New M2 beamline at CERN SPS
from the AMBER perspective

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The opportunity:

In the North Area at CERN, SPS beam of high-intensity and high-energy is hitting several primary targets. The secondary beams obtained supply different beamlines.

At the M2 beamline, unique-in-the-world beams are available:

– Muon beams of both charges

– Hadron beams of both charges

In a wide range of momenta: 50 – 280 GeV/c
From COMPASS to AMBER
## Physics Possibilities

...as expressed in the LoI:

### Phase-I

**AMBER Proposal Phase-I:**
http://cds.cern.ch/record/2676885?ln=en

<table>
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<th>Physics Goals</th>
<th>Beam Energy [GeV]</th>
<th>Beam Intensity [s⁻¹]</th>
<th>Trigger Rate [kHz]</th>
<th>Beam Type</th>
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<th>Earliest start time, duration</th>
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<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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<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>
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<tr>
<td>Input for Dark Matter Search</td>
<td>p̄ production cross section</td>
<td>20-280</td>
<td>5 · 10⁵</td>
<td>25</td>
<td>p</td>
<td>LH₂, LHe</td>
<td>2022 1 month</td>
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<tr>
<td>Heavy quark exotics</td>
<td>p̄-induced spectroscopy</td>
<td>12, 20</td>
<td>5 · 10⁷</td>
<td>25</td>
<td>p̄</td>
<td>LH₂</td>
<td>2022 2 years</td>
<td>target spectrometer: tracking, calorimetry</td>
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<tr>
<td>Drell-Yan</td>
<td>Pion PDFs</td>
<td>190</td>
<td>7 · 10⁷</td>
<td>25</td>
<td>π⁺</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>
<td>~100</td>
<td>10⁸</td>
<td>25-50</td>
<td>K⁺, K⁻, p̄</td>
<td>NH₃, C/W</td>
<td>2026 2-3 years</td>
<td>&quot;active absorber&quot;, vertex detector</td>
</tr>
<tr>
<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>
<td>non-exclusive 2026 1 year</td>
<td></td>
</tr>
<tr>
<td>Prompt Photons (RF)</td>
<td>Meson gluon PDFs</td>
<td>≥ 100</td>
<td>5 · 10⁶</td>
<td>10-100</td>
<td>K⁺, K⁻, π⁻</td>
<td>LH₂, Ni</td>
<td>non-exclusive 2026 1-2 years</td>
<td>hodoscope</td>
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<tr>
<td>K⁻-induced Spectroscopy (RF)</td>
<td>High-precision strange-meson spectrum</td>
<td>50-100</td>
<td>5 · 10⁶</td>
<td>25</td>
<td>K⁻</td>
<td>LH₂</td>
<td>2026 1 year</td>
<td>recoil TOF, forward PID</td>
</tr>
<tr>
<td>Vector mesons (RF)</td>
<td>Spin Density Matrix Elements</td>
<td>50-100</td>
<td>5 · 10⁶</td>
<td>10-100</td>
<td>K⁺, π⁻</td>
<td>from H to Pb</td>
<td>2026 1 year</td>
<td></td>
</tr>
</tbody>
</table>
The same beamline can provide muon and hadron beams.

At 190 GeV/c:
- Negative: 97% $\pi^-$, 2.5% $K^-$, < 1% $\bar{p}$
- Positive: 74% $p$, 24% $\pi^+$, 2% $K^+$
The muon beam

Pion weak decay:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

Only left-handed neutrinos

Polarized \( \mu^+ \): their spin must be antiparallel to their direction of flight
The physics questions to be answered:

The massive world we observe is made of protons – stable particles composed of quarks and gluons.

The variety of hadrons, mostly short-lived, and why their very different characteristics, Is the subject of Quantum Chromodynamics.
Emergence of Hadron Mass

How to understand that $\frac{M_\pi}{M_p} \sim 1/7$, while from constituent-quarks model one would expect $\sim 2/3$?

