QCD at FAIR workshop 2025
Physics perspectives with hadron beams for the next decade
22.-27. June 2025, Sicily, Italy

AMBER:
A QCD Facility at CERN

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06/24/2025

QCD Questions in the Context of AMBER

Understand hadron properties in terms of quarks and gluons

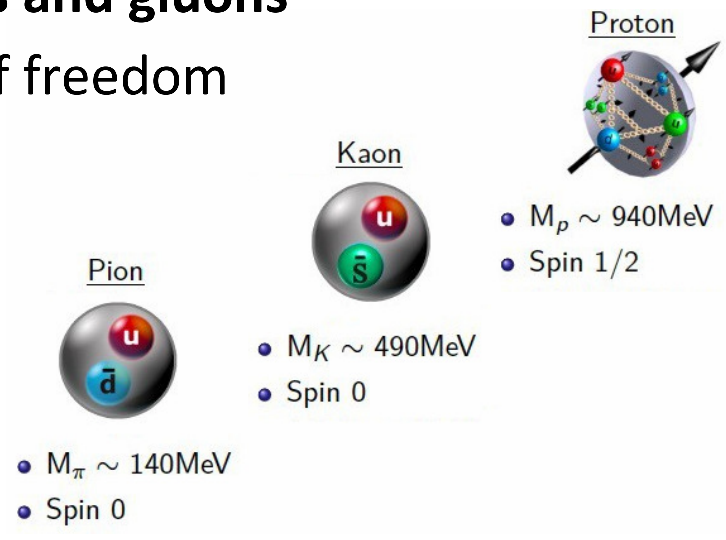
– Emergence of hadronic and nuclear degrees of freedom
– Confinement
– Masses: nucleon masses vs meson masses

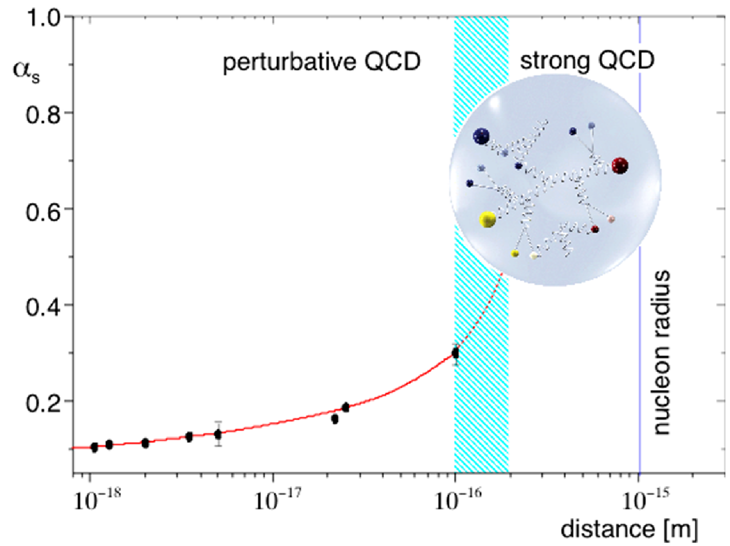
Experiment: Scattering and Spectroscopy

– Quark and gluon PDFs of pion, kaon, proton
– Excitation spectrum of hadrons
– Form factors, hadron radii
– Input to SM tests at colliders, beyond SM searches

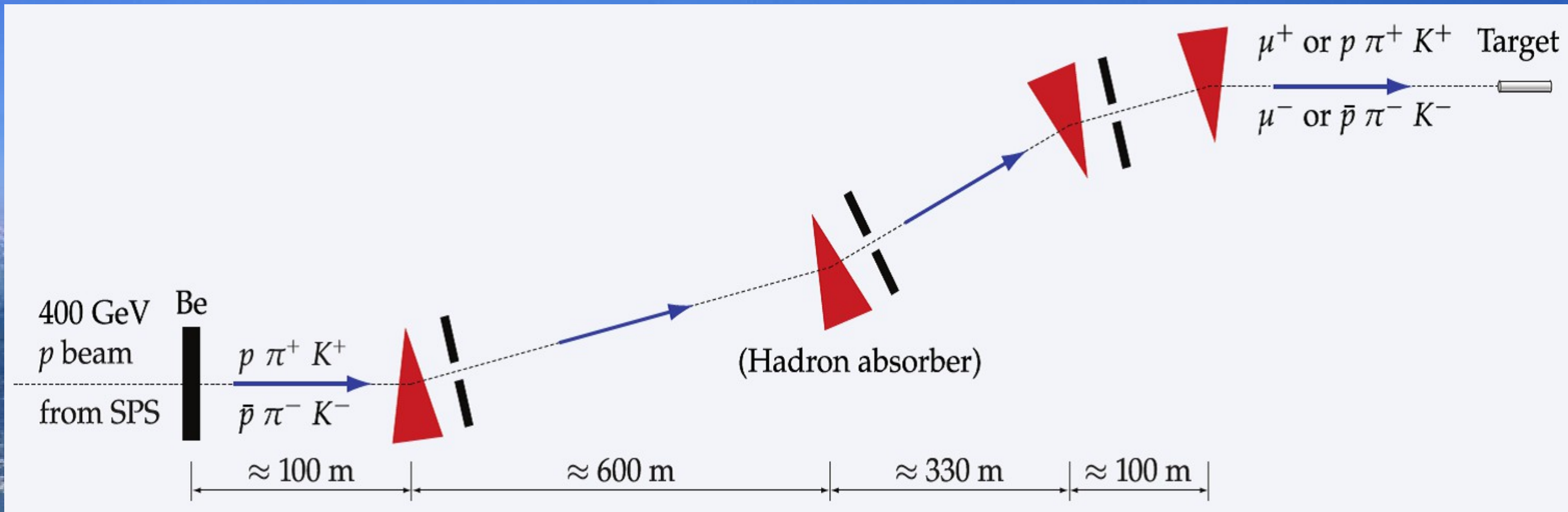
Quantitative theoretical approaches:

– Effective field theories
– Lattice QCD
– Continuum methods



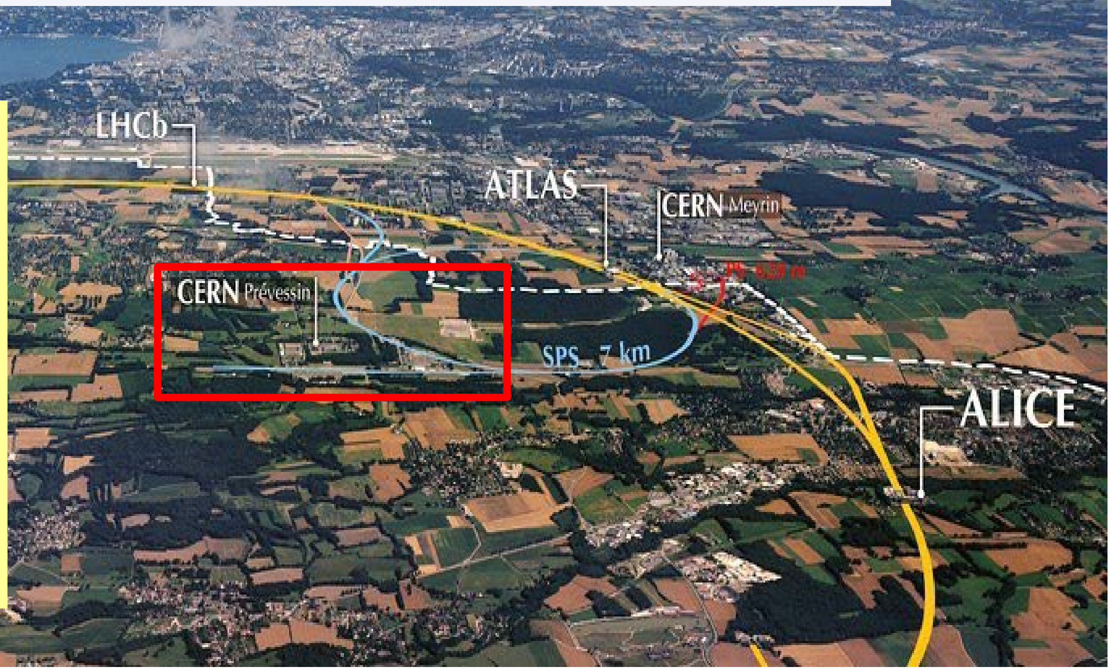


AMBER @ CERN: The M2 Beamline of the SPS



M2 beamline (EHN2):

- Most versatile beamline at CERN
- High-intensity beams of $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p$^{\pm}$
  - $\mu^{\pm}$: 90 - 180 GeV, up to $5 \cdot 10^7\, s^{-1}$
  - $h^{\pm}$: 60 - 250 GeV, up to $1.5 \cdot 10^7\, s^{-1}$
    up to $10^9\, s^{-1}$ without absorber
- Intensity limited by radioprotection

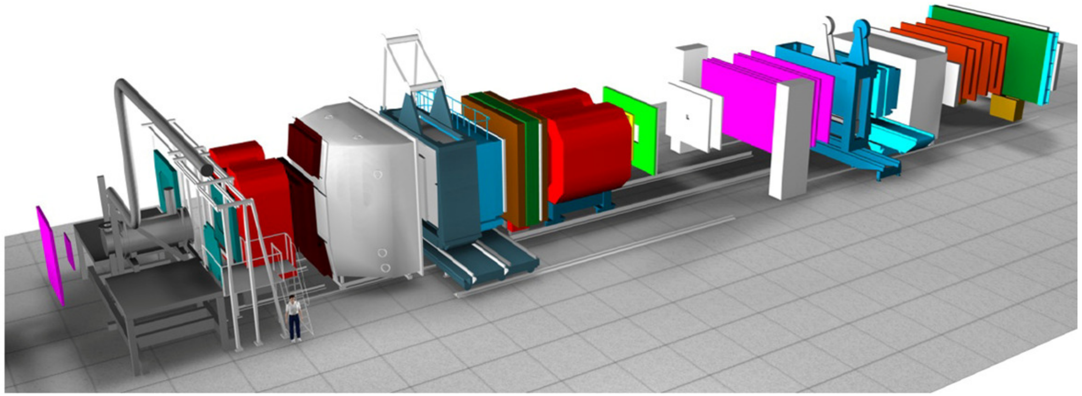


AMBER @ CERN SPS

AMBER
Apparatus for Meson and Baryon Experimental Research

- AMBER was approved as NA66 experiment in December 2020
- The Collaboration consists of ~200 physicists from 34 institutes

