AMBER

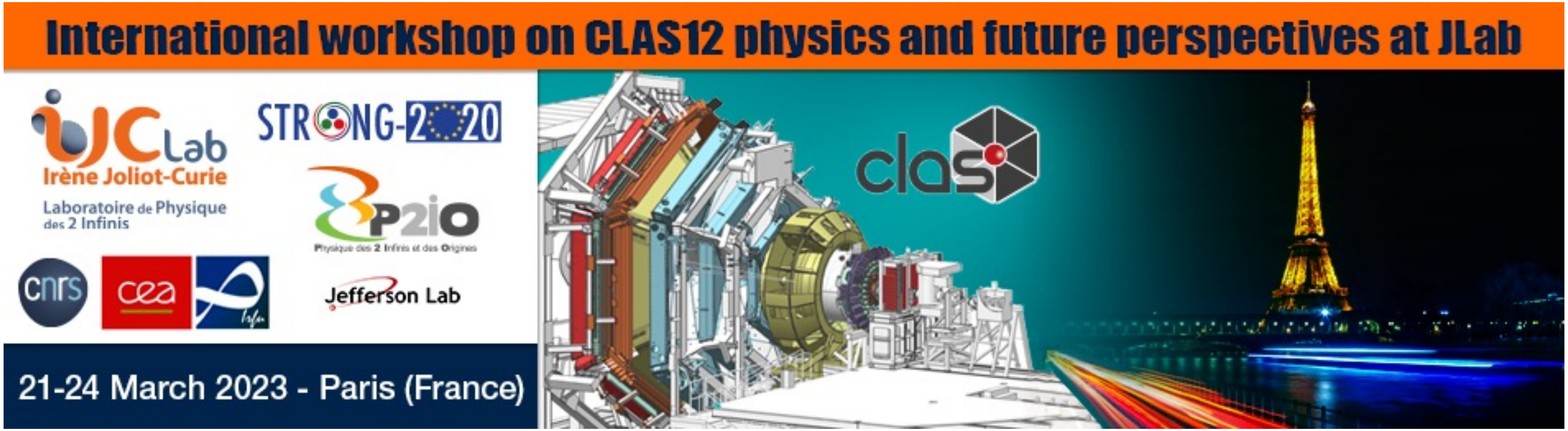
Apparatus for Meson and Baryon Experimental Research

A new QCD facility at the M2 beam line of the CERN SPS

Jan Friedrich

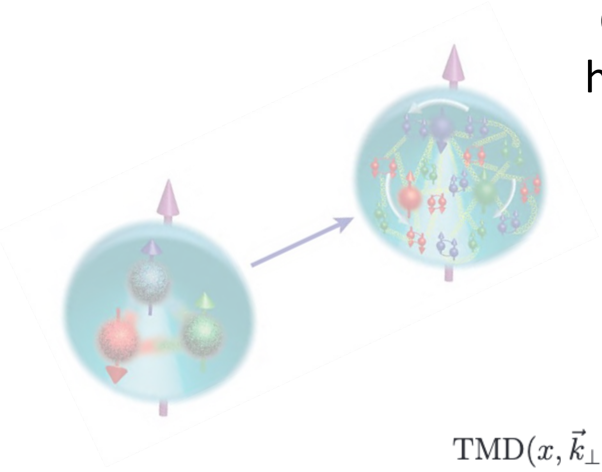
Technical University of Munich

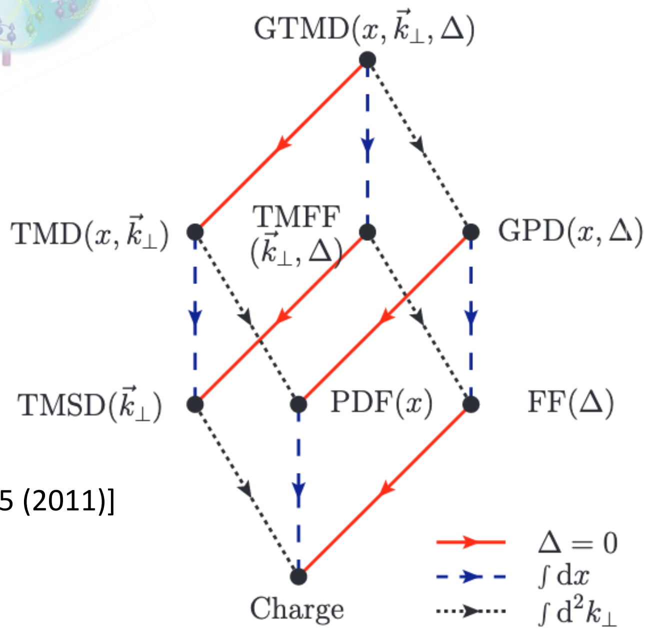
on behalf of the Collaboration



Open fundamental questions in QCD

QCD partons in hadronic systems

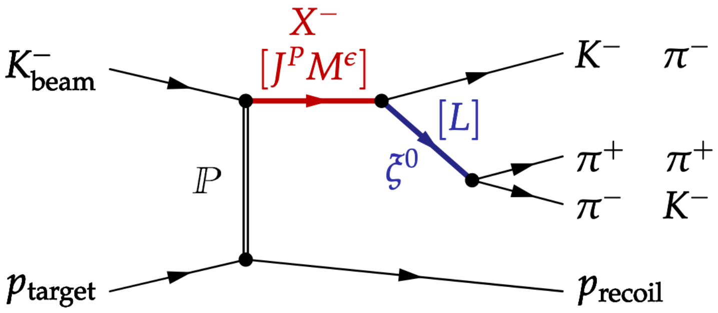


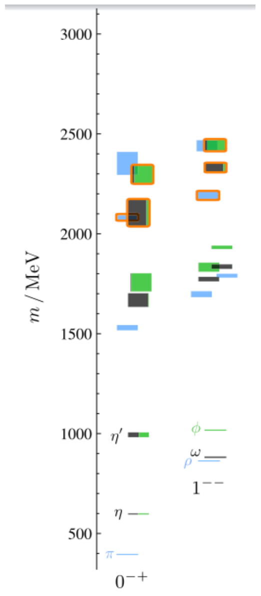


[from: Lorcé, Pasquini, Vanderhaeghen, JHEP05 (2011)]

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

Masses of the light hadrons

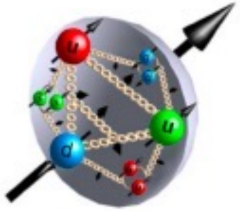
Pion

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

Kaon

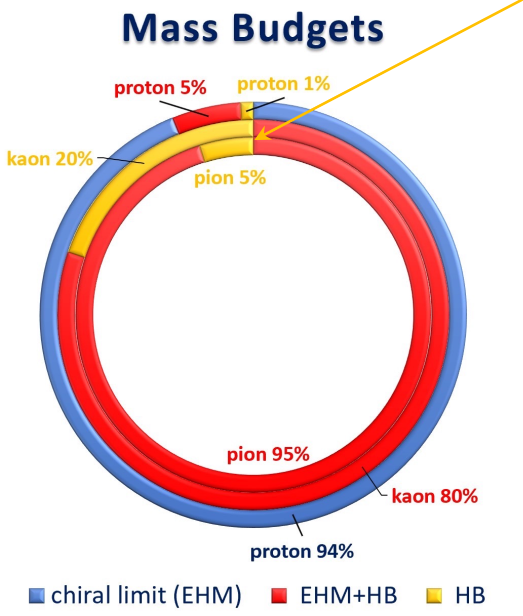
- $M_K \sim 490\text{MeV}$
- Spin 0
- 1 light and 1 “heavy” valence quarks

Proton



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

That’s what the Higgs story is about

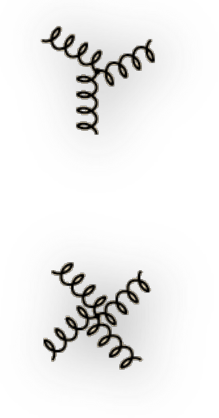


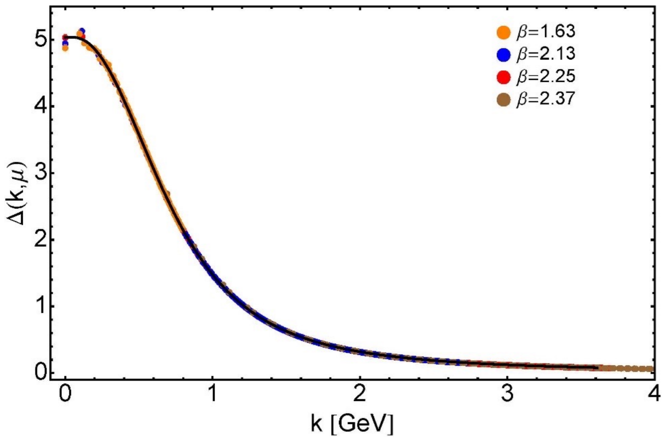
- As composite systems, we want to understand hadrons in terms of their constituents: the QCD quarks and gluons
- The Higgs mass of the valence quarks contributes only little to the physical hadron masses
- Pion-to-proton mass ratio of 1-to-7 differs much from the constituent-quark inspired value 2-to-3

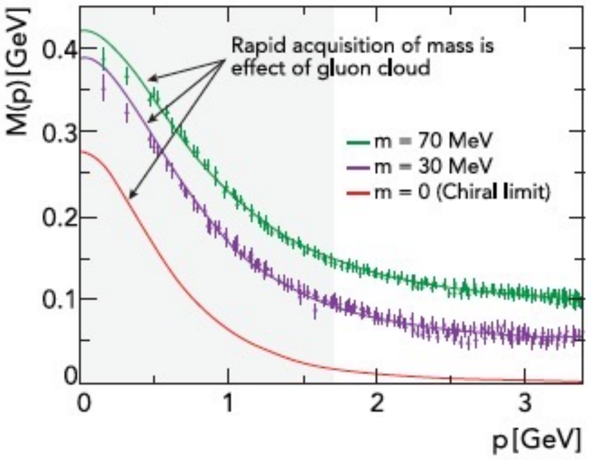
The Emergence of Hadron Mass is the main source of (visible) matter!

Emergent Hadron Mass

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





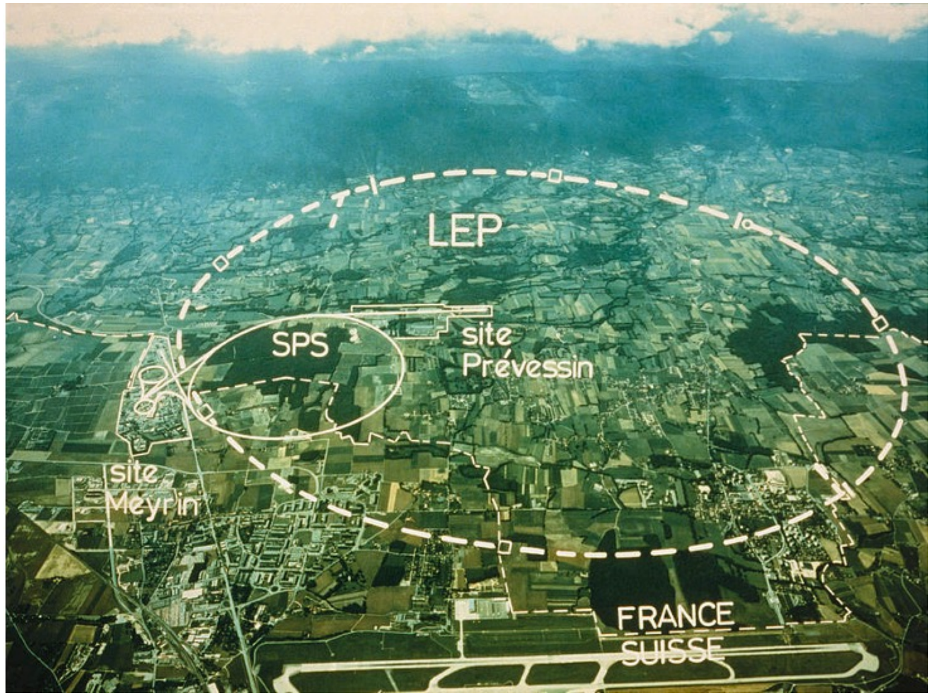


- Emergence of Hadron Mass is to some extent understood within continuum and lattice QCD calculations
- Prove and provide more input by measurement of

