AMBER experiment at CERN, SPS

AMBER (Apparatus for Meson and Baryon Experimental Research)

1. Intro AMBER
2. AMBER science questions
3. AMBER Phase-1 (pion case)
   - Di-muon production measurement (Drell-Yan and J/Ψ)
   - Proton Radius Measurement
4. AMBER Phase-2 (kaon case)
   - Di-muon production measurement (Drell-Yan and J/Ψ)
   - Prompt Photons
   - Kaon charge radius
   - Kaon induced diffractive scattering
5. Possible timeline
6. Summary

Oleg Denisov (INFN-Torino and CERN) on behalf of the AMBER collaboration

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

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There are two bearing columns of the facility:

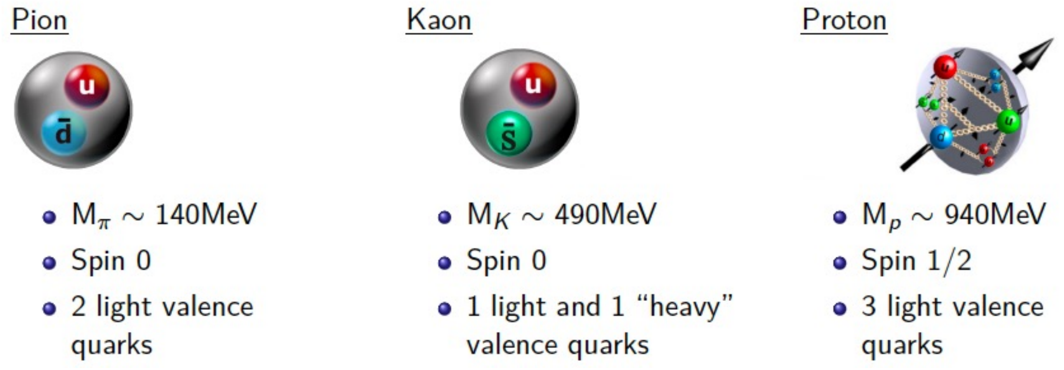
1. **Phenomenon of the Emergence of the Hadron Mass**
2. Proton spin (largely addressed by COMPASS and others, Phase-2)

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?

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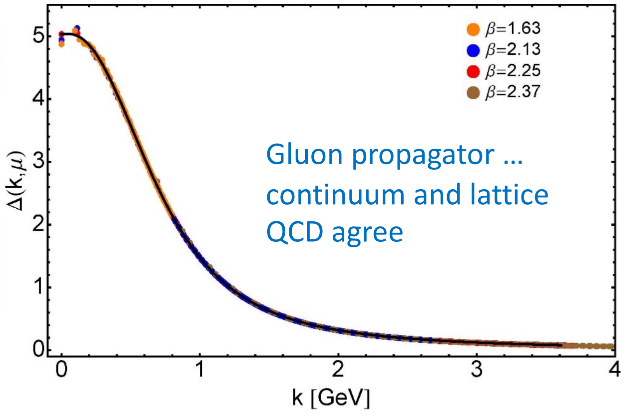
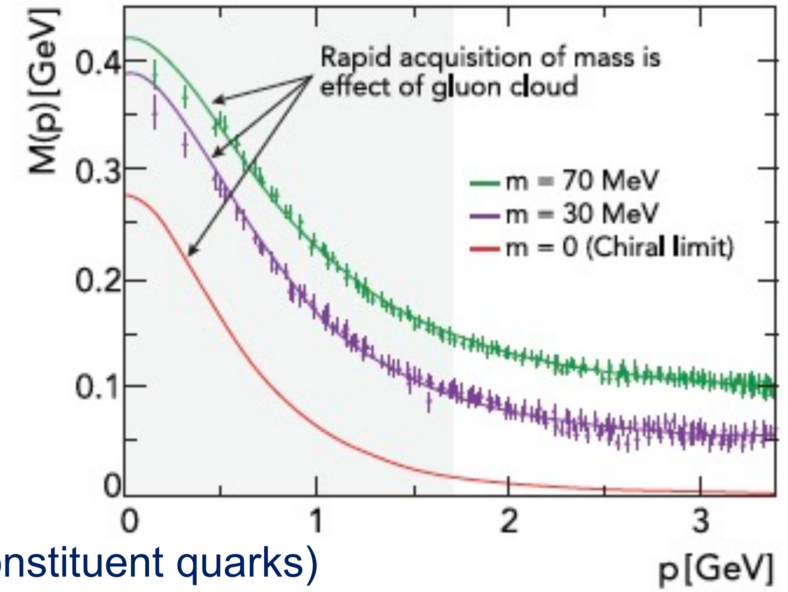
Intuitively one can expect that the answer to the question lies within SM, in particular within QCD. Why? Because of the dynamical mass generation in continuum QCD.

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?

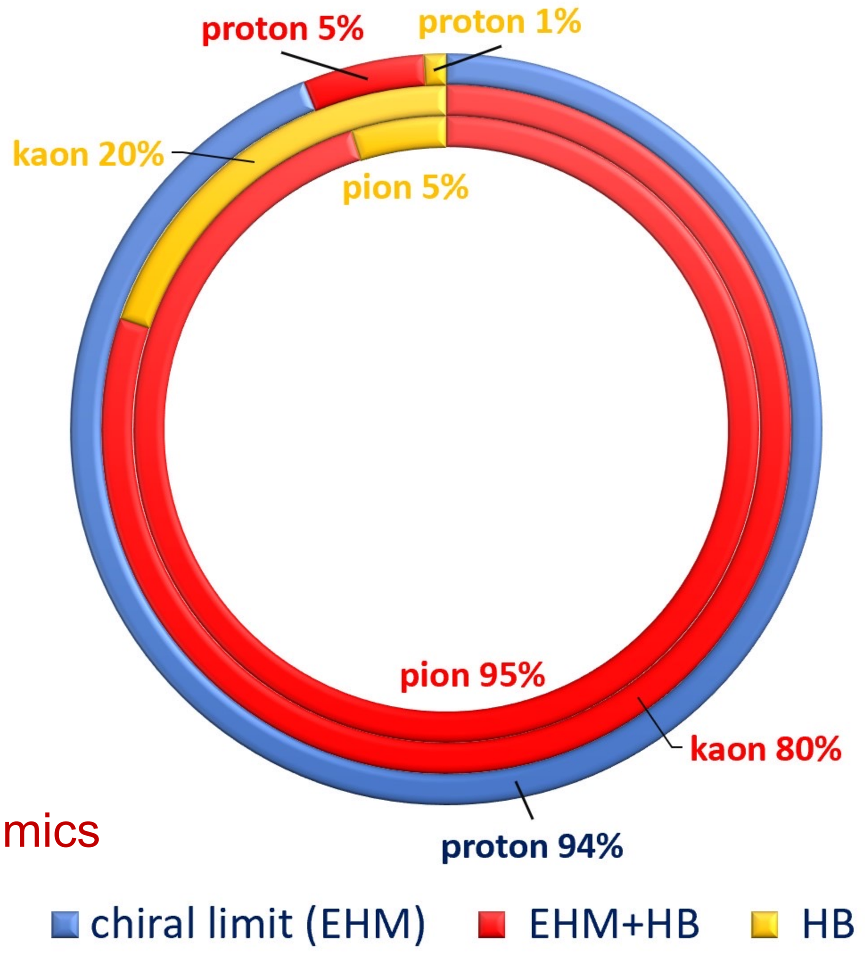
The answer is obviously NOT (SM paradigm):

