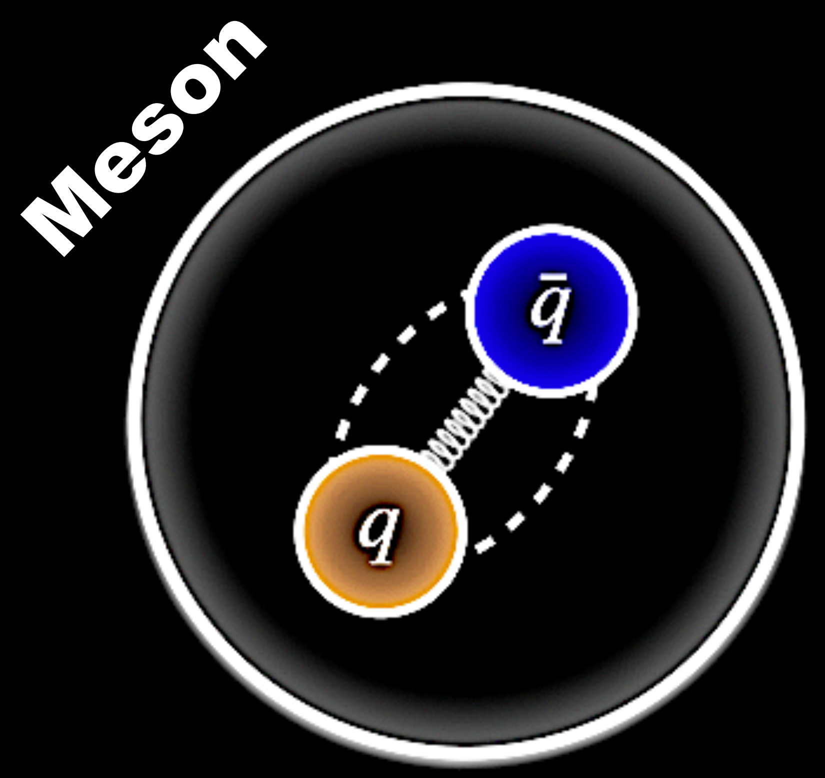
Exploring Photoproduced $\eta^{(\prime)}\pi^0$ Systems in the Search for Exotic Hadrons at GlueX

2025 European Physical Society Conference on High Energy Physics
— Marseille, France

QCD and Hadronic Physics

Zachary Baldwin | July 10, 2025

on behalf of the GlueX collaboration



Total angular momentum | $J = 0,1,2,\ldots$

Parity | $P = (-1)^{L+1}$

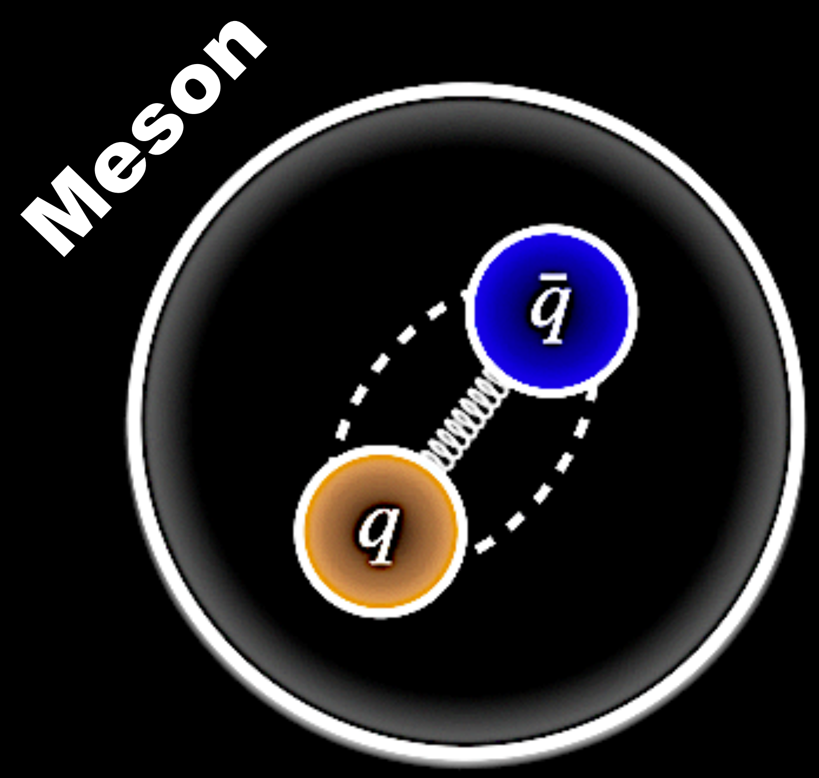
Charge Conjugation | $C = (-1)^{L+S}$

L is the relative orbital angular momentum of the q and $\bar{q}$

S is the total intrinsic spin of the $q\bar{q}$ pairs

Allowed J^{PC} quantum numbers

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^{--}



Total angular momentum | $J = 0,1,2,\ldots$

Parity | $P = (-1)^{L+1}$

Charge Conjugation | $C = (-1)^{L+S}$

L is the relative orbital angular momentum of the q and $\bar{q}$

S is the total intrinsic spin of the $q\bar{q}$ pairs

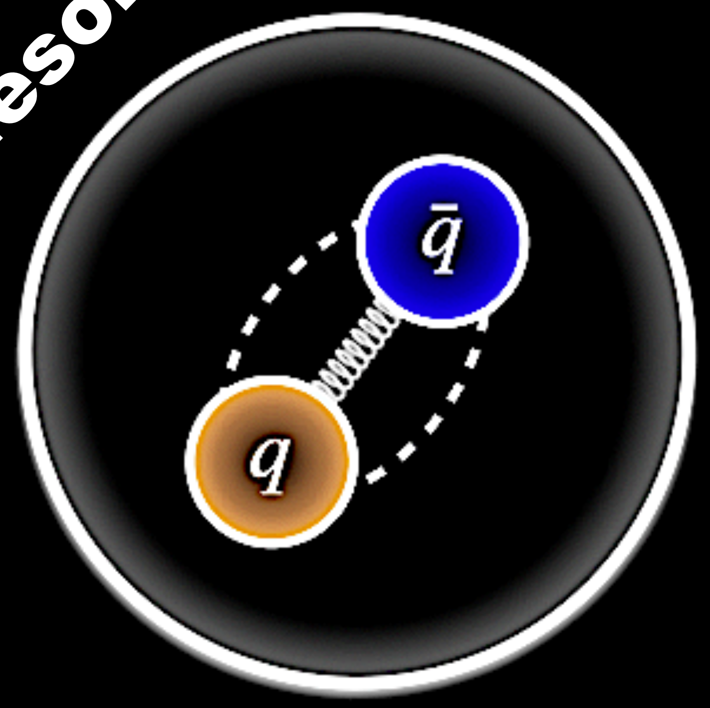
Allowed J^{PC} quantum numbers

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^{--}

Forbidden J^{PC} quantum numbers

$0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-}$

Observation of any system with quantum numbers forbidden in the constituent quark model, provides direct evidence for a non-$q\bar{q}$ configuration



Total angular momentum | $J = 0,1,2,\ldots$

Parity | $P = (-1)^{L+1}$

Charge Conjugation | $C = (-1)^{L+S}$

L is the relative orbital angular momentum of the q and $\bar{q}$

S is the total intrinsic spin of the $q\bar{q}$ pairs

Allowed J^{PC} quantum numbers

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^{--}

Forbidden J^{PC} quantum numbers

$0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-}$

Observation of any system with quantum numbers forbidden in the constituent quark model, provides direct evidence for a non-$q\bar{q}$ configuration

Do gluons play a larger role within the structure of hadrons?

Lattice QCD predicts the existence of mesons with explicit *gluonic excitations* (states absent in the constituent quark model) commonly referred to as *spin-exotic hybrid mesons*

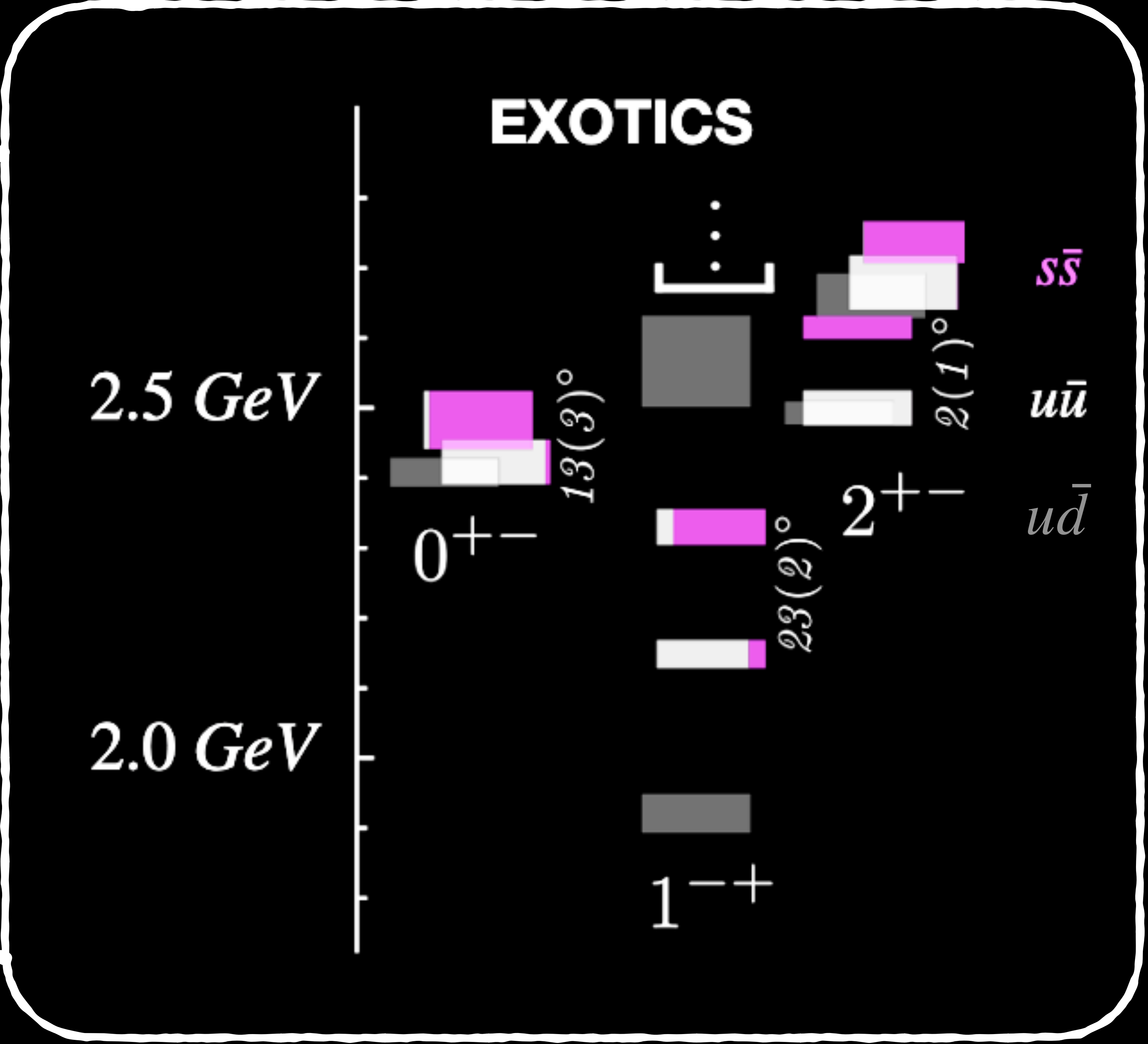
JLAB-THY-11-1314
TCD-MATH 11-02

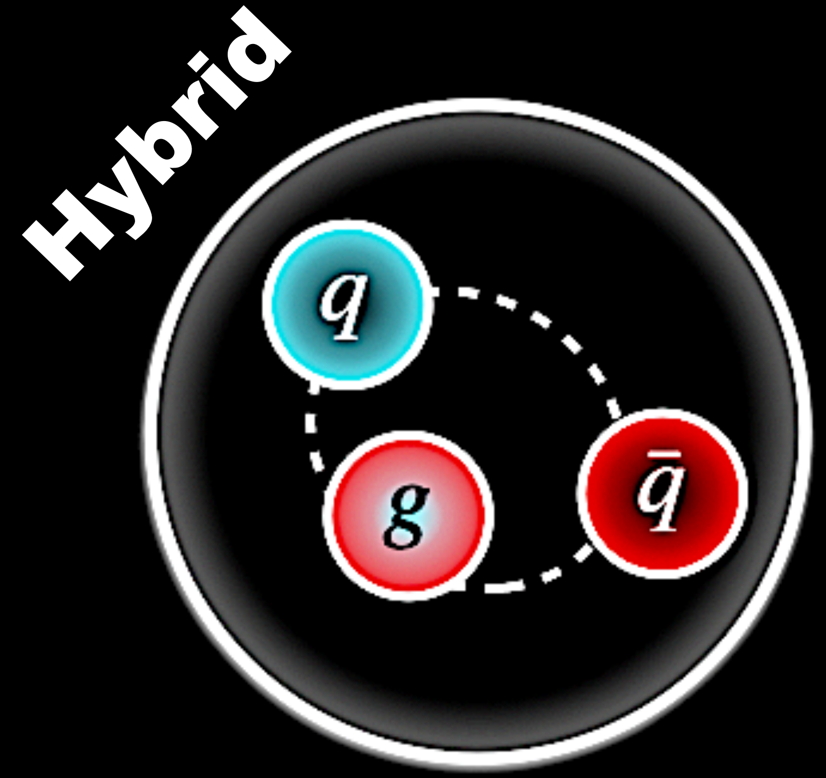
Isoscalar meson spectroscopy from lattice QCD

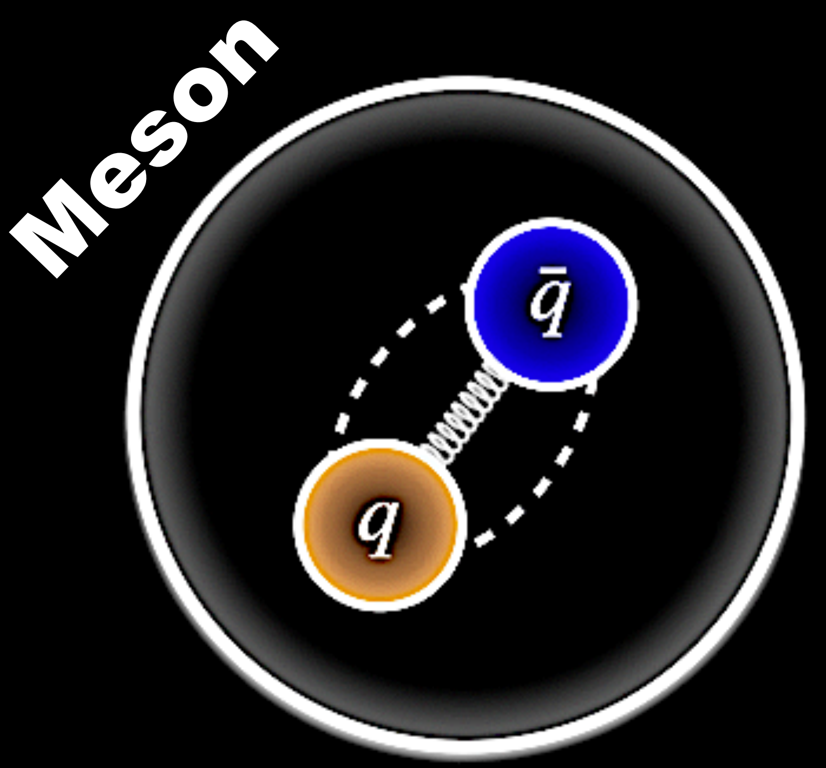
Jozef J. Dudek, Robert G. Edwards, Bálint Joó, Michael J. Peardon, David G. Richards, and Christopher E. Thomas
(for the Hadron Spectrum Collaboration)

arXiv:1102.4299v1 [hep-lat] 21 Feb 2011

J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)





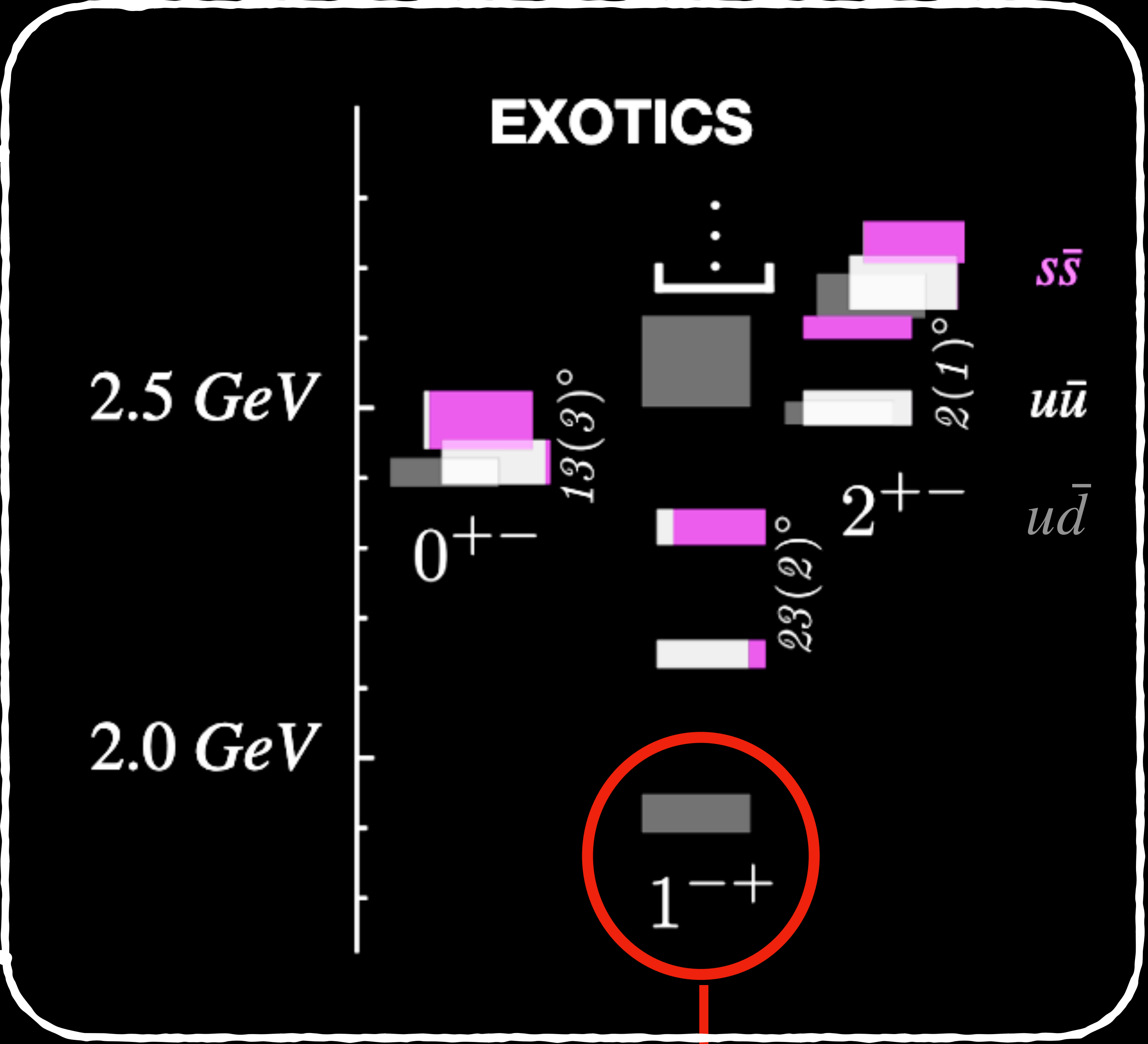


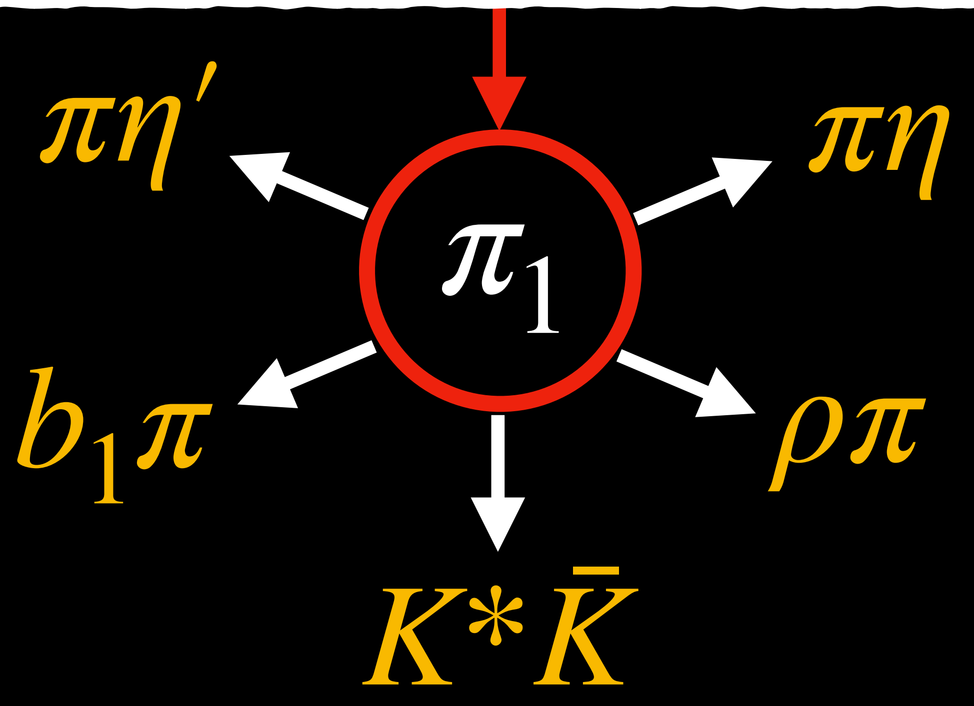
Lattice QCD predicts the existence of mesons with explicit *gluonic excitations* (states absent in the constituent quark model) commonly referred to as *spin-exotic hybrid mesons*

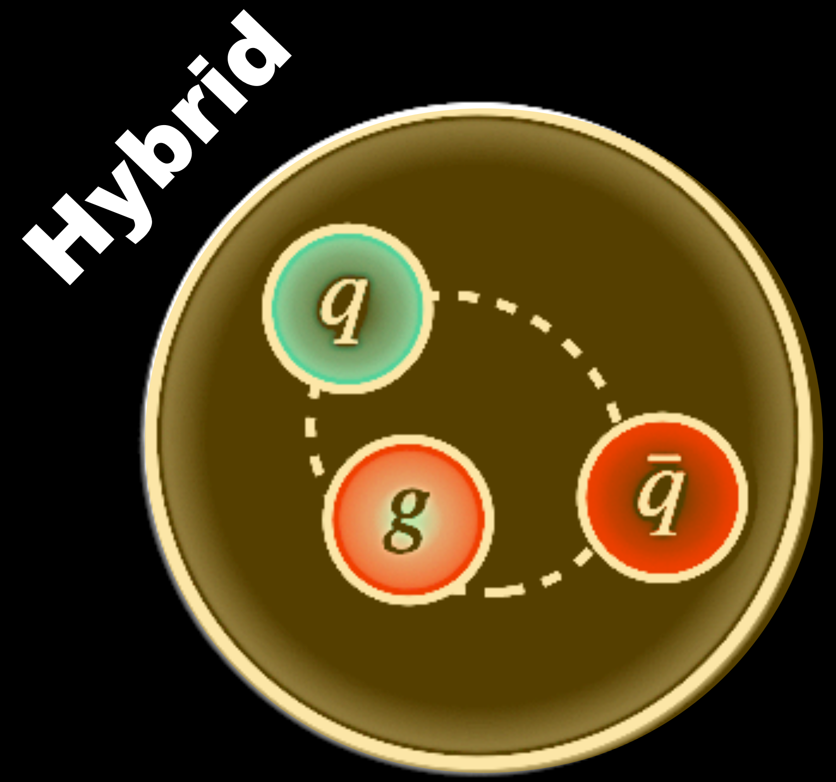

Isoscalar meson spectroscopy from lattice QCD

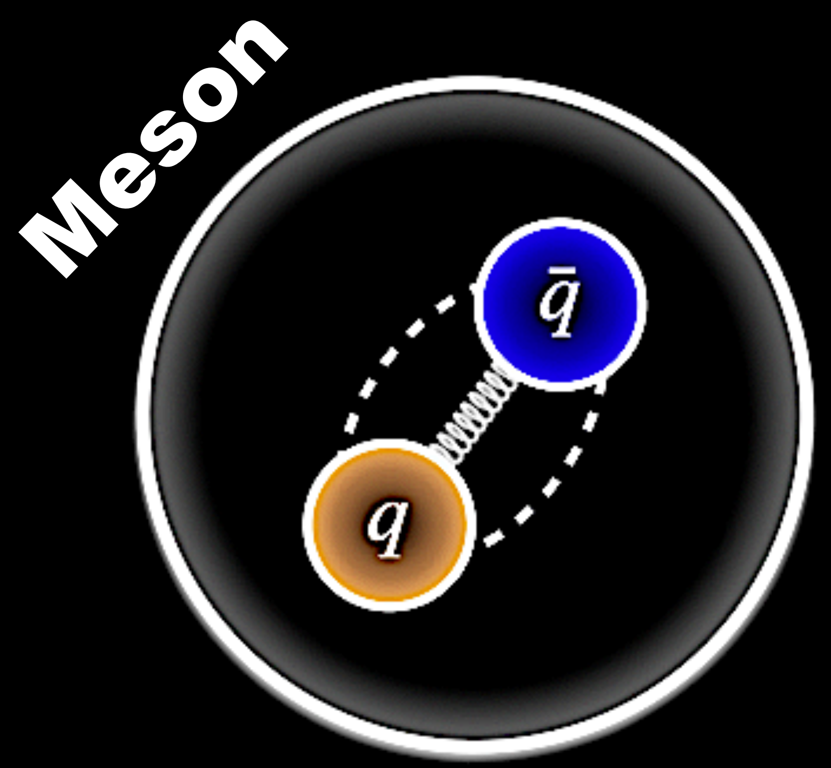
Jozef J. Dudek, Robert G. Edwards, Bálint Joó, Michael J. Peardon, David G. Richards, and Christopher E. Thomas (for the Hadron Spectrum Collaboration)

