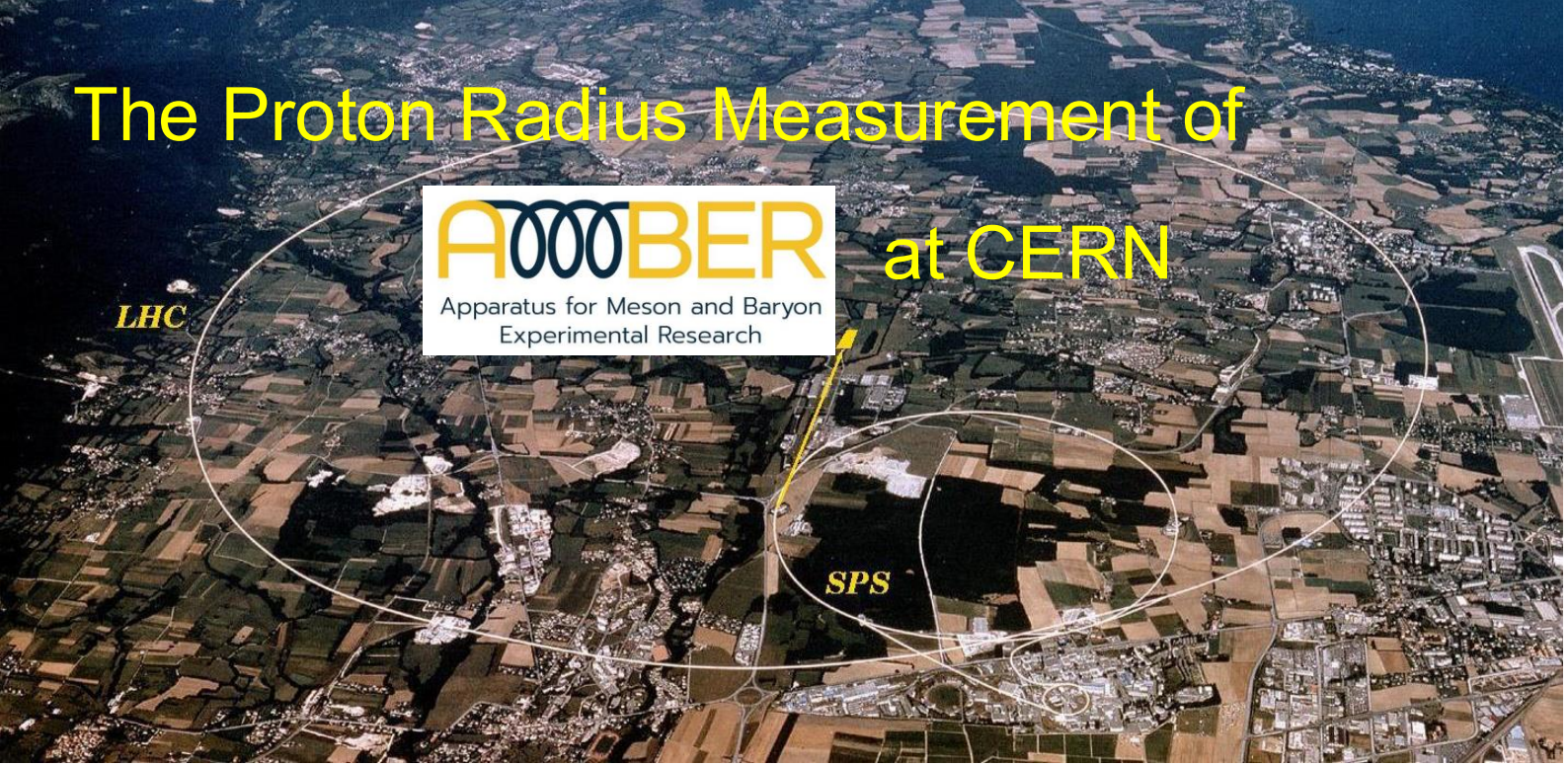
The Proton Radius Measurement of AMBER at CERN



AMBER
Apparatus for Meson and Baryon Experimental Research

Center for Frontiers in Nuclear Science

Workshop on NREC 2026 (the second workshop on Nuclear Radius Extraction Collaboration)

13.–17. Apr. 2026
Stony Brook University / Online

Jan Friedrich

Technische Universität München

14.4.2026

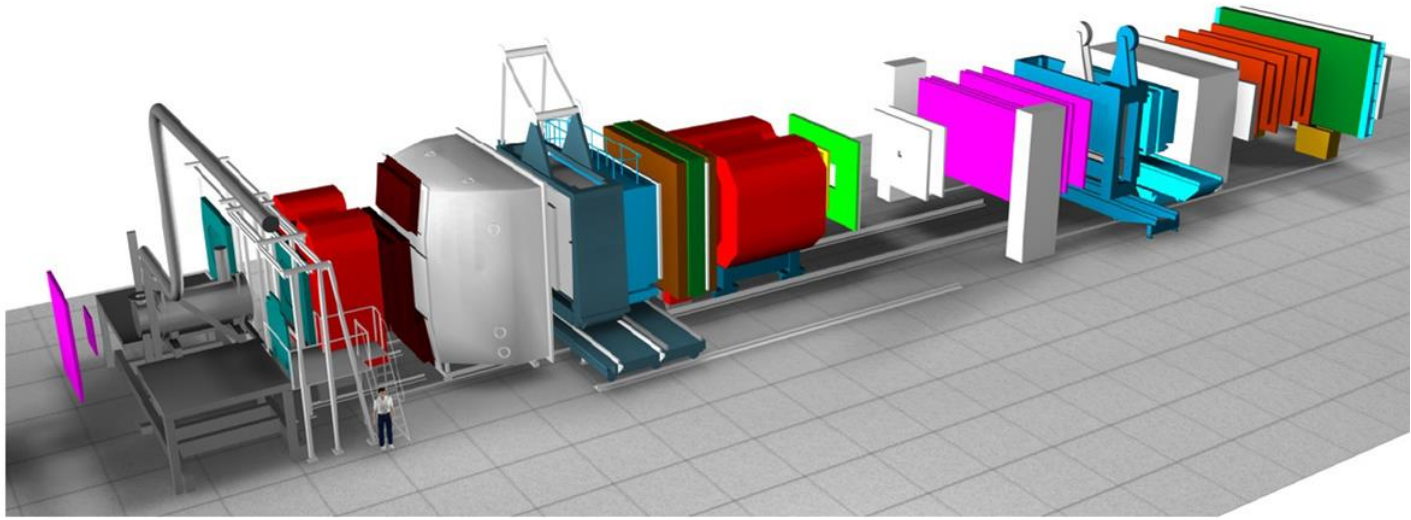
TUM LMU ORIGINS Excellence Cluster

Bundesministerium für Bildung und Forschung

on behalf of the AMBER Collaboration

Apparatus for Meson and Baryon Experimental Research

- AMBER has been approved as NA66 experiment in December 2020
- the Collaboration consists of ~200 physicists from 34 institutes
- at the M2 beamline at SPS
  muon and hadron beams 60 – 250 GeV
- AMBER inherited, extends and modernizes the 2-stage spectrometer of the COMPASS collaboration



- **Approved Phase I** physics:
  - $\bar{p}$ production cross-sections
  - proton radius
  - pion/kaon structure functions
- Intended **Phase II** physics (>LS4):
  - strange-meson spectroscopy
  - kaon polarizability
  - prompt-photon production

Measurement of G_E^p at small Q^2

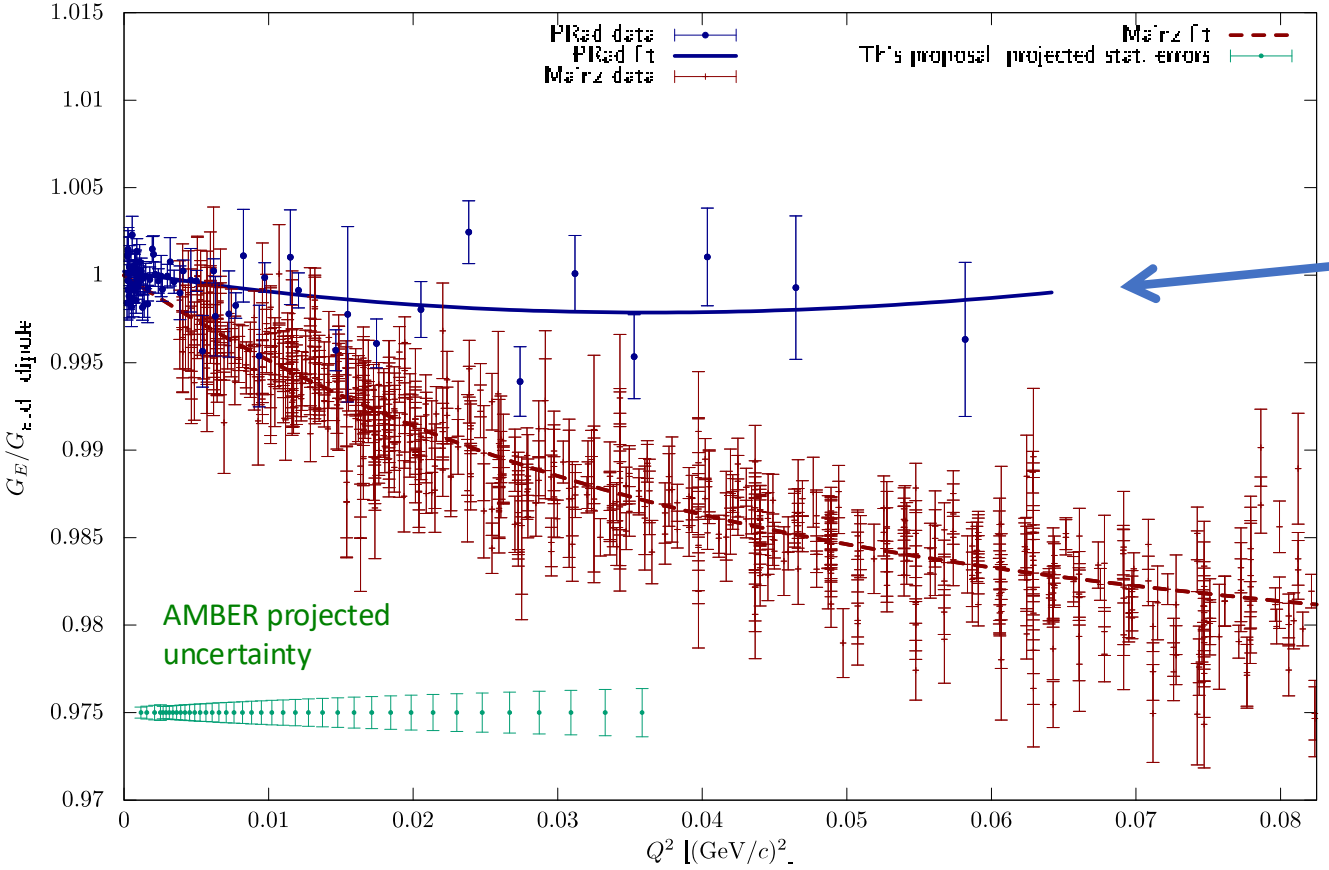
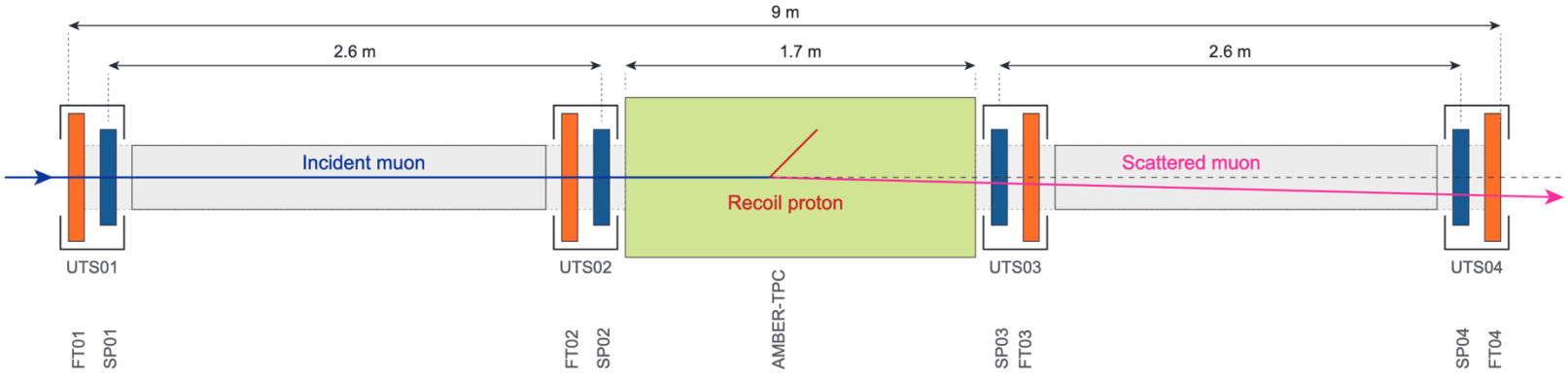
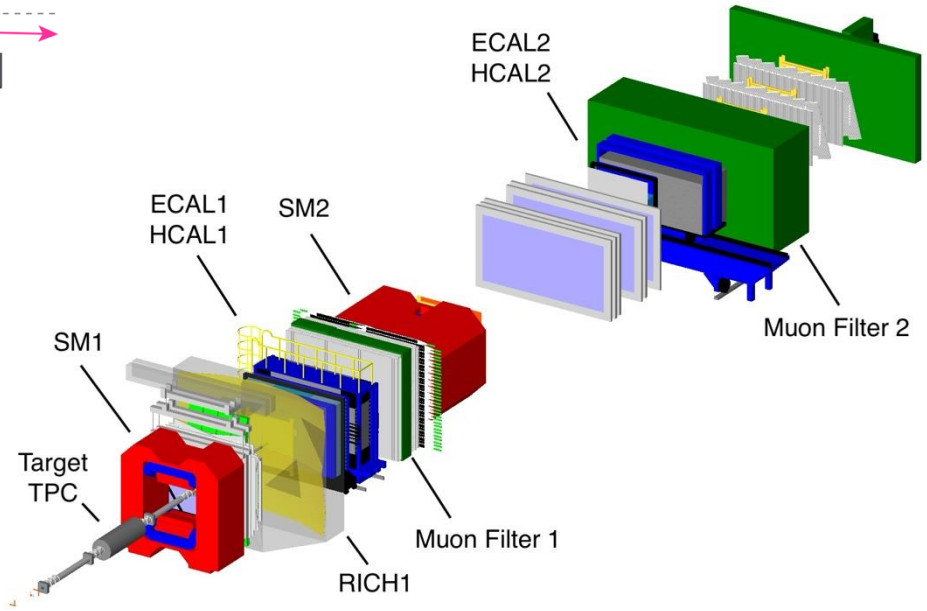


