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

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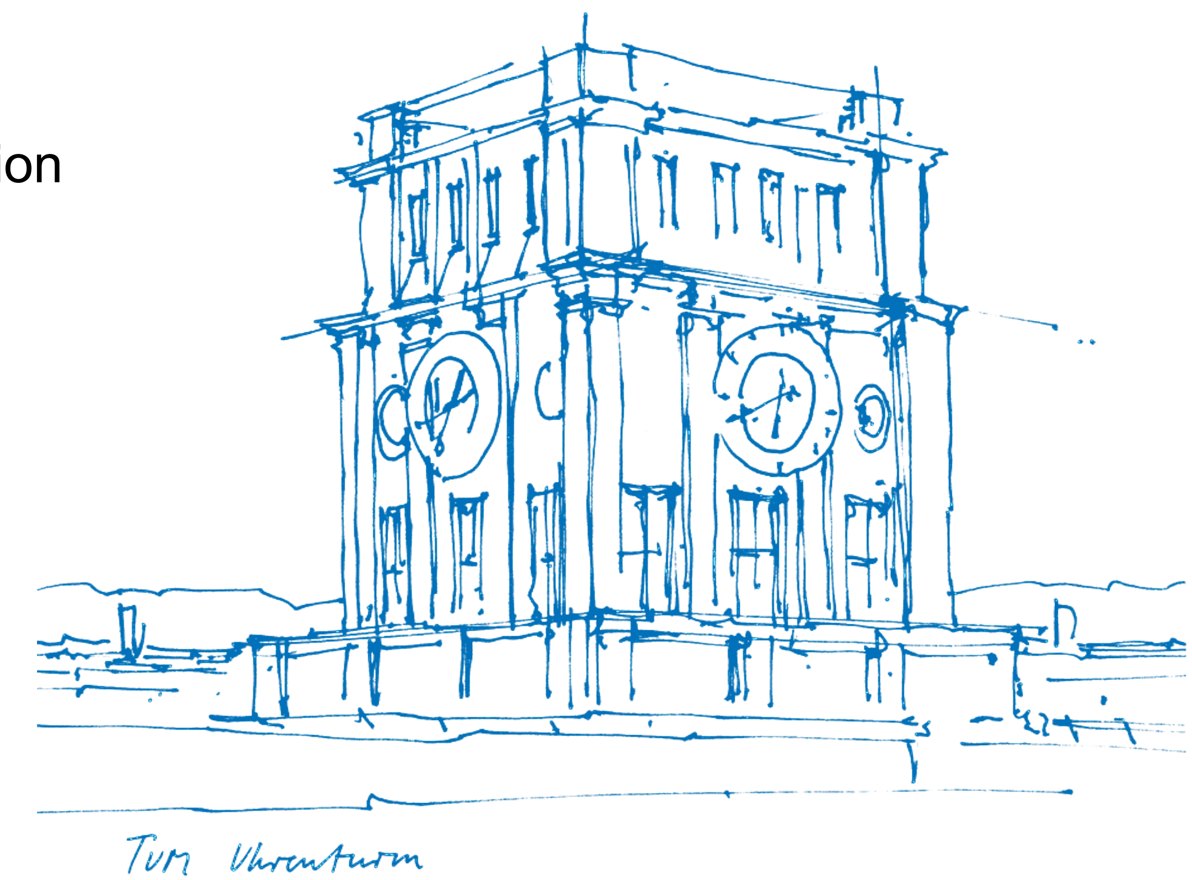
On behalf of the COMPASS++/AMBER Proto-Collaboration



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The Proton-Radius Puzzle

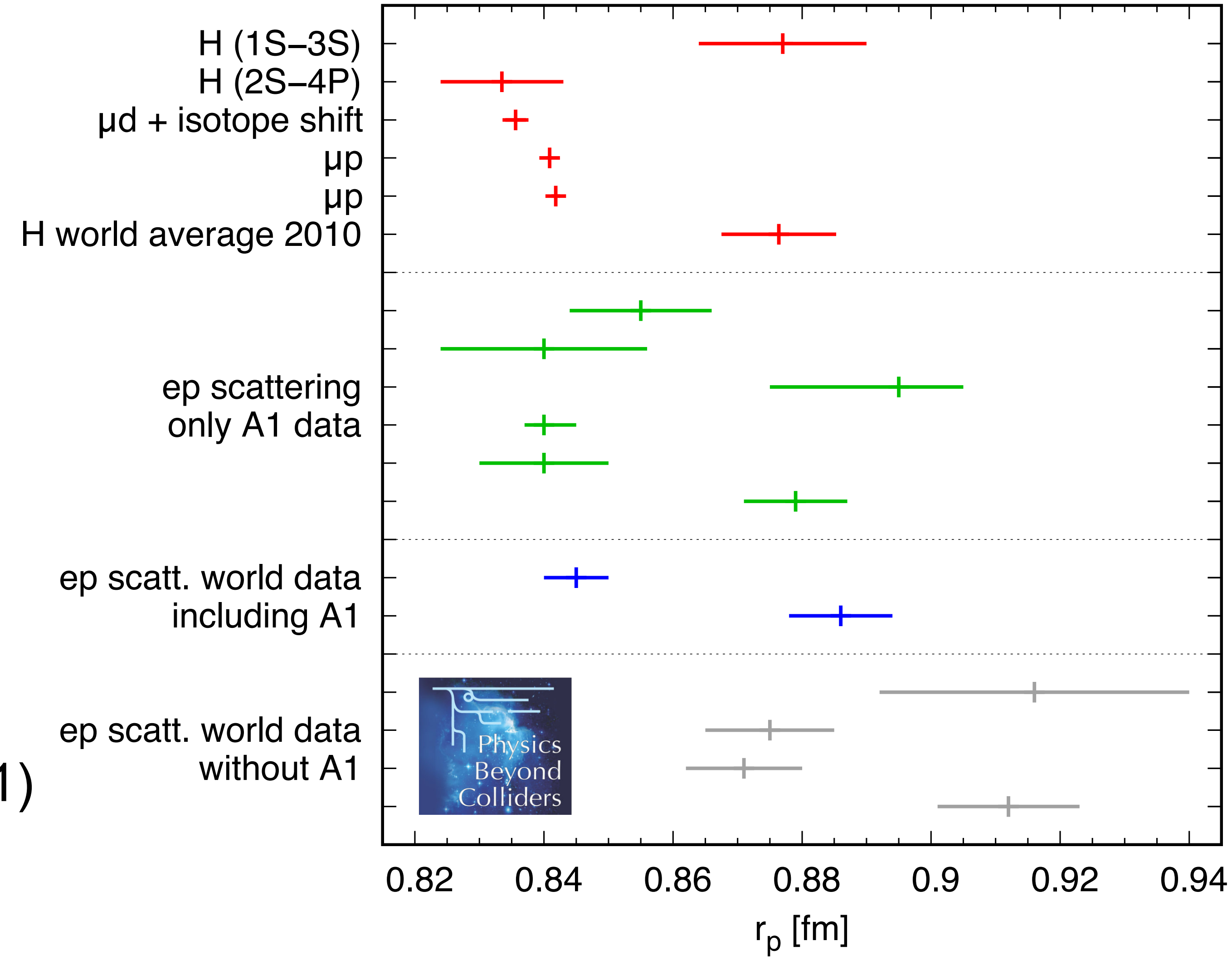
Data from spectroscopy and e-p scattering

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

PRoton Radius

MAINZER MIKROTRON

MAGIX

MESA
Mainz
Energy-recovering
Superconducting
Accelerator

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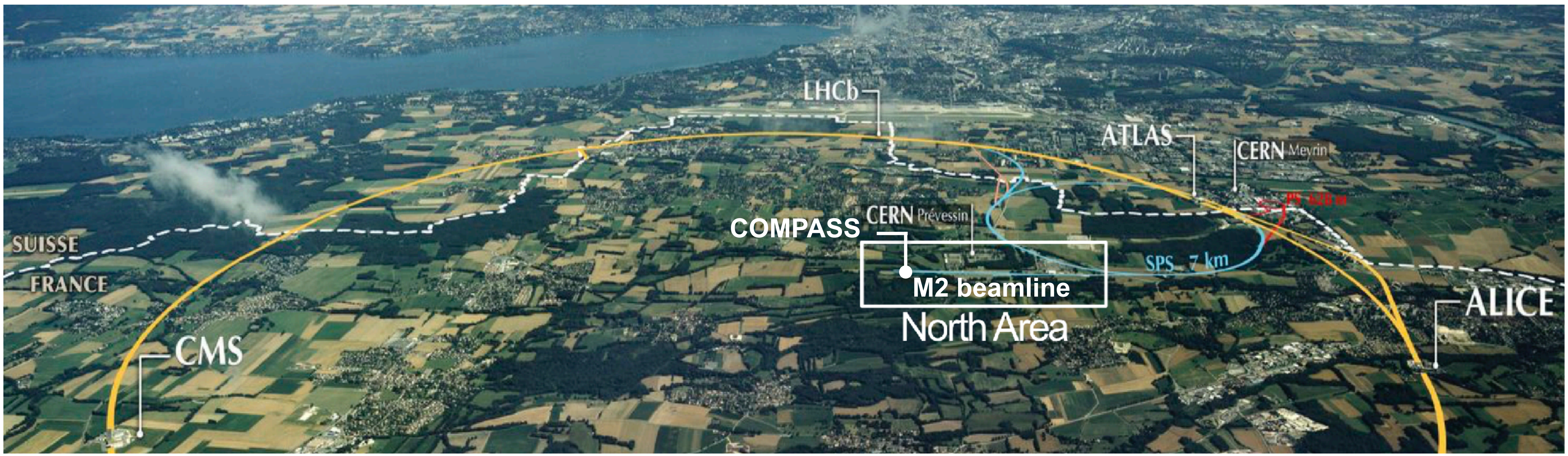
Beamline for High-Energy Muon Beams

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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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 $Q^2 = 0$:

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

- 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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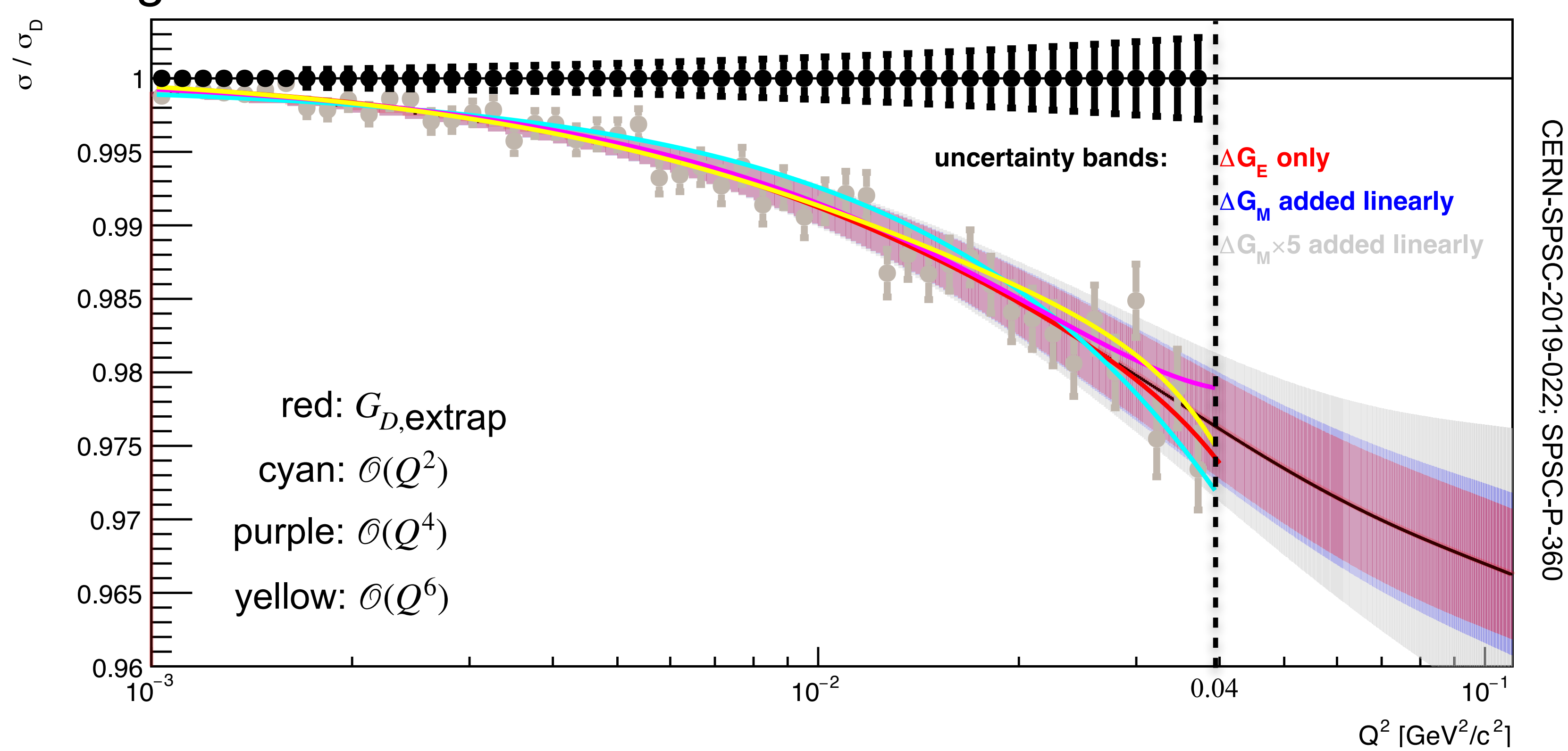
Proposal of a New Measurement

