Precision Measurements of Spin-Density Matrix Elements at GlueX

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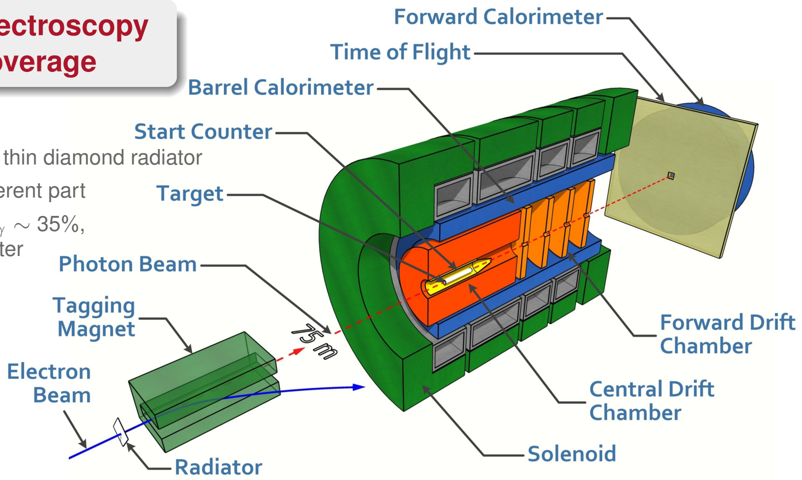
Jefferson Lab
Thomas Jefferson National Accelerator Facility

1. Introduction to Spin-Density Matrix Elements
   - $\rho(770) \to \pi^+\pi^-$
2. Preliminary Results
   - $\omega(782) \to \pi^+\pi^-\pi^0$ and $\pi^0\gamma$
   - $\Lambda(1520) \to K^- p$
3. Summary and Outlook

Light quark meson spectroscopy
with **full angular coverage**

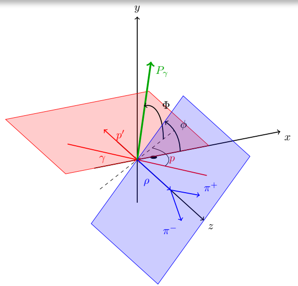
- Coherent Bremsstrahlung on thin diamond radiator
- Collimator to suppress incoherent part
- Linear polarization in peak $P_\gamma \sim 35\%$, measured by Triplet polarimeter
- Polarization rotated into 4 different orientations
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma$/s in peak



→ P. Pauli, Accessing glue through photoproduction measurements at GlueX (Thursday morning)

Production Mechanism
Spin-Density Matrix Elements

- **Spin-density matrix elements ρ^k_{ij}** describe the polarization of states, which is measured by the angular distribution of their decay products
- Information about polarization transfer is **input for production models**
- Linear beam polarization provides access to **nine** linearly independent SDMEs
- Intensity W is function of decay angles $\cos\vartheta$ and φ in the helicity frame, the direction Φ and the degree of the beam polarization P_γ



$$W(\cos\vartheta,\varphi,\Phi) = W^0(\cos\vartheta,\varphi) - \mathbf{P}_\gamma \cos(2\Phi) W^1(\cos\vartheta,\varphi) - \mathbf{P}_\gamma \sin(2\Phi) W^2(\cos\vartheta,\varphi)$$

$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

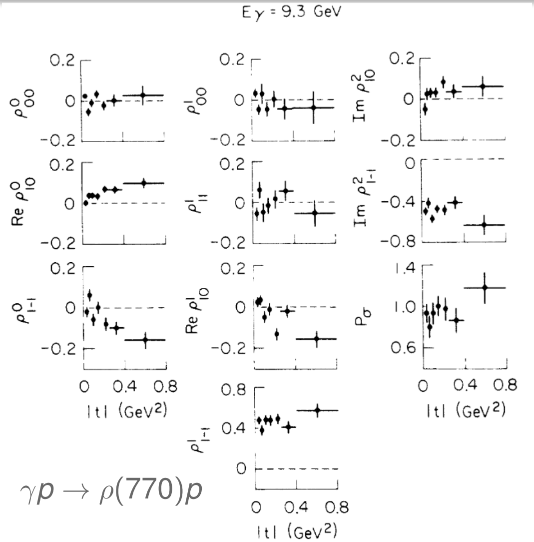
$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

