Search for Exotic Hadrons in $\eta(')\pi$

Malte Albrecht
Indiana University

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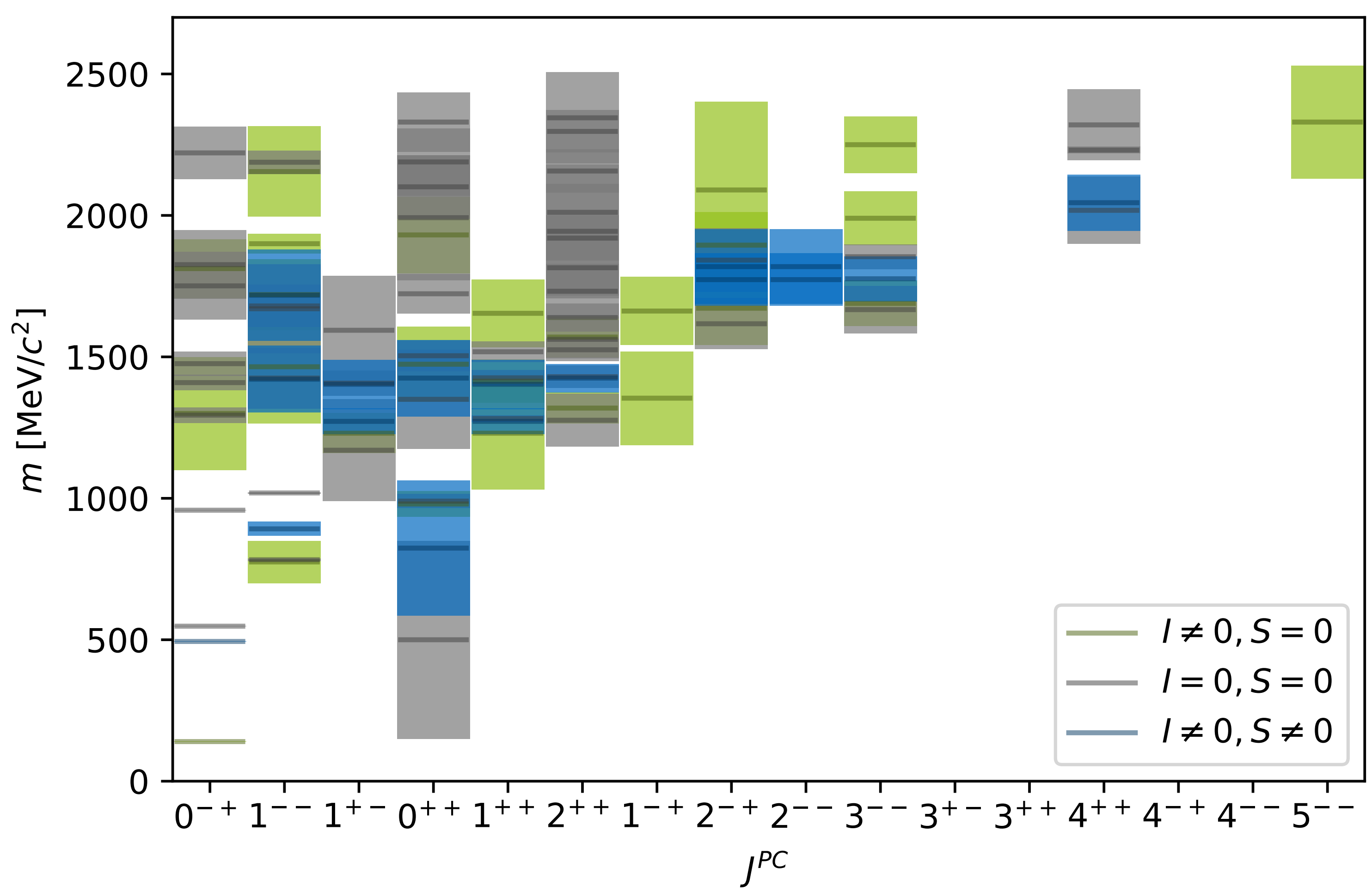
Challenges in the Light Hadron Sector

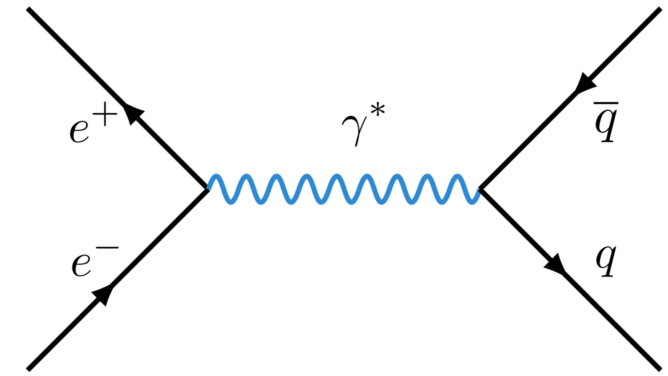
- Many broad and overlapping states discovered
- Assignment to multiplets ambiguous
- Fundamental to gain deeper understanding of strong interaction
- Ideally: Combine different **production** and **decay modes**

[Data from PDG2018]

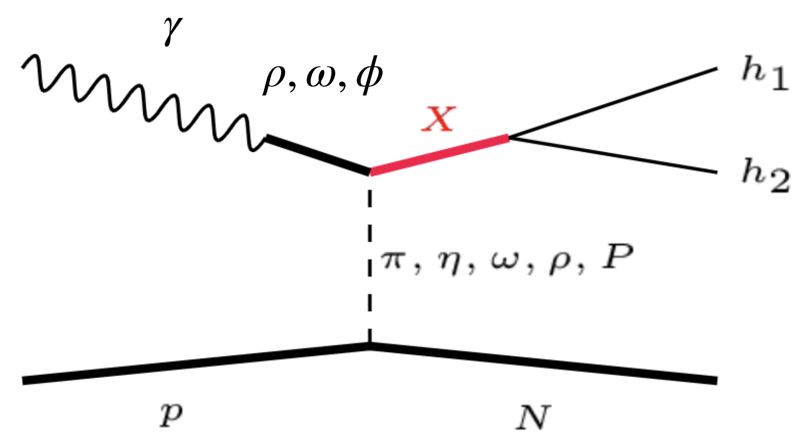


Production of Hadrons

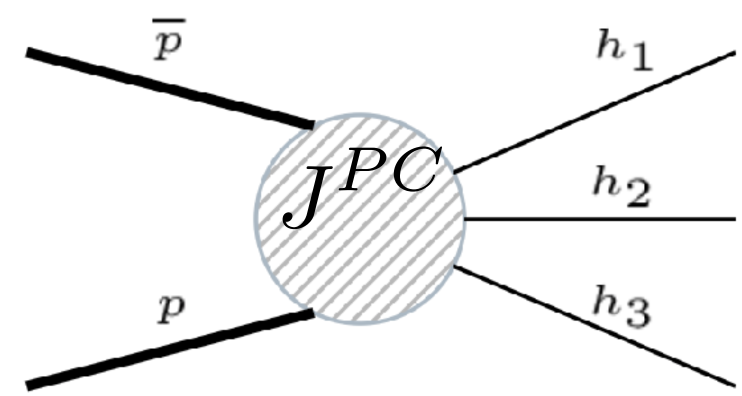
- **Electromagnetic probes**:
  - e^+e^- annihilation
    (CLEO, BaBar, Belle, BESIII, …)
    - Only direct production of $J^{PC} = 1^{--}$



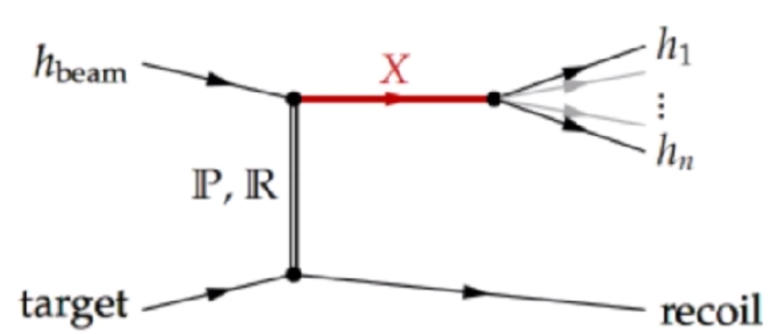
  - γN Photoproduction
    (GlueX, CLAS, CBELSA, …)



- **Hadronic probes:**
  - pp collisions (ATLAS, CMS, LHCb, …)
    = multiple quark-gluon collisions
  - $\overline{p}p$ annihilation (CB/LEAR, E835, PANDA)
    = annihilation of quark-antiquark pairs
    → All non-exotic J^{PC} directly accessible



  - πN collisions (COMPASS, …)

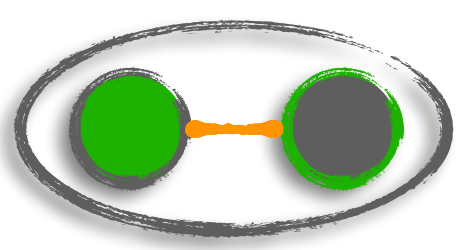


Beyond the Constituent Quark Model

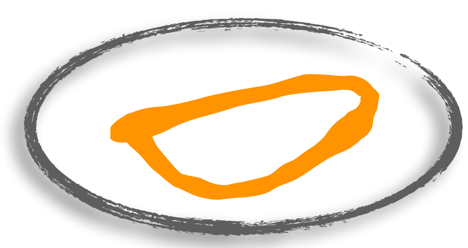
- Minimal allowed bound states of QCD: Mesons ($q\overline{q}$) and baryons (qqq)
- For mesons: $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

  Allowed: $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, ...$
  Forbidden: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...$

- Observation of state with J^{PC} forbidden for $q\overline{q}$: clear evidence for exotics
- Understanding QCD: What is the role of gluons (generation of mass, spin, …)?
- Configurations with additional gluonic degrees of freedom allowed:



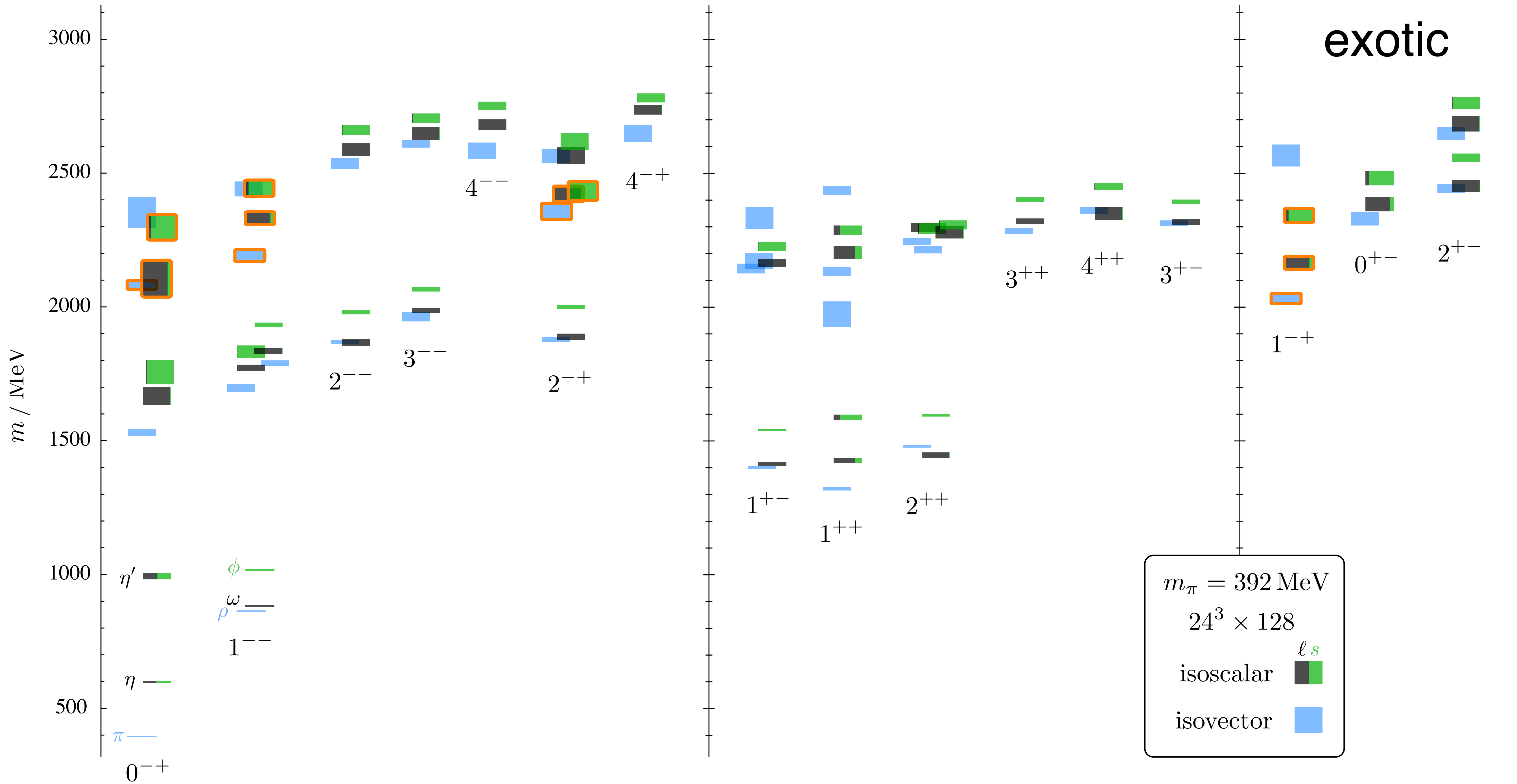
- Hybrids (mesons with excited gluonic degrees of freedom)



