Proton Radius within the AMBER Physics Program

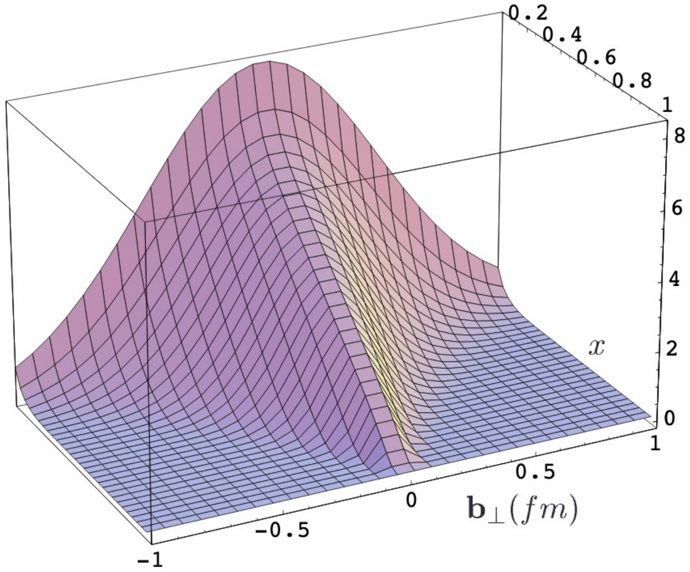
Apparatus for Meson and Baryon Experimental Research

Jan Friedrich

28.6.2023

Nucleon Structure

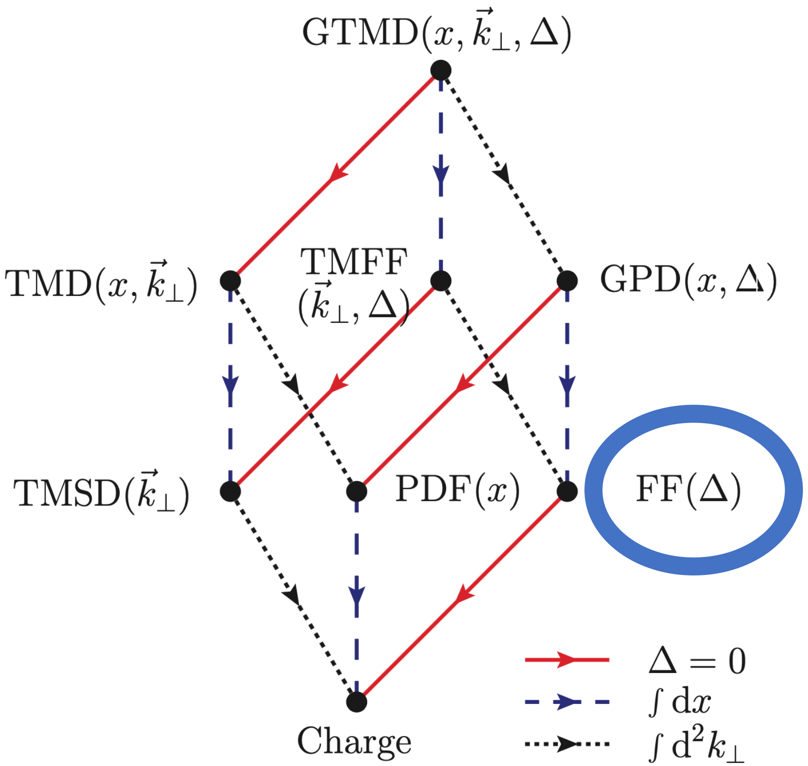
transverse extension *correlating* with the parton momentum distribution



from: **IMPACT PARAMETER SPACE INTERPRETATION FOR GENERALIZED PARTON DISTRIBUTIONS**

MATTHIAS BURKARDT

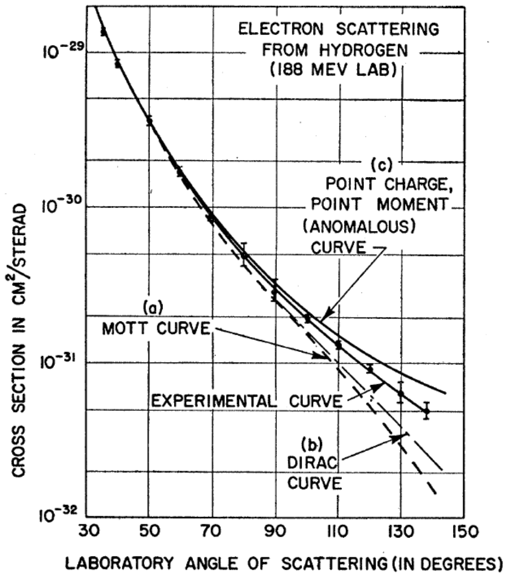
International Journal of Modern Physics A | Vol. 18, No. 02, pp. 173-207 (2003)



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

Proton Radius in ep-Scattering

1956: $r_p \approx 0.8$ fm



If qa is small, where a is the root-mean-square radius, all form factors reduce to the simple expansion

$$F = 1 - (q^2a^2/6) + \cdots . \qquad (19)$$

REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 3 JULY, 1956

Electron Scattering and Nuclear Structure*

Robert Hofstadter

Department of Physics, Stanford University, Stanford, California

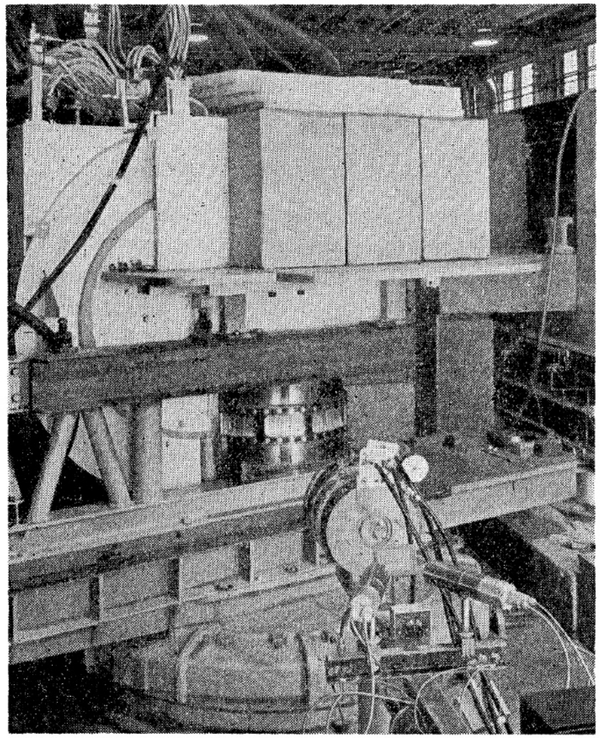
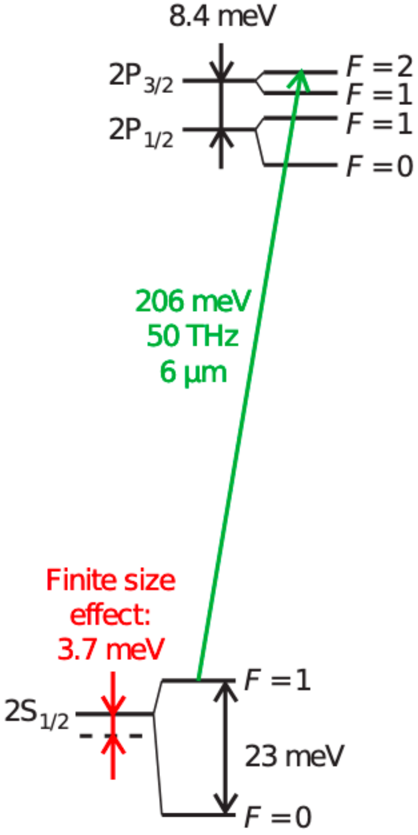


Fig. 15. The semicircular 190-Mev spectrometer, to the left, is shown on the gun mount. The upper platform carries the lead and paraffin shielding that encloses the Čerenkov counter. The brass scattring chamber is shown below with the thin window encircling it. Ion chamber monitors appear in the foreground.

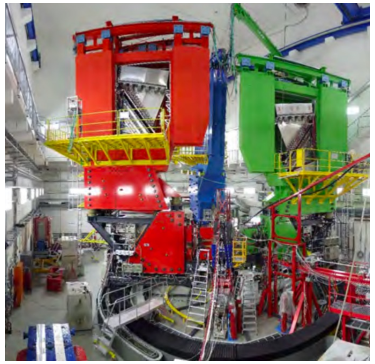
The low background has been achieved with the spectrometer, detector, and shield now to be described. A photograph of the apparatus is given in Fig. 15. It

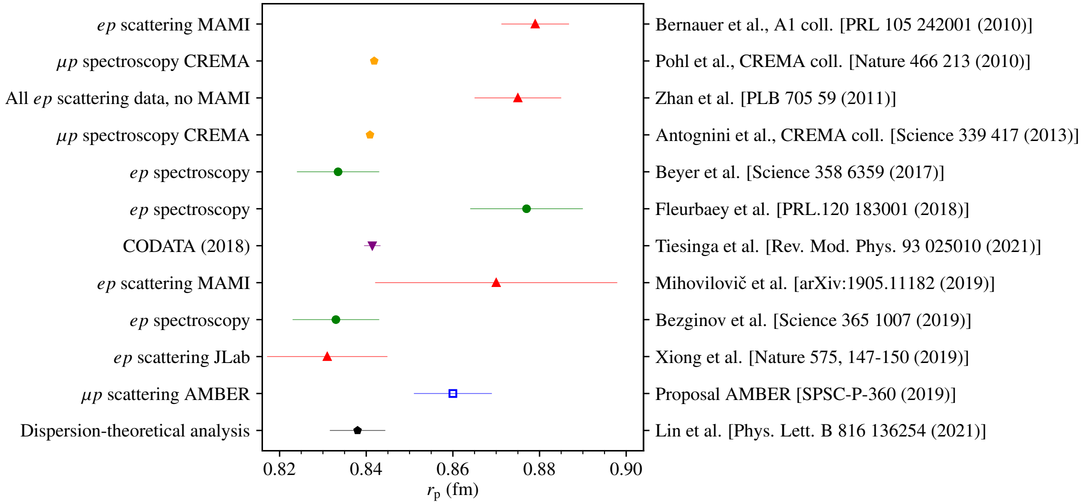
Still not settled?

