Carnegie Mellon University

U.S. DEPARTMENT OF ENERGY

Office of Science

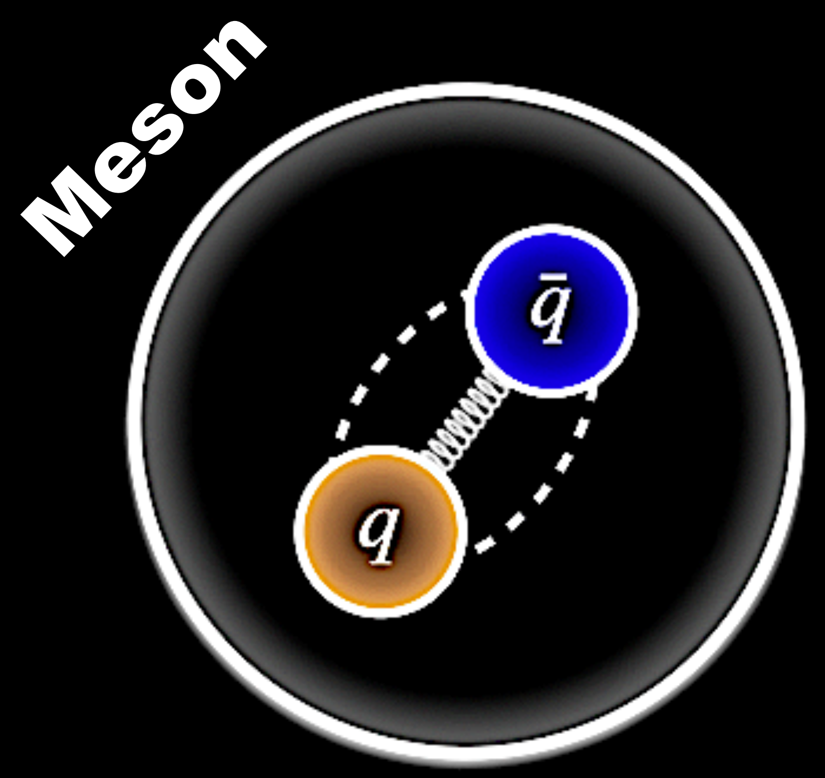
Exploring Photoproduced $\eta^{(\prime)}\pi^0$ Systems in the Search for Exotic Hadrons at GlueX

2026 Exotic Hadron Spectroscopy Workshop

The University of Cambridge

Zachary Baldwin | April 1, 2026

on behalf of the GlueX collaboration



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

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

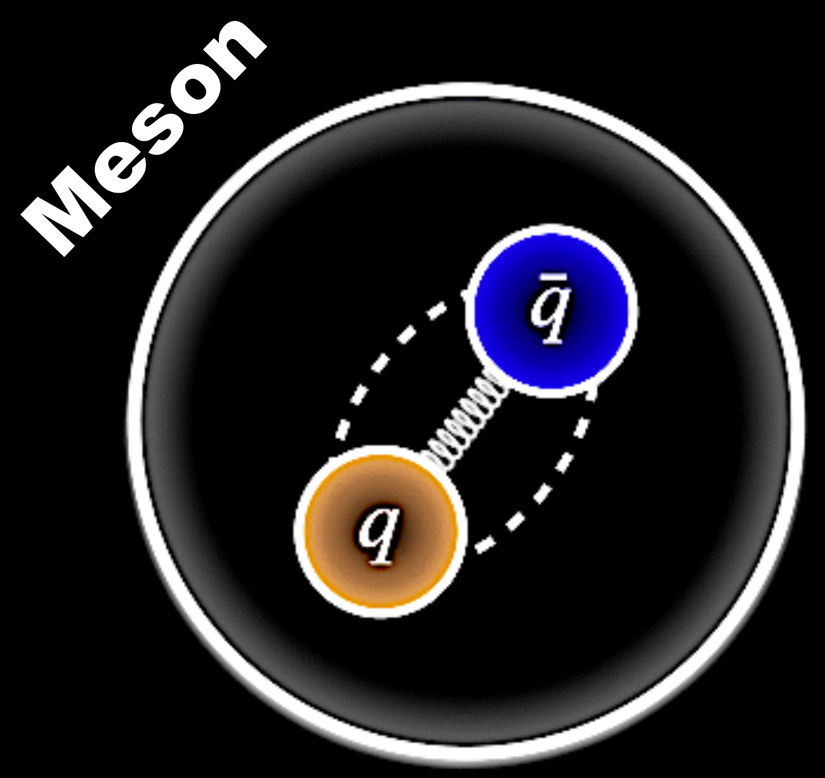
Charge Conjugation | $C = (-1)^{L+S}$

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^{--}



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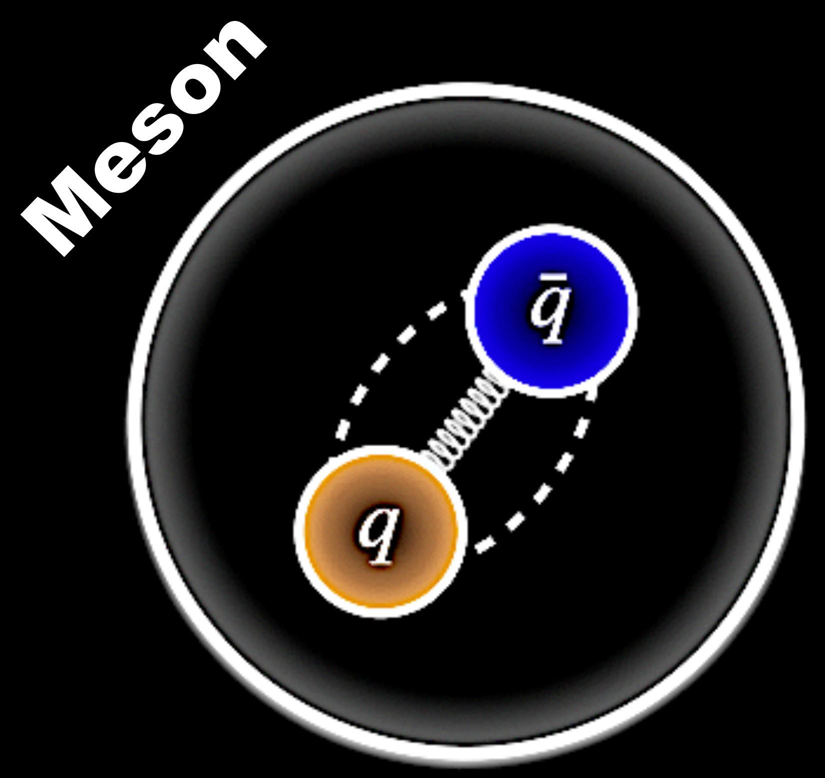
Observation of any system with quantum numbers forbidden in the constituent quark model, provides direct evidence for a non-$q\bar{q}$ configuration

Forbidden J^{PC} quantum numbers

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



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

Are observed *exotics* genuinely non-$q\bar{q}$ states or kinematic effects?

Lattice QCD predicts the existence of mesons with explicit *gluonic excitations* commonly referred to as *spin-exotic hybrid mesons*

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

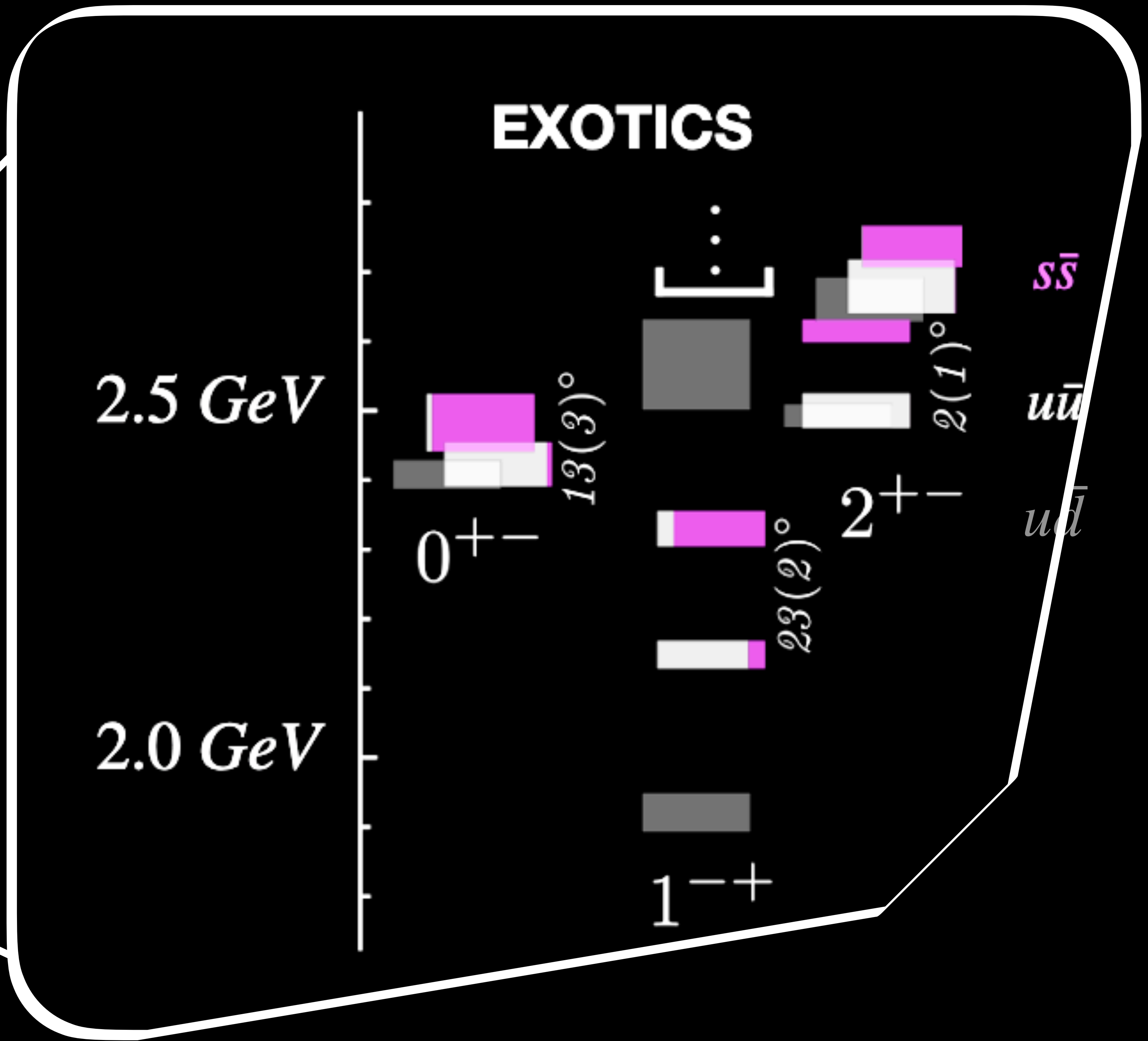

JLAB-THY-11-1314
TCD-MATH 11-02

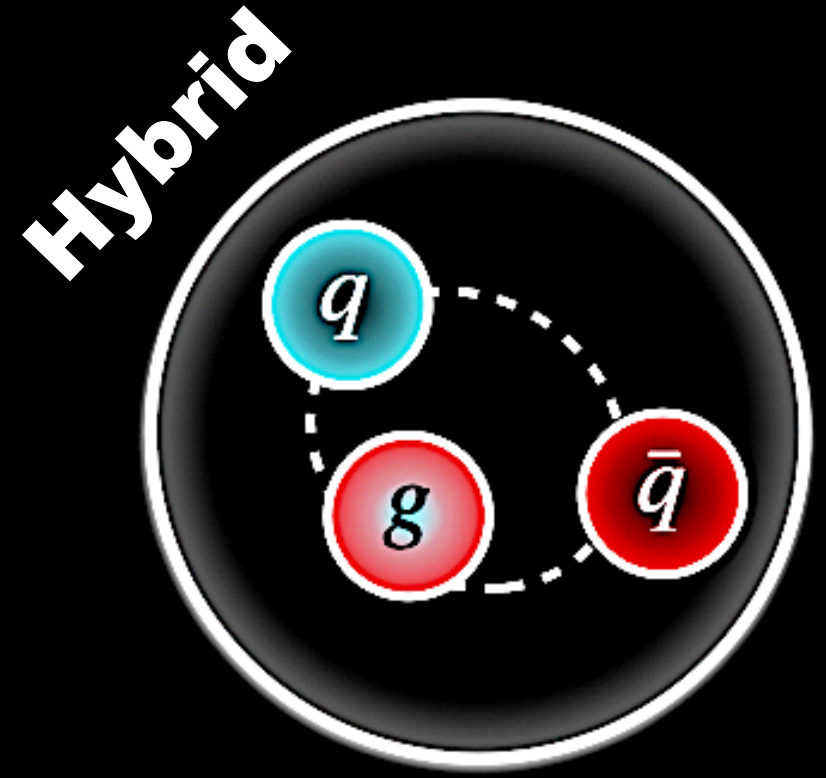
had/spec

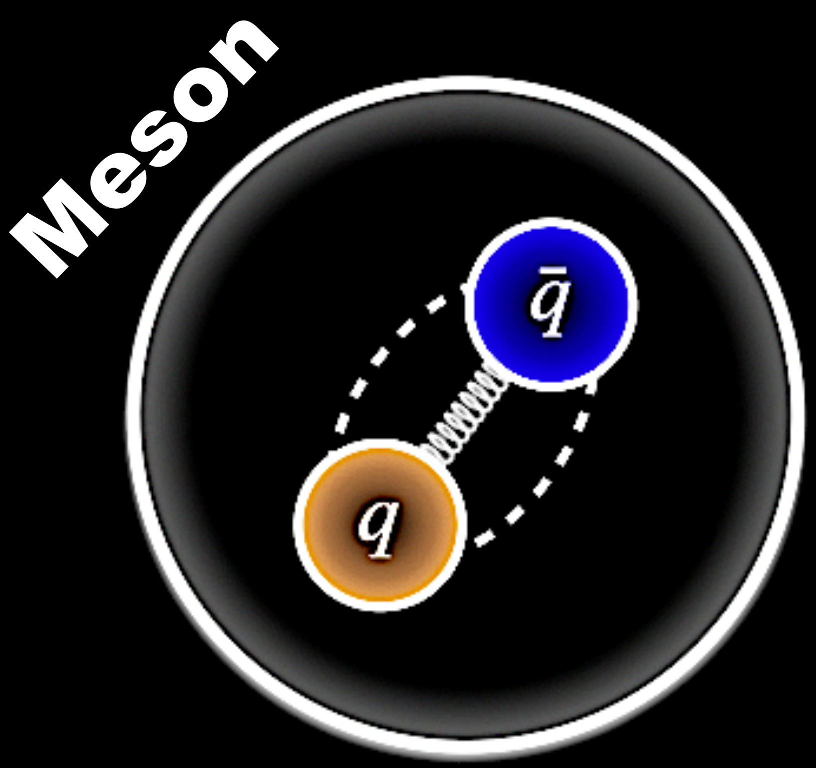
Isoscalar meson spectroscopy from lattice QCD

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







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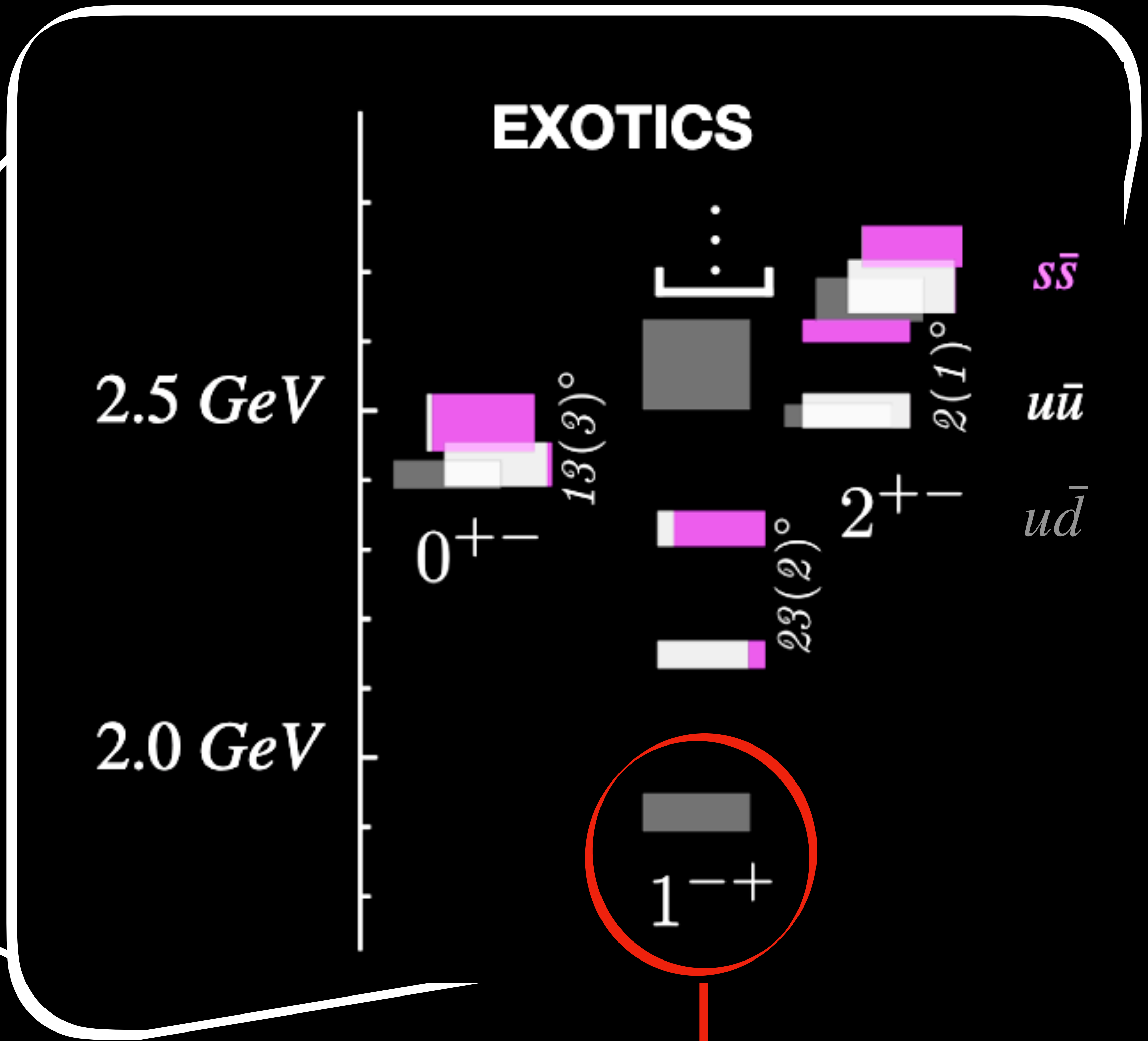

