Exploring Large-x Phase Space Boundaries at the EIC

Christopher Dilks

Workshop on TMD Studies from JLab to EIC

May 2021
\[ d^6\sigma = \frac{4\pi\alpha^2 s x}{Q^4} \times \]

\[
\begin{align*}
\{ & [1 + (1 - y)^2] \sum_{q,\bar{q}} e_q^2 f_q^u(x) D_i^q(z, P_{h1}^2) \\
+ & (1 - y) \frac{P_{h1}^2}{4\pi M_N M_h} \cos(2\phi'_0) \sum_{q,\bar{q}} e_q^2 h_{1/1}^{1/1}(x) H_i^{1/1}(z, P_{h1}^2) \} \\
\end{align*}
\]

\[
\begin{align*}
& - |S_1| (1 - y) \frac{P_{h1}^2}{4\pi M_N M_h} \sin(2\phi'_0) \sum_{q,\bar{q}} e_q^2 h_{1/1}^{1/1}(x) H_i^{1/1}(z, P_{h1}^2) \\
+ & |S_T| (1 - y) \frac{P_{h1}^2}{2M_h} \sin(\phi'_0 + \phi'_1) \sum_{q,\bar{q}} e_q^2 f_i^{1/1}(x) D_i^{1/1}(z, P_{h1}^2) \\
+ & |S_T| (1 - y - \frac{1}{2} y^2) \frac{P_{h1}^2}{M_N} \sin(\phi'_0 - \phi'_1) \sum_{q,\bar{q}} e_q^2 f_i^{1/1}(x) D_i^{1/1}(z, P_{h1}^2) \\
+ & |S_T| (1 - y) \frac{P_{h1}^2}{6\pi M_N M_h} \sin(3\phi'_0 - \phi'_1) \sum_{q,\bar{q}} e_q^2 h_{1/1}^{1/1}(x) H_i^{1/1}(z, P_{h1}^2) \\
+ & \lambda_e |S_2| (1 - y) \frac{P_{h1}^2}{M_N} \sum_{q,\bar{q}} e_q^2 g_i^{1/1}(x) D_i^{1/1}(z, P_{h1}^2) \\
+ & \lambda_e |S_T| (1 - y - \frac{1}{2} y) \frac{P_{h1}^2}{2M_h} \cos(\phi'_0 - \phi'_1) \sum_{q,\bar{q}} e_q^2 g_i^{1/1}(x) D_i^{1/1}(z, P_{h1}^2) \}
\end{align*}
\]

\[
S_1 \text{ and } S_T: \text{Target Polarizations; } \lambda_e: \text{Beam Polarization} \\
x: \text{momentum fraction carried by struck quark, } z: \text{fractional energy of hadron}
\]
TMD PDFs

- Boer-Mulders $t_1^B$
- Worm Gear $t_1^L$
- Transversity $t_T$
- Sivers $t_T^*$
- Pretzelosity $S_L$
- Worm Gear $S_T$

$S_L$ and $S_T$: Target Polarizations; $\lambda e$: Beam Polarization

$x$: momentum fraction carried by struck quark, $z$: fractional energy of hadron
TMD PDFs

Boer-Mulders $h^L_1$ - (1) - (2)
Worm Gear $h^R_L$ - (2) - (3)
Transversity $h^L_T$ - (1) - (2)
Sivers $h^L_\parallel$ - (1) - (3)
Pretzelosity $h^L_T$ - (2) - (3)
Worm Gear $h^L_T$ - (3) - (3)

$xh_1(x)$ - (1) - (2)

$-f_{1T;u\leftrightarrow p}[2\text{GeV}]$

$0.25$ $0.5$ $0.75$ $1.0$

$0.1$ $0.5$ $1.0$

$x \rightarrow 5 \cdot 10^{-3}$

$5 \cdot 10^{-2}$

$k_T[\text{GeV}]$

$S_L$ and $S_T$: Target Polarizations; $\lambda e$: Beam Polarization

$x$: momentum fraction carried by struck quark, $z$: fractional energy

C. Dilks
SIDIS Kinematic Coverage for Sivers and Collins

Current data for Collins and Sivers asymmetry:

- COMPASS $h_\perp^2; P_{hT} < 1.6$ GeV/c
- HERMES $\pi^0, K^0; P_{hT} < 1$ GeV/c
- JLab Hall-A $\pi^0; P_{hT} < 0.45$ GeV/c
- JLab 12
- STAR 500 GeV $-1 < \eta < 1$ Collins
- STAR 200 GeV $-1 < \eta < 1$ Collins
- STAR 500 GeV $1 < \eta < 4$ Collins
- STAR 200 GeV $1 < \eta < 4$ Collins
- STAR W bosons

EIC $\sqrt{s} = 140$ GeV, $0.01 \leq y \leq 0.95$
EIC $\sqrt{s} = 20$ GeV, $0.01 \leq y \leq 0.95$
Goal: measure asymmetries at large $x \sim 10^{-1}$

Could go to large $Q^2$, but asymmetry may decrease as $Q^2$ increases; very high $Q^2$ would push above PID limits

What are the limitations at small $Q^2$, large $x$?

Ideal situation: $(x,Q^2)$-overlap data from JLab to EIC, but what do we need to do to get there?
proton direction → electron direction
Limited by minimum y

Large x
Small $Q^2$
SIDIS Kinematic Coverage for Sivers and Collins

Current data for Collins and Sivers asymmetry:

- COMPASS $h_1^$: $P_{hT} < 1.6$ GeV/c
- HERMES $\pi^0$, $K^\pm$: $P_{hT} < 1$ GeV/c
- JLab Hall-A $\pi^0$: $P_{hT} < 0.45$ GeV/c
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- STAR 500 GeV -1 < $\eta$ < 1 Collins
- STAR 200 GeV -1 < $\eta$ < 1 Collins
- STAR 500 GeV 1 < $\eta$ < 4 Collins
- STAR 200 GeV 1 < $\eta$ < 4 Collins
- STAR W bosons

$Q^2$ (GeV$^2$)

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$10^{-6}$

$x$

EIC $\sqrt{s} = 140$ GeV, $0.01 \leq y \leq 0.95$

EIC $\sqrt{s} = 20$ GeV, $0.01 \leq y \leq 0.95$
SIDIS Kinematic Coverage for Sivers and Collins

Current data for Collins and Sivers asymmetry:

- COMPASS h^-; P_{T} < 1.6 GeV/c
- HERMES π^±; K^±; P_{T} < 1 GeV/c
- JLab Hall-A π^±; P_{T} < 0.45 GeV/c
- JLab 12
- STAR 500 GeV -1 < η < 1 Collins
- STAR 200 GeV -1 < η < 1 Collins
- STAR 500 GeV 1 < η < 4 Collins
- STAR 200 GeV 1 < η < 4 Collins
- STAR W bosons

EIC √s = 140 GeV, 0.01 ≤ y ≤ 0.95
EIC √s = 20 GeV, 0.01 ≤ y ≤ 0.95

y contours 5 x 41
√s = 28.65
y = 0.01
SIDIS Kinematic Coverage for Sivers and Collins

Current data for Collins and Sivers asymmetry:

- COMPASS $h_{1T}^-, P_{hT} < 1.6 \text{ GeV/c}$
- HERMES $p_{1T}^0, K^0, P_{hT} < 1 \text{ GeV/c}$
- JLab Hall-A $\pi^0, P_{hT} < 0.45 \text{ GeV/c}$
- JLab 12
- STAR 500 GeV $-1 < \eta < 1 \text{ Collins}$
- STAR 200 GeV $-1 < \eta < 1 \text{ Collins}$
- STAR 500 GeV $1 < \eta < 4 \text{ Collins}$
- STAR 200 GeV $1 < \eta < 4 \text{ Collins}$
- STAR W bosons

$y$ contours

$$y = 0.01$$
$$y = 0.03$$

$\sqrt{s} = 28.65$

$5 \times 41$
SIDIS Kinematic Coverage for Sivers and Collins

Current data for Collins and Sivers asymmetry:

- COMPASS $h_{+}^n$: $P_{hT} < 1.6$ GeV/c
- HERMES $\pi^{0,n}$, $K^{+}$: $P_{hT} < 1$ GeV/c
- JLab Hall-A $\pi^{n}$: $P_{hT} < 0.45$ GeV/c
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- STAR 500 GeV -1 < $\eta$ < 1 Collins
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$y$ contours
5 x 41
$\sqrt{s} = 28.65$

$y = 0.05$
$y = 0.03$
$y = 0.01$
SIDIS Kinematic Coverage for Sivers and Collins

Current data for Collins and Sivers asymmetry:

- **COMPASS** \( h^z; P_{ht} < 1.6 \text{ GeV/c} \)
- **HERMES** \( \pi^0, K^0; P_{ht} < 1 \text{ GeV/c} \)
- **JLab Hall-A** \( \pi^0; P_{ht} < 0.45 \text{ GeV/c} \)
- **JLab 12**
  - **STAR 500 GeV -1 < \eta < 1** Collins
  - **STAR 200 GeV -1 < \eta < 1** Collins
  - **STAR 500 GeV 1 < \eta < 4** Collins
  - **STAR 200 GeV 1 < \eta < 4** Collins
  - **STAR W bosons**

**y contours**
- 5 x 41
- \( \sqrt{s} = 28.65 \)

**Q^2 (GeV^2)**

**X**

\( EIC/\sqrt{s} = 140 \text{ GeV}, 0.01 \leq y \leq 0.95 \)

\( EIC/\sqrt{s} = 20 \text{ GeV}, 0.01 \leq y \leq 0.95 \)

**JLab 12 GeV**

y=0.05

y=0.03

y=0.01
EIC: study $p_T$ and $Q^2$ dependence of asymmetries in wide kinematic range

Comparisons with JLab, HERMES, and COMPASS, to pin down $p_T$ dependence and evolution

Non-overlapping regions between EIC and JLab could be problematic for evolution studies

Need control over reconstruction at low $y$ and low $p_T$
EIC Coverage Limits

**PID Acceptance Fractions**

| 18 GeV x 275 GeV | 18 GeV x 100 GeV | 10 GeV x 100 GeV | 5 GeV x 100 GeV | 5 GeV x 41 GeV |

**PID Limits**

- $\eta = -1$
  - $p < 6\text{ GeV}$
- $\eta = 1$
  - $p < 50\text{ GeV}$
- $\eta = -3.5$
- $\eta = 3.5$

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EIC Coverage Limits

PID Acceptance Fractions

PID Limits

- $\eta = -3.5$
- $p < 6\,\text{GeV}$
- $p < 7\,\text{GeV}$
- $p < 50\,\text{GeV}$

PID Acceptance Fractions

- 18 GeV x 275 GeV
- 18 GeV x 100 GeV
- 10 GeV x 100 GeV
- 5 GeV x 100 GeV
- 5 GeV x 41 GeV

limited to smaller $p_T$
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**EIC Coverage Limits**

**PID Acceptance Fractions**

- $\eta = -1$
- $p < 6 \text{ GeV}$
- $p < 7 \text{ GeV}$
- $p < 50 \text{ GeV}$
- $\eta = -3.5$

**PID Limits**

- $\eta = 1$

- $y$ contours for 5x41
  - $y = 0.05$
  - $y = 0.03$
  - $y = 0.01$

- $18 \text{ GeV} \times 275 \text{ GeV}$
- $18 \text{ GeV} \times 100 \text{ GeV}$
- $10 \text{ GeV} \times 100 \text{ GeV}$
- $5 \text{ GeV} \times 100 \text{ GeV}$
- $5 \text{ GeV} \times 41 \text{ GeV}$
SIDIS kinematics depends on what is used to reconstruct quantities such as $x$ and $Q^2$