- Glueballs (no valence quark content)

Hybrid search: Primary motivation for the construction of Hall-D / GlueX

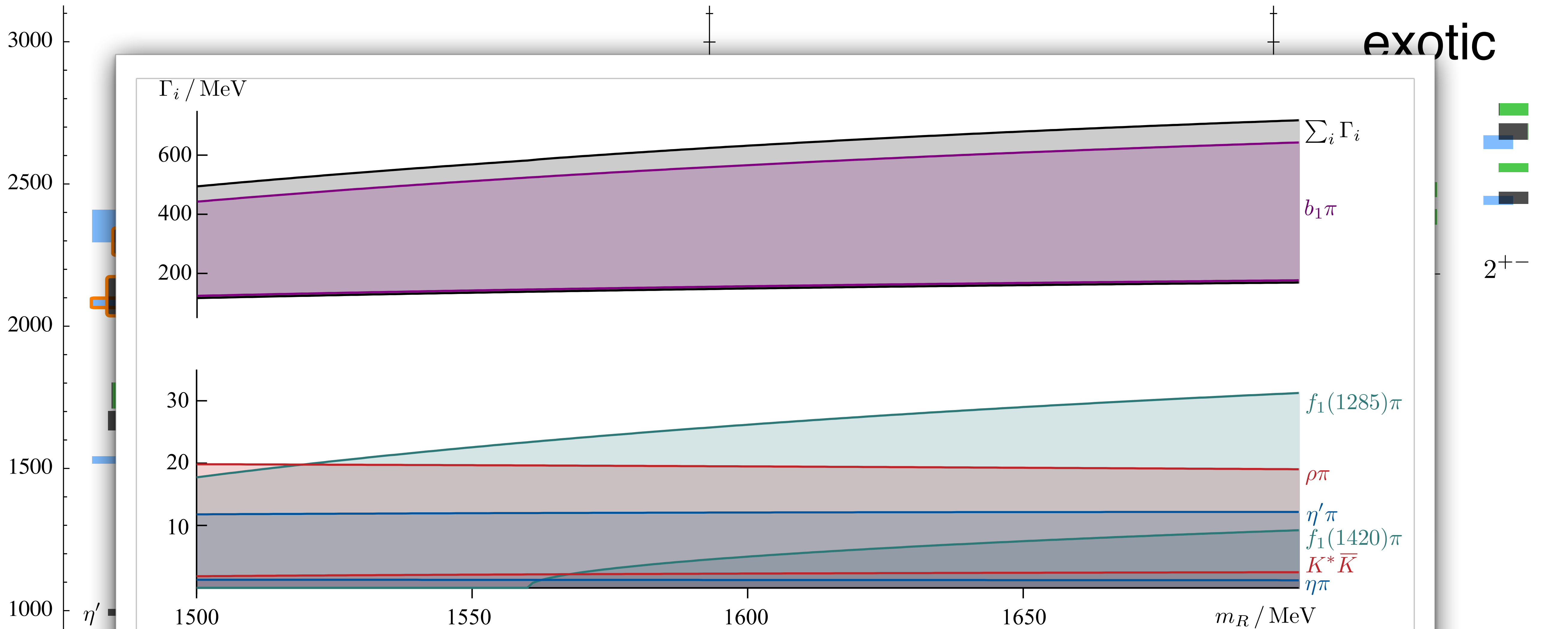
Light Quark Mesons from Lattice QCD



[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

- Lightest spin-exotic state: $J^{PC} = 1^{-+}$

Light Quark Mesons from Lattice QCD



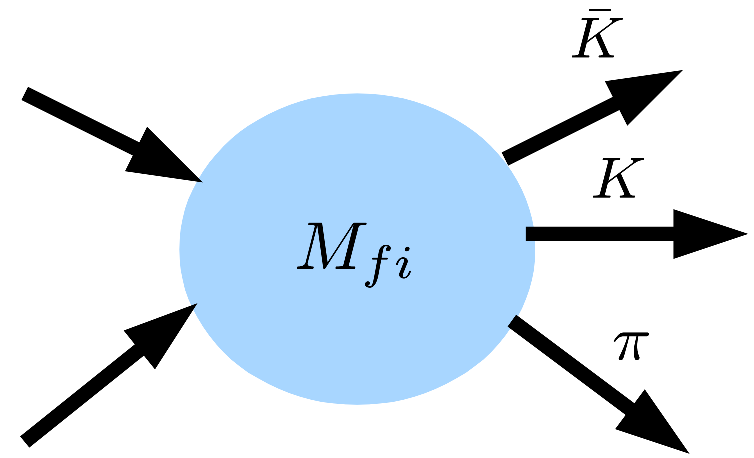
[Woss, Dudek, Edwards, Thomas, Wilson, PRD **103** (2021) 054502]

- Recent calculations: Large coupling of 1^{-+} state to axial vector-pseudoscalar channels
- Important to measure multiple decay modes to compare partial widths

[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

- Lightest spin-exotic state: $J^{PC} = 1^{-+}$

Partial Wave Analysis



- Coupling of the initial to the final state for a reaction is given by the matrix element
- **Goal**: Disentangle interfering contributions and measure spectroscopic properties
- Full kinematic information measured
  → Information about resonances encoded
  → Angular distributions: spin, parity
  → Invariant mass: ‘peak’ can indicate resonance
- Expand the complex amplitudes in a series of partial waves
  - Angular dependencies (e.g. $Y_l^m(\theta, \phi)$)
  - Dynamical part:
    - “Mass-dependent”: Breit-Wigner function, K-Matrix, …
    - “Mass-independent”: bin data in invariant mass, assume constant mass dependency within bin
  - Amplitudes add coherently → accounts for interference, allows to measure relative phases

