Status and plans of the AMBER experiment

AMBER

NA66/AMBER (Apparatus for Meson and Baryon Experimental Research)

1. Intro AMBER
2. AMBER science questions
3. AMBER Phase-1
   - Proton Radius Measurement
   - Antimatter production cross section
   - Di-muon production measurement (Drell-Yan and J/Ψ)
4. Upgrades
5. Possible timeline
6. Proton Radius Measurement test run 2021
7. Summary

Oleg Denisov (INFN-Torino) on behalf of the AMBER collaboration, CERN SPSC meeting, CERN, 10/06/2021

AMBER
more than 10 years-long effort

We have started to work on physics program
of possible COMPASS successor > 10 years ago.

A Number of Workshops has been organized,
for detail see AMBER web page:

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

CERN Accelerating science   Signed in as: odenisov (CERN)   Sign out

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

HOME | DOCUMENTS | WORKSHOPS | TALKS | CHRONOLOGY | MEETING DATABASE | ORGANISATION | WIKI

Welcome

Over the past four decades, measurements at the external beam lines of the CERN Super Proton Synchrotron (SPS) have received worldwide attention. The experimental results have been challenging Quantum Chromodynamics (QCD) as our theory of the strong interactions, thus serving as important input to develop improvements of the theory. As of today, these beam lines remain mostly unique and bear great potential for significant future advancements in our understanding of hadronic matter.

In the context of the Physics-beyond-colliders (PBC) initiative at CERN, the COMPASS++/AMBER (proto-) collaboration proposes to establish a "New QCD facility at the M2 beam line of the CERN SPS". Such an unrivalled installation would make the experimental hall EHN2 the site for a great variety of measurements to address fundamental issues of QCD. The proposed measurements cover a wide range in the squared four-momentum transfer Q^2: from lowest values of Q^2 where we plan to measure the proton charge radius by elastic muon-proton scattering, over intermediate Q^2 where we plan to study the spectroscopy of mesons and baryons by using dedicated meson beams, to high Q^2 where we plan to study the structure of mesons and baryons via the Drell-Yan process and eventually address the fundamental quest on the emergence of hadronic mass arxiv:1606.03909[nucl-th], arXiv:1905.05208[nucl-th].

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–003
SPSC-I-250
January 25, 2019

LoI submitted in January 2019
http://arxiv.org/abs/1808.00848
Apparatus for Meson and Baryon Experimental Research
> 270 authors

Letter of Intent:

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

COMPASS++†/AMBER‡

B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

AMBER science questions

There are two bearing columns of the facility:

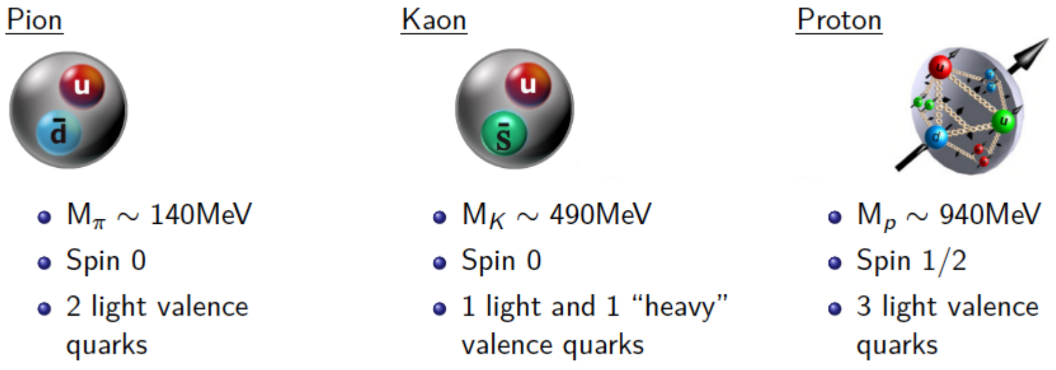
1. **Phenomenon of the Emergence of the Hadron Mass**
2. Proton spin (largely addressed by COMPASS and others, Phase-2)

How does all the visible matter in the universe come about and what defines its mass scale?

Great discovery of the Higgs-boson unfortunately does not help to answer this question, because:

✓ The Higgs-boson mechanism produces only a small fraction of all visible mass

✓ The Higgs-generated mass scales explain neither the “huge” proton mass nor the ‘nearly-masslessness’ of the pion



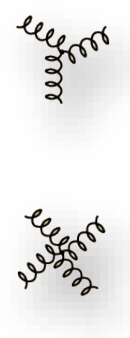
Higgs generated masses of the valence quarks:

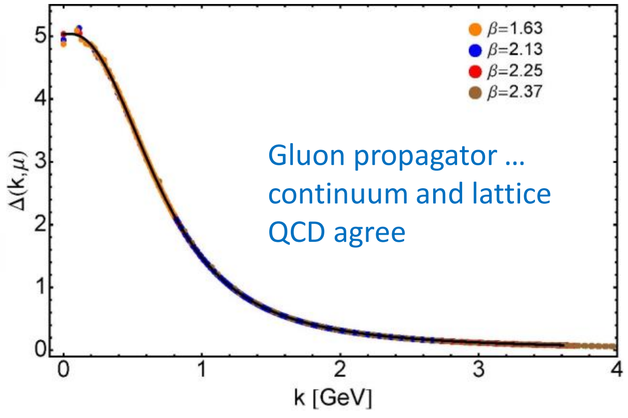
$M_{(u+d)}$~7 MeV $M_{(u+s)}$~100 MeV $M_{(u+u+d)}$~10 MeV

As Higgs mechanism produces a few percent of visible mass, Where does the rest comes from (EHM phenomenon)?

EHM phenomenon
What are the underlying mechanisms?

Intuitively one can expect that the answer to the question lies within SM, in particular within QCD. Why? Because of the dynamical mass generation in continuum QCD.

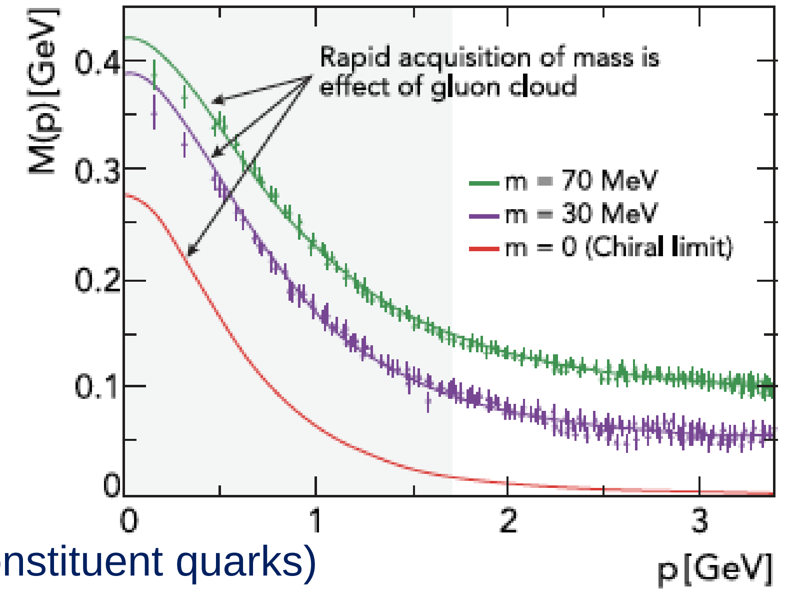




Truly "mass from nothing" phenomenon: Initially massless gluon produces dressed gluon fields which "generates" mass function that is large at infrared momenta

Dynamical mass generation in continuum quantum chromodynamics
J.M. Cornwall, Phys. Rev. D ***26*** ***(****1981) 1453*
… ~ 1000 citations

As quark can emit and absorb gluons It acquires its mass in infrared region because of the gluon "self-mass-generation" mechanism, so the visible (or emergent) mass of hadrons must be dominated by gluon component



(Constituent quarks)

Dressed-quark mass function M(p)

In order to "prove" that QCD underlies the EHM phenomenon we have to compare Lattice and Continuum QCD calculations with experimental data by measuring:

1. Quark and Gluon PDFs of the pion/kaon/proton
2. Hadron's radii (confinement)
3. Excited-meson spectra

EHM phenomenon

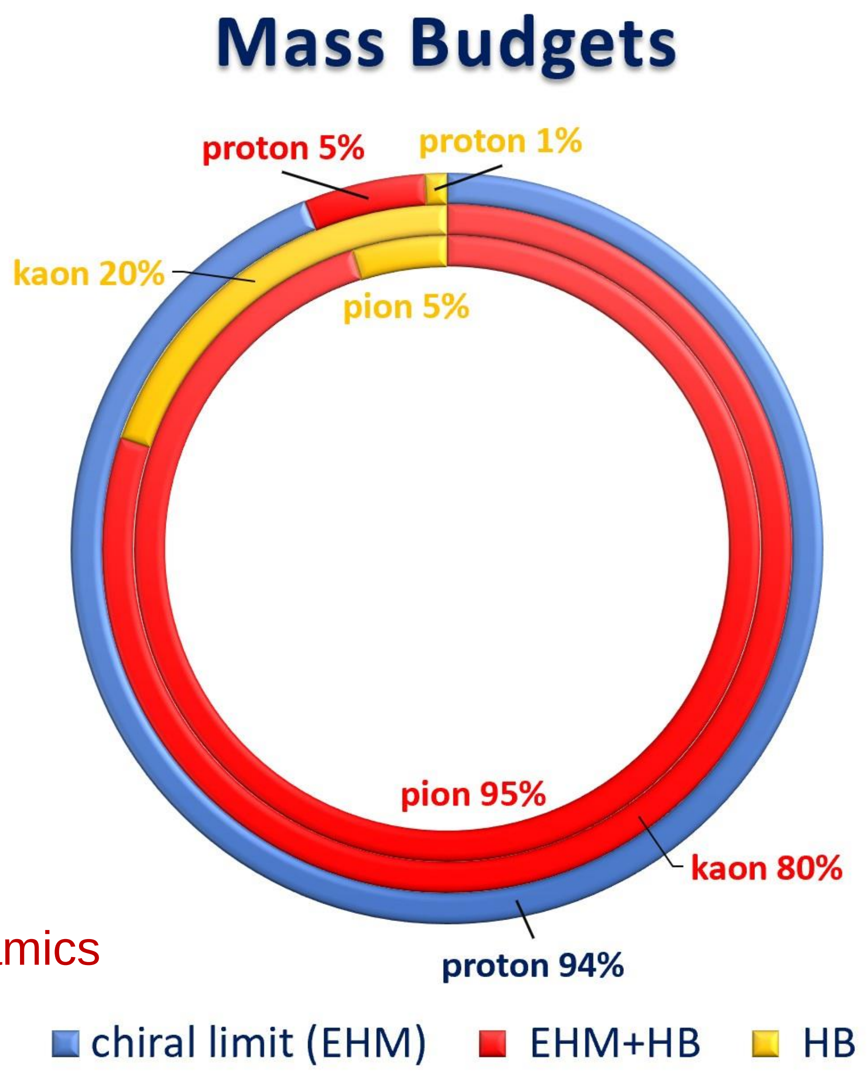
Is it enough to study the proton to understand SM?

The answer is obviously NOT (SM paradigm):

- proton is described by QCD … 3 valence quarks
- pion is also described by QCD … 1 valence quark and 1 valence antiquark
- expect $m_p \approx 1.5 \times m_\pi$ … but, instead $m_p \approx 7 \times m_\pi$

Proton and pion/kaon difference:

- In the chiral limit the mass of the proton remains basically the same
- Chiral limit mass of pion and kaon is “0” by definition (Nambu-Goldstone bosons)
- Different gluon content expected for pion and kaon
- Contribution from interplay with Higgs mechanism is different



Thus it is equally important to study the internal structure and dynamics of pions, kaons and protons

AMBER physics program

AMBER

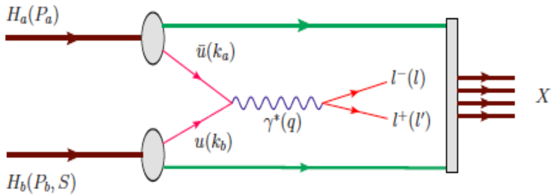
Questions to be answered:

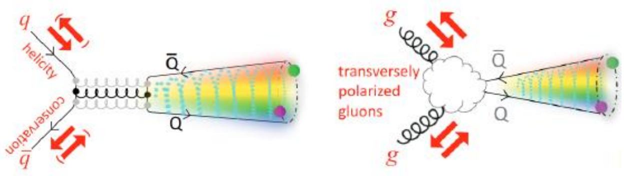
- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass .vs. Higgs)
- Internal quark-gluon structure and dynamics, especially important pion/kaon/proton striking differences

A series of workshops entitled "Perceiving of the EHM through AMBER@CERN(SPS)": **https://indico.cern.ch/event/1021402/**

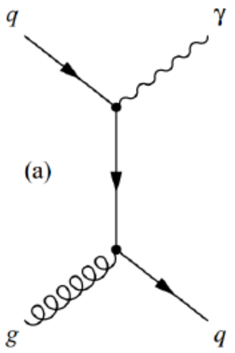
Methods:

Drell-Yan and J/Ψ

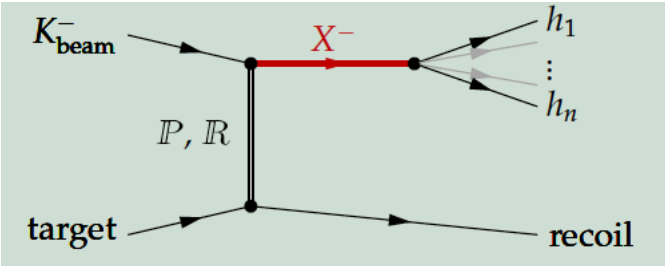


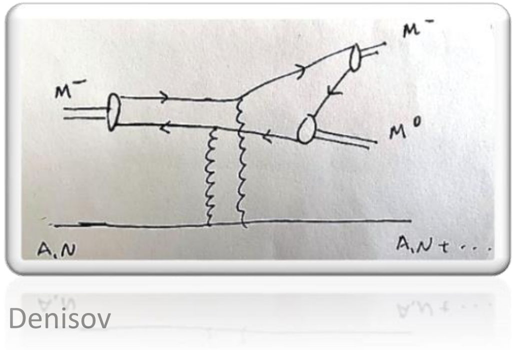


Prompt Photon Production

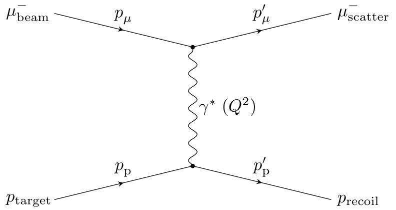


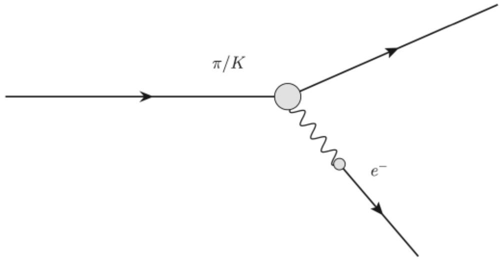
Diffractive scattering





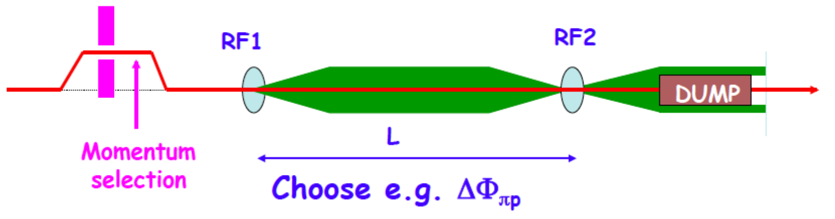
Elastic scattering



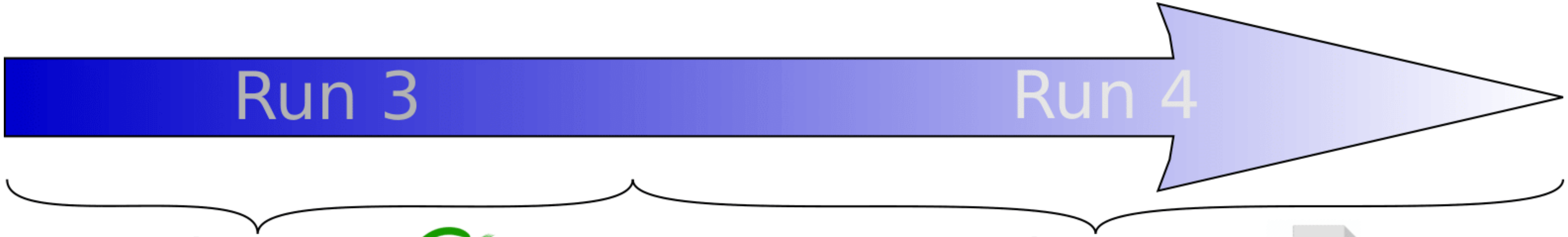


General AMBER timeline

Conventional muon/hadron M2 beams



$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$



Phase-1

Proton Radius Measurement
Antimatter production cross section
Pion structure (PDFs) via DY and charmonia