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

CERN Super Proton Synchrotron

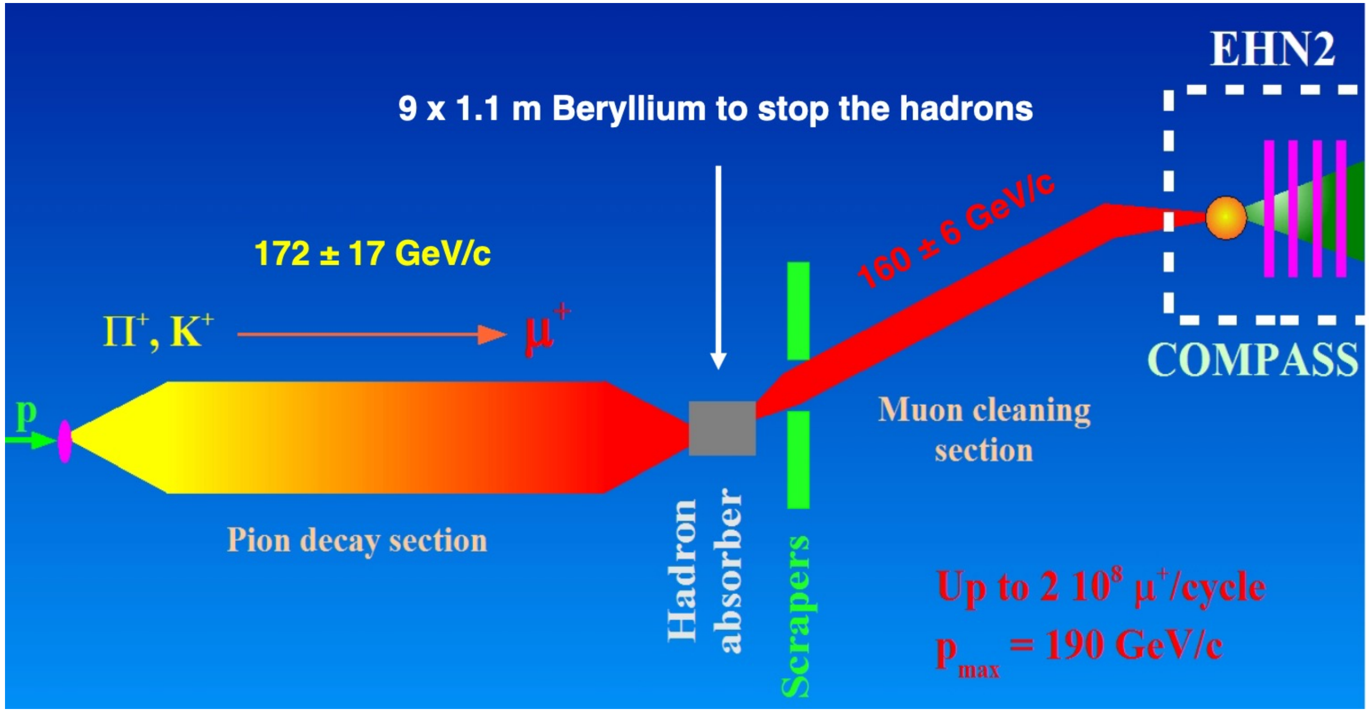
- Planning of accelerator for high energies up to 300 GeV at CERN started in 1971 (later reached: 450 GeV)
- First beam in the SPS 1976



- Proton-Antiproton collisions in the 1980s (UA1 and UA2), discovery of the heavy gauge bosons in collider mode
- Extracted beam lines: M2 for high-energy, high-intensity muons

SPS M2 beam line to EHN2

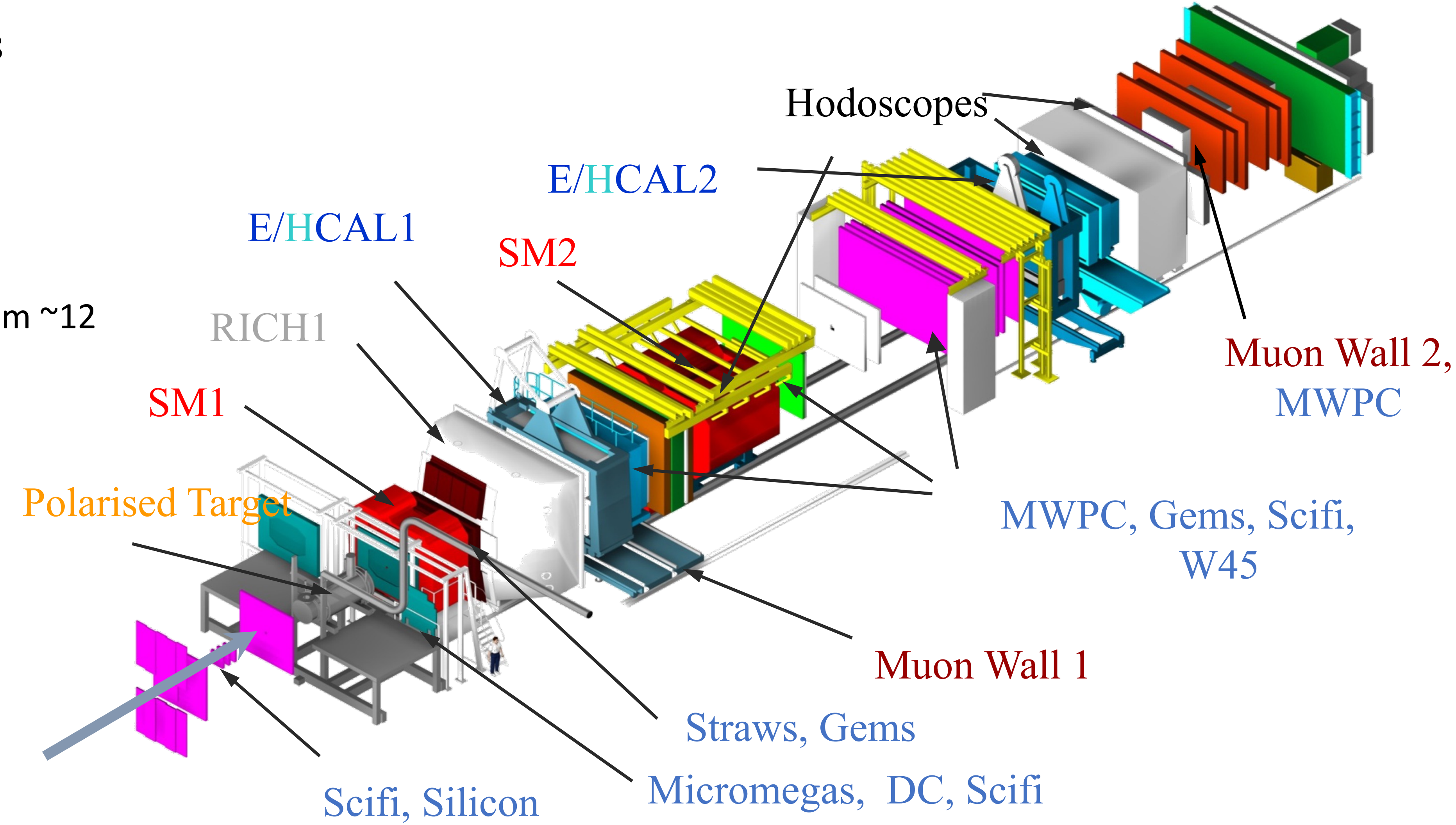
- max. 1.4e13 proton-per-pulse on T6 production target
- muons can be selected in the range 60 to 200 GeV
- without hadron absorber, also secondary hadron beams up to 280 GeV can be provided



- first users: European Muon Collaboration (EMC) proposal 1974, North-Area experiments NA2, NA9, NA28 until 1985
- New Muon Collaboration (NMC, NA37) and Spin Muon Collaboration (SMC, NA47) until 1996: Deep-inelastic pol. and unpol. muon scattering off the nucleons to understand their quark-gluon structure

COMPASS

- approved 1996 as NA58
- first technical run 2001
- last data taking 2022
- about 200 physicists from ~12 countries

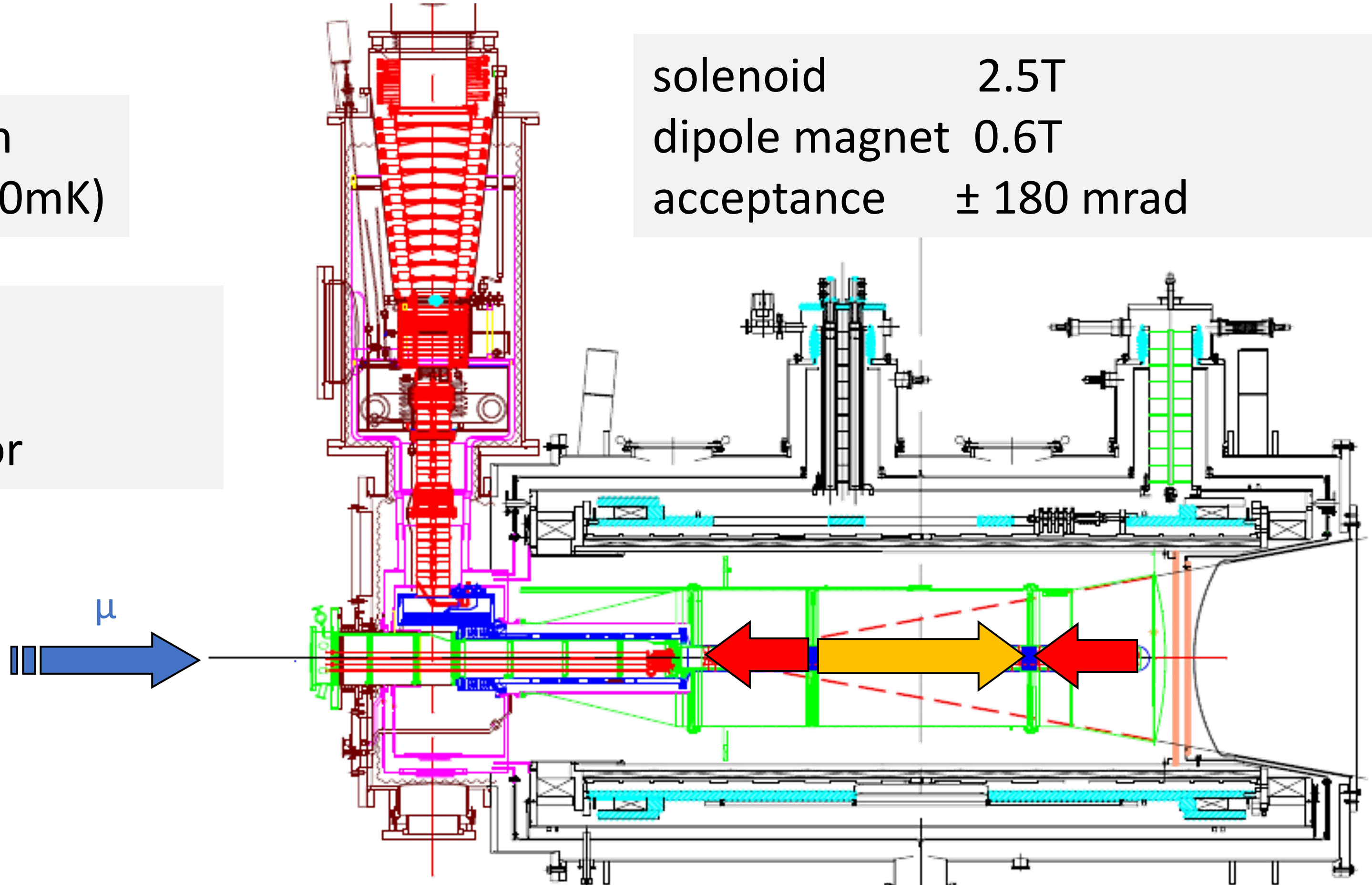


COMPASS Polarised target

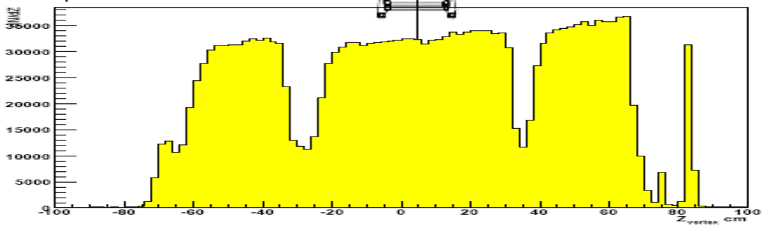
$^3He - ^4He$ dilution refrigerator (T ~50mK)

