Apparatus for Meson and Baryon Experimental Research

Hadron structure at AMBER

Carlos Azevedo on behalf of AMBER collaboration
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4th May 2022

DIS2022 – Santiago de Compostela, Spain

i3N
INSTITUTE FOR NANOSTRUCTURES, NANOMODELLING AND NANOFABRICATION
RESEARCH, INNOVATION AND ENGINEERING APPLICATIONS

AMBER and the emergence of hadron mass

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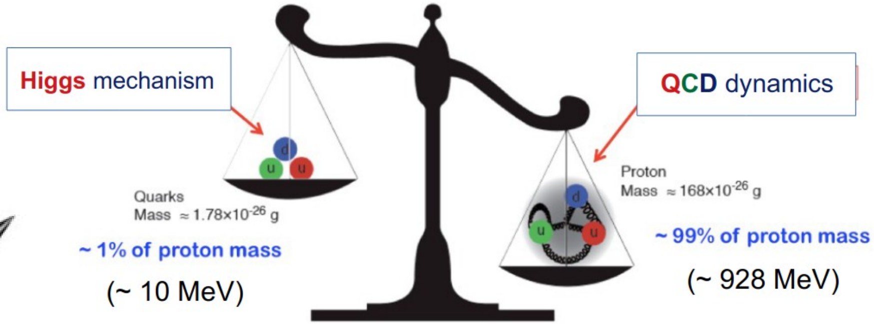
- The question:
  - How to understand that M_π/M_p ~ 1/7 while from constituent-quarks model one would expect ~2/3?
- Only 1% of the proton mass is due to the Higgs mechanism.



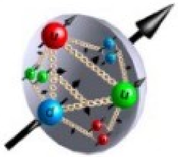
Pion

- $M_\pi \sim 140$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

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AMBER and the emergence of hadron mass

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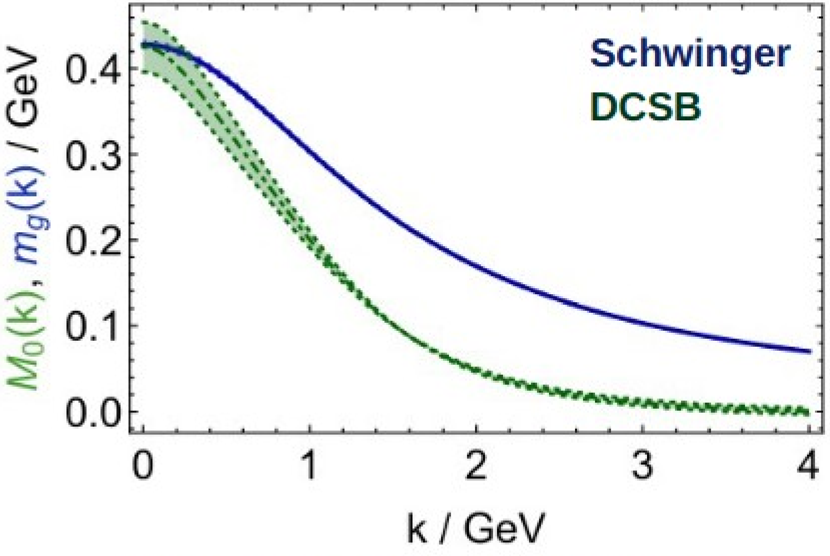
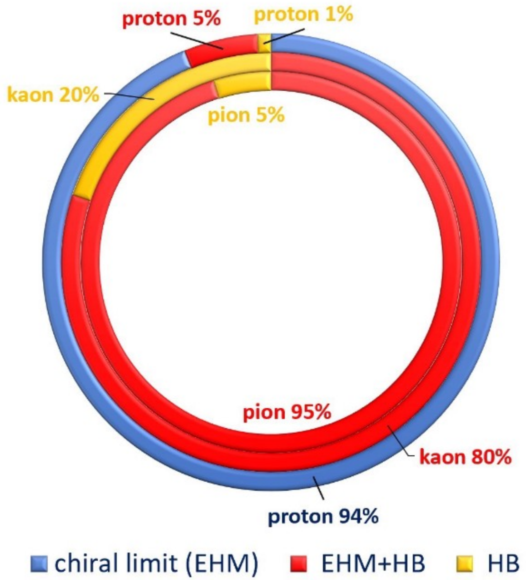
- Dynamic Chiral Symmetry Breaking of QCD leads to the quarks and gluons rapidly acquiring a running mass in the infrared limit



Gluon and quark *running masses*

Mass Budgets



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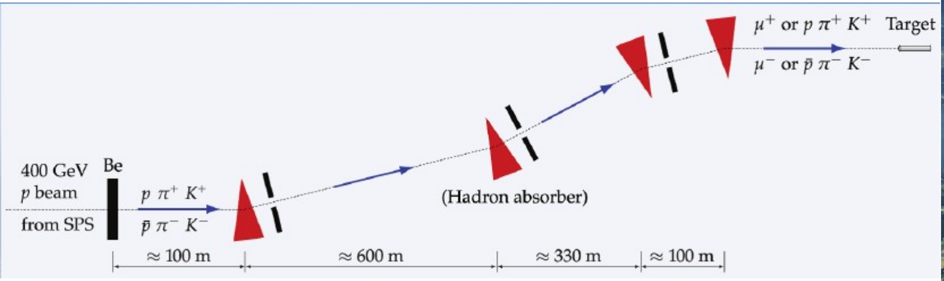
AMBER: The oportunity

Apparatus for Meson and Baryon Experimental Research

- 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
  - Wide range of momenta: 50 – 280 GeV/c
  - Intensity limited by radioprotection