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



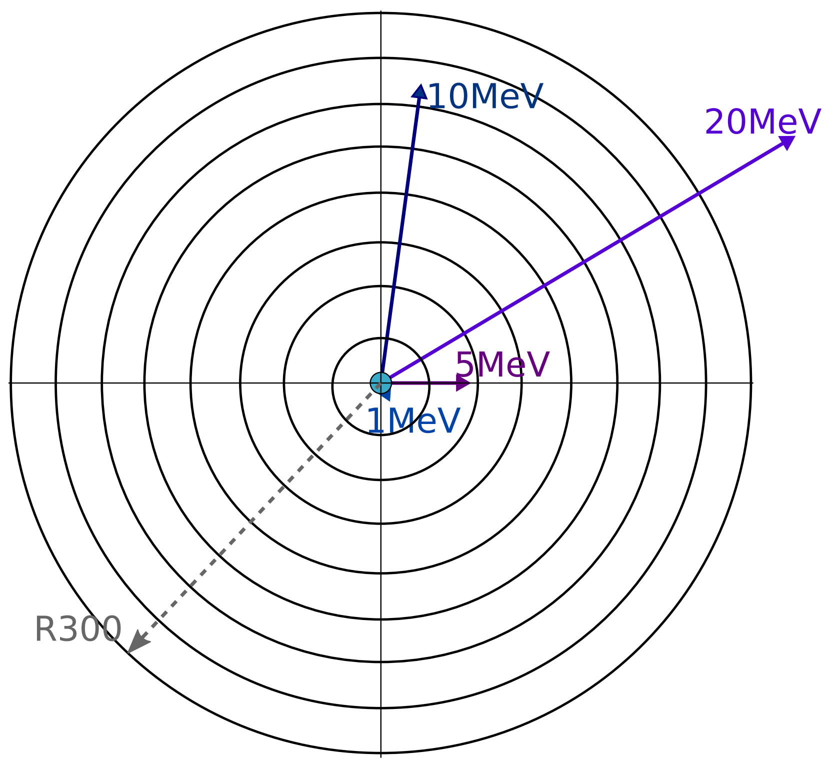
Detection of Low-Q^2 Recoil-Protons

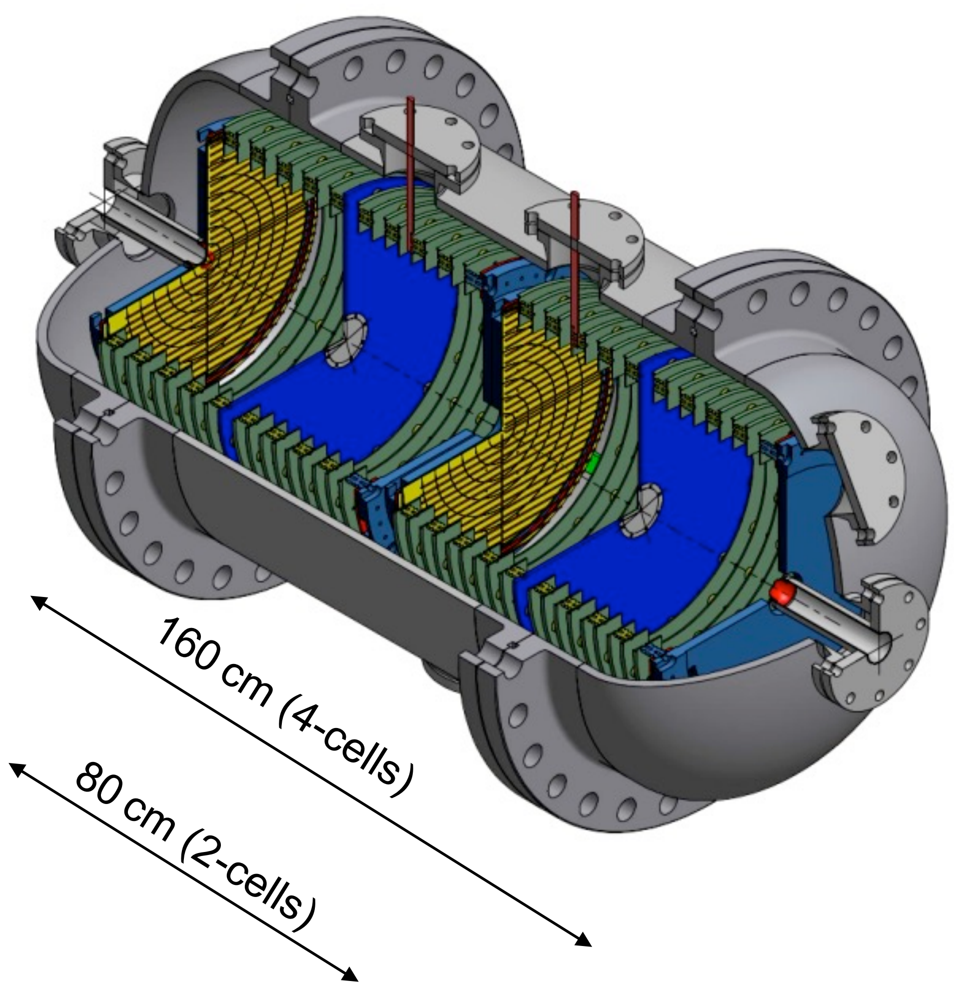
Pressurised hydrogen active-target TPC

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 length of hydrogen target





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

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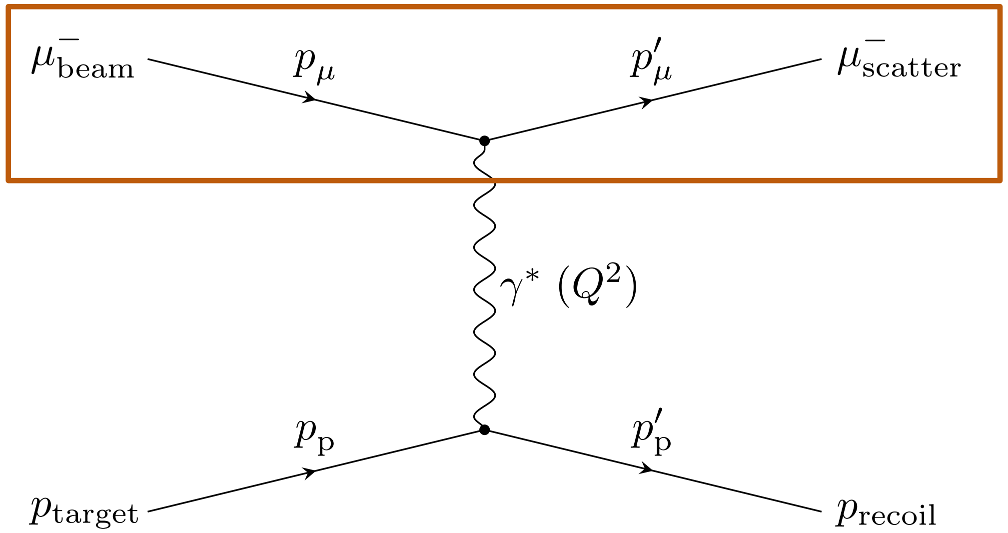
Control of Systematic Effects

Absolut calibration, inefficiencies, and background

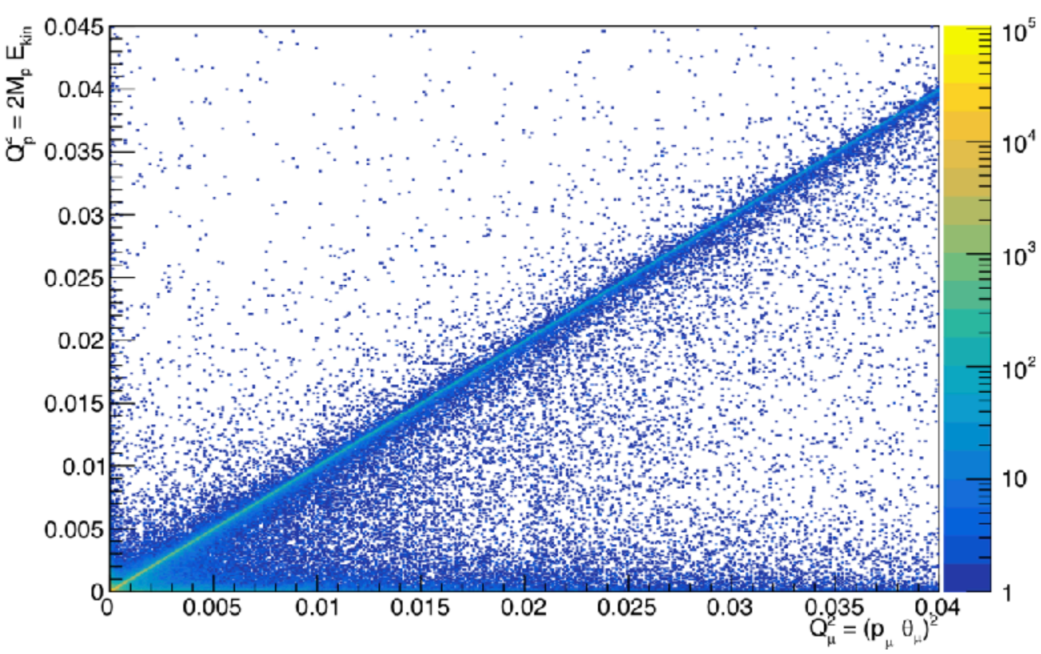
Understanding of systematic effects is crucial for precision.

- 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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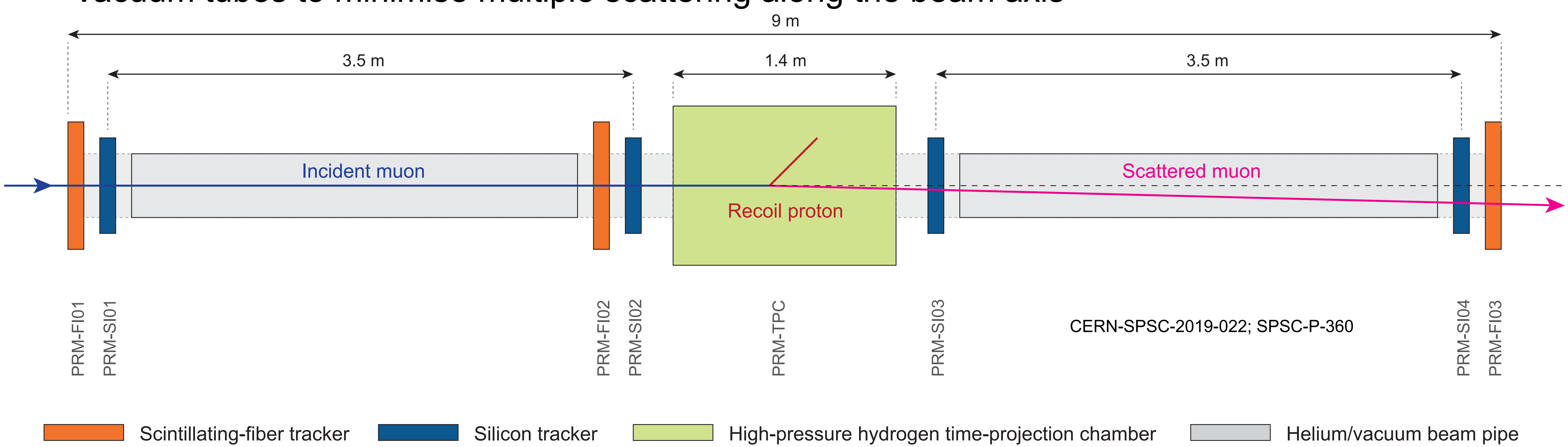
Layout of the Proton-Radius Setup

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.

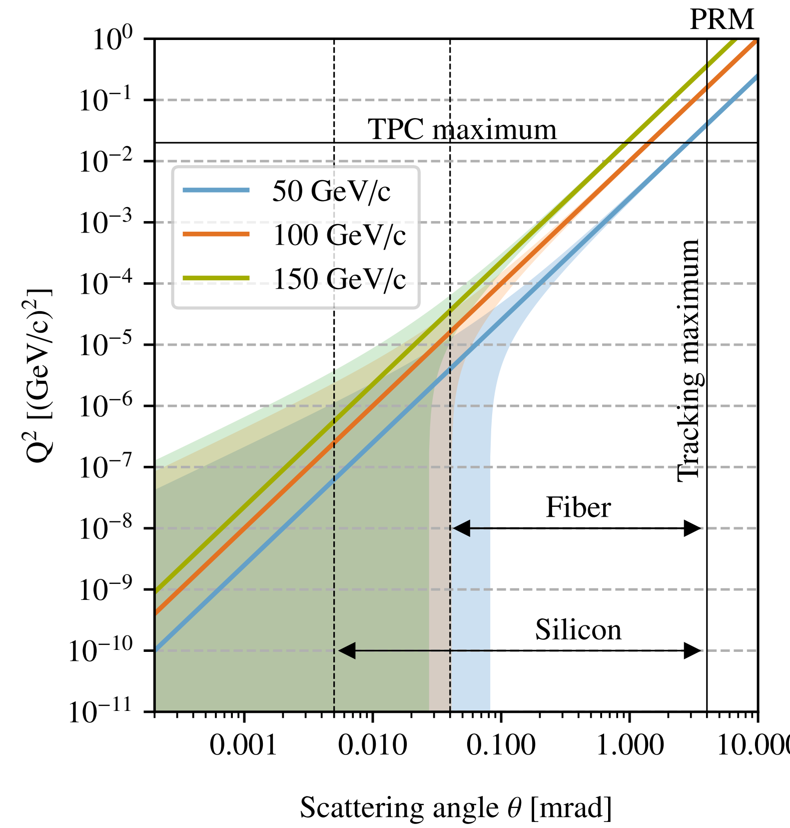
- Influence on scattering angle of muon
  → change in Q^2-spectrum

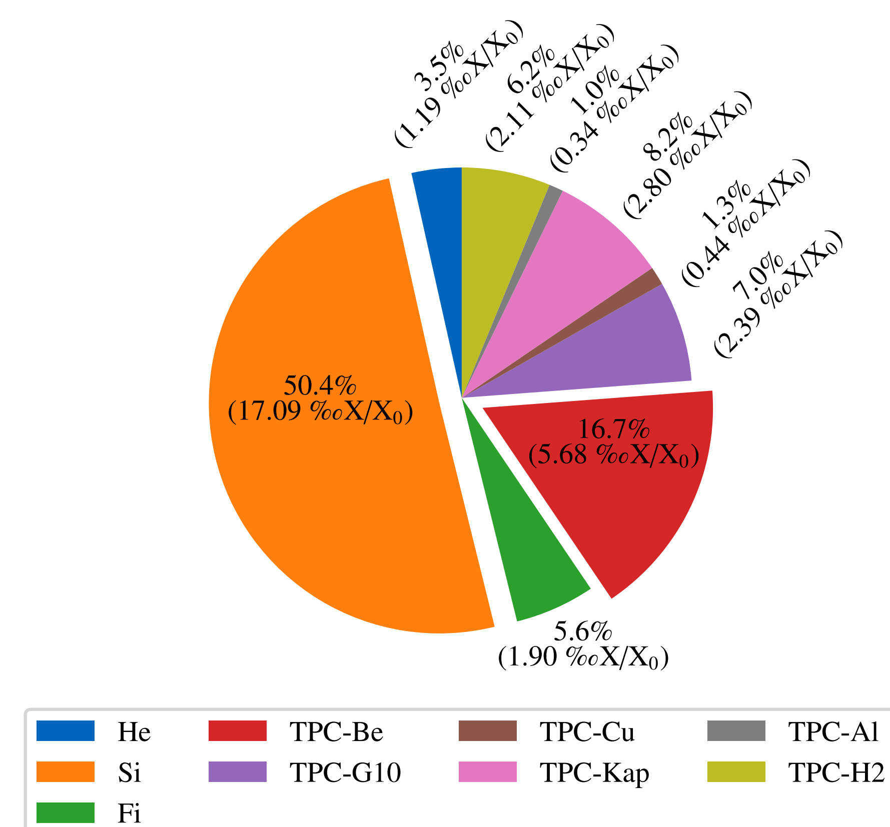
- Relative resolution at lowest proposed $Q^2 = 0.001\ \mathrm{GeV}^2/c^2$:
  → $(\Delta Q^2/Q^2)_{2\text{-cell}} = 13.8\ \%$ with $(X/X_0)_{2\text{-cell}} = 33.9$ ‰
  → $(\Delta Q^2/Q^2)_{4\text{-cell}} = 15.4\ \%$ with $(X/X_0)_{4\text{-cell}} = 41.5$ ‰

- 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





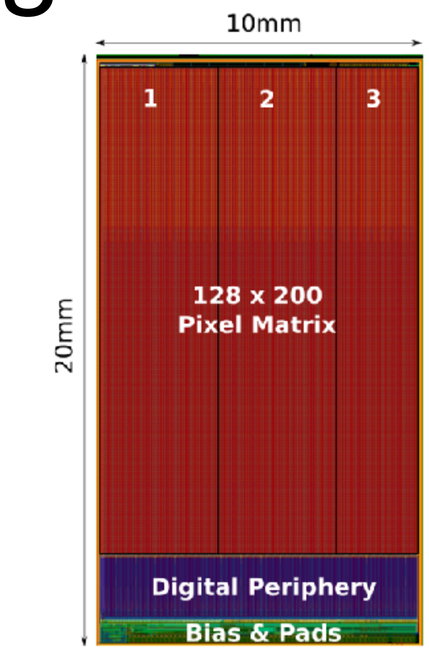
Muon Trigger and Tracking Detectors

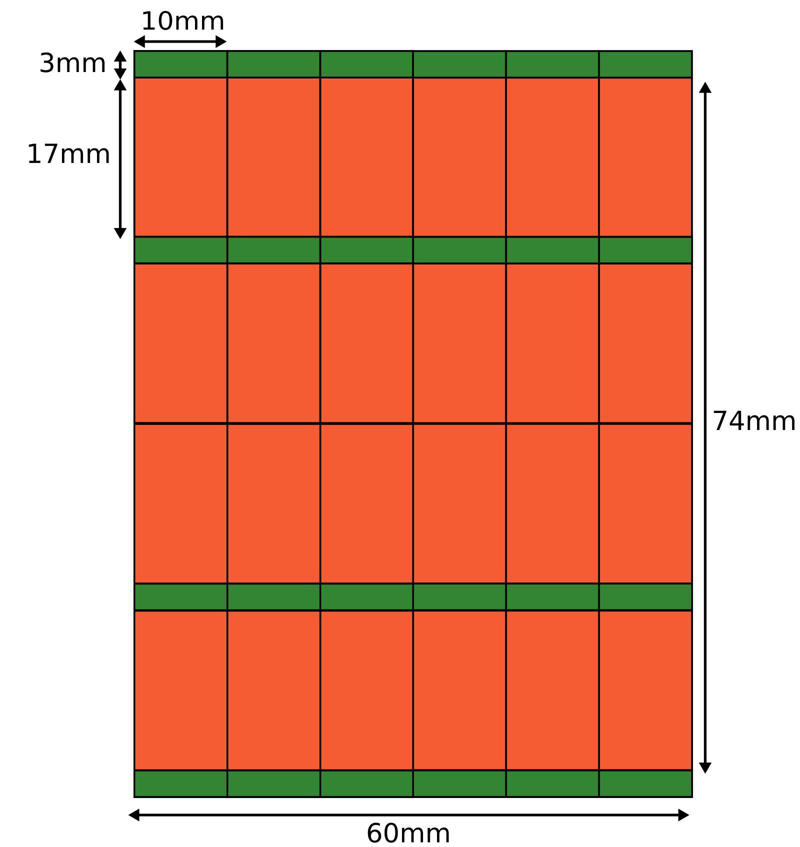
Current solutions for detectors

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

- Silicon detector - MuPix under investigation:
  → produced at KIT and used at MUSE
  → 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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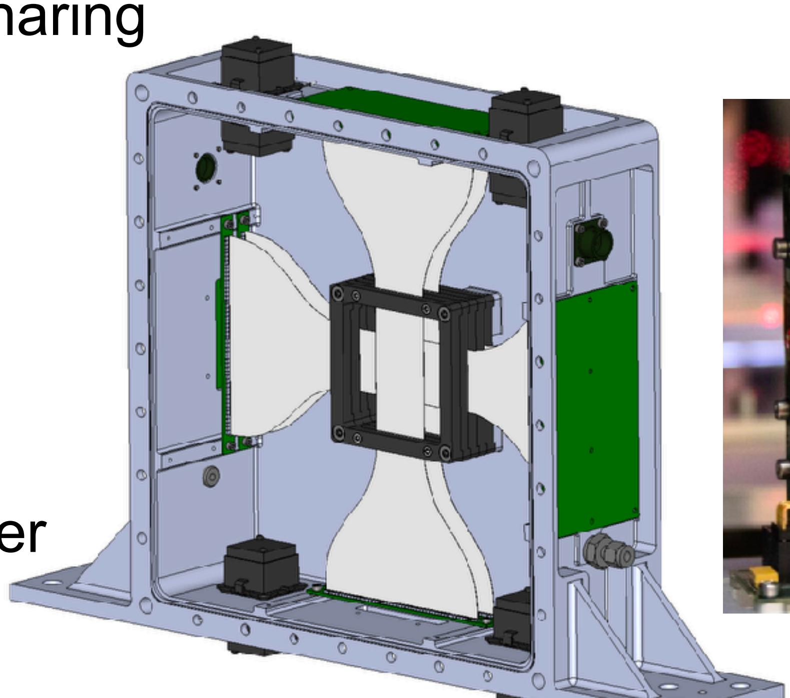

