AMBER

Apparatus for Meson and Baryon Experimental Research

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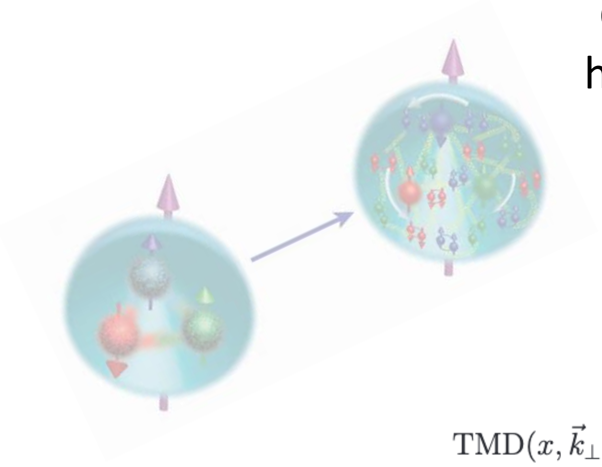
on behalf of the Collaboration

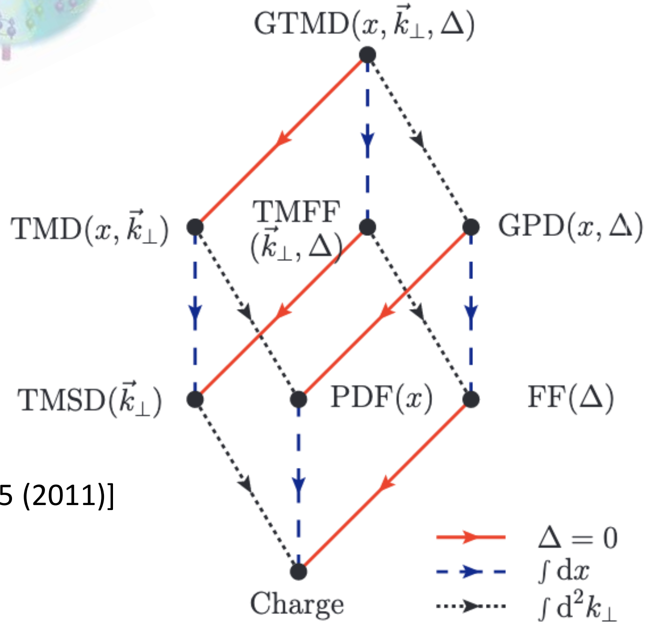
Physics Beyond Colliders Annual Meeting

8 November 2022

Open fundamental questions in QCD

QCD partons in hadronic systems

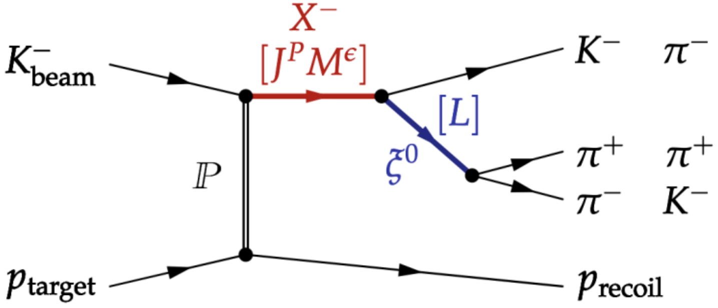




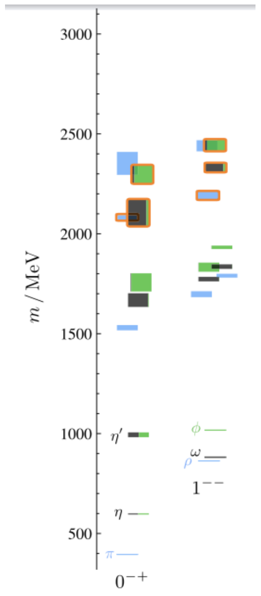
[from: Lorcé, Pasquini, Vanderhaeghen, JHEP05 (2011)]

The complete picture: Wigner distributions

The excitation scheme of hadronic systems



$J^{PC}_{X^-} M^{\varepsilon} \xi \pi L$



[from: B. Grube, EHM workshop (2020)]

Measurable quantities: (iso)spin-parity, masses, couplings and decay widths

Masses of the light hadrons

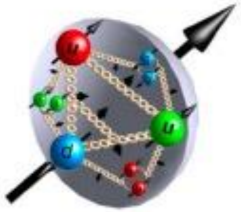
Pion

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

Kaon

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

Proton

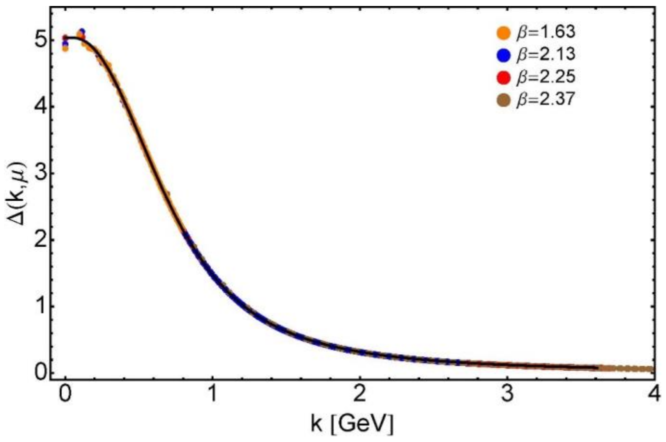


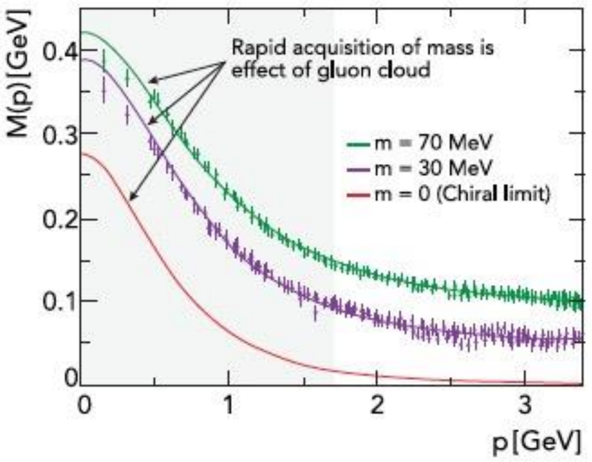
- $M_p \sim 940\text{MeV}$
- Spin 1/2
- 3 light valence quarks

- As composite systems, we want to understand hadrons in terms of their constituents: the QCD quarks and gluons
- The Higgs mass of the valence quarks contributes only little to the physical hadron masses
- Pion-to-proton mass ratio 1/7 much different from the constituent-quark inspired value of 2/3

Emergent Hadron Mass

- Dynamic generation of mass in continuum QCD
- Gluon self-interaction in the infra-red leads to gluon “self-mass generation”





- Emergence of Hadron Mass is to some extent understood within continuum and lattice QCD calculations
- Prove and provide more input by measurement of
  - Quark and gluon PDFs of pion, kaon and proton
  - Hadron radii as consequence of confinement
  - Mass spectra of excited mesons

AMBER physics programme

AMBER
Apparatus for Meson and Baryon Experimental Research

- Letter of Intent 2018 as COMPASS++/AMBER (arXiv:1808.00848) for upgrades and extensions of the setup
- Use of conventional and radio-frequency (RF) separated beams

- Proposal in two Phases
- Phase-1 approved by SPSC in December 2020
- Phase-2 in drafting stage, plan to submit in first half of 2023

- MoU draft close to final, signatures expected by end of 2022

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	$4\cdot10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2\cdot10^7$	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	$5\cdot10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\bar{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5\cdot10^7$	25	$\bar{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7\cdot10^7$	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 polarisa-bility & pion life time	~100	$5\cdot10^6$	>10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5\cdot10^6$	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	$5\cdot10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5\cdot10^6$	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.

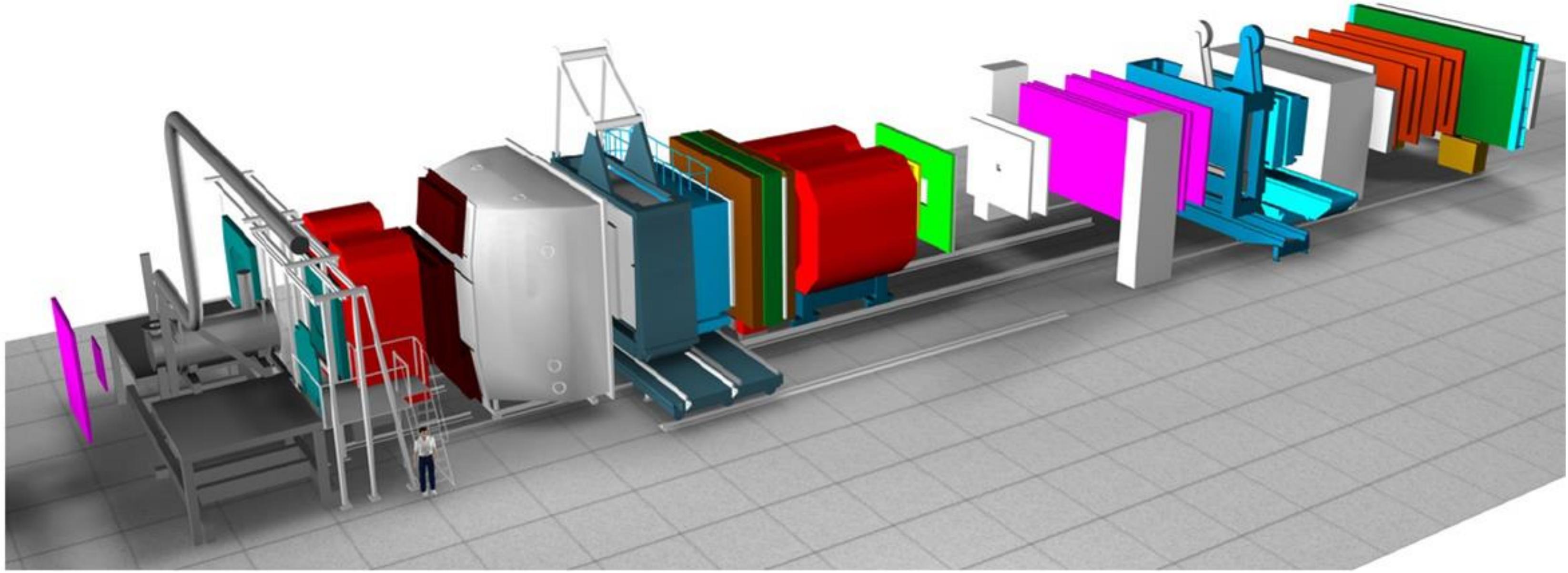
Phase-1
with conventional hadron and muon beams
2022 → 2028

