Proton-Radius Measurement in High-Energy Muon Scattering at COMPASS++/AMBER

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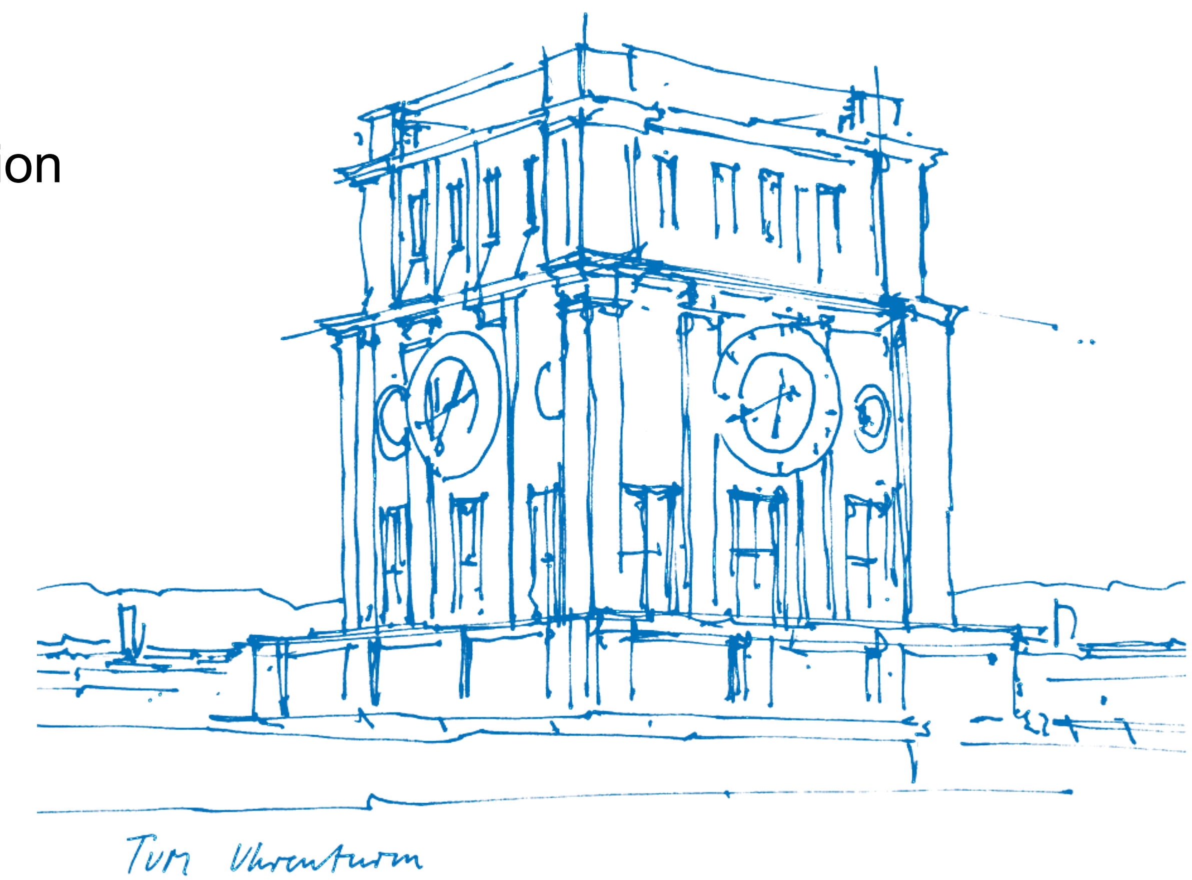
XVI International Workshop on Hadron Structure and Spectroscopy
June 25th 2019
Aveiro, Portugal

On behalf of the COMPASS++/AMBER Proto-Collaboration



The Proton-Radius Puzzle

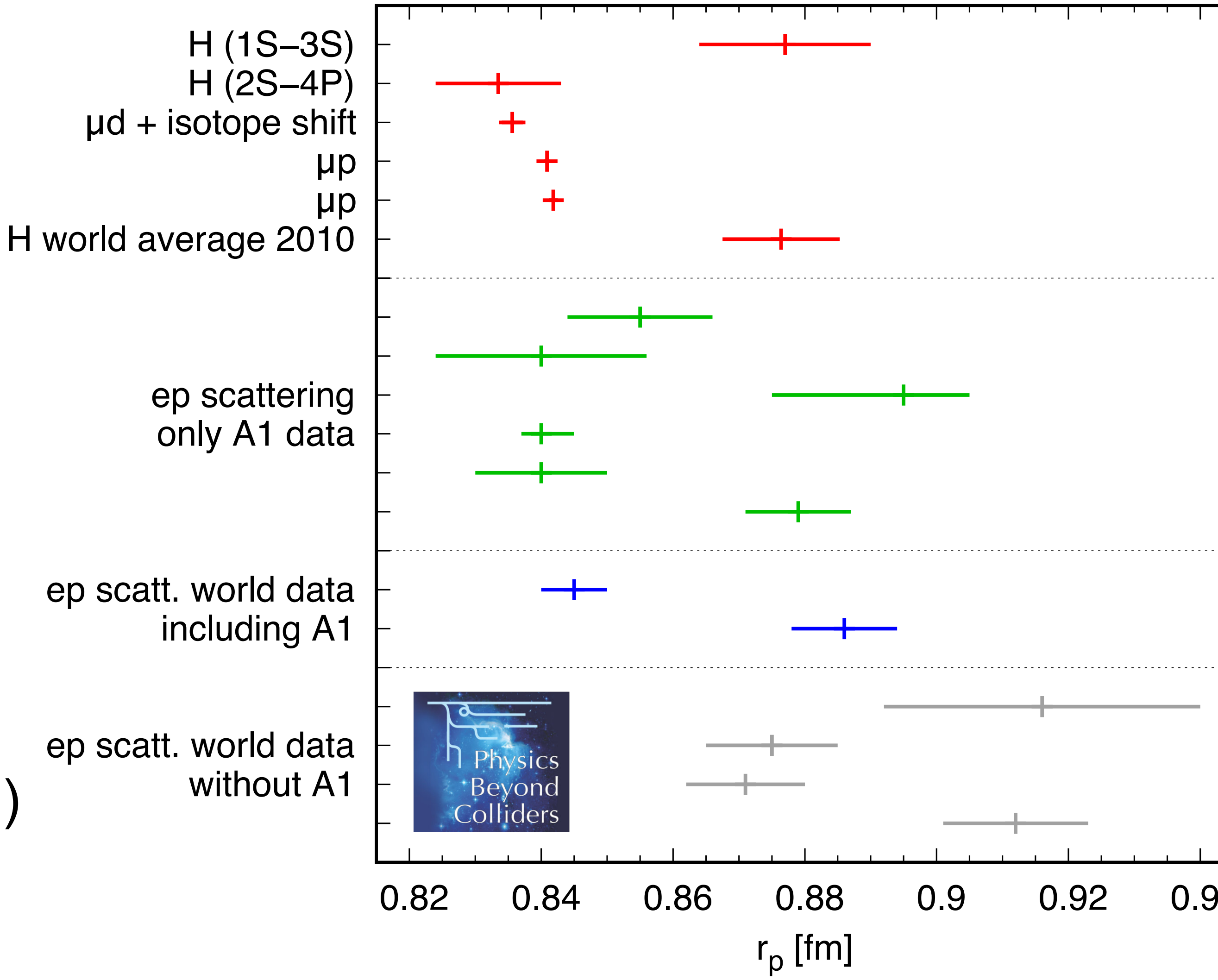
Data from spectroscopy and e-p scattering

Several experiments with different approaches measured the proton radius with contradicting results.

- Hydrogen spectroscopy:
  → muonic or ordinary hydrogen
  → highest precision using laser spectroscopy
  → favoured value of (0.841±0.01) fm

- Electron-hydrogen scattering:
  → measurement using momentum transfer
  → recent data: MAMI A1 (2010) or JLab (2011)
  → favoured value of (0.879±0.008) fm

- Two significantly different values obtained
  → the proton-radius puzzle



A. Dainese et al., PBC: QCD Working Group Report, 2019

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
- **Missing**: 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

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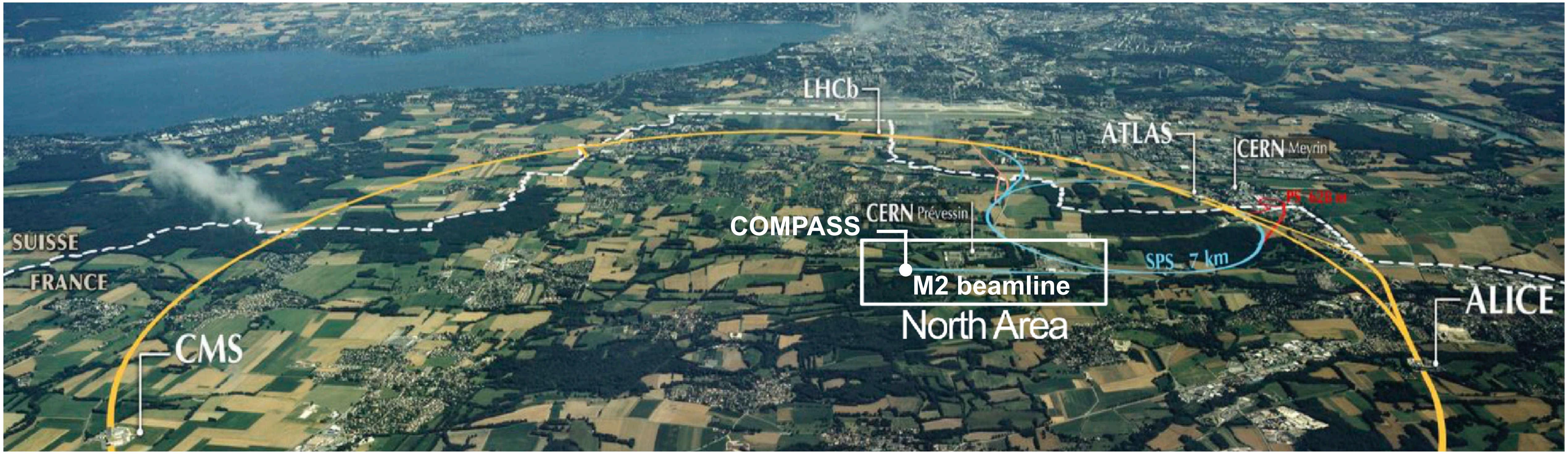
Beamline for High-Energy Muon Beams

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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How to Determine the Proton Radius?

Cross section, form factor, and the proton radius

Measurement of electric form factor allows to calculate proton radius.

- Electric form factor G_E defines the proton radius at momentum transfer $Q^2 = 0$:

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

- Access to form factors G_E^2 and G_M^2 in Rosenbluth separation of cross section:

$$\frac{\mathrm{d}\sigma^{\mu p \to \mu p}}{\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^2} R \left(\epsilon G_E^2 + \tau G_M^2\right)$$

$$R = \frac{\vec{p_\mu}^2 - \tau\left(s - 2m_p^2(1+\tau)\right)}{\vec{p_\mu}^2(1+\tau)} \quad \epsilon = \frac{E_\mu^2 - \tau\left(s - m_\mu^2\right)}{\vec{p_\mu}^2 - \tau\left(s - 2m_p^2(1+\tau)\right)} \quad \tau = \frac{Q^2}{(4m_P^2)}$$

- Suppress magnetic form factor G_M^2
  → requires $\tau \to 0$
  → Measurement at low-Q^2 values of $\mathcal{O}(<10^{-2})$

- Measurement at high-energy $\mathcal{O}$(10 - 100 GeV)
  → results in $\varepsilon \to 1$
  → cross-section directly proportional to G_E^2

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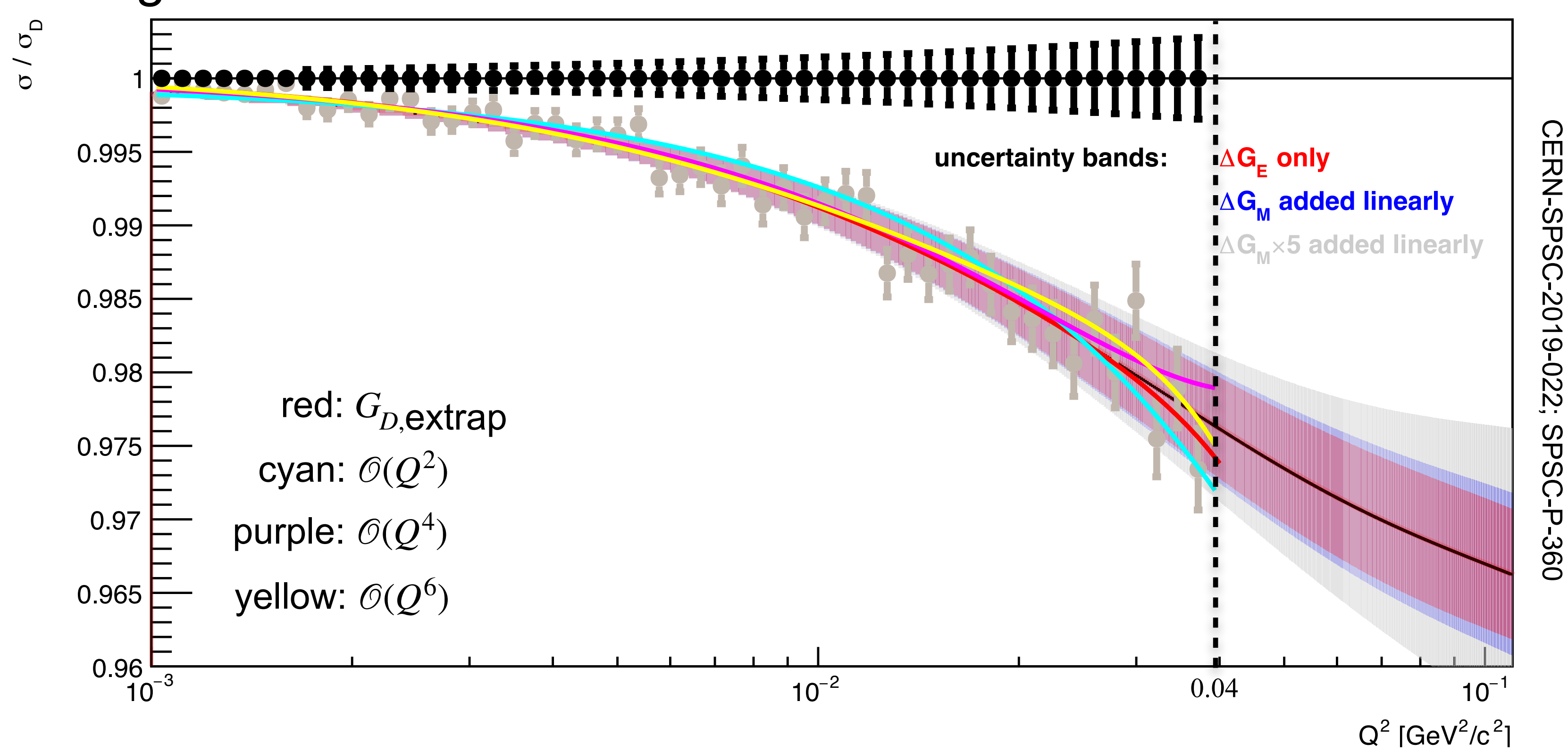
Proposal of a New Measurement

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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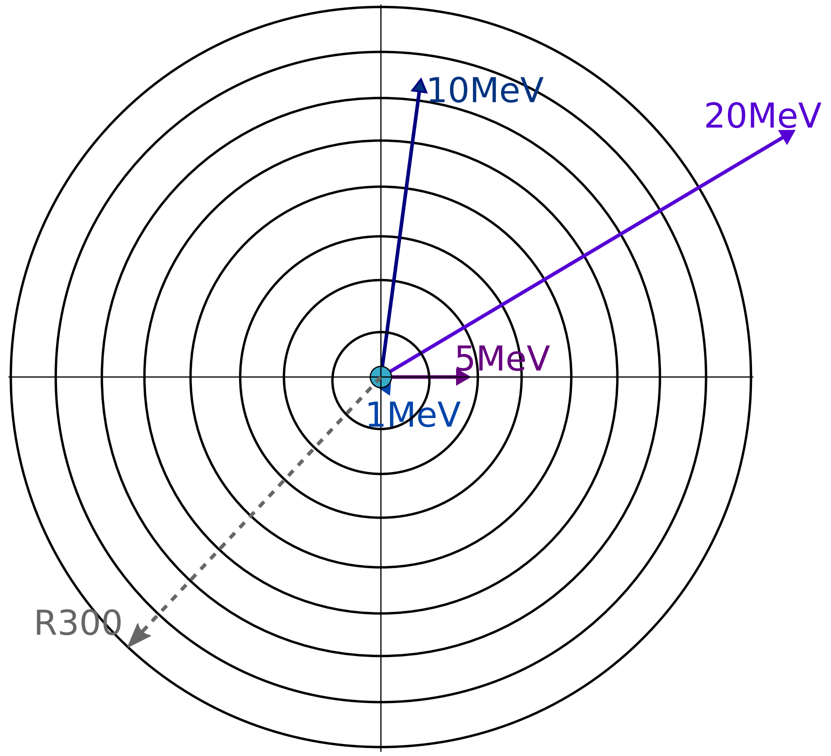
Detection of Low-Q^2 Recoil-Protons