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AMBER: NA66

Apparatus for Meson and Baryon Experimental Research

- AMBER:
  - Apparatus for Meson and Baryon Experimental Research
  - Approved as NA66 by the CERN Research Board in December 2020
  - Divided in 2 phases
    - Phase-1 (Approoved)
      - Proton Radius
      - Pion PDFs through Drell-Yan and Charmonium production
      - Antiproton production cross sections for Dark-Matter search
    - Phase-II (requiring RF-separeted beams to M2)
      - Proposal submition planned to 2022
      - Kaon and meson gluon PDFs
      - Strange spectroscopy
      - Meson charge radii

https://arxiv.org/pdf/1808.00848.pdf

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

CERN-SPSC-2019-003
SPSC-I-250
January 28, 2019

arXiv:1808.00848v6 [hep-ex] 25 Jan 2019

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS*

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AMBER: LOI and proposed measurements

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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	~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 polarisability & 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	

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Phase-I

Phase-II

http://cds.cern.ch/record/2676885/files/SPSC-P-360.pdf?version=3

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CERN

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

CERN-SPSC-2019-022 / SPSC-P-360

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

– Phase-1 –

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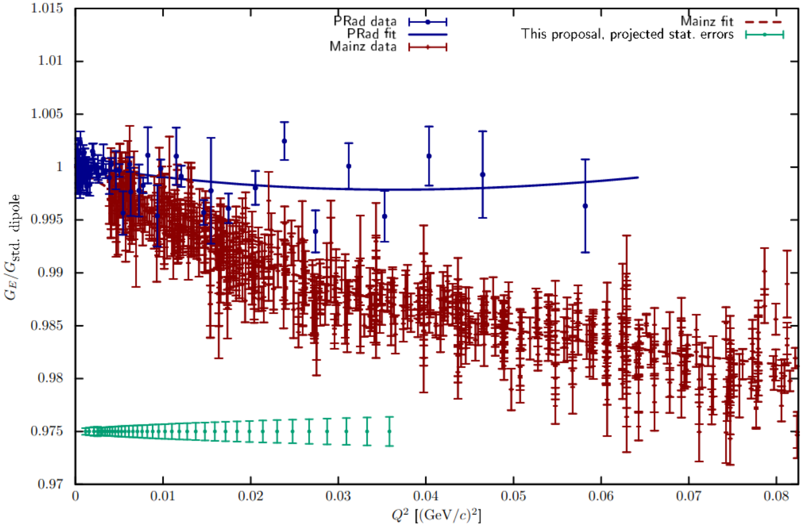
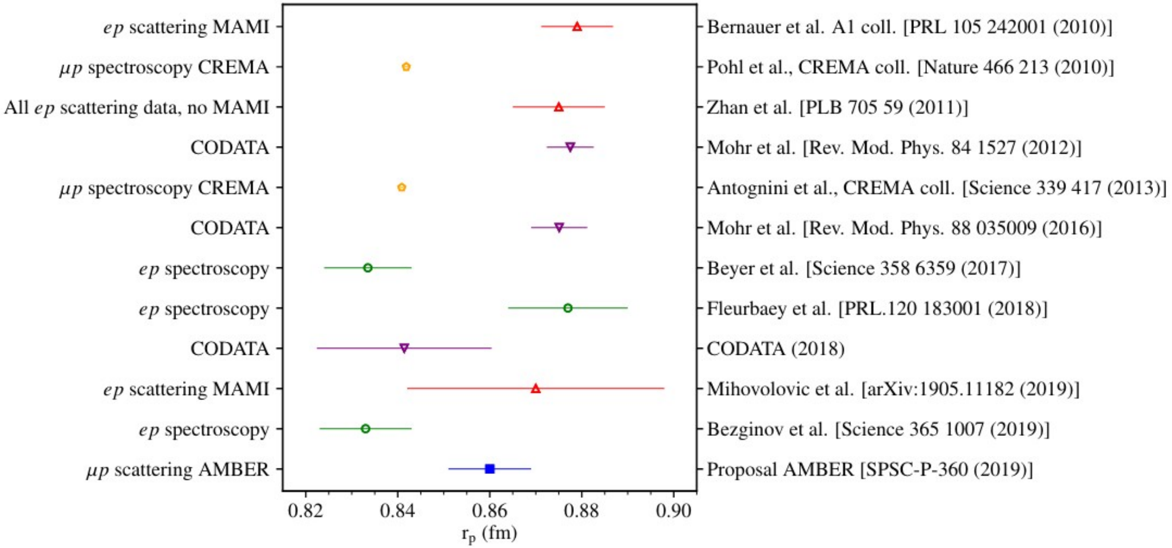
AMBER: The Proton Radius

- The puzzle of Proton Radius
  - Two types of measurement
    - Lepton-proton scattering
    - Hydrogen spectroscopy
    - Results differ by ~ 5 σ





- Why μp scattering?
  - Leptonic probe
  - Different systematic uncertainties
  - Much provide smaller radiative than *ep*
  - Provide precise data for global fit