Phase-2

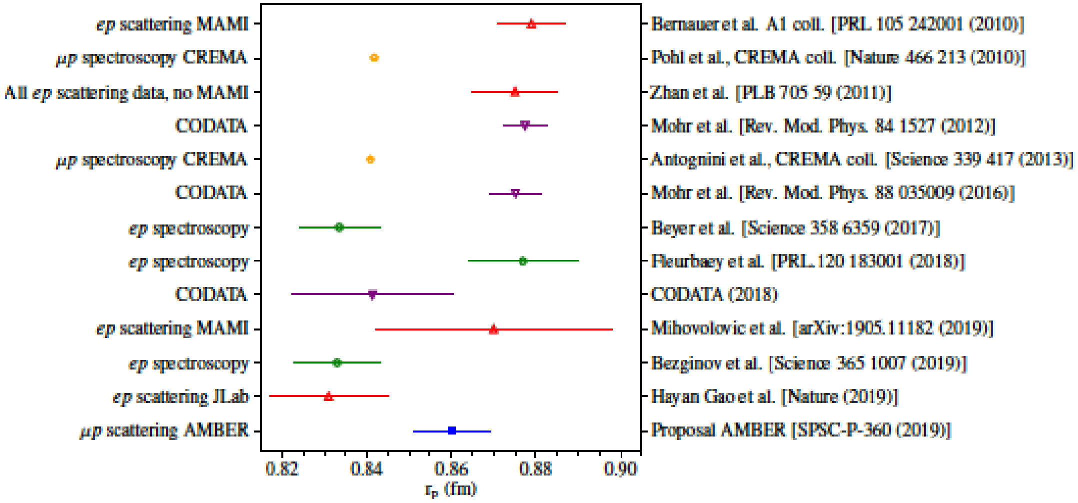
Kaon and pion structure (PDFs and PDAs)
High precision strange-meson spectrum
Kaon and pion charge radius
Kaon induced Primakoff reaction

Phase-1 Proposal approved by RB on 02/12/2020

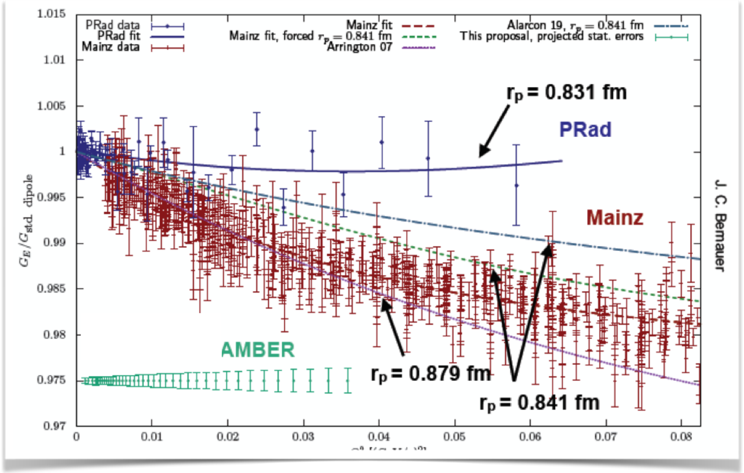
Phase-2 Proposal submission in the beginning of 2022

Proton Radius Measurement at AMBER (confinement)

AMBER



	ep	μp
Spectroscopy	New measurements with ▪ lower systematics ▪ new transitions	✔
Scattering	New measurements with ▪ lower systematics ▪ reaching lower Q^2 ProRAD, ULQ2, ISR @ MESA, PRad	No data yet. MUSE at PSI coming soon AMBER



statistical precision of the proposed measurement, down to Q^2 = 0,001 GeV^2/c^2, Cross section is normalised to the G_D - dipole form factor

$$< r_p^2 > = -6\hbar^2 \cdot \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2\to 0}$$

$$\frac{d\sigma^{\mu p\to\mu p}}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}R\left(\epsilon G_E^2 + \tau G_M^2\right) \qquad \epsilon = \frac{E_\mu^2 - \tau\left(s - m_\mu^2\right)}{\vec{p}_\mu^{\,2} - \tau\left(s - 2m_p^2(1+\tau)\right)} \qquad \tau = \frac{Q^2}{(4m_p^2)}$$

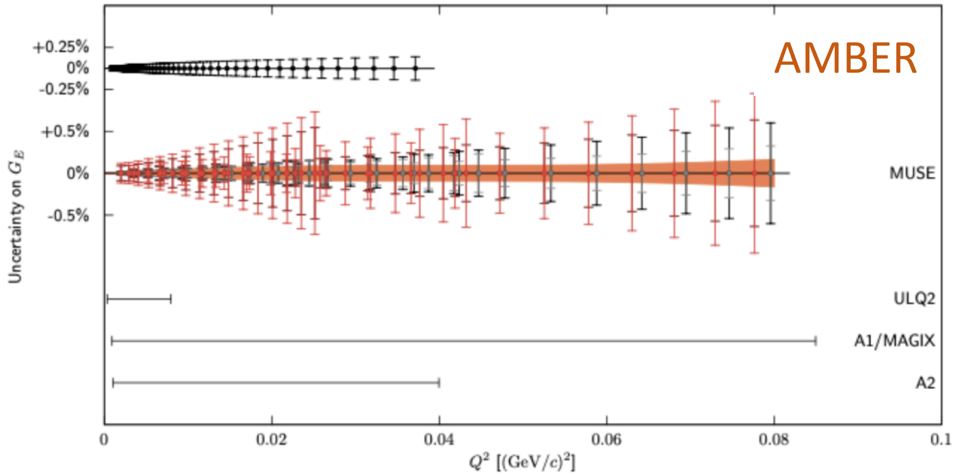
- Suppress magnetic form factor G_M^2
  - → Requires $\tau \to 0$
  - → Measurement at low-Q^2 values of $\mathcal{O}(<10^{-2})$
- Measurement at high-energy $\mathcal{O}$(10 - 100 GeV)
  - → Results in $\varepsilon \to 1$
  - → Cross-section directly proportional to G_E^2

Proton Radius Measurement at AMBER (confinement)

- A number of experiments is on the way in different laboratories
- There is a synergy between PRES at MAMI (E_e = 720 *MeV*) and AMBER ($E_\mu = 100\ GeV$):
  - The same type of active target (hydrogen filled TPC) will be used for both experiment
  - The same Q^2 range will be covered (10^{-3} - $4x10^{-2}$ GeV^2)
  - Mutual calibration of the transferred momentum
- Significant advantage of the AMBER measurement is much lower radiative corrections: for soft bremsstrahlung photon energy $E\gamma/E_{beam}$ ~ 0.01 QED corrections amount to ~15-20% for electrons and to ~1.5% for muons (AMBER will be able to make a control measurement with Electromagnetic Calorimeters).

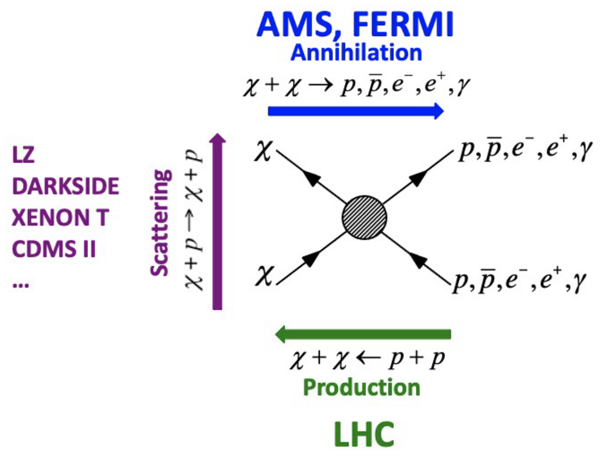
If compared to the muon scattering experiment at PSI (MUSE):

- Much cleaner experimental conditions (pure muon beam with less than 10^{-6} admixture of hadrons)
- Much higher beam momentum, thus contribution from magnetic form factor is suppressed (0.1-0.2 *GeV/c* vs 100 *GeV/c*)
- Small statistical errors achievable with the proposed running time

