EHM through AMBER at CERN-SPS

Oleg Denisov on behalf of the AMBER Collaboration, 2021/06/07

Outline

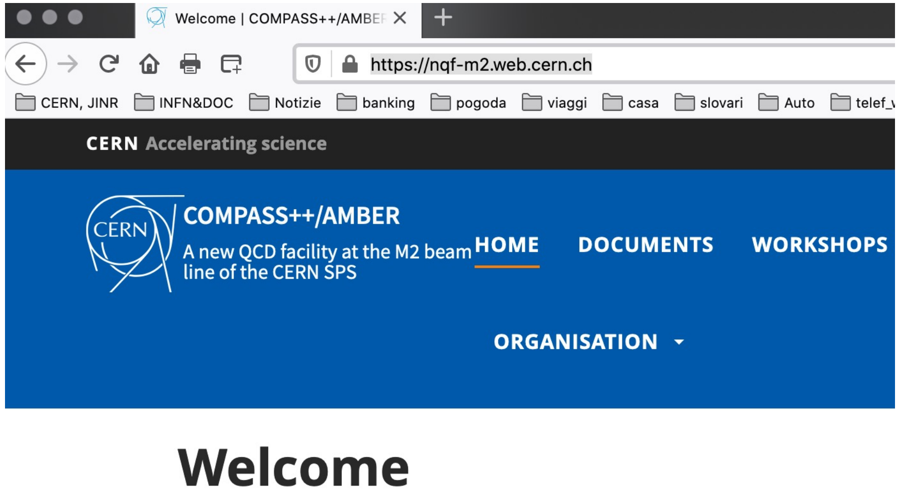
1. Intro AMBER
2. AMBER Science questions
3. Emergence of the Hadron Mass:
   - Drell-Yan
   - Charmonia production
   - Prompt photons
   - Spectroscopy
   - Proton radius
4. New ideas
5. AMBER Phase-1 possible time lines
6. Summary

AMBER
approximately 10 years-long effort, LoI is submitted in Jan. 2019

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://nqf-m2.web.cern.ch/



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

http://arxiv.org/abs/1808.00848

Apparatus for Meson and Baryon Experimental Research

> 270 authors

[hep-ex] 25 Jan 2019

Letter of Intent:

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

COMPASS++†/AMBER‡

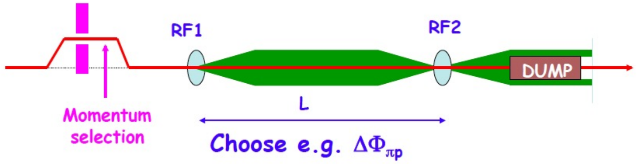
B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

AMBER (Apparatus for Meson and Baryon Experimental Research)
A New QCD Facility at CERN SPS M2 beam line

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	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	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	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 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.

Conventional muon/hadron M2 beams



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

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)

EHM:

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

Unfortunately, the Higgs-boson discovery (even if extremely important) does NOT help to answer the question:

✓ 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

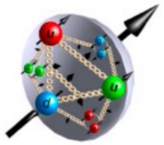
Pion

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

Kaon

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

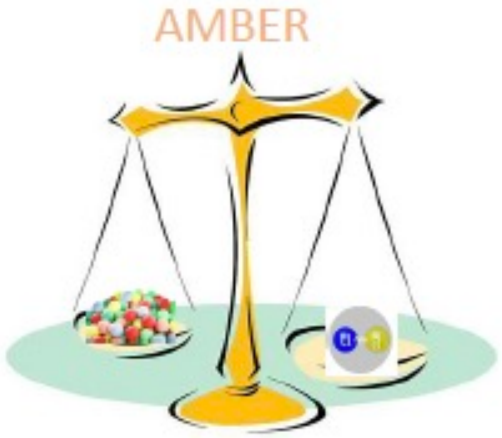
Proton



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

Higgs generated masses of the valence quarks:

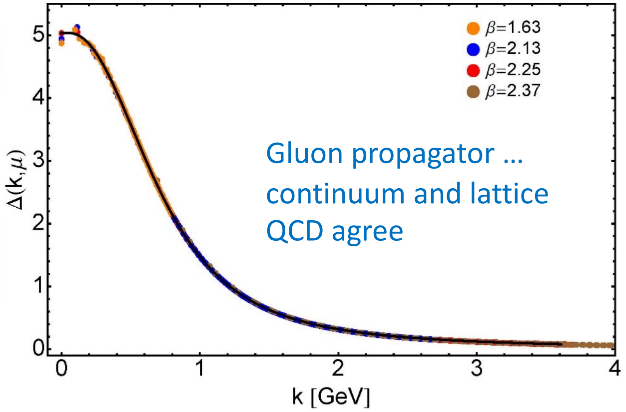
$M_{(u+d)}$ ~ 7 MeV $M_{(u+s)}$ ~ 100 MeV $M_{(u+u+d)}$ ~ 10 MeV



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

EHM phenomenon
(what is an underlying mechanism?)

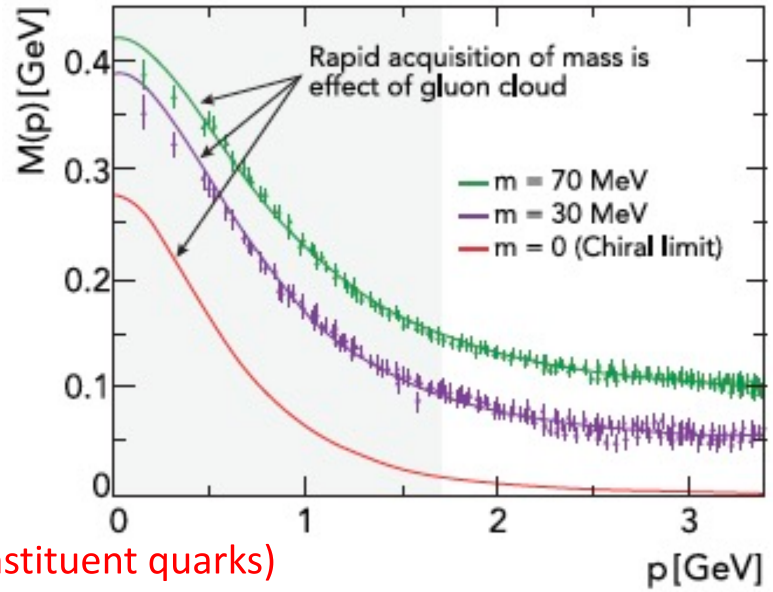
Intuitively one can expect that the answer to the question lies within SM, or strong QCD.
Why? Because of the dynamical mass generation in the continuum QCD.

