Meson Structure Study via Drell-Yan Production at AMBER Experiment

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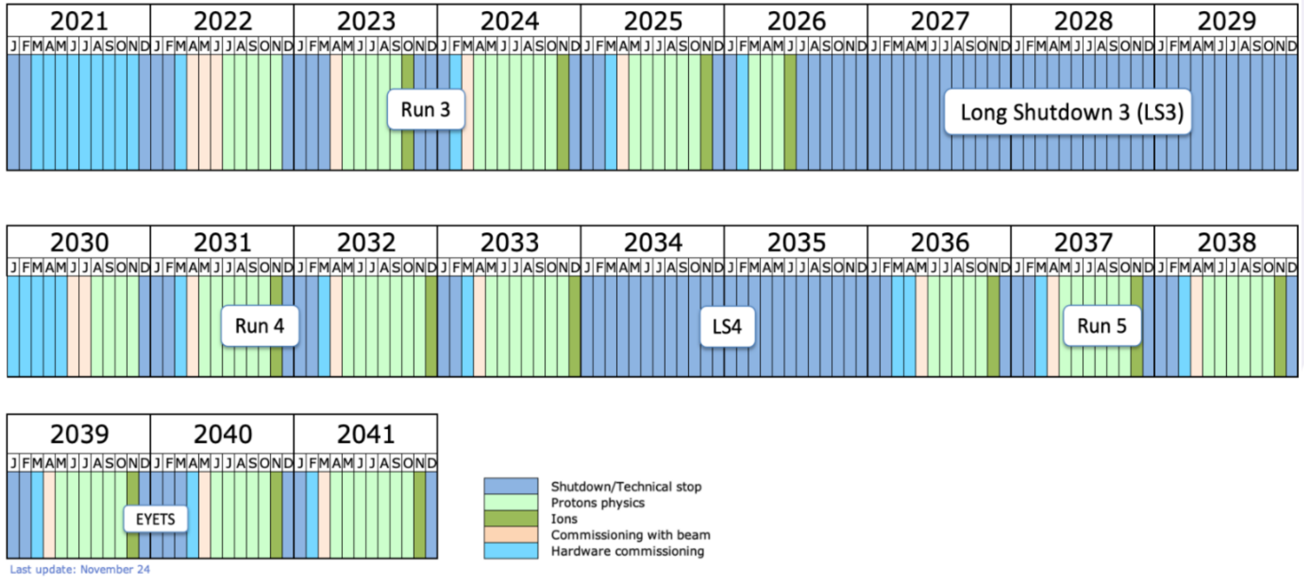
Apparatus for Meson and Baryon Experimental Research

- AMBER is the successor to the successful COMPASS experiment
- Officially approved as NA66 experiment in December 2020
- Consists of ~200 physicists from 34 institutes
- Operates at the M2 beamline at SPS with muon and hadron beams 60 – 250 GeV
- Inherited, extends and modernizes the 2-stage spectrometer of the COMPASS experiment

AMBER experiment timeline and physics program

2018: Letter of Intent arXiv:1808.00848
2020: AMBER Phase-I Proposal recommended by SPSC
2021 – 2022: First pilot run
2023: Data taking started
2026:



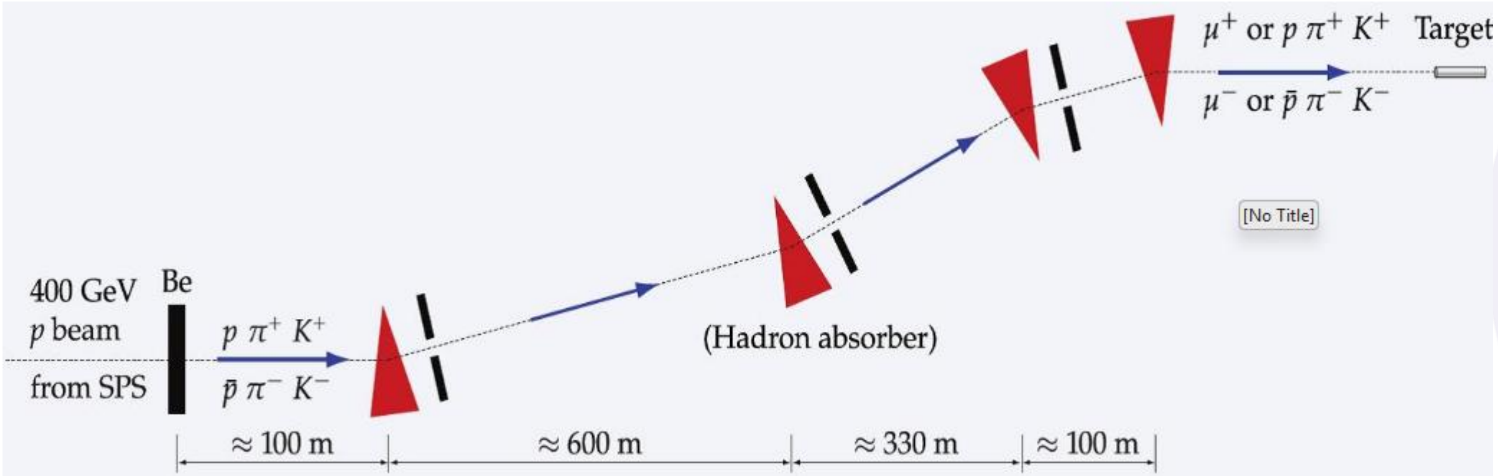
Phase-1: 2023 – 2031

- Approved by CERN RB in 2020
- pbar production cross section for dark matter searches
- Proton radius measurement with high-energy μ-p elastic scattering
- Meson structure measurement through Drell-Yan process

Phase-2: 2031 and beyond

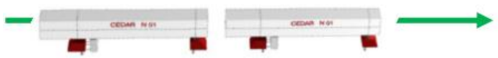
- Proposal in drafting stage
- High-intensity/purity kaon/pbar beam under investigation
- Dedicated Kaon-induced Drell-Yan measurement
- Direct photon measurement
- Kaon-induced spectroscopy
- …

AMBER beamline and apparatus

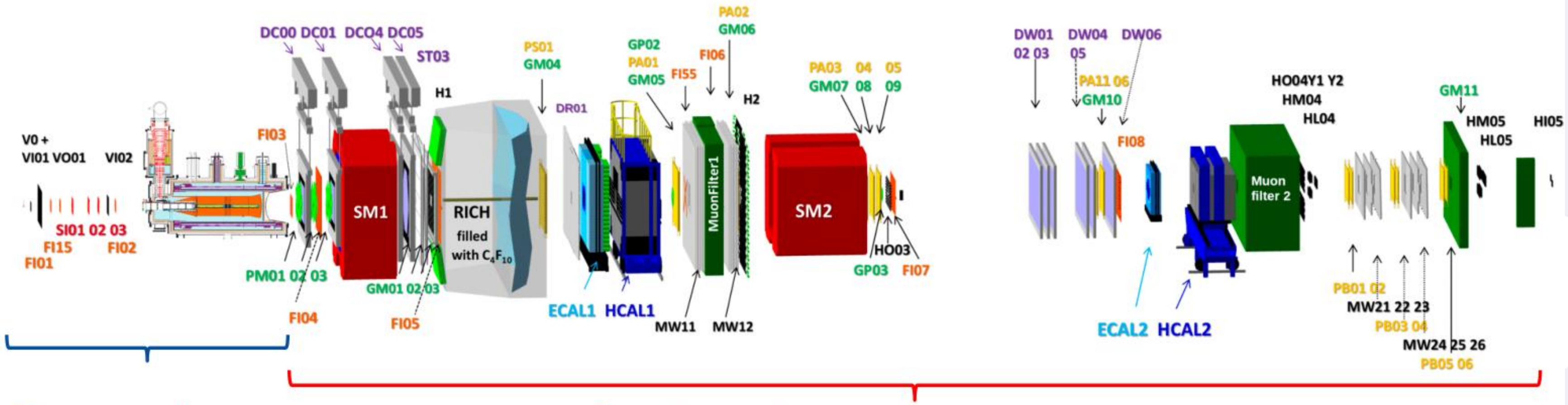


M2 beamline (EHN2)