Fermi's Golden Rule

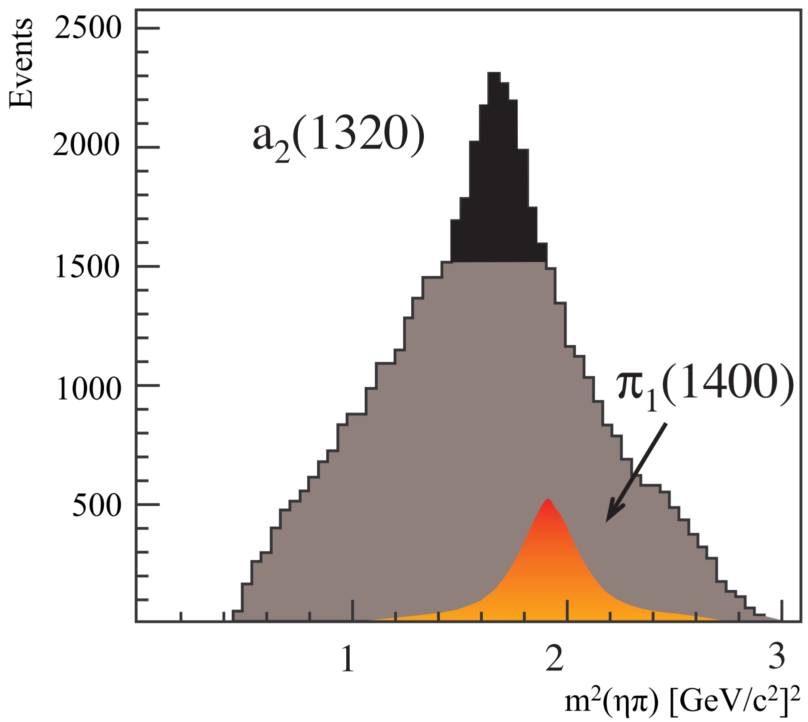
$$d\sigma \propto |M_{fi}|^2 d\phi_n$$

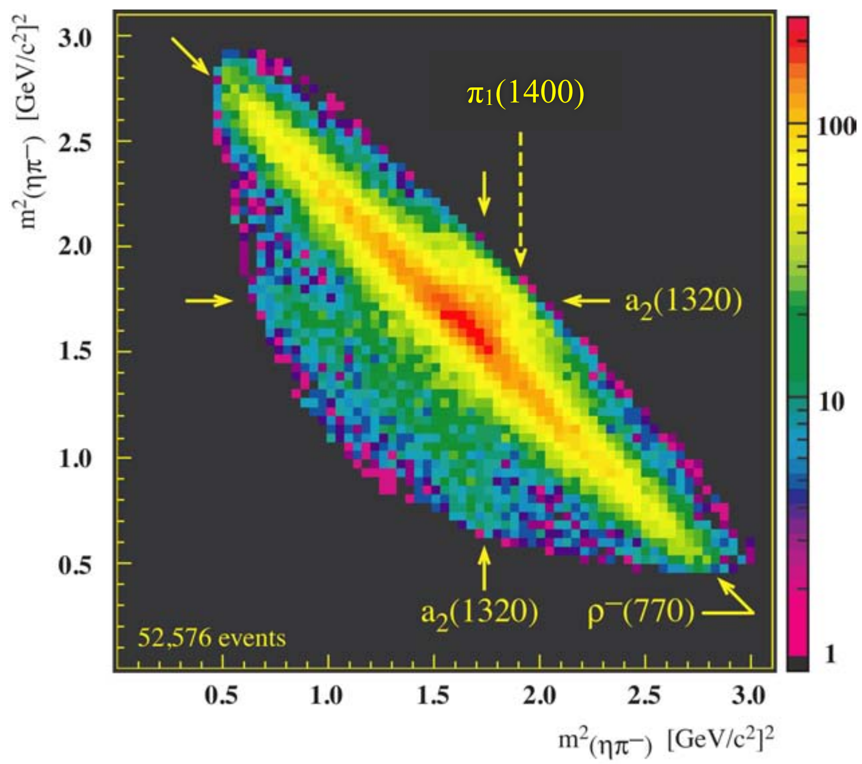
matrix element

n-body phase space element

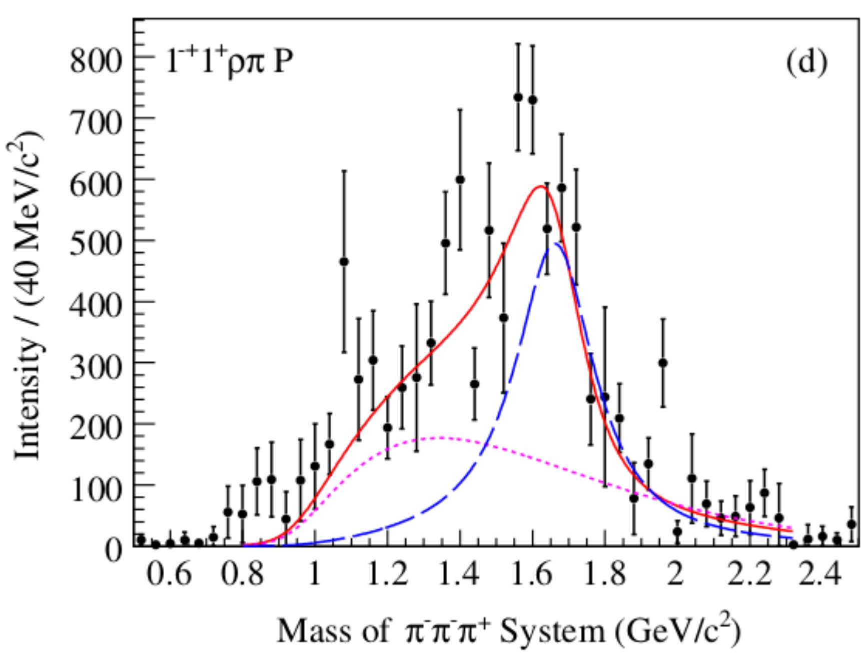
Hybrid Mesons

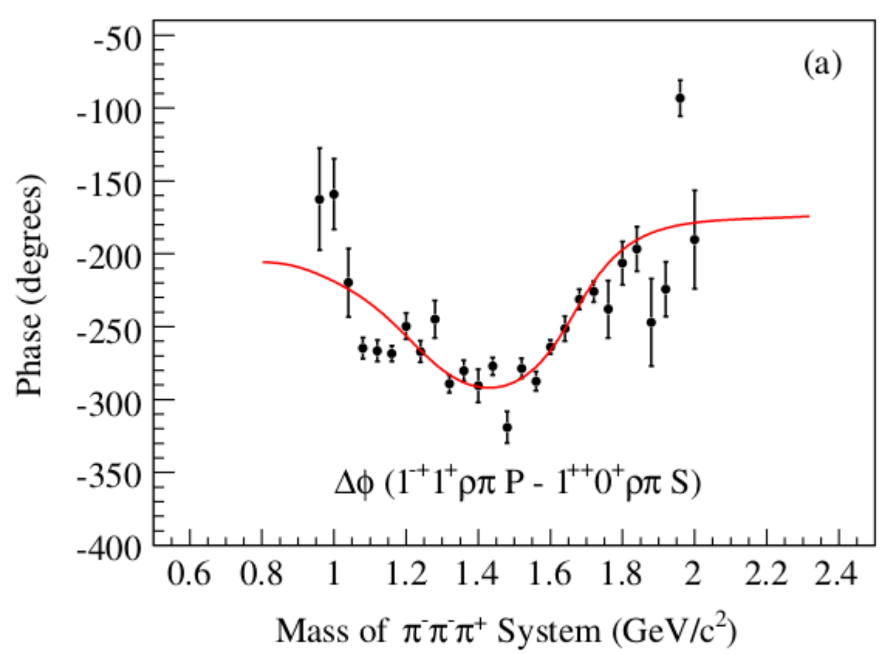
PLB 423, 175-184 (1998), Crystal Barrel



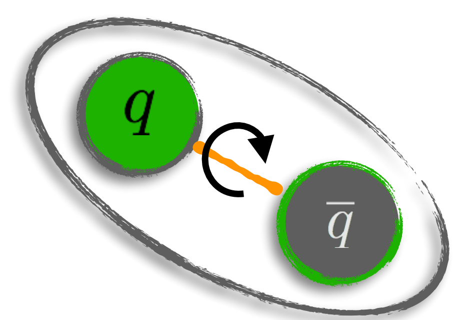


PRL 104, 241803 (2010), COMPASS





- Hints for spin-exotic states already in 1980s
- Observed at various experiments
- From PWA: $J^{PC} = 1^{-+}$
  - $\pi_1(1400)$ in $\eta\pi$
  - $\pi_1(1600)$ in $\eta'\pi, \rho\pi$
- Clear contribution of exotic wave
- Two genuine resonances?

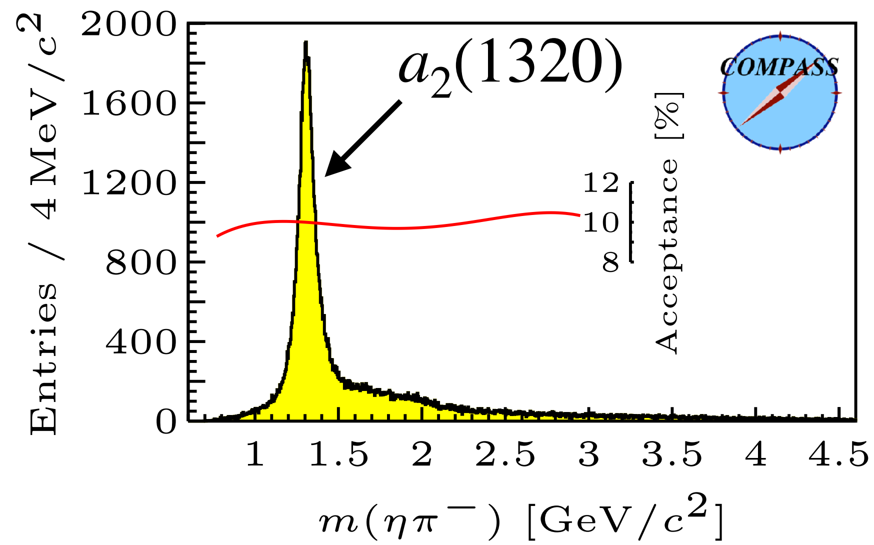


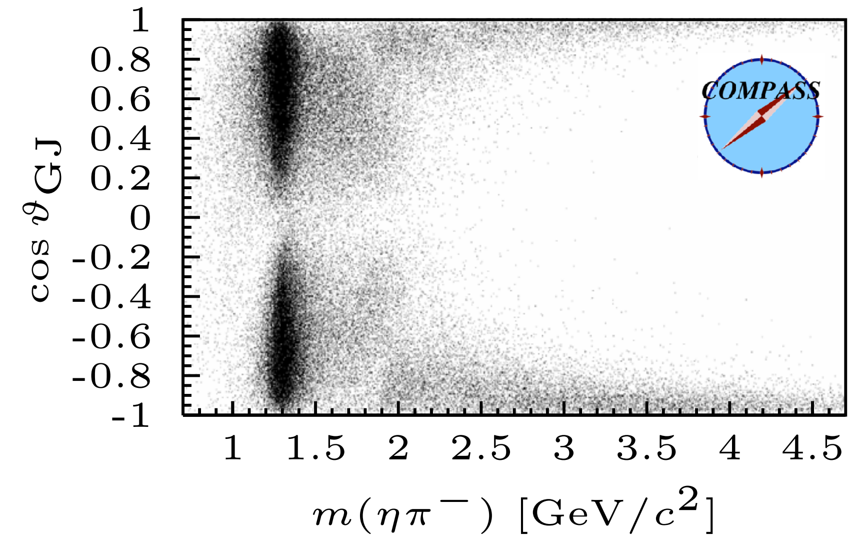
- Strongest evidence for π_1 contribution in $\eta\pi, \eta'\pi$ and $\rho\pi$ channels in πN and $\bar{p}p$ reactions
- Possible J^{PC} states for $\eta^{(\prime)}\pi$ system with orbital angular momentum L:

L	0	1	2	3	...
	S	P	D	F	
J^{PC}	0^{++}	1^{-+}	2^{++}	3^{-+}	...

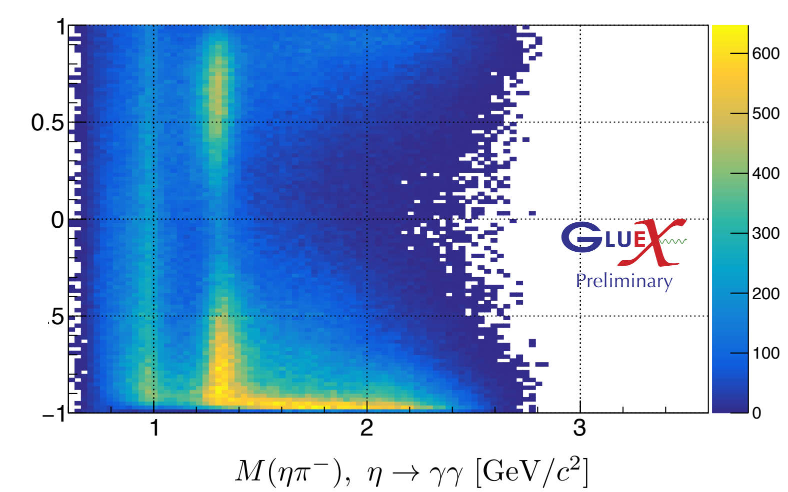
➡ $\eta^{(\prime)}\pi$ in an odd wave $(P, F, \ldots)$ has exotic quantum numbers

[Phys.Lett.B 740 (2015) 303]





[arXiv:2001.05404v1]



Search for Spin-Exotic Contribution in $\overline{p}p$ data

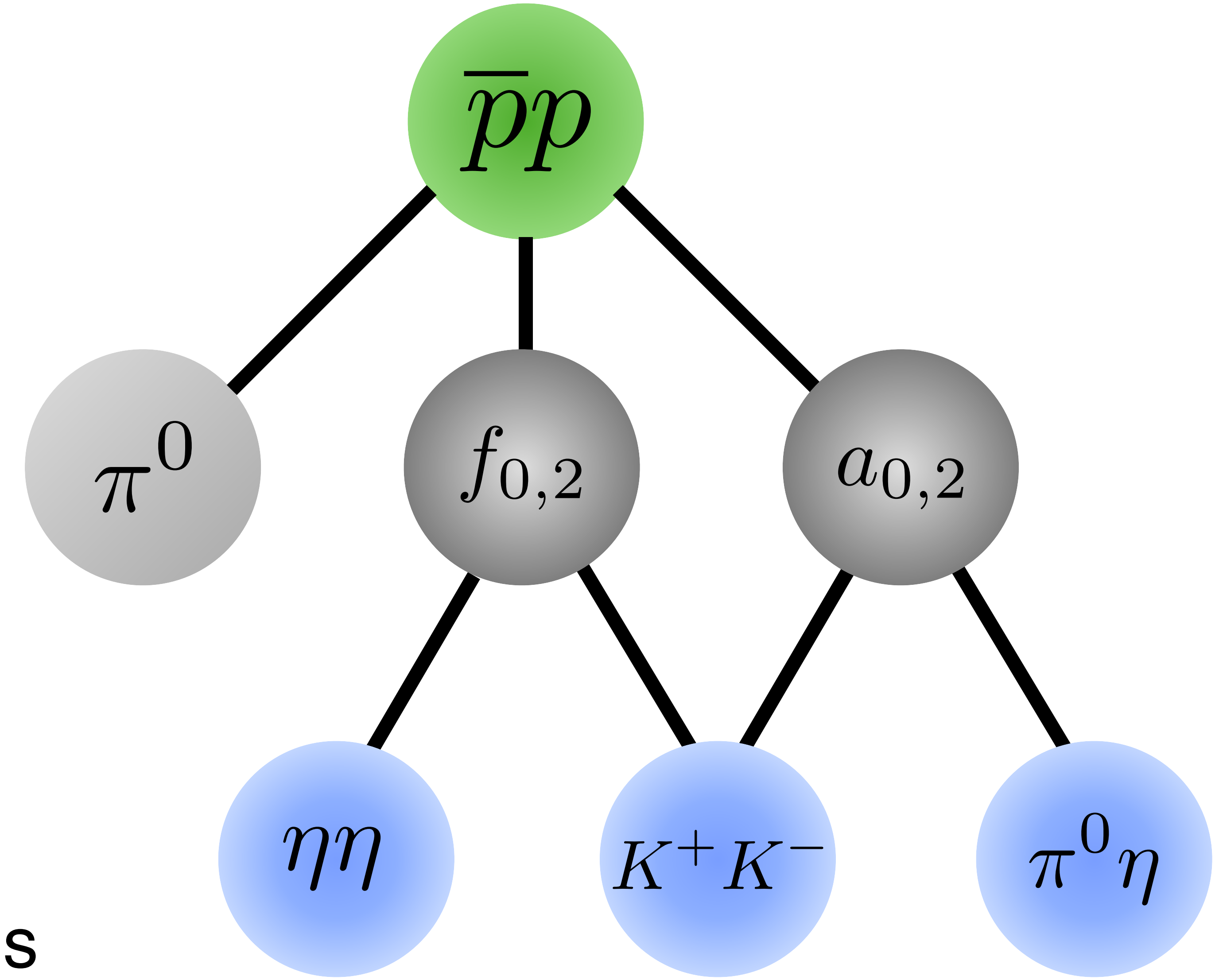
- Simultaneous analysis of

  $\bar{p}p \to K^+K^-\pi^0,\ \pi^0\pi^0\eta,\ \pi^0\eta\eta$

- Many resonances appear in 2 or all 3 channels

- Advantages: Common amplitudes, less fit parameters

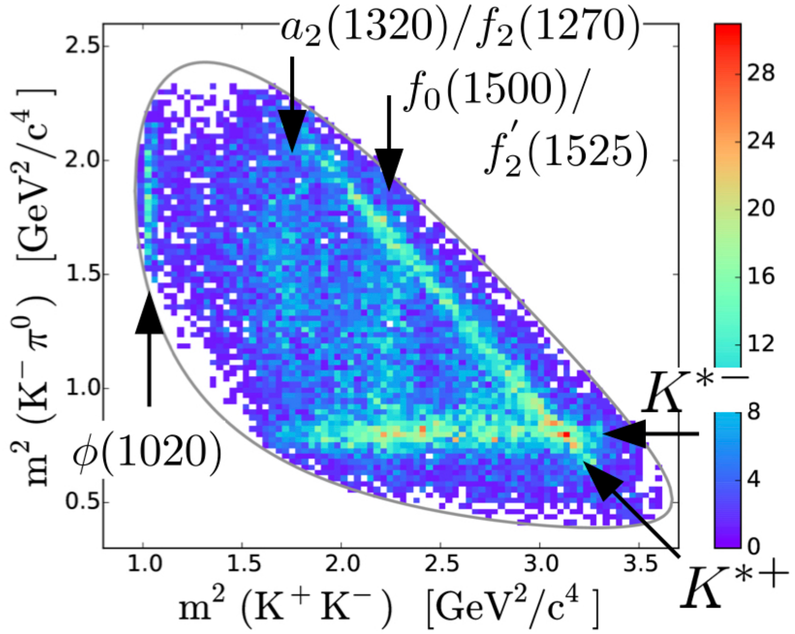
- Allows to separate contributions of different isospin



