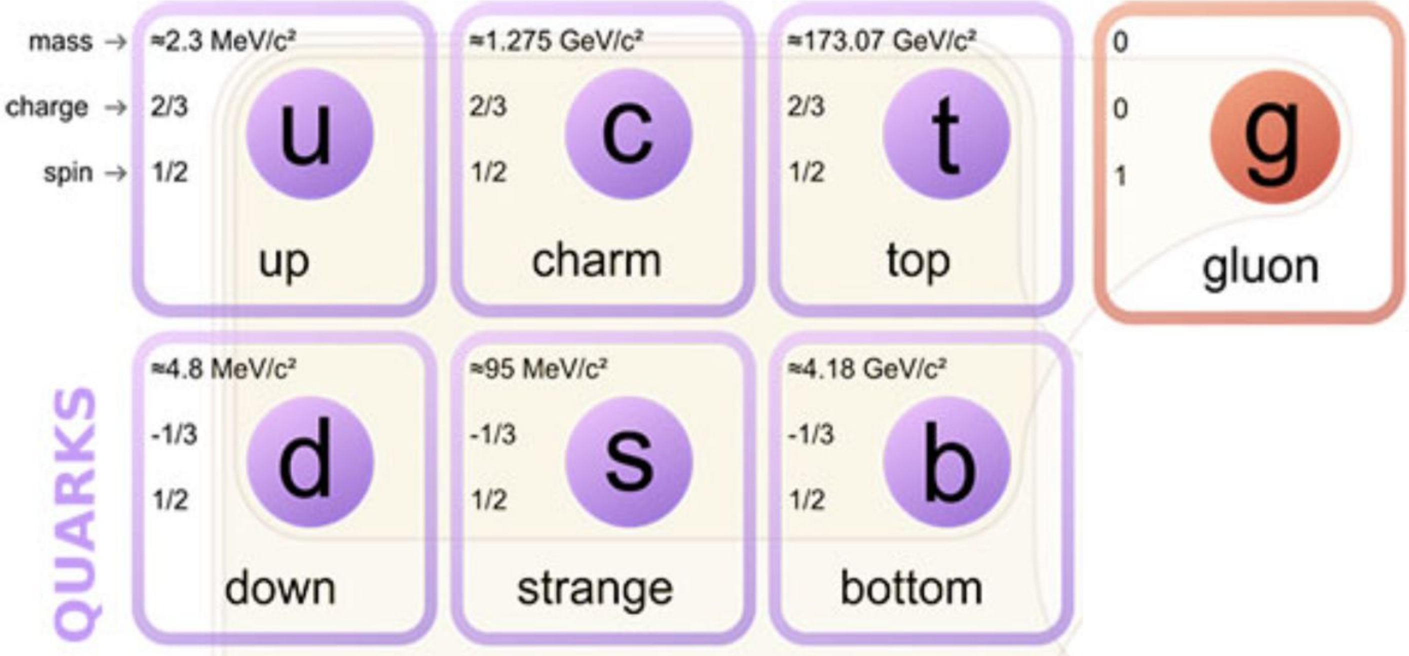
Study of $\gamma p \rightarrow \eta \pi^0 p \rightarrow 4\gamma p$ reaction at GlueX

Lawrence Ng
Florida State University

Quantum Chromodynamics

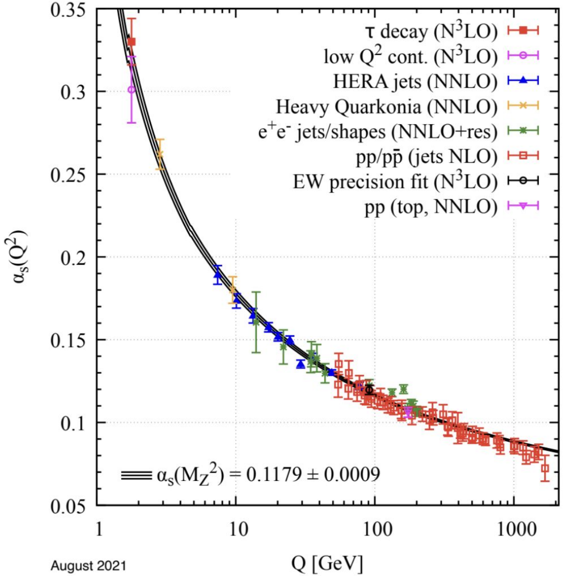
https://en.wikipedia.org/wiki/Standard_Model



“*Three **quarks** for Muster Mark!*” - Finnegans Wake

Quantum Chromodynamics

Particle Data Group, **Review of Particle Physics**,
Volume 2022, Issue 8, August 2022, 083C01,

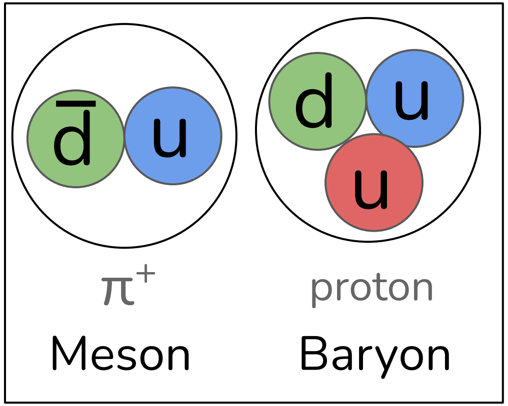


Low energy
Large distance
Non-perturbative

↔

High energy
Small distance
Perturbative

Non-perturbative Regime



Hadrons

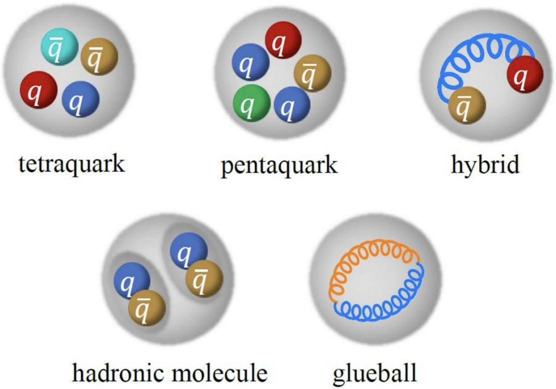
Asymptotic Freedom

Confinement - How does it arise?

Perturbative ~ Allows for high precision calculations
Non-perturbative ~ higher order terms to achieve same level of precision and may not converge at all!

Exotic Hadrons

- Existence predicted by Gell-mann and Zweig in 1964
- Systems of quark and gluons beyond the conventional meson ($q\bar{q}$) and baryon (qqq) states



https://indico.bnl.gov/event/11669/contributions/50918/attachments/36102/59226/PSQ%40EIC_FKGuo.pdf

- What color singlet states exist in nature?
- What is the role of gluons?

Study hybrid mesons to understand gluonic excitations

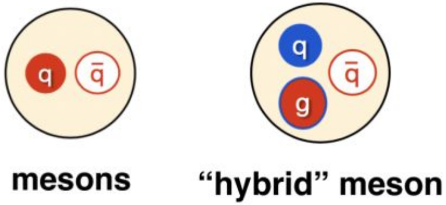
Hybrid Mesons

- ❖ Meson system has two spin ½ quarks in relative orbital motion
  - ➢ J^{PC} where $J=L+S$, $P=(-1)^{L+1}$, $C=(-1)^{L+S}$

- ❖ Hybrid mesons contain gluonic excitations that directly contribute to the wavefunction
  - ➢ **Exotic hybrid mesons** have J^{PC} not accessible as $q\bar{q}$
    - ■ 0^{+-}, 1^{-+}, 2^{+-}, ...
    - ■ Easier to search for since they do not mix with conventional states

L	S	J^{PC}	L	S	J^{PC}	L	S	J^{PC}
0	0	0^{-+}	1	0	1^{+-}	2	0	2^{-+}
0	1	1^{--}	1	1	0^{++}	2	1	1^{--}
			1	1	1^{++}	2	1	2^{--}
			1	1	2^{++}	2	1	3^{--}

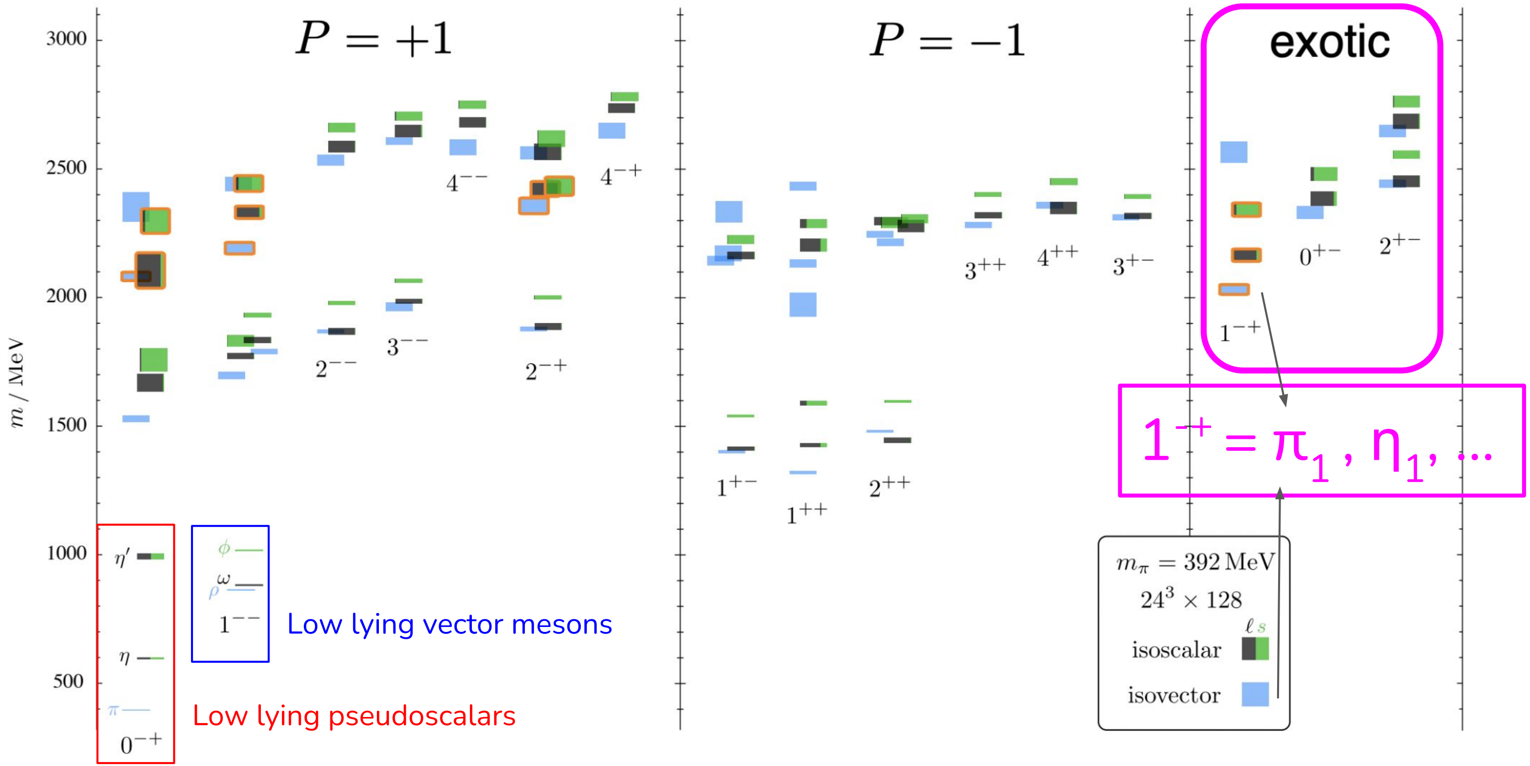
TABLE I. The allowed J^{PC} quantum numbers for $q\bar{q}$ systems.



So... where to search?

➡ *Theory Spectrum*

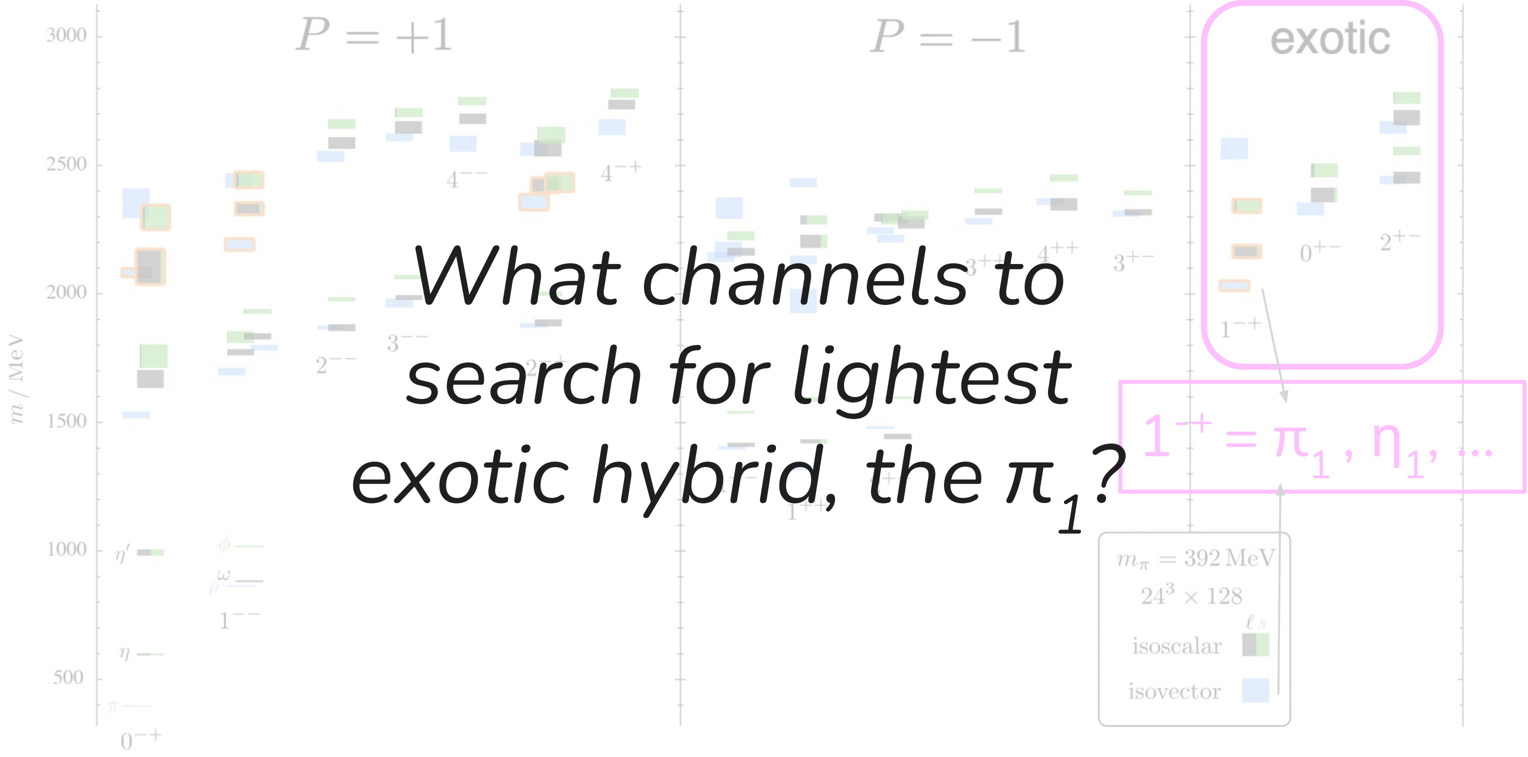
Lattice QCD: Light Meson Spectrum



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

- Lightest spin-exotic state: $J^{PC} = 1^{-+},\ M \approx 2\,\mathrm{GeV}/c^2$

Lattice QCD: Light Meson Spectrum

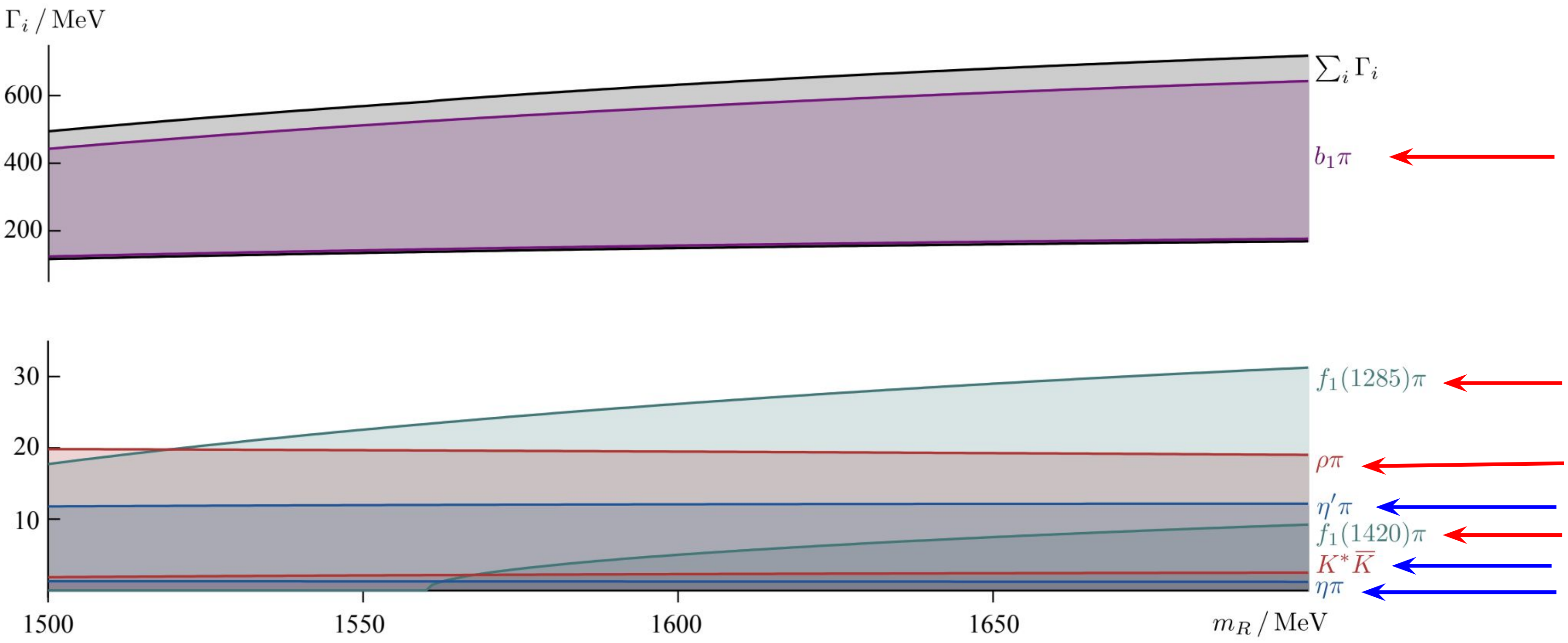


What channels to search for lightest exotic hybrid, the π_1?

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

- Lightest spin-exotic state: $J^{PC} = 1^{-+},\ M \approx 2\,\mathrm{GeV}/c^2$

Lattice QCD: π_1 Branching Fractions

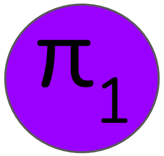


π_1 decay to vector-pseudoscalar >> two pseudoscalar final states

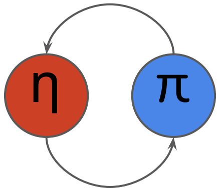
Tradeoff: vector-pseudoscalar states are more complicated to reconstruct

Why Search for the π_1 in $\eta\pi$?

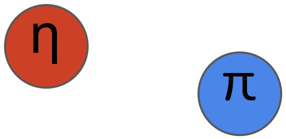
- J^{PC} of π and η ~ 0^{-+}
  - $S=0$, $J=L$, $P=(-1)^L$, $C=+$
  - Examples: $J^{PC} = 0^{++}, 1^{-+}, 2^{++}, 3^{-+}$ …
  - Odd-L impossible as a conventional meson
- Simpler reconstruction + η/π are narrow states



$J^{PC}=1^{-+}$



L=J=1



Decay as a “P-wave”

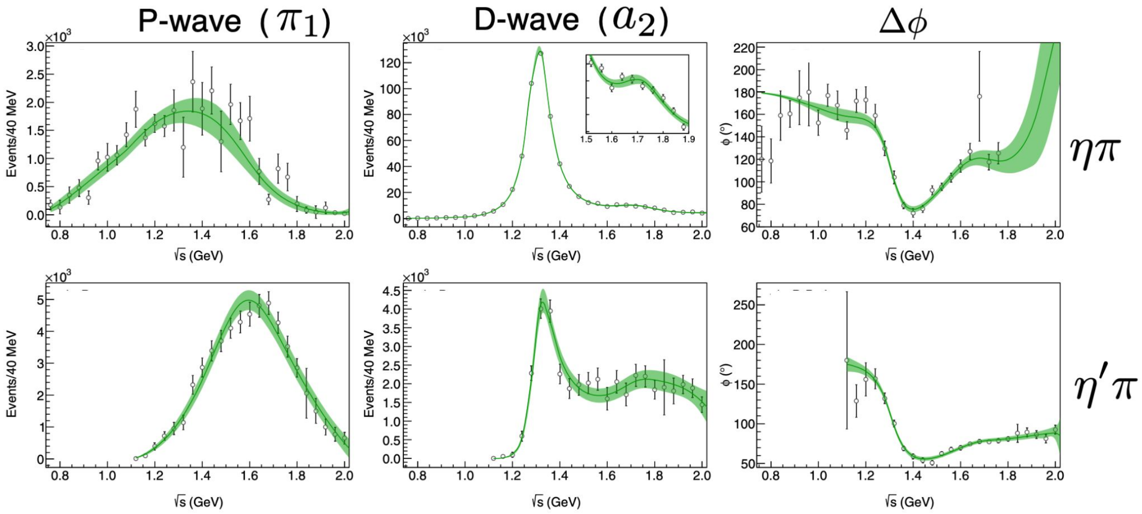
Borrow from spectroscopy
L=0 : S-wave
L=1 : P-wave
L=2 : D-wave
….

Recent Observations: COMPASS/JPAC

Long history of previous searches…

COMPASS (pion beam) published results on the η’π and ηπ system

Joint Physics Analysis Center (JPAC) described 1^{-+} wave with 1 pole, 2-channel K-Matrix



~155k Events in total

PRL **112** 042002 (2019)

Poles	Mass (MeV)	Width (MeV)
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

Crystal Barrel

- Coupled channel analysis of: $p\bar{p}\to K^+K^-\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$ + 11 ππ scattering datasets + COMPASS η’π and ηπ data

Confirms JPAC results

Eur. Phys. J. C (2020) 81:1056

Recent Observations: COMPASS/JPAC

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COMPASS (pion beam) published results on the η'π and **ηπ** system

reaction that I study!

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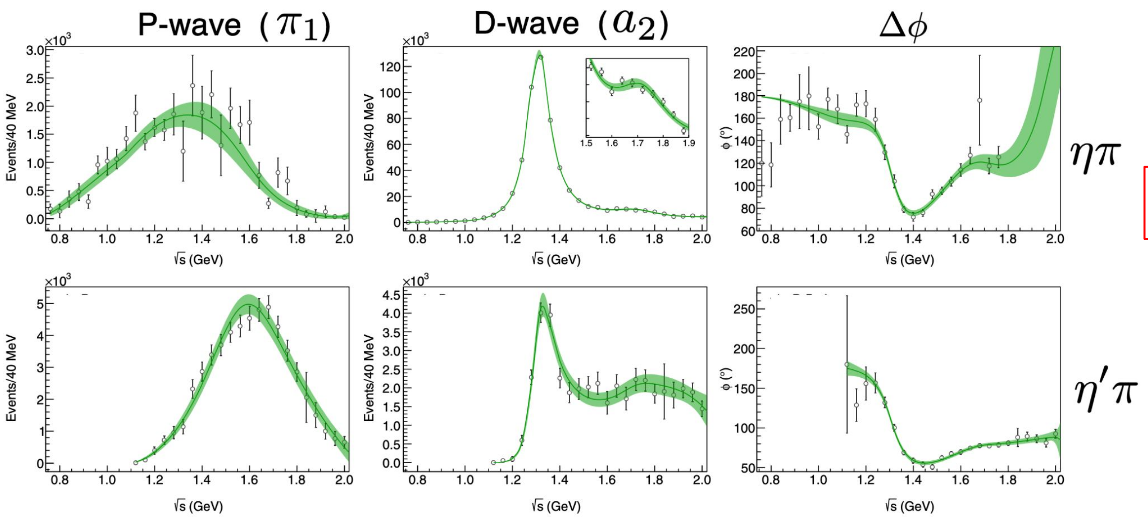

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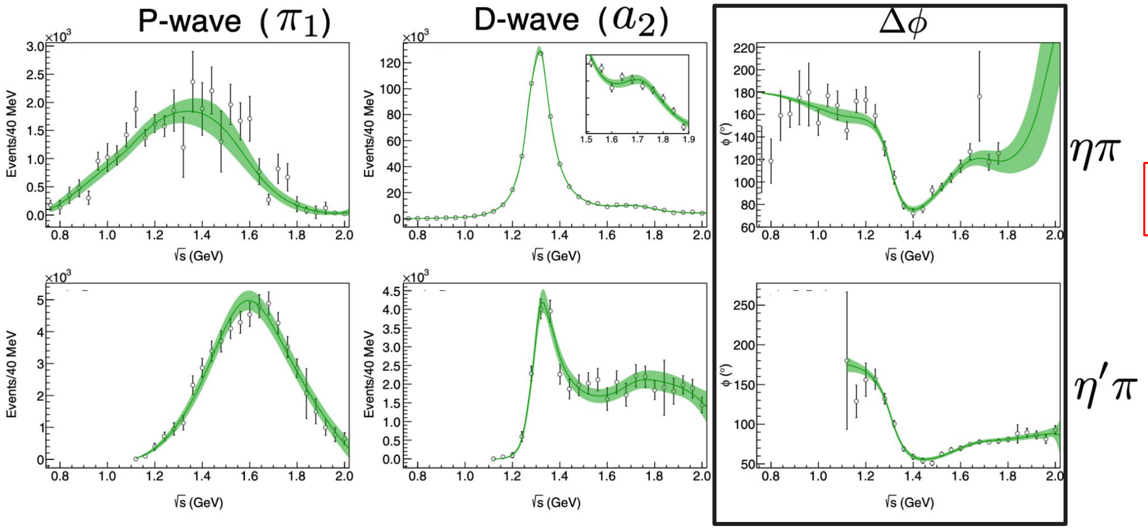

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PRL **112** 042002 (2019)

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Strong phase motion indicates ***Resonant*** *P-wave*

Crystal Barrel

- Coupled channel analysis of: $p\bar{p} \to K^+K^-\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$ + 11 ππ scattering datasets + COMPASS η'π and ηπ data

Confirms JPAC results

Eur. Phys. J. C (2020) 81:1056

Good experimental evidence for the π_1 in hadroproduction

What about other production mechanism?

Different mechanisms different ways to generate a signal

And, What about other hybrids?

