Investigating the Structure of Matter with the AMBER Experiment

AMBER

Apparatus for Meson and Baryon Experimental Research

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On behalf of the AMBER collaboration

FCT Fundação para a Ciência e a Tecnologia
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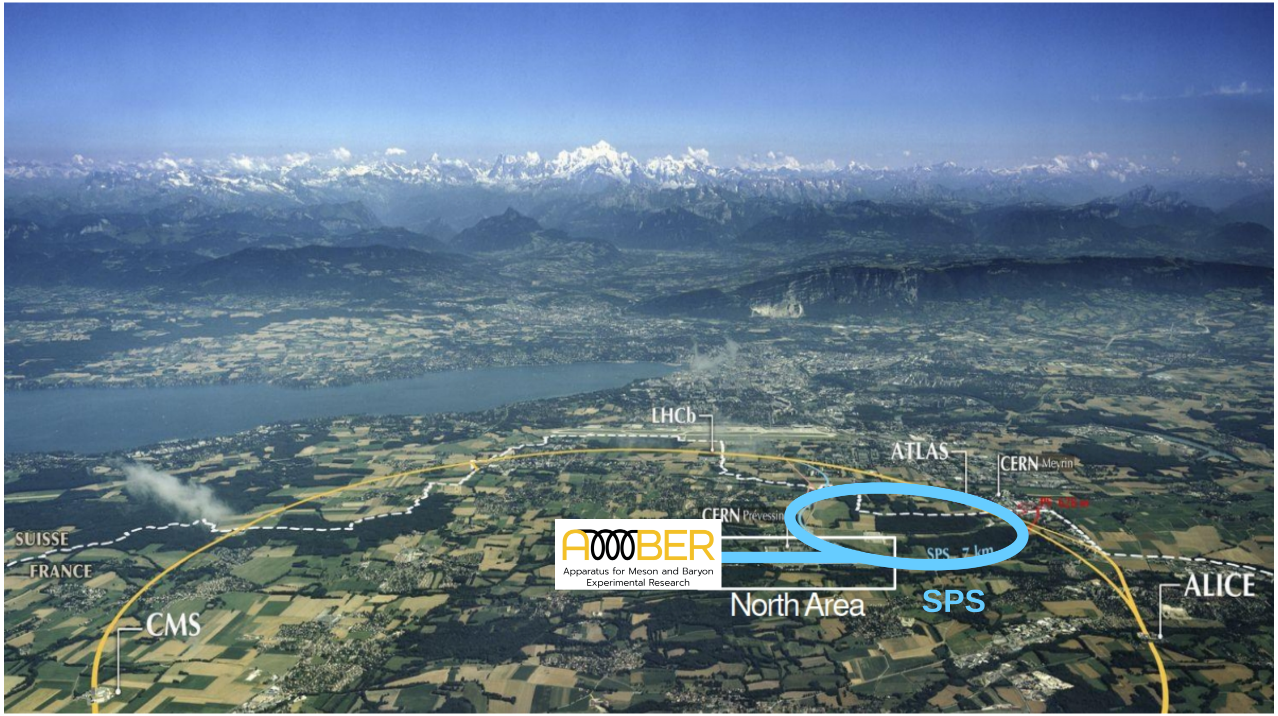
LIP LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

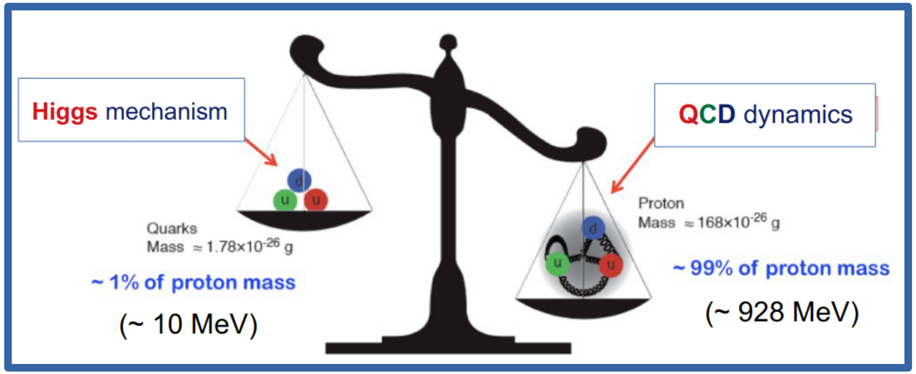
Apparatus for
Meson and
Baryon
Experimental
Research

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

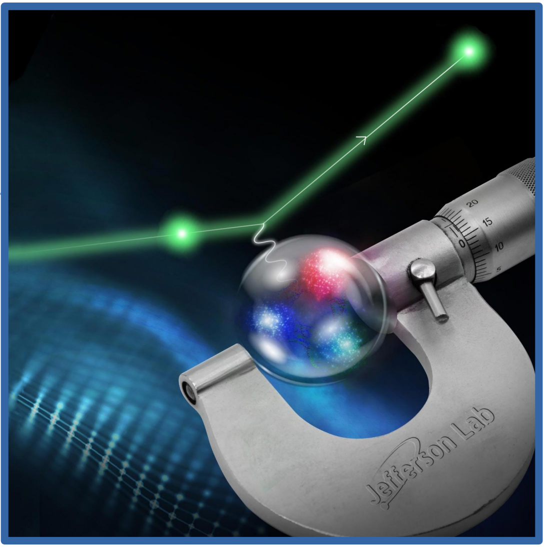


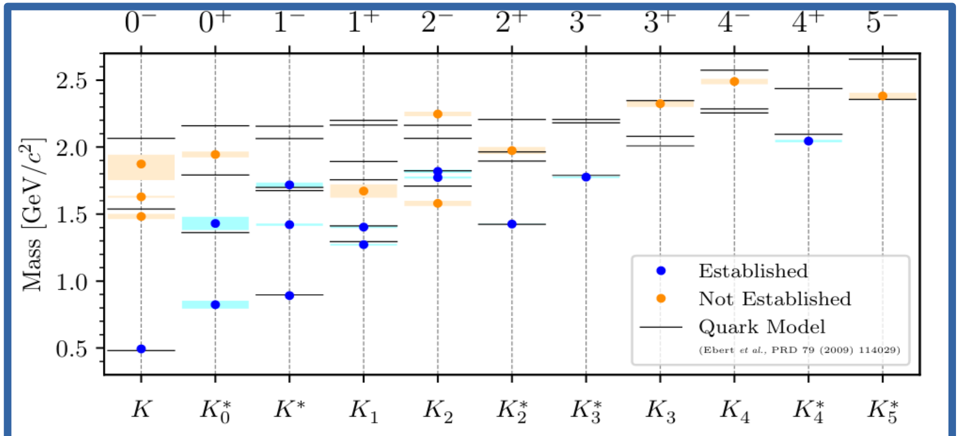
Motivation: the structure of hadronic matter

How hadrons acquire mass?



What about the proton radius? And Kaon radius?





Meson spectroscopy: strange sector

[Courtesy S. Wallner, TUM]

Exploring the particles zoo

...

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Proposed measurements at AMBER

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	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	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	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	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	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	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	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

...as expressed in the LoI:
https://arxiv.org/pdf/1808.00848.pdf

Phase I

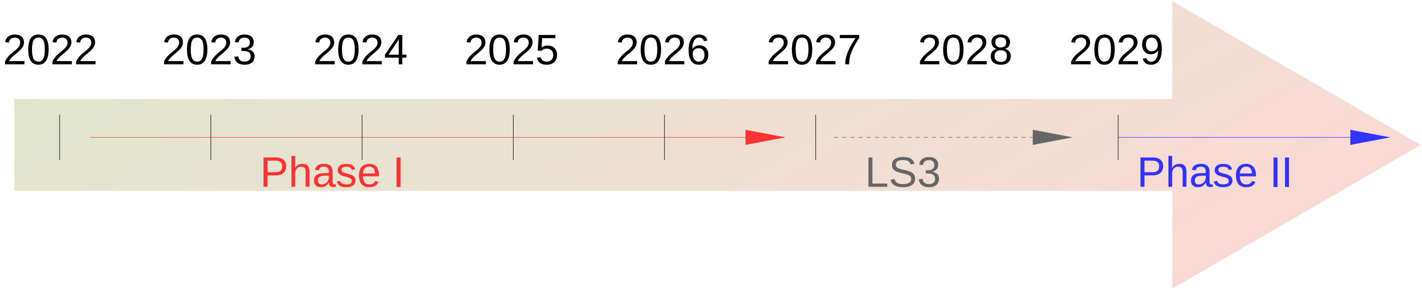
AMBER Proposal Phase I:
http://cds.cern.ch/record/2676885?ln=en

Phase II

Proposal in preparation

LoI (2018)

AMBER timeline



Phase I

- Proton radius measurement from μp elastic scattering
- Antiproton production cross section
- $\pi^{\pm}$ induced Drell-Yan for pion structure

Already approved!

