Database on Hadronic and Electromagnetic meson production up to $W = 2.5$ GeV

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The George Washington University

Based on work in collaboration with
R. Arndt, W. Briscoe, R. Workman

- GW DAC N* Program
- Critical role of the $\pi N$ analysis
- Recent CLAS $\gamma N \rightarrow \pi N$ data and multipole fits
- JLab efforts in pion electroproduction
- What’s next?

N* Analysis Workshop, JLab, Nov 4 - 5, 2006
HEPDATA at The Durham HEP Database
[http://durpdg.dur.ac.uk/HEPDATA/]

The Durham HEP Databases
from the Durham Database Group, at Durham University(UK).
Comments/Suggestions etc. to M.R.Whalley@durham.ac.uk

The Durham HEP REACTION DATA DataBase

For numerical data on total and differential cross sections, structure and
fragmentation functions, polarizations and other 'scattering' measurements
from a wide range of particle physics experiments,
either:
- search the full Reaction Data Database
or:
obtain selected data from one of our Data Reviews listed below.

These Data Reviews are published in the IoP's, Journal of Physics G -
Nuclear and Particle Physics. Electronic versions of the reviews can be
obtained through the relevant IoP links below.

- Structure Functions in DIS
- Single Photon Production in Hadronic Interactions
- Two-Photon Reactions leading to Hadron Final States
- Drell-Yan cross sections
- Inclusive particle production data in e+e- Interactions

Parton Distribution Function Server

Access the latest parton distribution codes plus on-line calculation and
graphical display of the distributions, for the CTEQ, GRV MRST and
Alekhin PDF sets. Includes also polarized parton distributions, and
also the code for the ZEUS 2002, ZEUS 2005 jet fit and H1 PDF
2000 pdfs.
See also LHAPDF-5.0.0 The Les Houches Accord PDFs (now hosted by
CEDAR-hepforge)

SPIRES UK Mirror Site

hep - Literature etc.
hepnames - Email IDS
experiments - Experiments
institutes - Institutes
conferences - Conferences

Related Links:
arXiv.org
uk.arXiv.org
CERN Preprints
GW SAID (Scattering Analysis Interactive Dial-in) Facility
[http://gwdac.phys.gwu.edu/]

CNS DAC Services [SAID Program]

- The Virginia Tech Partial-Wave Analysis Facility (SAID) has moved to GW!
- New features are being added and will first appear at this site. Suggestions for improvements are always welcomed.
- Once fully operational, this web page will become the main entry for the full range of services presently available through SAID.

Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation bar allow the user to access a number of features available through the SAID program.

Contact a member of our group if you are unfamiliar with the SSH version. If you enter choices which are unphysical, you may still get an answer (in accordance with the ‘garbage in, garbage out’ rule). Please report unexpected garbage-out to the management.

Note: These programs use HTML forms to run the SAID code. If unfamiliar with the options, run the default setup first. The output is an (edited) echo of an interactive session which would have resulted had you used the SSH version. If the default example fails to clarify the specific task you have in mind, we can help (just send an e-mail message).

All programs expect energies in MeV units. All of the solutions and potentials have limited ranges of validity. Some are unstable beyond their upper energy limits. Extrapolated results may not make much sense.

Increments: The programs will not allow an arbitrary number of points to be generated. As a rule, stay below 100.

ACKNOWLEDGMENTS

The CNS Data Analysis Center is partially funded by the U.S. Department of Energy, the Thomas Jefferson Lab, and the Research Enhancement Funds of The George Washington University, with strong support from the GW Northern Virginia Campus.
$N^*$ and $\Delta^*$ states coupled to $\pi N$

- One of the most convincing ways to study Spectroscopy of $N^*$ is $\pi N$ PWA

- GW DAC SAID program: $\pi N \rightarrow \pi N \Rightarrow \gamma N \rightarrow \pi N \Rightarrow \gamma^* N \rightarrow \pi N$
- $\pi N$ elastic amplitudes from fits to the observables: $\sigma^{tot}$, $d\sigma/d\Omega$, and $P$ (plus a few $R$ and $A$ measurements, 0.4 %)
- Contain resonances contributing to $\gamma N \rightarrow \pi N$
- Assuming dominance of 2 hadronic channels, can parametrize $\gamma N \rightarrow \pi N$ in terms of $\pi N \rightarrow \pi N$ amplitudes alone
- Resulting multipoles can be re-fitted in terms of Res/bckgr contributions or used as input to multi-channel fits with more elaborate constraints
- A comparison of various resonance-extraction methods gives a more reliable estimate of systematic (model) errors
Objective

• Our PWAs have been as model-independent as possible, so as to avoid bias when used in resonance extraction or coupled-channel analysis.

