Hadron structure as seen by the AMBER experiment

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on behalf of the AMBER Collaboration

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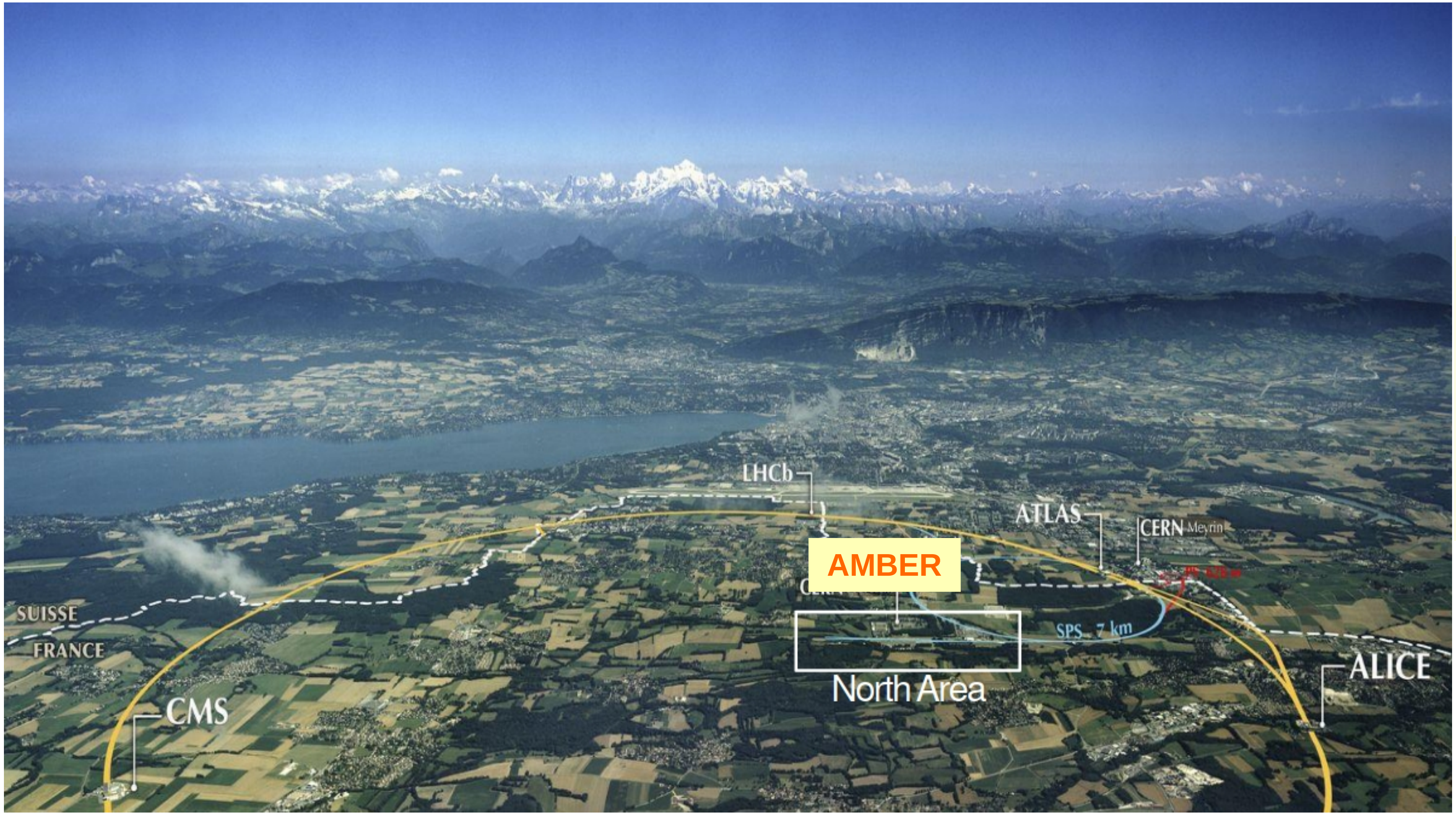
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Fundação para a Ciência e a Tecnologia

AMBER: at the North Area of the CERN-SPS



Apparatus for
Meson and
Baryon
Experimental
Research

Physics possibilities 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	$\bar{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\bar{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	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	$\sim$100	10^8	25-50	$K^\pm, \bar{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$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:

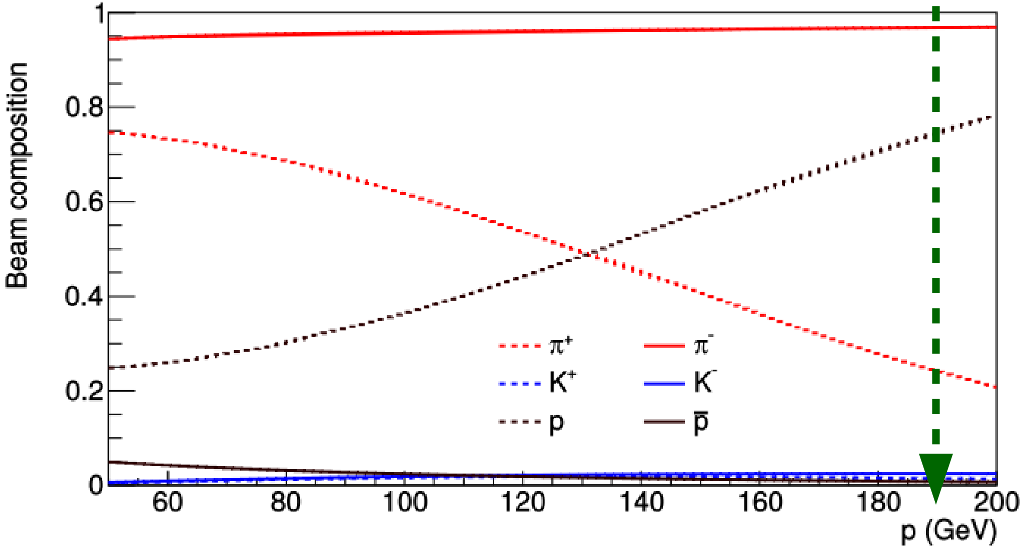
http://cds.cern.ch/record/2676885?ln=en

Phase-II

Proposal in preparation

...