- Most versatile beamline at CERN
- High-intensity beams of $\mu^\pm$, $\pi^\pm$, $K^\pm$, p
  - ❑ $\mu^\pm$: 90-180 GeV, up to 5E7/s
  - ❑ $h^\pm$: 60-250 GeV, up to 1E9/s with absorber
- Intensity limited by radioprotection requirements



CEDAR detector for beam PID



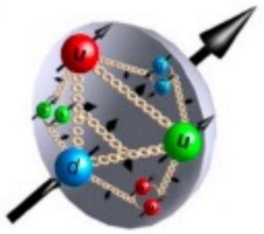
Beam: p, μ, π, K, (e) **Target region:** program-specific **Spectrometer:** common for all measurements

Versatile target area for different physics program

Redundant high-precision tracking with muon identification

Importance of the meson structure measurement

Proton



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

Pion

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

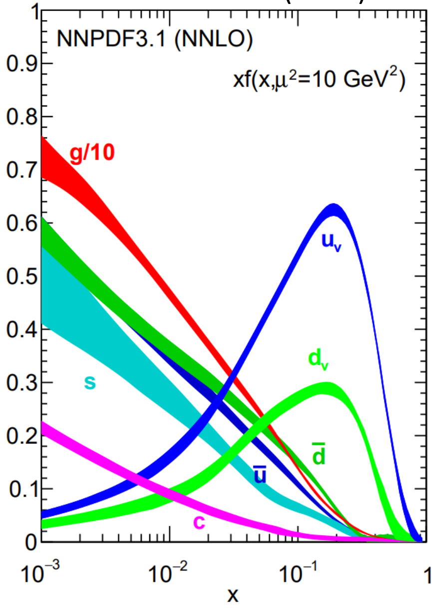
Kaon

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

- Lightest qqbar bound dstate
- Spin-0
- π/K comparison as a result of breaking SU(3) symmetry

Abundant experimental data

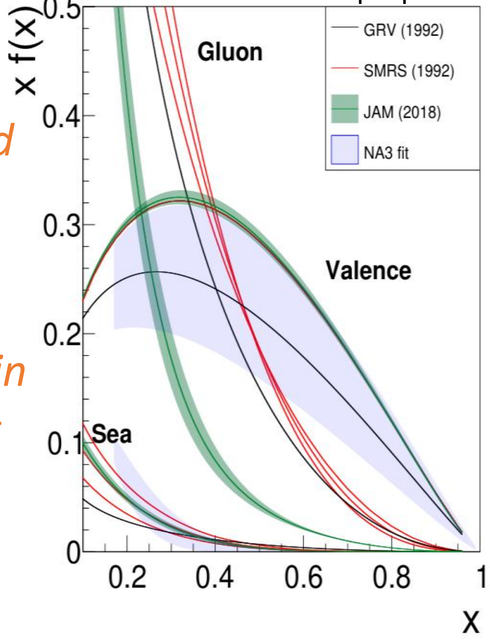
EPJ C77 (2017) 663



Limited old data

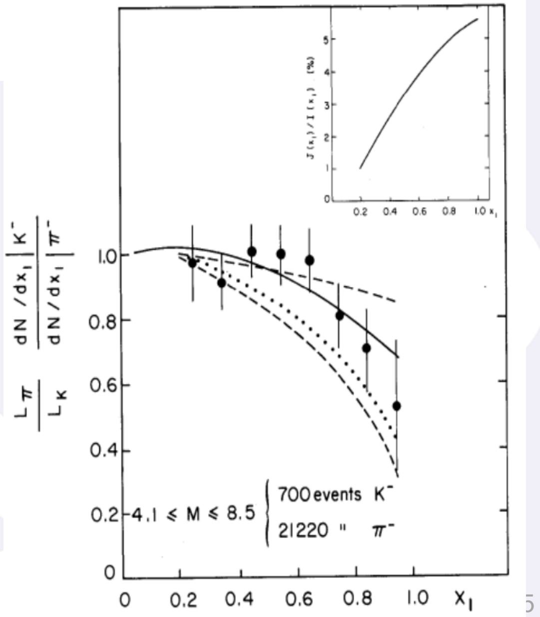
Sizable difference in global fits

AMBER proposal



Only ~700 events from NA3

NA3: PLB 93 (1980) 354



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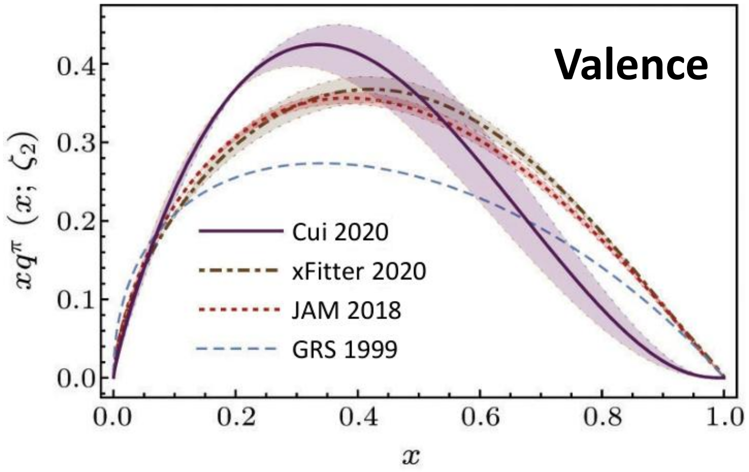
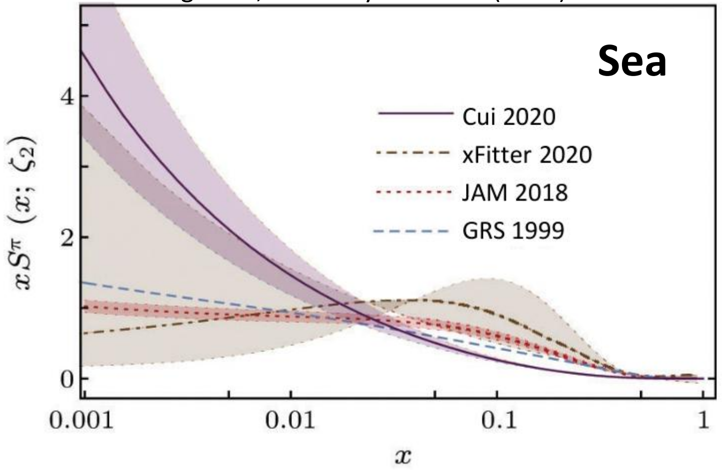
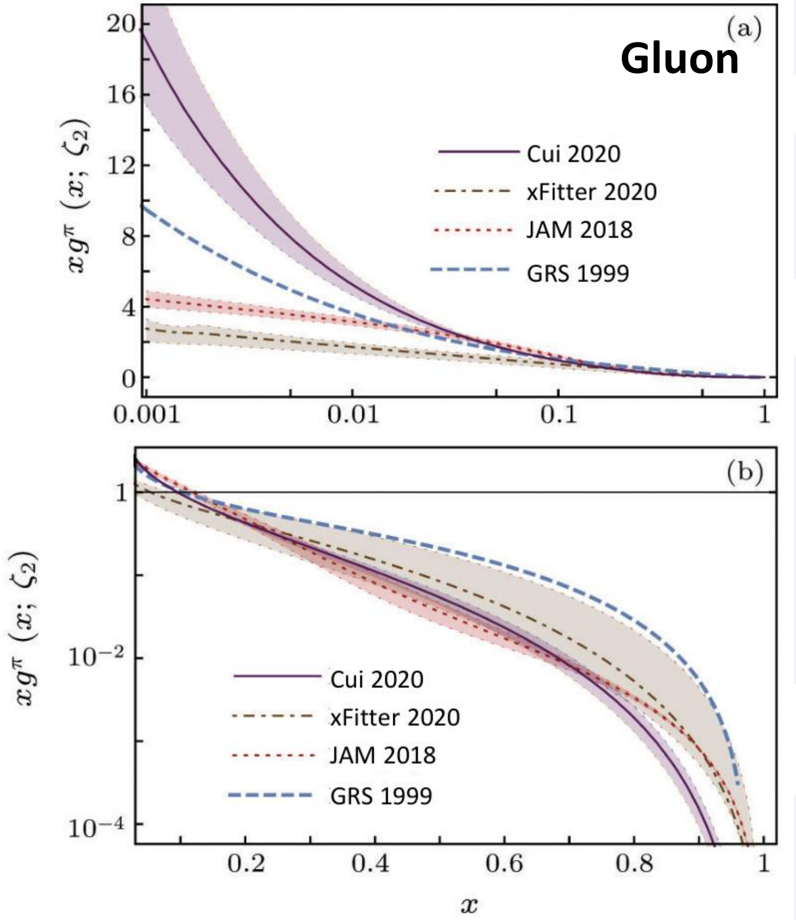
Current status of pion structure