Phase II

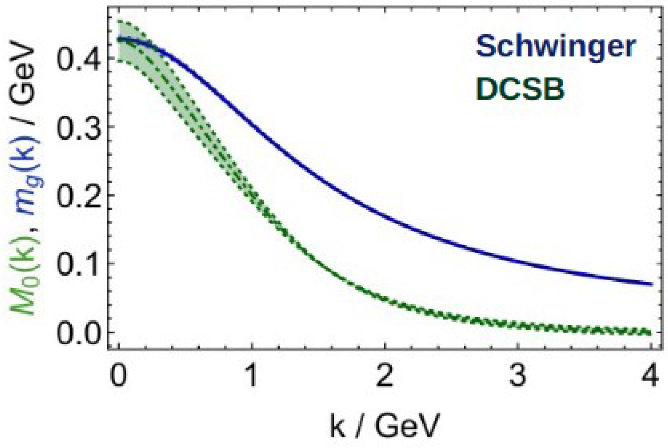
Measurements using mostly kaon beams, possibly RF-separated.

Presently under study.
A proposal is in preparation.

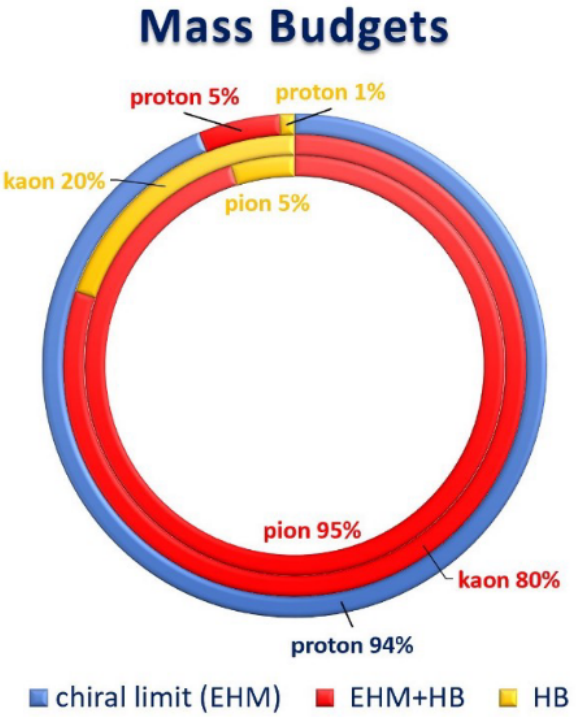
Emergence of hadron mass

AMBER: A QCD facility devoted to the study of EHM and related matters

Dynamic Chiral Symmetry Breaking leads to the quarks and gluons to rapidly acquire a running mass in the infrared limit



Gluon and quark *running masses*



Test it by measurements accessing the pion and kaon structure

Drell-Yan at AMBER: access to the pion structure

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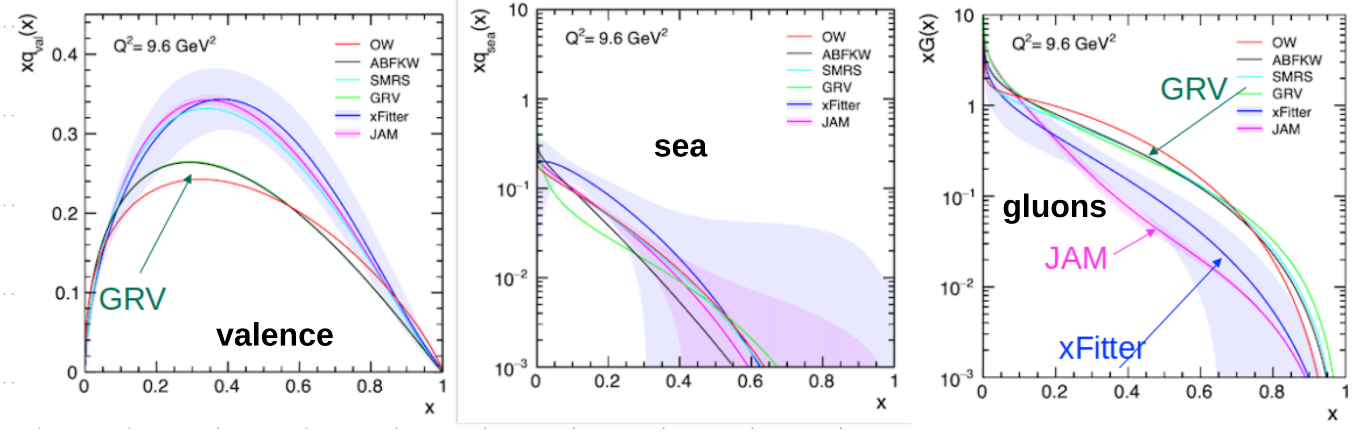
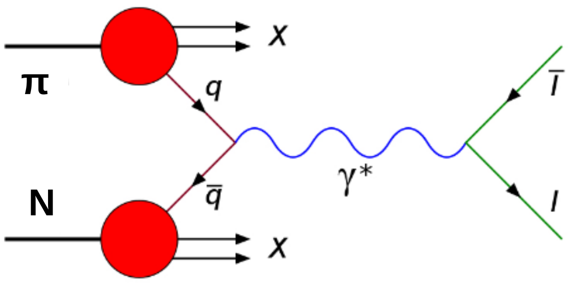
From: Chang et al. PRD 102, 054024 (2020)



Pion:
- The lightest of hadrons
- Goldstone boson of QCD
- Structure is poorly known

Drell-Yan:



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

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

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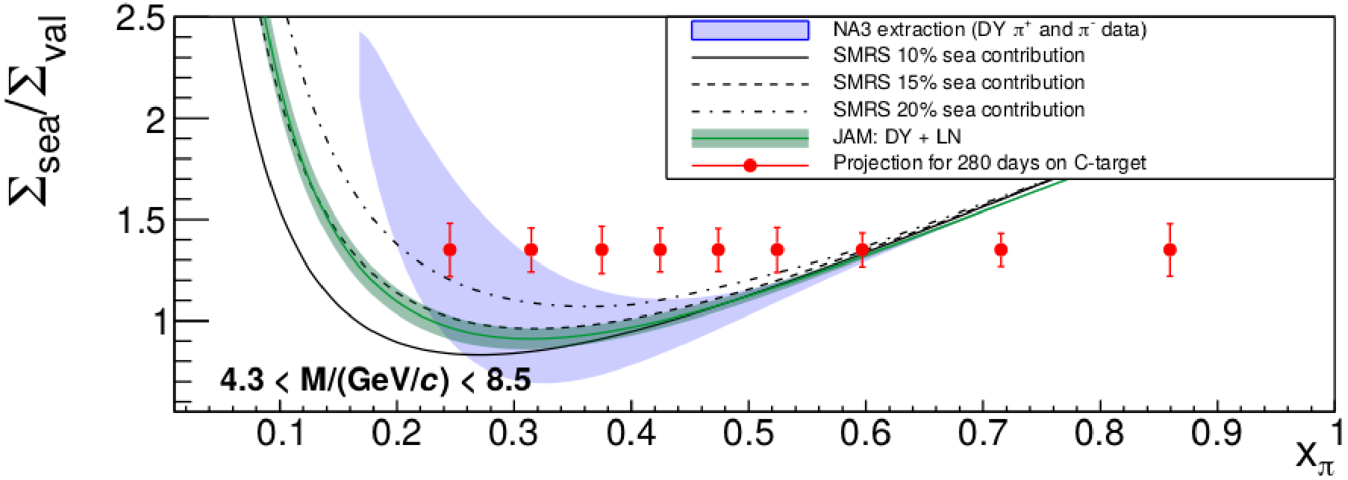
Pion-induced Drell-Yan with both beam charges



