Status and Plans of the AMBER Experiment

Apparatus for Meson and Baryon Experimental Research

1. *Introduction*
2. *Physics program*
   - *Proton radius in high-E muon scattering*
   - *Antiproton production cross-sections*
   - *Drell-Yan for pion and kaon structure*
3. *Hardware developments*
4. *Conclusions*

146th Meeting of the SPSC

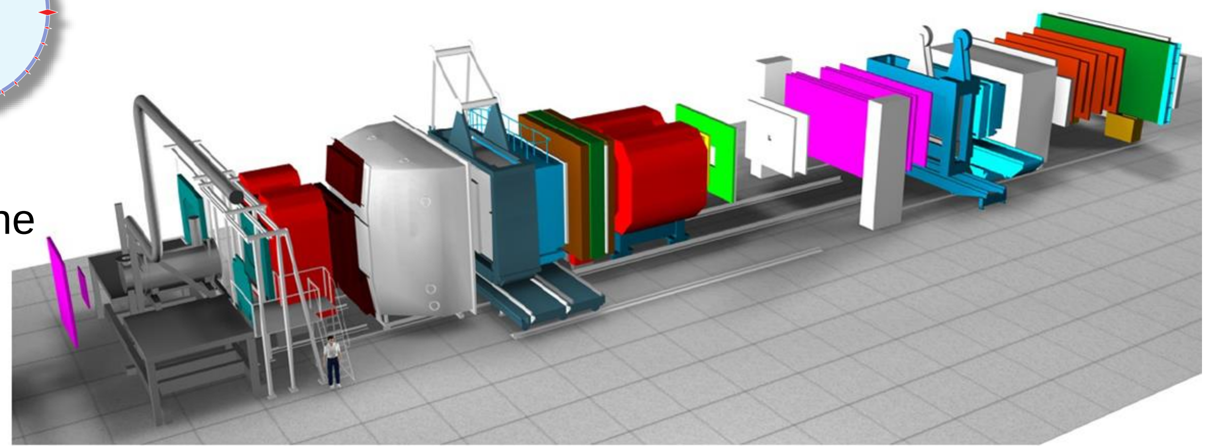
CERN 9.-10. June 2022

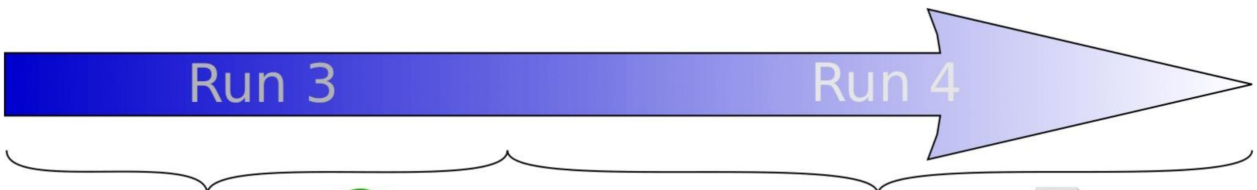
A new

AMBER
Apparatus for Meson and Baryon Experimental Research

Apparatus for Meson and Baryon Experimental Research

- Successor of COMPASS
- with appropriate extensions and modernisations
- at the CERN M2 beamline
- Collaboration of >200 physicists from 41 institutions, 14 countries





Phase-1 Proposal

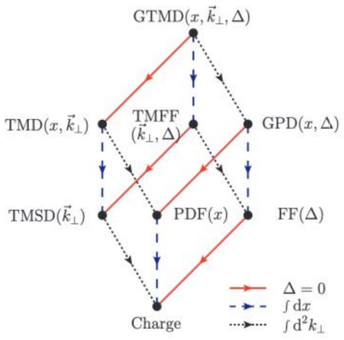
- Submitted 2018
- Approved by the CERN Research Board in Dec 2020

Phase-2

- Proposal submission planned for beginning 2023

Hadron Physics with AMBER

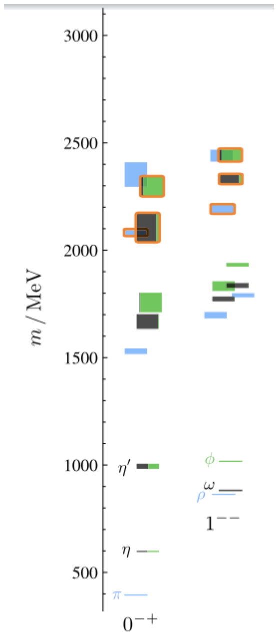
Apparatus for Meson and Baryon Experimental Research



- QCD partons in hadronic systems
- The excitation scheme of hadronic systems
- How do the hadron masses come about?

$J^{PC}_{X^-} M^{\varepsilon} \xi \pi L$

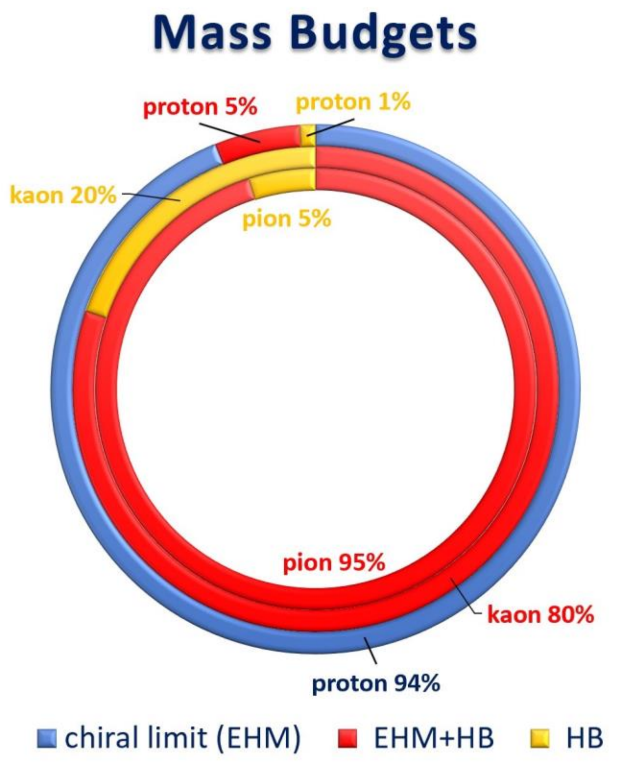
  - constituents: the QCD quarks and gluons
  - Small contribution of the Higgs mass of the valence quarks
  - Pion-to-proton mass ratio 1/7 vs. constituent quark expectation 2/3
- Dynamic generation of mass in continuum QCD
- Gluon self-interaction in the infra-red leads to gluon "self-mass generation"



- Emergence of Hadron Mass is to some extent understood within continuum and lattice QCD calculations
- Prove and provide more input by measurement of
  - Quark and gluon PDFs of pion, kaon and proton
  - Hadron radii as consequence of confinement
  - Mass spectra of excited mesons

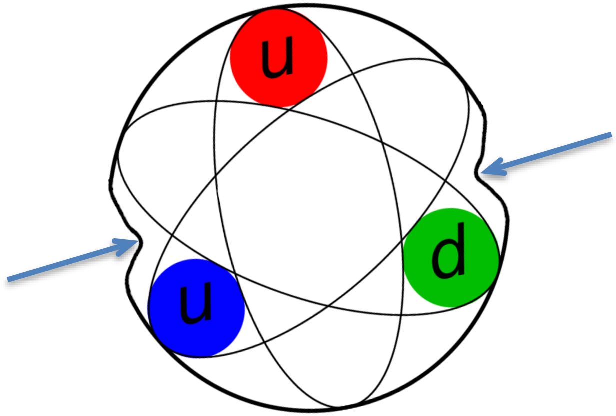
EHM for proton, pion and kaon

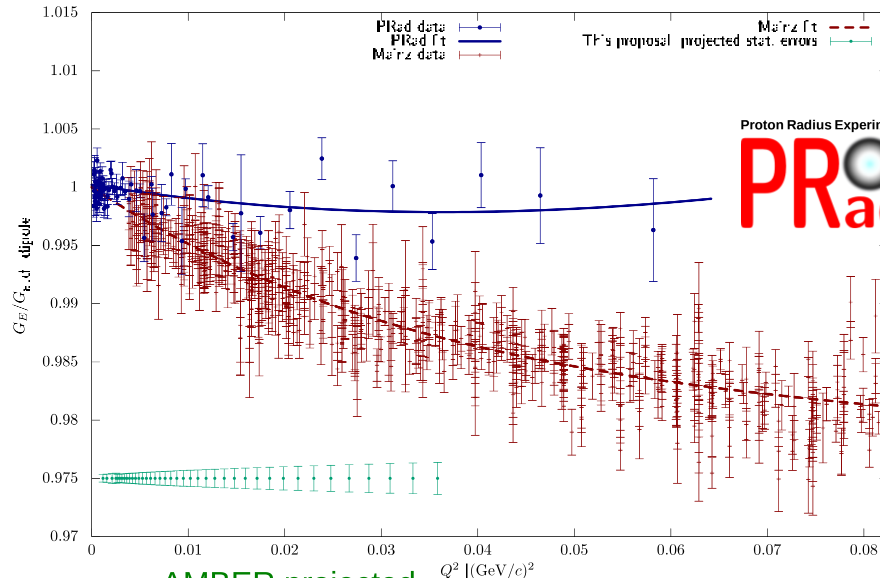
- The mass composition of the proton is structurally different from that of pions and kaons
- Pions and kaons are the Nambu-Goldstone bosons of the (approximate and spontaneously broken) chiral symmetry of strong interaction
- In the chiral limit
  - the mass of the proton remains basically unchanged
  - pions and kaons are massless



Thus for a full understanding the partonic structure of hadrons, the meson PDFs must be known on a similar level as those of the nucleon

