Critical role of the $\pi N$ analysis
Non-strange Resonances with $I = 1/2$ and $3/2$
Recent $\gamma n \rightarrow \pi N$ data and Multipole fits
JLab effort in $\gamma^* N \rightarrow \pi N$
Summary and Prospects
This workshop is dedicated to the memory of our friend and colleague, Dick Arndt.
GW DAC Research is Focused on Fivefold Way

- **PWA**: Partial-wave analysis of fundamental two- and three-body reactions

- **Experimental Program Support**: Analysis of final and preliminary data, determination of conflicting data, interpretation of new measurements, and studies of systematics and sensitivities required for the refinement of experimental proposals

- **Phenomenological and Theoretical Investigations**: Studies which bridge the gap between theory and experiment, including the methodology used in PWA

- **Databases**: Development of databases associated with the fundamental reactions

- **Development of the SAID Facility**: Creation of new software, including graphical representations, to disseminate our results (and the results of competing analyses which have often employed different methods)
GW DAC Database Development

- We update the SAID databases, develop and study PWAs, and keep current versions of phenomenological and theoretical models, both those of the CNS/DAC and other research groups, on a continual basis for relevant two- and three-body reactions of interest.

- These are made available to the nuclear and particle physics communities through web-based SAID: [http://gwdac.phys.gwu.edu/](http://gwdac.phys.gwu.edu/) and secure-shell interfaces
  
  ssh -X -C said@gwdac.phys.gwu.edu [no passwd] to the SAID Facility
For $p \rightarrow 2p$, we use log-likelihood while for the rest – least-squares technologies

- In the full database, one will occasionally find experiments which give conflicting results
- Some data with very large $\chi^2$ contributions have been excluded from our fits
- Redundant data are also excluded [these include $\sigma_{\text{tot}}$ based on $d\sigma/d\Omega$ already contained in the database]
- Measurements of pol observables ($P$, for instance) with uncertainties more than 0.2 are not included as they have little influence in our fits
- However, all available data have been retained in the database (the excluded data labeled as `flagged') so that comparisons can be made through our on-line facility

SAID Database below 4 GeV
[SAID: http://gwdac.phys.gwu.edu/]
Partial-Wave Analysis for N* and Δ*

Originally: PWA arose as the technology to determine amplitude of the reaction via fitting scattering data

[Solution of Ill-Posed Problem – Hadamard, Tikhonov, ea]

Resonances appeared as a by-product

That is the strategy of the GW/VPI πN PWA since 1987
N* and Δ* States coupled to πN

[SAID: http://gwdac.phys.gwu.edu/]

- GW SAID N* program consists of $\pi N \rightarrow \pi N \rightarrow \gamma N \rightarrow \pi N \rightarrow \gamma^* N \rightarrow \pi N$
  As was established by Dick Arndt on 1997

- Assuming dominance of 2-hadronic channels
  [$\pi N$ elastic & $\pi p \rightarrow \eta n$], we parameterize $\gamma^* N \rightarrow \pi N$ in terms of $\pi N \rightarrow \pi N$ amplitudes

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

- Non-strange objects in the PDG Listings come mainly from:
  Karlsruhe-Helsinki, Carnegie-Mellon-Berkeley, and GW/VPI

- The main source of EM couplings is the GW/VPI analysis

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Road Map for SAID Analysis of Scattering Data

- $\pi N$ PWA provides the base for Spectroscopy studies for non-strange baryons in all other processes.

- Our PWAs have been as model-independent as possible, so as to avoid bias when used:
  - In resonance extraction or
  - Coupled-channel analysis.