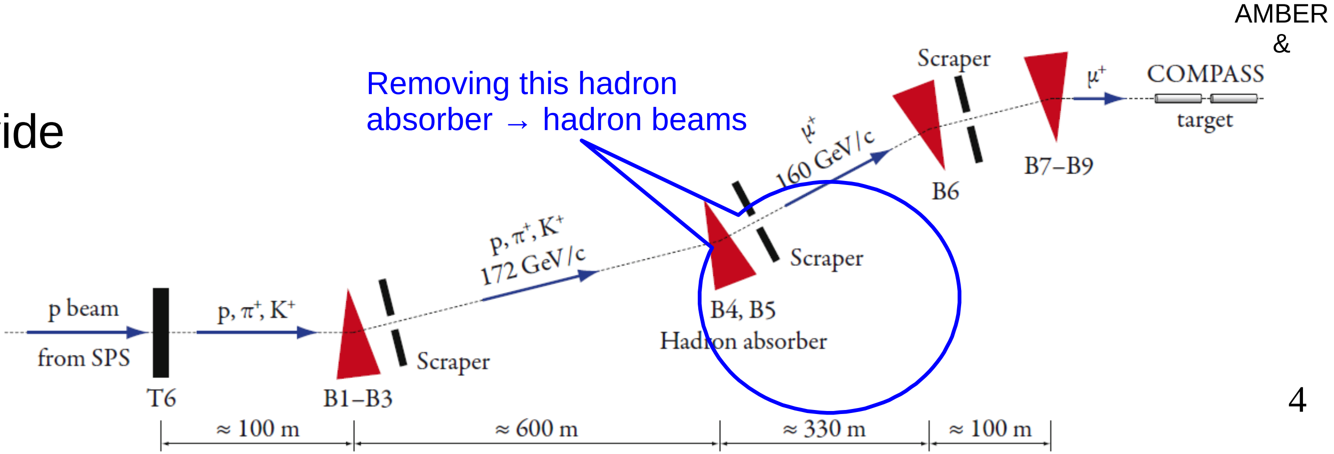
M2 beamline



At 190 GeV/c:

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

The same beamline can provide muon and hadron beams

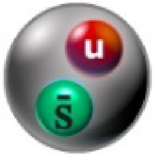


Emergence of Hadron Mass

Pion

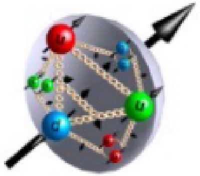
- $M_\pi \sim 140$MeV
- Spin 0
- 2 light valence quarks

Kaon



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

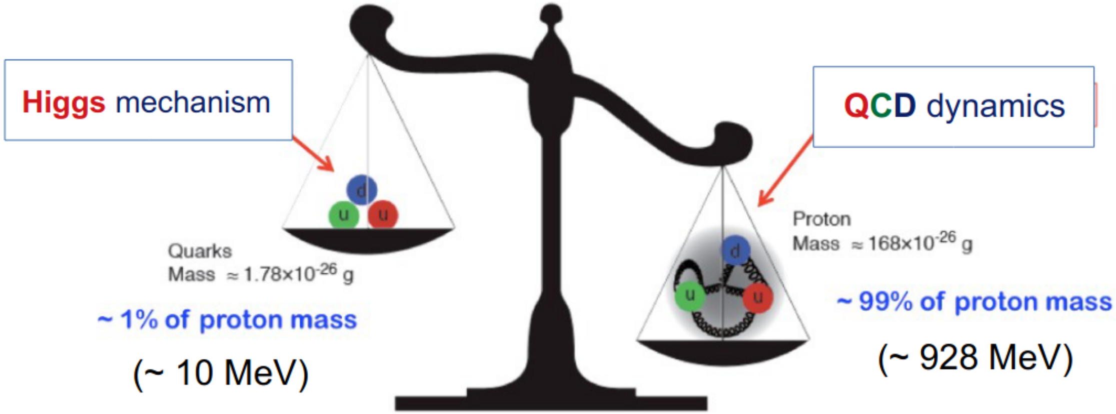
Proton



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

How to understand that $M_\pi/M_p \sim 1/7$, while from constituent-quarks model one would expect ~2/3?

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



EHM at AMBER

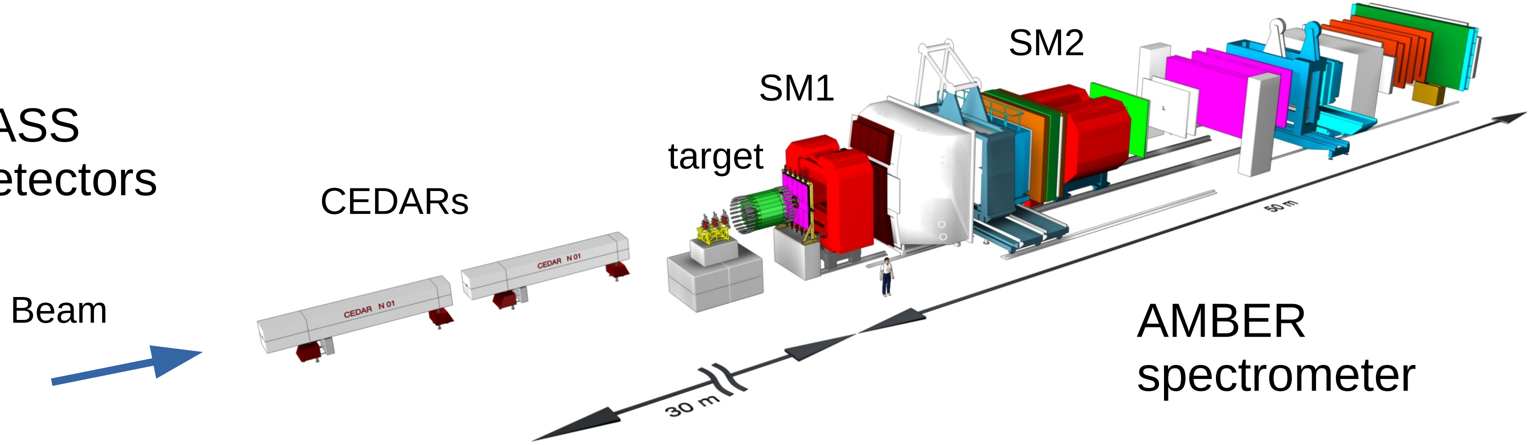
The Emergence of Hadron Mass is the leitmotiv for the various proposed measurements.

EHM is key for understanding QCD:
- Hadron charge radii
- Hadron masses
- Hadron spectroscopy
- Hadron structure

… and all this to be validated by:

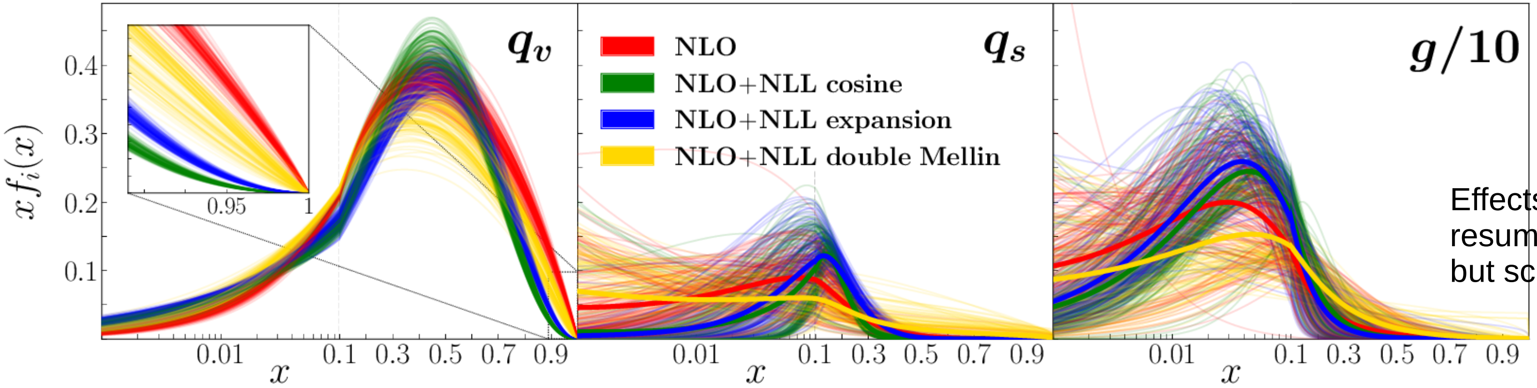
- Lattice calculations
- **Experimental measurements**

