A feasibility test for measuring the proton charge radius in high-energy muon-proton elastic scattering

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on behalf of the COMPASS collaboration

HISKP, Bonn University

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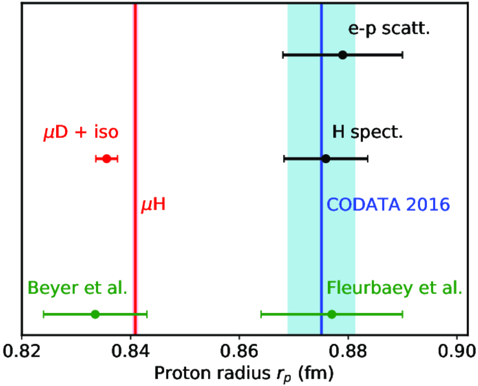
ECSAC 2019, Veli Lošinj

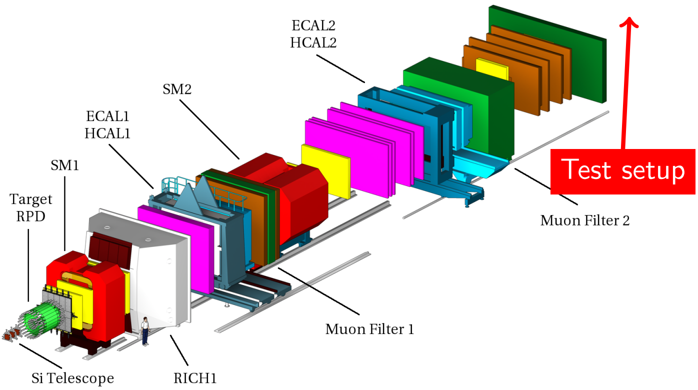
- Introduction
  - Proton radius puzzle
  - COMPASS
- 2018 test measurement
  - Setup
  - Analysis
  - Simulation
- Summary and Outlook

Proton charge radius:



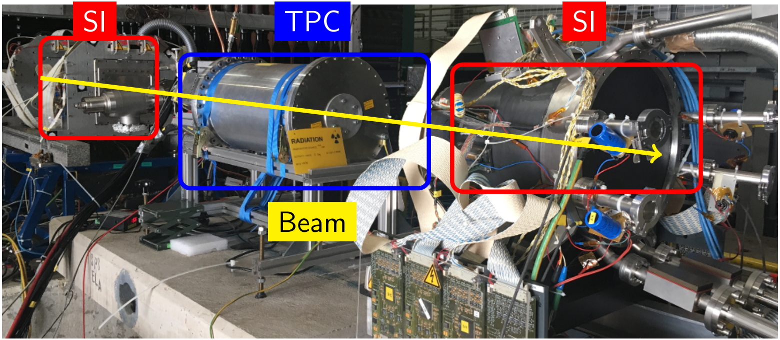
- Measure four-momentum transfer over a wide range ($0.001\,\text{GeV}^2 < Q^2 < 0.04\,\text{GeV}^2$)
- Uncertainty of 0.01 fm expected

R. Rengelink, PhD thesis, 2018



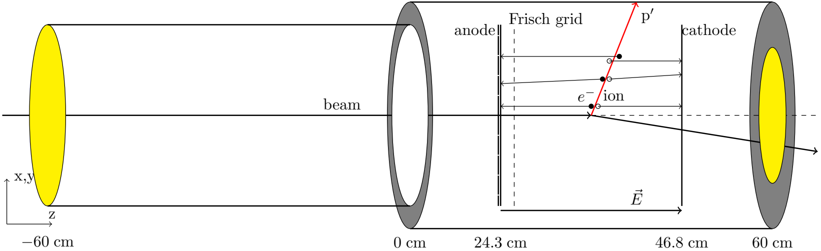
- Fixed-target experiment
- 190 GeV muon beam

[NIMA 779 (2015) 69]



- Silicon tracking stations are triggered by coincident scintillator signals.
- TPC is self-triggered.
- Different DAQ for silicon tracking stations and TPC.

Christian Dreisbach

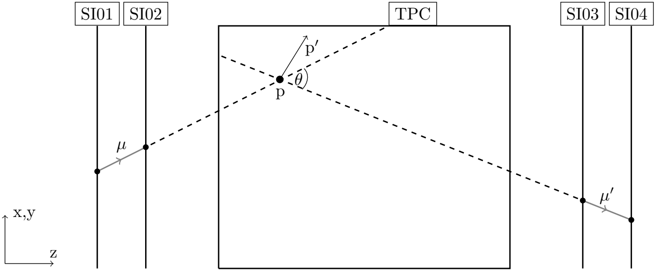

Frisch grid
p′
anode
cathode
beam
e^-
ion
x,y
z
$\vec{E}$
−60 cm
0 cm
24.3 cm
46.8 cm
60 cm

- Silicon tracking stations:
  - Detection of extremely small scattering angles
- Time projection chamber:
  - Background due to a wide muon beam
  - Detection of low energetic recoil protons
- Two independent DAQs are used

⇒ Is it possible to combine the information?

- How can the setup be improved?
  - Input from real data and simulations is needed.

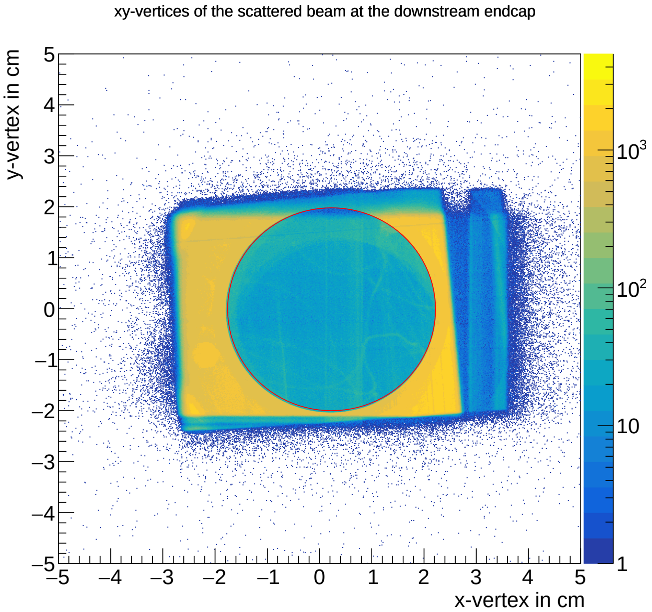
- Data reconstruction
  - Reconstruction of tracks in the upstream and downstream trackers (8 planes each) → direction of beam and scattered track
  - Vertexing → θ and vertex position



- Cuts
  - $\theta \geq 0.2\,\text{mrad}$ (Q^2=$1.44 \times 10^{-3}\,\text{GeV}^2$ for E_μ=190 GeV)
  - Radial cut at the position of the downstream TPC beam window and the cathode
- Alignment of silicon trackers with straight tracks

