



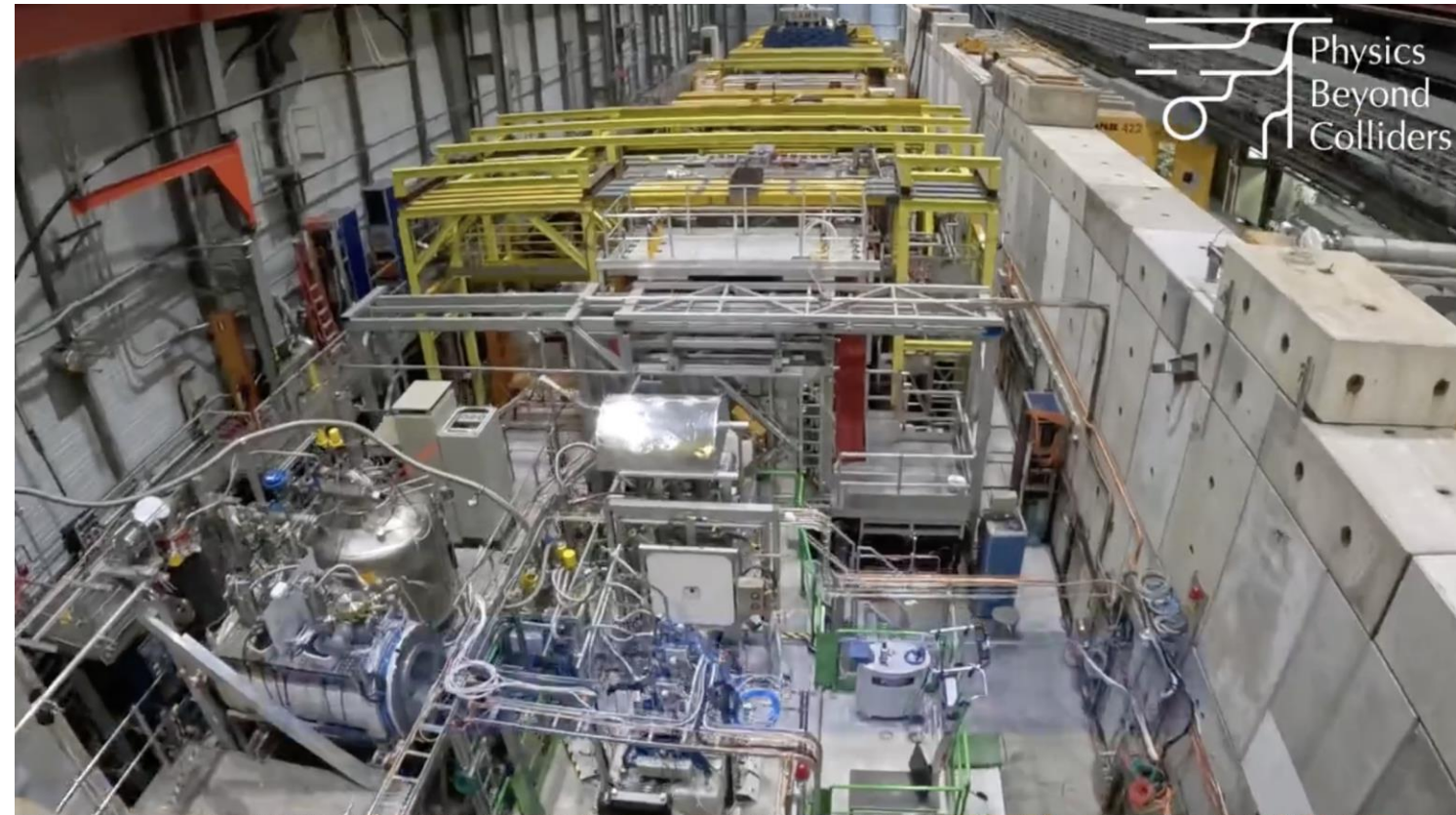
Series of talks: From COMPASS to AMBER: From Proton Spin Crisis to Hadron Mass Puzzle

10/09/2026, Sevilla, España



Outlook

1. Intro to AMBER
2. AMBER science question
3. Proton charge-radius measurement
4. Properties of unstable particles @AMBER:
 - Drell-Yan pairs and J/Psi production
 - Prompt Photons
 - Hadron radii
5. CERN North Area + M2 beam line consolidation and upgrade
6. Conclusions



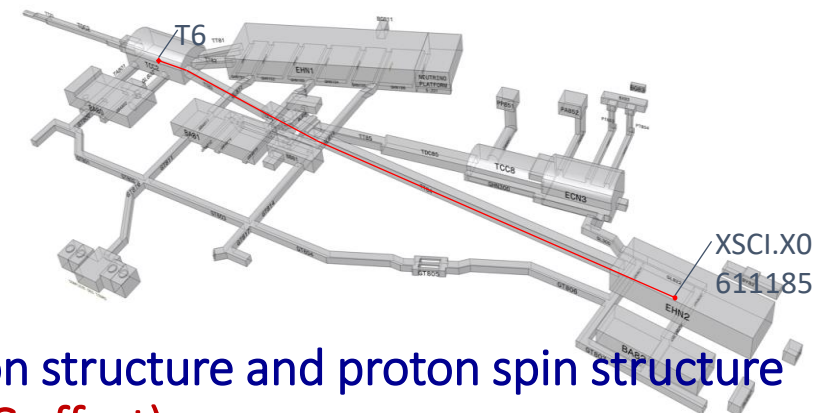
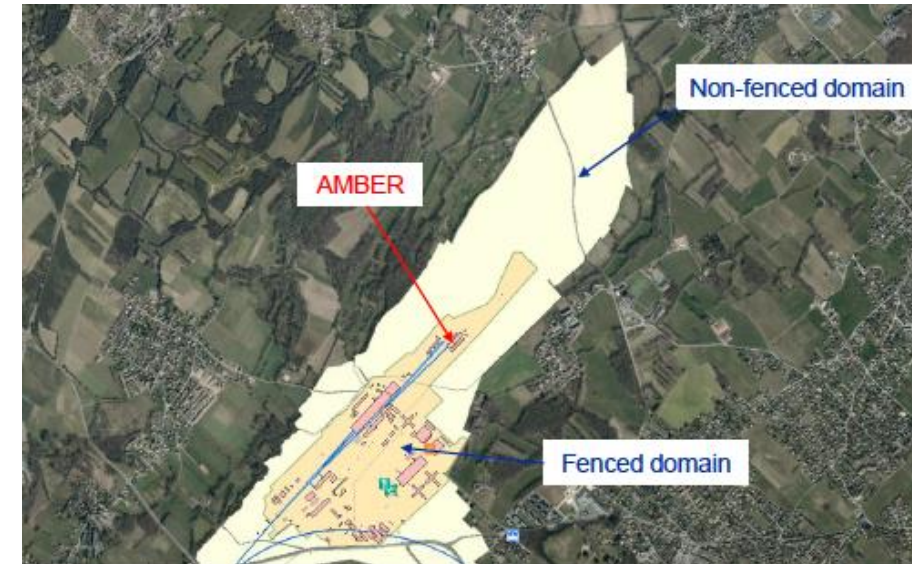
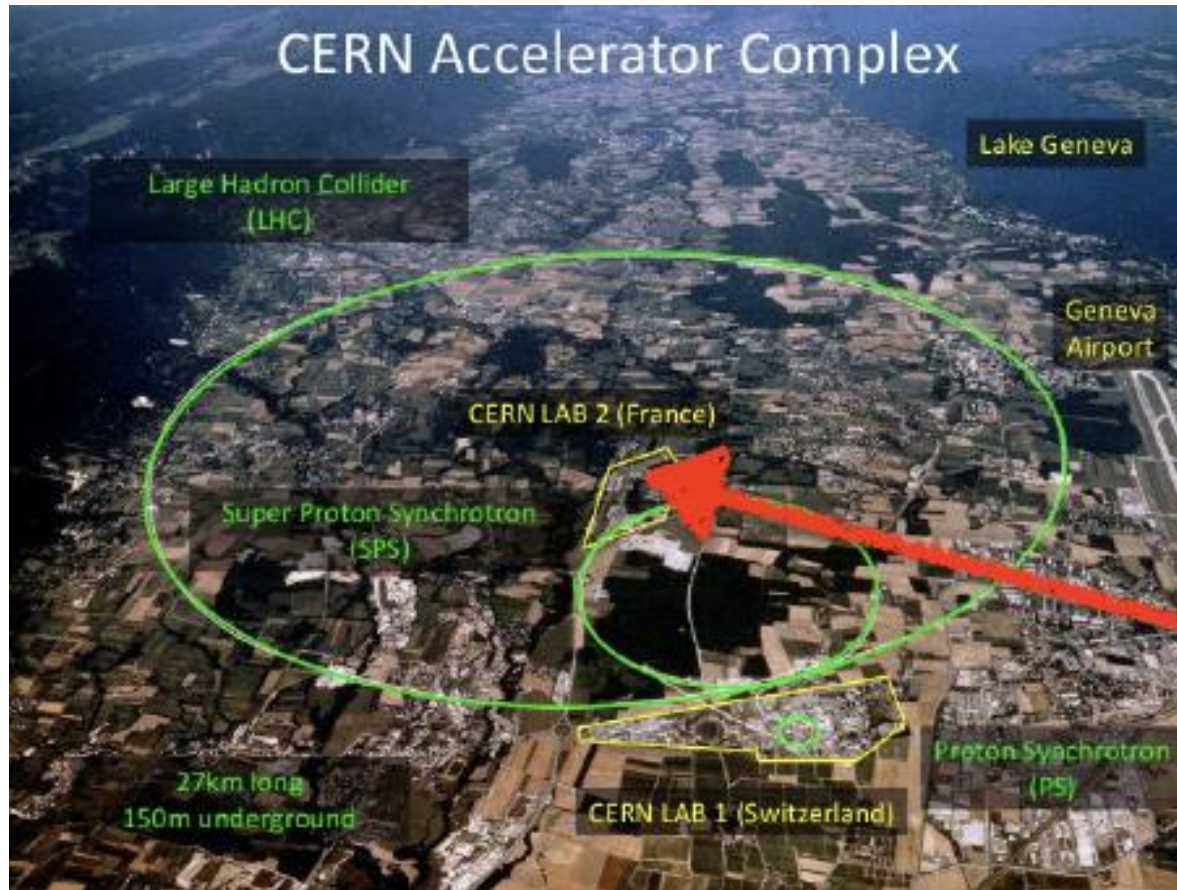
Dr. Oleg Yu. Denisov, senior researcher INFN section of Turin (Italy)
on behalf of the AMBER Collaboration

Materials/slides of Vincent Andrieux, Craig Roberts, Alessandro Bacchetta, Paolo Zuccon, Stephane Platchkov, Alexey Guskov, Stefan Wallner, Jan Friedrich, Stephan Paul, Stefan Diehl, Michela Chiosso, Bernhard Ketzer and other Colleagues have been used in this talk



AMBER facility is a successor of the COMPASS in a long row of Experiments which took place in the EHN2 experimental hall of the CERN North Area Laboratory (aka CERN-Prevessin or CERN Lab 2)

NA4 → EMC → NMC → SMC → COMPASS → AMBER



Known because of contribution to the study of the proton structure and proton spin structure
(Proton Spin Crisis and EMC effect)



- COMPASS & Co legacy:
 - Proton spin crisis is over: much more precise data on $\Delta\Sigma + \Delta G$, there is a very clear recipe to fill up the missing part of the proton spin – angular momentum → 3D case → TMDs and GPDs
 - Huge progress on Transversity
 - Unique pion diffractive scattering data set
- We found ourselves (TMDs sector as example) in Precision phase (Alessandro Bacchetta)
- More data to come in the next years from COMPASS, JLab, RHIC and later from high-luminosity facilities



GPS compass



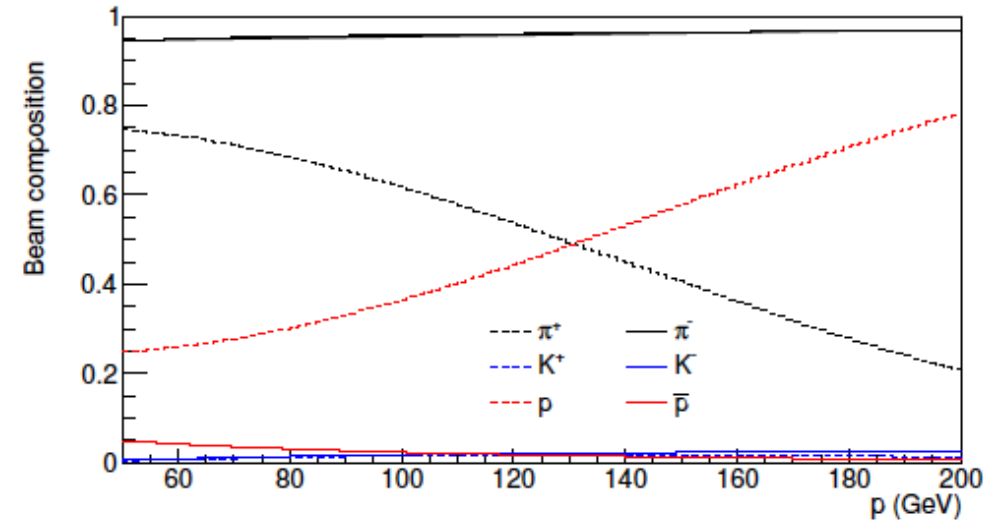
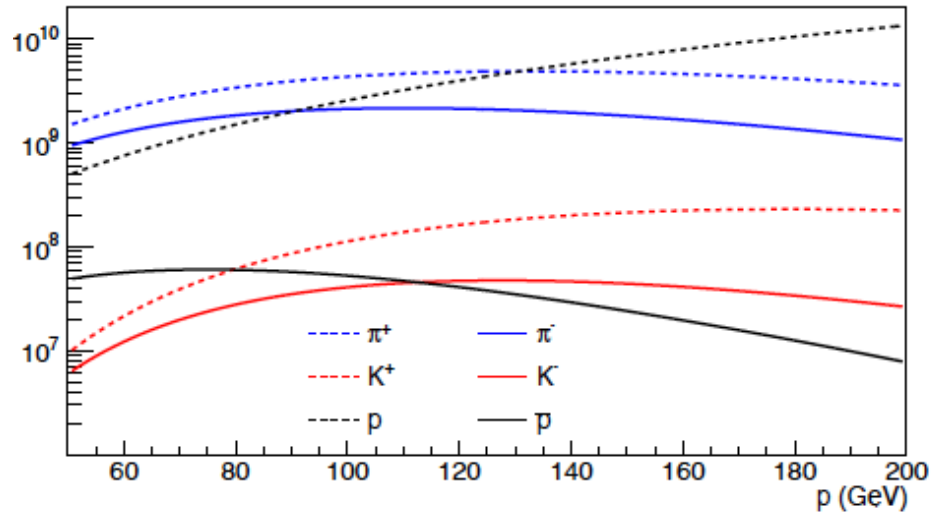
• Exploration • parton-model theory • first measurements	2002
• Consolidation • TMD factorization • many consistent measurements	2012
• Precision • full-fledged global analysis • precision measurements	2022

from IWHSS 2011

Proton SPIN&Co cannot be anymore the main AMBER Science Question because of:

- We did what we could
- A number of high luminosity programs (LHCb-Spin, SpinQuest, Jlab, EicC, EicC) will provide data in next years
- **Everything what can be done elsewhere but at CERN must be done elsewhere**
- **Wider physics program to attract new groups**

Precision



Basic features of the AMBER/EHN2 secondary beams (CERN SPS 400 GeV primary proton beam):

- **Hadron+/- beams, momentum range 50 – 250 GeV, up to 2×10^8 /sec**
- Muon+/- beams, momentum range 50 – 250 GeV, up to 5×10^7 /sec
- Electron/positron beams 20-60 GeV, up to 10^5 /sec

After ~10 years long effort, dozen of international workshops and hundreds of local meetings we came to conclusion:

High energy/High intensity Pion+/- and Kaon+/- beams are UNIQUE to study structure of UNSTABLE Particles.

Taking into account unique meson beam opportunities at EHN2 we Identify AMBER as a key contributor to the study of the Emergence of the Hadron Mass Phenomenon

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

As Higgs mechanism produces a few percent of visible mass, where does the rest comes from?

Pion



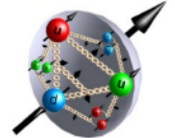
- $M_\pi \sim 140\text{MeV}$
- Spin 0
- 2 light valence quarks

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

Higgs generated masses of the valence quarks:

$$M_{(u+d)} \sim 7 \text{ MeV}$$

$$M_{(u+s)} \sim 100 \text{ MeV}$$

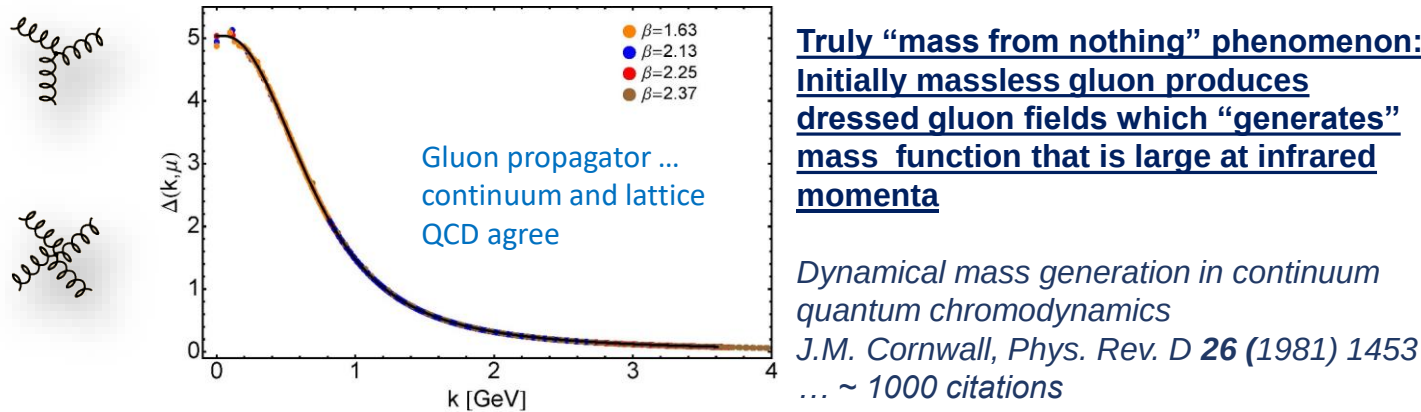
$$M_{(u+u+d)} \sim 10 \text{ MeV}$$



EHM phenomenon

What are the underlying mechanisms?

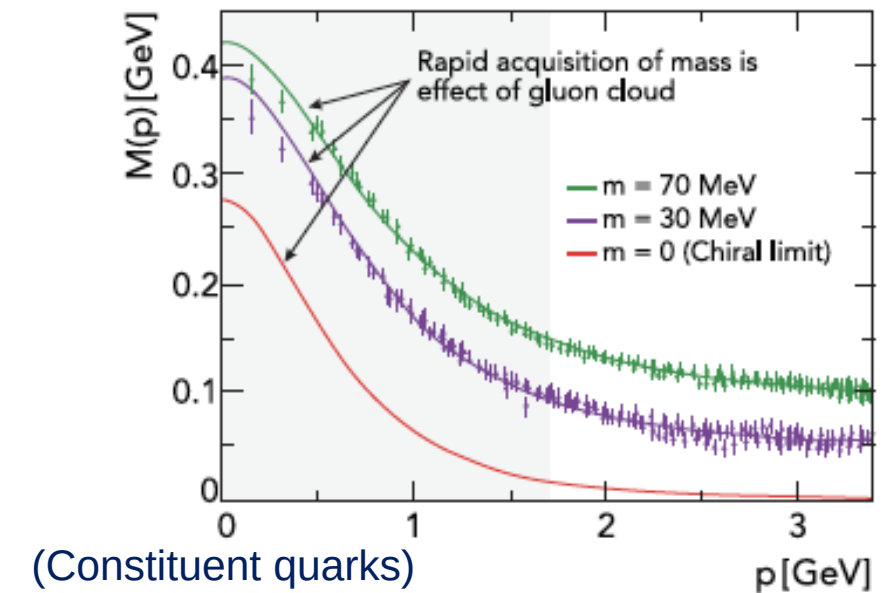
Intuitively one can expect that the answer to the question lies within SM, in particular within QCD.
Why? Because of the dynamical mass generation in continuum QCD.



