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Physics Department
Technical University of Munich

AMBER Proton Radius Measurement Programm: Status and Perspectives

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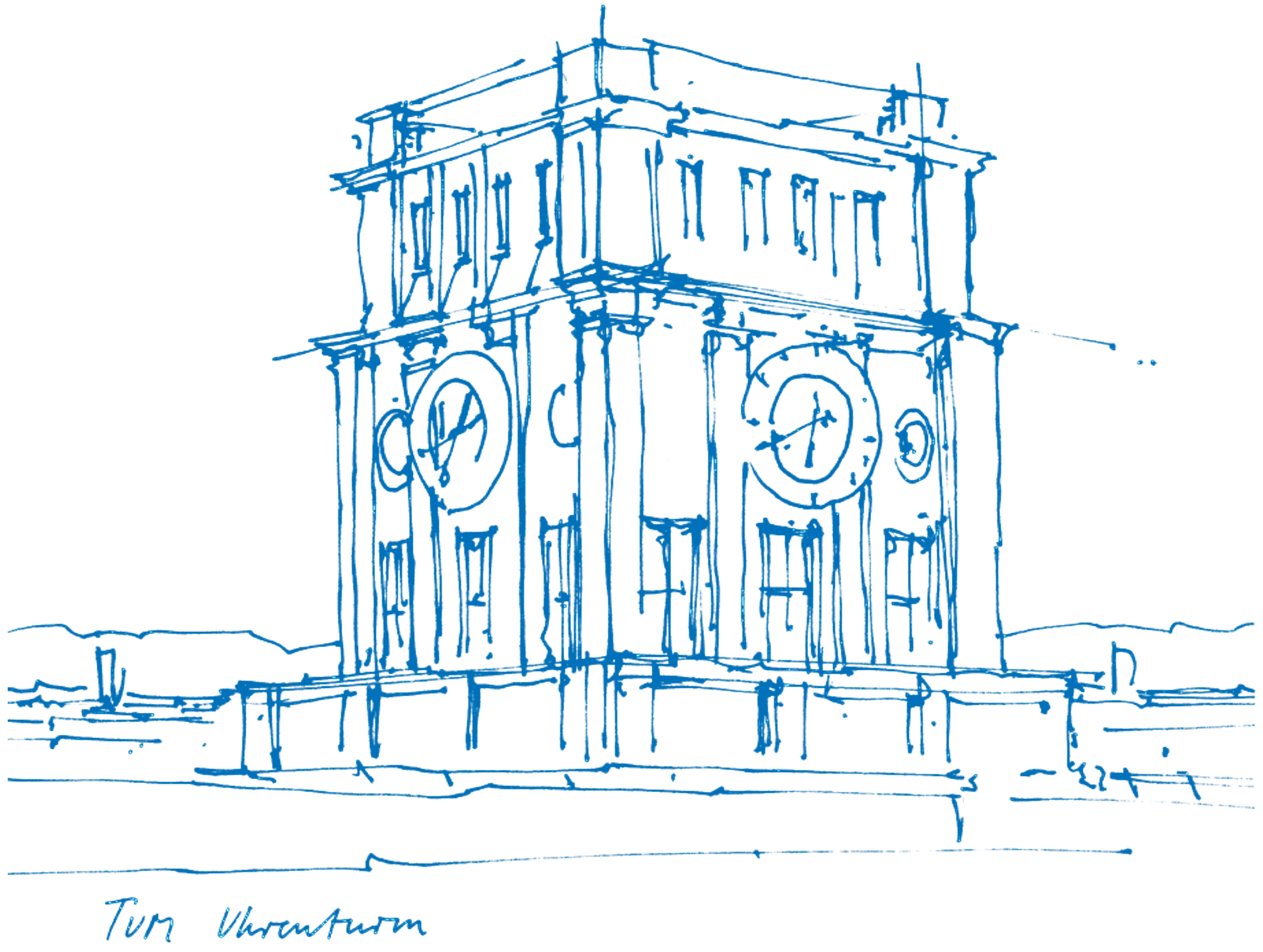
International Workshop on Hadron Structure and Spectroscopy
August 29th, 2022
CERN

On behalf of the *AMBER* Collaboration



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The Proton-Charge Radius

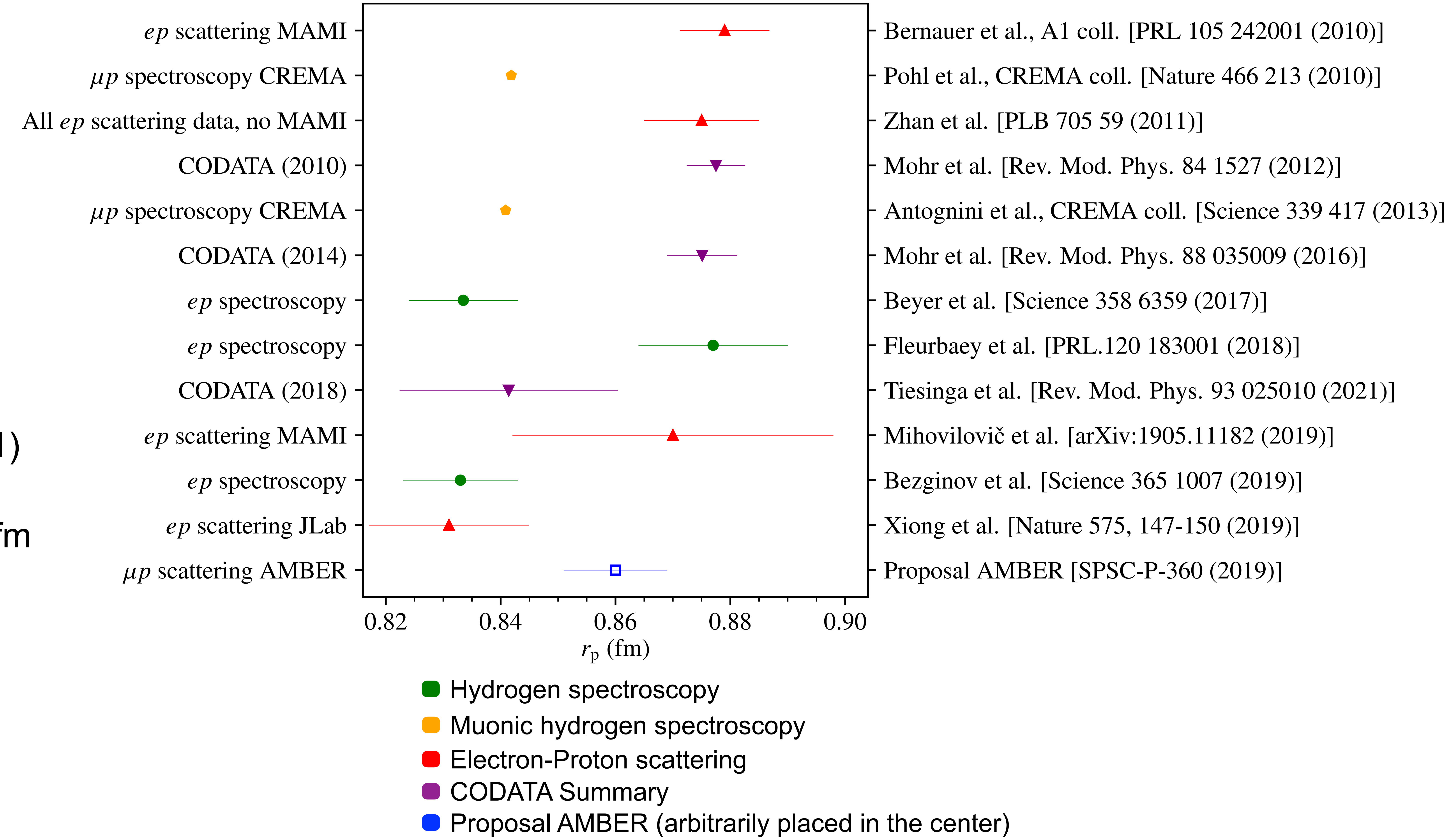
Data from spectroscopy and electron-proton scattering

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±0.001) fm

- Elastic electron-proton scattering:
  → Measurement using momentum transfer
  → Recent data: MAMI A1 (2010) or JLab (2011)
  → Favoured value of (0.879±0.008) fm
  → New in 2019: PRad value of (0.831±0.014) fm

- Two significantly different values obtained
  → The <u>proton-radius puzzle</u>



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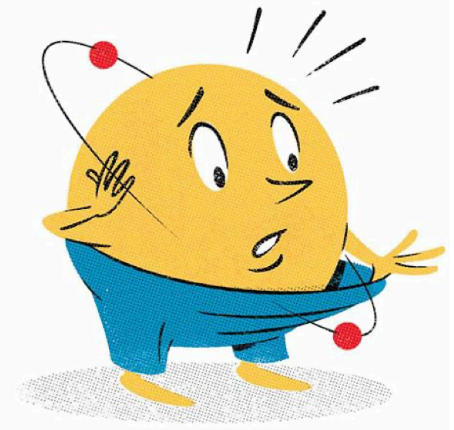
Upcoming Experiments Addressing the Puzzle

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
  → Recent publication of results: smaller value
  → PRad2: detector upgrade planned
- **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/electron-proton with $E_{e,\mu}$ < 140 MeV
  → Comparison of electron and muon scattering
  → Data production ongoing, more data to come
- **ULQ2/Tokuha:** electron-proton E_e = 20 – 60 MeV
- **ProRad@PRAE:** electron-protons E_e = 30 – 70 MeV

Proton Radius Experiment at Jefferson Lab



ULQ² collaboration (Ultra-Low Q²)

- **Missing**: muon-proton with E_μ of $\mathcal{O}$(10 - 100 GeV)

→ Data for high-energy elastic muon-proton scattering
→ Test of lepton universality
→ Different systematics compared to others
→ **Proton Radius Measurement @ AMBER**

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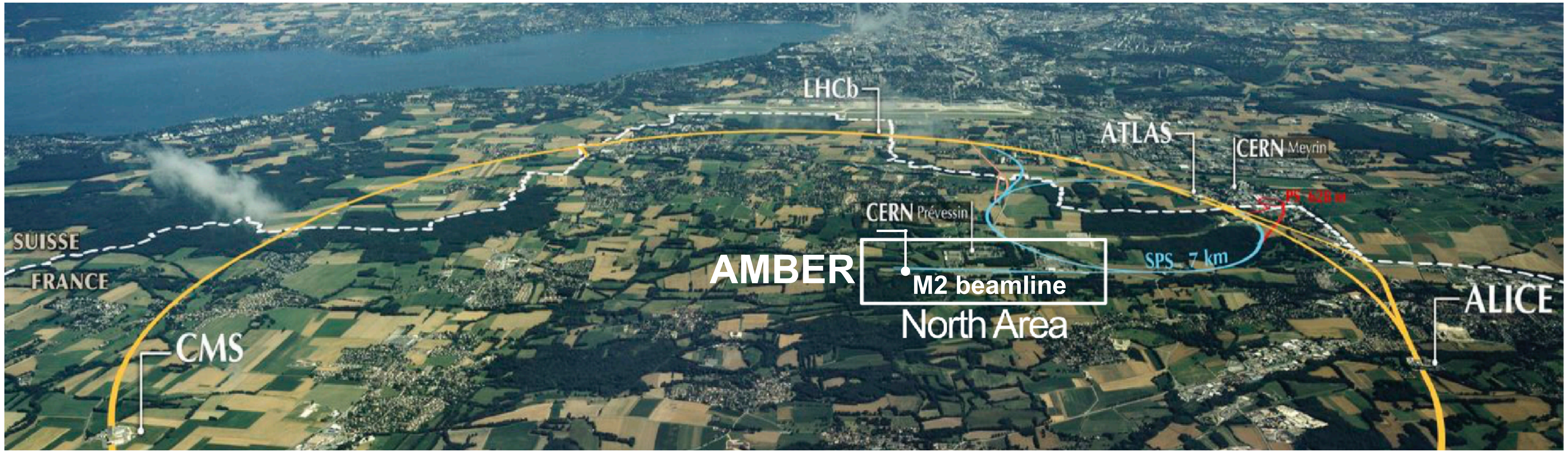
Location for High-Energy Muon Beams

The M2 beamline at *CERN's SPS*

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



CERN

- Muon momenta up to 200 GeV/*c* with a flux up to 10^7 μ/s — PRM: beam momentum of 100 GeV/*c* and 2 MHz beam rate
- After 25 years: *AMBER* as successor at *COMPASS* location started from 2021 with the first pilot run in October 2021
  → Broad physics program: PRM, Drell-Yan, anti-proton production cross-section, usage of radio-frequency separated beams

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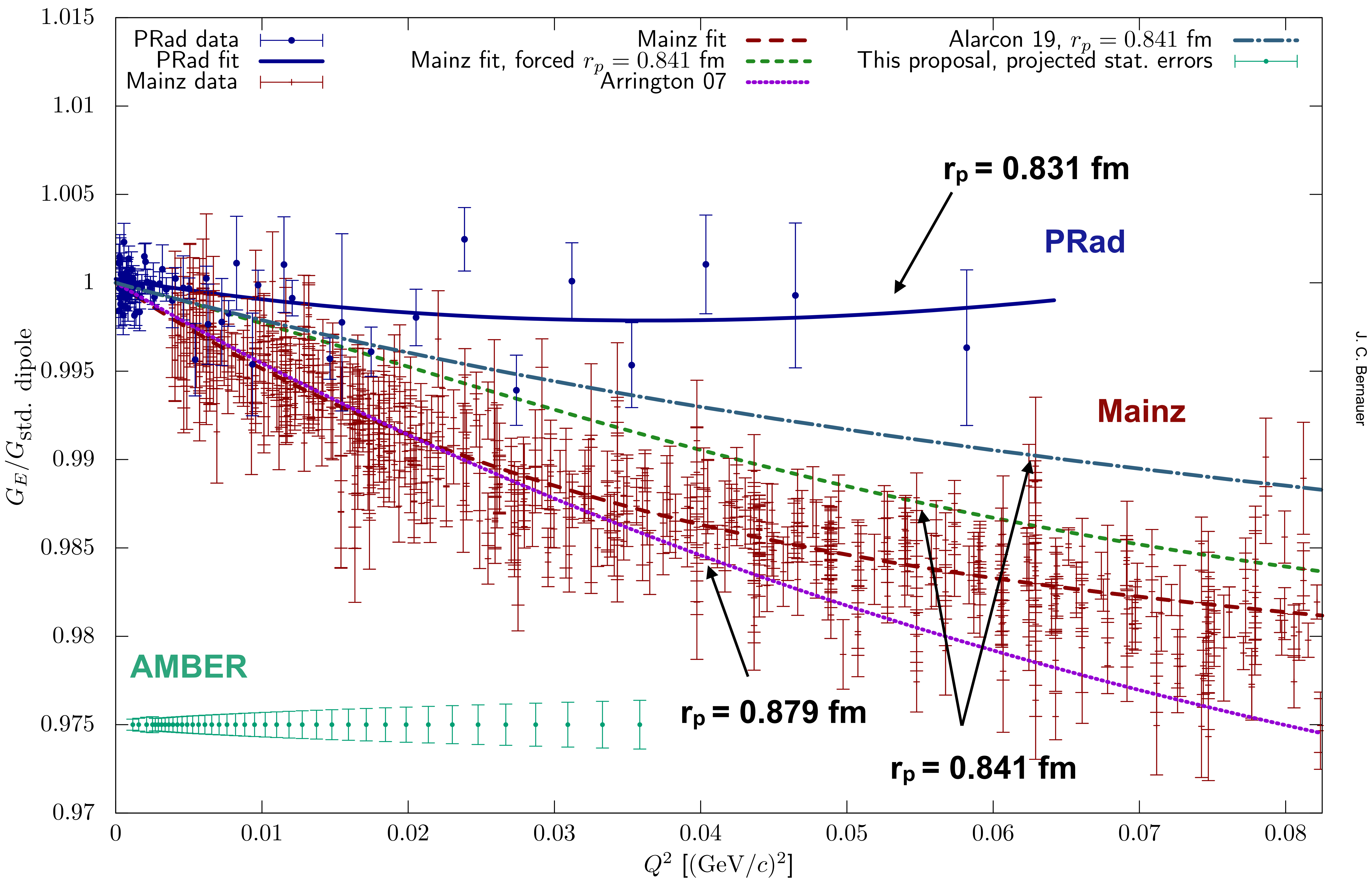
Proposal of a New Measurement

High-energy elastic muon-proton scattering

Measurement of the cross-section of elastic muon-proton scattering using the *CERN M2* beamline. (SPSC-P-360)

$$< r_p^2 > = -6\hbar^2 \cdot \frac{dG_E(Q^2)}{dQ^2}\Bigg|_{Q^2\to 0} \qquad \frac{\mathrm{d}\sigma^{\mu p\to\mu p}}{\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4} R\left(\epsilon G_E^2 + \tau G_M^2\right)$$

- Measure as close as possible to $Q^2 \to 0$
  - → suppress influences from higher order form-factor terms
  - → high-energy $\mathcal{O}$(10 - 100 GeV) — Cross-section ∝ G_E^2
- Disagreement on experimental data: PRad and MAMI
- Sufficient range to determine radius:
  - → Aimed precision of below 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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Layout of Proton-Radius Measurement

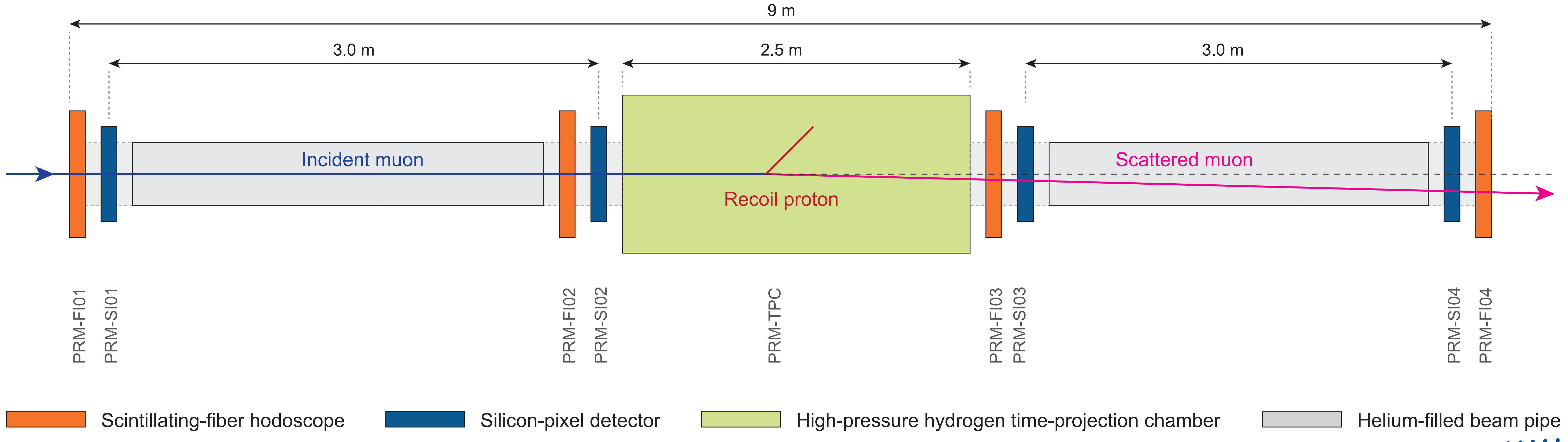
Measurement of low-Q^2 elastic-scattering events
New approach: Combined measurement of low-energetic recoil-protons and scattered muons at small scattering-angles.