J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)



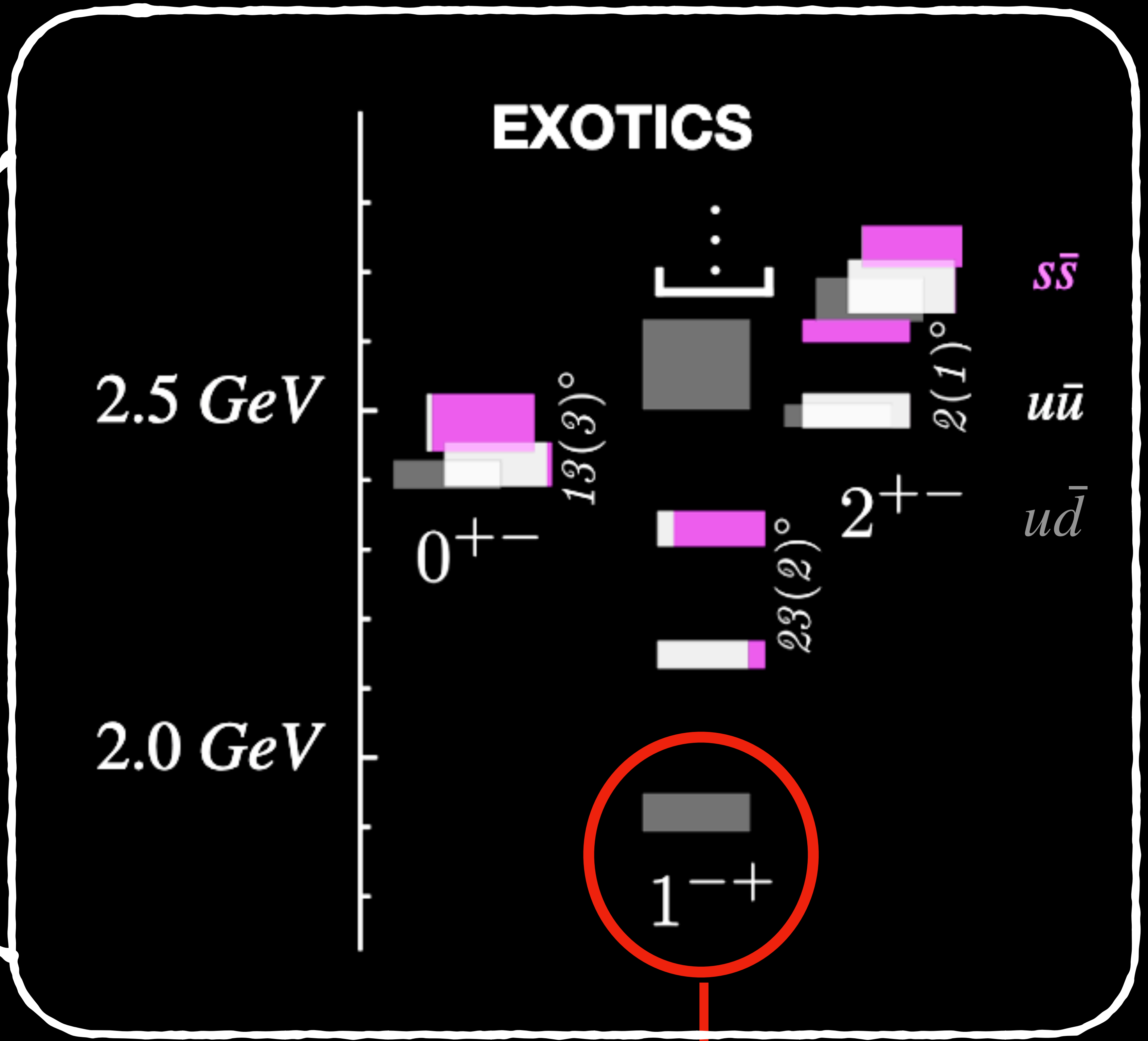


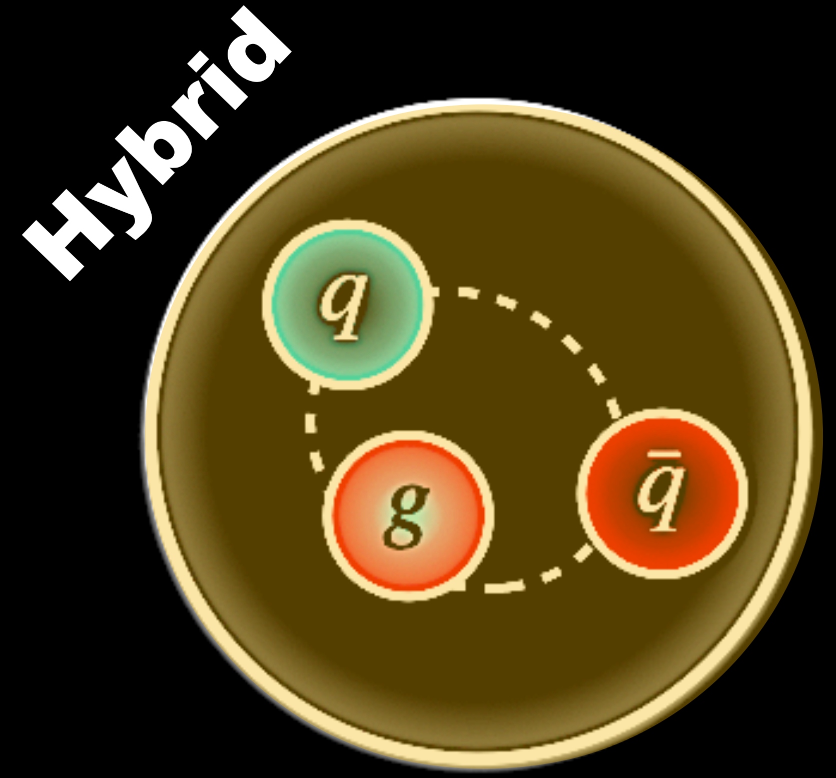


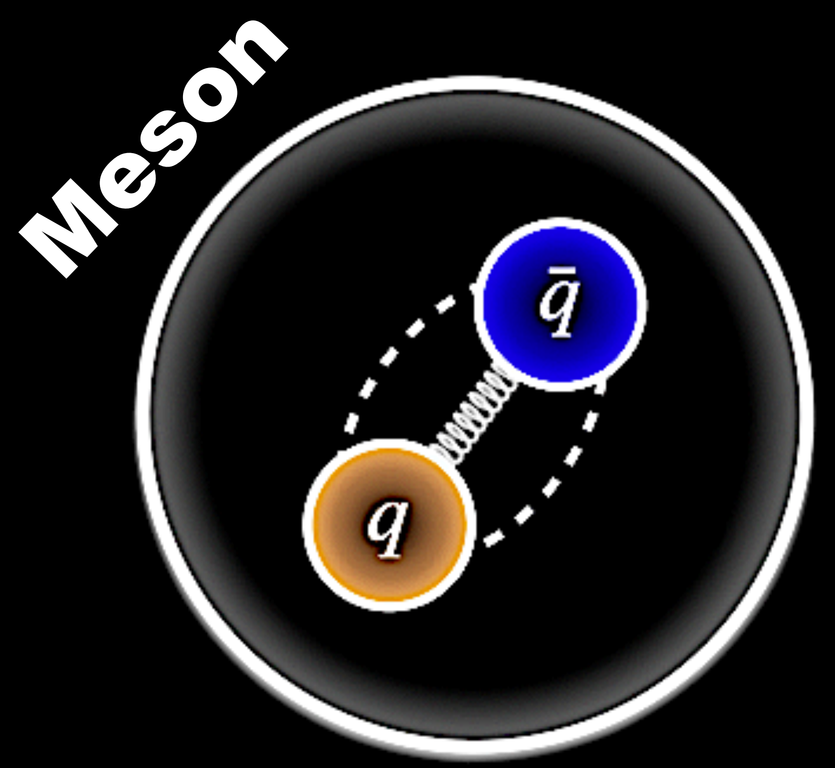


Lattice QCD predicts the existence of mesons with explicit *gluonic excitations* (states absent in the constituent quark model) commonly referred to as *spin-exotic hybrid mesons*

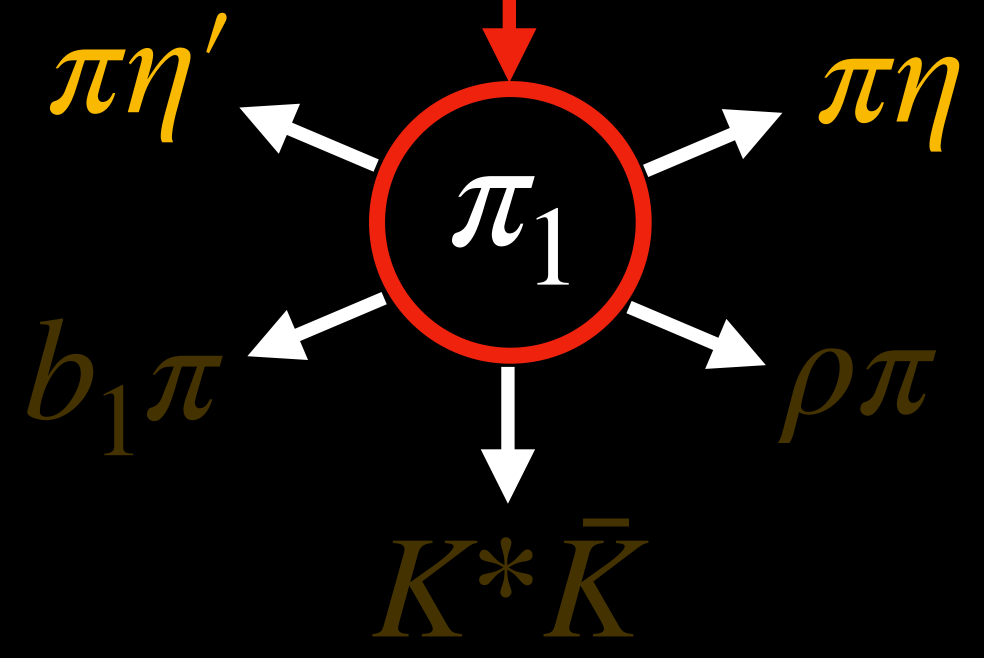
J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)





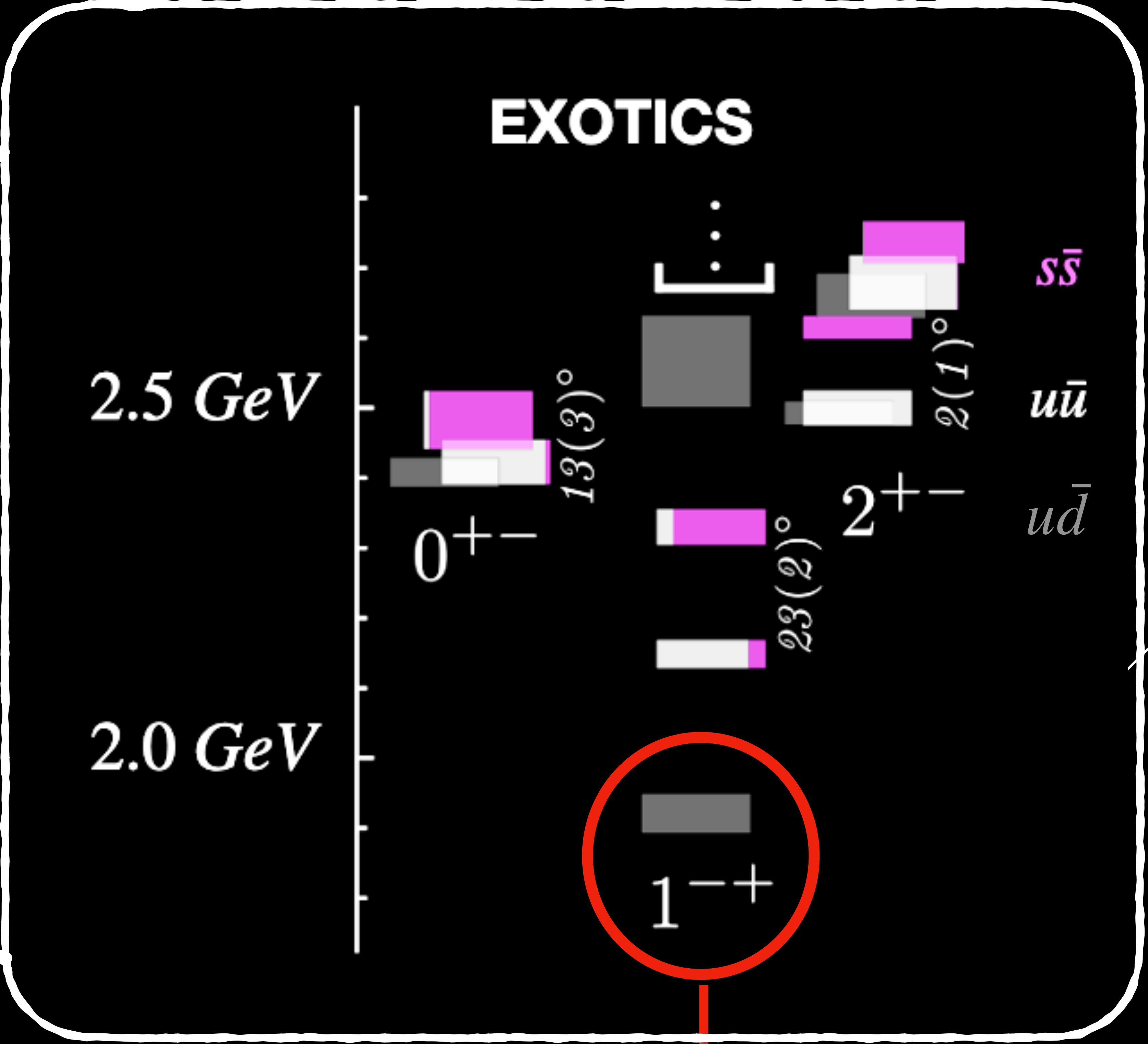


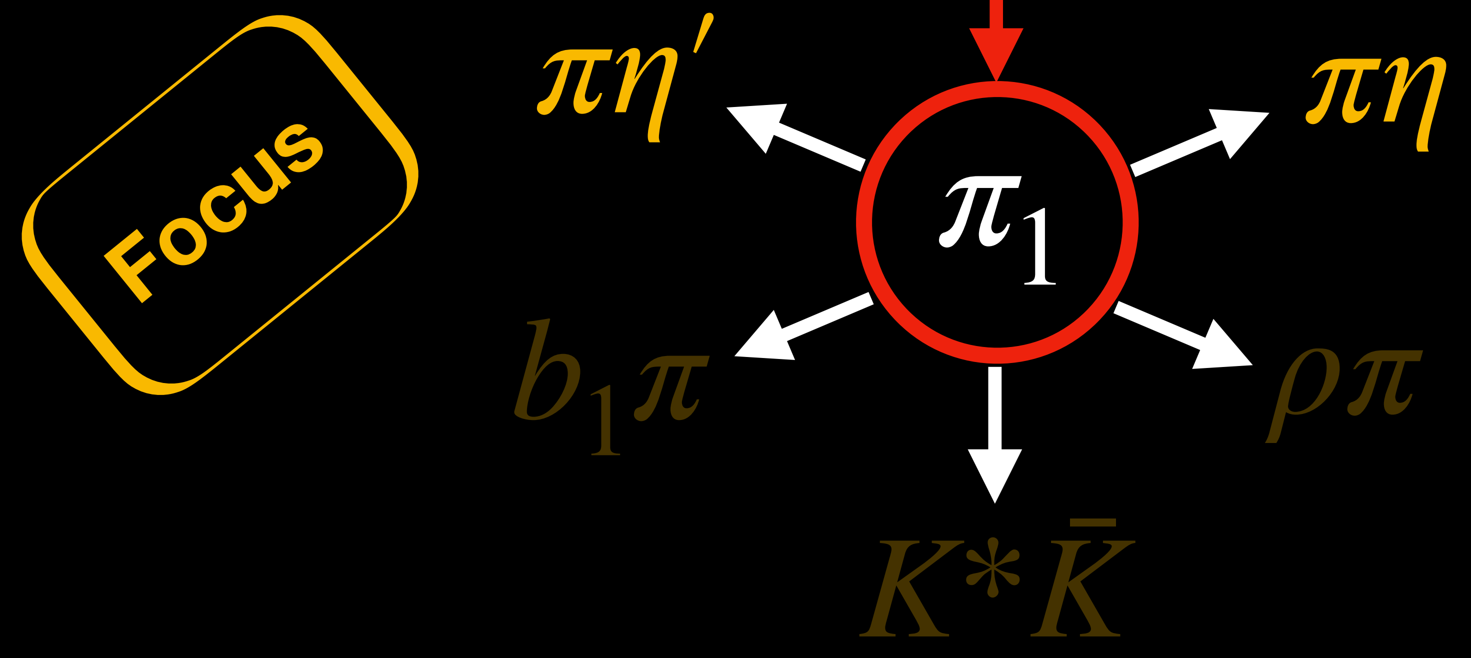
Focus



Lattice QCD predicts the existence of mesons with explicit *gluonic excitations* (states absent in the constituent quark model) commonly referred to as ***spin-exotic hybrid mesons***

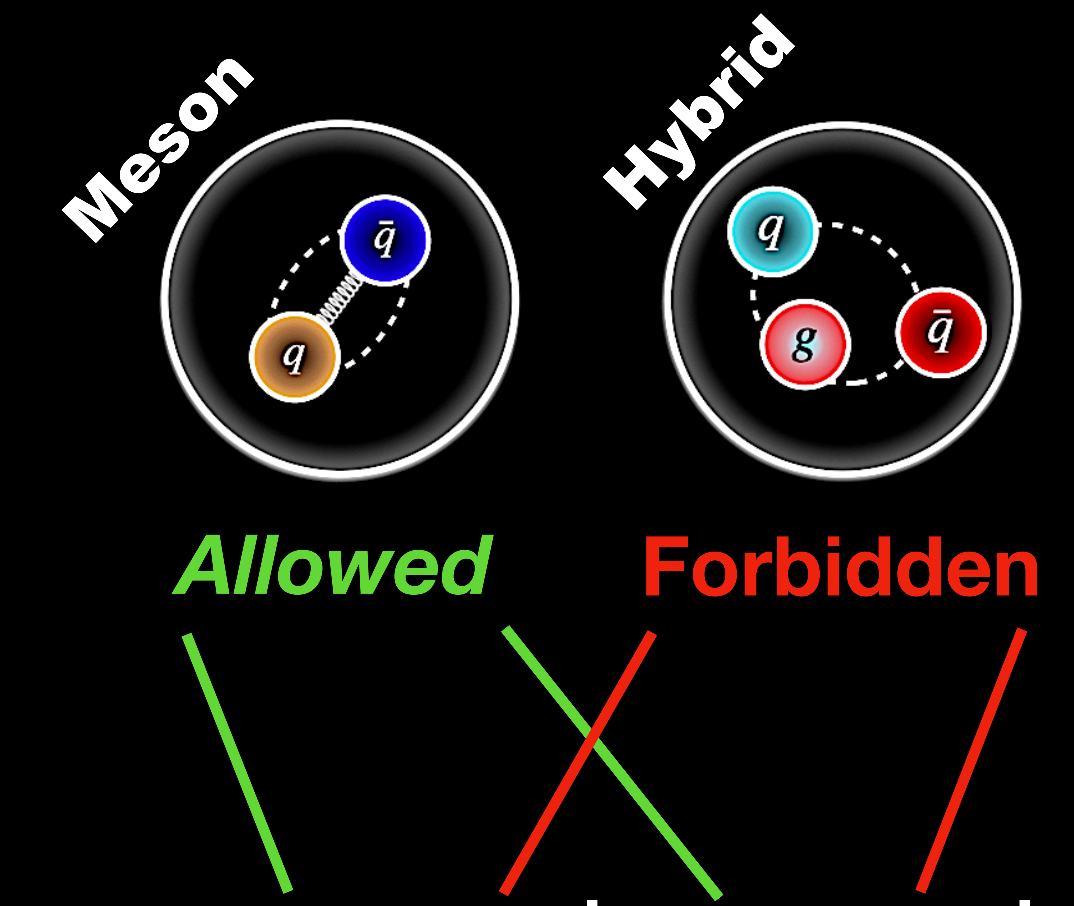
J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)



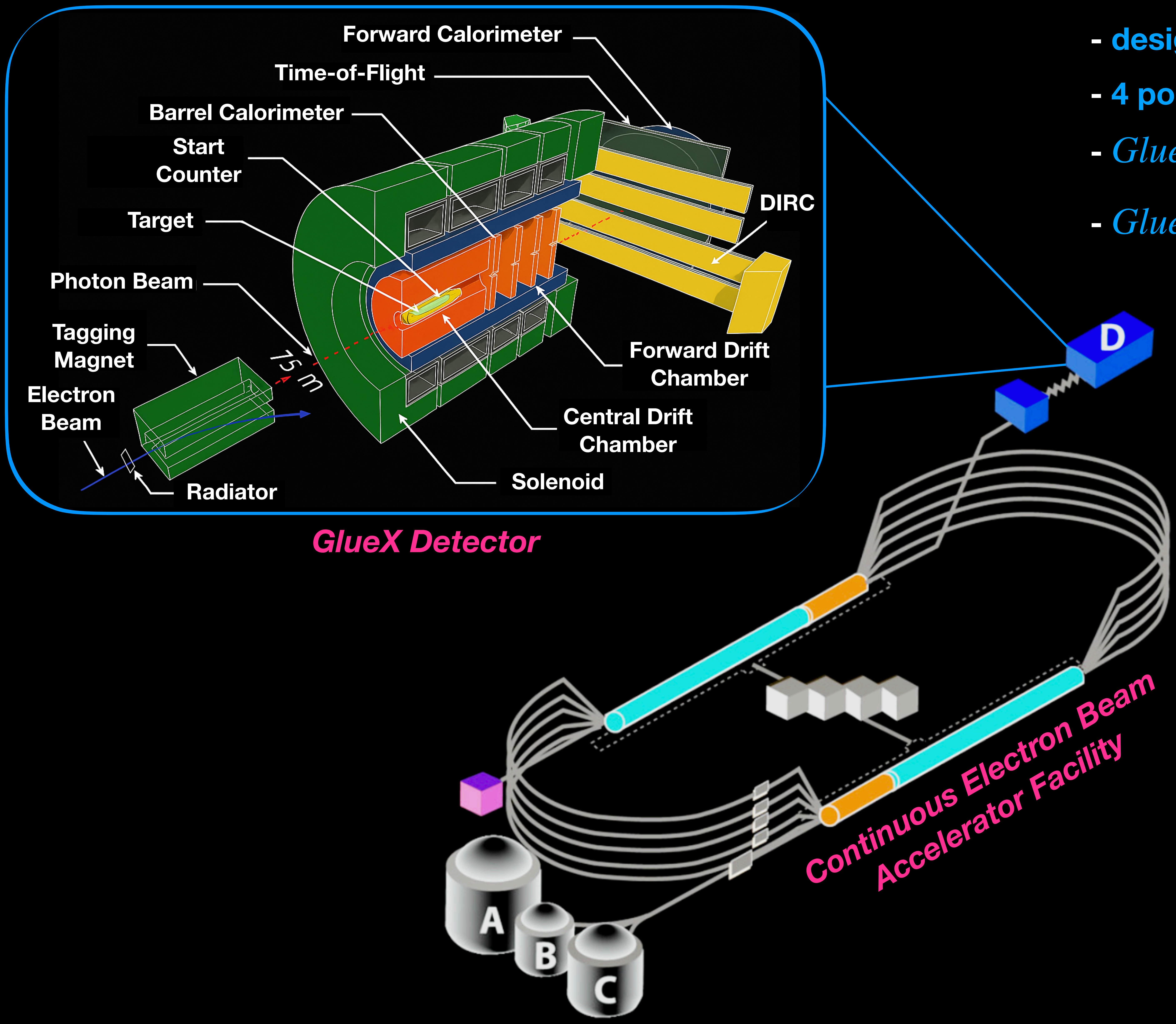


The $\eta\pi$ and $\eta'\pi$ channels are ideal for searches of spin-exotic hybrids