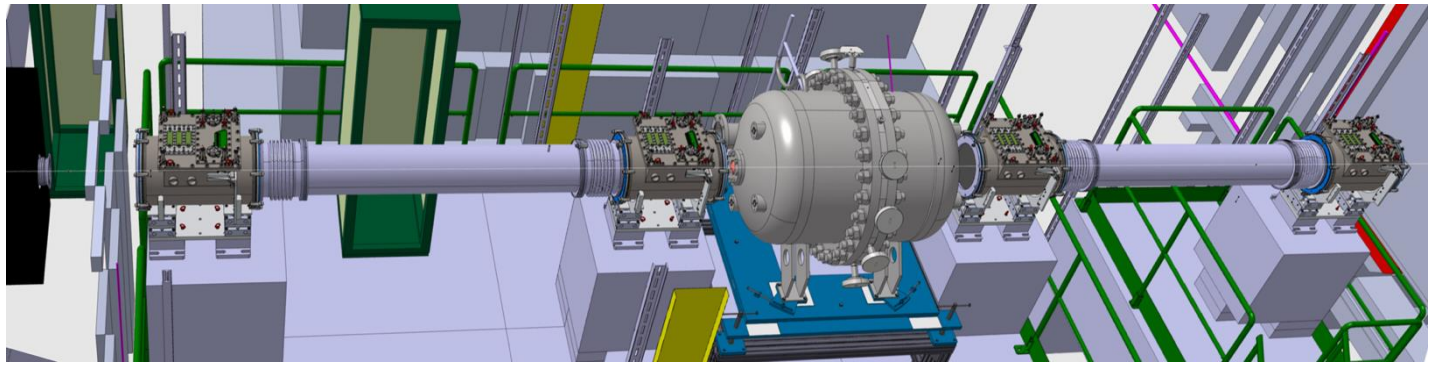
figure: J. Bernauer

Basic Idea of the AMBER measurement





- 100 GeV **muon** beam
- Active-target TPC with high-pressure H_2
- high-precision tracking and spectrometer for muon reconstruction
- goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4 \cdot 10^{-2}$ GeV^2
- Precision on the proton radius ~0.01 fm



New Equipment for PRM

High-pressure hydrogen TPC

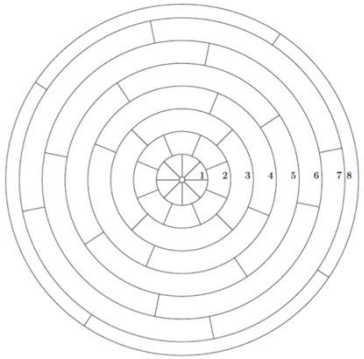
- Operation at 20 bar hydrogen pressure
- design with 2 drift cells
- Segmented anode plane
- reconstruction of proton recoil energy with ~50 keV precision

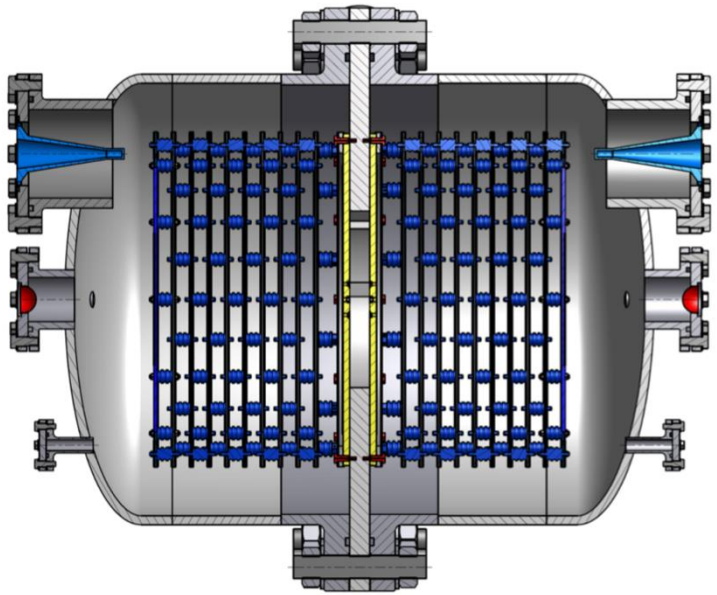
Unified Tracking Stations

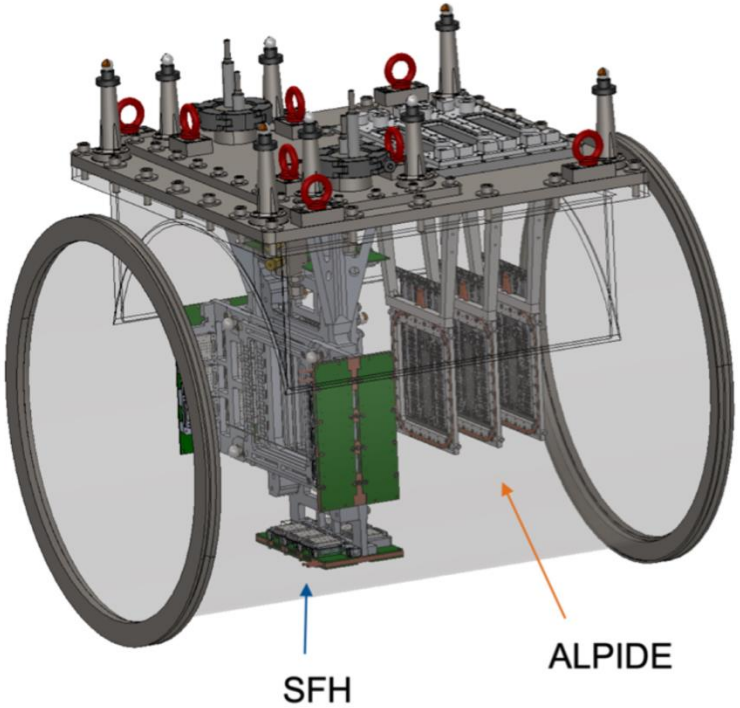
- Determine scattering angle of muon
- Consists of several layers of silicon pixel detectors (ALPIDE) and a scintillating-fiber hodoscope (SFH)

Free-running DAQ

- streaming data acquisition on first level: all detectors deliver data without external trigger
- high-level trigger on computer farm

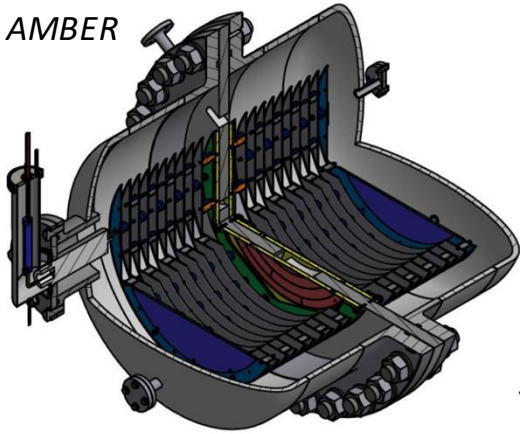






New High-Pressure Time Projection Chamber

CAD of the new AMBER TPC



- Cooperation with GSI/FAIR (Germany), later usage is foreseen at FAIR/R3B
- Successful overpressure tests at the production site (up to 32 bar)
- Leak rate under pressure and preliminary checks done at GSI, transported to CERN end of 2024