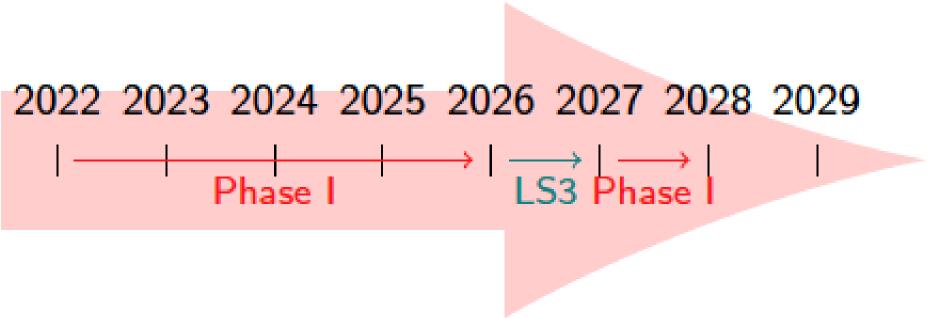
Phase-2
with conventional and rf-separated beams
2029 and beyond

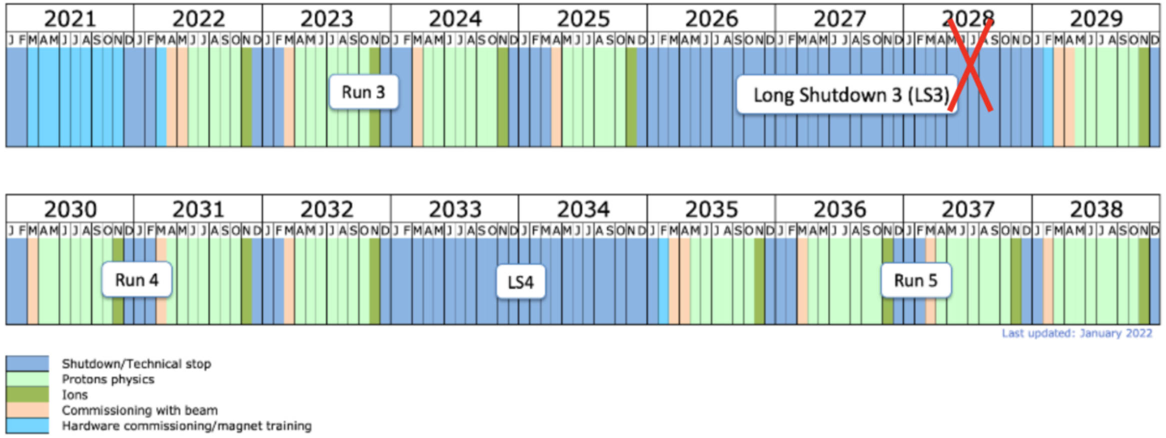
AMBER Collaboration and timelines

AMBER – Apparatus for Meson and Baryon Experimental Research

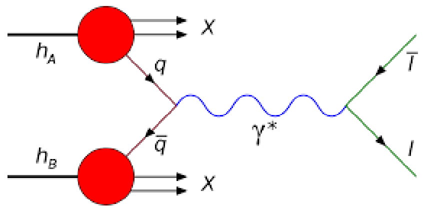
- Successor of COMPASS
- with appropriate extensions and modernisations
- at the CERN M2 beamline
- ~200 physicists from 34 institutes



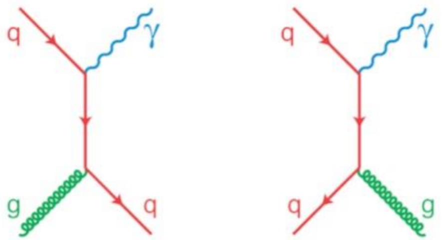




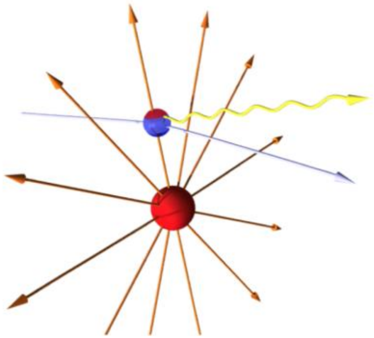
The ideas of the Phase-2 proposal



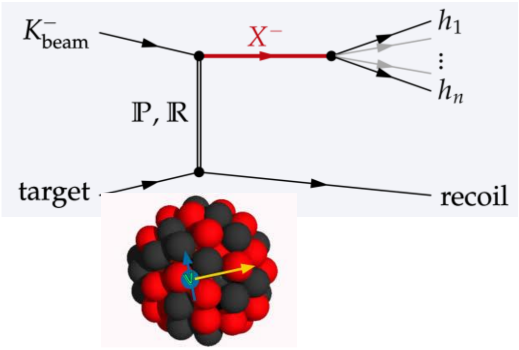
- Kaon structure via the Drell-Yan process



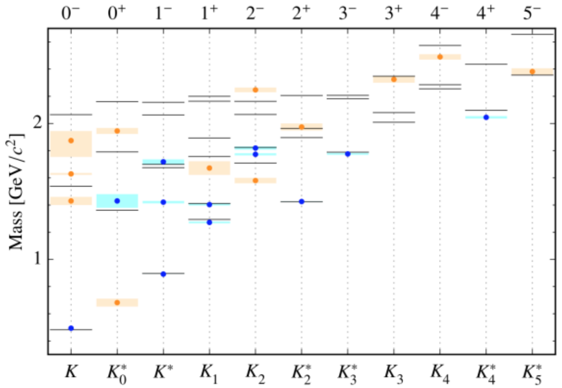
- Gluon structure of pions and kaons via prompt photons



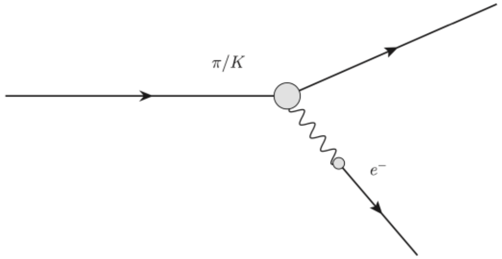
- Primakoff reactions to investigate Kaon-photon coupling: Kaon polarisability, $F_{KK\pi}$



- Diffractive production of vector mesons and di-jets to study distribution amplitudes