- 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

Mass Budgets



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

AMBER physics program

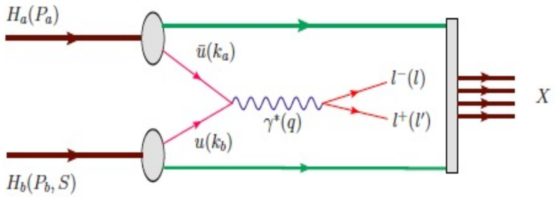
Questions to be answered:

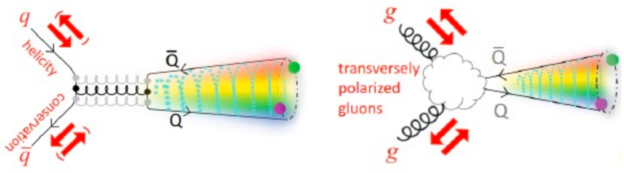
- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass .vs. Higgs)
- Internal quark-gluon structure and dynamics, especially important pion/kaon/proton striking differences

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

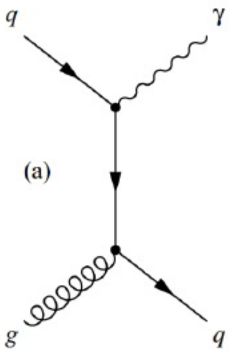
Methods:

Drell-Yan and J/Ψ

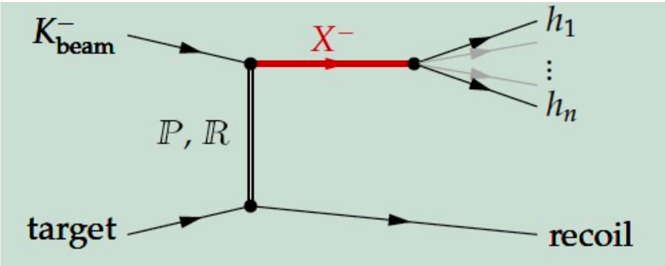


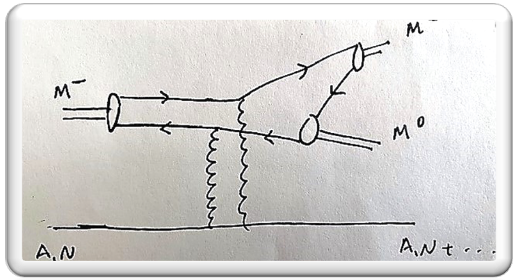


Prompt Photon Production

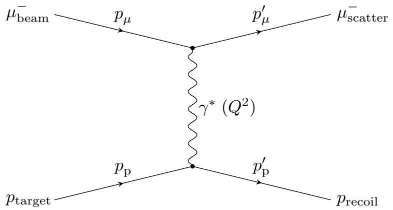


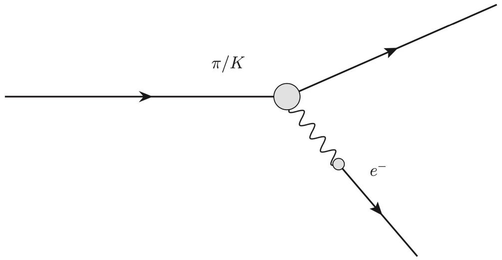
Diffractive scattering





Elastic scattering





General AMBER timeline

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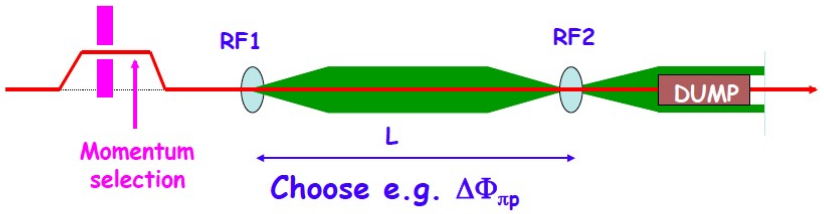
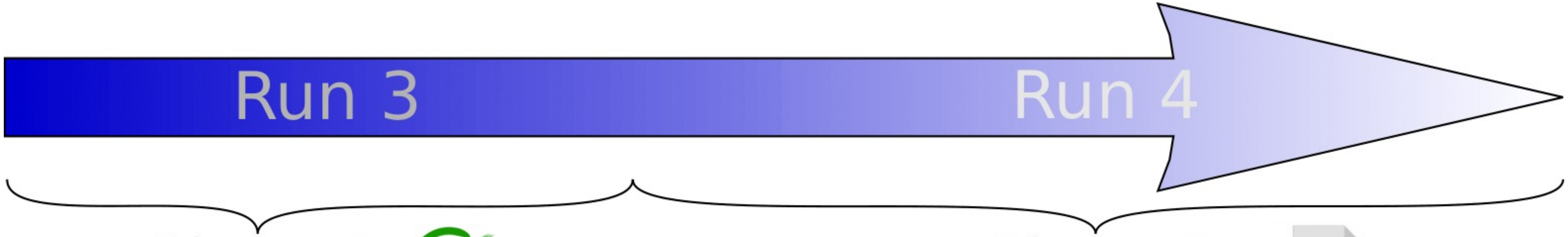
Conventional muon/hadron M2 beams



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



Phase-1

Phase-2

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

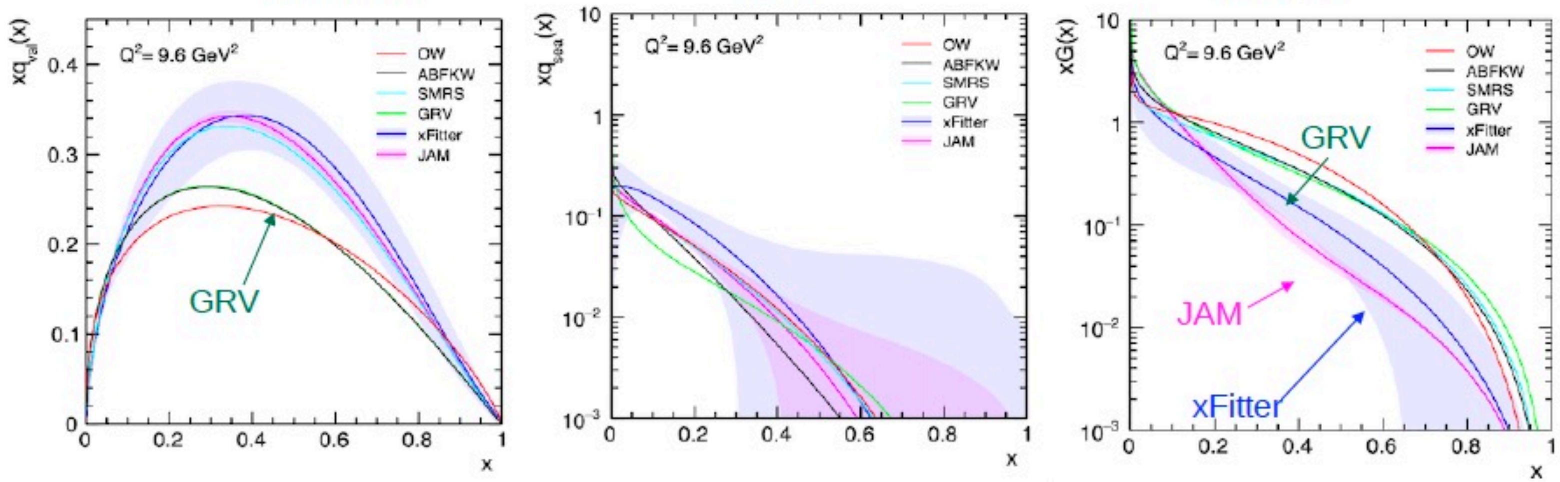
Kaon and pion structure (PDFs and PDAs)
High precision strange-meson spectrum
Kaon and pion charge radius
Kaon induced Primakoff reaction

