Physics from Drell Yan and Direct Photon Production with High Intensity Kaon and Anti-Proton Beams

Mini Workshop on the Physics at a Future SPS QCD Facility
June 20, 2018
Hadron Structure with Kaon- and Anti-Proton Beams

- Why Pion and Kaon Structure?
- RF separated Kaon and Anti-Proton Beams
- Apparatus
  - Kaon quark- and gluon-structure
    - Direct Photons
    - $(J/\psi)$
    - Drell-Yan
  - Anti-Proton Beam
    - Boer-Mulders
Towards Precision Measurements of Pion and Kaon Structure

Proton PDFs

Pion PDFs

Kaon PDFs

\[ \frac{U_K}{U_\pi}(x) \]


Hadron Structure with High Intensity Kaon and Anti-Proton Beams
Towards Precision Measurements of Pion and Kaon Structure

Knowledge of (unpolarized) proton PDFs currently driven by need of precise input for SM and BYSM physics at LHC

Two mechanisms for the emergence of mass in SM

- EW symmetry breaking provides current masses
- Strong Interaction chiral symmetry breaking leads to large hadron masses (>95% of visible mass)

Precise ab initio understanding of the strong interaction sector of the SM requires

- ability of precise calculations ab initio QCD
- precise experimental information on the structure of different hadrons and the hadronic mass spectrum
Precise Calculations ab Initio QCD

Large-momentum effective theory (LaMET)

Progress in the theoretical development of LaMET

- **Renormalization:**

- **Factorization:**

- **One-loop matching:**

- **Power corrections:**

- **Transverse momentum dependent parton distribution function:**
  Ji, Xiong, Sun, Yuan, 2015; Ji, Jin, Yuan, Zhang and Y.Z., 2018; Ebert, Stewart and Y.Z., in progress.

from Yong Zhao at Intersections, June 2018
Large-momentum effective theory (LaMET)

Accomplishment of lattice calculations with LaMET so far

- **Gluon helicity contribution to proton spin**
  - Gluon spin provides about half of the proton spin
    \( \chi \text{QCD Collaboration, 2017} \)

- **Unpolarized iso-vector quark distribution**
  - Gottfried sum rule violation, i.e., \( d(x) > \bar{d}(x) \)

- **Polarized iso-vector quark distribution**
  - Primitive results show \( \Delta \bar{u}(x) > \Delta d(x) \)

- **Transversity iso-vector quark distribution**
  - Primitive results show \( \delta d(x) > \delta \bar{u}(x) \)
    \( \text{H.-W. Lin et al. (LP3), 2016; ETMC Collaboration, 2016.} \)

- **Meson distribution amplitudes (PDA)**
  - Single-hump structure of pion PDA; Asymmetry of kaon PDA with respect to \( x=1/2 \)

- **Pion PDF**
  \( \text{LP3 collaboration, 2018; from Yong Zhao at Intersections, June 2018} \)
Other proposals

- Restoration of rotational symmetry to calculate higher moments

- OPE of flavor-changing current-current correlation

- OPE of the Compton amplitude
  A. J. Chambers et al. (QCDSF), 2017.

- Direct computation of the physical hadronic tensor

- Smeared Quasi-PDF with Gradient flow

- Pseudo-PDF (alternative to quasi-PDF)

- Lattice cross section

- Factorization of Euclidean correlations in coordinate space
In 5~10 years, expect:

- Lattice calculation of quark PDFs to be within 10% accuracy or even better;
- Constraints on the flavor structure of PDF at $x \sim 1$ and the sea quark distributions be better than experiments;
- Reaching smaller $x$ region with larger nucleon momentum;
- Lattice calculation of other distributions including TMD, GPD, gluon distributions, etc...

from Yong Zhao
at Intersections June 2018
(II) Precise Information on the Structure of Hadrons (and on their Mass Spectrum)

Future QCD Facility with RF-Separated Beams at the SPS

Example: $\frac{U_K}{U_\pi}(x)$

- Determine quark and gluon structure of the pion and kaon
- Verify Lattice QCD PDFs with high precision
- Gain quantitative understanding of chiral dynamics in both protons: $m_p \sim \text{Binding Energy} + \text{dressed quark masses}$ and mesons: $m_{\pi,K} \sim \text{Binding Energy} - \text{dressed quark masses}$ including the mass dependence.

ECT* Workshop on “Dilepton Production with Meson and Antiproton Beams” November 2017
Significant Interest in Meson Structure Measurements Elsewhere

**Meson structure using the Sullivan process at Jlab and possibly EIC**

![Diagram of the Sullivan process]

- Determine quark and gluon structure of the pion and kaon
- Verify Lattice QCD PDFs with high precision
- Gain quantitative understanding of chiral dynamics in both protons: \( m_p \sim \text{Binding Energy} + \text{dressed quark masses} \)
  - and mesons: \( m_{\pi,K} \sim \text{Binding Energy} - \text{dressed quark masses} \)
  - including the mass dependence.