Valence composition:

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

Flavour symmetry:

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

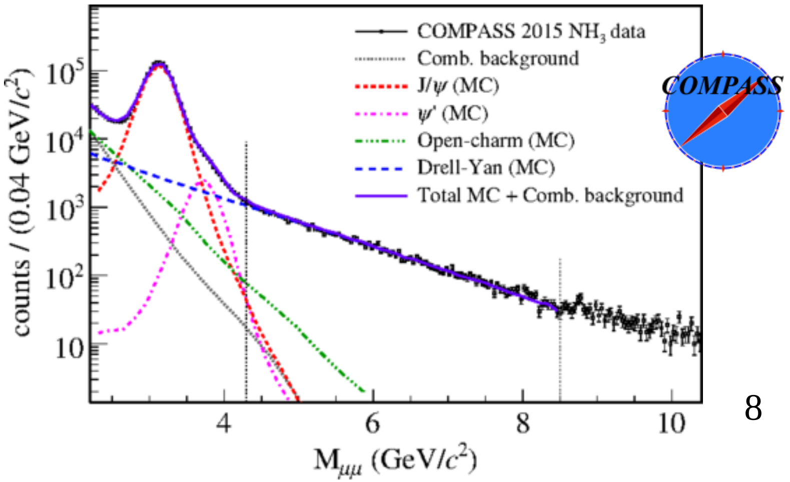
$$\bar{u}^{\pi}_{sea} = u^{\pi}_{sea} = \bar{d}^{\pi}_{sea} = d^{\pi}_{sea} = \bar{s}^{\pi}_{sea} = s^{\pi}_{sea}$$

Sea/valence separation (LO) from ratio of cross-section combinations:

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

LO: only sea-val and val-sea terms (numerator)

LO: only val-val terms (denominator)



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

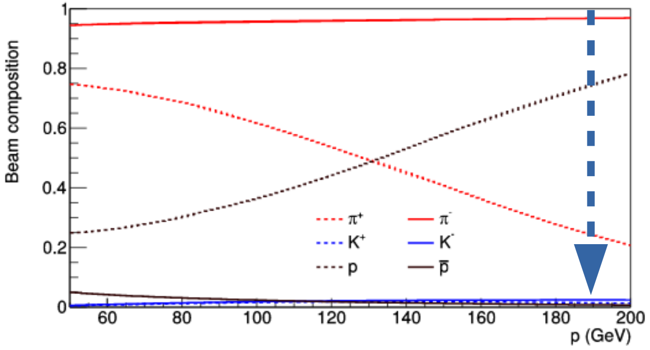
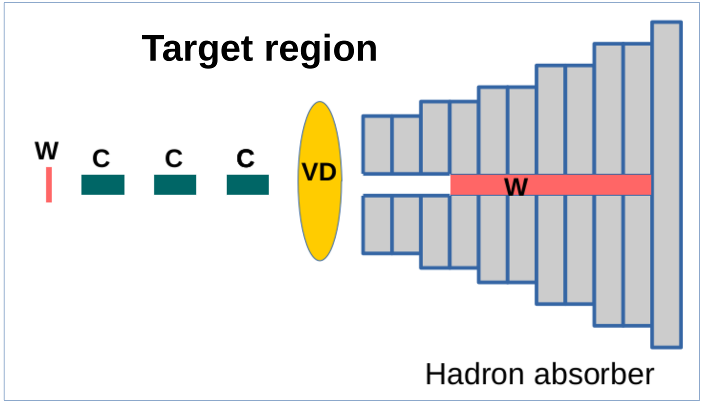


Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

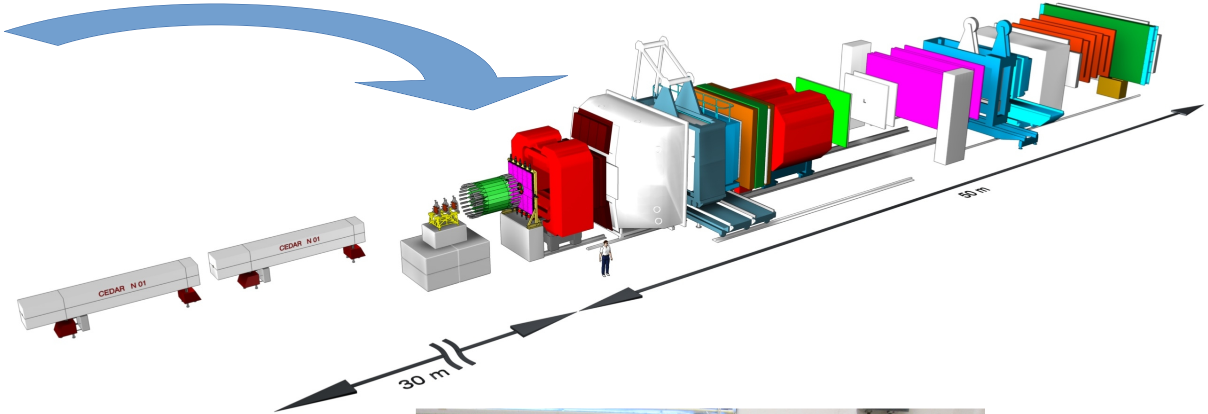
Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 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

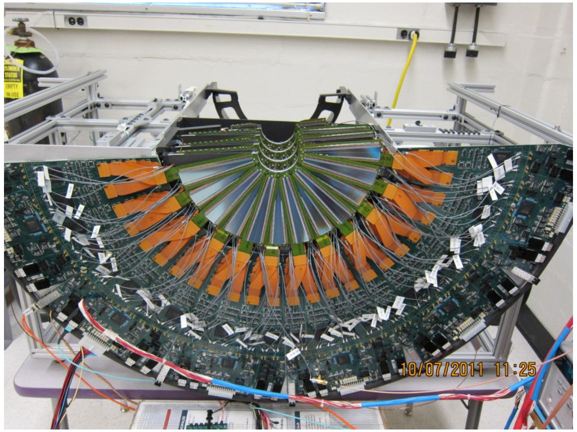
AMBER phase I: Drell-Yan setup



Experimental hall



FVTX detector
from PHENIX@RHIC



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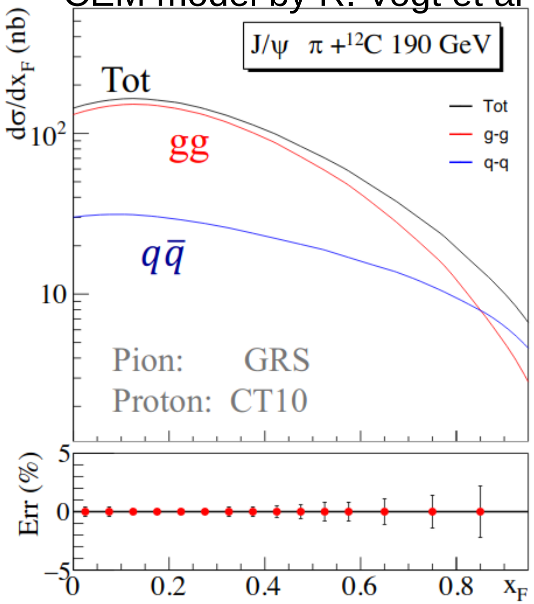
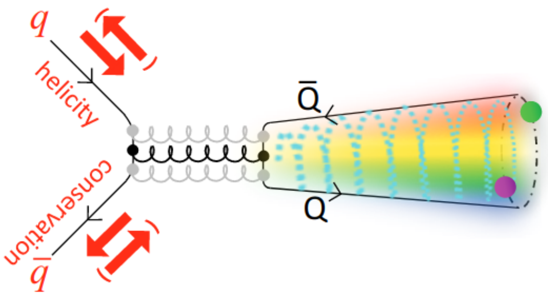
Gluon content in the pion

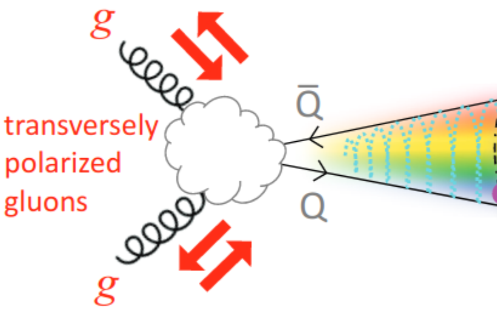
Simultaneously with Drell-Yan, also J/ψ and ψ(2S) production data are collected.

