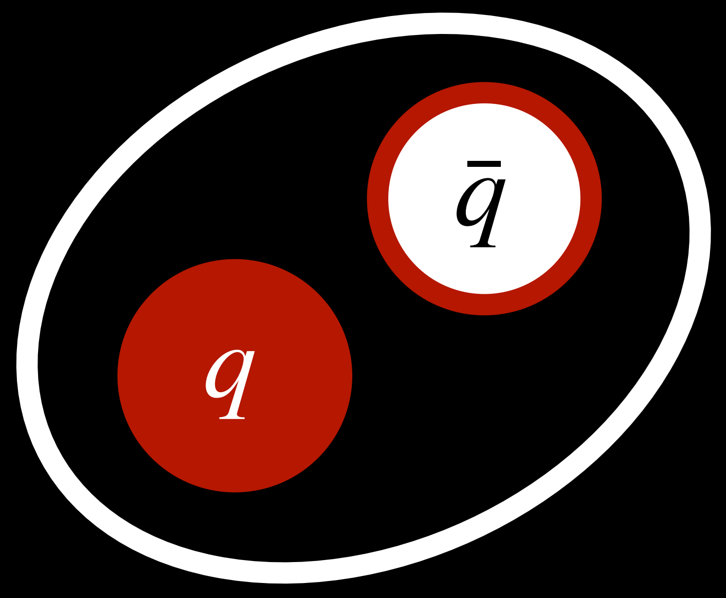
Exploring Photoproduced $\eta^{(\prime)}\pi^0$ Systems in the Search for Exotic Hadrons at GlueX

10^{th} International Conference QNP — Barcelona, Spain

Hadron Spectroscopy

Zachary Baldwin, July 8, 2024

Constituent Quark Model



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

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

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

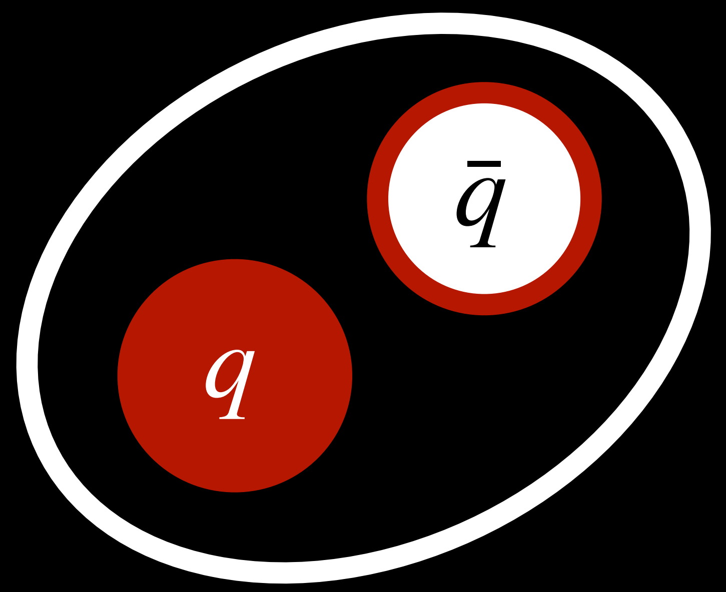
L is the relative orbital angular momentum of the q and $\bar{q}$

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^{--}

Constituent Quark Model



Total angular momentum | $J = 0,1,2,...$

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

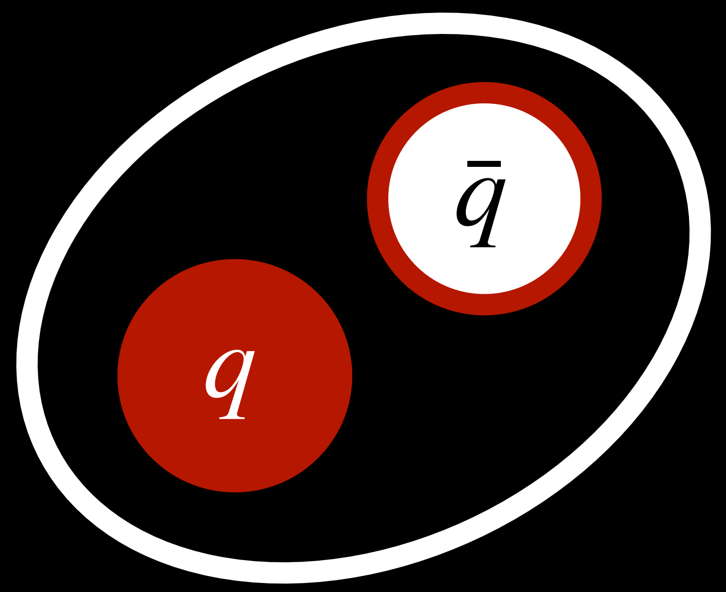
L	S	J^{PC}	L	S	J^{PC}	L	S	J^{PC}
0	0	0^{-+}	1	0	1^{+-}	2	0	2^{-+}
0	1	1^{--}	1	1	0^{++}	2	1	1^{--}
			1	1	1^{++}	2	1	2^{--}
			1	1	2^{++}	2	1	3^{--}

Forbidden J^{PC} quantum numbers

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

Discovering forbidden quantum numbers would be immediate evidence of a non-$q\bar{q}$ state

Constituent Quark Model



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

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

Discovering forbidden quantum numbers would be immediate evidence of a non-$q\bar{q}$ state

Do gluons play a larger role?