 ![Diagram showing the road map for SAID analysis](image-url)
GW DAC Search for N* and Δ*

- We are considering a resonance as a Pole in the complex plane which is not far away from the physical axis

- **Applied** directly to the data via \( BW + Bckgr \)

- **Assume:** \( S \rightarrow S_RS_B \) 
  \[
  S_R = 1 + 2iT_R \\
  T_R = (\Gamma_e/2) / [W_R - W - i(\Gamma_e/2 + \Gamma_I/2)] \\
  \Gamma = \Gamma_e + \Gamma_I \\
  \Gamma_e = \rho_e \Gamma R \\
  \Gamma_I = \rho_i \Gamma (1 - R) \\
  T_B = K_B(1 - iK_B)^{-1} \\
  K_B = a + b(W - W_R) + c
  \]

- **Map** \( \chi^2[W_R, \Gamma] \) while searching all other PW parameters
  Look for significant improvement

- **Subjective variables are**
  - Energy binning
  - Strength of constraints
  - Which PW to be searched

- **Standard PWA**
  - Tends (by construction) to miss narrow Resonances with \( \Gamma < 30 \text{ MeV} \)
  - Reveals only wide Resonances, but not too wide \( [\Gamma < 500 \text{ MeV}] \) and possessing not too small BR \( [\text{BR} > 0.04] \)

- **Modified PWA**
  - Allows to put a resonance by hands
  Then the search will allow to see how reliable/tolerable it is
GW DAC for \( \pi N \to \pi N \) & \( \pi^-p \to \eta n \)

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

- Energy dependent SP06/WI08 and associated SES
  - \( T = 0 - 2600 \) MeV
  - 4-channel Chew-Mandelstam K-matrix parameterization
  - 3 mapping variables: \( g^2/4\pi, a[\pi^-p], Eth \)
  - PWs = 30 \( \pi N \) \{15 \([I=1/2]\) + 15 \([I=3/2]\)\} + 4 \( \eta N \)
  - Prms = 99 \([I=1/2]\) + 89 \([I=3/2]\)

- 1st generation ('57-'79)
  - Used by CMB79 and KH84 analyses
  - 10k \( \pi^\pm p \) each & 1.5k CXS
  - 17% data is polarized

- 2nd generation ('80-'06)
  - SAID fits
  - 13k \( \pi^\pm p \) each, 3k CXS & 0.3k \( \pi^-p \to \eta n \)
  - 25% data is polarized
  - Meson Factories [LAMPF, TRIUMF, & PSI] are the main source of new measurements
  - There is no discrimination against data

- 3rd generation (06'+)
  - New data may come from J-PARC, GSI, FNAL MIPP, etc

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^-p \to \pi^-p )</td>
<td>13,354</td>
<td>27,136</td>
</tr>
<tr>
<td>( \pi^-p \to \pi^-p )</td>
<td>11,978</td>
<td>22,632</td>
</tr>
<tr>
<td>( \pi^-p \to \pi^0n )</td>
<td>3,115</td>
<td>6,068</td>
</tr>
<tr>
<td>( \pi^-p \to \eta n )</td>
<td>257</td>
<td>650</td>
</tr>
<tr>
<td>DR constraint</td>
<td>2,775</td>
<td>671</td>
</tr>
<tr>
<td>Total</td>
<td>31,479</td>
<td>57,157</td>
</tr>
</tbody>
</table>

\( [0 - 2600 \text{ MeV}] \to 10 \text{ data/MeV} \)

\( [550 - 800 \text{ MeV}] \to 1 \text{ data/MeV} \)

27 \( \sigma_{\text{tot}} \) and 37 \( P \) data above 800 MeV \( \to 0.03 \text{ data/MeV} \)

DRs have been derived from the first principles

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Igor Strakovsky 10
π⁻p→ηn Puzzle

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

- Several groups evaluated data before 1992
  - Cutkosky et al Phys Rev D 20, 2804 (1979)

- Most of Nimrod data do not satisfy requirements
  - [systematics (10% or more), momentum err (up to 50 MeV/c), and so on]
  - For that reason, we are not able to use them in π⁻p→π⁻p, π⁰n, and ηn PWAs

Nimrod was a 7 GeV proton synchrotron operating in the Rutherford Appleton Laboratory in UK between 1964 and 1978

[Debenham et al, Phys Rev D 12, 2545 (1975)]

[Brown et al, Nucl Phys B153, 89 (1979)]