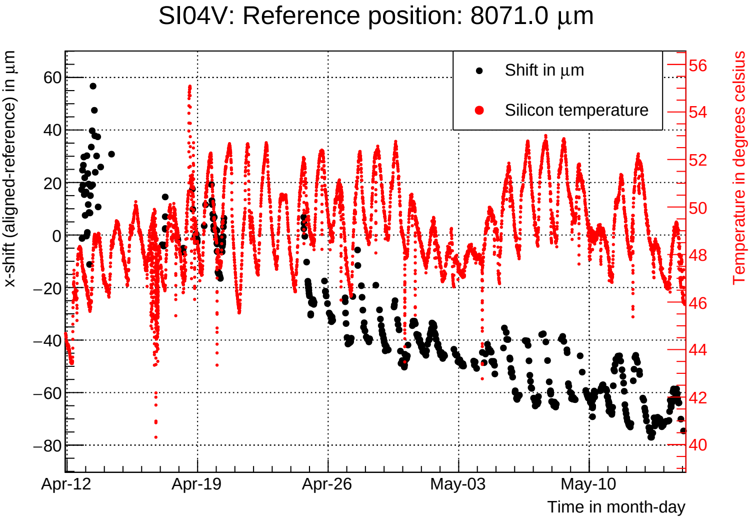
$\Rightarrow$ z-vertex resolution

- φ-distribution

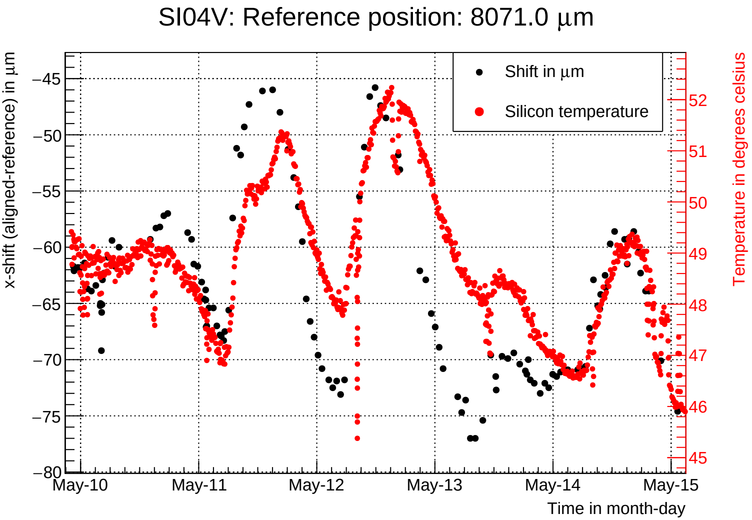

xy-vertices of the scattered beam at the downstream endcap
y-vertex in cm
x-vertex in cm
5
4
3
2
1
0
−1
−2
−3
−4
−5
10^3
10^2
10
1

- Straight tracks are reconstructed.
- The difference of the track at the detector to the detector hit position is called residual.
- The absolute values of the residuals of 100k events per run (few million events) are minimized.

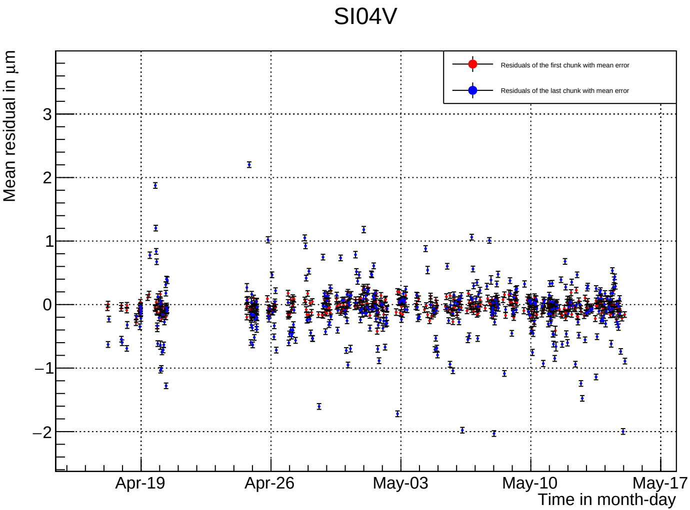
$\Rightarrow$ Shift of xy-coordinates of the detectors and the angle perpendicular to the beam.



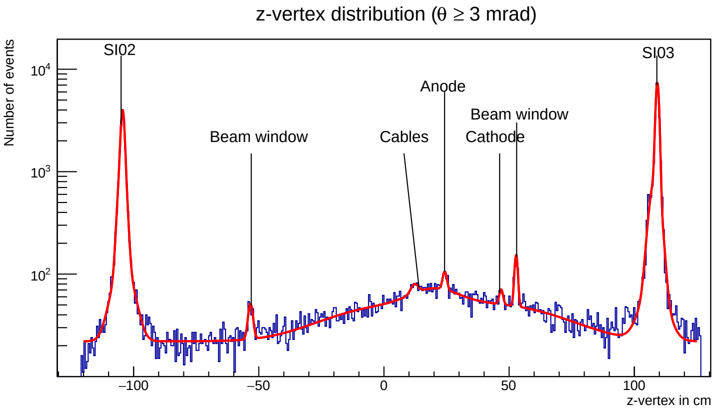
- Global shift of the detector position



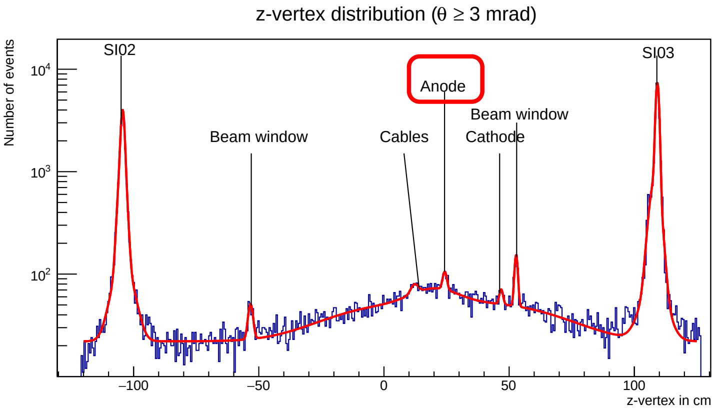
- Daily fluctuations
- Correlation with the silicon temperature



- Residuals are constant with time after the alignment.

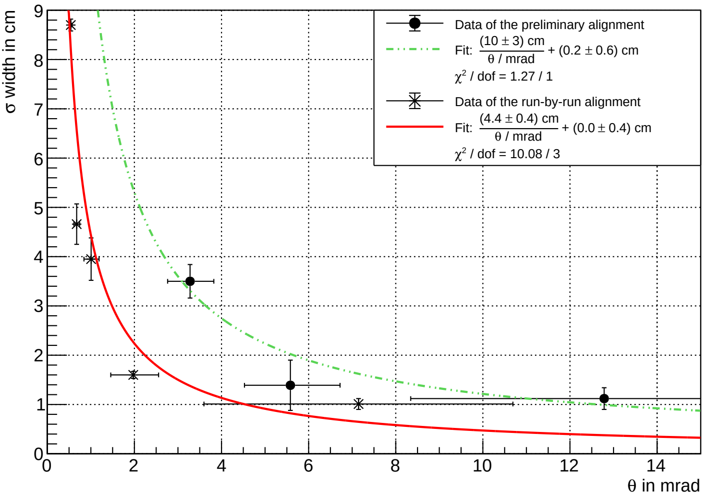


- The function is fitted over the whole range for different θ-bins.