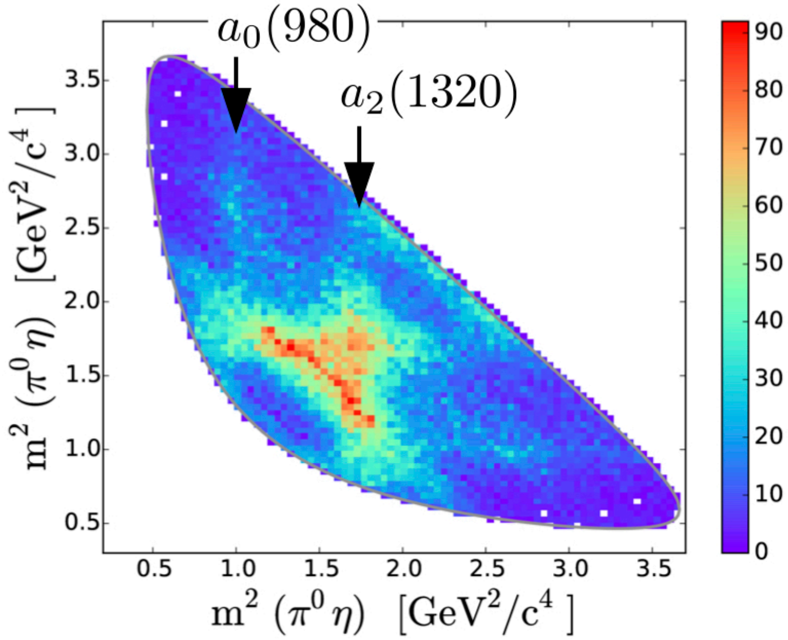
Coupled Channel Analysis

- Proper consideration of analyticity and unitarity
- Clean data samples ($p_{\overline{p}} = 0.9\,\mathrm{GeV}/c$):

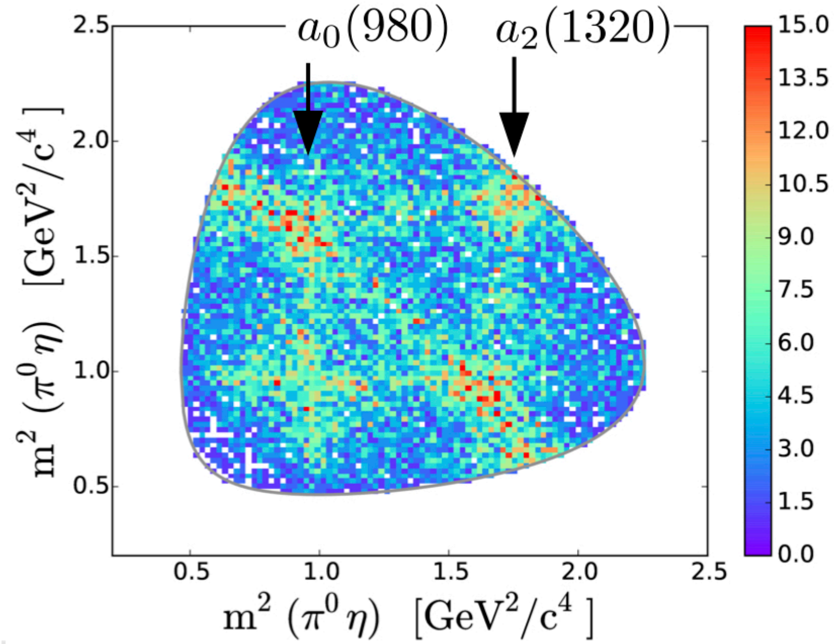
$K^+K^-\pi^0$ ($\sim$ 17.5k events)



$\pi^0\pi^0\eta$ ($\sim$ 90.4k events)



$\pi^0\eta\eta$ ($\sim$ 10.5k events)



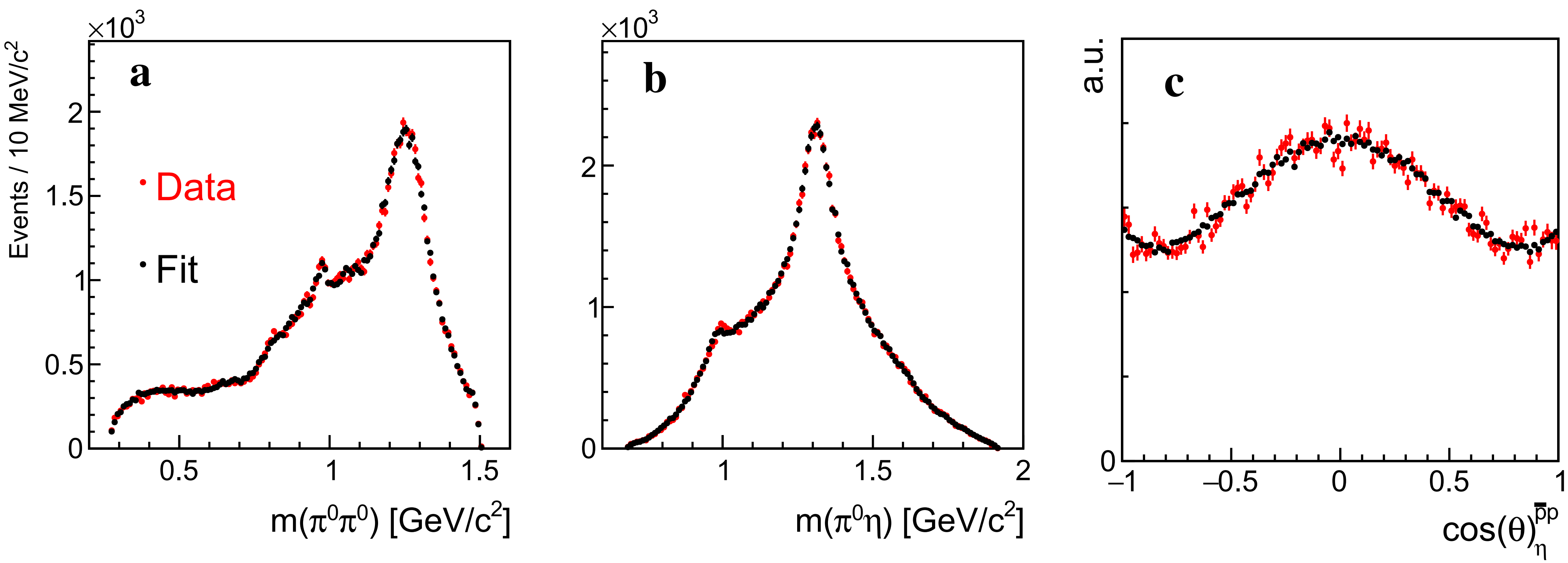
- Additional constraints by coupling to **scattering data** (phase&elasticity):

$I = 0$ $S-$ and $D-$wave $\pi\pi \rightarrow \pi\pi$, $K\overline{K}$, $\eta\eta$ $(\eta\eta')$,
$I = 1$ P-wave $\pi\pi \rightarrow \pi\pi$
PRD 83 (2011) 074004, Nucl.Phys.B 64 (1973) 134-162,
Nucl.Phys.B 269 (1986) 485, Nuov.Cim.A 80 (1984) 363

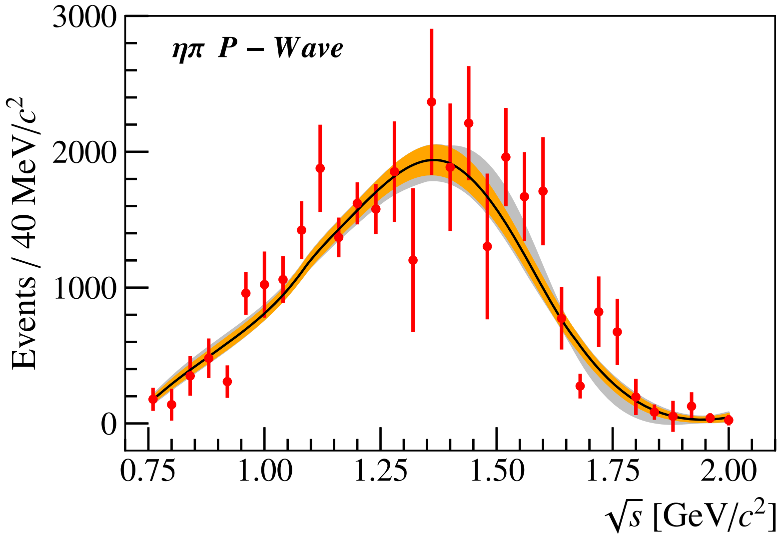
Coupled Channel Analysis: Fit Results

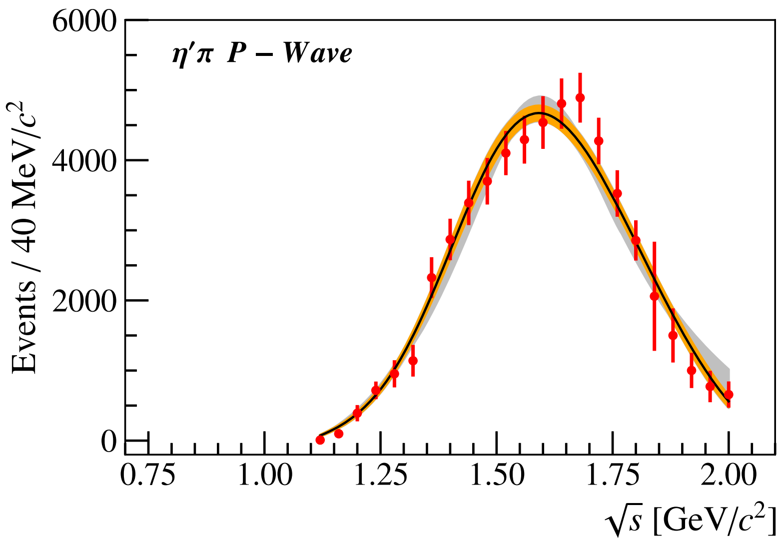
- K-Matrix descriptions for $f_0,\ f_2,\ \rho,\ a_0,\ a_2$ resonances
  - Pole parameters and coupling strengths are free parameters
  - Good description of data for $\overline{p}p$ channels and scattering data
- Significant contribution of spin-exotic ($J^{PC} = 1^{-+}$) wave!
- Extraction of a multitude of physics results:

[Eur. Phys. J. C **80,** 453 (2020)]



Results of Combined Fit with COMPASS Data





[Eur.Phys.J.C 81, 1056 (2021)]

- Extension of recent analysis of COMPASS data in $\eta\pi, \eta'\pi$ channels from Joint Physics Analysis Center
  [A.Rodas et.al. PRL 122, 042002 (2019)]

- Sophisticated description of 1^{-+} wave with single pole coupling to two channels

➡ Enhancements at 1.4GeV in $\eta\pi$, 1.6GeV in $\eta'\pi$ can be described by a single pole!

➡ $\pi_1(1400)$ and $\pi_1(1600)$ hybrid meson candidates are the same?