[Feltesse et al, Nucl Phys B93, 242 (1975)]
Partial Waves $[L(2I)(2J)]$

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

- **Overall**: the difference between KH and GW/VPI is rather small but... resonances may be essentially different

\[ N(2090)^* \]

\[ N(1710)^{***} \]

\[ N(2100)^* \]

\[ \Delta(1920)^{***} \]

\[ \Delta(1600)^{***} \]

\[ |\text{Im}T|^2 - |\text{Re}T|^2 \geq 0 \text{ [unitarity boundary]} \]

**PDG10** [K. Nakamura *et al* [RPP] J Phys G 37, 075021 (2010)]

**KA84** [R. Koch, Z Phys C 29, 597 (1985)]

**Data:**
\[ \pi^+p \rightarrow \pi^0p \text{ @ 1300 MeV} \]

**PWA:**

- **KA84**: Karlsruhe-Helsinki fit, 1984
- **KB84**: KH Barrelet corrected solution, 1997
- **SP06**: GW fit, 2006

**Old solutions** may be not able to reproduce new measurements

P\(^2 + R\)^2 + A\(^2 = 1\)

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PWA2011 Workshop, Washington, DC, May 2011
Summary of $N^*$ and $\Delta^*$ Finding from GW $\pi N$ PWA

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

- **Standard PWA**
  - Allows to determine the $N^*$s, $\Delta^*$s, and their quantum numbers using
    - The complex energy plane and
    - Breit-Wigner technique
  - Tends (by construction) to miss narrow Resonances with $\Gamma < 30$ MeV
  - Reveals only wide Resonances, but not too wide ($\Gamma < 500$ MeV) and possessing not too small BR (BR > 4%)

- **PDG10 states**

  - The latest GWU analysis (Arndt06) finds no evidence for those resonances

  - PDG10 ***
    - $\Delta(1600)_{P33}$, $N(1700)_{D13}$, $N(1710)_{P11}$, $\Delta(1920)_{P33}$
    - $N(1900)_{P13}$, $\Delta(1900)_{S31}$, $N(1990)_{F17}$, $\Delta(2000)_{F35}$,
    - $N(2080)_{D13}$, $N(2200)_{D15}$, $\Delta(2300)_{H39}$, $\Delta(2750)_{I313}$
    - $\Delta(1750)_{P31}$, $\Delta(1940)_{D33}$, $N(2090)_{S11}$, $N(2100)_{P11}$,
    - $\Delta(2150)_{S31}$, $\Delta(2200)_{G37}$, $\Delta(2350)_{D35}$, $\Delta(2390)_{F37}$

- **Our study** does suggest several ‘new’ $N^*$s and $\Delta^*$s:
  - PDG10 **** $\Delta(2420)_{H311}$
  - PDG10 *** $\Delta(1930)_{D35}$
  - PDG10 ** $N(2000)_{F15}$, $\Delta(2400)_{G39}$
  - PDG10 new $N(2245)_{H111}$
**SAID for Pion Photoproduction**

- **1st generation** - ('60-'90)
  - 10k data [85% bremsstrahlung data]
  - 30% data is polarized
  - [limited coverage, broad energy binning]
- **2nd generation** - ('90-'10)
  - SAID fits
  - 25k data [60% tagged data]
  - 30% data is polarized
  - Dearth of neutron data
- **3rd generation** - ('10+)
  - New data will come from JLab, MAMI-C, Spring-8, CB-ELSA, MAX-lab, etc

**Energy dependent SP09/MA09 and associated SES**

- E = 145 - 2700 MeV
- PWs = 60 [E & M multipoles]
- Prms = 210
- Constraint:  \( M = (\text{Born} + \alpha_R)(1 + iT_{\pi N}) + \alpha RT_{\pi N} + \text{higher terms} \)

**Reaction Data**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data (Dpol)</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma p \rightarrow \pi^0 p )</td>
<td>14,052 (3 %)</td>
<td>30,949</td>
</tr>
<tr>
<td>( \gamma p \rightarrow \pi^+ n )</td>
<td>8,510 (5 %)</td>
<td>16,240</td>
</tr>
<tr>
<td>( \gamma n \rightarrow \pi^- p )</td>
<td>2,432 (0 %)</td>
<td>5,248</td>
</tr>
<tr>
<td>( \gamma n \rightarrow \pi^0 n )</td>
<td>364 (0 %)</td>
<td>1,021</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25,358</strong></td>
<td><strong>53,458</strong></td>
</tr>
</tbody>
</table>

