Meson Production

INT 18-3: Probing Nucleons and Nuclei in High Energy Collisions

University of Washington, Seattle, 1 October – 16 November 2018
The 3D Hadron Structure

- **Meson Form Factors**
  - Most basic information about internal structure

- **GPDs**
  - Spatial imaging (exclusive DIS)

- **TMDs**
  - Confined motion in a nucleon (semi-inclusive DIS)

- **Requires**
  - High luminosity
  - Sophisticated detector systems
  - Polarized beams and targets
Meson Form Factors
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GPDs
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Deep Exclusive Meson Electroproduction

- In the limit of small $-t$, meson production can be described by the $t$-channel meson exchange (pole term)
  - Spatial distribution described by form factor

- At sufficiently high $Q^2$, the process should be understandable in terms of the “handbag” diagram – can be verified experimentally
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons [Collins, Frankfurt, Strikman, 1997]
Overview Form Factors

- **Pion and kaon form factors** are of special interest in hadron structure studies
  - The pion is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass. The kaon is the next simplest system containing strangeness.
  - **Clearest test case for studies of the transition from non-perturbative to perturbative regions**

- Recent advances and future prospects in experiments
  - Dramatically improved precision in $F_\pi$ measurements
    - **12 GeV JLab data have the potential to quantitatively reveal hard QCD’s signatures**
    - **EIC data have the potential to quantitatively reveal DCSB emergent mass generation**
Emergent- versus Higgs-Mass Generation

Twist-2 PDA at Scale $\zeta = 2 \text{ GeV}$

A solid (green) curve – pion $\leftrightarrow$ emergent mass is dominant;
B dot-dashed (blue) curve – $\eta_c \leftrightarrow$ primarily, Higgs mass generation;
C solid (thin, purple) curve – conformal limit result, $6x(1 - x)$; and
D dashed (black) curve – “heavy-pion”, i.e., a pion-like pseudo-scalar meson ($\sim \eta_s$) in which the valence-quark current masses take values corresponding to a strange quark $\leftrightarrow$ the border, where emergent and Higgs mass generation are equally important.

Un fortunately, experimental signatures of the exact PDA form are, in general, difficult.

- The PDA for the light-quark pion (A) is a broad, concave function, a feature of emergent mass generation.
- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a $\delta$-function at $x = \frac{1}{2}$.
- The sufficiently heavy $\eta_c$ meson (B), feels the Higgs mechanism strongly.
Meson Form Factor Data Evolution

Theory
- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

Experiment
- Capability to reliably access large $Q^2$ regime

Major progress on large $Q^2$ behavior of meson form factor
Measurement of $\pi^+$ Form Factor

- At low $Q^2$, $F_{\pi^+}$ can be measured directly via high energy elastic $\pi^+$ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25 \text{ GeV}^2$
    
    [Amendolia et al, NPB277,168 (1986)]
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012 \text{ fm}$

- At larger $Q^2$, $F_{\pi^+}$ must be measured indirectly using the “pion cloud” of the proton in exclusive pion electroproduction: $p(e,e'\pi^+)n – L/T separations$
  - Select pion pole process: at small $-t$ pole process dominates the longitudinal cross section, $\sigma_L$
    
  - Isolate $\sigma_L$ - in the Born term model, $F_{\pi^+}^2$ appears as
    
    $$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t - m_\pi^2)} \ g_{\pi NN}^2(t) \ Q^2 F_{\pi^+}^2 (Q^2, t)$$

    [In practice one uses a more sophisticated model]

[Horn et al., PRL 97, (2006) 192001]
Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(\nu)$ is linear in $\nu$ the meson pole dominates

- Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio

- \textit{Off-shell meson = On-shell meson} for $t<0.6$ GeV$^2$ ($\nu=31$) for pions and $t<0.9$ GeV$^2$ ($\nu_s\approx3$) for kaons

This means that pion and kaon structure functions can be accessed through the Sullivan process.
Experimental studies over the last decade have given confidence in the electroproduction method yielding the physical pion form factor

- Experimental studies include:
  - Take data covering a range in \(-t\) and compare with theoretical expectation
    - \(F_\pi\) values do not depend on \(-t\) – confidence in applicability of model to the kinematic regime of the data
  - Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
    - \(R_L\) approaches the pion charge ratio, consistent with pion pole dominance
  - Extract \(F_\pi\) at several values of \(t_{\text{min}}\) for fixed \(Q^2\)

\[ R_L = \frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2} \]

