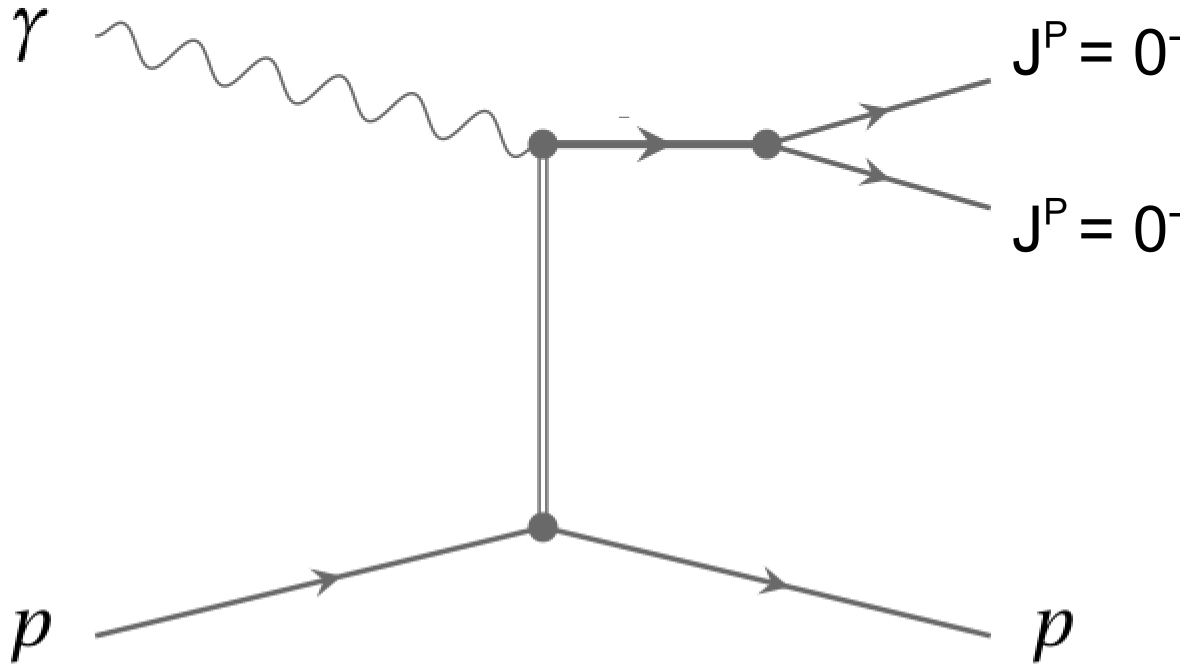
Amplitude Analysis of Two-Pseudoscalar Meson Systems at GlueX



4th Workshop on Future Directions in Spectroscopy Analysis (FDSA2022)

Alexander Austregesilo
Thomas Jefferson National Accelerator Facility
Newport News, Virginia

November 16, 2022

Special case ηπ: [M. Albrecht, Tue 14:05]

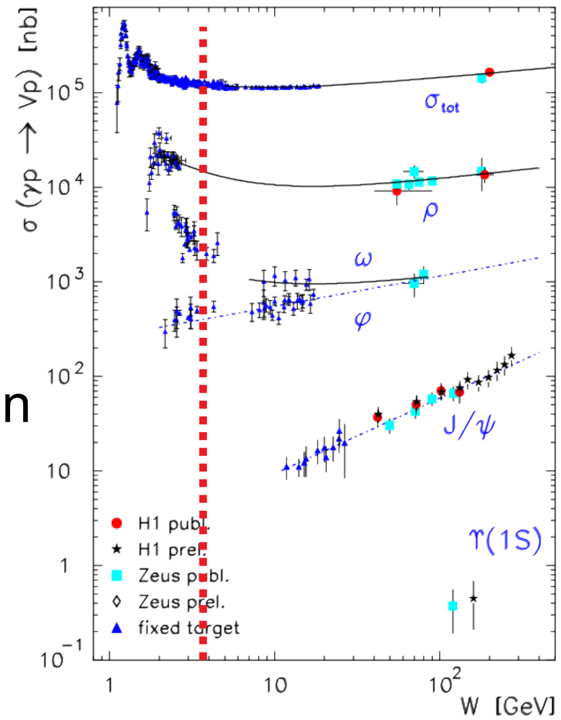
The GlueX Experiment in Hall D

Goal: Search for Hybrid Mesons

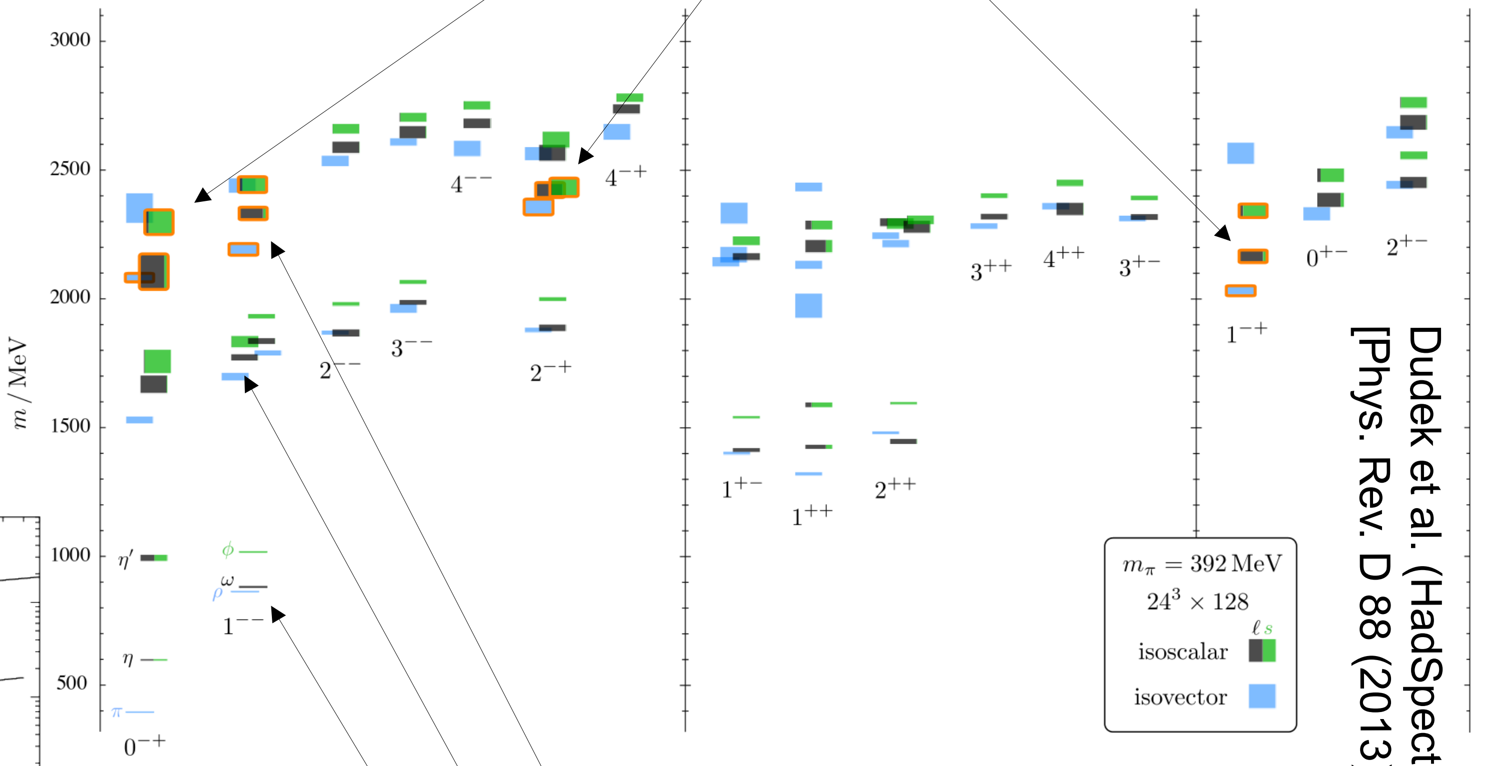
- Explore the light meson spectrum
- Establish multiplets
- Study states with both exotic and non-exotic quantum numbers

Vector Mesons:

- $J^{PC}=1^{--}$
- Abundant in photoproduction
- Limited information



Hybrid Candidates



Dudek et al. (HadSpect) [Phys. Rev. D 88 (2013), 094505]