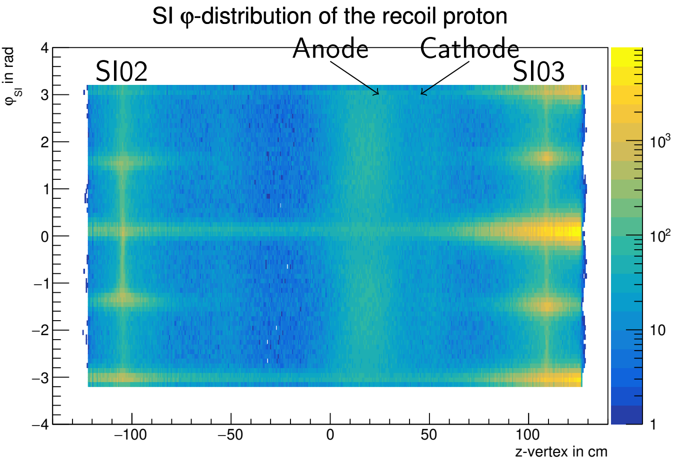


- The function is fitted over the whole range for different θ-bins.
- The σ-width of the anode peak defines the resolution.

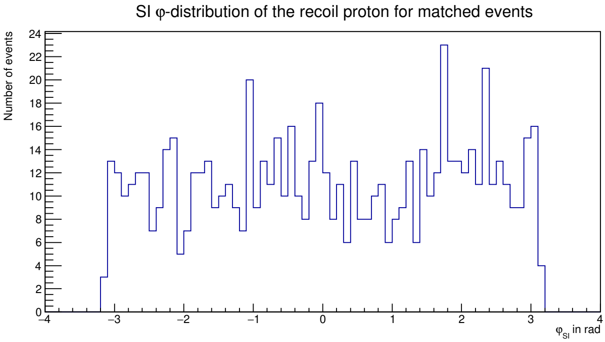
σ width of the anode peak



- The run-by-run alignment clearly improves the resolution.



- Visible peaks at $0, \pm\,\pi/2, \pm\,\pi$
- Origin seems to be the silicon stations



;

- φ-distribution of events matched with TPC is flat.

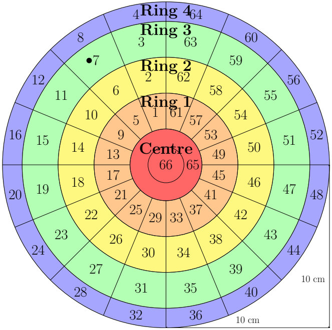
Trigger:

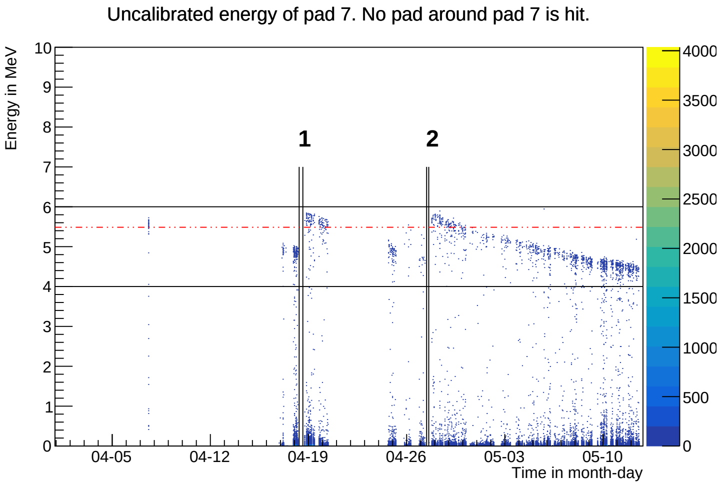
- One pad has an energy above 200, 300 keV

Analysis from PNPI colleagues:

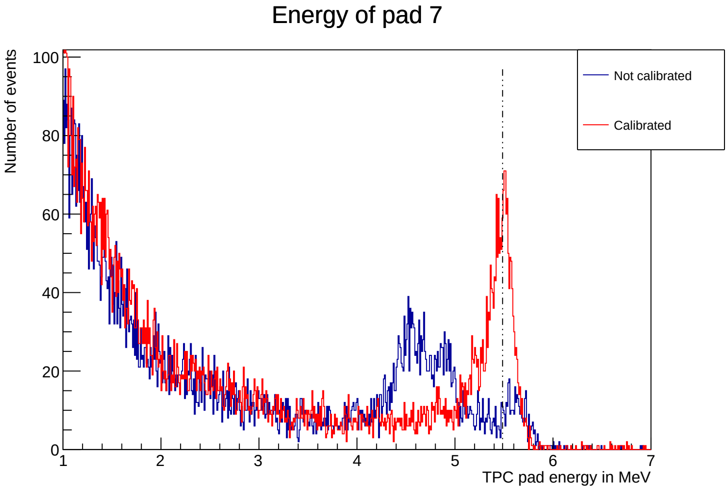
- Signal amplitudes are measured over $100\ \mu$s.
- The start and end time is given by the rising and trailing edge.
- The total energy is given by the integral of the signal above the pedestals
- Energy resolution of a single pad is between 22 keV to 36 keV.

$\Rightarrow$ Pad energies, start time and signal duration



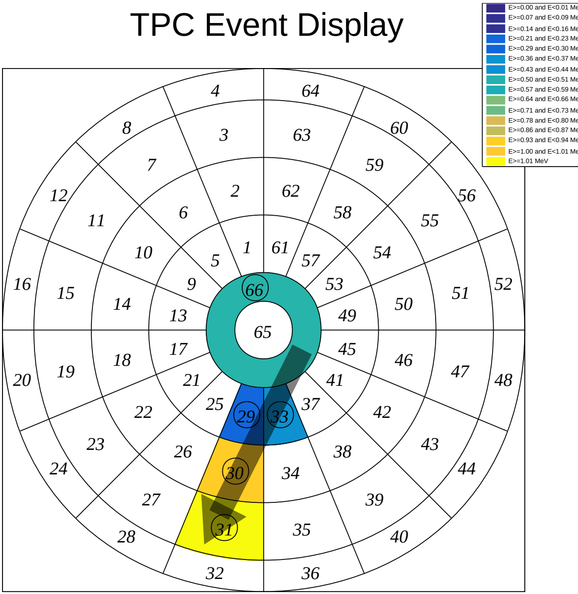


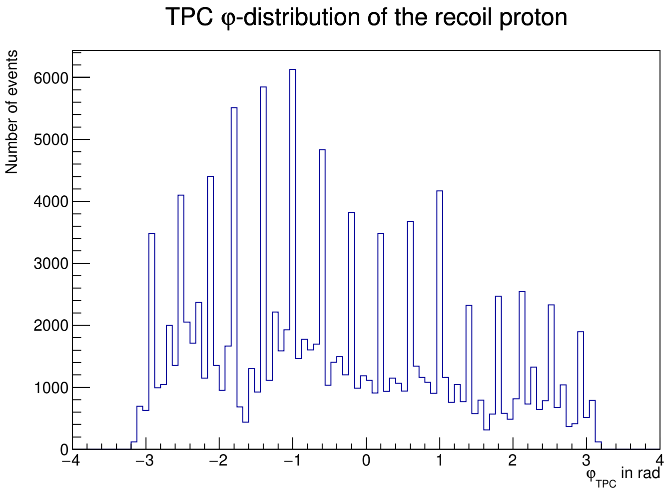
- Electron attachment takes place due to decreasing gas purity.
- Refills of the hydrogen gas are marked.