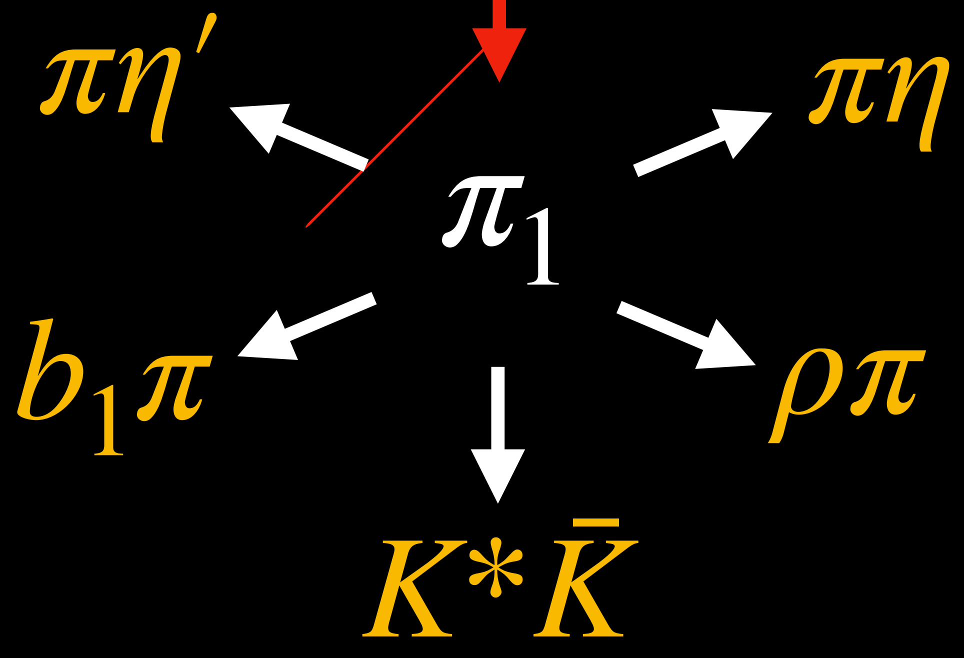

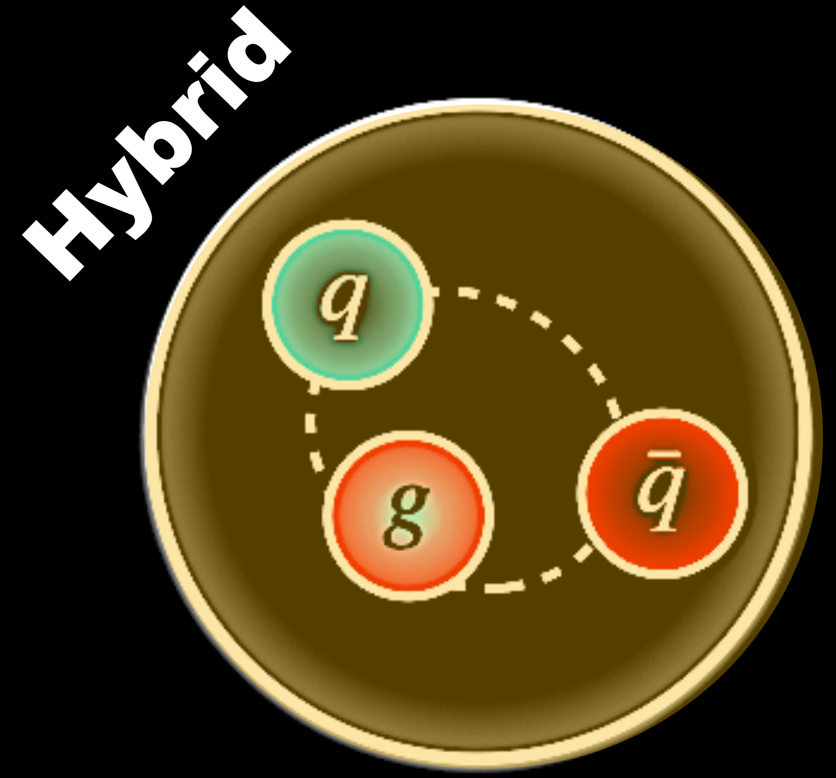

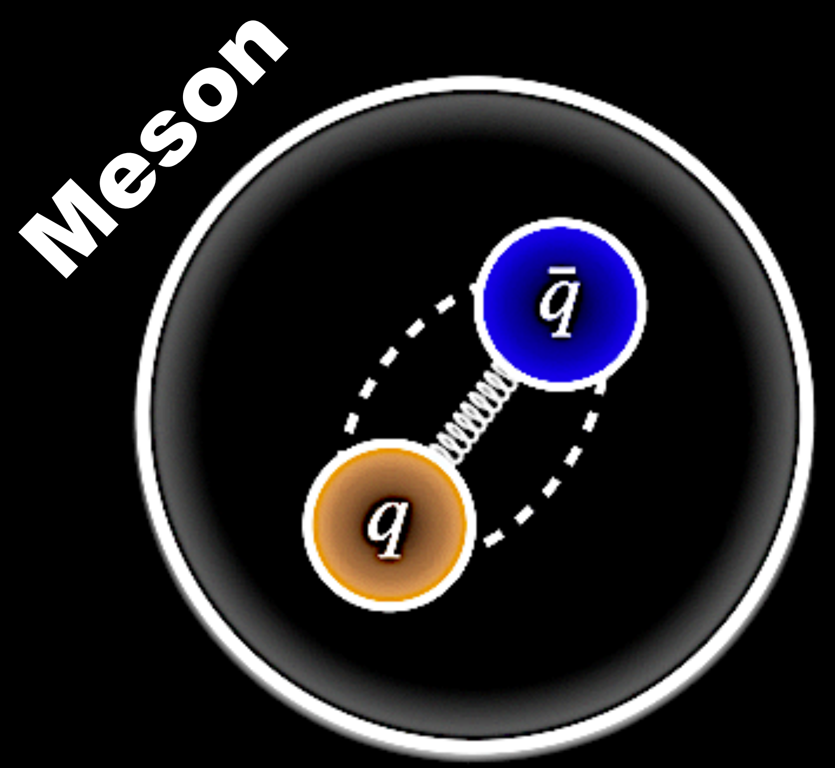

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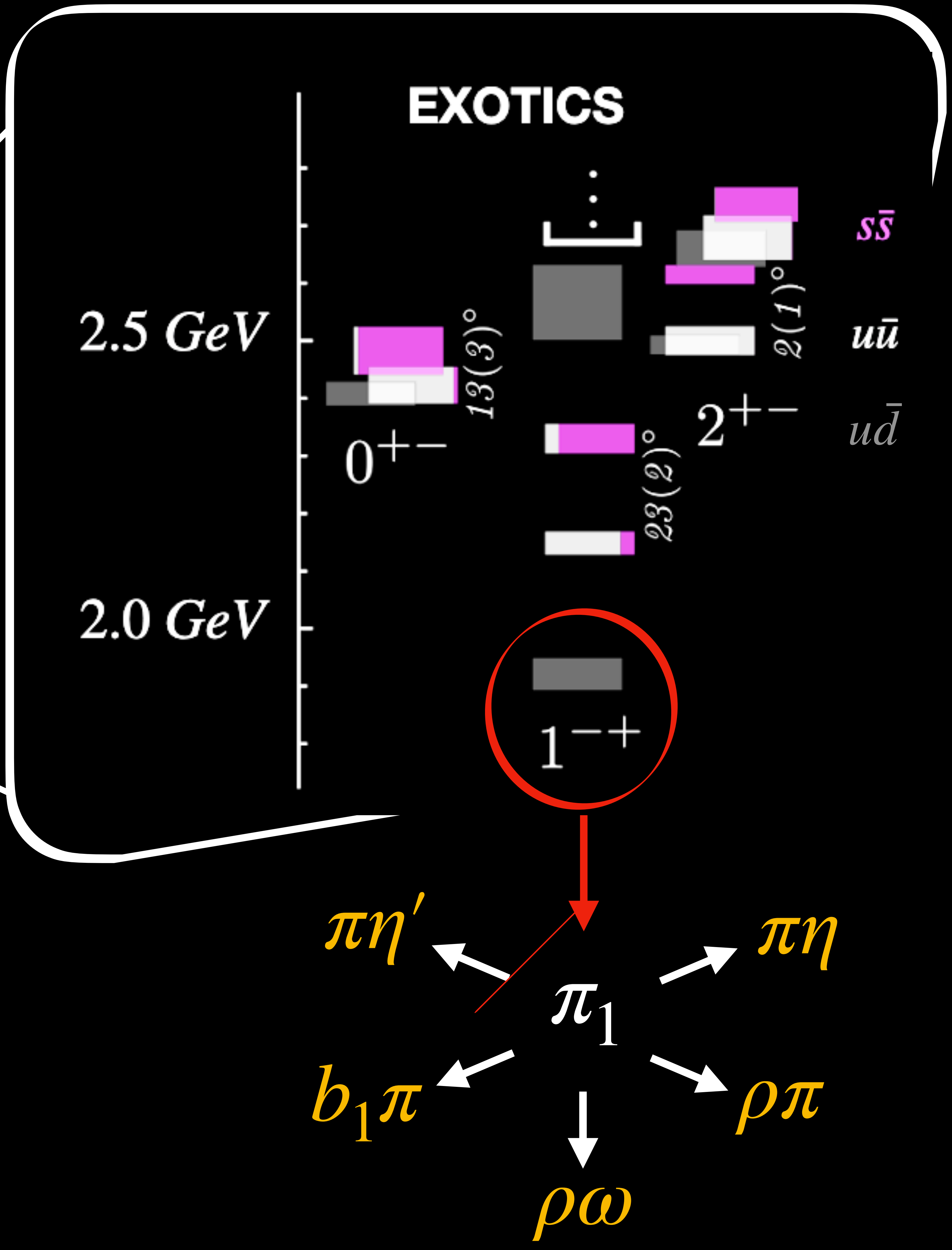

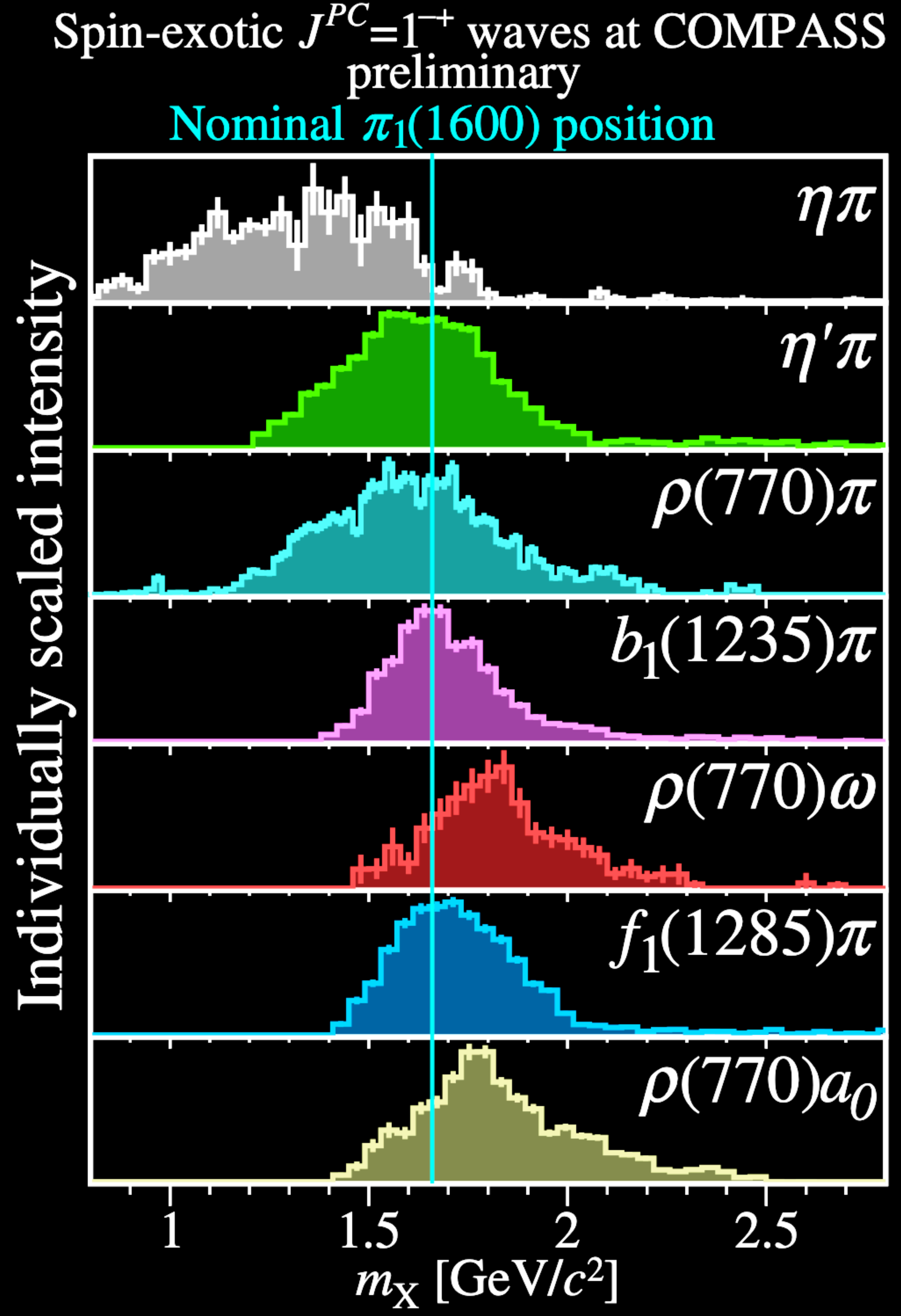

D. Spülbeck [on behalf of the COMPASS Collab], Proceedings of Science, HADRON (2026)

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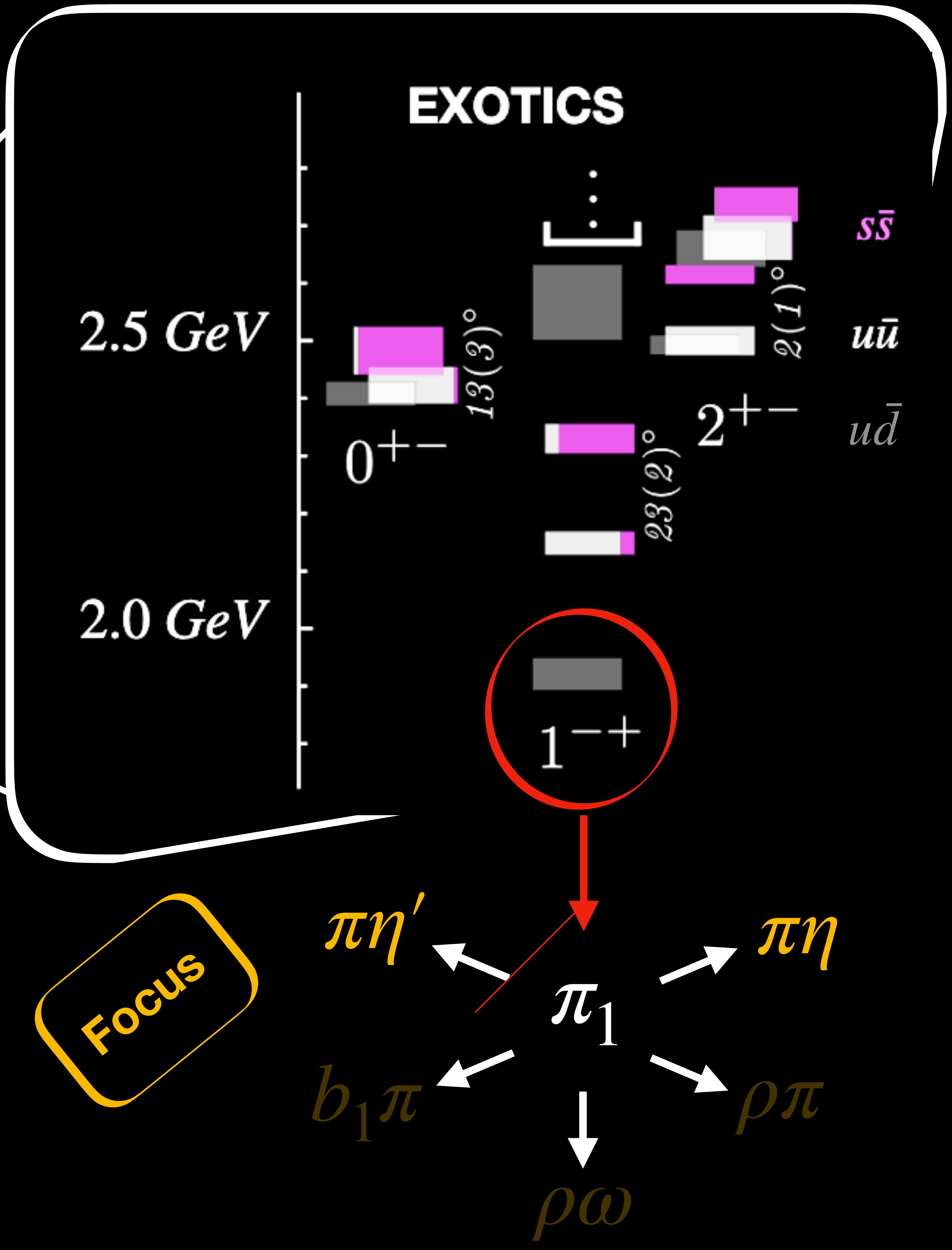

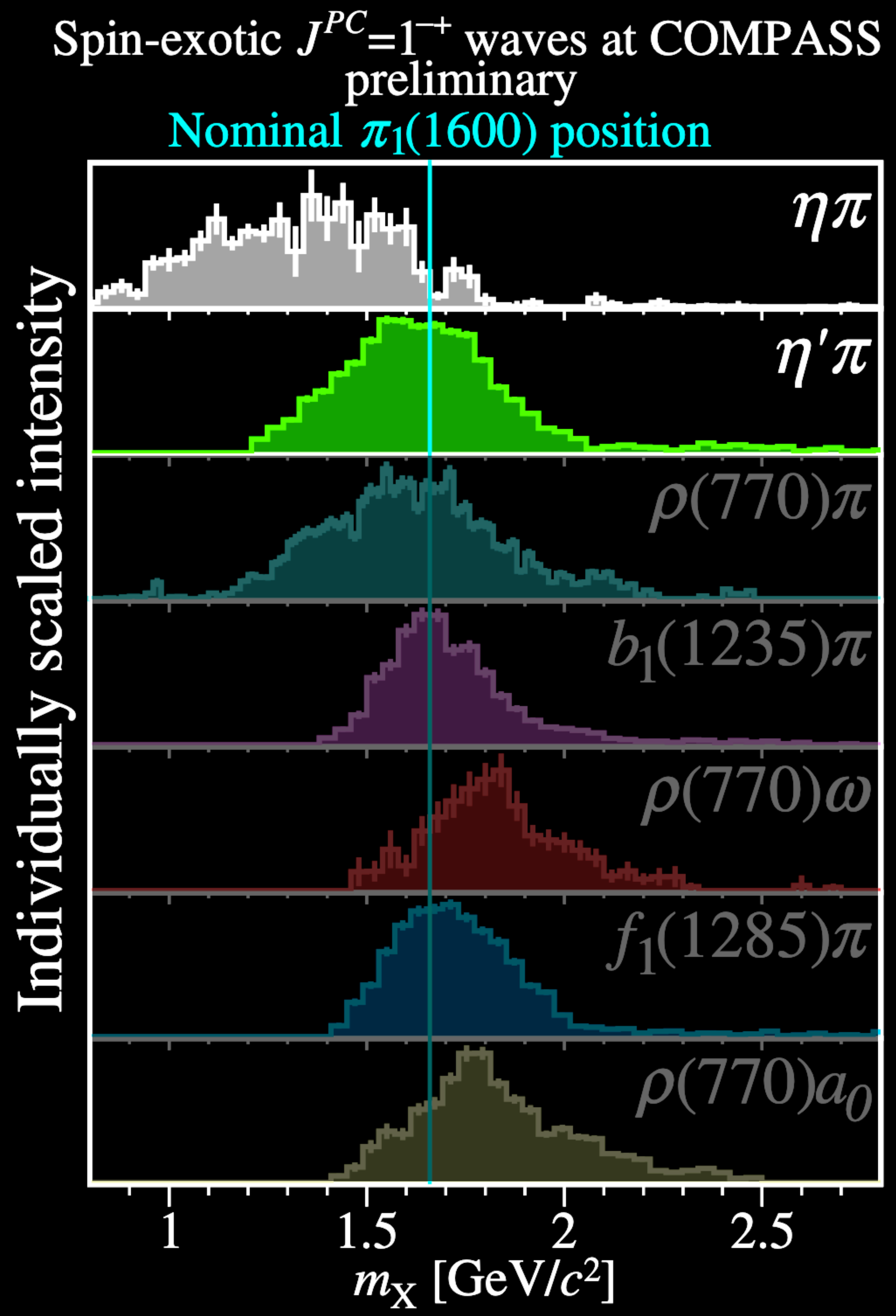

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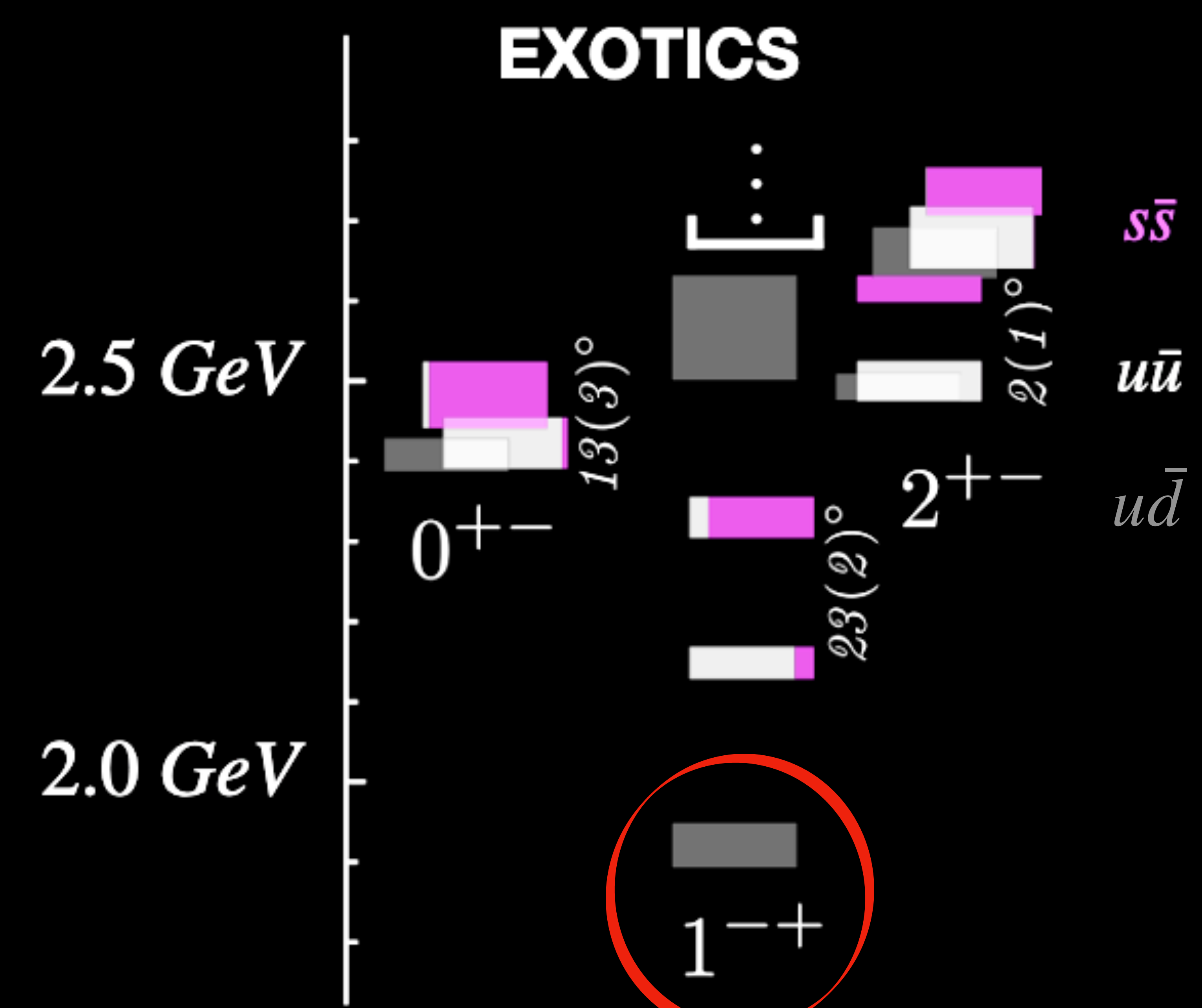