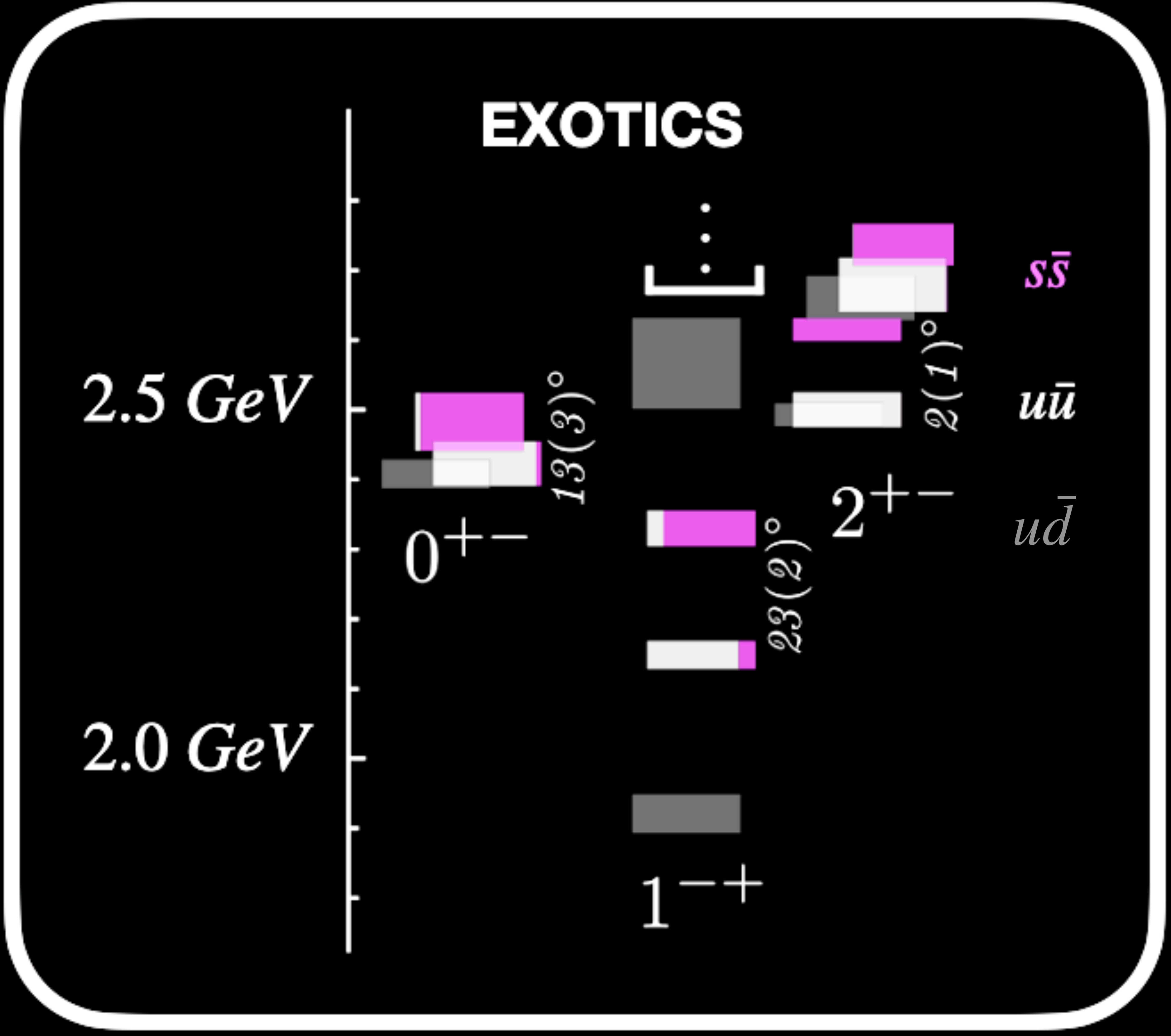
Lattice QCD predicts "gluonic excitations", confirming mesons that are not in constituent quark model known as exotic mesons


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

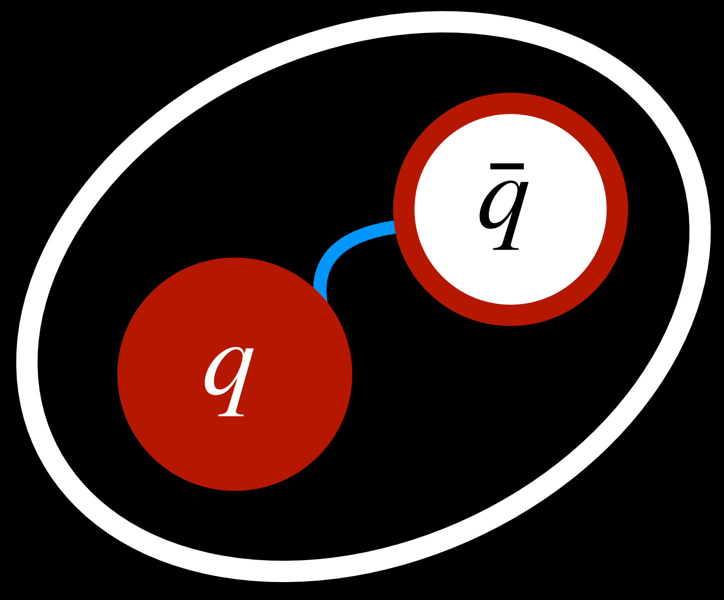
Isoscalar meson spectroscopy from lattice QCD

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

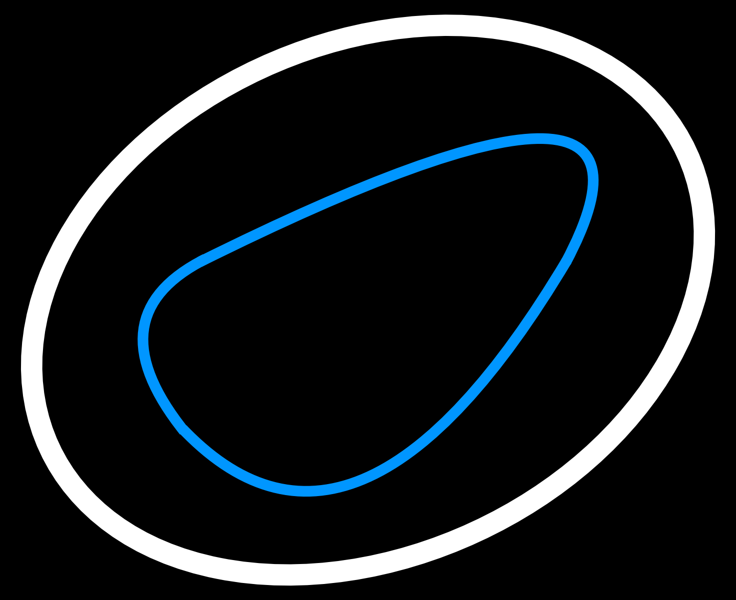
J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)