- Time-Projection-Chamber (TPC) as an active target to measure recoil protons
- Silicon trackers along long leaver-arm to measure small scattering-angles
- Scintillating fibers for timing and tracking

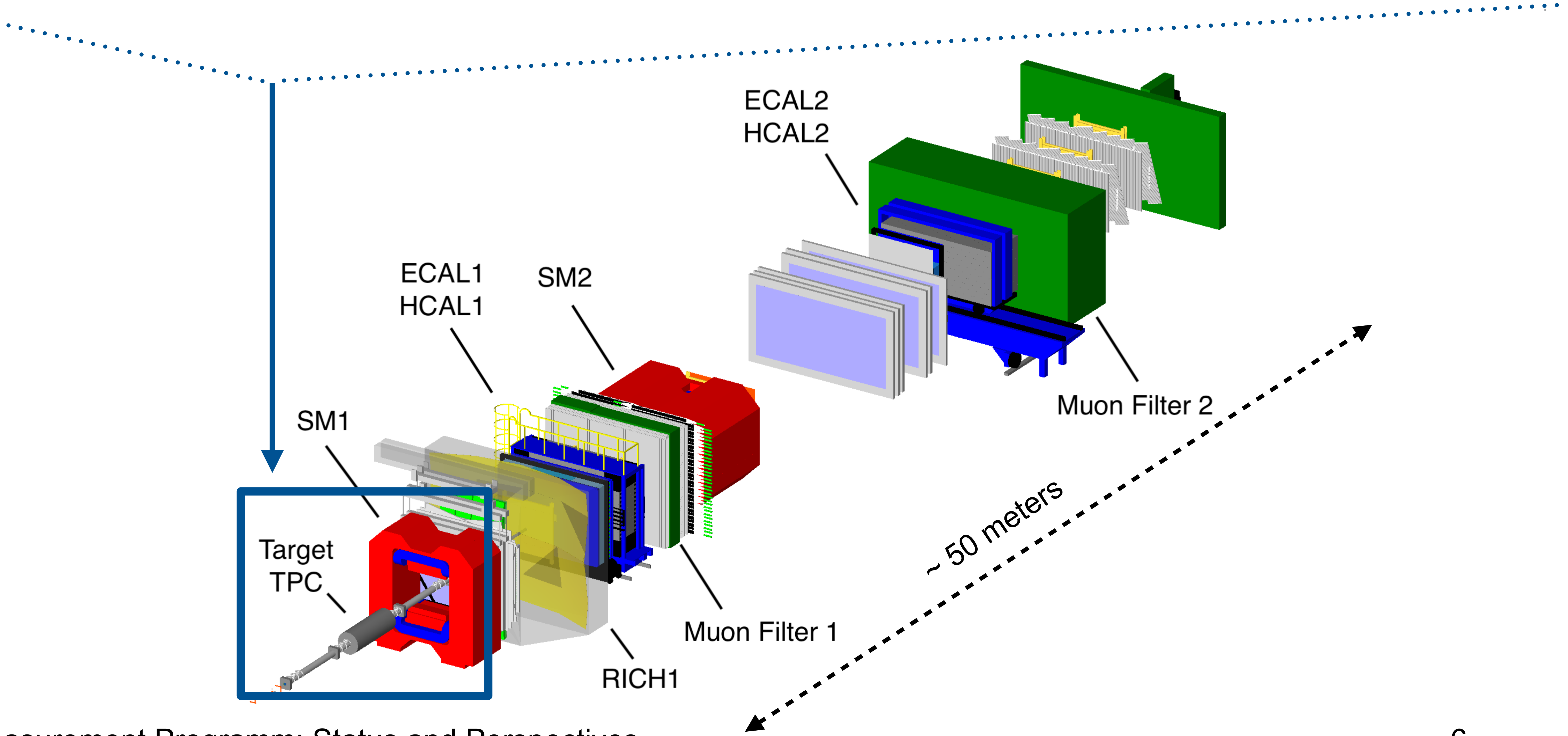
→ Combined in an Unified Tracking Station (UTS)

- New continuously-running DAQ required

- *AMBER* spectrometer:
  → Momentum measurement of scattered muon
  → Radiative background using electromagnetic calorimeter
  → Muon identification with muon filter and hodoscope



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



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Small Scattering-Angle Tracking

Unified Tracking Station — UTS

Dedicated station with high-resolution silicon pixel-detectors and scintillating fibers for muon tracking in the target area.

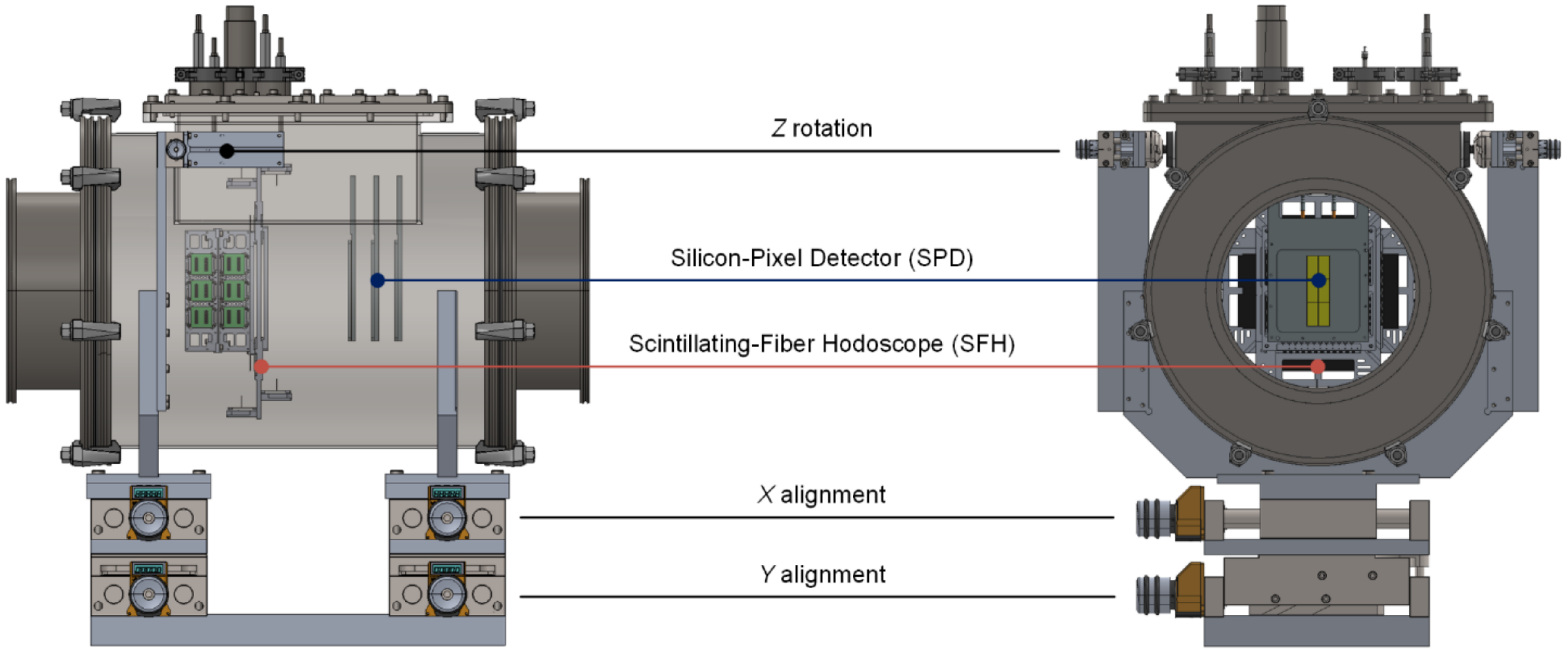
- Four stations in total planned
  → Two upstream and two downstream surrounding the TPC

- Three Silicon Pixel-Detector (SPD) planes:
  → Based on ALPIDE chips in covering an area of 9 x 9 cm^2
  → Spatial resolution of about 8 μm with 5-10 μs integration time
  → Problem of pile-up at larger beam rates

- Four Scintillating-Fiber Hodoscope (SFH) planes:
  → Based on 500 μm thick fibers with SiPM readout (9.6 x 9.6 cm^2)
  → Provide hit-time information for the SPD to disentangle pile-up

- Simplistic hit-time association between SFH and SPD shows promising efficiencies of > 99 % up to 10 MHz — further improved with full tracking

- Optimised material budget per station of about X/X_0 = 1.3 %



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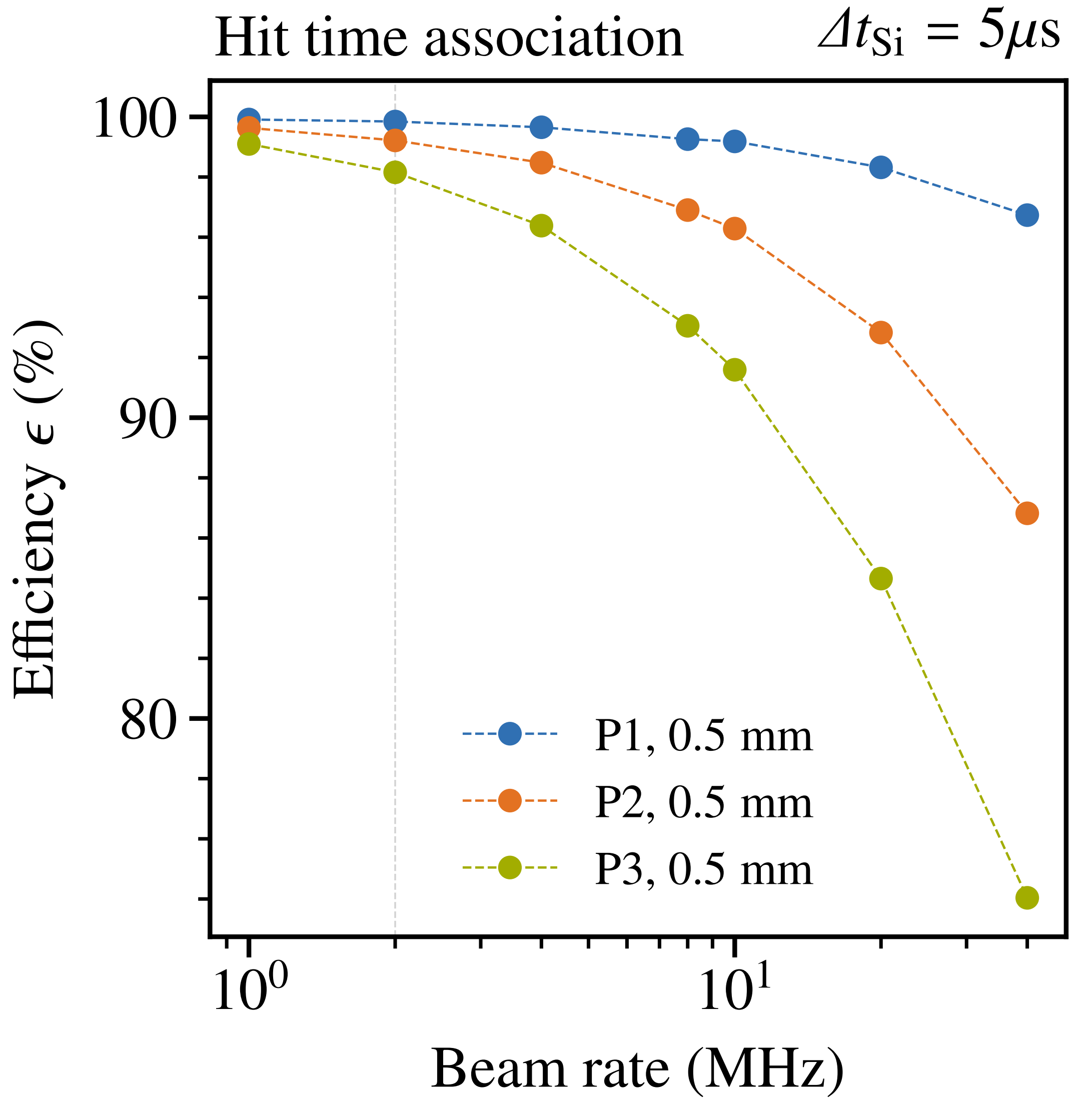