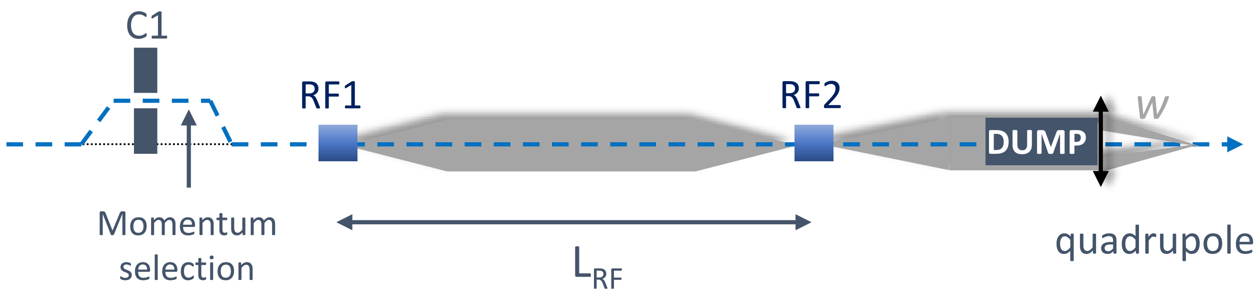


- Spectroscopy of mesons with strangeness



- Meson charge radii via electron scattering in inverse kinematics

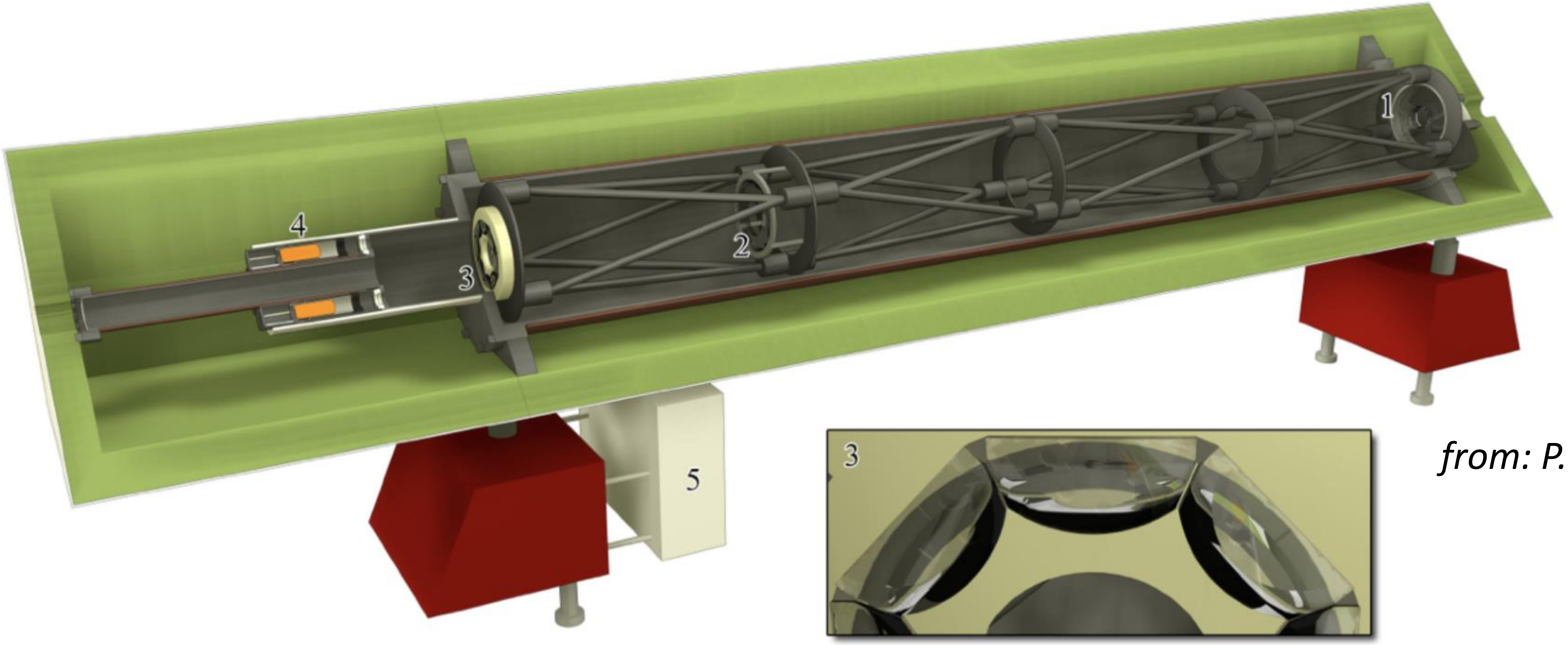
Conventional vs. rf-separated beams



- **Panofsky-Schnell-System** for beam particle species discrimination: same momentum but different velocities
  - For M2: Interest in K^- and antiproton beams
  - Technique and options covered in the following talk by F. Metzger
- **Increase of the purity** of the kaon (or antiproton) component
- **Same** or reduced **intensity** of the desired component (compared to original beam)
- Only possible at beam energies less than about 100 GeV
- Promising option for part of the program: Primakoff, spectroscopy, kaon radius
- For physics requiring high intensity and energy: **Upgraded conventional beam could be good alternative**

- Follow-up one-day workshop with the CERN accelerator group

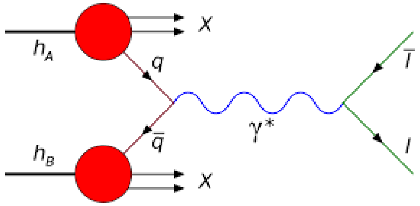
Beam PID by CEDARs



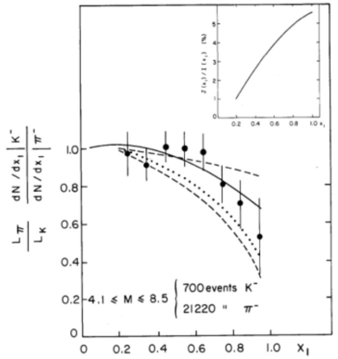
from: P. Jasinski, PhD thesis

- High-efficiency and high-purity beam particle identification is of key importance in all scenarios of hadron beams
- Optimum operation not only concerns mechanics and optics (temperature stabilization, photon detection), but as well parallelism of the incoming beam → material budget of the beamline

Kaon structure via the Drell-Yan process

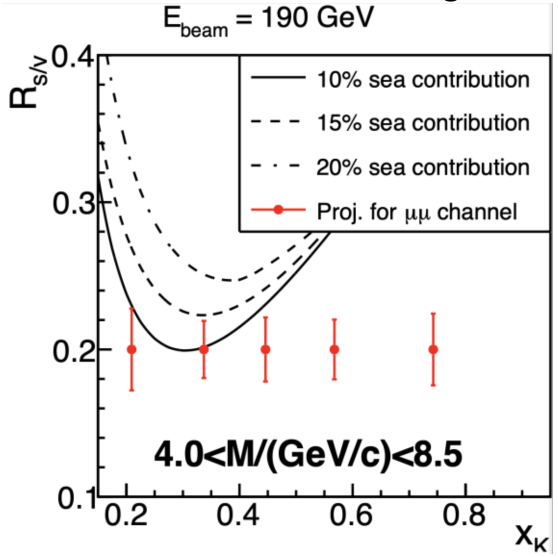


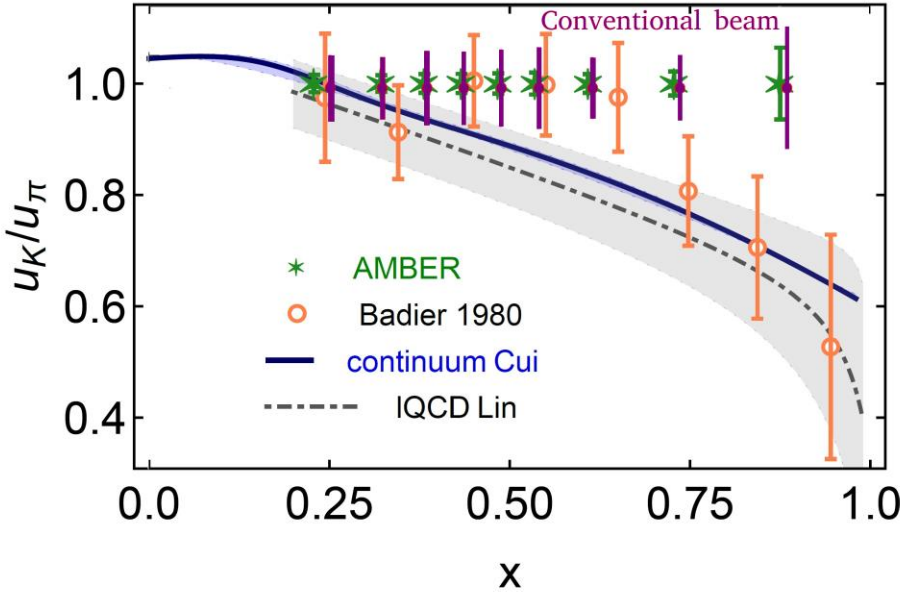
NA3: PLB 93 (1980) 354



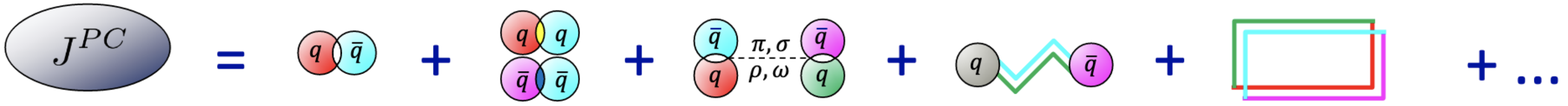
- Available data
  - Only 700 events from NA3
  - The kaon valence distributions are practically unknown
  - There is no data on kaon sea and gluon content
- Prospects for AMBER measurements
  - Kaon valence PDF: can be addressed with negative kaon beam
  - Kaon sea PDF: combine the two beam charges

$$R_{s/v} = \frac{\sigma(K^+)}{\sigma(K^+) + \sigma(K^-)}$$





Exotic mesons



$(q\bar{q})_0$ $(qq)_8(\bar{q}\bar{q})_8$ $(q\bar{q})_0(q\bar{q})_0$ $(q\bar{q})_8 g$ $(gg)_0$

Tetraquark Molecule Hybrid Glueball

Where are they?

How to identify them?

- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Flavor-exotic: $|Q|, |I_3|, |S|, |C| \geq 2$
- Comparison with models, lattice

Need:

- Large data sets with small statistical uncertainties
- Complementary experiments
  - production mechanisms
  - final states
- Advanced analysis methods
  - reaction models
  - theoretical constraints

Limitations at COMPASS

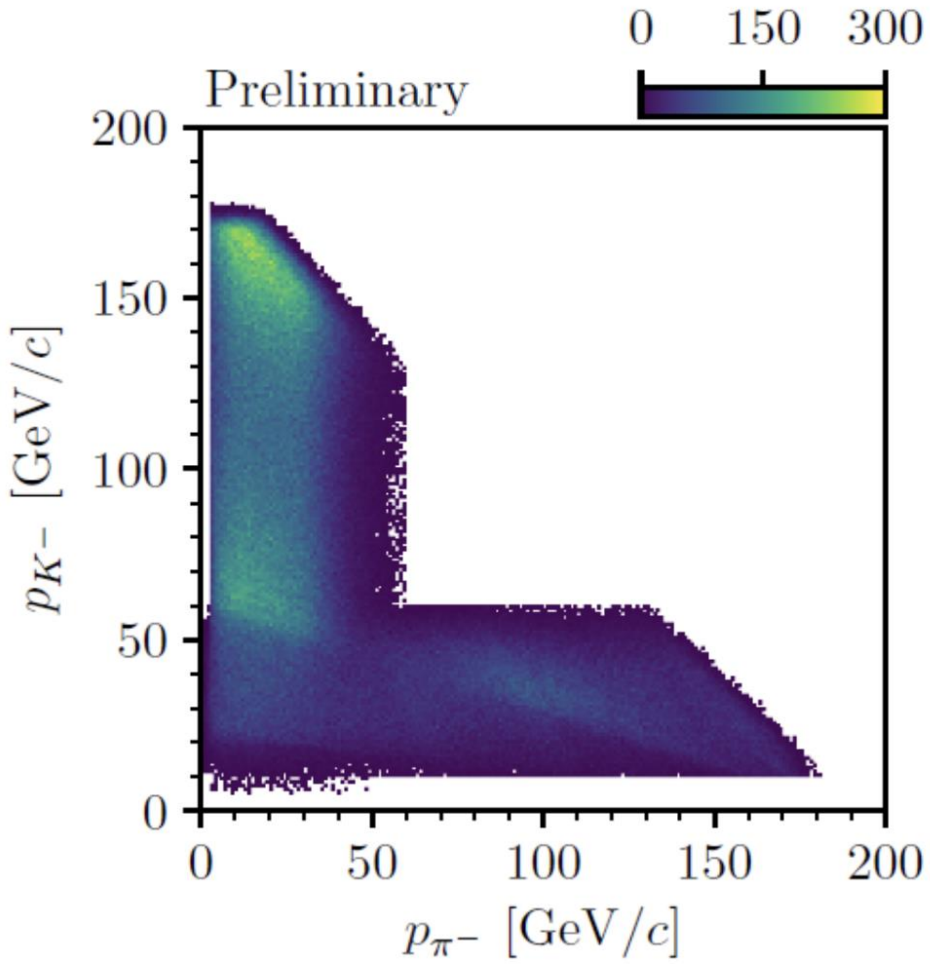
- Final-state particle identification does not cover full momentum range