- One peak at the correct energy (5.486 MeV) after the calibration

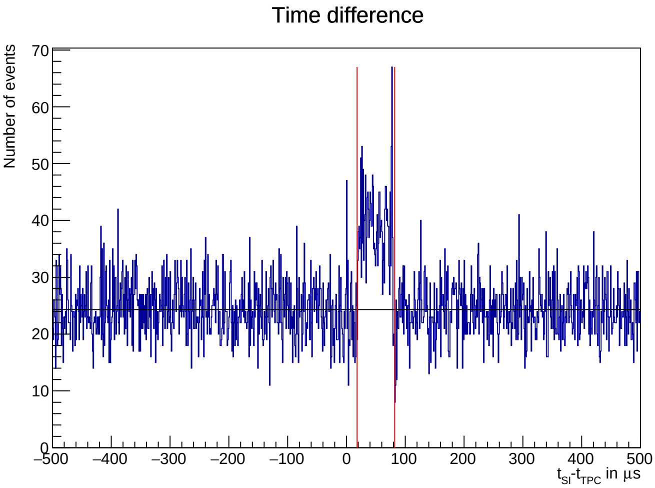
- For every ring the centre of gravity is calculated.
- With the centres from every ring, the direction of the proton is fitted.



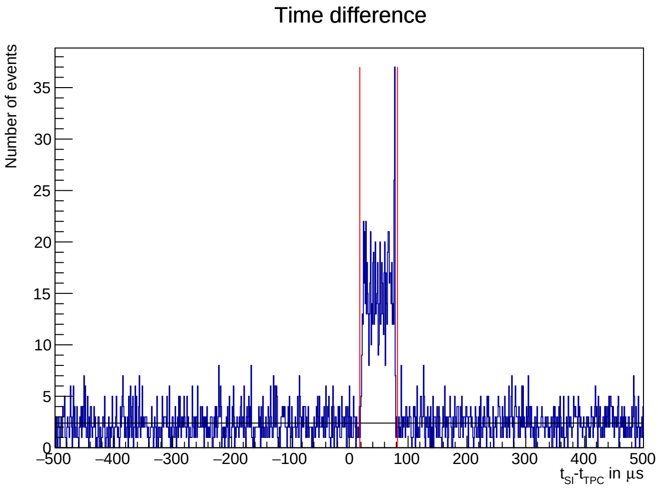


- The 16 spikes correspond to the broad pads.
- Less events between $2 - 3$ rad $\rightarrow$ enlarged threshold due to the α-source

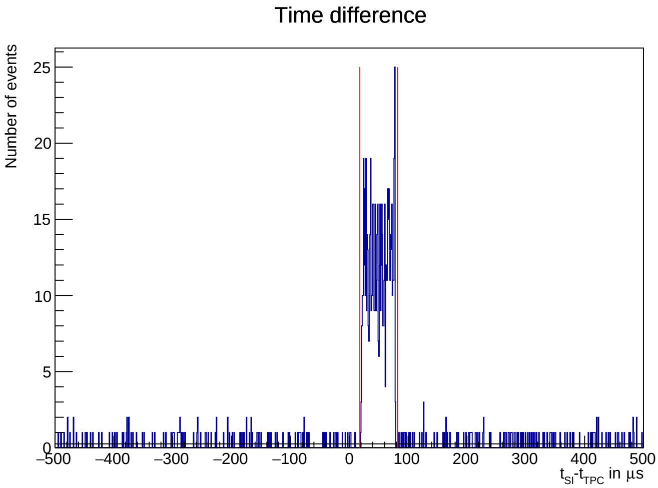
- Two independent detector systems
- Both systems store a time signal and an additional synchronization signal.
  - ⇒ A common time signal can be used and compared.
- Validate the correlation:
  - Drift velocity
  - Verify the assumption of a proton
  - Kinetic energy of the recoil proton
  - Direction of the recoil proton



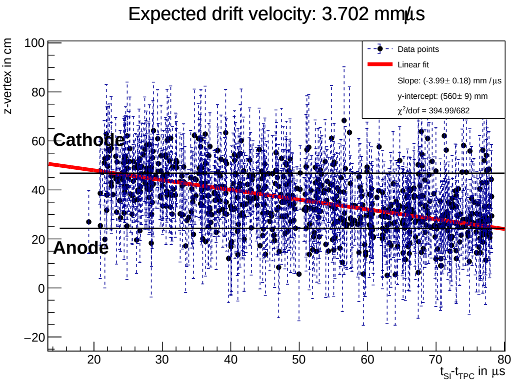
- 64 µs time window which is a bit larger than the expected drift time (60 µs).
- S/N$= 892/1555$



- Cut on the z-position to be between the anode and the cathode (enlarged by $1\ \sigma$ uncertainty).
- S/N$= 762/153$

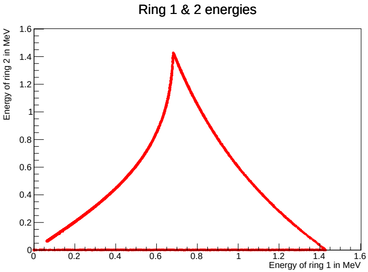


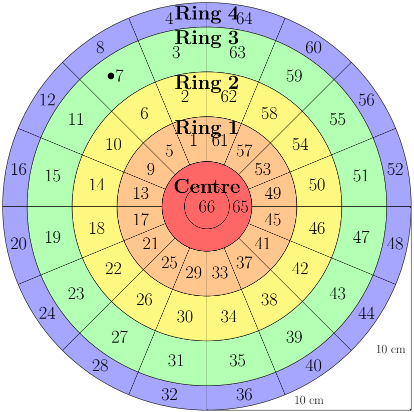
- One of the two central pads in the TPC has to be hit.
- S/N$= 700/16$



- The drift time increases with the distance to the anode.
- The measured drift velocity of $(3.99 \pm 0.18)\,\text{mm}\,\mu\text{s}^{-1}$ is larger than the estimated value of $3.70\,\text{mm}\,\mu\text{s}^{-1}$.
  - → Separate system to measure the drift velocity (low-intensity laser).