Factory Acceptance Test at the Danish production site, May 2024

Electrode and Readout Anode Structure

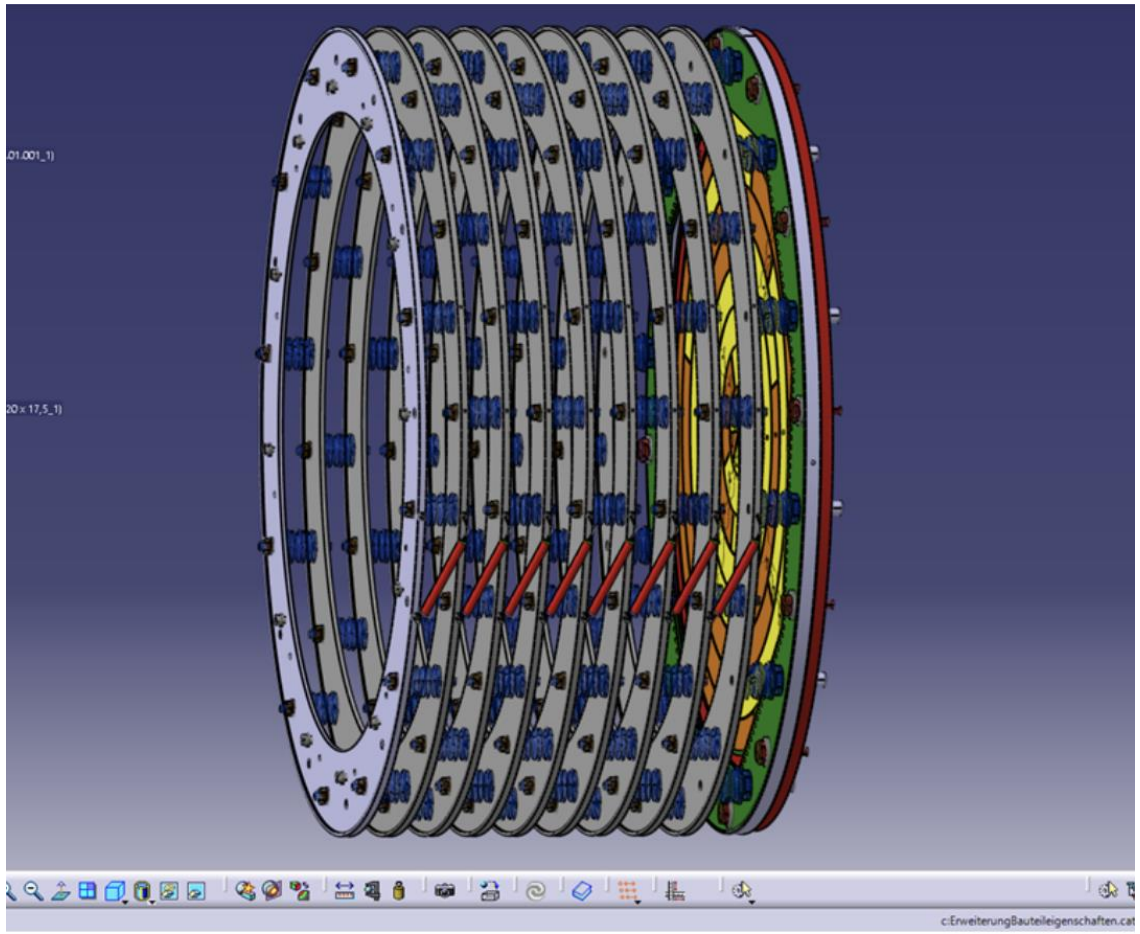
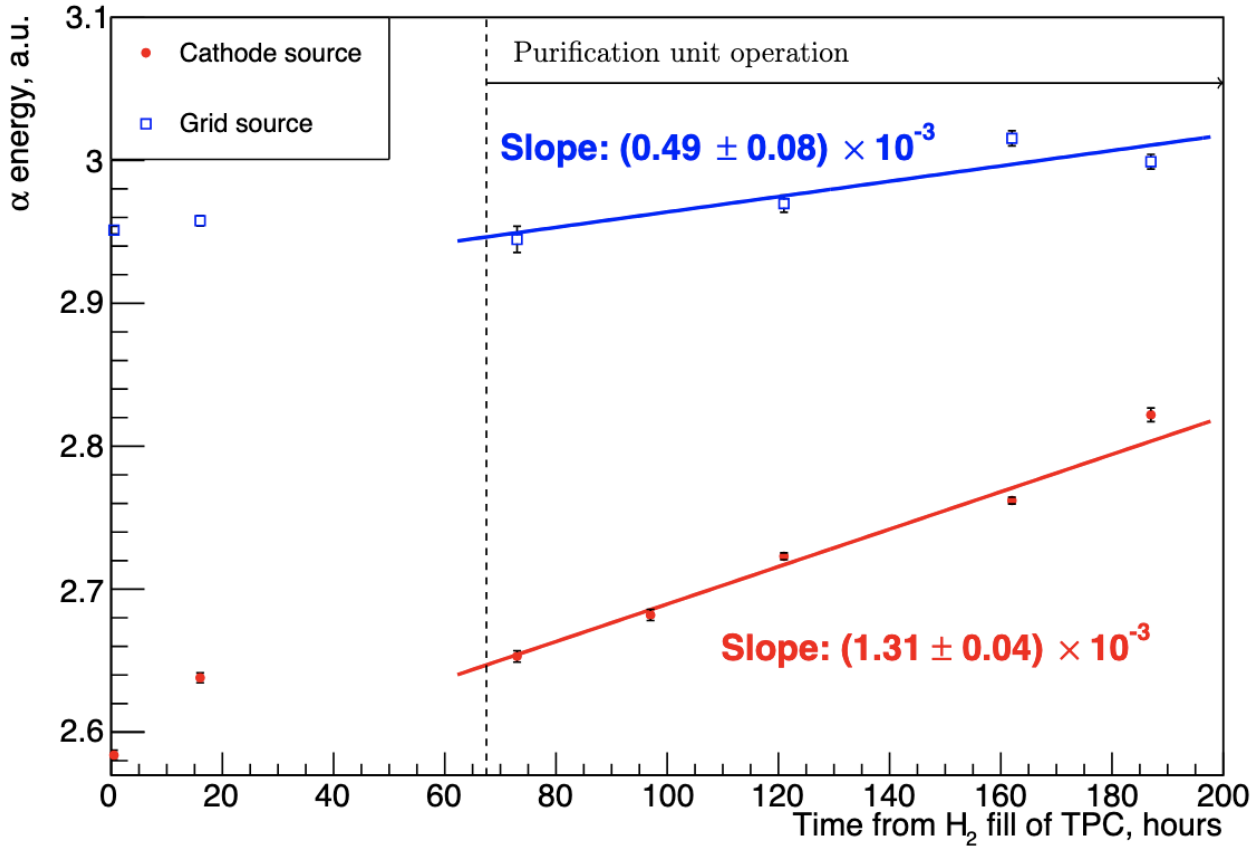


Fig. 26: CAD drawing of the TPC inner electrode structure.

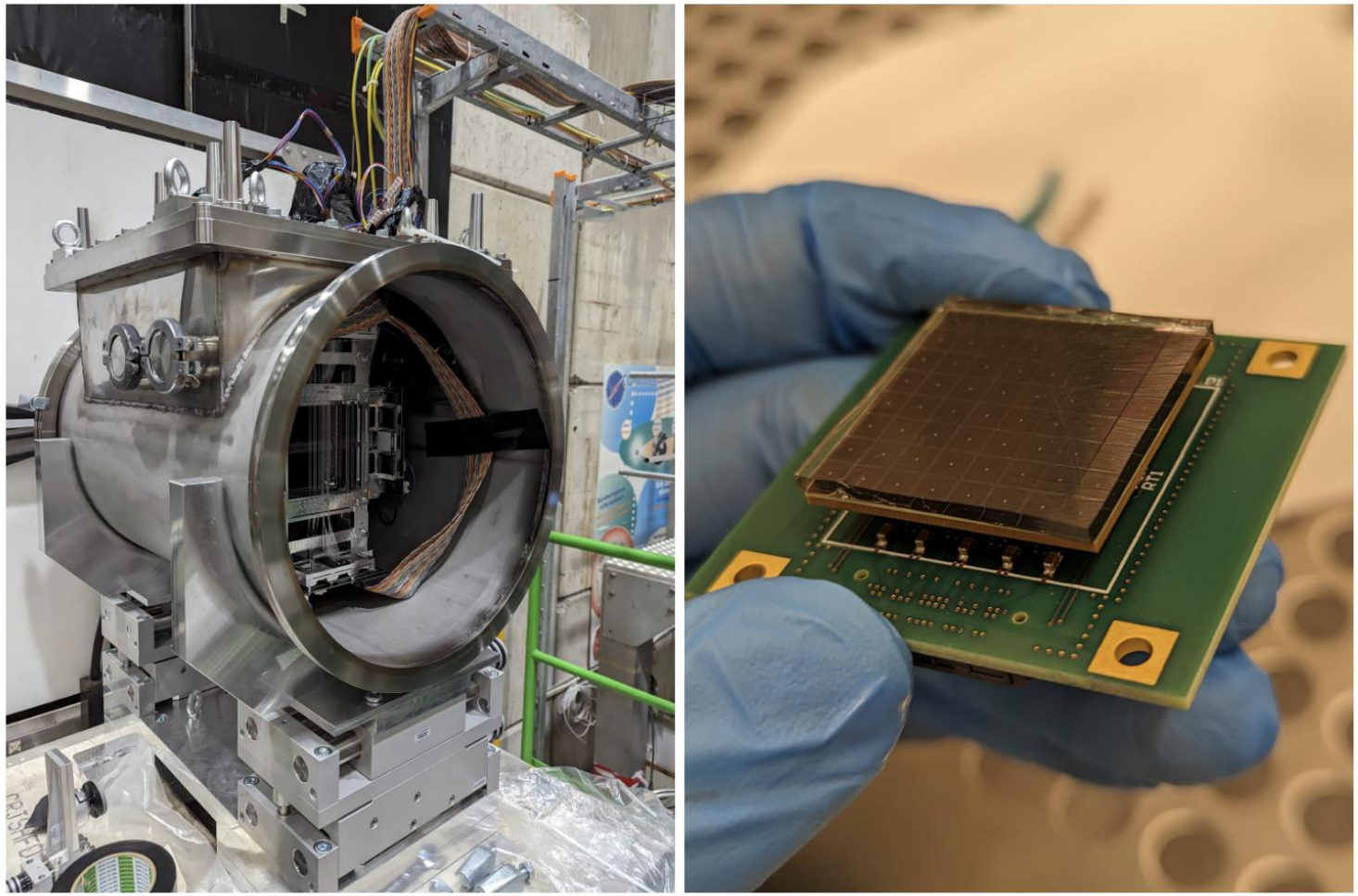
- Assembly finished at CERN in 2025
- at two positions, α sources are to be implemented that will provide calibration signals during data taking

