Proton-Radius Measurement in High-Energy Muon Scattering at COMPASS++/AMBER - Monte Carlo simulation of the Setup

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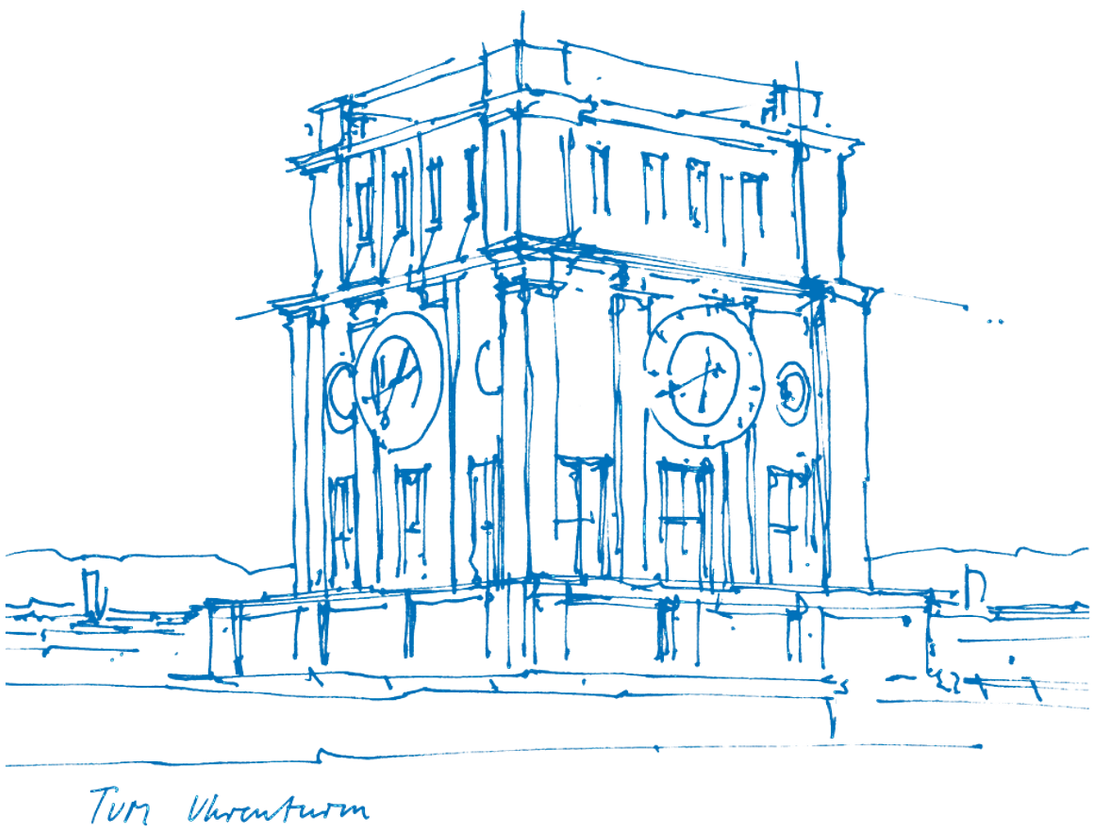

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Upcoming Experiments Addressing the Puzzle

New data from lepton-proton scattering

Several proposed and preparing experiments to solve the puzzle in the next years.

- **PRad**: electron-proton with $E_e = 1.1/2.2$ GeV
  → data taken in 2016: working on systematics
  → recent (preliminary) results: smaller value

- **MAMI**: electron-proton with $E_e < 750$ MeV
  → two new experiments in preparation

- **MAGIX-MESA**: electron-proton with $E_e < 150$ MeV
  → electric and magnetic form factor
  → new accelerator - start in 2024

- **MUSE**: muon/electon-proton with $E_{e,\mu} < 140$ MeV
  → comparison of electron and muon scattering
  → start of data taking in 2019

- **<u>Missing</u>**: muon-proton with E_μ of $\mathcal{O}$(10 - 100 GeV)
  → data for high-energy elastic muon-proton scattering
  → different systematics compared to other

Proton Radius Experiment at Jefferson Lab

PRadius

MAINZER MIKROTRON

MAGIX

MESA
Mainz
Energy-recovering
Superconducting
Accelerator

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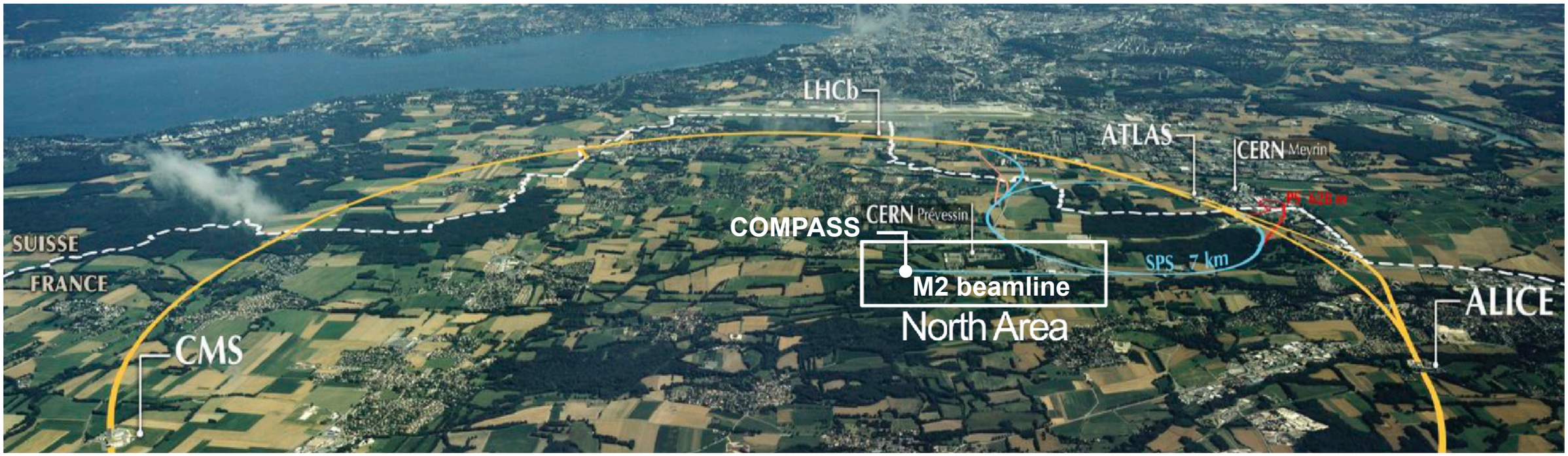
Beamline for High-Energy Muon Beams

The M2 beamline at CERN's SPS

Located at the North Area of CERN the unique M2 beamline provides a high-intensity muon beam.



- Muon momenta up to 200 GeV/c with a flux up to 10^7 μ/s
- Measurement could be performed at the site of the current COMPASS experiment

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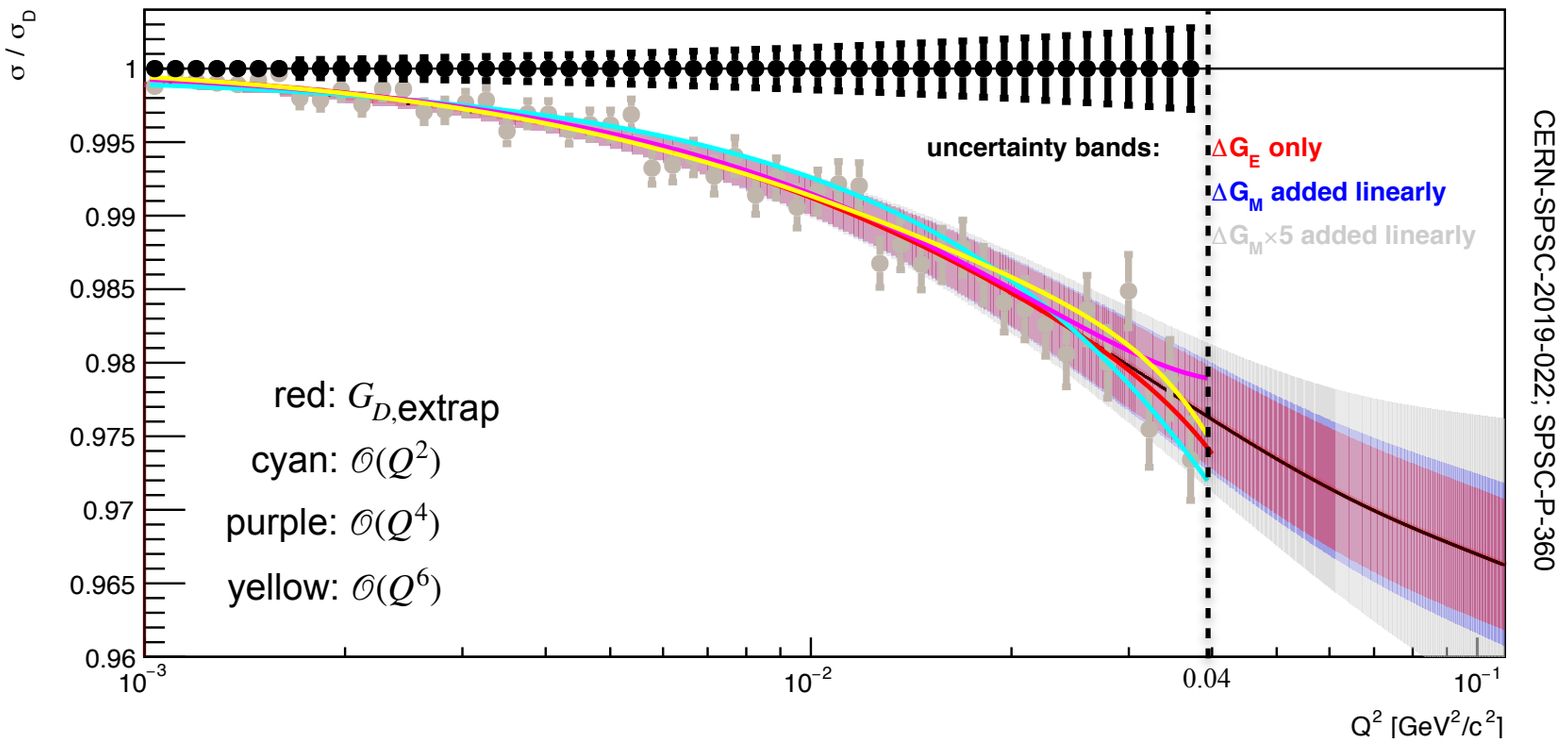
Proposal of a New Measurement

High-energy elastic muon-proton scattering
Measurement of the cross section of elastic muon-proton scattering using CERN's M2 beamline at the site of the current COMPASS experiment.

- Measure as close as possible to $Q^2 = 0$
- Sufficient range to determine radius
  → aimed precision of 1 %
  → aimed Q^2-range: 0.001 - 0.04 GeV^2/c^2

- Below $Q^2 = 0.001$ GeV^2/c^2:
  → deviation from point-like proton level of $\mathcal{O}(10^{-3})$
  → smaller than unavoidable systematic effects
- Above $Q^2 = 0.04$ GeV^2/c^2:
  → non-linearity of the cross section
  → predominant source of uncertainty



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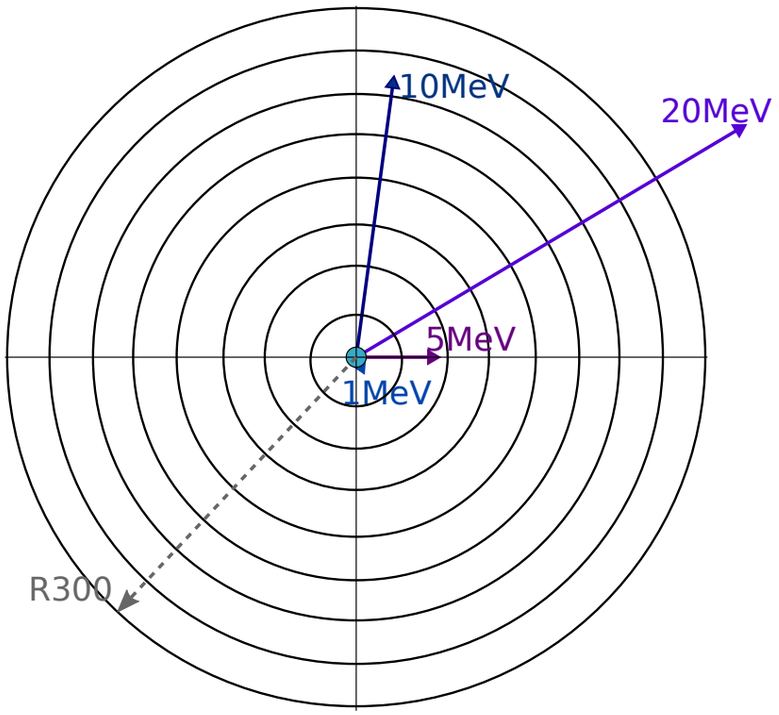
Detection of Low-Q^2 Recoil-Protons

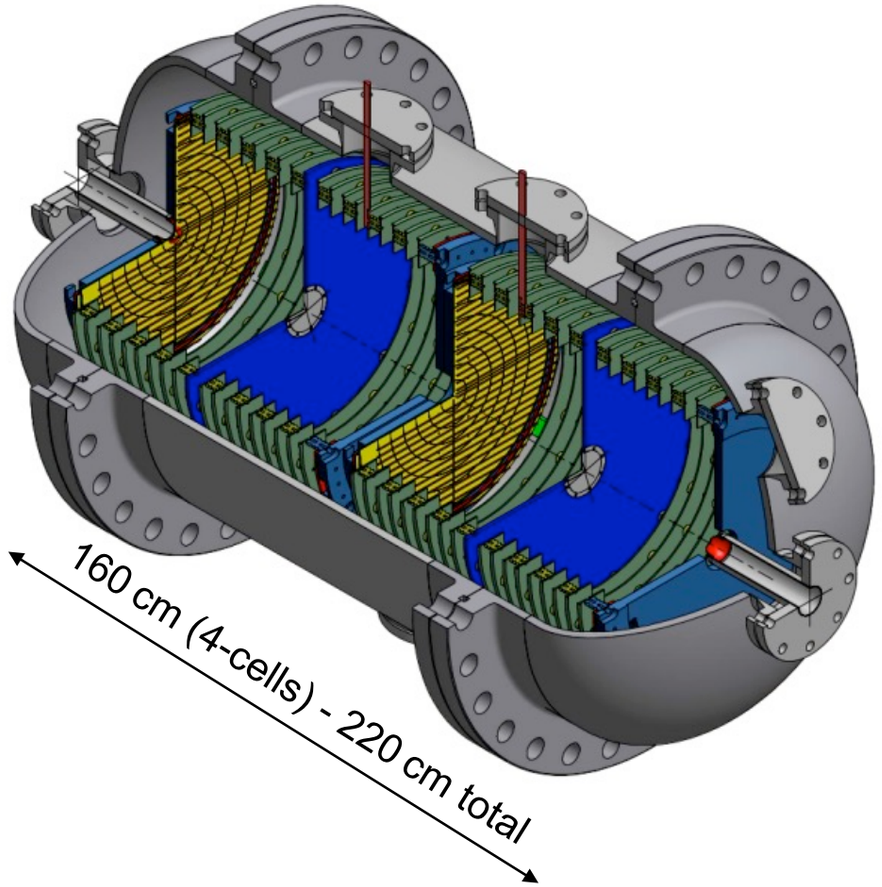
Pressurised hydrogen active-target TPC

Range of proton depends on momentum transfer.

- Low-Q^2 range
  → recoil-proton ranges of 70 - 300 mm
  → segmented read out structure



- Optimisation of geometry ongoing
  → optimal pressure settings for Q^2-range
  → optimal internal geometry



- Two pressure settings required
  → 20 bar ($0.0025\ GeV^2/c^2 < Q^2 < 0.04$)
  → 4 bar ($Q^2 < 0.0025\ GeV^2/c^2$)

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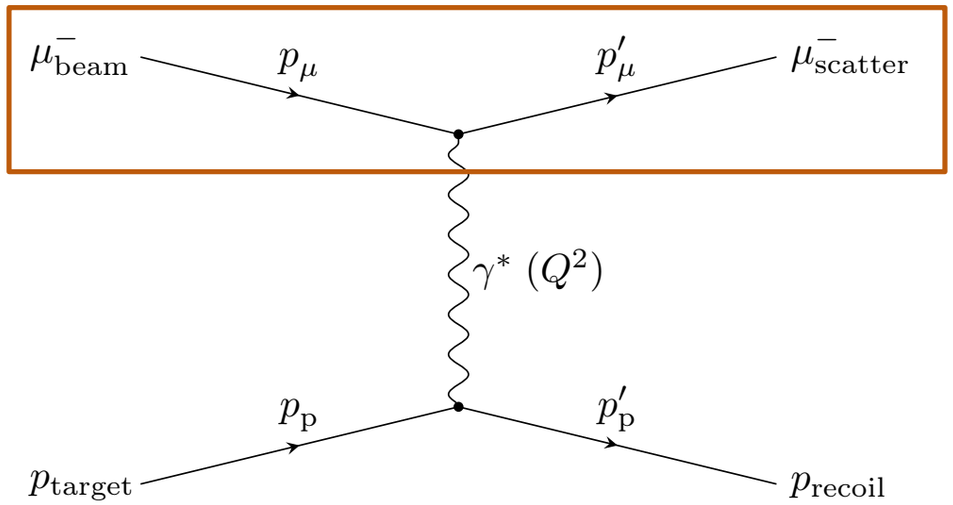
Control of Systematic Effects

Absolute calibration, inefficiencies, and background
Understanding of systematic effects is crucial for precision.

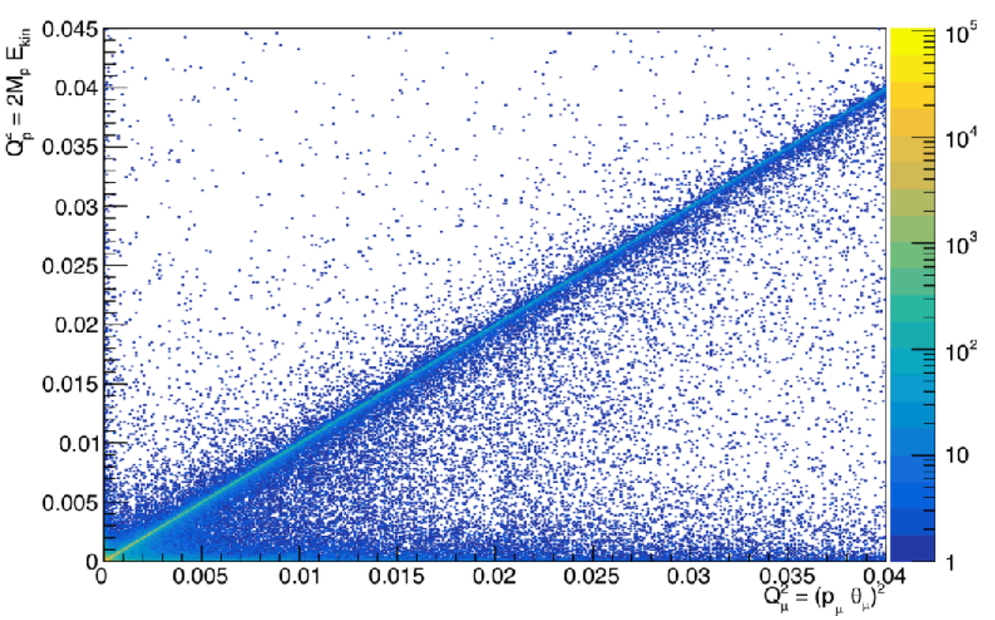
- Absolute calibration of the TPC recoil-proton energy-scale
- Inefficiencies in recoil-proton measurement
- Cross check of TPC measurement

Redundant measurement to control systematics
→ measurement of scattered muon kinematics



- Lepton-proton scattering accompanied by bremsstrahlung
  → NLO process on $\mathcal{O}(10^{-4})$ level for $E_\gamma > 500$ MeV
  → distortion of Q^2-spectrum

Usage of COMPASS spectrometer
→ understanding of background
→ muon momentum measurement



Next talk by Jan Friedrich!

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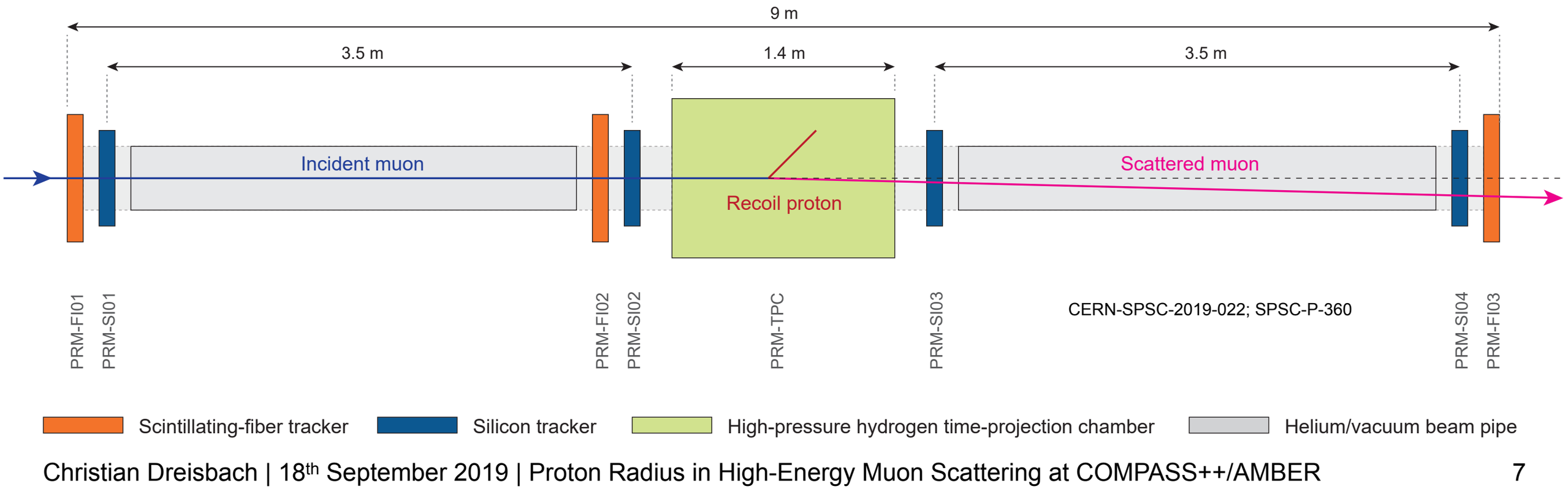
Layout of the Proton-Radius Setup

Components of the core setup

Precise recoil-proton and muon measurement with trigger on elastic events.