• An example is provided by our elastic $\pi N$ analysis:
  - Resonances are found through a search for poles in the complex plane and are not put in by hand as BW terms.
  - This distinction is important for more complicated structures, such as the $N(1440)P_{11}$ and $N(1535)S_{11}$.
  - Also, it is an issue in search for `missed' or `hidden' resonances.
Road Map for Multipoles from GW SAID Analyses of Scattering Data

- πN PWA provides the base for Spectroscopy studies for non-strange baryons in all other processes

\[ \pi N \rightarrow \pi N \] → \[ M_R, \Gamma, \text{and Residue Extraction} \]

\[ \gamma N \rightarrow \pi N \] → \[ \text{Multipole Extraction} \]

\[ eN \rightarrow e' \pi N \] → \[ M, E, S \text{ vs } Q^2 \]
**J-PARC** Facility (50 GeV Proton Synchrotron)

[http://j-parc.jp/NuclPart/index_e.html](http://j-parc.jp/NuclPart/index_e.html)

- **Priorities:**
  - QCD model dependent, EW, etc
  - Open for N* physics

πN → πN
→ ππN
→ πΔ
→ ηN
→ KΛ
→ KΣ
→ ρN

- J-PARC
- BNL
- IHEP
- PSI
- ITEP
- PNPI
Summary of Coupled Channel SP06 Fit of $\pi N$ and $\eta N$ data

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 74, 045205 (2006)]

- $T_{\pi} = 0 - 2600$ MeV [W = 1080 - 2460 MeV]
- $P_W = 15 \ [I=1/2] + 15 \ [I=3/2] + 5 \ [\eta N]$
- $P_{rms} = 93 \ [I=1/2] + 81 \ [I=3/2]$
- 4-channel Chew-Mandelstam K-matrix parameterization

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+p \rightarrow \pi^+p$</td>
<td>13344</td>
<td>27155</td>
</tr>
<tr>
<td>$\pi^-p \rightarrow \pi^-p$</td>
<td>11967</td>
<td>22702</td>
</tr>
<tr>
<td>$\pi^-p \rightarrow \pi^0n$</td>
<td>2933</td>
<td>6084</td>
</tr>
<tr>
<td>$\pi^-p \rightarrow \eta n$</td>
<td>257</td>
<td>626</td>
</tr>
<tr>
<td>DRs</td>
<td>3375</td>
<td>671</td>
</tr>
<tr>
<td>Total</td>
<td>31,876</td>
<td>57238</td>
</tr>
</tbody>
</table>

- Recent Contribution: HE, CHAOS
- HE, CHAOS
- ITEP-PNPI
- CB
- PSI
- CB

- In the future, J-PARC can contribute a lot of hadronic data

- 106 data above 800 MeV
- Very little Pol measurements
\[ \pi N \] Analysis Flow Chart

1. Intermediate Solution
   - Calculate DR Constraints
     - Fit DR + Data
       - No
         - Fit Converges?
           - Yes
             - \( \pi N \) and \( \eta N \) Amplitudes
               - Cook until DONE!
           - No
             - Same for EM cases
Influence of spin-rotation measurements on $\pi N$ PWA

[I. Alekseev et al/Phys Rev C 55, 2049(1997)]

• **ITEP**: $\pi^+p \rightarrow \pi^+p$

**KA84**: Karlsruhe-Helsinki

**KB84**: KH Barrelet corrected

**SP06**: GW DAC fit
**S-waves**

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 74, 045205 (2006)]

\[ N(2090)^* \]

\[ \Delta(2150)^* \]

\[ \Delta(1900)^{**} \]

- SP06 vs SES in Ampl
- SP06 vs KA84 in Ampl
- SP06 vs PDG06 in BW

**References**

- KA84 [R. Koch, Z Phys C 29, 597 (1985)]
P-waves

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 74, 045205 (2006)]

\[
\begin{align*}
P_{11} & \quad N(1710)^{***} \\
P_{31} & \quad \Delta(1750)^* \\
P_{13} & \quad N(1900)^{**} \\
P_{33} & \quad \Delta(1600)^{***} \quad \Delta(1920)^{***}
\end{align*}
\]
Where is Resonance?

- **Main techniques:**
  - Pole on complex energy plane
  - Breit-Wigner
  - Speed plot, $Sp(W)$

- **Additional:**
  - Argand plot, $Im(Re)$
  - Crossover energy, $ReA = 0$
  - Time-delay
  - *etc*
Complex Energy Plane for $S_{11}$ [FA02]

[R. Arndt, W. Briscoe, IS, R. Workman, M. Pavan, Phys Rev C 69, 035213 (2004)]

- **Poles:**
  - $1526-i65$ MeV
  - $1653-i91$ MeV

- **Branch-points:**
  - $\eta N$ thr: $1487-i0$ MeV
  - $\rho N$ thr: $1715-i73$ MeV