Hydrogen Gas Purification

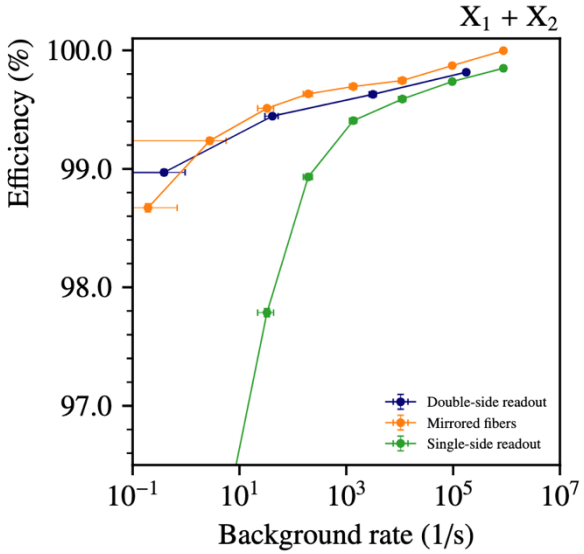


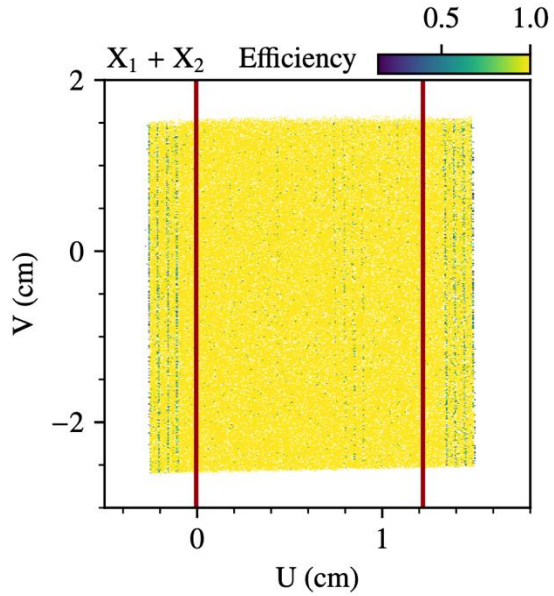
- Tests in 2023 with the old IKAR TPC and a new purification unit
- the increase of the amplitude from the α sources is a measure of the purity of the detector gas
- stronger effect by the cathode source (longer drifts)

Scintillating-Fiber Hodoscope



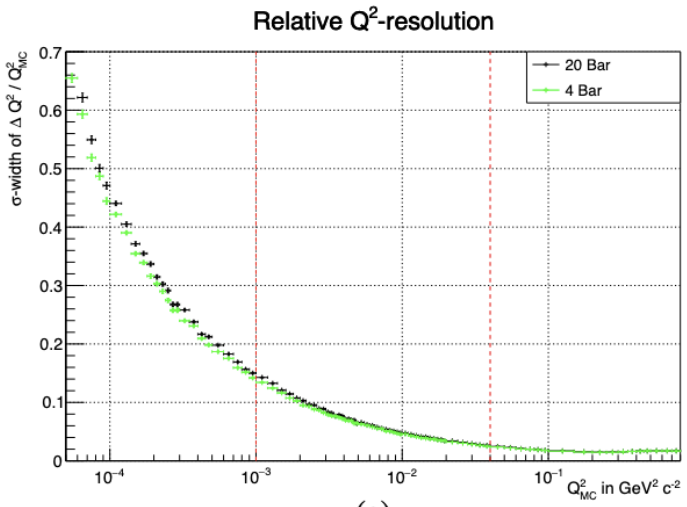
(a) UTS with SFH prototype in the target area. (b) Gel pad used to improve the SiPM-fiber coupling in the SFH prototype.



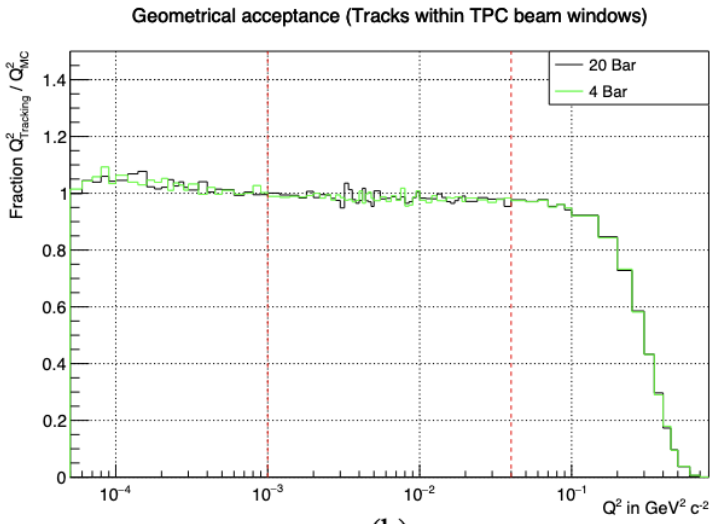


Simulation of the PRM Setup

- The AMBER setup for the Proton Radius Measurement has been implemented in a GEANT4 Monte-Carlo simulation
- from the reconstructed MC data, the achieveable resolution in Q^2 has been studied and found better than 15% in the targeted range $Q^2 > 10^{-3}\ \mathrm{GeV}^2$ for both TPC pressure settings at 4 and 20 bar
- the geometrical acceptance is found to be flat in the relevant Q^2 range



(a)



(b)

Tests and Schedule for PRM Data Taking

2018: First measurement of hydrogen TPC in high-energy muon beam

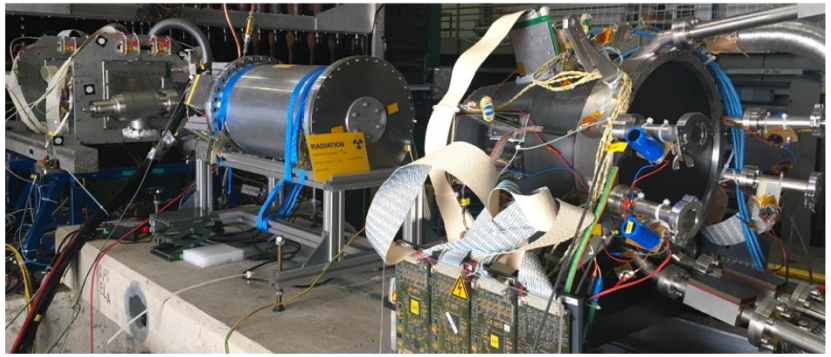
2021: First test run with IKAR TPC and already existing tracking detectors from COMPASS → *correlation between proton energy and muon scattering angle*

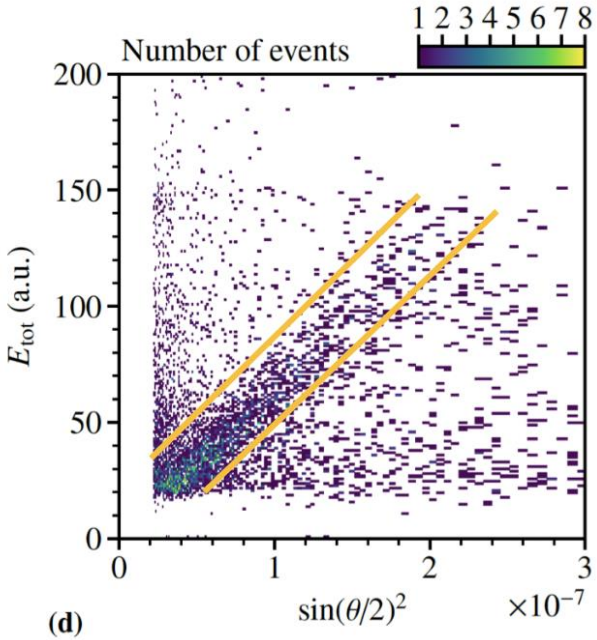
2023: Test run with new free-running DAQ (IKAR TPC, new tracking detector prototypes)

2024/25: Tests with new TPC and UTS prototypes

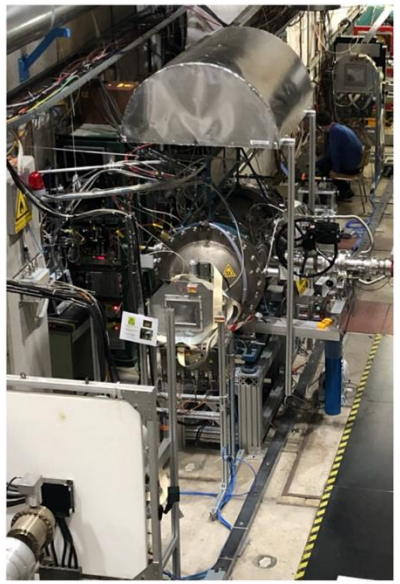
2026: first physics start with final detector setup planned for mid-May