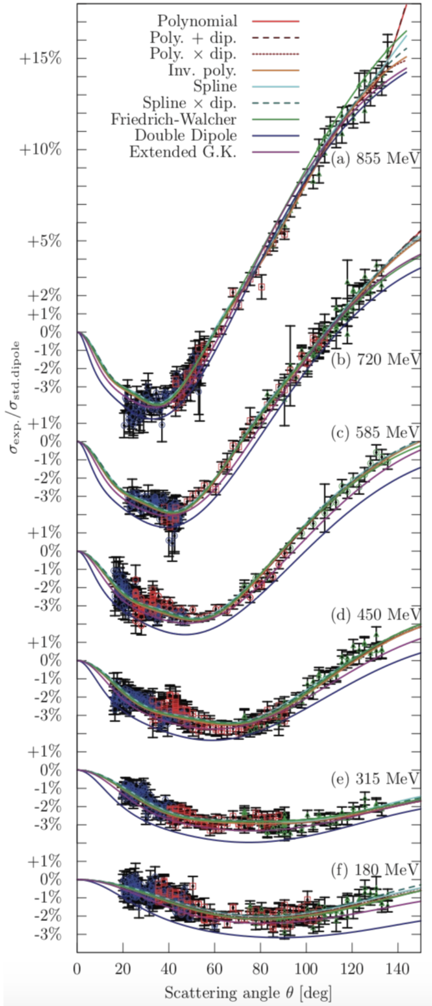
CREMA 2010



MAMI 2010



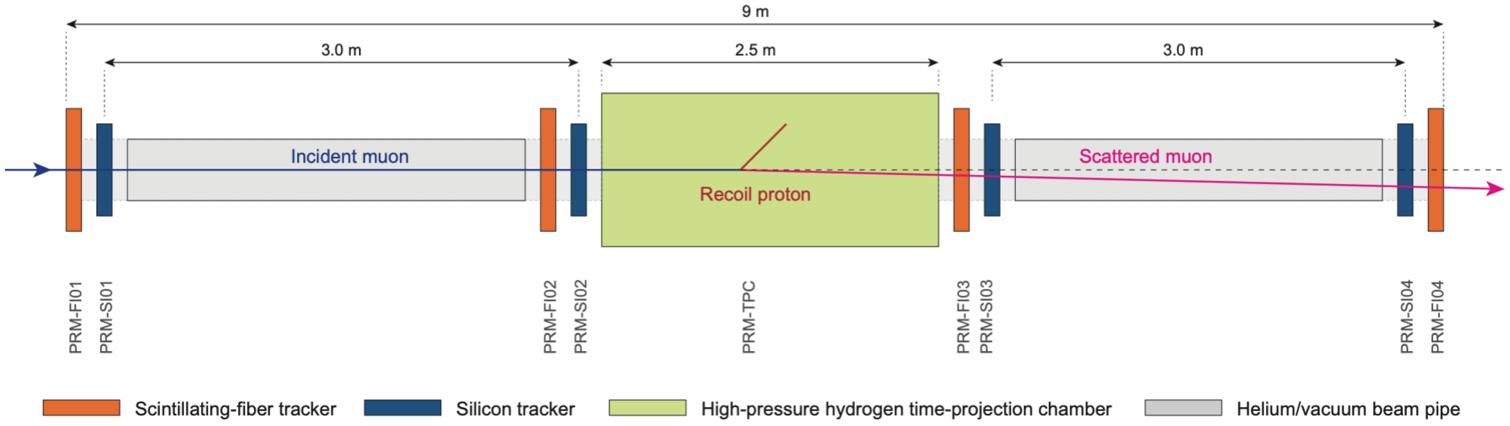


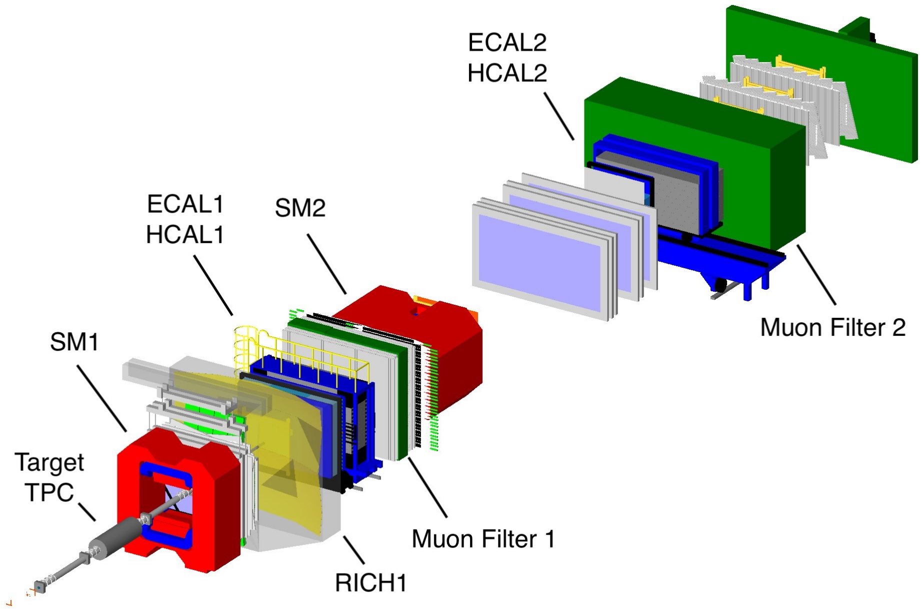


$r_p^{\mu p\ Lamb} \approx 0.84$ fm

$r_p^{elastic\ ep} \approx 0.88$ fm

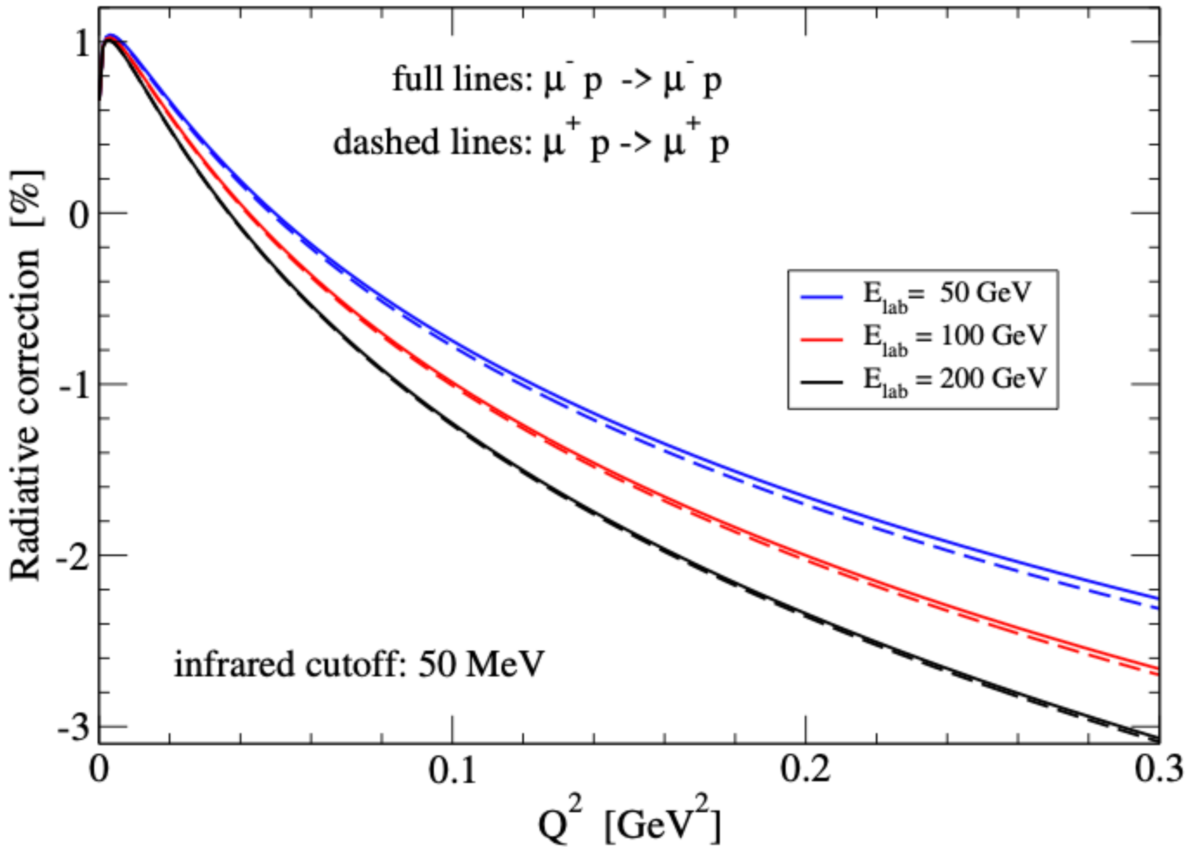
Basic Idea of the AMBER measurement

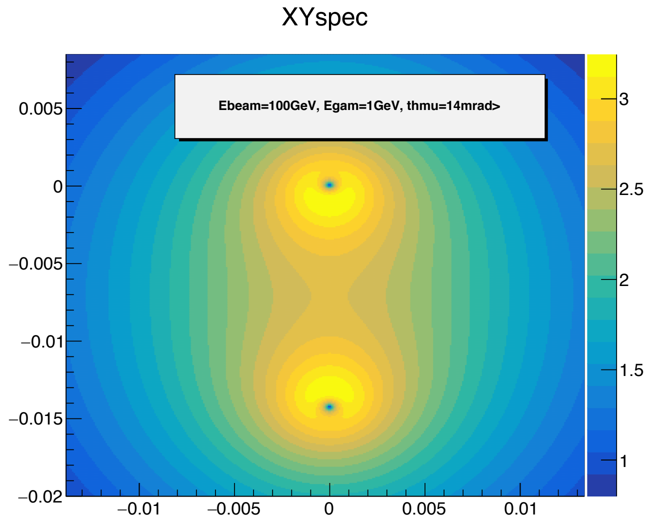


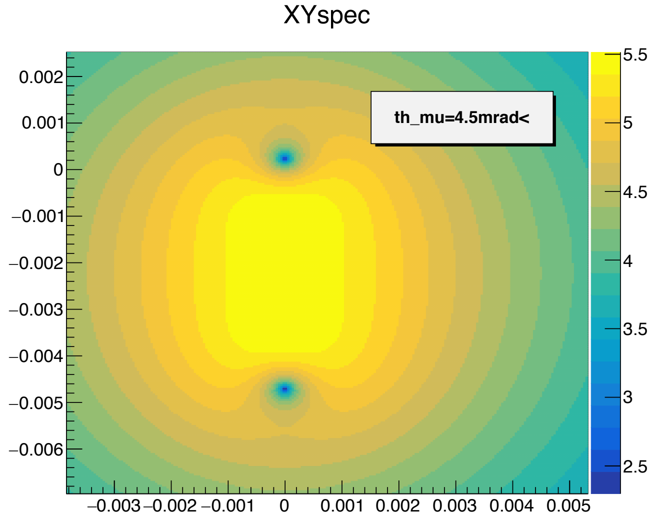


- 100 GeV **muon** beam
- Active-target TPC with high-pressure H_2
- high-precision tracking and spectrometer for muon reconstruction
- goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4{\cdot}10^{-2}$ GeV^2
- Precision on the proton radius ~0.01 fm

Radiative Corrections for μp Scattering



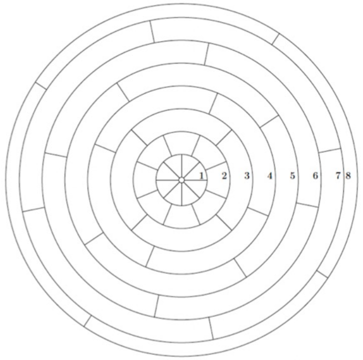


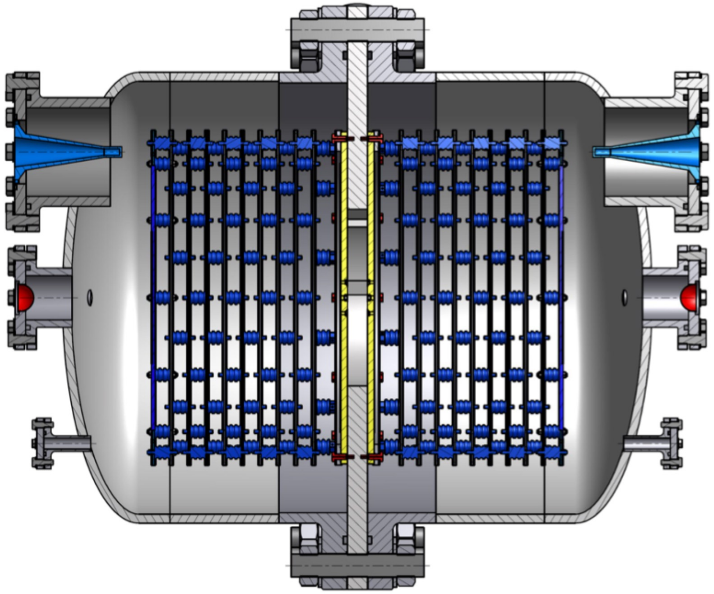


- Radiative corrections <1% for muon-proton scattering $Q^2 < 0.04\ \mathrm{GeV}^2$
- Calculations by N. Kaiser (TUM) *J. Phys. G* **37** 115005 (2010)
- Full MC generator foreseen – intensity forward bremsstrahlung photons can be checked in the experiment

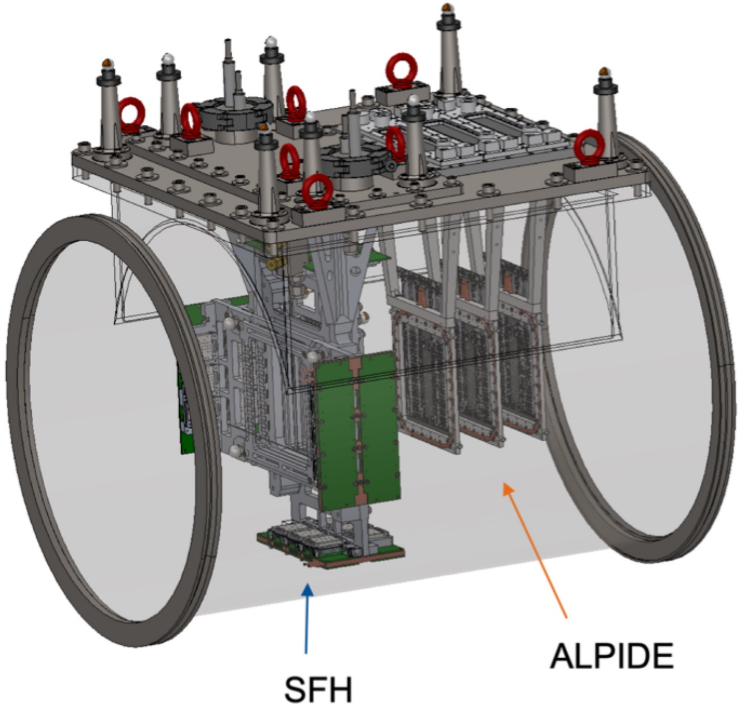
New Equipment for PRM

High-pressure hydrogen TPC
- Operation at 20 bar hydrogen pressure
- design with 2 drift cells
- Segmented anode plane
- reconstruction of proton recoil with ~50 keV precision





Unified Tracking Stations
- Determine scattering angle of muon
- Consists of several layers of silicon pixel detectors (ALPIDE) and a scintillating-fiber hodoscope (SFH)



Free-running DAQ
- streaming data acquisition on first level: all detectors deliver data without external trigger
- high-level trigger on computer farm

Tests and Schedule for PRM Data Taking

2018: First measurement of hydrogen TPC in high-energy muon beam

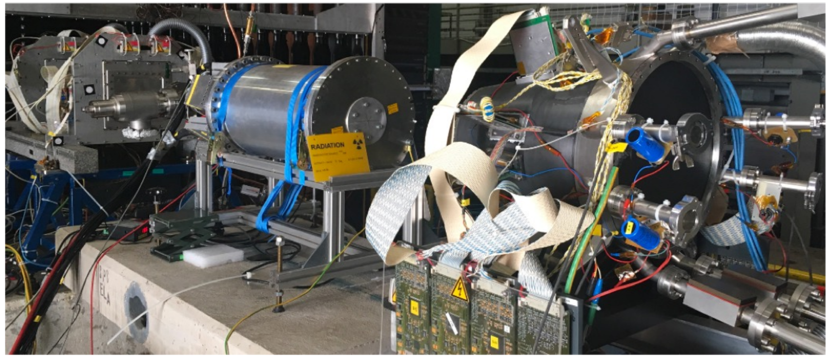
2021: First test run with IKAR TPC and already existing tracking detectors from COMPASS → *correlation between proton energy and muon scattering angle*