Cannot identify the full final state

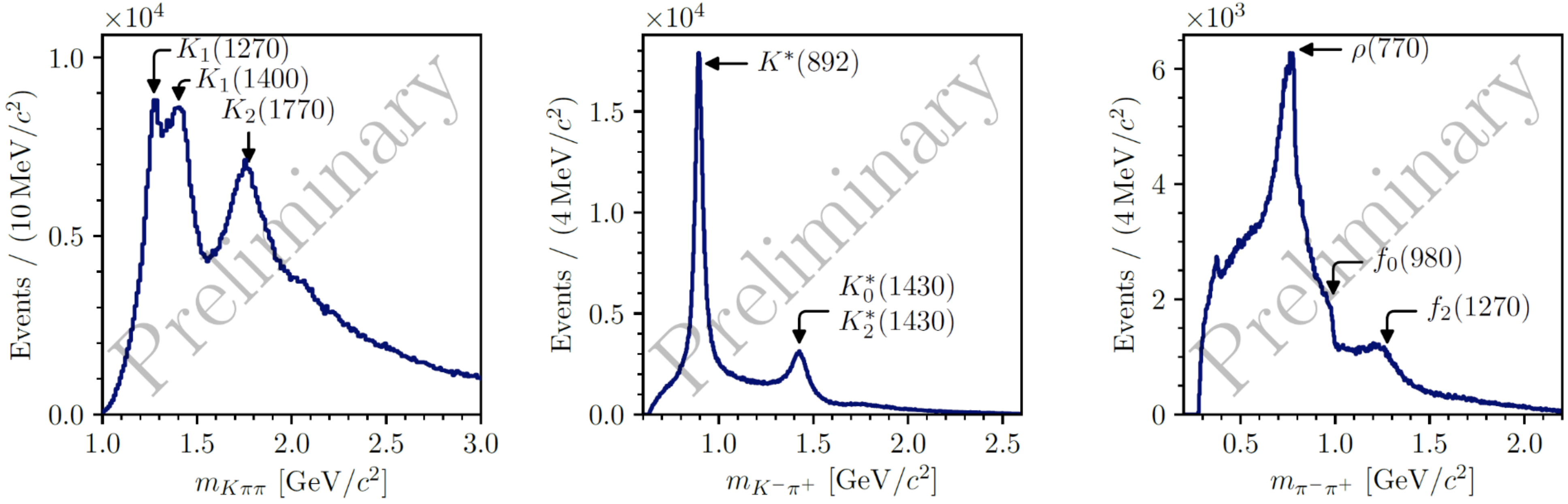
- Assume sample contains only $K^-\pi^-\pi^+$ events
  - Minimal PID: Need to know which of h^- is K^-
- Require only one of h^- to be identified
- Acceptance reduced by more than 1/3
- Almost no suppression of KKK, $\pi\pi\pi$, ...

Blind spot in experimental acceptance

- Decay amplitudes of different J^P are orthogonal
- Loss of orthogonality taking acceptance into account



COMPASS: $K^- \pi^- \pi^+$



Study reaction $K^- + p \to K^-\pi^-\pi^+ + p$ by tagging beam kaons (2.4%)

⇒ access to all kaon states: K_J, K_J^*

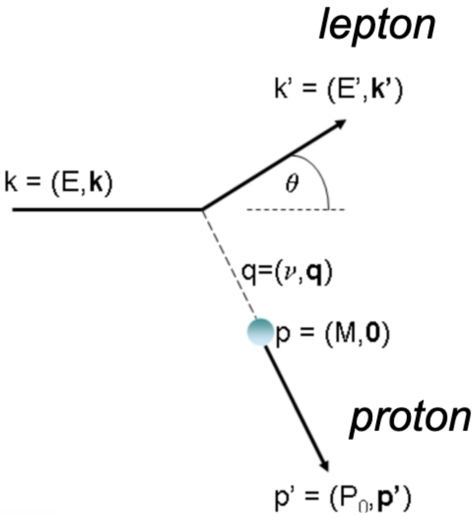
⇒ world's largest data set so far: 720 000 exclusive events (ACCMOR: 200k ev.)

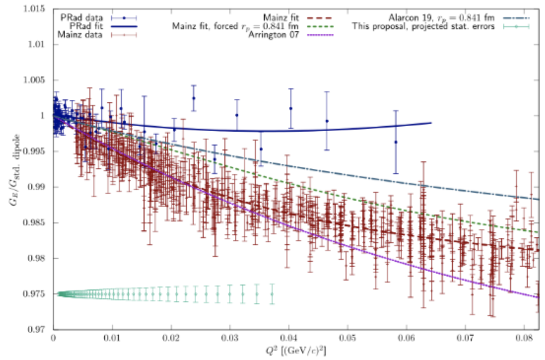
Goal for AMBER: collect $10 - 20 \times 10^6$ exclusive $K^-\pi^-\pi^+$ events

Hadron charge radii

Protons in hydrogen target (or other stable nuclei):
Measurement via elastic electron or muon scattering
Cross section:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R \left(\varepsilon G_E^2 + \tau G_M^2\right)$$

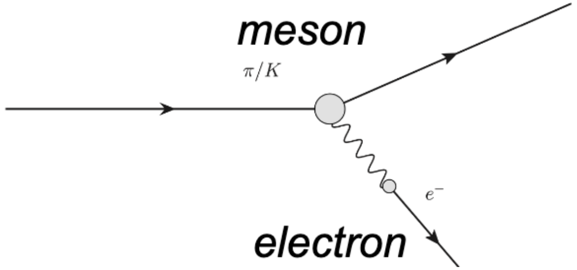




Charge radius from the slope of G_E

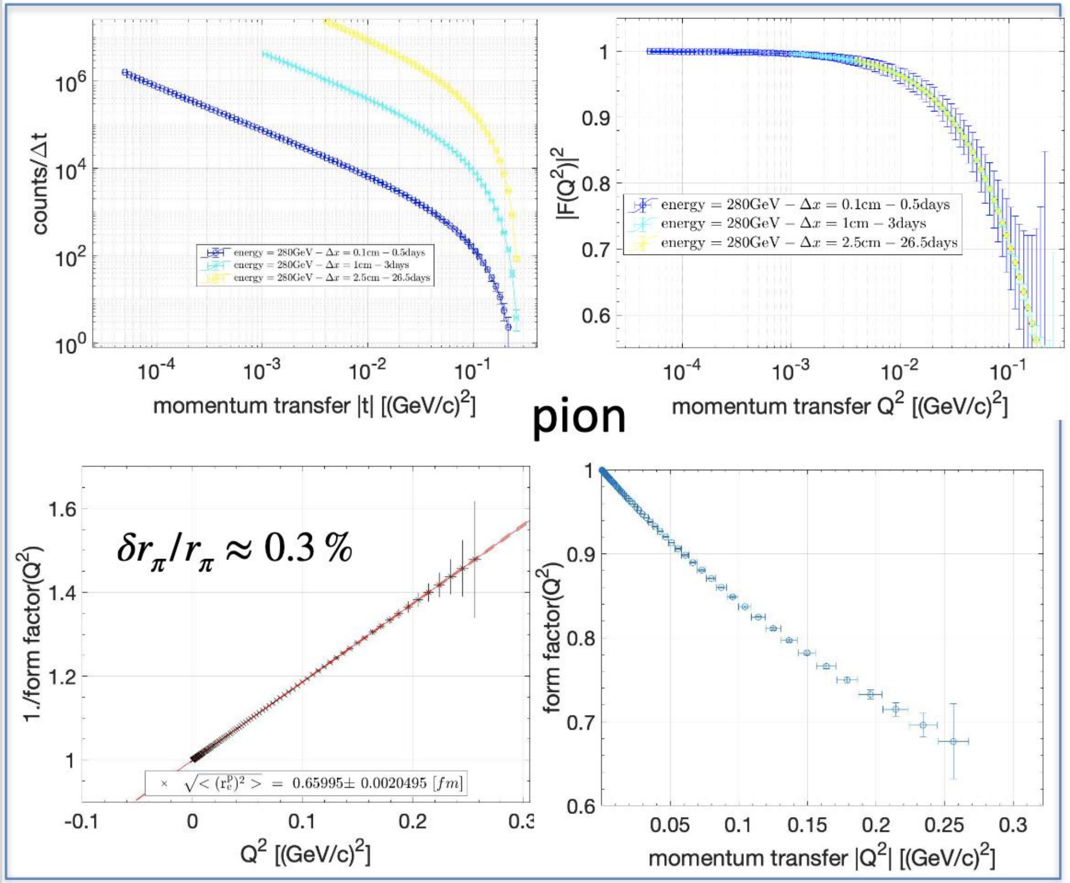
$$\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\right|_{Q^2\to 0}$$