$^6LiD/NH_3$ (d/p)
50/90% pol.
40/16% dil. factor

solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad



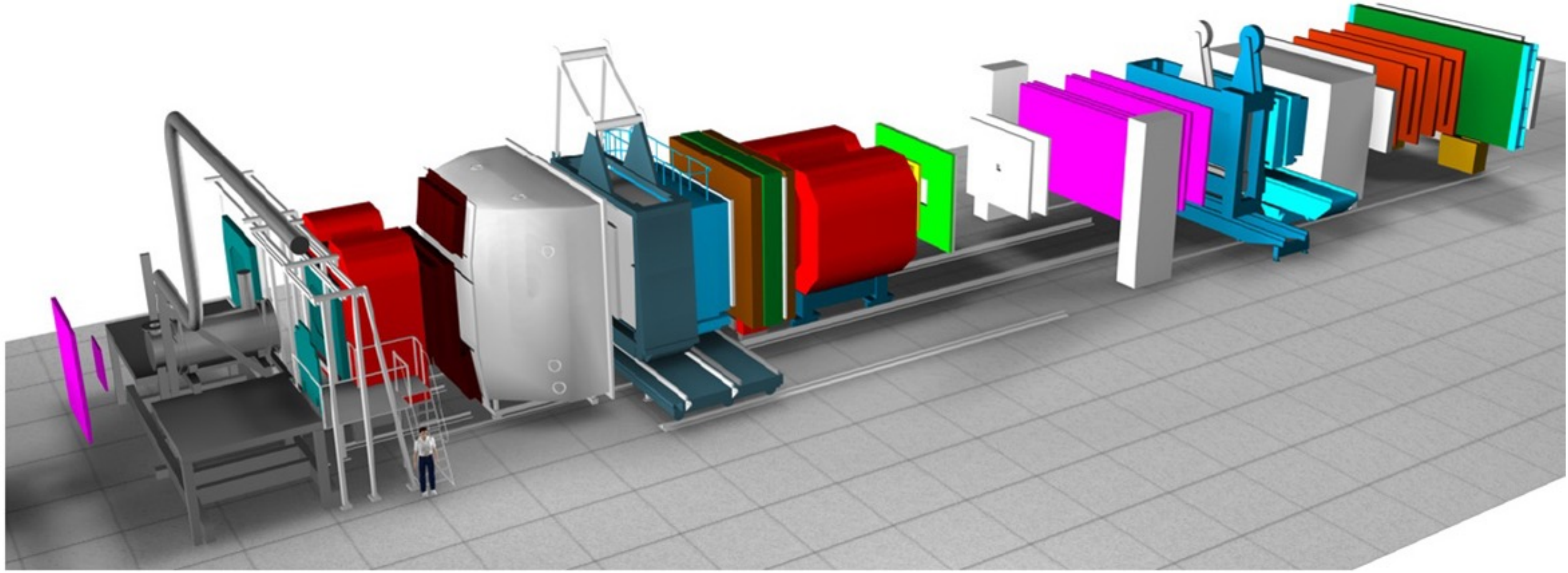
Reconstructed interaction vertices

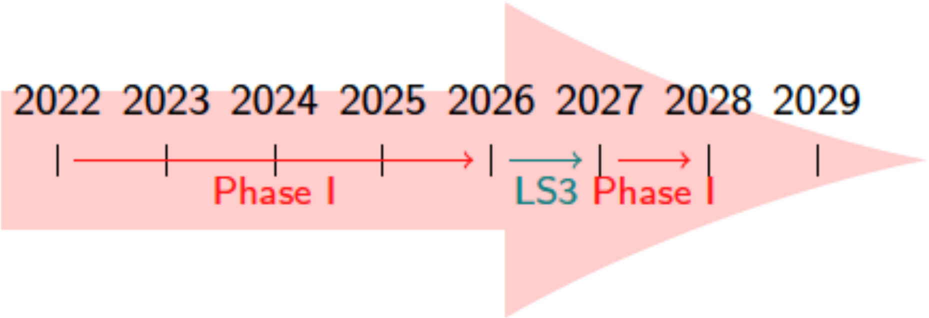


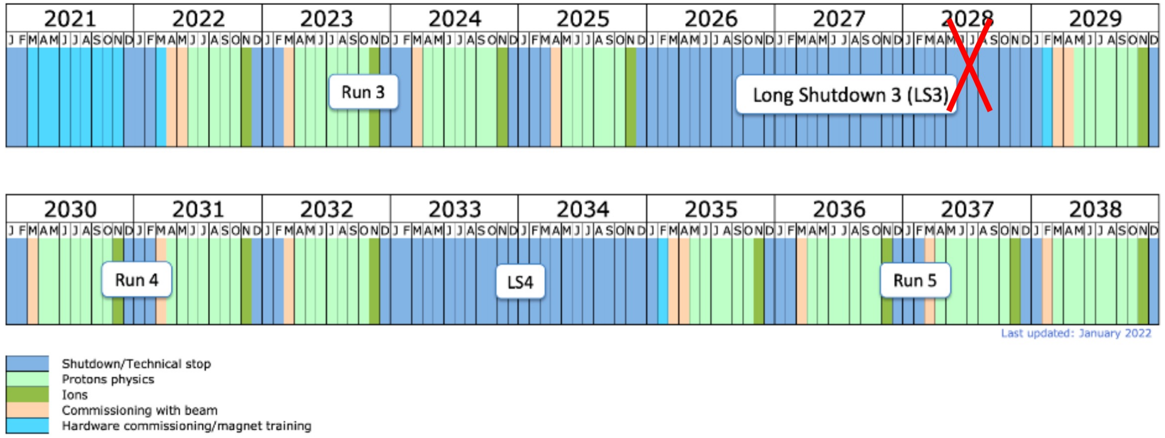
COMPASS is turning to AMBER

- Successor of COMPASS

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







AMBER physics programme

- 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, plan to submit in 2023

- MoU draft close to final, signatures expected this spring

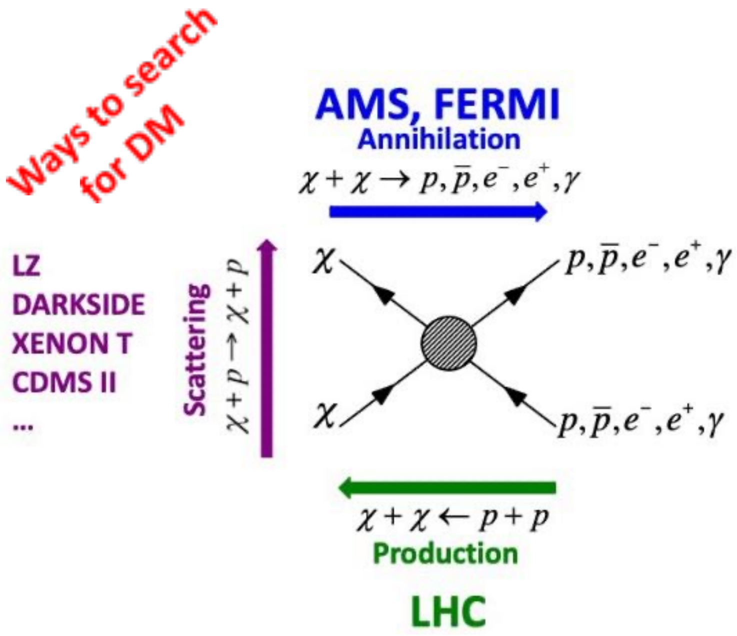
1) Antiproton production cross-sections for DM searches
2) Proton radius by high-energy muon scattering
3) Pion PDFs with Drell-Yan processes

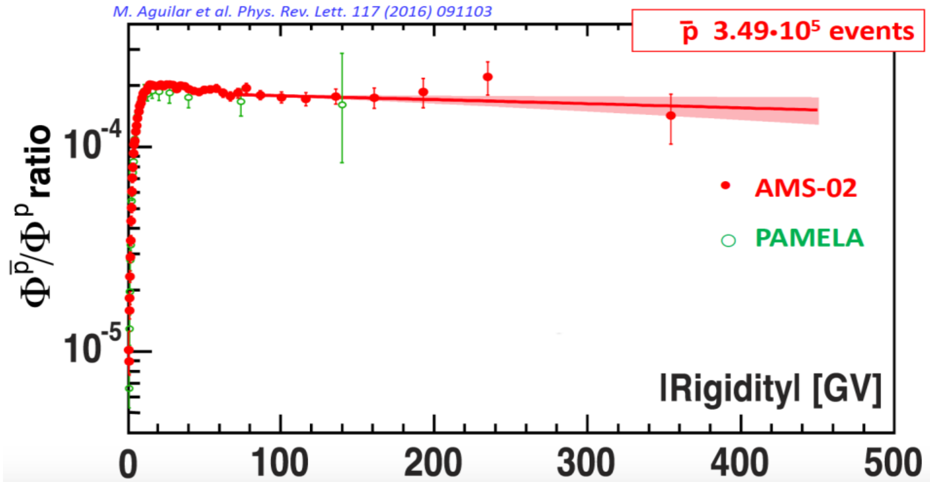
Phase-1
with conventional hadron and muon beams
2022 → 2028

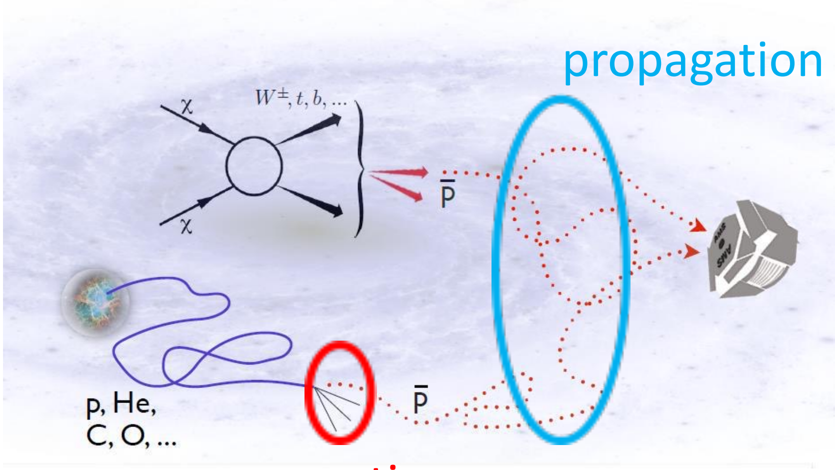
- Gluon PDFs of mesons
- Spectroscopy of strange mesons
- Meson charge radii
- Meson-photon reactions in Primakoff kinematics: polarisabilities, chiral couplings