Truly <u>mass from nothing phenomenon:</u>
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)

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

1. <u>Quark and Gluon PDFs of the pion/kaon/proton</u>
2. <u>Hadron's radii (confinement)</u>
3. <u>Excites meson states spectra</u>
4. <u>……….</u>

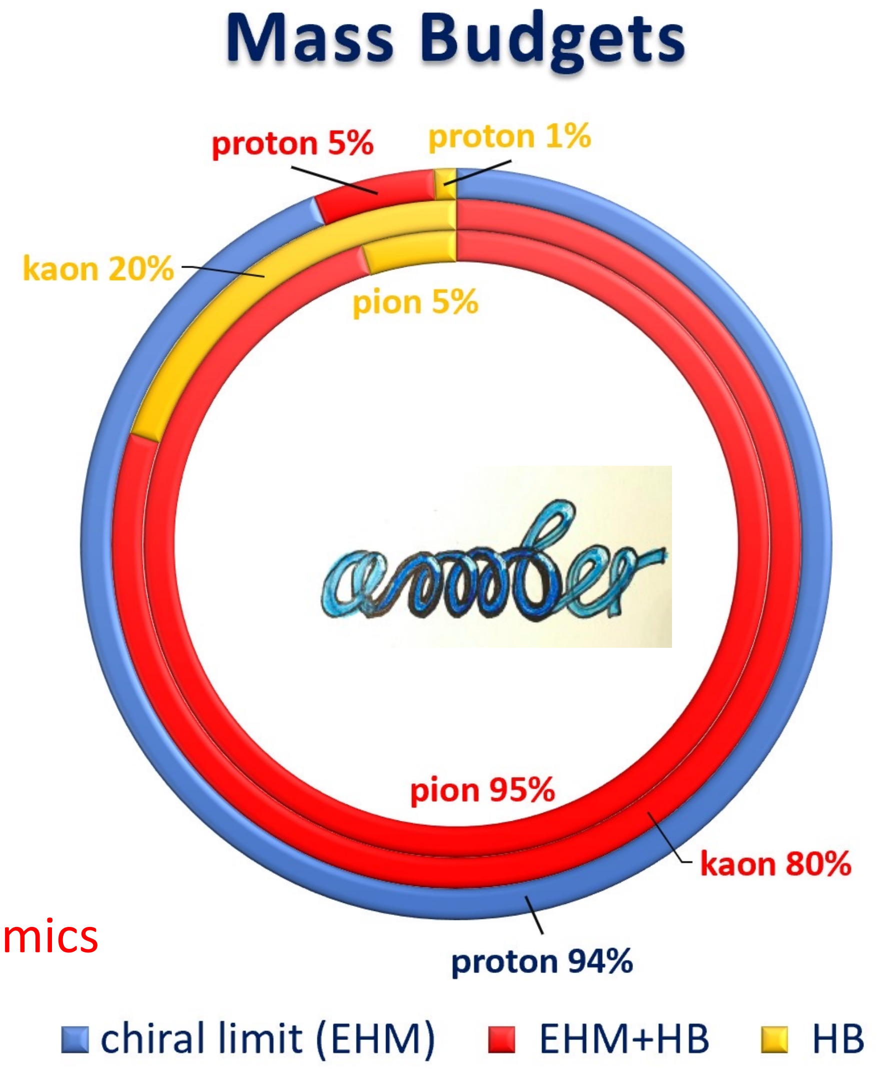
EHM phenomenon
does it enough to study proton to understood SM?

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:

- At chiral limit the mass of the proton remains basically the same
- Chiral limit mass of pion and kaon is by definition "0" (Nambu-Goldstone boson)
- Different gluon content expected for pion and kaon
- Interplay with Higgs mechanism is different



Thus it is equally important to study internal structure and dynamics of Pions/Kaons and protons

AMBER physics program
the issue of the emergence of the hadronic mass (EHM)

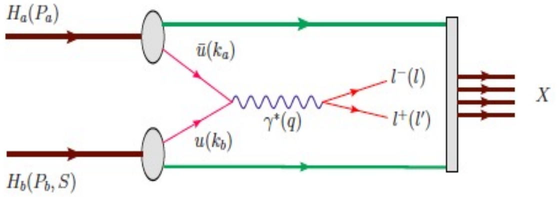
Questions to be answered:

- 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

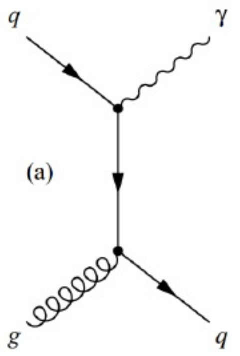
A series of workshops entitled "Perceiving of the EHM through AMBER@CERN(SPS)": **https://indico.cern.ch/event/1021402/**

Methods:

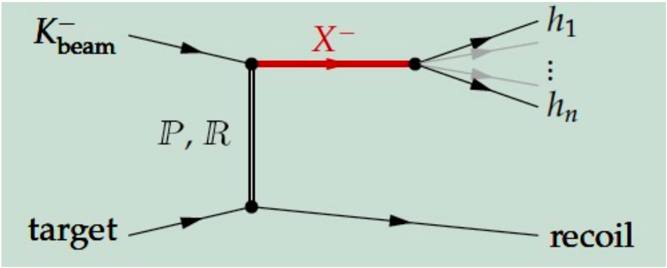
Drell-Yan and J/Ψ

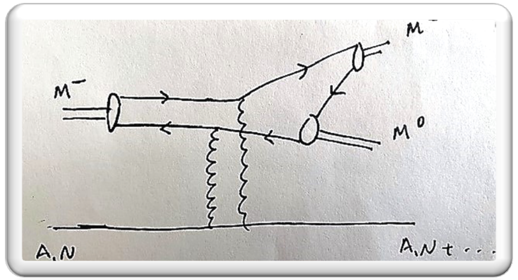


Prompt Photon Production

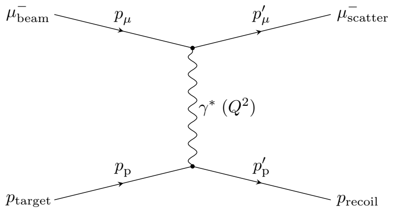


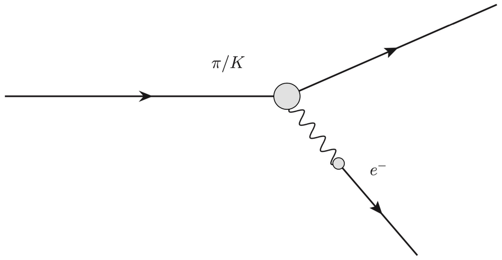
Diffractive scattering





Hadron radii





AMBER (PHASE-1 – approved by CERN RB on 02/12/2020)

