The Mu2e Experiment
Calibrating the Tracker Momentum Scale Using DIOs at 0.5 Tesla

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  - The Tracker
- Tracker Calibration
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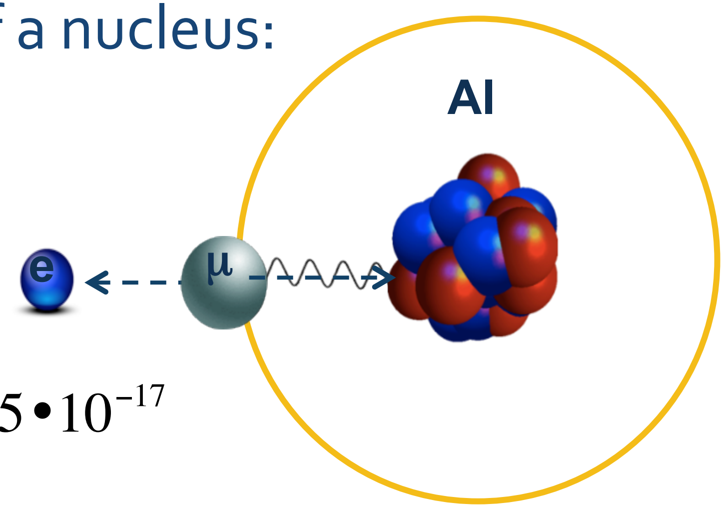
- Time Required for Calibration
- To Do List

Physics: Muon-to-Electron Conversion

- The goal of the Mu2e Experiment is the search for the conversion of muons into electrons in the field of a nucleus:

$$\mu^- + N \rightarrow e^- + N$$



- Single event sensitivity:

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \rightarrow e^- + A(Z,N))}{\Gamma(\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N))} \sim 2.5 \bullet 10^{-17}$$

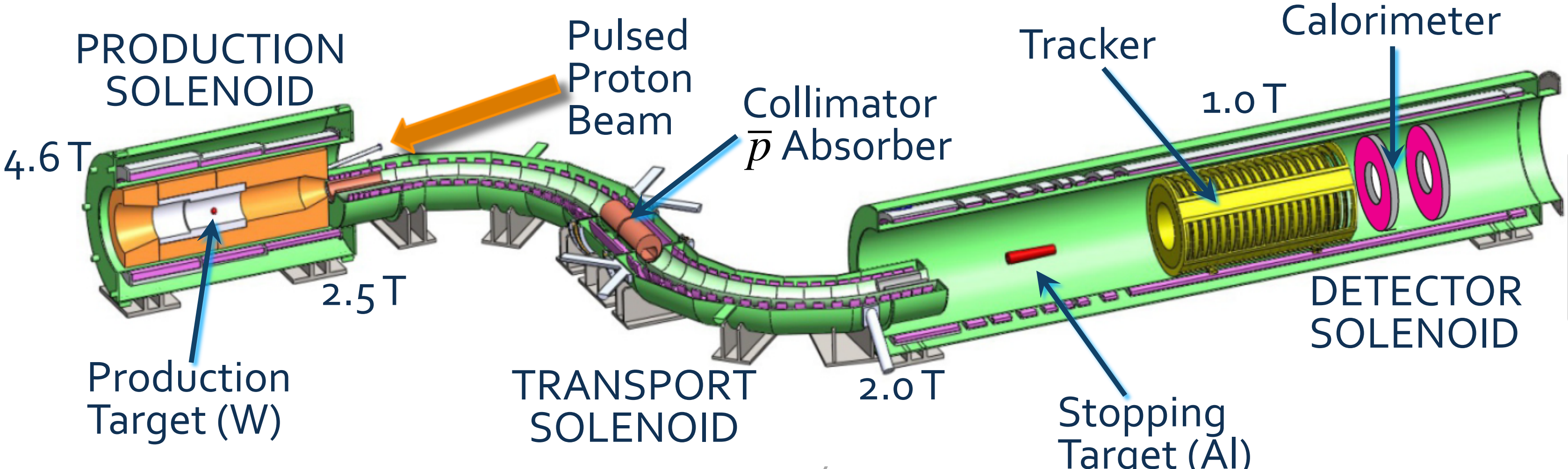
$\approx 10^4$ times better than the previous experiments

- Signal: Coherent conversion because the muon recoils off the entire nucleus and the kinematics are those of two-body decay:

$$E_{\mu e} = m_\mu - E_b(Z) - R_N(A) = 104.97\,MeV$$ (for Aluminum)

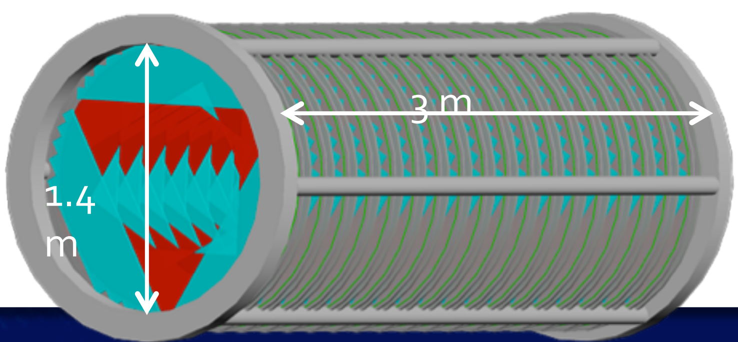
Mu2e Design: Overview (1/2)

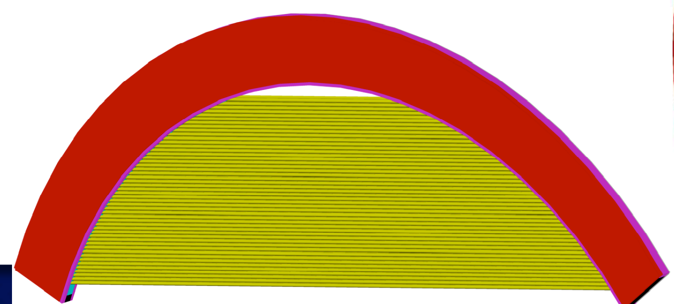
- Production Solenoid (PS): pulsed 8 GeV kinetic energy proton beam hits the tungsten production target and produces pions which decay into muons
- The muons are transported via the Transport Solenoid (TS) to the Detector Solenoid (DS) where they hit the aluminum stopping target
- Conversion electrons (CE) produced in the stopping target are measured in the tracker and the calorimeter

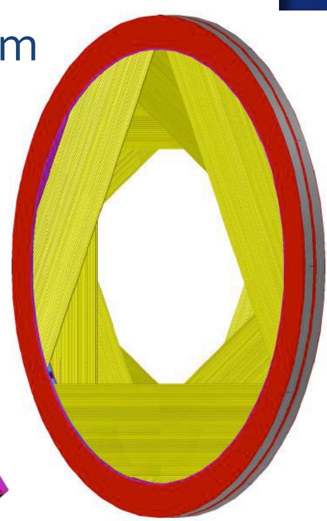


Mu2e Design: The Tracker (2/2)

- Measurement of the electron track momentum is THE Mu2e measurement
- The Mu2e tracker resides in the warm bore (evacuated to 10^{-4} Torr) of a superconducting solenoid: nearly uniform magnetic field of 1 T in the detector region
- 3 m long, 1.4 m in diameter; 23,040 straw tubes (5 mm diameter, 15 µm metalized mylar wall, 25 µm gold-plated tungsten sense wire)
- 2 layers of 48 straws make a panel, 6 rotated panels in 2 different planes make a station, 20 stations form the tracker
- gas mixture: $Ar:CO_2$ 80:20; active radial area from about 40 cm to 70 cm
- Readout: TDC, time division, ADC to separate highly ionizing protons

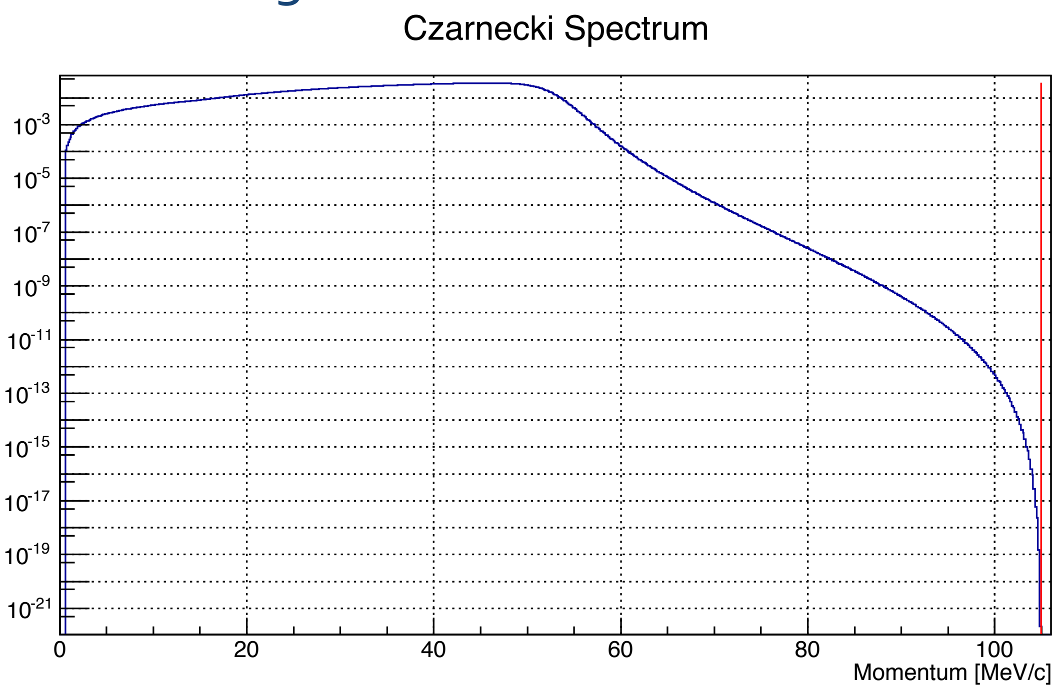






Tracker Calibration: DIO electrons (1/4)

- The main source of background, about 50%, is expected to be due to decay-in-orbit (DIO) electrons
  - the reconstructed momentum of candidate Conversion Electrons (CE) is the only means to reject the otherwise irreducible DIO background



Czarnecki et al., Phys. Rev. D 84, 013006 (2011)

Tracker Calibration: Goal (2/4)