Phase-2
with conventional (or rf-separated) beams
2029 and beyond

Antiproton production cross-sections

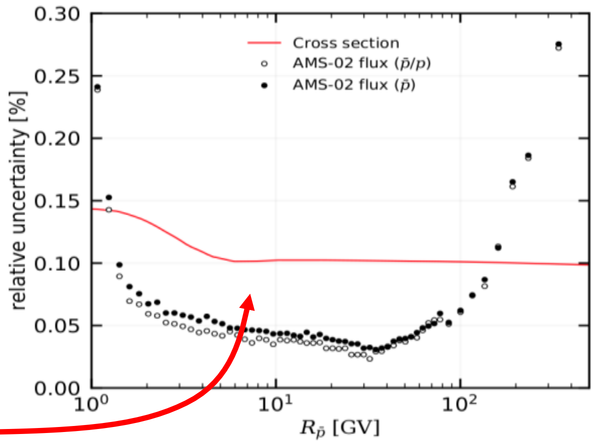


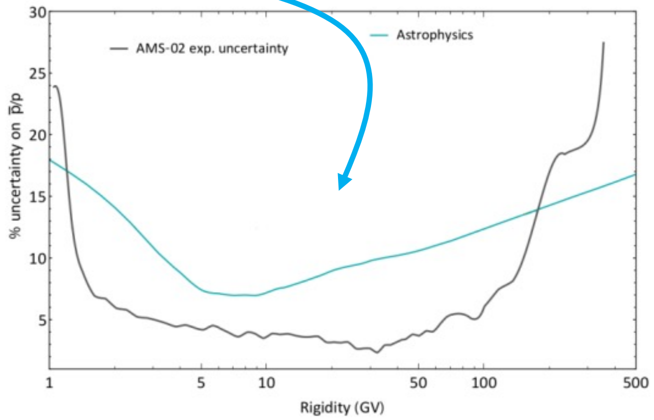




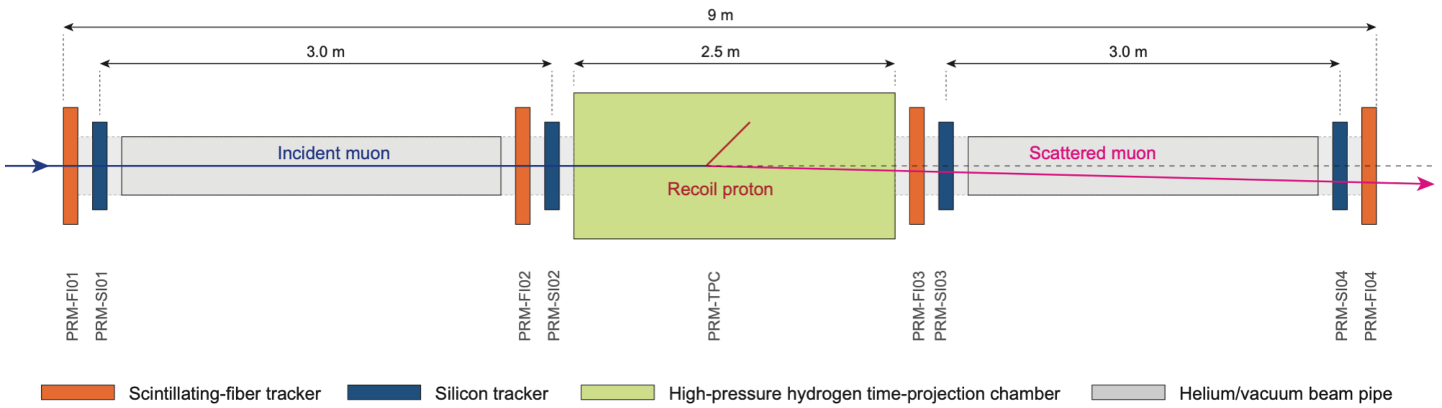
propagation

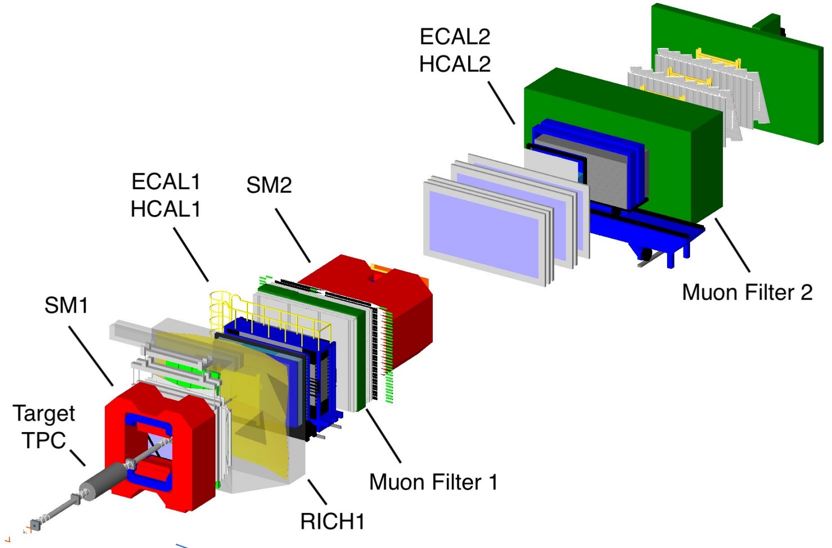
cross section





Proton radius

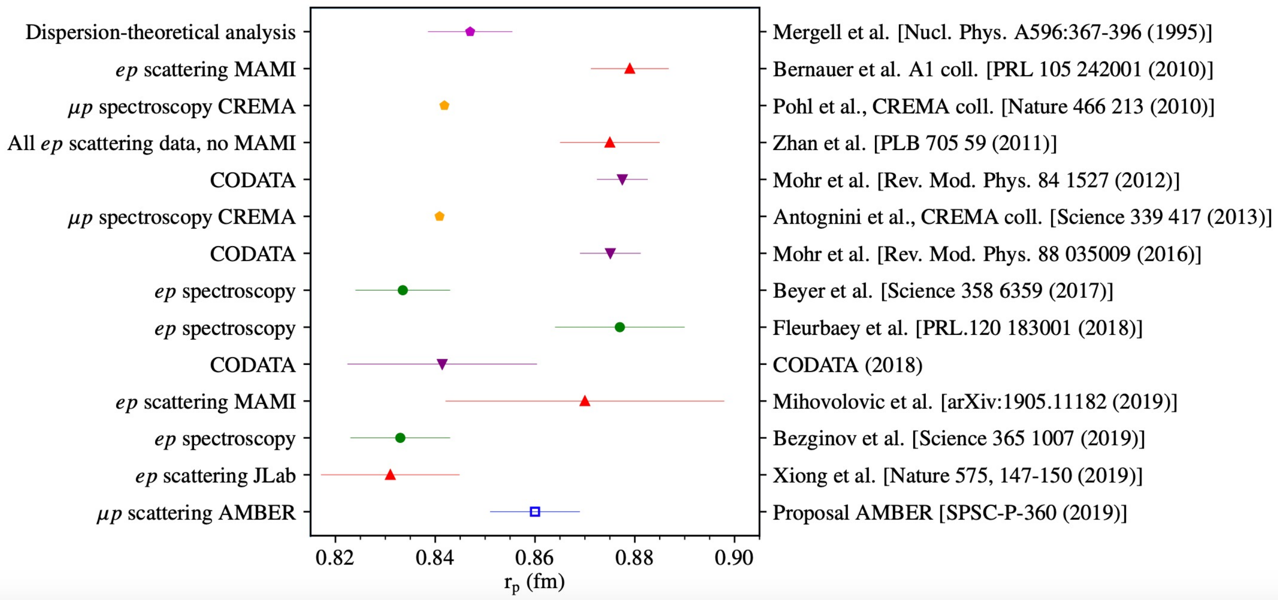




- 100 GeV muon beam
- Active-target TPC with high-pressure H_2
- goal: 70 million elastic scattering events in the $10^{-3} < Q^2 < 4{\cdot}10^{-2}$ GeV^2 range
- Precision on the proton radius ~0.01 fm
- Test run with small IKAR TPC in 2021, tracking detector tests in 2022
- Pilot run in 2023

Physics case

Proton radius puzzle



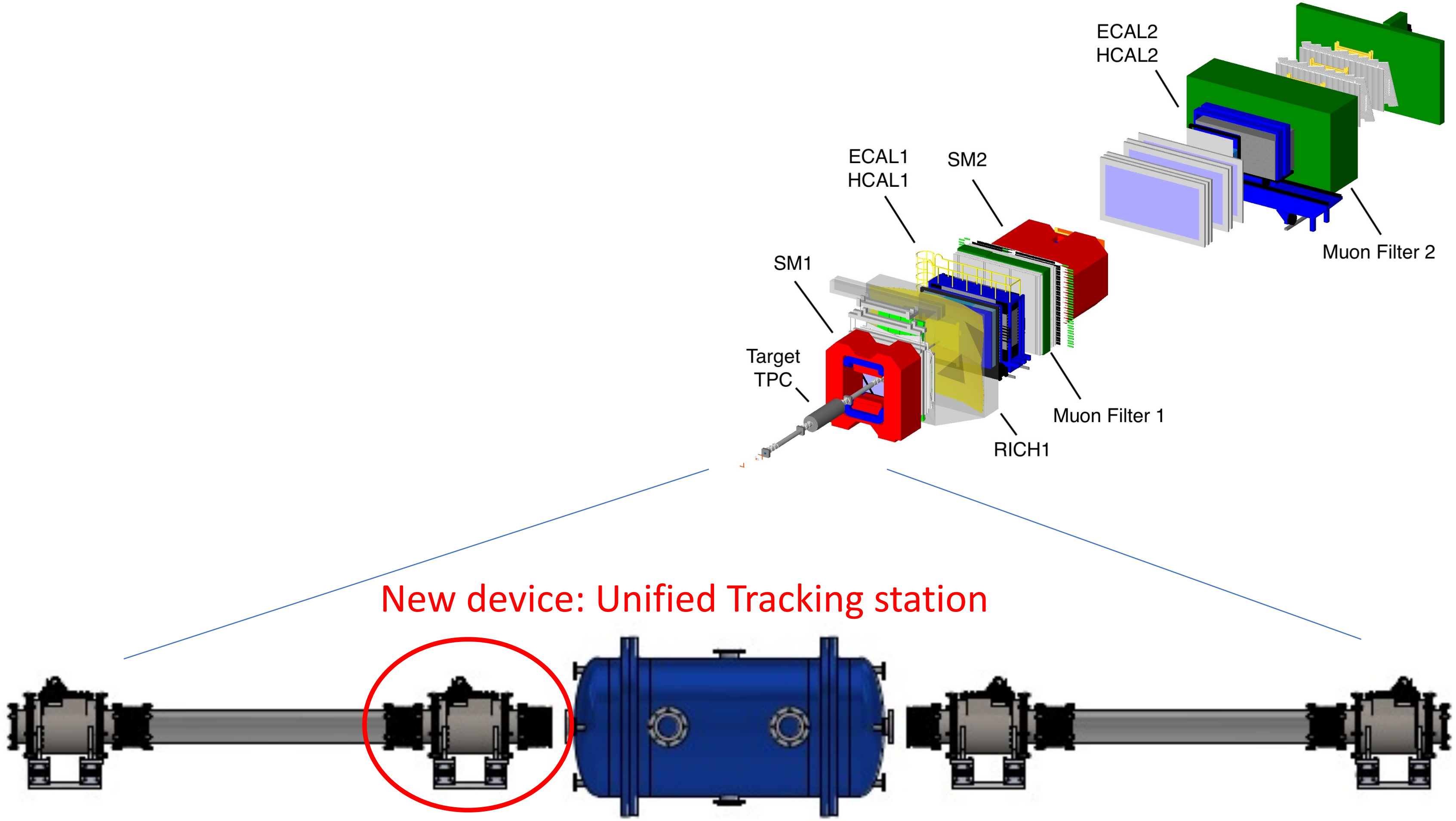
- Bremsstrahlung effect suppressed for muons
- possibility to control the small effect by measuring forward photons in ECAL2

from the Letter of Intent:

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	$\overline{p}$ production cross section	20-280	$5\cdot10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5\cdot10^7$	25	$\overline{p}$	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	$\sim$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 polarisa-bility & pion life time	$\sim$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.

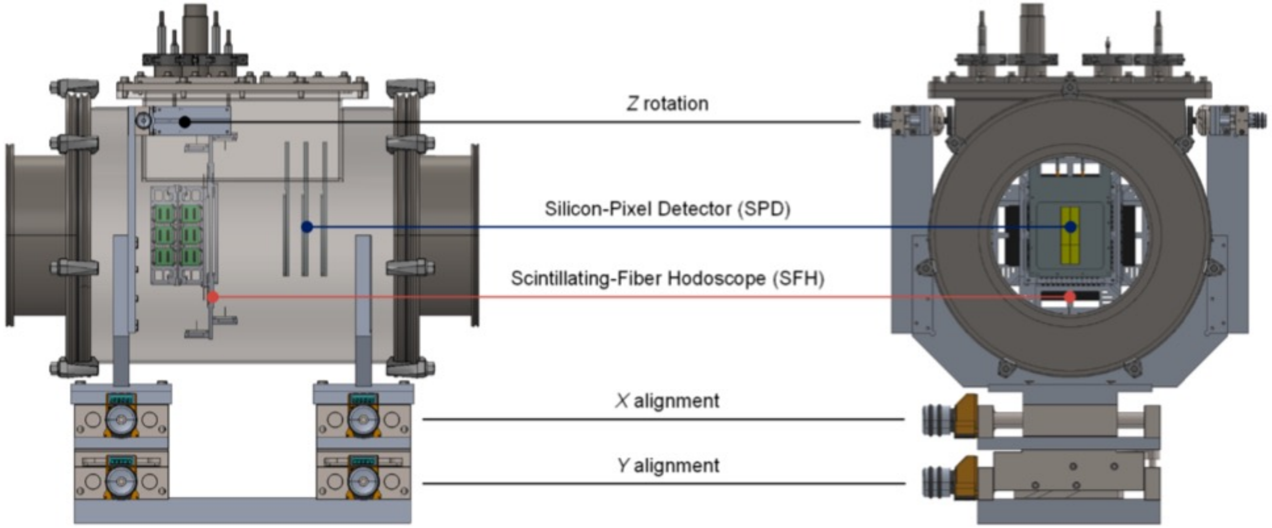
New equipment for AMBER PRM



Unified Tracking Station

Scintillating Fiber Hodoscope
for precise timing < 1 ns

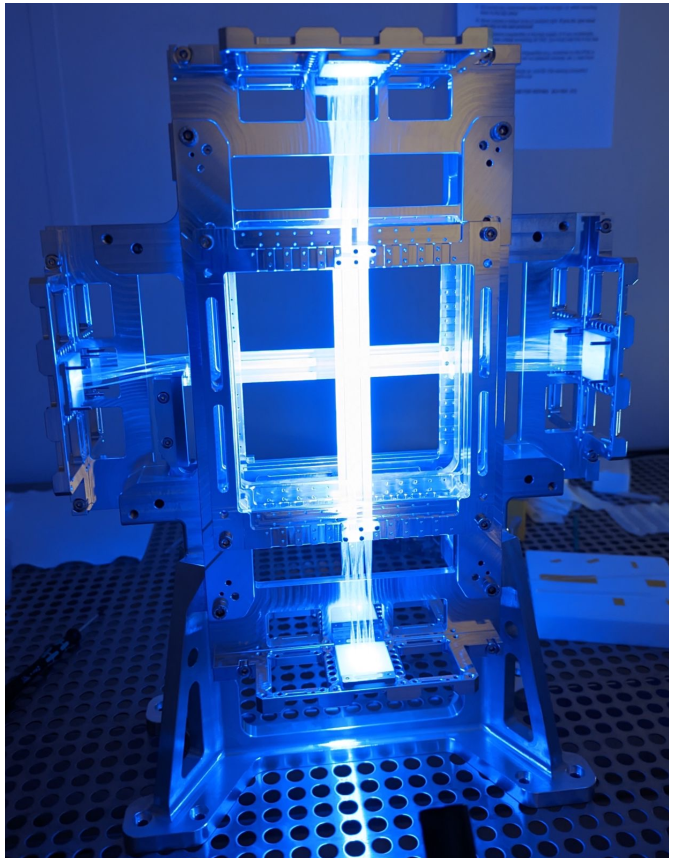
Silicon-pixel detectors (ALPIDE)
for high spatial resolution $\sim 10\ \mu$m