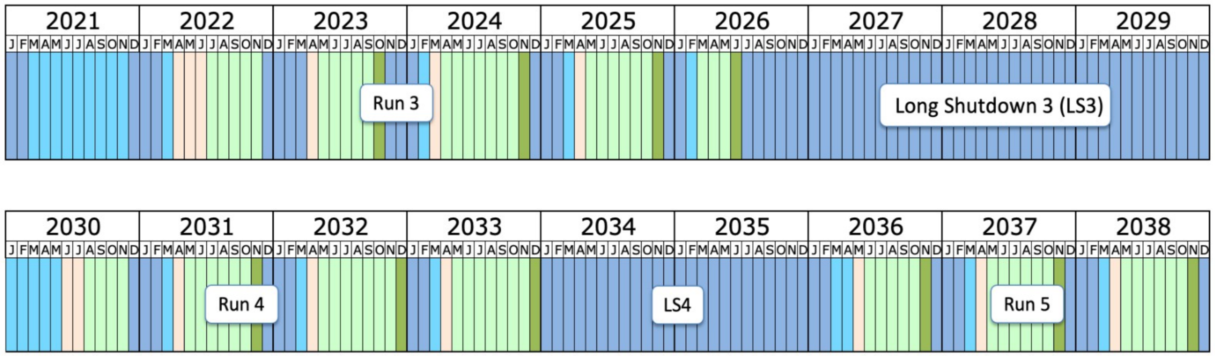
  → Many new groups
- AMBER inherited, extended and upgraded the 2-stage spectrometer of the COMPASS collaboration



- Muon and hadron beams 60 – 250 GeV at the M2 beamline at SPS

Phase-1: 2023 → 2031
- Conventional h/μ beams

Phase-2: 2031 → 2041
- High-intensity hadron beams (K, p)
- Proposal in drafting stage to be submitted in 2025



AMBER Physics Program

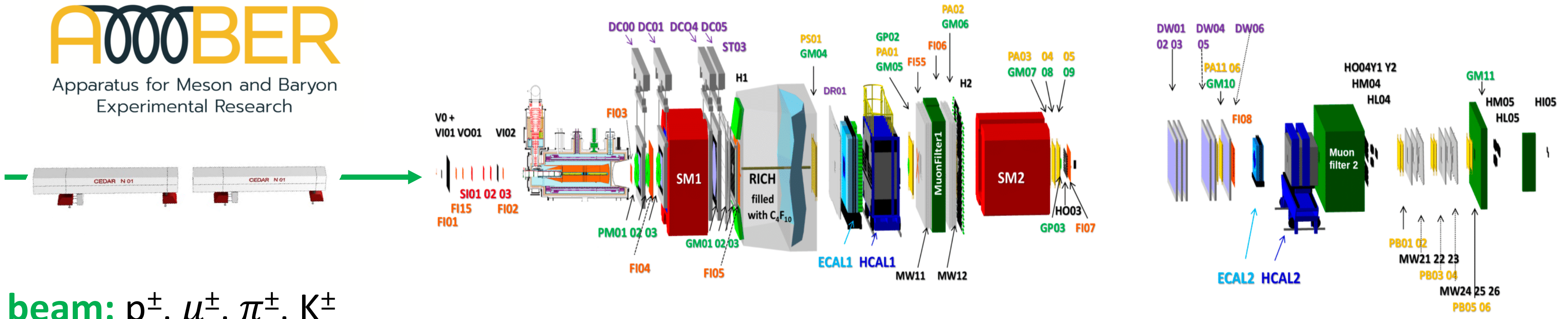
Phase 1: 2023 - 2031 **(conventional beams)**

- $\overline{\mathrm{p}}$ **production cross sections** for dark matter searches (pbarX)
- **Proton radius**: High-energy μ-p elastic scattering (PRM)
- **Pion PDFs**: Drell-Yan processes (DY)

Phase 2*:* 2031 - 2041 **(high intensity and high purity kaon beam)**

The AMBER experimental setup

Apparatus for Meson and Baryon Experimental Research



beam: $p^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$

target region: program-specific

spectrometer: common for all measurements

Phase 1:

- **pbarX:** 60 – 250 GeV p
- **PRM:** 100 GeV $\mu^\pm$
- **DY:** 190 GeV $\pi^\pm$
  + upgrade of CEDARs for beam PID

- **pbarX:** lHe/lH/lD target
- **PRM: H_2 TPC + Si pixel + fiber**
- **DY:** C, W target + absorber
  + **vertex detector**

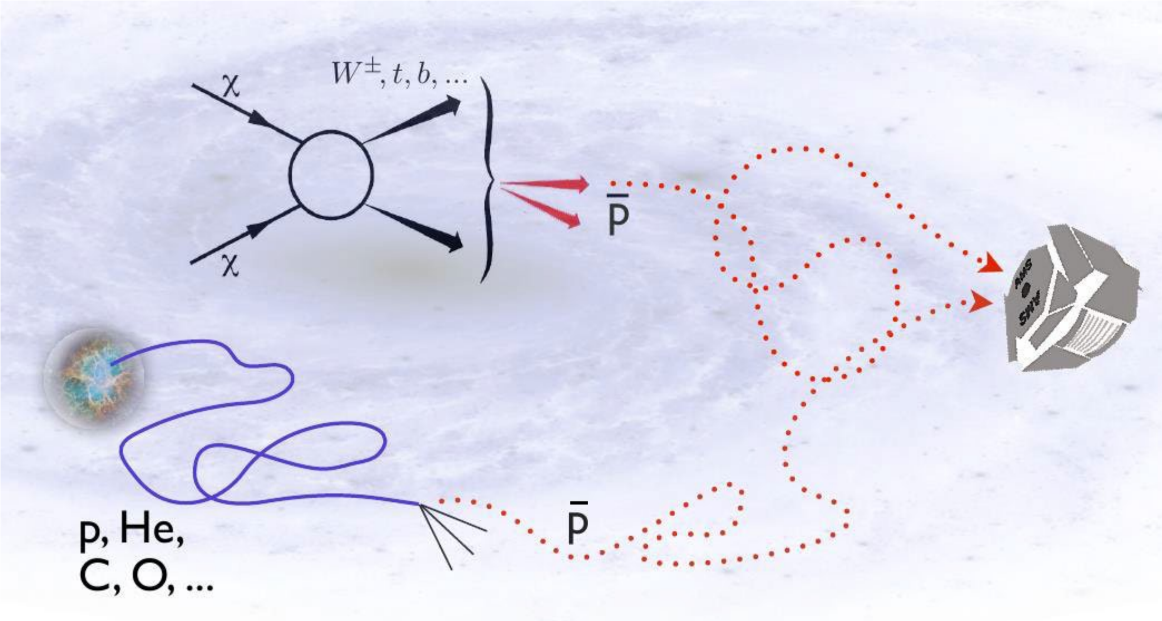
- New **free running DAQ**
- Upgrades of several detector systems: fiber hodo, ECAL
- New large-area **GEM** detectors

Phase 2:

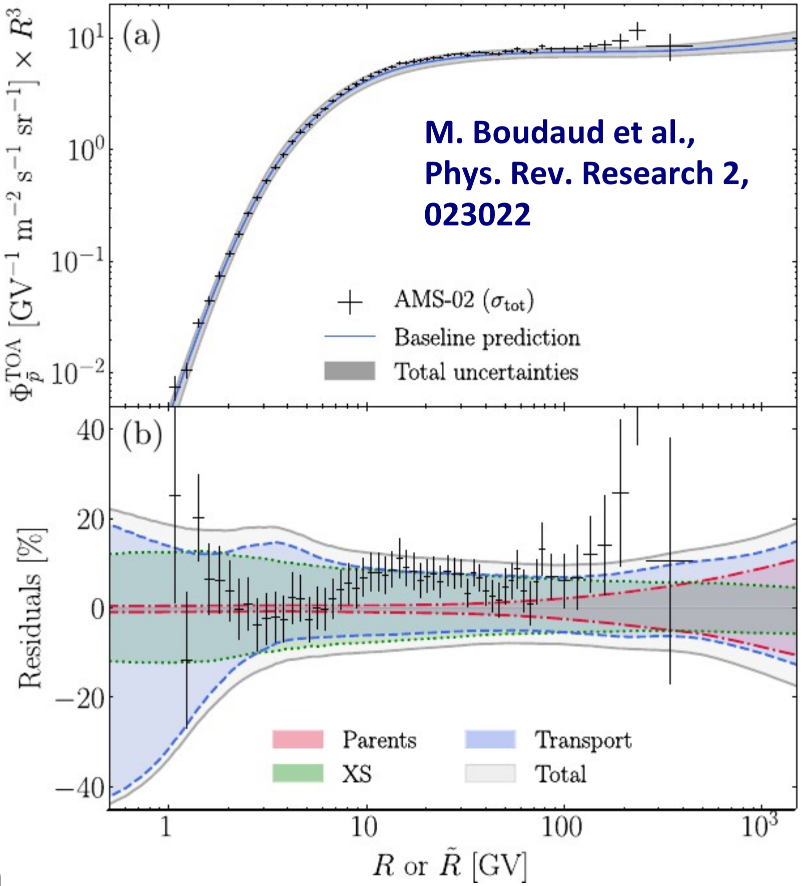
- **Beam line upgrade** for high-intensity / high-purity K beam
- Further target and detector upgrades (ECAL0, final state PID)

Antiproton Production Cross-Sections for Dark Matter Search

J. Heisig, MIAPP 2022



Flux vs Rigidity



AMS-02 (alpha magnet spectrometer):

