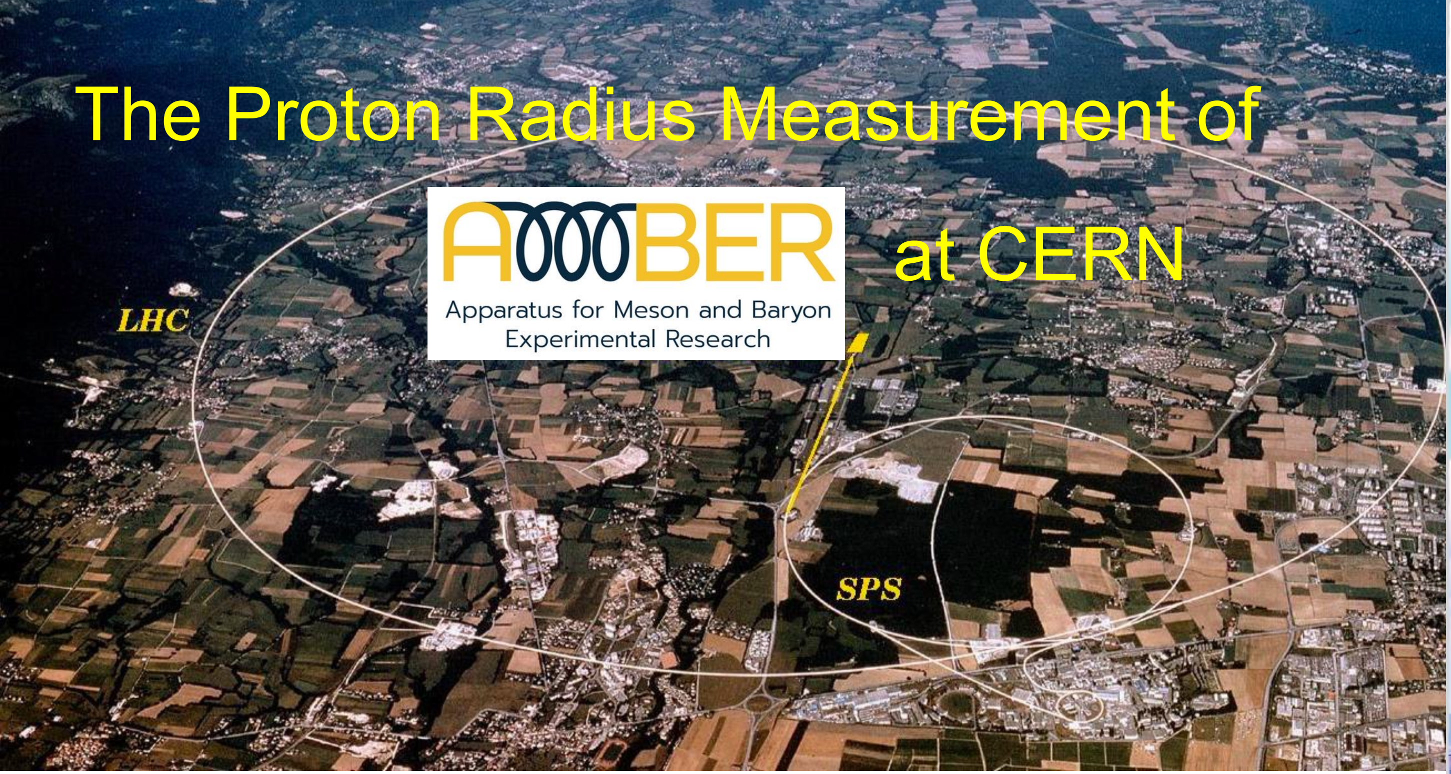
The Proton Radius Measurement of AMBER at CERN

AMBER
Apparatus for Meson and Baryon Experimental Research



Jan Friedrich

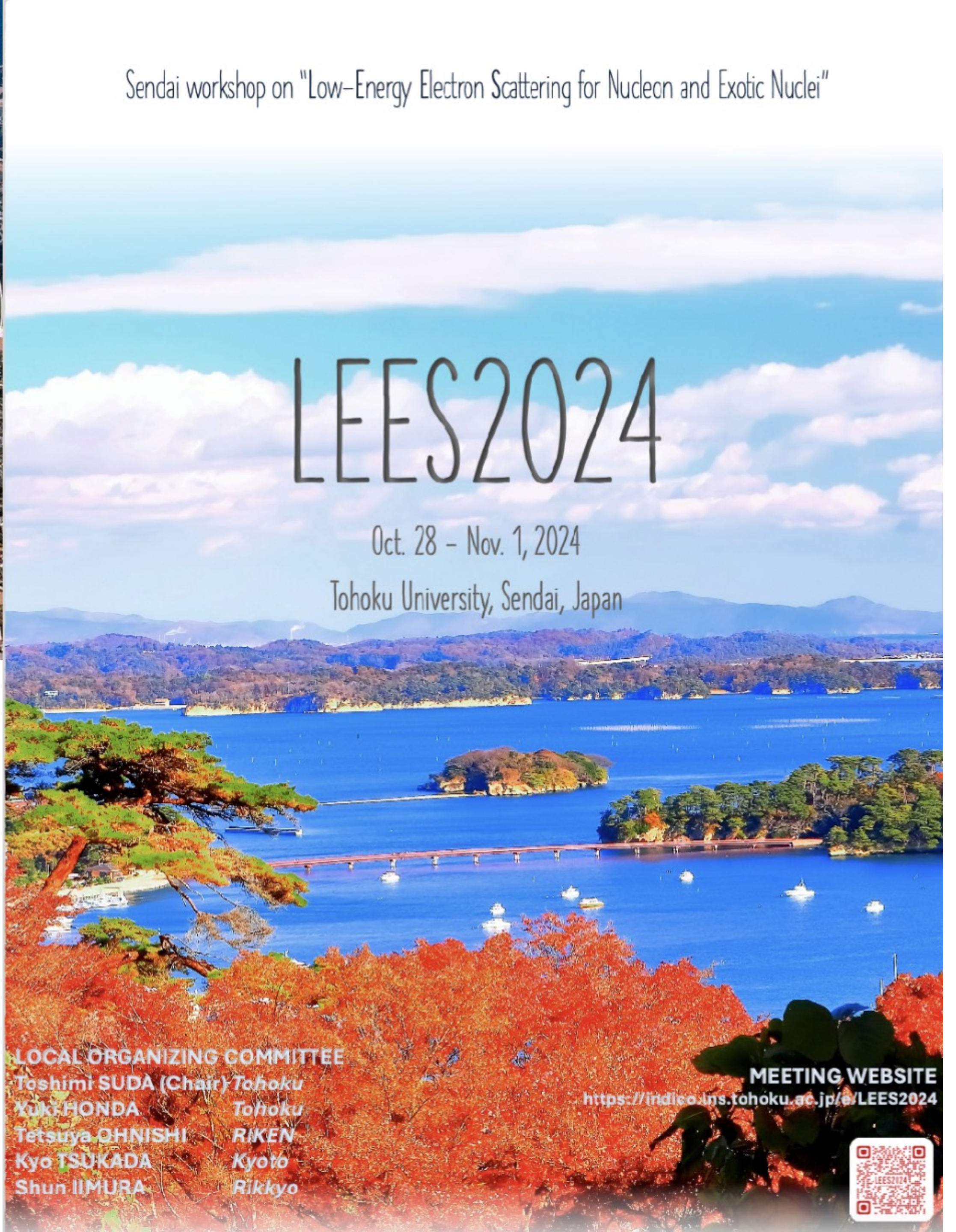
Technische Universität München

31.10.2024

ORIGINS Excellence Cluster

Bundesministerium für Bildung und Forschung

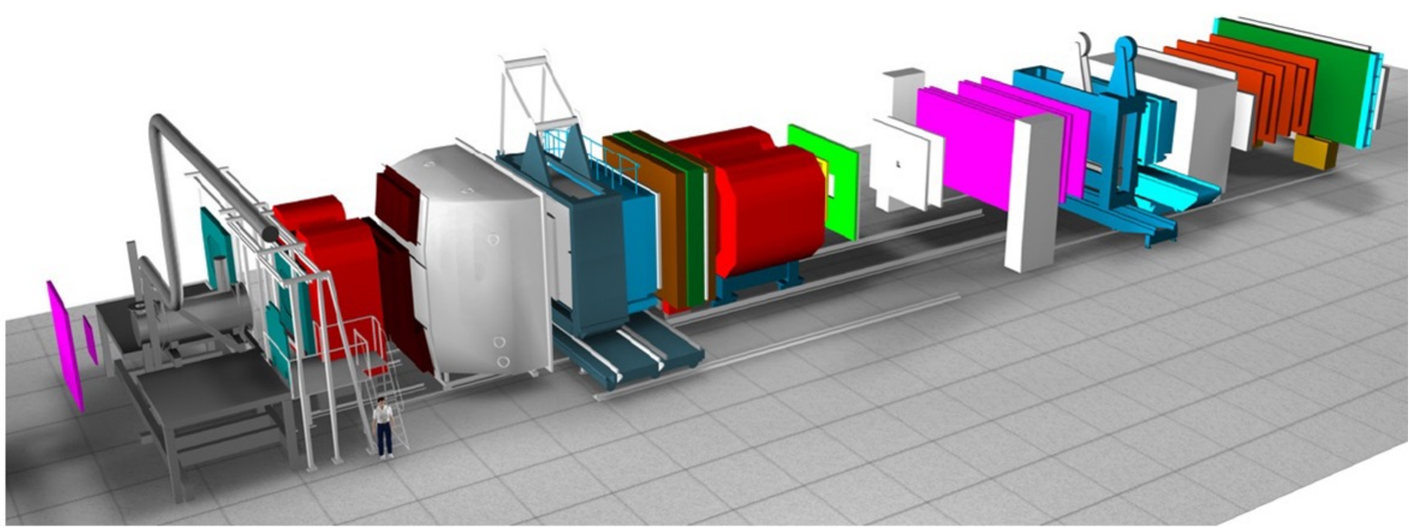
on behalf of the AMBER Collaboration



*A*pparatus for *M*eson and *B*aryon *E*xperimental *R*esearch

AMBER
Apparatus for Meson and Baryon Experimental Research

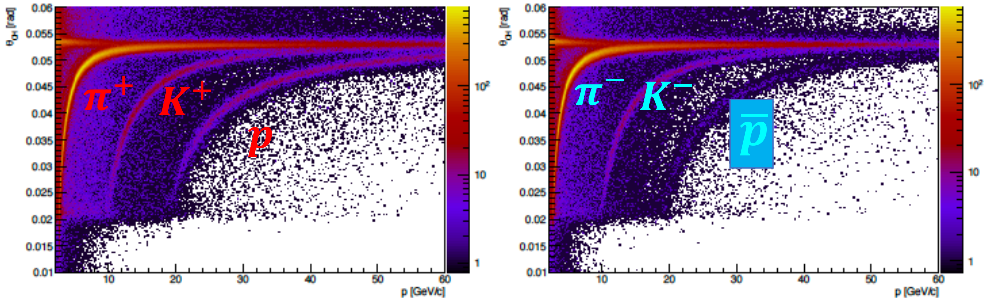
- AMBER has been approved as NA66 experiment in December 2020
- the Collaboration consists of ~200 physicists from 34 institutes
- at the M2 beamline at SPS muon and hadron beams 60 – 250 GeV
- AMBER inherited, extends and modernizes the 2-stage spectrometer of the COMPASS collaboration



- **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

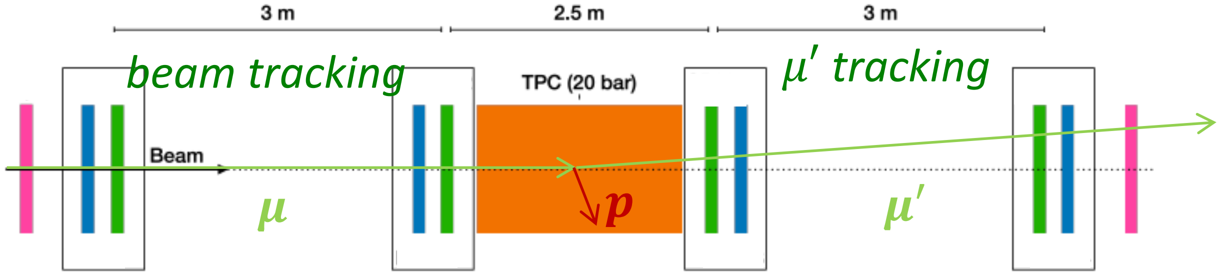
AMBER Phase-1 in a nutshell

- **Anti-proton production cross sections** in p-He and p-p collisions for constraining cosmic dark-matter search data: unique data sets in unexplored beam momentum range 60-250 GeV, successful p-He data taking in 2023, p-p and p-D in 2024

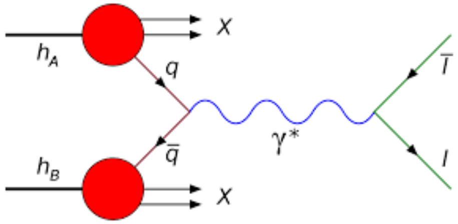


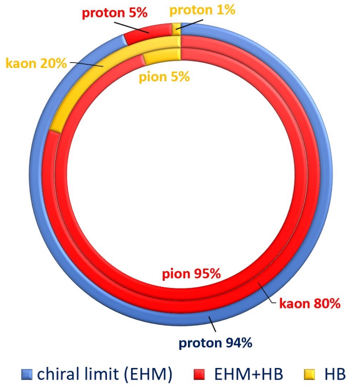
RICH PID: Cerenkov angle vs. momentum

- **Proton radius** via muon-proton scattering, recoiling proton and scattered muon are measured in coincidence: unique in terms of systematics control