UTS design and construction at TUM

Installation near the target position during the last weeks of COMPASS run 2022

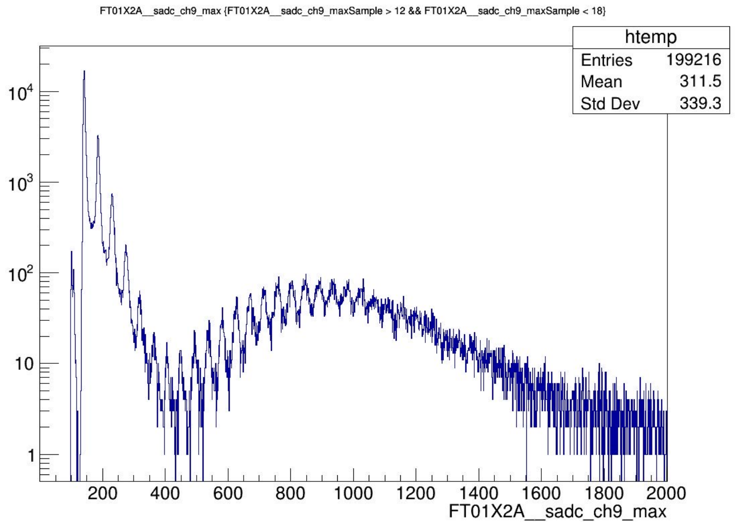
UTS – first test results



SFH (partly equipped) standing in lab

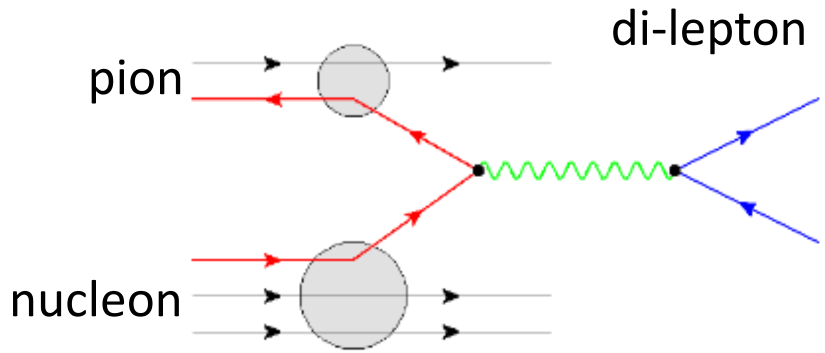
ALPIDEs and SFH hanging in UTS

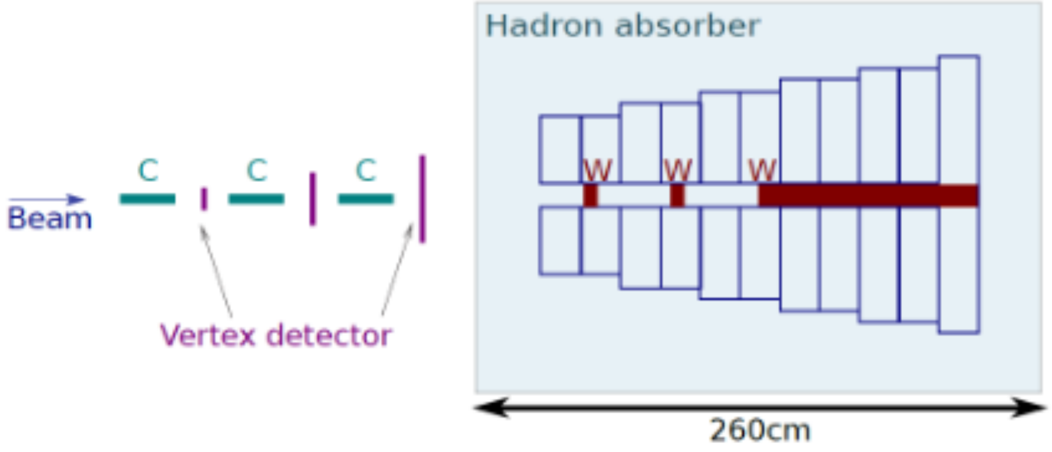
Successful operation of the tracking prototype detectors in November 2022



Promising online control of the SFH data

Drell-Yan and pion PDFs at AMBER

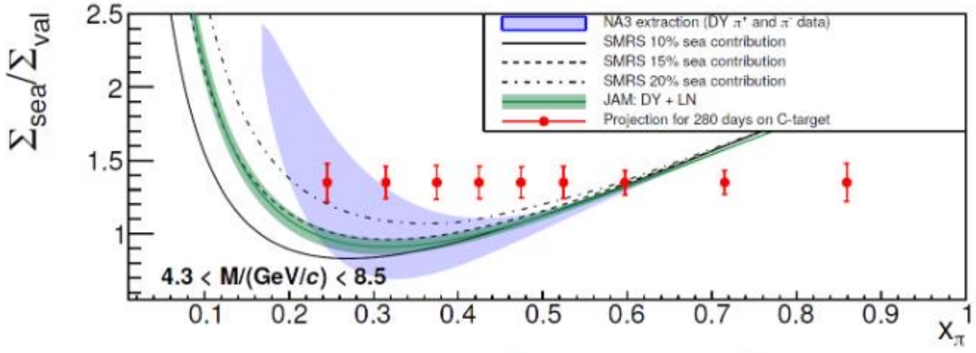




- Iso-scalar target (^{12}C) to minimize nuclear effects

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

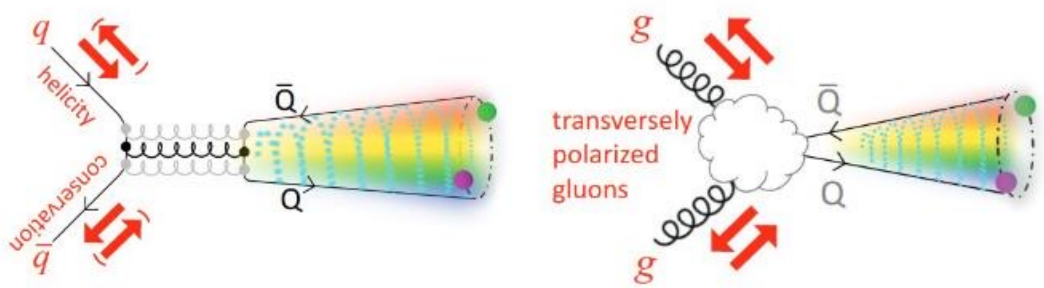
$$\frac{\Sigma_{\text{sea}}}{\Sigma_{\text{val}}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$

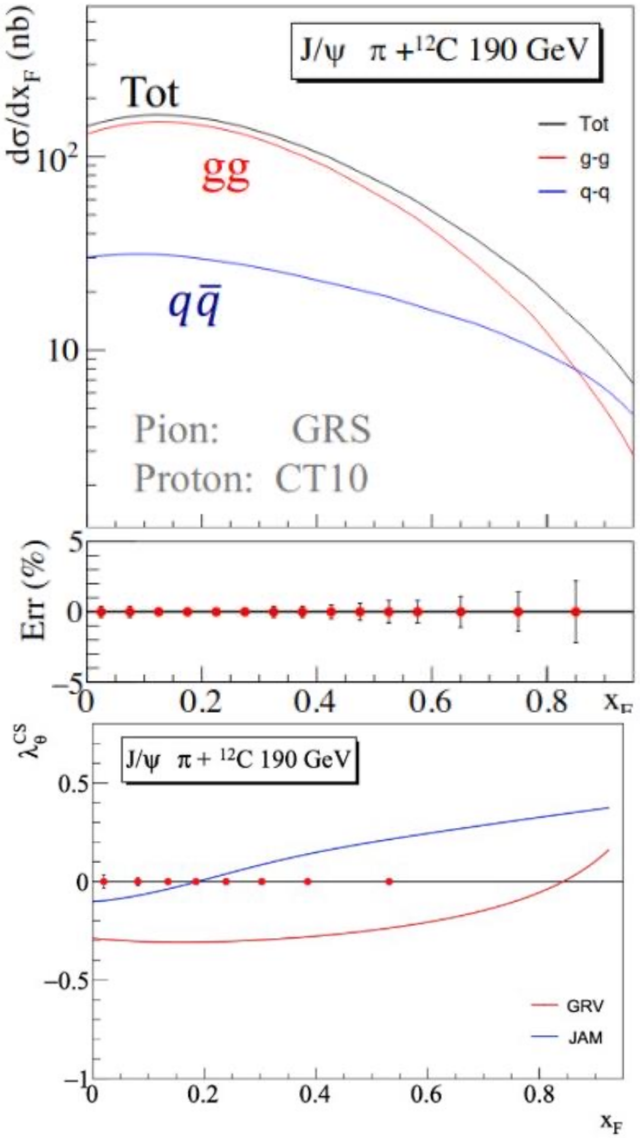


$$\sigma_{\text{DY}}^{\pi^+ A} \propto \sum_i (e_i)^2 \left[\bar{q}_i^{\pi^+} q_i^A + q_i^{\pi^+} \bar{q}_i^A\right]$$

- 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 in the dimuon channel (30-50x 'DY clean region')
- Inclusive measurements: prompt production can't be separated
- Expected significant feed-down from $\psi(2S)$, 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

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

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

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

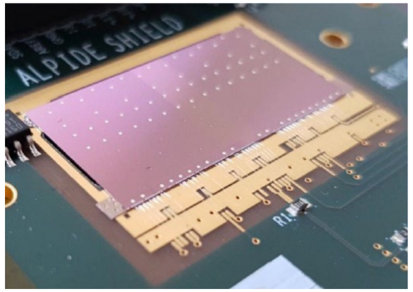
$\lambda = 0 \iff$ unpolarised

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

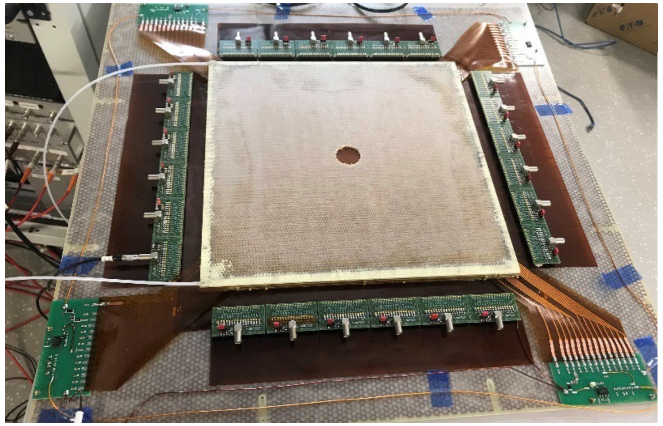
$gg \rightarrow J/\psi$

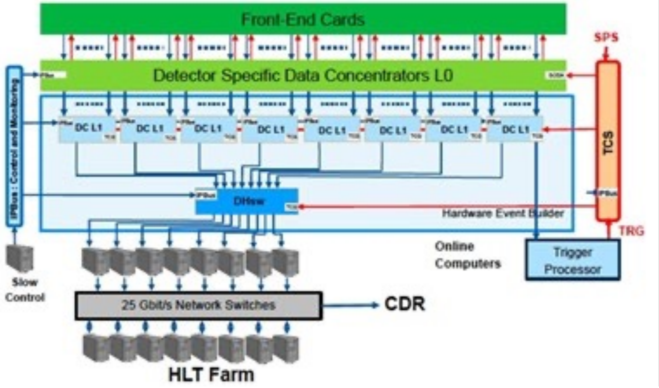
New hardware for Phase-1

- Triggerless DAQ and High-Level Trigger
- High-pressure hydrogen TPC
- C/W, LH2, LHe targets
- SciFi/Silicon Pixel tracking stations
- DY vertex detector
- Large-area MPGD detectors with self-triggering readout
- Self-triggered electronics for ECAL
- Upgrade CEDAR electronics for high rates

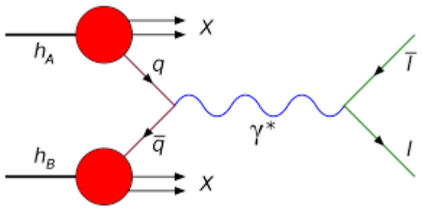


ECAL2 DAQ Hardware – Carrier Board III

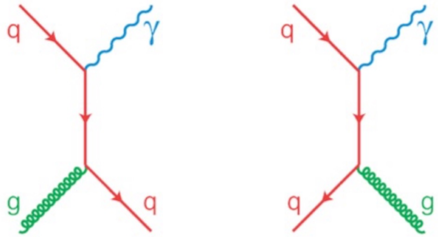




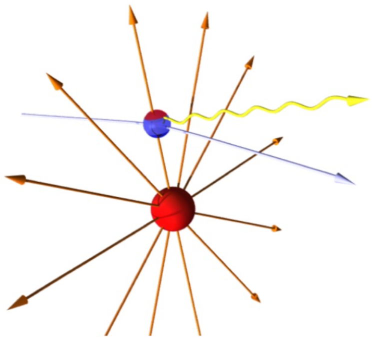
Physics ideas of the Phase-2 proposal



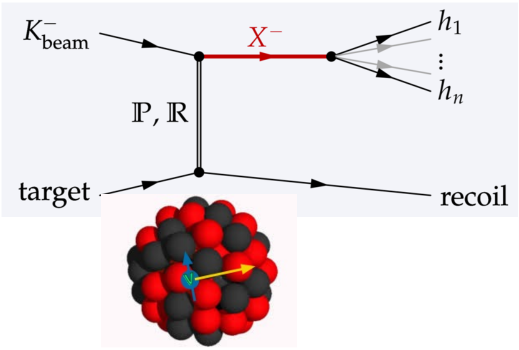
- Kaon structure via the Drell-Yan process



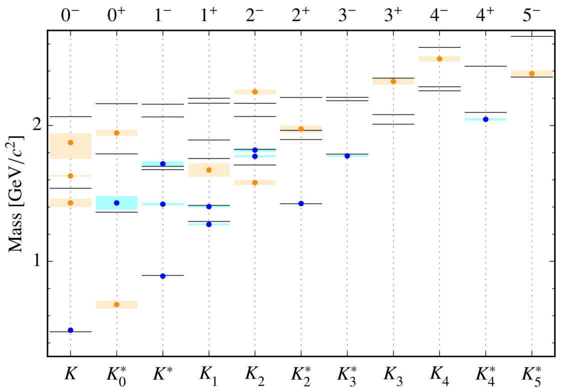
- Gluon structure of pions and kaons via prompt photons