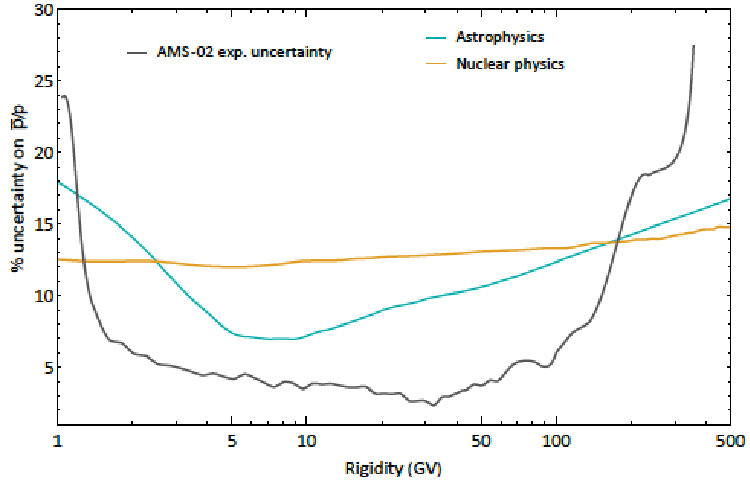


AMBER: Search for Dark Matter

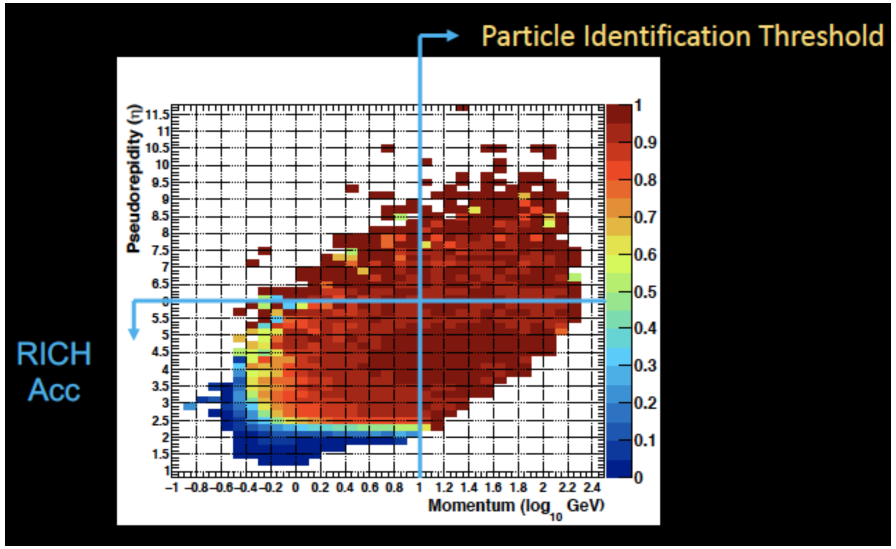
AMBER



- New AMS(2) data – the antiparticle flux is well known now (few % pres.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)
- Two types of processes contribute – SM interactions (proton on the inter-stellar matter with the production for example of antiprotons) and contribution from dark particle – antiparticle annihilation;
- In order to detect a possible excess in the antiparticles flux a good knowledge of inclusive cross sections of p-He interaction with antiparticles in the f.s. is a must, currently the typical precision is of 30-50%.



AMBER proton beam: from a few tens of *GeV/c* up to 250 *GeV/c*, in the pseudo-rapidity range $2.4 < \eta < 5.6$. Goal is to measure the double differential (momentum and pseudo-rapidity) antiproton production cross section from p+H and p+He at different proton momenta (50, 100, 190, 250 *GeV/c*).



AMBER antimatter production cross section

The impact of the proposed p + p measurements on constraining the production of cosmic anti-protons versus their kinetic energy. Each curve represents the fraction of anti-proton production phase space as constrained by AMBER cross section measurements in p-p, p-He and He-p channels, compared to NA61 (p-p) and LHCb (p-He) measurements

p-H channel, in three different energy ranges

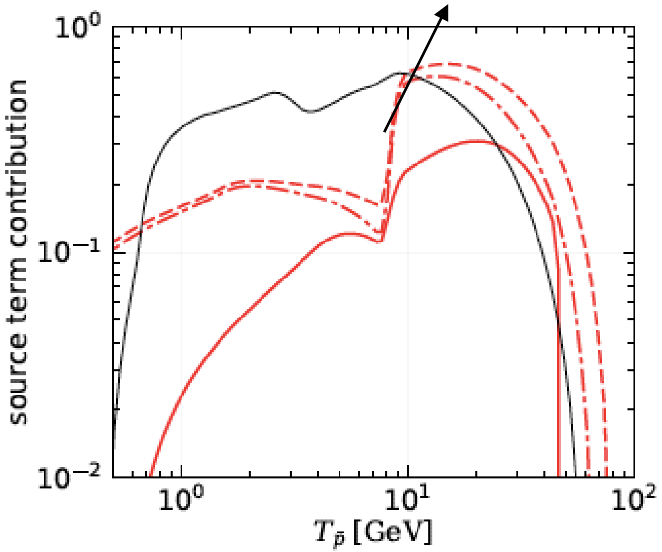
100-190 GeV/c

50-190 GeV/c

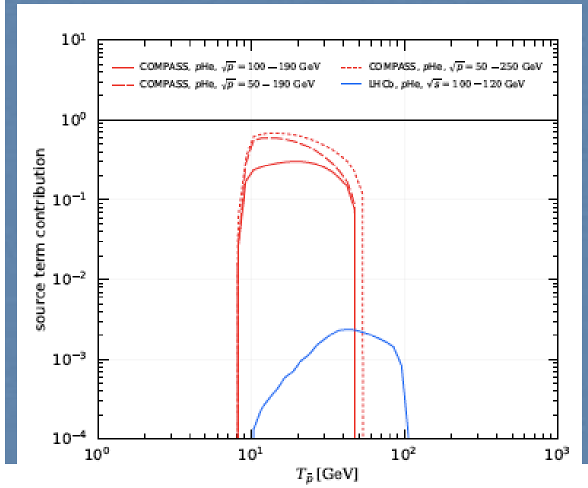
50 - 250 GeV/c

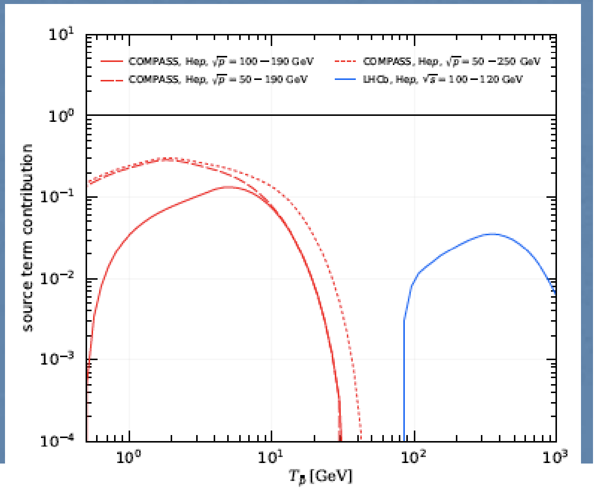
AMBER
LHCb

AMBER
NA61 (20-158 GeV/c)



p-He and He-p channels

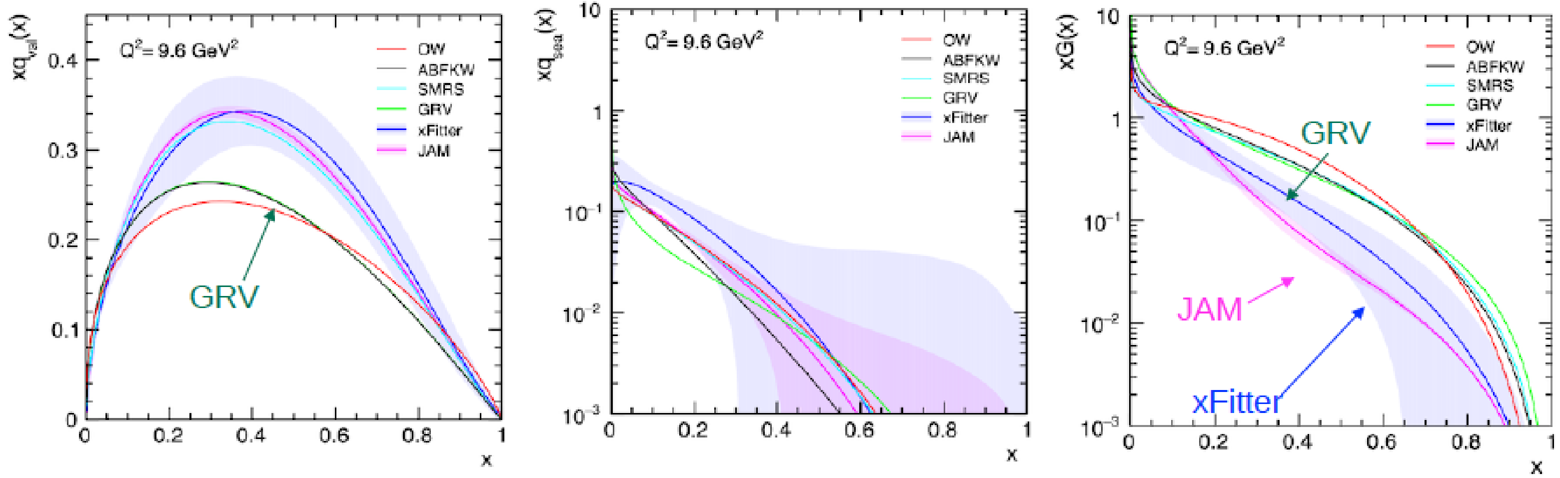




https://indico.cern.ch/event/820869/

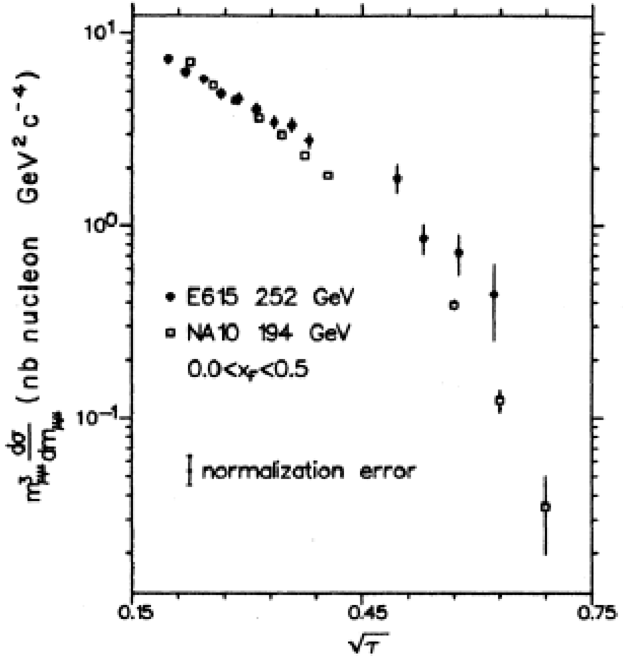
Pion induced Drell-Yan at AMBER
Status of the knowledge of the Pion structure

valence sea gluons



Chang et al, PRD 102, 054024 (2020)