Hybrid candidates

Excited vector mesons

Ground states

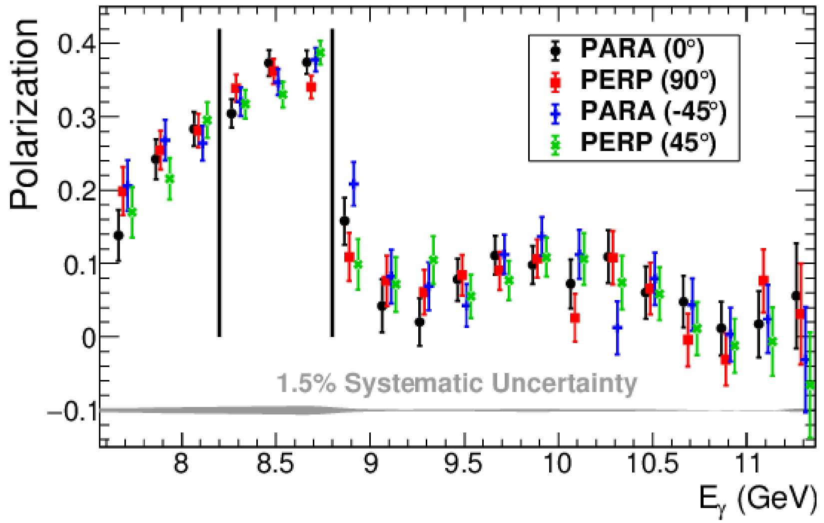
The GlueX Experiment in Hall D

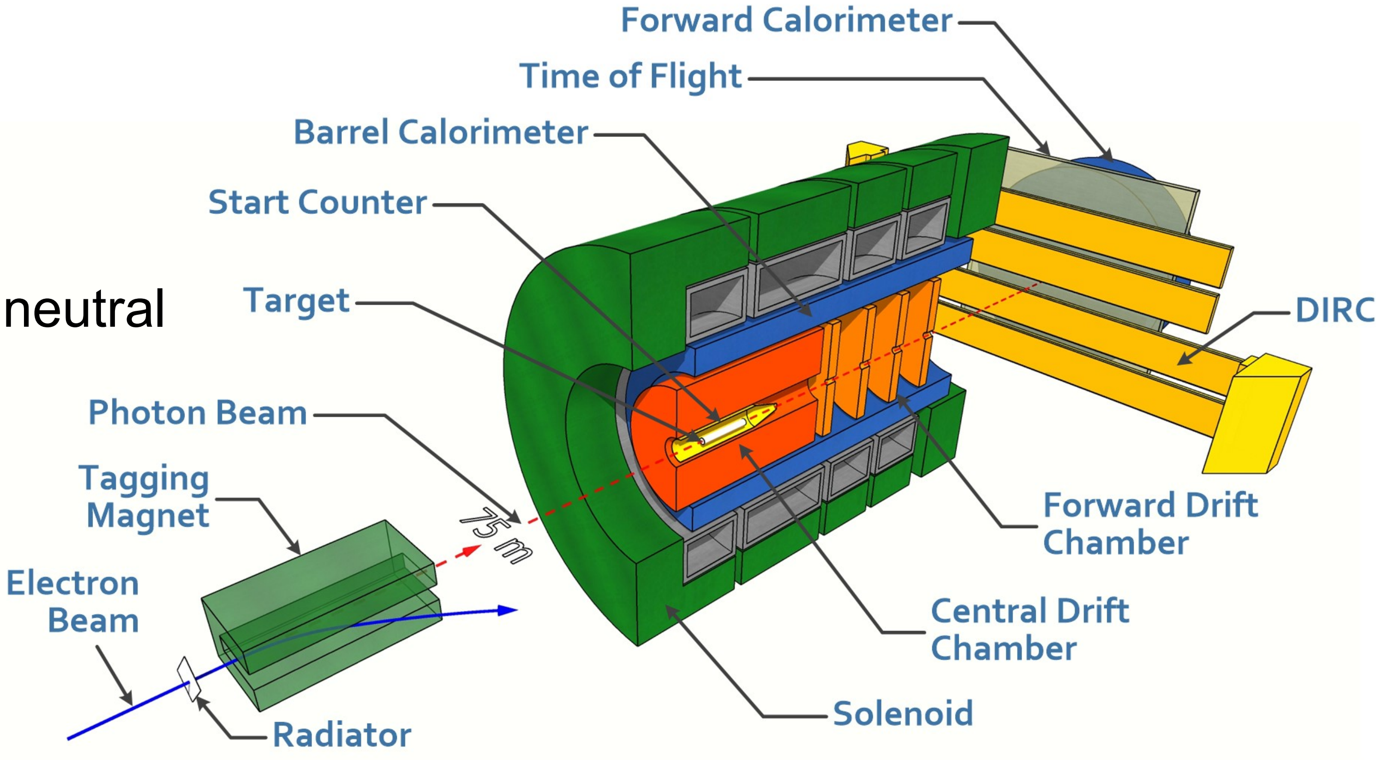
Linearly-polarized Photon Beam:

- Energy up to 12GeV
- Coherent Bremsstrahlung on diamond radiator
- Up to 40% polarization at 9GeV
- Energy tagged by scattered electrons

Experimental Apparatus:

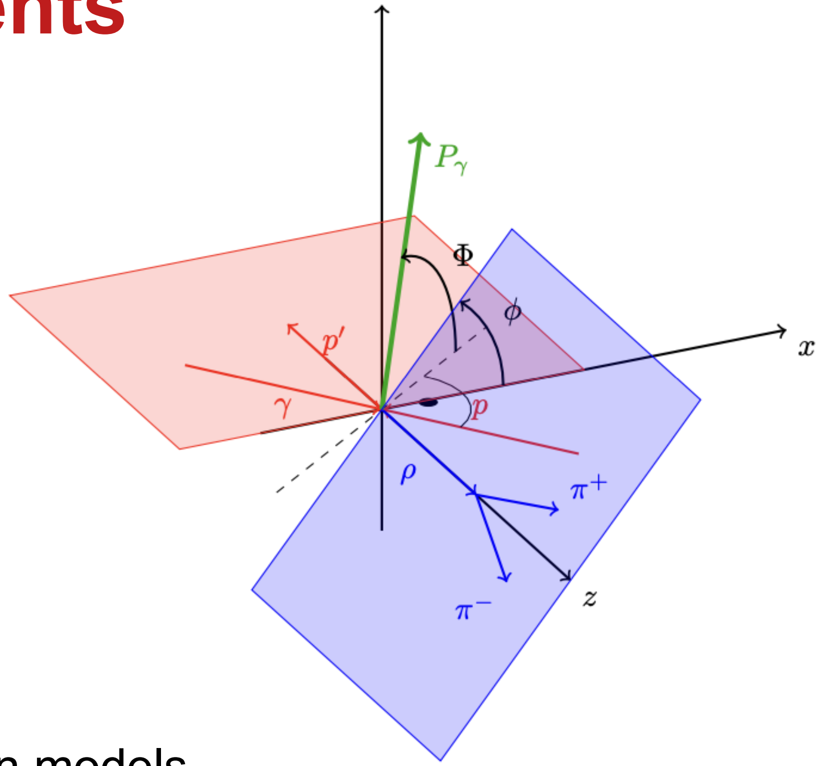
- Nearly complete coverage for charged and neutral particles in final state
- Data taking of Phase 1 complete: 125pb^{-1} in coherent peak
- Enhanced particle ID in Phase 2 (started in 2020)





[NIM A987, 164807 (2021)]

Vector Meson Spin-Density Matrix Elements



Motivation

- Detailed theory prediction, but previous measurements limited
- Sensitive to angular components of detector acceptance
- Multiple decay modes for some channels
- Development of partial-wave analysis tools for large data sets

Method

- SDMEs ρ_{ij}^k measured by angular distribution of decay products
- Linear beam polarization gives access to 9 SDMEs, input for production models
- Intensity expanded in $\cos\vartheta$, φ in helicity frame, direction Φ and magnitude P_γ of beam polarization