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

In order to “proof” 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 and PDAs of the pion/kaon/proton
2. Hadron’s radii (confinement)
3. Excited-meson spectra



Dressed-quark mass function $M(p)$

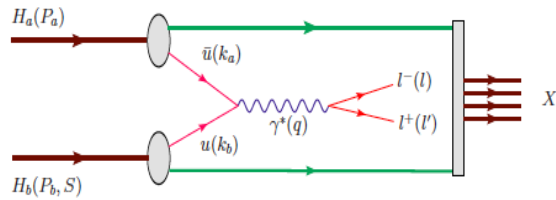
Questions to be answered:

- 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

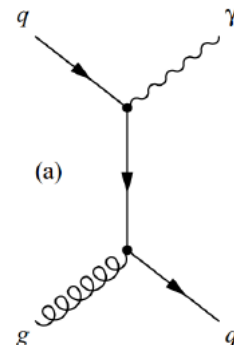
A series of workshops entitled
“Perceiving of the EHM through
AMBER@CERN(SPS)” we organised
In 2019-2022:
<https://indico.cern.ch/event/1021402/>

Methods:

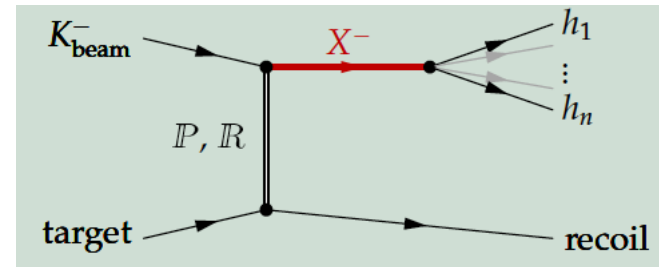
Drell-Yan (compl. to
Sullivan) and J/ψ



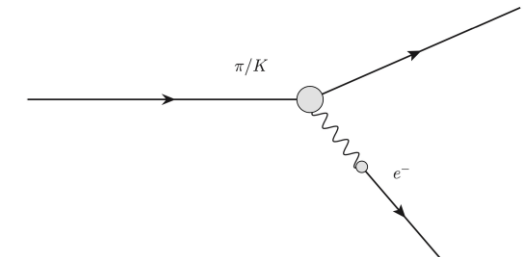
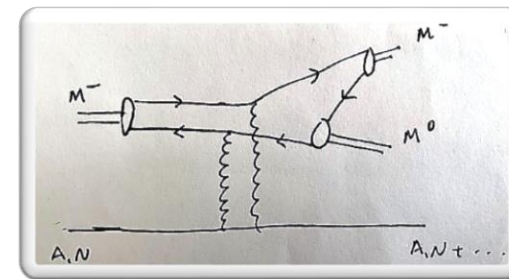
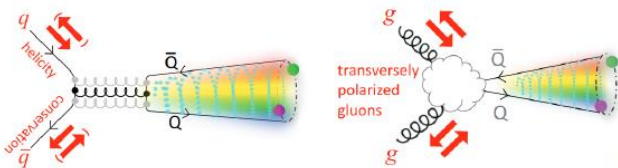
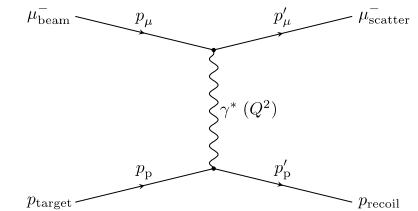
Prompt Photon Production



Diffractive scattering

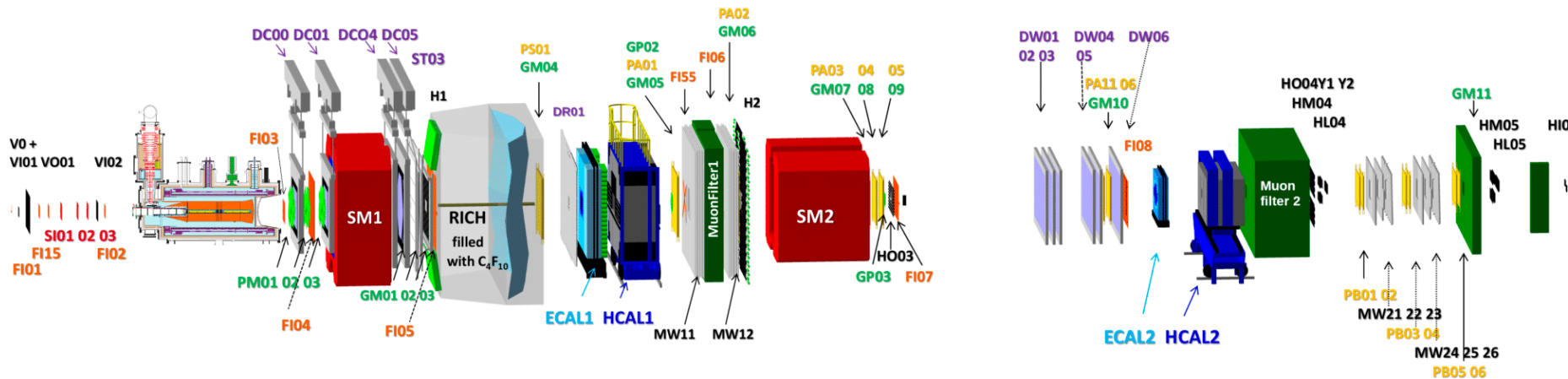


Elastic scattering

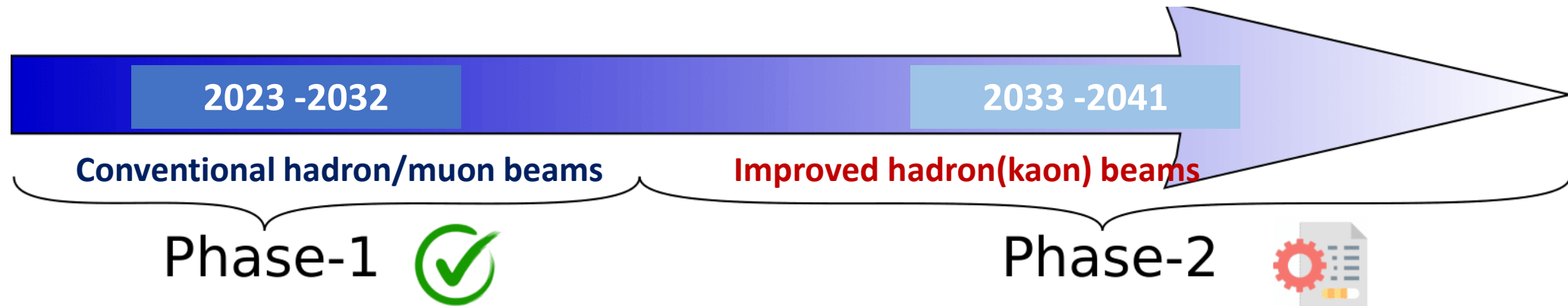




Apparatus for Meson and Baryon Experimental Research (AMBER, CERN, SPS, NA66)



Presently 35 institutes
from 14 countries, new
collaborators are welcome.



Proton Radius Measurement
Antimatter production cross section
Pion and kaon structure (PDFs) via DY and
J/Psi production

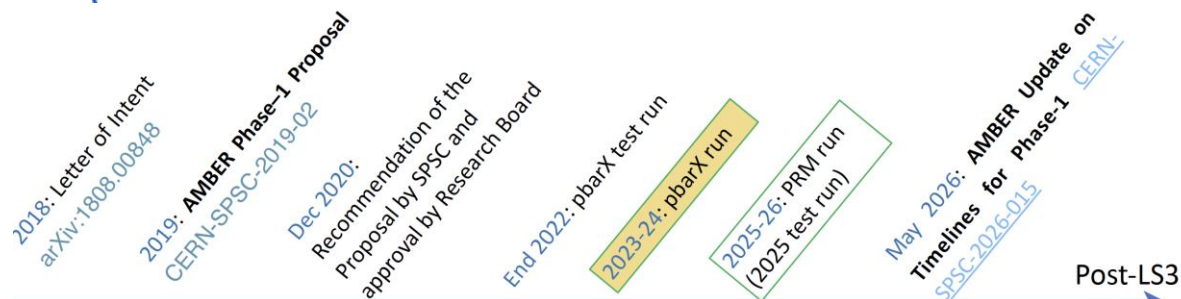
Phase-1 Proposal approved by RB on 02/12/2020

High precision strange-meson spectrum
Kaon and pion charge radii
Kaon induced Primakoff reaction
Prompt Photons Production

Phase-2 Proposal submission in 2027/28

What was achieved by AMBER so far:

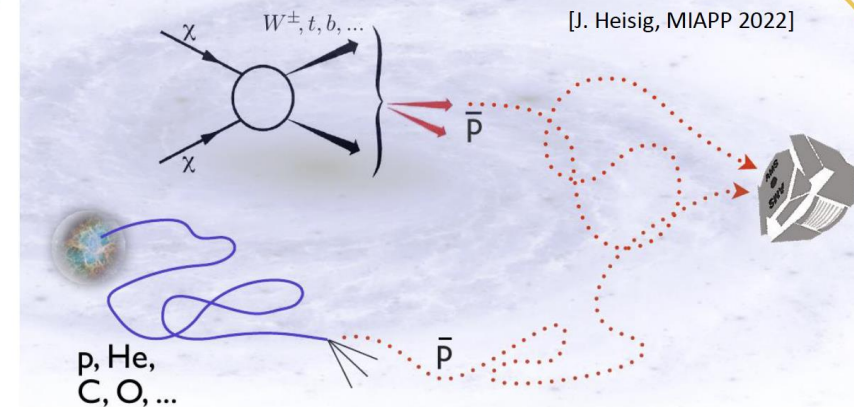
I. Antimatter Production Cross-section measurement (APX)



Phase-1: (conventional beams)

- $\bar{p}$ production cross section measurements for DM searches (pbarX)
- Proton electric form factor: high-energy μ -p elastic scattering (PRM)
- Meson PDFs: Drell-Yan processes (DY) and charmonium production

Phase-2: (high-intensity kaon beam) proposal in preparation



AMS-02: few percent level accuracy on cosmic antiparticle flux

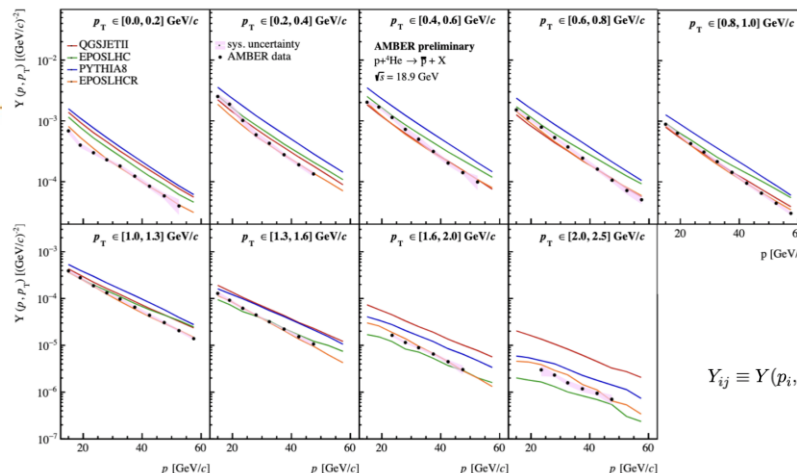
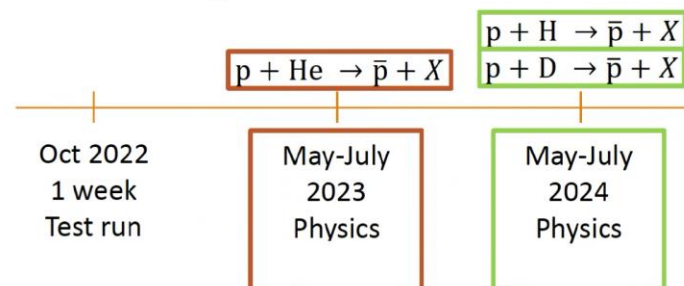
Limiting factor: large uncertainty in the $\bar{p}$ production cross section in $p-p$ and $p-^4\text{He}$ collisions

Accurate measurements over a wide energy range from 10 GeV to a few TeV are needed.

Scarce data available, especially for $p-^4\text{He}$ collisions

Another dedicated goal of the measurements: possible isospin asymmetry effects

Collected data @AMBER



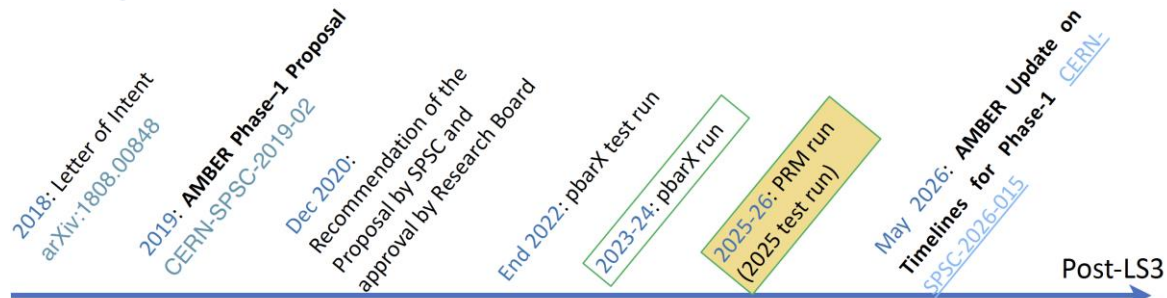
$$Y_{ij} \equiv Y(p_i, p_{T,j}) = \frac{1}{\Delta p_i \Delta p_{T,j}} \frac{N_{ij}^{\bar{p}}}{N_{\text{inel}}}$$

$p+\text{He}$: beam @60, 80, 100, 160, 190, 250 GeV/c

$p+\text{H} / p+\text{D}$: beam @80, 160, 250 GeV/c

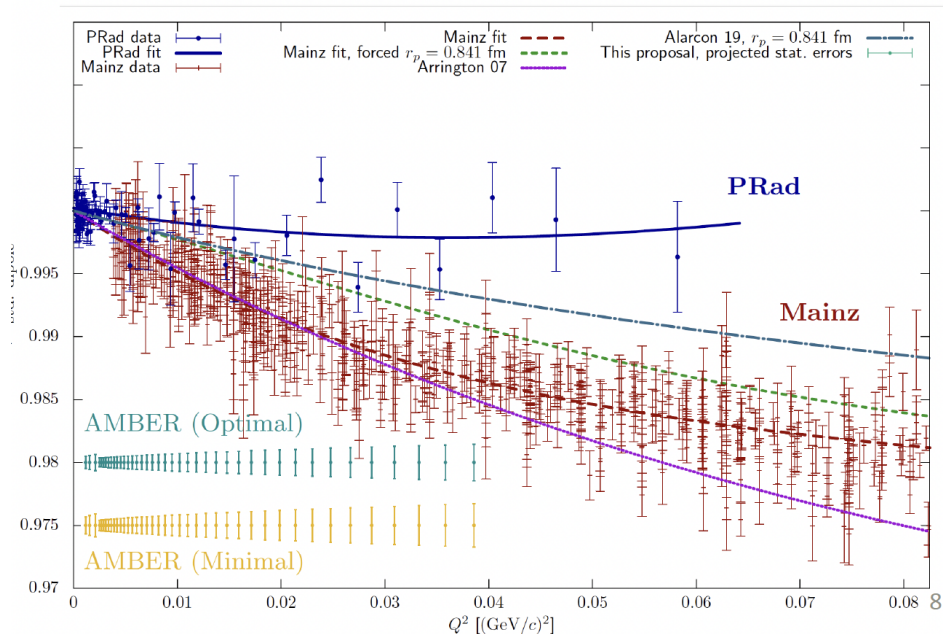
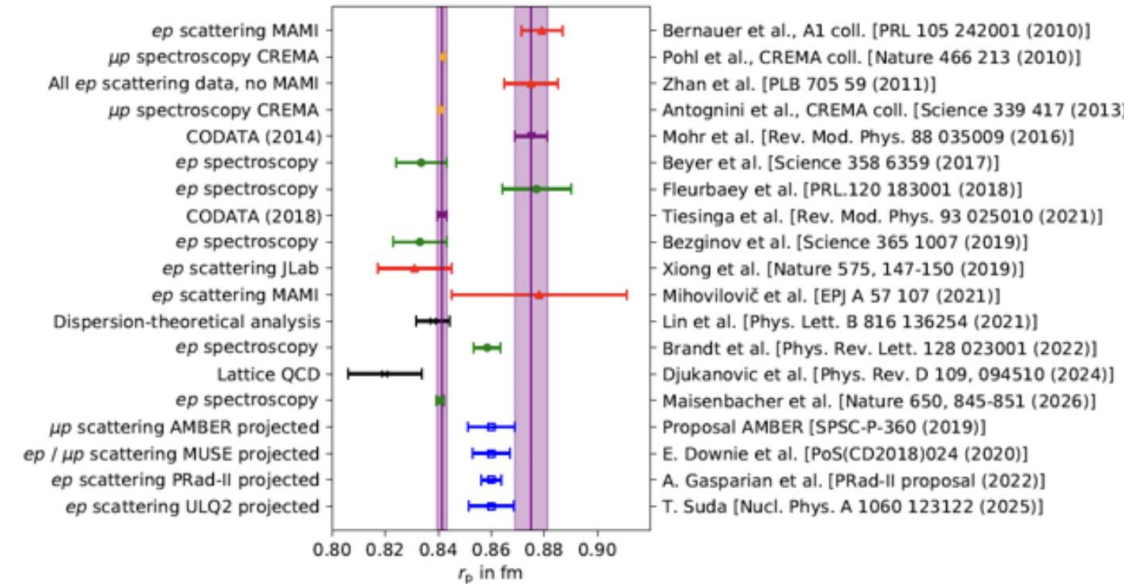
What was achieved by AMBER so far:

II. Proton Charge-Radius measurement (PRM) (1)



Phase-1: (conventional beams)

- $\bar{p}$ production cross section measurements for DM searches (pbarX)
- Proton electric form factor: high-energy μ -p elastic scattering (PRM)
- Meson PDFs: Drell-Yan processes (DY) and charmonium production



Why high-energy μ -p scattering?

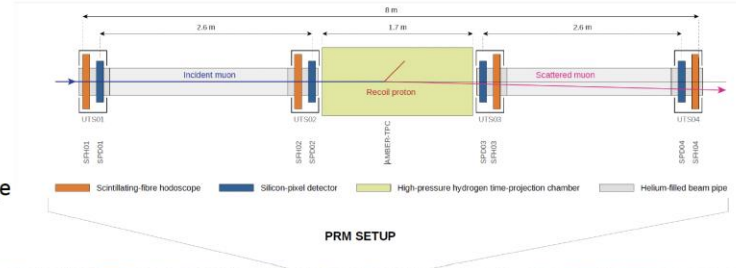
- form factor not understood
- use different leptonic probe
- different systematic uncertainties
- >10 x smaller radiative corrections than ep
- provide precise data for global fit
- test lepton universality

What was achieved by AMBER so far:

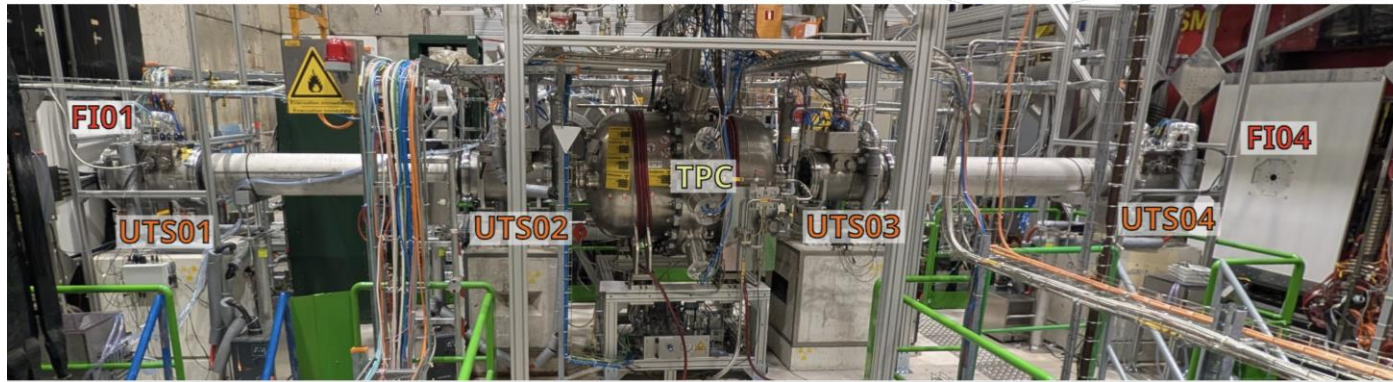
II. Proton Charge-Radius measurement (PRM) (2)

TPC: Direct measurement of recoil proton energy

- pure high-pressure H₂ as target and detector gas
- 2 × 40 cm drift cells, drift time $\sim 150 \mu s$
- energy resolution $< 6\%$ required for desired precision
- segmented readout planes $\Rightarrow$ reconstruction of p track
- 2 different pressure settings: 4 bar, 20 bar to cover Q^2 range



Precise determination of the scattering vertex



Collected ~ 1 PB of raw data, combining the main AMBER and TPC DAQ

Assuming a selection efficiency of 80 %, we estimate:

$\sim 1M$ events at 4 bara

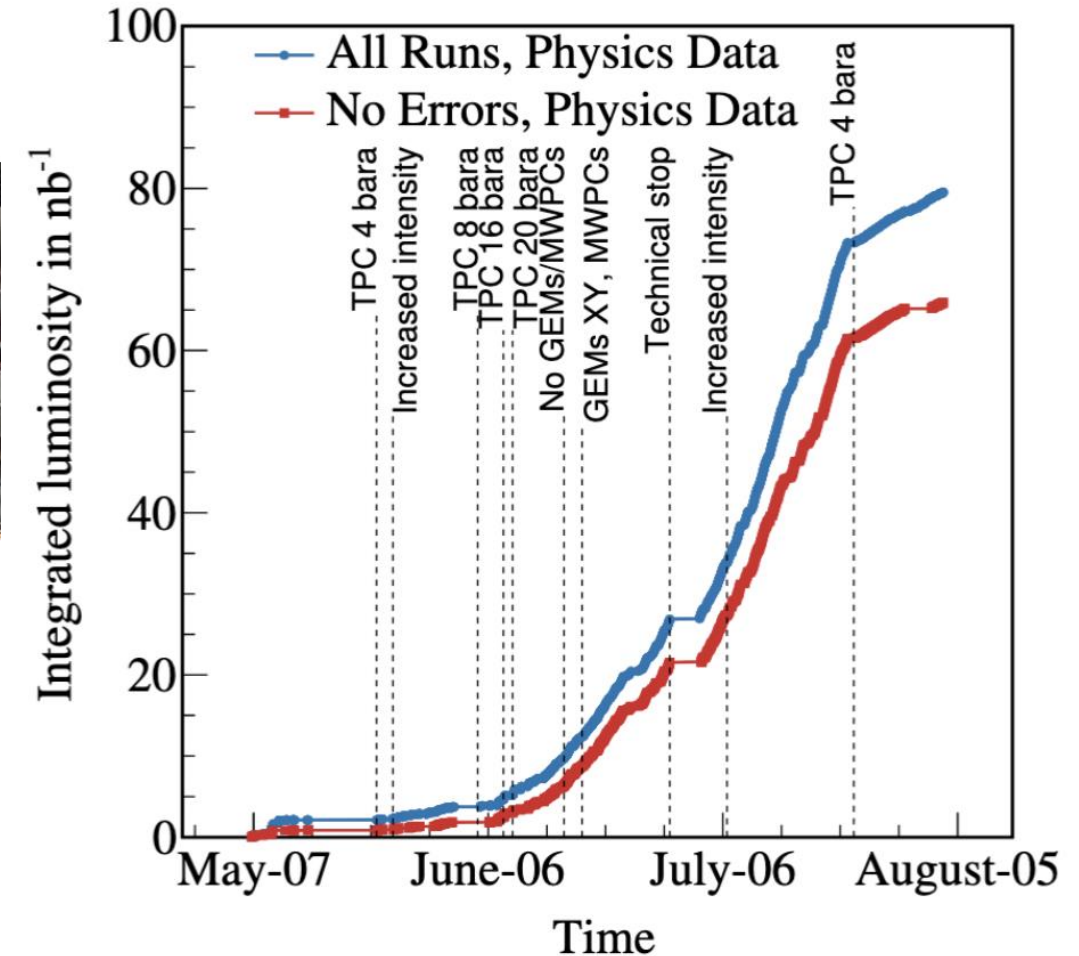
$\sim 12M$ events at 20 bara

over the full Q^2 range ($1 \times 10^{-3} \text{ GeV}^2/c^2 - 4 \times 10^{-2} \text{ GeV}^2/c^2$)

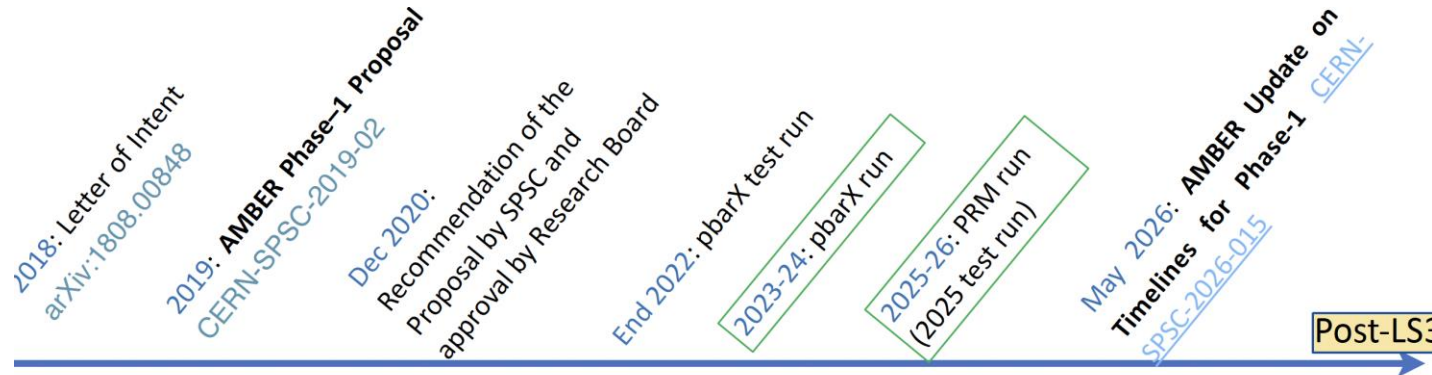
$\rightarrow$ very close to our updated estimate in May, thanks also to excellent SPS availability.

Update in May

Scenario	No. of events	Rel. stat. uncertainty on $\langle r_E^2 \rangle$
Full 2026 (111 days) [9]	22M	1.5%
Updated 2026 (70 days)	14M	1.8%
PRAD-I [11]		0.85%

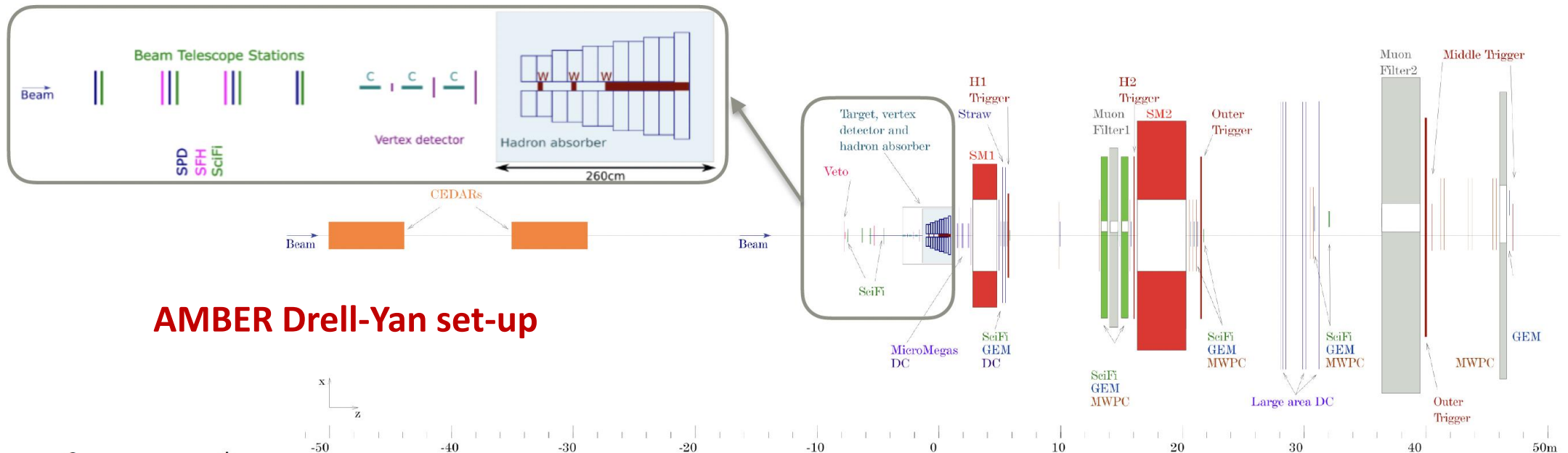


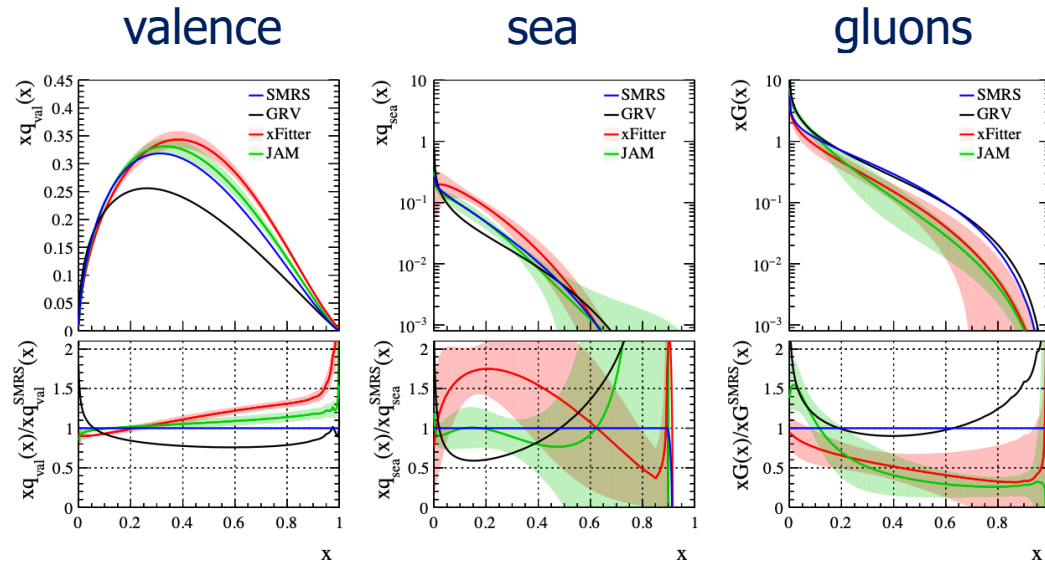
Preparation to the Phase-1 Drell-Yan experiment



Phase-1: (conventional beams)

- $\bar{p}$ production cross section measurements for DM searches (pbarX)
- Proton electric form factor: high-energy μ -p elastic scattering (PRM)
- **Meson PDFs: Drell-Yan processes (DY) and charmonium production**

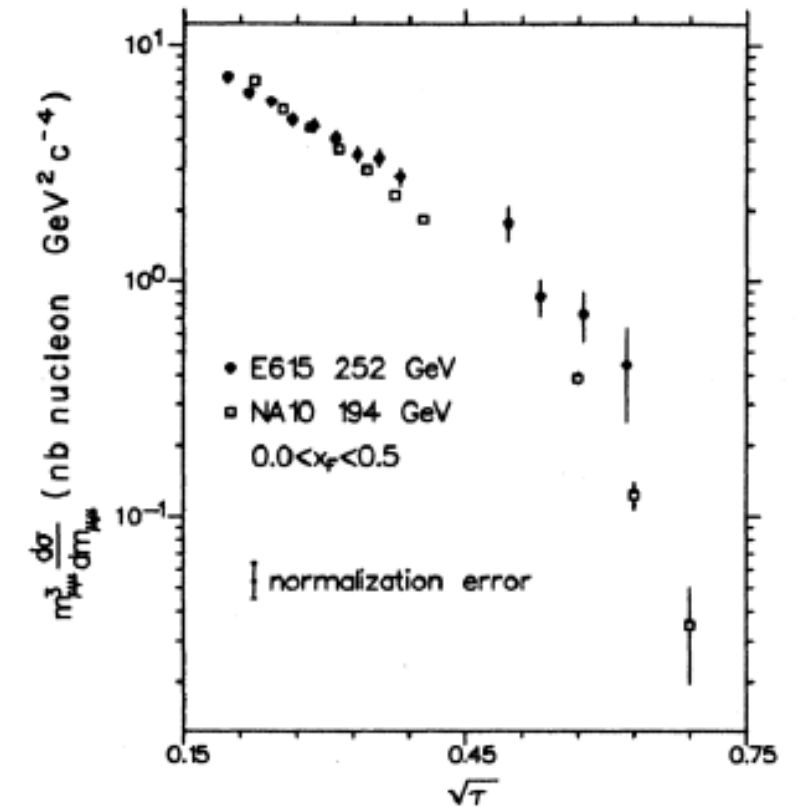




Pion structure status:

- 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

From: E615, PRD 1989

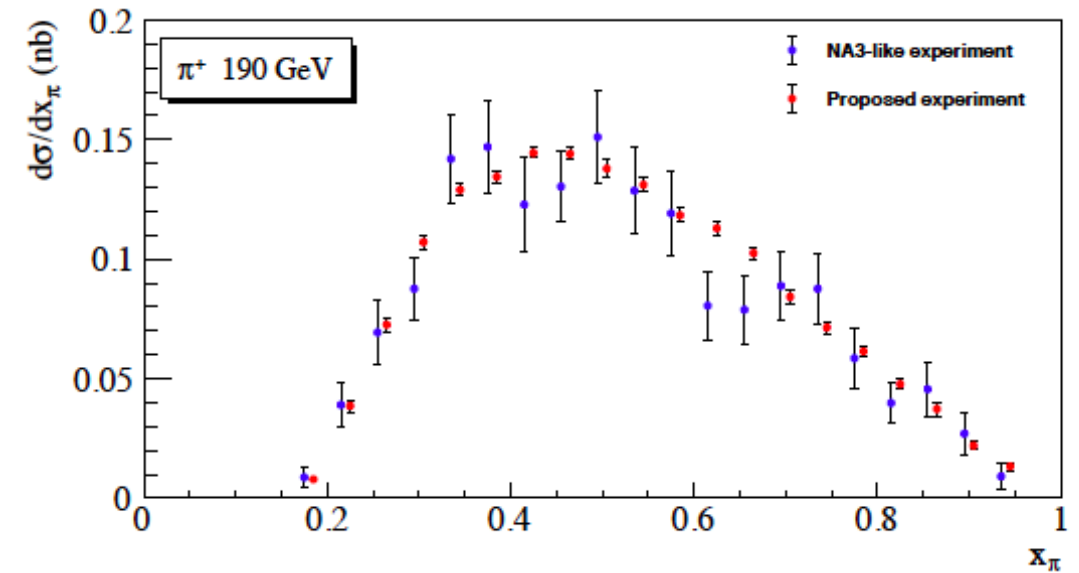
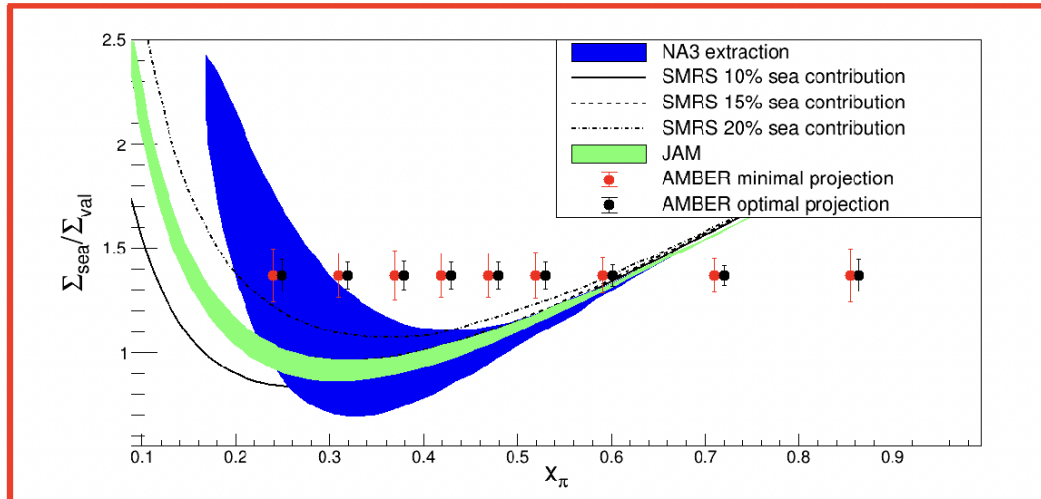


High-energy pion/kaon beams exclusively at CERN:

- Pion-and kaon-induced Drell-Yan dimuon production
- Will provide the largest pion and kaon induced DY and data sample within this decade
- Isoscalar ^{12}C target $\rightarrow$ minimize nuclear effects
- **pos. and neg. beams $\rightarrow$ Simultaneous access to the valence, sea and gluon content inside the pion**
- Dimuon mass resolution ~ 100 MeV

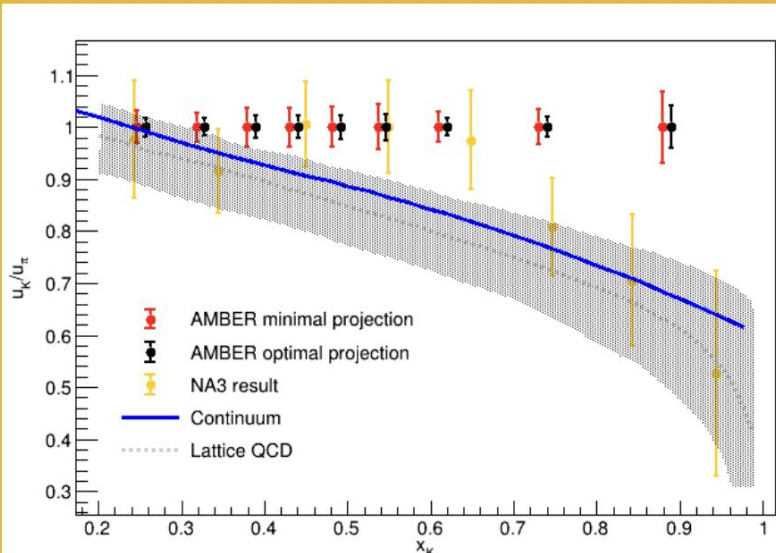
➤ AMBER aims at the first precise direct measurement of the pion sea contribution

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



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

Studying of the di-muon angular distributions (λ, μ, ν) provides a direct input to the EHM



Sole measurement from NA3

J. Badier et al., PLB93 354 (1984)

200 GeV K^- beam on 6 cm Pt target

700 kaon-induced Drell-Yan events

Scarce data on u-valence, No measurements on gluons,

No measurements on sea quarks

- With conventional meson beam, kaon-induced data collected at AMBER in parallel to the pion remains competitive (6x larger than NA3 data set after 2 years, in the minimal scenario)

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Channel	Beam	Target	Minimal (70 MHz)	Optimal (200 MHz)
Drell-Yan	π^+	75 cm C	2.9×10^4	8.3×10^4
	π^-	75 cm C	9.1×10^4	2.6×10^5
	π^+	2 cm W	1.2×10^4	3.3×10^4
	π^-	2 cm W	3.2×10^4	9.2×10^4
	$K^\pm$	75 cm C	4.2×10^3	1.2×10^4
J/ψ	π^+	75 cm C	1.2×10^6	3.4×10^6
	π^-	75 cm C	1.8×10^6	5.1×10^6
	$K^\pm$	75 cm C	5.7×10^4	1.6×10^5
$\psi(2S)$	π^+	75 cm C	2.2×10^4	6.2×10^4
	π^-	75 cm C	3.2×10^4	9.3×10^4

213 days with positive and 67 days with negative hadrons

At AMBER

Isoscalar target

Both beam charges

High statistics

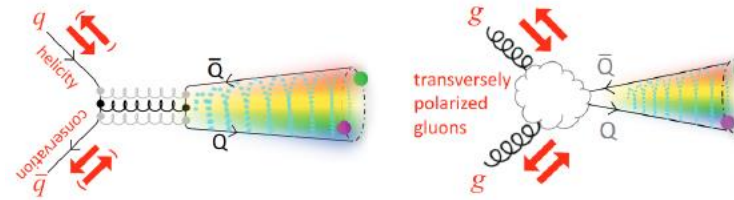
Experiment	Target	Beam	DY events	J/ψ events
NA3	Pt	$\pi^\pm$, 200 GeV	6700	236000
NA3	Pt	$K^\pm$, 200 GeV	700	—
NA10	W	π^- , 140–286 GeV	200000	—
NA10	D ₂	π^- , 286 GeV	7800	—
E615	W	$\pi^\pm$, 252 GeV	35000	—
COMPASS	NH ₃	π^- , 190 GeV	87000	2500000

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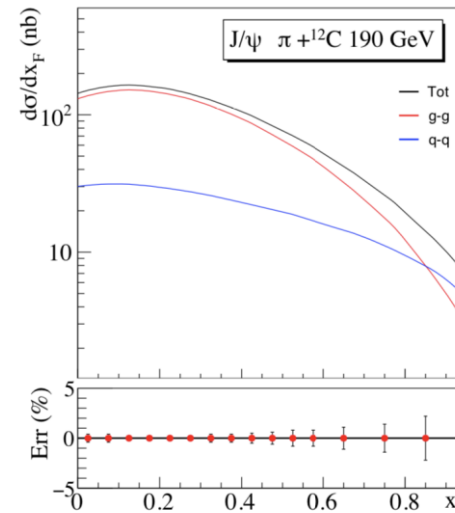
Collected simultaneously with DY data, with large counting rates

Physics objectives:

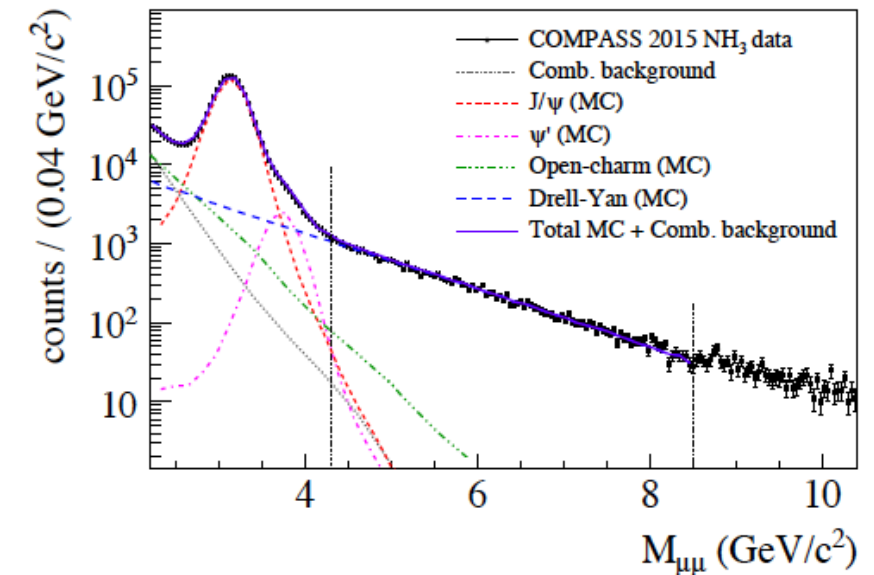
- Study of the J/ψ (charmonia) production mechanisms (gg -fusion vs $q\bar{q}$ -annihilation), comparison of **CEM** and **NRQCD**
- Probe gluon and quark PDFs of pion (arXiv:2103.11660v1 [hep-ph] 22 Mar 2021)
- $\Psi(2S)$ signal study, free of feed-down effect from χ_{c1} χ_{c2}



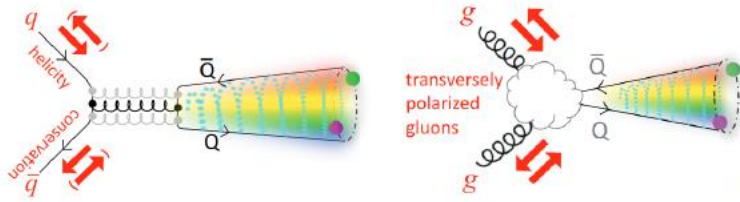
Cheung and Vogt, priv. comm.