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PHASE-1

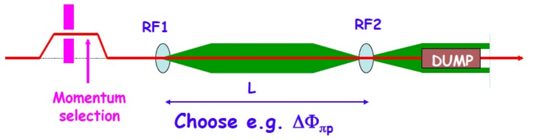
Conventional hadron and muon beams

2022 ➔ 2028

PHASE-2

Conventional and RF-separated Hadron/Hadron and muon beam

2029 and beyond



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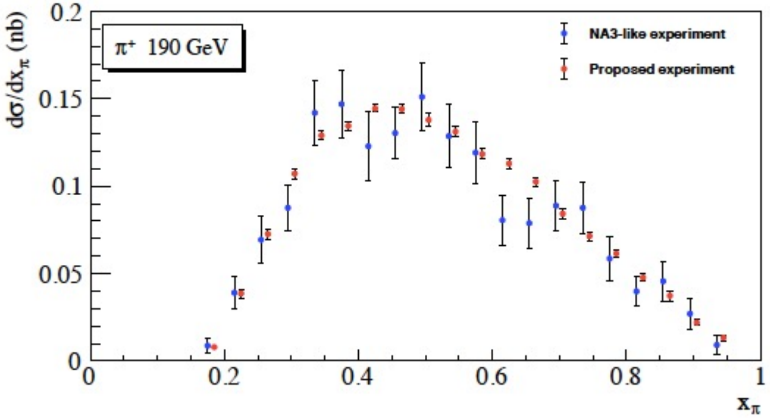
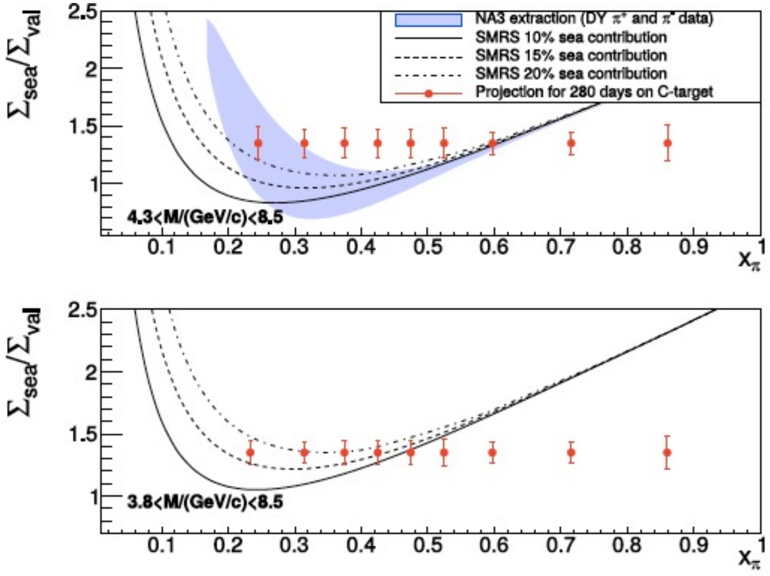
EHM
AMBER (pion induced DY)





Pion structure in pion induce 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^- 10:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda^{\pi}_{int}$)
  - Improvement of shielding to double the intensity is under investigation

PHASE-1

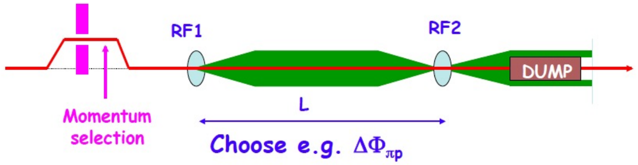
Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 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
This exp	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*

AMBER (kaon induced DY)

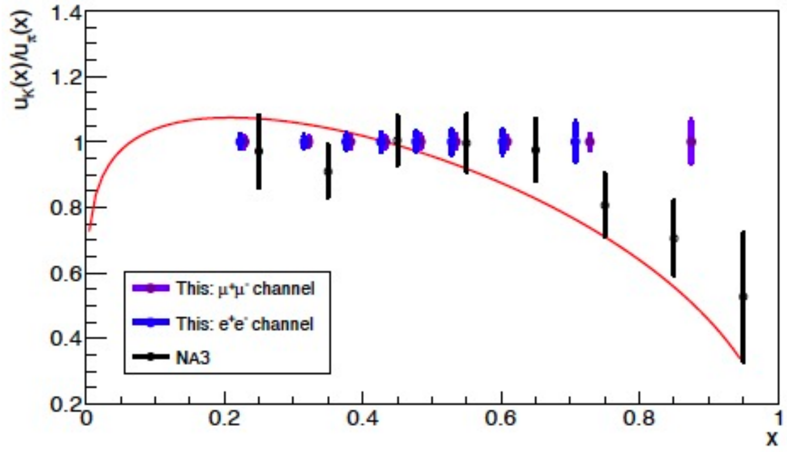
Extremely important to compare the gluon content of kaon and pion (emergent mass)

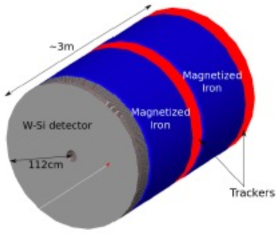
- **First ever DY measurements that could lead to kaon PDFs**
- Achievable statistics depends on beam energy and on kaon beam purity. Assuming $I = 7 \times 10^7\ s^{-1}$ with 30% kaons:
  - 40 kevents (K^-) and 5 kevents (K^+) @ 100 GeV
  - 25 kevents (K^-) and 3 kevents (K^+) @ 80 GeV



