A new method to calibrate the Mu2e momentum scale

CIPANP 2025, Madison, WI

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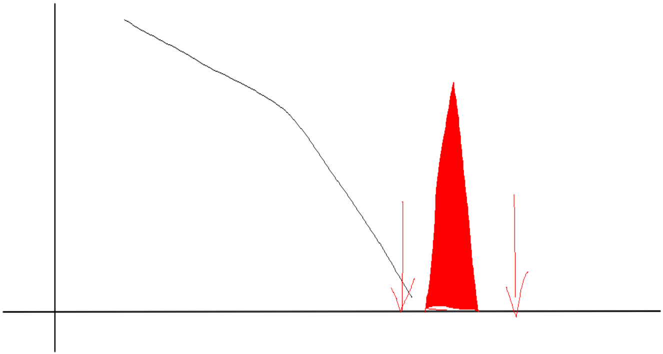
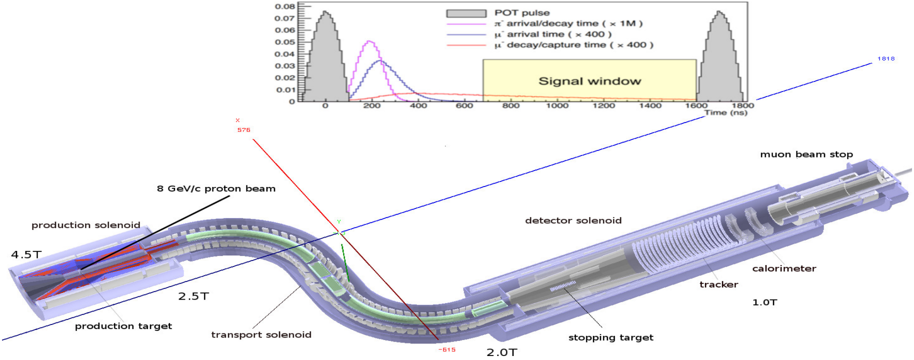
Final step of the search for $\mu^- \to e^-$ conversion on nuclei



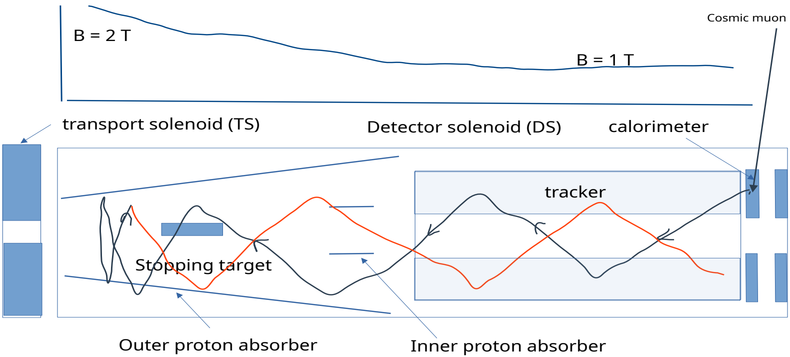
- Mu2e will search for $\mu^- \to e$ conversion on Al in two channels : $\mu^- \to e^-$ and $\mu^- \to e^+$
- The last step - look for a narrow peak at the kinematic endpoint of $e^-(e^+)$ spectrum
- expected momentum resolution - $\sim$ 1 MeV/c FWHM
- the physics requirement: $\sigma_P/P < $ 100 keV/c , or $\sigma_P/P < 10^{-3}$ at 100 MeV/c

Mu2e detector - a bird's view



- focus of this talk - what is [will be!) happening inside the the Mu2e detector solenoid (DS)

Pre-requisite to the scale calibration : calibration of the energy losses



- $P_{rec} = P_{true} - \Delta P_{eloss} + K_{scale} \cdot P_{true} + C_{misalignment} \cdot P^2$
- for Mu2e, the energy losses are the dominant source of corrections, ~ 1 MeV, or 10^{-2}
- plan to calibrate the energy losses using tracks U-turning in the DS magnetic bottle:
  - $P_1 - P_2 = 2 \times \Delta P_{eloss}$
- tracker alignment is well outside of the scope of this talk, assume done :)