Setup similar to COMPASS with added/upgraded detectors and target region



The pion structure

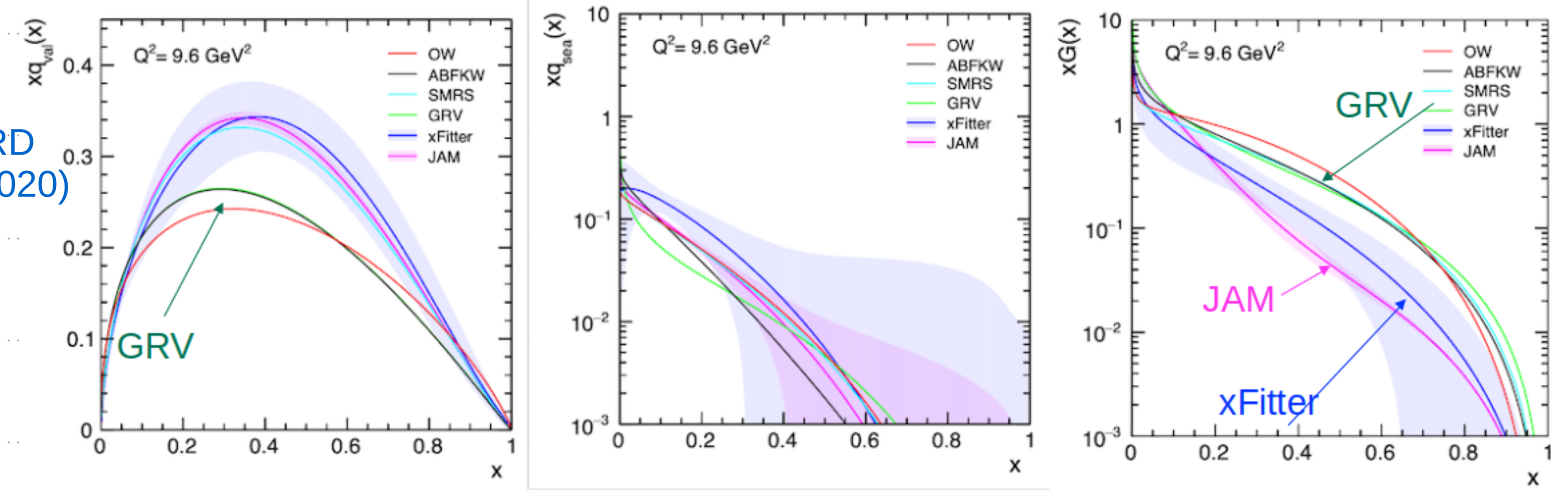
Valence **Sea** **Gluons**



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

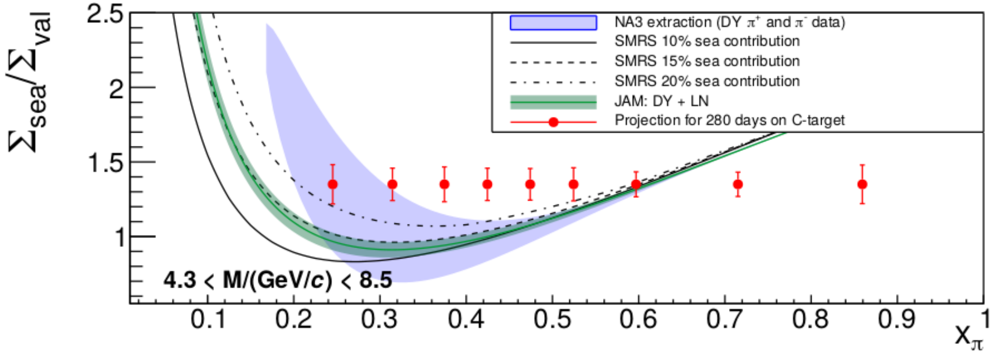
Definitions:

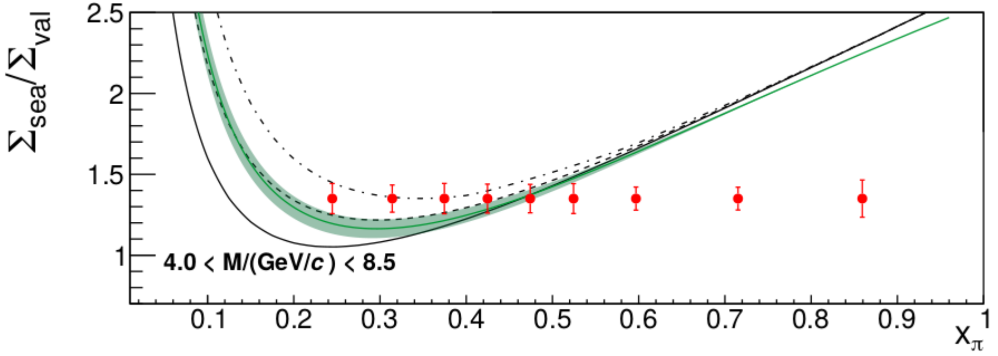
$$u_{val}^{\pi^+} = u^{\pi^+} - \bar{u}^{\pi^+} \text{ and } d_{val}^{\pi^-} = d^{\pi^-} - \bar{d}^{\pi^-}$$

And assuming flavour-symmetry:

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

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

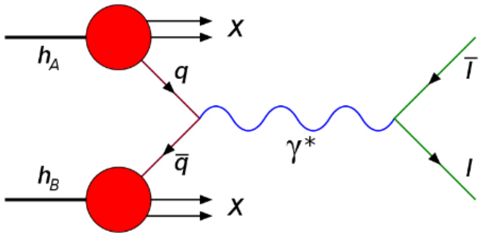




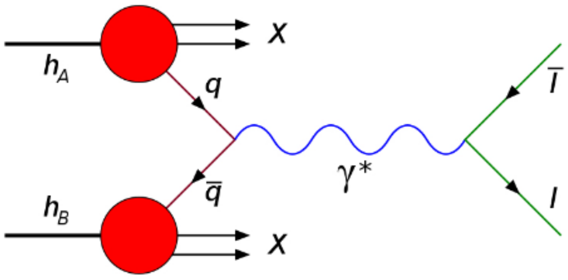
$$\frac{\Sigma_{sea}}{\Sigma_{valence}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$