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

Phase-2 Proposal submission in the beginning of 2022

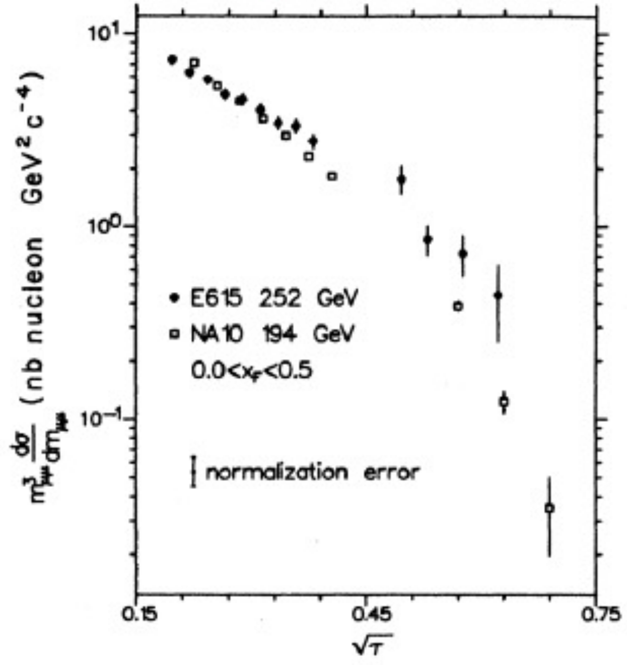
Pion induced Drell-Yan at AMBER
Status of the knowledge of the Pion structure

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

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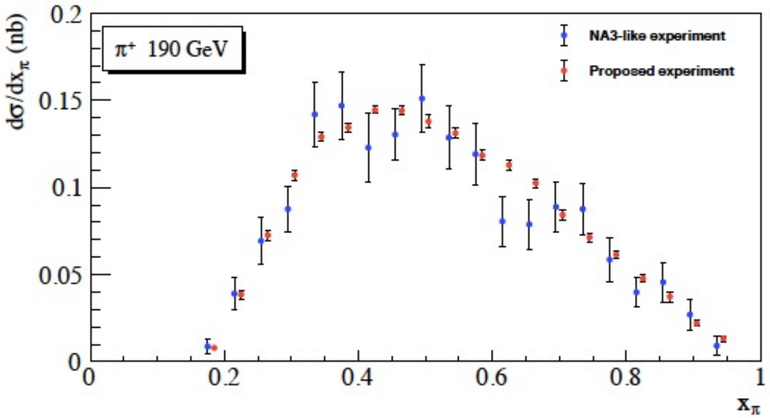
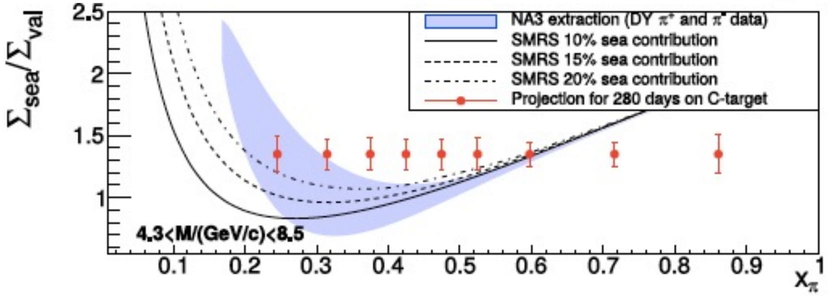
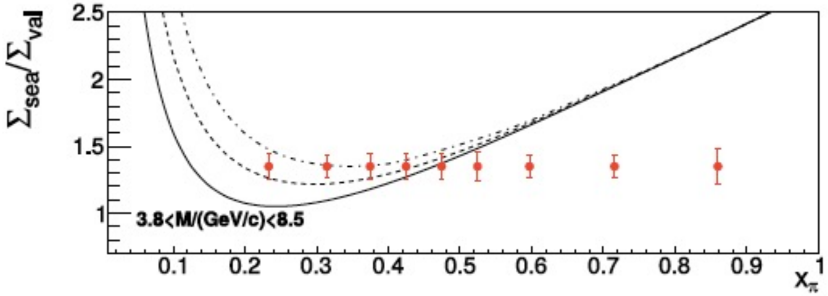


Pion structure in pion induced DY
Expected accuracy as compared to NA3

- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: 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





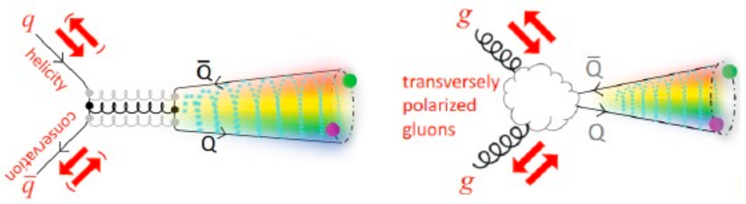
Sea quark content of pion can be accurately measured at AMBER for the first time