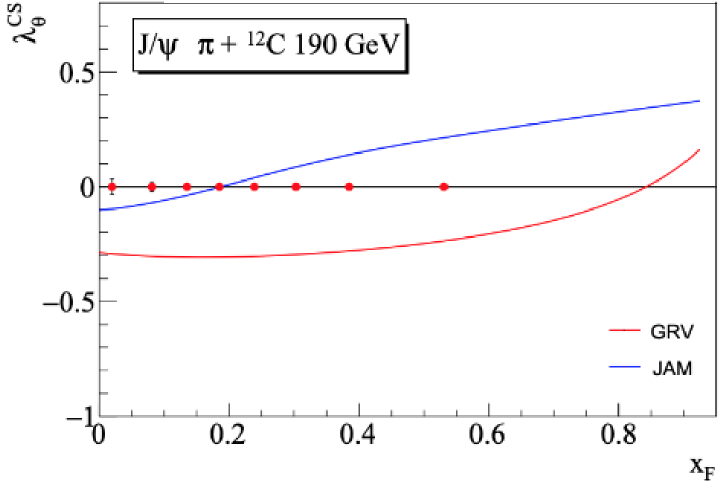
- Large statistics on J/ψ production at dimuon channel
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- In the low-p_T regime
- Expected to have dominance of 2 → 1 processes
- Use J/ψ polarization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

AMBER proposal, using CEM model by R. Vogt et al









Kaon structure: u_k/u_π

Kaons provide a window to 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

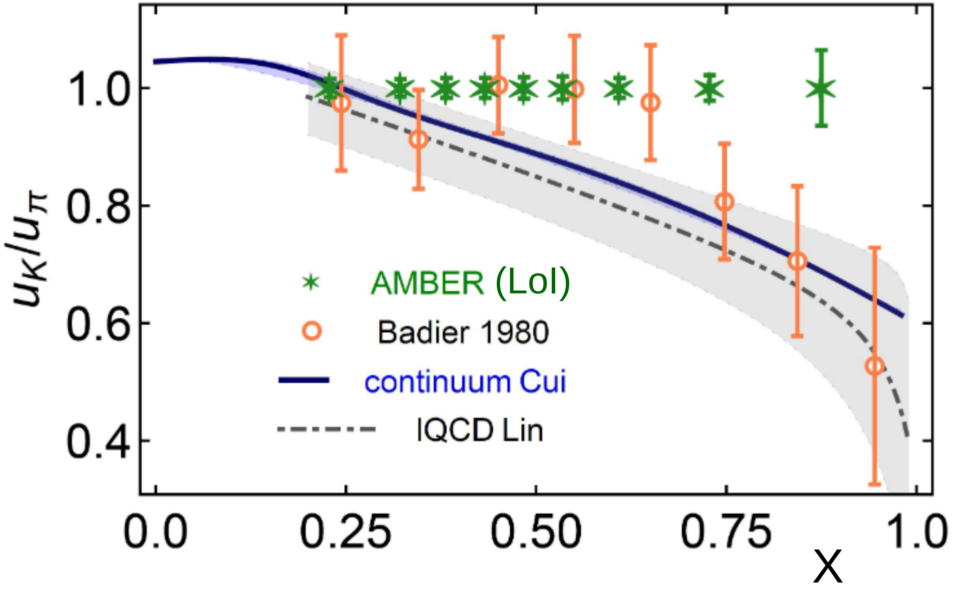
→ 700 kaon-induced Drell-Yan events

* AMBER (LoI):
Assumed an RF-separated beam of
2 x 10^7 kaons/second.

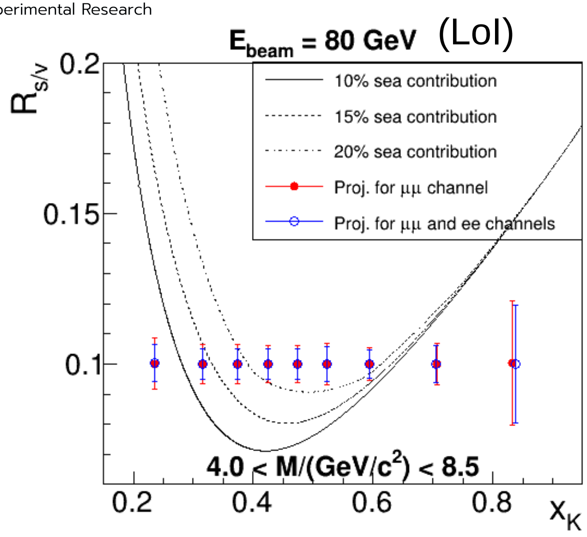
Latest news: this intensity with RF-separated beam is un-feasible.

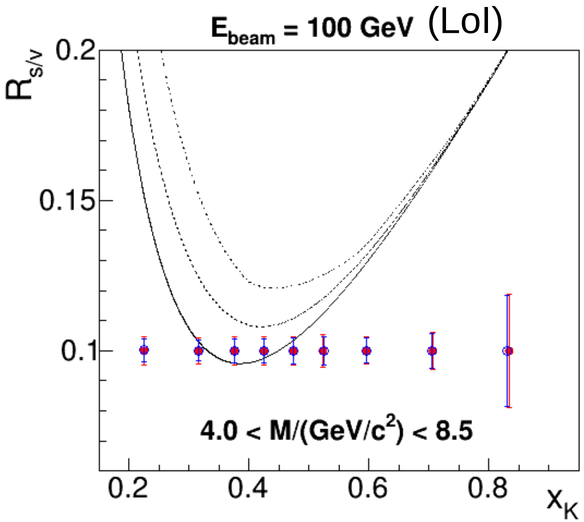
But the DY measurement with conventional beam remains competitive.

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

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

Higher beam momentum: access to lower x_K

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

- More statistics
- Better sensitivity at lower x_K

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J/Ψ production: gluon content in the kaon

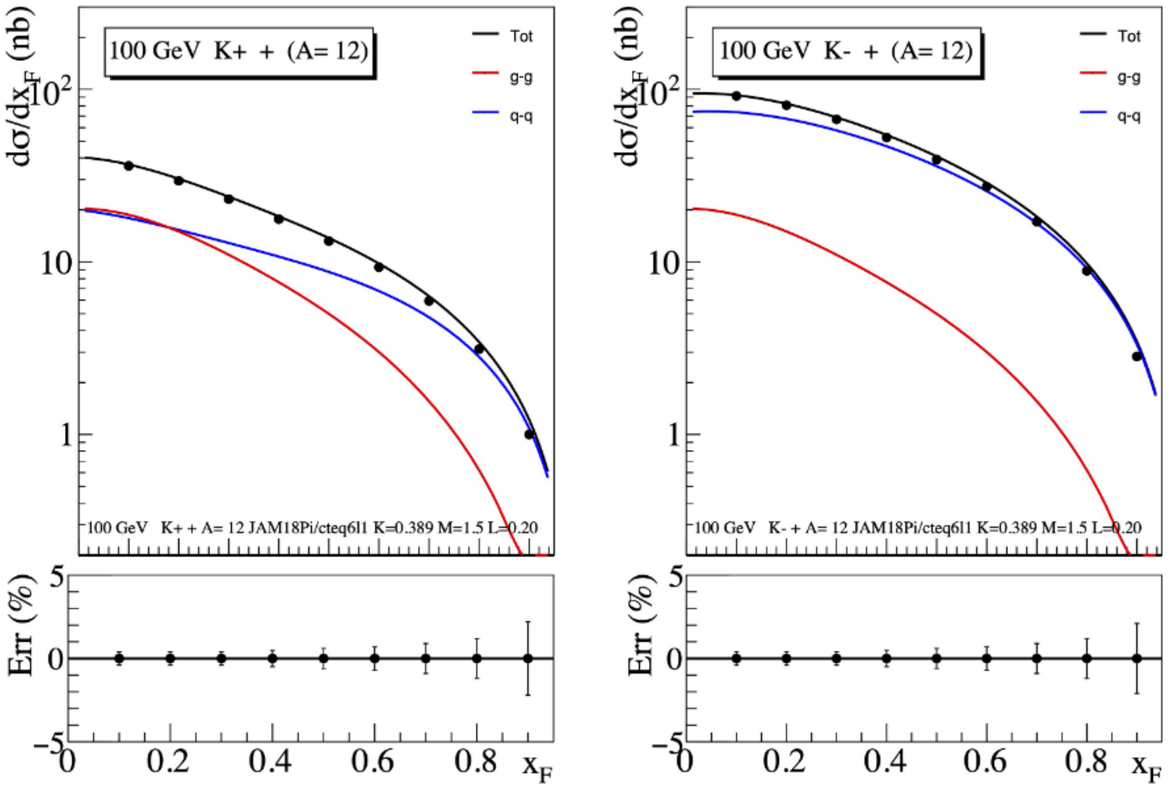
- Kaon-induced J/Ψ production data collected in parallel with kaon-induced Drell-Yan
- Large statistics
- Model-dependent access to the gluon distribution in kaons
- J/Ψ production cross section (LO):
  - gluon-gluon fusion
  - quark-antiquark annihilation