- Detect Q^2-values in the range of 0.001 - 0.04 GeV^2/c^2
  → pressurised hydrogen TPC as active target
- Redundant measurement: silicon detectors for measurement of scattered muon angle
- Trigger on scattered muons: scintillating-fiber detector to select elastic scattering events
- Vacuum tubes to minimise multiple scattering along the beam axis



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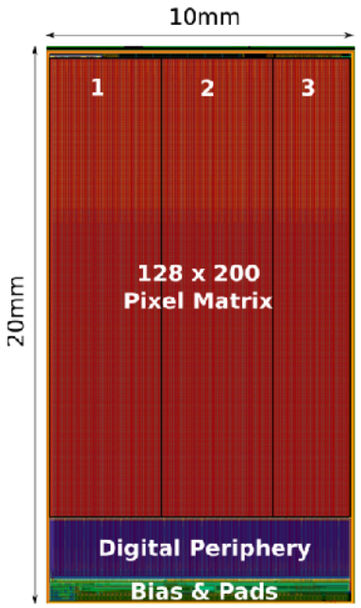
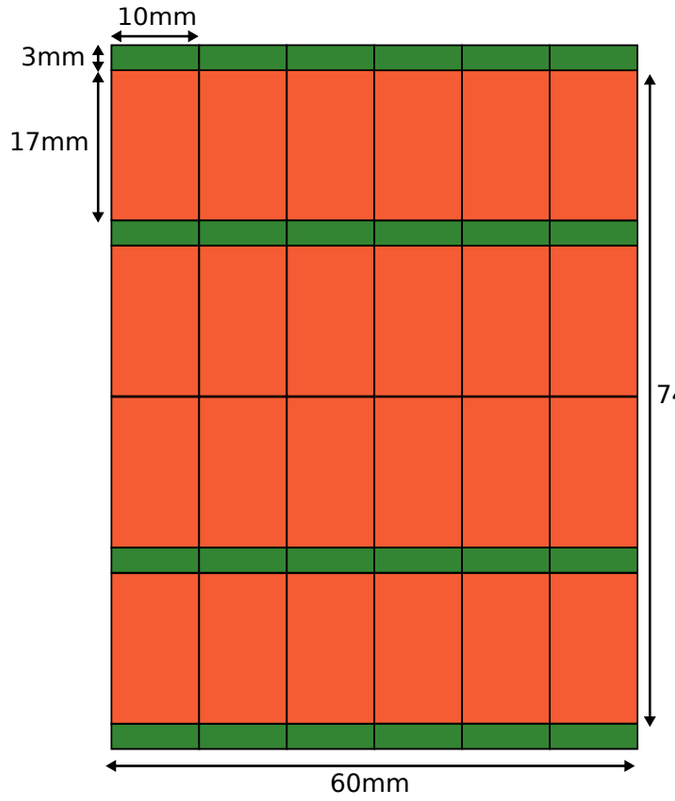
New Tracking System - Silicon Trackers

MuPix under investigation

Detector for precise muon tracking with low material budget.

- MuPix silicon detector under investigation:
  → produced at KIT and used at Mu3e
  → MuPix8 prototype: 1 x 2 cm², 128 x 200 pixels
  → thickness down to only 50 µm
  → 20-ns time resolution and 80-µm pixel size
  → spatial resolution of 5 µm with charge sharing
  → combination of several layers required





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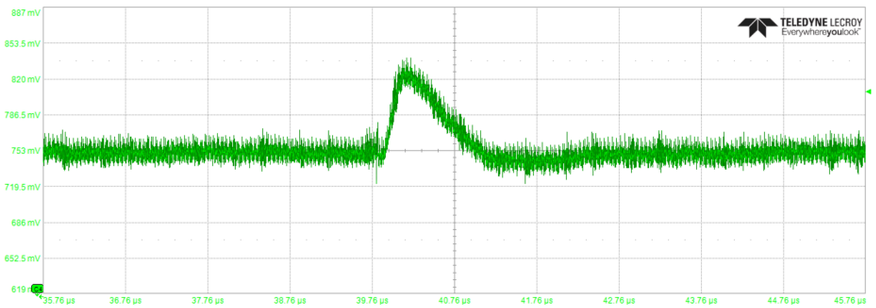
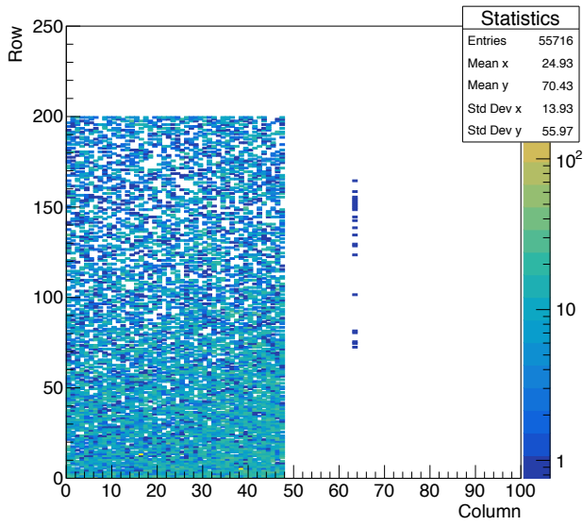
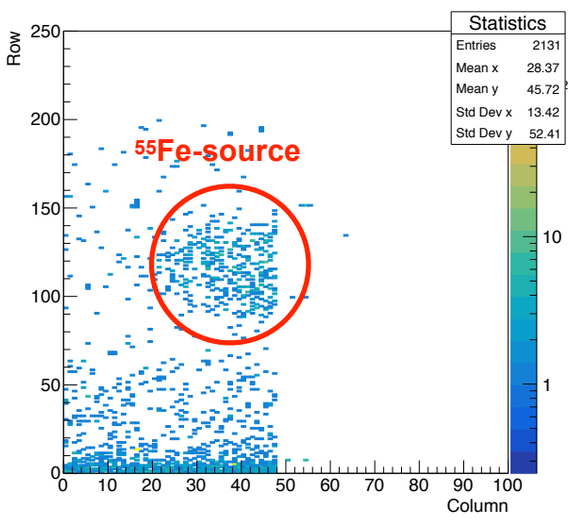
- Test setup currently in Munich
  → first results promising - still much work to do!







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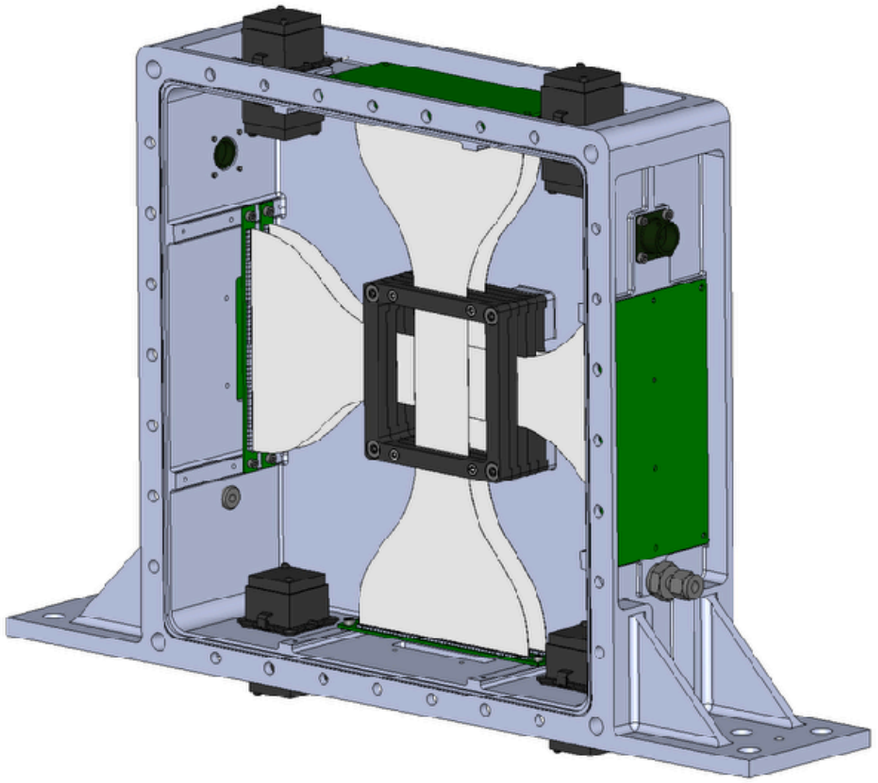
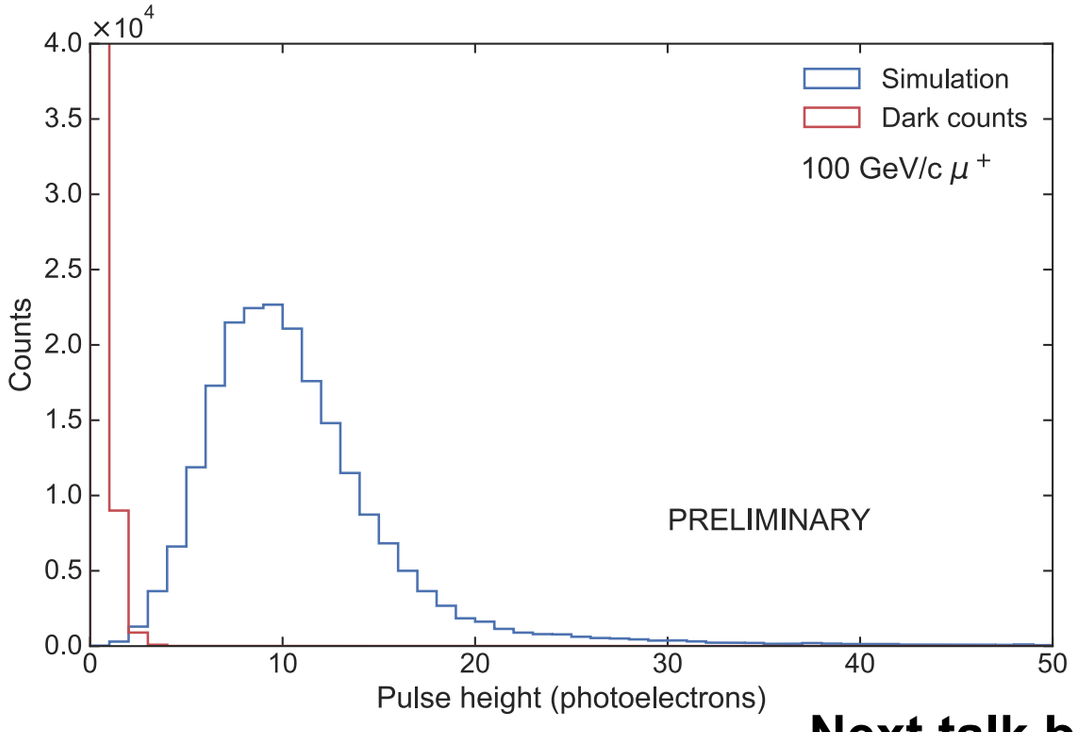
New Trigger System - Fiber Trackers

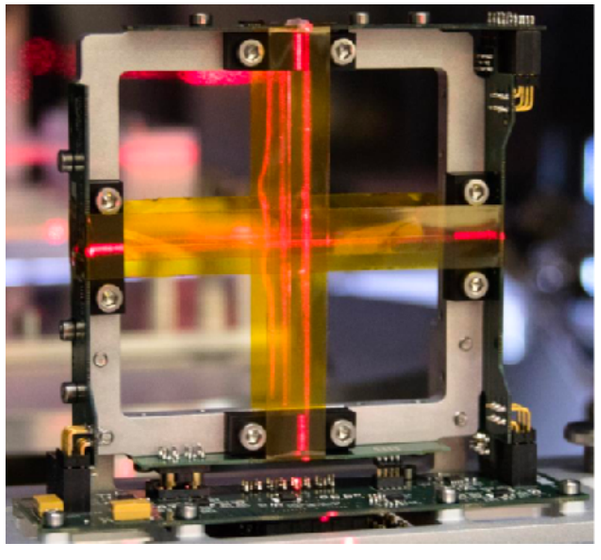
Fiber Trigger Array

Fiber detectors for triggering on deflected muons.

- Scintillating-fiber station:
  → 200-µm scintillating-plastic fibers
  → each fiber read out via SiPMT
  → four layers combined per station
  → total of 3 stations planned
  → challenge: only 10 photoelectrons per fiber







Next talk by Thomas Pöschl!

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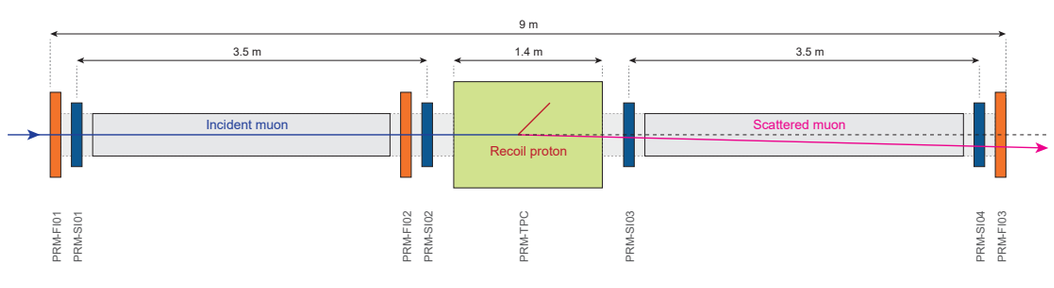
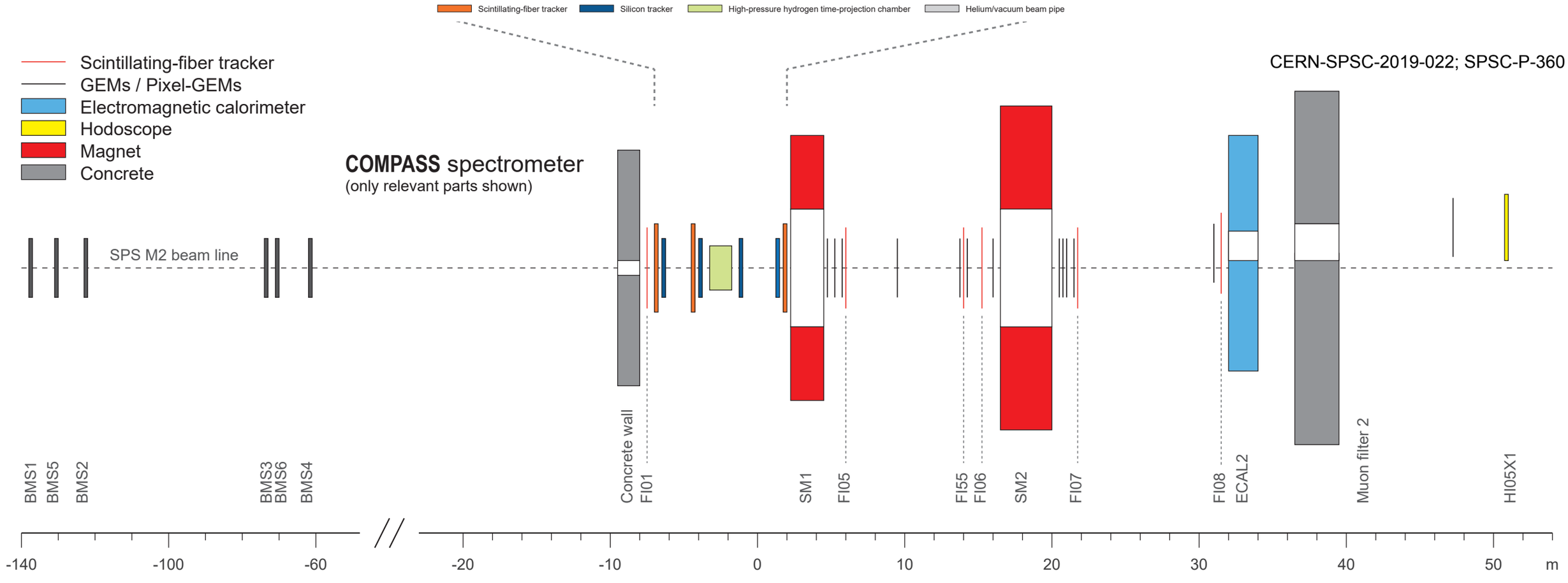
Layout of the Proton-Radius Setup

Advantages of using the COMPASS spectrometer

Measurement of muon momentum and understanding of background.





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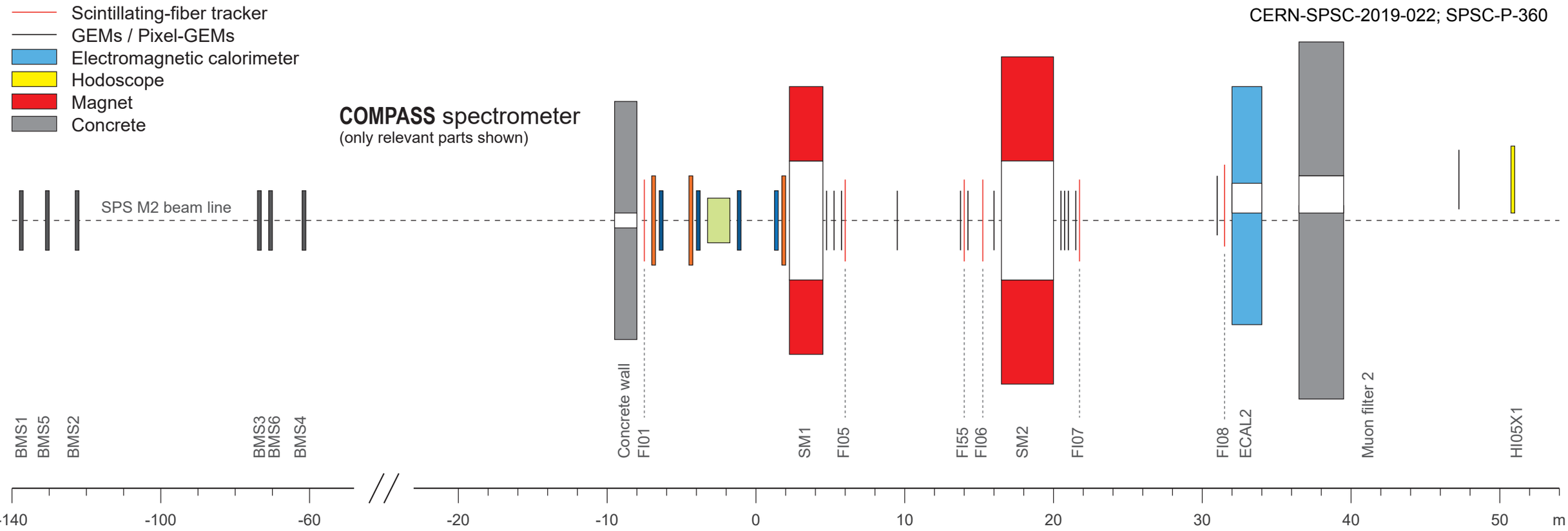

- COMPASS spectrometer
  → momentum measurement of scattered muon
  → radiative background using electromagnetic calorimeter
  → muon identification with muon filter and hodoscope

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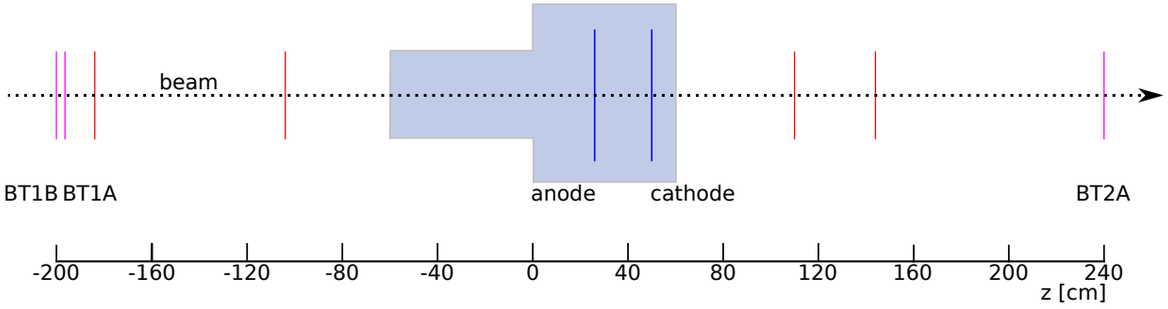
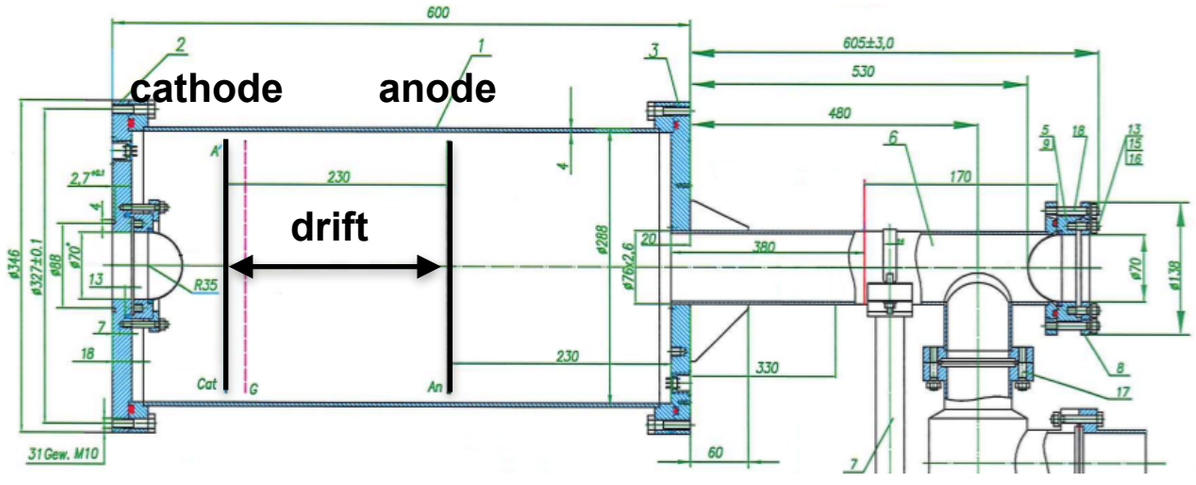
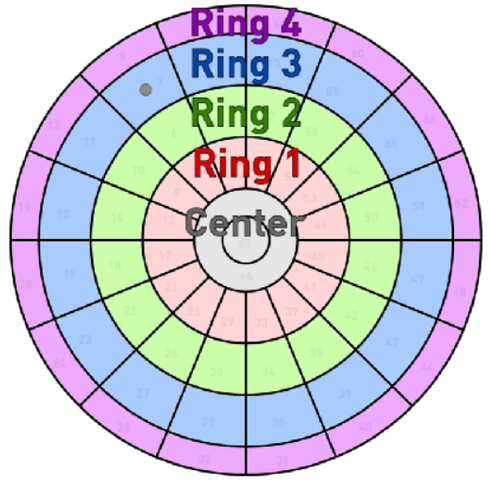
Beam Test in 2018

Feasibility test using TPC and silicon detectors
Two-month beam test parallel to COMPASS run with TPC and silicon trackers.