Exotic Hybrid

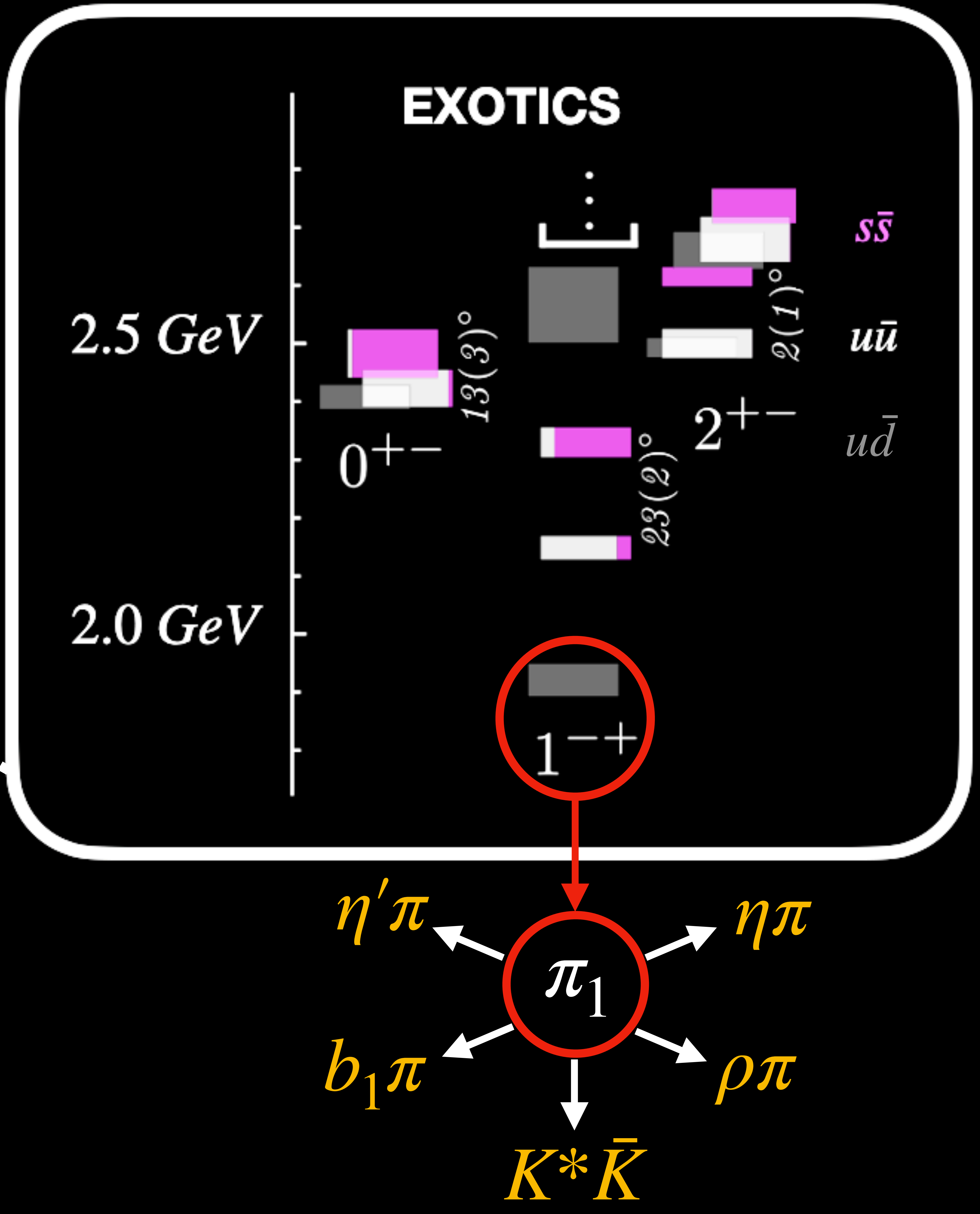


Glueball

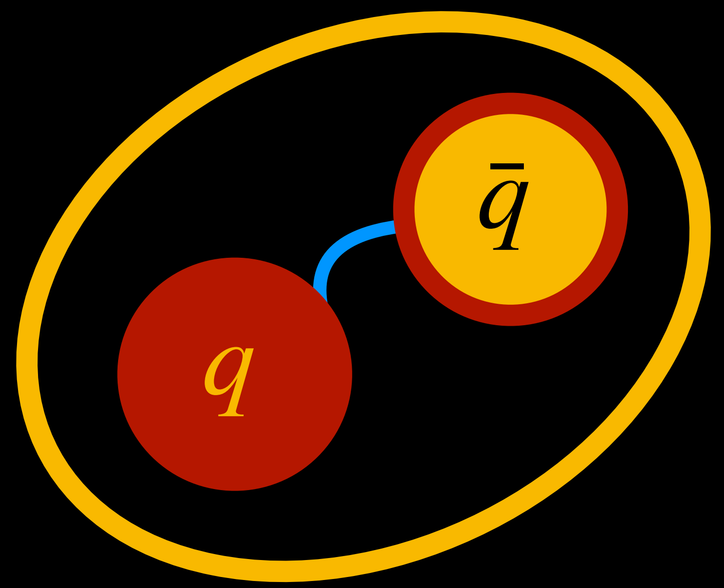


Lattice QCD predicts “gluonic excitations”, confirming mesons that are not in constituent quark model known as exotic mesons