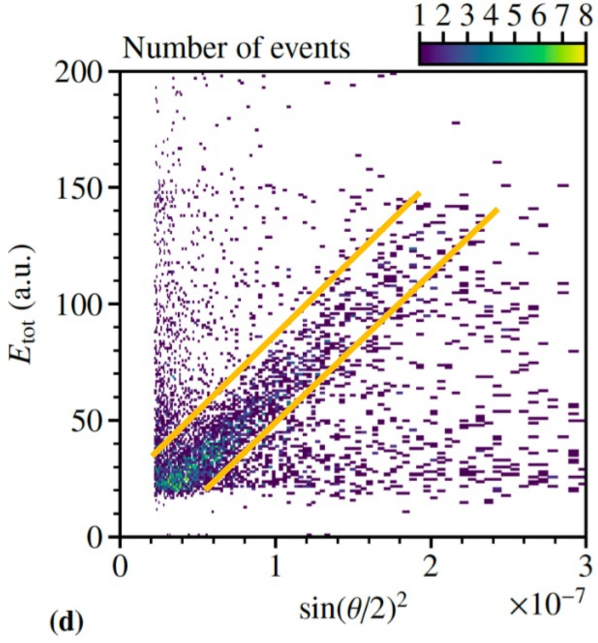
2023: Test run with new free-running DAQ (IKAR TPC, new tracking detector prototypes)

2024: Test run with IKAR TPC and UTS prototypes

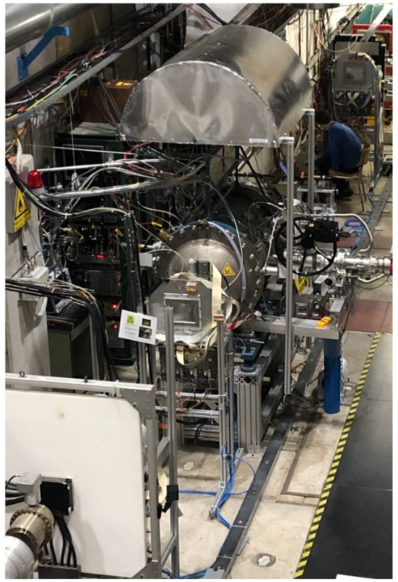
2025: Physics run with new TPC and final UTS

2018





2021



Figures: C. Dreisbach PhD Thesis (2022)

Measurement of G_E^p at small Q^2

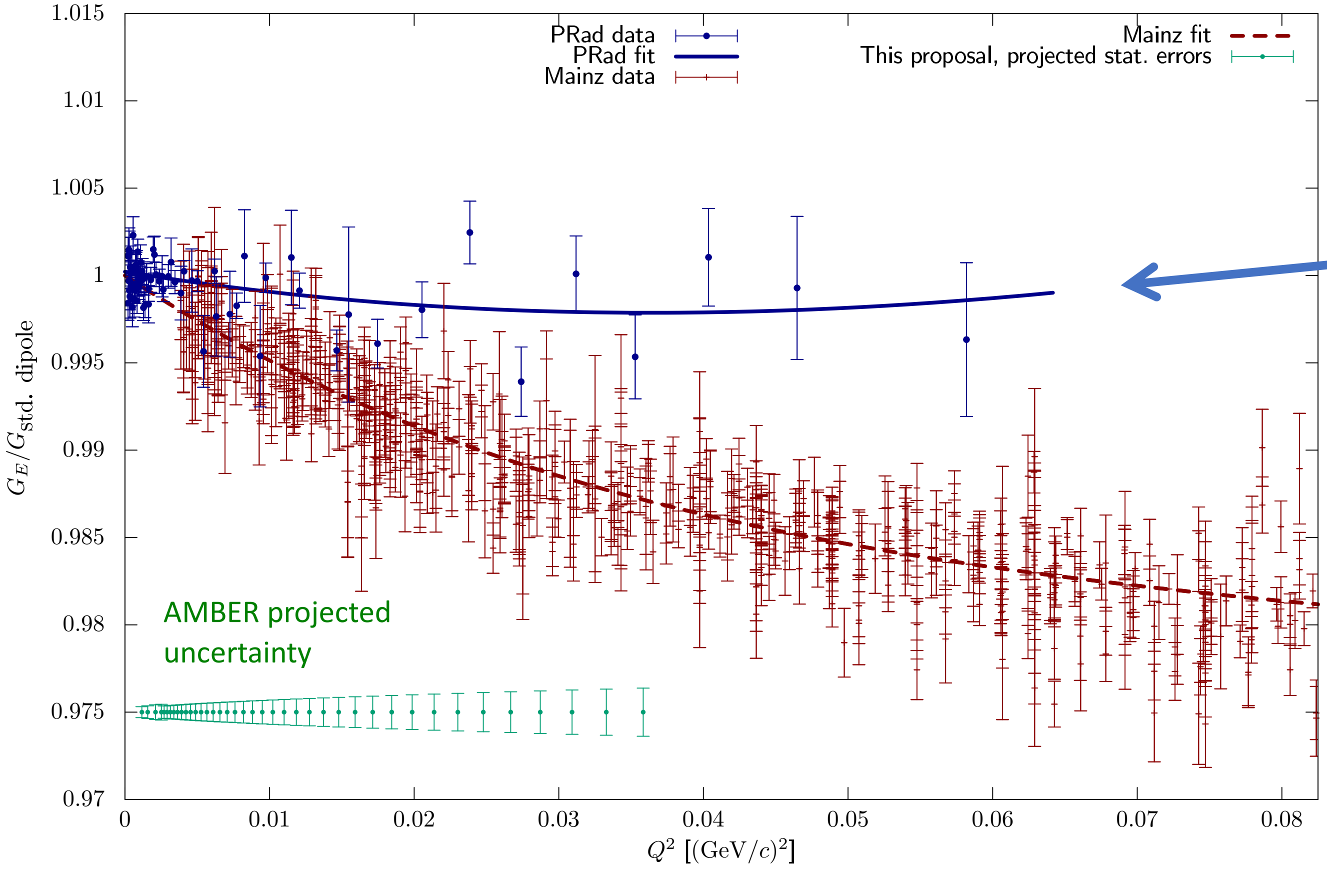


figure: J. Bernauer

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

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

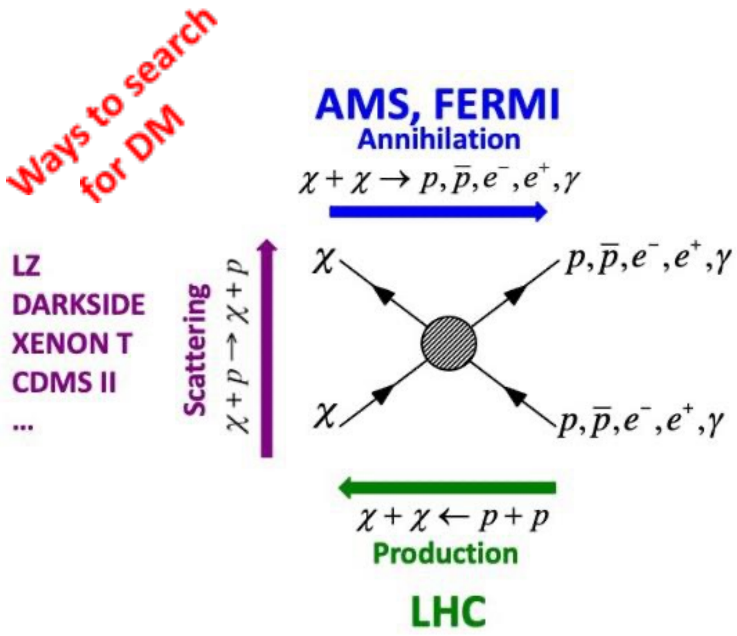
Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, 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 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	

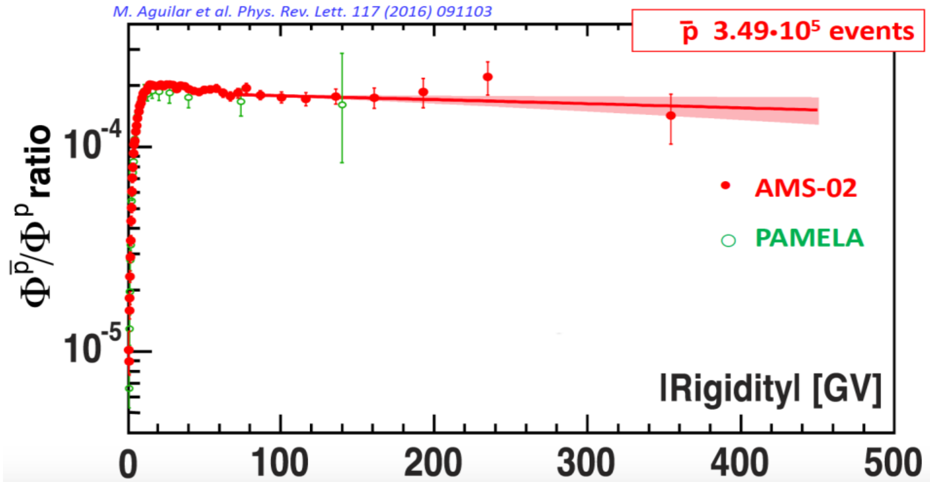
Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

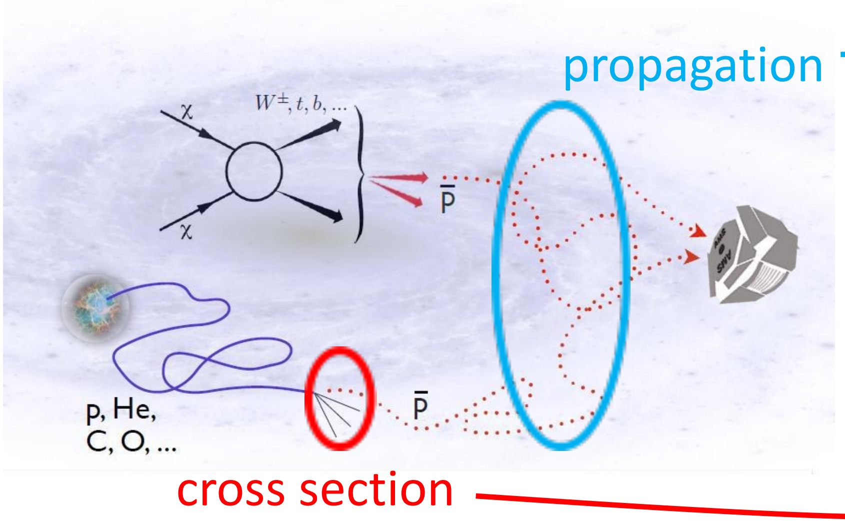
Phase-1
with conventional
hadron and muon
beams
2022 → 2028

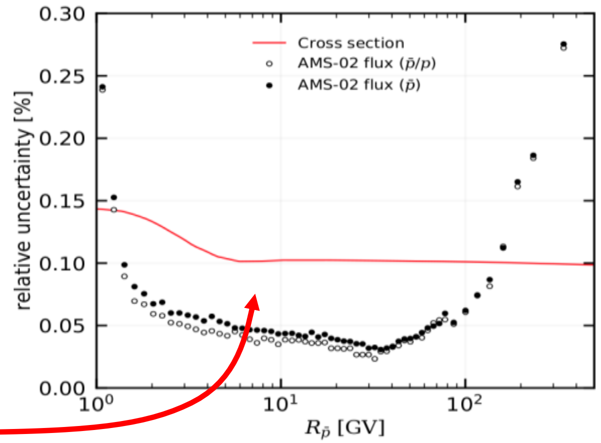
Phase-2
with conventional
and rf-separated
beams
2029 and beyond