- **Born**: no free parameters to fit

\( \pi N \) PWA [no theoretical input]

\( N(\gamma n) = 0.12 N(\gamma p) \)

** photon energy [GeV]**

\( (\gamma, p) \)

**Invariant mass [GeV]**

\( (\gamma, n) \)

**Much less known**

**5/23/2011**

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Proton Multipoles for SP09 [CLAS $\pi^0 p$ & $\pi^+ n$ data included]

[ M. Dugger et al/Phys Rev C 79, 065206 (2009)]

- **Overall:** the difference between MAID07 and SAID SP09 is rather small but...
  - Resonances may be essentially different

- MAID Ansatz has been used to determine EM couplings
- The statistical significance of any inconsistencies with the MAID analysis cannot be determined, as no uncertainties for photon helicity amplitudes estimation have been presented
- Significant changes have occurred at high energies
- Comparisons to earlier SAID fits and fit from the Mainz group show that the new SP09 solution is much more satisfactory at higher energies

- MAID07 does not include recent CLAS $\pi^0 p$ & $\pi^+ n$ and LEPS $\pi^0 p$ data

---

$S_{11} \ A_{1/2} = 100.9 \pm 3.0$ [66]
$A_{1/2} = 9.0 \pm 9.1$ [33]

$P_{11} \ A_{1/2} = -56.4 \pm 1.7$ [61]

$S_{31} \ A_{1/2} = 47.2 \pm 2.3$ [66]

$P_{33} \ A_{1/2} = -139.6 \pm 1.8$ [-140]
$A_{3/2} = -258.9 \pm 2.3$ [-265]

**CLAS for $\gamma n \rightarrow \pi^- p$**

- Complementary measurements of $\pi^-$ Photo Production, required for an isospin decomposition of the multipoles

- Principal $\pi^-$ experiments were done at Meson Factories: LAMPF, PSI, & TRIUMF

---

**PWA/Model:**
- **FA07** [No CLAS $\pi^-$]
- **MAID07** [No CLAS $\pi^-$]
- **WE09** [CLAS $\pi^-$ is in]

**CLAS g10:**
- $850 \mathrm{deg/d} \Omega$
- $E_\gamma = 1050 – 3500 \mathrm{MeV}$
- $\theta = 37 – 152 \mathrm{deg}$
- Stat = 3 %
- Syst = 7 %

---

**g13:**
- $\gamma D \rightarrow p \pi^- (p), 1.2 < E_\gamma (\mathrm{GeV}) < 1.4$

- No FSI included in both CLAS g10 & g13 [2% of statistics] data

- **G13 vs g10:**
  - broad angular coverage
  - smaller errs
  - smaller energy binning
FSI for $\gamma n \rightarrow \pi^- p$


- FSI plays a critical role in the state-of-the-art analysis
- Effect: 5% - 60%
  It depends on $E$ and $\theta$

Input: SAID $\gamma N \rightarrow \pi N, \pi N, NN$ amplitudes for 3 leading terms

DWF: CD-Bonn

$R_{FSI} = (d\sigma / d\Omega_{\pi p}) / (d\sigma^{IA} / d\Omega_{\pi p})$

Fermi motion included
FSI & $\gamma d \rightarrow \pi^- pp \rightarrow \gamma n \rightarrow \pi^- p$


$\gamma d \rightarrow \pi^- pp$ - No fit to the data

$\gamma n \rightarrow \pi^- p$

$R_{FSI} = (d\sigma/d\Omega_{\pi p})/(d\sigma^{IA}/d\Omega_{\pi p})$

-- $[IA + NN_{fsi}]/IA$
-- $[IA + (NN+\pi)_{fsi}]/IA$

$\theta(\pi^- - \pi^-)$

DESY [Bubble Chamber data]:
P. Benz e\textit{a} Nucl Phys B65, 158 (1973)

There is a sizeable FSI effect $R < 1$ from S-wave part of pp-FSI at small angles. This region narrows as the $E_\gamma$ increases.