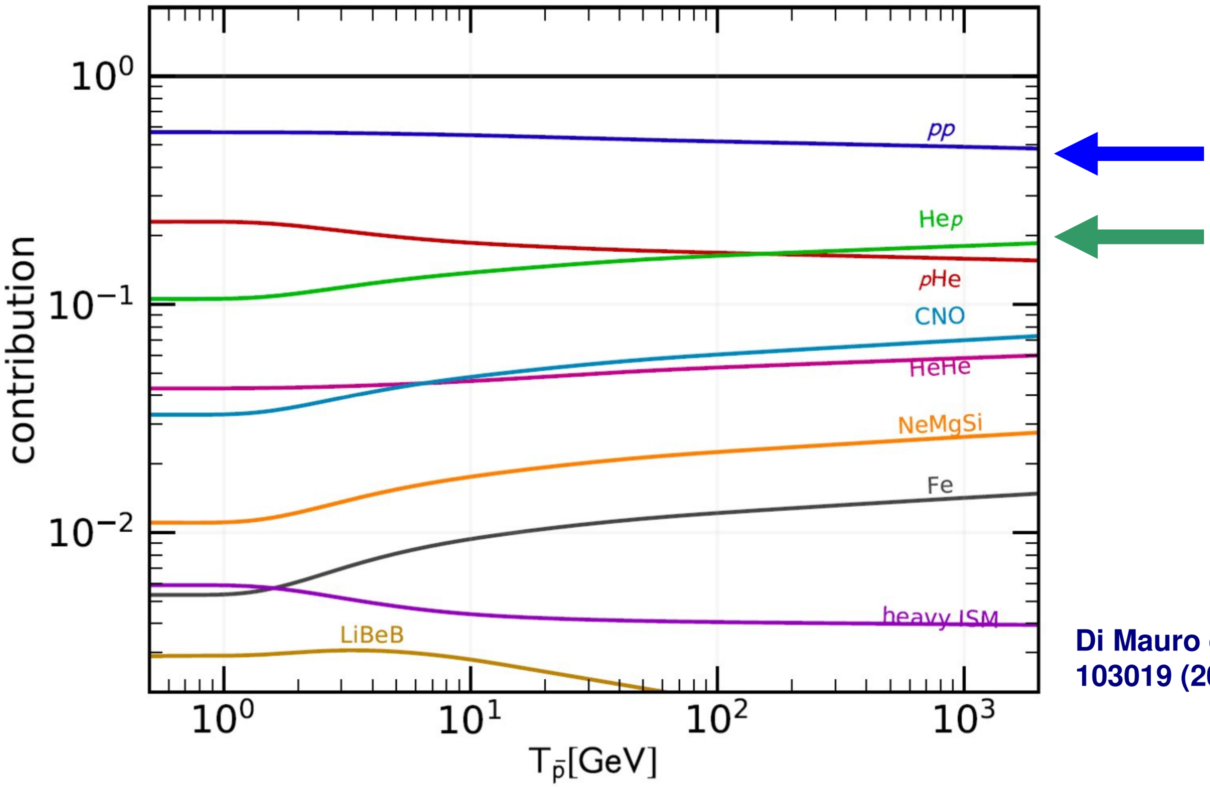
- Precise data on the cosmic antiparticle flux
- Sources: SM processes and dark matter annihilation

Rigidity: Charged particle's resistance to deflection in a magnetic field

Limiting factor: $\bar{p}$ production cross section uncertainties from collisions involving p and He (currently 30-50%!)

Antiproton Production in the Cosmic Radiation

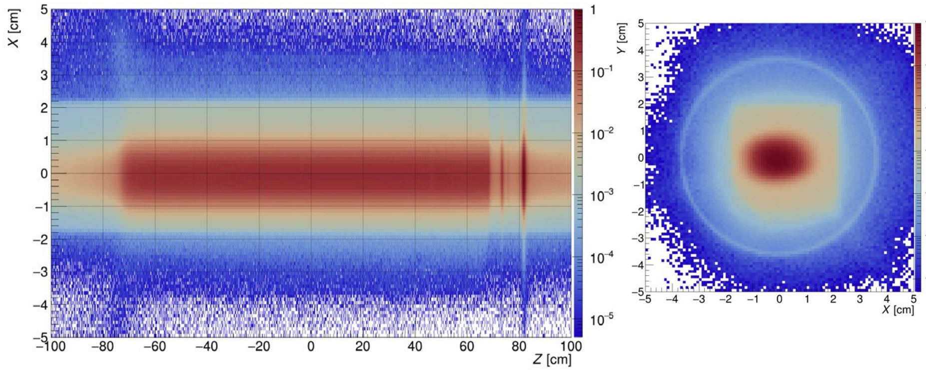
Sources of antiprotons:



Di Mauro et al., Phys. Rev. D 97, 103019 (2018)

- 90% of the reactions involve p and He
- $p + p \rightarrow \overline{p} + X$ Some measurements (NA49, NA61) with low statistics
- $p + {}^{4}He \rightarrow \overline{p} + X$ No data at relevant energies, only LHCb fixed target data at 4 TeV and 6.5 TeV

Antiproton Production Cross-Section Measurements by AMBER



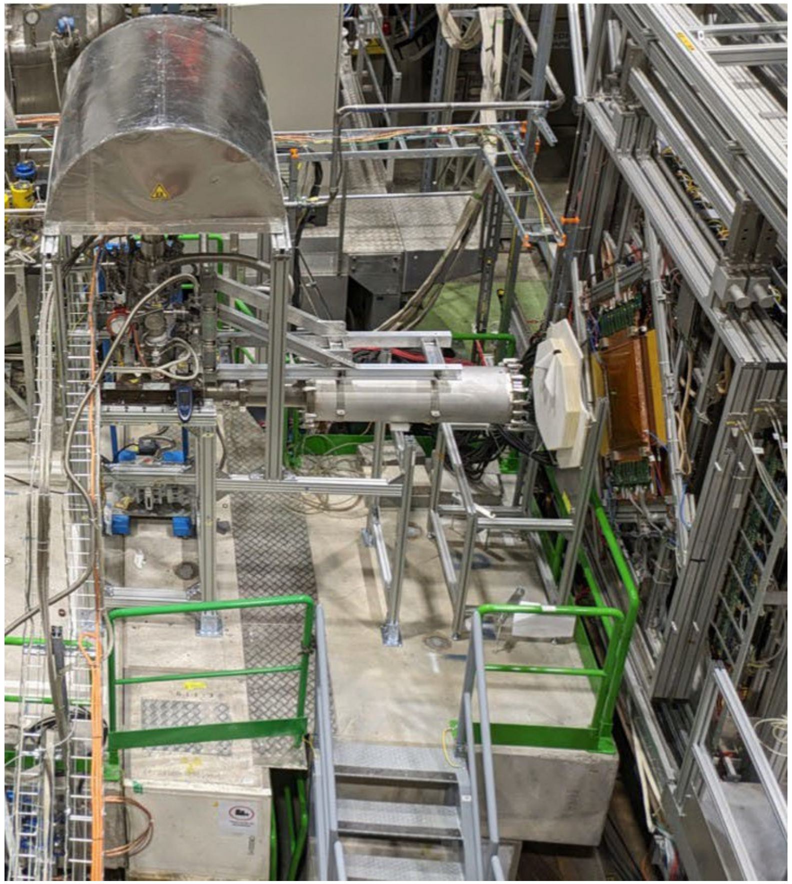
2023: $p + {}^4He \rightarrow \overline{\mathrm{p}} + X$

- Rate ~ 25k Events/s
- 6 collision energies:

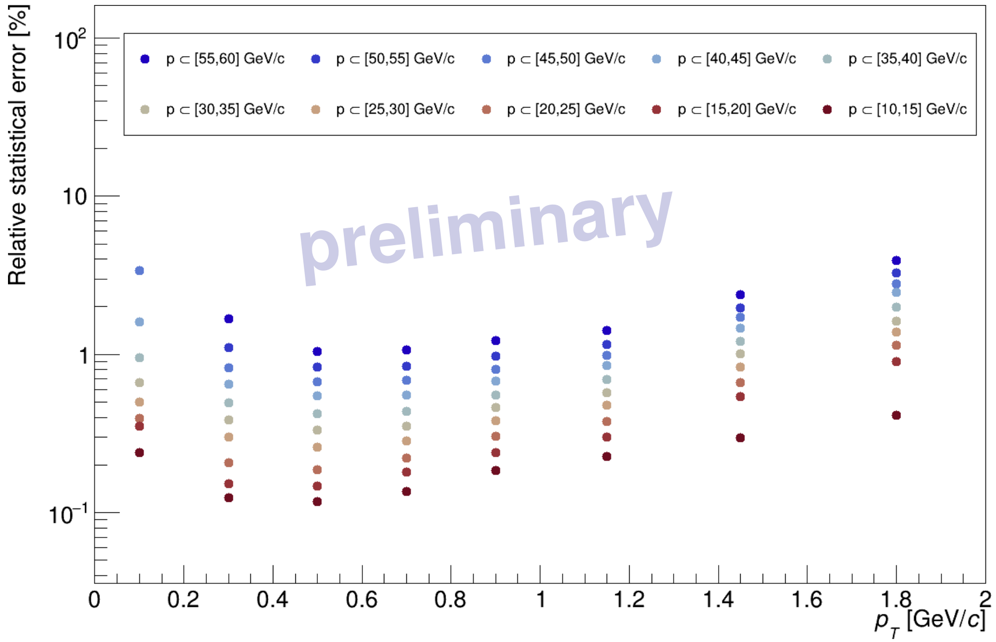
beam mom. [GeV/c]	colission energy $\sqrt{s}$ [GeV]
60	10.7
80	12.3
100	13.8
160	17.3
190	18.9
250	21.7

2024: $p + H \rightarrow \overline{\mathrm{p}} + X, \quad p + D \rightarrow \overline{\mathrm{p}} + X$

- Extract possible difference in $\overline{p}$ production on p and n
- Access difference in $\overline{\mathrm{p}}$ and $\overline{\mathrm{n}}$ production using crossed reactions $p + p \rightarrow \overline{\mathrm{p}} + X, \quad p + n \rightarrow \overline{\mathrm{p}} + X$
- 3 different beam momenta: 80, 160, 250 GeV/c



