Proton Radius in High-Energy Muon Scattering

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On behalf of the COMPASS++/AMBER Collaboration
and its Proton Radius Sub-Group

DIS 2019
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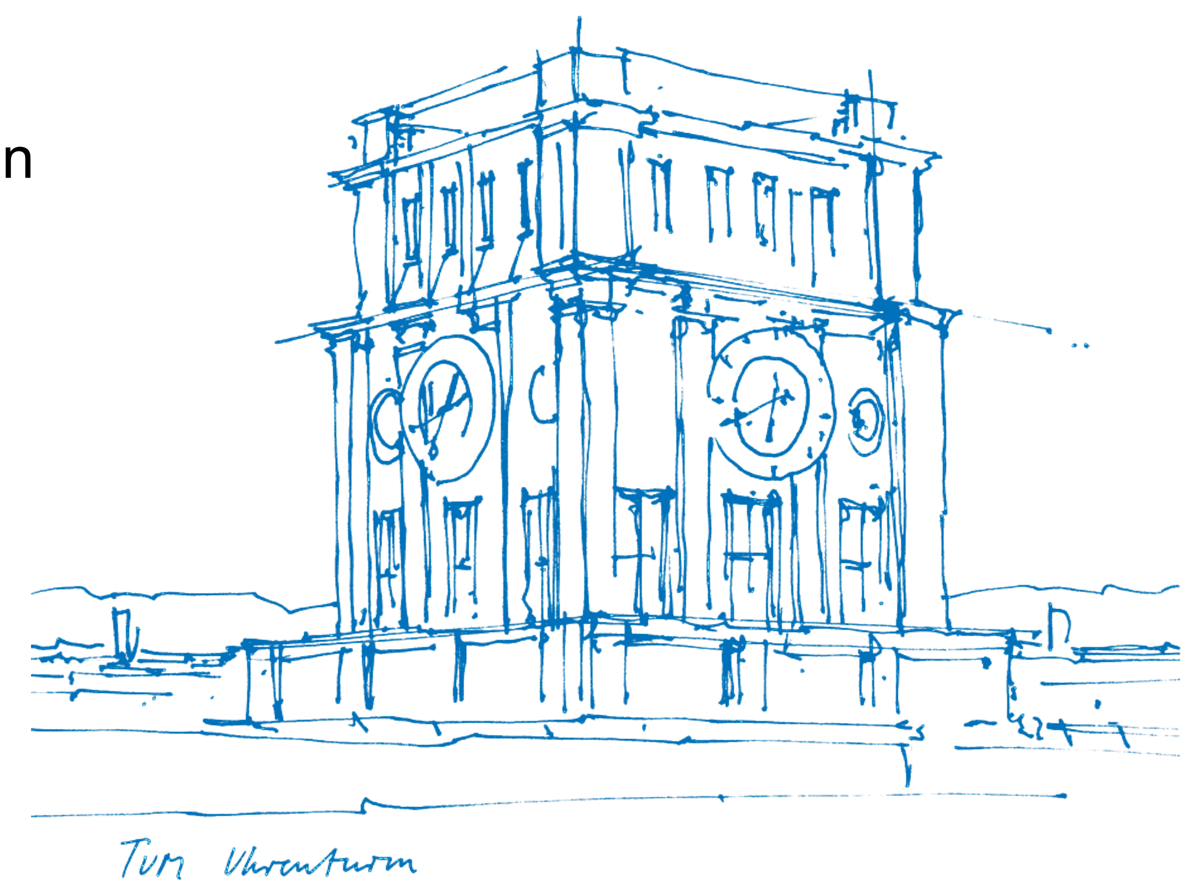
8-12 April



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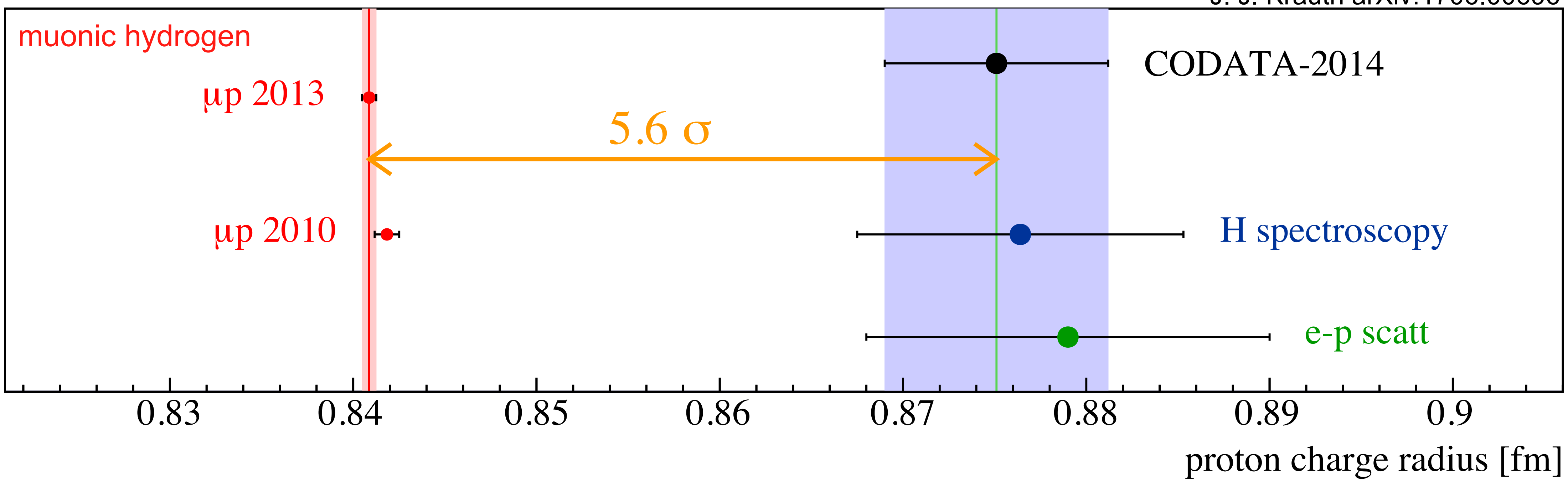
Proton Radius Puzzle

Proton radius charge radius from spectroscopy and e-p scattering

Persistent discrepancy between spectroscopy and scattering

J. J. Krauth arXiv:1706.00696



- Discrepancy between hydrogen and muonic hydrogen spectroscopy of more than 5σ
- Different fits to e-p data yield to different values

<u>Proposal:</u> Measure proton charge radius in high-energy μ-p elastic scattering

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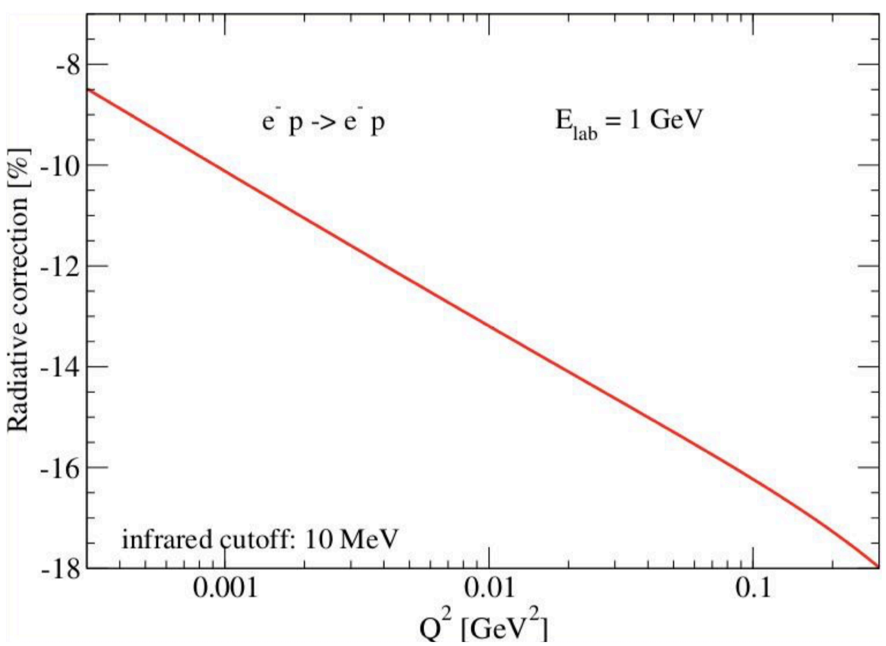
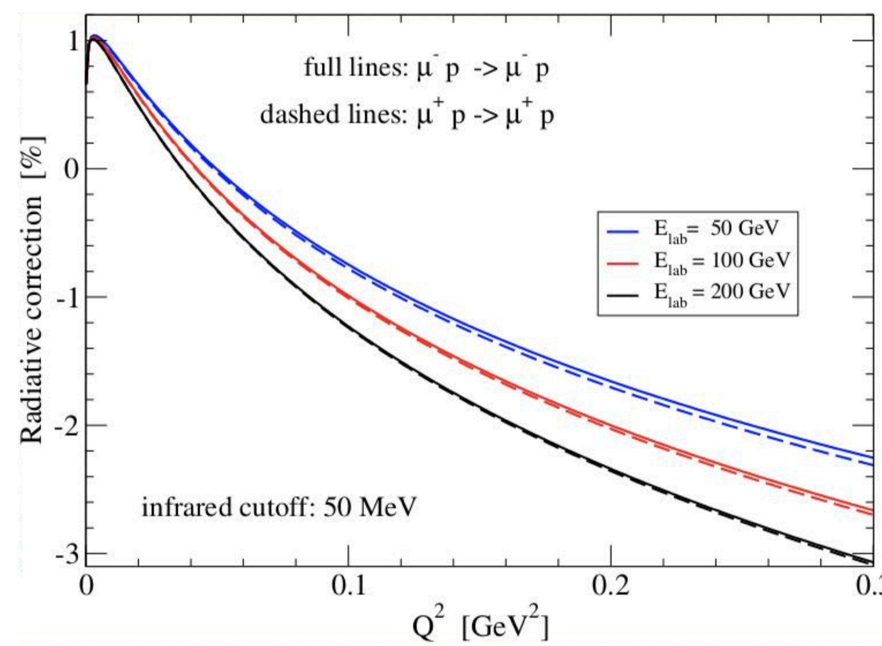
High-Energy Muon Scattering Advantages

$$\frac{d\sigma^{\mu p\to\mu p}}{dQ^2} = \frac{\pi\alpha^2}{Q^2 m_p^2 \vec{p}_\mu^{\,2}}\left[\left(G_E^2 + \tau G_M^2\right)\frac{4E_\mu^2 m_p^2 - Q^2(s-m_\mu^2)}{1+\tau} - G_M^2\frac{2m_\mu^2 Q^2 - Q^4}{2}\right] \quad \text{with} \quad \tau = \frac{Q^2}{4m_p}$$

- For small $Q^2 < m_\mu^2$ contributions of magnetic form factor G_M^2 proportional to m_μ^2 / E_μ^2
  → For high beam energies $E_\mu^2 > 100$ GeV effect is smaller than $O(10^{-6})$ and can be neglected





- Electron scattering - emitting of soft bremsstrahlung with energies $E_\gamma / E_{beam} \sim 1\%$
  → QED radiative corrections ~ 15-20% for electrons and ~ 1.5% for muons

<u>Advantage over e-p scattering:</u>
small QED radiative corrections and neglectable contribution from magnetic form factor

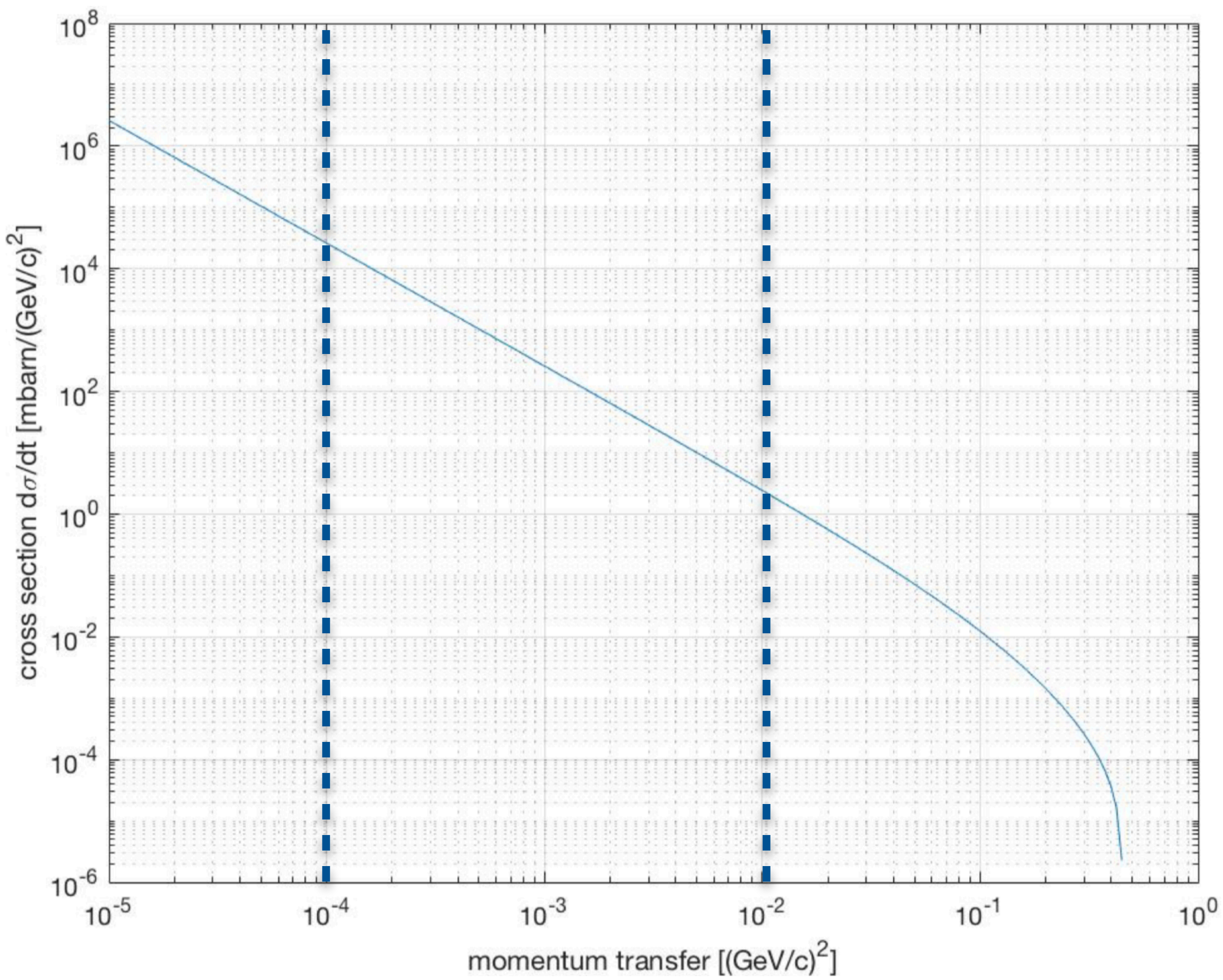
Proton Radius Measurement

Measurement at low-Q² values

Extract proton charge radius from fit of Q^2-data over a wide range.