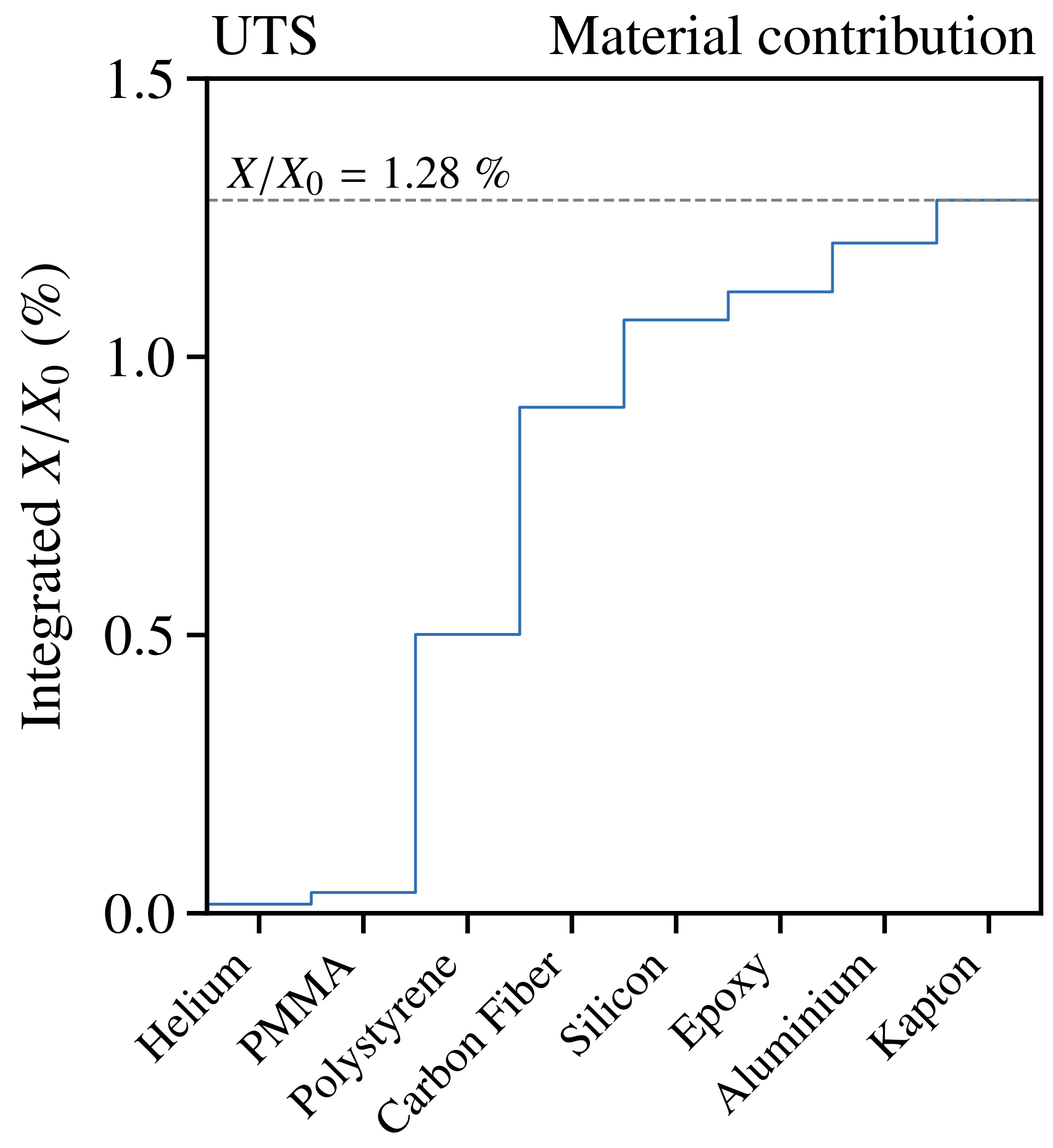

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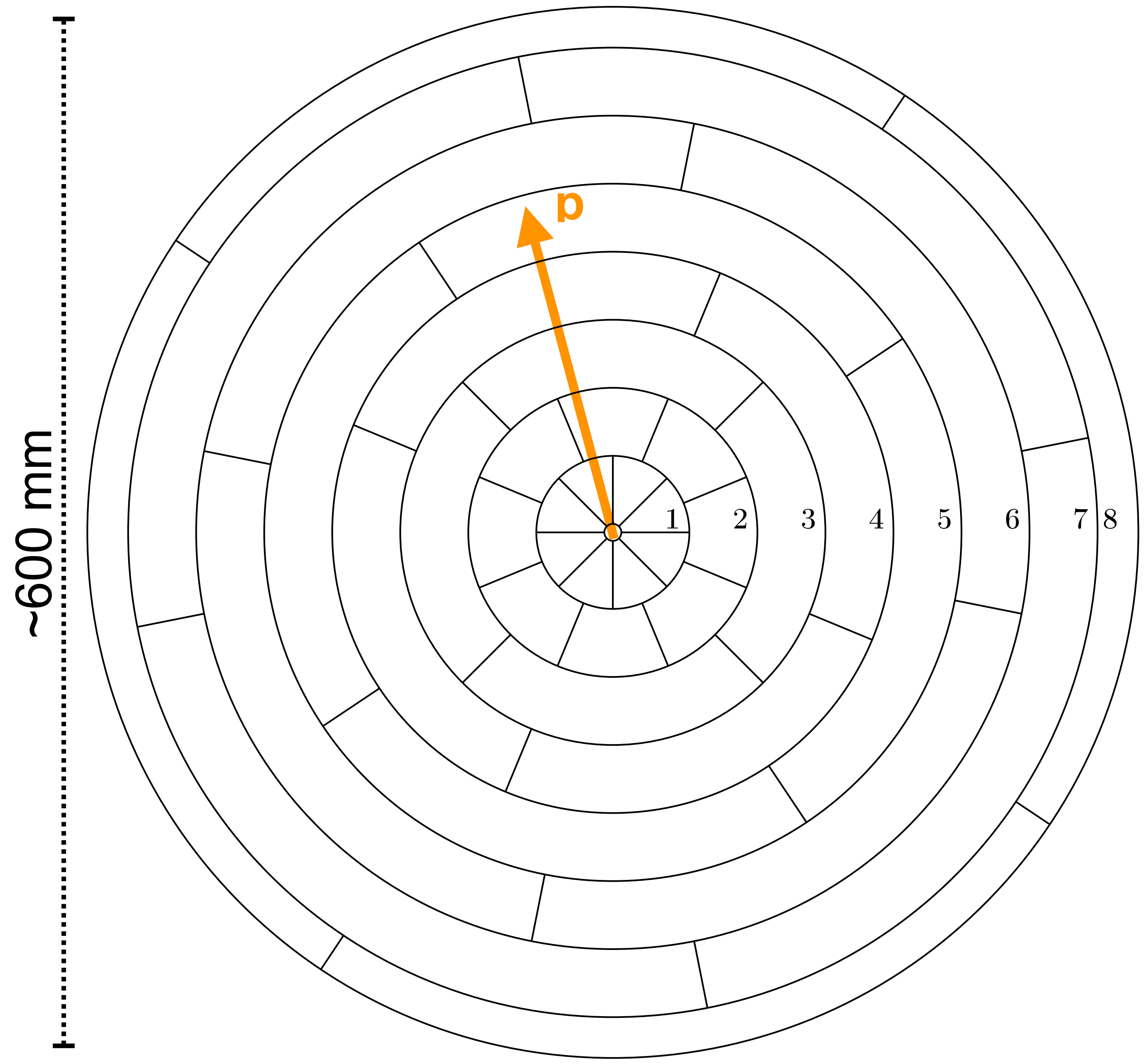
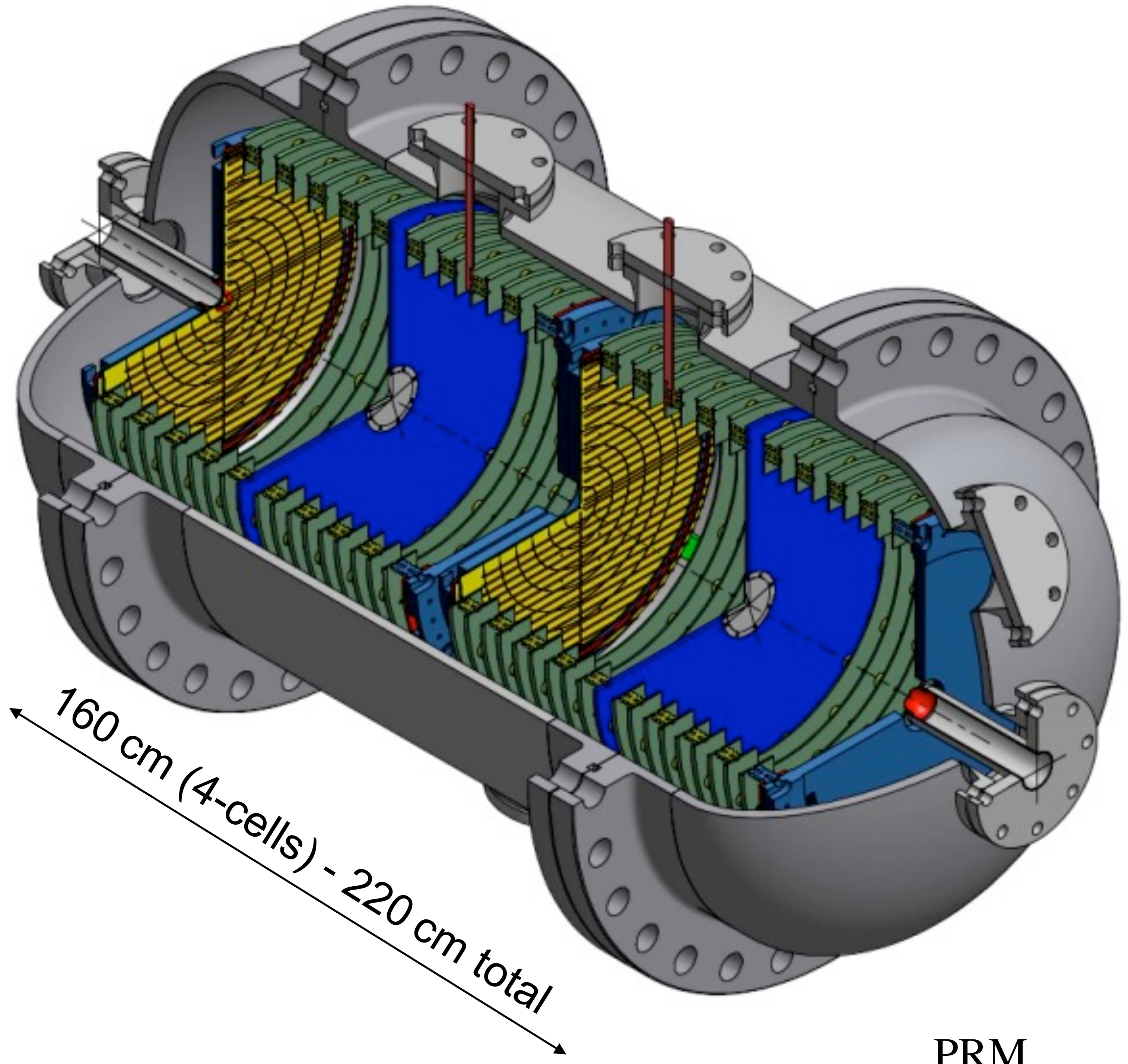
Detection of Low-Q^2 Recoil-Protons

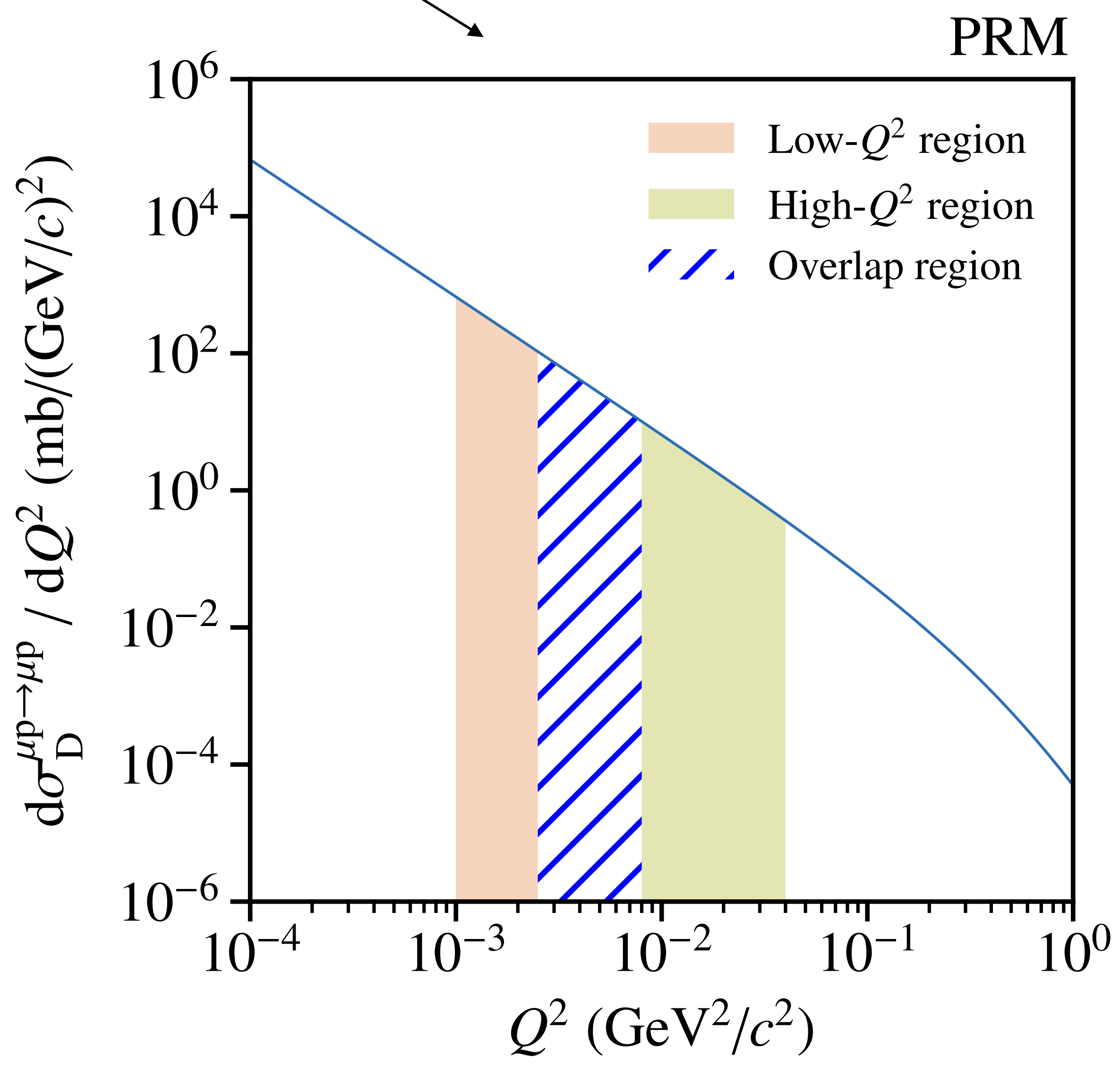
Pressurised hydrogen active-target TPC

Direct recoil-proton momentum measurement with active target.

- 4x 40 cm long drift cells
  → Hydrogen pressure up to 20 bar
  → Direct energy measurement without amplification
- Segmented readout plane for each cell:
  → Spatial and angular resolution (both θ and φ)
- Transmitted Q^2 affects range of recoil proton:
  → Recoil-proton ranges of 2 - 300 mm (and more)
- Active target: beam induced ionisation noise
  → Central beam region mostly affected
- Measurement at two pressure settings required:
  → 4 bar ($Q^2 < 0.0025$ GeV$^2/c^2$)
  → 20 bar (0.001 GeV$^2/c^2 < Q^2 < 0.04$ GeV$^2/c^2$)
  → Low-pressure region to correct noise at small-Q^2 events
  → Two overlapping datasets (estimate: 6 + 27 million events)
  → Energy resolution < 6 % required for aimed precision < 1 %







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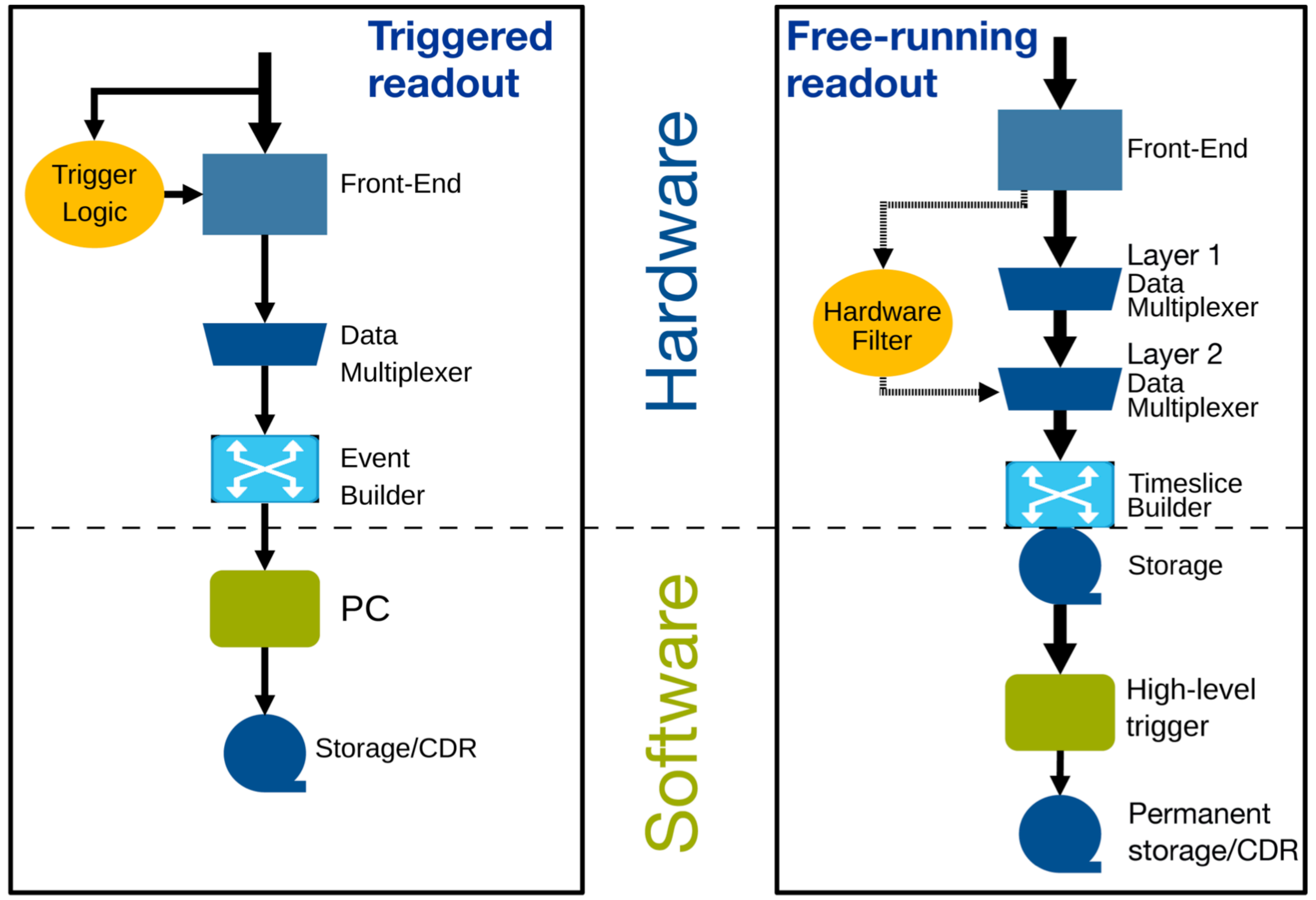
New Streaming DAQ with High-Level Trigger

New DAQ development for AMBER and PRM
Combination of slow and fast detectors with a continuous readout and software trigger logic for data reduction.

- Initially: Hardware trigger logic
  → Storage of data in front-end electronics up to $\mathcal{O}$(μs)
  → Example PRM: TPC drift time ~100 μs
- Transition: Trigger-less front-end electronics
  → Data stream sorted in time slices
  → Detector data ordered in time images based on to resolution
- Hardware event builder stores data
  → High-level trigger selects time slices + images
  → Example PRM trigger: TPC recoil proton event
- New DAQ hardware installed; tests are ongoing
- Conversion required from the new streaming format into an event definition



DOI: 10.1109/TNS.2021.3093701

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

Design Properties of the Core Setup

Setup optimised layout for small scattering-angle measurement
Core setup crucial for precise muon scattering-angle and recoil proton measurement.