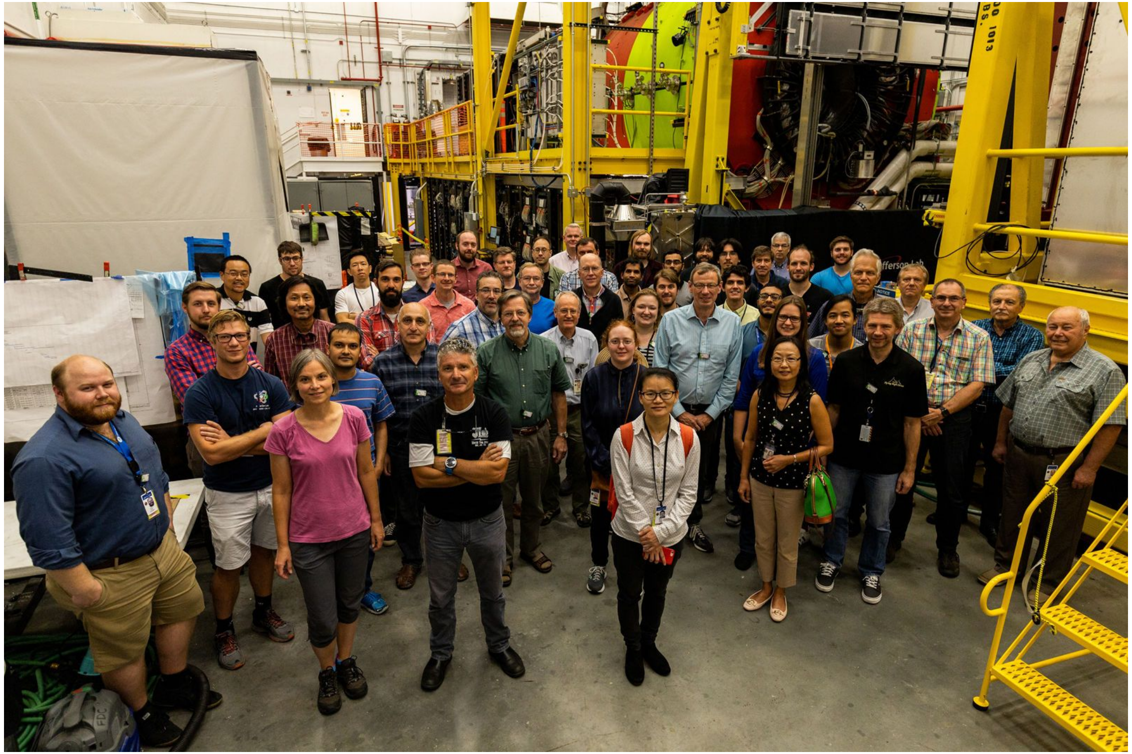
GlueX

Primary Purpose

- ❖ Understand confinement by mapping the light meson spectrum for hybrid and exotic mesons

Features

- ❖ Linearly Polarized Photon Beam
- ❖ High statistics



GlueX

Primary Purpose

- ❖ Understand confinement by mapping the light meson spectrum for hybrid and exotic mesons

Features

- ❖ Linearly Polarized Photon Beam
- ❖ High statistics

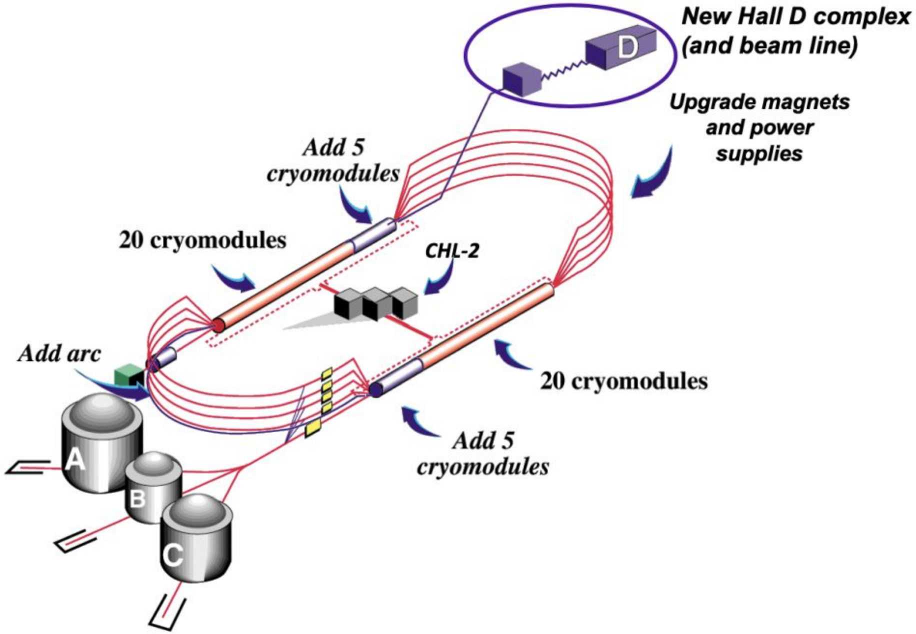
14 FSU Members ~10% of GlueX member list

Chandra S Akondi	Florida State University
Jason Barlow	Florida State University
Edmundo Barriga	Florida State University
Volker Crede	Florida State University
Sean Dobbs	Florida State University
Donavan Ebersole	Florida State University
Paul Eugenio	Florida State University
Jesse Hernandez	Florida State University
Daniel I Lersch	Florida State University
Lawrence Ng	Florida State University
Alexander I Ostrovidov	Florida State University
Saheli Rakshit	Florida State University
Alicia Remington	Florida State University
Gabriel Rodriguez	Florida State University

Jefferson Lab

Located in Newport News, VA
Contains 4 halls: A,B,C,D
GlueX at Hall D

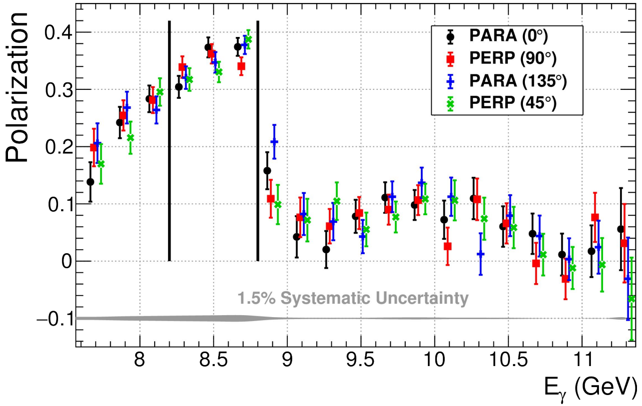
Continuous Electron Beam Accelerator Facility (CEBAF)
- 12 GeV polarized electron source

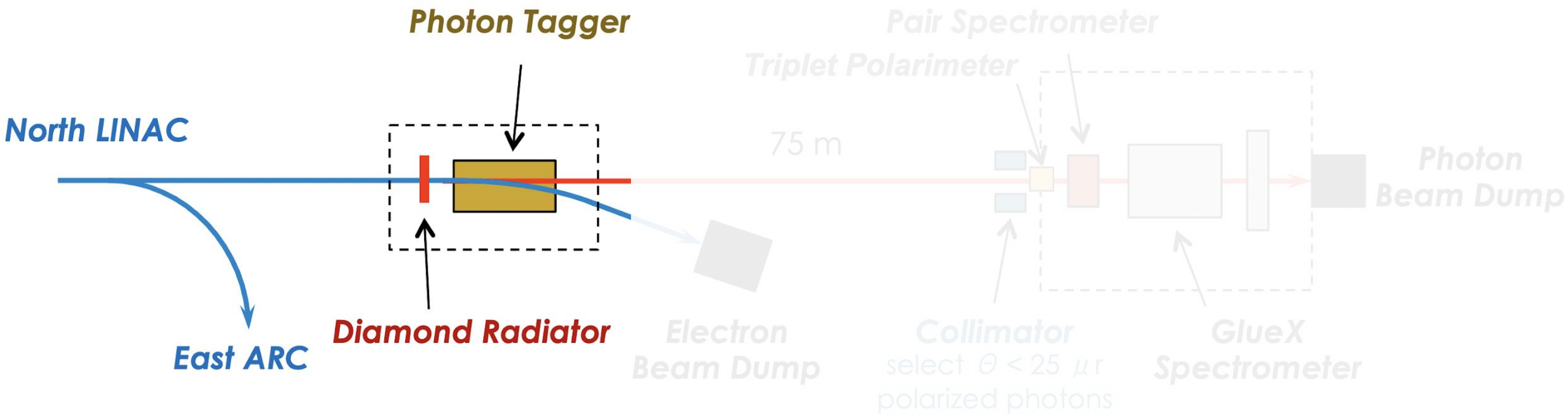


Hall D Photon Beamline

Linearly polarized photon beam!
Data taken in 2 pairs of orthogonal orientations

Coherent Peak ~35% Polarization





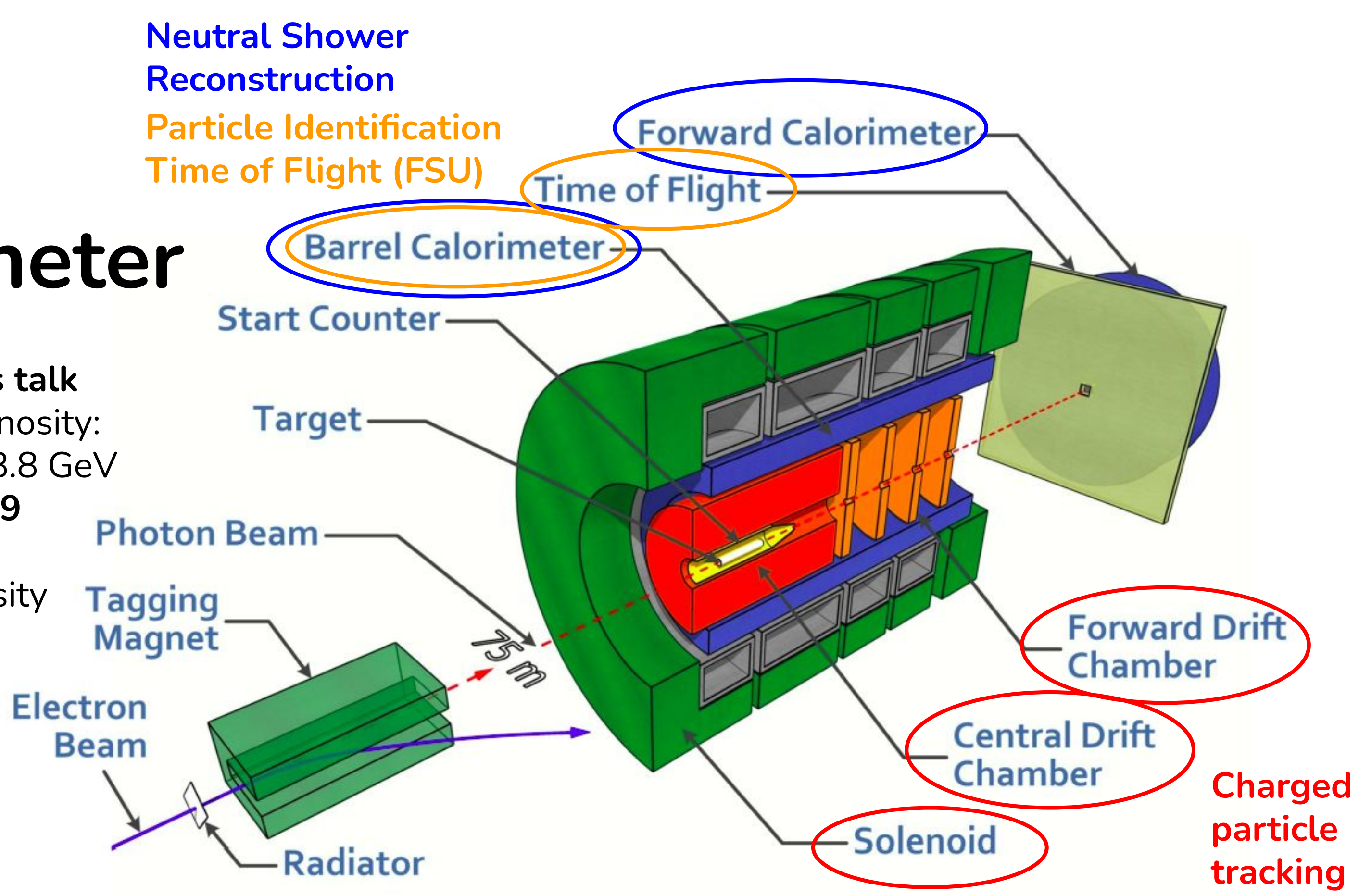
GlueX Spectrometer

Phase 1: **2017-2018**

- **Analyses in this talk**
- Integrated Luminosity: 118.2 pb^{-1} 8.2-8.8 GeV

Phase 2: **Started 2019**

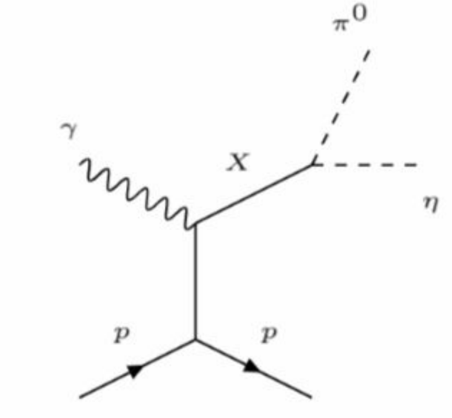
- Ends ~2025
- +(3-4)x Luminosity



Characterizing the $\gamma p \rightarrow \eta\pi^0 p \rightarrow 4\gamma p$ Spectrum at GlueX

Reaction of Interest

$\gamma p \rightarrow \eta\pi^0 p \rightarrow 4\gamma p$



SIGNAL REACTION

$t = (p_{recoil} - p_{target})^2$

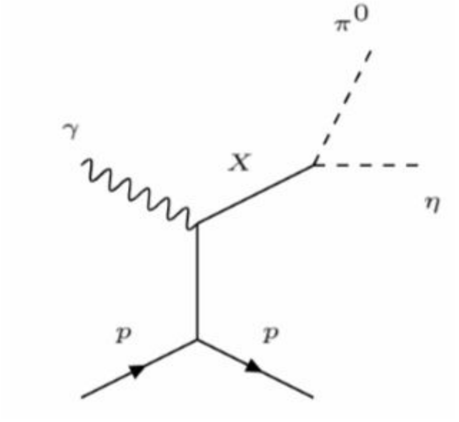
Select exclusive
$\gamma p \rightarrow 4\gamma p$ events

Select coherent peak (high polarization)
$8.2 < E_{Beam} < 8.8$ GeV

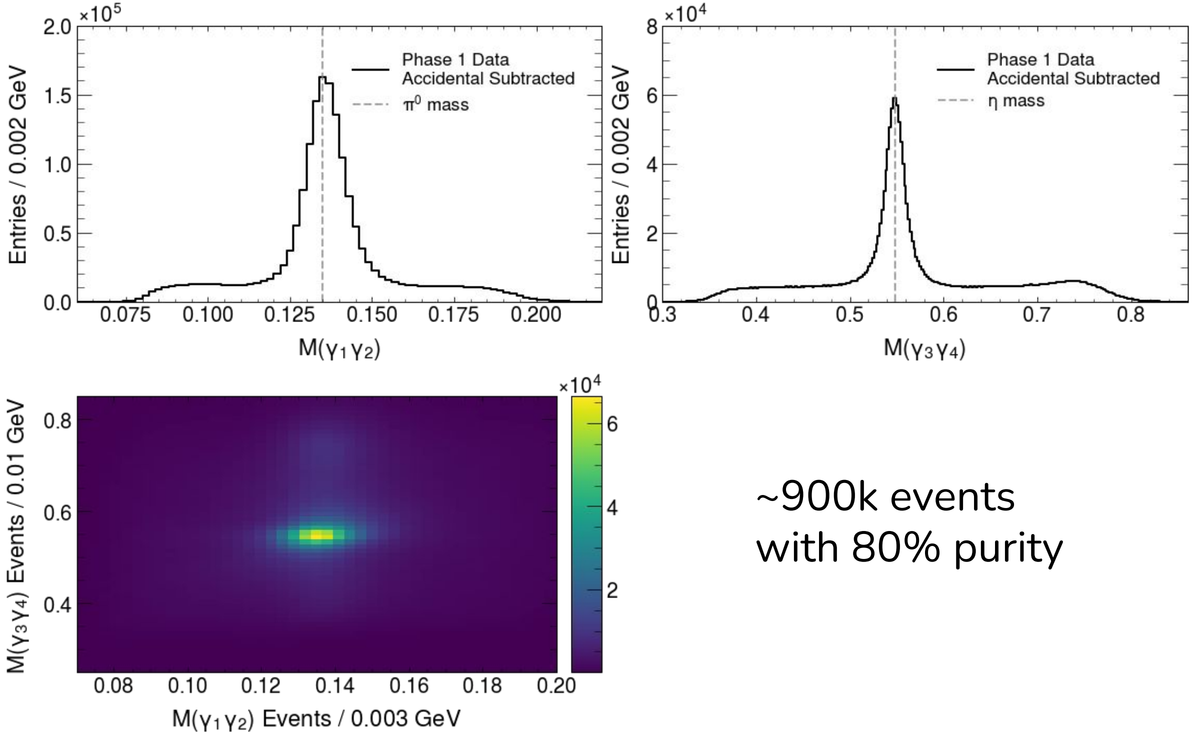
Reaction of Interest

π^0 candidate : $\gamma_1\gamma_2$
η candidate : $\gamma_3\gamma_4$

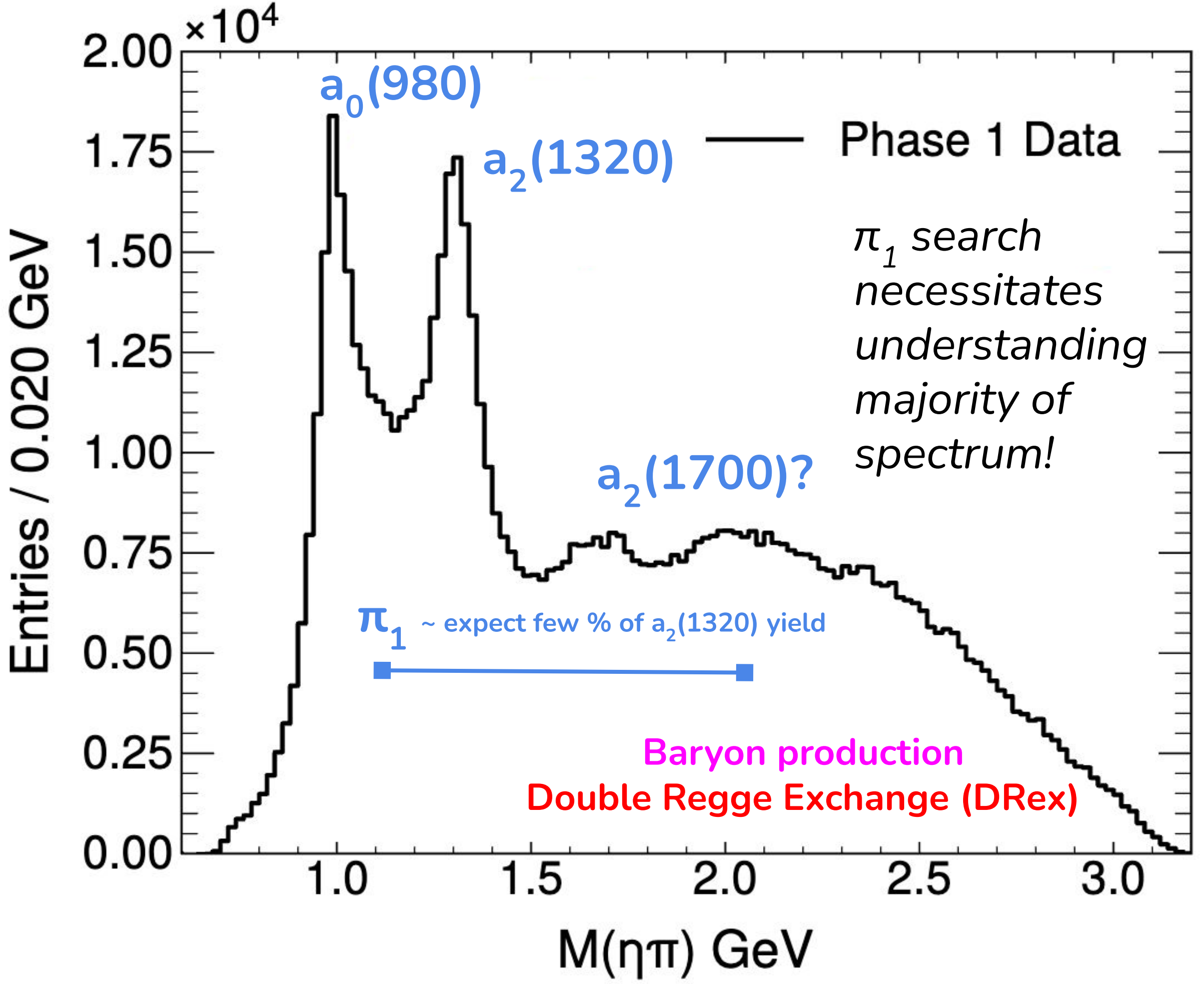
$\gamma p \to \pi^0 \eta p \to 4\gamma p$



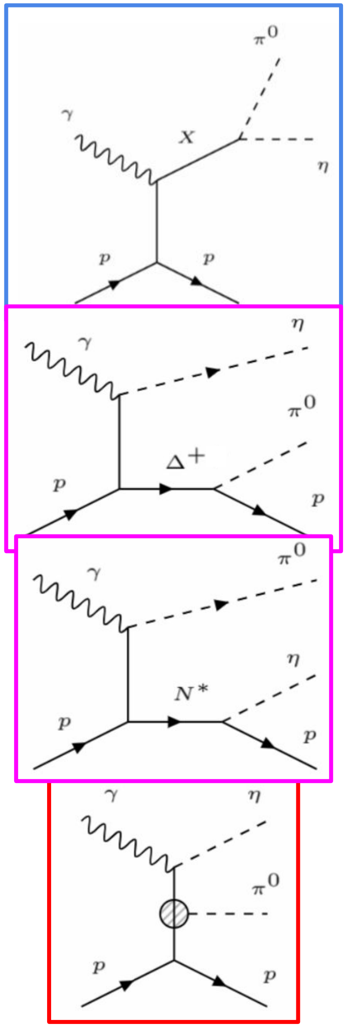
SIGNAL REACTION



~900k events
with 80% purity



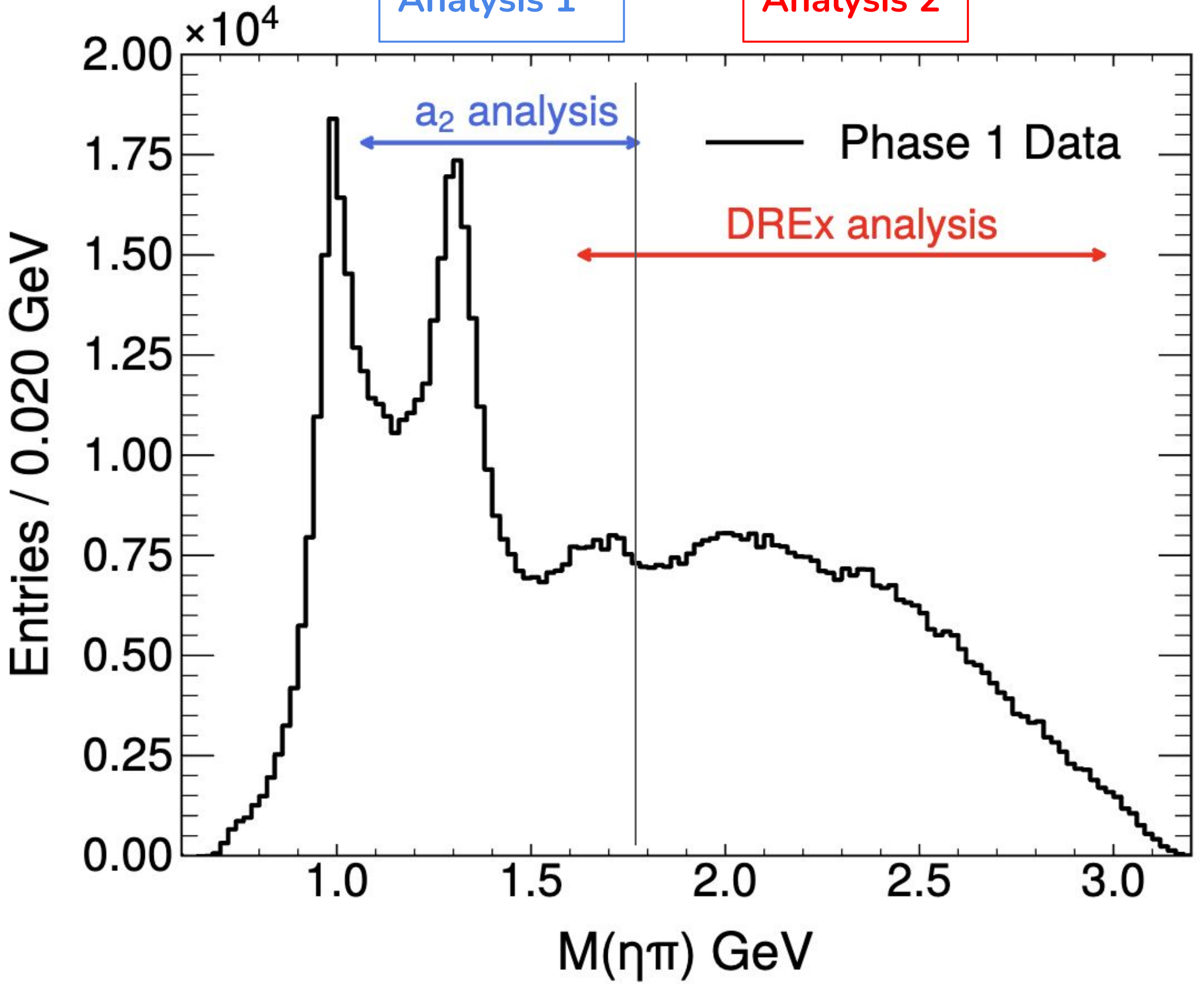
a0(980)
a2(1320)
Phase 1 Data
π1 search necessitates understanding majority of spectrum!
a2(1700)?
π1 ~ expect few % of a2(1320) yield
Baryon production
Double Regge Exchange (DRex)
×10^4
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
1.0
1.5
2.0
2.5
3.0
Entries / 0.020 GeV
M(ηπ) GeV

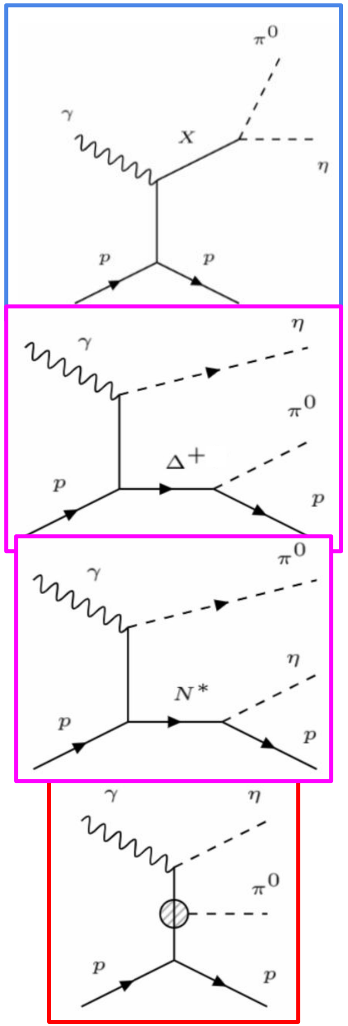


γ
X
π0
η
p
p
Δ+
N*

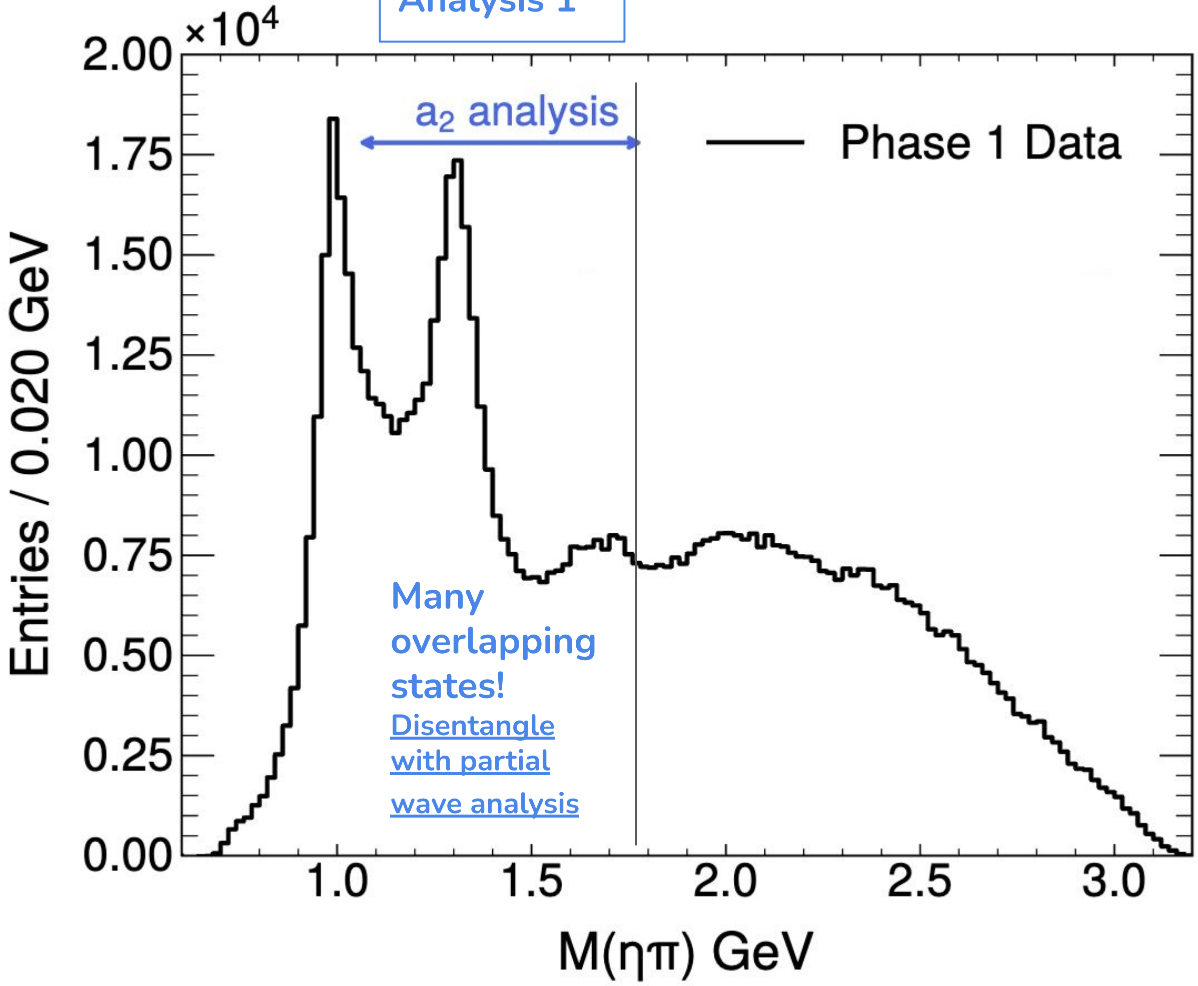
Analysis 1

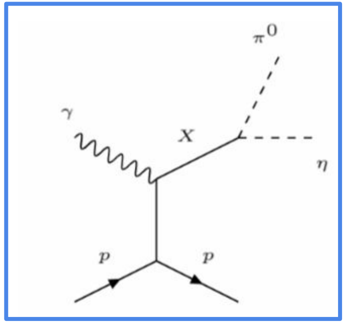
Analysis 2





Analysis 1

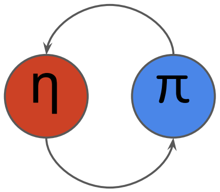




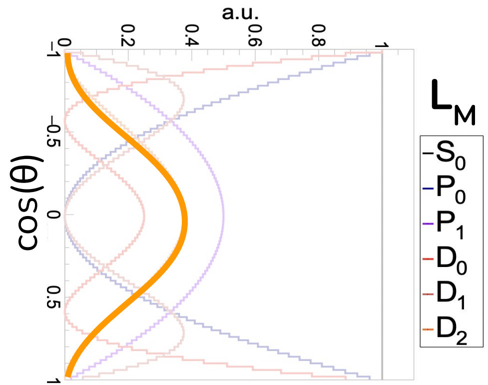
Why the $a_2(1320)$?