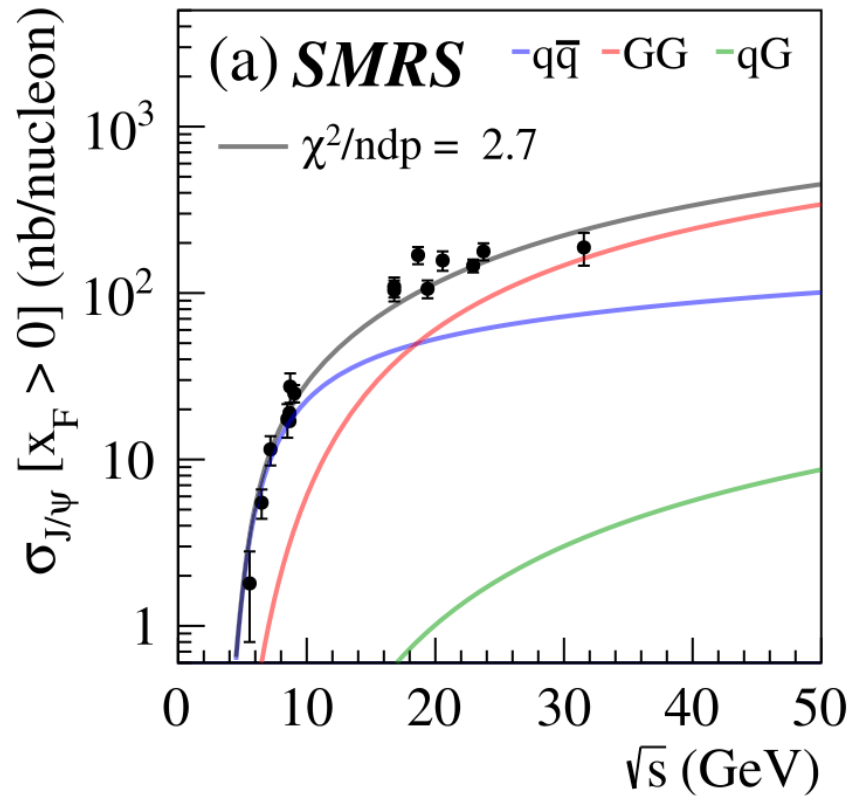
Improved CEM, CT10 + GRS99 global fit for proton/pion



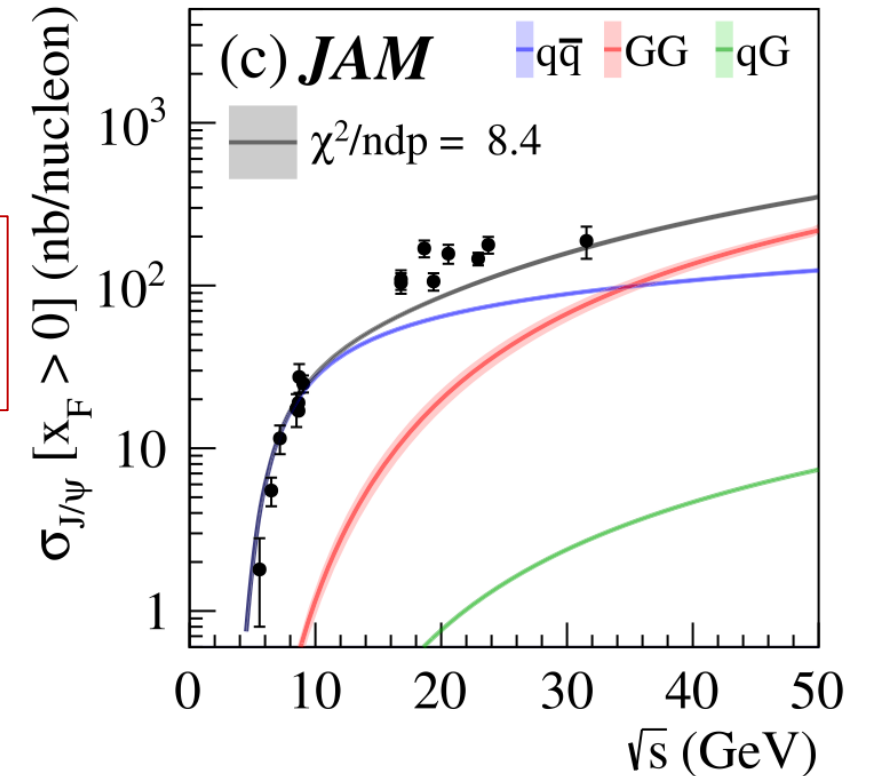
J/ψ	π^+	75 cm C	1.2×10^6	3.4×10^6
	π^-	75 cm C	1.8×10^6	5.1×10^6
	$K^\pm$	75 cm C	5.7×10^4	1.6×10^5



Model dependence of the J/ψ production cross section

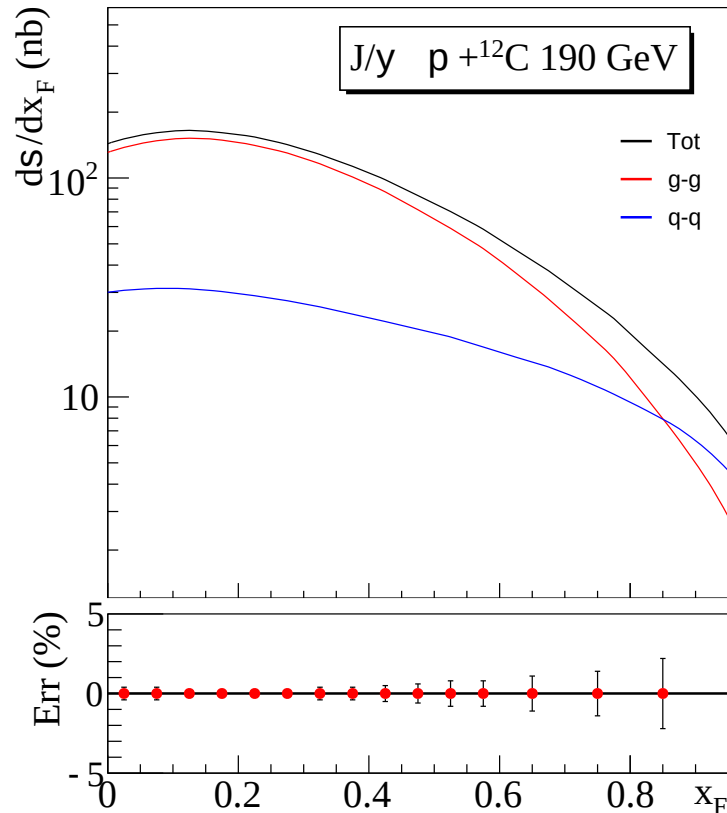


Relative contribution
From quarks and gluons
Very uncertain



SMRS vs JAM fits: strong dependence on the PDFs

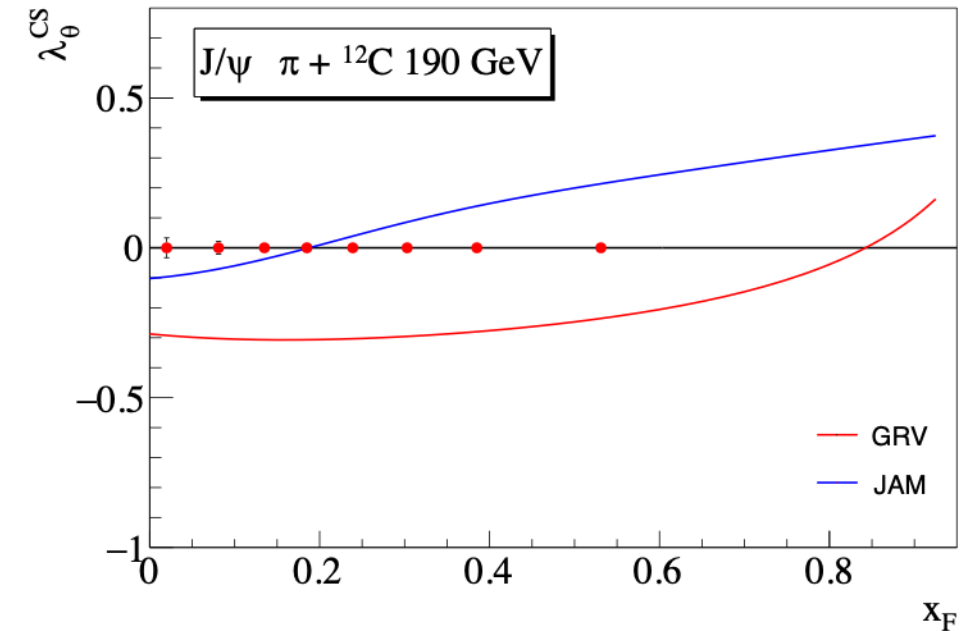
Cross section (ICEM)



Both x_F -distribution and polarization depend on the relative amount of quark/gluon content

Polarization (ICEM)

CHEUNG AND VOGT,
PRIV. COMM., 2020



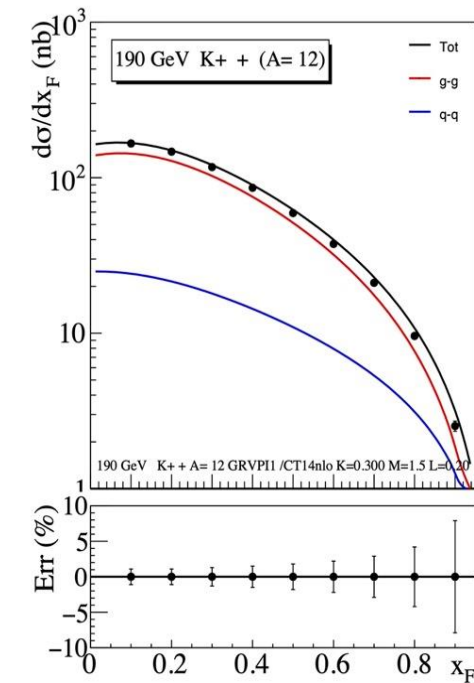
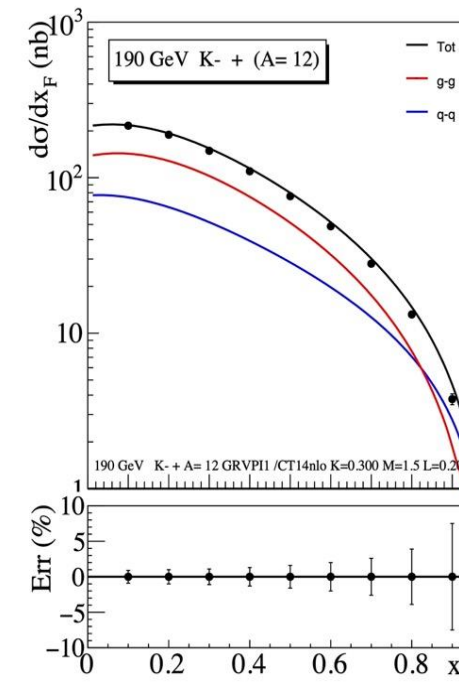
$$\frac{d\sigma^{J/\psi}}{d\Omega} \sim 1 + \lambda_{\theta}^{CS} \cos^2(\theta)$$

- From $q\bar{q} \rightarrow J_z = \pm 1 \rightarrow \lambda = -1$
- From $gg \rightarrow J_z = 0 \rightarrow \lambda = 1$

Nb of events: 25 000 K^-

32 000 K^+

- Identify the kaon component with the CEDARs
 - positive beam ($K = 1.5\%$)
 - negative beam ($K = 2.4\%$)
- Expected statistics
 - 210 days of positive beam (K^+)
 - 70 days of negative beam (K^-)
 - CEDARs efficiency: 60%



K⁻ and K⁺ -induced J/ψ cross sections direct access to the kaon valence PDF

J/ψ – access to the kaon valence PDF

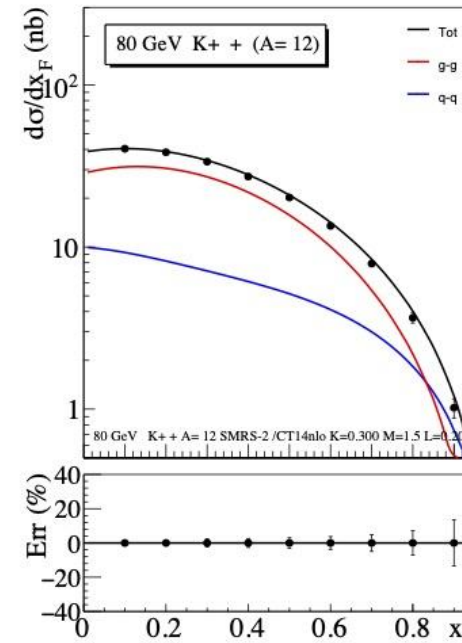
- Quark content in the kaon:
K⁺(u $\bar{s}$); K⁻($\bar{u}s$)
- Production cross section for K⁺ and K⁻



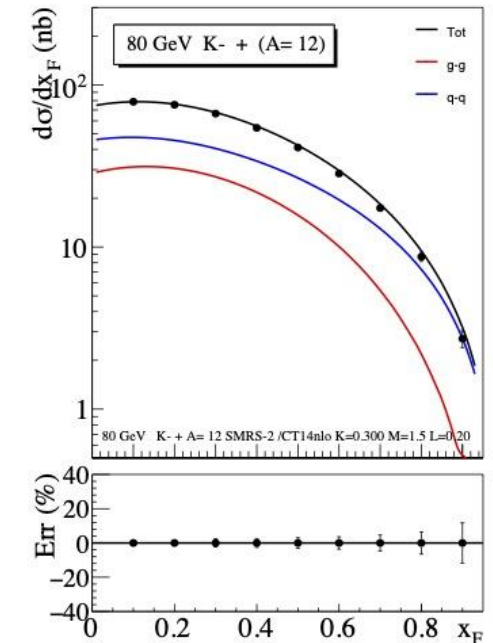
$$\begin{aligned}
 K^-(\bar{u}s) + p(uud) &\propto gg + \underbrace{[\bar{u}_v^K u_v^p]}_{\text{val-val}} + \underbrace{[\bar{u}_v^K u_s^p + s_v^K s_s^p]}_{\text{val-sea}} + \underbrace{[\bar{u}_s^K u_v^p]}_{\text{sea-val}} + \underbrace{[\bar{u}_s^K u_s^p + u_s^K \bar{u}_s^p + s_s^K \bar{s}_s^p + \bar{s}_s^K s_s^p]}_{\text{sea-sea}} \\
 K^+(u\bar{s}) + p(uud) &\propto gg + \underbrace{[---]}_{\text{val-val}} + \underbrace{[u_v^K \bar{u}_s^p + \bar{s}_v^K s_s^p]}_{\text{val-sea}} + \underbrace{[\bar{u}_s^K u_v^p]}_{\text{sea-val}} + \underbrace{[\bar{u}_s^K u_s^p + u_s^K \bar{u}_s^p + s_s^K \bar{s}_s^p + \bar{s}_s^K s_s^p]}_{\text{sea-sea}}
 \end{aligned}$$

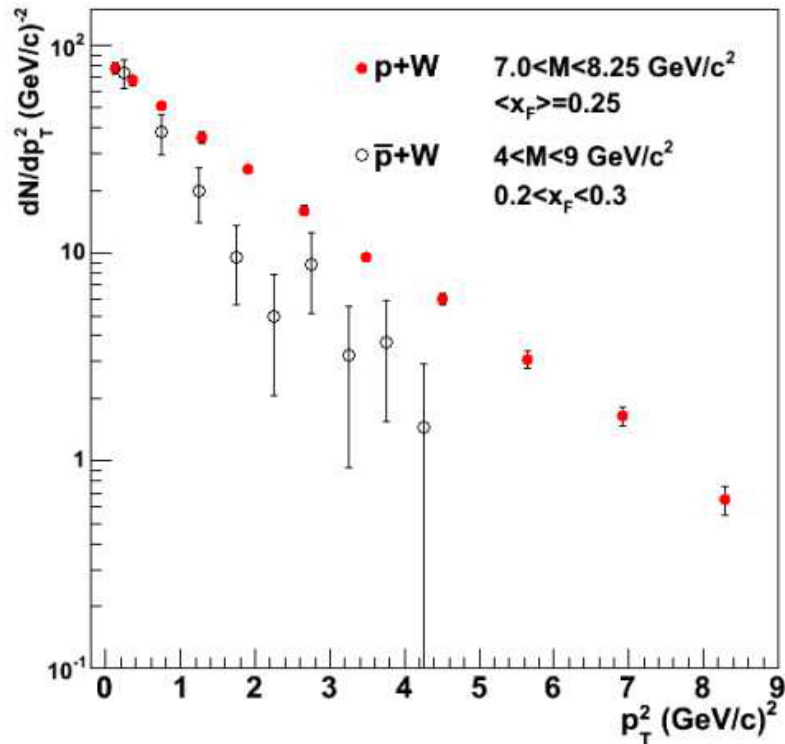
- The cross section difference isolates the val-val term: $\sigma(K^-) - \sigma(K^+) \propto \bar{u}_v^K u_v^p$

K⁺ beam



K⁻ beam





Study the difference between valence and sea quark TMD PDFs

Chiral quark soliton models suggest that the transverse momentum width of sea quarks in a proton may be as much as three times broader than that of the valence distribution

C. A. Aidala et al., Phys. Rev. D 89, 094002 (2014)

W. Oliver, H. R. Gustafson, L. W. Jones, M. Longo, T. Roberts, et al., AIP Conf.Proc. 45, 93 (1978).

E. Anassontzis, S. Katsanevas, E. Kiritsis, P. Kostarakis, C. Kourkouvelis, et al., Phys.Rev. D38, 1377 (1988).

→ Compare transverse momentum distributions for pA and $p\bar{b}A$ DY collisions

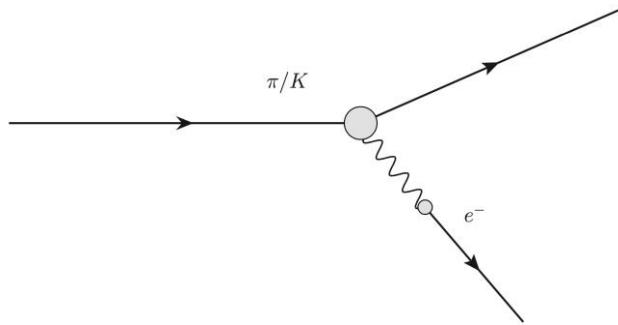
→ Use exactly the same beam energy + same x_1 , x_2 and Q .

pA case: (quark-in-proton) $\times$ (*antiquark-in-A*) TMD PDFs

$p\bar{b}A$ case: (*antiquark-in-antiproton*) $\times$ (quark-in-A) TMD PDFs

→ Difference of p_T distributions probes difference between valence and sea quarks

Precise measurements of pion and kaon radii will reveal the compositeness (confinement) scale for (near) Nambu-Goldstone bosons. At the moment there is basically no precise experimental information on kaon charge radius.



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

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

$$Q_{\text{max}}^2 = \frac{4p_b^2 m_e^2}{s}$$

Beam	E_b [GeV]	Q_{max}^2 [GeV ²]	$E'_{b,\text{min}}$ [GeV]	Relative charge-radius effect on c.s. at Q_{max}^2
π	190	0.176	17.3	~40%
K	190	0.086	105.7	~20%
	80	0.066	59.9	~15%
	50	0.037	41.3	~8%

For **kaons**, a significant increase of the form factor knowledge in the range $0.001 < Q^2 < 0.07$ appears in reach with AMBER using an **80 GeV rf-separated kaon beam**

S. R. Amendolia, et al. , Phys. Lett. B 178, 435 (1986)

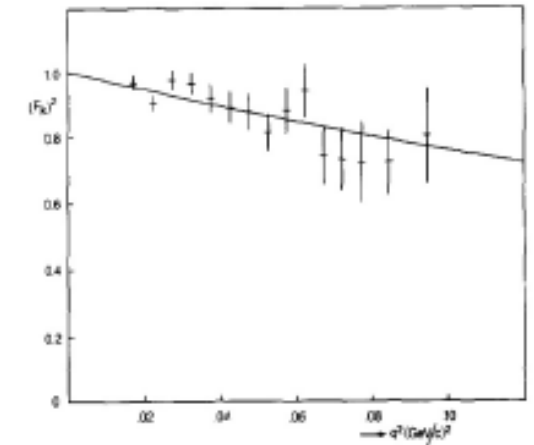
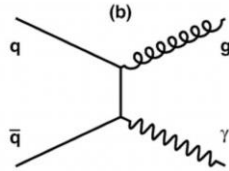
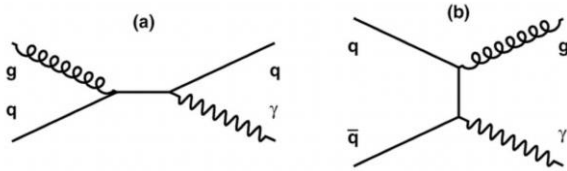


Fig. 3. The measured kaon form factor squared. The line corresponds to the pole fit with $\langle r^2 \rangle = 0.34 \text{ fm}^2$.