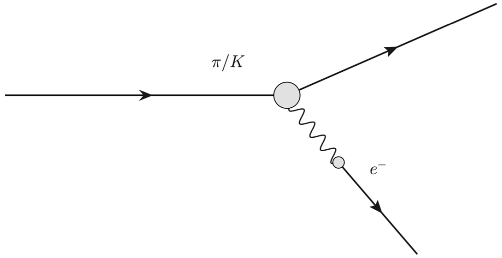
- Primakoff reactions to investigate kaon-photon coupling: kaon polarisability, $F_{KK\pi}$



- 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

Interested? We are open for more ideas, and people entering for analysis (also of existing data), simulation,…

Primakoff reactions of Kaon beams

COMPASS legacy: Measurements of fundamental **pion properties** relevant in Chiral Perturbation Theory

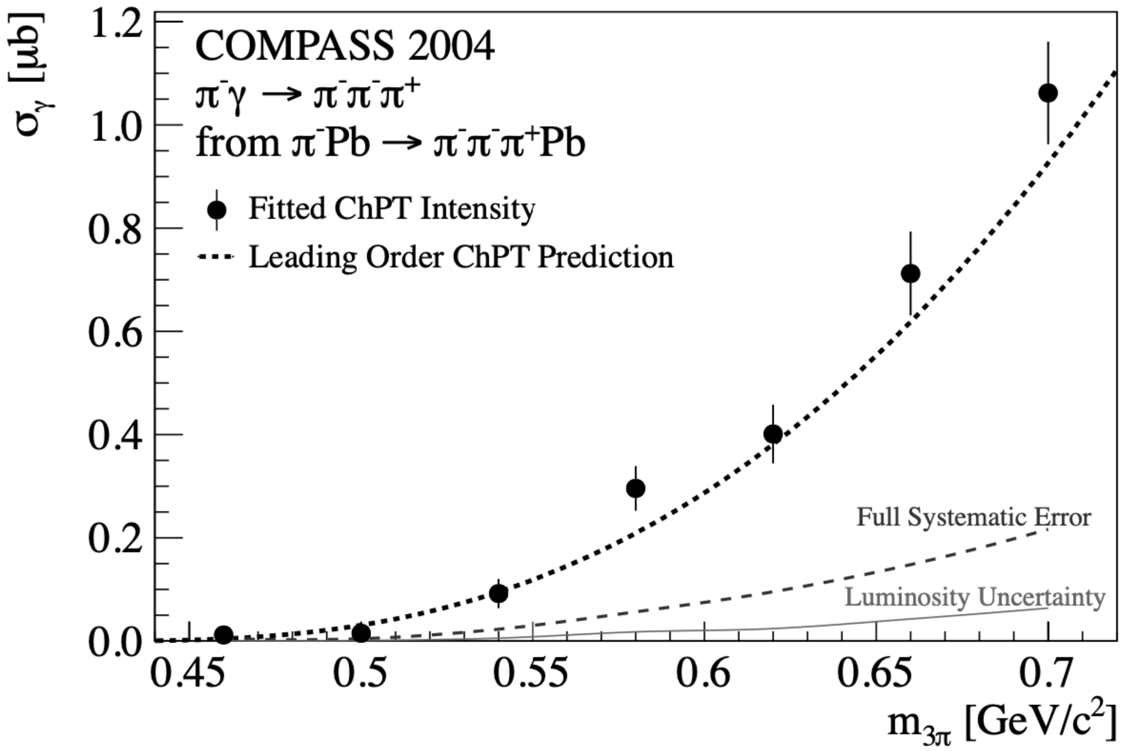
- Pion polarisability in $\pi\gamma \to \pi\gamma$ (PRL 114, 062002, 2015)

$$\alpha_\pi = \left(2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}\right) \cdot 10^{-4}\ \text{fm}^3$$

- Chiral dynamics in $\pi\gamma \to 3\pi$ (PRL 108, 192001, 2012)

- Chiral anomaly in $\pi\gamma \to \pi\pi^0$

$$F_{3\pi}^{\text{COMPASS,prelim}} = (10.3 \pm 0.1_{\text{stat}} \pm 0.6_{\text{syst}})\ \text{GeV}^{-3}$$



AMBER: **explore equivalent properties for Kaons**

- Chiral anomaly in $K\gamma \to K\pi^0$

Theory framework:

Eur. Phys. J. C (2021) 81:221
https://doi.org/10.1140/epjc/s10052-021-08951-x

THE EUROPEAN PHYSICAL JOURNAL C

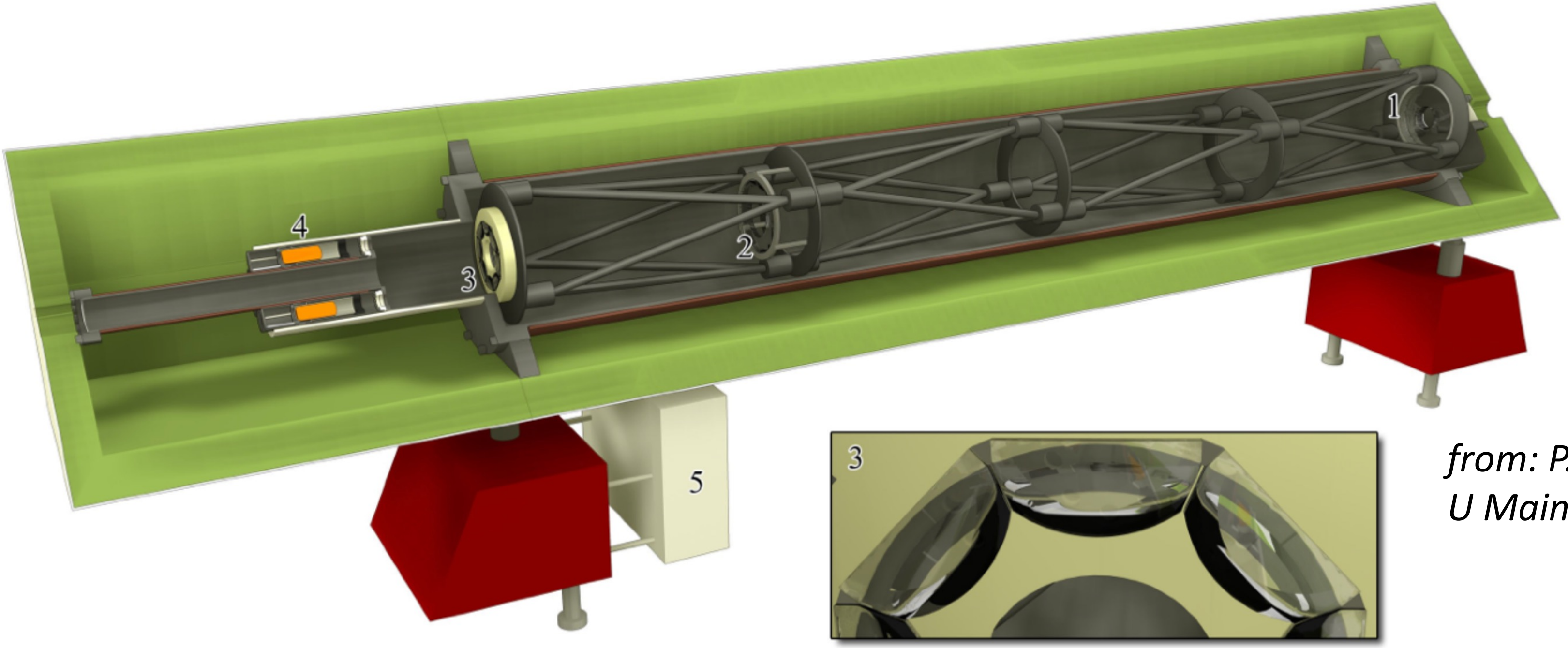
Regular Article - Theoretical Physics

Dispersive analysis of the Primakoff reaction $\gamma K \to K\pi$

Maximilian Dax[1,a], **Dominik Stamen**[1,b], **Bastian Kubis**[1,c]

[1] Helmholtz-Institut für Strahlen- und Kernphysik (Theorie) and Bethe Center for Theoretical Physics, Universität Bonn, 53115 Bonn, Germany

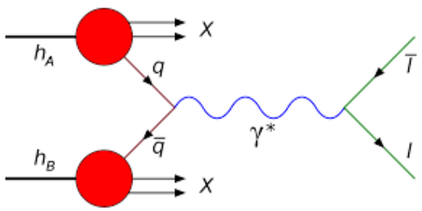
Beam PID by CEDARs



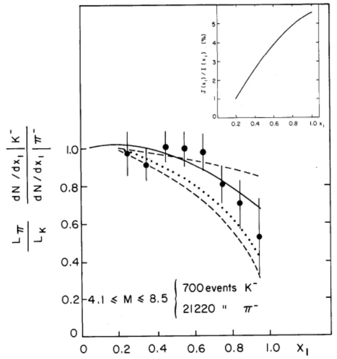
from: P. Jasinski, PhD thesis U Mainz

- 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

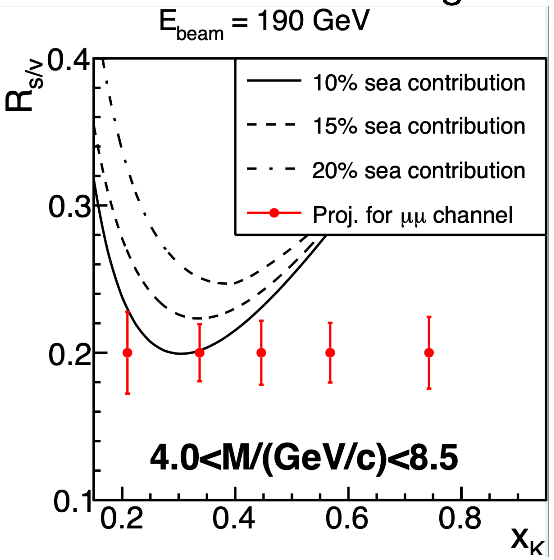


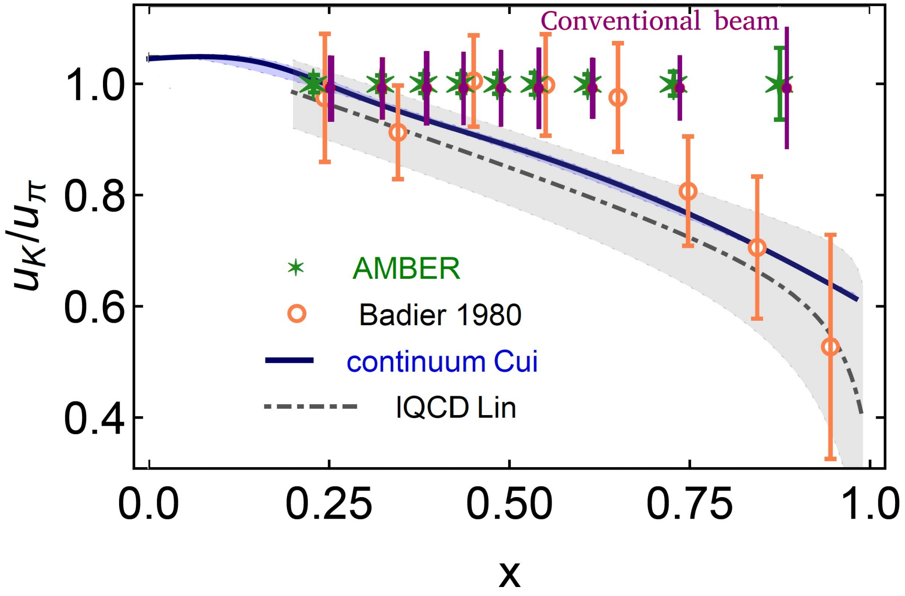
NA3: PLB 93 (1980) 354



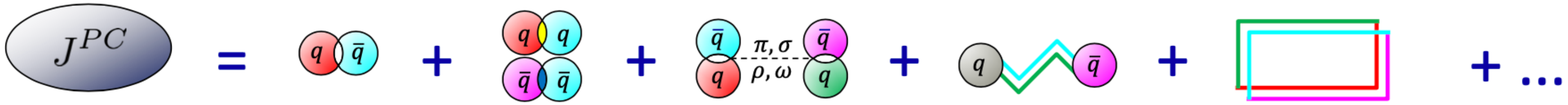
- Available data
  - Only 700 events from NA3
  - The kaon valence distributions are practically unknown
  - There is no data on kaon sea and gluon content
- Prospects for AMBER measurements
  - Kaon valence PDF: can be addressed with negative kaon beam
  - Kaon sea PDF: combine the two beam charges