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

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

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

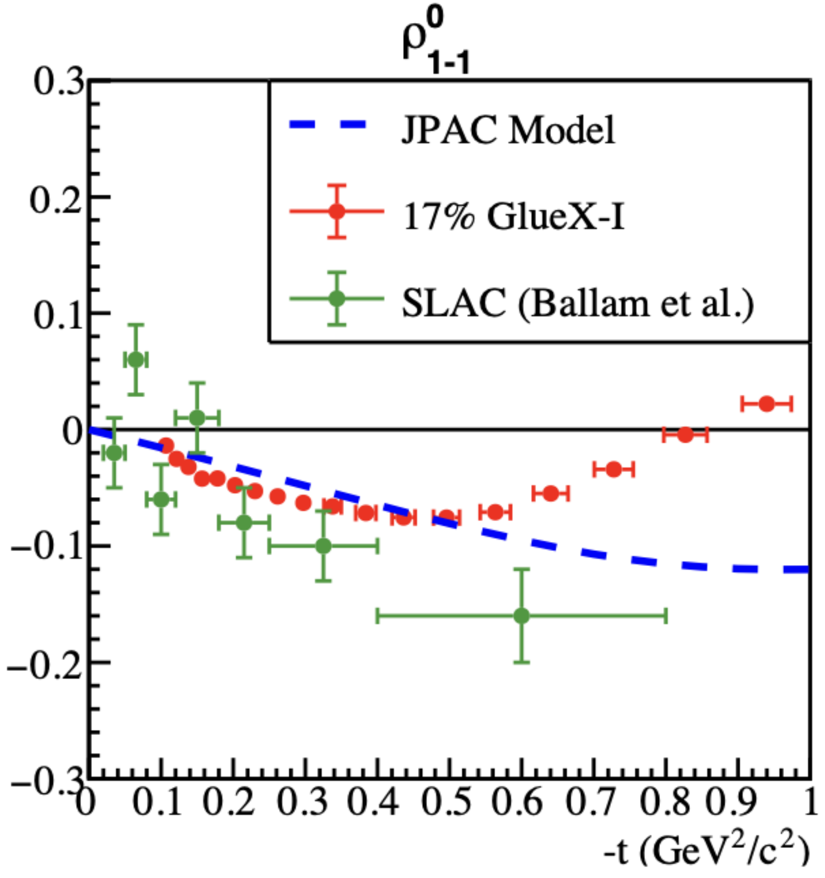
$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

ρ(770) Meson Spin-Density Matrix Elements

Results

- Focus on 17% of GlueX Phase I
- Combined fit of 4 orientations of polarization
- Statistical uncertainties nearly negligible
  → Detailed evaluation of systematic errors
- Excellent agreement with model (within limits of validity, t < 0.5 GeV^2) and previous measurements

Model: V. Mathieu et al. [PRD, 97 (2018), 094003]



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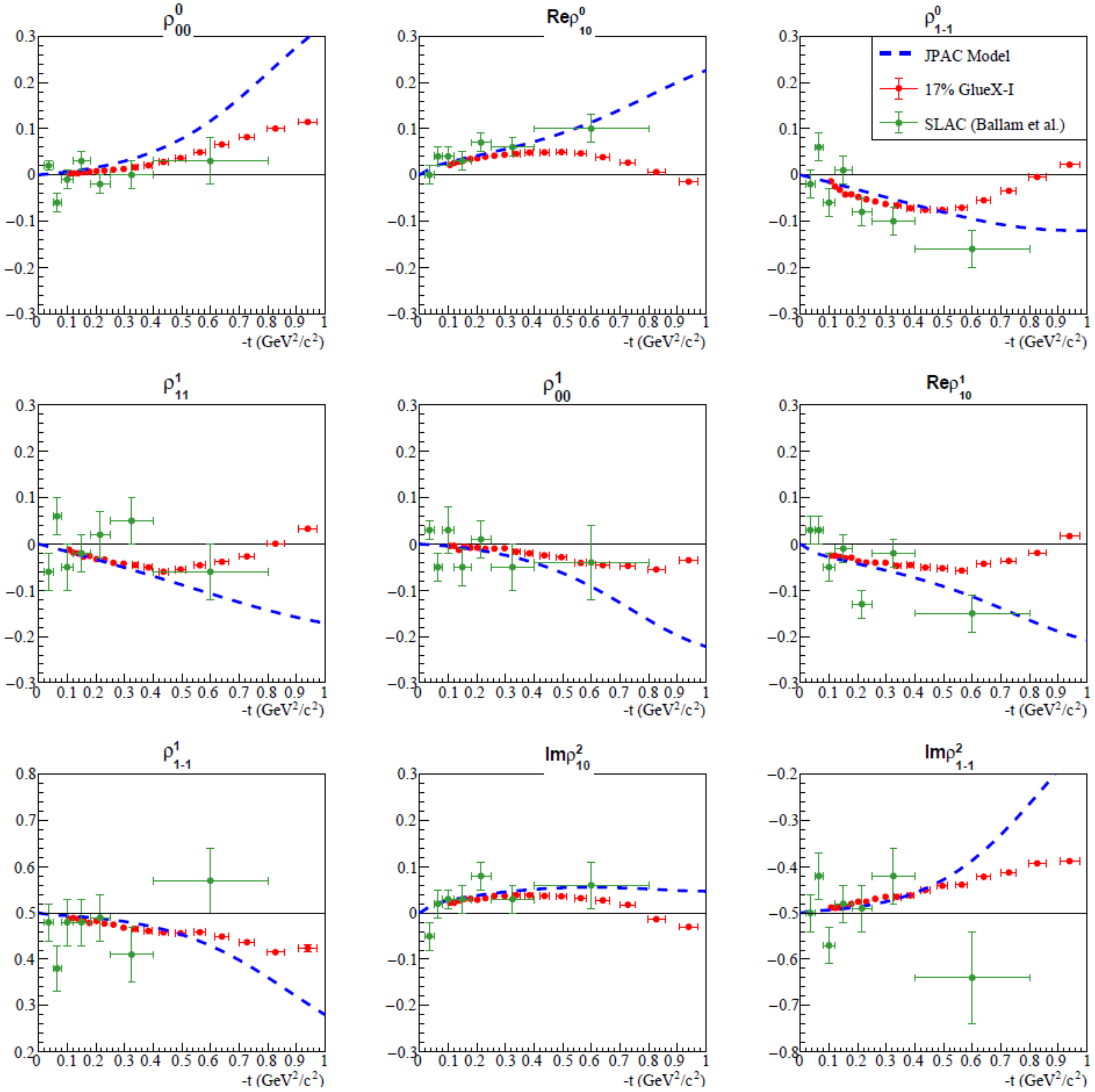
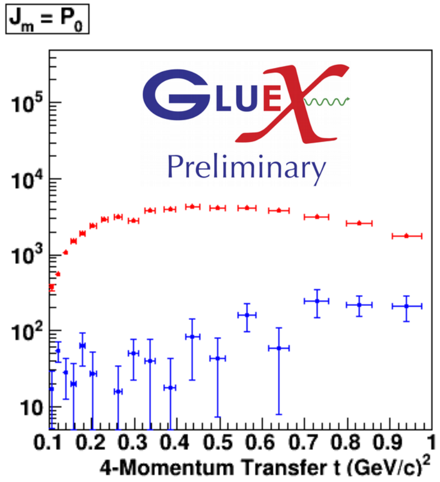
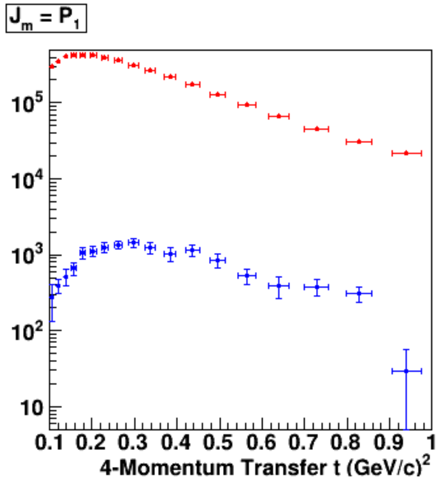
Relevance to exotic search:

- High-precision input for production models
- Improve and validate understanding of data and acceptance
- Develop and test high-precision multi-dimensional fit procedure



Polarized Reflectivity Amplitudes in $\pi^+\pi^-$





- Alternatively, the intensity can also be expanded into partial-wave amplitudes
- Reflectivity quantum number defined as product of naturality of parity exchange and produced resonance, as introduced for $\eta\pi$ system

- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega,\Phi) = Y_l^m(\Omega)e^{-i\Phi}$

$$I(\Omega,\Phi) = 2\kappa\sum_k \Big\{ (1-P_\gamma)\Big|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\mathrm{Re}[Z^m_\ell(\Omega,\Phi)]\Big|^2 + (1-P_\gamma)\Big|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Im}[Z^m_\ell(\Omega,\Phi)]\Big|^2 + (1+P_\gamma)\Big|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Re}[Z^m_\ell(\Omega,\Phi)]\Big|^2 + (1+P_\gamma)\Big|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\mathrm{Im}[Z^m_\ell(\Omega,\Phi)]\Big|^2 \Big\}$$

- **P_1^+ wave** dominant contribution as expected, but sizable fraction of P_0^+
- **Negative reflectivity** component very small as expected