Prompt Photons Production measurement at AMBER

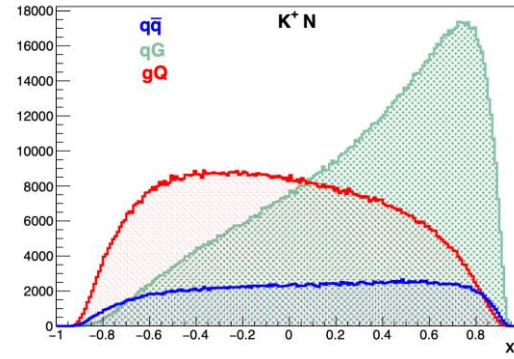
Prompt photons probe – direct access to the gluon content of the kaon.
At the moment there is no experimental information about gluon contribution in kaon.



$$\sigma_{\pi/KN \rightarrow \gamma X} = [\bar{q}Q + q\bar{Q}] + [gQ + qG]$$

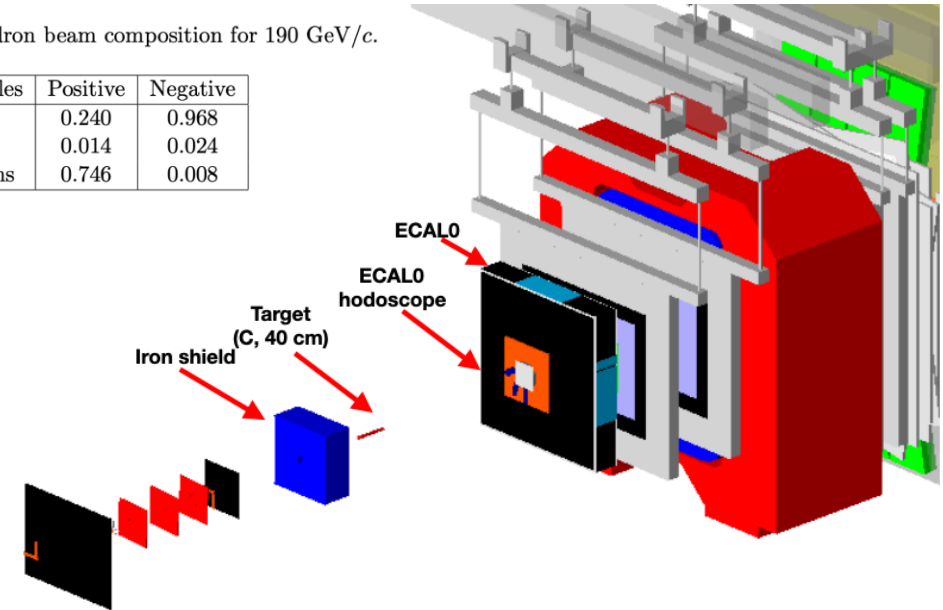
$$\sigma_{K^-} - \sigma_{K^+} \sim \bar{u}_K U_N$$

σ_{K^+} at $x_F < 0$ sensitive to gluon content

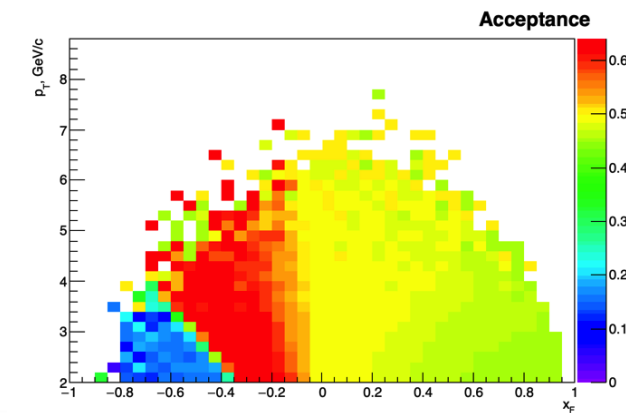
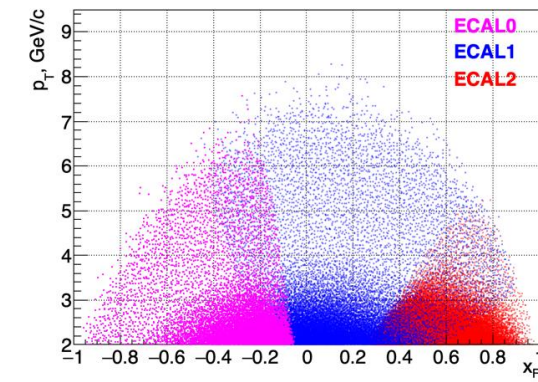
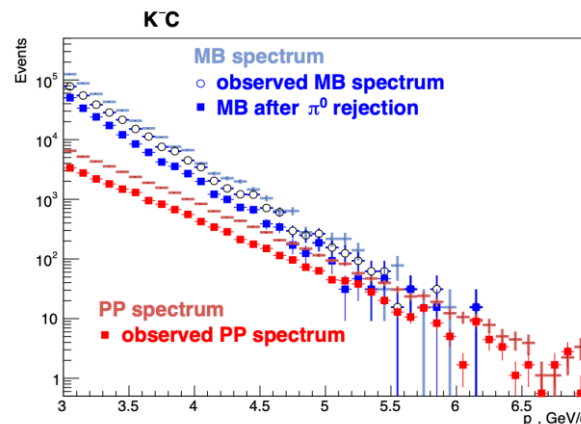
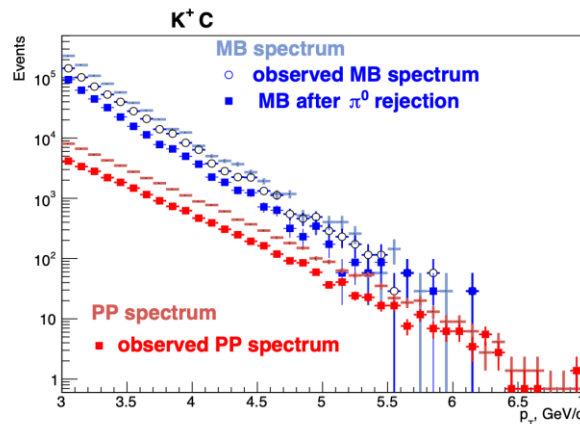


2 line hadron beam composition for 190 GeV/c.

Particles	Positive	Negative
Pions	0.240	0.968
Kaons	0.014	0.024
Protons	0.746	0.008

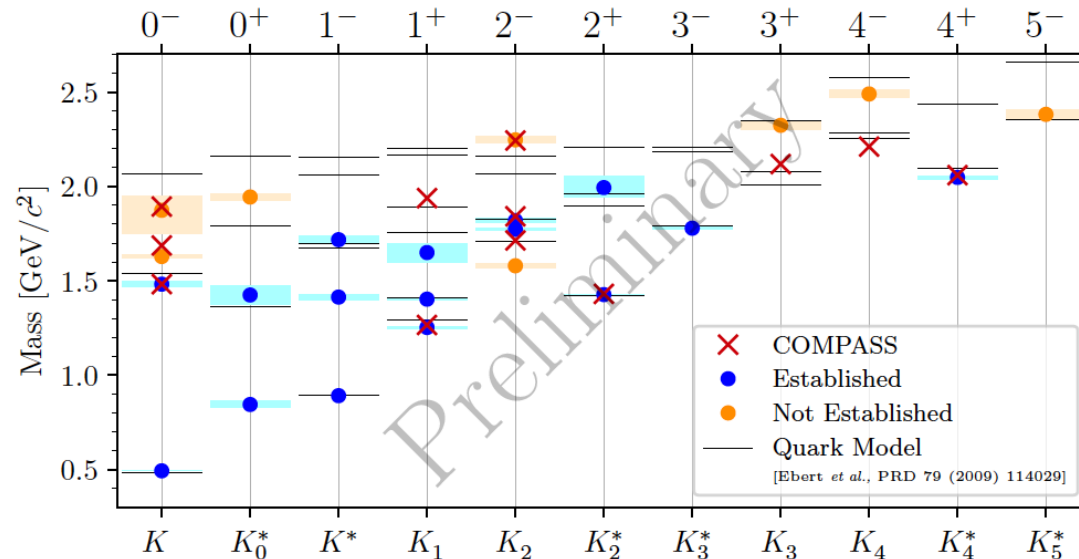


- 150 days of data taking shared between positive ($T_+ = 120$ days) and negative ($T_- = 30$ days) hadron beams with a duty factor of 70%
- 25 000 and 18 000 prompt photons with $p_T > 3$ GeV/c
- MC-based and data-driven minimum bias background subtraction



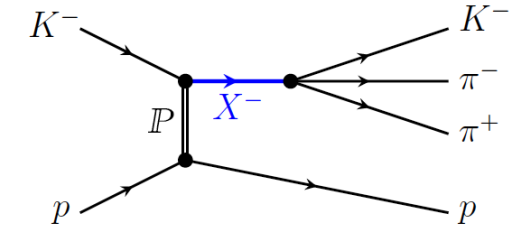
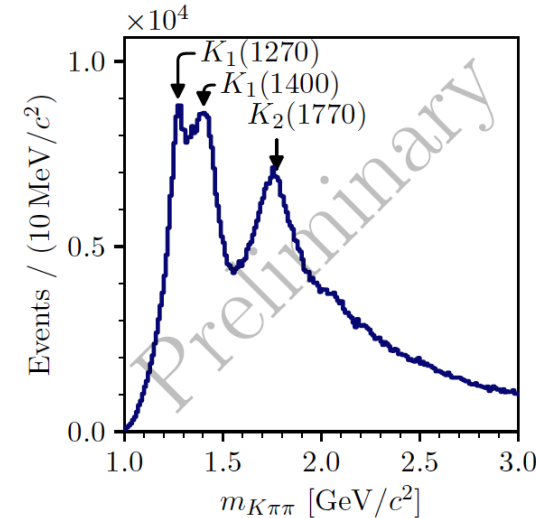
PDG lists 25 strange mesons

- ▶ 16 established states, 9 need further confirmation
- ▶ Missing states with respect to quark-model predictions
- ▶ Many measurements performed more than 30 years ago



Strange-Meson Spectroscopy with COMPASS

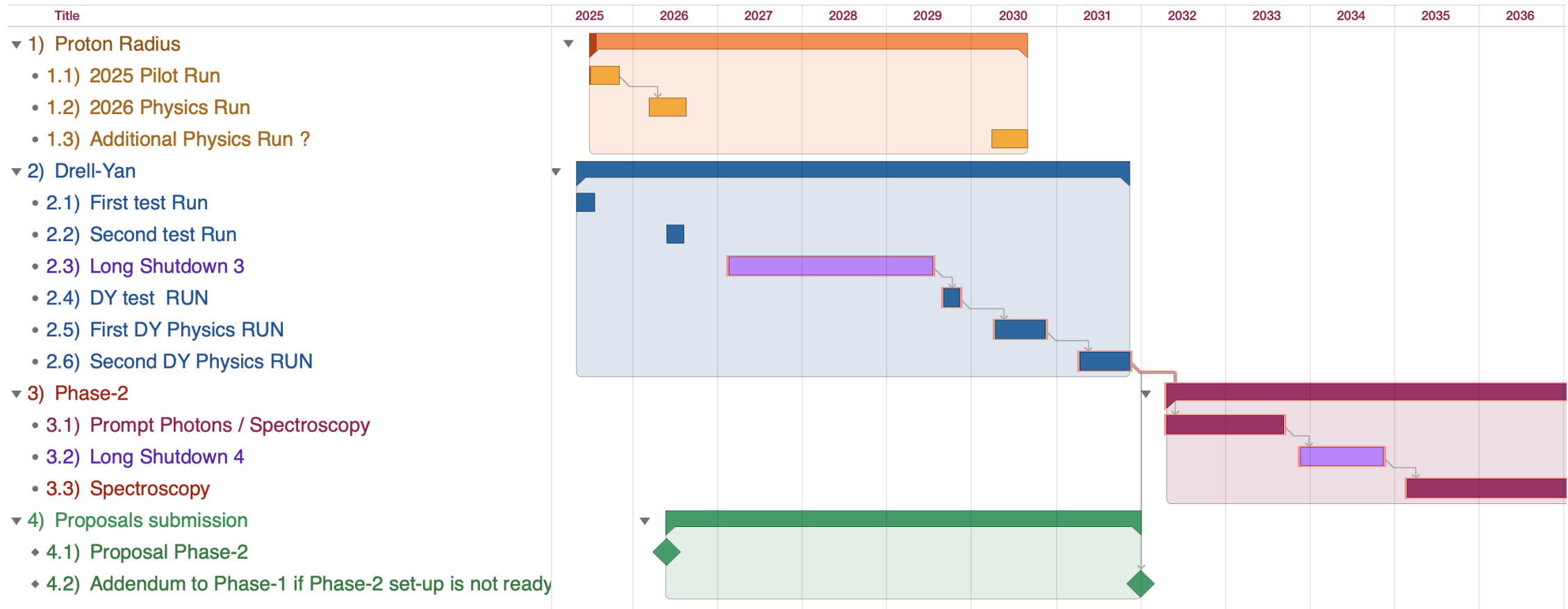
The $K^- \pi^- \pi^+$ Data Sample



- ▶ World's largest data set of about 720 k events
- ▶ Rich spectrum of overlapping and interfering X^-
 - ▶ Dominant well known states
 - ▶ States with lower intensity are "hidden"

AMBER QCD Facility, goal for Kaon induced Spectroscopy to Collect $10\text{-}20 \times 10^6$ $K^- \pi^+ \pi^-$ events using high-intensity high-energy kaon beam:

- Optimised Conventional Hadron beam line
- Higher wrt COMPASS beam intensity
- Better pion/kaon beam particles separation
- Much more powerful pid in the final state



We are in the beginning of a very long journey – consider to join if you see your interests...

AMBER WEB Page:
<https://amber.web.cern.ch/>



Summary: AMBER at CERN SPS



- We did a great job in COMPASS to understand better the proton spin structure, we are leaving a floor to the next generation high-luminosity facilities
- We are very happy that we managed with the approval of AMBER Phase-1 to provide long-term future for hadron physics at CERN (it was quite an effort taking into account uneasy neighbourhood of the LHC..)
- We are solid collaboration of 35 Institutions from 14 countries, ~180 physicists. Still we are looking for new motivated and skilful collaborators
- Data taking of the AMBER Phase-1 is ongoing
- Focus is on EHM related studies but of course we will measure as well unpolarised TMD PDFs of unstable particles.



Next AMBER-organized event: Physics At AMBER (PAW) & IWHSS at Camogli, Portofino Coast, Italia



PAW & IWHSS - Joint international Workshop 2026

12–14 Oct 2026
Hotel Cenobio dei Dogi
Europe/Zurich timezone





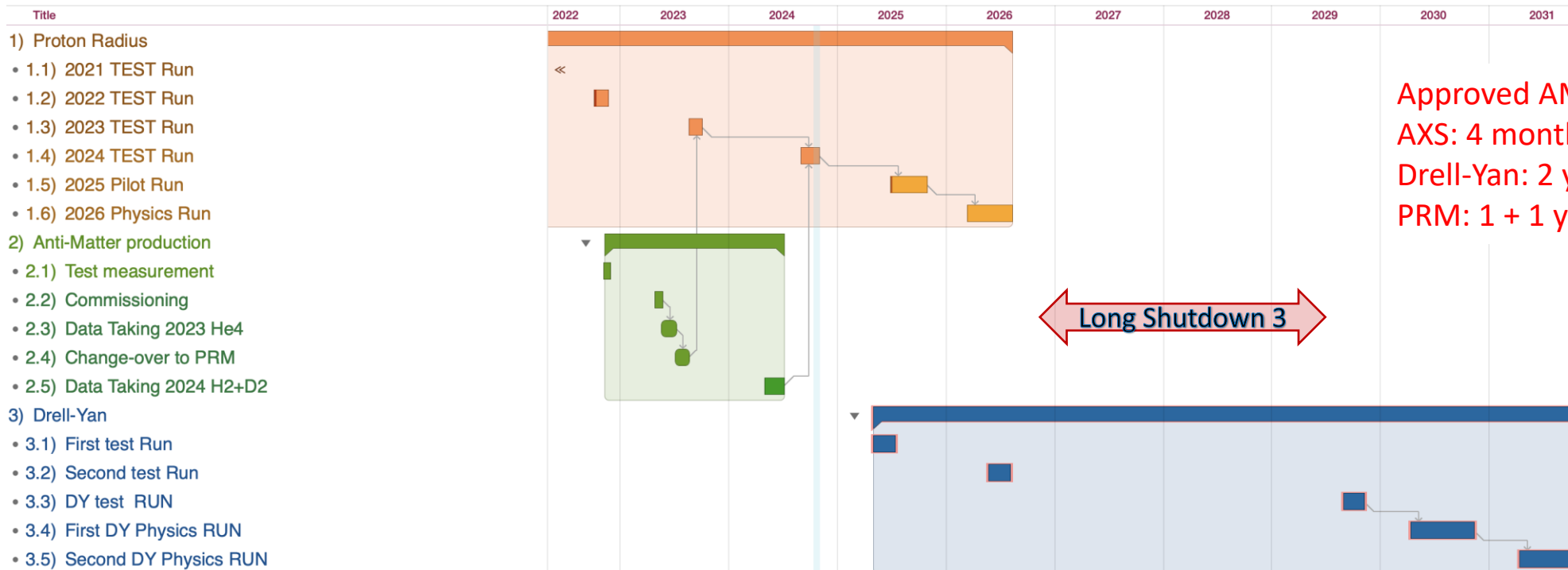
Spares



AMBER Phase-1 running plan

Milestones:

1. May 1st 2023, 2024 – Antimatter production Run (Std. DAQ)
2. Sep. 1st 2024 – PRM Test (FriDAQ, very limited setup)
3. July 1st – Oct. 31st 2025 – PRM Pilot (FriDAQ, limited setup)
4. March 15th - Aug. 8th 2026 – PRM Physics (FriDAQ, PRM setup)
5. Sep. 1st 2025, 2026 – DY Test (FriDAQ, all trackers + mu id)
6. Sep. 1st 2029 – DY test Run (FriDAQ, full Drell-Yan setup)
7. April 30th – Oct. 31st 2030/31 – DY Physics Run



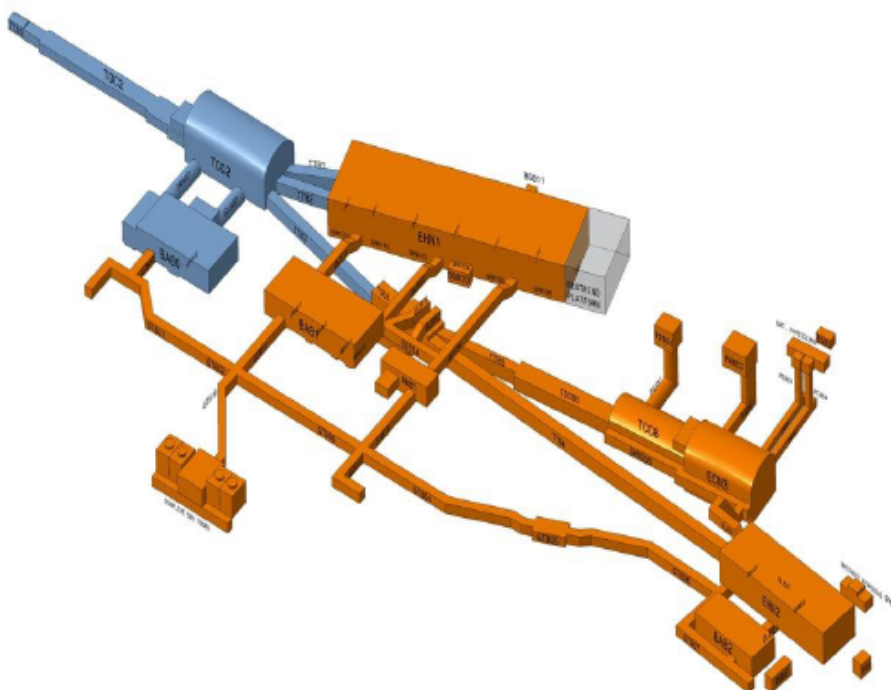
Approved AMBER Phase-1 Program:
AXS: 4 months
Drell-Yan: 2 years
PRM: 1 + 1 year (conditionally)

NA-CONS Scope/Roadmap

EDMS 2458866

Consolidation Phase 1:

2019 – 2028: primary areas (incl. BA2), BA80 & beamlines towards EHN1 & TDC8



Pre-Phase I			Phase I						Phase II						
LS2		Run 3						LS3		Run 4				LS4	
2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	
Power Converter Consolidation study		Power Converters in BA80: - PC & E.E. for vertex1&2 + H8 Morpurgo (YETS 21/22) 50% of the power converters 50% of availability recovered (TT20, TDC2, start of NA)								Power Converters BA81 & BA82: 50% of the power converters 100% of availability recovered					
Beam Instrum: review & analysis Crates consolidation Electrical non-conformities		Beam Instrumentation: 60% of consolidation								Consolidation & Upgrade for higher intensity: remaining 40%					
Civil Eng.: roof of gas barracks BA gate doors		Civil Engineering: BA80, 5 th cell for CT2 Light repairs elsewhere								Civil Eng.: EHN1, EHN2, ECN3, BA81, BA82					
Tech.Services: CT2, cooling plant, Chilled water piping, Irrad cables TDC2, Lift for TCC8		Technical Services: EL: BA80, TDC2, TCC2, UPS, secured network CV: underg. ventil, chilled water, cooling station, CT2, new cooling station for converters in BA80								Technical Services: EL: BA81, BA82, EHN1, EHN2, ECN3 CV: ventil. surf bldg., primary pumps circuits, new cooling station in BA81 and 82 (for PC) CRG: centrifugal helium pumps					
Safety: Gas network, Gas detection, ATEX ventil. SUSI 918, EHN2 video ECN3, EHN2		Safety (95%): - Underground & Surface Fire detection & Alarm. - Fire detection in false floors BA80 - Sprinklers underground (shafts) - Fire detection EHN2 galleries - Pilot test for new access control system								Safety (remaining 5%): - Fire detection in ventilation and in false floors for BA81 & BA82 - Access system deployment					

Consolidation Phase 2:

2029 – 2034: BA81, BA82, EHN1, EHN2 & associated beamlines

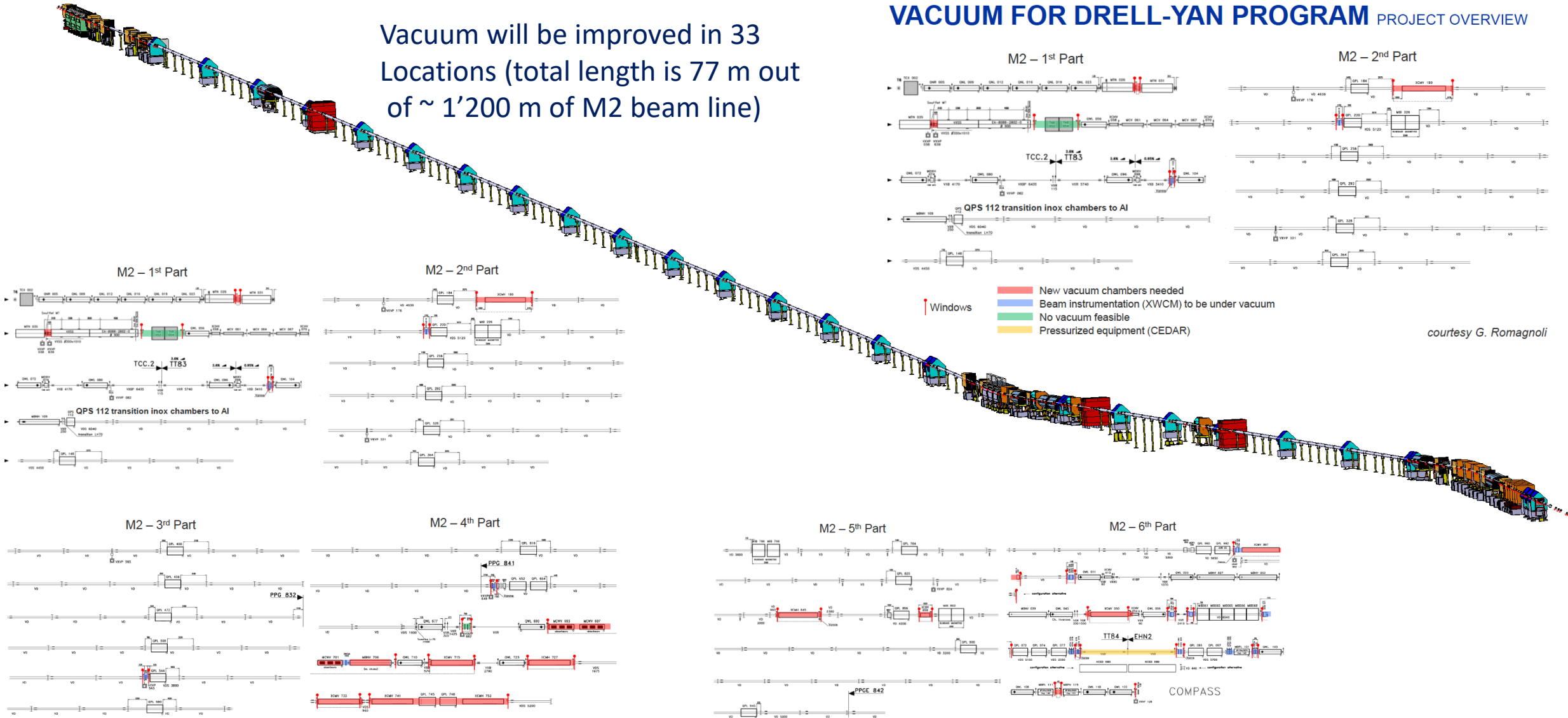


Status of the AMBER Facility preparations: AMBER/EHN2 beam line upgrade: vacuum improvements and beam line instrumentation

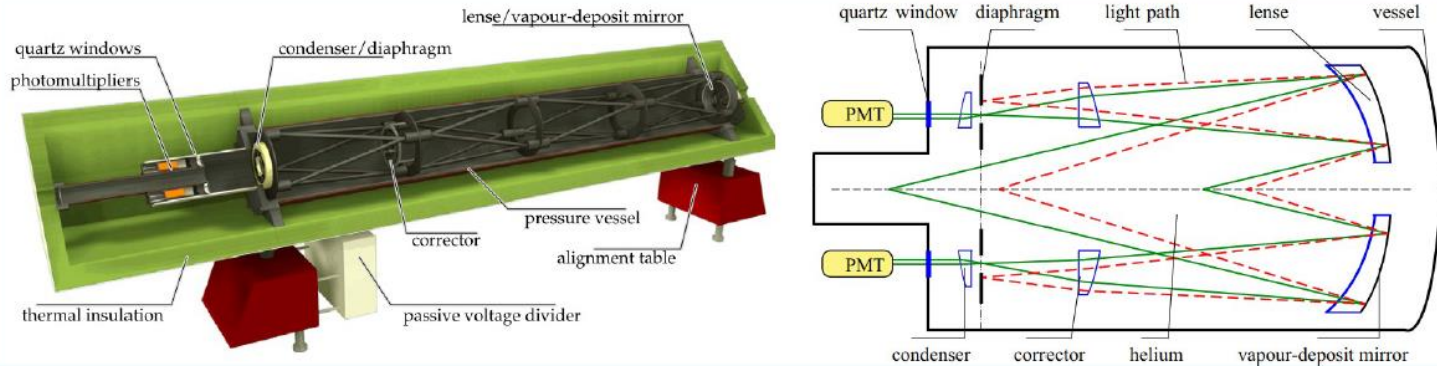


Vacuum will be improved in 33
Locations (total length is 77 m out
of ~ 1'200 m of M2 beam line)

VACUUM FOR DRELL-YAN PROGRAM PROJECT OVERVIEW



Cherenkov Differential counter with Achromatic Ring Focus



We (AMBER and CERN Beam Dep.) are improving on both hardware (mechanics, read out electronics) and methods. In 2023 we run a full hadron intensity beam test ($\sim 10^8$ hadrons/s) for CEDARs & new beam telescope and for the first time we clearly see kaon peak in likelihood distribution

CEDAR refurbishment YETS 2023/2024

M. Lino Diogo Dos Santos

The CEDAR open issues were compiled and reported at the end of the 2023 run. The two M2 CEDARs have been prioritized and refurbished:

M2 - SPXCEDN001 - CR000002
M2 - SPXCEDN001 - CR0000020

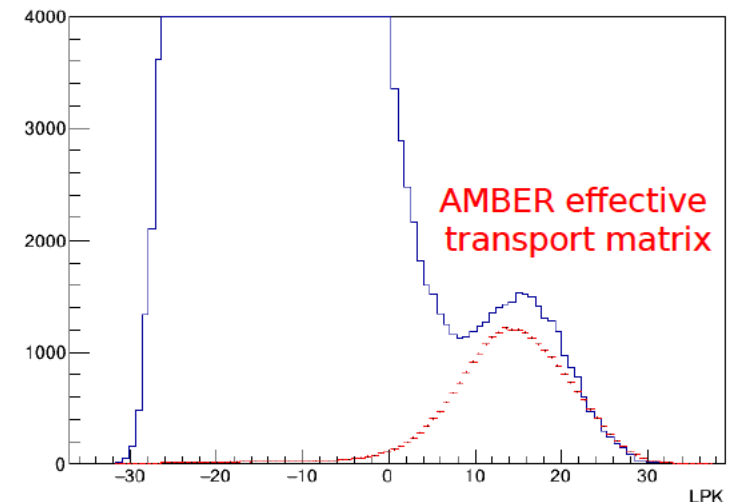
- Diaphragm – Mechanics Refurbishment
- Motor + Switches – Replacement
- Gas – Gas pipes refurbishment (correct sized shape etc.)
- Joints – Replacement
- Optics – Alignment
- XY Table – Table precision check / replacement
- Alignment – Realignment of CEDAR

For all CEDARS

- Installing new pressure sensors
- Validating new diaphragm movement algorithm
- Measuring quantum efficiency of spare PMTs – To requalify or discard the spare park of PMTs



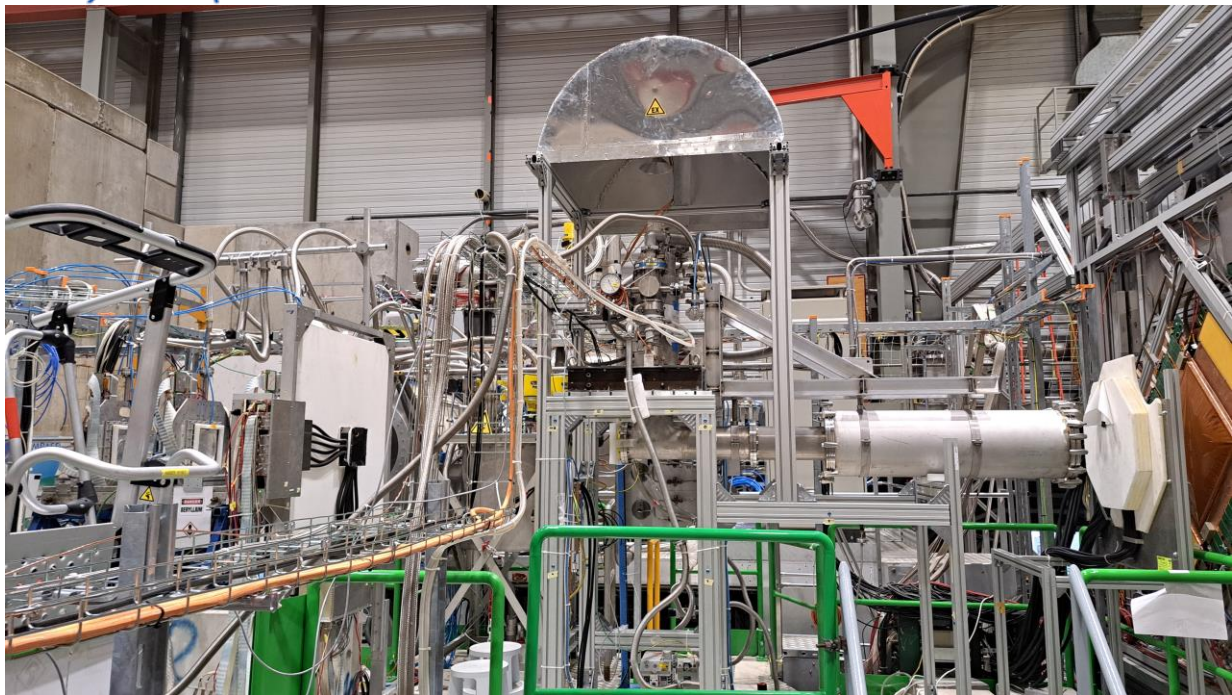
Courtesy: K. Bernhard-Novotny

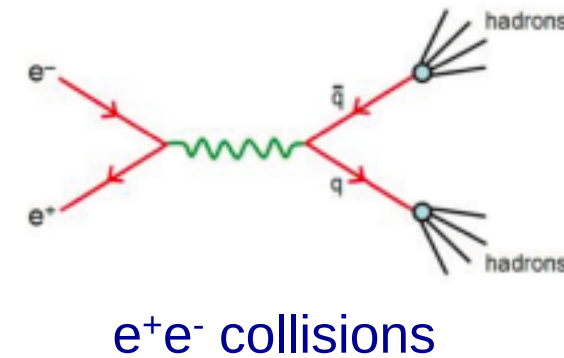
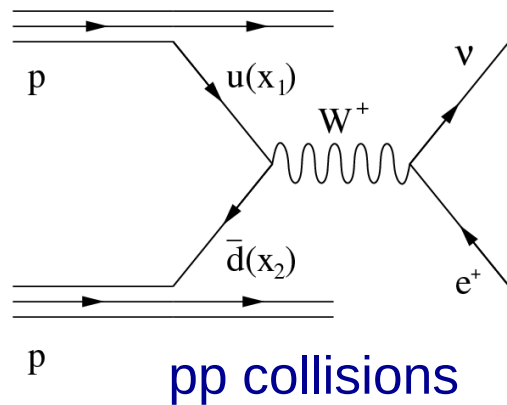
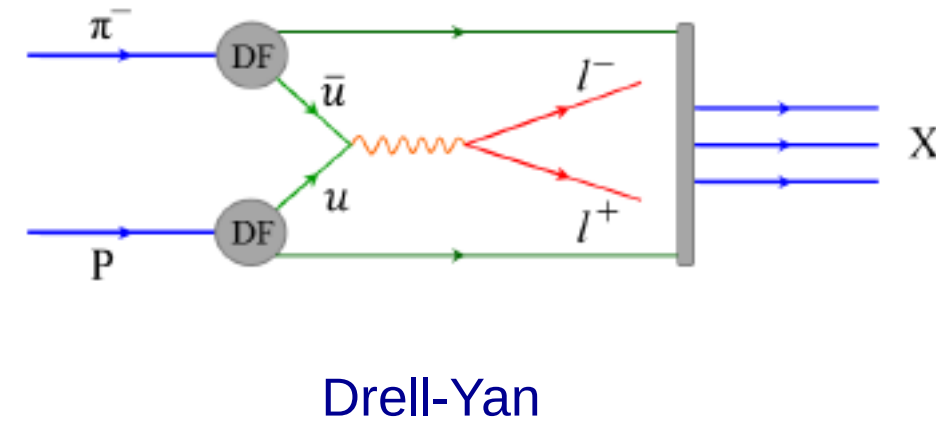
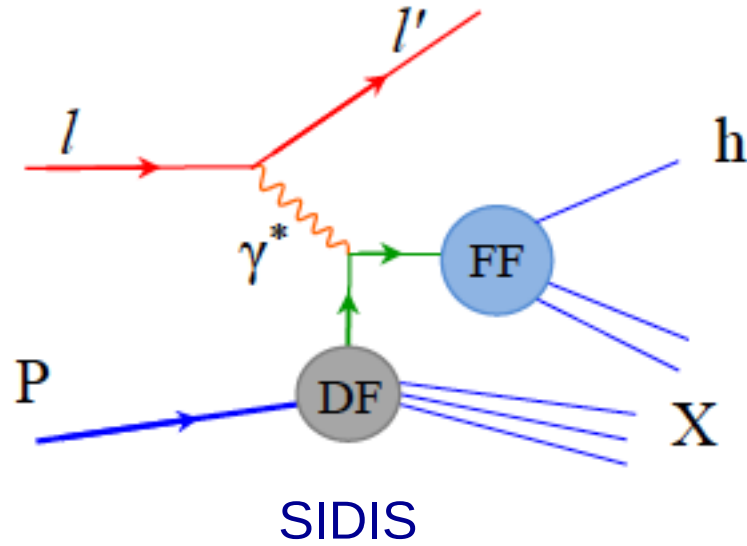




Status of the AMBER Facility preparations: 2024 APX run preparation

AMBER
Apparatus for Meson and Baryon
Experimental Research







Principles to be respected while preparing new experiment at CERN



Once we are started to think about successor of COMPASS and continuation of hadron physics at CERN apart of reasoning mentioned above we were guided by few CERN-established principles:

1. High scientific value of the proposed measurements, i.e. importance of science questions to be addressed by the experiment
2. Results awaited by a broad scientific community
3. **Uniqueness of the proposed experiments, everything what could be done somewhere else but at CERN should be done somewhere else**
4. **Results, once achieved should define the state of the art in the field for a long time**

Former two are sort of common, latter two are rather CERN-specific.



AMBER

more than 15 years-long effort



We have started to work on physics program of possible COMPASS successor > 15 years ago.

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

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

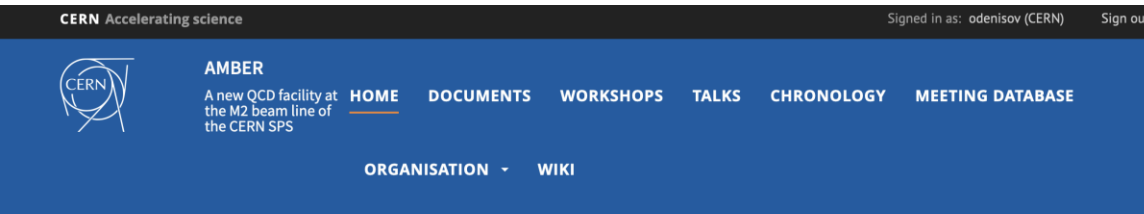
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



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

[LoI submitted in January 2019](http://arxiv.org/abs/1808.00848)
<http://arxiv.org/abs/1808.00848>

Apparatus for Meson and Baryon Experimental Research
> 270 authors



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\[nucl-th\]](https://arxiv.org/abs/1606.03909), [arXiv:1905.05208\[nucl-th\]](https://arxiv.org/abs/1905.05208).

