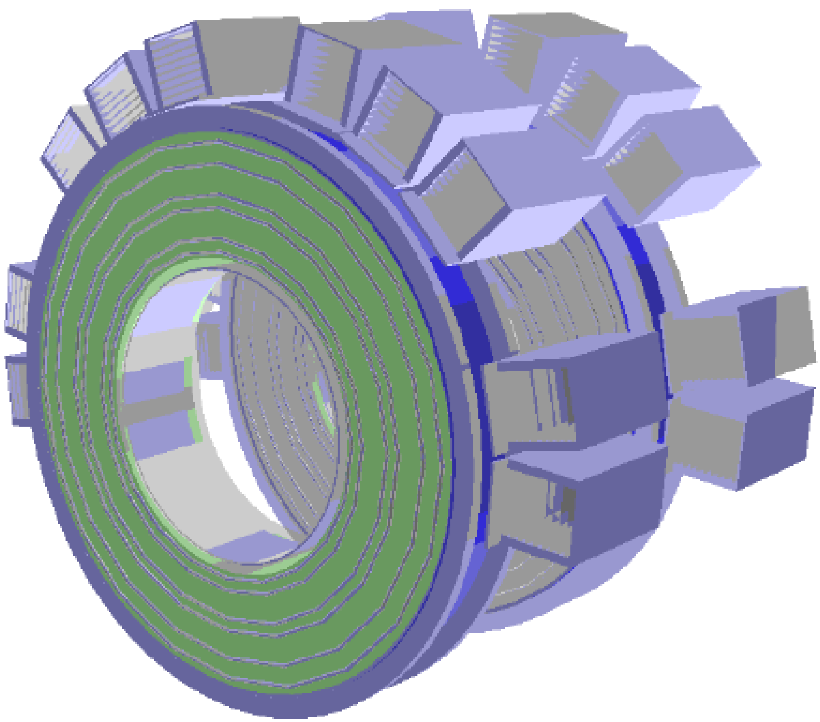
position reconstruction

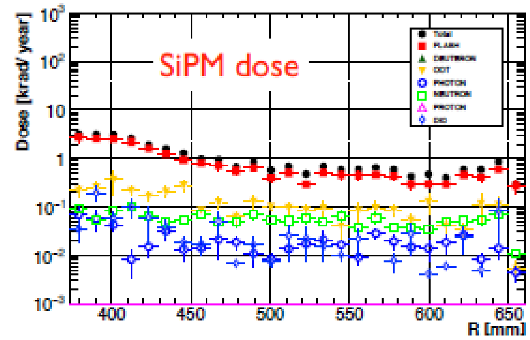
- ≤3 mm resolution achievable at 7 X_0 in calorimeter with no angle bias
- combination of methods will likely be the best approach
  - e.g., two-crystal methods for edge crystal hits

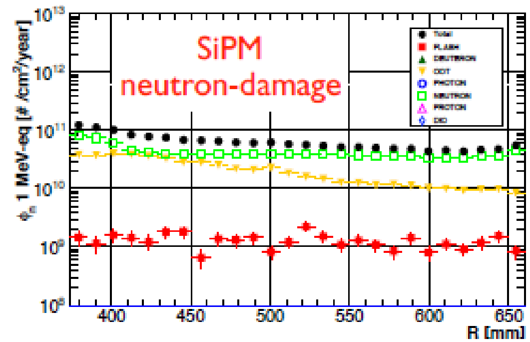
Mu2e Software Status.

Radiation studies

- High level geometry description allow us to estimate the expected dose and neutron flux in all the sensitive components: crystal and electronics
- These estimates are extremely relevant for the QA tests







