Perceiving the emergence of Hadron Mass through AMBER at CERN SPS

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Mass in the Standard Model and Consequences of its Emergence

Oleg Denisov on behalf of the AMBER Collaboration, Trento, Italy, 2021/04/20

Outline

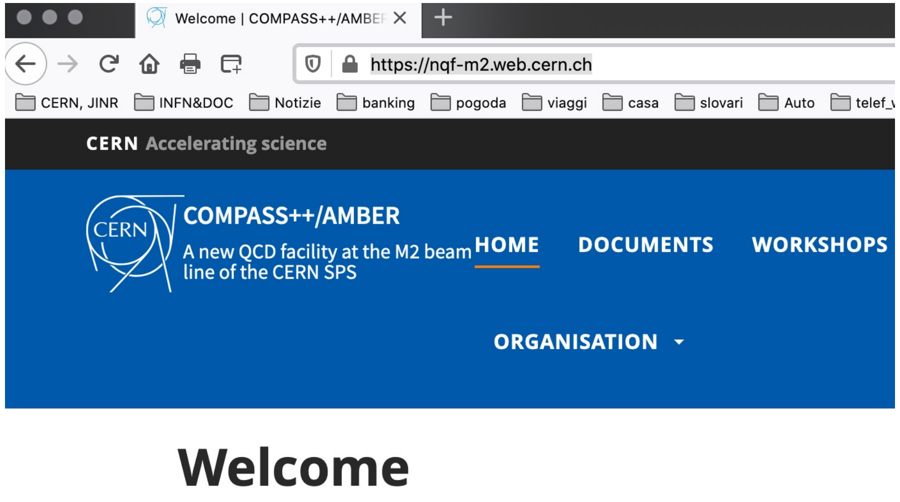
1. Intro/LoI AMBER
2. AMBER Physics case:
   - Emergence of the hadronic mass
   - Proton spin structure
3. Emergence of the Hadron Mass:
   - Drell-Yan
   - Charmonia production
   - Prompt photons
   - Spectroscopy
   - Proton radius
4. Proton spin structure
   - DVCS
   - Drell-Yan
5. New ideas
6. AMBER Phase-1
7. 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‡

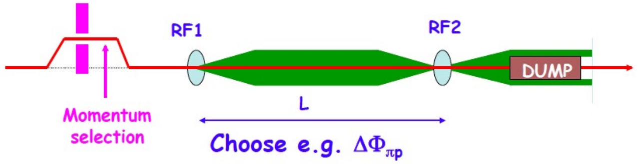
B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

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

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PHASE-1

Conventional hadron and muon beams

2022 ➔ 2027

PHASE-2

Conventional and RF-separated Hadron/Hadron and muon beam

2029 and beyond

Main bearing column of the AMBER is EHM

There are two bearing columns of the facility:

1. **Phenomenon of the emergence of the hadron mass**
2. **Proton spin (largely addressed by COMPASS)**

FIRST, 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

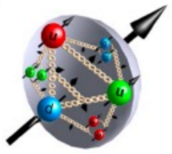
Pion

- $M_\pi \sim 140$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

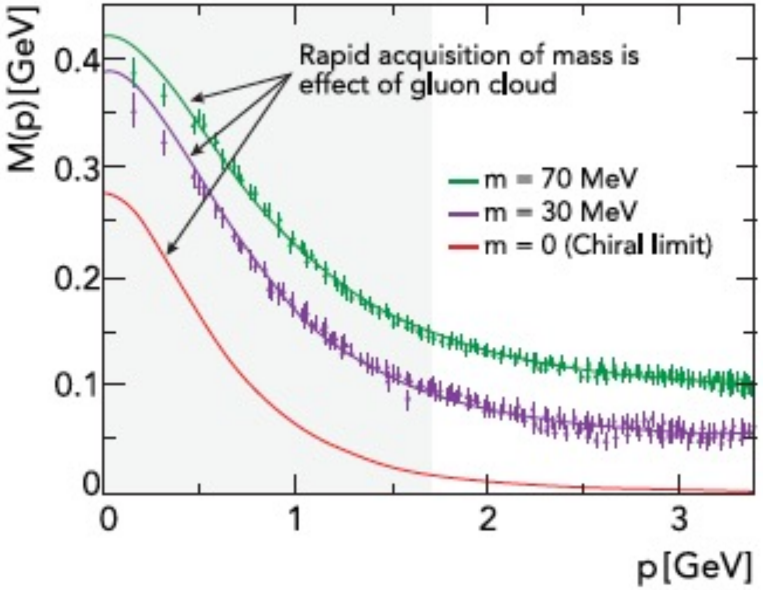
Higgs generated masses of the valence quarks:

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

As Higgs mechanism produces a few percent of visible mass, thus the mass scale is defined by QCD mechanisms

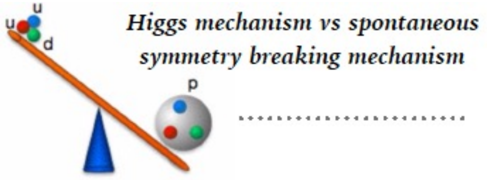
EHM
(mass budget in proton, different QCD mechanism for Nambu-Goldstone bosons)

Dressed-quark mass function M(p)



The proton mass in the chiral limit is close to its nominal mass, as quark «gain» a mass evolving in to constituent one as its momentum became smaller.

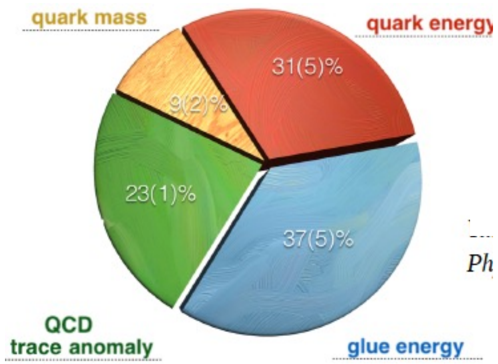
It is very different for pion and kaon (lightest Nambu-Goldstone modes) as they are massles in the chiral limit by definition.

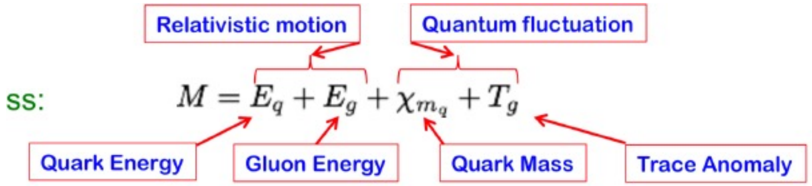


Does this mean that their gluon content is equally small and different from the proton once? ➔ Must Study PDFs

One of the possible proton mass decomposition (calculation on lattice)

Yi-Bo Yong et al., Phys.Rev.Lett. 121 (2018) no.21, 212001





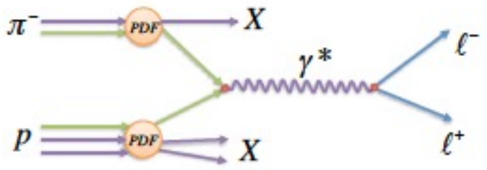
AMBER physics program
the issue of the emergence of the hadronic mass (EHM)

Questions to be answered:

- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass .vs. Higgs)
- Gluon content, especially important pion/kaon striking difference

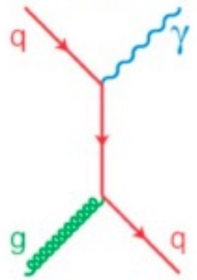
Methods:

Drell-Yan:



- 90's: NA3, NA10, E615
- 10's: COMPASS-II
- 20's: COMPASS++

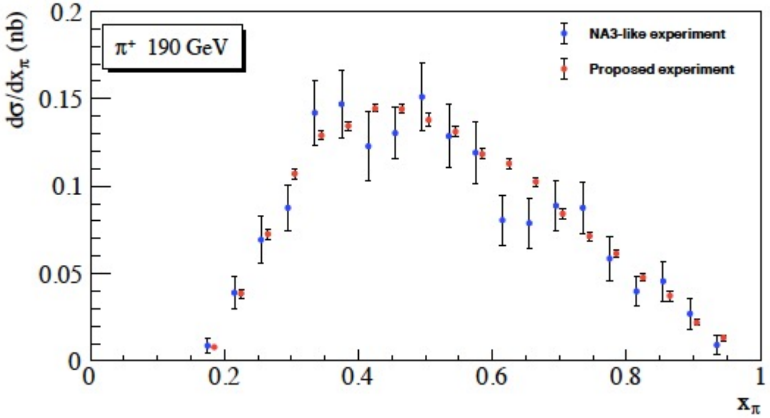
Prompt photon production:



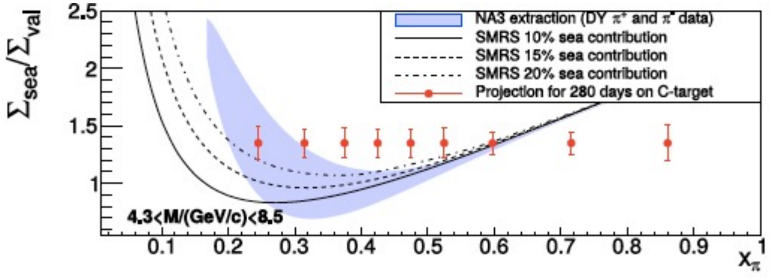
- 90's: NA24, W70
- 20's: COMPASS++

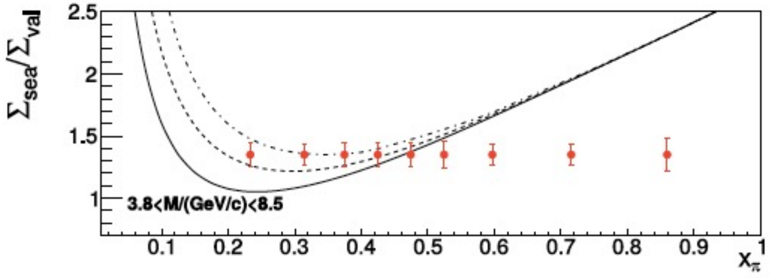
As well Charmonia production, pi/K diffractive scattering

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

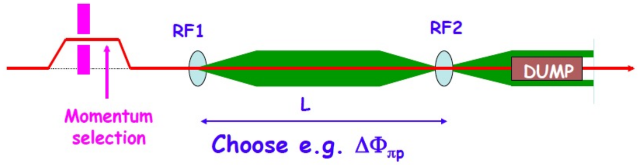
Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120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

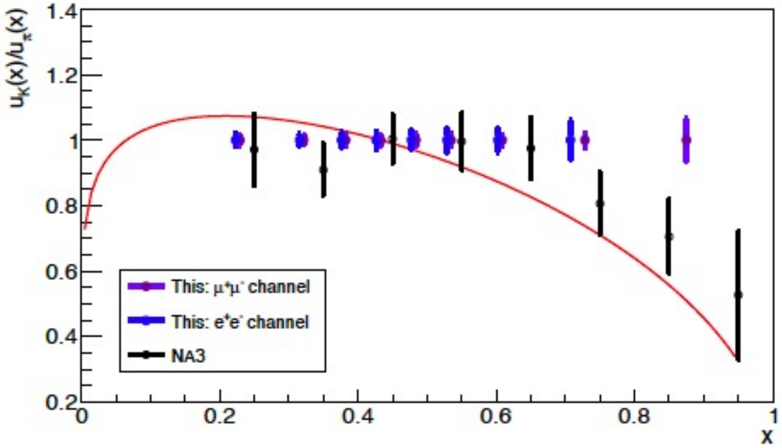
Extremely important to compare the gluon content of kaon and pion (emergent mass)