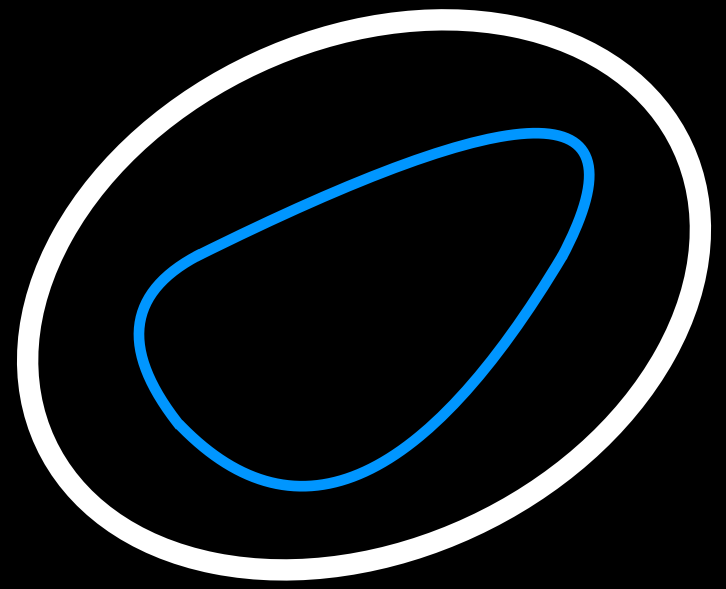
J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)