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





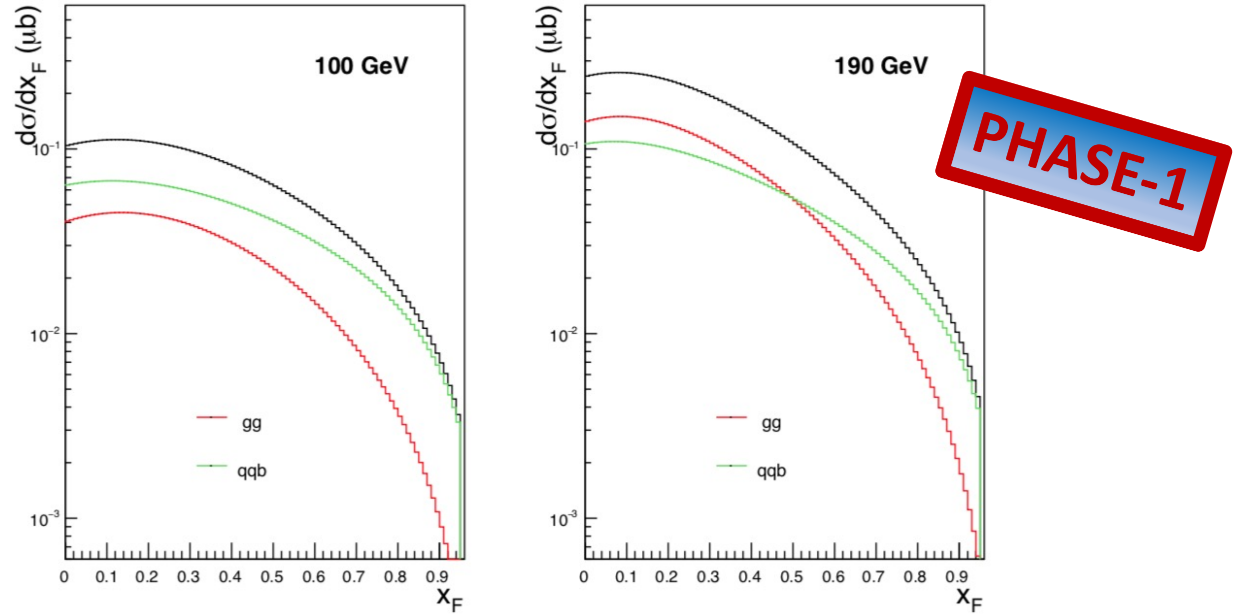
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	60	4.0 – 8.5	12,000	8,000
				70	4.0 – 8.5	18,000	10,900
				80	4.0 – 8.5	25,000	13,700
				100	4.0 – 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

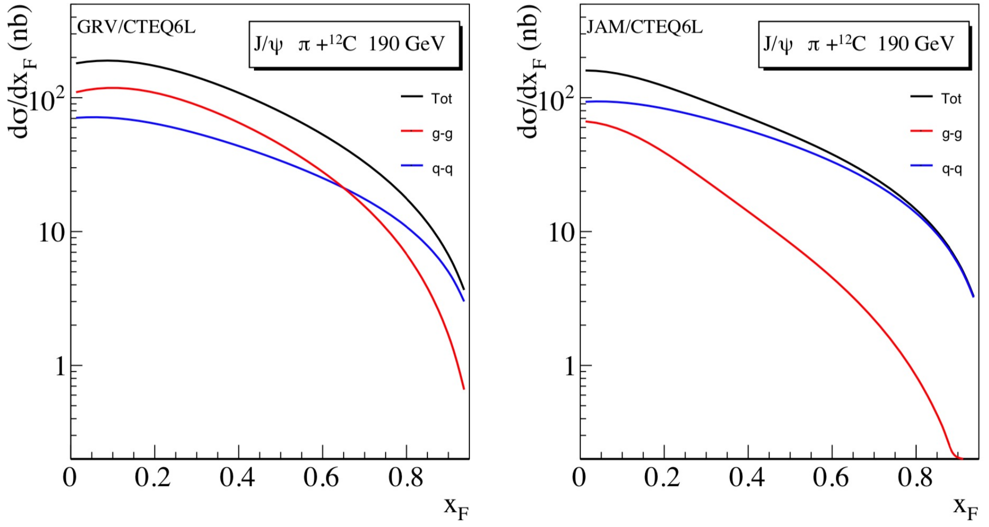
AMBER
Charmonium

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)
- $\boldsymbol{\Psi}$(2S) signal study, free of feed-down effect from and χ_{c1} χ_{c2}

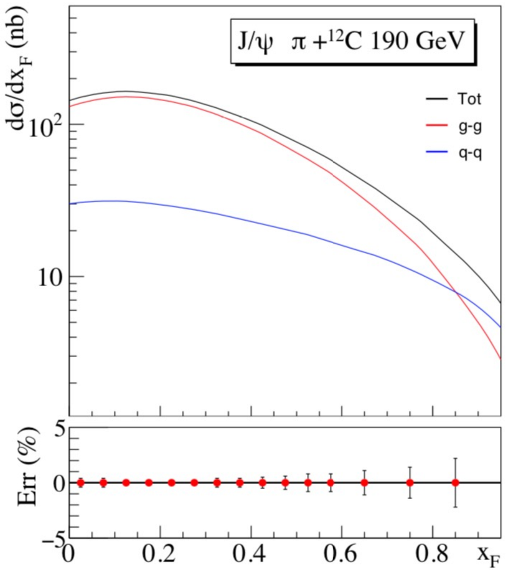


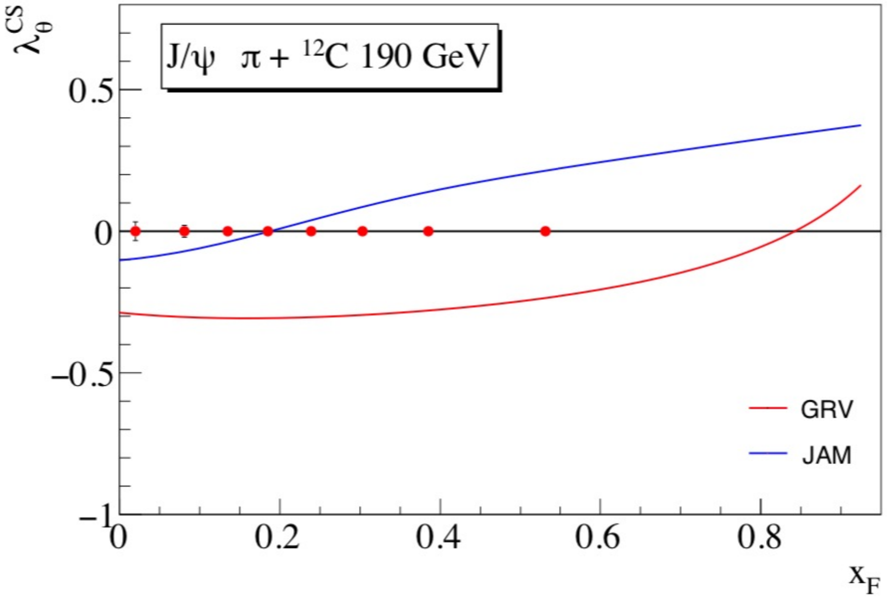


Method: Model depended separation of contributions from two competent processes using data collected with both positive and negative beams