- Parasitically to COMPASS Drell-Yan run
  → remaining muons of 190 GeV pion beam
- TPC: 8 bar hydrogen and 23 cm drift
- Four silicon stations with a size of 7x5 cm²
- Two distinct DAQ systems
  → event matching via time stamp







Tomorrow morning talk by Martin Hoffmann!

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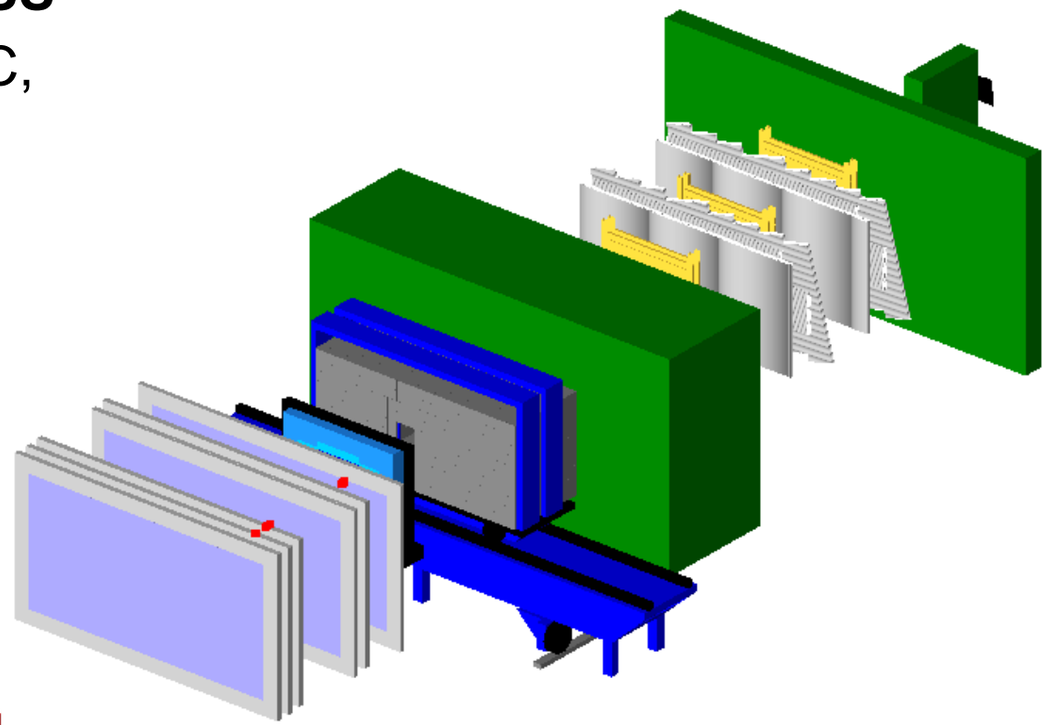
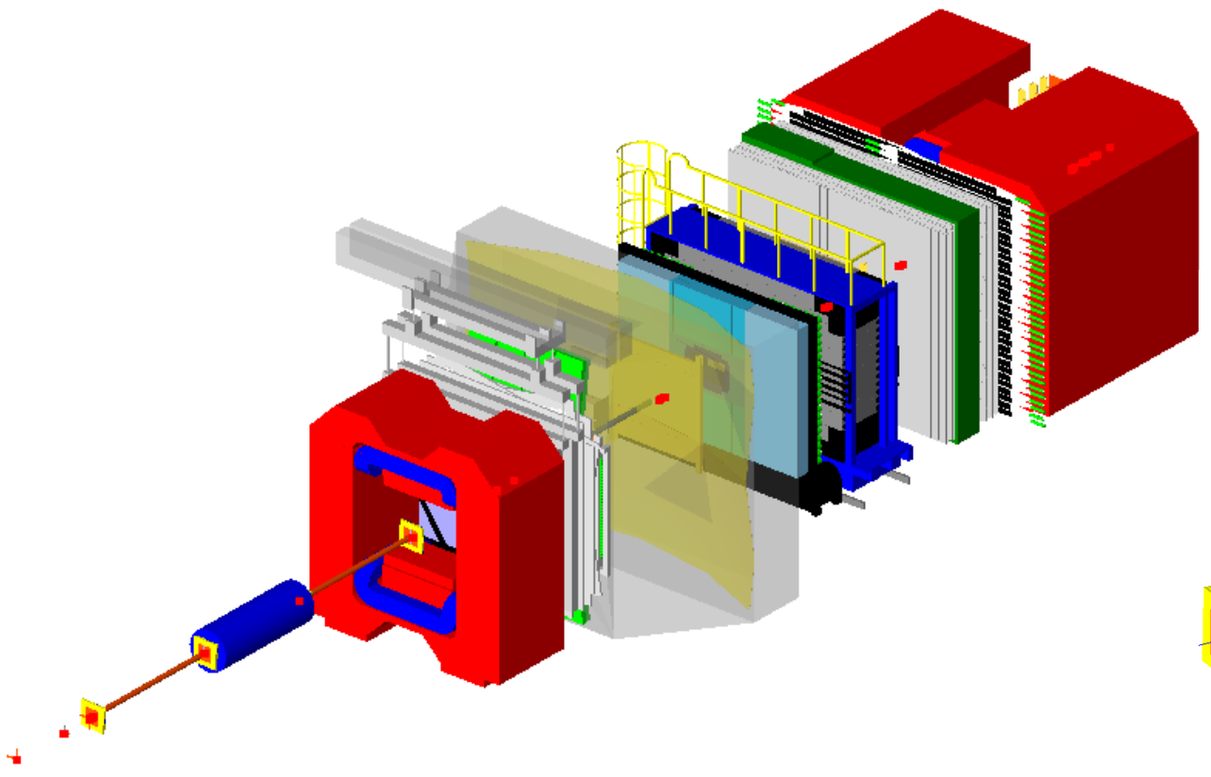
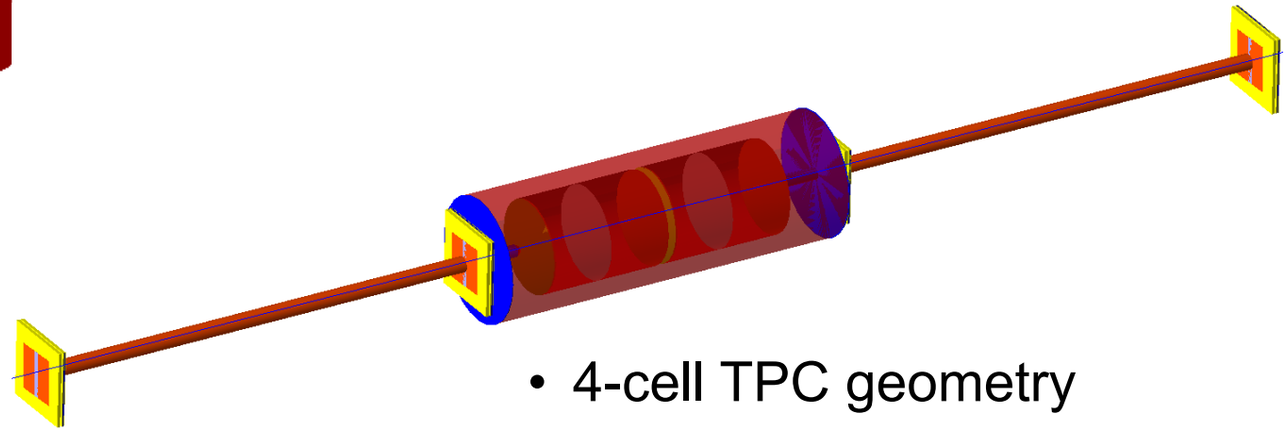
Monte Carlo Studies - Setup with Spectrometer

High-precision measurement using COMPASS
New target area with pressurised hydrogen TPC, helium tubes and silicon detectors and full spectrometer in GEANT4.

- Simulation of scattering in target TPC
- Track reconstruction using existing COMPASS tracking software (CORAL)







- 4-cell TPC geometry
- Pressurised hydrogen gas

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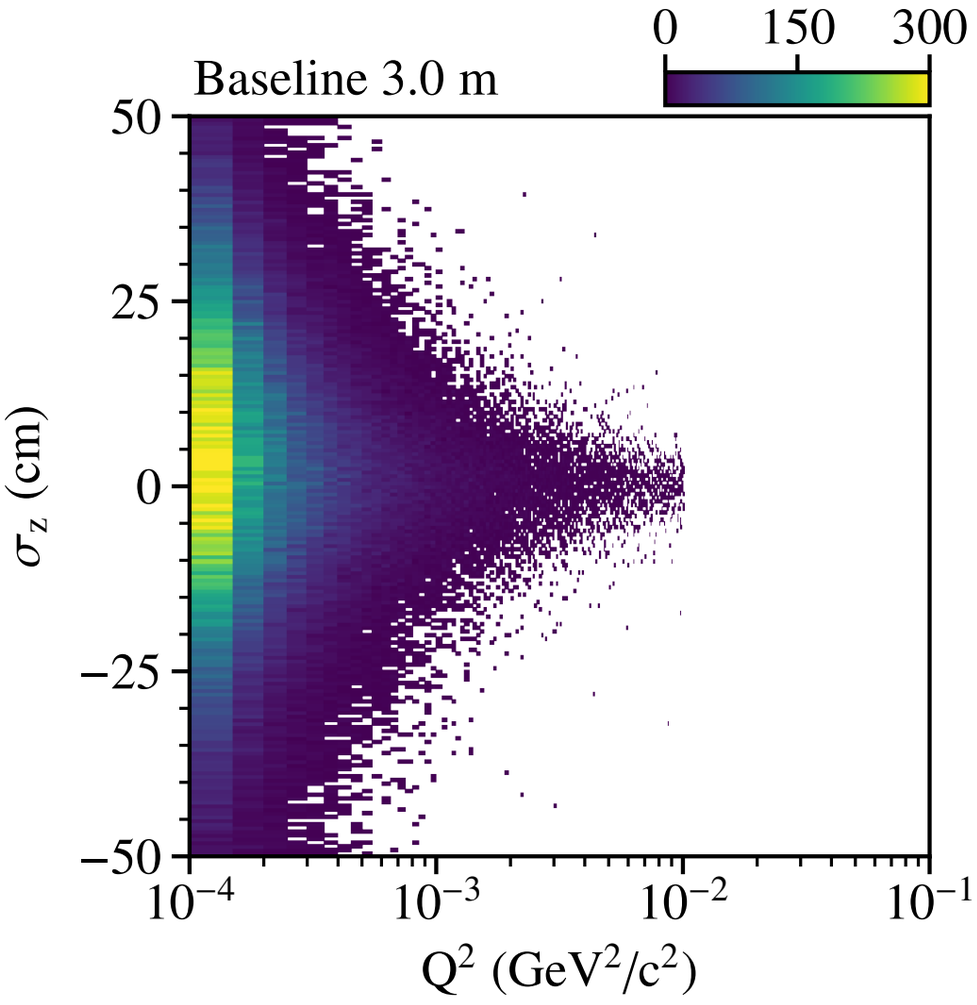
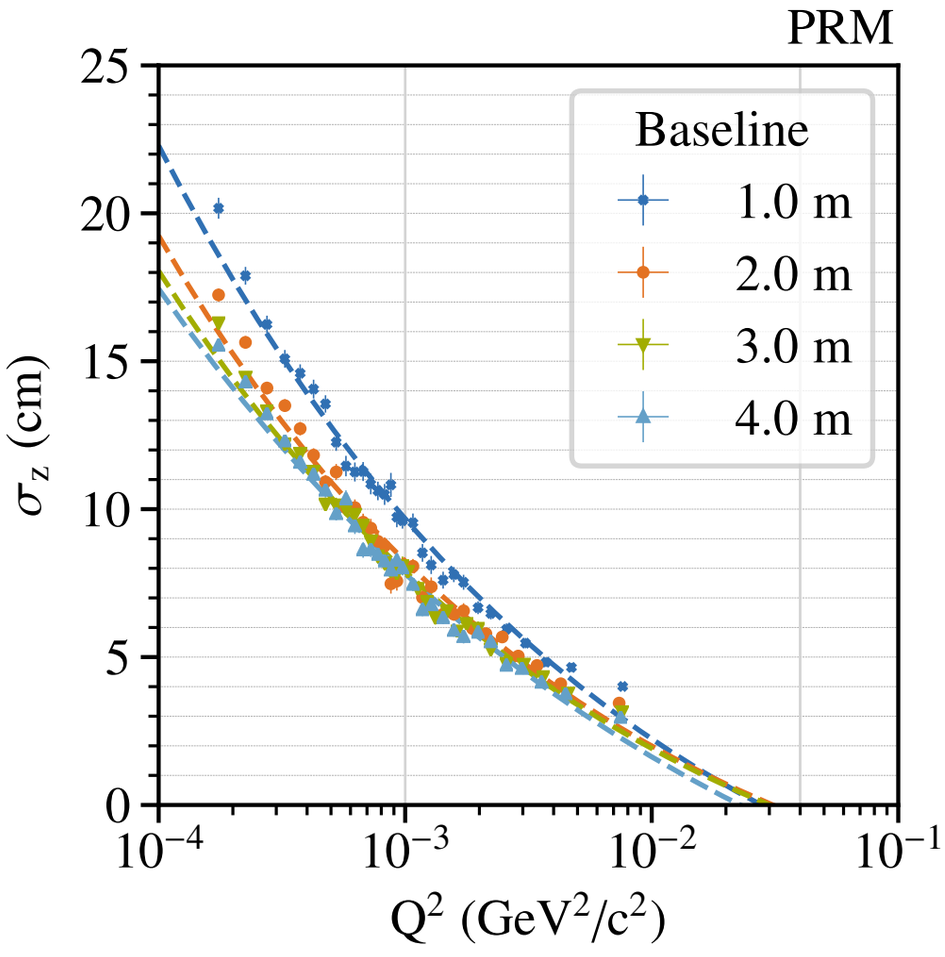
Monte Carlo Studies - Base Line Length

Baseline length influences resolution

Muon scattering reconstruction resolution determined by base line length.

- No major increase for base line > 3.0 m
  → resolution $\sigma_z \approx 8$ cm





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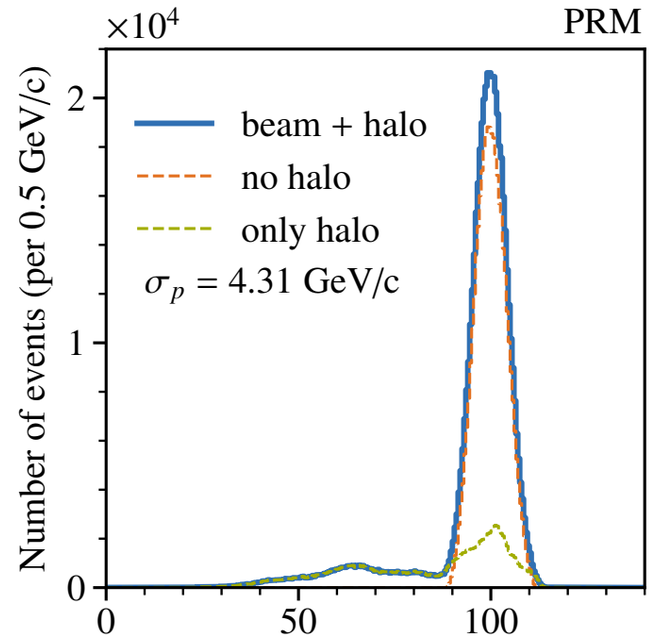
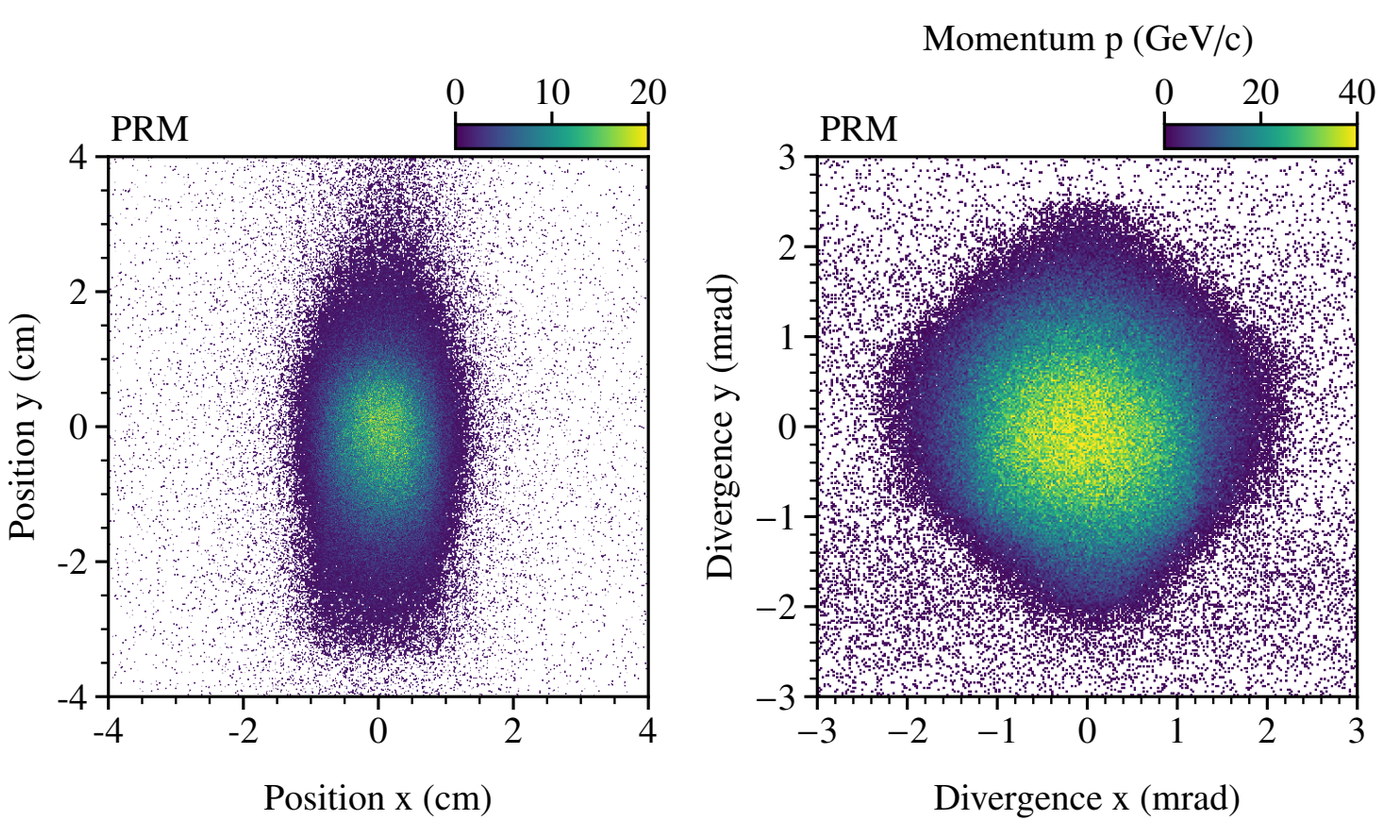
Monte Carlo Studies - Beam Properties

Intensity and size of muon beam

Beam properties are defined by setup geometry and detector properties.