From: E615, PRD 1989

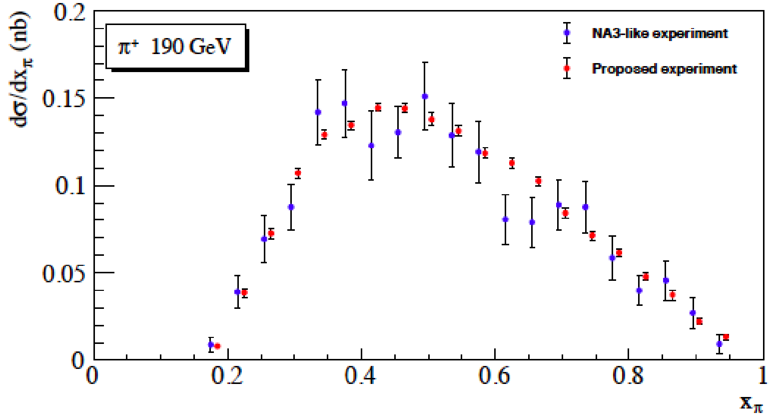


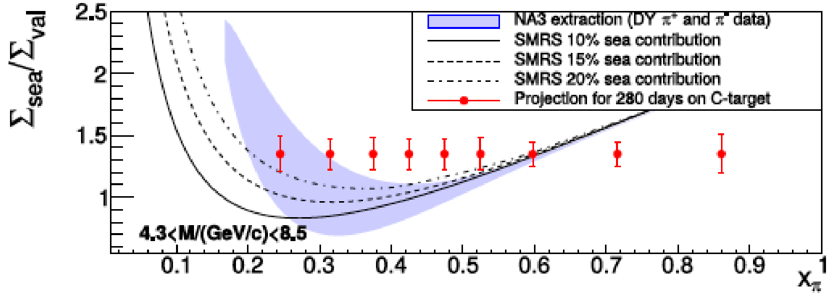
Pion structure status:

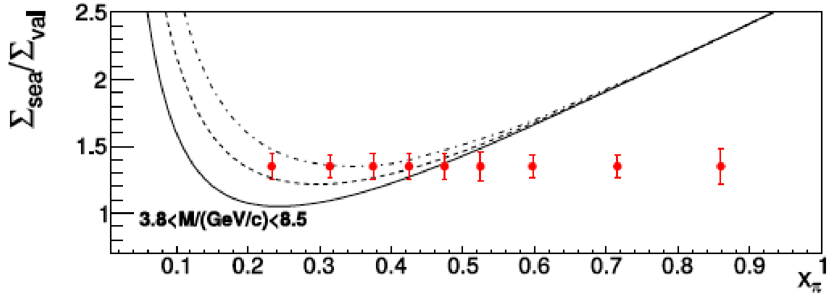
- Scarce data, poor knowledge of valence, sea and glue basically unknown
- Mostly heavy nuclear targets: large nuclear effects
- For some experiments, no information on absolute cross sections
- Two experiments (E615, NA3) have measured so far with both pion beam sign, but only one (NA3) has used its data to separate sea-valence quark contributions
- Discrepancy between different experiments (i.e. NA10, E615)
- Old data, no way to reanalyse them using modern approaches

Probing valence and sea quark contents of pion at AMBER

AMBER







Pion structure in pion induced DY
Expected accuracy as compared to NA3

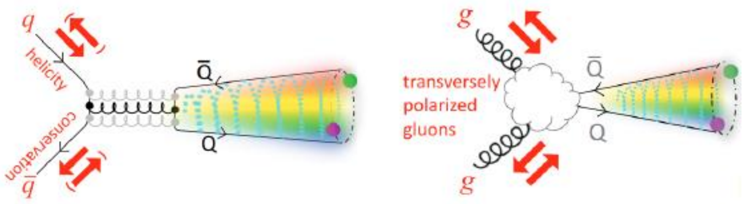
- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
- $\Sigma_S = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence
- Collect at least a **factor 10 more statistics** than presently available
- Minimize nuclear effects on target side
  - Projection for 2×140 days of Drell-Yan data taking
  - π^+ to π^- 3:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda^{\pi}_{int}$)
  - Improvement of shielding to double the intensity is under investigation

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
AMBER	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	21700 31000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	67000 91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5 4.0 – 8.5	8300 11700
		190	π^-	1.6×10^7	4.3 – 8.5 4.0 – 8.5	24100 32100

Isoscalar target + *Both positive and negative beams* + *High statistics*

Sea quark content of pion can be accurately measured at AMBER for the first time

Pion induced J/ψ at AMBER

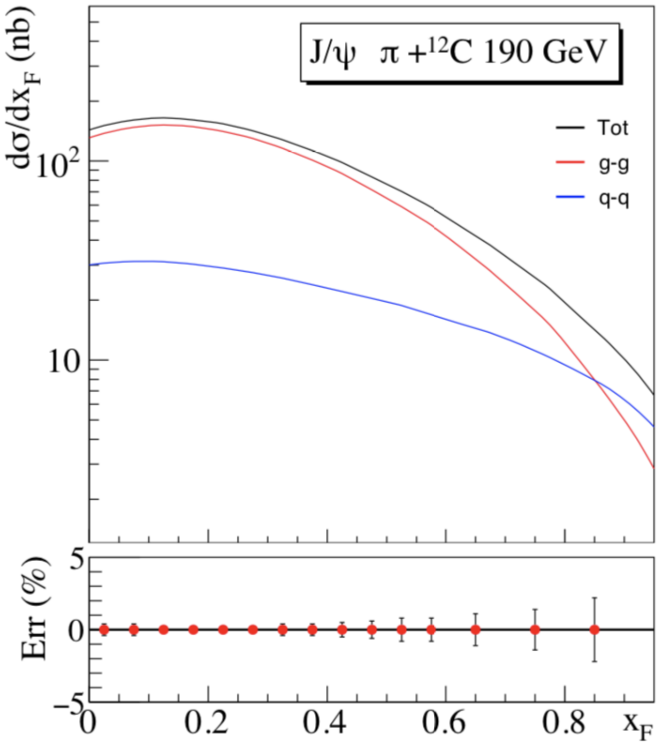


Collected simultaneously with DY data, with large counting rates

Physics objectives:

- Study of the J/ψ (charmonia) production mechanisms (*gg–fusion vs $q\bar{q}$–annihilation*), comparison of **CEM** and **NRQCD**
- Probe gluon and quark PDFs of pion (arXiv:2103.11660v1 [hep-ph] 22 Mar 2021)
- ***Ψ***(2S) signal study, free of feed-down effect from χ_{c1} χ_{c2}

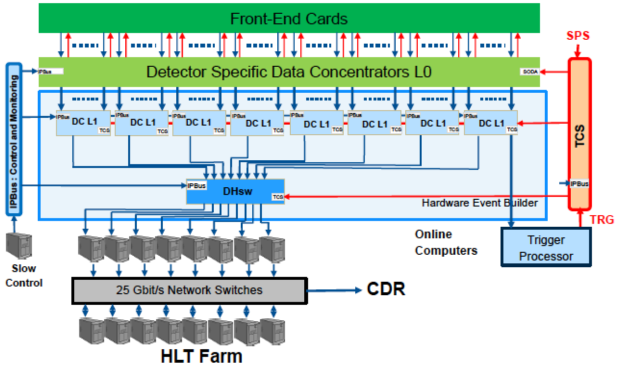
Cheung and Vogt, priv. comm.