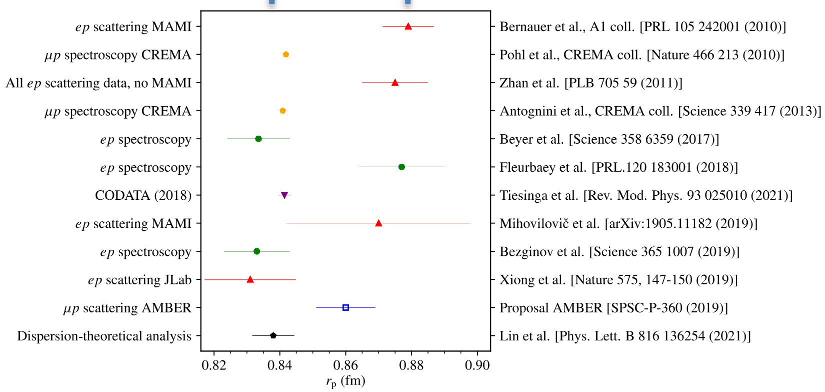
Proton radius





AMBER projected uncertainty

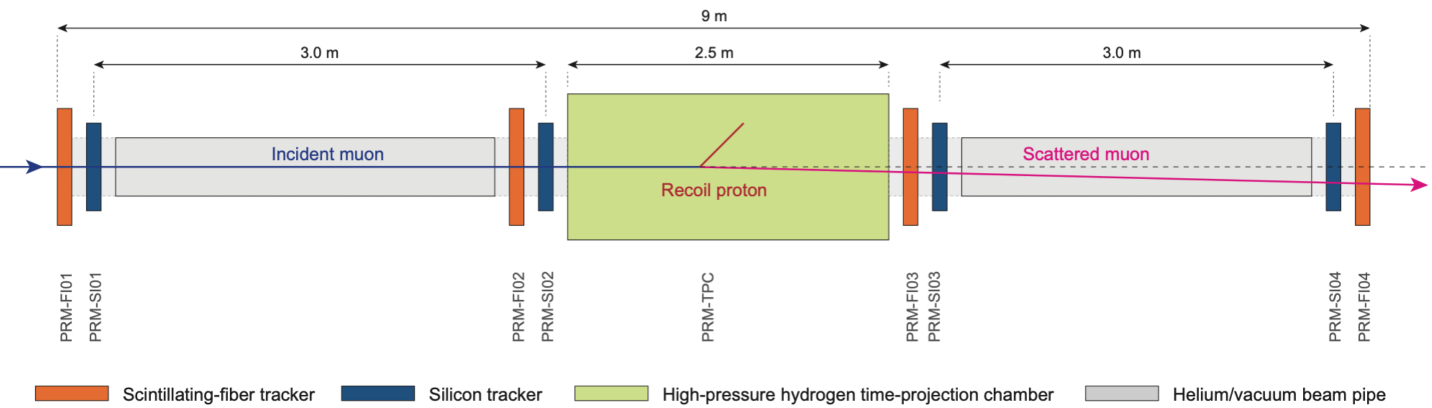
$$r^E_{p,exp} = 0.84 \ldots\ 0.88\ \text{fm}$$

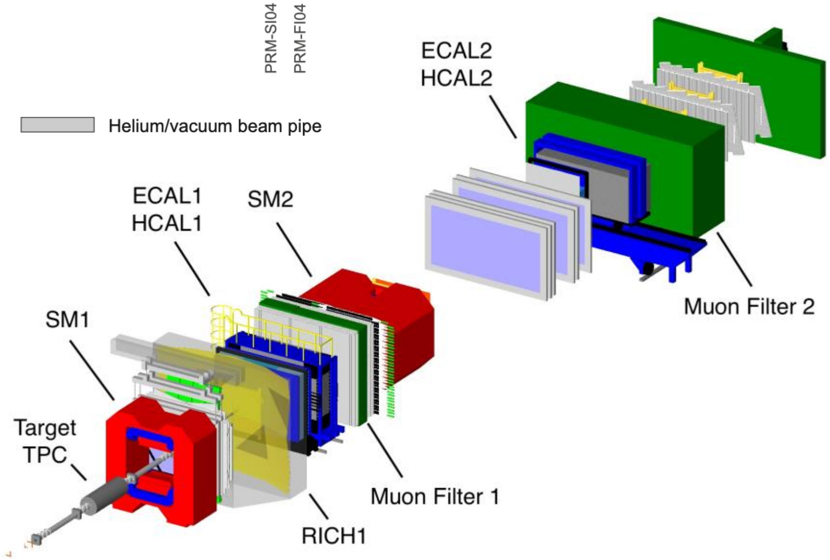


muon vs. electron scattering:

- different systematics (multiple scattering, energy loss, particle decay)
- much lower radiative effects for muons

Proton radius from muon-proton elastic scattering at high energy

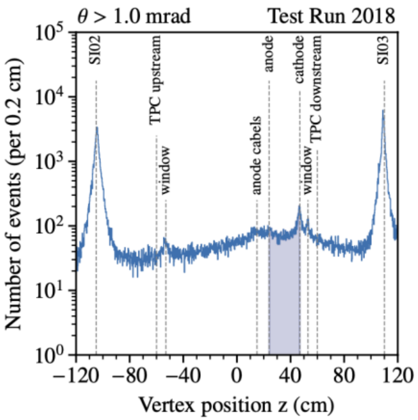


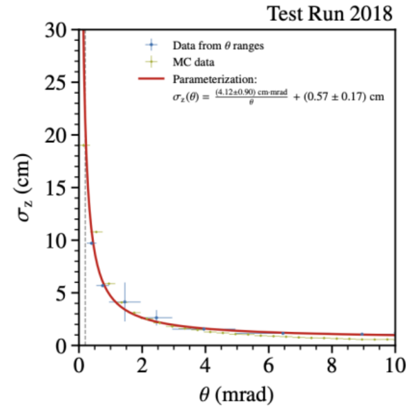


- 100 GeV muon beam
- Active-target TPC with high-pressure H_2
- goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4{\cdot}10^{-2}$ GeV^2
- Precision on the proton radius ~0.01 fm

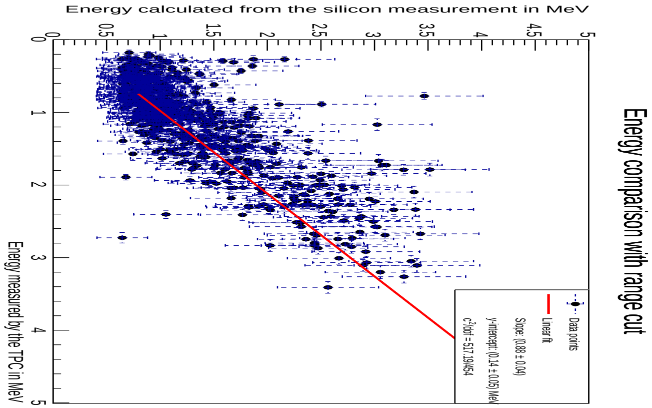
Proton Radius Measurement
Key results from first feasibility study 2018

- Resolution along beam of muon scattering in hydrogen (without using TPC information)