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*

Pion induced J/ψ at AMBER

AMBER

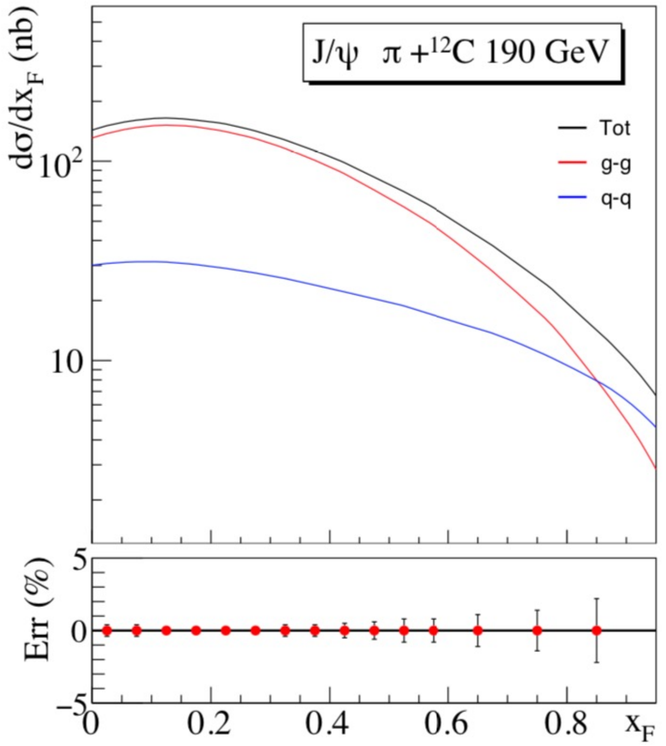


Collected simultaneously with DY data, with large counting rates

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}

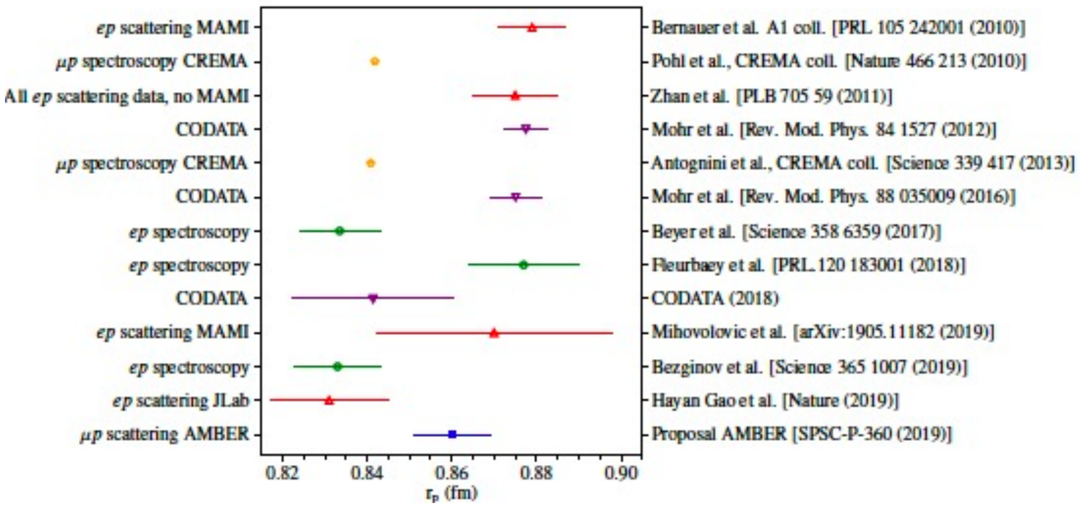
Cheung and Vogt, priv. comm.



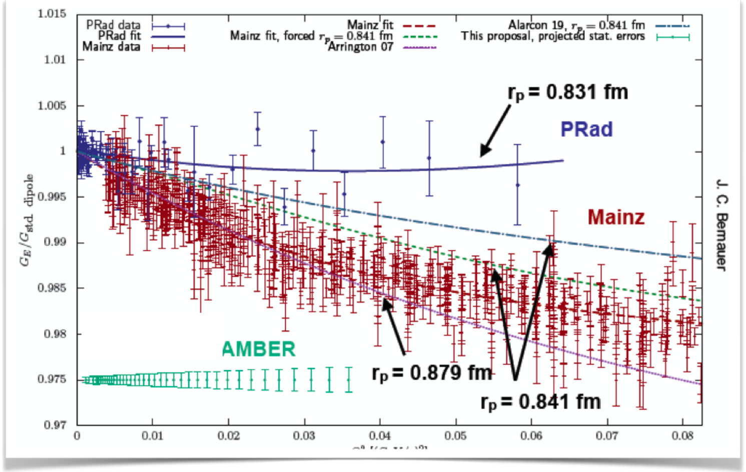
Improved CEM, CT10 + GRS99 global fit for proton/pion

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

Proton Radius Measurement at AMBER (confinement)



	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

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

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

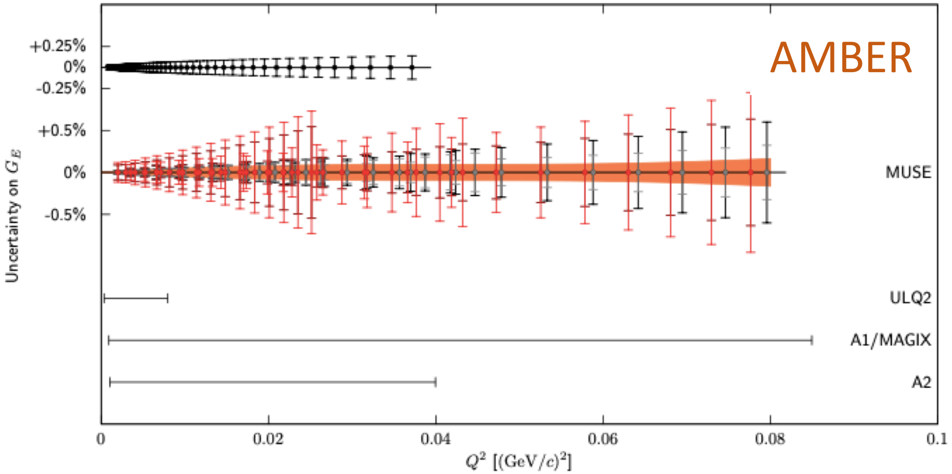
- Suppress magnetic form factor G_M^2
  → Requires $\tau \to 0$
  → Measurement at low-Q^2 values of $\mathcal{O}(<10^{-2})$
- Measurement at high-energy $\mathcal{O}$(10 - 100 GeV)
  → Results in $\varepsilon \to 1$
  → Cross-section directly proportional to G_E^2

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):

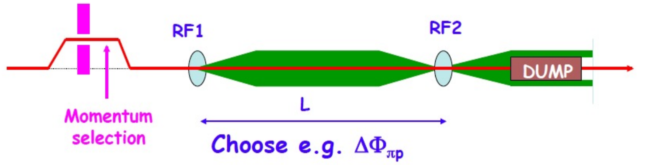
- Much cleaner experimental conditions (pure muon beam with less than 10^{-6} admixture of hadrons)
- Much higher beam momentum, thus contribution from magnetic form factor is suppressed (0.1-0.2 *GeV/c* vs 100 *GeV/c*)
- Small statistical errors achievable with the proposed running time



AMBER (kaon induced DY)