Cuts:
$p_p > 200$ MeV/c
$p_\pi > 200$ MeV/c

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New GRAAL $\Sigma$ for $\gamma n \rightarrow \pi^0 n$


- The difference between previous Pion Prod and new GRAAL measurements may result in significant changes in the neutron couplings

$\Sigma$ are 60% of the World $\pi^0 n$ data

GRAAL data are in

- The difference between previous Pion Prod and new GRAAL measurements may result in significant changes in the neutron couplings

$\chi^2$/dp

MAID07 100
SP09 223
MA09 3.1

No FSI included
New GRAAL $\Sigma$ for $\gamma n \rightarrow \pi^- p$

[G. Mandaglio et al Phys Rev C 82, 045209 (2010)]

- Previous $\gamma n \rightarrow \pi^- p$ measurements provided a better constraint vs $\gamma n \rightarrow \pi^0 n$ case

GRAAL data are in

No FSI included

$\chi^2/\text{dp}$

- MAID07: 27
- SP09: 89
- MA09: 4.9
Neutron Multipoles for MA09 [GRAAL $\pi^0n$ & $\pi^-p$ data included]

[G. Mandaglio et al Phys Rev C 82, 045209 (2010)]

- Overall: the difference between MAID07 and SAID MA09 is rather small but...
  Resonances may be essentially different

GRAAL data are in

PWA2011 Workshop, Washington, DC, May 2011
E$_0^+$ Neutron Multipole

[G. Mandaglio et al/ Phys Rev C 82, 045209 (2010)]

[GRAAL data are in]

[Modified MAID07]

[MAID07]

η–cusp is visible for MA09

1179 new $\Sigma$ vs. 167! [That is 50% of World $\pi^-p$ data]
Preliminary $\Sigma$ Measurement II
Forward $\gamma n \rightarrow \pi^- p$

No FSI included

$\chi^2$ from new SAID PWA fit: 2.6

SAID 09 | MAID 07
There were several attempts to estimate FSI for $\gamma d \rightarrow \pi^- pp$:

- Data: prlm by LEGS Collab at BNL

There are no estimations below and above the $\Delta$-region.

The effect from FSI is small and at lowest energies has a noticeable impact on $\Sigma$. 
**Coming \( \pi \) and \( \eta \) Photo Prod Data on Nucleon**

**On Proton:**
- Mike Dugger, ASU: \( \Sigma \) for \( \gamma p \to \pi^+ n, \pi^0 p \)
- Patrick Collins, ACU: \( \Sigma \) for \( \gamma p \to \eta p \)
- Hideko Iwamoto & Bill Briscoe, GW: \( E \) for \( \gamma p \to \pi^0 p \)
- Steffen Strauch, USC: \( E \) for \( \gamma p \to \pi^+ n \)
- Brian Vernarsky & Mike Dugger, ASU: \( E \& G \) for \( \gamma p \to \eta p \)
- Jo McAndrew & Dan Watts, EU: \( G \) for \( \gamma p \to \pi^+ n, \pi^0 p \)
- Patrick Collins, ACU: \( d \sigma/d\Omega \) for \( \gamma p \to \pi^0 p \)
- Hideko Iwamoto & Bill Briscoe, GW: \( T, H, F, \& P \) for \( \gamma p \to \pi^+ n \)
- Steffen Strauch, USC: \( C_x, C_z, \& P \) for \( \gamma p \to \pi^0 p \)
- Reinhard Beck, Bonn U: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Wei Luo & Charles Perdrisat, W&M: \( P \& C_x \) for \( \gamma p \to \pi^0 p, \eta p \)
- Derek Glazier & Dan Watts, EU: \( E \) for \( \gamma p \to \pi^0 p \)
- Viktor Kashevarov, INP: \( F \& T \) for \( \gamma p \to \pi^0 p, \eta p \)
- Kevin Fissum, Lund U/GW: \( E \& G \) for \( \gamma p \to \pi^0 p, \pi^+ n \)
- Andy Sandorfi, JLab: \( d \sigma/d\Omega \& \Sigma \) for \( \gamma p \to \pi^0 p \)
- David Hornidge, MTA & Sergey Prakhov, UCLA: \( \Sigma \) for \( \gamma n \to \pi^- n \)
- Wei Chen & Haiyan Gao, Duke U: \( \Sigma \) for \( \gamma n \to \pi^- p \)
- Daria Sokhan & Dan Watts, EU: \( \Sigma \) for \( \gamma n \to \pi^- p \)
- Paul Mattione & Dan Carman, JLab: \( E \) for \( \gamma n \to \pi^- p \)
- Andy Sandorfi, JLab & Franz Klein, ACU: \( d \sigma/d\Omega \) for \( \gamma n \to \pi^0 n \)
- Berndt Krusche, Basel U: \( d \sigma/d\Omega \& \Sigma \) for \( \gamma n \to \eta n \)
- Berndt Krusche, Basel U: \( d \sigma/d\Omega \) for \( \gamma n \to \pi^- p, \pi^0 n \)
- Berndt Krusche, Basel U: \( d \sigma/d\Omega \) for \( \gamma n \to \eta n \)
- Kevin Fissum, Lund U/GW & Bill Briscoe, GW: \( d \sigma/d\Omega \) for \( \gamma n \to \eta n \)
- Hajime Shimizu, Tahoku U: \( d \sigma/d\Omega \) for \( \gamma n \to \eta n \)
- Andy Sandorfi, JLab: \( E \& G \) for \( \gamma n \to \pi^- p, \pi^0 n \)