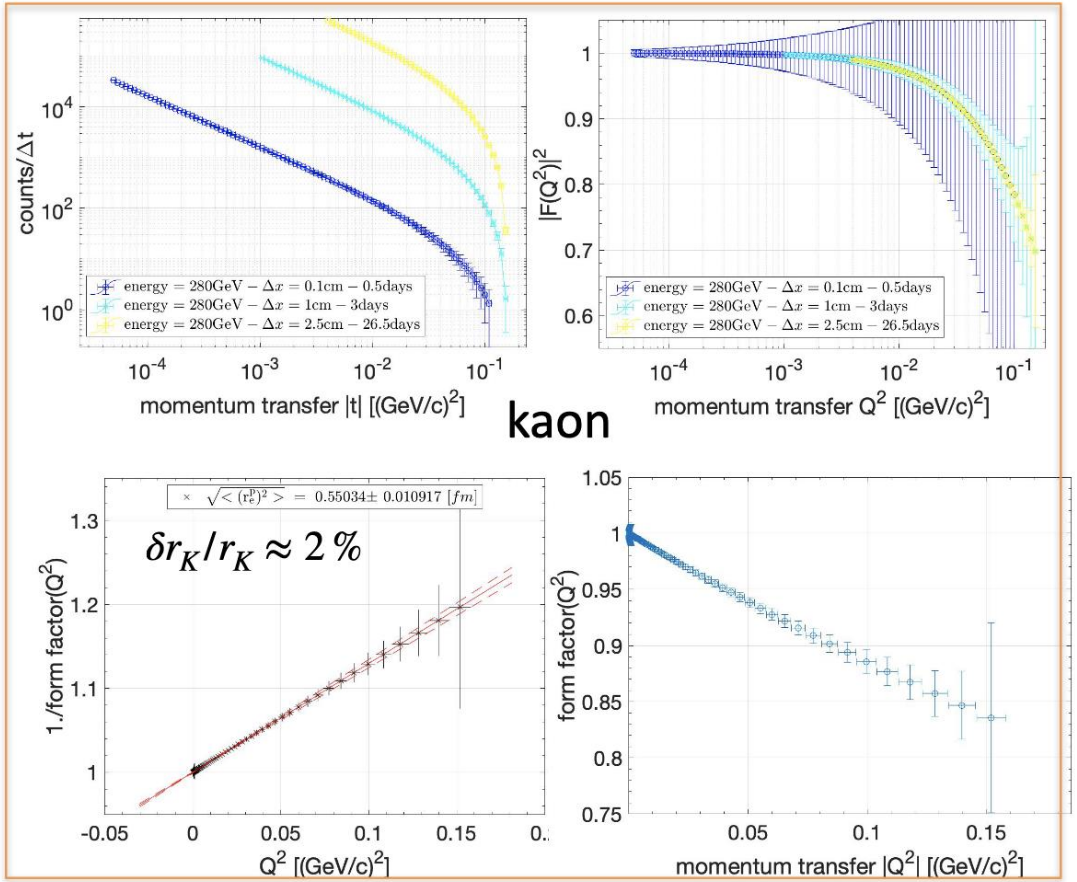
For unstable particles, electron scattering can only be realised in *inverse kinematics*



Simulations for pions and kaons

- **Assume 30 days of beam time (100% efficiency) - use pole description for FF**

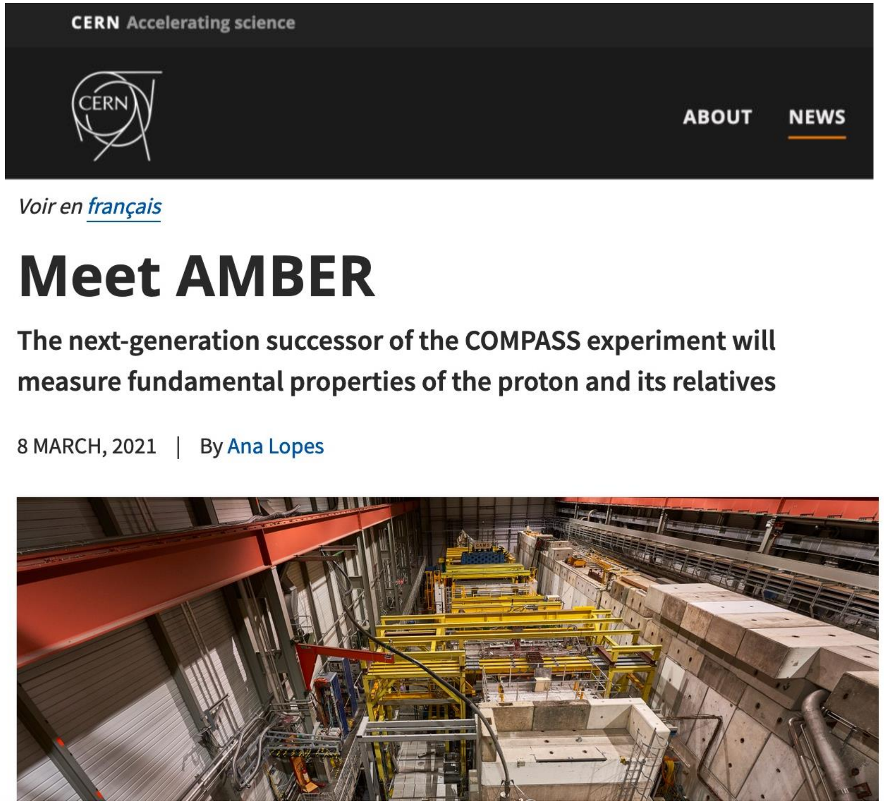




Conclusions

- NA66/AMBER at CERN has **started its Phase-1** of a broad hadron physics programme at the M2 beamline
- The physics cases of **Phase-2** are being worked on for a **proposal to SPSC in 2023**
- The options for **identifying and/or enriching the kaon beam component** are further studied – an enhanced conventional beamline may be equally acceptable or preferable for many of the investigated physics cases

https://home.cern/news/news/physics/meet-amber


CERN Accelerating science

ABOUT NEWS

Voir en français

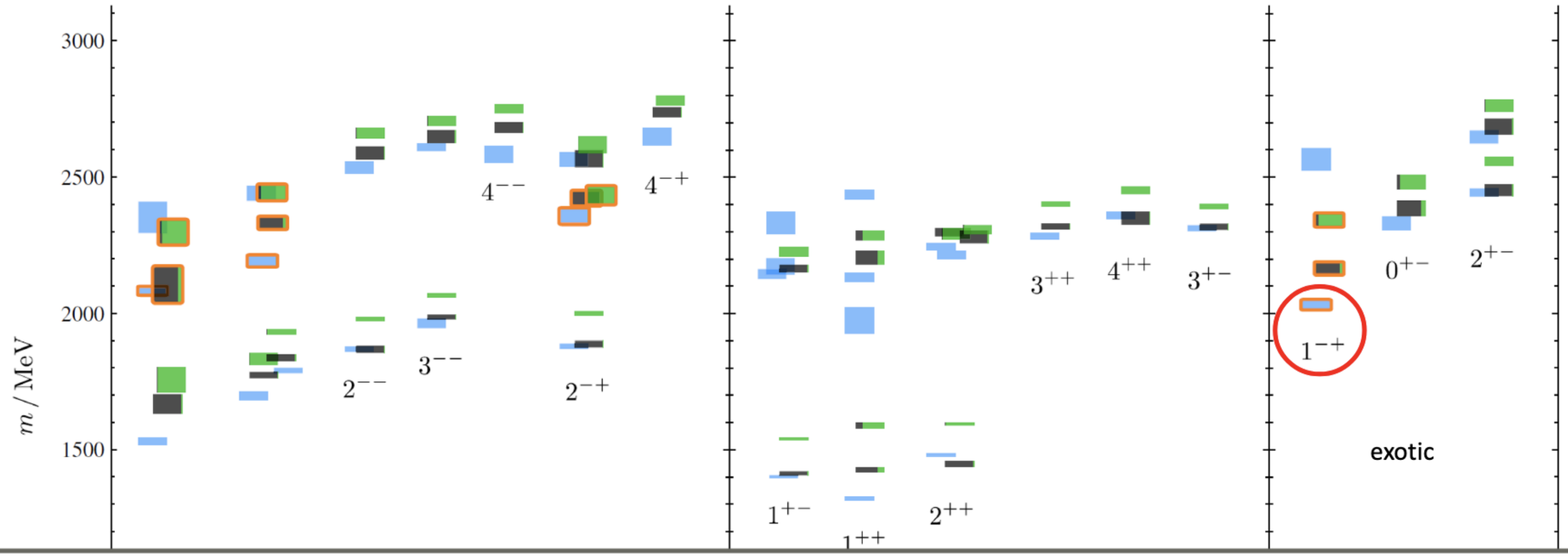
Meet AMBER

The next-generation successor of the COMPASS experiment will measure fundamental properties of the proton and its relatives

8 MARCH, 2021 | By Ana Lopes

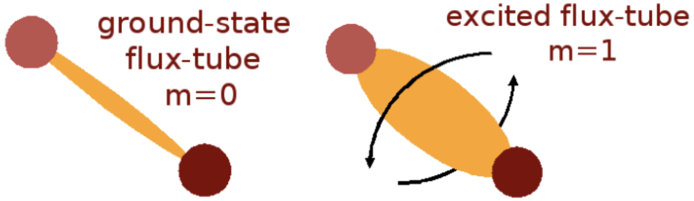
Backup

Hybrids: Lattice QCD



Hybrids:

- excitation of gluonic degrees of freedom
- angular momentum in flux tube
- lightest hybrid predicted to have $J^{PC} = 1^{-+}$



[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 88, 094505 (2013)]