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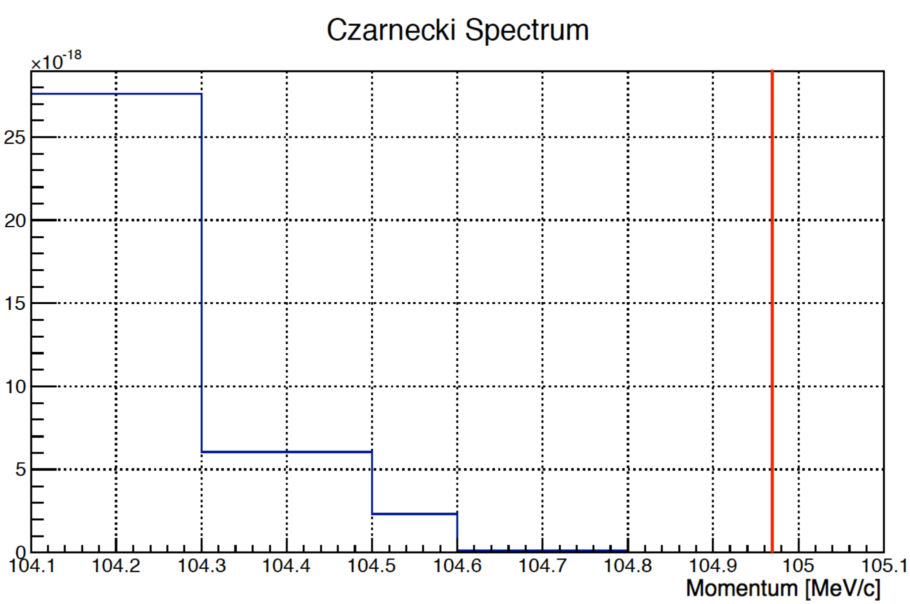
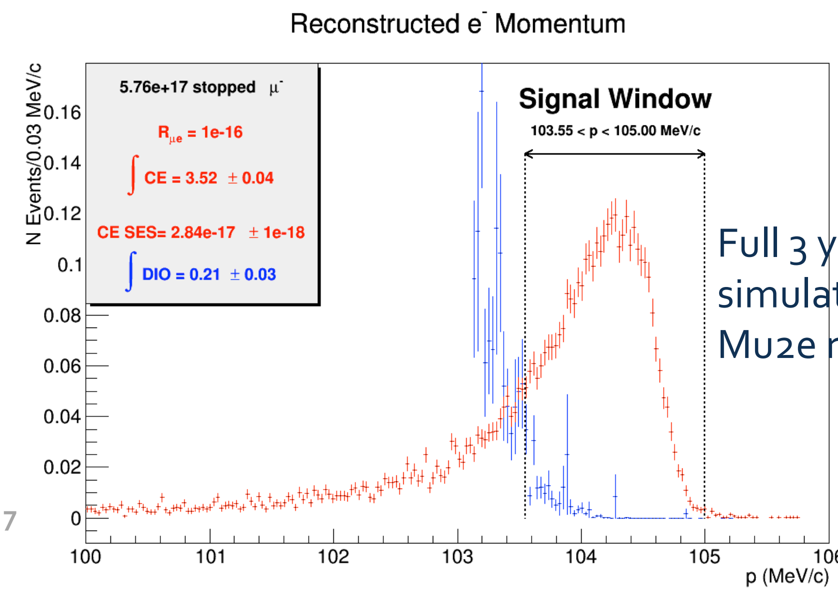
- The success of the experiment depends critically on the tracker calibration: alignment, measurement of the drift velocity and the amount of material in the tracker, determination of the false curvature and the momentum scale
- The momentum resolution in the high-end tail near the CE endpoint is critical to determine the separation between CEs and DIOs and thereby the sensitivity of the experiment

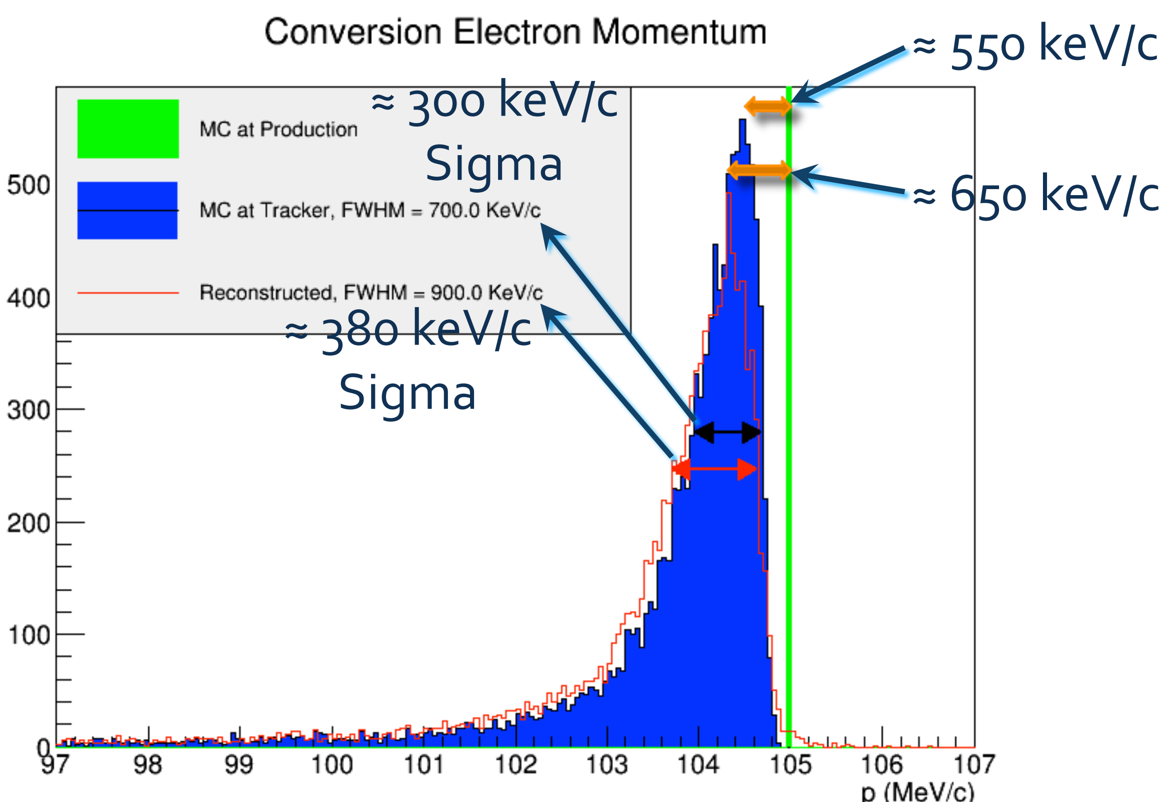




Full 3 years simulated Mu2e run

Tracker Calibration: Requirements (3/4)

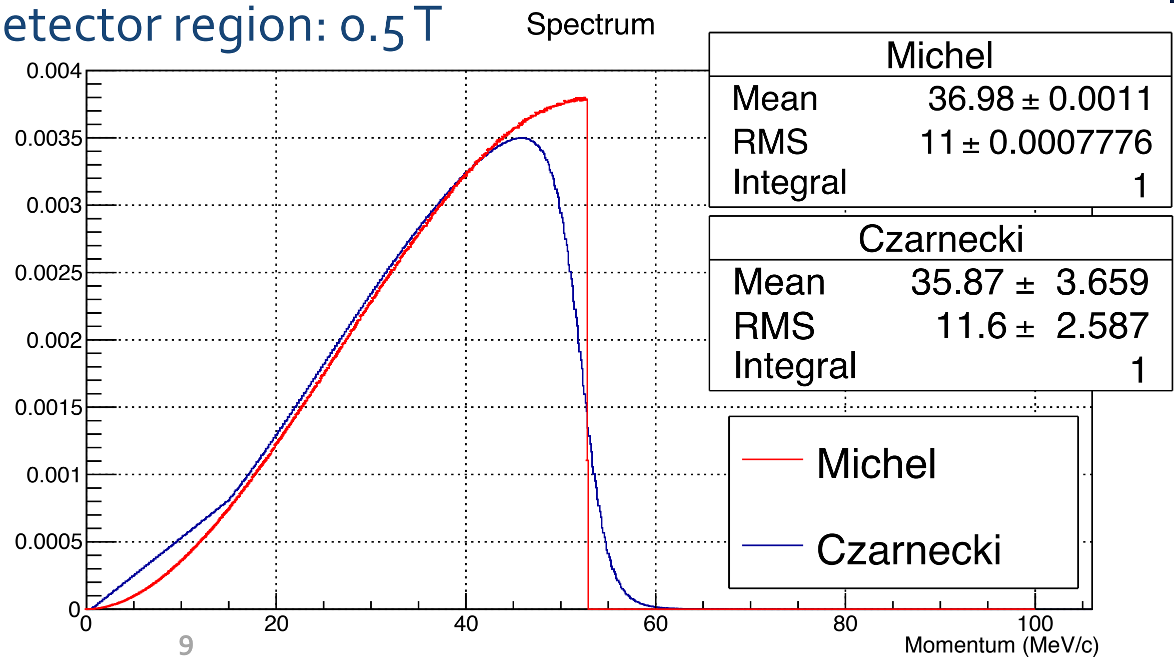
- Want systematics in the momentum reconstruction to be small compared to fluctuations of the energy losses



- Momentum scale accuracy: 0.1% (≈ 100 keV/c)
- Uncertainty on the DIO < 25%

Tracker Calibration: Strategy (4/4)

- In order to calibrate the tracker momentum response, a source of particles with known momentum is required
- Michel edge of the momentum spectrum for e^-/e^+ from $\mu \rightarrow e\,\nu\,\nu$ decays
  - Exploit the main background to calibrate the tracker
  - Dedicated runs:
    - reduced B in the detector region: 0.5 T
    - reduced beam intensity because of the high rate
  - Need to "extrapolate" the calibration to the nominal field (1 T)



Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (1/9)