Name	Pole mass (MeV/c^2)	Pole width (MeV)	$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ (%)	$\Gamma_{KK}/\Gamma_{\pi\eta}$ (%)
$a_2(1320)$	$1318.7 \pm 1.9^{+1.3}_{-1.3}$	$107.5 \pm 4.6^{+3.3}_{-1.8}$	$4.6 \pm 1.5^{+7.0}_{-0.6}$	$31 \pm 22^{+9}_{-11}$
$a_2(1700)$	$1686 \pm 22^{+19}_{-7}$	$412 \pm 75^{+64}_{-57}$	$3.5 \pm 4.4^{+6.9}_{-1.2}$	$2.9 \pm 4.0^{+1.1}_{-1.2}$
π_1	$1623 \pm 47^{+24}_{-75}$	$455 \pm 88^{+144}_{-175}$	$554 \pm 110^{+180}_{-27}$	–

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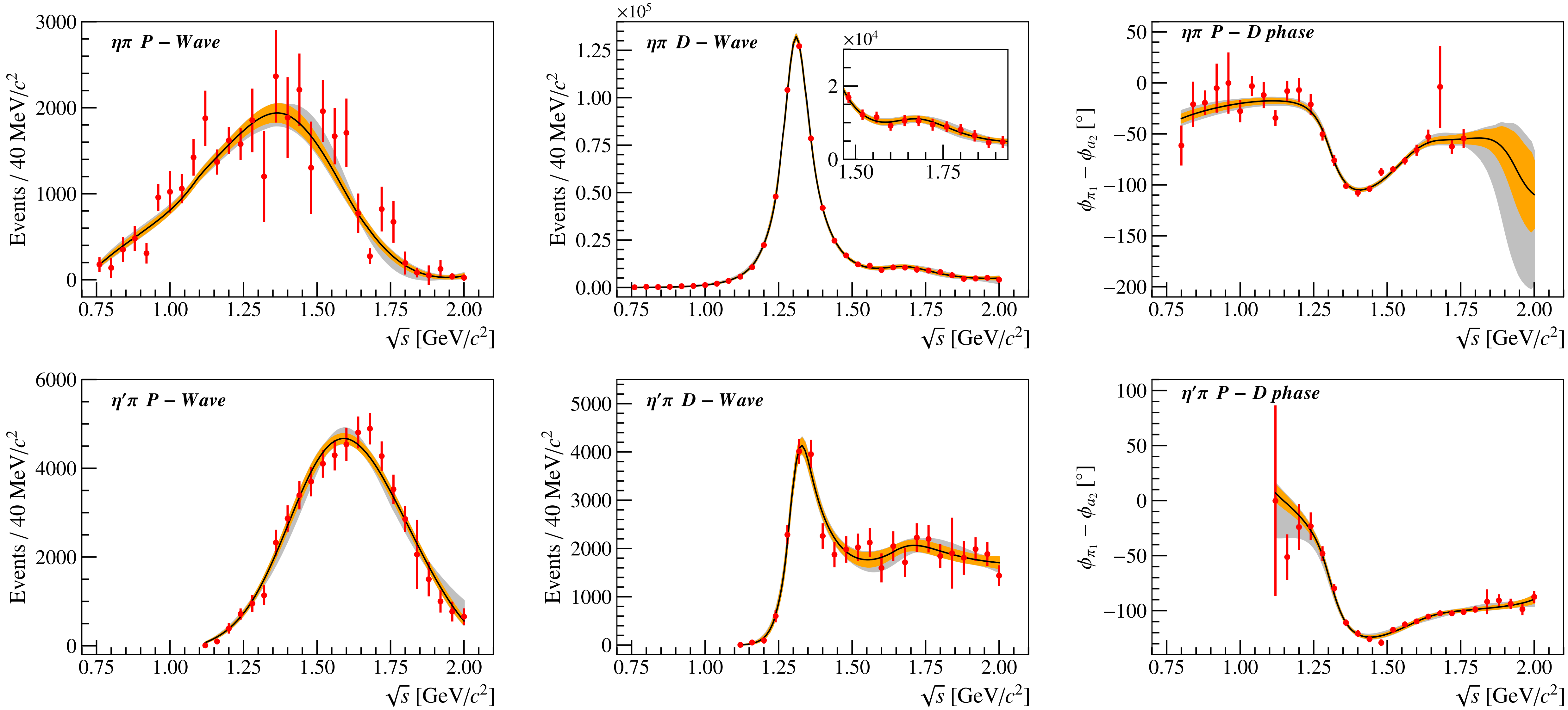

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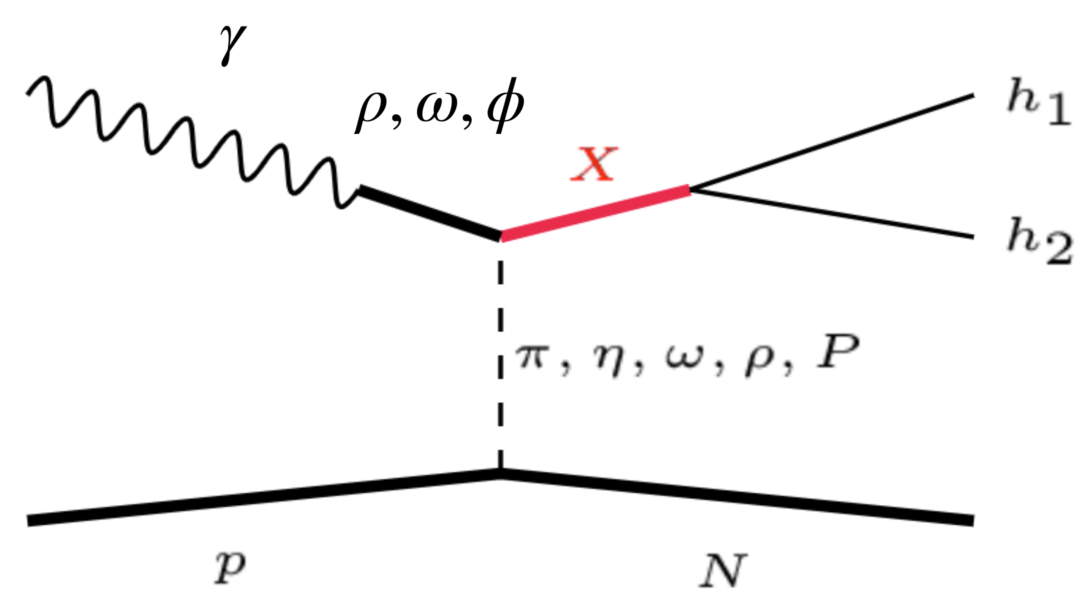
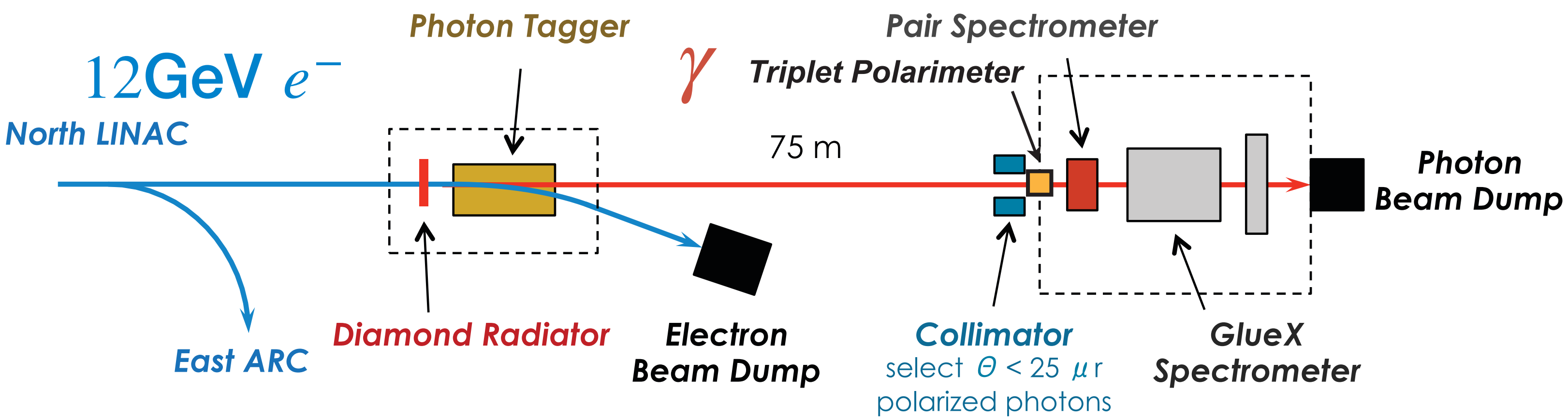
Spectroscopy using Photoproduction

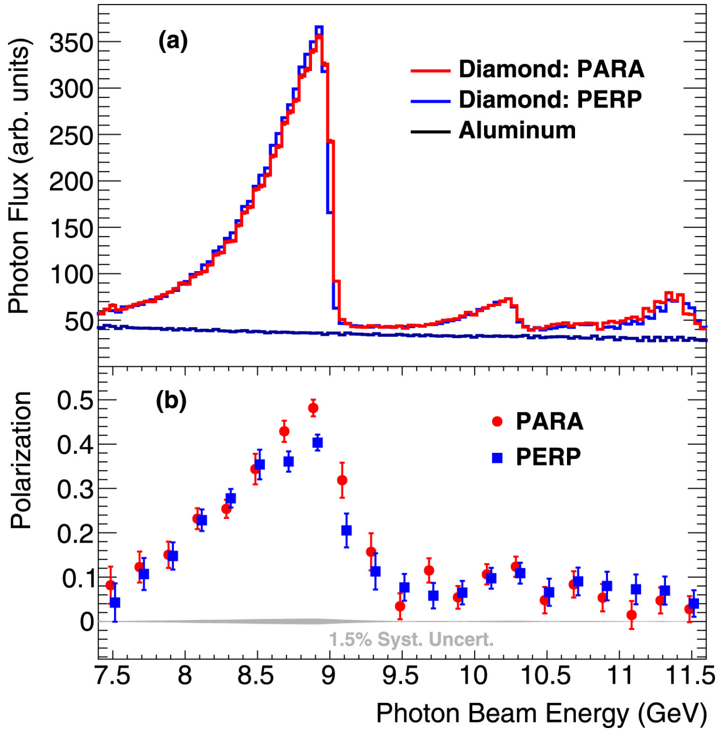
- Versatile process:
  - Incoming photon may oscillate to ϕ, ω, ρ (Vector Meson Dominance)
  - Various exchange particles possible
    - Linear beam polarization filters naturality of exchanged particle
  - Allows coupling to all lightest hybrid nonet states

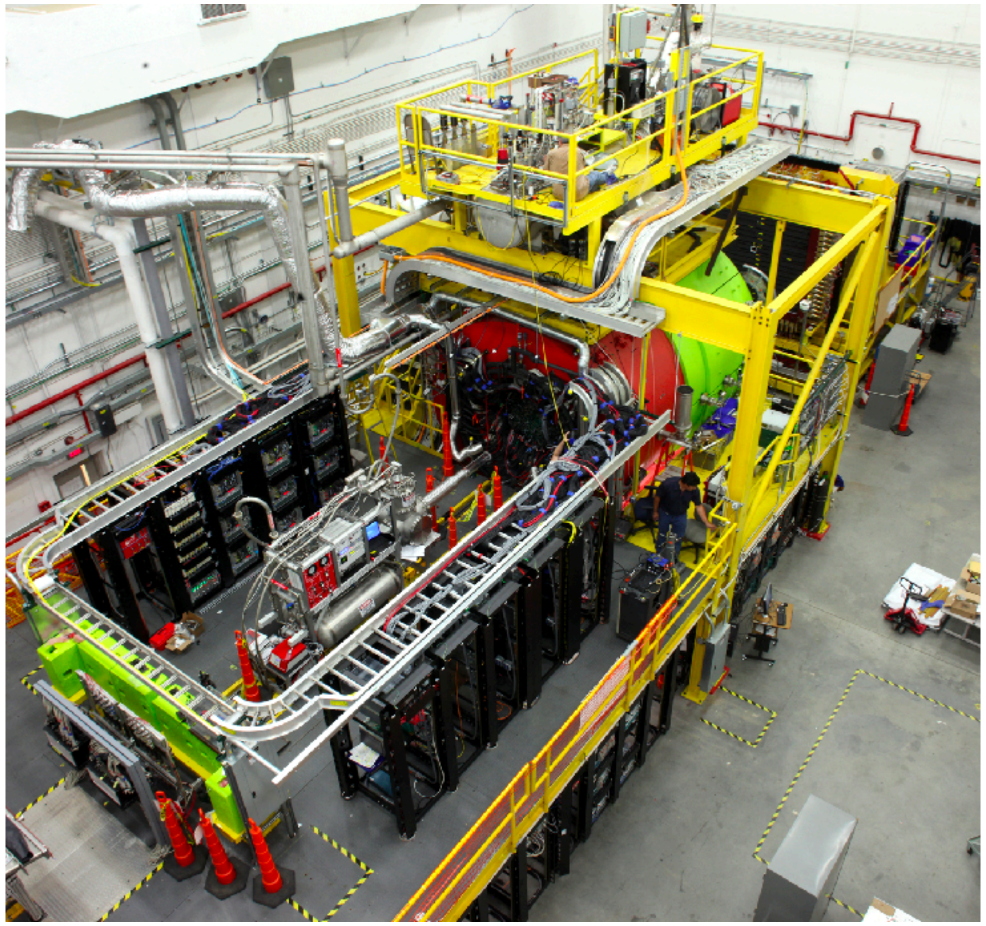


  - Production of mesonic resonances as well as target excitations
  - Ideal also for Baryon spectroscopy
    → background for meson production
- Complementary to πN reaction used by COMPASS, E852, VES