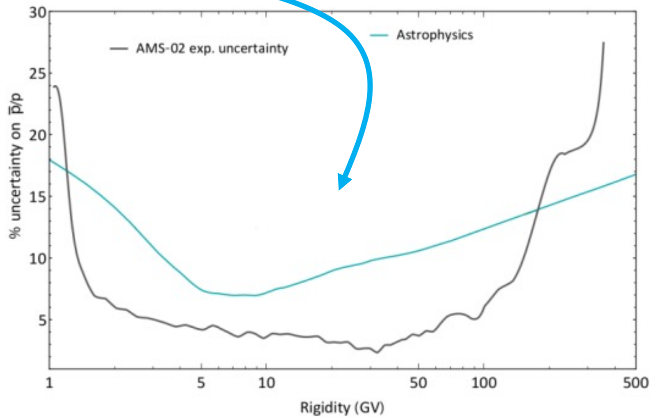
Antiproton production cross-sections





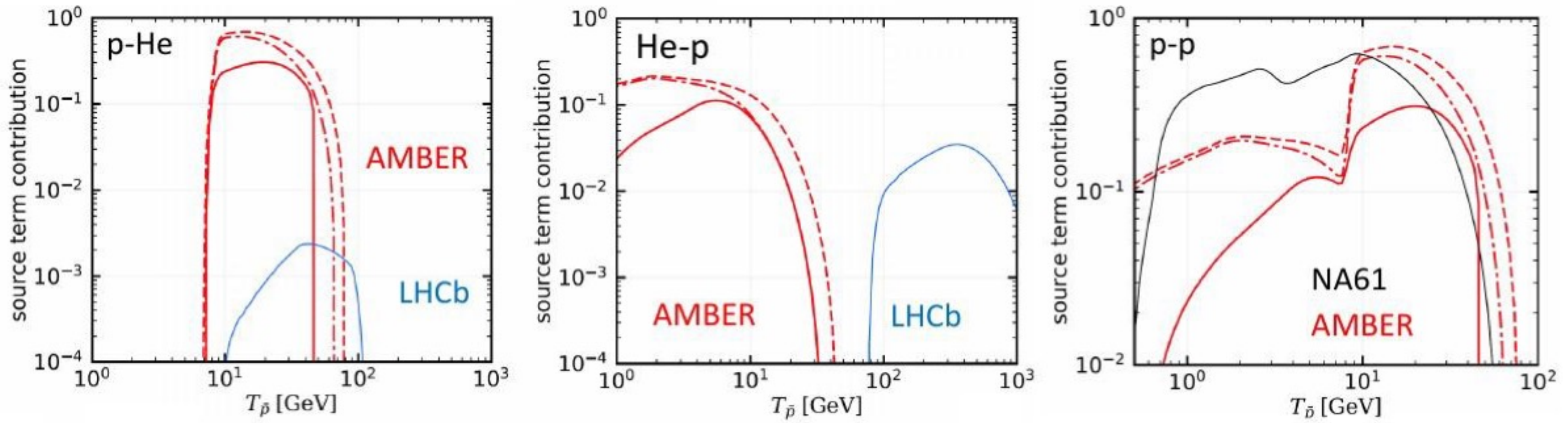


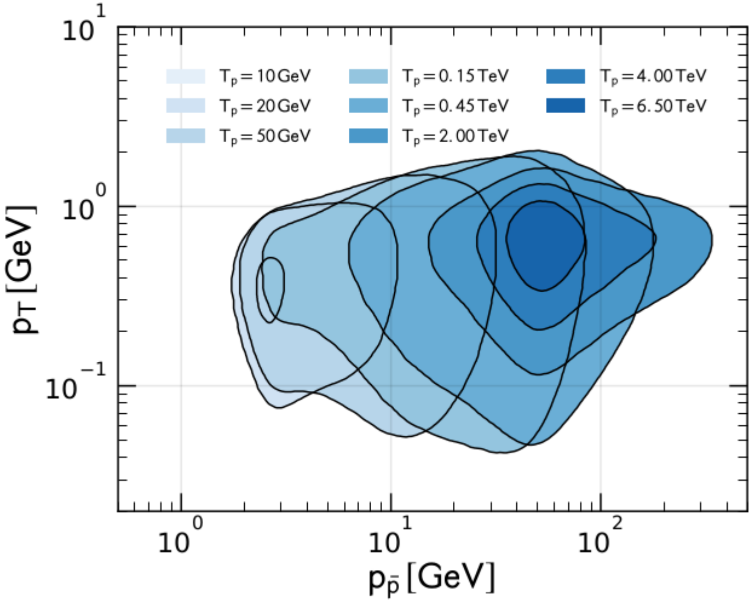




Antiproton measurements at AMBER

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



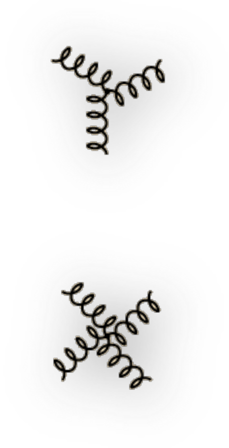


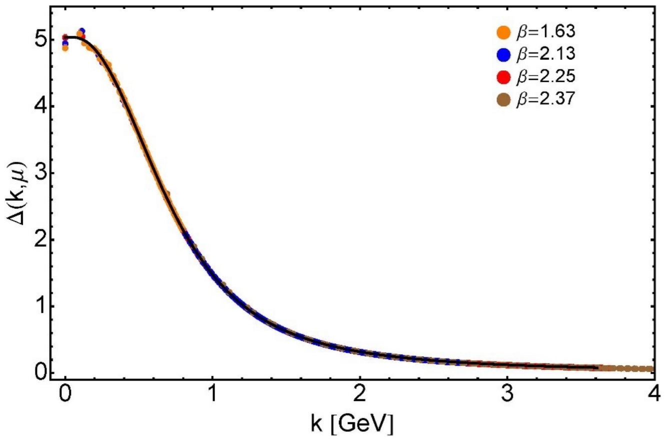
- Parameter space for the p-He channel corresponding to an exemplary fixed target experiment
- 3% relative uncertainty within the blue regions (30% outside)

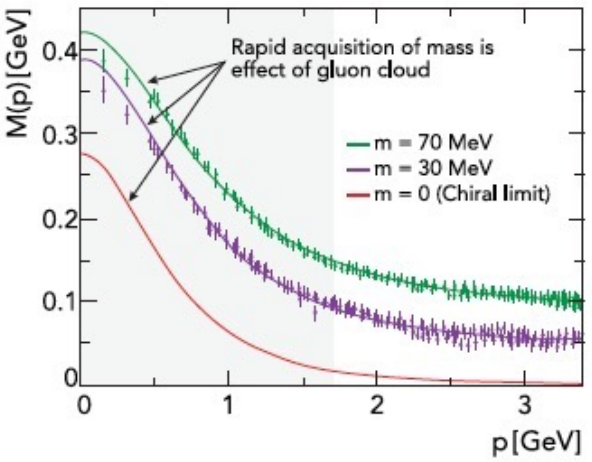
- Secondary *p* beam with 60, 80, 100, 160, 190, 280 GeV
- Liquid H_2 and He target
- Minimum bias trigger allowing beam intensity of $5 \cdot 10^5\ s^{-1}$
- Beam proton ID in CEDARs, antiproton ID in RICH
- Measure differential cross section in 10 bins in p_p & η
- 2.4<η<5.6
- Statistical uncertainty ≈ 0.5 − 1% per data point
- Total systematic uncertainty ≈ 5% (efficiencies, dead time)
- AMBER pilot run for antiproton production measurements end of 2022 (LD target, setup tests , rates)
- **We are currently taking data!**

Emergent Hadron Mass

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



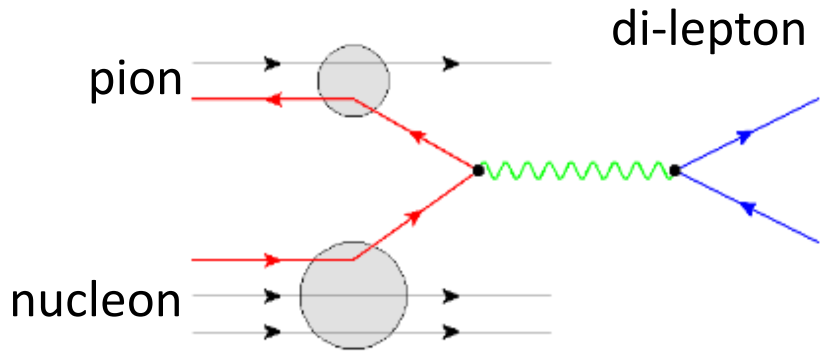




- Emergence of Hadron Mass is to some extent understood within continuum and lattice QCD calculations
- Prove and provide more input by measurement of

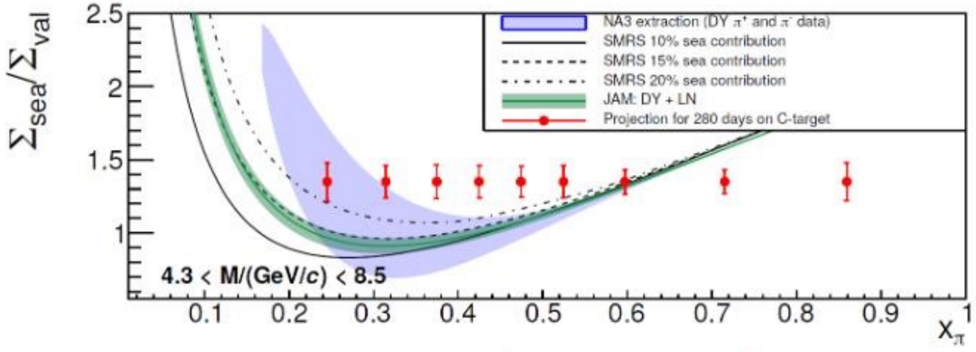
  - Quark and gluon PDFs of pion, kaon and proton
  - Hadron radii as consequence of confinement
  - Mass spectra of excited mesons

Drell-Yan and pion PDFs at AMBER



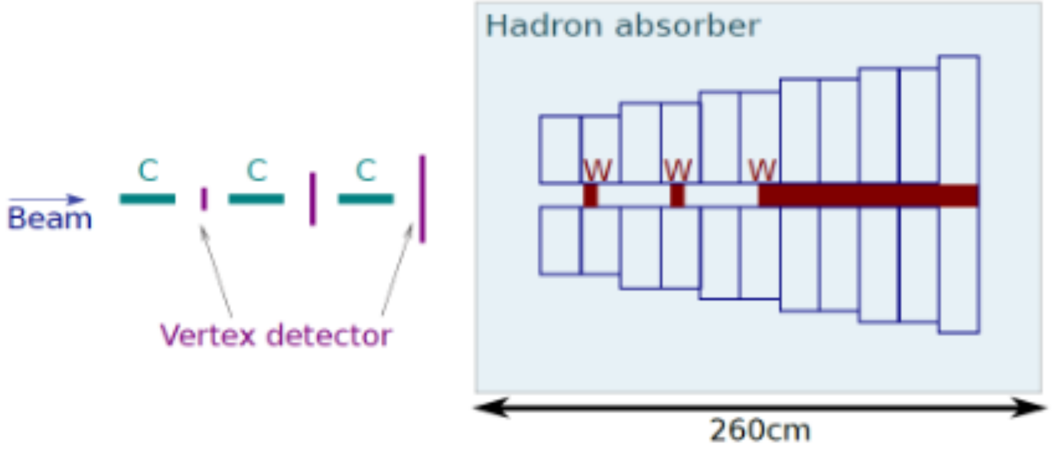
- Beams of positively and negatively charged pions to separate valence and sea contribution:

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



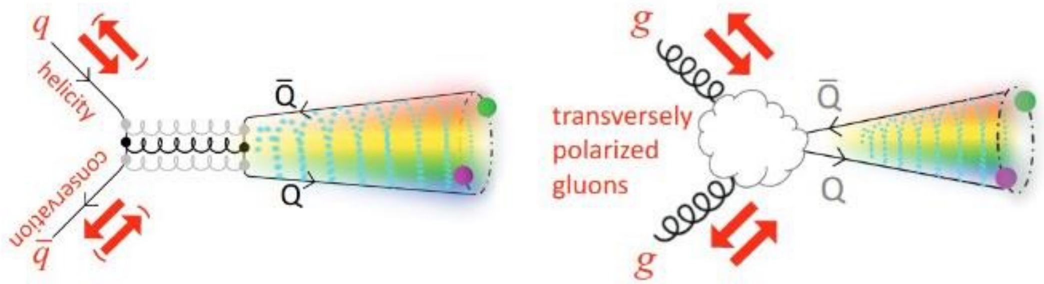
$$\sigma_{\text{DY}}^{\pi^+ A} \propto \sum_i (e_i)^2 \left[\bar{q}_i^{\pi^+} q_i^A + q_i^{\pi^+} \bar{q}_i^A\right]$$

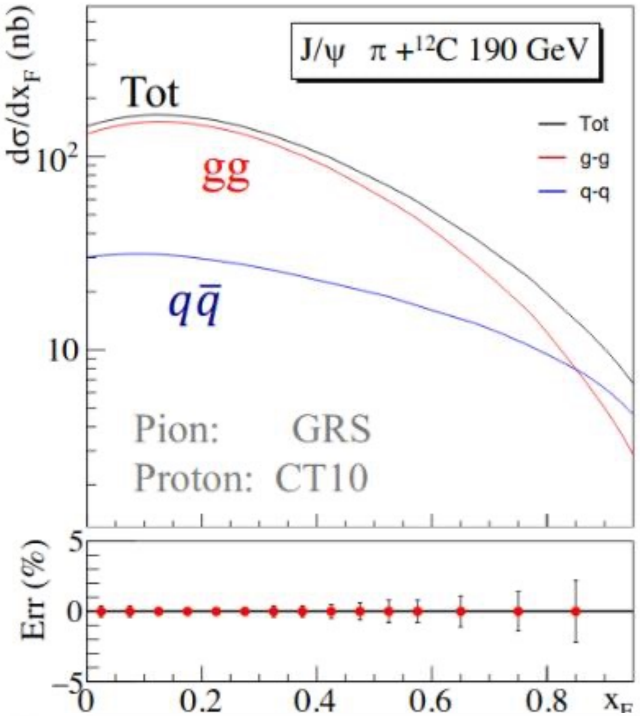
- 250k DY events expected (current available statistics 25k events)
- First precise and direct measurement of the sea quark distribution in the pion
- 190 GeV pion beam
- Target / vertex detector / hadron
- absorber
- Radiation protection
- Di-muon mass resolution of 100 MeV

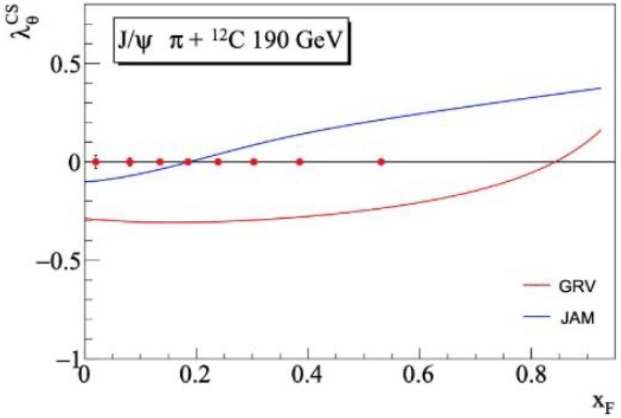


- Iso-scalar target (^{12}C) to minimize nuclear effects

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 can't be separated from the rest
- Expected significant feed-down: $\psi(2S)$, χ_{c1}, χ_{c2}
- Use J/ψ polarization to distinguish production mechanism: polarization is sensitive to relative contributions of quark- and gluon-induced productions