Schilling *et al.* [Nucl. Phy. B, 15 (1970) 397]

Previous Measurements

SLAC, Ballam *et al.* [Phy. Rev. D, 7 (1973) 3150]



$\gamma p \to \rho(770)p$

$\gamma p \to \rho(770)p$

- Few thousand events, 7 bins in t
- s-channel helicity conservation
- Dominated by natural parity exchange

$\gamma p \to \omega(782)p$

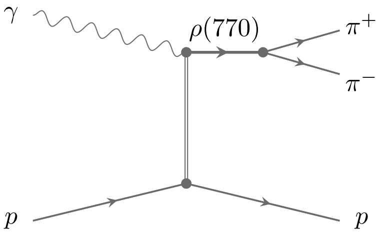
- Several hundred events, 3 bins in t

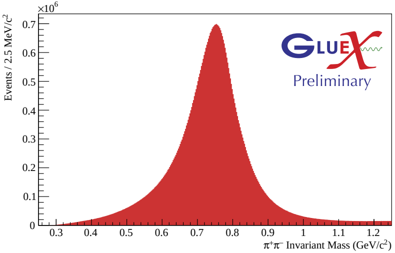
$\gamma p \to K^+\Lambda(1520)$

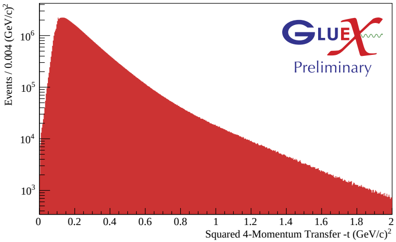
- No prior measurement at these energies

ρ-Meson Photoproduction

$\gamma p \to \rho(770) p$







- Largest hadronic cross section
- 17% of full GlueX-I data:
  $>$10M events in each of the 4 polarization orientations
- Good coverage in t between 0.1 and 1 $(\text{GeV}/c)^2$

Extraction of SDMEs

$$I(\Omega, \Phi) \propto W(\cos\vartheta, \varphi, \Phi) = W^0(\cos\vartheta, \varphi) - P_\gamma \cos(2\Phi) W^1(\cos\vartheta, \varphi) - P_\gamma \sin(2\Phi) W^2(\cos\vartheta, \varphi)$$

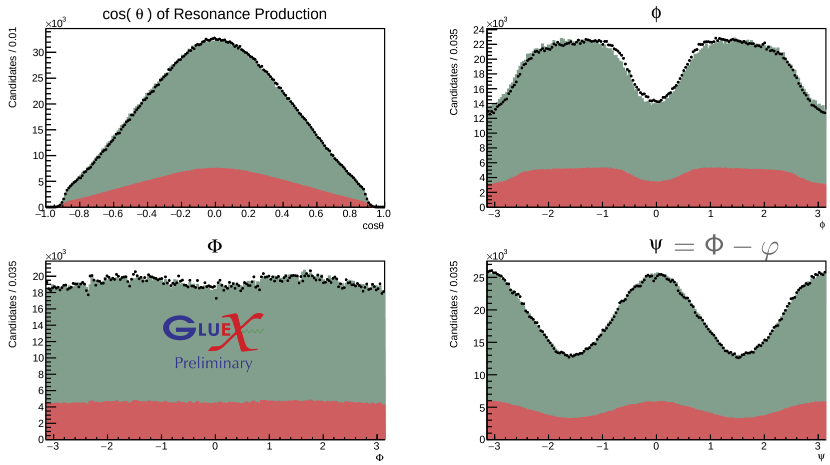
Partial-Wave Analysis Technique: Extended Maximum-Likelihood Fit