Exotic Hybrid

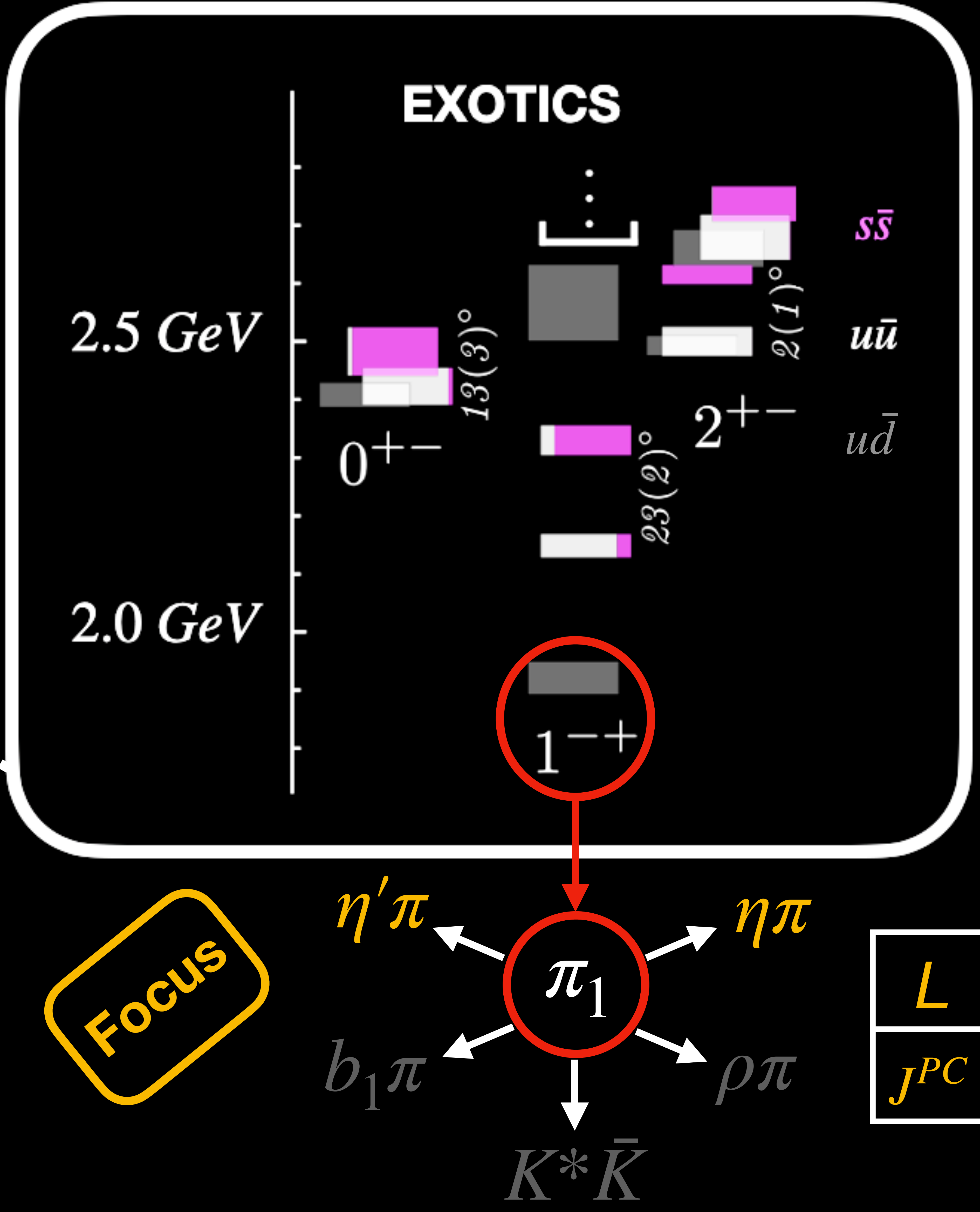


Glueball

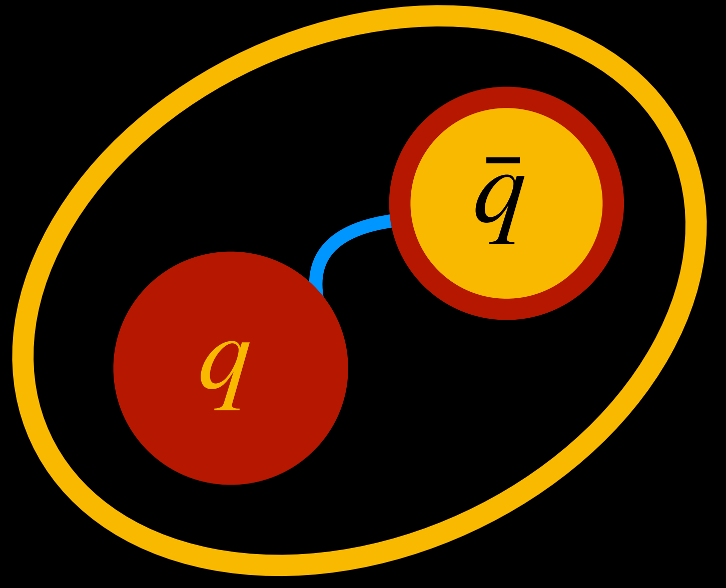


Lattice QCD predicts “gluonic excitations”, confirming mesons that are not in constituent quark model known as exotic mesons

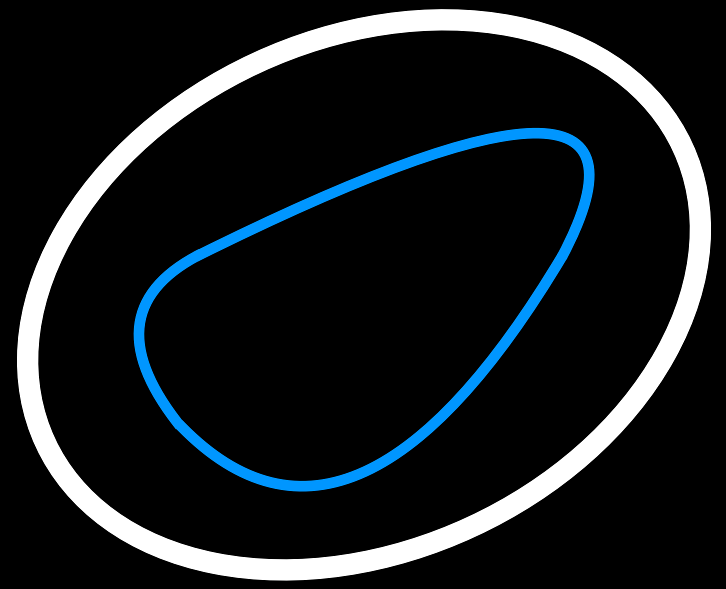
J. Dudek et al. [Hadron Spectrum Collab], Phys. Rev. D 83, 111502 (2011)



