Spectroscopy, gluon structure and polarisability of kaons in the new QCD facility at the M2 beam line at CERN SPS

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University of Warsaw

On behalf of COMPASS++/AMBER
The M2 beam line supplies muons ($\mu^\pm$) and hadrons ($\pi^\pm$, $K^\pm$, p, $\bar{p}$) to the North Area.
## Panorama of COMPASS data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment Details</th>
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<tbody>
<tr>
<td>2002 – 2004</td>
<td>nucleon structure $\mu$–d, 160 GeV, L and T polarised target</td>
</tr>
<tr>
<td>2005</td>
<td>CERN accelerator shutdown, increase of acceptance</td>
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<tr>
<td>2011</td>
<td>nucleon structure $\mu$–p, 200 GeV, L polarised target</td>
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<tr>
<td>2012</td>
<td>Primakoff reaction; DVCS/SIDIS test</td>
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<tr>
<td>2013</td>
<td>CERN accelerator shutdown, LS1</td>
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<tr>
<td>2014</td>
<td>Drell-Yan $\pi$–p reaction with T polarised target (test)</td>
</tr>
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<td>2015</td>
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<td>2016 – 2017</td>
<td>DVCS/SIDIS $\mu$–p, 160 GeV, unpolarised target</td>
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<td>2018</td>
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<td>2019 – 2020</td>
<td>CERN accelerator shutdown, LS2</td>
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<td>2021</td>
<td>nucleon structure $\mu$–d, 160 GeV, T polarised target</td>
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<td></td>
<td>(SPSC approved addendum $\Rightarrow$ A. Martin’s talk @ WG6)</td>
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</tbody>
</table>

### COMPASS I

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### COMPASS II

Kaons in the new QCD facility at CERN

DIS2019 3 / 25
Future: CERN accelerator schedule

LS = long shutdown of CERN accelerators

This talk

2019 2020 2021 2022 2023 2024 2025 2026 2027

transversity with pol deuteron target

COMPASS already approved

standard muon/hadron beams

LS3

RF: separated beams

Courtesy of Marcia Quaresma, COMPASS
RF-separated hadron beams: an idea

Panofsky-Schnell system with two RF cavities

- Particles $a,w$ are momentum-analysed
- Transverse kick by RF1 compensated/amplified by RF2
- Selection of a particle by selecting phase difference, $\Delta \phi$, e.g. $\Delta \phi_{\pi p}$:
  \[
  \Delta \phi = 2\pi (L_{12} f/c) (\beta_a^{-1} - \beta_w^{-1})
  \]
  for large $p$: $\beta_a^{-1} - \beta_w^{-1} = (m_a^2 - m_w^2)/2p^2$
- $L_{12}$ should increase as $p^2$ at given $f$; this limits beam momentum
- Expected: $p_K \gtrsim 80$ GeV, $p_{\bar{p}} \gtrsim 110$ GeV; sophisticated R&D needed!
- Intensity gains: $\sim 80$ for K, $\sim 50$ for $\bar{p}$ beams (now @ COMPASS: $10^5$ s$^{-1}$ of K$^-$)
  (standard h$^-$ beam is $\sim 97\%$ pions, $\sim 2.5\%$ kaons, $\sim 0.5\%$ antiprotons).

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Kaons in the new QCD facility at CERN
Kaon spectroscopy

COMPASS++/AMBER    LoI: hep-ex 1808.00848v6
Kaon spectroscopy with intense kaon beam

Excitation spectrum of strange mesons from PDG:
lines – relativistic quark model, blue – PDG summary table, orange – remaining ones

- Most PDG entries more than 30 years old
- Many K–states need confirmation and further studies
- Many QM predicted states are missing
- Hints for supernumerous states
- K spectra needed to analyse decays of heavy mesons (B, D,...)

K. Olive, Review of Particle Physics, Chinese Physics C40 (2016) 100001
Kaon beam may produce different final state (excited) kaons via Pomeron (diffractive production) or Regge exchange.

COMPASS collected about a million $K^{-}p \rightarrow K^{-}\pi^{+}\pi^{-}p$ events $\implies$ analysis is in progress.

RF separated beam may supply 50 millions events/year (50x world data) $\implies$ access to novel, accurate analysis methods.
Kaon spectroscopy with intense kaon beam...

