Simulation of $e^+ p \rightarrow e^+ p \pi^0$
with the CLAS12 simulation and reconstruction / analysis framework

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The work has been done during a stay at INFN Genova in cooperation with Marco Battaglieri, Andrea Cenentano, Derek Glazier and Raffaella de Vita
Outline

**Aim:** Simulation of the channel $e\,p \rightarrow e\,p\,\pi^0$

**Secondary aim:** Get the complete simulation and analysis chain working

**Steps of the simulation/analysis chain:**

- Generate physics data with AmpTools
- Simulate the response of the CLAS detector and the forward tagger with gemc
- Reconstruct the data with CLARA
- Convert the output to the HASPECT format (root)
- Do physics analysis with the HASPECT framework
**Step 1: Physics data generation with AmpTools**

- Andrea has provided a macro, which uses AmpTools to generate physics events for the channel $e^+ p \rightarrow e^+ p \pi^0$ based on amplitudes from Vincent.
- The beam energy has been set to 11 GeV.
- The macro contains the condition that electrons are only generated under a forward angle between $2.5^\circ$ and $4.5^\circ$ and with energies between 0.5 GeV and 4.5 GeV.

  → Only these electrons will be detected by the FT and act as part of the trigger for the MesonEx experiment.

  → The quasi real photons produced by the electrons scattered under a very small angle (low $Q^2$) are used for the photoproduction of the neutral pion.
• The generated events have been analyzed to get a first impression how the reaction kinematics will look like

**t-distribution**

- peak at $0.1 \, \text{GeV}^2$
- mean = $0.27 \, \text{GeV}^2$

**$Q^2$-distribution of the virtual photon**

- mean = $0.1 \, \text{GeV}^2$

$Q^2$ distribution is not exactly 0 like for a real photoproduction experiment

$\rightarrow$ Has to be considered by small corrections in the amplitude model
Reaction kinematics of the generated data

degree of transverse polarization of the virtual photon (epsilon):

<table>
<thead>
<tr>
<th>epsilon</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300000</td>
<td>0.4319</td>
<td>0.1781</td>
</tr>
</tbody>
</table>
The energy and the angle theta of the electron are only simulated within the acceptance range of the forward tagger (trigger condition).
Kinematics of the proton

- Nearly all protons are going to the central detector of CLAS12.
  Triggering on this part will be essential for the reconstruction of the studied channel!!!

**momentum**

- $P_{\text{proton} \text{ lab}}$
  - Entries: 300000
  - Mean: 0.4837
  - Std Dev: 0.3052

**theta proton CM frame**

**theta proton LAB frame**

- Energy vs. theta
- Theta proton /°
- E proton /GeV

- Theta proton /°
- Counts

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**Kinematics of the neutral pion**

- $\pi^0$ has a quite high energy and is emitted in forward directions.
- Information for $\pi^0$ can be used to calculate the gammas.
  - Random back to back distribution in the CM frame.
  - Boost to the LAB frame.

**Energy distribution of the pion**

<table>
<thead>
<tr>
<th>$E_{\pi^0_{\text{lab}}}$</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries: 300000</td>
<td>800</td>
</tr>
<tr>
<td>Mean: 8.269</td>
<td>700</td>
</tr>
<tr>
<td>Std Dev: 1.185</td>
<td>600</td>
</tr>
</tbody>
</table>

**Theta distribution of the pion**

<table>
<thead>
<tr>
<th>THEAT$<em>{\pi^0</em>{\text{lab}}}$</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries: 300000</td>
<td>40000</td>
</tr>
<tr>
<td>Mean: 3.384</td>
<td>35000</td>
</tr>
<tr>
<td>Std Dev: 2.15</td>
<td>30000</td>
</tr>
</tbody>
</table>
Calculated kinematics of the two \textit{gammas}.

- Many low energetic gammas
- Most gammas are detected by the forward tagger and the forward detector of CLAS12
Angle between the two gammas of the $\pi^0$ decay

Angle between the two gammas

- Narrow angle between the gammas for most of the pairs, but gamma clusters can be separated in most cases

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Step 2: Simulation of the detector response with gemc

- AmpTools provides the generated events in the lund format (text file) which is used as input for gemc.

- Simulation has been performed with a realistic resolution (RUNNO = 11).

- Simulation takes 1.2 - 1.5 s per event with 2 Intel i5 650 (3.2 GHz) cores (approx. 55000 events are simulated in 24 h).
  
  → Move to a cluster for larger event numbers.