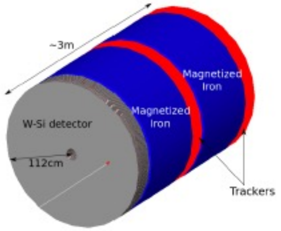
- **First ever DY measurements that could lead to kaon PDFs**
- Achievable statistics depends on beam energy and on kaon beam purity. Assuming $I = 7 \times 10^{7}\ s^{-1}$ with 30% kaons:
  - 40 kevents (K^-) and 5 kevents (K^+) @ 100 GeV
  - 25 kevents (K^-) and 3 kevents (K^+) @ 80 GeV



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





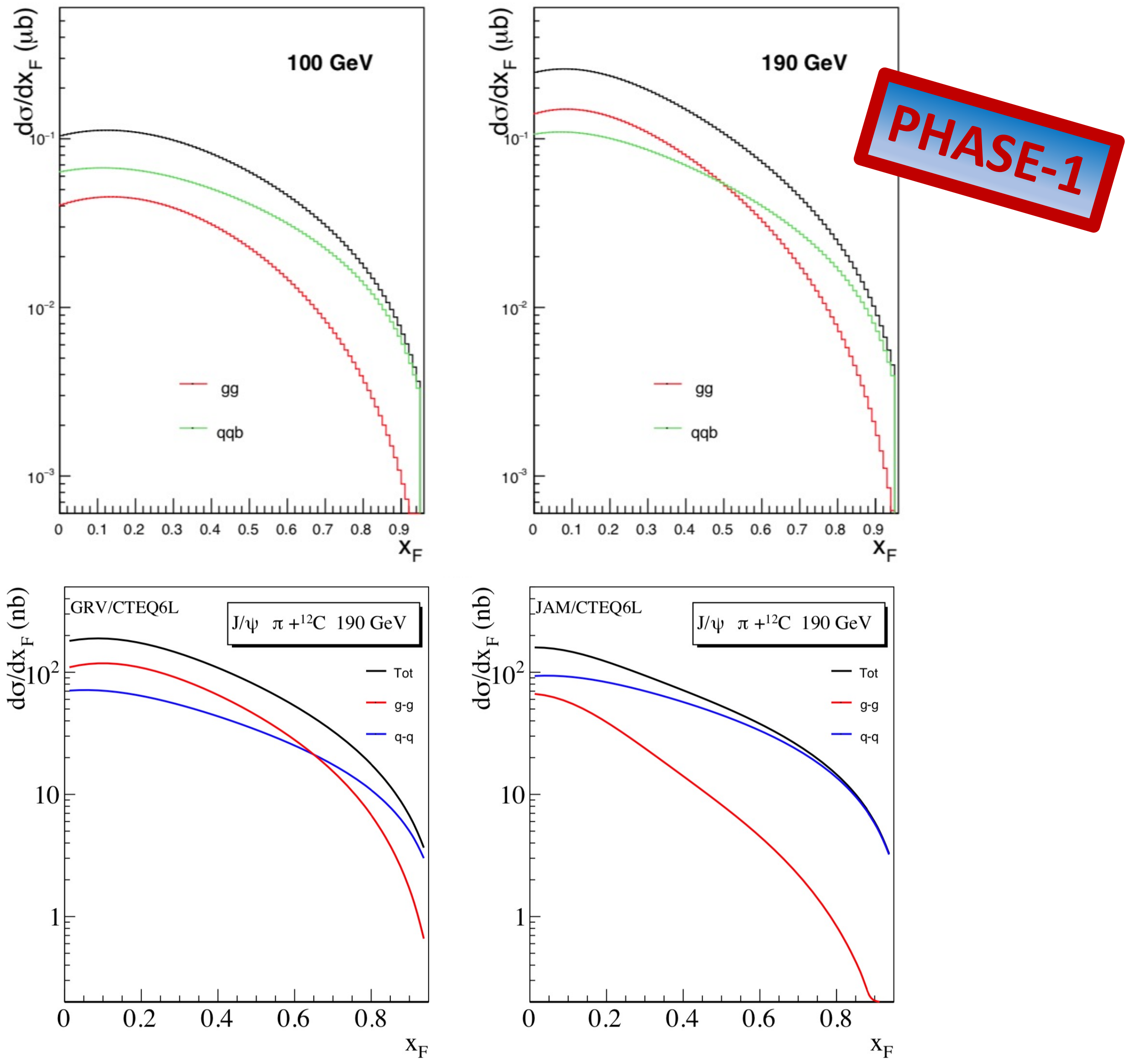
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	60	4.0 – 8.5	12,000	8,000
				70	4.0 – 8.5	18,000	10,900
				80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	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:

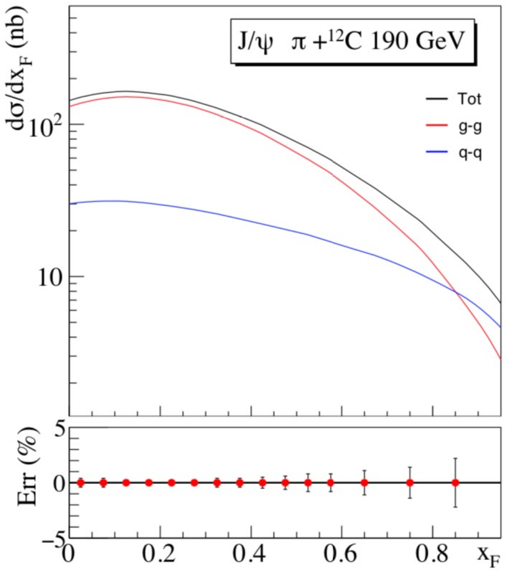
- Study of the J/ψ (charmonia) production mechanisms (*gg–fusion vs $q\bar{q}$–annihilation),* comparison of **CEM** and **NRQCD**
- Probe gluon and quark PDFs of pion
  (arXiv:2103.11660v1 [hep-ph] 22 Mar 2021)
- $\boldsymbol{\Psi}$(2S) signal study, free of feed-down effect from and χ_{c1} χ_{c2}

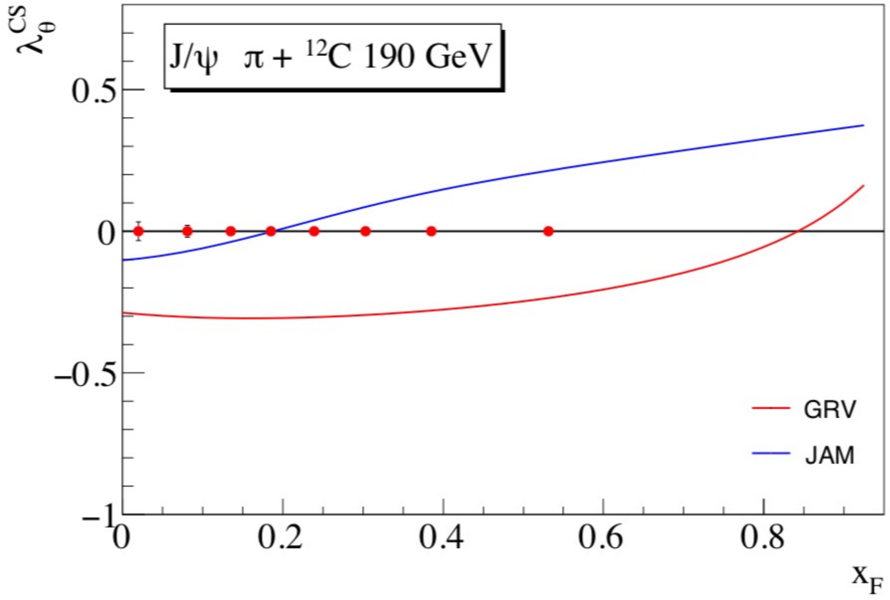


Method: Model depended separation of contributions from two competent processes using data collected with both positive and negative beams

AMBER
Charmonium

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





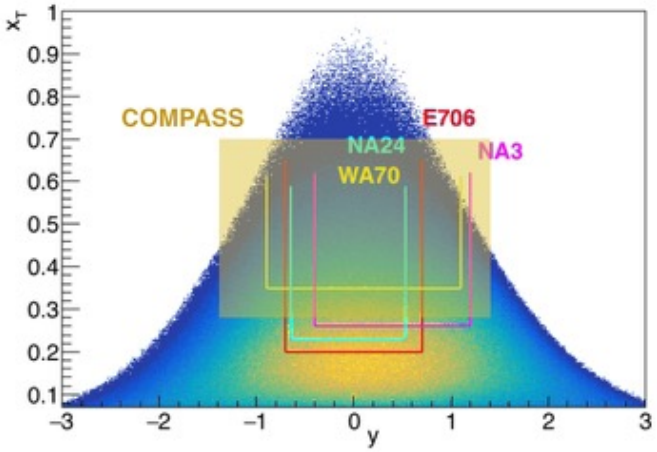
Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be, Fe, Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			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

PHASE-1

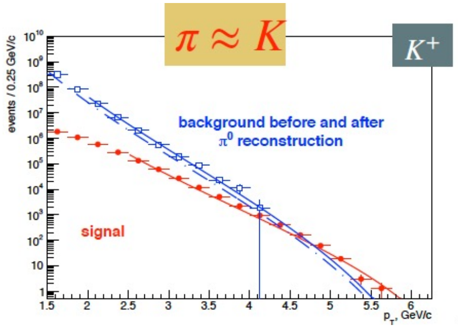
AMBER
Prompt Photons

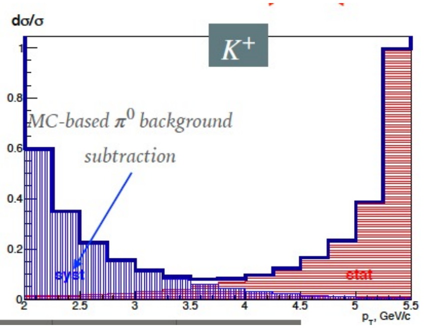
At the moment there is no experimental information about gluon contribution in kaon. Calculations based on Dyson-Schwinger equations predict 6 times smaller contribution at hadronic scale in respect to pion (Phys. Rev. D93 (7) (2016) 074021)

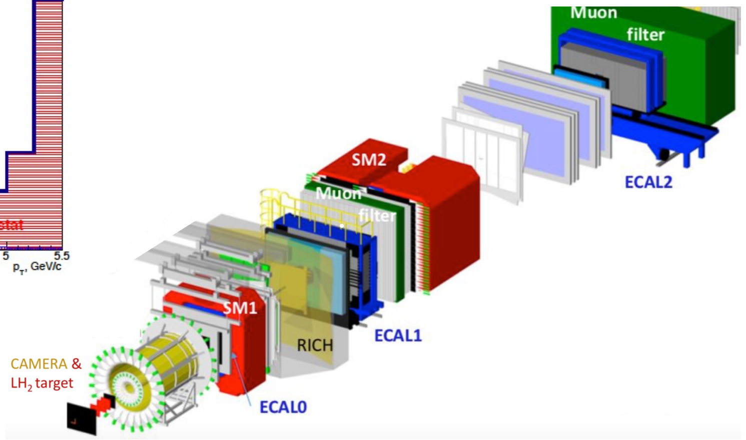
Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.