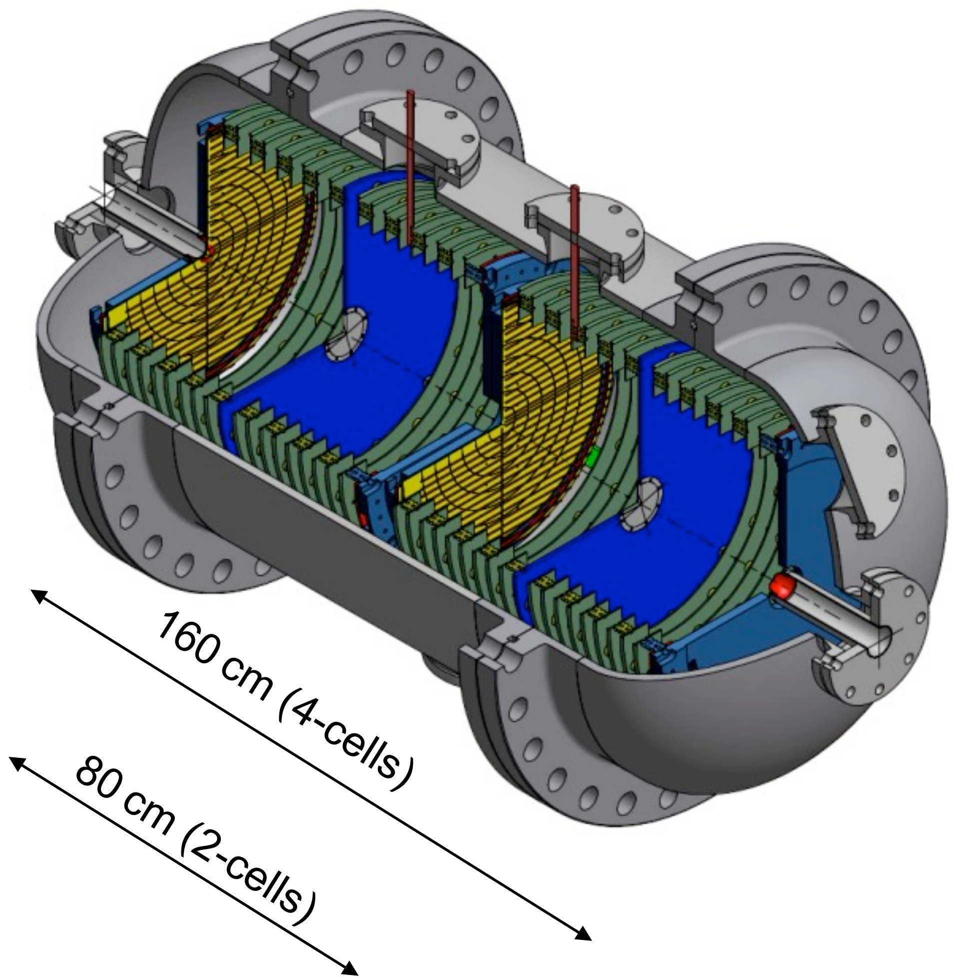
Pressurised hydrogen active-target TPC
Range of proton depends on momentum transfer.

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



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

- Optimisation of geometry ongoing
  → optimal pressure settings for Q^2-range
  → optimal length of hydrogen target



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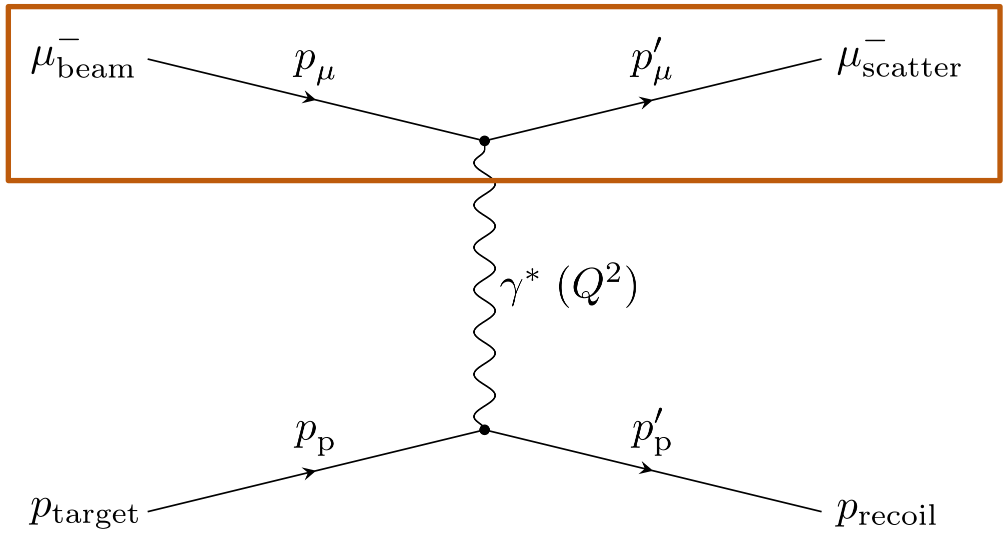
Control of Systematic Effects

Absolut calibration, inefficiencies, and background

Understanding of systematic effects is crucial for precision.

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

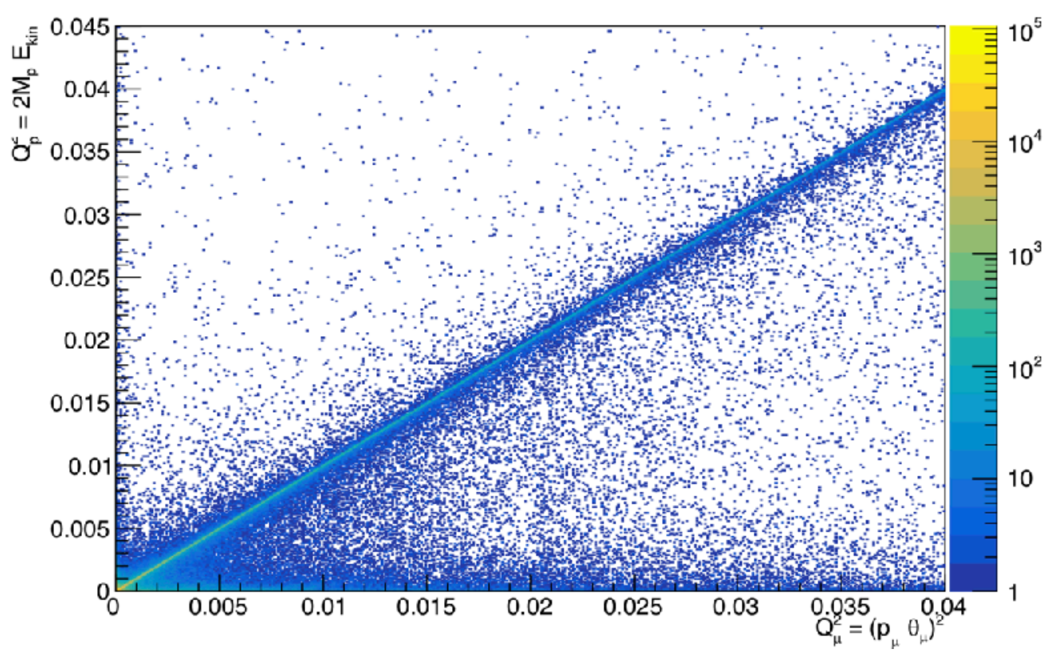


> Redundant measurement to control systematics
> → measurement of scattered muon kinematics

- 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

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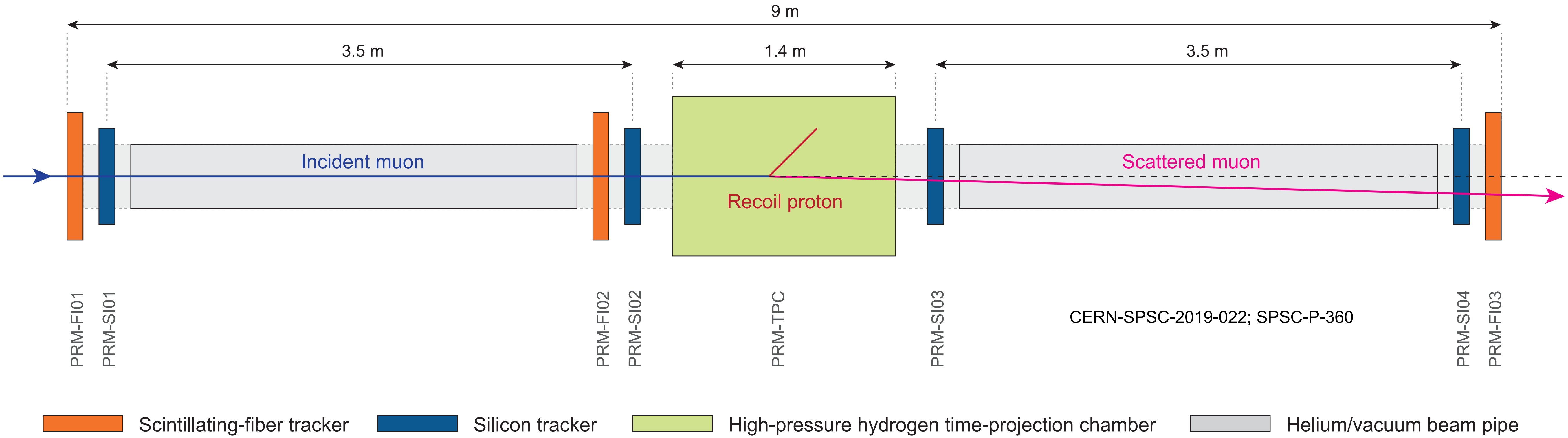
Layout of the Proton-Radius Setup

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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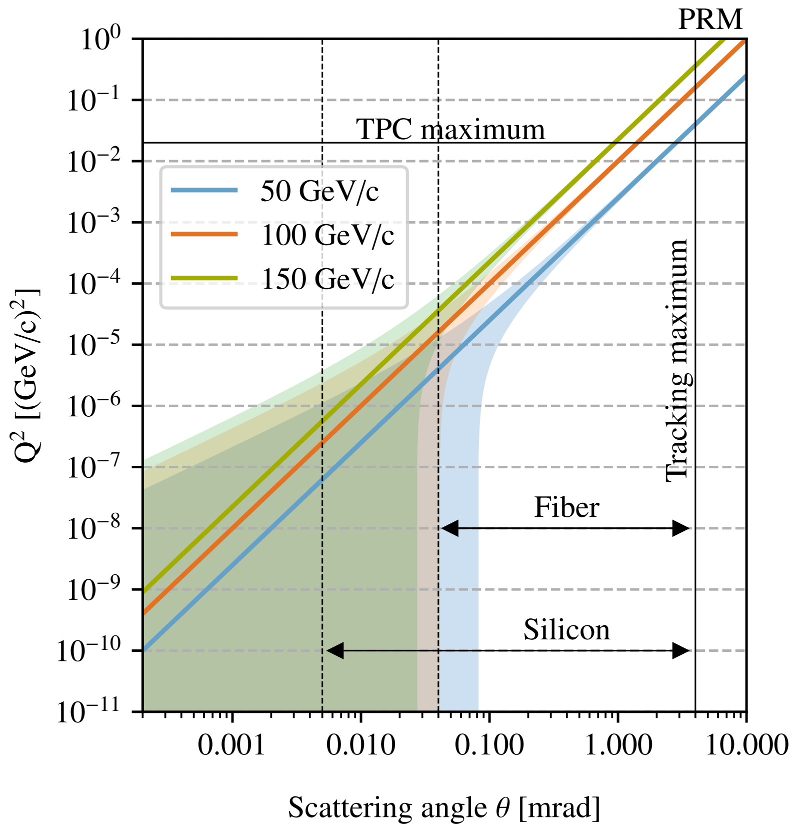
Influence of Multiple Scattering

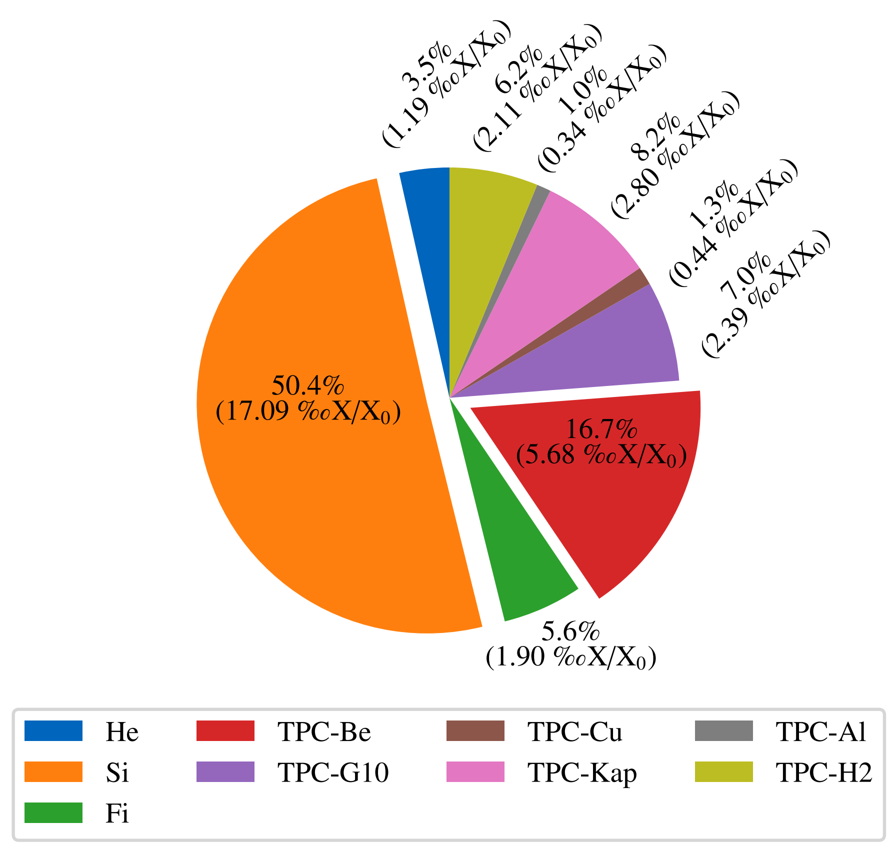
Scattering angle distorted by multiple scattering

Low-Q^2 values require a precise measurement of the small scattering angle.

- Influence on scattering angle of muon
  → change in Q^2-spectrum
- Relative resolution at lowest proposed $Q^2 = 0.001\ \mathrm{GeV}^2/c^2$:
  → $(\Delta Q^2/Q^2)_{\text{2-cell}} = 13.8\ \%$ with $(X/X_0)_{\text{2-cell}} = 33.9$ ‰
  → $(\Delta Q^2/Q^2)_{\text{4-cell}} = 15.4\ \%$ with $(X/X_0)_{\text{4-cell}} = 41.5$ ‰
- Fix contribution due to beryllium window of TPC
- Main contribution due to silicon detector material

Material budget must be precisely under control
→ detector geometries must be optimised





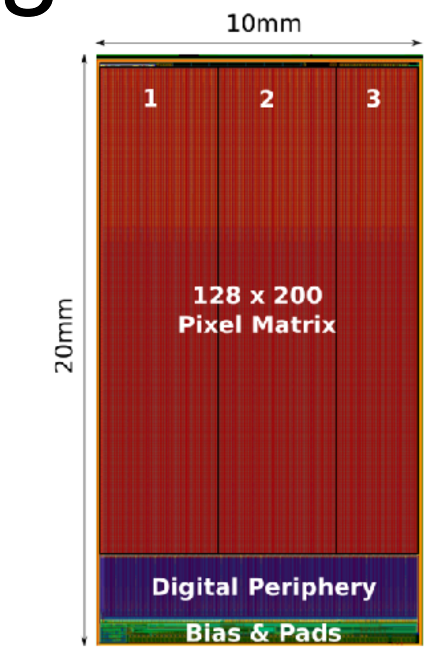
Muon Trigger and Tracking Detectors

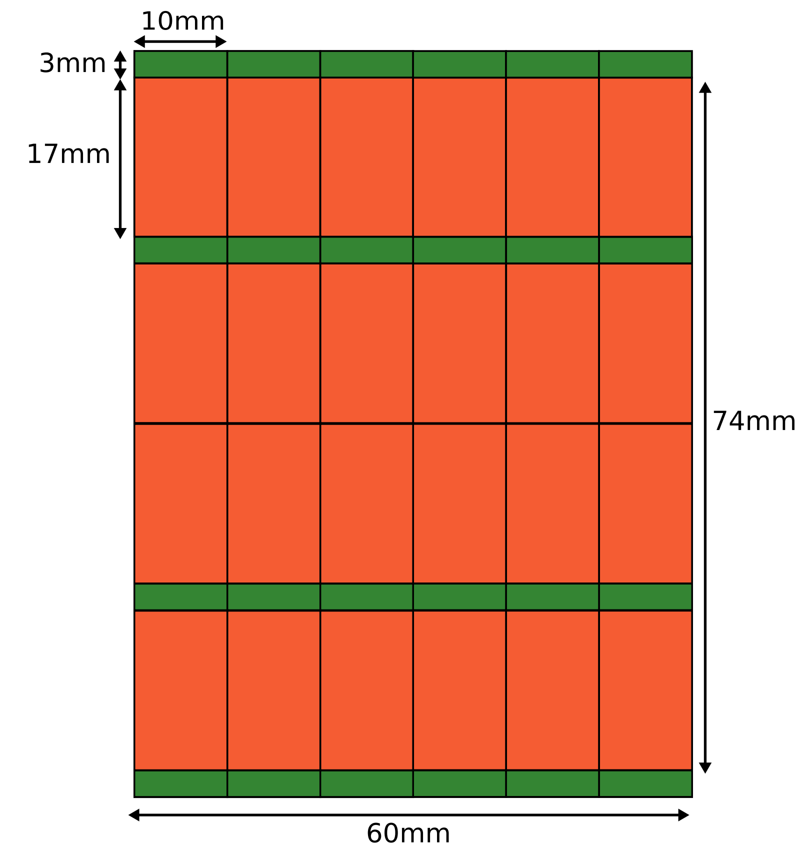
Current solutions for detectors

Silicon detectors for precise muon tracking triggered by scintillating-fiber triggers.