- **Pion and kaon partonic structure** via Drell-Yan processes: separate valence and sea contributions in unprecedented precision

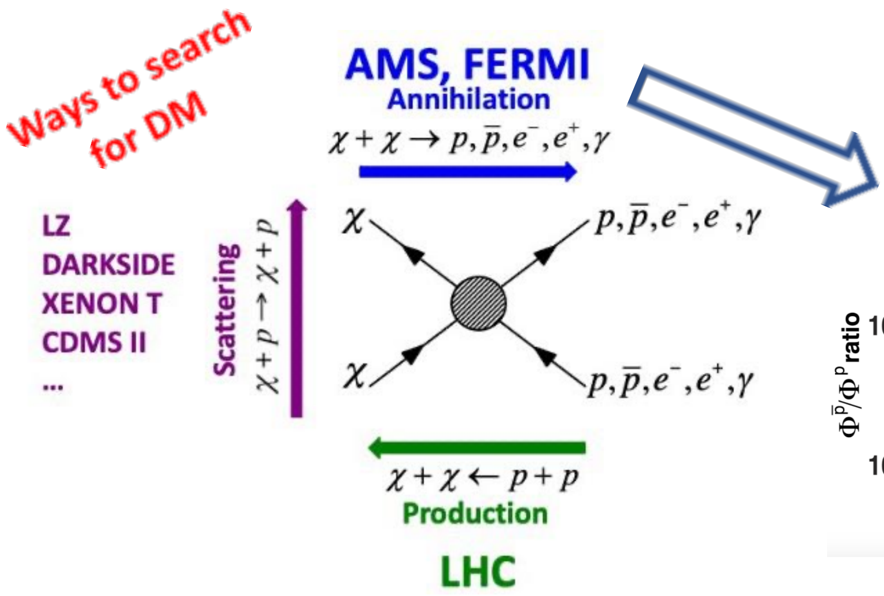


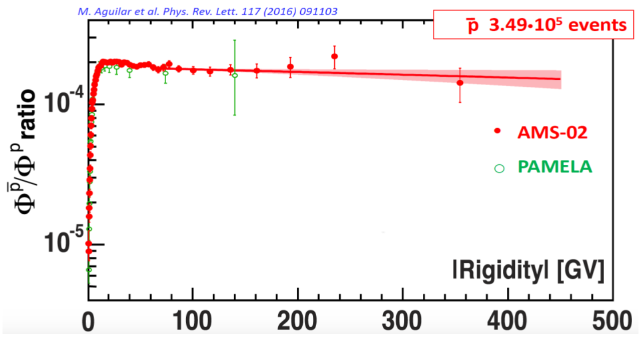


Mass budgets: **emergence** of the light-hadron masses is linked to both the QCD partonic structure and to confinement

plot courtesy C. Robert

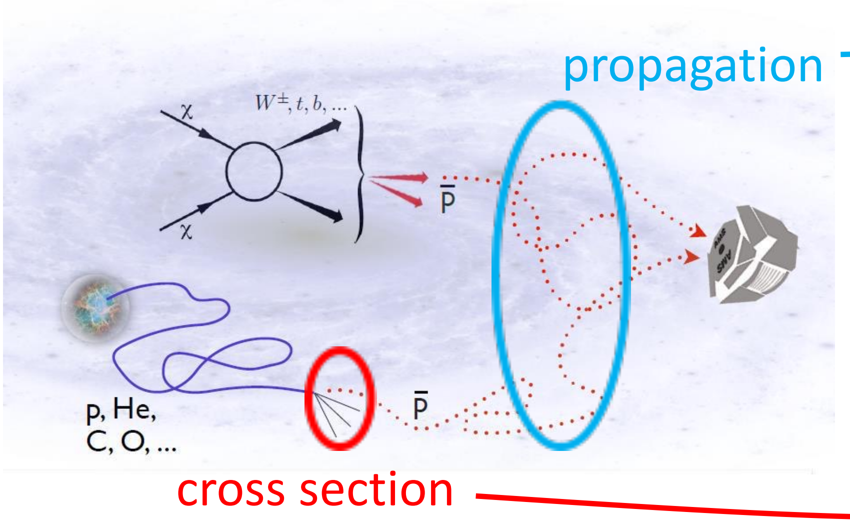
Antiproton production cross-sections for dark-matter searches

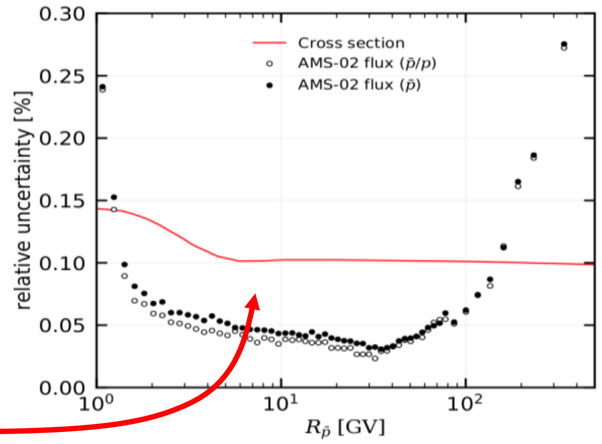


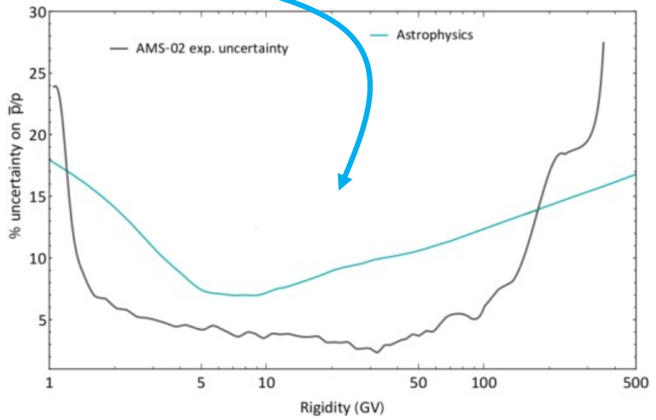


AMBER:

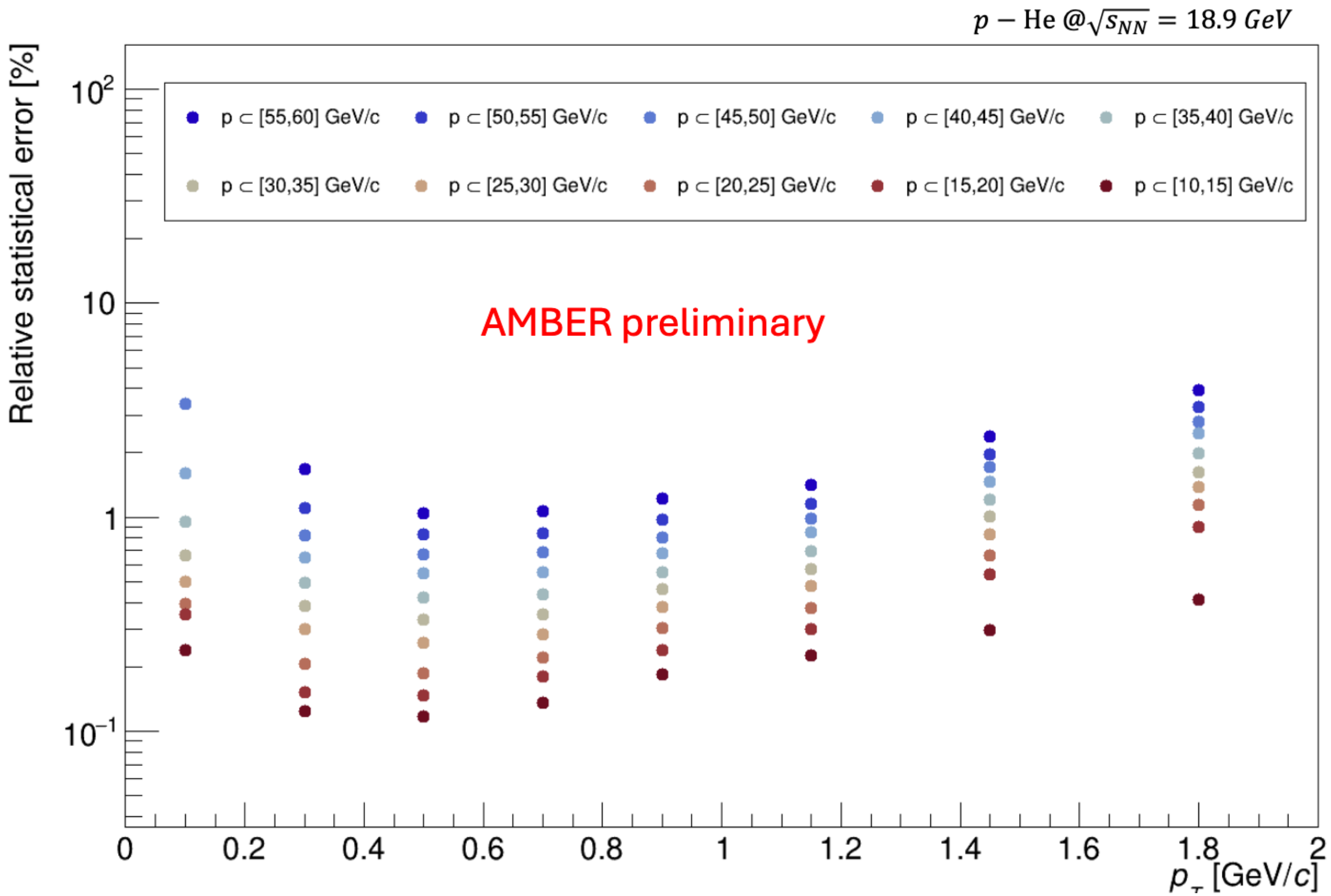
- Data for p-He collisions taken in summer 2023
- Data for p-p and p-D taken in 2024





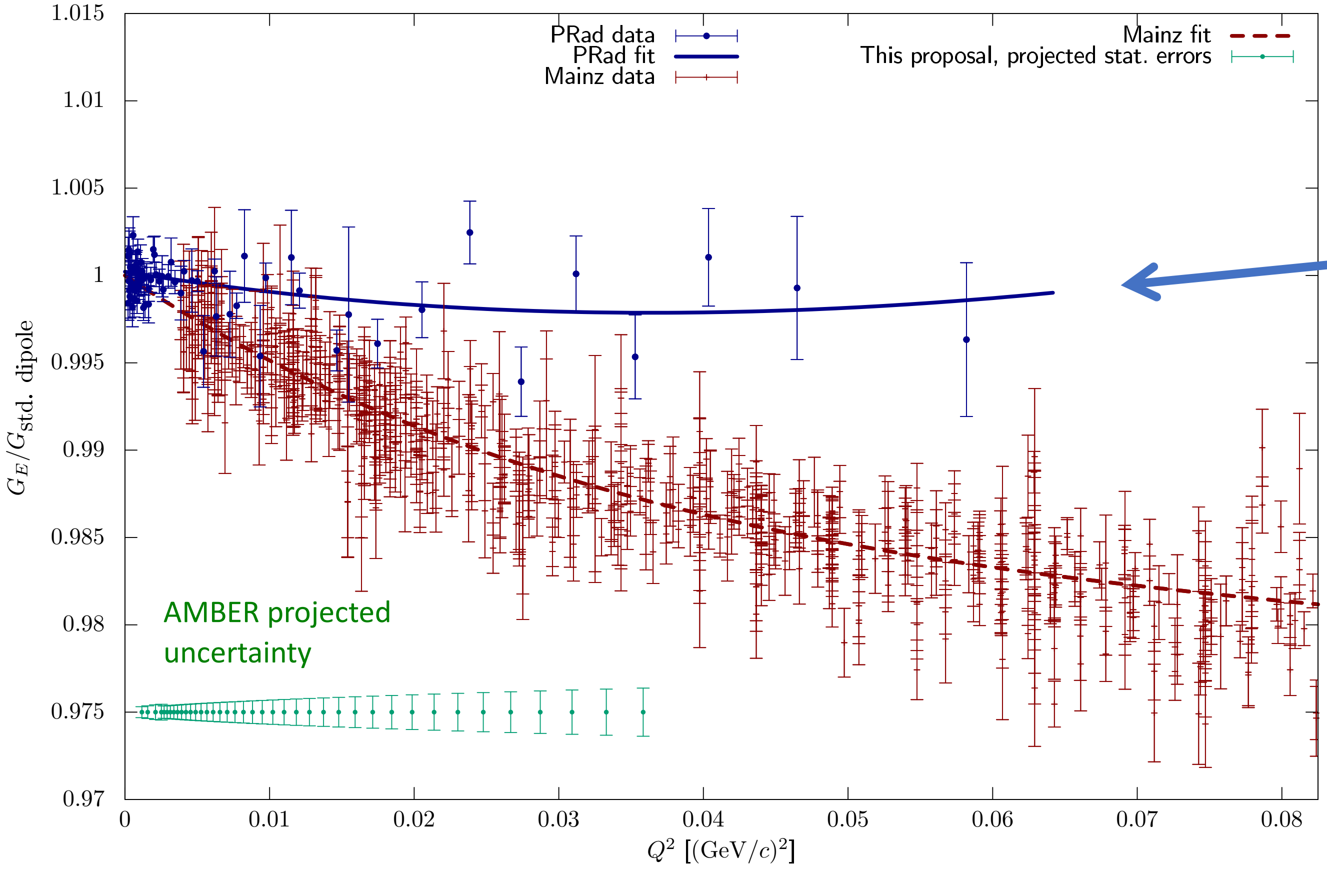


Antiproton production cross-sections: uncertainty estimates



- A preliminary analysis shows that we collected ~6million antiprotons in
  - p [10, 60] GeV/c
  - p_T [0, 2] GeV/c
- Statistical uncertainty in most bins < 1%
- Leading systematic uncertainties expected from:
  - Luminosity
  - RICH