**On Neutron:**
- Wei Chen & Haiyan Gao, Duke U: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Daria Sokhan & Dan Watts, EU: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Paul Mattione & Dan Carman, JLab: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Andy Sandorfi, JLab & Franz Klein, ACU: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Berndt Krusche, Basel U: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
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- Kevin Fissum, Lund U/GW & Bill Briscoe, GW: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Hajime Shimizu, Tahoku U: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)
- Andy Sandorfi, JLab: \( \sigma \)-tot for \( \gamma p \to \pi^0 n \)

*FSI is critical to determine Neutron Multipoles*
GW DAC for Pion Electro Prod

- Energy dependent SM08 and associated SES & SQS
- $W = 1080 - 2000$ MeV
- $Q^2 = 0 - 6$ GeV$^2$
- PWs = 60 [multipoles] $[J < 6]$
- Prms = 171
- Constraint: $\pi N +$ Pion Photo Prod PWAs [no theoretical input]

- 0.85 World Electro Prod = JLab CLAS

- PWA Problems:
  - Additional [S] Multipoles
  - $Q^2$ dependence

- Database Problems:
  - Most of data are unPolarized measurements
  - There are no $\pi^0 n$ data and very few $\pi^- p$ [no Pol measurements]
  That does not allow to determine $n$-couplings at $Q^2 > 0$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma^* p \rightarrow \pi^0 p$</td>
<td>55,766</td>
<td>81,284</td>
</tr>
<tr>
<td>$\gamma^* p \rightarrow \pi^- n$</td>
<td>51,312</td>
<td>80,004</td>
</tr>
<tr>
<td>Redundant</td>
<td>14,772</td>
<td>17,375</td>
</tr>
<tr>
<td>Total</td>
<td>121,850</td>
<td>178,663</td>
</tr>
<tr>
<td>$\gamma N \rightarrow \pi N$</td>
<td>25,358</td>
<td>53,458</td>
</tr>
<tr>
<td>All Photo*</td>
<td>147,208</td>
<td>232,121</td>
</tr>
<tr>
<td>$\pi N \rightarrow \pi N$</td>
<td>31,479</td>
<td>57,157</td>
</tr>
<tr>
<td>All $\pi N$</td>
<td>178,687</td>
<td>289,278</td>
</tr>
<tr>
<td>$\gamma^* n \rightarrow \pi^- p$</td>
<td>801</td>
<td></td>
</tr>
<tr>
<td>$\gamma^* n \rightarrow \pi^0 n$</td>
<td>No Data</td>
<td></td>
</tr>
</tbody>
</table>

