Studying meson and proton structure at the CERN M2 beam line

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ECT* Mapping parton distribution amplitudes and functions
September 10th-14th
Motivations

Pion
- $M_\pi \sim 140\text{MeV}$
- Spin 0
- 2 light valence quarks
- 2 TMD PDFs at LT

Kaon
- $M_K \sim 490\text{MeV}$
- Spin 0
- 1 light and 1 “heavy” valence quarks
- 2 TMD PDFs at LT

Proton
- $M_p \sim 940\text{MeV}$
- Spin 1/2
- 3 light valence quarks
- 8 TMD PDFs at LT

3 QCD objects, different structures, different properties, understanding differences and similarities teaches us about QCD
The concept of a composite nucleon structure may be tracked as far back as 1933 to the discovery of the anomalous magnetic moment of the proton [1]. This was explicitly formulated by Fermi and Marshall who noted in a 1947 paper [2] that experimental evidence pointed to the nucleon existing approximately 20% of the time in a virtual meson-nucleon state. The virtual meson "cloud" of the nucleon plays an important role in the understanding of the nucleon-nucleon interaction and the pion cloud in particular has always been considered critical to understanding the nucleon's long-range structure.

At shorter ranges, the role of mesons in electron-nucleon deep inelastic scattering (DIS) have also been investigated. In 1972 Sullivan [3] suggested that some fraction of the nucleon's anti-quark sea distribution may be associated with this pion content of the nucleon. For many decades these and numerous other theories that describe and/or utilize the meson cloud of the nucleon have advanced significantly (see [4, 5, 6] for some review). From partially conserved axial current to the success of chiral quark models, it is considered known that the nucleon has an associated meson cloud. In very stark contrast to the substantial body of theory associated with the meson cloud, however, experimental results remain few and far between. In a 1983 paper, Thomas commented that "...it is rather disturbing that no one has yet provided direct experimental evidence of an pion component in the nucleon" [7]. Even with results becoming available from Drell-Yan experiments at Fermilab, W production at RHIC, and di-ractive DIS at HERA and COMPASS, all discussed below, the "disturbing" situation is not yet been substantially improved.

Figure 1: Feynman diagram for electron scattering from the pion cloud of the nucleon $N$, with the initial nucleon at rest (the Sullivan process).

The 12 GeV upgrade of JLab presents new opportunities to study the mesonic structure of the nucleon. One such technique is to measure the contribution to electron Deep Inelastic Scattering (DIS) of the meson cloud of a nucleon target, as pointed out by Sullivan [3] (Fig. 1). This so-called Sullivan process was shown to persist even at large $Q^2$ scales. An immediate consequence of the Sullivan process is that the nucleon parton distributions contain a component which can be attributed to the meson cloud. This
Almost all what we know about pion structure

Example with three fits:

- Large uncertainties or not even at all
- Not enough data to directly constrain all PDFs $\rightarrow$ use of: Momentum Sum rules, constituent quark model...
- Sea no direct constraints

More data is needed, with better control of uncertainties, and full error treatment.

How to access the sea

**DIS with di-jet and leading neutron**

$$F_2^{L^{(3)}}(x_L = 0.73)/\Gamma_\pi, \Gamma_\pi = 0.13$$

**H1**

- **Wide x coverage**
- **Estimation of pion flux introduce a strong model dependence**

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**Drell-Yan NA3**

Badier *et al.*, Z. Phys. C18, 1983

- **Limited statistics:** 4.7k $\pi^-$-event (shown) and 1.7k $\pi^+$-event
- **Heavy nuclear target (Pt)**
Beam possibilities at the CERN M2 beamline

- High intensities available
- Almost pure $\pi^-$ beam
- Reasonable contribution of $\pi^+$ for positive beam
COMPASS-like spectrometer for initial simulation studies

- **Large acceptance:** $8 \text{ mrad} < \theta < 160 \text{ mrad}$

- **4× larger than previous Drell-Yan experiment**

- **Hadron absorber + nuclear targets**
Choice of target

- Isoscalar for sea-valence separation
- Minimize nuclear effect: Carbon
- Embedded in an absorber for high intensity
- Segmented with vertex tagging for flux and resolution
Expected accuracy compared to NA3 result