Analysis of combined dataEnergy in ring 1 and 2 of the TPC

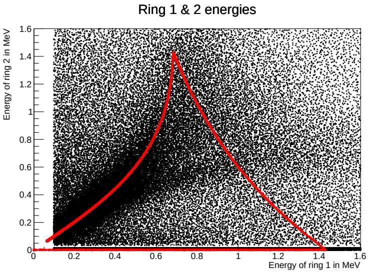


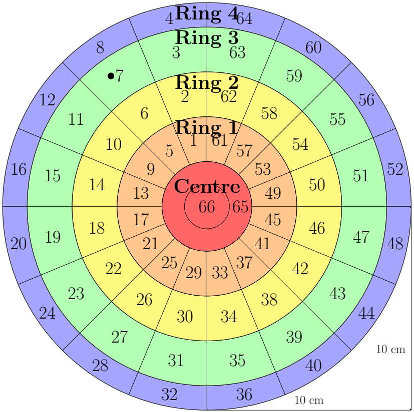


- Red: Simulation for protons

Alexander Inglessi

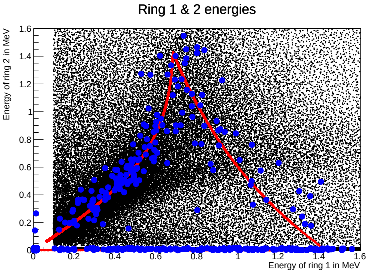
Analysis of combined dataEnergy in ring 1 and 2 of the TPC

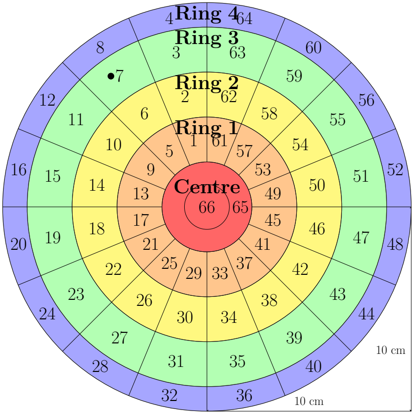




- Red: Simulation for protons
- Black: Data points

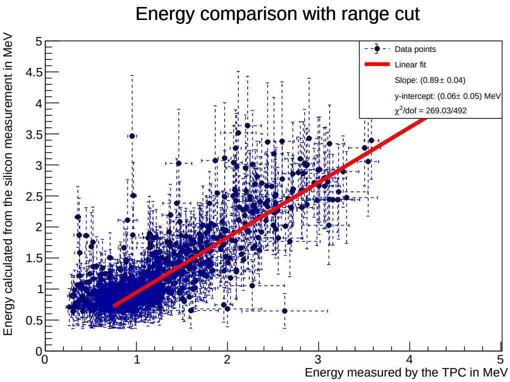
Alexander Inglessi



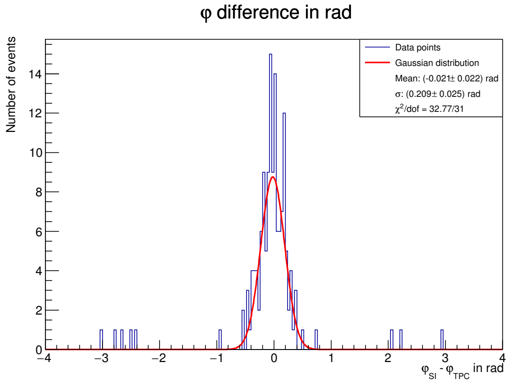


- Red: Simulation for protons
- Black: Data points
- Blue: Data points matched with silicons

Alexander Inglessi

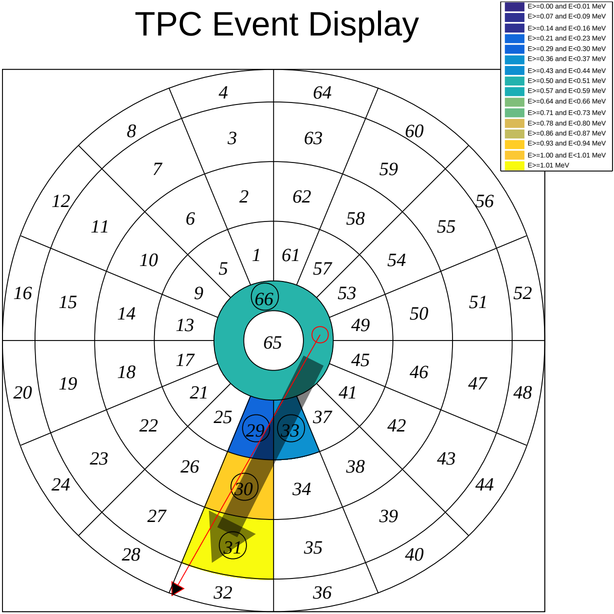


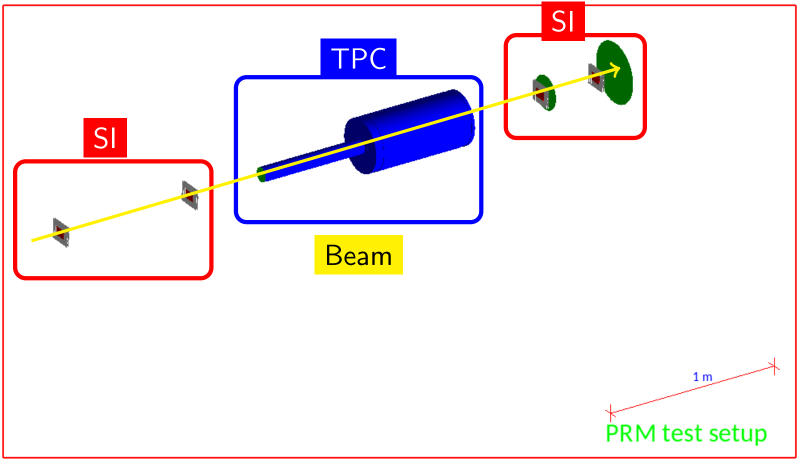
- Protons that could escape from the active TPC volume are taken out.
- Measured energies are correlated but the slope 0.89 ± 0.04 is smaller than 1.



- φ can be extracted from both data sets.
- The rotation was not known but determined from the measurement.
- There are less events because three hit rings are required.
- The width of the peak originates from the large TPC pads.