LO: only sea-val and val-sea terms

LO: only val-val terms



Pion-induced Drell-Yan at AMBER



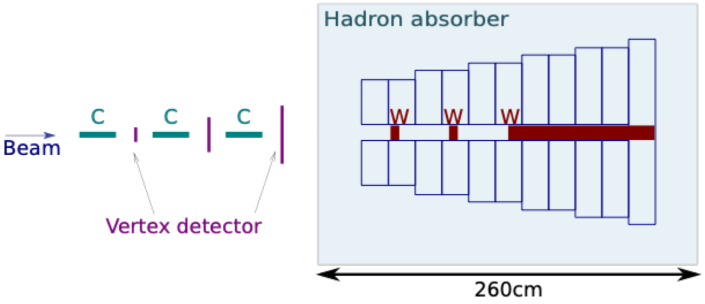


Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

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

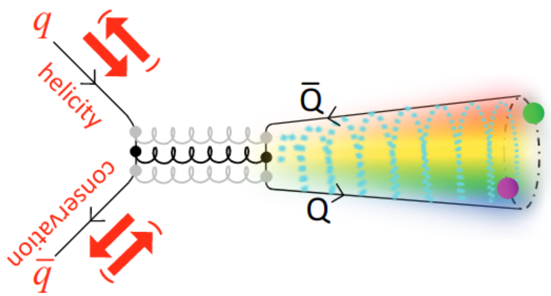
High statistics

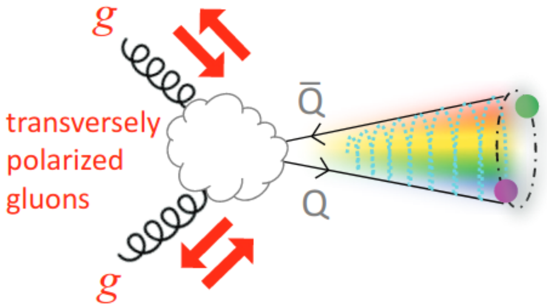
AMBER proposal

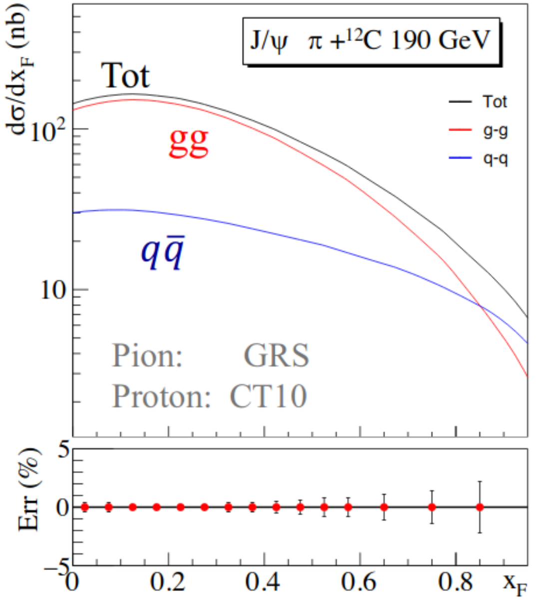
Gluon content in the pion

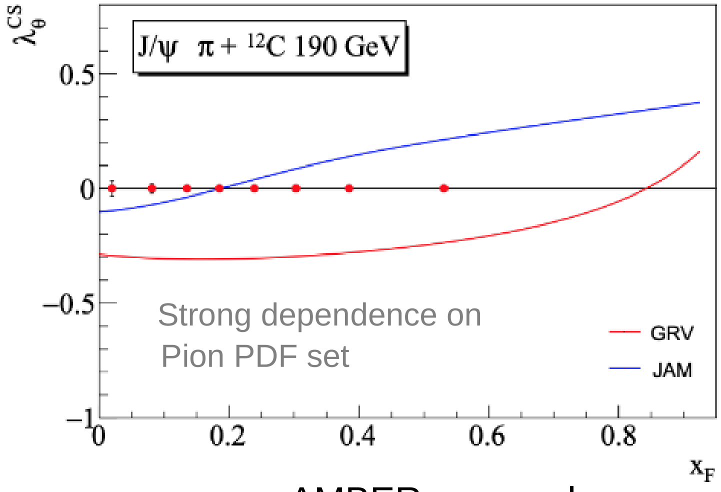
What can we learn from J/ψ production at AMBER?

- 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 $2 \rightarrow 1$ processes
- Use J/ψ polarization to distinguish production mechanism:



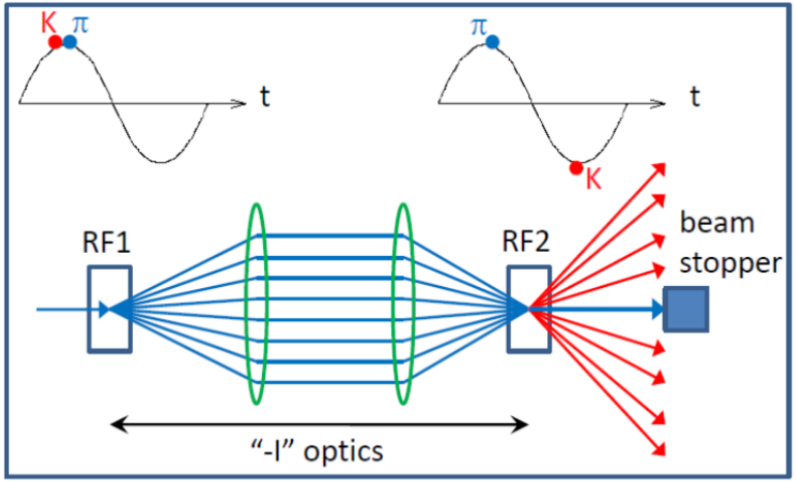






AMBER proposal

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 **high purity, 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**

But: how high can the beam intensity be?

Not enough for kaon-induced Drell-Yan…
Still, an optimal option for kaon polarizabilities, kaon charge radius, spectroscopy,...