- Silicon detector - MuPix under investigation:
  → produced at KIT and used at Mu3e
  → MuPix8 prototype: 1 x 2 cm^2,128 x 200 pixels
  → thickness down to only 50 μm
  → 20-ns time resolution and 80-μm pixel size
  → combination of several layers required
  → spatial resolution of 5 μm with charge sharing
  → talk by I. Konorov (tomorrow)

- Scintillating-fiber trigger:
  → 200-μm scintillating-plastic fibers
  → each fiber read out via SiPMT
  → four layers combined per station
  → challenge: only 6 photoelectrons per fiber





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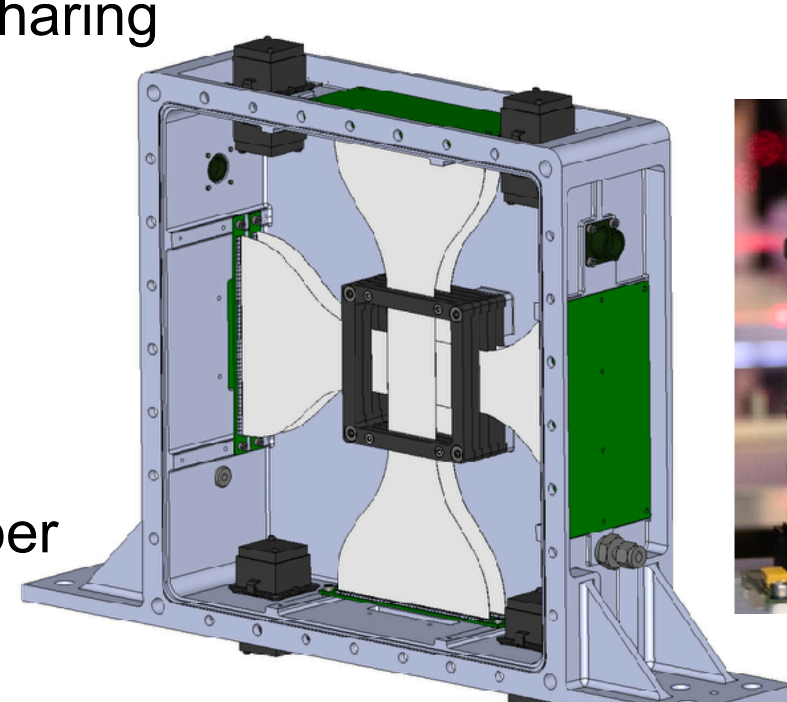
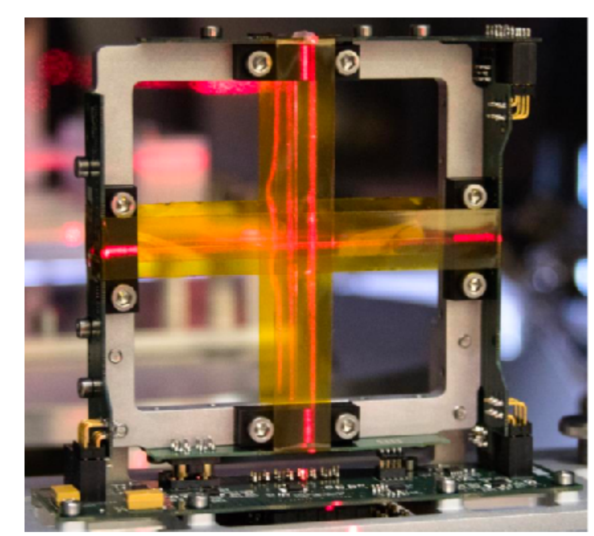
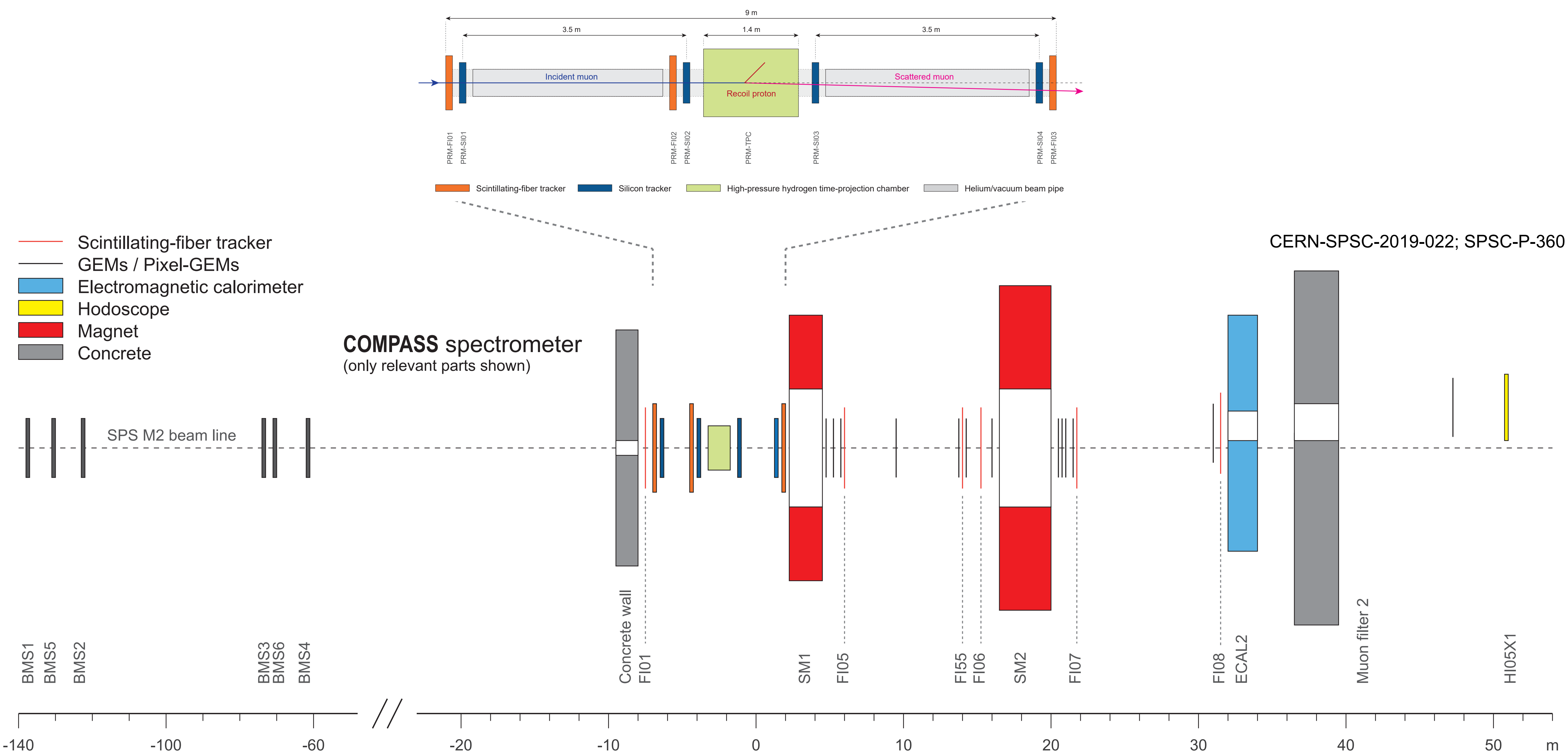




Layout of the Proton-Radius Setup

Advantages of using the COMPASS spectrometer

Measurement of muon momentum and understanding of background.



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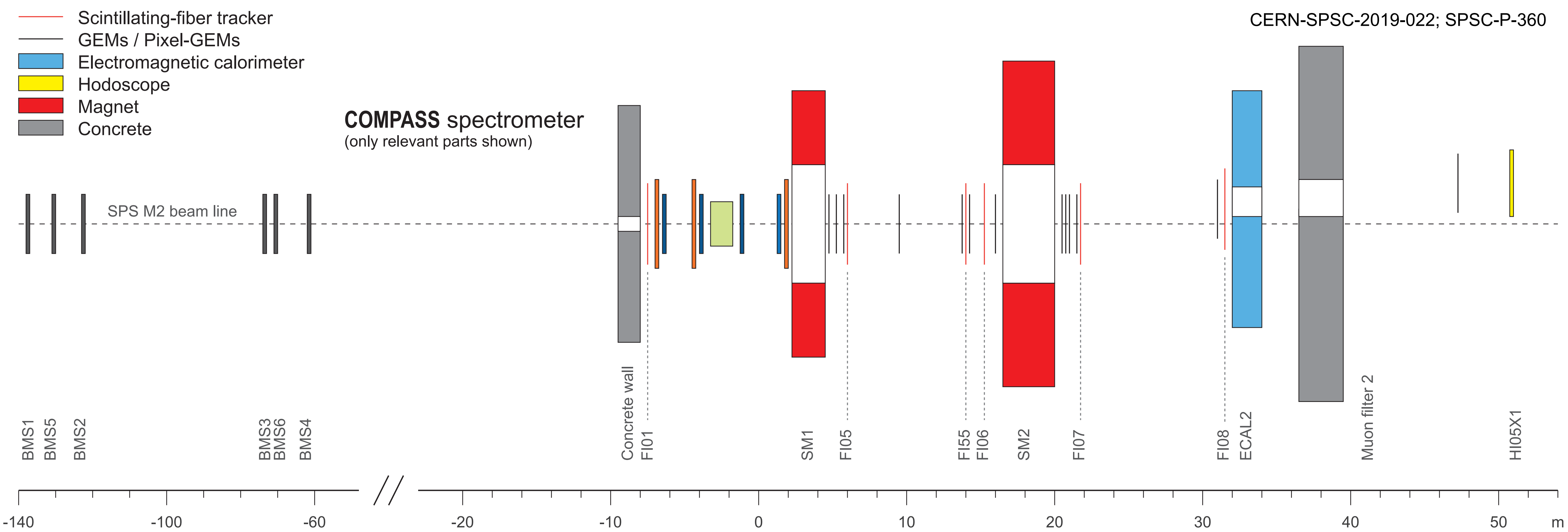
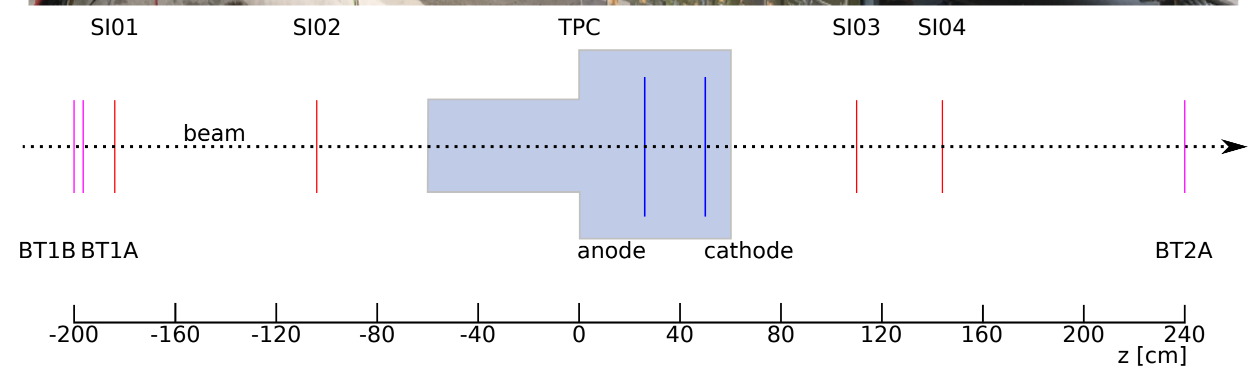


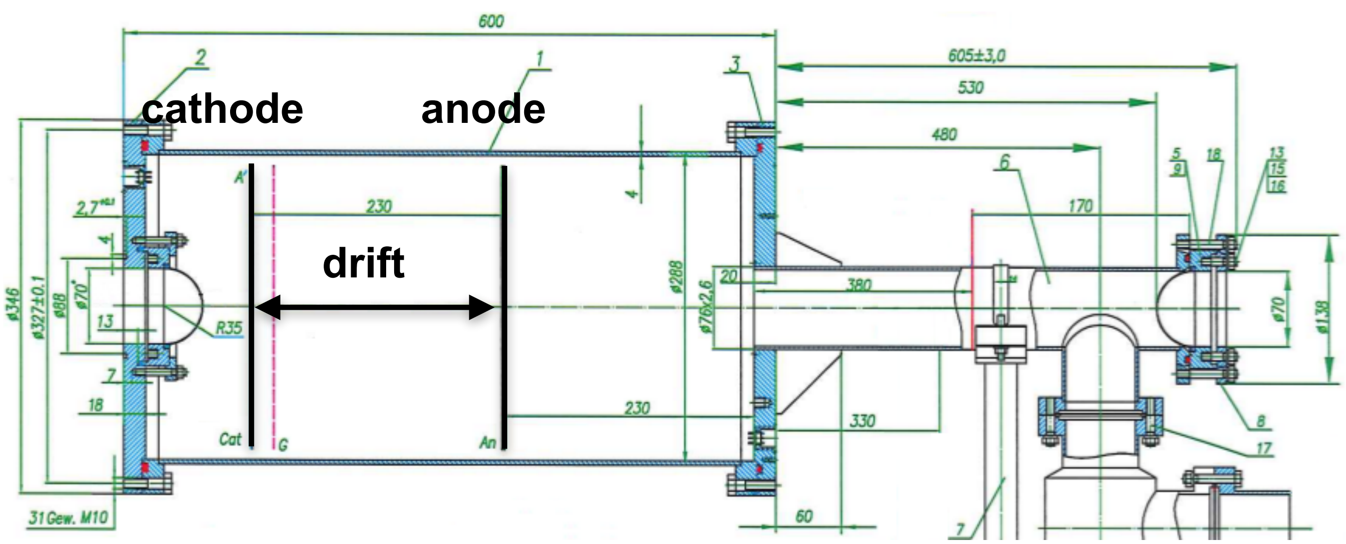
- COMPASS spectrometer
  → momentum measurement of scattered muon
  → radiative background using electromagnetic calorimeter
  → muon identification with muon filter and hodoscope

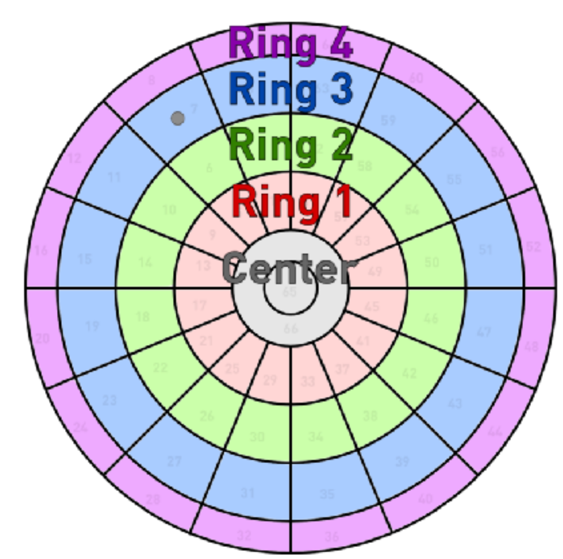
Beam Test in 2018

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 cm^2
- Two distinct DAQ systems
  → event matching via time stamp







