PyPWA

A SOFTWARE FRAMEWORK FOR PARTIAL WAVE ANALYSIS

g12-CLAS6 PWA

(JEFFERSON LAB)

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and
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Future Directions in Spectroscopy Analysis-JLab-Nov 2014
Outline

• Why PyPWA?
• Example: Baryon contamination
• JLab-PWA group (HallB-HallD-JPAC)
• g12: $n\pi\pi\pi$ and pKK
• Others: eg6 and g12-$\Delta\eta\pi$
• Summary
Future of Spectroscopy Analysis will be in the study resonances that are hidden?

- overlapping
- interfering
- wide
- small cross-sections
- non-resonant backgrounds
- ...

Furthermore

- Wave ambiguities
- Leakages
- Baryon contamination (JLab)

- More final state particles in the channel implies fewer ambiguities.
- Better known or larger acceptance implies less leakage.
- Better resolution implies less leakage.
Tagger System

**Electromagnetic Calorimeter**
lead/plastic scintillator, 1296 PMTs

**Torus Magnet**
6 Superconductive Coils

**Target** +
start counter

**Drift Chamber**
35,000 cells

**Time of Flight**
Plastic Scintillator,
684 PMTs

**Cherenkov Counter**
e/π separation, 256 PMTs

Carlos Salgado  JLab  November, 2014
g12 CLAS run

Search for new forms of hadronic matter in photoproduction

• Data taking completed in 2008
• Photon Energy up to 5.5 GeV
• More than 26 billion triggers (2-prong + 3-prong)
• Total Luminosity: 68 pb\(^{-1}\)
• Data processing completed and physics analysis in progress

Several exclusive channels are being analyzed

\[ \gamma p \rightarrow \pi^+\pi^+\pi^- (n) \]
\[ \gamma p \rightarrow (\pi^0)\pi^+\pi^- p \]
\[ \gamma p \rightarrow K^+K^+ (\Xi^{*-})(1530) \]
\[ \gamma p \rightarrow pK^+K^- (\eta\Phi) \]
\[ \gamma p \rightarrow (p\pi^+\Delta) \pi^- (\eta) \]
\[ \gamma p \rightarrow \pi^+K^+K^- (n) \]
\[ \gamma p \rightarrow e^+e^- p \]

Meson Spectroscopy
• Search for exotic mesons
• Study of Strangeonia
• ...

Baryon Spectroscopy
• Cascades
Search for $\pi_1 (1600)$

C. Bookwalter thesis - FSU g12

**SIGNAL**

$X = \omega(1320), \pi_3(1670), \pi_1(1600), ...$

$Y = \rho(770), \rho_3(1270), \rho_5(980), ...$

**Baryon BG**

$Y = \rho(770), \rho_3(1270), \rho_5(980), ...$

$Z = \Delta(1232), N(1520), N(1680), ...$

$p \rightarrow X \rightarrow Y \rightarrow \pi^+ \pi^-$

$\gamma$

$p \rightarrow Y \rightarrow \pi^+ \pi^-$

$\gamma$

$p \rightarrow Z \rightarrow \pi^+ \pi^-$

$n$
Baryon background cuts: $|t'| < 0.1$ \& $\theta_{\text{lab}}(\pi^+) < 25^\circ$

$\gamma p \rightarrow \pi^+\pi^+\pi^- n$ in g12 data

Copious baryon backgrounds present!
Baryon Contamination

Going to higher energies increase phase space: 5.75 to 9 GeV?
An experimental approach to deal with this problem is to introduce kinematical cuts with some discrimination between baryon and meson production. Since mesons are in general produced more in the lab forward direction than baryons, we can think of angular cuts to reduce baryon backgrounds.