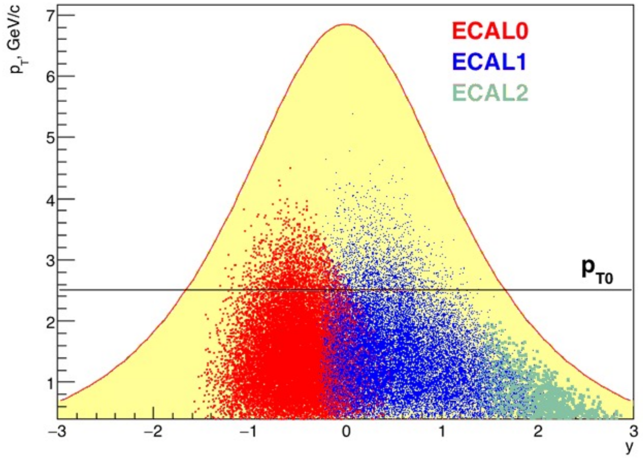


Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.



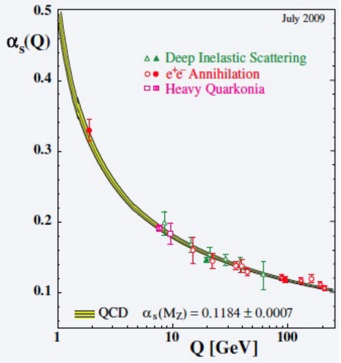






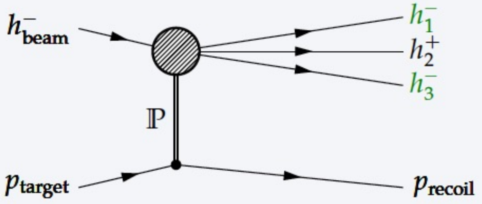
Hadron spectroscopy AMBER (kaon beam)

- 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

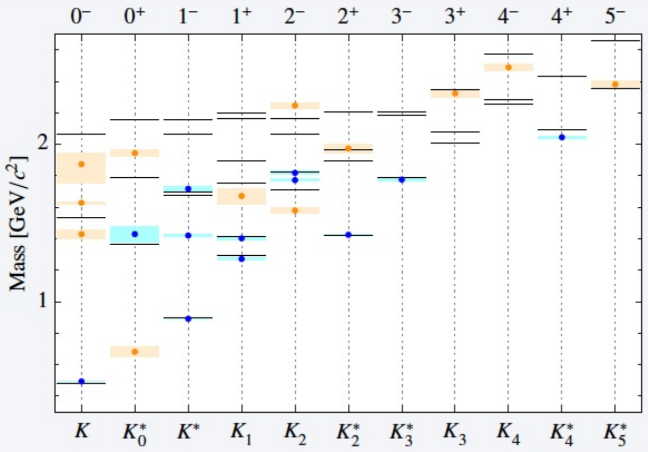
Measurement of **hadron spectra** and **hadron decays** gives valuable input to theory and phenomenology



- 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



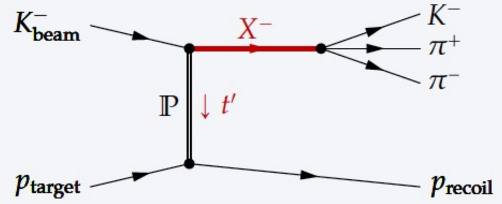
[Courtesy S. Wallner, TUM]

Boris Grube, TU München | Hadron Spectroscopy with Kaon Beam

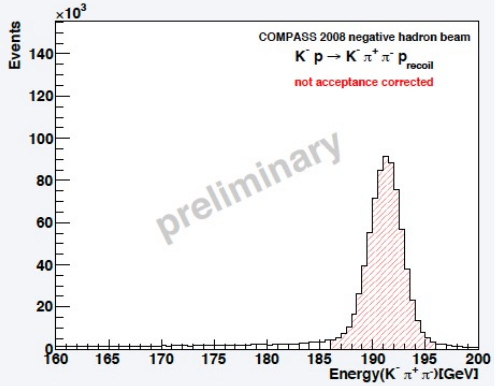
Many kaon states need confirmation

- 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. $8 \times 10^5\ K^-\pi^+\pi^-$ 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

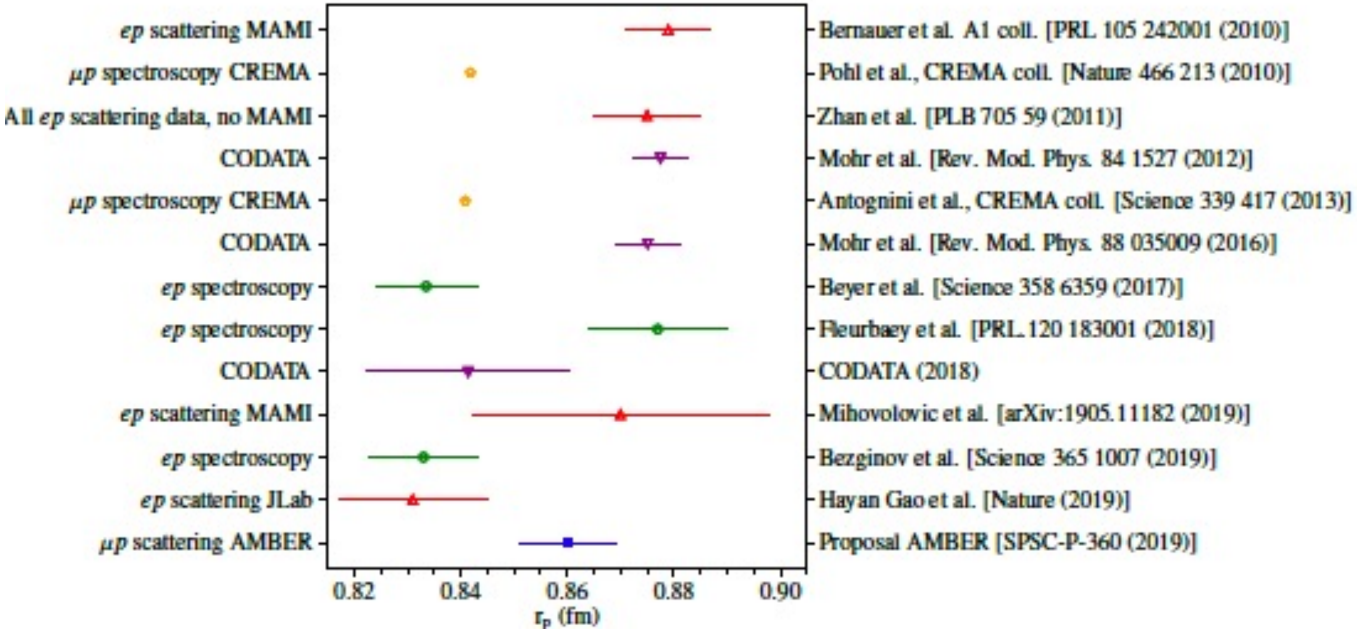
Future program

- *Goal:* collect 10 to 20 $\times 10^6\ K^-\pi^+\pi^-$ 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 $1.5\ \mathrm{GeV}/c^2$ (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 Radius Puzzle

PHASE-1



	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

- **Recent data points of spectroscopy and scattering experiments added**
- **Some trending towards the small-radius (0.84 fm) scenario**
- **Electron scattering analysis has determined a larger radius (0.88 fm), sources for the discrepancy still not clarified**
- **JLab result to be awaited; in case it points to a novel interpretation of lepton scattering data (radiative/energy loss/… corrections): precision measurement of the proton form factors, especially at lower Q^2 are urgently needed!**

Proton Radius Puzzle
(Set-up and Simulations)

PHASE-1

AMBER

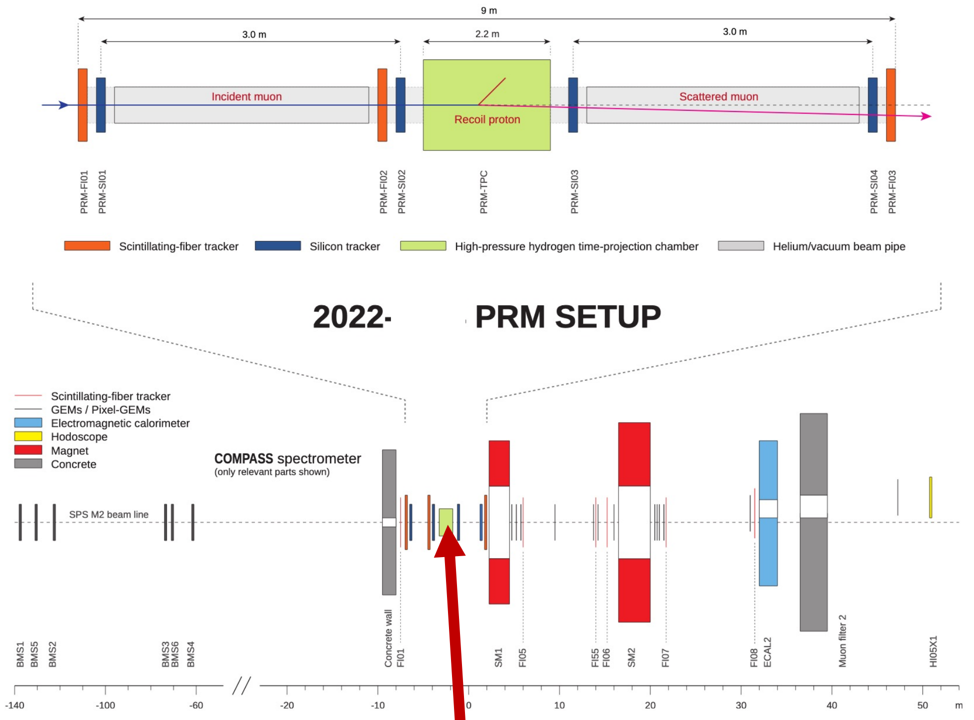
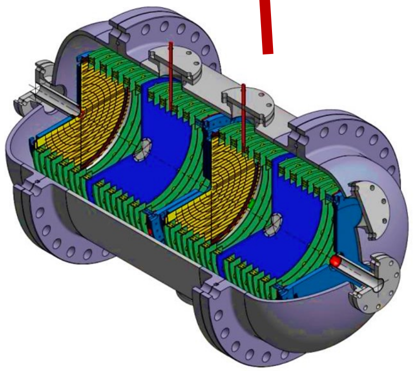
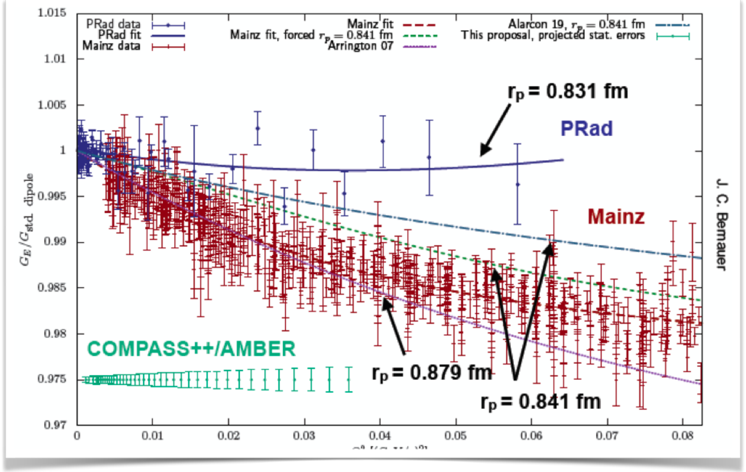


Figure 4: Layout of the experimental setup at the M2 beam line, highlighting the relevant parts of the COMPASS spectrometer and the additional detectors required for the proton radius measurement.



