1. Intro AMBER
2. AMBER science questions
3. AMBER Phase-1
   - Proton Radius Measurement
   - Antimatter production cross section
   - Di-muon production measurement (Drell-Yan and J/ψ)
4. Upgrades
5. Possible timeline
6. Proton Radius Measurement test run 2021
7. Summary
We have started to work on physics program of possible COMPASS successor > 10 years ago.

A Number of Workshops has been organized, for detail see AMBER web page:

https://amber.web.cern.ch/

Lol submitted in January 2019
http://arxiv.org/abs/1808.00848
Apparatus for Meson and Baryon Experimental Research > 270 authors
AMBER science questions

There are two bearing columns of the facility:

1. **Phenomenon of the Emergence of the Hadron Mass**
2. Proton spin (largely addressed by COMPASS and others, Phase-2)

**How does all the visible matter in the universe come about and what defines its mass scale?**

Great discovery of the Higgs-boson unfortunately does not help to answer this question, because:

- The Higgs-boson mechanism produces only a small fraction of all visible mass
- The Higgs-generated mass scales explain neither the “huge” proton mass nor the ‘nearly-masslessness’ of the pion

As Higgs mechanism produces a few percent of visible mass, Where does the rest comes from (EHM phenomenon)?

---

Higgs generated masses of the valence quarks:
- \( M_{(u+d)} \sim 7 \text{ MeV} \)
- \( M_{(u+s)} \sim 100 \text{ MeV} \)
- \( M_{(u+u+d)} \sim 10 \text{ MeV} \)
EHM phenomenon
What are the underlying mechanisms?

Intuitively one can expect that the answer to the question lies within SM, in particular within QCD. Why? Because of the dynamical mass generation in continuum QCD.

As quark can emit and absorb gluons it acquires its mass in infrared region because of the gluon “self-mass-generation” mechanism, so the visible (or emergent) mass of hadrons must be dominated by gluon component.

Truly “mass from nothing” phenomenon: Initially massless gluon produces dressed gluon fields which “generates” mass function that is large at infrared momenta.

Dynamical mass generation in continuum quantum chromodynamics
... ~ 1000 citations

In order to “prove” that QCD underlies the EHM phenomenon we have to compare Lattice and Continuum QCD calculations with experimental data by measuring:

1. Quark and Gluon PDFs of the pion/kaon/proton
2. Hadron’s radii (confinement)
3. Excited-meson spectra

Gluon propagator ... continuum and lattice QCD agree

Dressed-quark mass function $M(p)$
The answer is obviously NOT (SM paradigm):
- proton is described by QCD … 3 valence quarks
- pion is also described by QCD … 1 valence quark and 1 valence antiquark
- expect $m_p \approx 1.5 \times m_\pi$ … but, instead $m_p \approx 7 \times m_\pi$

Proton and pion/kaon difference:
- In the chiral limit the mass of the proton remains basically the same
- Chiral limit mass of pion and kaon is “0” by definition (Nambu-Goldstone bosons)
- Different gluon content expected for pion and kaon
- Contribution from interplay with Higgs mechanism is different

Thus it is equally important to study the internal structure and dynamics of pions, kaons and protons
AMBER physics program

Questions to be answered:

- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass vs. Higgs)
- Internal quark-gluon structure and dynamics, especially important pion/kaon/proton striking differences

Methods:

Drell-Yan and $J/\psi$  
Prompt Photon Production  
Diffractive scattering  
Elastic scattering

A series of workshops entitled “Perceiving of the EHM through AMBER@CERN(SPS)”: https://indico.cern.ch/event/1021402/
General AMBER timeline

Conventional muon/hadron M2 beams

Phase-1
Proton Radius Measurement
Antimatter production cross section
Pion structure (PDFs) via DY and charmonia

Phase-2
Kaon and pion structure (PDFs and PDAs)
High precision strange-meson spectrum
Kaon and pion charge radius
Kaon induced Primakoff reaction

Phase-1 Proposal approved by RB on 02/12/2020
Phase-2 Proposal submission in the beginning of 2022

Run 3
Run 4

\[ \Delta \Phi = 2\pi (L f / c) (\beta_1^{-1} - \beta_2^{-1}) \] with \( \beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2) / 2p^2 \)
Proton Radius Measurement at AMBER (confinement)

statistical precision of the proposed measurement, down to $Q^2 = 0.001$ GeV$^2$/c$^2$, Cross section is normalised to the $G_D$ - dipole form factor
Proton Radius Measurement at AMBER
(confinement)

- A number of experiments is on the way in different laboratories
- There is a synergy between PRES at MAMI ($E_e = 720 \ MeV$) and AMBER ($E_\mu = 100 \ GeV$):
  - The same type of active target (hydrogen filled TPC) will be used for both experiment
  - The same $Q^2$ range will be covered ($10^{-3}$ - $4 \times 10^{-2} \ GeV^2$)
  - Mutual calibration of the transferred momentum
- Significant advantage of the AMBER measurement is much lower radiative corrections: for soft bremsstrahlung photon energy $E_\gamma/E_{beam} \sim 0.01$ QED corrections amount to $\sim$15-20% for electrons and to $\sim$1.5% for muons (AMBER will be able to make a control measurement with Electromagnetic Calorimeters).