$$< r_p^2 > = -6 \cdot \frac{dG_E(Q^2)}{dQ^2}\Bigg|_{Q^2=0}$$

- Wide Q^2 range from 10^{-4} to 10^{-2} GeV^2
  → test stability of possible fit models
- Experimentally challenging especially for low Q^2
- New intended measurement at CERN's M2 beam line in 2022 using COMPASS++/AMBER spectrometer



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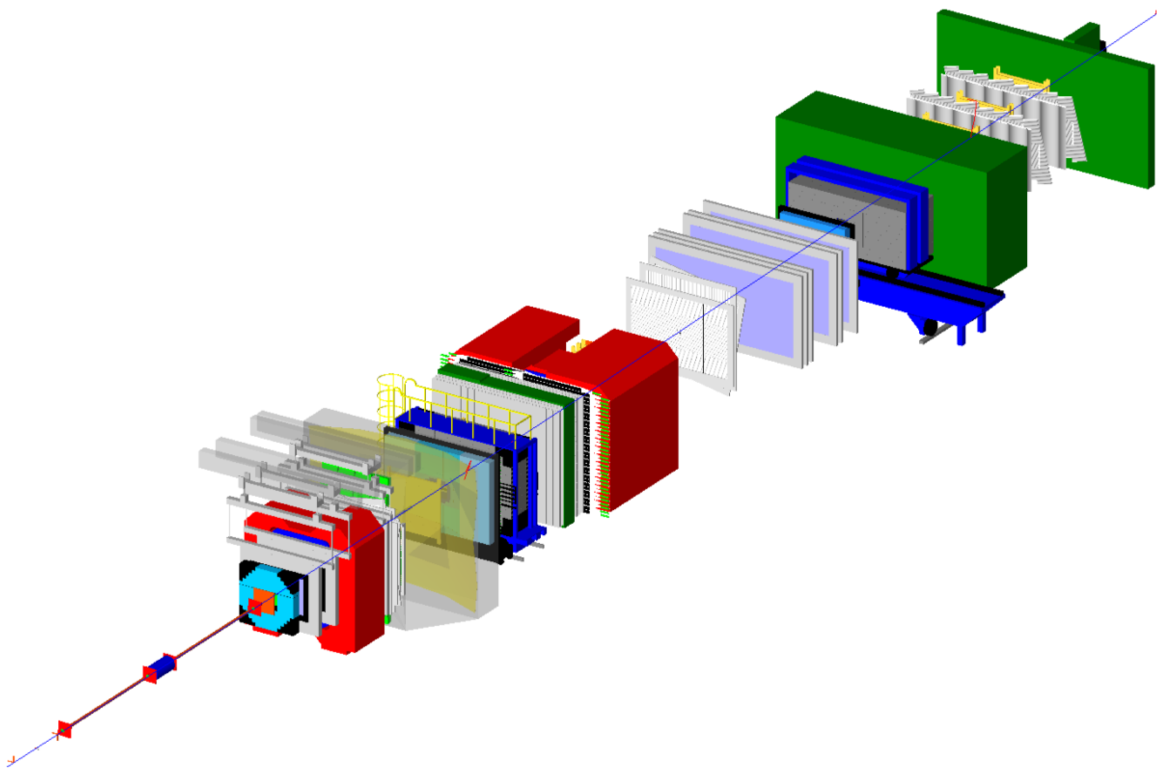
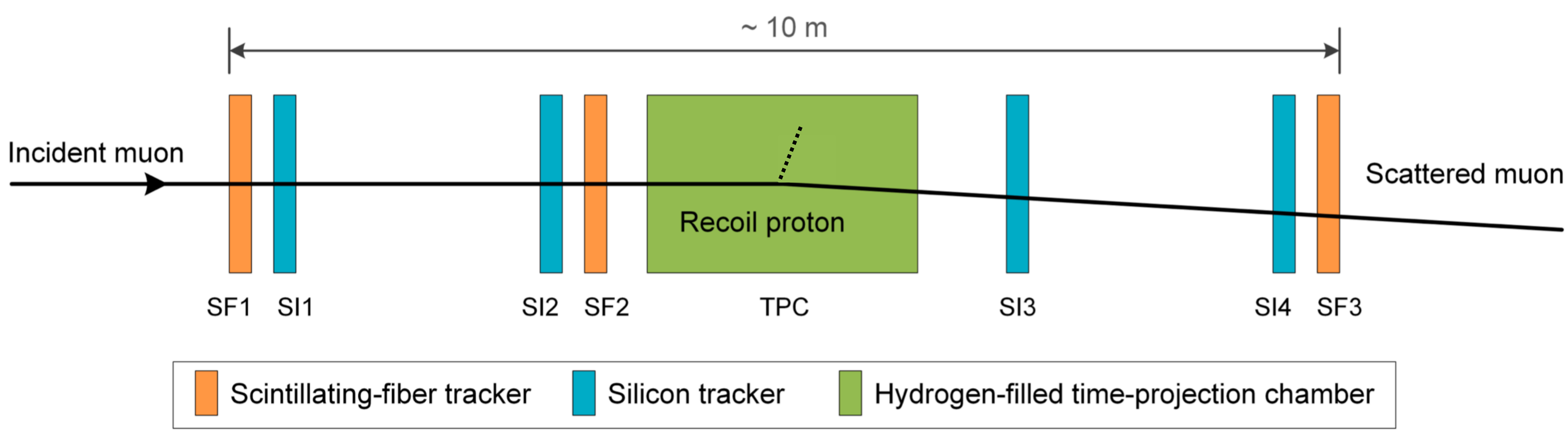
Layout of a possible COMPASS++/AMBER Setup

Measurement of low-Q^2 elastic scattering
Detection of low-energetic recoil-protons and scattered muons with small scattering angle.



- TPC as an active target with the ability to measure the low-energetic recoil-proton
- Silicon trackers to measure small scattering angles
- Fibers to trigger on scattered muon



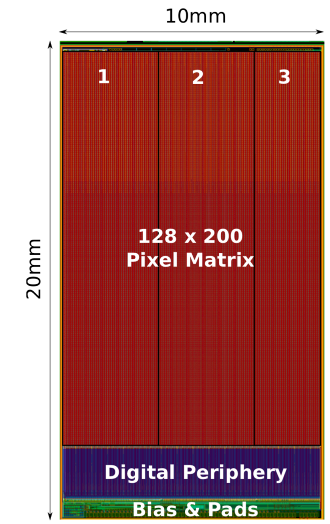
Detector Solutions for Proton Radius Measurement

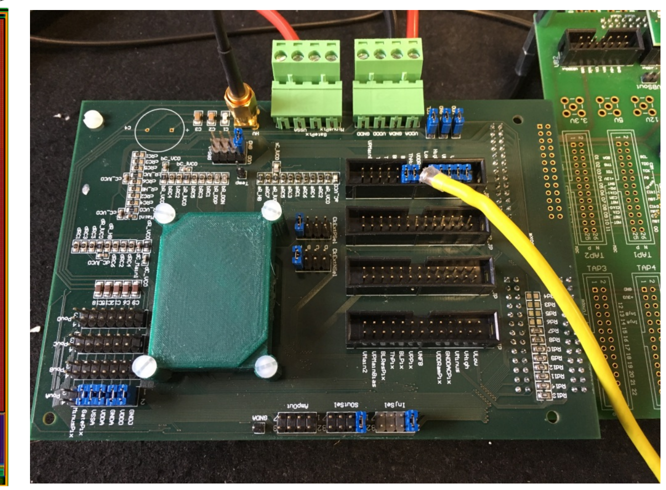
Tracking detectors, trigger stations and TPC
High-resolution silicon-pixel tracker combined with precise TPC triggered via scintillating fibers as kink trigger.

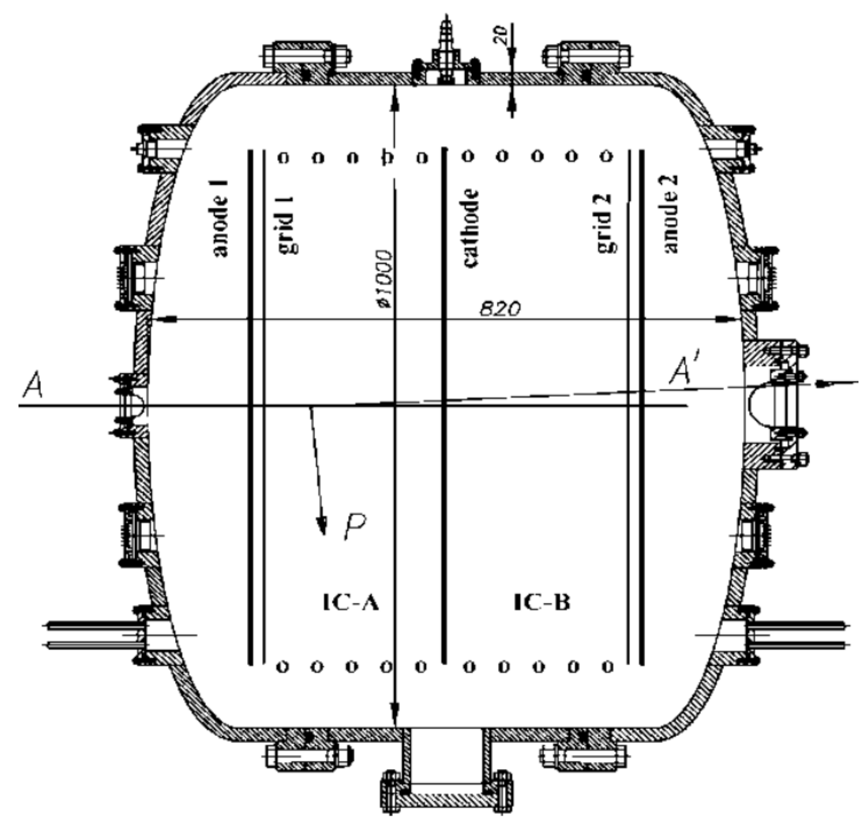
- Silicon Prototype MuPix8:
  - size: 1 x 2 cm², 128 x 200 pixels
  - 80 x 80 μm² pixel size
  - Thinned down to 50μm

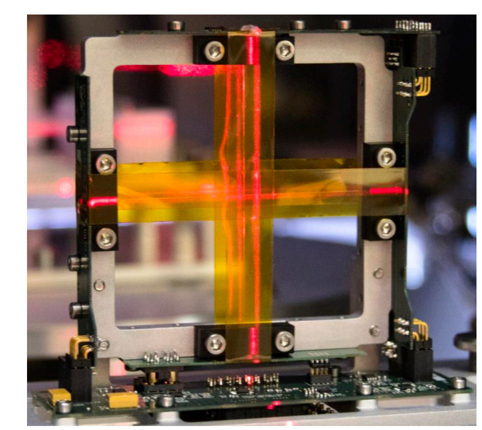
- Fiber Kink Trigger:
  - Trigger on small deflection of outgoing μ
  - 200 μm scintillating fiber with SiPMT
  - 2 or 4 projections

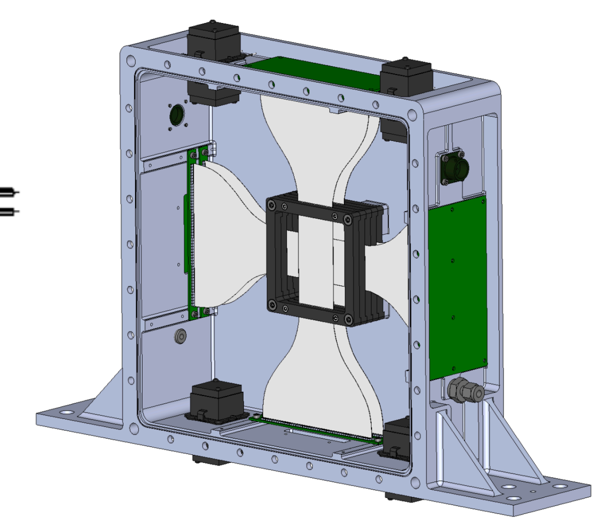
- TPC as Active Target:
  - Volume of 600 litres hydrogen up to 20 bar
  - Precise recoil detection from 0.5 to 20 MeV
  - Precision of drift velocity of 0.02%











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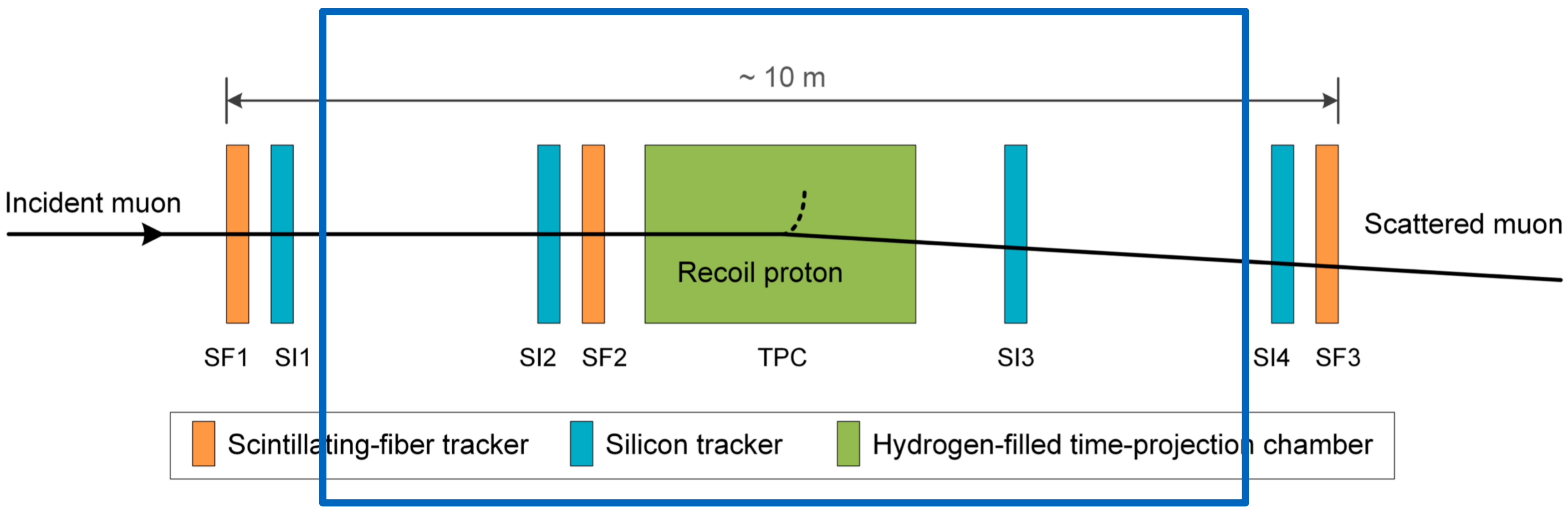
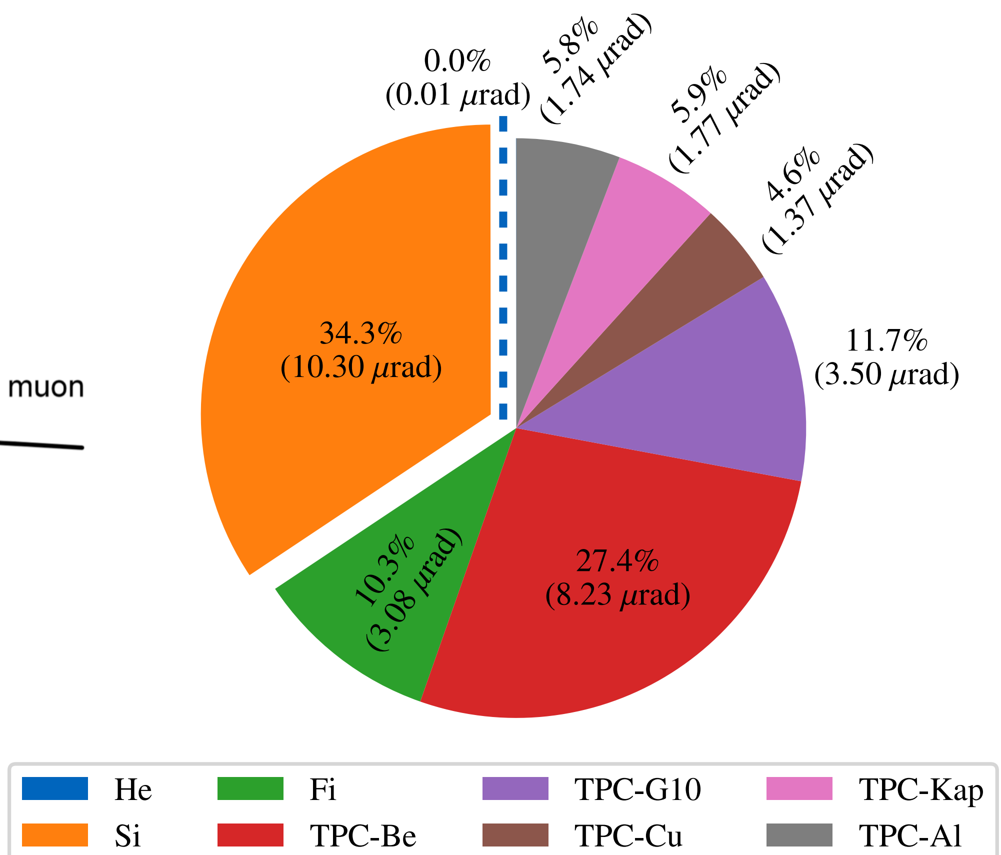
Material Budget and Multiple Scattering