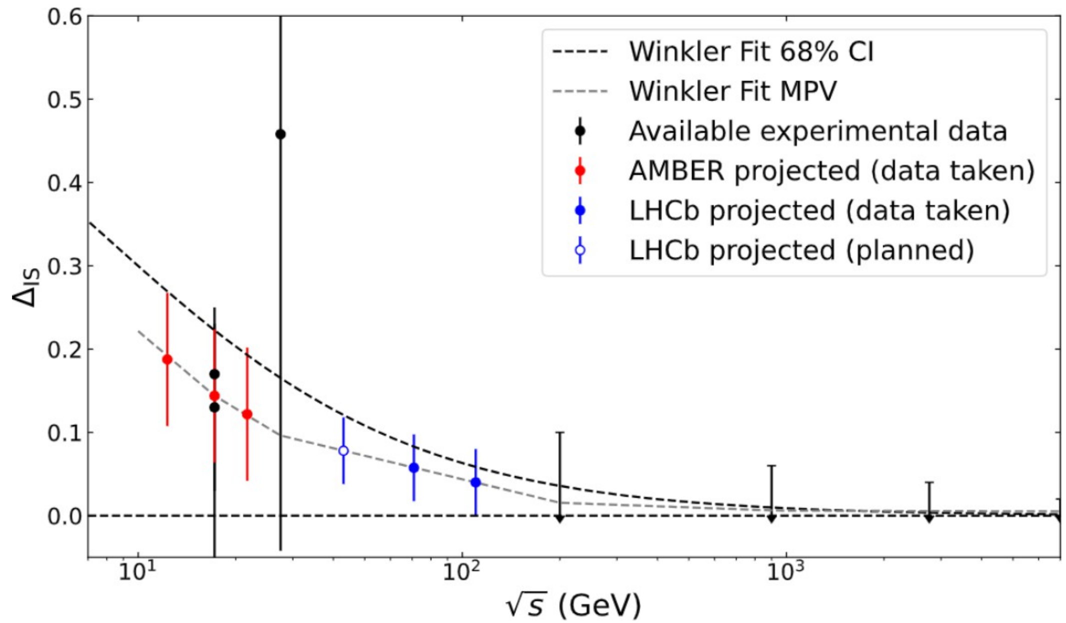
Dark Matter Search: Projected Uncertainties



AMBER
Apparatus for Meson and Baryon Experimental Research

Antiproton production cross-section uncertainties extracted from the already taken AMBER data

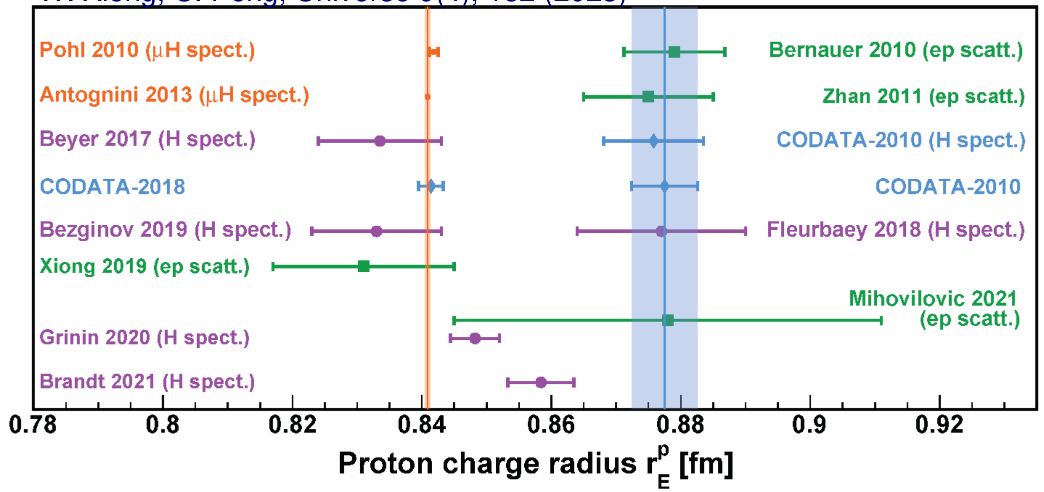
Winkler, JCAP02, 048 (2017)



Isospin factor:
Enhancement of antineutron over antiproton production

Proton Charge Radius Measurement

W. Xiong, C. Peng, Universe 9(4), 182 (2023)



Proton radius world data from CODATA since 2010

- muonic spectroscopy
- hydrogen spectroscopy
- electron scattering

Unique measurement with AMBER:

Elastic scattering of high-energy $\mu^{\pm}$ (100 GeV/c) on protons

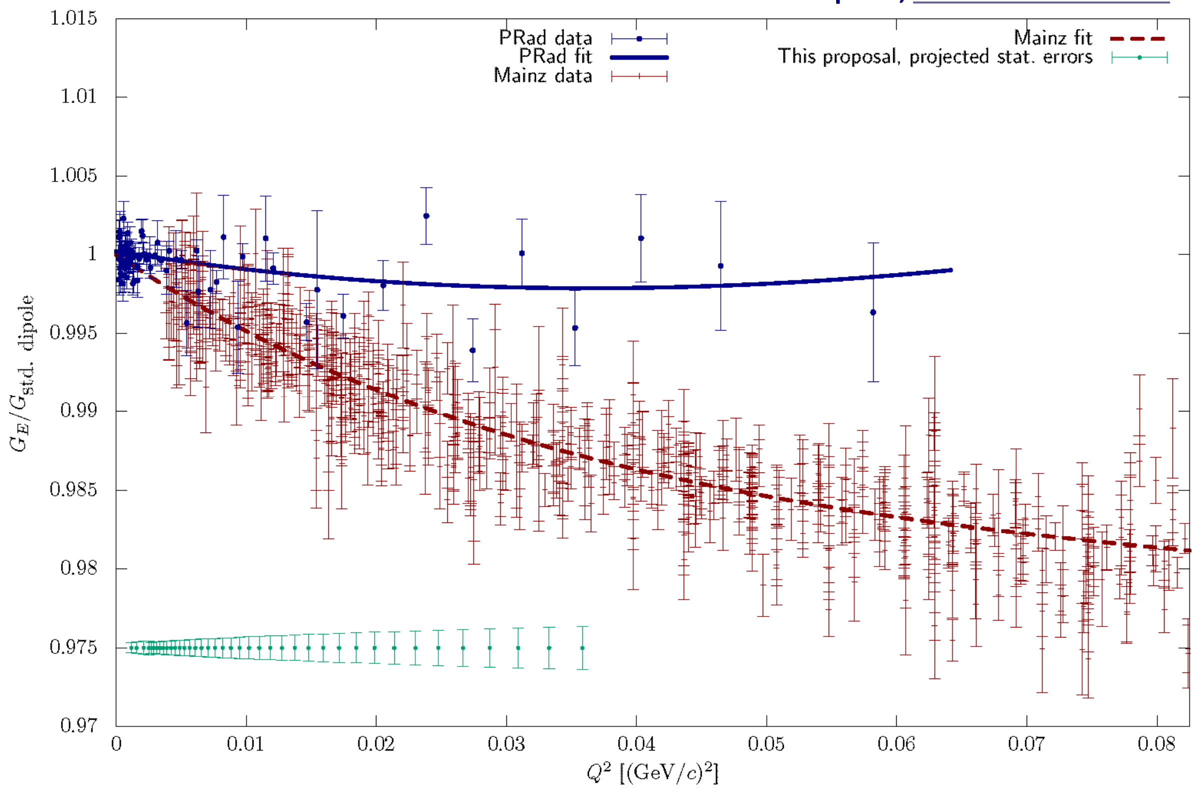
- Goal: 70 million elastic scattering events in the $10^{-3} < Q^2 < 4 \cdot 10^{-2}$ GeV^2 range
- Precision on the proton radius $\lesssim 0.01$ fm

Why μp scattering?	• Different leptonic probe • Different systematic uncertainties • Much smaller radiative corrections than ep • Provide precise data for global fit • Test of the lepton universality

Proton Charge Radius

$$\left(\frac{d\sigma}{d\Omega}\right)_{LAB} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{E'}{E}\right)\left[\frac{G_E^2+\tau G_M^2}{1+\tau}(\cos^2\frac{\theta}{2})+2\tau G_M^2\sin^2\frac{\theta}{2}\right]$$

AMBER Proposal, CERN-SPSC-2019-022

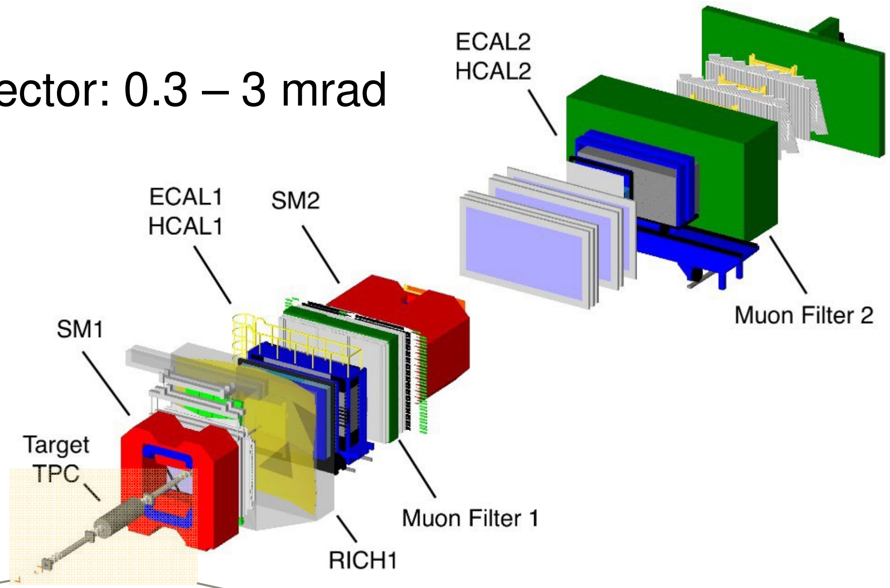


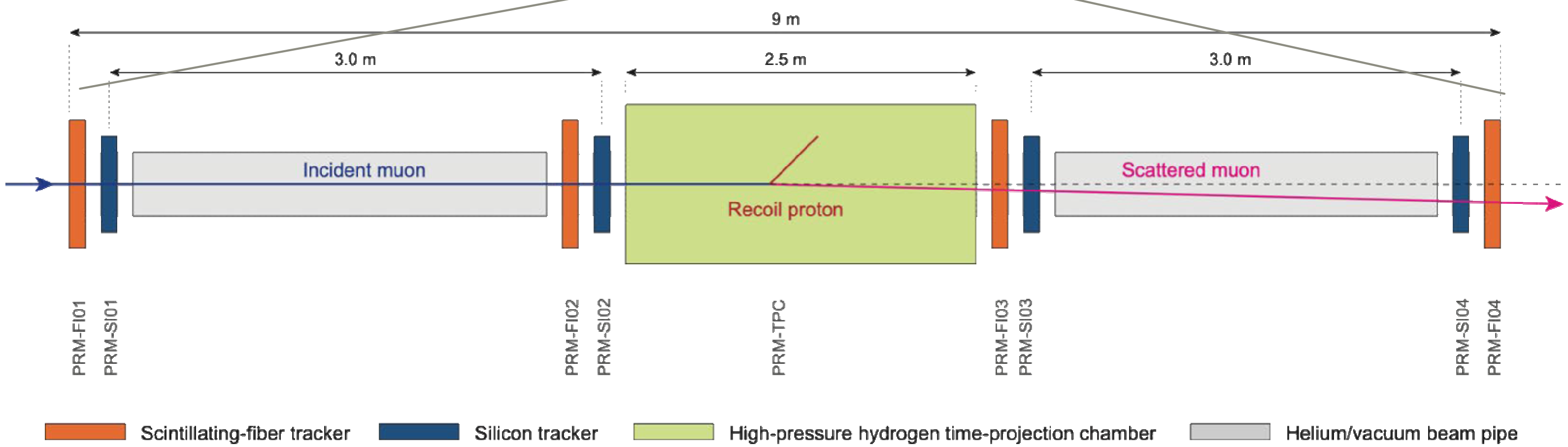
e p → e‘ p‘

$$\left\langle {r_E^p}^2 \right\rangle = -\frac{6}{G_E^p(0)}\frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