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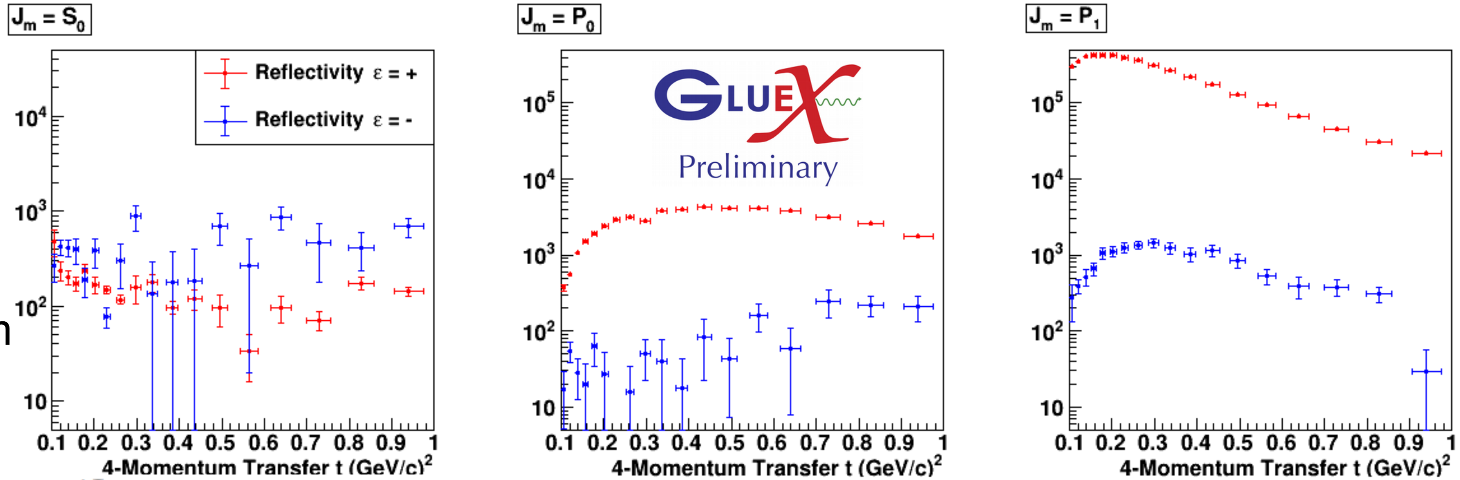

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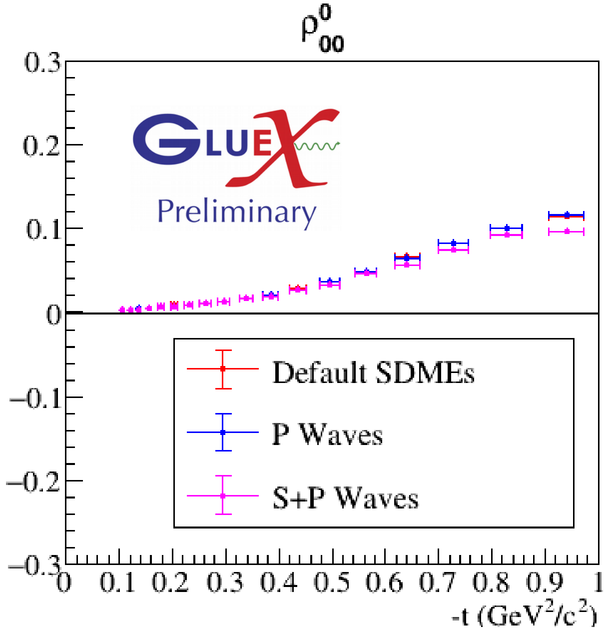
$$(1+P_\gamma)\Big|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Re}[Z^m_\ell(\Omega,\Phi)]\Big|^2 + (1+P_\gamma)\Big|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\mathrm{Im}[Z^m_\ell(\Omega,\Phi)]\Big|^2 \Big\}$$



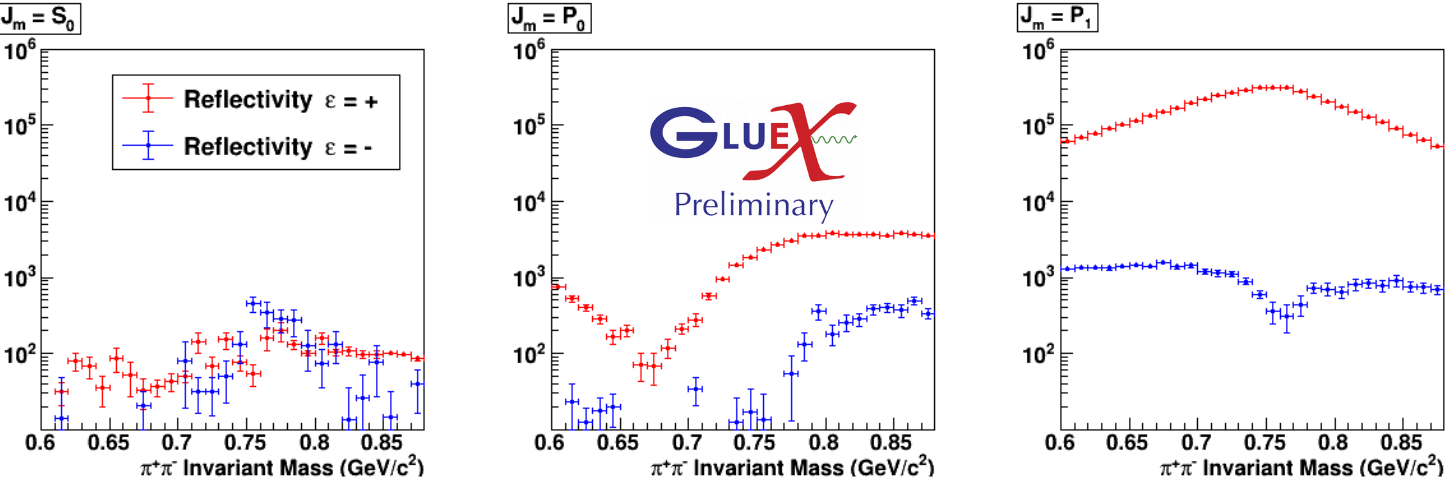
- **P_1^+ wave** dominant contribution as expected, but sizable fraction of P_0^+
- **Negative reflectivity** component very small as expected
- One-to-one correspondence between SDMEs and amplitudes:

  [Phys. Rev. D 100 (2019), 054017]

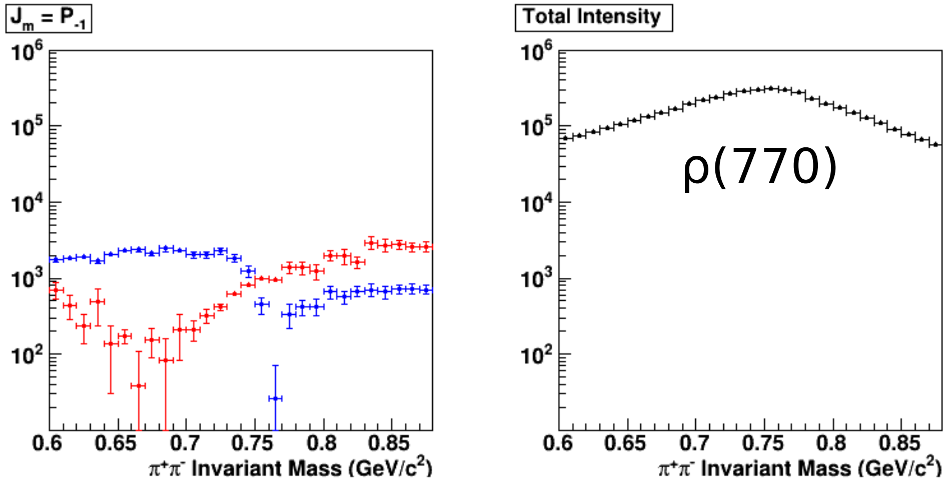
$${}^{(\epsilon)}\rho^{0,\ell\ell'}_{mm'} = \kappa\sum_k \Big([\ell]^{(\epsilon)}_{m;k}[\ell']^{(\epsilon)*}_{m';k}$$
$$+ (-1)^{m-m'}[\ell]^{(\epsilon)}_{-m;k}[\ell']^{(\epsilon)*}_{-m';k} \Big)$$

Polarized Reflectivity Amplitudes in $\pi^+\pi^-$

- Alternatively, the intensity can also be expanded into partial-wave amplitudes
- Reflectivity quantum number defined as product of naturality of parity exchange and produced resonance, as introduced for ηπ system