[Huber et al, PRL112 (2014)182501]


\[ F_\pi \]

\[ -t \text{ [GeV}^2\text{]} \]

\[ R_L \]

\[ -t \text{ [GeV}^2\text{]} \]
\( F_{\pi}+(Q^2) \) and \( F_{K^+}(Q^2) \) in 2018

- **Factor \( \sim 3 \)** from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA) \[L. \text{Chang, et al., PRL 111 (2013) 141802; PRL 110 (2013) 1322001}\]
  - Trend consistent with time like meson form factor data up to \( Q^2=18 \text{ GeV}^2 \) \[\text{Seth et al, PRL 110 (2013) 022002}\]

- **Recent developments**: when comparing the hard QCD prediction with a pion valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data
  \[I. \text{Cloet, et al., PRL 111 (2013) 092001}\]
\( F_{\pi^+}(Q^2) \) and \( F_{K^+}(Q^2) \) in 2018

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\[ \frac{F_{\pi^+}(Q^2)}{F_{K^+}(Q^2)} + \left( \frac{Q^2}{4\pi^2} \right) \]

**References:**


- [I. Cloet, et al., PRL 111 (2013) 092001]
Transverse charge densities allow interpretation of FFs in terms of physical charge density

Transverse charge densities are related to the Generalized Parton Distributions

\[ \rho_\pi(b) = \frac{1}{\pi R^2} \sum_{n=1}^{\infty} F_\pi(Q_n^2) \frac{J_0(X_n \frac{b}{R})}{[J_1(X_n)]^2} \]

\[ Q_n = \frac{X_n}{R} \]

Uncertainty in the analysis dominated by incompleteness error

- Estimated using the monopole as upper bound and a light front model as lower bound

\( \rho_\pi \) and \( \rho_p \) coalesce for \( 0.3 \text{ fm} < b < 0.6 \text{ fm} \); and so does \( \rho_{K^+} \)

It would be interesting to extract the transverse charge density for different flavors


[N.A. Mecholsky et al., Phys. Rev. C96 065207 (2017)]
JLab 12 GeV experiments have the potential to access the hard scattering scaling regime quantitatively for the first time – may also provide info on log corrections.

These results would also have implications for nucleon structure interpretation.
1. Regge-based (VR) model shows strong dominance of $\sigma_L$ at small $-t$ at large $Q^2$.
2. Assume $\sigma_L$ dominance
3. Measure the $\pi/\pi^+$ ratio to verify – it will be diluted (smaller than unity) if $\sigma_T$ is not small, or if non-pole backgrounds are large

- $5 \text{ GeV(e)} \times 100 \text{ GeV(p)}$
- Integrated luminosity:
  - $L=20 \text{ fb}^{-1}/\text{yr}$
- Identification of exclusive $p(e,e'\pi^+)n$ events
- 10% exp. syst. unc.
- $R=\sigma_L/\sigma_T$ from VR model, and $\pi$ pole dominance at small $t$ confirmed in $^2H \pi/\pi^+$ ratios
- 100% syst. unc. in model subtraction to isolate $\sigma_L$

Looks promising for measuring $F_\pi$. Can we measure kaon form factor at EIC?

Adapted from Garth Huber slides (PIEIC2018)
Impact of Future Data

\[ F_k(t) = \frac{1}{\pi} \int_0^\infty dt' \frac{\text{Im} F_k(t')}{t' - t + i \varepsilon} \]

Transverse density assuming very different behavior of the form factor

Ongoing: perhaps also interesting to see if any impact of mass-dependence of the meson form factor

\[ [\text{N.A. Mecholsky et al., Phys. Rev. C96 065207 (2017)}] \]

Towards the Pion/Kaon Structure Function

- Is there anything besides the meson elastic form factors that can be learned by isolating the One Pion Exchange Contribution?

- Sullivan was the first to consider the “Drell” process, with $\pi+X$ final states where $m_X^2$ grows linearly with $Q^2$.

- A simple calculation gives the minimum momentum transfer squared
  \[ t_{\text{min}} = (q - k)^2_{\text{min}} \to \infty \text{ as } Q^2 \to \infty \]
  - The requirement of being near the pion pole at $t = m_\pi^2$ can never be satisfied and processes of this type play no role in the scaling region.

- Similar consideration for offshellness as for meson FF – a well-constrained experimental analysis should be reliable in regions of -$t$. 