- Very prominent
- Unique angular distribution - hard for backgrounds to mimic
- Well known resonance properties: i.e. mass and width
- Need a “phase reference” to determine if π_1 is resonant
- **Measure the $a_2(1320)$ differential cross section**

Angular Distributions

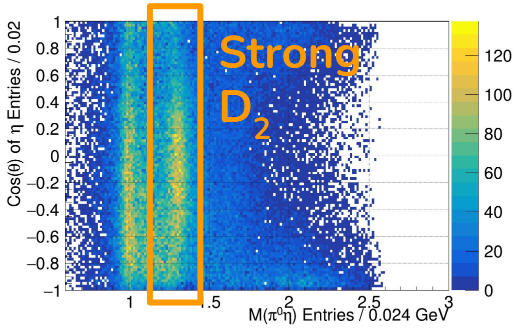


L=J

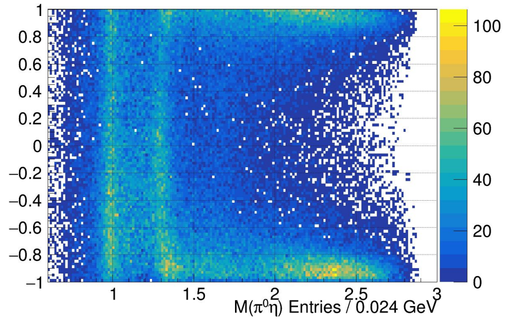


Expected angular distributions

$0.1 < -t < 0.3$ GeV^2

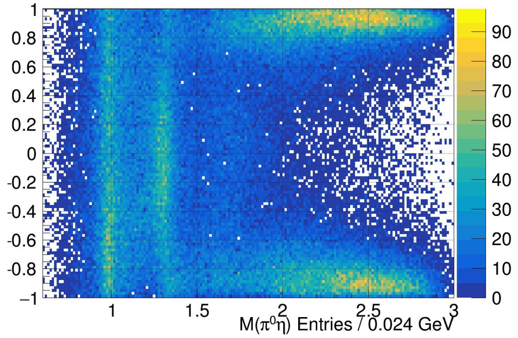


$0.3 < -t < 0.6$ GeV^2



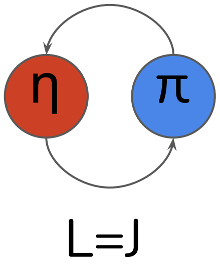
Phase-I data

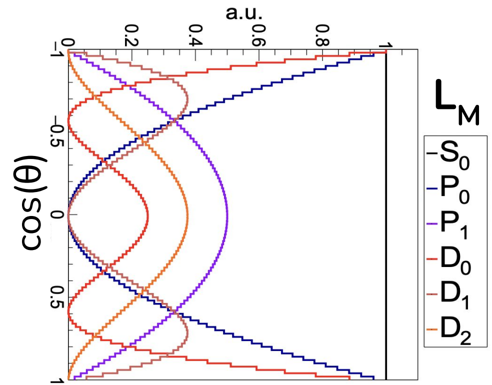
$0.6 < -t < 1.0$ GeV^2



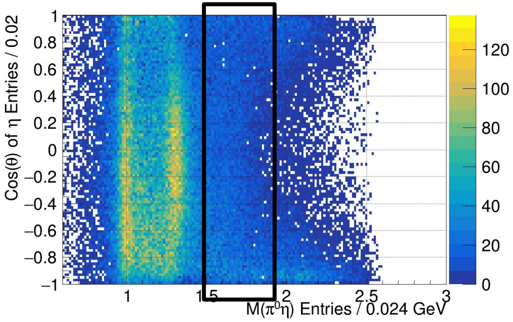
Can see major features of spectrum

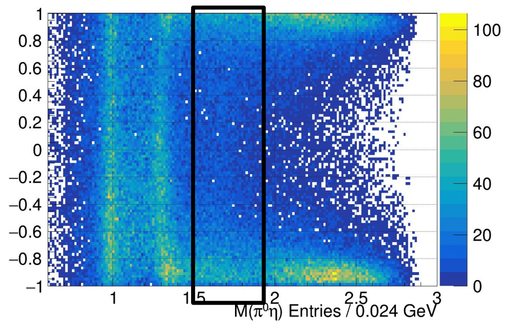
Angular Distributions



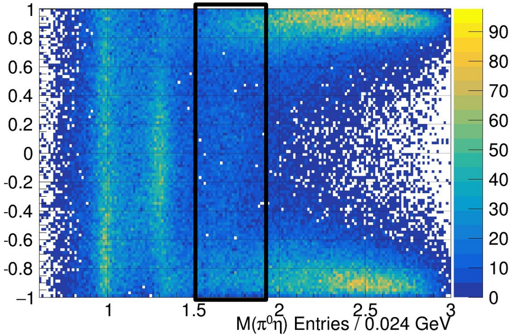


Expected angular distributions





Phase-I data



Potential $a_2(1700)$ contribution would interfere with $a_2(1320)$

Partial Wave Analysis

Definition: New polarized amplitudes incorporating beam polarization

Angular Intensity

$$I(\Omega, \Phi) = 2\kappa \sum_{k} \left((1 - P_\gamma) \left[\sum_{l,m} [l]^{(-)}_{m;k} \, \mathrm{Re}[Z^m_l(\Omega, \Phi)] \right]^2 + (1 - P_\gamma) \left[\sum_{l,m} [l]^{(+)}_{m;k} \, \mathrm{Im}[Z^m_l(\Omega, \Phi)] \right]^2 \right.$$

$$\left. + (1 + P_\gamma) \left[\sum_{l,m} [l]^{(+)}_{m;k} \, \mathrm{Re}[Z^m_l(\Omega, \Phi)] \right]^2 + (1 + P_\gamma) \left[\sum_{l,m} [l]^{(-)}_{m;k} \, \mathrm{Im}[Z^m_l(\Omega, \Phi)] \right]^2 \right)$$

Partial Wave Analysis

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$$\left. + (1+P_\gamma) \left[\sum_{l,m} [l]^{(+)}_{m;k} \, \mathrm{Re}[Z^m_l(\Omega,\Phi)] \right]^2 + (1+P_\gamma) \left[\sum_{l,m} [l]^{(-)}_{m;k} \, \mathrm{Im}[Z^m_l(\Omega,\Phi)] \right]^2 \right)$$

$Z_l^m(\Omega, \Phi) = Y_l^m(\Omega)e^{-i\Phi}$

Φ angle between polarization and production plane

$\Omega = \theta, \varphi$ are angles in the $\eta\pi$ rest frame "Gottfried-Jackson" (or "Helicity Frame")

Partial Wave Analysis

First time these polarized amplitudes are used!

Definition: New polarized amplitudes incorporating beam polarization

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

$Z_l^m(\Omega, \Phi) = Y_l^m(\Omega)e^{-i\Phi}$

Φ angle between polarization and production plane

$\Omega = \theta, \varphi$ are angles in the $\eta\pi$ rest frame "Gottfried-Jackson" (or "Helicity Frame")

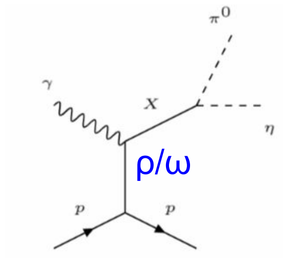
Polarization allows separation of the naturality of the exchange = {+,-}

Leading (+) Natural Parity Exchange: $J^P = 1^-$ ... (i.e. ρ, ω)

Leading (-) Unnatural Parity Exchange: $J^P = 1^+$ ... (i.e. b_1, h_1)

Goal: Fit to extract partial wave amplitudes $[\ell]_m^{(-/+)}$

Different resonances populate different amplitudes



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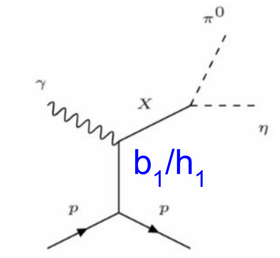


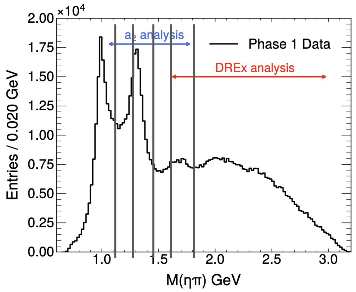
Differential Cross Section of the $a_2(1320)$

Mass independent fits - bin in M(ηπ)

Pros - greater model independence

Cons - lots of fit parameters

- more leakage and ambiguities



For example

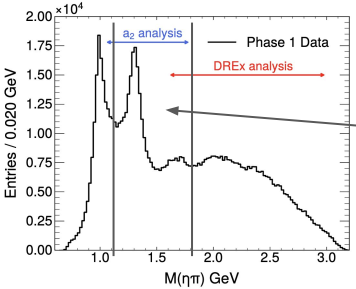
Differential Cross Section of the $a_2(1320)$

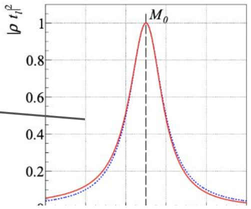
Mass independent fits - bin in M(ηπ)

Pros - greater model independence

Cons - lots of fit parameters

- more leakage and ambiguities





Resonance model

Mass dependent fits - include a resonance model

Semi-mass indep. = **Breit-Wigner for a_2(1320) and a_2(1700)** and **piecewise** constant mass dependence for **S-wave** to model the a_0(980) and pick up backgrounds

Differential Cross Section of the $a_2(1320)$

Mass independent fits - bin in M(ηπ)

Pros - greater model independence

Cons - lots of fit parameters

- more leakage and ambiguities

Mass dependent fits - include a resonance model

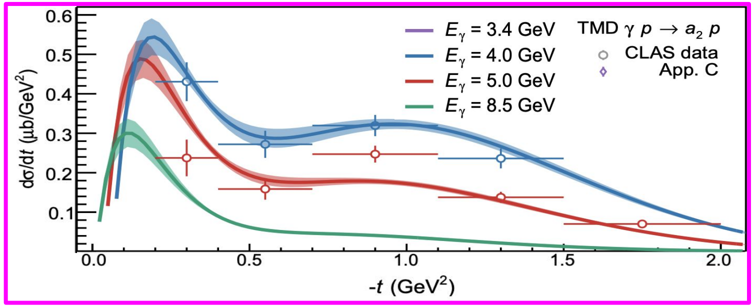
Semi-mass indep. = **Breit-Wigner for $a_2(1320)$ and $a_2(1700)$** and **piecewise** constant mass dependence for **S-wave** to model the $a_0(980)$ and pick up backgrounds

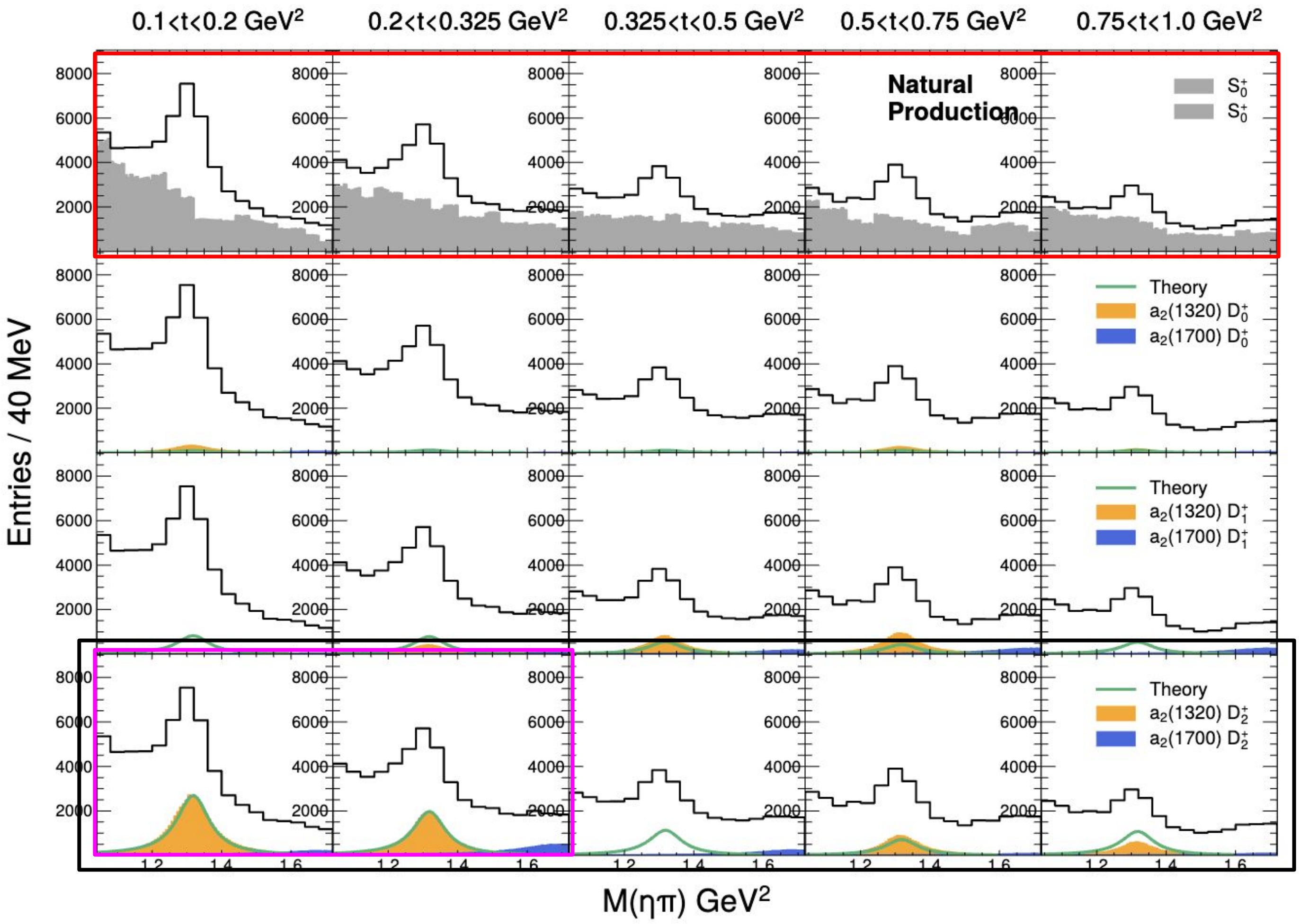
Tensor Meson Dominance Model - **model based on CLAS** photoproduction dσ/dt data for a_2 | no partial wave analysis | [3.5, 5.5] GeV

Chosen **waveset**: $S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+}, D_{-1}^{-}$

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

Measure dσ/dt in 5 bins on -t∈[0.1, 1.0] GeV²





Production via natural exchanges

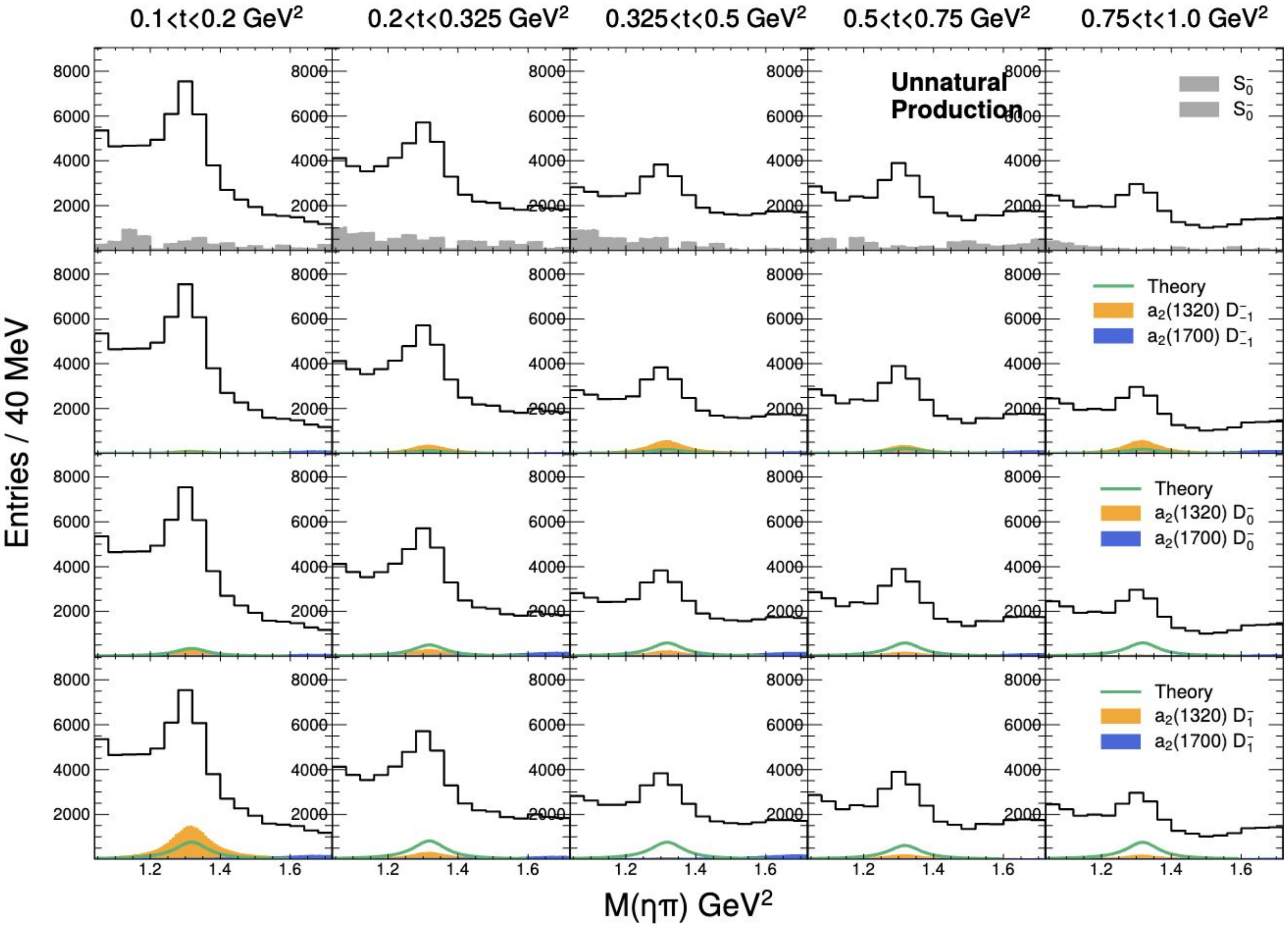
Theory predictions for a_2(1320)

Smooth/Strong S-wave intensity

Dominant D_2 in lowest t-bins as we had eyeballed

Strong t-dependence of m-projections!

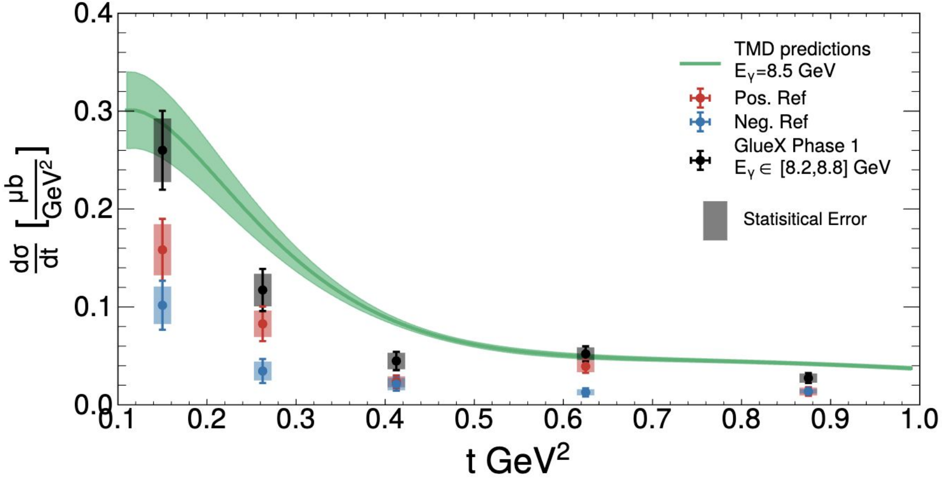
Results agree with mass independent fit results!

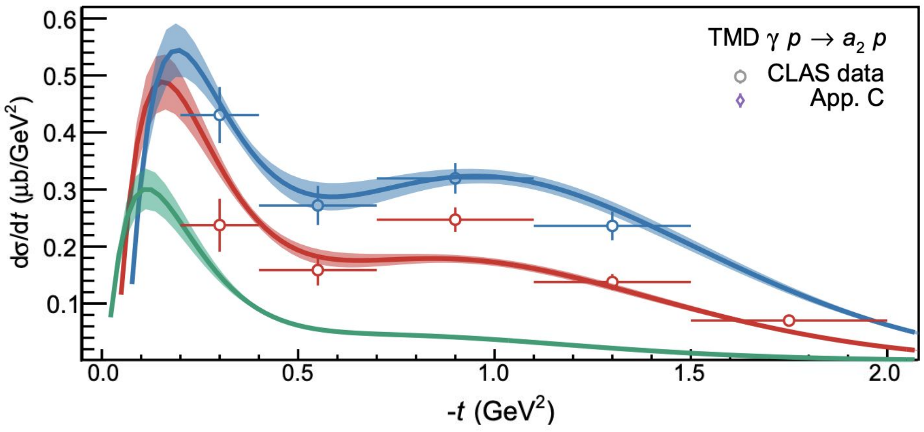


Production via unnatural exchanges

Smaller contributions overall

TMD model based on CLAS data with no PWA nor Polarization!

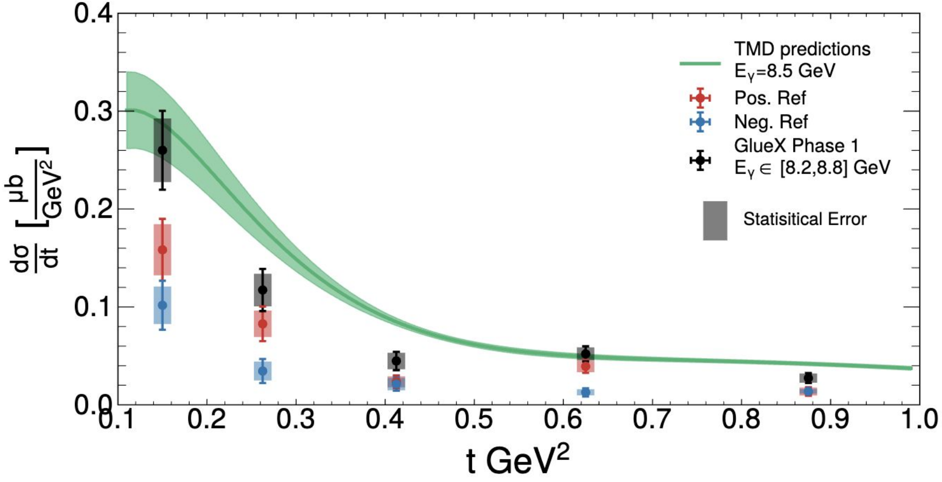


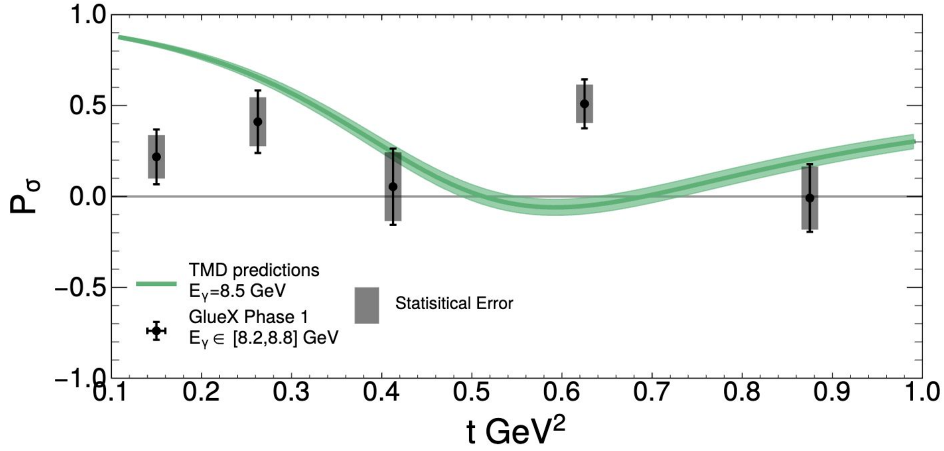


Comparison with theory

Theory predicts the dip in the cross section ~0.5 GeV^2 gets "filled in" at out energies

- Does not appear to be the case
- Dip is consistent with previous experimental data including CLAS



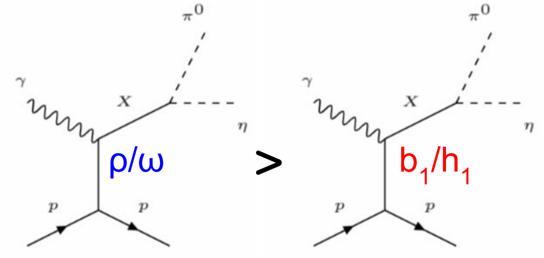


Comparison with theory

Theory predicts the dip in the cross section ~0.5 GeV^2 gets "filled in" at out energies

- Does not appear to be the case
- Dip is consistent with previous experimental data including CLAS

$$P_\sigma = \frac{\frac{d\sigma^+}{dt} - \frac{d\sigma^-}{dt}}{\frac{d\sigma^+}{dt} + \frac{d\sigma^-}{dt}}$$

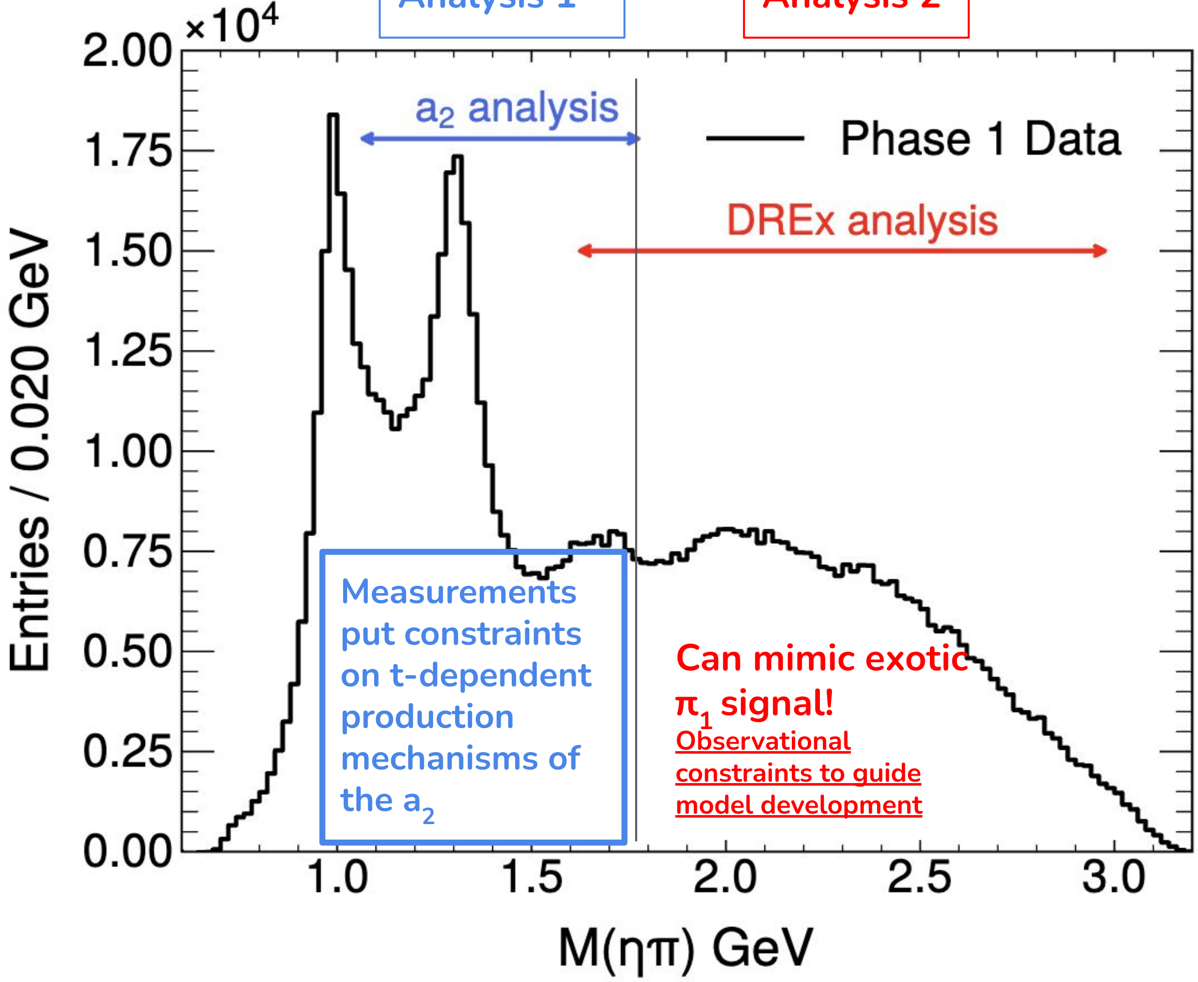


For leading exchanges we roughly get asymmetry between these two diagrams

First measurement using the new polarized amplitudes

Analysis 1

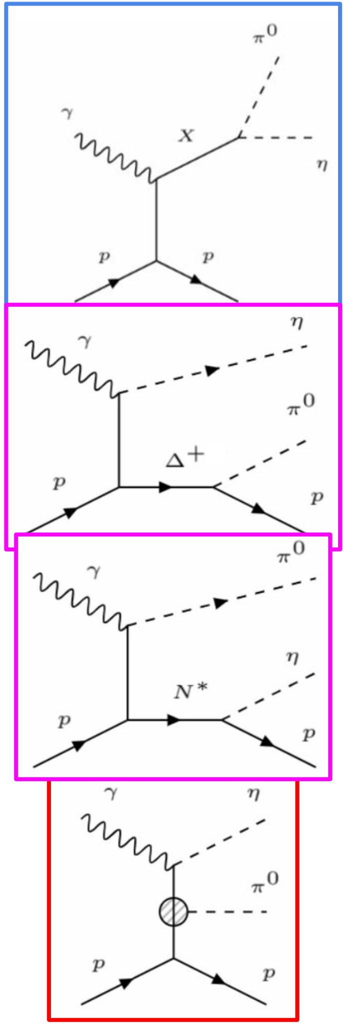
Analysis 2



Measurements put constraints on t-dependent production mechanisms of the a_2

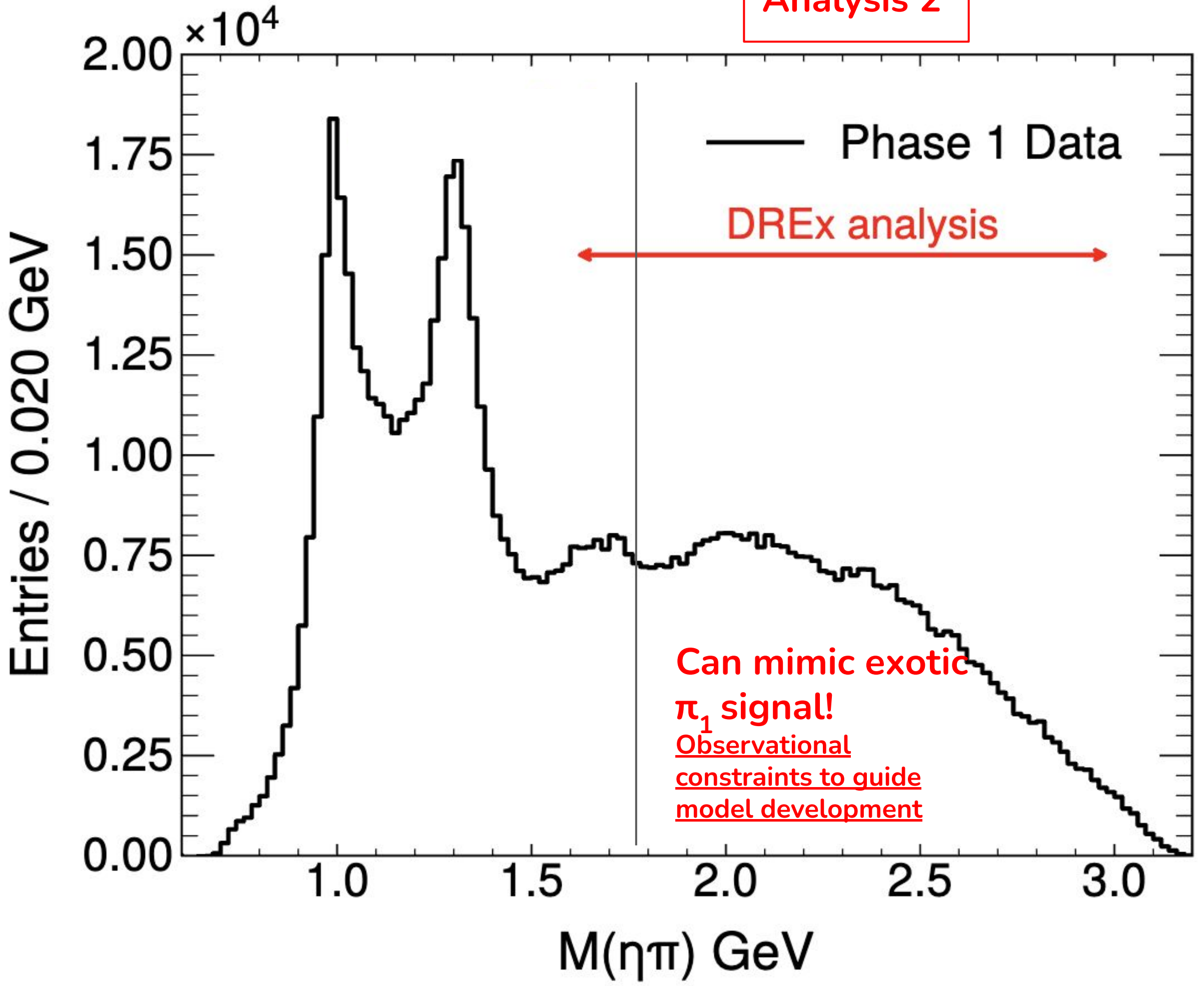
Can mimic exotic π_1 signal!

