L/T and flavor separation in $\pi^0$ electro-production (Hall A@Jlab)

J. Roche (Ohio U.)

DVCS2

• M. Mazouz et al., “Rosenbluth separation of the $\pi^0$ electro-production off the neutron”, PRL, Feb `17.
• M. Defurne, M. Mazouz et al., “Rosenbluth separation of the $\pi^0$ electro-production”, PRL, Aug `16.

DVCS1


Thesis:

• M. Defurne, U of Paris IV, Jun `15.
• E. Fuchey, Clermont U, Apr `11.
**γ/π⁰ Production: same GPDs??**

\[ γ^* \rightarrow Q^2 \rightarrow γ \]

- **Hard process:** \( x + \xi \)
- **Soft process:** \( x - \xi \)

**Diagram:**
- **Chiral even GPDs:**
  - Helicity of the parton is conserved

<table>
<thead>
<tr>
<th></th>
<th>Nucleon Helicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>unpolarized GPD</td>
<td>( H )</td>
</tr>
<tr>
<td>polarized GPD</td>
<td>( \tilde{H} )</td>
</tr>
</tbody>
</table>

**Table:**
- **Unpolarized GPD:**
  - \( H \)
  - \( E \)
- **Polarized GPD:**
  - \( \tilde{H} \)
  - \( \tilde{E} \)

**Chiral even GPDs:**
- Helicity of the parton is conserved

**Chiral-odd GPDs:**
- (helicity of the parton can flip in the top part of the process)

**Different scaling and additional GPDs**
Hall A/C  DVCS is part of a worldwide program

Timeline

- Pioneering results from non-dedicated experiments (Hall B and Hermes): ~2001
- First round of dedicated experiments (Hall A/B and Hermes): ~ 2005
- Second round of dedicated experiments (Halls A/B): ~2010
- Compelling DVCS program at JLab-12 GeV and Compass: 2014 and later

In the valence region (JLab)

Partially complimentary, overlapping

- Hall A: high accuracy (~5%): limited kinematic
- Hall B: wide kinematic range: limited accuracy (15+%)
The Hall A detector scheme

- Luminosity of $\sim 5 \times 10^{37}$ Hz/cm$^2$
- 208 PbF2 blocks
- 1 GHz digitizer
Trigger with *at least one* cluster in the calo.

Cosmics  
Clock  
Cerenkov  
S2m  
Gate

**DVCS TRIGGER**  
ARS

Triggers if a group of 2*2 blocks is above threshold

<table>
<thead>
<tr>
<th>DVCS3- kin</th>
<th>1 cluster</th>
<th>2 clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>36_1</td>
<td>100</td>
<td>23</td>
</tr>
<tr>
<td>36_2</td>
<td>100</td>
<td>27</td>
</tr>
<tr>
<td>36_3</td>
<td>100</td>
<td>26</td>
</tr>
</tbody>
</table>

In some case, this trigger is by-passed

Target-Calorimeter distance such that 2γ from π⁰ are separated by 3 blocks
2-clusters events used for DVCS analysis

Evaluation of $\pi^0$ contamination to DVCS signal

Monitoring and fine adjusting of energy calibration

- First pass: elastic calibration $p(e,e'p')$: invasive about every 4 weeks
- Second pass: $\pi^0$ calibration with about 1 day of data parasitic to DVCS data taking
Toward selecting $p(e,e'\pi^0)p'$ for physics

$t_i = t(e') - t(\gamma_i)$

- $e'\gamma_1\gamma_2$ all in coincidence
- $e'\gamma$ in coincidence but not with the other $\gamma$
- $\gamma_1\gamma_2$ in coincidence but not with $e'$
- $e'\gamma_1\gamma_2$ all in random coincidence.

- Software threshold of 500 MeV on each cluster
- Avoid the edge of the calorimeter to ensure full reconstruction of the EM shower.
Hard Exclusive Meson cross-section

\[
\frac{d^4\sigma}{dt d\phi dQ^2 d\chi_B} = \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, \chi_B, E_e) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{T\perp}}{dt} \cos(\phi) + \epsilon \frac{d\sigma_{T\perp\perp}}{dt} \cos(2\phi) \right]
\]

At first thought, if QCD factorization applies:

\(\sigma_L\) expected to dominate with \(\sigma_T\) suppressed by \(1/Q\).

But:

**DVCS1 results**


\(Q^2 = 2.3 \text{ GeV}^2\)

\(\chi_B = 0.36\)

\(\epsilon = 0.61\)

Similar results at:

- CLAS with \(\pi^0\)
- HERMES & Hall C with \(\pi^+\)
\[
\frac{d^4 \sigma}{dt d\phi dQ^2 dx_B} = \frac{1}{2\pi} \Gamma \gamma^* (Q^2, x_B, E_e) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1 + \epsilon)} \frac{d\sigma_{TL}}{dt} \cos(\phi) + \epsilon \frac{d\sigma_{TT}}{dt} \cos(2\phi) \right]
\]

<table>
<thead>
<tr>
<th>Setting</th>
<th>E (GeV)</th>
<th>Q^2 (GeV^2)</th>
<th>x_B</th>
<th>\epsilon</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Kin1</td>
<td>3.355 ; 5.55</td>
<td>1.5</td>
<td>0.36</td>
<td>(0.52 ; 0.84)</td>
</tr>
<tr>
<td>2010-Kin2</td>
<td>4.455 ; 5.55</td>
<td>1.75</td>
<td>0.36</td>
<td>(0.65 ; 0.79)</td>
</tr>
<tr>
<td>2010-Kin3</td>
<td>4.455 ; 5.55</td>
<td>2</td>
<td>0.36</td>
<td>(0.53 ; 0.72)</td>
</tr>
</tbody>
</table>

DVCS2 results

M. Defurne et al.
PRL 117, 26 (2015)

x_B=0.36
t-t_min=0.025 GeV^2
Why such a large $d\sigma_T$ contribution?

