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AMBER – A NEW QCD FACILITY

AND OTHER QCD INITIATIVES AT CERN/SPS

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KHuK Jahrestagung 2021

10.Dezember 2021

QUANTUM CHROMODYNAMICS

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QCD at strong coupling: emergence of hadronic and nuclear degrees of freedom

- Understand hadron properties in terms of constituents:
  - masses: proton vs pion and kaon
  - excitation spectrum
  - structure: size, form factors, parton distributions
  - confinement / deconfinement
- Input to precision collider observables, SM tests, BSM
- Quantitative theoretical approaches:
  - effective field theories
  - lattice QCD
  - continuum methods

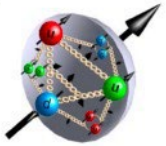
Pion

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

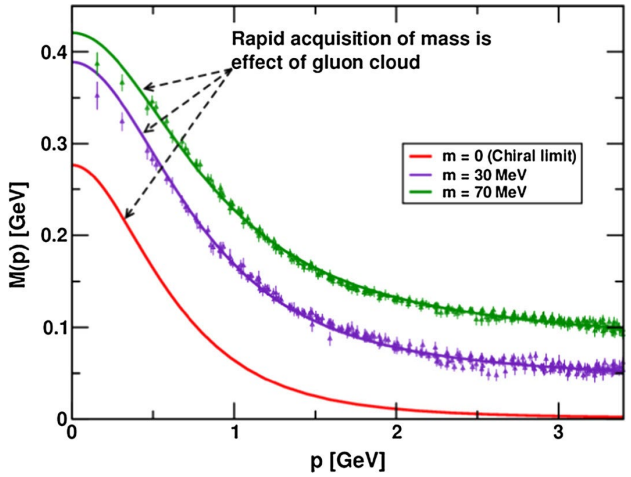
Kaon

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

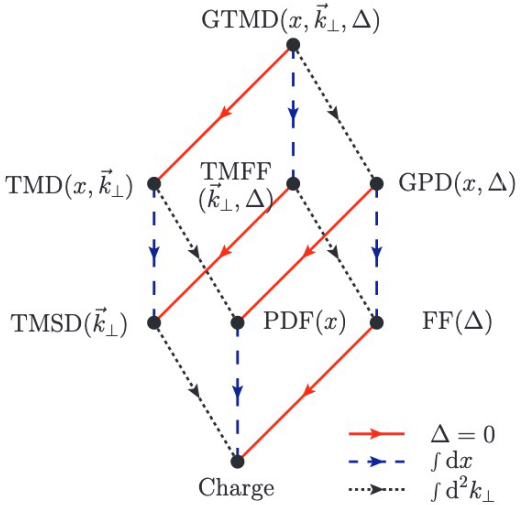
Proton

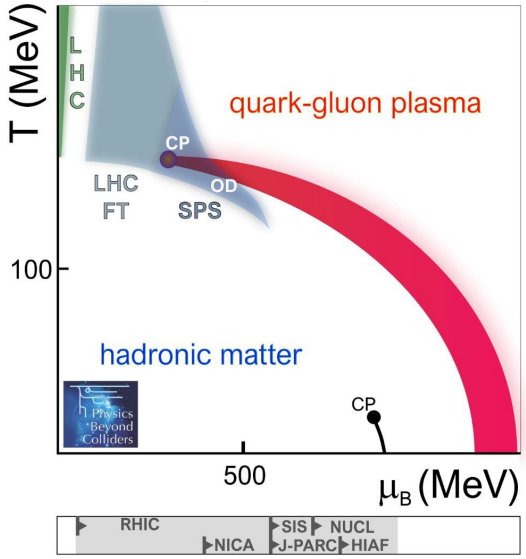


- $M_p \sim 940$MeV
- Spin 1/2
- 3 light valence quarks



Plot: dressed-quark mass function
curves: DSE [Bhagwat et al., 2003/2006]
data: LQCD [Bowman et al., 2005]





CERN SPS

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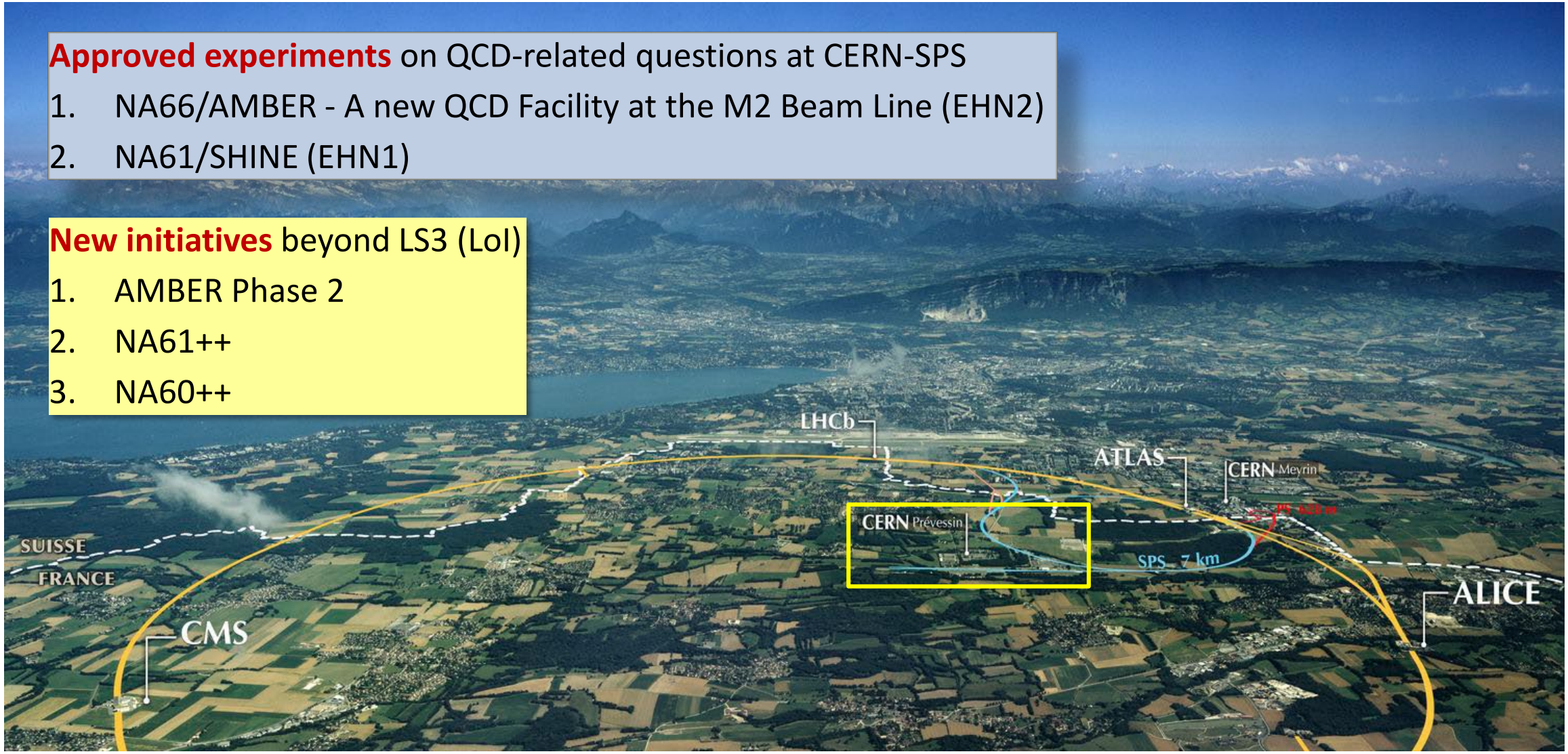
Approved experiments on QCD-related questions at CERN-SPS

1. NA66/AMBER - A new QCD Facility at the M2 Beam Line (EHN2)
2. NA61/SHINE (EHN1)

New initiatives beyond LS3 (LoI)

1. AMBER Phase 2
2. NA61++
3. NA60++



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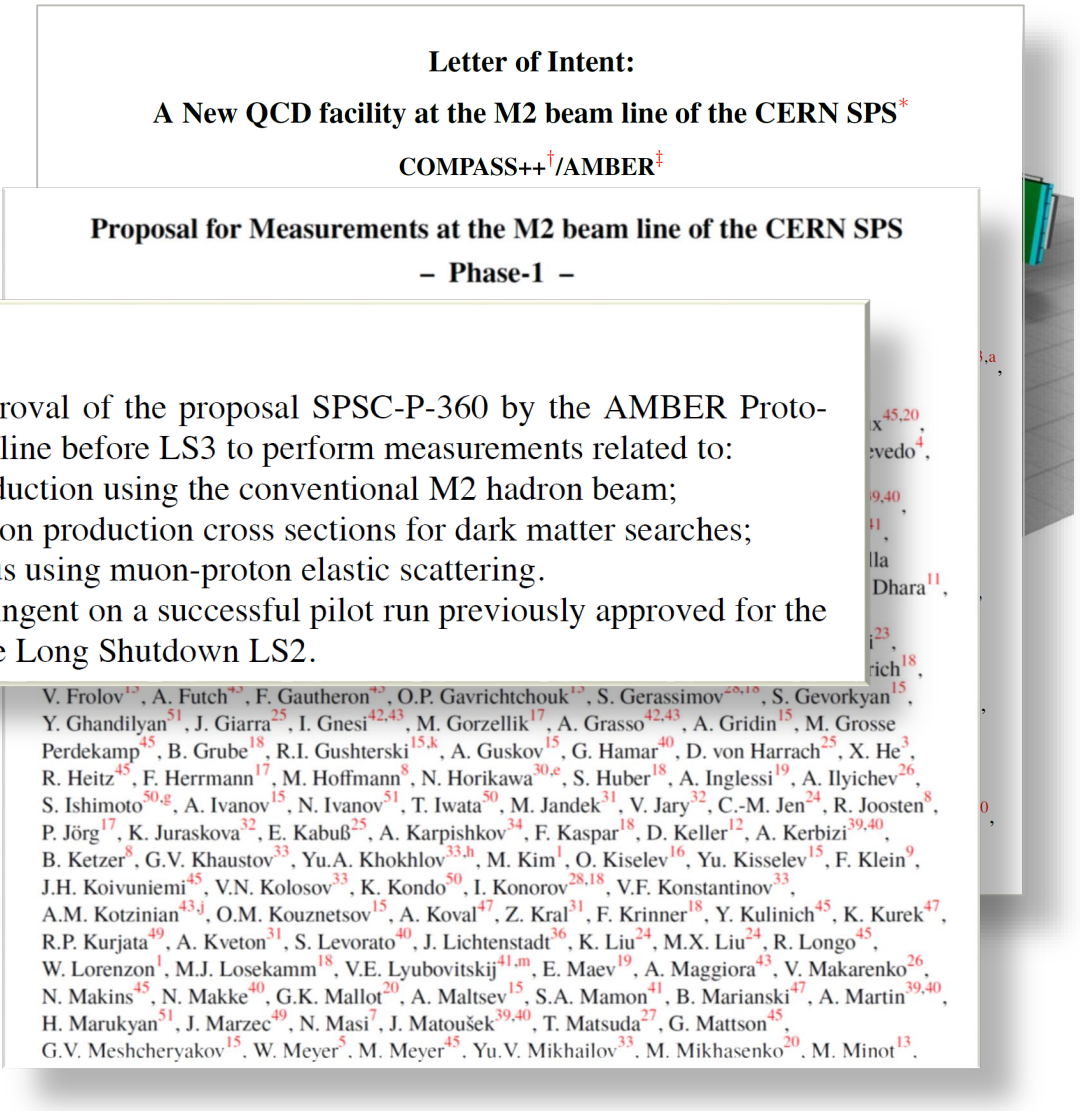
Apparatus for Meson and Baryon Experimental Research