- only odd-L waves in $\eta^{(\prime)}\pi$ provide access to exotic quantum numbers
- simplistic 2-body final states
- historically, consistent observations of exotic resonances signal observed



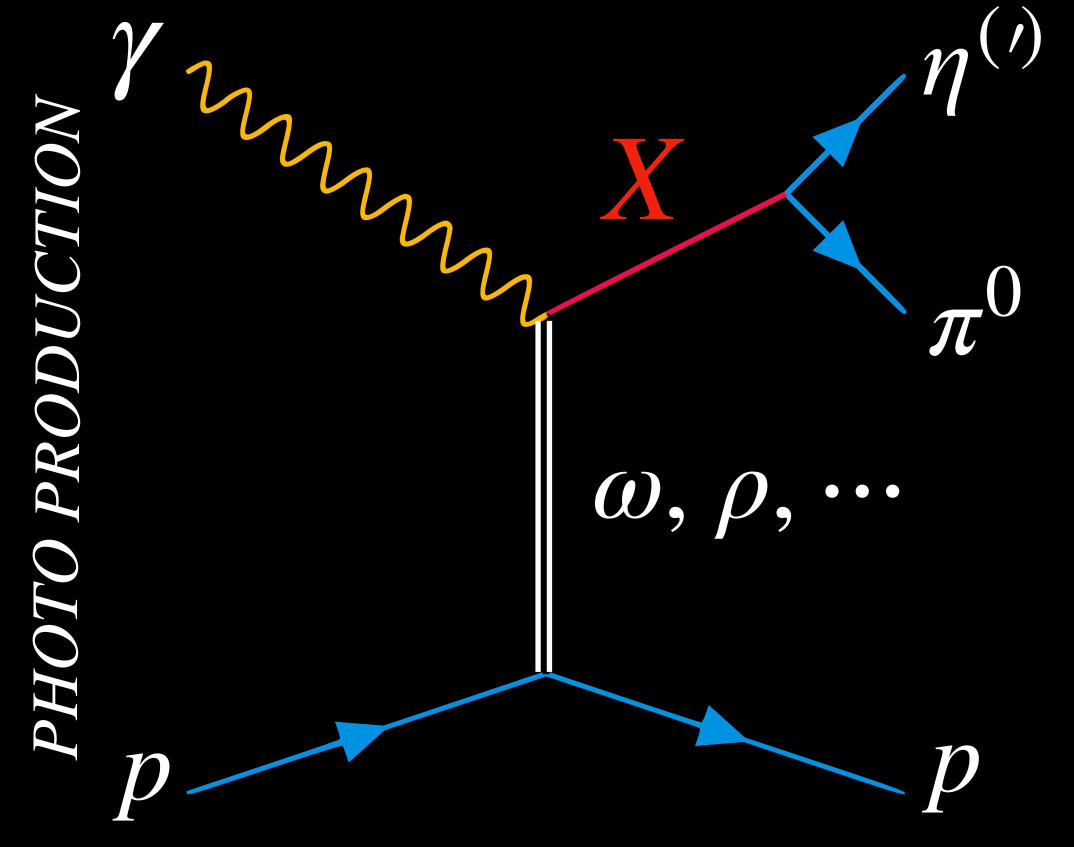
L	S	P	D	F	…
J^{PC}	0^{++}	1^{-+}	2^{++}	3^{-+}	…



- designed to reconstruct final state particles from $\gamma p \rightarrow pM$
- 4 polarization orientations
- *GlueX-I* collected $\int L = 125\ pb^{-1}$ in *coherent peak*
- *GlueX-II* ~ 3-4 times more (currently ongoing)

Photoproduction $\Rightarrow$ *extremely* versatile

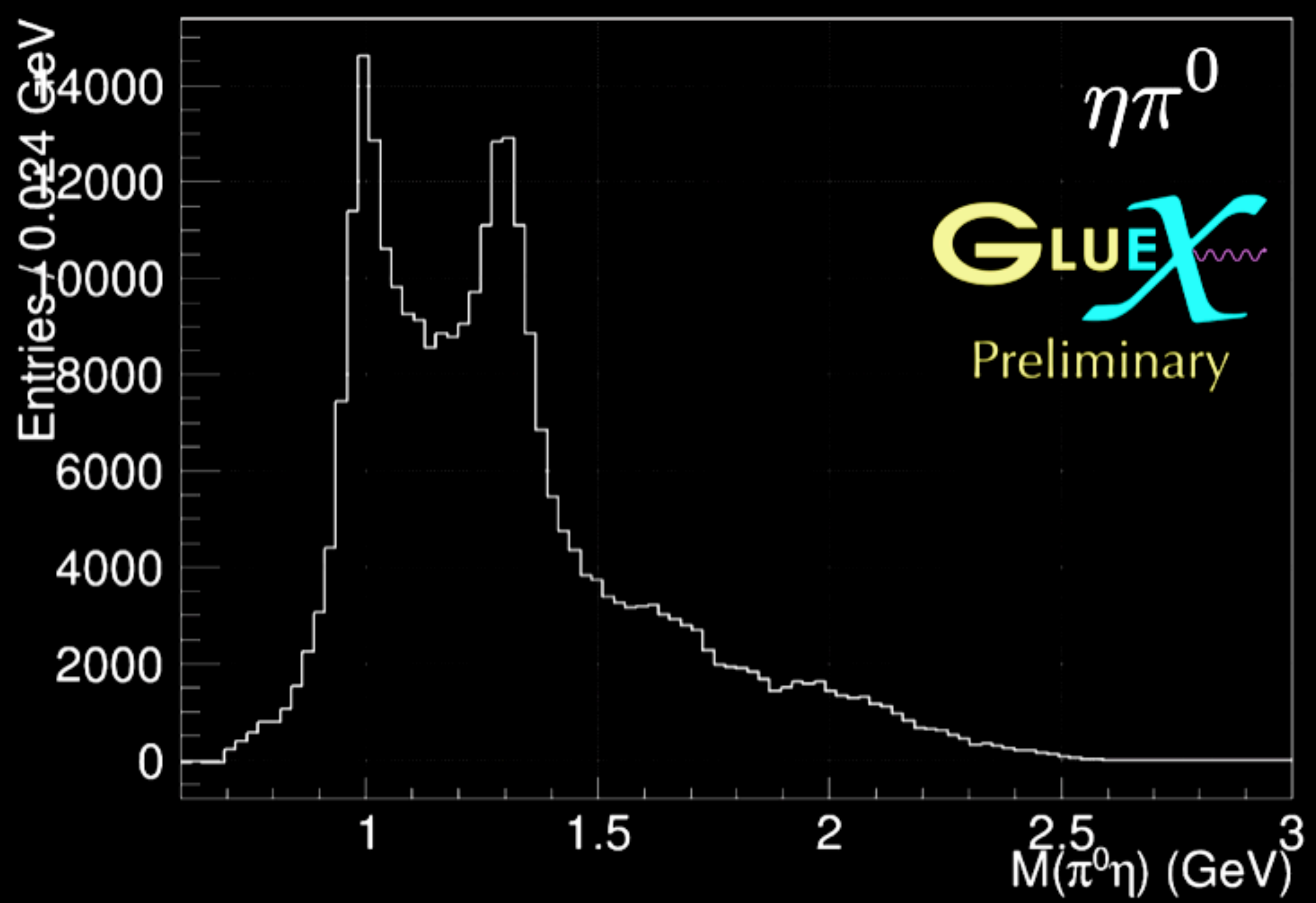
- access to large range of resonances
- complementary to hadroproduction (COMPASS, etc.)



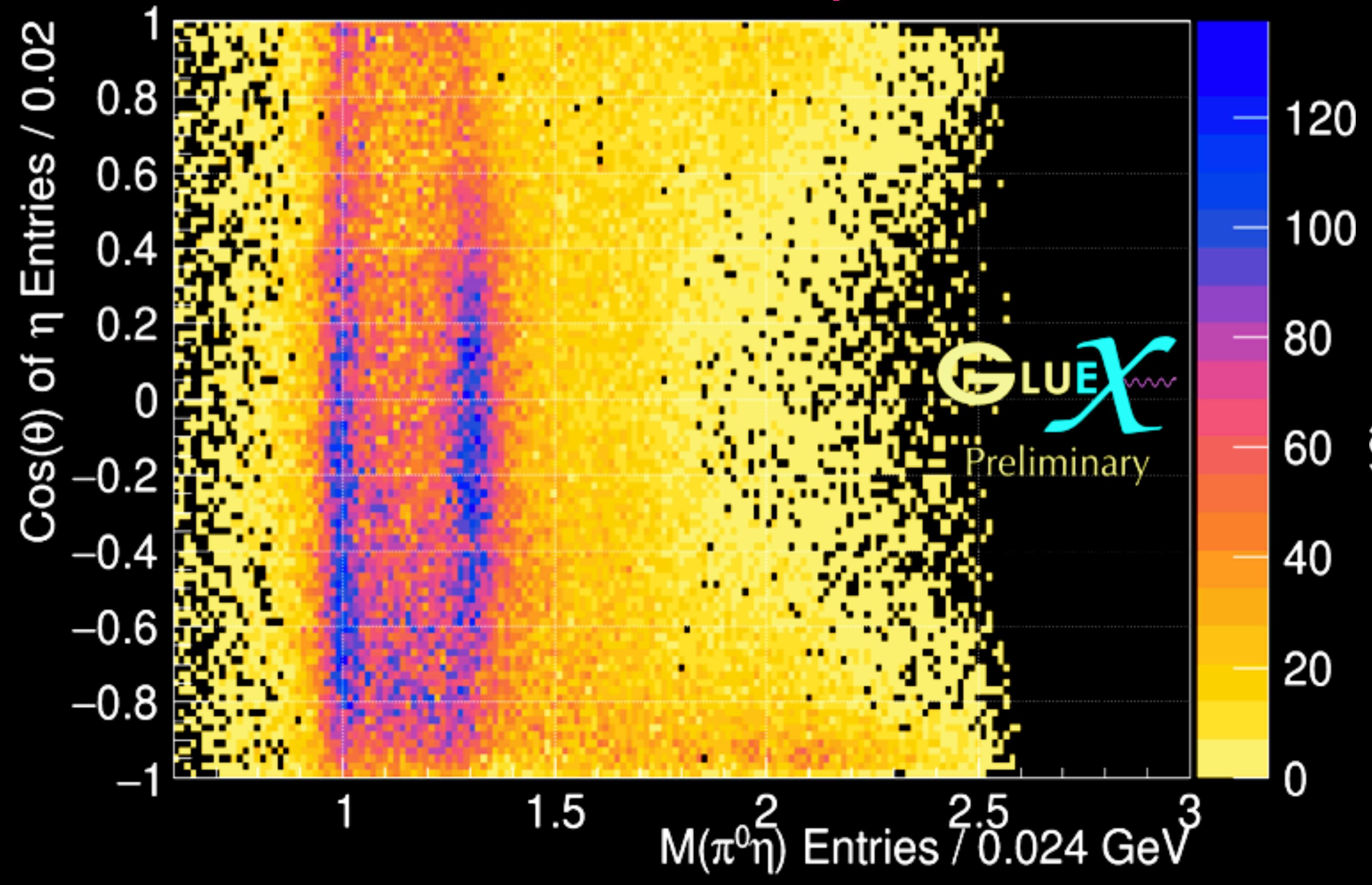
Start simple to understand production of less complex hadrons

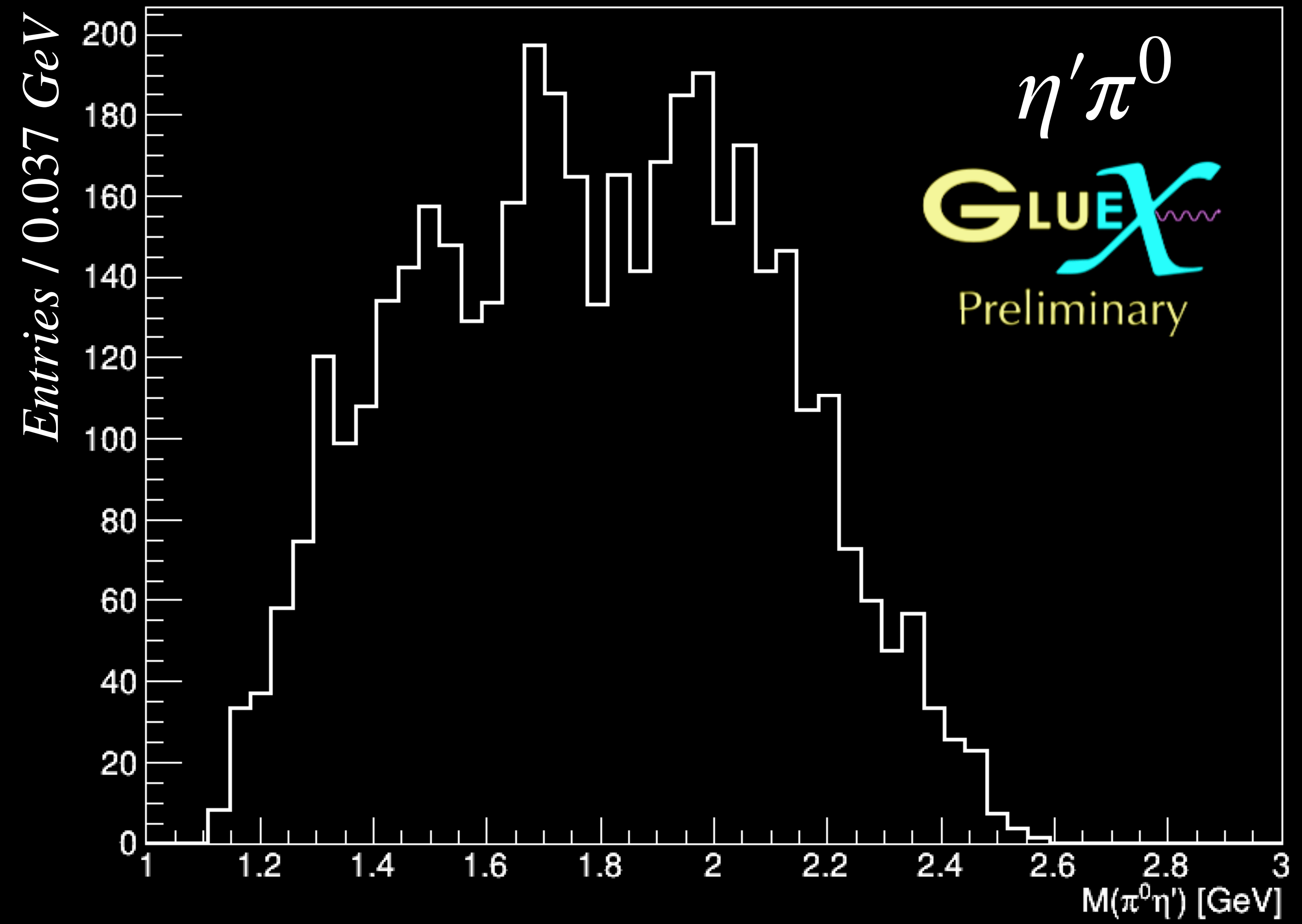
- study background, acceptance, non-resonant contributions, etc.

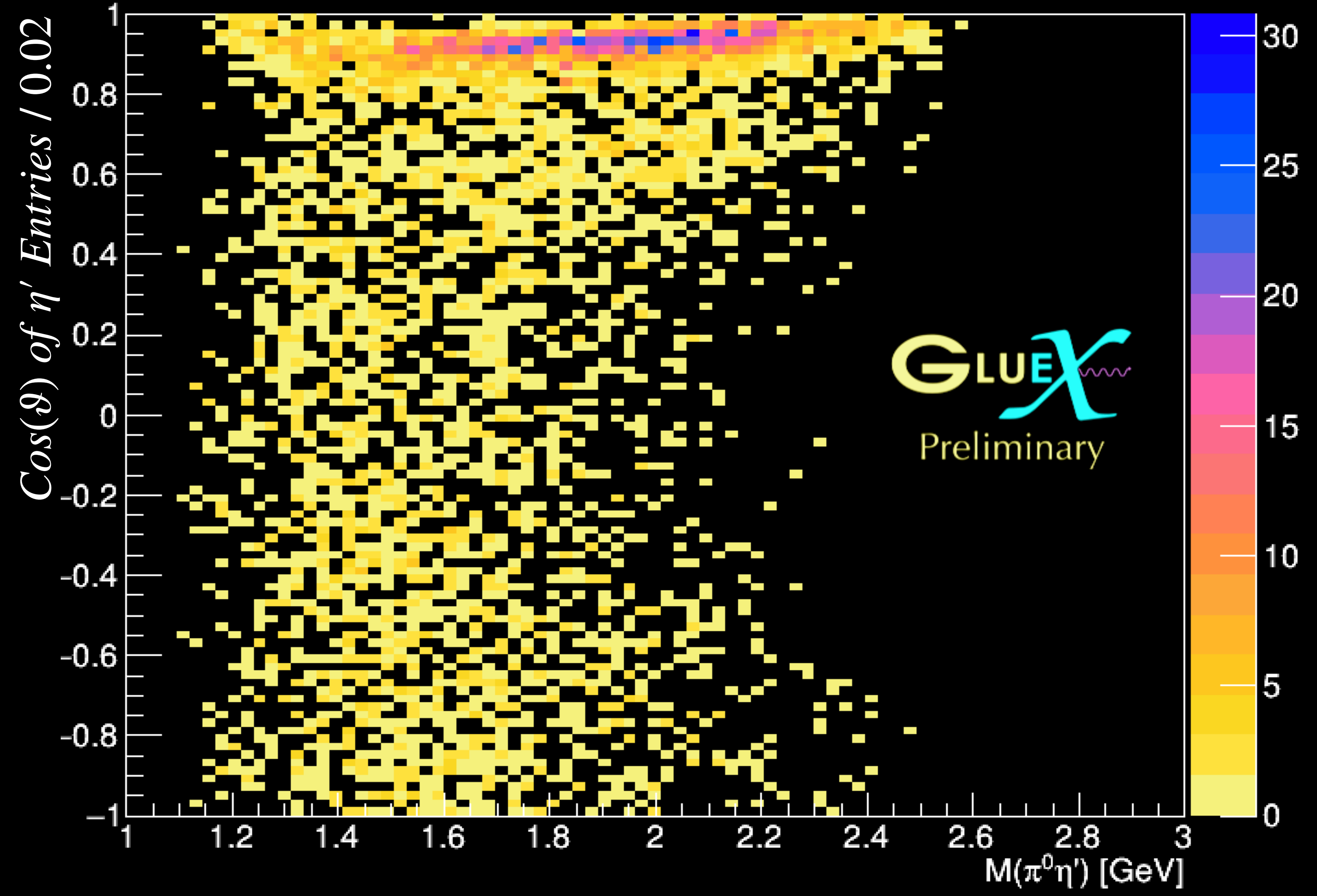
$0.1 < -t\ [GeV^2] < 0.3$



Not acceptance corrected

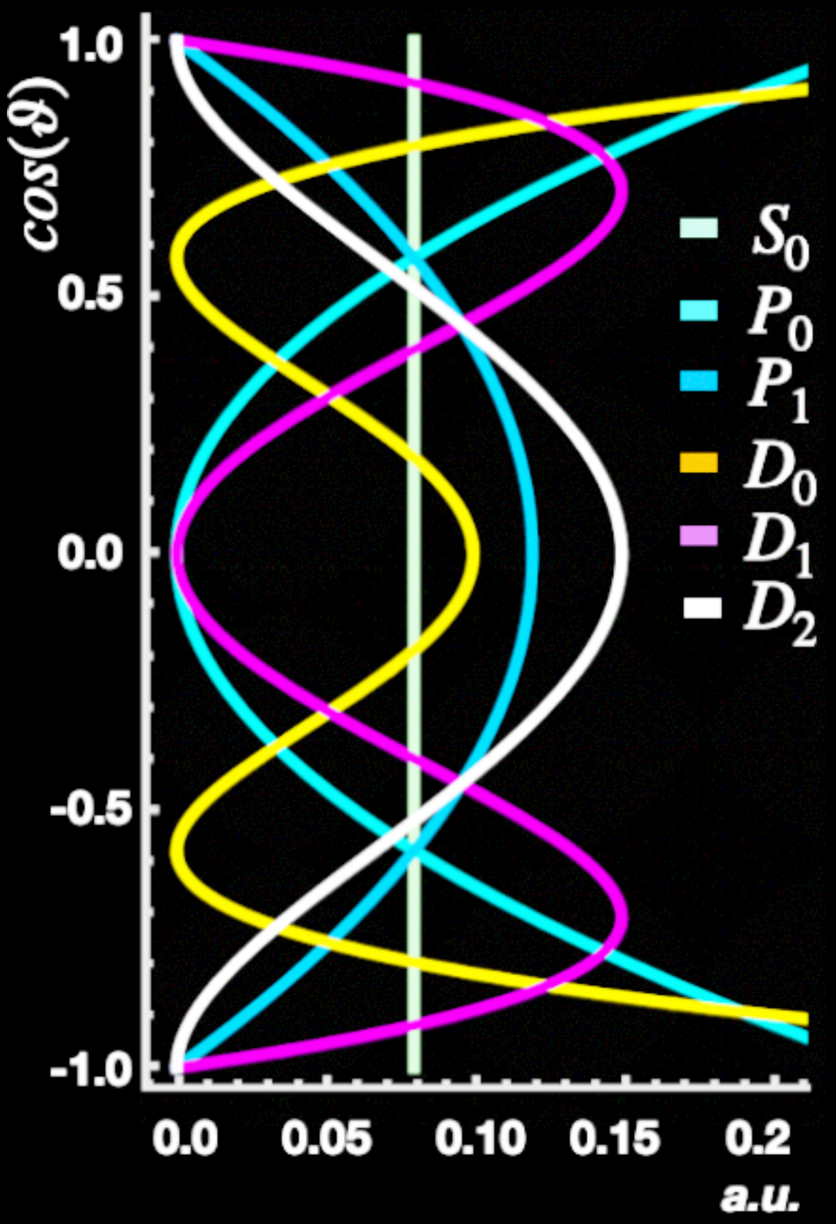






Neutral decay modes

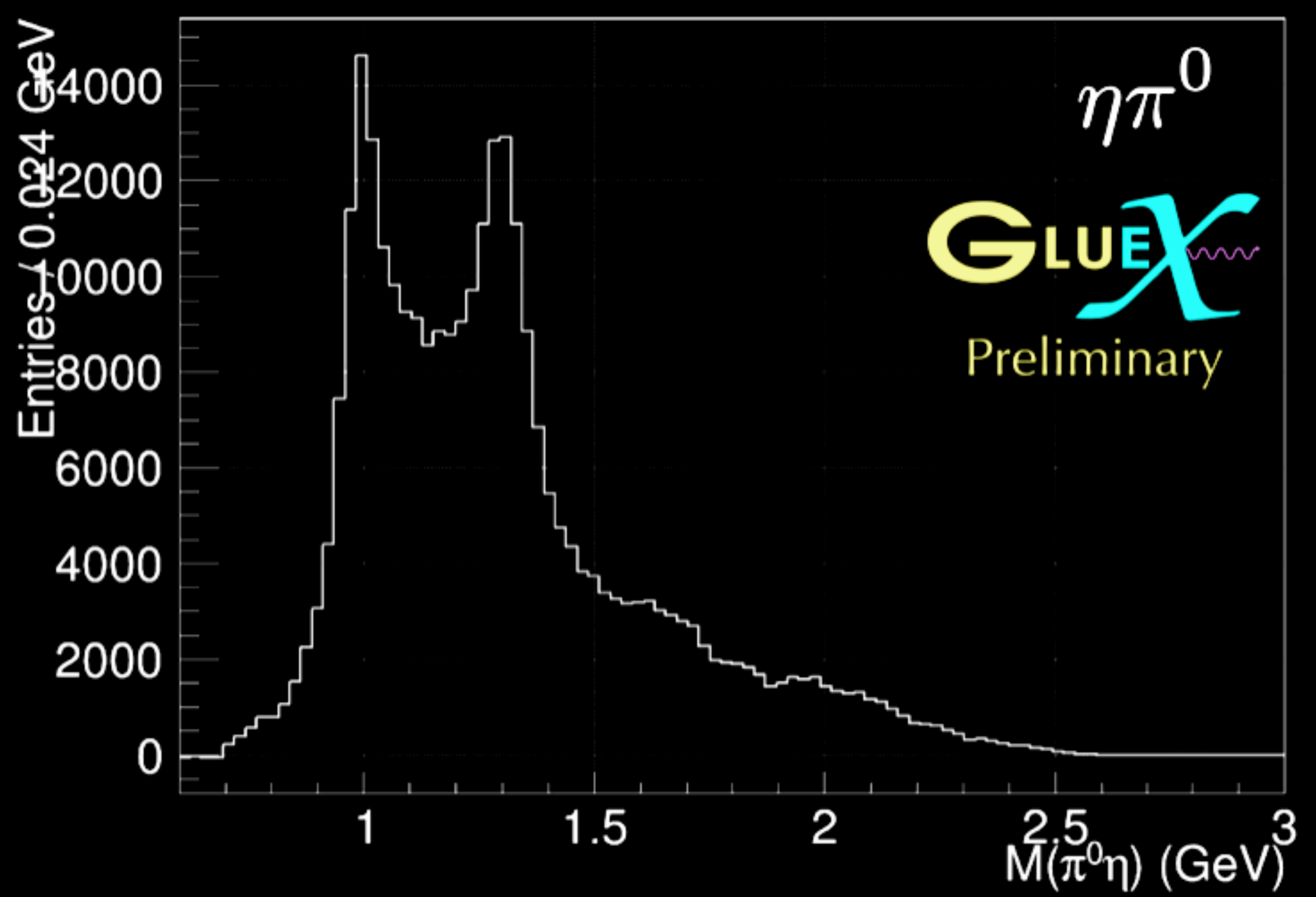
- $\eta\pi^0 \rightarrow 4\gamma$
- $\eta'\pi^0 \rightarrow 4\gamma\pi^+\pi^-$