- Silicon track (red):
- Interaction vertex
- Recoil proton direction
- Recoil proton energy

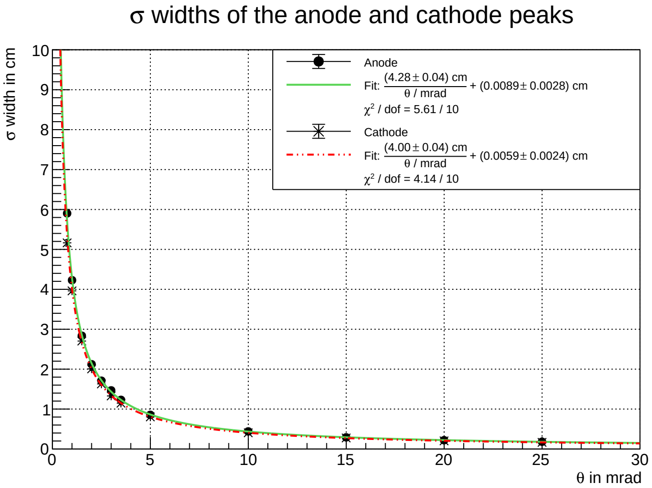




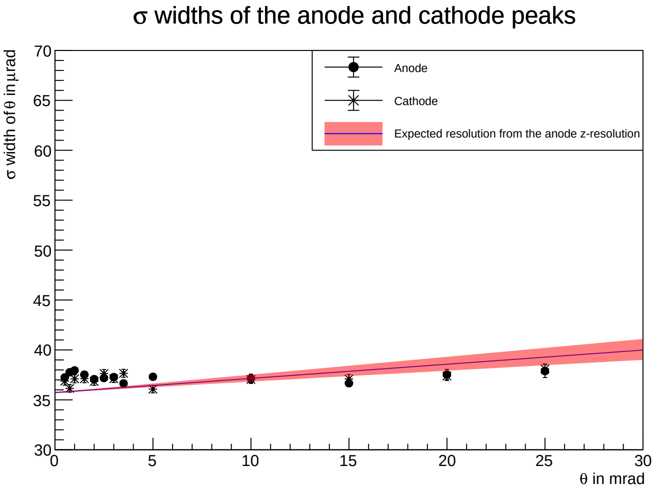
Test setup is implemented in Geant4.

- Creation of primary particles (μ,μ' and p')
- Particle propagation is done within Geant4.
- Silicon hits are smeared with 10.0 μm.
- Energy depositions in the TPC are summed up to the corresponding pad and smeared with 30 keV.

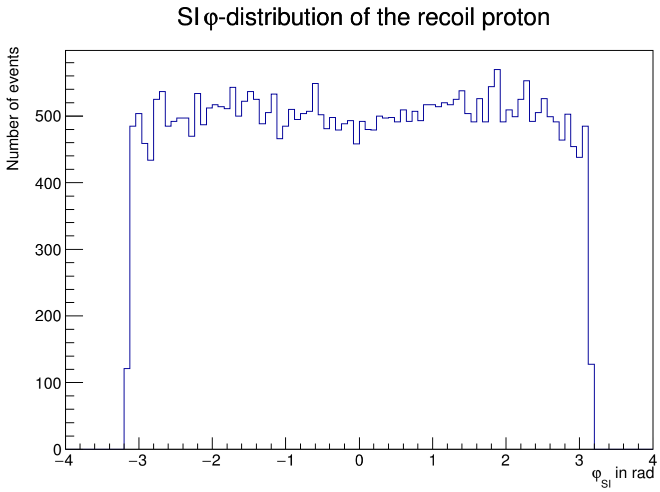
⇒ The reconstruction is the same like in real data.



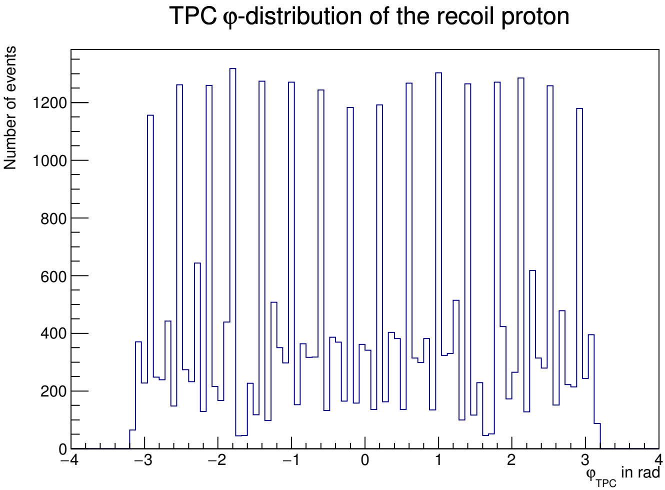
- Events are simulated at fixed θ-values
- Real data resolution: $\frac{(4.4 \pm 0.4)\,\mathrm{cm}}{\theta/\mathrm{mrad}} + (0.0 \pm 0.4)\,\mathrm{cm}$
- The cathode peak has a slightly better resolution



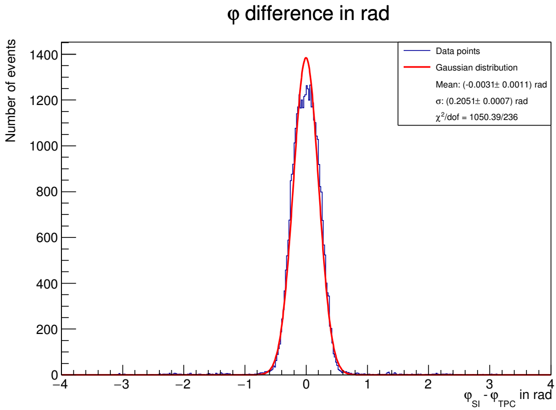
- An estimate for the θ-uncertainty can be calculated using the z-vertex resolution.
- The actual θ-resolution is rather constant.



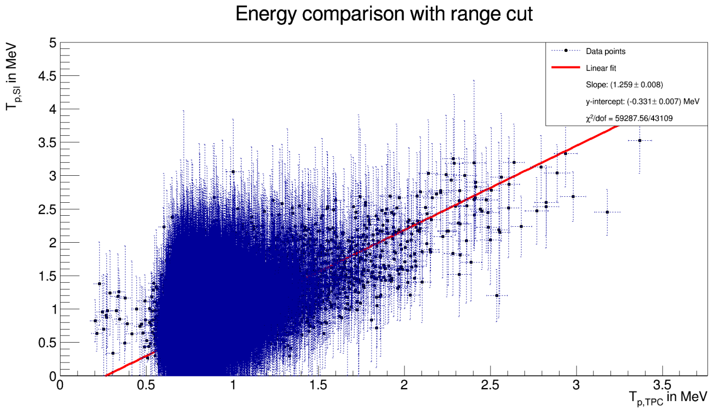
- θ is distributed according to the Rosenbluth formula between 0.5 to 5 mrad.
- The distribution is flat.



- 16 spikes visible



- Standard deviation Real Data: (209 ± 25) mrad
- Standard deviation Monte Carlo SI-TPC: (205.1 ± 0.7) mrad
- Standard deviation Monte Carlo SI-MC: (66.99 ± 0.26) mrad
- Standard deviation Monte Carlo TPC-MC: (189.5 ± 0.6) mrad



- θ is distributed according to the Rosenbluth formula between 0.18 to 5 mrad.
- Correlation is much worse than in real data $\rightarrow$ has to be understood
- Slope: 1.259 ± 0.008

Summary

- Events from both DAQs can be matched by using the timestamp.

$\Rightarrow$ Additional cuts improve the signal to noise ratio.

$\Rightarrow$ The extracted energy of both systems is correlated.

$\Rightarrow$ Tracks measured by the silicon trackers are in good agreement with the measurement of the TPC.

- The alignment massively improves the resolution of the silicon trackers.
- The measured z-vertex resolution is in agreement with the simulated values.

Further simulation tasks:

- Understanding the proton energy correlation.
- Beam energy spread should be added.
- Simulation of several muons for beam noise in the TPC during each event.