Proposal for Measurements at the M2 beam line of the CERN SPS – Phase-1 –

17



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

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

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

- 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 spin structure

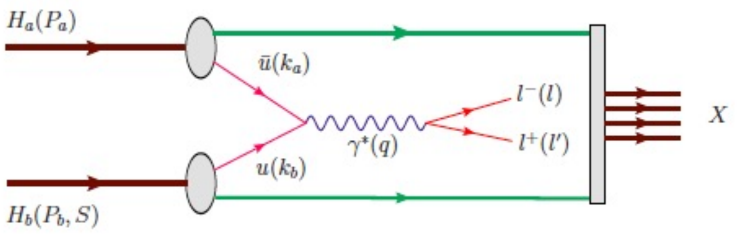
Huge progress has been done by COMPASS on resolving spin crisis and to study 3D structure of the nucleon in SIDIS, unpolarised DVCS and pion induced Polarised DY. The final year of the SIDIS running with transversely polarised deuteron target is approved BY SPSC and scheduled to 2021. This will finalise our data set to TMDs in SIDIS process.

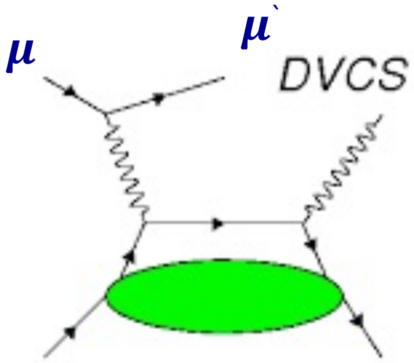
Still new, unique measurements can be done to access:

- Orbital momentum of quarks and gluons via polarised DVCS process
- TMDs, in particular Sivers and Boer-Mulders functions in a clean, nearly Model independent way via antiproton induced DY

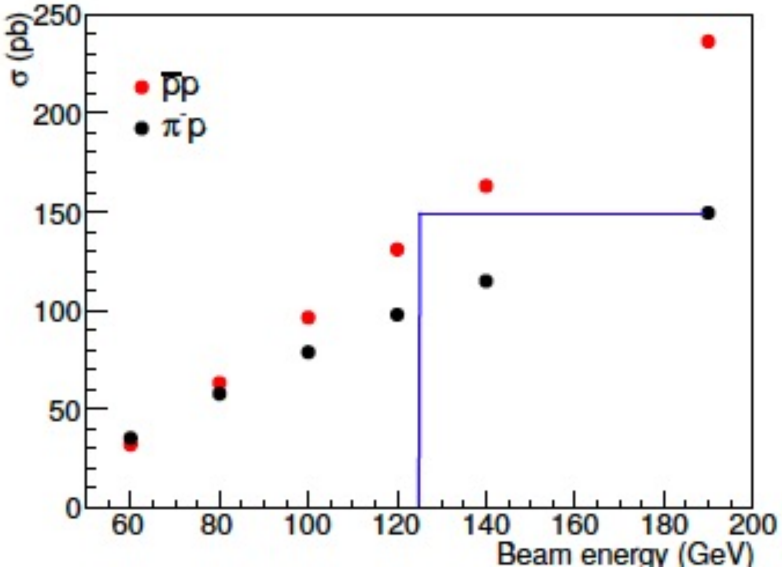
Methods:

Drell-Yan





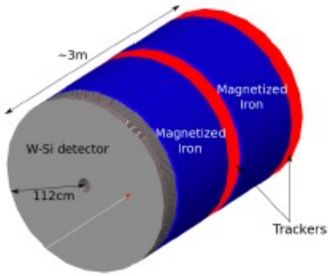
AMBER
TMDs in antiproton induced DY



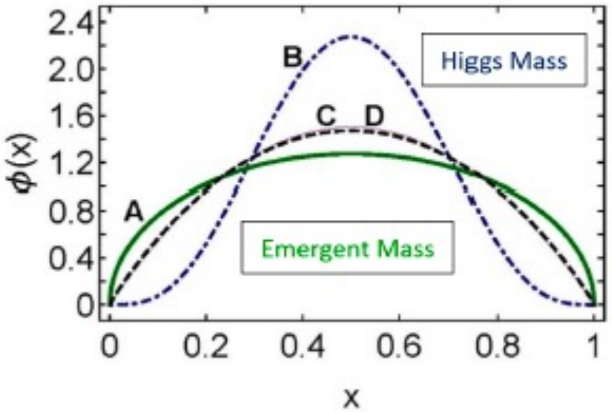
- cross-sections for $\bar{p}$ induced-DY at 120 GeV $\sim$ π^- induced-DY at 190 GeV
- Combined statistics from $\mu^+\mu^-$ and e^+e^- channels $\sim$ 2 years of COMPASS-II data taking

- Antiproton-induced polarised DY makes **TMD's extraction model independent**
- Allows to profit from good knowledge of proton PDFs (from SIDIS) and as alternative probe
  permits to test TMDs universality
- New data on all TMDs induced asymmetries in both High Mass and J/Ψ regions:
  1. Model independent Boer-Mulders (quark-spin – quark-k_T correl.) extraction (CPT equiv.)
  2. Model independent Transversity extraction
  3. Lam-Tung relation for antiprotons (QCD effects)
  4. Sivers asymmetry (nucleon-spin – quark-k_T correlations) with no uncertainty from pion PDFs
  5. Sivers function for gluons (J/Ψ regions)
  6. Flavour separated TMDs extraction
  7. EMC effects & flavour dependent EMC effects

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	e^+e^-
This exp.	110cm NH_3	$\bar{p}$	3.5×10^7	100	4.0 – 8.5	28,000	21,000
				120	4.0 – 8.5	40,000	27,300
				140	4.0 – 8.5	52,000	32,500

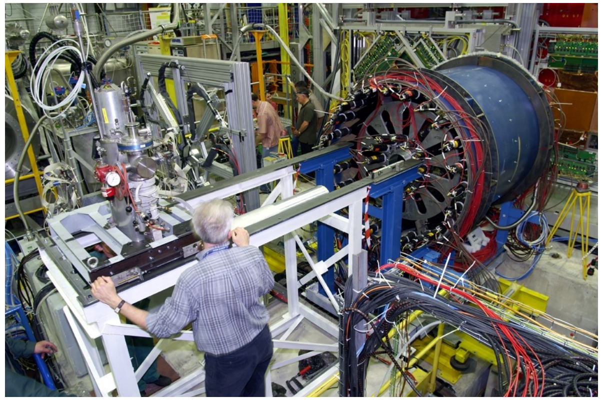


AMBER - New EHM-related ideas: PDA and meson radii

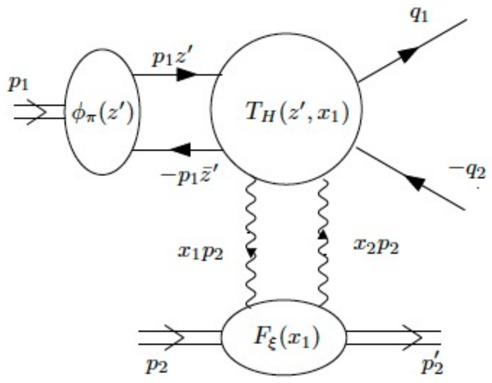


Where *x* is a fraction of hadron's longitudinal momentum carried by the quark in the imf.

Craig Roberts: 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);



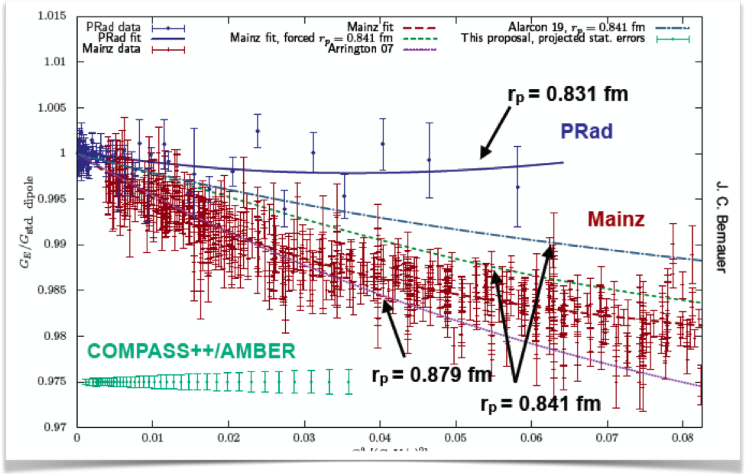
Fermilab E791 the only experimental data In di-jets production by 500 GeV π^- beam

AMBER robe: diffractive pion dissociation on a heavy target with very small *t'*, this is a coherent process where two quarks break apart producing hadron in the final state

In case of AMBER as our incoming beam energy is much smaller (typically 190 GeV) the hadron multiplicities will be lower in the final state, on the other hand we can select for example 2 hadron in the final state events. So we would like to know:

1. if such topology events can give an access to PDA
2. Observable ? – (similar to two-jets)

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

Craig Roberts: 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 – Proposal Phase-1

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–022
SPSC-P-360
September 30, 2019

51 institutions, ~260 authors,
19 new institutions with respect to COMPASS (Majority from USA, also Germany, Italy, Russia etc.)