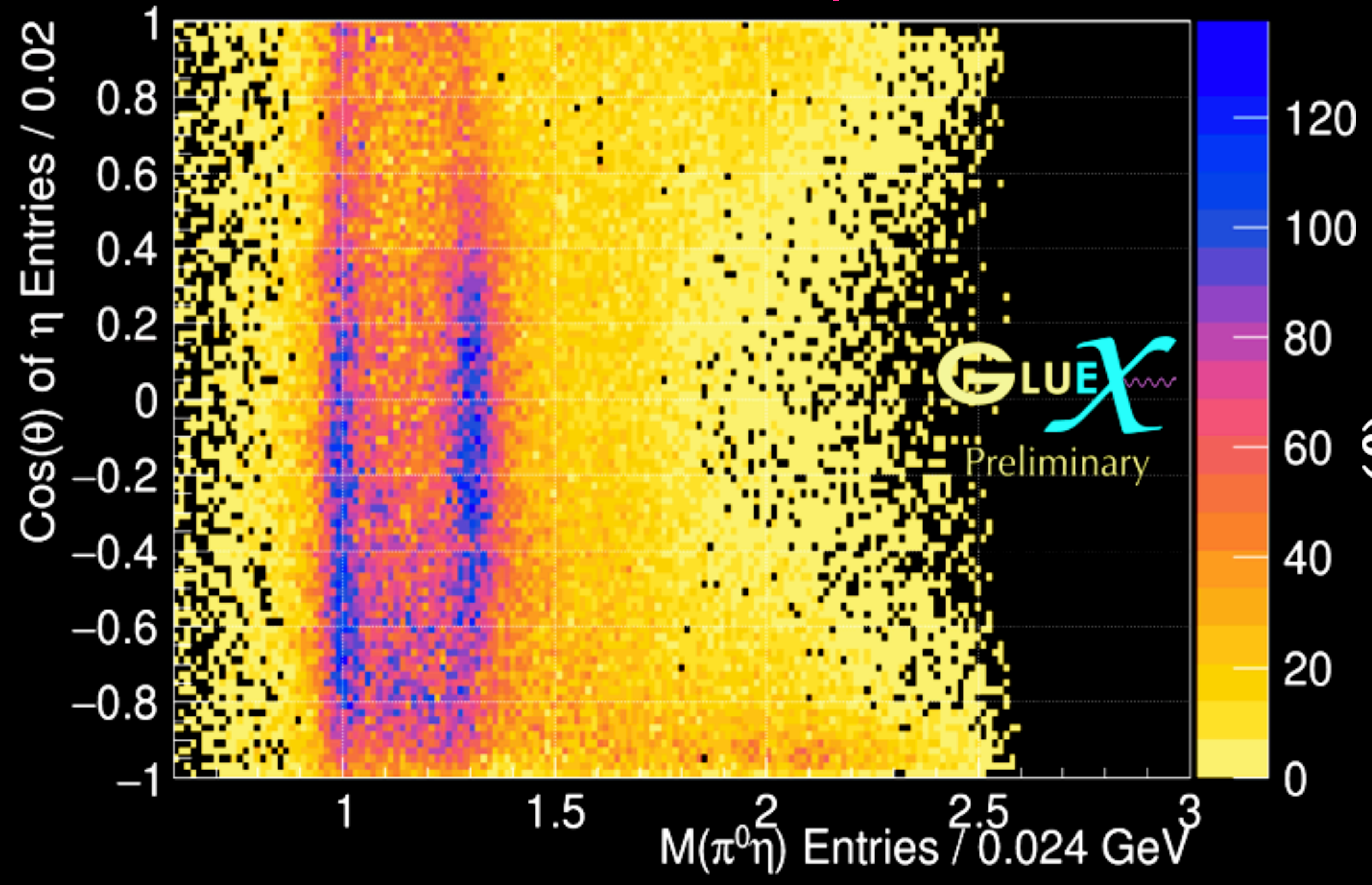
Charged decay modes also being analyzed ...

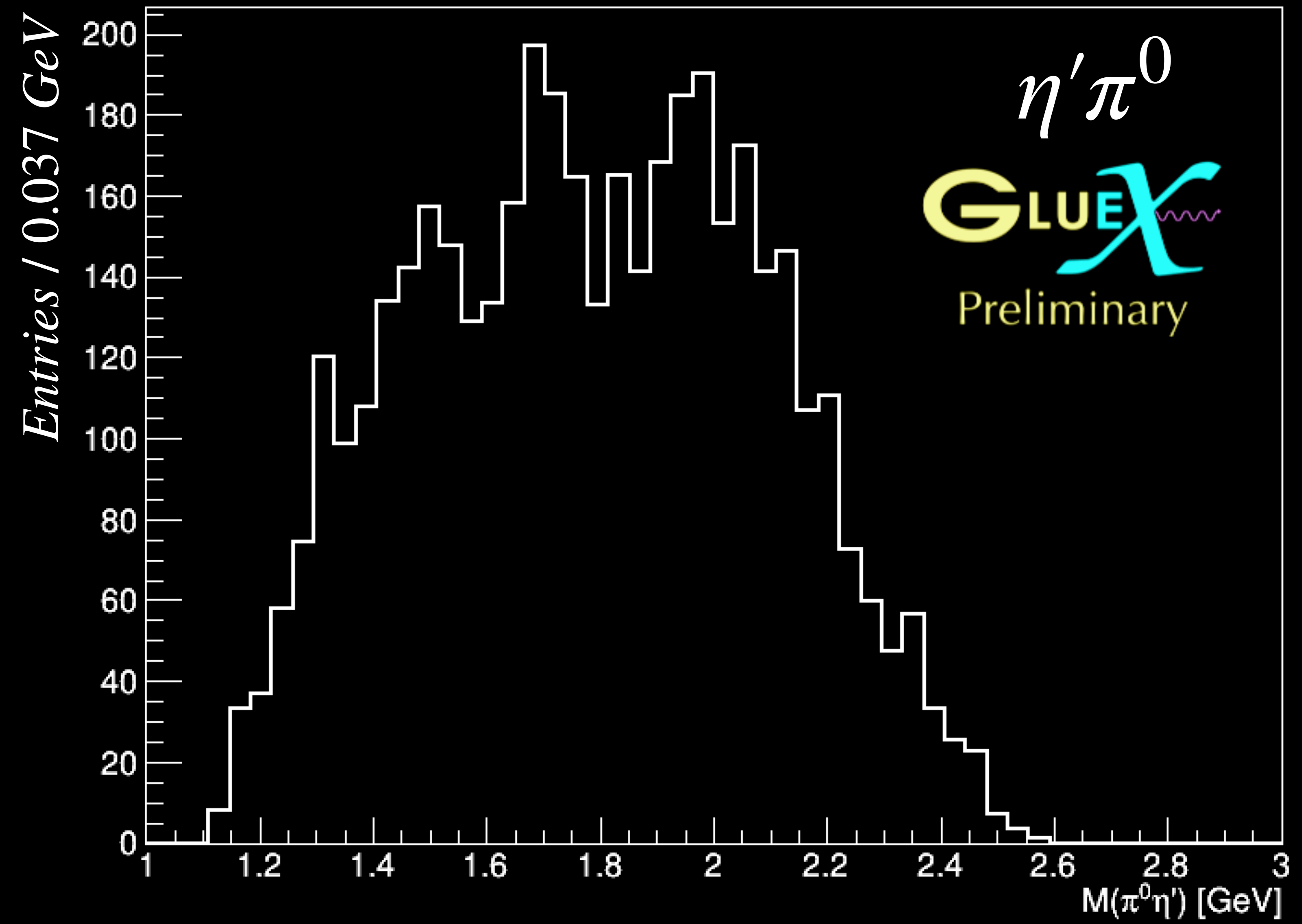
- $\eta^{(\prime)}\pi^-\Delta^{++}$ | $\Delta^{++} \rightarrow \pi^+ p$, $\eta' \rightarrow \eta\pi^+\pi^-$

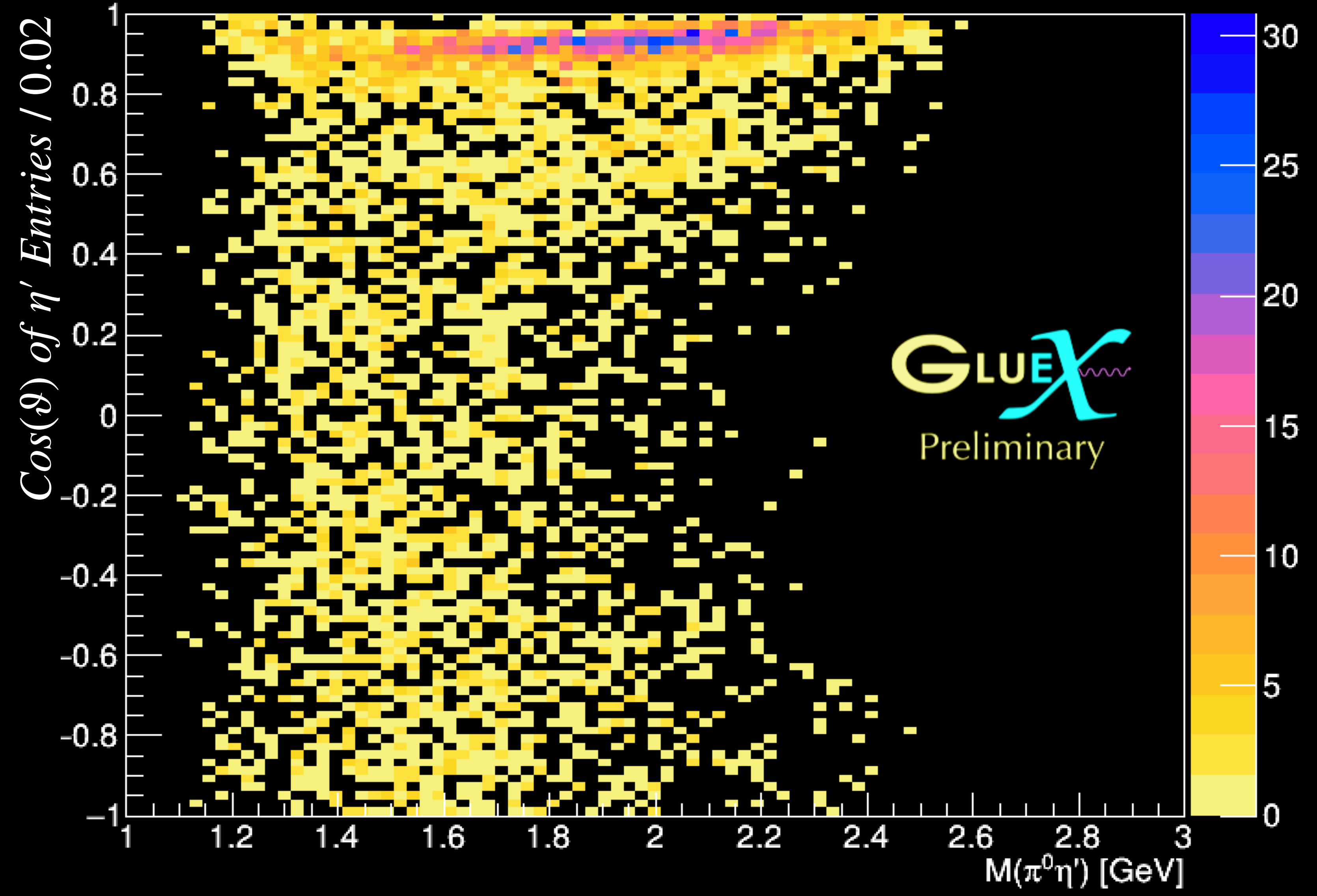
$0.1 < -t\ [GeV^2] < 0.3$



Not acceptance corrected

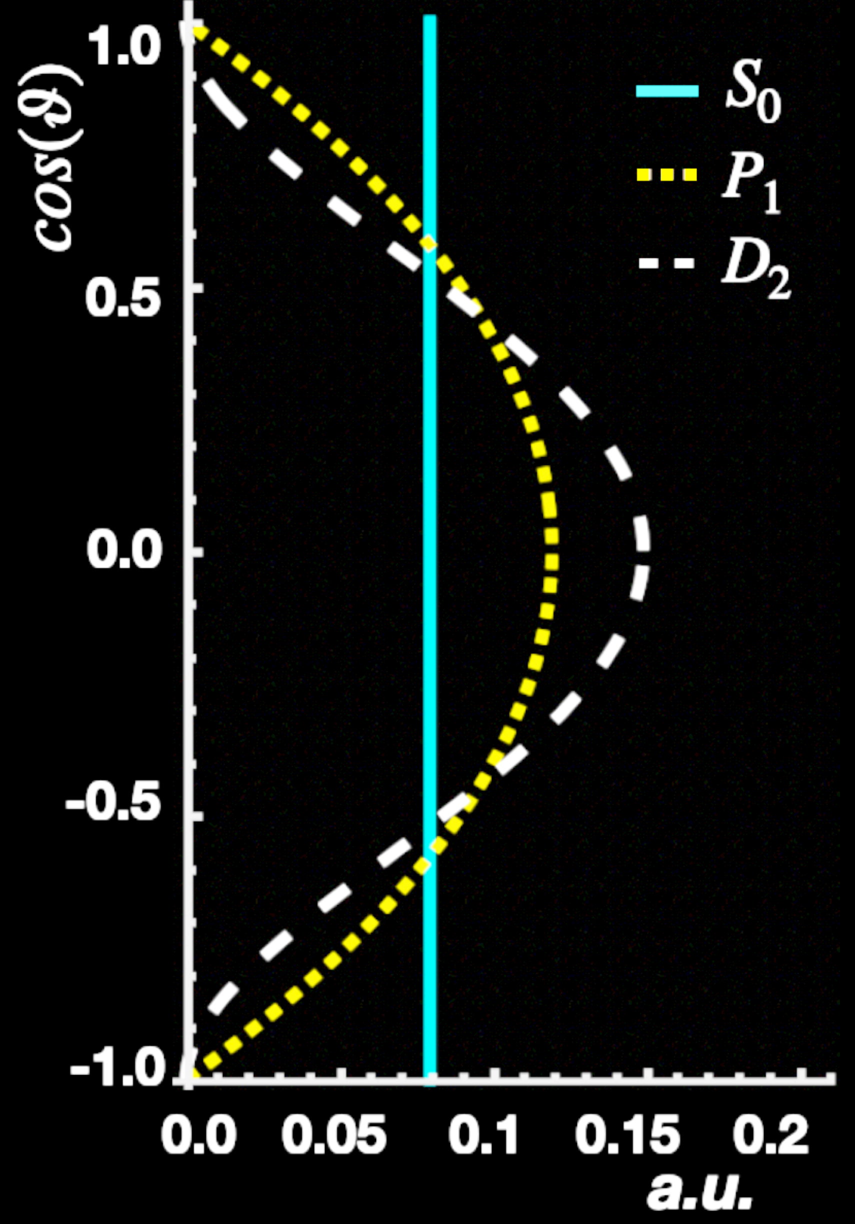






Neutral decay modes

- $\eta\pi^0 \rightarrow 4\gamma$
- $\eta'\pi^0 \rightarrow 4\gamma\pi^+\pi^-$



Dominant S_0 and D_2 contributions observed

Assume $a_2(1320)$ and $a_2(1700)$ are text book Breit-Wigner resonances

- share only 1 common phase parameter for each in the D_{waves}

S_{wave} contributions more complicated

- define *mass independent* piecewise parameterization

Individual fit results across -t

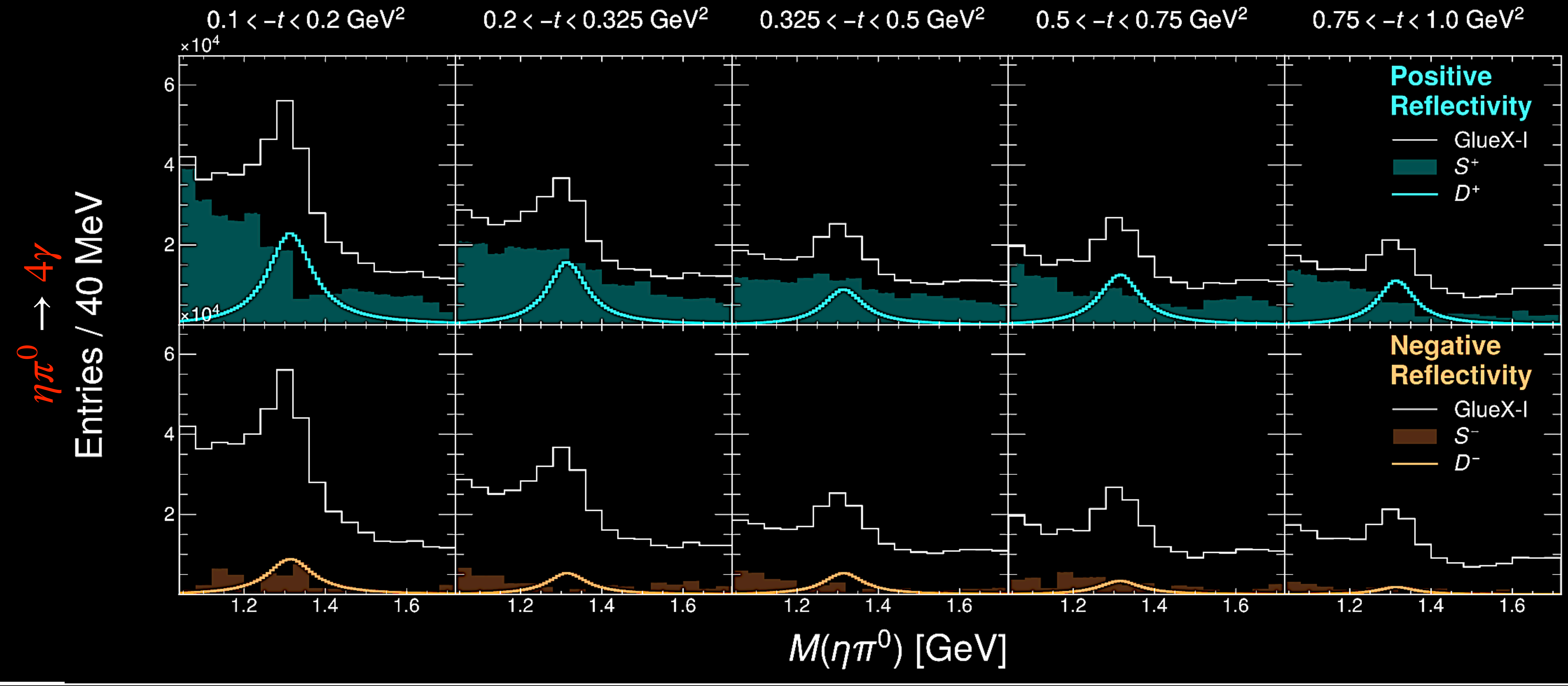
- coherent sums of (+) and (-) reflectivities
- + / - reflectivity → natural / unnatural

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

Why ?

Dominant contribution in the $\eta\pi^0$ channel

- reasonably isolated
- limited P_{Wave} contribution predicted
- use as reference for search of exotic π_1 in $\eta'\pi$



F. Afzal et al. [GlueX Collab], Phys. Rev. C 112, 015204 (2025)

Assume $a_2(1320)$ and $a_2(1700)$ are text book Breit-Wigner resonances

- share only 1 common phase parameter for each in the D_{waves}

S_{wave} contributions more complicated

- define *mass independent* piecewise parameterization

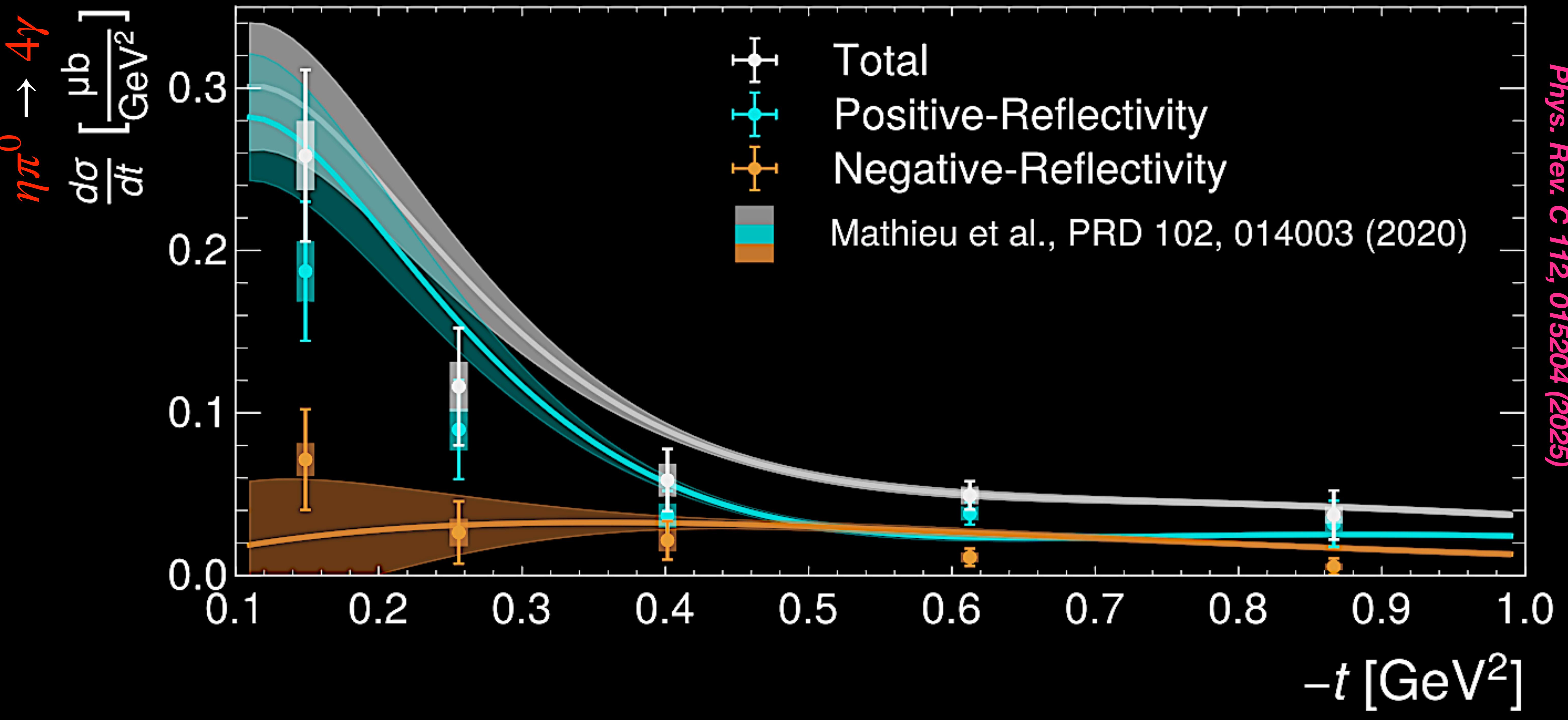
Individual fit results across -t

- coherent sums of (+) and (-) reflectivities
- + / - reflectivity → natural / unnatural

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

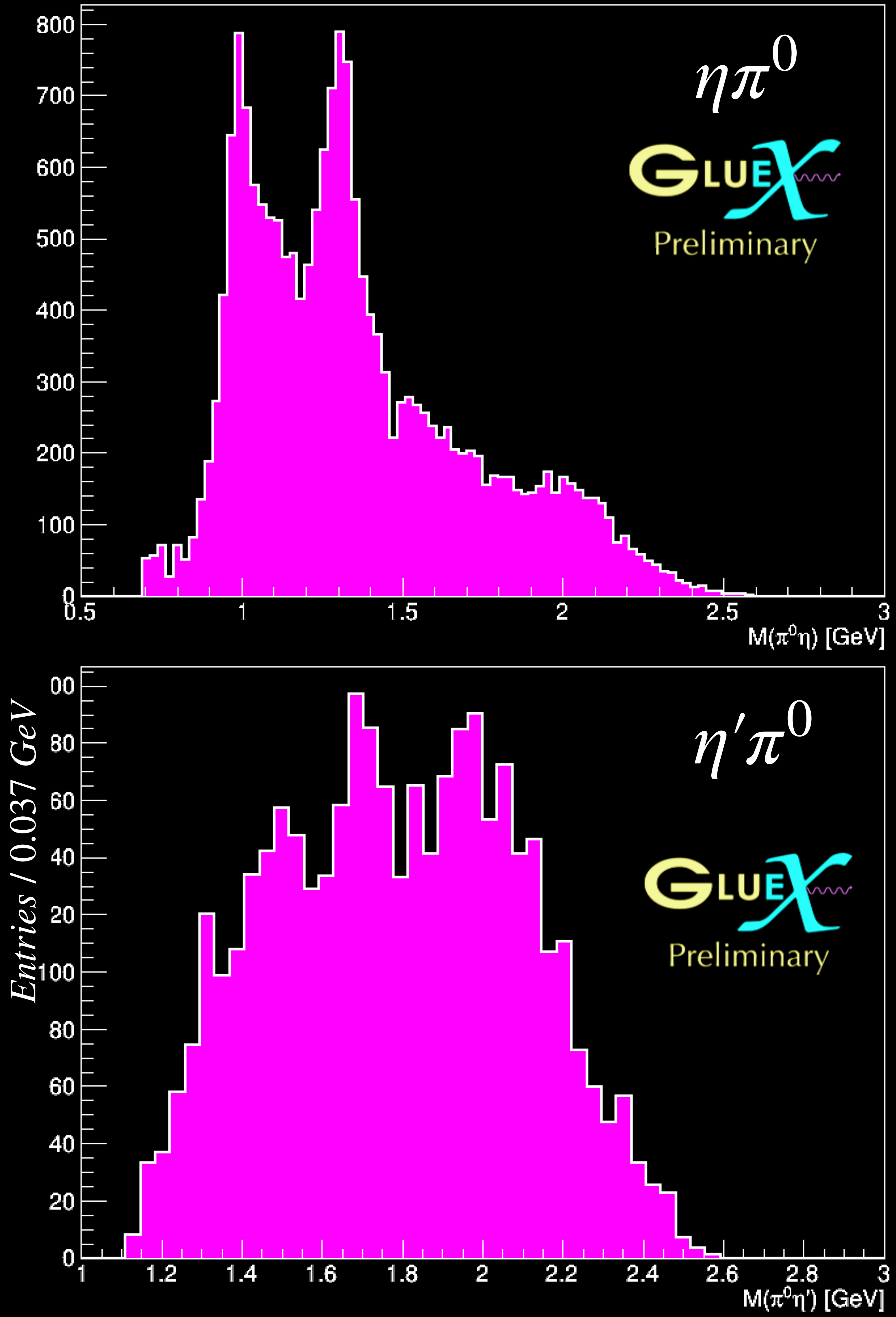
Decent agreement between JPAC predictions !