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







- Limited and decades-old data mostly with heavy nuclear targets: E615, NA3, NA10, etc.
- Measurements convoluted with nuclear effects
- Valence quarks PDFs are poorly constrained
- Sea and gluon content are essentially unknown

New measurement with higher statistics are urgently needed

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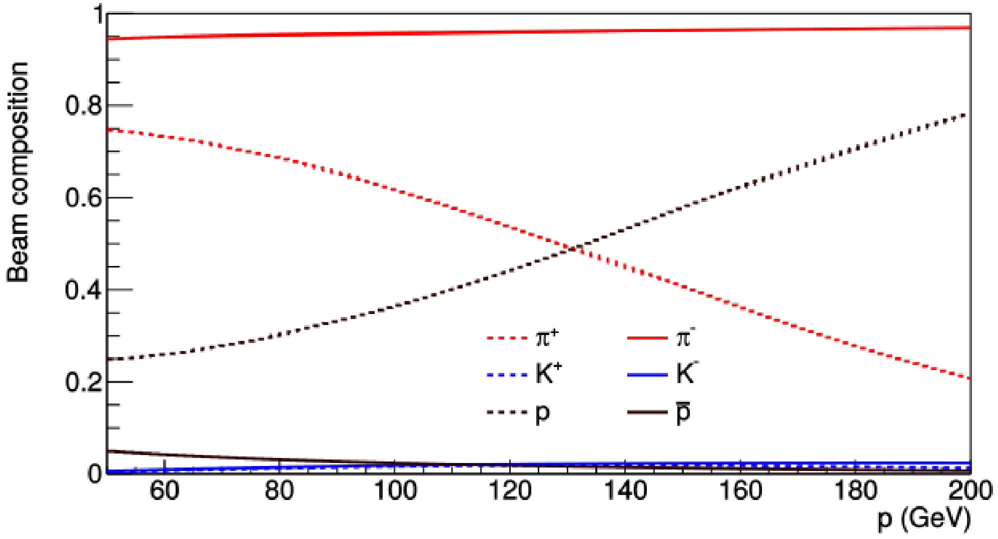
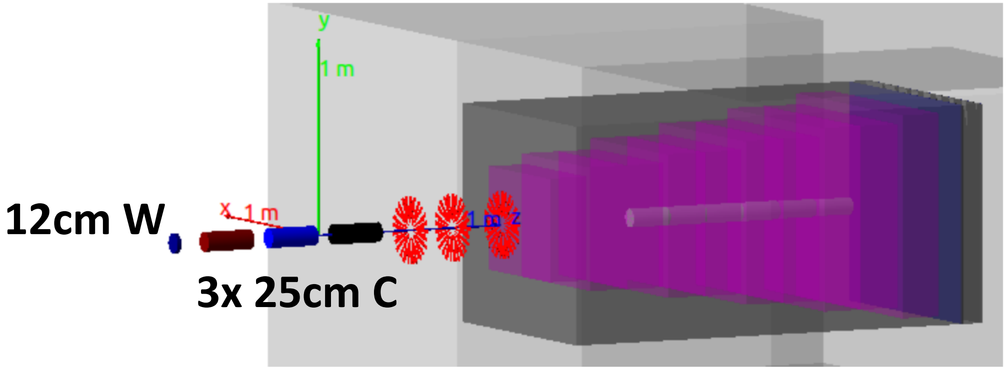
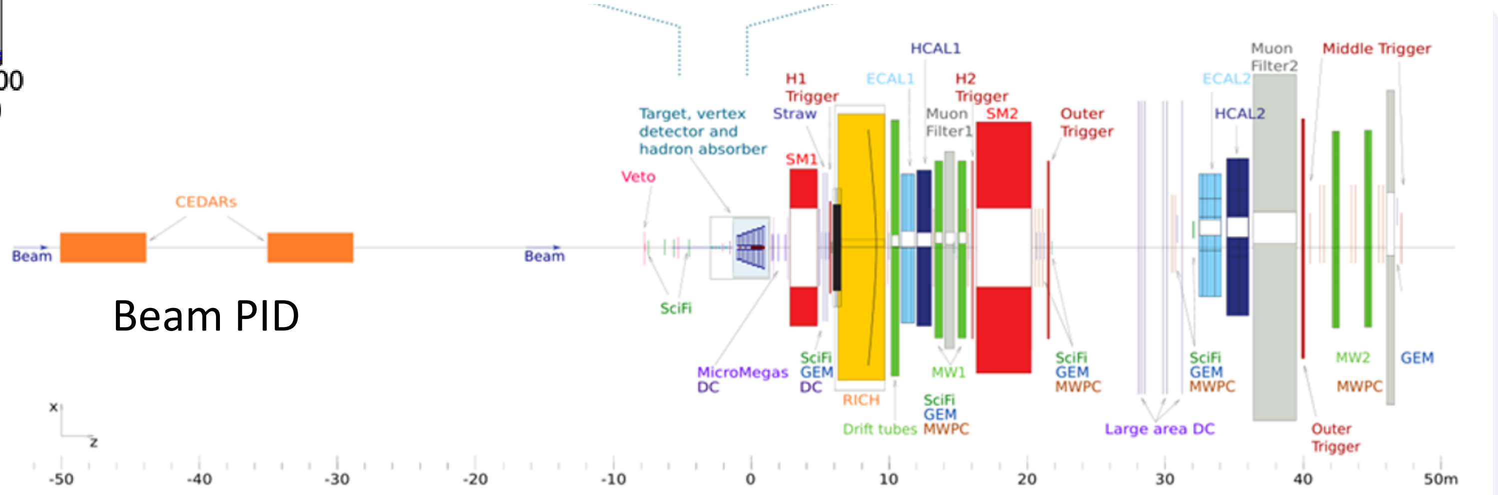
Experimental setup for Drell-Yan program



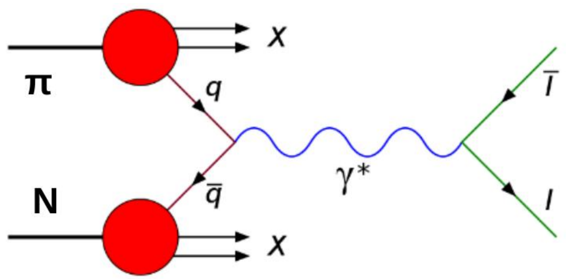




Conventional meson beam:

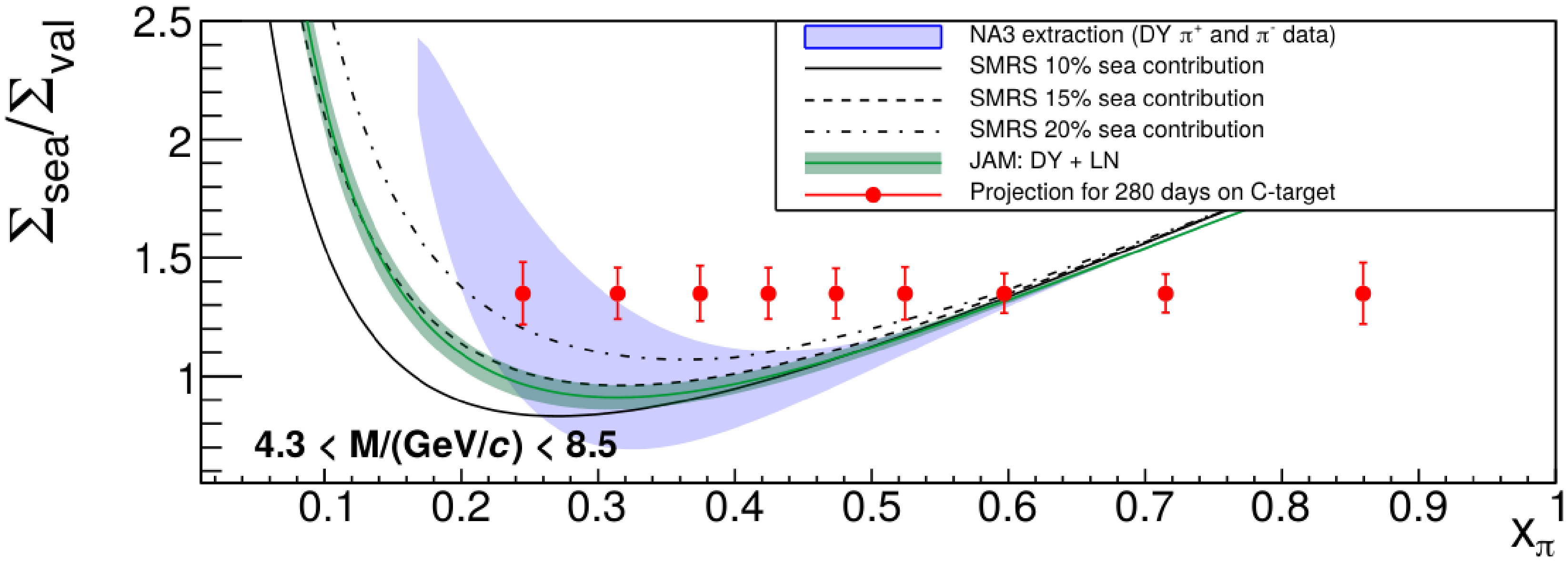
- Wide range of beam energy – currently planning 190 GeV
- Beam intensity up to $1x10^9$/spill limited by the radiation protection
- Time sharing between h^+/h^- = 3:1
- Pions and protons dominate, but kaon accounts for ~2%

Accessing pion structure at AMBER



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

Expected statistics after 280 days of running



$$\sum_{sea}^{\pi C} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$$

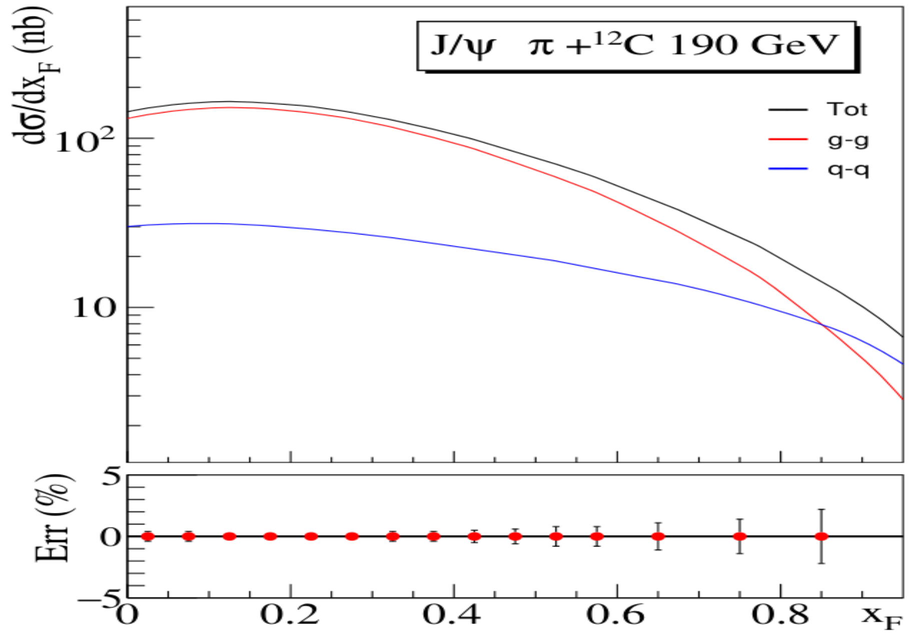
$$\sum_{val}^{\pi C} = -\sigma^{\pi^+ C} + \sigma^{\pi^- C}$$

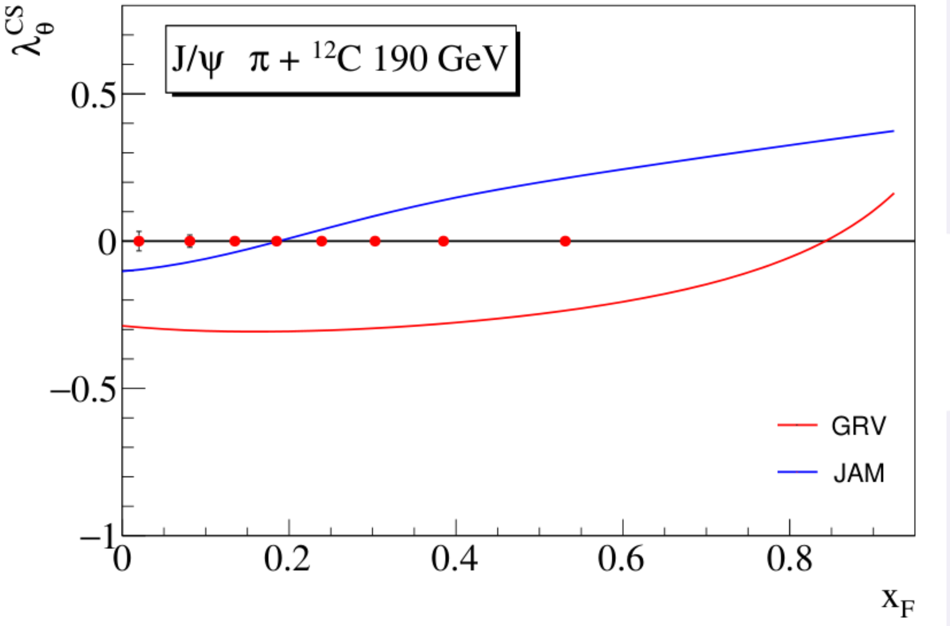
Pion gluon PDF through parallel J/ψ production