Output of the simulation: evio file
  
  → Has to be converted to the hipo format to pass it through the reconstruction.
gemc GUI for the visualization of the simulation
Step 3: Reconstruction of the events with CLARA

- CLARA is based on COATJAVA
- CLARA stores the reconstructed particles in a hipo database in which also the generated particles are kept
- In addition all information about the output of the detectors which contributed to the reconstructed events can be looked up in this database

To consider: In the used version of CLARA tracking in the CD had been deactivated to fix an issue
   - Protons in the CD are not reconstructed!
   - Issue is fixed in the recent version of CLARA

- The database can be directly accessed to view the events
- For further analysis the contained information have to be read out from the database and converted to the HASPECT format (root)
Overview for one event:

- The single banks can be selected for more information.
Reconstructed particles in CLAS12:

Reconstructed particles in the forward tagger:

→ FT particles are not included in the REC database so far

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Event monitor for the visualization of the hipo database

sector 1 and 4: pion is passing (green line) proton is going to CD (blue line)

sector 2 and 5: electron is passing (red line)
Step 4: Extraction of the content of the hipo database and conversion to the HASPECT format (root)

- **Plan for the future**: Get a direct root output from CLARA
  → The present conversion is only an intermediate solution

**a) Conversion from hipo to the lund format (txt)**

I have written a groovy script which reads all generated and reconstructed particles from CLAS12 and the Forward Tagger and writes it as lists in a modified lund format to a text file.

**b) Conversion from lund (txt) to root (HASPECT format)**

Derek provides a macro to convert the produced list of particles to the HAPECT format (root)

→ Conversion is working now 😊
Step 5: Analysis of the reconstructed data

Aim for the current reaction:

• Reconstruct $\pi^0$ from two detected gammas
• Compare the reconstructed electron with the generated to check if the reconstruction in the FT is working correctly
• Do first physics analyses

$\rightarrow$ In the used (not recent) version of CLARA protons are not reconstructed in the CD

$\rightarrow$ It is not clear if triggering on the CD will be possible at all in the experiment
  $\rightarrow$ This is mandatory to study this reaction

$\rightarrow$ Reconstruction of $\pi^0$ can be used for calibration of the FT
**Analysis: Topologies and distribution of gammas**

- Events with a proton in the FD are in the order of 0.44 % → Most protons go to the CD!

**Distribution of the gammas on the detectors:**

- a) Both gammas detected in the FT: 55.7 %
- b) One gamma detected in the FT: 30.6 %
- c) Both gammas detected in the forward calorimeter (FD): 6.7 %
- d) One gamma detected in the forward calorimeter (FD): 14.2 %

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Analysis: Reconstructed reaction kinematics

From now on: Take the topology with e⁻ gamma gamma gamma detected

- $Q^2$ and epsilon show the same range and a similar shape as for the generated data

• Expected is a single missing proton at 0.938 GeV/c²
Analysis: Reconstructed particle angles

- Electrons only detected in FT
  → Same as generated

- Most gammas detected in FT
  • Some also in FD (tail for $> 5^\circ$)
**Analysis: angle between electron and gammas (lab frame)**

- **average angle = 6.3°**
  - $\rightarrow$ ~ 20 cm at FT position
- **for most events > 4°**
- **average angle = 2.4°**
  - $\rightarrow$ ~ 8 cm at FT position (5 crystals)
- **for most events > 1.5°**
Analysis: Check for overlapping gammas

Compare **missing mass**, if both gammas are reconstructed and if only one gamma is reconstructed.

**both gammas reconstructed:**

**only one gamma reconstructed:**

Misidentified overlapping gammas would lead to a peak at ~ 1 GeV which is not observable in the left distribution.
Analysis: $\pi^0$ invariant mass reconstruction

- Topology with $e^-$ gamma gamma detected

$M_{\pi^0}$

136 MeV/c² reconstructed  \(\text{(lit.: 134.98 MeV/c}^2\text{)}\)

Resolution: 4.1 MeV/c²
Analysis: $\pi^0$ invariant mass reconstruction

**Now:**
both gammas have
to be detected by
the Forward Tagger
(most of the pairs
fulfill this condition)

**in addition:**
1 sigma cut on
missing proton mass

137 MeV/c$^2$ reconstructed  \((lit.: 134.98 \text{ MeV/c}^2)\)

**Resolution:** 3.9 MeV/c$^2$
Analysis:
Comparison of generated and reconstructed values

e⁻ in the FT
reconstructed – generated momentum

Resolution of the reconstructed virtual photon energy (ν):
→ Energy of the scattered electron minus energy of the initial electron

Resolution: 34.5 MeV/c
for 0.5 GeV < E < 4.5 GeV
E_{avg} = 2 GeV: res < 1.7 %
Analysis: Comparison of generated and reconstructed values