**Experimental requirements: beam ID**

- Upgrade CEDAR detectors (rate capability, thermal stability)
- Silicon beam telescope (resolution <40 µrad) needed for precise CEDAR PID

**Experimental requirements: spectrometer**

- improved Recoil Particle Detector
- new vertex detector; improved tracking, acceptance
- extended K ID in RICH 1 (a new RICH 0?): now 50% kaons in $K^-\pi^+\pi^-$ outside acceptance
- efficient detection of photons for $\pi^0$ reconstruction to access $K^-\pi^0\pi^0$ final states

**Competition**

- J-PARC K10 beam: high intensity ($10^7$ $K^-$ per spill) but low energy (2-10 GeV)
- GlueX @ JLab: $K_L^0$ beam: low intensity ($10^4$ s$^{-1}$), low energy (0.3-10 GeV)
- Decays of $\tau$ and of heavy mesons @ BES III, Belle II, LHCb: low statistics
- Conclusion: NO COMPETITORS
Kaon polarisability

COMPASS++/AMBER  Lol: hep-ex 1808.00848v6
Kaon polarisability via the Primakoff process

Electric ($\alpha$) and magnetic ($\beta$) polarisabilities (measured in fm$^3$):

For an extended object they are related to inner forces determining the substructure → QCD at low energy (e.g. chiral perturbation theory, $\chi$PT)

The most direct method of (exp. and th.) determination given by Primakoff (1951), originally for the $\pi^0 \rightarrow \gamma\gamma$ lifetime: using the electric field close to a nucleus as a source of quasi-real $\gamma$.

Polarisabilities measured through modifications of the bremsstrahlung (or Primakoff) reaction: $K^- Z \rightarrow K^- \gamma Z$ ($Z$ – nuclear charge)
COMPASS result for the pion polarisability, Primakoff method and assuming $\alpha_\pi + \beta_\pi = 0$:
(C. Adolph, PRL 114 (2015) 062002)
$\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \times 10^{-4} \text{fm}^3$

Predictions for kaons:

$\chi^\text{PT (one-loop approx)}$
if $\alpha_K + \beta_K = 0$
then $\alpha_K = (0.64 \pm 0.10) \times 10^{-4} \text{fm}^3$

Quark confinement model
if $\alpha_K + \beta_K = 1.0 \times 10^{-4} \text{fm}^3$
then $\alpha_K = 2.3 \times 10^{-4} \text{fm}^3$

Experimental result from kaonic atoms spectra (1973): $\alpha_K < 200 \times 10^{-4} \text{fm}^3$
Kaon polarisability via the Primakoff process ...cont’d

- **Experimental requirements**
  - 100 GeV/$c$ RF-separated kaon beam, $5 \times 10^6$ s$^{-1}$
  - spectrometer configuration as for the $\pi$ beam runs in 2009/2012 (CEDAR in the beam line, 0.3 $X_0$ Ni target, Si telescopes up- & downstream target)
  - trigger on high energy deposits in ECAL1, ECAL2
  - new DAQ system for trigger rates $\lesssim 100$ kHz

- **Results after 1 year run ($5 \times 10^{12}$ kaons)**
  - $6 \times 10^5$ $K^-\gamma$ events, $0.1 < x_\gamma < 0.6$, $M_{K\gamma} < 0.8$ GeV/$c^2$ ($x_\gamma = E_\gamma/E_{\text{beam}}$)
  - Statistical accuracy under assumption: $\alpha_K + \beta_K = 0$: $\sigma_{\text{stat}} = 0.03 \times 10^{-4}$ fm$^3$

- **Competition:** NO COMPETITORS

Figure on the right: courtesy of A. Guskov, COMPASS
Gluon structure of kaons

via 1) prompt-photon and 2) $J/\Psi$ production

COMPASS++/AMBER  LoI: hep-ex 1808.00848v6
Parton structure of mesons

Proton PDFs

Pion PDFs

Kaon PDFs


Courtesy of M.Grosse-Perdekamp, MiniWorkshop on Physics at a Future SPS QCD Facility, 2018
Kaon partonic structure vs $\pi$ structure

- A source of information on kaon structure (PDFs), presently unknown (the only exp. attempt: NA3 experiment at CERN in the 80-ties)

- Kaons have heavier valence quarks $\implies$ expect less glue in K than in $\pi$: $\sim 5\%$ (K) vs $\sim 30\%$ ($\pi$) vs $\sim 50\%$ (N)