Momentum scale: the magic of 10^{-3} level corrections

CDF Collaboration, Science 376, 170-176(2022)

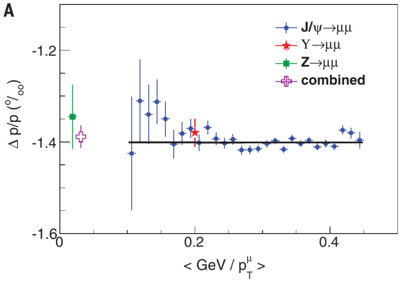
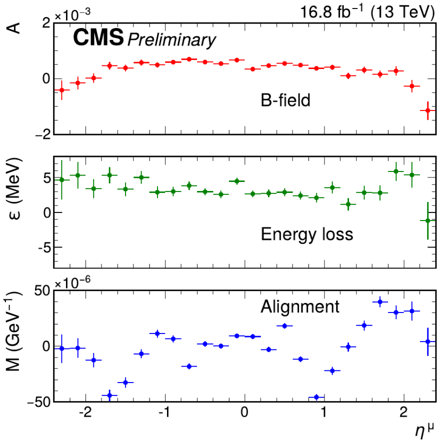


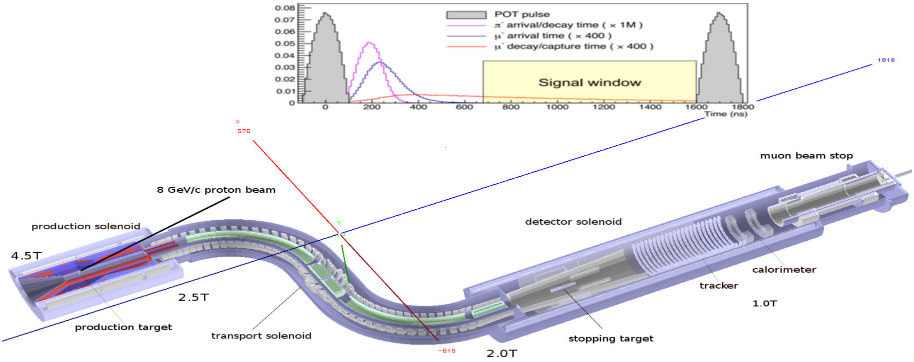
Fig. 2. Calibration of track momentum and electron's calorimeter energy.

Josh Bendavid, CERN MW seminar, Sep 17 2024



- HEP trackers seem to always require data-driven scale corrections at a level of $\sim 10^{-3}$
- MEG-II scale correction : 0.9991 ± 0.0001 (https://arxiv.org/pdf/2310.12865)

Exploiting Michel decays - how to switch to μ^+ beam ?



- the edge of the $\mu^+ \to e^+\nu\nu$ spectrum, P = 52.8 MeV/c, is an excellent calibration tool
- Mu2e runs with a negative muon beam
- to switch the beam polarity, rotate collimators in the middle of the transport solenoid by 180 deg

Michel decays

SINDRUM II, EPJC, v47, 2, p337-346 (2006)

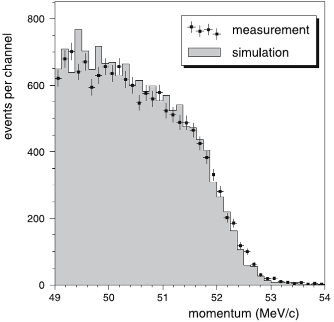
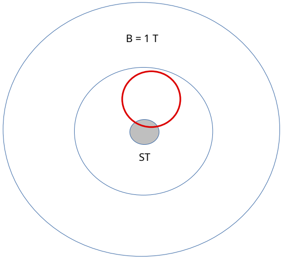
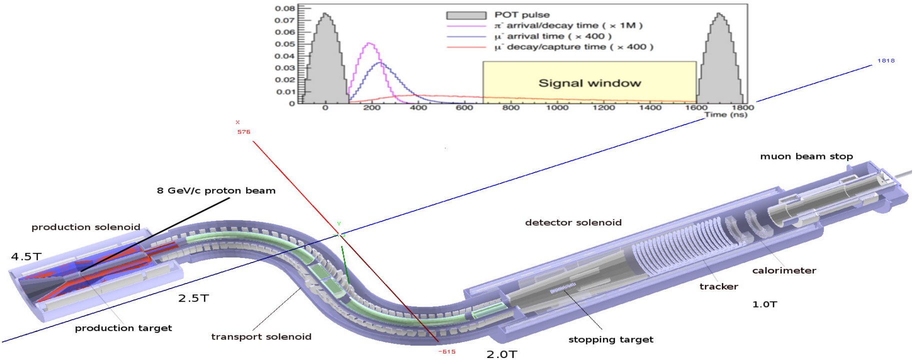