- Combined measurement of recoil-protons via TPC and muon scattering kinematics via tracking

- Tracking: final option 3 m baseline

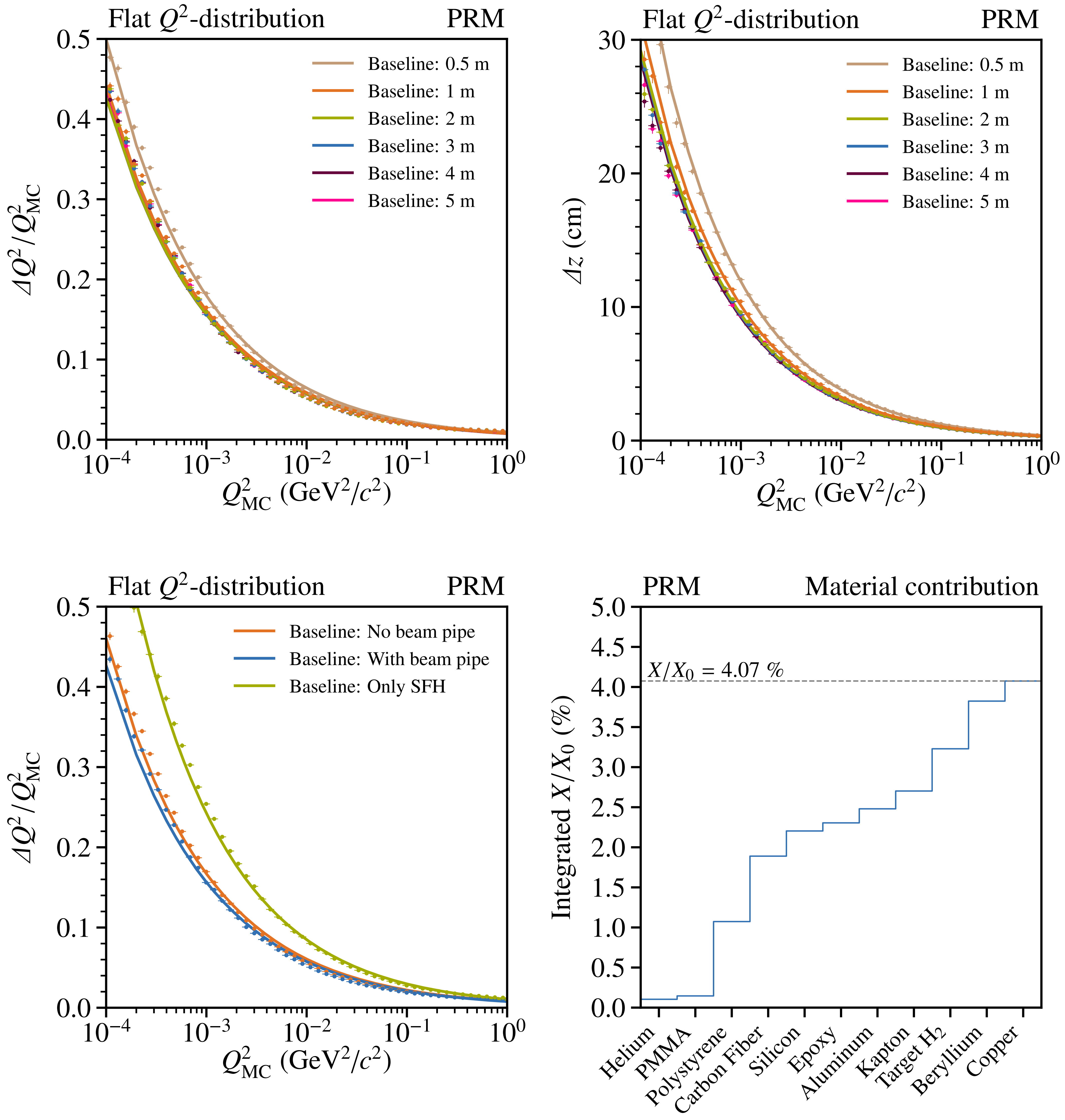
→ Relative Q^2-resolution of ~15 % — TPC recoil energy around 6 %
→ Vertex z-resolution of ~8 cm — combine with TPC drift time: $\mathcal{O}$(mm)

- Different studies performed:

→ Usage of helium-filled beam pipes further improves Q^2-resolution
→ Only using SFH worsens the Q^2-resolution by ~2x

- Low total material budget: $X/X_0 = 4.1$ % (θ_{MS} = 24 µrad)

→ Optimised UTS designs for the SFH and SPD
→ Very homogenous distribution around beam axis
→ TPC main contribution Beryllium beam windows (total $X/X_0 = 1.45$ %)



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Control of Systematic Effects

Absolute calibration, inefficiencies, and background

Understanding of systematic effects is crucial for precision.

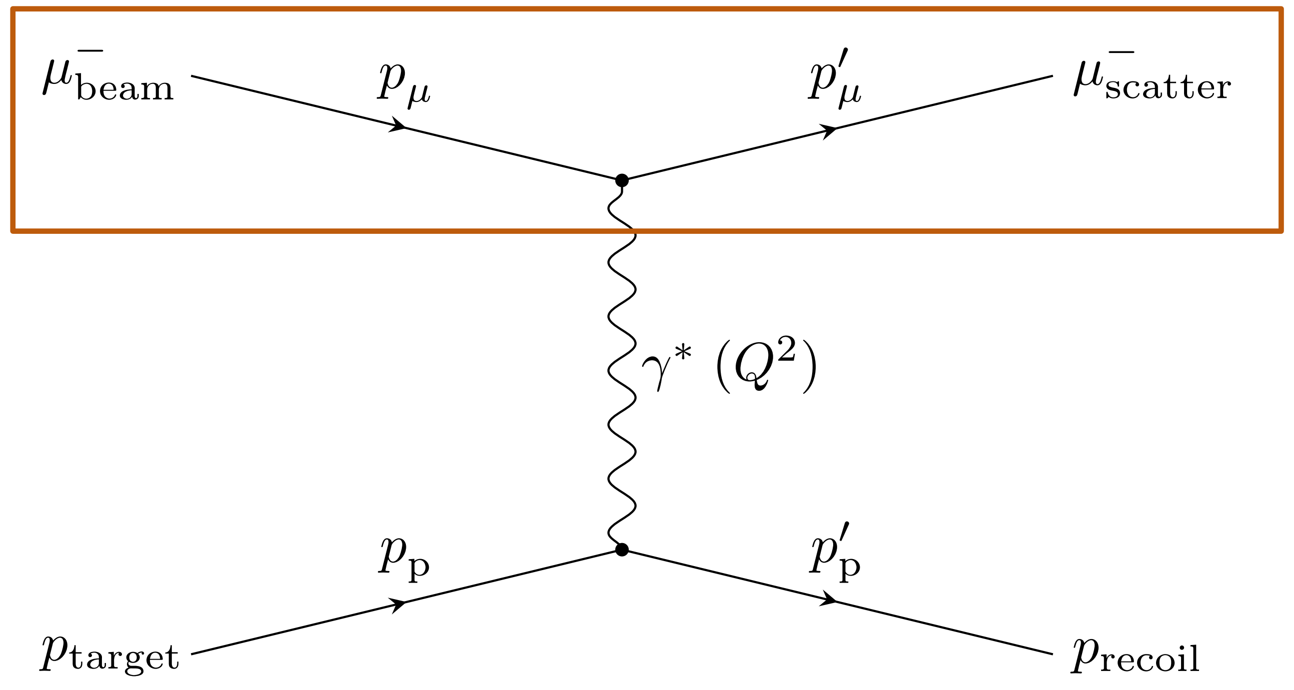
- Absolute calibration of the TPC recoil-proton energy-scale
- Inefficiencies in recoil-proton measurement
- Cross check of TPC measurement

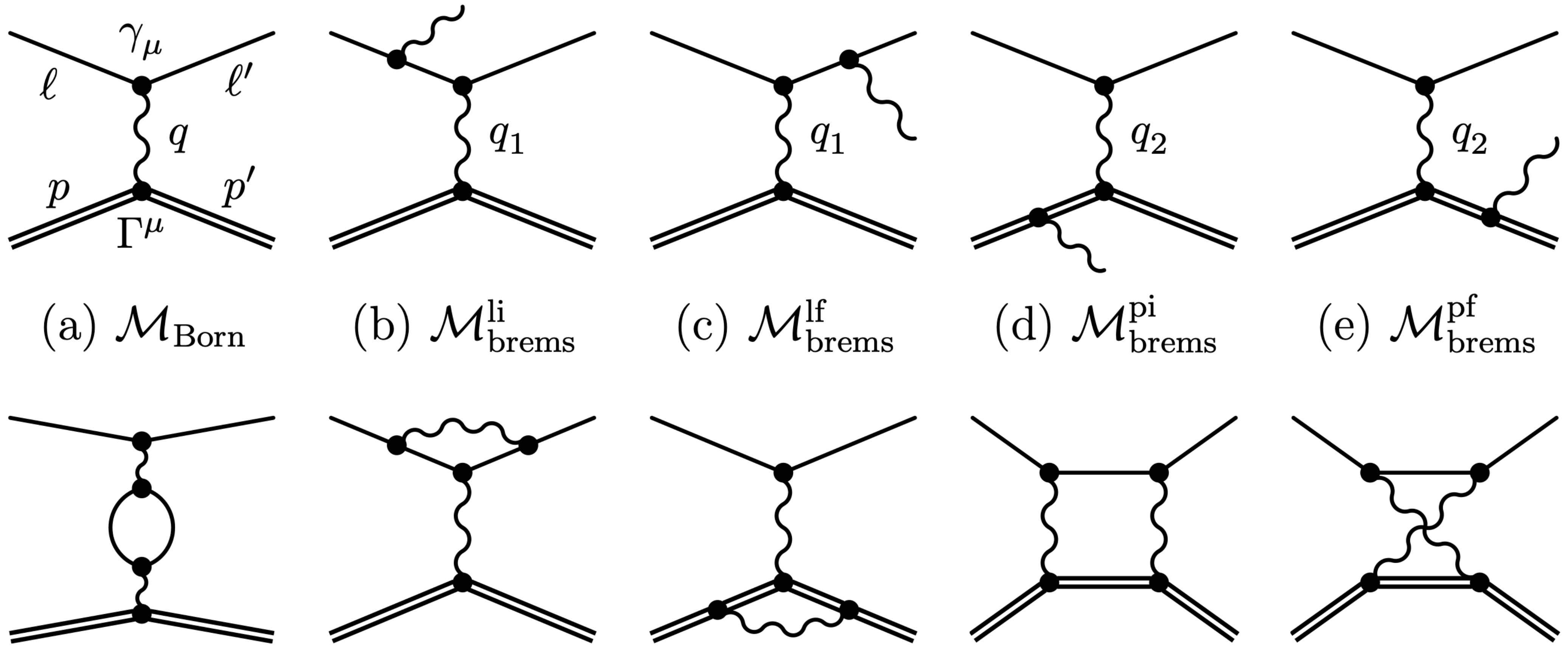
> Redundant measurement to control systematics
> → Measurement of scattered muon kinematics

- Lepton-proton scattering accompanied by bremsstrahlung

→ NLO process on $\mathcal{O}(10^{-4})$ level for $E_\gamma > 500$ MeV
→ Distortion of Q^2-spectrum
→ For muons: lower radiative corrections compared to electrons

> Usage of *AMBER* spectrometer — tracking and calorimetry
> → Understanding of background
> → Muon momentum measurement





(a) $\mathcal{M}_{\text{Born}}$ (b) $\mathcal{M}^{\text{li}}_{\text{brems}}$ (c) $\mathcal{M}^{\text{lf}}_{\text{brems}}$ (d) $\mathcal{M}^{\text{pi}}_{\text{brems}}$ (e) $\mathcal{M}^{\text{pf}}_{\text{brems}}$

(f) $\mathcal{M}_{\text{vac}}$ (g) $\mathcal{M}^{\ell}_{\text{vert}}$ (h) $\mathcal{M}^{p}_{\text{vert}}$ (i) $\mathcal{M}_{\text{box}}$ (j) $\mathcal{M}_{\text{xbox}}$

ESEPP arXiv:1401.2959

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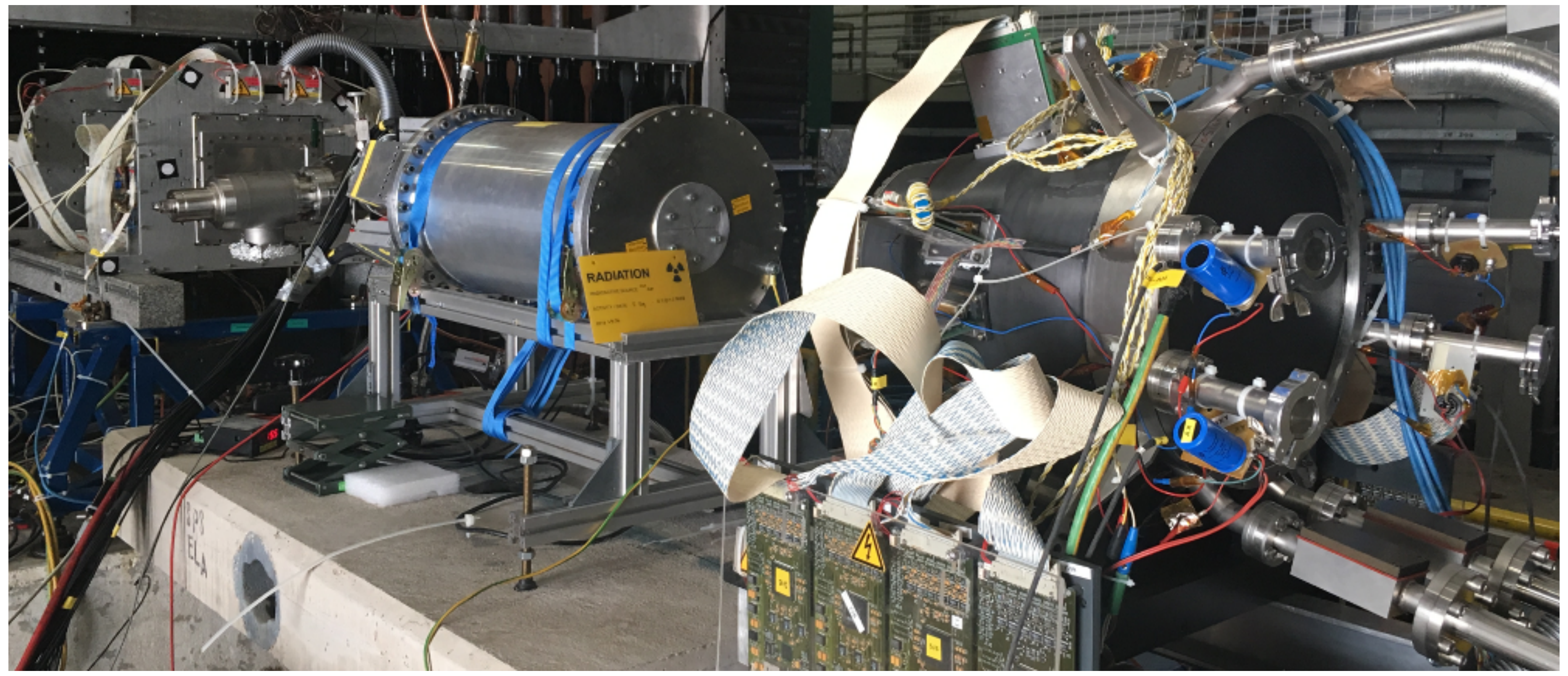
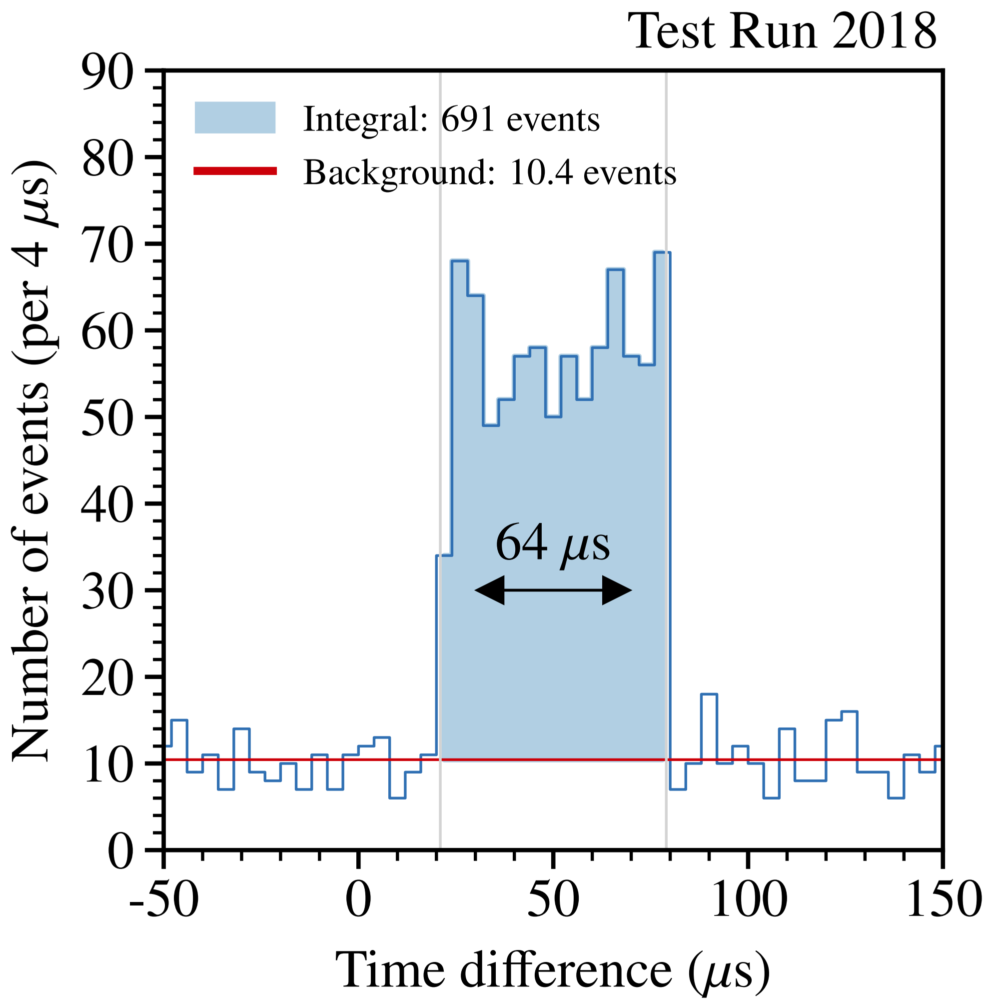
First Test Measurement performed in 2018