Focus

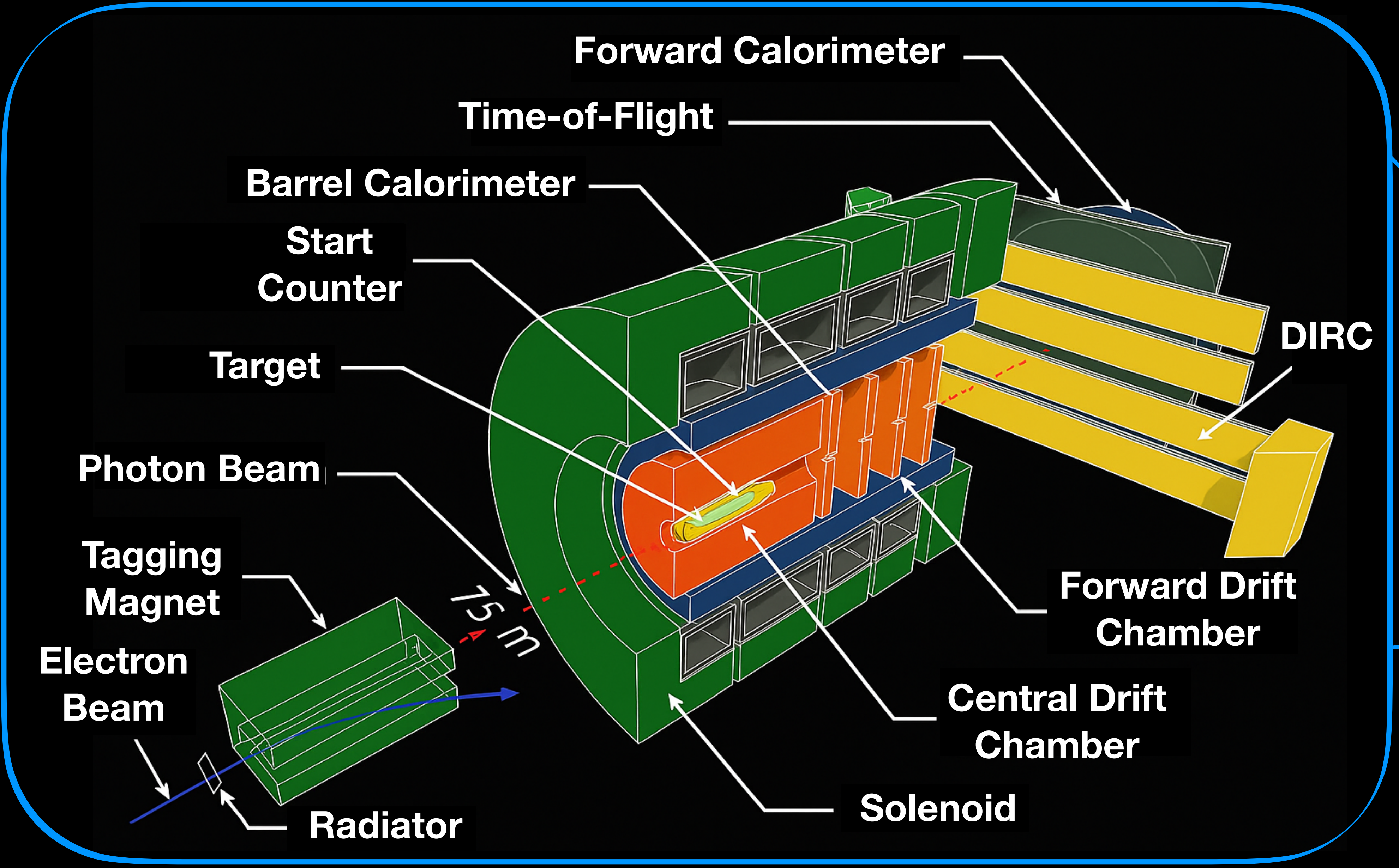
$\pi_1 \rightarrow \pi\eta'$, $\pi\eta$, $b_1\pi$, $\rho\pi$, $\rho\omega$

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

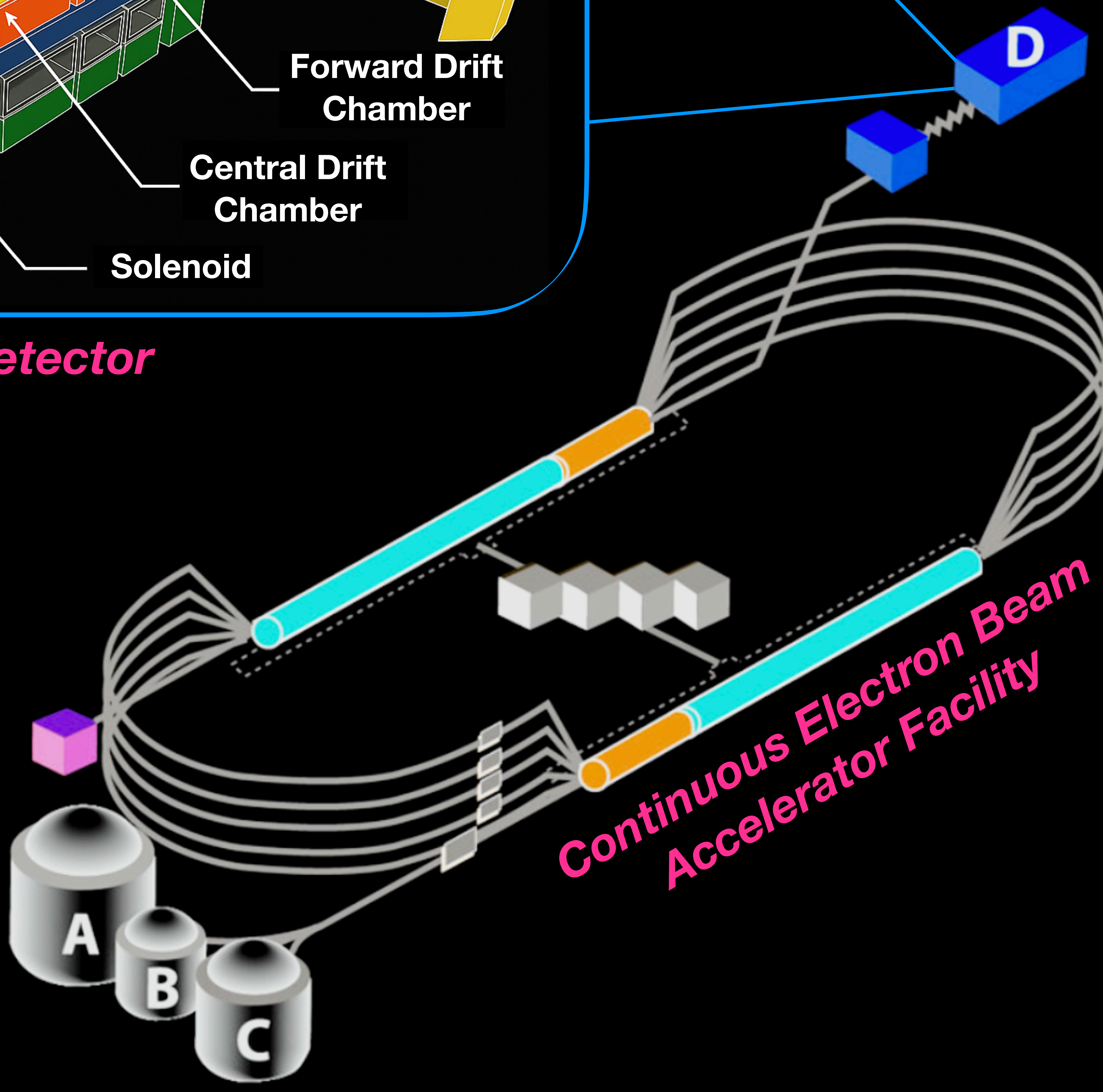
- all odd-L waves in $\eta^{(\prime)}\pi$ provide access to exotic quantum numbers
- simplistic 2-body final states
- historically, consistent observations of exotic resonances signal observed

Allowed Forbidden

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



GlueX Detector



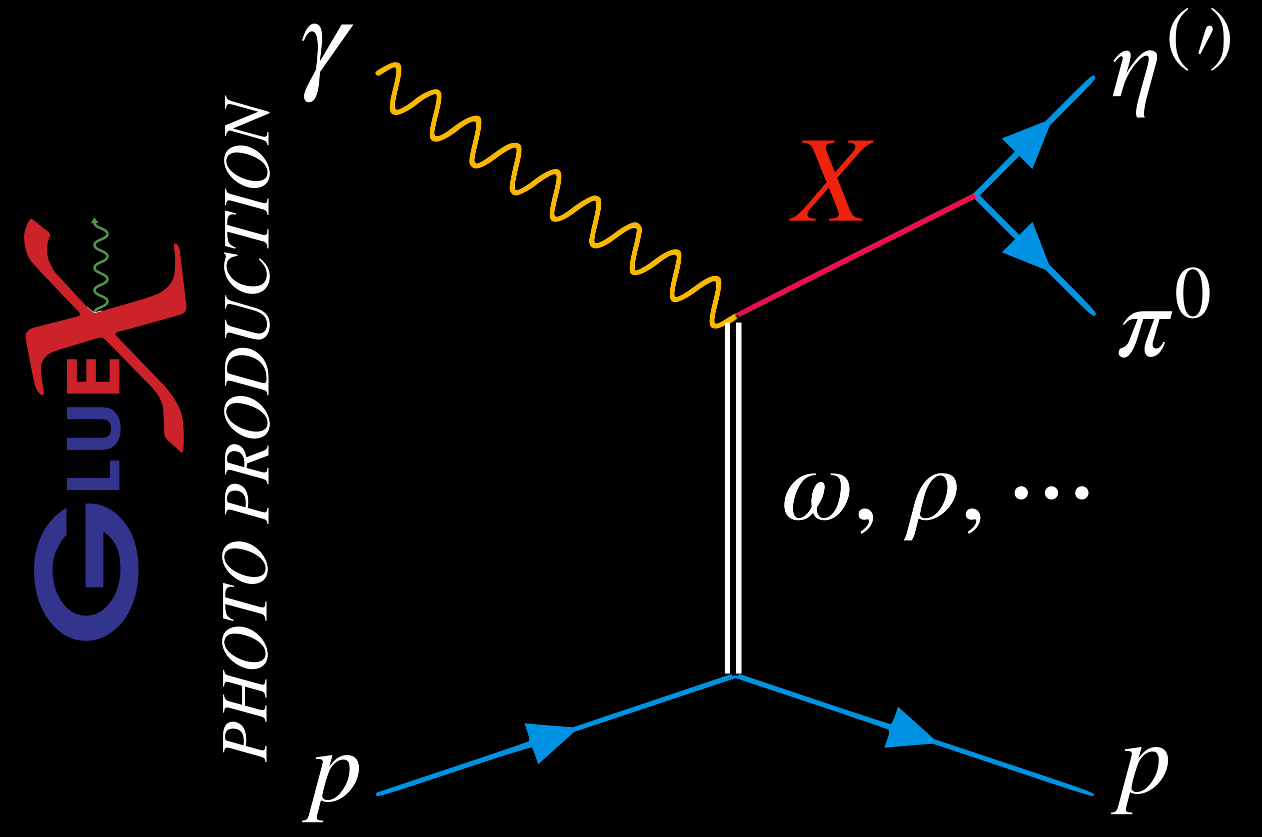
- designed to reconstruct final state particles from $\gamma p \rightarrow pM$
- 4 polarization orientations
- *GlueX-I* collected $\int L = 125\ pb^{-1}$ in *coherent peak*
- *GlueX-II* ~ 3-4 times more (currently ongoing)

Photoproduction ⇒ *extremely* versatile

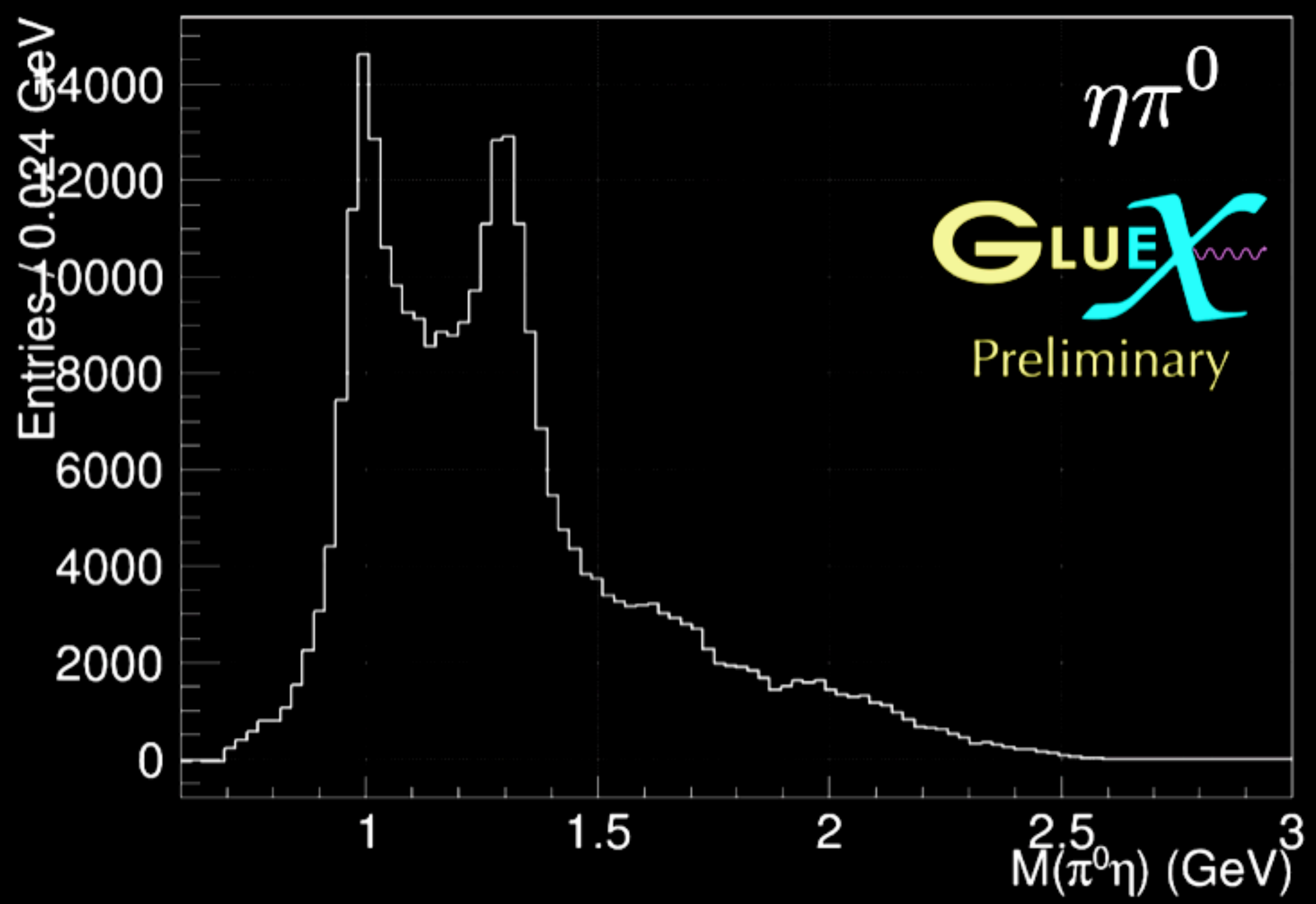
- access to large range of resonances
- complementary to hadroproduction (COMPASS, etc.)

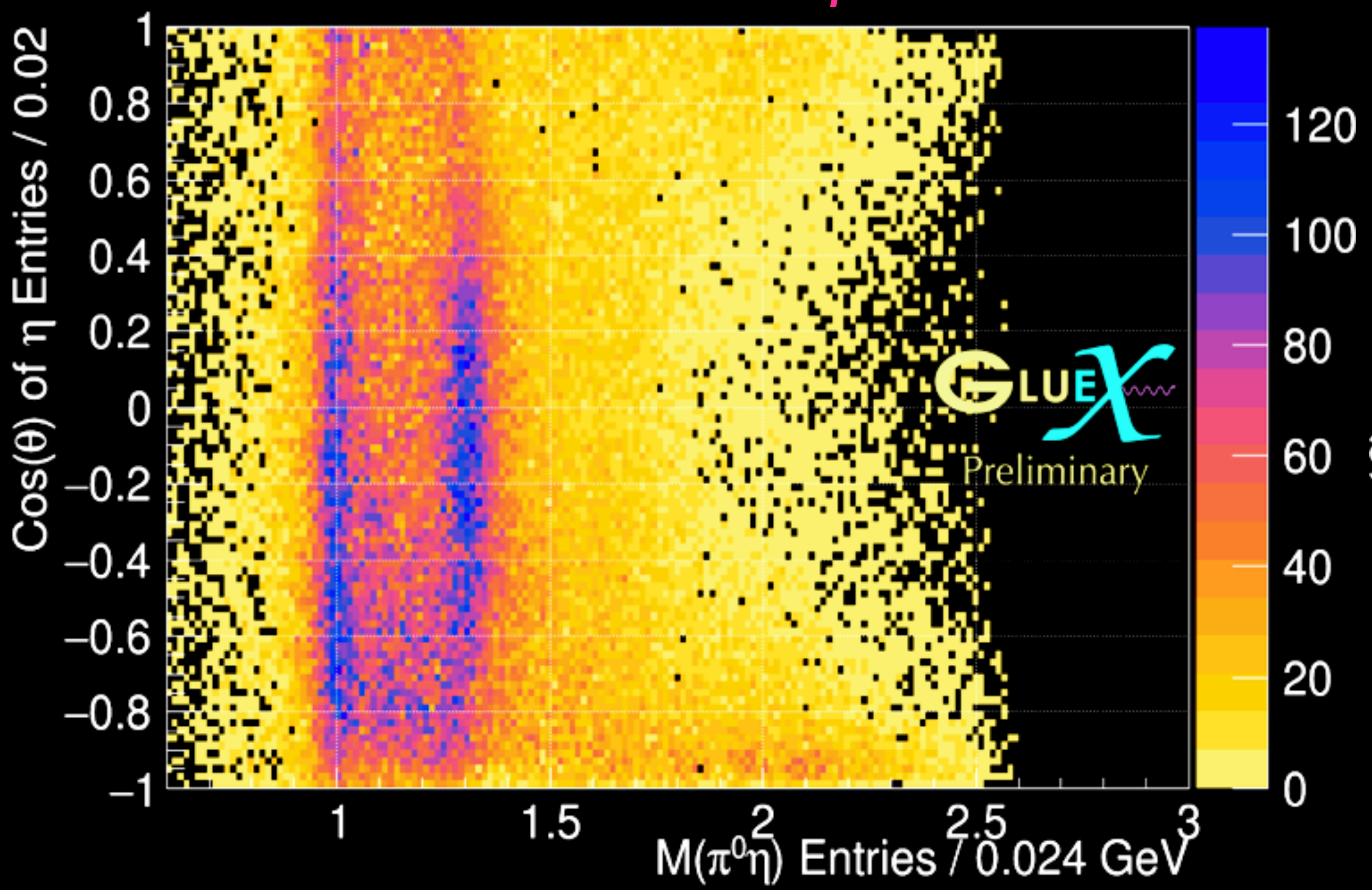
{ Start *simple* to understand production of less complex hadrons }

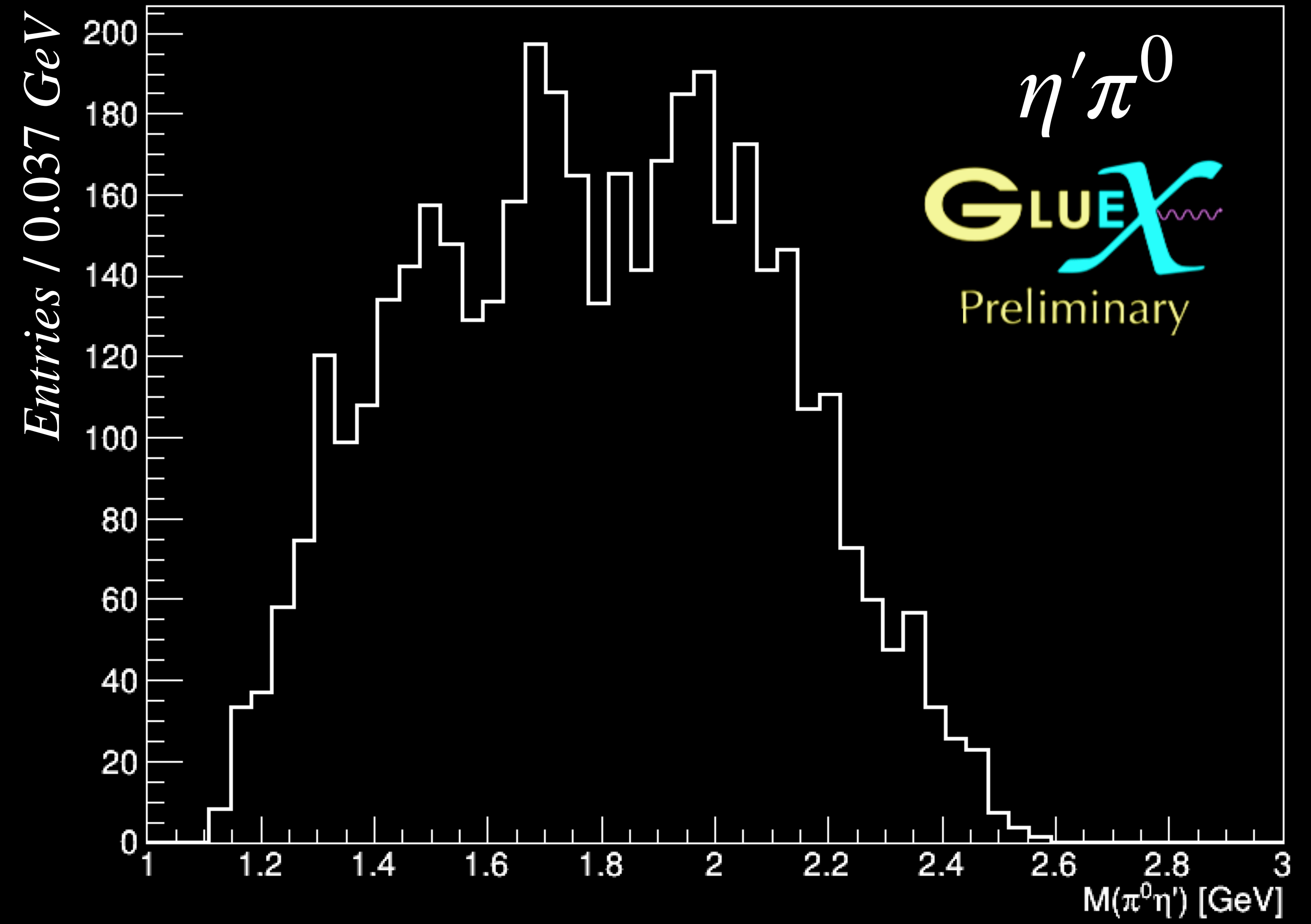
- study background, acceptance, non-resonant contributions, etc.