Observational constraints to guide model development

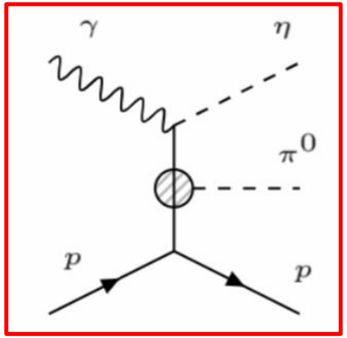


Analysis 2

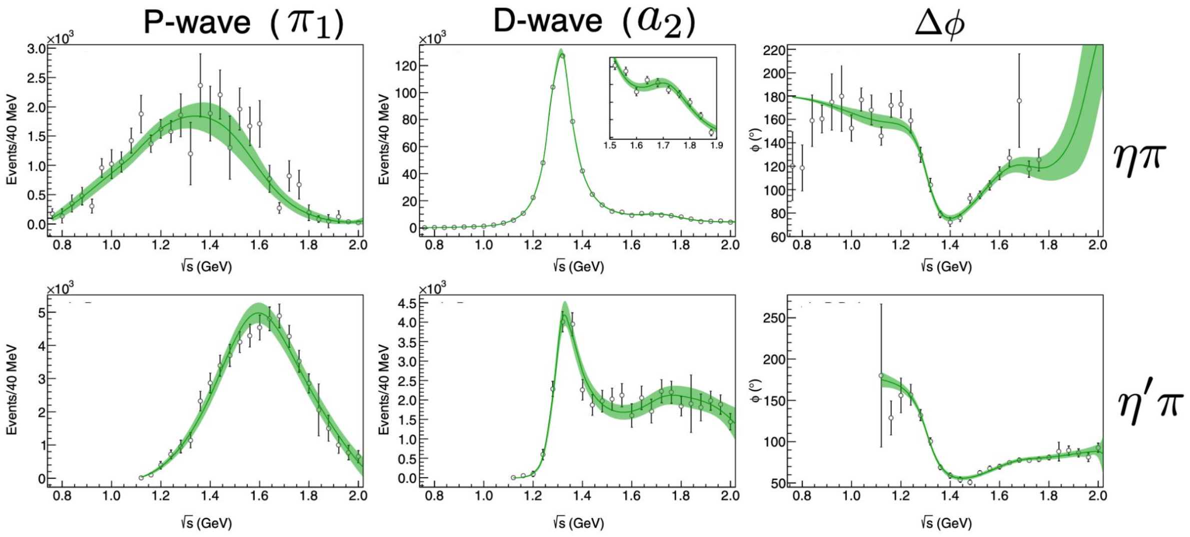
Double Regge Exchange



Can mimic exotic π_1 signal!
Observational constraints to guide model development



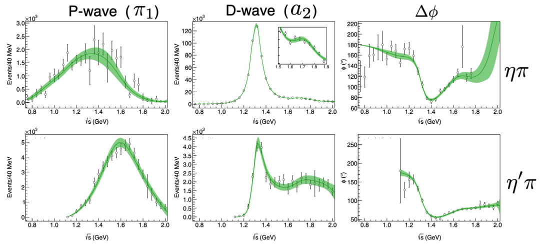
Importance of DREx



Partial wave analysis results

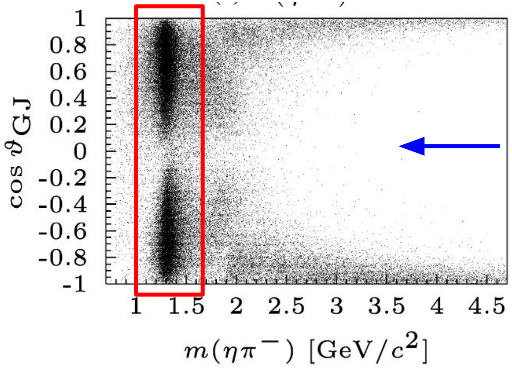
Look at COMPASS results again!

Importance of DREx

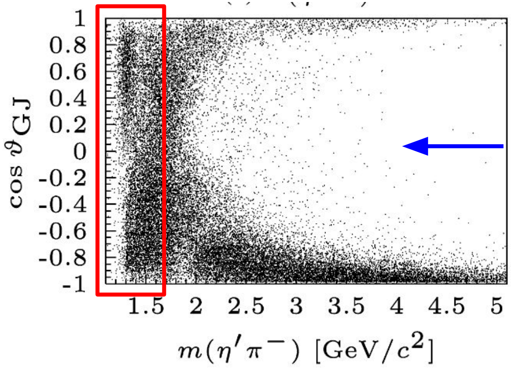


Look at COMPASS results again!

Underlying fitted angular distributions



ηπ



η'π

1) Recall all odd-L waves are exotic in $\eta^{(\prime)}\pi$

Familiar strong a_2 in ηπ and η'π (interfered)

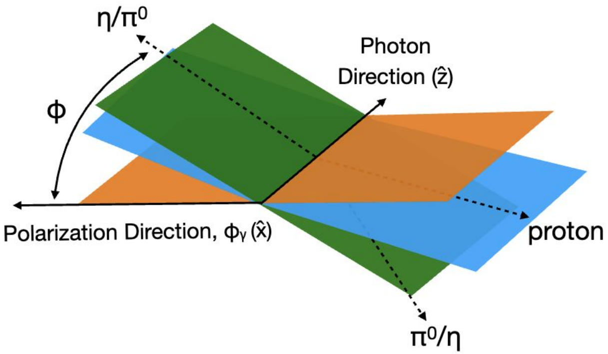
2) Interference between odd-L (i.e. π_1) and even-L (i.e. a_2) waves ➡ asymmetric angular distributions!

asymmetric angular distributions ~~➡~~ unique signature of an exotic

3) Signature of DREx is these "wings" that dominate at high mass also produce asymmetric angular distributions

How to constrain DREx contribution in π_1 region?

Beam Asymmetry



Stichel's Theorem = For linear polarized beam, cross section can be split into two components: one component parallel to reaction plane another perpendicular

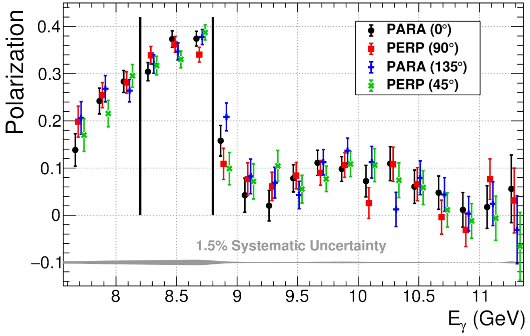
$$\frac{d\sigma}{dt} = \frac{d\sigma_\perp}{dt} + \frac{d\sigma_\parallel}{dt}$$

$\sigma_\perp$: Unnatural exchanges only

$\sigma_{//}$: Natural exchanges only

Define **Beam Asymmetry**

$$\Sigma = \frac{\frac{d\sigma_\perp}{dt} - \frac{d\sigma_\parallel}{dt}}{\frac{d\sigma_\perp}{dt} + \frac{d\sigma_\parallel}{dt}}$$



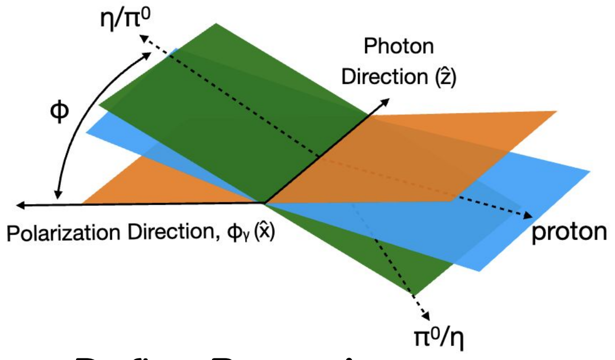
Recall data taken in 2 pairs of orthogonal orientations

Construct **Yield Asymmetry** to extract ∑

$$Y_A = \frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = \frac{(P_\perp + P_\parallel)\Sigma\cos 2\phi}{2 + (P_\perp - P_\parallel)\Sigma\cos 2\phi}$$

We measure Yields Y
F_R = flux ratio ~ 1
P = polarization magnitude ~35%

Beam Asymmetry



Stichel's Theorem = For linear polarized beam, cross section can be split into two components: one component parallel to **reaction plane** another perpendicular

$$\frac{d\sigma}{dt} = \frac{d\sigma_\perp}{dt} + \frac{d\sigma_\parallel}{dt}$$

$\sigma_\perp$: Unnatural exchanges only

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Define **Beam Asymmetry**

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Construct **Yield Asymmetry** to extract ∑

$$Y_A = \frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = \frac{(P_\perp + P_\parallel)\Sigma\cos 2\phi}{2 + (P_\perp - P_\parallel)\Sigma\cos 2\phi}$$

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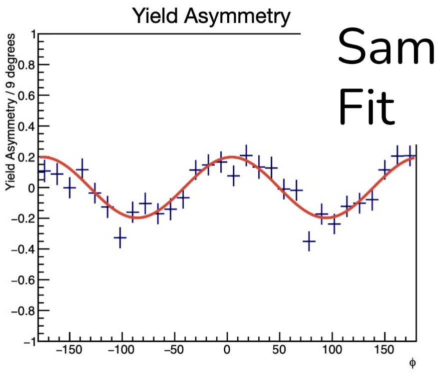


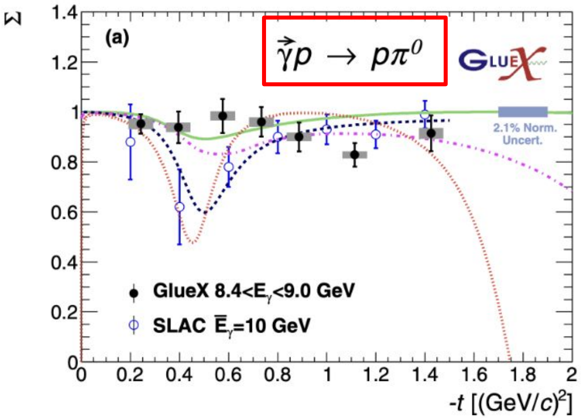
Sample Fit

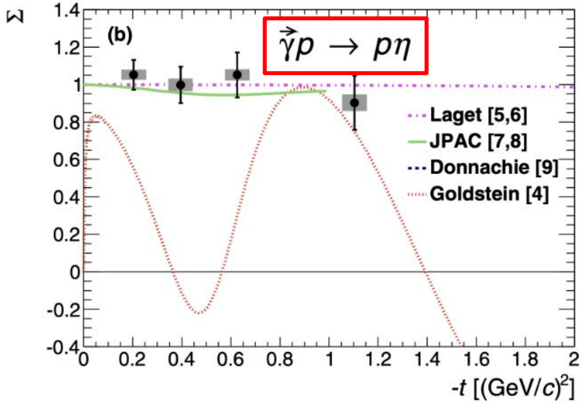
φ

∑~0.57

Natural exchange dominant

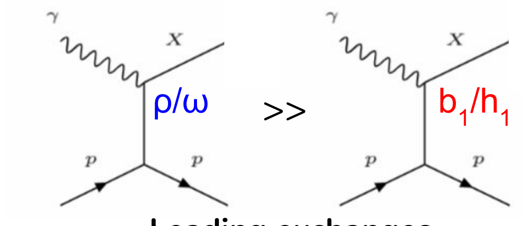
Previous GlueX ∑ Measurements





Photoproduction of single psuedoscalars: π^0 and η

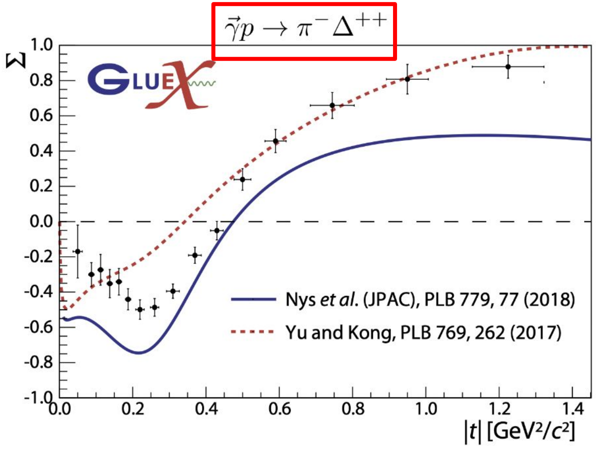
- ∑~1 = Almost all natural exchanges



Leading exchanges

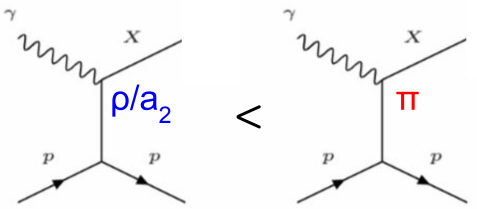
Natural exchanges
Unnatural exchanges

Previous GlueX ∑ Measurements



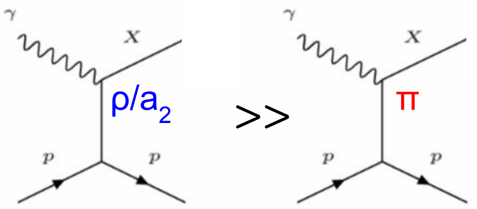
Photoproduction of π^- shows significant t-dependence

Low t



Leading exchanges

High t



Leading exchanges

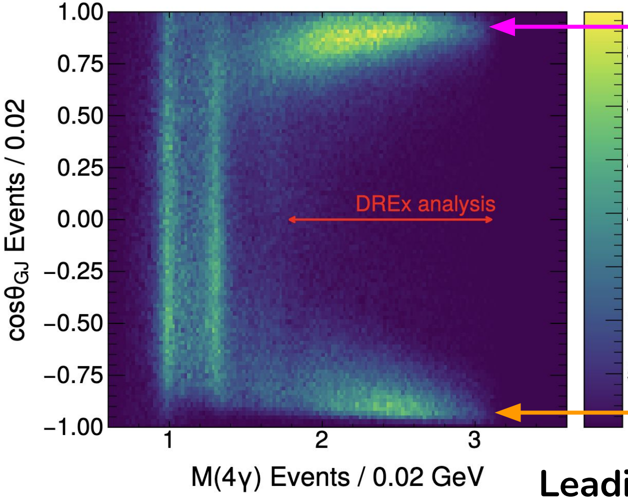
Natural exchanges

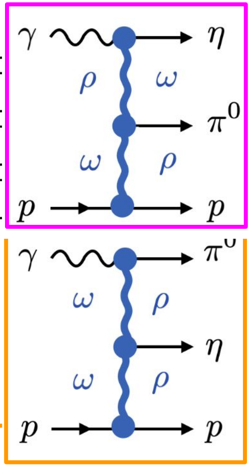
Unnatural exchanges

Measuring ∑ constrains production mechanism

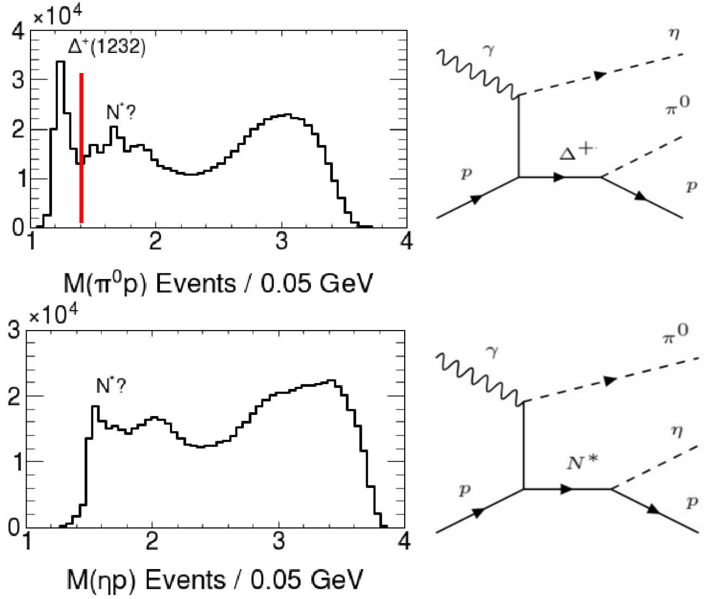
Double Regge ∑ Measurement

GlueX Phase-I data





Leading order diagrams

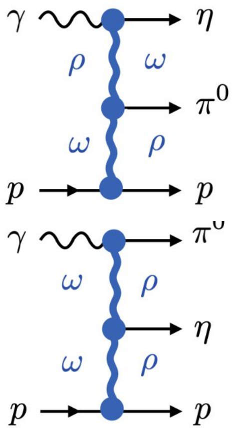


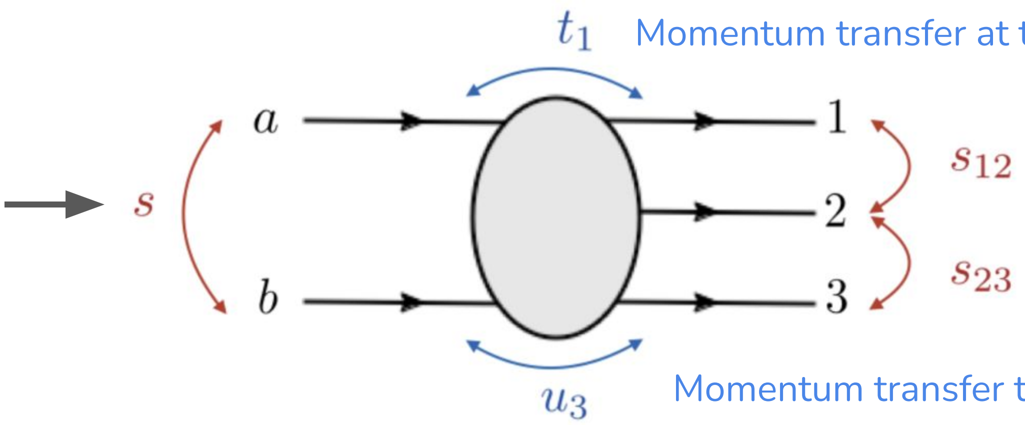
Asymmetric production of processes can produce angular asymmetry just as a signal for a π_1 exotic would!

Baryon production very similar diagrams ➡ very similar parts of phase space!

Double Regge ∑ Measurement

t_1: $t_\eta = (p_\gamma - p_\eta)^2$, $t_\pi = (p_\gamma - p_\pi)^2$





Measure beam asymmetry at the top vertex Σ_{t1} as a function of s_{12} / s_{23} / u_3

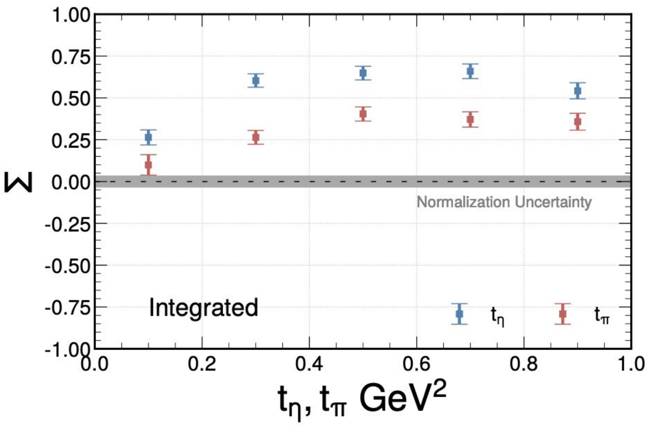
Additional bins should help separate baryon production

Compare results from $\gamma p \to \eta\pi^0 p$ ***(this talk)***

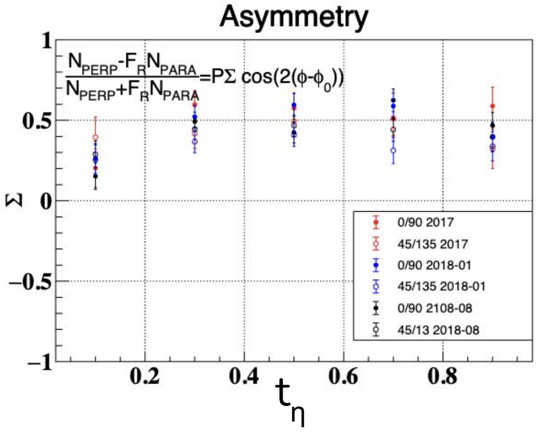
$\gamma p \to \eta\pi^- \Delta^{++}$ ***(Complementary channel, Courtesy of Colin Gleason)***

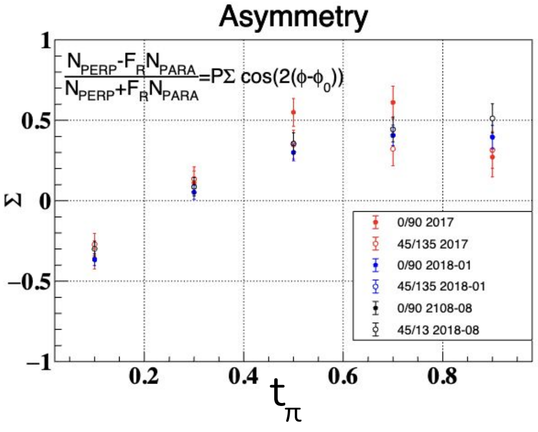
Select ∑ Results

$\eta\pi^0$

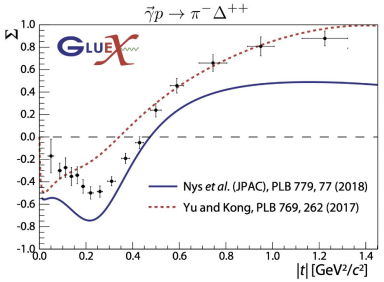


$\eta\pi^-$

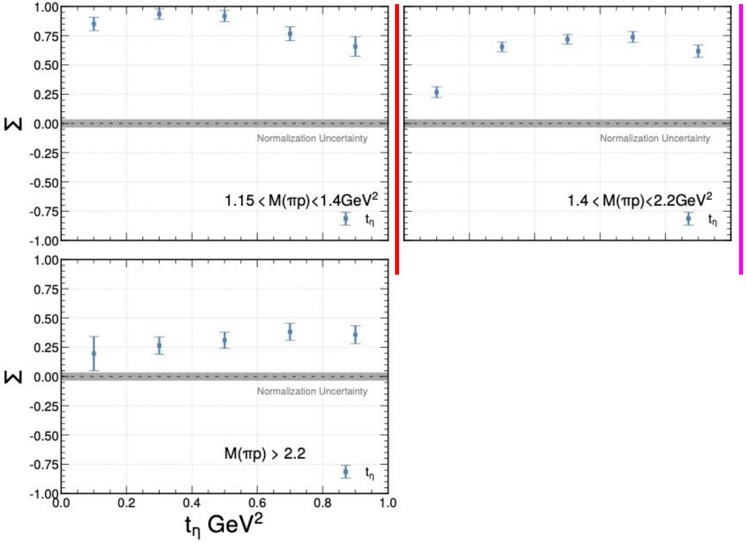


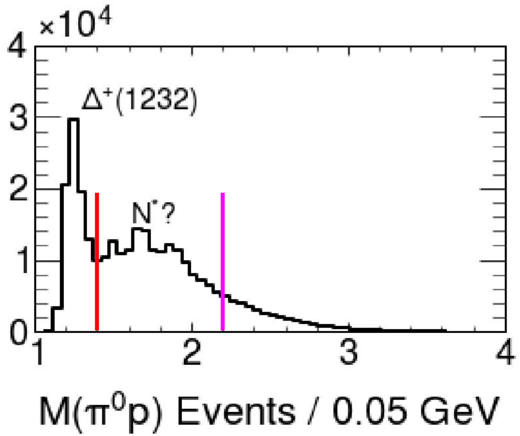


- No additional bins in s_{12} / s_{23} / u_3
- t_η very similar between channels, cross section dominated by natural exchanges, ∑~0.4
- t_π for t_1<0.5 much more like $\gamma p \to \pi^- \Delta^{++}$ but saturates to become similar to the $\eta\pi^0$ channel



Select Σ Results: Σ_η binned in M(πp)





$\eta\pi^0$

Δ^+ removed for all measurements in the $\eta\pi^0$ channel but interesting to probe here
Σ~1 in the Δ^+ dominated region
Σ~0.6 where N^* resonances populate
Σ~0.3 at large M(πp)
πp baryons produced mostly through natural exchanges

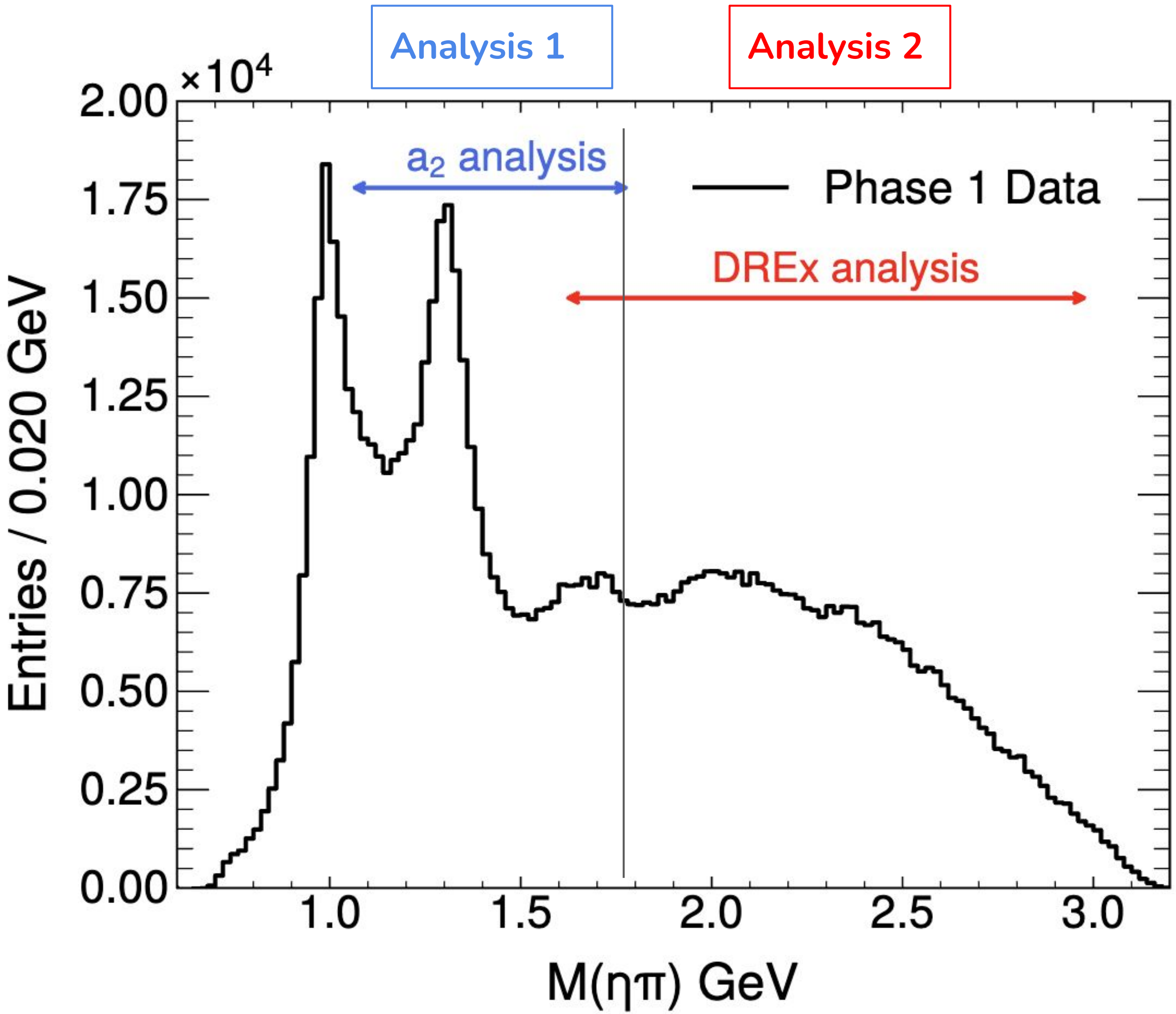
First observational constraints on double Regge process in photoproduction

Summary

π_1 contribution expected to be small, requires characterization of the majority of the M(ηπ) spectrum

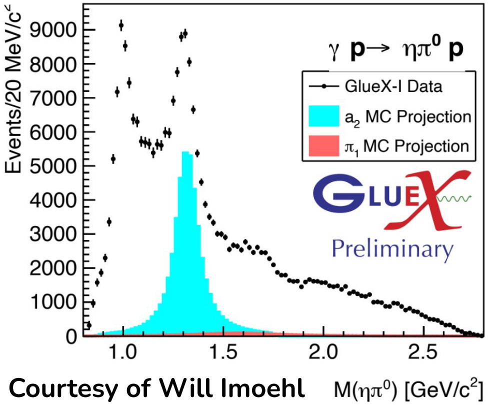
Presented first analysis using new polarized amplitudes to measure a_2 differential cross section

Presented first measurement to set observational constraints on double Regge production mechanisms in photoproduction

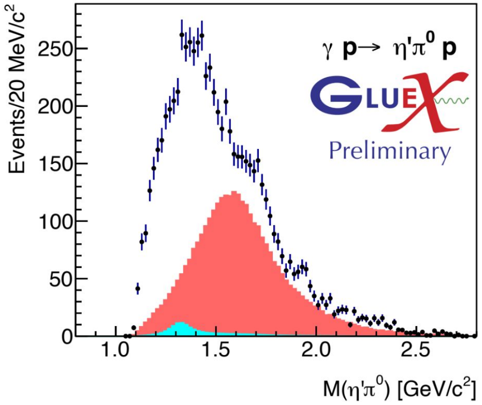


Pathway to the π_1

- Currently, GlueX is setting π_1 cross section upper limit based on γp->ωππp and lattice QCD results
  - Project cross section upper limits into ηπ and η'π yield upper limits



Courtesy of Will Imoehl



a_2 cross sections measured for this dissertation used as an **input**

Yield(a_2) >> Yield(π_1) in ηπ
Yield(a_2) << Yield(π_1) in η'π

***Next (few) Steps**: Perform **coupled channel analysis** to constrain the a_2 and π_1 contributions across ηπ and η'π*

Thank you!