- Angular distribution

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

$\lambda = +1 \iff J_z = \pm 1$

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

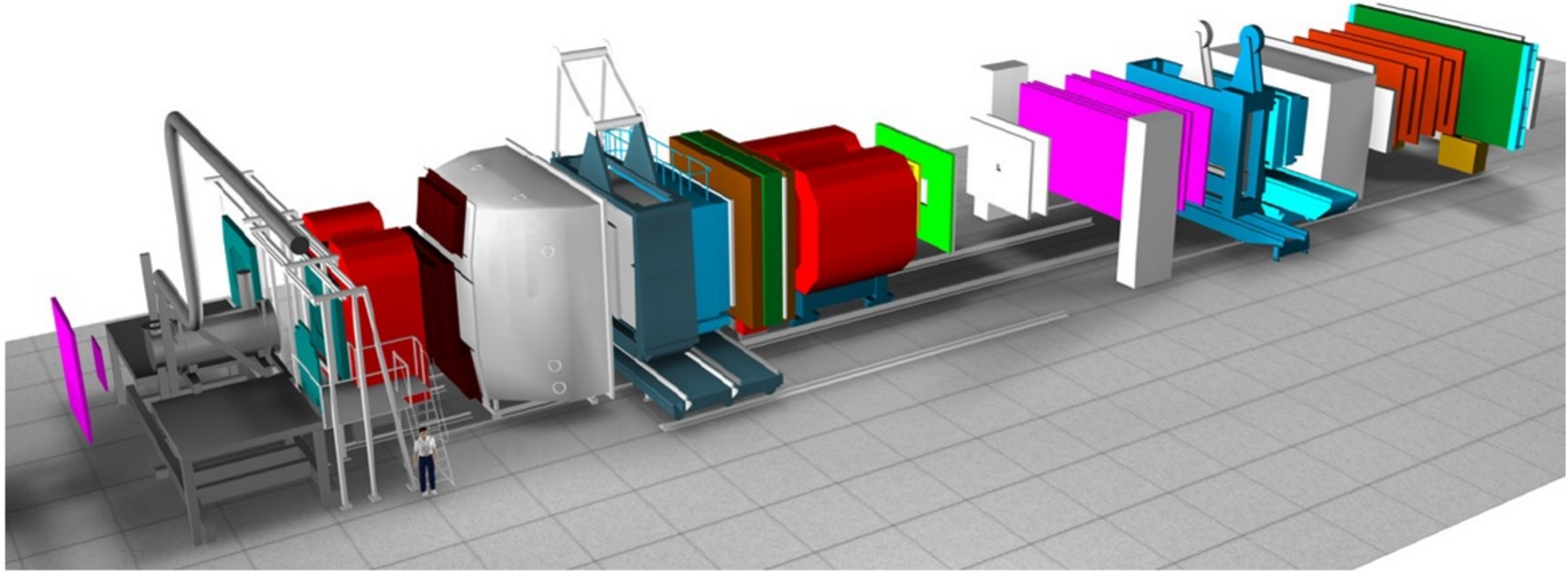
$\lambda = 0 \iff$ unpolarised

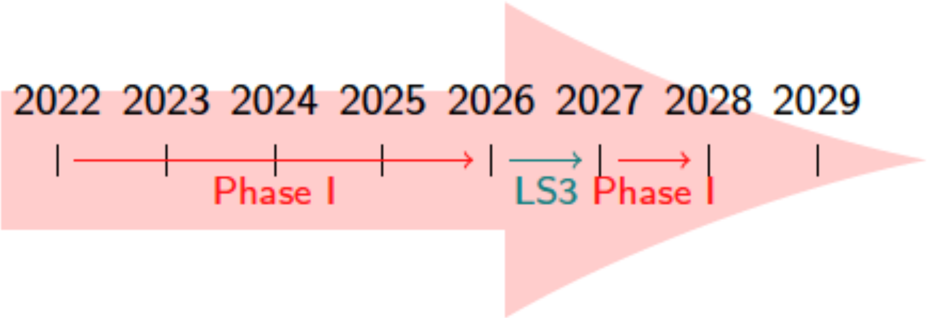
$\lambda = -1 \iff J_z = 0$

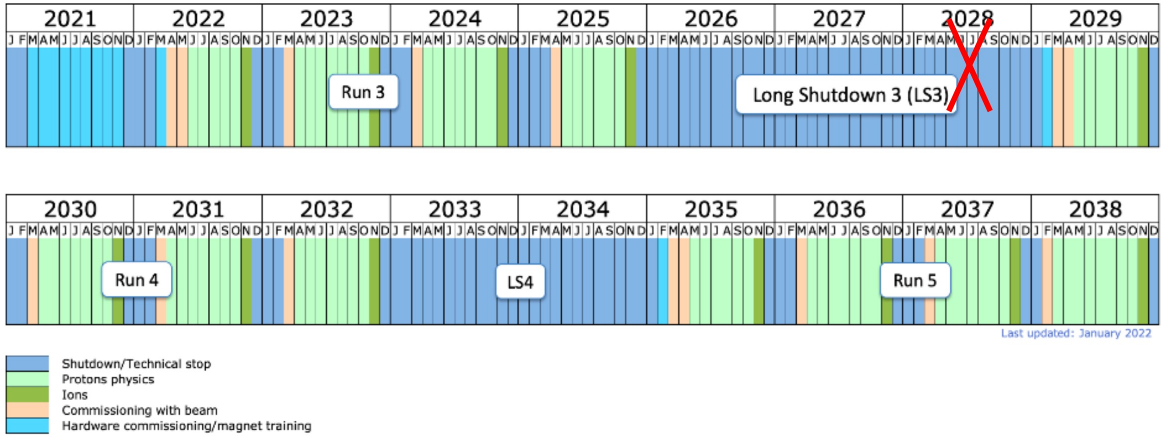
$gg \rightarrow J/\psi$

AMBER Collaboration and timelines

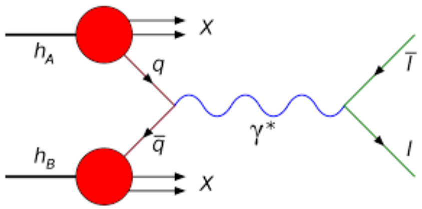
- Successor of COMPASS
- with appropriate extensions and modernisations
- at the CERN M2 beamline
- ~200 physicists from ~34 institutes



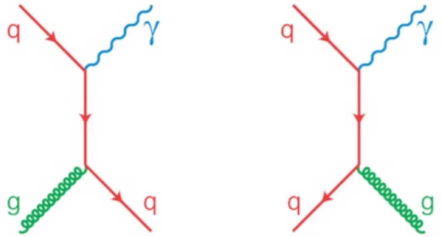




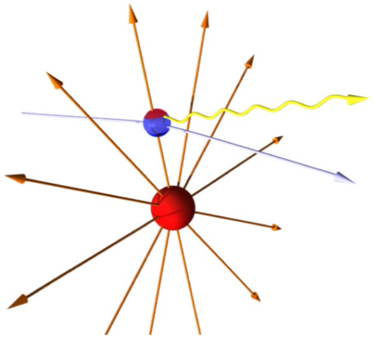
The ideas of the Phase-2 proposal



- Kaon structure via the Drell-Yan process

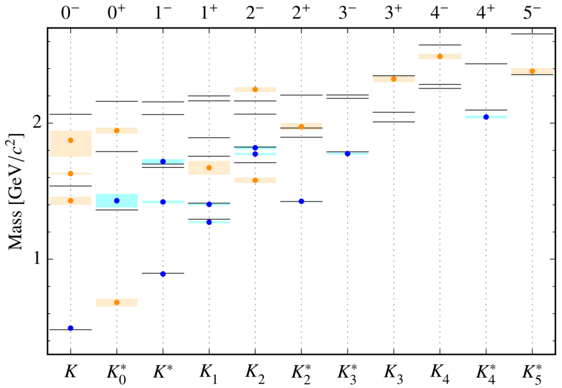


- Gluon structure of pions and kaons via prompt photons

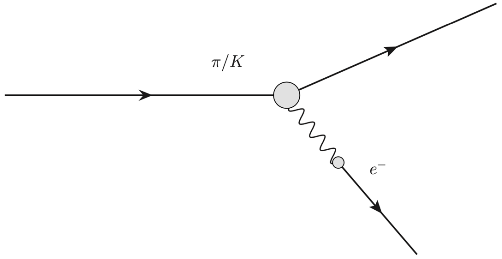


- Primakoff reactions to investigate kaon-photon coupling: kaon polarisability, $F_{KK\pi}$

- Generalized Parton Distributions in DVCS and HEMP



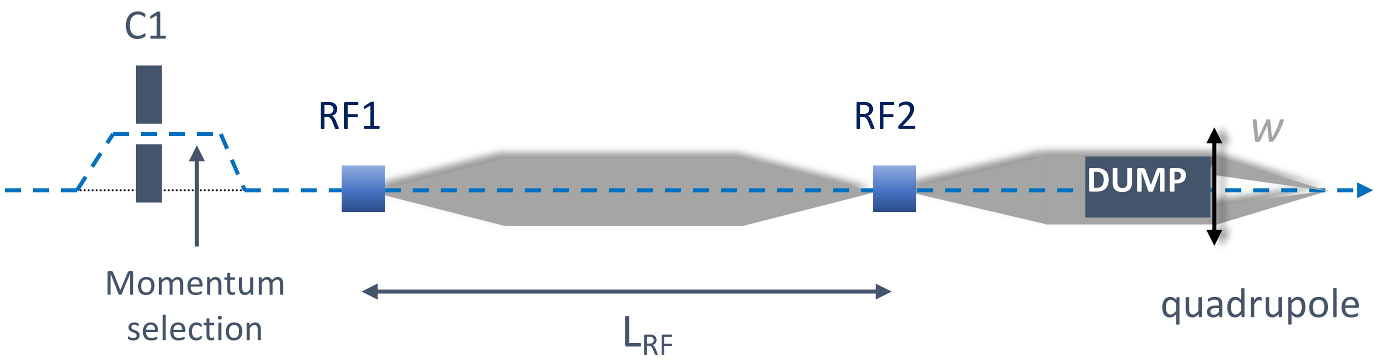
- Spectroscopy of mesons with strangeness



- Meson charge radii via electron scattering in inverse kinematics

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

Conventional vs. rf-separated beams

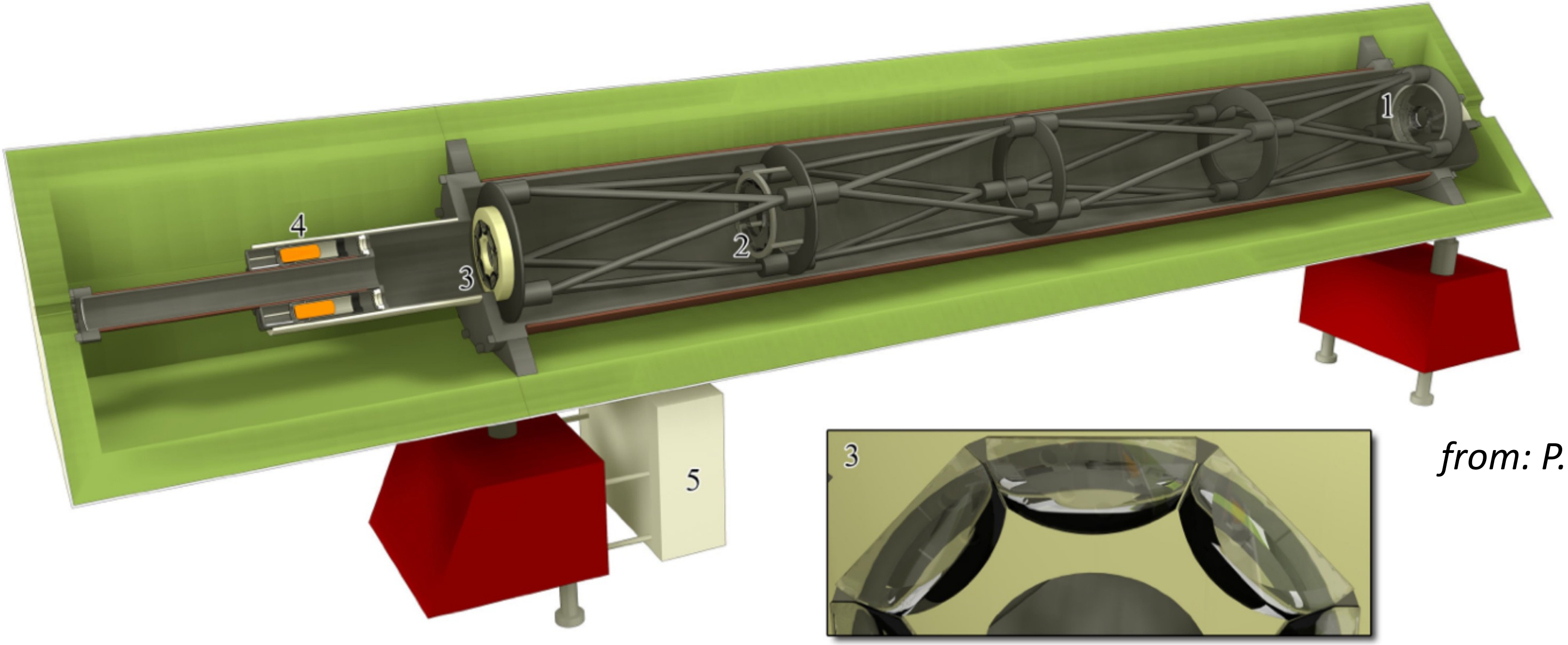


- **Panofsky-Schnell-System** for beam particle species discrimination: same momentum but different velocities
  - For M2: Interest in K^- and antiproton beams
- **Increase of the purity** of the kaon (or antiproton) component
- **Same** or reduced **intensity** of the desired component (compared to 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 is the best alternative**

discussed in detail in 2021 and 2022

Beam PID by CEDARs

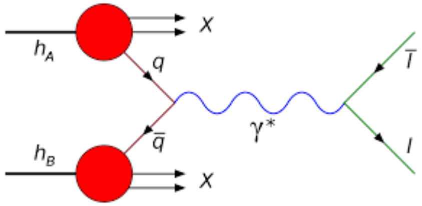
AMBER
Apparatus for Meson and Baryon Experimental Research