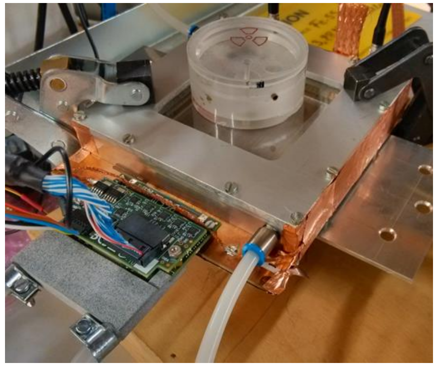
Improved CEM, CT10 + GRS99 global fit for proton/pion

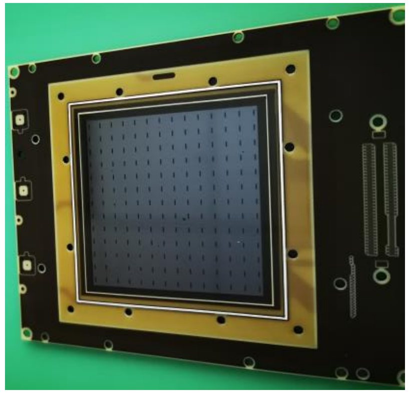
Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be, Fe, Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [133]	p	450	p	301000
	d			312000
HERA-B [134]	C	920	p	152000
COMPASS 2015	110 cm NH_3	190	π^-	1000000
COMPASS 2018				1500000
AMBER	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

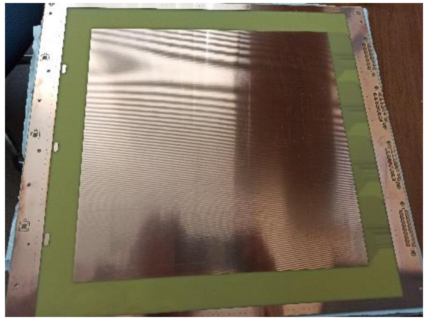
AMBER Hardware Developments



- New triggerless DAQ system, new front-end electronics and trigger logic compatible with triggerless readout
- New large-size PixelGEM detectors
- New large-area micro-pattern gaseous detectors (MPGD)
- High-rate-capable CEDARs detectors (beam line)
- A new RICH-0 detector to extend significantly phase space coverage (lower momenta)

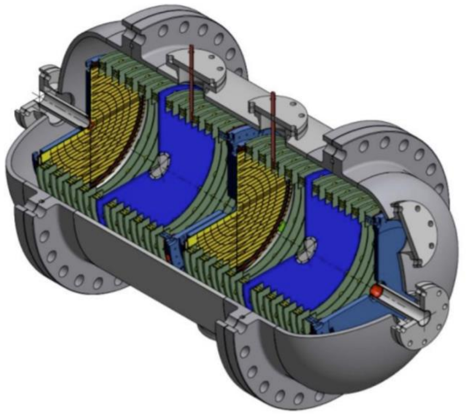


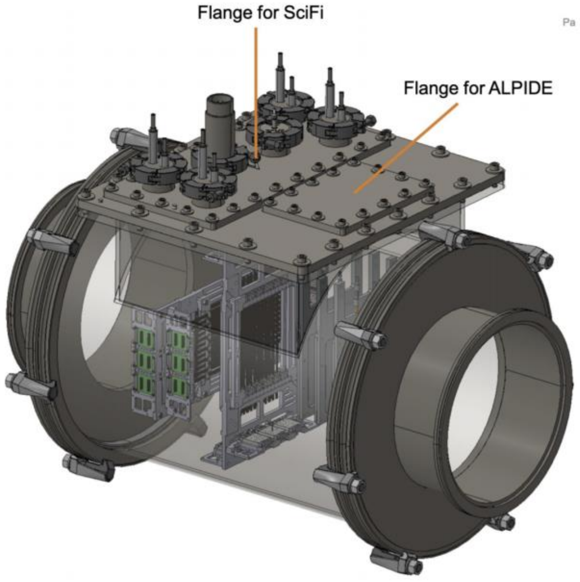




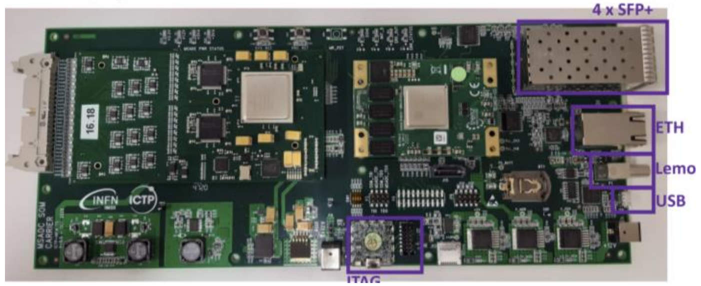
Phase-1 Hardware Development

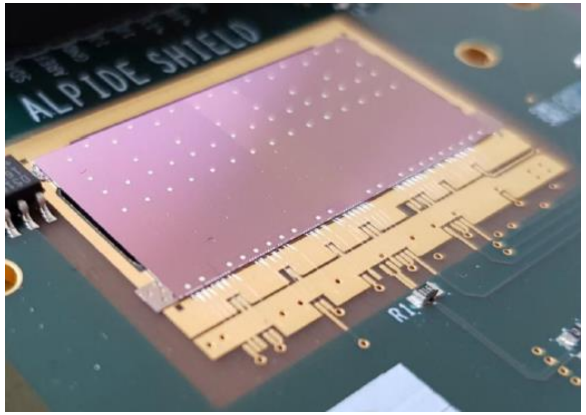
- High-pressure hydrogen filled active TPC (PRM)
- Combined scintillating fibres / silicon tracking system (4 stations) (PRM)
- Triggerless electromagnetic calorimeter electronics (PRM)
- High rate capable silicon-based vertex detector (DY)
- New high-purity and high efficiency di-muon trigger (DY)