Letter of Intent:

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

COMPASS++[†]/AMBER[‡]

B. Adams^{13,12}, C.A. Aidala¹, R. Akhunzyanov¹⁴, G.D. Alexeev¹⁴, M.G. Alexeev⁴¹, A. Amoroso^{41,42},



AMBER PHASE-1 (proposal submitted in Sep. 2019, approved in Dec. 2020)



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

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	$\mu^\pm$	$NH_3^\dagger$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\bar{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\bar{p}$ -induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	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	$K^\pm, \bar{p}$	$NH_3^\dagger$, 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
Conventional hadron and muon beams
2022 → 2025
Improved conventional Hadron/Hadron beam
2027 → 2030

PHASE-2
Improved conventional Hadron/Hadron and muon beam
2029 and beyond

The answer is obviously NOT (SM paradigm):

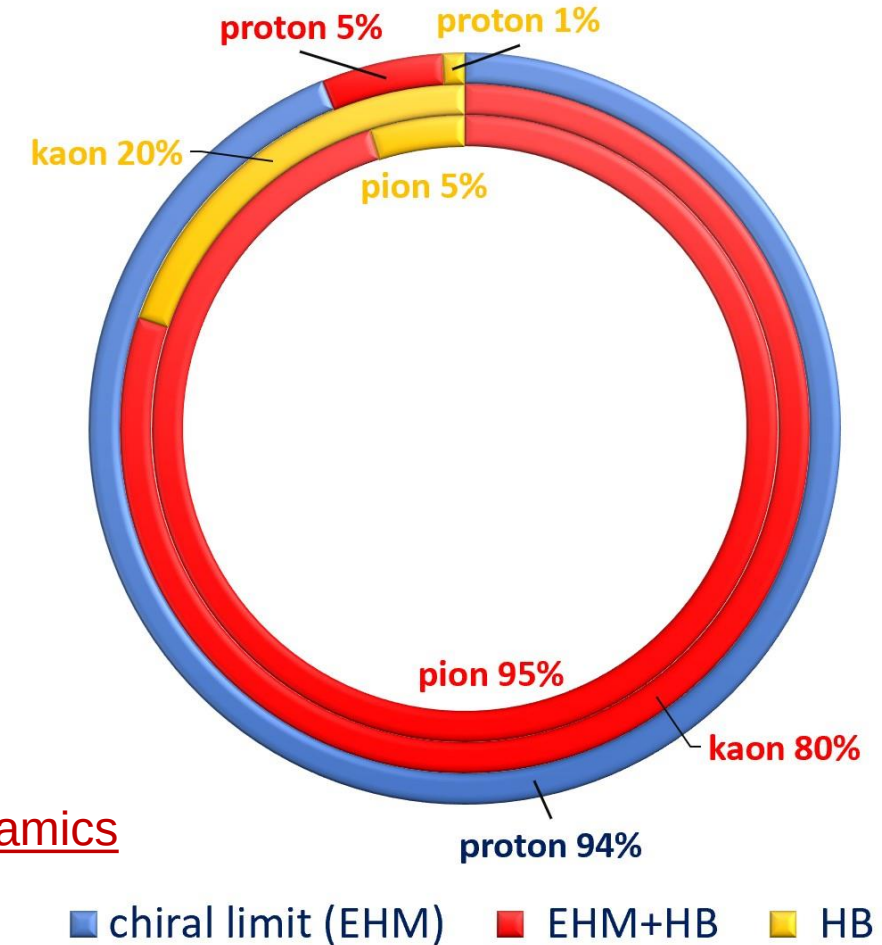
- proton is described by QCD ... 3 valence quarks
- pion is also described by QCD ... 1 valence quark and 1 valence antiquark
- expect $m_p \approx 1.5 \times m_\pi$... but, instead $m_p \approx 7 \times m_\pi$

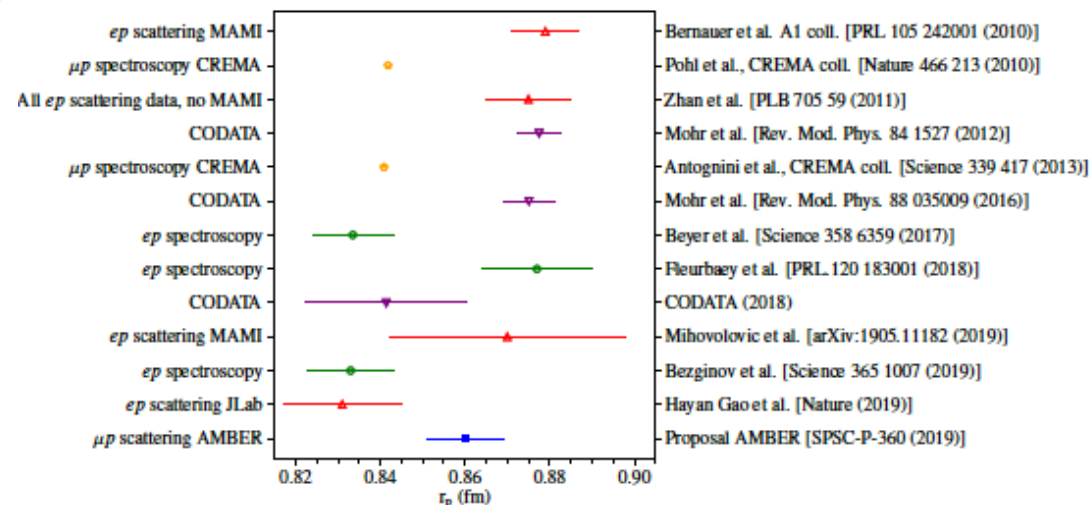
Proton and pion/kaon difference:

- 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

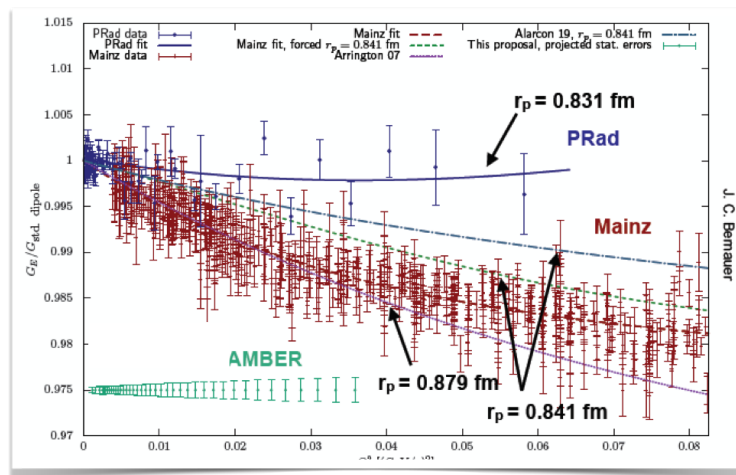
Thus it is equally important to study the internal structure and dynamics of pions, kaons and protons

Mass Budgets





	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 $Q^2 = 0,001 \text{ GeV}^2/c^2$, Cross section is normalised to the G_D - dipole form factor

$$\begin{aligned} \langle r_p^2 \rangle &= -6\hbar^2 \cdot \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2 \rightarrow 0} \\ \frac{d\sigma^{\mu p \rightarrow \mu p}}{dQ^2} &= \frac{4\pi\alpha^2}{Q^4} R \left(\epsilon G_E^2 + \tau G_M^2 \right) \quad \epsilon = \frac{E_\mu^2 - \tau(s - m_\mu^2)}{\vec{p}_\mu^2 - \tau(s - 2m_p^2(1 + \tau))} \quad \tau = \frac{Q^2}{(4m_p^2)} \end{aligned}$$

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



Proton Radius Experiment at Jefferson Lab

PRoton
radius



MESA
Mainz
Energy-recovering
Superconducting
Accelerator

PAUL SCHERRER INSTITUT
PSI

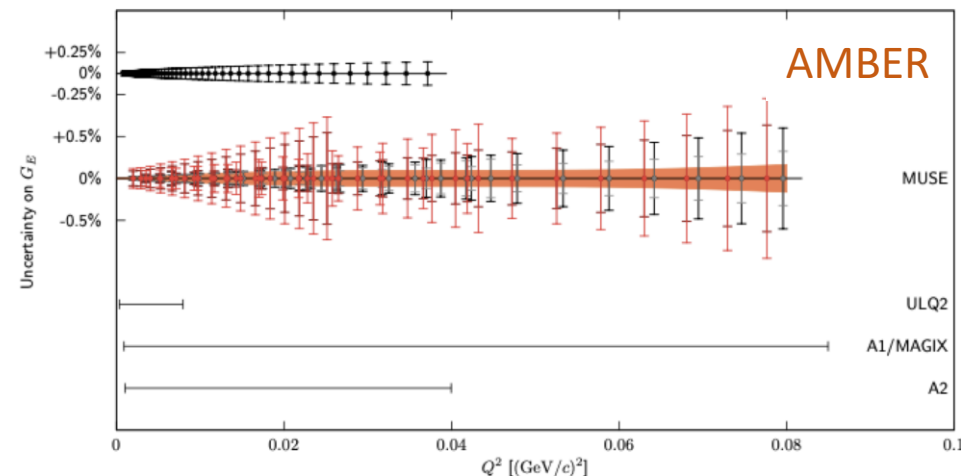
Proton Radius Measurement at AMBER (confinement)

AMBER
Apparatus for Meson and Baryon
Experimental Research

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

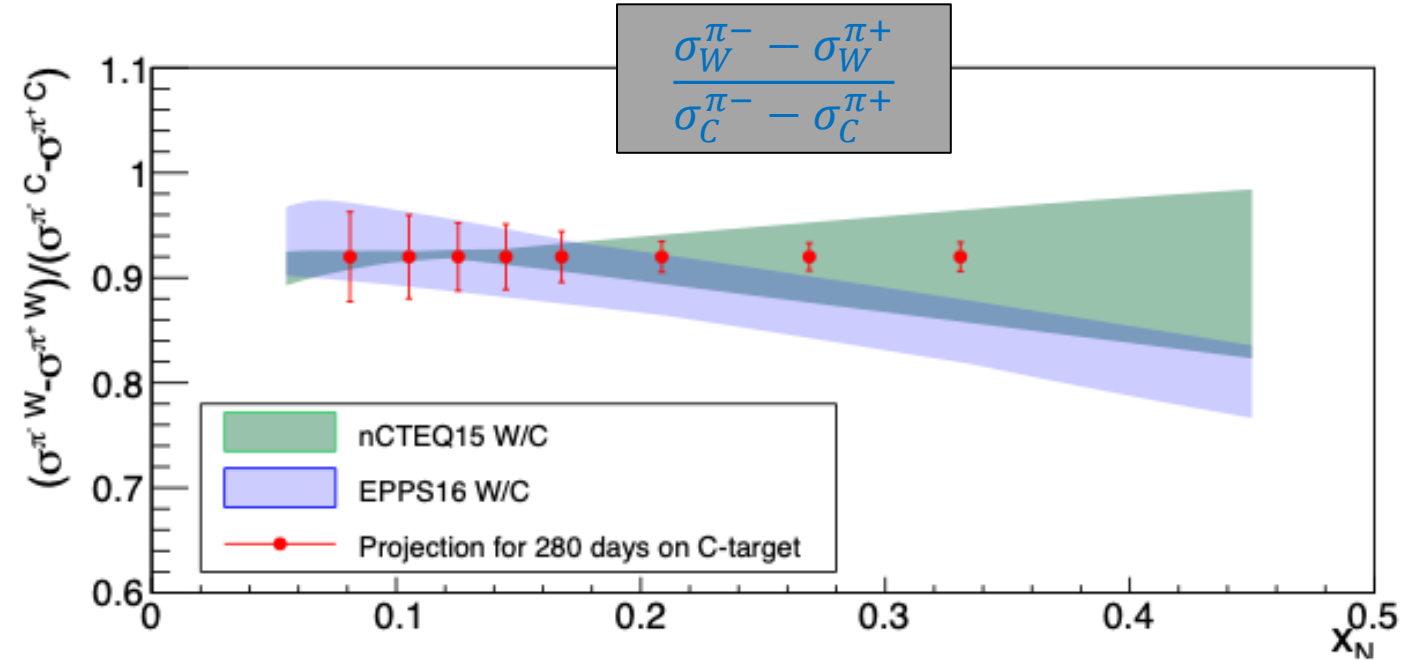
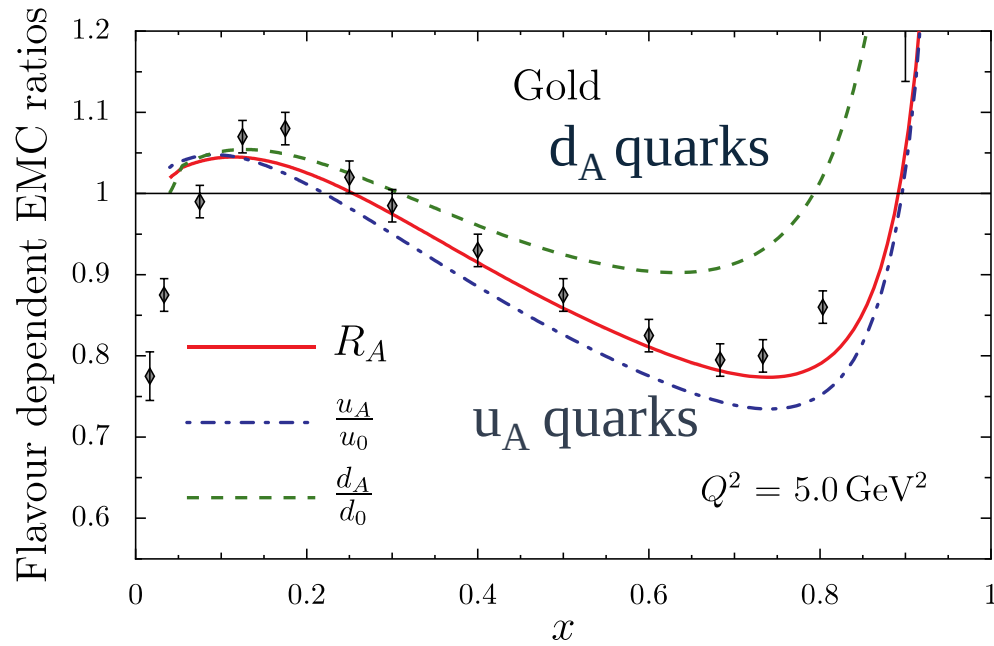
If compared to the muon scattering experiment at PSI (MUSE):

- 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 ($0.1\text{-}0.2 \text{ GeV}/c$ vs $100 \text{ GeV}/c$)
- Small statistical errors achievable with the proposed running time

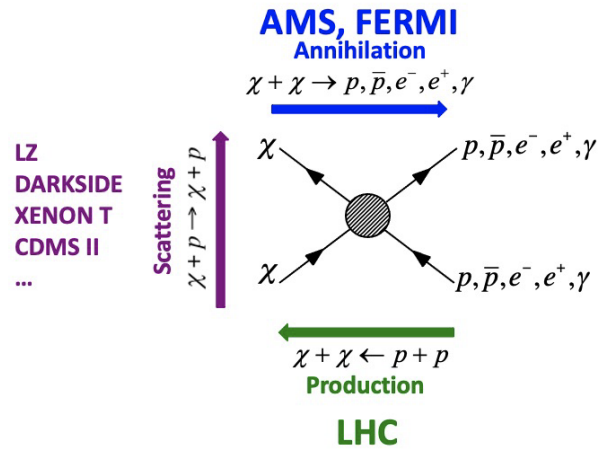


Goal-4: Flavor dependence of the EMC effect

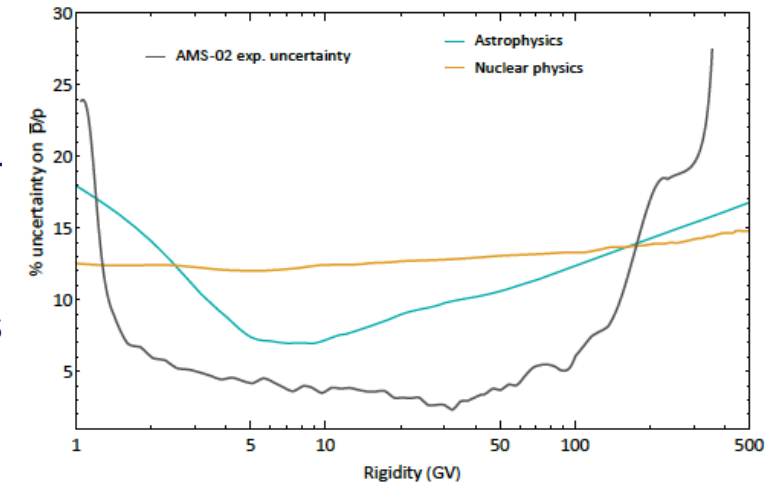
- Prediction: Cloët, Benz and Thomas (2009):
 - “...for $N \neq Z$ nuclei, the u and d quarks have distinct nuclear modifications.”*



Can be accessed ONLY through parity-violating DIS (JLAB) or with AMBER@CERN

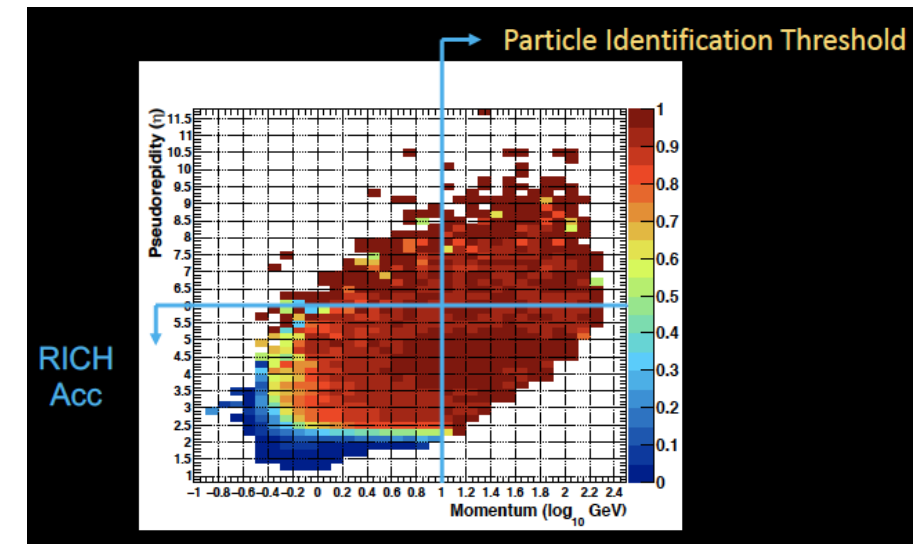


- New AMS(2) data – the antiparticle flux is well known now (few % pres.)
(<http://dx.doi.org/10.1103/PhysRevLett.117.091103>)
- Two types of processes contribute – SM interactions (proton on the inter-stellar matter with the production for example of antiprotons) and contribution from dark particle – 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).

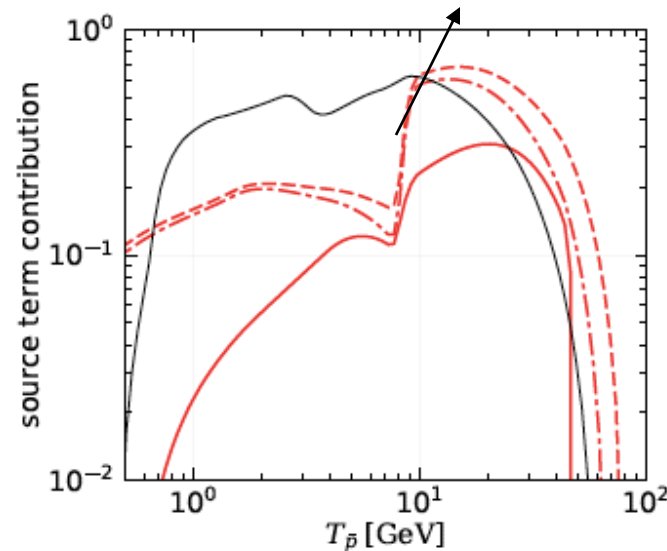
In 2023 we had successfully performed first data taking with He for six Incoming proton momentum in the range 60 – 250 GeV



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

AMBER
NA61 (20-158 GeV/c)



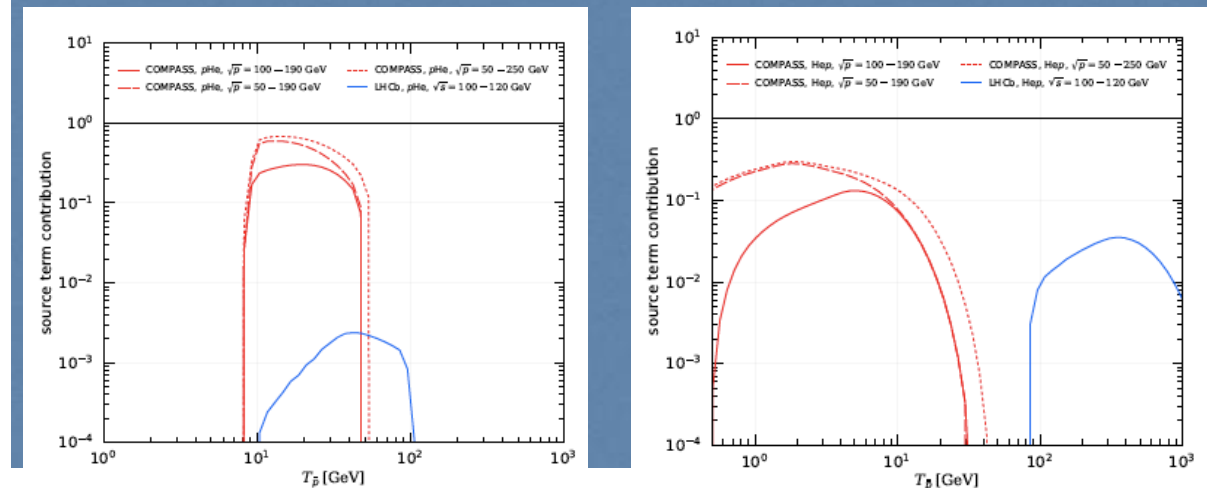
100-190 GeV/c

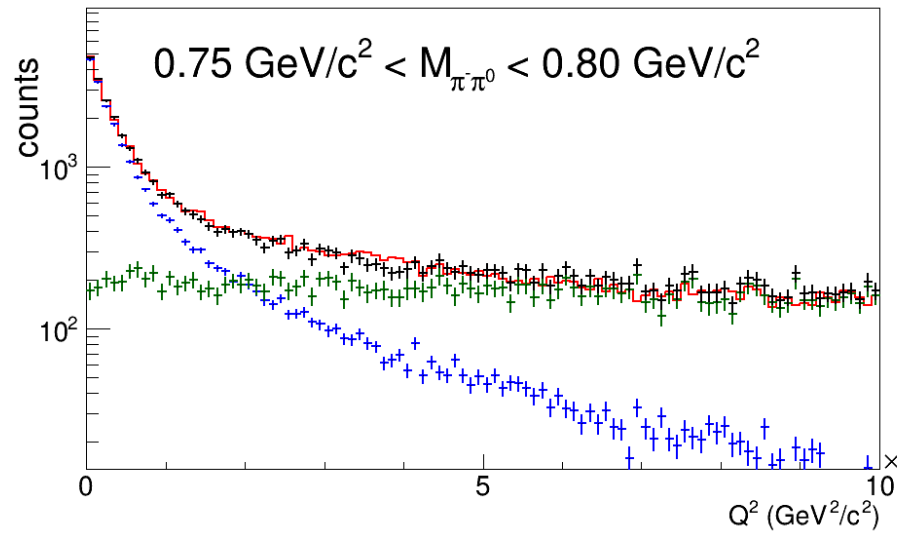
50-190 GeV/c

50 - 250 GeV/c

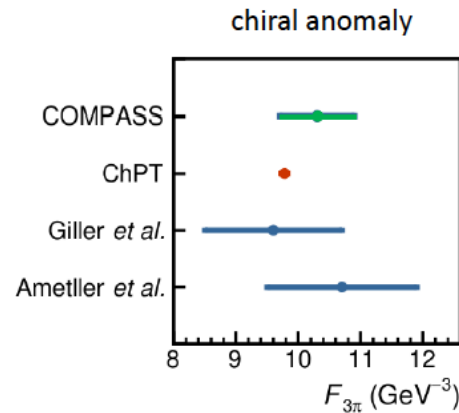
AMBER
LHCb

p -He and He- p channels





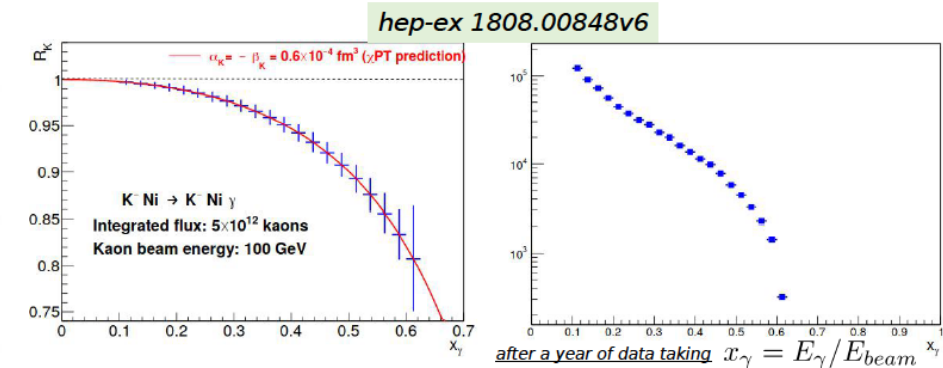
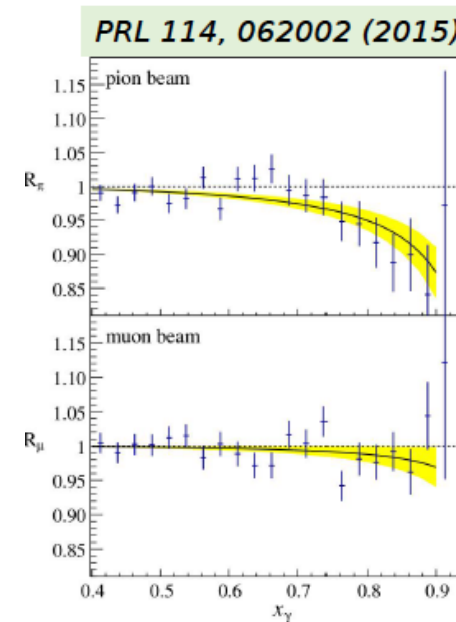
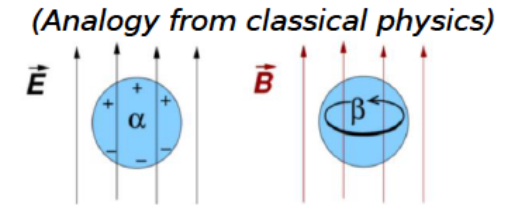
— Data
— Primakoff MC
— 3π MC
— Sum of MC contributions