Multiple scattering limits lowest accessable Q^2

Measurable scattering angle is limited due to multiple scattering as example for a beam momentum of 100 GeV.





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Q^2 Requirements

Limited by resolutions and multiple scattering
Measurable Q^2 range depends on fiber and silicon resolution and on proton range in TPC.

$$Q^2 \approx 4E^2 \sin^2\left(\frac{\theta}{2}\right)$$

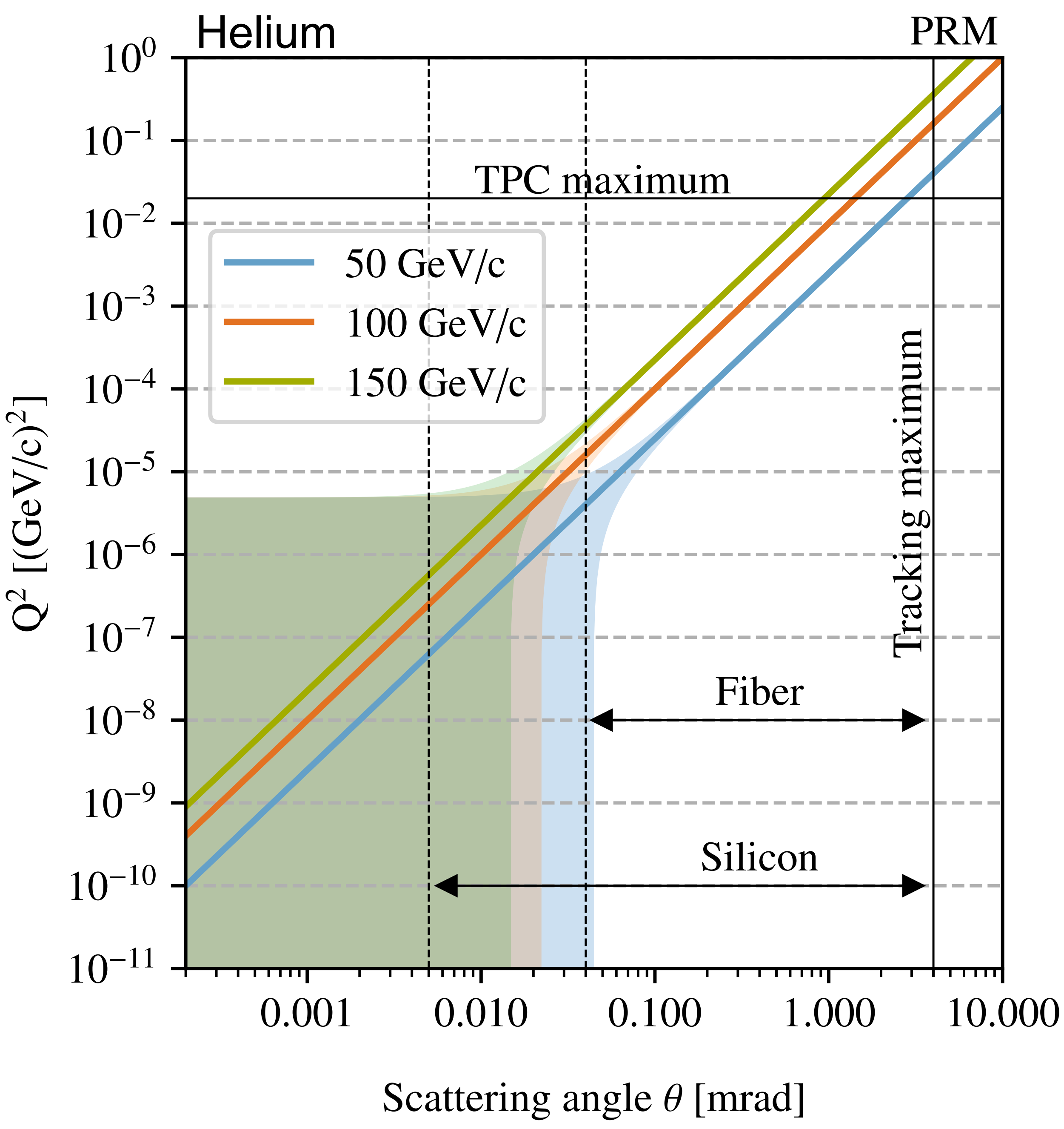
- Baseline: 5 meters

- Fiber “Kink" trigger:
  - Spatial resolution: Δd = 200 μm
  - Angular resolution: $\Delta\theta = 4 \cdot 10^{-2}$ mrad
  - Q^2 resolution: $\Delta Q^2 = 10^{-5}$ GeV^2

- Silicon:
  - Spatial resolution: Δd = 25 μm
  - Angular resolution: $\Delta\theta = 5 \cdot 10^{-3}$ mrad
  - Q^2 resolution: $\Delta Q^2 = 10^{-7}$ GeV^2

- TPC maximal Q^2 value: $2 \cdot 10^{-2}$ GeV^2

- Multiple Scattering:
  - $\Delta\theta_{MS} = 2.2 \cdot 10^{-2}$ mrad
  - $\Delta Q^2 = 4.6 \cdot 10^{-6}$ GeV^2



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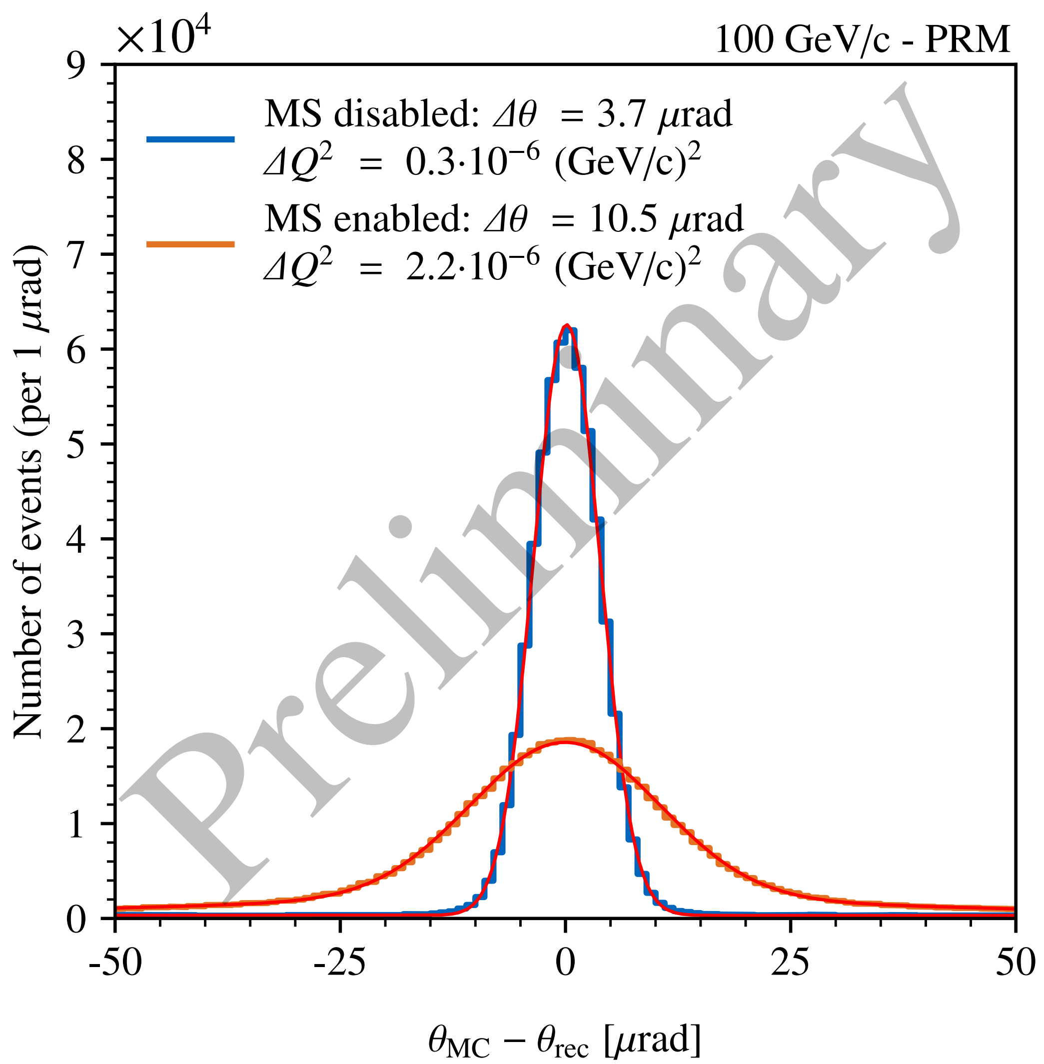
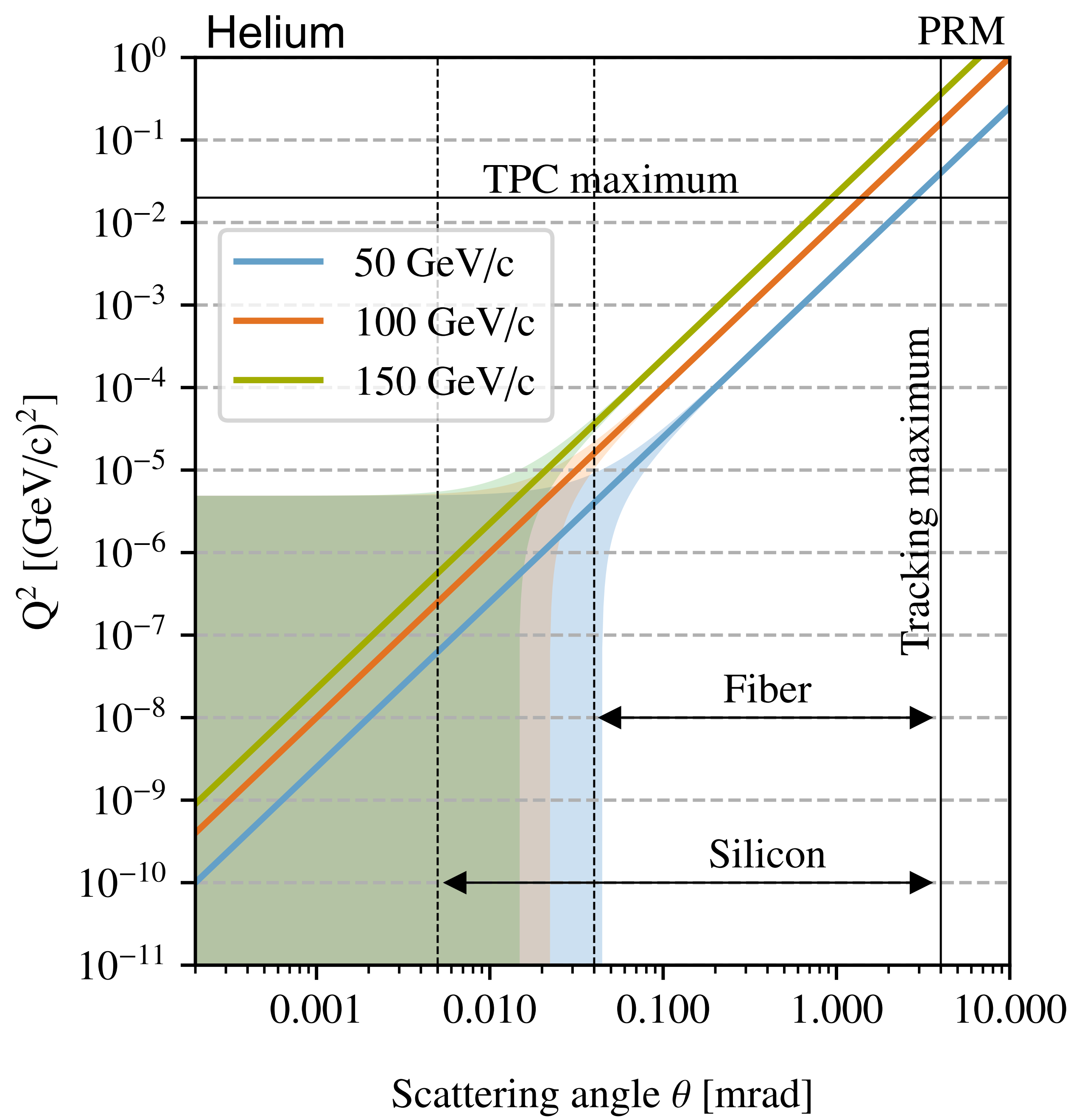




Proton Radius Test Measurement at COMPASS

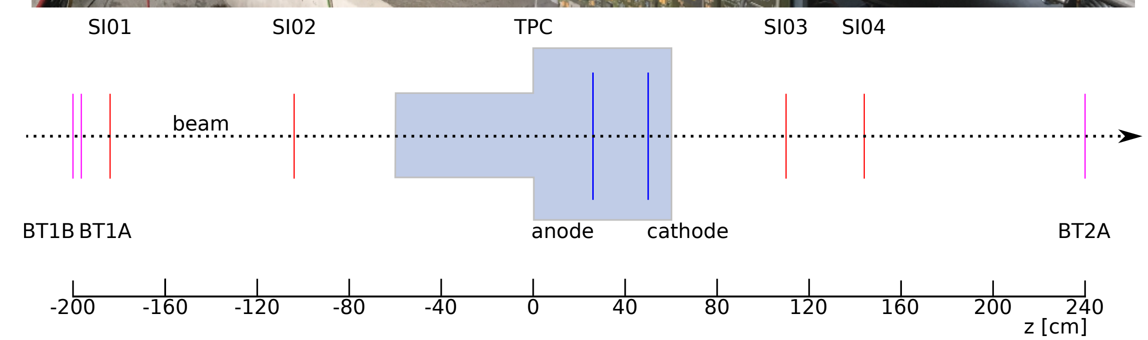
Test setup performed to study feasibility
Combination of silicon detectors and a TPC as active target with separated DAQ systems.

