The New AMBER Experiment at CERN

By Jochen Schittkowski

Catarina Quintans, LIP-Portugal
On behalf of the AMBER Collaboration

2nd November 2023
EINN Conference, Pafos, Cyprus

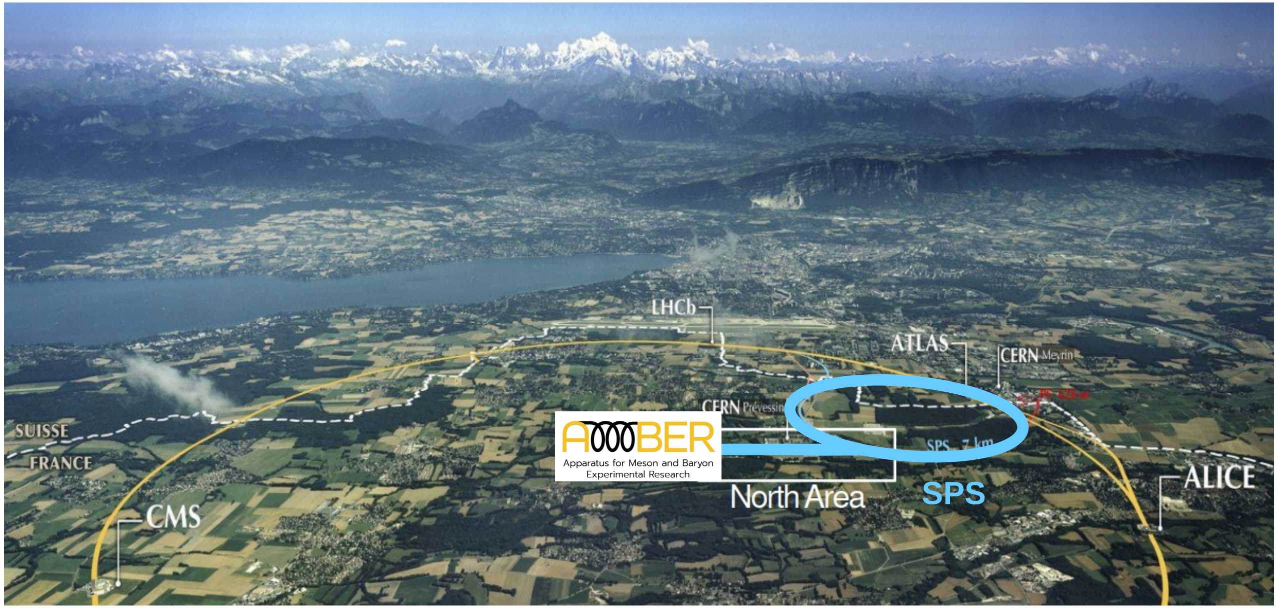
AMBER
Apparatus for Meson and Baryon
Experimental Research

FCT Fundação para a Ciência e a Tecnologia
Grant CERN/FIS-PAR/0016/2021

LIP LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Apparatus for
Meson and
Baryon
Experimental
Research

A new fixed-target experiment at the M2 beamline of the CERN/SPS north-area



~ 200 physicists
from 34 institutes

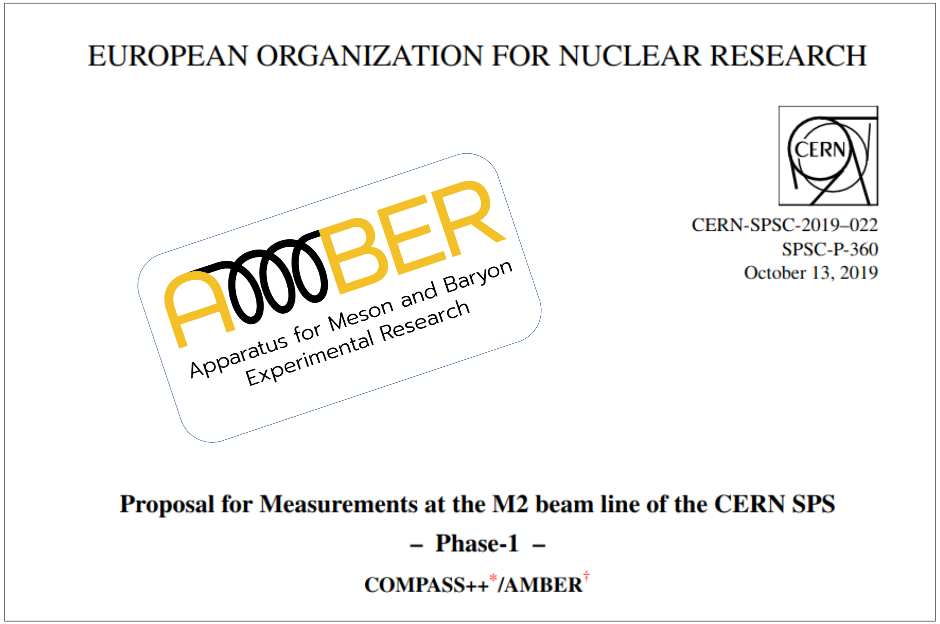
A QCD Facility: studies of Hadron Physics, from Structure to Spectroscopy

The AMBER timeline

NEW

- Letter of Intent, in 2018
- Scientific proposal for phase I, in 2019
- CERN approval in December 2020
- First physics data taking: 2023

- Scientific proposal for phase II, in preparation



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

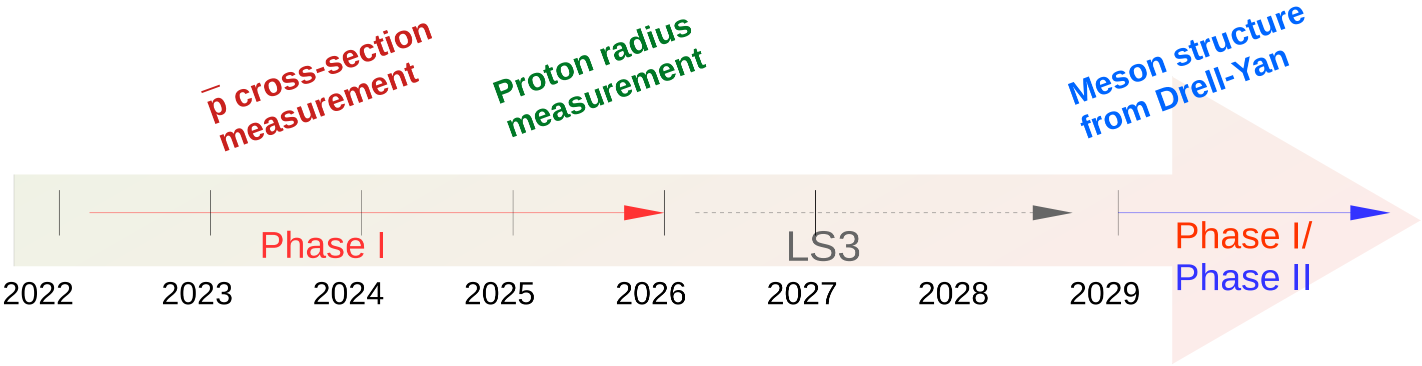
AMBER
Apparatus for Meson and Baryon Experimental Research

CERN-SPSC-2019–022
SPSC-P-360
October 13, 2019

Proposal for Measurements at the M2 beam line of the CERN SPS

– Phase-1 –

COMPASS++*/AMBER†



$\bar{p}$ cross-section measurement

Proton radius measurement

Meson structure from Drell-Yan

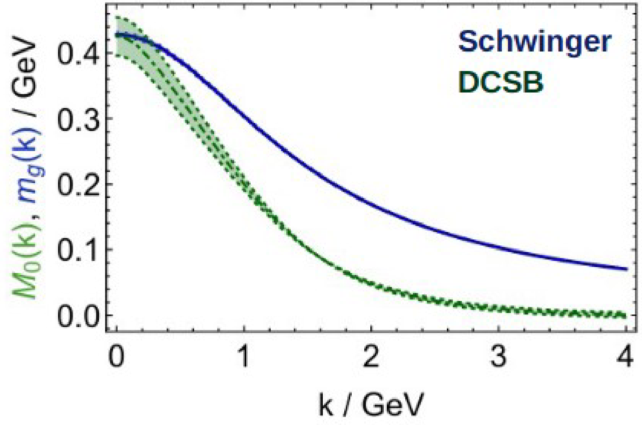
Phase I

LS3

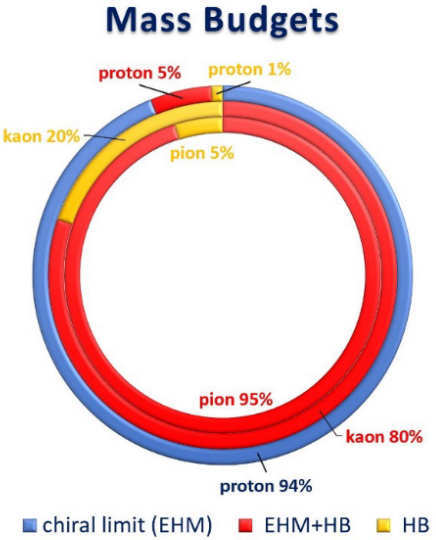
Phase I/
Phase II

2022 2023 2024 2025 2026 2027 2028 2029

Emergence of Hadron Mass and Structure



Gluon and quark *running masses*



In QCD, via Dynamic Chiral Symmetry Breaking

Understand how hadrons acquire the observable masses, out of “nothing”:

Higgs mechanism contributes only a small part

↳ In the proton: 1%

EHM mechanism (i.e. quarks and gluons dynamics) significant contribution

↳ In the proton: ~94%

Also the interference between HB and EHM plays a role

↳ In the kaon: ~80%. In the pion: ~95%

Measurements of meson structure are crucial to confirm it!