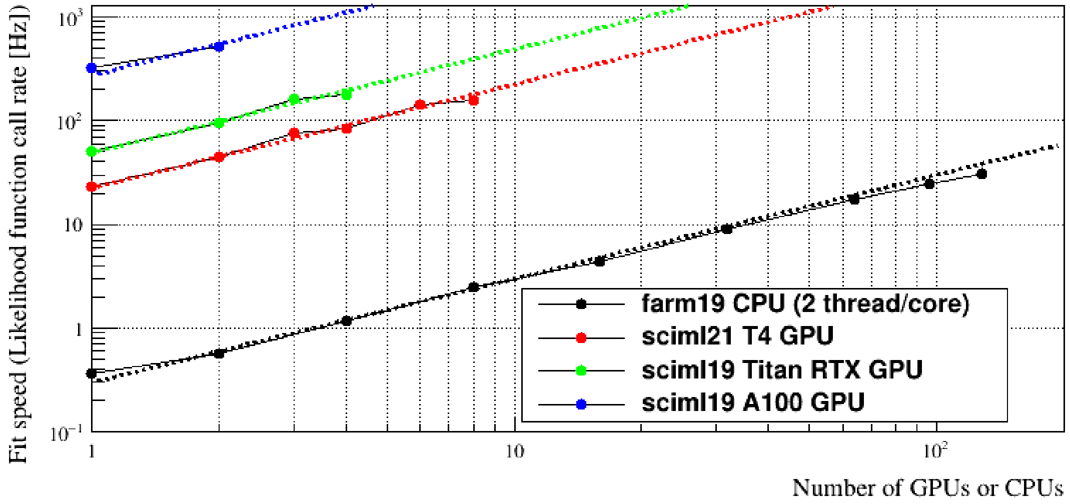
- Mass dependence of amplitudes show interesting features
- Large ππ data set will be used to study and validate new amplitudes: mathematical ambiguities and fit stability
- Extension to higher invariant masses
  → access to excited vector meson spectrum

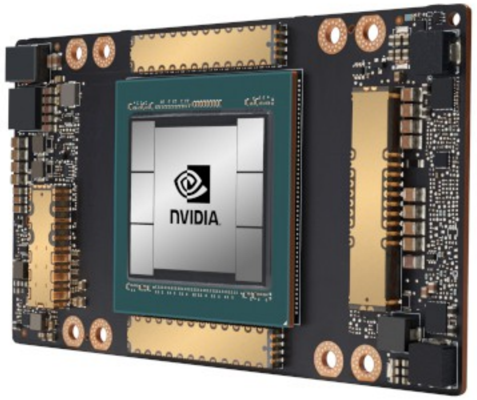


BUT: Introduction of J=2 requires up to 10 additional amplitudes
Computationally demanding, possibly similar stability problems as in ηπ

Advanced Methods for Hybrid Meson Searches

- Maximum-likelihood fit of complex models to large data sets is computationally expensive
- Tremendous speed-up on Graphics Processing Units (GPUs), but limited availability for general purpose at Jefferson Lab, previous generation with small memory (TitanRTX, T4)
- Increase pool of suitable hardware at Jefferson Lab (A100)





Machine Learning and Artificial Intelligence

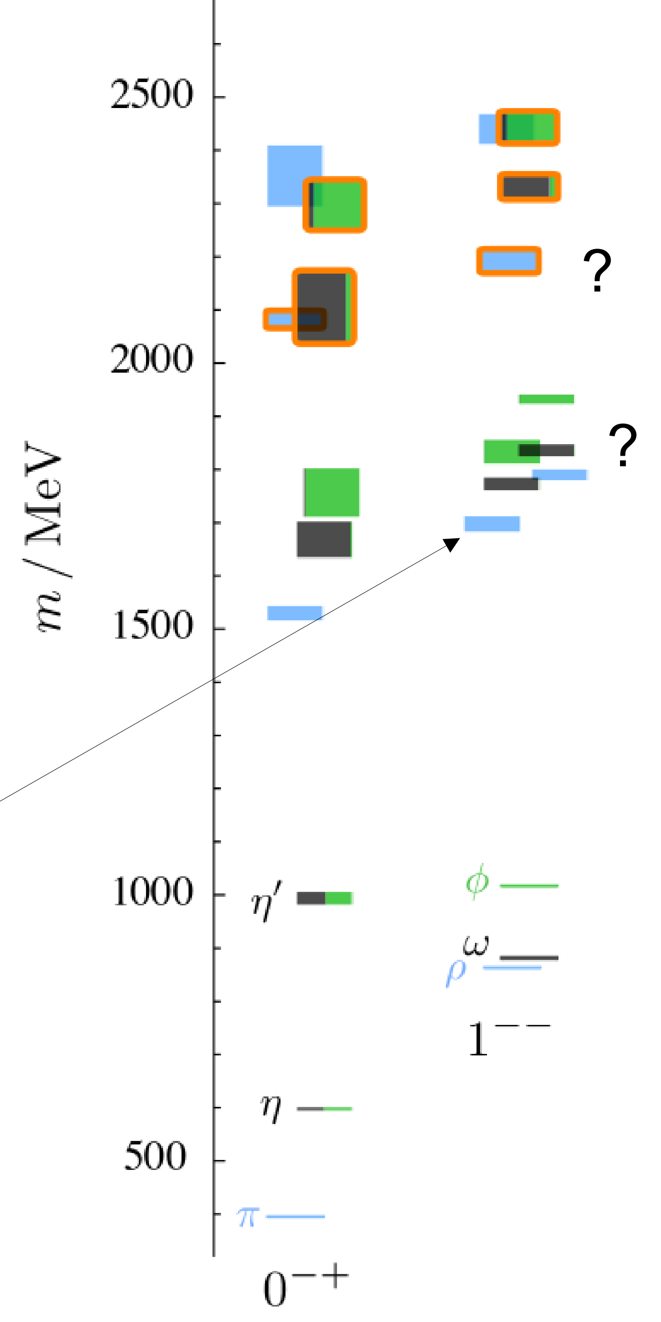
- AI/ML methods ideal for complex, multi-dimensional parameter spaces
- Exploration and implementation of AI/ML techniques for model selection and fitting
- GlueX is already using AI/ML for detector control and data reconstruction

Excited Vector Meson Spectrum

- Detailed LQCD prediction in $J^{PC}=1^{--}$ sector
- Hybrid mesons with conventional quantum numbers
- Assignment to resonances in PDG unclear
- Potential for important contributions

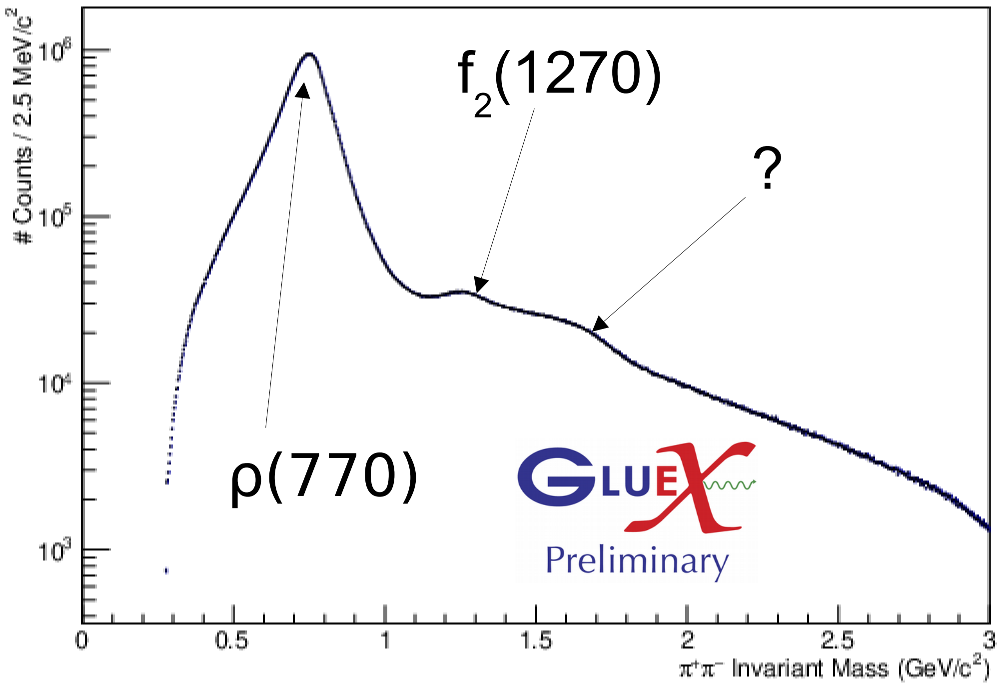
Name	Mass (MeV)	Width (MeV)	Decay	Established
ρ(1450)	1465 ± 25	400 ± 60	ππ, KK, ...	yes
ρ(1570)	1570 ± 70	144 ± 90	ωπ	no
ρ(1700)	1720 ± 20	250 ± 100	ππ, ωπ, ρπ	yes
ρ(1900)	1900	10 - 160	6π	no
ρ(2150)	2030 - 2255	70 - 460	ππ, KK	no