Hall-D at Jefferson Lab

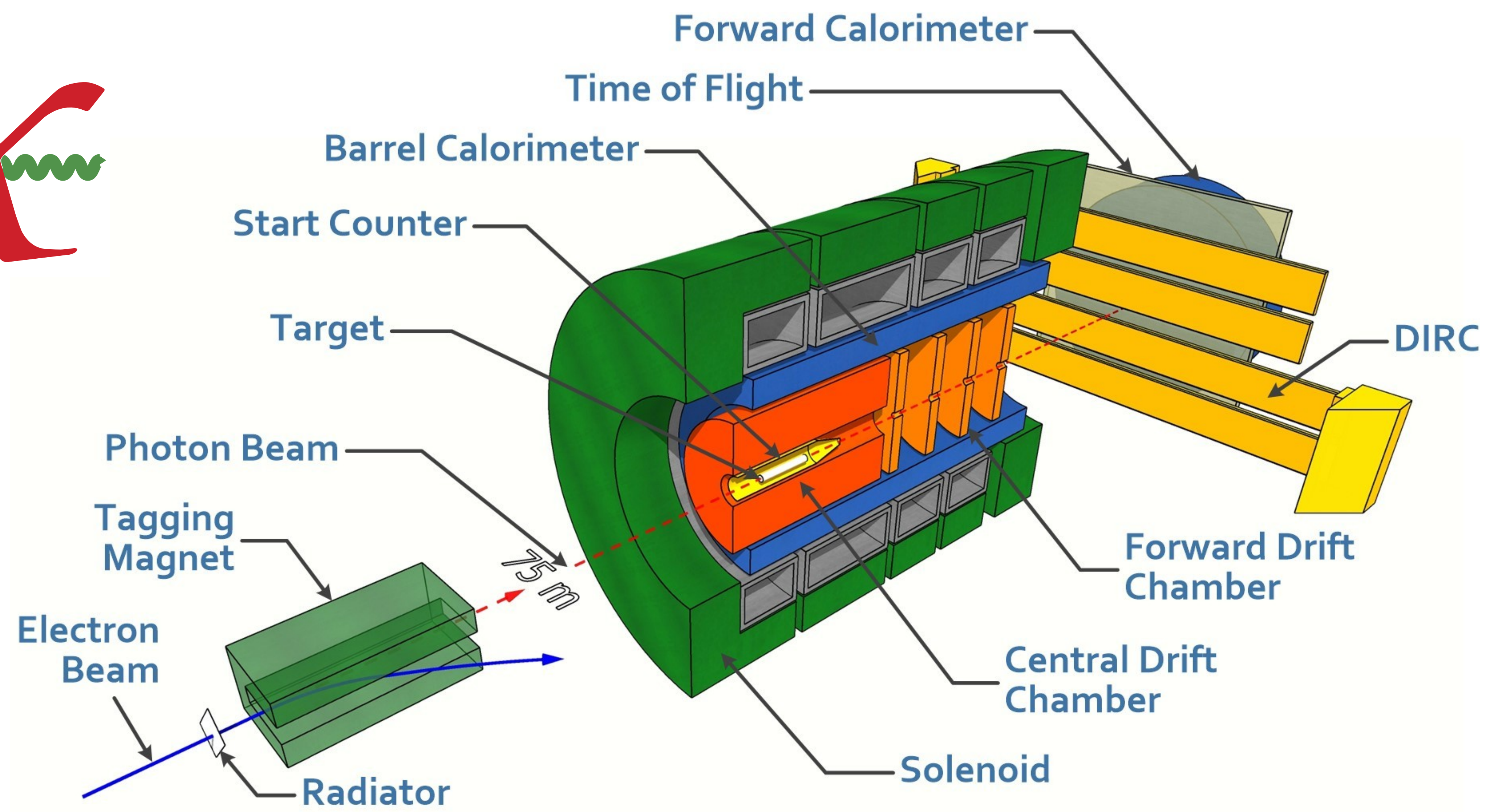






- JeffersonLab: Four main experimental halls
- CEBAF accelerator provides 12 GeV electron beam
- Hall-D: Linearly polarized photon beam produced via bremsstrahlung from thin radiator

The GlueX Experiment



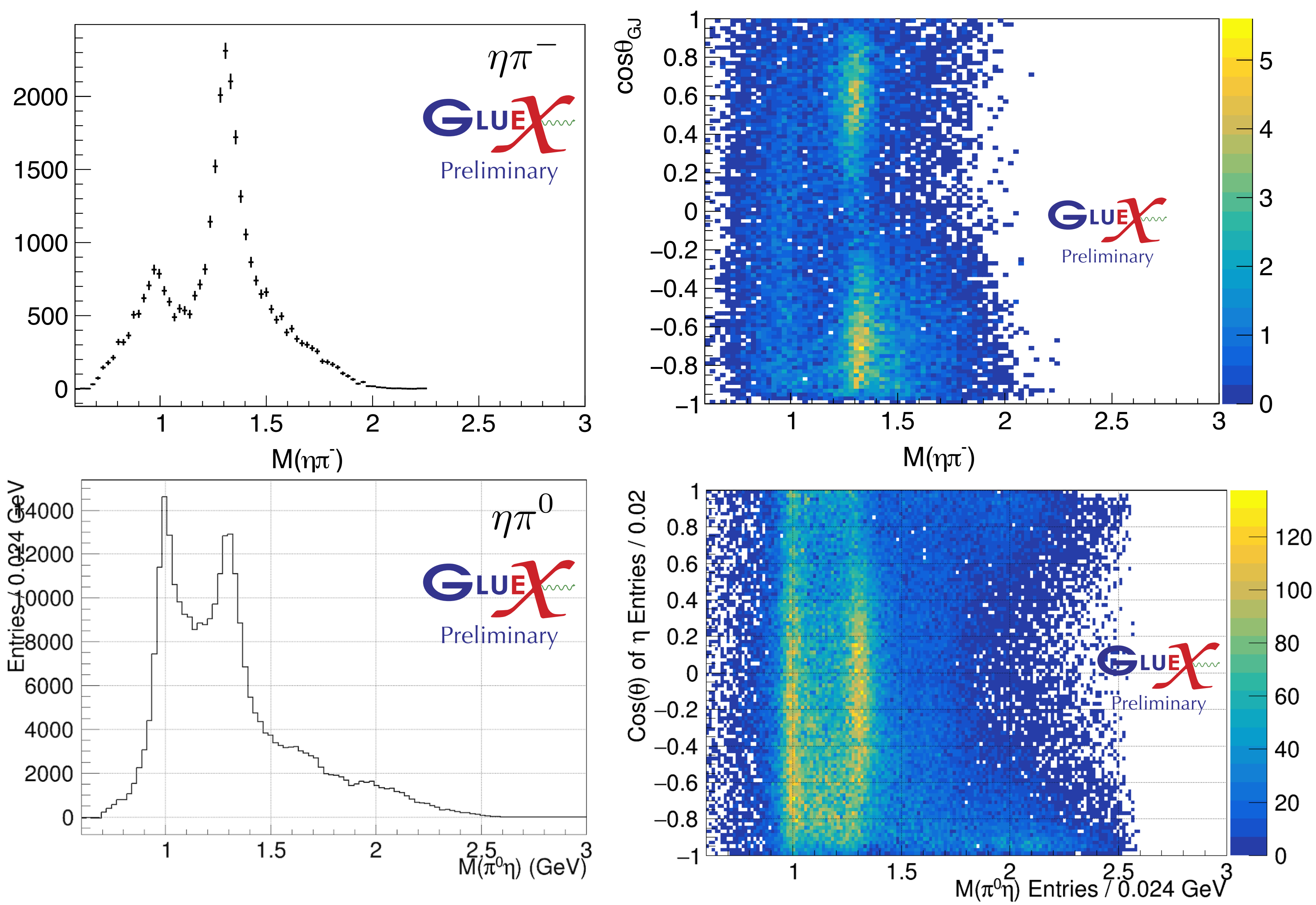
- Linearly polarized, tagged photon beam (P≈40%) impinging on Liquid Hydrogen Target
- Four polarization orientations, coherent peak: ~8.2-8.8 GeV
- Large acceptance for charged and neutral final state particles

$\gamma p \to \pi\eta N$ at GlueX

- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX

- Clear signals at $a_0(980)$ and $a_2(1320)$ masses

$0.1 < -t < 0.3$ GeV^2

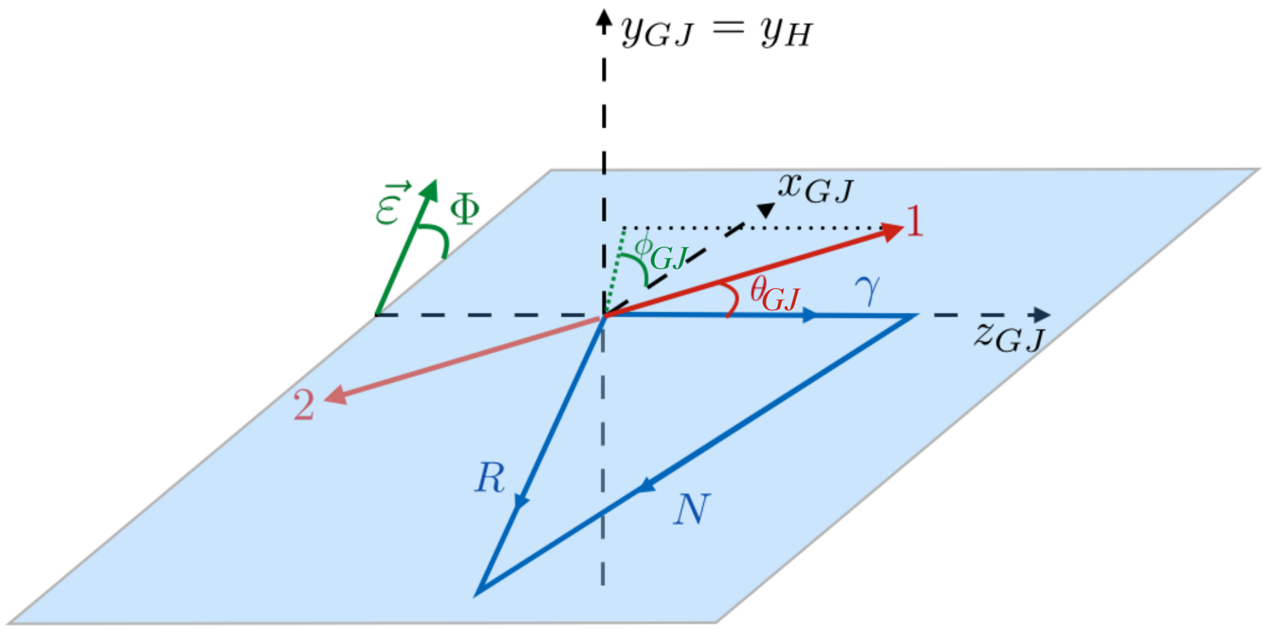


- Angular distribution of $a_2(1320)$ signal clearly different between charged and neutral channels

Definition of Amplitudes

- Described by three angles: $\cos(\theta)_\eta$ and ϕ_η in the $\eta\pi$ rest frame, angle Φ between polarization vector and production plane

- Amplitudes incorporate beam polarization, are eigenstates of reflectivity $\epsilon = \pm 1$



[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

- High-energy t-channel picture: 'reflectivity' fixes the product of naturalities of the exchange particle and the produced resonance

  Naturality: $\eta = P(-1)^J$

  natural parity $\eta = +1$ for: $J^P = 0^+, 1^-, 2^+, \ldots$

  unnatural parity $\eta = -1$ for: $J^P = 0^-, 1^+, 2^-, \ldots$

- In case of $\eta\pi$:
  positive (negative) reflectivity = natural (unnatural) parity exchange