2018





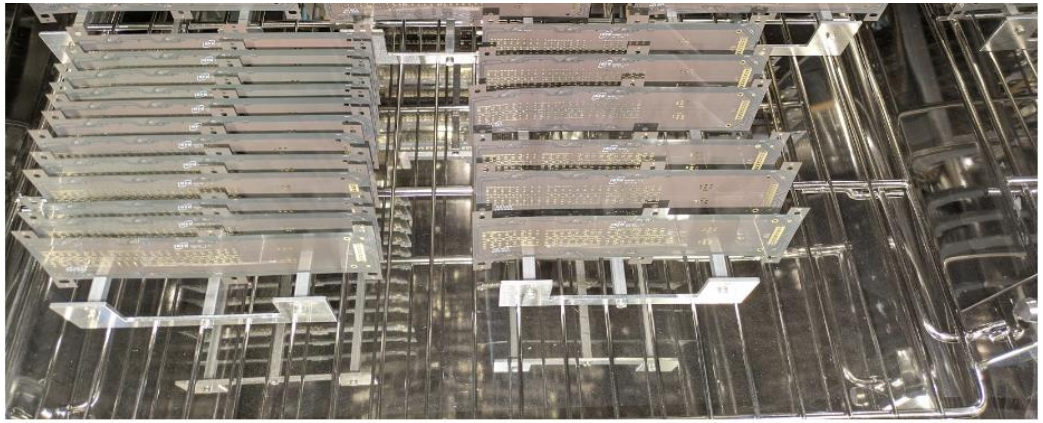
2021

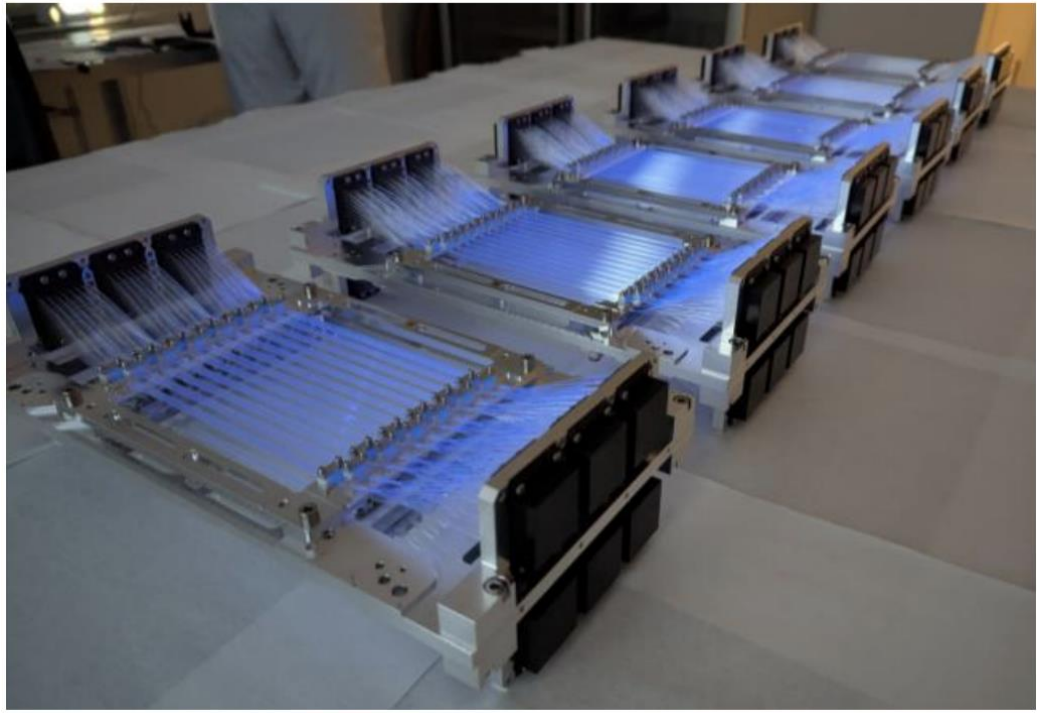


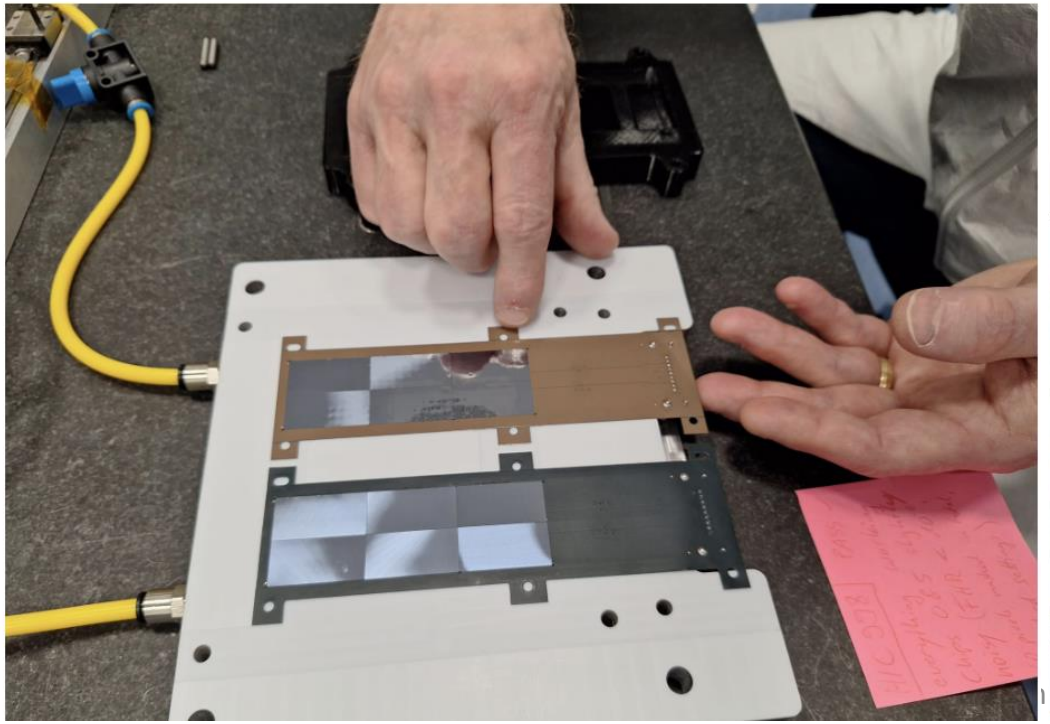
Figures: C. Dreisbach PhD Thesis (2022)