- **Zero:**
  - $1578-i38$ MeV

- **BWs:**
  - $W_R = 1546.7 \pm 2.2$ MeV
  - $\Gamma = 178.0 \pm 12.0$ MeV
  - $W_R = 1651.2 \pm 4.7$ MeV
  - $\Gamma = 130.6 \pm 7.0$ MeV
Complex Energy Plane for $P_{11}$ [SP06]

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 74, 045205 (2006)]

• Pole 1: 1359-i82 MeV

• Pole 2: 1388-i83 MeV

• BW: $W_R = 1485.0 \pm 1.2$ MeV, $\Gamma = 248 \pm 18$ MeV

• Poles of the $P_{11}$ amplitude

• Branch-point $[\pi\Delta \ thr]$ [1350-i50 MeV]

• Branch-point $[\eta N \ thr]$ [1487-i0 MeV]

• Two poles at 2 different Riemann sheets, both are very near to the branch-point $[\pi\Delta\ thr]$, and the additional branch-point $[\eta N\ thr]$

• A simple BW does not account for such complexity

• Pole 2: 1388-i83 MeV
$P_{11}$ via Argand and Speed plots

- Is standard BW an appropriate form to extract $N(1440)$ from the set of several nearby singularities [2 poles and $\pi\Delta$, $\eta N$ branch-points with a very prominent cut]?!!

- $\text{Sp}(W) = |dT/dW|$ peak at $W=M$ (pole) at $\text{NonRes} \to 0$ [$G. \text{Hoehler, } \pi N \text{ Newslett. (1993)}$]

- Above 1400 MeV, $\text{Sp}(W)$ is flat

$W = 1080 \pm 220 \text{ MeV}$
Direct Measurements of $N(1440)P_{11}$

- **BEPC:** $e^+e^- \to J/\psi \to p\pi^-\bar{n} + \bar{p}\pi^+n$
  [M. Ablikim *et al.* (BES Collaboration)
  hep-ex/0405030]

- **SATURNE II:** $\alpha p \to \alpha' X$
  [H.P. Morsch and P. Zupranski,
  Phys Rev C 61, 024002 (2000)]

\[\begin{align*}
\text{\(p\pi^-\bar{n}\)} & \quad \Leftarrow \text{PWA: } J^P=1/2^+ \quad M=1358\pm 6\pm16 \text{ MeV} \quad \Gamma= 179\pm26\pm50 \text{ MeV} \\
\text{\(\bar{p}\pi^+n\)} & \quad \Leftarrow \text{Looks similar as pole at 1st sheet in GW } \pi N \\
\text{\(\omega = E_{\alpha'} - E_{\alpha}\)} & \quad \text{M}=1390\pm20 \text{ MeV} \quad \Gamma= 190\pm30 \text{ MeV} \\
\end{align*}\]
N(1710)P_{11} - What was Known


<table>
<thead>
<tr>
<th>Ref</th>
<th>Mass(MeV)</th>
<th>Width(MeV)</th>
<th>PWA-BW</th>
<th>1710 [inp]</th>
<th>~40 [est]</th>
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</thead>
<tbody>
<tr>
<td>KH79</td>
<td>1723±9</td>
<td>120±15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMU80</td>
<td>1700±50</td>
<td>90±30</td>
<td></td>
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<tr>
<td>KSU92</td>
<td>1717±28</td>
<td>480±230</td>
<td></td>
<td>1710</td>
<td></td>
</tr>
<tr>
<td>GW06</td>
<td>not seen</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Ref</th>
<th>Re(MeV)</th>
<th>-2xIm(MeV)</th>
<th>PWA-Pole</th>
<th>1690±20</th>
<th>80±20</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMU80</td>
<td>1690±20</td>
<td>80±20</td>
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<tr>
<td>CMU90</td>
<td>1698</td>
<td>88</td>
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<td></td>
<td></td>
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<tr>
<td>KH93</td>
<td>1690</td>
<td>200</td>
<td>[Sp(W)]</td>
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<tr>
<td>GW06</td>
<td>not seen</td>
<td></td>
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- The spread of $\Gamma$, $\Gamma_\pi/\Gamma$, and $\Gamma_\eta/\Gamma$, selected by PDG, is very large.
- $\Gamma$ is too large, $\geq 100$ MeV.
- If this state is related to the $\Theta^+$ then it would be more natural for the same unitary multiplet (with $\Theta^+$ and N*) to have comparable widths.
Direct Anti-Evidences for $N(1710)P_{11}$

- **CLAS** single- and double-charged-pion electroproduction off protons data in an isobar approach at $W = 1100$ to $1780$ MeV and $Q^2 = 0.65$ GeV$^2$
  [I. Aznauryan et al, Phys Rev C 72, 045201 (2005)]:
  'At $Q^2 = 0$, the coupling of the resonance $N(1710)P_{11}$ to $\gamma N$ is small. Our analysis showed that this resonance make minor contribution to the resonant electroproduction cross section'