Only 1% of the proton mass is due to the Higgs mechanism.
Emergence of Hadron Mass

Dynamic Chiral Symmetry Breaking of QCD leads to the quarks and gluons rapidly acquiring a running mass in the infrared limit.

Gluon and quark **running masses**
The Emergence of Hadron Mass is the leitmotiv for the various proposed measurements.

EHM is key for understanding QCD, a theoretical approach that addresses:

- Hadron charge radii
- Hadron masses
- Hadron spectroscopy
- Hadron structure

... and all this to be validated by:

- Lattice calculations
- **Experimental measurements**
1) The proton charge radius puzzle

Status in October 2019:

Two types of measurements: **lepton-proton scattering** and **hydrogen spectroscopy** leading to discrepant results → ~ 5 σ
Proton radius at AMBER

The proton charge radius can be accessed via the electromagnetic form factors. Experimentally, AMBER will measure the **elastic muon-proton scattering** for this:

\[
\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^4 m_p^2 p^2 \mu^2} \left[ \left( G_E^2 + \tau G_M^2 \right) \frac{4E^2 m_p^2 Q^2 (s - m^2_\mu)}{1 + \tau} - G_M^2 \frac{2m^2_\mu Q^2 - Q^4}{2} \right]
\]

\[
\langle r_E^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}_{Q^2 \to 0}
\]
Muon-proton high energy scattering

- 100 GeV muon beam
- Active-target TPC with high-pressure H$_2$
- goal: 70 million elastic scattering events in the $10^{-3} < Q^2 < 4 \cdot 10^{-2}$ GeV$^2$ range
- Precision on the proton radius $\sim 0.01$ fm
- Pilot run with smaller TPC in 2021
2) The pion structure

Extractions including Drell-Yan data and leading-neutron DIS data

Effects of threshold resummation included, but scheme dependent

Chang et al. PRD 102, 054024 (2020)

JAM, arXiv:2108.05822
Drell-Yan at AMBER: access to pion structure

Definitions:

\[ u_{\text{val}}^{\pi^+} = u^{\pi^+} - \overline{u}^{\pi^+} \quad \text{and} \quad d_{\text{val}}^{\pi^+} = d^{\pi^+} - \overline{d}^{\pi^+} \]

And assuming flavour-symmetry:

\[ u_{\text{val}}^{\pi^+} = d_{\text{val}}^{\pi^+} = \overline{u}_{\text{val}}^{\pi^+} = \overline{d}_{\text{val}}^{\pi^+} \]

\[ u_{\text{sea}}^{\pi} = u_{\text{sea}}^{\pi} = d_{\text{sea}}^{\pi} = d_{\text{sea}}^{\pi} = \overline{u}_{\text{sea}}^{\pi} = \overline{d}_{\text{sea}}^{\pi} \]

\[ \frac{\Sigma_{\text{sea}}}{\Sigma_{\text{valence}}} = \frac{4\sigma^{\pi^+} - \sigma^{\pi^-}}{-\sigma^{\pi^+} + \sigma^{\pi^-}} \]

\[ \begin{align*}
&\quad \text{LO: only sea-val and val-sea terms} \\
&\quad \text{LO: only val-val terms}
\end{align*} \]
Pion-induced Drell-Yan at AMBER

Isoscalar target
Both beam charges
High statistics
what can we learn from J/ψ production at AMBER?