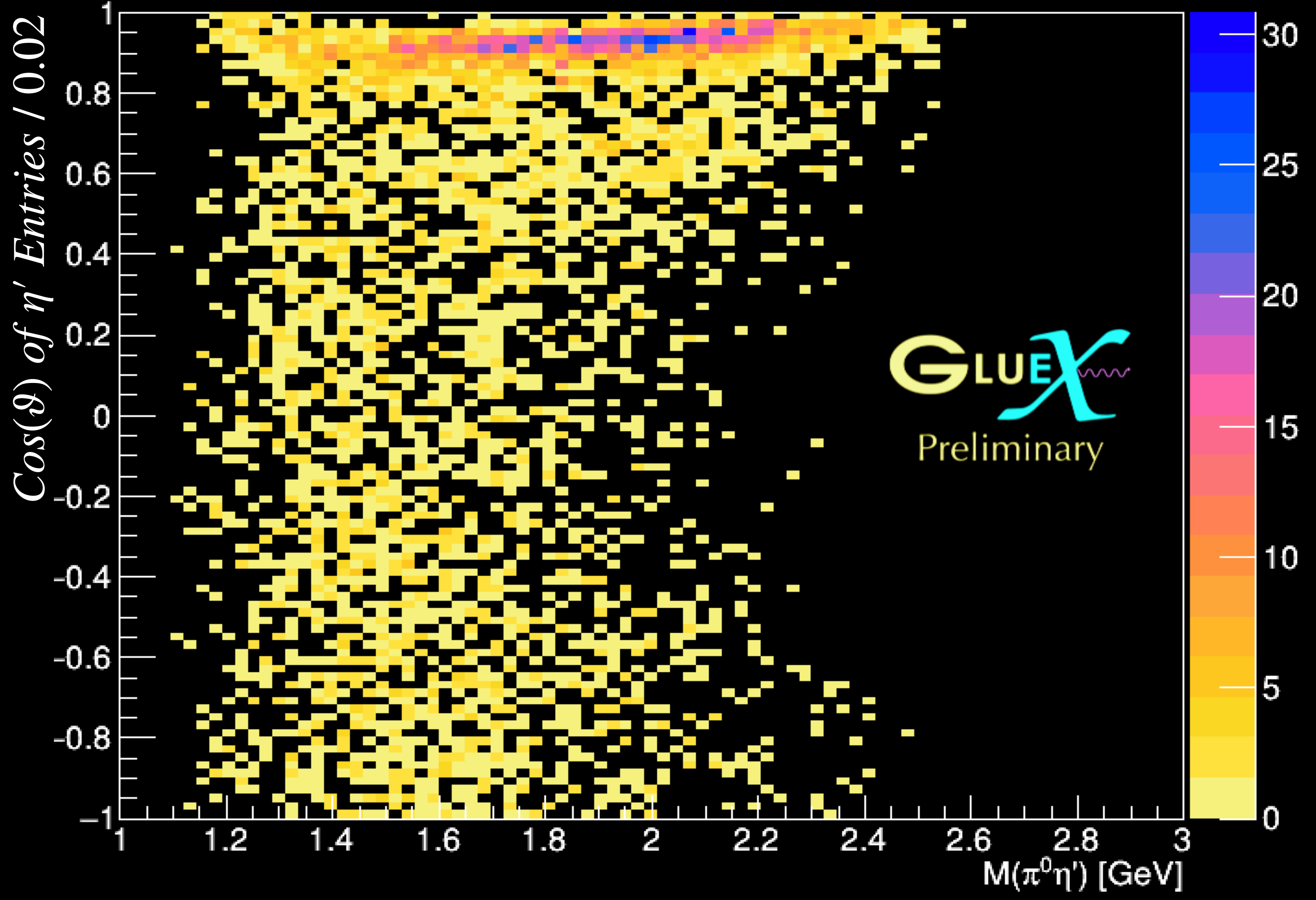


$0.1 < -t\ [GeV^2] < 0.3$



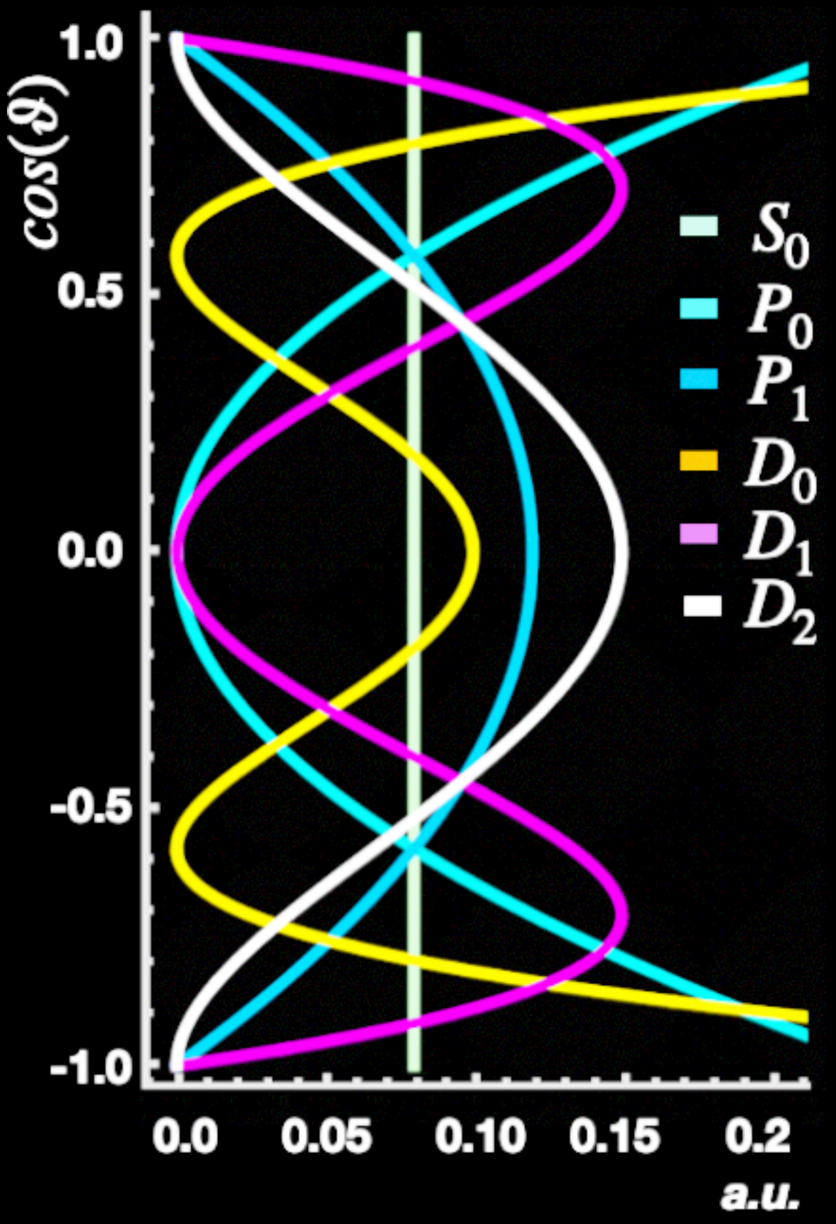






Neutral decay modes

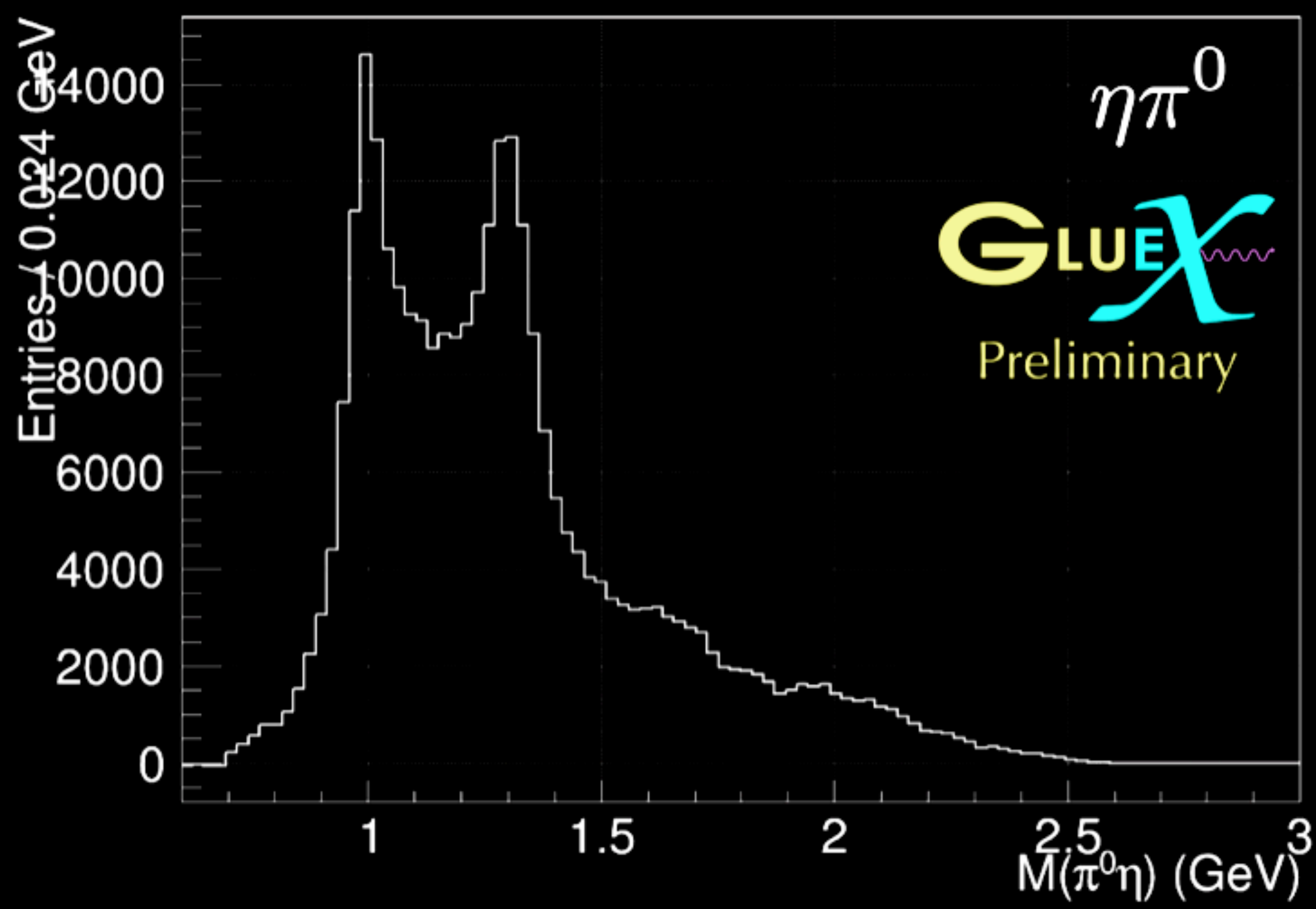
- $\eta\pi^0 \rightarrow 4\gamma$
- $\eta'\pi^0 \rightarrow 4\gamma\pi^+\pi^-$



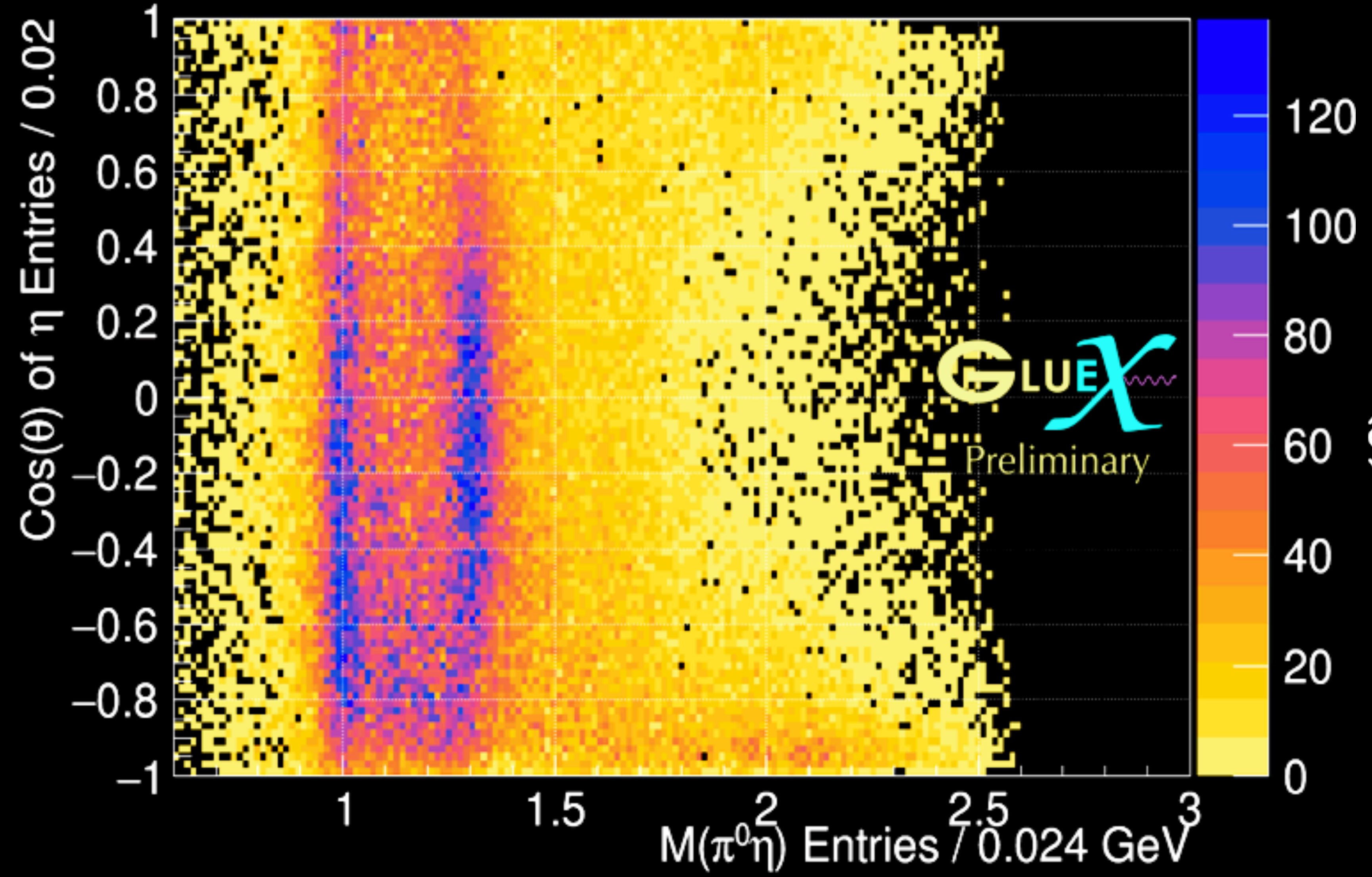
Charged decay modes also being analyzed …

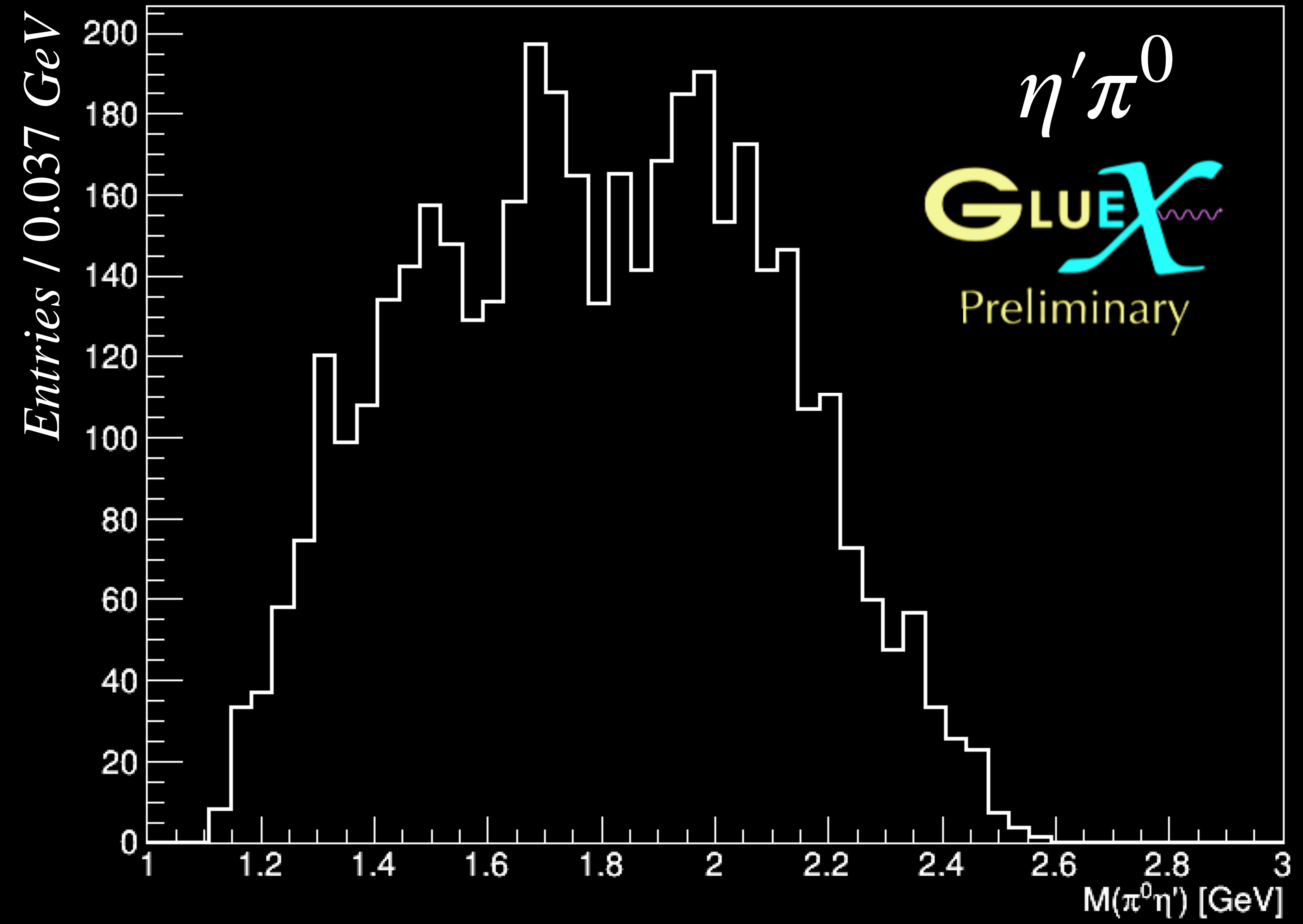
- $\eta^{(\prime)}\pi^-\Delta^{++}$ | $\Delta^{++} \rightarrow \pi^+ p$, $\eta' \rightarrow \eta\pi^+\pi^-$

