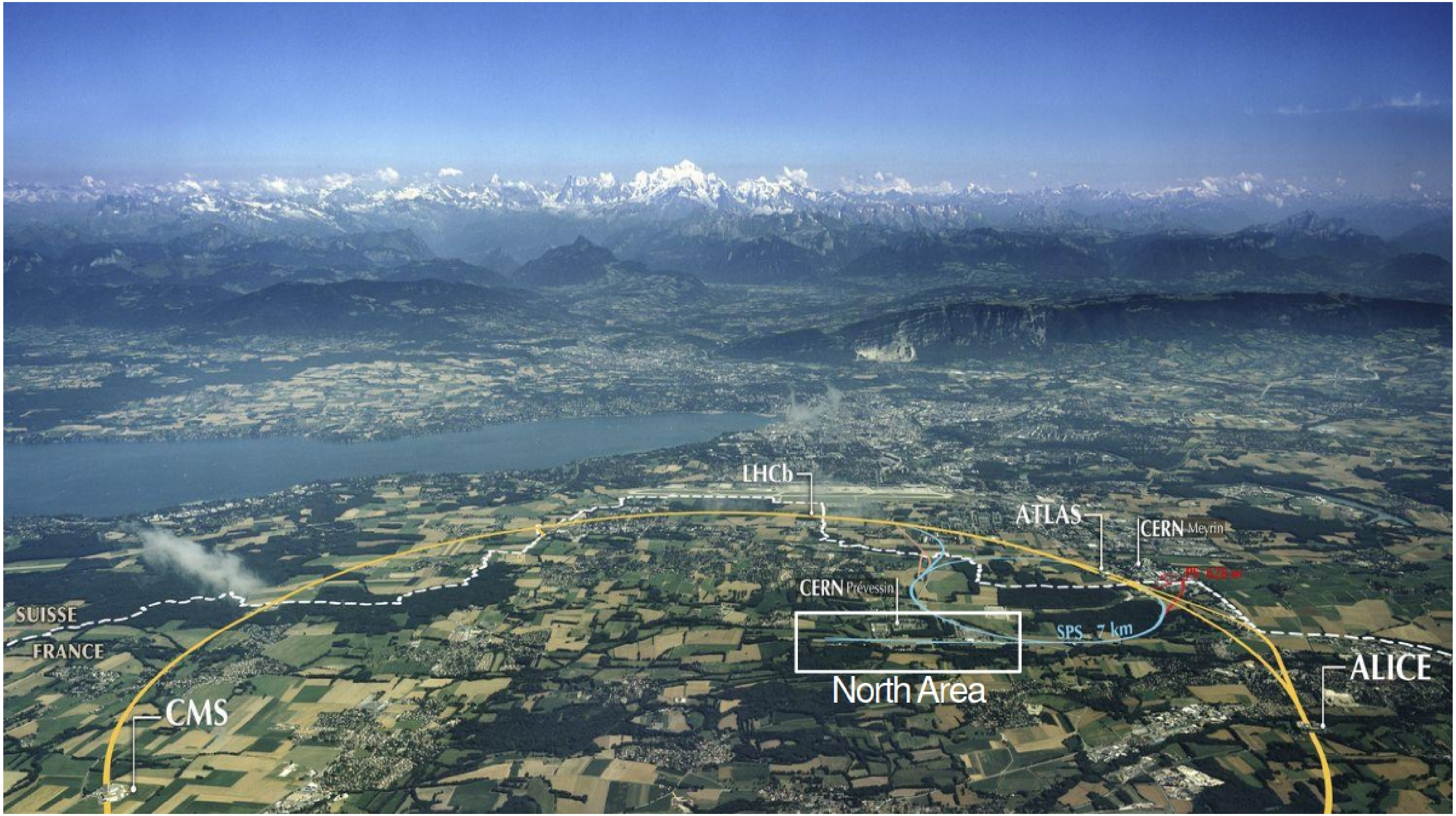
New M2 beamline at CERN SPS
from the AMBER perspective

Catarina Quintans, LIP-Lisboa
18 October 2021, School on the Physics of Baryons

Lis Watkins, Urban Sketchers

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Fundação para a Ciência e a Tecnologia


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
North Area
ALICE
CMS

The opportunity:

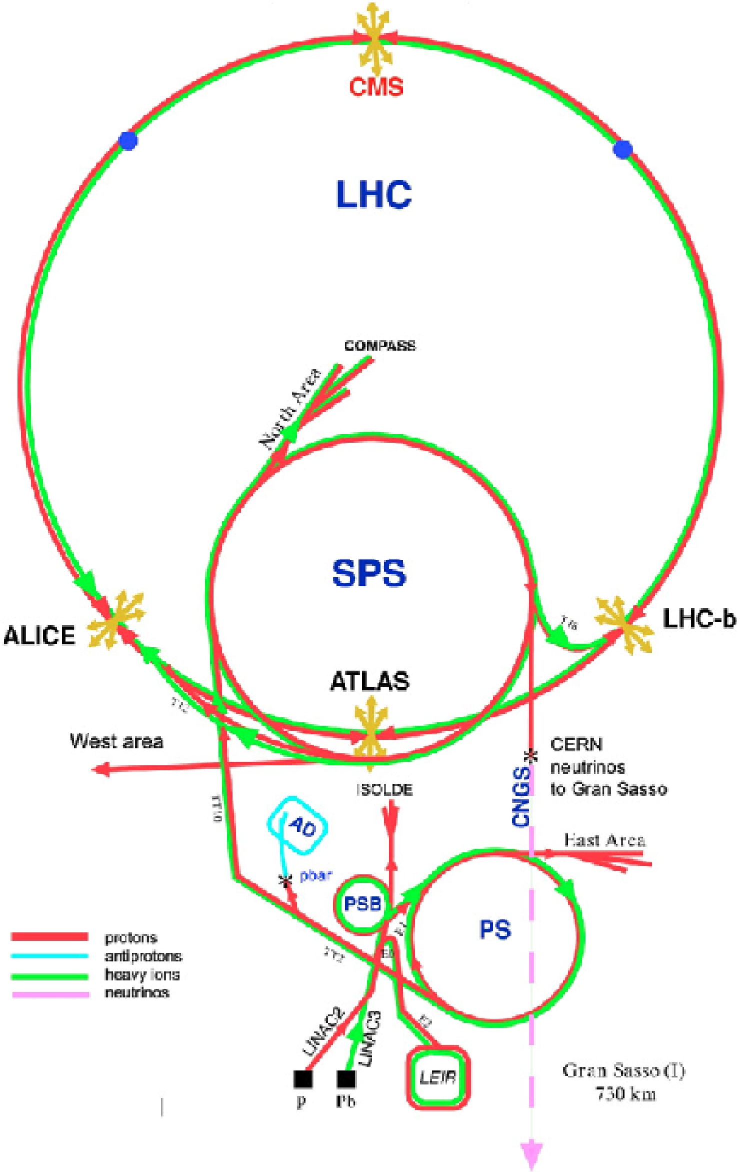
In the North Area at CERN, SPS beam of high-intensity and high-energy is hitting several primary targets. The secondary beams obtained supply different beamlines

At the M2 beamline, unique-in-the-world beams are available:

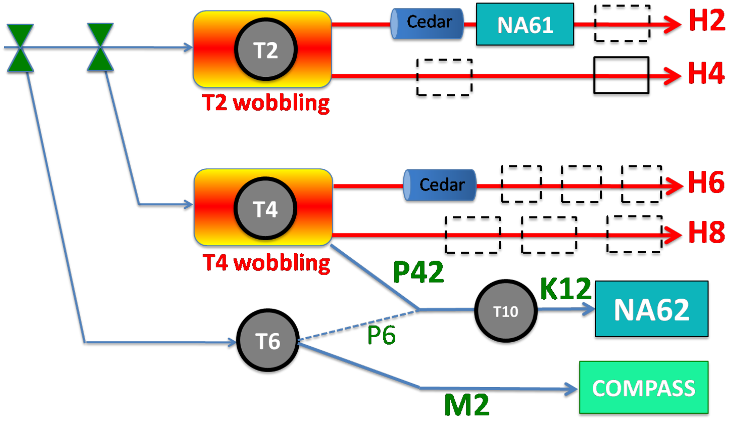
– Muon beams of both charges

– Hadron beams of both charges

In a wide range of momenta: 50 – 280 GeV/c


CMS
LHC
COMPASS
North Area
SPS
ALICE
LHC-b
ATLAS
West area
CERN
neutrinos
to Gran Sasso
ISOLDE
CNGS
AD
pbar
East Area
PSB
PS
LINAC2
LINAC3
LEIR
p
Pb
Gran Sasso (I)
730 km
protons
antiprotons
heavy ions
neutrinos


T10 target
ECN3
EHN2
K12
M2
EHN1 Neutrino Platform
P42
EHN1
H2, H4, H6, H8
T2, T4, T6 targets
TT20 transfer line


T2
Cedar
NA61
H2
H4
T2 wobbling
T4
Cedar
H6
H8
T4 wobbling
P42
T10
K12
NA62
T6
P6
COMPASS
M2

From COMPASS to AMBER

The COMPASS experiment. (Image: CERN)