Figure 22: $3\pi-n\pi$ scatter plots. Top row: $m(3\pi)$ vs $m(n\pi^-)$; Middle row: $m(3\pi)$ vs $m(n\pi_2^+)$; Bottom row: $m(3\pi)$ vs $m(n\pi_1^+)$. Left column: before any low $-t$ and $\pi^+_{1(2)}$ small lab angle cuts; Middle column: after low $-t$ and $\pi^+_{1(2)}$ small lab angle cuts; Right column: after low $-t$ cut, but with $\pi^+_{1(2)}$ lab angles $\geq 30^\circ$. 
Unpolarised 4.8-5.2 GeV photon beam

- Clear evidence of non-exotic $2^{++}$ state $a_2(1320)$
- No-evidence of exotic $1^{-+}$ state $\pi_1(1600)$ at the expected yield
Baryon background removal
- Large contribution from $\gamma p \rightarrow p\Delta$, $\gamma p \rightarrow pN$ processes
- We limit our sample to events with low $t'$
  - Also events with low-angle slow $\pi^+$
  - 510K events remain from $6M \gamma p \rightarrow \pi^+\pi^-\pi^- n$ events with $E_\gamma > 4.4$ GeV (494K from $M_{\pi\pi}$ between 1 and 2 GeV)

$|t'| < 0.105$
$\theta_{\text{lab}}(\pi^+) < 25^\circ$ (both)

**Mass($n\pi^+$) Before Selection**
**Mass($n\pi^-$) Before Selection**
**Mass($n\pi^0$) Before Selection**

**Mass($n\pi^+$) After Selection**
**Mass($n\pi^-$) After Selection**
**Mass($n\pi^0$) After Selection**

$e^{-3.9t'}$

Sharp $t'$ dependence consistent with $\pi$-exchange production
PWA: $2^{--} \left[ f_2(1270)\pi \right]_S$ Intensity

PWA: $2^{++} \left[ f_2(1270)\pi \right]_S$ Intensity

PWA: Intensity by $J^{PC}$

Intensities by $J^{PC}$

Major waves

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^\prime$</th>
<th>$L$</th>
<th>$Y$</th>
<th># waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{++}$</td>
<td>$1^\pm$</td>
<td>$S$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$1^{++}$</td>
<td>$1^\pm,0^+$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>3</td>
</tr>
<tr>
<td>$1^{++}$</td>
<td>$0^-,1^\pm$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>3</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>$1^\pm$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>$0^-,1^\pm$</td>
<td>$S,P,D$</td>
<td>$f_0(1270),\rho(770)$</td>
<td>9</td>
</tr>
</tbody>
</table>

+ isotropic background wave
PWA: $1^{-+}$ Intensity

Accounts for up to 3% of total intensity

PWA: $2^{-+} \left[ f_2(1270) \right]_{D}$ Intensity

- More $M = 0$ issues
- Small signals (2%) cleanly extracted in $f_2 \pi$
  $M = 1$
PWA: $1^{-} - 2^{-}$ phase motion

- No resonant $1^{-}$ phase motion observed!
JLab-PWA group
HallD-HallB-JPAC

JPAC: M. Pennington, A. Szczepaniak, Igor Danilkin, Cesar Fernandez-Ramirez, Meng Shi, Peng Guo

Hall-B: Diane Schott, Veronique Ziegler, Will Phelps, Rafael Badui, Lei Guo, Dennis Weygand, Viktor Mokeev

Hall-D: Elton Smith, Mark Ito, Simon Taylor, Yi Qiang, Mark Dalton, Carlos Salgado

- every other Friday @ 10:00 am Eastern (B101)
- e-mail list: jlab-pwa@jlab.org

since July 2012

https://wiki.jlab.org/pwawiki/index.php/Main_Page
A physics model that extends the isobar model; i.e. to consider baryon vertices, Deck-effect vertices. Furthermore other theoretical amplitude we would like to include (we had coded the Veneziano single- and double-Regge-B5 Veneziano amplitudes).

- Analyticity, Unitarity, crossing
- Regge theory
- Dispersion relations
- ...

Cesar Fernandez-Ramirez  Meng-Shi
Vincent Mathieu          B5 Model
Decided to start from

\[ \Upsilon p \rightarrow pK^+(K^-) \]

g12 CLAS run -

6.7M events after ID/KF

Monday, November 17, 2014
KK mass

```plaintext
nt.m_kk:nt.tM {nt.in.ebeam >4.4 && nt.m_kk >1.08}
```
Interesting region for strangeonia
Problems of destroying “factorization”