- Large statistics on J/ψ production at dimuon channel
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- In the low-pT regime
- Expected to have dominant contribution from $2 \rightarrow 1$ processes
- Use J/ψ polarization to distinguish production mechanism:

Strong dependence on Pion PDF set
3) A detour: the antiproton production cross section

Needed as input to the Dark Matter searches: for example to interpret AMS data.

\[ \bar{p} \text{ production } x\text{-section uncertainties from } p-p \text{ and } p-\text{He collisions is a limiting factor to know the } \bar{p}/p \text{ flux ratio expected} \]
$\bar{p}$ cross section at AMBER

- Secondary proton beams from SPS at 50, 100 and 190 and 280 GeV/c
- Liquid Hydrogen and Helium targets
- Antiprotons identified using RICH

Plots:
Impact of AMBER in constraining the $\bar{p}$ production versus kinetic energy.
Opportunities, further ahead in the future:

Radio-frequency separated hadron beams

AMBEX Phase-II
Radio-frequency separation is a technique where some particle species end dumped in a beam stopper, while the chosen ones (dependent on distance “l”) provide a cleaner, still intense, beam.

\[ \Delta \phi \approx \frac{\pi fL}{c} \frac{m_w^2 - m_u^2}{p^2} \]

**R&D from CERN Beams Department**

- \( K^\pm \) beams with 60 – 100 GeV/c
- \( \bar{p} \) beam with 80 – 110 GeV/c

**Question:** but how high can the beam intensity be?
4) Kaon structure: $u_k/u_\pi$

Kaon structure: a window to the region of interference between the Higgs mechanism and the EHM mechanism

The only available experimental data:

Na3 → 200 GeV K⁻ beam on 6 cm Pt target

700 kaon-induced Drell-Yan events

AMBER kaon-induced Drell-Yan
Kaon structure: valence and sea

First-ever kaon sea-valence separation: using both charges kaon beams

\[ R_{s/v} = \frac{O^{K^+C}}{O^{K^-C} - O^{K^+C}} \propto u_v^K u_v^p \]

Higher beam momentum: access to lower \( x_K \)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam type</th>
<th>Beam intensity (part/sec)</th>
<th>Beam energy (GeV)</th>
<th>DY mass (GeV/c^2)</th>
<th>DY events ( \mu^+\mu^- )</th>
<th>DY events ( e^+e^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA3</td>
<td>6cm Pt</td>
<td>K^-</td>
<td>????</td>
<td>200</td>
<td>4.2 - 8.5</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>AMBER</td>
<td>100cm C</td>
<td>K^-</td>
<td>( 2.1 \times 10^7 )</td>
<td>80</td>
<td>4.0 - 8.5</td>
<td>25,000</td>
<td>13,700</td>
</tr>
<tr>
<td>AMBER</td>
<td>100cm C</td>
<td>K^+</td>
<td>( 2.1 \times 10^7 )</td>
<td>80</td>
<td>4.0 - 8.5</td>
<td>40,000</td>
<td>17,700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \pi^- )</td>
<td>( 4.8 \times 10^7 )</td>
<td>80</td>
<td>4.0 - 8.5</td>
<td>65,500</td>
<td>29,700</td>
</tr>
</tbody>
</table>

\( E_{beam} = 80 \text{ GeV} \)

\( E_{beam} = 100 \text{ GeV} \)
Kaon-induced Drell-Yan in AMBER

If using kaons from RF-separated beams, the momentum must be < 100 GeV/c

In a fixed-target experiment, the lower beam momentum implies smaller angular acceptance

In order to keep the dilepton acceptance \( \sim 40\% \) \( \rightarrow \) Compress the spectrometer

“Active absorber”:
- Trackers
- Magnetic field
- Large area
- Compact
**J/Ψ production: an access to the gluon content in the kaon**

- J/Ψ data collected in parallel with kaon-induced Drell-Yan
- Large statistics
- Model-dependent access to the gluon distribution in kaons
- J/Ψ production cross section (LO):