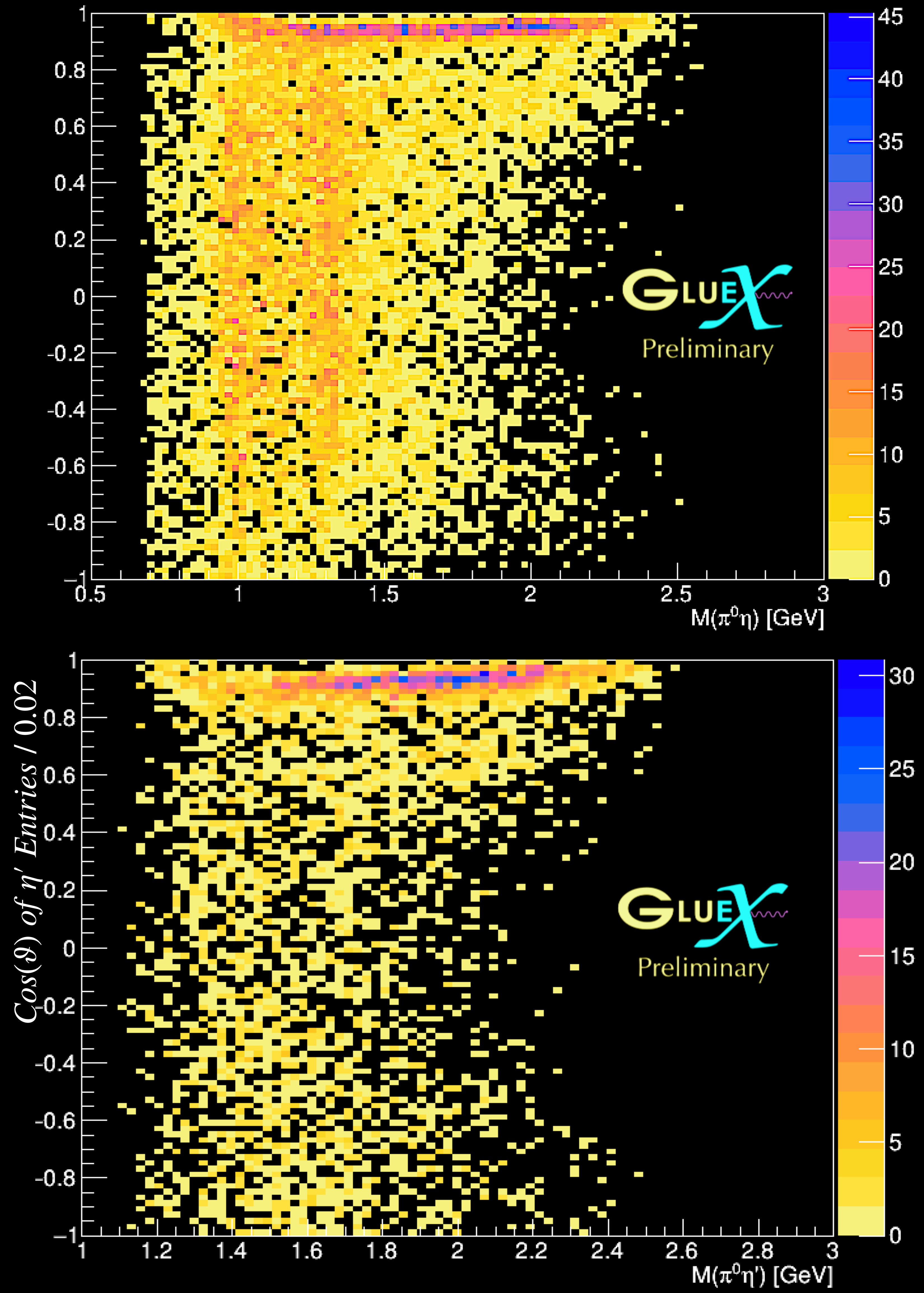
- the first measurement of the $a_2(1320)$ polarized photoproduction cross section



F. Afzal et al. [GlueX Collab], Phys. Rev. C 112, 015204 (2025)

$0.1 < -t\ [GeV^2] < 0.3$

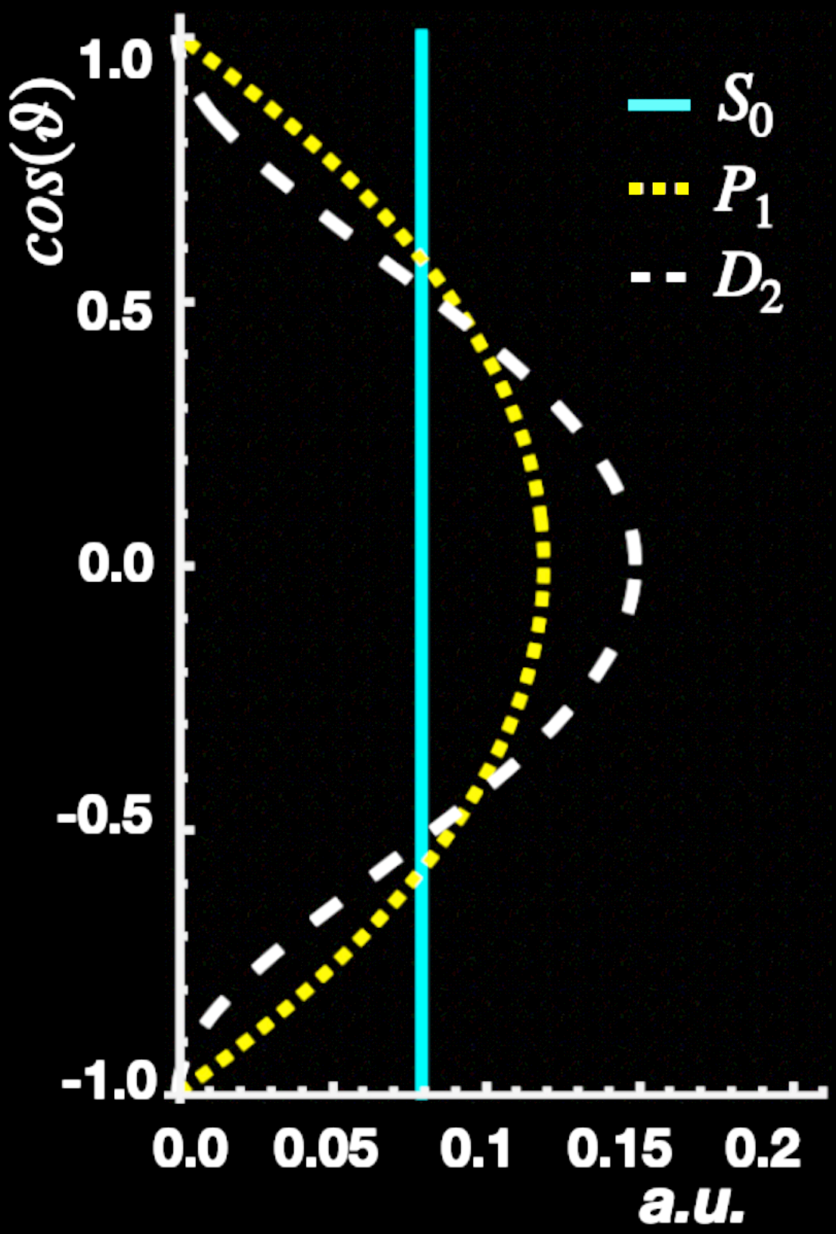




Neutral decay modes

- $\eta\pi^0 \rightarrow 4\gamma\pi^+\pi^-$
- $\eta'\pi^0 \rightarrow 4\gamma\pi^+\pi^-$

Same final state



Analyzing a different final state for the same channel

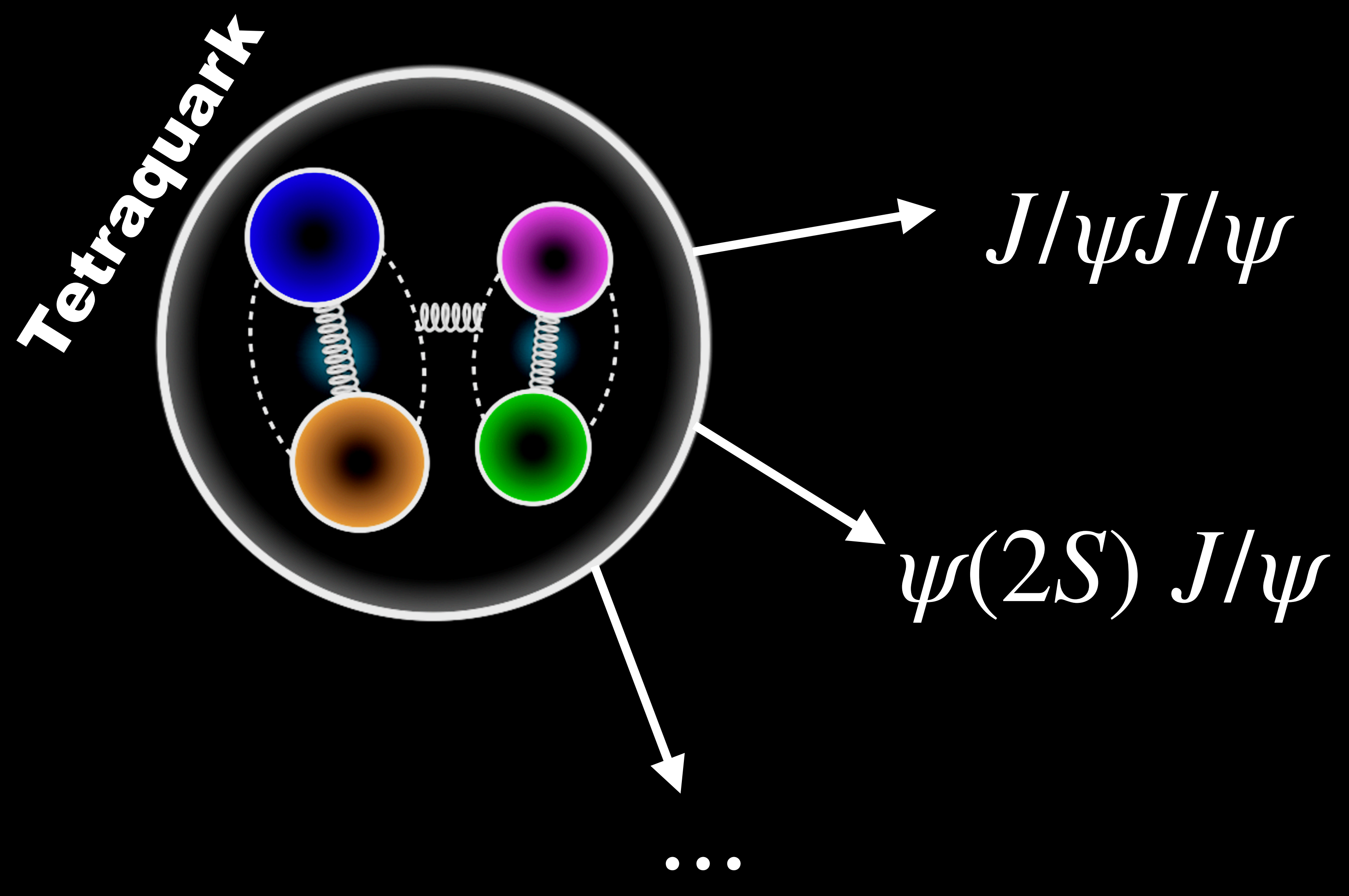
- cross-validation
- completeness of amplitude solutions
- channel dependent backgrounds

Nature of strong interactions:

- governed by non-perturbative QCD
- allows resonance formation and decay across multiple channels

Motivation from experimental reality ⇒ LHCb

- each final state provides only partial access to the underlying pole structure



highly populated spectrums
=
overlapping & interfering resonances

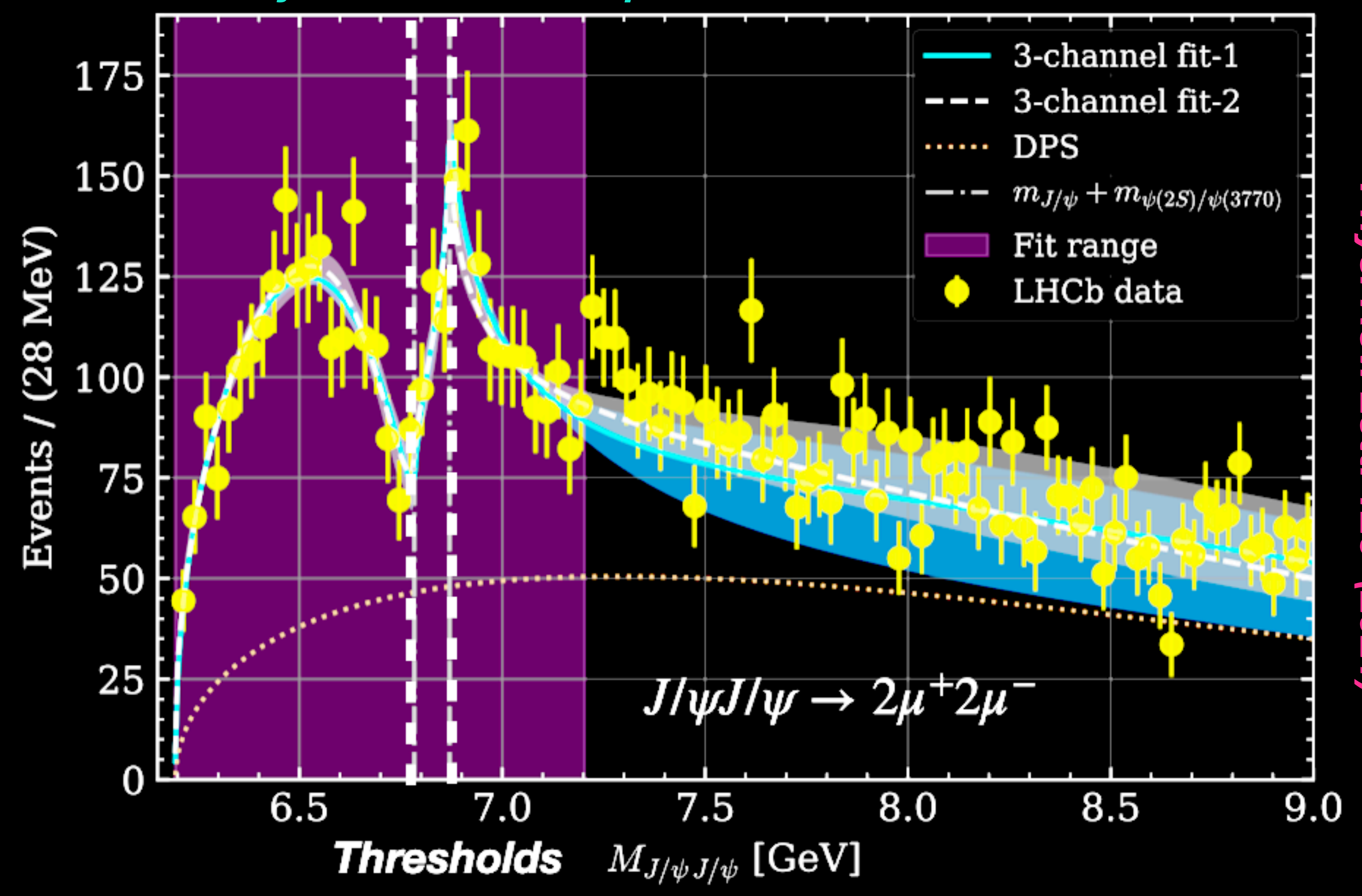
- resonances (peaks) not always appear as peaks (resonances)

Overall, single channel *analyses cannot fully disentangle complex interference or threshold behavior*

Pole structure is process-independent
(the resonance's nature is fixed)

∴ production and decay can shape the spectrum, but not the resonance itself

Theory Prediction Example



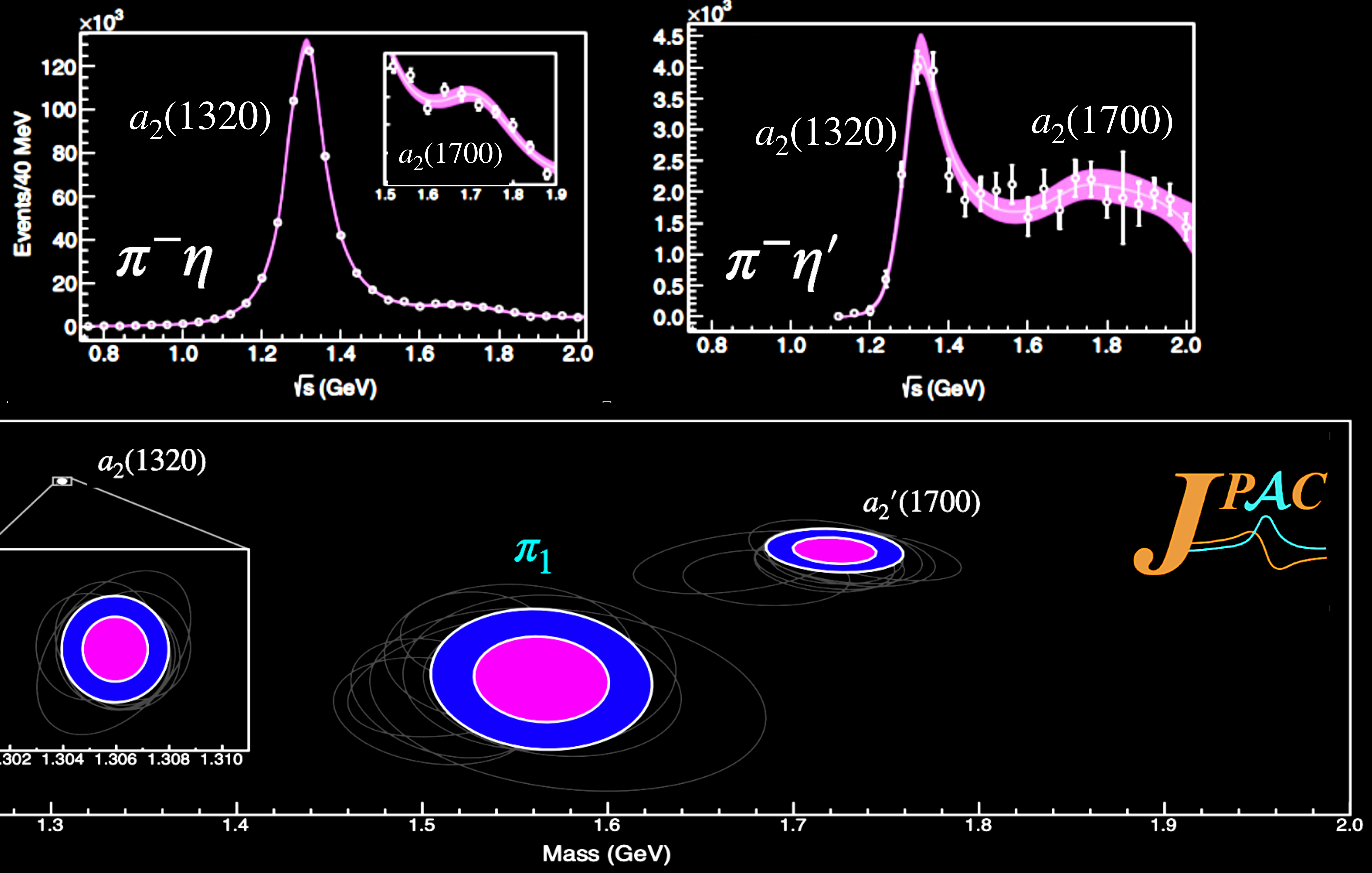
Xiang-Kun Dong et al., Phys. Rev. Lett. 126 (2021)

JPAC analysis utilizing COMPASS data

- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
- describes dominate a_2 resonances and the π_1

Modeled amplitudes using the analytic, unitary N/D formalism

- extraction of poles more rigorous than Breit-Wigner approach



A. Rodas et al.
[Joint Physics Analysis Center], PRL 122, 042002 (2019)

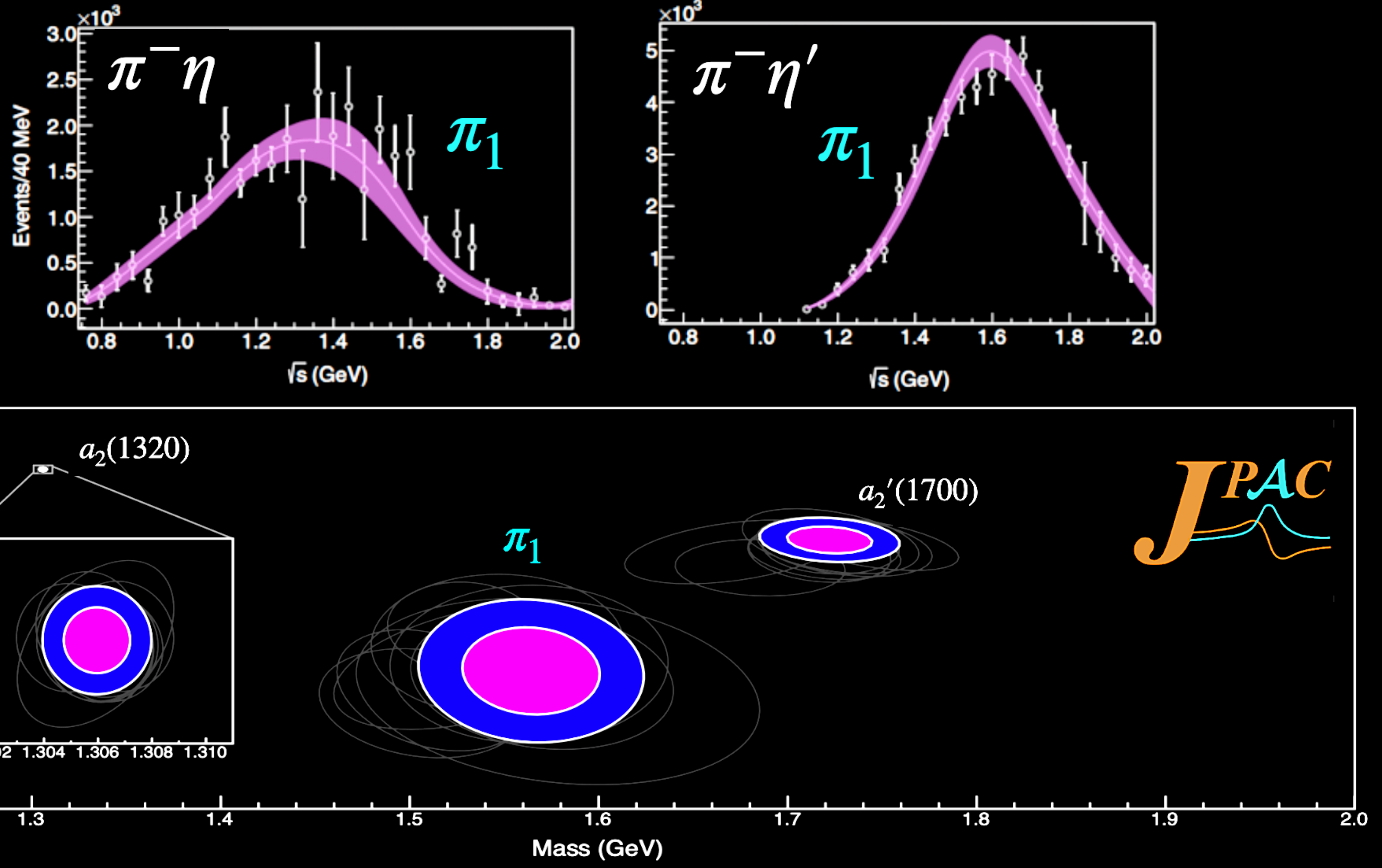
JPAC analysis utilizing COMPASS data

- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
- describes dominate a_2 resonances and the π_1