Proton Charge Radius @ AMBER

- Measurement of the **recoil proton** energy in a high-pressure pure H_2 active target TPC: 500 keV – 20 MeV
- **Muon scattering angle** measured by vertex detector: 0.3 – 3 mrad
- **Muon momentum and PID** measurement in the AMBER spectrometer
- **Radiative background** measurement in ECAL
- New continous streaming DAQ





High-Pressure Time Projection Chamber

Direct measurement of recoil proton energy:

- 2 x 40 cm drift cells, filled with pure high-pressure H_2 as target and detector gas

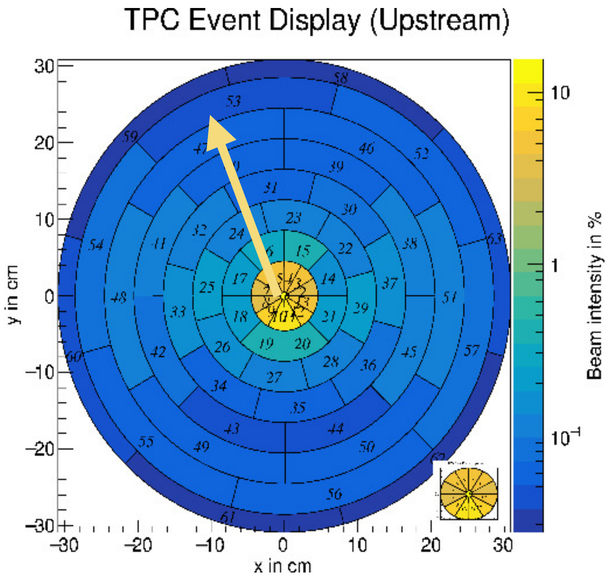
  → Drift time ~ 150µs

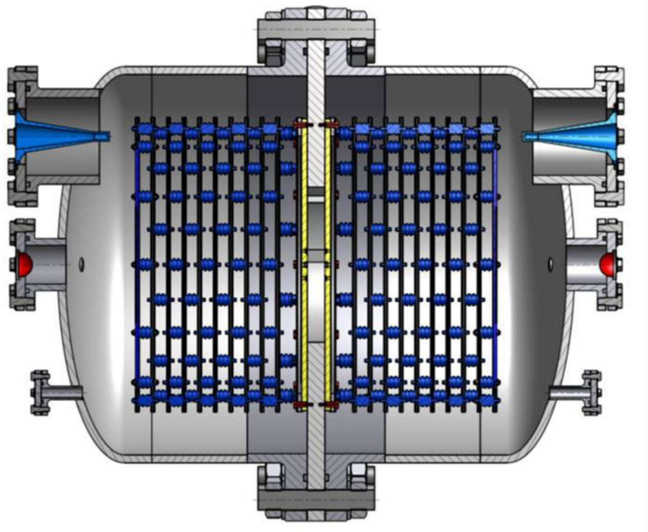
  ⟶ Energy resolution < 6% required for desired precision

  ⟶ Segmented readout plane for each cell

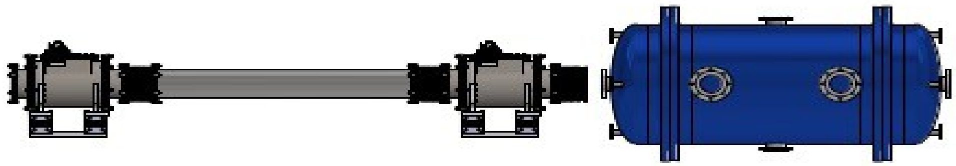
    → Reconstruction of the proton track

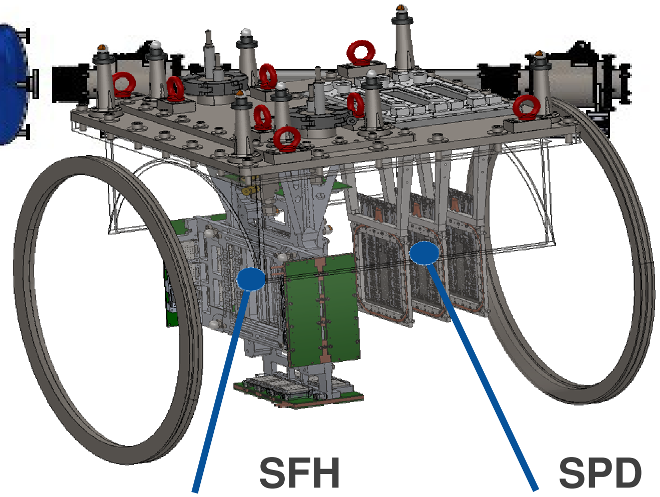
  ⟶ 2 different pressure settings: 4 bar, 20 bar to cover the Q^2 range





Muon Vertex Detection

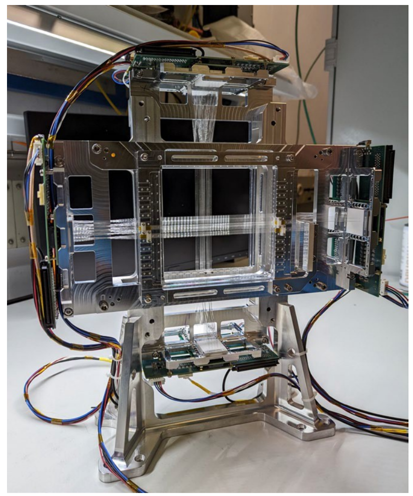




High-precision tracking system:

- 4 stations of MAPS (SPD) and a scintillating-fiber hodoscope (SFH), size ~ 9 × 9 cm^2
- μ scattering angle ~ 20 μrad

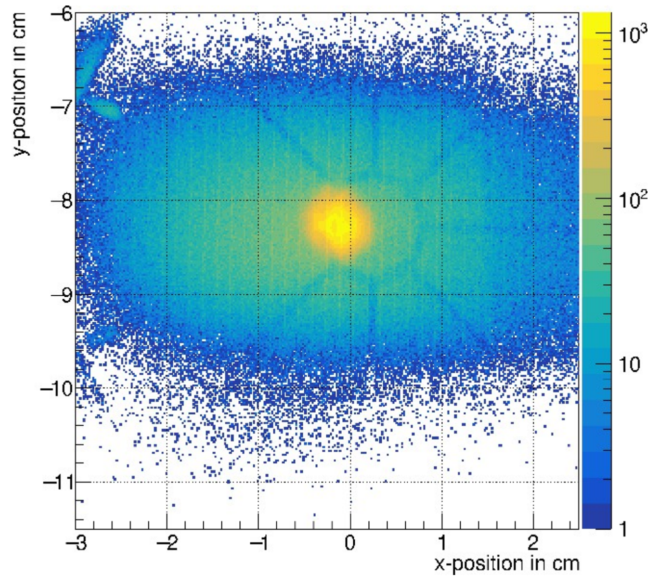
SPD:
- Monolithic active pixel sensors (MAPS)
- 29 µm x 27 µm pixel size, ~8 µm spatial resolution
- Thickness 50 µm
- 3 planes (18 sensors each) per station
- ~ 2 µs time resolution