Possible improvements for the measurement at COMPASS++/AMBER in 2022/2023:

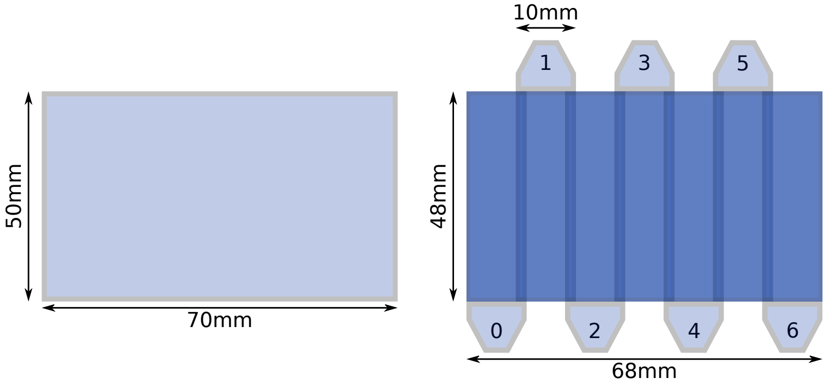
- Temperature stabilization of the silicon trackers.
- Avoid gas impurities to minimize attachment.
- Separate system to measure the drift velocity (low-intensity laser).
- Small pads would be better for a precise direction information but low-noise readout is the first priority.

$\Rightarrow$ Different pad structures can be simulated and used.

Backup

- Two monolithic and one segmented scintillator in coincidence function as a trigger

Christian Dreisbach



- Two monolithic and one segmented scintillator in coincidence function as a trigger

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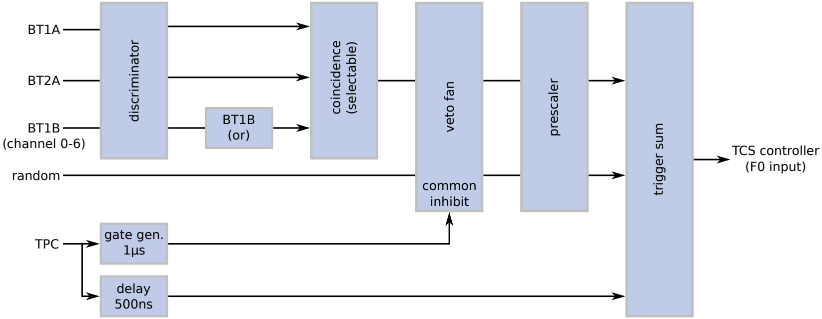
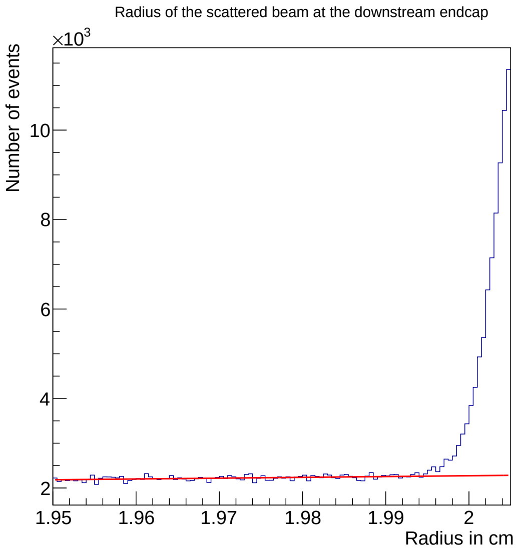
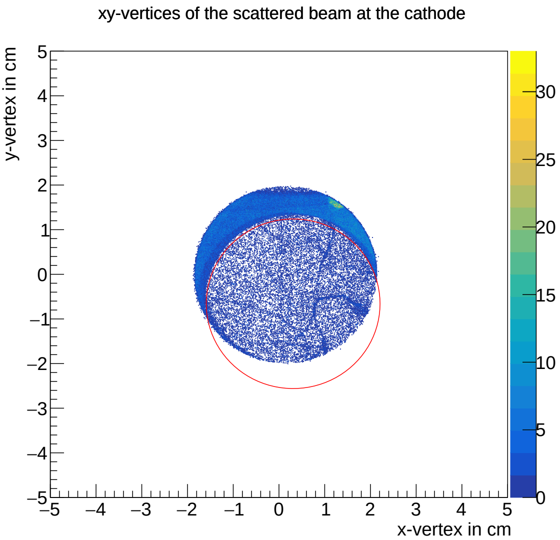
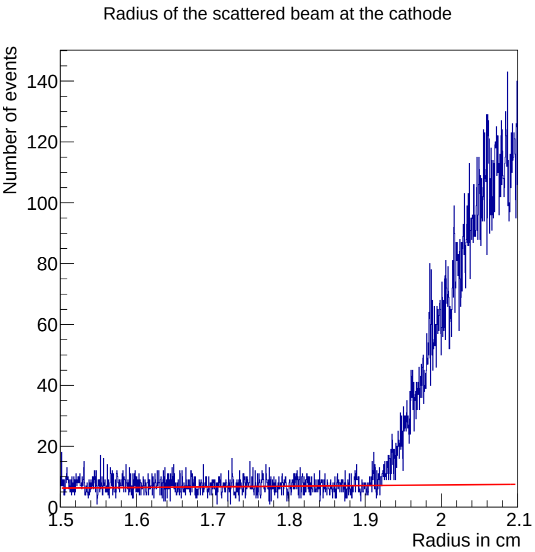


Christian Dreisbach



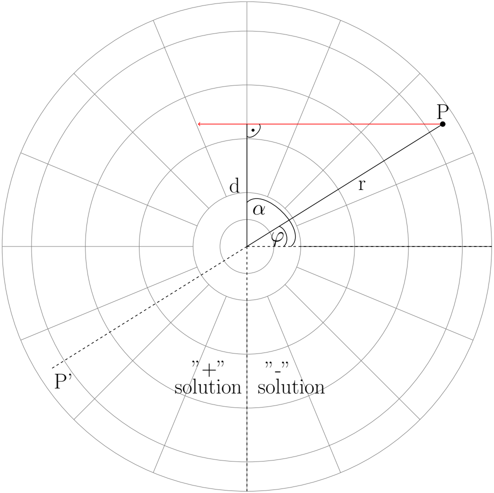
A radius of 1.99 cm is chosen for the cut.


xy-vertices of the scattered beam at the cathode
y-vertex in cm
x-vertex in cm
5
4
3
2
1
0
−1
−2
−3
−4
−5
30
25
20
15
10
5
0

