Meson Structure with Dilepton Production

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

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In collaboration with Wen-Chen Chang and Stephane Platchkov
Outline

- Overview of Drell-Yan experiments with meson beams
- What have we learned from these experiments
- What we would like to learn in the future
- Summary and outlook
First Dimuon Experiment

\[ p + U \rightarrow \mu^+ + \mu^- + X \quad 29 \text{ GeV proton} \]

Lederman et al. PRL 25 (1970) 1523

Experiment originally designed to search for neutral weak boson (\(Z^0\))

Missed the J/\(\Psi\) signal!

“Discovered” the Drell-Yan process
The Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES *

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

\[ p + \bar{p} \rightarrow (\mu^+ \mu^-) + \cdots. \] (1)

Our remarks apply equally to any colliding pair such as \((pp), (\bar{p}p), (\pi p), (\gamma p)\) and to final leptons \((\mu^+ \mu^-), (e\bar{e}), (\mu \nu), \text{and} (e\nu)\).

(4) The full range of processes of the type (1) with incident \(p, \bar{p}, \pi, K, \gamma, \text{etc.}, \) affords the interesting possibility of comparing their parton and antiparton structures.
## List of Drell-Yan experiments with $\pi^-$ beam

### Experiments at CERN and Fermilab

<table>
<thead>
<tr>
<th>Exp</th>
<th>$P$ (GeV)</th>
<th>targets</th>
<th>Number of D-Y events</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA11</td>
<td>175</td>
<td>Be</td>
<td>500 (semi-exclusive)</td>
</tr>
<tr>
<td>WA39</td>
<td>40</td>
<td>W ($H_2$)</td>
<td>3839 (all beam, $M &gt; 2$ GeV)</td>
</tr>
<tr>
<td>NA3</td>
<td>150, 200, 280</td>
<td>Pt ($H_2$)</td>
<td>21600, 4970, 20000 (535, 121, 741)</td>
</tr>
<tr>
<td>NA10</td>
<td>140, 194, 286</td>
<td>W ($D_2$)</td>
<td>$\sim$84400, $\sim$150000, $\sim$45900 (3200, --, 7800)</td>
</tr>
<tr>
<td>E331/E444</td>
<td>225</td>
<td>C, Cu, W</td>
<td>500</td>
</tr>
<tr>
<td>E326</td>
<td>225</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>E615</td>
<td>80, 252</td>
<td>W</td>
<td>4060, $\sim$50000</td>
</tr>
</tbody>
</table>

- Relatively pure $\pi^-$ beam
- Relatively large cross section due to $\bar{u}d$ contents in $\pi^-$
### List of Drell-Yan experiments with $\pi^+$ beam

<table>
<thead>
<tr>
<th>Exp</th>
<th>P (GeV)</th>
<th>targets</th>
<th>D-Y events</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA39</td>
<td>40</td>
<td>W (H₂)</td>
<td></td>
</tr>
<tr>
<td>NA3</td>
<td>200</td>
<td>Pt (H₂)</td>
<td>1750 (40)</td>
</tr>
<tr>
<td>E331/E444</td>
<td>225</td>
<td>C, Cu, W</td>
<td></td>
</tr>
</tbody>
</table>

- Require beam particle identification to reject large proton content
- Smaller DY cross section due to $\bar{d}u$ contents in $\pi^+$
- Very few DY data with $\pi^+$ beam
## Drell-Yan experiments with $K^-$ beam

<table>
<thead>
<tr>
<th>Exp</th>
<th>$P$ (GeV)</th>
<th>targets</th>
<th>D-Y events</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA39</td>
<td>40</td>
<td>W ($H_2$)</td>
<td></td>
</tr>
<tr>
<td>NA3</td>
<td>150, 200</td>
<td>Pt</td>
<td>688, 90</td>
</tr>
</tbody>
</table>

## Drell-Yan experiments with $K^+$ beam

<table>
<thead>
<tr>
<th>Exp</th>
<th>$P$ (GeV)</th>
<th>targets</th>
<th>D-Y events</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA39</td>
<td>40</td>
<td>W ($H_2$)</td>
<td></td>
</tr>
<tr>
<td>NA3</td>
<td>200</td>
<td>Pt</td>
<td>170</td>
</tr>
</tbody>
</table>