Definition of Amplitudes

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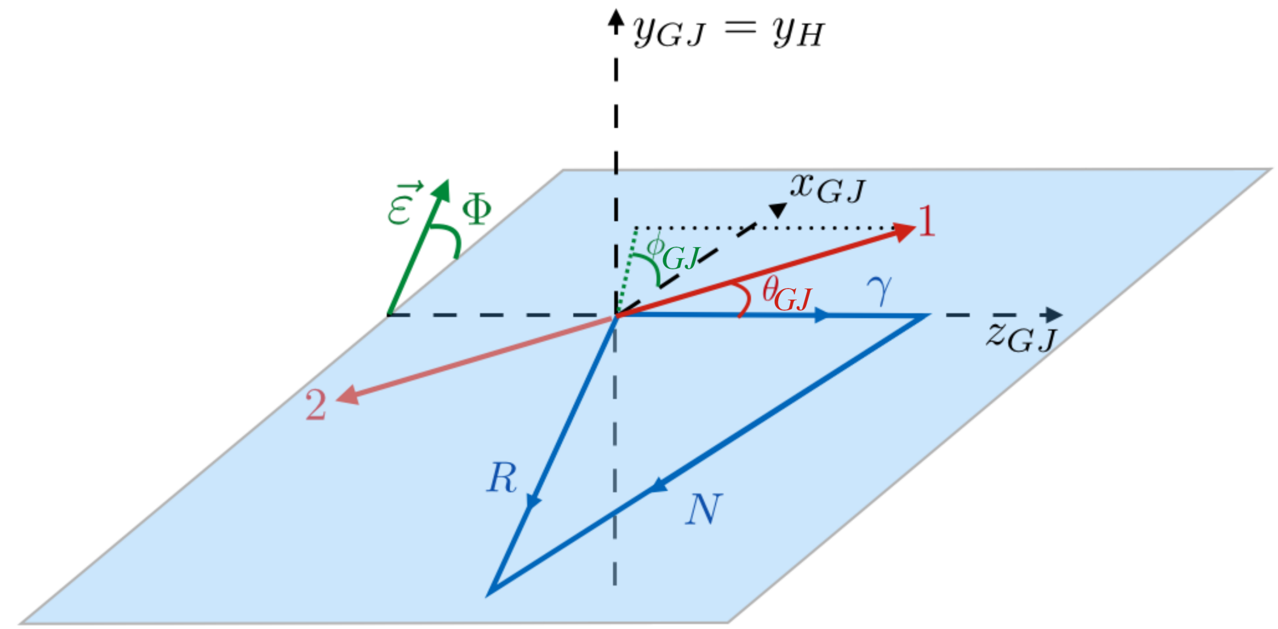


[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

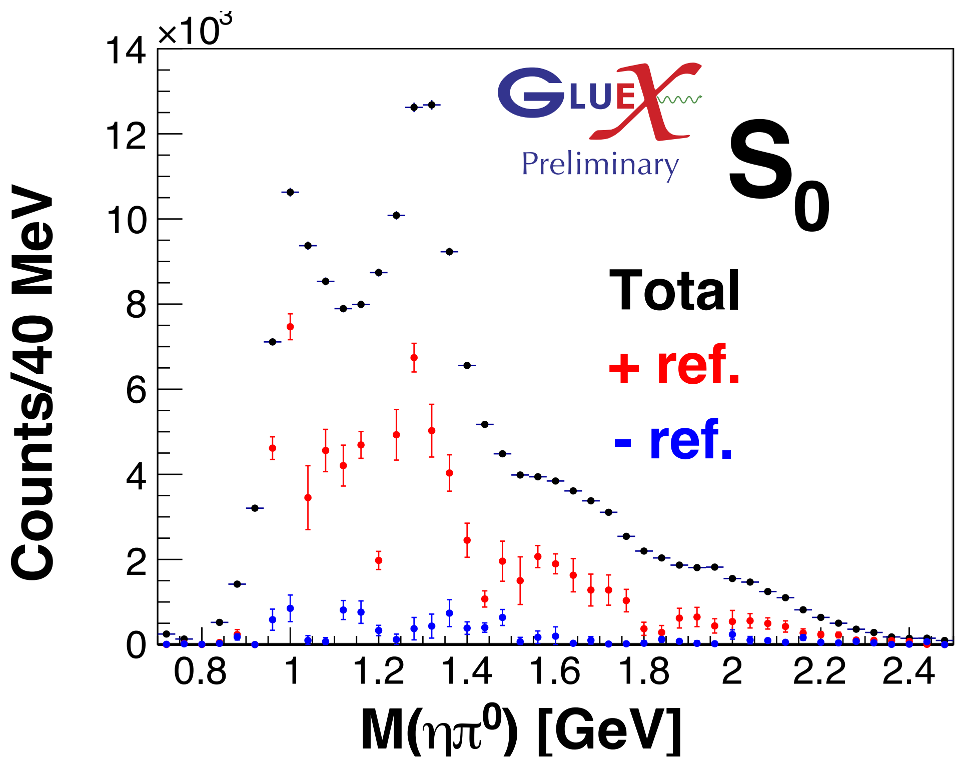
- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega,\Phi) = Y_l^m(\Omega)e^{-i\Phi}$

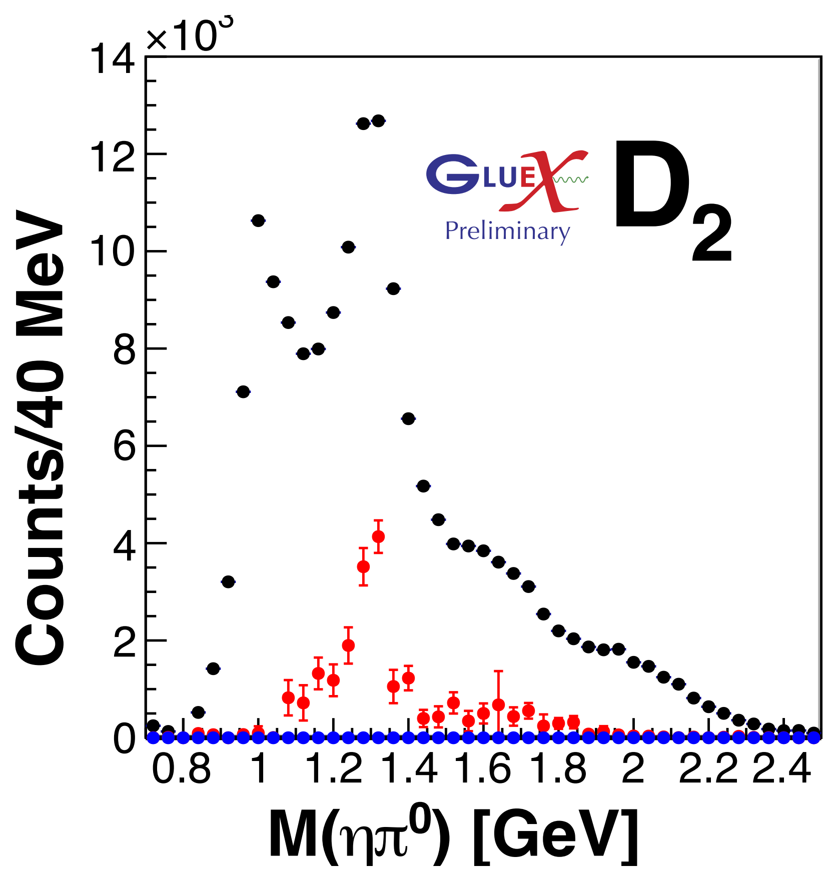
$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma)\left|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\mathrm{Re}[Z_\ell^m(\Omega,\Phi)]\right|^2 + (1-P_\gamma)\left|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Im}[Z_\ell^m(\Omega,\Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Re}[Z_\ell^m(\Omega,\Phi)]\right|^2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

- Complexity: Positive and negative reflectivity, $m = -l \ldots l$ allowed

- Frequent exchange with JPAC

Fit to $\gamma p \rightarrow \pi^0 \eta p$ data ($0.1 < -t < 0.3\,\mathrm{GeV}^2$)





- Combined fit, all polarization orientations
- Large S-wave, positive reflectivity contribution
  - Non-resonant?
  - Contribution from other resonance(s)? ($a_2(1700), a_0(1450), \ldots$)
- Clear signal in $m = +2$ D-wave
- Waveset based on Tensor Meson Dominance model:

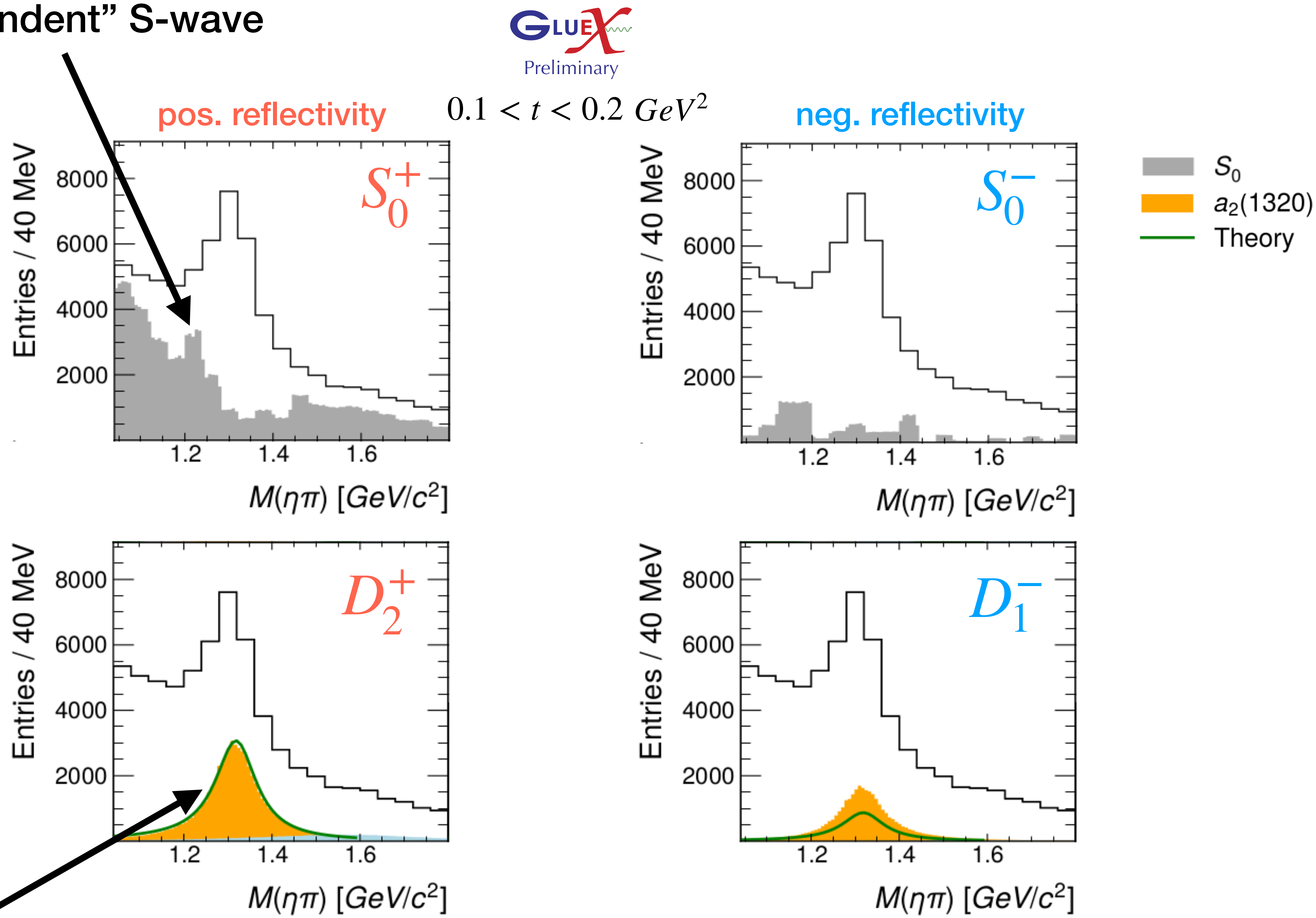
$$L^{\epsilon}_{m} = S^{\pm}_{0}, D^{\pm}_{0}, D^{\pm}_{1}, D^{+}_{2}, D^{-}_{-1}$$

[V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)]

- Perform semi - mass independent fit to extract a_2 contribution - will anker P-wave extraction

Semi-Model Independent Fit ($\gamma p \to \pi^0 \eta p$)