Modified factorization approach proposed by

- Ahmad, Golstein and Liuti (Phys.Rev.D79, 054014 (2009))

In these models:

- Factorization is possible because of the specific make up of the mesons (singularities cancellations),
- Twist-3 Distribution amplitudes couple with transversity GPDs.

\[
\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu^2}{Q^8} \left[ (1 - \xi^2)|F_T|^2 - \frac{t'}{8m^2} |2F_T + E_T|^2 \right]
\]

\[
\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu^2}{Q^8} \frac{t'}{16m^2} |2\tilde{F}_T + E_T|^2,
\]

\[
\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \approx 2.5 \text{ GeV} > \text{experimental } Q (\text{less than } 1.4)\]
DVCS2 results: fully separated contributions

G-H-L ('11)

G-K

Small $d\sigma_L$, large $d\sigma_T$: models ok on these
Wrong sign and Q dependence on $d\sigma_{TL}$ and $d\sigma_{TT}$
$d\sigma_{TL}$ sizeable $\Rightarrow d\sigma_L$ is small but not null
At $Q^2=1.75$ GeV$^2$ and $x_B=0.36$, half of the data taken on a LD2 target.

Below the two pions threshold:

$$D(e, e'\pi^0)X = d(e, e'\pi^0)d + n(e, e'\pi^0)n + p(e, e'\pi^0)p.$$
Events with missing mass squared below 0.95 GeV$^2$:
- are divided in 12 x 2 x 5 x 30 bins in $\phi$, $E$, $t$ and $M_x^2$

  $\phi$, $E$ allow for $L$, $T$, $LT$ and $TT$ separation
  $M_x^2$ allows for the $n/d$ separation

- fitted with eight cross-section function structure

\[ d\sigma_{\Lambda}^{n,d}(t) \]
\[ \Lambda = T, L, LT, TT \]

$Q^2=1.75$ GeV$^2$ and $x_B=0.36$

$E=4.45$ GeV
\[ <t'> = 0.025 \text{ GeV}^2 \]

$E=5.55$ GeV
\[ <t'> = 0.021 \text{ GeV}^2 \]
DVCS2n results: fully separated contributions

$Q^2 = 1.75 \text{ GeV}^2$ and $x_B = 0.36$

\[ \frac{d\sigma_T}{dt} = \Lambda \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2 \right] \]

\[ \frac{d\sigma_{TT}}{dt} = \Lambda \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2 . \]

\[ \bar{E}_T = 2\tilde{H}_T + E_T \]

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Goloskokov and Kroll
DVCS2n results: flavor separation

\[ |\langle H_T^{p,n} \rangle|^2 = \frac{1}{2} \left| \frac{2}{3} \langle H_T^{u,d} \rangle + \frac{1}{3} \langle H_T^{d,u} \rangle \right|^2 \]

account for the unknown phase variation between u and the d amplitude \( \gamma^*q \to q'\pi^0 \) convoluted with \((H,E)_T\)

Goloskokov and Kroll

\( Q^2 = 1.75 \text{ GeV}^2, \quad x_B = 0.36 \)
E12-06-114: high impact experiment

50% of PAC allocation taken in between 2014 and 2016
E12-13-010: “DVCS” at 11 GeV in Hall C

- Energy separation of the DVCS cross section
- Higher $Q^2$: measurement of higher twist contributions
- Low $x_B$ extension (thanks to sweeping magnet)

Q$^2$ vs $x_B$ coverage in Halls A and C:
- Hall C 11 GeV
- Hall C 8.8 GeV
- Hall C 6.6 GeV
- Hall A 11 GeV
- Hall A 8.8 GeV
- Hall A 6.6 GeV
- Hall A 5.75 GeV

Tentative running: ~ 2019-20 ??
E12-13-010: electro-production of $\pi^0$ in Hall C

FIG. 3: Projected uncertainties for the $Q^2$ dependence of $\sigma_L$ and $\sigma_T$ at fixed $x_B=0.36$, 0.5. The points are plotted assuming the GK model predictions. Also shown are the hard scattering (HS, $R=\sigma_L/\sigma_T$ $1/Q^{-2}$) and the DIS (DIS, $R 1/Q^2$) expectation, and the model predictions of the VGL (Regge) model. The points at $Q^2=5.1$ and $6.0$ GeV$^2$ in the right panel are scaled from the $x_B=0.6$ setting in Table III and include events from the Hall A DVCS experiment [28] for the low beam energy in the L/T separation where appropriate. The point at $Q^2=5.5$ GeV$^2$ also includes events from the Hall A experiment for the low beam energy in the L/T separation.
Outlook

- Our scheme is to measure electro-production of $\pi^0$ parasitically to DVCS.
  - We have published $\pi^0$ data on proton and neutron for all our 6GeV data.
  - We have data on tape at 12 GeV (one energy only).
  - We will take data at 12 GeV with NPS (multiple energies).

- Our data support the dominance of $\sigma_T$ measured by HERMES and CLAS and explained by the modified factorization approach proposed by Liu and by Kroll.
  - Can experiment provide data that would further “test” this modified factorization scheme?

- We have published a first flavor separation of the $<HT>$ and $<ET>$. A limiting factor to the precision of this measurement is the relative phase between the $u$ and $d$ amplitudes. This could be mitigated by exclusive $p(\gamma^*,\eta p)$ data.
  - Is this worth it?