Apparatus for Meson and Baryon Experimental Research

Spectroscopy

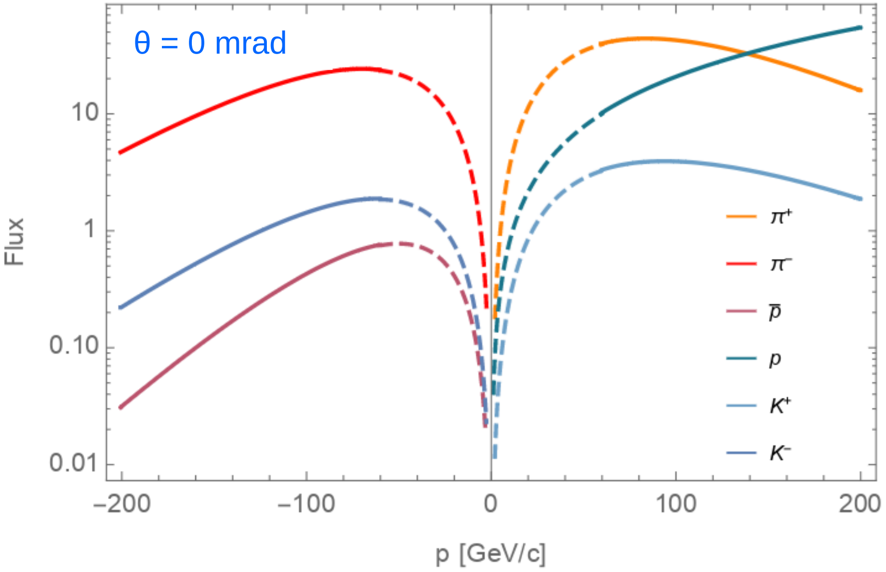
Charge radii

AMBER: a QCD Facility for Hadron Physics related measurements

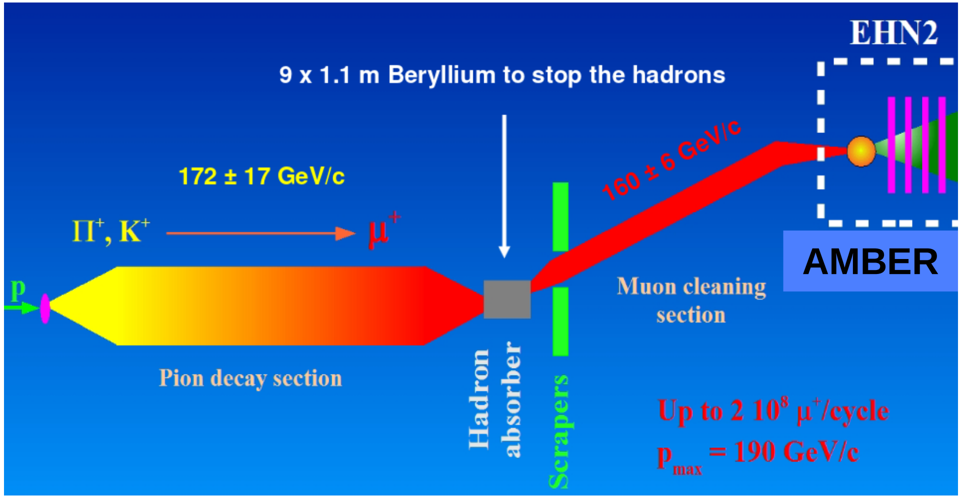
Polarizabilities

Structure

M2 beamline: beam composition



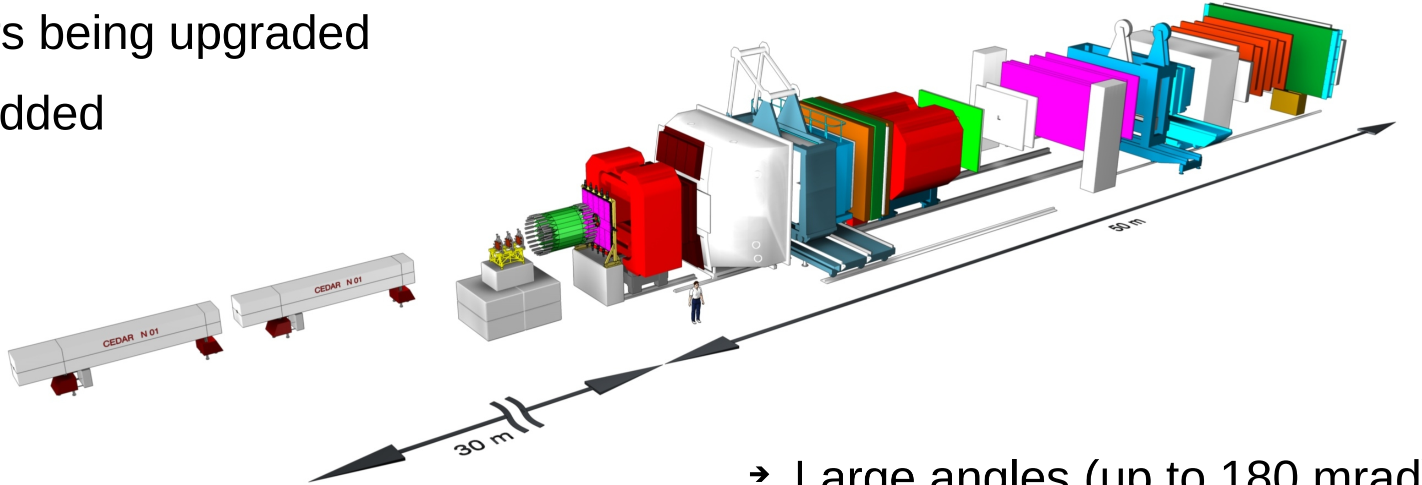
- Hadron beams of both charges
- Wide range of momenta: 50 to 280 GeV/c
- Moderate to high intensities: 100 kHz to 100 MHz

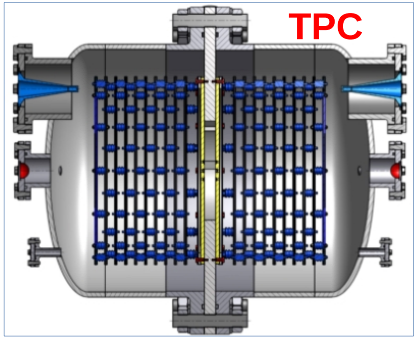


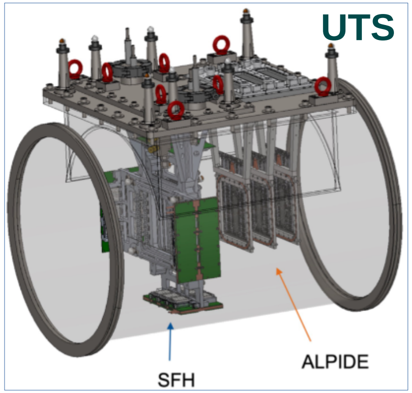
- Muon beam from hadron decays
- Clean, thanks to hadron absorber+scrappers
- Wide range of momenta: 100 to 200 GeV/c
- Intense beam, up to 50 MHz

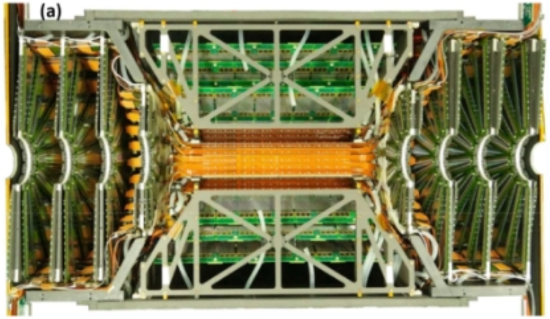
AMBER spectrometer

- COMPASS spectrometer as starting point
- Several detectors being upgraded
- New detectors added







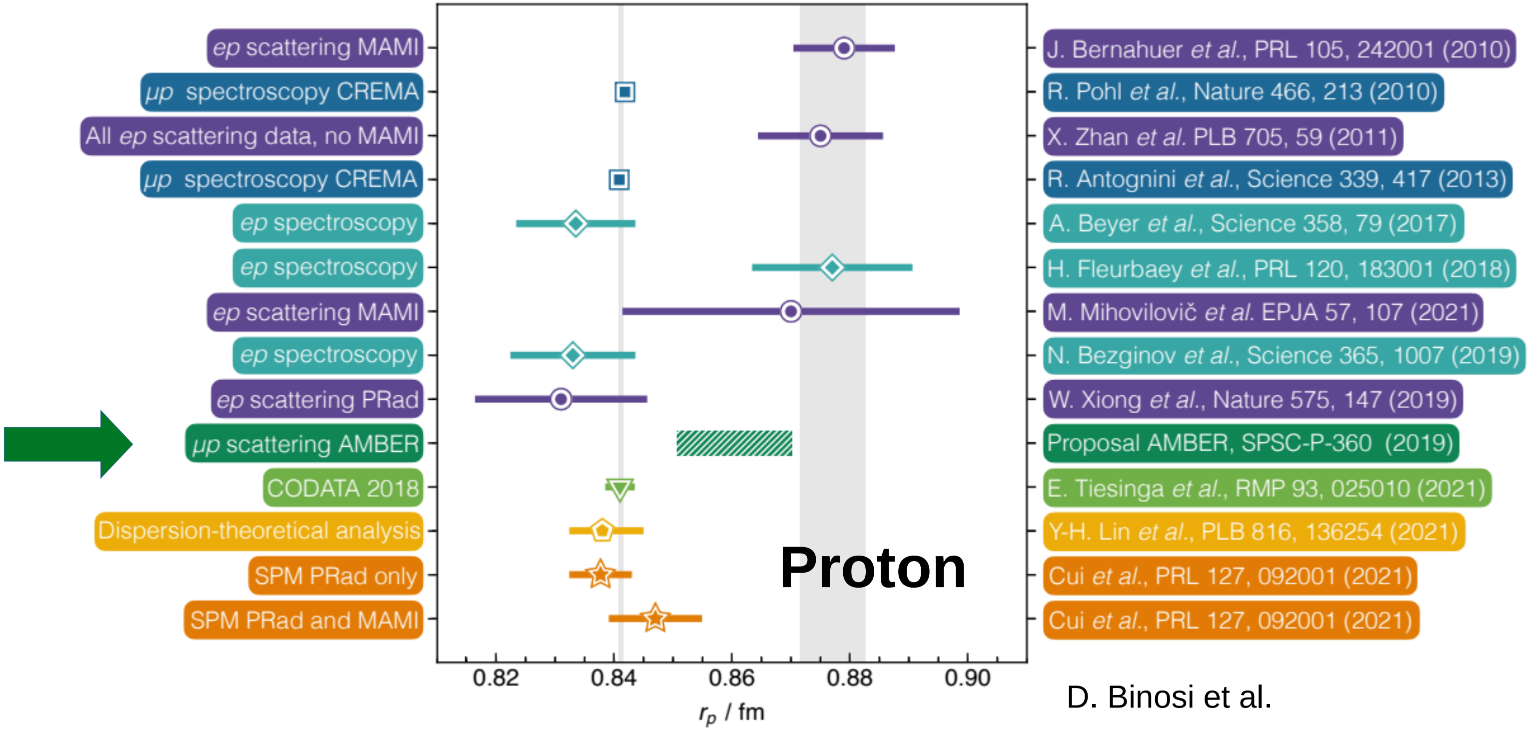


FVTX detector from PHENIX@RHIC (LANL)