- Model:

$$c_{reco} = c_{true} + \beta + \alpha \cdot c_{true} + \ldots$$

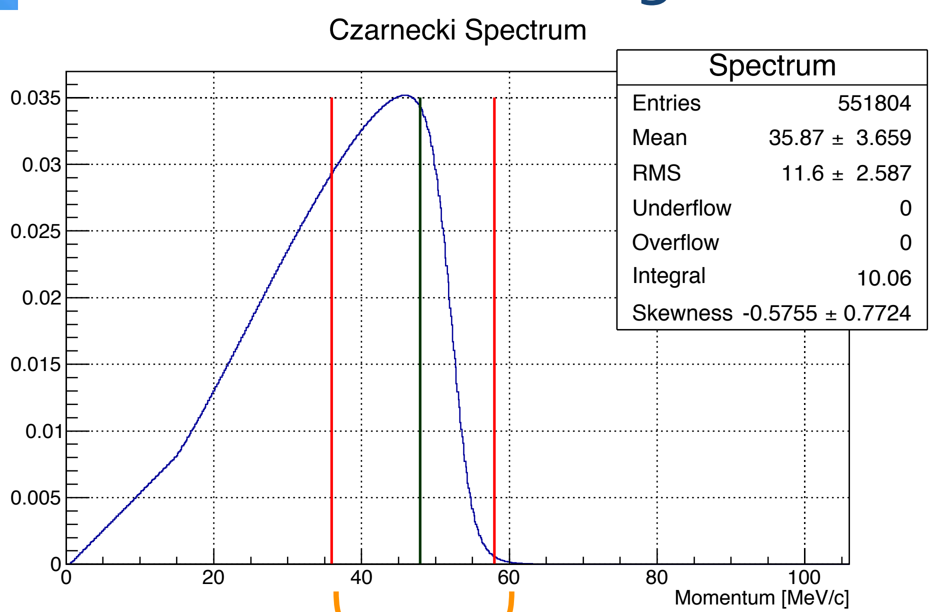
C: curvature
β: false curvature
α: momentum scale

- Normal acquisition runs: B = 1 T, ≈ 2 × 10^4 DIOs/μBunch
- Most DIO electrons go into the central hole
- Calibration runs at 0.5 T require reduced beam intensity
- A factor of 10^3 seems achievable: 10 due to the number of protons/μBunch and factor of 100 could come from defocusing the beam, resulting in ≈ 20 DIOs/μBunch

Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (2/9)

- Effect of the false curvature β is small
- Signal sample: generate in average 20 DIO electrons/μBunch at 0.5 T
- Tried to factorize the problem: tracker momentum response ⊗ tracking efficiency ⊗ czarnecki spectrum → expected momentum spectrum

Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (3/9)

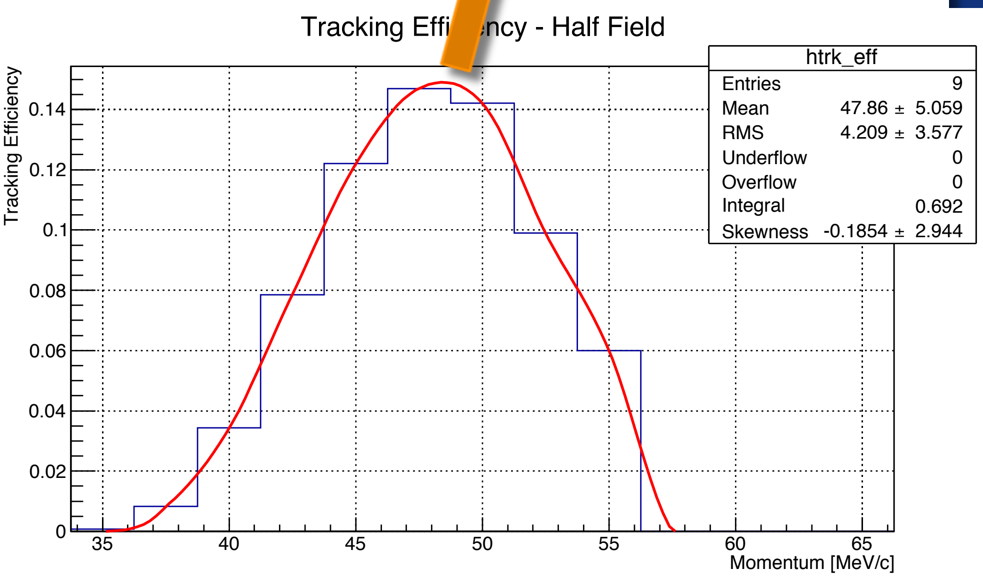


$p_{max\_eff} \approx 48$ MeV/c

Acceptance:

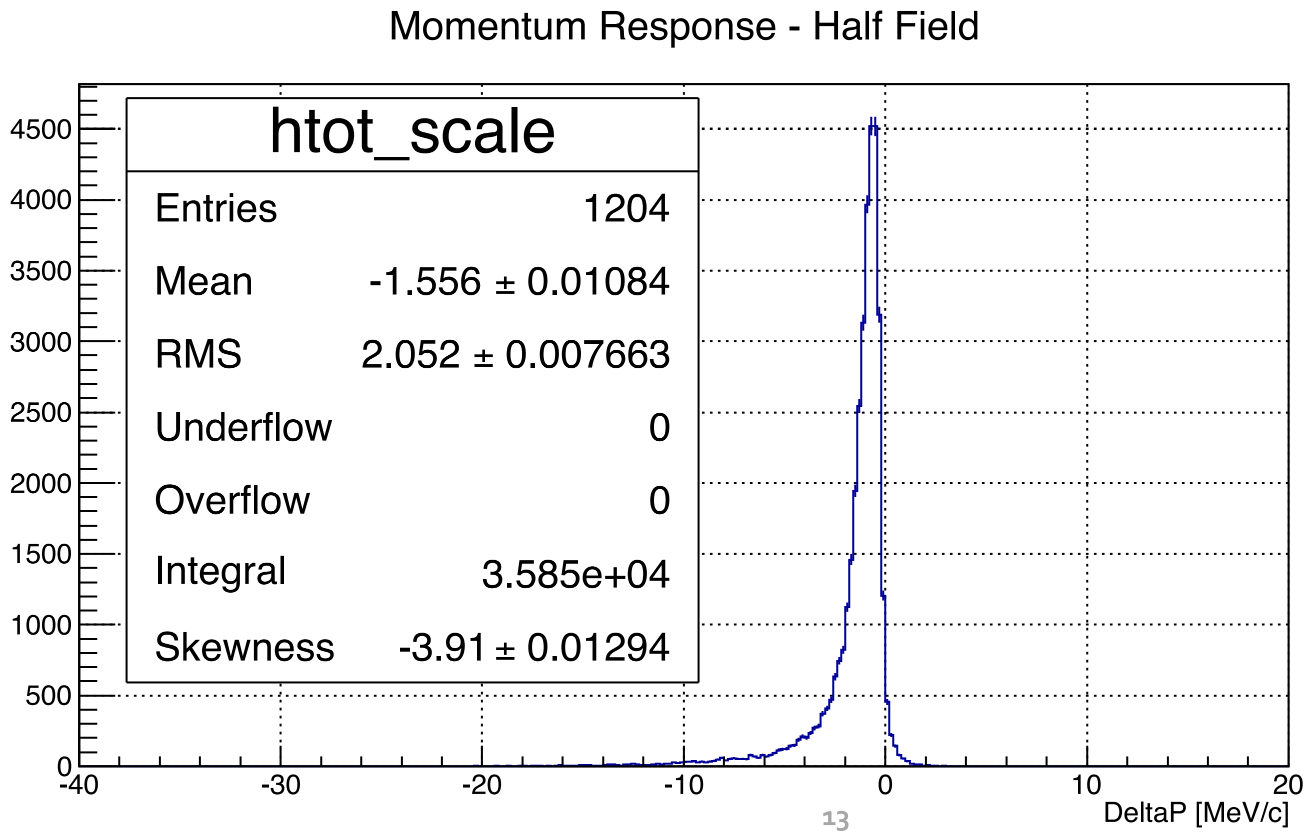
$\approx (1 \pm 20\%) \times p_{max\_eff}$

Narrow band device



Calibrating the tracker momentum scale using DIOs at 0.50 Tesla (4/9)

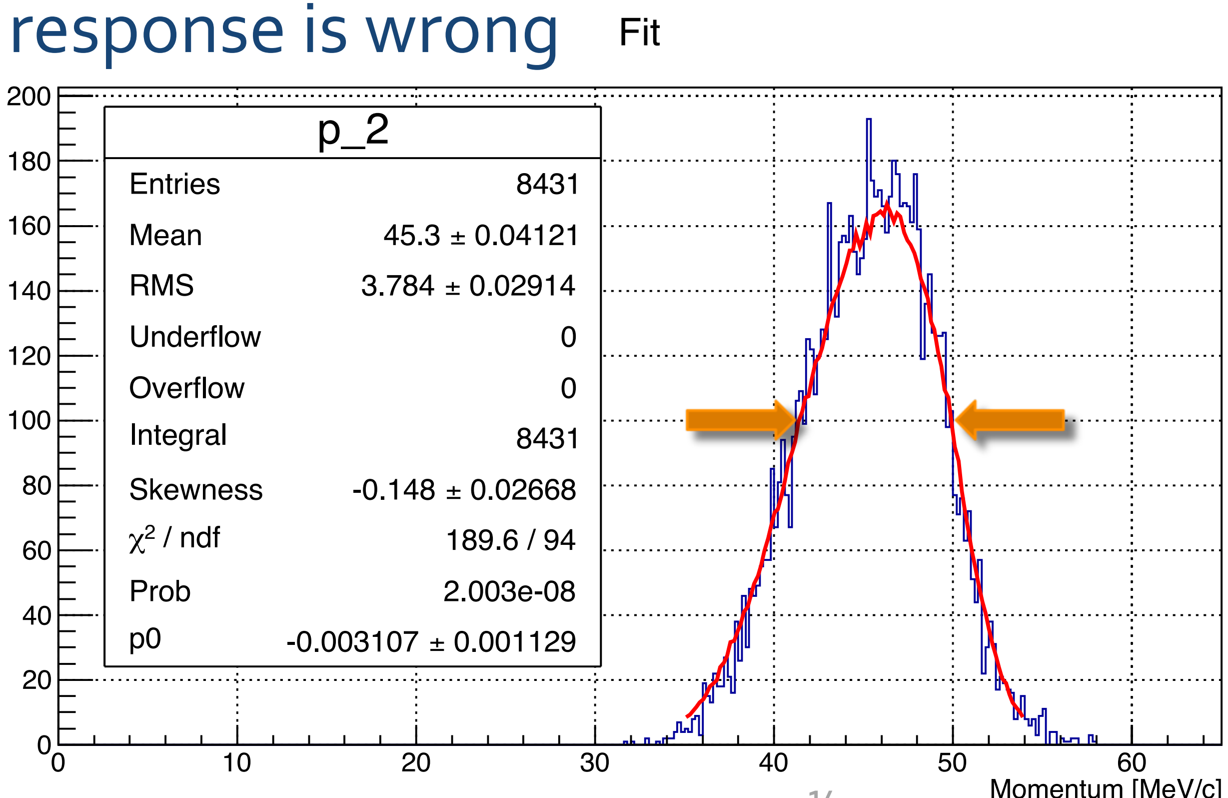
- Assuming that the momentum response does not change by varying the momentum



Tracker Momentum Response

Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (5/9)