- Much larger cross section leads 20x more statistics accessing both gluon and quark content of the pion
  - ❑ Largest pion-induced J/ψ sample on a light isoscalar target, meaningful statistics shortly after data-taking starts in 2029
- The polarization of J/ψ, i.e. the λ parameter in the angular distribution $1 + \lambda\cos^2\theta$, provide an independent constraint on the relative contribution from the qqbar and gg process
  - ❑ For gg, $\lambda = +1$
  - ❑ For qqbar, $\lambda = -1$

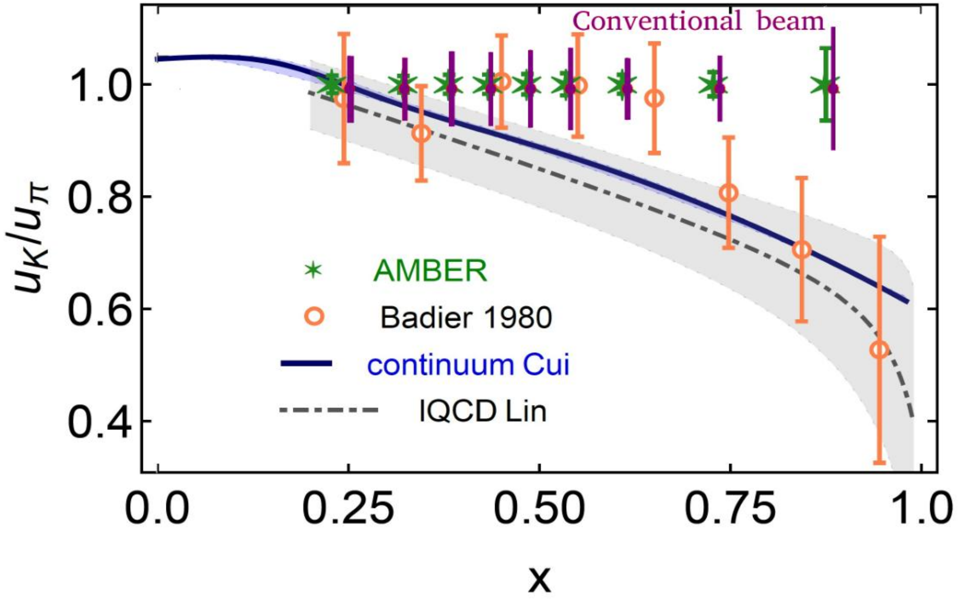
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

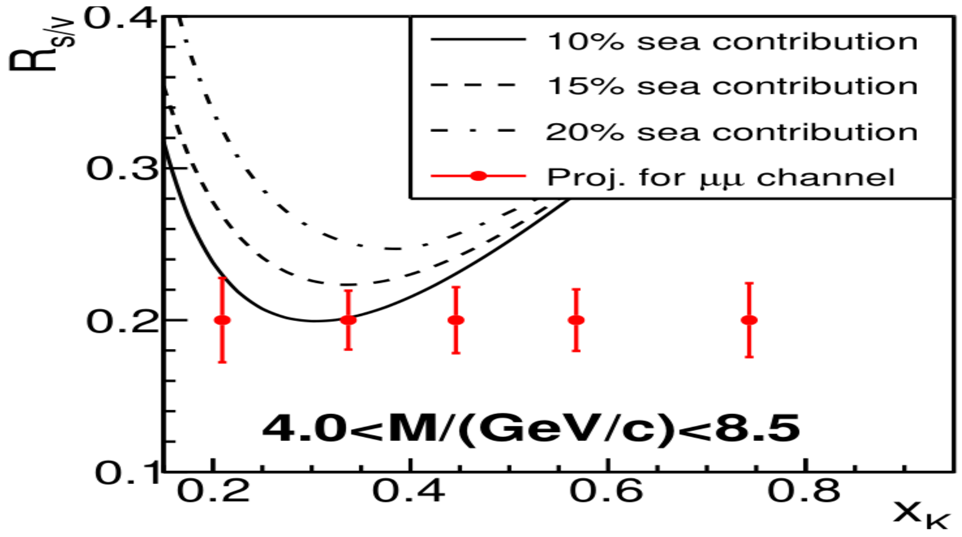
Expected statistics after 280 days of running





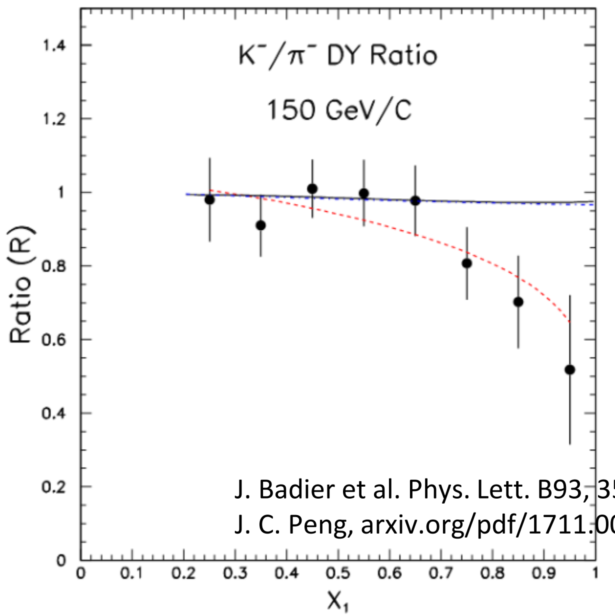
Kaon structure using conventional meson beam