- 2500 $\gamma p \rightarrow K^+\Lambda$ data below $W = 2500$ MeV in a multipole approach
  [T. Mart and A. Sulaksono, nucl-th/0609077]:
  'The $3^*$ resonance $N(1710)P_{11}$ that has been used in almost all isobar models within both single-channel and multi-channel approaches is found to be insignificant to the $K^+\Lambda$ photoproduction by both SAPHIR and CLAS data'

- Combined analysis of **CLAS** $2\pi$ electroproduction data at photon virtualities from 0.5 to 1.5 GeV$^2$ and for $W$ from 1400 to 1900 MeV
  [V. Mokeev, PC 2006]:
  'Electroproduction strength $\sqrt{(A_{1/2}^2 + S_{1/2}^2)}$ for $N(1710)P_{11}$ should be below 0.02 GeV$^{-1/2}$'
Conclusion from Modified $\pi N$ PWA for $S$- and $P$-waves
(dedicated for the search for narrow states, $\Gamma < 30$ MeV)

- 1680 MeV – only one partial wave ($P_{11}$) reveals the effect: support to the resonance, $\Gamma_{\pi N} < 0.5$ MeV
- 1730 MeV – $P_{11}$ may also reveal a resonance with $\Gamma_{\pi N} < 0.3$ MeV but differently: Res is still possible, if accompanied by different corrections
- The Res at 1730 MeV may appear in $P_{13}$ or $S_{11}$ (less probable), if accompanied by different corrections [eg, thresholds: $N_\omega(1720)$, $N_\rho(1715)$ ?, $K\Sigma(1685)$]
- The rest of partial waves ($D_{15}$, etc) do not support narrow states
Direct Evidences for $N(1680)P_{11}$ in $\gamma n \rightarrow \eta n$

- **GRAAL**: Very preliminary backward $\gamma n \rightarrow \eta n$
  [V. Kuznetsov, hep-ex/0601002, NSTAR 2005, Oct 2005]

- **CB-ELSA**: Very preliminary $\sigma(\gamma n \rightarrow \eta n)$

- No correction
- Correction for Fermi motion
- Independent CB-ELSA measurements confirm the GRAAL observation
- $\eta$MAID does not reproduce both $p$ and $n$ data well

Narrow state?
Summary of N* and Δ* finding from πN and ηN Scattering
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 74, 045205 (2006)]

- **Standard PWA** reveals only wide Resonances, but not too wide
  \( (\Gamma < 500 \text{ MeV}) \) and possessing not too small BR \( (> 4\%) \)

- **Standard PWA** (by construction) tends to miss narrow Resonances
  with \( \Gamma < 30 \text{ MeV} \)

- **Our study** does not support several N* and Δ* reported by PDG2006:
  
  *** \( \Delta(1600)P_{33}, \ N(1700)D_{13}, \ N(1710)P_{11}, \ \Delta(1920)P_{33} \)
  
  ** \( N(1900)P_{13}, \ \Delta(1900)S_{31}, \ N(1990)F_{17}, \ \Delta(2000)F_{35}, \ N(2080)D_{13}, \)
  
  * \( \Delta(1750)P_{31}, \ \Delta(1940)D_{33}, \ N(2090)S_{11}, \ N(2100)P_{11}, \ \Delta(2150)S_{31}, \)
  
  ** Our study does suggest several ‘new’ N* and Δ*:
  
  **** \( \Delta(2420)H_{311} \)
  
  *** \( \Delta(1930)D_{35}, \ N(2600)I_{111} \) [no pole]
  
  ** \( N(2000)F_{15}, \ \Delta(2400)G_{39} \)

  new \( N(2245)H_{111} \) [CLAS ?]
\( \pi N \to \pi \pi N \) in Isobar Model


- \( \pi N \to \pi \pi N \) is essential above 1300 MeV, \( \sigma_{2\pi N} \sim \sigma_{\text{inel}} \)

- 241,214 events for \( \pi N \to \pi \pi N \) have been analyzed in Isobar-model PWA at \( W = 1320 \) to 1930 MeV

- That is the main source of \( \pi N \) inelastic amplitudes and \( \rho N \) with \( \pi \Delta \) contribution

- This analysis is rather old and there are no new analyses
Recent $\pi N \rightarrow \pi\pi N$ Measurements