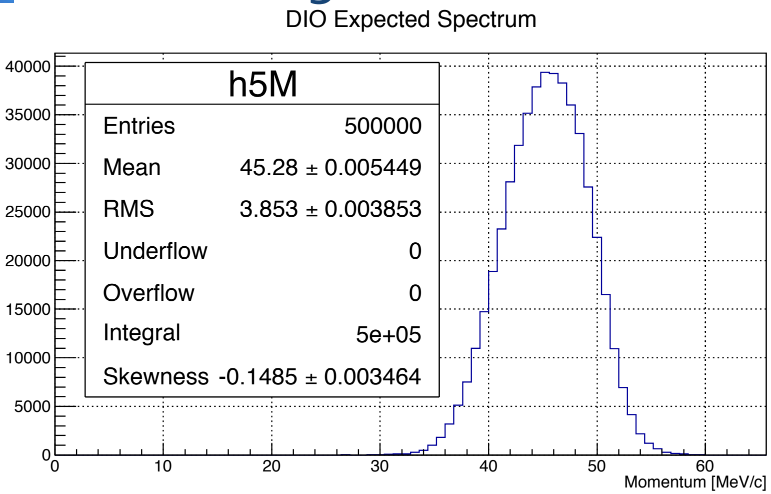
- At the required level of accuracy (0.1%) verified that the assumption of momentum-independent tracker response is wrong



$\alpha = -0.003 \pm 0.001$

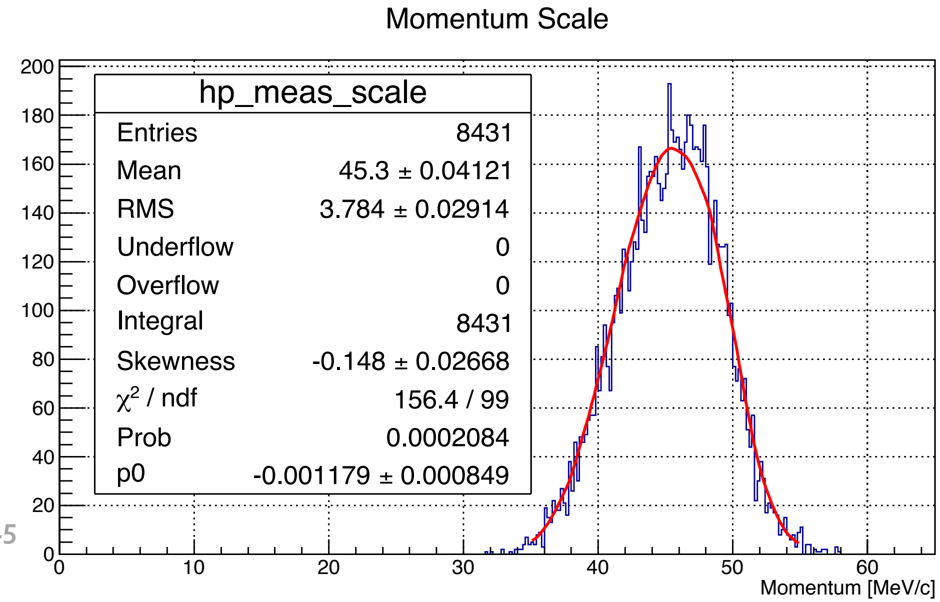
Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (6/9)

- Reconstruct the expected momentum spectrum by sampling a high statistics DIO sample used as a template



Interpolation of the expected momentum spectrum: function model to fit the reconstructed momentum spectrum

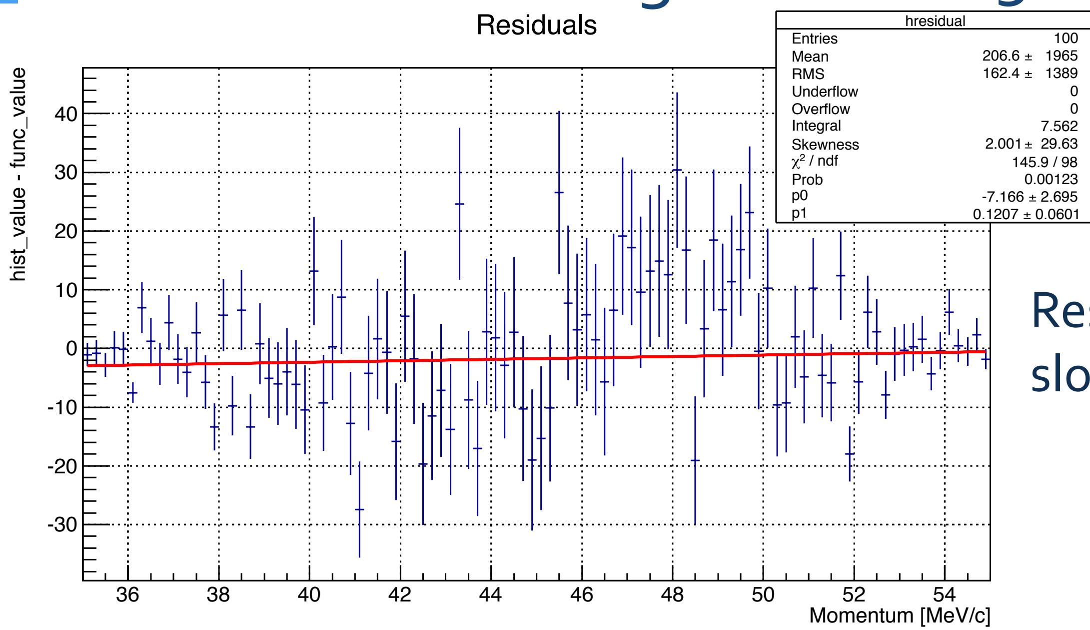
$\alpha = -0.0012 \pm 0.0008$



Track quality cut: $\chi^2/dof < 3$

500,000 generated events; x2 more statistics would allow to reach ≈ 100 keV/c (0.1%) accuracy → 10^6 DIOs

Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (7/9)

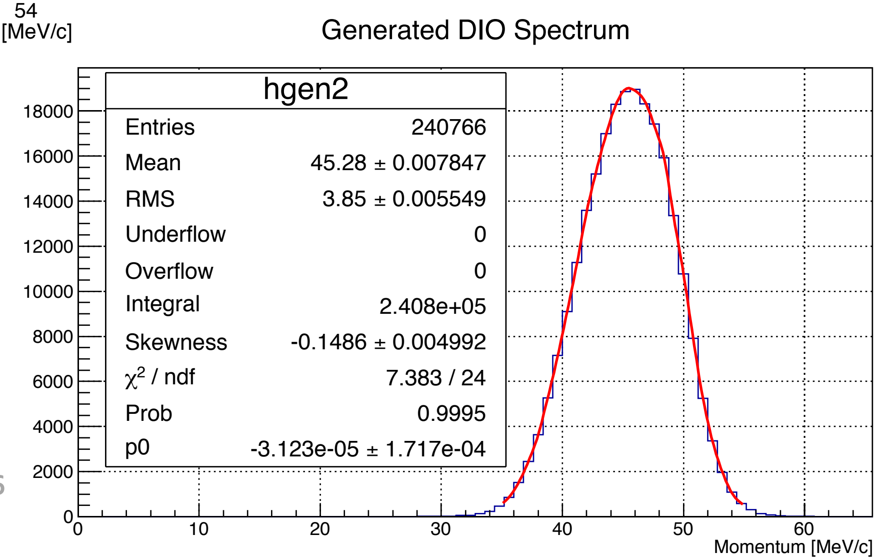


Residuals:

slope = 0.12 ± 0.06

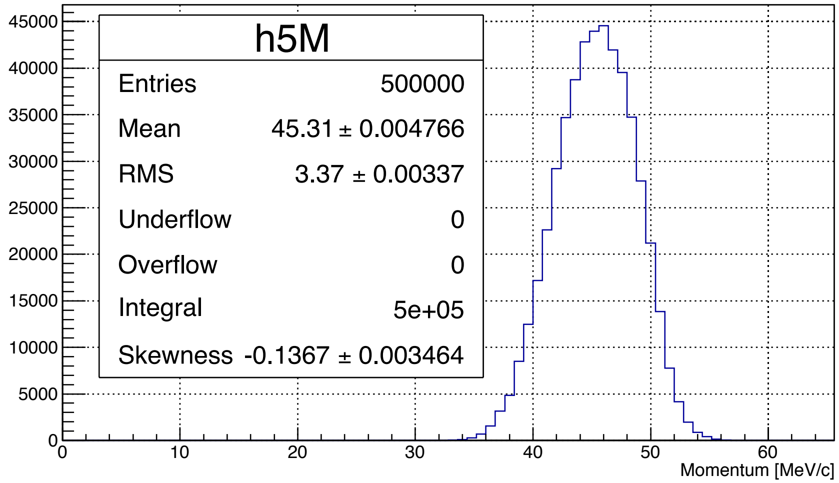
Track quality cut: $\chi^2/\mathrm{dof} < 3$

Check the systematics introduced by the fit function



Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (8/9)