Apparatus for
Meson and
Baryon
Experimental
Research

physics possibilities

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

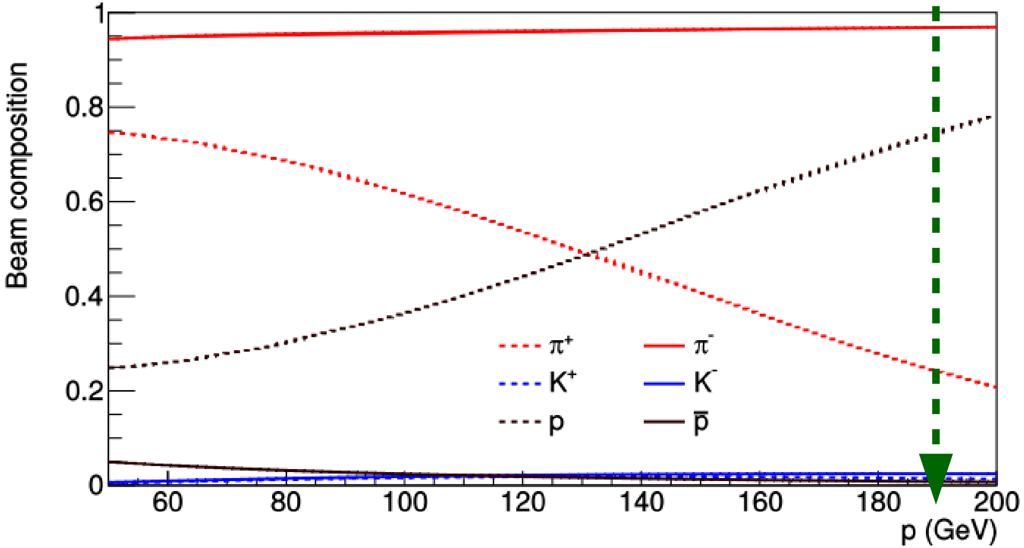
Phase-I (first five programs)

AMBER Proposal Phase-I:

http://cds.cern.ch/record/2676885?ln=en

Phase-II (last five programs)

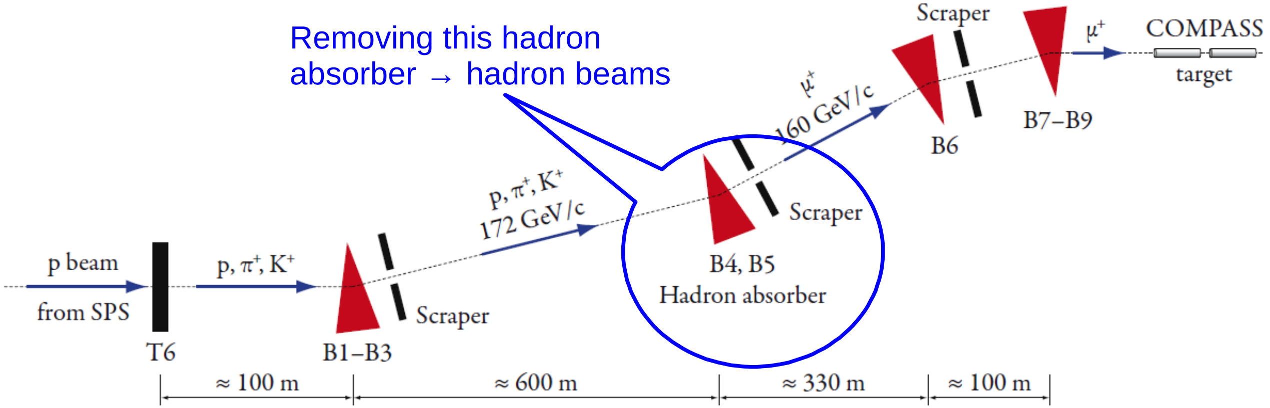
M2 beamline



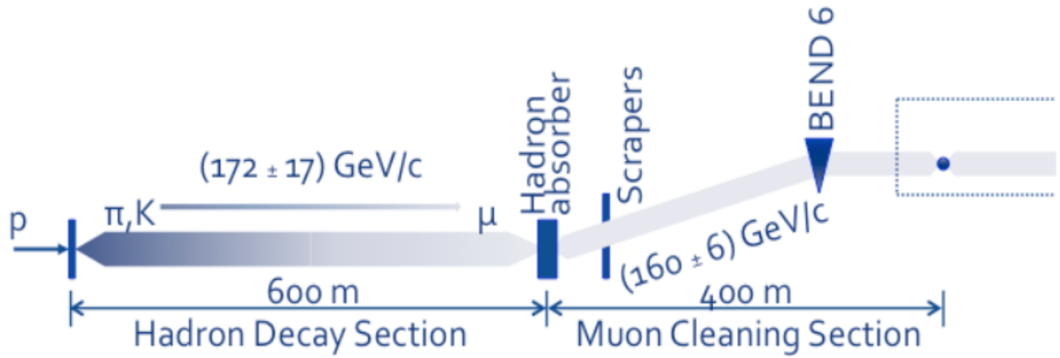
At 190 GeV/c:

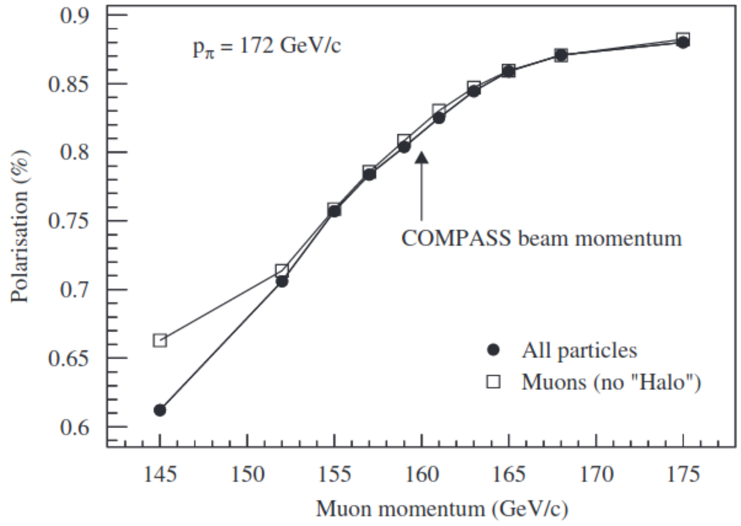
- Negative: 97% $\boldsymbol{\pi^-}$, 2.5% $\mathbf{K^-}$, < 1% $\bar{\mathbf{p}}$
- Positive: 74% **p**, 24% $\boldsymbol{\pi^+}$, 2% $\mathbf{K^+}$

The same beamline can provide muon and hadron beams



The muon beam



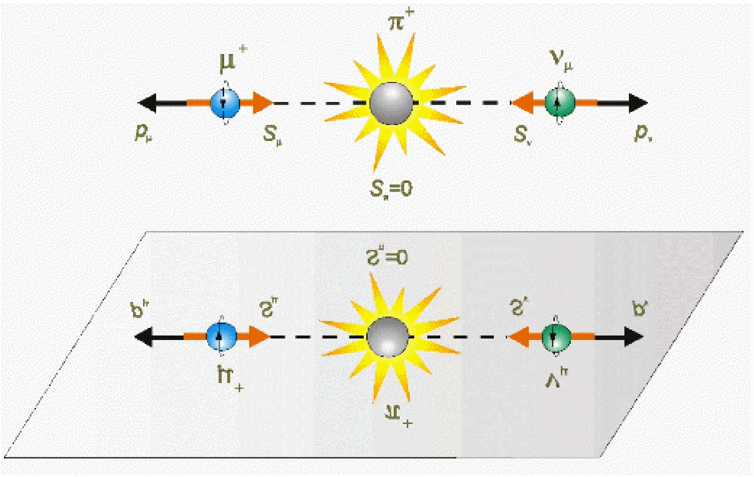


Pion weak decay:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

Only left-handed neutrinos

Polarized μ^+:
their spin must be antiparallel to their direction of flight



The physics questions to be answered:

The massive world we observe is made of protons – stable particles composed of quarks and gluons.

The variety of hadrons, mostly short-lived, and why their very different characteristics,
Is the subject of Quantum Chromodynamics.

Emergence of Hadron Mass

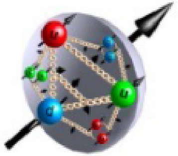
Pion

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

Kaon

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

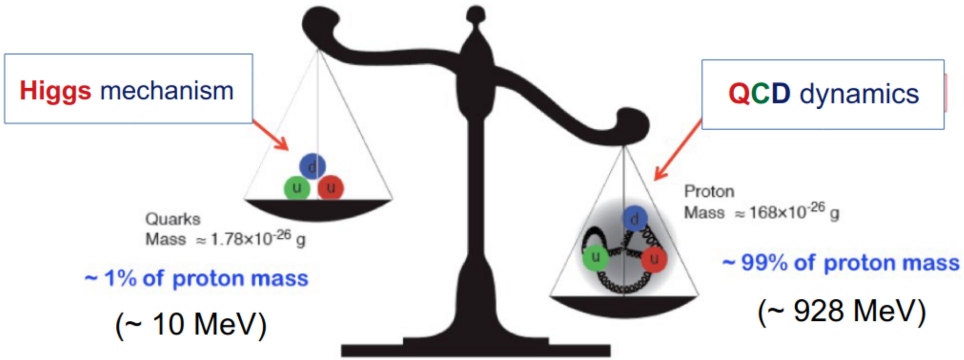
Proton



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

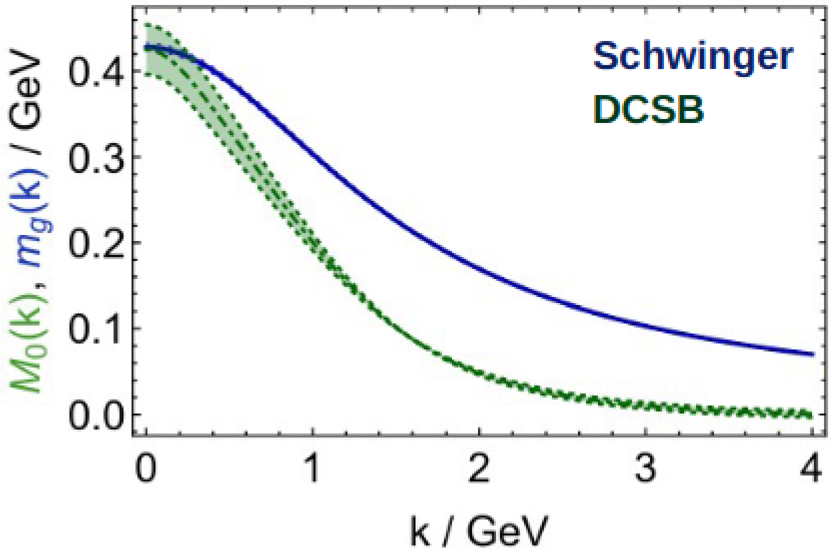
How to understand that M_π/M_p ~ 1/7, while from constituent-quarks model one would expect ~2/3?