Limitations at COMPASS

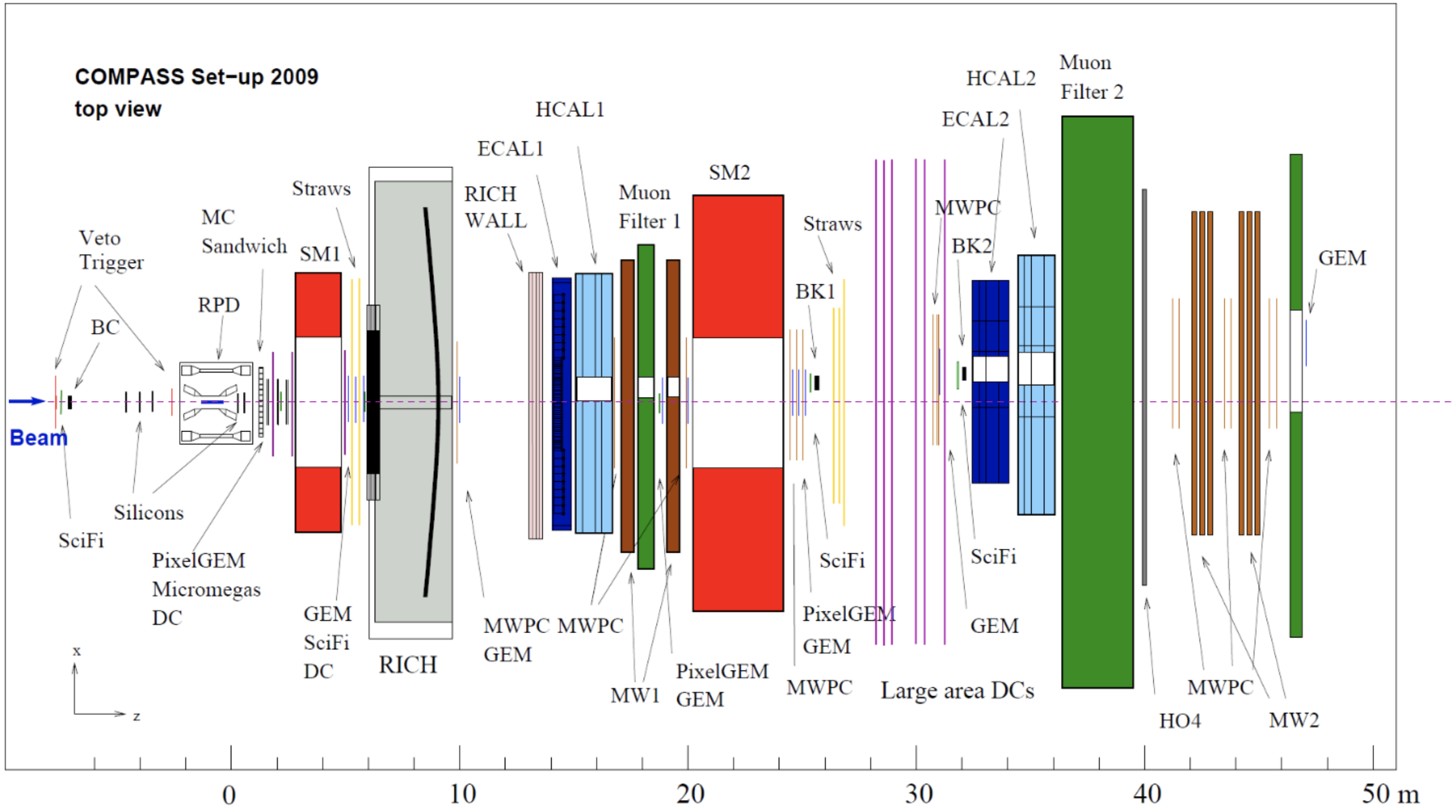
- Only about 2.4 % K^- in negative hadron beam
  - ➥ Low number of kaons
    (Sample for strange-mesons about 150-times smaller than sample for non-strange mesons)
- About 35× more π^- in negative hadron beam
  - ➥ Background from π^- diffraction

Likelihood-based CEDAR PID

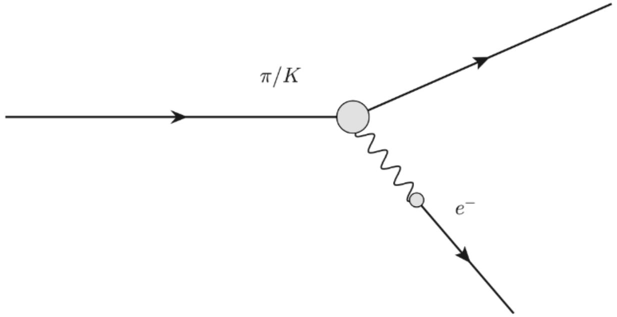
- Finite beam inclination at CEDAR position limits CEDAR PID
- Use information from precisely measured inclination of the beam-particle track
  - Spatial position of beam particle precisely measured at COMPASS target
  - Spatial position at COMPASS target related to beam inclination at CEDAR position by beam optics
- High efficiency of about 85 % and low π^- impurity of about 3 %

Setup for strange-meson spectroscopy

- hadron BMS
- CEDARs
- 2-stage spectrometer
- lH2 target
- RPD
- Si trackers
- ECAL 0, 1, 2
- RICH-0, RICH-1, RICH-2



Kinematics for different beam particles



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

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

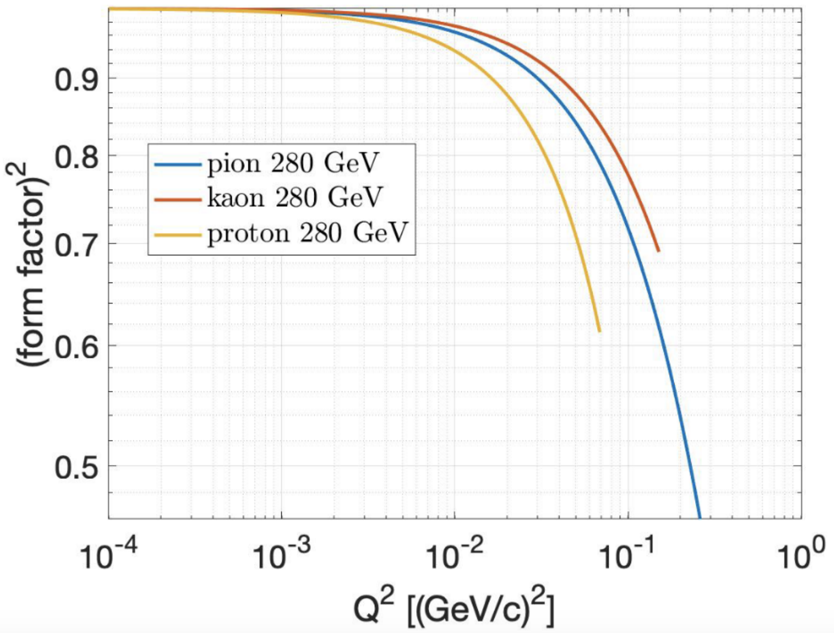
$$s = 2E_b m_e + m_b^2 + m_e^2$$

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

Beam	E_{beam} [GeV]	Q^2_{max} [GeV²]	$E^{min}_{scatter}(Q^2 \sim 10^{-4})$ [GeV]	$E^{electron}_{max}$ Q^2_{max} [GeV]	$E_e^{lab-equivalent}$ [GeV]
π	280	0,268	17.2	173	1,030
K	280	0.15	105.2	84.7	0,29
K	80	0,021	59.7	20.2	0,072
K	50	0,009	41.3	8.7	0,047
p	280	0.07	155.3	34.3	0,152

Q2 range and radius effect

- large values of Q²: higher sensitivity to charge distribution —> $< r_E^2 >$
- small values of Q²: smaller extrapolation uncertainties to Q² = 0 and $\frac{dF(Q^2)}{dQ^2}|_{Q^2=0}$

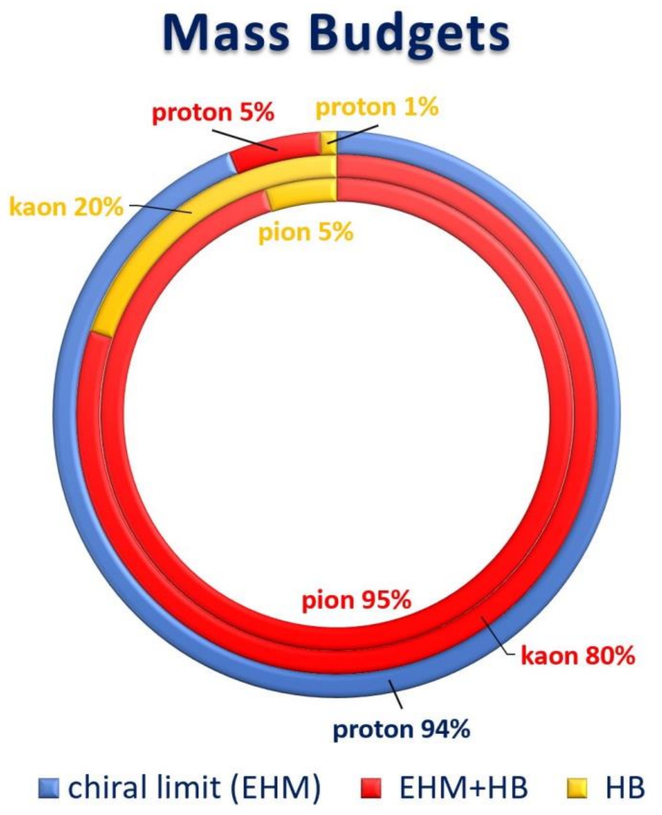


Beam	E_{beam} [GeV]	Q^2_{max} [GeV²]	Relative charge-radius effect on σ(Q²)
π	280	0,268	~54%
K	280	0,15	~30%
K	80	0,021	~5%
K	50	0,009	~2-3%
p	280	0,070	~28%

Mass budgets for proton, pion and kaon

- The mass composition of the proton is structurally different from that of pions and kaons
- Pions and kaons are the Nambu-Goldstone bosons of the (approximate and spontaneously broken) chiral symmetry of strong interaction
- In the chiral limit
  - the mass of the proton remains basically unchanged
  - pions and kaons are massless

Thus for a full understanding the **partonic structure** of hadrons, the **meson PDFs** must be known on a similar level as those of the nucleon