Measurement of G_E^p at small Q^2



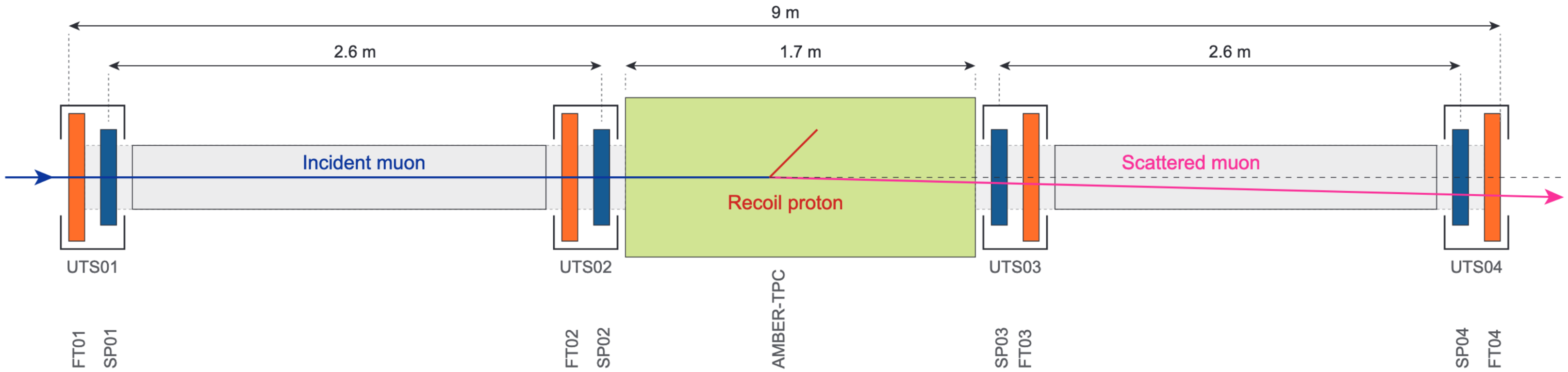
Proton Radius Experiment at Jefferson Lab

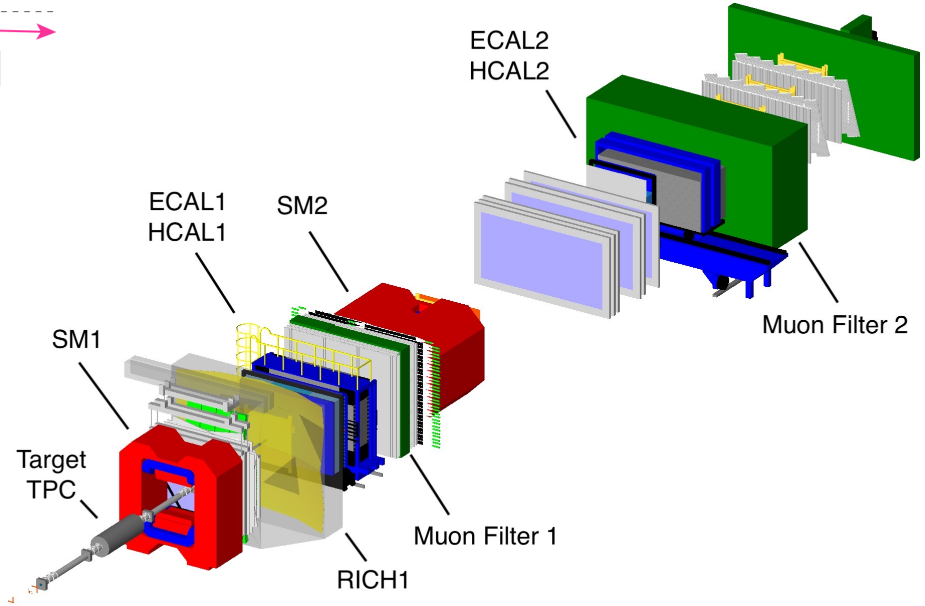
PRoton Radius

MAINZER MIKROTRON

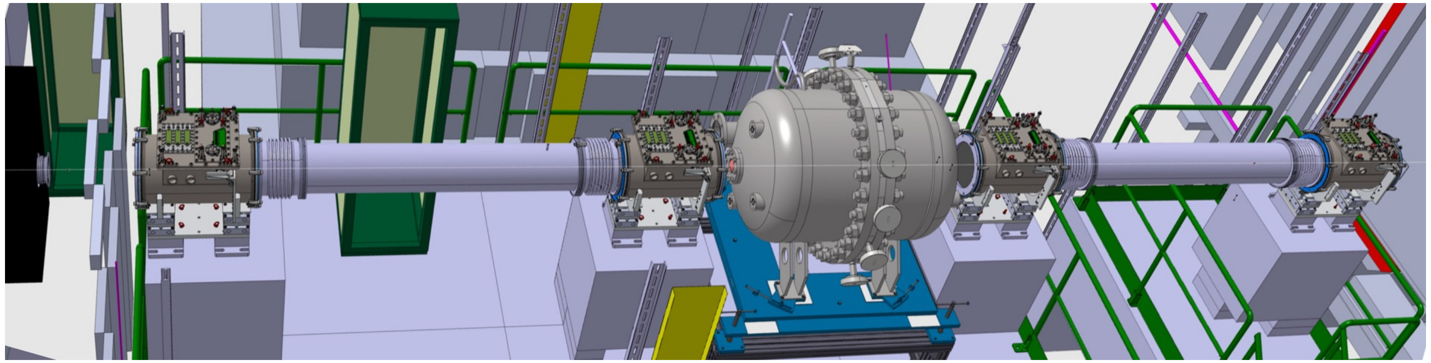
figure: J. Bernauer

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

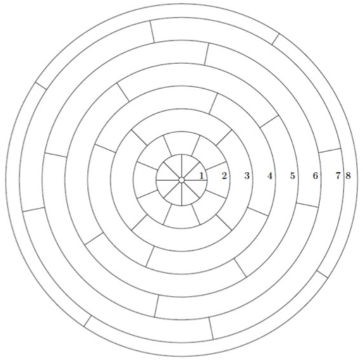


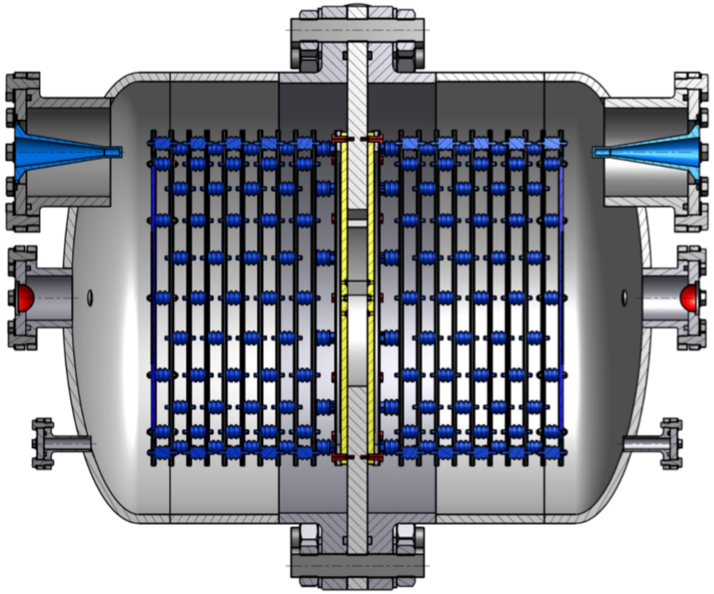
New Equipment for PRM

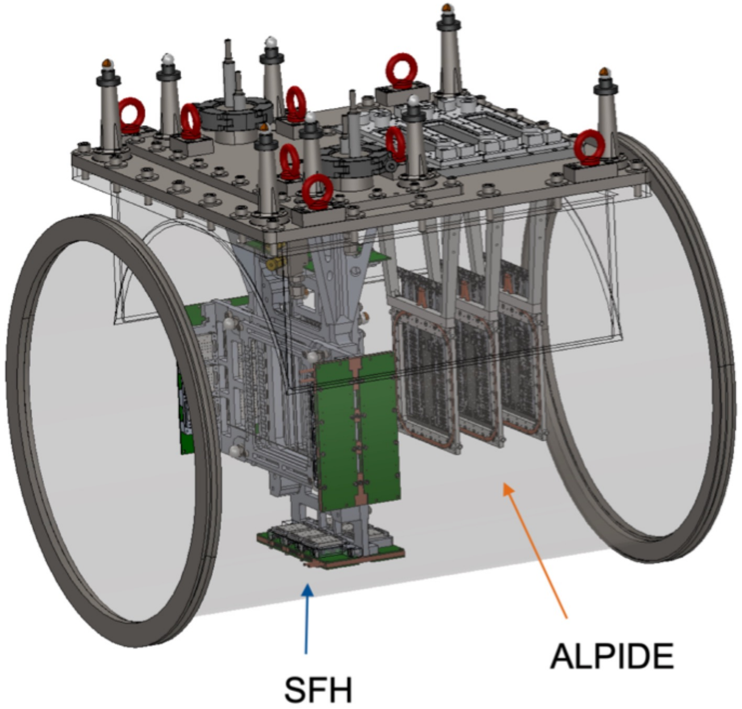
High-pressure hydrogen TPC
- Operation at 20 bar hydrogen pressure
- design with 2 drift cells
- Segmented anode plane
- reconstruction of proton recoil energy with ~50 keV precision