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

– Phase-1 –

COMPASS++*/AMBER†

B. Adams[14,13], C.A. Aidala[1], G.D. Alexeev[15], M.G. Alexeev[42,43], A. Amoroso[42,43], V. Andrieux[45,20],

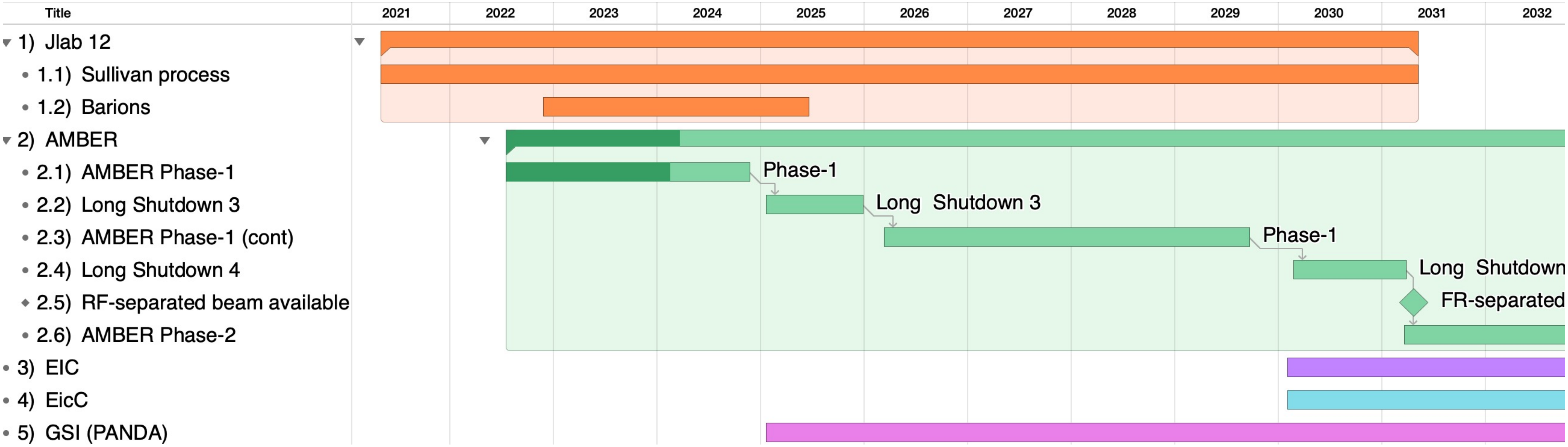
AMBER – Phase - 1
Running plan

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

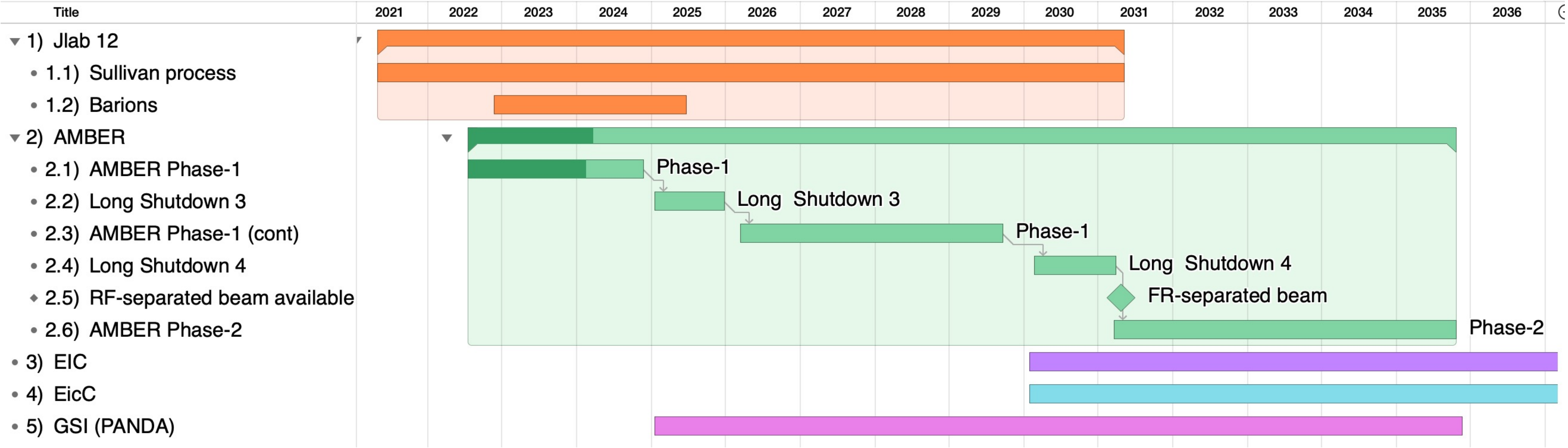
PRM: 2022-2023

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

BACK UP

AMBER General Upgrades

Major part of the spectrometer on floor since 2001,
substantial upgrade is required

– New front-end electronics (FEE) and trigger logics that are compatible with triggerless readout, which include an FPGA-based TDC with time resolution down to 100 ps and a digital trigger that is capable of rates up to 100-200 kHz (Sec. 5.2.1).

– New large-size PixelGEMs as replacement and spares for existing large-area GEMs (Sec. 5.2.2).

– New large-area micro-pattern gaseous detectors (MPGD) based on GEMs or Micromegas technology to replace existing MWPCs (Sec. 5.2.3).

– High-rate-capable CEDARs (Sec. 5.2.4) for all hadron-beam programmes to identify the desired beam particle.

– The existing RICH-1 will be required by the spectroscopy programmes (Secs. 3.2 and 4.2), the anti-matter cross section measurement (Sec 3.3), and the Primakoff programme (Sec. 4.5). A new, high-aperture RICH-0 would be desirable for these programmes in order to identify hadrons at lower momenta (Sec. 5.2.5).

AMBER Specific Upgrades

- muon-proton elastic scattering (more in Sec. 5.3.2): high-pressure active TPC target (similar to A2 at MAMI) or hydrogen tube surrounded by SciFis; SciFi trigger system on scattered muon; silicon trackers to veto on straight tracks (kink trigger).
- Hard exclusive reactions (more in Sec. 5.3.3): 3-layer silicon detector inside the existing but modified transversely polarised NH_3 target, which operates at very low temperature, for tracking of the recoil proton produced in DVCS, as well as for PID via dE/dx. Alternatively: SciFis.
- Input for DMS: liquid helium target.
- $\overline{p}$-induced spectroscopy (more in Sec. 5.3.4): target spectrometer (tracking, barrel calorimeter) similar to WASA at COSY [199]; target: LH2, foil, wire.
- Drell Yan: high-purity and high-efficiency dimuon trigger; dedicated precise luminosity measurement; dedicated vertex-detection system; beam trackers; targets: ^{6}LiD ↑, and C/W.
- Drell-Yan (RF) (see also Sec. 5.3.5): due to the lower beam energy, a wide aperture will be needed (up to ±300 mrad): a "magnetised spectrometer" (active absorber) is under consideration. It could possibly be similar to Baby MIND at JParc [200] ("3-in-1" detector, spectrometer magnet, absorber).
- Prompt Photons (RF): 20-30 cm steel absorber upstream of the target; new hodoscope upstream of the existing electromagnetic calorimeter ECAL0; transparent setup with as little material as necessary.
- K-induced spectroscopy (RF): uniform acceptance; existing electromagnetic calorimeters; recoil TOF detector (see Fig. 21, called "RPD" there).

Short term COMPASS-II future (2021)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2017–XXX
SPSC-X-XXX
October 2, 2017

d-Quark Transversity

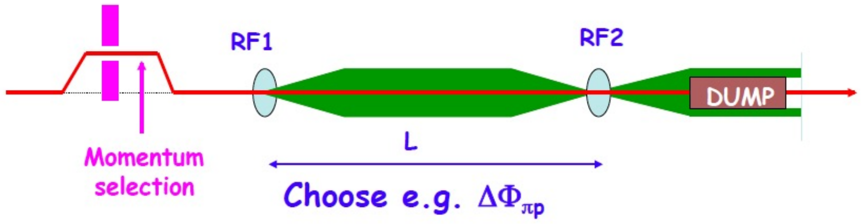
Transverse Deuteron Run (2021) was approved by CERN Research Board in June 2018

)34 / SPSC-P-340-ADD-1

The COMPASS Collaboration
and
PNPI

v2.1 3.10.2017 9:17

RF separated antiproton/kaon beam – a missing ingredient in the spin/mass crises resolving



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

"Normal" h^- beam composition: ~97% (π) ~2.5%(K) ~0.5% (pbar)

Assumptions:

– 8×10^7 antiprotons for 10^{13} ppp (10 seconds) (optimistic estimate by Lau Gatignon);
– we assume here 4×10^{13} protons.

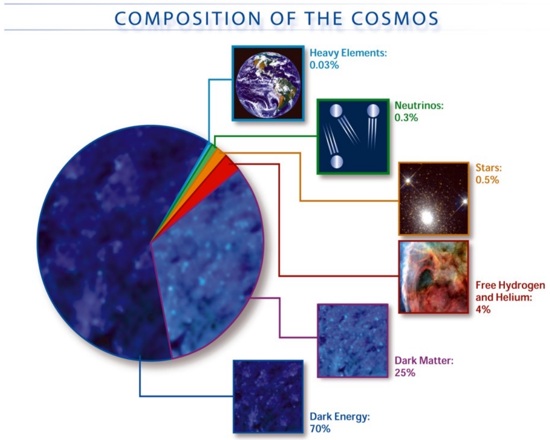
Antiprotons RF separated beam: 3.2×10^7 /s - Gain is a factor of 50 compared to the standard h^- beam for Drell-Yan experiment (~1% of h^- beam 6×10^7 /s dominated by π^-)

Using the same assumption for RF separated kaon beam, possible kaon beam intensity is 8×10^6 /s - Gain is a factor of 80 compared to to the standard "spectroscopy" h^- beam

High intensity RF separated beam will provide unique opportunities for Hadron Spectroscopy, Drell-Yan physics, Prompt Photon production etc.

Search for Dark Matter
Absolute cross section measurement p+He--> pbar+X

PHASE-1

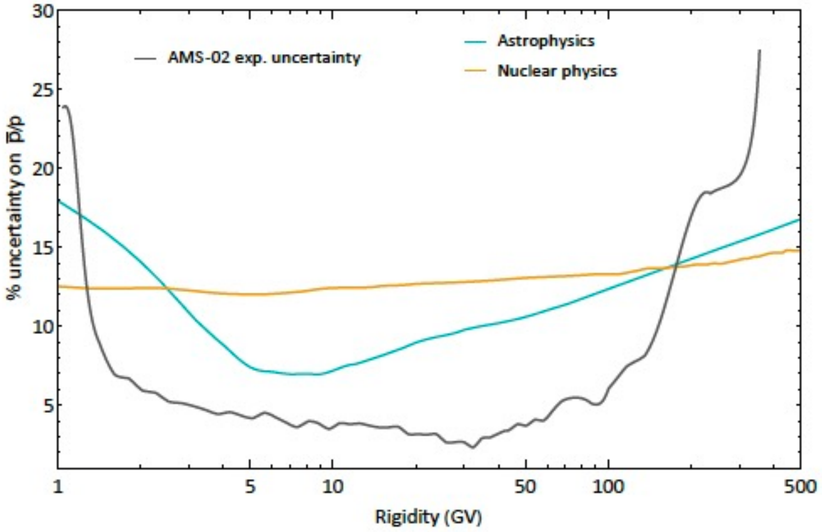


-New AMS(2) data – the antiparticle flux is well known now (few % pres.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)
- Two type of processes contribute – SM interactions (proton on the ISM with the production for example antiprotons in the f.s.) and contribution from dark particle – antiparticle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

COMPASS++ from a few tens of GeV/c up to 250 GeV/c, in the pseudorapidity range 2.4 < h < 5.6.
We performed simulation with TGEANT (GEANT4 based COMPASS MC), using FLUKA generator or the internal TGEANT generator:
2009 COMPASS hadron setup, 190 GeV beam.

Italian contributors (new to COMPASS):
AMS: P. Zuccon, F. Nozzoli (UniTN, TIFPA and INFN),
N. Masi, L. Quadrani, A. Contin (UniBO and INFN),
Theoretical Physicist: F. Donato, M. Kosmeier (UniTO e INFN)

Goal is to measure the double differential (momentum and pseudorapidity) anti-p cross production from p+p and p+He at different proton momenta (50, 100, 190, 250 GeV/c).