$$K^-(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

$$K^+(u\bar{s})+p(uud)\propto gg+\left[---\right]+\left[u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

val-val | val-sea | sea-val | sea-sea

Using Color Evaporation Model (Int.J.Mod.Phys. A 10 (1995) 3043) and JAM18 "pion" PDFs (PRL 121, 152001 (2018))



(AMBER LoI)

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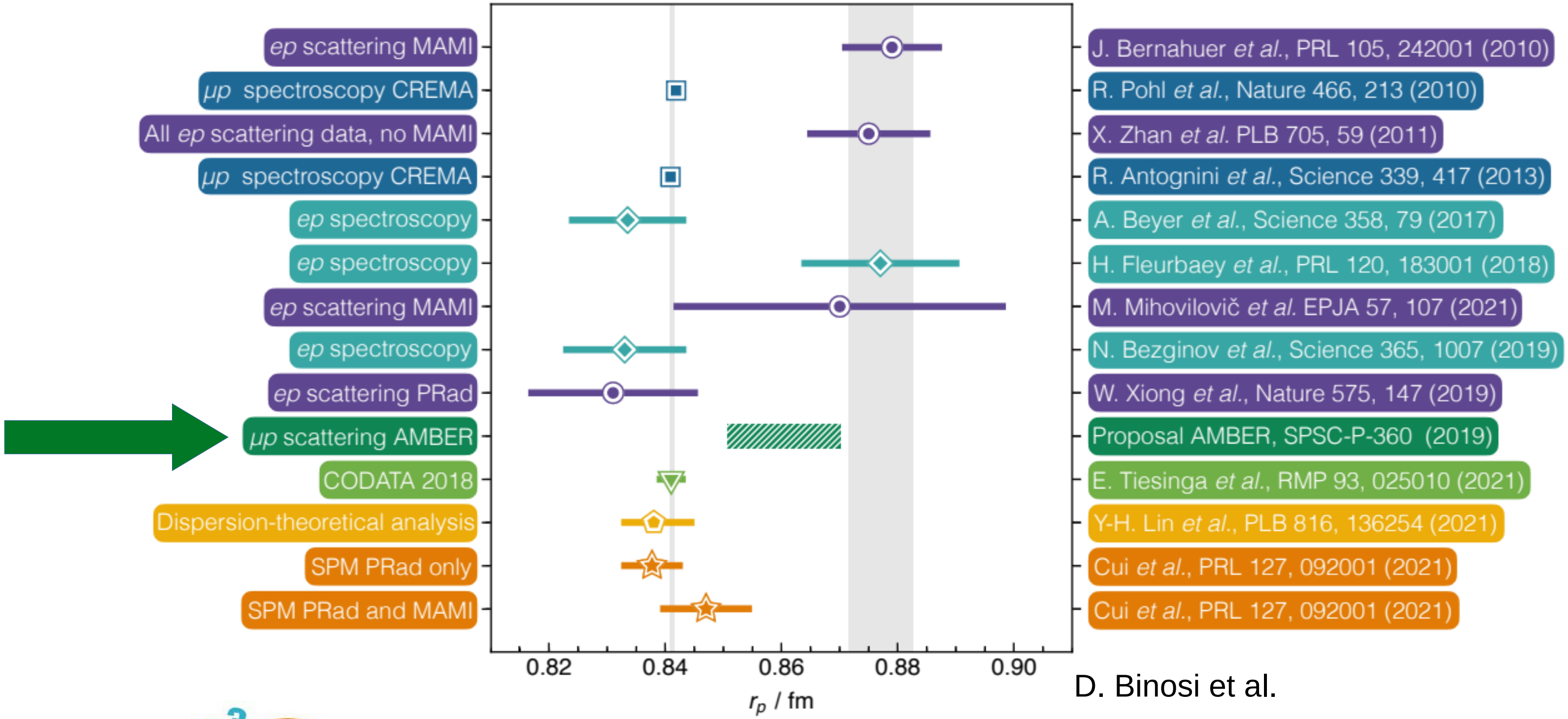
Hadron charge radii

an expression of the link between EHM and confinement

Proton



D. Binosi et al.

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

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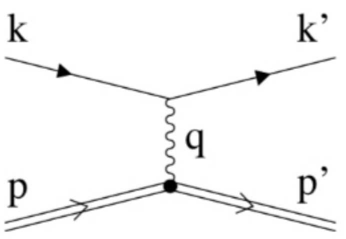
Proton radius from lepton-p elastic scattering

The proton charge radius can be accessed via the electromagnetic form factors.
Experimentally, AMBER will measure the **elastic muon-proton scattering**:



G_E, G_M

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

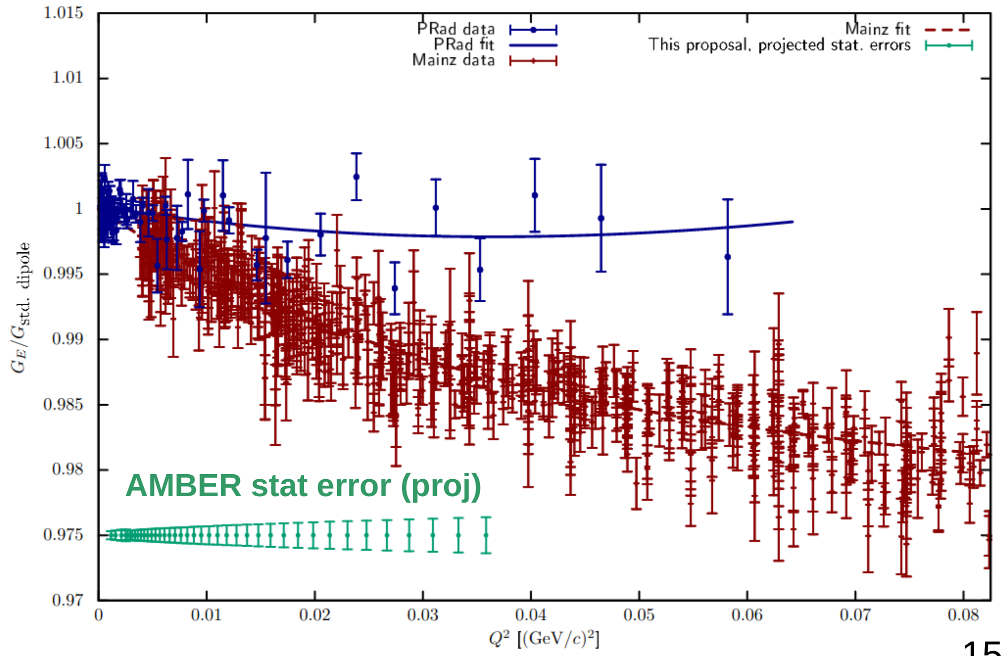
$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \right|_{Q^2 \to 0}$$

ep elastic scattering:

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

PRad form factors in clear contradiction with Mainz data

But: large radiative corrections to take into account



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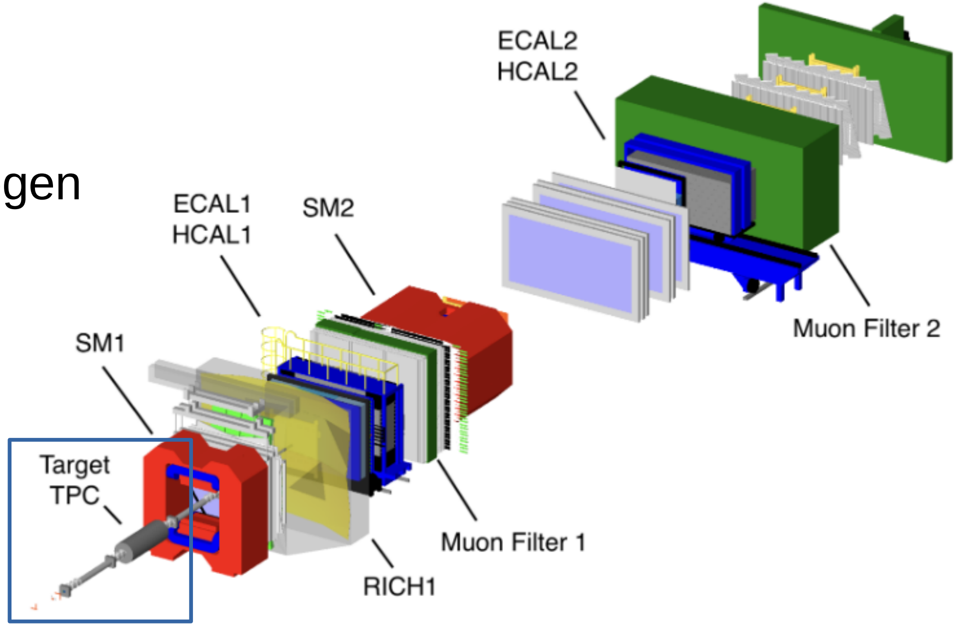
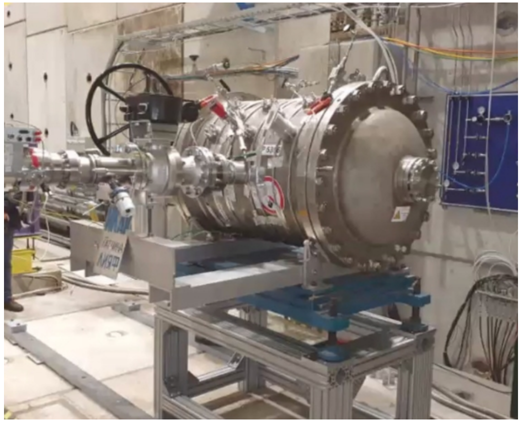
Proton radius at AMBER: μp scattering

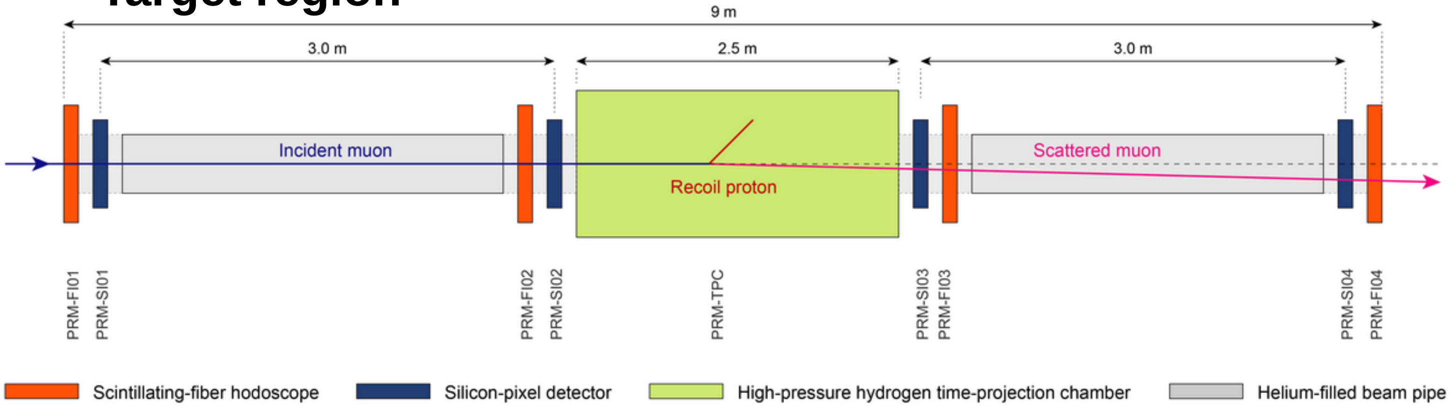
- 100 GeV muon beam
- Active target TPC filled with pressurised hydrogen
- Goal: 70 million elastic scattering events in $10^{-3} < Q^2 < 4 \times 10^{-2}$ GeV²
- Small radiative corrections
- Precision on proton radius ~0.01 fm



IKAR TPC



Target region



Meson charge radii

$$r_\pi^2 = -\frac{6}{F_\pi(0)} \frac{d}{dQ^2} F_\pi(Q^2)\Big|_{Q^2=0}$$

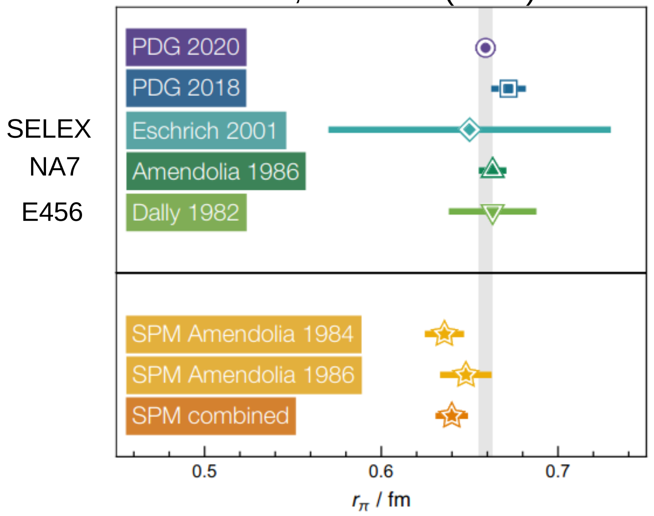
Pion and kaon radii: measured with much less precision than that of proton

Pion radius

Measurements of pion scattering at low Q^2, done in the 1980's

$r_\pi = 0.659 \pm 0.004$ fm (PDG 2020)

Z.-F.Cui et al, PLB 822 (2021) 136631

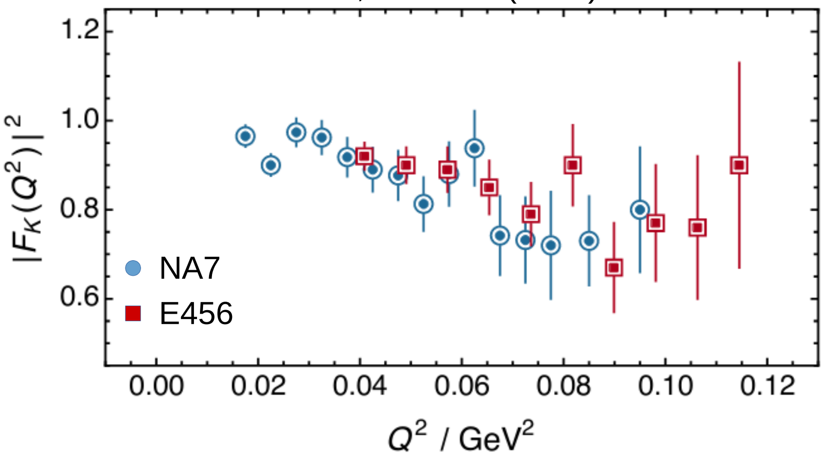


Kaon radius

Practically unknown

$r_K = 0.560 \pm 0.031$ fm (PDG 2020)