Almost...

Additional Studies (Machine Learning)

JPAC

PHYSICAL REVIEW D **105,** L091501 (2022)

Letter

Deep learning exotic hadrons

L. Ng,[1,*] Ł. Bibrzycki,[2,†] J. Nys,[3,‡] C. Fernández-Ramírez,[4,5,§] A. Pilloni,[6,7,8,∥] V. Mathieu,[9,10] A. J. Rasmusson,[11] and A. P. Szczepaniak[11,12,13]

(Joint Physics Analysis Center)

Study pentaquarks using neural networks

Carnegie Supernova Project-II: Near-infrared spectral diversity and template of Type Ia Supernovae

Jing Lu (陆晶),[1] Eric Y. Hsiao (蕭亦麒),[1] Mark M. Phillips,[2] Christopher R. Burns,[3] Chris Ashall,[4] Nidia Morrell,[2] Lawrence Ng,[1] Sahana Kumar,[1] Melissa Shahbandeh,[5,6] Peter Hoeflich,[1] E. Baron,[7,8] Syed Uddin,[9] Maximilian D. Stritzinger,[10] Nicholas B. Suntzeff,[9] Charles Baltay,[11] Scott Davis,[1] Tiara R. Diamond,[12] Gaston Folatelli,[13,14] Francisco Förster,[15,16] Jonathan Gagné,[17,2] Lluís Galbany,[18,19] Christa Gall,[20] Santiago González-Gaitán,[21] Simon Holmbo,[10] Robert P. Kirshner,[22,23] Kevin Krisciunas,[9] G. H. Marion,[24] Saul Perlmutter,[25,26] Priscila J. Pessi,[27] Anthony L. Piro,[3] David Rabinowitz,[11] Stuart D. Ryder,[28,29] and David J. Sand[30]

Alternative approach to template generation Conditional variational autoencoders

Give thanks!
Eat a pie

Thank You!

Gave thanks!
$\eta\pi$

Backup

Beam Energy Selections	$8.2 < E_\gamma < 8.8$ GeV
Charged Track Selections	$\left\|\vec{P}\right\| \geq 0.3\ \text{GeV} \cdot c^{-1}$ $52\ \text{cm} \leq d_z \leq 78\ \text{cm}$ $\frac{dE}{dx}\|_{\text{CDC}} \geq 10^{-6}\ (0.9 + e^{3.0-\frac{3.5[\|\vec{P}\|+0.05]}{0.93827}})$
Neutral Shower Selections	$E \geq 0.1$ GeV $2.5^o \leq \theta \leq 10.3^o \qquad \theta > 11.9^o$
Exclusivity Selections	Unused Energy $= 0.0$ GeV Missing Mass Squared $\leq 0.05\ \text{GeV}^2$ $\chi^2 \leq 13.277 \qquad with\ 4\ DOF$
Event Counting	Accidental Subtraction: see Equation 2.7 Sideband Subtraction: see Table 2.3

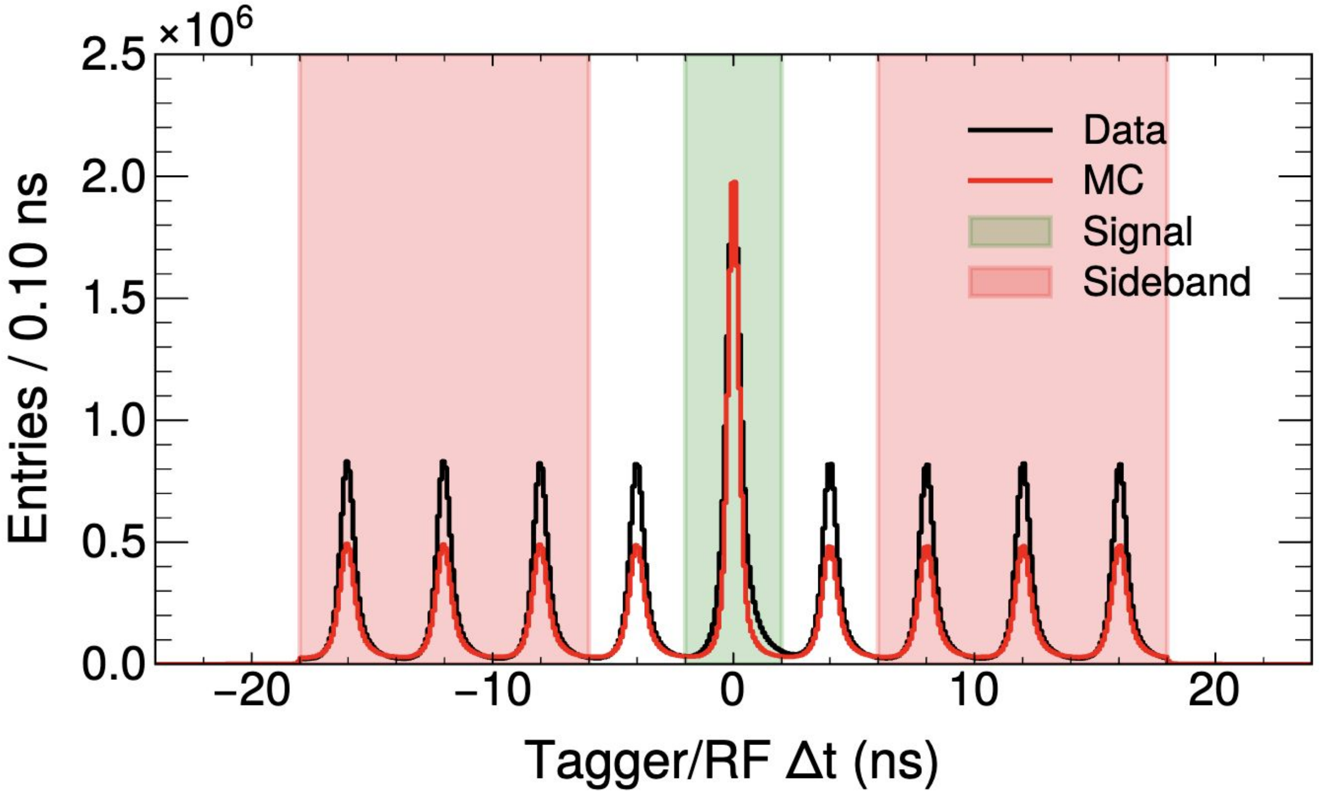
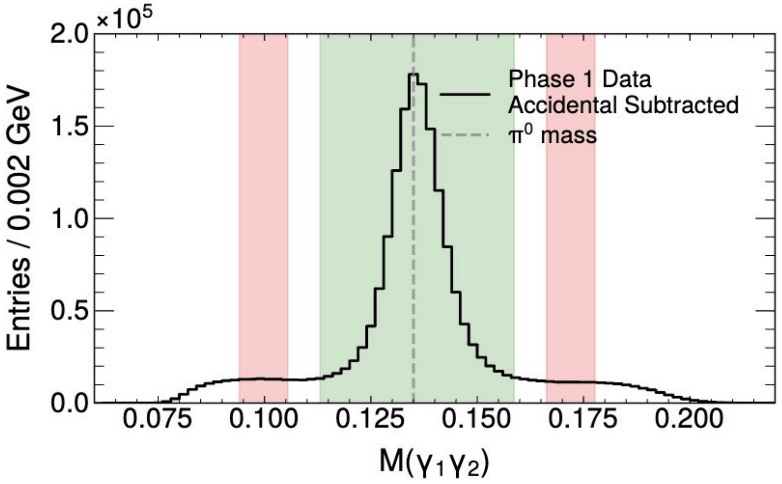
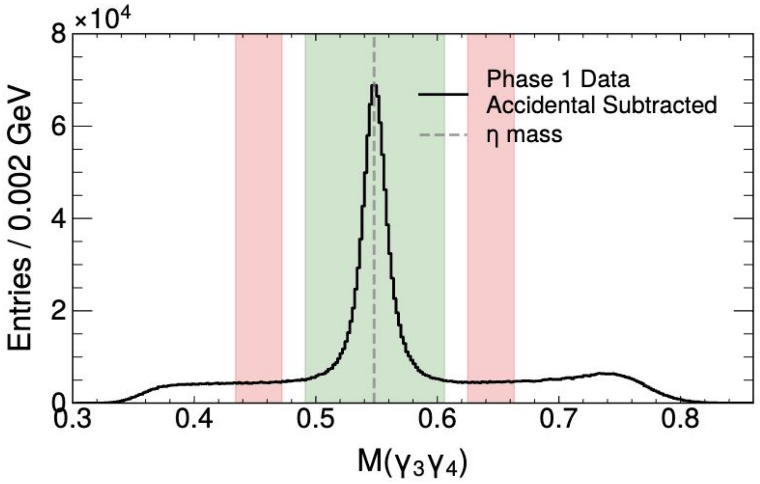
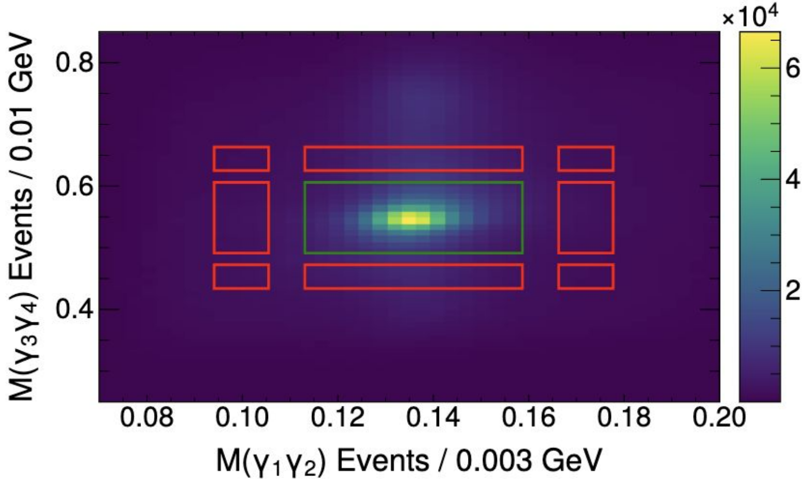


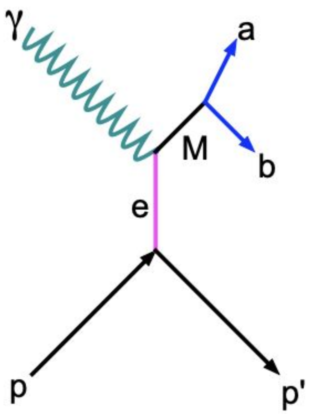
Figure 2.3: Distribution of the tagger time with respect to the RF time. Events in the coherent peak have been selected.

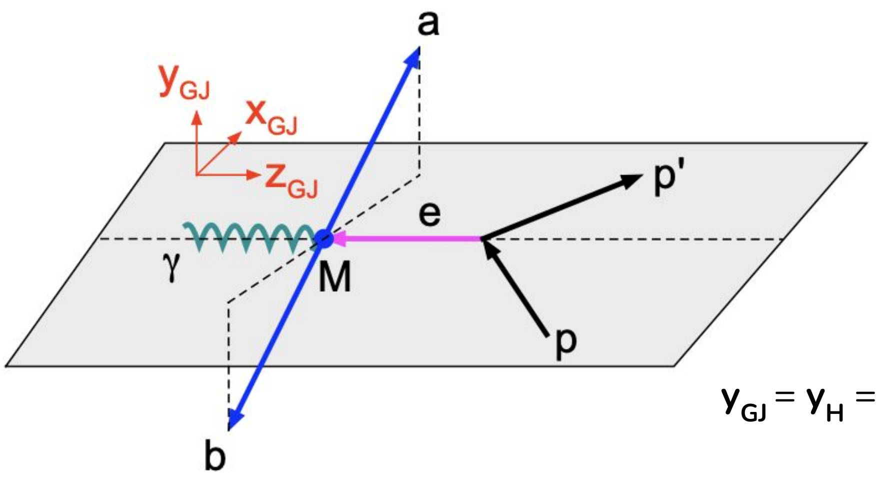




Sideband Subtraction

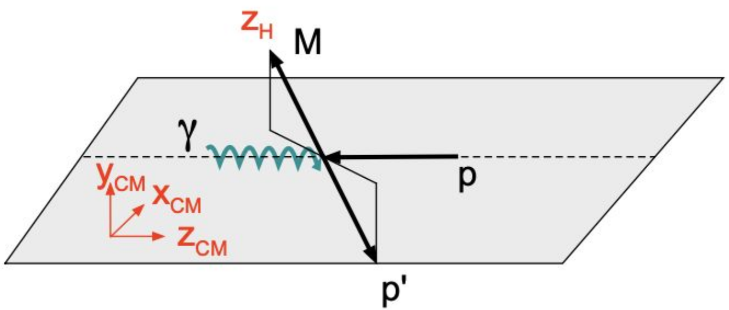


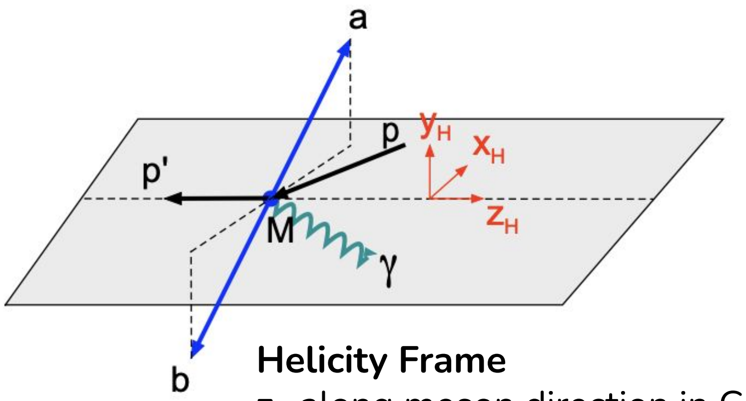




Gottfried-Jackson Frame
z_{GJ} along photon direction

$y_{GJ} = y_H$ = normal to production plane

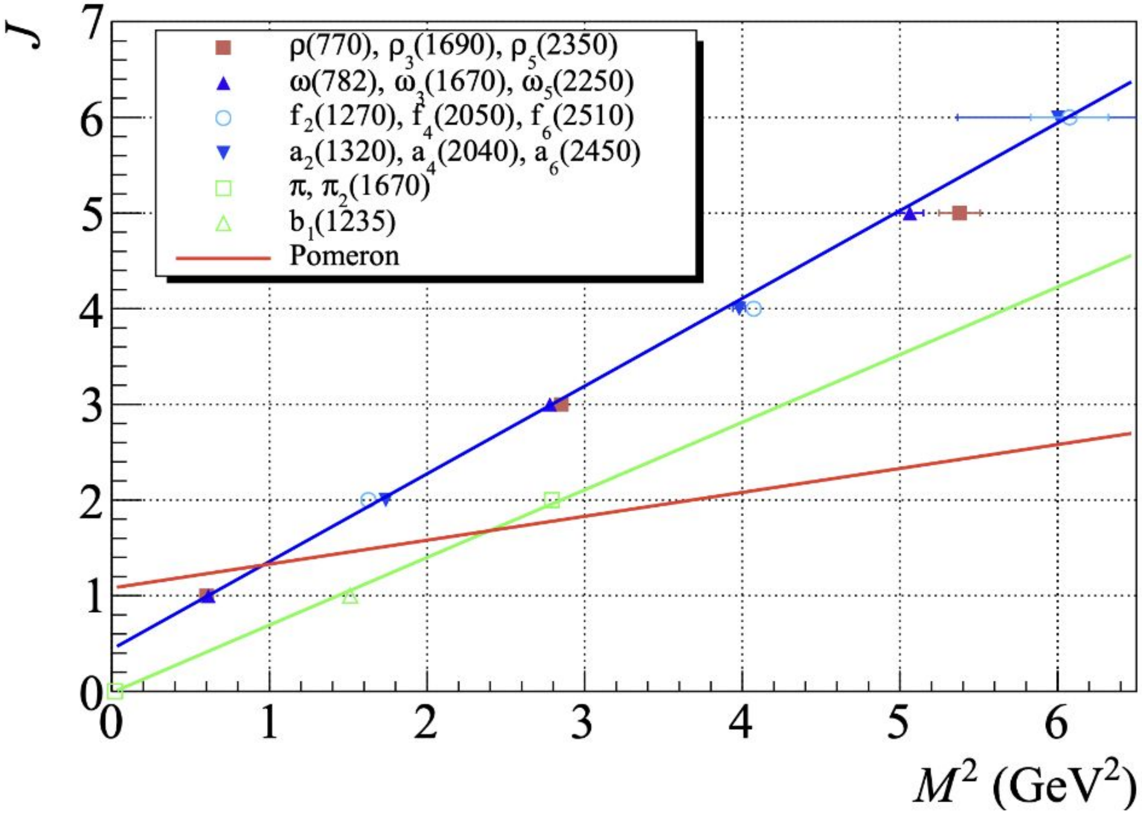




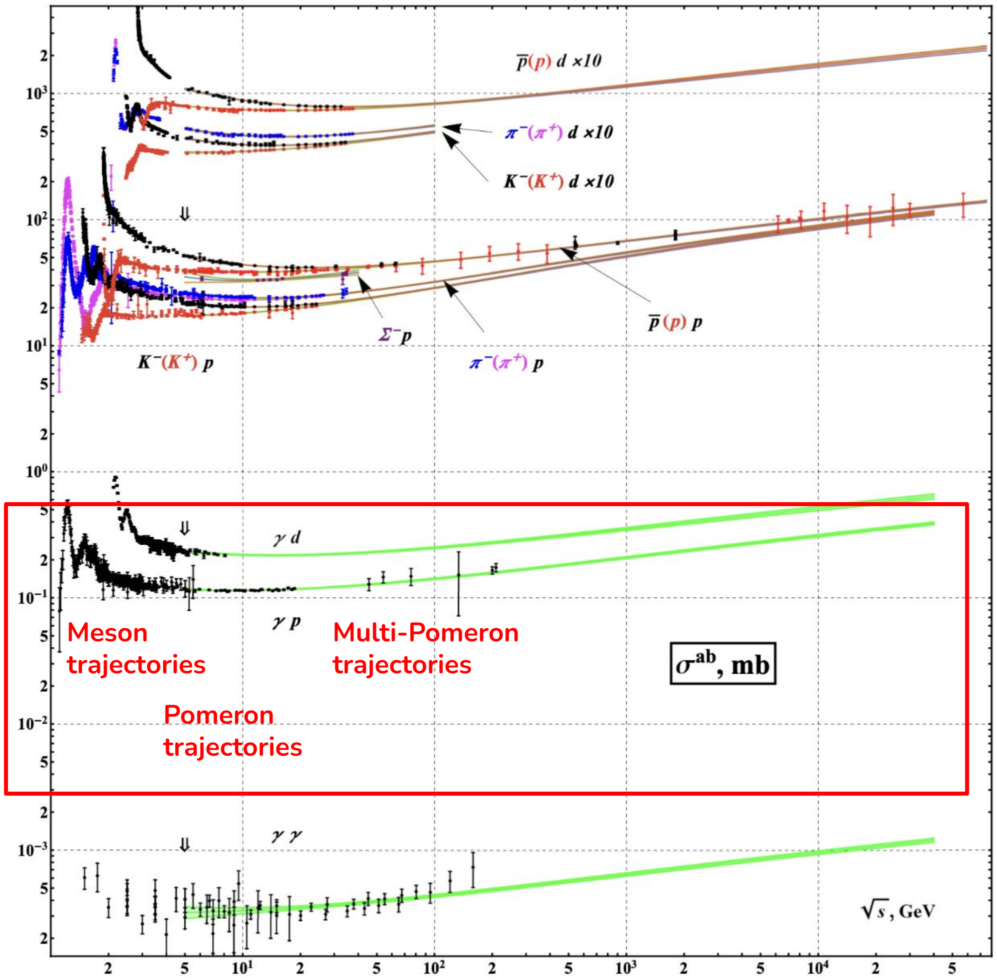
Helicity Frame
z_H along meson direction in CM frame

https://halldweb.jlab.org/DocDB/0048/004829/005/coordinates.pdf

Regge Trajectory



Total hadronic cross section

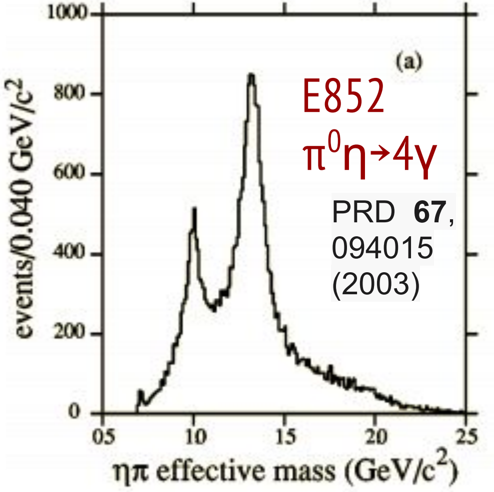


$$\sigma \sim s^{\alpha(0)-1}$$

Meson trajectories: α(0)<0.5
Pomeron trajectory: α(0)~1
Multi-Pomeron exchange

$\pi_1(1400)$

Mode	Mass (GeV)	Width (GeV)	Experiment	Reference
$\eta\pi^-$	1.405 ± 0.020	0.18 ± 0.02	GAMS	[121]
$\eta\pi^-$	1.343 ± 0.0046	0.1432 ± 0.0125	KEK	[123]
$\eta\pi^-$	1.37 ± 0.016	0.385 ± 0.040	E852	[127]
$\eta\pi^0$	1.257 ± 0.020	0.354 ± 0.064	E852	[129]
$\eta\pi$	1.40 ± 0.020	0.310 ± 0.050	CBAR	[130]
$\eta\pi^0$	1.36 ± 0.025	0.220 ± 0.090	CBAR	[131]
$\rho\pi$	1.384 ± 0.028	0.378 ± 0.058	Obelix	[132]
$\rho\pi$	~ 1.4	~ 0.4	CBAR	[133]
$\eta\pi$	1.354 ± 0.025	0.330 ± 0.035	PDG	[118]



E852
$\pi^0\eta \to 4\gamma$

PRD **67**, 094015 (2003)

$\pi_1(1600)$

Mode	Mass (GeV)	Width (GeV)	Experiment	Reference
$b_1\pi$	1.58 ± 0.03	0.30 ± 0.03	VES	[171]
$b_1\pi$	1.61 ± 0.02	0.290 ± 0.03	VES	[141]
$b_1\pi$	~ 1.6	~ 0.33	VES	[125]
$b_1\pi$	1.56 ± 0.06	0.34 ± 0.06	VES	[126]
$f_1\pi$	1.64 ± 0.03	0.24 ± 0.06	VES	[126]
$\eta'\pi$	1.58 ± 0.03	0.30 ± 0.03	VES	[171]
$\eta'\pi$	1.61 ± 0.02	0.290 ± 0.03	VES	[141]
$\eta'\pi$	1.56 ± 0.06	0.34 ± 0.06	VES	[126]
$\rho\pi$	1.593 ± 0.08	0.168 ± 0.020	E852	[143]
$\eta'\pi$	1.597 ± 0.010	0.340 ± 0.040	E852	[145]
$f_1\pi$	1.709 ± 0.024	0.403 ± 0.080	E852	[146]
$b_1\pi$	1.664 ± 0.008	0.185 ± 0.025	E852	[147]
$b_1\pi$	~ 1.6	~ 0.23	CBAR	[149]
$\rho\pi$	1.660 ± 0.010	0.269 ± 0.021	COMPASS	[153]
$\eta'\pi$	1.670 ± 0.030	0.240 ± 0.050	CLEO-c	[150]
all	$1.662^{+0.008}_{-0.009}$	0.241 ± 0.040	PDG	[118]

PPNP **82,** pg. 21-58 (2015)

- Many experimental observations of 1^{-+} aka the π_1
- Models suggest 1.4 GeV is too low
- $\pi_1(1600)$ has much richer set of observations and statistics
- JPAC provided a resolution by performing a coupled channel analysis on COMPASS ηπ data

Crystal Barrel (2020)

Crystal Barrel (proton-antiproton collider)

- Coupled channel analysis of: $p\bar{p} \to K^+K^-\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$
  - π_1 wave coupling to $\pi^0\eta$ in $p\bar{p} \to \pi^0\eta\eta$

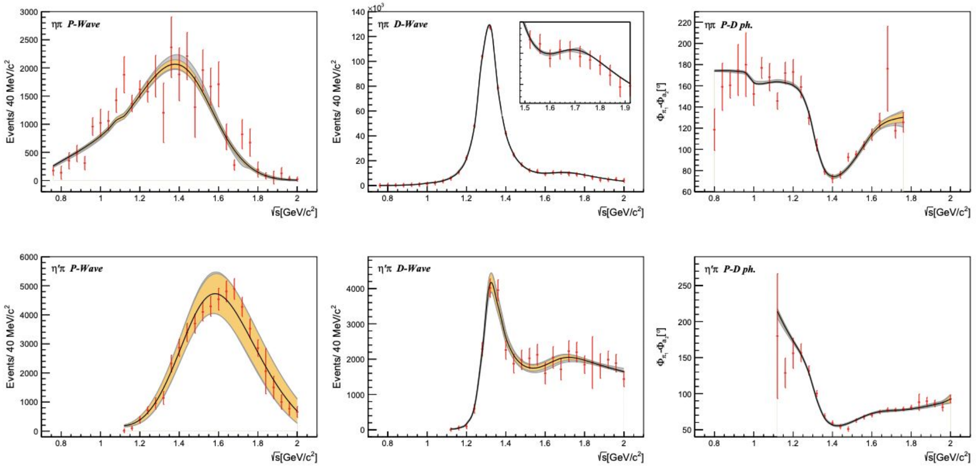
Then... they did another analysis

- Including 11 different ππ scattering datasets
- Including πη' and πη results from COMPASS

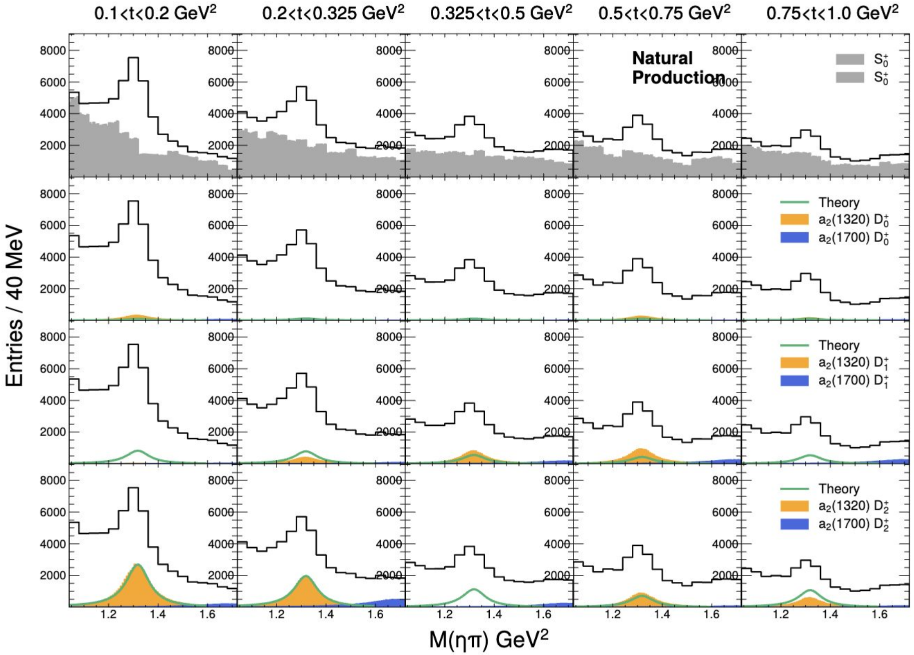
~120k Events in total (~90k in $\pi^0\eta\eta$)

Eur. Phys. J. C (2020) 80:453

Eur. Phys. J. C (2020) 81:1056



$$\sigma = \frac{N}{\epsilon * \text{Flux} * \text{Target} * \Gamma(a_2(1320) \rightarrow \eta\pi^0)\Gamma(\eta \rightarrow 2\gamma)\Gamma(\pi^0 \rightarrow 2\gamma)}$$



ε = efficiency can be estimated from simulations

Flux measured by pair spectrometer

Target = target thickness = known property of our LH_2 target

Γ = Branching fractions taken from Particle Data Group (PDG)

We have all the ingredients!