Fig. 8. Endpoint region of the positron momentum spectrum from the decay $\mu^+ \to e^+\nu\overline{\nu}$



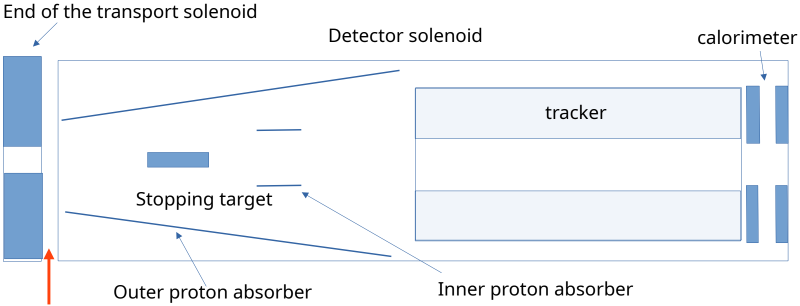
- the Mu2e detector is optimized for 100 MeV/c particles
- at nominal magnetic field B = 1T, reconstruct tracks down to P $\sim$ 80 MeV/c
- to get e^+ from Michel decays within the acceptance, need to reduce the B-field by $\sim x2$
- ... and extrapolate the scale correction back to the nominal B-field

Another calibration line: $\pi^+ \to e^+\nu$ decays of stopped π^+'s



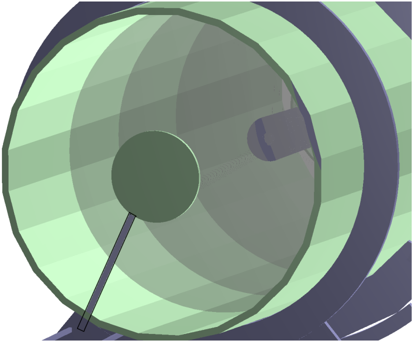
- $\pi^+ \to e^+\nu$ decays at rest produce monochromatic E = 69.8 MeV positrons
- the strategy: switch to positive beam, stop π^+'s, reconstruct positrons from their decays
- still need to reduce the B-field, now down to $\sim$ 70%
- pions arrive to the detector solenoid in 200-300 ns, and only a minor fraction survives
- overwhelming background from $\mu^+ \to e^+\nu\nu$ decays in flight which need to be suppressed

Suppressing muon decays in flight: where to do it?



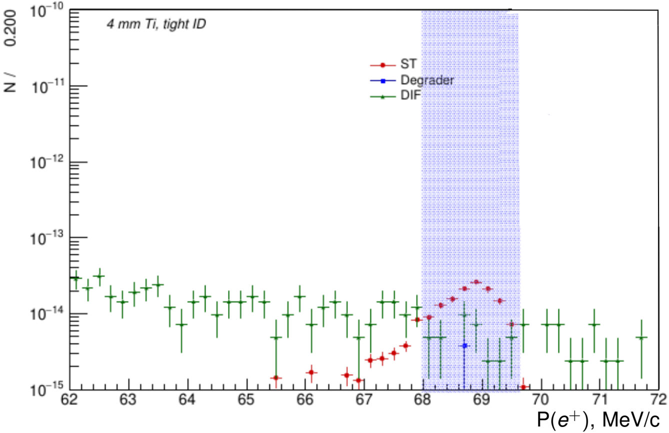
- to suppress muon decays in flight, need a removable absorber inserted into the beam
- space in the detector is very limited
  - μ^- captures in the stopping target generate $\sim 10^1$ neutrons/ns and 10^0 protons/ns
  - they are absorbed by the two polyethylene absorbers, the inner and the outer ones
- however, a narrow gap between the transport and detector solenoids is available