Only 1% of the proton mass is due to the Higgs mechanism.

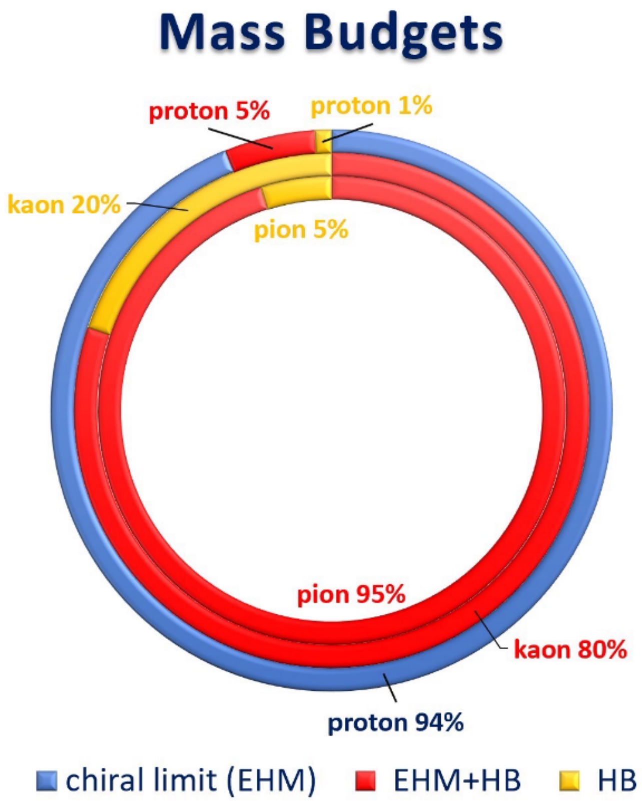


Emergence of Hadron Mass

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



Gluon and quark *running masses*



EHM at AMBER

The Emergence of Hadron Mass is the leitmotiv for the various proposed measurements.

EHM is key for understanding QCD, a theoretical approach that addresses:

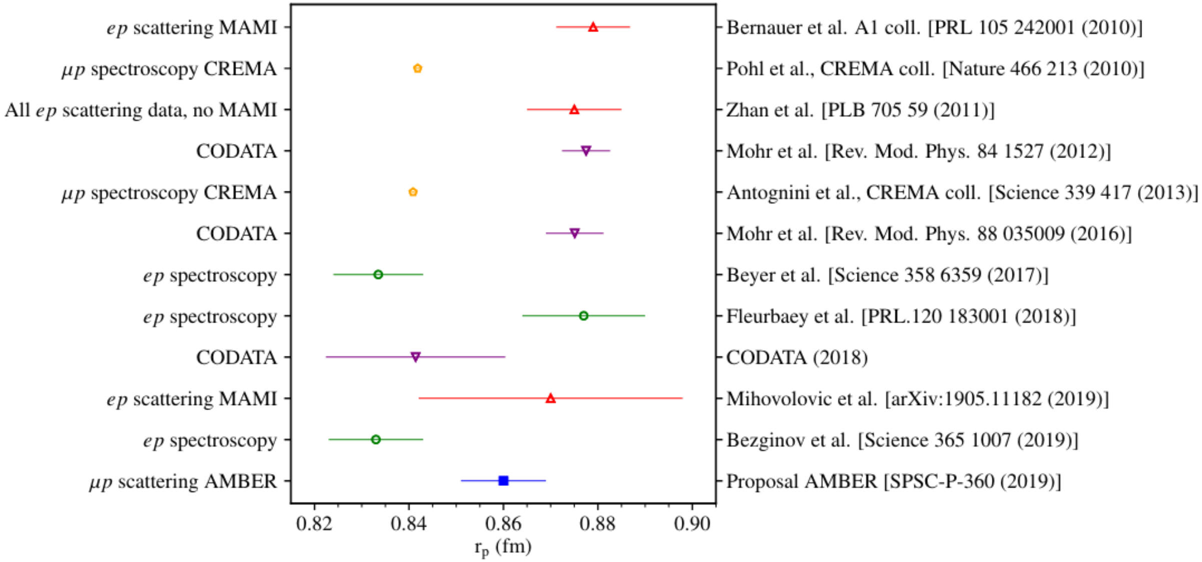
- Hadron charge radii
- Hadron masses
- Hadron spectroscopy
- Hadron structure

… and all this to be validated by:

- Lattice calculations
- **Experimental measurements**

1) The proton charge radius puzzle

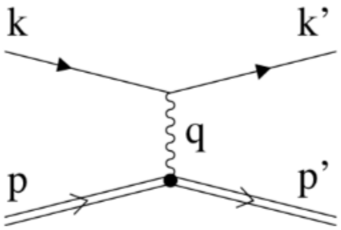
Status in October 2019:



Two types of measurements: **lepton-proton scattering** and **hydrogen spectroscopy** leading to discrepant results → ~ 5 σ

Proton radius at AMBER

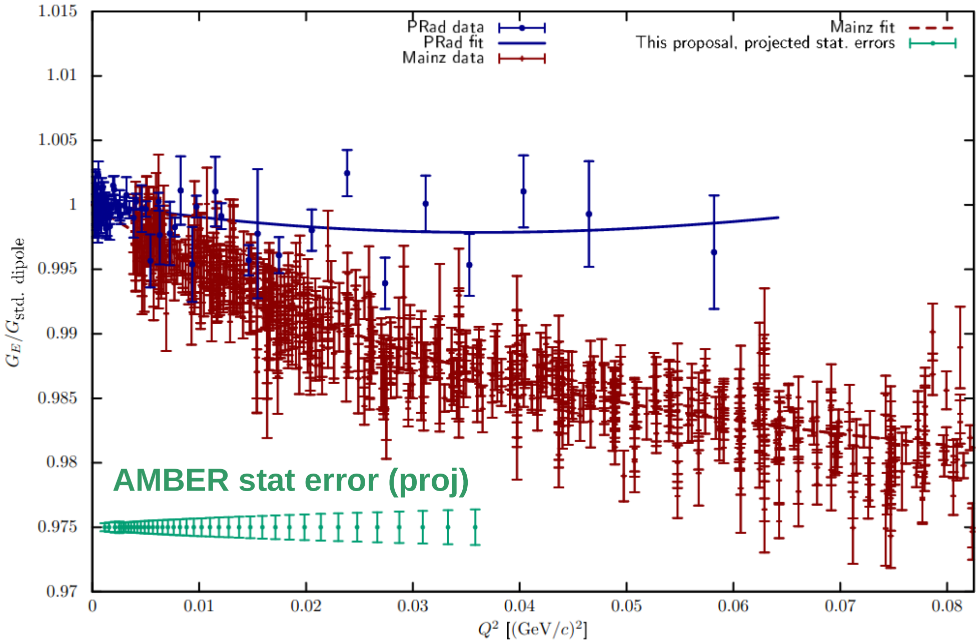
The proton charge radius can be accessed via the electromagnetic form factors.
Experimentally, AMBER will measure the **elastic muon-proton scattering** for this:



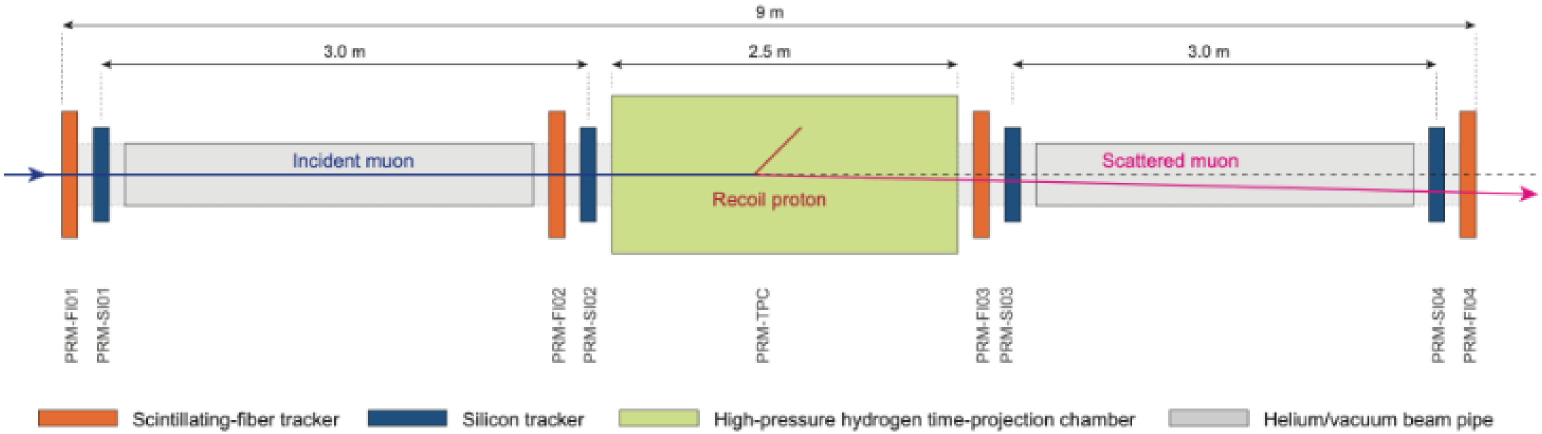
G_E, G_M

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

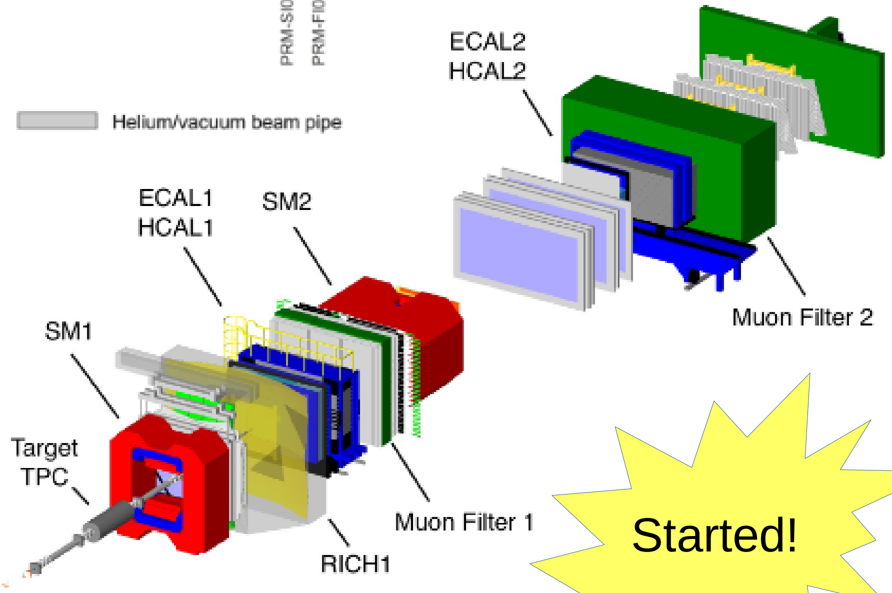
$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2 \to 0}$$