Example Plot

Bar Center

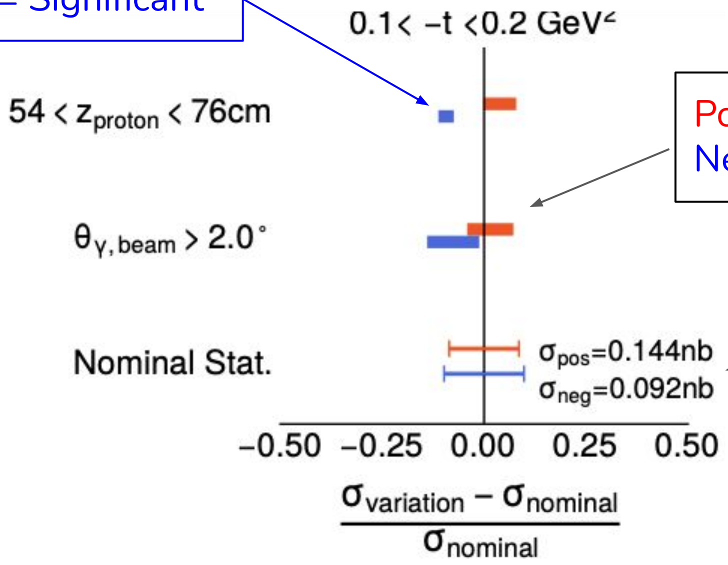
$$N_{barlow} = \frac{|x_{nom} - x_{vary}| / x_{nom}}{\text{sqrt}(|\sigma(x)_{nom}^2 - \sigma(x)_{vary}^2|) / x_{nom}}$$

Bar Width

t-bin

$N_{barlow} \sim 5$ = Significant

Variations



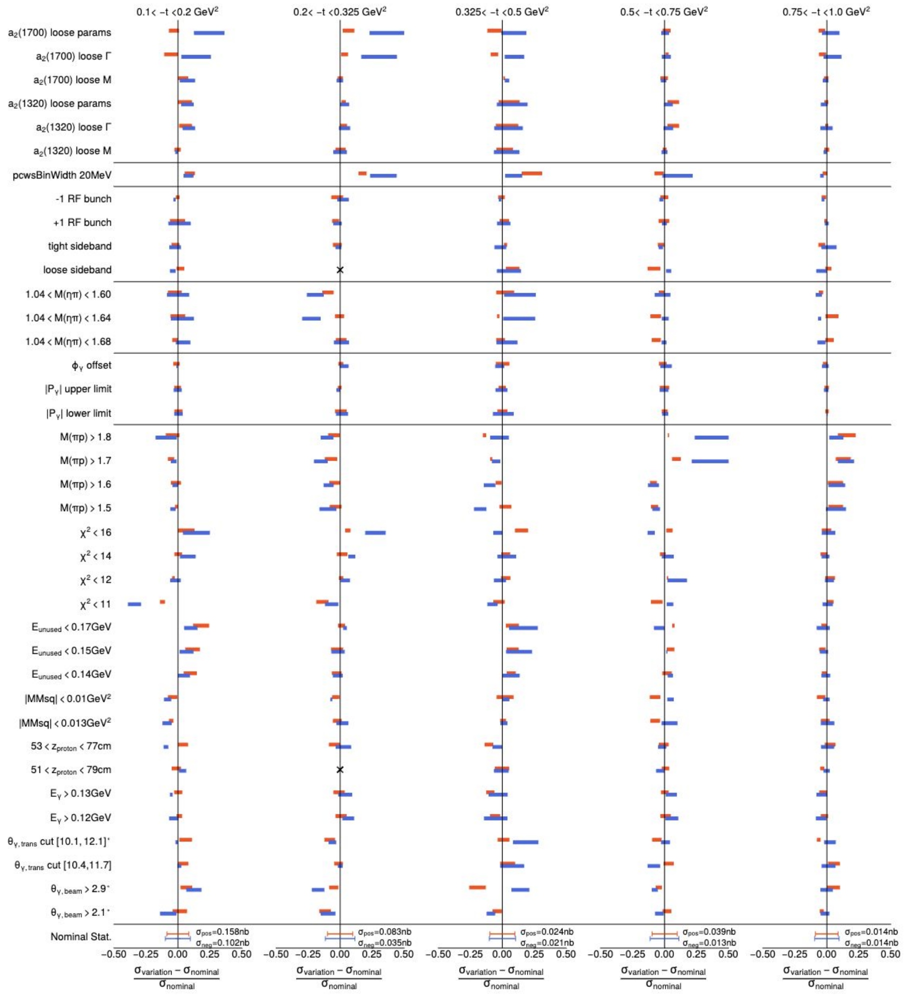
Positive Reflectivity
Negative Reflectivity

Nominal values and statistical uncertainty

Cross Section Percent Deviation

Significant if N_{barlow} > A where A set to 4

https://arxiv.org/pdf/hep-ex/0207026.pdf



D-wave parameterization

S-wave parameterization

Event counting

Fit Range

Polarization

General event selections

Breit-Wigner Resonances

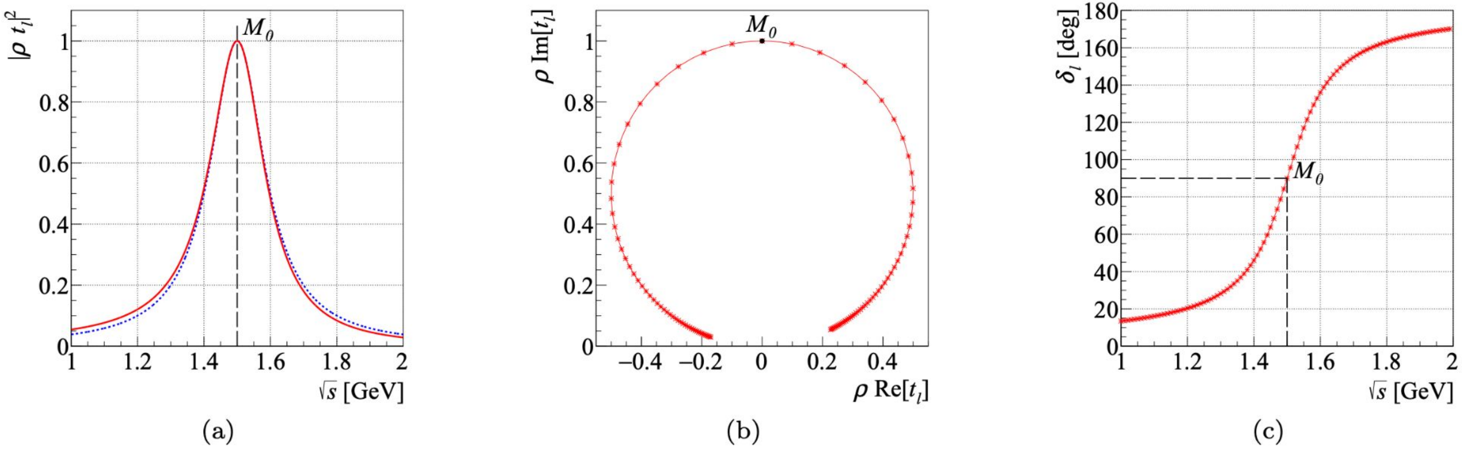


Figure 10: Breit–Wigner amplitude for elastic scattering through a fictitious resonance in the two-body partial wave with orbital angular momentum ℓ with mass $M_0 = 1500\,\text{MeV}$ and constant width $\Gamma_0 = 200\,\text{MeV}$. (a) Modulus squared of (red) the relativistic, Eq. (87), and (blue) the non-relativistic Breit-Wigner, Eq. (85). (b) Imaginary versus real part (Argand diagram), (c) phase δ_ℓ as a function of $\sqrt{s}$ for the relativistic Breit-Wigner amplitude. The points in (b) and (c) are spaced equidistantly in 10 MeV bins of $\sqrt{s}$ with s increasing in counter-clockwise direction from 1 to 2 GeV.

Prog. Part. Nucl. Phys. 113 (2020) 103755

TMD predictions overestimating GlueX measurements

- TMD scaled by 50% to agree with CLAS

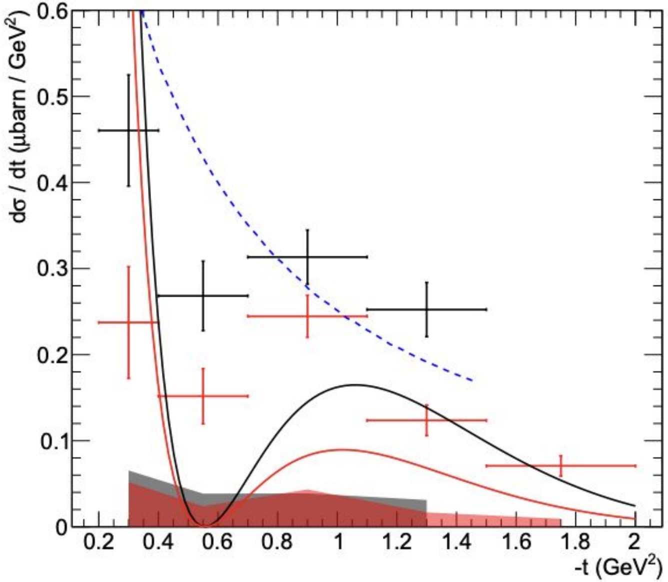


FIG. 3. Differential cross section $d\sigma/dt$ for the reaction $\gamma p \to a_2(1320)p$, for $E_{\mathrm{beam}} = 3.5$–$4.5\,\mathrm{GeV}$ (black) and $E_{\mathrm{beam}} = 4.5$–$5.5\,\mathrm{GeV}$ (red). The vertical error bars show the statistical uncertainty, whereas horizontal error bars correspond to the $-t$ bins width. The bottom bands show the systematic uncertainty. The continuous lines are predictions from the JPAC model [27], computed respectively for a beam energy of 4 GeV (black) and 5 GeV (red). The blue dashed line is the prediction from the model by Xie *et al.* [28], for beam energy 3.4 GeV. *For better readability, this was scaled vertically by a factor* $\times 0.5$.

Q-Factors

3 main items

- Multivariate combo-based weighting technique
  - **Multivariate side-band subtraction using probabilistic event weights** - M. Williams , M. Bellis and C. A. Meyer --- Journal of Instrumentation 4 10003(2009)
- Knowledge of signal + background distribution of at least one variable (reference)
- Procedure for all combos
  - Under some phase space find *k* nearest neighbors to combo *i*
  - Fit the reference variable for the *k* neighbors
  - Calculate signal fraction/probability = *Q-Factor*
- Used in many other papers

PRL **122** 162301 (2019)

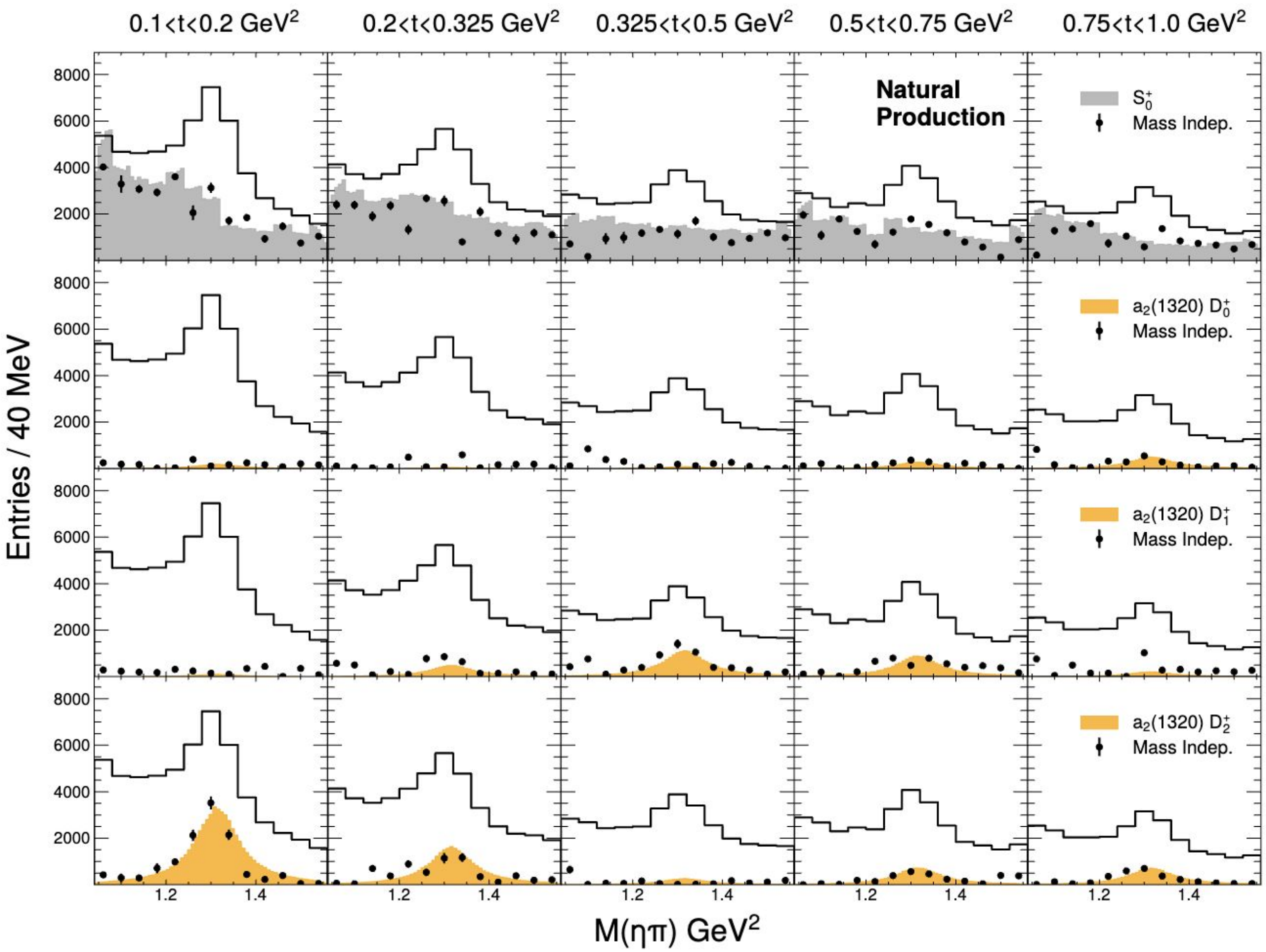
First Measurements of the Double-Polarization Observables F , P , and H in ω Photoproduction off Transversely Polarized Protons in the N* Resonance Regi
CLAS Collaboration (P. Roy (Florida State U., Tallahassee (main)) *et al.*). Dec 5, 2018. 7 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.16, 162301**

Eur. Phys. J. C (2020) 80:453

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$ at 900 MeV/c and of $\pi\pi$-Scattering Data
M. Albrecht (Ruhr U., Bochum) *et al.*. Sep 16, 2019.

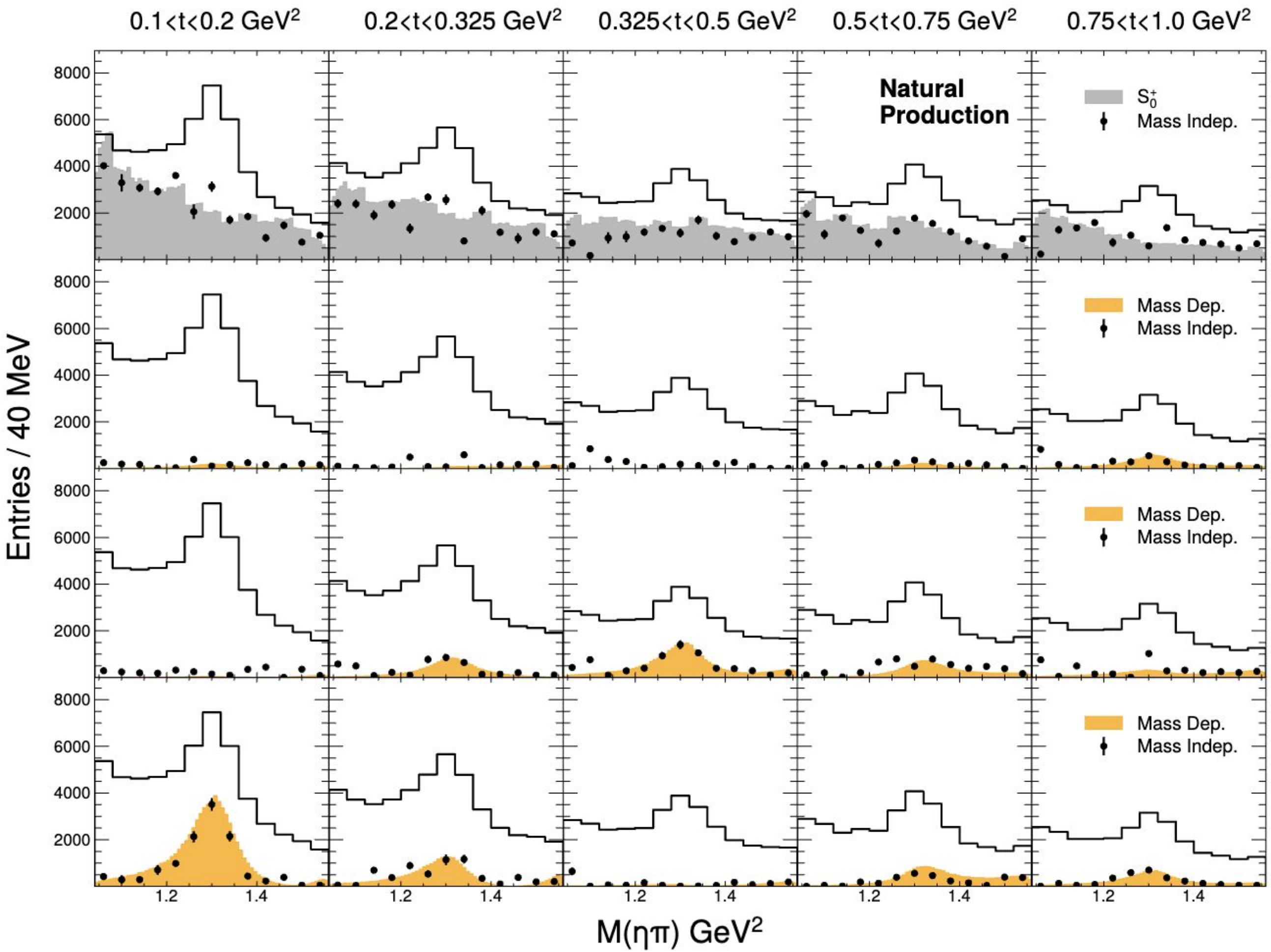
Spin Density Matrix of the ω in the Reaction $\bar{p}p \rightarrow \omega\pi^0$
Crystal Barrel Collaboration (C. Amsler (Zurich U.) *et al.*). Oct 14, 2014. 12 pp.
Published in **Eur.Phys.J. C75 (2015) no.3, 124**

Eur. Phys. J. C (2015) 75:124



Comparing Mass Independent and Mass Dependent fits

Breit-Wigner for $a_2(1320)$



Comparing Mass Independent and Mass Dependent fits

Breit-Wigner for $a_2(1320)$ AND $a_2(1700)$

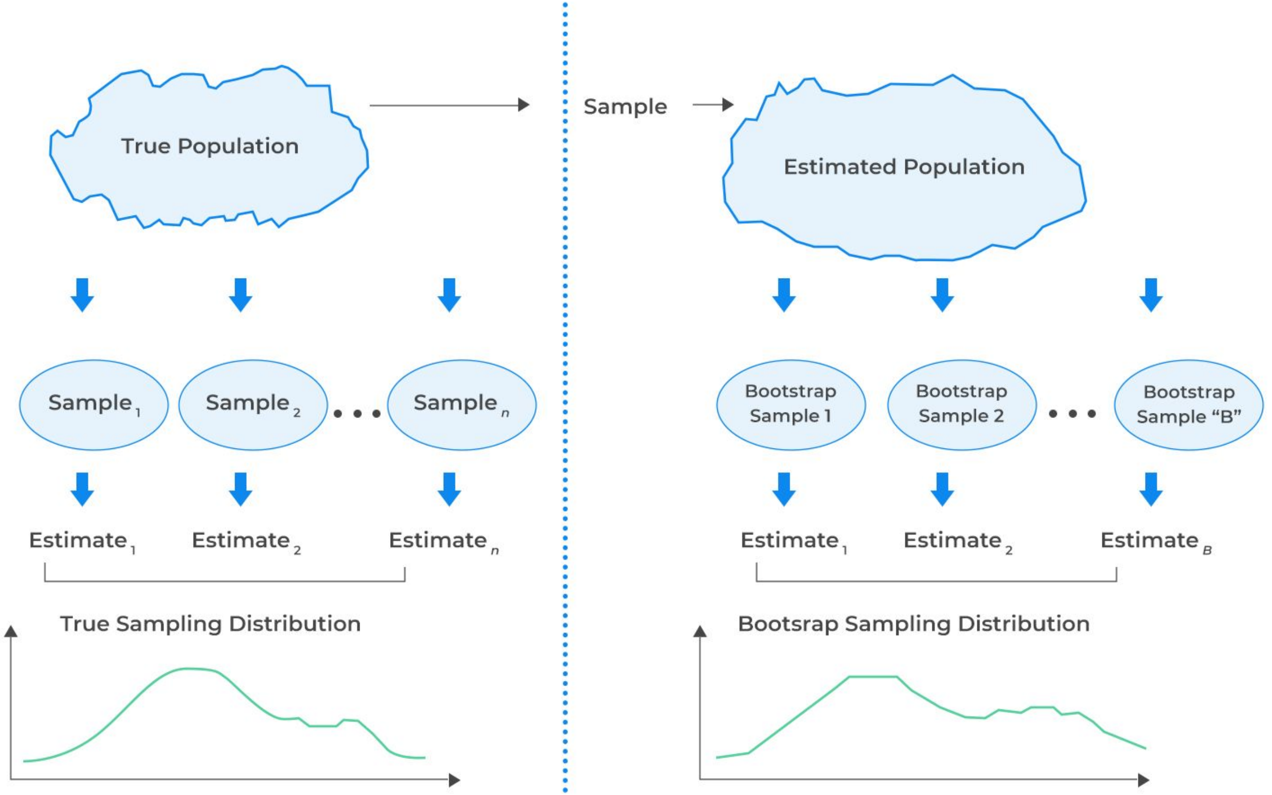
Bootstrap resampling

Draw bootstrapped samples with **replacement** from the sample

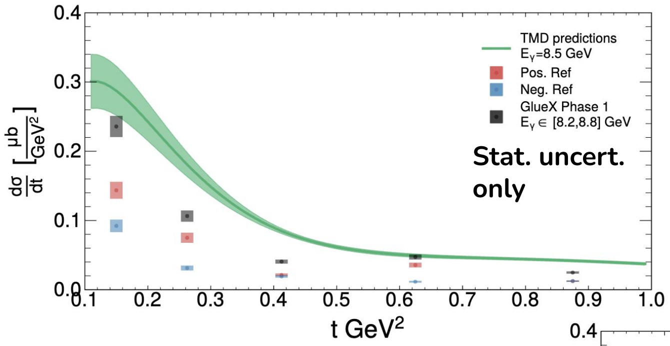
Calculate some statistic

Repeat N times

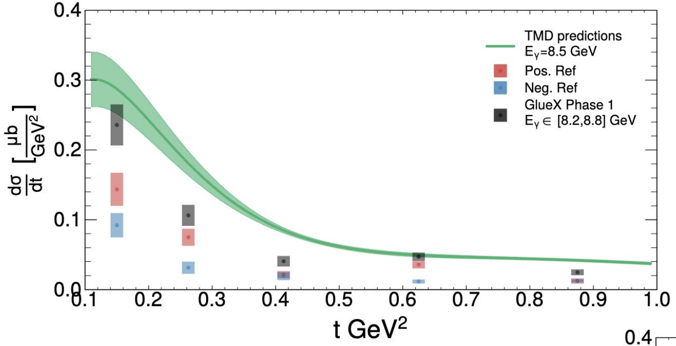
Distribution formed by the N statistic estimates is the bootstrap sampling distribution



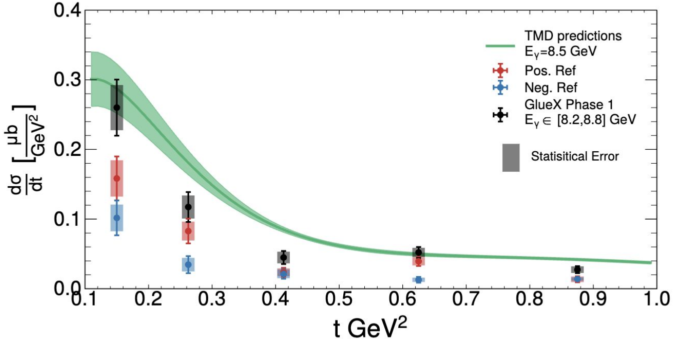
https://analystprep.com/cfa-level-1-exam/quantitative-methods/resampling/attachment/bootstrap-resampling-method/



Obtain better **statistical uncertainty** estimates via bootstrap resampling



Include **systematic uncertainty** estimates
i.e. model dependence, event selections, reconstruction efficiencies



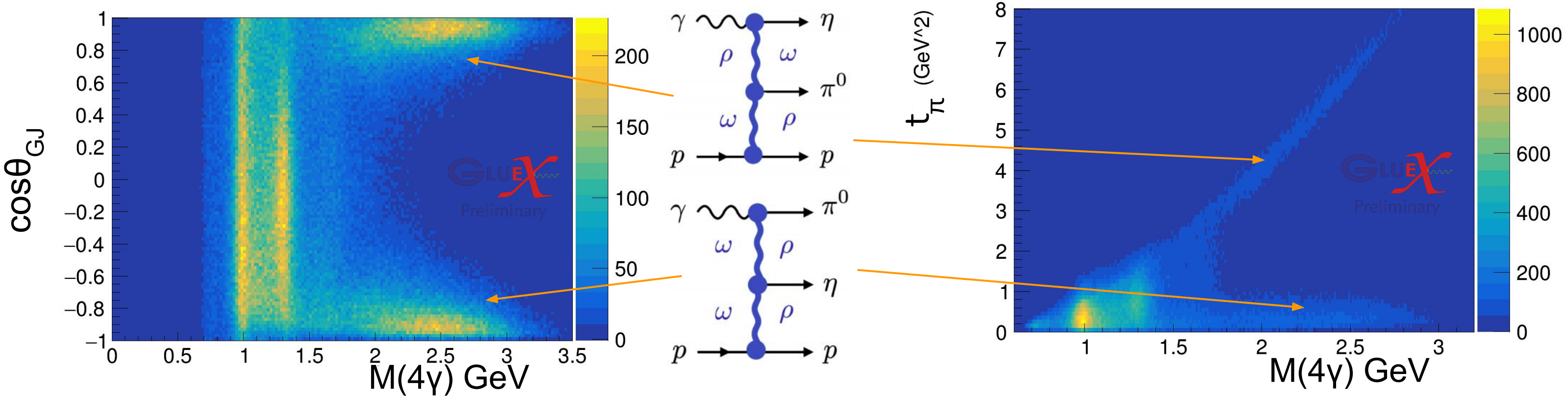
Differential cross section

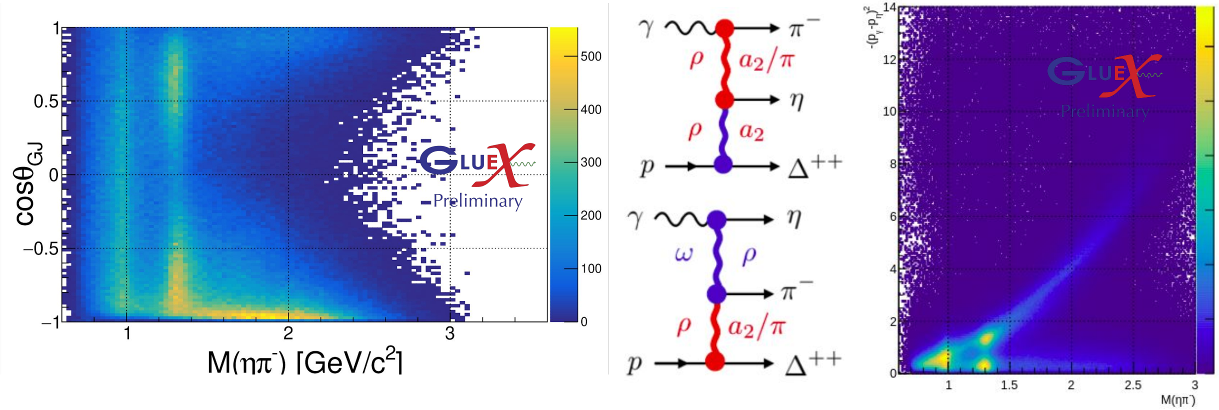
Pos. Ref. = Natural Exchange component

Neg. Ref. = Unnatural Exchange component

TMD predictions

Double Regge Exchange



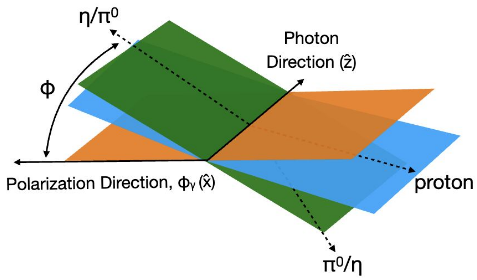


Clear separation of processes at high mass

π exchange has **unnatural** parity

ρ, ω, a_2 exchanges have **natural** parity

Beam Asymmetry



Stichel's Theorem = Cross section can be split into two components: one component parallel to **reaction plane** another perpendicular

$$\frac{d\sigma}{dt} = \frac{d\sigma_\perp}{dt} + \frac{d\sigma_\parallel}{dt}$$

$\sigma_\perp$: Unnatural exchanges only

$\sigma_{//}$: Natural exchanges only

→

Define **Beam Asymmetry**

$$\Sigma = \frac{\frac{d\sigma_\perp}{dt} - \frac{d\sigma_\parallel}{dt}}{\frac{d\sigma_\perp}{dt} + \frac{d\sigma_\parallel}{dt}}$$