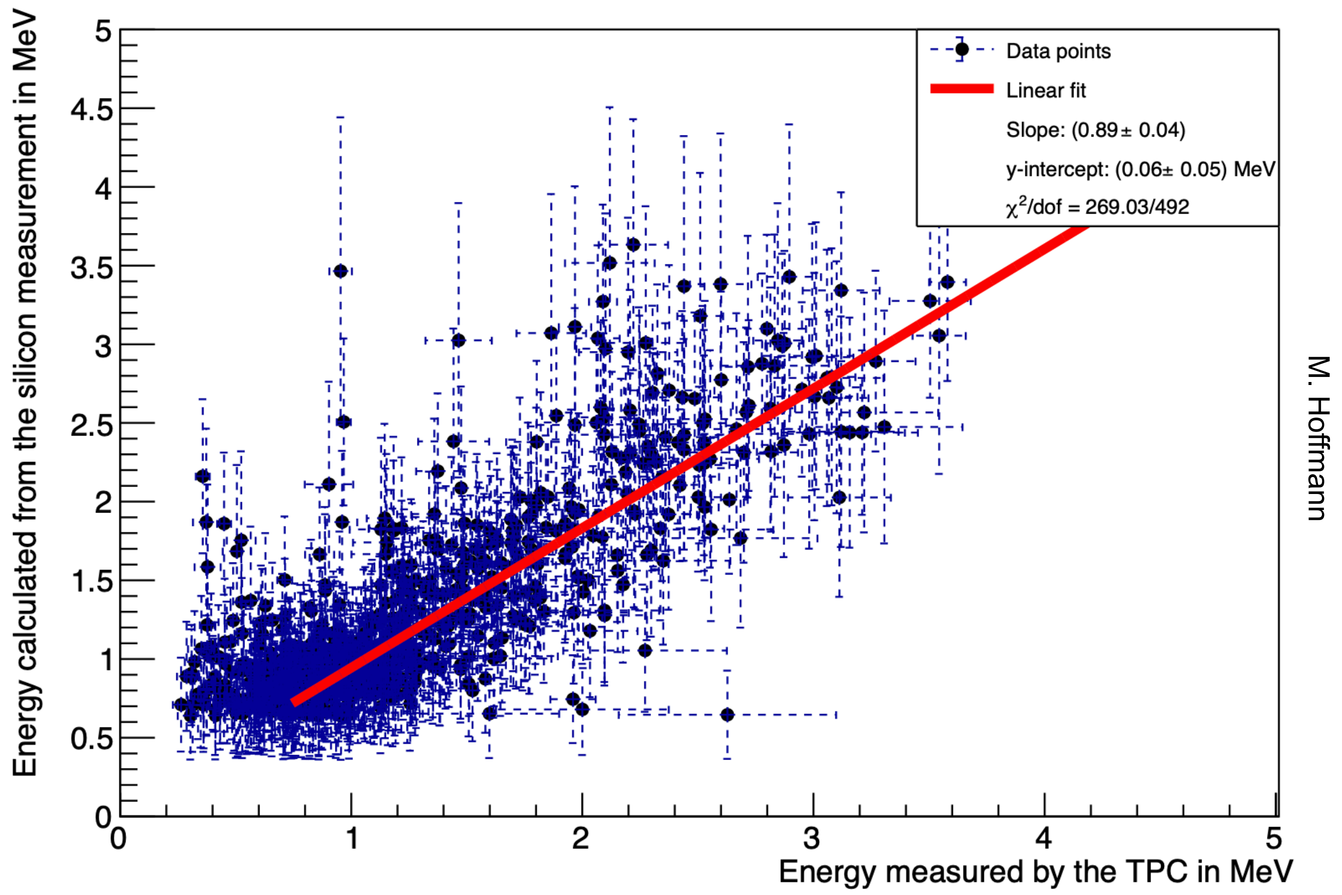
Feasibility test-measurement in 2018

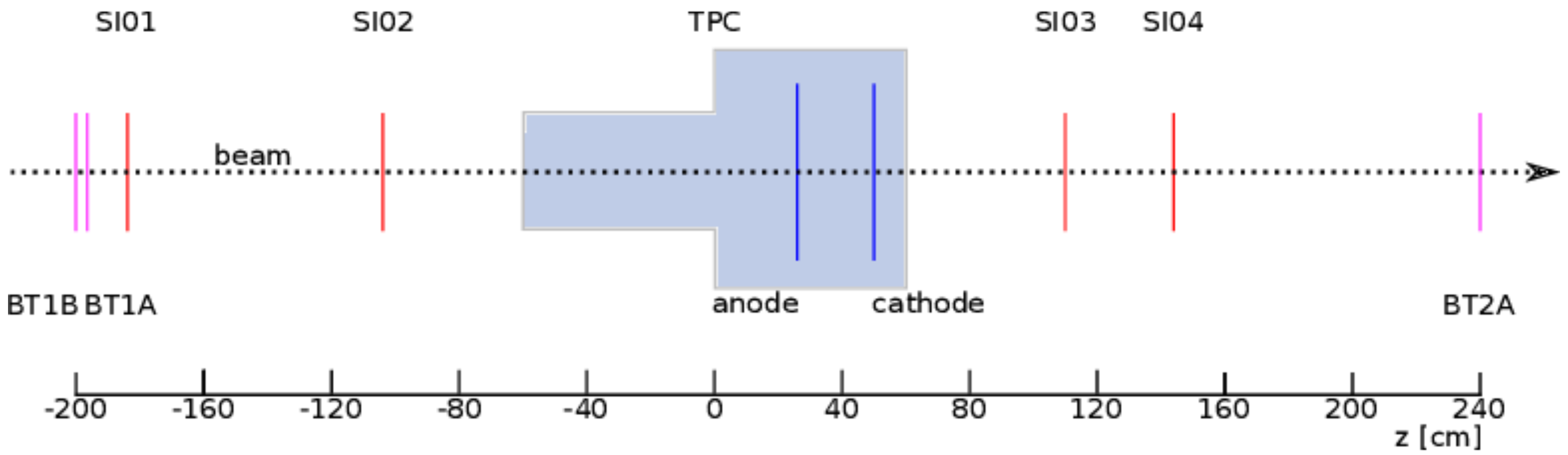
Using a simple setup with TPC (ACTAF2), silicon tracking-detectors and beam trigger.

- Goal: Proof-of-principle — working setup as in this “simple” manner
- Setup made use of parasitic *COMPASS* beam at a downstream test location
- General issue: combination of “slow” TPC with “fast” tracking detectors
- Synchronisation of two dedicated DAQ systems based on common timestamp
- First insigne on the beam-noise studies in a high-rate muon beam
- Association of muon tracks with recoil-proton events in the TPC matches expectation









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AMBER PRM - Pilot Run in October 2021

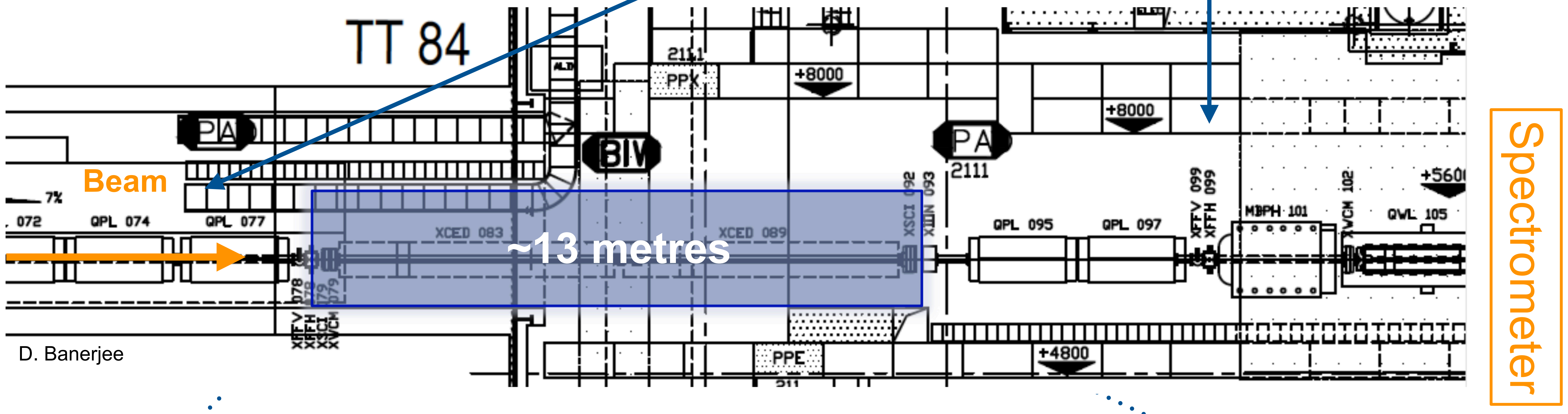
Pilot run required prior to a possible main run
Setup with close-to-final layout of the measurement to study overall properties of the setup in the test beam location in the M2 beam line.

- 21 days dedicated data taking (06.10. — 27.10.)
- Comparable geometry and beam settings

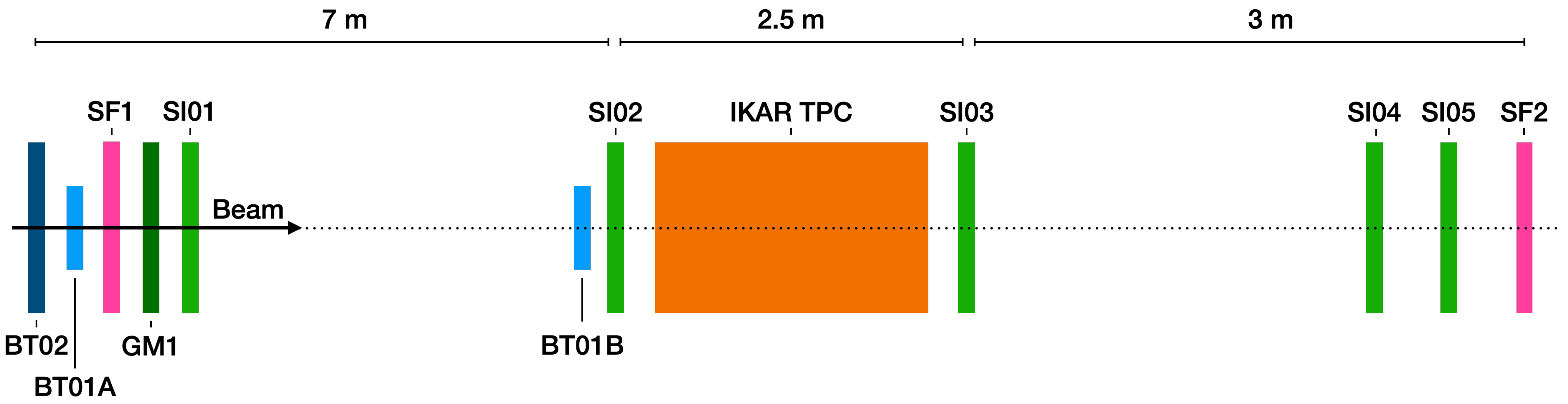
- TPC — downscaled: 2 chambers, p_{max} = 8 bar (IKAR):
  → Study beam-induced noise for different beam rates
  → Examine pressure and temperature effects
  → Evaluate readout structure

- Tracking — existing sci-fis, silicons and spectrometer
  → Provide tracking along TPC for studies
  → Produce data set for muon-proton event-matching
  → Evaluate spectrometer performance

Challenge:
- Inclined beam by 3.6 mrad
- Bending and focusing towards spectrometer required!



D. Banerjee



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First Preliminary Results — TPC

First look into the TPC data

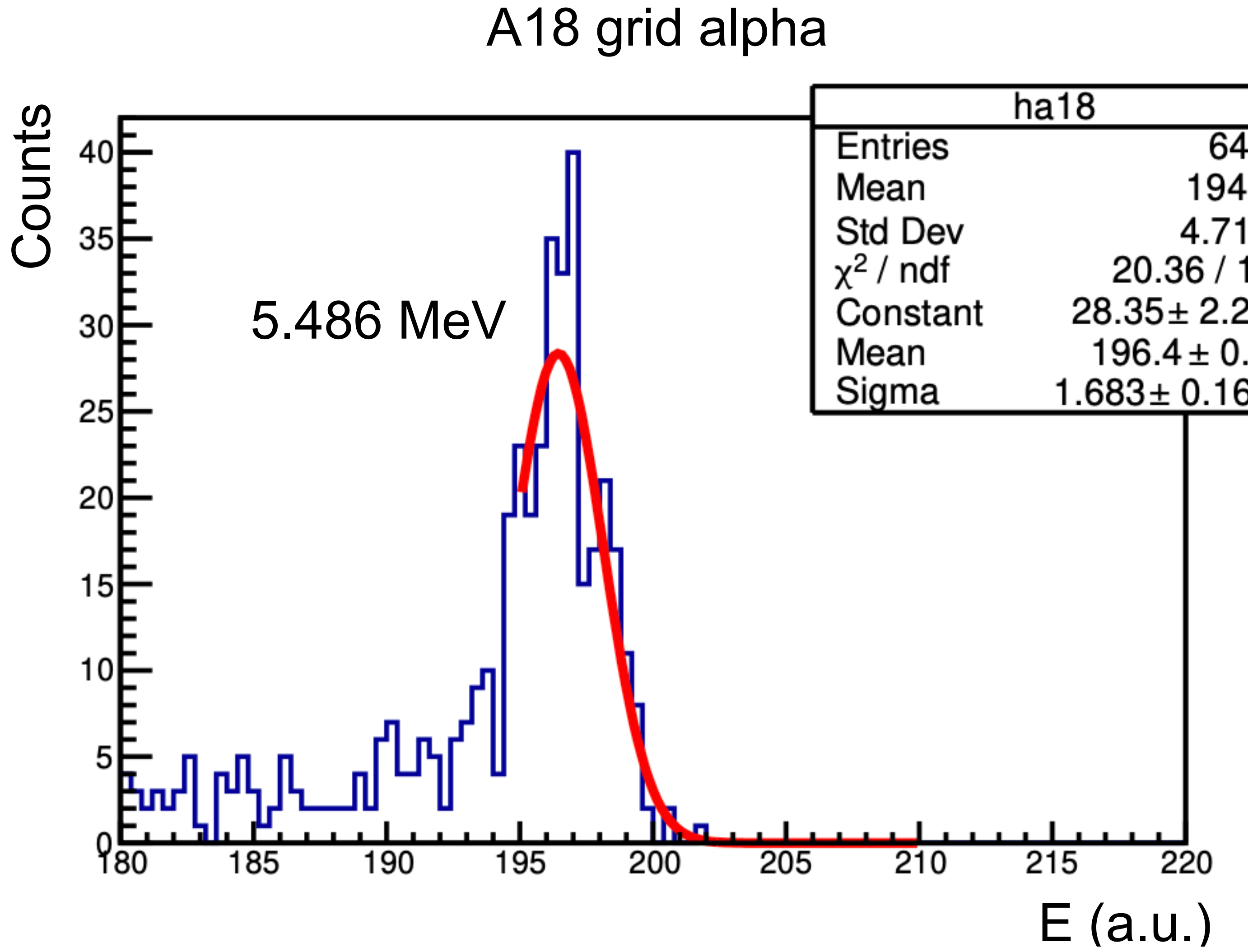
TPC data analysis ongoing. Focus on the study of the energy resolution.

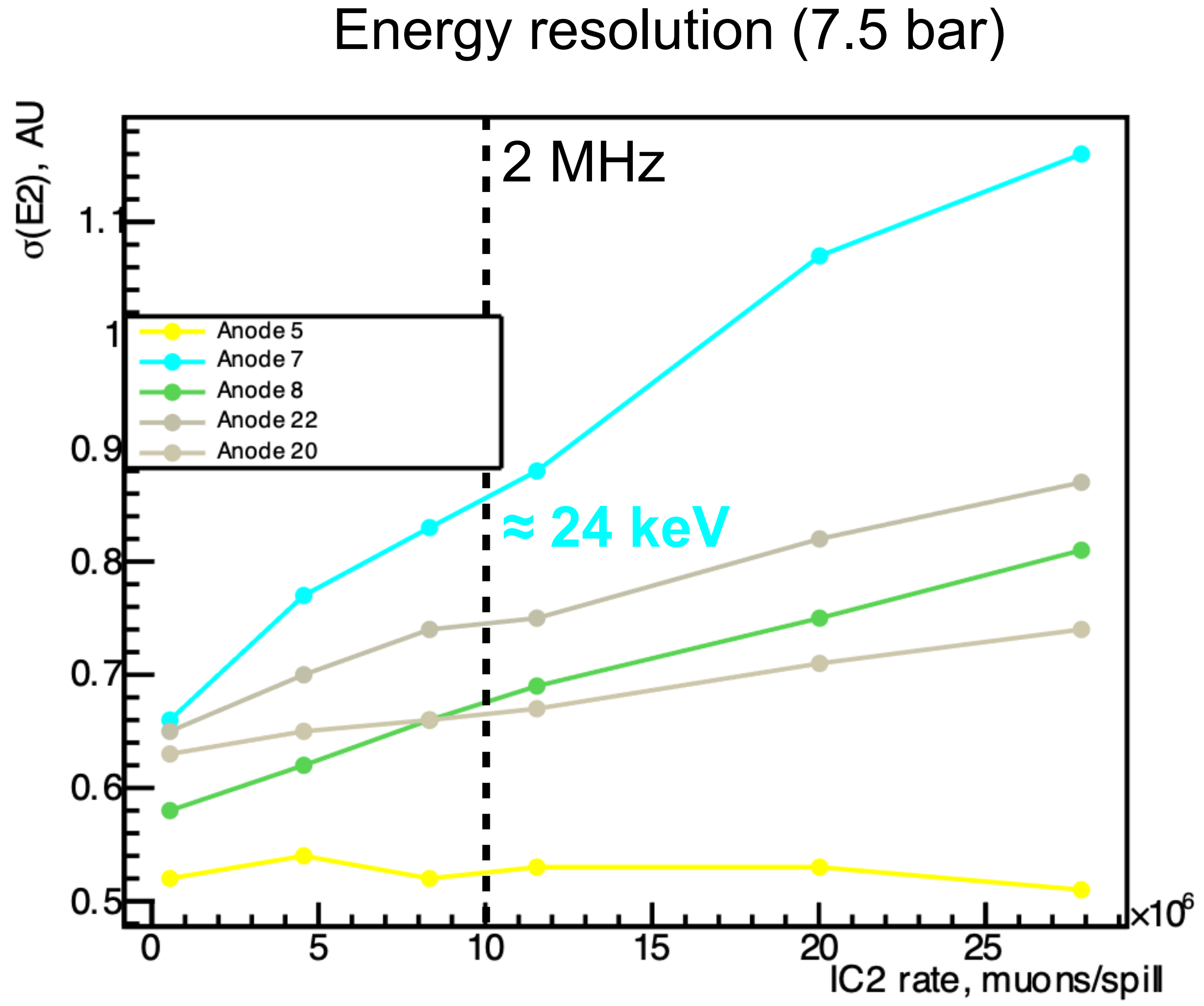
- Preliminary energy calibration based on different α-source (grid/cathode)
  → Challenge: self-absorption / signal splitting / gas attachment
  → Studies and work is on-going