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AMBER: The Proton Radius

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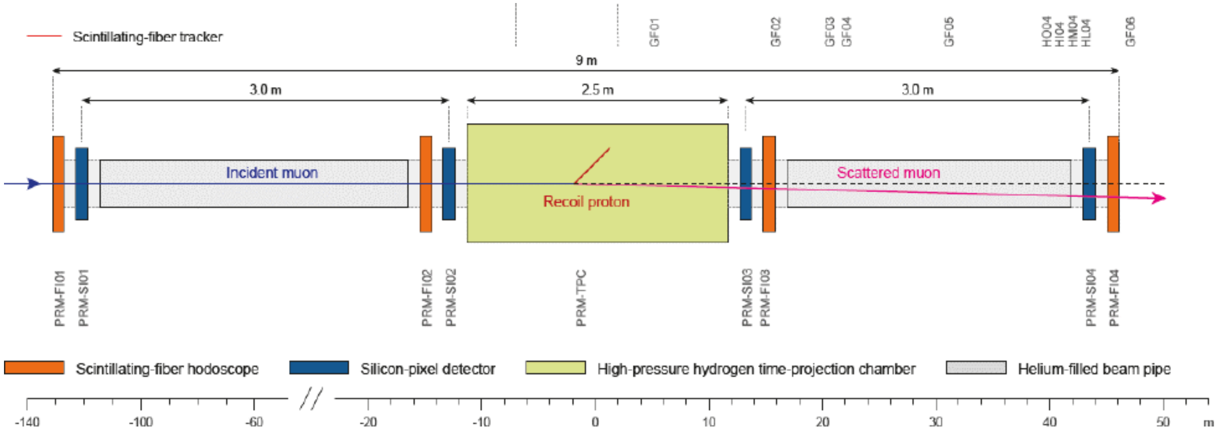
- Challenging measurement
  - High-intensity 100 GeV μ beam: $2 \cdot 10^6\ s^{-1}$
  - Simultaneous detection of scattered μ and recoil p
  - Re-use upgraded COMPASS spectrometer
  - Active-target TPC: up to 20 bar H_2
  - Free-streaming DAQ: minimize trigger bias, latency of TPC
  - Goal: 70Mev. in $10^{-3} < Q^2 < 0.04\ GeV^2$
  - Expected precision $\lesssim 0.01$ fm



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AMBER: Indirect DM searches

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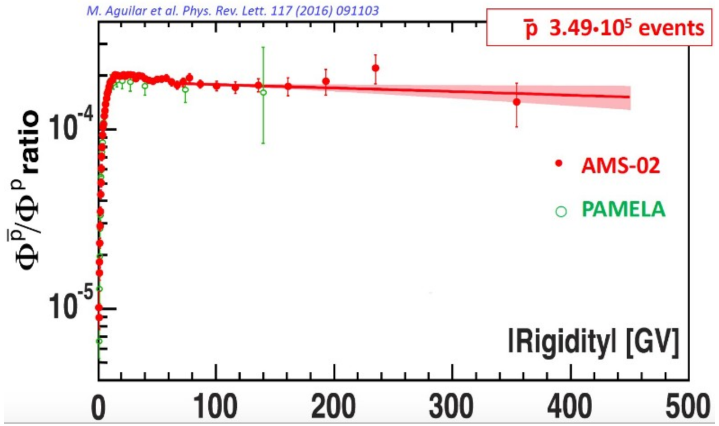
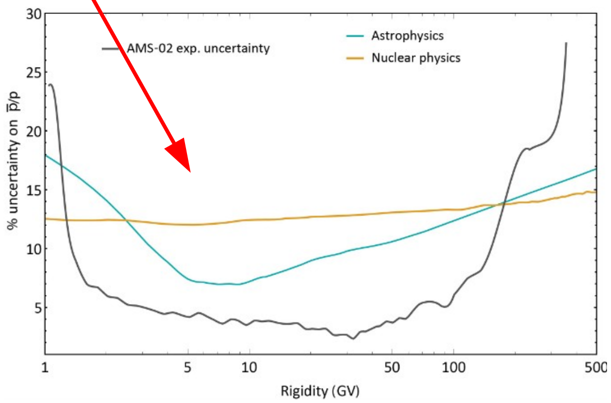
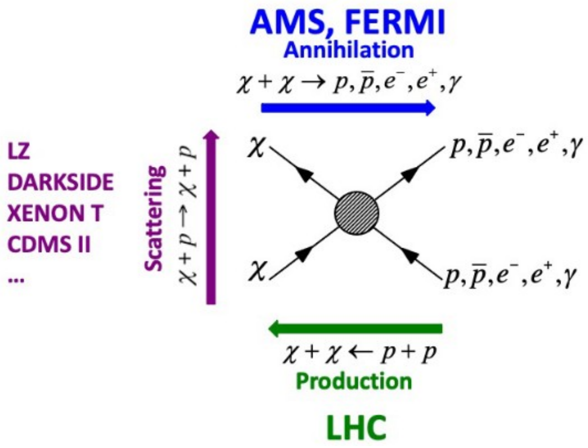
- Needed as input to the Dark Matter searches:
  - For example to interpret AMS data.

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







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AMBER: Antiproton Production

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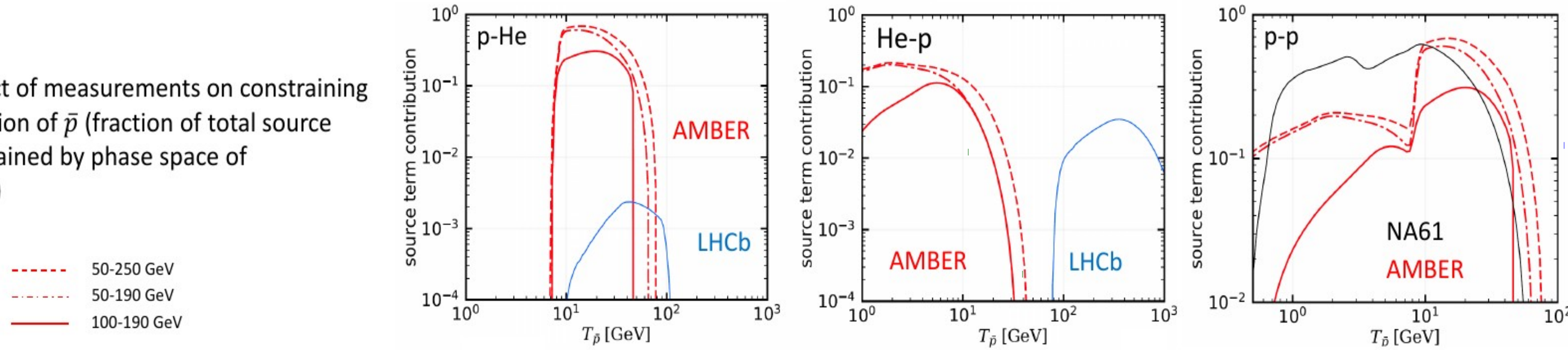
- Secondary p beam with 50, 100, 150, 200, 280 GeV
- Minimum bias trigger $\Rightarrow$ beam intensity of $5 \cdot 10^5\ s^{-1}$
- Liquid H_2 and He target
- Proton ID in CEDARs, antiproton ID in RICH
- Measure differential cross section in 10 bins in p momentum and pseudo-rapidity $2.4 < \eta < 5.6$
- Statistical uncertainty ≈ 0.5 – 1% per data point
- Total systematic uncertainty ≈ 5% (efficiencies, dead time)