- Scattered electron
- Hadrons
- Some mixture

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**i) Leptonic variables**

$$ q \equiv q_i = k_2 - k_1, \quad y_i = p_1 \cdot (k_1 - k_2) / p_1 \cdot k_1 $$

**ii) Hadronic variables**

$$ q \equiv q_h = p_2 - p_1, \quad y_t = p_1 \cdot (p_2 - p_1) / p_1 \cdot k_1 $$

**iii) Jacquet-Blondel variables**

$$ Q_{JB}^2 = (\vec{p}_{2,\perp})^2 / (1 - y_{JB}), \quad y_{JB} = \Sigma / (2E(k_1)) $$

$$ \Sigma = \sum_i (E_i - p_{i,z}) $$

**iv) Mixed variables**

$$ q = q_i, \quad y_m = y_{JB} $$

**v) Double angle method**

$$ Q_{DA}^2 = \frac{4E(k_2)^2 \cos^2(\theta(k_2)/2)}{\sin^2(\theta(k_2)/2) + \sin(\theta(k_2)/2) \cos(\theta(k_2)/2) \tan(\theta(p_2)/2)}, \quad y_{DA} = 1 - \frac{\sin(\theta(k_2)/2)}{\sin(\theta(k_2)/2) + \cos(\theta(k_2)/2) \tan(\theta(p_2)/2)}; $$

$$ Q_{y\theta}^2 = 4E(k_2)^2 (1 - y_{JB}) \frac{1 + \cos(\theta(k_2))}{1 - \cos(\theta(k_2))}, \quad y_{y\theta} = y_{JB} $$

**vi) $\theta y$ method**

$$ Q_{\Sigma}^2 = \frac{\left(\vec{k}_2, \perp\right)^2}{1 - y_\Sigma}, \quad y_\Sigma = \frac{\Sigma + E(k_2)[1 - \cos(\theta(k_2))]}{s \Sigma} $$

**vii) $\Sigma$ method**

$$ Q_{e\Sigma}^2 = Q_e^2, \quad y_{e\Sigma} = \frac{Q_e^2}{s E_\Sigma} $$

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Mean relative deviation in $z$ $(10\times100)$

### Electron Method

- $y = 0.05$
- $y = 0.01$

### Double Angle Method

- $y = 0.05$
- $y = 0.01$

### JB Method

- $y = 0.05$
- $y = 0.01$

### Mixed Method

- $y = 0.05$
- $y = 0.01$

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A. Vossen, EIC Yellow Report Meeting, June 2020
Mean relative deviation in $p_T$ (10x100)

- **Electron method**
  - $y = 0.05$
  - $y = 0.01$

- **Double angle method**
  - $y = 0.05$
  - $y = 0.01$

- **JB method**
  - $y = 0.05$
  - $y = 0.01$

- **Mixed method**
  - $y = 0.05$
  - $y = 0.01$
### z and $p_T$ Resolutions

#### z resolutions

<table>
<thead>
<tr>
<th>EIC $5 \times 41$</th>
<th>$x$ range</th>
<th>$Q^2$ range (GeV$^2$)</th>
<th>0.0001–0.003</th>
<th>0.003–0.01</th>
<th>0.01–0.03</th>
<th>0.03–0.1</th>
<th>0.1–0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30–100</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.011</td>
<td>0.029</td>
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<tr>
<td></td>
<td></td>
<td>10–30</td>
<td>–</td>
<td>–</td>
<td>0.014</td>
<td>0.021</td>
<td>0.080</td>
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<td></td>
<td></td>
<td>5–10</td>
<td>–</td>
<td>0.017</td>
<td>0.020</td>
<td>0.088</td>
<td>0.17</td>
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<tr>
<td></td>
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<td>3–5</td>
<td>–</td>
<td>0.017</td>
<td>0.044</td>
<td>0.14</td>
<td>0.13</td>
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<tr>
<td></td>
<td></td>
<td>1–3</td>
<td>0.017</td>
<td>0.032</td>
<td>0.11</td>
<td>0.17</td>
<td>–</td>
</tr>
</tbody>
</table>