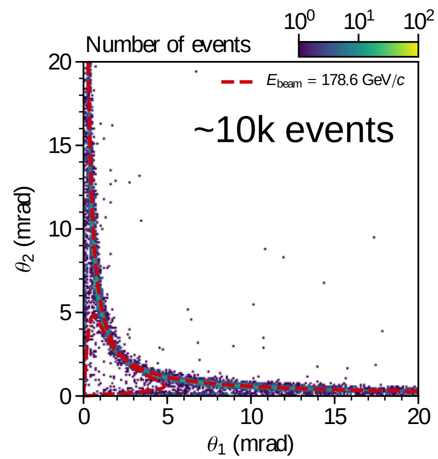


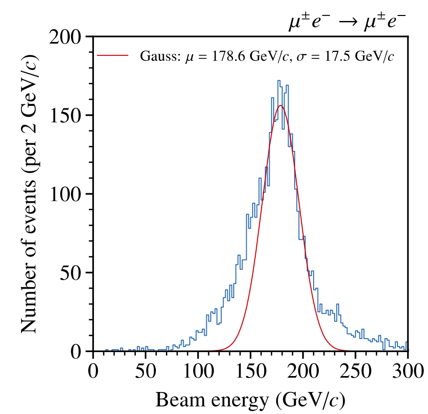


- Correlation of muon angle and proton recoil energy

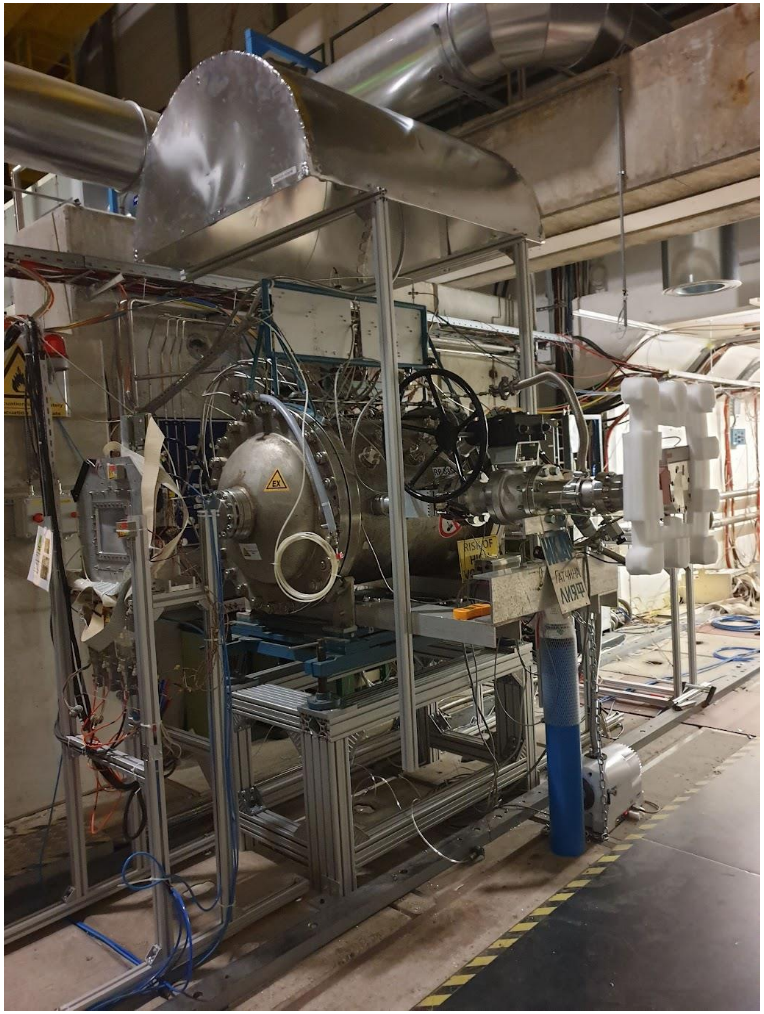


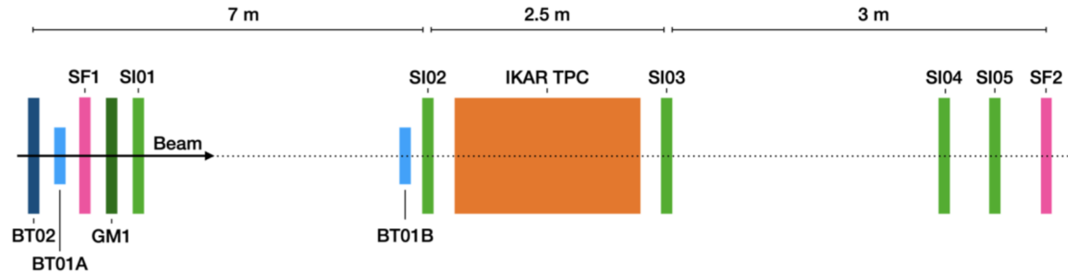
- Reconstruction of elastic muon-electron scattering and beam energy from angles alone

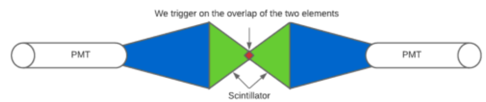


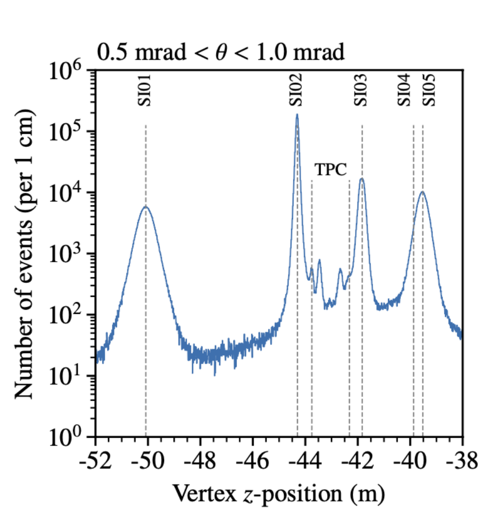


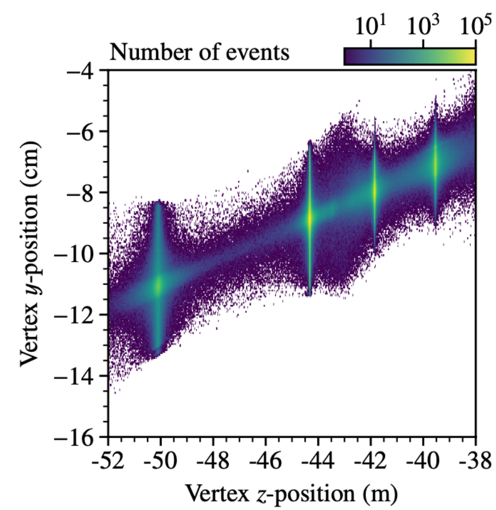
Preliminary results from the 2021 test run