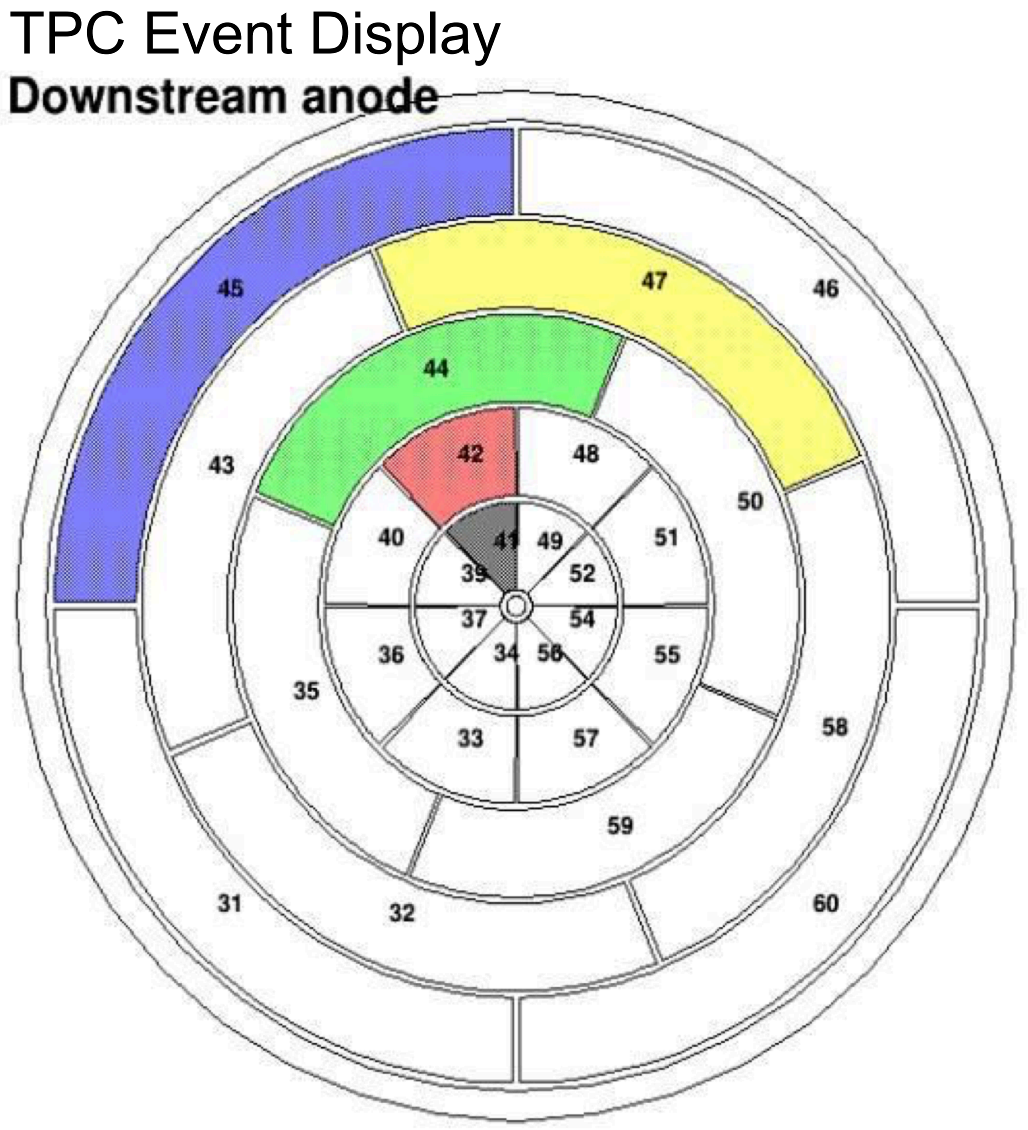
- Induced beam noise measured at different rates

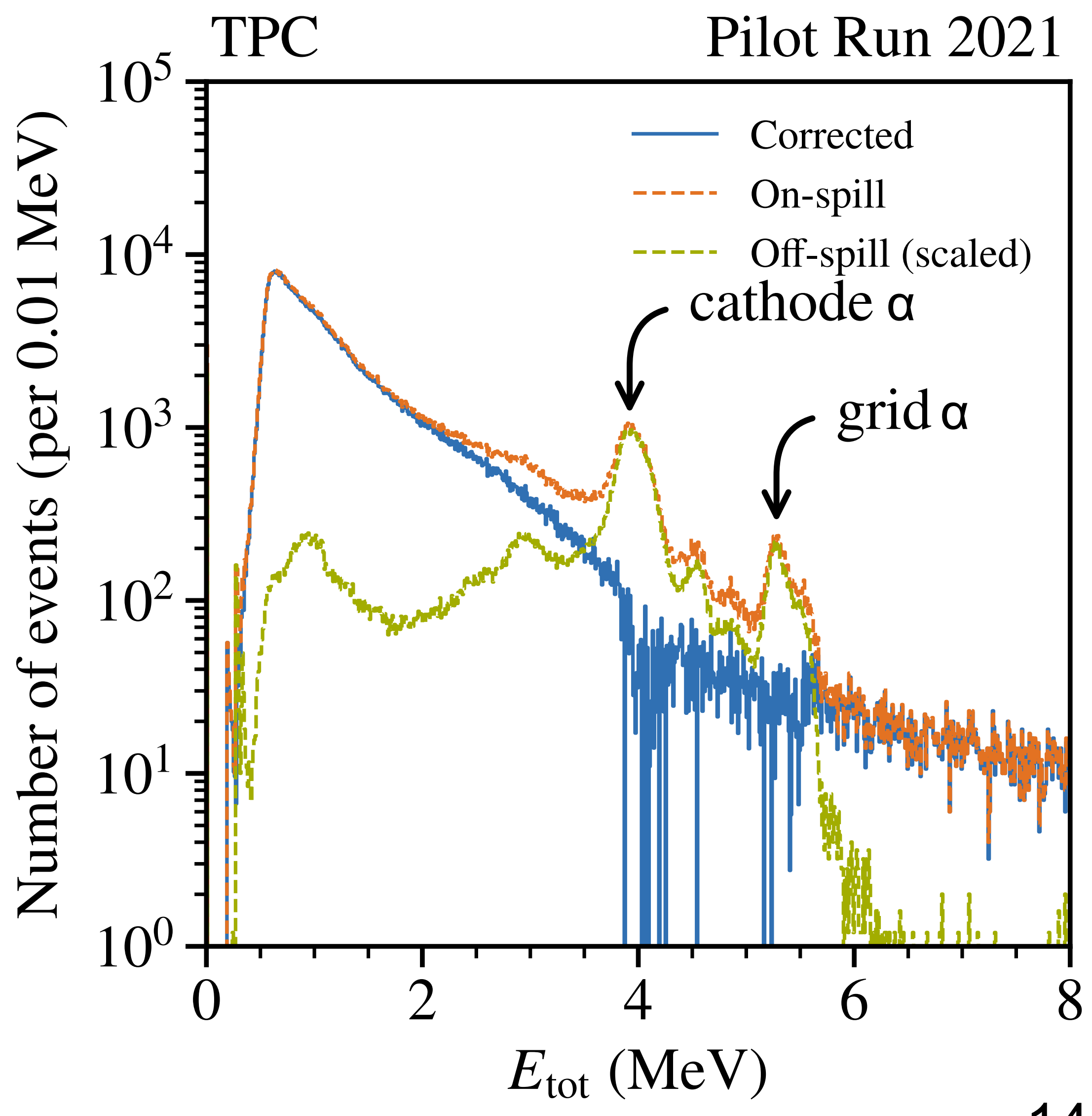
- Energy resolution dependence on rate, pressure, drift voltage and pad position is under investigation — but for now: as expected

- Recoil proton events under investigation
  → Energy calibration / pad plane alignment ongoing
  → Promising data for muon-proton matching









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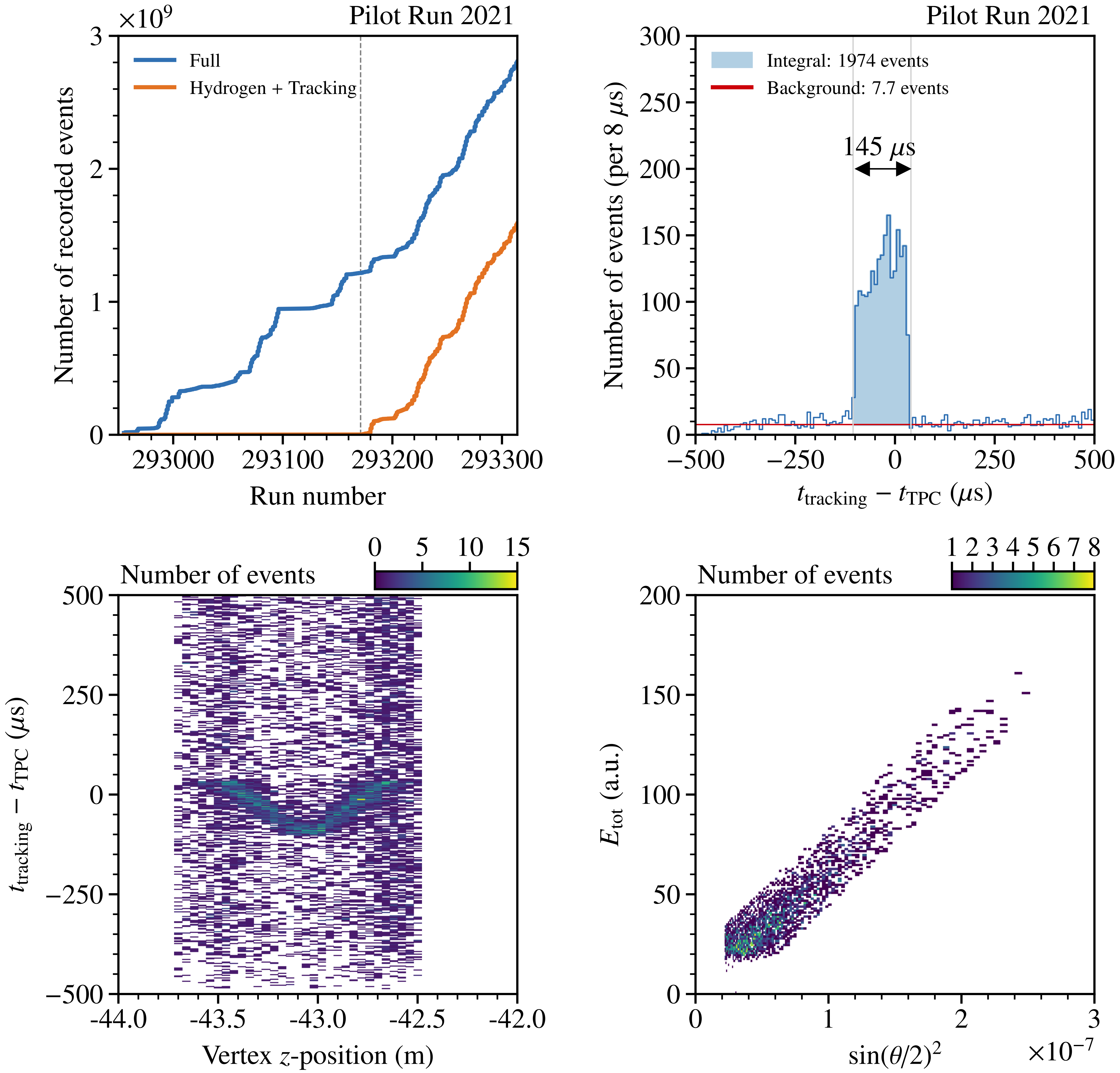
First Preliminary Results — Event Matching

Muon tracking correlated with recoil proton

Correlation of scattering events based on combined data taking.

- Two dedicated DAQ systems for TPC and tracking
  → Event association based on common timestamp
- About 4 days of combined data taking with TPC and tracking
  → Total of 1.6×10^9 events recorded
  → About 2000 correlated events found
  → But: About 10k events expected from cross-section and TPC rate
  → Further clarification of the difference ongoing
- Correlated events reassemble expected behaviour:
  → Drift time of TPC as expected
  → Correlation between muon vertex *z*-position and drift time
  → Correlation between TPC energy and muon angle
- Next:
  → Refine tracking and include spectrometer: extract Q^2-spectra
  → Evaluate TPC energy resolution based on tracking



Perspective: Inverse Kinematics — Elastic Hadron-Electron Scattering

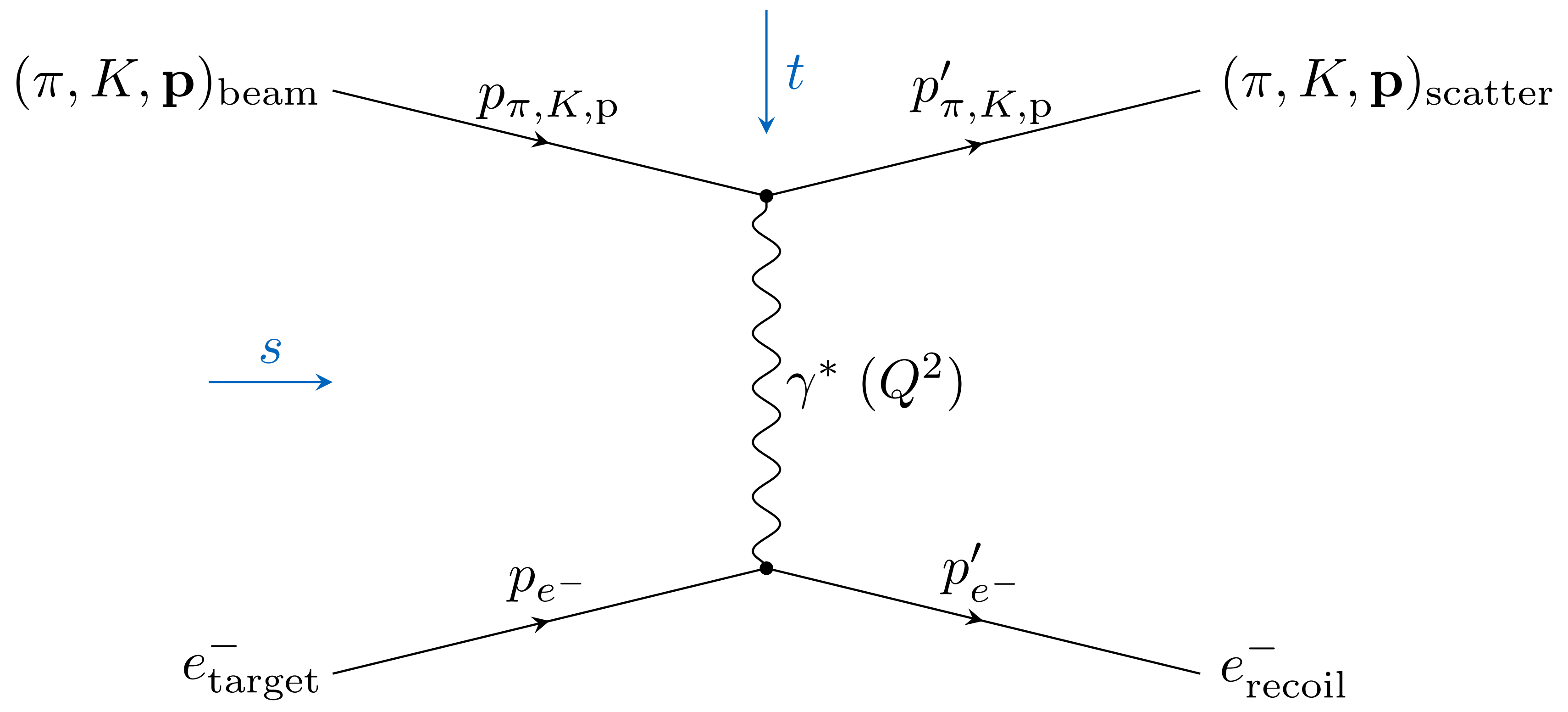
Elastic Hadron-Electron Scattering

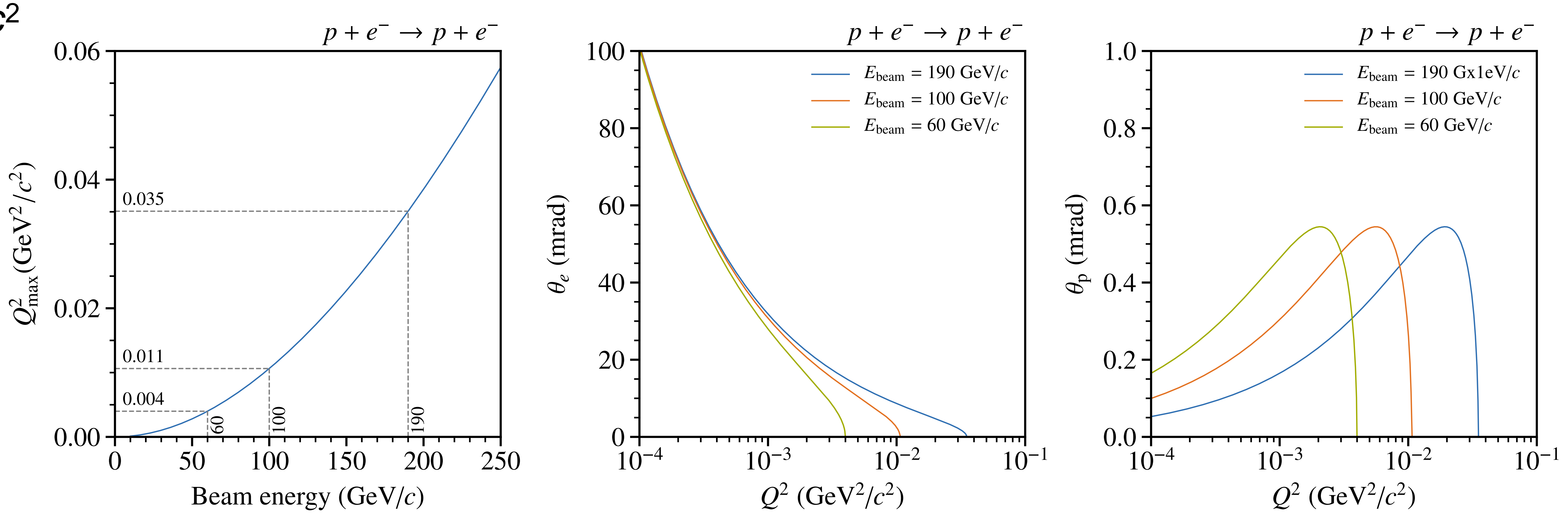
As example, usage of a solid thin target (Be) and measurement of outgoing hadron and electron angle to determine momentum transfer — extract radii of hadrons.