Suppressing $\mu^+ \to e^+\nu\nu$ decays in flight: pion degrader



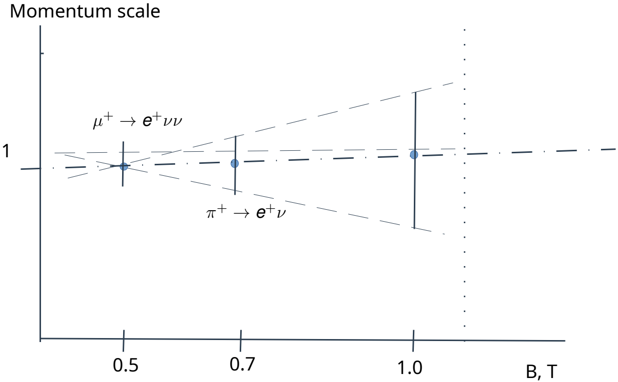
- pion degrader: an arm with an attached absorber disk
- the arm is moved in and out of the beam by a 50mNm piezoelectric stepmotor
- when in the beam, suppresses the muon decays in flight

$\pi^+ \to e^+\nu$ decays of stopped pions



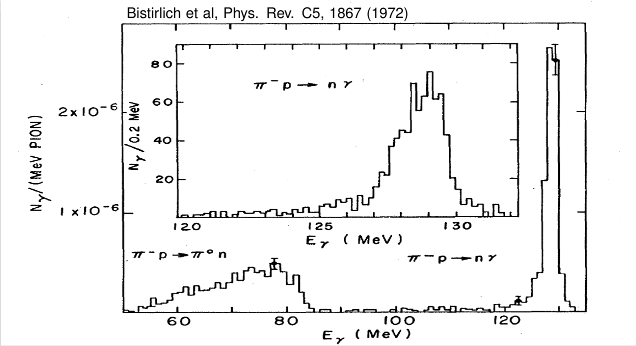
- optimal degrader thickness corresponds to $\sim$ 4mm of Ti
- expect to reconstruct a positron peak from $\pi^+ \to e^+\nu$ with S/B $\sim$ 3-4
- calibration run: about 1000 event per day, the same topology as the signal
- background subtraction results in additional, 20-30 keV/c level, systematics

Caveats of the momentum scale extrapolation



- with two measurements, can extrapolate the scale correction to B = 1T
- the error propagation math: contribution of $\pi^+ \to e^+\nu$ gets amplified by a factor of 2.5
- that brings the total uncertainty close to 100 keV/c

Radiative pion capture on hydrogen



- is there a process which produces monochromatic particles with E $\sim$ 100 MeV ?
  - radiative capture of stopped negative pions in hydrogen !
- $\pi^- + p \to n + \gamma$ ($\sim$ 40%) and $\pi^- + p \to n + \pi^0(\gamma\gamma)$ ($\sim$60%)
- the first channel yields monochromatic photons with E = 129.4 MeV
- how to proceed:
  - use $\pi^- + p \to n + \gamma$ channel, produce 129.4 MeV photons
  - convert photons in the detector : $\gamma \to e^+e^-$,
  - reconstruct tracks of e^+ and e^-, use their total energy for the scale calibration

Can’t use hydrogen target, but how about polyethylene ?