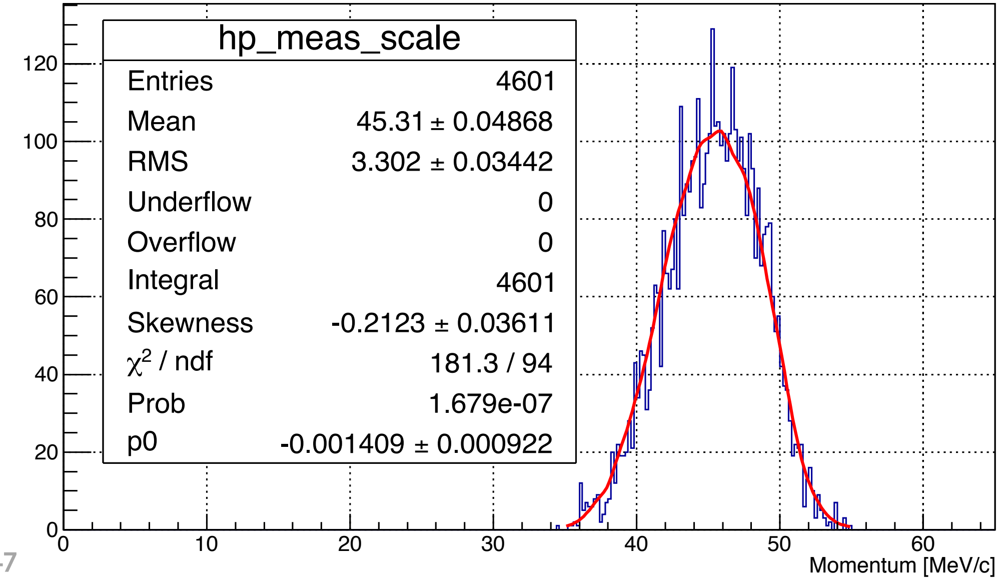
DIO Expected Spectrum



Expected momentum spectrum

$\alpha = -0.0014 \pm 0.0009$

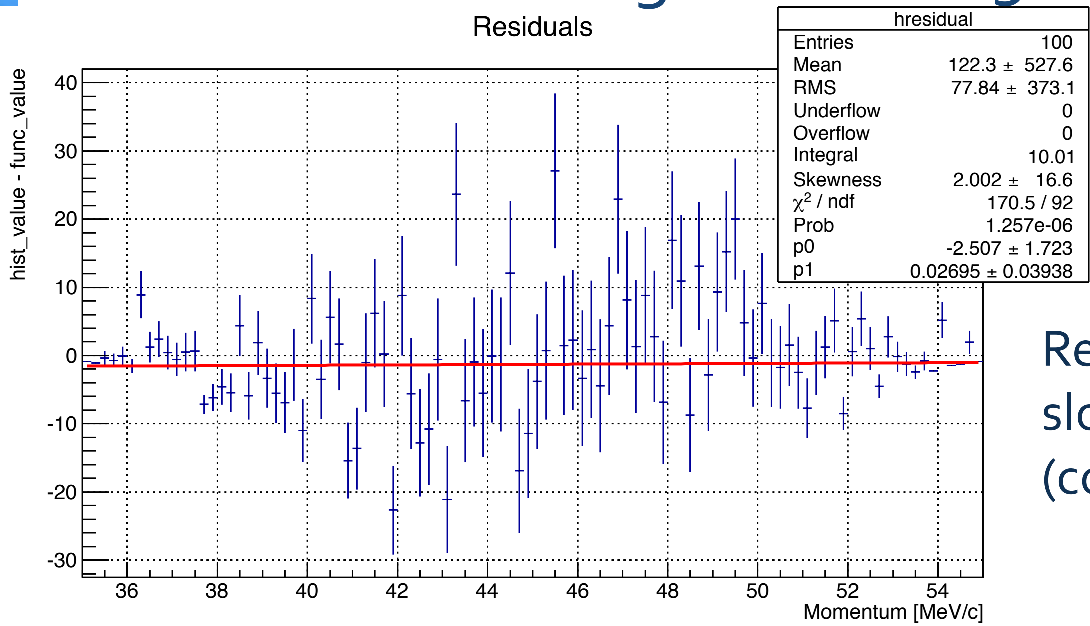
Momentum Scale



Standard set of track quality cuts

500,000 generated events;
x2 more statistics would allow to reach ≈ 100 keV/c (0.1%) accuracy
→ 10^6 DIOs

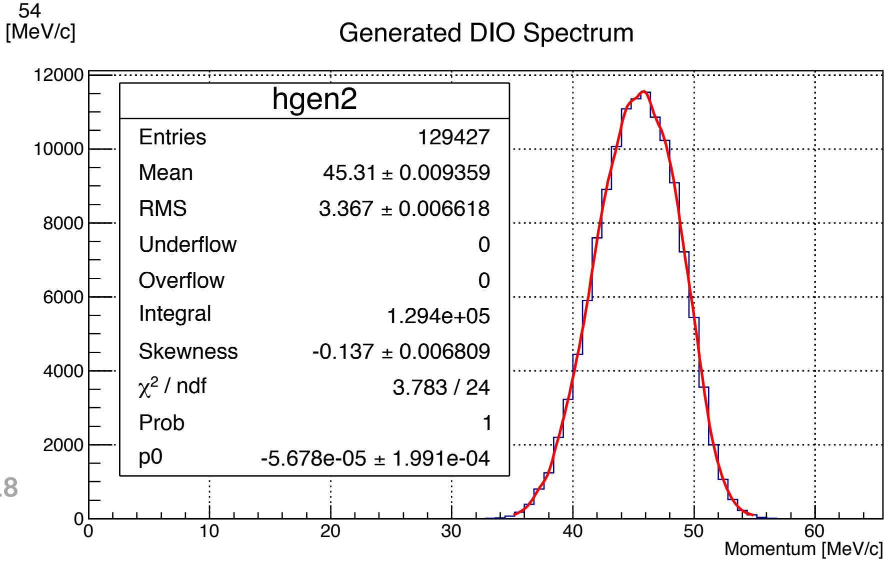
Calibrating the tracker momentum scale using DIOs at 0.5 Tesla (9/9)



Residuals:
slope = 0.03 ± 0.04
(compatible with zero…?)

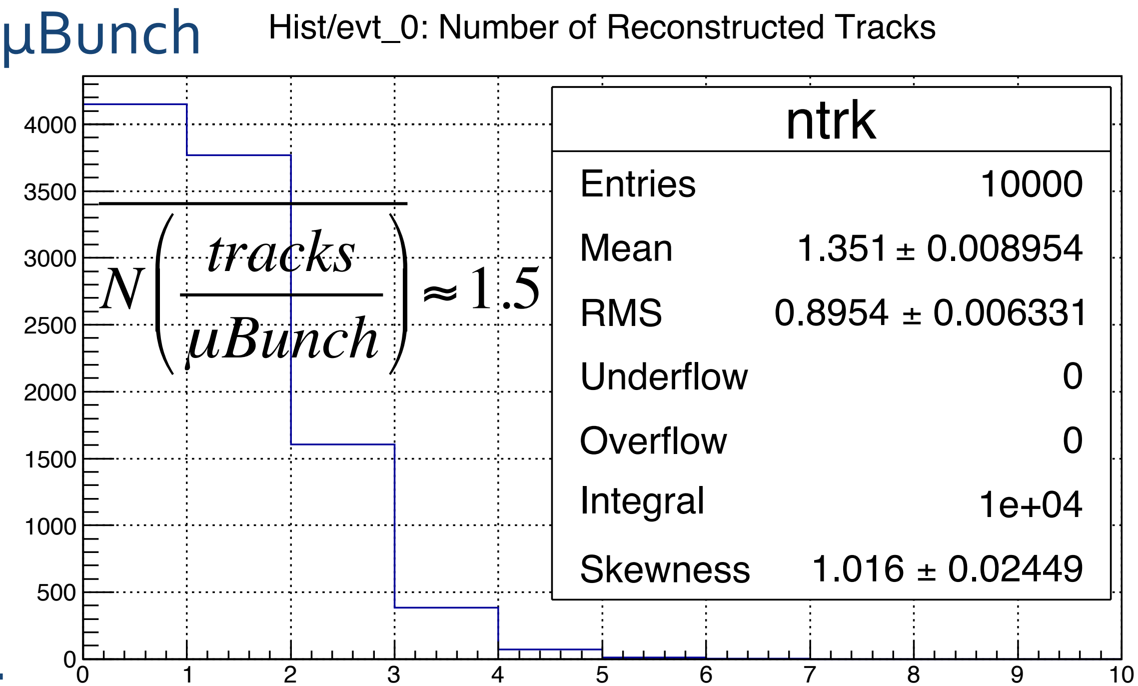
Standard set of track quality cuts

Check the systematics introduced by the fit function



Time Required for Calibration (1/3)

- Dedicated runs required for calibration: expected ≈ 20 DIOs/μBunch
- Suppose also the backgrounds scale by 10^{-3} factor: DIOs dominate the event size



$$\overline{N\left(\frac{tracks}{\mu Bunch}\right)} \approx 1.5$$

- No trigger so the required bandwidth:

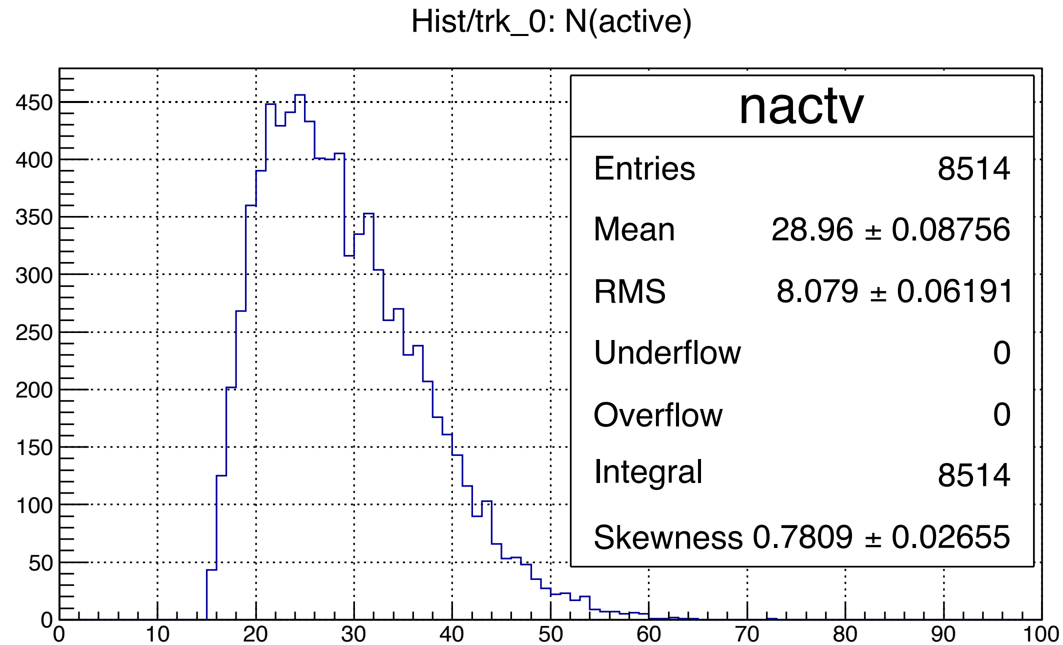
$$B\left(\frac{Bytes}{s}\right) = N\left(\frac{Bytes}{hit}\right) \times \overline{N\left(\frac{hits}{\mu Bunch}\right)} \times N\left(\frac{\mu Bunch}{s}\right)$$

Time Required for Calibration (2/3)

$$\overline{N\left(\frac{hits}{\mu Bunch}\right)} \approx 50 \leftarrow 30\overline{\left(\frac{hits}{track}\right)} \times 1.5\overline{\left(\frac{track}{\mu Bunch}\right)}$$

$$N\left(\frac{\mu Bunch}{s}\right) \approx 192000$$

≈ 256,000 for each supercycle, 1.33 s



$$N\left(\frac{Bytes}{hit}\right) \approx 12 \leftarrow$$ 2 x 16 bits + 6 x 10 bits = 92 bits

(2 x 16 bits: TDC; 6 x 10 bits: ADC)