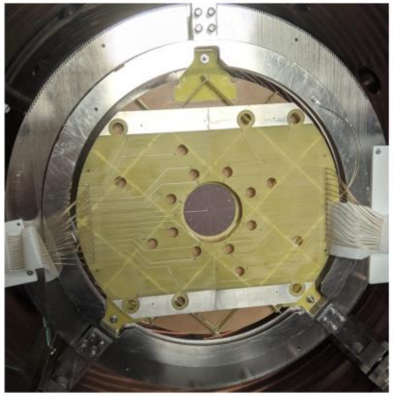


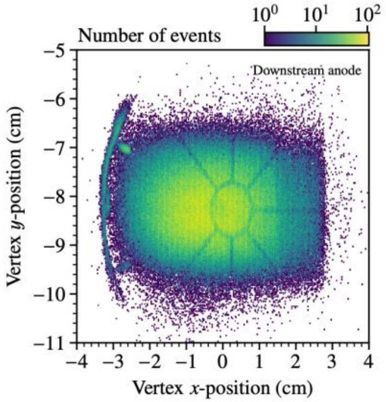


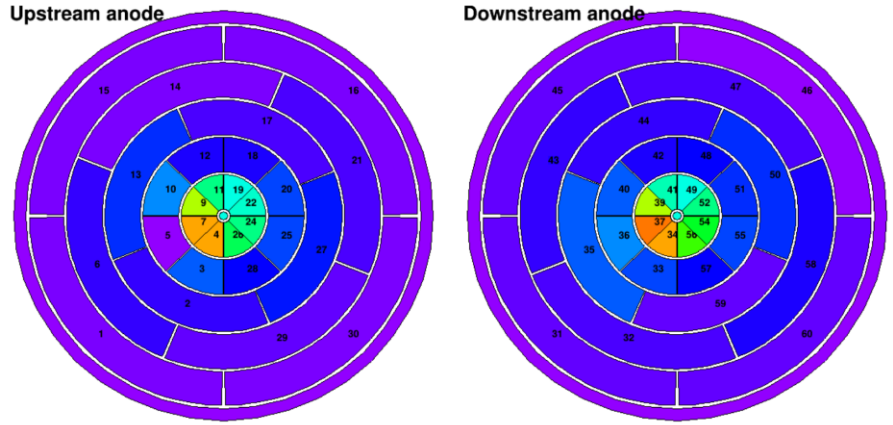


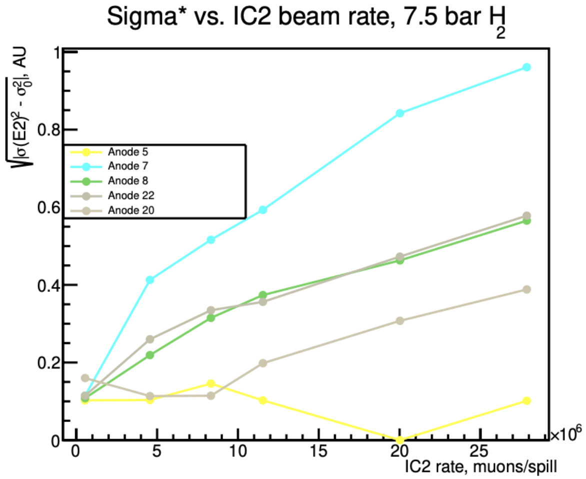


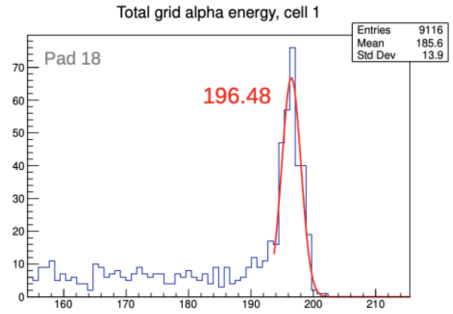
2021 IKAR TPC performance

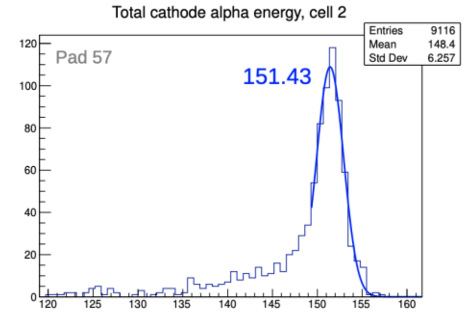






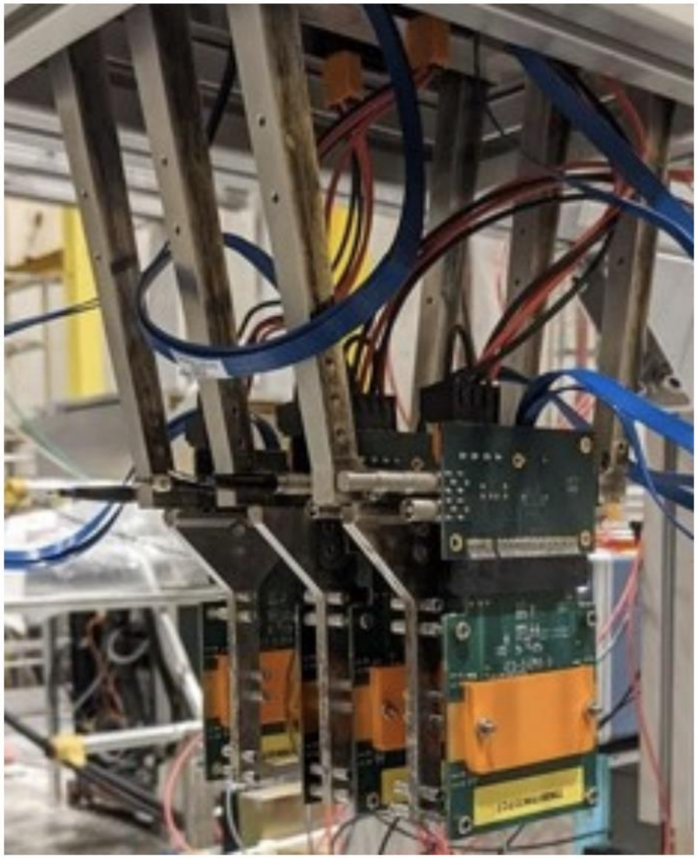


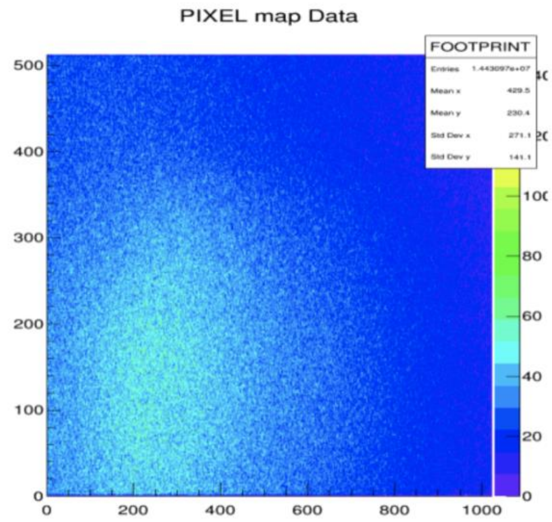


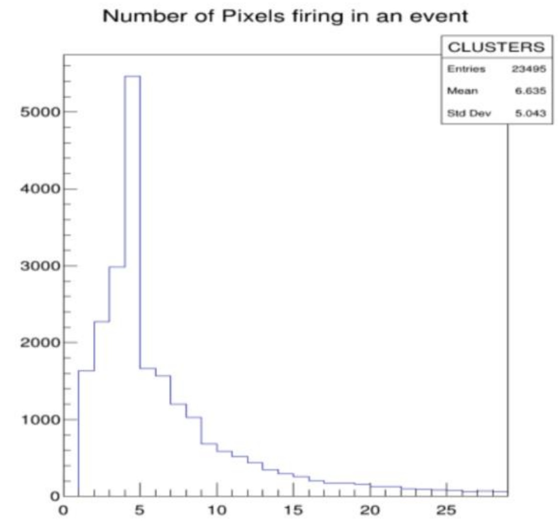


- Linear increase of noise with beam intensity
- Ongoing: alpha calibration (~40 keV energy resolution)

ALPIDE tests in 2021







- Beam profile and multiplicity (*d* at COSY) : Performance of detectors tested at 1 and 2 MHz
- Preparations for tests in 2022: new firmware and MOSAIC readout software
- Hardware for multiplexers exists for the test setup (1/3 of final configuration)
- ALPIDE licencing still not settled

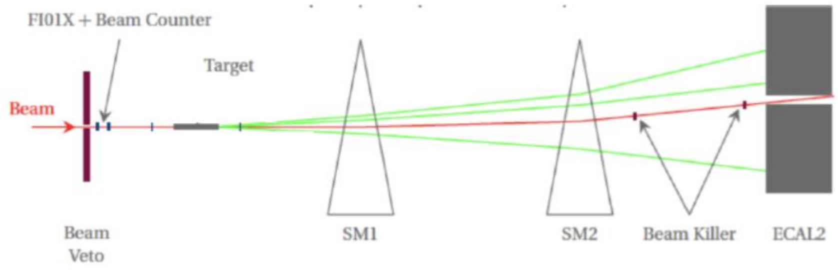
Proton radius – next steps

- **Test run in autumn 2022** for the tracking detectors
- In parallel / interleaved with COMPASS data taking (earliest in mid-October)
- New free-running DAQ

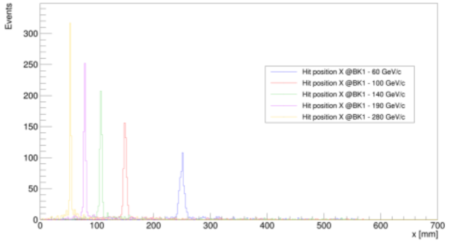
- **First data taking in autumn 2023**
- New main TPC probably not yet available
- Measurement with IKAR TPC (as in 2021 test run)
- Achievable statistics compared to Proposal reduced by factor 8

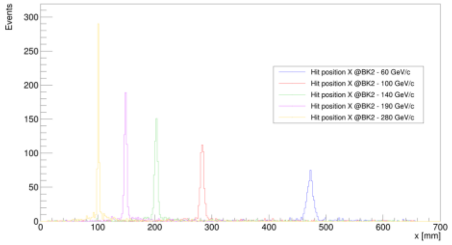
Antiproton production cross-sections

- Input for dark-matter searches in cosmic observations
- Measurement of $\bar{p}$ production cross-sections by protons on helium and hydrogen targets
- Beam energies 60, 100, 140, 190, 280 GeV
- Minimum-bias trigger with non-interacting beam veto



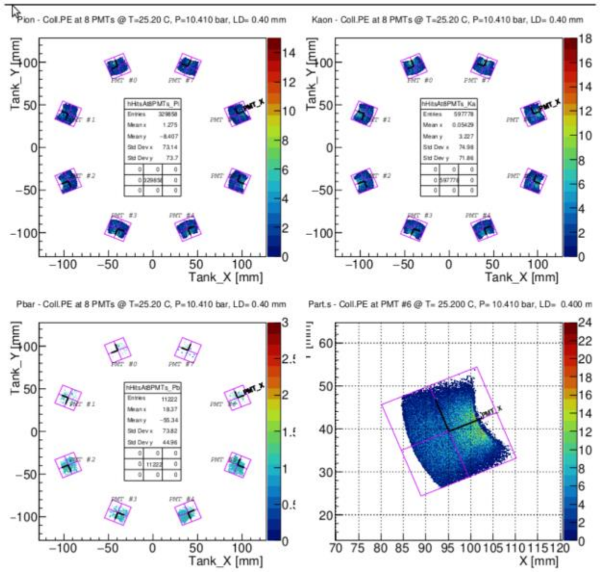
- Ongoing: Full Geant4 MC simulation to optimize e.g. placement of beam killers 1 and 2 (resp. scaling of SM1)



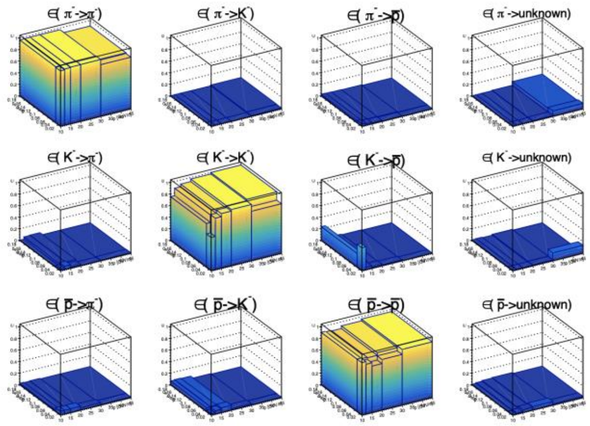


Key detectors for beam and $\bar{p}$ identification: CEDAR and RICH

- The operation of the CEDAR beam PID detectors needs to the studied for all planned beam energies
- Improvements in 2018 regarding PMs, readout and thermal insulation
- Ongoing: implementation into TGEANT simulation



- The RICH detector is used to identify the produced antiprotons
- Ongoing: optimization of the RICH selection procedure for antiprotons
- MC and COMPASS 2009 data

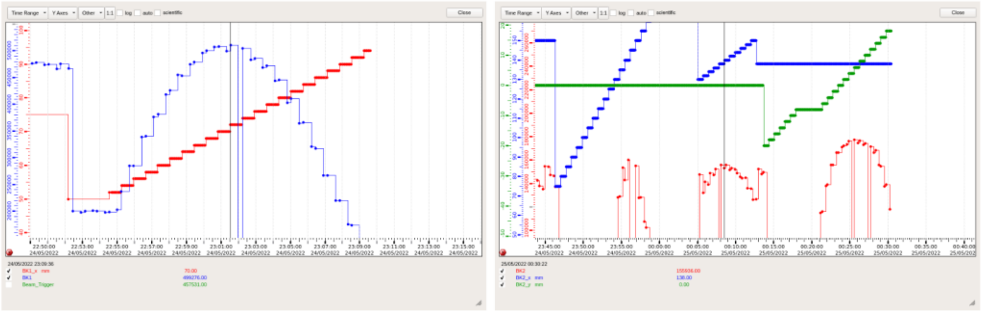


Antiproton production: Plans for 2022 and 2023

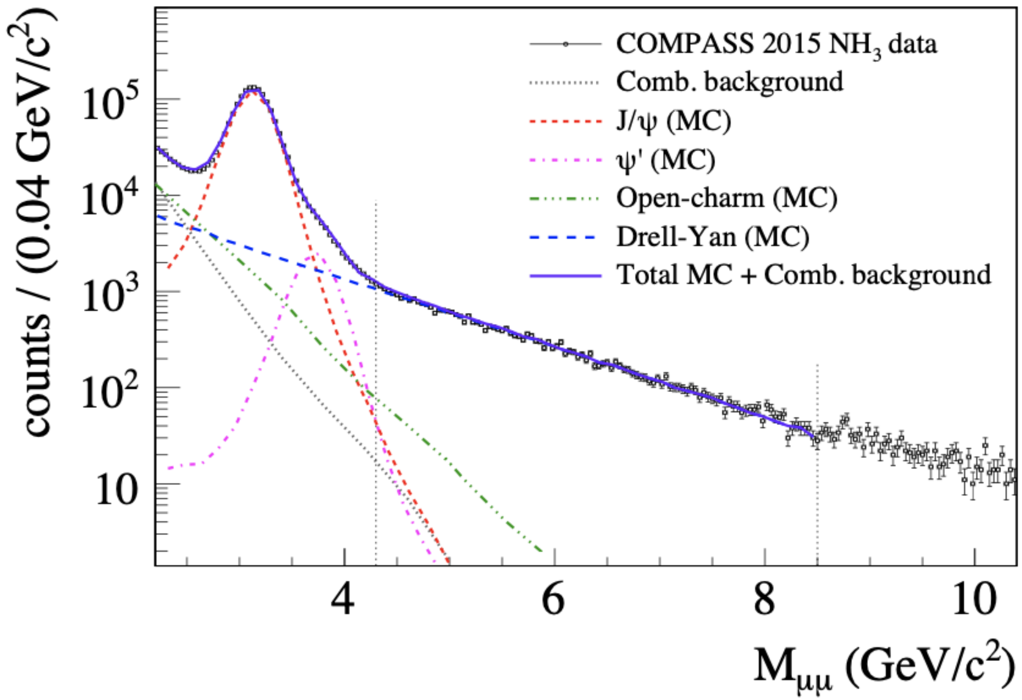
- **Test run in autumn 2022** with the cryogenic polarized LiD target (1 week)
- High target density will require trigger pre-scaling
- Three beam energies planned: 60, 190, 250 GeV
- Study full spectrometer and especially RICH performance