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

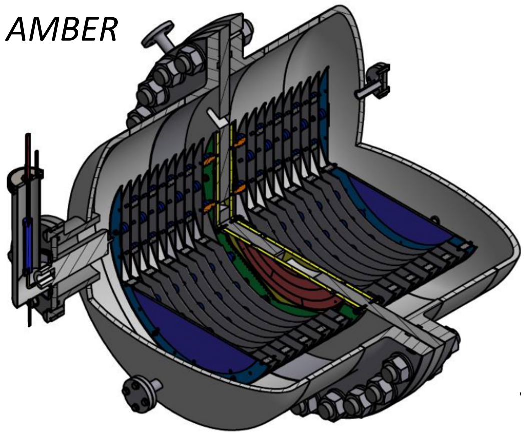






New High-Pressure Time Projection Chamber

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, now transported to CERN

Factory Acceptance Test at the Danish production site, May 2024

Electrode and Readout Anode Structure

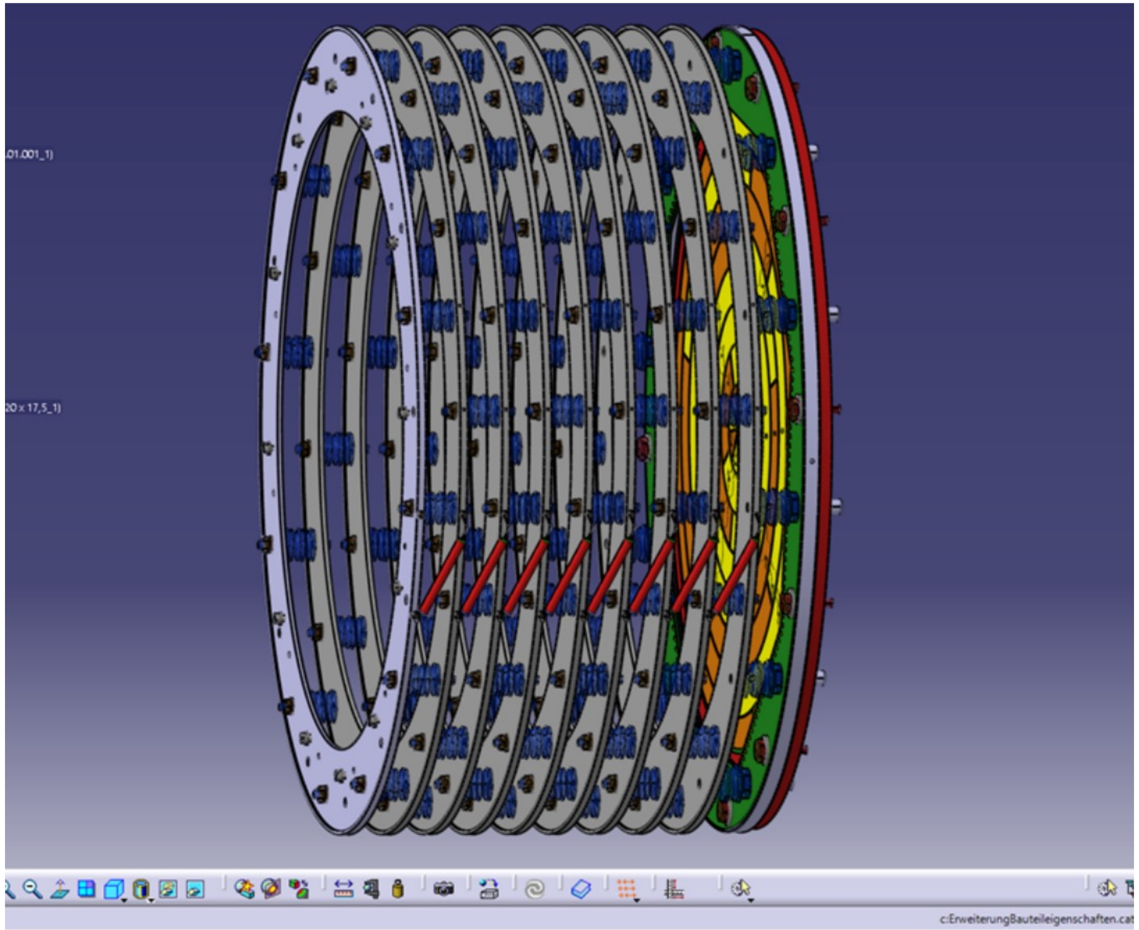
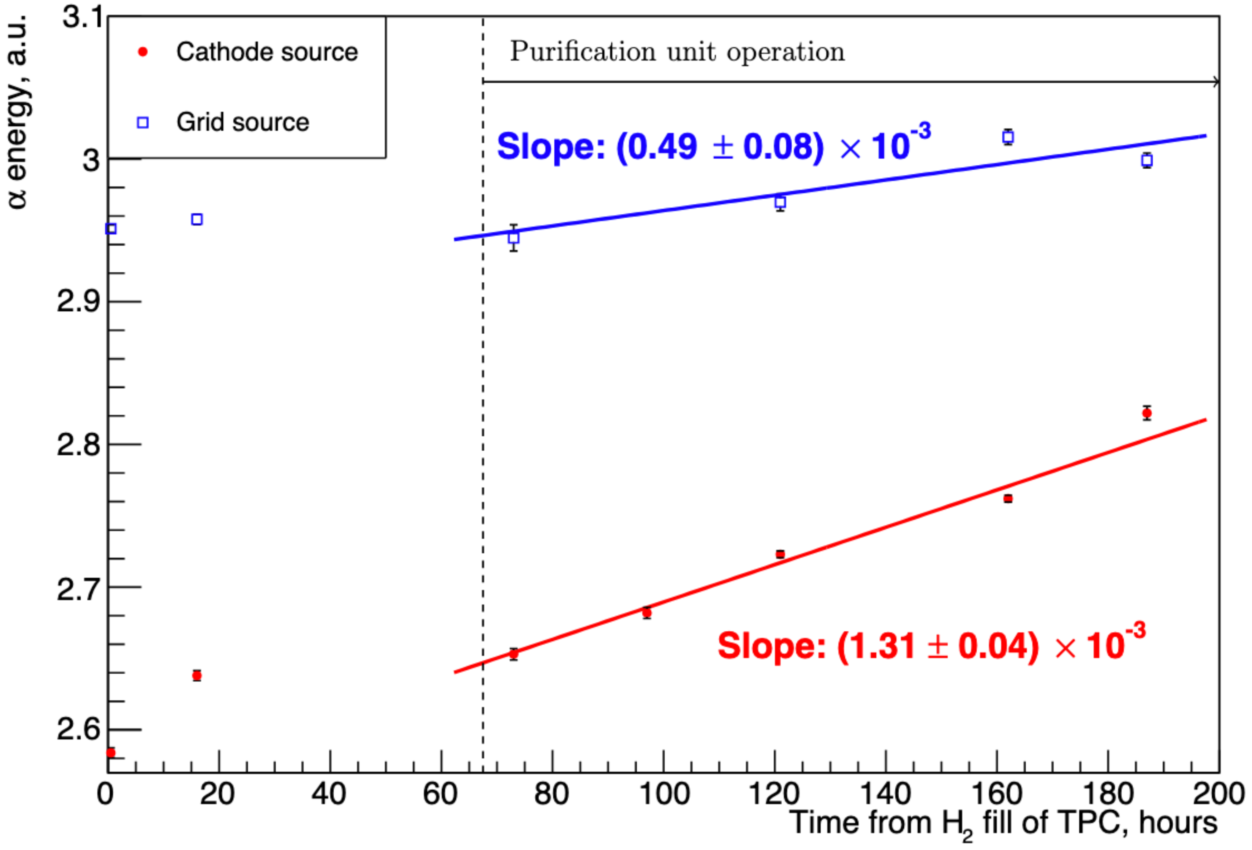


Fig. 26: CAD drawing of the TPC inner electrode structure.

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

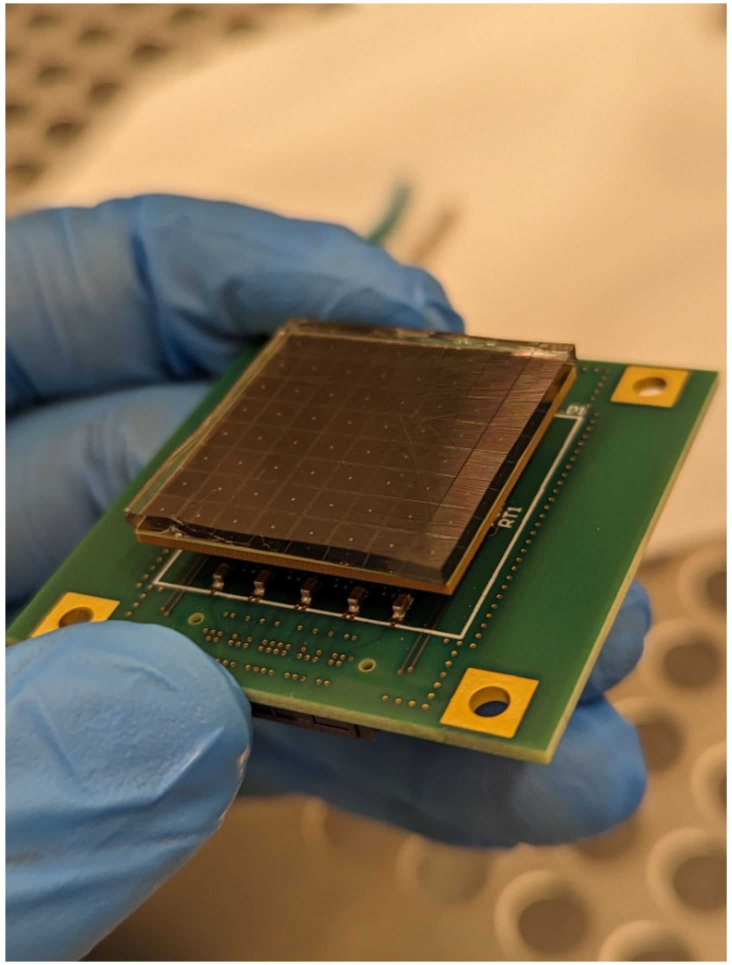
Hydrogen Gas Purification



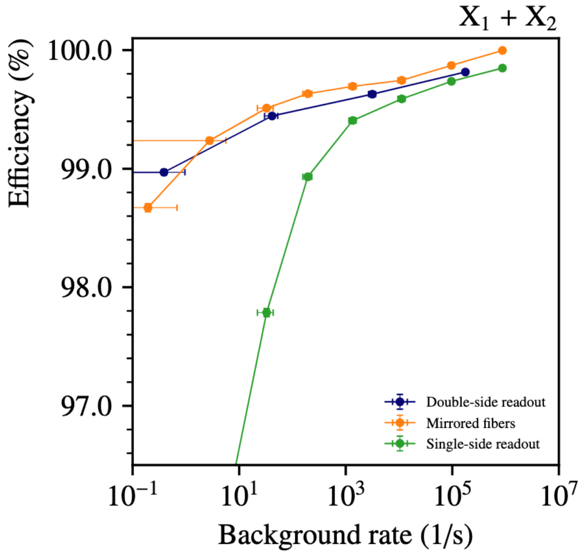
- Tests in 2023 with the old IKAR TPC and a new purification unit
- the increase of the amplitude from the α sources is a measure of the purity of the detector gas
- stronger effect by the cathode source (longer drifts)

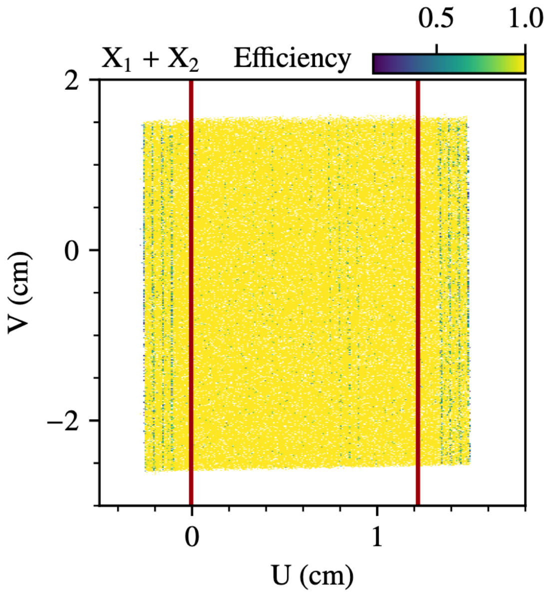
Scintillating-Fiber Hodoscope

(a) UTS with SFH prototype in the target area.



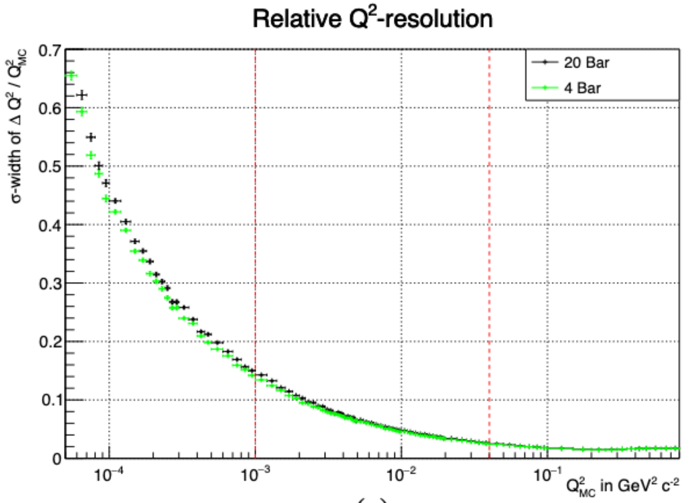
(b) Gel pad used to improve the SiPM-fiber coupling in the SFH prototype.



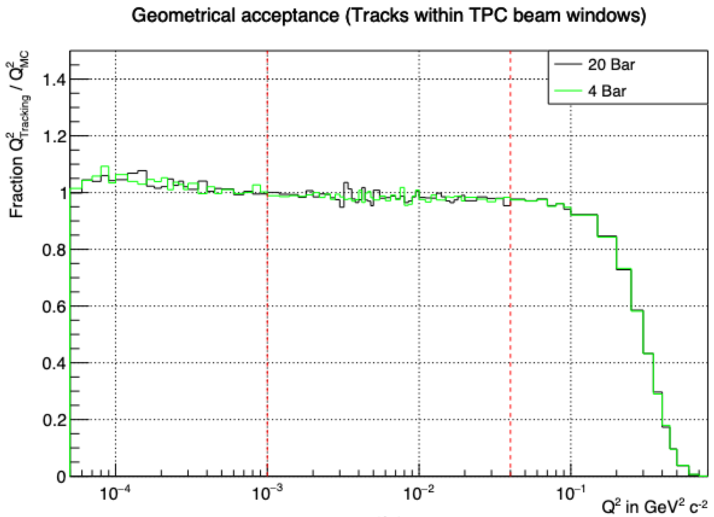


Simulation of the PRM Setup

- 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 $Q^2 > 10^{-3}$ 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

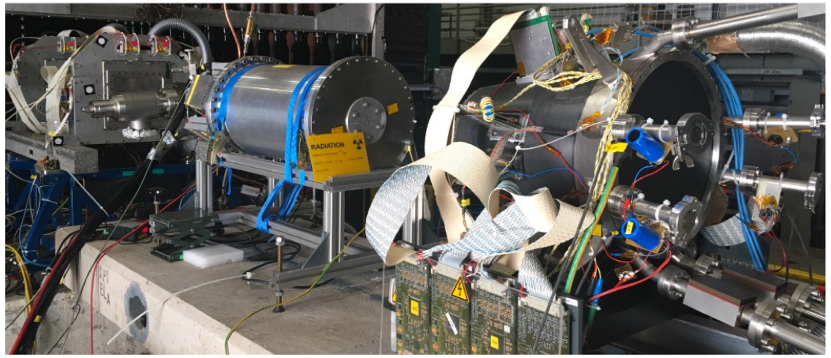
2021: First test run with IKAR TPC and already existing tracking detectors from COMPASS → *correlation between proton energy and muon scattering angle*

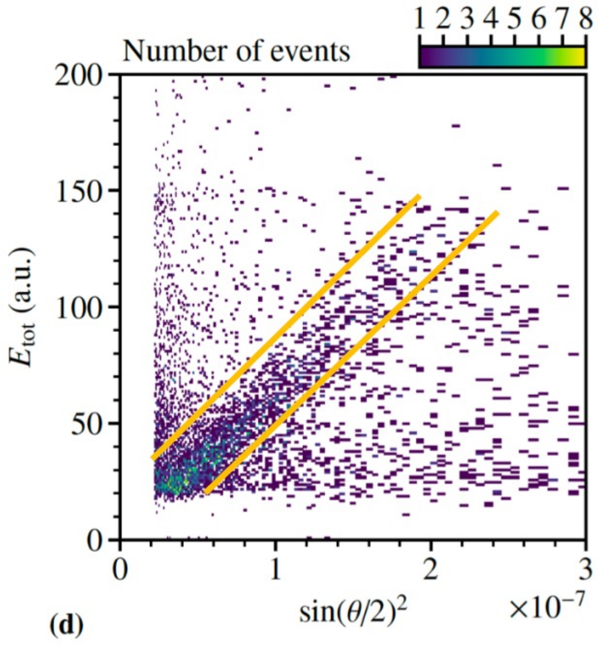
2023: Test run with new free-running DAQ (IKAR TPC, new tracking detector prototypes)