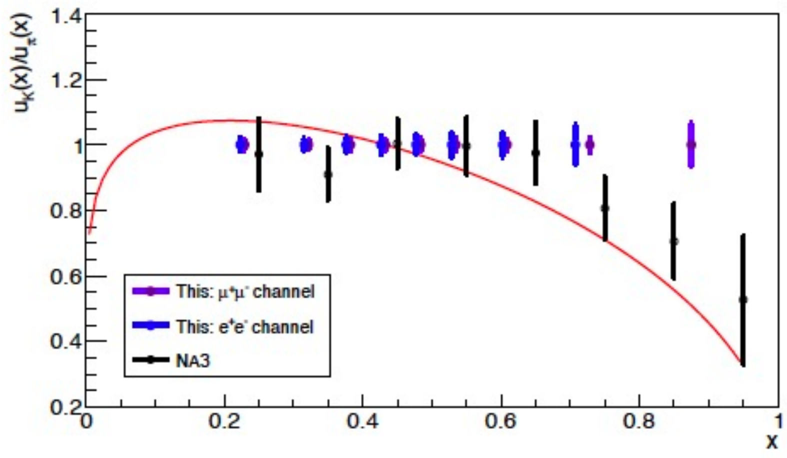
Extremely important to compare the gluon content of kaon and pion (emergent mass)

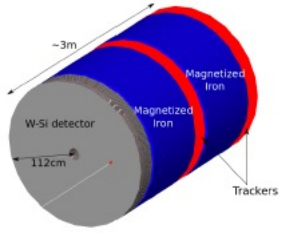
- **First ever DY measurements that could lead to kaon PDFs**
- Achievable statistics depends on beam energy and on kaon beam purity. Assuming $I = 7 \times 10^7\ s^{-1}$ with 30% kaons:
  - 40 kevents (K^-) and 5 kevents (K^+) @ 100 GeV
  - 25 kevents (K^-) and 3 kevents (K^+) @ 80 GeV



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

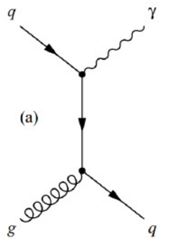
Projected statistical errors after 140 days of running, compared to NA3 stat. errors





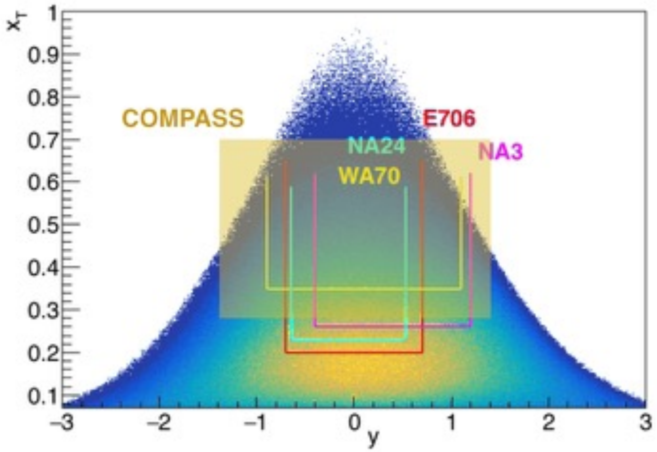
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	60	4.0 – 8.5	12,000	8,000
				70	4.0 – 8.5	18,000	10,900
				80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
				120	4.0 – 8.5	54,000	20,700
		K^+	2.1×10^7	60	4.0 – 8.5	1,000	600
				70	4.0 – 8.5	1,800	900
				80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
				120	4.0 – 8.5	8,000	2,400
This exp.	100 cm C	π^-	4.8×10^7	60	4.0 – 8.5	31,000	20,500
				70	4.0 – 8.5	50,800	25,400
				80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000
				120	4.0 – 8.5	123,600	39,800

AMBER (Prompt Photons)

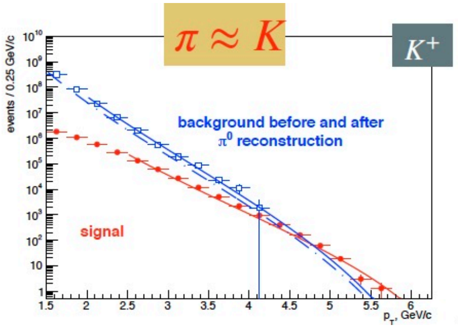


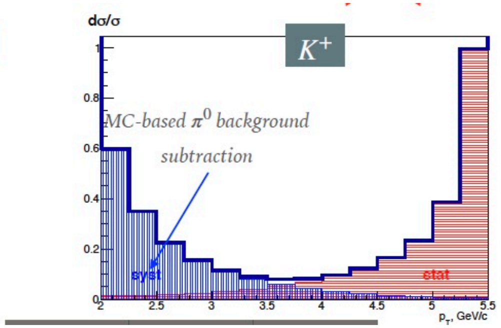
Prompt photons probe – direct access to the gluon content of the kaon.
At the moment there is no experimental information about gluon contribution in kaon.

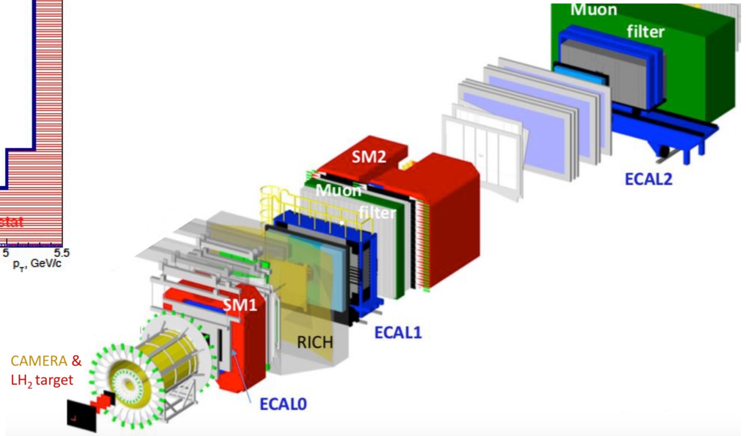
Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.

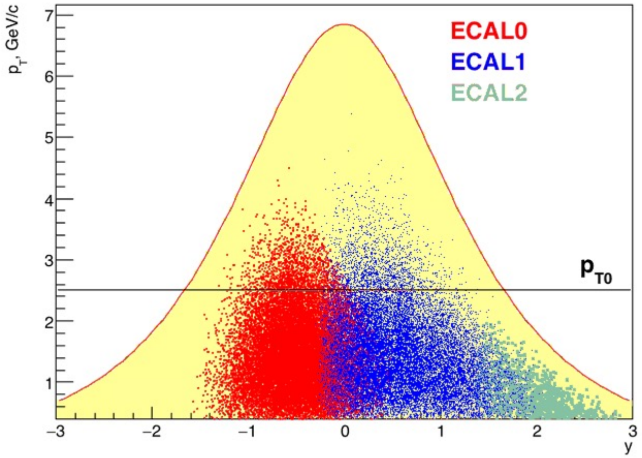


Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.









AMBER (Kaon and pion charge radius)

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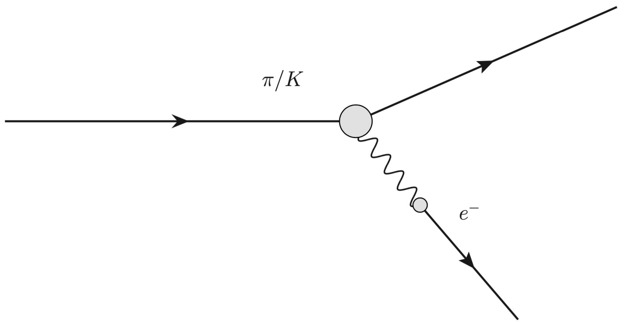
Precise measurements of pion and kaon radii will reveal the compositeness (confinement) scale for (near) Nambu-Goldstone bosons. At the moment there is basically no precise experimental information on kaon charge radius.