#### $p_T$ resolutions

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<tr>
<th>EIC $5 \times 41$</th>
<th>$x$ range</th>
<th>$Q^2$ range (GeV$^2$)</th>
<th>0.0001–0.003</th>
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<tr>
<td></td>
<td></td>
<td>30–100</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.030</td>
<td>0.15</td>
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<tr>
<td></td>
<td></td>
<td>10–30</td>
<td>–</td>
<td>–</td>
<td>0.022</td>
<td>0.059</td>
<td>0.24</td>
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<td>5–10</td>
<td>–</td>
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<td>0.040</td>
<td>0.17</td>
<td>0.34</td>
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<tr>
<td></td>
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<td>3–5</td>
<td>–</td>
<td>0.025</td>
<td>0.069</td>
<td>0.21</td>
<td>0.29</td>
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<td>1–3</td>
<td>0.021</td>
<td>0.035</td>
<td>0.11</td>
<td>0.19</td>
<td>–</td>
</tr>
</tbody>
</table>

*kinematics reconstructed from electron

$0.4 \text{GeV} < P_{hT} < 0.6 \text{GeV}$,

$0.4 < z < 0.5$

$0.05 < y < 0.95$

study from Xiaqing Li
### x Resolutions

#### Compare different $y_{\text{min}}$ values

<table>
<thead>
<tr>
<th>$0.01 &lt; y &lt; 0.95$</th>
<th>$x$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2$ range (GeV$^2$)</td>
<td>0.0001–0.01</td>
</tr>
<tr>
<td>10–100</td>
<td>–</td>
</tr>
<tr>
<td>5–10</td>
<td>0.00018</td>
</tr>
<tr>
<td>3–5</td>
<td>0.00039</td>
</tr>
<tr>
<td>1–3</td>
<td>0.00072</td>
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</tbody>
</table>

<table>
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<tr>
<th>$0.05 &lt; y &lt; 0.95$</th>
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<td>10–100</td>
<td>–</td>
</tr>
<tr>
<td>5–10</td>
<td>0.000018</td>
</tr>
<tr>
<td>3–5</td>
<td>0.00039</td>
</tr>
<tr>
<td>1–3</td>
<td>0.00066</td>
</tr>
</tbody>
</table>

*kinematics reconstructed from electron*
Goal: Explore low-y region (large x, small $Q^2$):
Vary minimum y limit, and check impact on $p_T$, $q_T/p_T/z$, and $q_T/Q$

- Event generation: 1M events from pythaeRHIC (6), 5x41 GeV
- Fast simulation: eic-smear (via ESCalate v1.1.0)
- Kinematics reconstruction: highest-E electron

Event Selection Criteria
- $\pi^+\pi^-$ dihadron channel
- $W > 3$ GeV
- $y_{\text{min}} < y < 0.95$ (vary $y_{\text{min}}$)
- $z_{\text{pair}} < 0.95$
- $z_{\text{pion}} > 0.2$ (effectively $z_{\text{pair}} > 0.4$)
- pion $p_{T,\text{lab}} > 100$ MeV (tracking limit)
- pion $x_F > 0$
- $Q^2 > 1$ GeV² (generator level)

Two x bins:
- Small x: $x < 0.05$
- Large x: $x > 0.05$

Two z bins:
- 0.2 < $z$ < 0.3
- 0.3 < $z$ < 1

note: some plots use notation $p_{\text{perp}}$ or $p_\perp$; they denote the same as $p_T$: the component of the pion momentum transverse to q, in the proton rest frame
TMD Region Classification

high $q_T/Q \rightarrow$ collinear

low $q_T/Q \rightarrow$ TMD

$e^{y_{B,b}}, \frac{m}{Q}, \frac{q_T}{Q}$

$e^{-y_{B,b}}, \frac{m}{Q}, \frac{q_T}{Q}$
$Q^2$ vs. $x$ for selected dihadrons

$5 \times 41$ GeV
ep $\rightarrow$ e$\pi^+\pi^-X$
following plots show ratio of $y > y_{\text{min}}$ yield to total yield, for 2 values of $y_{\text{min}}$