- Collect at least a **factor 10 more statistics** than presently available
- Aim at the first precise direct measurement of the pion sea contribution

\[ \Sigma_{val} = \sigma_{\pi^-}^C - \sigma_{\pi^+}^C : \text{only valence-valence} \]
\[ \Sigma_{sea} = 4\sigma_{\pi^+}^C - \sigma_{\pi^-}^C : \text{no valence-valence} \]
Renewed interest in pion structure

- Recent reanalysis at NLL
- Agreement restored between DSE and data
- Sea and gluon from GRS
- Nuclear effects ignored

- First MC global QCD analysis ("model dependence")
- Hera data (DIS with leading neutron) included
- Clear impact on sea and gluon distribution

Direct data would constrain the circled area and check the method.
Foreseen meson structure measurements

Tagged DIS at JLab → See talk by C. Keppel

- Same approach as H1 and Zeus:
  - Test of pion cloud
  - Caveat: Model dependence from the unknown pion flux

Provide complementary data at large $x$

Same process is also foreseen for the future EIC to reach very low $x$
## Pion induced Drell-Yan statistics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam energy (GeV)</th>
<th>Beam type</th>
<th>Beam intensity (part/sec)</th>
<th>DY mass (GeV/c^2)</th>
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<td></td>
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<td></td>
<td></td>
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<td>9,000</td>
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</table>

Also 100 of thousands of J/ψ available for free
Parallel studies

Energy loss: → See talk by S. Platchkov

- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state
- Fixed target regime especially suited
- Comparison between DY and $J/\psi$ complementary information

Flavour dependent EMC effect:

Iso-vector $\rho^0$ mean field generated in $N \neq Z$ nuclei can modify nucleon’s $u$ and $d$ PDF differently

- NA3 $\pi$ on Pt favours flavour dependence
- Omega $\pi$ on W not conclusive
- Meson induced Drell-Yan process tags flavours
Using two $\pi$ beam charges and two targets, one can add constraints on the EMC flavour dependence.

**Should play a significant role in nPDFs uncertainties and EMC effect**
What do we know about kaon structure?

Limited statistics: 700 events with $K^-$
Sensitivity to SU(3)$_f$ breaking
Mostly only model predictions

Interesting observation: At hadronic scale gluons carry only 5% of K’s momentum vs $\sim$30% in $\pi$
Scarce data on $u$-valence
No measurements on gluons
No measurements on sea quarks

How to improve the situation?

C. Chen et al., PRD 93 074021, 2016
Unique opportunities with RF separated beam

- Deflection with 2 cavities
- Relative phase $= 0 \rightarrow$ dump
- Deflection of wanted particle given by
  \[ \Delta \phi \approx \frac{\pi fm^2}{c} \frac{m_w^2 - m_u^2}{p^2} \]

To keep good separation:

$L$ should increase as $p^2$ for a given $f \rightarrow$ limits the beam momentum

Initial expectations before further R&D:

- $\sim 80$ GeV Kaon beam
- $\sim 110$ GeV Anti-proton beam
Kaon RF separated

**DY cross-section**

- Highest beam energy to access low $x$
- Highest beam energy to increase signal/bgd ratio
- Favorable also COMPASS-like apparatus

**Prompt photon cross-section**

- $p_T > 2.5 \text{ GeV}/c$
- $q\bar{q} \rightarrow q\bar{q} \gamma \text{ for } K^+, K^-$
- $q\bar{q} \rightarrow g\gamma \text{ for } K^-$
- Geom. acceptance

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Improvement of acceptance

Requirements: Active absorber
- Trackers
- Magnetic field
- Good resolution for vertexing
- Large area
- Capability to collect $e^+e^-$ DY pairs

Initial detector consideration:
Combination of
- Baby-Mind detector
  M. Antonova et al. arXiv:1704.08079
- W-Si detectors, a la BNL

\begin{itemize}
  \item AnDY
  \item Phenix MPCEX
  \item Phenix NCC
\end{itemize}
Projections for Kaon structure

- More data points and more precise compared to NA3
- Discriminating power between models
- 1 year with $2 \times 10^7$ s$^{-1}$ 100 GeV $K^-$ beam
- $\pi$ taken simultaneously

Unique and Promising
Projections for valence/sea separation for Kaons

- **First** measurement of sea in kaons
- Requires an additional year with $K^+$ beam to complement the former $K^-$ data
- Assuming the intensity for $K^+$ and $K^-$: $2 \times 10^7$ s$^{-1}$
Parallel measurement: $J/\psi$ production

Purely strong interaction: all partons contribute on the same footing

Using two kaon beam charges, one can access:

- $\bar{u}^K u^N \propto \sigma^K_1 - \sigma^K_2$
- Infer the kaon gluon distribution in a model dependent way
Gluon structure in Kaon through prompt photon production

- Model independent way
- Large cross-section
- Large acceptance
- Experimentally difficult (huge background)

No competitors
Unpolarised Drell-Yan angular dependencies

\[
\frac{dN}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left( 1 + \lambda \cos^2(\theta) + \mu \sin(2\theta) \cos(\phi) + \frac{\nu}{2} \sin^2(\theta) \cos(2\phi) \right)
\]

In naive Drell-Yan model, no $k_T$ and no QCD processes involving gluons:

\[
\lambda = 1, \quad \mu = 0, \quad \nu = 0
\]

The Lam-Tung relation, derived from the fermionic nature of quarks, predicts:

\[
1 - \lambda - 2\nu = 0
\]

Analog of DIS Callan-Gross relation for Drell-Yan
Recent evidence in terms of QCD: radiative effects describe well data at large $q_T$
- J.-C. Peng et al. PLB 758, 384 (2016)
- M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)

Boer Mulders expected at low $q_T \rightarrow$ fixed target regime
Verify Lam-Tung relation for Kaon beam
To single out Boer Mulders effects very precise data are necessary

→ See talk by J.-C. Peng
Transverse momentum dependent PDFs

So far, I talked only about mesons but what about the nucleon?

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>U</strong></td>
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<tr>
<td><img src="image" alt="Nucleon" /></td>
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<tr>
<td><img src="image" alt="Quark" /></td>
</tr>
<tr>
<td><img src="image" alt="Spin" /></td>
</tr>
<tr>
<td><img src="image" alt="Transverse Momentum" /></td>
</tr>
</tbody>
</table>

At LO QCD, the nucleon can be decomposed into 8 twist-2 TMD PDFs.

Using a transversally polarised target, one can access in SIDIS as well as in Drell-Yan:

- Sivers
- Transversity
- Pretzelosity
Drell-Yan and SIDIS cross-section modulations

SIDIS:
\[
\frac{d\sigma}{dx dy dz d\phi_h dP^2_{hT}} \bigg|_{\text{LO}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{y^2}{2x}\right) \sigma_U \left\{ 1 + \epsilon A_{UU}^{\cos(2\phi_h)} \cos(2\phi_h) + \epsilon A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \epsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \right\}
\]

DY:
\[
\frac{d\sigma}{d^4 q d\Omega} \bigg|_{\text{LO}} = \frac{\alpha^2}{F q^2} \sigma_U \left\{ \left(1 + \cos^2(\theta) + \sin^2(\theta) A_{UU}^{\cos(2\phi)} \cos(2\phi)\right) + \epsilon A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + \epsilon A_{UT}^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) + \epsilon A_{UT}^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \right\}
\]
Synergy DY vs SIDIS

<table>
<thead>
<tr>
<th>DY:</th>
<th>SIDIS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^{\cos(2\phi)}_{UU}$</td>
<td>$A^{\cos(2\phi_h)}_{UU}$</td>
</tr>
<tr>
<td>$A^{\sin(\phi_S)}_{UT}$</td>
<td>$A^{\sin(\phi_h-\phi_S)}_{UT}$</td>
</tr>
<tr>
<td>$A^{\sin(2\phi-\phi_S)}_{UT}$</td>
<td>$A^{\sin(\phi_h+\phi_S)}_{UT}$</td>
</tr>
<tr>
<td>$A^{\sin(2\phi+\phi_S)}_{UT}$</td>
<td>$A^{\sin(3\phi_h-\phi_S)}_{UT}$</td>
</tr>
<tr>
<td>$\propto h_{1,h}^{\perp q}$</td>
<td>$\propto h_{1,p}^{\perp q}$</td>
</tr>
<tr>
<td>$\propto f_{1_T,p}^{1_T}q$</td>
<td>$\propto f_{1,p}^{1_T}q$</td>
</tr>
<tr>
<td>$\propto h_{1,h}^{\perp q}$</td>
<td>$\propto h_{1,p}^{\perp q}$</td>
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<td>$\propto h_{1_T,p}^{\perp q}$</td>
</tr>
</tbody>
</table>

TMD PDFs are **universal** but final state interaction (SIDIS) vs. initial state interaction (DY) $\rightarrow$ **Sign flip** for naive T-odd TMD PDFs