The role of gluons in pions

Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

\[ f_{\pi} E_{\pi}(p^2) = B(p^2) \]

Adapted from Craig Roberts:

- The most fundamental expression of Goldstone’s Theorem and DCSB in the SM
- Pion exists if, and only if, mass is dynamically generated – “because of B, there is a pion”
- On the other hand, in absence of the Higgs mechanism, the pion mass \( m_\pi = 0 \) – the pion mass \( m_\pi^2 \) is entirely driven by the current quark mass (for reference, for the \( \rho \), only 6% of its mass \( m_\rho^2 \) is driven by this).

What is the impact of this for gluon parton distributions in pions vs nucleons? One would anticipate a different mass budget for the pion and the proton.
The role of gluons in the chiral limit

In the chiral limit, using a parton model basis: the entirety of the proton mass is produced by gluons and due to the trace anomaly

\[ \langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_N^2 \]

In the chiral limit, for the pion \( (m_\pi = 0) \):

\[ \langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0 \]

Sometimes interpreted as: in the chiral limit the gluons disappear and thus contribute nothing to the pion mass.

This is unlikely as quarks and gluons still dynamically acquire mass – this is a universal feature in hadrons – so more likely a cancellation of terms leads to “0”

Nonetheless: are there gluons at large \( Q^2 \) in the pion or not?
The Incomplete Hadron: Mass Puzzle

“Mass without mass!”

Proton: Mass ~ 940 MeV
preliminary LQCD results on mass budget,
or view as mass acquisition by $D\chi$SB
Kaon: Mass ~ 490 MeV
at a given scale, less gluons than in pion
Pion: Mass ~ 140 MeV
mass enigma – gluons vs Goldstone boson

- **EIC expected contributions in:**
  - trace anomaly:
    - $\Upsilon$, $J/\Psi$, $\Upsilon$
    - Upsilon production near the threshold

- **EIC’s expected contribution in:**
  - Quark-gluon energy:
    - $\propto$ quark-gluon momentum fractions
      - In $\pi$, $K$ and $N$ with DIS and SIDIS
      - $\pi$ and $K$ with Sullivan process

See talk by J. Qiu
World Data on pion structure function $F_2^\pi$

**HERA**

$Q^2 = 7.0 \text{ GeV}^2$

$Q^2 = 15 \text{ GeV}^2$

$Q^2 = 30 \text{ GeV}^2$

$Q^2 = 60 \text{ GeV}^2$

$Q^2 = 120 \text{ GeV}^2$

$Q^2 = 240 \text{ GeV}^2$

$Q^2 = 480 \text{ GeV}^2$

$Q^2 = 1000 \text{ GeV}^2$

- ZEUS 95–97
- $F_2^\pi \text{ SMRS}$
- $F_2^\pi \text{ GRV}$

**EIC**

Here example for 5 GeV $e^-$ and 50 GeV $p$

- $Q^2 = 3.75$
- $Q^2 = 15$
- $Q^2 = 60$
- $Q^2 = 240$

- $EIC$ kinematic reach down to a $x = \text{few } 10^{-3}$
- Lowest $x$ constrained by HERA
Landscape for $p$, $\pi$, K structure function after EIC

Proton: much existing from HERA

EIC will add:
- Better constraints at large-$x$
- Precise $F_2^n$ neutron SF data

Pion and kaon: only limited data from:
- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

EIC will add large ($x,Q^2$) landscape for both pion and kaon!

Phase space for 5 GeV $e^-$ and 50 GeV $p$
First MC global QCD analysis of pion PDFs

- Using Fermilab DY and HERA Leading Neutron data

- JLab 12 GeV: Tagged Pion and Kaon TDIS
- Also prospects for kaon DY at COMPASS and pion and kaon LN at EIC

Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data

Implications for “TDIS” (Tagged DIS) experiments at JLab


\[ \text{DY} = \pi N \text{ Drell-Yan} \]

\[ \text{LN} = \text{Leading Neutron} \]
Obtain $F_2^n$ by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.

Obtain $F_2^\pi$ and $F_2^K$ by Sullivan process and extrapolate the measured $t$-dependence as compared to DSE-based models.

Need excellent detection capabilities, and good resolution in $-t$. 
Global Fits with Existing Data and EIC Projections

- 5 GeV(e⁻) x 100 GeV(p)
- 0.1 < y < 0.8
- EIC pseudodata fitted with existing data

Work ongoing:
- Why did the curves shift?
- The pion D-Y data, even if not many, already do constrain the curves surprisingly well – due to the various sum rules?
- Curves to improve with the EIC projections, especially for kaon as will have similar-quality data.