- Large angles (up to 180 mrad) and momentum coverage
- Final state PID from RICH
- Hadron beam PID from CEDARs
- 2 sets of ECAL+HCAL
- Triggerless DAQ

Proton charge radius measurement: physics motivation

Hadron radii are an expression of the link between EHM and QCD confinement

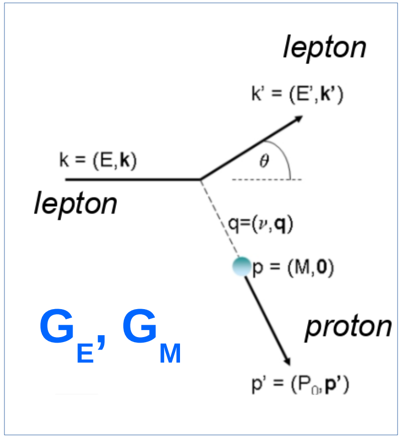


D. Binosi et al.

Two types of measurements:
lepton-proton scattering and **hydrogen spectroscopy,** leading to discrepant results

Muon-proton elastic scattering

The proton charge radius can be accessed via the electromagnetic form factors:



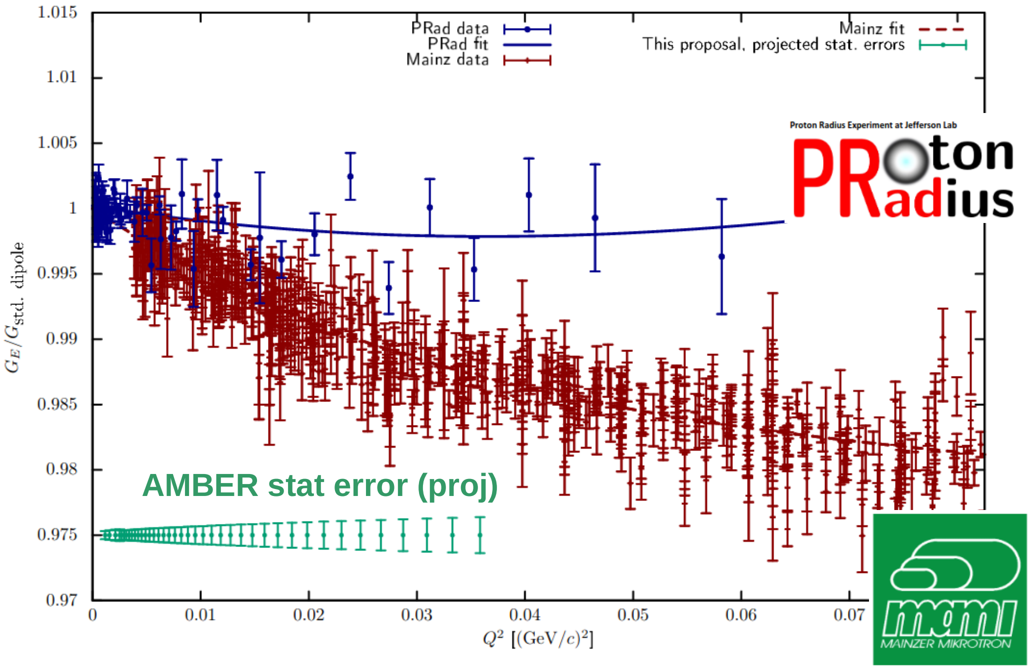
$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^4\, m_p^2\, \vec{p}_\mu^{\,2}} \left[\left(G_E^2 + \tau\, G_M^2\right) \frac{4E_\mu^2 m_p^2 - Q^2(s - m_\mu^2)}{1+\tau} - G_M^2\, \frac{2m_\mu^2 Q^2 - Q^4}{2} \right]$$

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

New PRad measurements favor low values of r
(Nature, 575 (2019) 147)

PRad form factors in clear contradiction with Mainz data

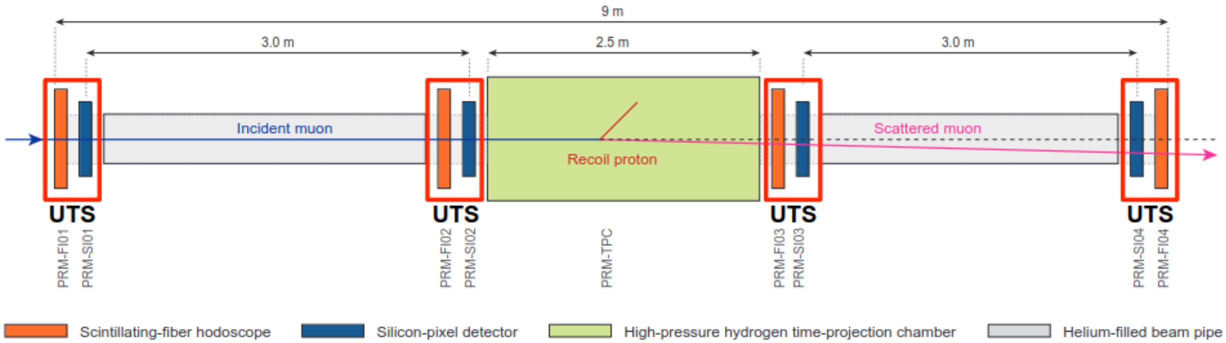
But: ep has large radiative corrections to take into account

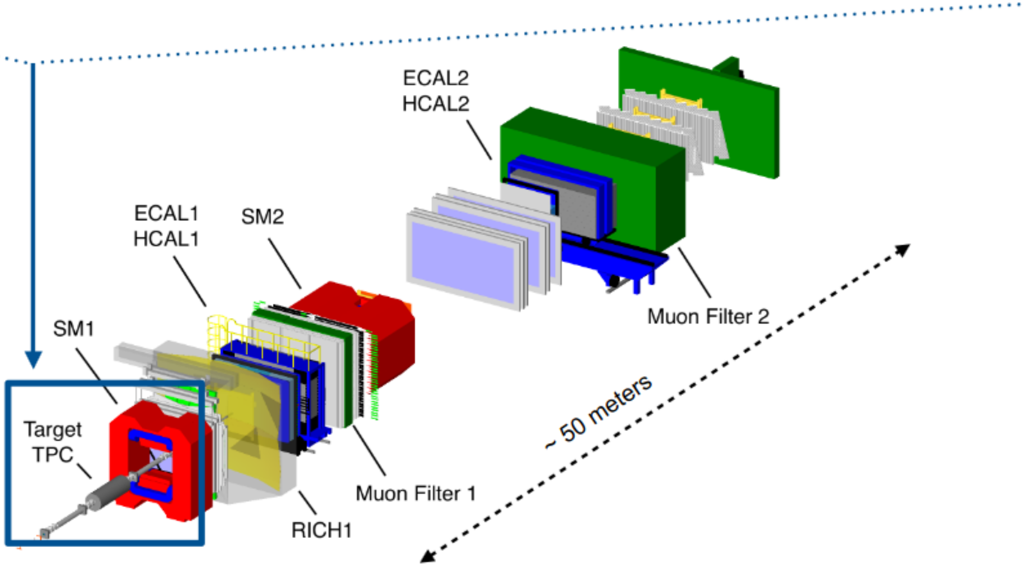


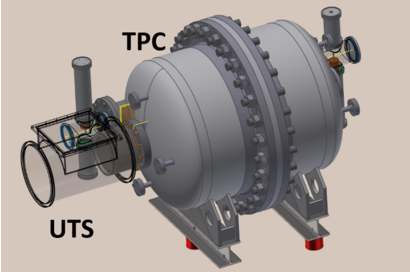
Proton charge radius measurement: setup

Muon proton elastic scattering

- 100 GeV muon beam, 2 x 10^6 μ/s
- Time Projection Chamber (TPC) filled with hydrogen (up to 20 bar): **active target**
- Recoil proton measured at TPC, incoming and scattered muons detected in the Unified Tracking Stations (UTS)
- Small scattering angle (100 μrad): $Q^2_{min} = 10^{-3}$ $(GeV/c)^2$

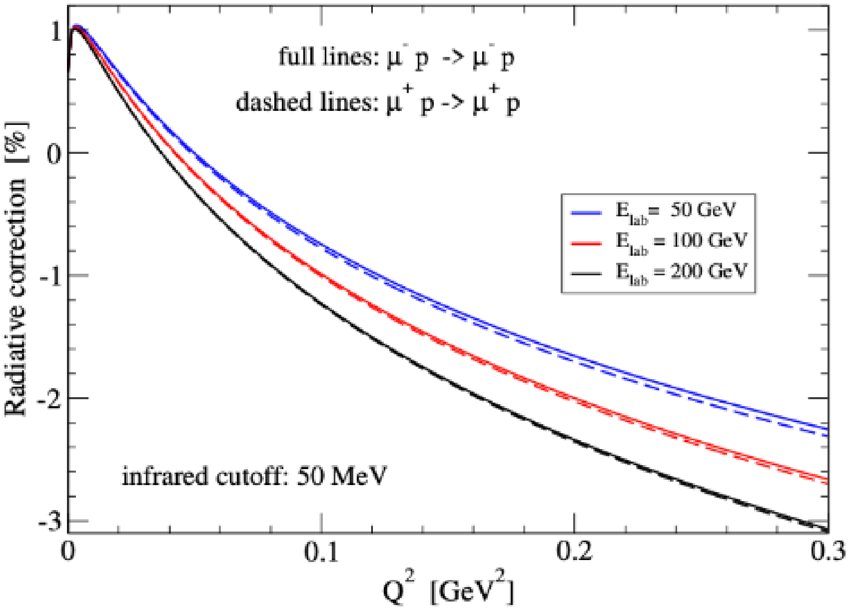






AMBER goals for the proton radius measurement

Advantage: small radiative corrections



Calculation by N. Kaiser (TUM)

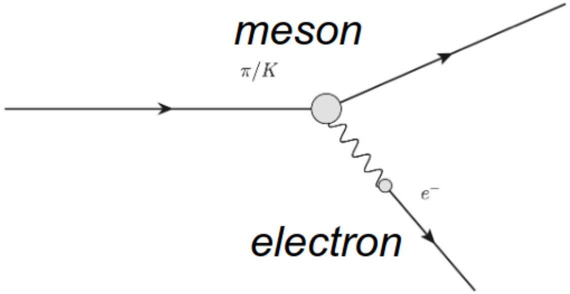
- Radiative corrections < 1% for $Q^2<0.04$ (GeV/c)^2