Modeled amplitudes using the analytic, unitary N/D formalism

- extraction of poles more rigorous than Breit-Wigner approach

A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

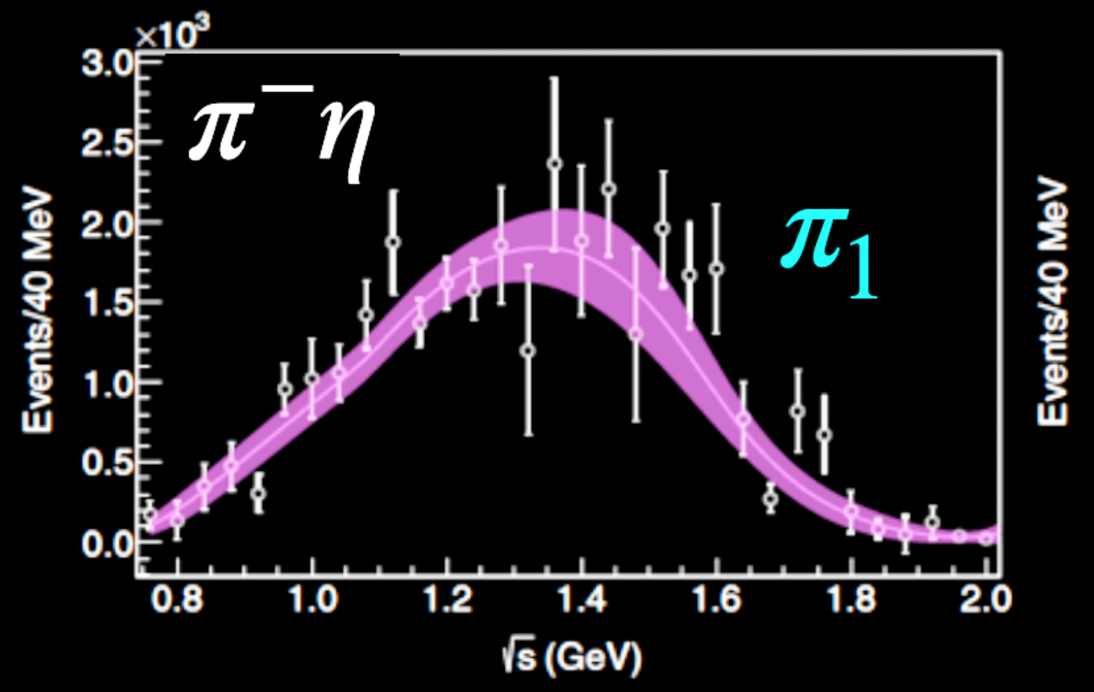


JPAC analysis utilizing COMPASS data

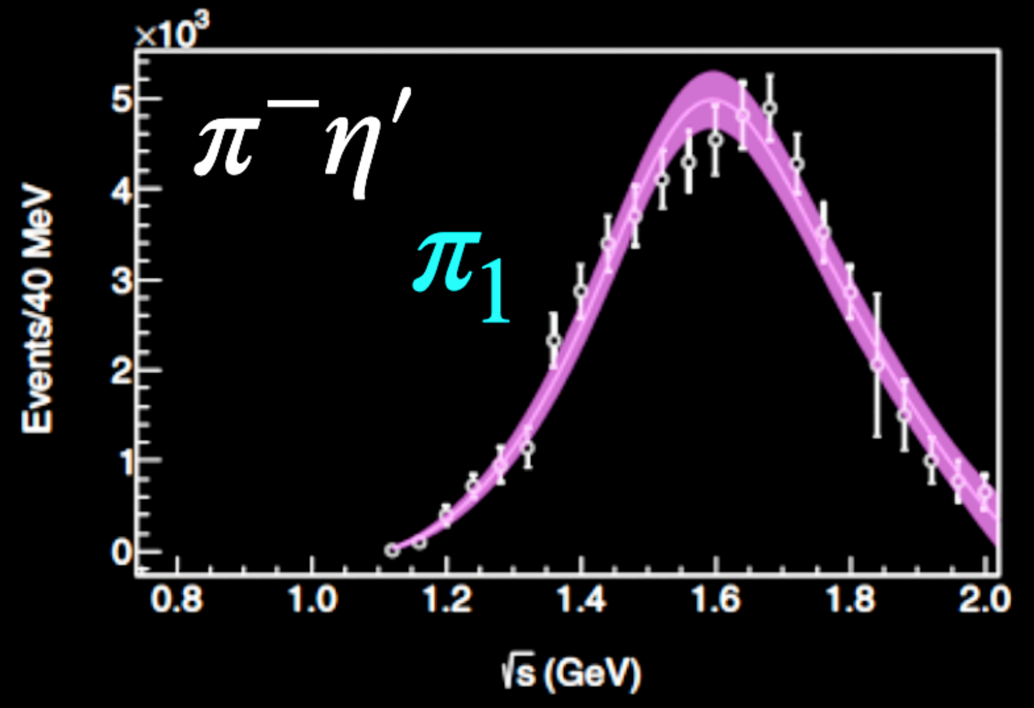
- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
- describes dominate a_2 resonances and the π_1

Modeled amplitudes using the analytic, unitary N/D formalism

- extraction of poles more rigorous than Breit-Wigner approach



2 poles or 1 pole ?

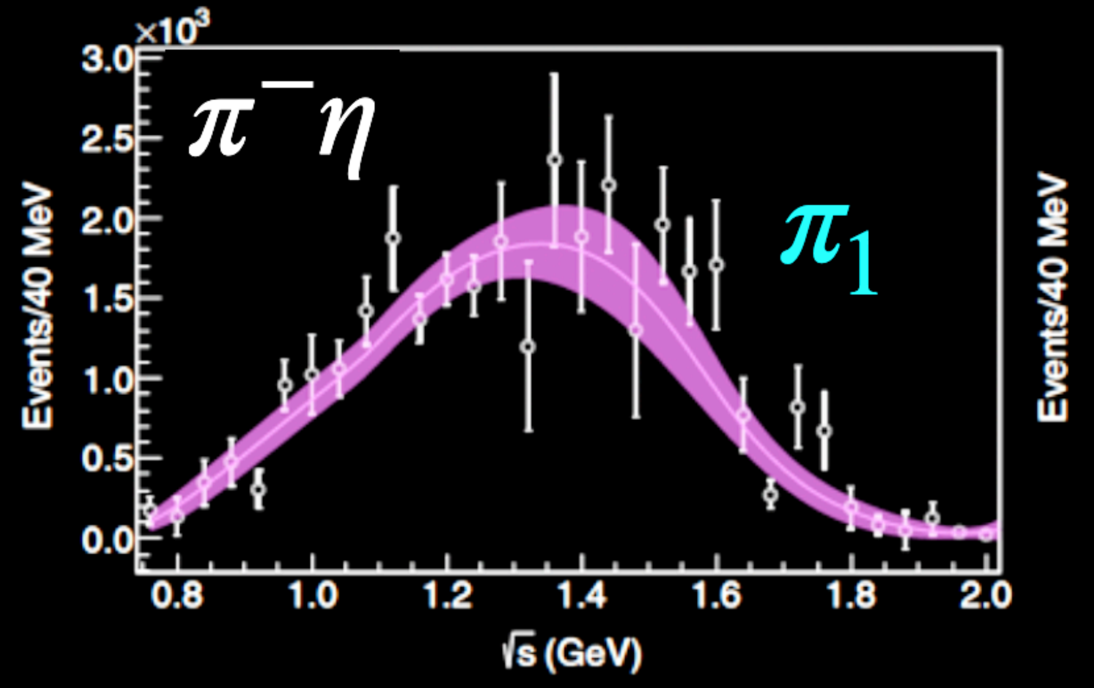


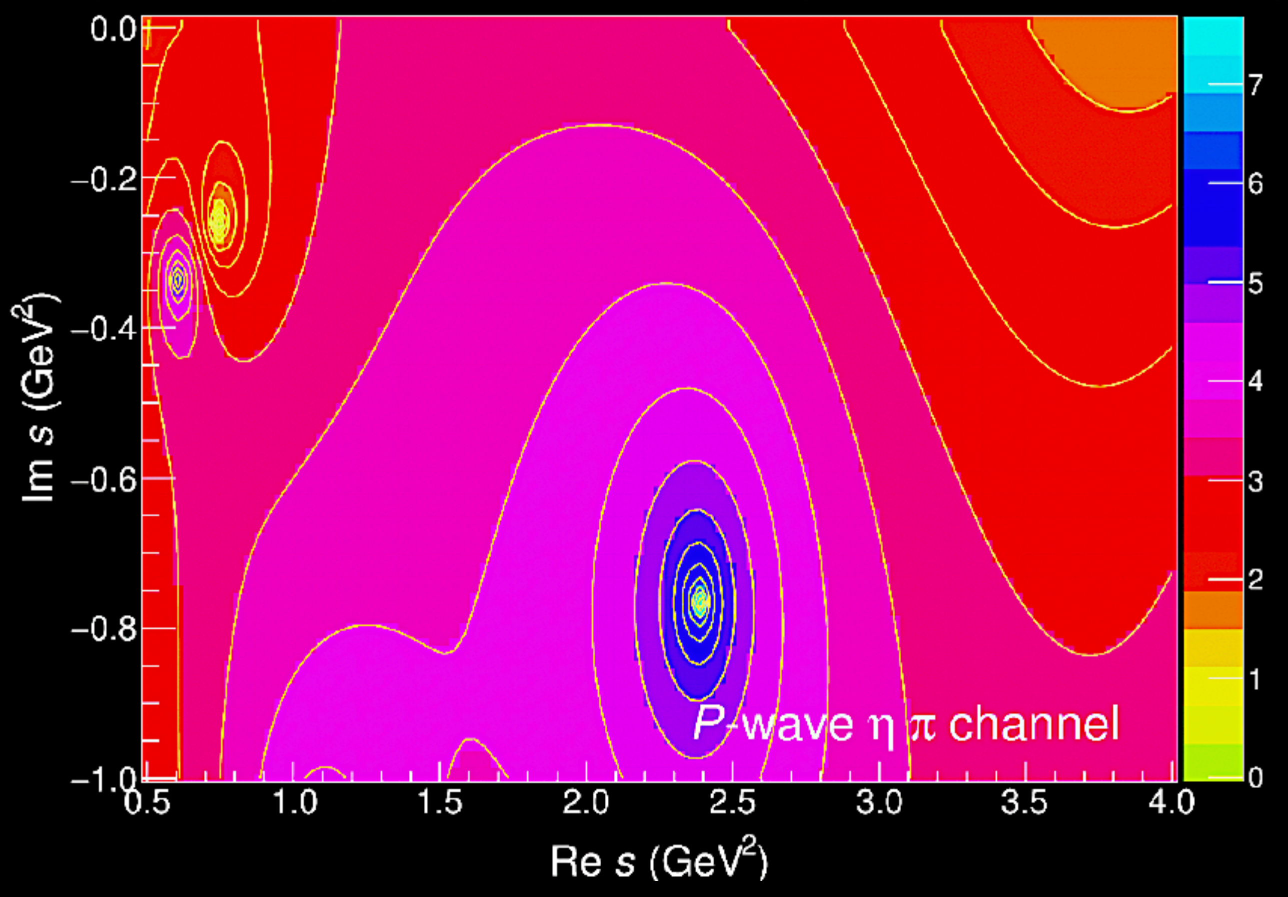
JPAC analysis utilizing COMPASS data

- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
- describes dominate a_2 resonances and the π_1

Modeled amplitudes using the analytic, unitary N/D formalism

- extraction of poles more rigorous than Breit-Wigner approach





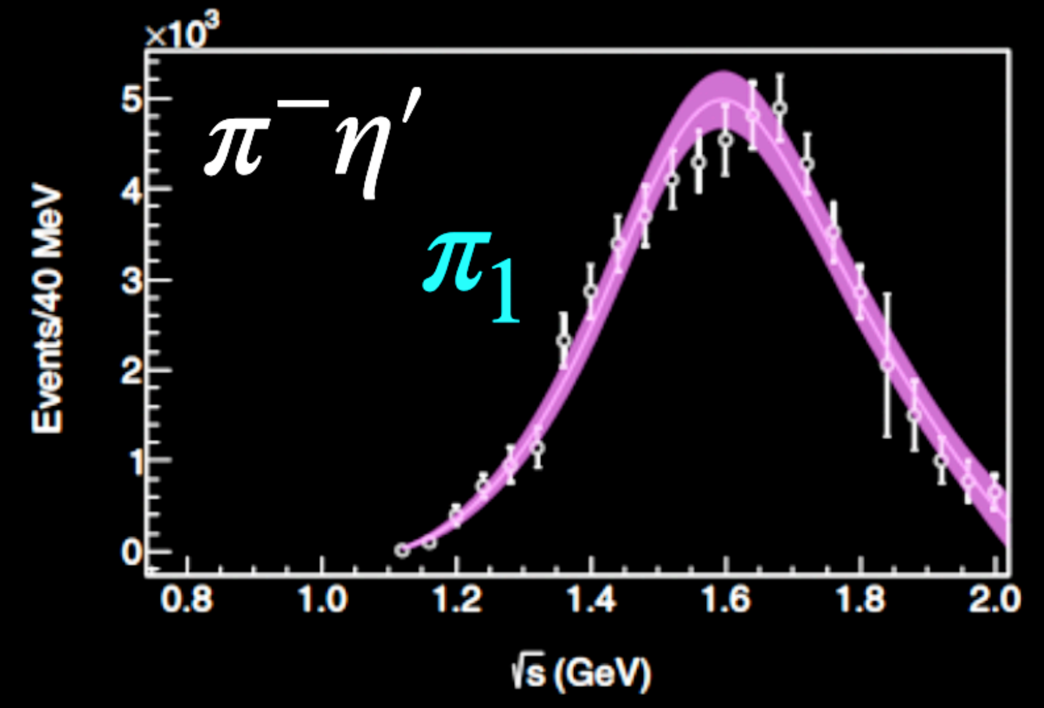
Alessandro Pilloni Slides

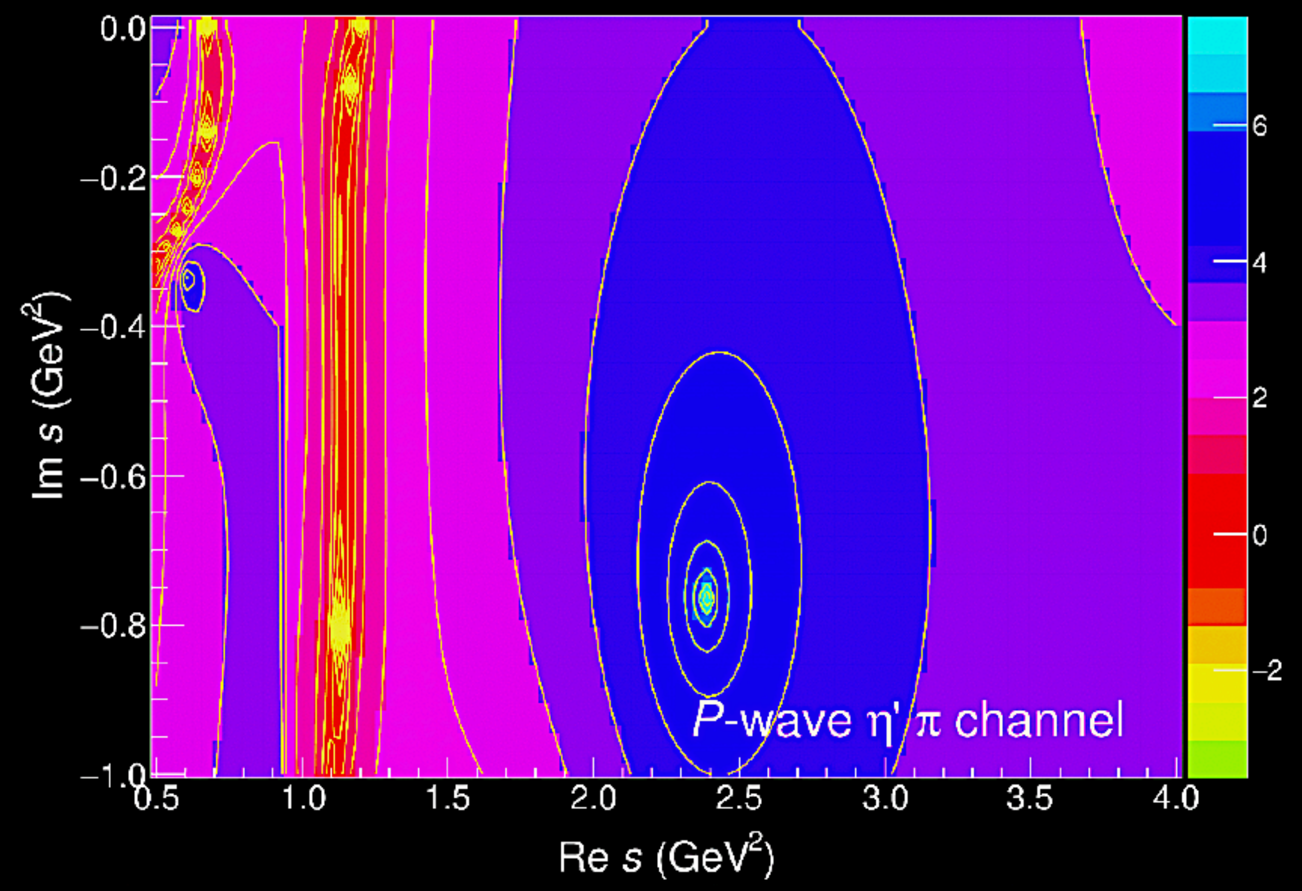
2 poles or 1 pole ?

Non-uniform pole residue

- the pole's strength redistributes differently between the P_{Wave} amplitudes in $\eta\pi$ & $\eta'\pi$
- in $\eta'\pi$ the pole's strength Shifts towards heavier s

Only a coupled analysis could capture this aspect



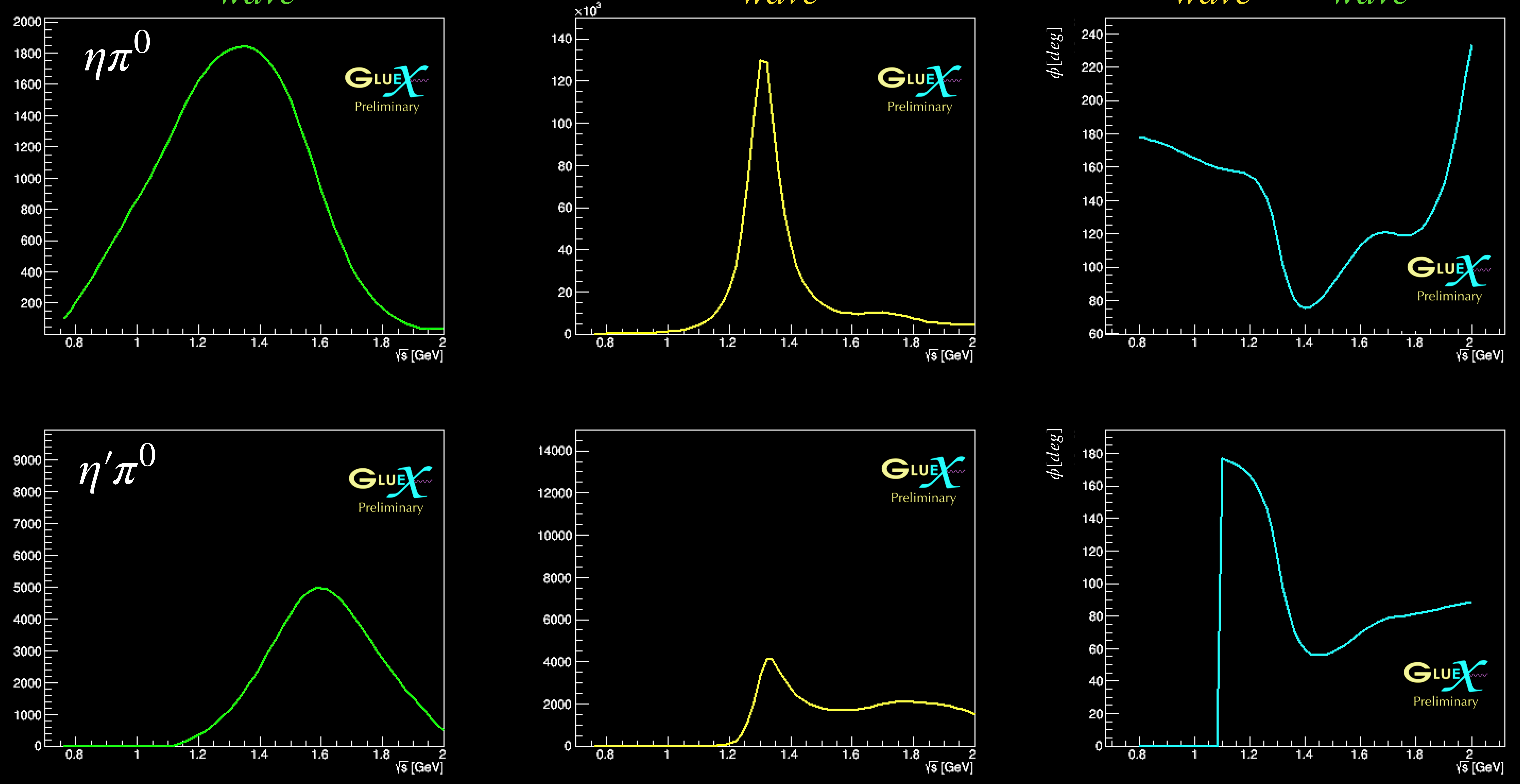


$$A_i^J(s) = q^{J-1}\, p_i^J \sum_k n_k^J(s) \left[D^J(s)^{-1} \right]_{ki}$$

Numerator

Denominator

D_{wave} | P_{wave} | $P_{wave} - D_{wave}$ ph.



Code developed to perform JPAC's N/D method to GlueX data

Parameterization is universal, can use these to fit photoproduced $\eta\pi$ and $\eta'\pi$!