- Maximum beam rate for TPC
  → Beam flux $\Phi_\mu = 2 \cdot 10^6/s$
- Beam energy scenarios
  → E_μ = 100 GeV - measurement
  → E_μ = 60 GeV - systematic studies
- Small beam spread
  → $\sigma_E < 5$ GeV/c
- Narrow beam at target position
  → $\sigma_{x,y} < 0.5$ cm
- Small dispersion along target region
  → $\sigma_{dx/dz,dy/dz} < 1.0$ mrad





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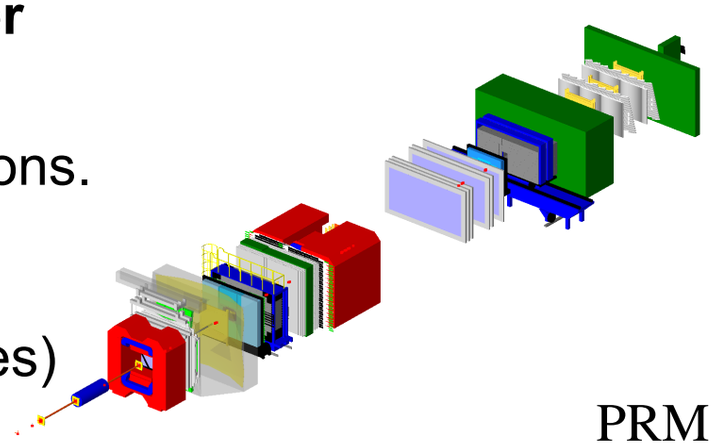
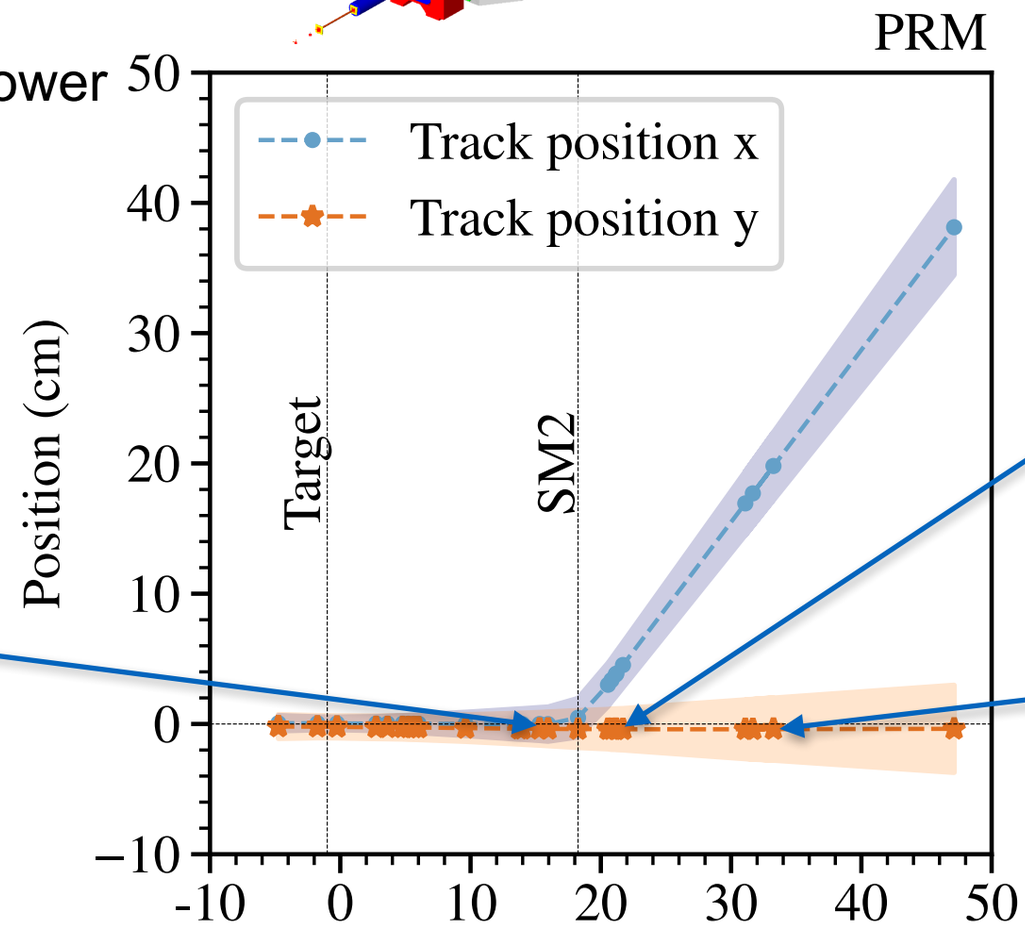
Monte Carlo Studies - Spectrometer Optimisation

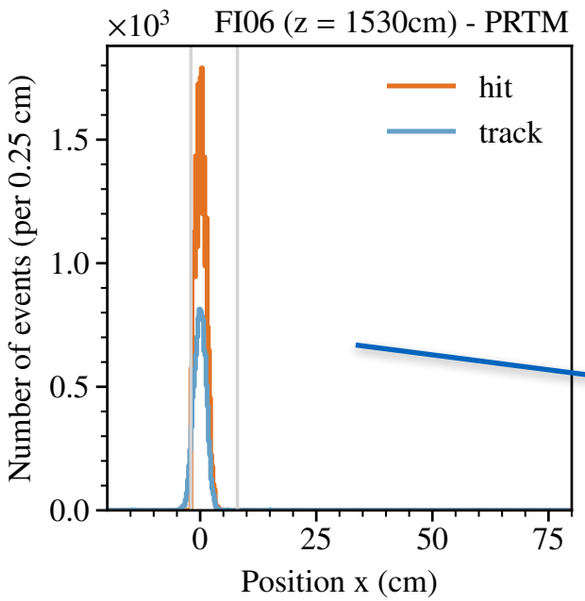
Track position along spectrometer

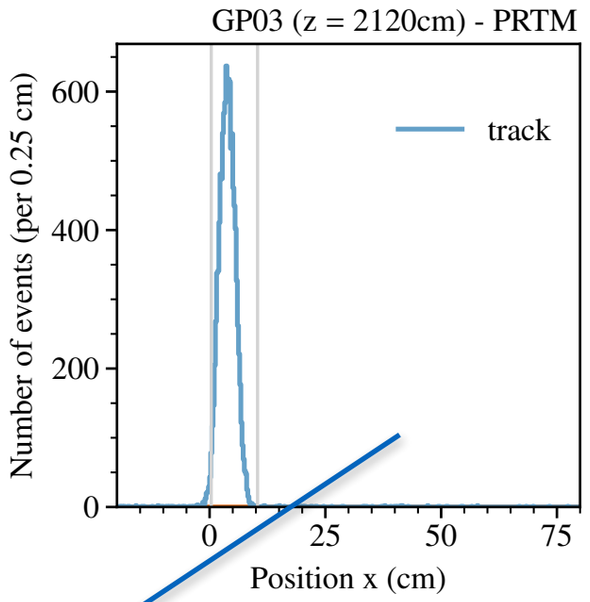
Different operation of COMPASS spectrometer influences track positions.

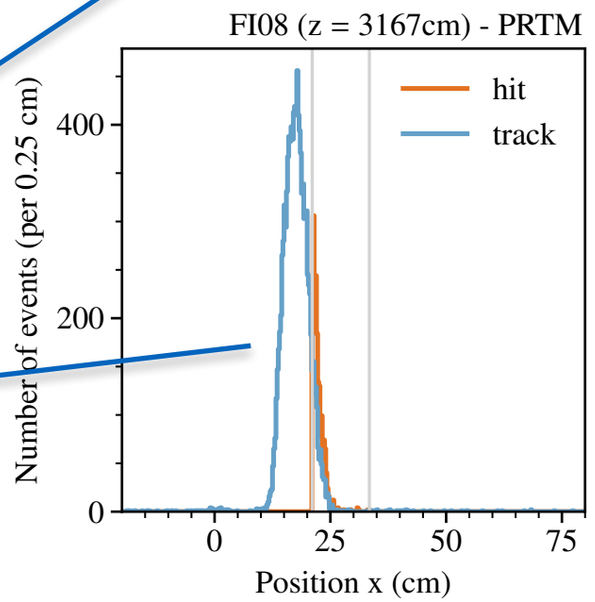
- Only one magnet operated (SM2).
  → Change in reconstruction (Zones)
- Beam energy 60GeV lower
  → deflection differs











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Monte Carlo Studies - Beam Energy Resolution

Absolute beam energy resolution for Q^2

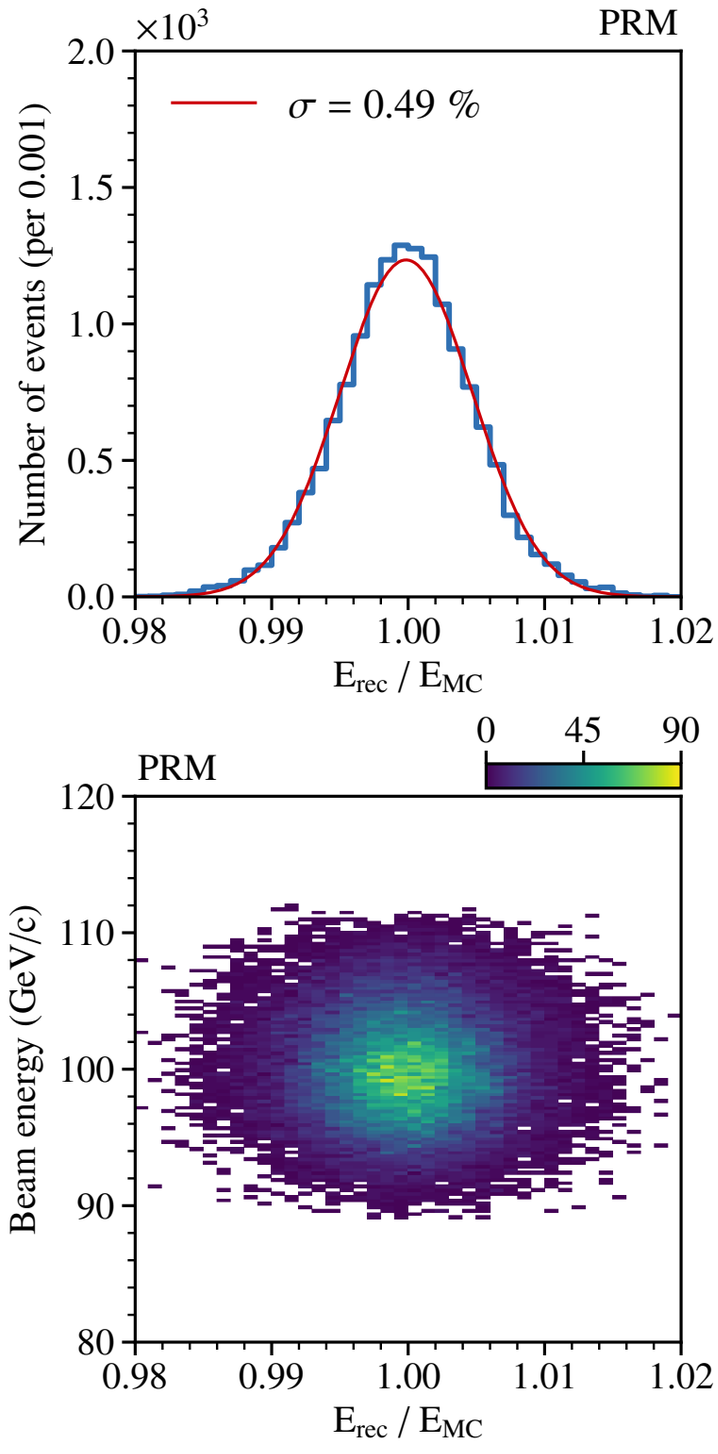
Beam energy precision influences precision on proton charge radius.

- TPC calibration requires high precision of beam momentum measurement
  → anode signals and proton energy T_R.
  → T_R scale calibration required
- Compare scattering angles and momenta:

$$Q^2 = 2m_p T_R \qquad 2m_p T_R = (p_\mu \theta_\mu)^2$$

  → beam momentum known < 0.2%
  → currently in simulation 0.5%

- Alternative:
  MAMI e-scattering for TPC calibration



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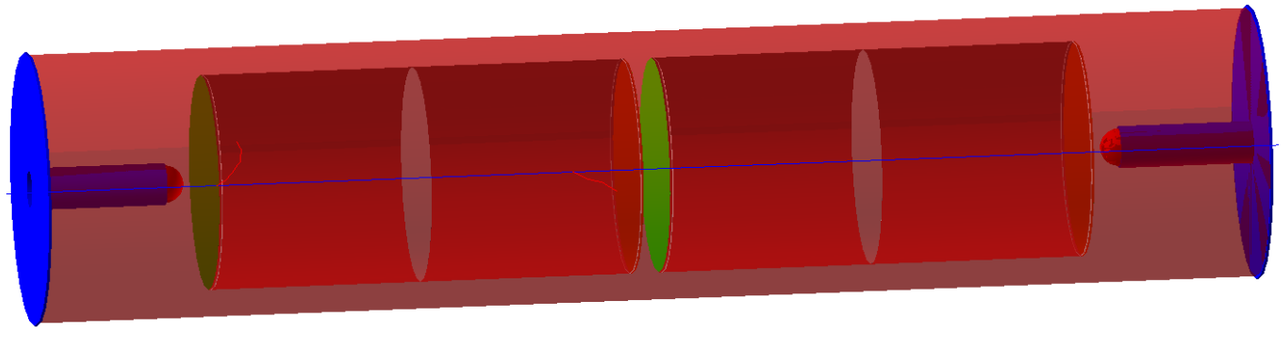
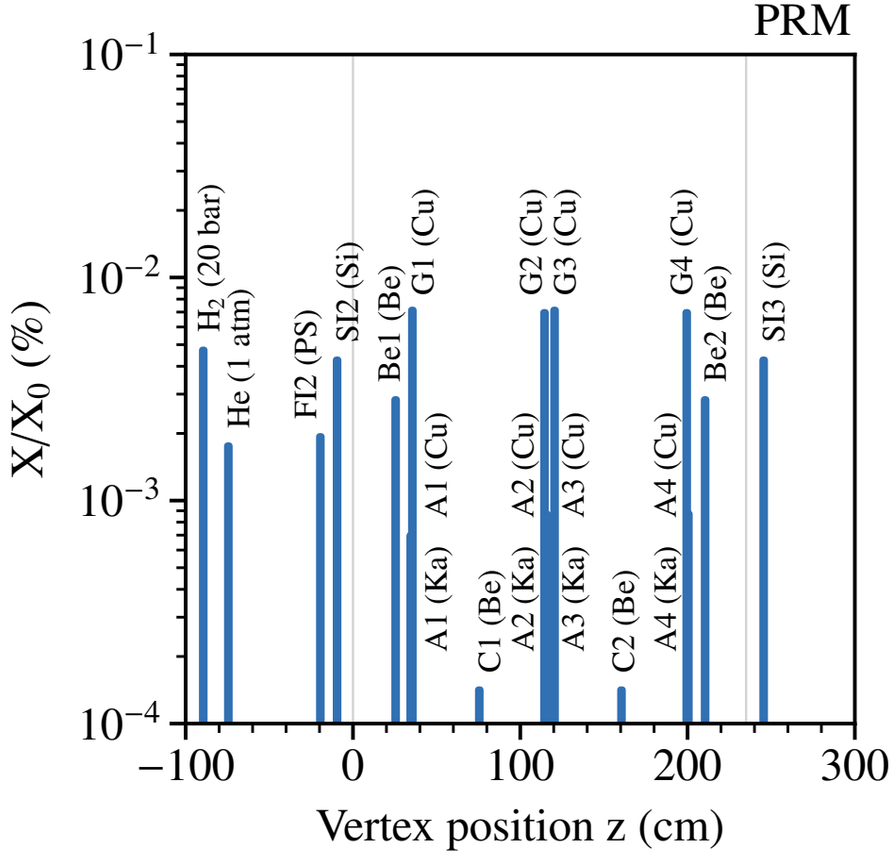
Monte Carlo Studies - Material in TPC

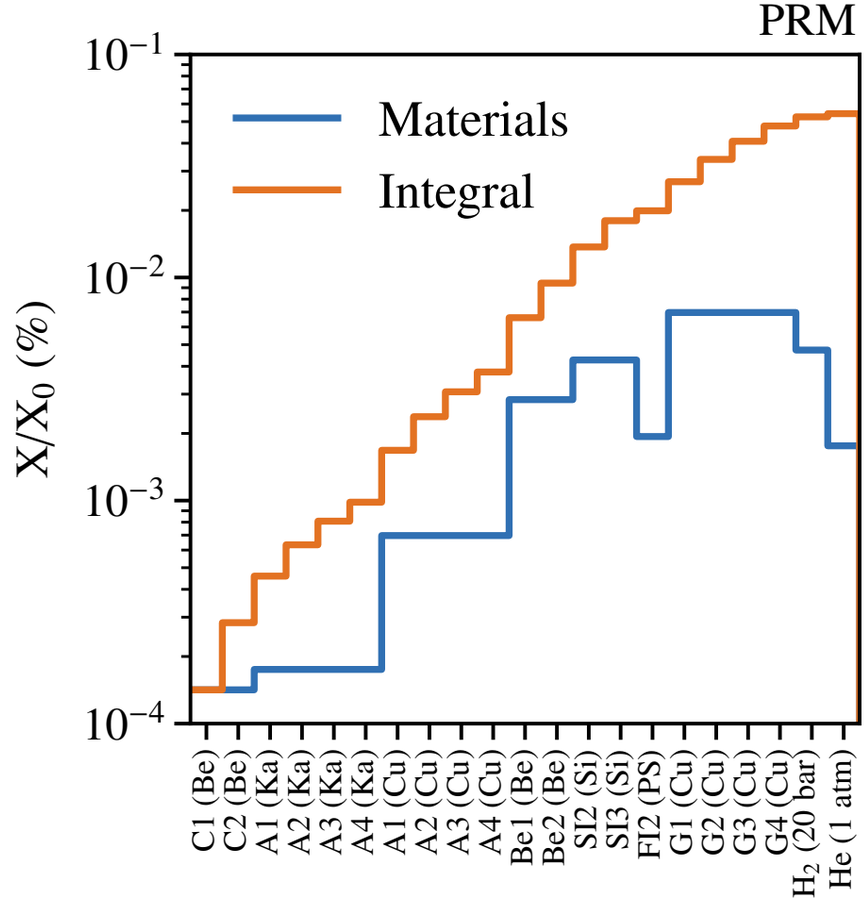
Description of TPC

Main detector for high-precision measurement requires a high-precision simulation.



- Study material effects in detail.
  → More precise descriptions required!





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Monte Carlo Studies - Scattering Angle Resolution

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

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

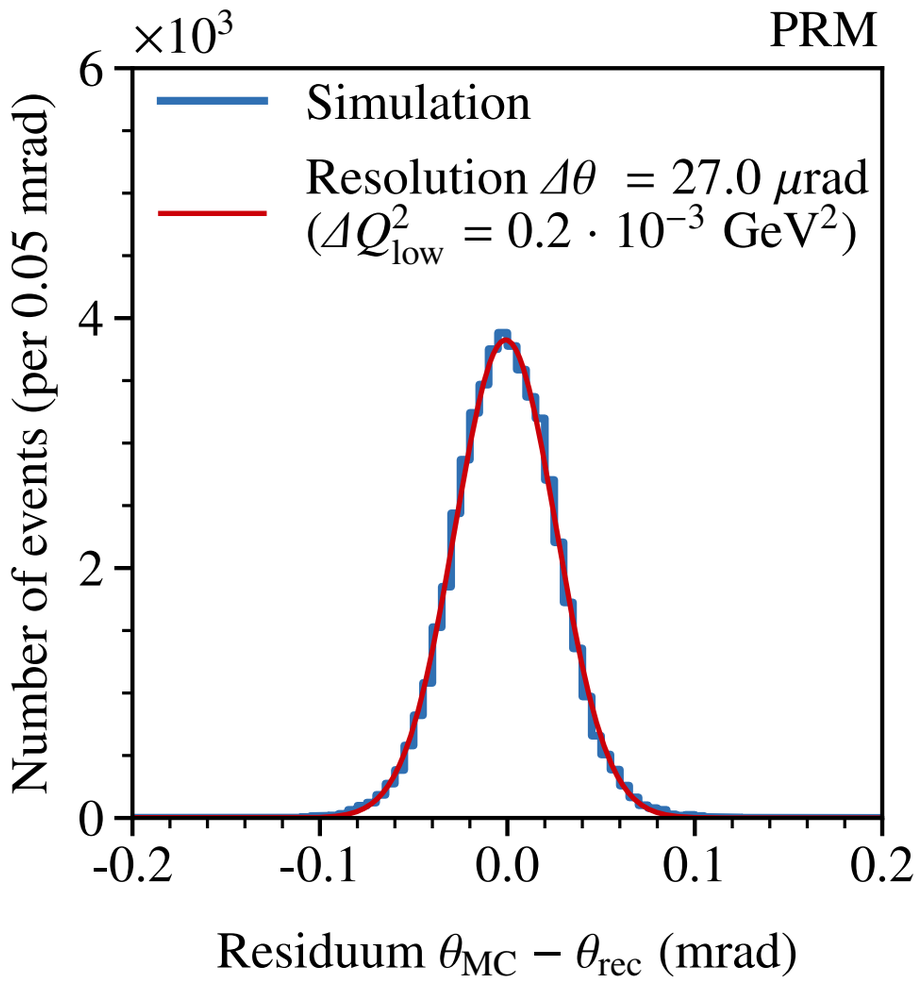
$$\Delta\theta = \frac{13.6\ \text{MeV}}{\beta c p} z\sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

$$\Delta Q^2(\theta) = \sqrt{(\Delta\theta)^2\left[\frac{\delta Q^2}{\delta\theta}\right]} = \sqrt{(\Delta\theta)^2\left[4E^2 \sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right)\right]^2}$$

- Multiple Scattering:
  → calculated: $x/X_0 = 53.89$ ‰ ($\Delta\theta_{MS,C} = 28.06$ µrad)
  → simulated: $\Delta\theta = 27.00$ µrad (SI: $\Delta\theta \approx 6$ µrad)
  → resolution: $\Delta Q^2/Q^2 = 17.8$ % GeV² ($Q^2 = 10^{-3}$)

- Measure Q^2 by TPC not depending on MS

- Important for redundancy / matching



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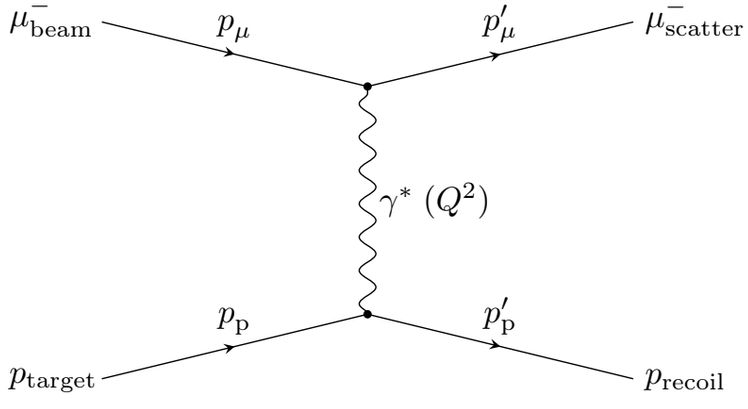
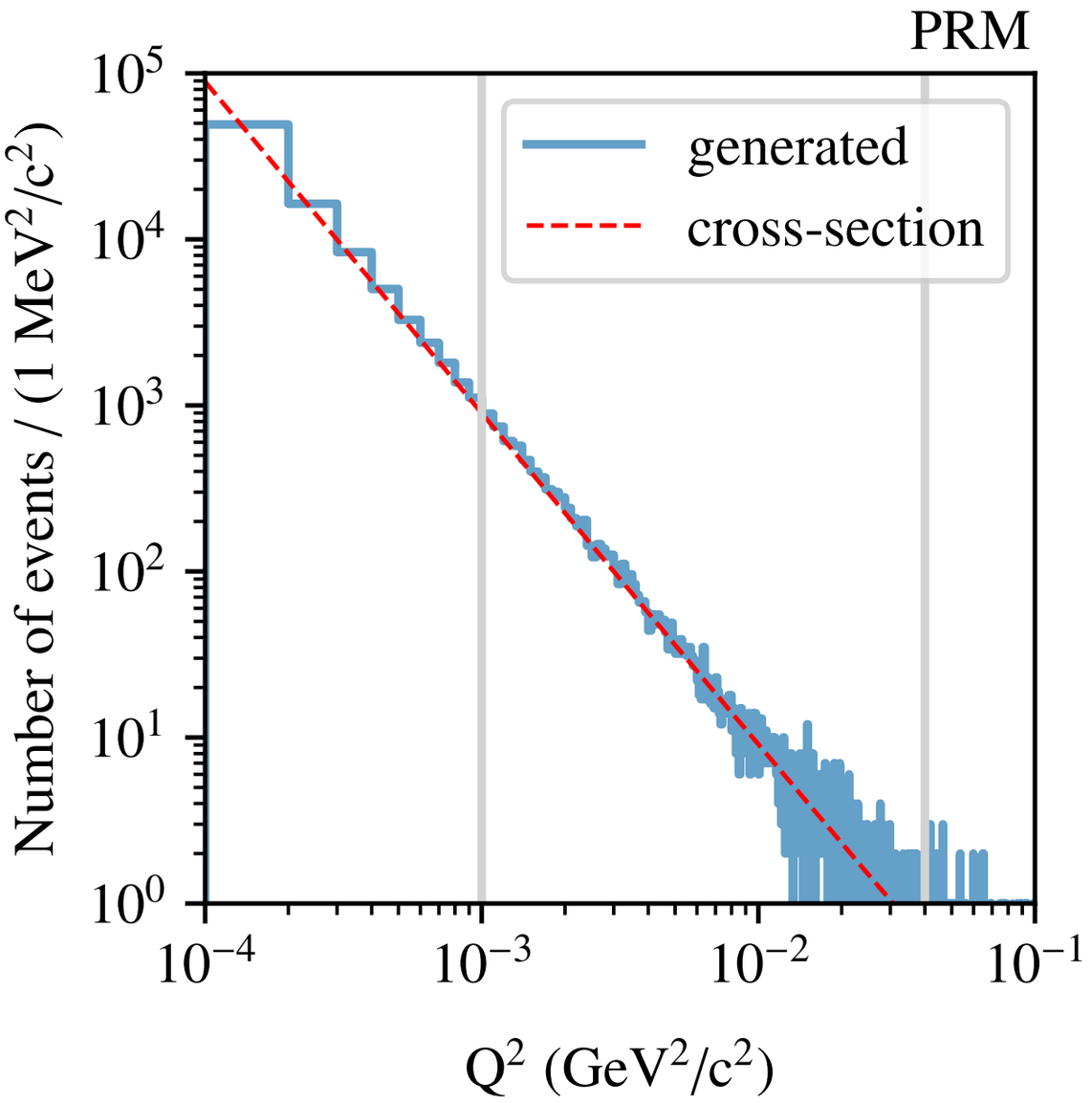
Monte Carlo Studies - Event Generation

Simulate elastic muon-proton scattering
Kinematic based on simple cross-section for momentum transfer.