Muon-proton high energy scattering

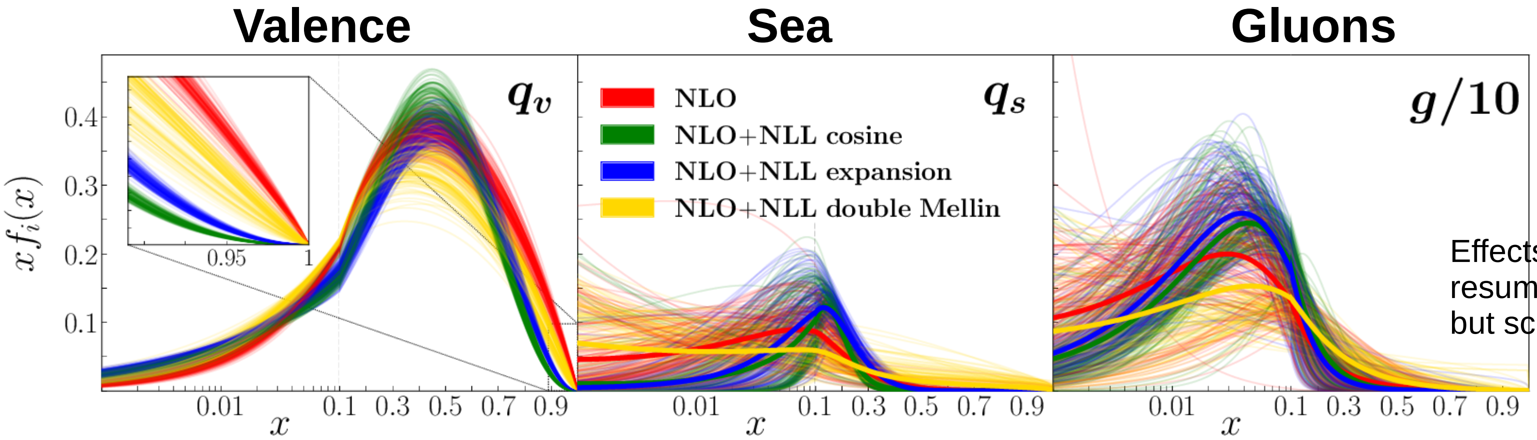


- 100 GeV muon beam
- Active-target TPC with high-pressure H_2
- goal: 70 million elastic scattering events in the $10^{-3} < Q^2 < 4{\cdot}10^{-2}$ GeV^2 range
- Precision on the proton radius ~0.01 fm
- Pilot run with smaller TPC in 2021



Started!

2) The pion structure

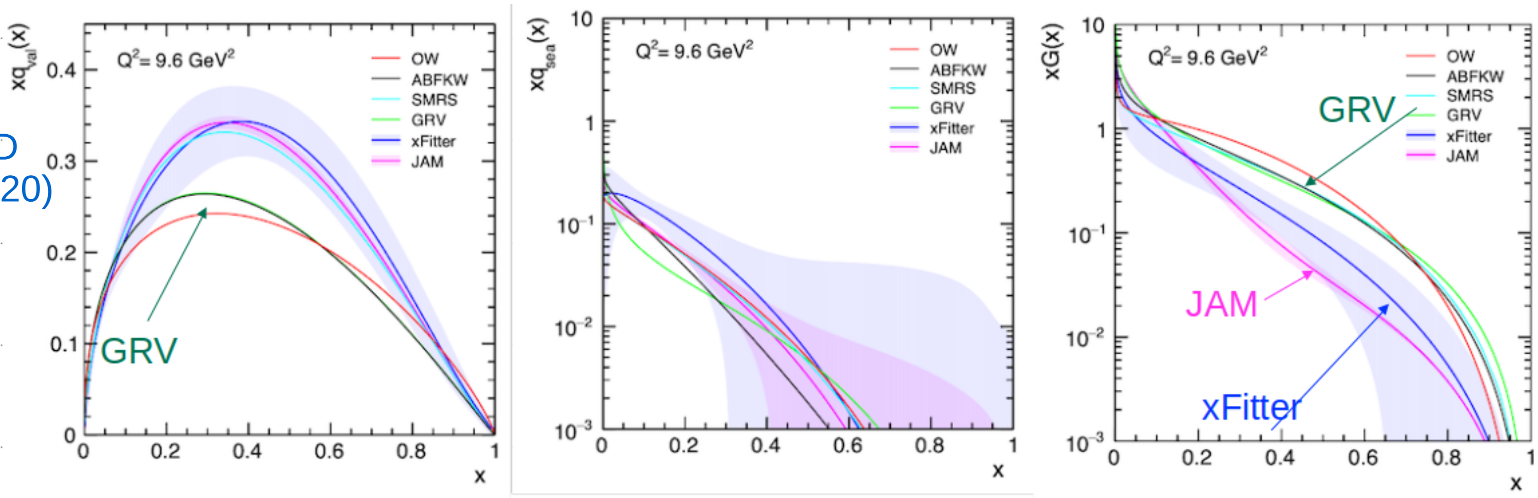


Effects of threshold resummation included, but scheme dependent

Extractions including Drell-Yan data and leading-neutron DIS data

JAM, arXiv:2108.05822

Chang et al. PRD 102, 054024 (2020)



Drell-Yan at AMBER: access to pion structure

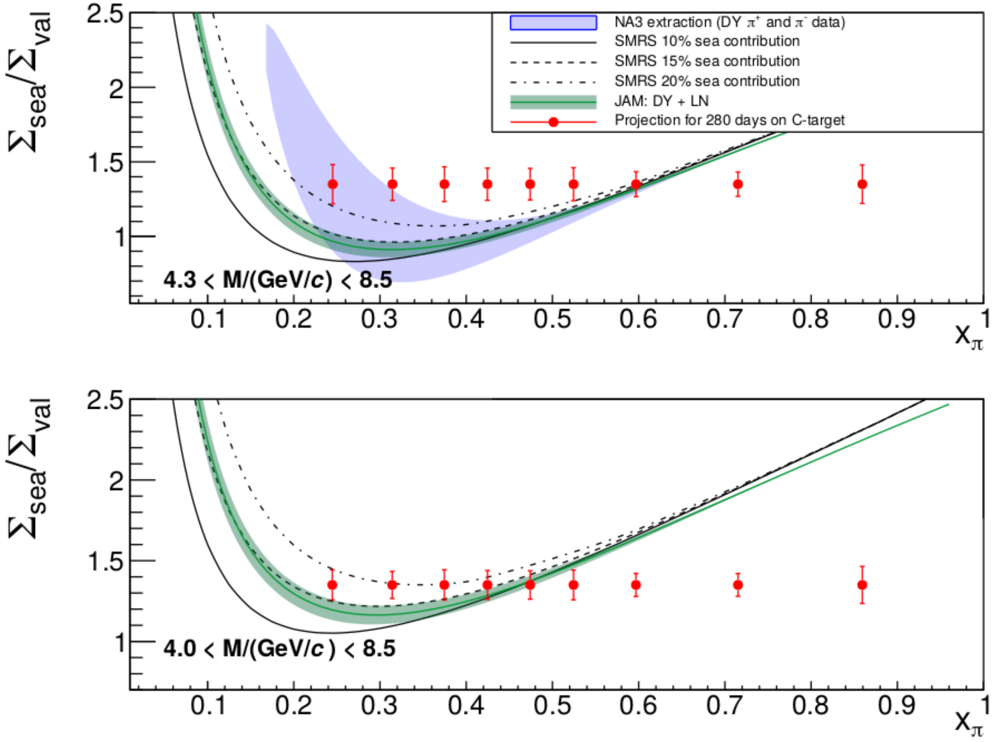
Definitions:

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

And assuming flavour-symmetry:

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

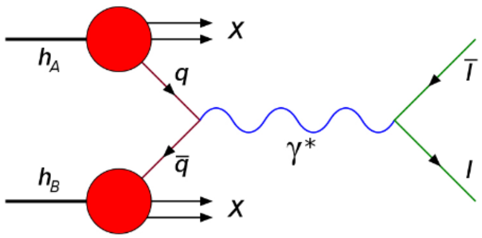
$$\bar{u}_{sea}^{\pi} = u_{sea}^{\pi} = \bar{d}_{sea}^{\pi} = d_{sea}^{\pi} = \bar{s}_{sea}^{\pi} = s_{sea}^{\pi}$$