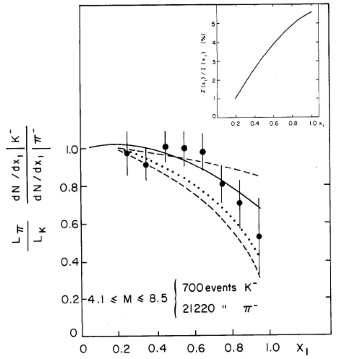
from: P. Jasinski, PhD thesis

- 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

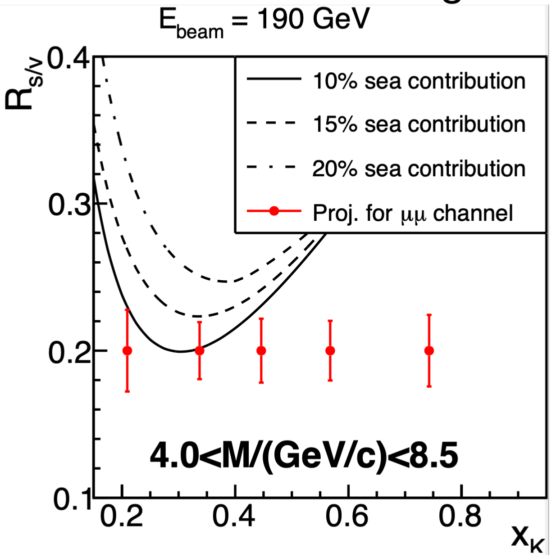


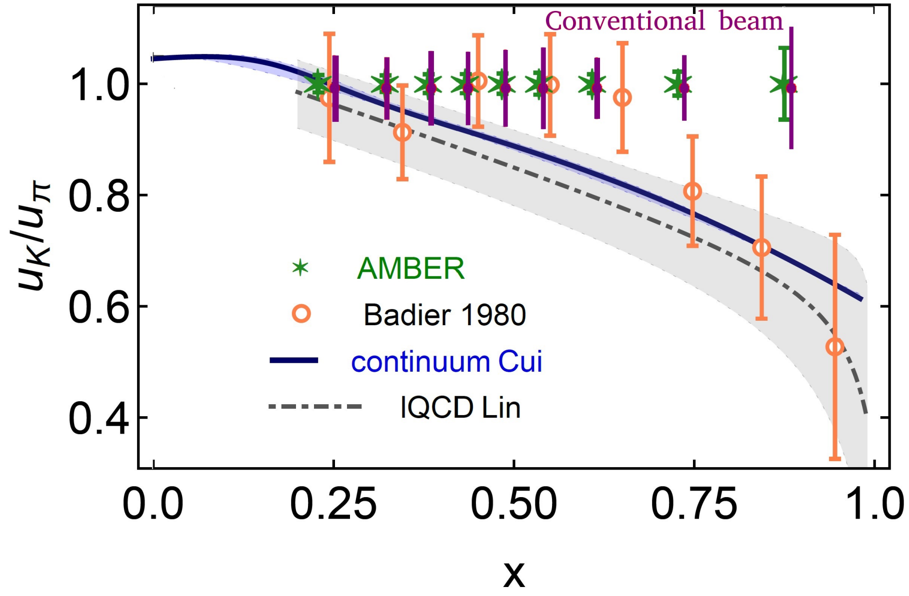
NA3: PLB 93 (1980) 354



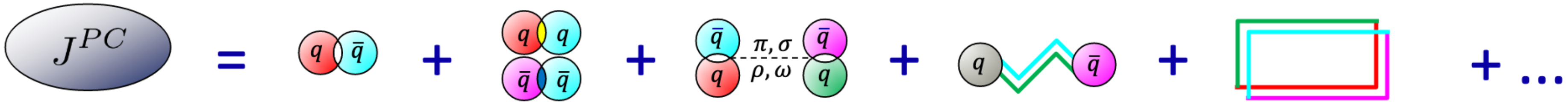
- Available data
  - Only 700 events from NA3
  - The kaon valence distributions are practically unknown
  - There is no data on kaon sea and gluon content
- Prospects for AMBER measurements
  - Kaon valence PDF: can be addressed with negative kaon beam
  - Kaon sea PDF: combine the two beam charges

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





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

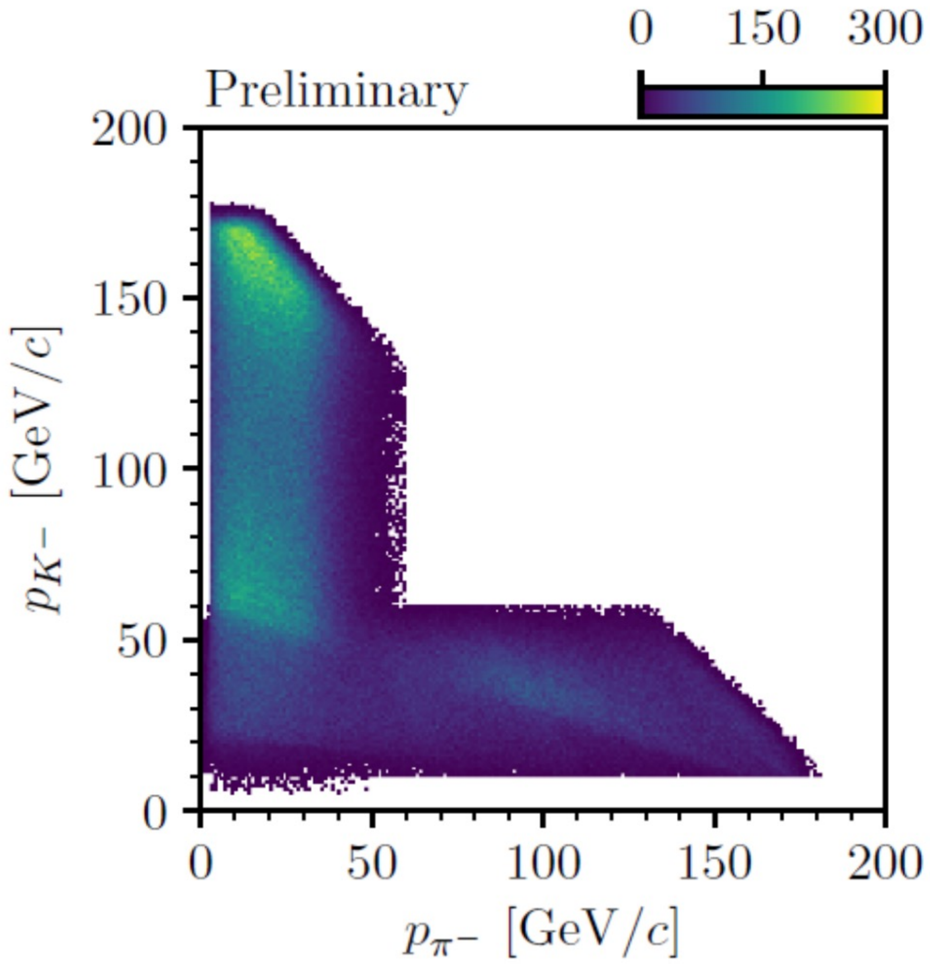
- Final-state particle identification does not cover full momentum range

Cannot identify the full final state

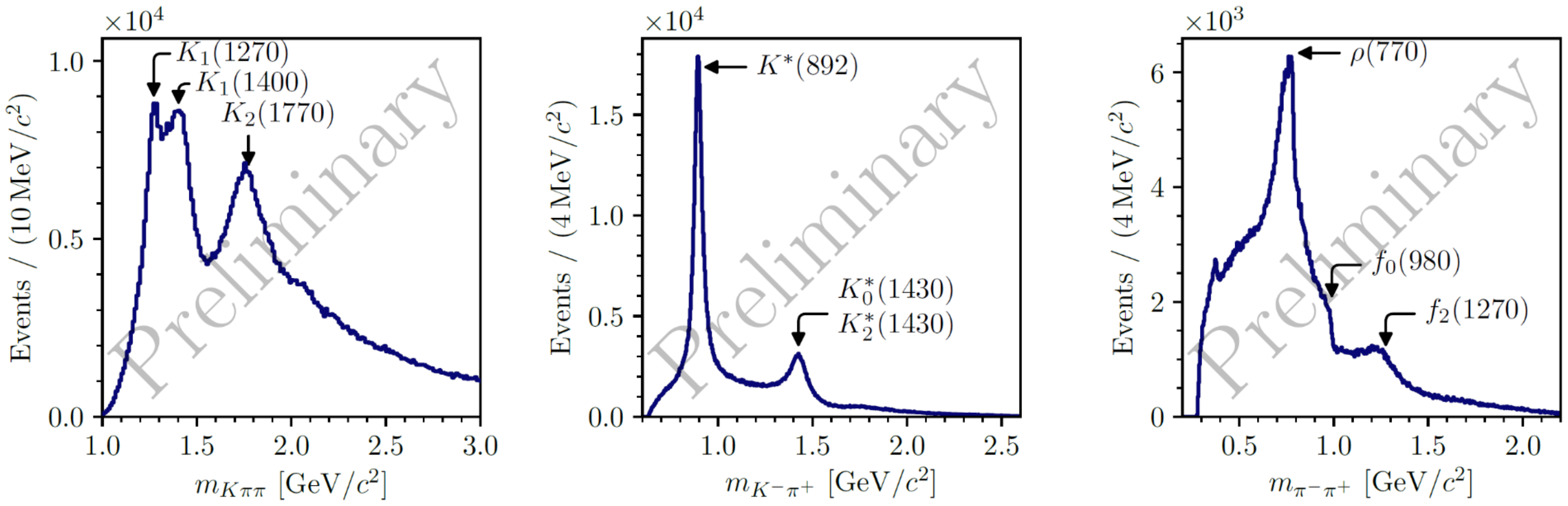
- Assume sample contains only $K^-\pi^-\pi^+$ events
  - Minimal PID: Need to know which of h^- is K^-
- Require only one of h^- to be identified
- Acceptance reduced by more than 1/3
- Almost no suppression of KKK, $\pi\pi\pi$, ...

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

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

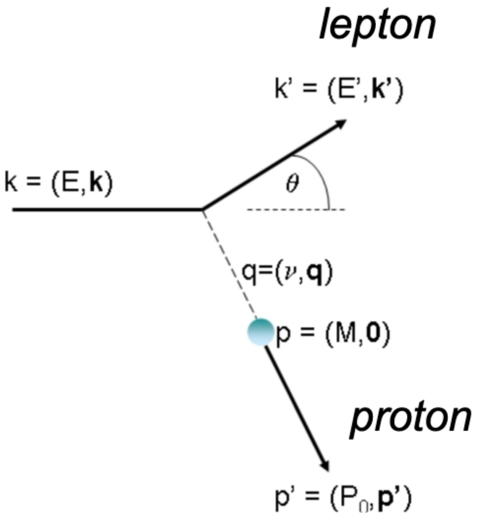
⇒ world‘s largest data set so far: 720 000 exclusive events (ACCMOR: 200k ev.)

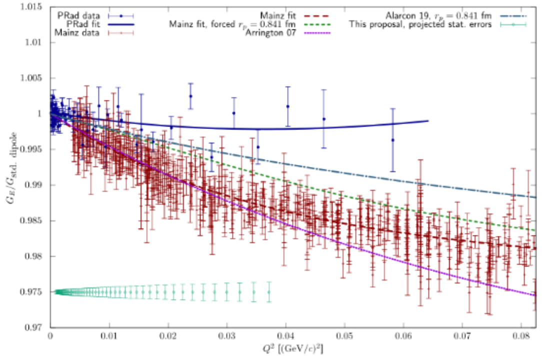
Goal for AMBER: collect $10 - 20 \times 10^6$ exclusive $K^-\pi^-\pi^+$ events

Hadron charge radii

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

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

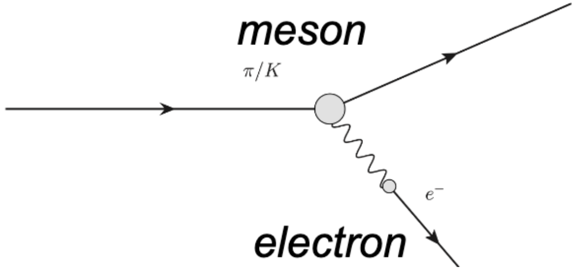




Charge radius from the slope of G_E

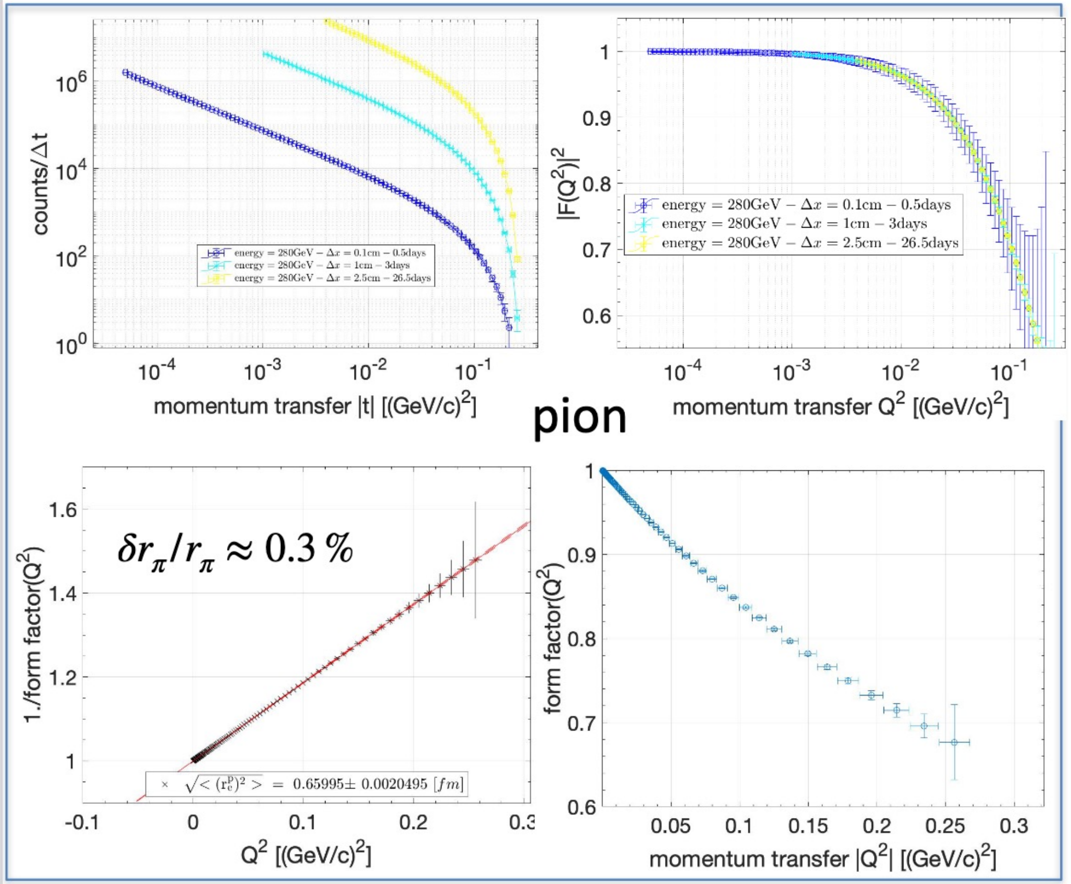
$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \right|_{Q^2 \to 0}$$