2024: Tests with UTS prototypes

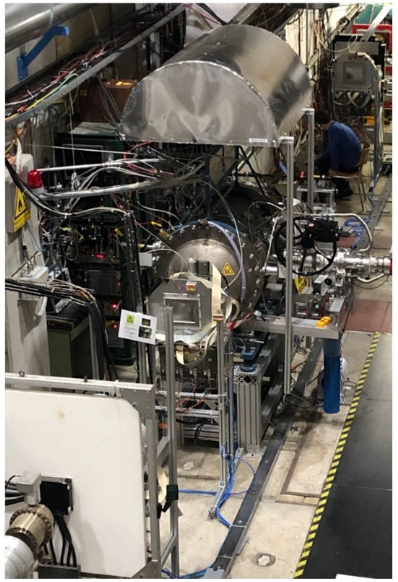
2025: Physics run with new TPC and final UTS

2018



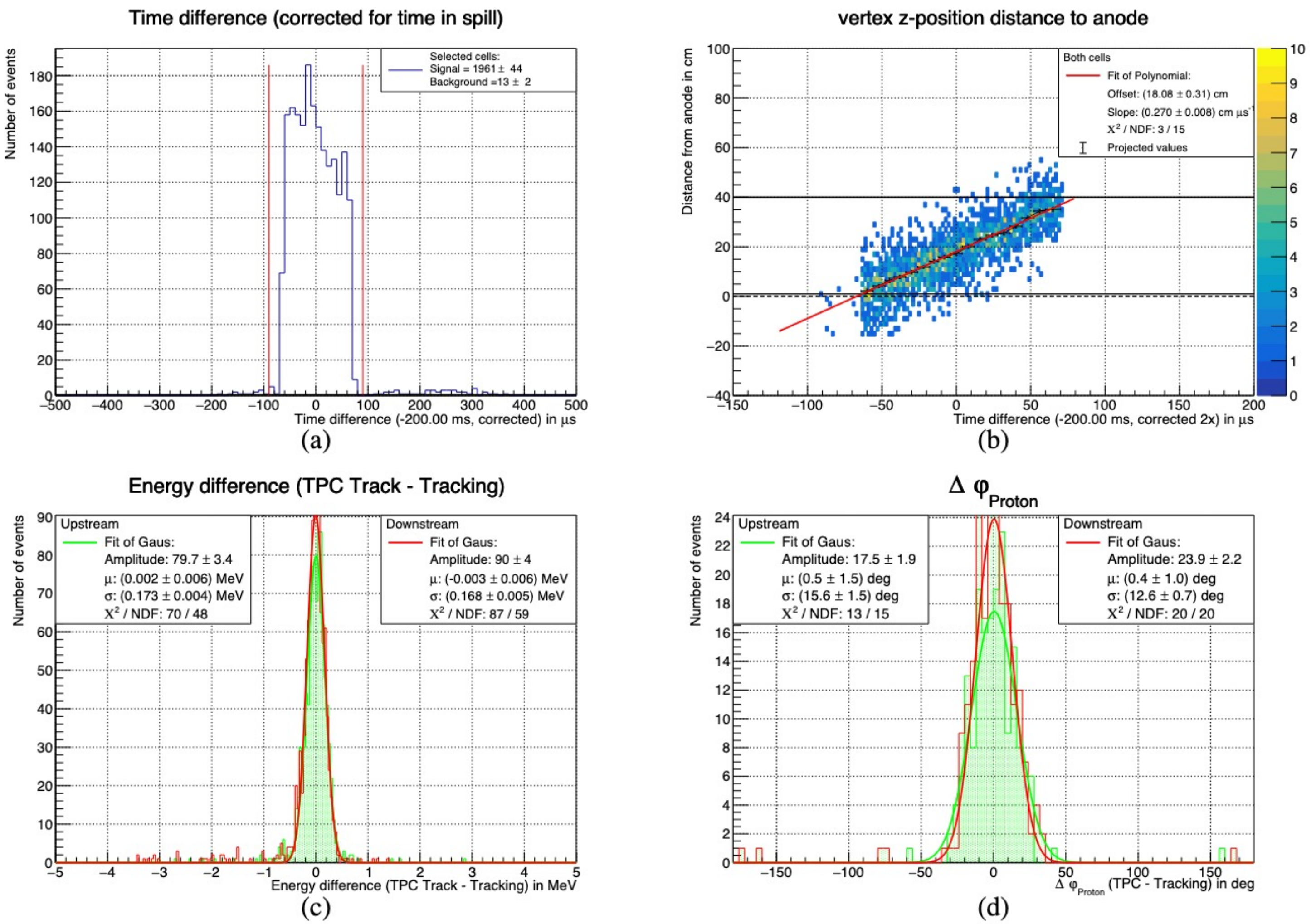


2021



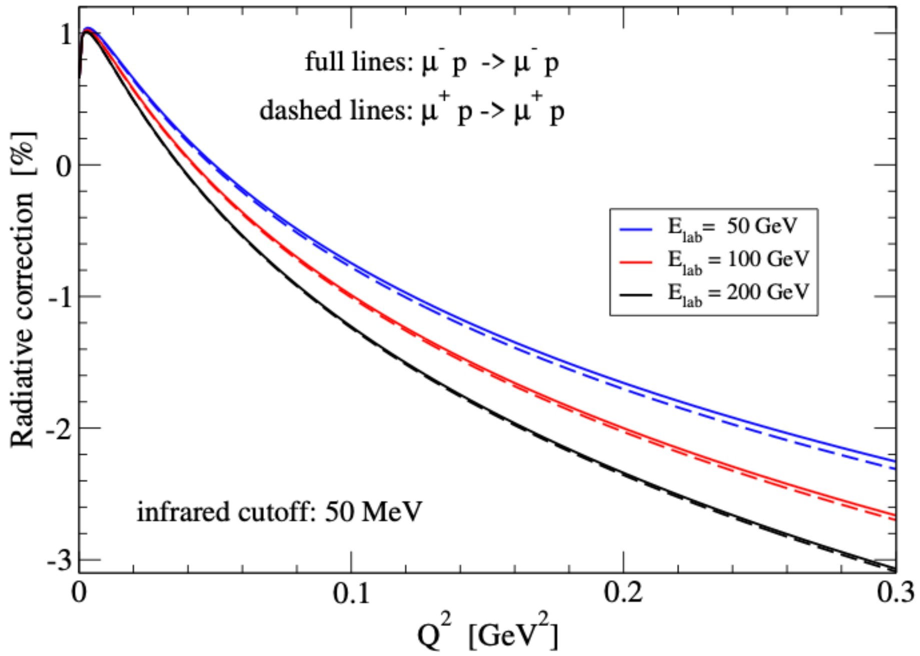
Figures: C. Dreisbach PhD Thesis (2022)

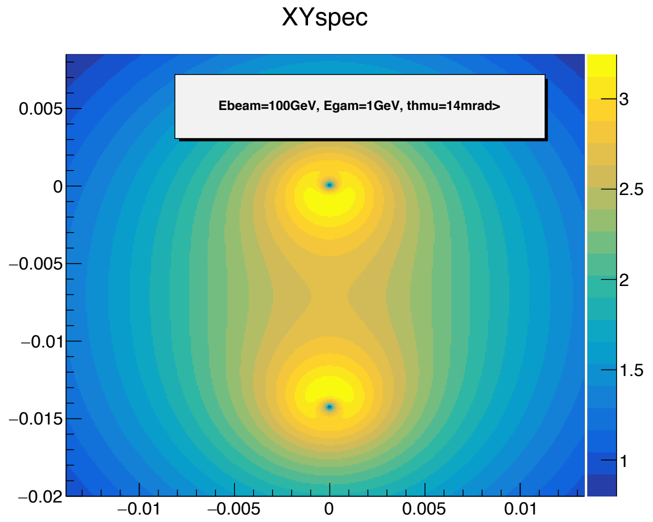
Test Data Analysis

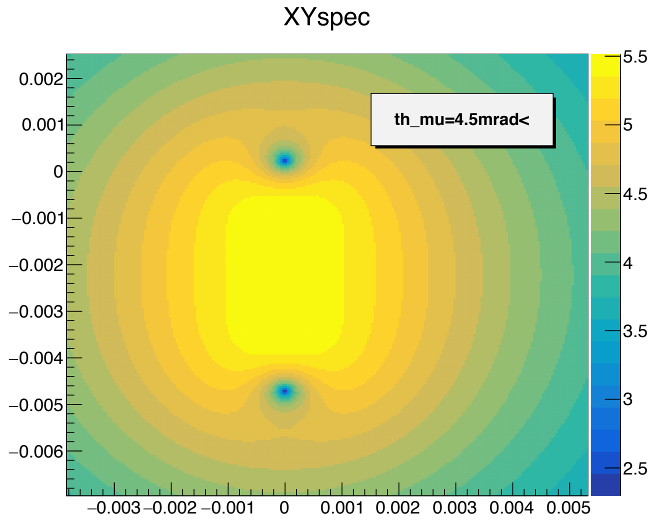


- With the 2021 test data, the correlations of the **muon scattering** and the **proton recoils** in the IKAR TPC were studied in detail
- in the coincidence time, the effect of the **drift** in the TPC gas could be identified, this will serve to control the purity of the elastic scattering events
-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

Radiative Corrections for μp Scattering





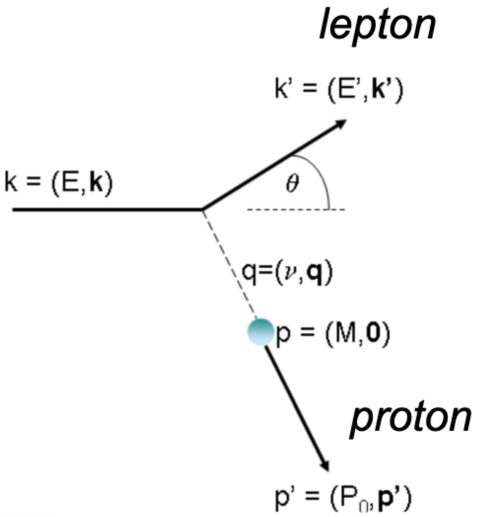


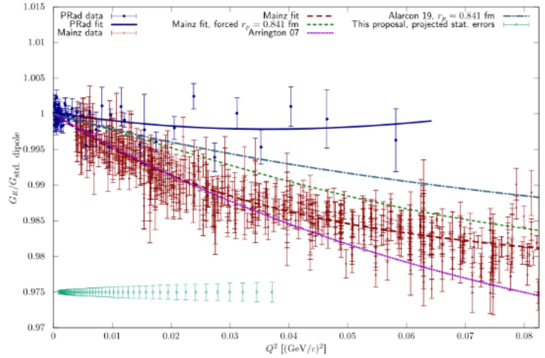
- Radiative corrections <1% for muon-proton scattering $Q^2 < 0.04\ \mathrm{GeV}^2$
- Calculations by N. Kaiser (TUM) *J. Phys. G* **37** 115005 (2010)
- Full MC generator foreseen – intensity forward bremsstrahlung photons can be checked in the experiment
- Collaboration with McMule team on implementation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

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:

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

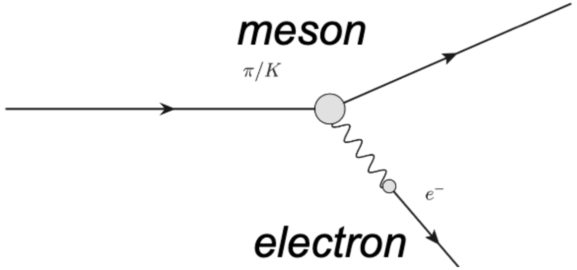




Charge radius from the slope of G_E

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

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

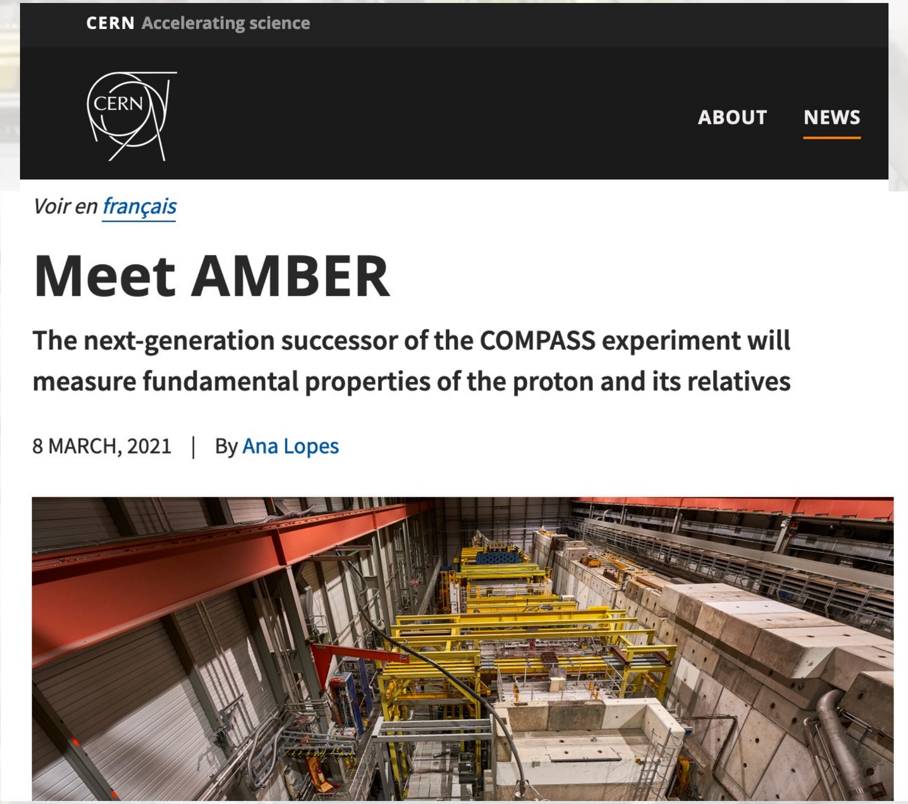


Conclusions

- NA66/AMBER at CERN has **started its Phase-1** of a broad hadron physics programme at M2
- The physics cases of **Phase-2** are being worked on for a separate proposal
- Data taking for anti-proton production cross-sections in p-He, p-p and p-D completed, analysis ongoing