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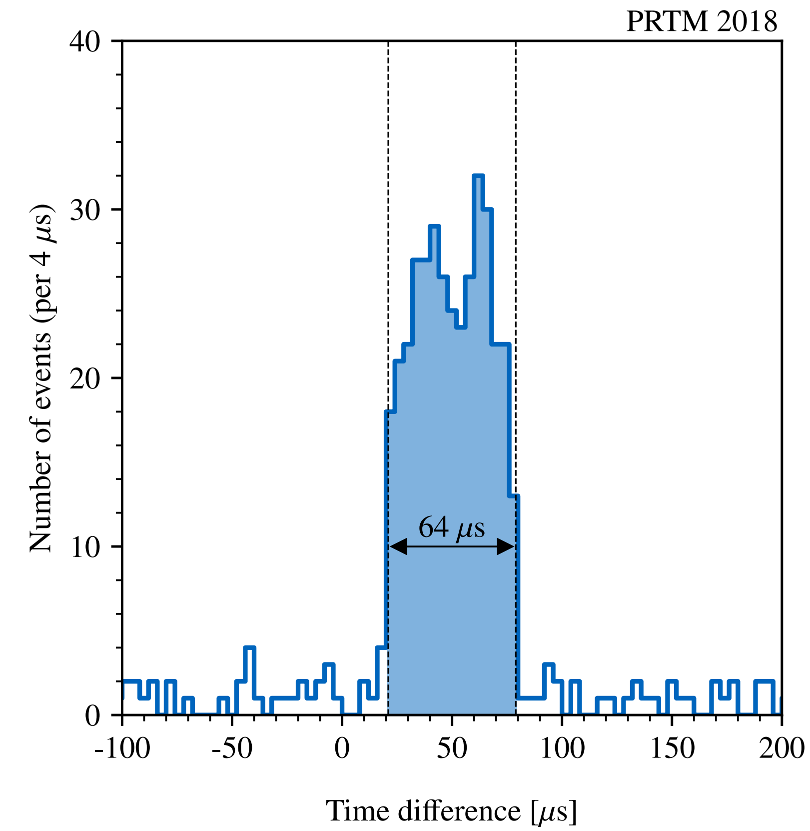
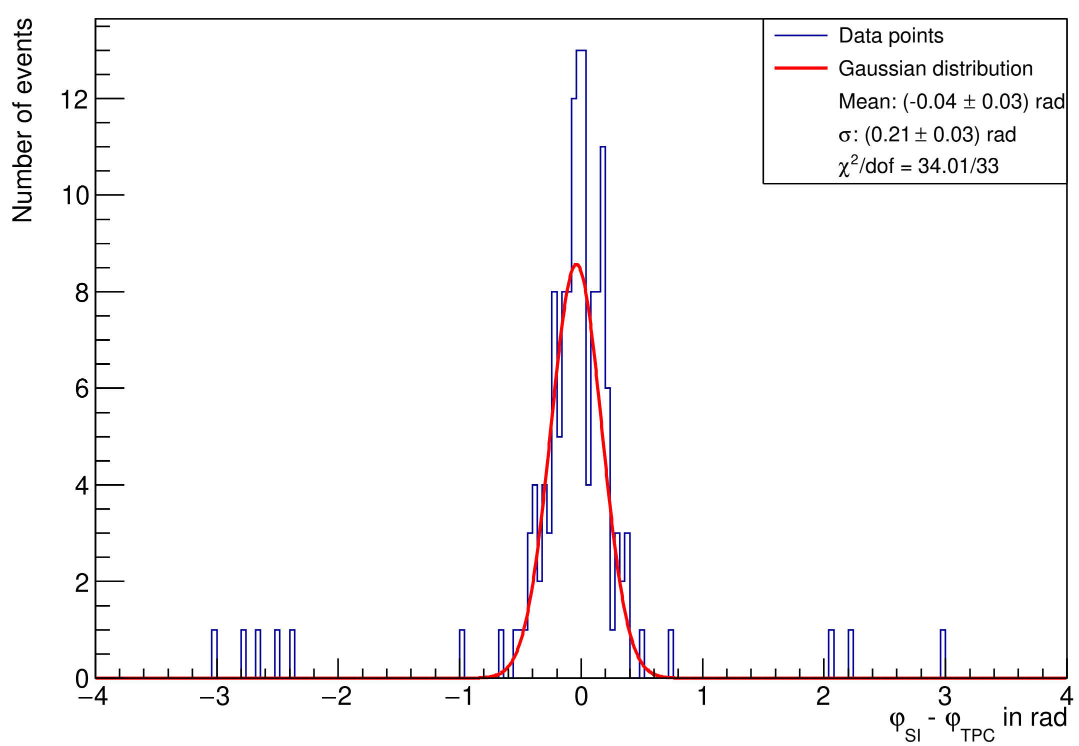
Results of the Beam Test in 2018

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





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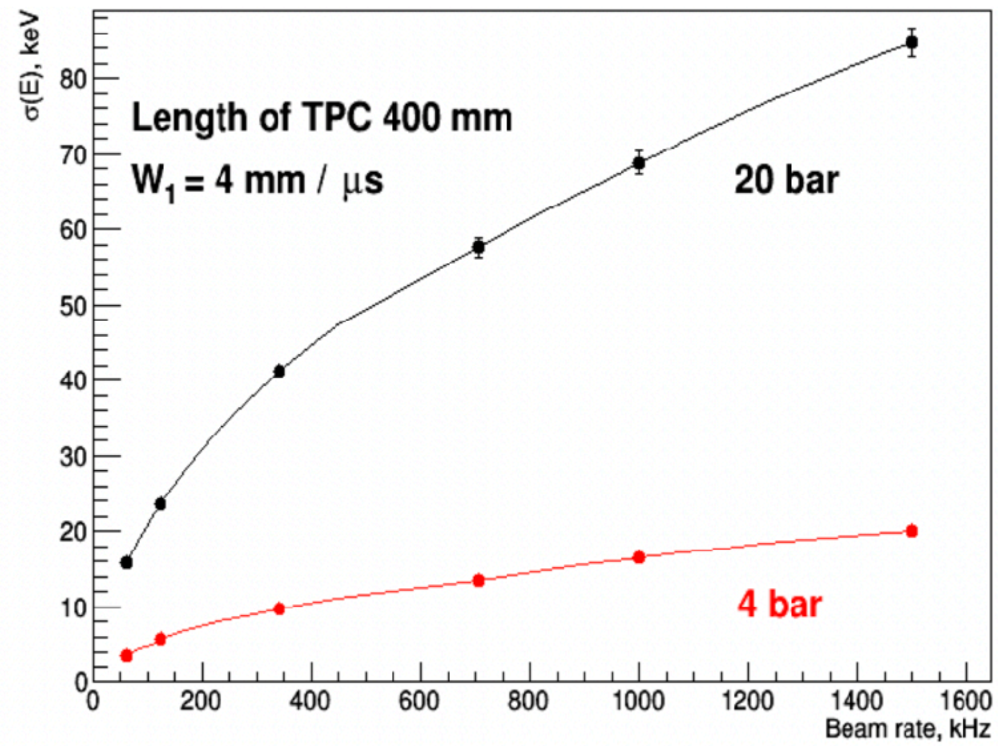

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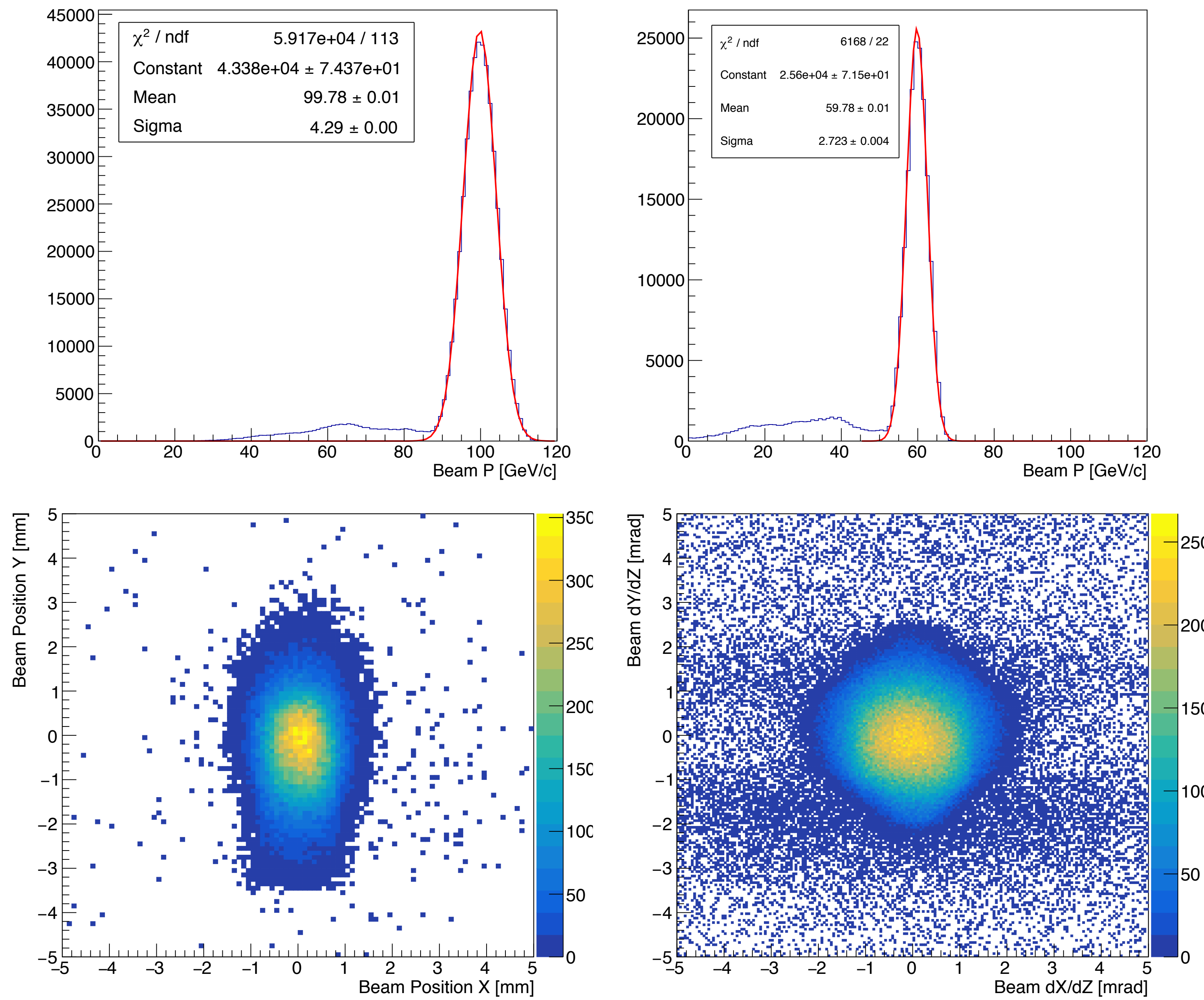
Beam Properties

Intensity and size of muon beam

Beam properties are defined by 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
- Narrow beam at target position
  → $\sigma_{x,y} < 1$ cm
- Small dispersion along target region
  → $\sigma_{dx/dz,dy/dz} < 0.5$ mrad



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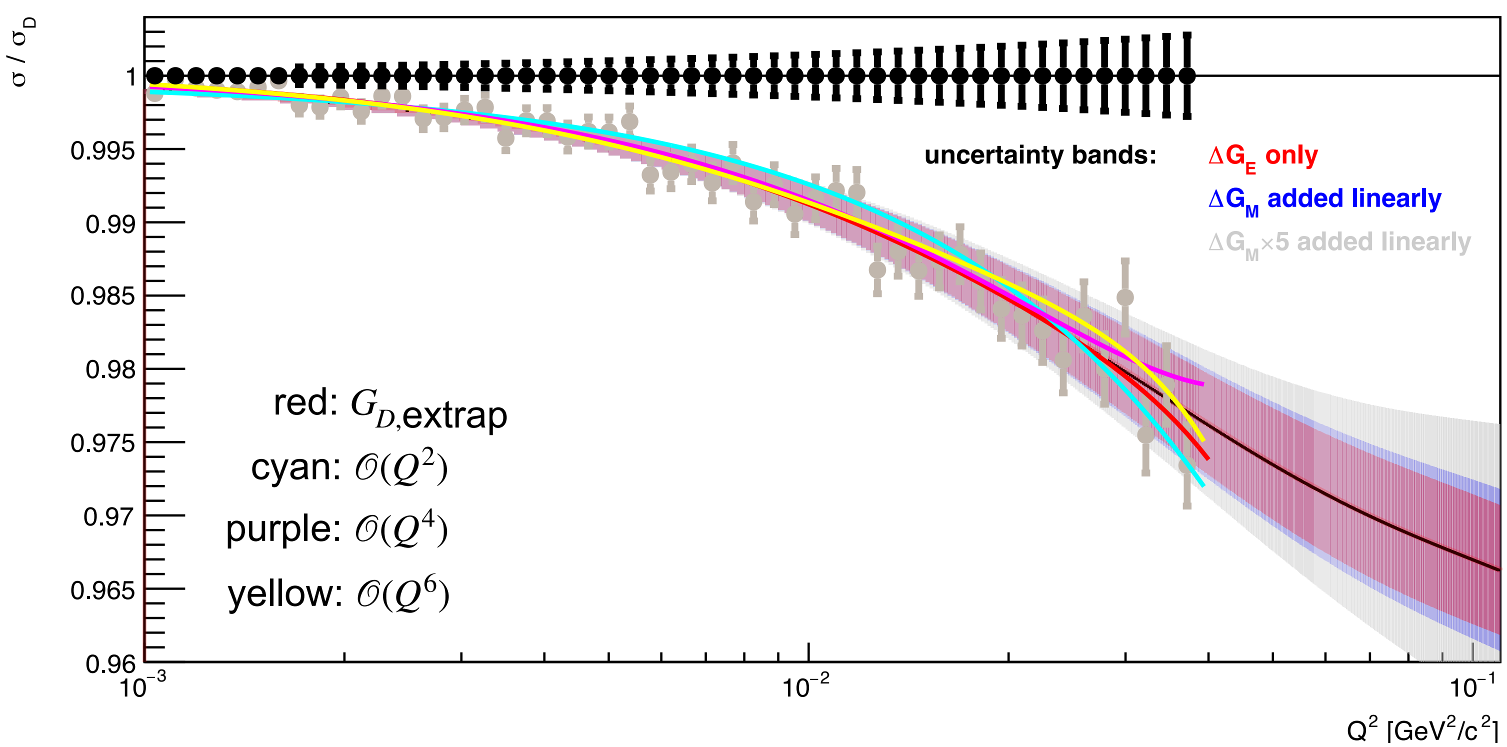
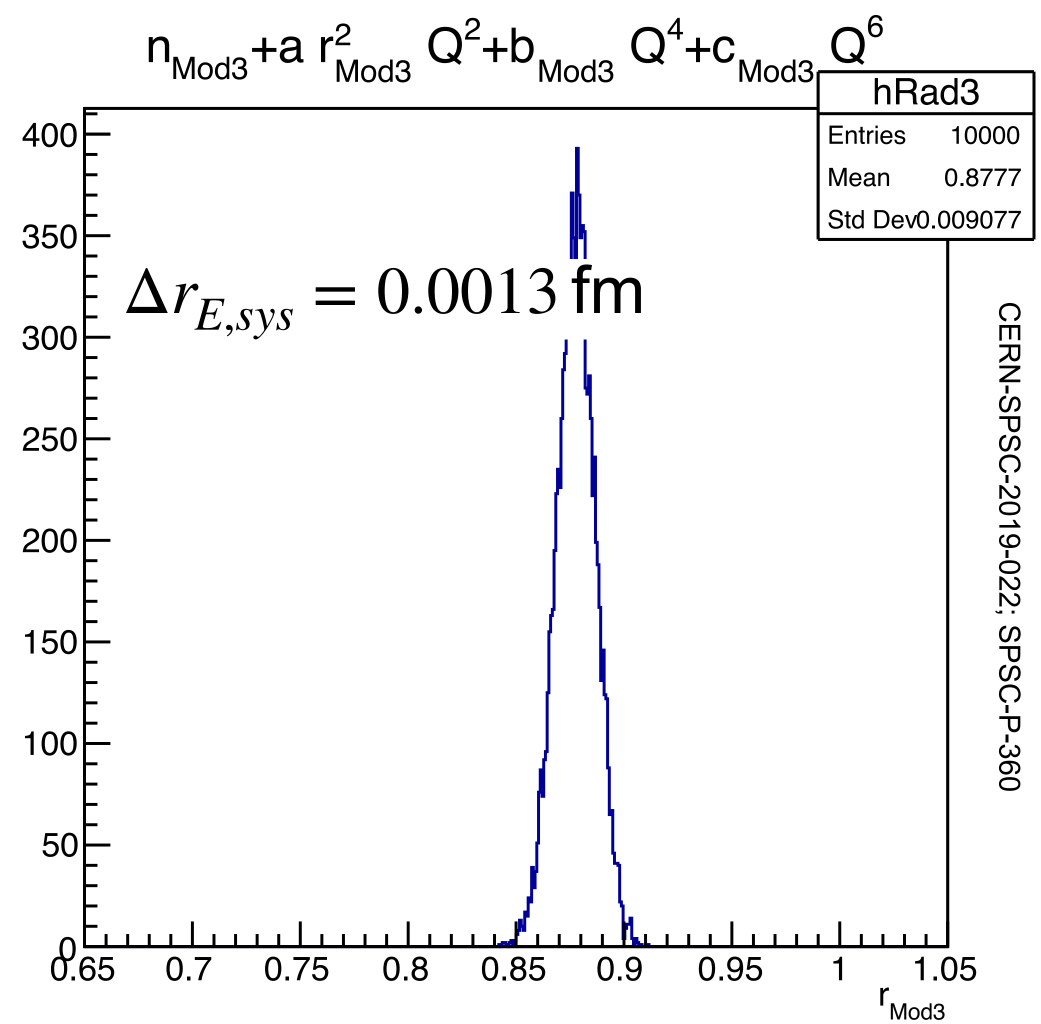
Test of Statistical Precision and Beam Time

Example using a model

MAMI A1 data as input and replicas in bins fitted with polynomials up to $\mathcal{O}(Q^{2n})$.