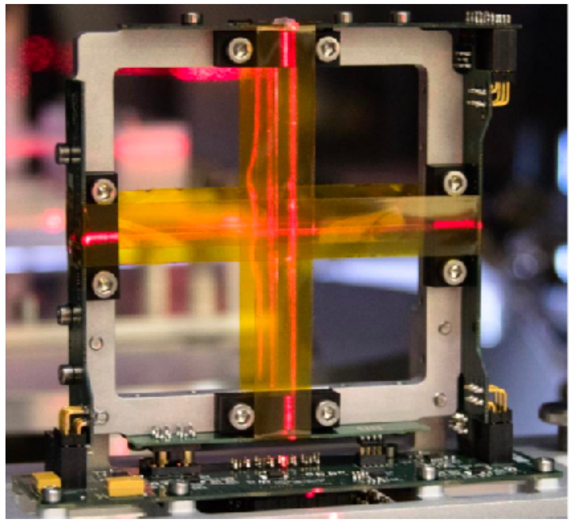

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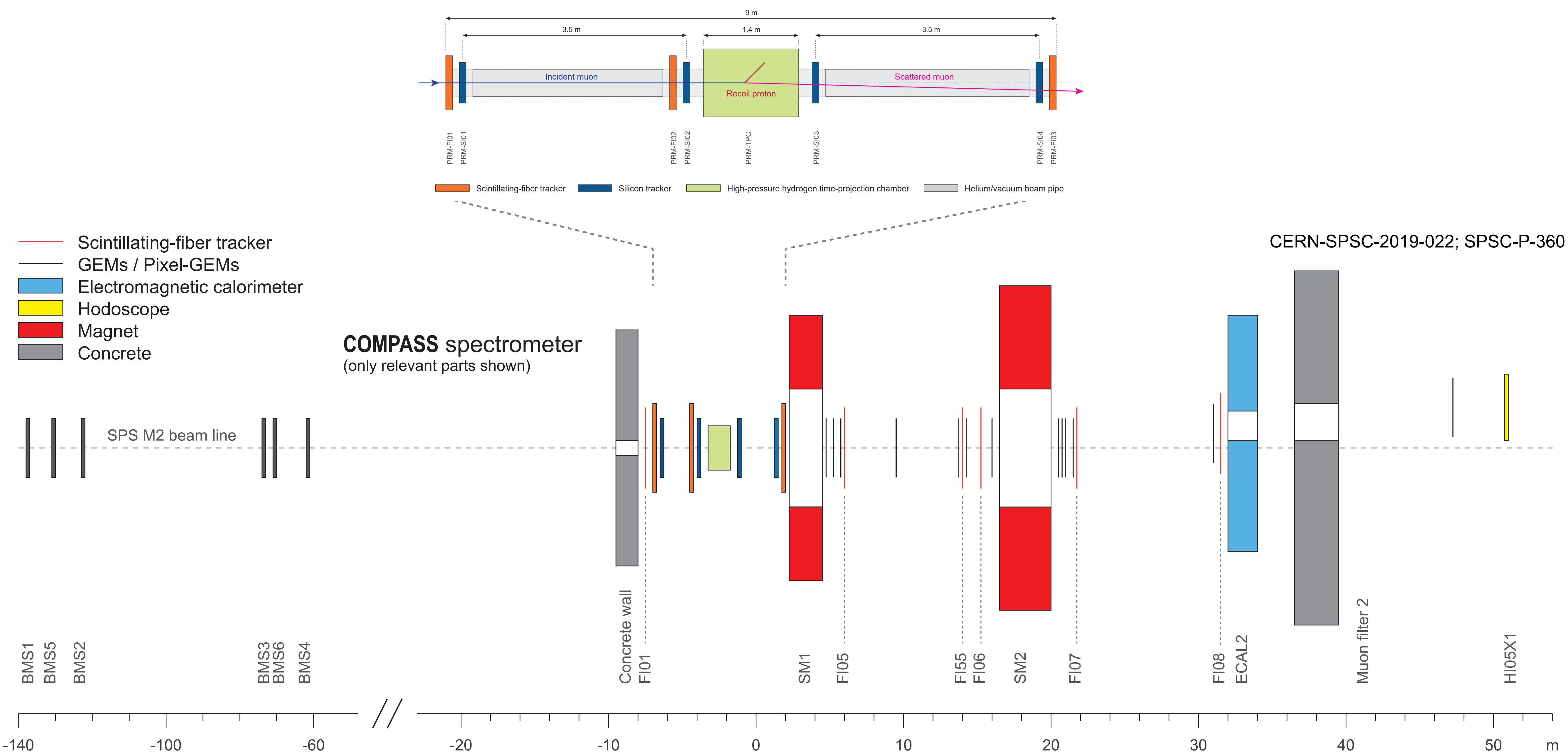
Layout of the Proton-Radius Setup

Advantages of using the COMPASS spectrometer

Measurement of muon momentum and understanding of background.



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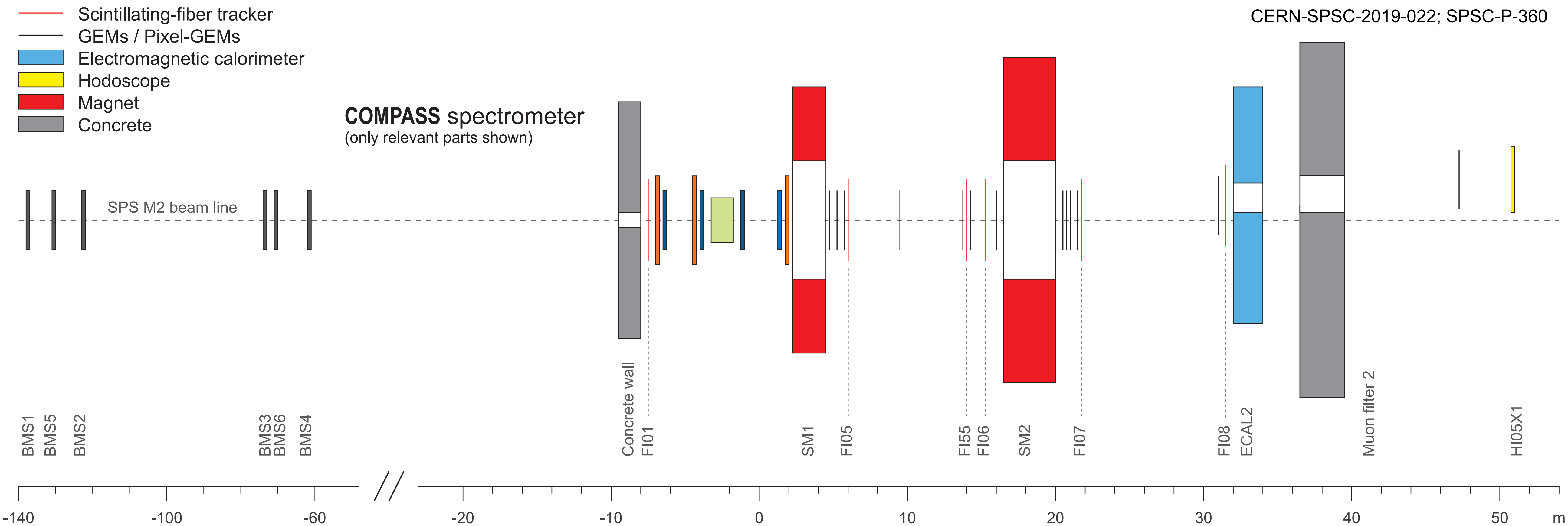
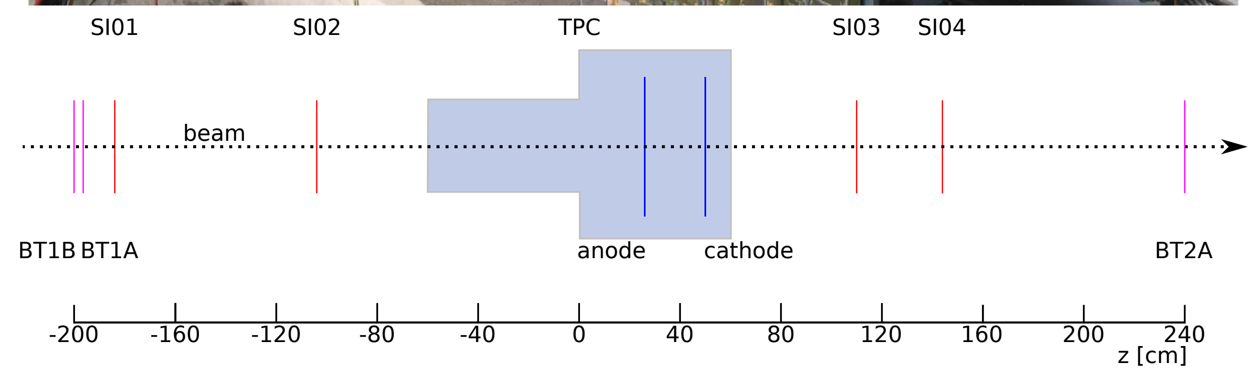


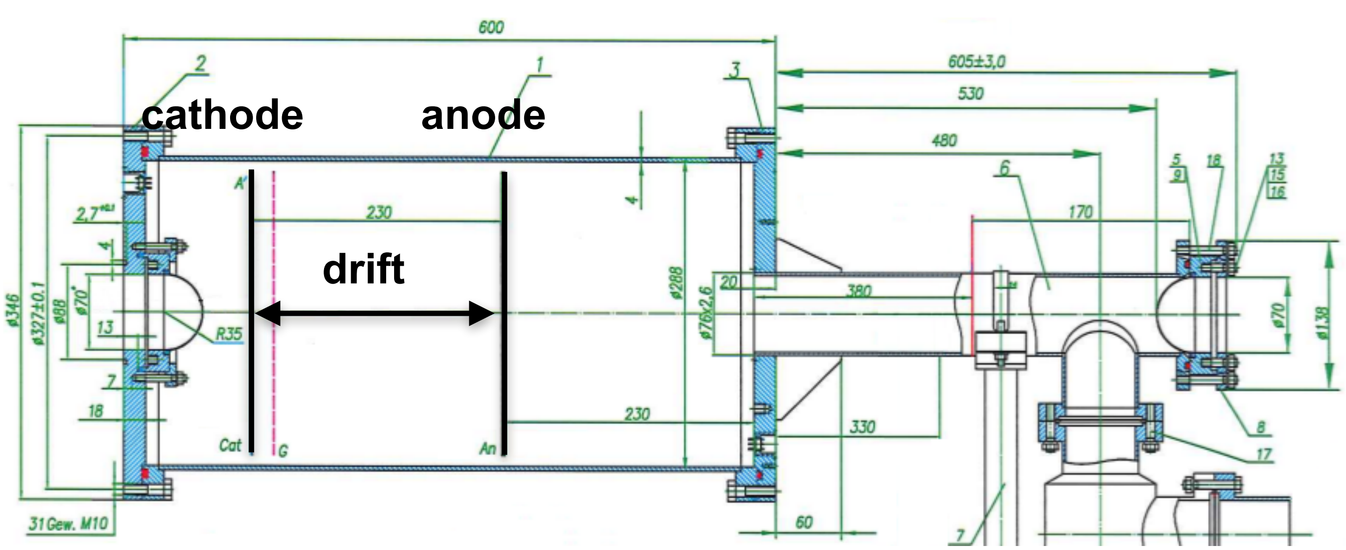
- COMPASS spectrometer
  → momentum measurement of scattered muon
  → radiative background using electromagnetic calorimeter
  → muon identification with muon filter and hodoscope

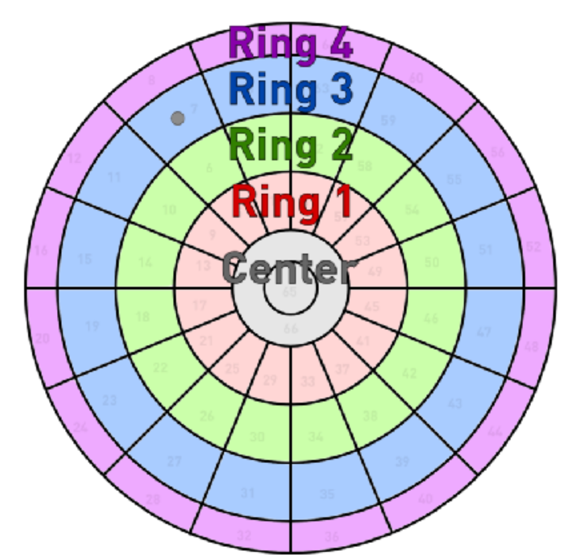
Beam Test in 2018

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

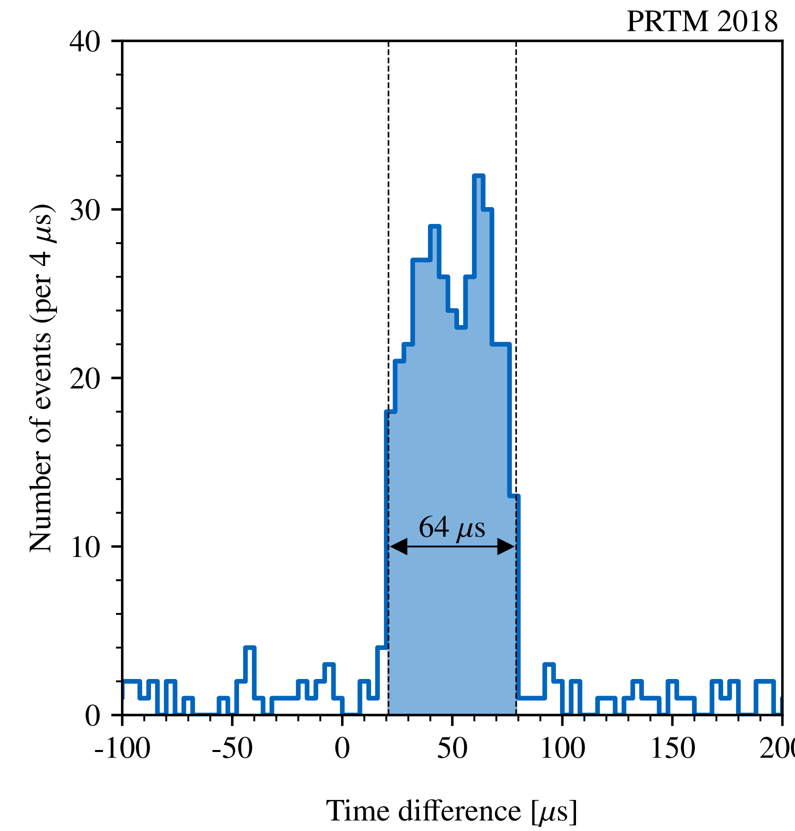
- Parasitically to COMPASS Drell-Yan run
  → remaining muons of 190 GeV pion beam
- TPC: 8 bar hydrogen and 23 cm drift
- Four silicon stations with a size of 7x5 cm^2
- Two distinct DAQ systems
  → event matching via time stamp