PDG [Prog. Theor. Exp. Phys. 2022 (2022), 083C01]

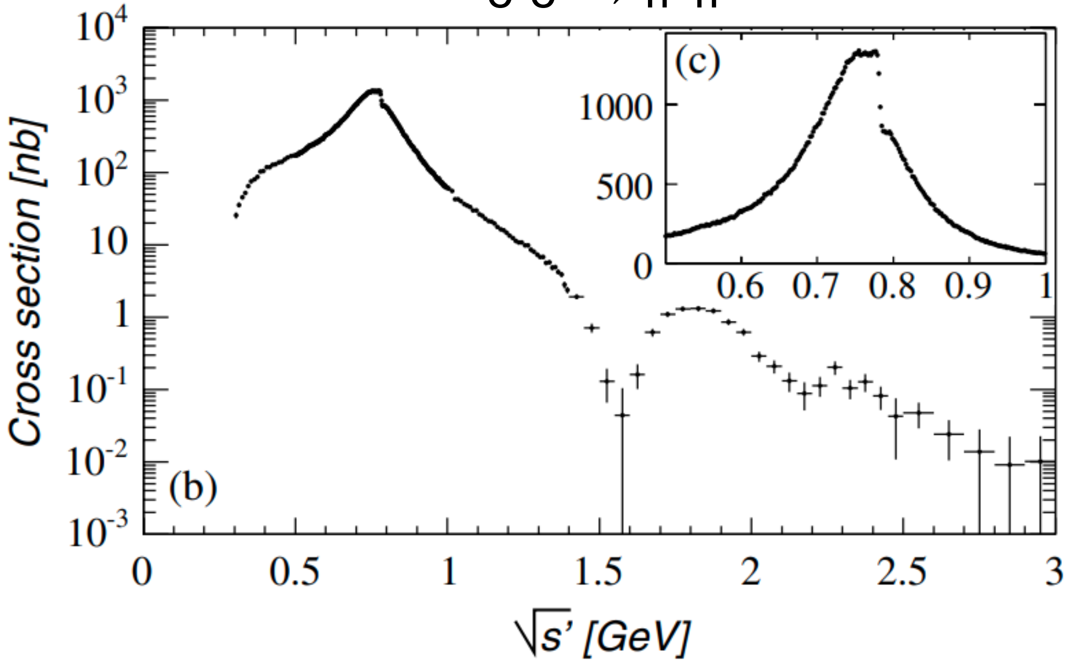


Excited Vector Meson Decay into $\pi^+\pi^-$

- Abundant in GlueX data set
- Photoproduction complementary to e^+e^- annihilation
- Polarized reflectivity amplitudes established in $\eta\pi$ and with $\rho(770)$
- Dominant transfer of linear polarization from photon beam constrains production



- $e^+e^- \to \pi^+\pi^-$



[Phys. Rev. Lett. 103 (2009), 231801]

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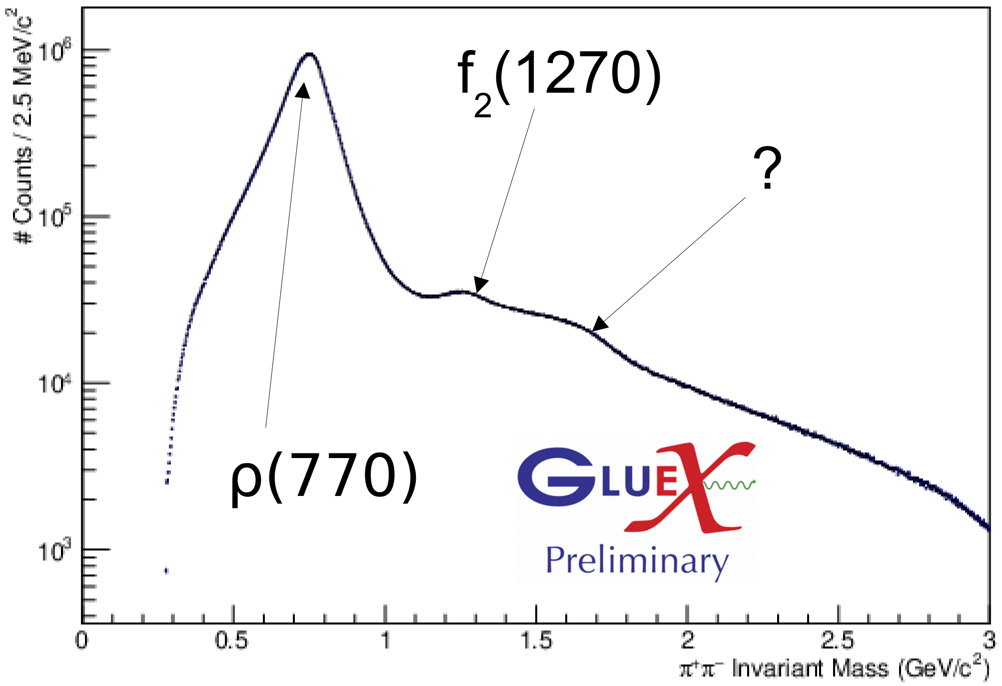
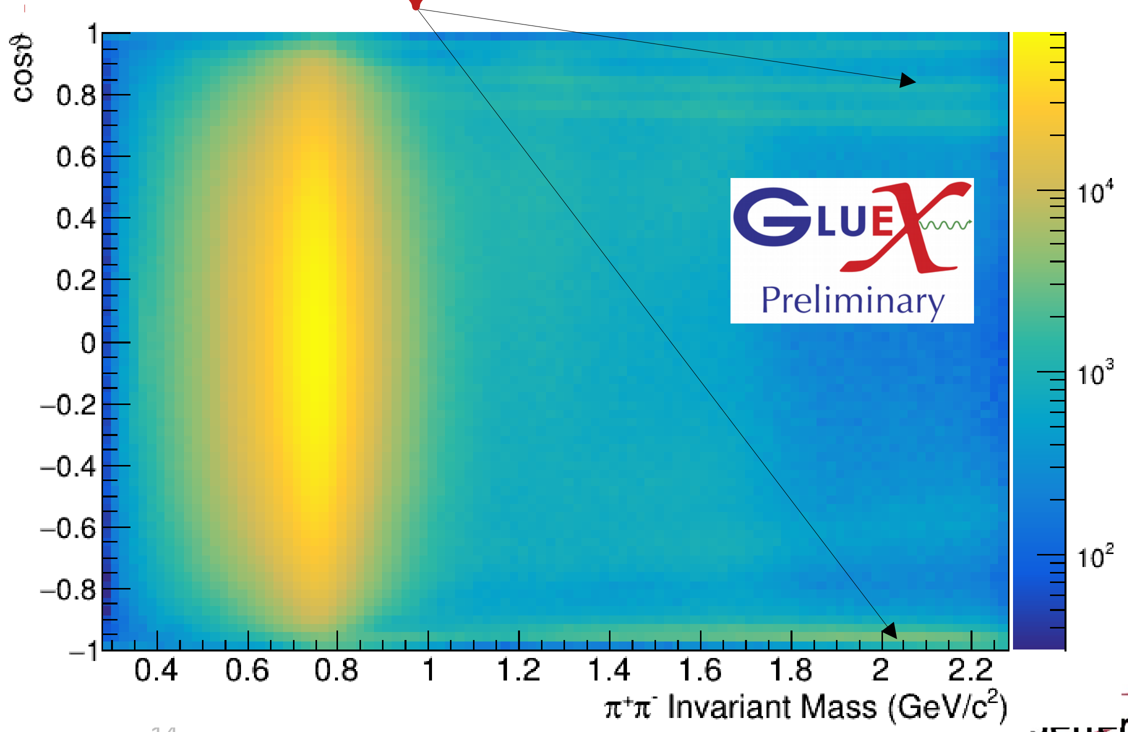
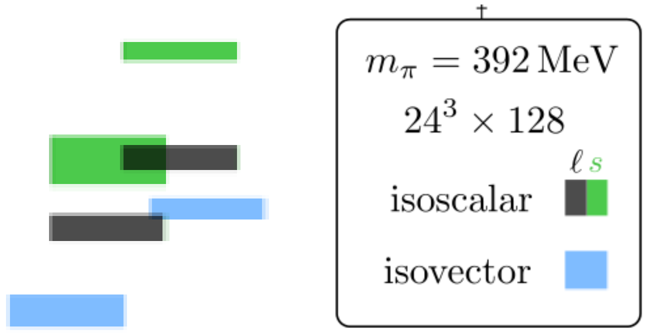
- Photoproduction complementary to e^+e^- annihilation
- Polarized reflectivity amplitudes established in $\eta\pi$ and with $\rho(770)$
- Dominant transfer of linear polarization from photon beam constrains production
- Unprecedented detail accessible, **but** target excitation and double-Regge exchange background