AMBER
Charmonium

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





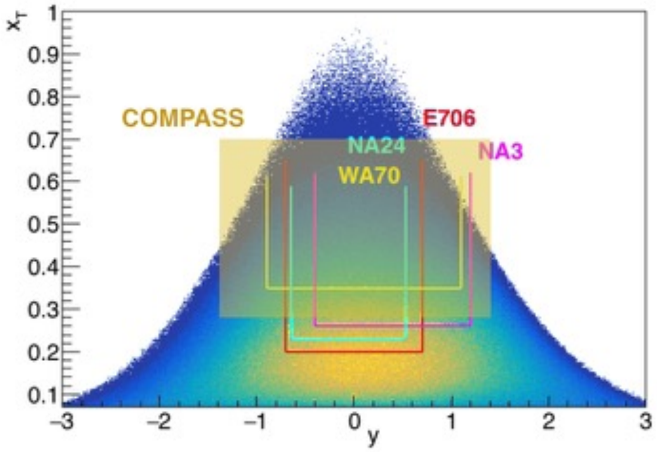
PHASE-1

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

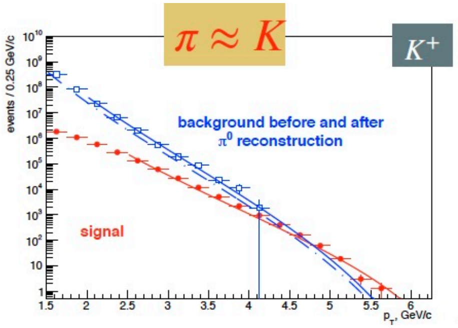
AMBER
Prompt Photons

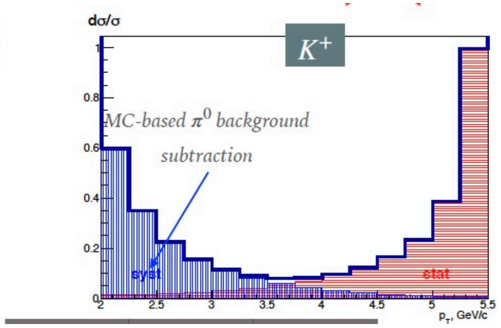
At the moment there is no experimental information about gluon contribution in kaon. Calculations based on Dyson-Schwinger equations predict 6 times smaller contribution at hadronic scale in respect to pion (Phys. Rev. D93 (7) (2016) 074021)

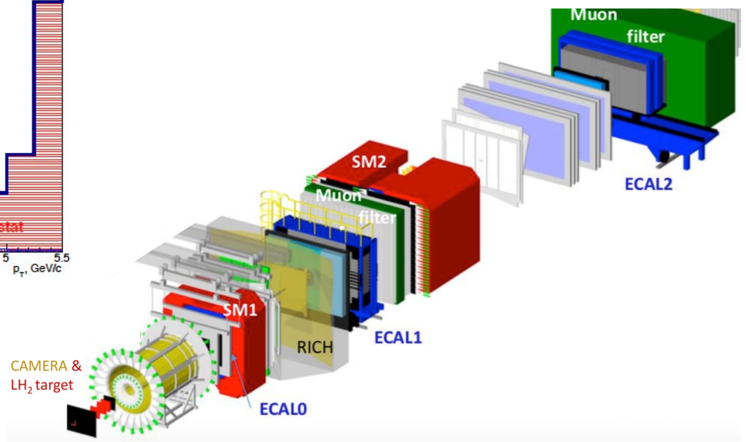
Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.

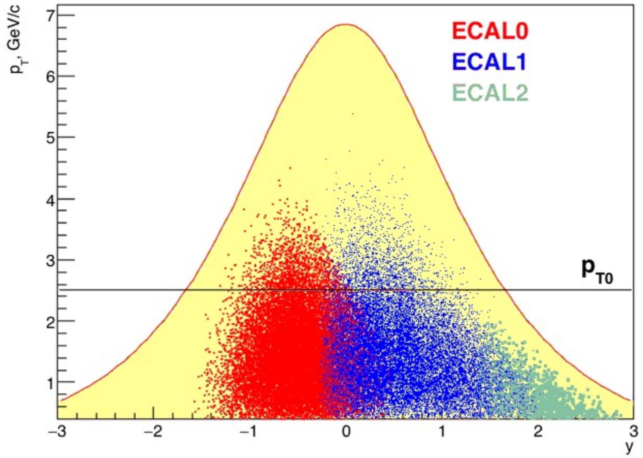


Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.



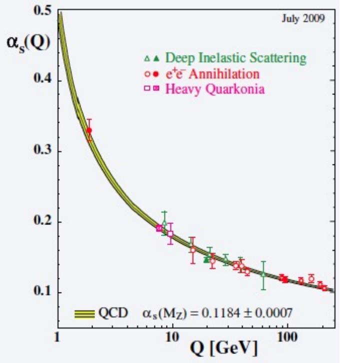






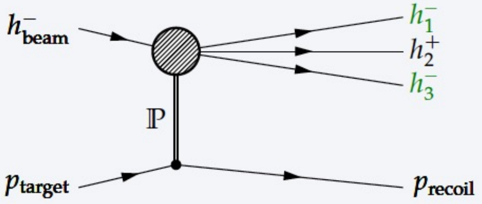
Hadron spectroscopy AMBER (kaon beam)

- Binding of quarks and gluons into hadrons governed by low-energy (long-distance) regime of QCD
- Least understood aspect of QCD
  - Perturbation expansion in α_s not applicable
  - Revert to models or numerical simulation of QCD (lattice QCD)
- Details of binding related to hadron masses
  - Only small fraction of proton mass explained by Higgs mechanism $\Rightarrow$ most generated dynamically