- Successor experiment of COMPASS
- New groups (Yerivan, Bologna, Trento, Miyazaki, Chubu, Warsaw, Gatchina, Moscow, Samara, Cordoba, Michigan, Virginia, Argonne, Los Alamos, Stony Brook)
- LoI 2018: arXiv:1808.00848
- Extension and upgrade of spectrometer
- M2: most versatile beam line at CERN
- Conventional and RF-separated beams


Letter of Intent:

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

COMPASS++†/AMBER‡

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

– Phase-1 –

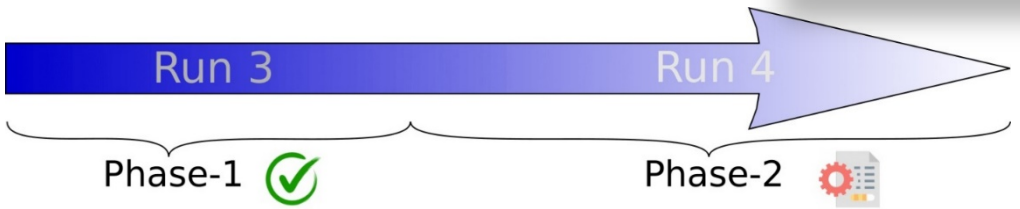
V. Frolov[15], A. Futch[42], F. Gautheron[42], O.P. Gavrichtchouk[15], S. Gerassimov[28,18], S. Gevorkyan[15], Y. Ghandilyan[51], J. Giarra[25], I. Gnesi[42,43], M. Gorzellik[17], A. Grasso[42,43], A. Gridin[15], M. Grosse Perdekamp[45], B. Grube[18], R.I. Gushterski[15,k], A. Guskov[15], G. Hamar[40], D. von Harrach[25], X. He[3], R. Heitz[45], F. Herrmann[17], M. Hoffmann[8], N. Horikawa[30,e], S. Huber[18], A. Inglessi[19], A. Ilyichev[26], S. Ishimoto[50,g], A. Ivanov[15], N. Ivanov[51], T. Iwata[50], M. Jandek[31], V. Jary[32], C.-M. Jen[24], R. Joosten[8], P. Jörg[17], K. Juraskova[32], E. Kabuß[25], A. Karpishkov[34], F. Kaspar[18], D. Keller[12], A. Kerbizi[39,40], B. Ketzer[8], G.V. Khaustov[33], Yu.A. Khokhlov[33,h], M. Kim[1], O. Kiselev[16], Yu. Kisselev[15], F. Klein[9], J.H. Koivuniemi[45], V.N. Kolosov[33], K. Kondo[50], I. Konorov[28,18], V.F. Konstantinov[33], A.M. Kotzinian[43,j], O.M. Kouznetsov[15], A. Koval[47], Z. Kral[31], F. Krinner[18], Y. Kulinich[45], K. Kurek[47], R.P. Kurjata[49], A. Kveton[31], S. Levorato[40], J. Lichtenstadt[36], K. Liu[24], M.X. Liu[24], R. Longo[45], W. Lorenzon[1], M.J. Losekamm[18], V.E. Lyubovitskij[41,m], E. Maev[19], A. Maggiora[43], V. Makarenko[26], N. Makins[45], N. Makke[40], G.K. Mallot[20], A. Maltsev[15], S.A. Mamon[41], B. Marianski[47], A. Martin[39,40], H. Marukyan[51], J. Marzec[49], N. Masi[7], J. Matoušek[39,40], T. Matsuda[27], G. Mattson[45], G.V. Meshcheryakov[15], W. Meyer[5], M. Meyer[45], Yu.V. Mikhailov[33], M. Mikhasenko[20], M. Minot[13],

SPSC 139, Oct. 2020

The Committee **recommends** approval of the proposal SPSC-P-360 by the AMBER Proto-Collaboration to use the M2 beam-line before LS3 to perform measurements related to:

(i) Drell-Yan and J/Psi production using the conventional M2 hadron beam;
(ii) proton-induced antiproton production cross sections for dark matter searches;
(iii) the proton charge radius using muon-proton elastic scattering.

The proton-radius program is contingent on a successful pilot run previously approved for the first year of SPS operation after the Long Shutdown LS2.



Phase-1 Proposal: CERN-SPSC-2019-022

- Submission 2019
- Approved as NA66 by the CERN Research Board in Dec 2020

Phase 2:

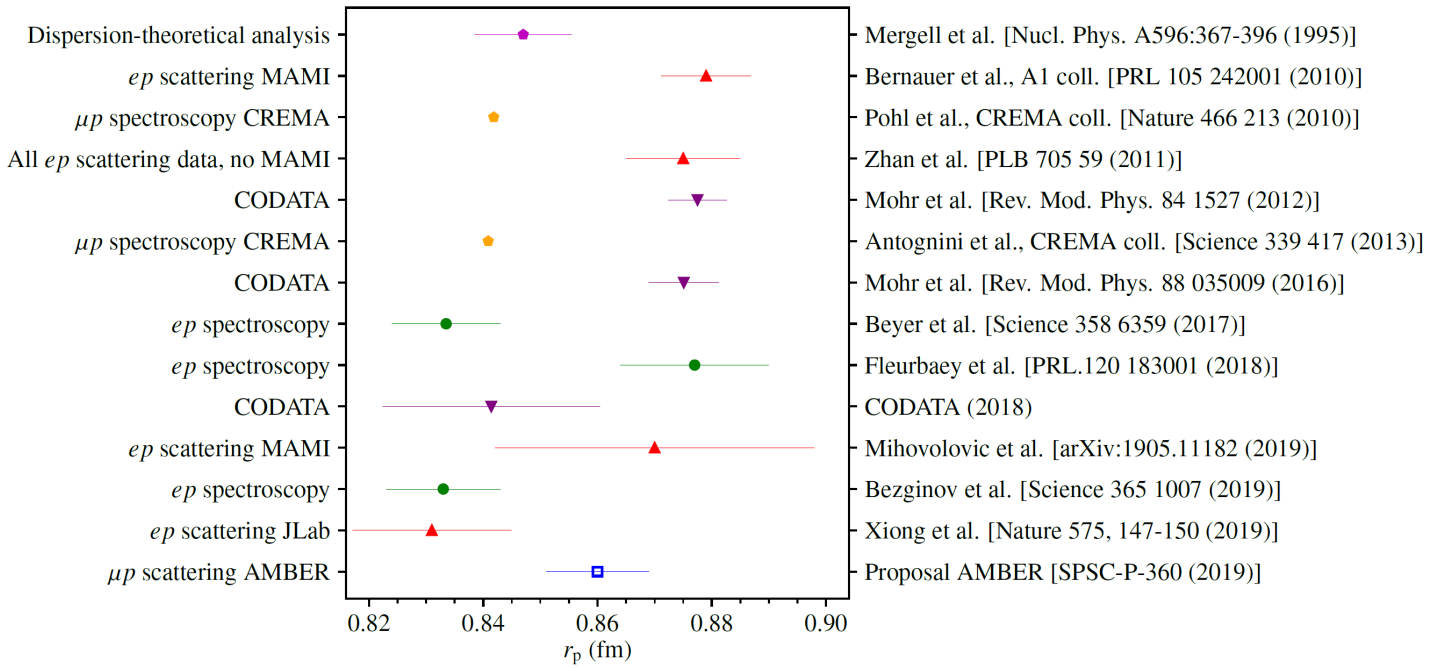
- Proposal submission planned for 2022

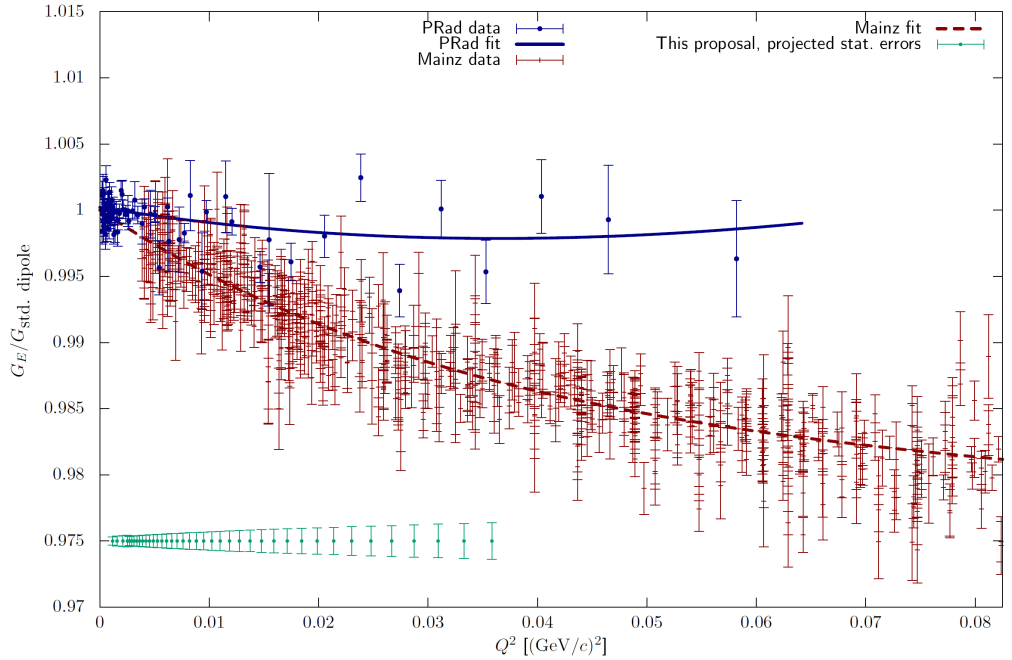
AMBER PHASE 1 – PROTON RADIUS

History:

- 2017: Initial proposal by German groups
- First discussion within COMPASS-II
- 2018: Feasibility test
- 2018: AMBER LoI ⇒ PBC
- 2019: AMBER Proposal ⇒ SPSC
- 2021: Pilot run

PROTON CHARGE RADIUS – STATUS



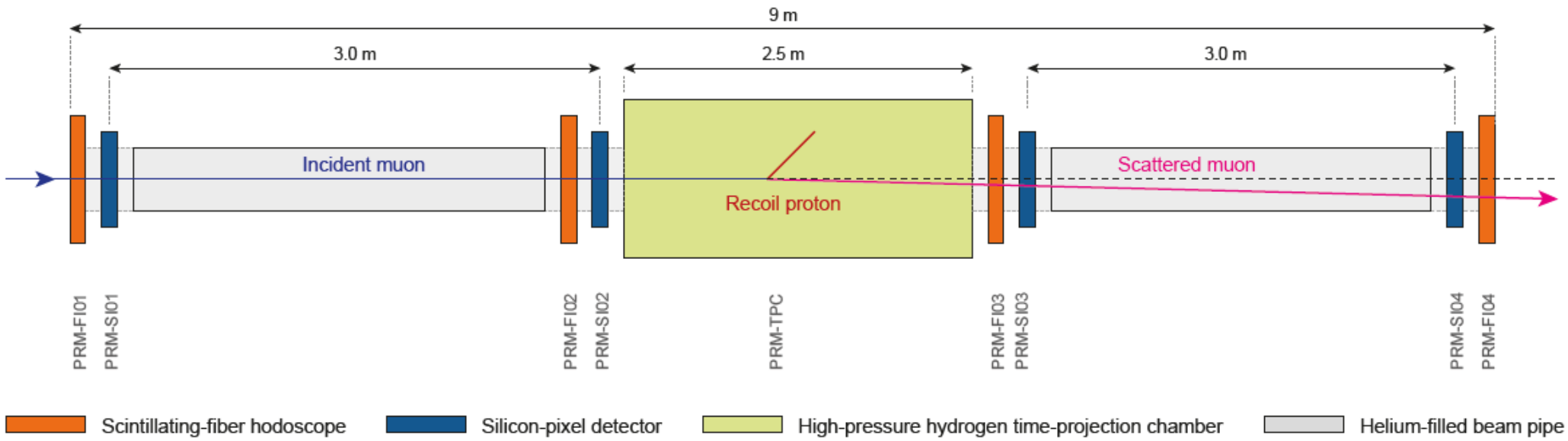


	ep	μp
Scattering	New measurements: • Lower systematics • Lower Q^2	Not measured yet • MUSE @ PSI • AMBER @ CERN
Spectroscopy	New measurements: • Lower systematics • New transitions	Done (CREMA)

Why μp scattering?

- different leptonic probe
- different systematic uncertainties
- much smaller radiative corrections than ep
- provide precise data for global fit

AMBER – MEASUREMENT OF PROTON RADIUS



Challenging measurement

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

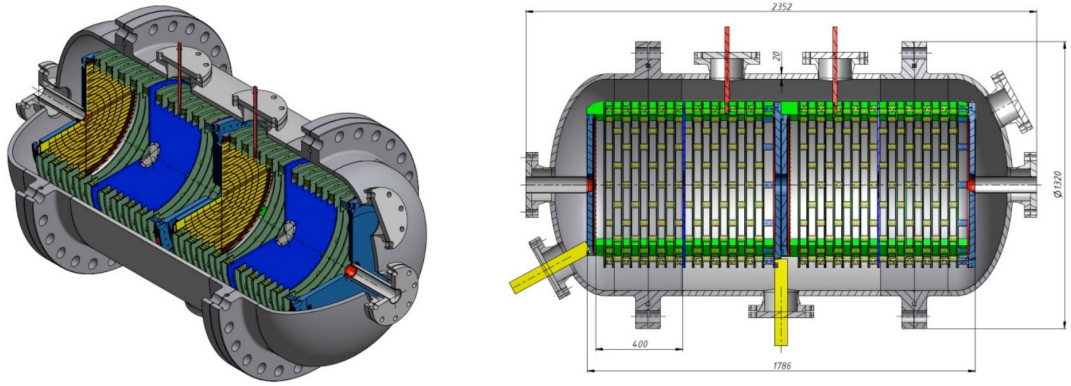


Figure 45: Engineering design for the four-cell hydrogen TPC.

AMBER – PROTON RADIUS PILOT RUN 2021

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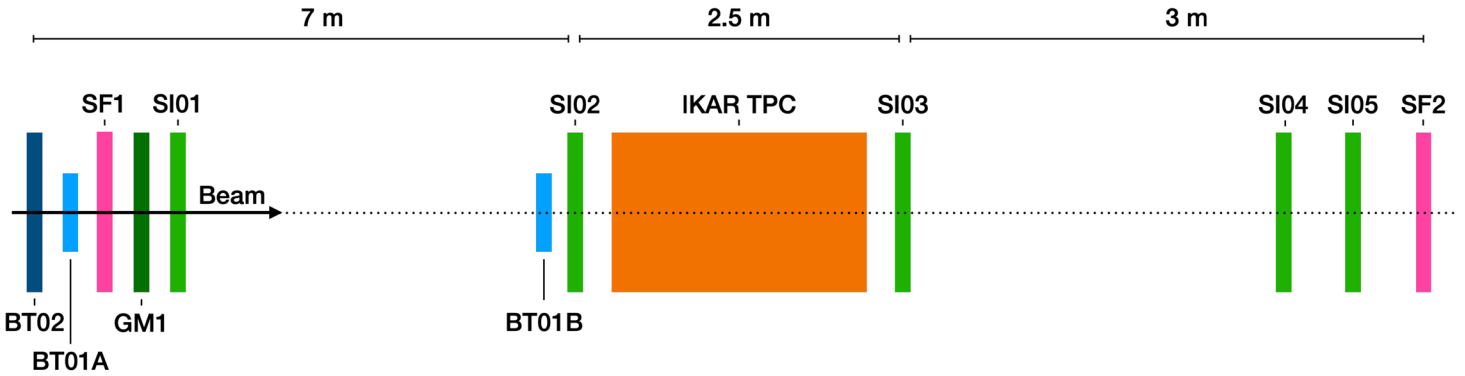
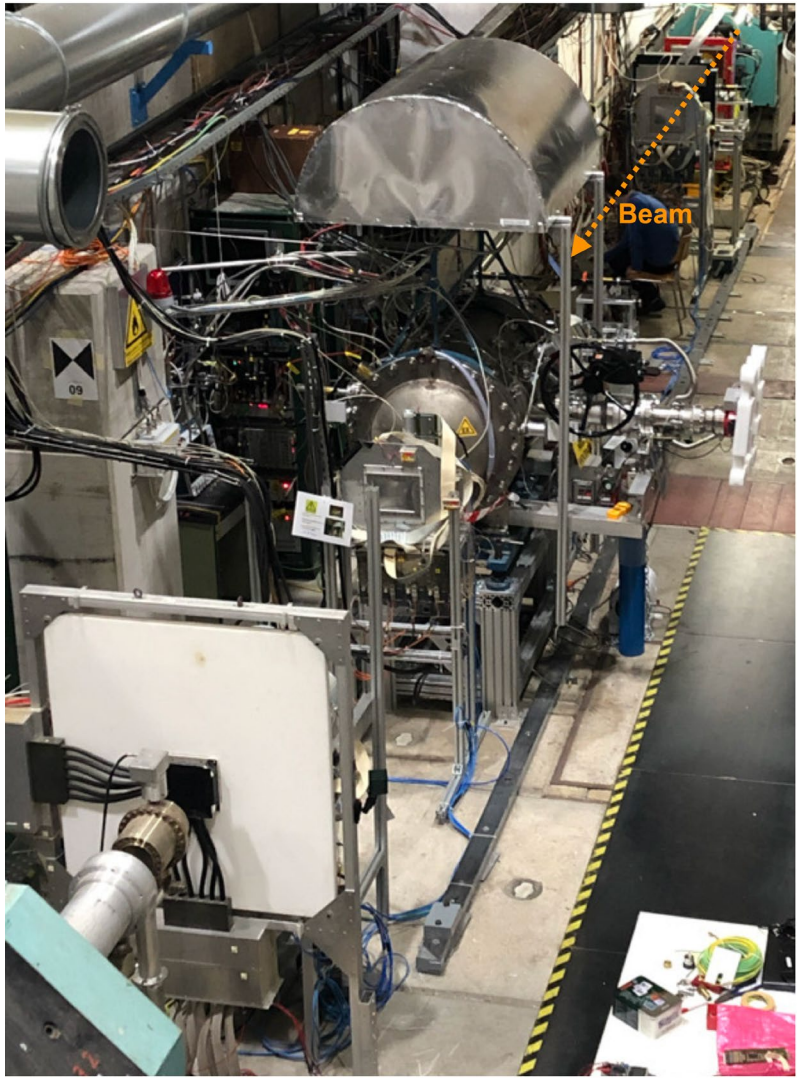
- Prerequisite for proton-radius physics run
- Took place from 6 - 27 Oct. 2021
- Goals:
  - ✓ – test high-pressure (8 bar) TPC prototype (IKAR) with high-intensity μ beam
  - ✓ – test target tracking system (existing Silicon strip + SciFi)
  - ✓ – test muon momentum reconstruction (only SM2)
  - ✓ – test Silicon Pixel detectors (ALPIDE) with self-triggering readout
  - ✓ – test GEM detector with self-triggering readout
  - – test AMBER DAQ ⇒ to be done during winter shutdown
  - – match muon and recoil proton tracks ⇒ analysis ongoing