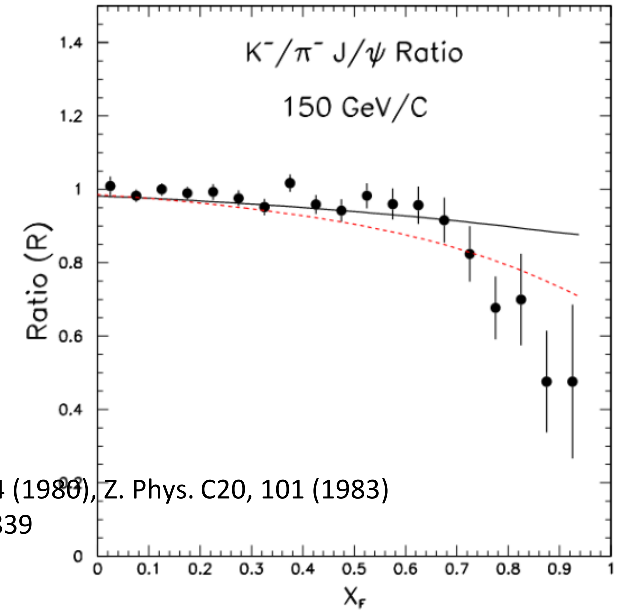




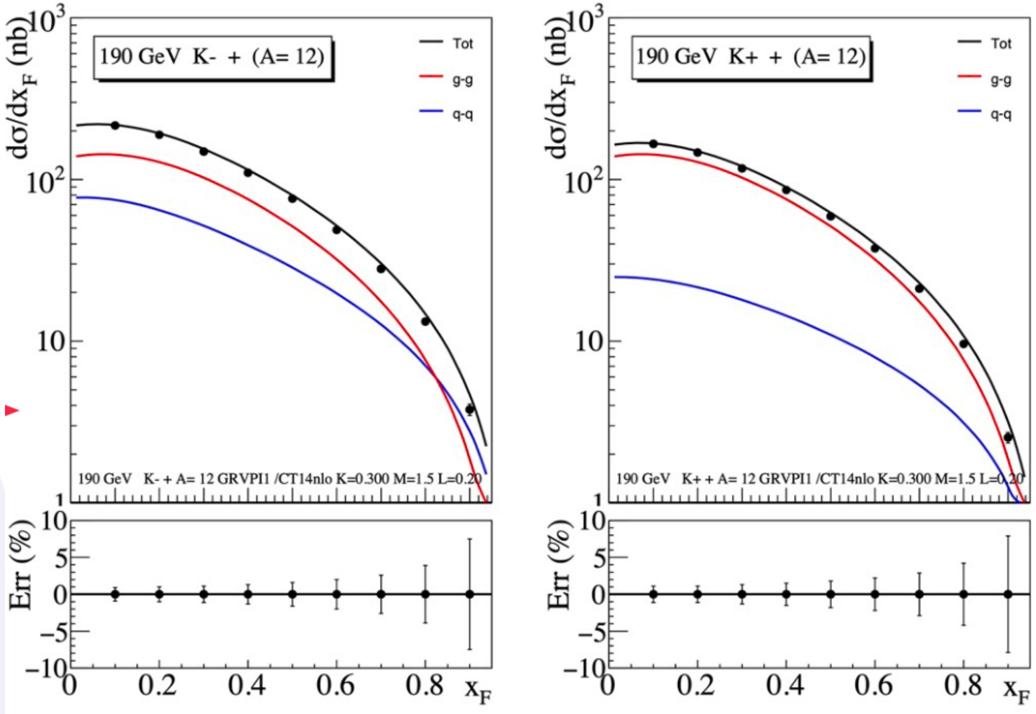
- Small kaon "contamination" (~2%) in the convention meson beam already gives us access to the kaon structure within the approved beam time in AMBER Phase-I
- DY cross section radio of K+C over π+C provides the measurement of the valance quark distribution in the kaon. Difference between K^+ and K^- probes the sea quark distribution.
- One years of data-taking with conventional beam yields data sample 3x larger than existing NA3 data

Kaon-induced J/ψ production





J. Badier et al. Phys. Lett. B93, 354 (1980), Z. Phys. C20, 101 (1983)
J. C. Peng, arxiv.org/pdf/1711.00839

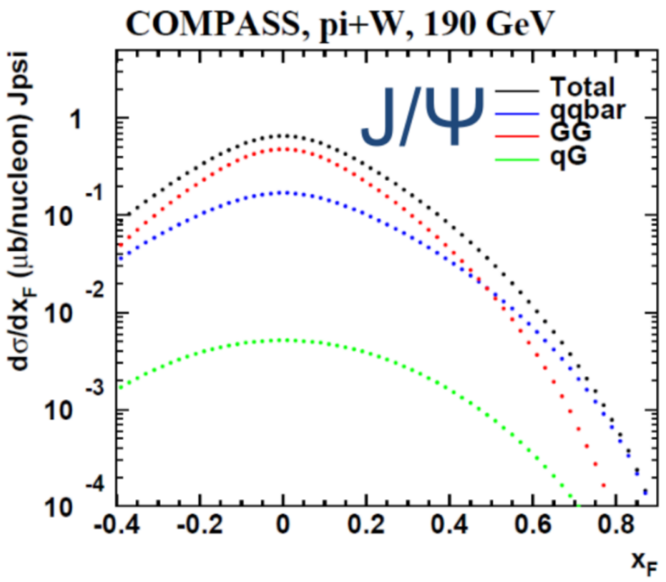


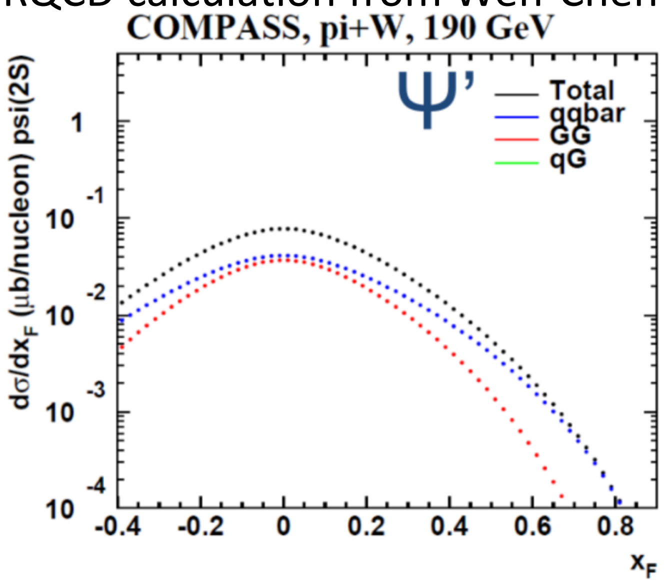
- Large amount of statistics collected in parallel with kaon-induced DY process
- NA3 measurement of K/π ratio showed similar behavior at higher xF, indicating softer u-valance quark distribution in kaon
- At AMBER energy, production is dominated by the gg process, allowing model-dependent access to gluon distribution in kaons
- With one year of data taking at high intensity, AMBER expects to collect 25000 K^- events and 32000 K^+ events

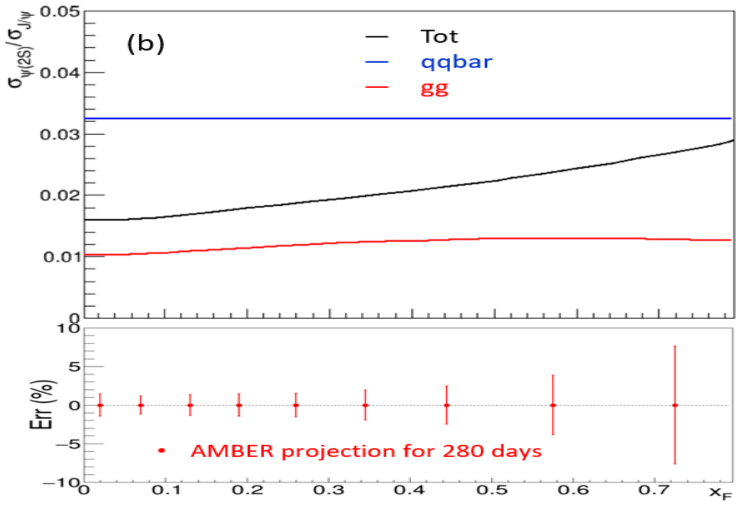
Additional probe through ψ' production

- Improved mass resolution from the vertex detector enables access to parallel ψ' production
  - ❑ Additional access to the gluon content in the meson
  - ❑ Free from the feed down from χ_{cJ} states
  - ❑ Insights into the charmonia production mechanism