Hadrons reflect workings of QCD at low energies

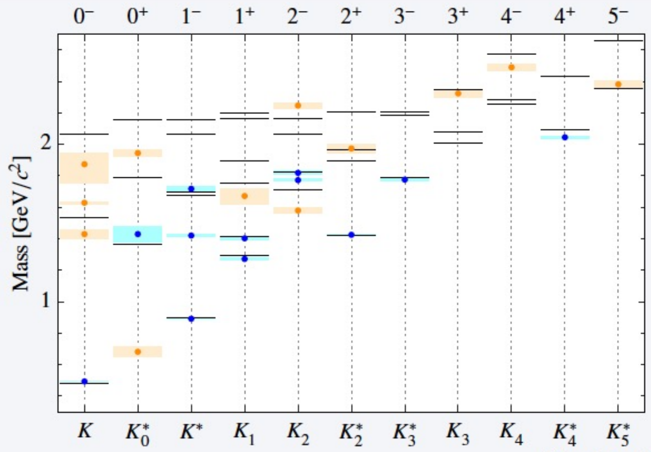
Measurement of **hadron spectra** and **hadron decays** gives valuable input to theory and phenomenology



- Diffractive production of excited kaon states X^- that decay into $K^-\pi^+\pi^-$
- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
  - Distinguish K^- from π^- over wide momentum range

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



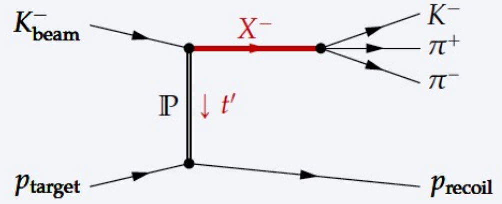
[Courtesy S. Wallner, TUM]

Boris Grube, TU München | Hadron Spectroscopy with Kaon Beam

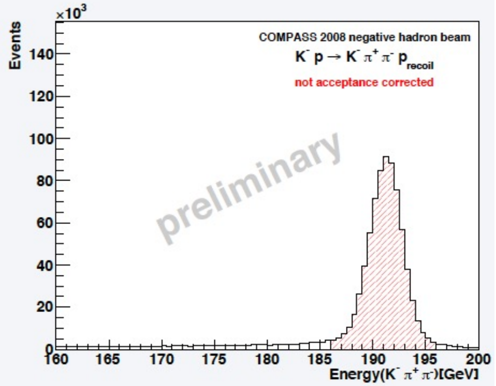
Many kaon states need confirmation

- 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)

Hadron spectroscopy AMBER (kaon beam)



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



Work in progress: improving analysis

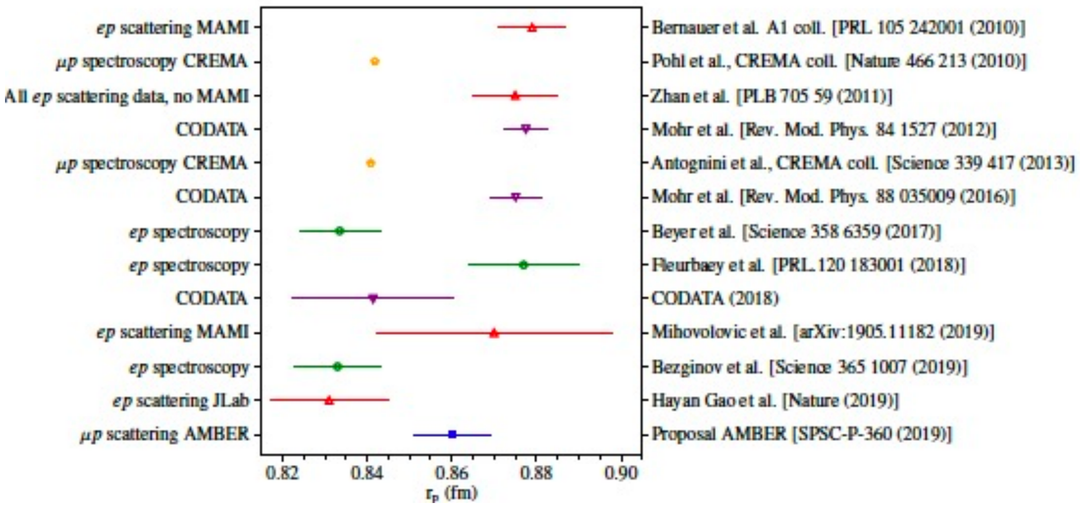
- Improved beam PID + data sample from 2009 run
  $\Rightarrow$ ca. 8×10^5 $K^-\pi^+\pi^-$ events
  $\Rightarrow$ world's largest data set (4× WA03)
- Improved PWA model $\Rightarrow$ clearer resonance signals
- Resonance-model fit $\Rightarrow$ extraction of $K^-\pi^+\pi^-$ resonances and their parameters

Future program

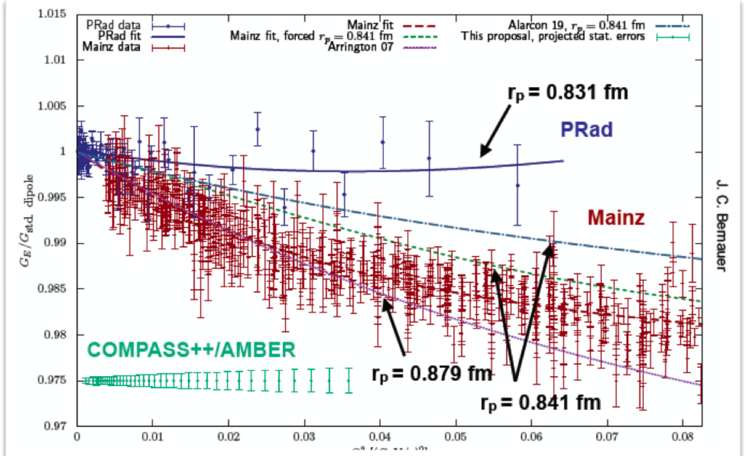
- *Goal:* collect 10 to 20×10^6 $K^-\pi^+\pi^-$ events using high-intensity RF-separated kaon beam
  - Would exceed any existing data sample by at least factor 10
  - *High physics potential:* rewrite PDG for kaon states above $1.5\,\mathrm{GeV}/c^2$ (like LASS and WA03 did 30 year ago)
  - Precision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

Measurement of kaon Compton scattering via the Primakoff effect and an RF separated beam for determination of the kaon polarisability, and kaon-photon induced strange meson production