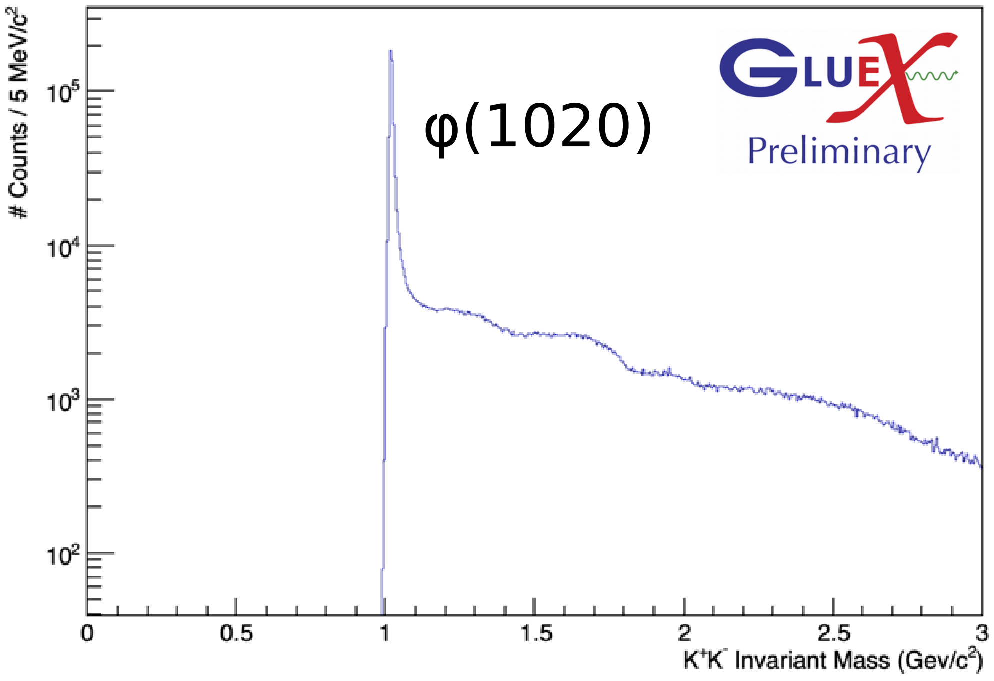




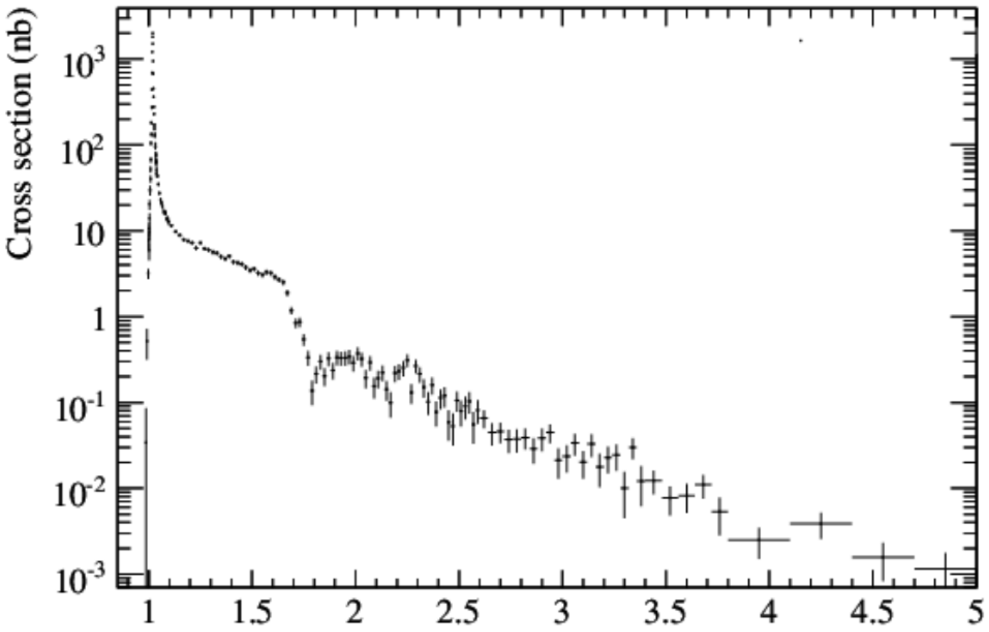
Excited Vector Meson Decay into K^+K^-

- Abundant in GlueX data set
- Photoproduction complementary to e^+e^- annihilation
- Distinguish light and strange quark composition of states
- GlueX-II with upgraded PID valuable





- $e^+e^- \rightarrow K^+K^-$



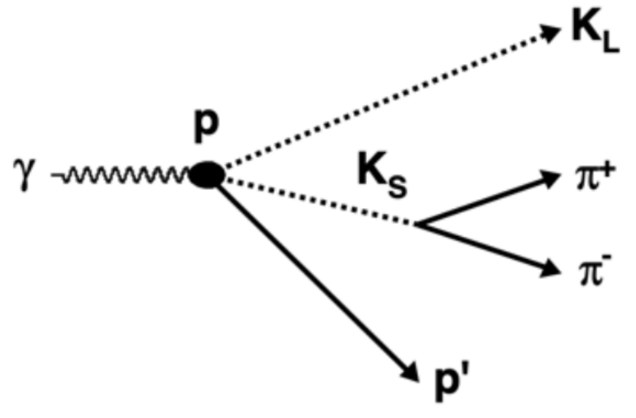
[Phys. Rev. D 88 (2013), 032013]

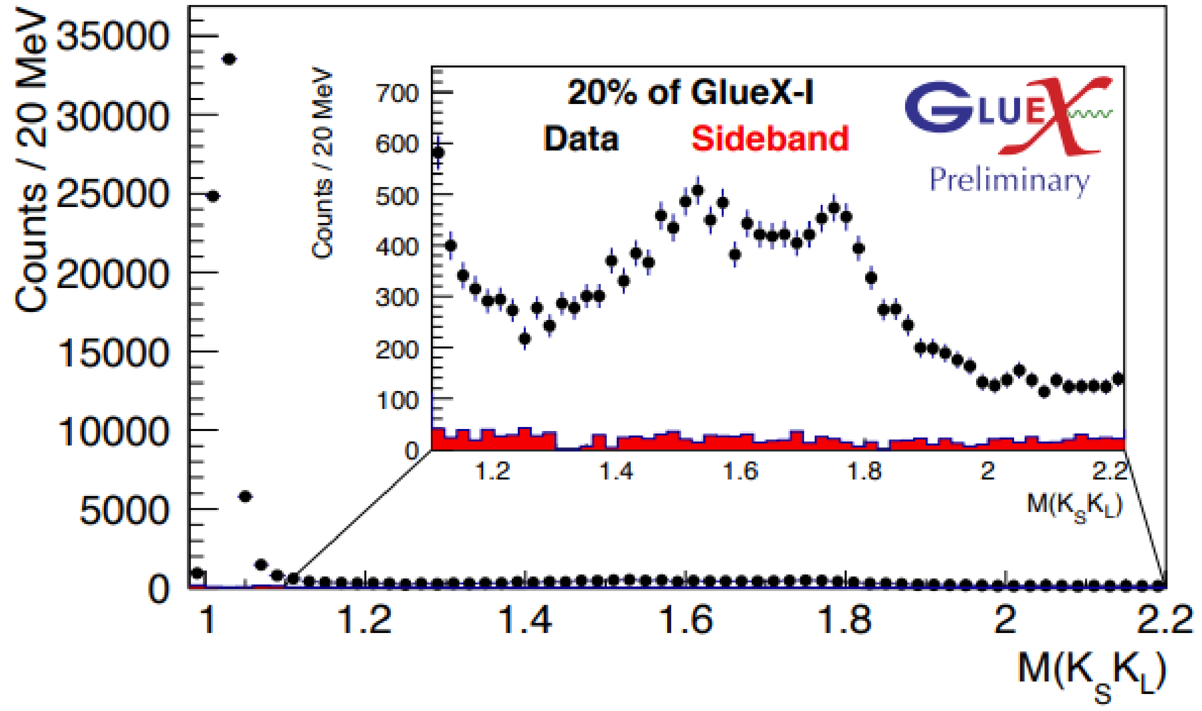
Jefferson Lab
Thomas Jefferson National Accelerator Facility