Reconstruction of the **electron angle in the FT**

reconstructed - generated

<table>
<thead>
<tr>
<th>electron_theta_gen-rec</th>
<th>electron_phi_gen-rec</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Theta Distribution" /></td>
<td><img src="image2.png" alt="Phi Distribution" /></td>
</tr>
<tr>
<td>Entries: 8263</td>
<td>Entries: 8263</td>
</tr>
<tr>
<td>Mean: $-0.02125$</td>
<td>Mean: $-0.2738$</td>
</tr>
<tr>
<td>Std Dev: 0.07404</td>
<td>Std Dev: 1.073</td>
</tr>
<tr>
<td>$\chi^2 / ndf$: 239.1 / 38</td>
<td>$\chi^2 / ndf$: 57.29 / 74</td>
</tr>
<tr>
<td>Constant: $5440 \pm 78.9$</td>
<td>Constant: $424.7 \pm 7.0$</td>
</tr>
<tr>
<td>Mean: $-0.02016 \pm 0.00066$</td>
<td>Mean: $-0.2831 \pm 0.0095$</td>
</tr>
<tr>
<td>Sigma: $0.05903 \pm 0.00054$</td>
<td>Sigma: $0.6873 \pm 0.0102$</td>
</tr>
</tbody>
</table>

**res(theta) = 0.06°**  
**res(phi) = 0.69°**
Analysis:
Determination of the angular dependence of the cross section

- Reaction is defined by a leptonic and a hadronic plane

**Leptonic plane** is defined by the ingoing and outgoing electron

**Hadronic plane** is defined by the $\pi^0$ and the outgoing proton

- Determine the phi angle of the $\pi^0$ in the CM frame of the photo production
Analysis:
Determination of the angular dependence of the cross section

- The cross section should show a constant offset and a \( \cos(2\,\phi) \) modulation.
- **But:** For our kinematic region (low \( Q^2 \)) the modulation seems to be completely suppressed \( \rightarrow \) Only constant offset is visible.
- The reconstructed data is dominated by the acceptance, which causes the fall of the cross section to both sides.
Analysis:
Determination of the angular dependence of the cross section

- A very small modulation can be obtained by increasing the value of the residuum g2 in the amplitude model.
Simulation of

\[ e + p \rightarrow e + p + \pi^+ + \pi^- \]
• Amplitudes for the reaction provided by Vincent

• Calculate generated events with AmpTools like for the first reaction
Momentum and angular distributions of the proton

- Protons mainly hit the central detector ( > 35°)
- Only a small fraction will be detected by the forward detector (5° – 35°)
- Triggering on protons in the CT will be mandatory for this reaction
Momentum and angular distributions of the charged pions

- The charged pions will be detected in the forward detector
- Some will also hit the FT
Dalitz plot for the generated particles

\[ M_{\rho\pi^+}^2 \text{ vs } M_{\pi^+\pi^-}^2 \]
Simulation and reconstruction

• Simulate the detector response with gemc ✓

• Reconstruct the events with CLARA ✓

• Convert the output to the HASPECT format (root) ✓

→ Particle ID has been done manually for charged particles, since it is not implemented in CLARA yet

• Use the analysis framework to analyze the data ✓

→ Details are the same as for the first reaction
Only protons in the FD are reconstructed

But: Most Protons go to the CD
a) **Proton**: Reconstructed momentum and theta

For the following plots, the $e p \pi^+ (\pi^-)$ topology has been selected

**proton momentum**

- Typical proton momentum: 0.5 – 4 GeV
- Protons are only detected in FD (< 35°)
- Tracking in CD (> 35°) was not available in the used CLARA version

**proton theta**

- [Histogram and scatter plot for proton momentum and theta]
b) $\pi^+$ reconstructed momentum and theta

- Pion momentum goes up to 8 GeV
- Most Pions are detected in the FD
- Results for $\pi^-$ are similar, but acceptance difference due to the magnetic field causes a slightly different behavior, especially at small momenta.
Invariant mass of $p\pi^+$ and $p\pi^-$ and $\pi^+\pi^-$ and Dalitz plots

For the following plots, the $e p \pi^+ \pi^-$ topology has been selected

• More statistics is needed to identify resonances
Outlook

• Complete simulation – reconstruction – analysis chain is working
• Two channels have been passed through the complete chain

Next steps:
• Increase the statistics of $p \pi^+ \pi^-$
• Do physics analyses for $p \pi^+ \pi^-$
• Define trigger conditions for the mesonEx experiment
• Simulate / analyze additional channels

A documentation of the single steps is available on the HASPECT wiki under the following link:

https://wiki.ge.infn.it/haspect/index.php/Ppi0