Q$^2$-Data

New CLAS data are coming
Summary and Prospects

Where we are now

- \( \pi N \) analysis is crucial for the N* program
- Extended \( \pi N \) elastic and Pion Prod analyses are done up to \( W = 2.5 \) GeV
- \( \pi N \rightarrow \eta N \) and Eta Photo Prod analyses are done up to \( W = 1.65 \) GeV

What we have to do

- JLab FROST & HD-ICE, CB@MAMI-C, LEPS, CB-ELSA, & MAX-lab data could yield surprises
- Prod measurements on the `neutron' target are necessary to determine neutron couplings at \( Q^2 = 0 \) GeV^2
- Complete experiment would make possible a direct reconstruction of helicity amplitudes for PseudoScalar meson Photo Prod
- Proton Electro Prod PWA is included 125k data up to \( W = 2 \) GeV and \( Q^2 = 6 \) GeV^2

What to Expect when we are Expecting

- \( Q^2 \) evaluation of Resonance couplings up to very large \( Q^2 \)
- Neutron Electro Prod measurements are necessary to determine neutron couplings at \( Q^2 > 0 \)
- Can we reach an asymptotic regime as PQCD predicted?
- With JLab 12 GeV upgrade the spectroscopy program will extend to strange baryons
THANK YOU
THANK YOU.
Forward Cross-Sections for $\pi^0$ Photo Prod

[M. Dugger et al/ Phys Rev C 76, 025211 (2007)]

- Forward [< 40 deg in CM] measurements above E = 1200 MeV are 5% of the world data, they are Brem, and 30 years old
- No Forward measurements above E = 2100 MeV

Data:
- CLAS g1c [2007] [5%]
- CB-ELSA [2005] [15%]
- LEPS [2007] [10%]
- Brem before 1977

PWA/Model:
- FA07
- MAID07 [No CLAS+LEPS data in]
- Gießen [No CLAS+LEPS data in]
- BoGa [No CLAS+LEPS data in]

[No MAID07 & Gießen above 1650 MeV]


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- There is a disagreement at forward angles
  - CLAS vs CB-ELSA
  - SAID vs MAID

- Forward data are sensitive to highest N* [most of them are inelastic]
No prior comprehensive tagged $\pi^+n$ measurements above 800 MeV

Near its upper energy limit ($W = 2$ GeV), MAID07 exhibits structures not seen in the data.
Effect of Double-Pol Hall A data in fits to Pion Photo Prod
[R. Arndt, IS, R. Workman, Phys Rev C 67, 048201 (2003)]

- \( \gamma p \rightarrow \pi^0 p \) at 1900 MeV
- DNPL: T
  - [P.J. Bussey et al Nucl Phys B159, 383 (1979) plus]
  - Hall A: 22 \( C_x \), 21 \( C_z \) below 2 GeV
    - [K. Wijesooriya et al Phys Rev C 66, 034614 (2002)]

- No fits, predictions only

- Hall A data does allow to reproduce previous DNPL measurements for T-asymmetry well

[Courtesy of Wei Luo, March 2011]

That is not artifact!

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CLAS $\Sigma$ Beam Asymmetry in Pion Photo Prod

- New $\Sigma$ for pion reactions [g8b] will overlap previous measurements
- Above 1500 MeV, many of g8b data will be new to the world

\[ \gamma p \rightarrow p \pi^0 \quad \gamma p \rightarrow n \pi^+ \]

- CLAS $E_p = 1025 – 2075$ MeV
  $\theta = 46 – 134$ deg

[Courtesy of Mike Dugger, MENU2010]

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CLAS FROST for Helicity Asymmetry E for $\gamma p \rightarrow \pi^0 n$

$$E = \frac{1}{D_f P_T P_y} \frac{N_{3/2} - N_{1/2}}{N_{1/2} + N_{3/2}}$$

[Courtesy of Hideko Iwamoto, Feb 2011]

Preliminary

- No fits, predictions only
CLAS FROST for Helicity Asymmetry $E$ for $\gamma p \rightarrow \pi^+ n$

Circularly polarized beam – longitudinally polarized target (analysis USC)

- No fits, predictions only

[Courtesy of Steffen Strauch, APS 2010]
MAMI-B for $C_x$ - Transferred Pol from Circ Pol $\gamma: p(\gamma, \pi^0)p$