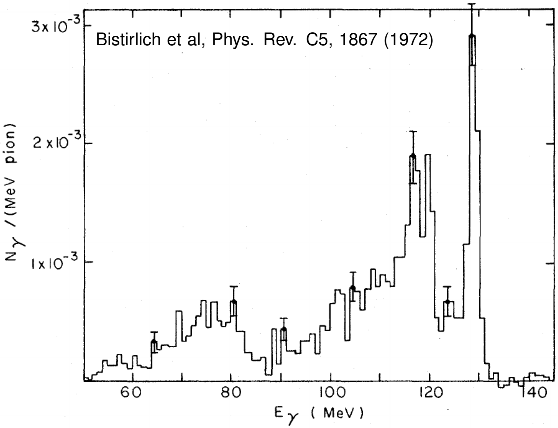
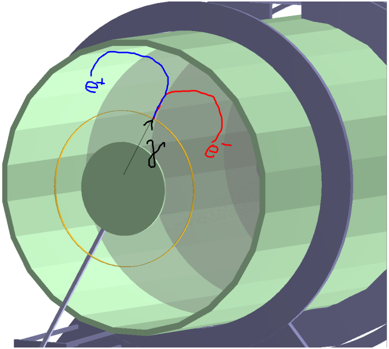


FIG. 9. Photon energy spectrum from π^- capture in CH_2.

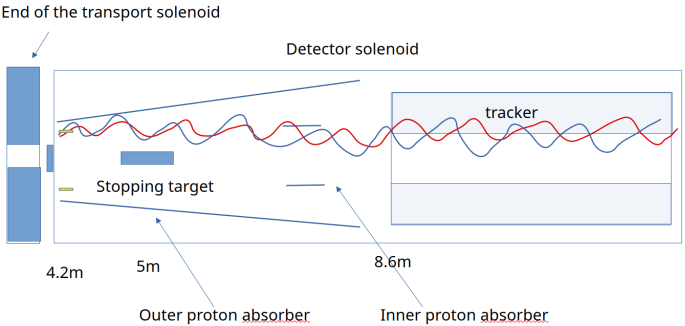
- pion capture in CH_2 target: a well-identified peak from $\pi^- + p \to n + \gamma$ (e^+e^-)
- probability for a pion stopped in CH_2 to be captured by a proton is 1.3%
- can be used for momentum scale calibration

Modifications to the pion degrader



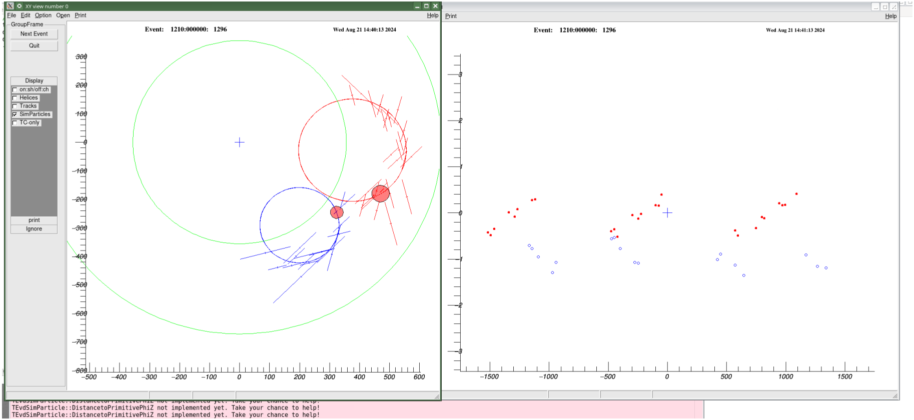
- producing 129.4 MeV photons: replace the Ti degrader disk with the CH_2 disk
- converting the photons: add a photon converter at R = 27 cm
  - converter: 100 um thick gold foil supported by a carbon foam ring (not shown)
  - the support ring adds $\sim$ 0.03% X_0, about 10% of that of the gold foil

How to detect the conversion pairs ?



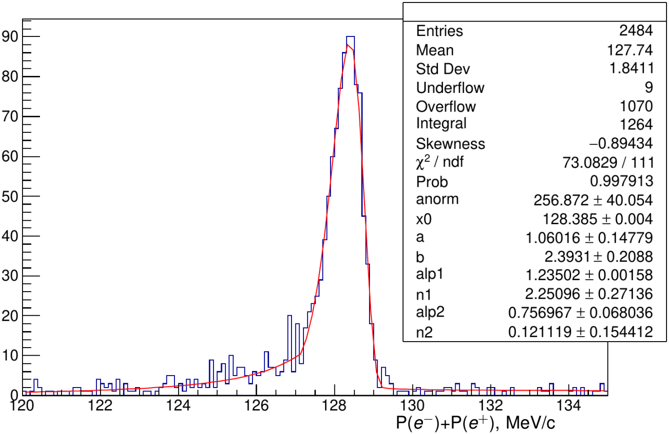
- the tracker is 4m downstream of the production point
- the e^+ and e^- from a conversion travel in vacuum missing most of the material
- produced at R = 27 cm, particles with P $>$ 40 MeV/c enter the tracker fiducial
- can be done at B = 1 T !