- Generate events according to cross-section:
  → studies on shape-depending effects
  → time-consuming for statistics/studies
  → radius extraction efficiency (model)
  → for studies - generate events flat
- Beam file and materiel based vertex-z position as input
- Calculate resulting kinematics:





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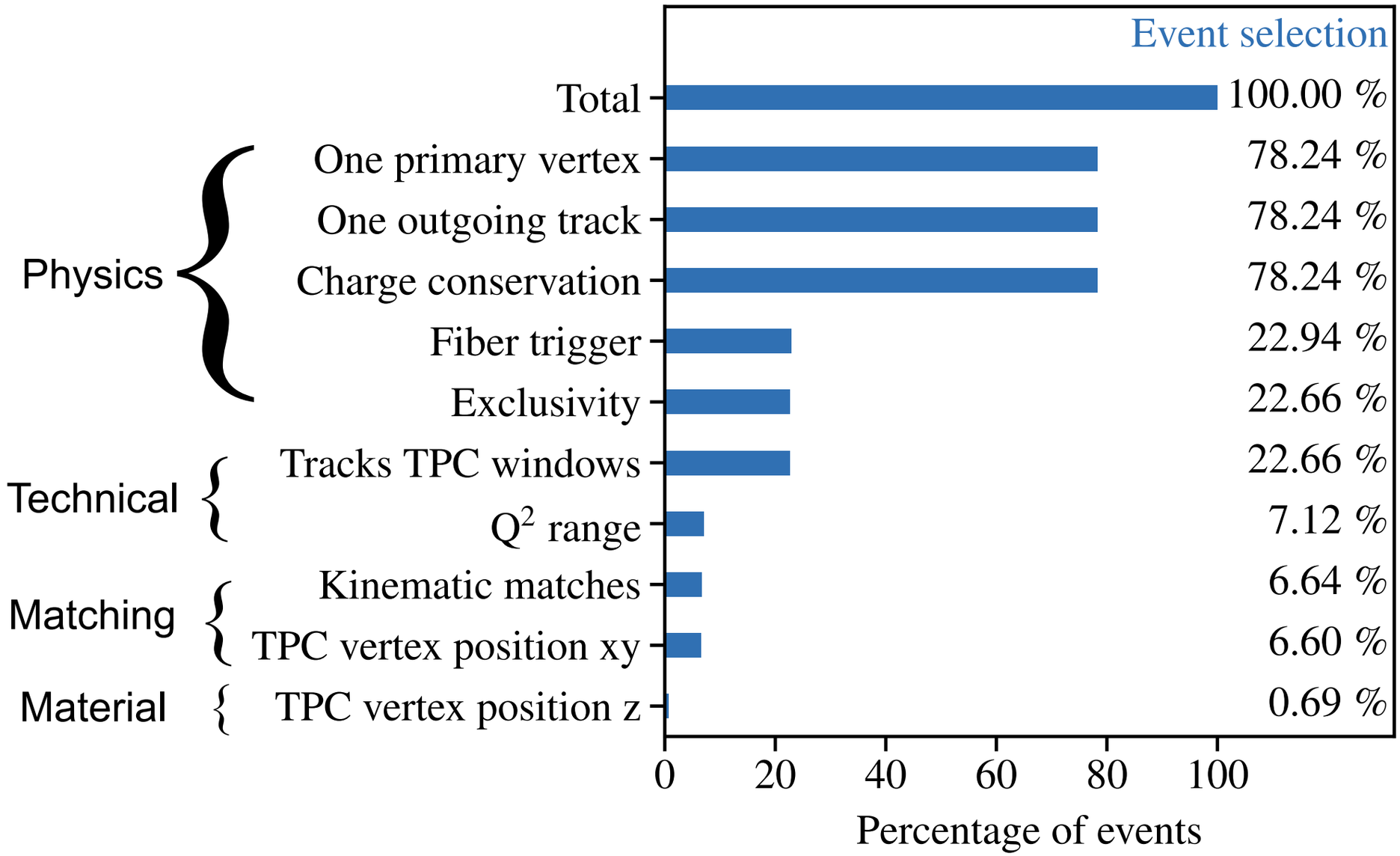
Monte Carlo Studies - Event Selection

Basic events selection for studies

Different selection criteria to obtain a clean data sample.



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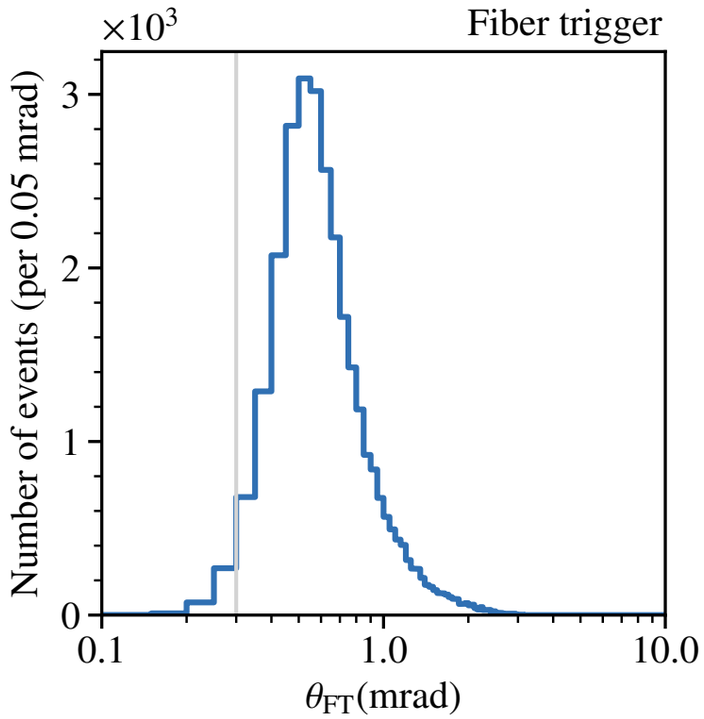
Monte Carlo Studies - Event Selection

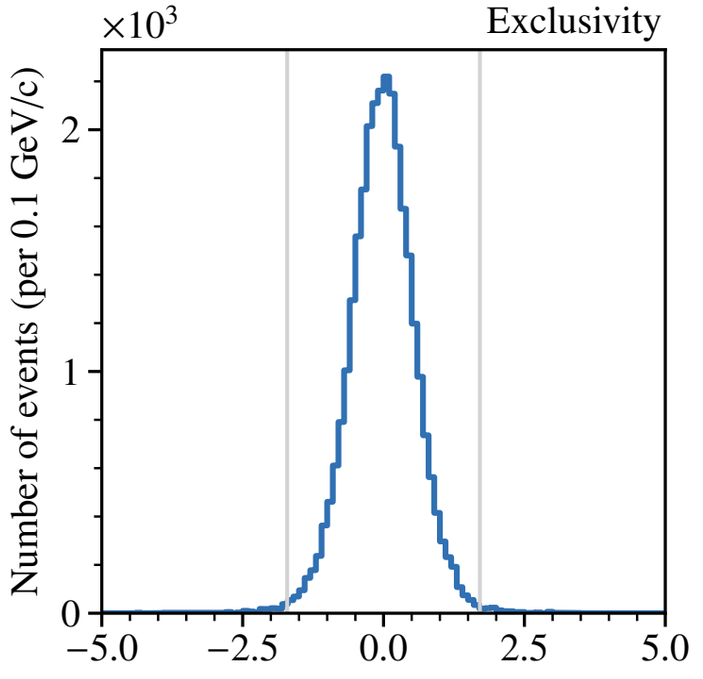
Physics criteria

Fiber decision as physics trigger and exclusivity of measured and reconstructed beam energy.

- Fiber trigger criteria:
  → events deviating from a straight line
  → simplified by only 3 tracking stations
  → influences measured scattering angle
  → depends on vertex z-position



- Exclusivity for beam:
  → measured and reconstructed energy
  → avoid missing momentum
  → influences momentum transfer



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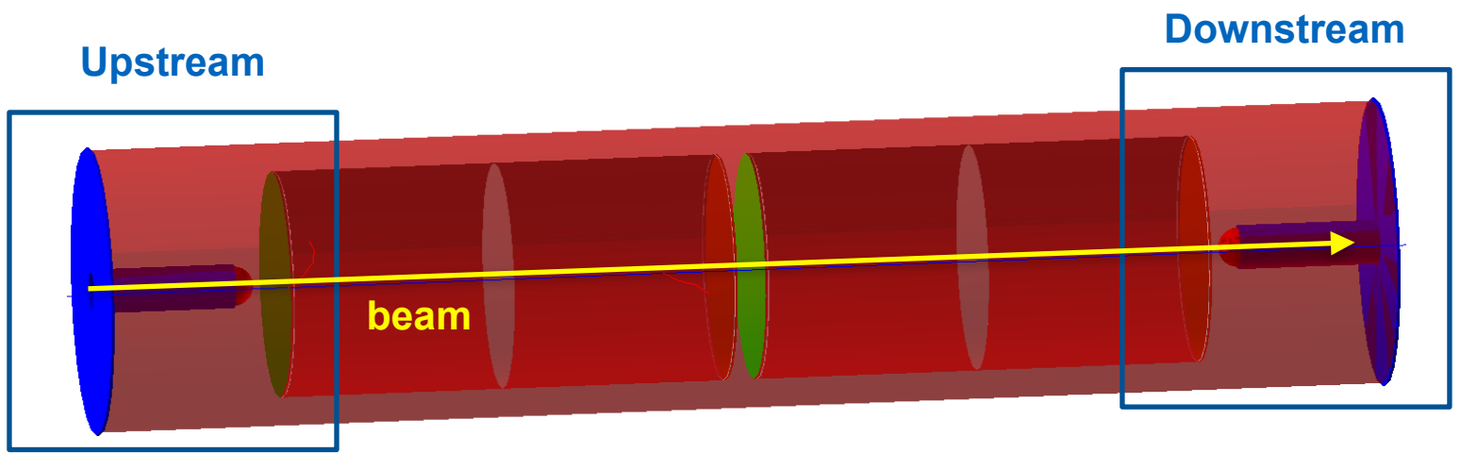
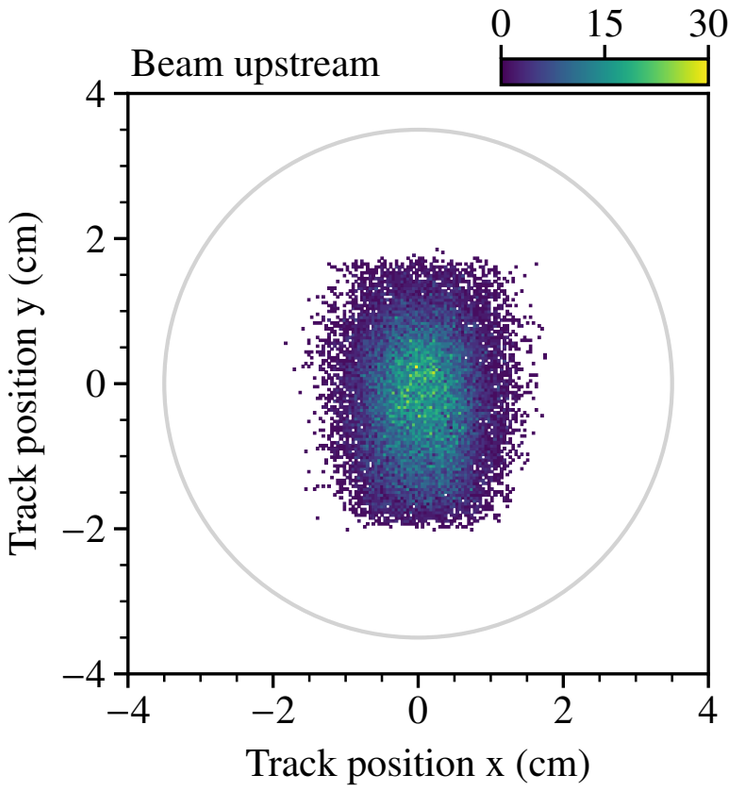
Monte Carlo Studies - Event Selection

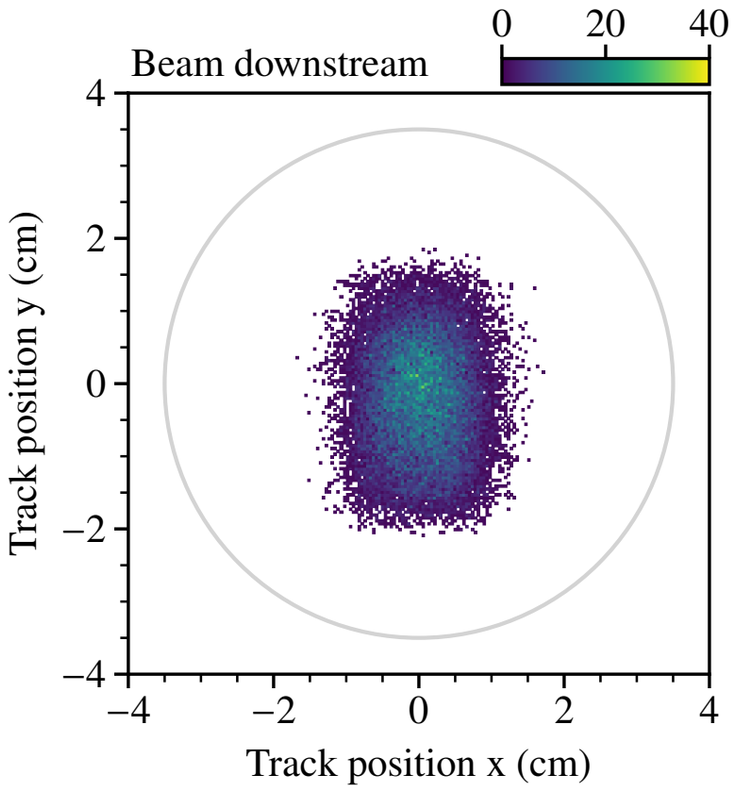
Avoid material

Material causes multiple scattering and influences scattering angle.

- Pressurised TPC windows
  → avoid material entrance and exit
- Ensure fixed target volume in TPC for luminosity calculation







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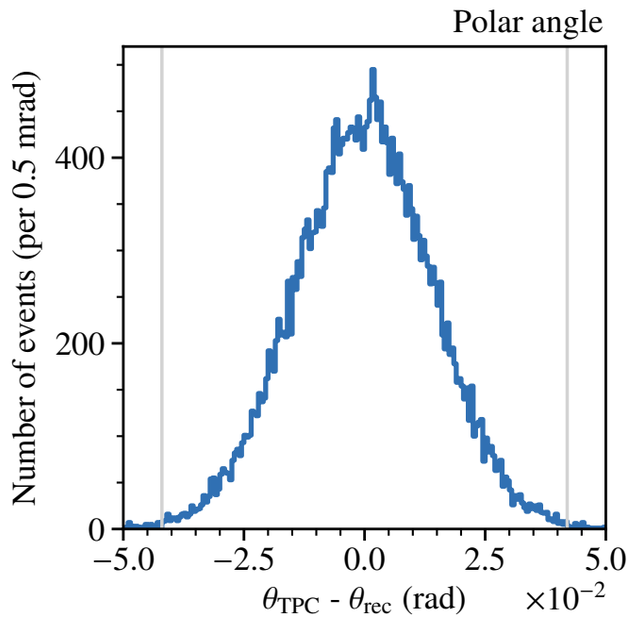
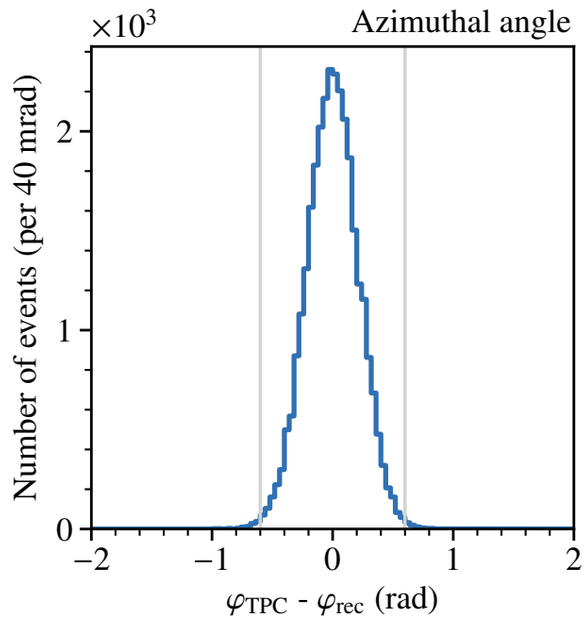
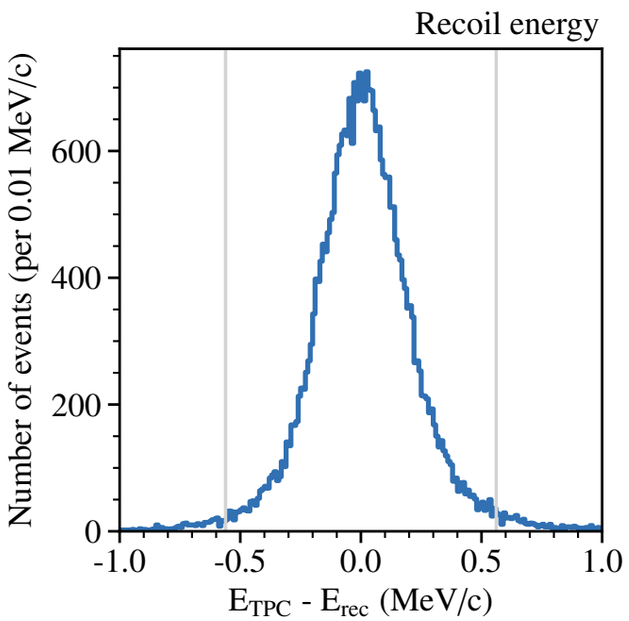
Monte Carlo Studies - Event Selection

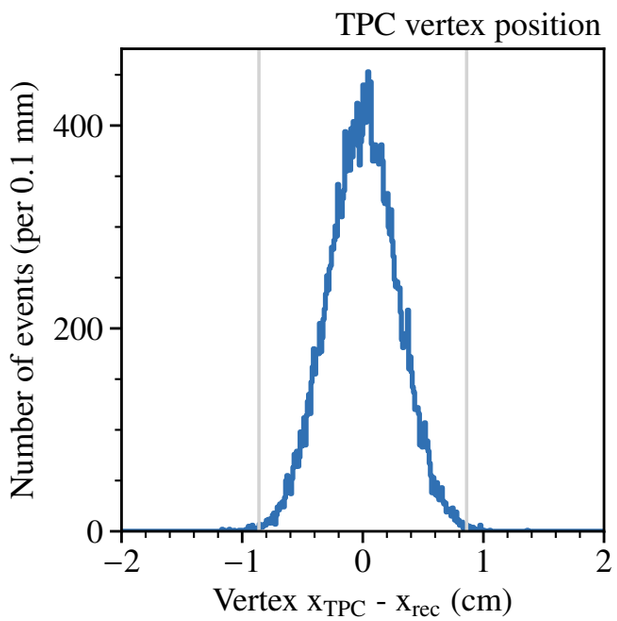
Matching of muon and recoil proton
Redundant measurement of muon and recoil proton - use kinematic for event matching.