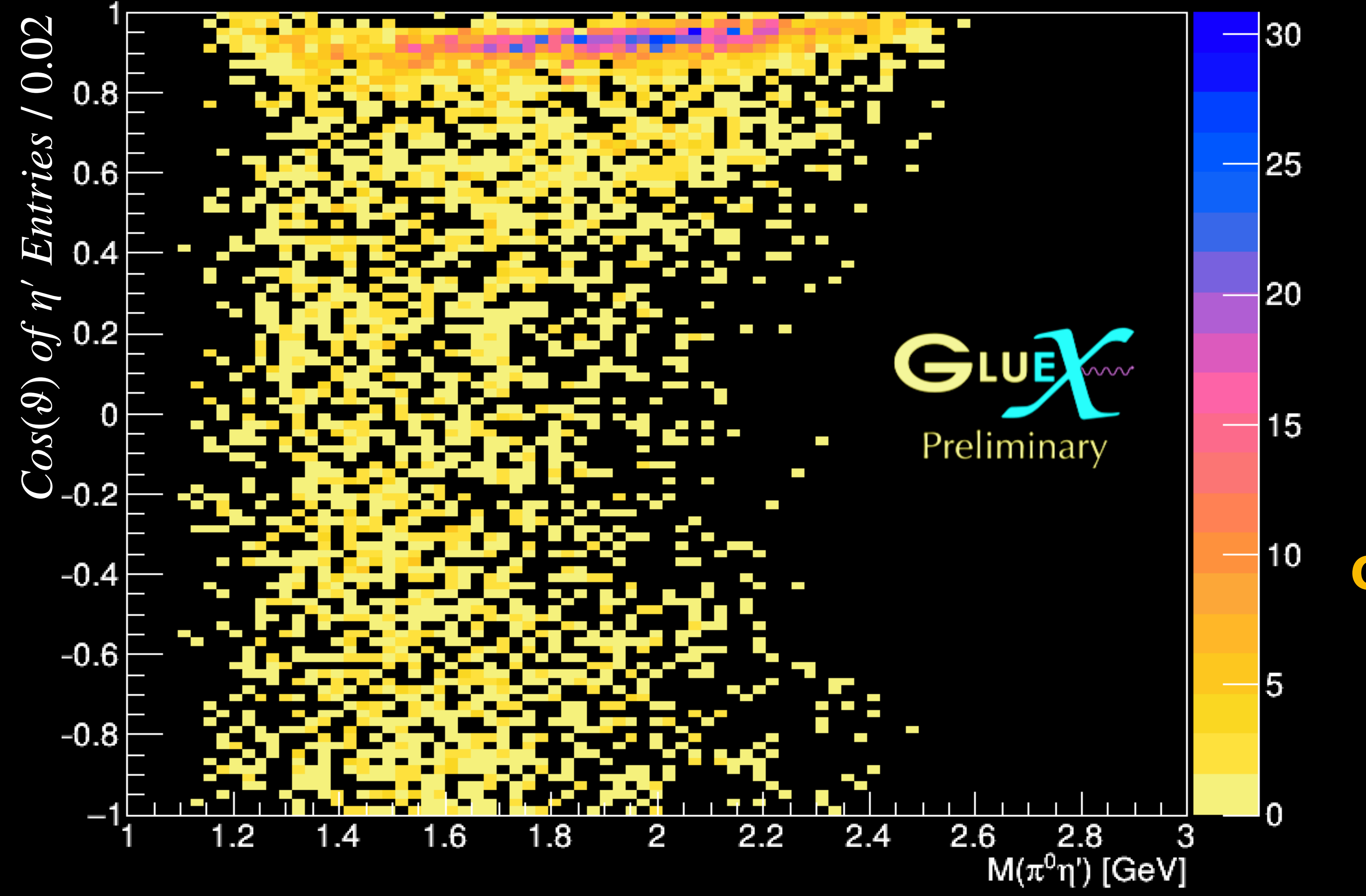
$0.1 < -t\ [GeV^2] < 0.3$



Not acceptance corrected







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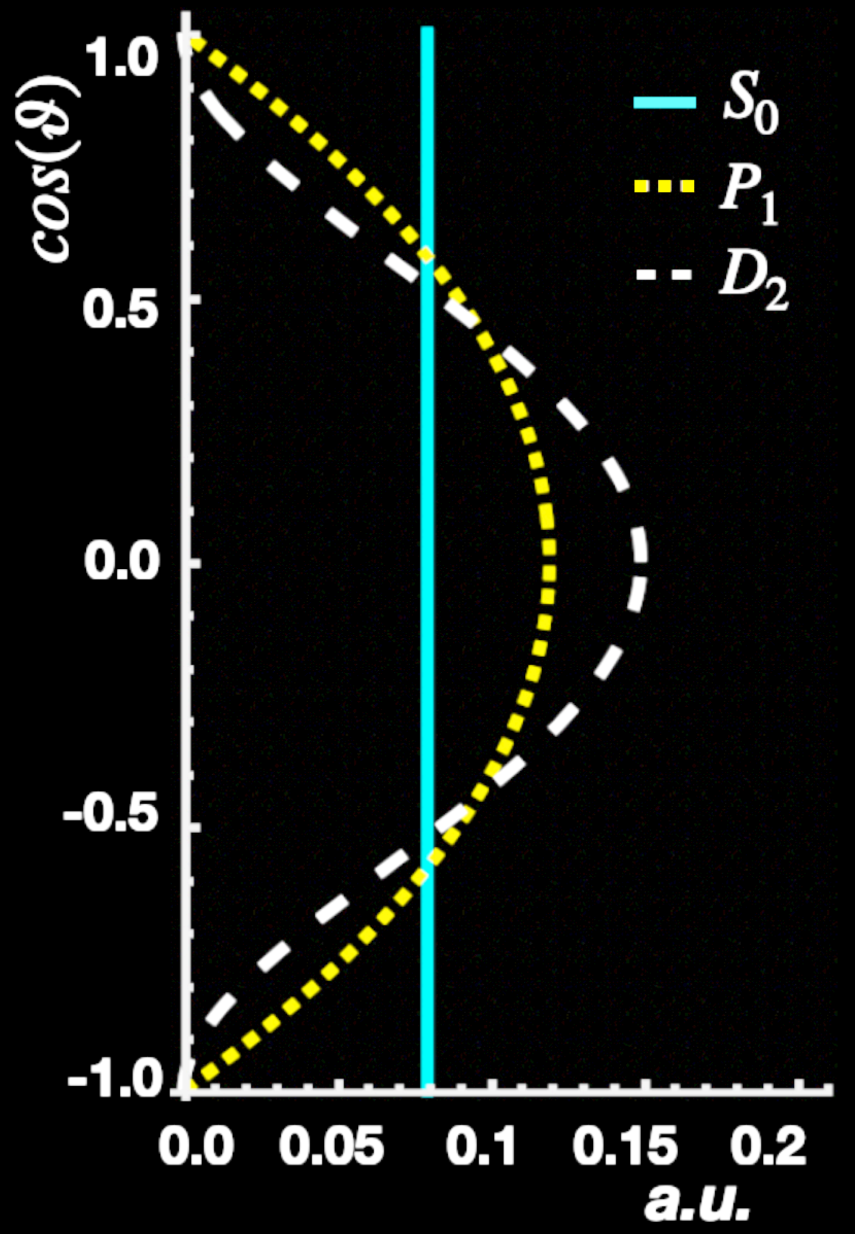
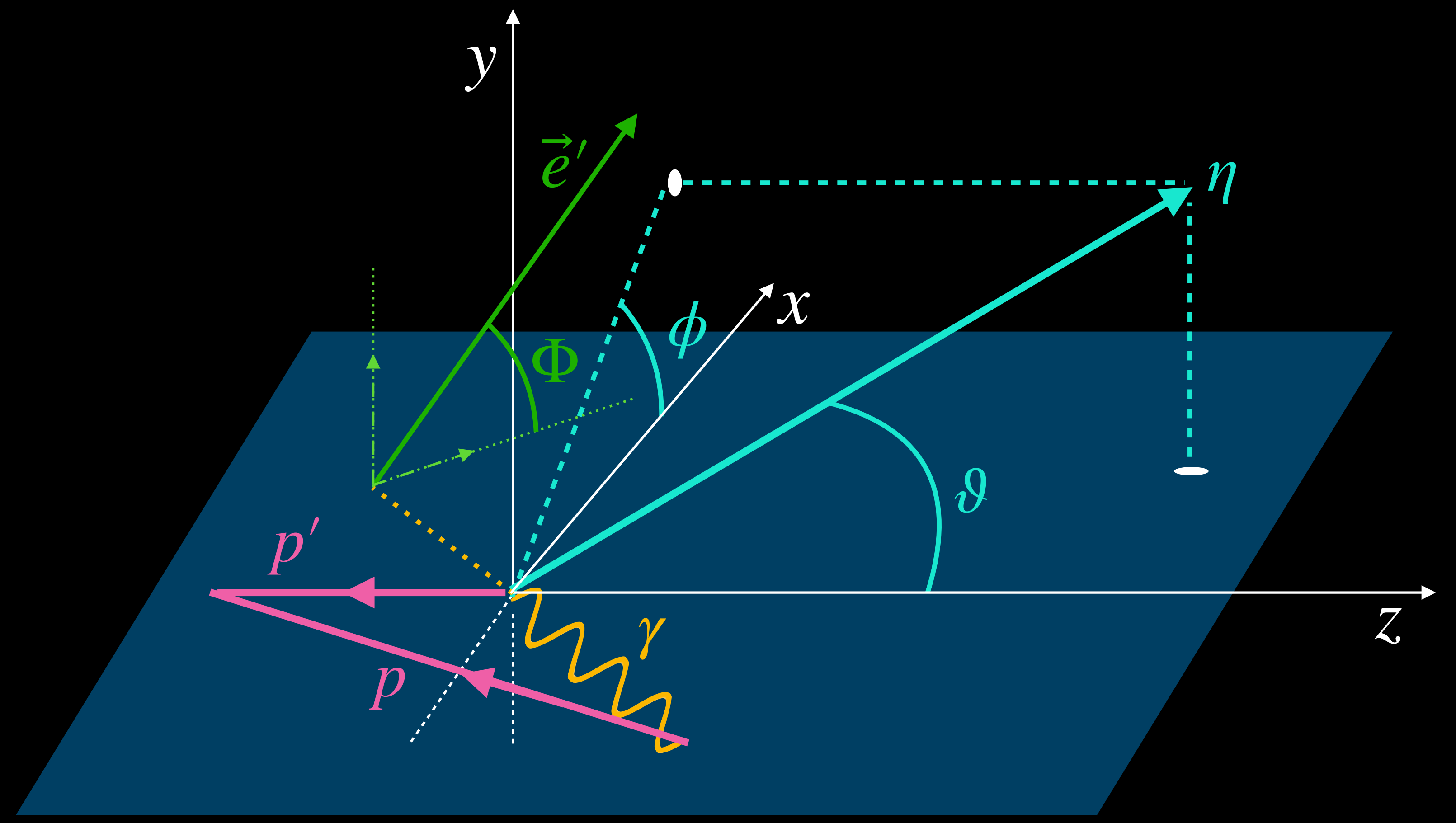


Dominant S_0 and D_2 contributions observed

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

- 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
  $\Phi \rightarrow$ between the polarization and production plane



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

- reflectivity corresponds to exchange being natural (+) and unnatural (-) parity
- 4x more amplitudes than hadroproduction

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

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

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 $-t$

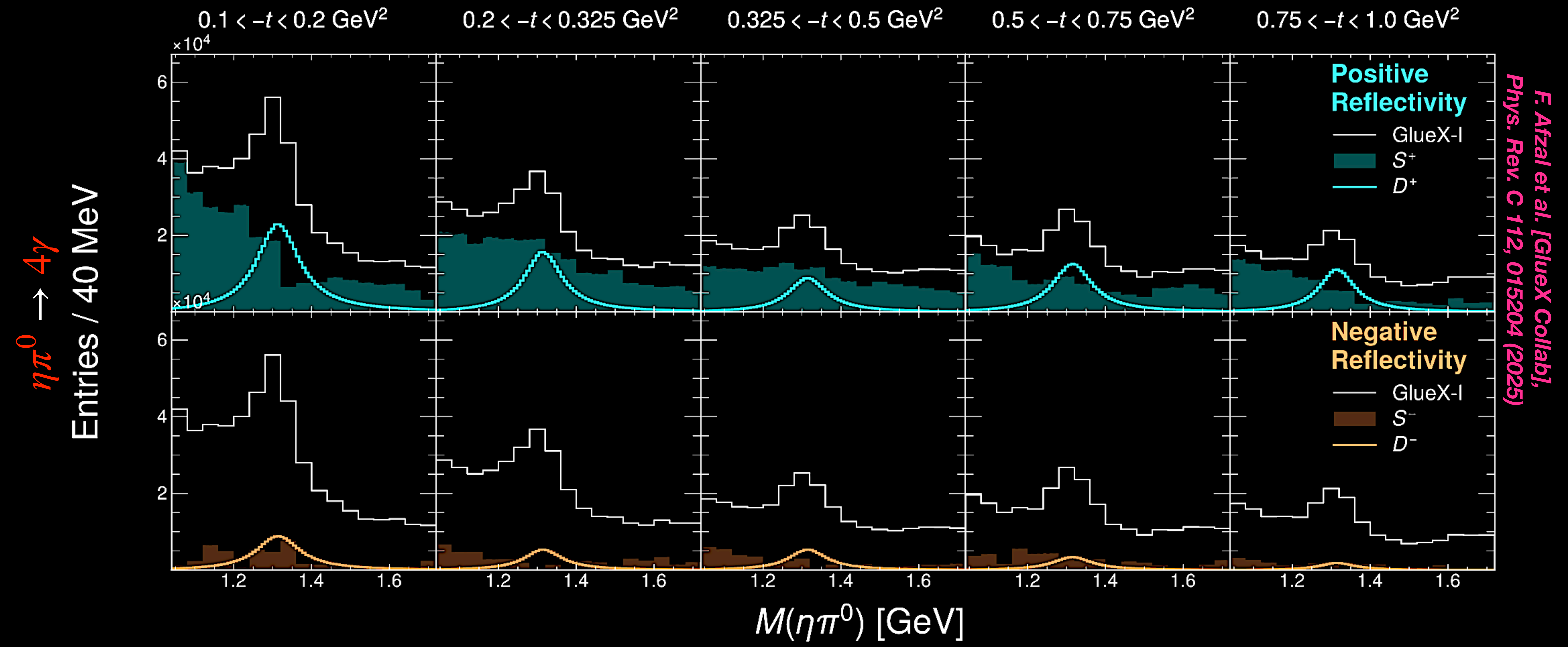
- incoherent sums of (+) and (-) reflectivities

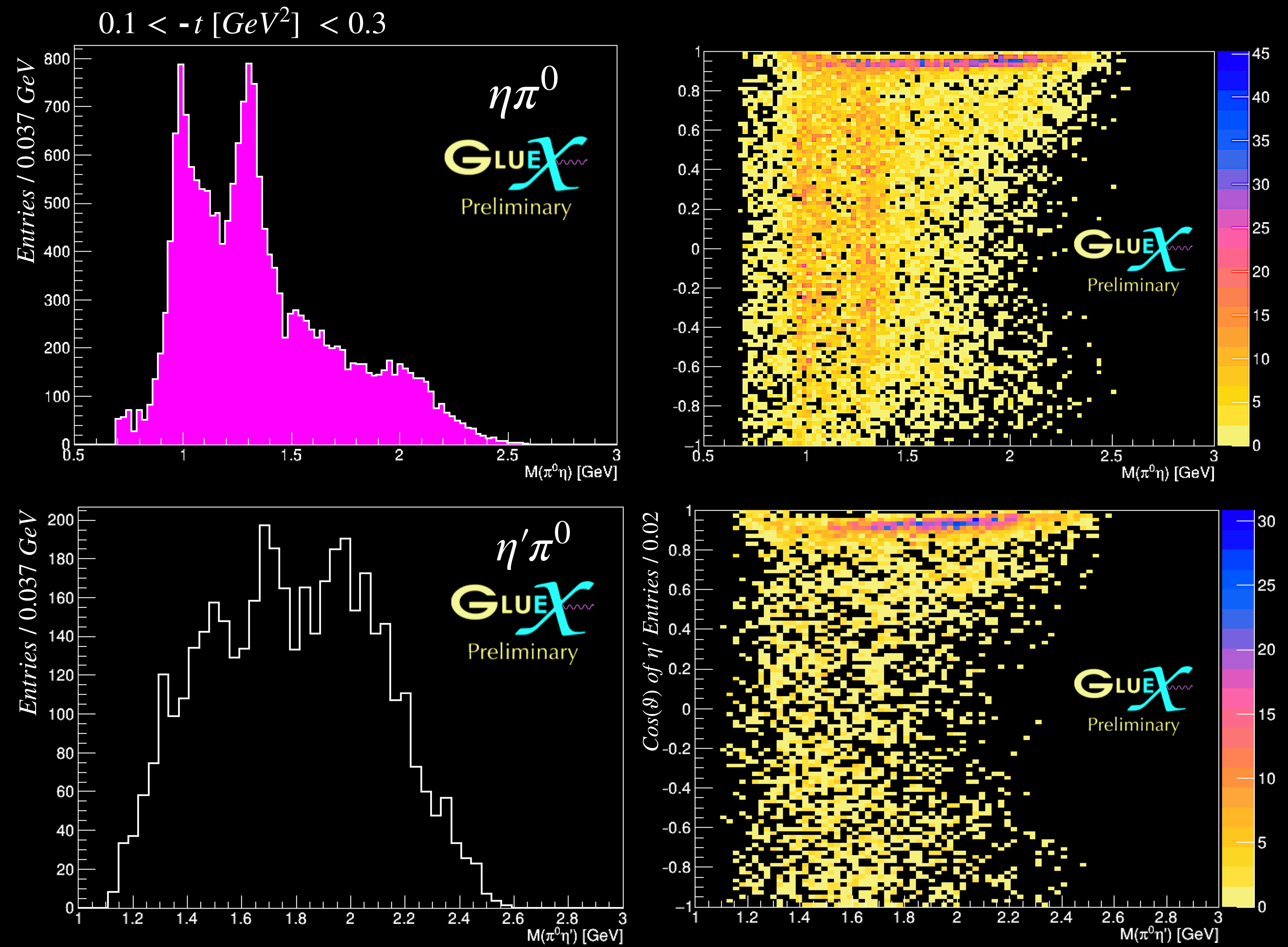
$$\eta = P(-1)^J$$

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 $\eta'\pi$





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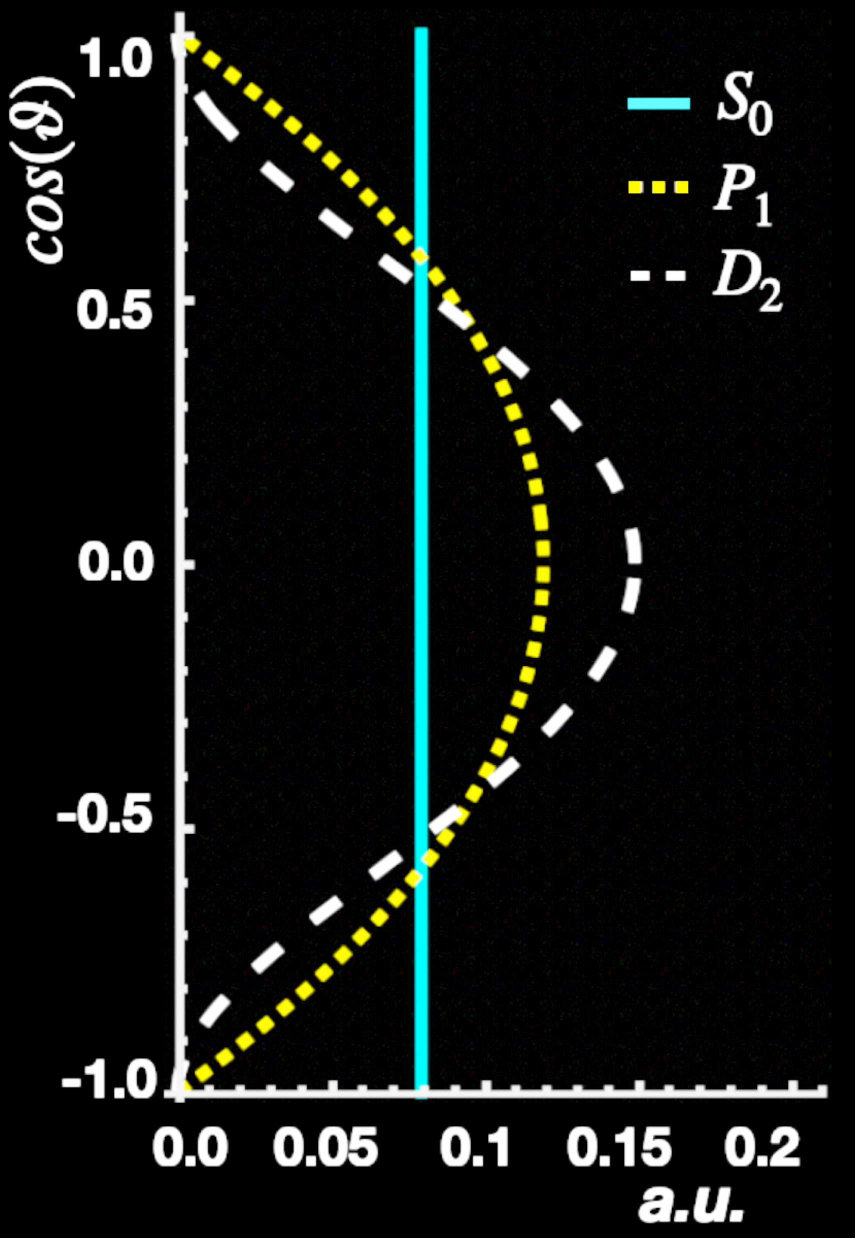
} Same final state



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

Spectra are not observables of resonance structure

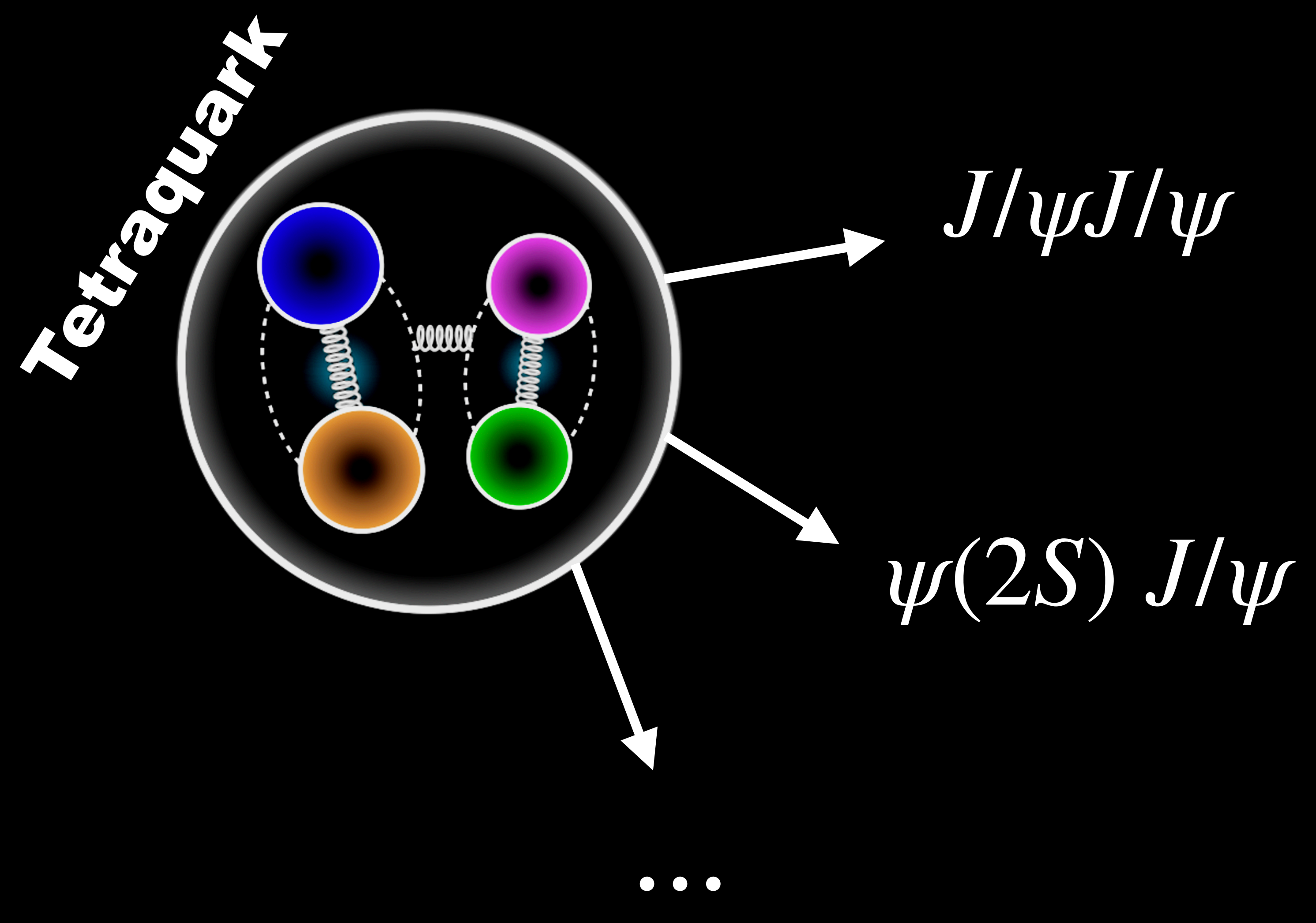
- measured distributions depend on production dynamics
- a single decay channel samples only a projection of the full S-matrix