- Successful test runs in 2021 and 2023, using the IKAR TPC (smaller).
- Pilot Run in 2024, with the final TPC and UTS
- Physics data taking in 2025
- Goal: 70 million elastic scattering events
- Precision on the proton radius ~0.01 fm

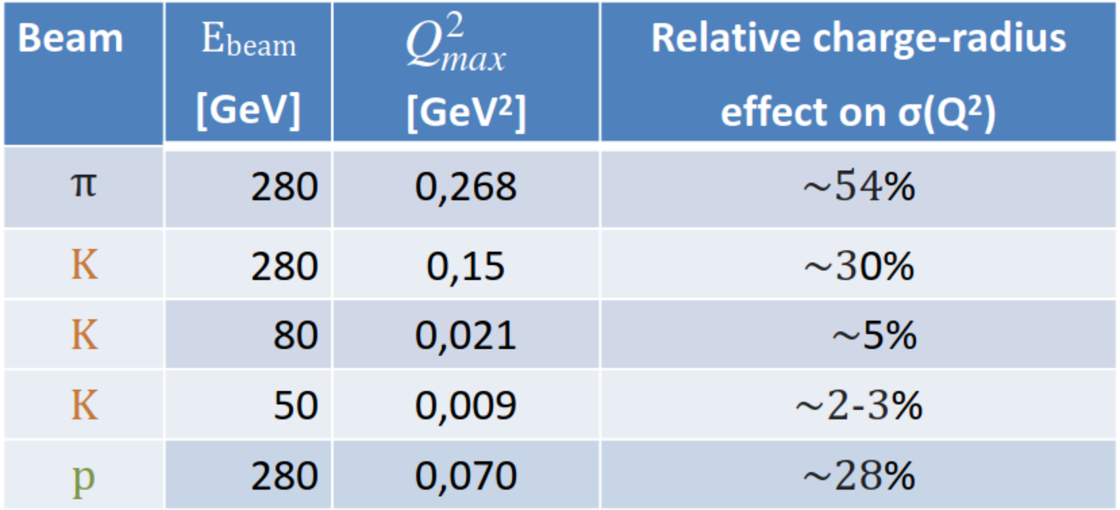
New York Times

Meson charge radii at AMBER

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



- Large Q² range : higher sensitivity to the charge distribution $\langle r^2_E \rangle$



Beam	E_{beam} [GeV]	Q^2_{max} [GeV²]	**Relative charge-radius effect on σ(Q²)**
π	280	0,268	~54%
K	280	0,15	~30%
K	80	0,021	~5%
K	50	0,009	~2-3%
p	280	0,070	~28%

$$K^- e^-_{target} \rightarrow K^- e^-$$

$$Q^2 \approx 2m_e \cdot E_e$$

$$s = 2E_b m_e + m_b^2 + m_e^2$$

$$Q^2_{max} = \frac{4 \cdot m_e^2 \cdot p_b^2}{s} = 4 \cdot p_{cm}^2$$

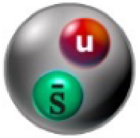
AMBER phase II

Understanding EHM: π and K structure

Pion

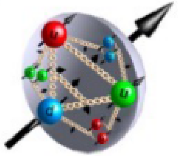
- $M_\pi \sim$ 140MeV
- Spin 0
- 2 light valence quarks

Kaon



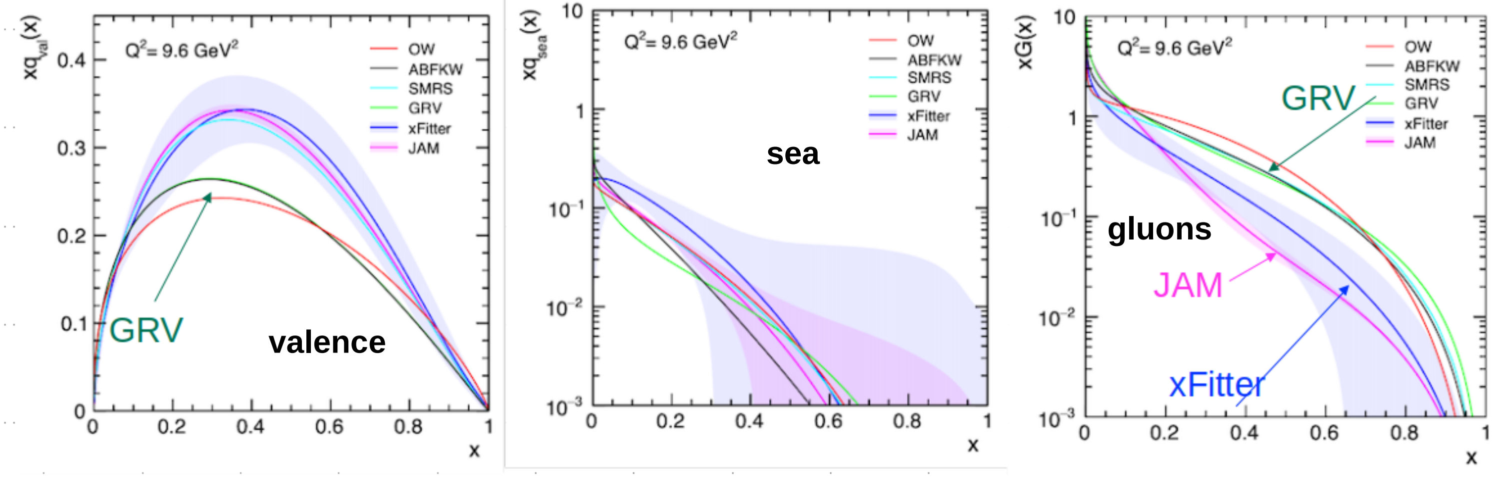
- $M_K \sim$ 490MeV
- Spin 0
- 1 light and 1 “heavy” valence quarks

Proton



- $M_p \sim$ 940MeV
- Spin 1/2
- 3 light valence quarks

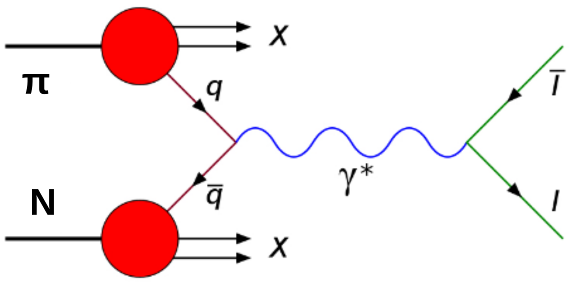
From: Chang et al. PRD 102, 054024 (2020)



Pion:

- ➔ The lightest of hadrons
- ➔ Goldstone boson of QCD
- ➔ Discrepant global fit results

Drell-Yan at AMBER: access to π and K structure



Pion-induced Drell-Yan is the most direct way to access the structure of pions.

π-DY measurements were done by past experiments:
NA3 and NA10 at CERN, E615 at Fermilab.
More recently: **COMPASS at CERN**

NEW!

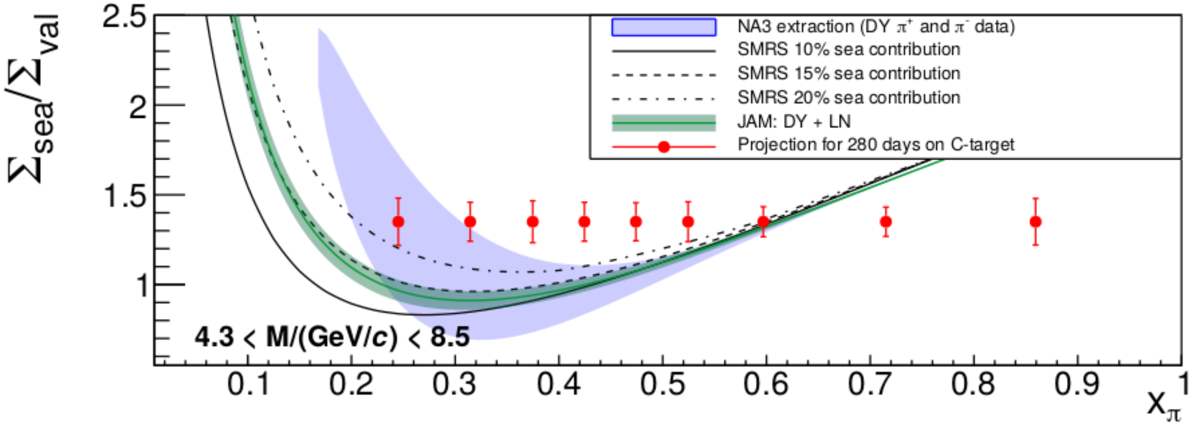
$u^{\pi^+}_{val} = u^{\pi^+} - \bar{u}^{\pi^+}$ and $d^{\pi^-}_{val} = d^{\pi^-} - \bar{d}^{\pi^-}$

and assuming flavour-symmetry, the use of **both beam charges** allows for sea/valence separation:

$$\boxed{\frac{\Sigma_{sea}}{\Sigma_{valence}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}}$$