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AMBER PHASE 1 – PION PDF

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PION STRUCTURE – CURRENT STATUS

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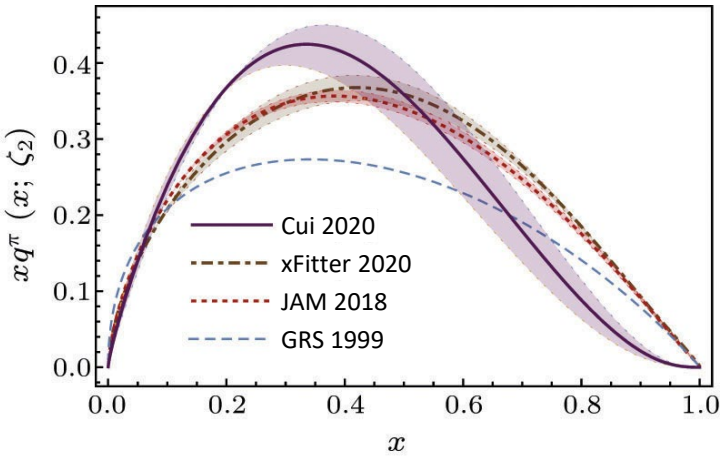
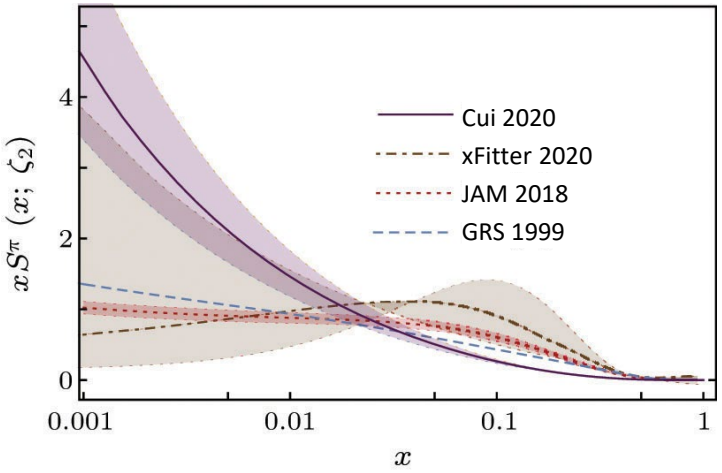
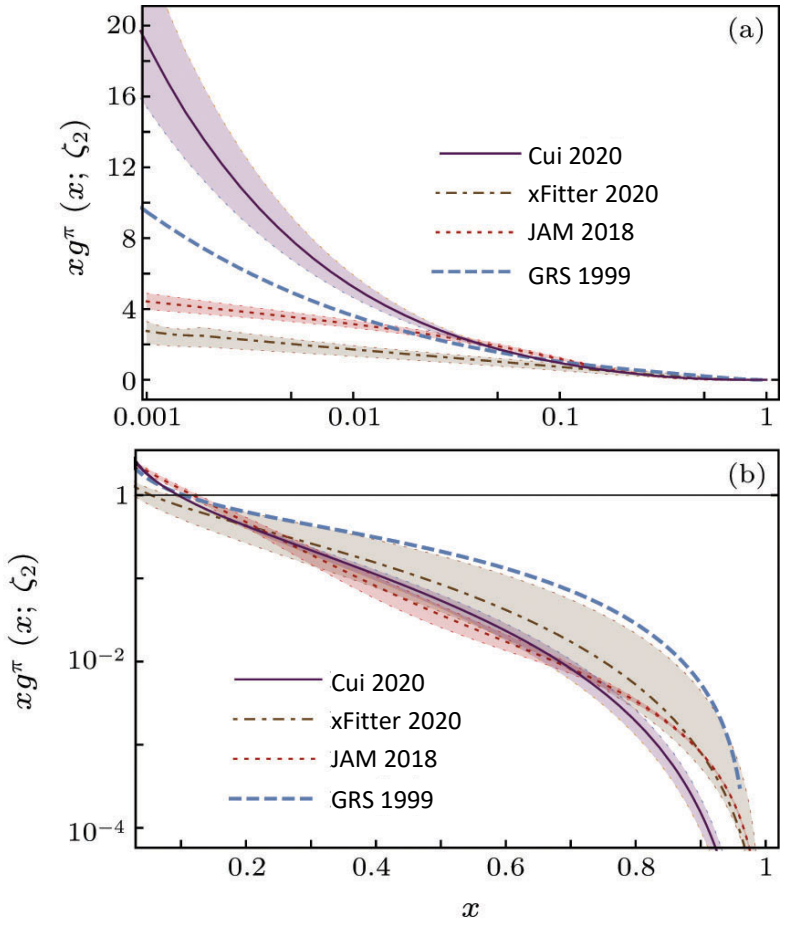
Valence quarks



Sea quarks



Gluons



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

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

PION VALENCE AND SEA QUARK PDFS AT AMBER

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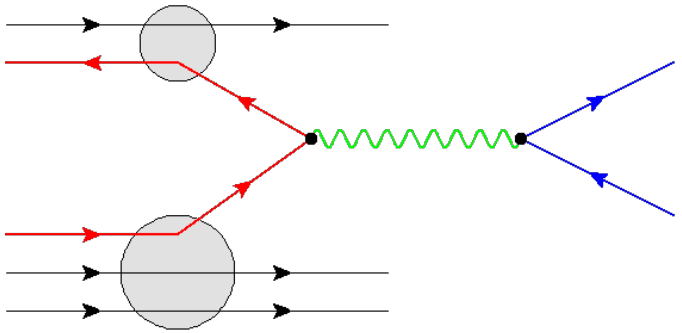
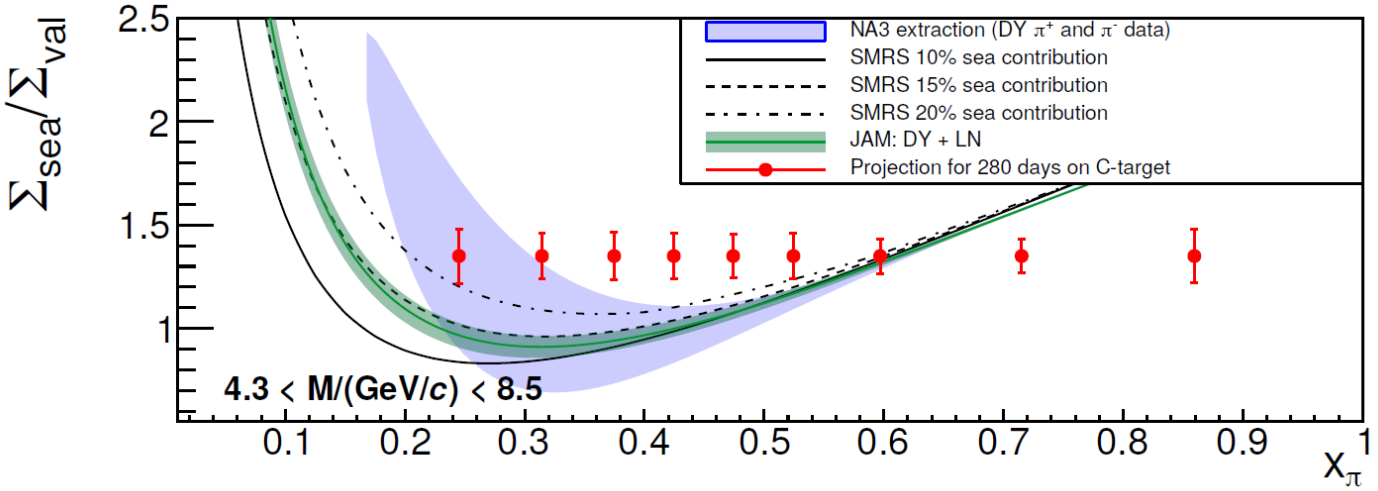
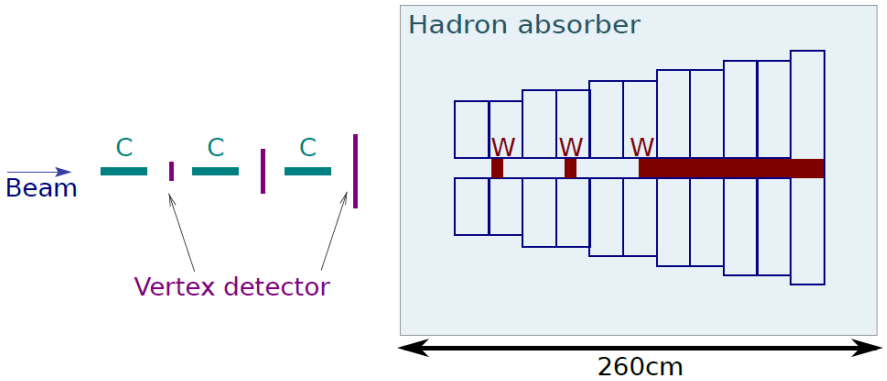




- Pion-induced Drell-Yan dimuon production
- Isoscalar ^{12}C target ⇒ minimize nuclear effects
- π^+ and π^- beams ⇒ separate valence and sea

$$\Sigma_{\text{val}} = -\sigma^{\pi^+} + \sigma^{\pi^-} \qquad \text{only valence-valence}$$

$$\Sigma_{\text{sea}} = 4\sigma^{\pi^+} - \sigma^{\pi^-} \qquad \text{sea-valence / valence-sea}$$



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

Goals:

- 10× more data than currently available (25k DY events)
- First precise and direct measurement of the sea quark distribution in the pion

Setup:

- 190 GeV π beam
- Dedicated target, vertex detector, hadron absorber
- Dimuon mass resolution ~ 100 MeV