Plots: impact of measurements on constraining the production of $\bar{p}$ (fraction of total source term constrained by phase space of experiment)



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The pion structure - Status

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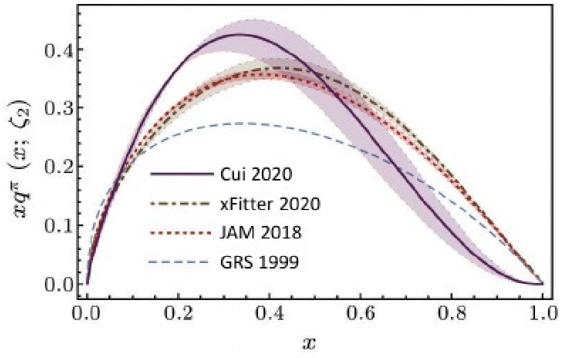
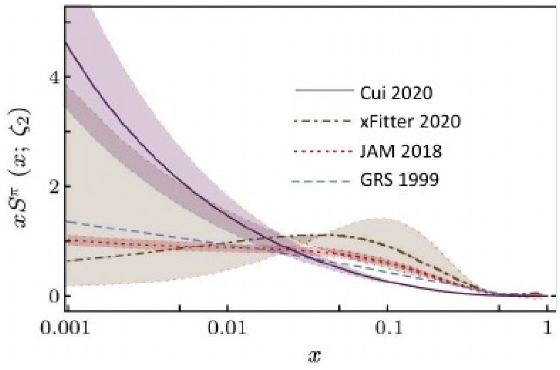
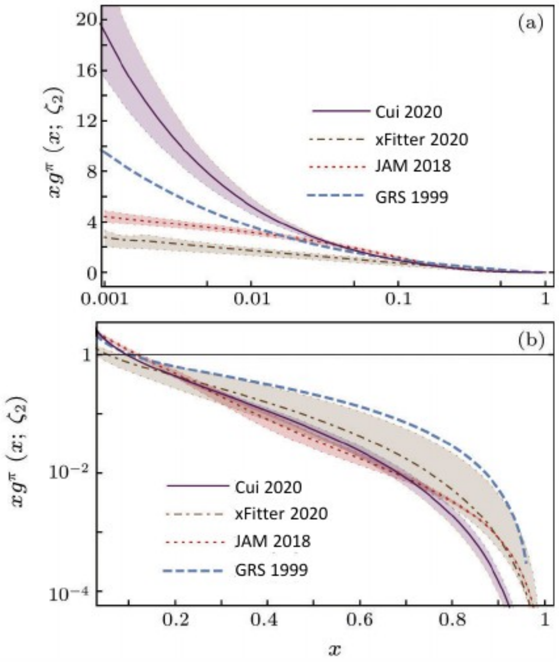
Valence quarks



Sea quarks



Gluons



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

- Scarce / old data: E615, NA3, NA10,...
- Mostly heavy nuclear targets ⇒ large nuclear effects
- Discrepancy between experiments
- Valence PDF poorly constrained
- Sea and gluon PDFs basically unknown
- More and precise data urgently needed

AMBER: access to pion structure through Drell-Yan

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Apparatus for Meson and Baryon Experimental Research

- Pion-induced Drell-Yan dimuon production
  - Isoscalar ^{12}C target
    - Minimize nuclear effects
  - π^+ and π^- beams
    - Separate valence and sea
  - Goals:
  - 10× more data than currently available
    - 25k DY events
  - First precise and direct measurement of the sea quark distribution in the pion

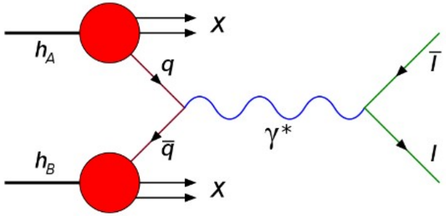

Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

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
This exp	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

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AMBER: access to pion structure through Drell-Yan

Apparatus for Meson and Baryon Experimental Research

Definitions:

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

And assuming flavour-symmetry:

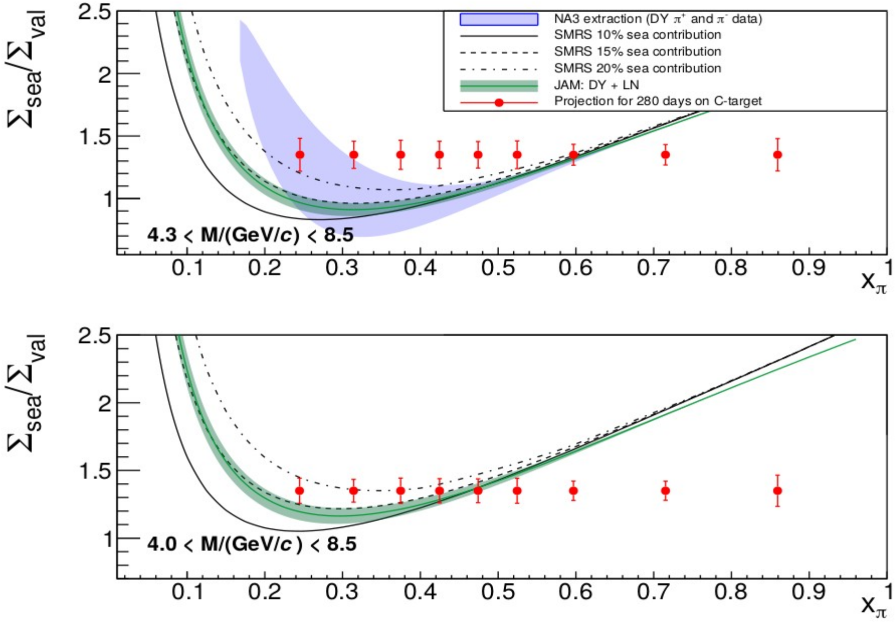
$$u_{val}^{\pi^+} = \bar{d}_{val}^{\pi^+} = \bar{u}_{val}^{\pi^-} = d_{val}^{\pi^-}$$

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

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

→ LO: only sea-val and val-sea terms

→ LO: only val-val terms



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AMBER: Drell-Yan setup

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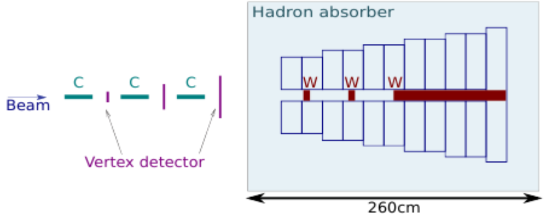
- 190 GeV π beam
- Dedicated target
- Vertex detecto
- Hadron absorber
- Dimuon mass resolution ~ 100 MeV



3 carbon targets of 25cm length

2 tungsten targets of 6cm length

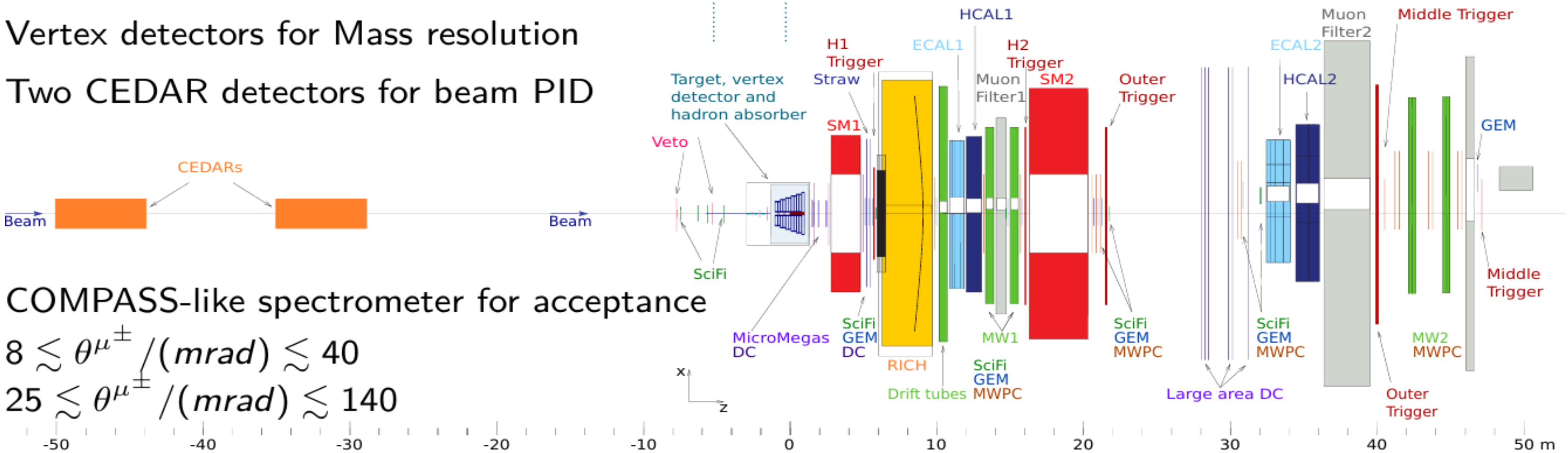
(alternative 2cm length W upstream)

2024 Drell-Yan setup

Hadron absorber for high intensity

Vertex detectors for Mass resolution

Two CEDAR detectors for beam PID



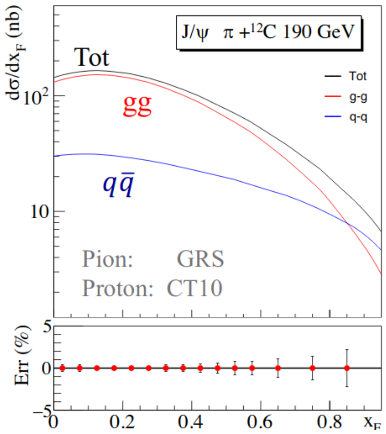
COMPASS-like spectrometer for acceptance