Exotic Hybrid



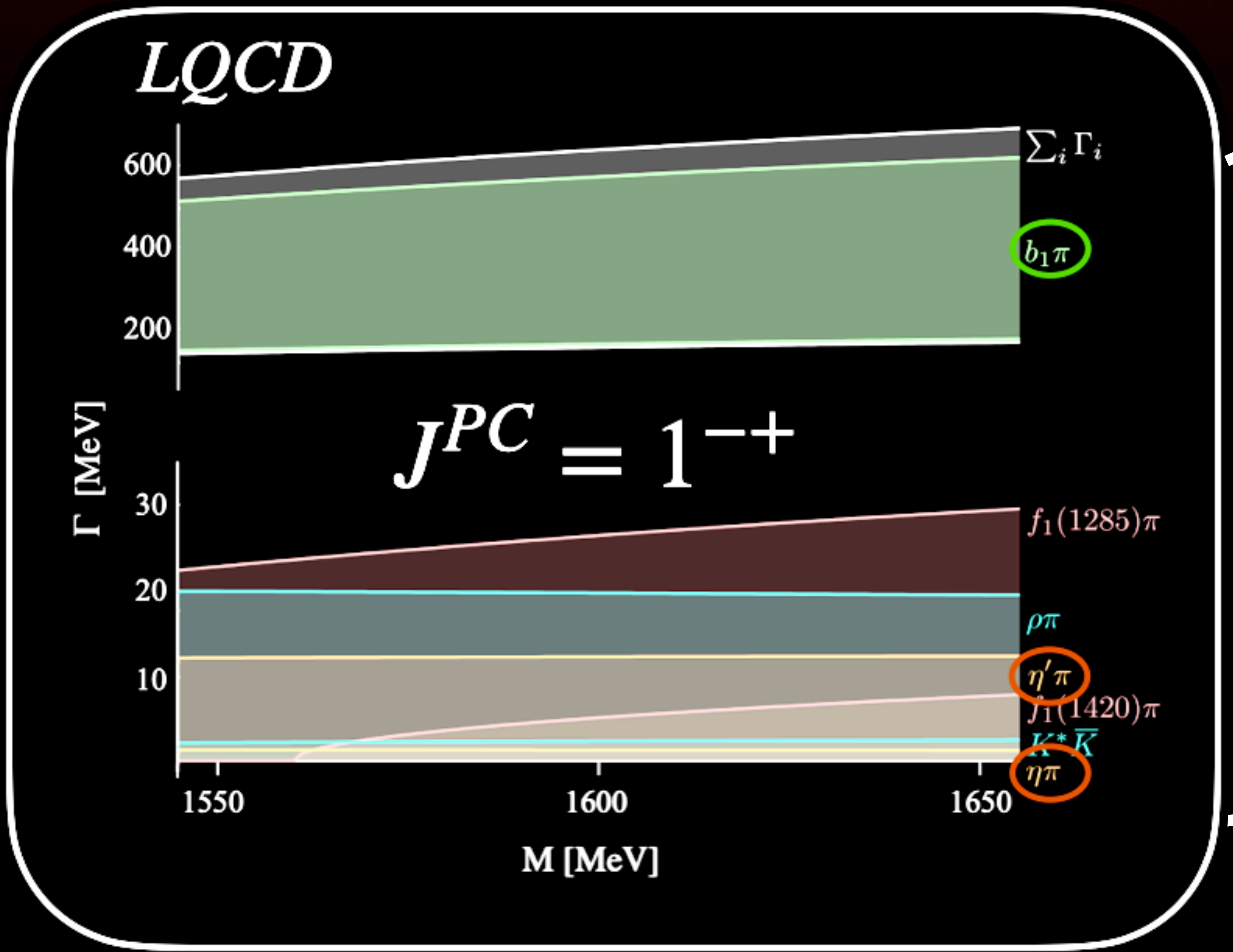
Glueball



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

$LQCD$ calculations provide insight into 1^{-+} state decay modes

	Γ_i/MeV
$\eta\pi$	$0 \rightarrow 1$
$\eta'\pi$	$0 \rightarrow 12$
$b_1\pi$	$139 \rightarrow 529$

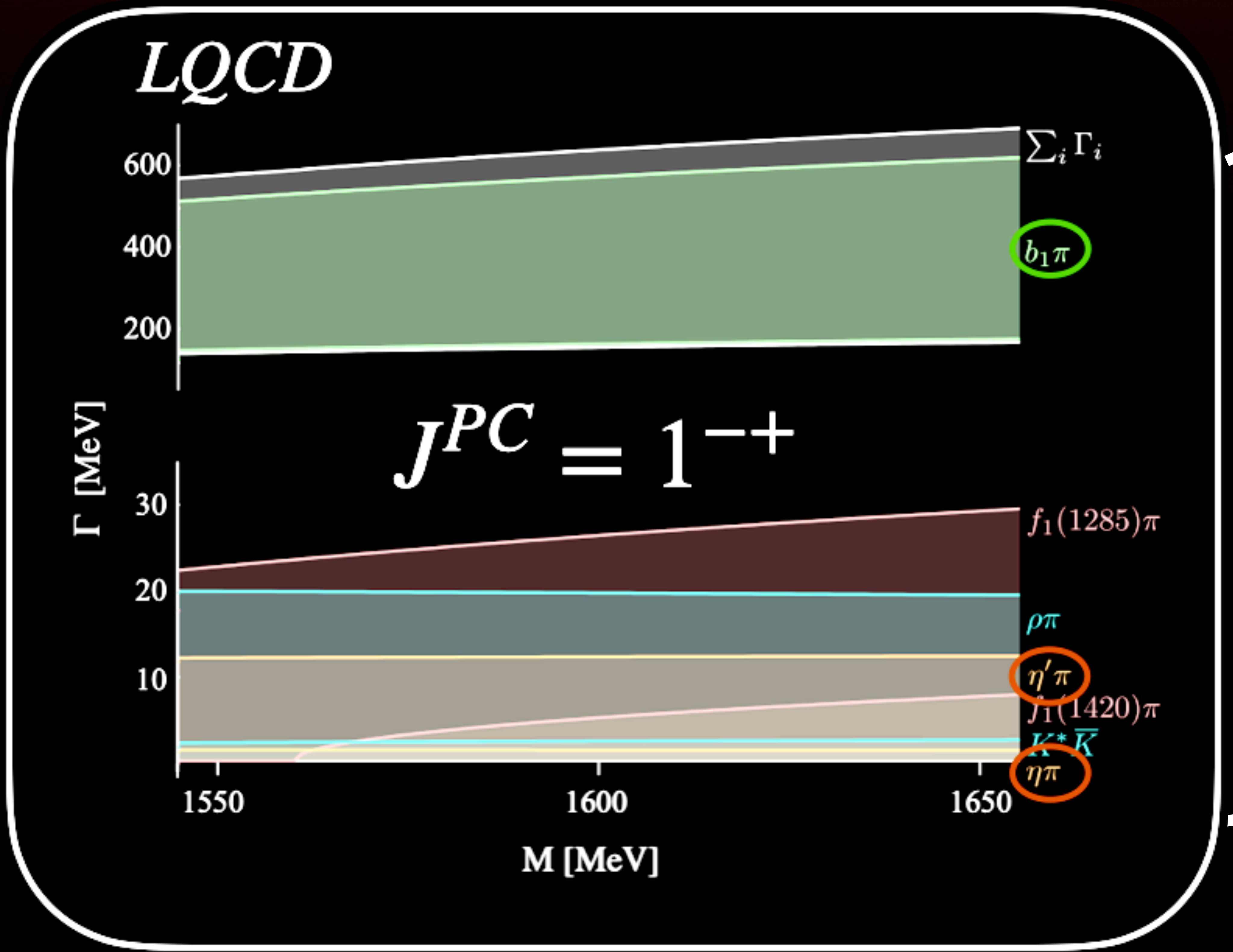


A. Woss et al. [Hadron Spectrum Collab], Phys. Rev. D 103, 054502 (2021)

What percentage of π_1 is expected in $\eta^{(\prime)}\pi^0$?

LQCD calculations provide insight into 1^{-+} state decay modes

	Γ_i / MeV
$\eta\pi$	$0 \rightarrow 1$
$\eta'\pi$	$0 \rightarrow 12$
$b_1\pi$	$139 \rightarrow 529$



$$\frac{B(\pi_1 \rightarrow b_1\pi)}{B(\pi_1 \rightarrow \eta\pi)} > \frac{139}{1} > 100$$

$$\frac{B(\pi_1 \rightarrow b_1\pi)}{B(\pi_1 \rightarrow \eta'\pi)} > \frac{139}{12} > 10$$