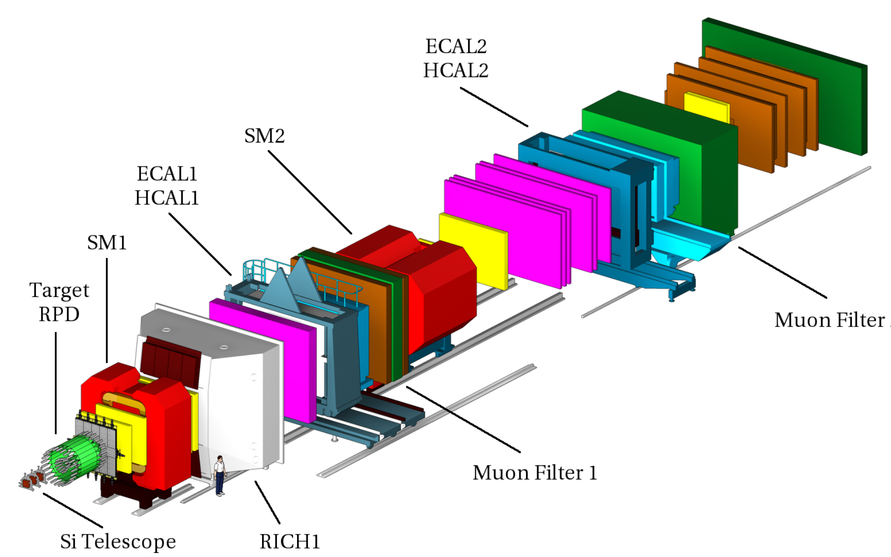
- Test setup downstream of COMPASS during 2018 Drell-Yan data taking
- Use remaining muons from 190 GeV/c beam

- Test of separate DAQ systems - TPC and tracking
- Correlate events in silicon detectors with TPC events via time stamp, tracking and kinematics.
  → Identification of possible recoil candidates

- Beam-rate studies (background and readout)
- Test TPC with broad beam

- Collect experience for the future measurement





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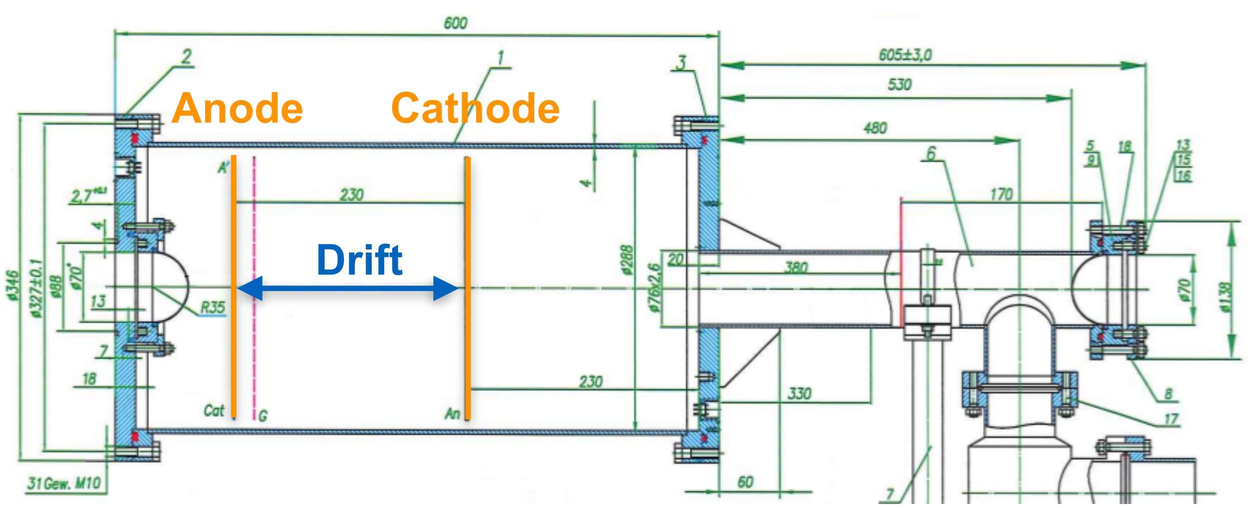
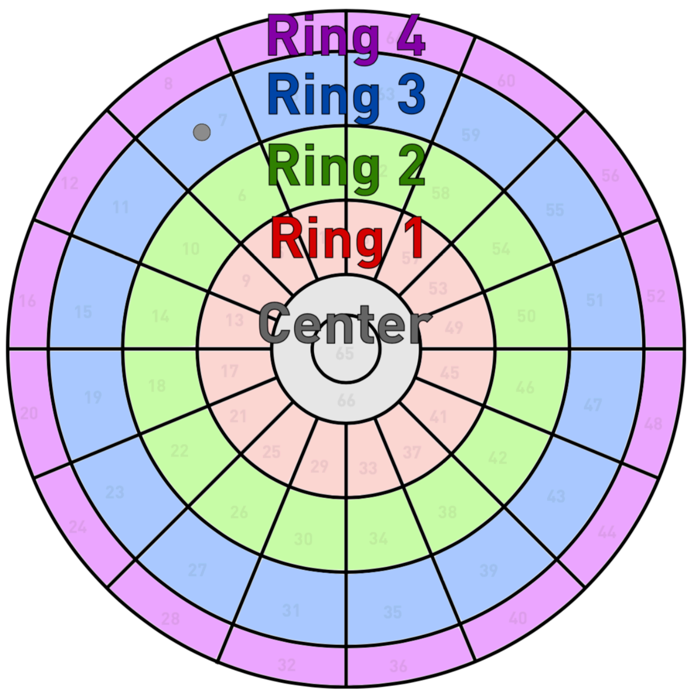
ACTAF2/R3B prototype – beam test at MAMI, 2017





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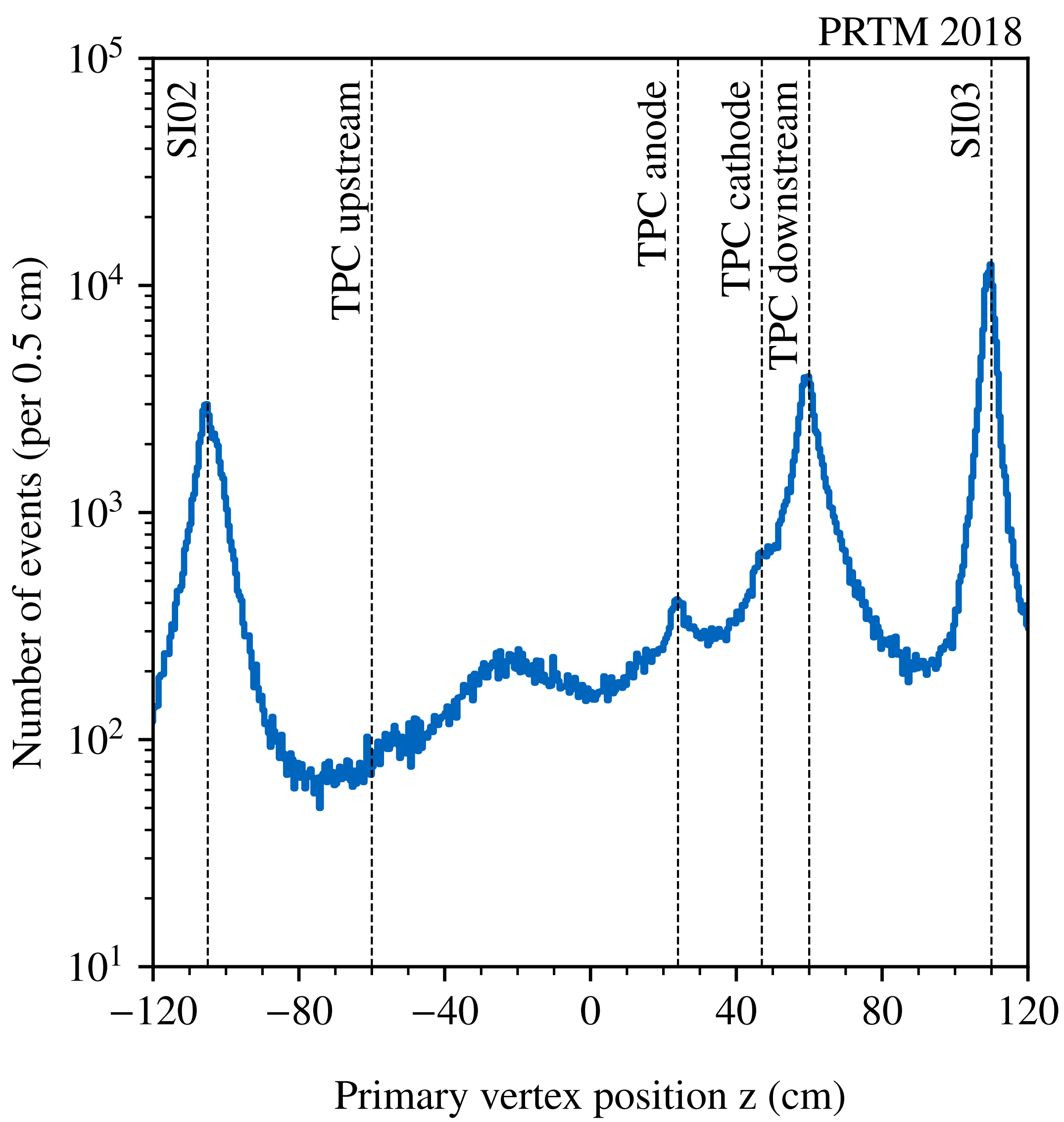
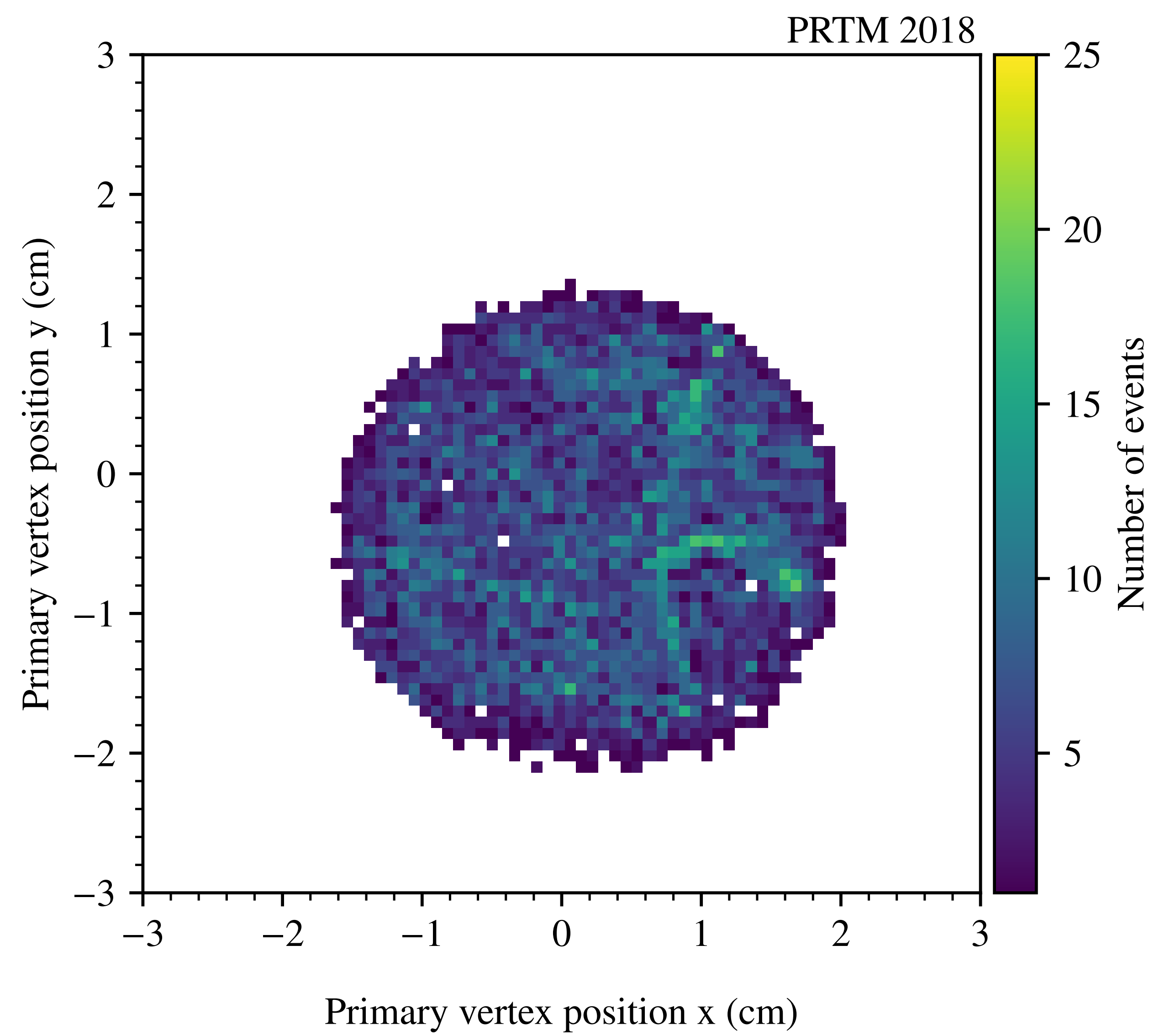
Primary Vertex Distributions

Vertex distribution along xy- and z-direction

Setup elements clearly visible in vertex distributions.