Z.-F.Cui et al, PLB 822 (2021) 136631



Kaon charge radius at AMBER

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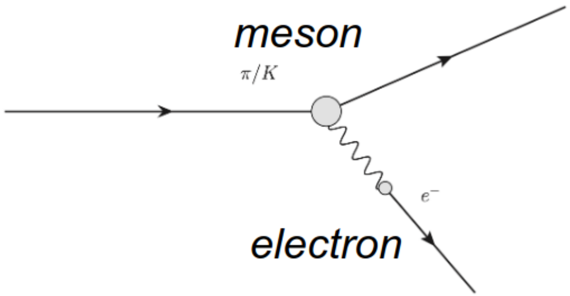
For unstable particles, electron scattering can only be done in inverse kinematics



- Large Q^2 range : higher sensitivity to the charge distribution $<r^2_E>$

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%

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

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

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

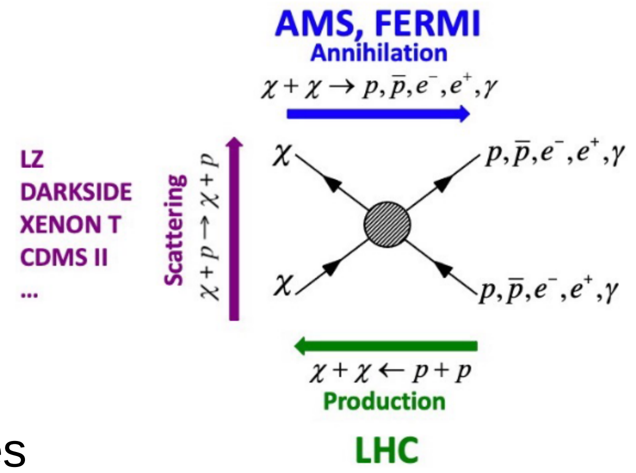
$$Q^2_{max} = \frac{4 \cdot m_e^2 \cdot p_b^2}{s} = 4 \cdot p_{cm}^2$$

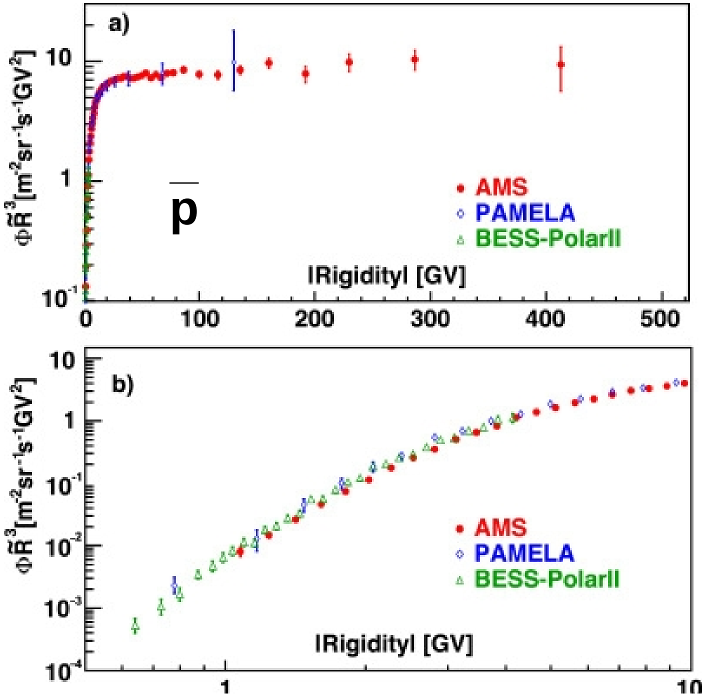
A recent idea to be explored further...

A detour: antiproton production cross section

Dark Matter searches in Astroparticle Physics:

Search for excess in antiparticle fluxes

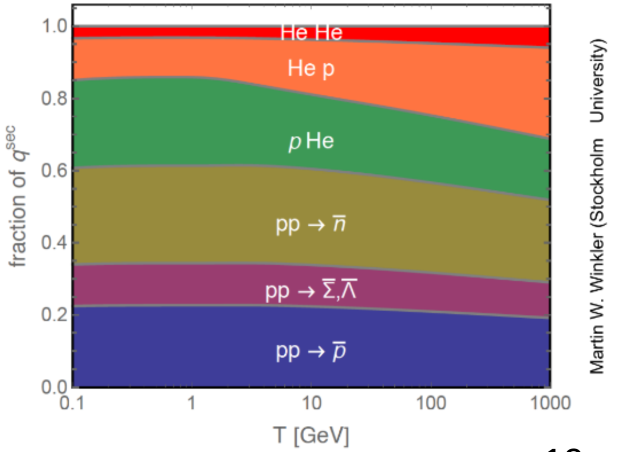




AMS-02, Phys. Rep. 894 (2021) 1-116

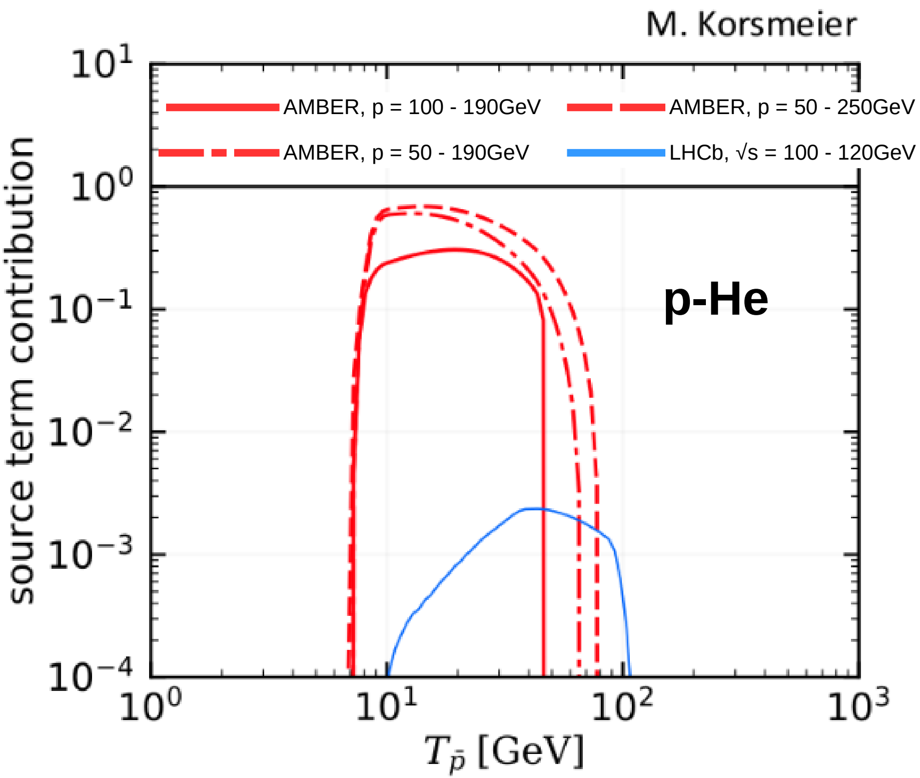
We need good accuracy in the predicted/measured natural fluxes

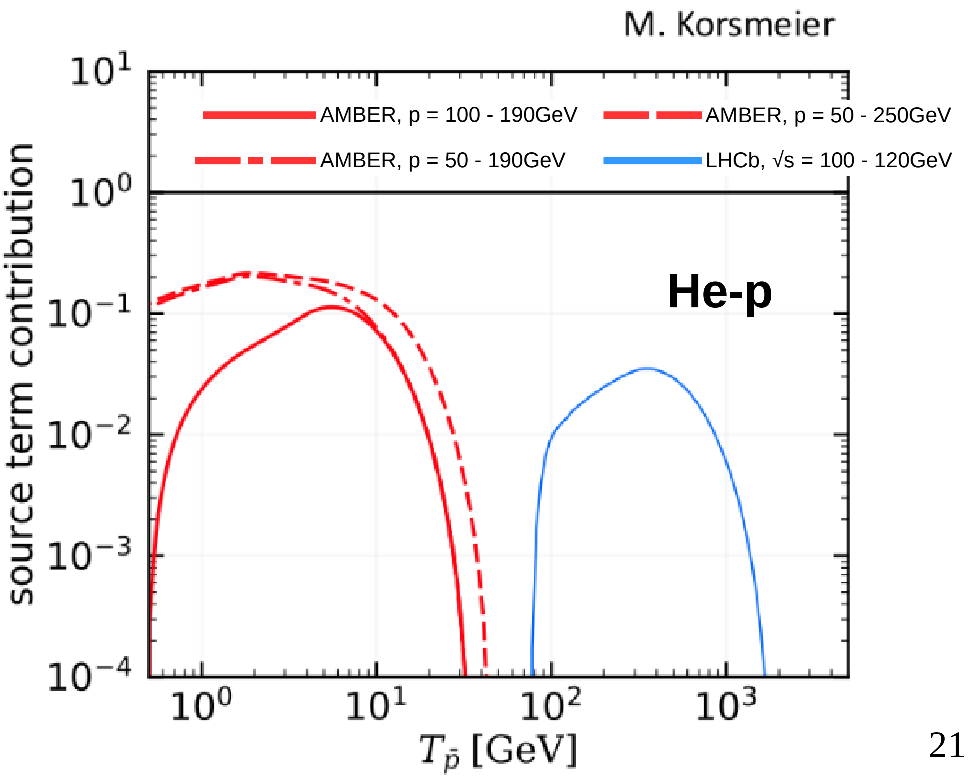
Fraction origin of $\bar{p}$ from cosmic ray interactions with the interstellar medium: very important to measure p-He and He-p reactions