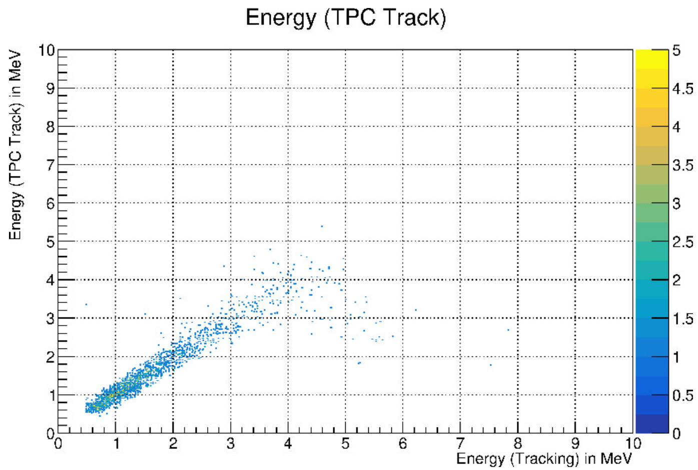


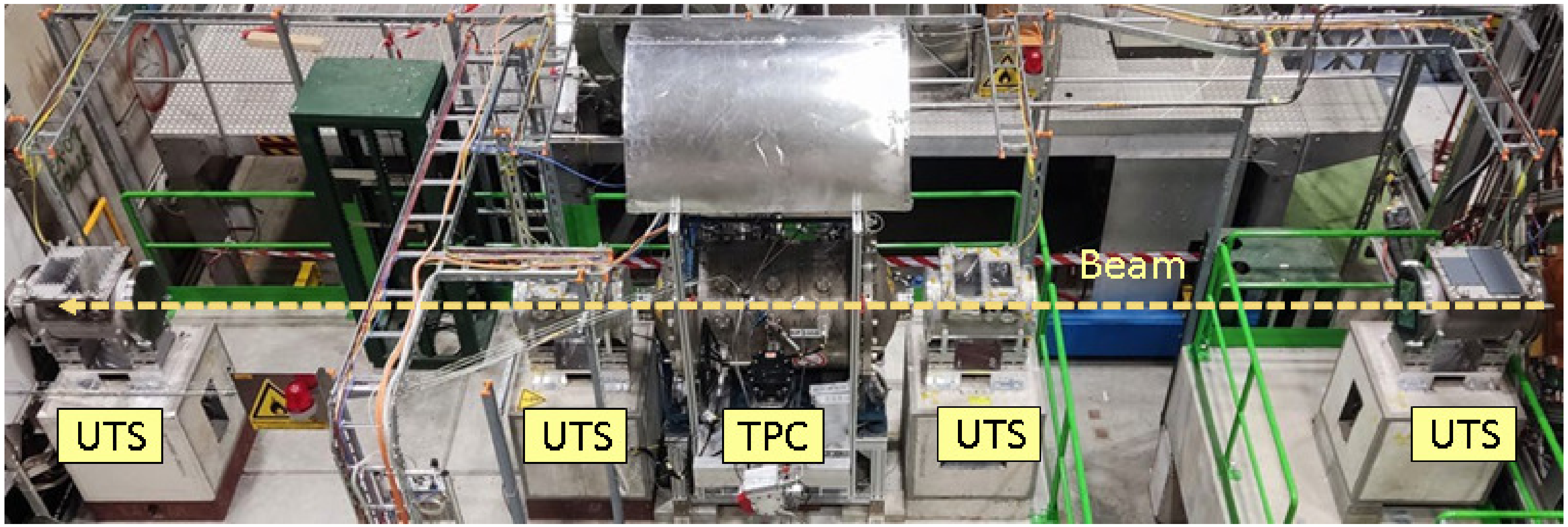
SFH:
- 4 planes of square scintillating fibers (500 µm thickness)
- 192 fibers per plane, with SiPM readout of individual fibers

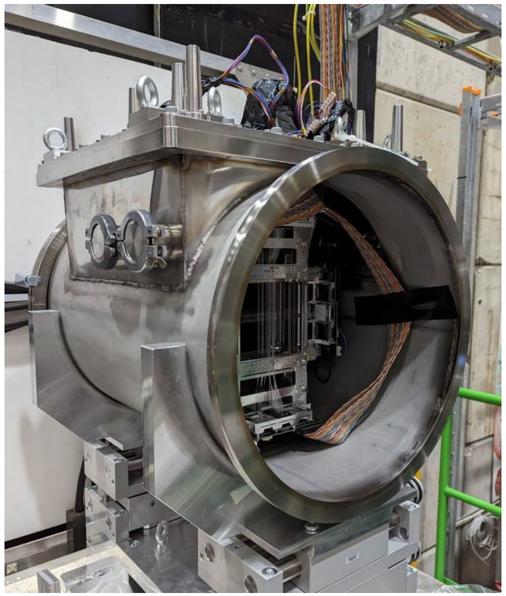
Proton Radius: Status and Plans

- Prototype tests in 2021 and 2023
- Assembly of new TPC and tracking detectors ongoing
- Pilot run and first physics data with new TPC planned for 2025
- Full physics run in 2026 (extension of run-3)



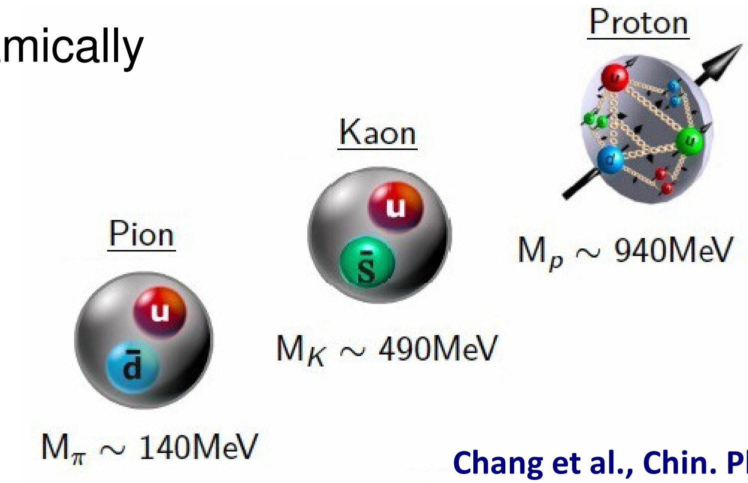






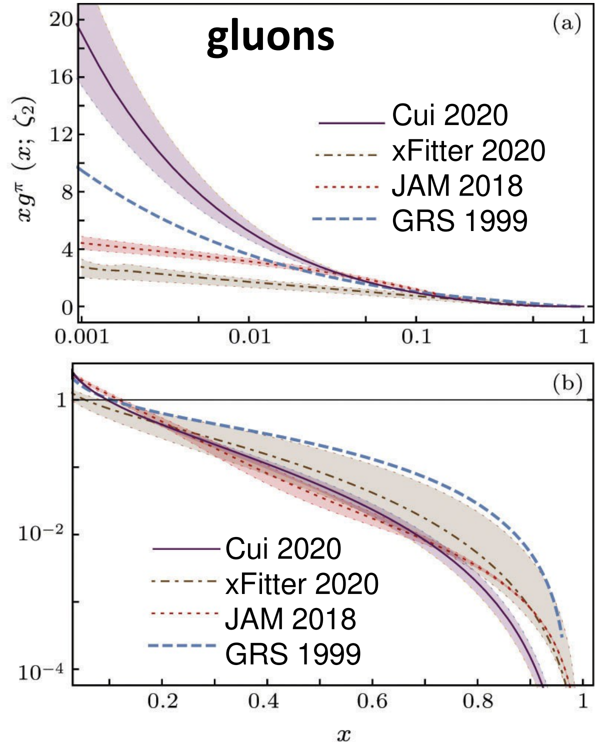
Pion Structure – Current Status

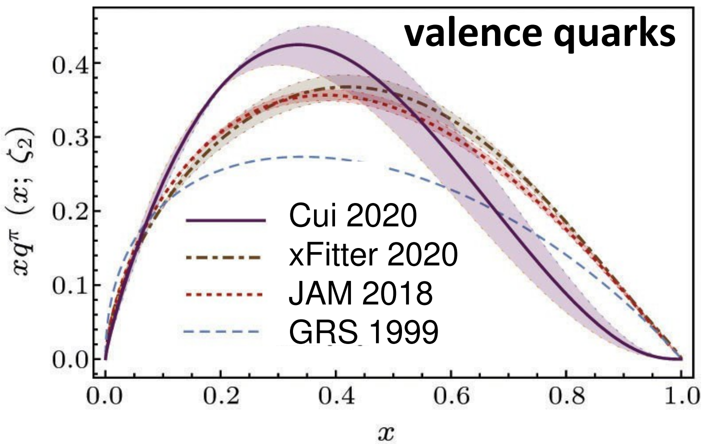
- The major part of the **hadron mass** is generated dynamically by **QCD dynamics of the partons**
- TMDs (PDFs) describe the 3D (1D) distribution of the partons in the momentum space
- A comparison of meson and nucleon TMDs (PDFs) can help us to better understand the generation of the hadron mass

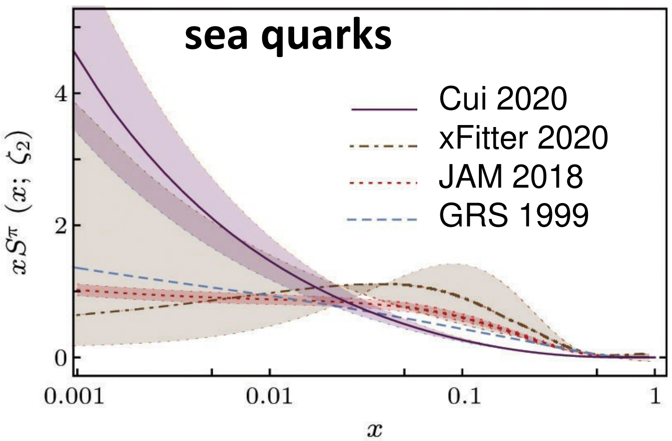


- So far, only scarce / old data for pion (kaon) TMDs and PDFs: E615, NA3, NA10,…
  - ⟶ Valence quark PDF poorly constrained
  - ⟶ Sea quark and gluon PDFs basically unknown
  - ⟶ Data mostly for heavy nuclear targets (large nuclear effects)

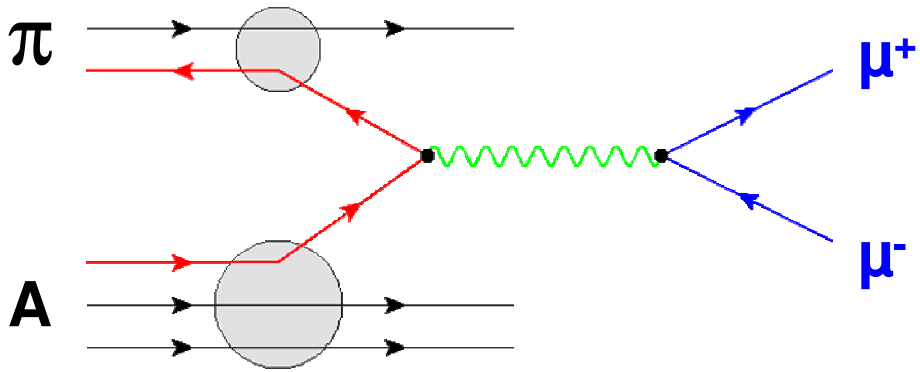
Chang et al., Chin. Phys. Lett. 38 (2021) 081101