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:

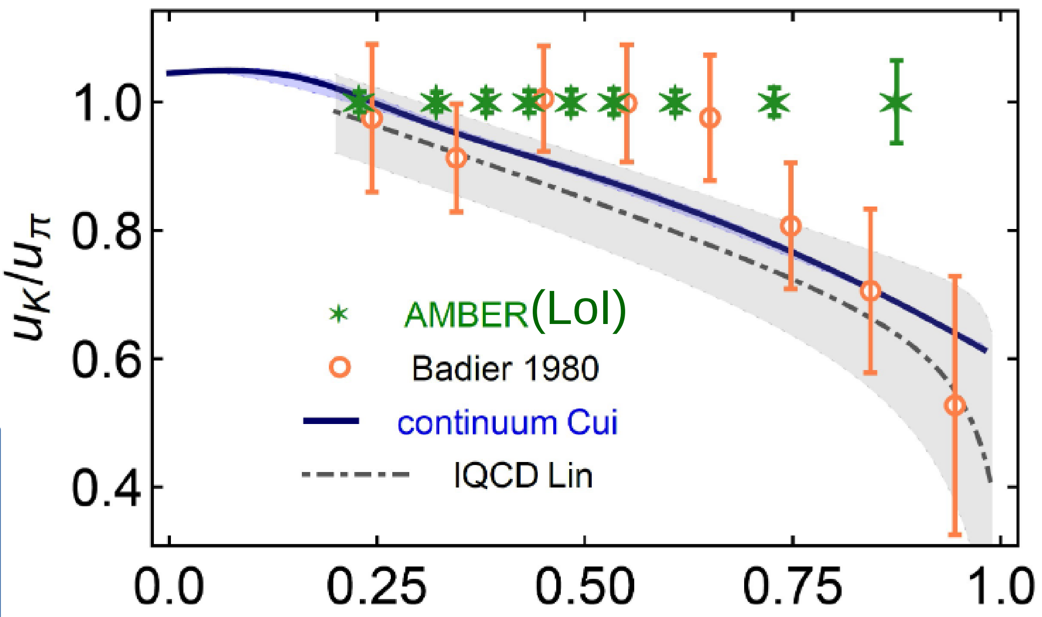
NA3 → 200 GeV K⁻ beam on 6 cm Pt target

700 kaon-induced Drell-Yan events

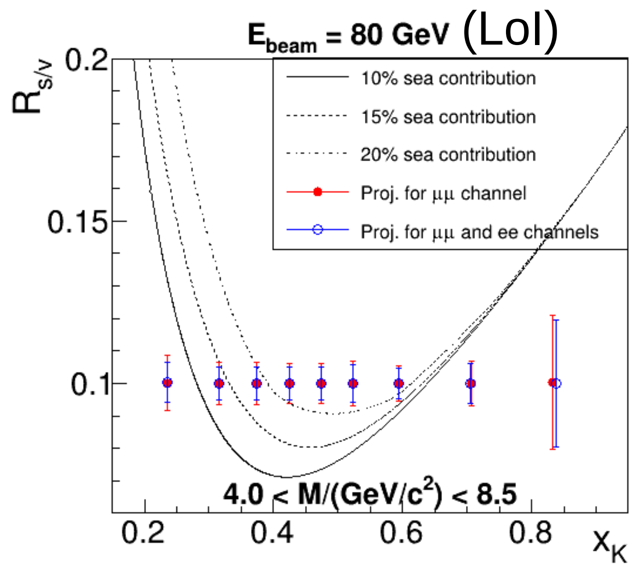
* AMBER (LoI):
Assumed an RF-separated beam of 2 x 10^7 kaons/second.

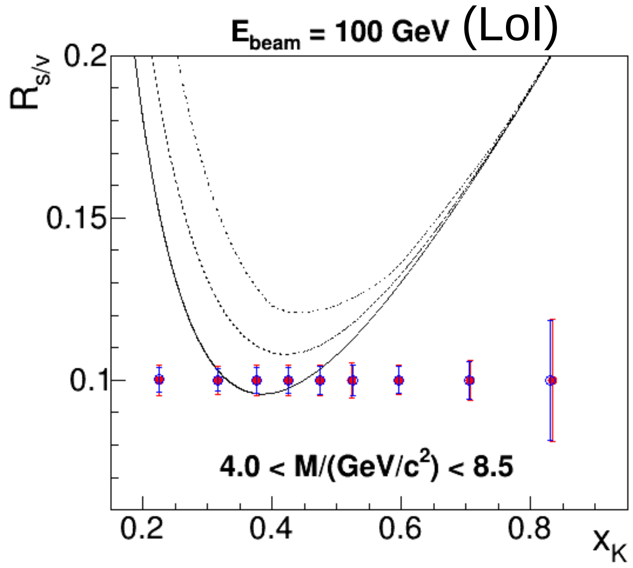
With a conventional beam – from improved beamline and beam telescope – the AMBER statistics goal scales down by a significant amount. But there would be important gain wrt NA3.

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

Kaon-induced Drell-Yan in AMBER

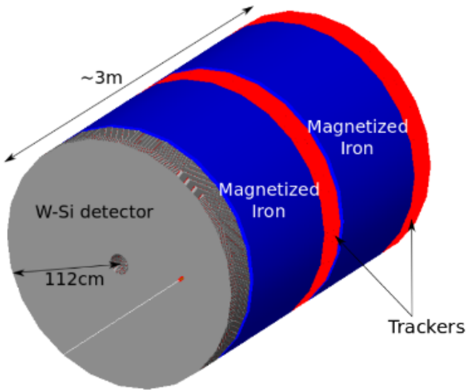
In a fixed-target experiment, in order to increase the geometrical acceptance:

→ Compress the spectrometer

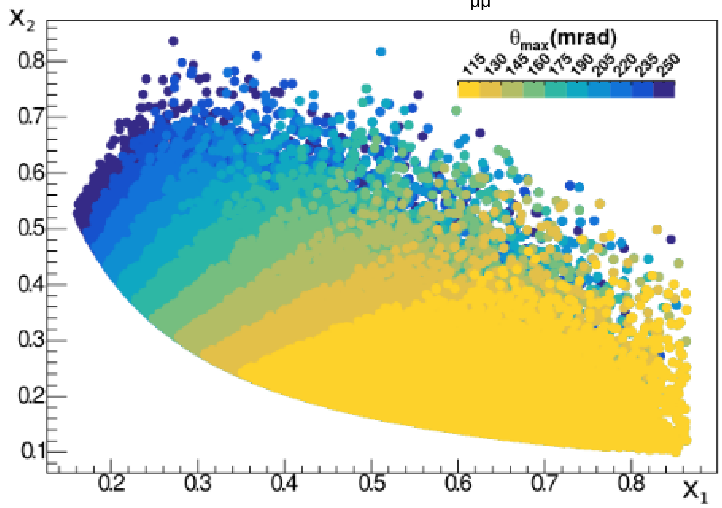
In order to improve the resolution:

"Active absorber":

- Trackers
- Magnetic field
- Large area
- Compact



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



(AMBER LoI)

For access to semi-inclusive processes:

→ A telescope upstream of the active absorber

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

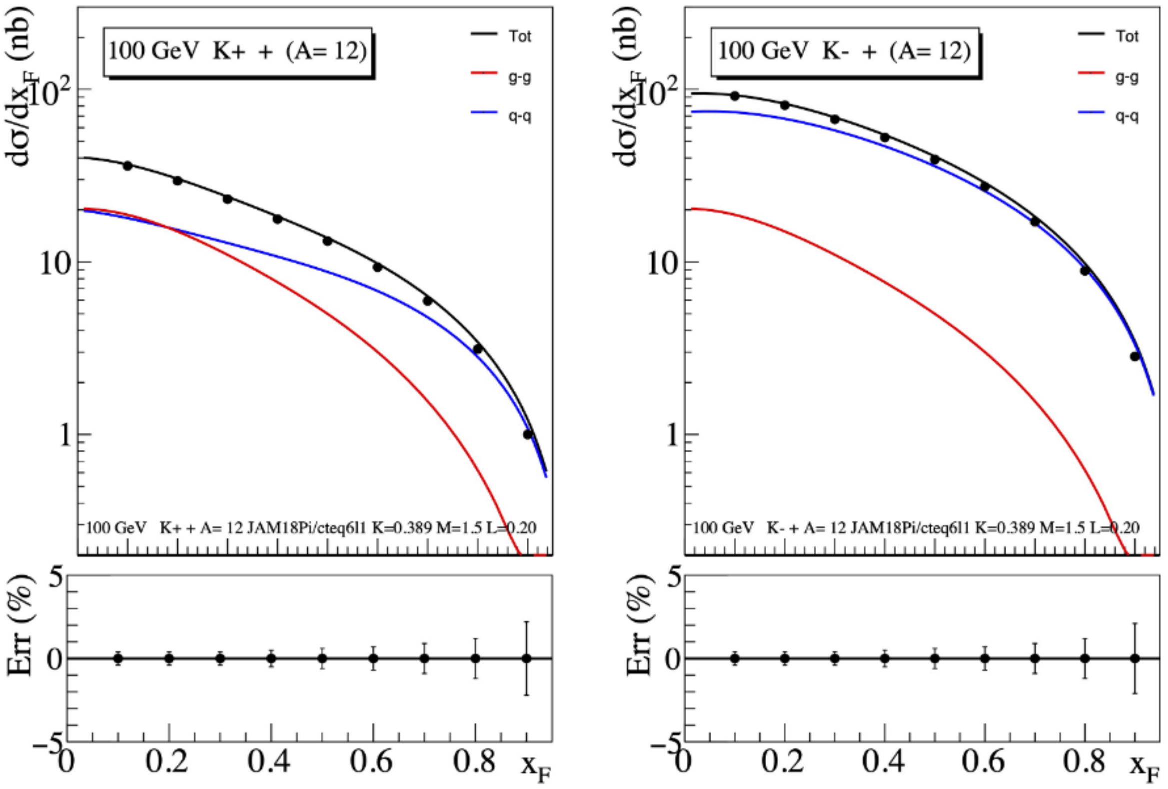
Using Color Evaporation Model (Int.J.Mod.Phys. A 10 (1995) 3043)
and JAM18 “pion” PDFs (PRL 121, 152001 (2018))

- 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):

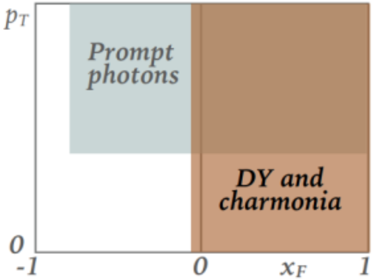
$$K^-(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K \bar{s}_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

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

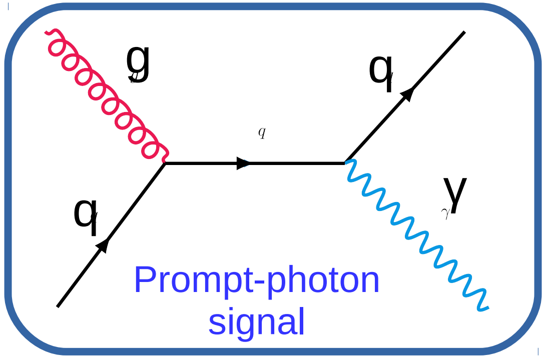
val-val | val-sea | sea-val | sea-sea

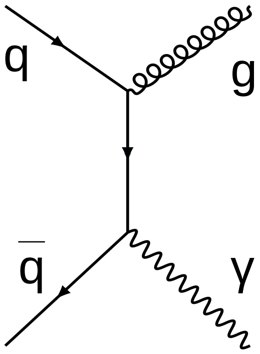


(AMBER LoI)

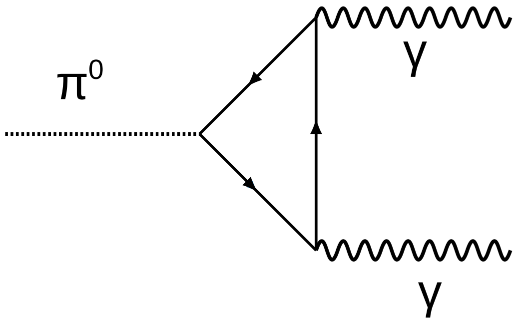


Another way: Prompt-photons clean access to the gluon distribution in kaon





background



Minimum bias photons background

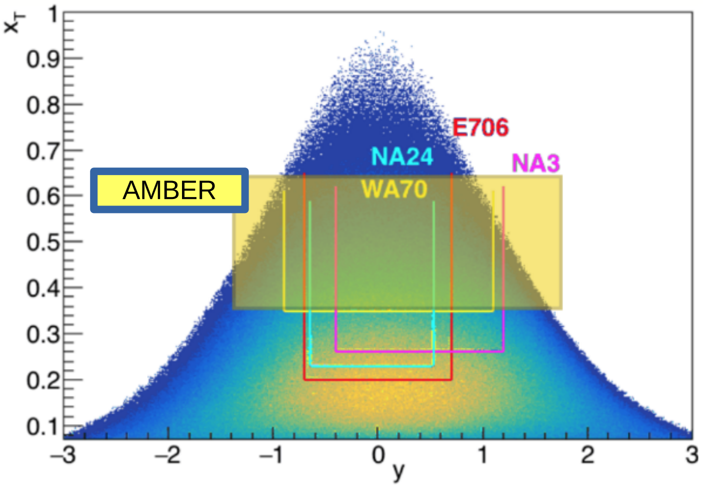
Direct access to the gluon PDF at $x_g^K > 0.05$, $Q^2 \sim p_T$