Gluon PDF of the pion

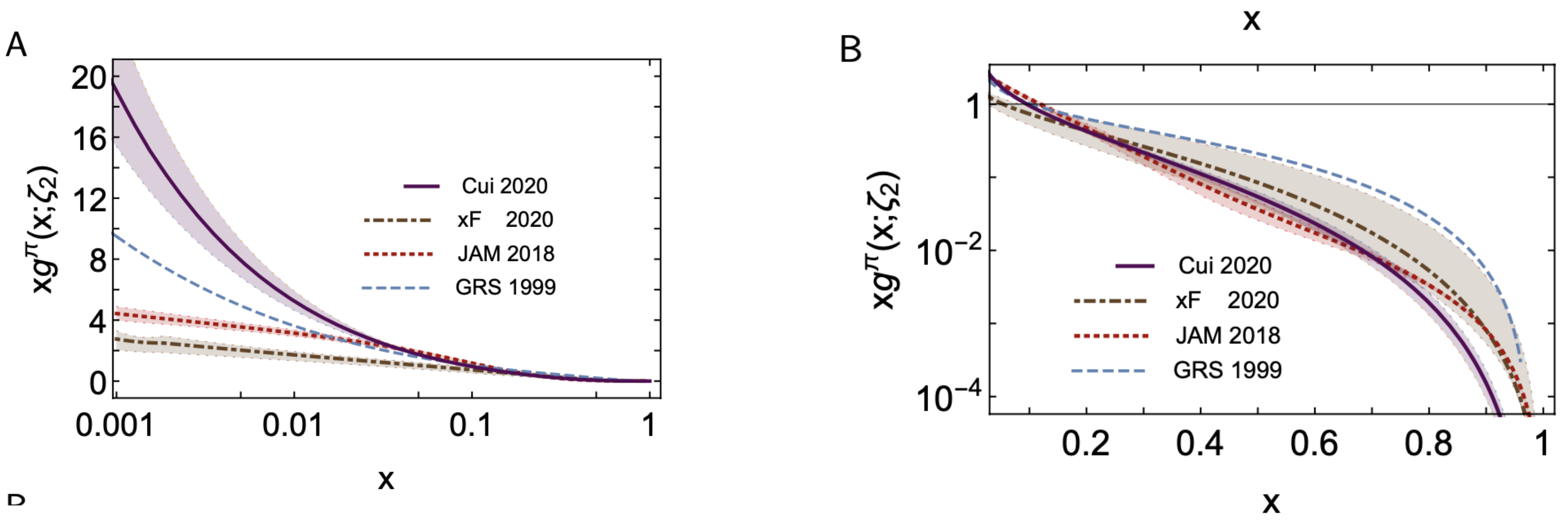
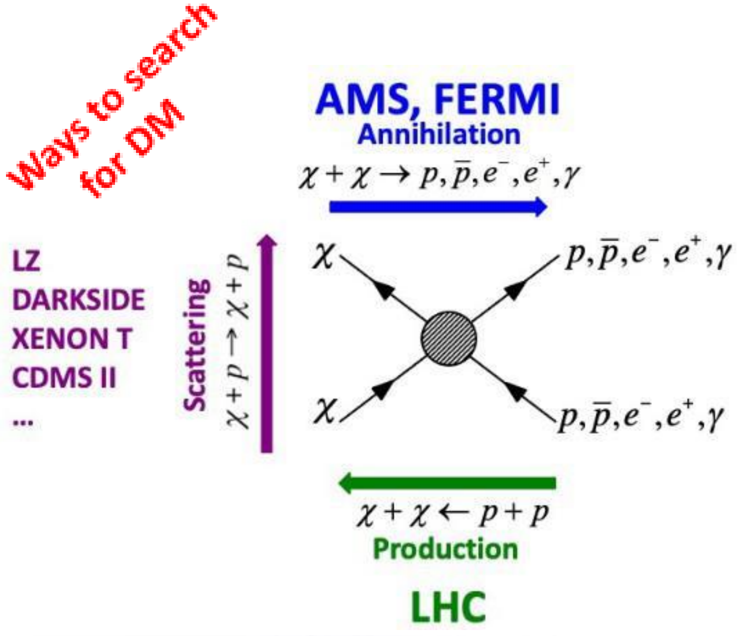
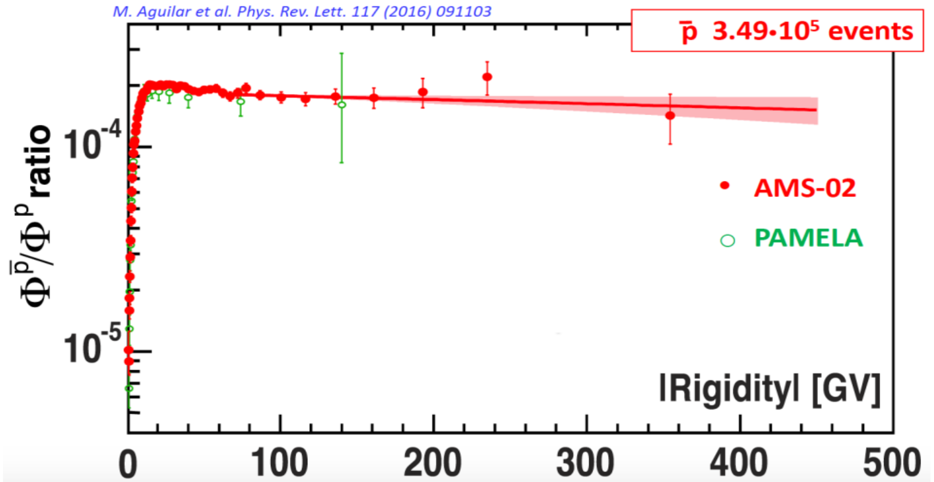


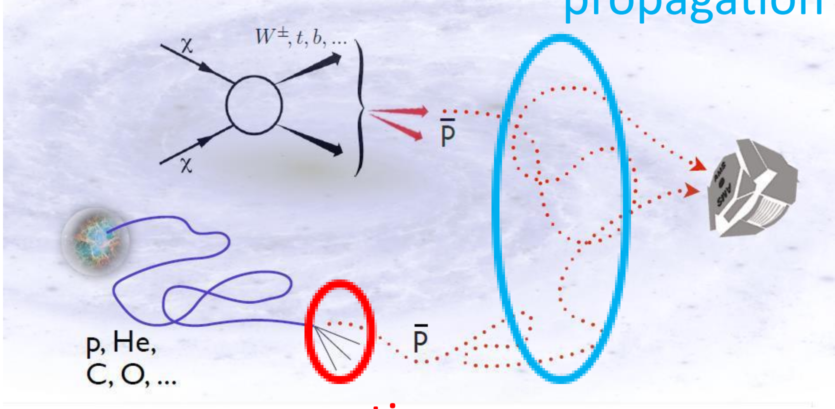
FIG. 4. Glue distribution, $xg^{\pi}(x, \zeta_2 = 2\,\text{GeV})$: solid purple curve, prediction from Ref. [43]. Panel A highlights low-x and Panel B, large-x. The band surrounding this curve expresses a conservative estimate of uncertainty in the prediction, obtained by varying ζ_H by $\pm 10\%$. Comparisons are selected fits to data: dashed blue curve, [32]; dotted red curve and associated band, [33]; dot-dashed brown curve and band, [34].