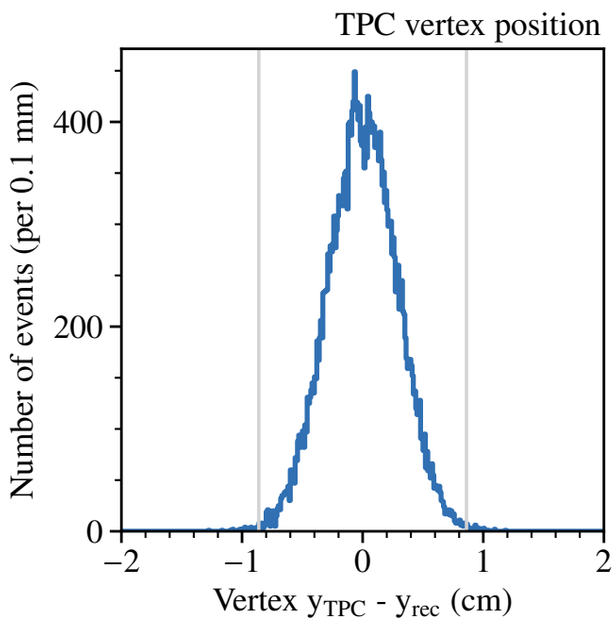
- Kinematics to predict recoil proton:
  → recoil proton energy
  → polar and azimuthal angles
  → position in xy-plane











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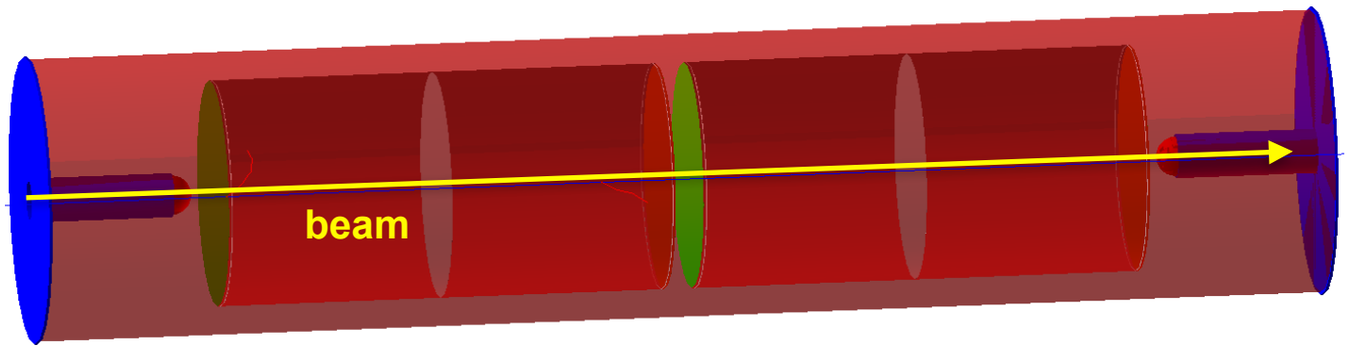
Monte Carlo Studies - Event Selection

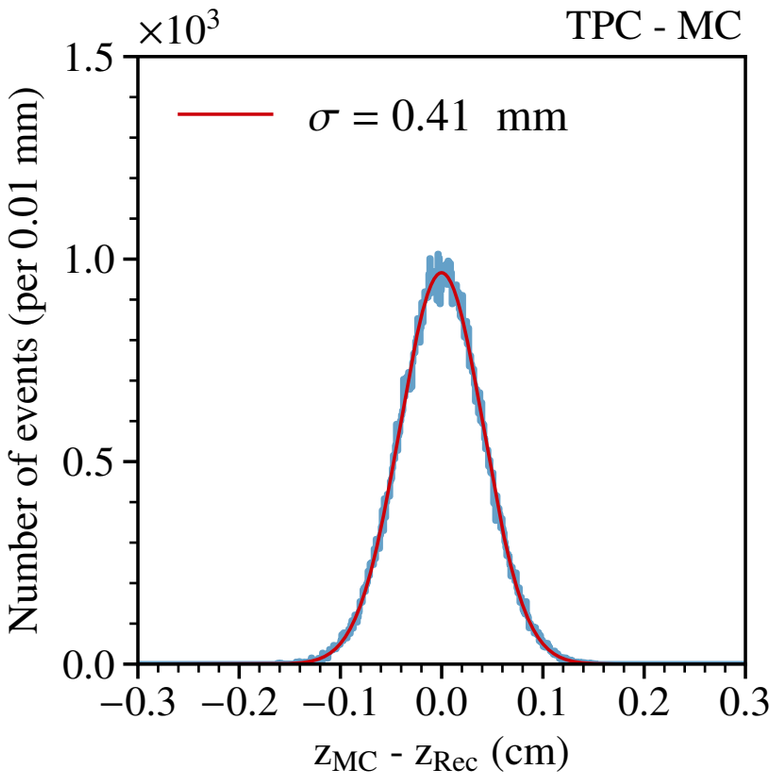
Material in TPC

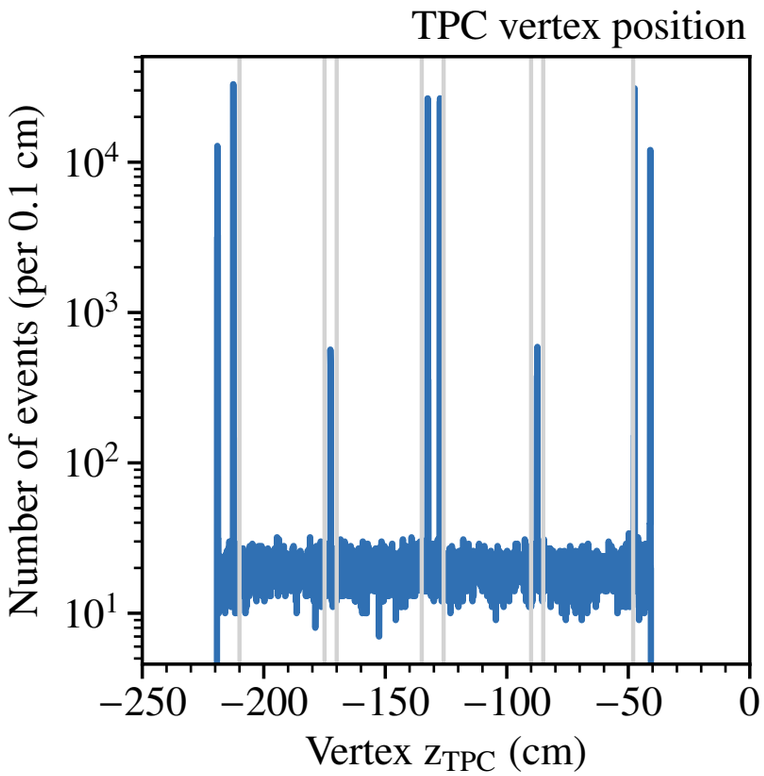
Drift time measurement with outer trigger time stamp allows precise selection.

- Drift time and vertex-z position:
  → drift time resolution 40 ns
  → vertex-z resolution 160 µm
  → but electron diffusion 380 µm

→ total: $\sigma_{z,\,TPC} = 412$ µm resolution







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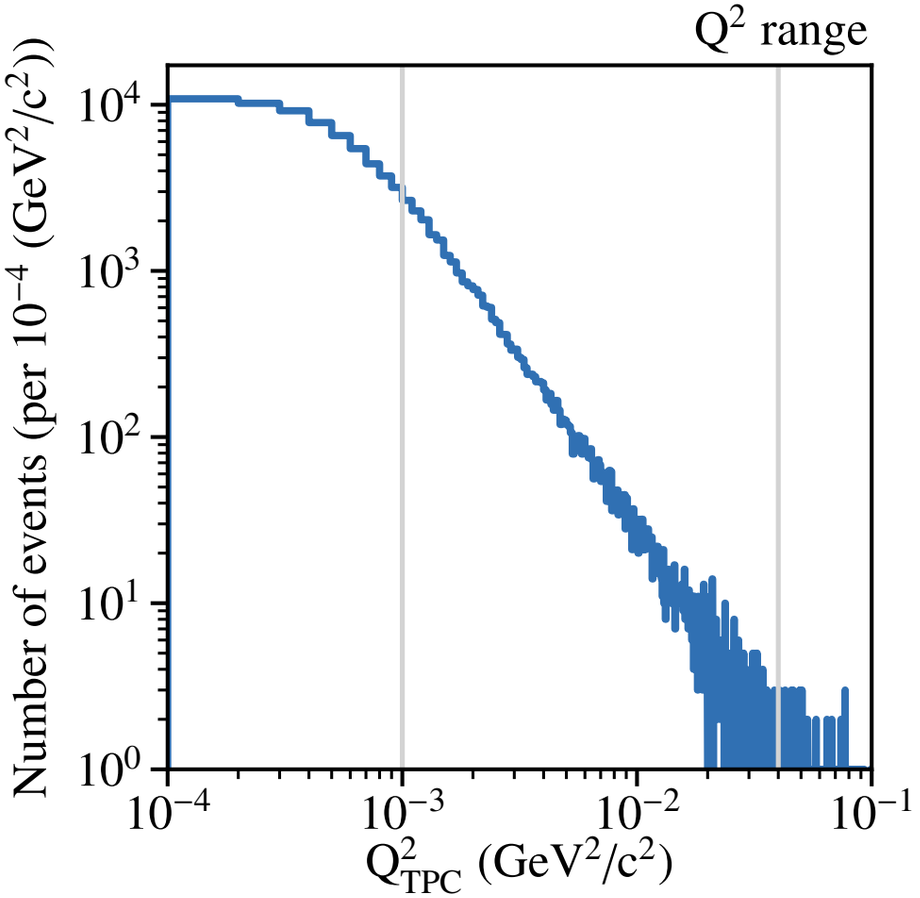
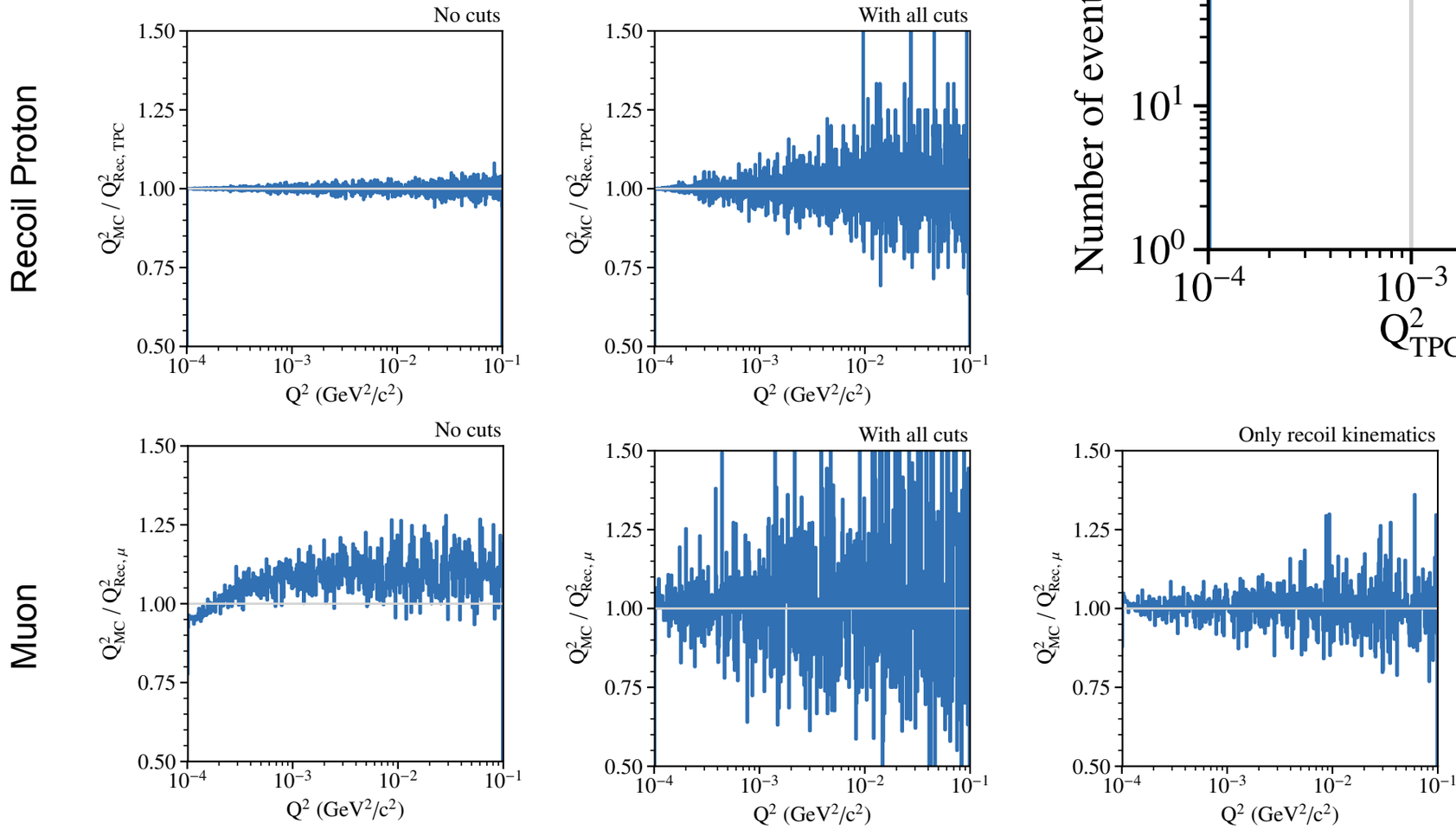
Monte Carlo Studies - Event Selection

Measured Q^2-spectrum

Q2-spectrum restricted to aimed range and should not be influenced by event selection criteria

- Comparison between generated and reconstructed and selected events.





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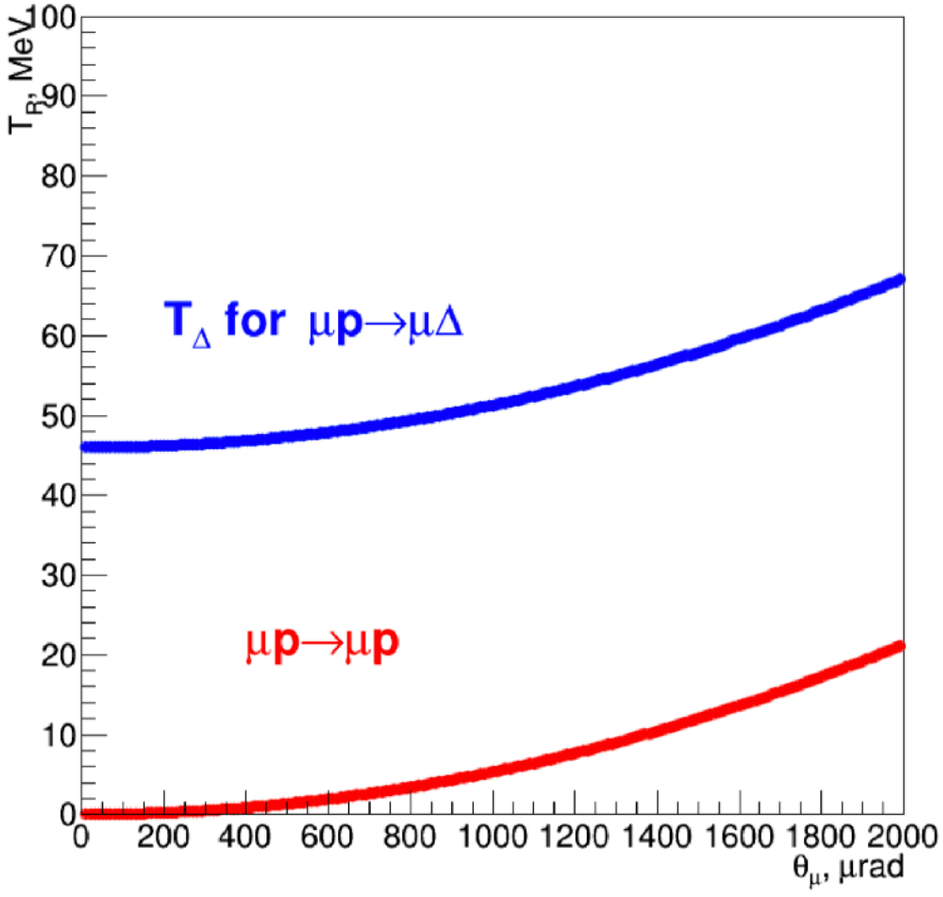
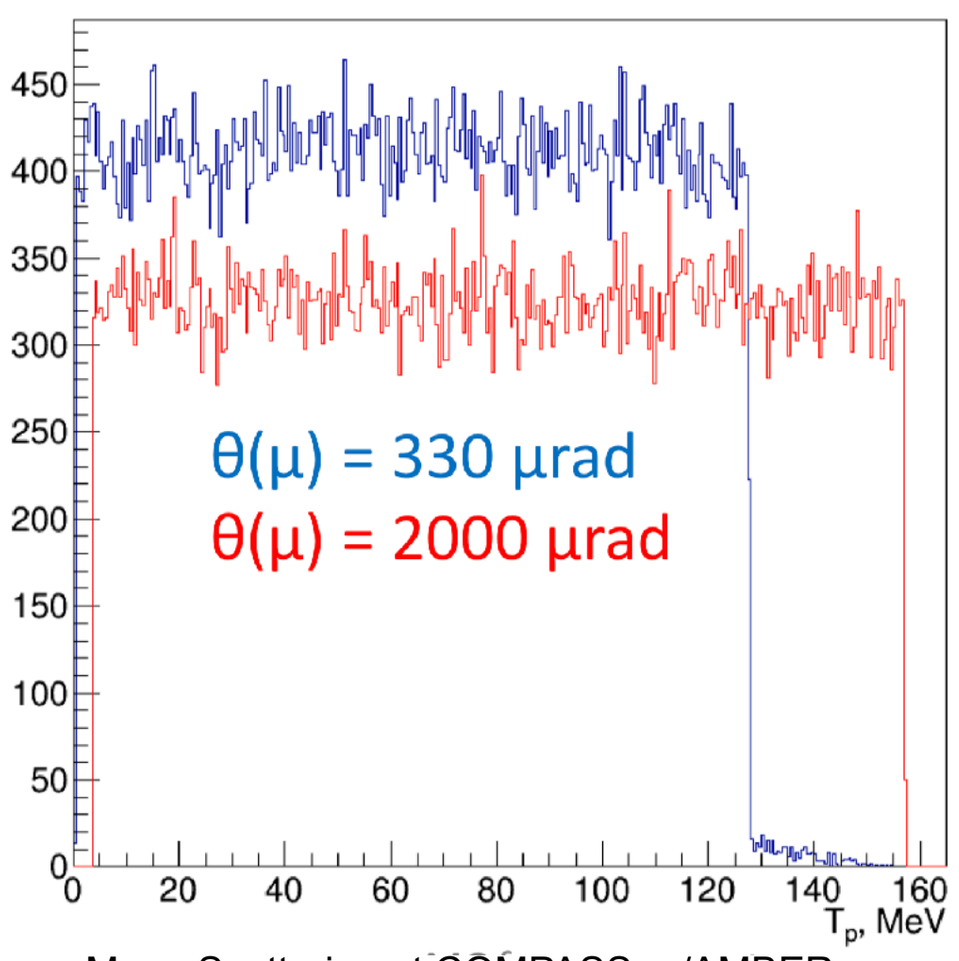
Monte Carlo Studies - Inelastic Background

Example of Δ-production

- 2-body Δ(1232) production as proxy process for inelastic reactions
- Only a fraction of protons from Δ decay have energies below 20 MeV
- Angular distributions from Δ decays can be separated from elastic process
  → kinematics of angle and energy can be used for separation





Things we definitely have to do

- Detailed description of the TPC and its response (gas, readout, material)
- Selection criteria: Background like excitations, radiative photons, electrons in gas, etc.
- Optimise TPC Readout structure according to beam properties and vice versa, energy resolution
- Environment effects: misalignment studies - Run-By-Run alignment, temperature and pressure influences
- Event matching efficiency between TPC recoil proton and muon scattering
- Influence of beam halo component on active target TPC, trigger and detectors - vetos
- Implement planned detectors (silicon, fibres, TPC) fully in Monte Carlo and reconstruction
- …

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Summary

- Many performed, some running and several proposed experiments:
  → missing: measurement of the proton charge radius via **high-energy μ-p elastic scattering**
- Unique location: CERN M2 beamline in combination with the COMPASS spectrometer
- Providing a high-energy μ-p elastic scattering data set of about 70 million events
  → Q^2-range: 0.001 - 0.04 GeV^2/c^2
  → aimed statistical precision for this measurement of the proton charge radius: 1 %
- Estimated beam time about 140 days + required systematic studies (polarity, beam momentum, pressure)
- New development ongoing - TPC, silicon detectors, fiber triggers and DAQ
- Test beam in 2018 provided promising results and experience

Proposal was handed in end of May to SPS Experiments Committee (CERN)
(CERN-SPSC-2019–022, SPSC-P-360)
Update ongoing!

Outlook

- More detailed studies of systematics required to support the aimed precision
- Full Monte Carlo description of final setup to study driving parameters for geometry and detector development - especially systematics
- Comparison of this measurement with other upcoming measurements like MUSE at PSI
- Further development and studies of prototypes for silicon detector, fiber trigger and TPC
- Absolute energy scale of beam and measured Q^2 required - different approaches under study
- First beam tests foreseen in 2021
  → 20 days dedicated tests in addition to the transverse-deuteron run of COMPASS
  → further testing downstream of COMPASS in parallel
- First data taking proposed in 2022 / 2023

Update of proposal until next SPSC meeting (15th October 2019)

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Thank you for your attention

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Further information

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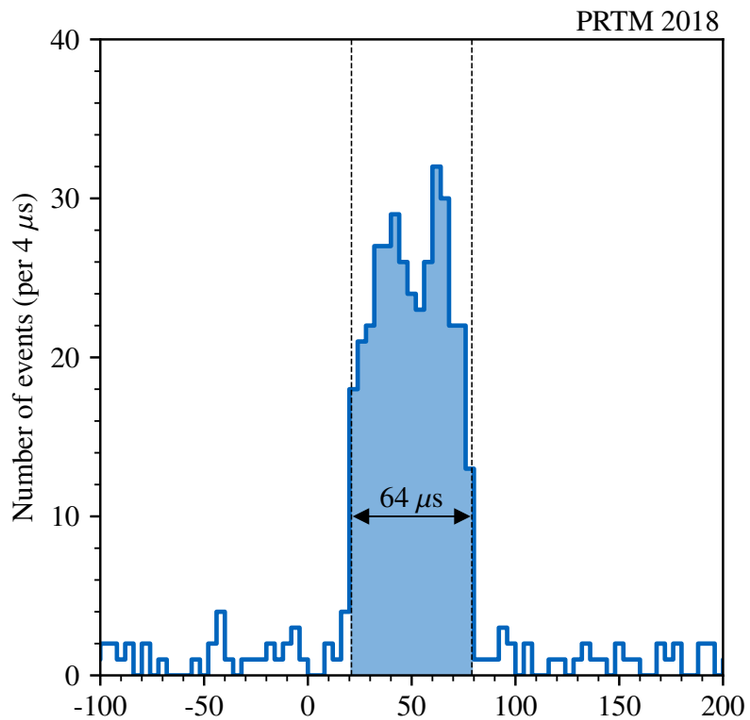
Results of the Beam Test in 2018

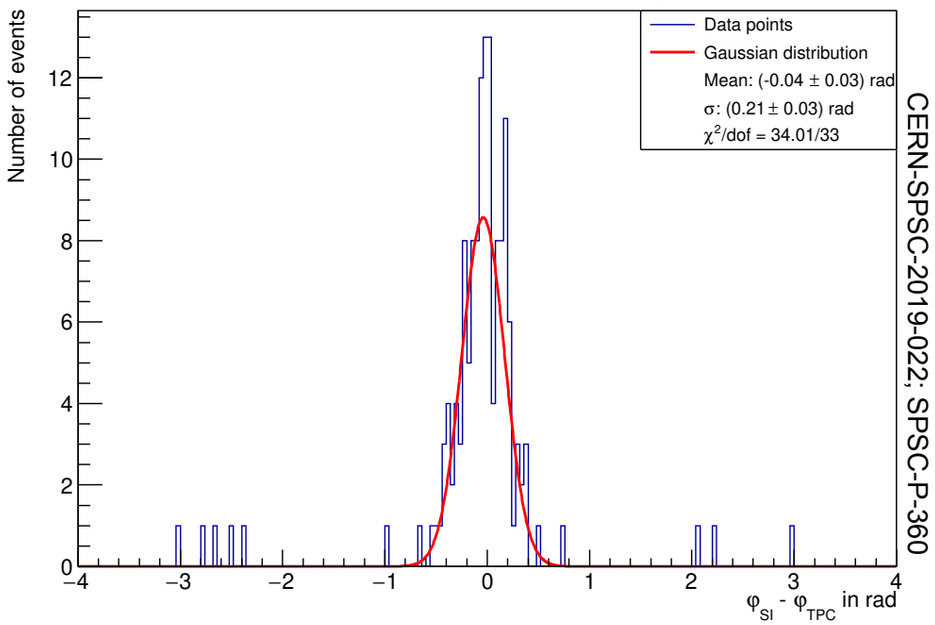
Feasibility test using TPC and silicon detectors
Two-month beam test parallel to COMPASS run with TPC and silicon trackers.