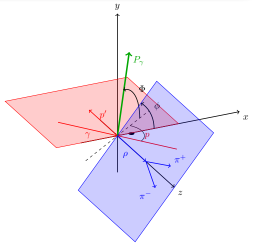
$$\ln L = \underbrace{\sum_{i=1}^{N} \ln I(\Omega_i, \Phi_i)}_{\text{Signal Events}} - \underbrace{\sum_{j=1}^{M} \ln I(\Omega_j, \Phi_j)}_{\text{Background}} - \underbrace{\int d\Omega d\Phi\, I(\Omega, \Phi)\, \eta(\Omega, \Phi)}_{\text{Normalization Integral}}$$

- Maximize by choosing SDMEs such that the intensity fits the observed N events
- Background subtracted in likelihood
- Normalization integral evaluated by a phase-space Monte Carlo sample with the unbinned, multi-dimensional acceptance $\eta(\Omega) = 0/1$
- Computation of sums optimized for GPU acceleration, $\approx 200\times$ speed

Fit Evaluation

Example bin: $t \approx 0.138\,\mathrm{GeV}^2$



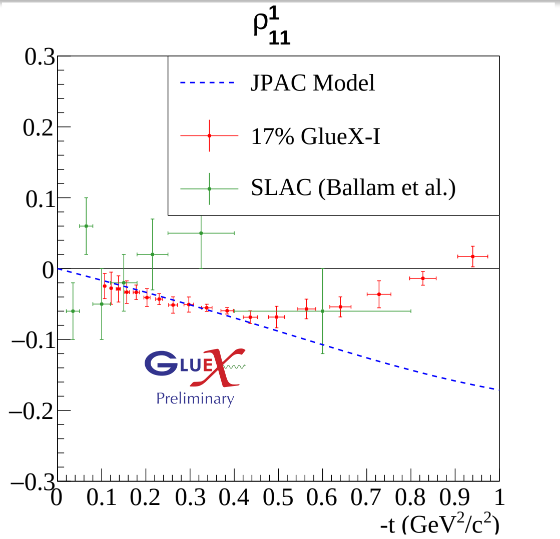


- Data
- Accidental BG
- Weighted MC

- Canceling of detector effects
- Small inconsistency in φ

ρ-Meson Photoproduction

$\gamma p \to \rho(770) p$

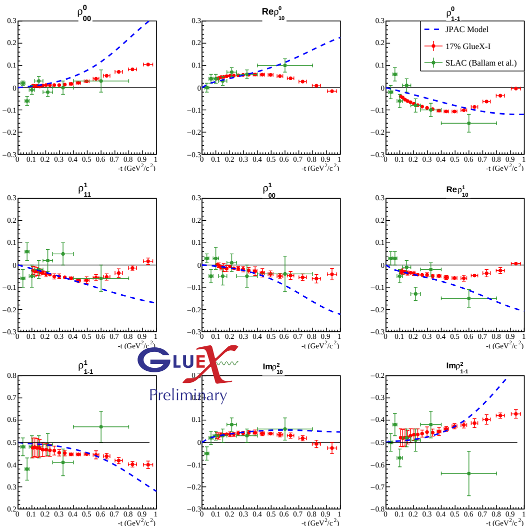


- Combination of 4 orientations with constraints
- Systematics dominate uncertainties
- Agreement with model for $-t < m^2(\rho(770))$

Mathieu *et al.* [Phy. Rev. D, 97 (2018) 094003]

ρ-Meson Photoproduction

$\gamma p \to \rho(770) p$



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Evaluation of systematic uncertainties

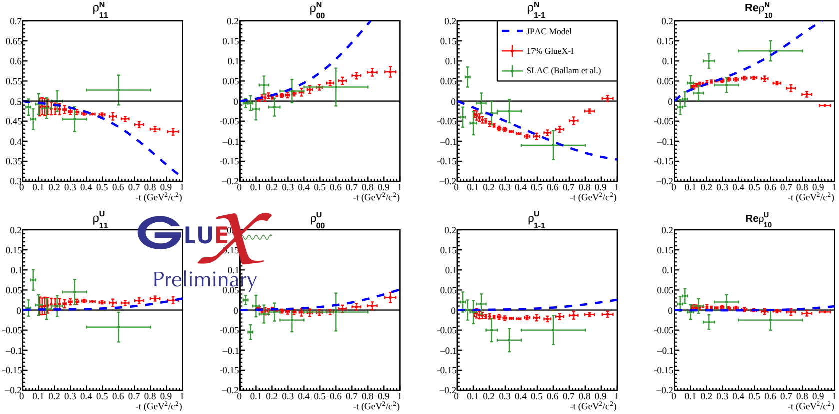
- 4 orientations $\Rightarrow$ 4 separate data sets
- Requirement for precise understanding of multi-dimensional acceptance
- External measurement of beam polarization