If compared to the muon scattering experiment at PSI (MUSE):
- Much cleaner experimental conditions (pure muon beam with less than $10^{-6}$ admixture of hadrons)
- Much higher beam momentum, thus contribution from magnetic form factor is suppressed ($0.1$-$0.2 \ GeV/c$ vs $100 \ GeV/c$)
- Small statistical errors achievable with the proposed running time
- New AMS(2) data – the antiparticle flux is well known now (few % pres.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)
- Two types of processes contribute – SM interactions (proton on the inter-stellar matter with the production for example of antiprotons) and contribution from dark particle – antiparticle annihilation;
- In order to detect a possible excess in the antiparticles flux a good knowledge of inclusive cross sections of p-He interaction with antiparticles in the f.s. is a must, currently the typical precision is of 30-50%.

AMBER proton beam: from a few tens of GeV/c up to 250 GeV/c, in the pseudo-rapidity range 2.4 < \eta < 5.6. Goal is to measure the double differential (momentum and pseudo-rapidity) antiproton production cross section from p+H and p+He at different proton momenta (50, 100, 190, 250 GeV/c).
The impact of the proposed p + p measurements on constraining the production of cosmic anti-protons versus their kinetic energy. Each curve represents the fraction of anti-proton production phase space as constrained by AMBER cross section measurements in p-p, p-He and He-p channels, compared to NA61 (p-p) and LHCb (p-He) measurements.

**p-H channel, in three different energy ranges**

AMBER

NA61 (20-158 GeV/c)

100-190 GeV/c

50-190 GeV/c

50 - 250 GeV/c

AMBER LHCb

**p-He and He-p channels**

https://indico.cern.ch/event/820869/
Pion structure status:

- Scarce data, poor knowledge of valence, sea and glue basically unknown
- Mostly heavy nuclear targets: large nuclear effects
- For some experiments, no information on absolute cross sections
- Two experiments (E615, NA3) have measured so far with both pion beam sign, but only one (NA3) has used its data to separate sea-valence quark contributions
- Discrepancy between different experiments (i.e. NA10, E615)
- Old data, no way to reanalyse them using modern approaches
Probing valence and sea quark contents of pion at AMBER

Sea quark content of pion can be accurately measured at AMBER for the first time

Pion structure in pion induced DY
Expected accuracy as compared to NA3

Sea quark content of pion can be accurately measured at AMBER for the first time
Collected simultaneously with DY data, with large counting rates

Physics objectives:

- Study of the $J/\psi$ (charmonia) production mechanisms ($gg$-fusion vs $q\bar{q}$-annihilation), comparison of CEM and NRQCD


- $\Psi(2S)$ signal study, free of feed-down effect from $\chi_{c1}$ $\chi_{c2}$

Improved CEM, CT10 + GRS99 global fit for proton/pion
AMBER Hardware Developments

- New triggerless DAQ system, new front-end electronics and trigger logic compatible with triggerless readout
- New large-size PixelGEM detectors
- New large-area micro-pattern gaseous detectors (MPGD)
- High-rate-capable CEDARs detectors (beam line)
- A new RICH-0 detector to extend significantly phase space coverage (lower momenta)
Phase-1 Hardware Development

- High-pressure hydrogen filled active TPC (PRM)
- Combined scintillating fibres / silicon tracking system (4 stations) (PRM)
- Triggerless electromagnetic calorimeter electronics (PRM)
- High rate capable silicon-based vertex detector (DY)
- New high-purity and high efficiency di-muon trigger (DY)
Possible timeline for the AMBER Phase-1 measurements

1) Proton Radius
   - 1.1) 2021 test run
   - 1.2) 2022 data taking
   - 1.3) 2023 data taking

2) Anti-Matter production
   - 2.1) Test measurement
   - 2.2) Data Taking 2023

3) Drell-Yan
   - 3.1) First year
   - 3.2) Second Year

4) COMPASS SIDIS
   - 4.1) COMPASS SIDIS 2021
   - 4.2) COMPASS SIDIS 2022

Starting point depends of the semiconductors availability on the market
Layout of Proton Radius Measurement in 2022

Upstream part of the AMBER spectrometer for PRM
Proton Radius Measurement 2021 test run

Main Goal to be reached: Proof-of-principle of all new detector equipment

- Test the IKAR TPC in dedicated 20 days of beam (CEDAR position)
  - determine the noise/background induced by the muon beam, detect proton recoils correlated with scattered muons
- Test of the unified tracking detector station
  - operate one detector station with prototypes of both the silicon-pixel detector and the scintillating-fibre hodoscope
- Test of the new DAQ system (possible for TPC in park position)
  - operate new free-running DAQ system for readout for all new detector components
Proton Radius Measurement 2021 test run

IKAR TPC (currently at CERN):
→ 2x drift cells with 400 mm length
→ New adapted field-shaping rings
→ Anode structure: identical structure, but with smaller diameter wrt final TPC
→ Operation pressure of max. 10 bar
→ New power-supplies and front-end electronics
  • Ready for first pressure test
  • Dedicated gas-purification system will be used

Combined Silicon-Fibre tracking station:
→ 2x+2y planes of 500 μm scintillating fibre 9.6x9.6 cm²
→ 3 planes of pixel-silicons 9x9 cm² (pixel size 28x28 μm)
→ Operation pressure of max. 10 bar
→ New power-supplies and front-end electronics
  • Small distance between the Silicon-pixel detectors and the Scintillating-Fibre Hodoscope
  • Allow for independent access and cooling infrastructure
  • Compatible with beam line elements for the He volume
Summary: AMBER at CERN SPS

- A wide and extremely competitive physics program brought together, strong interest in the hadron physics community
- ~40 Institutions and 12 countries, 189 full members (PhD and higher), growing up
- Collaboration structure is basically fixed, MoU is in preparation
- Important next step – proton radius measurement test run in 2021
BACK UP
AMBER in the CERN news


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
Improved CEM, CT10 + GRS99 global fit for prot./pion