- **First Data taking in 2023**
- First full spectrometer commissioning by the AMBER collaboration
- Use of the polarized target as liquid-He target
- Cover at least the beam energies 60, 100, 190, 250 GeV

- Preparation of the setup: using data with different beam energies for optimizing the beam killer positions

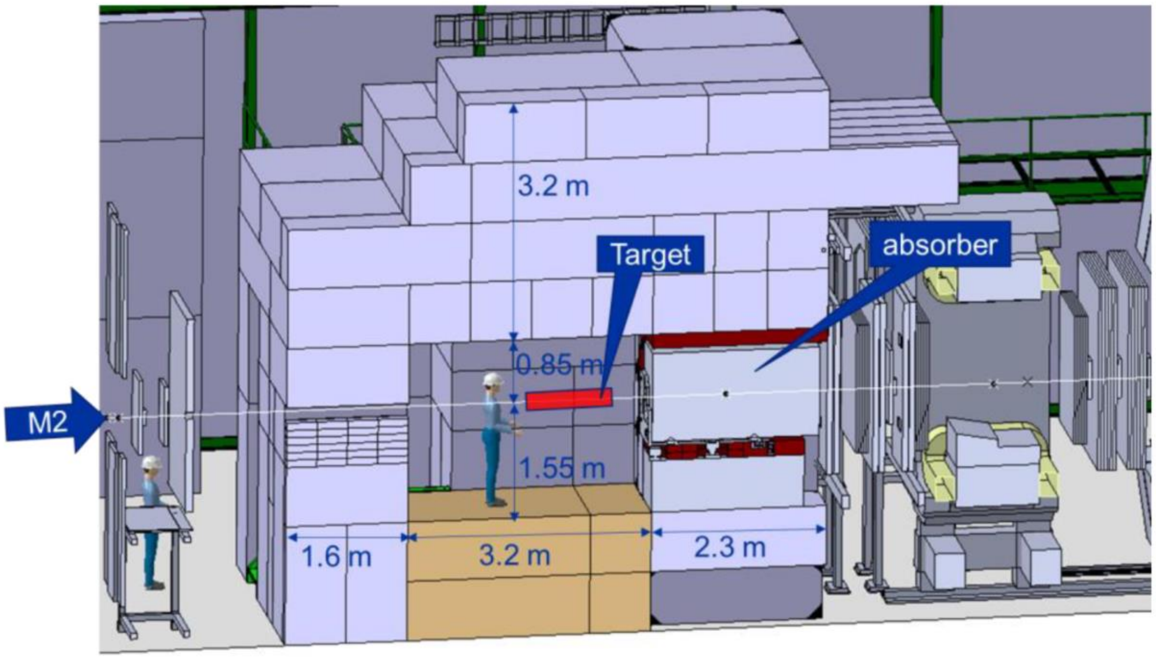


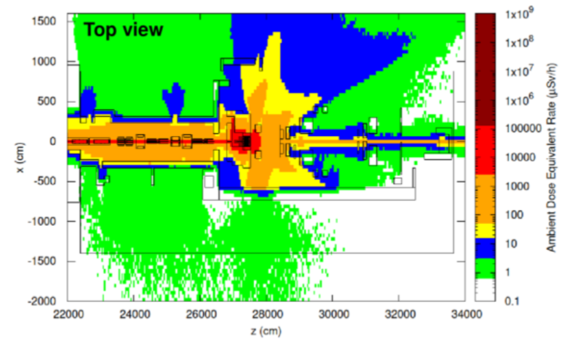
Drell-Yan cross-section measurements to study meson structure



- The high-energy, high-intensity M2 hadron beams allow to measure Drell-Yan pairs, cleanest in the range 4.3 to 8.5 GeV
- Main limitation: radio-protection aspects and spatial and mass resolution
- For kaon/pion separation: operation of CEDAR beam PID

Drell-Yan planned setup and RP



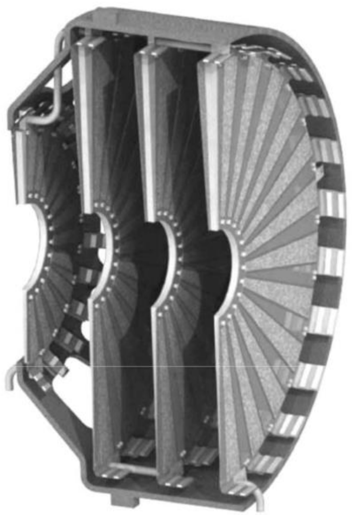


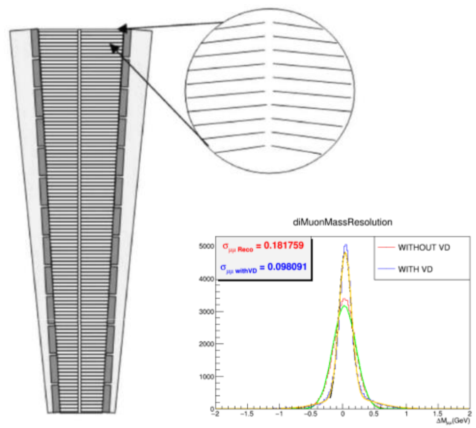
Area	Annual dose limit (year)	Ambient dose equivalent rate: permanent occupancy	Ambient dose equivalent rate: low occupancy	Sign (RADIATION)
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	
Supervised	6 mSv	3 µSv/h	15 µSv/h	
Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	SIMPLE CONTROLLED / CONTRÔLÉE SIMPLE
Limited Stay	20 mSv	-	2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ
High Radiation	20 mSv	-	100 mSv/h	HIGH RADIATION / HAUTE RADIATION
Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY DÉFENSE D'ENTRER

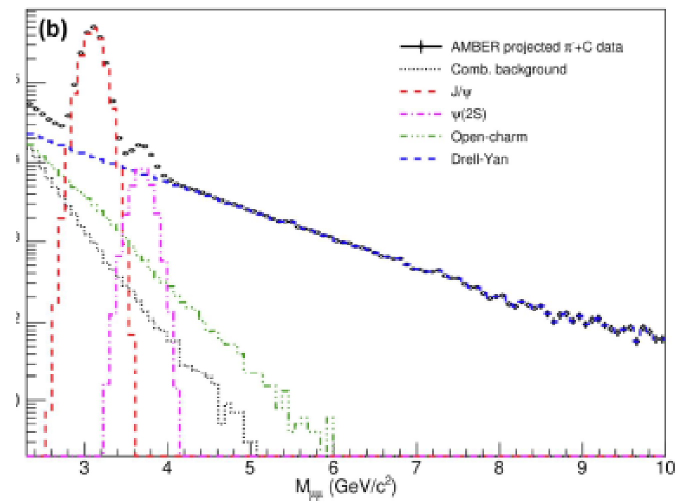
Radiation Area (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited)

- Foreseen enhancement of the radiation shielding: junction TT84/EHN2, door PPE221 (CEDAR detector access)
- Shielding of target area: 2m walls, 3.2m roof
- Total gain of possible intensity compared to COMPASS run: 67%

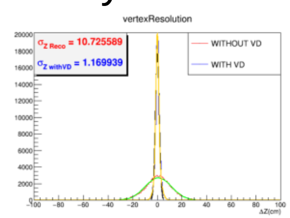
Track reconstruction enhancements for Drell-Yan

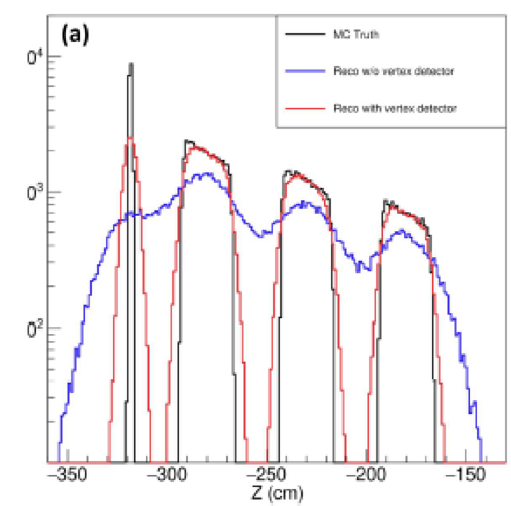




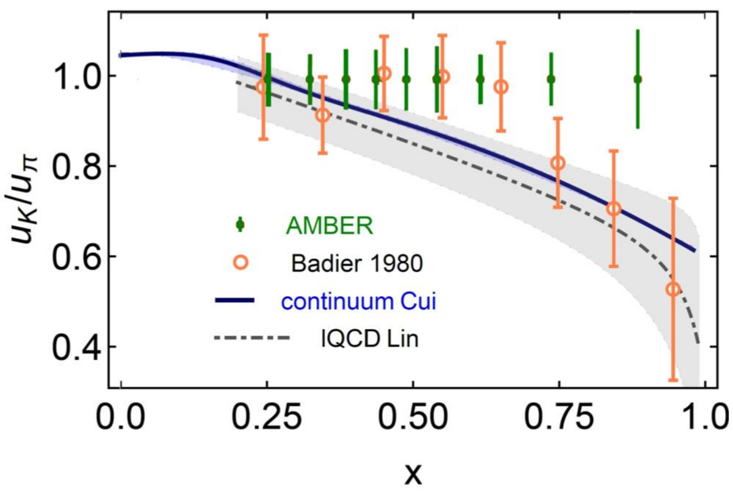


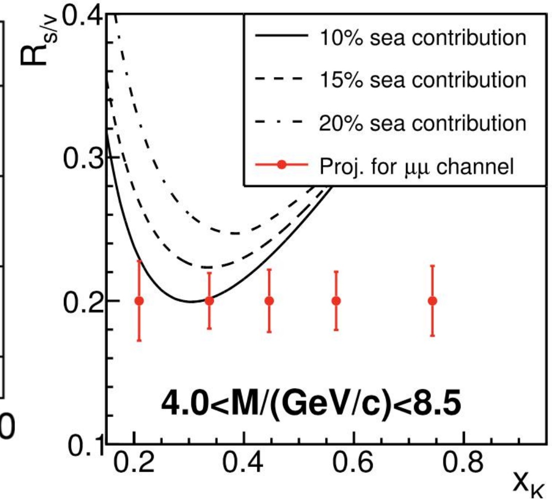
- To be placed between target and hadron absorber
- We investigate to employ a vertex detector similar to FVTX (PHENIX): silicon microstrips with 75 μm pitch
- Enhancement of di-muon mass resolution by about x2, the vertex resolution by x8