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

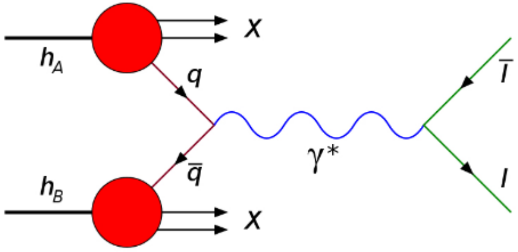
LO: only sea-val and val-sea terms

LO: only val-val terms



Pion-induced Drell-Yan at AMBER

Approved



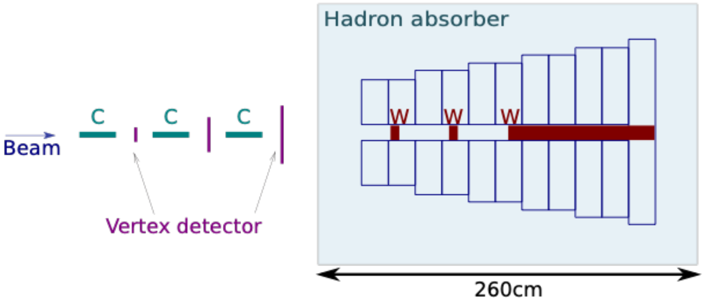


Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

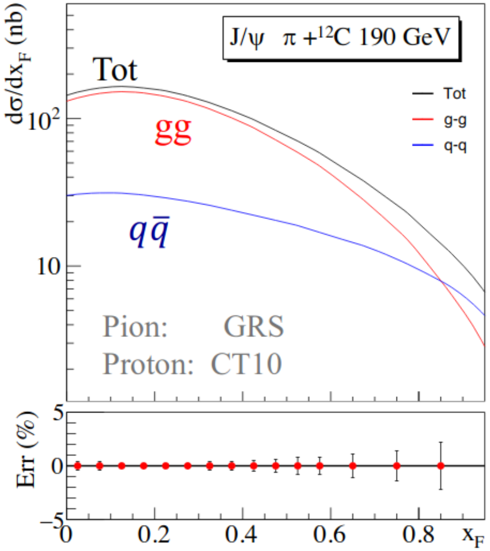
Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120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

Isoscalar target

Both beam charges

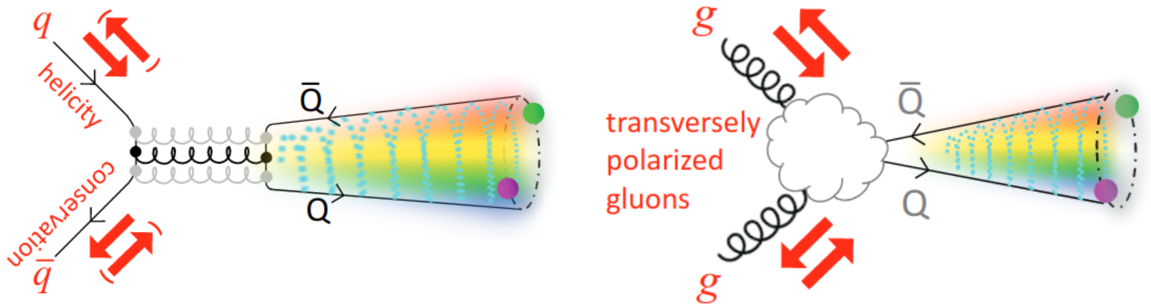
High statistics

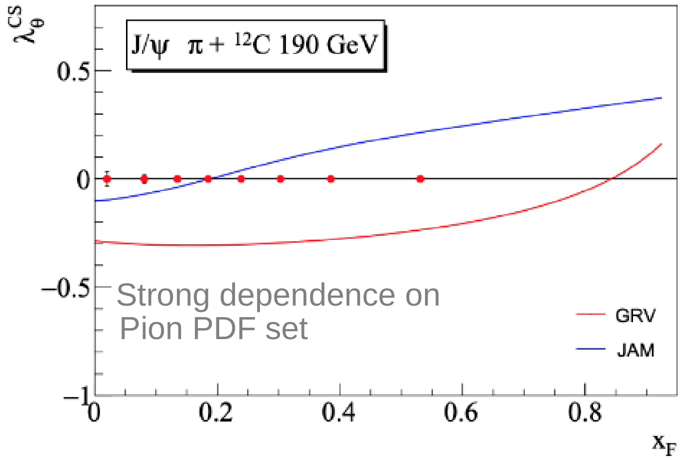
Gluon content in the pion



what can we learn from J/ψ production at AMBER?

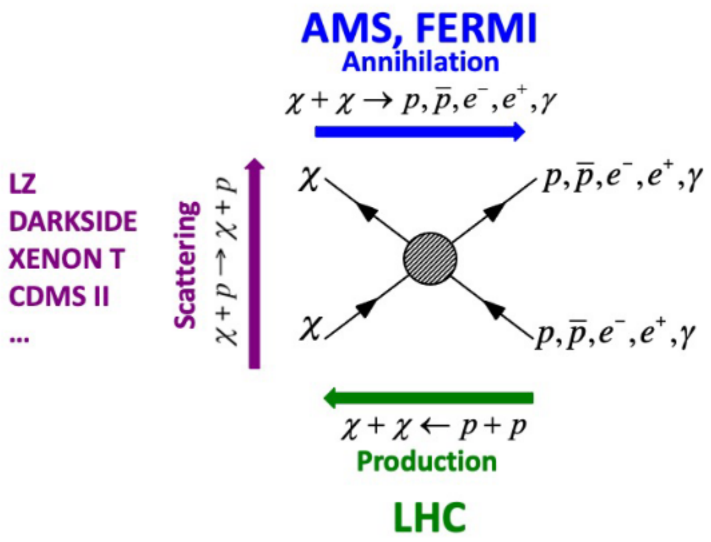
- Large statistics on J/ψ production at dimuon channel
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- In the low-pT regime
- Expected to have dominant contribution from $2\rightarrow1$ processes
- Use J/ψ polarization to distinguish production mechanism:



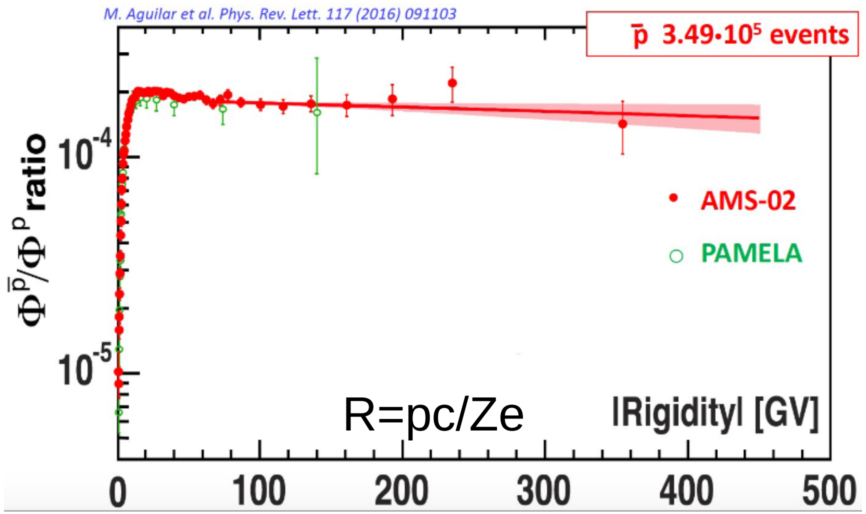


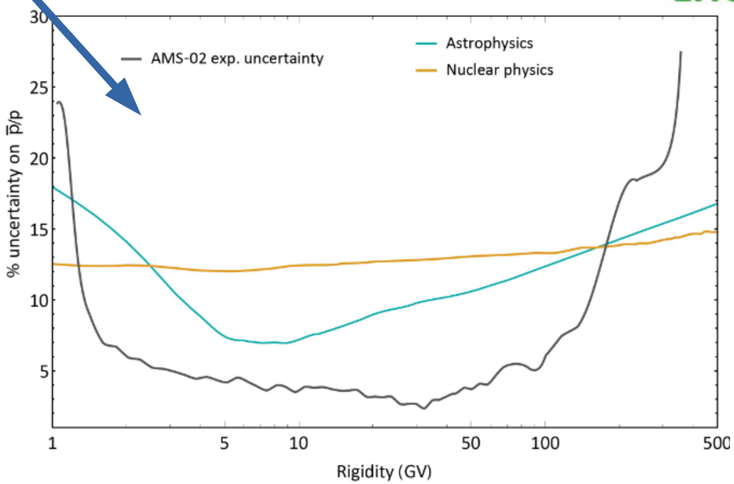
3) A detour: the antiproton production cross section

Needed as input to the Dark Matter searches:
for example to interpret AMS data.



$\bar{p}$ production x-section uncertainties from p-p and p-He collisions is a limiting factor to know the $\bar{p}$/p flux ratio expected