\[ \mathcal{F}(\vec{p}) = -\ln \mathcal{L} = - \sum_{i=1}^{N} \ln \left[ \sum \text{ext. spins} (\mathcal{M}\mathcal{M}^*) \right] + \eta_x \frac{1}{N_a} \sum_{i} \sum_{\text{ext. spins}} (\mathcal{M}\mathcal{M}^*). \] (9)

\[ I(\tau) = \sum_{k} \sum_{b,b'} \epsilon_A(\tau)^{\epsilon_k V_b^{k}\epsilon V_{b'}^{k*} \epsilon A_{b'}^{*}(\tau)} \]

\[ -\ln \mathcal{L} \propto \sum_{i=1}^{N} \ln \left[ \sum_{k,c} \rho_{\gamma} \sum_{b,b'} \epsilon V_{b}^{k}\epsilon V_{b'}^{k*} \epsilon A_{b}(\tau_i) \epsilon A_{b'}^{*}(\tau_i) \right] - \eta_x \sum_{k} \sum_{b,b'} \epsilon V_{b}^{k}\epsilon V_{b'}^{k*} \epsilon \Phi_{b,b'}^{x} \]

Normalization

Integrals
PyPWA
A Partial-Wave-Analysis Software Framework

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Abstract

We describe a software framework used to perform Partial Wave Analysis (PWA) with the goal of extracting resonance information from multiparticle final states. The software is directed to photoproduction experiments using linear polarized beams. This software can also be used to extract model parameters from data by performing extended likelihood fits. Although general amplitudes can be use, the framework includes a very specific realization of the Isobar model, with extensions to include Deck-type and baryon vertices corrections. We describe the step-by-step precesses leading to a full PWA of data. A tutorial and examples are also included. Most of the code is in Python, but hybrid code (in Cyhon or Fortran) has been used when appropriate. Scripting for use of the JLab Linux computer farm, parallel coprocessors (Xeon-Phi or GPUs) are also included. The goal of this software framework is to create an user friendly environment of fast executing code to perform PWA.
Our goal is to write a very flexible PWA package that interface with different languages, codes and formats.

- GUI driven use of JLab resources (i.e., Farms).
- Hybrid programming, where languages are used as they are adequate for the specific task and then interfaced. For example, Python being a high-level programming language makes a better scripting language to “glue” several programming modules, and Fortran and C are more basic languages with much faster number-crunching looping.
- Vectorization works by exploiting the combined add-multiply unit of the Intel Xeon Phi
- Include full documentation (tutorials examples...)
- Many options for optimization (i.e. minimization algorithms) and plotting tools
PyPWA software environment is flexible, completely open, and ready-made for integration with external tools (modules). It provides a collection of modules with lots of functions and classes that can be contained in a single file simplifying bookkeeping. Interfacing with Fortran, C and C++ code is made easy; there very efficient toolkits for data computing (Numpy and Scipy) and graphics (Matplotlib) that are easy to interface and offer fast array handling, many options for optimization (i.e. minimization algorithms) and plotting tools.
GUI driven
PyPWA: A Partial-Wave-Analysis Software Framework

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We describe a software framework used to perform Partial Wave Analysis (PWA) with the goal of extracting resonance information from multiparticle final states. The software is directed to photoproduction experiments using linear polarized beams. The software can also be used to extract model parameters by comparing model and data, by performing extended likelihood fits. Although very general models from amplitudes can be use, the framework includes a very specific realization of the isobar model, with extensions to include Deck-type and baryon vertices corrections. We describe the step-by-step processes leading to a full PWA of data. We also describe the Monte Carlo approach to simulate data given a set of resonances and waves, or the waves parameters found in a previous fit to the data. Examples are also included.

Most of the code is written in Python, but hybrid code (in Cython or Fortran) has been used when appropriate. The software is directed to be used at Jefferson Lab, therefore is specifically adapted to Jefferson Lab Scientific Computing resources. Scripting for use of the JLab Linux computer farm, parallel coprocessors (Xeon-Phi or GPUs) are included. The goal of this software framework is to create a user friendly environment of fast executing code to make PWA easier at JLab.
Welcome to PyPWA!