## Drell-Yan experiments with $\bar{p}$ beam

<table>
<thead>
<tr>
<th>Exp</th>
<th>$P$ (GeV)</th>
<th>targets</th>
<th>D-Y events</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA39</td>
<td>40</td>
<td>W ($H_2$)</td>
<td></td>
</tr>
<tr>
<td>NA3</td>
<td>150, 200</td>
<td>Pt</td>
<td>275, 32</td>
</tr>
<tr>
<td>E537</td>
<td>125</td>
<td>W, Cu, Be</td>
<td>380</td>
</tr>
</tbody>
</table>
Ratio of \((\pi^- + A) / (p + A)\) Drell-Yan cross sections

\[
R = \frac{(d^2 \sigma_{DY} / dMdy)^{\pi+N}}{(d^2 \sigma_{DY} / dMdy)^{p+N}}
\]

\[
\approx \frac{4\bar{u}_\pi(x_1)u_N(x_2) + d_\pi(x_1)d_N(x_2)}{4u_p(x_1)\bar{u}_N(x_2) + d_p(x_1)d_N(x_2)}
\]

\[
\approx \left(\frac{\bar{u}_\pi(x_1)}{u_p(x_1)}\right)\left(\frac{u_N(x_2)}{\bar{u}_N(x_2)}\right)
\]

Black: valence

Red: sea

Rapid rise in \(R\) at large \(M\) reflects the rise in valence/sea ratio as \(x\) increases:

\[
\frac{u_N(x_2)}{\bar{u}_N(x_2)}
\]

From E331/E444
Ratios of \((\pi^+ + C) / (\pi^- + C)\) Drell-Yan cross sections

\[ R = \frac{\sigma_{DY}(\pi^+ + C)}{\sigma_{DY}(\pi^- + C)} \]

\[ \simeq \frac{V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)} = \frac{A + B}{4A + B} \]

\[ 1/4 \leq R \leq 1 \]
$(\pi^- + W)$ versus $(\bar{p} + W)$ Drell-Yan cross sections

Valence quark $x$-distribution in pion is broader than that in antiproton (proton)

E537, 125 GeV
How to determine the valence quark distribution in pion?

Compare \((\pi^- + D)\) with \((\pi^+ + D)\) Drell-Yan cross sections

\[
\sigma_{DY}(\pi^- + D) \propto 4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)
\]

\[
\sigma_{DY}(\pi^+ + D) \propto V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)
\]

\[
\sigma_{DY}(\pi^- + D) - \sigma_{DY}(\pi^+ + D) \propto 3V_\pi(x_1)V_N(x_2)
\]

Only the valence-quark term remain!

Only very low statistics data for \(\sigma_{DY}(\pi^+ + D)\) are available!

See Londergan et al., PL B361 (1995) 110
How to determine the valence quark distribution in kaon?

Compare \((K^- + D)\) with \((K^+ + D)\) Drell-Yan cross sections

\[
\sigma_{DY}(K^- + D) \propto 4V^u_K(x_1) V^u_N(x_2) + 4V^u_K(x_1) S^u_N(x_2) + V^s_K(x_1) \bar{S}^u_N(x_2) \\
+ 5S^s_K(x_1) V^u_N(x_2) + 10S^s_K(x_1) S^u_N(x_2) + 2S^s_K(x_1) \bar{S}^u_N(x_2)
\]

\[
\sigma_{DY}(K^+ + D) \propto 4V^u_K(x_1) S^u_N(x_2) + V^s_K(x_1) \bar{S}^u_N(x_2) \\
+ 5S^s_K(x_1) V^u_N(x_2) + 10S^s_K(x_1) S^u_N(x_2) + 2S^s_K(x_1) \bar{S}^u_N(x_2)
\]

\[
\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V^u_K(x_1) V^u_N(x_2)
\]

Only the valence-quark term remain!

\(\sigma_{DY}(K^+ + D)\) is more sensitive to kaon's sea-quark content than \(\sigma_{DY}(K^- + D)\)

(eespecially data at low \(x_1\) and large \(x_2\) (negative \(x_F\)) region!)