<table>
<thead>
<tr>
<th>SIDIS</th>
<th>DY</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{1_T,q}^{1_T}q</td>
<td><em>{SIDIS} = -f</em>{1_T,q}^{1_T}q</td>
</tr>
<tr>
<td>$h_{1,q}^{\perp q}</td>
<td><em>{SIDIS} = -h</em>{1,q}^{\perp q}</td>
</tr>
</tbody>
</table>

Crucial test of **TMD framework in QCD**
SIDIS TSA in HM range
COMPASS, PLB 770 (2017) 138

\[ A^{\sin(\phi_h + \phi_s)} \propto h_{1,q}^T \otimes H_{1,q}^h \]

\[ A^{\sin(3\phi_h - \phi_s)} \propto h_{1,T,q}^T \otimes H_{1,q}^h \]

\[ A^{\sin(\phi_s)} \propto f_{1,T,q}^T \otimes D_{1,q}^h \]

DY TSA in MH range
COMPASS, PRL 119 112002 (2017)

\[ A^{\sin(2\phi_{CS} - \phi_s)} \propto h_{1,q}^\perp \otimes h_{1,p}^h \]

\[ A^{\sin(2\phi_{CS} + \phi_s)} \propto h_{1,T,q}^\perp \otimes h_{1,q}^h \]

\[ A^{\sin(\phi_s)} \propto f_{1,T,q}^\perp \otimes f_{1,T,p}^h \]

Transversity
Pretzelosity
Sivers

Vincent Andrieux (UIUC/CERN)
Trento Sep-2018
Sivers $A^\sin(\phi_h-\phi_s) \propto f_{1T,p}^\perp q \otimes D_{1q}^h$

Transversity $A^\sin(\phi_h+\phi_s) \propto h_{1,p}^q \otimes H_{1q}^h$

Pretzelosity $A^\sin(3\phi_h-\phi_s) \propto h_{1T,p}^\perp q \otimes H_{1q}^h$

SIDIS: All sizeable except Pretzelosity

DY:
- Sivers found at 1 sigma from zero
- Pretzelosity pretty large
- Still large uncertainties
Focus on Sivers sign change

DGLAP (2016)
M. Anselmino et al., JHEP 1704 (2017) 046

TMD-1 (2014)
M.G. Echevarria et al., PRD 89 074013

TMD-2 (2013)
P. Sun, F. Yuan, PRD 88, 114012

Favour sign-change scenario

Second data taking campaign, ongoing!
Anti-proton with a RF separated beam

Possibility to study valence proton TMD PDFs in a model free way

- Cross-sections for $\bar{p}$ induced-DY at 120 GeV $\sim \pi^-$ induced-DY at 190 GeV
- Combined statistics from $\mu^+\mu^-$ and $e^+e^-$ channels $\sim$ 2 years of COMPASS-II data taking
- With active absorber: better acceptance in $\theta_{CS}$

<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/c²)</th>
<th>DY events $\mu^+\mu^-$</th>
<th>DY events $e^+e^-$</th>
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<td>140</td>
<td>4.0 – 8.5</td>
<td>52,000</td>
<td>32,500</td>
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</table>
Anti-proton beam: Synergy DY and SIDIS

Additional insight with $\bar{p}$ on Boer Mulders (private exchange with Andreas Metz)

- Transversity modulation less affected by QCD effects
- Smooth matching between TMD approach and QCD

$\rightarrow$ Extract transversity from SIDIS $A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,q} \otimes H_{1\perp h}$ measurements

- Use DY measured $A^{\sin(2\phi-\phi_S)} \propto h_{1,h} \otimes h_{1,p}$ and SIDIS transversity knowledge

Obtain Boer-Mulders $h_{1,q}$ for proton and meson with antiproton and meson beams

Complementary to SIDIS, where Cahn effects can be difficult to disentangle from Boer-Mulders effects
A new QCD facility

- Letter of Intent
  arXiv:1808.00848
  DY, Spectroscopy, muon-p elastics scattering, . . .

- A web page

- Can register to stay informed

New ideas and collaborators are welcome
Near term future: Current beams

- **Precise** determination of pion structure and valuable inputs for nuclear effects (nPDFs, EMC, \( J/\psi \), ...)