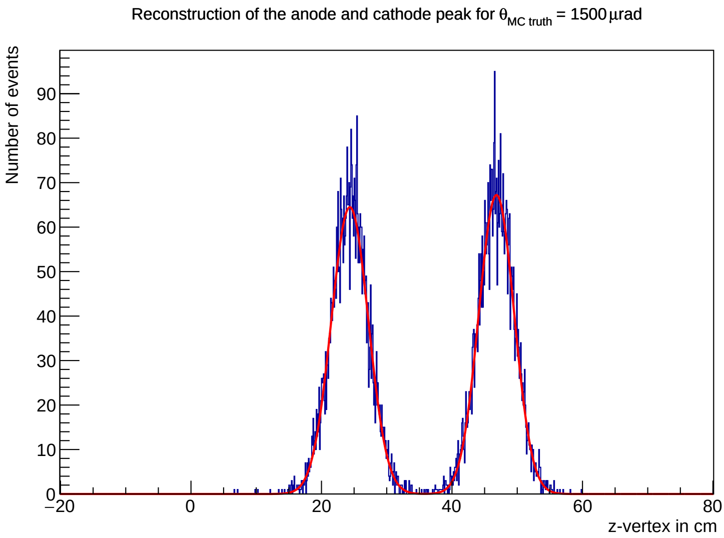


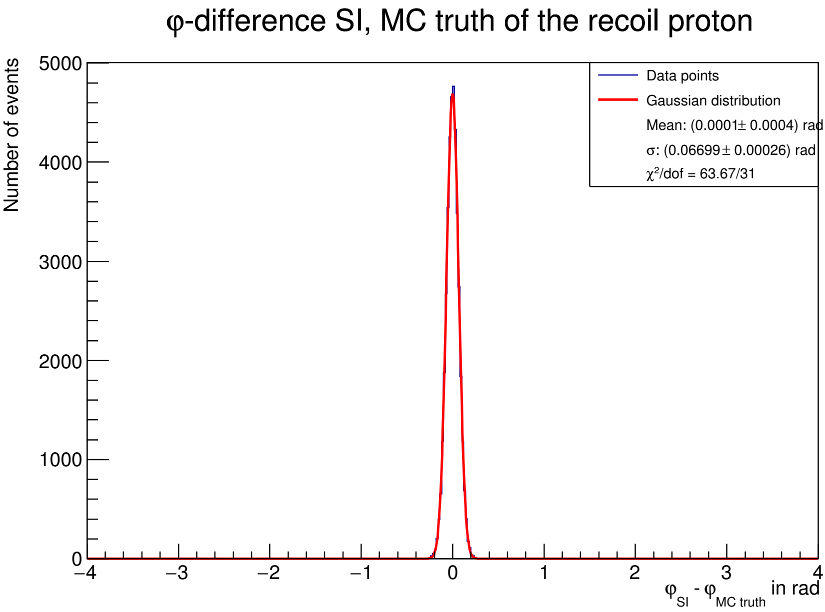
A radius of 1.9 cm is chosen for the cut.

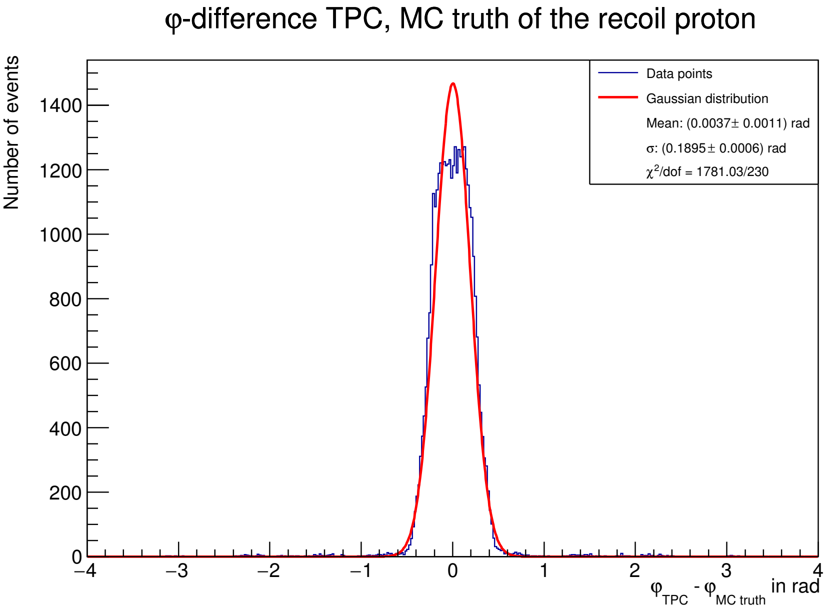
θ_{min}/mrad	θ_{max}/mrad	σ/cm
Preliminary alignment		
2.580	4.150	3.50 ± 0.34
4.150	7.480	1.39 ± 0.51
7.480	–	1.12 ± 0.22
Run-by-run alignment		
0.500	0.590	8.70 ± 0.12
0.590	0.790	4.66 ± 0.41
0.790	1.310	3.95 ± 0.43
1.310	3.010	1.60 ± 0.07
3.010	–	1.01 ± 0.11



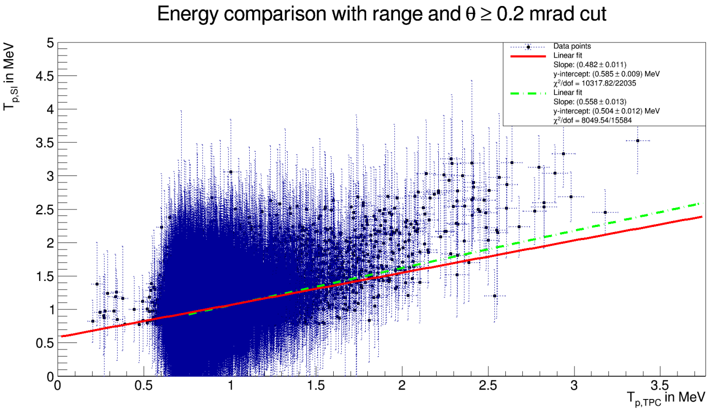
$$r(\varphi) = \frac{d}{\cos(\alpha - \varphi)};$$ and the inverted function $$\varphi(r) = \alpha \pm \arccos\left(\frac{d}{r}\right)$$


Reconstruction of the anode and cathode peak for $\theta_{MC\ truth}$ = 1500 μrad
Number of events
0
10
20
30
40
50
60
70
80
90
−20
0
20
40
60
80
z-vertex in cm


φ-difference SI, MC truth of the recoil proton
Number of events
5000
4000
3000
2000
1000
0
−4
−3
−2
−1
0
1
2
3
4
φ_SI - φ_MC truth in rad
Data points
Gaussian distribution
Mean: (0.0001± 0.0004) rad
σ: (0.06699 ± 0.00026) rad
χ²/dof = 63.67/31


φ-difference TPC, MC truth of the recoil proton
Number of events
1400
1200
1000
800
600
400
200
0
−4
−3
−2
−1
0
1
2
3
4
φ_TPC - φ_MC truth in rad
Data points
Gaussian distribution
Mean: (0.0037± 0.0011) rad
σ: (0.1895± 0.0006) rad
χ²/dof = 1781.03/230

Energy correlation SI-TPC



- The slope is much smaller than 1 after the cut on θ.
- Slope starting at $T_{\text{p,TPC}} = 0$: 0.482 ± 0.011
- Slope starting at $T_{\text{p,TPC}} = 0.744\,\text{MeV}$: 0.558 ± 0.013
- Due to the cut on the scattering angle, the symmetry of uncertainties is broken.