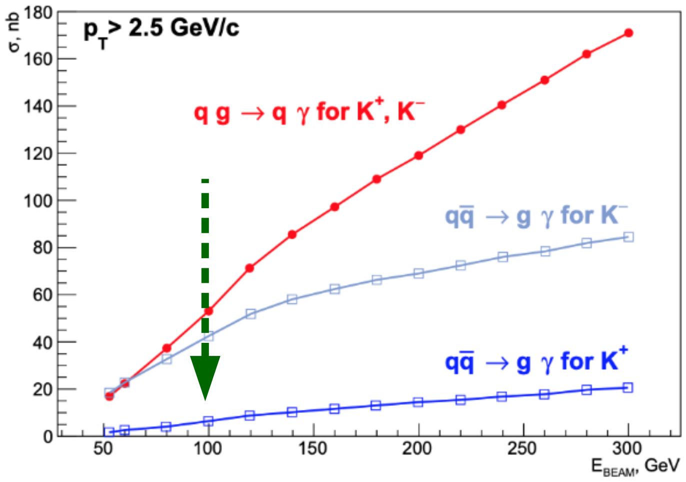
K^+ beam: minimize bkg

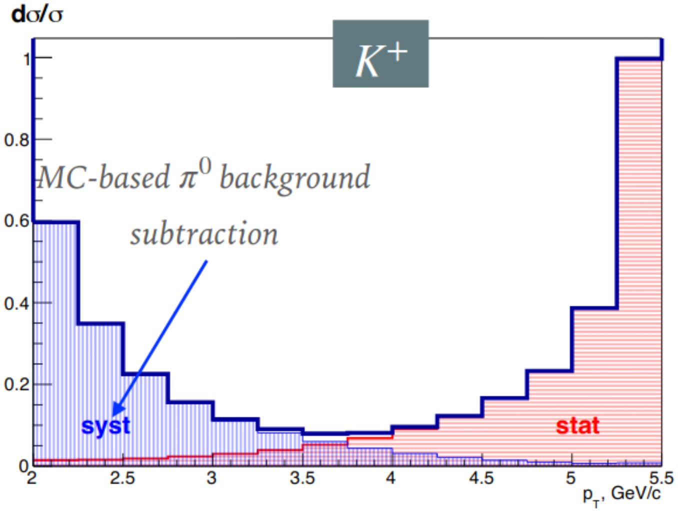
$p_T^\gamma > 2.5$ GeV/c: minimize photon background

100 GeV K^+ beam on a long liquid H_2 target

Kaon-induced prompt-photon production







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

LoI, In 140 days

Latest RF-separation studies suggest that this statistics goal must be re-assessed (scale-down by factor 20-40)

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

Meson radii

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

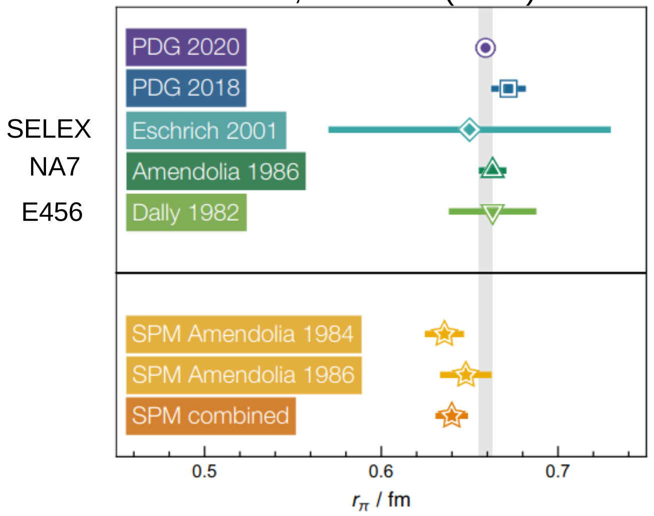
Pion and kaon radii: an expression of the link between EHM and confinement

Pion radius

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

r_π=0.659 ± 0.004 fm (PDG 2020)

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

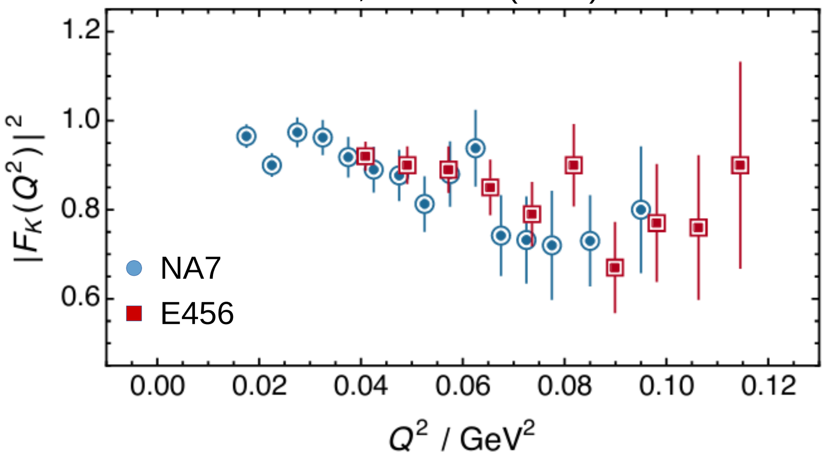


Kaon radius

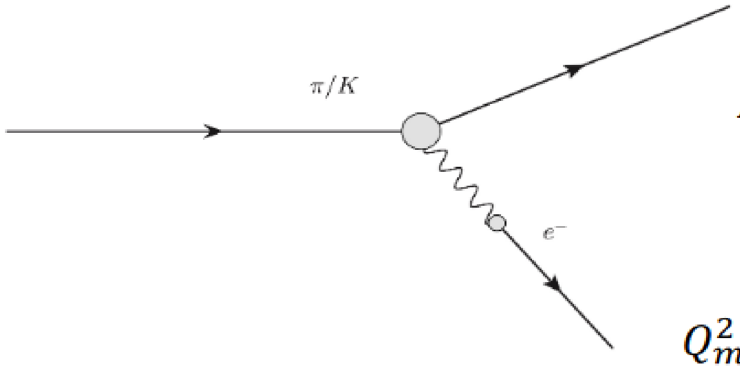
Practically unknown

r_K=0.560 ± 0.031 fm (PDG 2020)