$5 \times 41 \text{ GeV}$

$ep \rightarrow e\pi^+\pi^-X$
$y_{\text{min}} = 0.03$

$0.2 < z < 0.3$

$0.3 < z < 1$

low $p_T$ region has relatively larger suppression

correlation between fragmenting particle and spin larger at high $z$, where suppression by $y_{\text{min}}$ is worse
$p_T$ Distributions for varying $y_{\text{min}}$ in 2 bins of $z$

$y_{\text{min}} = 0.05$

$0.2 < z < 0.3$

suppression worse at higher $y_{\text{min}}$, but similar relative trend

$0.3 < z < 1$

note: suppression trends for $q_T$ look similar (see backup slides)
$$y_{\text{min}} = 0.03$$

0.2 < z < 0.3

0.3 < z < 1

high $q_T/Q$ is much more suppressed than low $q_T/Q$
$p_T$ Distributions for varying $y_{\text{min}}$ in 2 bins of $q_T/Q$

$y_{\text{min}} = 0.03$

$q_T/Q < 0.25$

suppression localized to low $p_T$

(see backup slides for comparison with $q_T/Q<1$)

$q_T/Q > 1.0$

suppression worsens as $p_T$ decreases
In high-x bin, as $y_{\text{min}}$ increases, minimum $Q^2$ increases → imparts limits on $q_T/Q$

In low-x bin, minimum $Q^2$ stays at 1 GeV$^2$ for any $y_{\text{min}}$

$Q^2$ vs. $x$ for selected dihadrons
In high-\(x\) bin, as \(y_{\text{min}}\) increases, minimum \(Q^2\) increases → imparts limits on \(q_T/Q\)

Similar story for \(q_T/Q\) vs \(p_T\) correlation (see backup slides)
$y_{\min}$ does not affect boundaries in low-$x$ bin, since minimum $Q^2$ is not affected.
Vector Meson Decays → Muddy the Waters for Interpretation

ep → eπ^+π^−X
ep → e(ρ → π^+π^-)X

- Select ρ → π^+π^- dihadrons, and calculate q_T/Q using the ρ, vs. using the π^+
- Pion q_T/Q~1 could correspond to ρ-meson q_T/Q<<1
- VM decays can confuse TMD region classification
- Trend unaffected by y_{min} cuts

* data not smeared!
Summary

- Interested in TMDs at large x (x>0.05), where spin-orbit correlations are likely relevant
  - Large $Q^2$ may have smaller asymmetries
  - Better to look at small $Q^2$, where electron and hadron are detected at small scattering angles
  - Minimum y restricts phase space at large x and small $Q^2$

- Overlap from JLab to EIC vital for evolution studies, providing a more complete picture
  - Limitations at low-y at the EIC:
    - Smaller $p_T$
    - Poorer resolutions ($z$, $p_T$, x)
  - Increasing minimum y causes:
    - Losses at small $p_T$ and small $q_T$
    - Localized losses at small $p_T$ for $q_T/Q$<0.25
    - Larger losses at large $q_T/Q$ than at small $q_T/Q$
    - Increase minimum $Q^2$ (given x>0.05)

- Vector mesons muddy the waters
  - A pion with large $p_T/z/Q$, considered outside the TMD region, could come from a VM with small $p_T/z/Q$, well within the TMD region
backup
Kinematic Coverage for $y > 0.025$

H. Avakian, REF2020, Dec 9
\( \pi^+ q_T/Q \) vs. \( p_{\text{perp}} \), for Full \( Q^2 \) and \( 0.05 < x < 1 \)

- \( y > 0.01 \)
- \( y > 0.05 \)

Increasing \( Q^2 \) and \( y \)
\( \pi^+ q_T/Q \) vs. \( p_{\text{perp}} \), for Full \( Q^2 \) and \( 0.05 < x < 1 \)

- \( y > 0.03 \) cut applied
- Increasing \( Q^2 \) and \( y \)
$\pi^+ q_T/Q$ vs. $p_{perp}$, for Full $Q^2$ and $0.05<x<1$