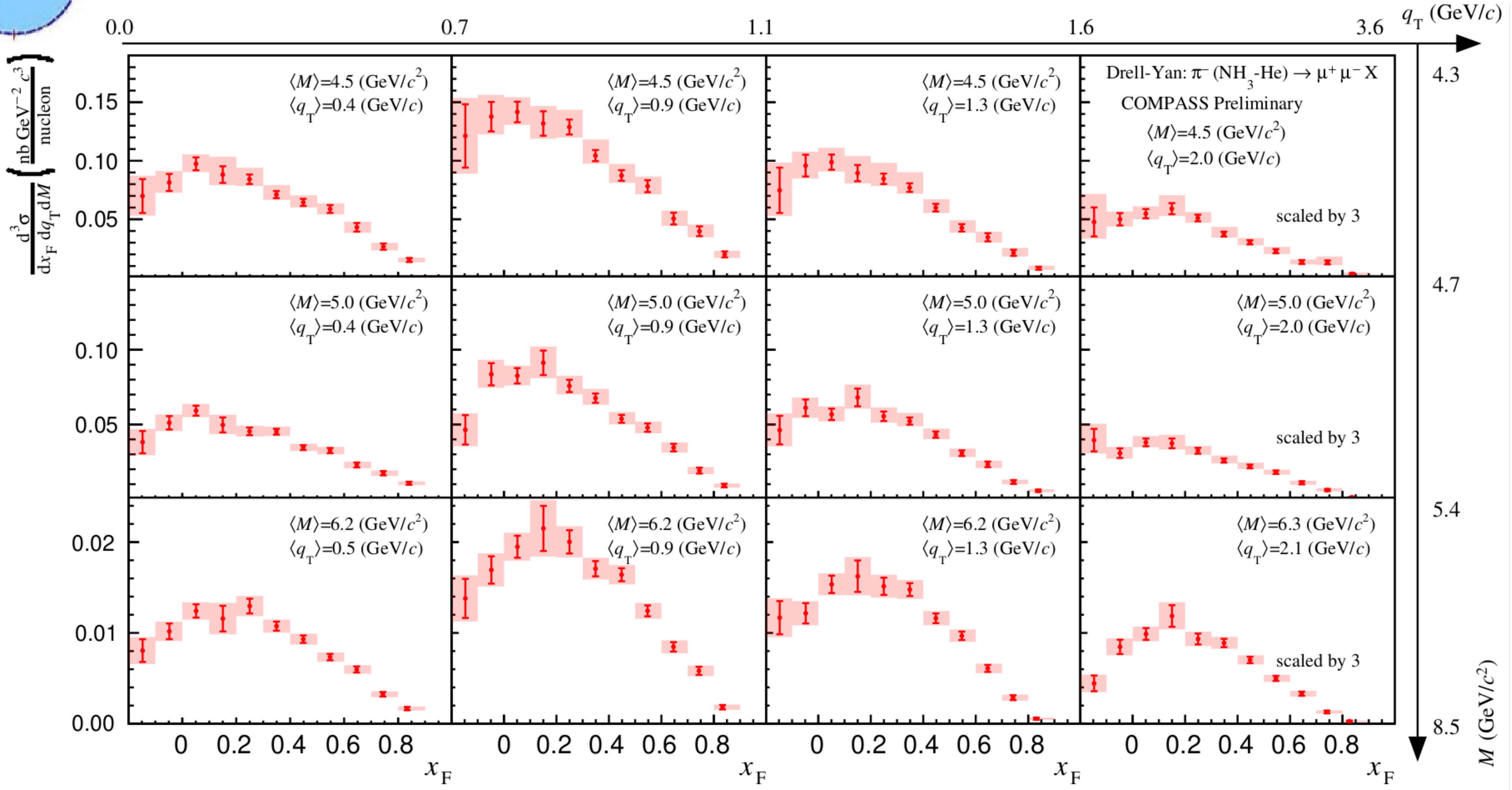
LO: only sea-val and val-sea terms

LO: only val-val terms



New COMPASS pion-induced Drell-Yan cross section results

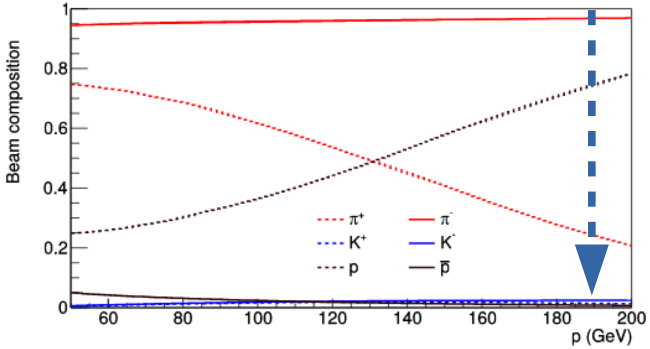
V. Andrieux (COMPASS), SPIN 2023 and ECT* Workshop



Pion-induced Drell-Yan expected statistics

- A conventional hadron beam, but both beam charges
- Time sharing 3:1 (π^+:π^-) to minimize uncertainty in sea/valence observable
- Beam particle identification using Cherenkov counter detectors

Hadron beam composition at the M2 beamline



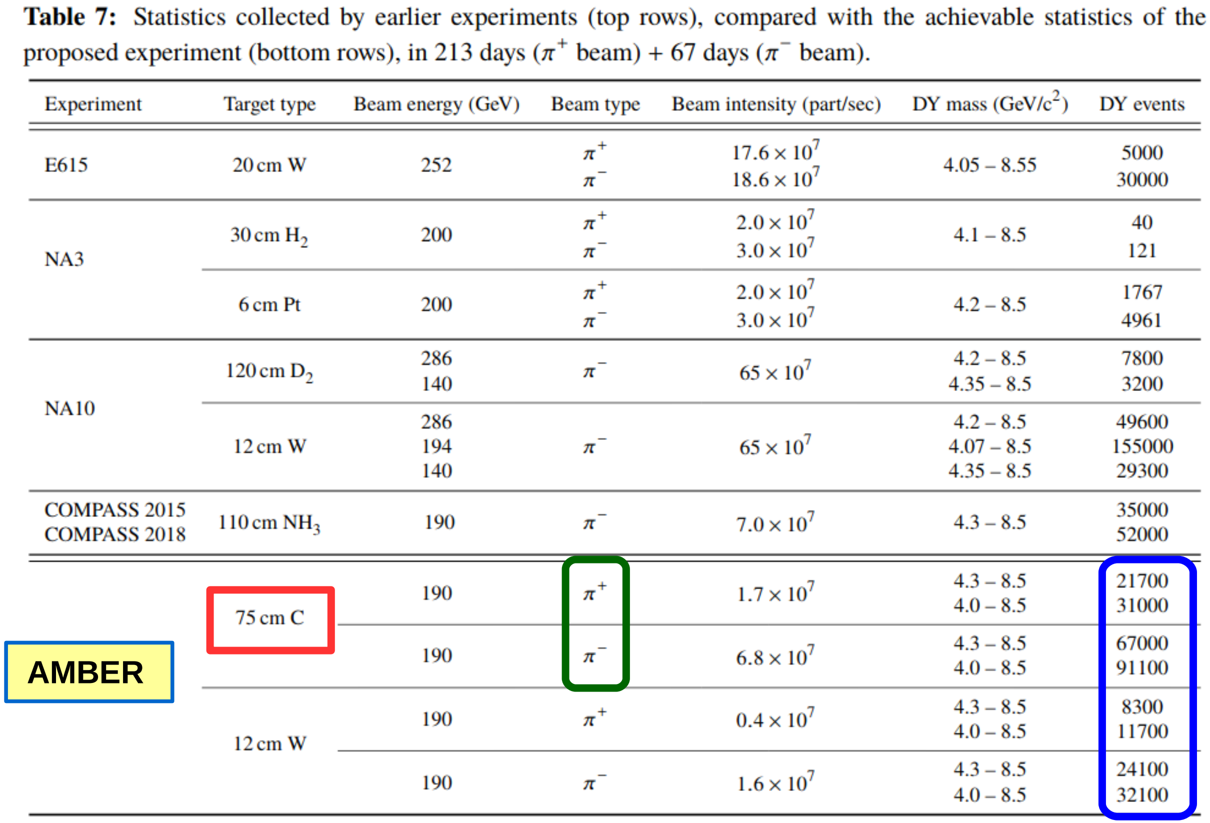
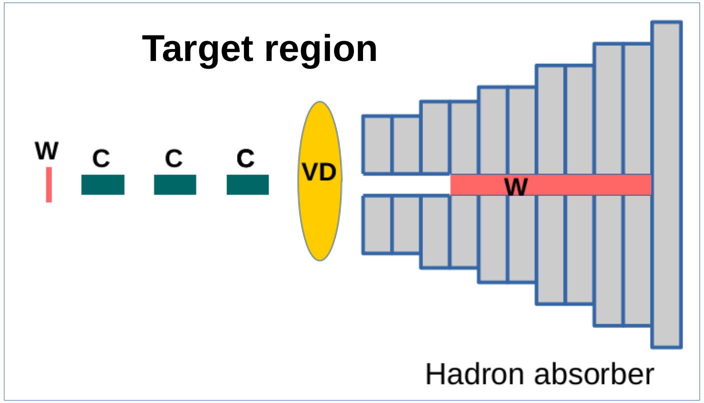


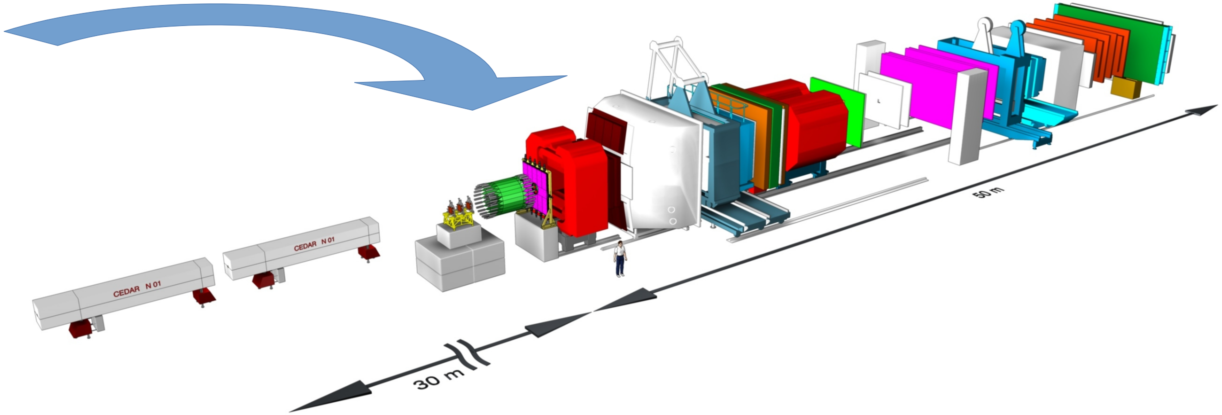
Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
AMBER	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	21700 31000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	67000 91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5 4.0 – 8.5	8300 11700
		190	π^-	1.6×10^7	4.3 – 8.5 4.0 – 8.5	24100 32100