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

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

$$Q^2_{max} = \frac{4p_b^2 \, m_e^2}{s}$$

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

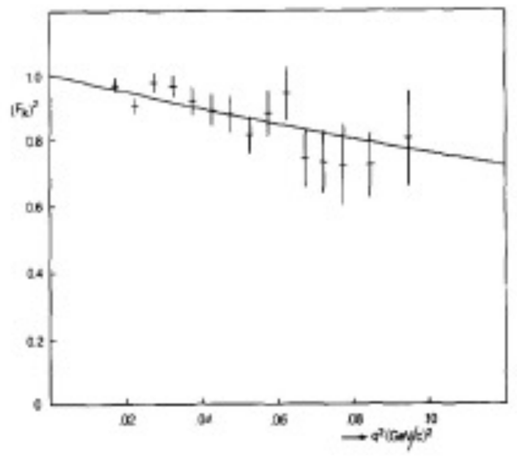


Fig. 3. The measured kaon form factor squared. The line corresponds to the pole fit with $\langle r^2 \rangle = 0.34 \text{ fm}^2$.

Beam	E_b [GeV]	Q^2_{max} [GeV²]	$E'_{b,min}$ [GeV]	Relative charge-radius effect on c.s. at Q^2_{max}
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%

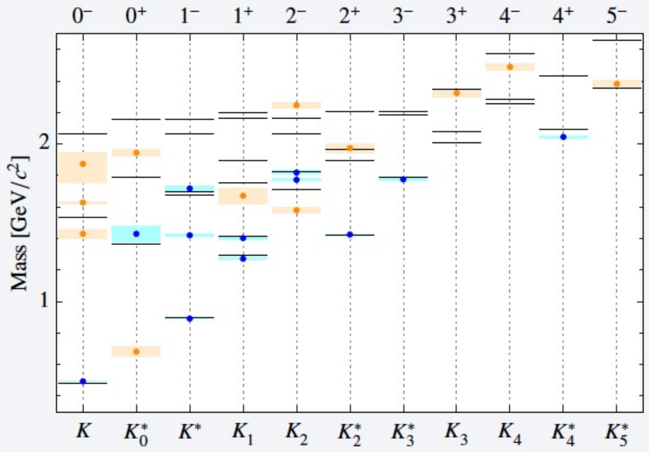
For kaons, a significant increase of the form factor knowledge in the range $0.001 < Q^2 < 0.07$ appears in reach with AMBER using an *80 GeV rf-separated kaon beam*

Hadron spectroscopy AMBER (kaon beam)

AMBER

PDG 2016: 25 kaon states below 3.1 GeV/c^2

- Only 12 kaon states in summary table, 13 need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states

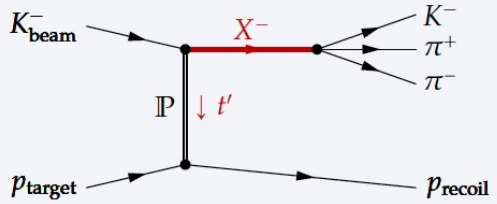


[Courtesy S. Wallner, TUM]

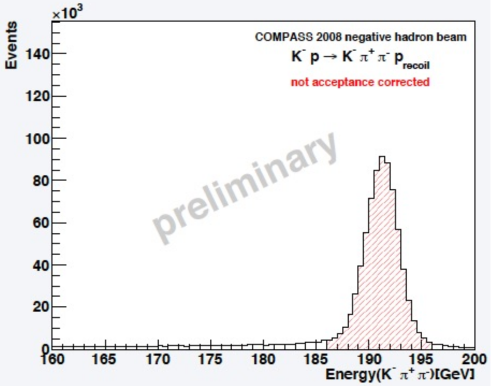
Boris Grube, TU München | Hadron Spectroscopy with Kaon Beam

Many kaon states need confirmation

- Little progress in the past
  - Most PDG entries more than 30 years old
  - Since 1990 only 4 kaon states added to PDG (only 1 to summary table)



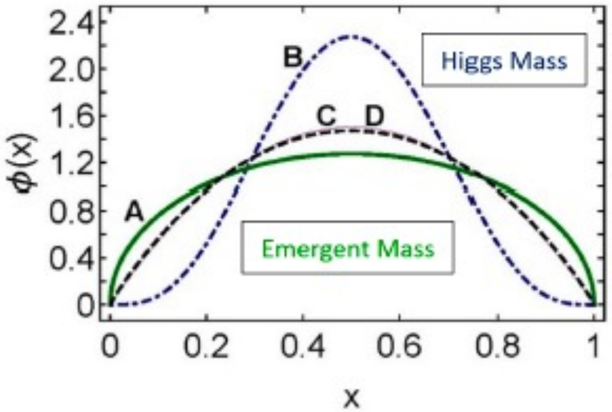
- From 2008 data taking campaign
- 270 000 events
- $0.07 < t' < 0.7\ (\text{GeV}/c)^2$
- Exclusivity ensured by measuring recoil proton
  - Also suppresses target excitations



Future program

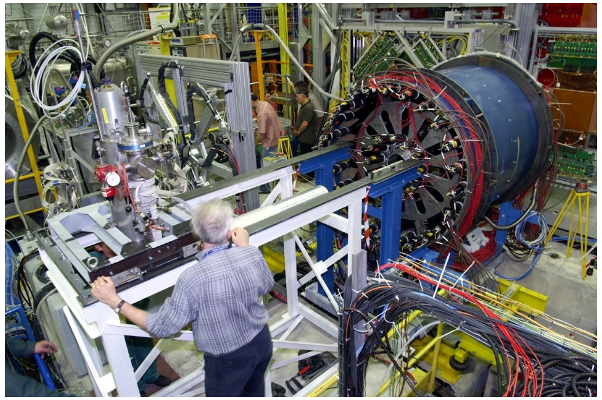
- *Goal:* collect 10 to 20 $\times 10^6$ $K^-\pi^+\pi^-$ events using high-intensity RF-separated kaon beam
  - Would exceed any existing data sample by at least factor 10
  - *High physics potential:* rewrite PDG for kaon states above 1.5 GeV/c^2 (like LASS and WA03 did 30 year ago)
  - Precision study of $K\pi$ S-wave
- Requires experimental setup with uniform acceptance over wide kinematic range (including PID and calorimeters)
- No direct competitors

AMBER - New EHM-related ideas: PDA



Where *x* is a fraction of hadron's longitudinal momentum carried by the quark in the imf.

Pion and kaon distribution amplitudes (DAs) nearest thing in quantum field theory to a Schredinger wave function; consequently, fundamental to understanding π and K structure. Modern theory predicts that EHM is expressed in the x-dependence of pion and kaon DAs.