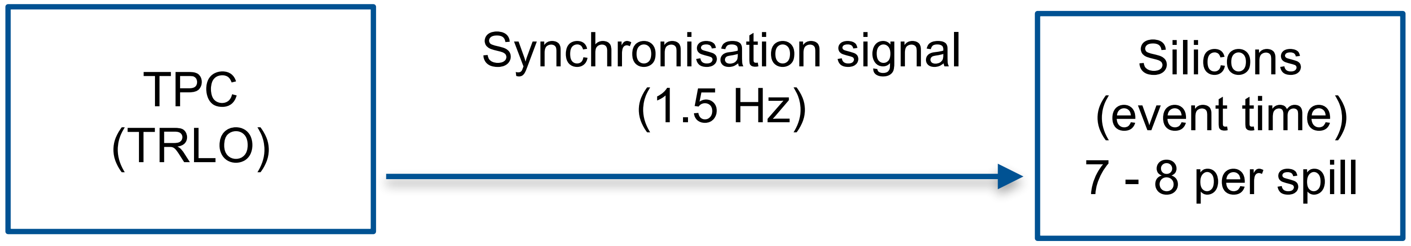


Combining two DAQ Systems via Time Stamp

Synchronisation using time stamps

Events from separate TPC and silicon DAQ tagged with time stamp.

- TRigger LOgic (TRLO) time stamp with 100 MHz resulting in a time resolution of 10 ns
- Synchronisation of time stamps during SPS spill



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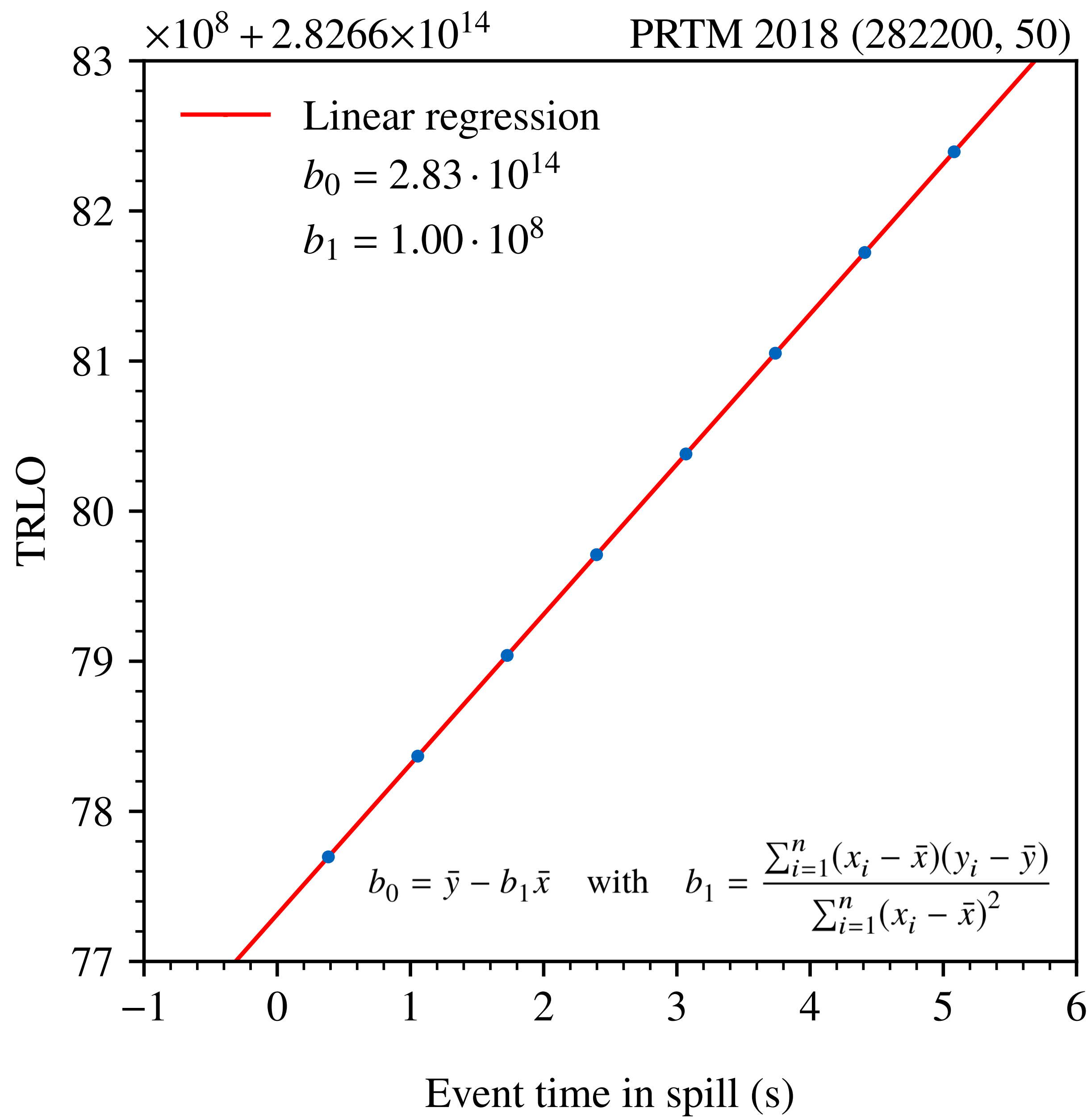

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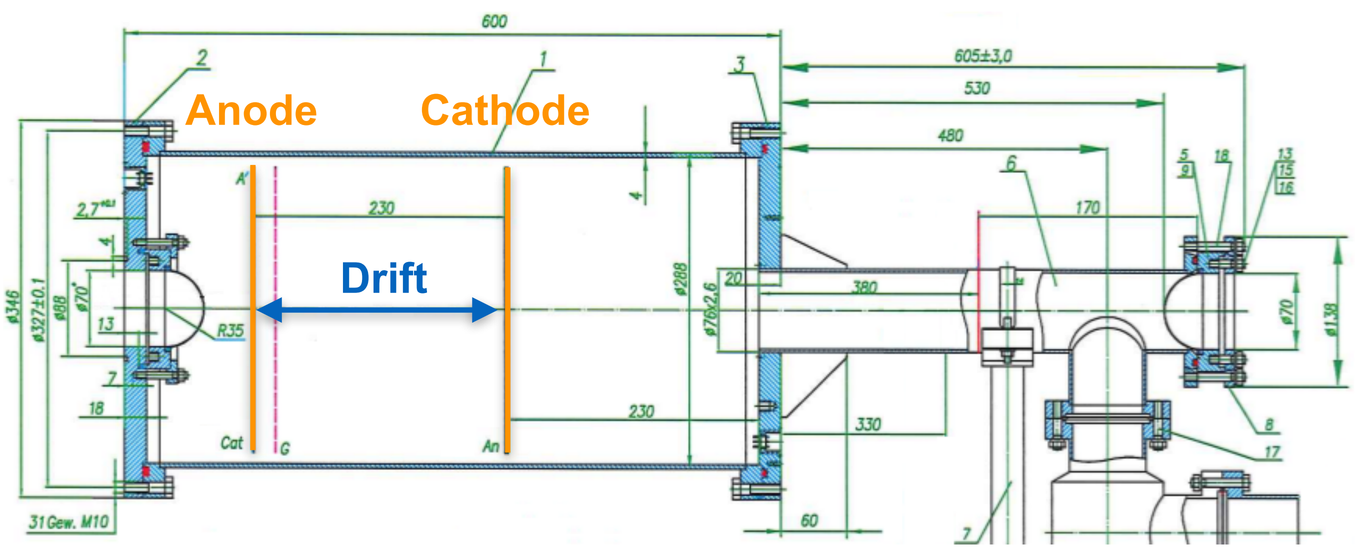
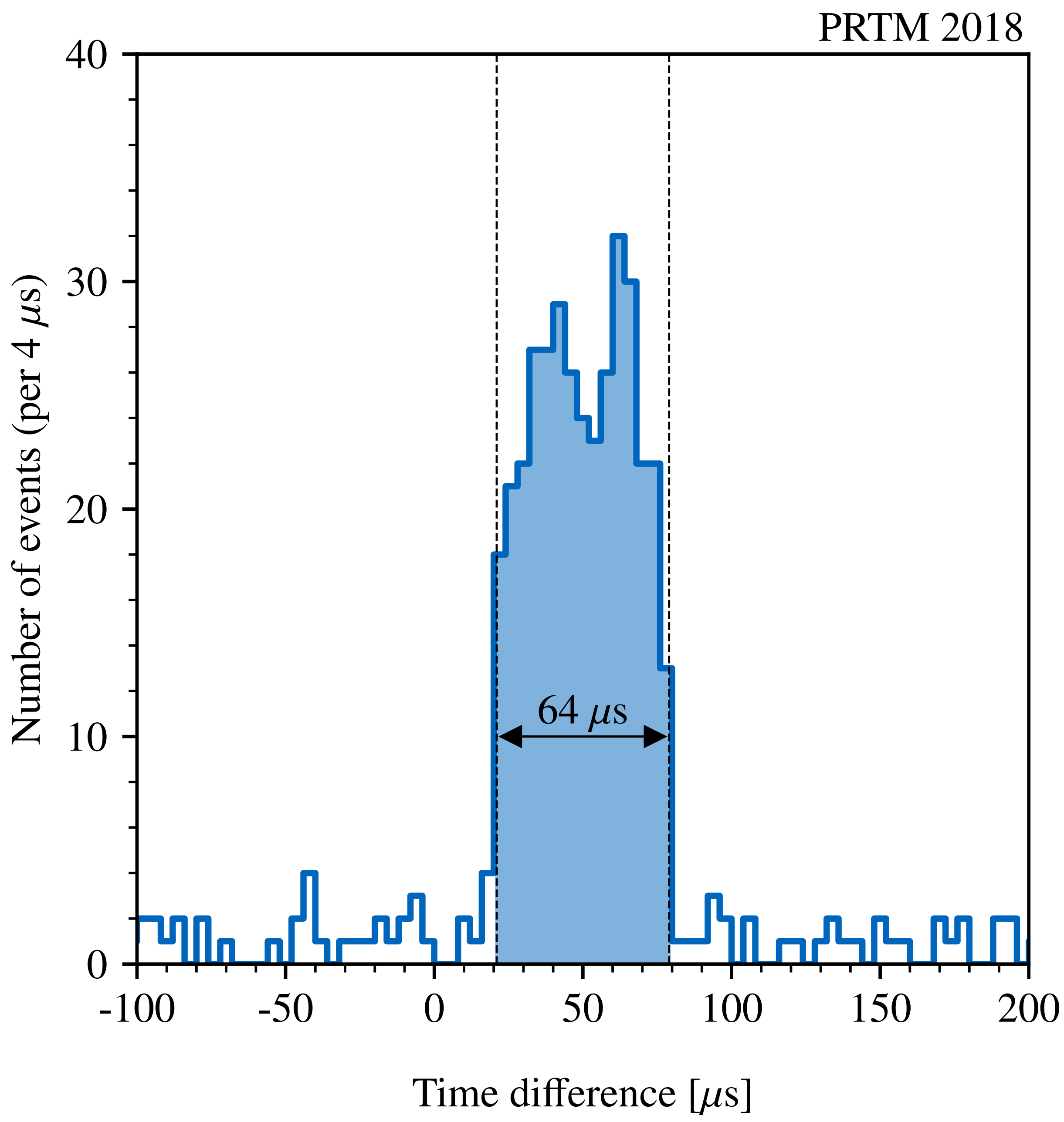
Combining two DAQ Systems via Time Stamp

Coincidence of TPC and Silicon events
Coincidence events within the drift-time window of the TPC.

- 64 µs drift-time window of TPC = width of coincidence peak
- Event matching - ongoing work correlating Silicon tracker events with TPC events.





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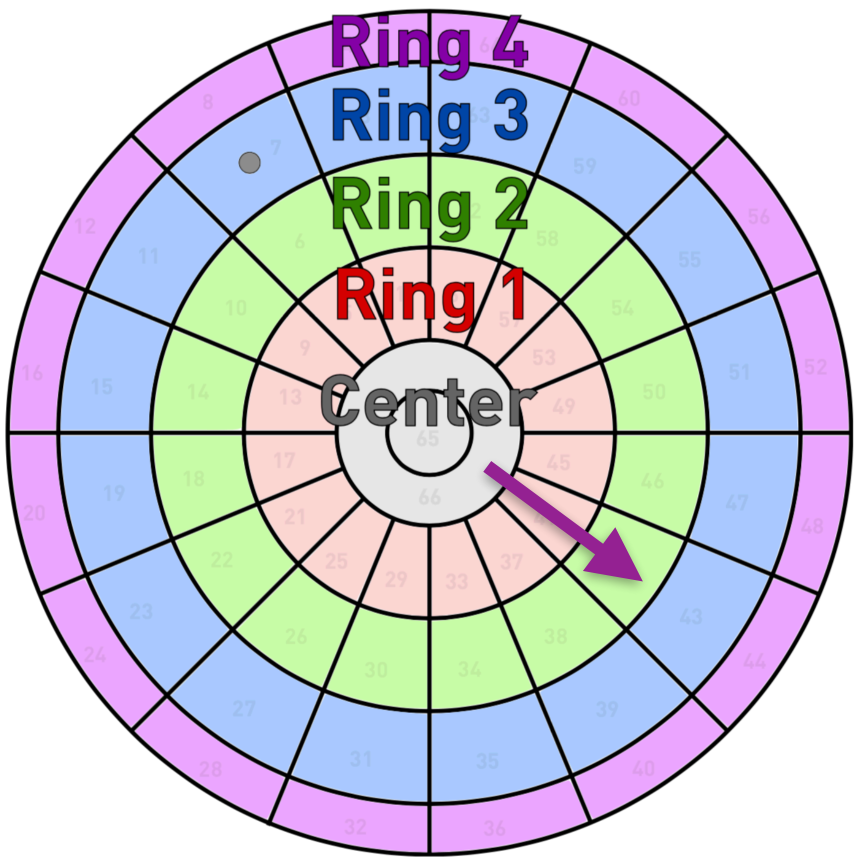
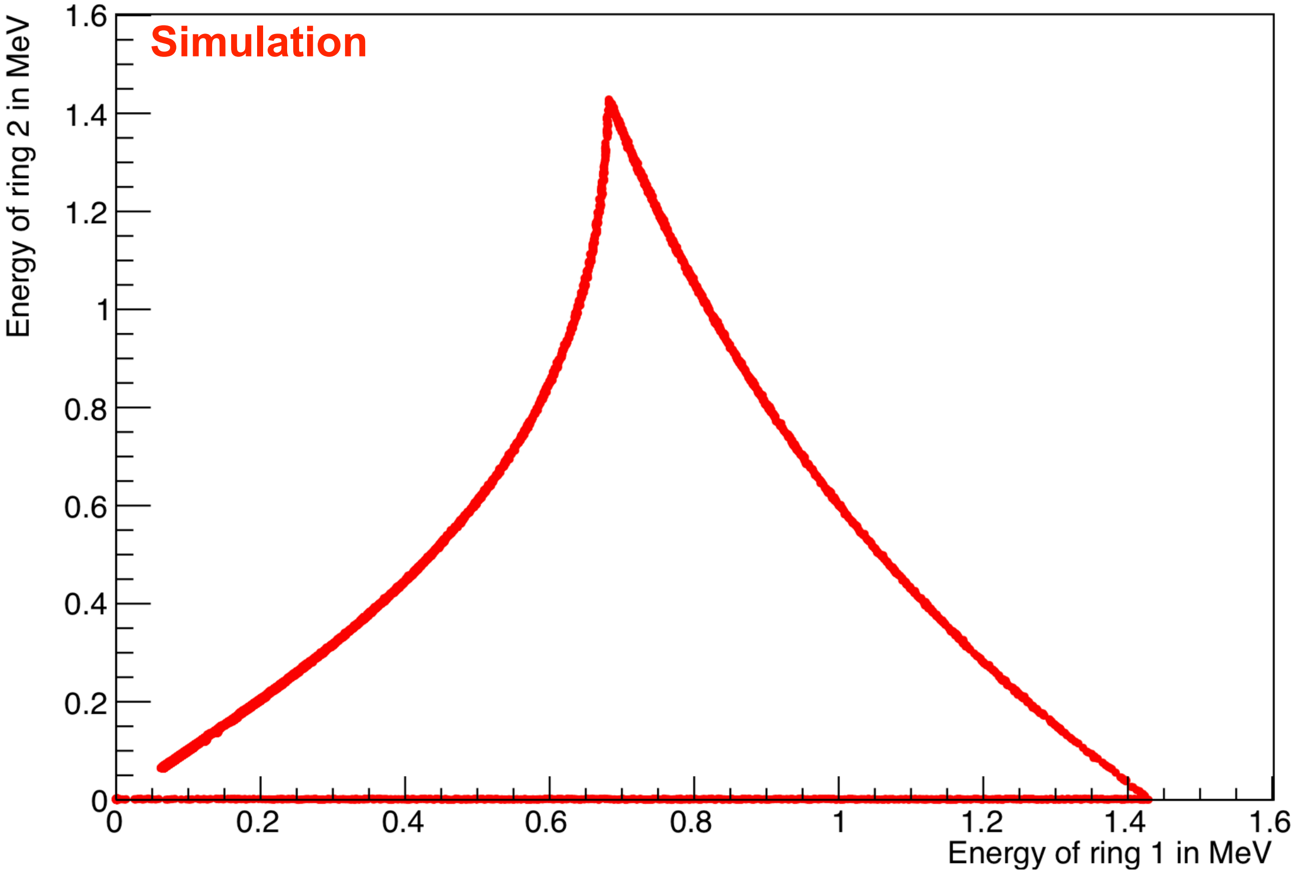
Kinematic matching of TPC events with tracking