PION GLUON PDF AT AMBER

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In parallel: study of J/ψ **production**: $\pi + A \to J/\psi + X$

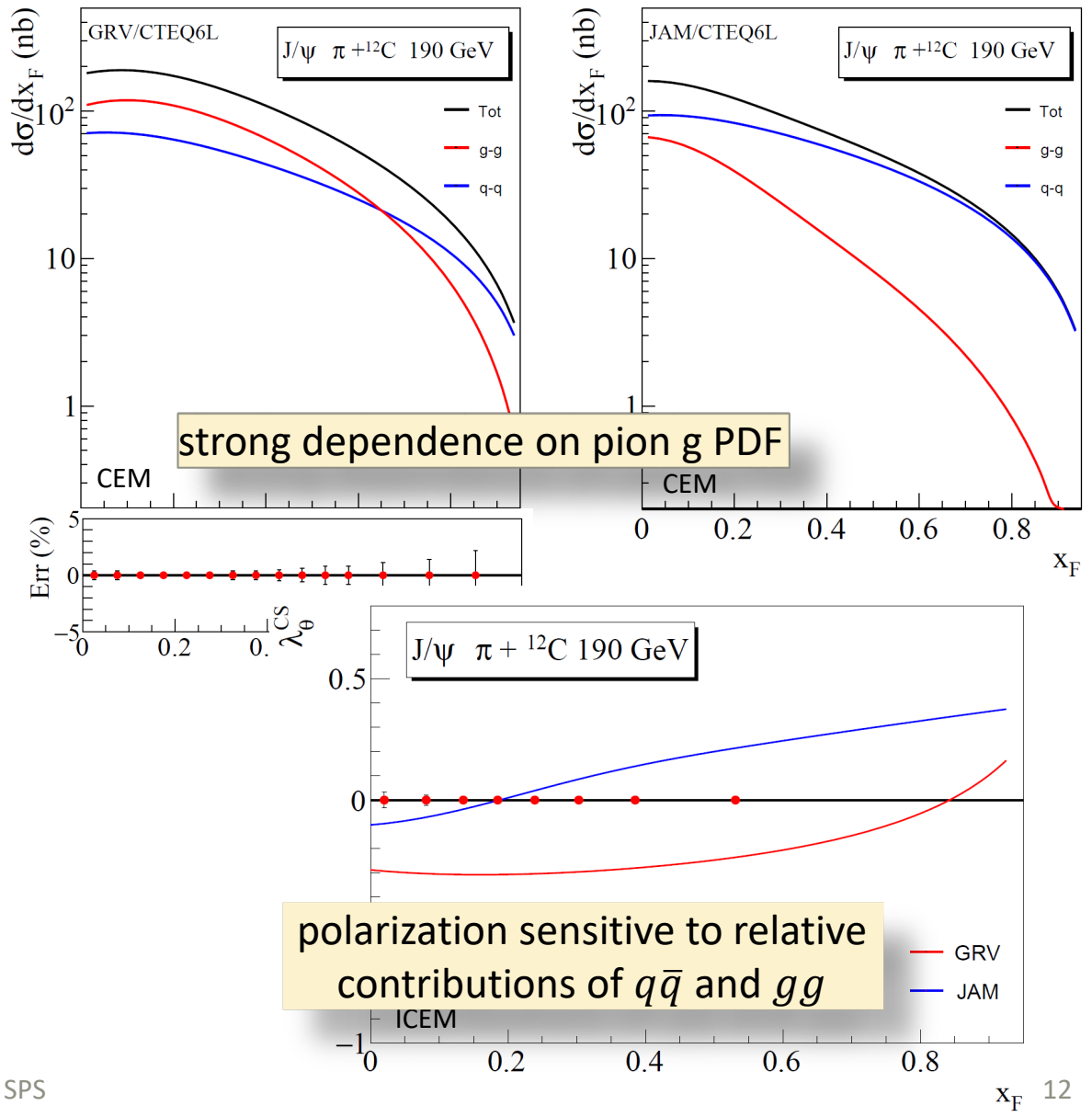
- Dominated by $q\bar{q}, gg \to J/\psi$ at low $p_T < M(J/\psi)$
  $\Rightarrow$ access to gluon PDF of pion
- Cross section 30-50 × larger than DY

  $\Rightarrow$ measure differential distributions with >1M ev.
- Measurement of (π^+, p) and π^-
- But: J/ψ production mechanism not well known at low p_T (CEM vs NRQCD)

Additional observable: J/ψ **polarization**

- $J^{PC} = 1^{--}, J_z = -1, 0, +1$
- Angular distribution $\dfrac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1 + \lambda \cos^2\theta$
  - $\lambda = +1 \Leftrightarrow J_z = \pm 1$ $\quad q\bar{q} \to J/\psi$
  - $\lambda = 0 \Leftrightarrow$ unpolarized
  - $\lambda = -1 \Leftrightarrow J_z = 0$ $\quad gg \to J/\psi$

[V. Cheung et al., PRD 98 (2018) 114029]



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AMBER PHASE 1 – ANTIPROTON PRODUCTION CROSS SECTION FOR DM SEARCHES

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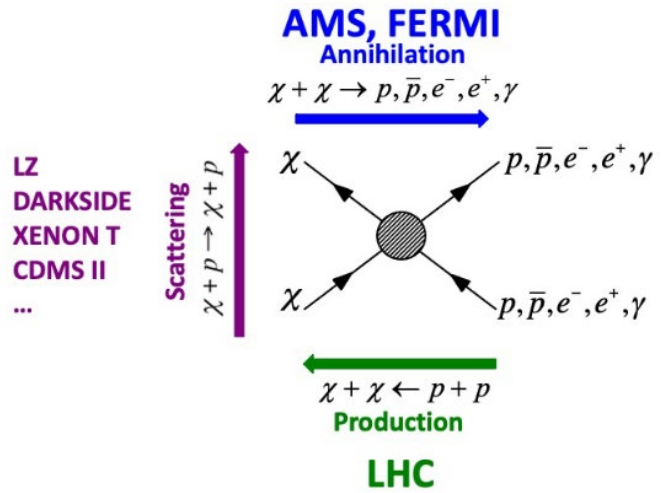
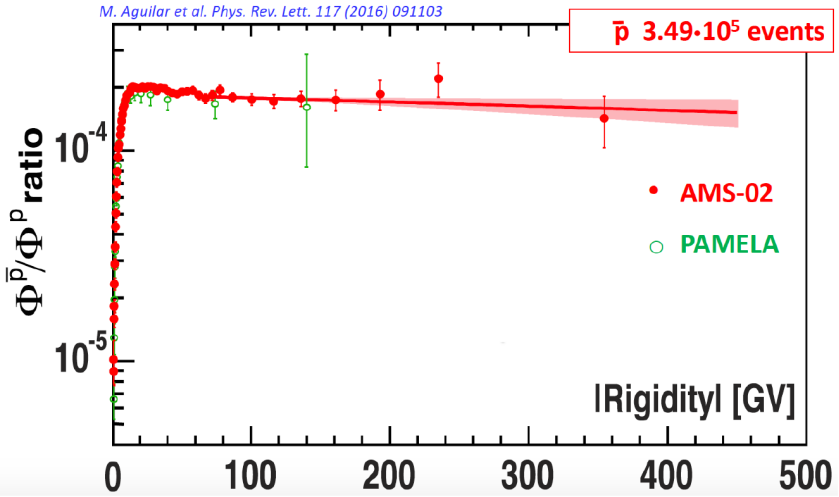
INDIRECT DM SEARCHES

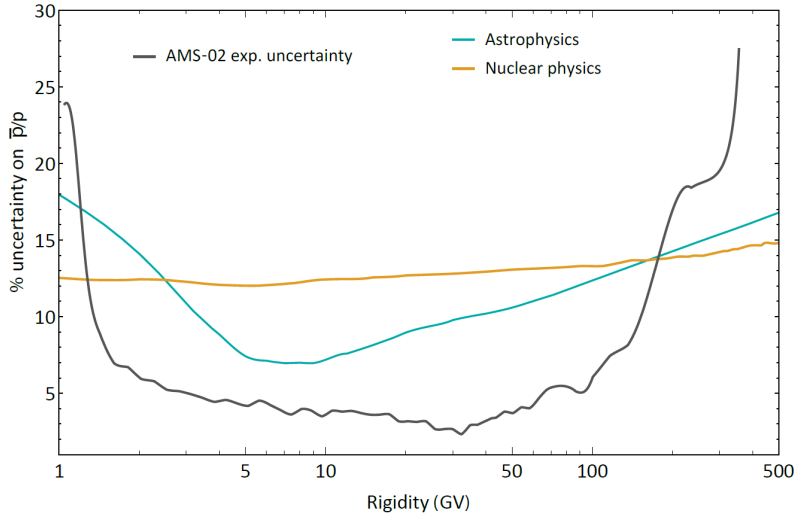
AMS-02:

- Precise data on cosmic antiparticle flux
- Sources: SM processes and DM annihilation

- Limiting factor: $\bar{p}$ production cross section uncertainties from collisions involving p and He (currently 30-50%!)
  - $p + p \rightarrow \bar{p} + X$ some measurements (NA49, NA61)
  - $p +^4 He \rightarrow \bar{p} + X$ only LHCb at 4 TeV and 6.5 TeV