Precision gluon constraints of pion and kaon pdfs are possible.

R. Trotta, V. Berdnikov, N. Mecholsky, T. Horn, I. Pegg, N. Sato et al., 2018+
Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry some 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale.
- At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale.

Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- Heavier quarks radiate less readily than lighter quarks.
- Heavier quarks radiate softer gluons than do lighter quarks.
- Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- Momentum conservation communicates these effects to the kaon's u-quark.
Exploring the 3D Nucleon/Meson Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction ($x_{Bj}$) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- Deep Exclusive Scattering (DES) cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) $x$ at a transverse location $b$.

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum ($k_T$) of a parton and transverse momentum ($p_T$) created during the [parton $\rightarrow$ hadron] fragmentation process.
Towards GPD flavor decomposition: DVMP

- Relative contribution of $\sigma_L$ and $\sigma_T$ to cross section are of great interest for nucleon structure studies

- Described by 4 (helicity non-flip) GPDs:
  - $H, E$ (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)

- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector: $\rho^0/\rho^+ / K^*$ select $H, E$
  - Pseudoscalar: $\pi, \eta, K$ select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$

- Reaction mechanism can be verified experimentally - L/T separated cross sections to test QCD Factorization

- Recent calculations suggest that leading-twist behavior for light mesons may be reached at $Q^2=5-10$ GeV$^2$

- JLab 12 GeV can provide experimental confirmation in the few GeV regime
Results from 6 GeV JLab

- Data demonstrate the technique of measuring the $Q^2$ dependence of $L/T$ separated cross sections at fixed $x/t$ to test QCD Factorization
  - Consistent with expected factorization, but small lever arm and relatively large uncertainties
  - GPD models cannot reproduce $\rho^0$ data at small $W$

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$\pi^+$


$K^+$


$\rho^0$

$Q^2=3.8\text{ GeV}^2$

GK (full)  
GK (sea and gluons)  
VGG (valence and sea)  
GK (valence)

Here, compare with P. Kroll’s GPD model (circles=$\sigma_L$, diamonds=$\sigma_T$)

- Solid symbols are data
  - $\sigma_L$ is comparable to $\sigma_T$ at $Q^2=2.4$ GeV$^2$

- Open symbols model calculations
  - Model overpredicts $\sigma_T$
  - Model underpredicts $\sigma_L$

- Separated cross section data over a large range in $Q^2$ are essential for:
  - Testing factorization and understanding dynamical effects in both $Q^2$ and $-t$ kinematics
  - Interpretation of non-perturbative contributions in experimentally accessible kinematics
Setting the stage for EIC – pion production

JLab12: confirming potential for nucleon structure studies

- **E12-07-105 (P12):** Measure the $Q^2$ dependence of the $\pi$ electro production cross section at fixed $x$ and $-t$
  - Factorisation theorem predicts $\sigma_L$ scales to leading order as $Q^{-6}$

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$-t$ (GeV/c$^2$)</th>
</tr>
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<tbody>
<tr>
<td>0.3</td>
<td>1.5-2.7</td>
<td>2.0-2.6</td>
<td>0.1</td>
</tr>
<tr>
<td>0.4</td>
<td>2.1-6.0</td>
<td>2.0-3.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>3.9-8.5</td>
<td>2.0-2.8</td>
<td>0.5</td>
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</tbody>
</table>

Considered for running in 2020+
Setting the stage for EIC – kaon production

- **E12-09-011 (KAONLT):** Separated L/T/LT/TT cross section over a wide range of $Q^2$ and $t$

  *E12-09-011 spokespersons: T. Horn, G. Huber, P. Markowitz*

### JLab 12 GeV Kaon Program features:
- First cross section data for $Q^2$ scaling tests with kaons
- Highest $Q^2$ for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above $W=2.2$ GeV

#### Now running in Hall C at Jlab (2018/19)

<table>
<thead>
<tr>
<th>$x$</th>
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<th>$-t$ (GeV/c)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.2</td>
<td>0.4-3.0</td>
<td>2.5-3.1</td>
<td>0.06-0.2</td>
</tr>
<tr>
<td>0.25</td>
<td>1.7-3.5</td>
<td>2.5-3.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.40</td>
<td>3.0-5.5</td>
<td>2.3-3.0</td>
<td>0.5</td>
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[blue points from M. Carmignotto, PhD thesis (2017)]
Transverse Contributions may allow for probing a new set of GPDs