Energy loss in TPC readout rings

Coincidence events within the drift-time window of the TPC.





- Energy deposition in neighbouring rings correlated

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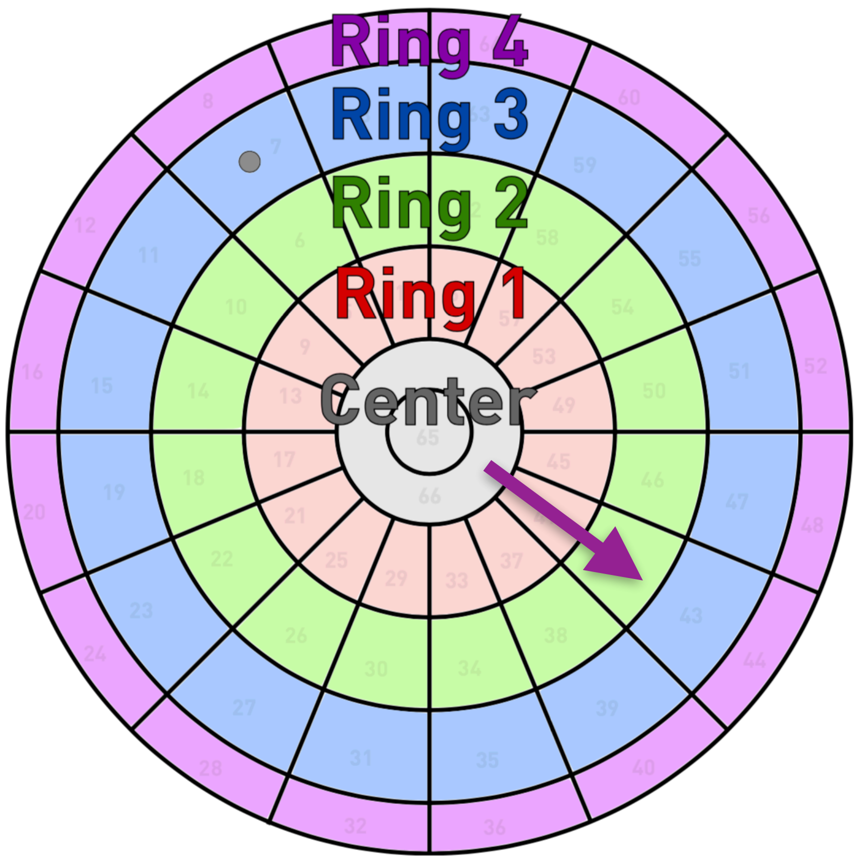

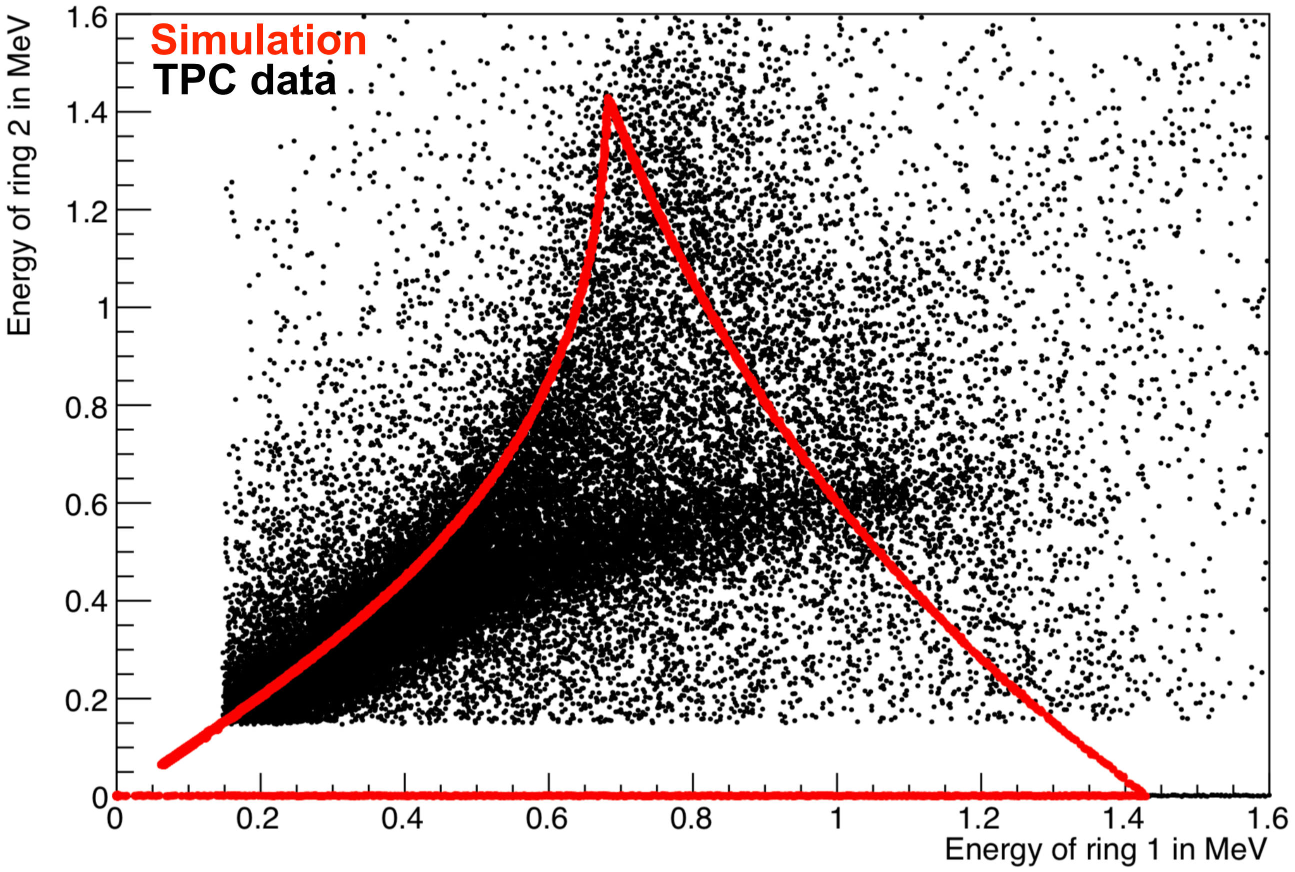

- Energy deposition in neighbouring rings correlated
- TPC data matches expected behaviour

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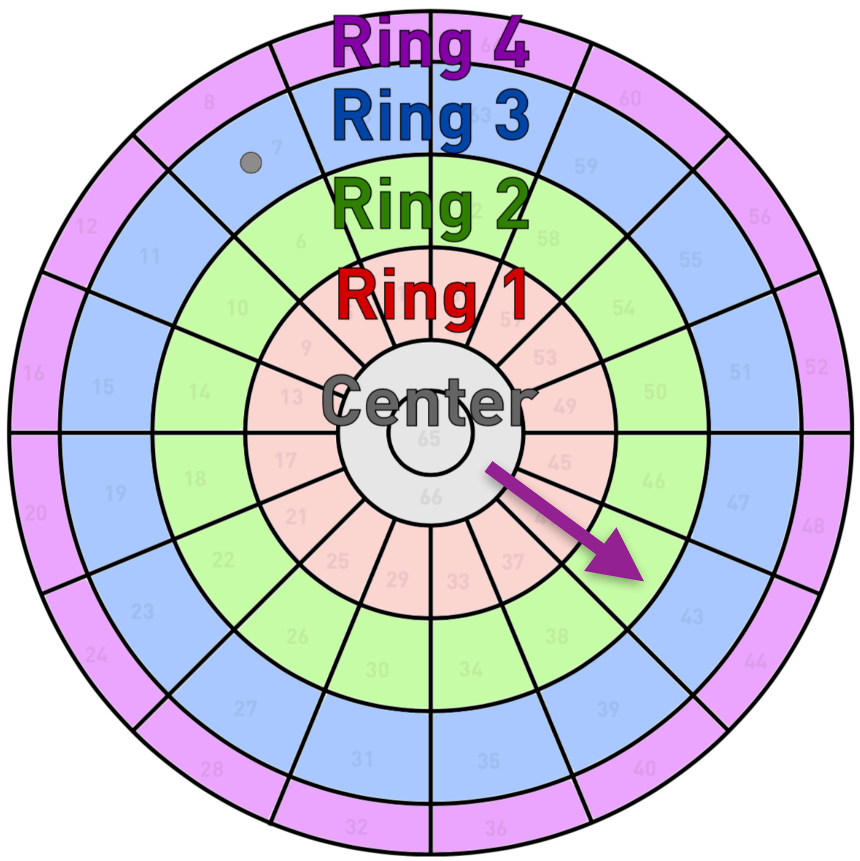

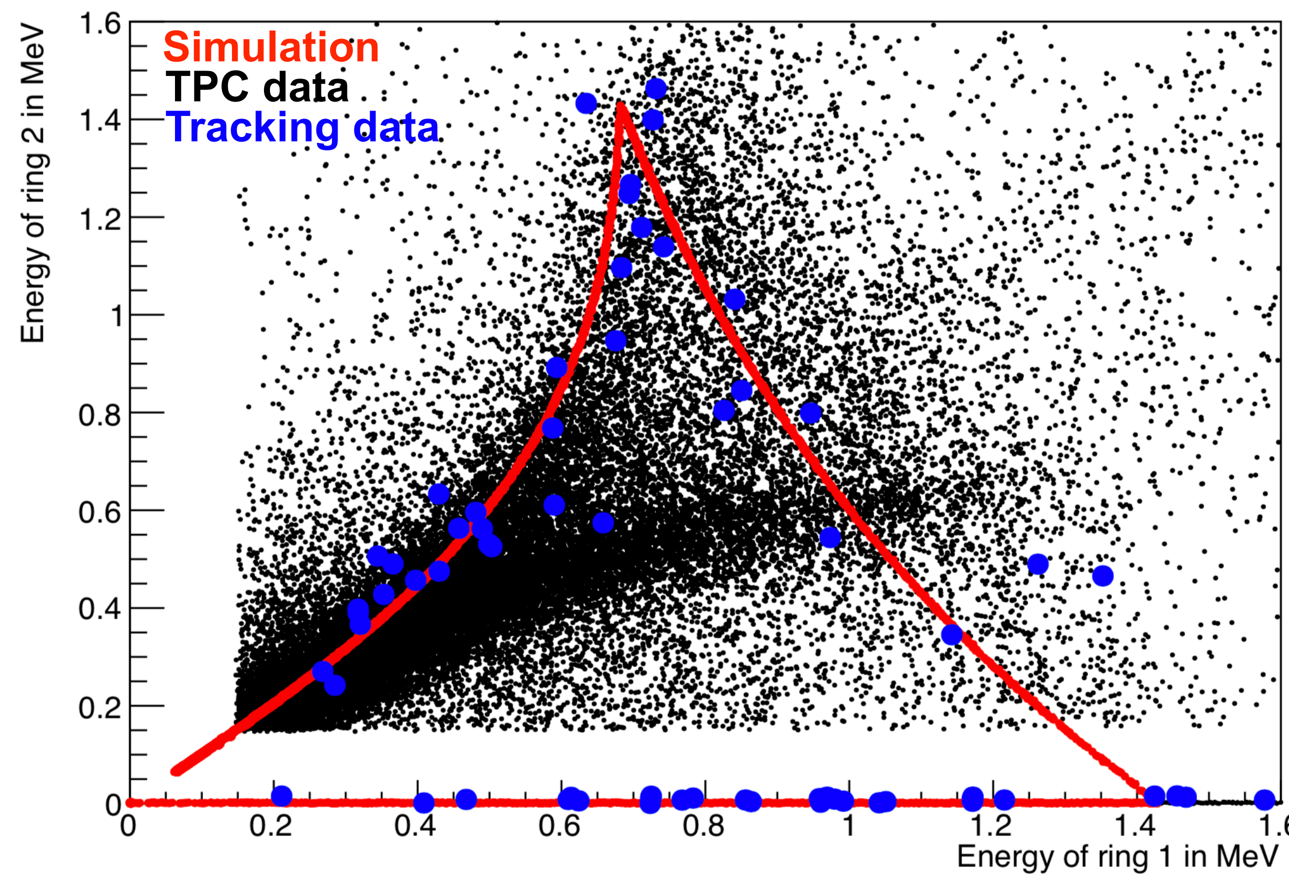

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- Tracking data machetes expected behaviour