AMBER impact on the $\bar{p}$ flux source term

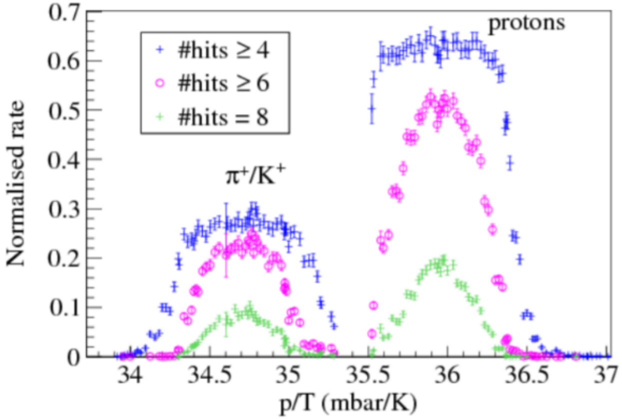
AMBER can vary the proton beam energy in the range 50 – 250 GeV

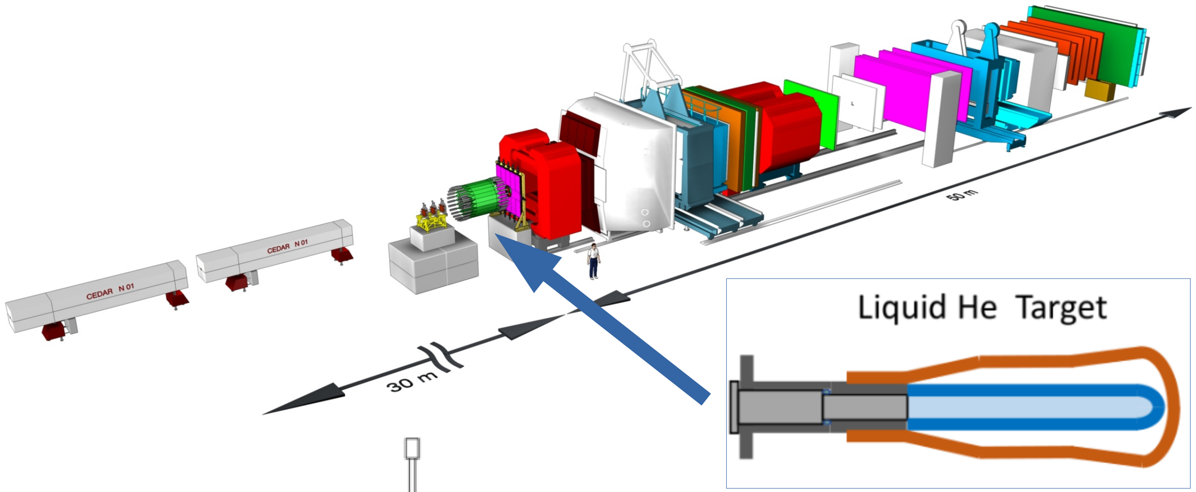




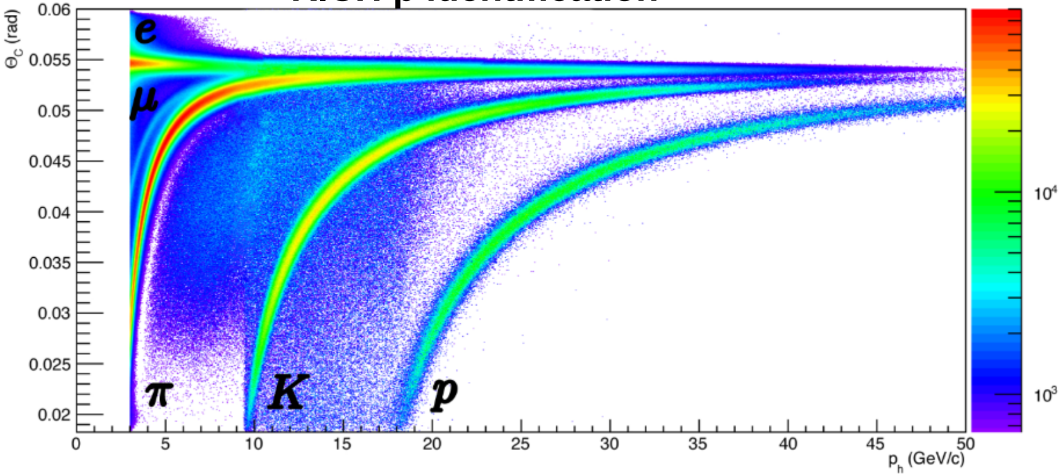
Antiproton cross section at AMBER

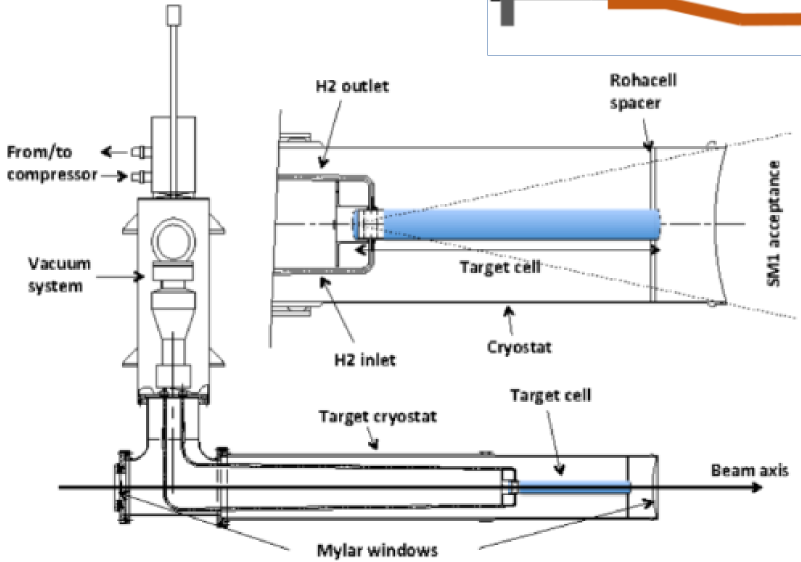
CEDAR beam identification





RICH $\overline{p}$ identification





AMBER
Apparatus for Meson and Baryon Experimental Research

Summary

The AMBER experiment at the CERN M2 beamline is a new “QCD Facility” to investigate the Emergence of Hadron Mass

AMBER phase I was approved in December 2020, for measurements on:

- Proton radius from muon-proton elastic scattering
- Antiproton cross-sections – input for Dark Matter searches
- Pion structure from pion-induced Drell-Yan and Charmonium production

An upgrade of the M2 beamline will provide radio-frequency separated hadron beams.
High purity kaon beams are being proposed for a phase II of AMBER:
Light meson spectroscopy using kaon beams
Gluon content in the kaon from direct-photon production } not discussed today
Kaon charge radius from elastic kaon-electron scattering

Conventional beams from improved beamline and with improved beam telescope are being considered as an alternative for kaon-induced Drell-Yan, in order to study kaon structure.