- 4 Chiral-odd GPDs (parton helicity flip)
- A large transverse cross section in meson production may allow for accessing helicity flip GPDs

- Model predictions based on handbag in good agreement with 6 GeV data
  - [Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A45, 112 (2011)]
  - [Ahmad, Goldstein, Liuti, PRD 79 (2009)]

- Exclusive $\pi^0$ data may also be helpful for constraining non-pole contributions in $F_\pi$ extraction

\[ \tilde{H}_\pi = \frac{1}{3\sqrt{2}} [2\tilde{H}_u + \tilde{H}_d] \]

\[ \sigma_T = \frac{4\pi\alpha_e}{2\kappa} \frac{\mu^2}{Q^4} \left[ (1 - \xi^2) |<HT>|^2 - \frac{t'}{8m^2} |<E_T>|^2 \right] \]
Setting the stage for EIC – $\pi^0$ production

- Relative L/T contribution to $\pi^0$ cross section important in probing transversity – verify reaction mechanism
  - If $\sigma_T$ large: access to transversity GPDs
- Results from Hall A suggest that $\sigma_L$ in $\pi^0$ production is non-zero up to $Q^2=2$ GeV$^2$
- Need to understand $Q^2/t$ dependence for final conclusion on dominance of $\sigma_T$

M. Defurne et al, PRL 117 (2016) no.26, 262001

**E12-13-010** will provide essential data on $\sigma_T$ and $\sigma_L$ at higher $Q^2$ for reliable interpretation of 12 GeV GPD data
EIC: Quark Imaging through Meson Production

Physics interest

- Transverse imaging of nonperturbative sea quarks and gluons
- Information about meson wave function: spin/flavor structure

Mesons select definite charge, spin, flavor component of GPD

- $J/\psi, \phi$ - gluon
- $\rho^0$ - gluon + singlet $q$
- $\rho^+, K^*$ - non-singlet $q$
- $\pi, K, \eta$ - non-singlet $\Delta q$

Exclusive meson production

\[ \gamma^* N \rightarrow M + B \]

- Requires $Q^2 \sim 10\text{GeV}^2$ for dominance of “pointlike” configurations $\rightarrow$ pQCD
EIC: Gluon Imaging with $J/\psi$

- Transverse spatial distributions from exclusive $J/\psi$, and $\phi$ at $Q^2 > 10$ GeV$^2$
  - Transverse distribution directly from $\Delta_T$ dependence
  - Reaction mechanism, QCD description studied at HERA

- Physics interest
  - Valence gluons, dynamical origin
  - Chiral dynamics at $b \approx 1/M_\pi$
    - [Strikman, Weiss 03/09, Miller 07]
  - Diffusion in QCD radiation

- Existing data
  - Transverse area $x < 0.01$ [HERA]
  - Larger $x$ poorly known [FNAL]
Gluon Imaging: Valence Gluons

- Transverse imaging of valence gluons through exclusive J/ψ, φ

- Imaging requires
  - Full t-distribution for Fourier transform
  - Non-exponential? Power-like at |t|>1 GeV²?
  - Electroproduction with Q²>10 GeV²: test reaction mechanism, compare different channels, control systematics

- Experimentally need:
  - Recoil detection for exclusivity, wide coverage in t with high resolution
  - Luminosity ~ 10^{34}, electroproduction, high-t

First gluon images of the nucleon at large x!

Hyde, Weiss '09
Gluon imaging: gluon vs. singlet quark size

- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA: $\text{Area}(q + \bar{q}) > \text{Area}(g)$
  - Dynamical models predict difference: pion cloud, constituent quark picture
    [Strikman, Weiss 09]
  - No difference assumed in present pp MC generators for LHC!

- EIC: gluon size from $J/\psi$, singlet quark size from DVCS
  - $x$-dependence: quark vs. gluon diffusion in wave function
  - Detailed analysis: LO $\rightarrow$ NLO [Mueller et al.]