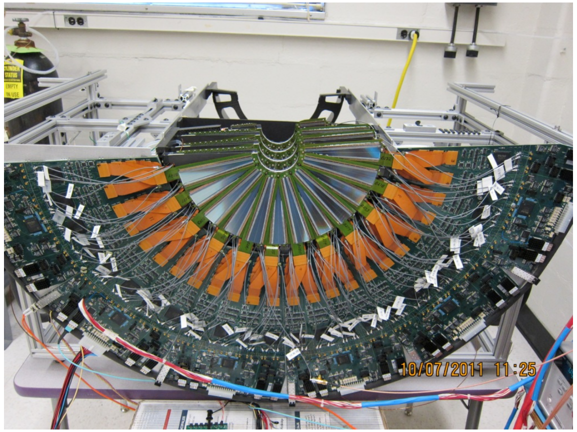
From the AMBER proposal

AMBER phase I: Drell-Yan setup





Experimental hall

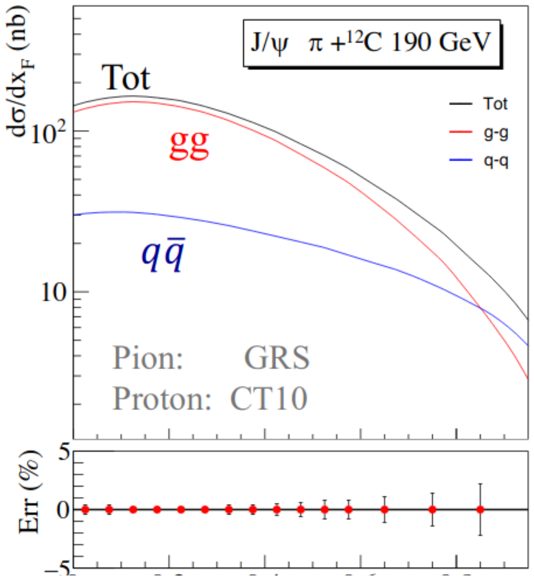


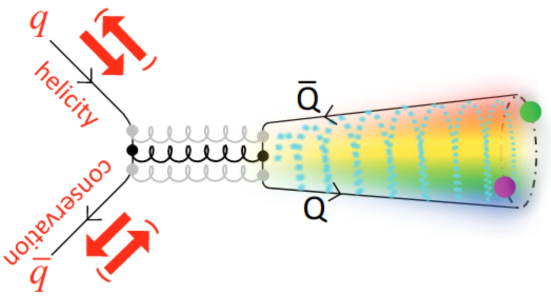
FVTX detector
from PHENIX@RHIC

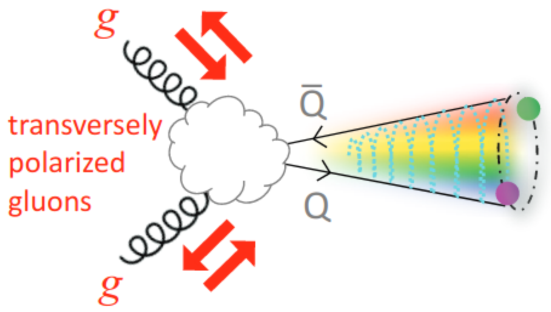
Gluon content in the pion

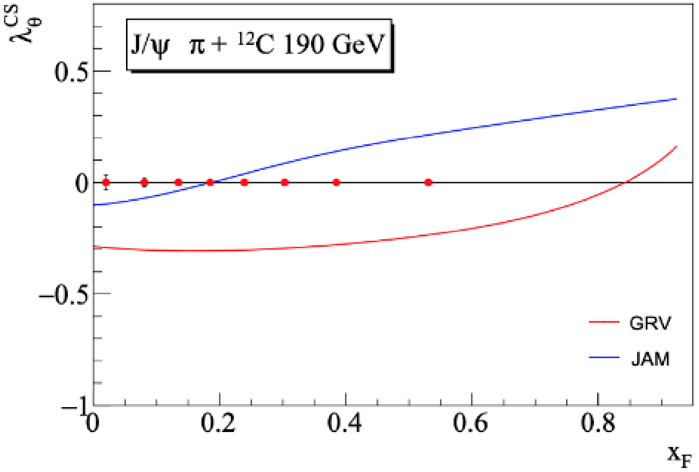
Simultaneously with Drell-Yan, also J/ψ and ψ(2S) production data are collected.

- Large statistics on J/ψ production at dimuon channel
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- In the low-p_T regime
- Expected to have dominance of 2→ 1 processes
- Use J/ψ polarization to distinguish production mechanisms:









Kaon structure (phases I / II): u_k/u_π

Kaons allow to access the region of interference between the
Higgs mechanism and the EHM mechanism

The only available experimental data:

NA3 → 200 GeV K^- beam on 6 cm Pt target

700 kaon-induced Drell-Yan events

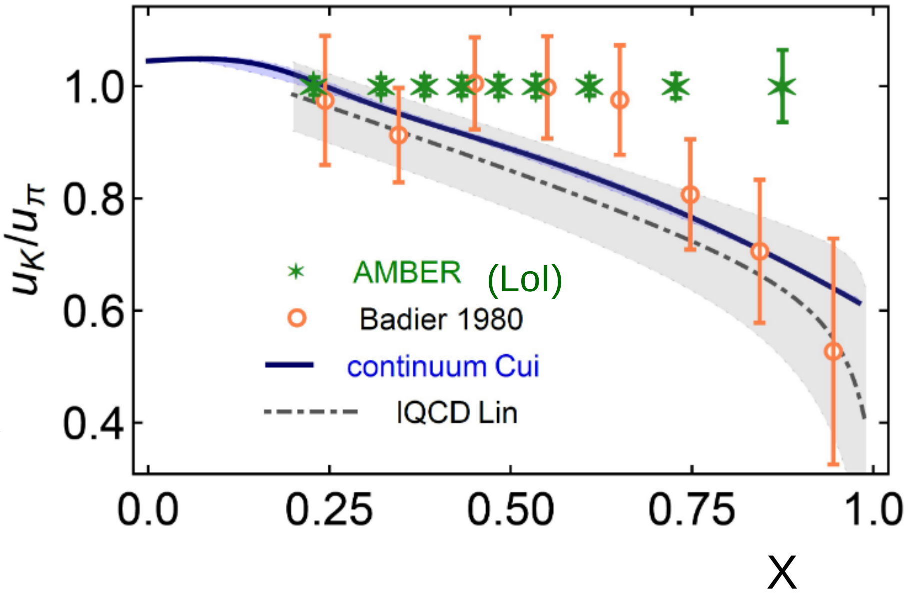
* AMBER (LoI):
Assumed an RF-separated beam of 2 x 10^7 kaons/second – not feasible

But the Drell-Yan measurement with conventional beam (1.5% K^+/h^+, 2.4% K^-/h^- content, at 190 GeV beams) remains competitive.

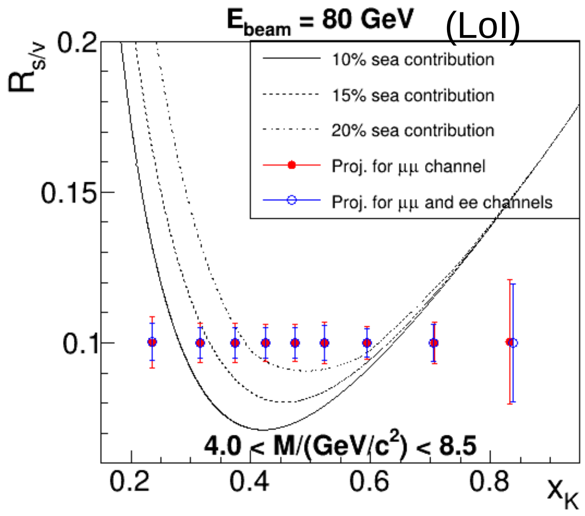
Maximize the number of kaon-induced DY events by:

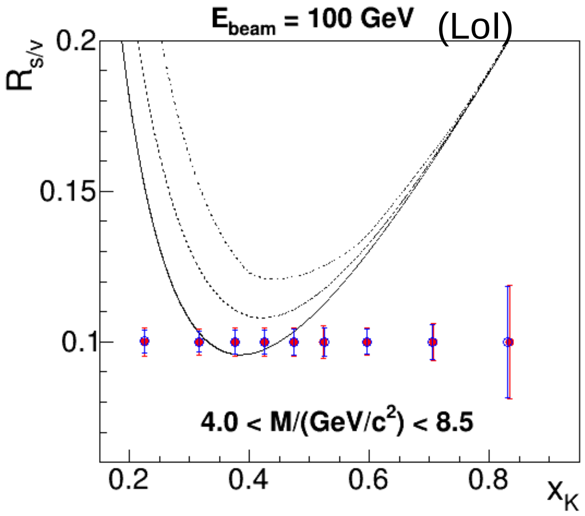
- Some sections of the beamline under vacuum;
- Reduce the beam divergence;
- Improve CEDARs stability, efficiency and maximum rate capability.

Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516



Kaon structure: valence and sea





First-ever kaon sea-valence separation:
using both charges kaon beams

$$R_{s/v}=\frac{\sigma^{K^+C}}{\sigma^{K^-C}-\sigma^{K^+C}} \longrightarrow \propto u_v^{K} u_v^{p}$$

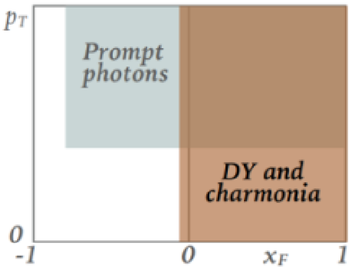
Higher beam momentum: access to lower x_K

Simulations to be re-done.
If using a conventional beam, it might be more advantageous to go for E_{beam}=190 GeV

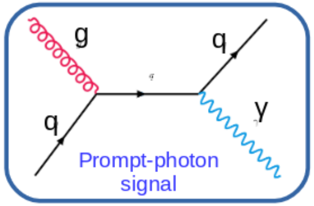
- More statistics
- Better sensitivity at lower x_K

Kaon structure: gluon contribution

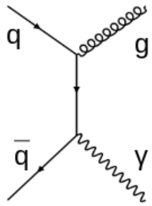
Direct photon production measurement (phase II)