- $y>0.05$ cut applied
- $y>0.01$
- $y>0.05$

Increasing $Q^2$ and $y$.
\(\pi^+ q_T/Q\) vs. \(z\), for Full \(Q^2\) and \(0.05 < x < 1\)

\(y > 0.00\) (actually \(y > 0.01\))

\(<q_T/Q>\)

(black points)
$\pi^+ q_T/Q$ vs. $z$, for Full $Q^2$ and $0.05 < x < 1$

$y > 0.03$
$\pi^+ q_T/Q$ vs. $z$, for Full $Q^2$ and $0.05 < x < 1$

$y > 0.05$
Kinematics Reconstruction Methods

Fraction of events staying in bin (10x100)

Jacquet-Blondel Method

Double Angle Method

C. Dilks
Low $Q^2$ and large $x$ kinematics in EIC: $P_T$-distributions

For large $x(x>0.05)$ large $y$ cuts can significantly change $P_T$-distributions
$p_T$ Distributions for varying $y_{\text{min}}$ in 2 bins of $q_T/Q$

$y_{\text{min}} = 0.05$

$q_T/Q < 0.25$

$q_T/Q > 1.0$

suppression worse at higher $y_{\text{min}}$, but similar relative trend
q_T/Q Distributions for varying $y_{\text{min}}$

$y_{\text{min}} = 0.05$

$0.2 < z < 0.3$

$0.3 < z < 1$
$p_T$ Distributions for varying $y_{min}$ in 2 bins of $q_T/Q$

$y_{min} = 0.03$

$q_T/Q < 0.25$

$q_T/Q < 1.0$

C. Dilks
$y_{\text{min}} = 0.05$

$q_T/Q < 0.25$

$q_T/Q < 1.0$
\( q_T \) Distributions for varying \( y_{\text{min}} \) in 2 bins of \( z \)

\( y_{\text{min}} = 0.03 \)

\[ 0.2 < z < 0.3 \]

\[ 0.3 < z < 1 \]

Similarly, low \( q_T \) has larger relative suppression.

C. Dilks
$q_T$ Distributions for varying $y_{\text{min}}$ in 2 bins of $z$

$y_{\text{min}} = 0.05$

$0.2 < z < 0.3$

$0.3 < z < 1$
$0.2 < z < 0.3$

$0.3 < z < 1$

$q_T/Q$ Distributions for varying $y_{\text{min}}$ in 4 quantiles of $Q^2$

$y_{\text{min}} = 0.03$
$q_T/Q$ Distributions for varying $y_{\text{min}}$

$y_{\text{min}} = 0.05$ in 4 quantiles of $Q^2$

$1 < Q^2 < 1.3 \text{ GeV}^2$

$1.3 < Q^2 < 1.9$

$1.9 < Q^2 < 3.5$

$3.5 < Q^2$

$0.2 < z < 0.3$

$0.3 < z < 1$
Vector Meson Decays $\rightarrow$ Muddy Waters for Interpretation

- High-$z$ $\rho \rightarrow$ Small-$z$ Pion
- $p_T$'s are somewhat similar
- High-$q_T$ pion from small-$q_T$ $\rho$
**DIS Electron**

Low $Q^2$

- DIS $e$ mom., $1 < Q^2/GeV^2 < 10$
- All kinematics for $e+p$ 18 GeV on 275 GeV
- All yields for $\int \mathcal{L} dt = 10 \text{ fb}^{-1}$

High $Q^2$

- DIS $e$ mom., $10 < Q^2/GeV^2 < 100$
- DIS $e$ mom., $100 < Q^2/GeV^2 < 10000$

**SIDIS Pion**

Low $x$

- SIDIS $\pi$ mom., $10^{-5} < x < 5 \times 10^{-4}$
- SIDIS $\pi$ mom., $5 \times 10^{-4} < x < 10^{-2}$
- SIDIS $\pi$ mom., $10^{-2} < x < 1$

High $x$