Long term future: RF-separated beams

- **Unprecedented** studies of Kaon structure
- **Unique** opportunity to study proton valence TMD PDFs in a model free way

Many other valuables measurements described in the LoI for both short and long term future
BACKUP
Background less than 4% in $4.3 < M_{\mu\mu}/(GeV) < 8.5$
Target choice and sea-valence separation

With $\pi^+$ and $\pi^-$ beam and isoscalar target:

$$\sigma(\pi^+ d) \propto \frac{4}{9} [u^\pi \cdot (\bar{u}^p_s + \bar{d}^p_s)] + \frac{4}{9} [\bar{u}^\pi_s \cdot (u^p + d^p)] + \frac{1}{9} [\bar{d}^\pi \cdot (d^p + u^p)] + \frac{1}{9} [d^\pi_s \cdot (\bar{d}^p_s + \bar{u}^p_s)]$$

$$\sigma(\pi^- d) \propto \frac{4}{9} [u^\pi_s \cdot (\bar{u}^p_s + \bar{d}^p_s)] + \frac{4}{9} [\bar{u}^\pi \cdot (u^p + d^p)] + \frac{1}{9} [\bar{d}^\pi \cdot (d^p + u^p)] + \frac{1}{9} [d^\pi \cdot (\bar{d}^p_s + \bar{u}^p_s)]$$

- Assumption:
  - Charge conjugation and SU(2)$_f$ for valence:
    $$u^\pi_v = \bar{u}^\pi_v = \bar{d}^\pi_v = d^\pi_v$$
  - Charge conjugation and SU(3)$_f$ for sea:
    $$u^\pi_s = \bar{u}^\pi_s = u^\pi_s = \bar{u}^\pi_s = \bar{d}^\pi_s = d^\pi_s = \bar{d}^\pi_s = d^\pi_s = s^\pi_s = \bar{s}^\pi_s = s^\pi_s = \bar{s}^\pi_s$$

- Two linear combination
  - Only valence sensitive:
    $$\Sigma^D_v = -\sigma_v^{\pi^+} + \sigma_v^{\pi^-} \propto \frac{1}{3} u^\pi_v (u^p_v + d^p_v)$$
  - Sea sensitive:
    $$\Sigma^D_s = 4\sigma_s^{\pi^+} - \sigma_s^{\pi^-}$$

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<td>4.0 – 8.5</td>
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<td>4.0 – 8.5</td>
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<td>4.0 – 8.5</td>
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<td>39,800</td>
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</table>

Achievable statistics of the new experiment, assuming $2 \times 140$ days of data taking with equal time sharing between the two beam charges. For comparison, the collected statistics from NA3 is also shown.
### Requirements per topic

<table>
<thead>
<tr>
<th>Program</th>
<th>Beam Energy [GeV]</th>
<th>Beam Intensity [/s]</th>
<th>Trigger Rate [kHz]</th>
<th>Beam Type</th>
<th>Target</th>
<th>Hardware Additions</th>
<th>R</th>
<th>C</th>
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</thead>
<tbody>
<tr>
<td>Proton radius</td>
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<td>100</td>
<td>$\mu^\pm$</td>
<td>H2</td>
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<td>GPD E</td>
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<td>10</td>
<td>$\mu^\pm$</td>
<td>NH3†</td>
<td>recoil silicon, modified PT magnet</td>
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<td>Anti-matter</td>
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<td>25</td>
<td>$p$</td>
<td>LH2, LHe</td>
<td>recoil TOF</td>
<td>×</td>
<td>×</td>
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<tr>
<td>Spectroscopy $\bar{p}$</td>
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<td>25</td>
<td>$\bar{p}$</td>
<td>LH2</td>
<td>target spectrometer: tracking, calorimetry</td>
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<td>$\pi^\pm$</td>
<td>C/W</td>
<td>vertex detector</td>
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<td>$10^8$</td>
<td>25-50</td>
<td>$K^\pm, \bar{p}$</td>
<td>NH3†, $\bar{p}$ C/W</td>
<td>&quot;active absorber&quot;, vertex detector</td>
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<td>Ni</td>
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<td>$K^+$</td>
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<td>$K^-$</td>
<td>LH2</td>
<td>recoil TOF</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Requirements for the future programs at the M2 beam line after 2021. Standard muon beams are in blue, standard hadron beams in orange, and RF-separated hadron beams in red. The common baseline is the COMPASS-II setup without RICH-1. “R” refers to RICH-1 and if possible RICH-0, “C” to CEDARs.