- **New data came late** (most of them are total Xsections):

  \begin{itemize}
  \item \textbf{W = 1078 to 1127 MeV:}
    \begin{itemize}
    \item $\pi^- p \rightarrow \pi^0 \pi^0 n$ \hspace{1cm} [\textbf{BNL}: J. Lowe \textit{et al/Phys Rev C 44}, 956 (1991)]
    \end{itemize}
  \item \textbf{W = 1221 to 1356 MeV:}
    \begin{itemize}
    \item $\pi^+ p \rightarrow \pi^+ \pi^+ n$ \hspace{1cm} [\textbf{PNPI}: A. Kravtsov \textit{et al/Nucl Phys B 134}, 413 (1978)]
    \item $\pi^+ p \rightarrow \pi^+ \pi^+ n$ \hspace{1cm} [\textbf{TRIUMF}: M. Sevior \textit{et al/Phys Rev Lett 66}, 2569 (1991)]
    \item $\pi^+ p \rightarrow \pi^+ \pi^0 p$ \hspace{1cm} [\textbf{LAMPF}: D. Pocanic \textit{et al/Phys Rev Lett 72}, 1156 (1994)]
    \item $\pi^- p \rightarrow \pi^- \pi^- \pi^+ n$ [\textbf{TRIUMF}: M. Kermani \textit{et al/Phys Rev C 58}, 3419 (1998)]
    \item $\pi^- p \rightarrow \pi^- \pi^+ n$ \hspace{1cm} [\textbf{CERN}: G. Kernel \textit{et al/Z Phys C 48}, 201 (1990)]
    \item $\pi^- p \rightarrow \pi^- \pi^+ n$ [\textbf{TRIUMF}: J. Lange \textit{et al/Phys Rev Lett 80}, 1597 (1998)]
    \end{itemize}
  \item \textbf{W = 1213 to 1527 MeV:}
    \begin{itemize}
    \item $\pi^- p \rightarrow \pi^0 \pi^0 n$ \hspace{1cm} [\textbf{BNL}: S. Prakhov \textit{et al/Phys Rev C 69}, 045202 (2004)]
    \end{itemize}
  \item \textbf{W = 1257 to 1302 MeV:}
    \begin{itemize}
    \item $\pi^+ p \rightarrow \pi^+ \pi^- \pi^- n$ [\textbf{TRIUMF}: M. Kermani \textit{et al/Phys Rev C 58}, 3431 (1998)]
    \end{itemize}
  \item \textbf{W = 1300 MeV:}
    \begin{itemize}
    \item $\pi^- p \rightarrow \pi^+ \pi^- n$ \hspace{1cm} [\textbf{PSI}: R. Mueller \textit{et al/Phys Rev C 48}, 981 (1993)]
    \end{itemize}
  \item \textbf{W = 2060 MeV:}
    \begin{itemize}
    \item $\pi^- p \rightarrow \pi^- \pi^+ n$ [\textbf{ITEP}: I. Alekseev \textit{et al/Phys At Nucl 61}, 174 (1998)]
    \end{itemize}
  \end{itemize}
Electromagnetic Probe

\[ \pi N \rightarrow \pi N \]
\[ \rightarrow \pi \pi N \]
\[ \rightarrow \pi \Delta \]
\[ \rightarrow \eta N \quad \Rightarrow \text{FROST: Eugene} \]
\[ \rightarrow K \Delta \quad \Rightarrow \text{HD: Phil} \]
\[ \rightarrow K \Sigma \]
\[ \rightarrow \rho N \]
Summary of FA06 Pion Photoproduction Analysis
(CLAS $\pi^0 p$ g1c data included)

[R. Arndt, W. Briscoe, IS, R. Workman, M. Dugger, J. Ball, P. Collins, E. Pasyuk, B. Ritchie, in progress]

- $E_\gamma = 145 - 3000$ MeV  \quad \text{[}W = 1080 - 2460$ MeV\text{]}
- $PWs = 48$ [multipoles]
- $Prms = 161$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data (DPol)</th>
<th>$\chi^2$</th>
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<tbody>
<tr>
<td>$\gamma p \rightarrow \pi^0 p$</td>
<td>15052 (13 %)</td>
<td>35048</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \pi^+ n$</td>
<td>7991 (6 %)</td>
<td>15969</td>
</tr>
<tr>
<td>$\gamma n \rightarrow \pi^- p$</td>
<td>2333 (0 %)</td>
<td>4259</td>
</tr>
<tr>
<td>$\gamma n \rightarrow \pi^0 n$</td>
<td>148 (0 %)</td>
<td>364</td>
</tr>
<tr>
<td>Total</td>
<td>25,524</td>
<td>55640</td>
</tr>
</tbody>
</table>

Recent Contribution:
- MAMI-B, GRAAL, CB-ELSA, Hall A, \textbf{CLAS}
- MAMI-B, GRAAL, Hall A, CB, Hall A

Coming soon:
- CLAS
- CLAS
- CLAS, BNL

FROST HD
CLAS $\gamma p \rightarrow \pi^0 n$ g1c and CB-ELSA with GRAAL

[M. Dugger et al, in progress]