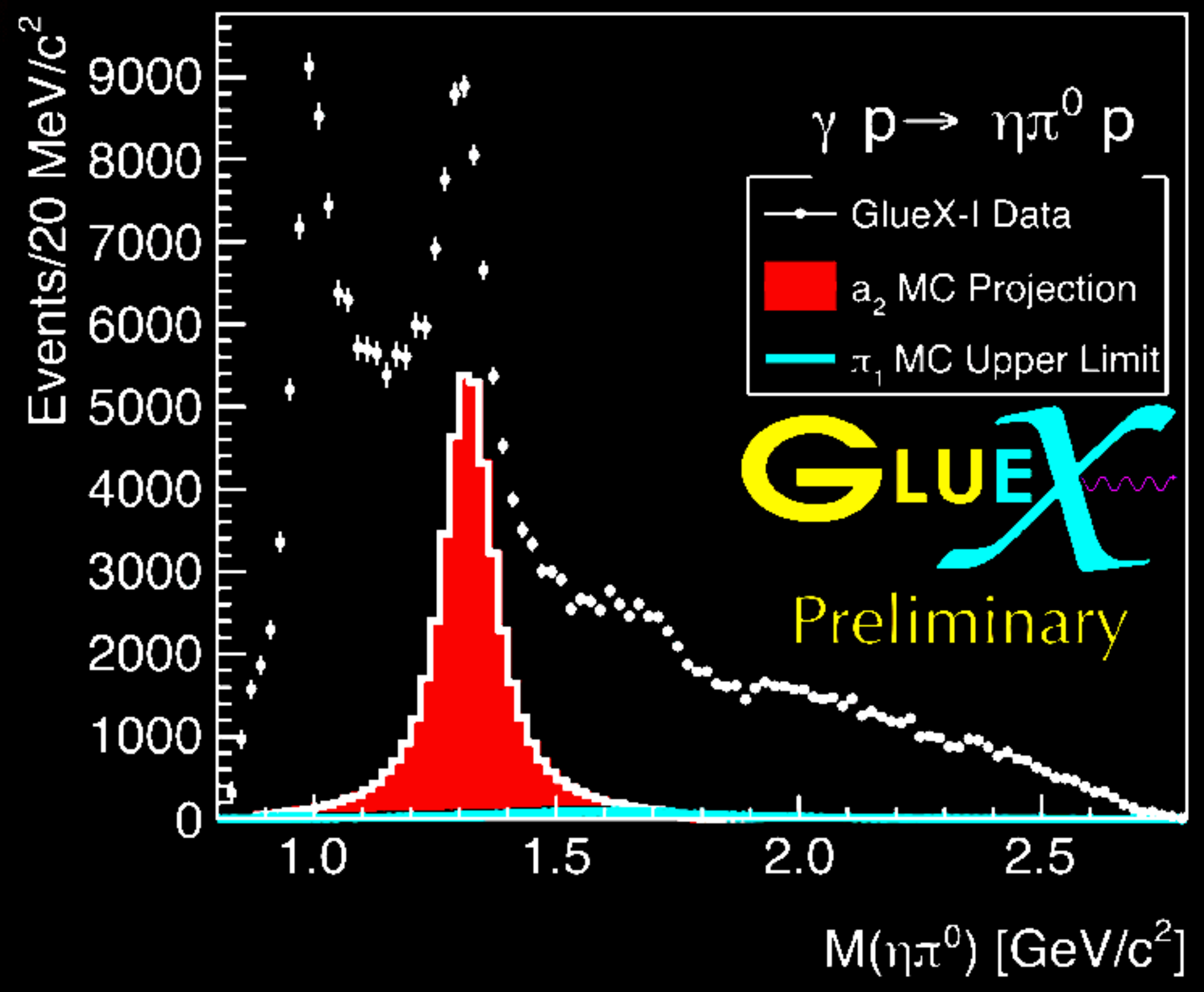
$$B(\pi_1 \rightarrow \eta\pi) \lesssim 1\,\%$$

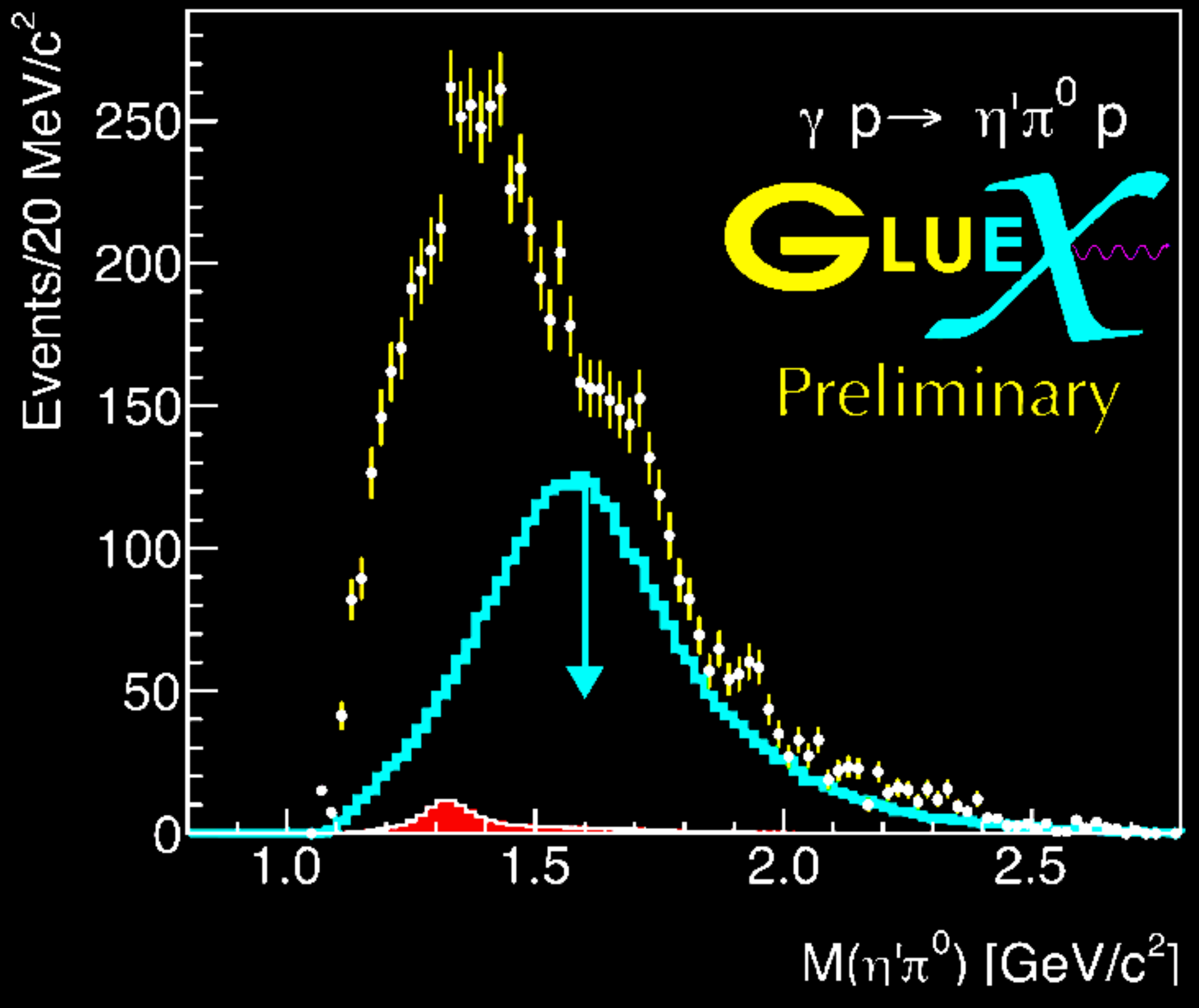
$$B(\pi_1 \rightarrow \eta'\pi) \lesssim 10\,\%$$