Antiproton production cross-sections

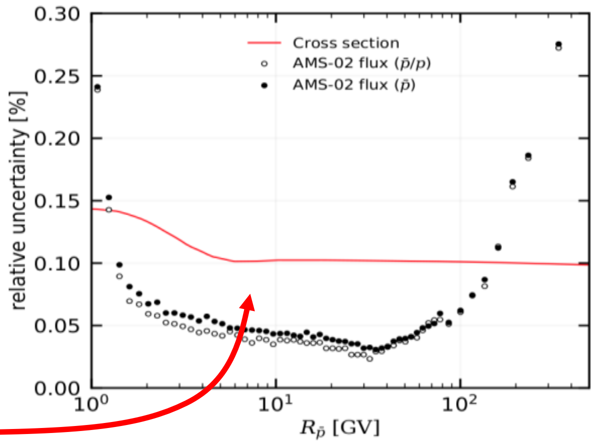


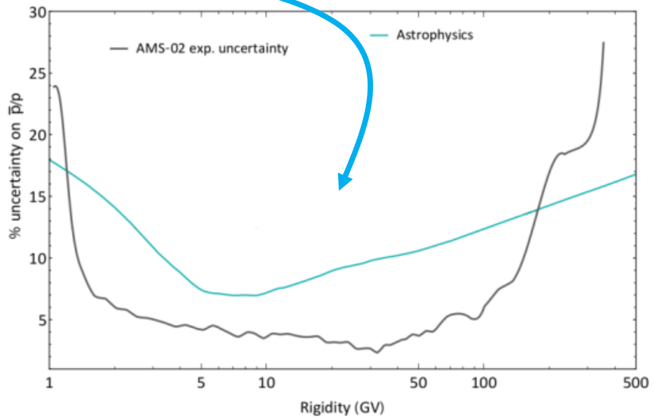


propagation



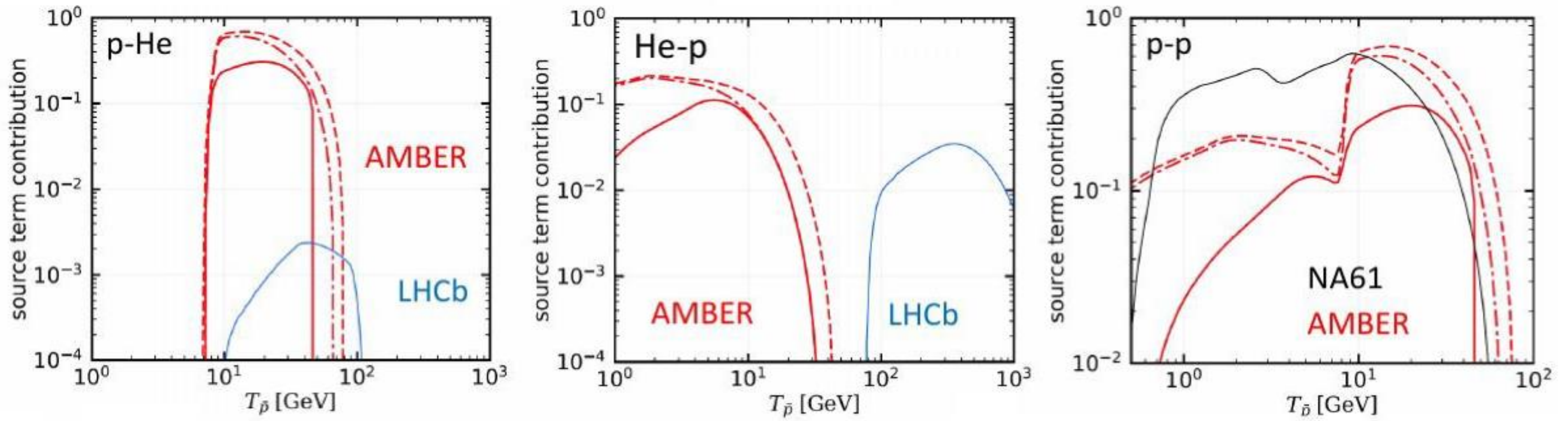
cross section

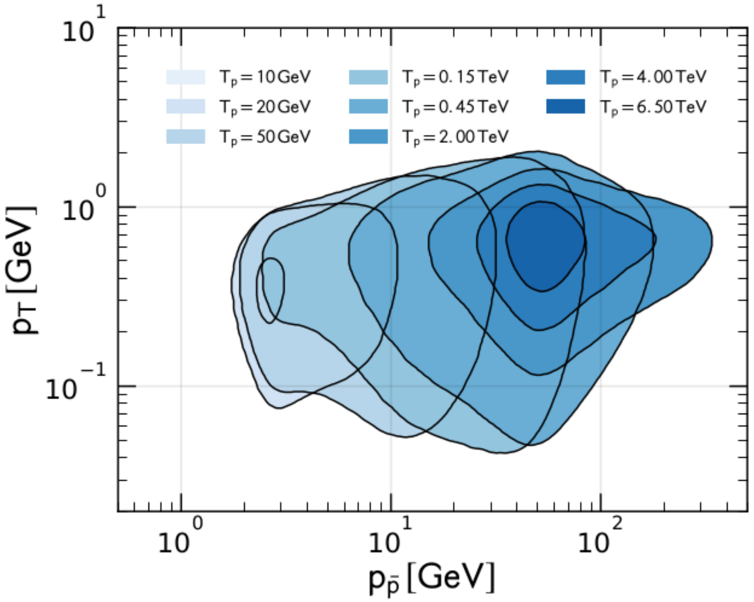




Antiproton measurements at AMBER

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

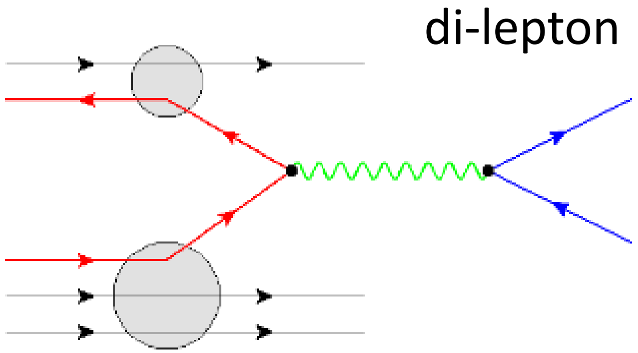


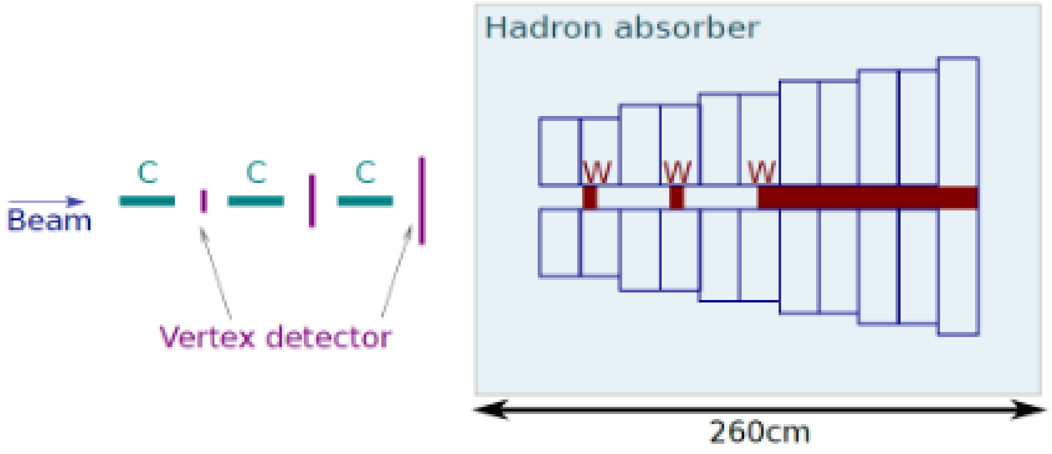


- Parameter space for the p-He channel corresponding to an exemplary fixed target experiment
- 3% relative uncertainty within the blue regions (30% outside)

- Secondary *p* beam with 50, 100, 150, 200, 280 GeV
- Liquid H_2 and He target
- Minimum bias trigger allowing beam intensity of $5 \cdot 10^5\ s^{-1}$
- Beam proton ID in CEDARs, antiproton ID in RICH
- Measure differential cross section in 10 bins in p_p & η
- 2.4<η<5.6
- Statistical uncertainty ≈ 0.5 − 1% per data point
- Total systematic uncertainty ≈ 5% (efficiencies, dead time)
- AMBER pilot run for antiproton production measurements is scheduled in the end of 2022 (LD target, setup tests , rates)
- **Main run is planned to 2023**

Drell-Yan and pion PDFs at AMBER

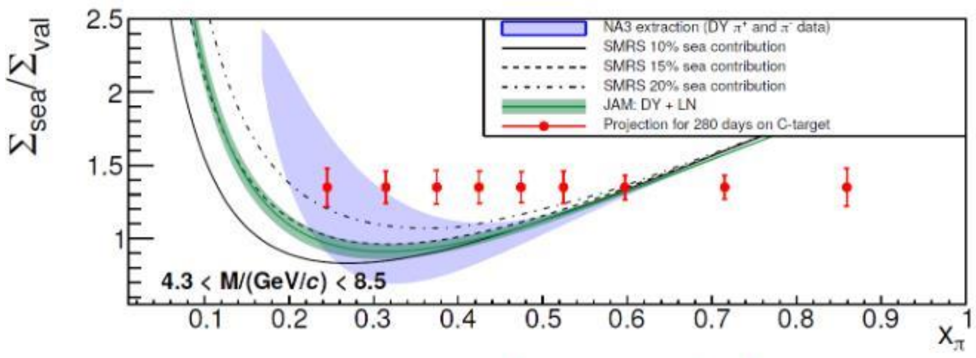




- Iso-scalar target (^{12}C) to minimize nuclear effects

- Beams of positively and negatively charged pions to separate valence and sea contribution:

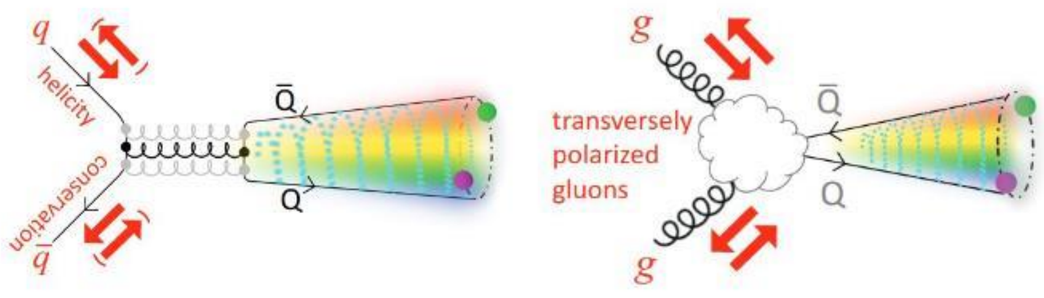
$$\frac{\Sigma_{\text{sea}}}{\Sigma_{\text{val}}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$

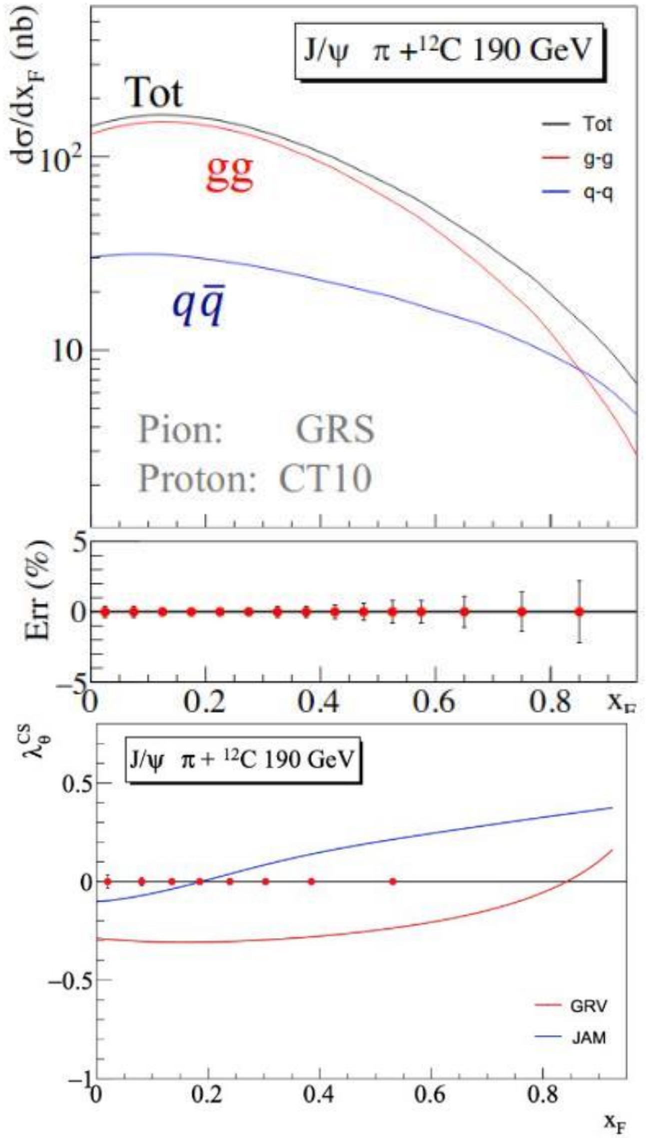


$$\sigma_{\text{DY}}^{\pi^+ A} \propto \sum_i (e_i)^2 \left[\bar{q}_i^{\pi^+} q_i^A + q_i^{\pi^+} \bar{q}_i^A\right]$$

- 250k DY events expected (current available statistics 25k events)
- First precise and direct measurement of the sea quark distribution in the pion
- 190 GeV pion beam
- Target / vertex detector / hadron
- absorber
- Radiation protection
- Di-muon mass resolution of 100 MeV

J/ψ production at AMBER





- Large statistics on J/ψ production at dimuon channel (30-50x 'DY clean region')
- Inclusive measurements: due to the hadron
- absorber prompt production from the rest can't be separated
- Expected significant feed-down: $\psi(2S)$, χ_{c1}, χ_{c2}
- Expected to have dominant contribution from 2→1 processes
- Use J/ψ polarization to distinguish production mechanism: polarization is sensitive to relative contributions of quark- and gluon-induced productions

- Angular distribution

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda \cos^2\theta$$

$\lambda = +1 \;\Leftrightarrow J_z = \pm 1$

$q\bar{q} \rightarrow J/\psi$

$\lambda = 0 \;\Leftrightarrow$ unpolarised

$\lambda = -1 \;\Leftrightarrow J_z = 0$

$gg \rightarrow J/\psi$