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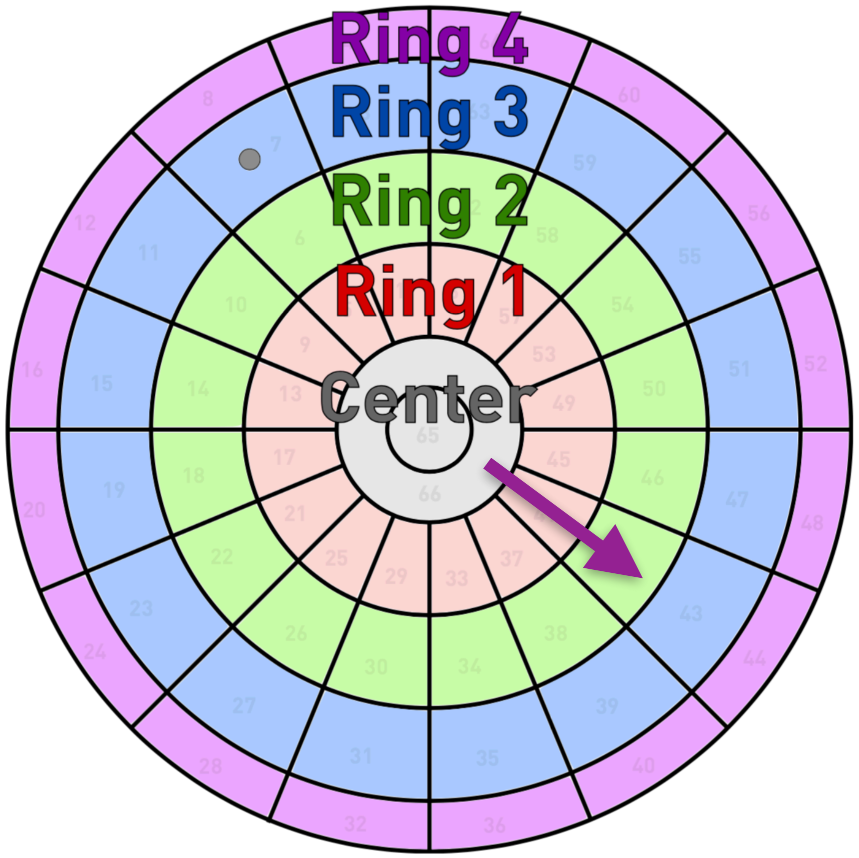

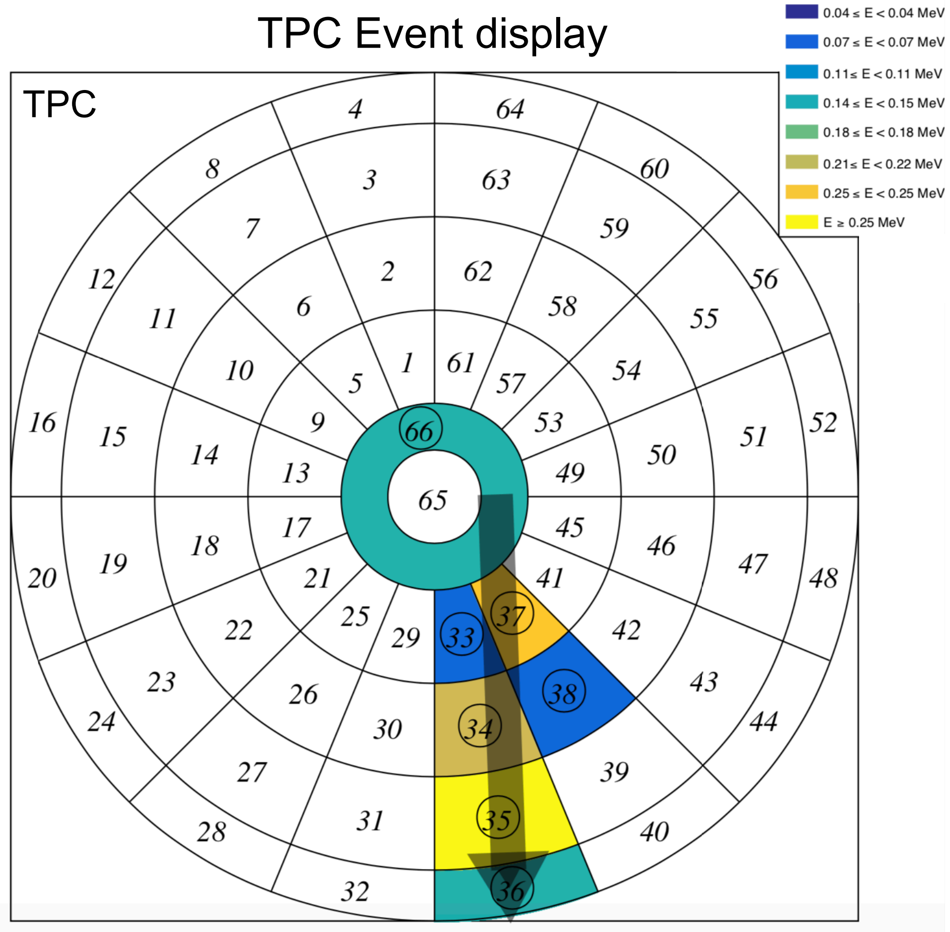

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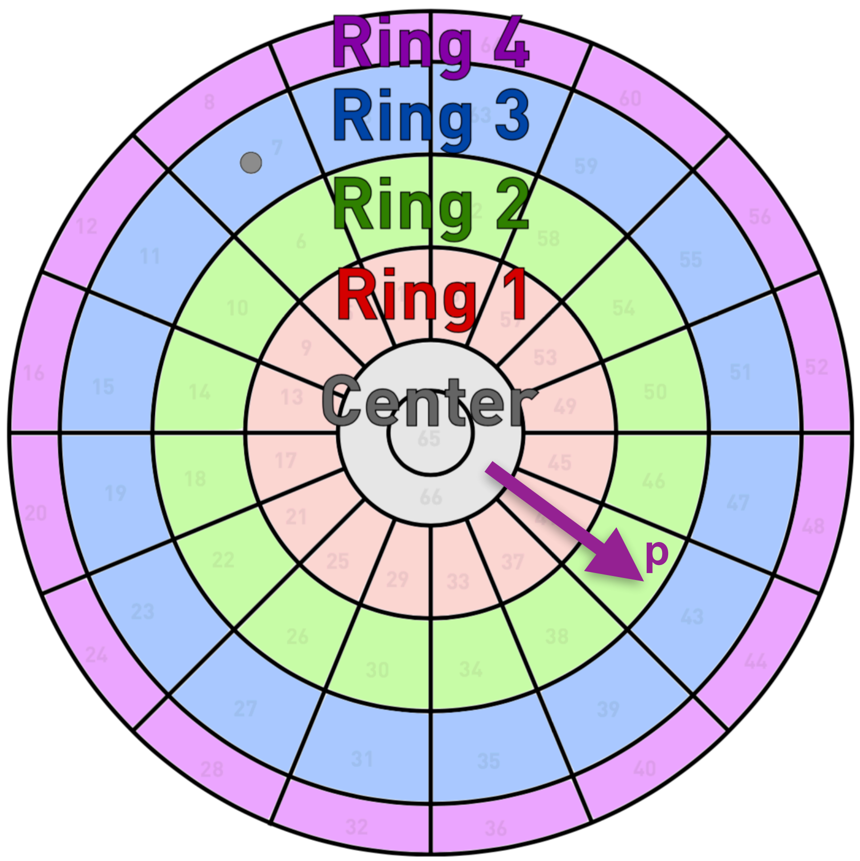

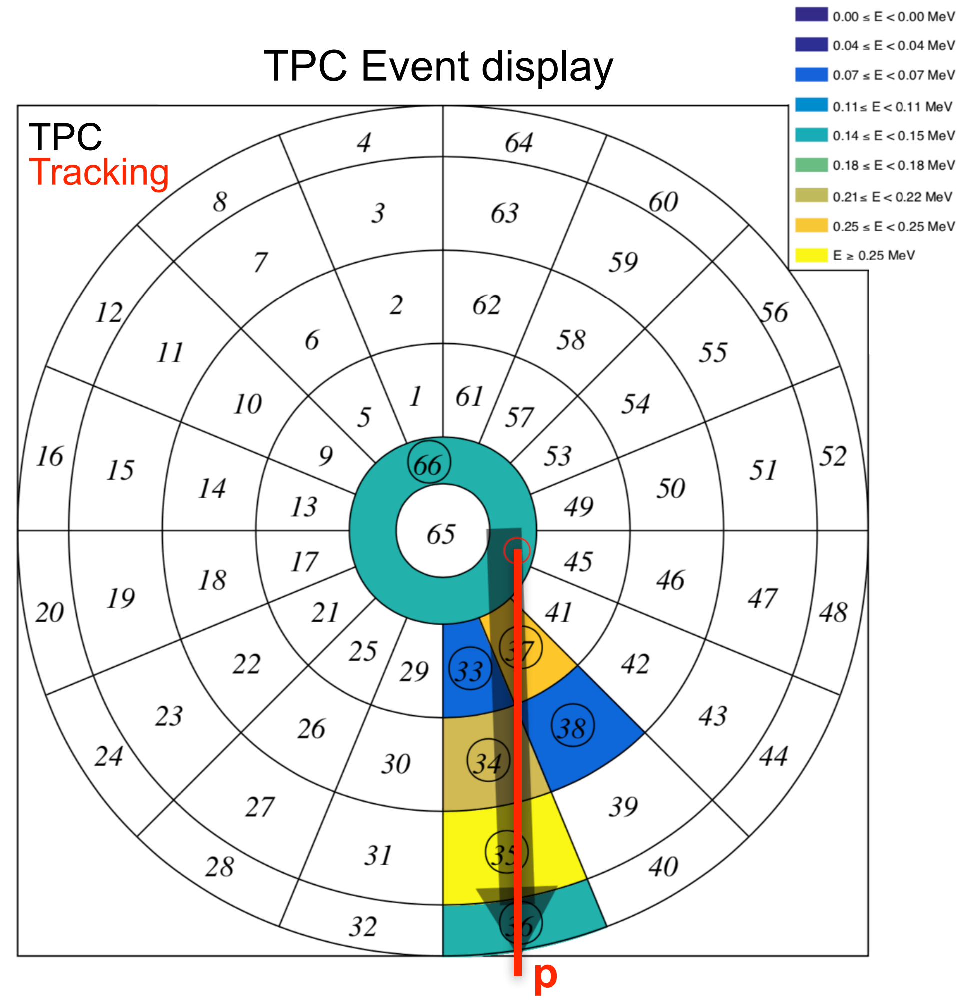

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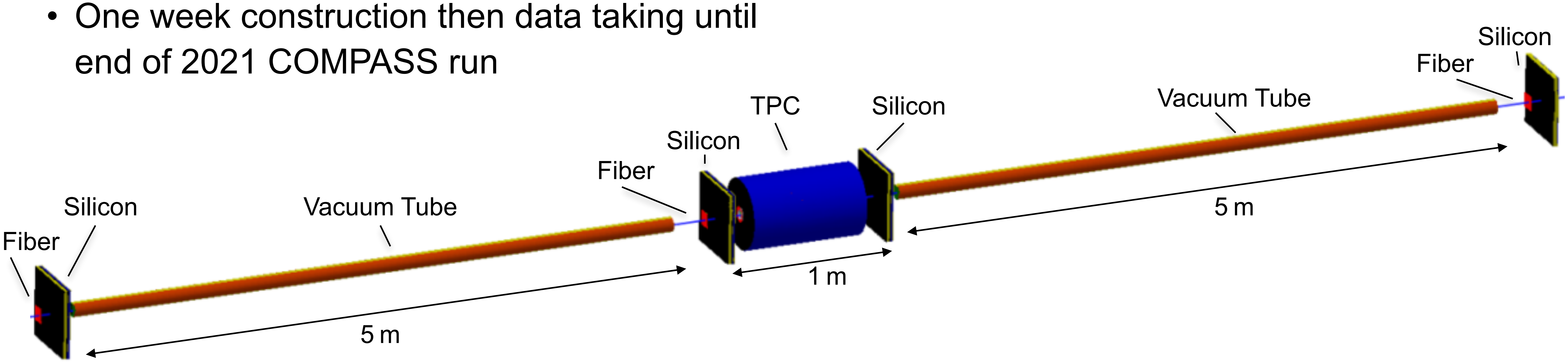
Planning 2021 Final Test Setup

Full setup upstream of spectrometer
Silicons, Fibers and TPC together with vacuum tubes installed for final test before 2022.

- Vacuum tubes to reduce multiple scattering
- New silicon detectors for precise tracking
- New fiber detectors for trigger on scattered muon
- Silicon and fiber detectors positioned inside vacuum tube
- One week construction then data taking until end of 2021 COMPASS run



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Summary and Outlook

Things under study

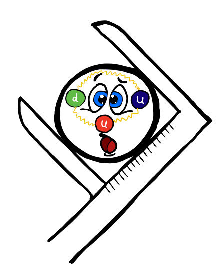
- COMPASS spectrometer: Final decision on spectrometer layout
- Final designs for silicon, fiber and TPC: Definition of kinematic window and trigger criteria
- Final beam properties: Optics, energy and rate with respect to detector capabilities
- Stability of setup: Minimise temperature fluctuations, especially in front of the beam tunnel, crucial for TPC
- Procedures for alignment, calibration and quality control
- Precise matching: using kinematics for event matching
- Trigger rate estimation: DAQ requirements

Things we already demonstrated successfully

- Event matching via TRLO time stamps: Operation of two separate DAQ systems works
- Multiple scattering crucial: Limitation of measurable Q^2 and helium bag or vacuum tubes requirement in target area
- Silicon, TPC and Fiber detector development ongoing: Promising way

Timelines:

- 2021: Feasibility test upstream of COMPASS
- 2022: Main run in target area of COMPASS



Final proposal foreseen within this year!