**CLAS**: 620 DSG
$E_\gamma = 675–2875$ MeV
$\theta = 40–150$ deg
Stat = 3 %
Syst = 5 %

**CB-ELSA**: 1106 DSG
$E_\gamma = 320–2890$ MeV
$\theta = 30–140$ deg
Stat = 5 %
Syst = 5 % (> 1.3 GeV)
Syst = 15 % (< 1.3 GeV)

**GRAAL**: 861 DSG +441 $\Sigma$
$E_\gamma = 550–1540$ MeV
$\theta = 49–162$ deg
Stat = 5 %
Syst = 2.3 %
Forward dynamics is a problem

- CLAS
- CB-ELSA
- SMO2 [no CB-ELSA, GRAAL]
- FDX6 [incl CB-ELSA, GRAAL]
- FD16 [plus CLAS]
- FA06 [plus 3*CLAS]

- One might note the need for more-forward measurements of the $\pi^0 p$ cross section and
- Complementary measurements of $\pi^{+-}$ photoproduction, required for an isospin decomposition of the multipoles
- The database presently in the SAID is quite skimpy above 2 GeV
- So (hopefully) FROST will help firm up this region
Samples of Multipoles (CLAS $\pi^0 p$ $g1c$ data included in FA06)
SAID and MAID for $\gamma p \rightarrow \pi^+ n$

[M. Dugger et al. very prlm CLAS g1c data]

- $E_\gamma = 675 - 2275$ MeV
- $\theta = 30 - 140$ deg
- Stat = 7 %
- Syst = 5 %

No prior comprehensive tagged measurements
SAID and MAID for $\gamma n \rightarrow \pi^- p$

[T. Mibe et al. very-very prlm CLAS g10 data]

- No prior comprehensive tagged measurements
- Principal experiments were done using pion beams at Meson Factories
- Duke group, H. Gao, promised to complete analysis of g10 data
Effect of double-polarization data in fits to single-pion photoproduction

[R. Arndt, IS, R. Workman, Phys Rev C 67, 048201 (2003)]

- $\gamma p \rightarrow \pi^0 p$ at 1900 MeV
- DNPL: $T$
- Hall A: $C_x, C_z$


There are 22 $C_x'$ and 21 $C_z'$ below 2 GeV
Recent $\gamma N \rightarrow \pi \pi N$ Database

- $W = 1190$ to $1555$ MeV
  - $\gamma p \rightarrow \pi^+ \pi^0 n$ [MAMI-B: W. Langgaertner et al/Phys Rev Lett 87, 052001 (2001)]
  - $\gamma p \rightarrow \pi^0 \pi^0 p$ [MAMI-B: M. Kotulla et al/Phys Lett B 578, 63 (2004)]
- $W = 1277$ to $1543$ MeV
  - $\gamma p \rightarrow \pi^0 \pi^0 N$ [MAMI-B: A. Braghieri et al/Phys Lett B 363, 46 (1995)
    J. Ahrens et al/Phys Lett B 624, 173 (2005)]
- $W = 1313$ to $1543$ MeV:
  - $\gamma n \rightarrow \pi^- \pi^0 p$ [MAMI-B: A. Zabrodin et al/Phys Rev C 55, 1617 (1997)
    Phys Rev C 60, 055201 (2000)]
- $W = 1449$ to $1922$ MeV:
  - $\gamma p \rightarrow \pi^0 \pi^0 p$ [GRAAL: Y. Assafiri et al/Phys Rev Lett 90, 222001 (2003)]
- $W = 1277$ to $1543$ MeV:
  - $\gamma p \rightarrow \pi^+ \pi^0 n$ [MAMI-B: J. Ahrens et al/Phys Lett B 551, 49 (2003)]
- $W = 1350$ to $2300$ MeV:
  - $\gamma p \rightarrow \pi^+ \pi^- p$ [CLAS: S. Strauch et al/Phys Rev Lett 95, 162003 (2005)]
### World $\gamma^*N \to \pi N$ Database, before and outside JLab

<table>
<thead>
<tr>
<th>Lab</th>
<th>$\pi^0p$</th>
<th>$\pi^+n$</th>
<th>$\pi^-p$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS</td>
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<tr>
<td>AMPS</td>
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<tr>
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<tr>
<td>Cornell</td>
<td></td>
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<td>727</td>
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<tr>
<td>DESY</td>
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<td>2135</td>
<td></td>
<td>7553</td>
</tr>
<tr>
<td>DNPL</td>
<td>6206</td>
<td>2841</td>
<td>789</td>
<td>9833</td>
</tr>
<tr>
<td>Harvard</td>
<td>91</td>
<td>605</td>
<td>8</td>
<td>704</td>
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<tr>
<td>Mainz</td>
<td>579</td>
<td>21</td>
<td></td>
<td>600</td>
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<tr>
<td>MIT</td>
<td>131</td>
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<td>131</td>
</tr>
<tr>
<td>Saclay</td>
<td></td>
<td>12</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>13011</td>
<td>6812</td>
<td>890</td>
<td>20,713</td>
</tr>
</tbody>
</table>