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



Kaon charge radius



$$K^- \, e^-_{target} \to K^- \, e^-$$

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

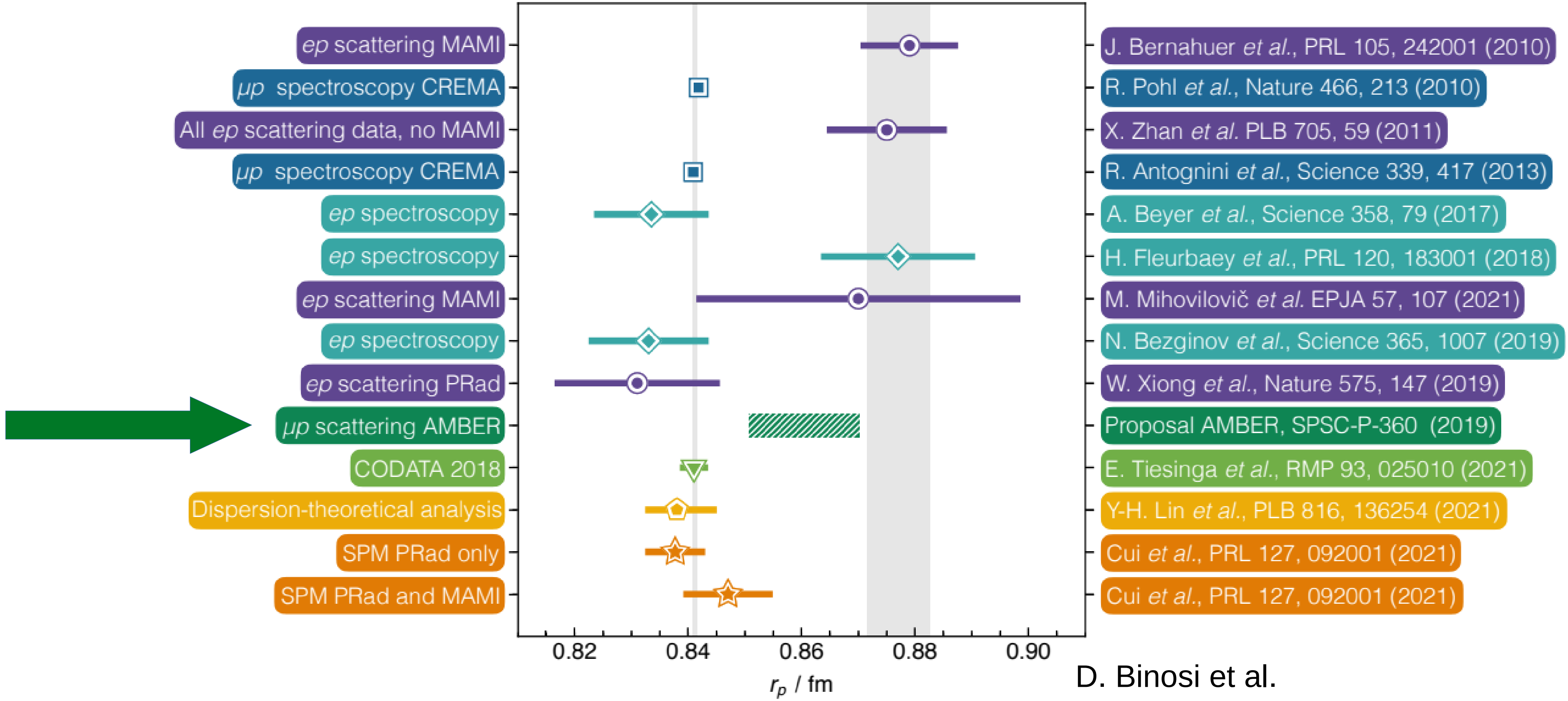
$$Q^2_{max} = \frac{4p_b^2 \, m_e^2}{s}$$

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

$0.001 < Q^2 < 0.07$ GeV^2

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%

The proton charge radius



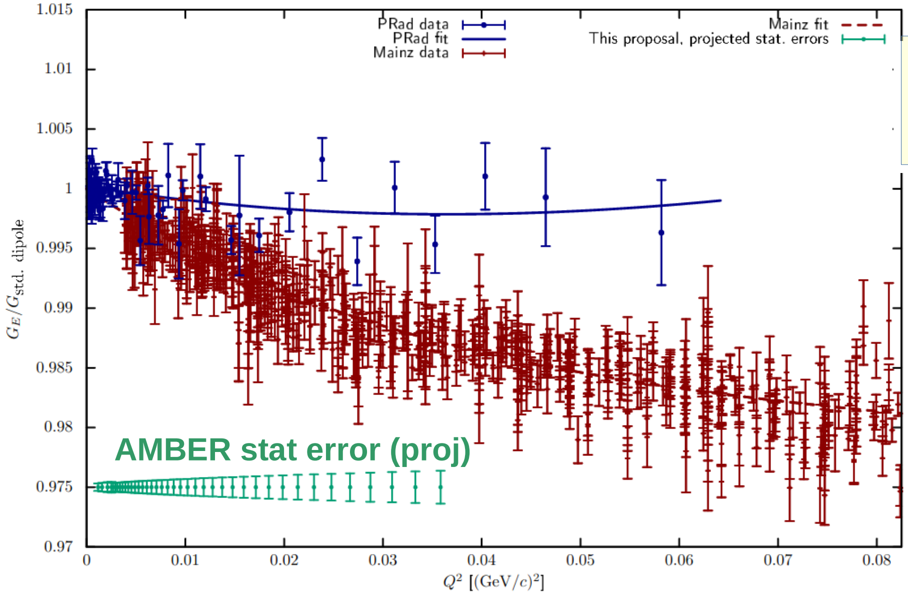
D. Binosi et al.

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

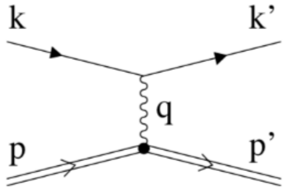
Proton radius at AMBER

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

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

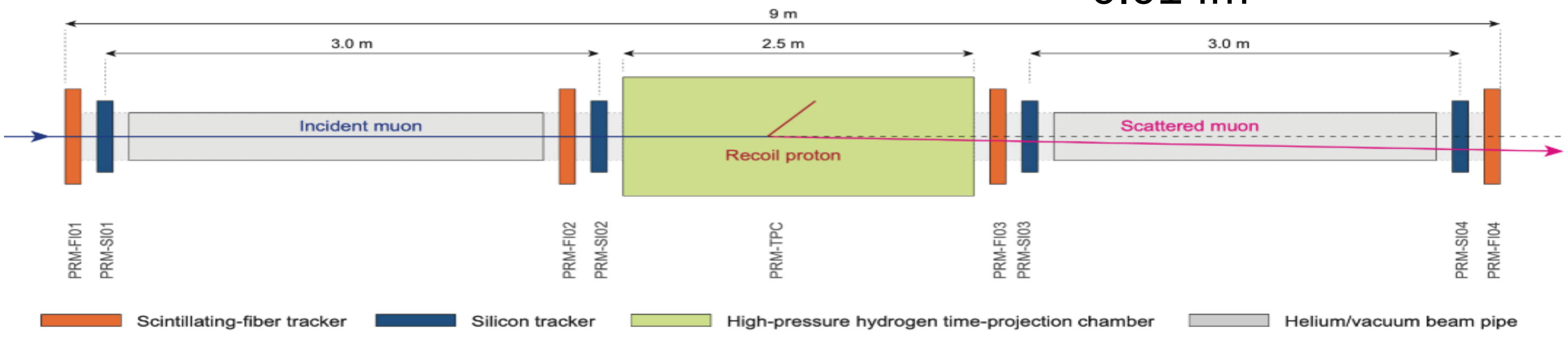


- 100 GeV muon beam
- Active target TPC, filled with lH_2
- Goal: 70 million elastic scattering events in $10^{-3} < Q^2 < 4\times10^{-2}$ GeV²
- Precision on proton radius ~0.01 fm



G_E, G_M

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



...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 (not discussed here)

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:

- Gluon content in the kaon from direct-photon production
- Kaon charge radius from elastic kaon-electron scattering
- Light meson spectroscopy using kaon beams (not discussed here)

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.