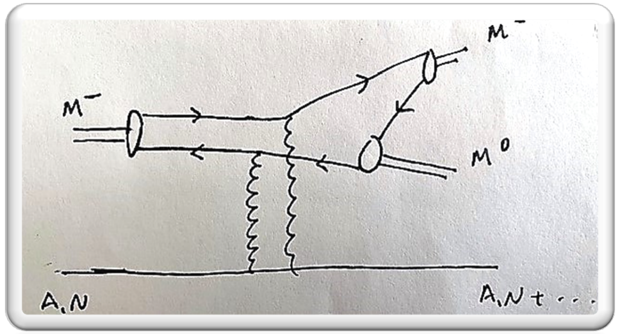


A solid (green) emergent mass generation is dominant (pion);
B dot-dashed (blue) curve: Higgs mechanism is the primary source of mass generation (C-meson);
C solid (thin, purple) curve (asymptotic prole, 6x(1 - x);

Fermilab E791 the only experimental data In di-jets production by 500 GeV π^- beam

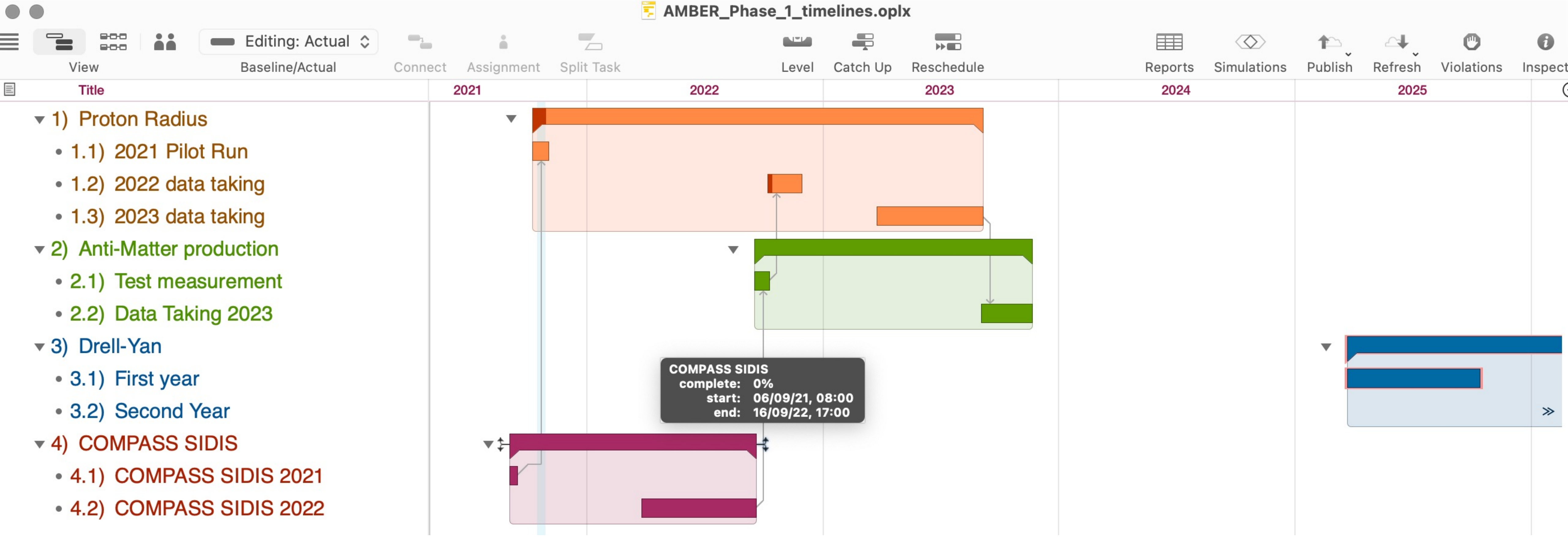
AMBER case:
Because of the relatively small beam energy we can obtain information on meson DAs via di-meson final states:

- Only first Melin momentums of DAs
- Two additional LFWFs (diagram at the right):
    - Additional $\frac{1}{k_t^8}$ suppression to the cross section
    - Integration over the loop means pointwise information on x-dependence il lost