Time Required for Calibration (3/3)

$$B \approx 120\,\frac{MBytes}{s} \;\rightarrow\; \approx 100000\,\frac{events}{s} \;\leftarrow\; \approx 1200\,\frac{Bytes}{event}$$

$\approx 10^6$ required events → $\approx$ 10 seconds needed for calibration

ORDER OF MAGNITUDE

VERY PROMISING

Data Logger is capable of reading and writing the disk array at a maximum rate of ≈ 600 MBytes/s → maximum event rate that can be handled ≈ 500,000 events/s

FEASIBLE

To Do List

- Deal with current issues
- Measure the false curvature β
- Radiative corrections
- Full simulation included all backgrounds
- Introduce the false curvature and momentum scale in the simulation
- Use μ^+:
  - Only stopped (μ^- captured): better defined edge in momentum spetrum → better resolution
  - Need to rotate TS collimators (positively charged particles): required days to perform calibration
  - Problably to use together with μ^- (fast calibration)

Thank you for the attention

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Backup Slides

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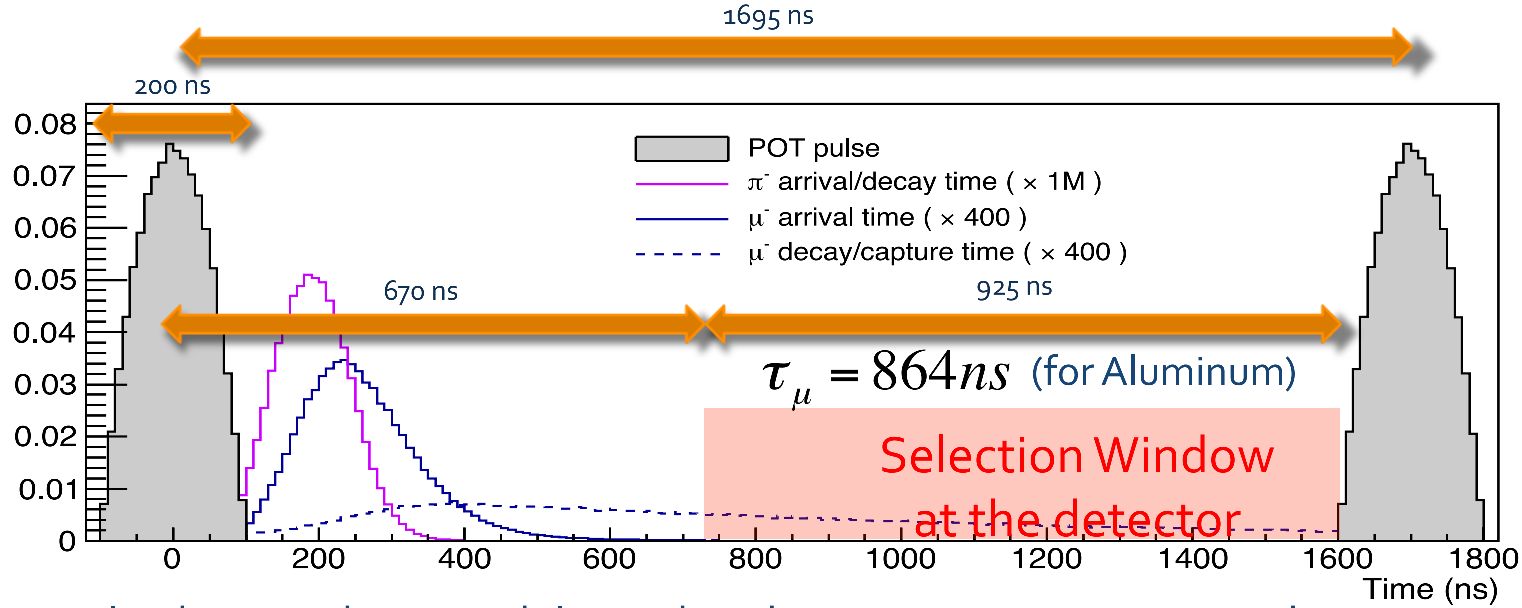
Physics: CLFV

- Before the discovery of neutrino oscillations: lepton flavor changing processes forbidden in the Standard Model (SM)
- After the discovery of neutrino oscillations: mixing among lepton families → lepton flavor violating (LFV) processes
- The rate at which charged lepton flavor violation (CLFV) occurs is model dependent and can vary over many orders of magnitude:
  - SM extension results in an amplitude of the process: $\left(\frac{\Delta m_{ij}^2}{M_W^2}\right)^2 < 10^{-50}$
  - New Physics (NP): charged leptons mixing

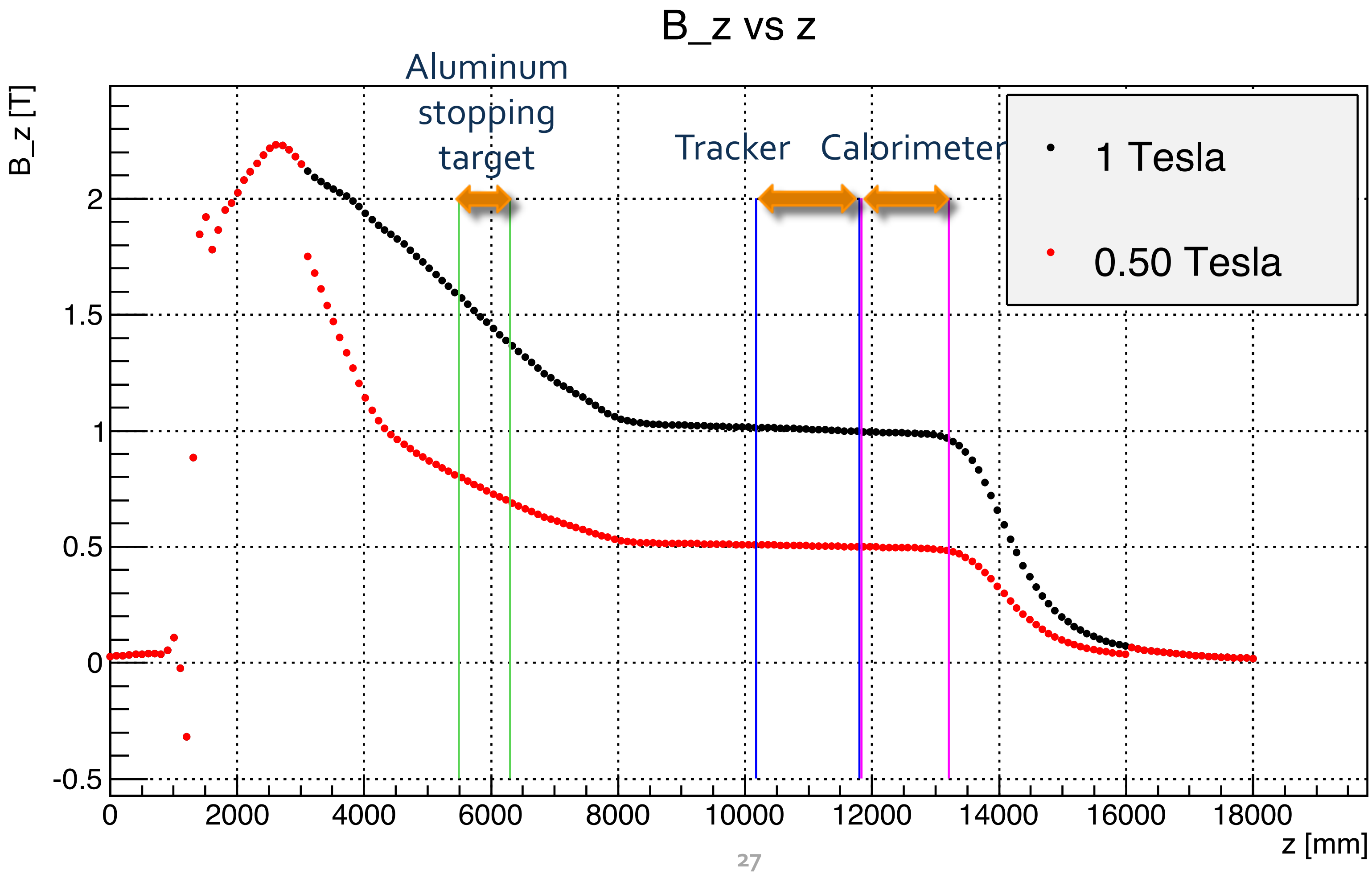
unobservable

Pulsed Proton Beam



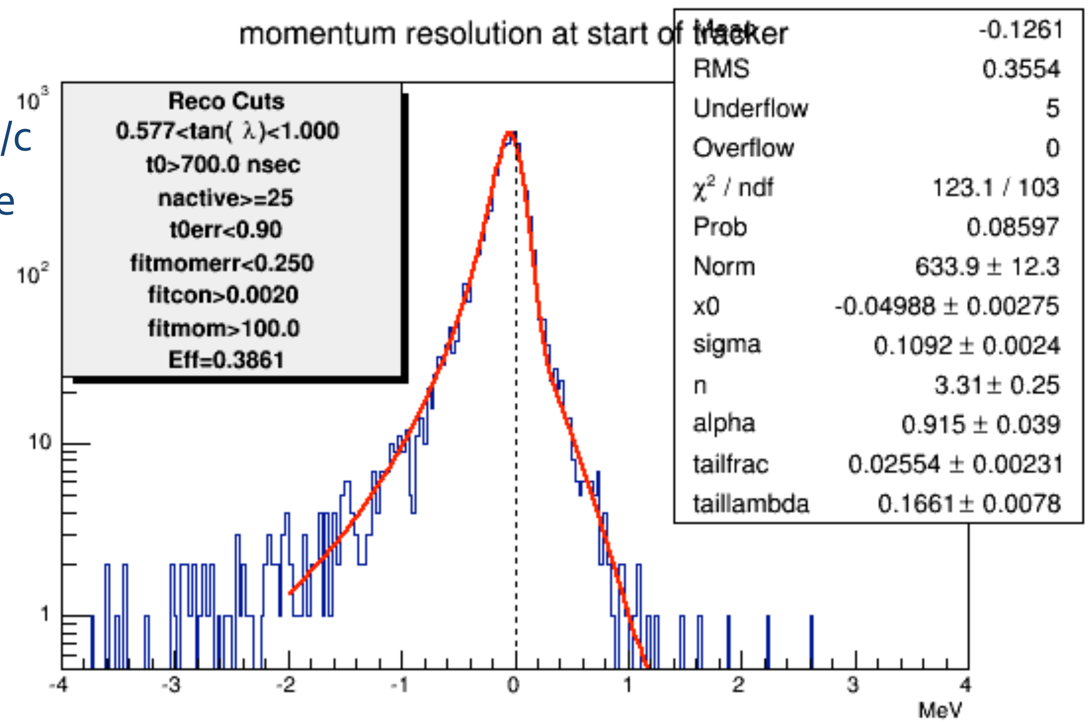
- A pulsed proton beam is delivered to the Mu2e experiment in order to suppress the backgrounds between pulses
- The acquisition time window is placed after 670 ns with respect to the center of the μBunch in order to reject electrons coming from the decay of pions
- Beam extinction must be as low as possible (< 10^{-10}) because protons between two consecutive pulses is a source of additional background