ρ-Meson Photoproduction

$\gamma p \to \rho(770)p$

Spin-density matrix can be separated in contributions from **natural** and **unnatural** parity exchange in the *t* channel

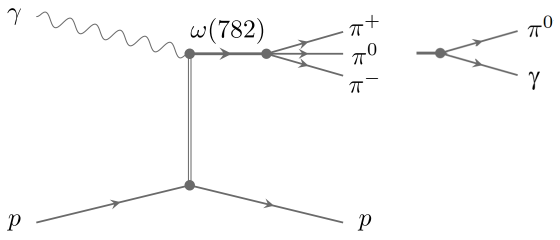
$\rho^{N,U}_{ik} = \frac{1}{2}(\rho^0_{ik} \mp (-1)^i \rho^1_{-ik})$ from Schilling *et al.* [Nucl. Phy. B, 15 (1970) 397]

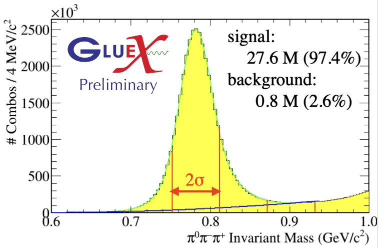


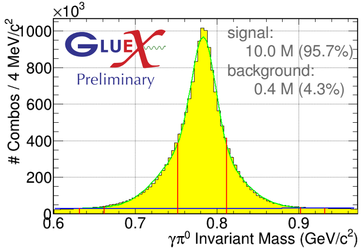
- $t \to 0$: only $\rho^N_{11} \neq 0$ $\Rightarrow$ $s-$channel helicity conservation
- All t: Natural parity exchange dominates

ω-Meson Photoproduction

$\gamma p \to \omega(782) p$





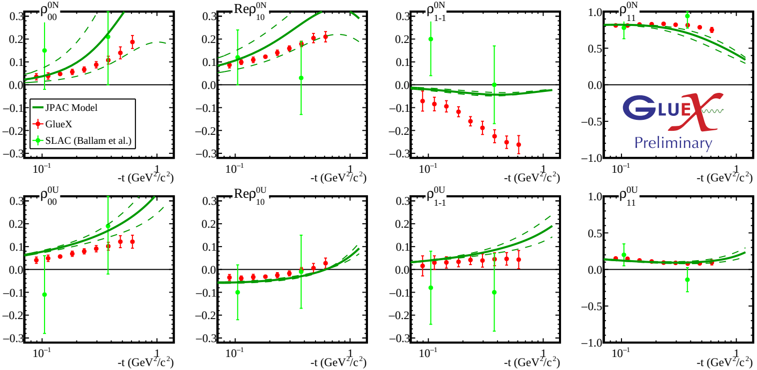


- Full GlueX-I data, large cross section
- Different decay modes, very small background

Powerful tool to evaluate systematic uncertainties

ω-Meson Photoproduction

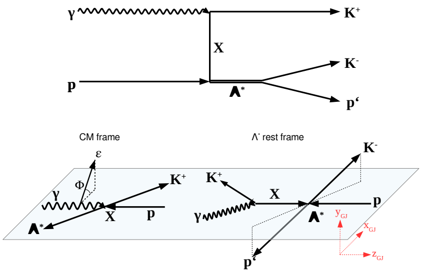
$\gamma p \to \omega(782)p \quad , \quad \omega \to \pi^+\pi^-\pi^0$