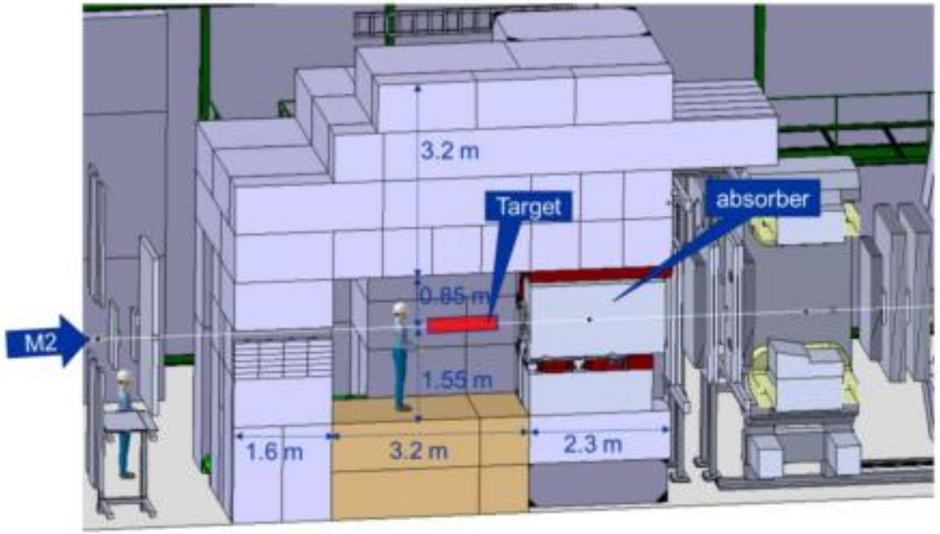
NRQCD calculation from Wen-Chen





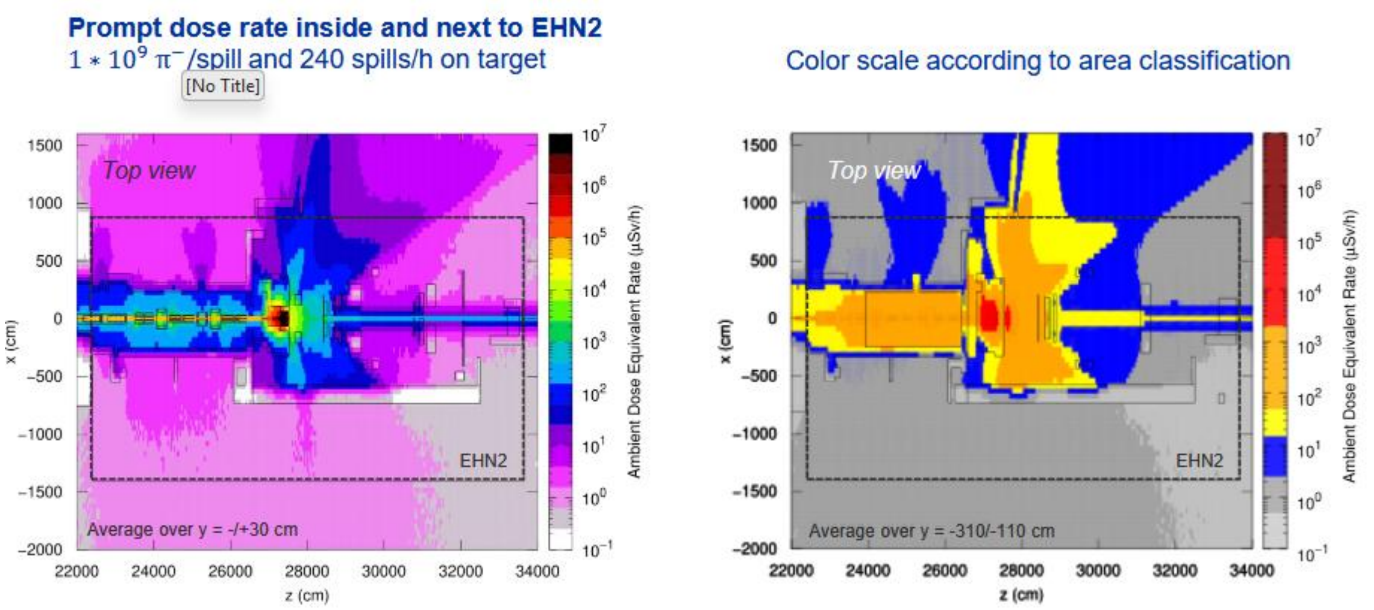


Experimental challenges: radioprotection



To push for higher intensity, careful design optimization of the target bunker shielding to:

- Contain the radiation
- Minimize the environmental impact
- Comply with rad safety regulations



- Simulation assuming 1E9 π^-/spill, 240 spills/h on target showed additional shielding allowed significant improvement of the dose rates in the accessible area
- Spectrometer upgrades with more rate-tolerant detectors, and streaming DAQ are also underway to take advantage of the high beam rate

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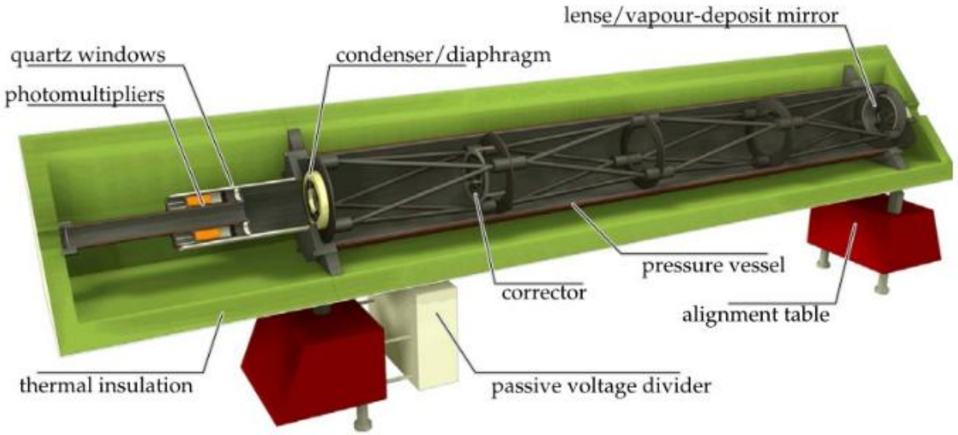
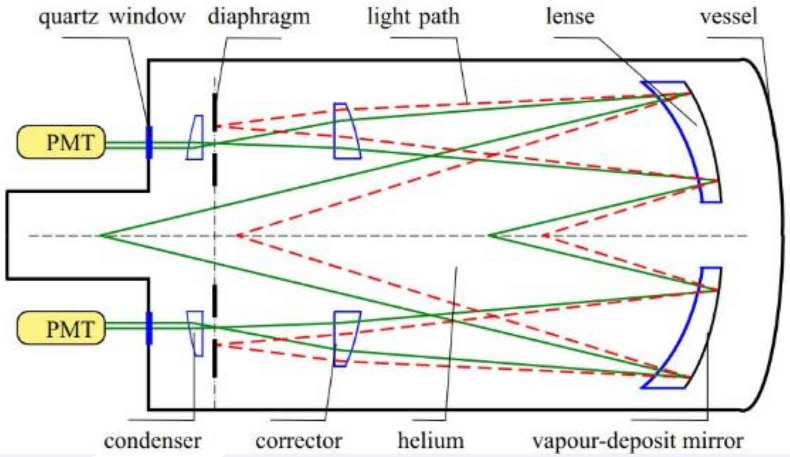
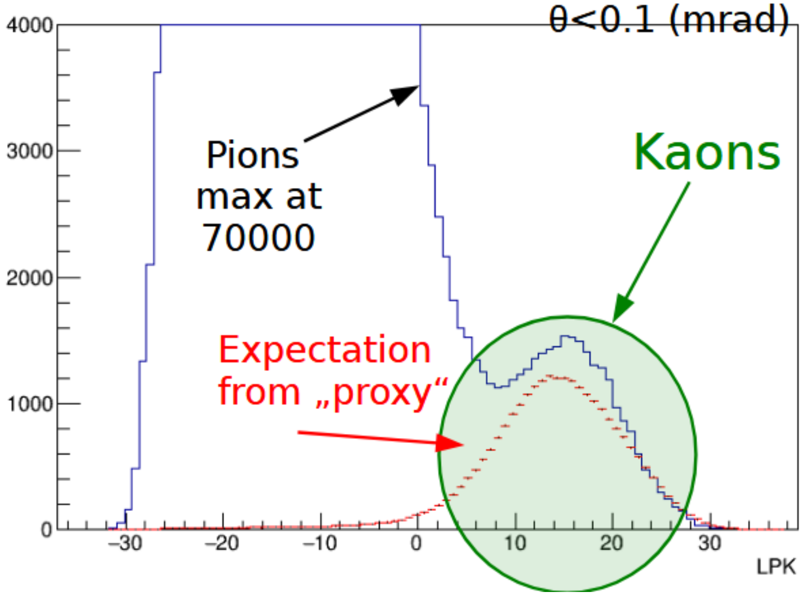
Experimental challenges: beam PID