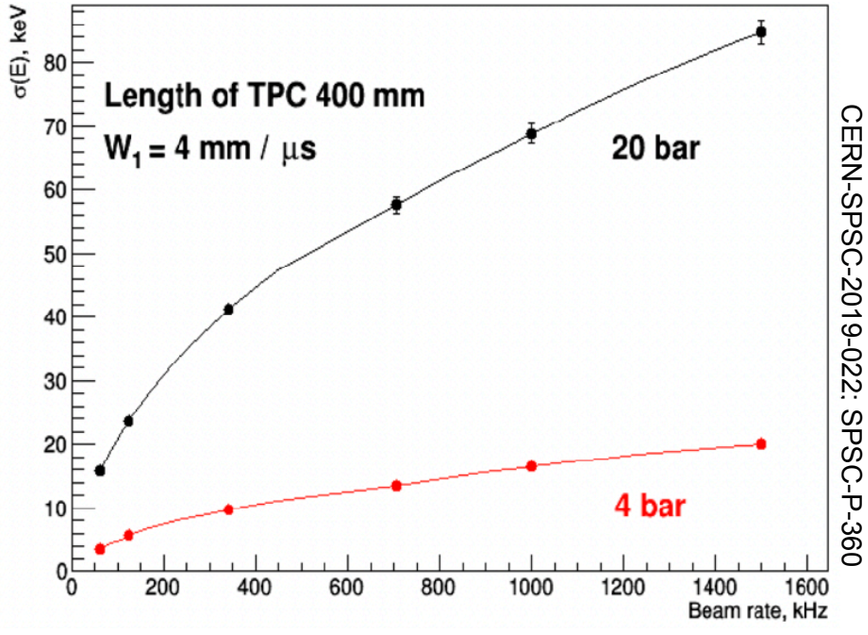
- Time correlation of TPC and silicon events
  → 23 cm drift correspond to 64 µs drift time



- High purity of events in reconstructed polar angle φ
  → width corresponds to readout segmentation

- “Beam noise” due to beam intensity crucial for TPC





Tomorrow morning talk by Martin Hoffmann!

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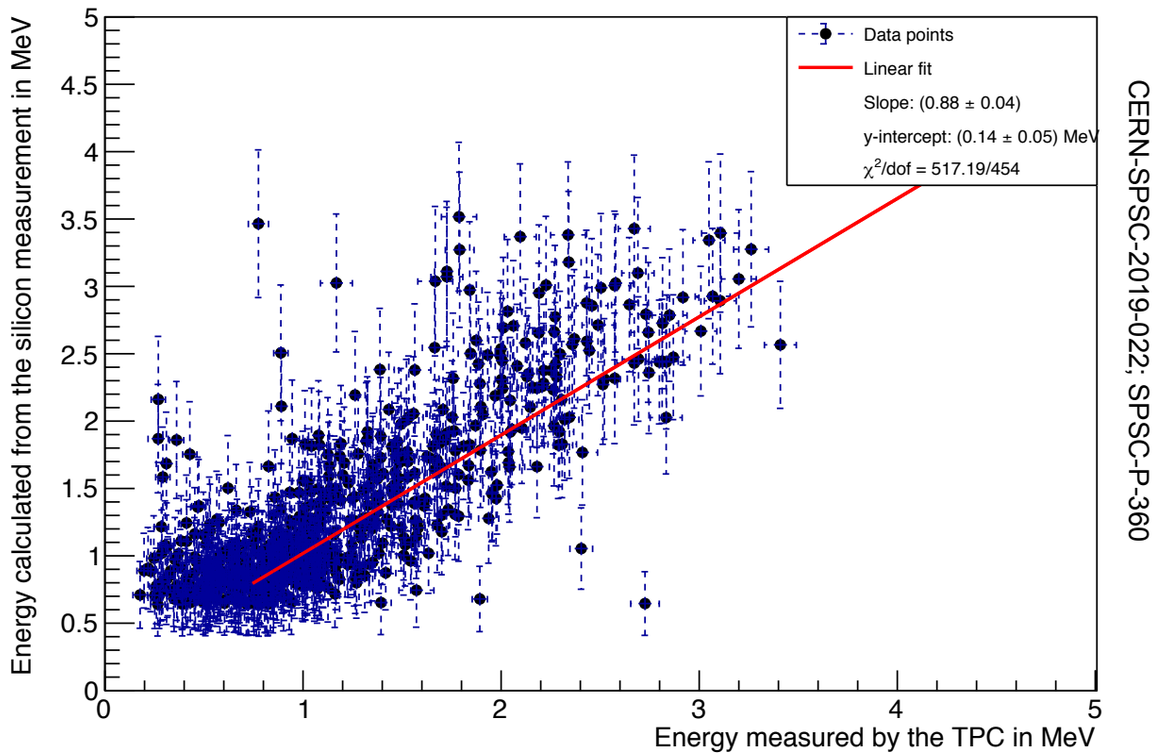
Results of the Beam Test in 2018

Basic detector setup for tested in 2018
Two month test parallel to COMPASS run with TPC and silicon tracking stations.

- Recoil proton energies determined by both detector systems
  → Resolution obtained by TPC 3x better
  → Proposed setup: increase resolution by factor 2
- Important experience was gathered along with know-how of a future analysis of the proposed measurement



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Goal of this Measurement and Requirements

Different models for the radius extraction

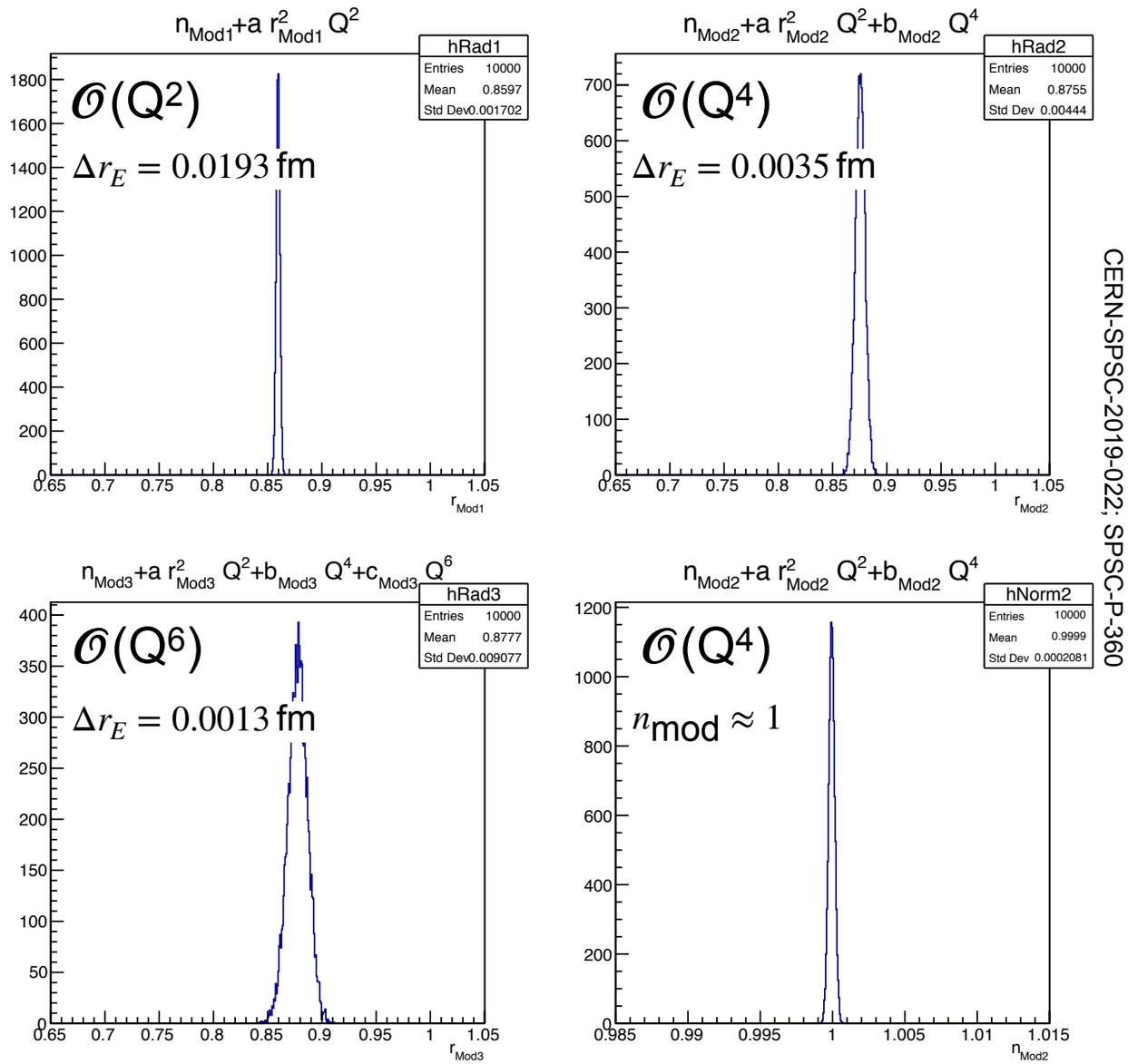
Q^2-dependency of cross section can be fitted with polynomials up to $\mathcal{O}(Q^{2n})$.

- 70 million elastic events in proposed Q^2-range fitted to MAMI data ($r_{E,MAMI} = 0.879$ fm)
- Truncated series of $G_E(Q^2)$:

$$G_E(Q^2) = n\left(1+a_2'Q^2+a_4'Q^4+a_6'Q^6+a_8'Q^8+\ldots\right)$$

- 3 parameters $\mathcal{O}(Q^4)$: n, a_2, a_4
  → sys 0.0035 fm, stat 0.0040 fm
- 4 parameters $\mathcal{O}(Q^6)$: n, a_2, a_4, a_6
  → sys 0.0013 fm, stat 0.0090 fm

Measurement the proton radius with a statistical precision on the level of 1% achieved with 70 million events



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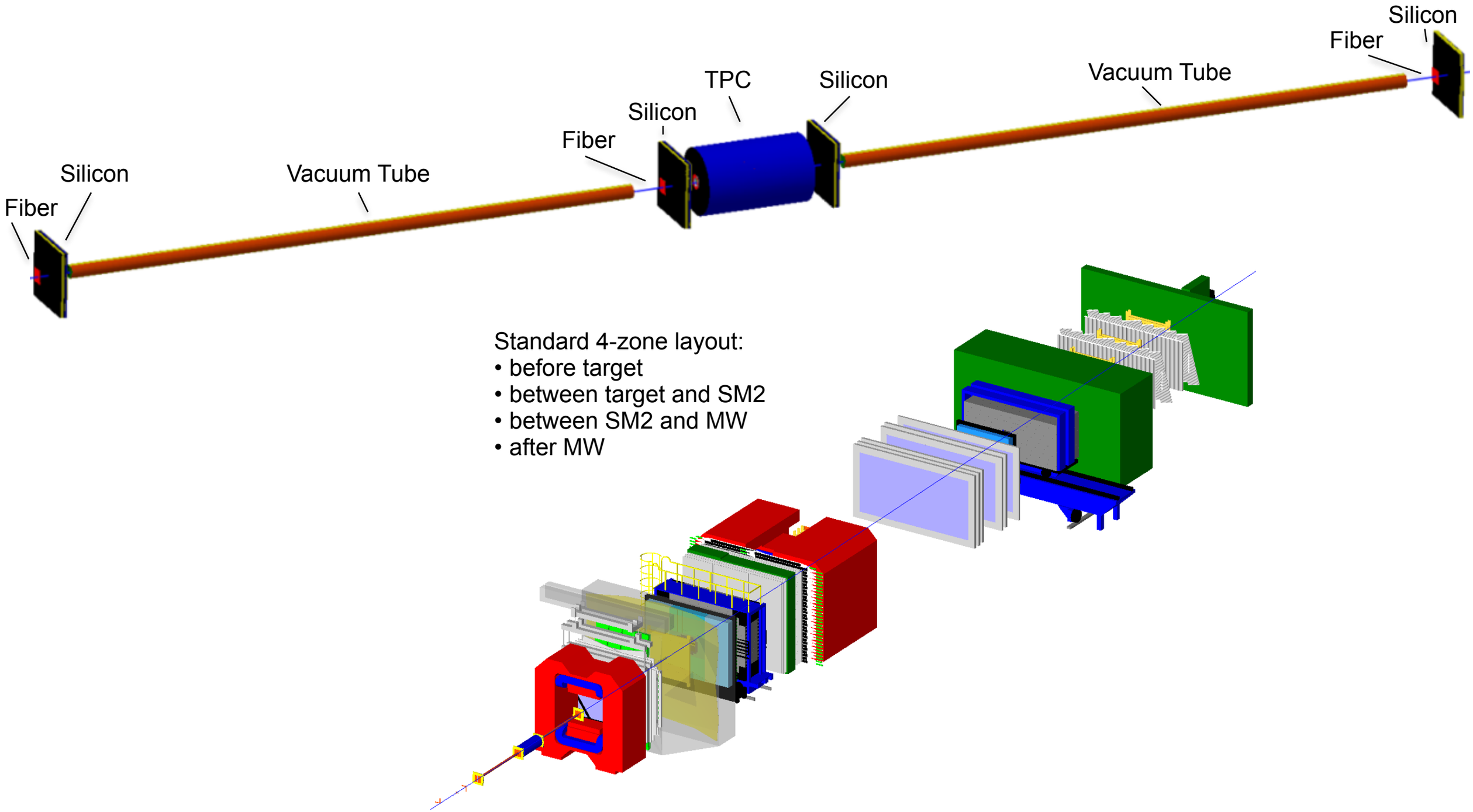
Layout of the Setup



Standard 4-zone layout:
- before target
- between target and SM2
- between SM2 and MW
- after MW

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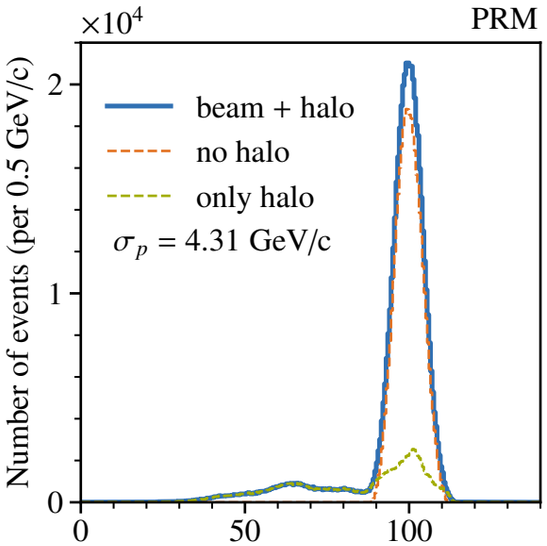
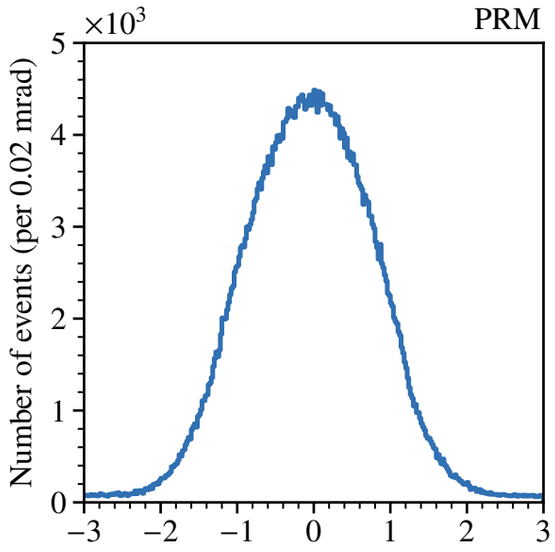
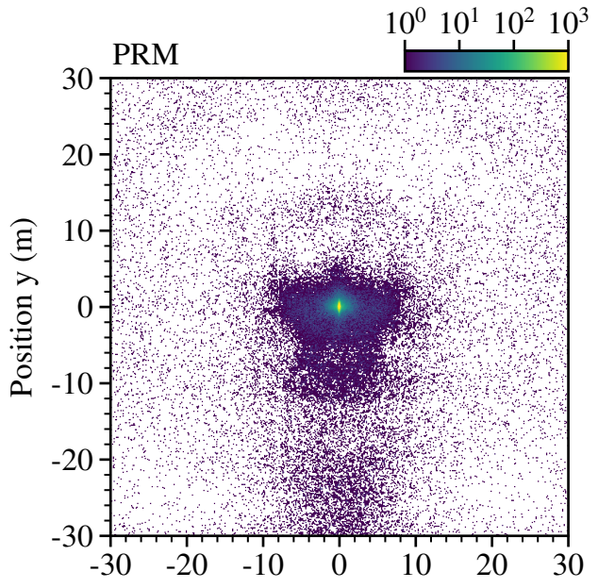
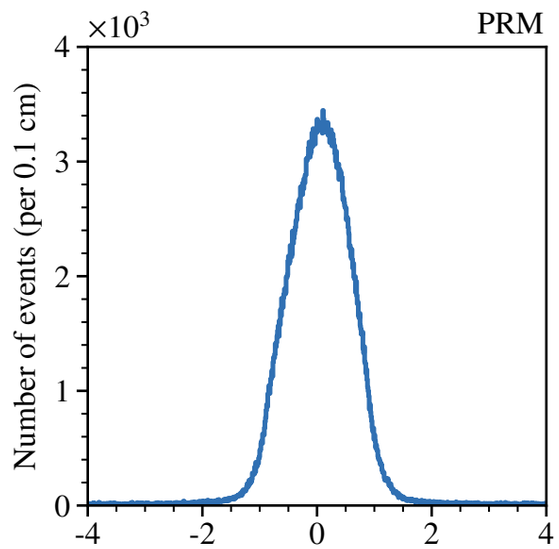
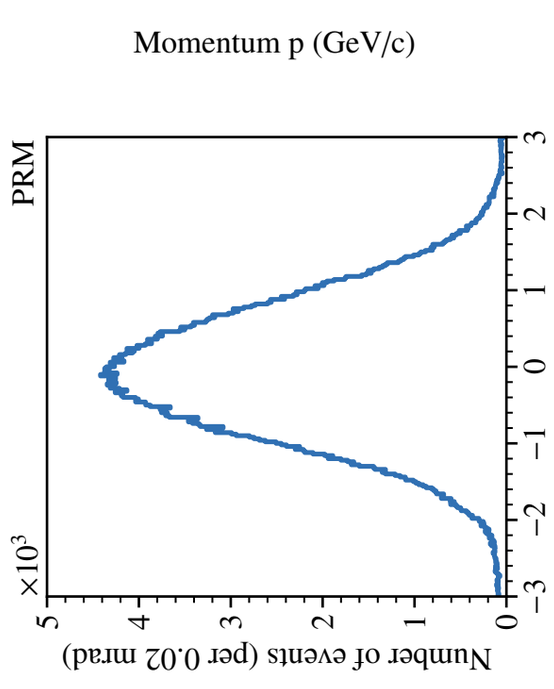
Beam Properties