- Natural parity exchange dominates, but unnatural contributions important
- Qualitative agreement with JPAC model $\rightarrow$ strong constraints for Regge models
- Precise modeling of experimental acceptance important

$\gamma p \to K^+ \Lambda(1520)$
$\Lambda(1520) \to K^- p$

- Target excitation: very different kinematics
- Full angular distribution of $\Lambda(1520)$ decay is described by **spin-density matrix elements ρ^k_{ij}**
- Linear beam polarization provides access to **nine** linearly independent SDMEs ($\rho^0_{33} + \rho^0_{11} = 0.5$)
- Intensity ***W*** is expressed as function of angles **$\cos\vartheta$, φ, Φ** and degree of polarization ***P_γ***



$$W(\cos\vartheta, \varphi, \Phi) = W^0(\cos\vartheta, \varphi) - \mathbf{P}_\gamma \cos(2\Phi) W^1(\cos\vartheta, \varphi) - \mathbf{P}_\gamma \sin(2\Phi) W^2(\cos\vartheta, \varphi)$$

$$W^0(\cos\vartheta, \varphi) = \frac{3}{4\pi}\left(\rho^0_{33}\sin^2\vartheta + \rho^0_{11}\left(\frac{1}{3} + \cos^2\vartheta\right) - \frac{2}{\sqrt{3}}\mathrm{Re}\rho^0_{31}\sin 2\vartheta\cos\varphi - \frac{2}{\sqrt{3}}\mathrm{Re}\rho^0_{3-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^1(\cos\vartheta, \varphi) = \frac{3}{4\pi}\left(\rho^1_{33}\sin^2\vartheta + \rho^1_{11}\left(\frac{1}{3} + \cos^2\vartheta\right) - \frac{2}{\sqrt{3}}\mathrm{Re}\rho^1_{31}\sin 2\vartheta\cos\varphi - \frac{2}{\sqrt{3}}\mathrm{Re}\rho^1_{3-1}\sin^2\vartheta\cos 2\varphi\right)$$

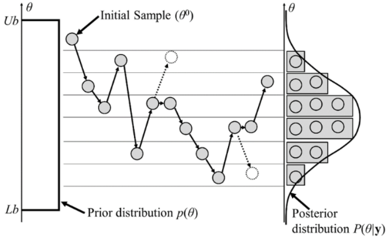
$$W^2(\cos\vartheta, \varphi) = \frac{\sqrt{3}}{2\pi}\left(\mathrm{Im}\rho^2_{31}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{3-1}\sin^2\vartheta\sin 2\varphi\right)$$

$\gamma p \to K^+\Lambda(1520)$

$\Lambda(1520) \to K^- p$

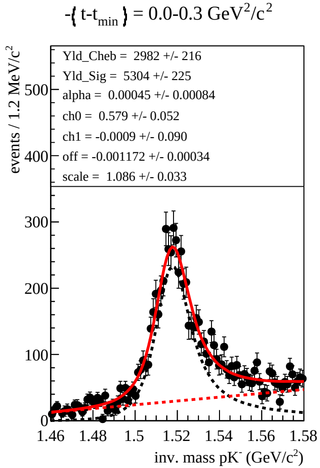
Event Selection

- sPlot weighting technique for background subtraction
- Accessible t range: 0.2 - 1.8 $(\mathrm{GeV}/c)^2$
- 17% of GlueX-I data set:
  $\rightarrow$ about 32,200 events