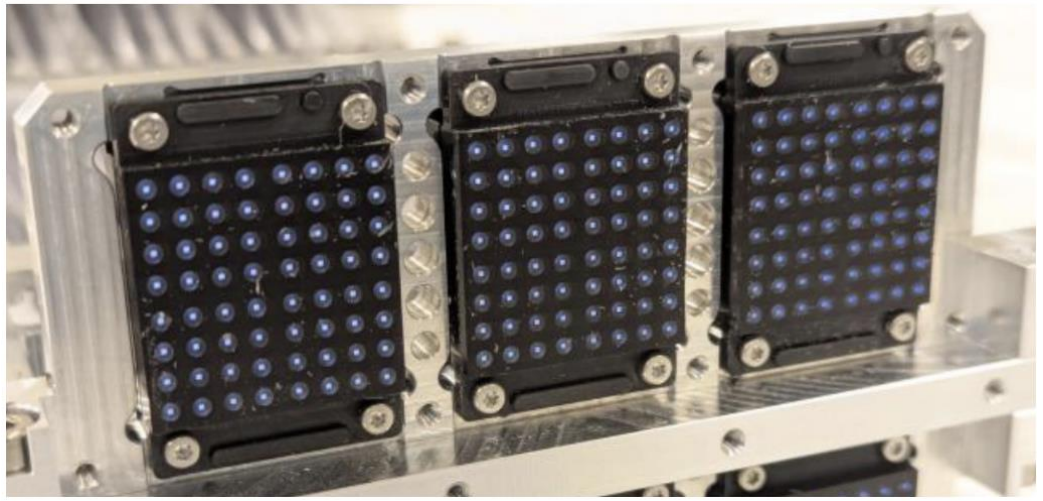
AMBER target area 2026

Trackers on track

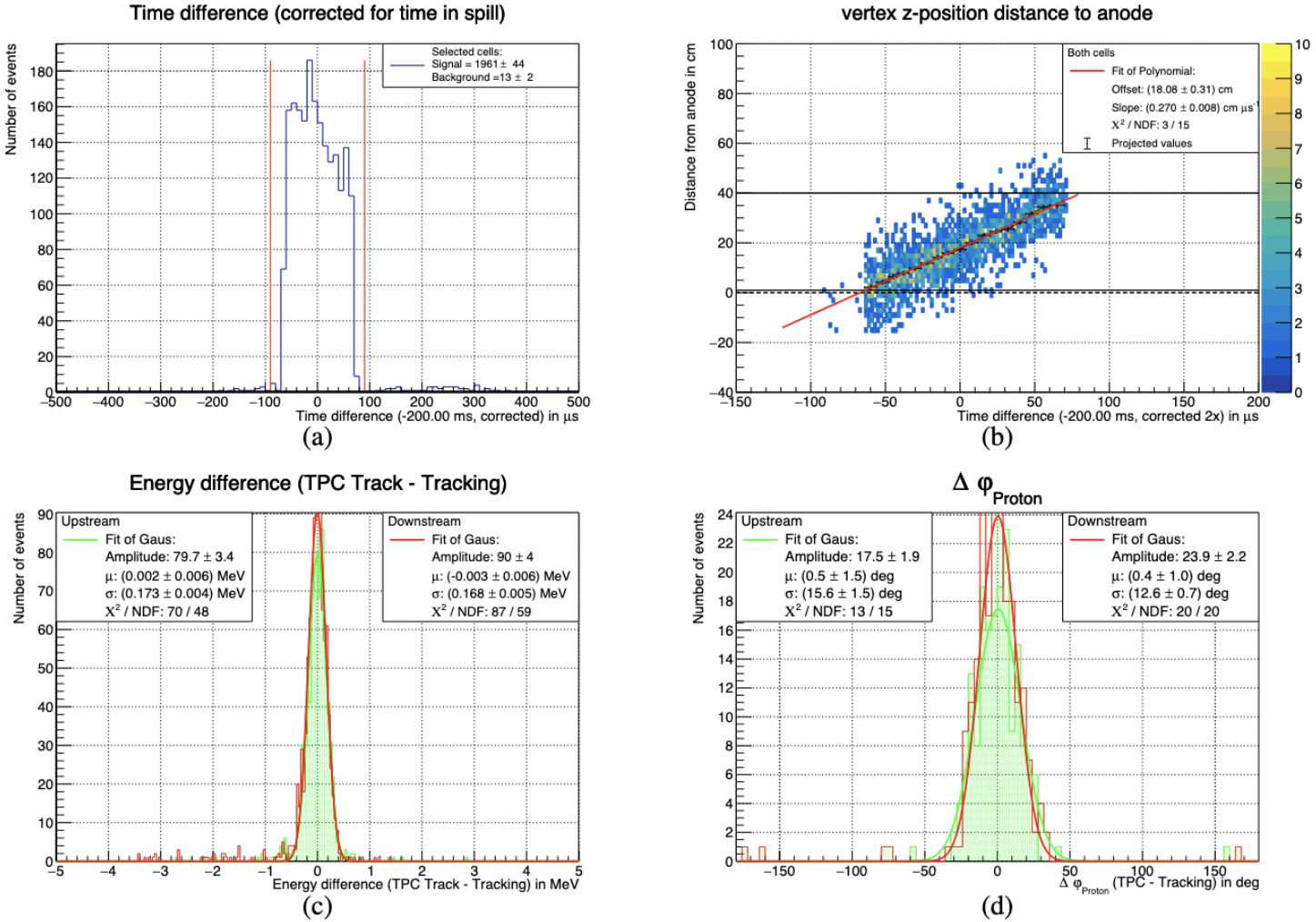






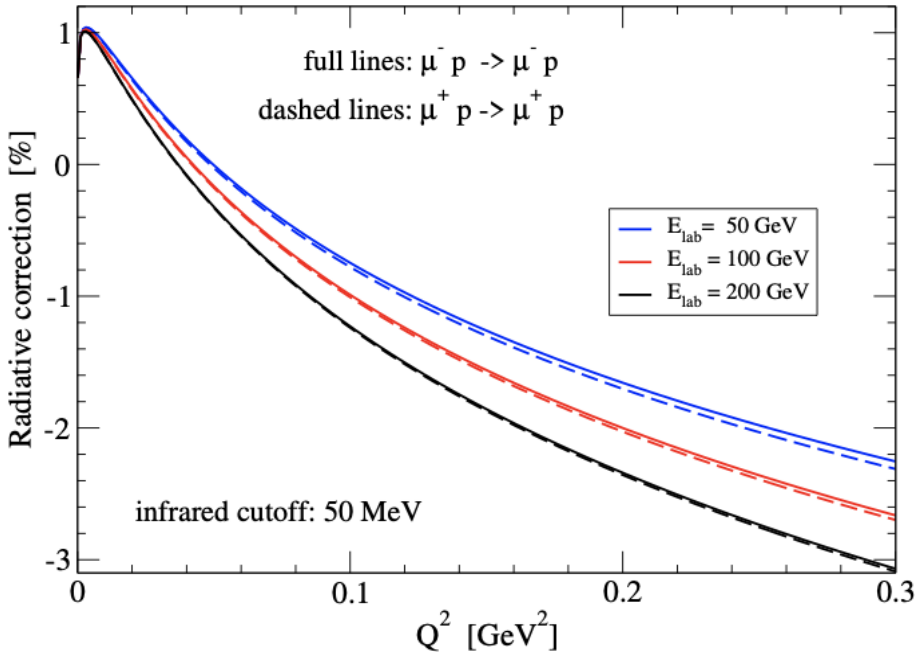


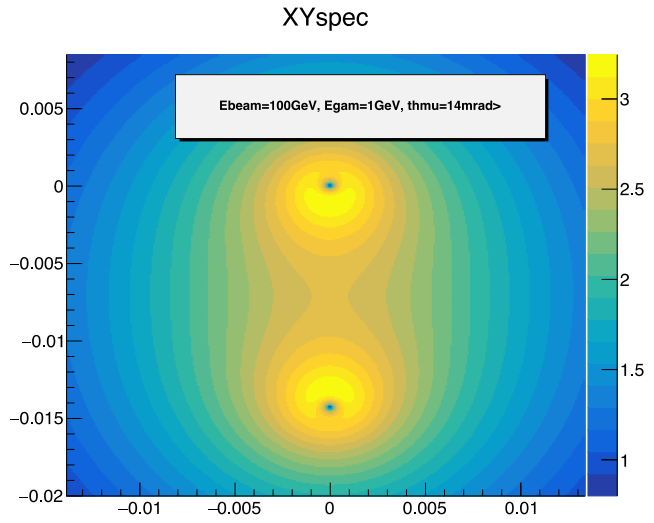
Test Data Analysis

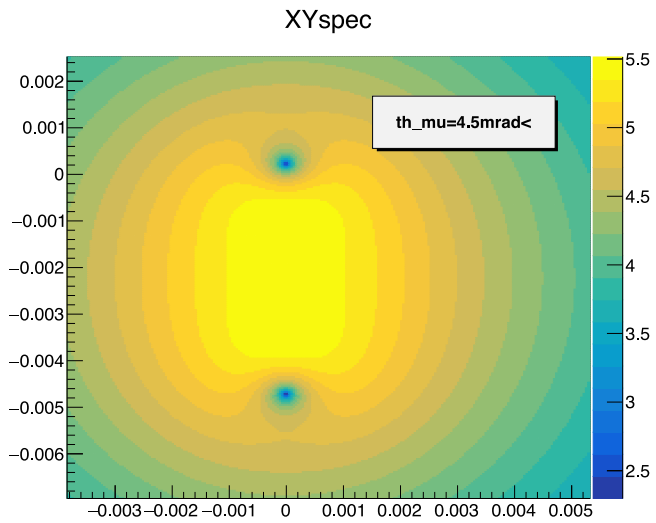


- With the 2021 test data, the correlations of the **muon scattering** and the **proton recoils** in the IKAR TPC were studied in detail
- in the coincidence time, the effect of the **drift** in the TPC gas could be identified, this will serve to control the purity of the elastic scattering events
- the expected correlations in $E_{kin} = Q^2/2M_p$ and in the azimuthal angle could also be shown

Radiative Corrections for μp Scattering

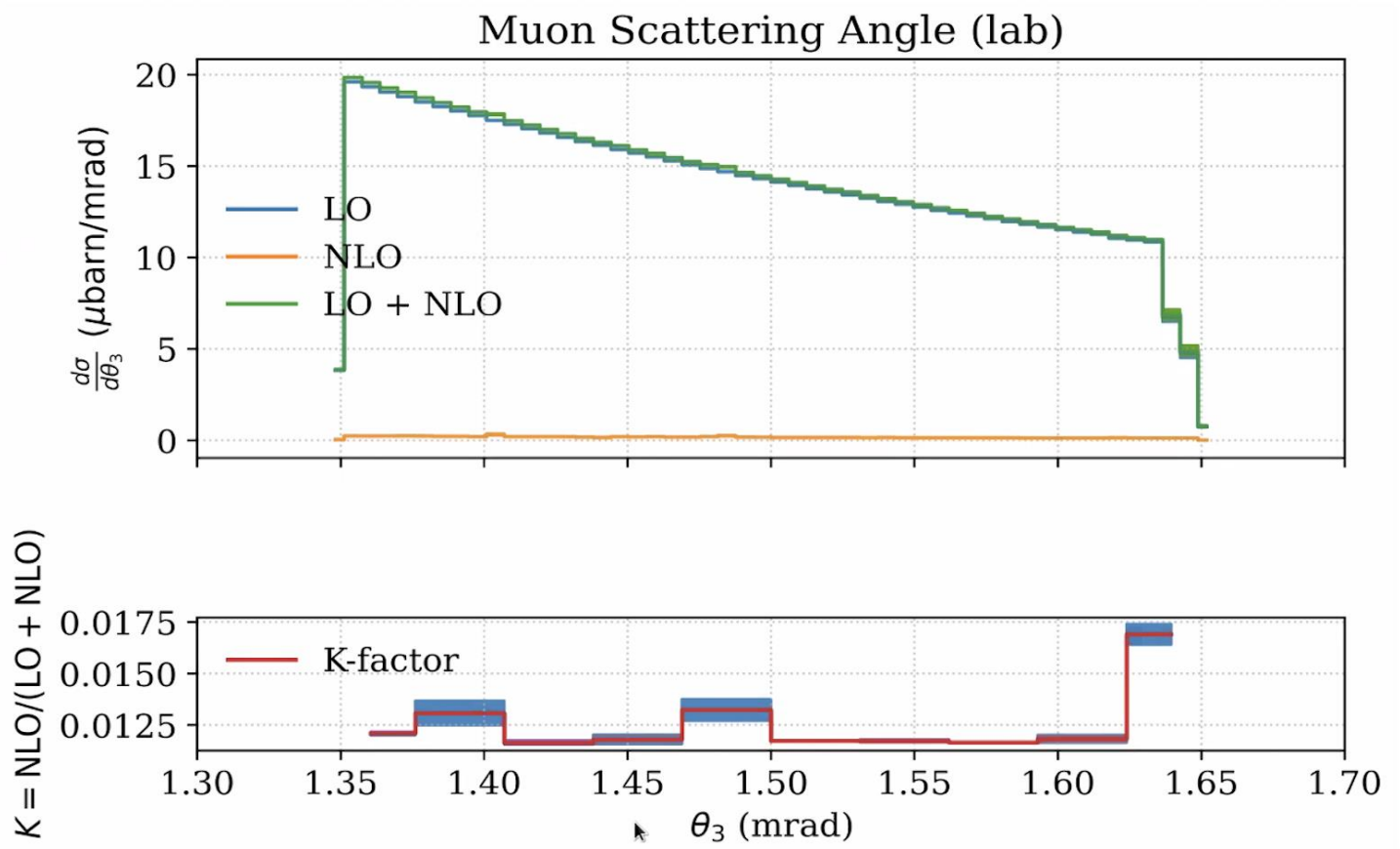






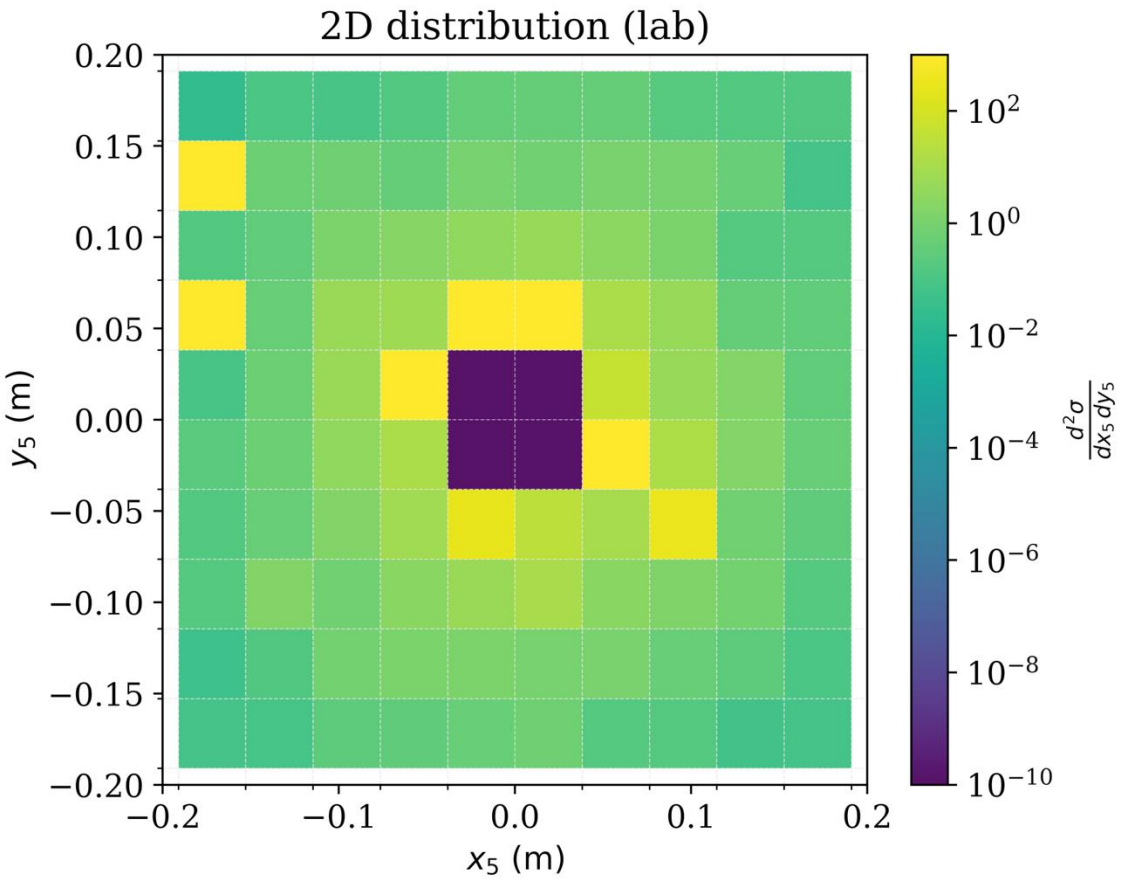
- Radiative corrections <1% for muon-proton scattering $Q^2 < 0.04\ \mathrm{GeV}^2$
- Calculations by N. Kaiser (TUM) *J. Phys. G* **37** 115005 (2010)
- Full MC generator foreseen – intensity forward bremsstrahlung photons can be checked in the experiment
- Collaboration with McMule team on implementation of higher-order corrections for the AMBER kinematics

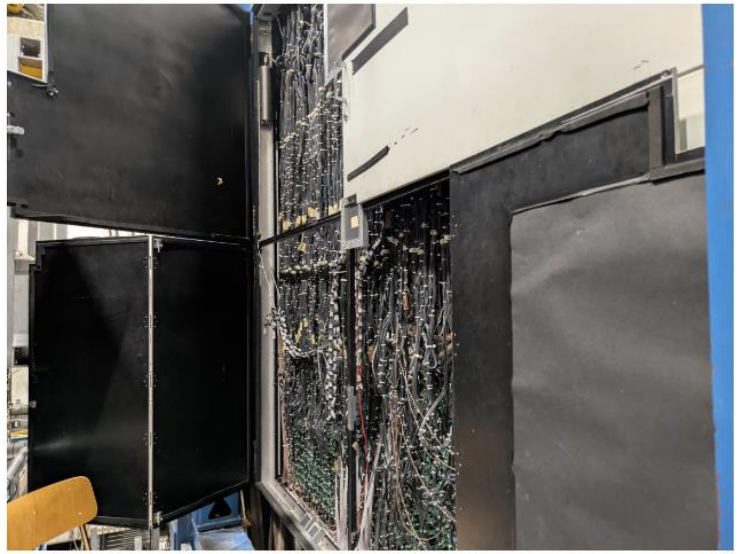
McMule for AMBER PRM

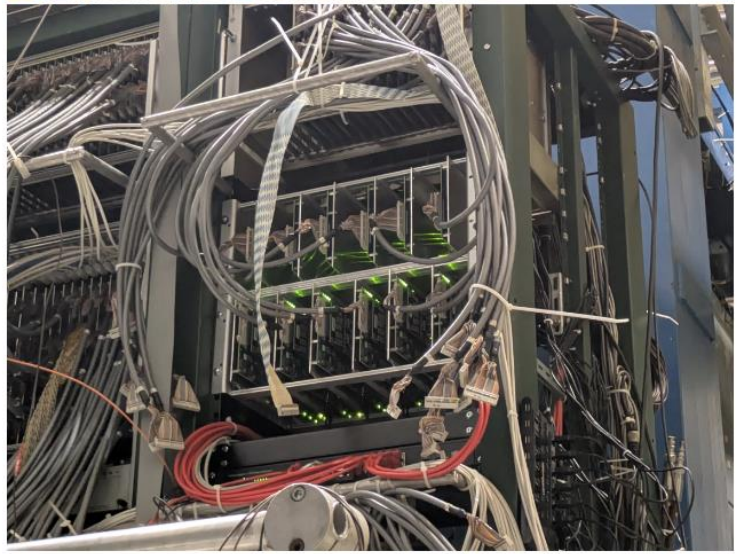


- Collaboration of AMBER and McMule team has (re)started in 2026 (TUM master thesis M. Leibelt)
- Intermediate goal: two-dimensional distributions in order to confirm the expected distribution of forward photons
- Longer term: Event generator for full simuation of the experiment including RC