Detector Solenoid (DS): Magnetic Field Map



Tracker Intrinsic Resolution

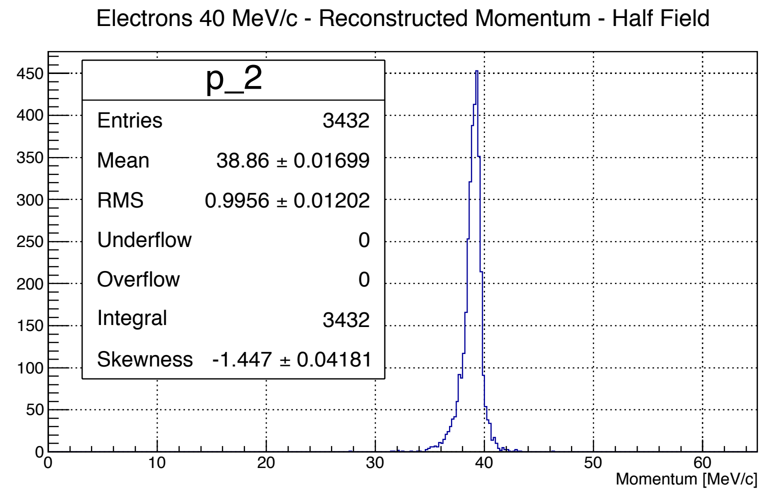
- The intrinsic tracker resolution is shown in figure below
- A fit is performed with a Crystal Ball function in order to model the energy loss in the tracker:
  - Core resolution ≈ 110 KeV/c
  - Exponential slope ≈ 200 KeV/c
  - Relative area of the high-side exponential tail ≈ 2%
- The 50 keV/c shift is due to inconsistency between the energy loss models used in simulation and reconstruction

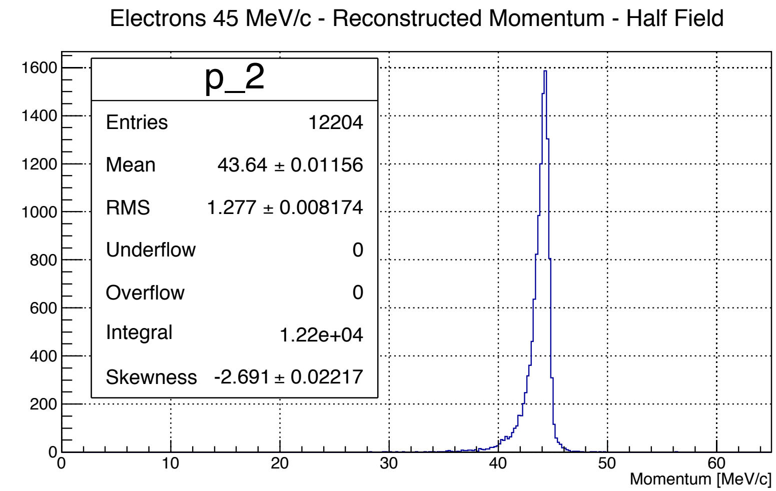


“Set C” cuts

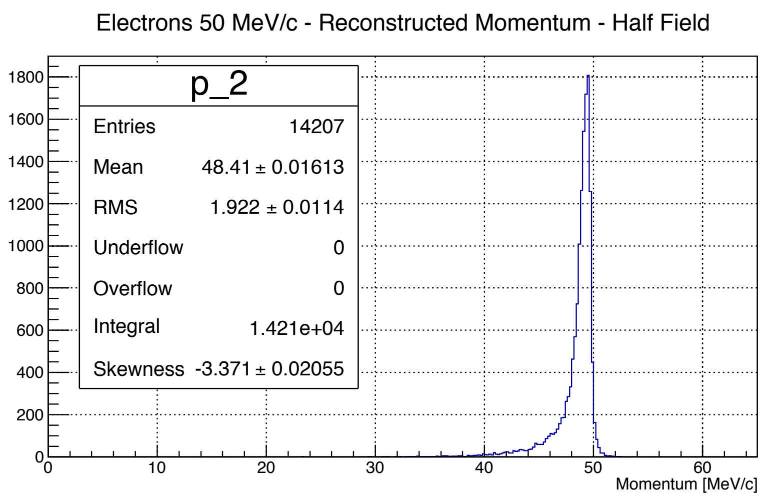
Parameter	**Cut Value**
Kalman Fit Status	Successful Fit
Number of active hits	$N_{active} \geq 25$
Fit consistency	$\chi 2$ consistency > $2x10^{-3}$
Estimated reconstructed momentum error	$\sigma_p < 250$ keV/c
Estimated track t_0 error	$\sigma_t < 0.9$ nsec
Minimum track transverse radius	-80 mm < d_0 < 105 mm
Maximum track transverse radius	450 mm < d_0+2/ω < 680 mm
Track t_0 (livegate)	700 ns < t_0 < 1695 ns
Polar angle range (pitch)	$45° < \theta < 60°$

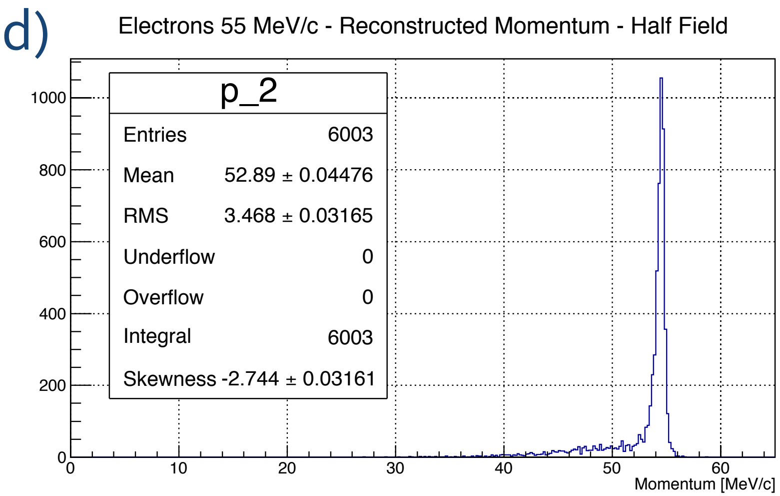
Calibrating the tracker momentum scale using DIOs at 0.50 Tesla





Tracker momentum response for different momentum values at half magnetic field (100,000 monochromatic electrons generated)





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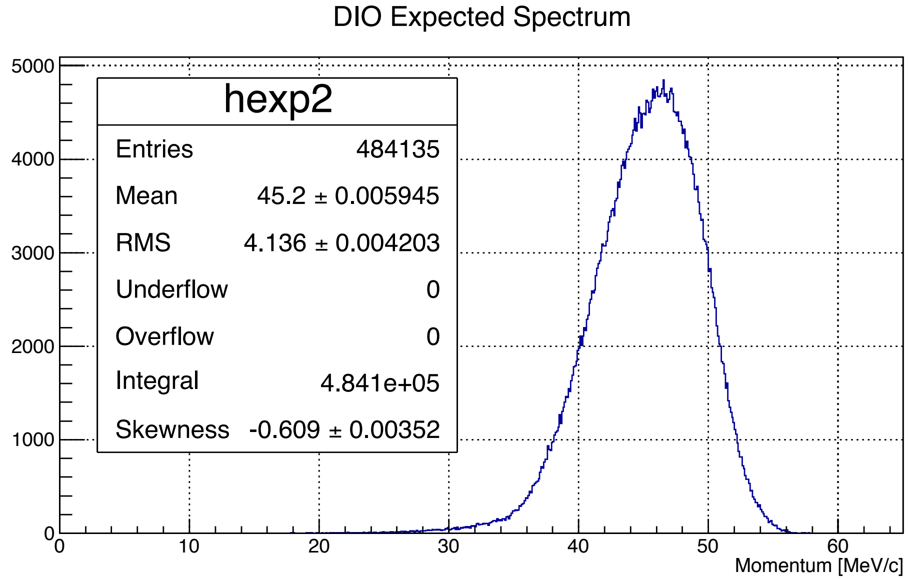
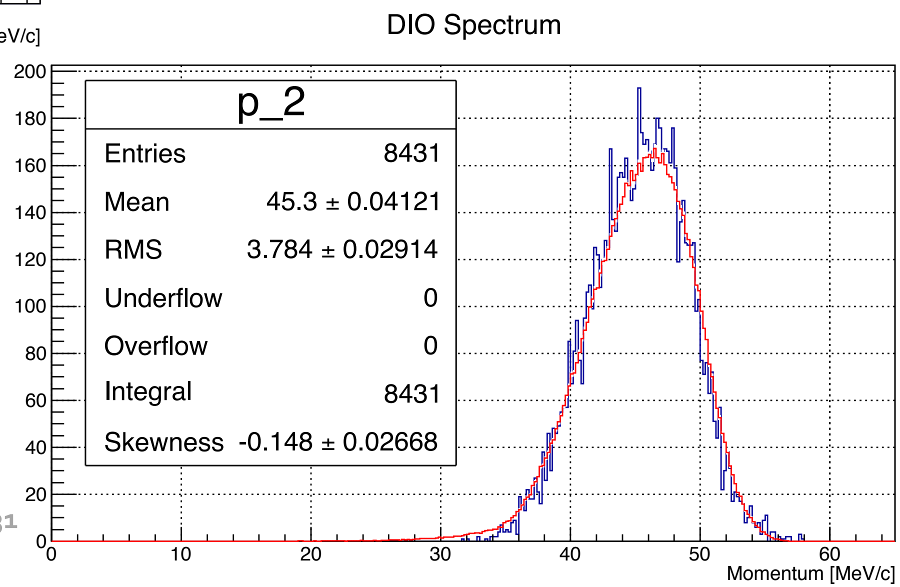
Calibrating the tracker momentum scale using DIOs at 0.50 Tesla