How does a $\gamma \rightarrow e^+e^-$ event look like in the Mu2e tracker



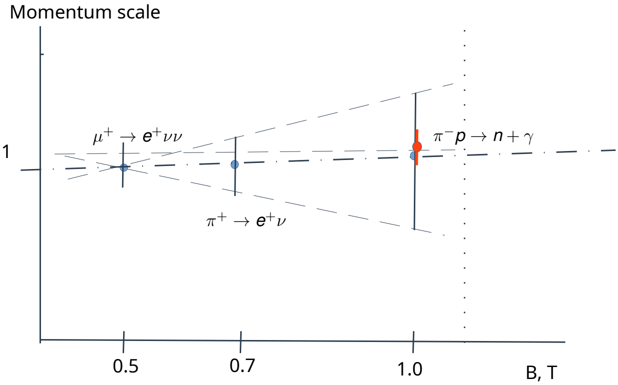
- red track: e^-, blue track: e^+, small red circles: clusters in the calorimeter
- the circles are tangent to each other (!)
- easily recognizable in phi-Z view

Reconstruction of the photon momentum



- a scalar sum of P(e^-)+P(e^+) makes an excellent proxy to P_γ
- for a 100 um thick gold converter, FWHM $\sim$ 1 MeV, the MP energy loss of the same order
- expected yield: $\sim$ 1000 events/day,
- the fit uncertainty on the peak position better than 10 keV

Combining the three measurements together



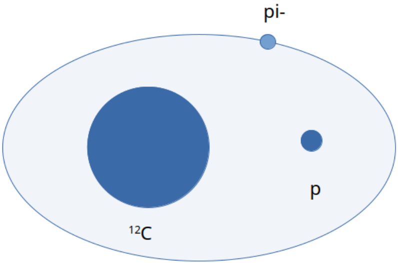
- perform three measurements
- over-constrain determination of the momentum scale
- get reliable estimate of the systematic uncertainties

Summary

- Mu2e plans to exploit three physics processes the calibrate the momentum scale in situ: $\mu^+ \to e^+\nu\nu$, $\pi^+ \to e^+\nu$, and $\pi^- p \to n\gamma$ (RPC on hydrogen)
- the measurements need to be performed at different B-field values, one of them - at full field, B= 1 T
- with all three carried out, expect the systematic uncertainty on the reconstructed momentum to be well within the experimental requirements ($< 100 keV/c$) at 100 MeV/c

Backup

Radiative pion capture, hydrogen compounds



Bistirlich et al, Phys. Rev. C5, 1867 (1972)

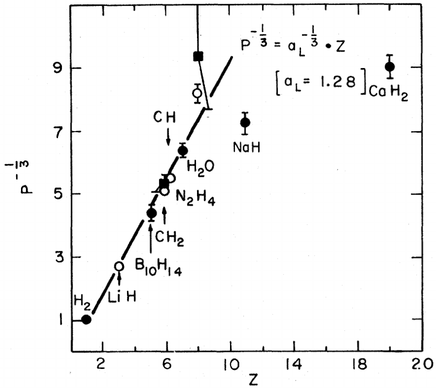


FIG. 10. Relative probability for the capture of pions on protons in hydrogenous compounds. Plotted is the

- however, can't put a hydrogen target inside the detector
- a hydrogen-containing compound material instead ? CH_2 ?
- in hydrogeous compounds pions form meso-molecules, consisting of 2 atoms
- the probability for a stopped pion to be captured by a H atom in CH_2 is about 1.3% (ref ..)