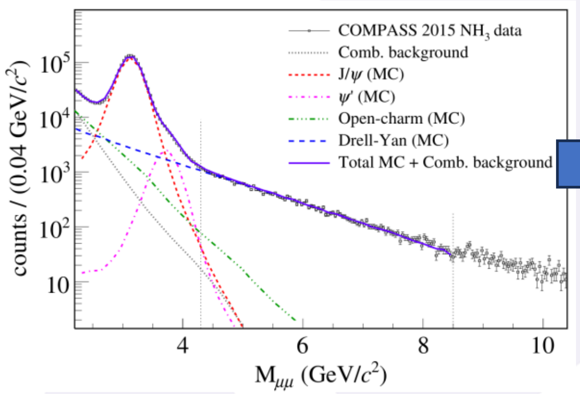


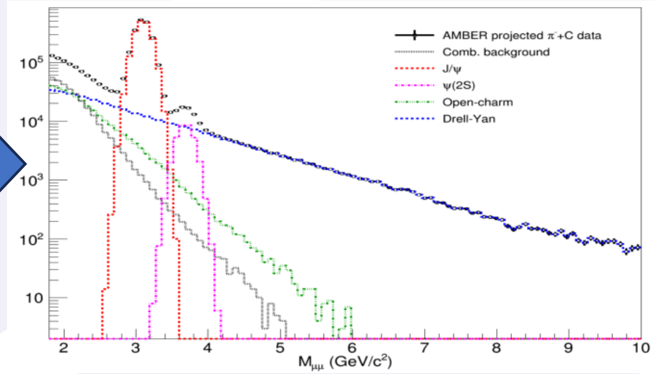


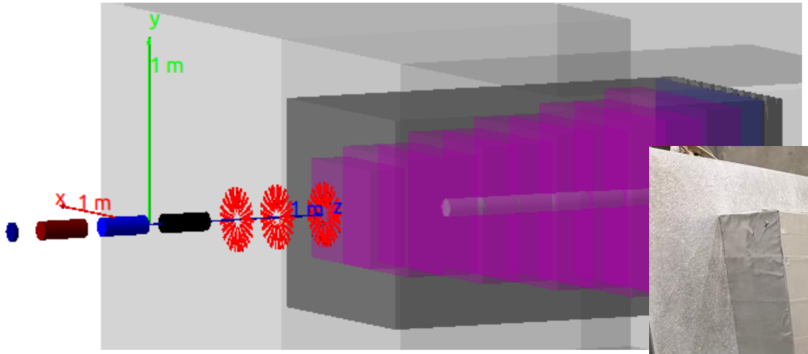
- To harness the limited kaon statistics from the conventional hadron beam, efficient beam PID is key
- Two CEDAR detectors for beam PID are completely refurbished by CERN and will be tested again in 2026
- COMPASS developed likelihood method to beam divergence to improve the beam PID efficiency
- AMBER took additional test data to verify the detector and analysis method works at high intensity

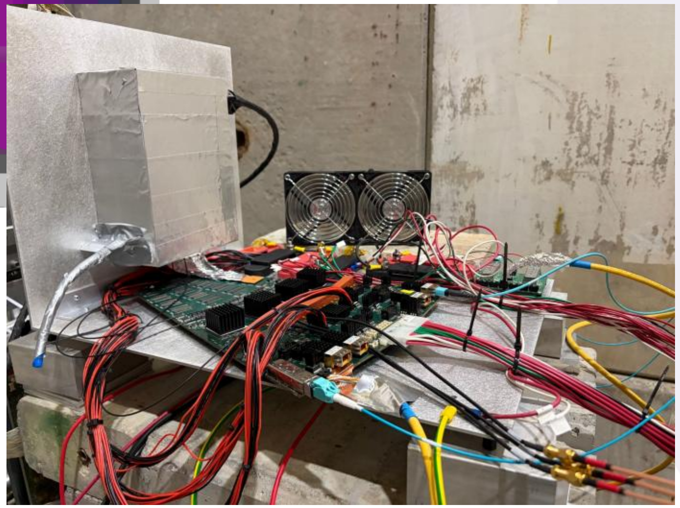
Experimental challenges: mass/vertex resolution

- A new silicon strip vertex detector right after the last carbon target to improve the vertex and mass reconstruction
- Prototype detector just completed beam test at CERN, and full detector planed for the long run after LS3









Preliminary simulation shows that the addition of vertex detector improves the mass resolution from ~200 MeV down to 100-150 MeV, the vertex resolution from ~12 cm down to <3 cm

- Allows a lower mass cut for DY (4.3 GeV -> 4 GeV)
- Suppresses the combinatorial background through tighter vertex cut
- Might even allow us to access low-mass DY events
- Enables clean access to ψ'

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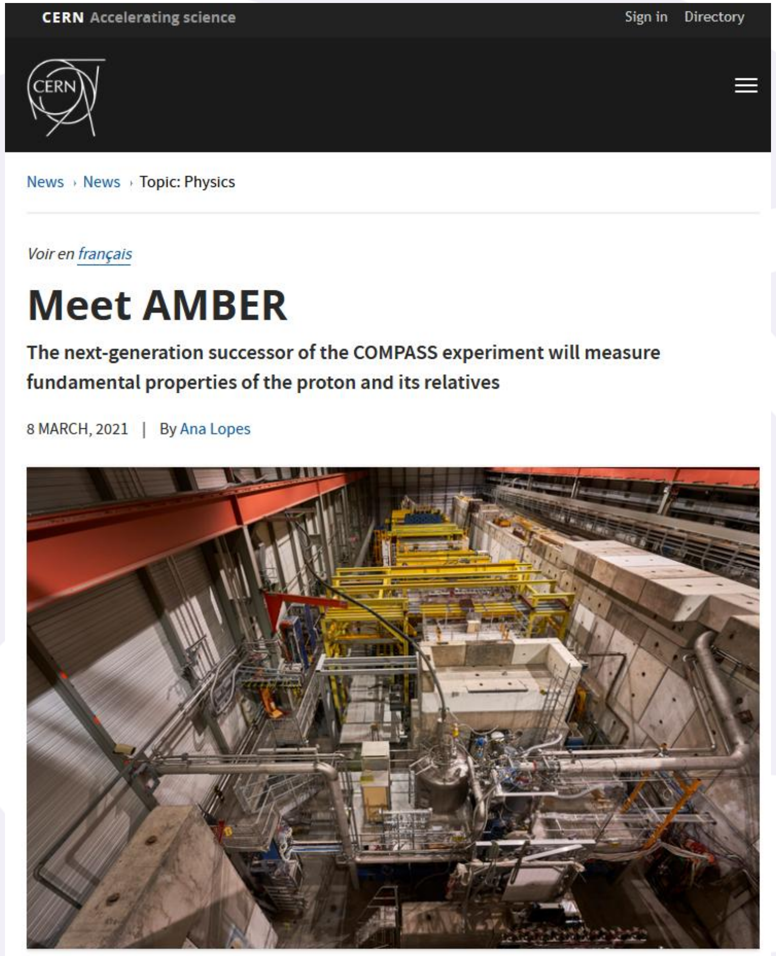
Summary and outlook

- AMBER's DY program in the approved Phase-I will provide the largest pion-induced DY and charmonia data sample within this decade.
  - ❑ Simultaneous access to the valance, sea and gluon content inside the pion
  - ❑ Complementary to and constrains the EIC measurements in the next decade
- With conventional meson beam, kaon-induced data collected in parallel to the pion remains competitive (6x larger than NA3 data set after 2 years)
- Tremendous ongoing effort by CERN and AMBER collaboration to improve the beam intensity and spectrometer capabilities – expect 2-3x more statistics when we start the 2-yr production running after long shutdown



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