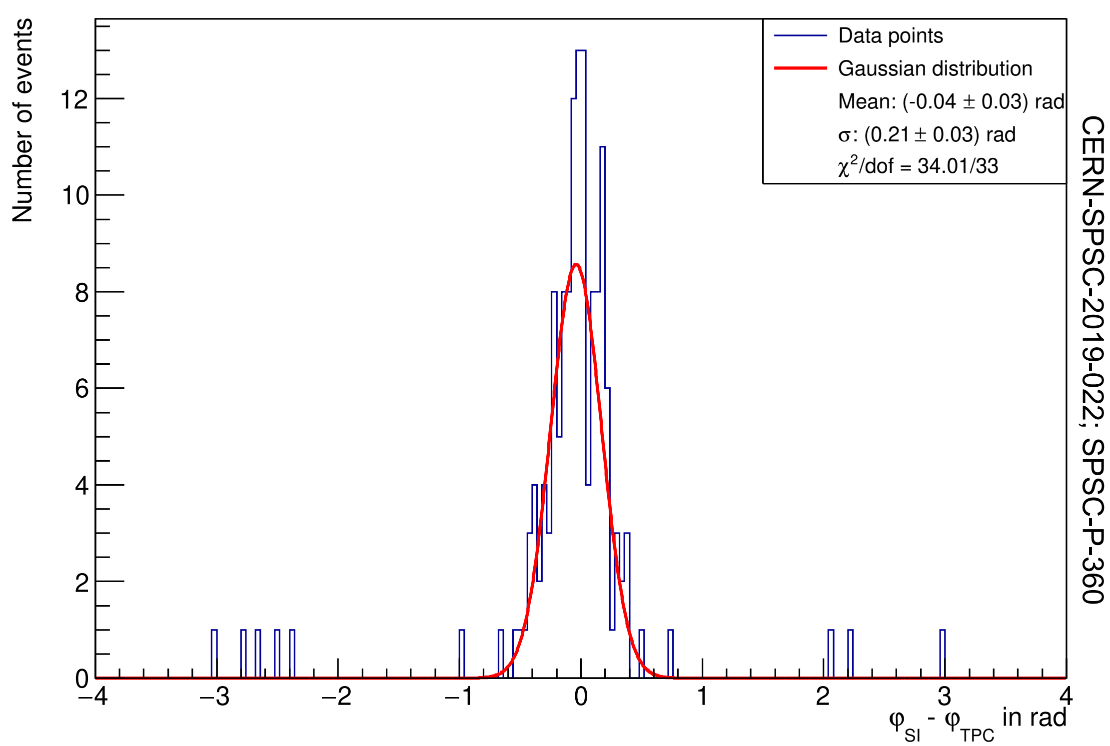
Results of the Beam Test in 2018

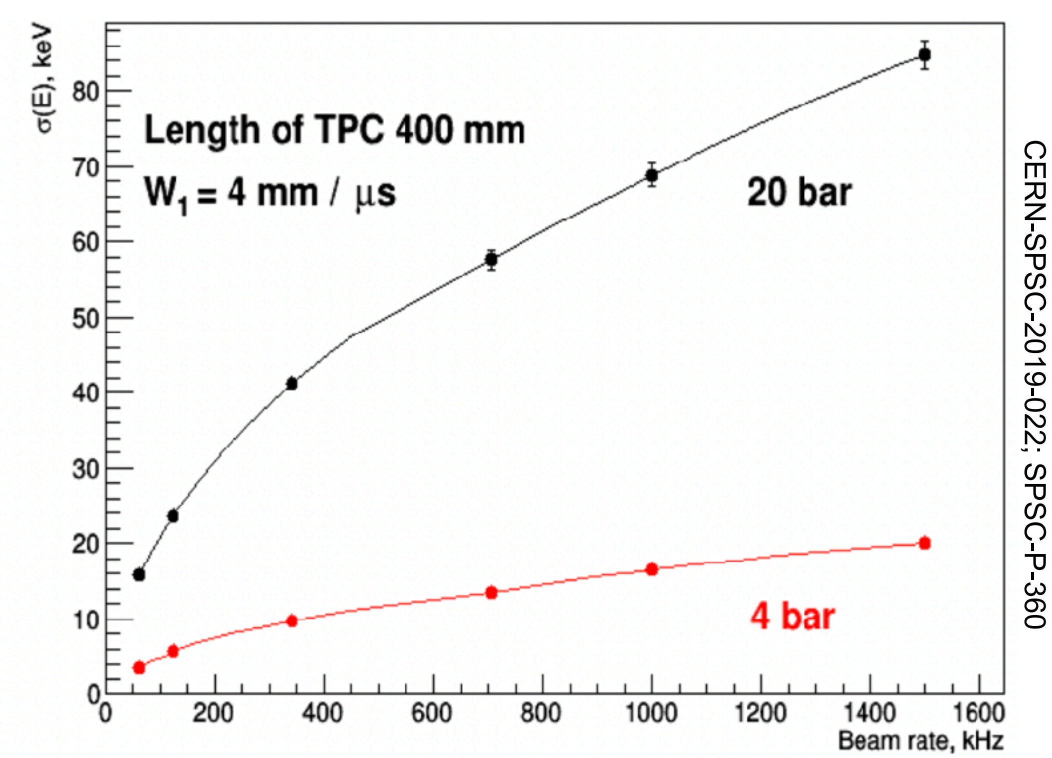


Feasibility test using TPC and silicon detectors

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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Beam Properties

Intensity and size of muon beam

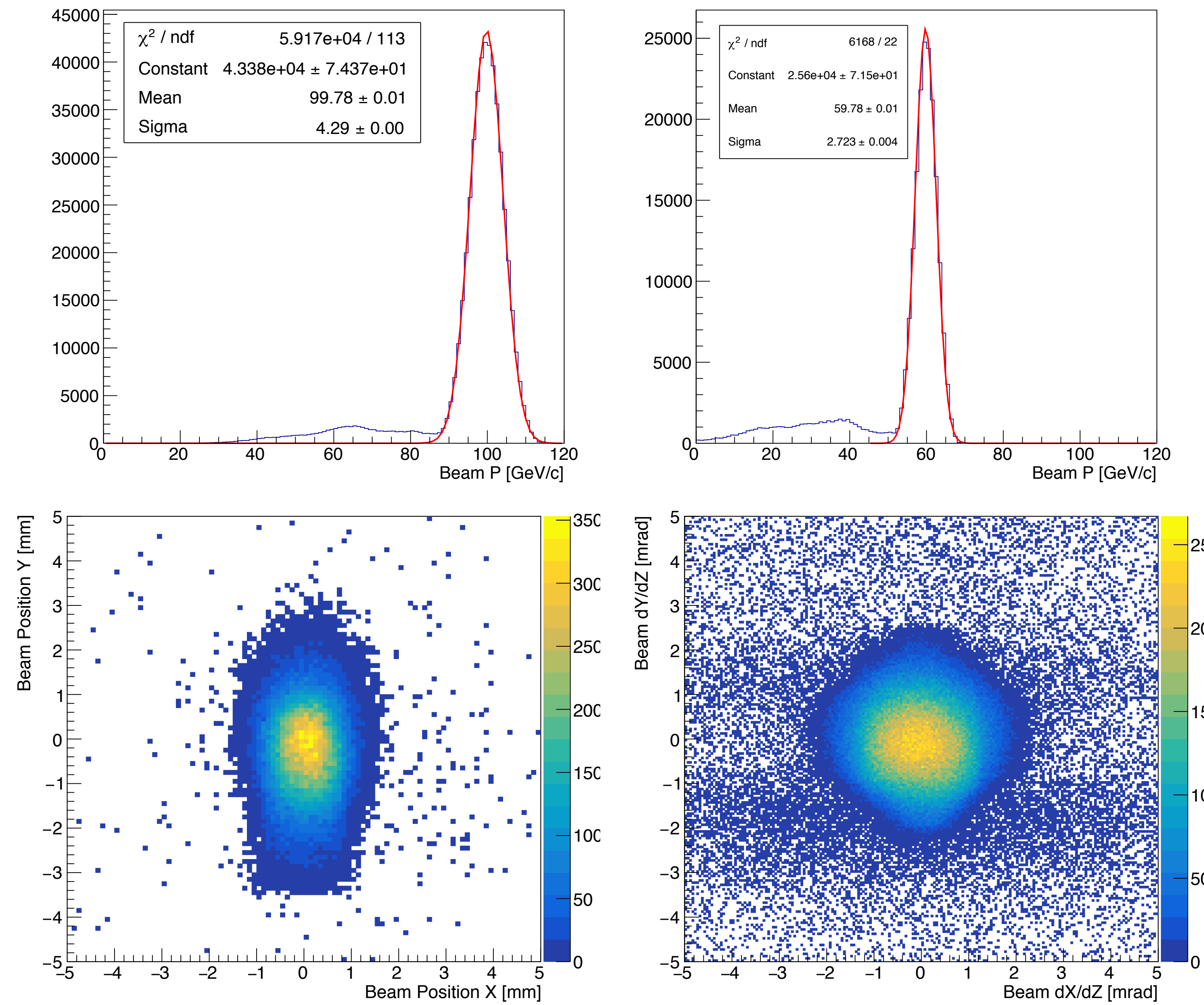
Beam properties are defined by geometry and detector properties.

- 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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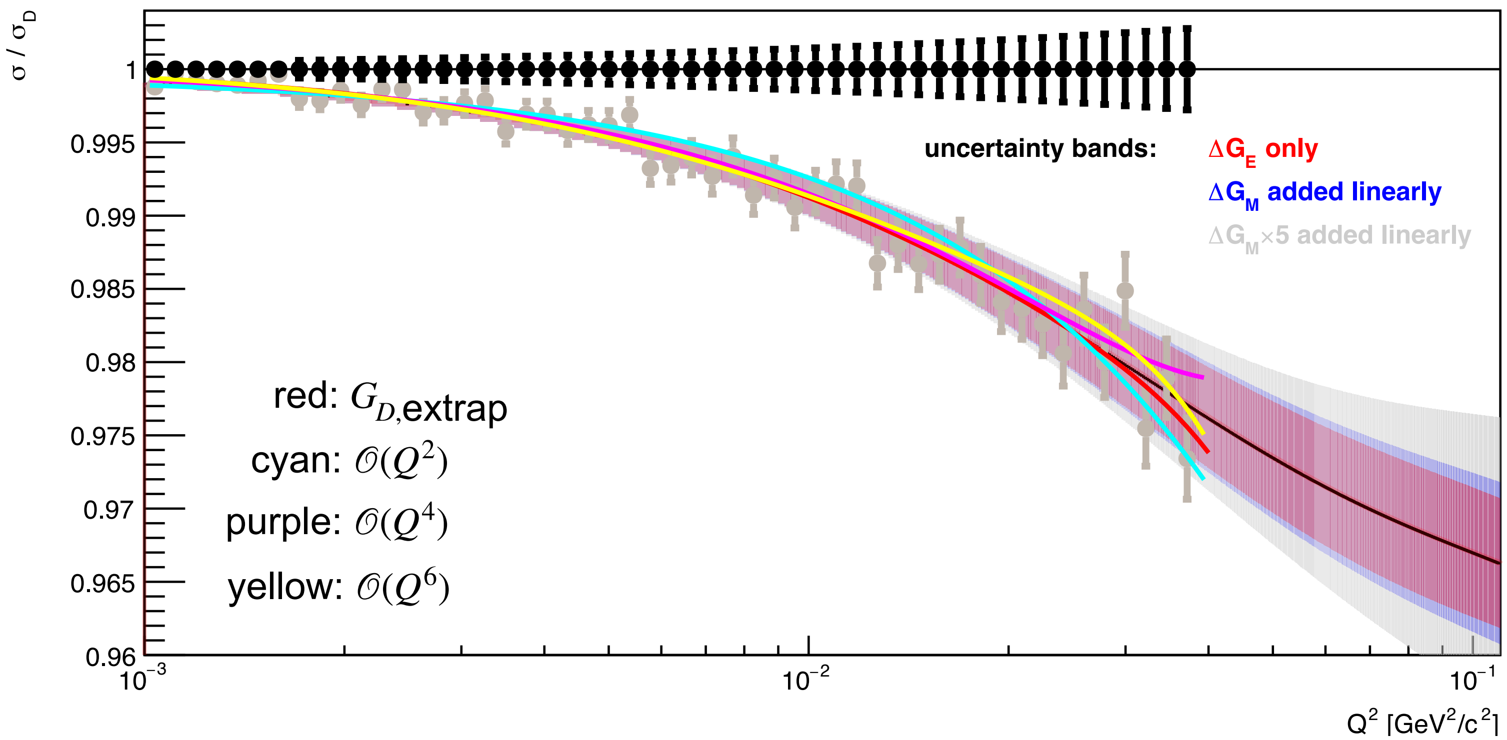
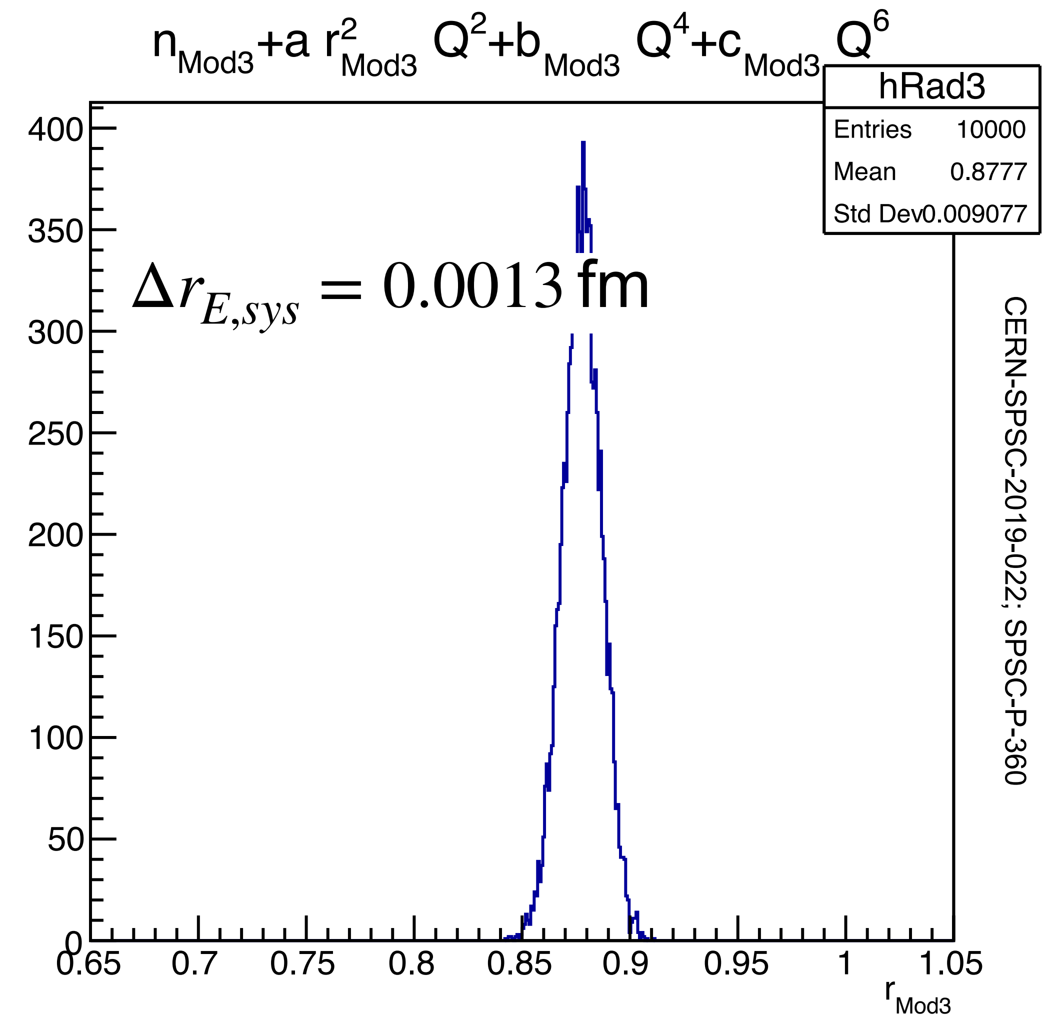
Test of Statistical Precision and Beam Time

Example using a model

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





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- 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

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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
- Absolut energy scale of beam and measured Q^2 required - different approaches under study
- First beam test foreseen in 2021, parasitically to transverse-deuteron run of COMASS
- First data taking proposed in 2022 / 2023