Source Listing

**dataTypes**

- gampEvent
- gampParticle
- resonance
- wave
- fileHandlers
- bampReader
- gampReader
- getWavesGen
- dataTypes
- gampEvent
- gampParticle
- resonance
- wave
- utilities
- brietWigner
- chunks
- dataSimulator
- minuitLikelihood
- OHMIntensity
- randM
- model
- complexV
- getPhi
- intensity
- magV
- normInt
- nTrue
- prodAmp
- spinDensity

Indices and tables

- Index
- Module Index
- Search Page

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**dataTypes**

This module contains the various data types used within the PWA project.

**gampEvent**

```python
class pythonPWA.dataTypes.gampEvent, gampEvent(particles=[1], accepted=None, raw=None)
```

This class represents a single gamp event. That is to say that this class contains a set of particles and a flag to specify if this event is accepted into the filtered data set.

**gampParticle**

```python
class pythonPWA.dataTypes.gampParticle, gampParticle(particleID=None, particleCharge=None, particleXMomentum=None, particleYMomentum=None, particleZMomentum=None, particleE=None)
```

This class represents a particle described in a single line of a .gamp file.

```python
toString()
```

Returns a string of the particle data members delimited by newlines.

**resonance**

```python
class pythonPWA.dataTypes.resonance, resonance(cR=1.0, wR=1.0, r0=0.5, phase=0.0)
```

This class represents a resonance.

```python
toString()
```

Returns a string of the resonance data members delimited by newlines.

**wave**

```python
class pythonPWA.dataTypes.wave, wave(epsilon=0.0, complexamplitudes=[1], w0=1.000, r0=100.0, beta=0.0, k=0)
```

This class represents a PWA wave.

```python
toString()
```

Returns a string of all the wave properties delimited by newlines.
Jlab web-page - Tutorials and links
wiki - github JeffersonLab/PyPWA
Sphinx generated: docs
Experimental Physics Computing

The batch farm contains 116 nodes with 8, 16 or 32 cores:

- **2013**: 24 nodes, 16 core 2.6 GHz Xeon (Ivy Bridge), 32 GB memory, dual 1 TB disks, DDR IB
- **2012**: 32 nodes, 16 core 2.0 GHz Xeon (Sandy Bridge), 32 GB memory, dual 500 GB disks, DDR IB
- **2011**: 2 nodes, 32 core 2.0 GHZ AMD, 64 GB memory, 1 TB disk, SDR IB
- **2011**: 18 nodes, 8 core 2.53 GHz Xeon (Westmere), 24 GB memory, dual 500 GB disk, SDR IB
- **2010**: 24 nodes, 8 core 2.4 GHz Xeon (Nehalem), 24 GB memory, 500 GB disk, SDR IB
- **2009**: 16 nodes, 8 core 2.4 GHz Xeon (Nehalem), 24 GB memory, 500 GB disk, SDR IB

The batch farm runs mostly serial jobs which spend part of their time in wait states for file I/O, and so the number of cores is slightly oversubscribed by the batch system, with 1,800 job slots available for the 1,400 available cores. Hyperthreading is enabled for the Xeons, giving the appearance of 2,800 cores. Memory per core is typically 2GB, depending on the node generation. Jobs with larger memory requirements than 2 GB can still run by declaring their memory requirements. The batch system will leave slots on the same node unused so as to effectively allocate that memory to the larger job.

**Farm Networking**

All farm nodes are connected to both the Ethernet fabric and the Infiniband fabric, where the IB fabric is used for high speed access to the file servers. About half of the nodes have SDR cards (single data rate IB, 10 Gb/s), recycled from the decommissioned 2006 LQCD 6n cluster. The latest nodes have DDR cards (double data rate IB, 20 Gb/s), recycled from the decommissioned 2007 LQCD 7n cluster. Up to 22 nodes are connected to an SDR or DDR switch. These "leaf" switches have uplinks to a farm "core" DDR switch, which in turn has a pair of uplinks to an adjacent QDR LQCD switch, and from there they can reach the file systems.

By using Infiniband, the total file system bandwidth into the farm can now be >3 GBytes/s, sufficient for 40 nodes to be streaming data to or from their local disks concurrently. For additional information on the file system, see the next chapter on Disk Servers.
The HPC / LQCD batch system includes 3 Infiniband clusters (3 generations of Intel CPUs), 3 GPU clusters with 5 types of GPU cards, and one small cluster with Xeon Phi accelerators.