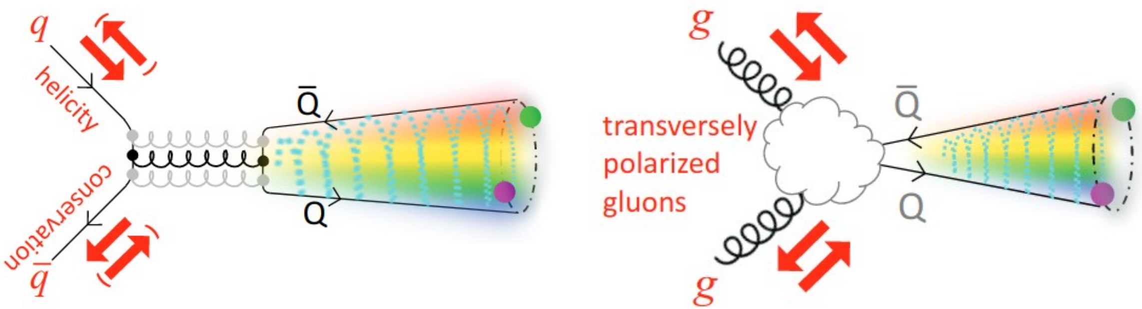
$8 \lesssim \theta^{\mu^{\pm}} / (mrad) \lesssim 40$

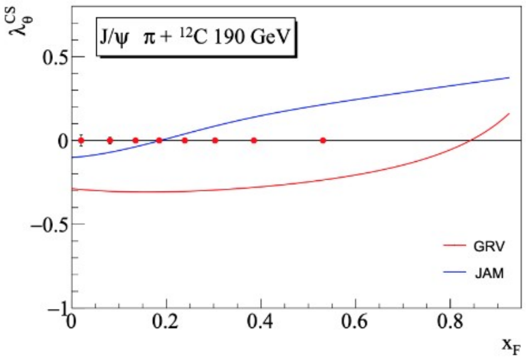
$25 \lesssim \theta^{\mu^{\pm}} / (mrad) \lesssim 140$

AMBER: Access 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→1 processes
  - Use J/ψ polarization to distinguish production mechanism:







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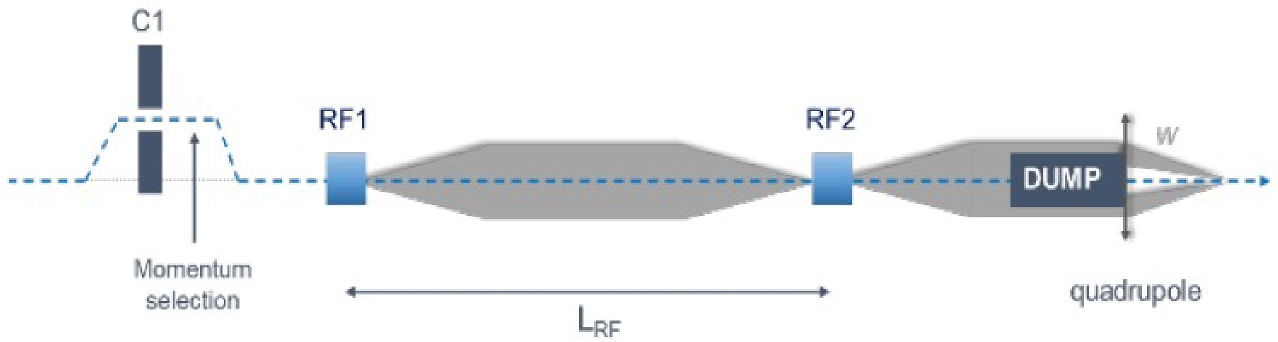
AMBER: PHASE-II

Apparatus for Meson and Baryon Experimental Research

- RF- Separated beams
  - Particle species: same momenta but different velocities, $\Delta p/p \sim 1\%$
  - Time-dependent transverse kick by RF cavities in dipole mode
  - Longitudinal separation of particle species by L_{RF}
  - RF1 kick compensated or amplified by RF2, depending on phase difference:
    - $\Delta\varphi = 2\pi(L_{RF} f/c)(\beta_1^{-1} - \beta_2^{-1})$
  - Dump of unwanted species
  - $K^{\pm}$ beams with 60-100 GeV/c
  - $\bar{p}$ beam with 80-110 GeV/c

Panofsky-Schnell-System with two cavities (CERN 68-29)



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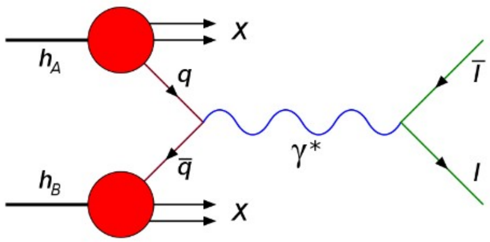
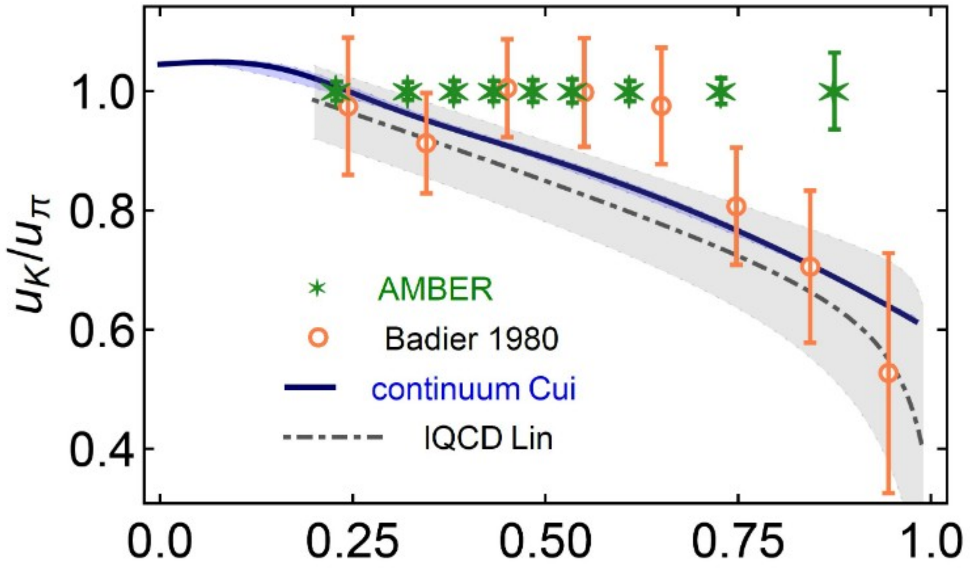
AMBER: Kaon structure: u_K/u_π