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

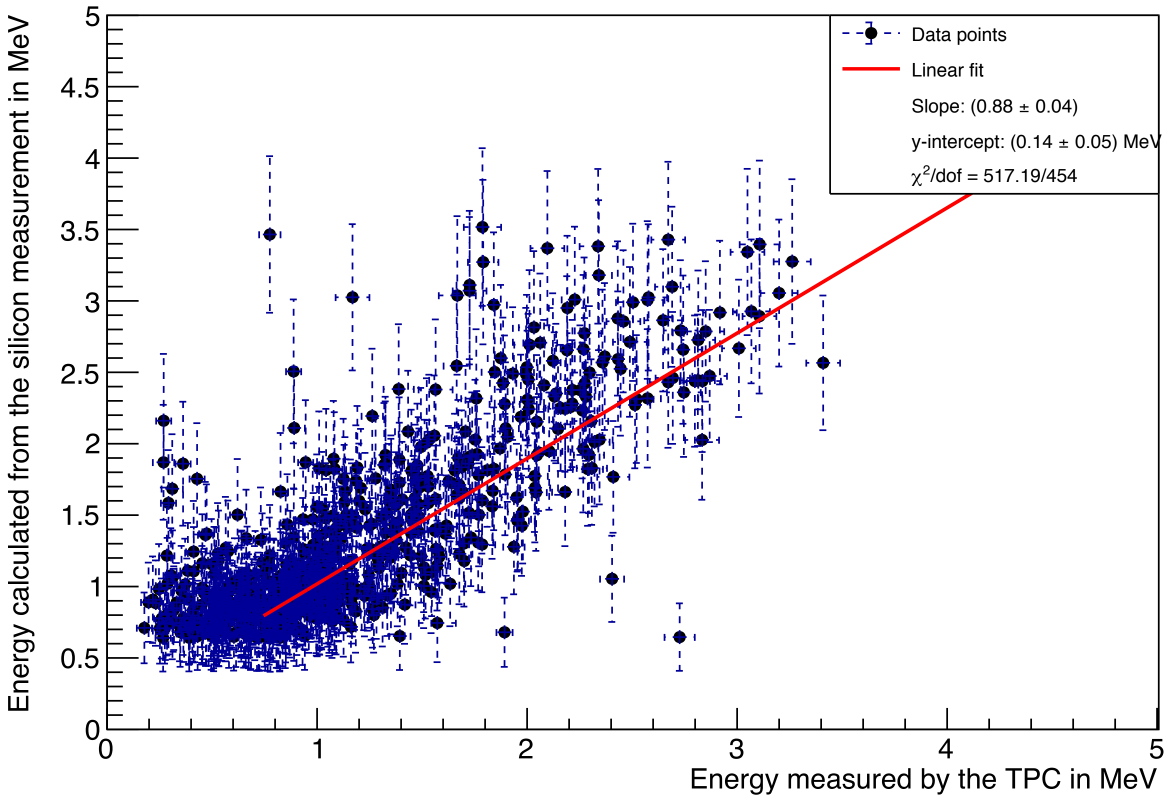
Thank you for your attention

Further information

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

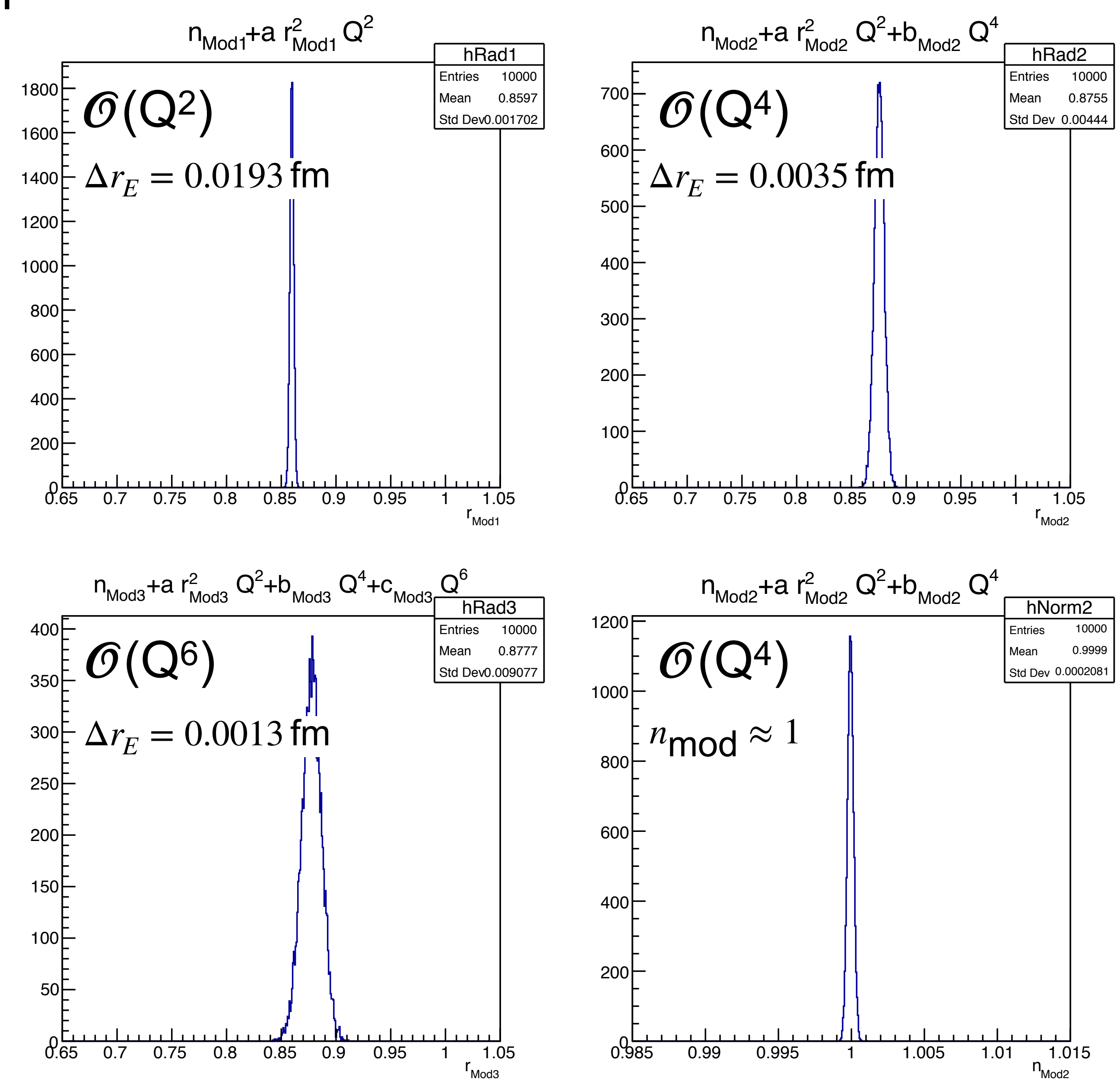
Different models for the radius extraction

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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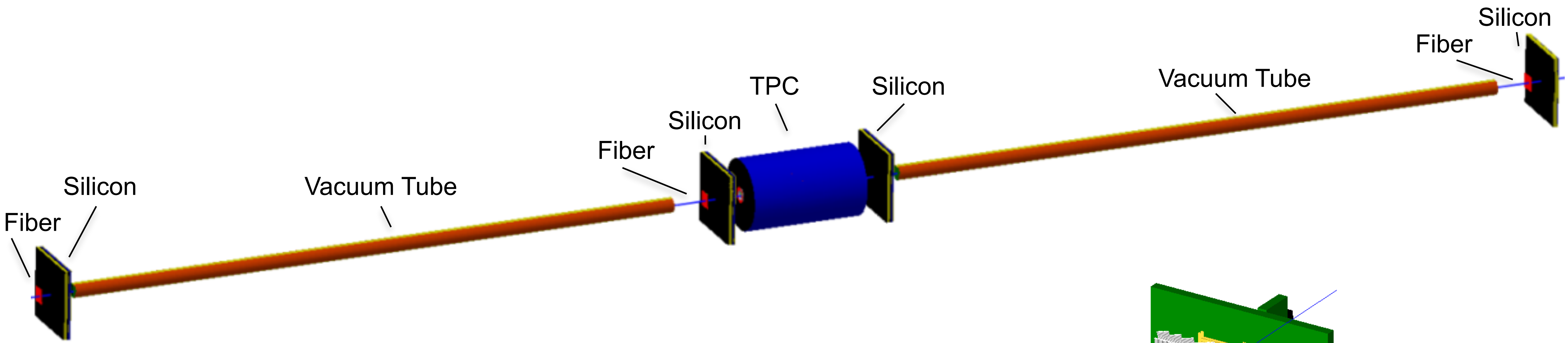
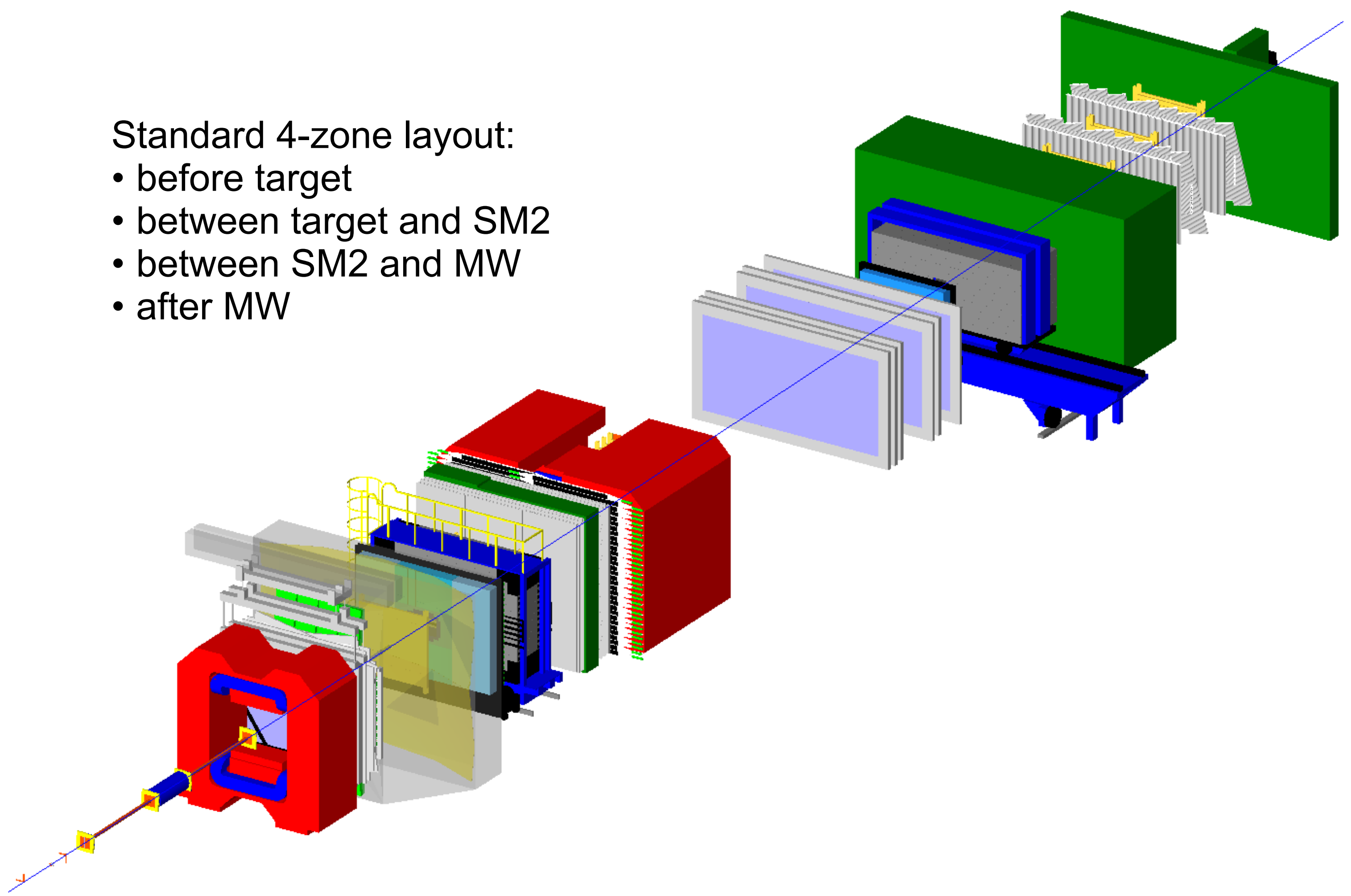
Layout of the Setup



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



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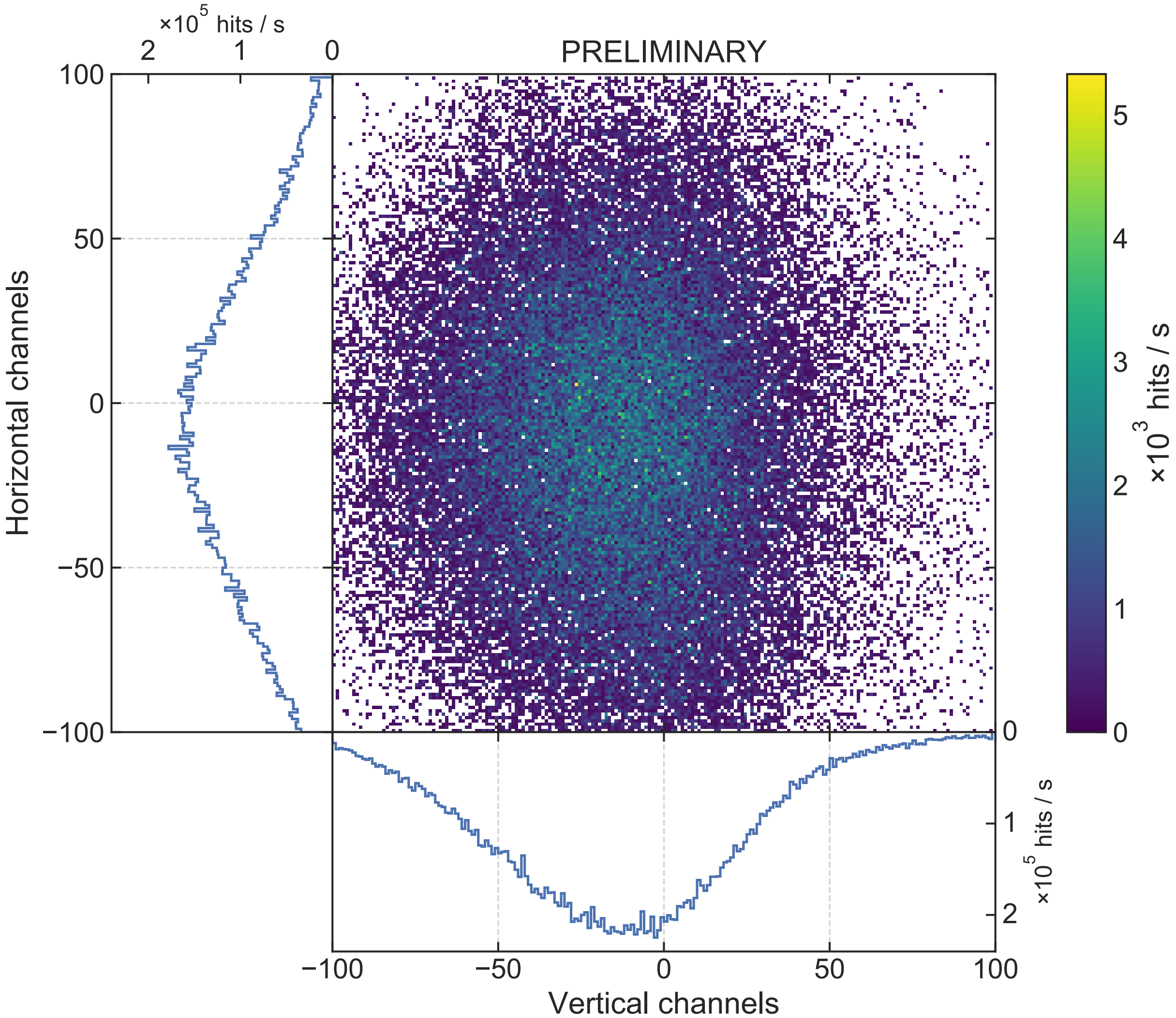
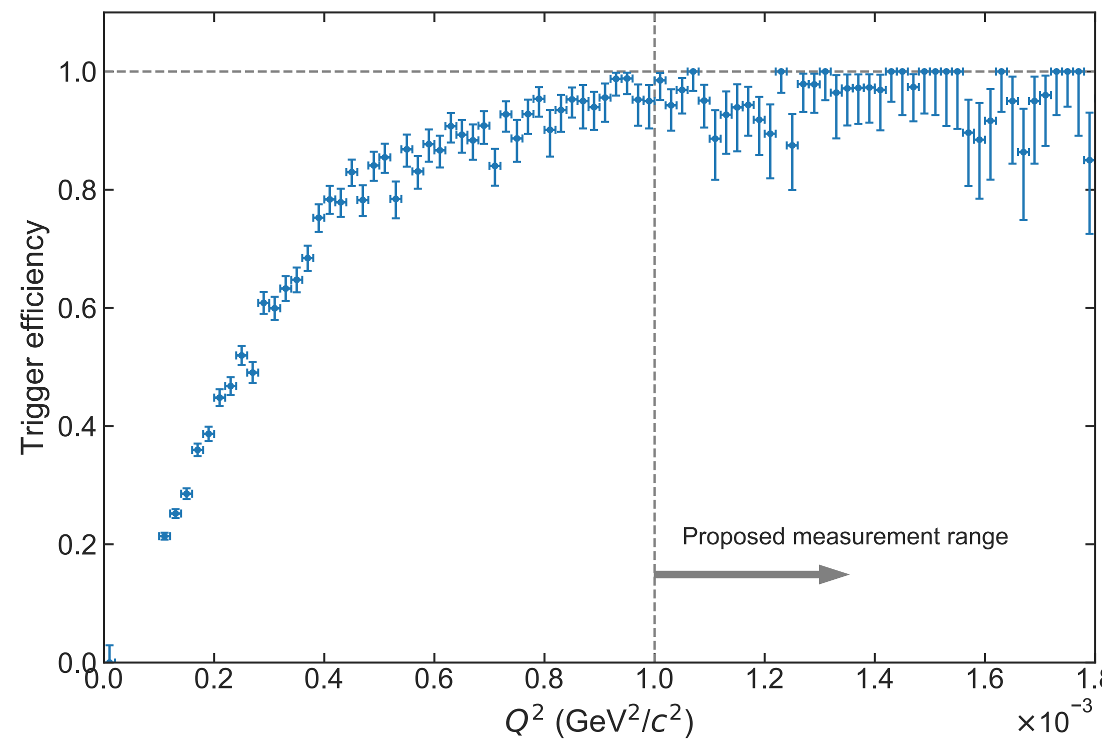
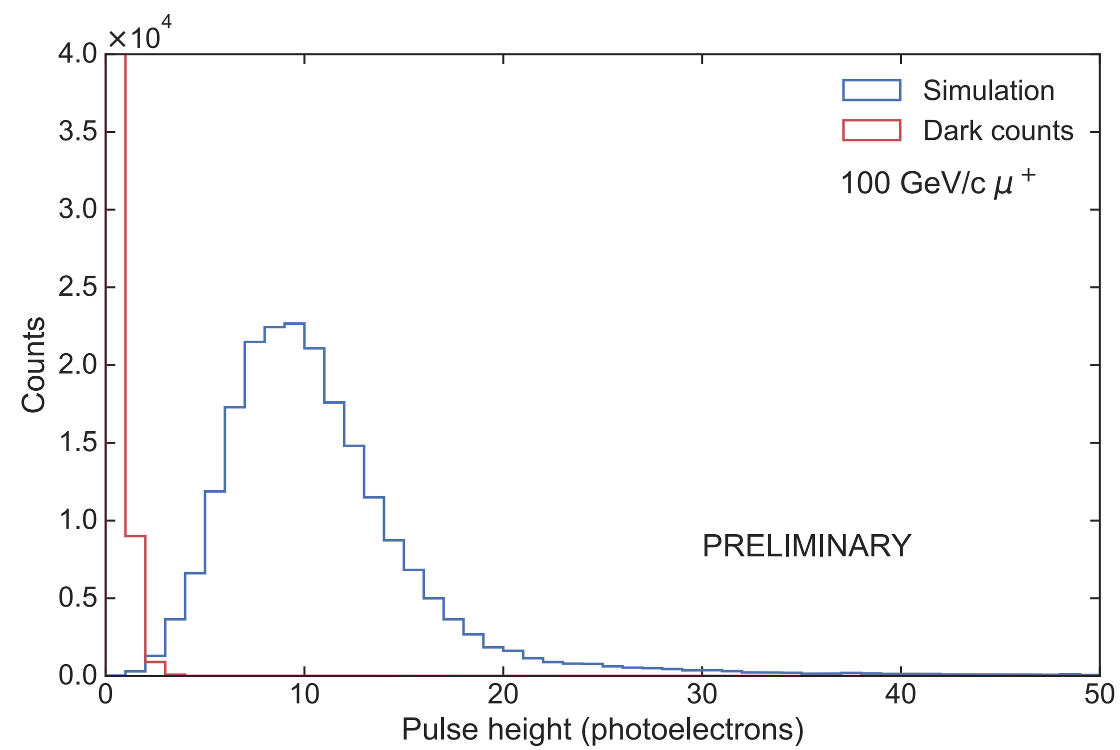
Fiber Trigger Efficiency