Pion Valence and Sea Quark PDFs at AMBER



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

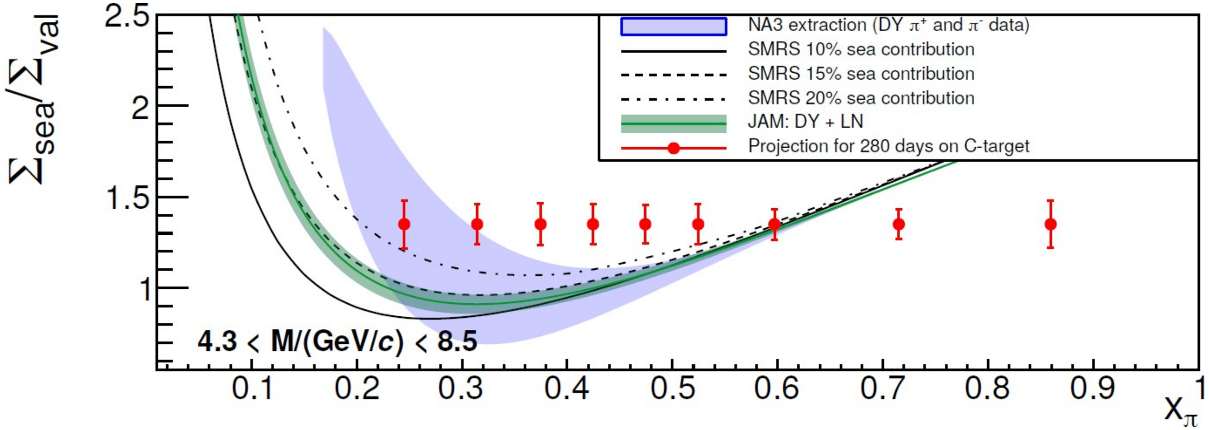
- Pion-induced Drell-Yan dimuon production
- Isoscalar ^{12}C target ⇒ minimize nuclear effects
- π^+ and π^- beams ⇒ separate valence and sea

$\Sigma_{\mathrm{val}} = \sigma^{\pi^-} - \sigma^{\pi^+}$ only valence-valence

$\Sigma_{\mathrm{sea}} = 4\sigma^{\pi^+} - \sigma^{\pi^-}$ sea-valence / valence-sea

Goals for AMBER:

- 10× more data than currently available
- First precise and direct measurement of the sea quark distribution in the pion



AMBER Proposal, CERN-SPSC-2019-022

AMBER
Apparatus for Meson and Baryon Experimental Research

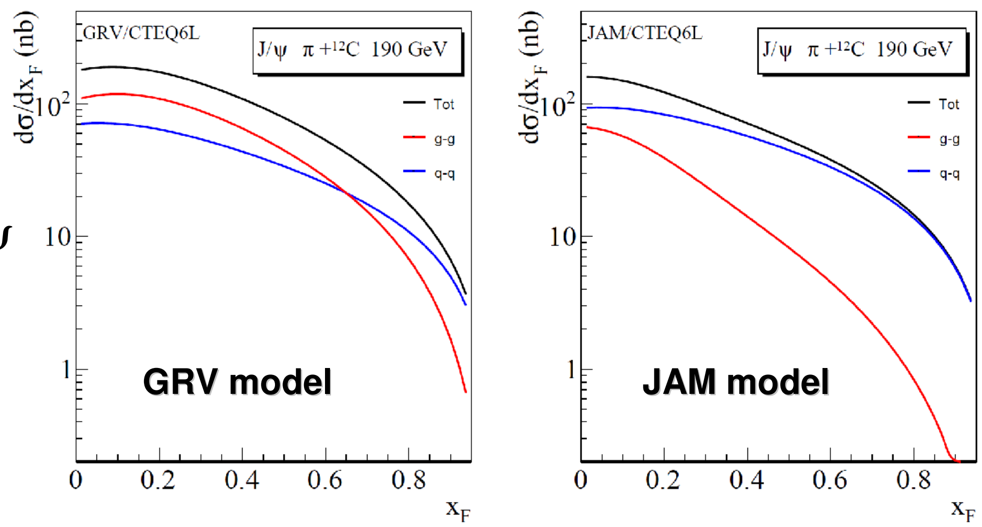
Pion Gluon PDFs at AMBER

In parallel: Study of J/ψ **production**

$$\pi + A \rightarrow J/\psi + X$$

- Measurement with π^+ and π^- beams
- At low $p_T < M(J/\psi)$: Dominated by $q\bar{q}$, $gg \rightarrow J/\psi$
  $\Rightarrow$ Access to gluon PDF of pion
- Cross section 30-50 × larger than DY
  $\Rightarrow$ Measure differential distributions

V. Cheung et al., PRD 98 (2018) 114029

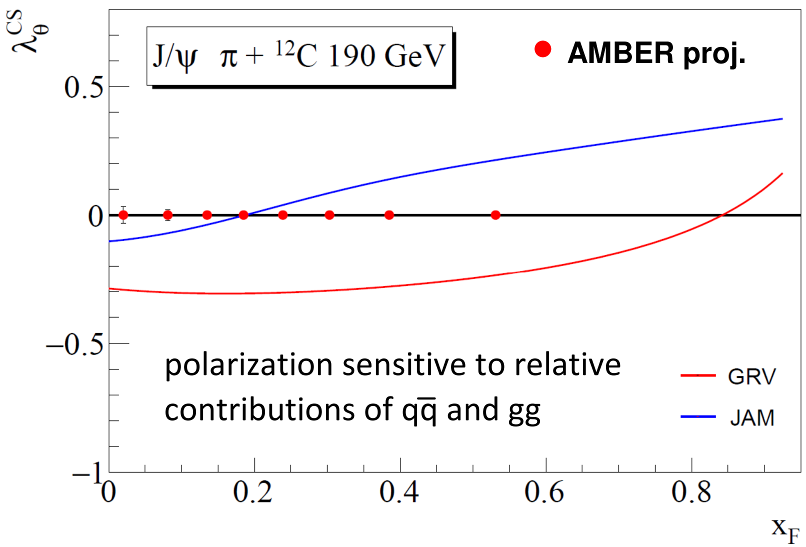


But: J/ψ production mechanism not well known at low p_T

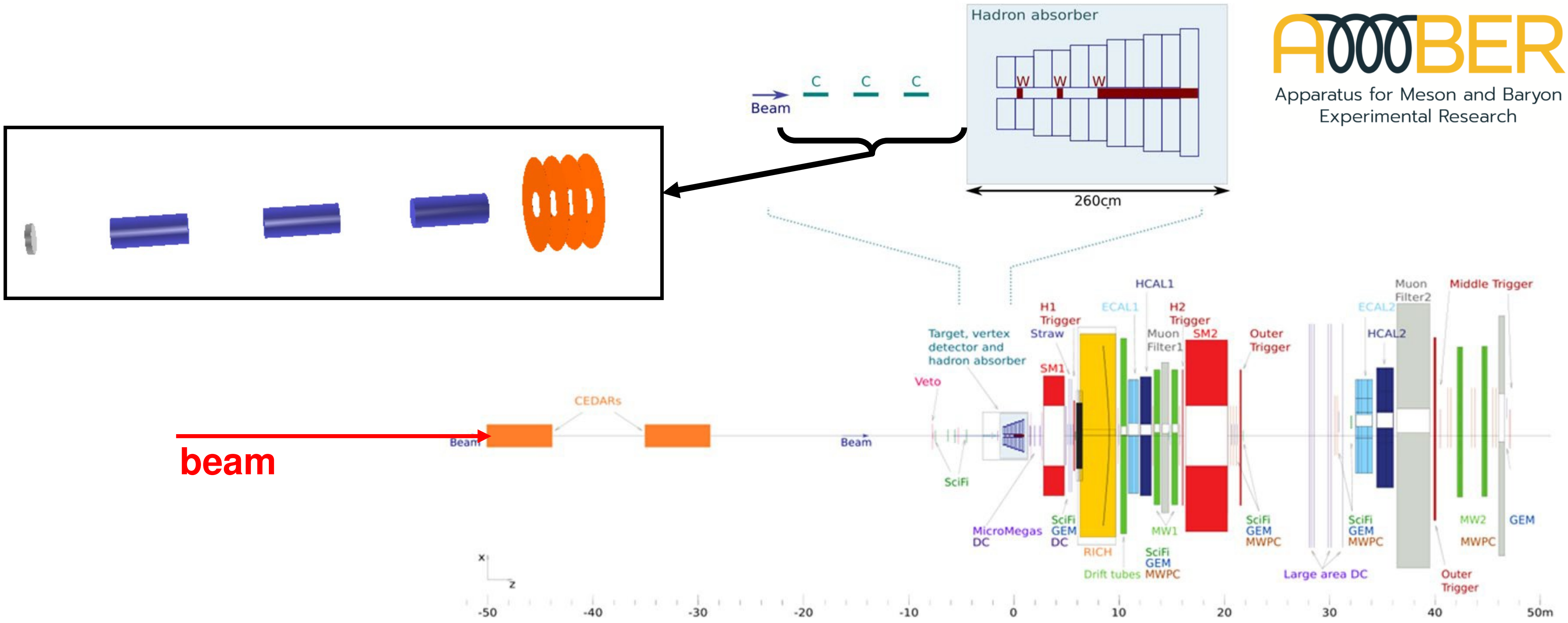
Additional observable: J/ψ **polarization**

- $J^{PC} = 1^{--}$, $J_z = -1, 0, +1$
- Angular distribution $\dfrac{d\sigma}{d\cos\theta} \propto 1 + \lambda\cos^2\theta$

  - $\lambda = +1 \Leftrightarrow J_z = \pm 1 \quad q\bar{q} \rightarrow J/\psi$
  - $\lambda = 0 \Leftrightarrow$ unpolarized
  - $\lambda = -1 \Leftrightarrow J_z = 0 \quad gg \rightarrow J/\psi$



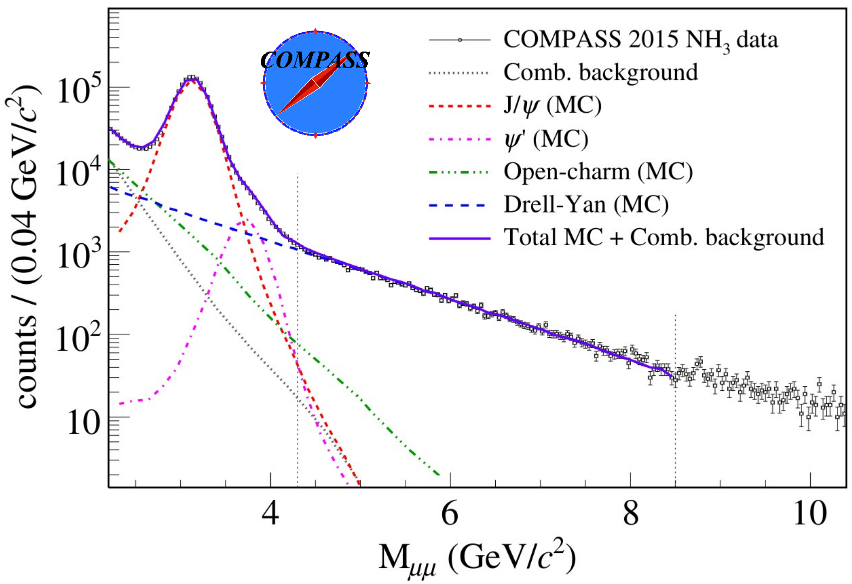
The Drell-Yan Experimental Setup at AMBER