Getting the forward ECAL ready



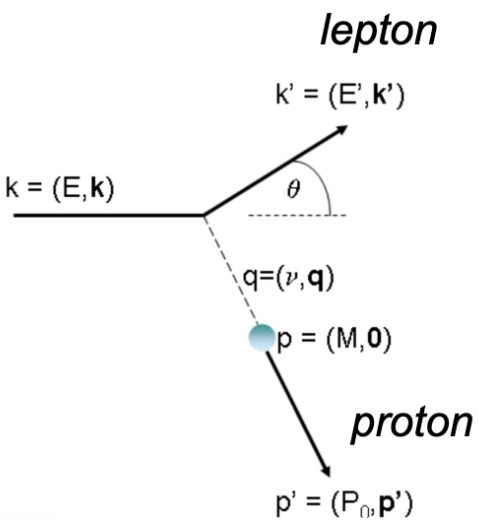


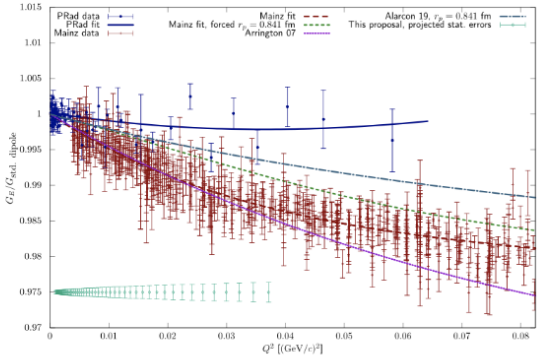


On the agenda for AMBER phase 2: Hadron charge radii

Protons in hydrogen target (or other stable nuclei):
Measurement via elastic electron or muon scattering
Cross section:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R \left(\varepsilon G_E^2 + \tau G_M^2\right)$$

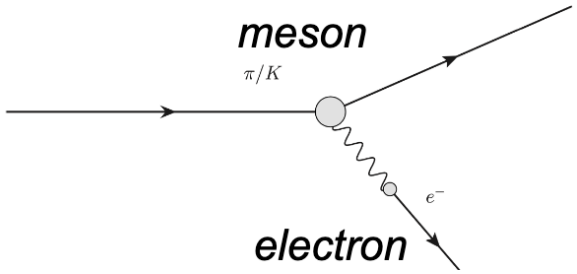




Charge radius from the slope of G_E

$$\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\right|_{Q^2\to 0}$$

For unstable particles, electron scattering can only be realised in *inverse kinematics*

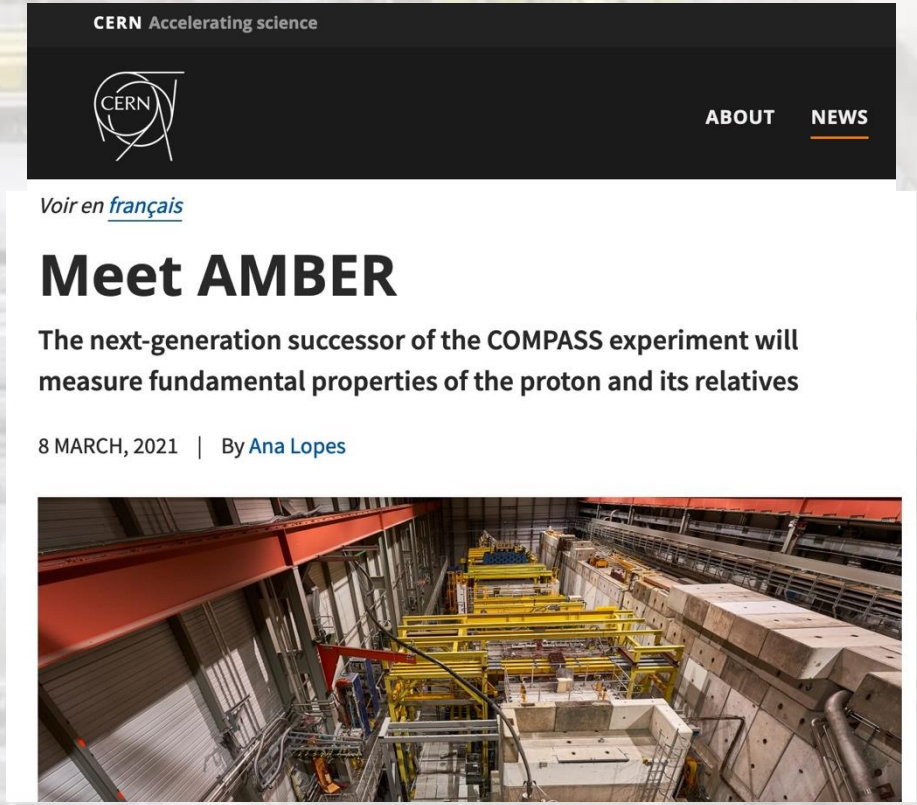


Conclusions

- NA66/AMBER at CERN has **started its Phase-1** of a broad hadron physics programme at M2

- **Proton Radius Measurement at AMBER**
  - new detector equipment under constructions: active-target TPC, muon tracking system, free-running DAQ
  - proof-of-principle from several test runs, analysis completed
  - **Preparations for the first physics run ongoing**

https://home.cern/news/news/physics/meet-amber


CERN Accelerating science

ABOUT NEWS

Voir en français

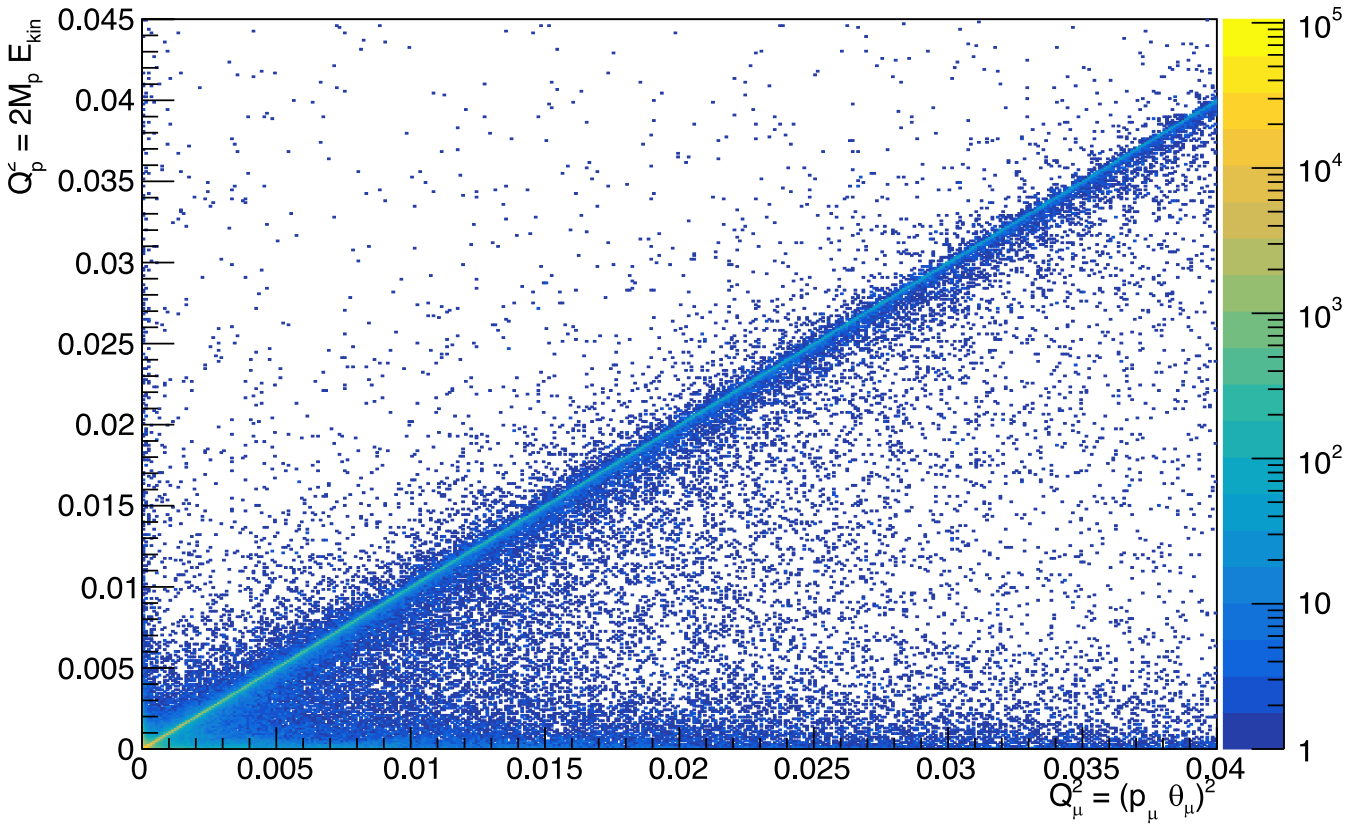
Meet AMBER

The next-generation successor of the COMPASS experiment will measure fundamental properties of the proton and its relatives