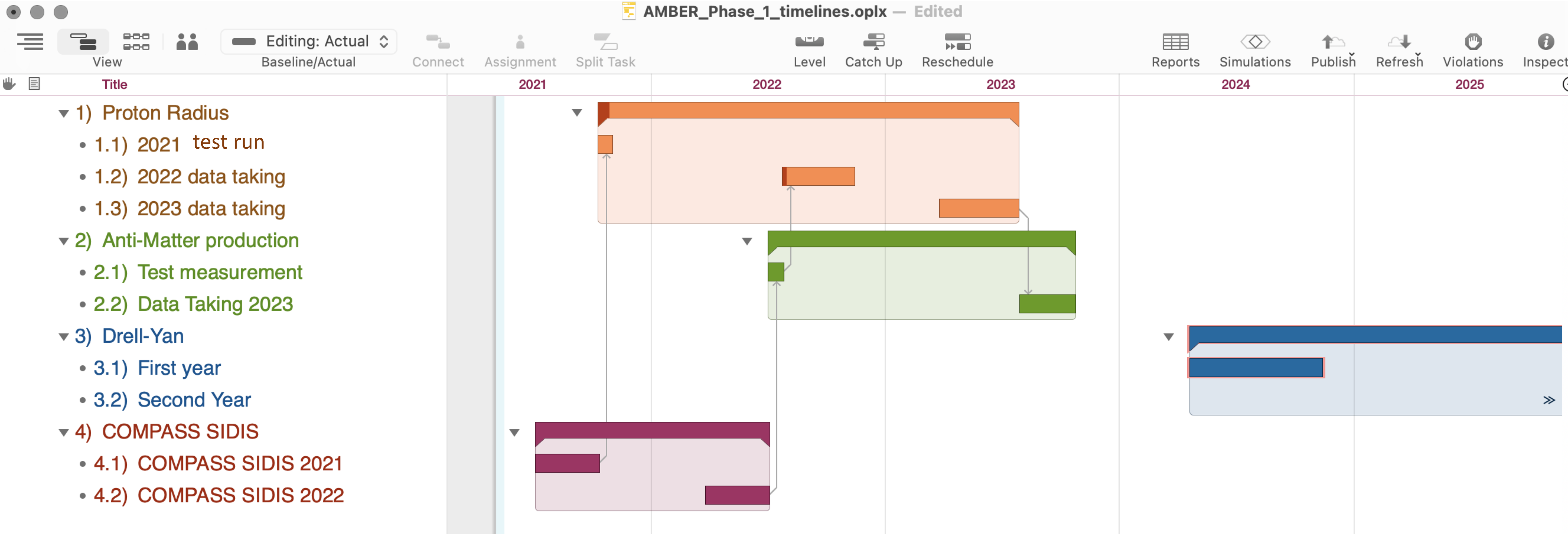
ECAL2 DAQ Hardware – Carrier Board III





Possible timeline for the AMBER Phase-1 measurements

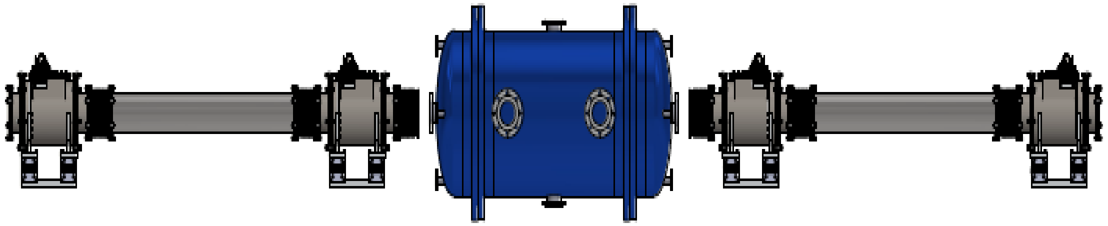
AMBER

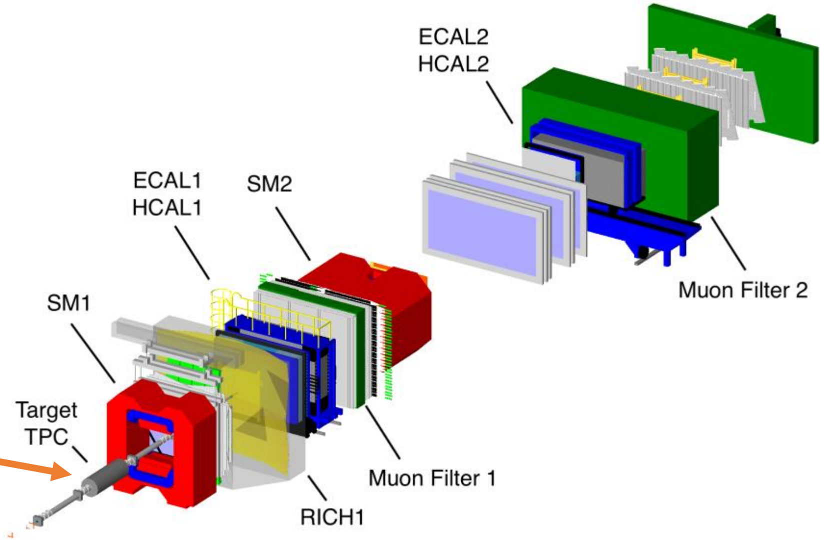


Starting point depends of the semiconductors availability on the market

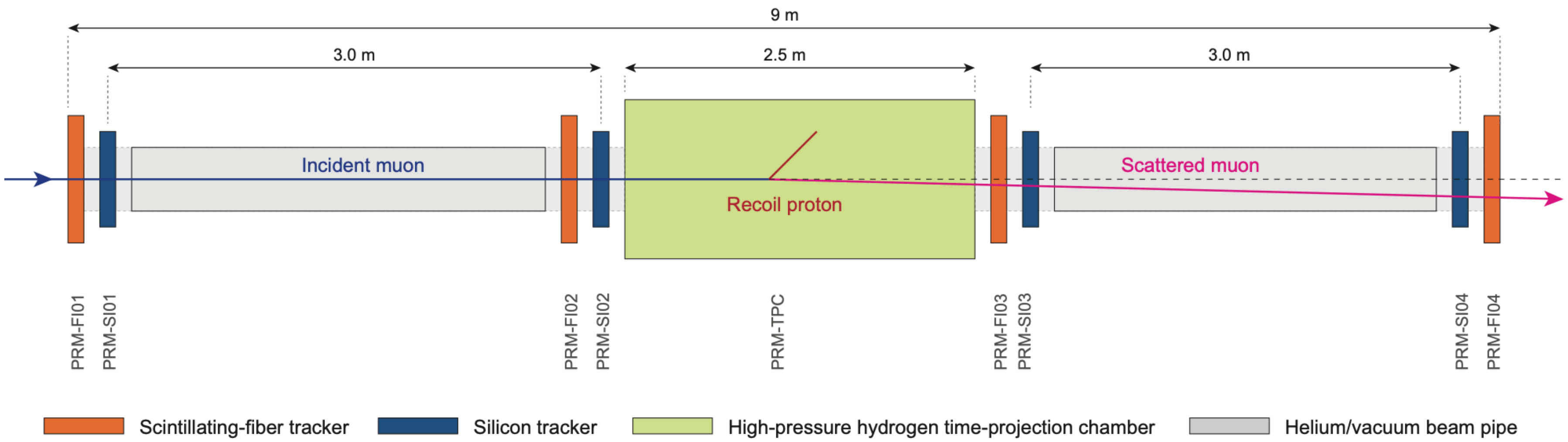
AMBER

Layout of Proton Radius Measurement in 2022





Upstream part of the AMBER spectrometer for PRM



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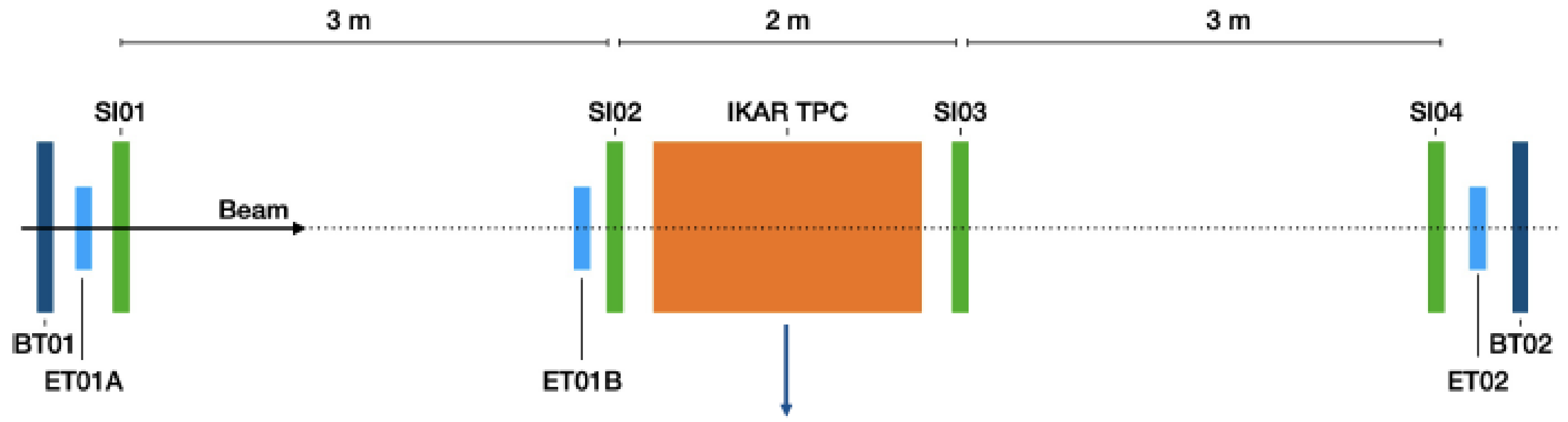
Proton Radius Measurement 2021 test run

Main Goal to be reached: **Proof-of-principle of all new detector equipment**

- Test the IKAR TPC in dedicated 20 days of beam (CEDAR position)
  - determine the **noise/background induced by the muon beam**, detect proton recoils correlated with scattered muons
- Test of the unified tracking detector station
  - operate one detector station with prototypes of both the **silicon-pixel detector** and the **scintillating-fibre hodoscope**
- Test of the new DAQ system (possible for TPC in park position)
  - operate new **free-running DAQ** system for readout for all new detector components



Proton Radius Measurement 2021 test run

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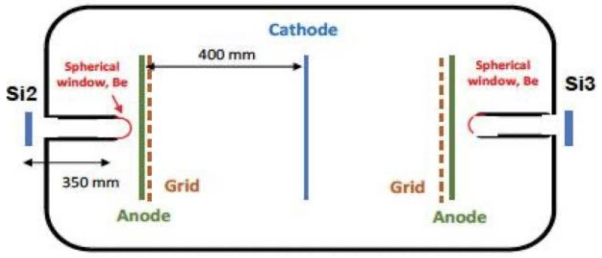
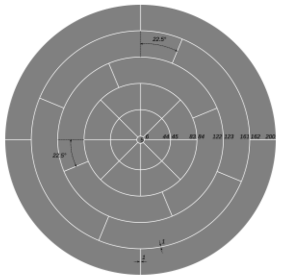
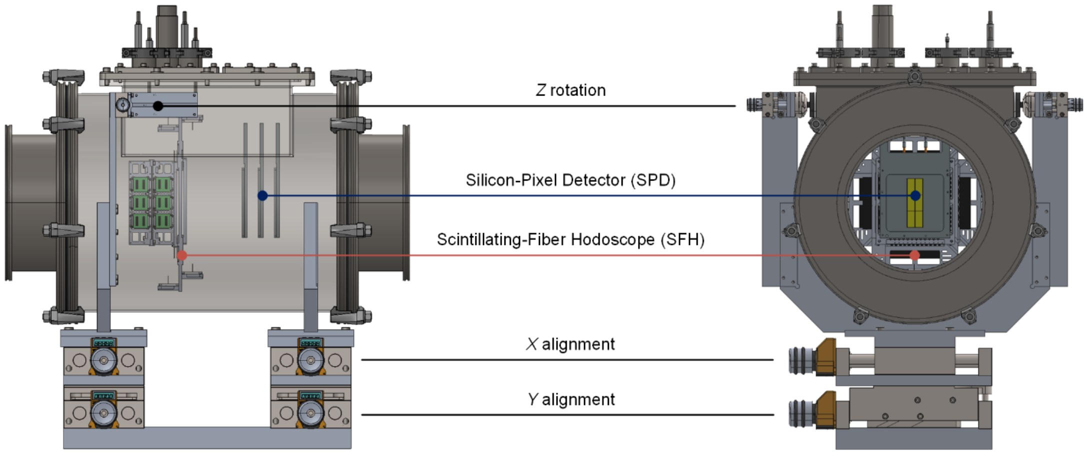
IKAR TPC (currently at CERN):
- → 2x drift cells with 400 mm length
- → New adapted field-shaping rings
- → Anode structure: identical structure, but with smaller diameter wrt final TPC
- → Operation pressure of max. 10 bar
- → New power-supplies and front-end electronics
- Ready for first pressure test
- Dedicated gas-purification system will be used