- Polynomial fit with $\mathcal{O}(Q^6)$ and four free parameters:
  → statistical precision 0.0090 fm
- 70 million events required for statistical precision of 1 %
  → about 140 days of data taking depending on final geometry

Summary

- Discrepancy between scattering and spectroscopy experiments - Proton Radius Puzzle
- 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 depending on final geometry
- New development ongoing - TPC, silicon detectors, fiber triggers and DAQ *(Talk by I. Konorov)*
- 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)

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
- Comparison of this measurement with other upcoming measurements like MUSE at PSI
- Further development and studies of prototypes for silicon detector and fiber trigger
- 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)

Thank you for your attention

Further information

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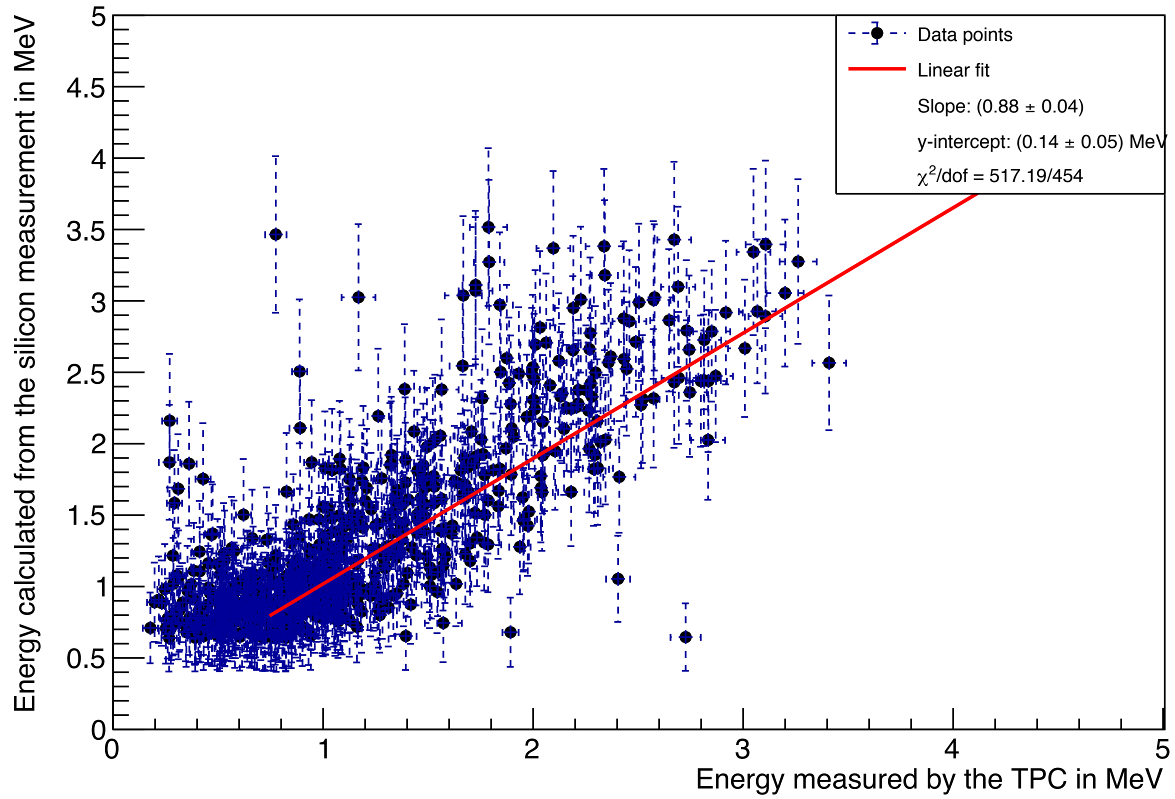
Results of the Beam Test in 2018

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

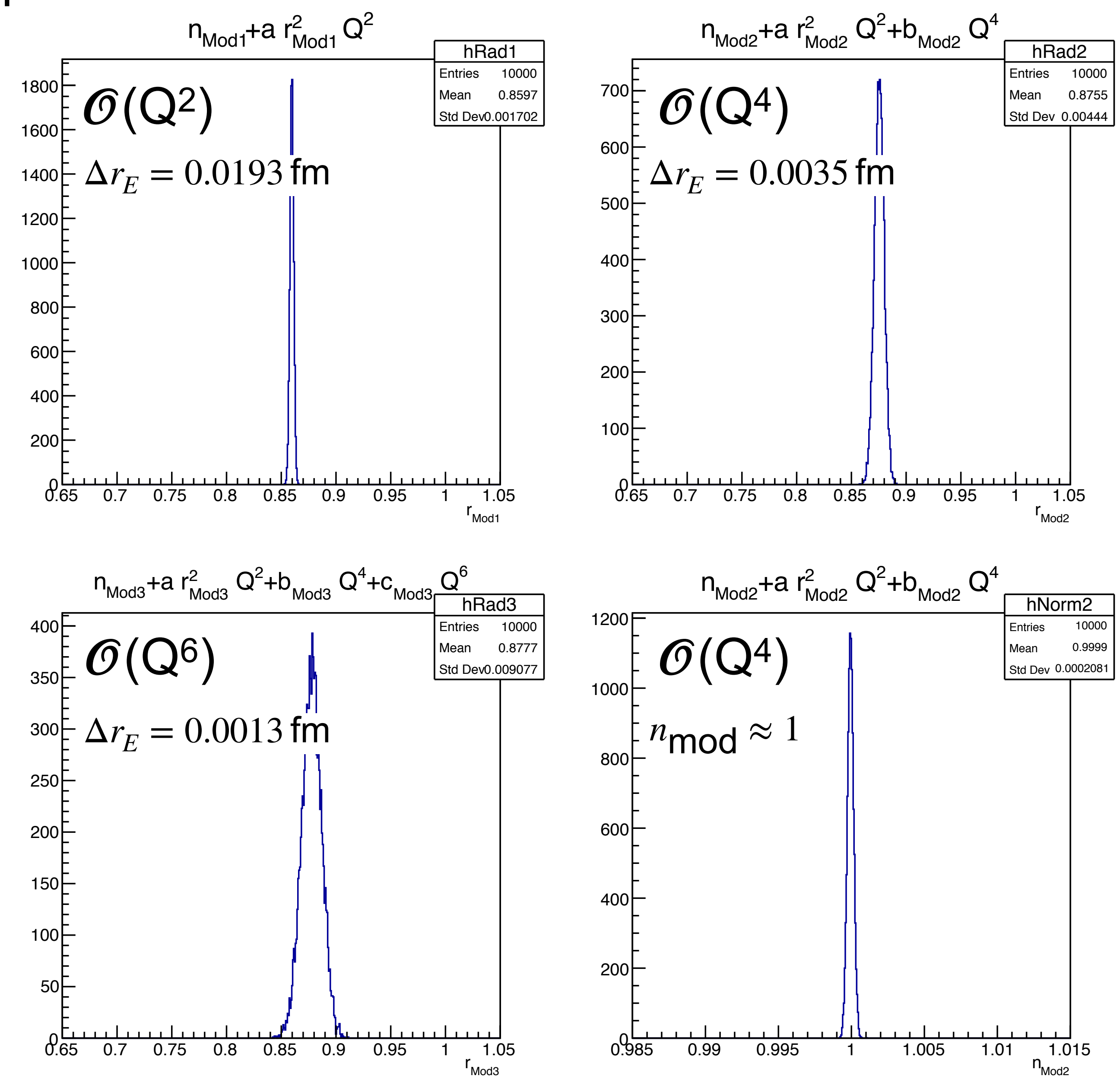
Different models for the radius extraction

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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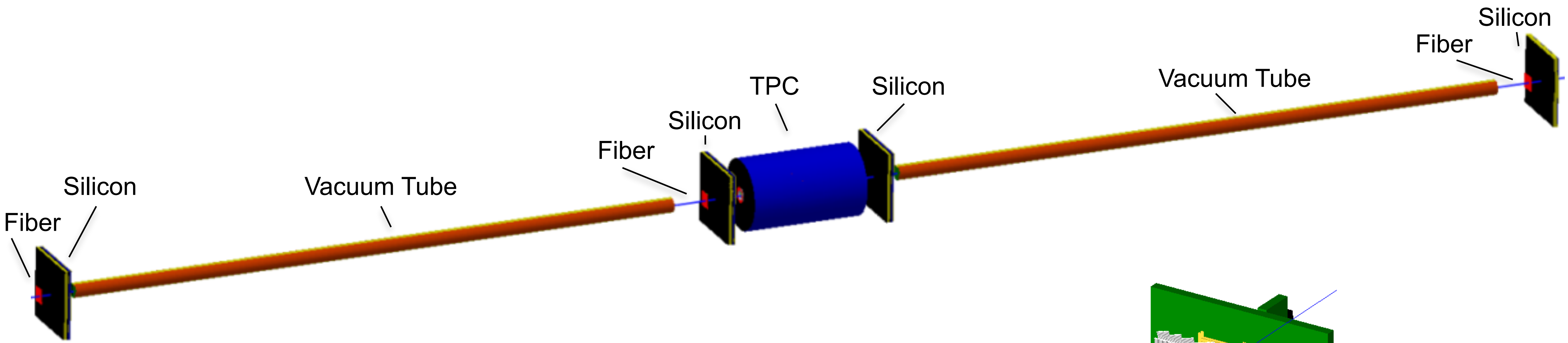
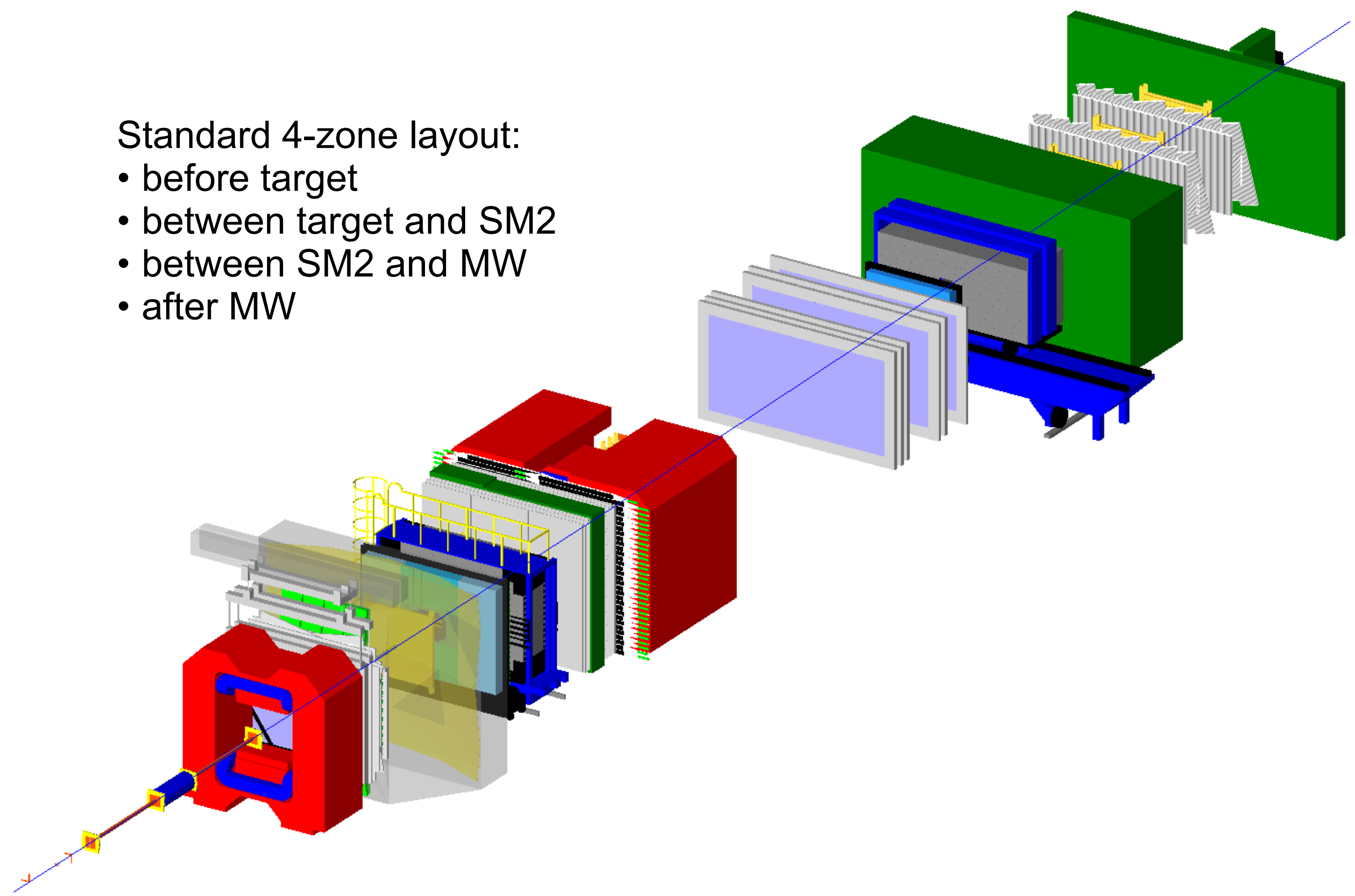
Layout of the Setup