- **Proton Radius Measurement**
  - new detector equipment under constructions: active-target TPC, muon tracking system, free-running DAQ
  - proof-of-principle from several test runs, analysis completed
  - **first running in 2025, high-statistics data taking planned for 2026**

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


CERN Accelerating science

ABOUT NEWS

Voir en français

Meet AMBER

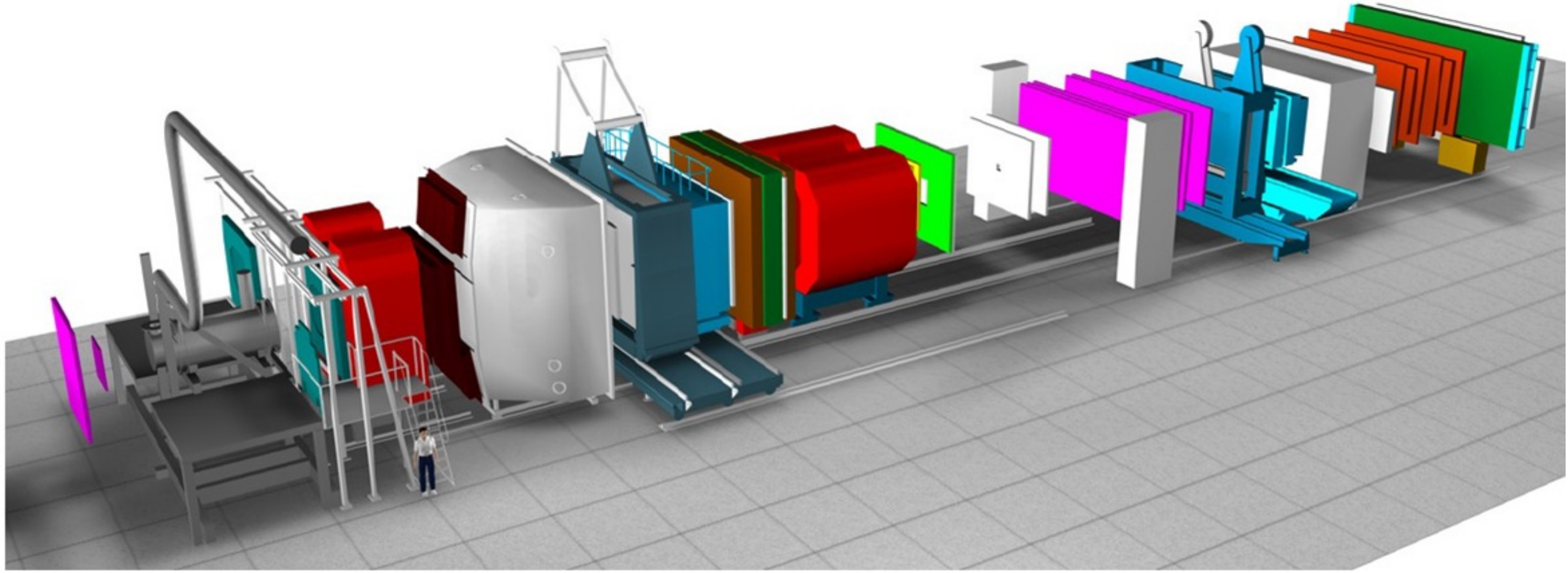
The next-generation successor of the COMPASS experiment will measure fundamental properties of the proton and its relatives

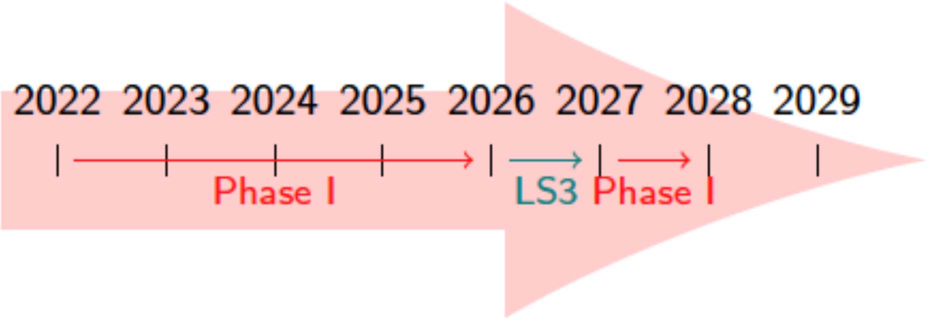
8 MARCH, 2021 | By Ana Lopes

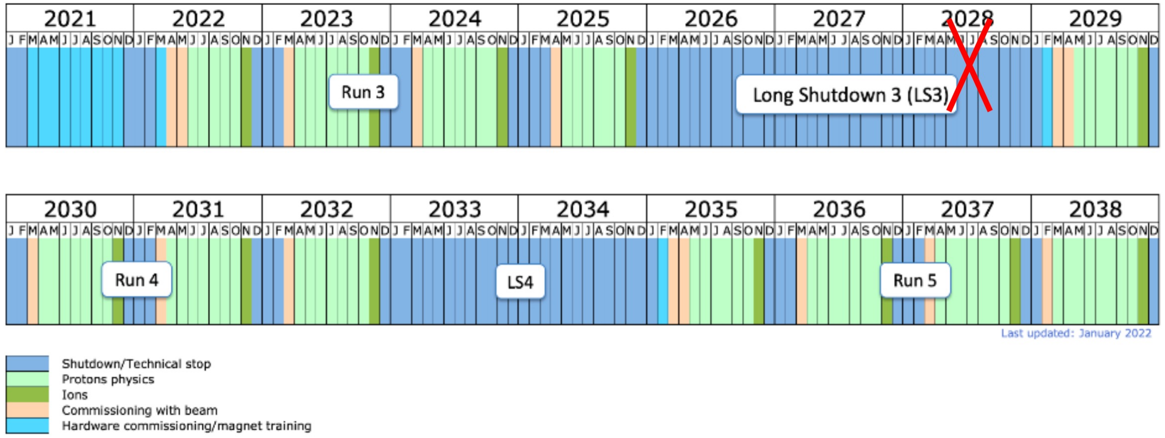
Backup

AMBER Collaboration and timelines

- Successor of COMPASS
- with appropriate extensions and modernisations
- at the CERN M2 beamline
- ~200 physicists from ~34 institutes







AMBER physics programme

AMBER
Apparatus for Meson and Baryon Experimental Research

- Letter of Intent 2018 as COMPASS++/AMBER (arXiv:1808.00848) for upgrades and extensions of the setup
- Use of conventional and radio-frequency (RF) separated beams

- Proposal in two Phases
- Phase-1 approved by SPSC in December 2020
- Phase-2 in drafting stage

- MoU draft close to final, signatures expected by end of 2022

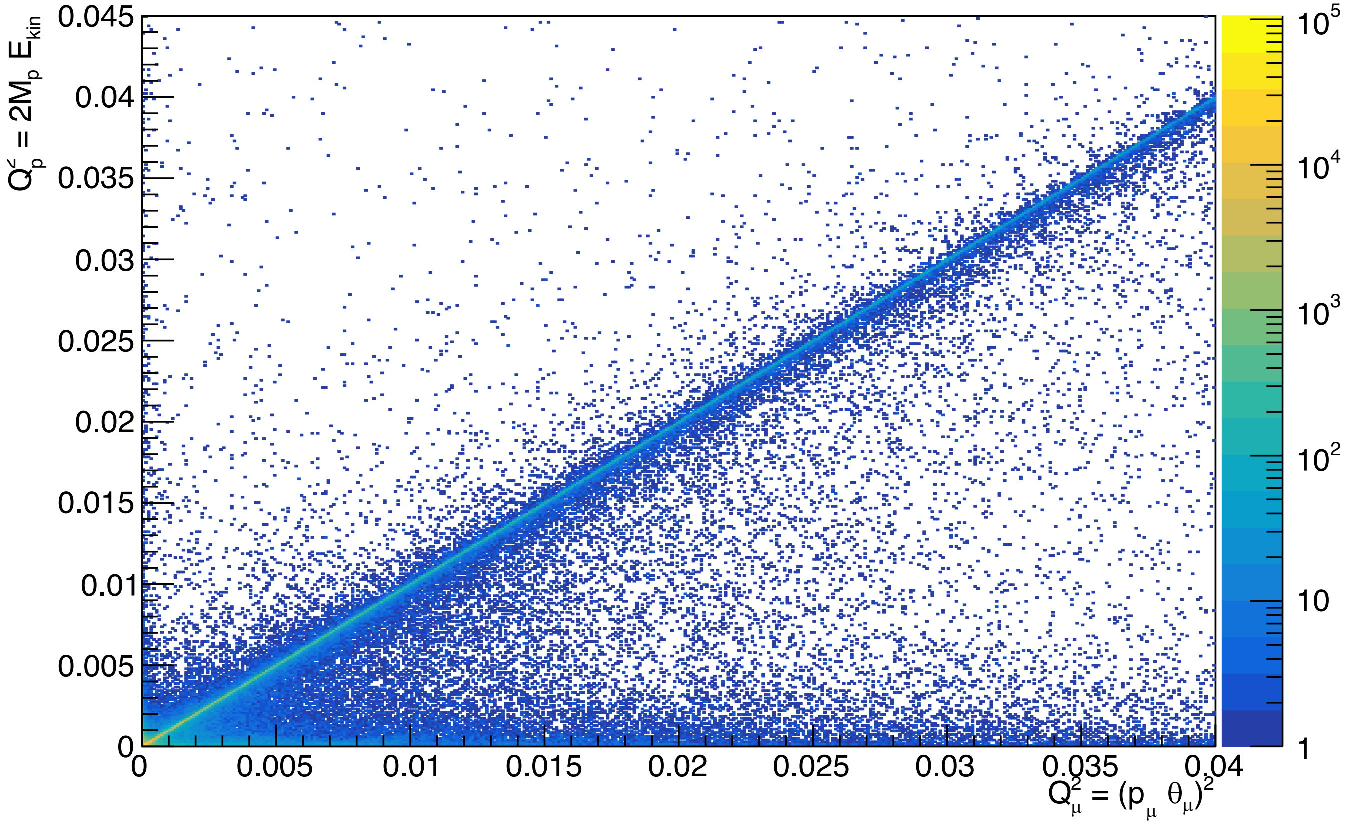
Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD *E*	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Phase-1
with conventional hadron and muon beams
2022 → 2028