Cross section given by:

$$\sigma(\phi) = \sigma_0(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma))$$

φ_γ polarization angle = {0, 45, 90, -45}

P_γ polarization magnitude ~ 0.35

Observed yields given by:

$$Y_\perp \propto N_\perp(1 + P_\gamma \Sigma \cos 2\phi)$$

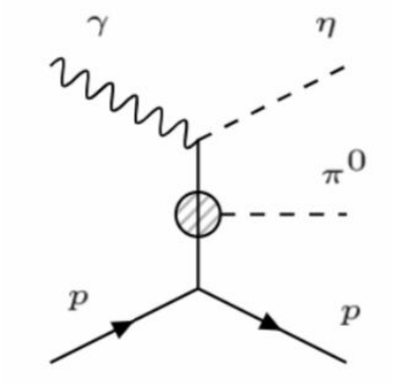
$$Y_\parallel \propto N_\parallel(1 - P_\gamma \Sigma \cos 2\phi)$$

Construct **Yield Asymmetry** to extract ∑

$$Y_A = \frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = \frac{(P_\perp + P_\parallel)\Sigma \cos 2\phi}{2 + (P_\perp - P_\parallel)\Sigma \cos 2\phi}$$

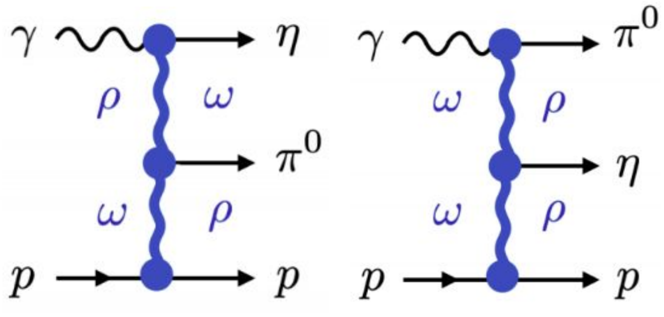
F_R = flux ratio, known quantity

Non-Resonant Deck Production



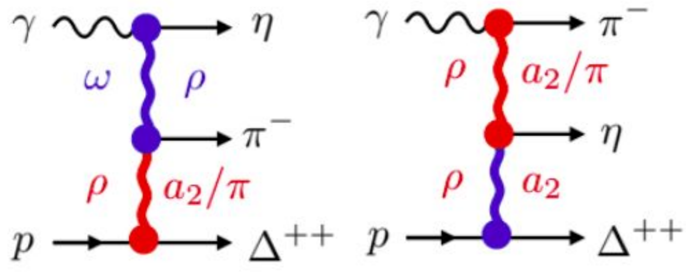
Define:
$$t_\eta = (p_\gamma - p_\eta)^2$$
$$t_\pi = (p_\gamma - p_\pi)^2$$

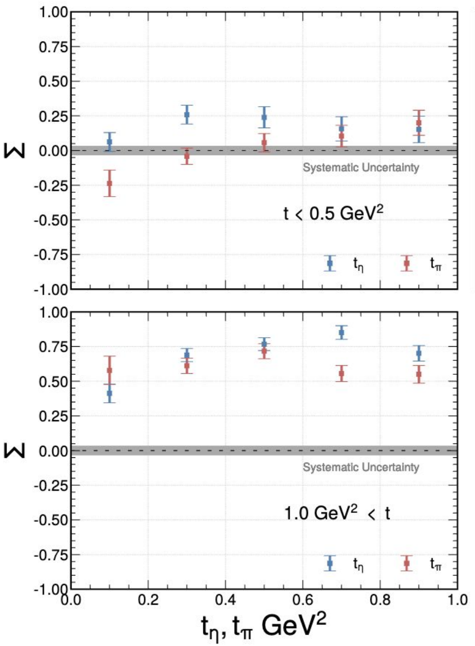
γp → $\pi^0\eta$ p → 4γ p

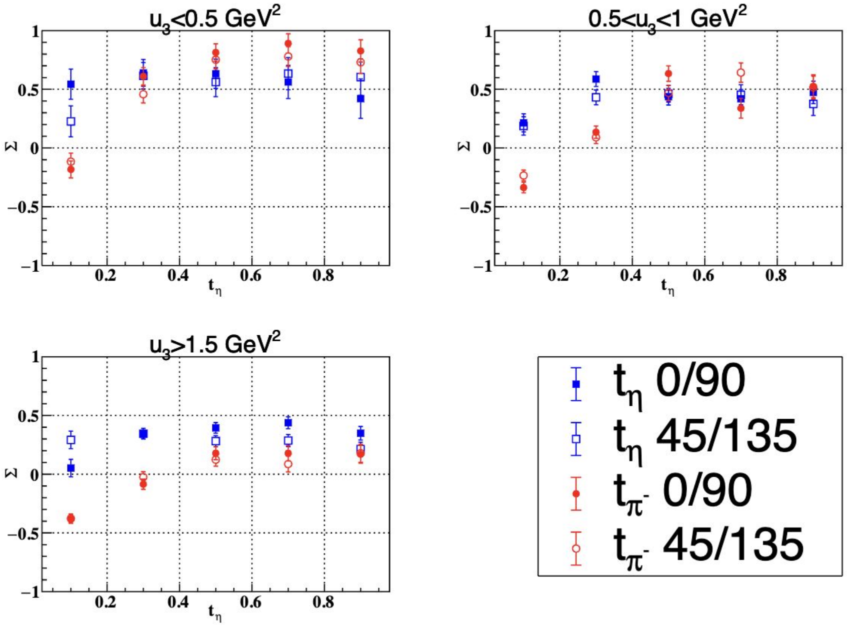


γp → $\pi^-\eta$ Δ^{++} → 2γ π^- Δ^{++}

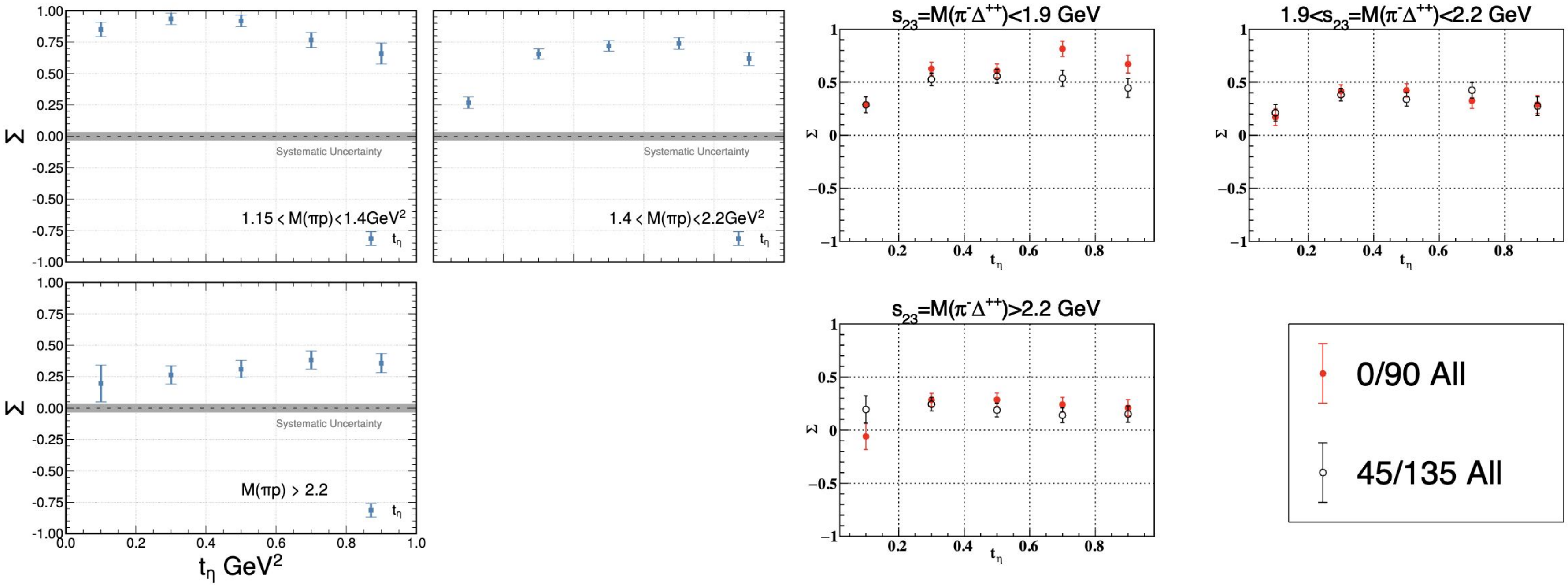
Charged plots courtesy of Colin Gleason



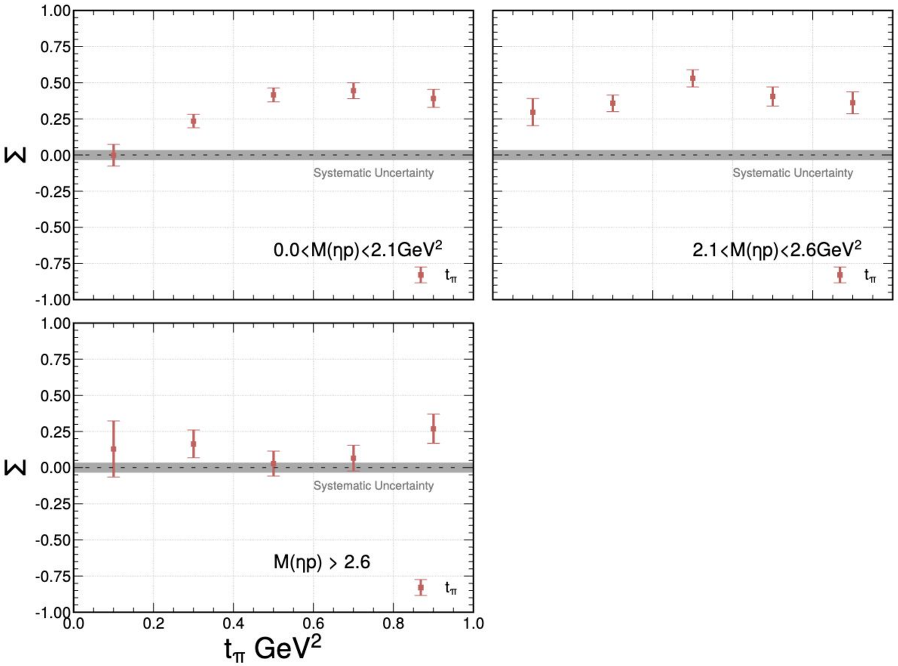


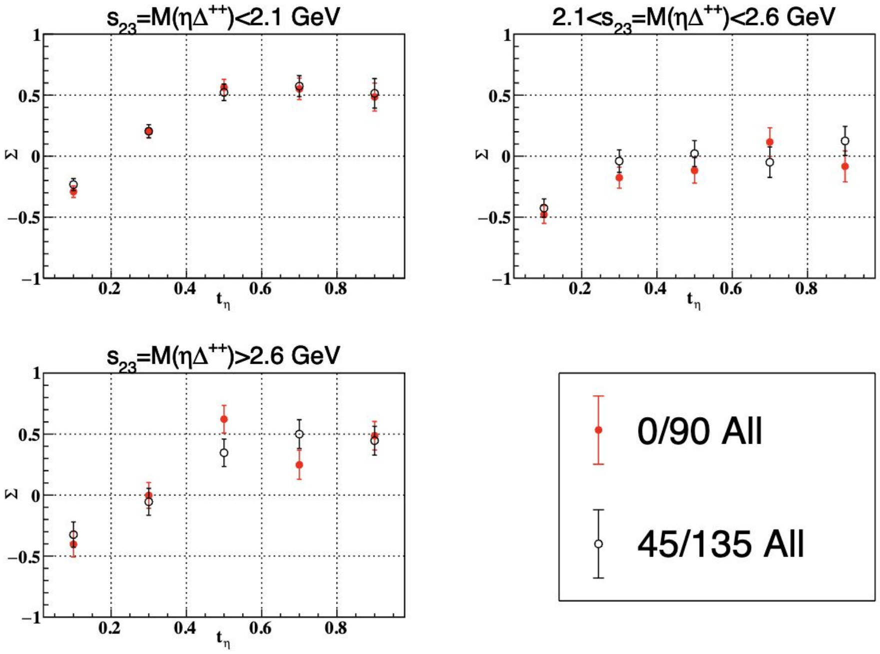


$\sum_{t1}$ binned in u_3

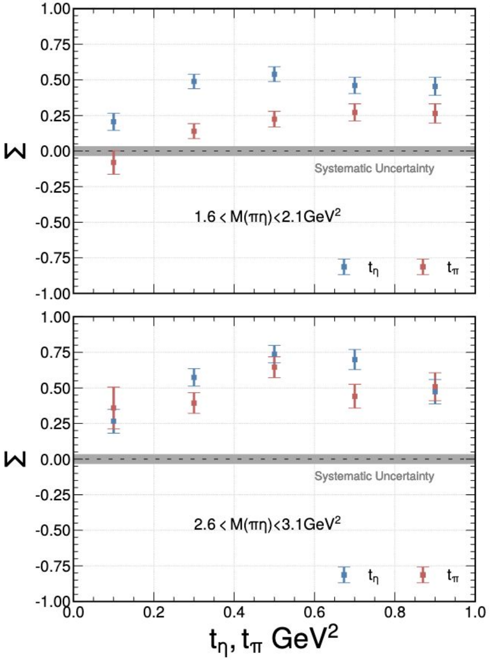


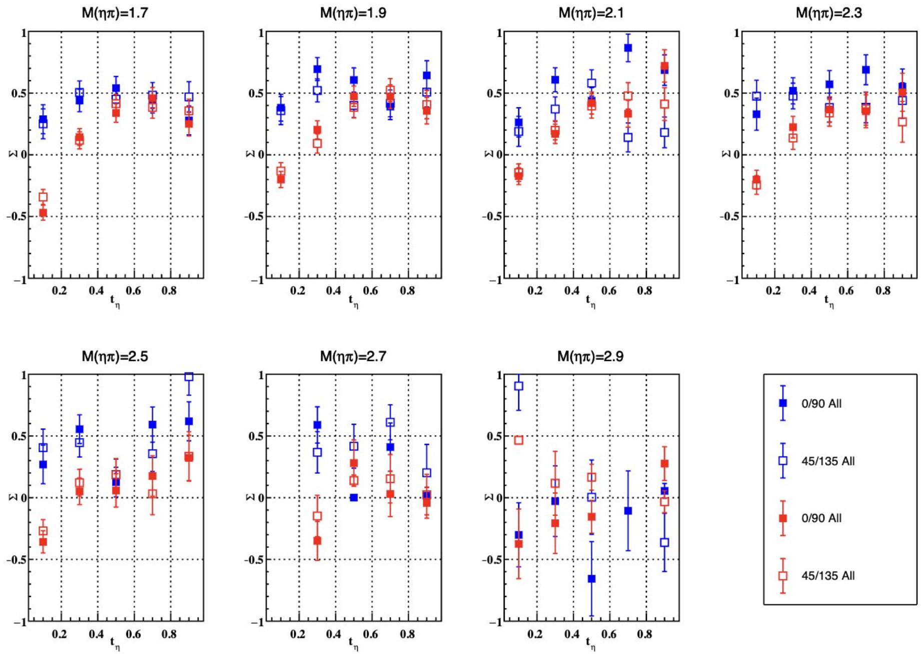
Σ_η binned in M(πp)





$\sum_{\pi}$ binned in M(ηp)





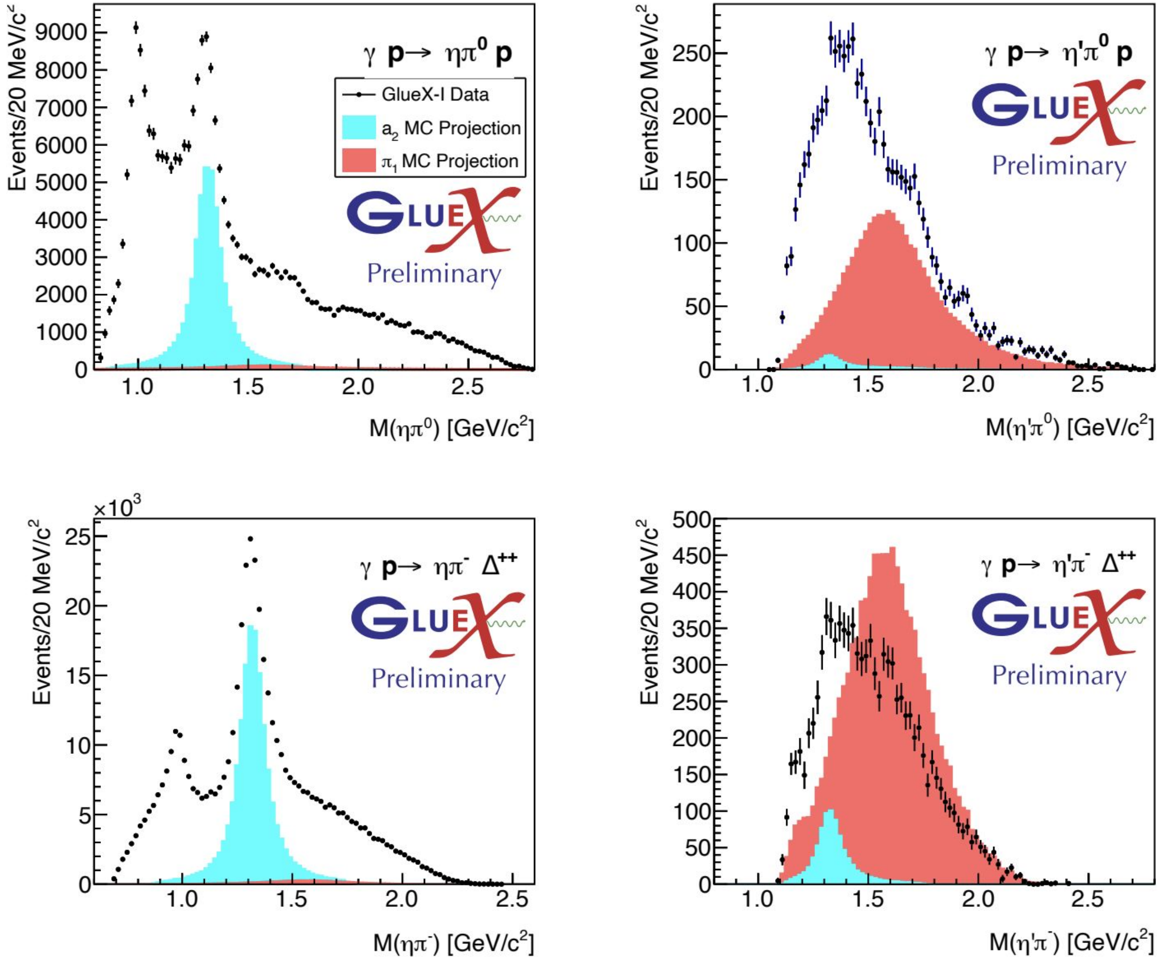
Σ_{t1} binned in s_{12}

π_1 upper limit at GlueX

1) Measure cross sections in several γp->ωππp reactions
2) Use isospin relations to isolate I=1 component
3) Fit cross section assuming only $a_2(1320)$ and π_1 contributions

Projections of the $a_2(1320)$ MC and π_1 upper limits onto the GlueX data

π_1 is the vast majority of the spectrum in η'π



https://halldweb.jlab.org/DocDB/0059/005953/001/GHP_DRAFT.pdf

Deep Learning Exotic Hadrons

PHYSICAL REVIEW D **105**, L091501 (2022)

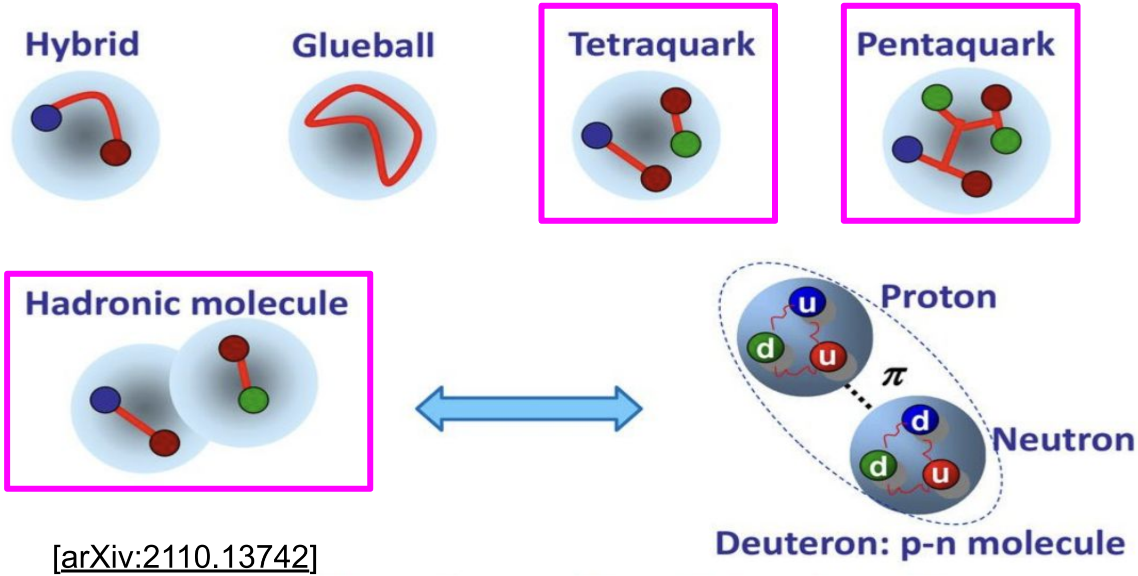
Letter

Deep learning exotic hadrons

L. Ng,[1,*] Ł. Bibrzycki,[2,†] J. Nys,[3,‡] C. Fernández-Ramírez,[4,5,§] A. Pilloni,[6,7,8,‖]
V. Mathieu,[9,10] A. J. Rasmusson,[11] and A. P. Szczepaniak[11,12,13]

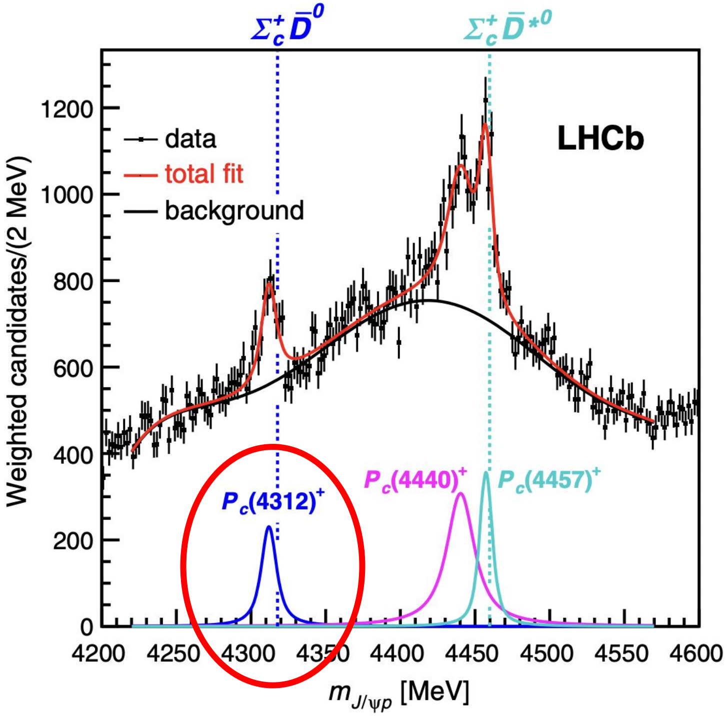
(Joint Physics Analysis Center)

Part 2: Neural Networks and Hadron spectroscopy



[arXiv:2110.13742]

Lineshape → Microscopic origins



Phys. Rev. Lett. 122, 222001 June 2019

Top down:

Develop a microscopic model and fit to data

1. Assigns physical interpretation
2. Biased to assumed dynamics

Bottom up:

Develop minimally biased amplitudes based on basic principles

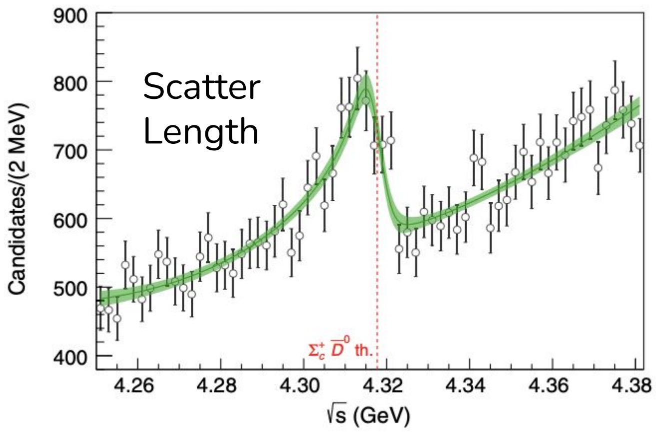
1. Harder to deduce the nature but possible
2. Less bias

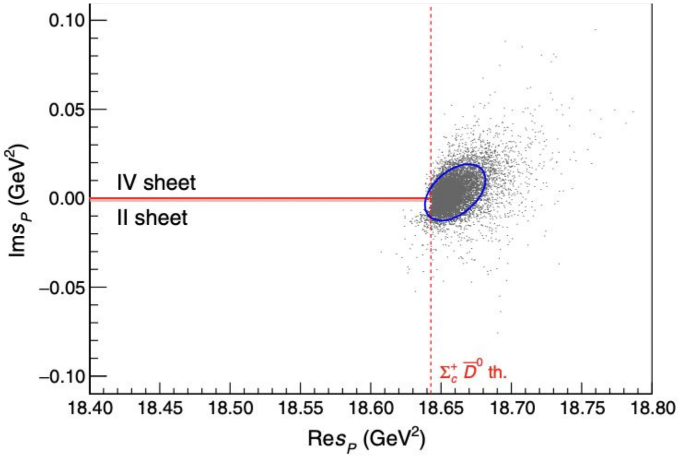
Results

Minimally biased: Reaction amplitudes respecting S-matrix principles
Two channels: $J/\psi p$ (channel 1) and $\Sigma_c^+ \bar{D}^0$ (channel 2)

Location of the poles of amplitude when channels decouple determine the nature

Suggest $P_c(4312)^+$ is virtual (unbound) state - not strong enough to bind Σ_c^+ and $\bar{D}^0$ to form a molecule





Phys. Rev. Lett. 123, 092001 August 2019

Neural Networks

Use those minimally biased amplitudes to develop a training set

Alternative tool to analyze and interpret data as opposed to a standard χ^2 fit for a single hypothesis

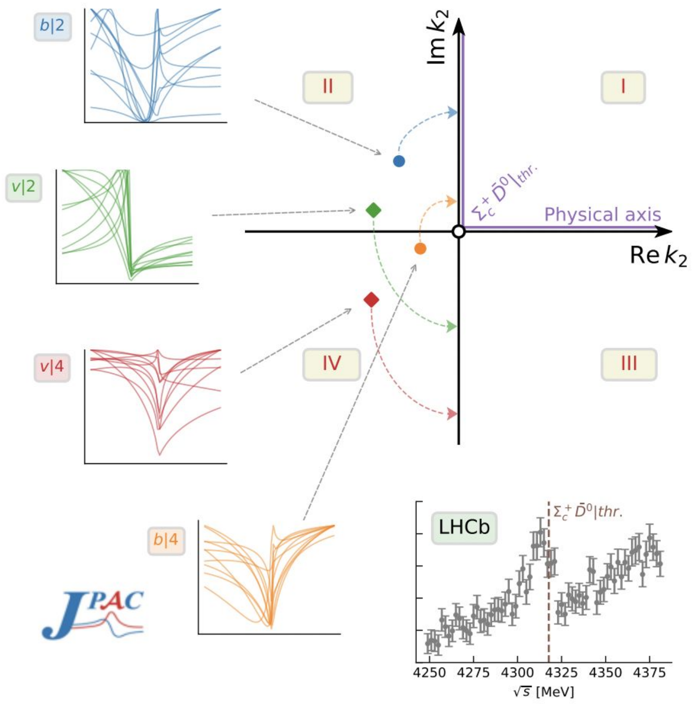
- Multi-class prediction
- Understand the impact of lineshape features to the class assignment

<u>Outline for the rest of the talk</u>

1. Training set
2. Neural Network architecture
3. Feature impact and explainable AI
4. Results

Training set

$$T(s) = \frac{M_{22} - ik_2}{(M_{11} - ik_1)(M_{22} - ik_2) - M_{12}^2}$$



T(s) encodes dynamics of J/ψp rescattering
Poles = zeros of denominator

Complex momentum plane split into 4 sheets
Poles can only lay on II and IV sheet

Migration of poles when channels decouple ($M_{12} \to 0$)
$M_{22} < 0$ = bound state in $\Sigma_c^+ \bar{D}^0$ channel
$M_{22} > 0$ = virtual (unbound) state

Data generated for wide range of model parameters and over a larger energy range

Classify:
{bound, II}, {bound, IV}, {virtual, II}, {virtual, IV}
Inputs:
Spectrum (incorporating noise and resolution)