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



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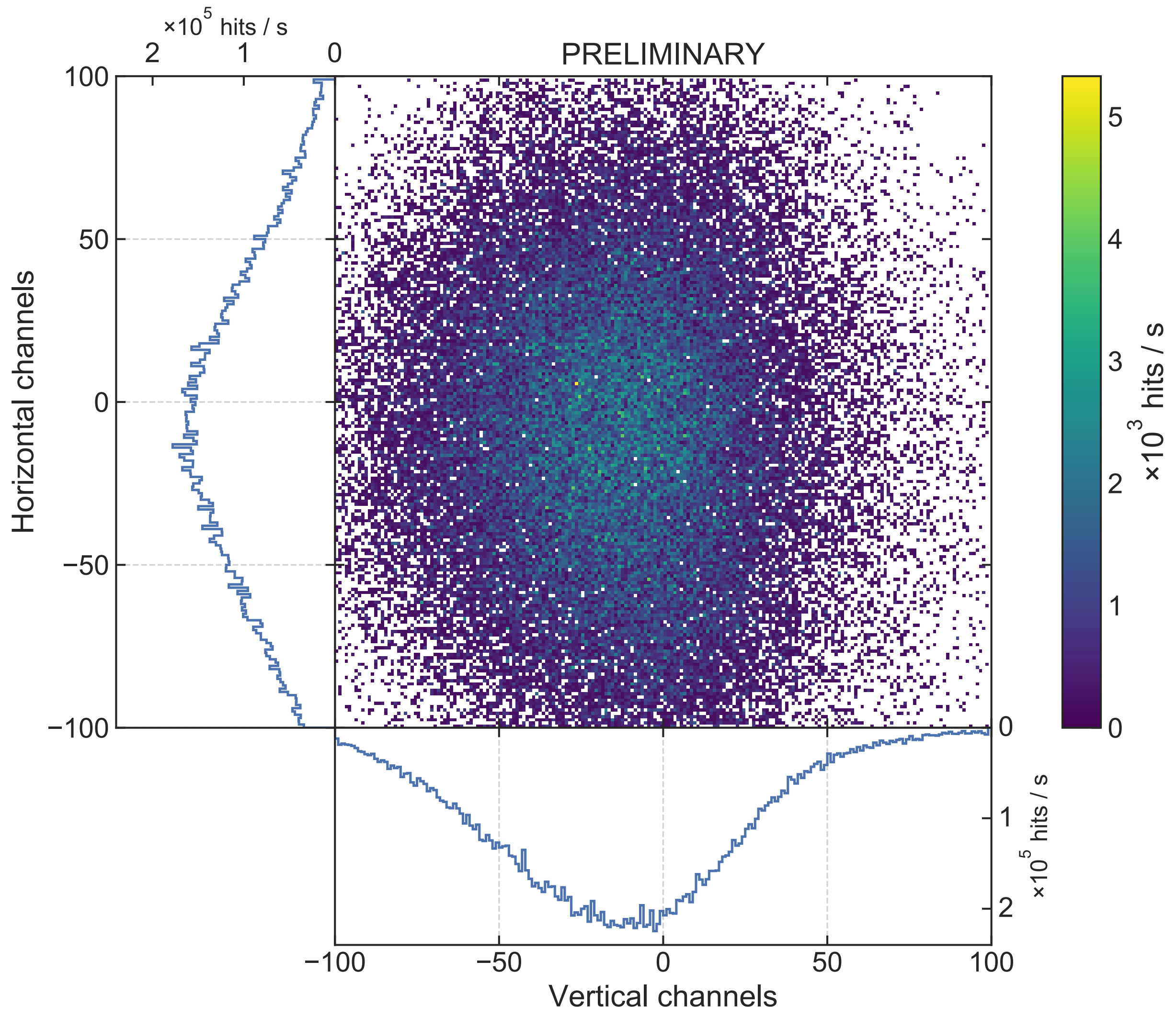
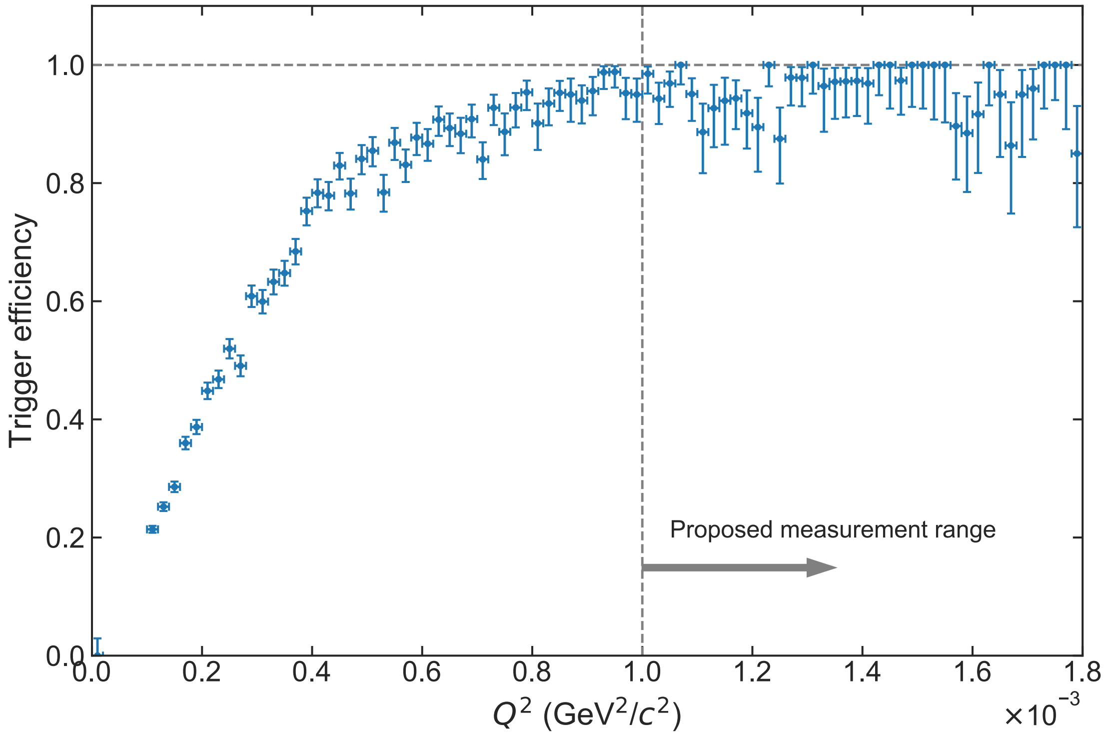
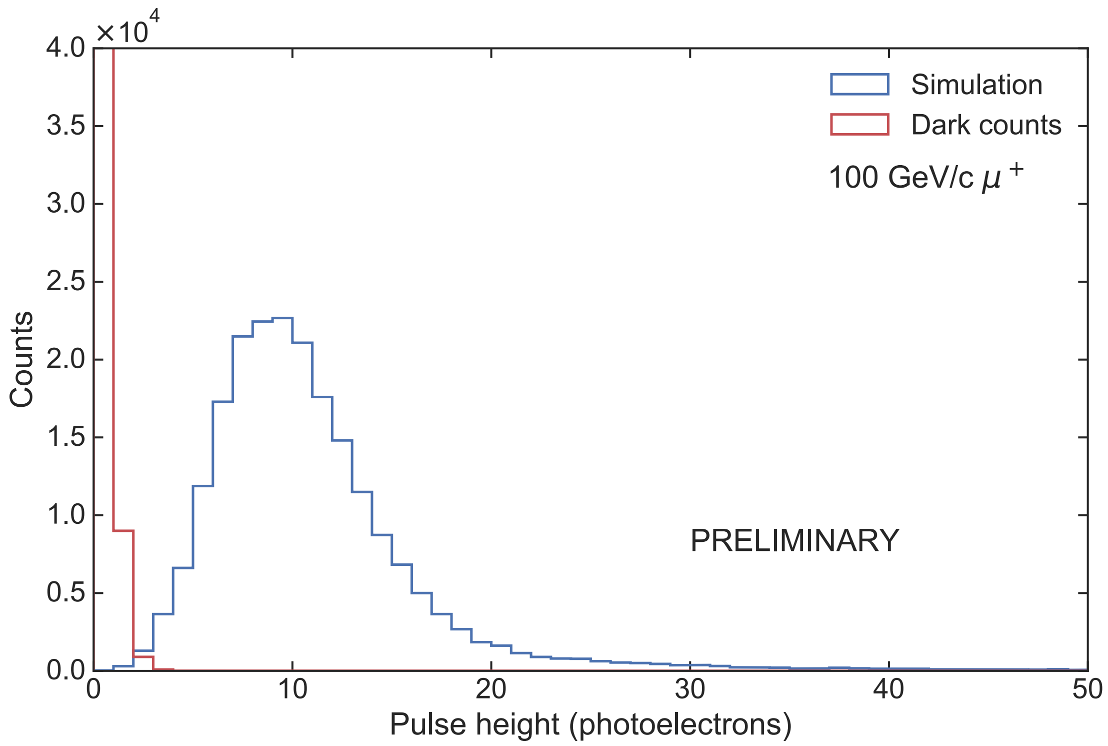
Fiber Trigger Efficiency







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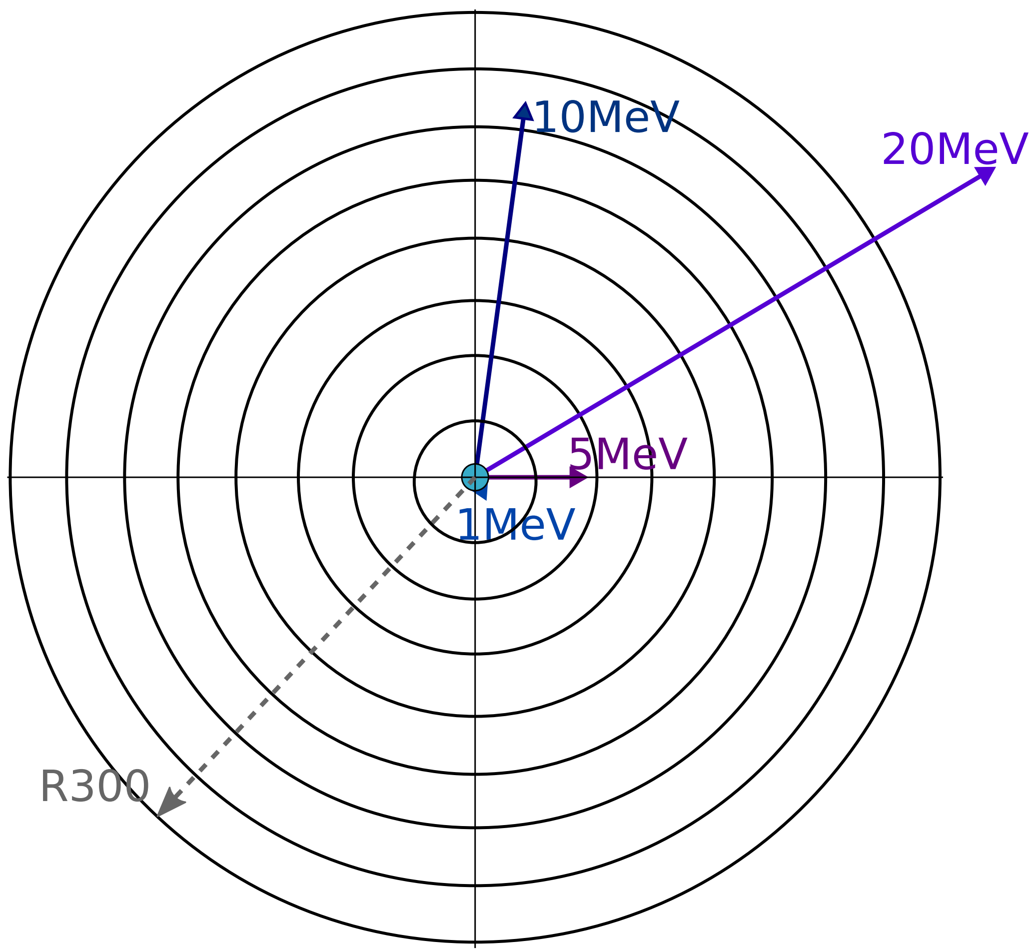
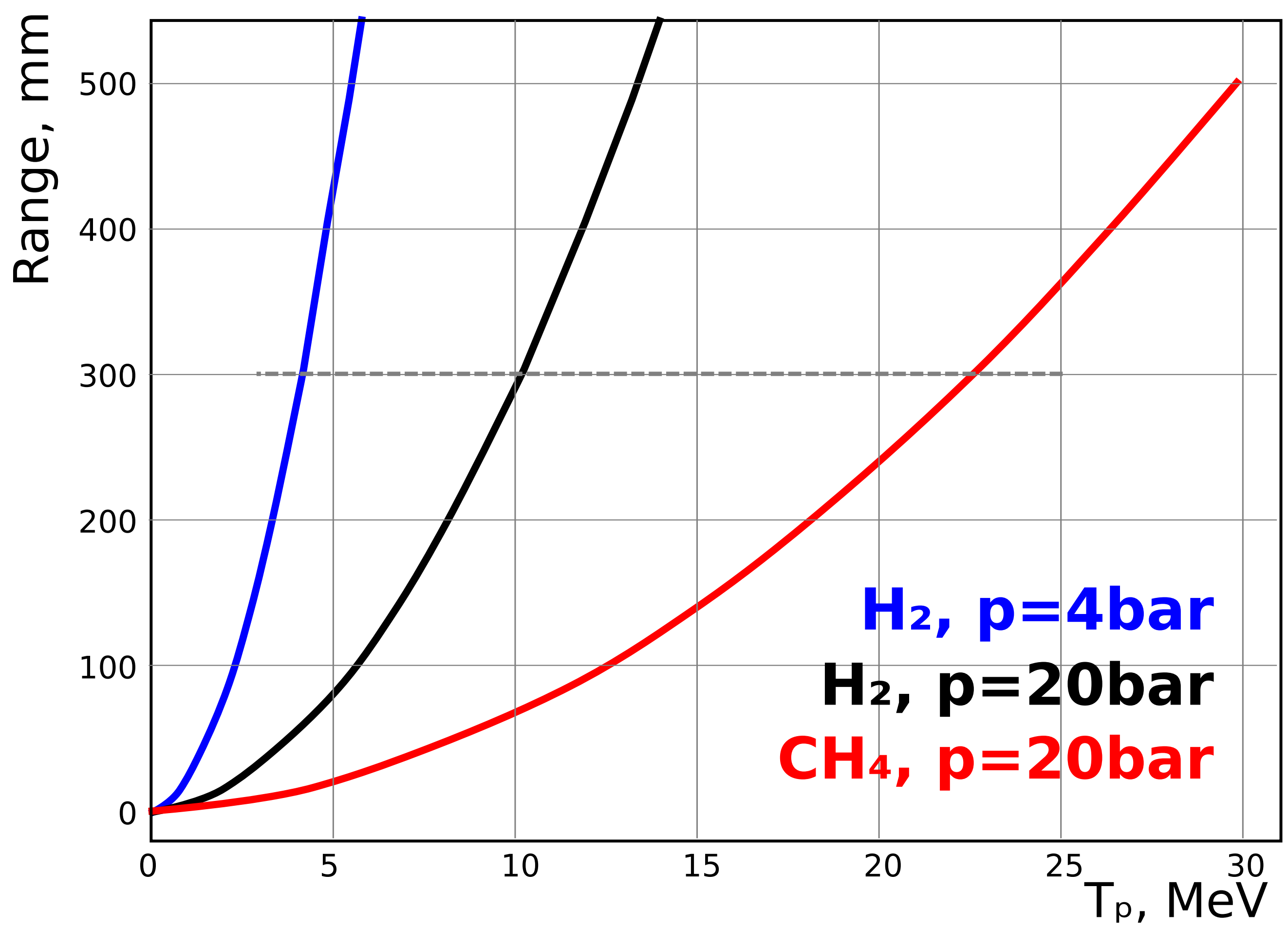
TPC Proton Ranges





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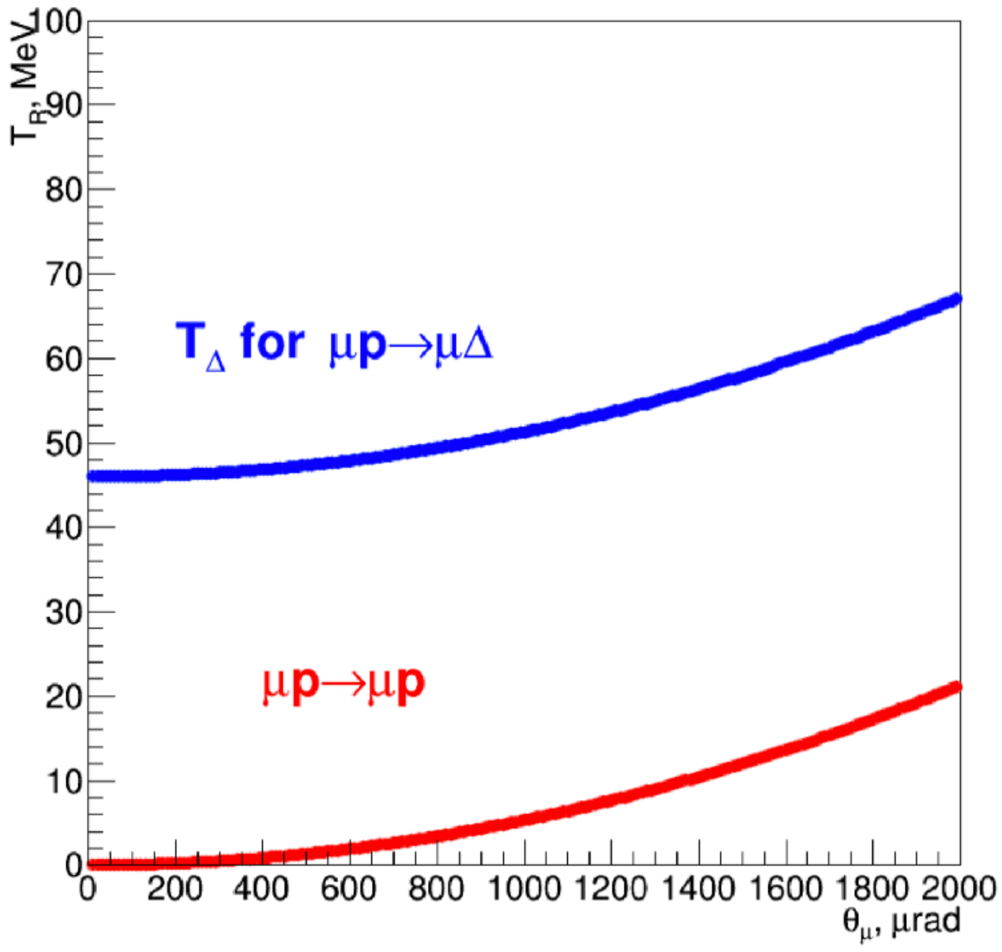
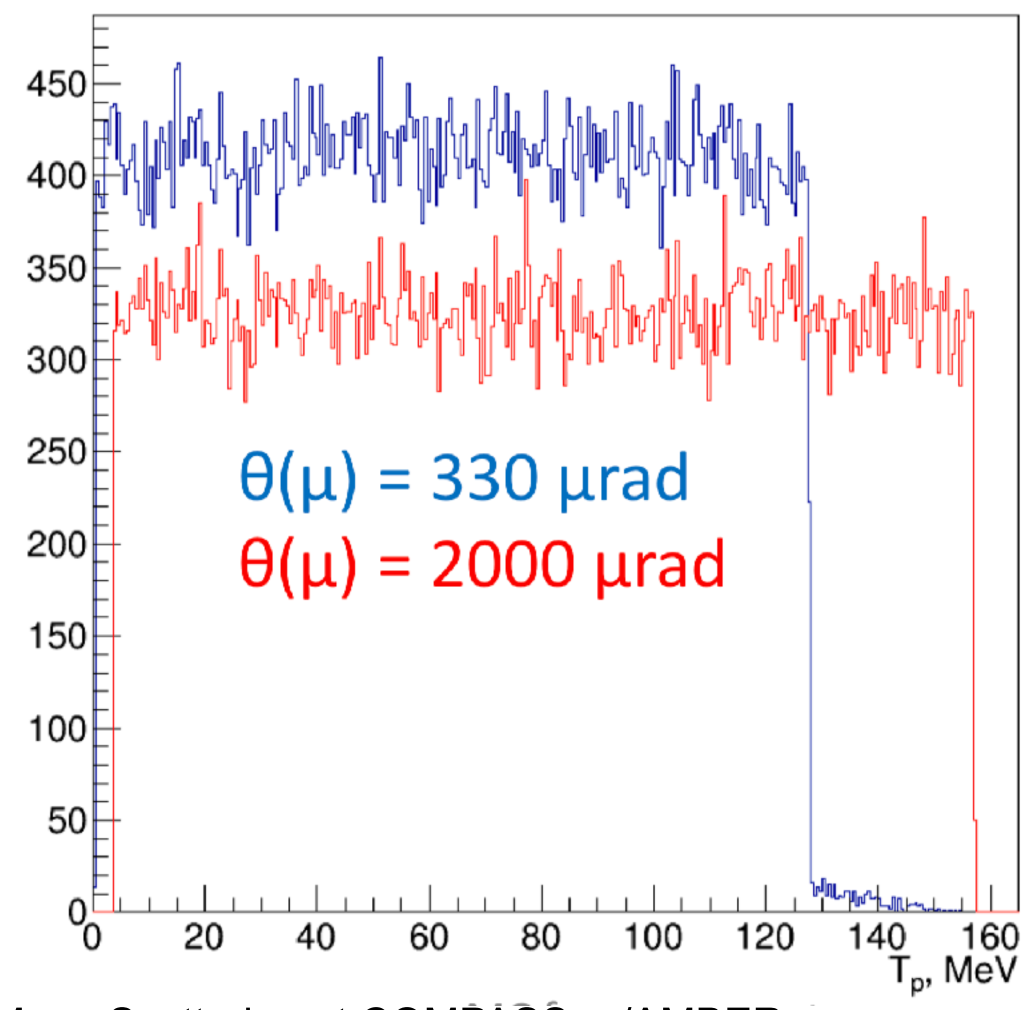
Inelastic Background