- **numerical evaluation of amplitudes from the formalism produces correct line shapes from A. Rodas, et al.**

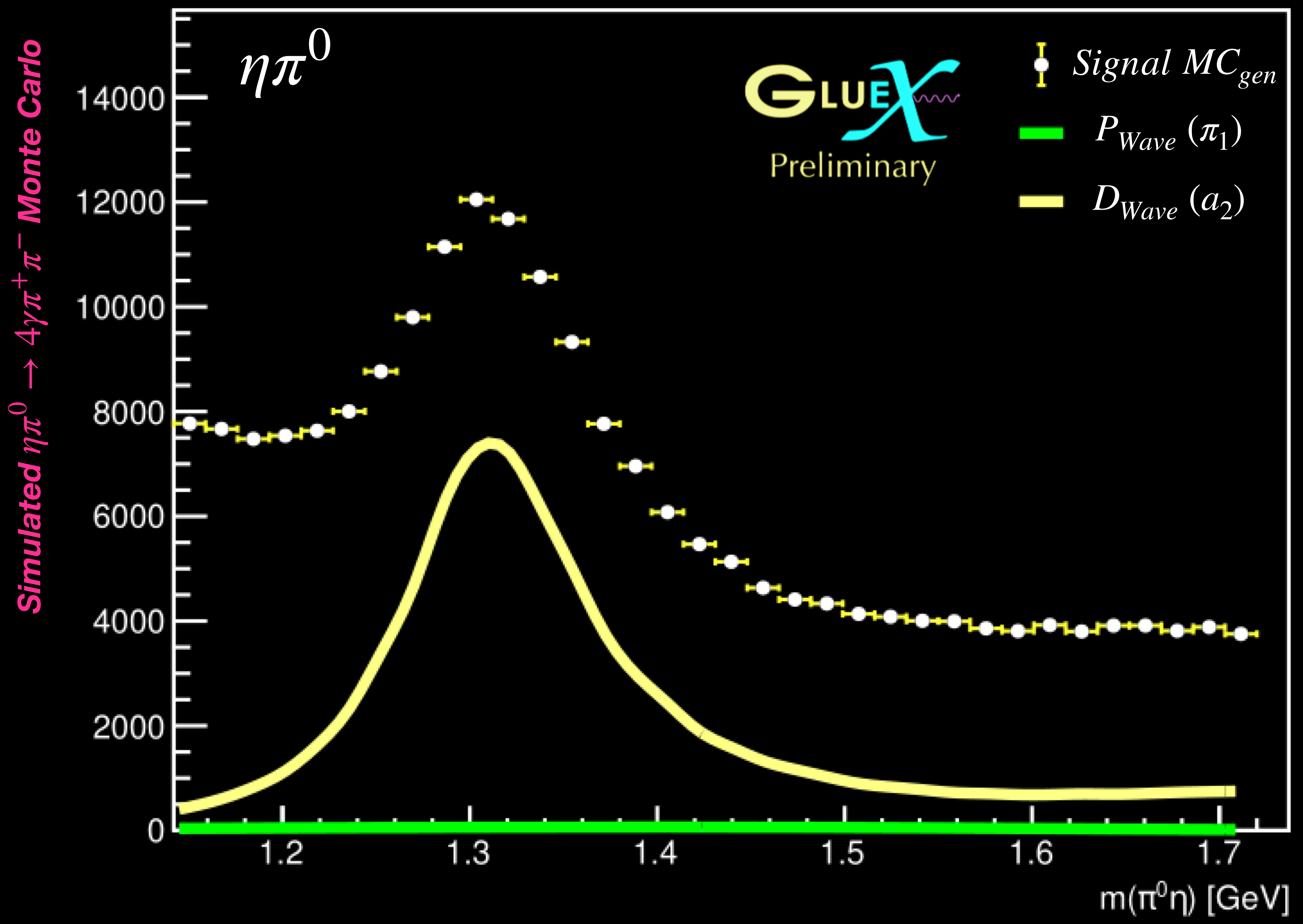
Note: currently assumes Pomeron exchange and normalization by the π beam momentum q

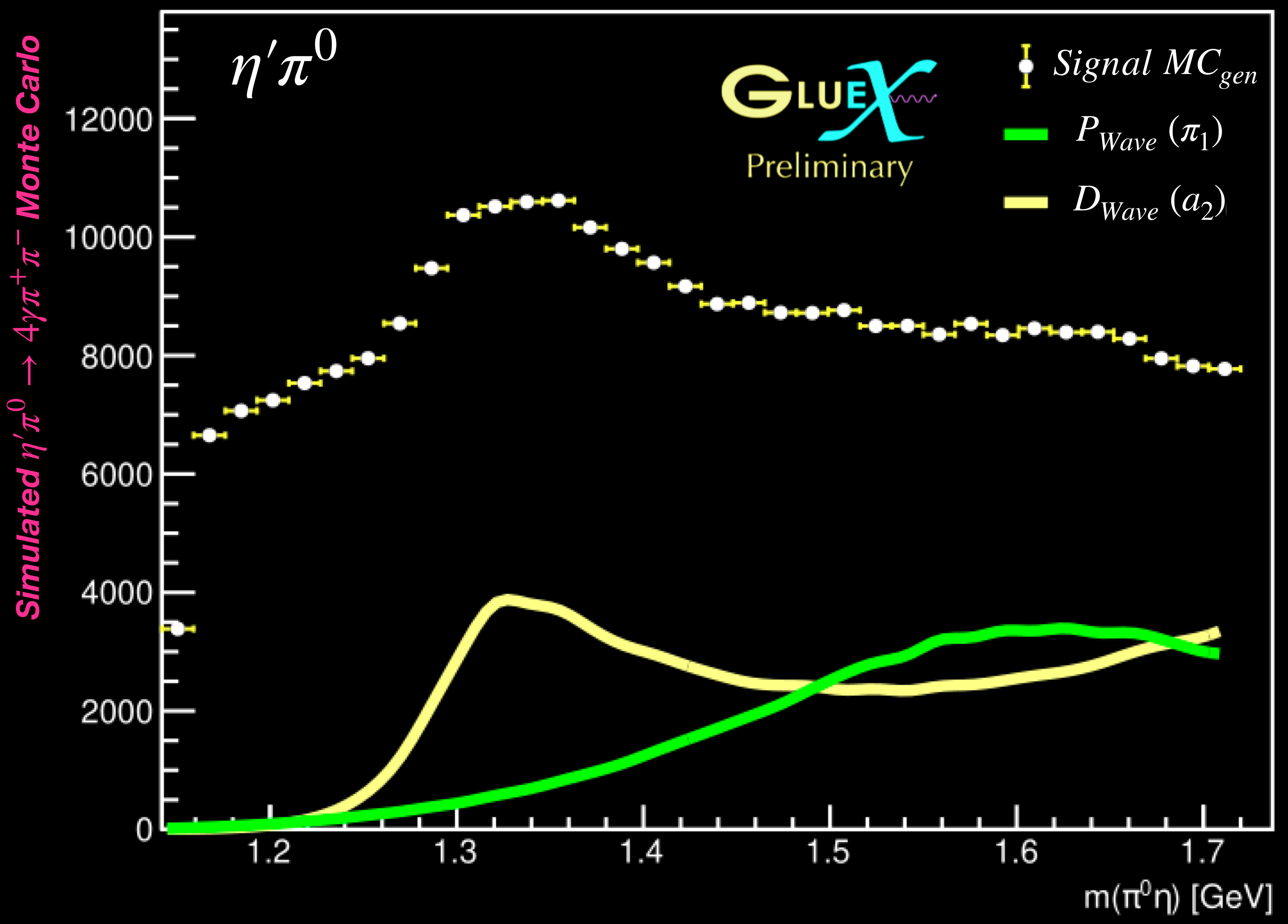
JPAC correcting this for GlueX

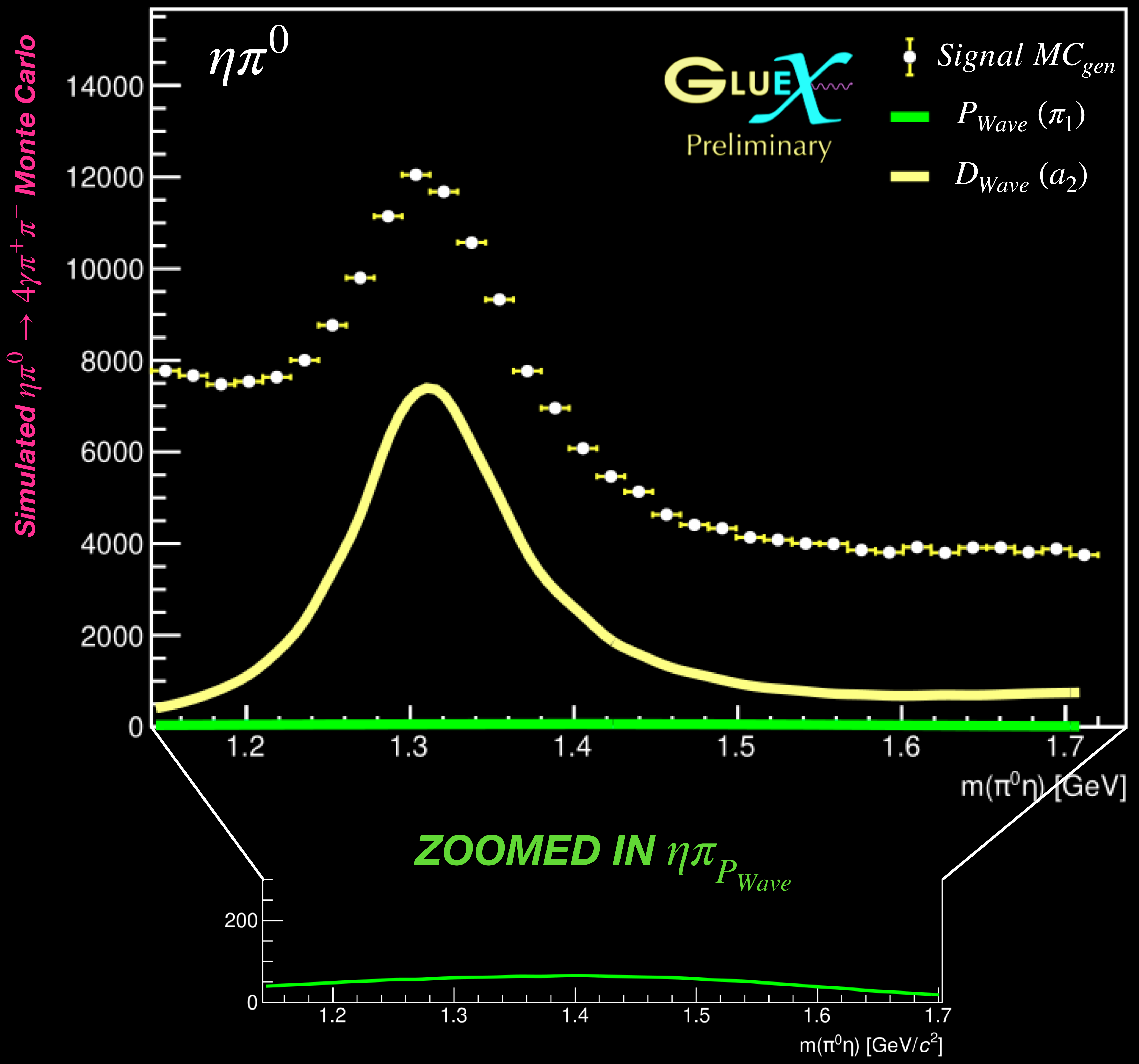
Input-Output check with generated signal Monte Carlo for photoproduction kinematics using coupled channel approach

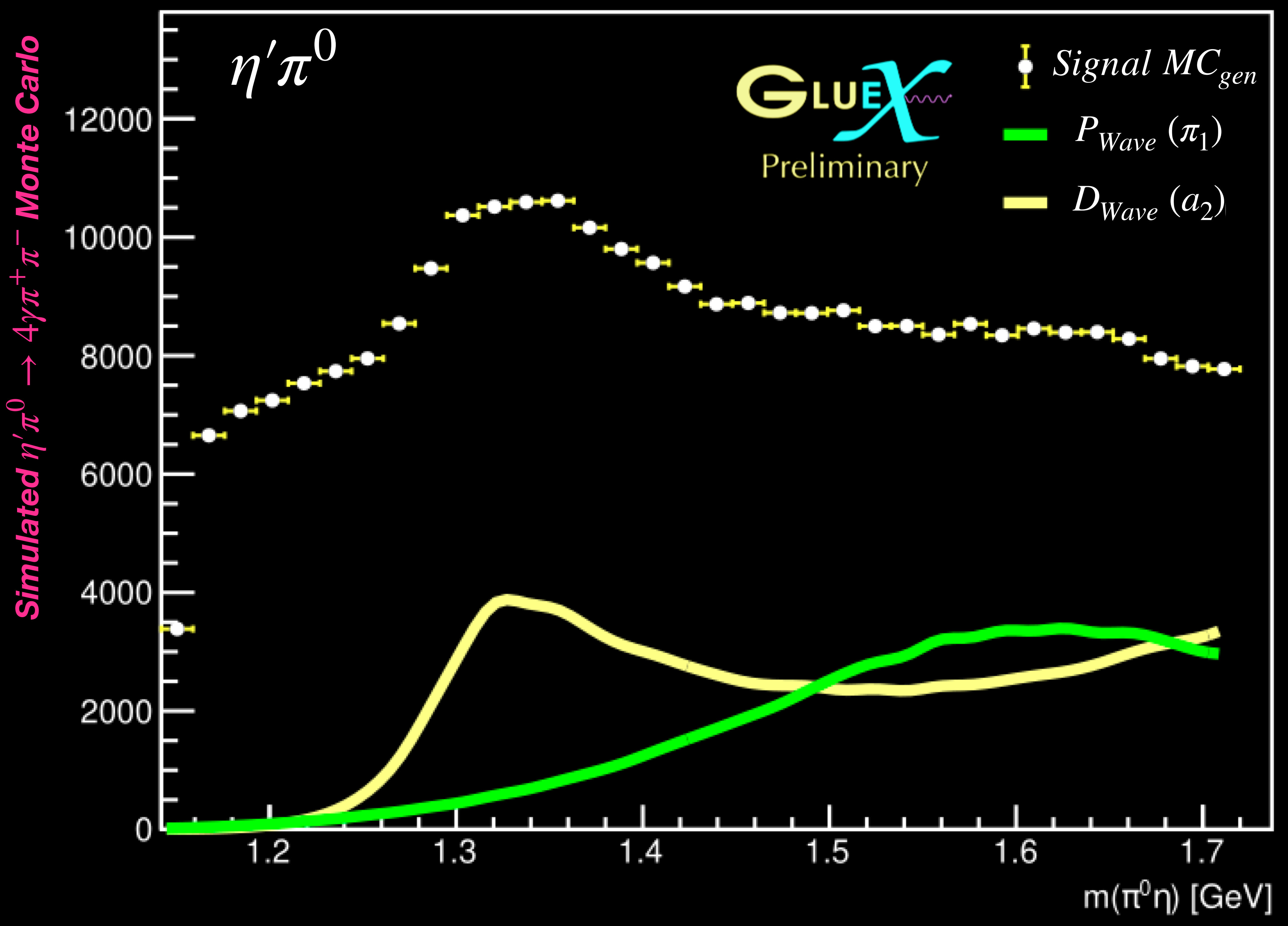
- lines shapes remain consistent to expected pole positions
- extremely small P_{wave} in $\eta\pi^0$ channel compared to $\eta'\pi^0$ → consistent with recent first photoproduced upper limit cross sections of the spin exotic candidate

F. Afzal et al. [GlueX Collab], Phys. Rev. Lett. 133, 261903 (2024)







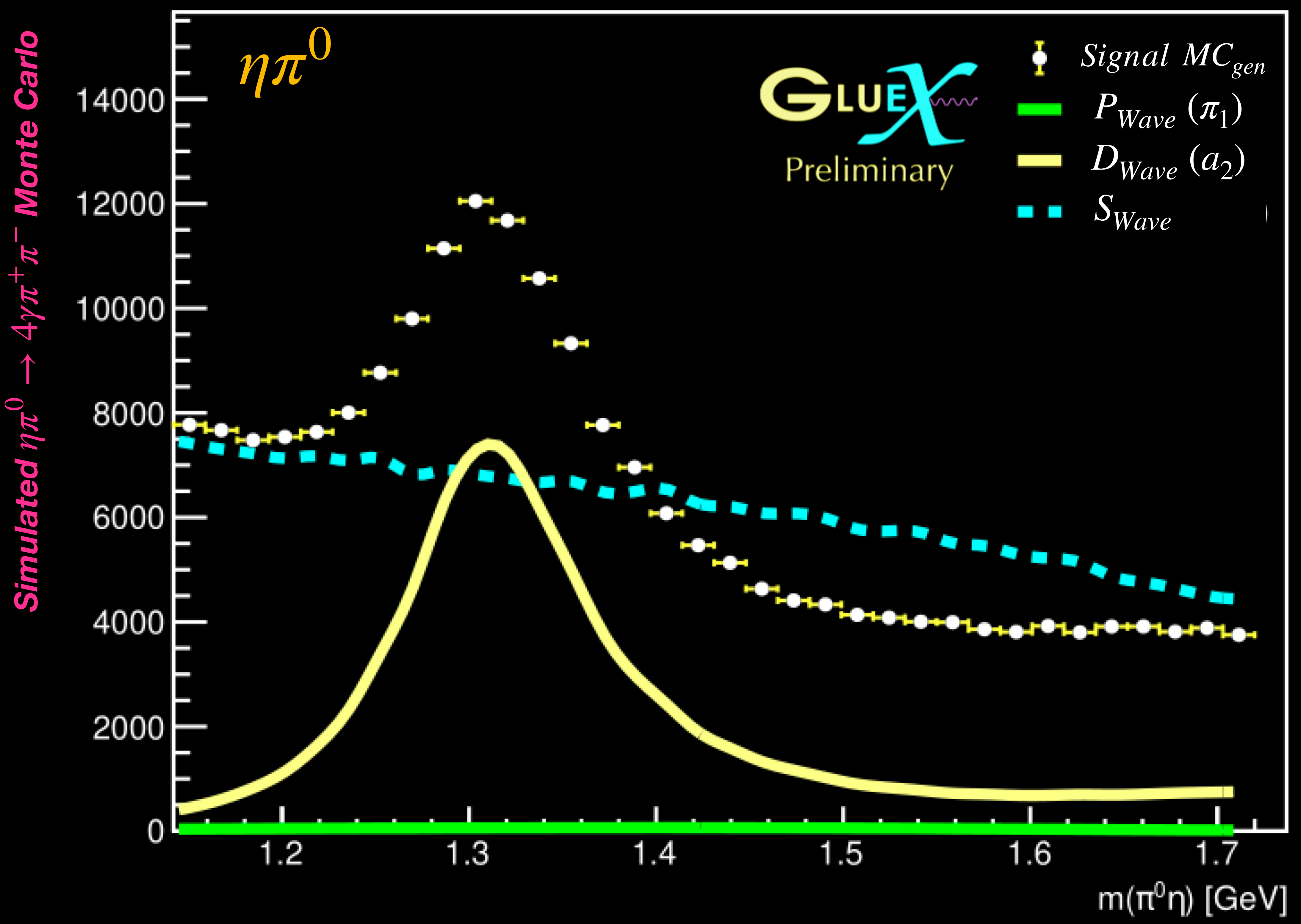


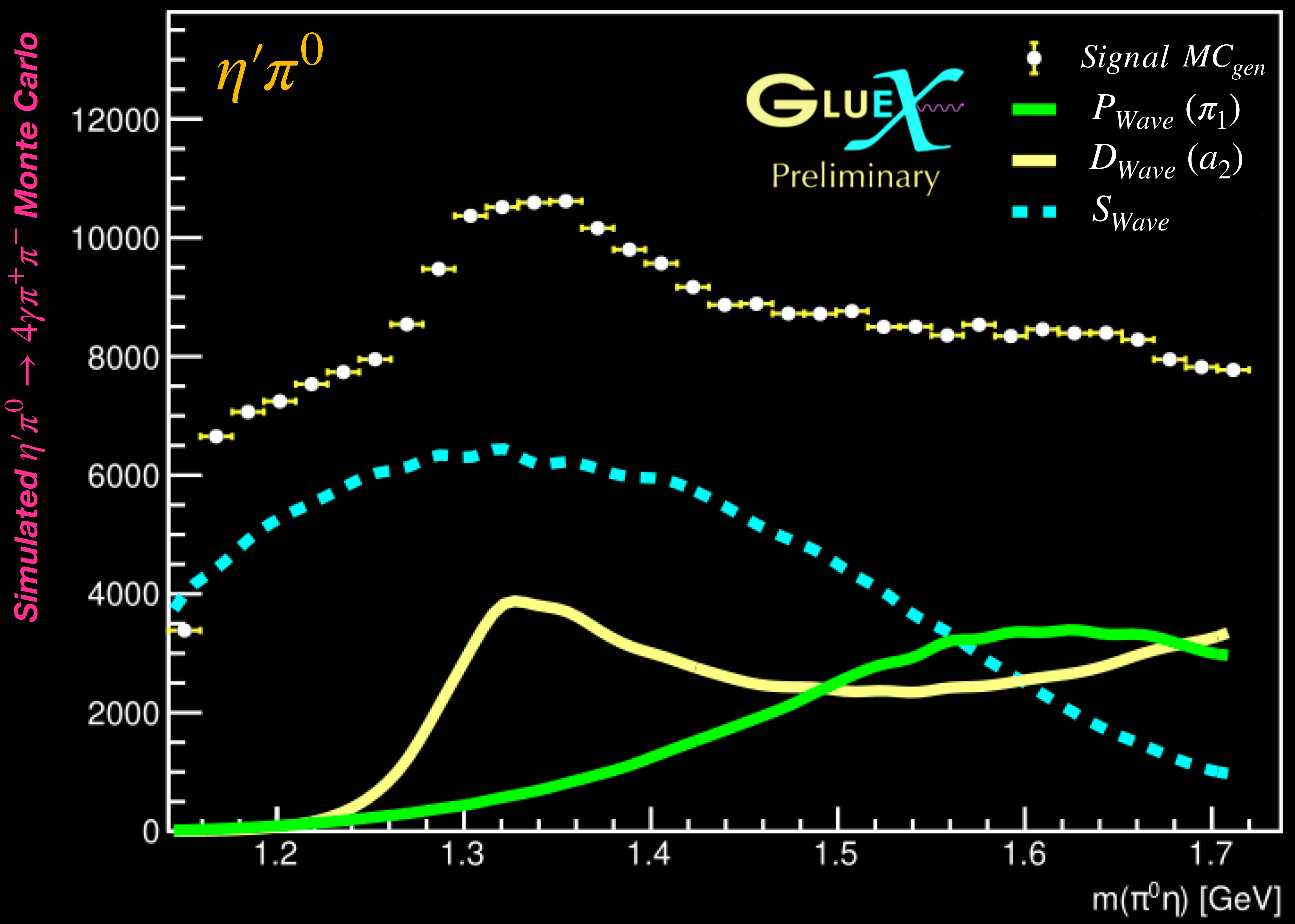
- P_{wave} contribution is non-zero in $\eta\pi^0$ channel

Input-Output check with generated signal Monte Carlo for photoproduction kinematics using coupled channel approach

- lines shapes remain consistent to expected pole positions
- extremely small P_{wave} in $\eta\pi^0$ channel compared to $\eta'\pi^0$ → consistent with recent first photoproduced upper limit cross sections of the spin exotic candidate
- S_{wave} contributions = challenges

F. Afzal et al. [GlueX Collab], Phys. Rev. Lett. 133, 261903 (2024)

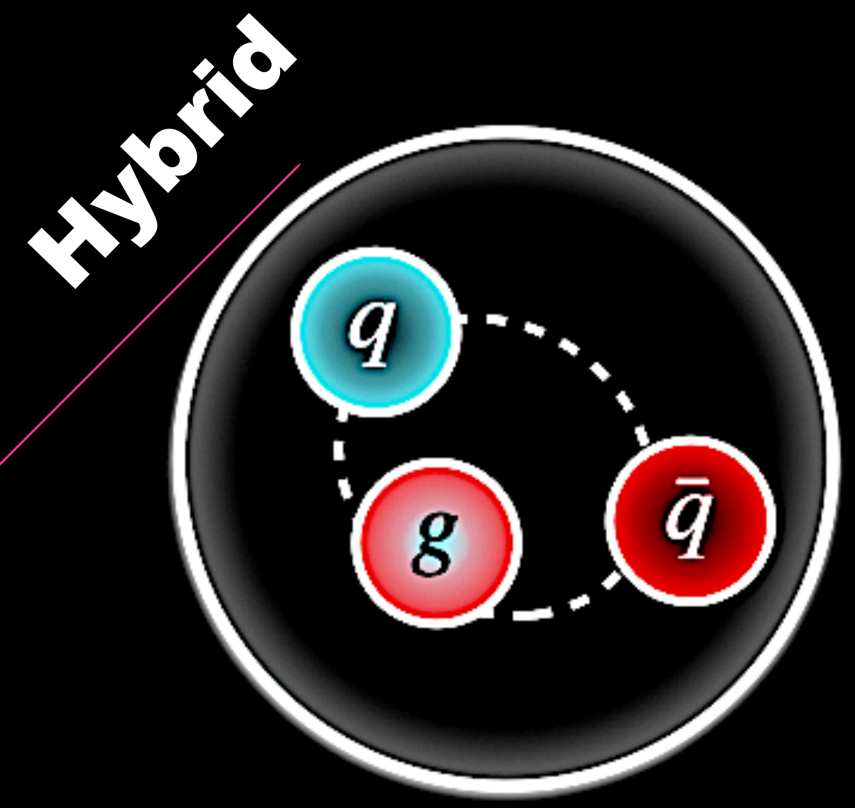




GlueX has collected large quantity of photoproduced data

- recent results extracted a_2 cross section which will be used as a reference signal
- can analyze production mechanisms using polarization info
- strong effort to look for *exotic hybrid* π_1 meson in $\eta^{(\prime)}\pi$ systems using several different analysis methods
- first look into utilizing coupled channel methods at GlueX

  other parameterizations (KMatrix, etc.) also being leveraged



Next immediate steps:

- further analyze both neutral and charged $\eta^{(\prime)}\pi$

  extract a_2^- cross section, perform moment extraction, etc.
- continue I/O studies with Monte Carlo → perform coupled fits to data

EXCITING TIMES FOR EXOTICS SEARCHES!

GlueX acknowledges the support of several funding agencies and computing facilities

gluex.org/thanks

U.S. DEPARTMENT OF ENERGY Office of Science

Some of this material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under contract number DE- SC0014664. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of DOE, ORAU, or ORISE.