Combined Silicon-Fibre tracking station:
- → 2x+2y planes of 500 μm scintillating fibre 9.6x9.6 cm^2
- → 3 planes of pixel-silicons 9x9 cm^2 (pixel size 28x28 μm)
- → Operation pressure of max. 10 bar
- → New power-supplies and front-end electronics
- Small distance between the Silicon-pixel detectors and the Scintillating-Fibre Hodoscope
- Allow for independent access and cooling infrastructure
- Compatible with beam line elements for the He volume







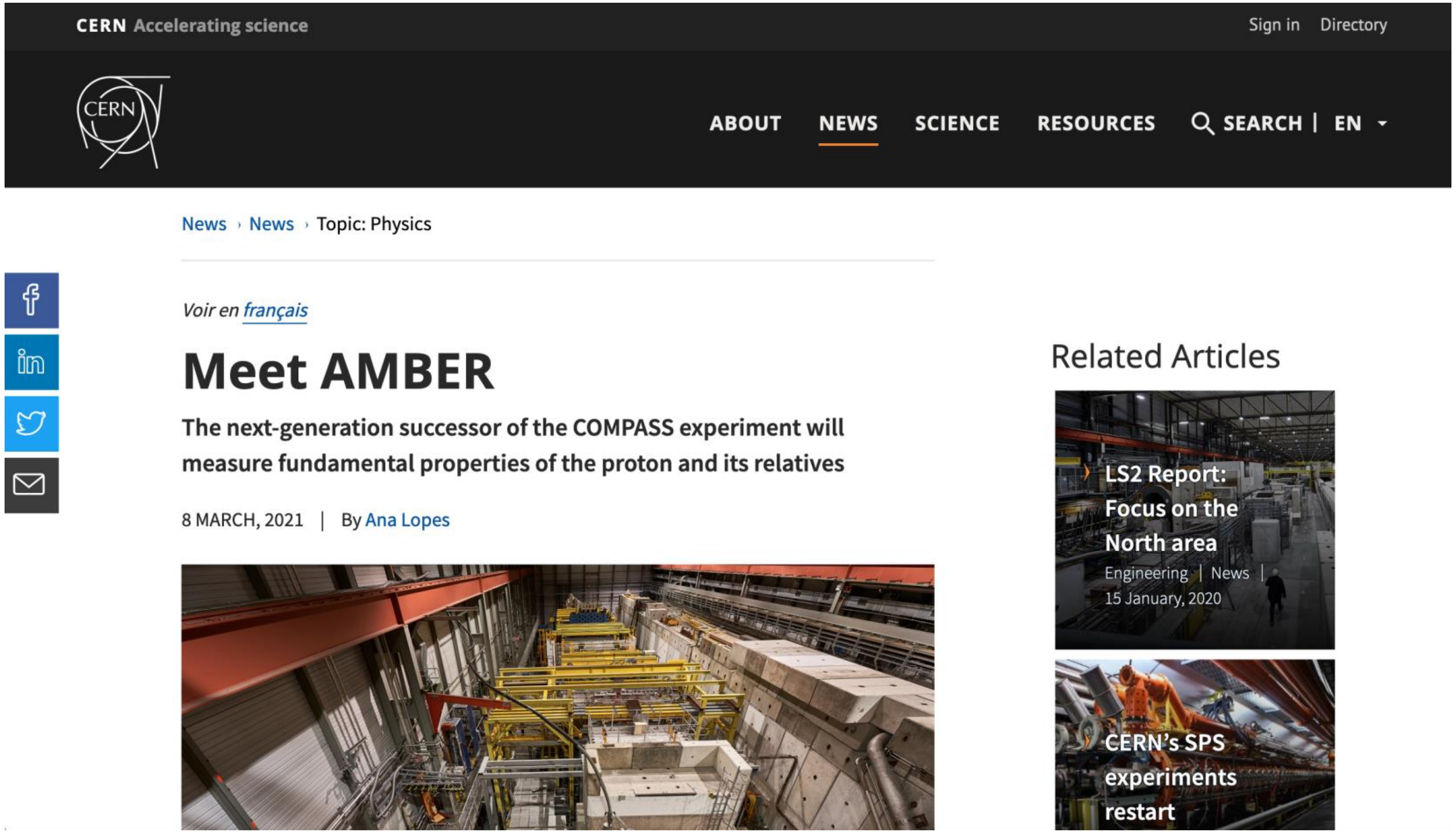
Summary: AMBER at CERN SPS

- A wide and extremely competitive physics program brought together, strong interest in the hadron physics community
- ~40 Institutions and 12 countries, 189 full members (PhD and higher), growing up
- Collaboration structure is basically fixed, MoU is in preparation
- Important next step – proton radius measurement test run in 2021

BACK UP

AMBER in the CERN news

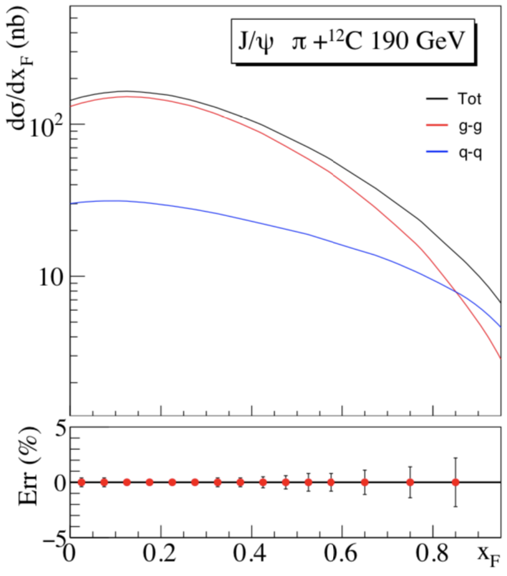
https://home.cern/news/news/physics/meet-amber

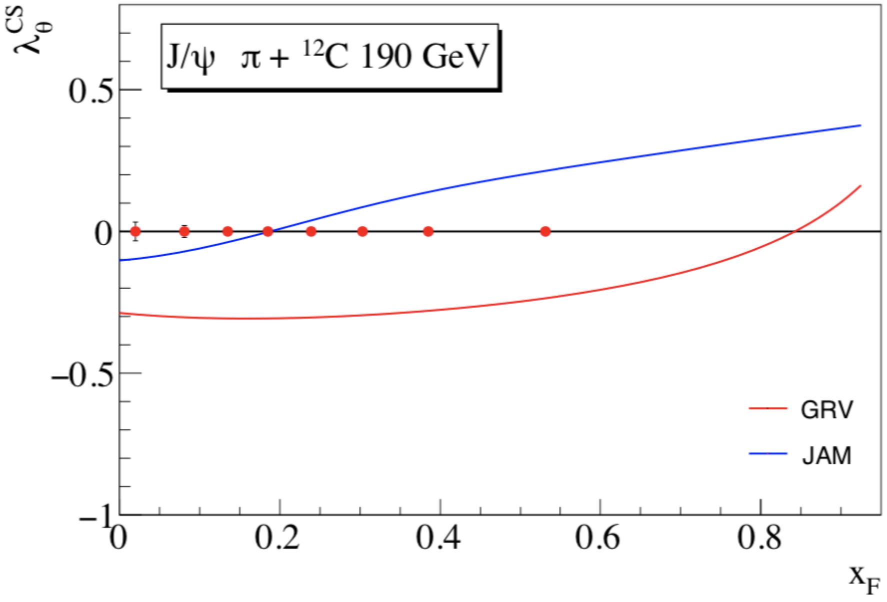


AMBER Charmonium

AMBER

Improved CEM, CT10 + GRS99 global fit for prot./pion





PHASE-1

Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be, Fe, Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [133]	p	450	p	301000
	d			312000
HERA-B [134]	C	920	p	152000
COMPASS 2015	110 cm NH_3	190	π^-	1000000
COMPASS 2018				1500000
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Oleg Denisov