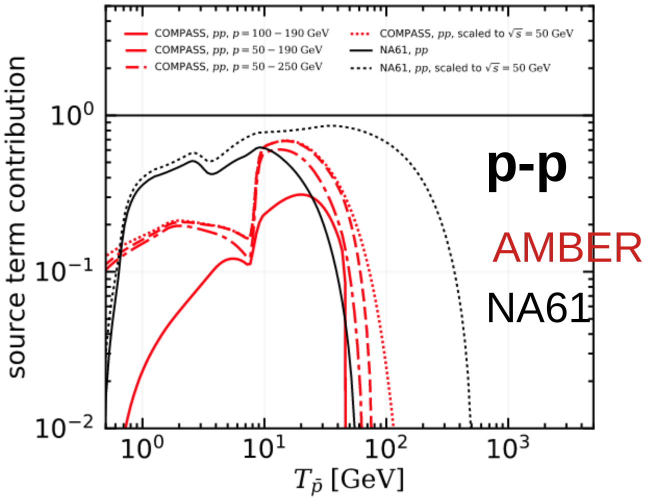




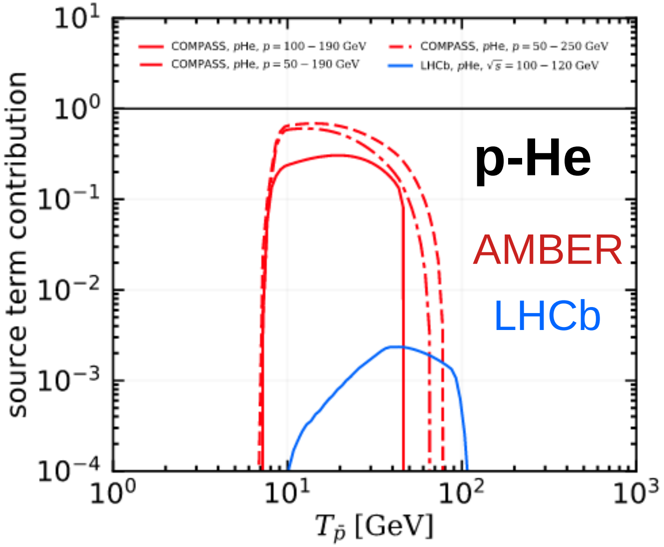
$\bar{p}$ cross section at AMBER

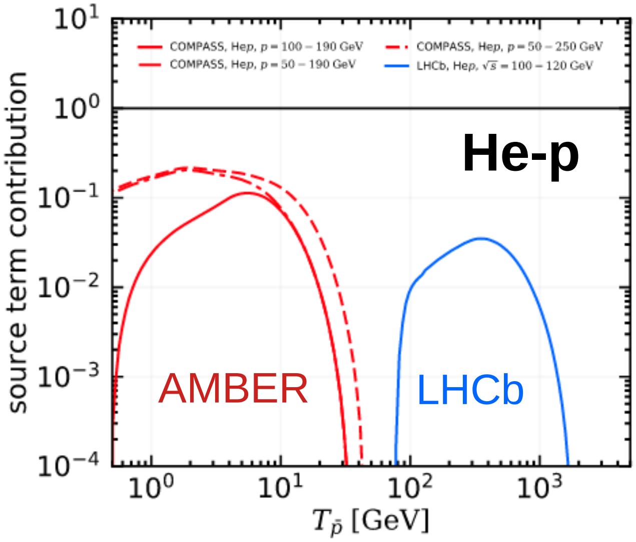
- Secondary proton beams from SPS at 50, 100 and 190 and 280 GeV/c
- Liquid Hydrogen and Helium targets
- Antiprotons identified using RICH

Approved



Plots:
Impact of AMBER in constraining the $\bar{p}$ production versus kinetic energy.



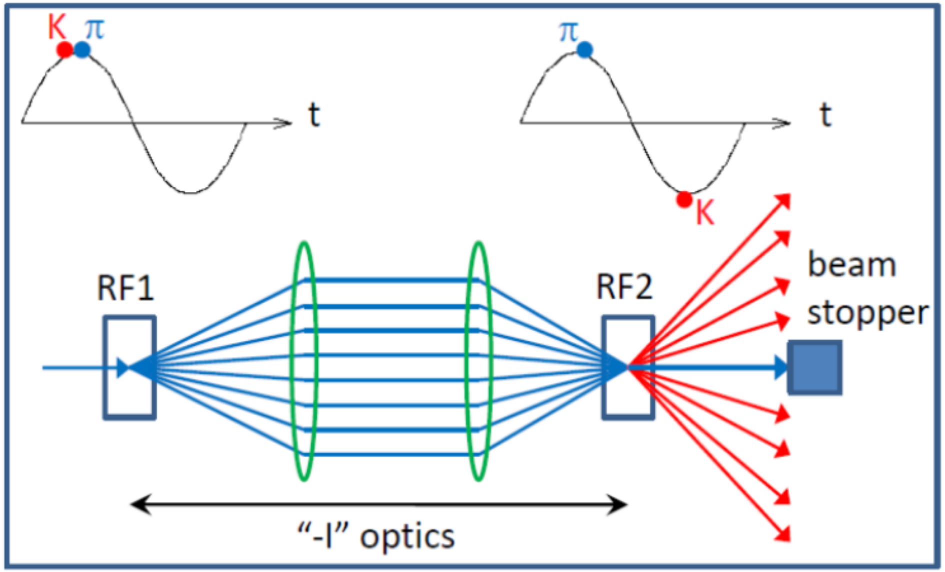


Opportunities, further ahead in the future:

Radio-frequency separated hadron beams

AMBER Phase-II

Upgraded M2 beamline: RF-separated beams



Radio-frequency separation is a technique where some particle species end dumped in a beam stopper, while the chosen ones (dependent on distance "l") provide a **cleaner, still intense, beam**.

$$\Delta\phi \approx \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$$

R&D from CERN Beams Department

- **$K^{\pm}$ beams with 60 – 100 GeV/c**
- **$\bar{p}$ beam with 80 – 110 GeV/c**

Question: but how high can the beam intensity be?

4) Kaon structure: u_k/u_π

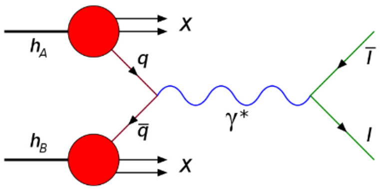
Kaon structure: a window to the region of interference between the Higgs mechanism and the EHM mechanism

The only available experimental data:

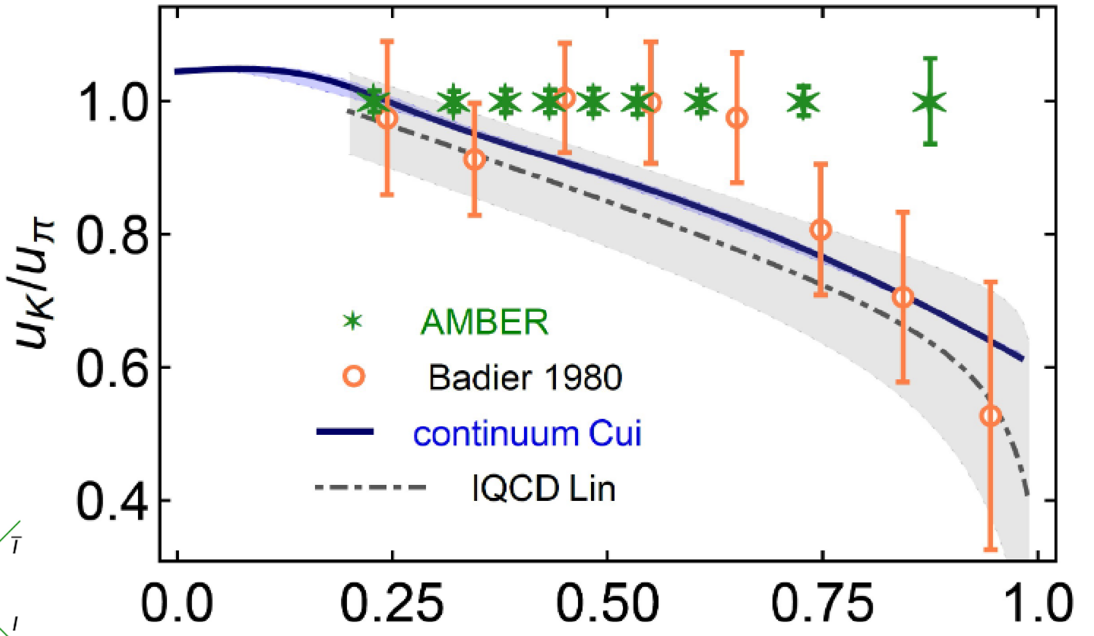
NA3 → 200 GeV K^- beam on 6 cm Pt target

700 kaon-induced Drell-Yan events

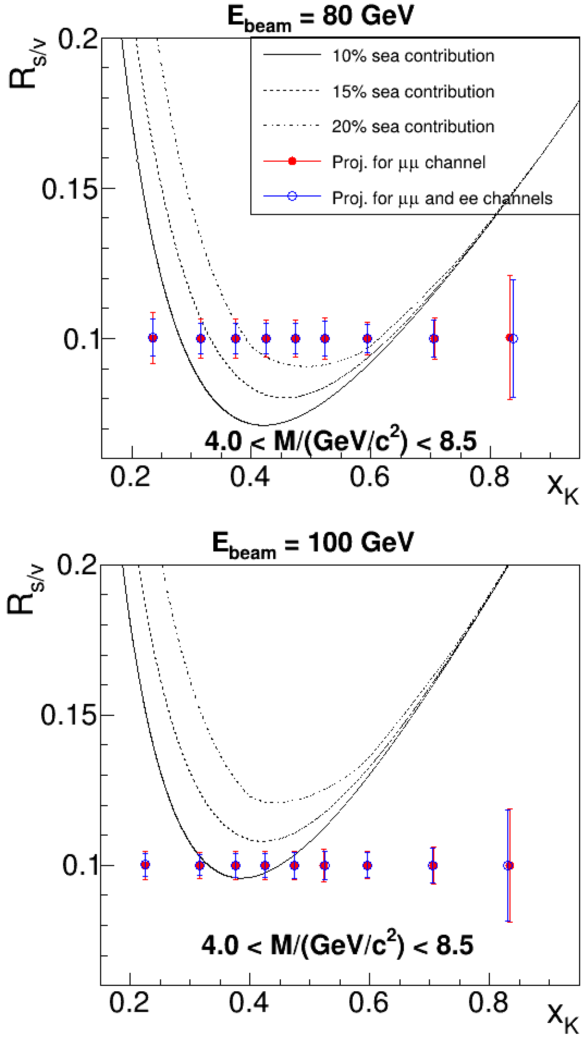
AMBER kaon-induced Drell-Yan



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

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c²)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6cm Pt	K^-	????	200	4.2 – 8.5	700	0
AMBER	100cm C	K^-	2.1×10^7	80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
		K^+	2.1×10^7	80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
AMBER	100cm C	π^-	4.8×10^7	80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000