- Most of them are unpolarized measurements
- There is no $\pi^0n$ data
Recent Jlab $\gamma^*N\to\pi N$ Measurements

**Hall B:**

$\pi^0 p$ DSG: $W = 1100 - 1700$ MeV, $Q^2 = 0.4 - 1.8$ GeV$^2$
- $W = 1100 - 1400$ MeV, $Q^2 = 3.0 - 6.0$ GeV$^2$
  [K. Joo et al/Phys Rev Lett 88, 122001 (2002)]
- $W = 1100 - 1400$ MeV, $Q^2 = 0.65$ GeV$^2$
  [M. Ungaro et al/Phys Rev Lett 97, 112003 (2006)]

Spol: $W = 1100 - 1300$ MeV, $Q^2 = 0.4, 0.65$ GeV$^2$
- $W = 1100 - 1300$ MeV, $Q^2 = 0.5 - 1.5$ GeV$^2$
  [K. Joo et al/Phys Rev C 68, 032201 (2003)]
- $W = 1100 - 1300$ MeV, $Q^2 = 0.3 - 0.6$ GeV$^2$
  [A. Biselli et al/Phys Rev C 68, 035202 (2003)]

$\pi^+ n$ DSG: $W = 1100 - 1600$ MeV, $Q^2 = 0.3 - 0.6$ GeV$^2$
- $W = 1100 - 1300$ MeV, $Q^2 = 0.4, 0.65$ GeV$^2$
  [K. Joo et al/Phys Rev C 70, 042201 (2004)]
- $W = 1100 - 1800$ MeV, $Q^2 = 0.35 - 1.5$ GeV$^2$

**Hall A:**

$\pi^0 p$ DSG: $W = 1100 - 1900$ MeV, $Q^2 = 0.9 - 1.1$ GeV$^2$
- $W = 1230$ MeV, $Q^2 = 1.0$ GeV$^2$
  [G. Laveissiere et al/Phys Rev C 69, 045203 (2004)]
  [J. Kelly et al/Phys Rev Lett 95, 102001 (2005)]

**Hall C:**

$\pi^0 p$ DSG: $W = 1100 - 1400$ MeV, $Q^2 = 2.8, 4.0$ GeV$^2$
- $W = 1900 - 2000$ MeV, $Q^2 = 0.6 - 1.6$ GeV$^2$
  [V. Frolov et al/Phys Rev Lett 82, 45 (1999)]
  [J. Volmer et al/Phys Rev Lett 86, 1713 (2001)]

- **World = \( \frac{3}{4} \) JLab + \( \frac{1}{4} \) Others**
- **More JLab Data are coming from all Halls**
Preliminary $R_{EM}$ and $R_{SM}$ ratios for $P_{33}$ vs $Q^2$

[Carsten Arndt, W. Briscoe, IS, and R. Workman, SOH, Greece, April, 2006; nucl-th/0607017]

- The large M-multipole is not significantly different in these analyses.
- Differences for the E-multipole are much larger.

- GW: $-1.79 \pm 0.18\%$

- JLab Mainz Bates ELSA

- MAID05 DMT S-L

- SP06 & SQS

- Lattice05
Summary and Projects

• $\pi N$ analysis is important to $N^*$ program
• Extended $\pi N$ and $\gamma N$ analyses by 0.5 GeV (up to $W = 2.5$ GeV)
• Coupled-channel fit of $\pi N \rightarrow \pi N$ and $\pi N \rightarrow \eta N$ data results in $\eta N \rightarrow \eta N$ amplitudes

• There is input to $\gamma p \rightarrow \eta p$ fits (1595 data below 2900 MeV)
• Pion Electroproduction PWA will include 100k data up to $W = 2.5$ GeV and $Q^2 = 6$ GeV$^2$

• FROST data could yield surprises
• Neutron Electroproduction measurements will benefit determination of neutron couplings
Backup
• $N(1440)P_{11}$ is fully elastic
• For $N(1535)S_{11}$ and $N(1650)S_{11}$, $\sum (\Gamma_i/\Gamma) > 1$
• There is no contribution from $\rho N$, $\pi\Delta$, and $\pi\pi N$ decay channels
• There are no multipoles to compare with
### SP06 and FA02 vs KH80 and KA84 with Giessen (to 1500 MeV)

[V. Shklyar et al, Phys Rev C 71, 055206 (2005)]