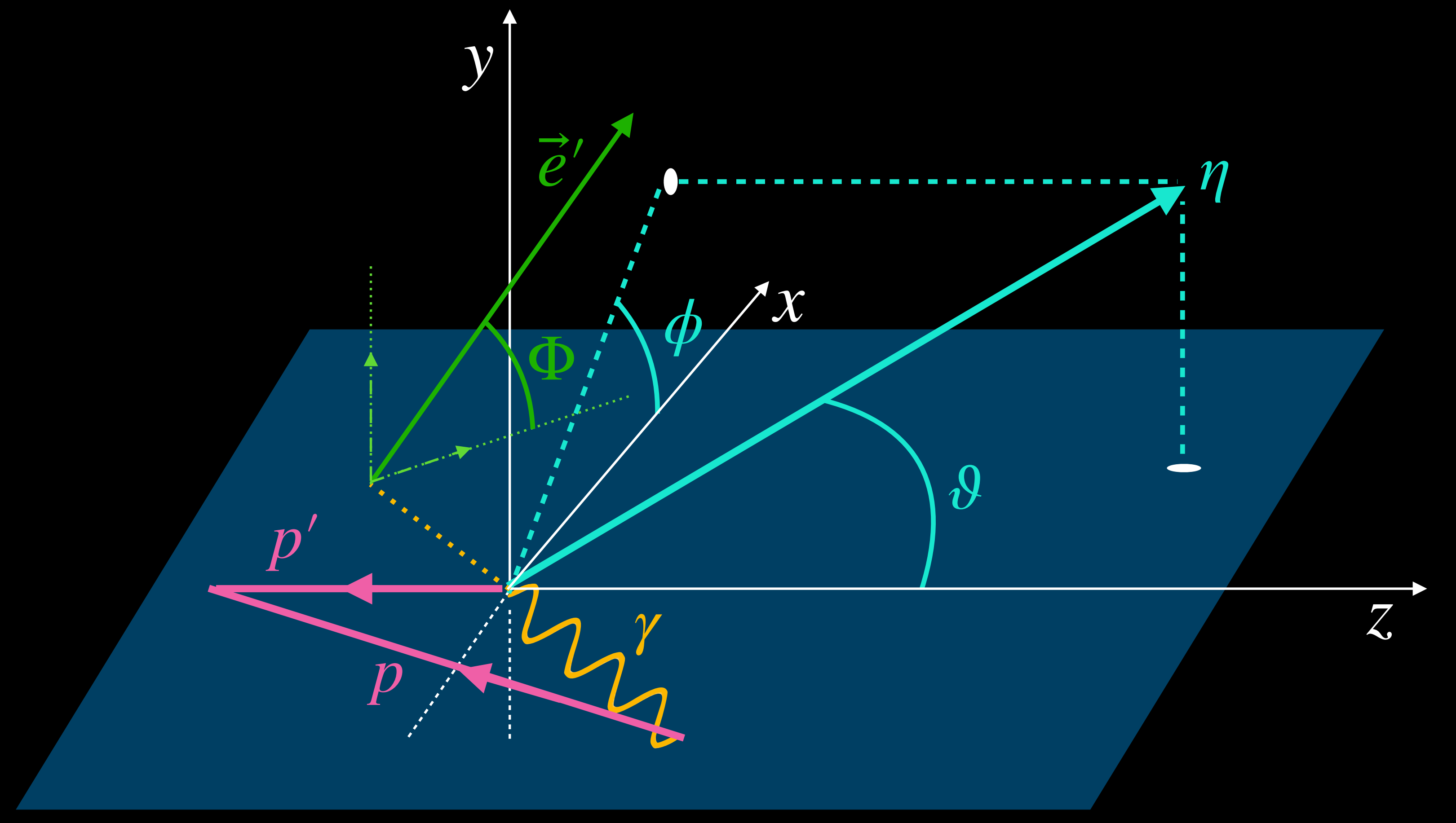
BACKUP SLIDES

Describes all two-pseudoscalar systems (i.e. all $\eta^{(\prime)}\pi$)

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

Described by 3 angles: $\cos\vartheta_{\eta^{(\prime)}}$, $\phi_{\eta^{(\prime)}}$ — in the resonance frame

$\Phi \rightarrow$ btw the polarization and production plane



V. Mathieu et al. [JPAC], PRD 100, 054017 (2019)

Reflectivity corresponds to exchange being natural ($+1$) and unnatural (-1) parity

4x more amplitudes than hadro-production

$$\Rightarrow \mathcal{I}(\Omega, \Phi) = 2\kappa \sum_k \Big\{ (1-P_\gamma)\Big|\sum_{l,m} [l]_m^{(-)}\,\mathcal{Re}[Z_l^m(\Omega,\Phi)]\Big|^2 + (1-P_\gamma)\Big|\sum_{l,m} [l]_m^{(+)}\,\mathcal{Im}[Z_l^m(\Omega,\Phi)]\Big|^2 +$$

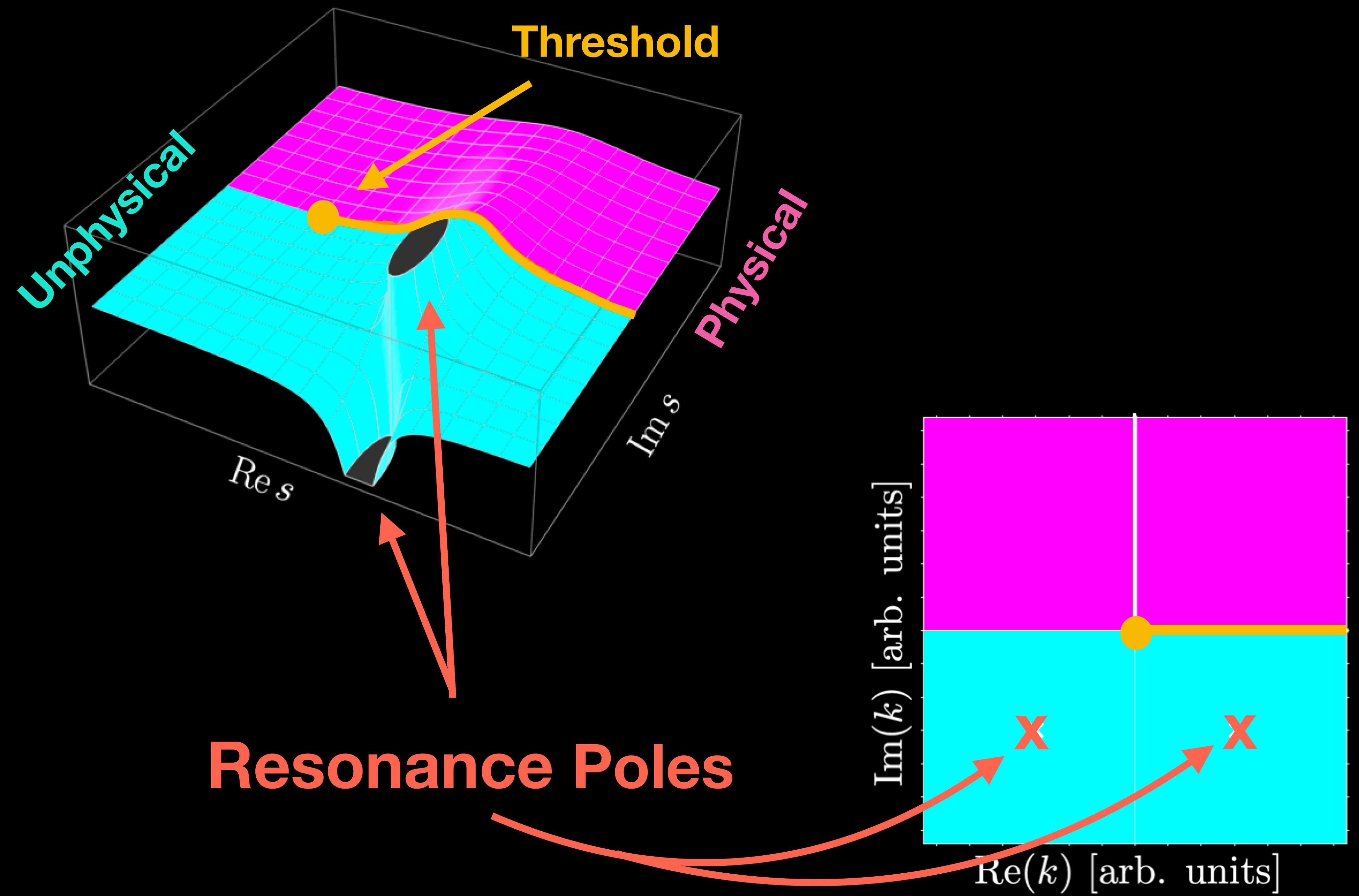
$$(1+P_\gamma)\Big|\sum_{l,m} [l]_m^{(+)}\,\mathcal{Re}[Z_l^m(\Omega,\Phi)]\Big|^2 + (1+P_\gamma)\Big|\sum_{l,m} [l]_m^{(-)}\,\mathcal{Im}[Z_l^m(\Omega,\Phi)]\Big|^2 \Big\}$$

In QFT → resonances correspond to poles of the S-matrix in the complex energy plane

- these poles lie off the real energy axis, reflecting the unstable nature of resonances

- not directly visible, but influence observables (i.e. cross sections)

- resonance position and width → encoded in complex pole location



Breit-Wigner functions are the historical standard for describing resonances

- *algebraically simple*

- *work well for isolated, narrow resonances*

useful first approximation!

But…

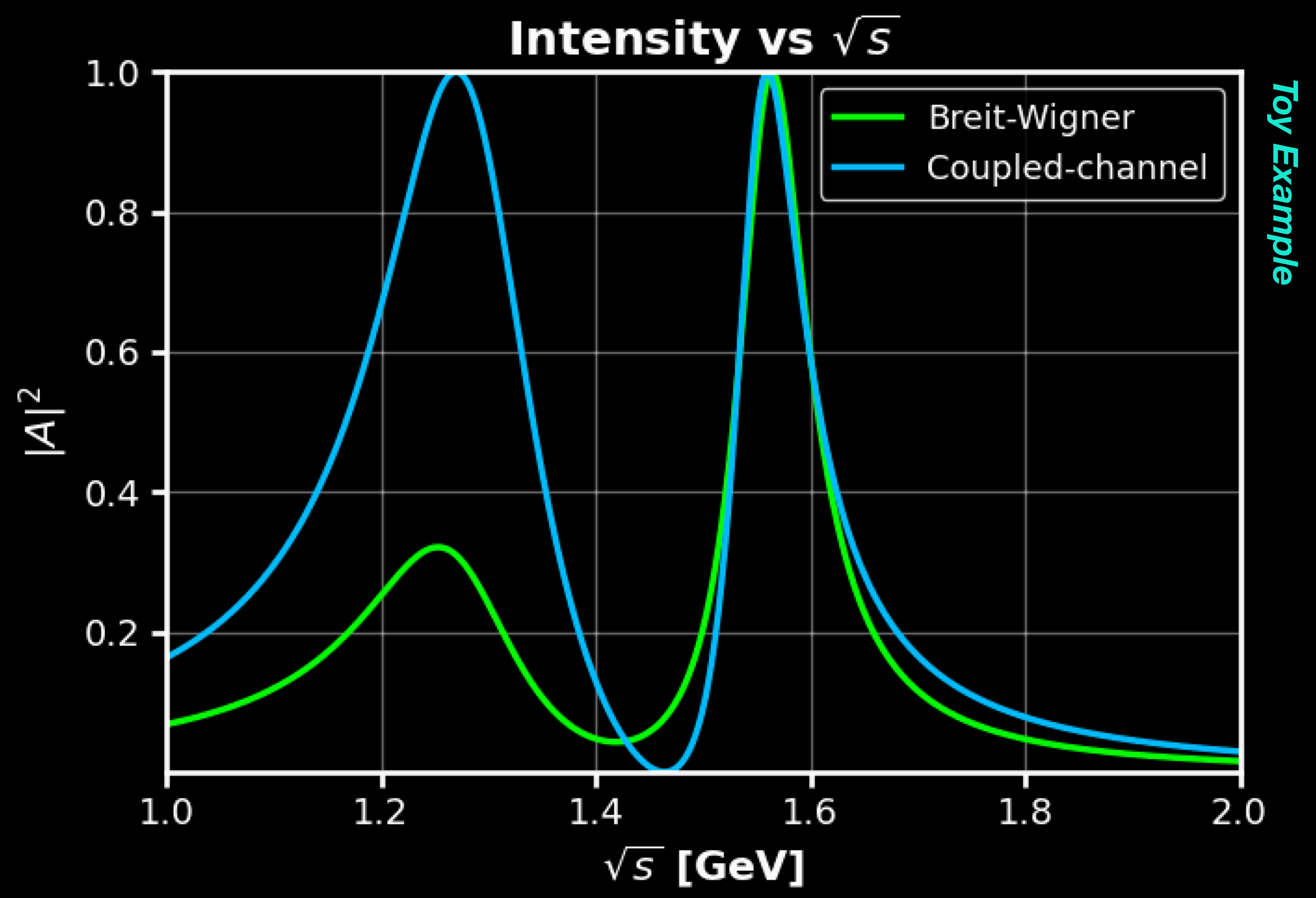
- fails to conserve total probability in multi-channel scattering

- do not account for:
  1) coupled-channel effects
  2) overlapping resonances
  3) nearby thresholds

To understand what a true resonance is,
we must ask where its pole position lies … not where its bump appears!

Overlapping resonances interfere differently depending on model

- **BW**: underestimates interference
- **CC**: enhances the first peak through self-consistent interference across poles



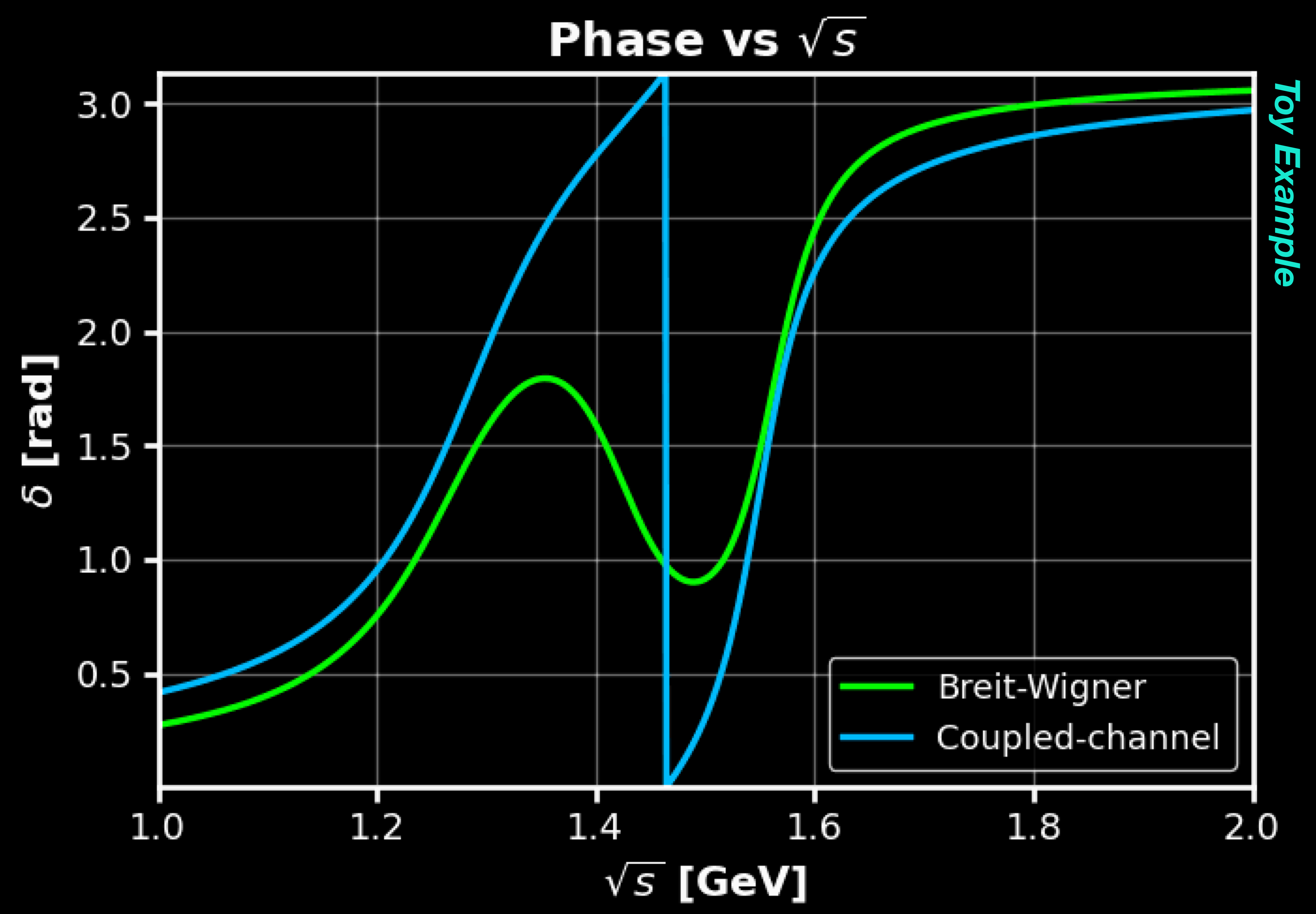
PHASE MOTION

ARGAND LOOP

Overlapping resonances interfere differently depending on model

- **BW**: no threshold structure and ignores threshold effects
- **CC**: shows a non-analytic phase jump showcasing multiple channel feedback

INTENSITY EVOLUTION



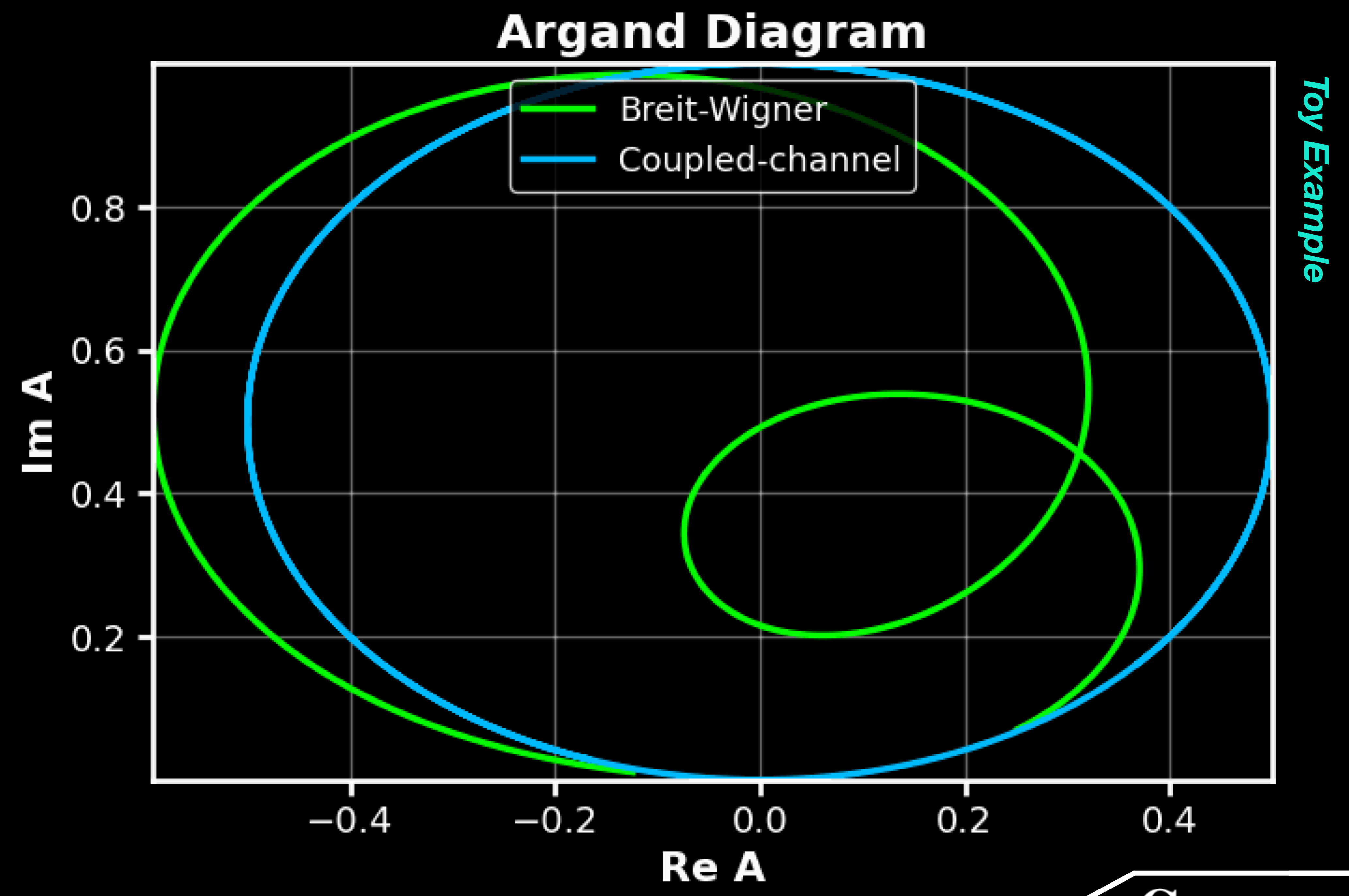
ARGAND LOOP

INTENSITY EVOLUTION

PHASE MOTION

Overlapping resonances interfere differently depending on model

- **BW**: erratic, non-unitary motion
- **CC**: clean, unitary counter-clockwise trajectory



Formalism following the approach in *Rodas, A et al* gives the production amplitude as:

Angular Momentum Barrier Factors

Production Term (smooth, real functions)

$$A_i^J(s) = q^{J-1} p_i^J \sum_k n_k^J(s) \left[D^J(s)^{-1} \right]_{ki}$$

KMatrix

$$K_{ki}^J(s) = \sum_R \frac{g_k^{J,R} g_i^{J,R}}{m_R^2 - s} + c_{ki}^J + d_{ki}^J s$$

$$D_{ki}^J(s) = \left[K^J(s)^{-1} \right]_{ki} - \frac{s}{\pi} \int_{s_k}^{\infty} ds' \frac{\rho N_{ki}^J(s')}{s'(s' - s - i\epsilon)}$$

Analytic Denominator Matrix

In order to use the previous results on photoproduced data - need to fix the following parameters⋯

$$n_k^J(s) = \sum_{i=0}^{3} a_i^{(J,k)} T_i\left(\frac{s}{s+1}\right)$$

$$K_{ki}^J(s) = \sum_R \frac{g_k^{J,R} g_i^{J,R}}{m_R^2 - s} + c_{ki}^J + d_{ki}^J s$$

$a \rightarrow$ Chebyshev Coefficients

$g \rightarrow$ Final State Couplings

$c, d \rightarrow$ Backgrounds in K-Matrix

⋯ and the only parameters floated in the fit are the complex photocouplings ⋯

$$A_i^J(s) = \beta^P \cdot q^{J-1}(s) \cdot p_i^J(s) \cdot \sum_{k=1}\left(\sum_{n=0}^{3} a_n^{(J,k)} T_n\left(\frac{s}{s+1}\right)\right) \cdot \left[D^J(s)^{-1}\right]_{ki}$$

⋯ in each reflectivity (+/−)

N/D parameters from JPAC supplemental

Coefficient	$\eta\pi$	$\eta'\pi$
a_0^P	408.75	−47.05
	356 ± 334	−43 ± 39
a_1^P	−632.57	65.84
	−547 ± 534	59 ± 63
a_2^P	281.48	−20.96
	240 ± 255	−17 ± 30
a_3^P	−57.98	1.20
	−47 ± 63	0 ± 8
a_0^D	−247.80	230.92
	−247 ± 28	233 ± 79
a_1^D	413.91	−290.66
	415 ± 39	−290 ± 125
a_2^D	−190.94	176.88
	−192 ± 39	177 ± 83
a_3^D	59.25	−3.82
	61 ± 29	−1 ± 62

K-matrix background	
$c^P_{\eta\pi,\eta\pi}$	−15.43
	−14.77 ± 7.22
$c^P_{\eta\pi,\eta'\pi}$	−67.22
	−65.28 ± 13.91
$c^P_{\eta'\pi,\eta'\pi}$	−190.73
	−184.19 ± 38.21
$d^P_{\eta\pi,\eta\pi}$	1.82
	1.93 ± 2.24
$d^P_{\eta\pi,\eta'\pi}$	7.64
	7.59 ± 5.09
$d^P_{\eta'\pi,\eta'\pi}$	63.85
	60.54 ± 18.59
$c^D_{\eta\pi,\eta\pi}$	−2402.56
	−2385.05 ± 273.87
$c^D_{\eta\pi,\eta'\pi}$	462.60
	469.55 ± 55.87
$c^D_{\eta'\pi,\eta'\pi}$	−86.60
	−92.25 ± 28.11
$d^D_{\eta\pi,\eta\pi}$	−614.58
	−608.35 ± 49.32
$d^D_{\eta\pi,\eta'\pi}$	164.72
	166.85 ± 17.46
$d^D_{\eta'\pi,\eta'\pi}$	−42.19
	−44.45 ± 11.59

Resonating terms	
$g^P_{\eta\pi}$	−0.68
	−0.55 ± 0.38
$g^P_{\eta'\pi}$	−13.12
	−13.12 ± 0.95
$m^2_{P,1}$	3.52
	3.52 ± 0.08
$g^D_{\eta\pi,1}$	5.63
	5.64 ± 0.34
$g^D_{\eta'\pi,1}$	−3.77
	−3.78 ± 0.10
$m^2_{D,1}$	1.86
	1.86 ± 0.02
$g^D_{\eta\pi,2}$	147.79
	147.17 ± 9.88
$g^D_{\eta'\pi,2}$	−33.39
	−34.07 ± 3.41
$m^2_{D,2}$	8.06
	8.06 ± 0.30