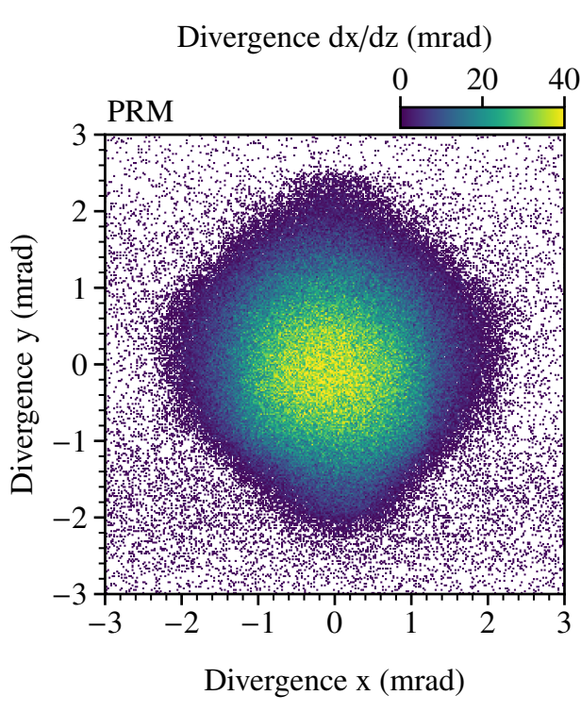


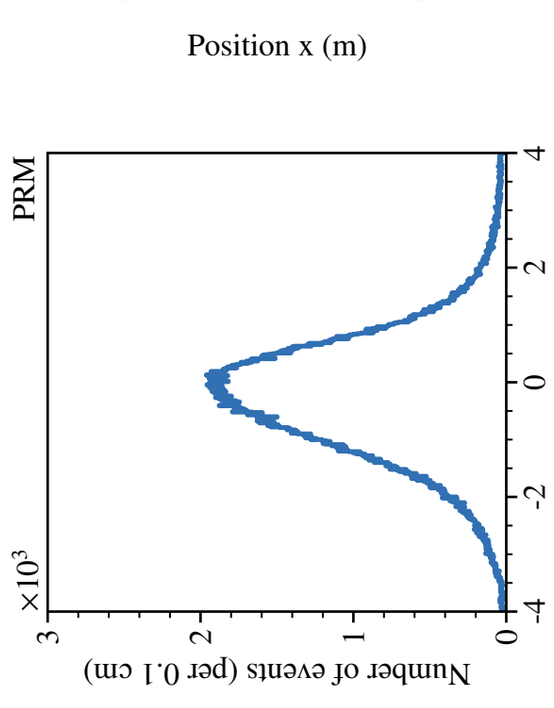


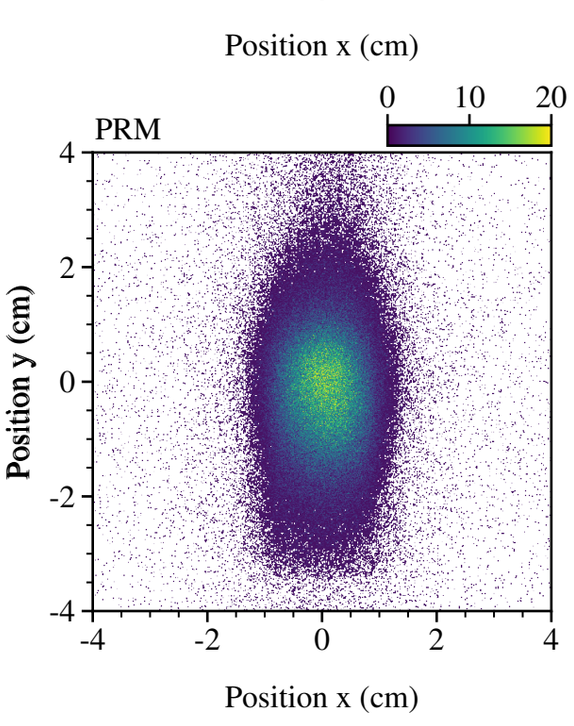












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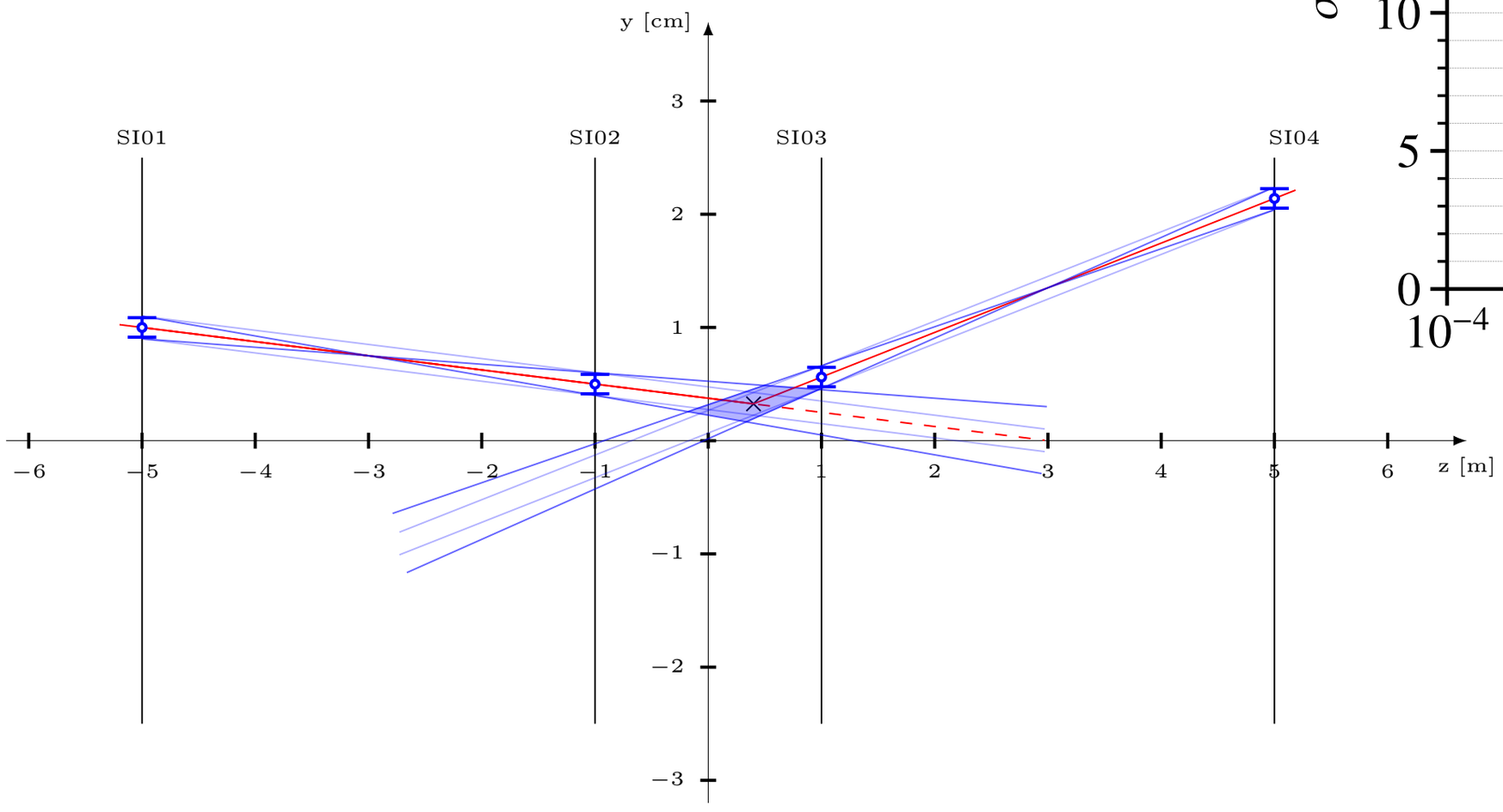
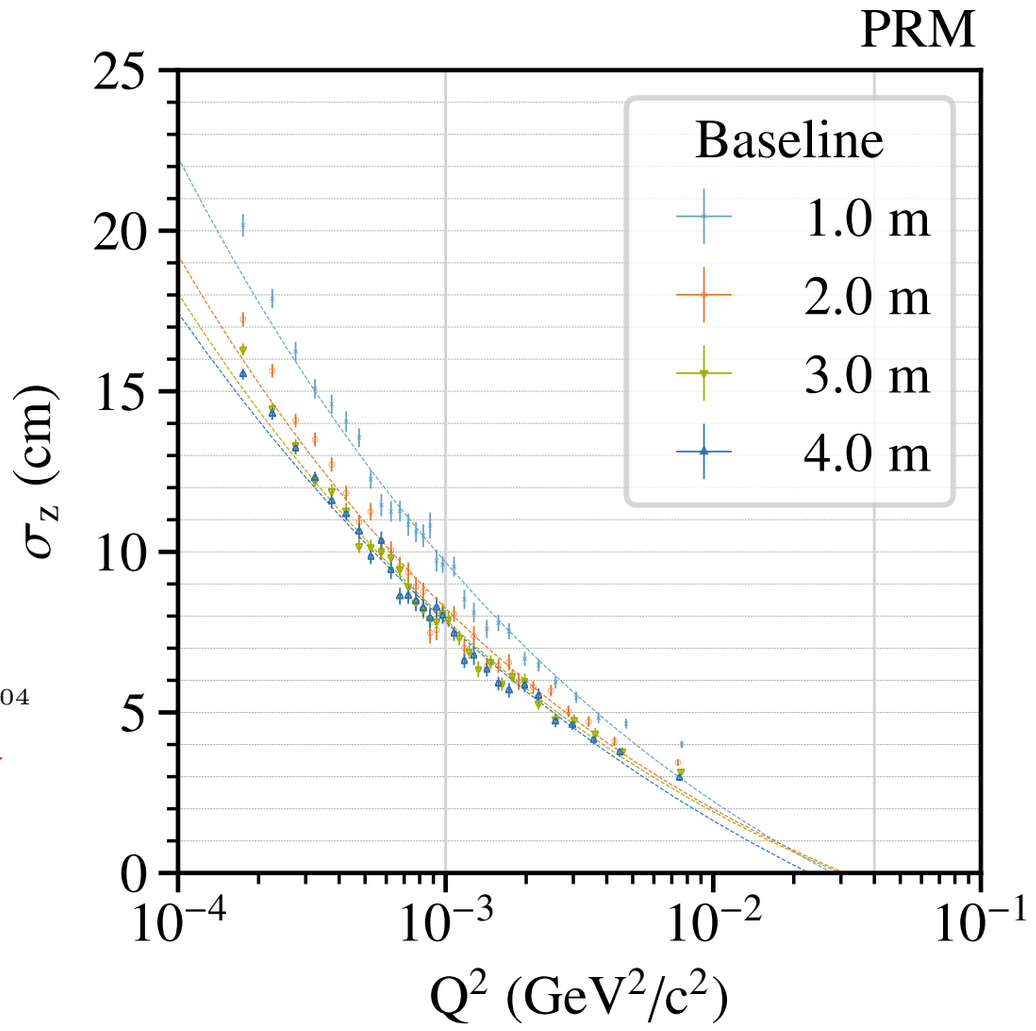
Monte Carlo Studies - Baseline Length

Studies on setup geometry

Target distance, baseline and spacial resolution influence vertex-z resolution.





Material Budget

material	planes	d/plane [cm]	density ρ [g/cm^3]	X_0 [g/cm^2]	x/X_0 [‰]	contribution [%]
Environment and tracking:						
Dry Air	2	300.00	0.00120	36.62	22.94	
Helium*	2	300.00	0.00016	94.32	1.19	3.02
Fibre (polystyrene)*	4	0.02	1.04	43.79	1.90	5.63
Silicon*	8	0.02	2.33	21.82	21.82	50.63
TPC components (2-cell version):						
Hydrogen (4 bar)	2	40.00	0.00033	63.05	0.52	
Hydrogen (20 bar)*	2	40.00	0.00166	63.05	2.63	6.24
TPC-Anode (Kapton)*	2	0.040	1.42	40.58	2.80	8.30
TPC-Anode (Cu)*	2	0.002	1.40	12.86	0.44	1.29
TPC-Anode (G10)*	2	0.020	1.80	30.17	2.39	7.07
TPC-Cathode (Al)*	1	0.003	2.70	24.01	0.34	1.00
TPC-Window (Be)*	2	0.100	1.85	65.19	5.68	16.82
Total:					33.74	100.00

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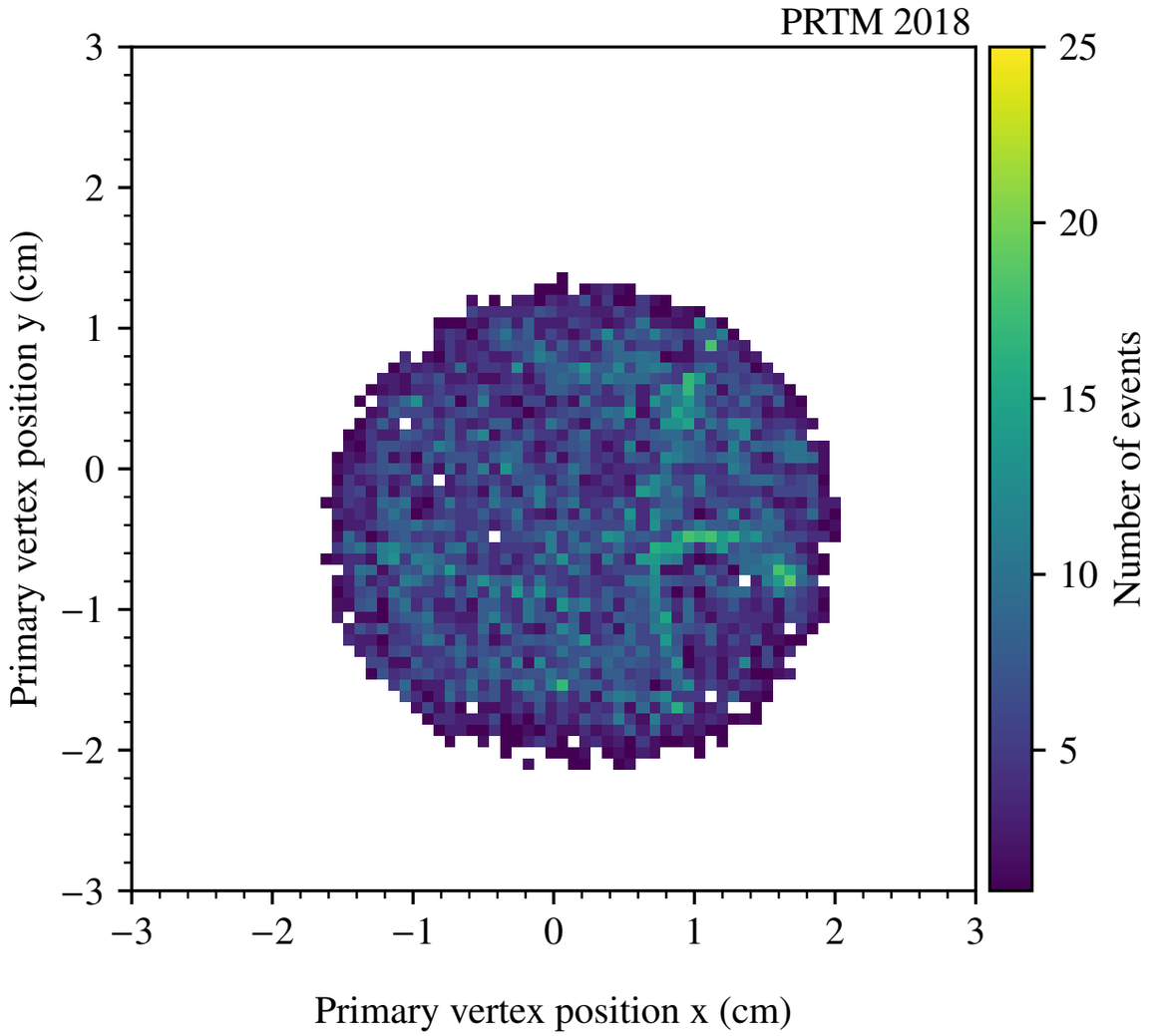
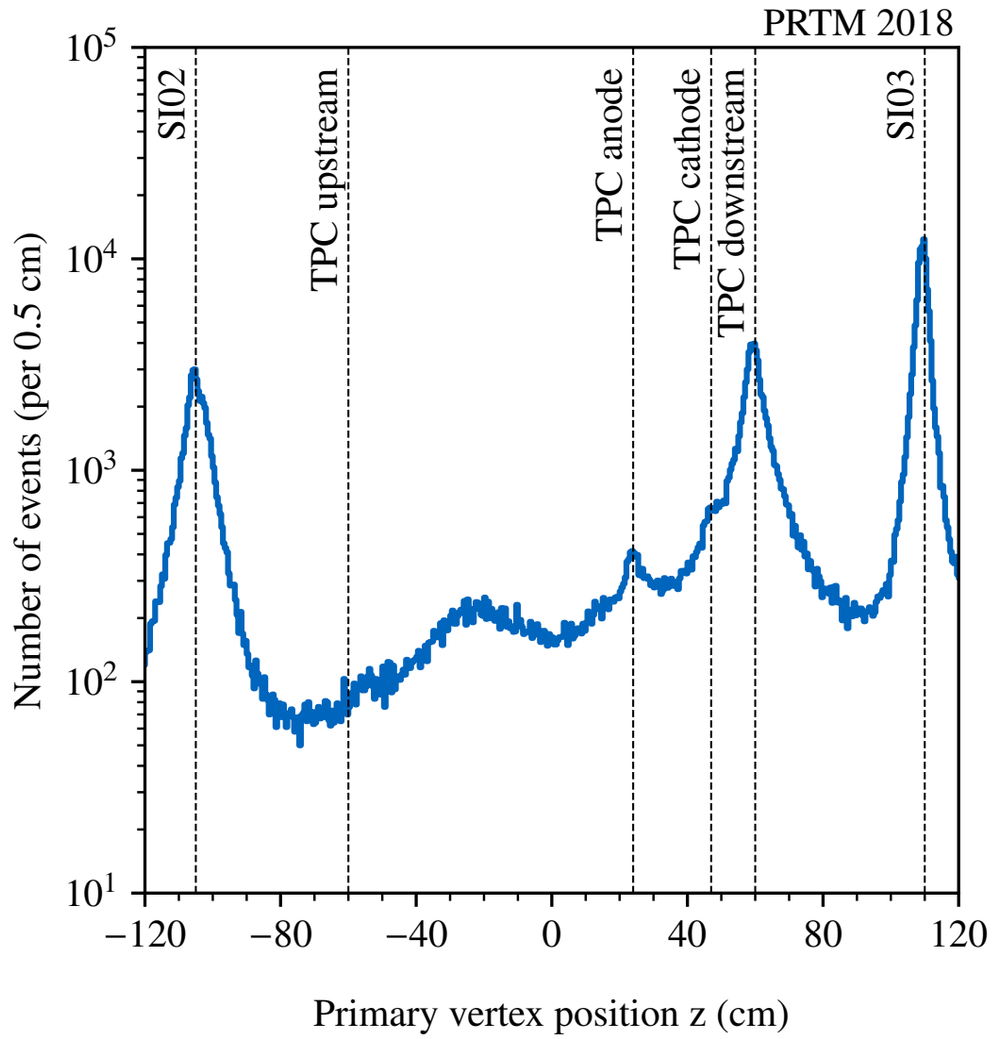
Vertex Distributions of Test Setup 2018





Institute for Hadronic Structure and Fundamental Symmetries
Physics Department
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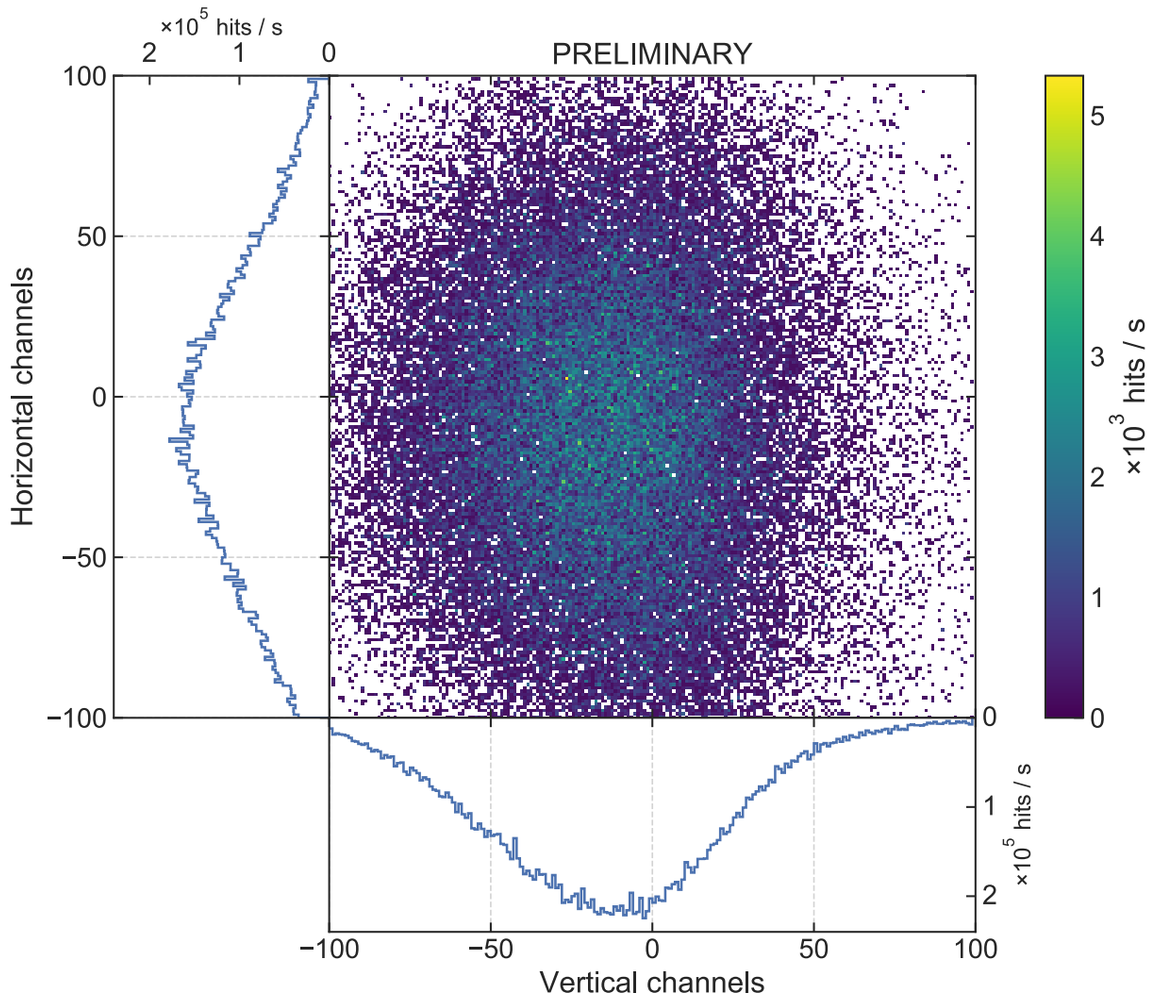
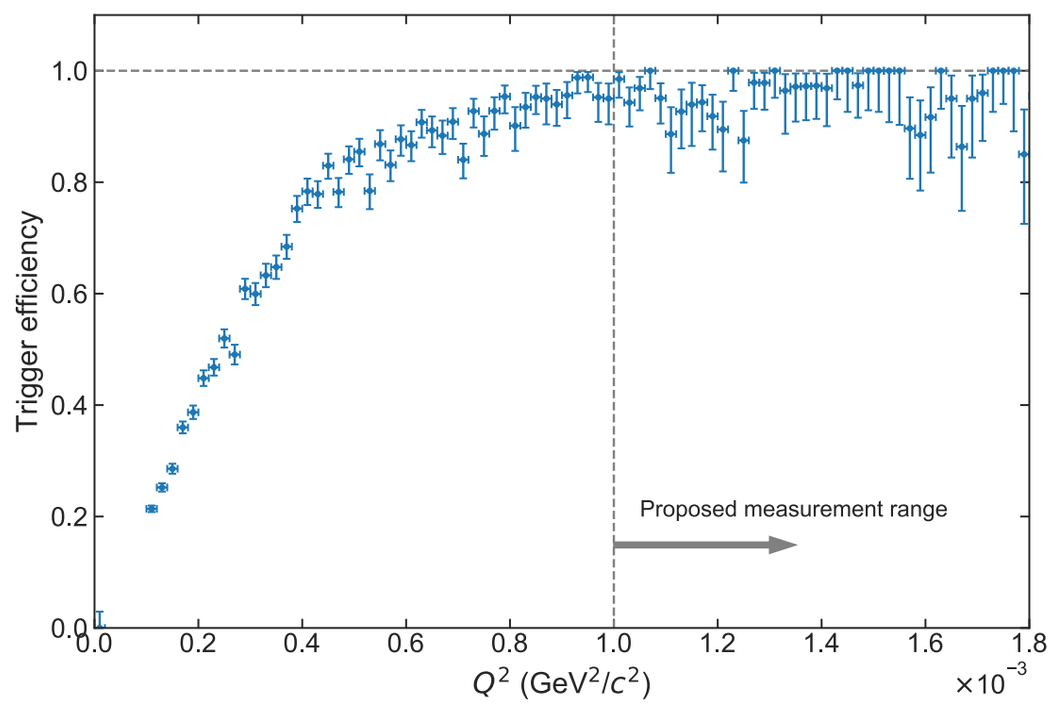
Monte Carlo Studies - Fiber Trigger Efficiency





CERN-SPSC-2019-022; SPSC-P-360