- Can be applied for instance: proton, pions and kaons
- Also possible: Access to G_M with different beam momenta

- In the proton case:
  → For G_E complementary measurement to Mainz, PRad, PSI
  → G_M possible first measurement for $Q^2 < 0.08\ \mathrm{GeV}^2/c^2$
  (MAMI, Phys. Rev. C 90, 015206 (2014))

- Maximal Q^2 depends on beam momentum
- But: challenging kinematic region
  → Electrons: scattering angles up to 30 mrad
  ($Q^2 = 10^{-3}\ \mathrm{GeV}^2/c^2$)
  → Protons: scattering angles between 50 to 500 µrad
  → Beneficial: variation of beam momenta





Schedule for Proton-Charge Radius Measurement

Planning for the upcoming three years

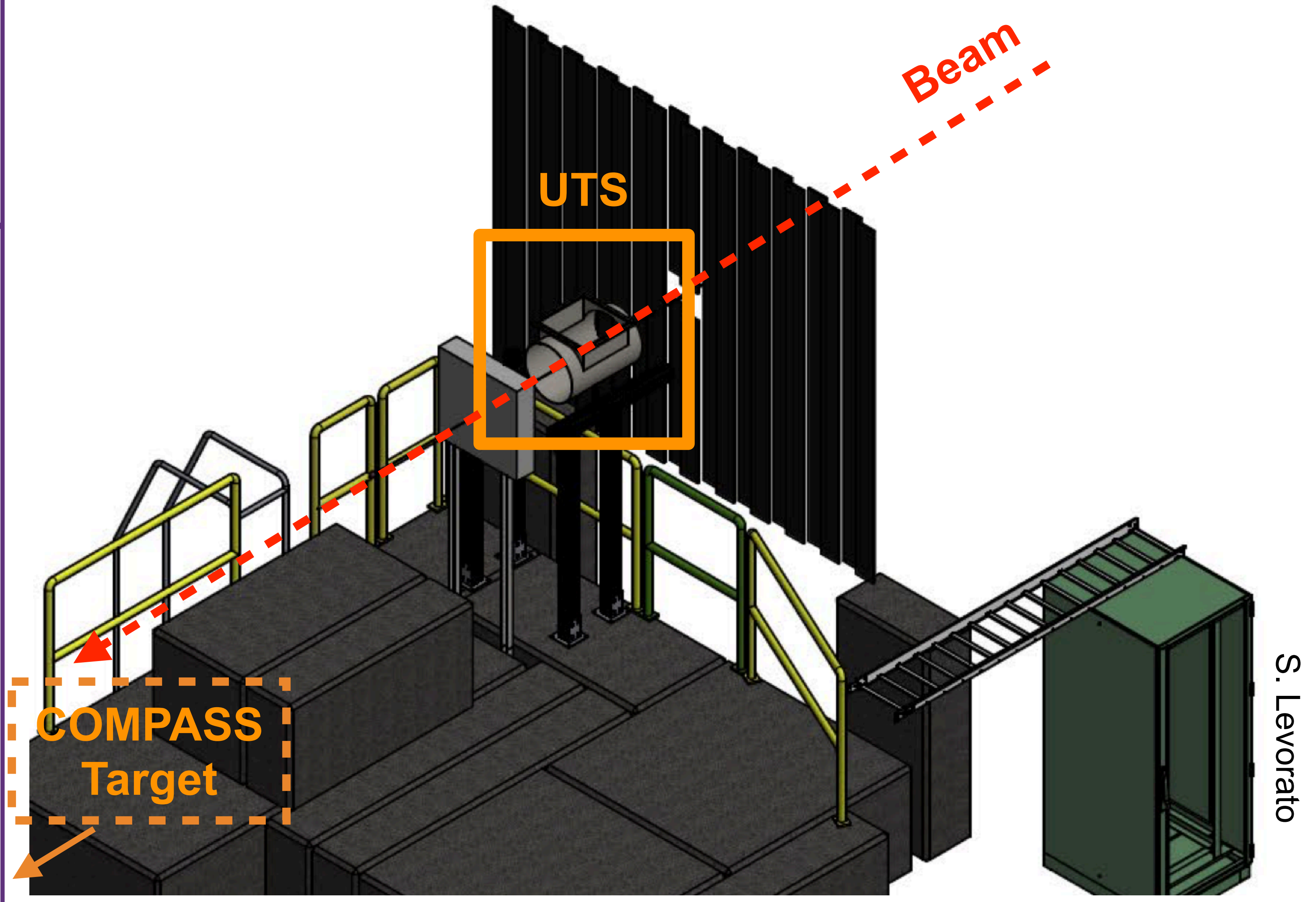
Schedule for the setup, preparation and pilot run with an anticipated following main data-taking and concluding systematic studies — conditional approved in case of a successful pilot run.

Phase	Year	Task	Time (days)	Particle	p (GeV)	Rate (μ/s)	Comment
Ia	2021	Preparation	100	μ^+/μ^-	160	$10^5 - 10^7$	Parasitic testing of single components
Ib	2021	Pilot run	20	μ^+/μ^-	100	$2 \cdot 10^6$	CEDAR location, down-scaled setup
IIa	~~2022~~ mid 2023/2024	Data taking	43	μ^+/μ^-	100	$2 \cdot 10^6$	Q^2: $1.0 \cdot 10^{-3}$ – $8 \cdot 10^{-3}$ GeV$^2/c^2$
IIb	~~2022~~	Data taking	107	μ^+/μ^-	100	$2 \cdot 10^6$	Q^2: $2.5 \cdot 10^{-3}$ – $4 \cdot 10^{-2}$ GeV$^2/c^2$
~~IIIa~~	~~2023~~	~~Empty target~~	~~50~~	~~μ^+~~	~~100~~	~~$2 \cdot 10^6$~~	~~Empty TPC~~
~~IIIb~~	~~2023~~	~~Energy dep.~~	~~25~~	~~μ^+/μ^-~~	~~60~~	~~$2 \cdot 10^6$~~	~~Multiple scat. and scat. angle~~
~~IIIc~~	~~2023~~	~~Energy dep.~~	~~25~~	~~μ^+/μ^-~~	~~150~~	~~$2 \cdot 10^6$~~	~~Multiple scat. and scat. angle~~

Postponed

Schedule from May 2019

2022: Beam Tests:
- UTS installation mid of October
- New triggerless DAQ



Summary and Outlook

High-energy elastic muon-proton scattering — Proton Radius Measurement @ *AMBER*
Preparations are ongoing with promising developments so far.

- New measurement approach based on elastic muon-protons scattering at high beam momentum
  → Redundant measurement to also control systematic effects
  → Radiative corrections smaller compared to electron-proton scattering
  → Additional dataset to contribute to a solution of the puzzle
  → So far: conditionally approved based on a successful pilot run

- Test and pilot runs are in agreement with expectations and helped with the design of the setup

- Additional studies ongoing:
  → Extension of the Q^2-range up to 0.08 GeV^2/c^2 using dE/dX
  → Beam momentum calibration based on elastic muon-electron scattering

- Preparations are ongoing — but: challenging time schedule
  → New detector systems with novel triggerless DAQ — beam tests this year
  → Installation and commissioning of the setup envisaged starting mid in 2023

- Possible main physics data taking could start beginning of 2024

Thank you for your attention

How to Determine the Proton Radius?

Cross section, form factor, and the proton radius

Measurement of electric form factor allows to extract 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:

$$\frac{\mathrm{d}\sigma^{\mu p\to\mu p}}{\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4} R\left(\epsilon G_E^2 + \tau G_M^2\right) \quad \text{with} \quad R = \frac{\vec{p_\mu}^2 - \tau\left(s - 2m_p^2(1+\tau)\right)}{\vec{p_\mu}^2(1+\tau)} \quad \epsilon = \frac{E_\mu^2 - \tau\left(s - m_\mu^2\right)}{\vec{p_\mu}^2 - \tau\left(s - 2m_p^2(1+\tau)\right)} \quad \tau = \frac{Q^2}{(4m_P^2)}$$

- Suppress magnetic form factor G_M

→ 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 $\varepsilon \to 1$

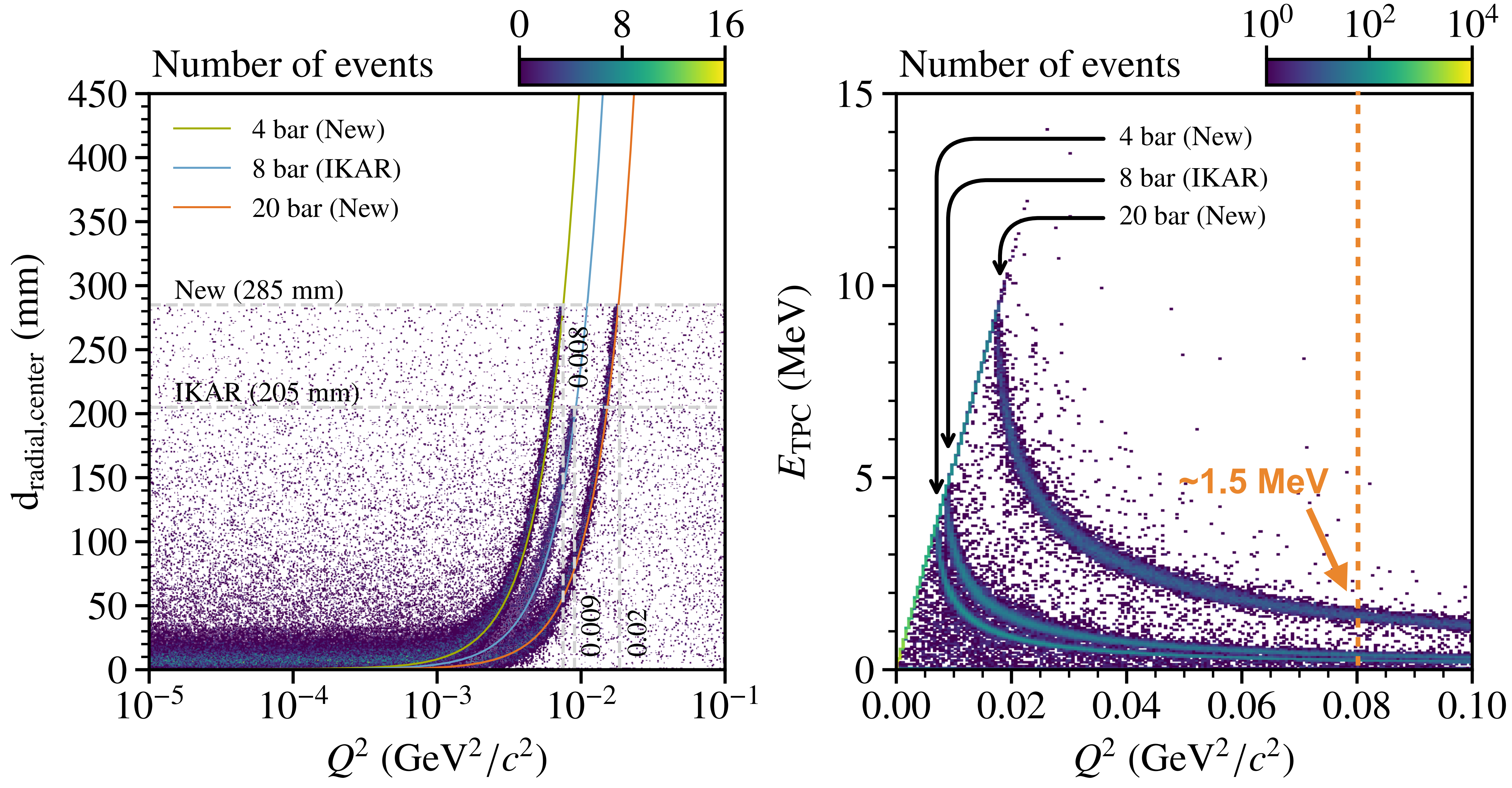
→ Cross-section directly proportional to G_E^2

Extension of Q^2-Range based on Energy Loss

Limited range due to TPC radial size and pressure

Possible increase the maximal Q^2 to cover a larger range allows studying of the large-Q^2 influence and be more comparable to experiments like MAMI and JLab.

- Proton track length depends on pressure and Q^2:
  - → IKAR TPC: 8 bar and 205 mm radial size: $Q^2 = 0.009\,\mathrm{GeV}/c^2$
  - → New TPC: 20 bar and 285 mm radial size: $Q^2 = 0.02\,\mathrm{GeV}/c^2$
- Studies ongoing to extend the Q^2-range up to $Q^2 = 0.08\,\mathrm{GeV}/c^2$ by using energy loss along the proton path
  - → First estimations show a resolution of 0.5 to 4.4 % of initial proton energy (requirement < 6 %)
  - → Further work with simulation and obtained real data ongoing
- Method can be validated, especially at larger Q^2, using the muon tracking result
- Influence on the precision and required statistics under study



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Beam Momentum Calibration — Elastic Muon-Electron Scattering

Kinematic correlation to calibrate beam momentum measurement

Beam momentum measurement needs to be calibrated to determine Q^2 from muon scattering angle.

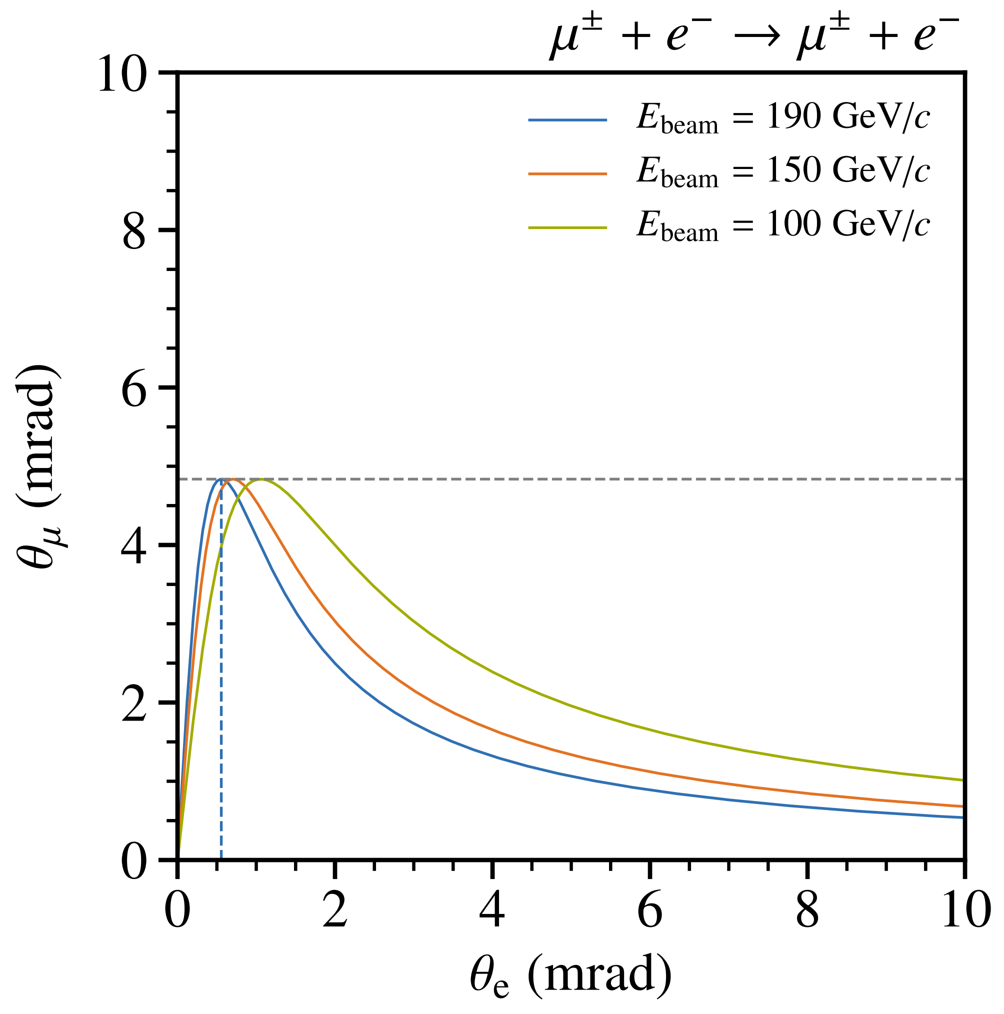
- Angular correlation between muon and electron allows to extract. the incoming muon momentum
  → Challenge: No unique correlation — two solutions