highly populated spectrums
=
overlapping & interfering resonances

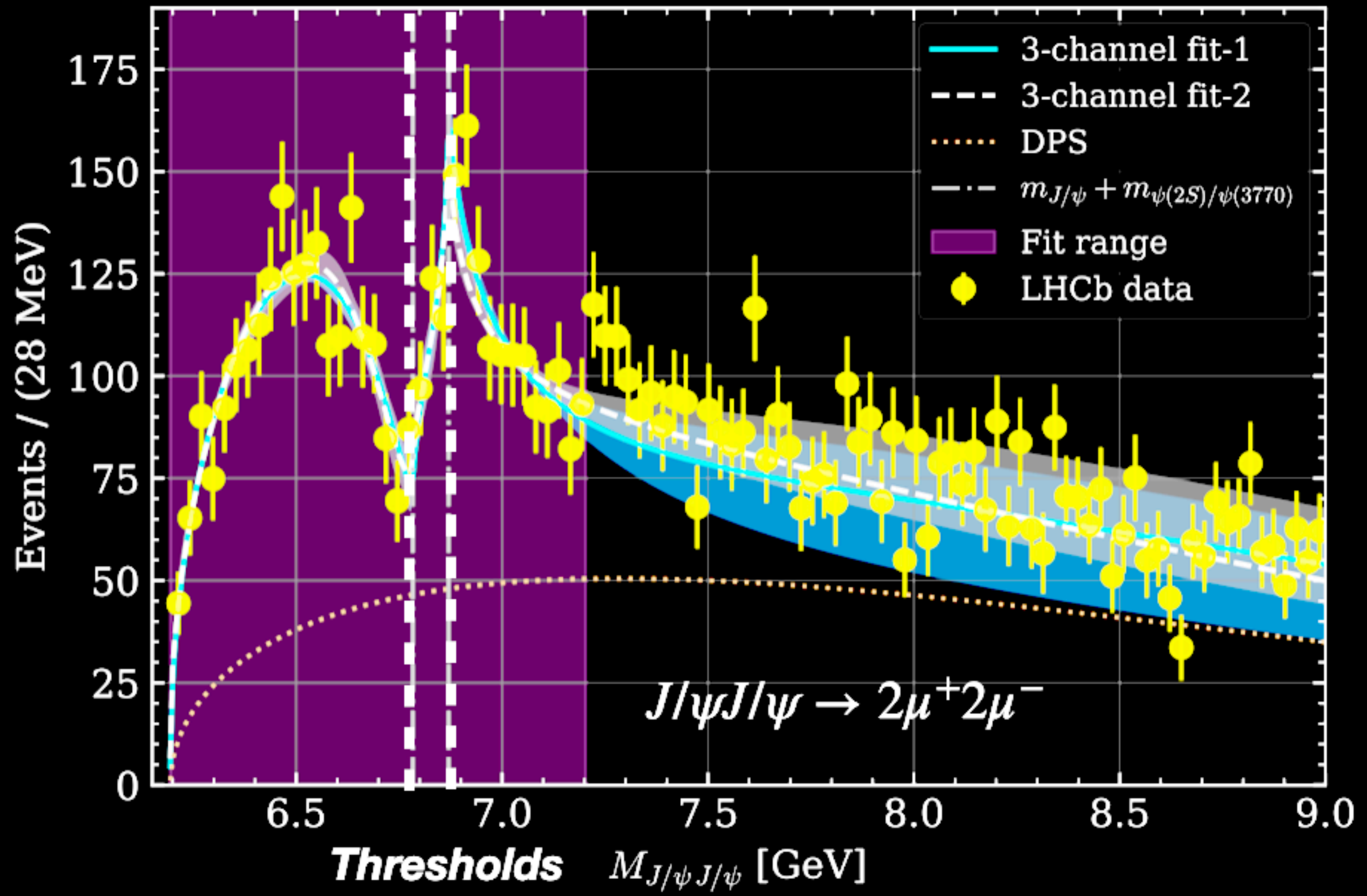
Overall, single channel *analyses cannot fully disentangle complex interference or threshold behavior*

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

$\therefore$ production and decay can shape the spectrum, but not the resonance itself



Theory Prediction Example



Xiang-Kun Dong et al., Phys. Rev. Lett. 126, 132001 (2021)

JPAC analysis utilizing COMPASS data $\rightarrow N(s)/D(s)$

- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
- describes dominate a_2 resonances and the π_1
- poles identified via analytic continuation (zeros of $D(s)$), not peak positions

Angular Momentum Barrier Factors

Production Term (smooth, real functions)

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

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

Analytic Denominator Matrix

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

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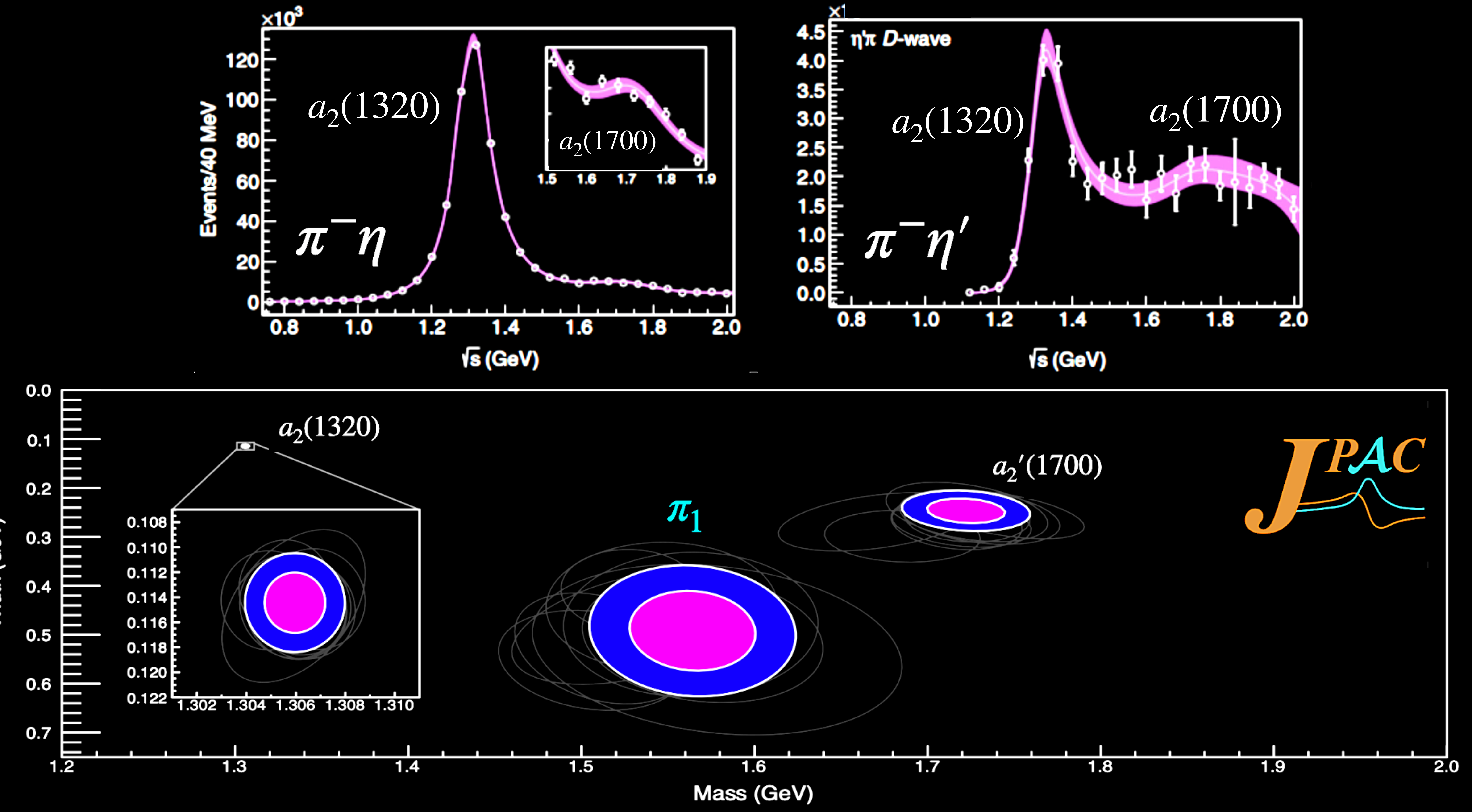
A single pole explains structures in multiple channels with shifted peaks

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



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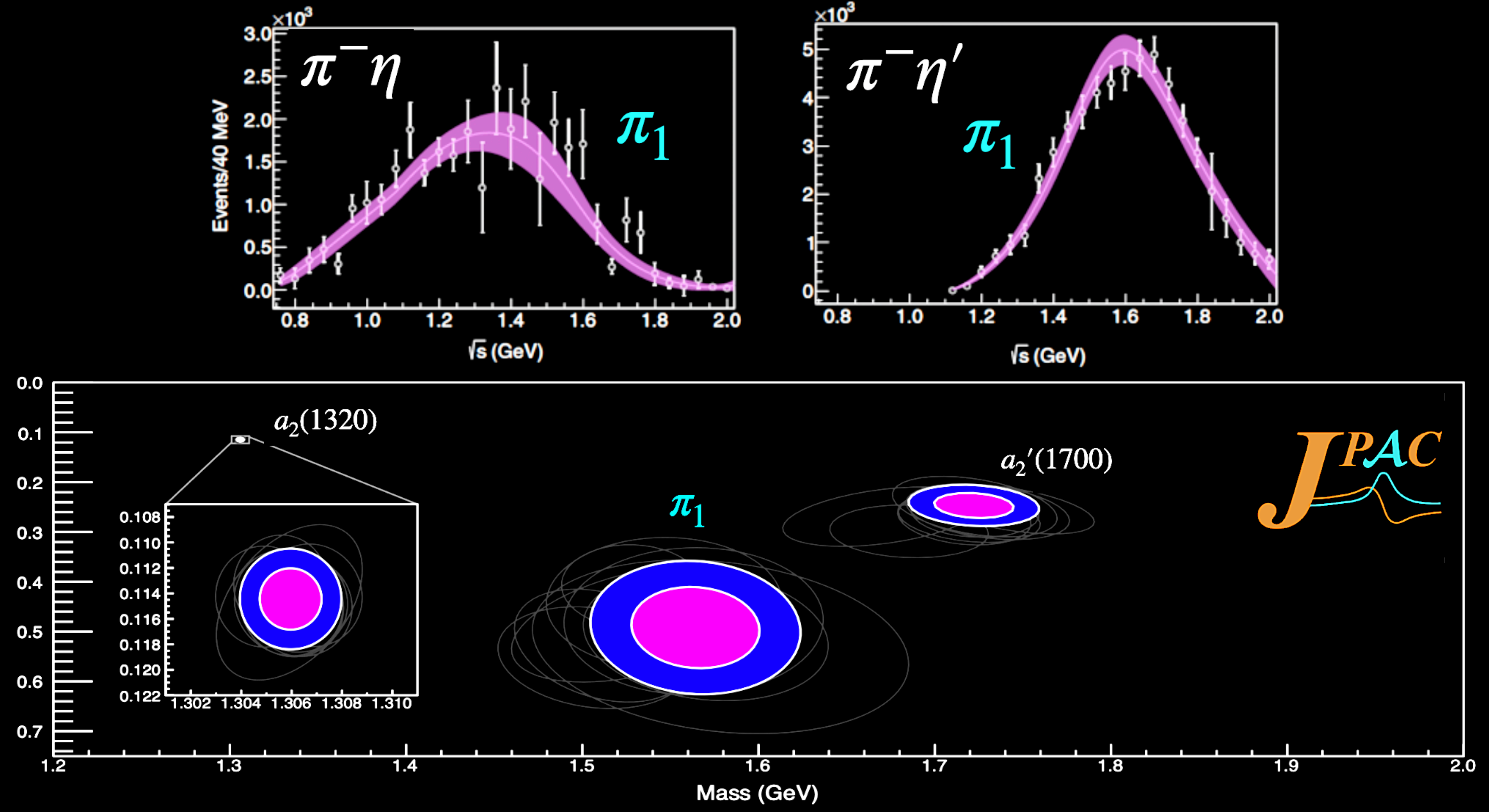

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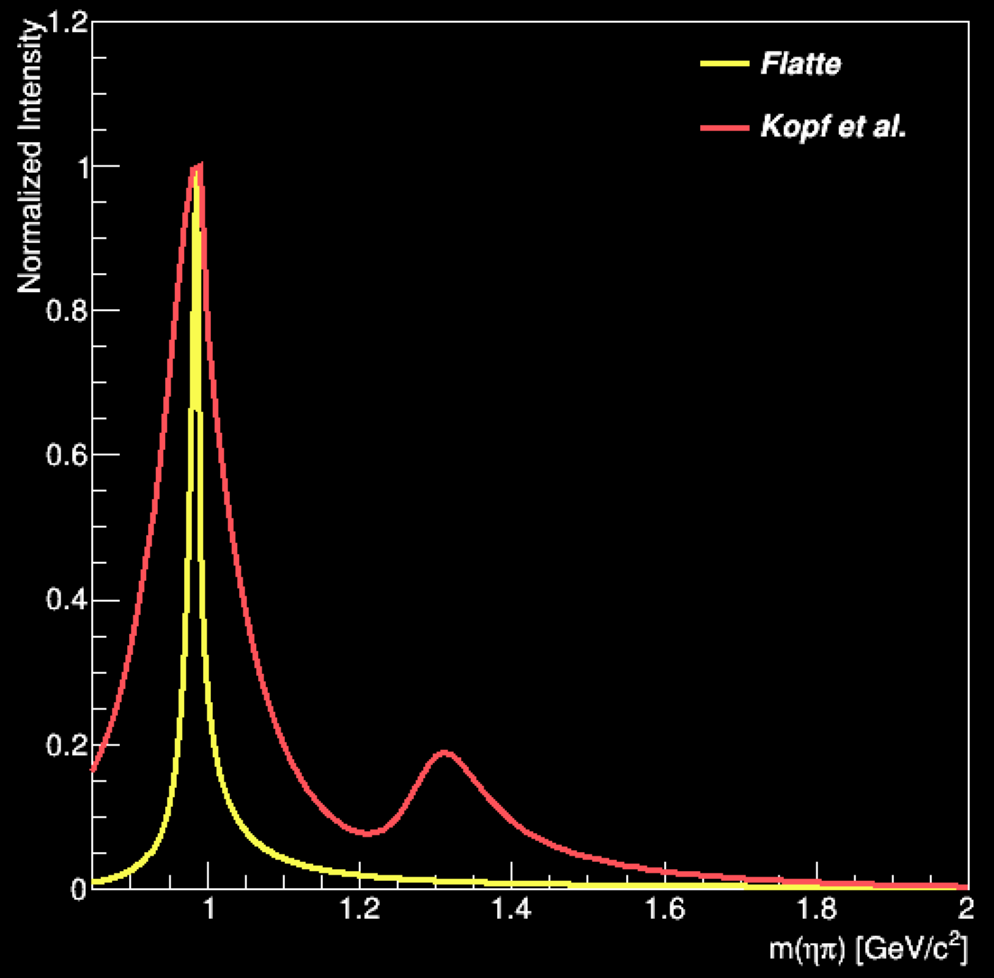
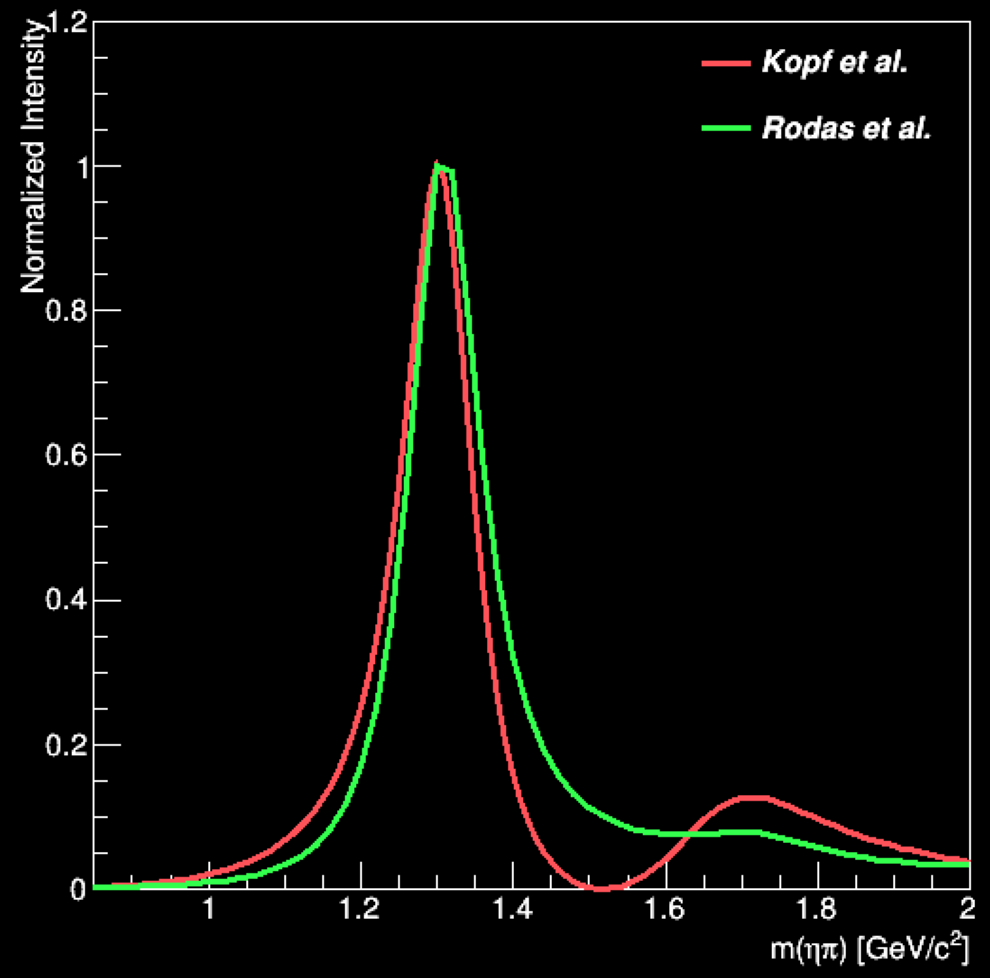
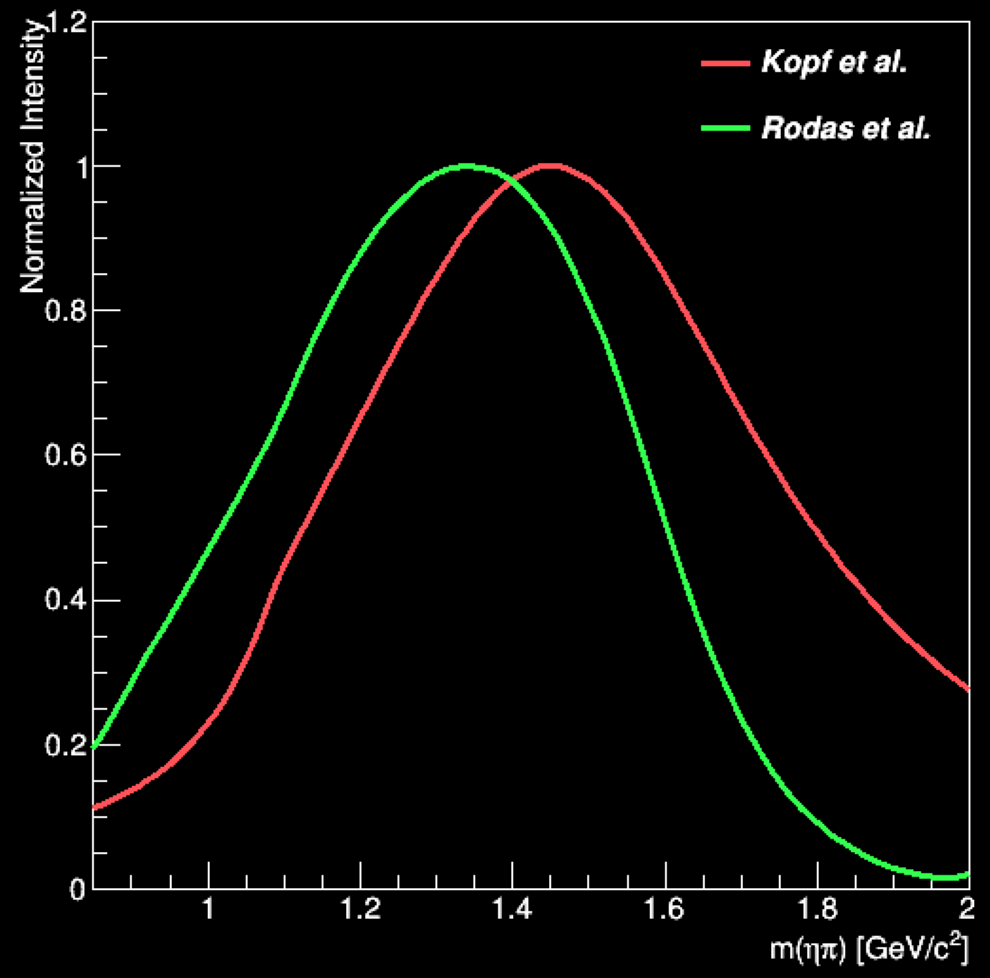
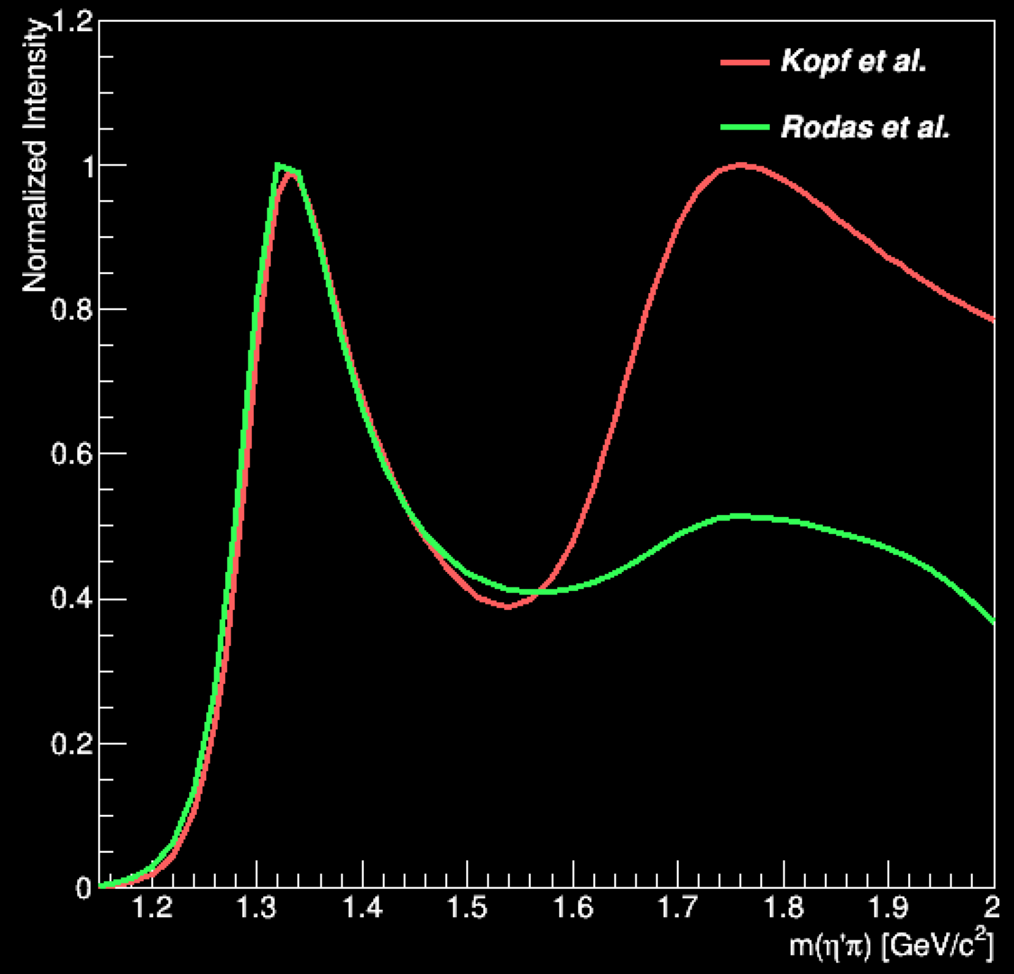
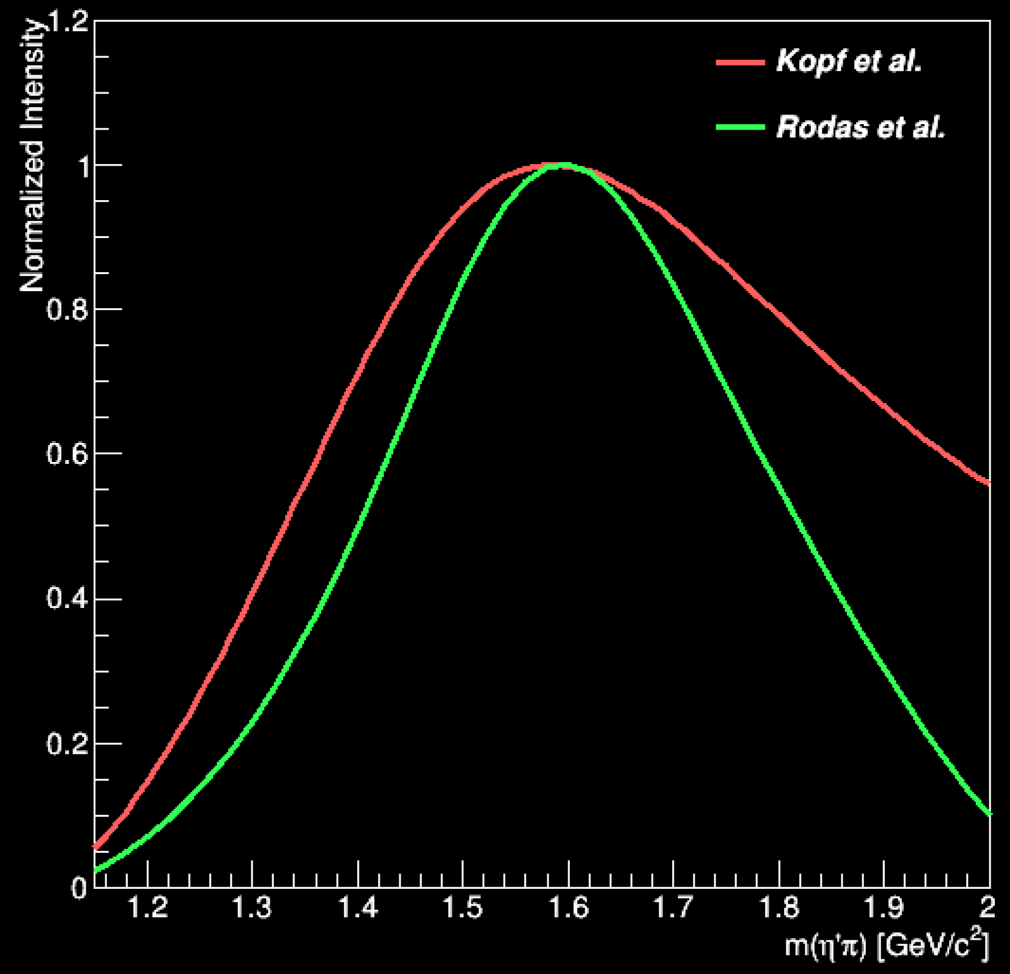
S_{wave} D_{wave} P_{wave}