ANTIPROTON PRODUCTION AT AMBER

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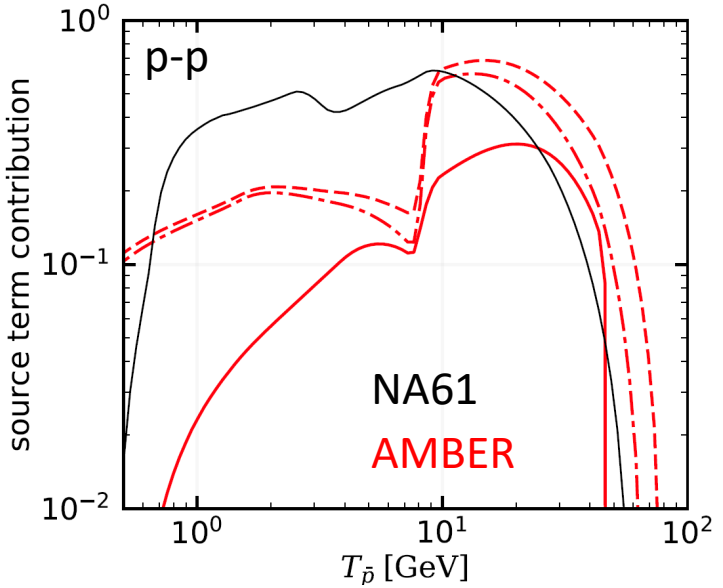
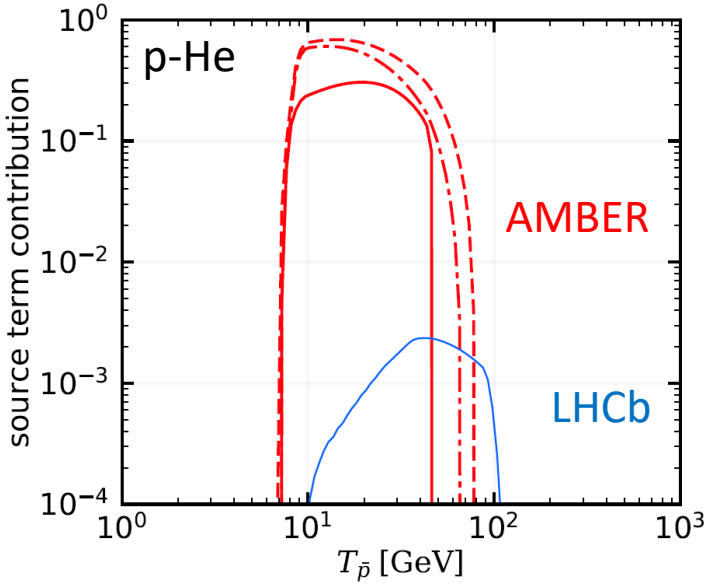
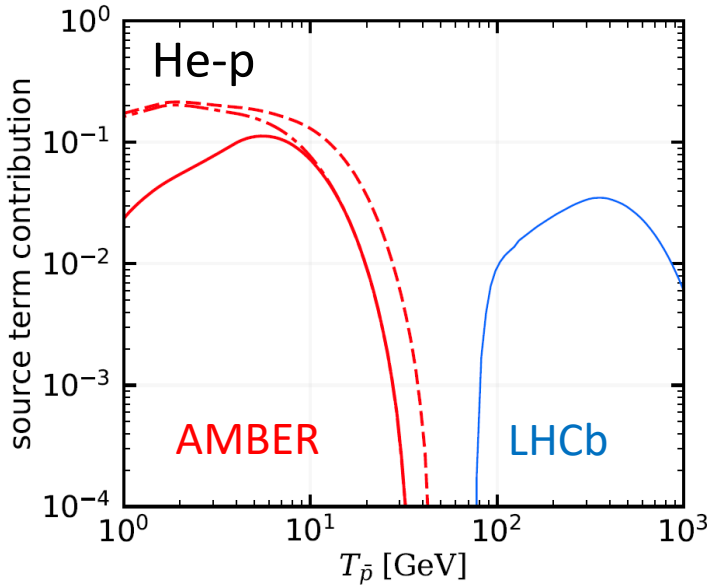
- Secondary p beam with 50, 100, 150, 200, 280 GeV
- Minimum bias trigger $\Rightarrow$ beam intensity of $5 \cdot 10^5\ s^{-1}$
- Liquid H2 and He target
- Proton ID in CEDARs, antiproton ID in RICH
- Measure differential cross section in 10 bins in $\bar{p}$ momentum and pseudo-rapidity $2.4 < \eta < 5.6$
- Statistical uncertainty $\approx 0.5 - 1\%$ per data point
- Total systematic uncertainty $\approx 5\%$ (efficiencies, dead time)



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





50-250 GeV
50-190 GeV
100-190 GeV

AMBER PHASE 1 - TIMELINE

Year	Activity	Duration	Beam
2021	Proton radius test measurement	20 days	μ
2022	Proton radius measurement	120 (+40) days	μ
	Antiproton production test measurement	10 days	p
2023	Antiproton production measurement	20(+10) days	p
	Proton radius measurement	140 (+10) days	μ
2024	Drell-Yan: pion PDFs and charmonium production	$\lesssim$ 2 years	p, K^+, π^+,
2024+	mechanism		$\bar{p}$, K^-, π^-

Conventional muon and hadron beams

2021 $\Rightarrow$ ~2028

NEW EQUIPMENT FOR PHASE 1

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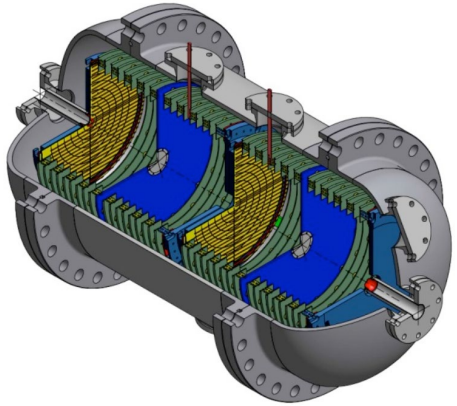
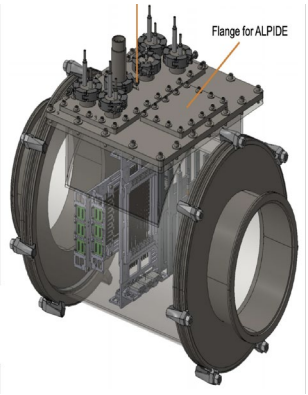
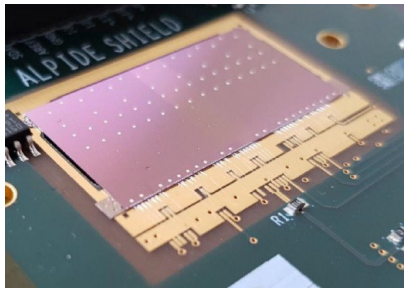
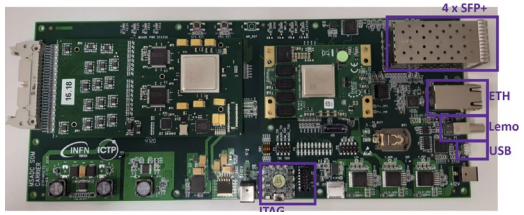
- Triggerless DAQ and HLT (Freiburg, Mainz, Munich, Prague, Tomsk, Warsaw)
- High-pressure hydrogen TPC (PNPI, GSI, Glasgow)
- C/W, LH2, LHe target (Lisbon, CERN, Prague, Virginia, Yamagata)
- PRM SciFi/Silicon Pixel tracking stations (Freiburg, Munich, Torino)
- DY vertex detector (Argonne, Illinois, Los Alamos, Torino)
- Large-area MPGD detectors with self-triggering readout (Bonn, CERN EP-DT, Torino, JINR)
- Self-triggered electronics for ECAL (Munich, Trieste, Warsaw)
- Upgrade CEDAR electronics for high rates (CERN, Warsaw)