COMPASS++/AMBER antimatter production x-section

PHASE-1

We show 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 as constrained by our cross-section measurements p-p, p-He and He-p channels, compared to NA61 (p-p) and LHCb (p-He) measurements

p-p channel, in three different energy ranges

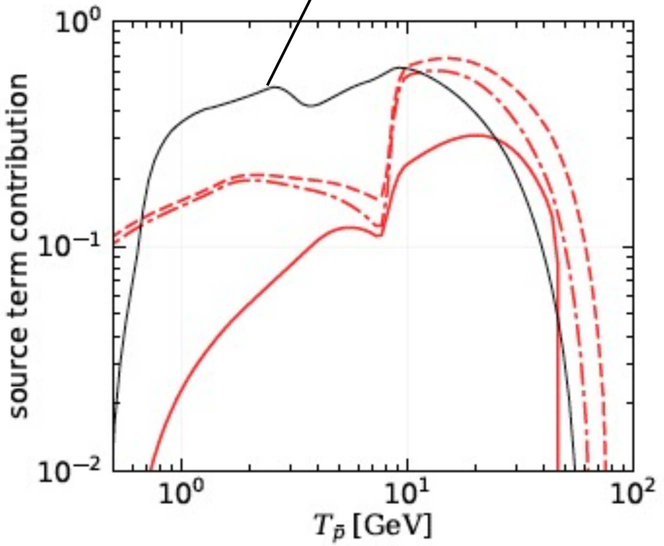
100-190 GeV/c

50-190 GeV/c

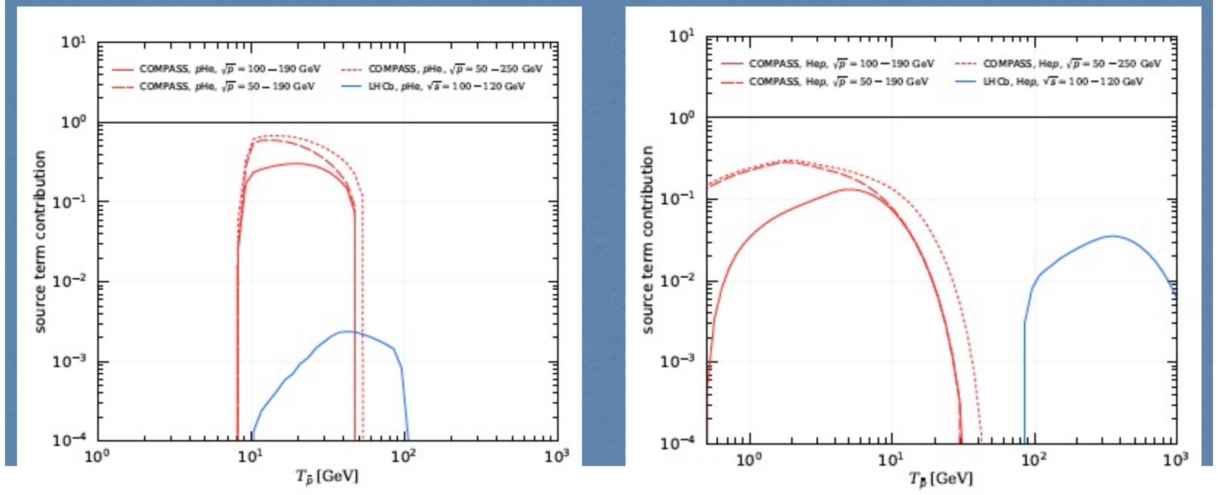
50 - 250 GeV/c

COMPASS
LHCb

COMPASS
NA61 (20-158 GeV/c)



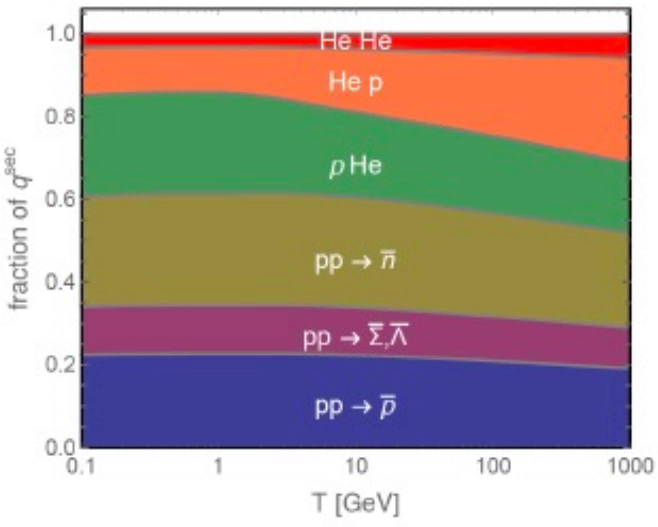
p-He and He-p channels



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

The dominant reactions are those involving protons and Helium (p+ p; p+^{4}He; ^{4}He+p; ^{4}He+^{4}He).

the interactions involving ^{4}He as target or projectile represent about 40% of the pbar production over the whole energy spectrum



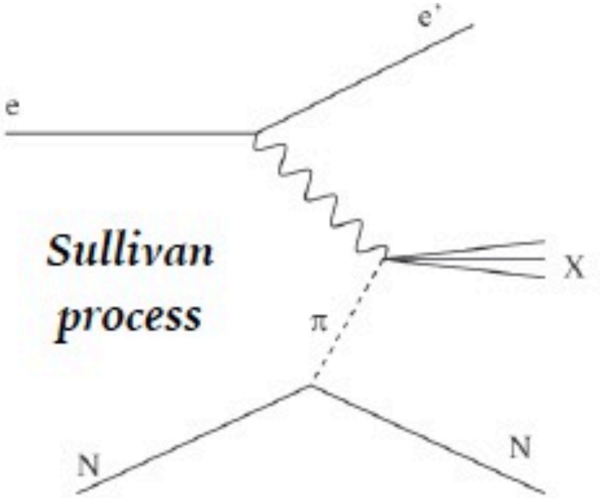
our measurement will pin down the production of anti-protons in a relevant kinetic energy region.

Combined with the LHCb measurements at very high energy, the new data would yield the necessary kinematic coverage.

This would contribute to a significant reduction of the uncertainty on the expected amount of secondary anti-protons produced by spallation of primary cosmic rays on the interstellar medium

Competitors

*Pion and kaon partonic structure can be accessed by model-dependent way via **Sullivan process** at **JLab** and **EIC**. The **J-PARC** kaon beam has too low momentum for such kind of measurements.*



We are not aware of any other plans to measure kaon polarisabilities

*Kaon spectroscopy: **Belle II, BES III, LHCb:** in decay of τ-lepton and D-mesons only states with mass below 1.8 GeV will be accessible. Limited dataset from decay of B-mesons. **GlueX (JLab):** photoproduction of KKππ final state. **J-PARC** - spectroscopy with low-momentum kaon beam.*

Short term COMPASS-II future (2021)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2017–XXX
SPSC-X-XXX
October 2, 2017

d-Quark Transversity

Transverse Deuteron Run (2021) was approved by CERN Research Board in June 2018

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Instrumentation I
General purpose spectrometer upgrades

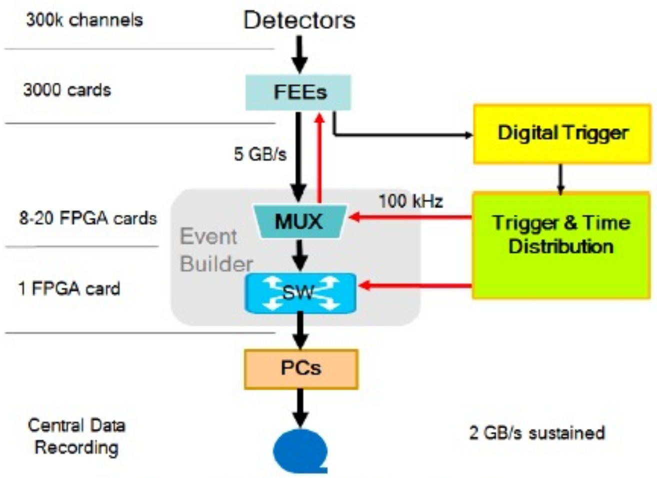


Figure 41: The new DAQ architecture.

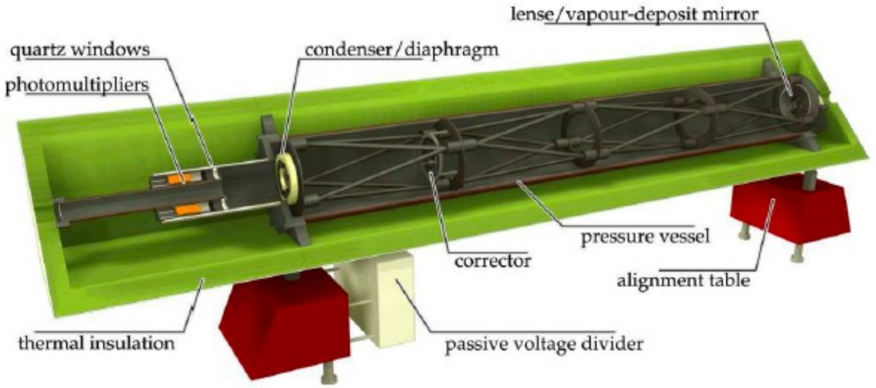


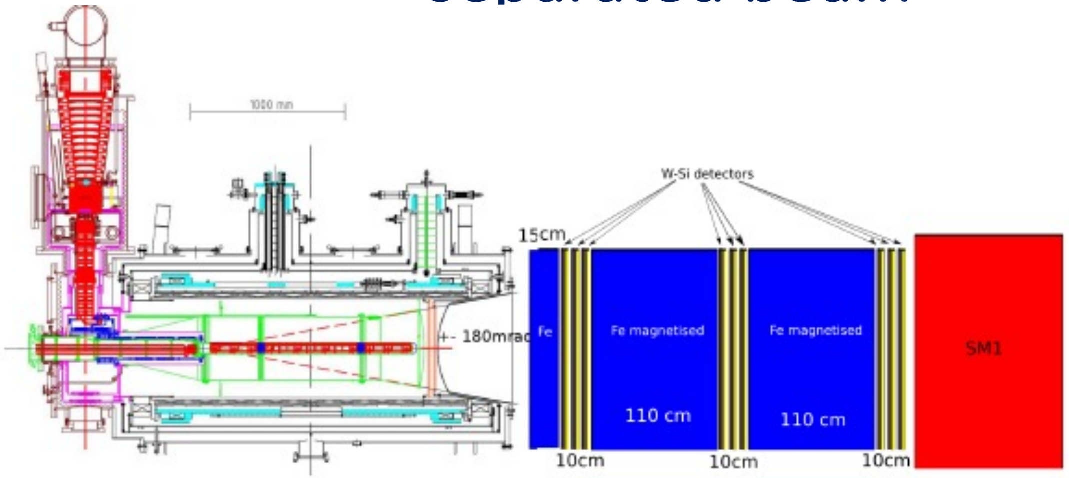
Figure 42: CEDAR 2018 upgrade for better rate and thermal stability.

– New front-end electronics (FEE) and trigger logics that are compatible with triggerless readout, which include an FPGA-based TDC with time resolution down to 100 ps and a digital trigger that is capable of rates up to 100-200 kHz (Sec. 5.2.1).

– New large-size PixelGEMs as replacement and spares for existing large-area GEMs (Sec. 5.2.2).

– New large-area micro-pattern gaseous detectors (MPGD) based on GEMs or Micromegas technology to replace existing MWPCs (Sec. 5.2.3).