Network Architecture

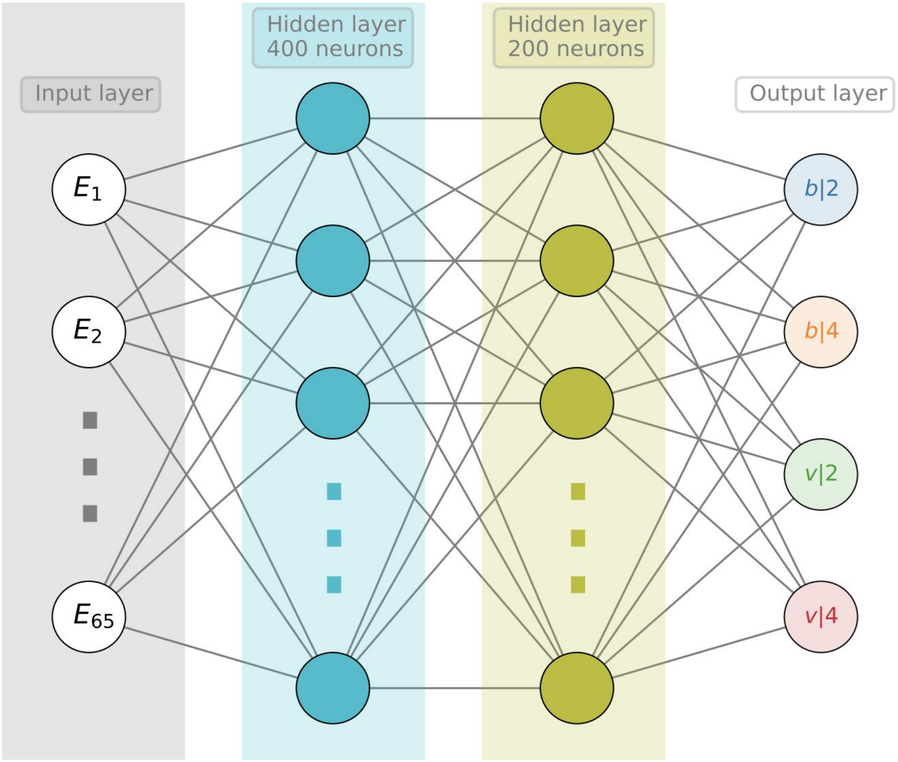
Fixed input size (65) + 2 hidden layers (ReLU activation) +
Output layer size (4, for each class)

Dropout included in between hidden layers

- Randomly zero nodes with some probability [0.2, 0.5]
- Prevents overfitting (regularization)
- Allows determination of classification probability uncertainty

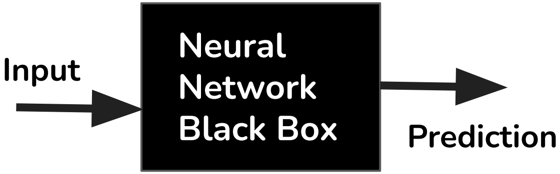
Output / Loss = Softmax output + Multiclass cross-entropy

Optimized stochastically with Adam, batch-size 1024



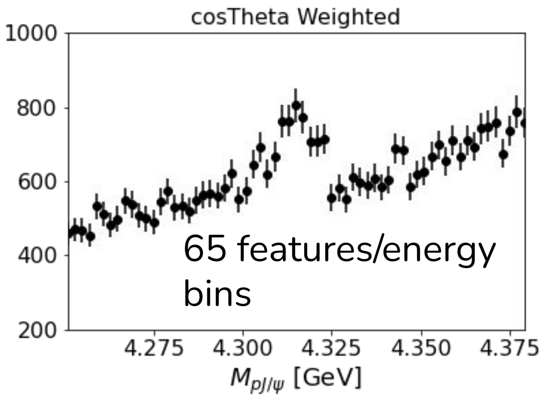
Game Theory: Determining player contribution

Explainable AI

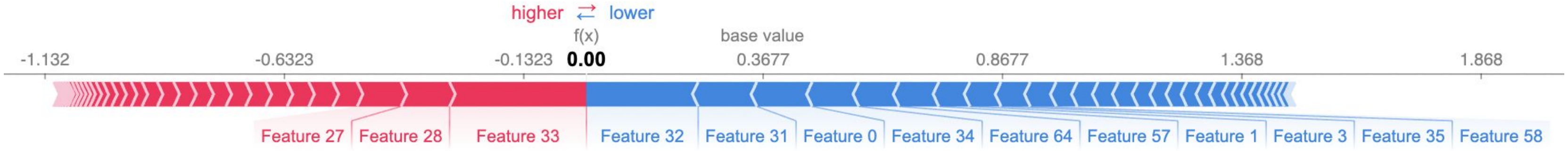


- How to split money among a group of players?
  - Determining contributions of a feature to the loss function
- Fairness:
  - Additivity - Sum of values = total money
  - Consistency - More contribution = more money
- Only ONE fair way of doing this - Shapely values
  - Lloyd Shapely won a nobel prize in economics
  - His father, Harlow Shapely - Astronomer - first to determine correct position of the sun in the Milky way
  - Harlow's student, Georges Lemaitre - first derived Hubble's Law and first estimation of hubble constant in 1927 - nominated twice for Nobel Prize

Shapely Values



- ❖ Average marginal contribution across all feature coalitions
- ❖ Coalition - Set of features of any size
- ❖ Marginal Contribution - Changes to prediction with feature included in a coalition
- ❖ Additive local explanations
  - ➢ For **each** spectrum we can determine how much each energy bin contributes to the overall response (classification probability)



Determining the energy/input window

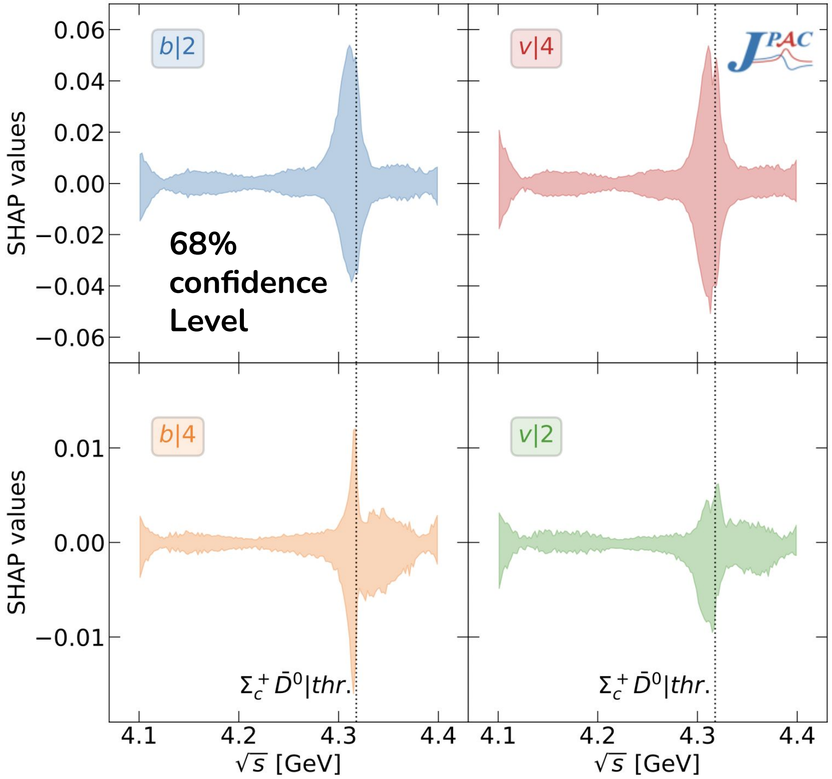
Typically the input window depends on some heuristic

Train a network using a wider energy/feature window = [4.1, 4.4] GeV
Use **SH**apley **A**dditive **E**xplanations (**SHAP python package**)
Determines feature importance

+(-) SHAP values push a network to predict into(outside) a given class

Large abs(SHAP) = high feature importance

Select energy region → [4.251, 4.379] GeV
+ Retrain



Network Performance

Network trained using various amounts of noise

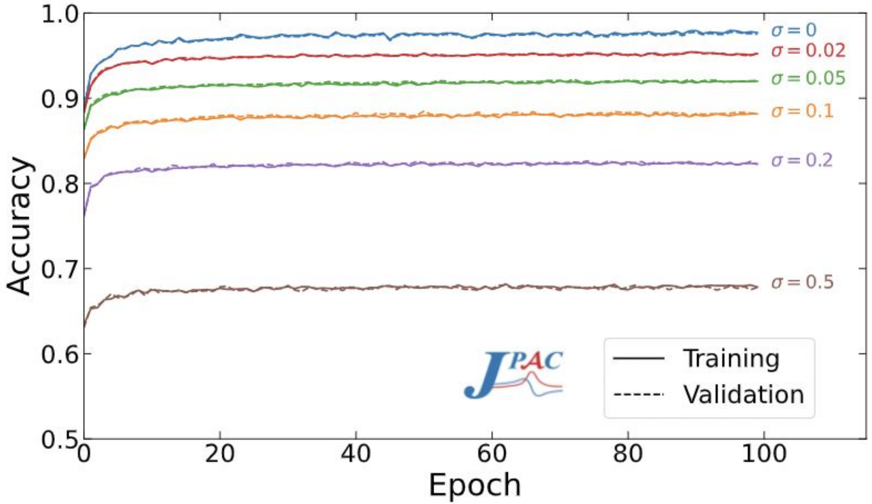
LHCb data ~ 5% noise

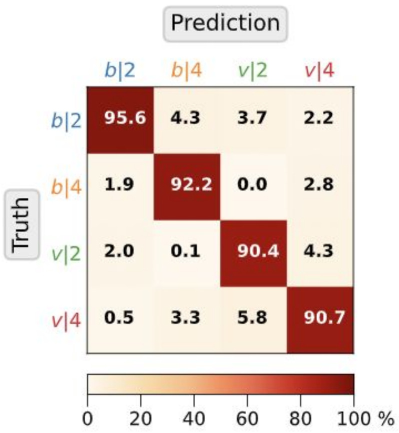
Network saturates > 90% accuracy

Confusion matrix for 5% noise normalized column-wise

Probability point estimates for LHCb data

	$b\|2$	$b\|4$	$v\|2$	$v\|4$
$\cos\theta_{P_c}$-weighted	0.6%	< 0.01%	1.1%	98.3%
$m_{Kp} > 1.9\,\mathrm{GeV}$	1.4%	< 0.1%	1.6%	97.0%
m_{Kp} all	5.4%	< 0.1%	21.0%	73.6%



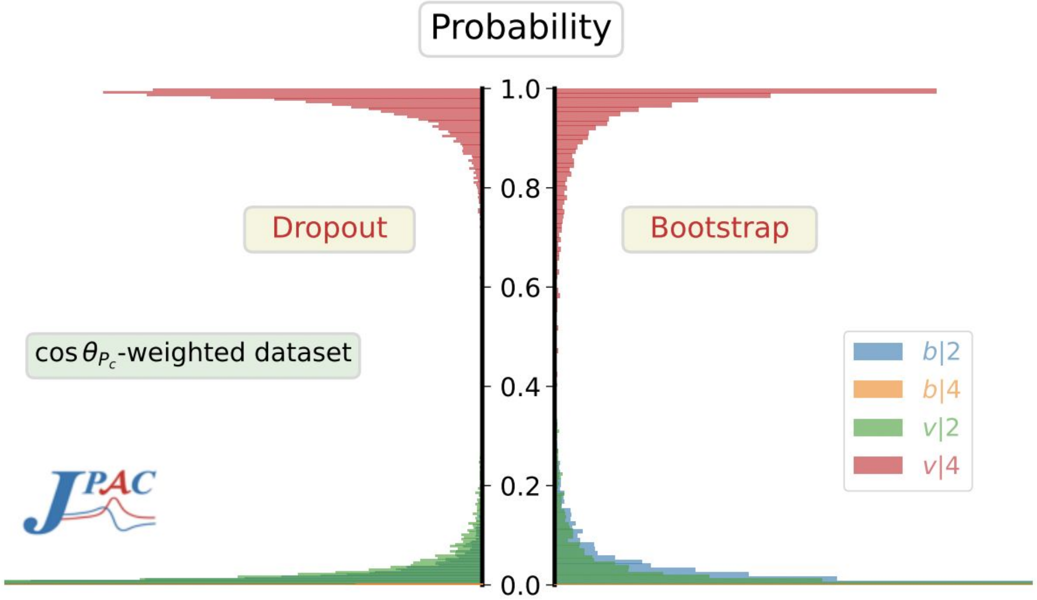


Exploring Uncertainties

Dropout
Approximate deep Gaussian process a Bayesian probabilistic model
arXiv:1506.02142

Bootstrap
Resample LHCb data around its uncertainties, pass through network with dropout off

Good agreement between approaches



Uncertainties on the softmax probabilities strongly favor v|4 class

Conclusion

- ❖ Prescription to develop a neural network to investigate exotic lineshapes
- ❖ Incorporates noise and resolution
- ❖ Shapley values to determine regions importance
- ❖ Prediction uncertainty quantification through dropout and bootstrapping
- ❖ Pentaquark case study favors virtual state interpretation of $P_c(4312)^+$
- ❖ Numerous future prospects

Carnegie Supernova Project-II:

Near-infrared spectral diversity of Type Ia supernova

Carnegie Supernova Project-II: Near-infrared spectral diversity and template of Type Ia Supernovae

Jing Lu (陆晶) ,[1] Eric Y. Hsiao (蕭亦麒) ,[1] Mark M. Phillips,[2] Christopher R. Burns,[3] Chris Ashall,[4]
Nidia Morrell,[2] Lawrence Ng,[1] Sahana Kumar,[1] Melissa Shahbandeh,[5,6] Peter Hoeflich,[1] E. Baron,[7,8]
Syed Uddin,[9] Maximilian D. Stritzinger,[10] Nicholas B. Suntzeff,[9] Charles Baltay,[11] Scott Davis,[1]
Tiara R. Diamond,[12] Gaston Folatelli,[13,14] Francisco Förster,[15,16] Jonathan Gagné,[17,2] Lluís Galbany,[18,19]
Christa Gall,[20] Santiago González-Gaitán,[21] Simon Holmbo,[10] Robert P. Kirshner,[22,23] Kevin Krisciunas,[9]
G. H. Marion,[24] Saul Perlmutter,[25,26] Priscila J. Pessi,[27] Anthony L. Piro,[3] David Rabinowitz,[11]
Stuart D. Ryder,[28,29] and David J. Sand[30]

Approach 2: Study the NIR spectral diversity of SNe~Ia and build an improve NIR spectral template

Credit: JWST

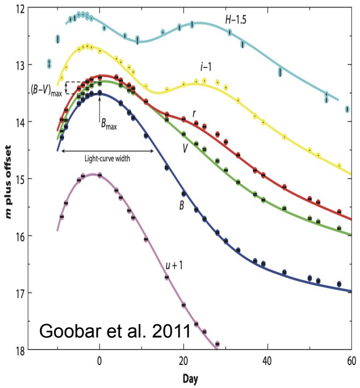
Observations

Credit: Yuri Beletsky Magellan, LCO

- *Evolution effect*
- *Dust Extinction*

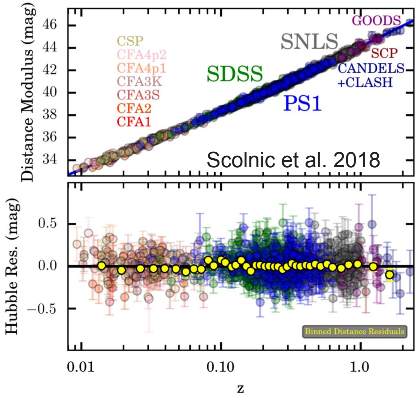
Selection bias

Photometric Calibrations



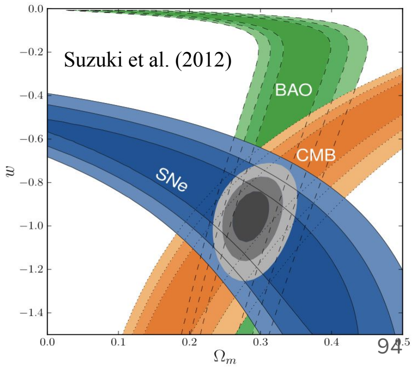
Calibration

Light Curves Fitting → μ



LC fitting

Statistics → H_0, Ω, w



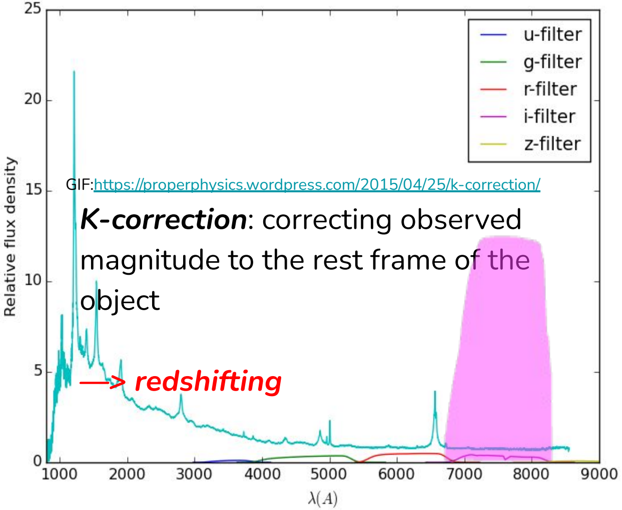
Systematic Uncertainties !

Light Curves fitters covers NIR ➔ Need spectral template!

SNooPy	SALT3-NIR	BayeSN
Burns et al. 2011	Pierel et al. 2022	Mandel et al. 2022

SNooPy

- Use Hsiao template (Hsiao 2009) for K-correction



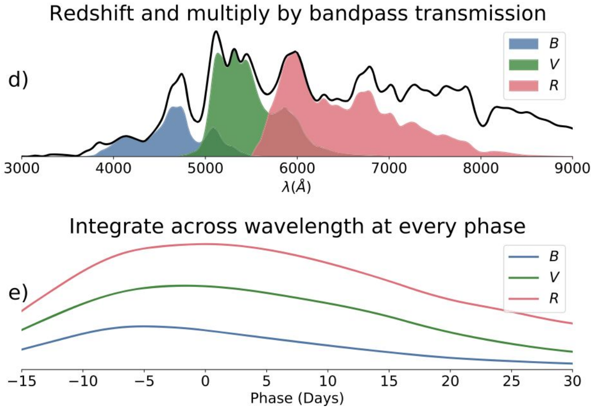
GIF: https://properphysics.wordpress.com/2015/04/25/k-correction/

K-correction: correcting observed magnitude to the rest frame of the object

SALT3-NIR

- Spectral model

- "Native" K-correction

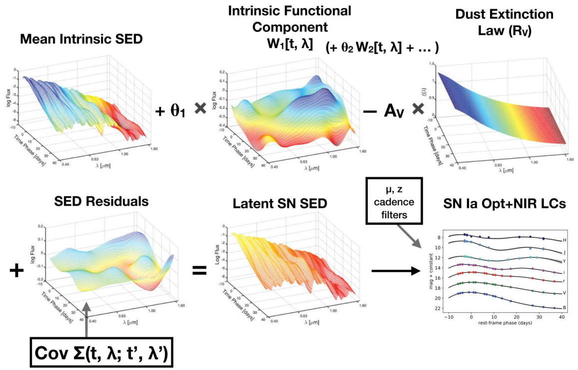


Kenworthy et al. 2021 (SALT3)

BayeSN

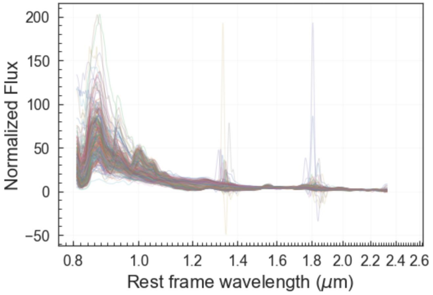
- Spectral model (use Hsiao template as the baseline)

- "Native" K-correction



Mandel et al. 2022

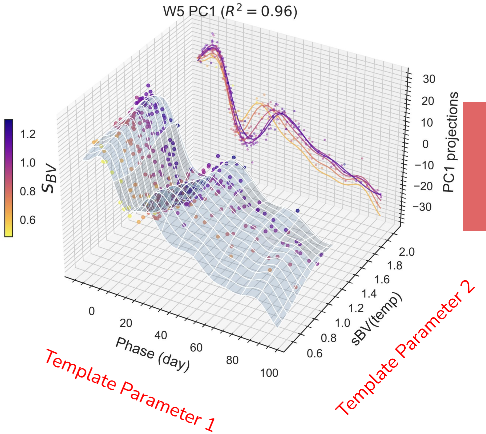
Gaussian Process Regression
to include external parameters
+
Select top-N eigenvectors



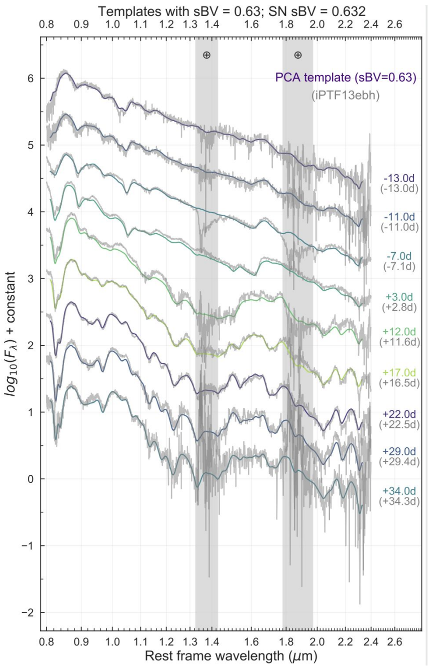
Input

~400 NIR supernovae spectra

PCA “encoder”

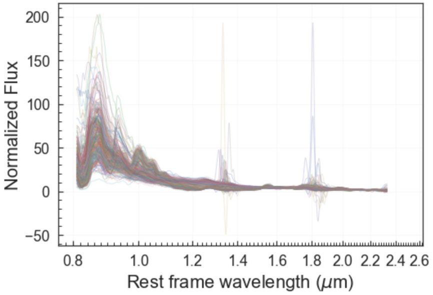


PCA “decoder”



Output

Templates for **any** (s_{BV}, epoch) parameters

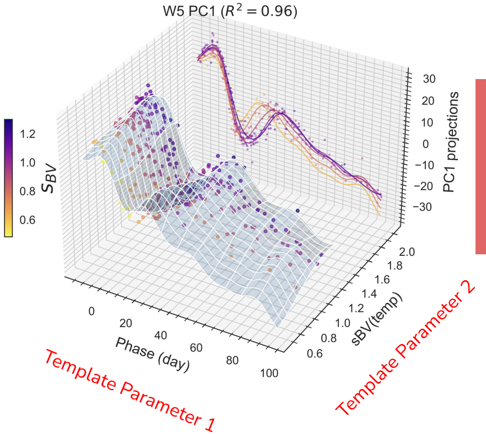


Input

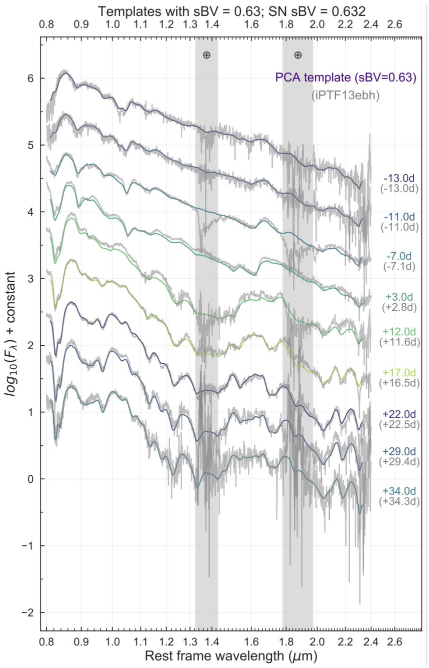
~400 NIR supernovae spectra

Condition both networks on template parameters
+
Choice of latent space dimension

Neural Network Encoder



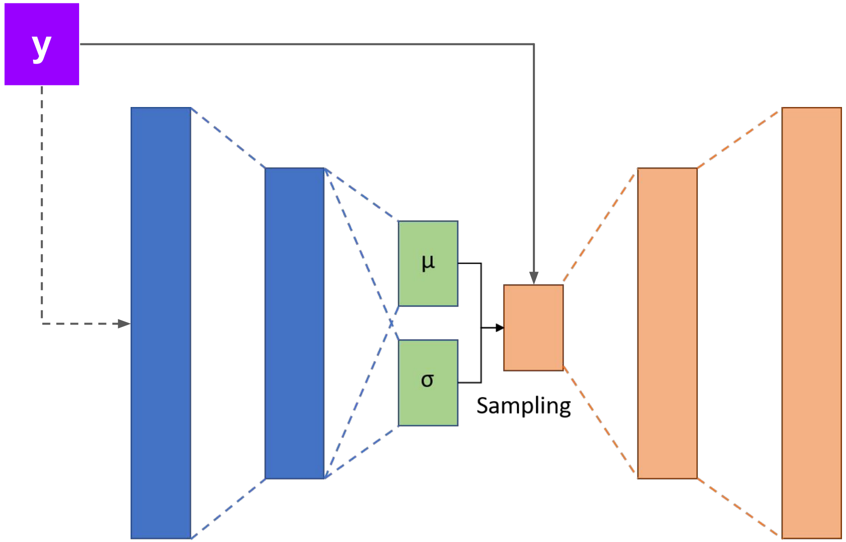
Neural Network Decoder



Output

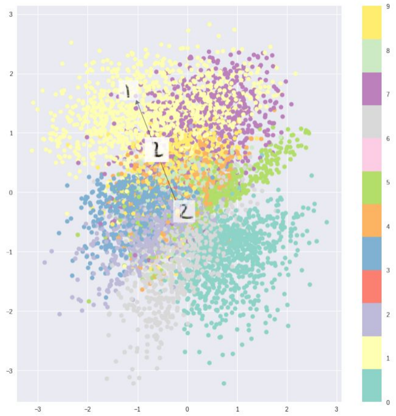
Templates for **any** (s_{BV}, epoch) parameters

(Conditional) Variational Autoencoder

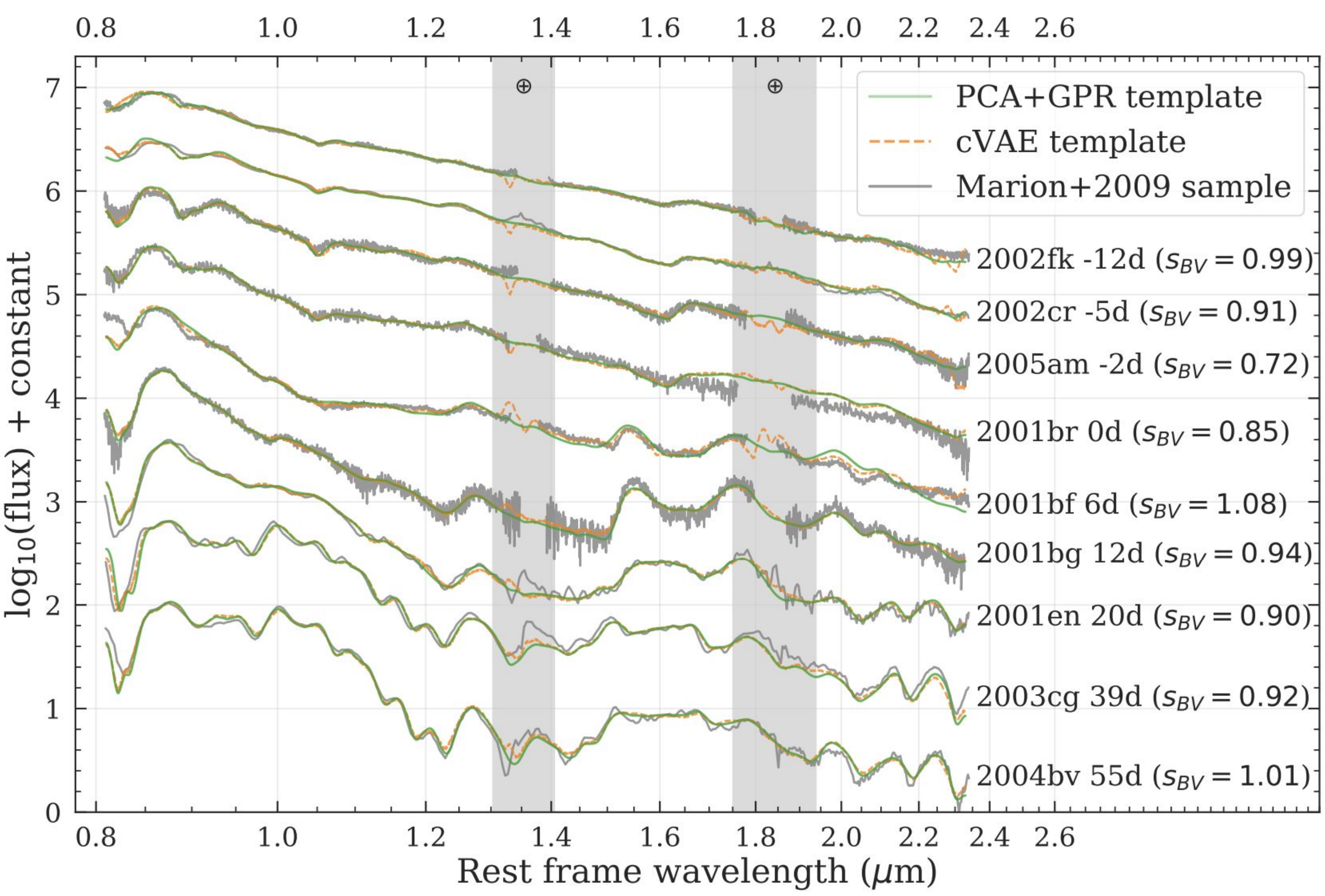


X = input spectra
y = template parameters

- Input spectra mapped to a probability distribution (Gaussian) vs a single point
- Gives probabilistic outputs
- Optimization/Loss function
  - Regularizing term forces distribution to be closely clustered
  - Reconstruction loss term forces clusters to be distinct



Example of VAE latent space with MNIST numbers dataset



Both techniques perform similarly

cVAE more prone to noise in shaded telluric regions where data is bad

More real data or samples through data augmentation via bootstrap can improve performance

No need for wavelength interpolation nor stitching