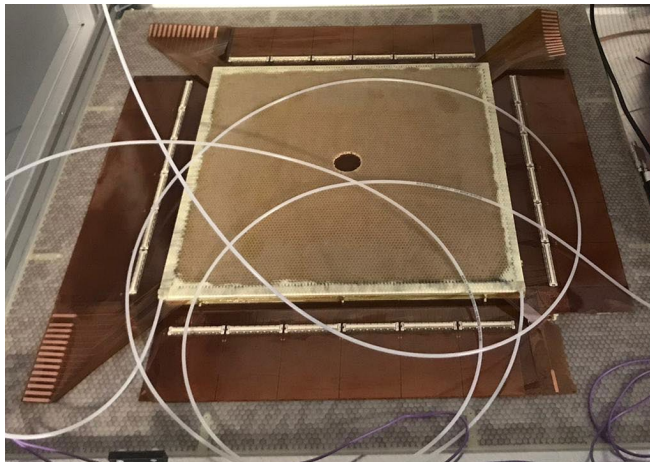


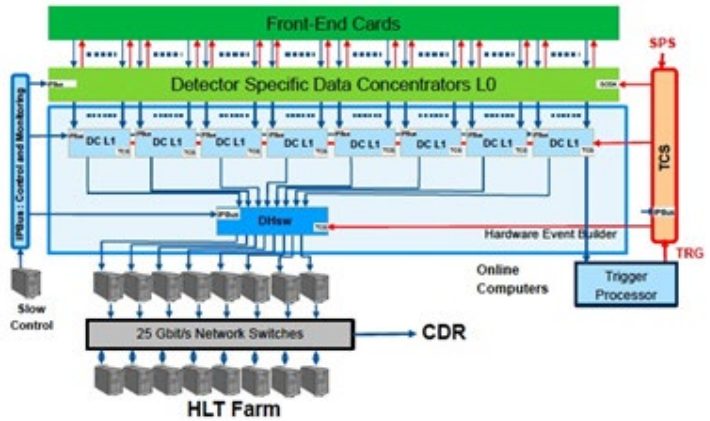




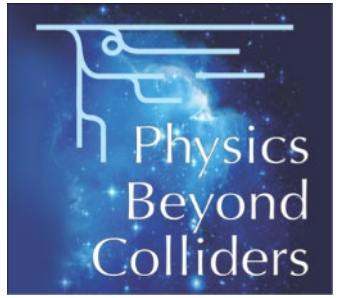
ECAL2 DAQ Hardware – Carrier Board III

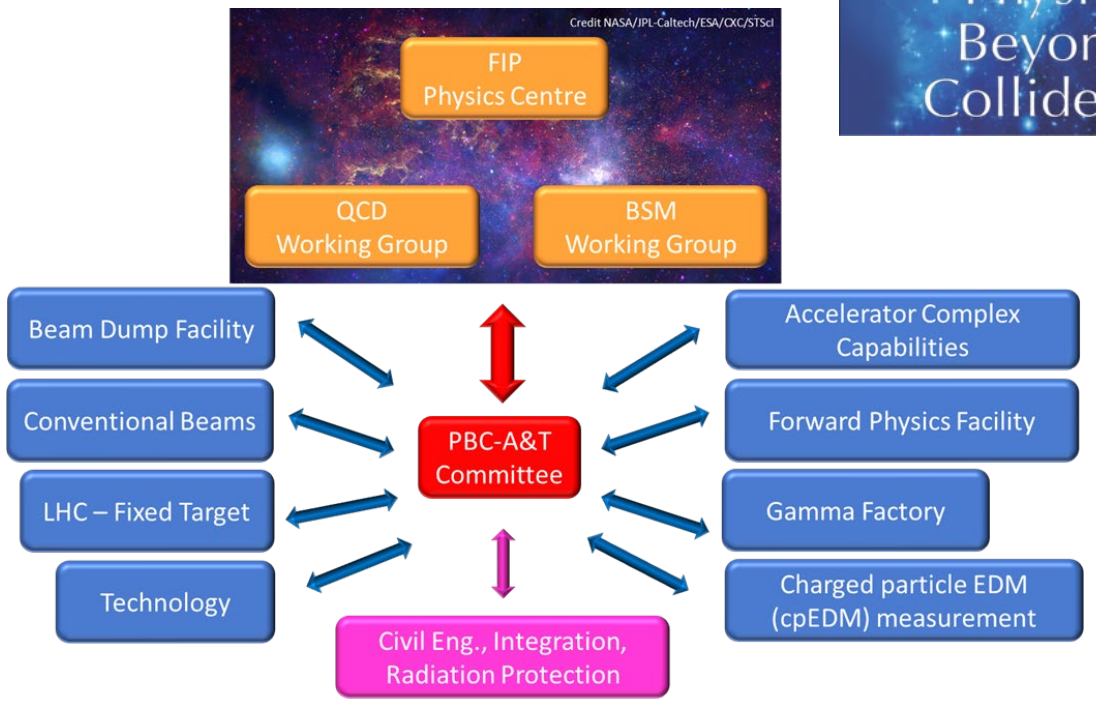






QCD INITIATIVES BEYOND RUN3





AMBER PHASE 2 – LOI

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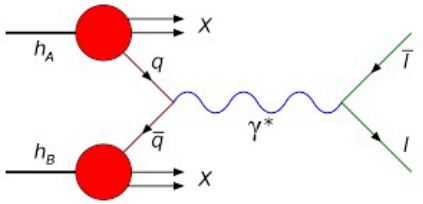
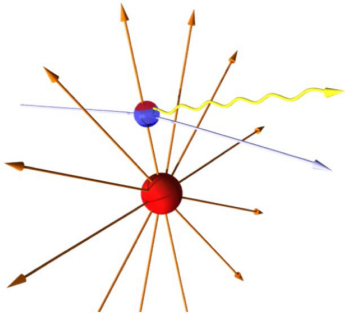
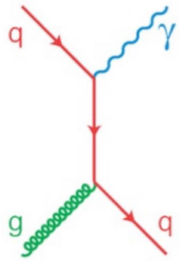
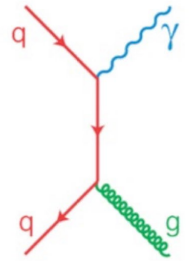
Conventional and RF-separated beams

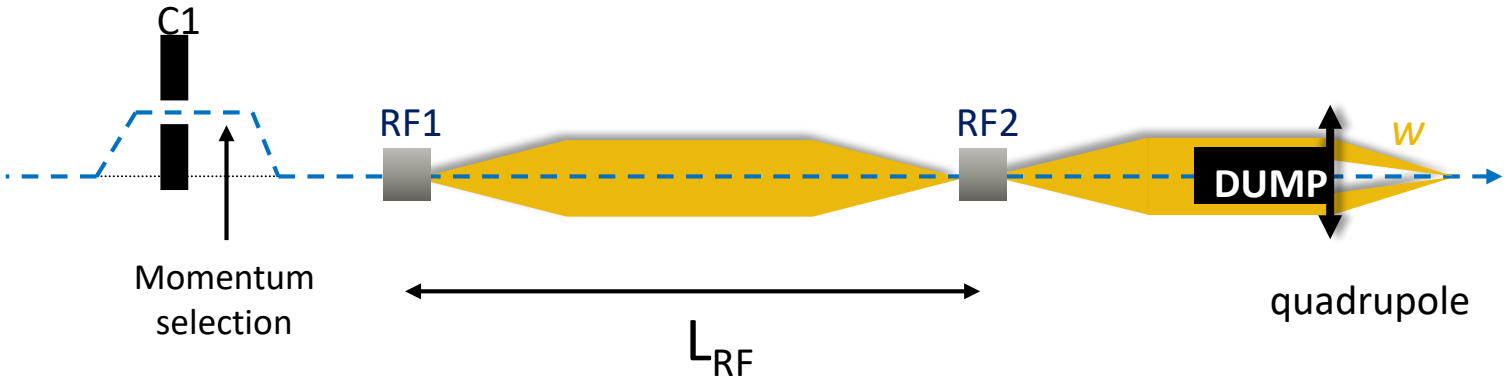
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	∼100	10^8	25-50	$K^{\pm}, \bar{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisability & pion life time	∼100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^{\pm}$ $\pi^{\pm}$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^{\pm}, \pi^{\pm}$	from H to Pb	2026 1 year	

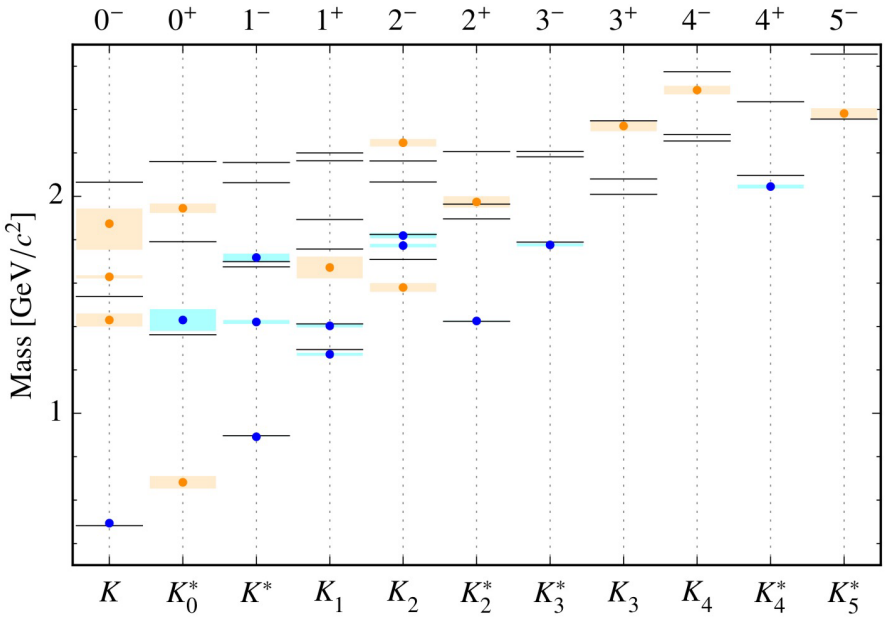












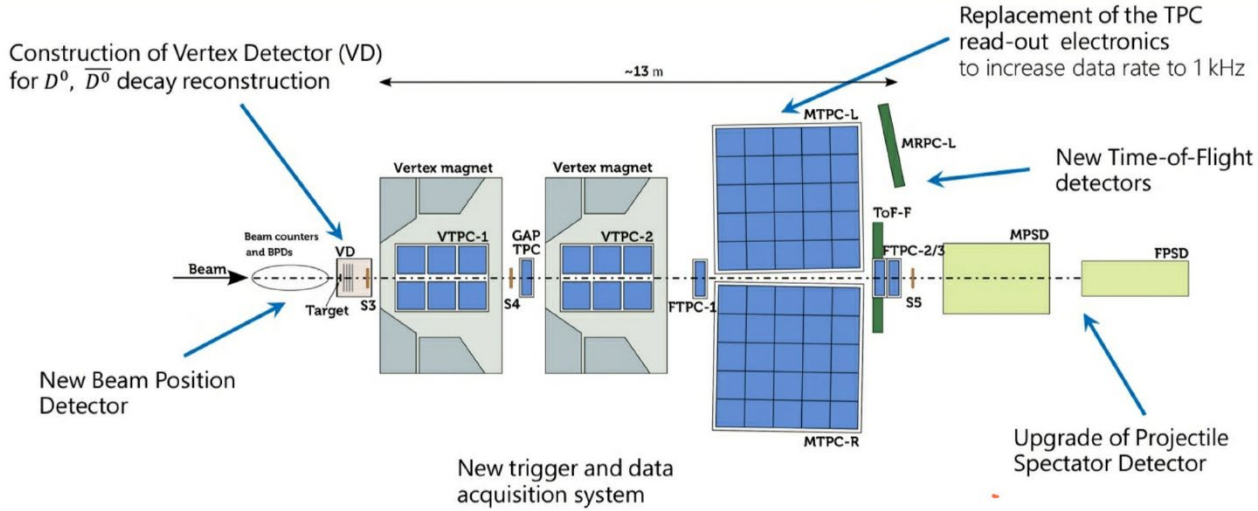
NA61++

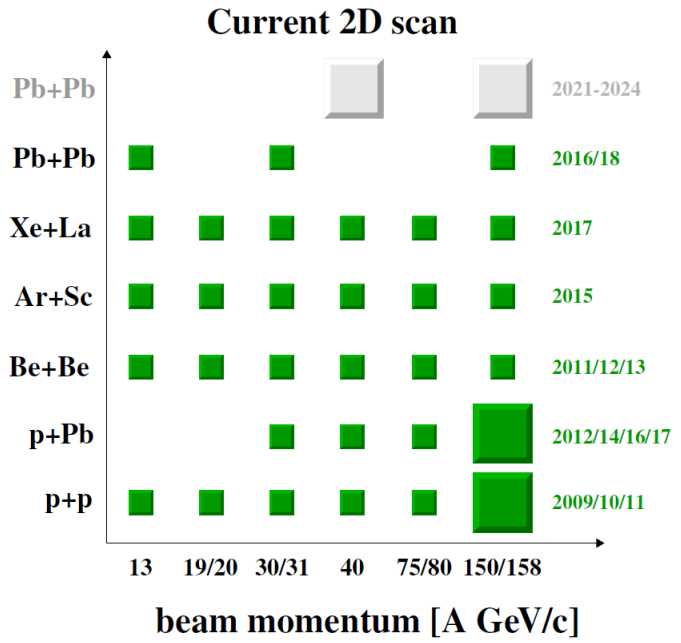
Run-3: NA61/SHINE

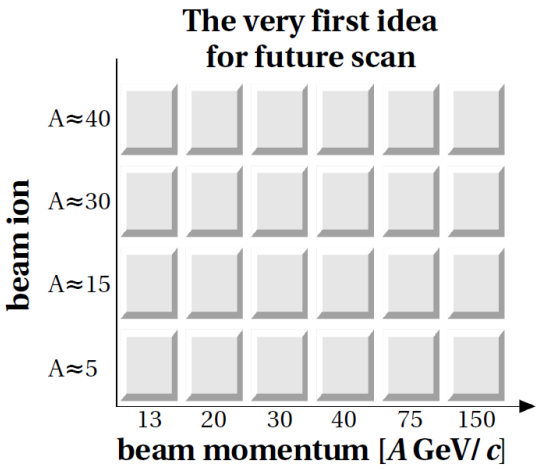
- Detector upgrades for direct open-charm measurements
- Search for critical point of strongly interacting matter
- Hadron measurements for ν and cosmic ray physics