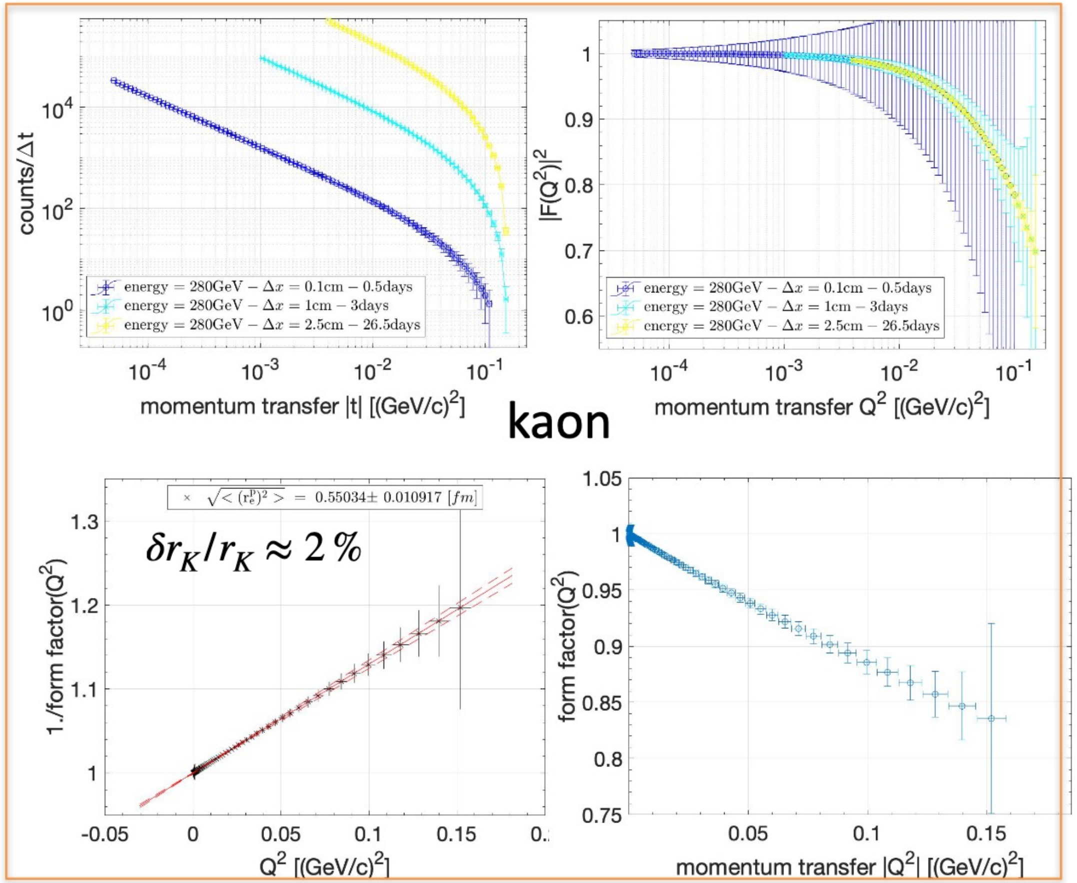
For unstable particles, electron scattering can only be realised in *inverse kinematics*



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 separate proposal
- Data taking for anti-proton production almost completed
- **Proton Radius Measurement**: preparations ongoing, pilot run in fall 2024, beam time 2025

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

CERN Accelerating science

ABOUT NEWS

Voir en *français*

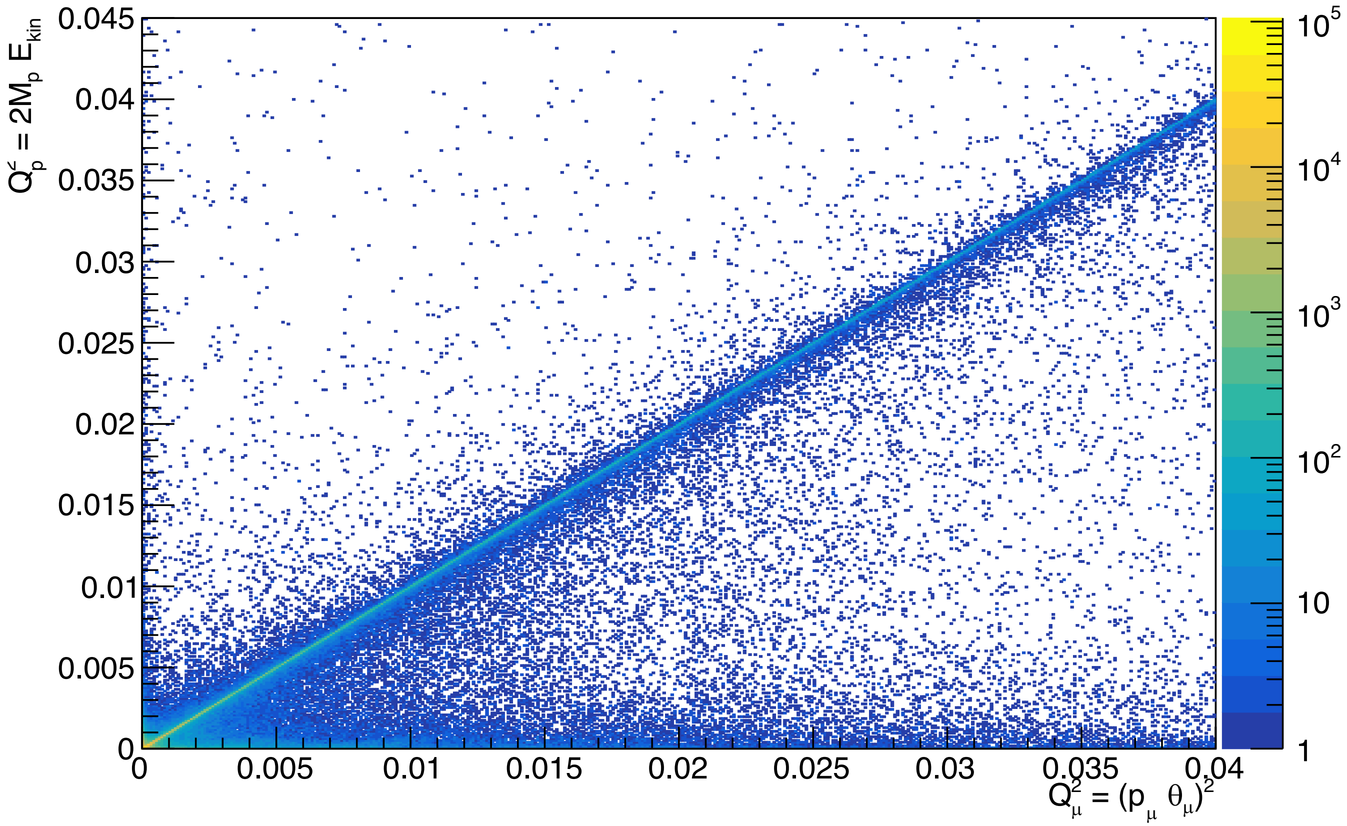
Meet AMBER

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

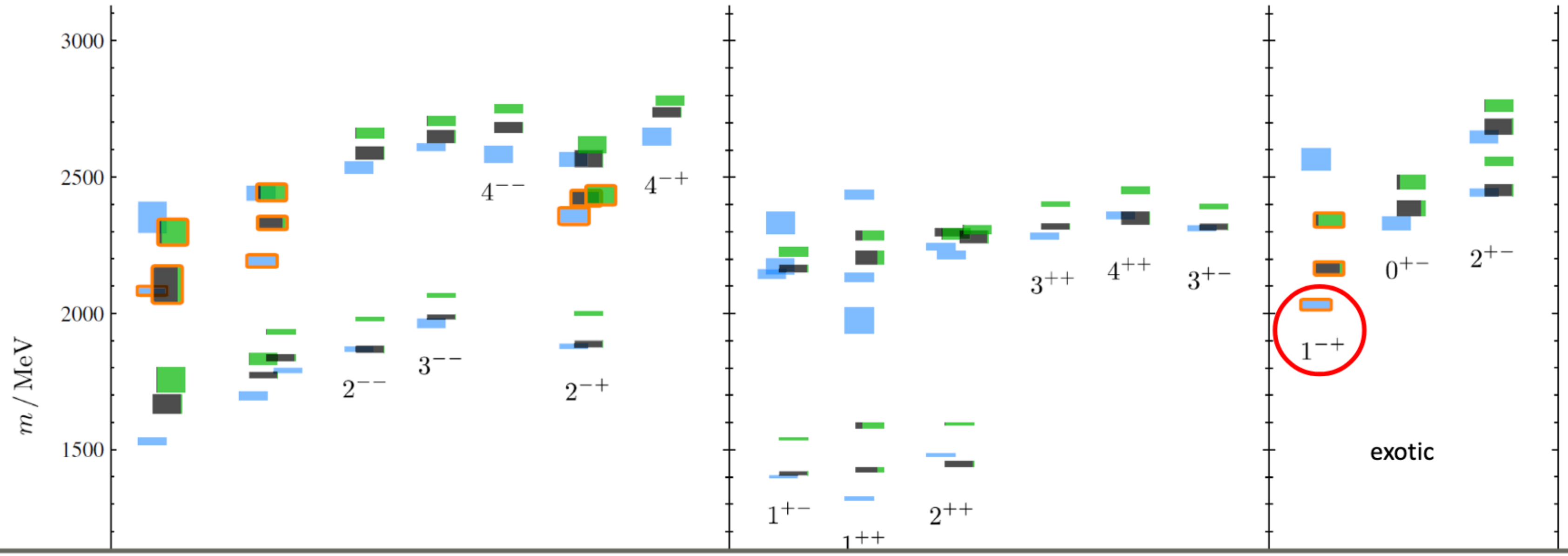
8 MARCH, 2021 | By Ana Lopes

Backup

Impact of photon emission on the muon-proton correlation

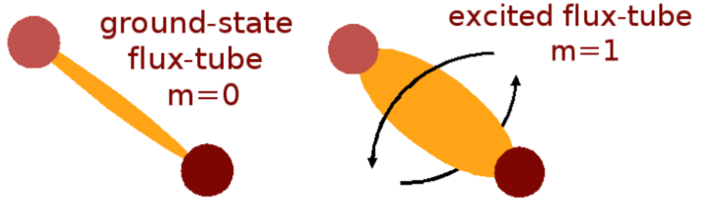


Hybrids: Lattice QCD



Hybrids:

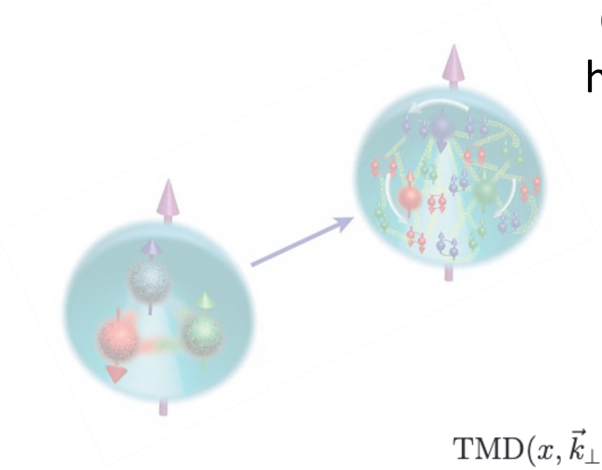
- excitation of gluonic degrees of freedom
- angular momentum in flux tube
- lightest hybrid predicted to have $J^{PC} = 1^{-+}$