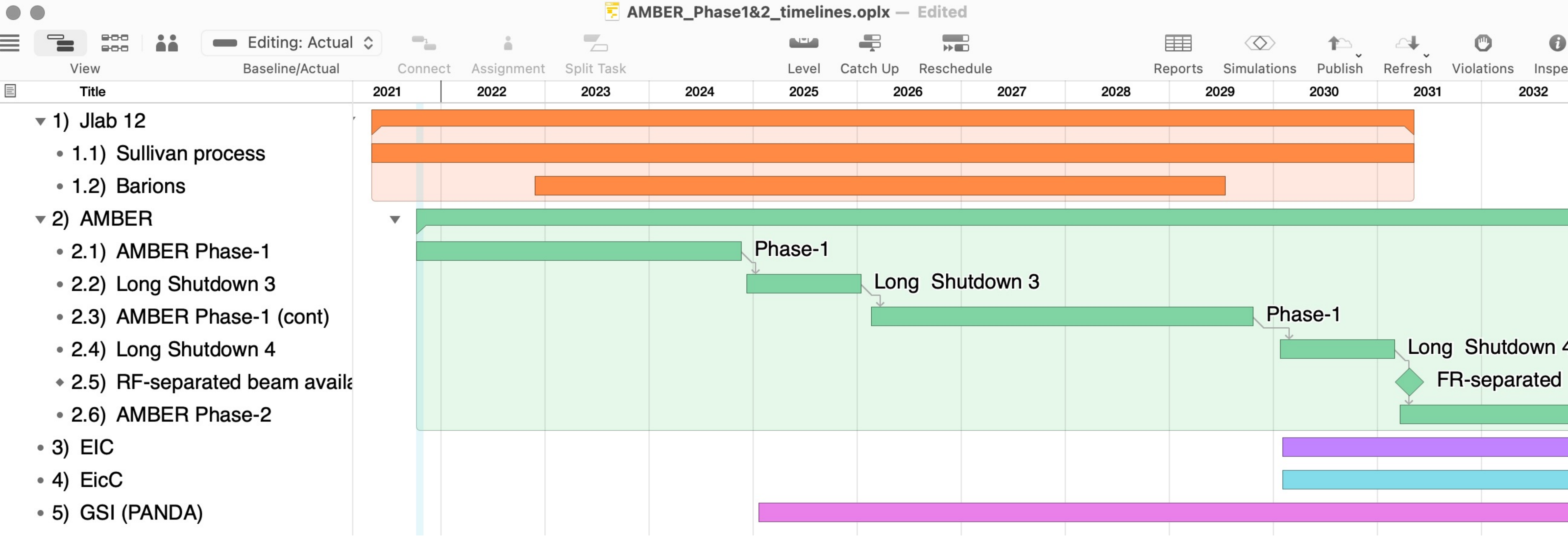
AMBER

Possible timeline for the AMBER Phase-1 measurements



Starting point depends of the semiconductors availability on the market

EHM through experimental studies



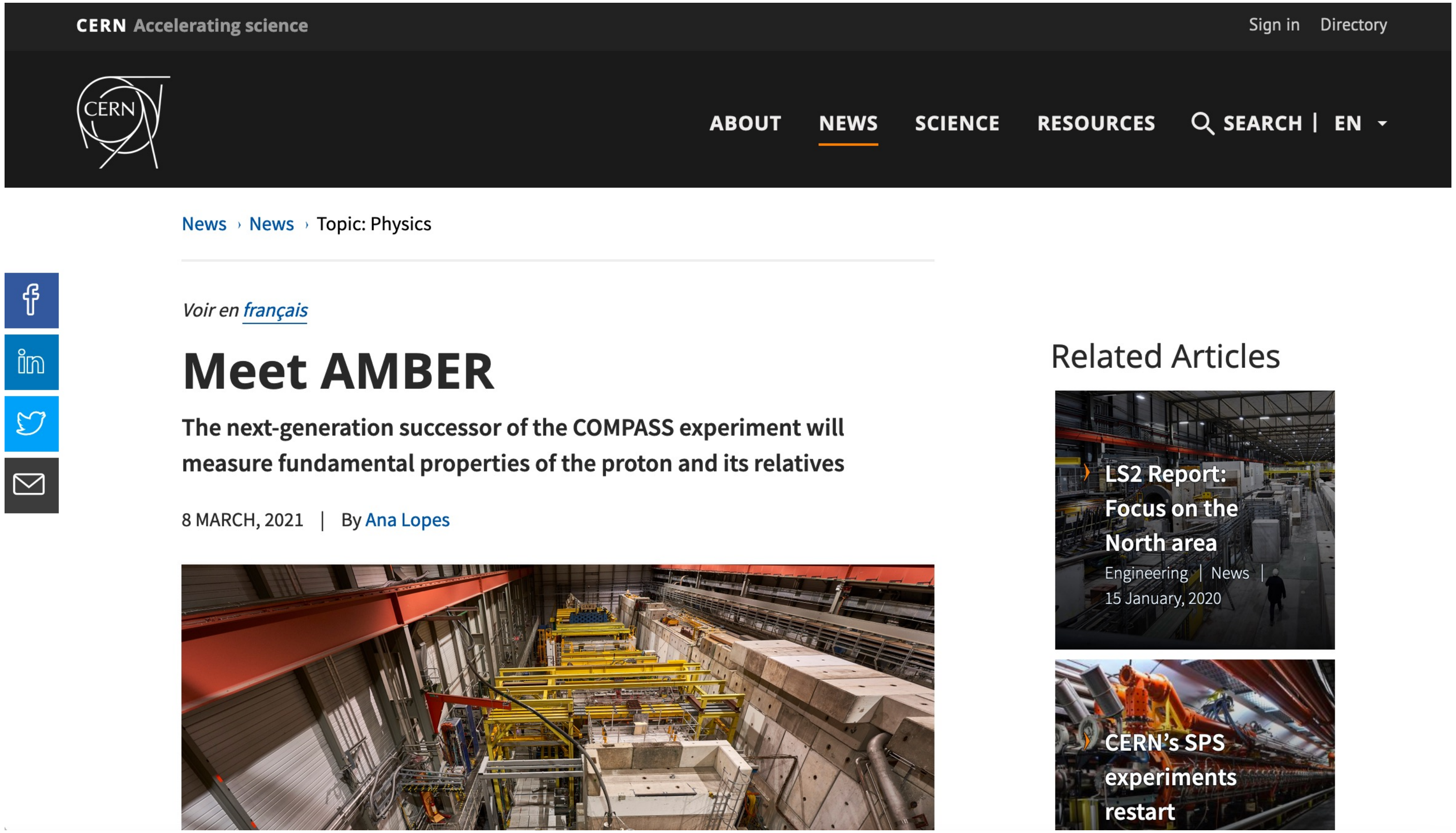
Summary: AMBER at CERN SPS

- 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 will be discussed with CERN management in Nov. 2021
- Main goal of the AMBER Phase-1: high precision study of the pion structure, right now we are taking first data on proton radius measurement (test run)
- Rf-separated high energy and intensity kaon beams at AMBER Stage-2 is unique instrument to study kaon

BACK UP

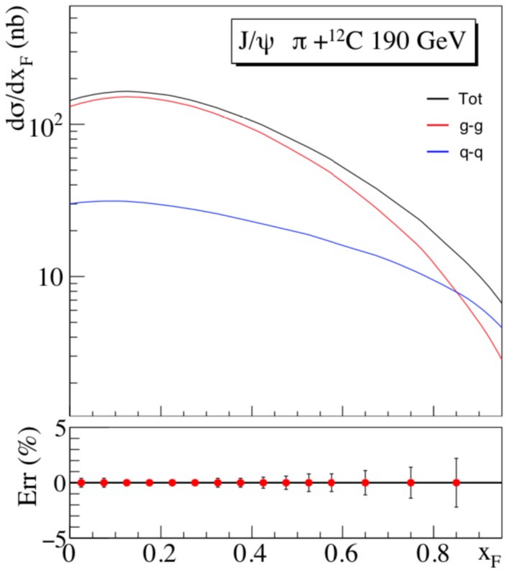
AMBER in the CERN news

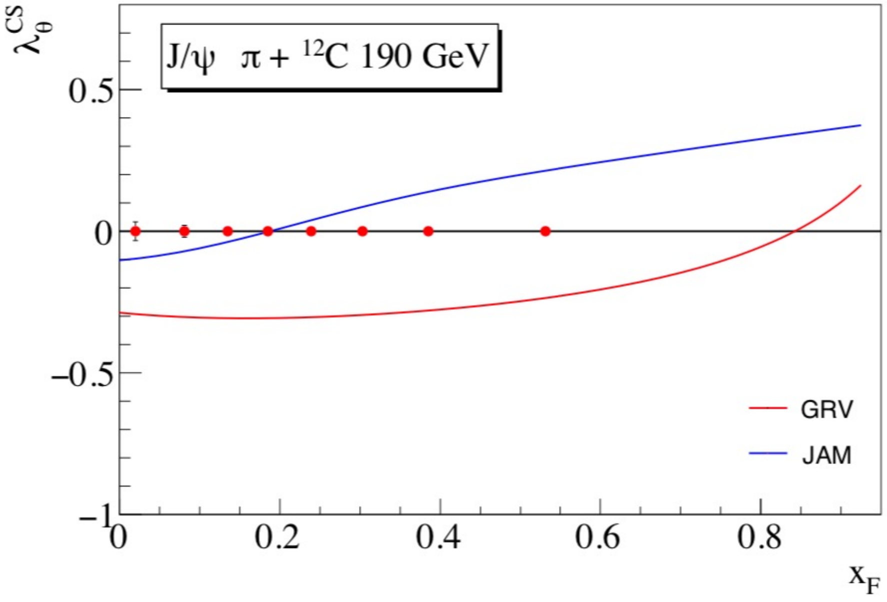
https://home.cern/news/news/physics/meet-amber



AMBER
Charmonium

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





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

PHASE-1