Proton-charge Radius Measurement at AMBER (confinement, EHM)



	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 AμBER



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

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

- 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

statistical precision of the proposed measurement, down to Q2 = 0,001 GeV^2/c^2, Cross section is normalised to the G_D - dipole form factor

Proton-charge Radius Measurement at AMBER (confinement, EHM)

Proton Radius Experiment at Jefferson Lab

PRoton Radius

mami MAINZER MIKROTRON

MAGIX

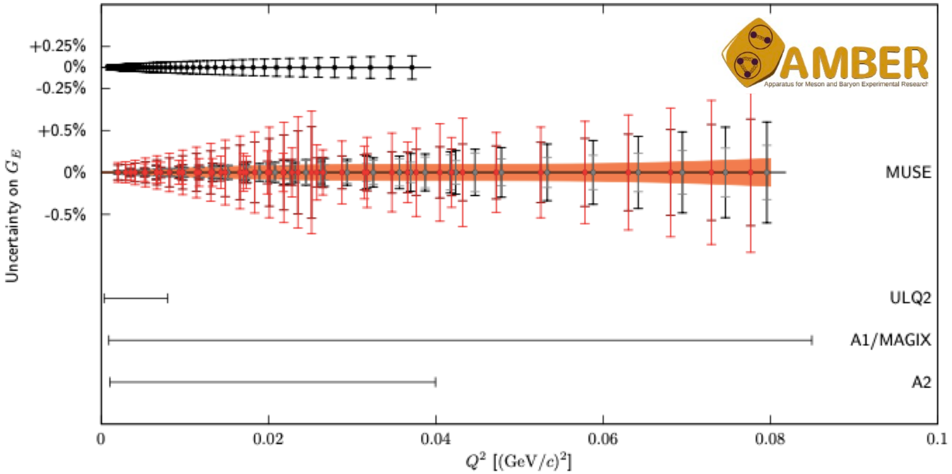
MESA Mainz Energy-recovering Superconducting Accelerator

PAUL SCHERRER INSTITUT PSI

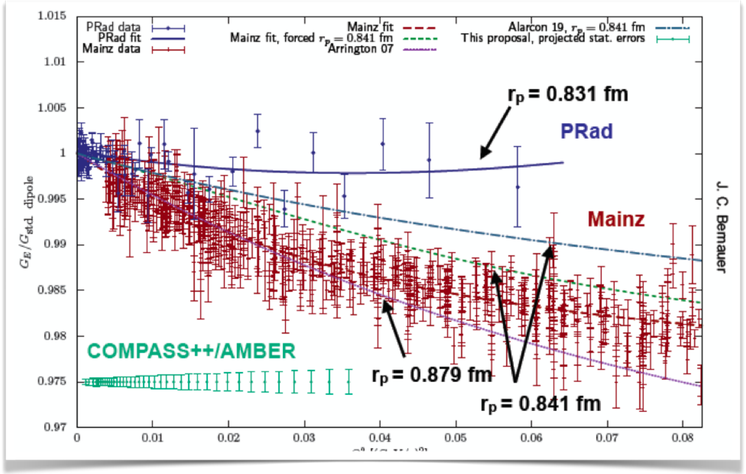
- A number of experiments are on the way in different laboratories
- There is a synergy between PRES at MAMI (E_e = 720 *MeV*) and AMBER ($E\mu = 100\ GeV$):
  - The same type of active target (hydrogen filled TPC) will be used for both experiment
  - The same Q^2 range will be covered (10^{-3} - $4x10^{-2}$ 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 another 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 (100-200 *MeV/c* vs 100 *GeV/c*)
- Small statistical errors achievable with the proposed running time



AMBER - New EHM-related ideas:
PDA and meson radii



statistical precision of the proposed measurement, down to Q2 = 0,001 GeV^2/c^2, Cross section is normalised to the G_D - dipole form factor

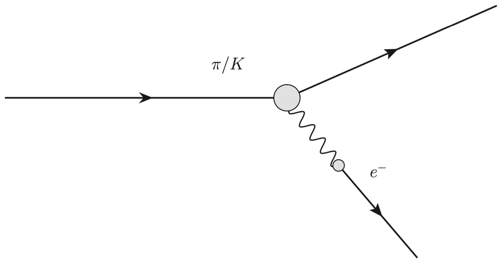
C.R.: Precise measurements of pion and kaon radii will reveal the compositeness (confinement) scale for (near) Nambu-Goldstone bosons.

Very few data on mesons radii:

S. R. Amendolia, et al., A Measurement of the Space - Like Pion Electromagnetic Form-Factor, Nucl. Phys. B 277 (1986) 168.

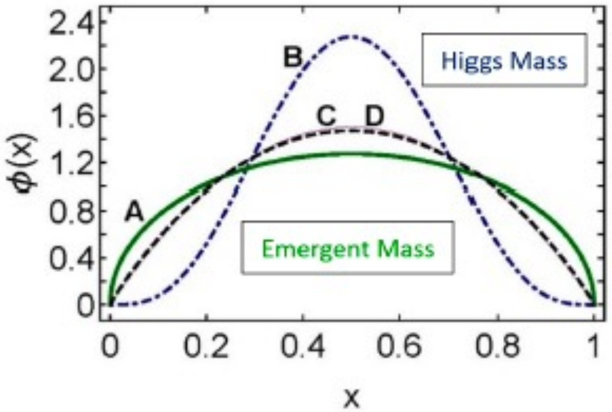
I. M. Gough Eschrich, et al., Measurement of the Sigma- Charge Radius by Sigma- Electron Elastic Scattering, Phys. Lett. B 522 (2001) 233

S. Amendolia, et al., A Measurement of the Kaon Charge Radius, Phys. Lett. B 178 (1986) 435.



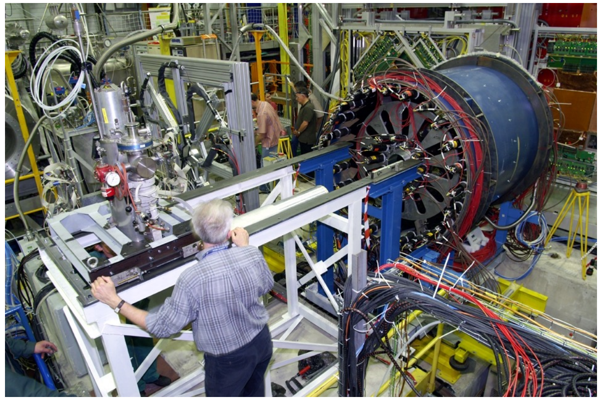
We are studying know the feasibility of such an experiments using AMBER's high intensity pion and kaon beams

AMBER - New EHM-related ideas: PDA and meson radii



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

C.R.: 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.