See Londergan al., PL B380 (1996) 393
Attempts to extract the pion valence quark distribution

\[ F^{\pi}(x) = 0.72x^{0.5}(1-x)^{0.46} \]

\[ F^{\pi}(x) = 0.90x^{0.5}(1-x)^{1.27} \]

\[ F^{\pi}(x) = 2.43x^{0.5}(1-x)^{1.57} \]

\[ F^{\pi}(x) = Ax^{0.45}(1-x)^{1.17} \]
Attempts to extract the pion valence quark distribution

$$F_\pi(x) = Ax^{0.442}(1-x)^{1.248}$$

$$F_\pi(x) = Ax^{0.6}(1-x)^{1.26}$$

A global fit to all data is needed
Four pion PDF sets available at LHAPDF library

- **OW-P (PRD 30, 943 (1984))**
  - LO QCD
  - $J/\Psi$ data from NA3 and WA39; D-Y data from E537 and NA3
Four pion PDF sets available at LHAPDF library

- **SMRS** (PR D45, 2349 (1992))
  - NLO QCD
  - NA10 and E615 D-Y data,
    WA70 direct photon data

- Need new global fits to all existing data
- Need new experimental data with pion and kaon beams
Kaon PDF from $(K^- + D) / (\pi^- + D)$ Drell-Yan ratios

From NA3; 150 GeV, Pt target

\[ R = \frac{\sigma_{DY}(K^- + D)}{\sigma_{DY}(\pi^- + D)} \]

\[ \approx \frac{4V^u_K(x_1)V_N(x_2) + 4V^u_K(x_1)S_N(x_2) + V^s_K(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \]

\[ R \approx (1 - x)^{0.18 \pm 0.07} \Rightarrow \text{softer } u\text{-valence in kaon than in pion} \]
Comparison between data and theory

- **Nambu-Jona-Lasinio model**

- **Dyson-Schwinger Equation**
$(K^- + \text{Pt}) / (\pi^- + \text{Pt})$ ratios for $J/\Psi$ production

From NA3; 150 GeV, Pt target

Ratios for D-Y

Ratios for $J/\Psi$

Similar behavior at large $x_F$ for D-Y and $J/\Psi$ production?
Comparison between data and CEM calculations

\[(K^- + Pt) / (\pi^- + Pt)\] ratios for J/Ψ production

same pdf for \(K^-\) and \(\pi^-\)

modified pdf for \(K^-\)

Modified kaon PDF has the u\(\bar{u}\) valence quark distribution multiplied by \((1-x)^{0.18}\) and the strange quark distribution divided by \((1-x)^{0.18}\)

The \(K / \pi\) ratios of J/Ψ production at large \(x_F\) might indicate a softer \(\bar{u}\) in \(K^-\) than in the pion, similar to the D-Y data?
Dilepton data with meson beams at COMPASS

- Drell-Yan data from 2015: 4.3 – 8.5 GeV/c²

190 GeV π⁻ beam

See talks of M. Perdekamp and W.C. Chang

- Prospect of RF-separated kaon and antiproton beams in the future
Three proton parton distributions describing transverse momentum and/or transverse spin

1) Transversity

Three transverse quantities:

1) Nucleon transverse spin
   \( \vec{S}_N^\perp \)

2) Quark transverse spin
   \( \vec{S}_q^\perp \)

3) Quark transverse momentum
   \( \vec{k}_q^\perp \)

\( \Rightarrow \) Three different correlations

2) Sivers function

Correlation between \( \vec{s}_q^\perp \) and \( \vec{S}_N^\perp \)

3) Boer-Mulders function

Correlation between \( \vec{s}_q^\perp \) and \( \vec{k}_q^\perp \)
One pion parton distribution describing transverse momentum and transverse spin

Two transverse quantities:
1) Quark transverse spin
   \[ \vec{s}_q^\perp \]
2) Quark transverse momentum
   \[ \vec{k}_q^\perp \]
⇒ One correlation

1) Boer-Mulders function

Correlation between \( \vec{s}_q^\perp \) and \( \vec{k}_q^\perp \)
It can be measured in Drell-Yan process

Boer-Mulders functions:

- Unpolarized Drell-Yan:

\[ d\sigma_{DY} \propto h_1^\perp(x_q)h_1^\perp(x_{\bar{q}})\cos(2\phi) \]

- Drell-Yan does not require knowledge of the fragmentation functions

- T-odd TMDs are predicted to change sign from DIS to DY

(Boer-Mulders and Sivers functions)

Remains to be tested experimentally!
Boer-Mulders function $h_1^\perp$

- $h_1^\perp$ represents a correlation between quark's $k_T$ and transverse spin in an unpolarized hadron (analogous to Collins function)
- $h_1^\perp$ is a time-reversal odd, chiral-odd TMD parton distribution
- $h_1^\perp$ can lead to an azimuthal dependence with $\nu \propto \left( \frac{h_1^\perp}{f_1} \right) \left( \frac{\bar{h}_1^\perp}{\bar{f}_1} \right)$

$$h_1^\perp(x, k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16 \kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

$\kappa_1 = 0.47$, $M_C = 2.3$ GeV

$\nu > 0$ implies valence BM functions for pion and nucleon have same signs

Boer, PRD 60 (1999) 014012
Can one test the predicted sign-change from DIS to D-Y for pion’s B-M function?