Instrumentation II
Spectrometer upgrades for Drell-Yan measurements with RF-separated beam



- Investigate the possibility to use W-Si detectors, a la PHENIX (NCC, MPC-EX)
- Dead zone with radius of 9 cm (12 cm) for angles below 90 mrad (120 mrad)
- Outter radius: 112 cm for angles up to 300 mrad

Initial detector consideration:

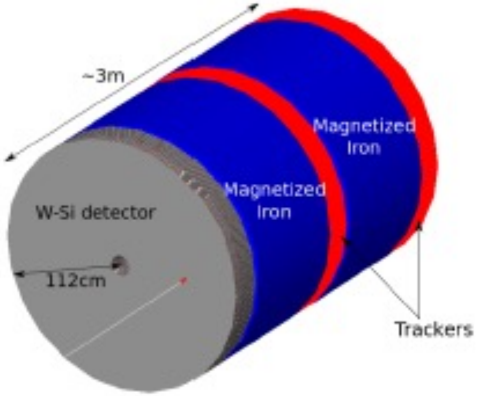
Combination of

- Baby-Mind detector

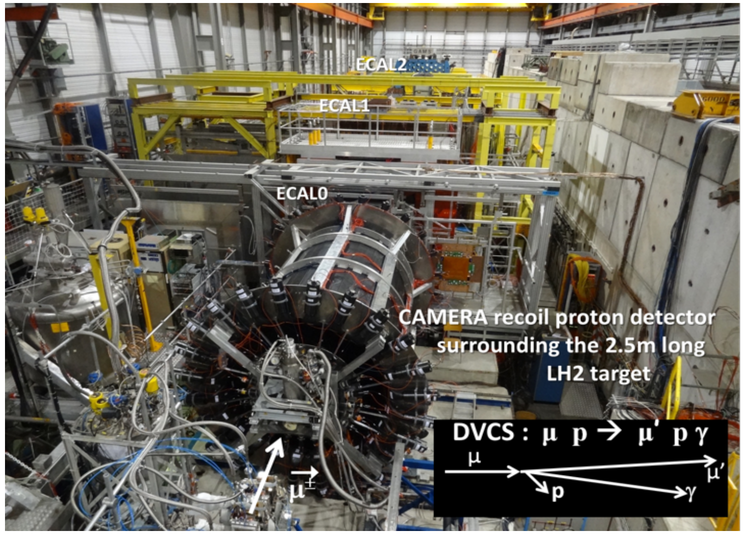
  M. Antonova *et al.* arXiv:1704.08079

- W-Si detectors, a la BNL

  AnDY | Phenix MPCEX | Phenix NCC



Instrumentation III
Upgraded/new Polarised Target



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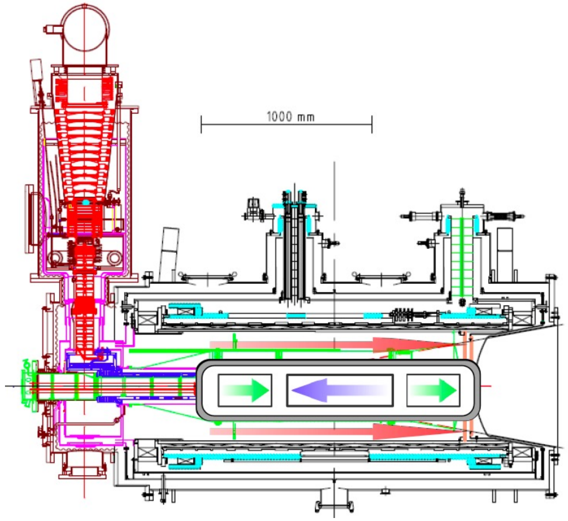
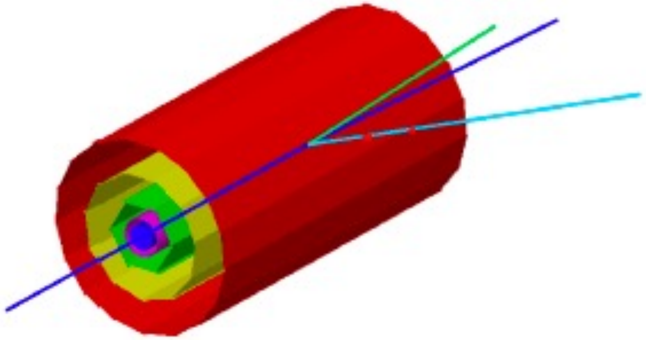
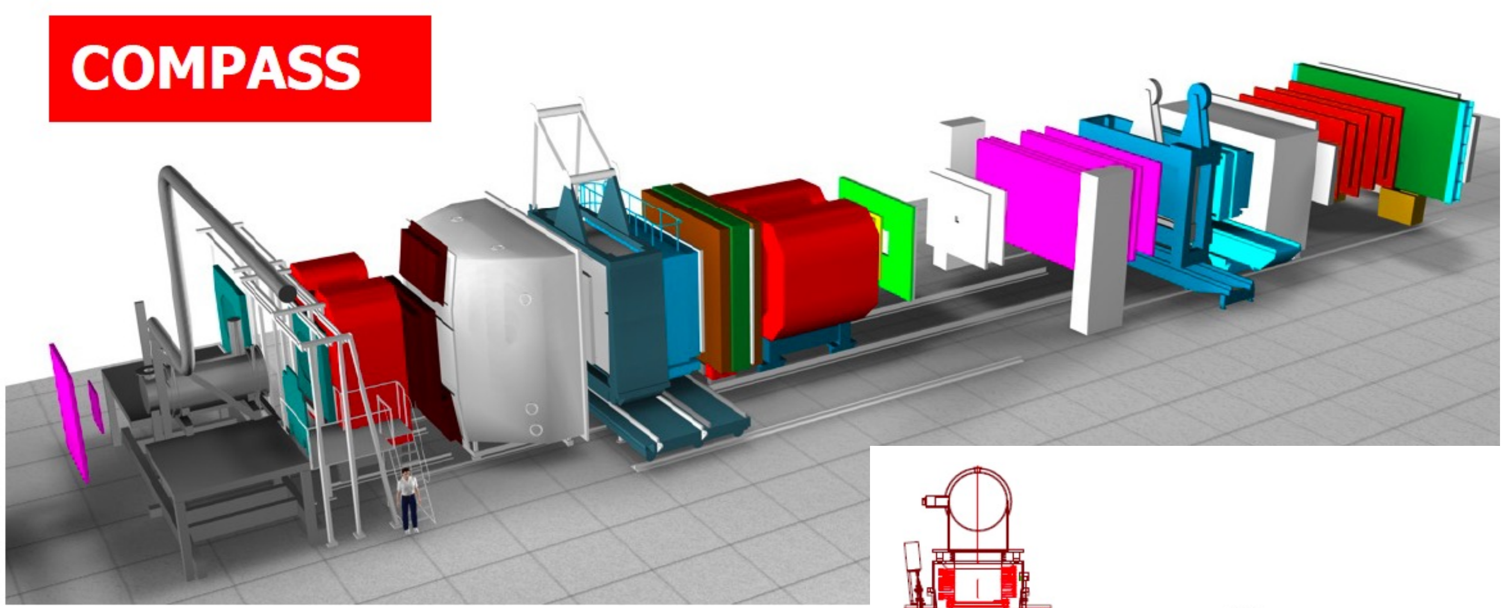
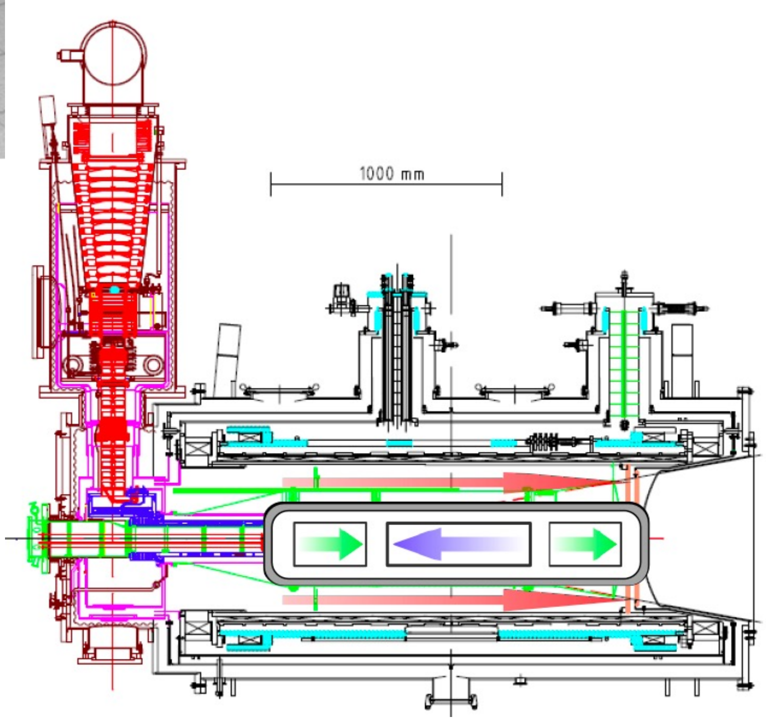




Otherwise entirely new polarised target already designed in order to
Operate with the integrated Recoil detector

COMPASS Spectrometer at SPS M2 beam line (CERN)





Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

1. Muon, electron or hadron beams with the momentum range 20-250 GeV and intensities up to 10^8 particles per second
2. Solid state polarised targets (NH_3 or ^6LiD) as well as liquid hydrogen target and nuclear targets
3. Powerful tracking (350 planes) and PiD systems (Muon Walls, Calorimeters, RICH)

- **Settings for data taking and systematic studies**

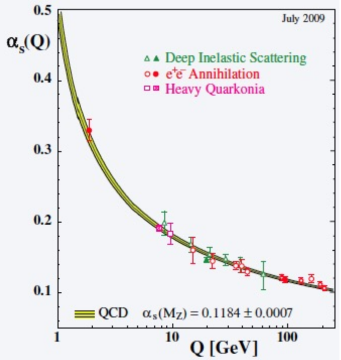
- Improve understanding of systematics using different beam polarities, beam momenta and TPC pressure settings.

Beam setting	TPC pressure setting	Duration	Purpose
μ^+, 100 GeV	20 bars	92 days	$2.5 < Q^2/(10^{-3}\mathrm{GeV}^2) < 40.0$
μ^+, 100 GeV	4 bars	67 days	$1.0 < Q^2/(10^{-3}\mathrm{GeV}^2) < 8.0$
μ^-, 100 GeV	4 bars	67 days	control of charge dependence
μ^+, 60 GeV	4 bars	34 days	control of energy dependence

- Optimised pressure settings for kinematic region
- Control systematic uncertainties:
  → beam polarity - control charge dependent effects
  → beam momentum - control energy dependent effects
- Time estimate:
  → data taking: about 160 days
  → systematic studies: about 100 days

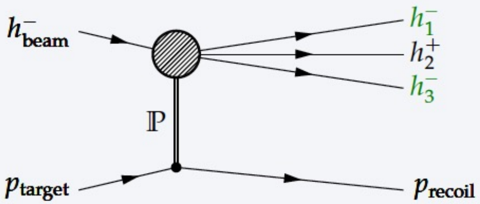
Hadron spectroscopy COMPASS++/AMBER (kaon beam)

- 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

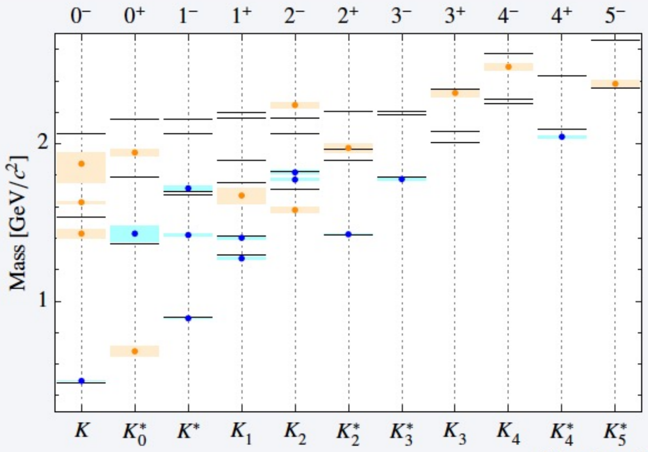
Measurement of **hadron spectra** and **hadron decays** gives valuable input to theory and phenomenology