$E_{\gamma} = 425$ MeV
$E_{\gamma} = 475$ MeV
$E_{\gamma} = 550$ MeV
$E_{\gamma} = 650$ MeV
$E_{\gamma} = 750$ MeV
$E_{\gamma} = 850$ MeV
$E_{\gamma} = 975$ MeV
$E_{\gamma} = 1225$ MeV
$E_{\gamma} = 1300$ MeV

Pion angle in CM (Deg)

[Courtesy of Dan Watts, N*2009]

SP09 gives $329/63$
1x weighting for Cx* gives $187/63$
4x weighting (forced fit) gives $175/63$

Forced Fit results indicate that more Pol measurements required for constraint of a solution

No fits, predictions only

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CB@MAMI-C for F & T Asymmetries for $\gamma p \rightarrow \pi^0 n$

$P^2 + \Sigma^2 + \Omega^2 + \Theta^2 + \Theta^2 + G^2 = 1$

$FG + \Sigma T = P + EH$

[Very preliminary]

+$\eta$-thr

No fits, predictions only

[Courtesy of Viktor Kashevarov, Feb 2011]
LEGS @ BNL [HD-ICE Target] for E & G Asymmetries for $\gamma p \rightarrow \pi N$

No fits, predictions only

[Courtesy of Andy Sandorfi, Apr 2010]

MAID07

SAID09

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CLAS & CB-ELSA for G Asymmetry for $\gamma p \rightarrow \pi^0 n$

- No fits, predictions only

[Courtesy of Reinhard Beck, MENU2010]

[Courtesy of Jo McAndrew, CLAS Meeting 2011]
Our data show a dip near $W = 1670$ MeV in $\sigma_t$ and its association with a significant dip in the forward $d\sigma/d\Omega$.

This feature was missed or questionable in the analysis of previous data.
The question is – can Electro Prod experiment reach asymptotic regime as PQCD predicted?

**PQCD:** $R_{EM} = +1 \ @ \ Q^2 \to \infty$

**GW:** $R_{EM} = -1.79 \pm 0.18 \%$

**PQCD:** $R_{SM} = 0 \ @ \ Q^2 \to \infty$

- **No recent CLAS $\pi^+$ and DoblP $\pi^0$ in this GW fit**
- Agreement between Lattice and GW looks good
- Large M-multipole is not significantly different in different resonance extractions
- Differences for E-multipole are much larger

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Minimization and Normalization Factor for πN PWA [$\chi^2$/Data]

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

- **Modified $\chi^2$ function, to be minimized**

$$\chi^2 = \sum_i \left( \frac{X\theta_i - \theta_i^{\text{exp}}}{\epsilon_i} \right)^2 + \left( \frac{X - 1}{\epsilon_X} \right)^2$$

- **Normalization freedom** provides a significant improvement for our best fit results, we cannot ignore exp input

- For **nonSAID**, the Normalization constants were searched to minimize $\chi^2$ (no adjustment of the partial waves was possible)

- $\theta_i^{\text{exp}}$ measured, $\epsilon_i$ stat error, $\theta_i$ calculated, $X$ norm const, $\epsilon_X$ its error

- **GW solutions look realistic & stable vs previous and models**

<table>
<thead>
<tr>
<th>$\chi^2$/Data</th>
<th>SP06</th>
<th>FA02</th>
<th>KA84</th>
<th>EBAC</th>
<th>Gießen</th>
<th>BoGa</th>
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<td>$\pi^-p \rightarrow \eta n$</td>
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<td>2.5</td>
<td>10.5</td>
<td></td>
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</table>

FA02 [R. Arndt ea Phys Rev C 69, 035213 (2004)]
KA84 [R. Koch, Z Phys C 29, 597 (1985)]
Gießen [V. Shklyar ea Phys Rev C 71, 055206 (2005)]
BoGa: [A. Sarantsev ea (2009)]

SAID: $W < 2500$ MeV
KA84: $W < 2900$ MeV
EBAC: $W < 1910$ MeV
Gießen: $W < 2000$ MeV
BoGa: $W < 2260$ MeV

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