No coupled-channel parameterization of S_{wave} in $\eta' \pi$

Numerically evaluation of amplitudes from Rodas, *et al*. & other coupled-channel models to GlueX data

Scattering and pole structures are universal

- can use published results to fit photoproduced $\eta\pi$ and $\eta'\pi$!

Other methods:

Flatté

S. M. Flatté, Phys. Lett. B 63, 224 (1976)

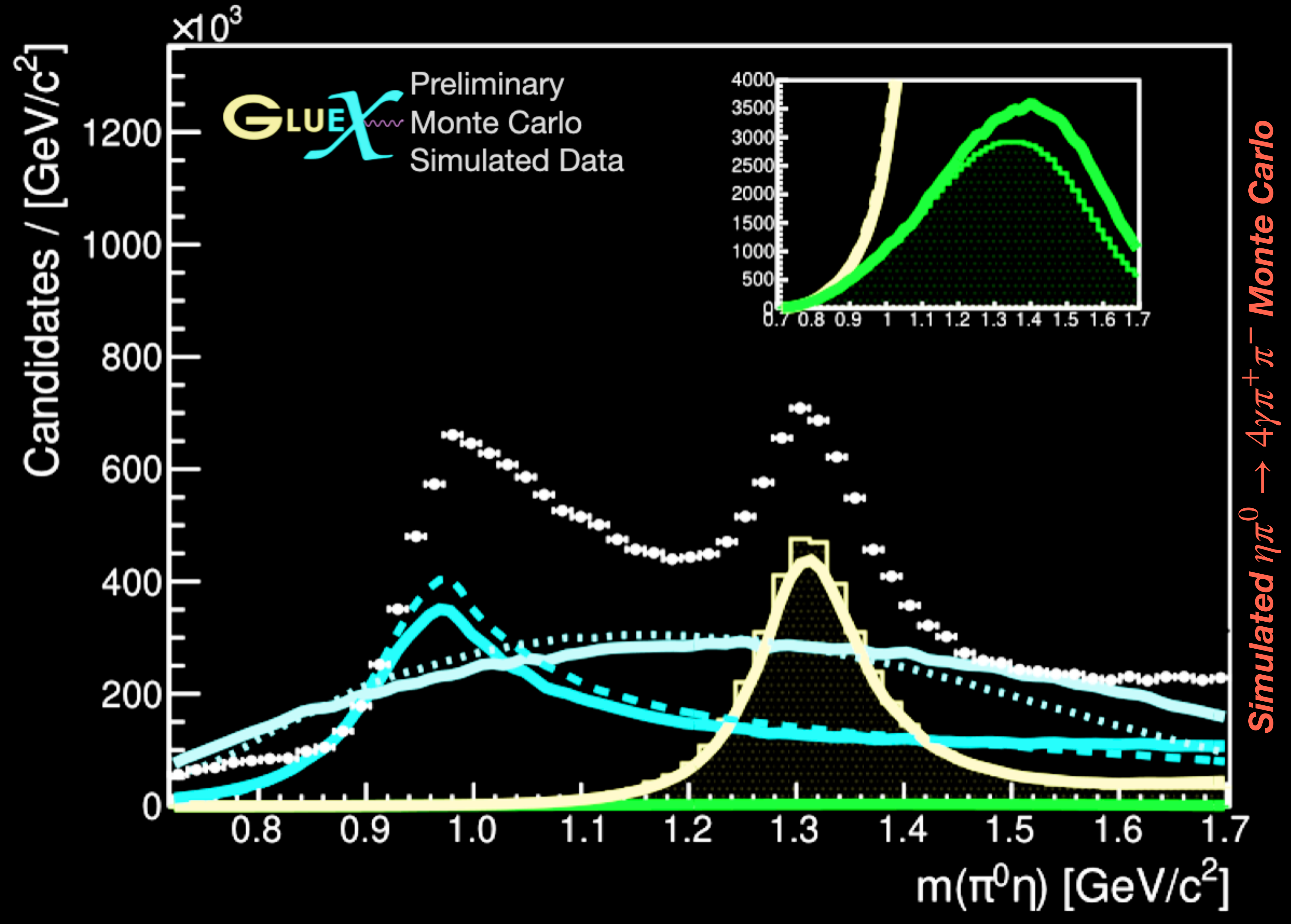
Kopf, *et al*.

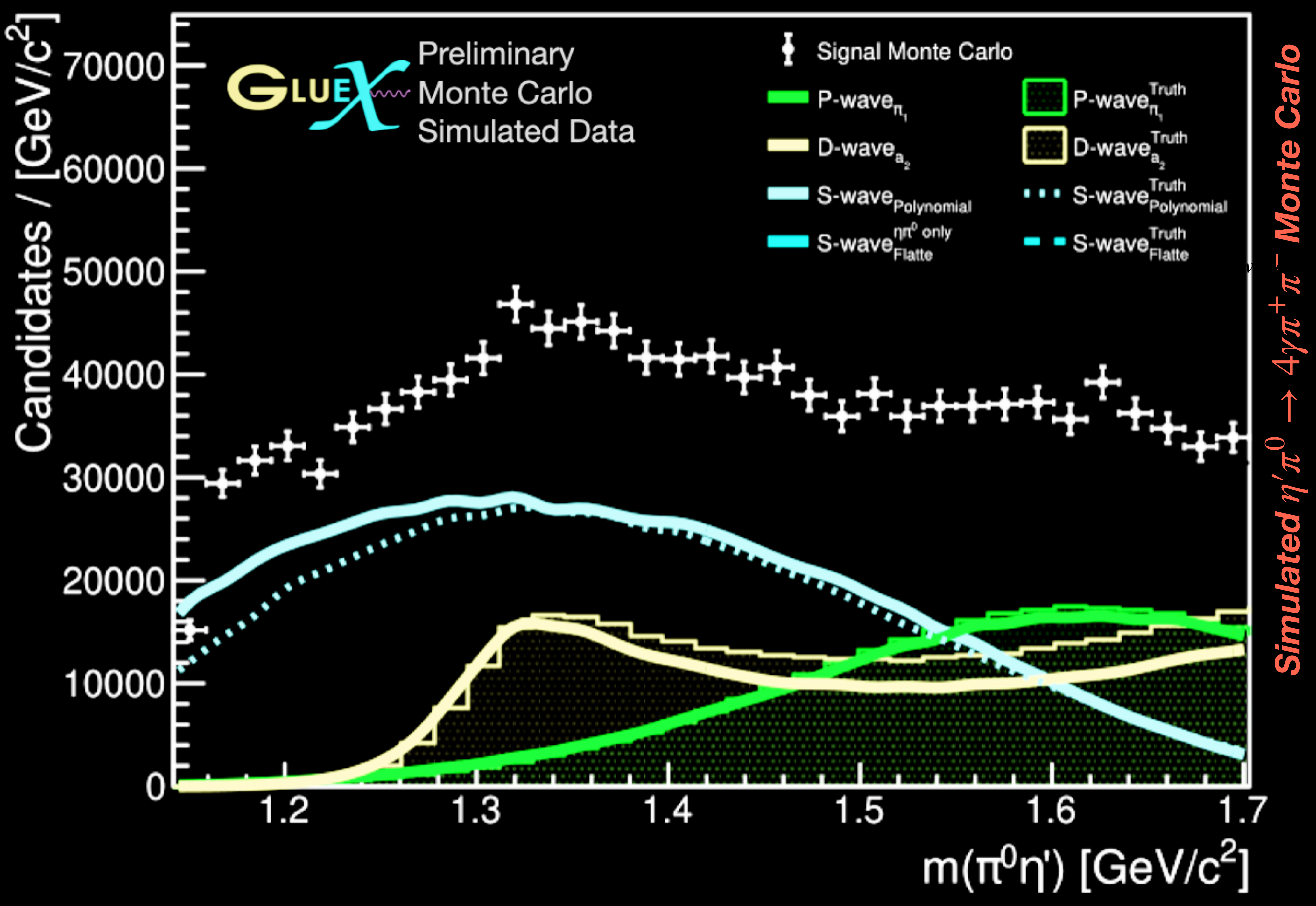
B. Kopf et al., *Eur. Phys. J. C* 81, 1056 (2021)

Note: for applications to photoproduction, models need tweaking

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

- lines-shapes remain consistent to the truth
- extremely small P_{wave} in $\eta\pi^0$ channel compared to $\eta'\pi^0$
- S_{wave} contributions = greater difficulty (especially in $\eta'\pi$)





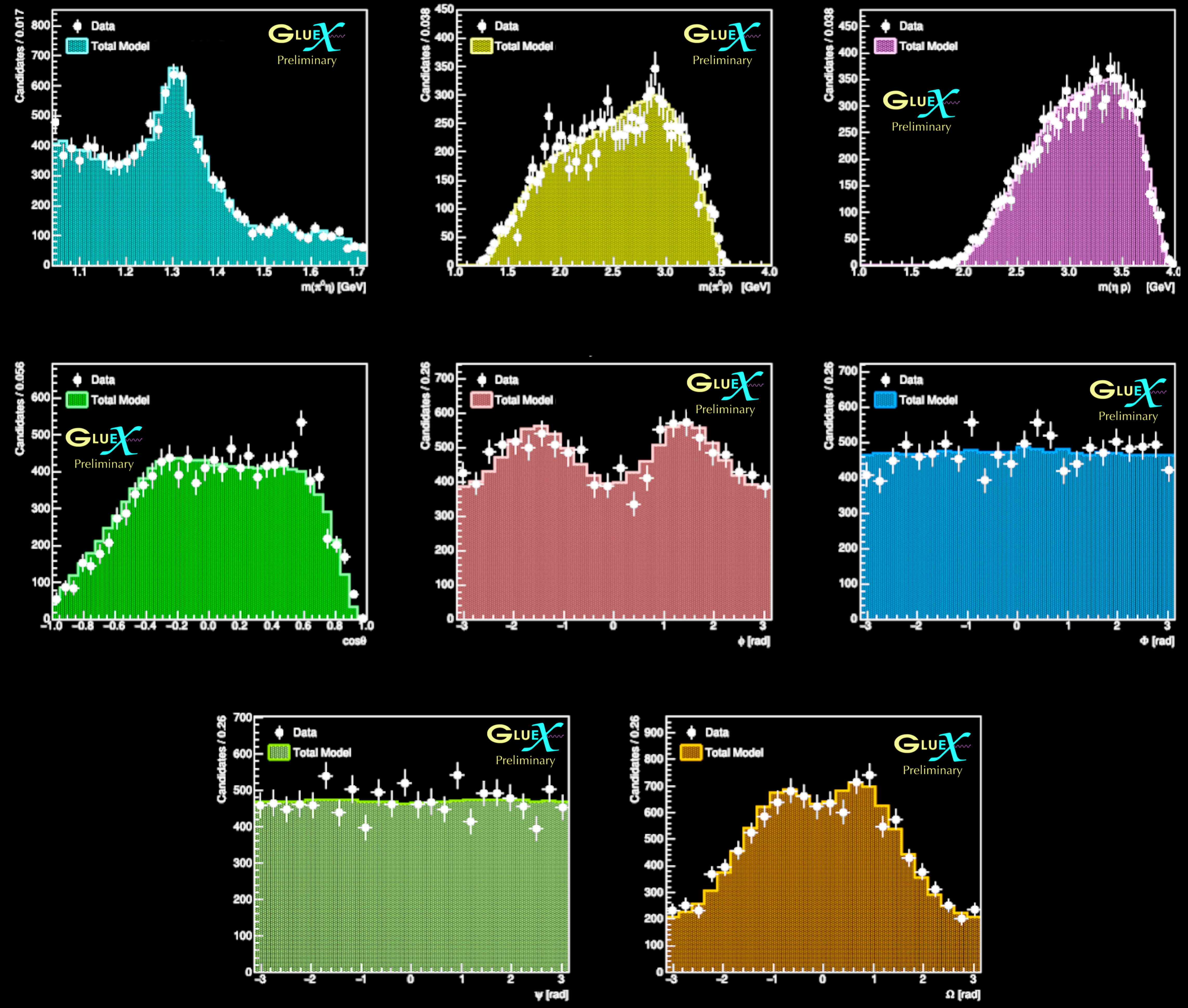
Decompose angular components into spherical harmonics $Y_l^m(\Omega)$

- moment decomposition is *unique*
- determine sensitivity to exotic contributions

No direct access to partial wave amplitudes

- BUT can calculate moments from partial waves

EXAMPLE: PWA fit results projected onto masses and angles



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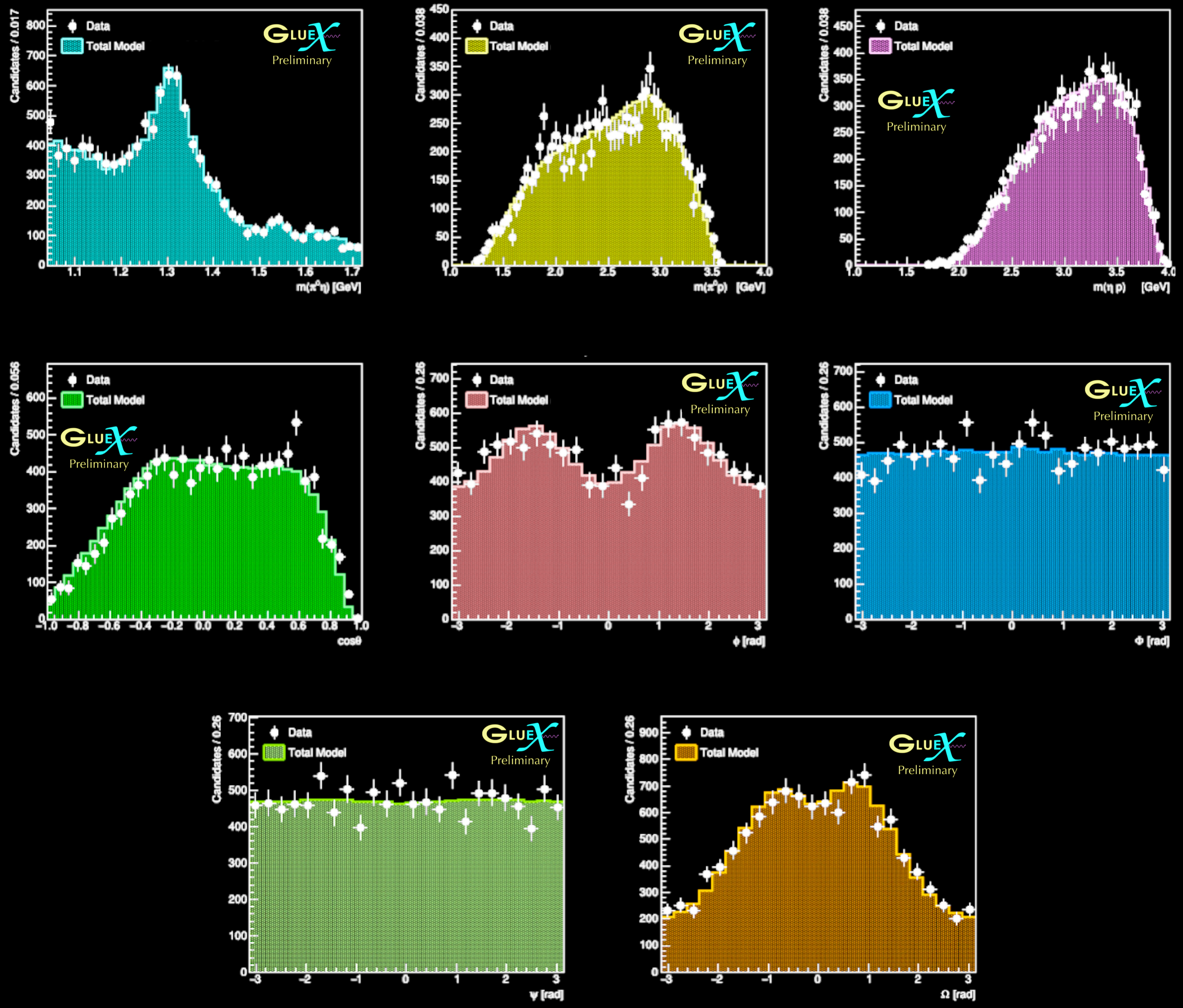
PRO	CON
- model independence	- abstract - does not provide direct access to physical amplitudes
- computationally simple	- interpretation = ambiguous with out theory