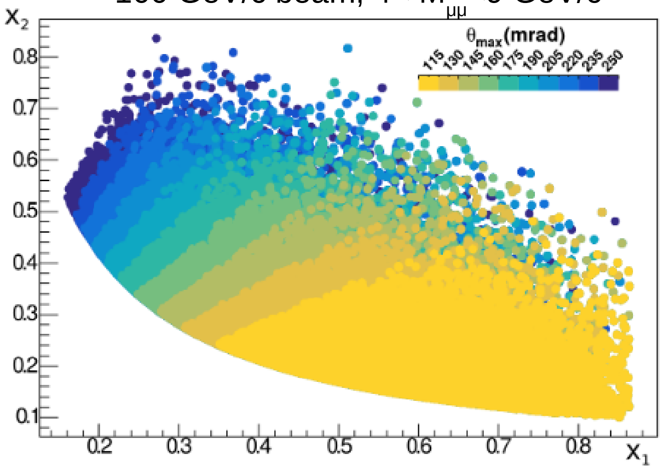
Kaon-induced Drell-Yan in AMBER

If using kaons from RF-separated beams, the momentum must be < 100 GeV/c

In a fixed-target experiment, the lower beam momentum implies smaller angular acceptance

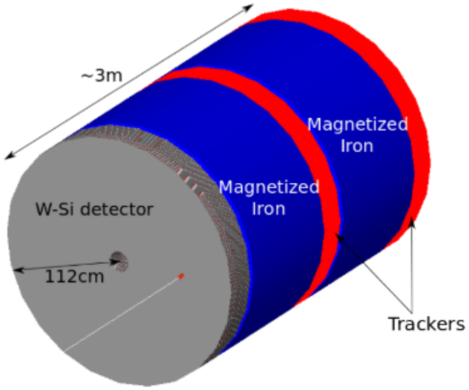
In order to keep the dilepton acceptance ~40% → Compress the spectrometer

100 GeV/c beam, $4 < M_{\mu\mu} < 9$ GeV/c²



“Active absorber”:

- Trackers
- Magnetic field
- Large area
- Compact



J/Ψ production: an access to the gluon content in the kaon

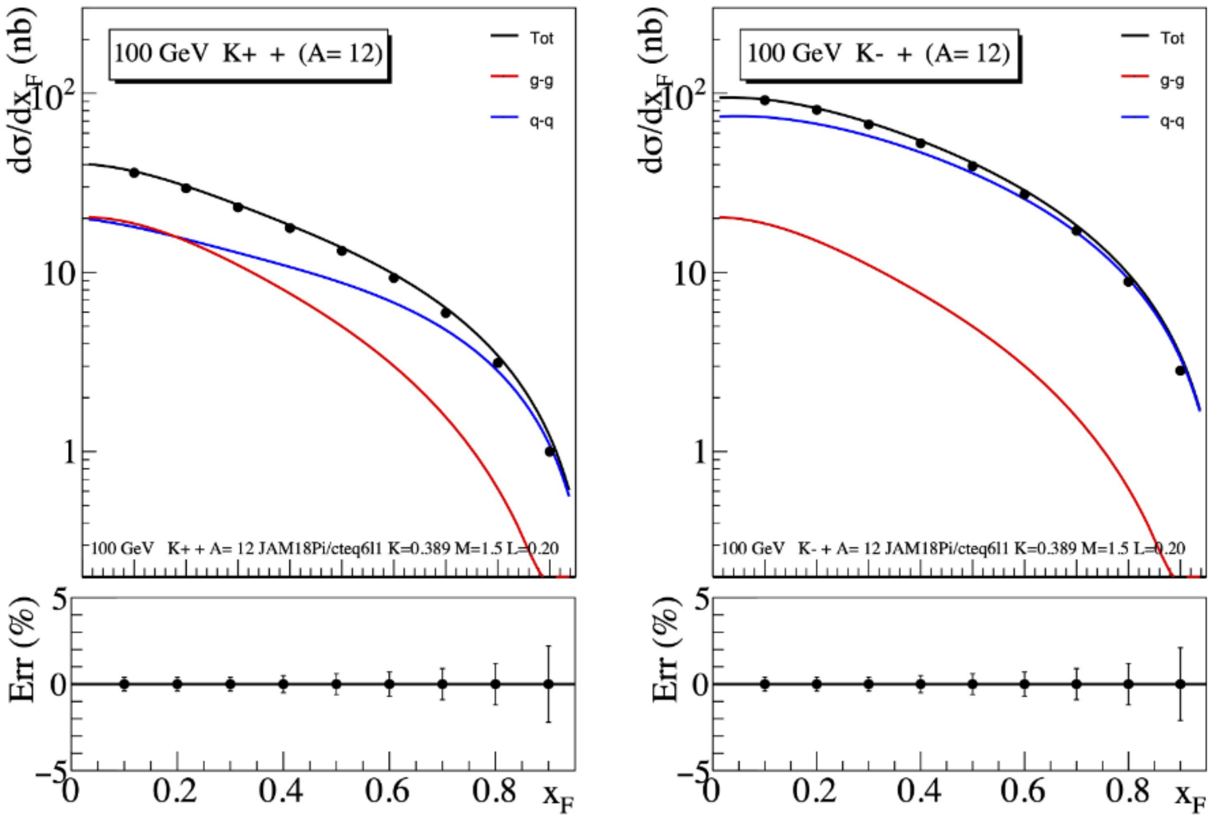
Using Color Evaporation Model (Int.J.Mod.Phys. A 10 (1995) 3043)
and JAM18 “pion” PDFs (PRL 121, 152001 (2018))

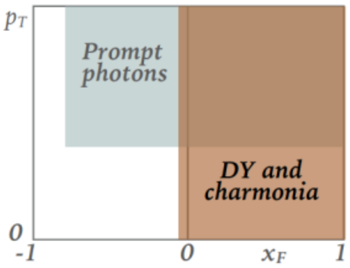
- J/Ψ data collected in parallel with kaon-induced Drell-Yan
- Large statistics
- Model-dependent access to the gluon distribution in kaons
- J/Ψ production cross section (LO):

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

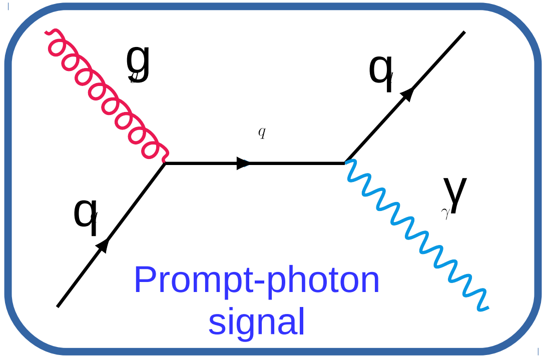
$$K^+(u\bar{s})+p(uud) \propto gg+\left[---\right]+\left[u_v^K \bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K \bar{u}_s^p+s_s^K \bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

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

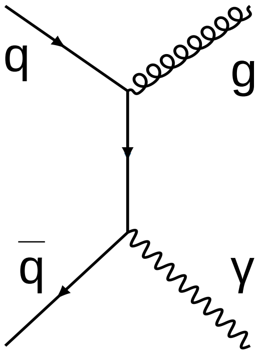




5) Prompt-photons: clean access to the gluon distribution in kaon

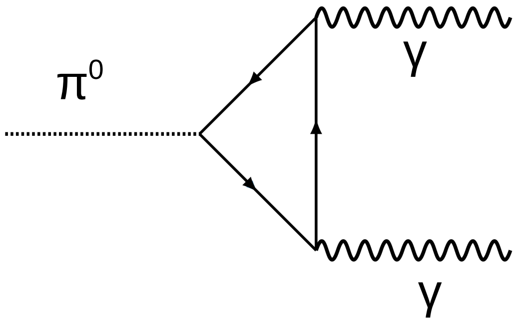


Direct access to the gluon PDF at $x_g^K > 0.05$, $Q^2 \sim p_T$



background

K^+ beam: minimize bkg

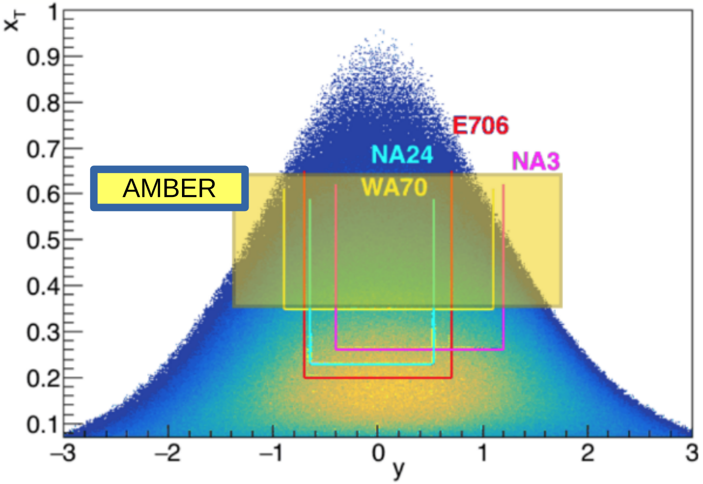


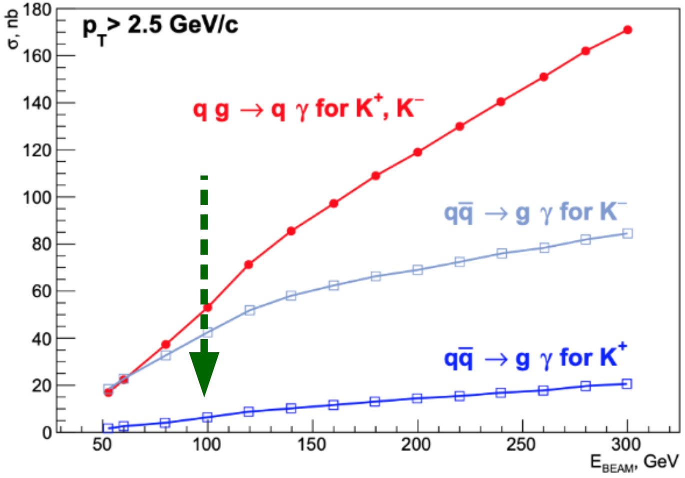
Minimum bias photons background

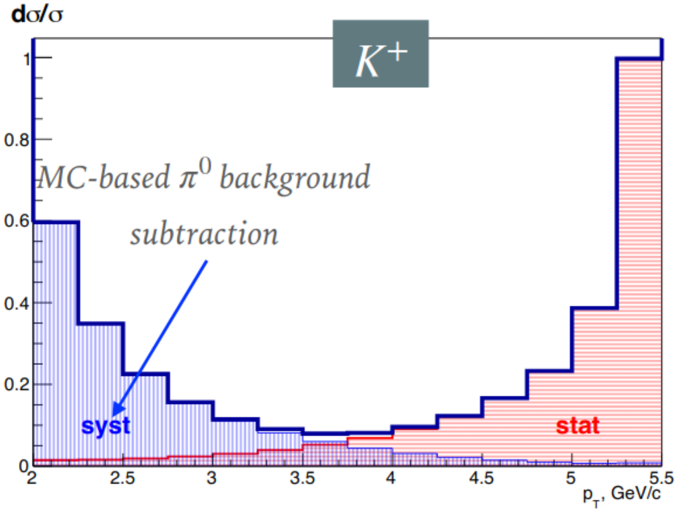
$p_T^\gamma > 2.5$ GeV/c: minimize photon background