5) Prompt-photons: clean access to the gluon distribution in kaon

Direct access to the gluon PDF at $x_g^K > 0.05, Q^2 \sim p_T$

Minimum bias photons background

$\pi^0$ background

$\gamma$ signal

$\gamma$ background

Prompt-photon signal

100 GeV $K^+$ beam on a long $IH_2$ target
**Kaon-induced prompt-photon production**

\[ x_T = 2p_T / \sqrt{s} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam type</th>
<th>Beam Intensity (part/sec)</th>
<th>Beam Energy (GeV)</th>
<th>( \int L ) (pb(^{-1})</th>
<th>p_T ) range (GeV/c)</th>
<th>prompt-photon events</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA70</td>
<td>1m lH(_2)</td>
<td>( \pi^+ )</td>
<td>( 2.5 \times 10^6 )</td>
<td>280</td>
<td>1.3</td>
<td>( 4 &lt; p_T &lt; 7 )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \pi^- )</td>
<td>( 1.25 \times 10^7 )</td>
<td>280</td>
<td>3.5</td>
<td>( 4 &lt; p_T &lt; 7 )</td>
<td>—</td>
</tr>
<tr>
<td>AMBER</td>
<td>2m lH(_2)</td>
<td>( K^+ )</td>
<td>( 2 \times 10^7 )</td>
<td>100</td>
<td>50</td>
<td>( p_T &gt; 2.5 )</td>
<td>( 3.4 \times 10^6 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \pi^+ )</td>
<td>( 2 \times 10^7 )</td>
<td>100</td>
<td>50</td>
<td>( p_T &gt; 2.5 )</td>
<td>( 3.4 \times 10^6 )</td>
</tr>
</tbody>
</table>
6) Kaon beam: an opportunity for strange-meson spectroscopy

From the 25 strange mesons listed presently in the PDG, 13 still need experimental confirmation:

- 3 predicted $K_j^*$ states missing. Searches via $K^*p$ scattering, like $K^*p \rightarrow K\pi\eta$ or through heavy meson and $\tau$ decays

- 11 predicted $K_j$ states missing. Searches via heavy meson and $\tau$ decays to multi-body final states

$X$: strange-meson

Searched for and characterized with Partial Wave Analysis
7) Meson radii

Pion and kaon radii: an expression of the link between EHM and confinement

**Pion radius**

Measurements of pion scattering at low $Q^2$, done in the 1980’s

$r_\pi = 0.659 \pm 0.004$ fm (PDG 2020)

**Kaon radius**

Practically unknown

$r_K = 0.560 \pm 0.031$ fm (PDG 2020)
Kaon charge radius

80 GeV RF-separated beam: kaon – electron elastic scattering, to access the kaon form factor

$$0.001 < Q^2 < 0.07 \text{ GeV}^2$$

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

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

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

<table>
<thead>
<tr>
<th>Beam</th>
<th>$E_b$ [GeV]</th>
<th>$Q^2_{\text{max}}$ [GeV$^2$]</th>
<th>$E'_{b,\text{min}}$ [GeV]</th>
<th>Relative charge-radius effect on c.s. at $Q^2_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>190</td>
<td>0.176</td>
<td>17.3</td>
<td>$\sim 40%$</td>
</tr>
<tr>
<td>$K$</td>
<td>190</td>
<td>0.086</td>
<td>105.7</td>
<td>$\sim 20%$</td>
</tr>
<tr>
<td>80</td>
<td>0.066</td>
<td>59.9</td>
<td></td>
<td>$\sim 15%$</td>
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<tr>
<td>50</td>
<td>0.037</td>
<td>41.3</td>
<td></td>
<td>$\sim 8%$</td>
</tr>
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</table>
The AMBER experiment at the CERN M2 beamline is a new “QCD Facility” to investigate the Emergence of Hadron Mass

**AMBER phase-I** was approved in December 2020, for measurements on
- Proton radius from muon-proton elastic scattering
- Pion structure from pion-induced Drell-Yan and Charmonium production
- Antiproton cross-sections – input for Dark Matter searches

The planned upgrade of the M2 beamline will provide radio-frequency separated hadron beams. High purity kaon beams are being proposed for a **phase-II of AMBER**:
- Kaon structure from kaon-induced Drell-Yan and Charmonium production
- Gluon content in the kaon from direct-photon production
- Light meson spectroscopy using kaon beams
- Kaon charge radius from elastic kaon-electron scattering
- ...

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