- 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

Kaon-induced Drell-Yan



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



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AMBER: Kaon structure: valence and sea

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- First-ever kaon sea-valence separation:
  - Using kaon beams of both charges
  - Higher beam momentum: access to lower x_K

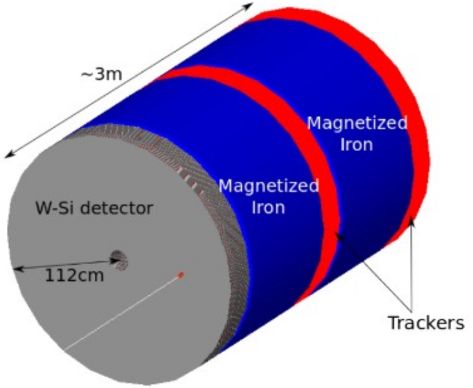
$$R_{s/v} = \frac{\sigma^{K^+C}}{\sigma^{K^-C} - \sigma^{K^+C}} \longrightarrow \propto u_v^K u_v^p$$

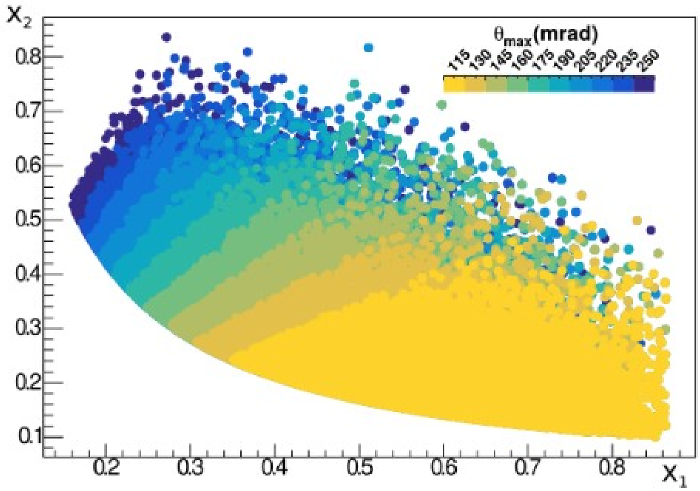
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6cm Pt	K^-	????	200	4.2 – 8.5	700	0
This exp.	100cm C	K^-	2.1×10^7	80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
		K^+	2.1×10^7	80	4.0 – 8.5	2,800	1,300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

AMBER: Kaon-induced Drell-Yan

Apparatus for Meson and Baryon Experimental Research

- Requirements
  - Momentum < 100 GeV/c
  - Lower beam momentum implies smaller angular acceptance
  - To keep the dilepton acceptance ~40% → Compress the spectrometer
  - "Active absorber":
    - Trackers
    - Magnetic field
    - Large area
    - Compact





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

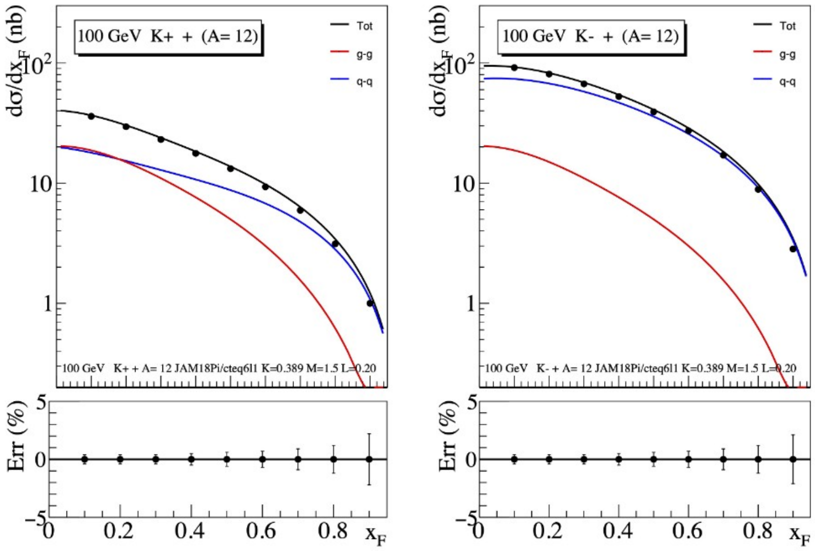
AMBER
Apparatus for Meson and Baryon Experimental Research

- 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):

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

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

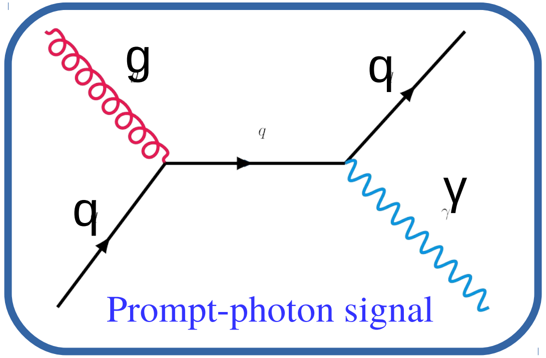
val-val   val-sea   sea-val   sea-sea



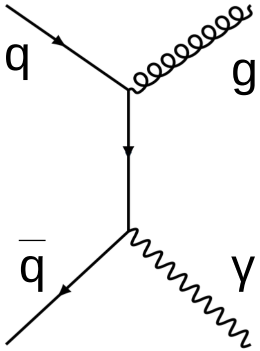
Using Color Evaporation Model
Int.J.Mod.Phys. A 10 (1995) 3043
JAM18 “pion” PDFs (PRL 121, 152001 (2018))