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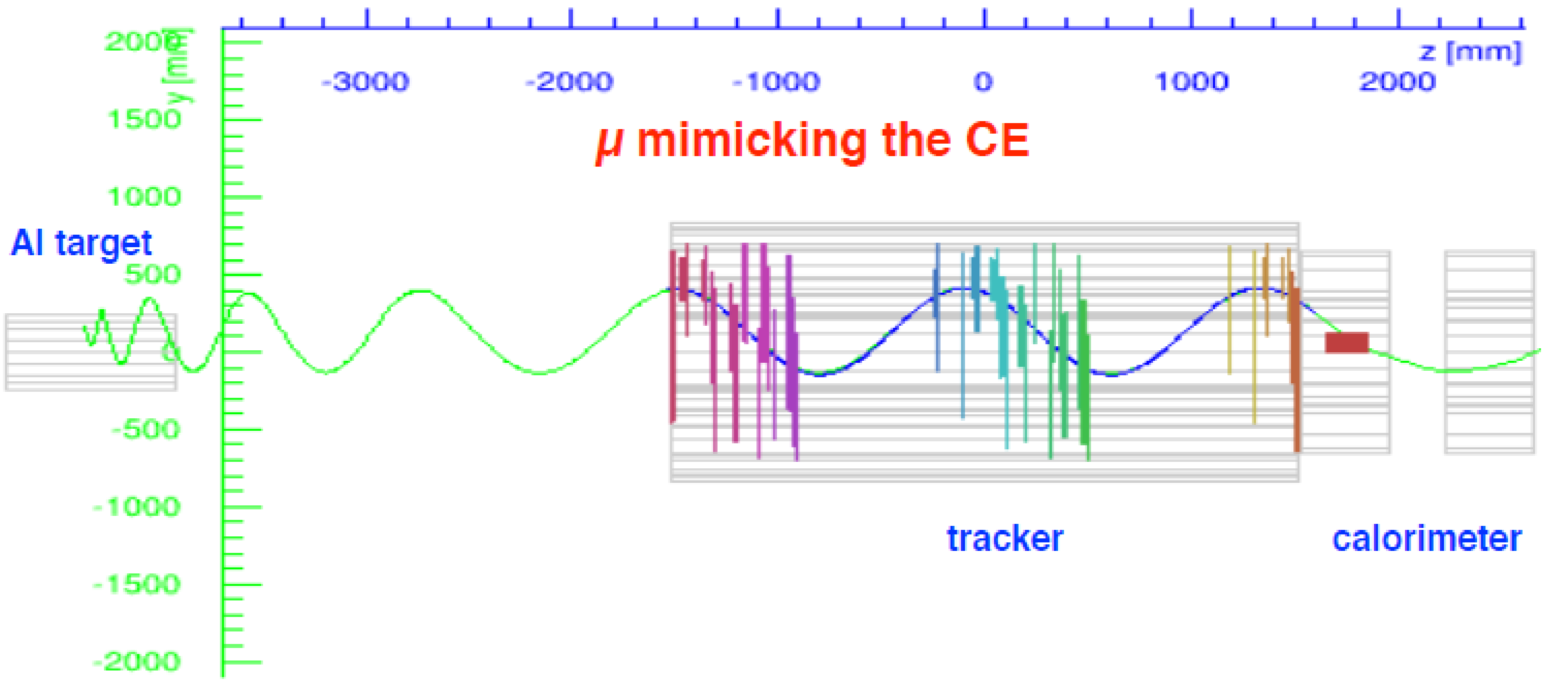
FNAL - April 27 2017

Mu2e Software Status.

Particle identification

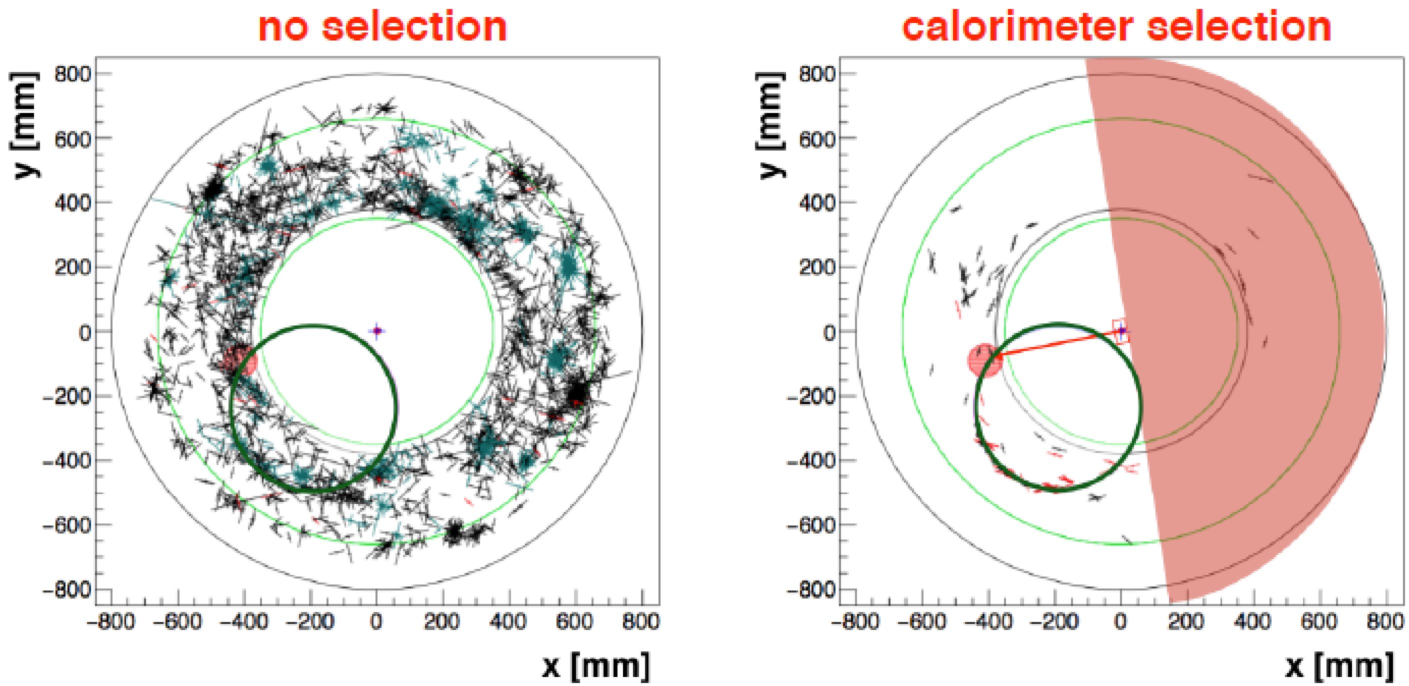
- Cosmic μ mimicking the conversion electron represent a dangerous background: expectation rate ~ 1 per day!
- Combining calorimeter and tracker allows to suppress it