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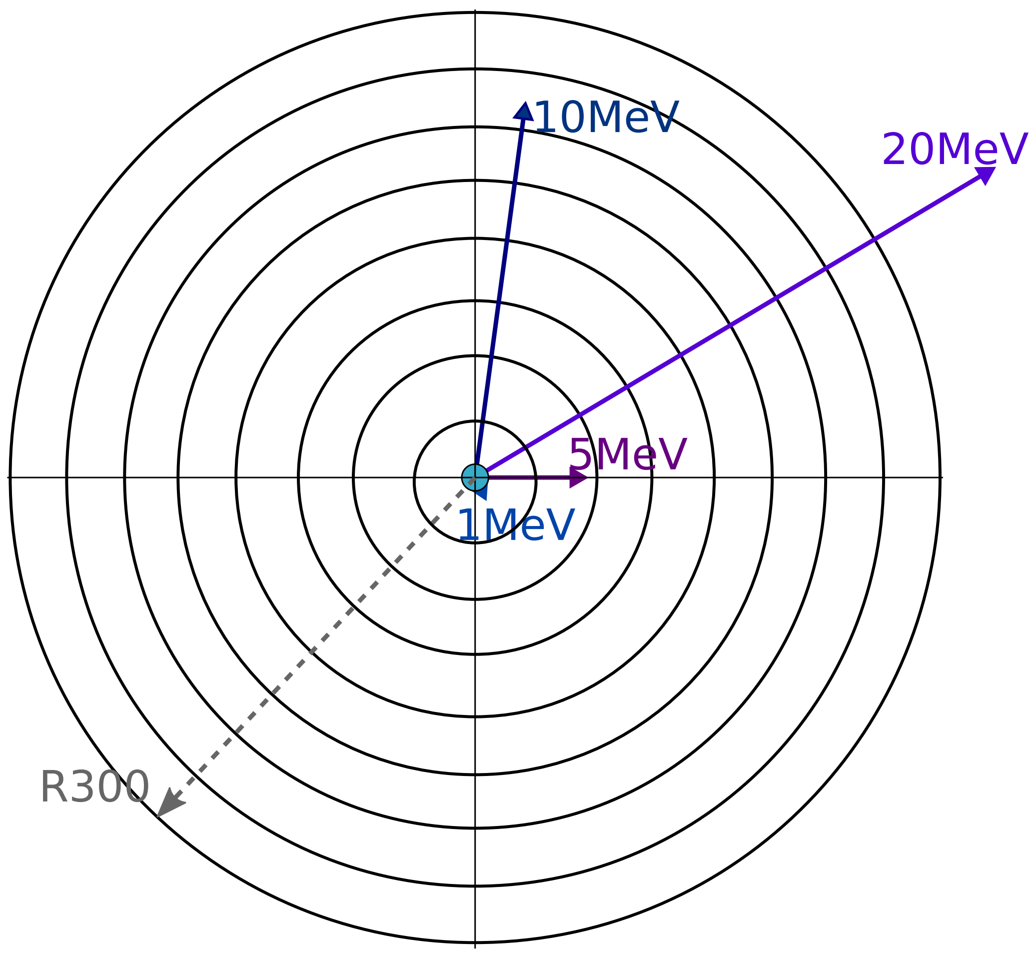
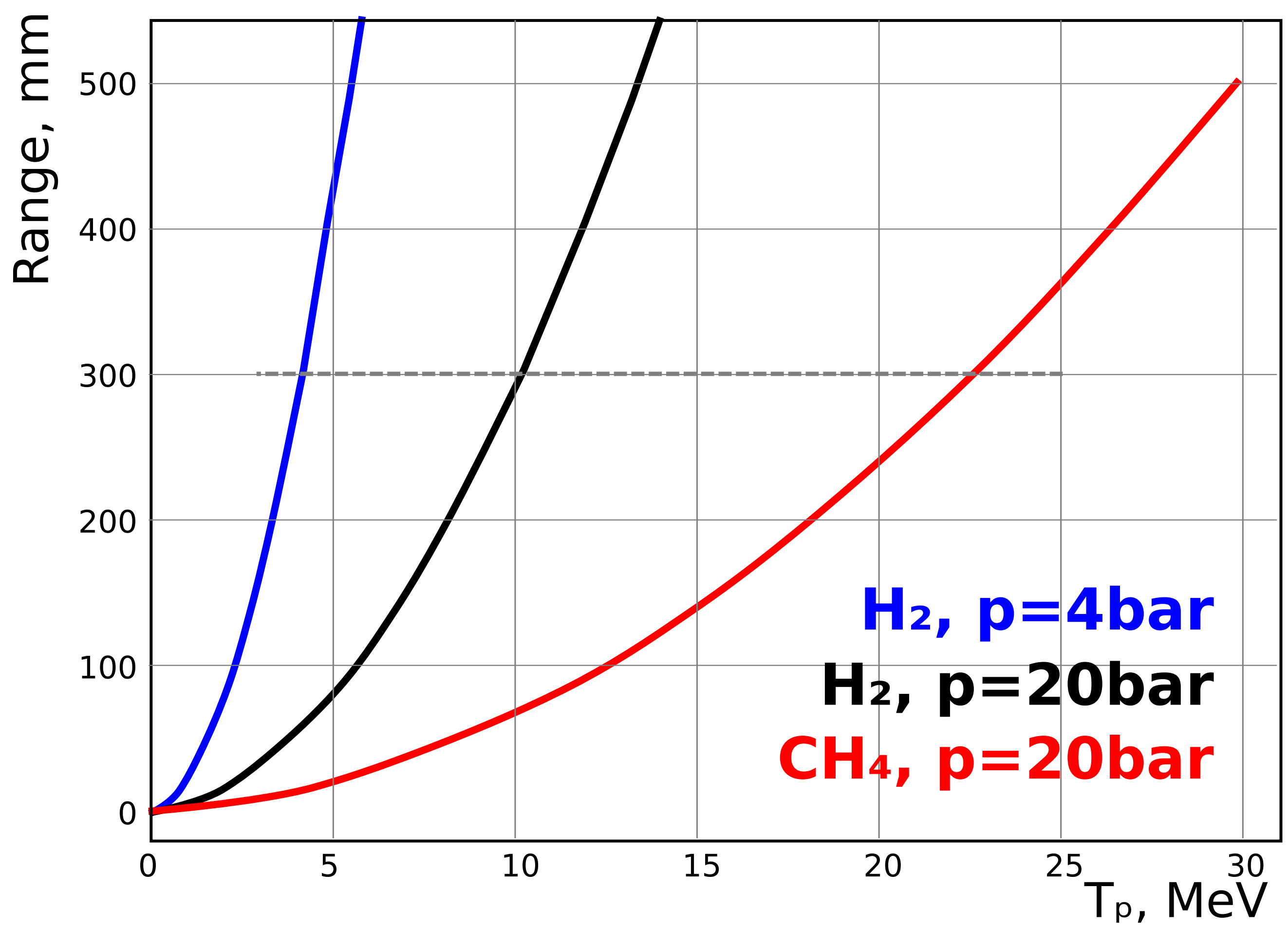
TPC Proton Ranges





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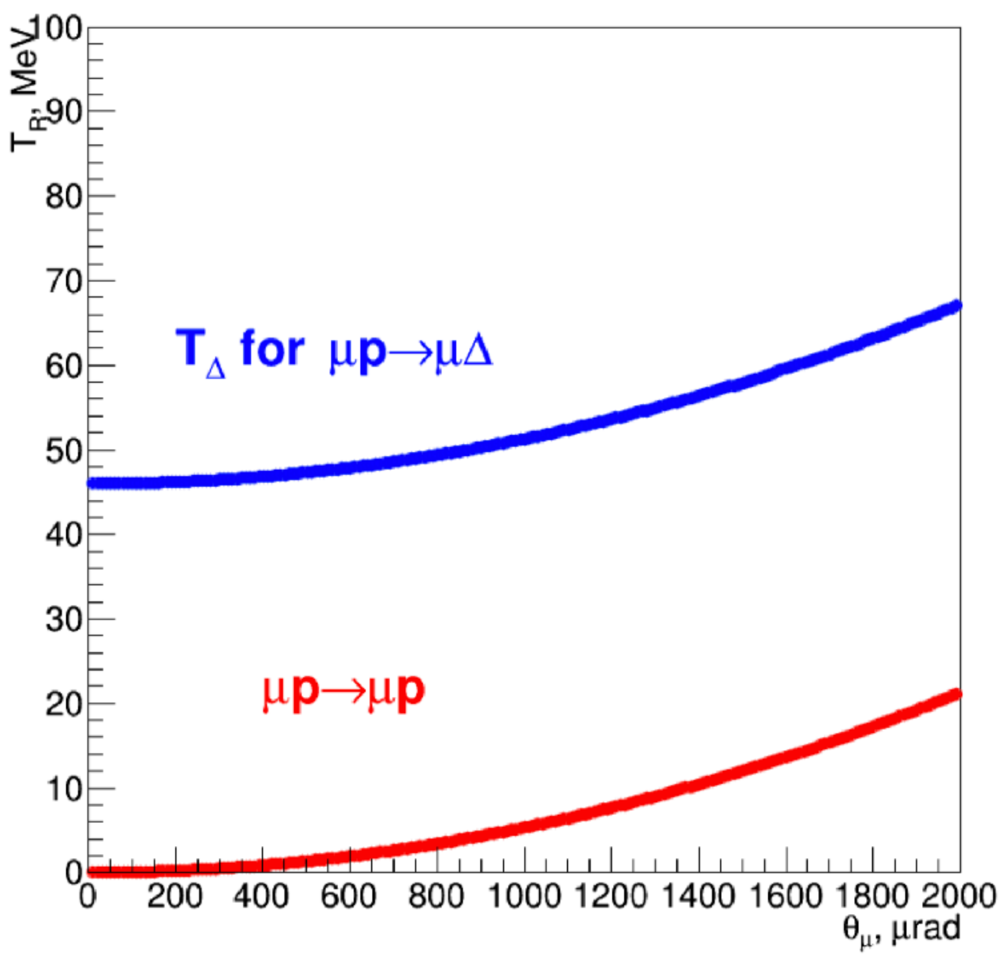
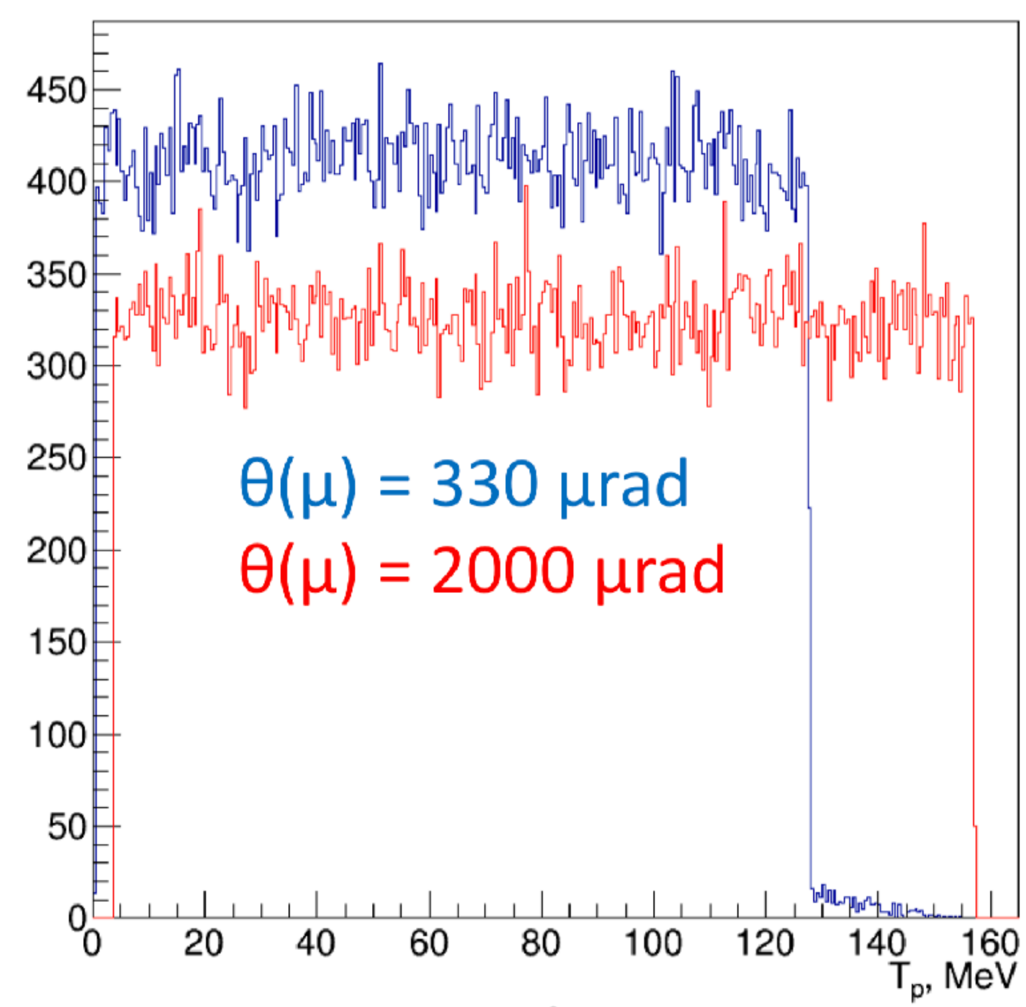
Inelastic Background