Backup

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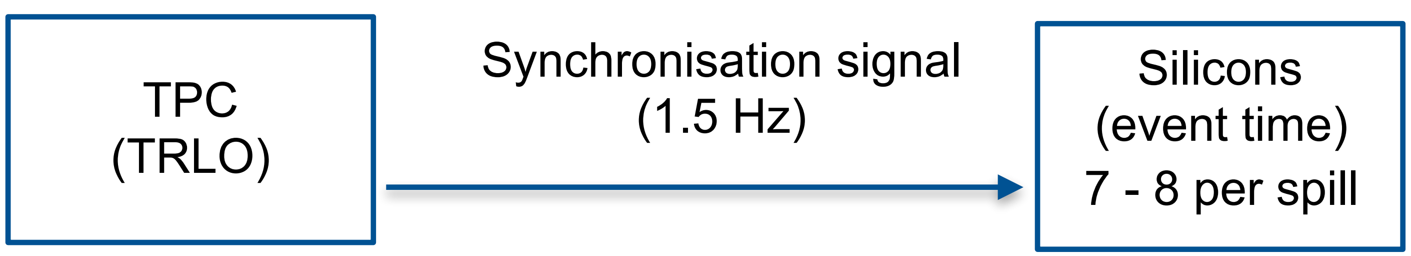

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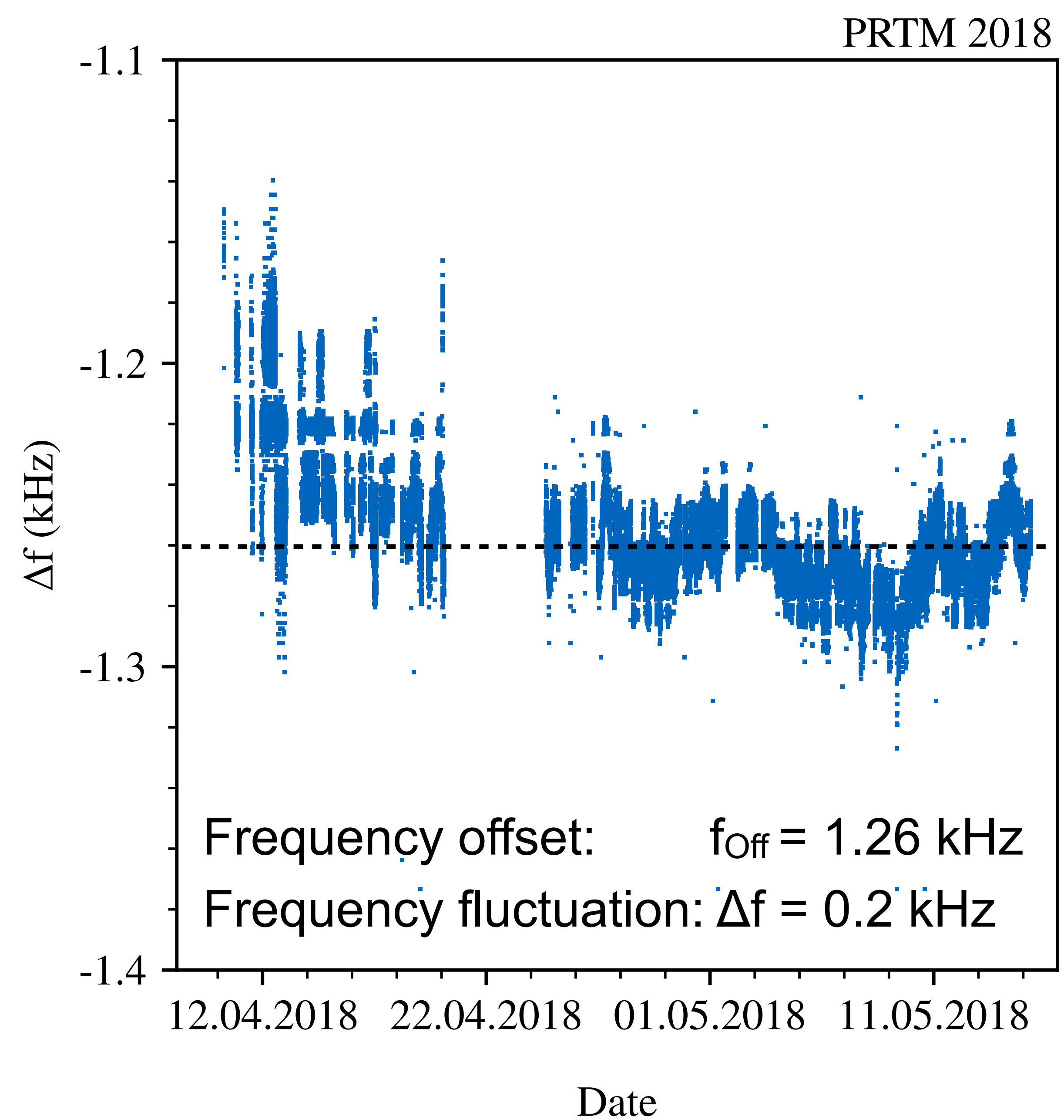

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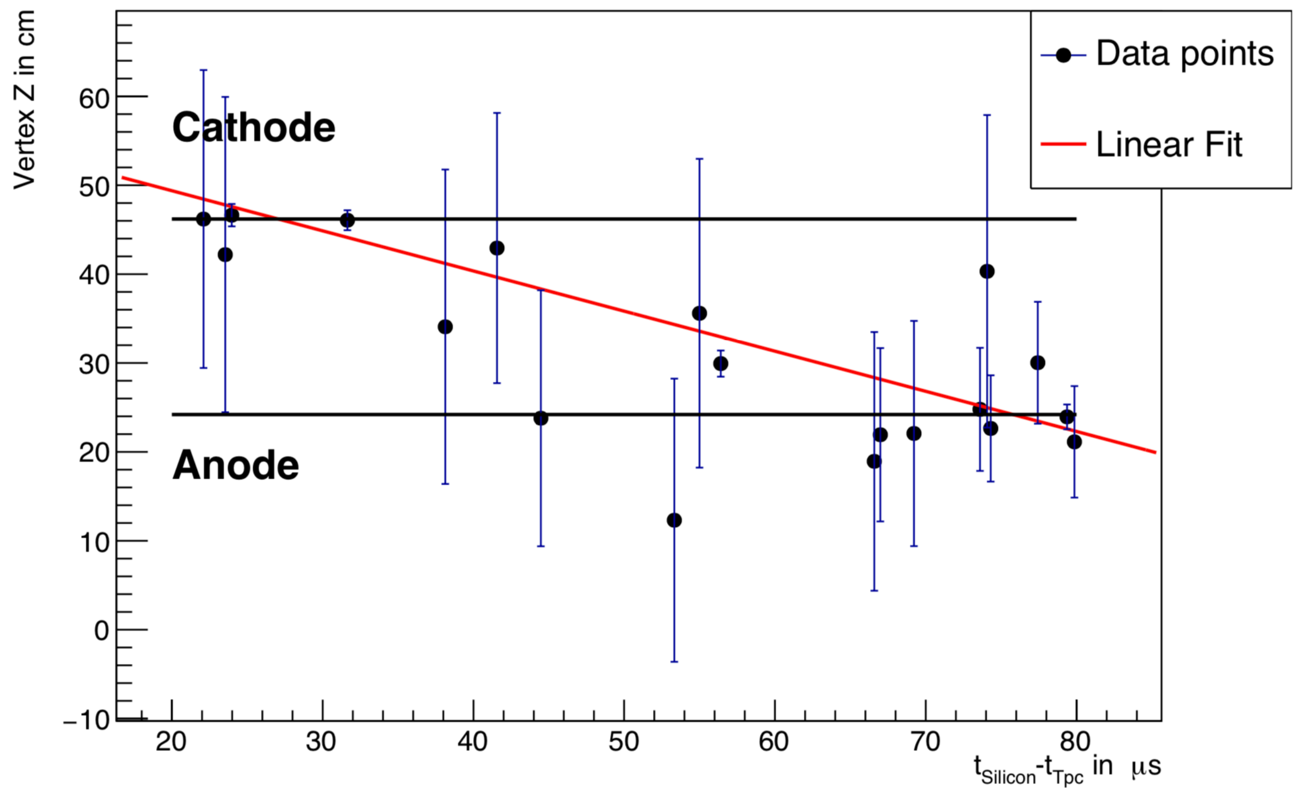
Drift Velocity Studies in TPC

Time difference correlated with vertex position
Correlation between drift time in TPC and position between cathode and anode.

- 22 cm drift volume between cathode and anode
- Low statistics due to large z-vertex resolution and resulting event selection (θ > 0.5 mrad)
- Linear behaviour visible → extract drift velocity
  - Measured v_{drift} = (4.51±0.29) mm/μs
  - Expected v_{drift} = 3.80 mm/μs



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Vertex distribution and z-resolution

Time difference correlated with vertex position

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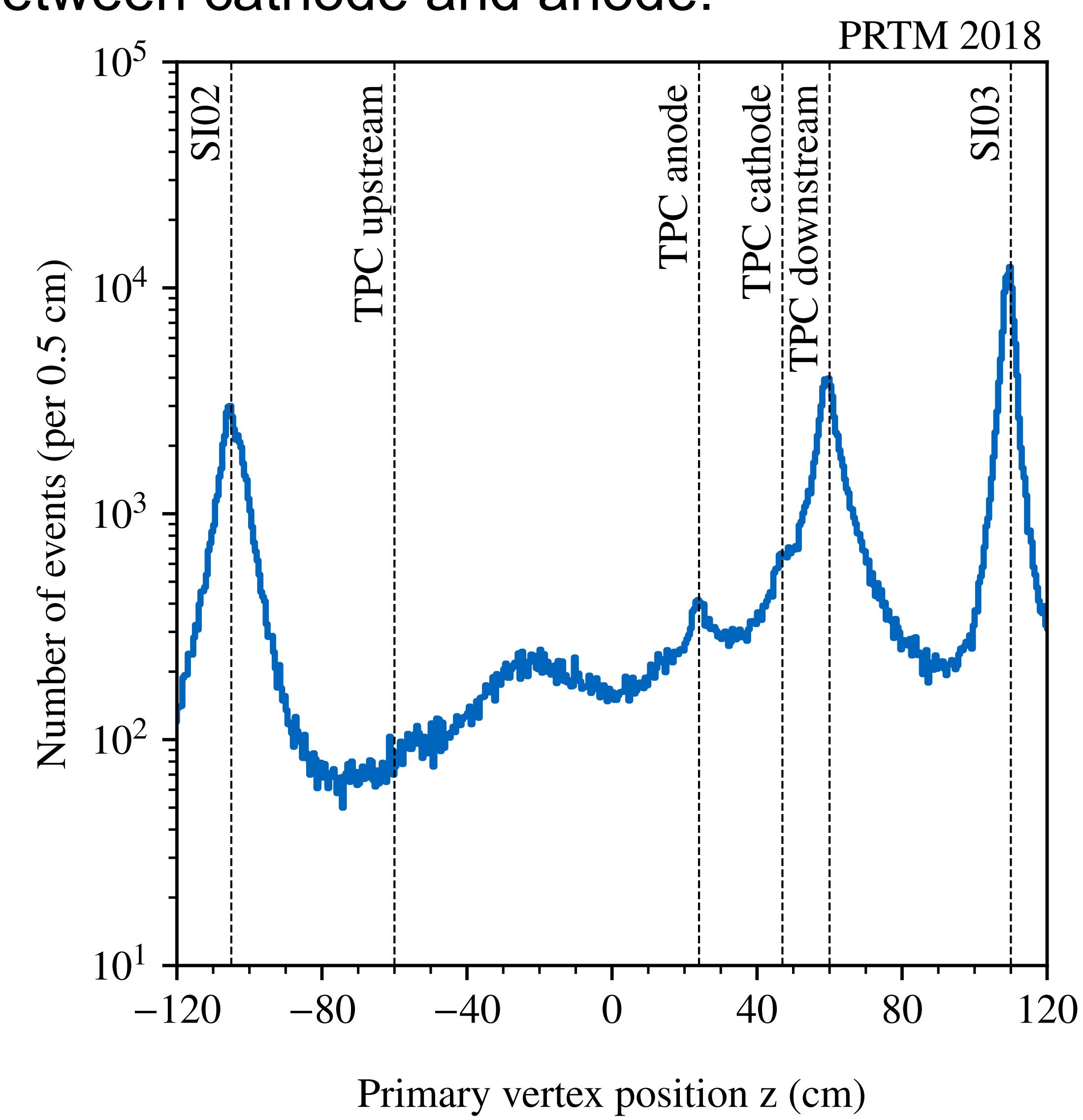

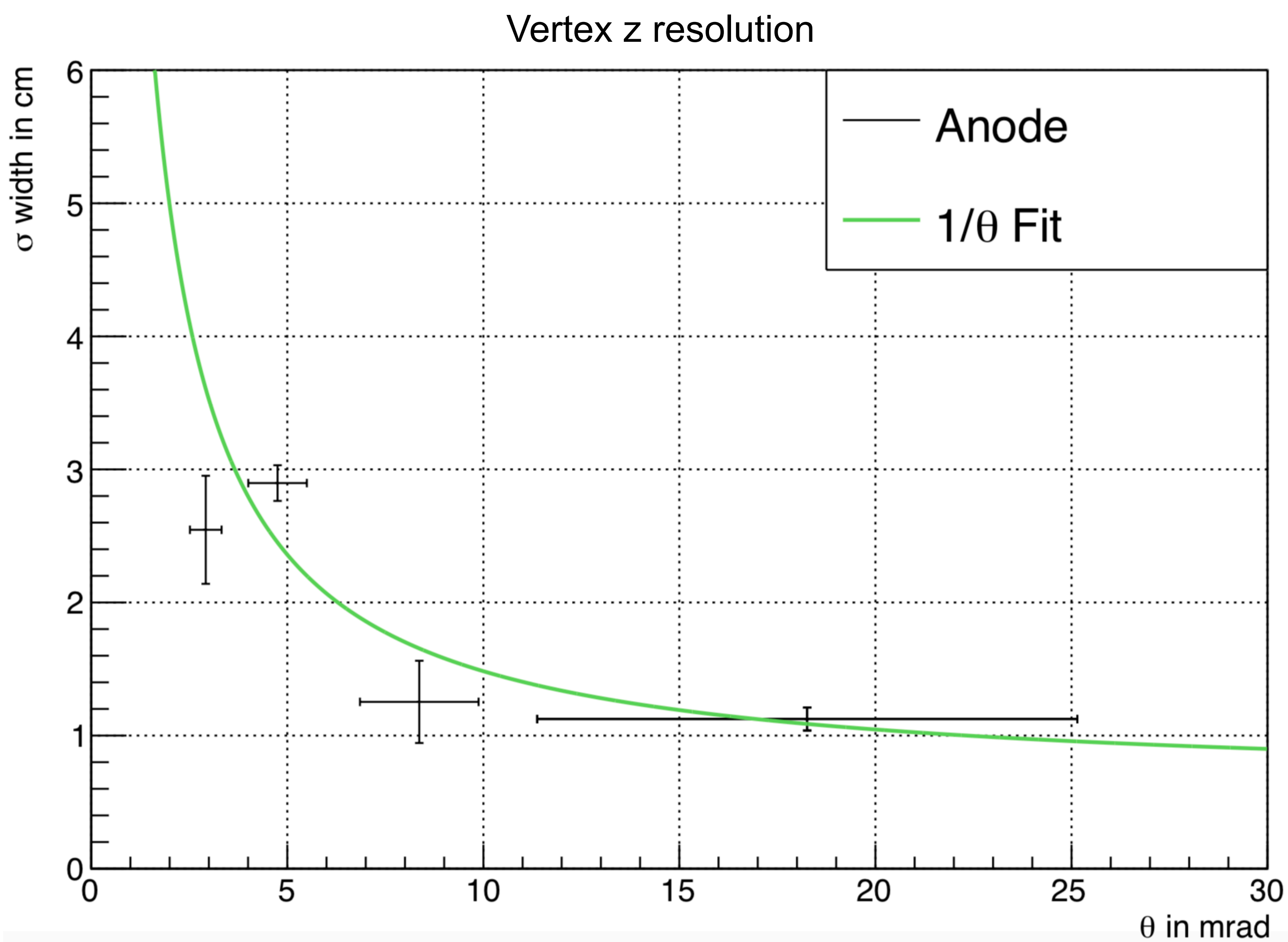

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Vertex distribution and z-resolution

Vertex z resolution comparison between MC and RD

Comparison shows same 1/θ behaviour for both, but a factor two discrepancy.