Mu2e Software Status.

Calorimeter-seeded track search

- Cluster time and position are used for filtering the straw hits and seed the pattern recognition in the tracker
- Improves robustness of the track search



- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = Conversion Electron track

Mu2e Software Status.

Test Beam

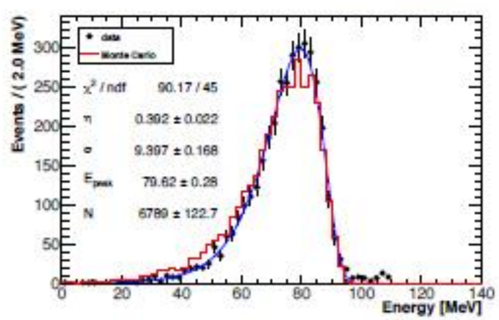
- Mu2e Offline is also used to simulate the expected response of the calorimeter prototypes
  - One test beam analyses already finalized
  - New test beam with "module 0" is ongoing!


Measurement of the energy and time resolution of a undoped CsI + MPPC array for the Mu2e experiment

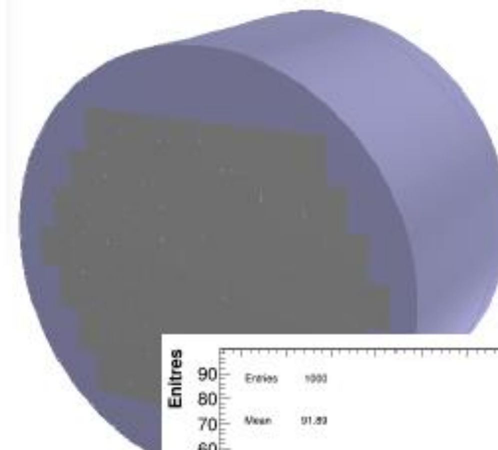
arXiv:1702.03720

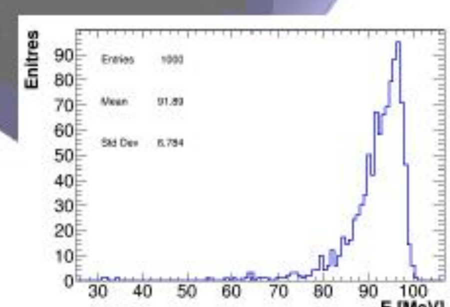
submitted on JINST

previous prototype



Calorimeter module 0





Summary.

An enormous amount of work has gone into preparing the g-2 software chain ready for the start of the experiment.
Beam simulations are fully implemented and being used to study beam dynamics.

Detailed Simulations of all detector components are in place and reconstruction algorithms have been developed.

MUSE funded researchers have played a major role in all of this:

- implementation of the EDM into the beam simulation.
- development of simulation/reconstruction code for the trackers.
- implementation of the Runge-Kutta extrapolation code to determine muon decay points.
- general development and de-bugging of the software chain.

Development of the software for Mu2e is ongoing.

- used to estimate the expected radiation dose in critical component design.
- used to estimate background to genuine conversion electrons and to develop a background suppression algorithm.
- used to develop track reconstruction in the straw tracker.
- used to simulate expected response of test beam calorimeter prototypes.