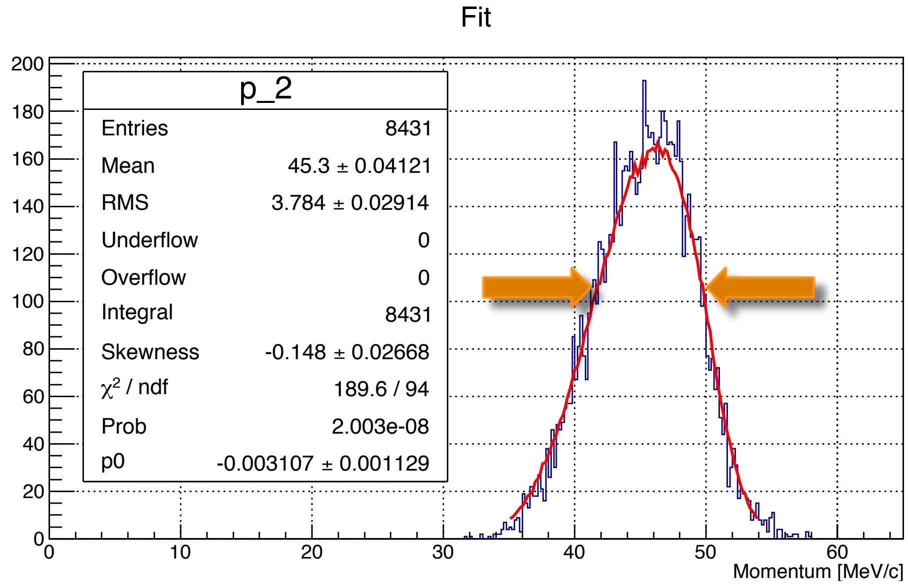


Interpolation of the expected momentum spectrum: function model to be used to fit the reconstructed momentum spectrum



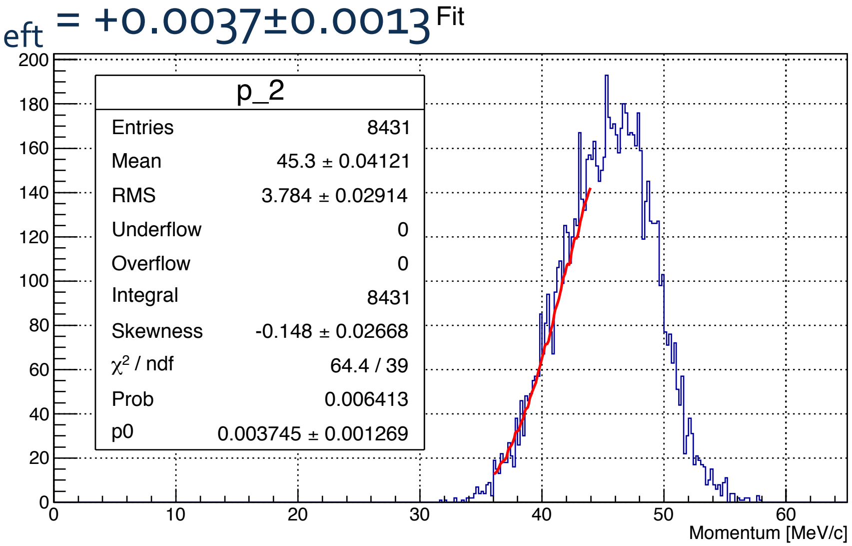
Overlap between the reconstructed (blue) and the expected (red) spectrum

Calibrating the tracker momentum scale using DIOs at 0.50 Tesla

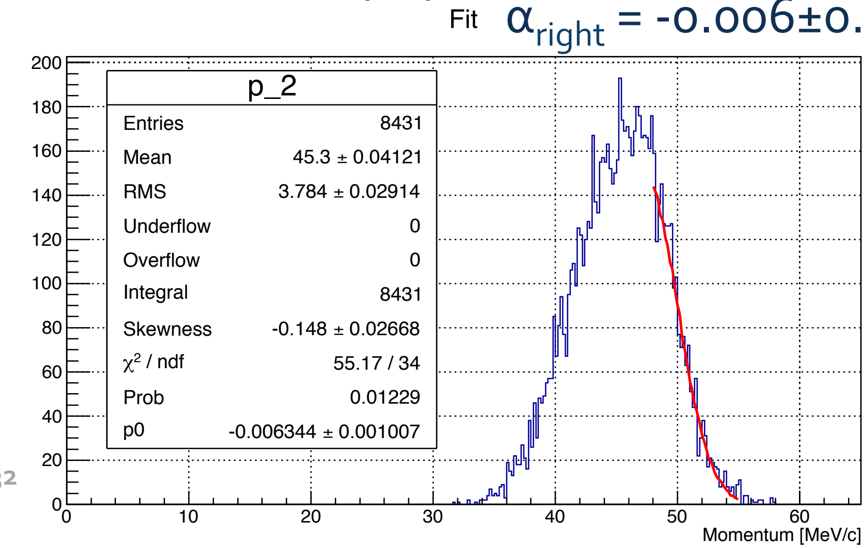


$\alpha = -0.003 \pm 0.001$

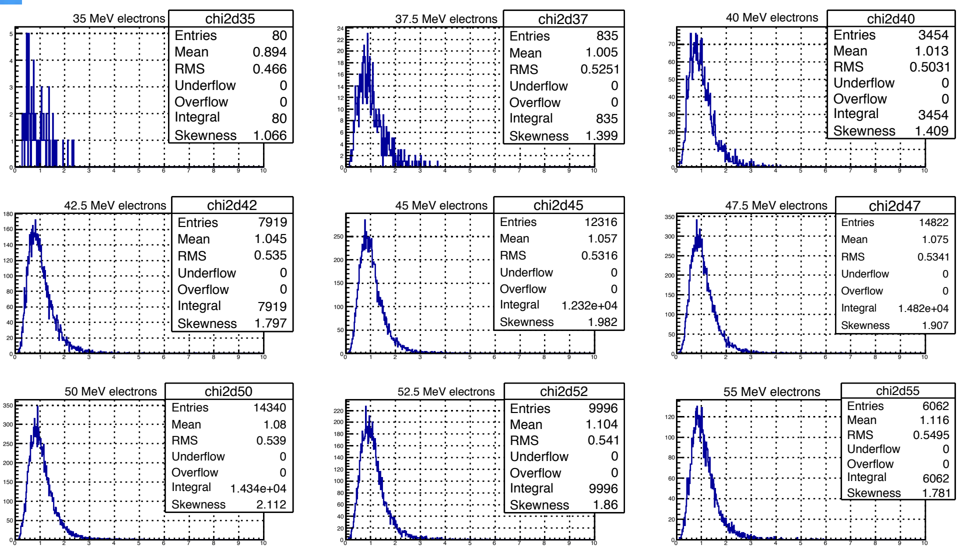
$\alpha_{left} = +0.0037 \pm 0.0013$

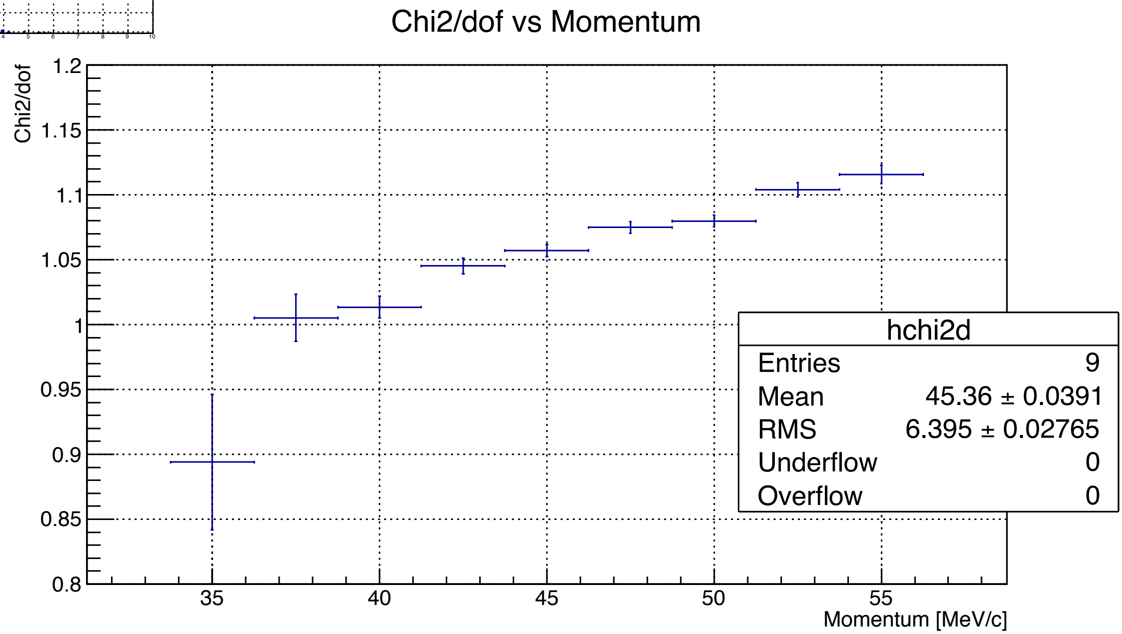


$\alpha_{right} = -0.006 \pm 0.001$



Chi2/DoF


35 MeV electrons
chi2d35
Entries 80
Mean 0.894
RMS 0.466
Underflow 0
Overflow 0
Integral 80
Skewness 1.066
37.5 MeV electrons
chi2d37
Entries 835
Mean 1.005
RMS 0.5251
Underflow 0
Overflow 0
Integral 835
Skewness 1.399
40 MeV electrons
chi2d40
Entries 3454
Mean 1.013
RMS 0.5031
Underflow 0
Overflow 0
Integral 3454
Skewness 1.409
42.5 MeV electrons
chi2d42
Entries 7919
Mean 1.045
RMS 0.535
Underflow 0
Overflow 0
Integral 7919
Skewness 1.797
45 MeV electrons
chi2d45
Entries 12316
Mean 1.057
RMS 0.5316
Underflow 0
Overflow 0
Integral 1.232e+04
Skewness 1.982
47.5 MeV electrons
chi2d47
Entries 14822
Mean 1.075
RMS 0.5341
Underflow 0
Overflow 0
Integral 1.482e+04
Skewness 1.907
50 MeV electrons
chi2d50
Entries 14340
Mean 1.08
RMS 0.539
Underflow 0
Overflow 0
Integral 1.434e+04
Skewness 2.112
52.5 MeV electrons
chi2d52
Entries 9996
Mean 1.104
RMS 0.541
Underflow 0
Overflow 0
Integral 9996
Skewness 1.86
55 MeV electrons
chi2d55
Entries 6062
Mean 1.116
RMS 0.5495
Underflow 0
Overflow 0
Integral 6062
Skewness 1.781


Chi2/dof vs Momentum
Chi2/dof
Momentum [MeV/c]
hchi2d
Entries 9
Mean 45.36 ± 0.0391
RMS 6.395 ± 0.02765
Underflow 0
Overflow 0