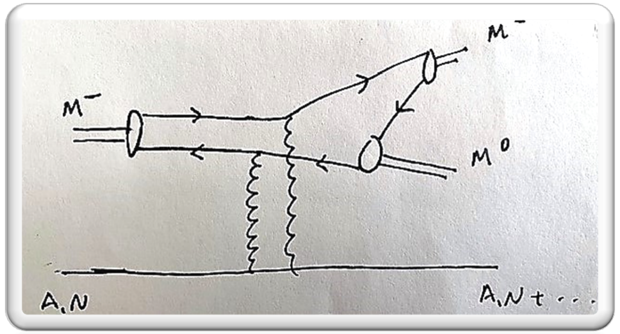


A solid (green) emergent mass generation is dominant (pion);
B dot-dashed (blue) curve: Higgs mechanism is the primary source of mass generation (C-meson);
C solid (thin, purple) curve (asymptotic prole, 6x(1 - x);

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



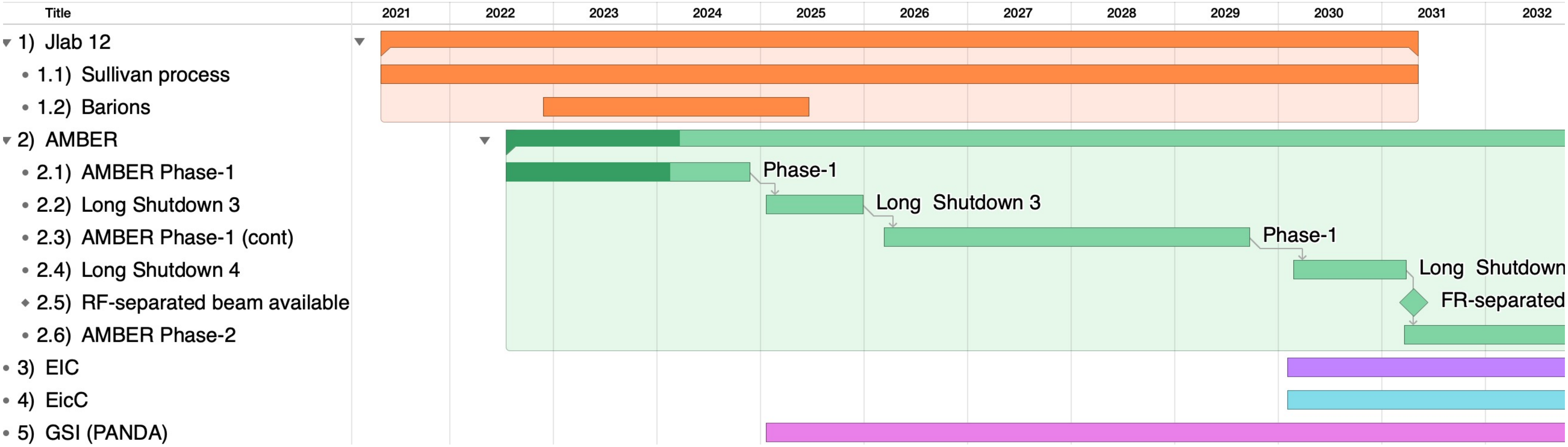
AMBER – Phase - 1
Running plan

We will start AMBER Phase-1 program with proton radius measurement, then antimatter production cross-section and Drell-Yan:

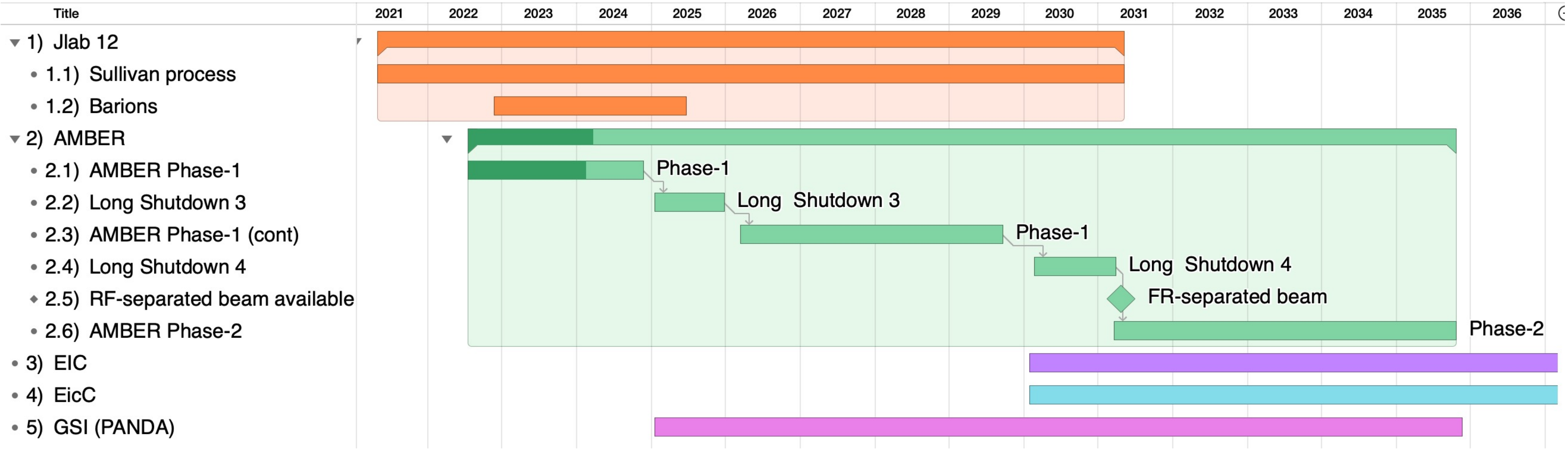
PRM: 2022-2023

AMP: 2023-2024

Drell-Yan: starting 2024



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

- Main bearing column of the AMBER is Emergence of the Hadron Mass phenomenon

- Our knowledge on pion structure will be much improved after AMBER Phase-1 measurements

- Radio-frequency separated high intensity kaon beam is unique instrument for kaon structure/spectroscopy study at AMBER Phase-2