AMBER: Prompt-photons

- Clean access to the gluon distribution in kaon
- 100 GeV K^+ beam on a long LH_2 target

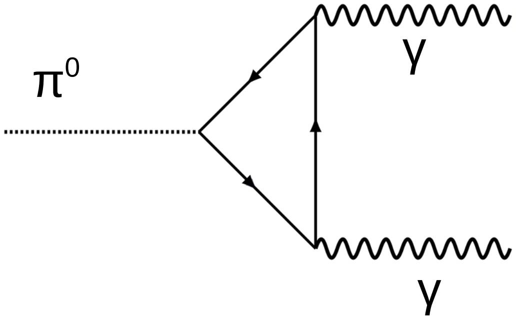


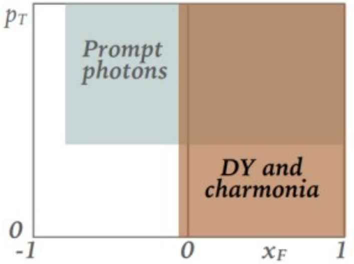
Direct access to the gluon PDF at $x_g^k > 0.05$, $Q^2 \sim p_T$



Background

K^+ beam: minimize bkg



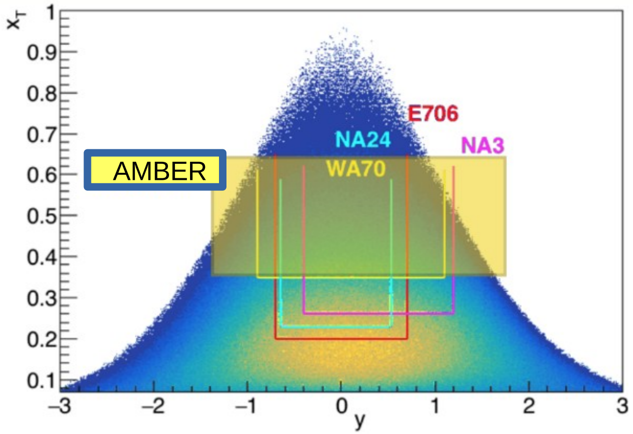


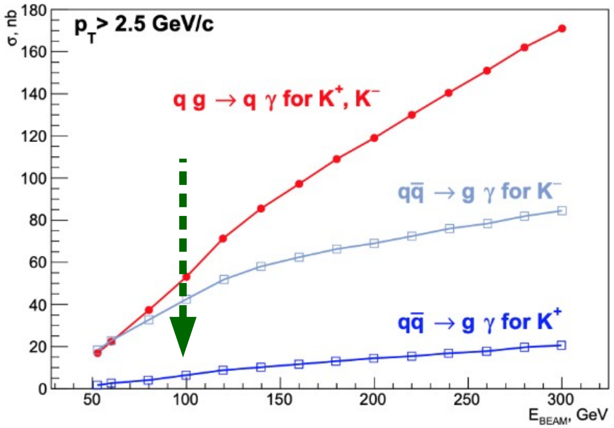
Minimum bias photons background

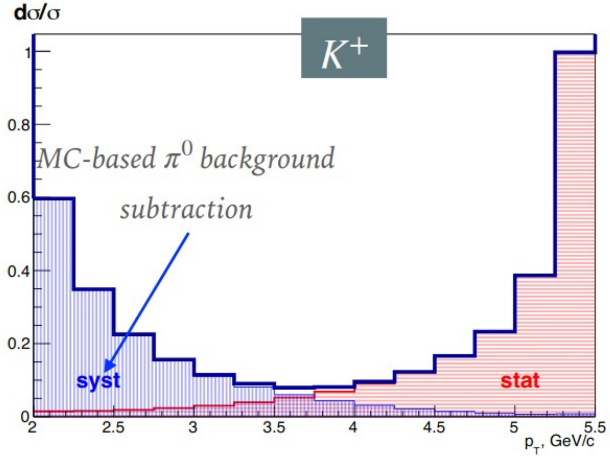
$p_T^\gamma > 2.5$ GeV/c:

minimize photon background

AMBER: 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	$4 < p_T < 7$	—
This exp	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

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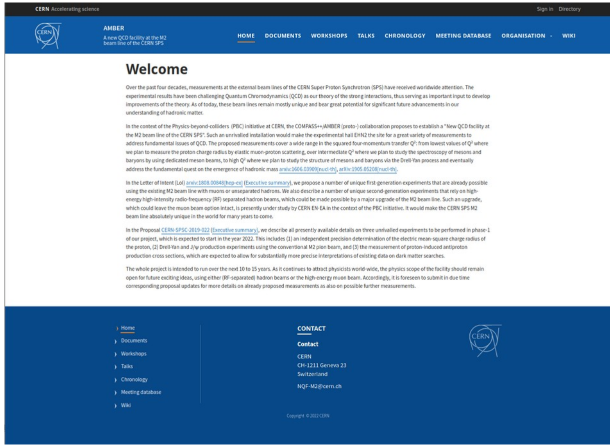
AMBER: Summary

Apparatus for Meson and Baryon Experimental Research

- 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/



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