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





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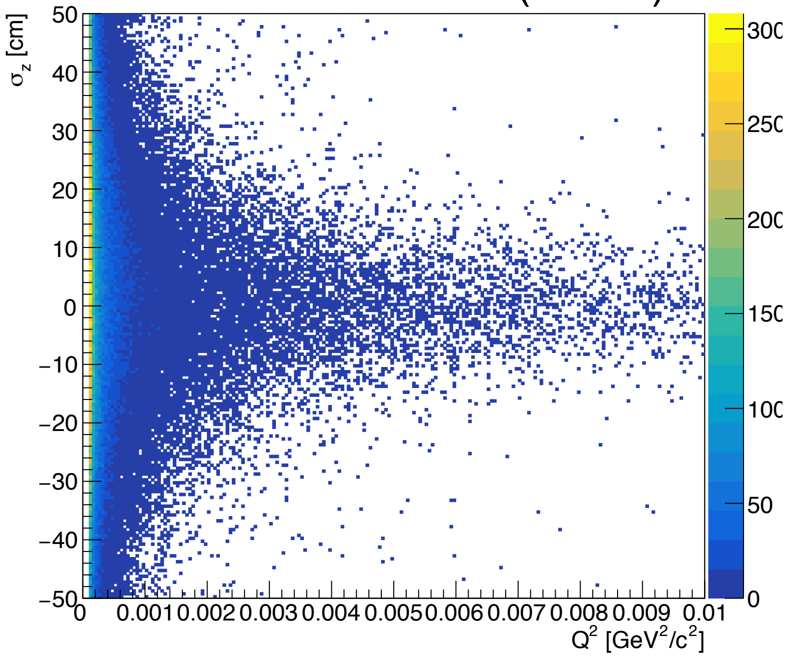
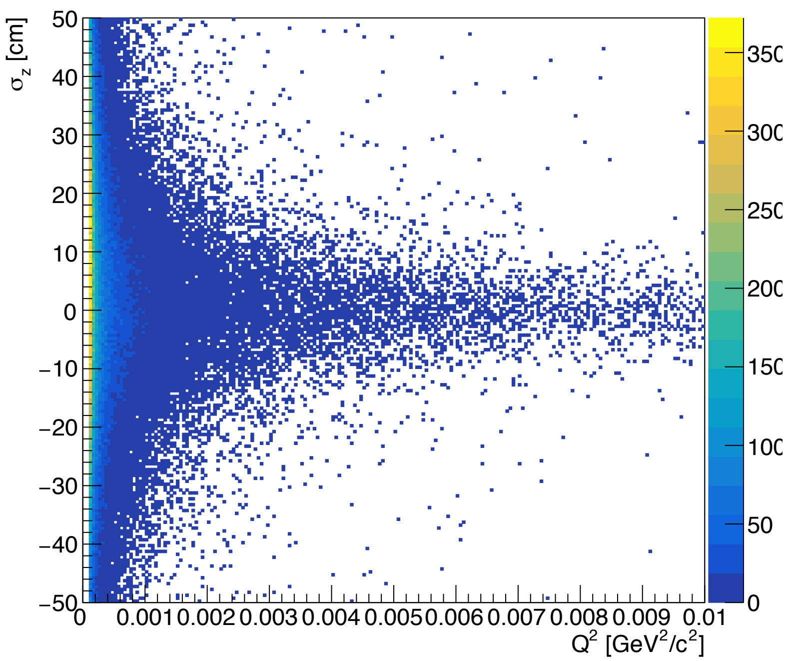
Studies on Geometries

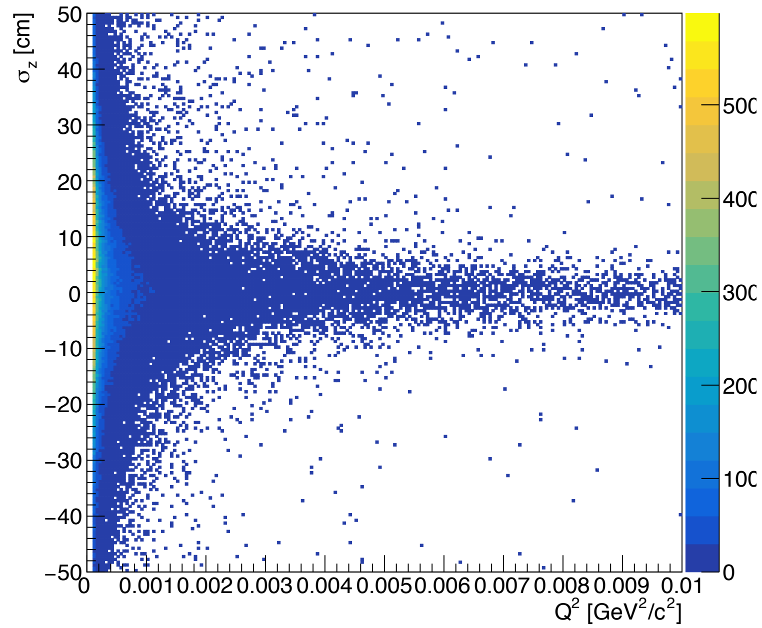
0.8m - 2.1m - 0.3m (PRTM)

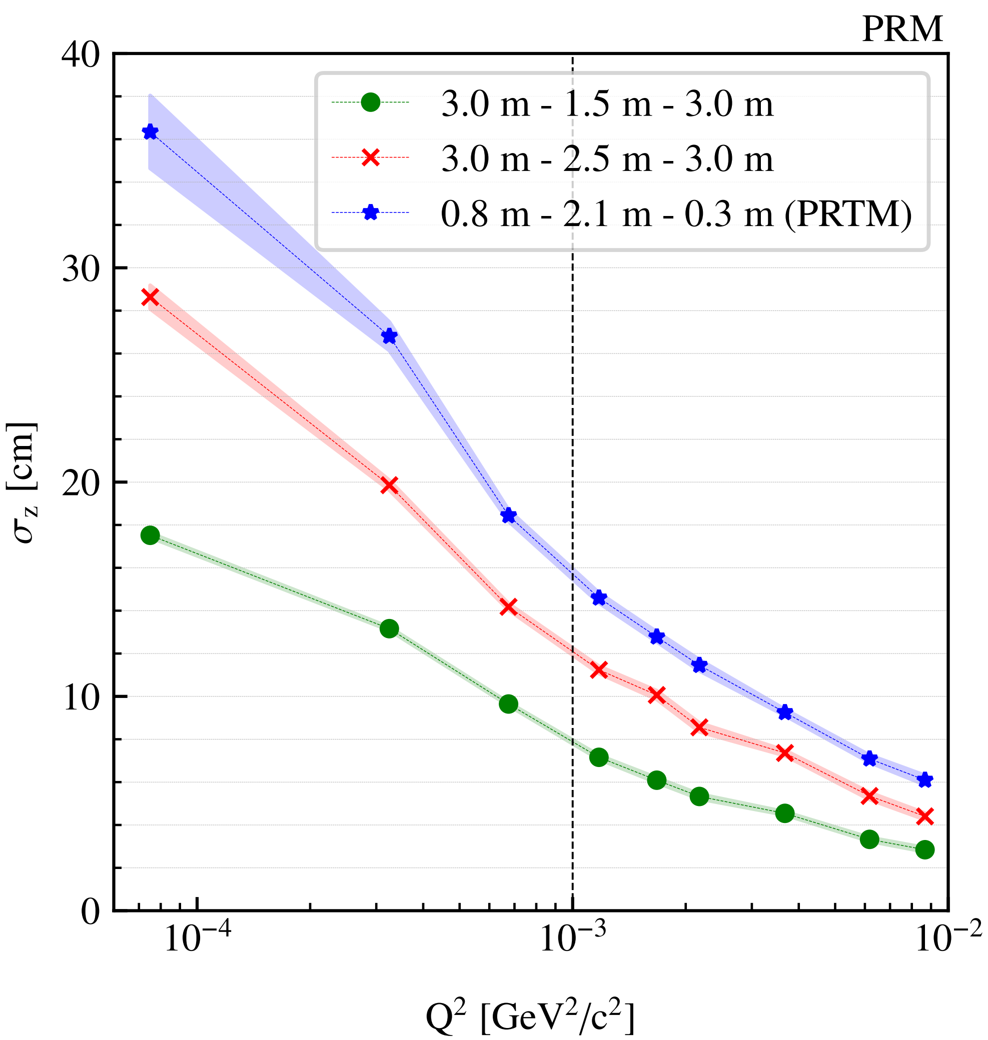


3.0m - 2.5m - 3.0m



3.0m - 1.5m -3.0m





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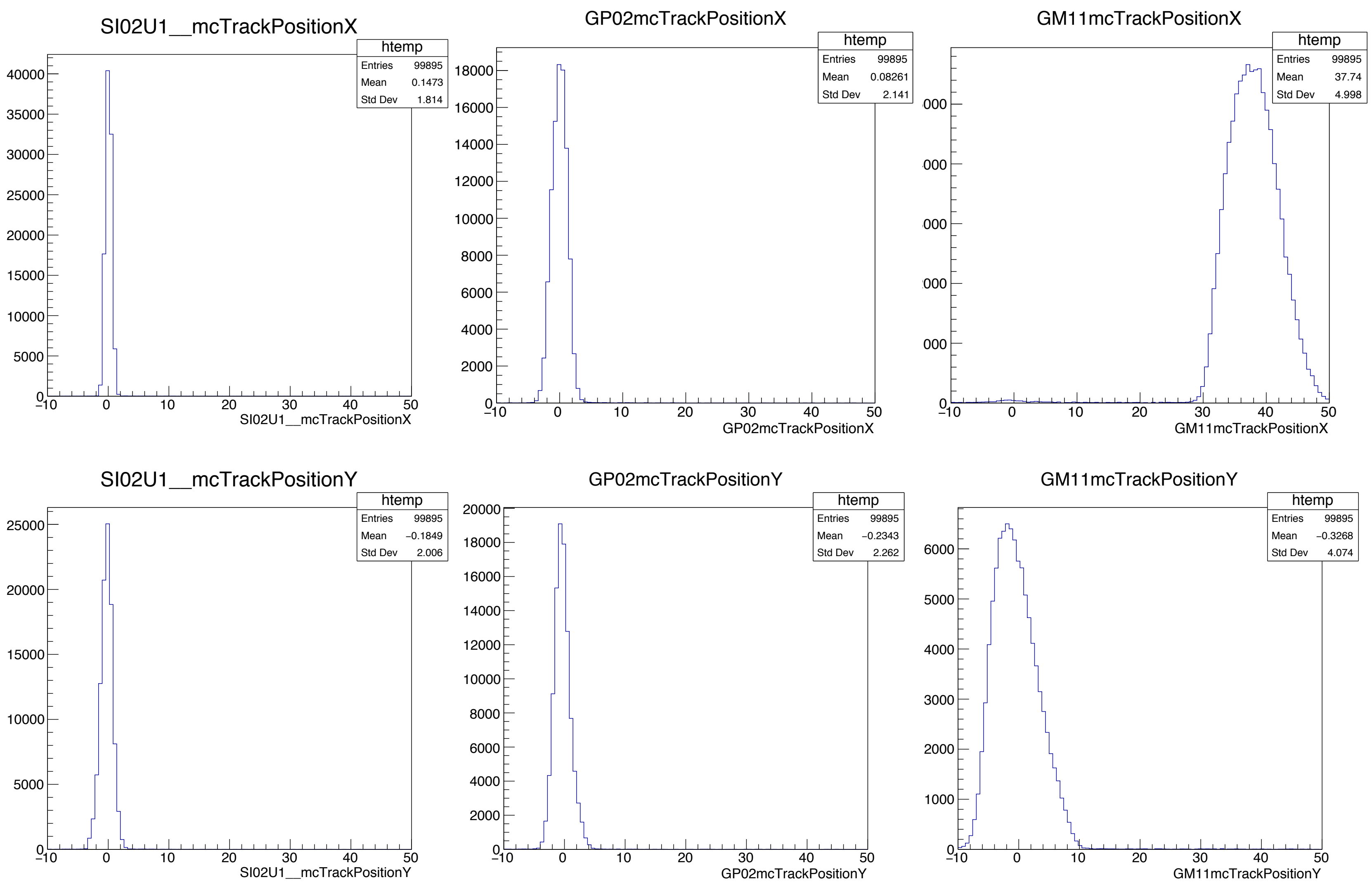
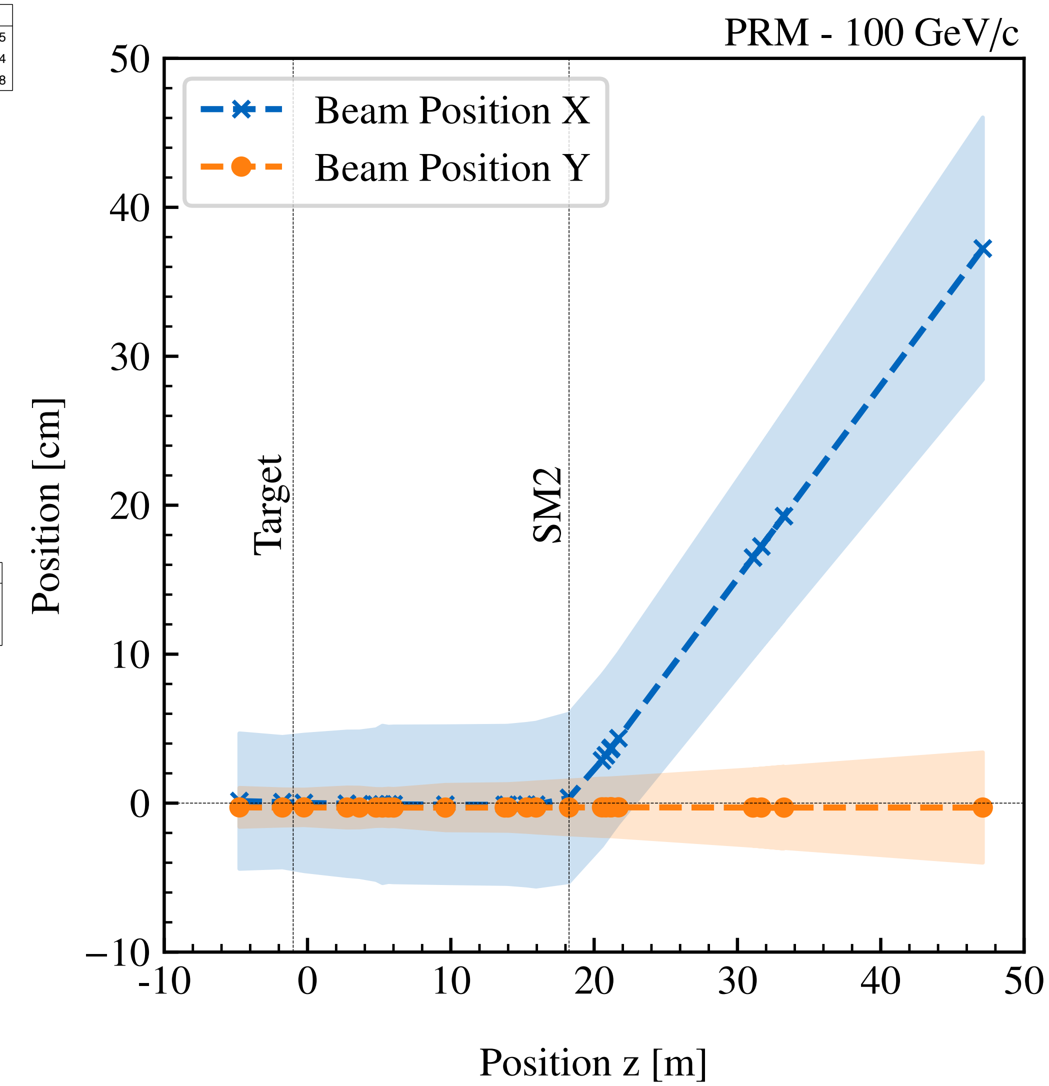
Studies on Beam Properties