Phase-2
with conventional and rf-separated beams
2029 and beyond

Impact of photon emission on the muon-proton correlation



Recirculating Hydrogen Gas System

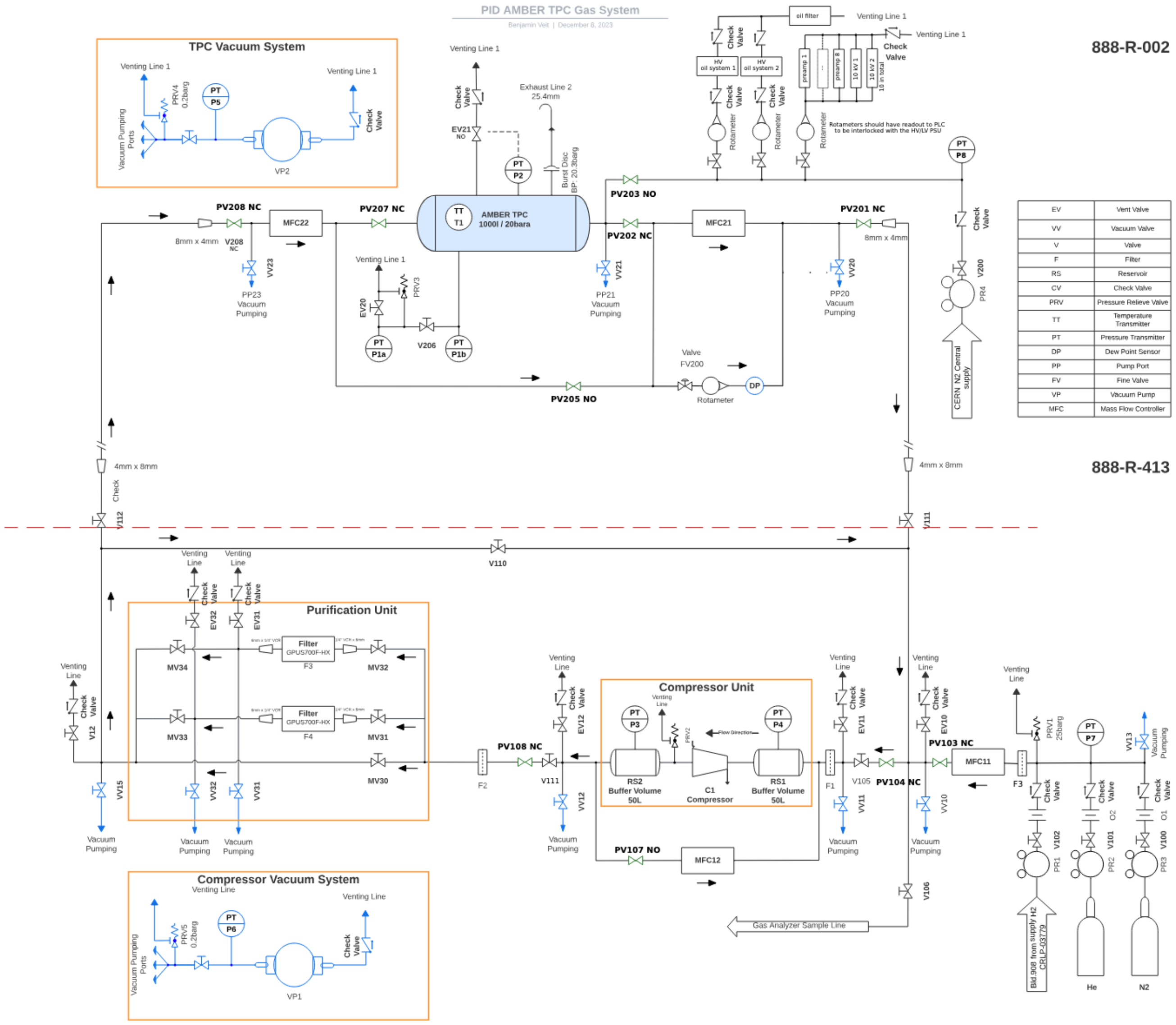


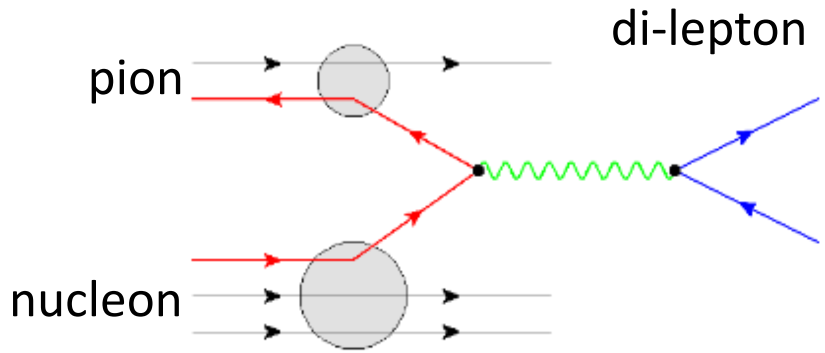
Fig. 27: TPC gas re-circulation and cleaning system.

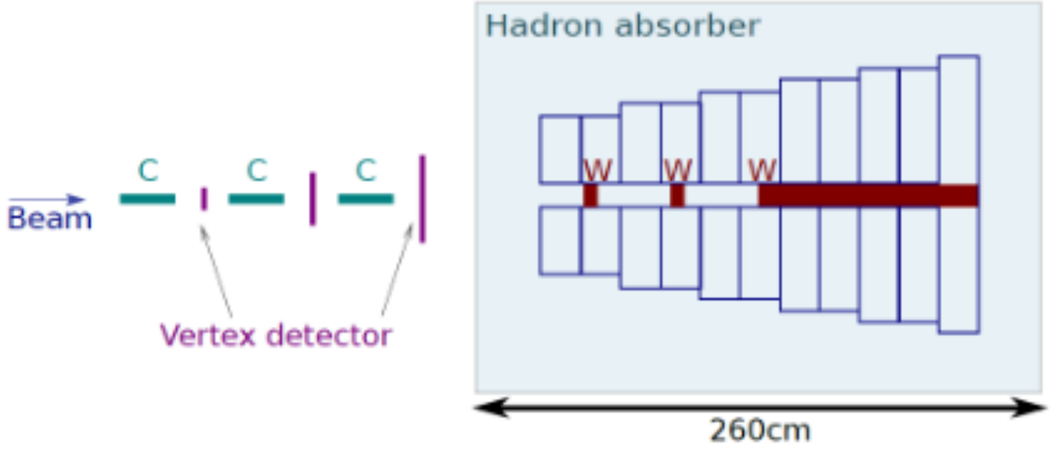
The whole detector and the gas system, due to the usage of hydrogen, have been evaluated by an external company, and the risk assessment document was started. Several requirements and recommendations are taken into account for the design of the detector systems and surrounding elements.

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**.

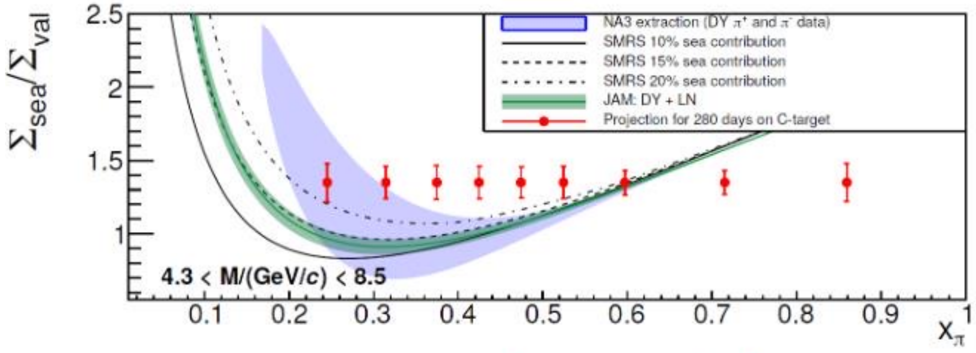
Drell-Yan and pion PDFs at AMBER





- Beams of positively and negatively charged pions to separate valence and sea contribution:

$$\frac{\Sigma_{\text{sea}}}{\Sigma_{\text{val}}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$

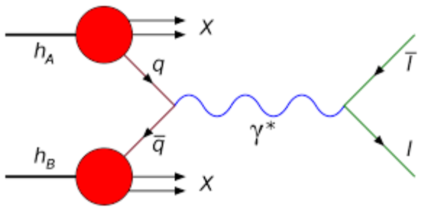


$$\sigma_{\text{DY}}^{\pi^+A} \propto \sum_i (e_i)^2 \left[\bar{q}_i^{\pi^+} q_i^A + q_i^{\pi^+} \bar{q}_i^A\right]$$

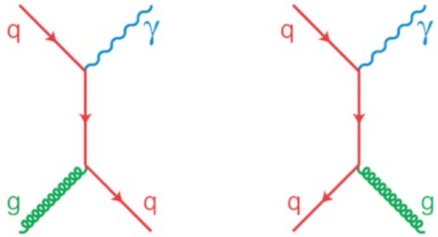
- 250k DY events expected (current available statistics 25k events)
- First precise and direct measurement of the sea quark distribution in the pion
- 190 GeV pion beam
- Di-muon mass resolution of 100 MeV

dedicated talk (M. Chiosso) in the *Nucleon Structure in DIS* parallel session

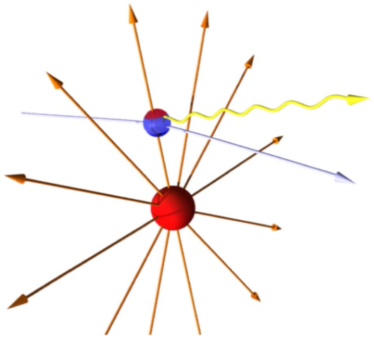
The ideas of the Phase-2 proposal



- Kaon structure via the Drell-Yan process

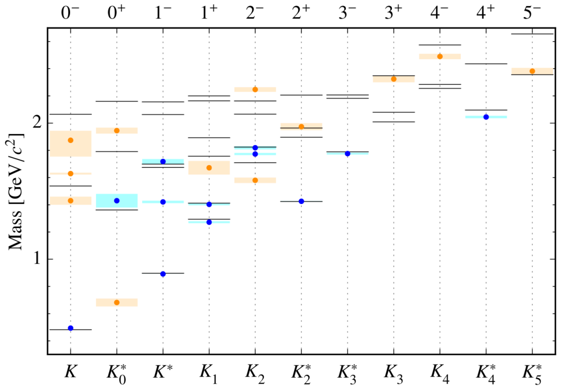


- Gluon structure of pions and kaons via prompt photons

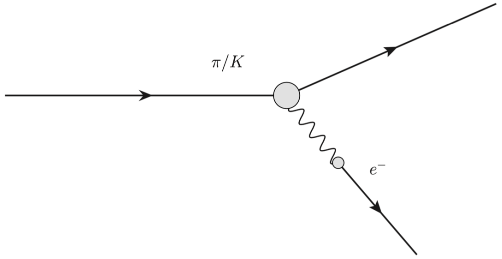


- Primakoff reactions to investigate kaon-photon coupling: kaon polarisability, $F_{KK\pi}$

- Generalized Parton Distributions in DVCS and HEMP



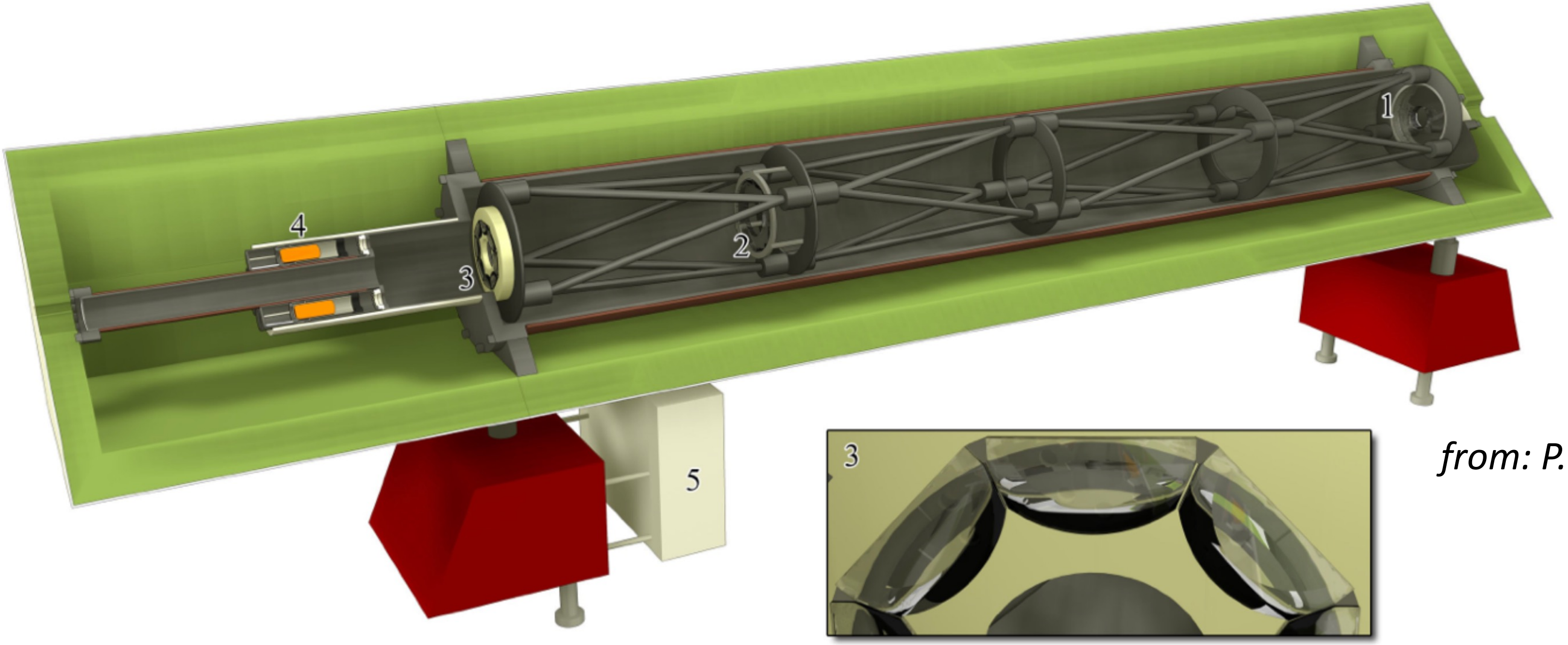
- Spectroscopy of mesons with strangeness



- Meson charge radii via electron scattering in inverse kinematics

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

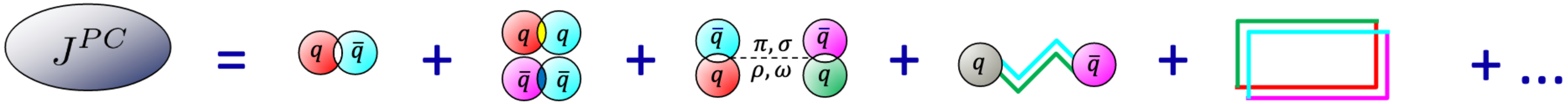
Beam PID by CEDARs



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

Exotic mesons



$(q\bar{q})_0$ $(qq)_8(\bar{q}\bar{q})_8$ $(q\bar{q})_0(q\bar{q})_0$ $(q\bar{q})_8 g$ $(gg)_0$

Tetraquark Molecule Hybrid Glueball

Where are they?