1) From NA10 pion Drell-Yan data, one deduces that the product of the pion valence quark B-M function and the proton valence quark B-M function is positive. Using $u$-quark dominance, we have:

$$h_{1,u}^{\perp,DY}(p) \cdot h_{1,u}^{\perp,DY}(\pi) > 0$$

Therefore, either

a) $h_{1,u}^{\perp,DY}(p) > 0; h_{1,u}^{\perp,DY}(\pi) > 0$ (sign – change)

or

b) $h_{1,u}^{\perp,DY}(p) < 0; h_{1,u}^{\perp,DY}(\pi) < 0$ (no sign – change)

2) In polarized $\pi – p$ D-Y, the $\sin(\phi + \phi_S)$ modulation is sensitive to the sign of $h_{1,u}^{\perp,DY}(\pi)$ (being measured at COMPASS)

3) Need to measure the sign of pion's B-M function in DIS

HOW?
SIDIS on the meson cloud of proton at EIC

**TSIDIS (Tagged Semi-Inclusive DIS)**

**TSIDIS**

\[ e^- + p \rightarrow e^-' + n + \pi^\pm + x \]

underlying process:

\[ e^- + \pi^+ \rightarrow e^-' + \pi^\pm + x \]

1) An independent check of pion's PDF

2) Could allow valence-sea flavor separation

- Detected \( \pi^- \) is most likely from \( \bar{u} \) (or \( d \)) sea in \( \pi^+ \)
- Detected \( \pi^+ \) is most likely from valence \( u \) (or \( \bar{d} \)) in \( \pi^+ \)

3) Pion B-M function is extracted from \( \cos 2\phi \) modulation
Exclusive dilepton production in $\pi N$ interaction

$$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$$


Probe pion distribution amplitude ($\phi_\pi$) and nucleon GPD ($\tilde{H}, \tilde{E}$)

**Bjorken variable**

$$\tau = \frac{Q'^2}{s-M^2}$$

**Skewness**

$$\eta = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$$

\[
\frac{d\sigma}{dQ'^2 \ dt \ d(\cos \theta) \ d\varphi} = \frac{\alpha_{em}}{256 \pi^3} \frac{\tau^2}{Q'^6} \sum_{\lambda', \lambda} |M_{0\lambda', \lambda}|^2 \sin^2 \theta
\]

\[
M_{0\lambda', \lambda}(\pi^- p \to \gamma^* n) = -ie \frac{4\pi}{3} \frac{f_\pi}{Q'} \frac{1}{(p+p')^+} \bar{u}(p', \lambda') \left[ \gamma^+ \gamma_5 \tilde{H}^{du}(\eta, t) + \gamma_5 \frac{(p'-p)^+}{2M} \tilde{E}^{du}(\eta, t) \right] u(p, \lambda)
\]

\[
\tilde{H}^{du}(\eta, t) = \frac{8\alpha_s}{3} \int_{-1}^{1} dz \frac{\phi_{\pi}(z)}{1-z^2} \int_{-1}^{1} dx \left[ \frac{e_d}{-\eta-x-i\varepsilon} - \frac{e_u}{-\eta+x-i\varepsilon} \right] \left[ \tilde{H}^d(x, \eta, t) - \tilde{H}^u(x, \eta, t) \right]
\]
Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC

Summary

- Meson and Kaon parton distributions
  - New territory for theory and experiment
  - Unique opportunity at COMPASS
  - Complementary to JLab/EIC tagged DIS programs
- Pion's TMD (Boer-Mulders function)
  - Test sign-change prediction for pion B-M function
- Exclusive Drell-Yan with $\pi^-$ and $K^-$ beams
  - Probe pion and kaon distribution amplitudes
  - First measurement seems feasible at J-PARC