Measurement possible using a K^+ beam on a long liquid H_2 target

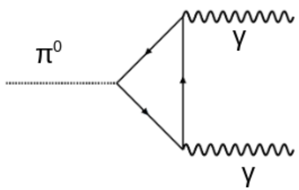


Direct access to the gluon PDF at $x_g^K > 0.05$, $Q^2 \sim p_T$



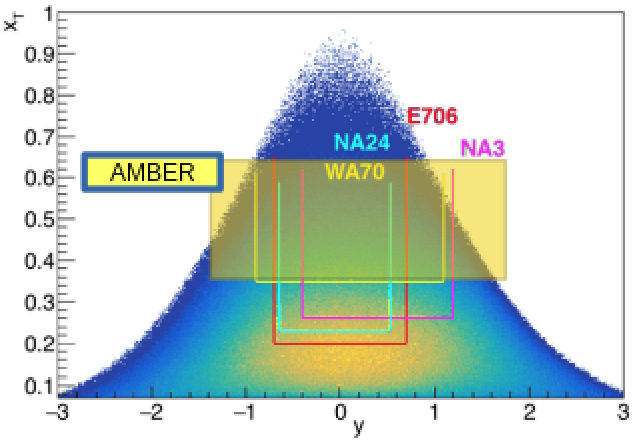
background

K^+ beam: minimize bkg

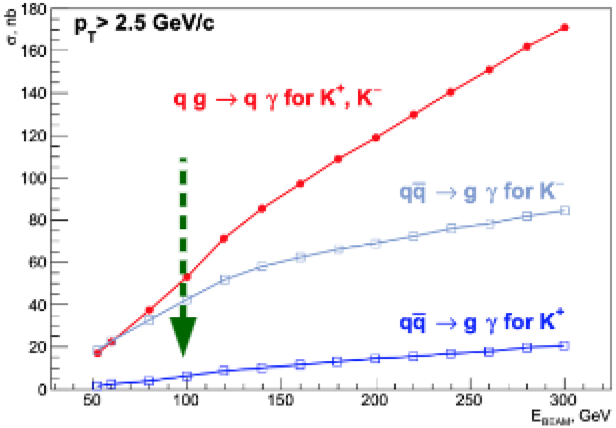


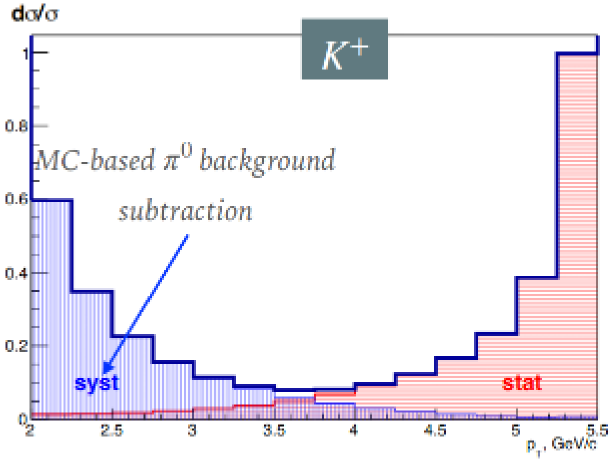
Minimum bias photons background

p_T^γ>2.5 GeV/c: minimize photon background



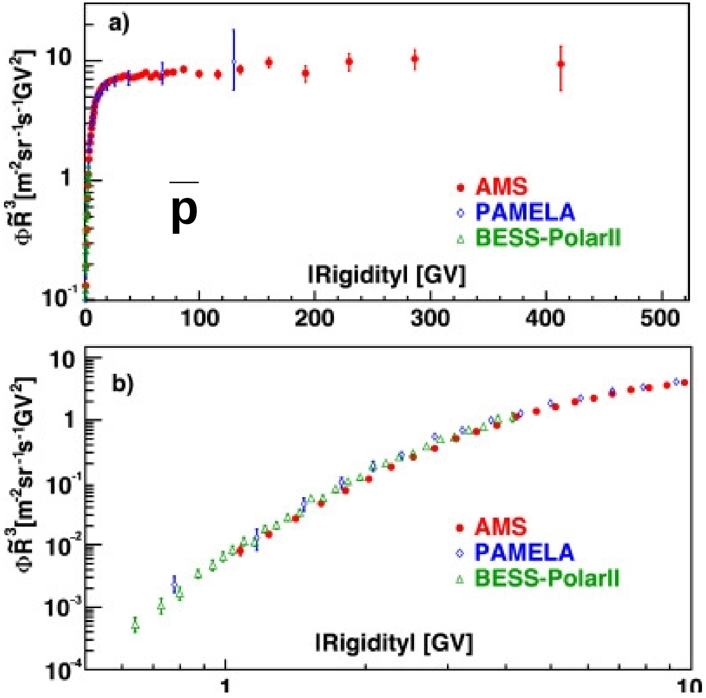
$x_T = 2p_T/\sqrt{s}$



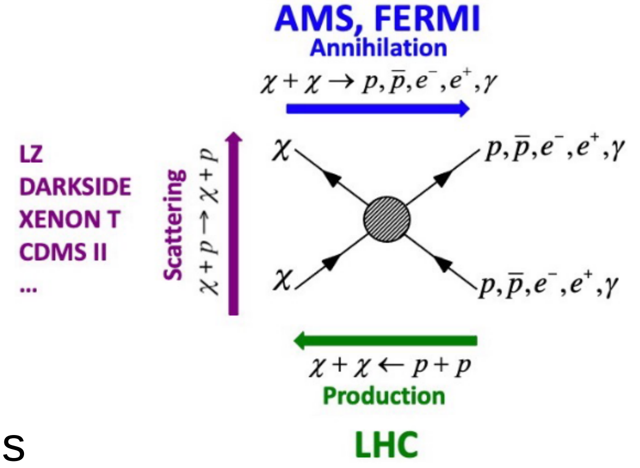


Antiproton production cross section (phase I)

Dark Matter searches in Astroparticle Physics:
Search for excess in antiparticle fluxes



AMS-02, Phys. Rep. 894 (2021) 1-116



AMS, FERMI
Annihilation
$\chi + \chi \rightarrow p, \bar{p}, e^-, e^+, \gamma$

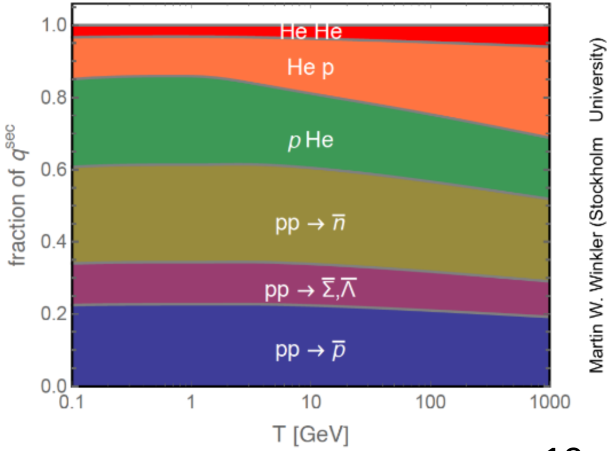
LZ
DARKSIDE
XENON T
CDMS II
...

Scattering
$\chi + p \rightarrow \chi + p$

$\chi + \chi \leftarrow p + p$
Production
LHC

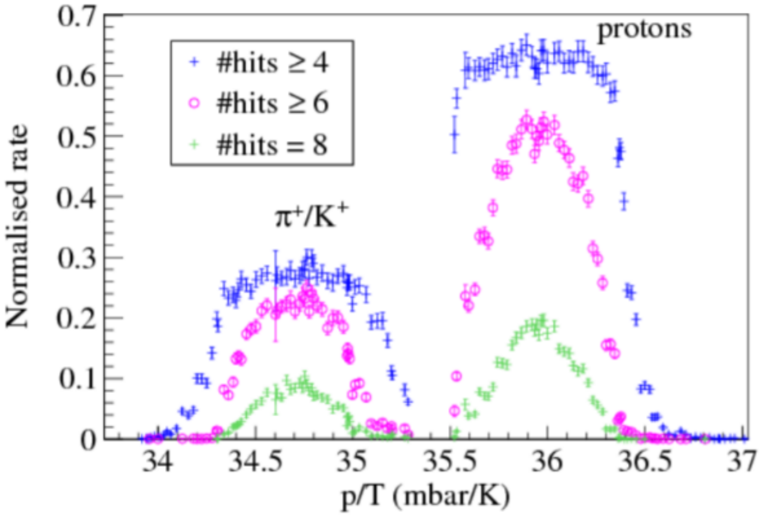
We need good accuracy in the predicted/measured natural fluxes

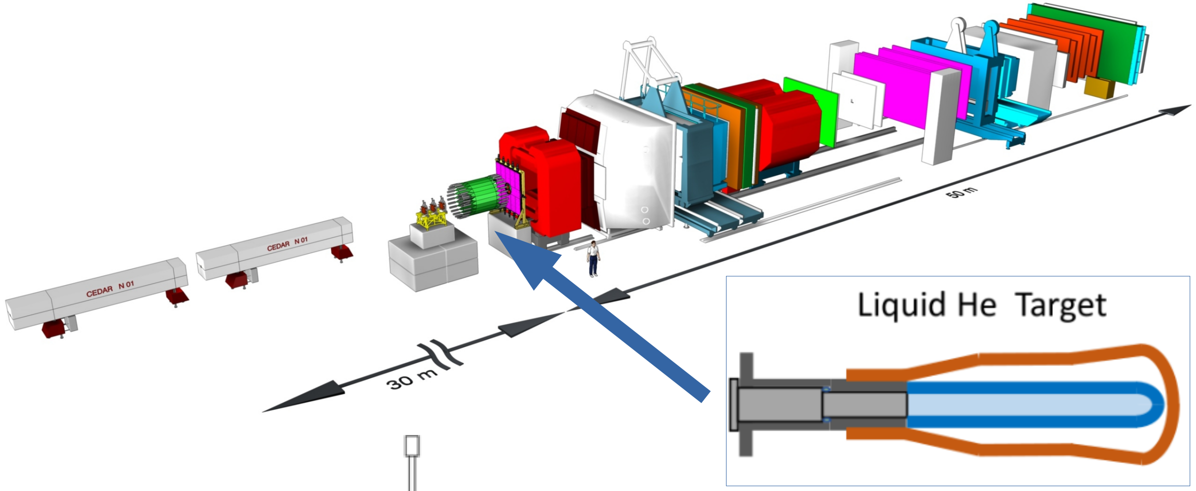
Fraction of $\bar{p}$ from cosmic ray interactions with the interstellar medium:
very important to measure p-He and He-p reactions