Detailed differential image of nucleon’s partonic structure

Sandacz, Hyde, Weiss
Spatial structure of non-perturbative sea
- Closely related to JLab 12 GeV
  o Quark spin/flavor separations
  o Nucleon/meson structure

Simulation for $\pi^+$ production assuming 100 fb$^{-1}$ of e-p with 5(e$^-$) on 50(p) GeV ($s=1000$ GeV$^2$)
- V. Guzey, C. Weiss: Regge model
- T. Horn: empirical $\pi^+$ parameterization

Proton energies of 50-100 GeV have advantage to ensure exclusivity

(Deep) exclusive pion electroproduction at EIC can reach up to $Q^2$~50 GeV$^2$ assuming 100 fb$^{-1}$ of e-p (roughly one year of running at $10^{34}$ luminosity)
EIC: Transverse *strange* sea quark imaging

- Do strange and non-strange sea quarks have the same spatial distribution?
  - $\pi N$ or $K\Lambda$ components in nucleon
  - QCD vacuum fluctuations
  - Nucleon/meson structure

- Rate estimate for $K\Lambda$ using an empirical fit to kaon electroproduction data from DESY and JLab assuming 100 fb$^{-1}$ of e-p with 5(e$^-$) on 50(p) GeV

- Proton energies of 50-100 GeV have advantage to ensure exclusivity

Exclusive kaon electroproduction at EIC can reach up to $Q^2 \sim 30$ GeV$^2$
(assuming 100 fb$^{-1}$, roughly one year running at $10^{34}$ luminosity)

Pushes **luminosity towards $> 10^{34}$**, also at lower energy
Transverse polarization example

- Deformation of transverse distribution by transverse polarization of nucleon
  - Helicity flip GPD $E$, cf. Pauli ff

- EIC: exclusive $\rho$ and $\varphi$ production with transversely polarized beam
  - Excellent statistics at $Q^2>10$ GeV$^2$
  - Transverse polarization natural for collider

\[
\frac{\sigma \uparrow - \sigma \downarrow}{\sigma \uparrow + \sigma \downarrow} \propto \frac{\text{Im}(\mathcal{H}E^*)}{|\mathcal{H}|^2 + \text{corr}}.
\]

Horn, Weiss ‘09
EIC – Versatility and Luminosity is Key

Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?


- $L_{\text{EIC}} = 10^{34} = 1000 \times L_{\text{HERA}}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly $10^{-3}$ for a small $-t$ bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for $-t < 0.6$ (0.9) GeV2, we gain at least a decade as compared to HERA/COMPASS.
Beyond transverse imaging

- Longitudinal correlations in nucleon
  - GPDs at $x' \neq x$: correlated qqbar pairs in nucleon
    - QCD vacuum structure, relativistic nature of nucleon
  - EIC: reveal correlations through exclusive meson, $\gamma$ at $x > 0.1$, $Q^2$ dependence

  ...needs kinematic coverage way beyond JLab 12 GeV

- Orbital motion of quarks/gluons
  - TMD and orbital motion from SIDIS
    - Major component of the EIC program
  - Connection with GPDs
    - Unintegrated distributions, Ji sum rule

  ...should be discussed together
Summary

- Meson form factor measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD
  - Pion and kaon form factor extractions up to high $Q^2$ possible ($\sim 9$ and $\sim 6 \text{ GeV}^2$)
  - Pion form factor measurement at EIC looks feasible, can one also measure the kaon form factor?

- Beyond 12 GeV, EIC provides interesting opportunities to map pion and kaon structure functions over a large $(x, Q^2)$ landscape – White Paper in progress…
  - Access to pion/kaon structure functions at EIC looks feasible
  - Can one probe the pion GPD at EIC?

- Exclusive meson production data play an important role in quark and gluon imaging studies
  - L/T separated cross sections essential for transverse nucleon structure studies – may allow for accessing new type of GPDs
  - Synergy with theory/lattice essential for data interpretation – are we ready?
EIC: Exclusive Meson Production Perspectives

- **Energies**
  - More symmetric energies favorable, 5 on 50 seems to be a sweet spot for exclusive meson production
  - Lower energies essential for $\varepsilon$ range in pseudoscalar L/T separations (pion form factor)

- **Kinematic reach**
  - Need $Q^2$>10 GeV\(^2\) (pointlike configurations)
  - $x$ range between 0.001 and 0.1 overlapping with HERA and JLab 12 GeV
  - $s$-range between 200 and 1000 GeV\(^2\)

- **Luminosity**
  - Non-diffractive processes (exclusive $\pi$ and $K$ production) require high luminosity for low rates, differential measurements in $x$, $t$, $Q^2$
  - Kaons push luminosity $>$10\(^{34}\)

- **Detection**
  - Recoil detection for exclusivity, $t$-range
JLab 12 GeV: Kaons from 2018 Data!