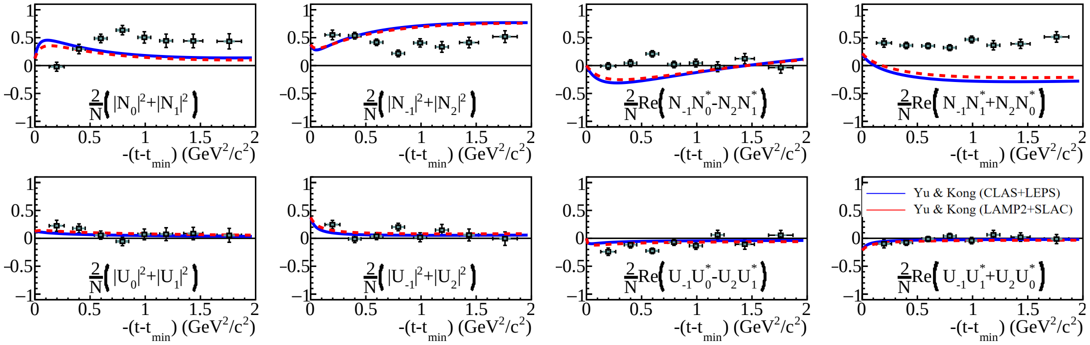
Markov-Chain Monte Carlo

- Numerical exploration of full parameter space
- Better estimation of correlated uncertainties



Hyperon Photoproduction

$\gamma p \rightarrow K^+\Lambda(1520)$



- **First ever polarized measurement**
- **Natural parity exchange** contributions dominate
- Theory models fitted to previous results, show significant deviations

Summary

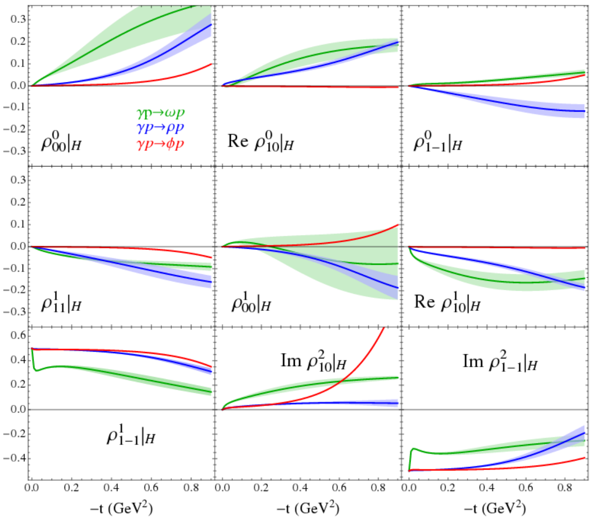
- **Unique data sets** under active analysis
- Statistical precision by **orders of magnitude** higher than previous experiments
- Unprecedented study of **production mechanism and polarization transfer**
- Sensitivity to detailed understanding of detector acceptance

Outlook

- Several analyses close to publication
- Understanding of detector acceptance and methods **essential for precision hadron spectroscopy**
- **Partial-Wave Analysis framework** for large data sets is under active development
- Information about production mechanism essential for constraining wave set

Acknowledgments: gluex.org/thanks

JPAC Model



- Regge model, fit to SLAC data
- Detailed prediction for t-dependence of ρ, ω and ϕ meson production
- s-channel helicity conservation at $t = 0$

Mathieu *et al.* [Phy. Rev. D, 97 (2018) 094003]

Fit Performance

AmpTools (Indiana University)

$$\ln L = \underbrace{\sum_{i=1}^{N} \ln I(\Omega_i)}_{\text{Signal Events}} - \underbrace{\sum_{j=1}^{M} \ln I(\Omega_j)}_{\text{Background}} - \underbrace{\int d\Omega \, I(\Omega)\, \eta(\Omega)}_{\text{Normalization Integral}}$$

Example bin: $t \approx 0.138\,\text{GeV}^2$

- Several million signal and background events
- Several million MC events
- Amplitude depends on parameters, cannot be precalculated
- Single thread CPU: $\approx 20\,\text{min}$
- Optimized code on GPU: < 10 seconds
- Systematic studies require $O(10^3)$ fits

AmpTools Performance

- Test in 2014 on Indiana U.'s Cray XE6/XK7 with Tesla K20 GPUs: fit is based on an application to BESIII data, but similar computational challenges can be expected for GlueX
- Observations: excellent CPU-only scaling up to 1,000 processes doing a single minimization, single GPU provides about 200x speed gain
- Continue to develop features that let users tune performance

Example: GlueX optimization for SDME fit

- Initial fit: 2060 seconds to converge
- AmpTools memory optimizations: 547 seconds to converge
- Add GPU acceleration: 5 seconds to converge
- All fits had identical solutions