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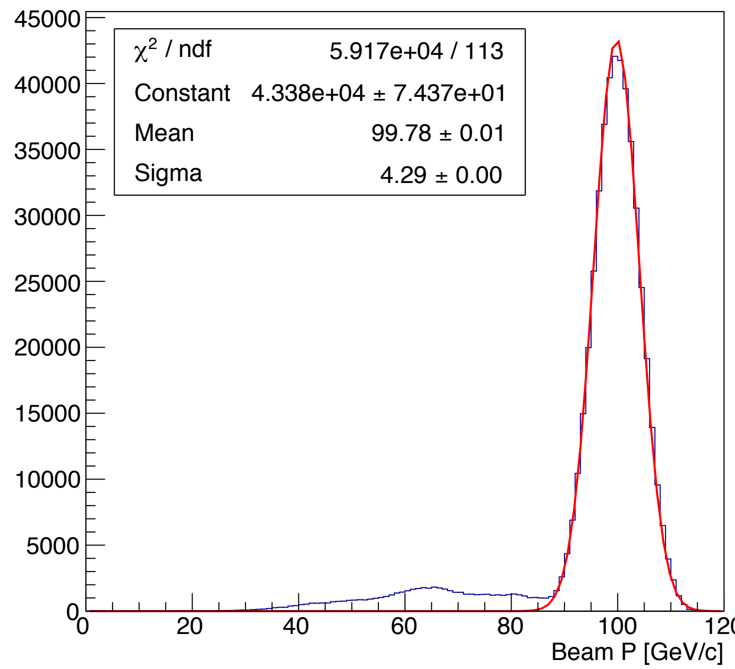
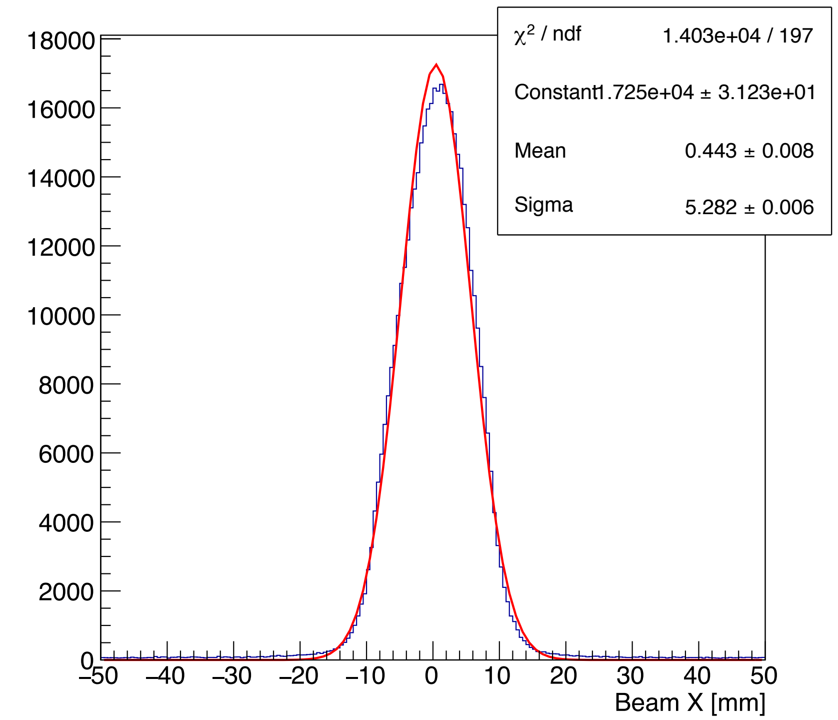
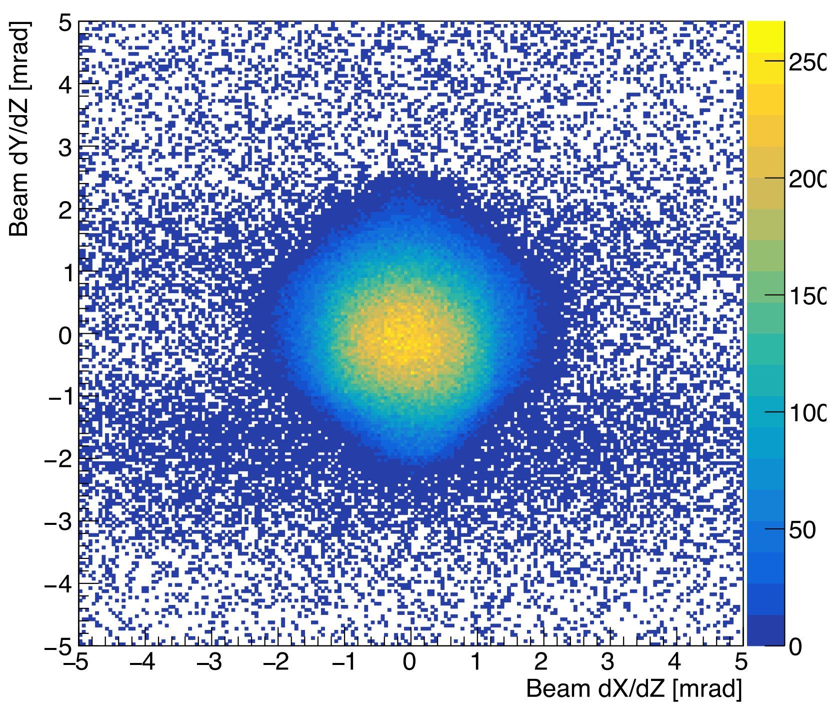
Beam Properties (100 GeV/c)

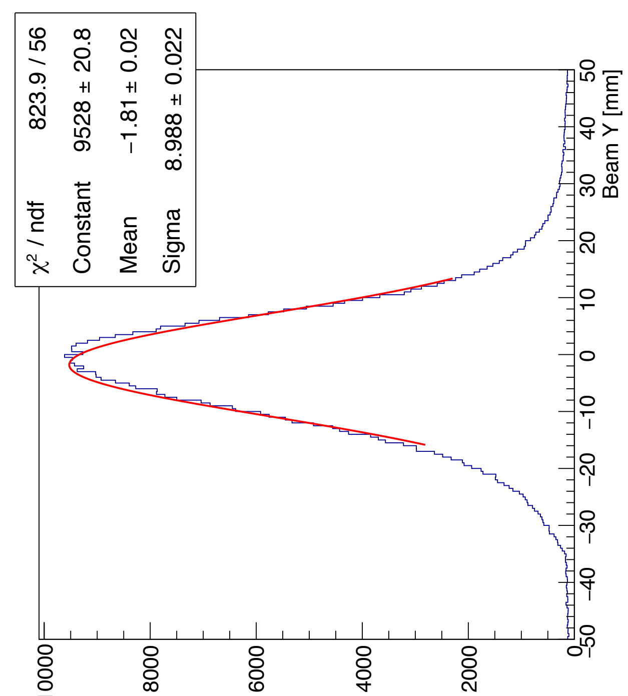


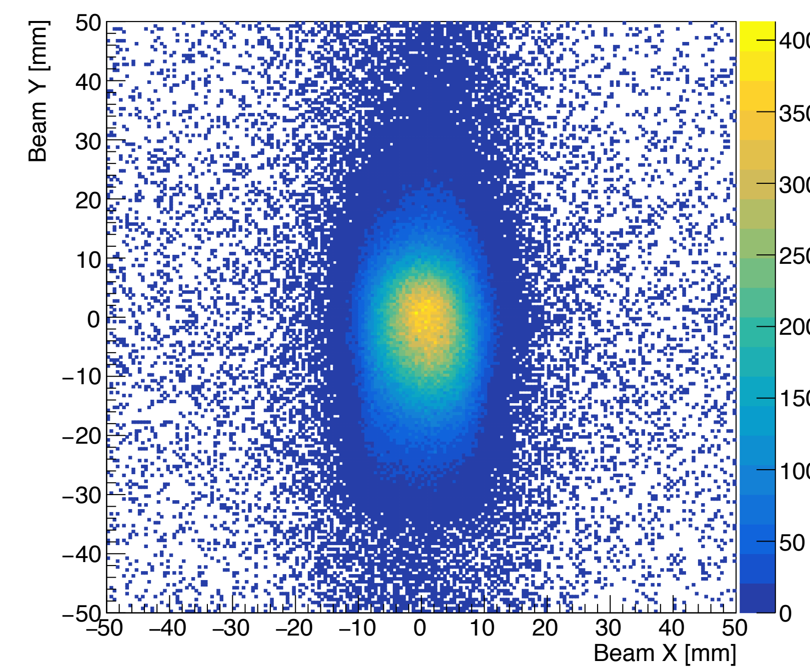
Beam file available:

- Focused at z = -1000 mm
- Mostly parallel over 8 meters
- Contains tagged halo component









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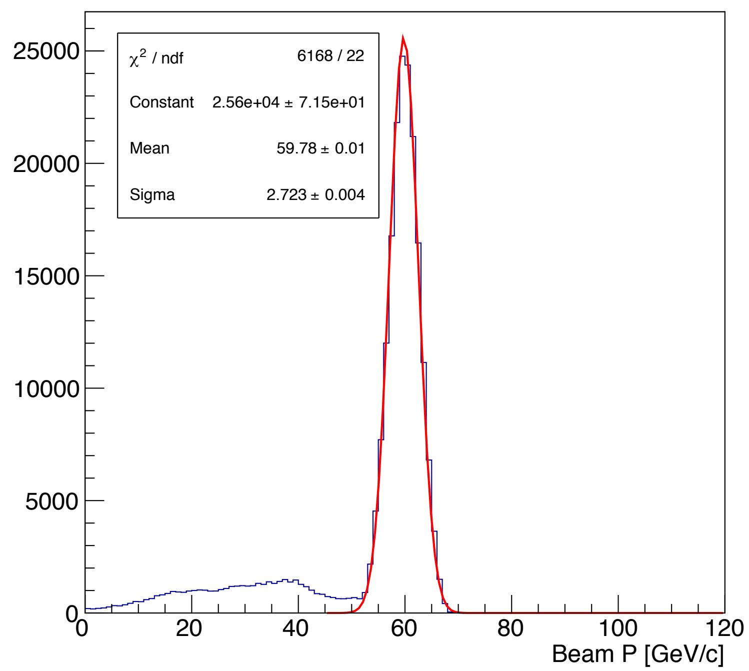
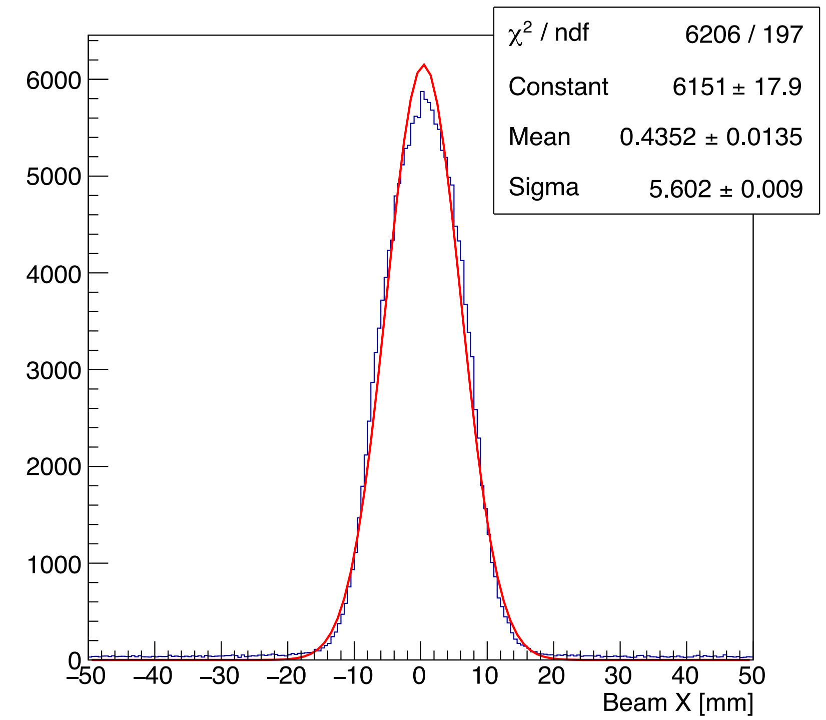
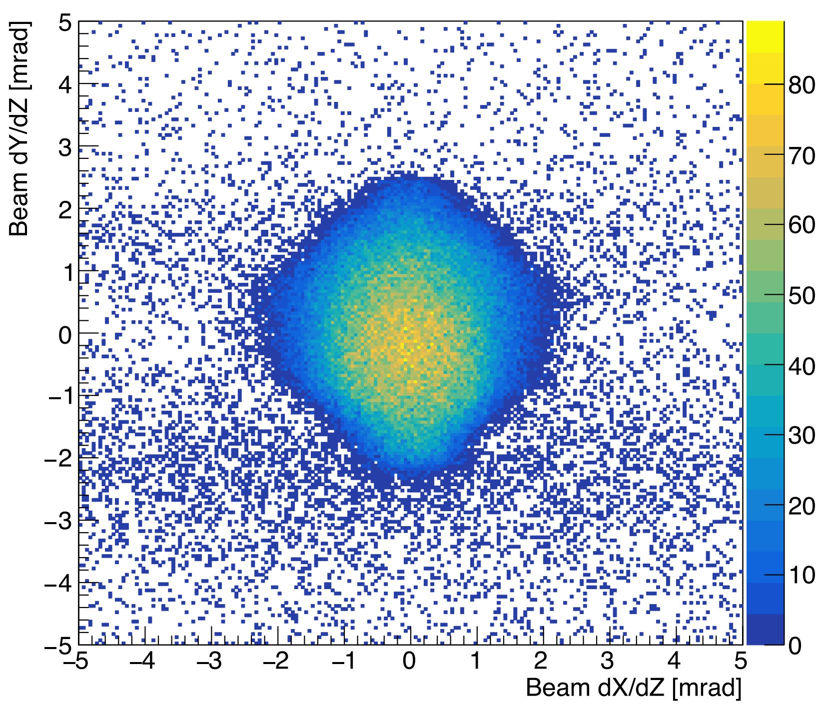
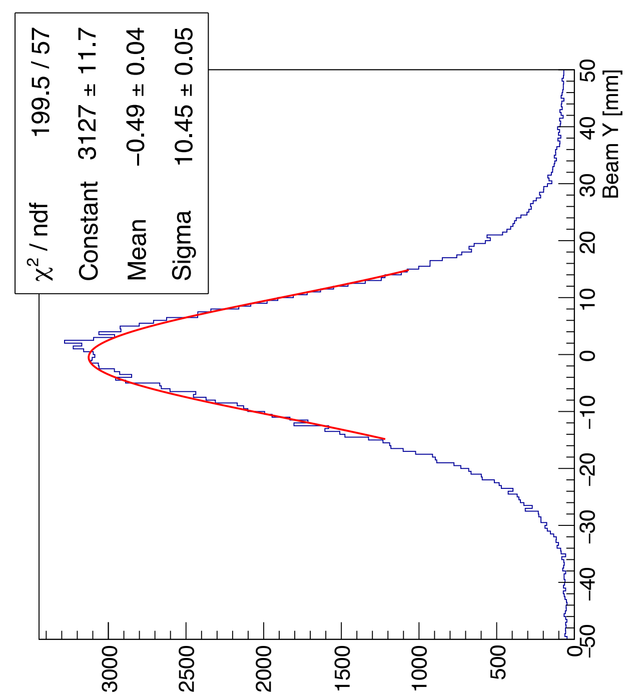
Beam Properties (60 GeV/c)

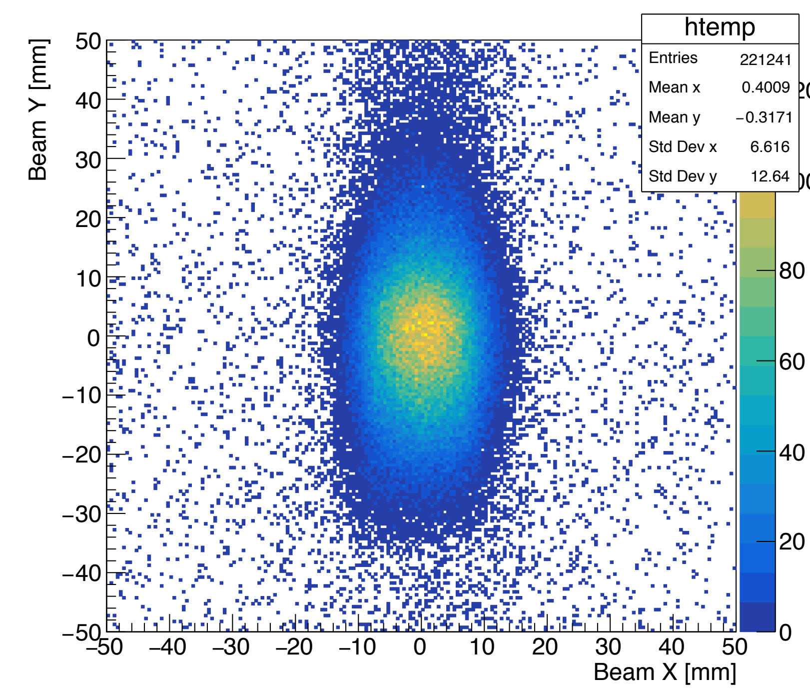


Beam file available:
- Focused at z = -1000 mm
- Mostly parallel over 8 meters
- Contains tagged halo component









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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