<table>
<thead>
<tr>
<th>Reac</th>
<th>SP06</th>
<th>FA02</th>
<th>KH80</th>
<th>KA84</th>
<th>Giessen</th>
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<td>Norm</td>
<td>UnN</td>
<td>Norm</td>
<td>UnN</td>
<td>Norm</td>
</tr>
<tr>
<td>π⁺p</td>
<td>1.8</td>
<td>5.3</td>
<td>1.8</td>
<td>5.8</td>
<td>2.1</td>
</tr>
<tr>
<td>π⁻p</td>
<td>1.8</td>
<td>5.9</td>
<td>2.0</td>
<td>6.0</td>
<td>3.3</td>
</tr>
<tr>
<td>cxs</td>
<td>1.7</td>
<td>2.8</td>
<td>1.7</td>
<td>3.3</td>
<td>2.6</td>
</tr>
<tr>
<td>ηn</td>
<td>2.4</td>
<td>10.1</td>
<td>2.5</td>
<td>4.6</td>
<td></td>
</tr>
</tbody>
</table>

- Number of datapoints for KH80, KA84, and Giessen corresponds to the modern SAID database
S-waves

[V. Shklyar et al, Phys Rev C 71, 055206 (2005)]

\[\text{ImT-T}^* T < \text{ImT} \text{ [unitarity limit]}\]

- SP06 vs SES in Ampl
- SP06 vs Giessen in Ampl
- SP06 vs PDG2006 and Giessen in BW
P-waves

[V. Shklyar et al, Phys Rev C 71, 055206 (2005)]
Pion induced Xsections

\[ \pi^+ p_{\text{tot}} \]
\[ \pi^+ p_{\text{el}} \]
\[ \pi^+ p_{\text{elastic}} \]

\[ \pi^- p_{\text{tot}} \]
\[ \pi^- p_{\text{el}} \]
\[ \pi^- p_{\text{elastic}} \]

\[ \pi N \rightarrow \pi N \]
\[ \rightarrow \pi \pi N \]
\[ \rightarrow \pi \Delta \]
\[ \rightarrow \eta N \]
\[ \rightarrow K \Delta \]
\[ \rightarrow K \Sigma \]
\[ \rightarrow \rho N \]

\[ \sqrt{s} \text{ GeV} \]

Cross section (mb)

J-PARC
BNL
IHEP
PSI
ITEP-PNPI
Complex Plane vs BW fits

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 74, 045205 (2006)]

BW fit:
- $\Gamma$
- $\Gamma_{\pi N}$

Poles of amplitudes
- $P_{11}$ has 1 BW and 2 poles
- $P_{31}, D_{35},$ and $G_{39}$, possessed large $W_I$, do not allow well determ on-shell Res prms

Branch points:
- $[\pi\Delta \text{ thr}] [1350-i50 \text{ MeV}]$
- $[\eta N \text{ thr}] [1487-i0 \text{ MeV}]$
- $[\rho N \text{ thr}] [1715-i73 \text{ MeV}]$
Pion production Xsections

\[ \gamma p_{\text{tot}} \]

\[ \gamma N \rightarrow \pi N \]
\[ \rightarrow \pi \pi N \]
\[ \rightarrow \pi \Delta \]
\[ \rightarrow \eta N \quad \Rightarrow \text{FROST}: \text{Eugene} \]
\[ \rightarrow K \Lambda \quad \Rightarrow \text{HD}: \text{Phil} \]
\[ \rightarrow K \Sigma \]
\[ \rightarrow \rho N \]

Cross section (mb)

\[ \sqrt{s} \text{GeV} \]

\[ P_{\text{lab}} \text{ GeV/c} \]

\[ P_{d} \text{ GeV/c} \]

\[ \gamma d_{\text{total}} \]

\[ \gamma P_{\text{total}} \]

\[ \gamma P_{\text{tot}} \]

thr
Helicity-dependent photoabsorption Xsections on the nucleon
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C 72, 058203 (2005)]

• $\rho N$, $\pi\Delta$, and $\pi\pi N$ contribution to total photoabsorption is significant

○ CB-ELSA for GDH integrand
Phys Rev Lett 94, 162001 (2005)]
Mainz $\gamma p \rightarrow \pi^+ n$ GDH Measurements

[J. Ahrens et al/Phys Rev C 74, 045204 (2006)]
$\gamma p \rightarrow \pi^+ n$, 600 - 2000 MeV

[M. Dugger et al. very prlm CLAS g1c data]
Sensitivity of the EM Couplings Extraction $I=1/2$

(Separation of Res and NonRes)

[R. Arndt, W. Briscoe, IS, R. Workman, L. Tiator, in progress]
$P_{33}$ Multipoles from $\gamma^* N \rightarrow \pi N$

[R. Arndt, W. Briscoe, IS, and R. Workman, Proceedings of Workshop on Shape of Hadrons, Athens, Greece, April, 2006; nucl-th/0607017]

- The large Magnetic multipole is not significantly different in these analyses.
- Differences for the Electric multipole are much larger.

(through $G$-wave)