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





Exotic mesons



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

Tetraquark Molecule Hybrid Glueball

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

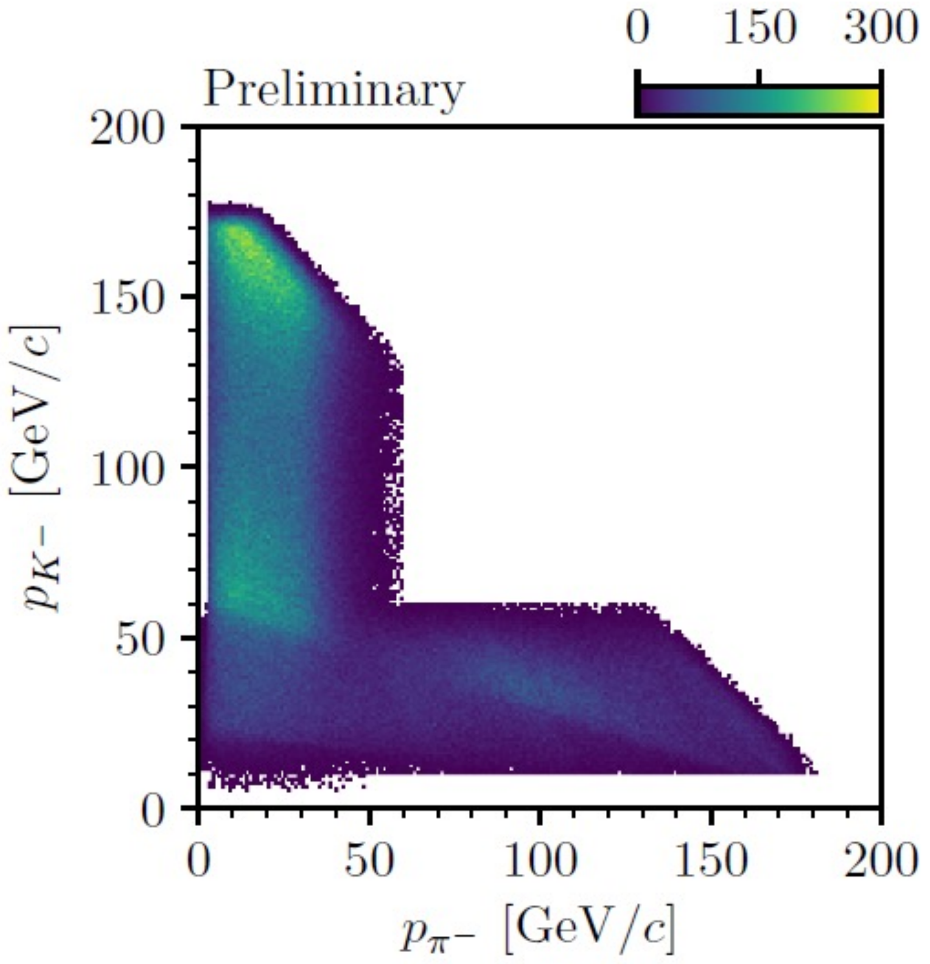
Need:

- Large data sets with small statistical uncertainties
- Complementary experiments – production mechanisms – final states
- Advanced analysis methods

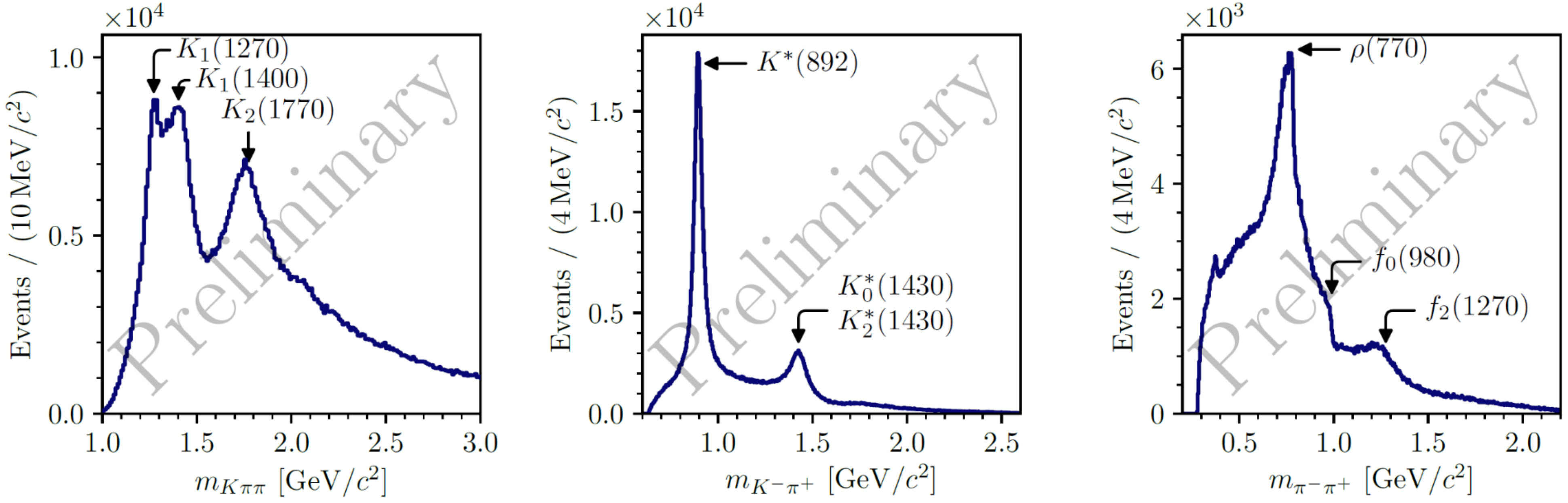
reaction models theoretical constraints

Limitations at COMPASS

- For e.g. the $K^-\pi^-\pi^+$ final state in diffractive scattering, the two negative particles have to be distinguished
- RICH detector has a blind kinematic corner (for 190 GeV beam)
- Difficult to take into account in a PWA



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



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

$\Rightarrow$ access to all kaon states: K_J, K_J^*

$\Rightarrow$ 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

Conclusions

- NA66/AMBER at CERN has **started its Phase-1** of a broad hadron physics programme at the M2 beamline
  - anti-p production cross-sections
  - proton radius in high-E muon scattering
  - pion parton structure via Drell-Yan

- The physics cases of **Phase-2** are being worked on for a **proposal to SPSC in 2023**

NuPECC LRP2024 Community input

30 May 2022 to 30 October 2022

125. AMBER at CERN
The AMBER collaboration, approved by the CERN SPS Committee as north-area experiment NA66, pursues a broad programme in hadron structure and hadron spectroscopy using a versatile spectrometer setup at the CERN SPS M2 beam-line.

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

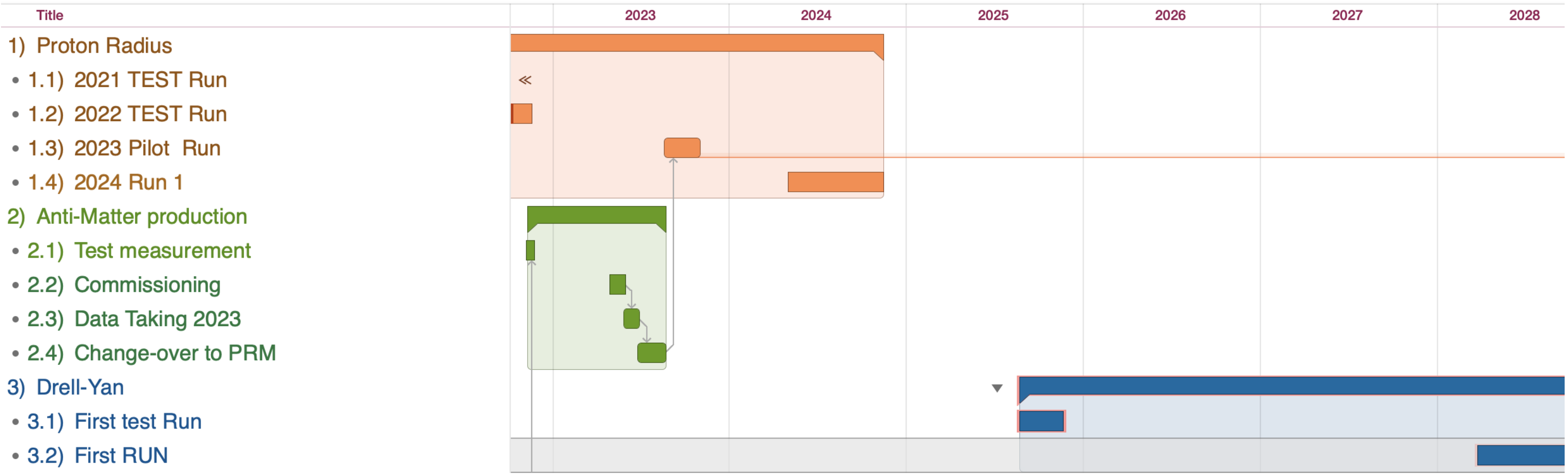
Meet AMBER

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

8 MARCH, 2021 | By Ana Lopes

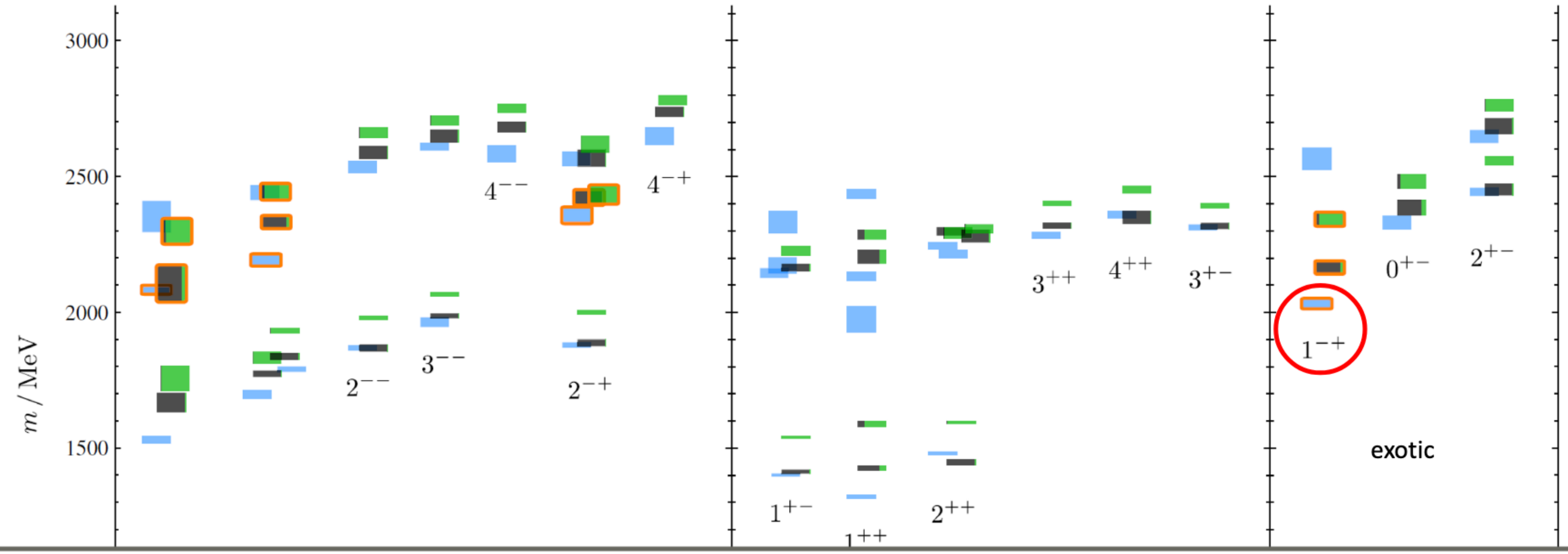
https://amber.web.cern.ch

Backup



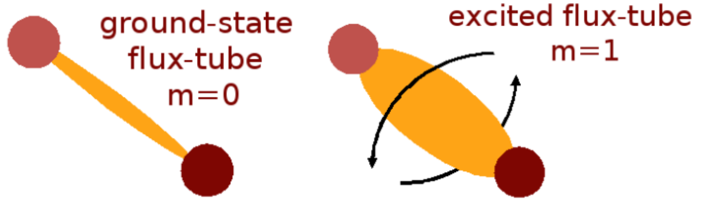
Title
2023
2024
2025
2026
2027
2028
1) Proton Radius
• 1.1) 2021 TEST Run
• 1.2) 2022 TEST Run
• 1.3) 2023 Pilot Run
• 1.4) 2024 Run 1
2) Anti-Matter production
• 2.1) Test measurement
• 2.2) Commissioning
• 2.3) Data Taking 2023
• 2.4) Change-over to PRM
3) Drell-Yan
• 3.1) First test Run
• 3.2) First RUN