**FIG. 1.** The Sullivan process in which the virtual photon scatters off the meson cloud in the nucleon.

*Argonne workshop on Pion and Kaon Structure at an Electron-Ion Collider, June 2017*

**JPARC:** secondary beamlines for DY physics at low energy.
RF Separated Kaon and Anti-Proton Beams at SPS-M2 after LS3 for LHC Luminosity Upgrades

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

To keep good separation, $L$ should increase as $p^2 \rightarrow$ limits the beam momentum

- Kaon  With the current RP limits, for total beam flux of $7 \times 10^7$ particles/s:
  - $I_{K^-} \sim 2 \times 10^7$/s at 100 GeV
  - $I_{K^+} \sim 2 \times 10^7$/s at 100 GeV
- High intensity antiproton beam:
  - $\sim 5 \times 10^7$ with current RP
Apparatus

- **targets:** $H$, polarized $NH_3$, $C$

- **experimental probes:**
  - $e^+e^-$ and $\mu^+\mu^-$ Drell Yan pairs
  - direct photons
  - $J/\psi$

- **instrumentation:**
  - Updated COMPASS spectrometer optimized for different experimental probes
  - New large acceptance DY spectrometer for electron (W-Si Calorimeter, PHENIX NCC & MPC-EX) and muon DY (Magnetized Iron Detector, Baby MIND)

- Ample room for ideas and contributions!
Kaon Gluon Distribution from Direct Photon Production

Gluon Compton

Annihilation

In addition, fragmentation photons: 10-20%

Kinematic coverage:
Previous experiments vs COMPASS

Cross sections vs E_{beam} for partonic processes

MC simulation using current COMPASS detector configuration for GPDs:

p_{T} > 2.5 GeV/c and 1.4<y<18
140 days \rightarrow 0.85 \times 10^6 events

Hadron Structure with High Intensity Kaon and Anti-Proton Beams
**Kaon DY - MC Projections, $E_{\text{beam}}=80,100,120$ GeV**

expected DY yields: at 100 GeV ~ 58k $K^-$, 7k $K^+$

<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>
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<td>6cm Pt</td>
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<td>$K^-$</td>
<td>$2.1 \times 10^7$</td>
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<td>4.0 – 8.5</td>
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<td>$K^+$</td>
<td></td>
<td>100</td>
<td>4.0 – 8.5</td>
<td>40,000</td>
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<tr>
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<td></td>
<td></td>
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<td>120</td>
<td>4.0 – 8.5</td>
<td>54,000</td>
<td>20,700</td>
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<td>This exp.</td>
<td>100cm C</td>
<td>$K^+$</td>
<td>$2.1 \times 10^7$</td>
<td>80</td>
<td>4.0 – 8.5</td>
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<td>1,300</td>
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<td></td>
<td>100</td>
<td>4.0 – 8.5</td>
<td>5,200</td>
<td>2,000</td>
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<td></td>
<td>120</td>
<td>4.0 – 8.5</td>
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<td>This exp.</td>
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<td>4.0 – 8.5</td>
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<td>100</td>
<td>4.0 – 8.5</td>
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<td>120</td>
<td>4.0 – 8.5</td>
<td>123,600</td>
<td>39,800</td>
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Kaon DY - MC Projections, $E_{\text{beam}}=80, 100, 120$ GeV
for Sea to Valence Ratio: $R_{S/V}$

- Dense & not too long for counting rate and acceptance considerations
- Isoscalar for sea-valence separation: J.T. Londergan et al., PLB 380 (1996)
  - $\Sigma_S = \sigma_{DY}^{K^+D}$: Sensitive to valence and sea terms
  - $\Sigma_V = \sigma_{DY}^{K^-D} - \sigma_{DY}^{K^+D} = \frac{4}{9} \bar{u}_V^K (u^p + d^p)$: only valence sensitive
- Low $A$ to minimize nuclear effect: Carbon target

First measurement of Sea to Valence Ratio and precise measurement of quark distributions (earlier slides)
Anti-Proton DY – TMDs -> Boer-Mulders Function (BMF)

Cross sections for $\pi^-$ and $\bar{p}$ induced Drell Yan

$\bar{p}$ BMF

$$A_T^{\cos(2\varphi_{CS} - \varphi_S)} \propto h_{1,\bar{p}}^q \otimes h_{1,\bar{p}}^q$$

Target transversity

Clean measurement of $\bar{p}$ BMF

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<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></td>
<td>120</td>
<td>4.0 – 8.5</td>
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<td></td>
<td>140</td>
<td>4.0 – 8.5</td>
<td>52,000</td>
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</tbody>
</table>

Table 3: Achievable statistics of the new experiment with an active absorber and 140 days of beam time.
Summary

- LaMET in Lattice QCD enables ab initio quantitative analysis of hadron structure.
- Comparison with precision data on the quark and gluon structure of mesons will provide the information needed for a systematic study of chiral dynamics and the emergence of the large hadron masses.
- A future QCD facility with RF separated beams at the SPS will provide precise information on pion and kaon structure without significant model dependencies.
- Anti proton beams allow clean access to important TMDs that are difficult to extract from SIDIS.