- Two-year run gives PDF precision as in $\pi$

- Unknown gluons in K may be accessed via gluon Compton $(qg \to \gamma q)$ (with annihilation $(q\bar{q} \to \gamma g)$ as a background) in the prompt-$\gamma$ production, e.g. Kp$\to \gamma$ X

- Factorisation theorem $\implies$ cross section:
  $$d\sigma_{AB \to \gamma X} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_A^a f_B^b d\sigma_{ab \to \gamma x} + d\sigma_{fragm.}.$$

  $(a,b = \text{partons in hadrons } A, B; \quad d\sigma_{fragm.} = \text{fragmentation photons, } \lesssim 20\%)$.

WA70, E706 expts measured of $d\sigma_{\pi N \to \gamma X}$ for gluon determination in $\pi$. 

Courtesy of V. Andrieux, ECT* Workshop 2018

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Gluon distribution in $K^+$ via prompt $\gamma$ production

- Measurement of $E d^3 \sigma_{K^+p \rightarrow \gamma X} / dp^3$ for the following conditions:
  $p_T > 2.5$ GeV/$c$, $-1.4 < y < 1.8$, $E_{K^+} = 100$ GeV $\Rightarrow x_g > 0.05$, $Q^2 \sim p_T^2$.

$$x_T = \frac{2p_T}{\sqrt{s}} \text{ vs } y$$

$$\sigma \text{ vs } E_{\text{beam}} @ g_\pi(x, Q^2) = g_K(x, Q^2)$$

- $K^-$ beam also planned to be used
- Main contribution to systematics (dominating over statistics):
  photons from decays of secondary $\pi^0$ and $\eta$, especially at low $p_T$.

Gluon distribution in $K^+$ via prompt $\gamma$ production... cont’d

Experimental requirements:

- Beam: $K^+$ of 100 GeV/$c$ or higher and intensity $5 \times 10^6$ $K^+/s$
- CEDAR to remove non-$K$ particles in the beam
- Target: 2m long, liquid $H_2$, $\sim 0.2X_0$ or a solid, low-$Z$ material
- Present electromagnetic calorimeters ECAL0, ECAL1, ECAL2 suffice for detecting prompt photons and suppress $\pi^0$ background.

$p_T$ vs $y$, COMPASS 2017 setup

2017 COMPASS acceptance vs $p_T$

- Other: shielding upstream the target, tracking detector in front of ECAL0,...
- 140 days of running, $p_T > 2.5$ GeV/$c$, $-1.4 < y < 1.8 \implies 0.85 \times 10^6$ $qg \rightarrow \gamma q$ evts
- Competition: NO COMPETITORS
Gluon distribution in K via J/Ψ production

- A complementary method to infer gluon distribution in K: KN → J/Ψ X → μμ X; q̅q annihilation and gg fusion contributions to the cross section

- Large cross section ∼100 nb/nucleon at low x_F at ‘COMPASS’ energies

- ...but J/Ψ production mechanism strongly model-dependent

- however using both K± beams, K⁺ = (u̅s), K⁻ = (ūs), greatly helps:

  \[ \bar{u}^{K^-} v^N \propto \sigma^{J/Ψ} - \sigma^{K^+} \rightarrow \bar{u}^{K^-} \]

  all other terms cancel

- The remaining gg part (and thus gluons in K) can therefore be inferred in a model dependent way, e.g. Colour Evaporation Model (here K± ¹²C).

- spectrometer acceptance to be increased e.g. an active hadron absorber with tracking magnetic field, large acceptance for μμ pairs

- light isoscalar target, ¹²C ?

- 1+1 year running with K⁺ & K⁻; ∼ 10^6 J/ψ evts

- no high-energy, high-intensity K beams planned in the world

- Competition: NO COMPETITORS
# Requirements for future programmes @ the M2 beam line after 2021