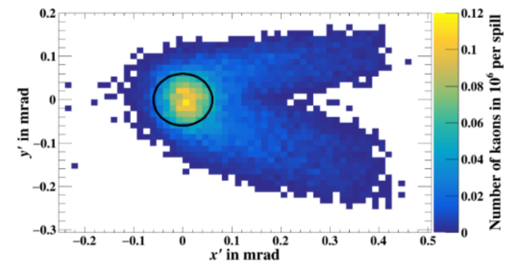


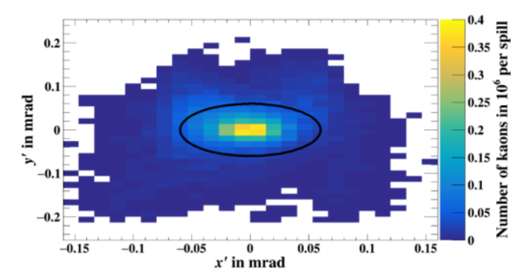
Drell-Yan process for Kaons



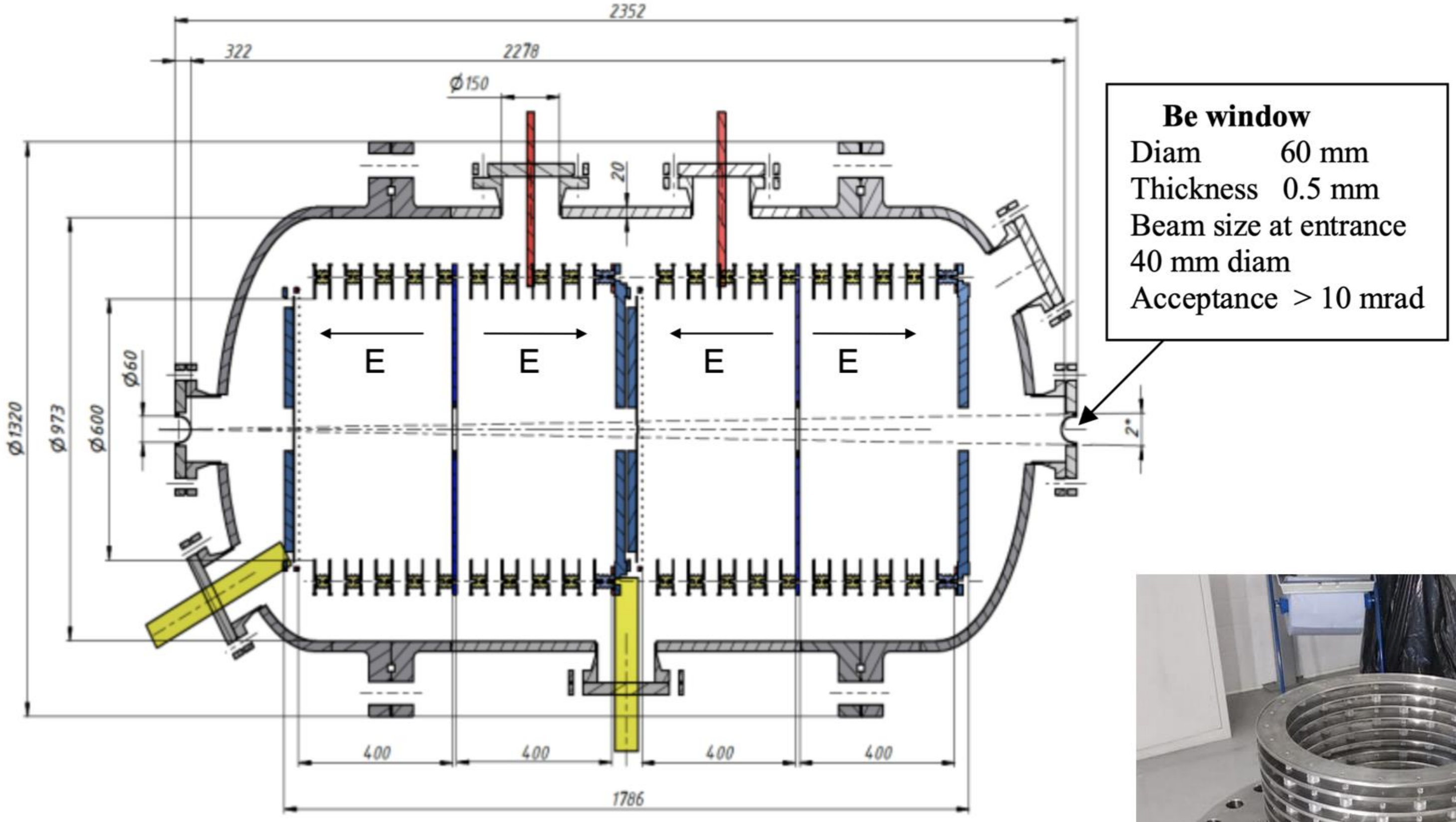


- The initially investigated rf-separation technique turned out to not be of use to the Drell-Yan program (total kaon intensity is not increased)
- Enhance the kaon number: optimize the material budget in the beam line (e.g. throughgoing vacuum – to be investigated by BE-EA) and the CEDAR operation
- Total gain of possible intensity compared to COMPASS run: 37%

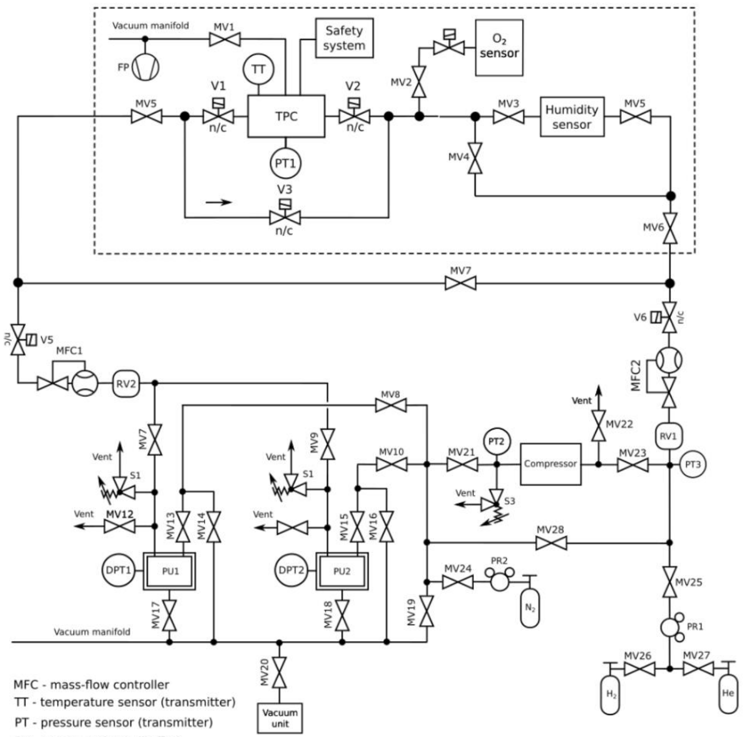




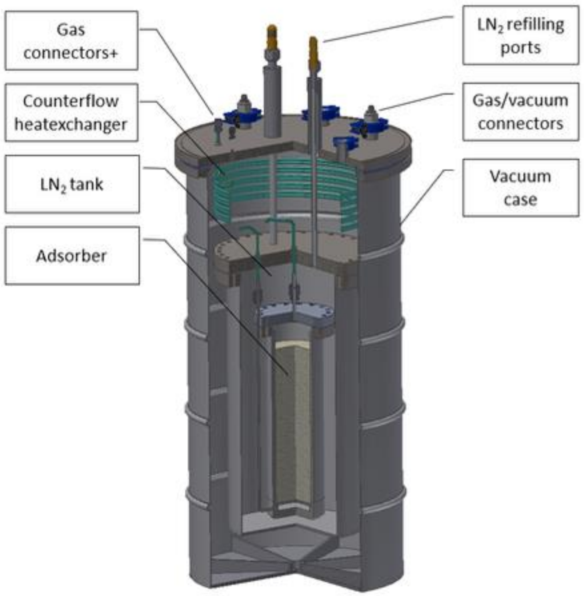
Hardware: TPC



- Acquisition of pressure volume: common project of GSI Darmstadt and German AMBER groups
- Inner structures: production and test setup at PNPI