Post-LS3: NA61++

- Fine-grained energy scan with light and medium-mass ions to study onset of fireball
- Measurements of heavy hadron resonances in p-p interactions
- Measurements of hadron emission from LBNF and Hyper-K replica targets
- Data for flux predictions in n experiments using very low-energy beams







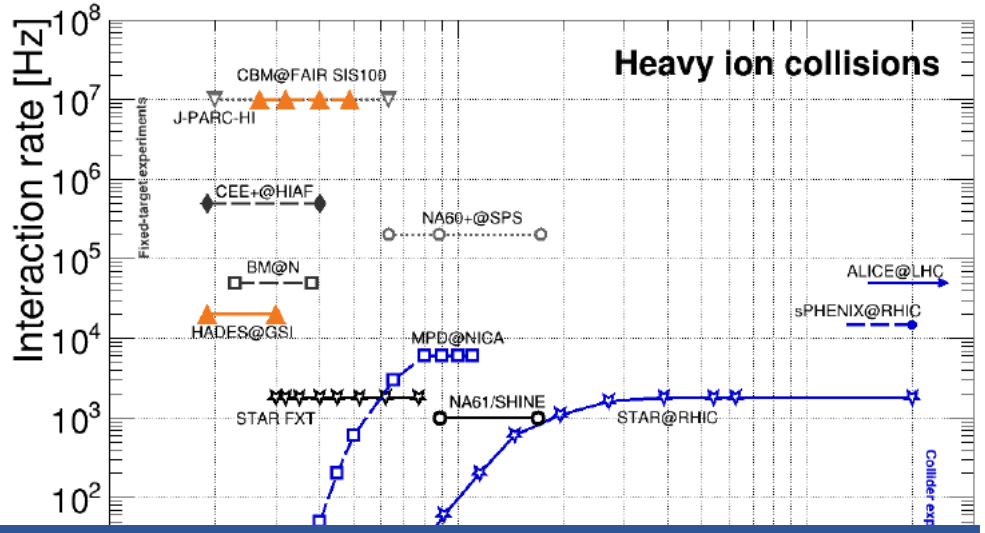
NA60++

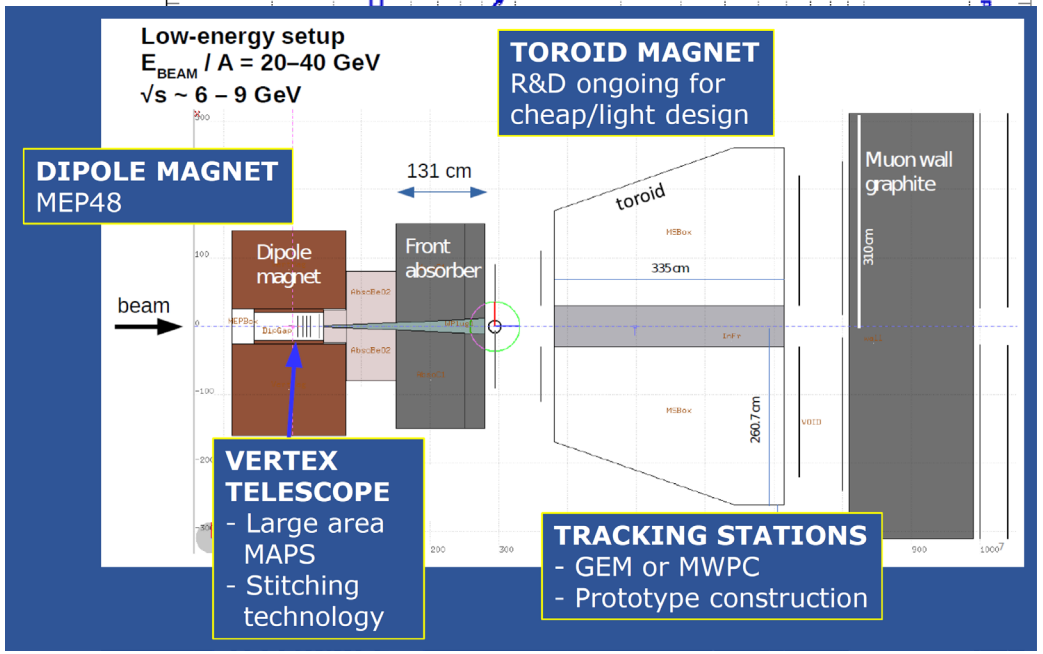
Study of hard and electromagnetic processes at SPS at high μ_B

- Thermal dimuons from QGP ⇒ caloric curve of 1st-order phase transition
- $\rho - a_1$ modifications ⇒ chiral symmetry restoration
- Quarkonium suppression ⇒ deconfinement
- Production of charmed hadrons ⇒ QGP transport properties
- Strangeness production ⇒ QGP chemistry

Setup:

- Cover wide range of collision energies (Pb-Pb, p-A)
- Large interaction rates ($> 10^5$ Hz)
- Varying length of muon spectrometer
- New location: EHN1 H8
  - ⇒ no conflict with NA62 in ECN3
  - ⇒ impact of reduced intensity being studied
- Detector R&D: synergies with HL-LHC
- Starting to draft LoI





[E. Scomparin, PBC workshop, Dec. 2021]

SUMMARY AND OUTLOOK

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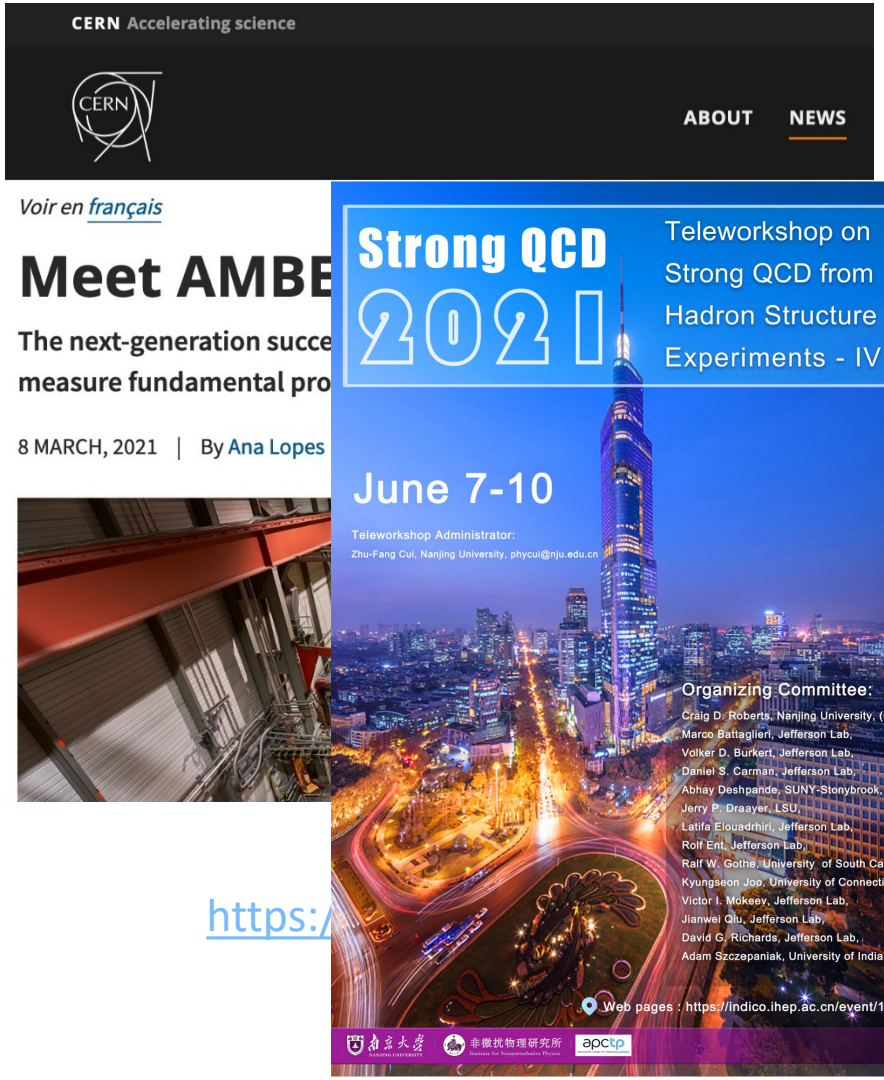
- **NA66/AMBER** is a new experiment at CERN dedicated to study fundamental questions related to the emergence of hadron properties from QCD
- **Phase 1 approved** by CERN
  - Proton radius with high-intensity muon beam
  - Pion PDFs in Drell-Yan processes
  - Antiproton-production cross sections for DM searches

- **New initiatives** on QCD-related measurements at SPS beyond LS3 being studied in the framework of PBC at CERN
  - **AMBER Phase 2**: kaon PDFs, strange spectroscopy, etc.
  - RF-separated beams to M2 $\Rightarrow$ worldwide unique facility
  - **NA60+, NA61+**: QCD phase diagram at high μ_B

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



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