- 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



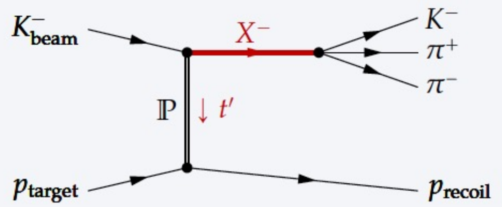
[Courtesy S. Wallner, TUM]

Boris Grube, TU München | Hadron Spectroscopy with Kaon Beam

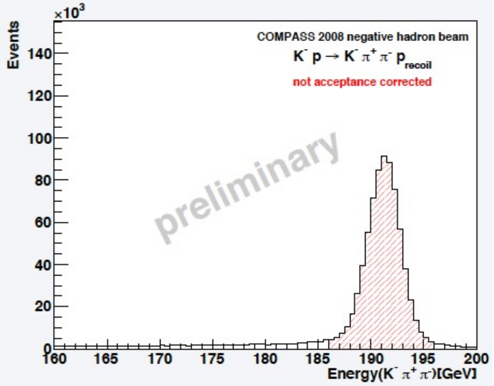
Many kaon states need confirmation

- 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 COMPASS++/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 $\times 10^6$ $K^-\pi^+\pi^-$ 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

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

M2 Fixed Target Experiment Beyond 2020

COMPASS beyond 2020 Workshop

21 Mar 2016, 08:05 → 22 Mar 2016, 17:10 Europe/Zurich

222-R-001 (CERN)

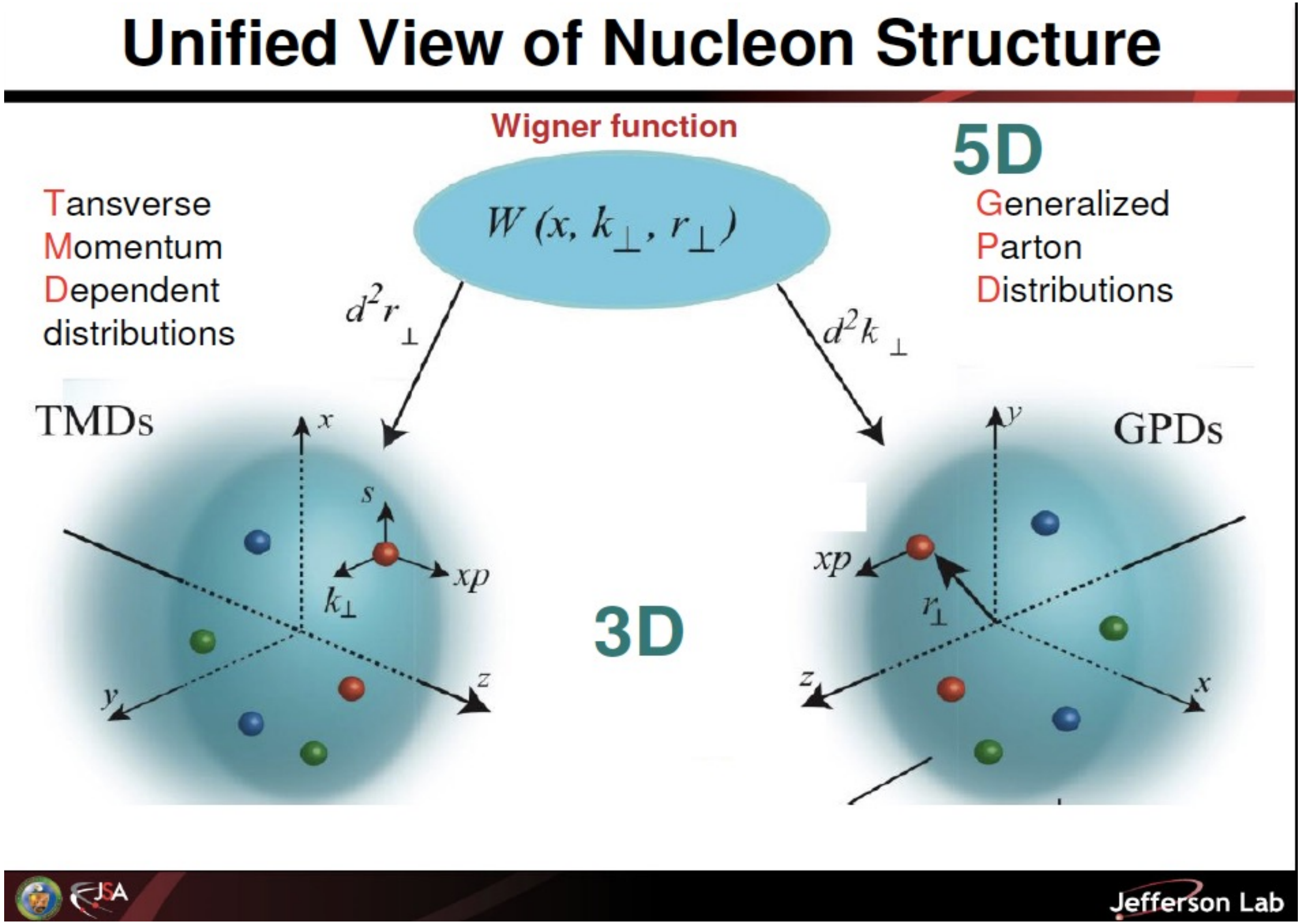
Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- Reviews of the various physics domains: TMDs, GPDs, FFs, spectroscopy, exotics, tests of ChPT, astrophysics

- Reviews of physics results expected in the next 10 years from major labs around the world

- Good attendance (>100 physicists), large interest
- 11 "outside" review talks – Jefferson Lab, RHIC, Fermilab, KEK (Japan) BEPC II (IHEP, Beijing), NICA (JINR, Dubna), CERN (After, LHCb), GSI (Panda), J-PARC (Japan), EIC – China;
- 7 COMPASS talks (chronol.) – SIDIS, GPDs, Chiral Dynamics, astrophysics (dark matter), Drell-Yan, hadron spectroscopy;
- 2 "round-table"-like discussions on possible future with hadron and muon beams;
- Outcome of the Workshop:
    - **RF Separated antiproton/kaon beam would provide a unique opportunity for future fixed target COMPASS-like program at CERN**
    - Existing muon and hadron beam allows to extend current COMPASS program by doing unique or first class measurements of exclusive processes, SIDIS and Drell-Yan

3D structure



T-odd TMDs (Sivers, Boer-Mulders) restricted universality SIDIS ⇔ DY

The time-reversal odd character of the Sivers and Boer-Mulders PDFs lead to the prediction of a sign change when accessed from SIDIS or from Drell-Yan processes:

↪ Check the predictions:

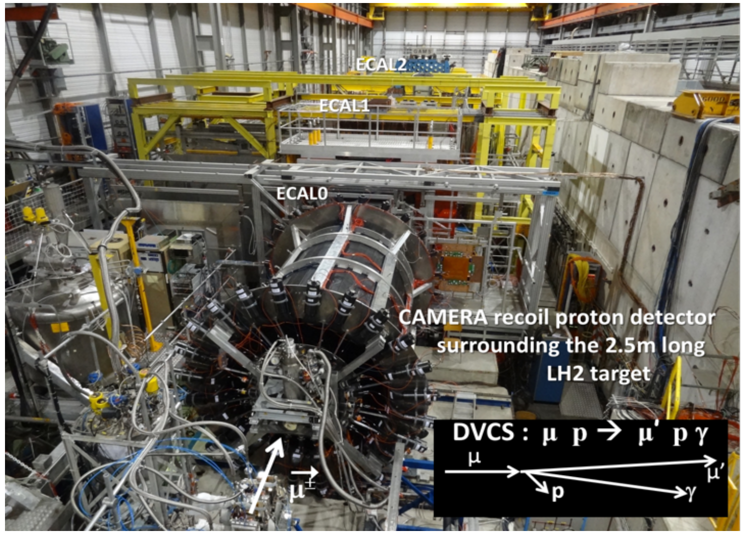
$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$

$$h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

Its experimental confirmation is considered a crucial test of non-perturbative QCD.

1. In case sign change is not confirmed we have to rethink TMD PDF factorisation – major problem of the TMD approach
2. Sivers function is very important by itself as gives a model-dependent access to Angular Momentum of partons

COMPASS++/AMBER: GPD
Access to the quark/gluon orbital moment



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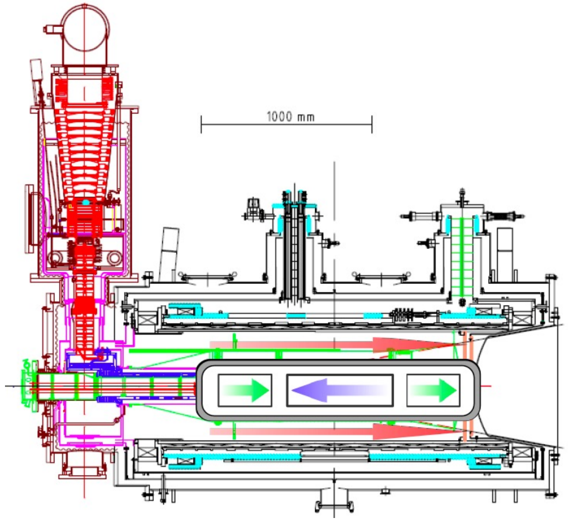

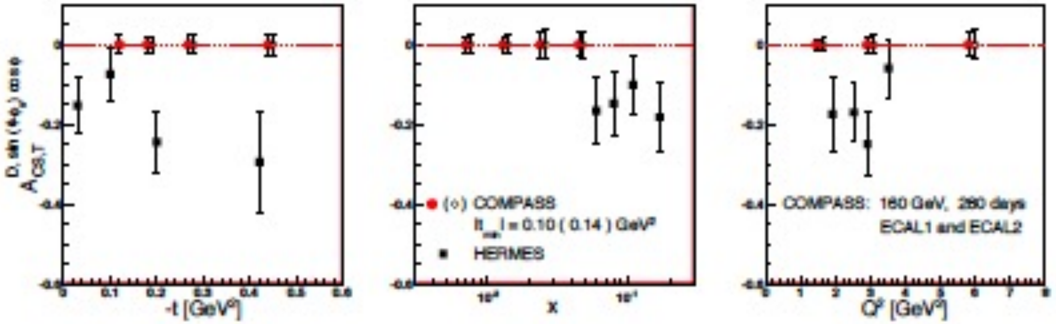

Figure 4: Expected statistical accuracy of $A_{CS,T}^{D,\sin(\phi-\phi_s)\cos\phi}$ as a function of $-t$, x_B and Q^2 from a 280 days measurement with the COMPASS spectrometer, using a 160 GeV muon beam and a transversely polarised NH_3 target. Solid and open circles correspond to a minimum accessible $|t_{min}|$ of 0.10 GeV^2 and 0.14 GeV^2, respectively. Also shown is the asymmetry $A_{U,T}^{\sin(\phi-\phi_s)\cos\phi}$ measured at HERMES [29] with its statistical errors. Figure from ref. [35].