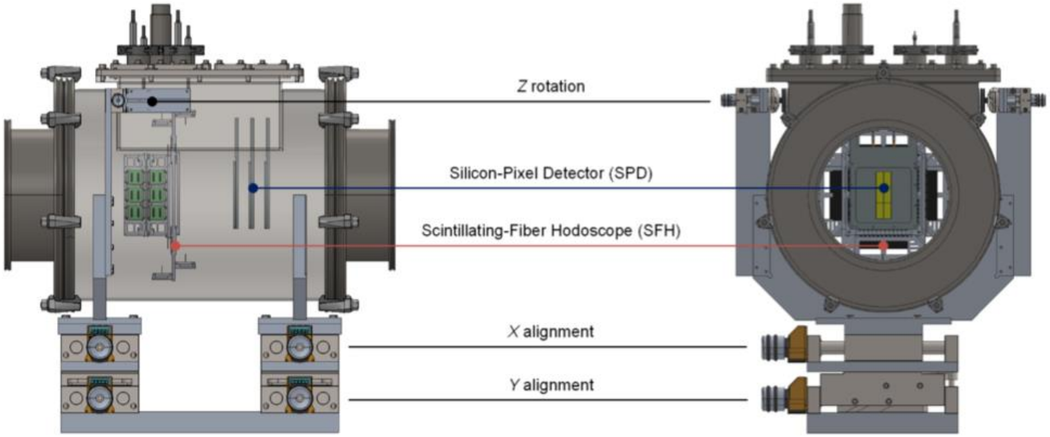


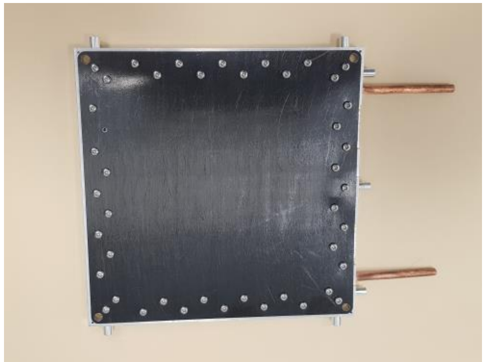
MFC - mass-flow controller
TT - temperature sensor (transmitter)
PT - pressure sensor (transmitter)
RV - reserve volume (buffer)
V - operated valve (n/c - normally closed)
MV - manual valve
SV - safety valve
PU - purification unit
PR - pressure reducer
DPT1- differential pressure sensor (transmitter)

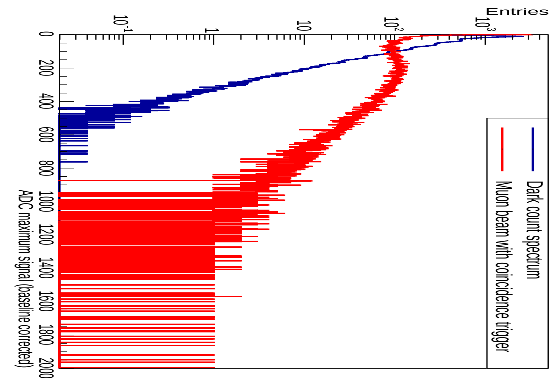


- Design and operation studies at PNPI
- Under investigation with CERN safety

Unified Tracking Station and Silicon pixel detector







- ALPIDE cooling carrier plate, prototype testing ongoing
- Scintillating-fiber hodoscope: first amplitude spectra from tests in COMPASS beam, May 2022

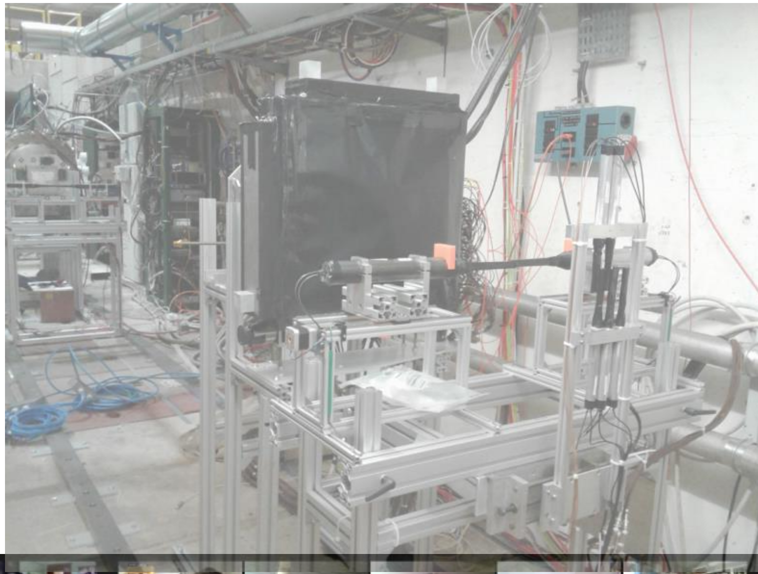
DAQ achievements

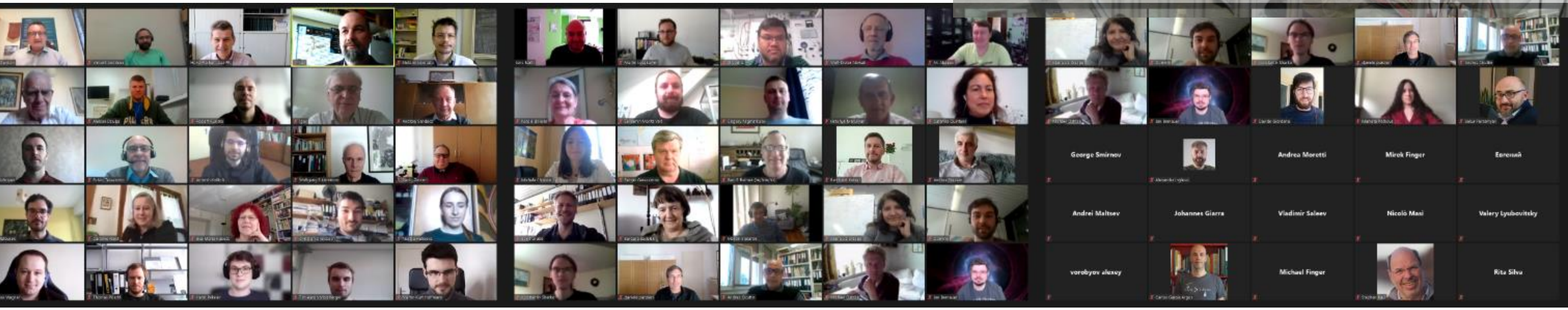
- Novel architecture for a streaming read out, development since 2018
- Allow for combining data from slow (e.g. TPC) and fast detectors (e.g. SFH)
- Raw data processing of about 5 GB/sec, total data ~9PB per run period
- Reduction through high-level trigger (HLT), e.g. a kink reconstruction for PRM
- Installation of DAQ infrastructure started in 2021, partly tested during the test run already
  - 1GB/sec for a single readout computer
  - 300-800 MB/sec for HLT computing node (depending on complexity)
  - Event building: time slice builder with full speed 5GB/sec tested using FPGA-based data generation
- Total data amount may be reduced by up to orders of magnitude

ECAL2 DAQ Hardware – Carrier Board III

Conclusions

- The AMBER Collaboration is pursuing a broad and exciting hadron physics programme
- Proposal was approved by SPSC in 2020
- Drafting of the Memorandum of Understanding well advanced
- Possibilities for future of the Russian participation to be awaited

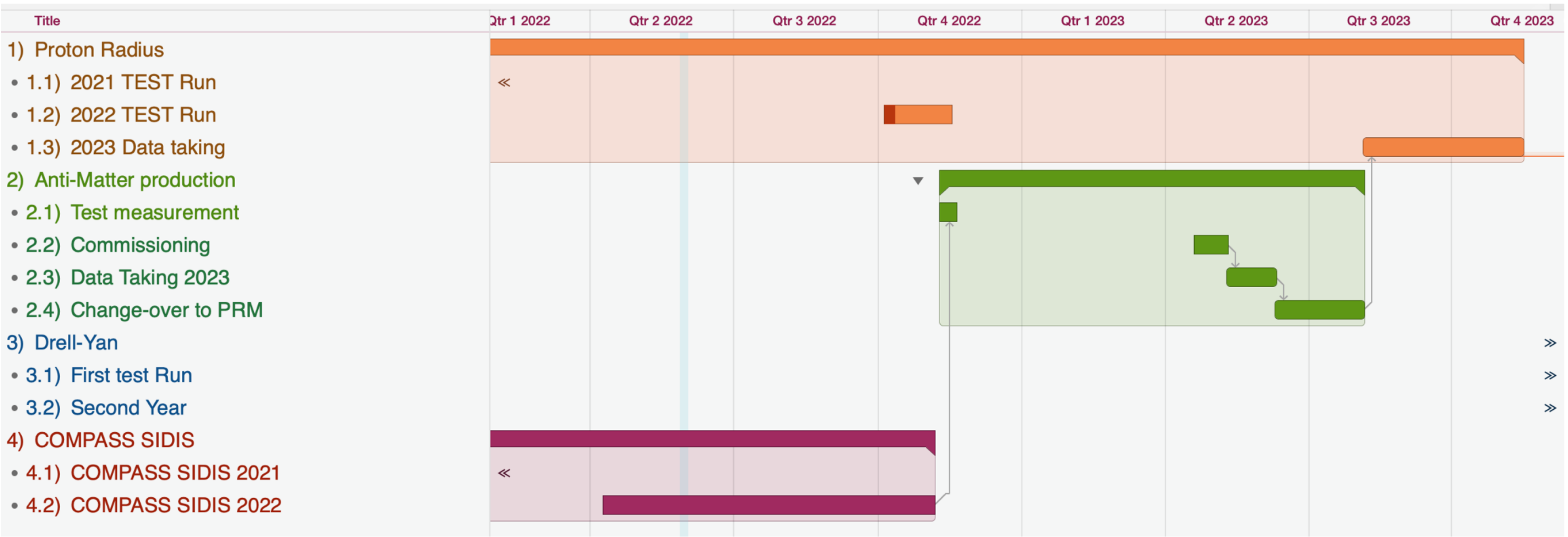


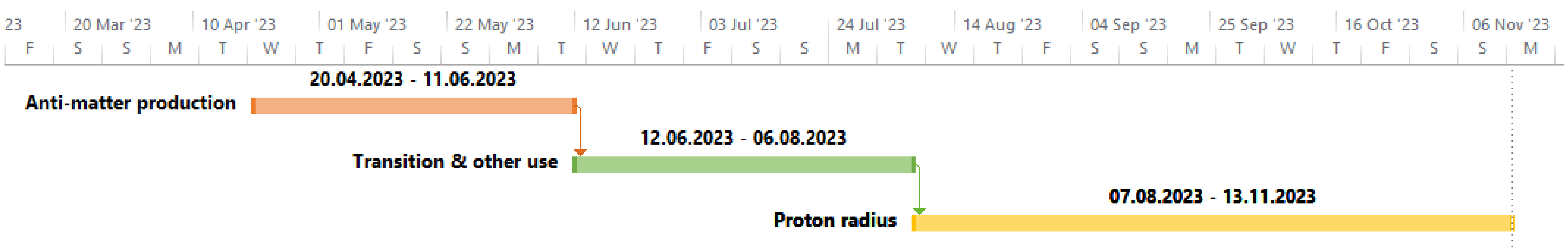


- Meetings only virtual up to now – first in-person Collaboration meeting planned for September

