Status and Plans of the AMBER Experiment

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

**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

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

\[ r_{p,\text{exp}}^E = 0.84 \ldots 0.88 \text{ fm} \]

- **Proton Radius Experiment at Jefferson Lab**
  - **muon vs. electron scattering:**
    - different systematics (multiple scattering, energy loss, particle decay)
    - much lower radiative effects for muons

**AMBER projected uncertainty**

- Bernauer et al., A1 coll. [PRL 105 242001 (2010)]
- Pokl et al., CREMA coll. [Nature 466 213 (2010)]
- Zhan et al. [PLB 705 59 (2011)]
- Antognini et al., CREMA coll. [Science 339 417 (2013)]
- Beyer et al. [Science 358 6559 (2017)]
- Plecháč et al. [PRL 120 183001 (2018)]
- Tsirigotti et al. [Rev. Mod. Phys. 93 025010 (2021)]
- Milová et al. [arXiv:1905.11142 (2019)]
- Bezujev et al. [Science 363 1007 (2019)]
- Xiong et al. [Nature 575, 147-150 (2019)]
- Proposal AMBER [SPSC-P-160 (2019)]
- Lin et al. [Phys. Lett. B 816 136254 (2021)]
Proton radius from muon-proton elastic scattering at high energy

- 100 GeV muon beam
- Active-target TPC with high-pressure H₂
- goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4 \cdot 10^{-2}$ GeV²
- 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 be 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

- 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%

9.6.2022
Jan Friedrich
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
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%
• Acquisition of pressure volume: common project of GSI Darmstadt and German AMBER groups
• Inner structures: production and test setup at PNPI
TPC gas recirculation system

- 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
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

<table>
<thead>
<tr>
<th>Title</th>
<th>Qtr 1 2022</th>
<th>Qtr 2 2022</th>
<th>Qtr 3 2022</th>
<th>Qtr 4 2022</th>
<th>Qtr 1 2023</th>
<th>Qtr 2 2023</th>
<th>Qtr 3 2023</th>
<th>Qtr 4 2023</th>
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<td>1) Proton Radius</td>
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<td>2) Anti-Matter production</td>
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<td>2.4) Change-over to PRM</td>
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<td>3) Drell-Yan</td>
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<td>3.1) First test Run</td>
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<td>4) COMPASS SIDIS</td>
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- **Anti-matter production**: 20.04.2023 - 11.06.2023
- **Transition & other use**: 12.06.2023 - 06.08.2023
- **Proton radius**: 07.08.2023 - 13.11.2023
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
9.6.2022

Jan Friedrich

[Image of a Gantt chart showing project timeline]
### AMBER physics program (as of LoI)

<table>
<thead>
<tr>
<th>Program</th>
<th>Physics Goals</th>
<th>Beam Energy [GeV]</th>
<th>Beam Intensity [s^-1]</th>
<th>Trigger Rate [kHz]</th>
<th>Beam Type</th>
<th>Target</th>
<th>Earliest start time, duration</th>
<th>Hardware additions</th>
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<tbody>
<tr>
<td>muon-proton elastic scattering</td>
<td>Precision proton-radius measurement</td>
<td>100</td>
<td>4 \cdot 10^6</td>
<td>100</td>
<td>(\mu^\pm)</td>
<td>high-pressure H2</td>
<td>2022, 1 year</td>
<td>active TPC, SciFi trigger, silicon veto, recoil silicon, modified polarised target magnet</td>
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<td>Hard exclusive reactions</td>
<td>GPD E</td>
<td>160</td>
<td>2 \cdot 10^7</td>
<td>10</td>
<td>(\mu^\pm)</td>
<td>NH3 (\uparrow)</td>
<td>2022, 2 years</td>
<td>recoil silicon, target spectrometer, tracking, calorimetry</td>
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<td>Input for Dark Matter Search</td>
<td>(\bar{p}) production cross section</td>
<td>20-280</td>
<td>5 \cdot 10^3</td>
<td>25</td>
<td>(p)</td>
<td>LH2, LHe</td>
<td>2022, 1 month</td>
<td>liquid helium target, target spectrometer, tracking, calorimetry</td>
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<td>(\bar{p})-induced spectroscopy</td>
<td>Heavy quark exotics</td>
<td>12, 20</td>
<td>5 \cdot 10^7</td>
<td>25</td>
<td>(\bar{p})</td>
<td>LH2</td>
<td>2022, 2 years</td>
<td>target spectrometer, tracking, calorimetry</td>
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<td>Drell-Yan</td>
<td>Pion PDFs</td>
<td>190</td>
<td>7 \cdot 10^7</td>
<td>25</td>
<td>(\pi^\pm)</td>
<td>C/W</td>
<td>2022, 1-2 years</td>
<td>&quot;active absorber&quot;, vertex detector, recoil TOF, forward PID</td>
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<tr>
<td>Drell-Yan (RF)</td>
<td>Kaon PDFs &amp; Nucleon TMDs</td>
<td>(\sim 100)</td>
<td>10^8</td>
<td>25-50</td>
<td>(K^+, p)</td>
<td>NH3 (\uparrow), C/W</td>
<td>2026, 2-3 years</td>
<td>&quot;active absorber&quot;, vertex detector</td>
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<td>Primakoff (RF)</td>
<td>Kaon polarisability &amp; pion life time</td>
<td>(\sim 100)</td>
<td>5 \cdot 10^6</td>
<td>&gt; 10</td>
<td>(K^-)</td>
<td>Ni</td>
<td>non-exclusive, 2026, 1 year</td>
<td>hodoscope</td>
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<tr>
<td>Prompt Photons (RF)</td>
<td>Meson gluon PDFs</td>
<td>(\geq 100)</td>
<td>5 \cdot 10^6</td>
<td>10-100</td>
<td>(K^+, \pi^\pm)</td>
<td>LH2, Ni</td>
<td>non-exclusive, 2026, 1 year</td>
<td>recoil TOF, forward PID</td>
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<td>(K)-induced Spectroscopy (RF)</td>
<td>High-precision strange-meson spectrum</td>
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<td>25</td>
<td>(K^-)</td>
<td>LH2</td>
<td>2026, 1 year</td>
<td>hodoscope</td>
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<td>Vector mesons (RF)</td>
<td>Spin Density Matrix Elements</td>
<td>50-100</td>
<td>5 \cdot 10^6</td>
<td>10-100</td>
<td>(K^\pm, \pi^\pm)</td>
<td>from H to Pb</td>
<td>2026, 1 year</td>
<td>recoil TOF, forward PID</td>
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</table>

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
Unified Tracking Station
Two beam tests of the prototype ALPIDE detectors have been done in 2021/22:

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

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