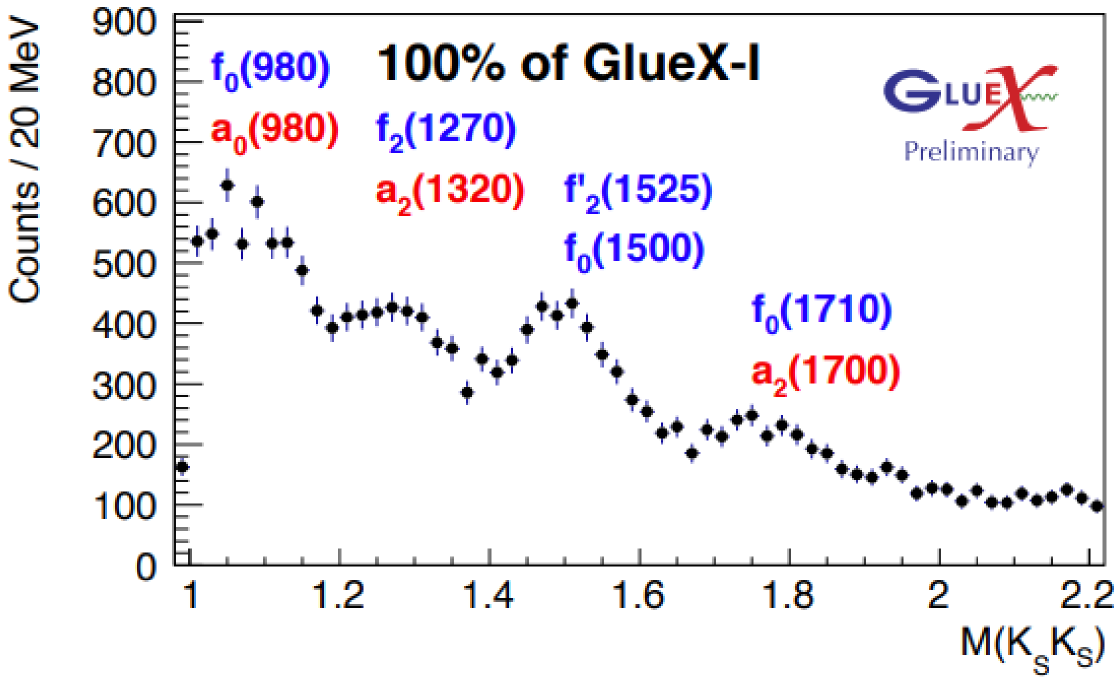
Study of the K_SK_L and K_SK_S Systems

Gabriel A. Rodrigez Linera (FSU)

- K_SK_L complementary to K^+K^- without need for Particle ID
- Promising initial study under way
- K_SK_S background to study scalar and tensor meson spectrum

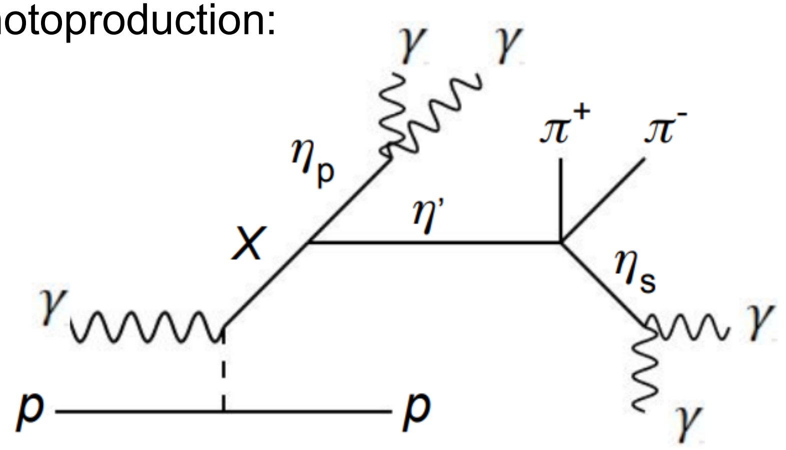




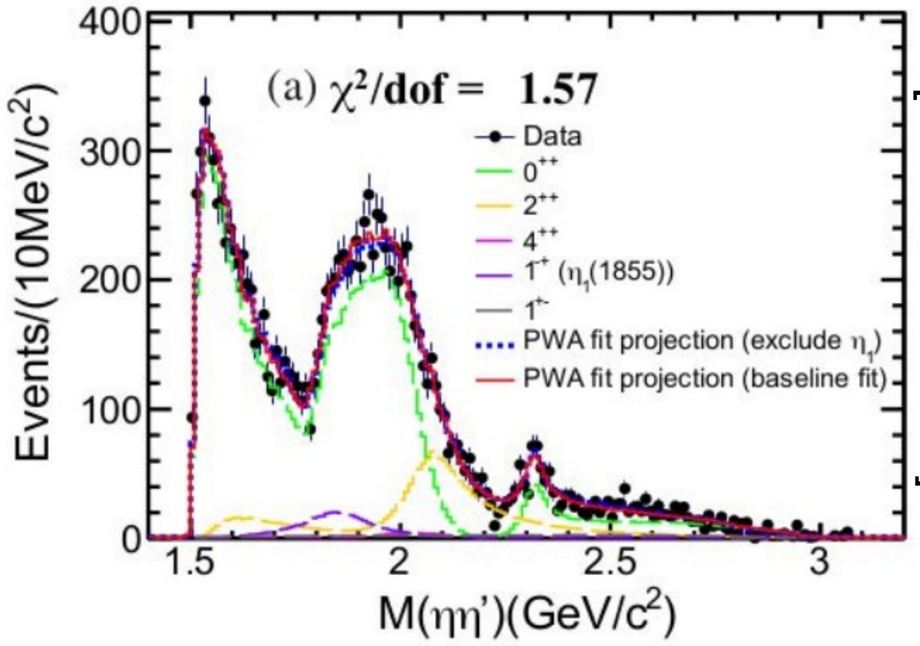


Candidate for Exotic Meson in ηη’

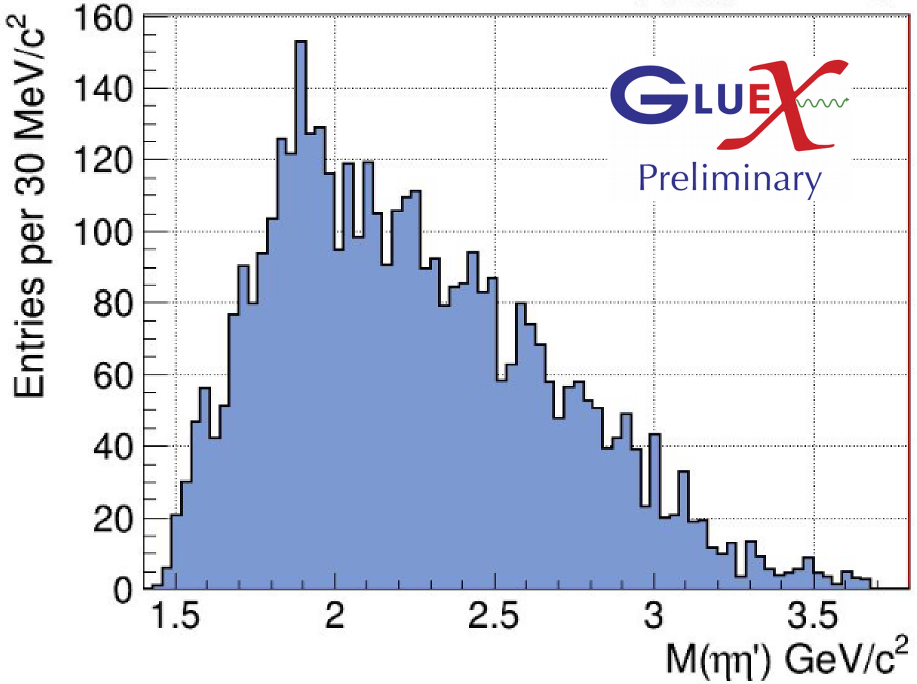
- Isoscalar partner of the $\pi_1(1600)$: η_1
- BES-III recently reported evidence for in $\eta_1(1855)$ in $J/\psi \to \eta\,\eta'\,\gamma$ (~15k events in 2 decay modes)
- GlueX recently started studying this final state in photoproduction:



- We obtain about 2k events with GlueX-I, expect 3-4x increase with GlueX-II + other possible final states
- Framework for amplitude analysis of two-pseudoscalar meson final state ready
- Potential for independent confirmation, first observation in photoproduction



[arXiv:2202.00621]



Summary and Outlook

- Extraction of SDMEs for ρ(770) photoproduction with unprecedented precision
- Synergy with ηπ final states through polarized reflectivity amplitudes
- Extension of studies to larger ππ masses promises results on excited vector mesons and potential hybrid candidates
- Established framework will also be used for KK systems to access flavor

Collaboration with Phenomenology

- Input for production models
- Validated amplitudes for two-pseudoscalar systems open the door for several exciting results in the light meson sector
- Synergy for the application of modern technology (GPUs, AI/ML)