Backup

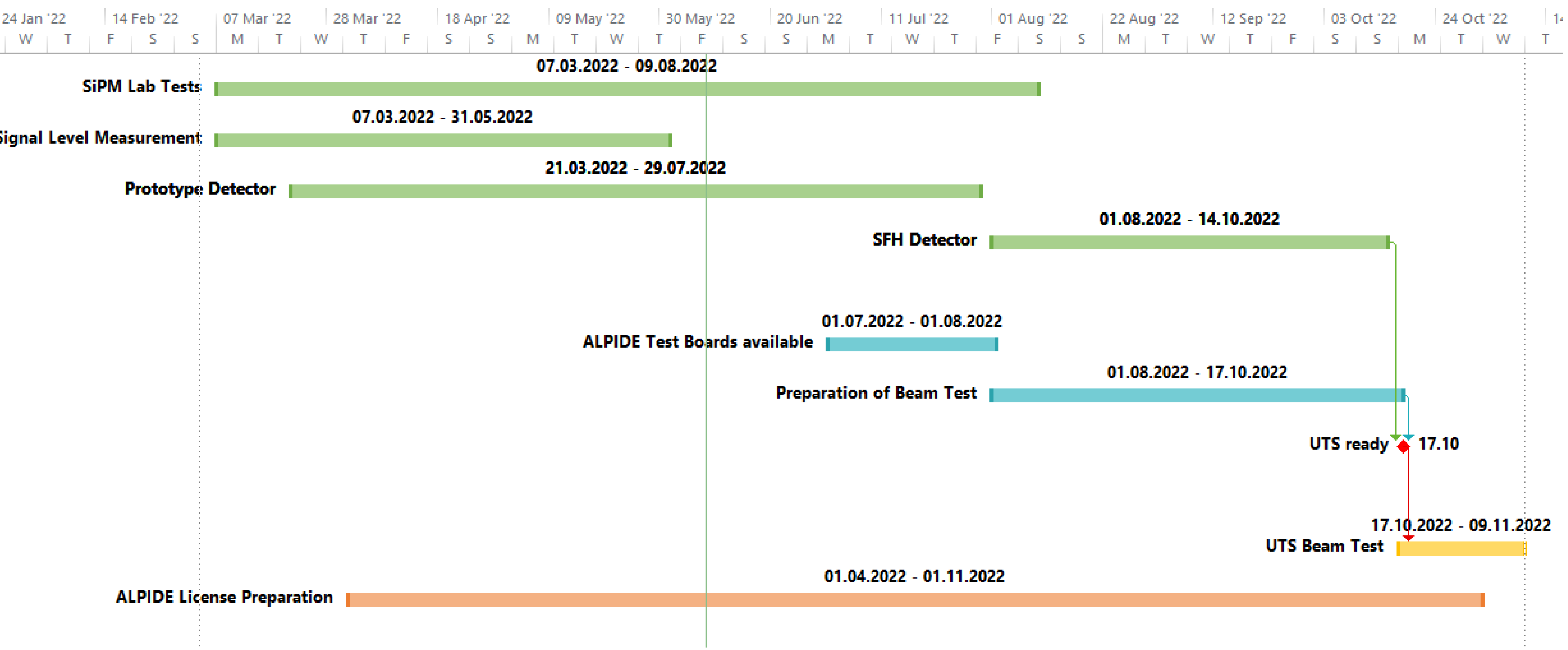
AMBER Timelines 2022-23





Russian groups

- Implicit agreement within the Collaboration on the condemnation of the Russian invasion and the war in Ukraine on Feb. 28, 2022
- Up to present, continuation of the collaboration with the Russian AMBER groups according the regulations (depending on institutes)
- Negotiations with CERN RD J. Mnich: Contributions of Russian groups to AMBER on the level of 25% of the resources, important know-how – hard to quantify


24 Jan '22
14 Feb '22
07 Mar '22
28 Mar '22
18 Apr '22
09 May '22
30 May '22
20 Jun '22
11 Jul '22
01 Aug '22
22 Aug '22
12 Sep '22
03 Oct '22
24 Oct '22
SiPM Lab Tests
07.03.2022 - 09.08.2022
Signal Level Measurement
07.03.2022 - 31.05.2022
Prototype Detector
21.03.2022 - 29.07.2022
SFH Detector
01.08.2022 - 14.10.2022
ALPIDE Test Boards available
01.07.2022 - 01.08.2022
Preparation of Beam Test
01.08.2022 - 17.10.2022
UTS ready
17.10
UTS Beam Test
17.10.2022 - 09.11.2022
ALPIDE License Preparation
01.04.2022 - 01.11.2022

AMBER physics program (as of LoI)

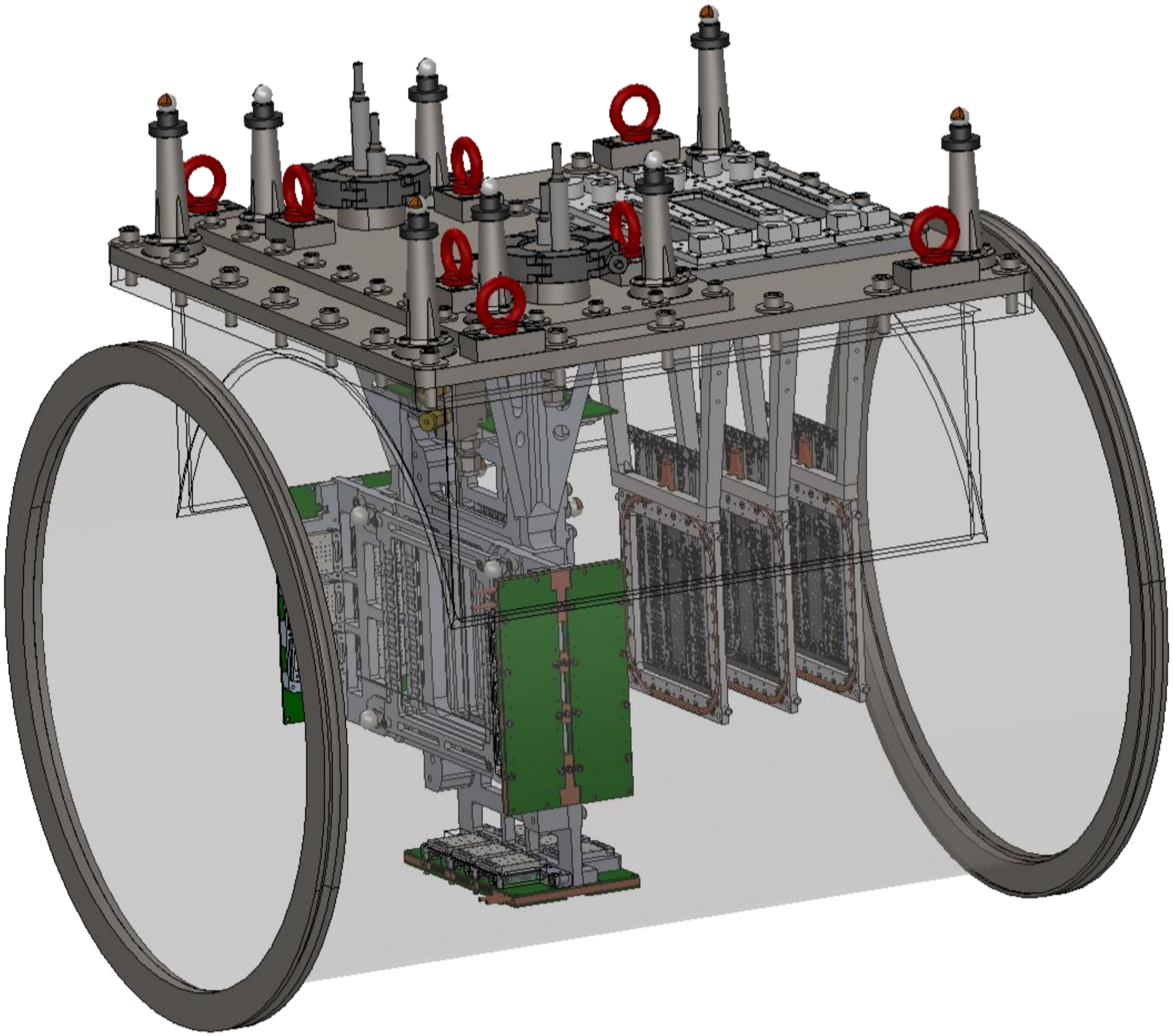
Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4\cdot10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2\cdot10^7$	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	$5\cdot10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5\cdot10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7\cdot10^7$	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	$5\cdot10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5\cdot10^6$	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	$5\cdot10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5\cdot10^6$	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.

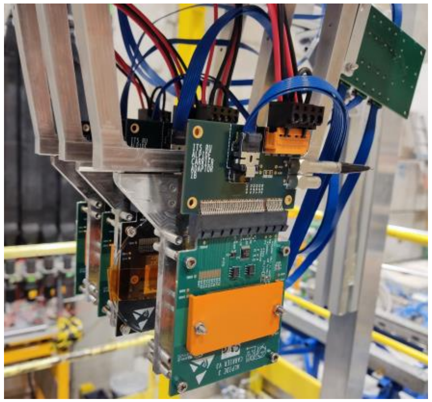
Phase-1
with conventional
hadron and muon
beams
2022 → 2028

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

Unified Tracking Station



ALPIDE testing - details



Two beam tests of the prototype ALPIDE detectors has been done in 2021/22:

CERN(2021) : 4 detectors (single chip with ALICECarrier card);
Read out – ALICE MOSAIC DAQ bord;

Julich(2022): ALICE single chip carrier, MOSAIC read Out (preliminary data rate studies, rate up to 2MHz Per sensor)