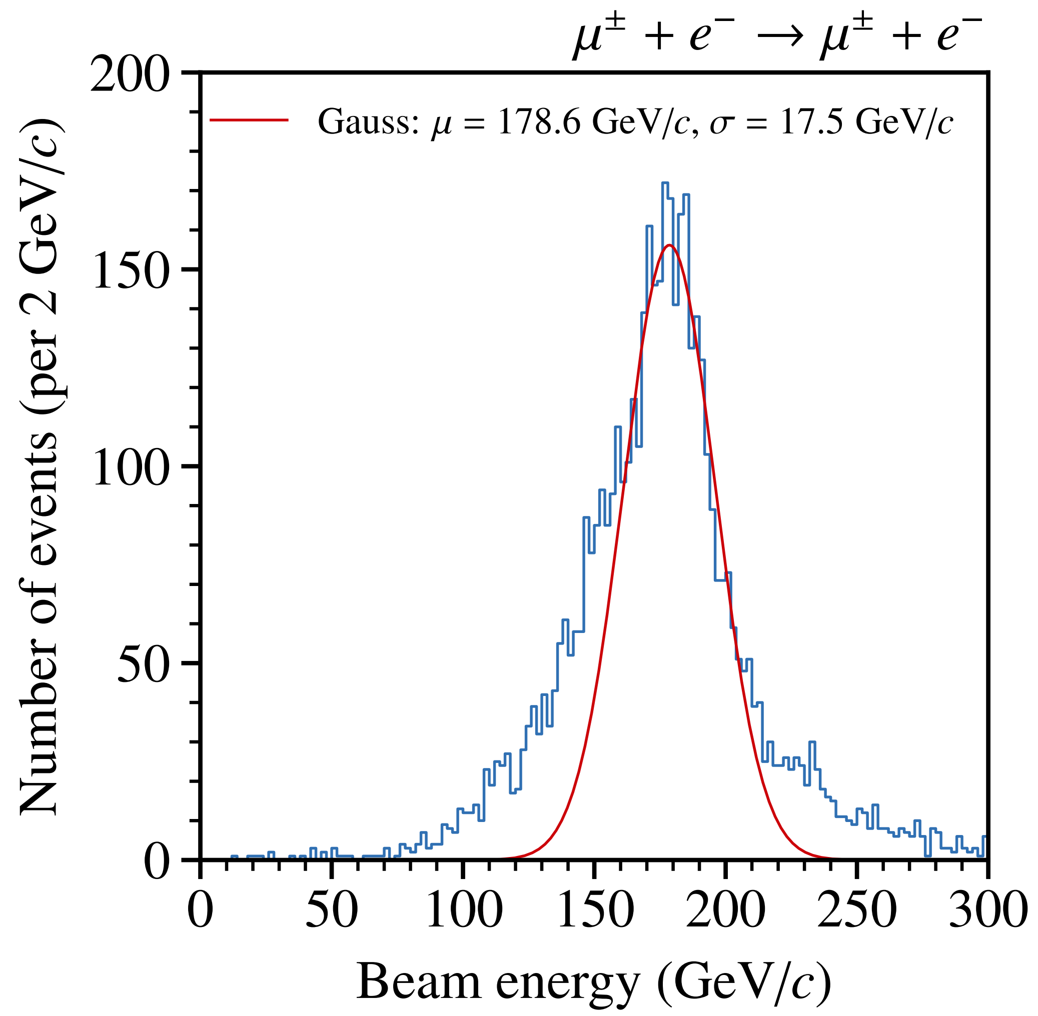
- First look into the 2018 test run data on elastic muon-electron scattering to extract angular correlation and reconstruct beam momentum
  → Broad momentum distribution of parasitic beam in the test area

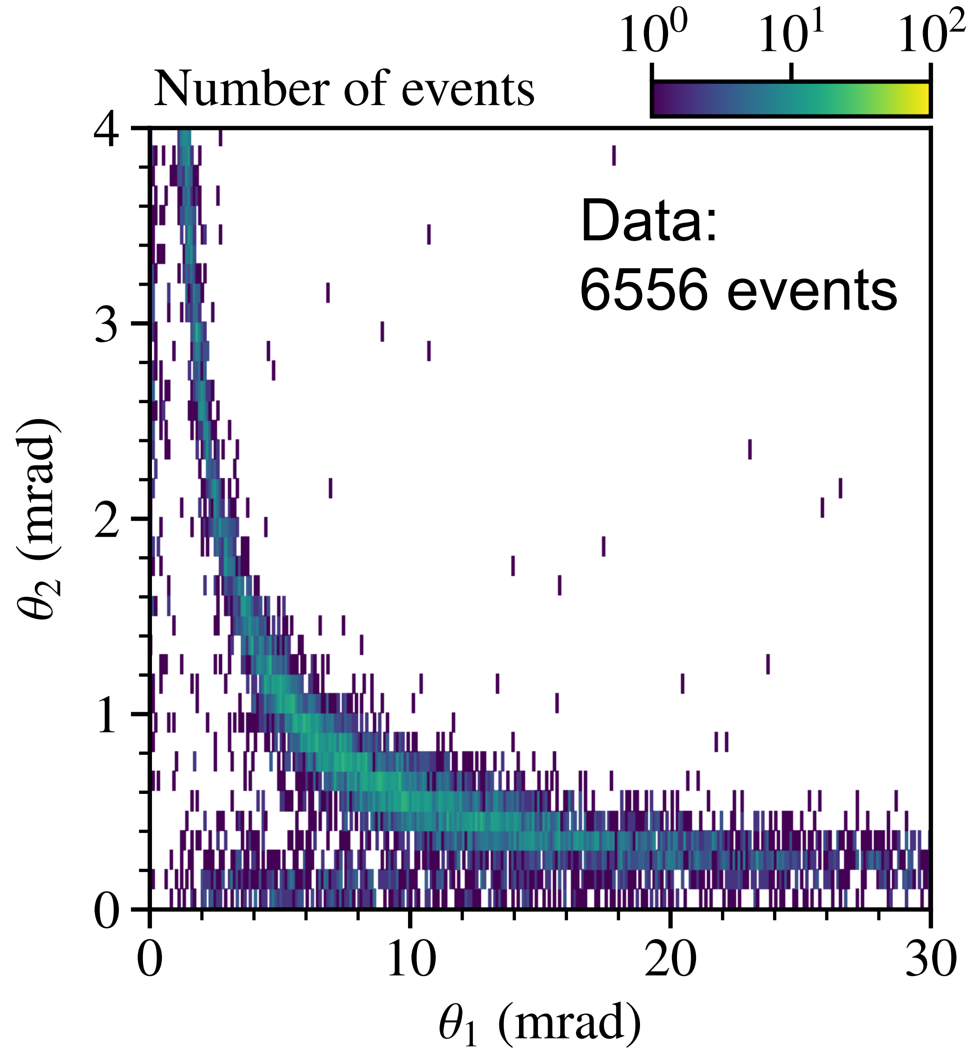
- In 2018: Comparable result with MuonE test at same location
  → For us arbitrary angles: no muon-electron identification

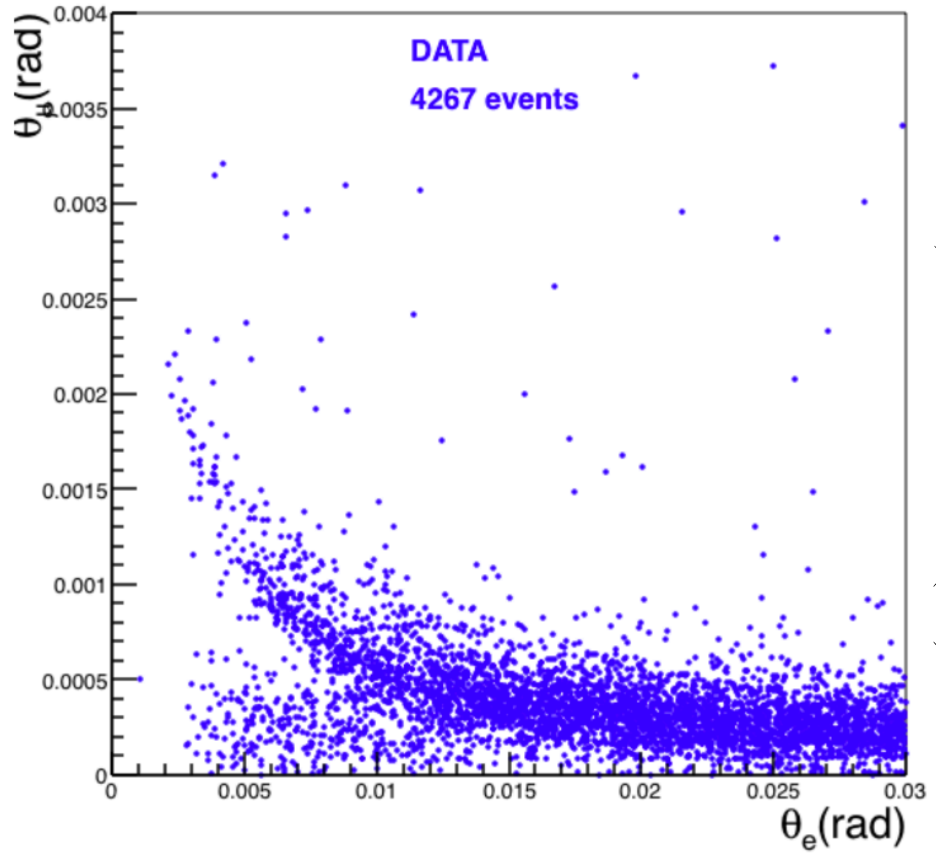
- Studies ongoing on data and simulation to further refine the method

- Idea can be further extended towards elastic hadron-electron scattering









G. Abbiendi et al., Journal of Instrumentation **16** (2021) P06005

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Up Next: UTS Beam Test

Parasitic beam test of new UTS
First combined beam test of SPD and SFH combined in the UTS at the *COMPASS* target location in parasitic mode.

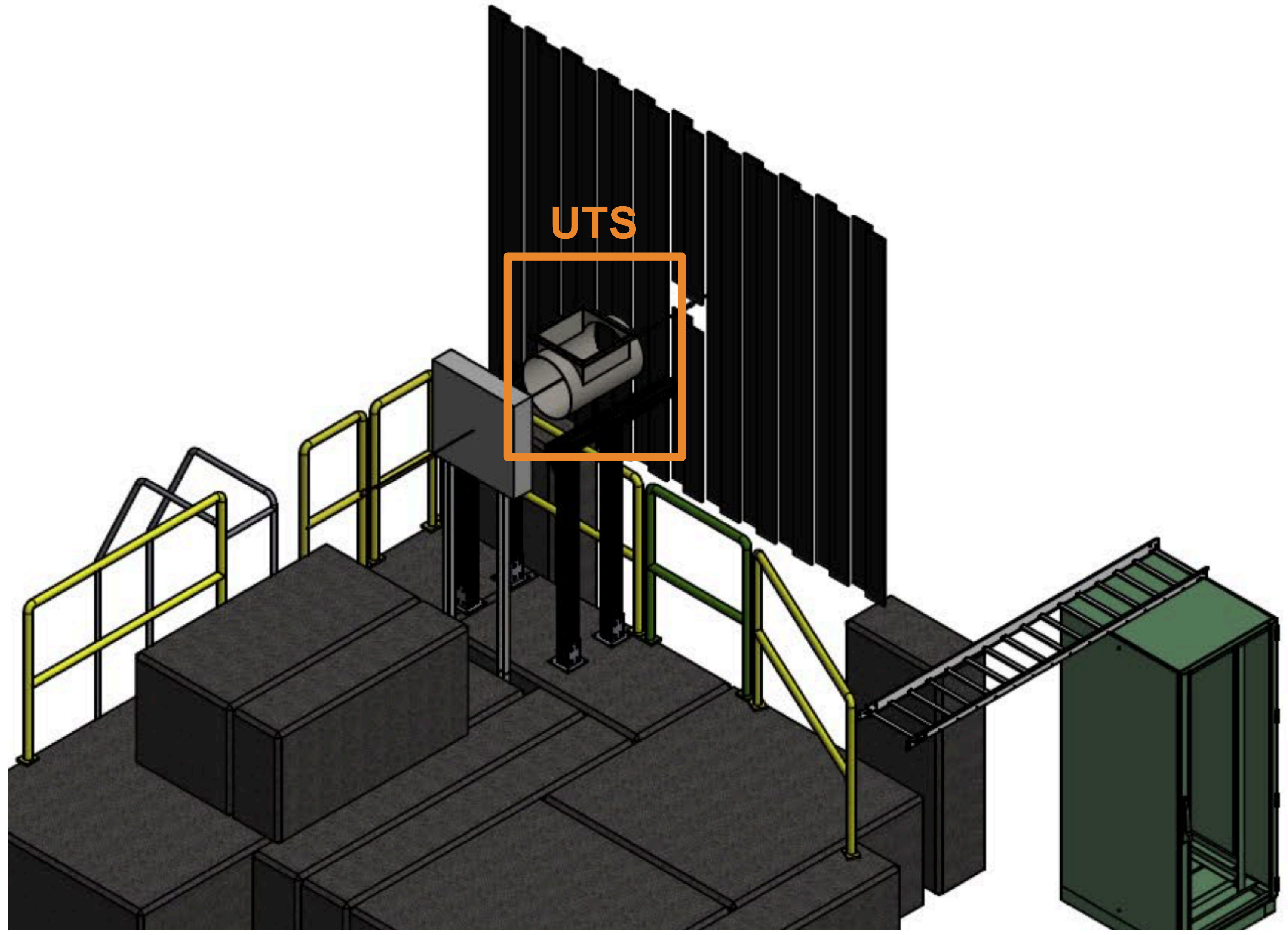
- Position close-to-final
  → Installation foreseen mid of October
  → Comparable beam properties in terms of size and rate (adjustable)
  → UTS will be sandwiched between SciFi and Silicon detectors

- Validation of spatial and timing resolution of the SPD and SFH

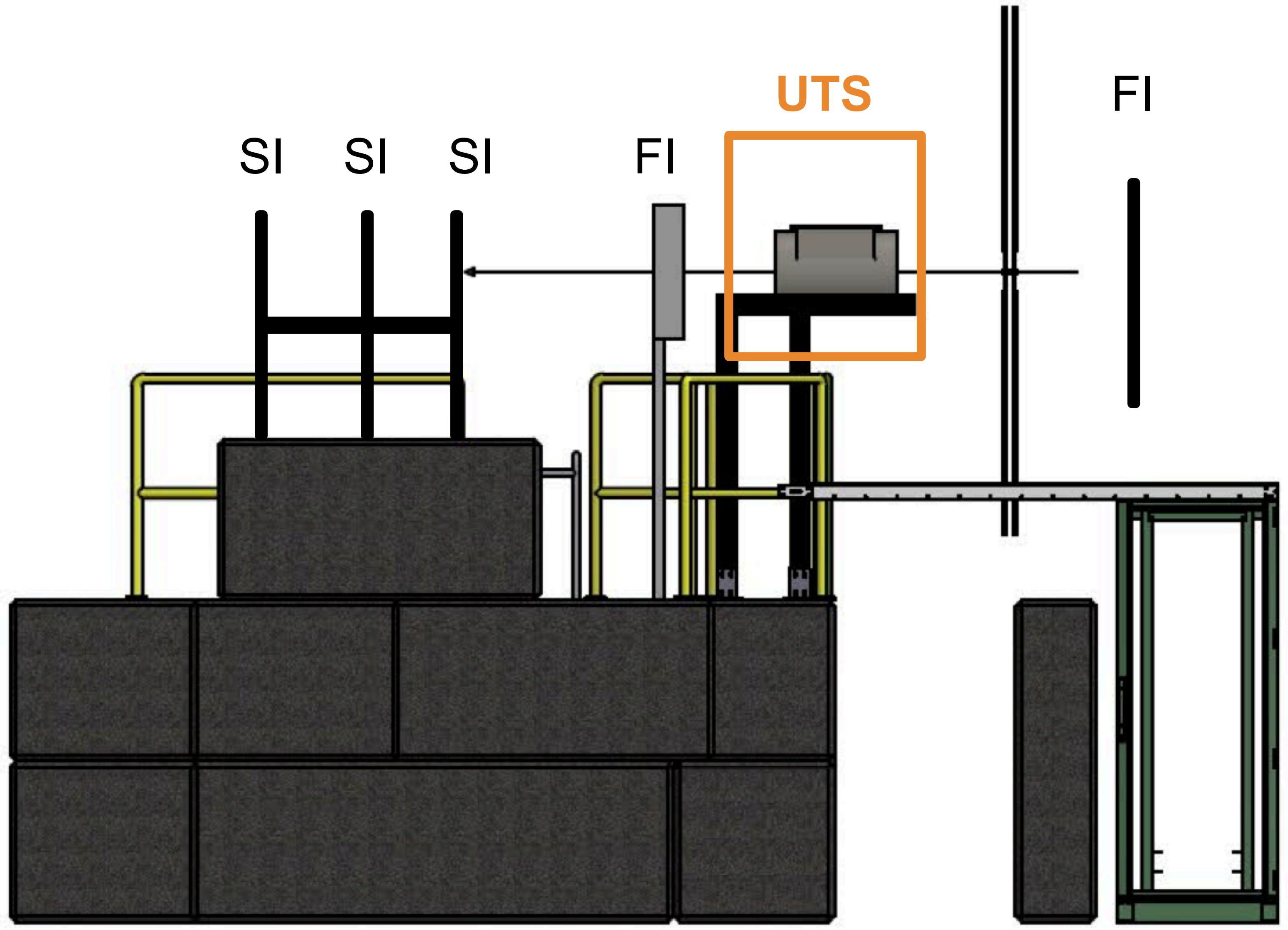
- Validation of required hit-time matching between SPD and SFH to disentangle pile-up hits in the SPD
  → Study beam rate dependence

- Usage of existing triggered DAQ as well as new streaming DAQ system

- Results will refine the detector layout used for the final version



S. Levorato



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