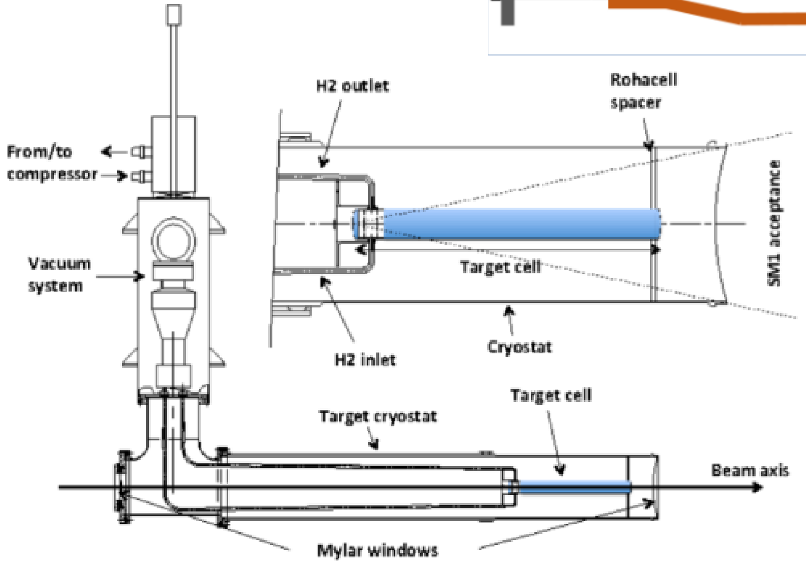


Antiproton cross section at AMBER

CEDAR beam identification

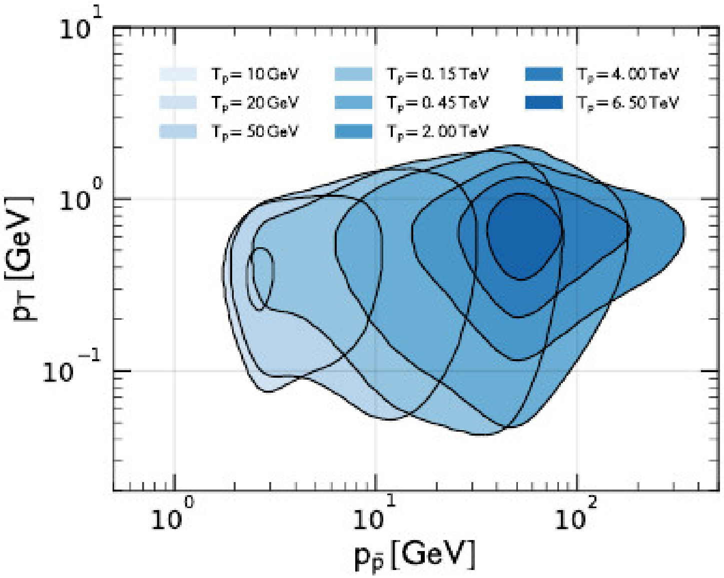






- Identify the proton beam particle using CEDAR
- Identify produced antiprotons using RICH
- A scan in beam momentum

AMBER 2023: $\bar{p}$ production cross section from p+He

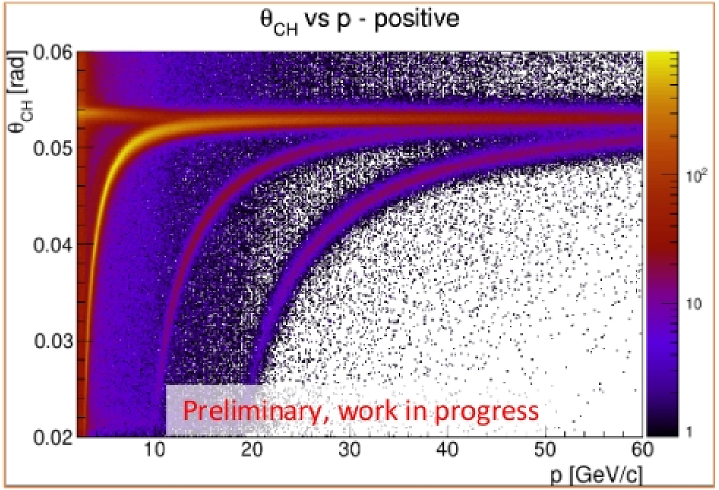


Parameter space to cover, for different proton beam energies (shades of blue) for 3% uncertainty in the cross section of

$p + He \rightarrow \bar{p} + X$

- Measurement of p+He collisions at AMBER done in May/June 2023, varying the proton beam energy in the range 60 – 250 GeV.
- Projected statistical error of the measurement is < 1% over most of the phase space covered.

NEW



Preliminary, work in progress

Particle identification at RICH

Kaon polarizabilities (phase II)

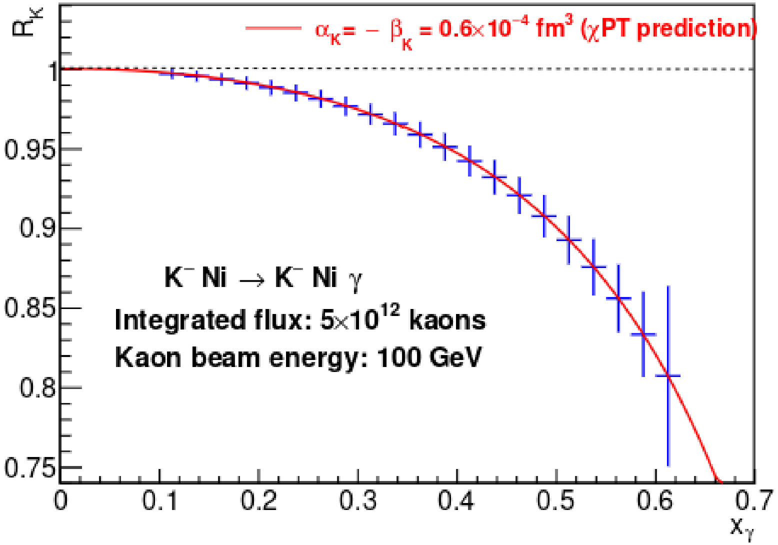
Electric and magnetic polarizabilities: in response to an external electromagnefic field.
Strength of the effect predicted by Chiral Perturbation Theory: $\alpha_K = (0.64 \pm 0.10) \times 10^{-4}$ fm³
while quark confinement model predicts: $\alpha_K = 2.3 \times 10^{-4}$ fm³

Experimentally, only an upper limit:
$\alpha_K < 200 \times 10^{-4}$ fm³ (CL=90%) x-ray spectroscopy of kaonic atoms (1973)

Primakoff reactions:
Charged particles passing by nuclei at high momentum and large distance interact mainly by one-photon exchange.

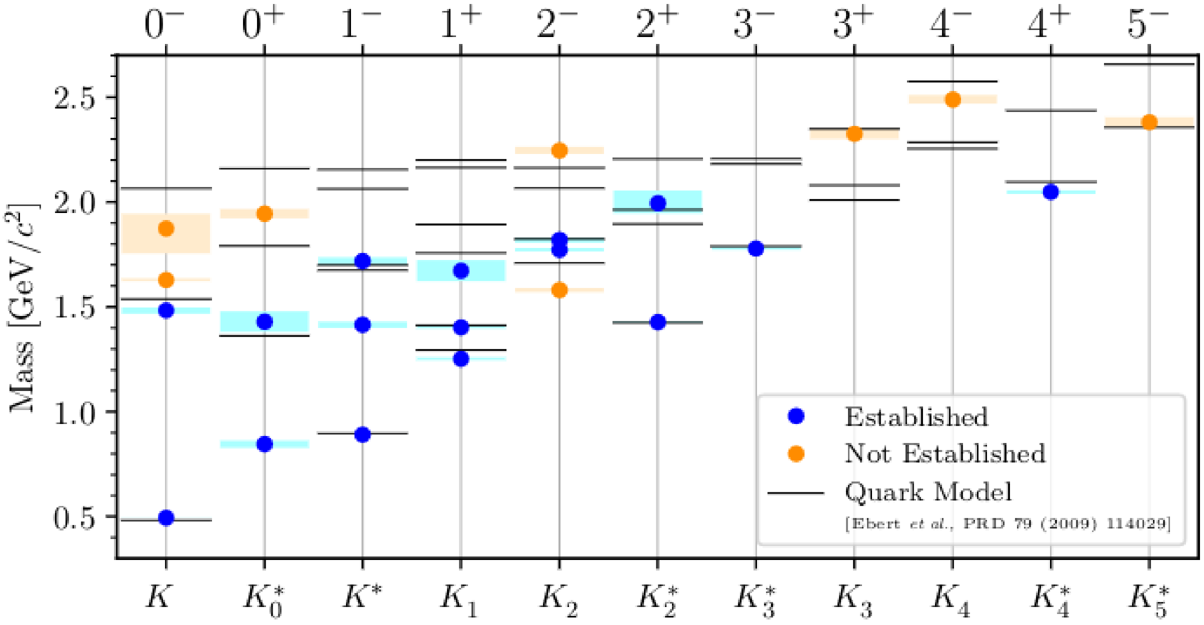
$K^- \text{Ni} \rightarrow K^- \gamma \text{ Ni}$

- K⁻ beam of 100 GeV/c
- Nickel target
- Beam intensities up to 5 MHz
- Trigger from ECALs



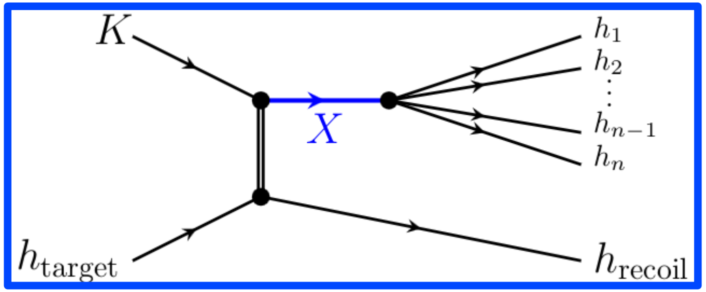
R_K: ratio of cross section measured with real kaon to that expected with hypothetical point-like kaon.

Hadron spectroscopy: strange sector (phase II)



Many states predicted but not yet observed.

Measurements of high energy Kaon beam diffractive scattering



AMBER goals:

- At least 10x the COMPASS samples
- Final-state particles PID with full momentum coverage
- Large, uniform acceptance

Summary:

The AMBER experiment at the M2 beamline of CERN/SPS started data taking in 2023

The physics motivation is a better understanding of the Emergence of Hadron Mass and the observable effects that steam from it:

- ➔ Hadron radii
- ➔ Hadron structure
- ➔ Meson polarizabilities
- ➔ Strange sector hadron spectroscopy

First measurement was the antiproton production cross section in p+He collisions, important to interpret antiparticle fluxes in context of Dark Matter searches.

Pion and kaon induced Drell-Yan measurements, and a proton radius measurement from muon-proton elastic scattering will follow.

A new proposal, for a 2nd phase of measurements is in preparation.

Stay tuned!