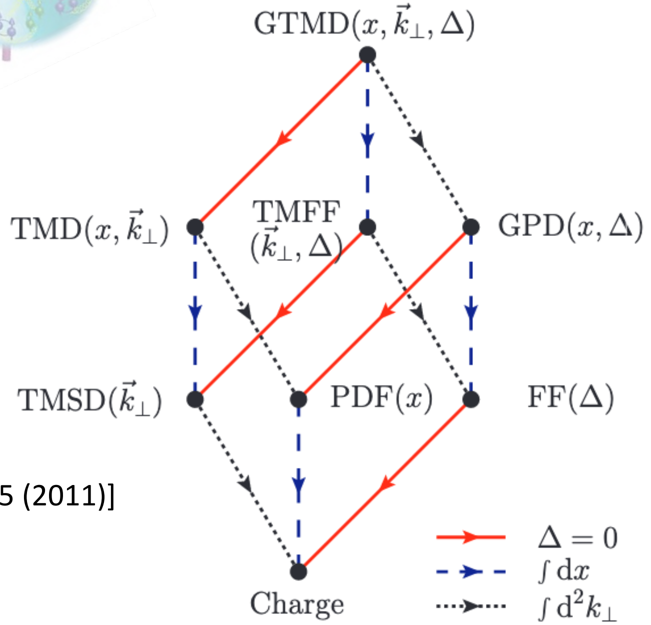


[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 88, 094505 (2013)]

Open fundamental questions in QCD

QCD partons in hadronic systems

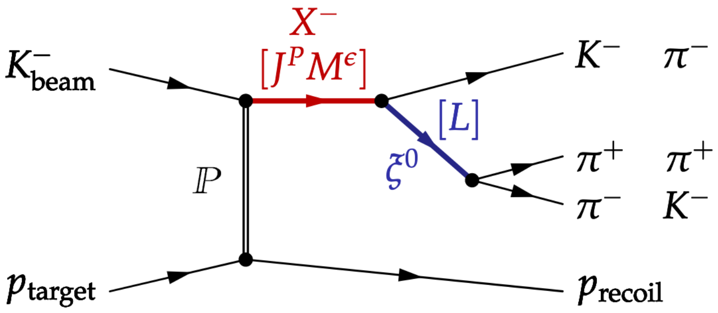


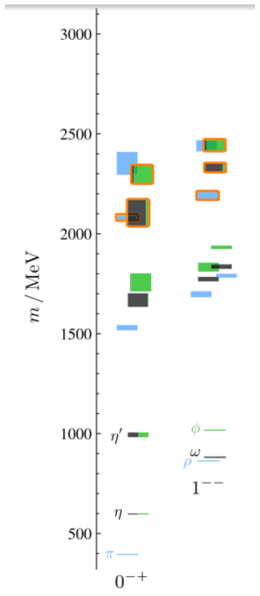


[from: Lorcé, Pasquini, Vanderhaeghen, JHEP05 (2011)]

The complete picture: Wigner distributions

The excitation scheme of hadronic systems





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

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

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

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

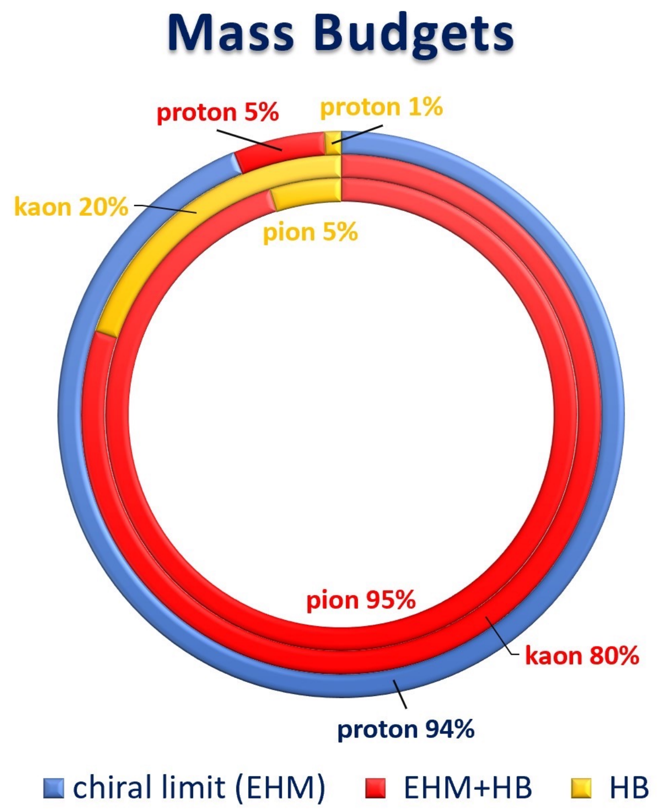
Likelihood-based CEDAR PID

- 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 %

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

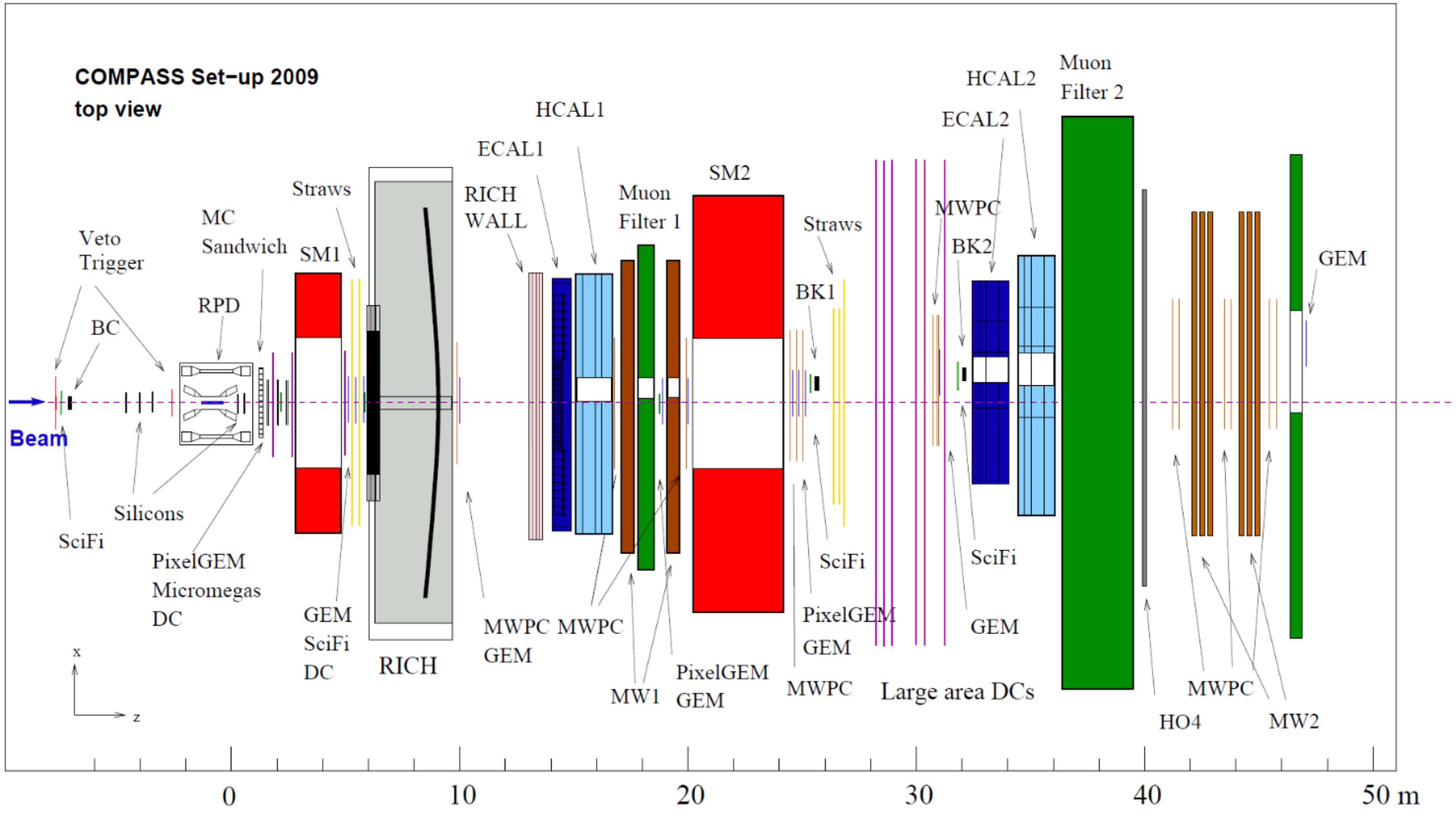
Thus for a full understanding the **partonic structure** of hadrons, the **meson PDFs** must be known on a similar level as those of the nucleon



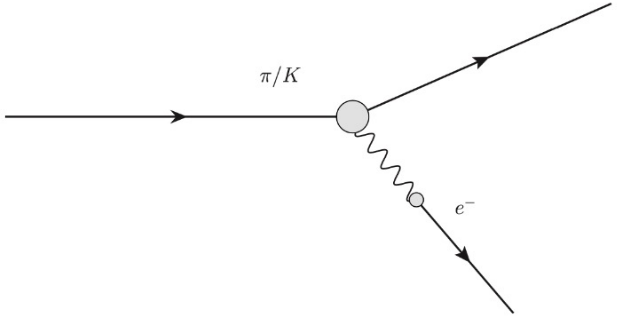
Setup for strange-meson spectroscopy

AMBER
Apparatus for Meson and Baryon Experimental Research

- 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



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

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

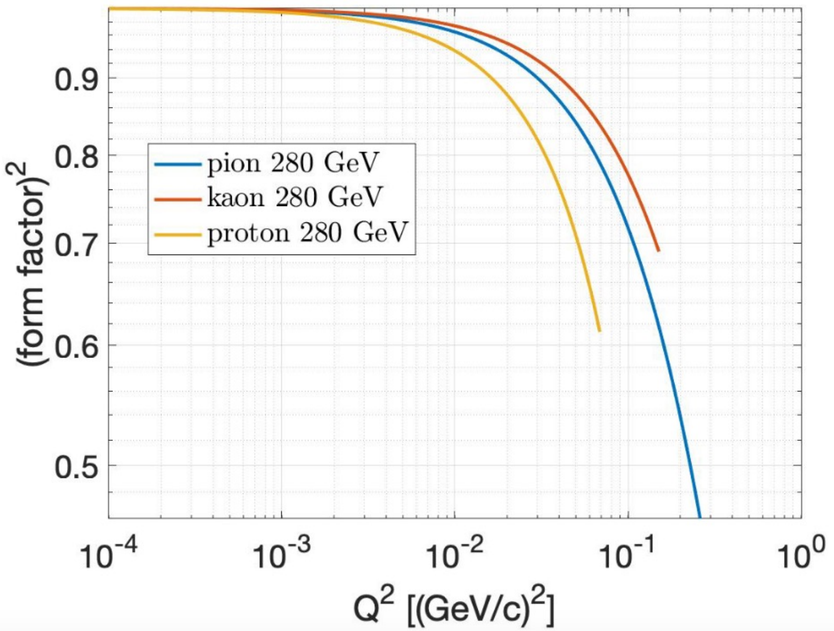
$$s = 2E_b m_e + m_b^2 + m_e^2$$

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

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%

Gluon PDF of the pion

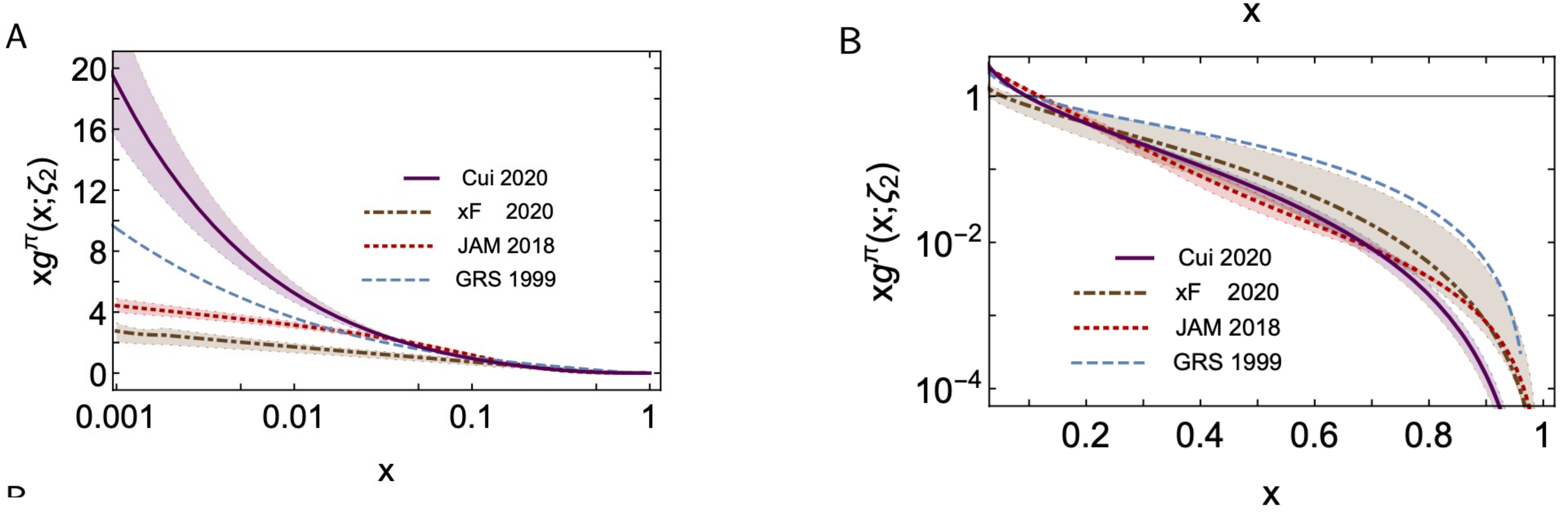


FIG. 4. Glue distribution, $xg^\pi(x, \zeta_2 = 2\,\text{GeV})$: solid purple curve, prediction from Ref. [43]. Panel A highlights low-x and Panel B, large-x. The band surrounding this curve expresses a conservative estimate of uncertainty in the prediction, obtained by varying ζ_H by $\pm 10\%$. Comparisons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