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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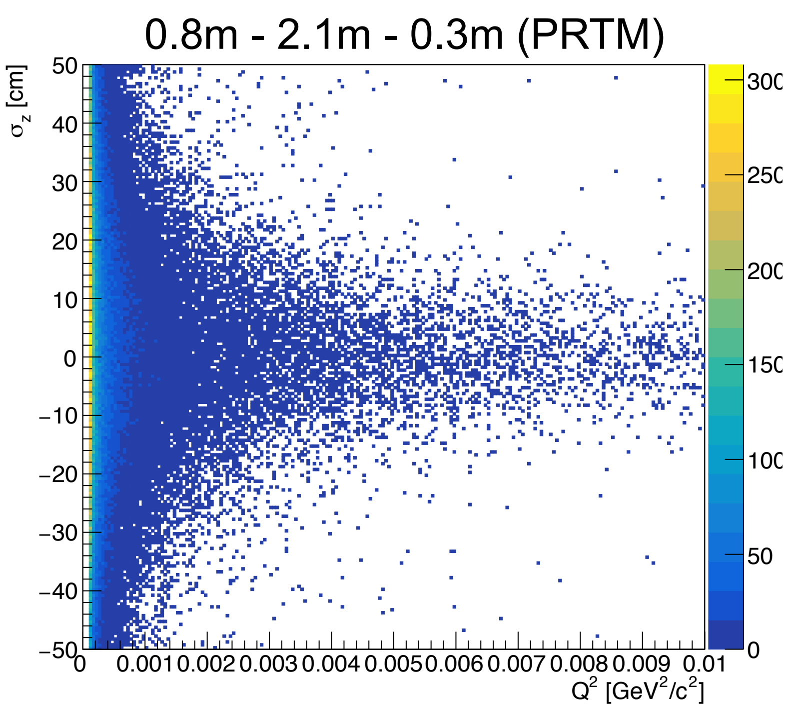
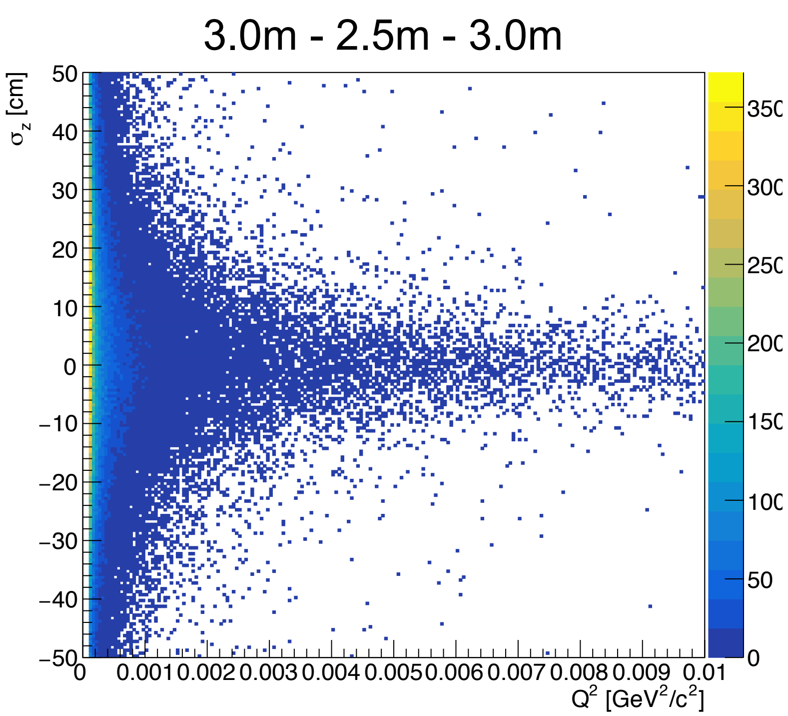
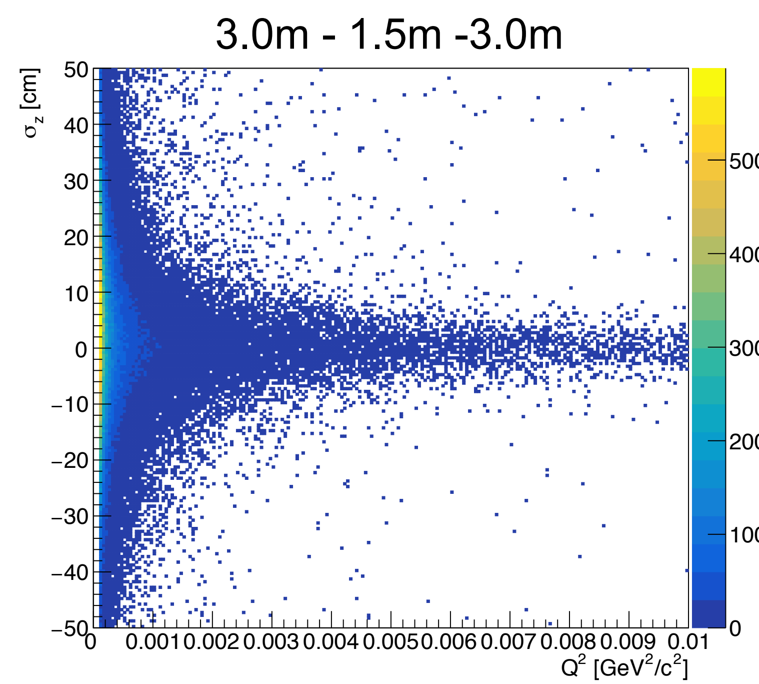
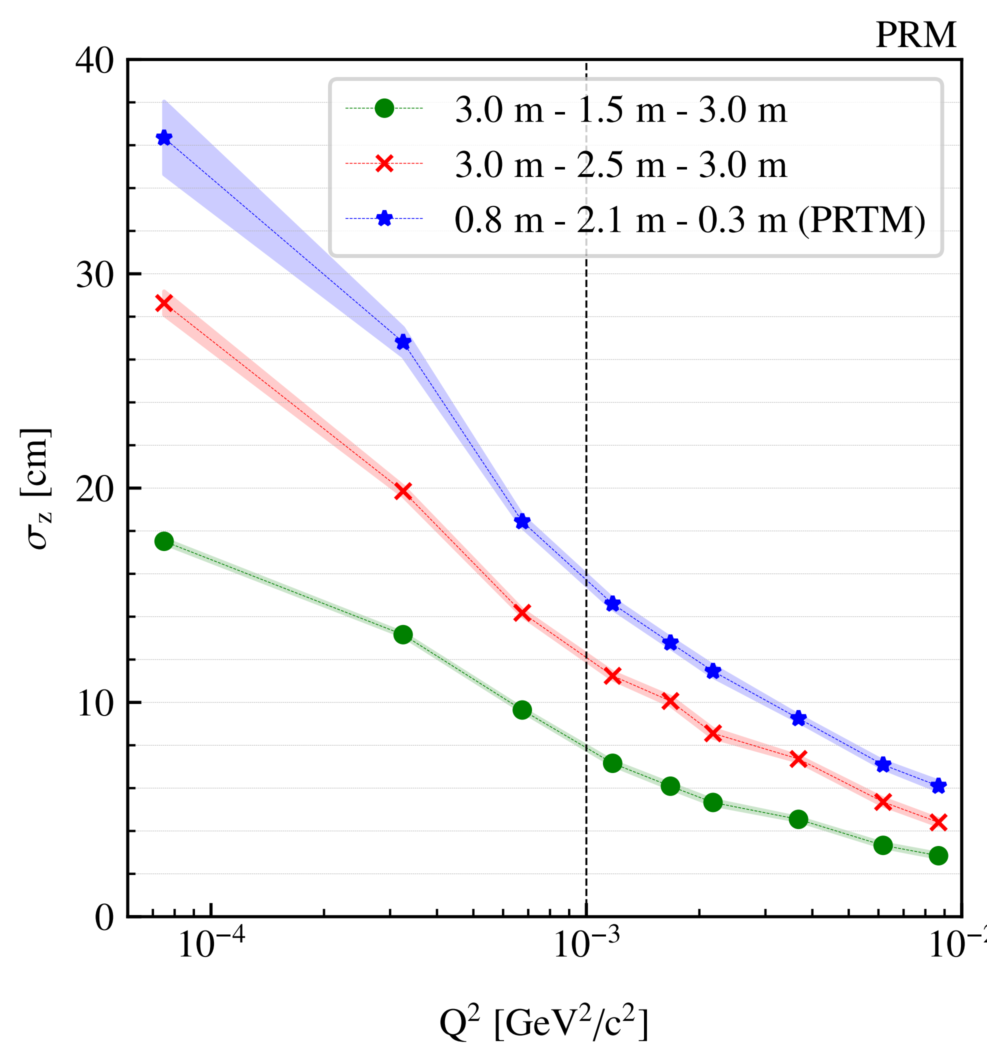
Studies on Geometries









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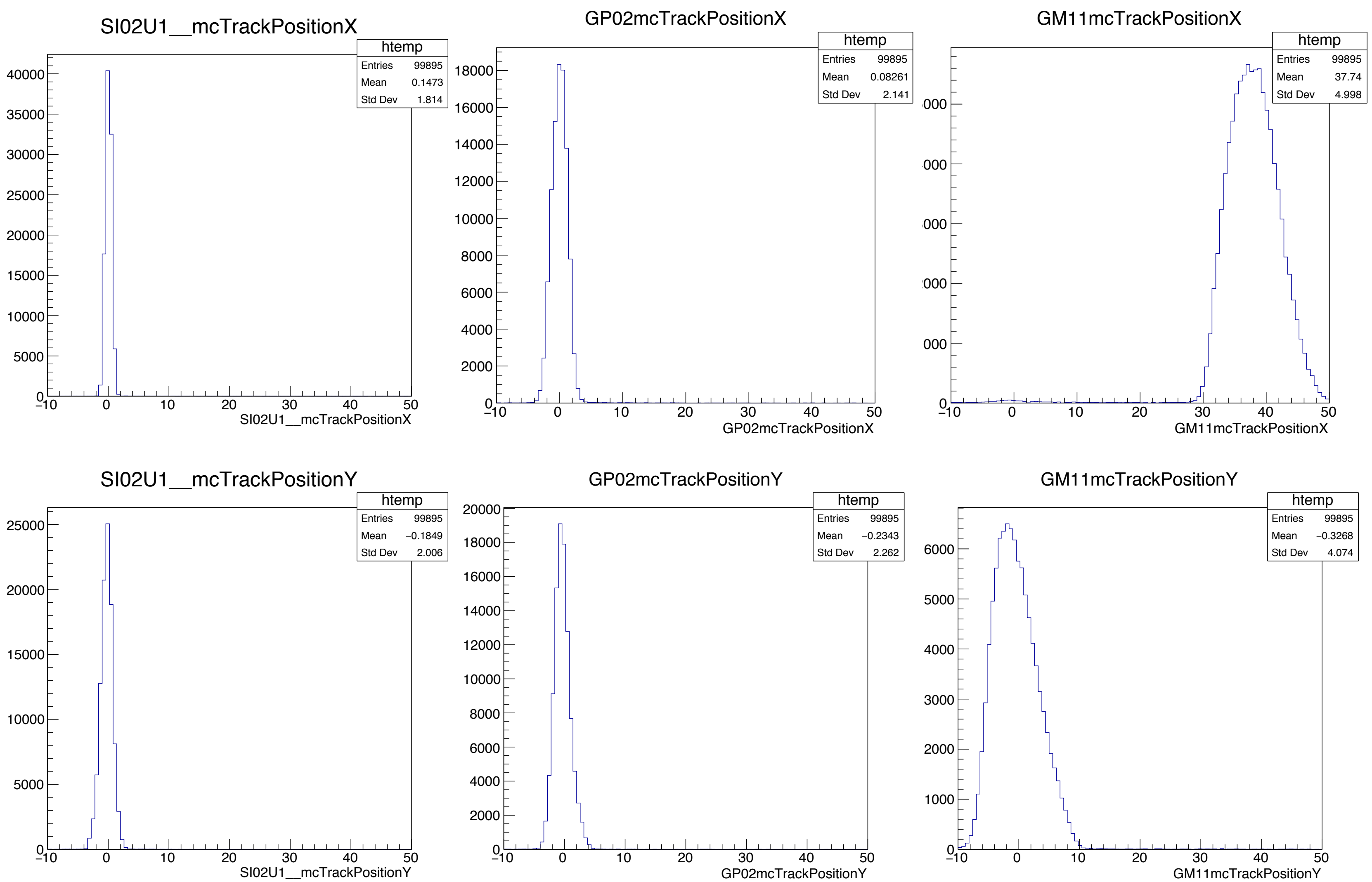
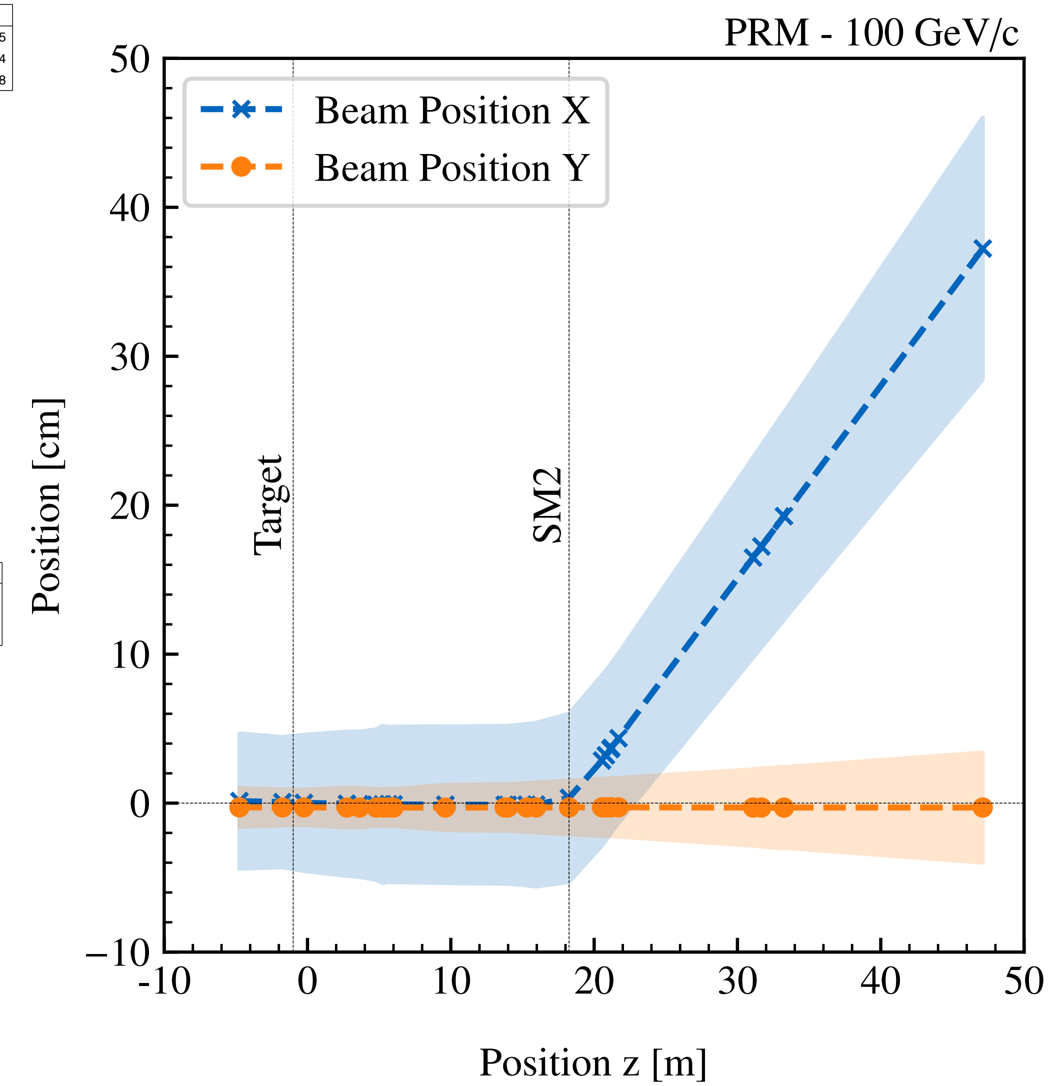
Studies on Beam Properties