<table>
<thead>
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<th>Program</th>
<th>Physics Goals</th>
<th>Beam Energy [GeV]</th>
<th>Beam Intensity [s⁻¹]</th>
<th>Trigger Rate [kHz]</th>
<th>Beam Type</th>
<th>Target</th>
<th>Earliest start time, duration</th>
<th>Hardware additions</th>
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<tbody>
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<td>muon-proton elastic scattering</td>
<td>Precision proton-radius measurement</td>
<td>100</td>
<td>4 · 10⁶</td>
<td>100</td>
<td>µ⁺</td>
<td>high-pressure H₂</td>
<td>2022 1 year</td>
<td>active TPC, SciFi trigger, silicon veto,</td>
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<tr>
<td>Hard exclusive reactions</td>
<td>GPD $E$</td>
<td>160</td>
<td>2 · 10⁷</td>
<td>10</td>
<td>µ⁺</td>
<td>NH₃</td>
<td>2022 2 years</td>
<td>recoil silicon, modified polarised target magnet</td>
</tr>
<tr>
<td>Input for Dark Matter Search</td>
<td>$\bar{p}$ production cross section</td>
<td>20-280</td>
<td>5 · 10⁷</td>
<td>25</td>
<td>$p$</td>
<td>LH₂, LHe</td>
<td>2022 1 month</td>
<td>liquid helium target</td>
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<tr>
<td>$\bar{p}$-induced spectroscopy</td>
<td>Heavy quark exotics</td>
<td>12, 20</td>
<td>5 · 10⁷</td>
<td>25</td>
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<td>target spectrometer: tracking, calorimetry</td>
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<tr>
<td>Drell-Yan</td>
<td>Pion PDFs</td>
<td>190</td>
<td>7 · 10⁴</td>
<td>25</td>
<td>$\pi$⁺</td>
<td>C/W</td>
<td>2022 1-2 years</td>
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<td>Drell-Yan (RF)</td>
<td>Kaon PDFs &amp; Nucleon TMDs</td>
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<td>Primakoff (RF)</td>
<td>Kaon polarisability &amp; pion life time</td>
<td>~100</td>
<td>5 · 10⁶</td>
<td>&gt; 10</td>
<td>$K$⁻</td>
<td>Ni</td>
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<td>Prompt Photons (RF)</td>
<td>Meson gluon PDFs</td>
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<td>5 · 10⁶</td>
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<td>$K$-induced spectroscopy (RF)</td>
<td>High-precision strange-meson spectrum</td>
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<td>Vector mesons (RF)</td>
<td>Spin Density Matrix Elements</td>
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B. Badelek (Warsaw)  
Kaons in the new QCD facility at CERN  

Lol, hep-ex 1808.00848v6  
DIS2019 20 / 25
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**Outlook**

- **COMPASS facility** is very successful in studies of nucleon structure and spectroscopy.

- “**COMPASS Beyond 2020**” (March 2016) and “Physics Beyond Colliders” (ongoing from Sept. 2016) workshops at CERN reveal a strong and active interest of the community in this physics.

- **COMPASS++/AMBER** presented a Letter-of-Intent concerning the long-term future, hep-ex 1808.00848v6, with a rich programme, chiefly on the $\mu$-p elastic scattering, Drell-Yan physics and hadron structure. **Proposal coming in 2019** (see also talks by V. Andrieux, S. Gevorkyan, Ch. Dreisbach at this WG7 and A. Martin at WG6).

   Apart of existing muon and hadron, **new RF-separated K and $\bar{p}$ beams** open new possibilities in hadron structure studies.

- **New groups are welcome to join and contribute!**
SPARES
Versatile COMPASS facility at the M2 beam line at CERN

Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: $^6$LiD, NH$_3$
Liquid H$_2$ and nuclear targets
Beams: 160 (200) GeV $\mu^\pm$
190 GeV hadrons
$2(1) \times 10^8$/spill


B. Badelek (Warsaw)
COMPASS++/AMBER: new QCD facility
at the M2 beam line of the CERN SPS

- Long term plans for future (> 2021) experiment
  in the new QCD facility at the M2 beam line at CERN SPS
  → LoI: hep-ex 1808.00848v6; PBC (QCD WG report): hep-ex 1901.04482v1
  (see also talks by V. Andrieux, S. Gevorkyan and Ch. Dreisbach at this WG7).

  - renewed collaboration (COMPASS++/AMBER)
  - proton radius measurement in $\mu p \rightarrow \mu p$
  - muon and hadron ($\pi$, K, $\bar{p}$) beams
  - conventional- and newly designed RF-separated K and $\bar{p}$ beams
  - 7–8 year endeavour

- Planning began in March 2016: “Beyond 2020” workshop at CERN.
- Intertwined with “Physics Beyond Colliders” initiative at CERN (>Sept. 2016).
- Assessment by the European Strategy Group expected in 2020.
- Proposal to appear in 2019