EXAMPLE: PWA fit results projected onto masses and angles



Decompose angular components into spherical harmonics $Y_l^m(\Omega)$

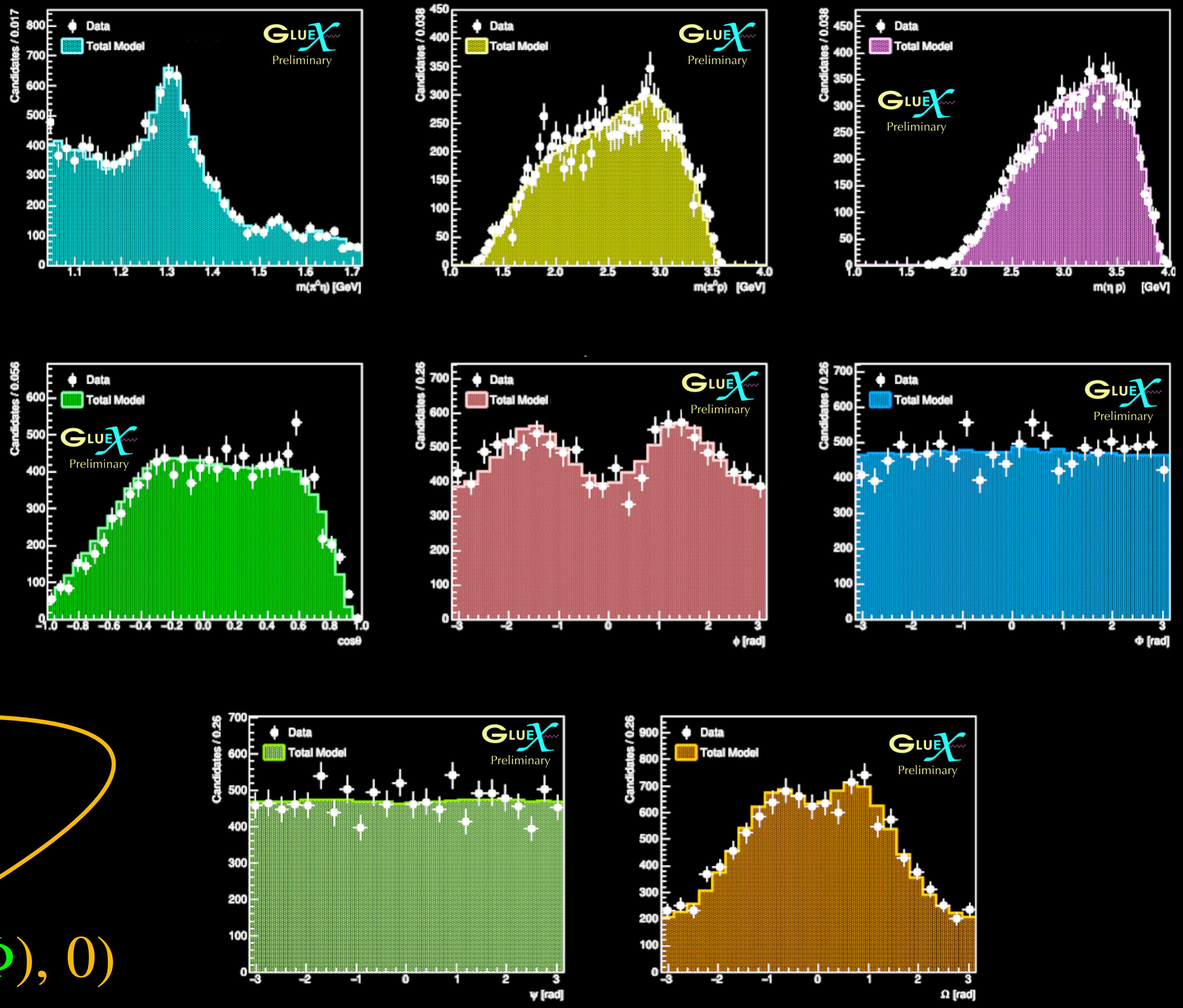
- moment decomposition is *unique*
- determine sensitivity to exotic contributions

No direct access to partial wave amplitudes

- BUT can calculate moments from partial waves

PRO	CON
- model independence	- abstract - does not provide direct access to physical amplitudes
- computationally simple	- interpretation = ambiguous with out theory

EXAMPLE: PWA fit results projected onto masses and angles



$$\mathcal{I}(\Omega, \Phi) = \sum_{\alpha=0} \mathcal{I}_\alpha(\Omega) P_\gamma^\alpha(\Phi)$$

Linearly polarized γ

$$P_\gamma^\alpha(\Phi) = (1, \, -P_\gamma \cos(2\Phi), \, -P_\gamma \sin(2\Phi), \, 0)$$

$$\mathcal{I}(\Omega, \Phi) = \mathcal{I}_0(\Omega) - \mathcal{I}_1(\Omega) P_\gamma \cos(2\Phi) - \mathcal{I}_2(\Omega) P_\gamma \sin(2\Phi)$$

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

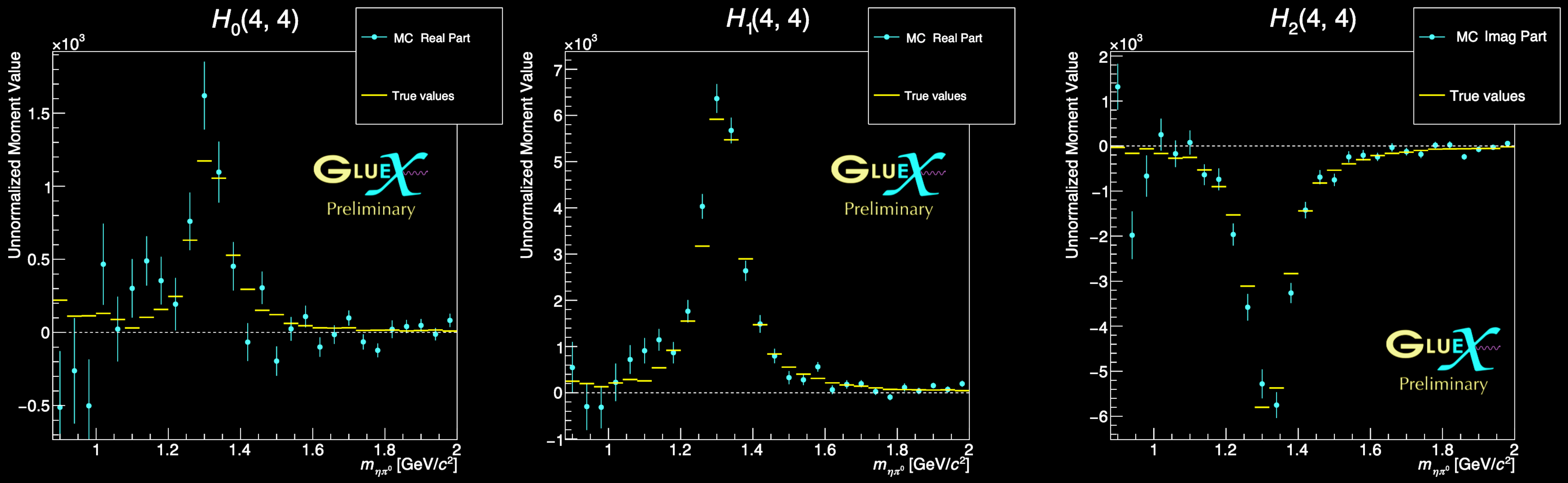
$$\mathcal{I}_0(\Omega) = \sum_{L,M}^{\infty} \sqrt{\frac{2L+1}{4\pi}} H_0(L,M) Y_l^m(\Omega)$$

$$\mathcal{I}_{1,2}(\Omega) = -\sum_{L,M}^{\infty} \sqrt{\frac{2L+1}{4\pi}} H_{1,2}(L,M) Y_l^m(\Omega)$$

$H_0(L,M) \rightarrow$ intensity-like (phase-insensitive)

$H_1(L,M) \rightarrow$ polarization dependent cosine interference

$H_2(L,M) \rightarrow$ polarization dependent sine interference (phase-sensitive)



EXAMPLE: Monte Carlo I/O with simulated $a_2(1320)$

$H_i(4,4)$ contains clear $a_2(1320)$ signal

- partial wave description of the amplitude
  Model Dependent
- moment description of the angular intensity
  Model Independent

Utilizing the same model used in the first measurement of $a_2(1320)$ polarized photoporduction cross section

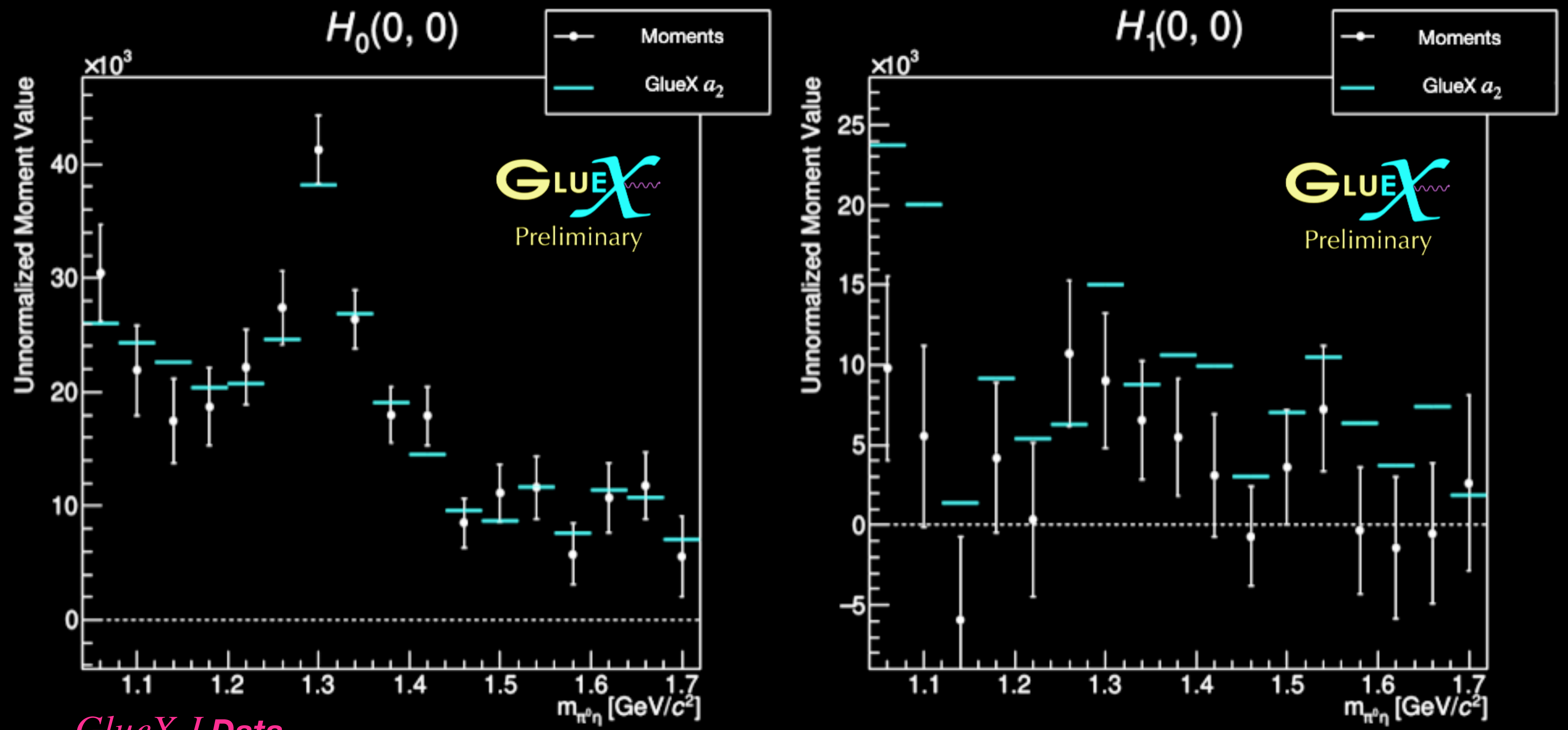
F. Afzal et al. [GlueX Collab], Phys. Rev. C 112, 015204 (2025)

$\mathcal{A}^{piecewise}$

GlueX $a_2(1320)$ paper

$\mathcal{A}^{BW}_{a_2} + \mathcal{A}^{BW}_{a'_2}$

$$\mathcal{A} = \mathcal{A}_{S_{wave}} + \mathcal{A}_{P_{wave}} + \mathcal{A}_{D_{wave}} + \cdots$$



GlueX-I **Data**

$H_2(0,0) = 0$ *due to symmetries*

Utilizing the same model used in the first measurement of $a_2(1320)$ polarized photoporduction cross section

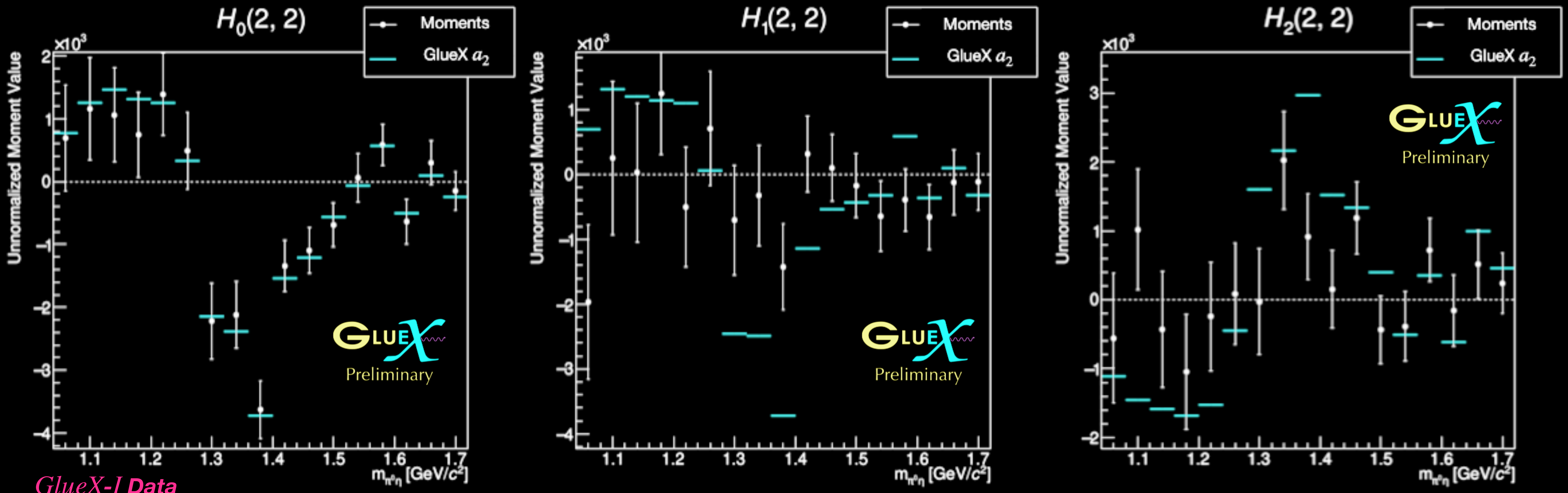
F. Afzal et al. [GlueX Collab], Phys. Rev. C 112, 015204 (2025)

$\mathcal{A}^{piecewise}$

GlueX $a_2(1320)$ paper

$\mathcal{A}^{BW}_{a_2} + \mathcal{A}^{BW}_{a_2'}$

$$\mathcal{A} = \mathcal{A}_{S_{wave}} + \mathcal{A}_{P_{wave}} + \mathcal{A}_{D_{wave}} + \cdots$$



GlueX-I **Data**

S_{wave}

Piecewise

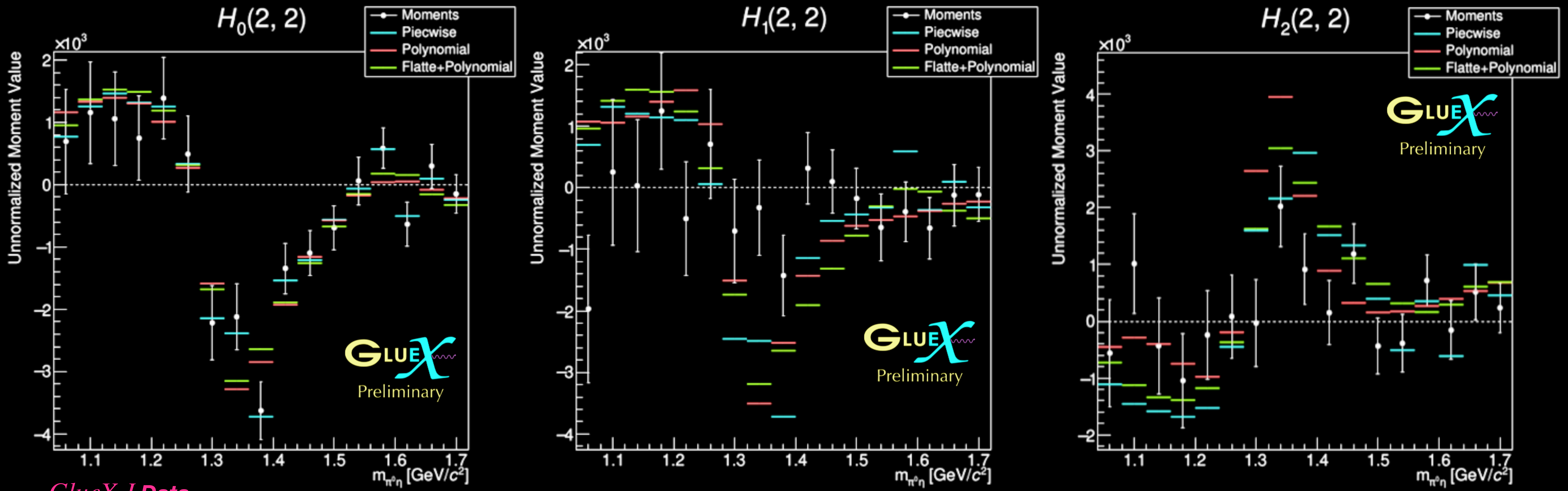
Polynomial

coupled-channel

Flatté $+$ *Polynomial*

Overall, strong agreement across differing models

- global χ^2 across mass bins roughly equal



GlueX-I **Data**

P_{wave} → coupled-channel

$Kopf,\ et\ al\ P_{wave}$

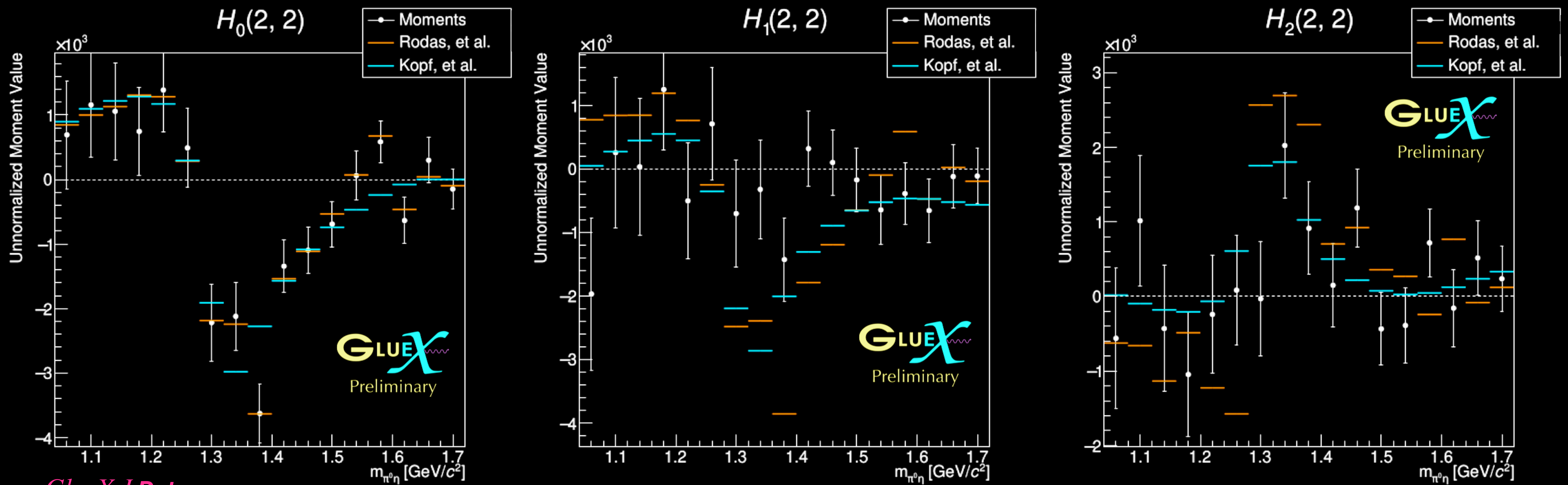
$Rodas,\ et\ al\ P_{wave}$

D_{wave} → coupled-channel

$Kopf,\ et\ al\ D_{wave}$

$Rodas,\ et\ al\ D_{wave}$

Decent agreement still in $H_i\,(2,2)$



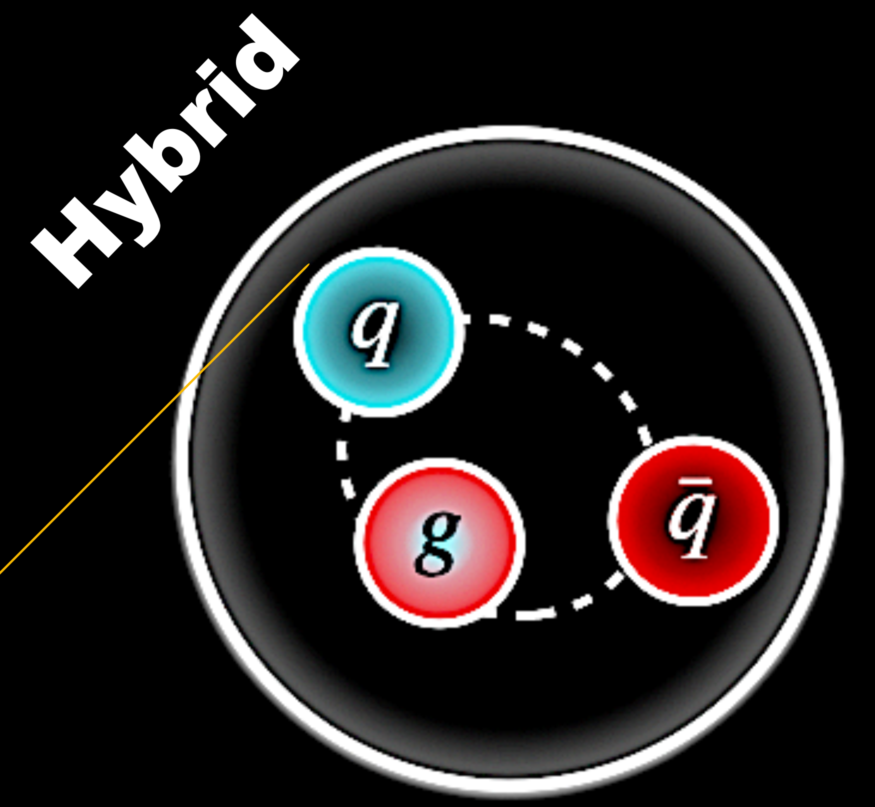
GlueX-I **Data**

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 information
- 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

- extraction of moment decomposition from data



Next immediate steps:

- further analyze coupled-channel systematics
- perform model comparison studies

EXCITING TIMES
FOR
EXOTICS SEARCHES
AT
GLUEX

GlueX acknowledges the support of several funding agencies and computing facilities

gluex.org/thanks

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BACKUP SLIDES

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

- incoherent sums of (+) and (-) reflectivities

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

Decent agreement between JPAC TMD model

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