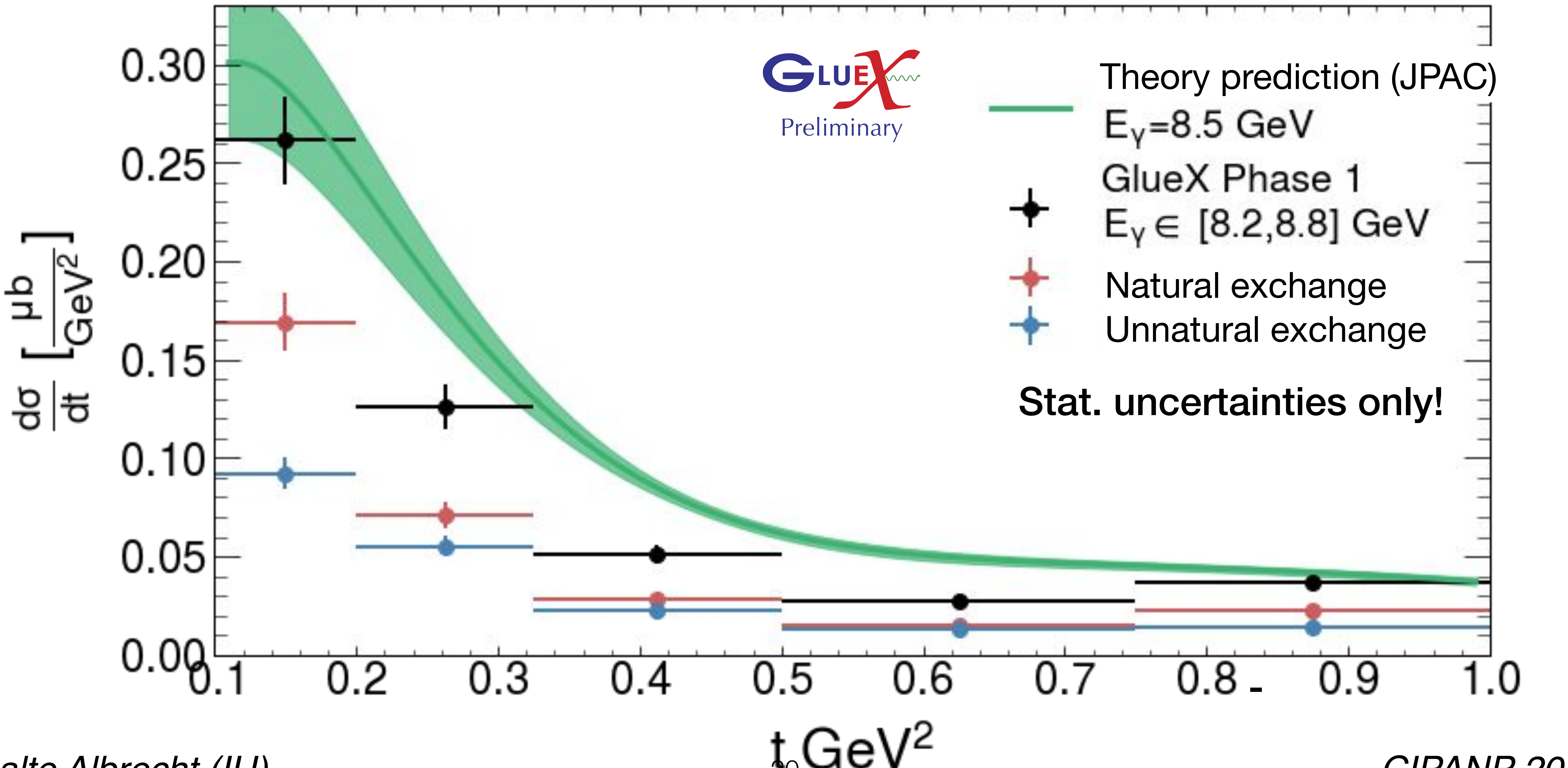
“mass-independent” S-wave



$a_2(1320)$: **Breit-Wigner**

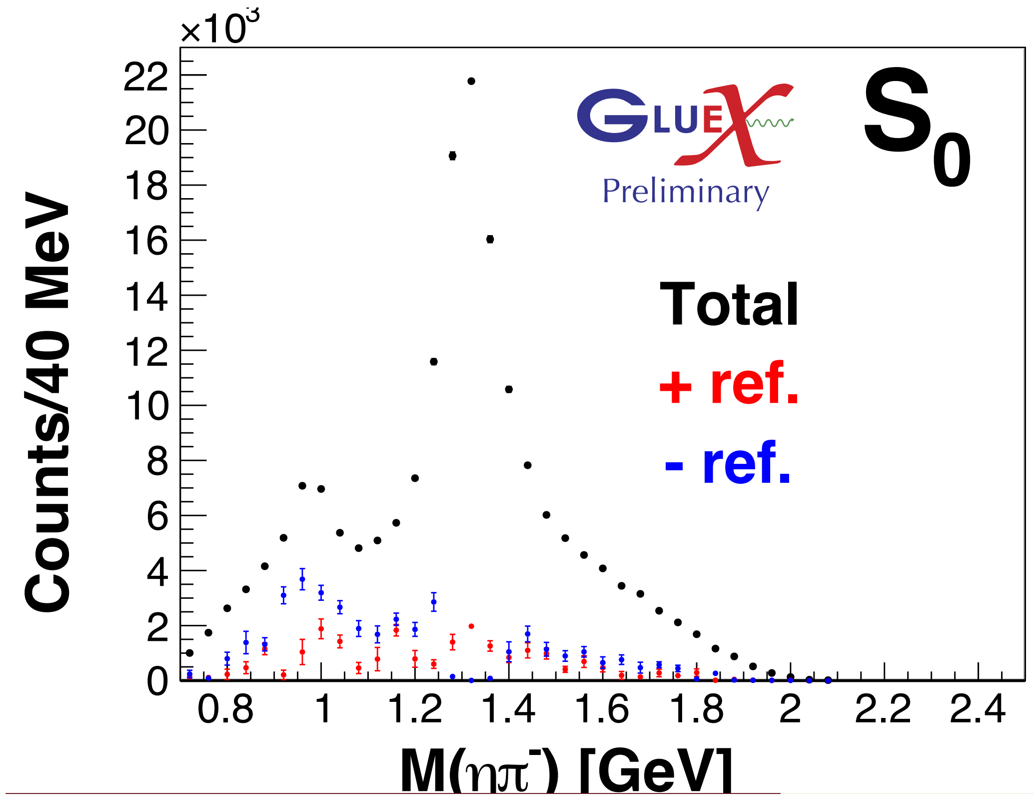
Extracted Cross Section

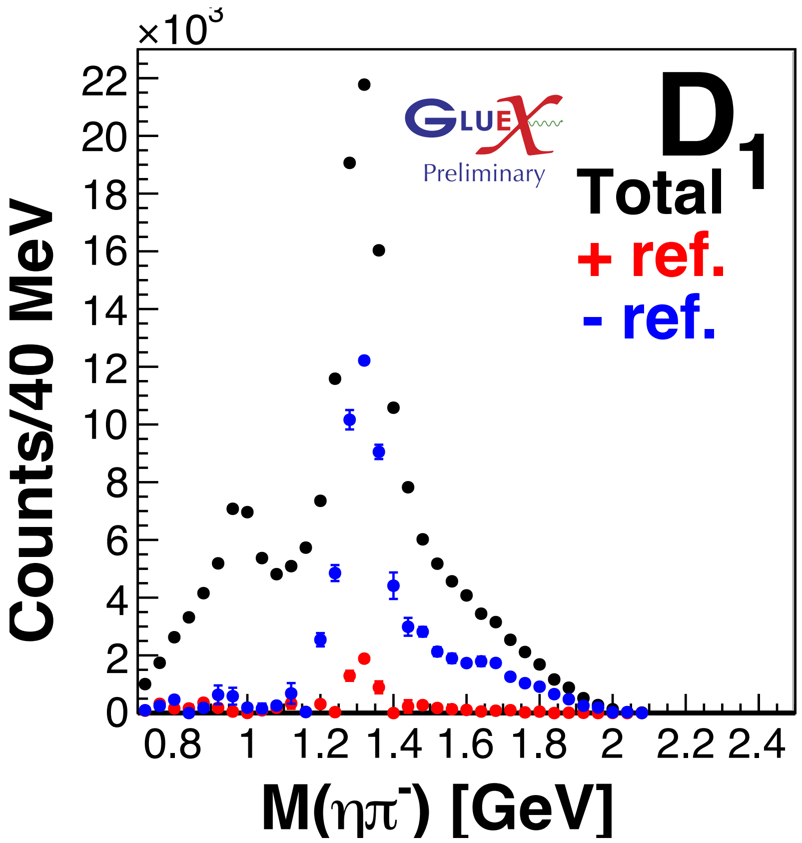
- Including $a_2(1700)$ has impact on result, tail underneath $a_2(1320)$
  → More sophisticated model being tested together with JPAC
- Good agreement with theory prediction
- Extraction of cross section well advanced, systematic checks started



Fit to $\gamma p \to \pi^- \eta \Delta^{++}$ data ($0.1 < -t < 0.3\,\mathrm{GeV}^2$)

- Combined fit, all polarization orientations
- Dominant S-wave contribution in negative reflectivity component
    - Large contribution in $a_0(980)$ mass region
- Clear signal in $m = +1$ D-wave ($a_2(1320)$), negative reflectivity
    - Expected for unnatural parity exchange (pion exchange)
    - Tail in D1 wave related to $a_2(1700)$?





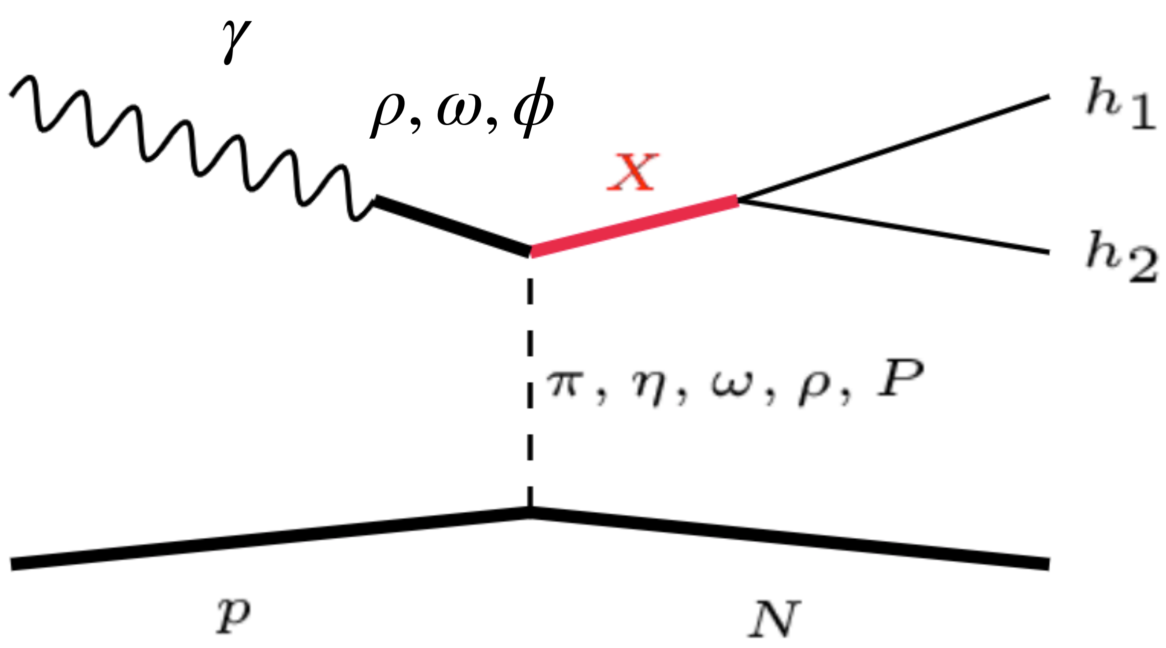
Comparison: Charged and Neutral Channels

$\eta\pi^0$:

- Dominated by positive reflectivity, $a_2(1320)$ signal in $m = 2$ wave at low t

➡ ρ, ω exchange (natural parity)

- Intriguing comparison: $a_2(1320)$ produced exclusively in helicity-2 state in $\gamma\gamma$-fusion
  [(L3) Phys.Lett.B 413(1997) 147;
  (Belle) Phys.Rev.D 80(2009), 032001]



$\eta\pi^-$:

- Dominated by negative reflectivity, $a_2(1320)$ signal in $m = 1$ wave at low t

➡ π exchange (unnatural parity)

- D-wave structure evolves with -t
- Investigation of a_2 production goal for near-term publication
- Groundwork for understanding weaker P-wave contribution

Summary

- Fascinating new results on hybrid meson candidates in recent years
- Very active field, results from different experiments / production processes
  - First observation of spin-exotic contribution in $\bar{p}p$ annihilation in flight
  - Coupling with COMPASS data on $\eta\pi$ and $\eta'\pi$ strengthens interpretation as one underlying pole
- Unique situation for GlueX:
  High quality photoproduction data sets available, analyses underway
  - Partial wave analysis tools being used and further developed
  - a_2 cross section measurements in $\eta\pi$ channels will anker P-wave extraction
  - Highly productive and valuable collaboration with theorists (JPAC)

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