100 GeV K^+ beam on a long lH_2 target

Kaon-induced prompt-photon production





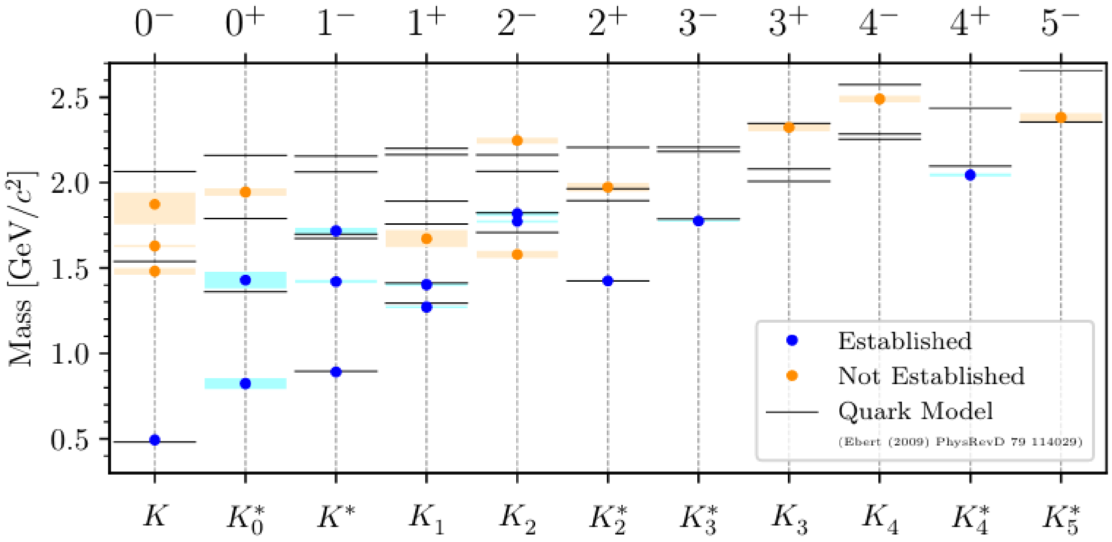


$x_T = 2p_T/\sqrt{s}$

In 140 days

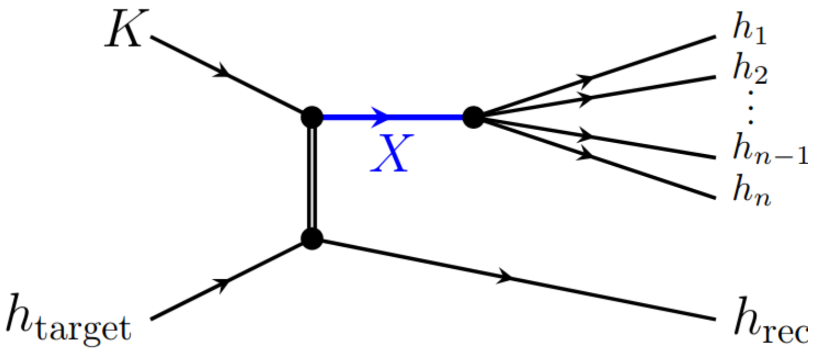
Experiment	Target type	Beam type	Beam Intensity (part/sec)	Beam Energy (GeV)	$\int \mathcal{L}$ (pb^{-1})	p_T range (GeV/c)	prompt-photon events
WA70	1m lH_2	π^+	2.5×10^6	280	1.3	$4 < p_T < 7$	—
		π^-	1.25×10^7	280	3.5	$4 < p_T < 7$	—
AMBER	2m lH_2	K^+	2×10^7	100	50	$p_T > 2.5$	3.4×10^6
		π^+	2×10^7	100	50	$p_T > 2.5$	3.4×10^6

6) Kaon beam: an opportunity for strange-meson spectroscopy



From the 25 strange mesons listed presently in the PDG, 13 still need experimental confirmation:

- 3 predicted K^*_j states missing. Searches via $K^{\pm}p$ scattering, like $K^{\pm}p \rightarrow K\pi n$ or through heavy meson and τ decays
- 11 predicted K_j states missing. Searches via heavy meson and τ decays to multi-body final states



X: strange-meson
Searched for and characterized with **Partial Wave Analysis**

7) Meson radii

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

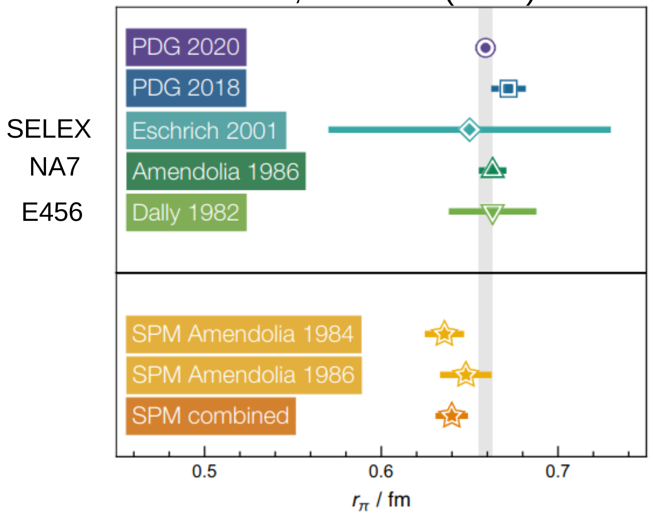
Pion and kaon radii: an expression of the link between EHM and confinement

Pion radius

Measurements of pion scattering at low Q², done in the 1980' s

r_π=0.659 ± 0.004 fm (PDG 2020)

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

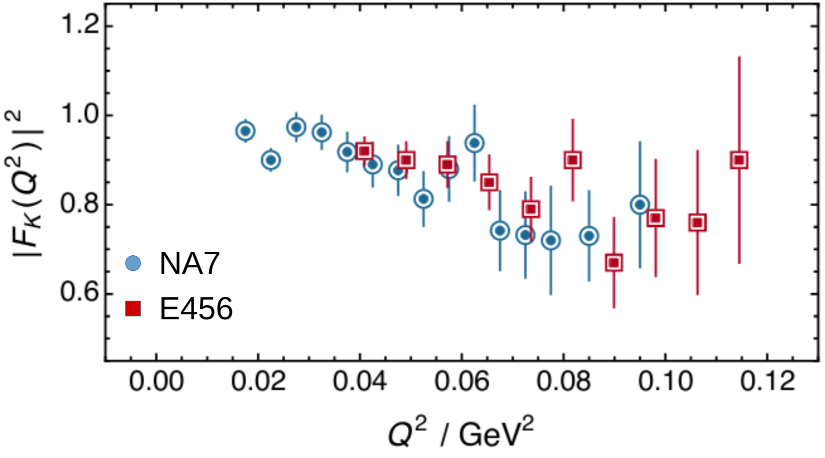


Kaon radius

Practically unknown

r_K=0.560 ± 0.031 fm (PDG 2020)

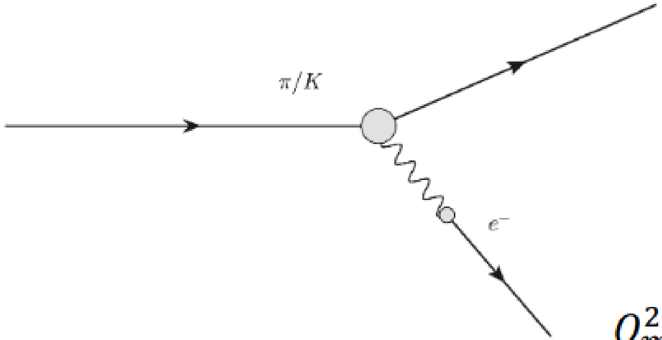
Z.-F.Cui et al, PLB 822 (2021) 136631



Kaon charge radius

80 GeV RF-separated beam:
kaon – electron elastic scattering,
to acces the kaon form factor

$0.001 < Q^2 < 0.07$ GeV²



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

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

$$Q^2_{max} = \frac{4p_b^2 \, m_e^2}{s}$$

Beam	E_b [GeV]	Q^2_{max} [GeV²]	$E'_{b,min}$ [GeV]	Relative charge-radius effect on c.s. at Q^2_{max}
π	190	0.176	17.3	~40%
K	190	0.086	105.7	~20%
	80	0.066	59.9	~15%
	50	0.037	41.3	~8%

...In 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
- Pion structure from pion-induced Drell-Yan and Charmonium production
- Antiproton cross-sections – input for Dark Matter searches

The planned 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:

- Kaon structure from kaon-induced Drell-Yan and Charmonium production
- Gluon content in the kaon from direct-photon production
- Light meson spectroscopy using kaon beams
- Kaon charge radius from elastic kaon-electron scattering
- ...

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