How to identify them?

- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Flavor-exotic: $|Q|, |I_3|, |S|, |C| \geq 2$
- Comparison with models, lattice

Need:

- Large data sets with small statistical uncertainties
- Complementary experiments
  - production mechanisms
  - final states
- Advanced analysis methods
  - reaction models
  - theoretical constraints

Limitations at COMPASS

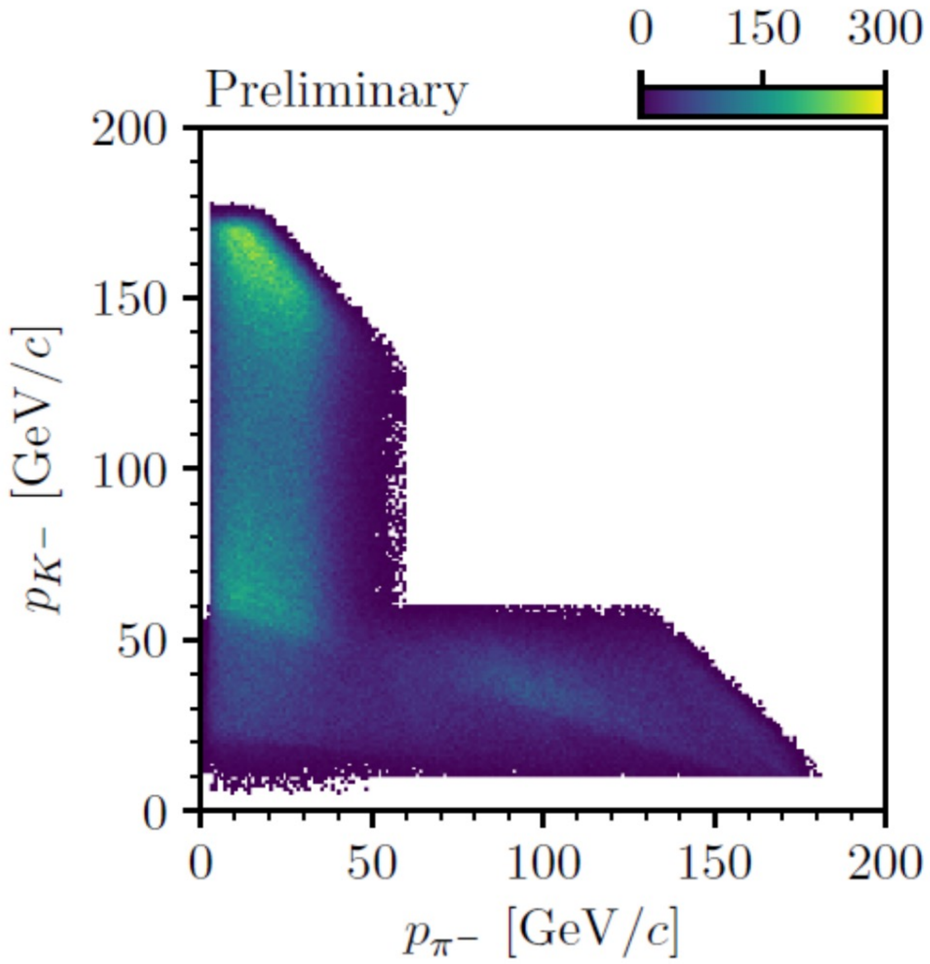
- Final-state particle identification does not cover full momentum range

Cannot identify the full final state

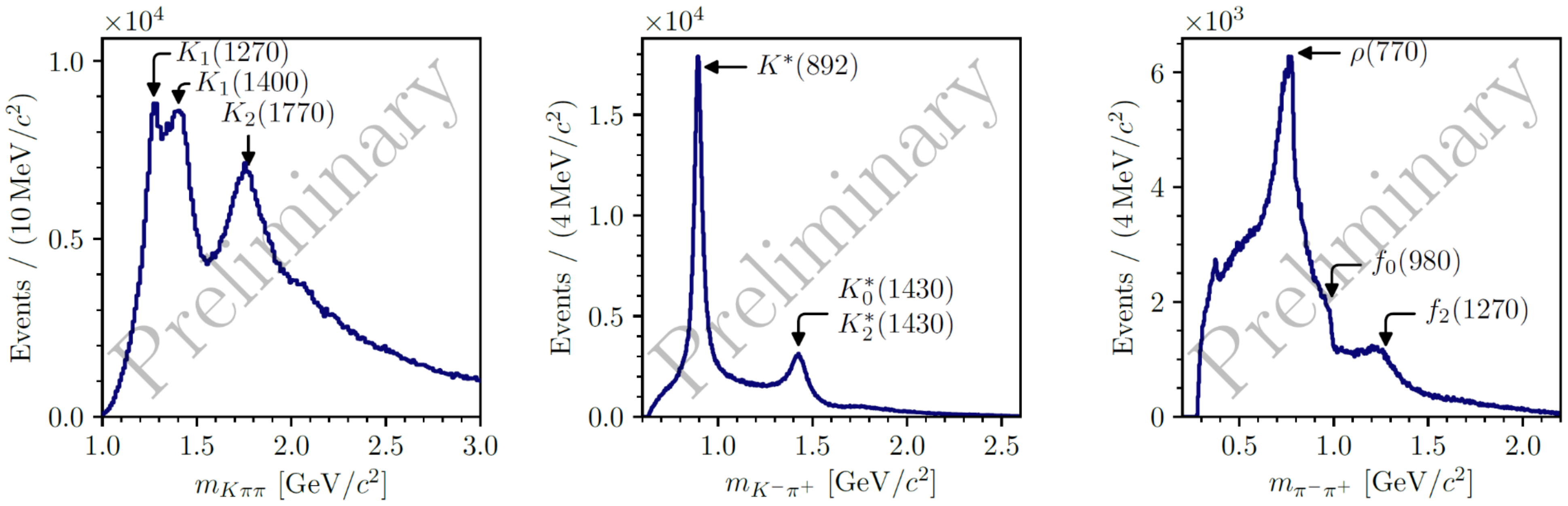
- Assume sample contains only $K^-\pi^-\pi^+$ events
  - Minimal PID: Need to know which of h^- is K^-
- Require only one of h^- to be identified
- Acceptance reduced by more than 1/3
- Almost no suppression of KKK, $\pi\pi\pi$, ...

Blind spot in experimental acceptance

- Decay amplitudes of different J^P are orthogonal
- Loss of orthogonality taking acceptance into account



COMPASS: $K^- \pi^- \pi^+$



Study reaction $K^- + p \rightarrow K^-\pi^-\pi^+ + p$ by tagging beam kaons (2.4%)

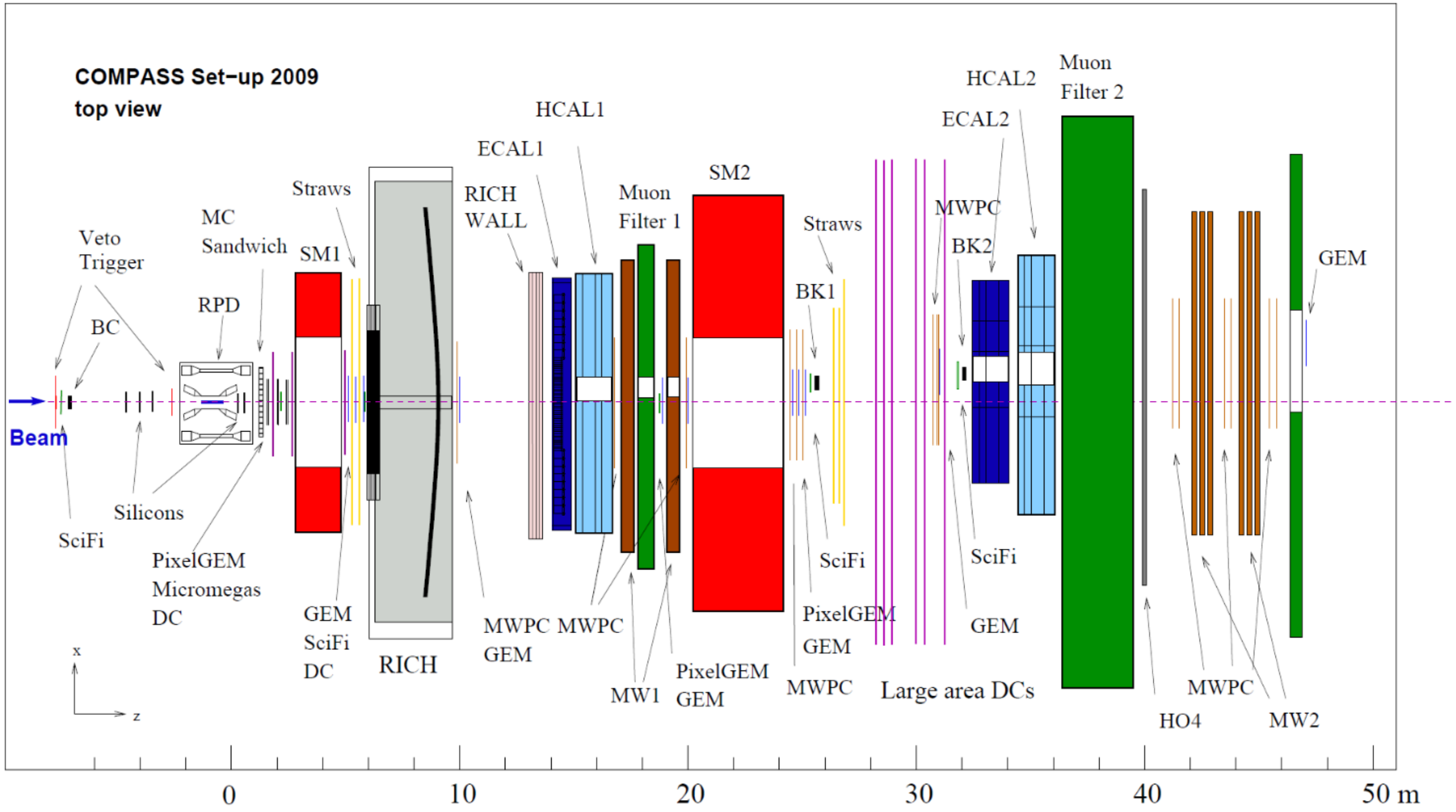
⇒ access to all kaon states: K_J, K_J^*

⇒ world's largest data set so far: 720 000 exclusive events (ACCMOR: 200k ev.)

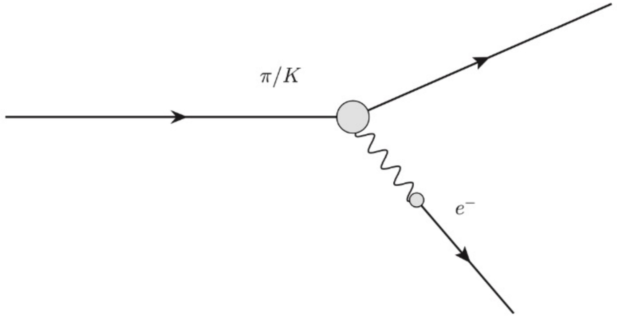
Goal for AMBER: collect $10 - 20 \times 10^6$ exclusive $K^-\pi^-\pi^+$ events

Setup for strange-meson spectroscopy

- hadron BMS
- CEDARs
- 2-stage spectrometer
- lH2 target
- RPD
- Si trackers
- ECAL 0, 1, 2
- RICH-0, RICH-1, RICH-2



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

Sendai 1974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Am Ketenlager 43
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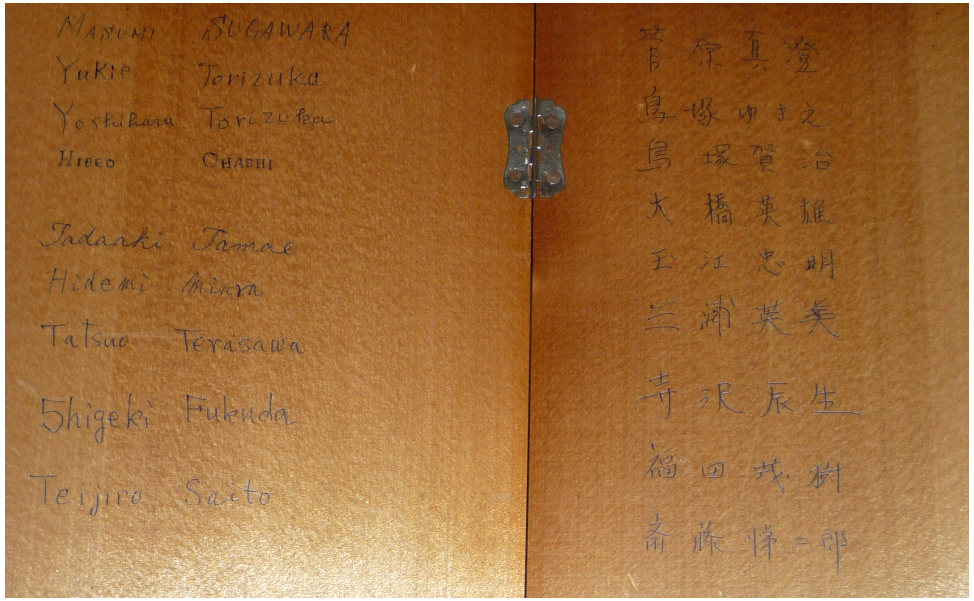
航空郵便
ちば あきこ せんせい より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