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

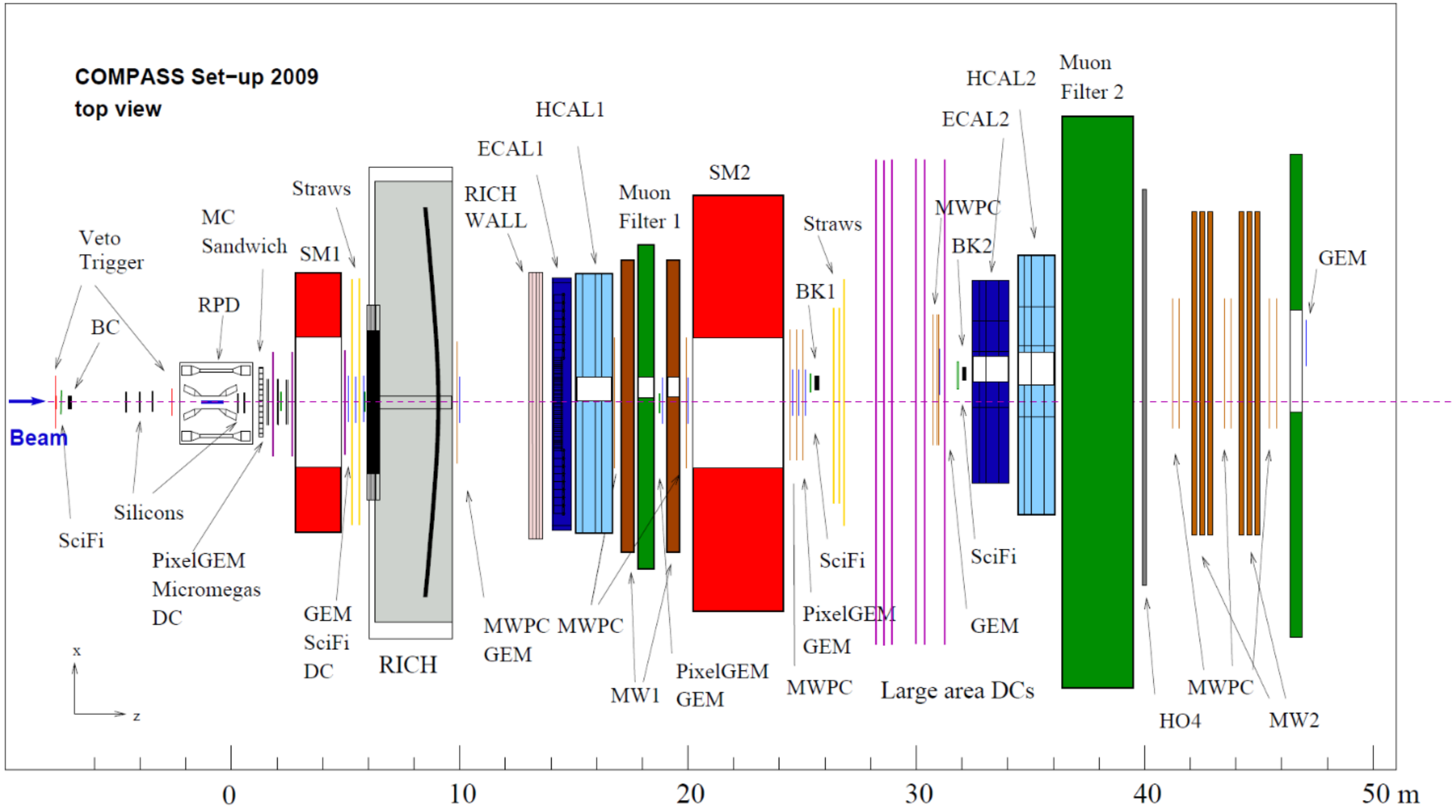
- Only about 2.4 % K^- in negative hadron beam
  - ➥ Low number of kaons
    (Sample for strange-mesons about 150-times smaller than sample for non-strange mesons)
- About 35× more π^- in negative hadron beam
  - ➥ Background from π^- diffraction

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 %

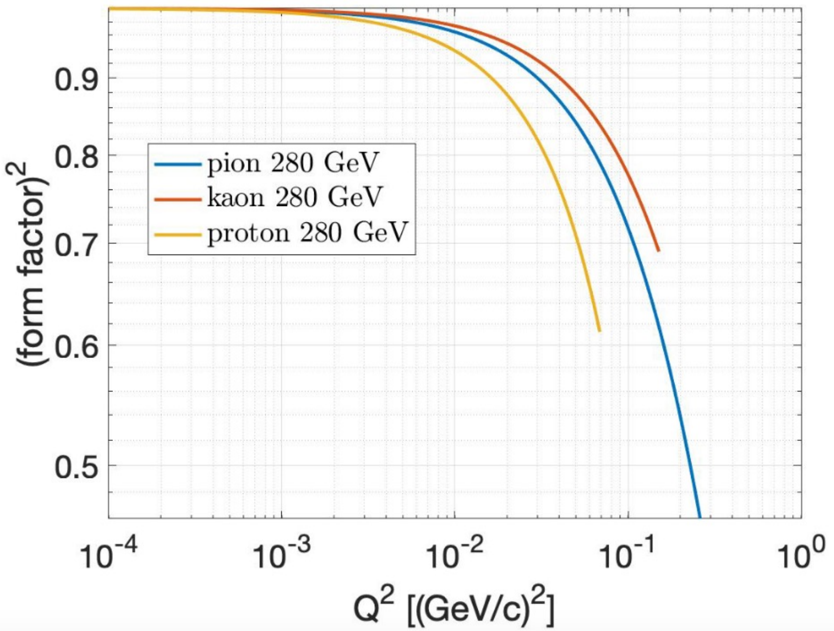
Setup for strange-meson spectroscopy

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



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%

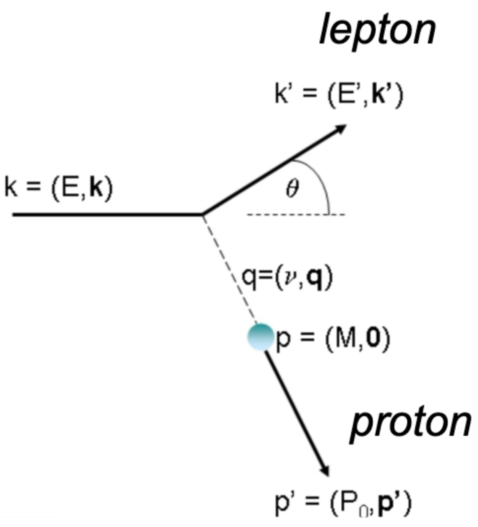
Hadron charge radii

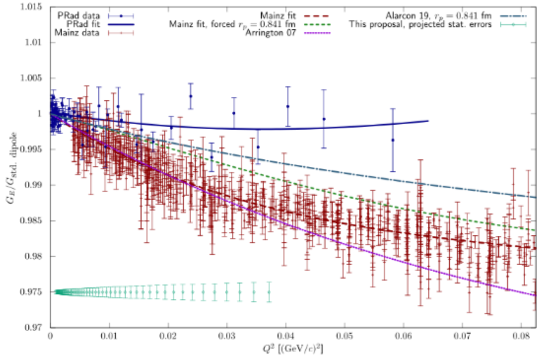
Protons in hydrogen target (or other stable nuclei):
Measurement via elastic electron or muon scattering
Cross section:

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

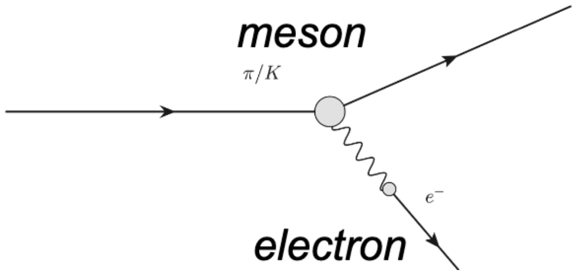
Charge radius from the slope of G_E

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





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



Gluon PDF of the pion

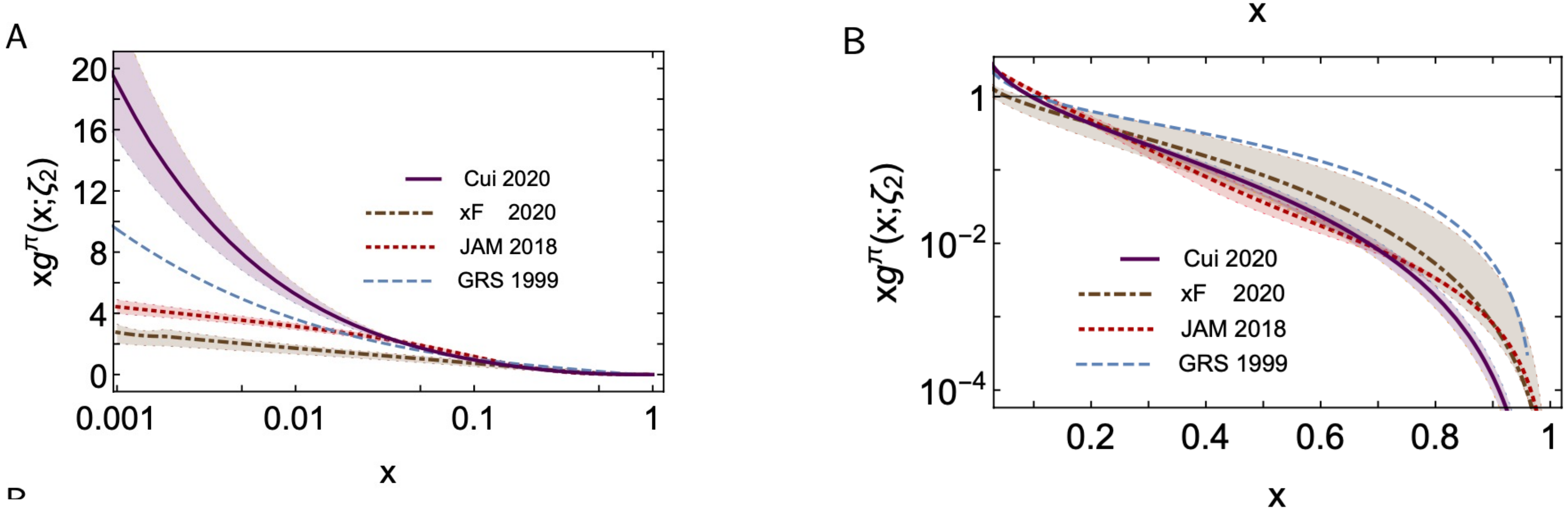
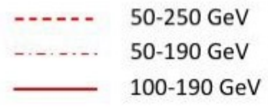
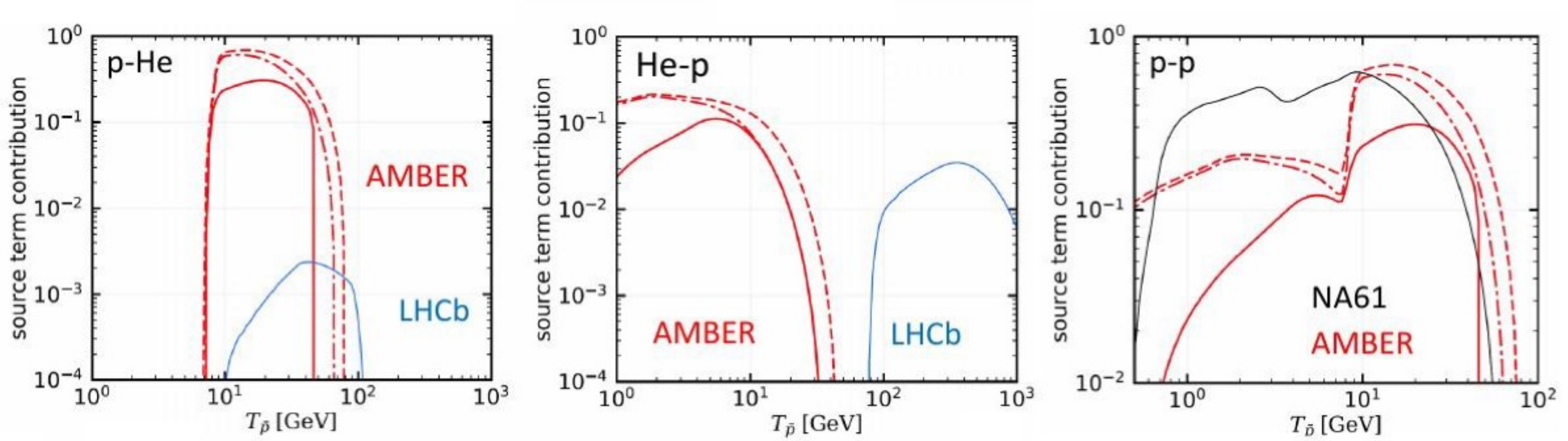


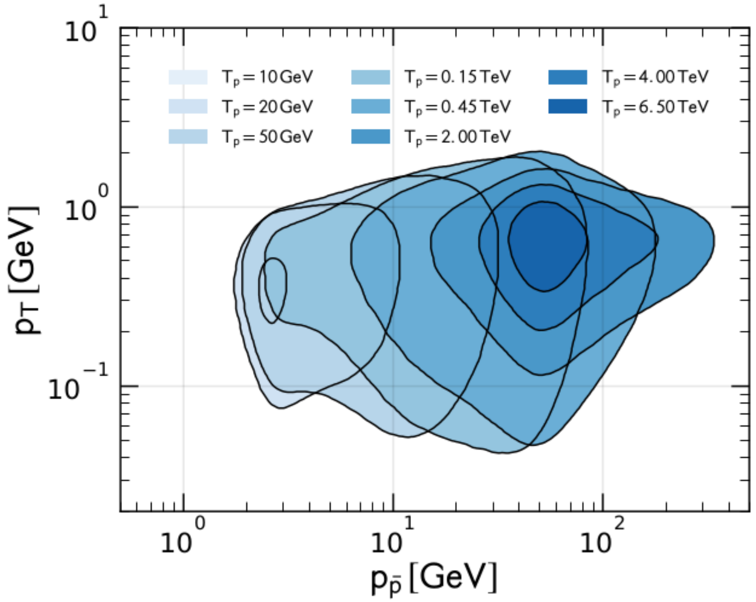
FIG. 4. Glue distribution, $xg^{\pi}(x, \zeta_2 = 2\,\text{GeV})$: solid purple curve, prediction from Ref. [43]. Panel A highlights low-x and Panel B, large-x. The band surrounding this curve expresses a conservative estimate of uncertainty in the prediction, obtained by varying ζ_H by $\pm 10\%$. Comparisons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

Antiproton 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**