8 MARCH, 2021 | By Ana Lopes

Backup

Impact of photon emission on the muon-proton correlation



Recirculating Hydrogen Gas System

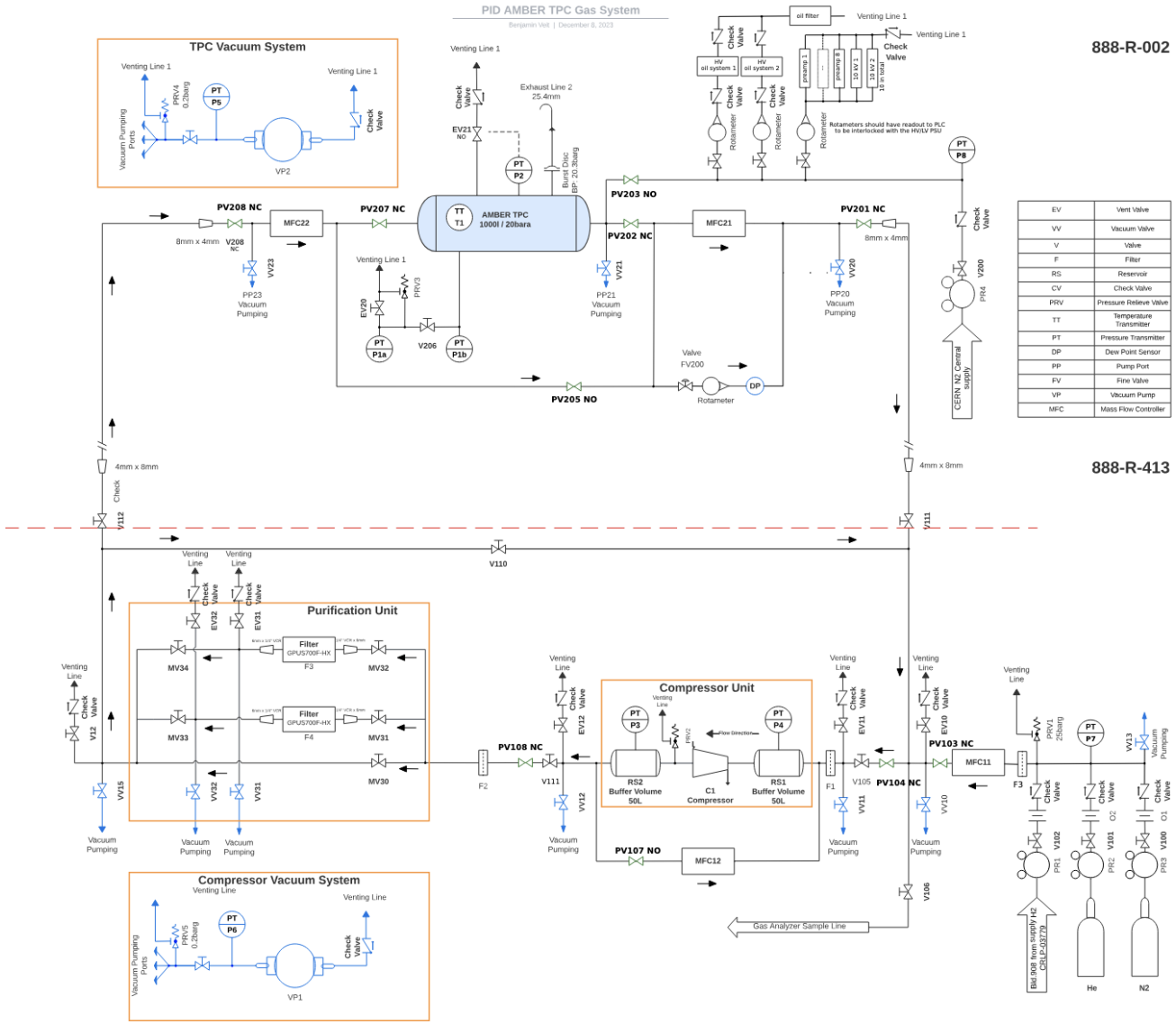


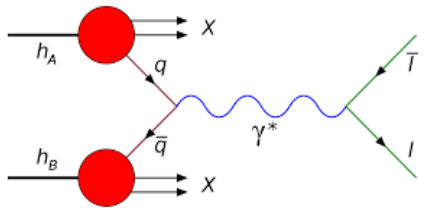
Fig. 27: TPC gas re-circulation and cleaning system.

The whole detector and the gas system, due to the usage of hydrogen, have been evaluated by an external company, and the risk assessment document was started. Several requirements and recommendations are taken into account for the design of the detector systems and surrounding elements.

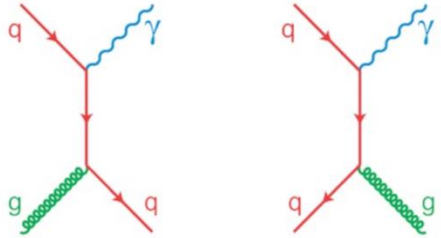
Many thanks to CERN EP-DT, CERN HSE and GSI for support and help of the challenging issues with risk assessment and safety procedures!

The choice of the elements for the gas system is made taking into account the functionality and requirements according to the risk assessment. The elements are being procured and the whole system is supposed to be put together in **autumn 2024**.

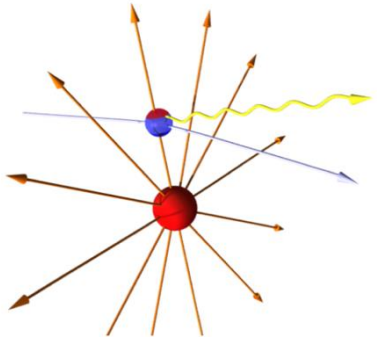
The ideas of the Phase-2 proposal



- Kaon structure via the Drell-Yan process

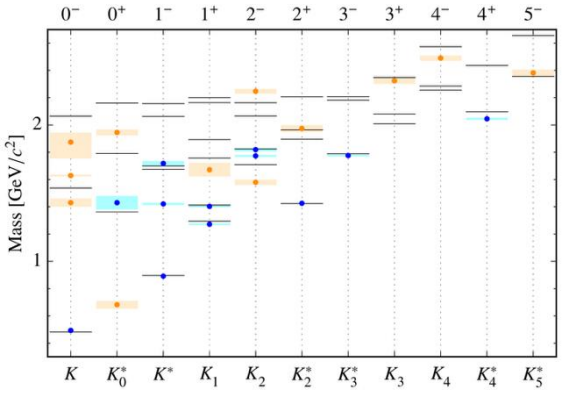


- Gluon structure of pions and kaons via prompt photons

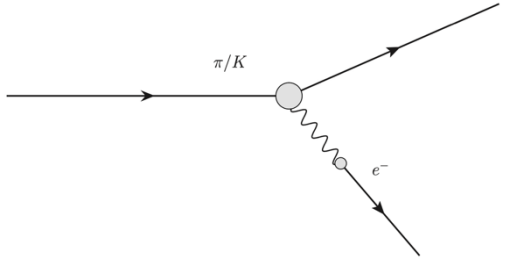


- Primakoff reactions to investigate kaon-photon coupling: kaon polarisability, $F_{KK\pi}$

- Generalized Parton Distributions in DVCS and HEMP



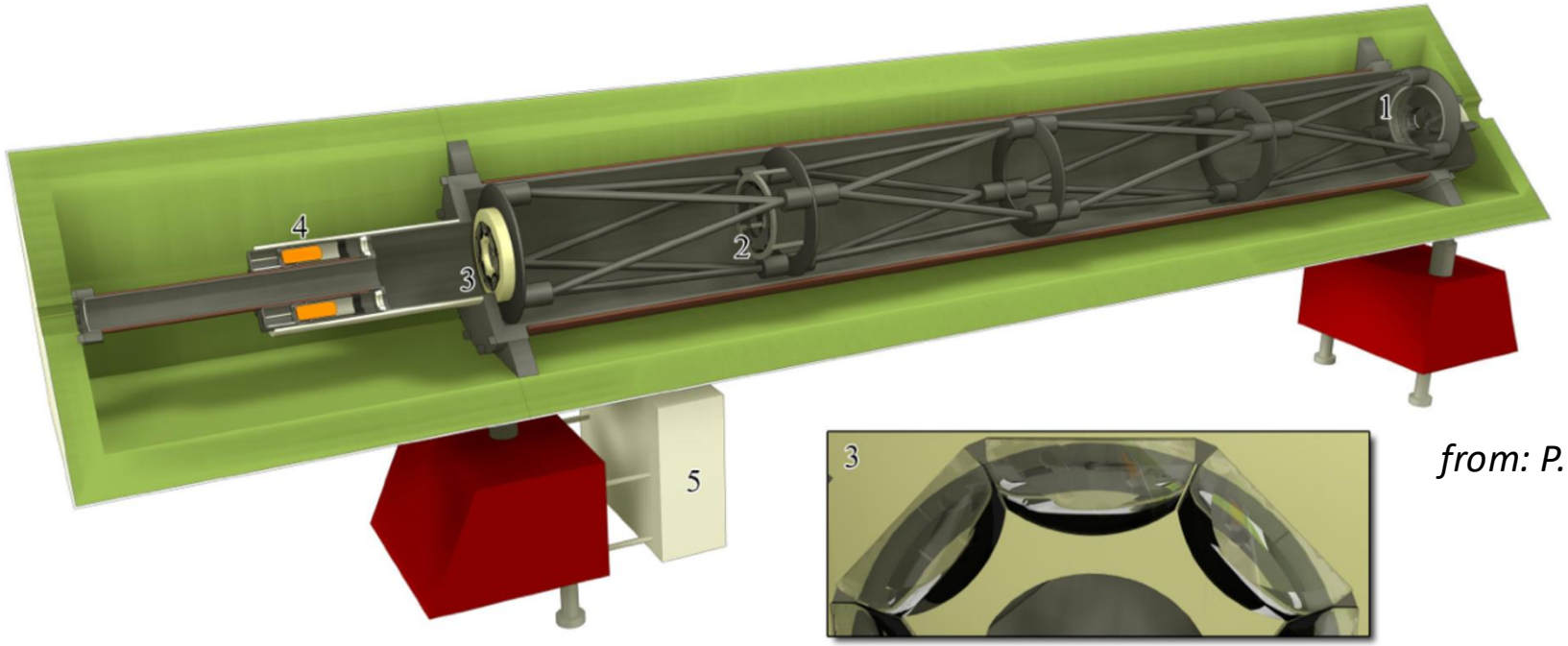
- Spectroscopy of mesons with strangeness



- Meson charge radii via electron scattering in inverse kinematics

- Diffractive production of vector mesons and di-jets to study distribution amplitudes

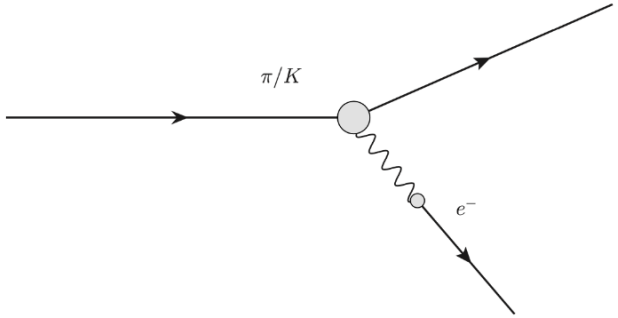
Beam PID by CEDARs



from: P. Jasinski, PhD thesis

- High-efficiency and high-purity beam particle identification is of key importance in all scenarios of hadron beams
- Optimum operation not only concerns mechanics and optics (temperature stabilization, photon detection), but as well parallelism of the incoming beam → material budget of the beamline

Kinematics for different beam particles



$$K^- \, e^-_{target} \rightarrow K^- \, e^-$$

$$Q^2 \approx 2m_e \cdot E_e$$

$$s = 2E_b m_e + m_b^2 + m_e^2$$

$$Q^2_{max} = \frac{4 \cdot m_e^2 \cdot p_b^2}{s} = 4 \cdot p_{cm}^2$$

Beam	E_{beam} [GeV]	Q^2_{max} [GeV²]	$E^{min}_{scatter}(Q^2 \sim 10^{-4})$ [GeV]	$E^{electron}_{max}$ Q^2_{max} [GeV]	$E_e^{lab-equivalent}$ [GeV]
π	280	0,268	17.2	173	1,030
K	280	0.15	105.2	84.7	0,29
K	80	0,021	59.7	20.2	0,072
K	50	0,009	41.3	8.7	0,047
p	280	0.07	155.3	34.3	0,152