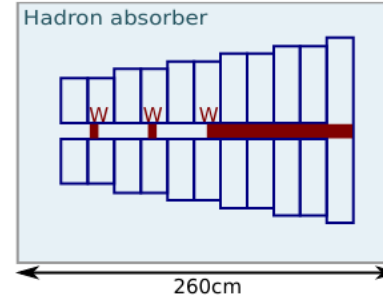
Dominik Ecker's talk of 08/06/23

Polarizabilities

Interaction between **hadron** and **external electromagnetic field** described by parameters α , β (LO), encoding information about its internal structure

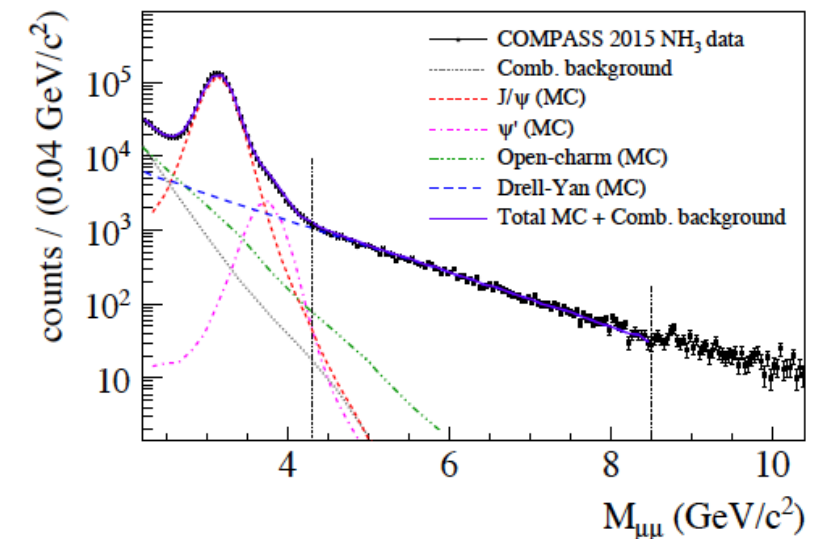
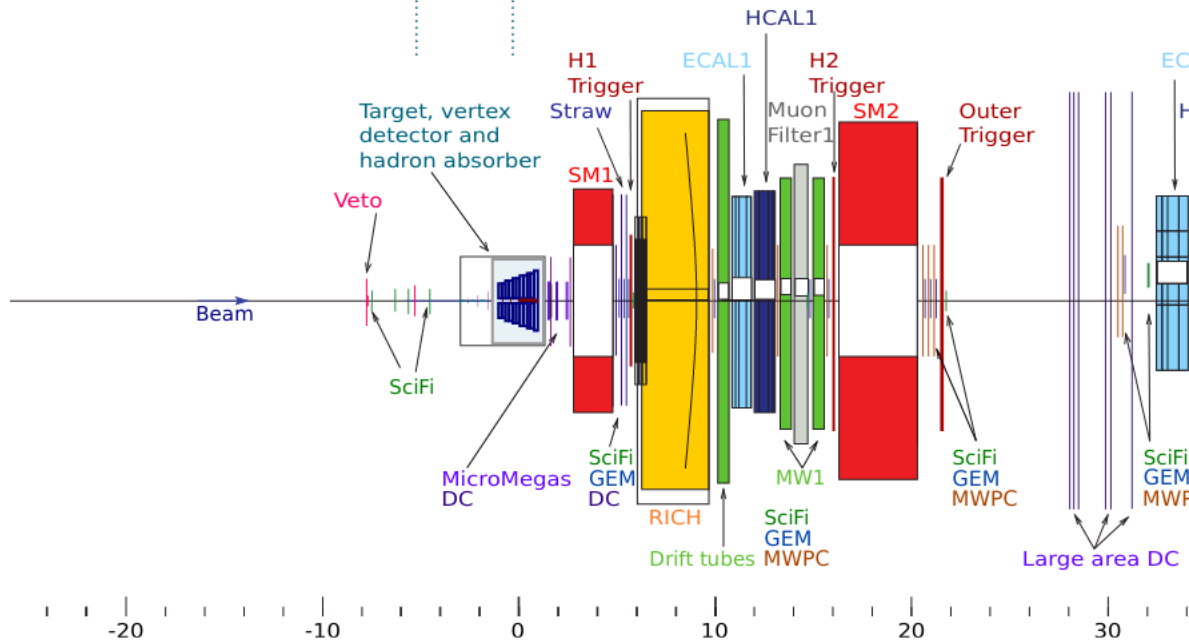


2024 Drell-Yan setup



Drell-Yan process is a low cross-section process:

- High intensity hadron beam
- Carbon and Tungsten nuclear targets
- Hadron absorber to protect Spectrometer from a very high secondary flux
- Vertex Detector to compensate loses in resolution because of the absorber in order to improve mass and space resolution



Drell-Yan experiment preparation II

Proposal by LANL group to reuse PHENIX Silicon Vertex Detector

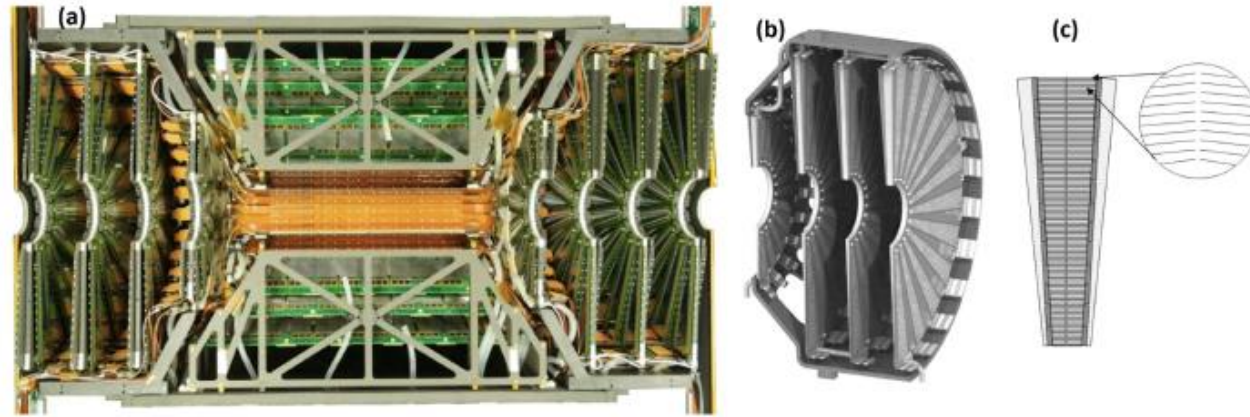
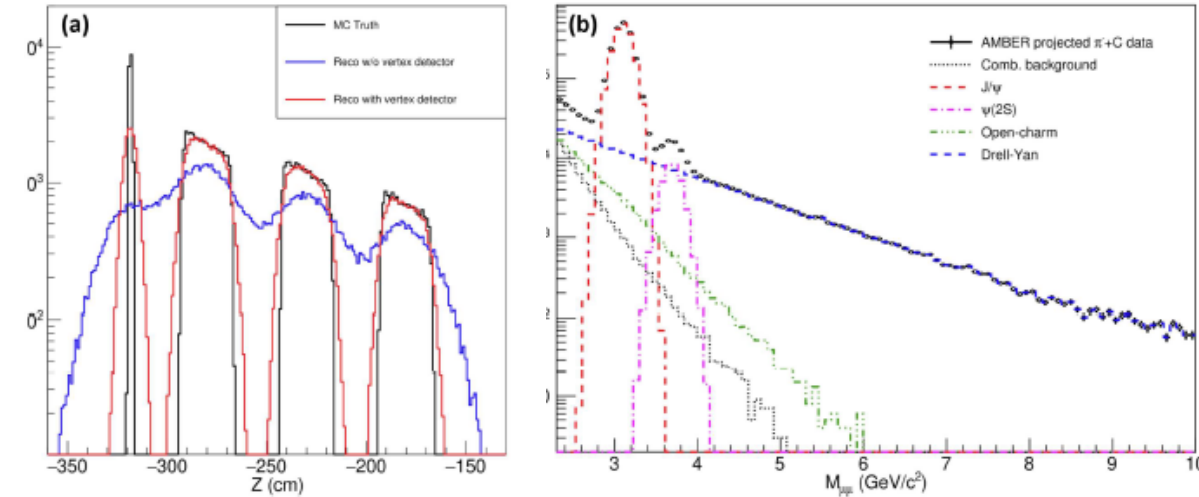


Figure 7 (a) A completed half FVTX detector, with sensors, frontend electronics, supporting structures, and cooling system. Two half FVTX endcaps are shown on either end. The overall length is about 80 cm. (b) A structural illustration of one endcap of the FVTX. One small disk and three large disks are included in one endcap. (c) A segment (wedge) of the FVTX sensor. Each wedge holds two columns of the silicon strips as shown in the zoomed-in portion.

Table 1 Summary of the FVTX specifications.

Silicon sensor thickness (μm)	320
Strip pitch (μm)	75
Number of strips per column	1664
Inner radius of silicon (mm)	44
Outer radius of silicon (mm)	168.8
Strip length at inner radius (mm)	3.4
Strip length at outer radius (mm)	11.5
Pulse timing (ns)	30
Number of wedges per disk	48



Active silicons mini-strip sensors plus front-end ASIC,
the FPHX chip bonded directly on sensors

- Time resolution: $\sim \text{ns}$
- Spatial resolution: $\sim 20\mu\text{m}$

Simulations and optimisation of the
apparatus and reconstruction ongoing

Preliminary:

$$\rightarrow \sigma_{\mu\mu} \sim 110 \text{ MeV}/c^2$$

$$M_{\mu\mu} > 4.3 \text{ GeV}/c^2 \rightarrow M_{\mu\mu} > 4.0 \text{ GeV}/c^2:$$

$\Rightarrow \sim 50\%$ gain in DY statistics

Drell-Yan experiment preparation III

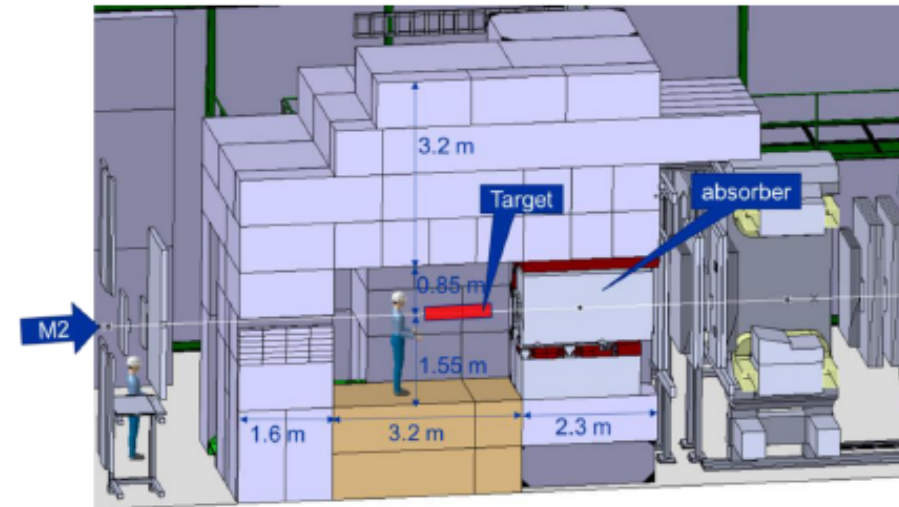
Toward doubling of the incoming beam intensity (TO)

Study and optimisation of the shielding to:

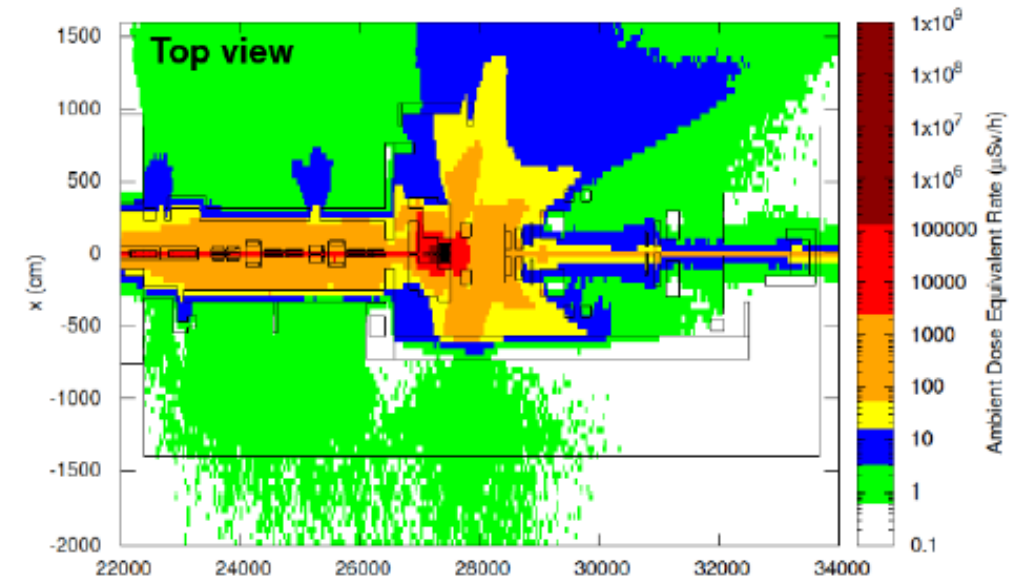
- Contain the radiation
- Minimise the environmental impact
- Comply with regulations

⇒ Compatible with $2 \times$ current Intensities

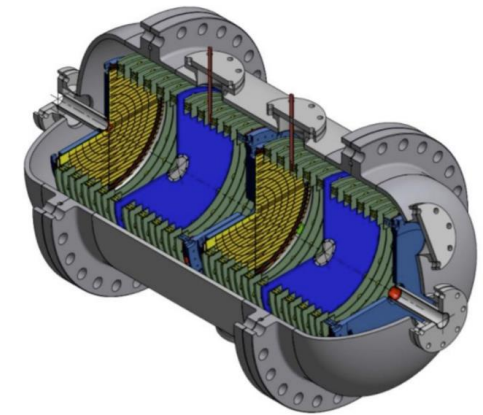
⇒ ECR to be submitted



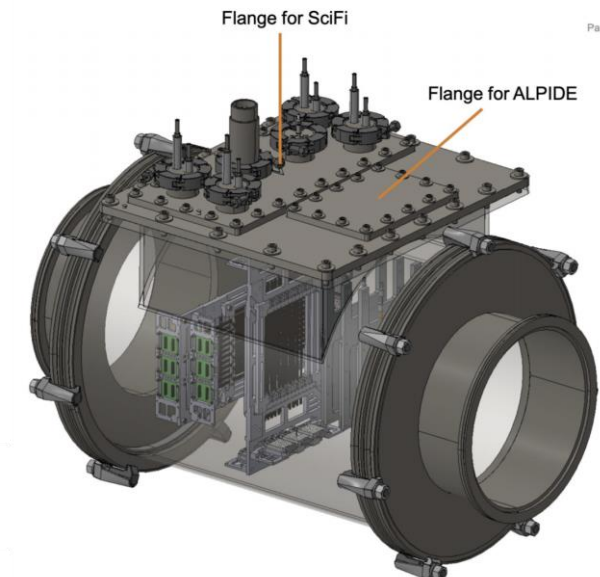
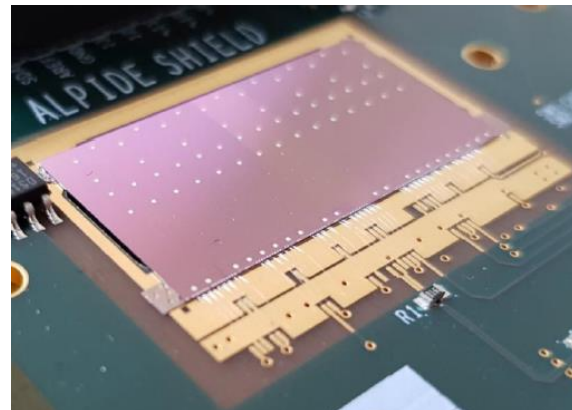
	Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign
			permanent occupancy	low occupancy	
	Non-designated	1 mSv	0.5 μ Sv/h	2.5 μ Sv/h	
Radiation Area	Supervised	6 mSv	3 μ Sv/h	15 μ Sv/h	
	Simple Controlled	20 mSv	10 μ Sv/h	50 μ Sv/h	
	Limited Stay	20 mSv	-	2 mSv/h	
	High Radiation	20 mSv	-	100 mSv/h	
	Prohibited	20 mSv	-	> 100 mSv/h	
					Controlled Area



- 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)



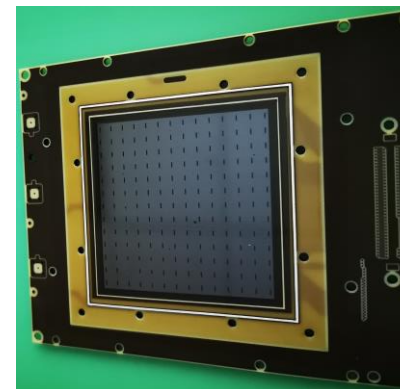
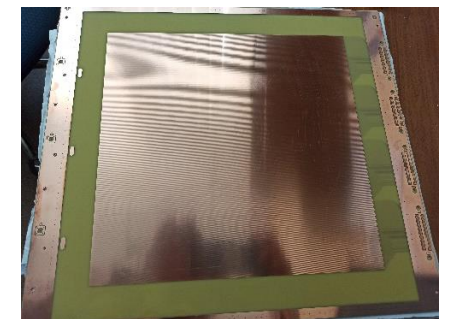
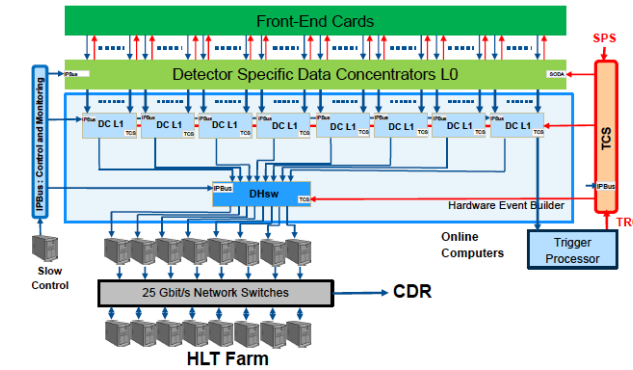
ECAL2 DAQ Hardware – Carrier Board III





Status of the AMBER Facility preparations: AMBER Spectrometer Upgrades 1

- 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 (MicroMegas)
- High-rate-capable CEDARs detectors (beam line)
- A new RICH-0 detector to extend significantly phase space coverage (lower momenta)



Unified Tracking Station