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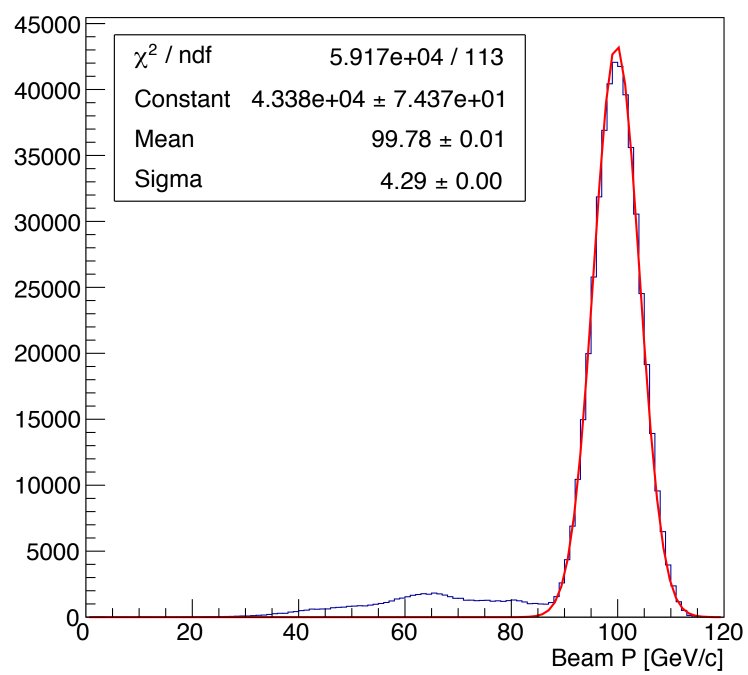
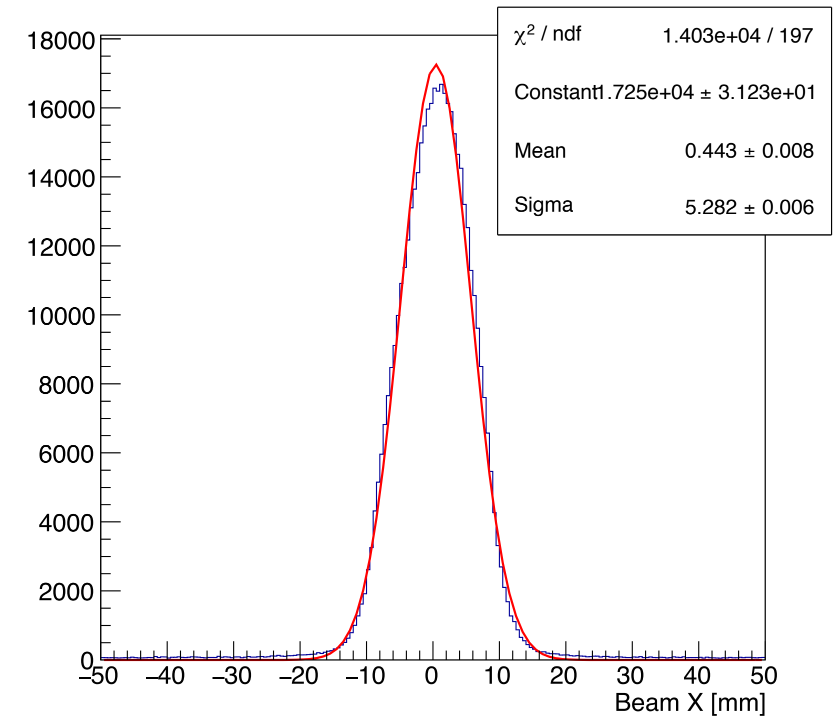
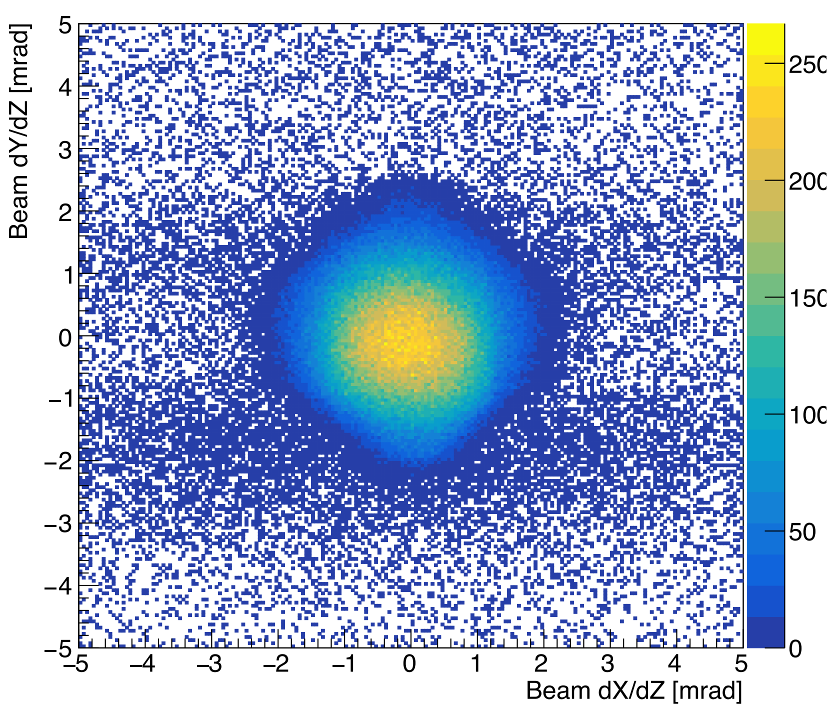
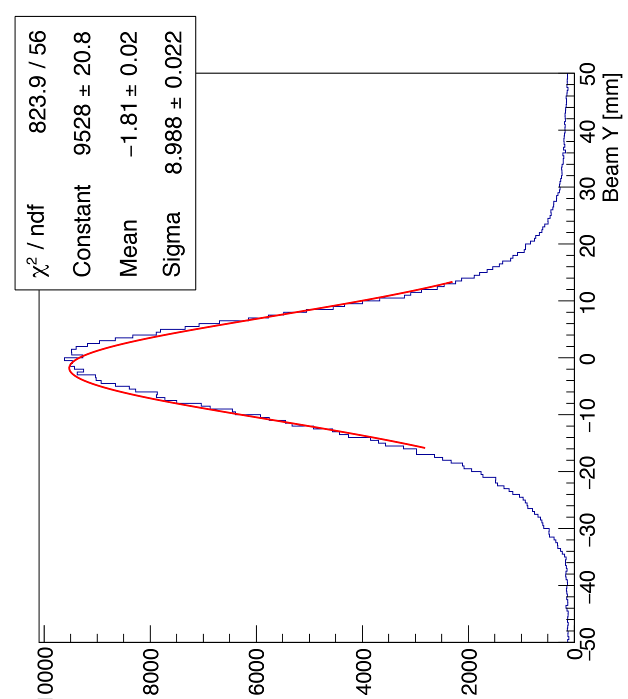
Beam Properties (100 GeV/c)

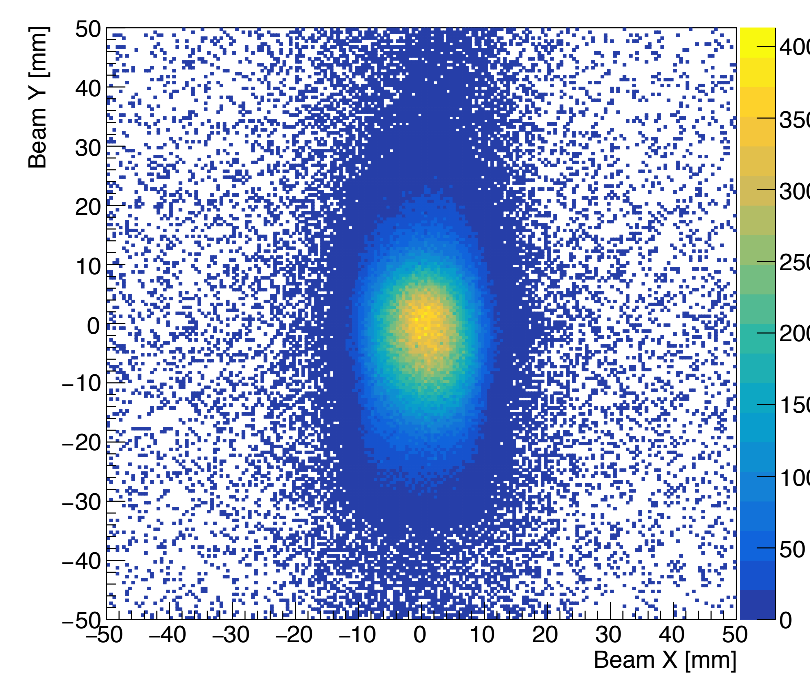


Beam file available:
- Focused at z = -1000 mm
- Mostly parallel over 8 meters
- Contains tagged halo component









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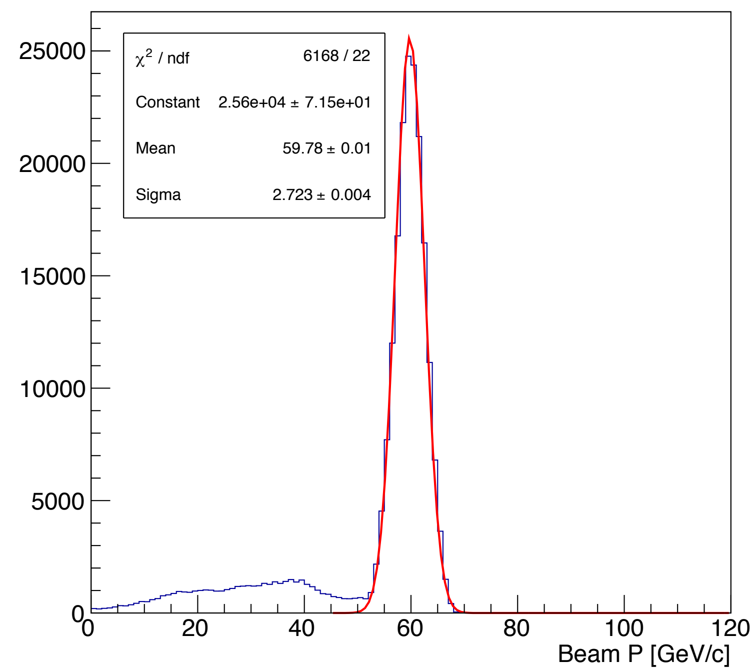
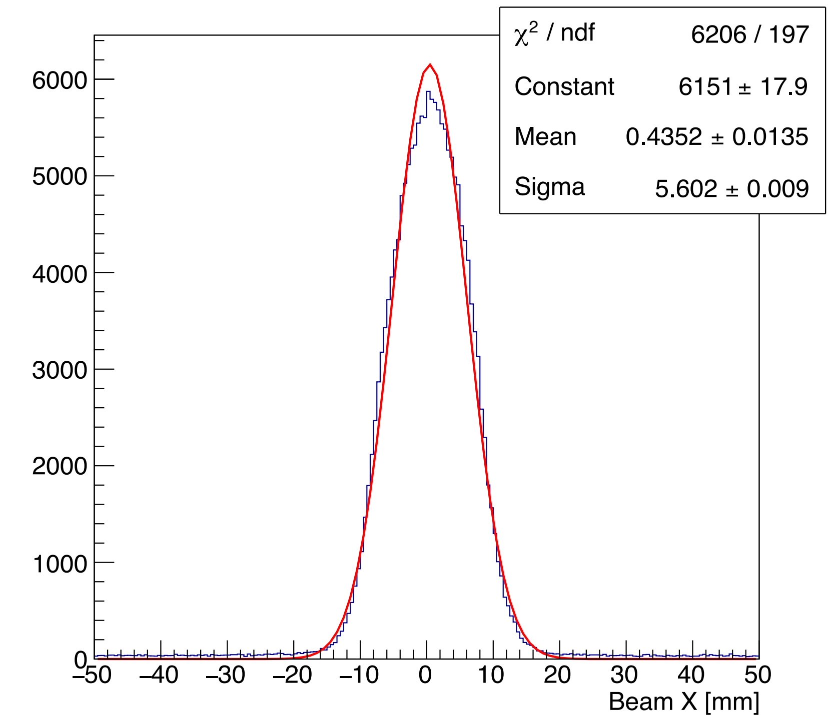
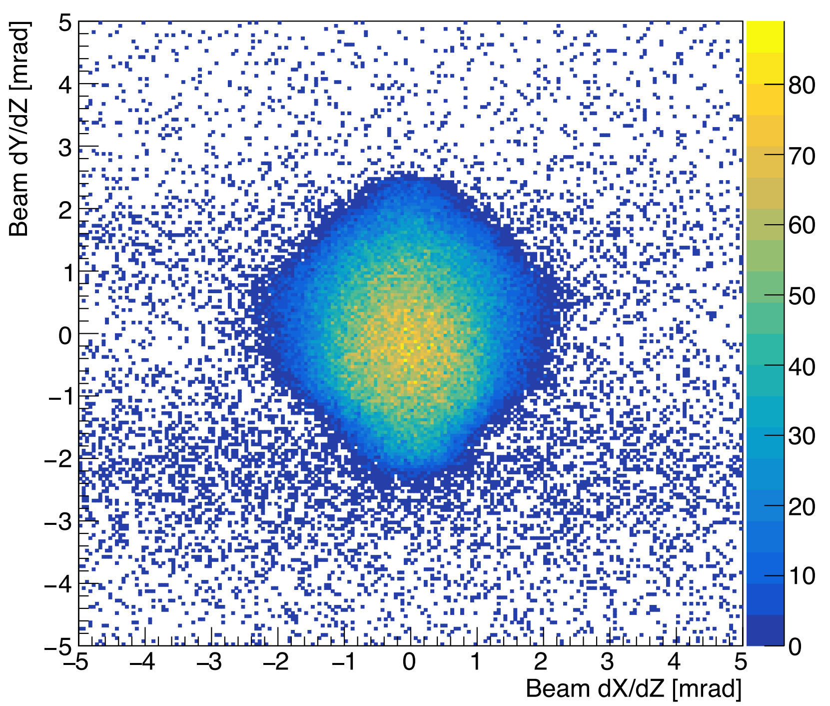
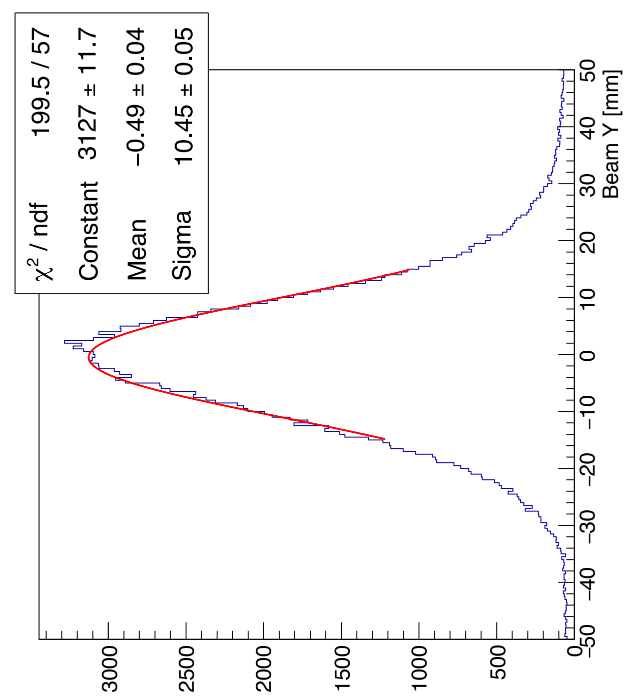
Beam Properties (60 GeV/c)

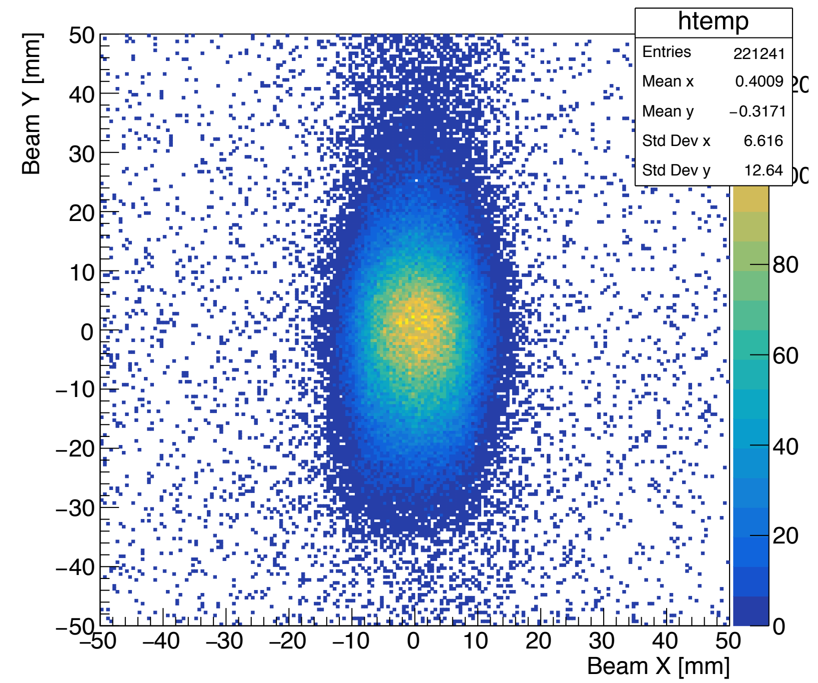


Beam file available:
- Focused at z = -1000 mm
- Mostly parallel over 8 meters
- Contains tagged halo component









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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