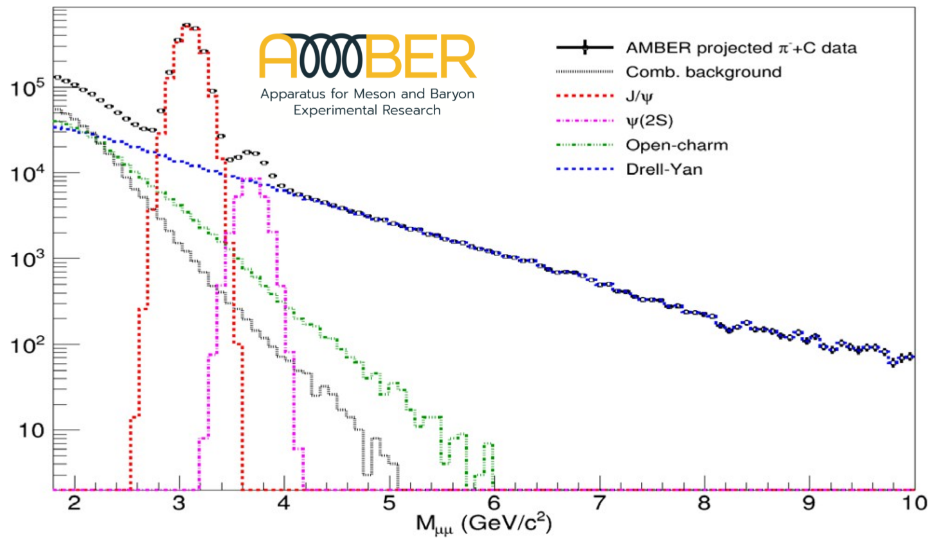


DY program @ AMBER: $\pi^{\pm} + N \rightarrow \mu^{+}\mu^{-} + X$ (190 GeV π beam)

- 3 carbon targets + hadron absorber
- Add a silicon vertex detector after the last C target
- New beam telescope for backtracking to CEDARs

AMBER: A Vertex Detector for Drell-Yan Measurements





Advantages of the vertex tracker:

- Improves the mass resolution from ~200 MeV down to 100 - 150 MeV
- Improves the vertex resolution from ~12 cm down to < 3 cm
- Allows a lower mass cut for DY (4.3 GeV/c^2 → 4.0 GeV/c^2)
- Suppresses the combinatorial background through tighter vertex cut
  - ➔ Enables clean access to ψ'
  - ➔ Might even allow us to access DY events below the J/ψ mass

AMBER phase 2 physics program

Phase 1: 2023 **-** 2031 **(conventional beams)**

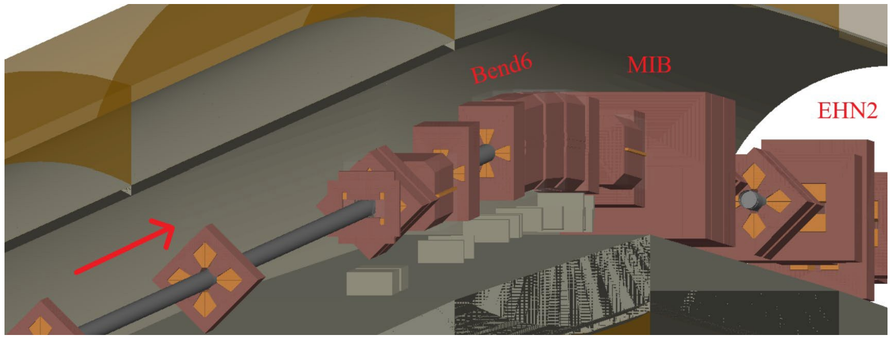
Phase 2*:* 2031 - 2041 **(high intensity and high purity kaon beam)**

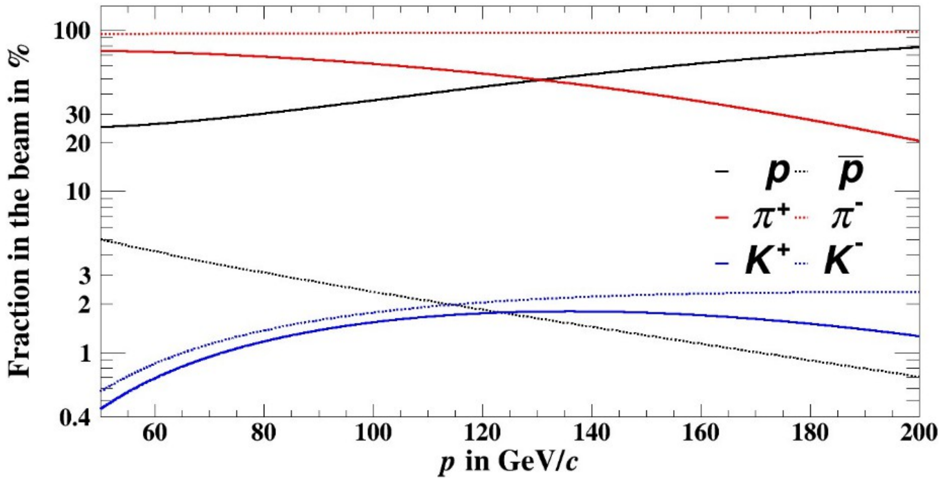
- Kaon quark and gluon PDFs via DY, prompt photons
- Strange meson spectroscopy in diffractive production
- Meson charge radii
- Meson-photon reactions in Primakoff kinematics
- New ideas?

High Intensity Kaon Beams for Phase 2

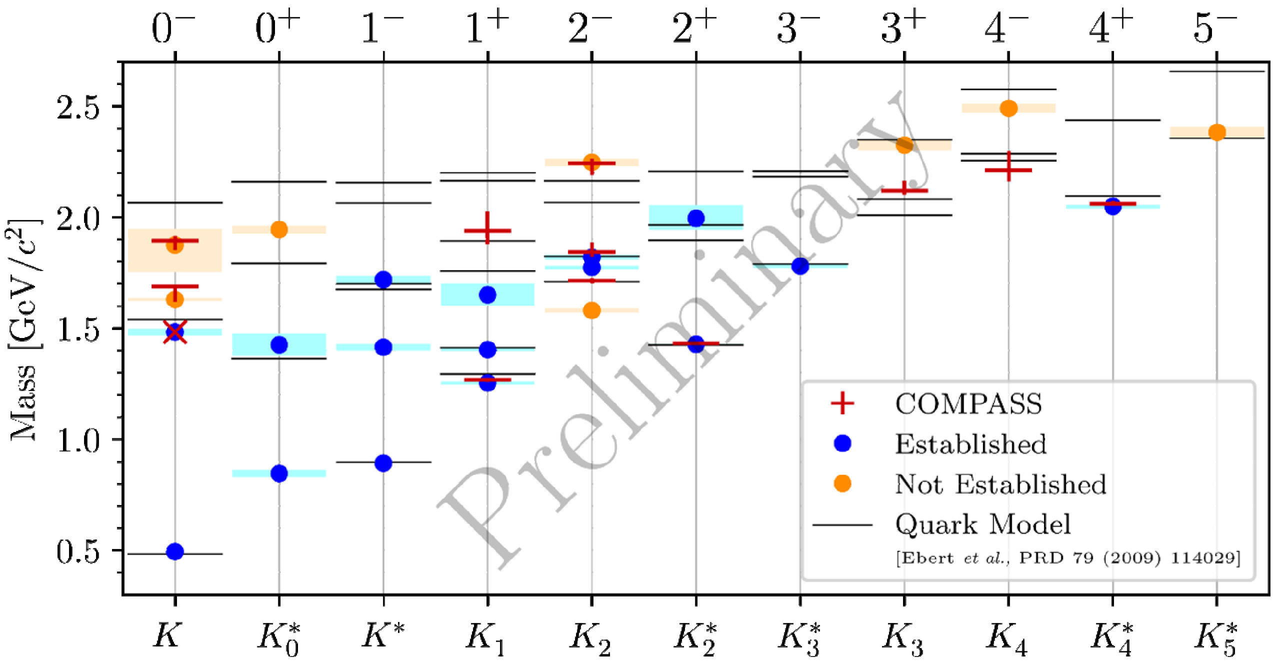
Requirements:

- Highest possible intensity of Kaons in the secondary beam
  - ⇒ RF separation
  - ⇒ Optimized transport of the conventional mixed beam
- High-efficiency / high-purity beam particle identification
- Final-state PID at higher momenta (depending on beam momentum)
- Full solid-angle coverage for photons / electrons





Strange Meson Spectroscopy



- 25 kaon states listed by PDG (M < 3.1 GeV)
- 9 of those need confirmation
- Many predicted quark-model states still missing
- Most measurements performed more than 30 years ago

COMPASS:

- 11 strange mesons found ➔ To be published soon
- Evidence for 3 excited K states
- Quark model only predicts 2: K(1460), K(1830)?
- K(1690) ➔ Candidate for exotic strange meson
- Statistically and systematically limited: 720k events, PID

AMBER phase 2:

- Beamline upgrade
- Improved beam K identification
- Improved final-state K ID
- Full solid-angle coverage for photons / electrons
- **Goal:** 20×10^6 exclusive $K^-\pi^-\pi^+$ events

Summary

- **NA66/AMBER** is a new and unique experiment at CERN dedicated to study fundamental questions related to the emergence of hadron properties from QCD

- **Phase-1 started in 2023**

  ⟶ Antiproton-production cross sections for dark matter searches

  ⟶ Proton radius with a high-intensity muon beam

  ⟶ Pion PDFs in Drell-Yan processes

- **Phase-2:** Measurements with high-intensity hadron / Kaon beam

  ⟶ Kaon and pion gluon PDFs, strange meson spectroscopy, meson charge radii, …

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Bundesministerium für Bildung und Forschung