**Infiniband Clusters**

- **12s** (2012 Sandy Bridge) -- 275 nodes, 16 cores, 32 GB memory, QDR Infiniband (40 Gb/s).
- **10q** (2010 QDR) -- 224 nodes, 8 cores, 24 GB memory, QDR IB.
- **9q** (2009 QDR) -- 328 nodes, 8 cores, 24 GB memory, QDR IB.

**MIC / Xeon Phi Cluster**

- **12m** (2012 MIC) -- 16 nodes, 16 cores, 64 GB memory, FDR (56 Gb/s) IB.

**GPU Clusters** are organized as four clusters according to the generation of the host servers:

- **12k** (2012 Kepler) -- 42 nodes, 16 cores, 128 GB memory, quad K20m, FDR IB.
- **11g** (2011 gpu) -- 8 nodes, 8 cores, 48 GB memory, quad C2050, QDR IB.
- **10g** (2010 gpu) -- 53 nodes, 8 cores, 48 GB memory, quad GPU (mix), QDR/SDR IB.
- **9g** (2009 gpu) -- 62 nodes, 8 cores, 48 GB memory, quad GPU (mix), SDR IB.

All clusters (partitions) have 2 IB uplinks into the main disk server Infiniband fabric, and access all of the filesystems except some of the /group areas over Infiniband.
Event Selection

- To reconstruct $\eta$, the missing mass off of the $p\pi^+\pi^-$ was used in combination with the $\gamma\gamma$.

- Selected the $\eta$ and fit the kinematic variables using conservation of $E$ and $p$ to improve tracks.

- The fitter is given the assumption the neutral particle is $\eta$. The kinematic fitter refits the kinematic variables under this assumption and returns a probability of the assumption being correct.
Baryon Selection: $\gamma p \rightarrow \Delta^{++} X$, $\Delta^{++} \rightarrow p\pi^+$

$M(p\pi^+) < 1.3$ GeV

$M(\eta\pi^-)$

$M(p\pi^+) \rightarrow \Delta^{++}$

$M(\eta\pi^-) \rightarrow \alpha_0, \alpha_2$

Entries = 36926.0

Entries = 8710.0
PWA: Mass Independent Fit

\[ J^{PC} m = 1^{-+1}, \ 2^{++1} \]

\[ J^{PC} m = 0^{++0} \]

- The strongest contribution is from the D wave.
- The S wave shows a broad background with 1/2 the intensity of the D wave.
\[ \gamma p \rightarrow \Delta^{++} \eta \pi^- \]

- Fit with \( a_2 \) and constant background
- Mass: \( 1.32 \pm 0.01 \) GeV
- Width: \( 0.14 \pm 0.01 \) GeV
- No exotic was concluded to be seen in the final fit.
- This is the first look into \( \eta \pi^- \) using photoproduction!
eg6: Meson spectroscopy in coherent production off $^4$He

- search for exotics in $\pi\eta$, $\pi\eta'$ final states - $\pi_1$ (1400)
- 6 GeV electron beam on target on high pressure gas target
- All neutrals triggers (no scattered electron measured)
- recoiling nucleus detected in Radial TPC
- hadronic final state detected in CLAS
- PWA greatly simplify: $C=-1$ and NPE only allowed ($\omega$ exchange)
- No baryon background

STATUS
- data taking completed in fall 2009
- Reconstruction of data in progress
Summary

Meson Spectroscopy together with LQCD calculations promise to provide a window to detailed studies of **strong interactions** at intermediate energies.

**PyPWA - High-statistics Photoproduction with Linear Polarization:**
Two Hadron Spectroscopy program at Jefferson Lab
- CLAS12 using a beam of “quasi-real” photons
- GlueX using a linearly polarized photo beam

**Partial Wave Analysis progress:**
- Theory: improve models - include more amplitudes in PWA
- Computing: increase computer efficiency - Parallel computing - vectorization of existing code (GPU, Xeon Phi). Faster / user friendly.
- Algorithms: Minimization/Optimization (Genetic Algorithms,...)

For a good understanding of the meson spectrum we will need to analyze data from different beams (production mechanisms), different channels (coupled channel analysis) and consider an **improvement in our models and analysis (software & hardware) tools** accordingly with the expected high statistics experiments.