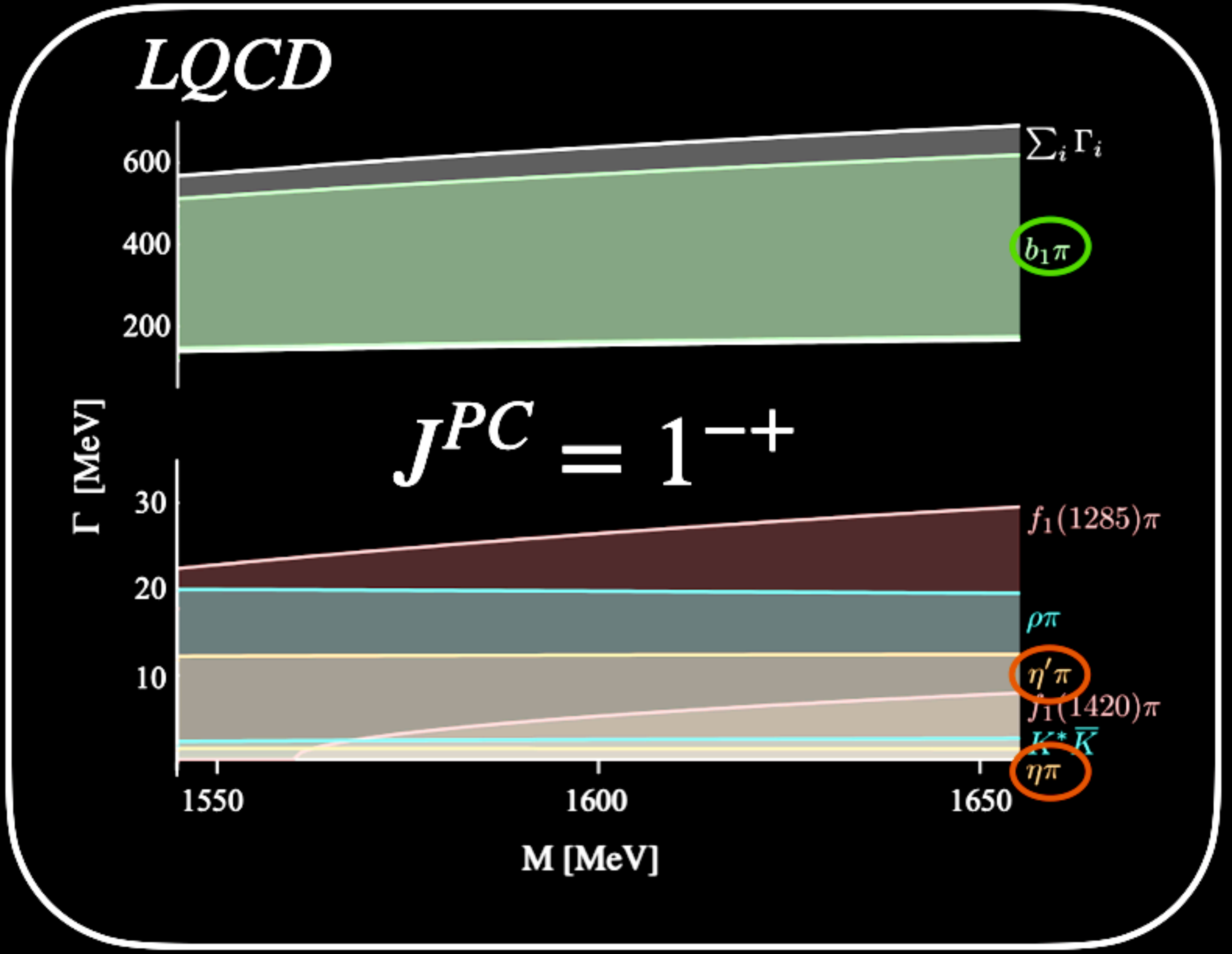
A. Woss et al. [Hadron Spectrum Collab], Phys. Rev. D 103, 054502 (2021)

HOT OFF THE PRESS

A.Fzal et al. An upper limit on the photoproduction cross section of the spin-exotic $\pi_1(1600)$, arXiv (2024)



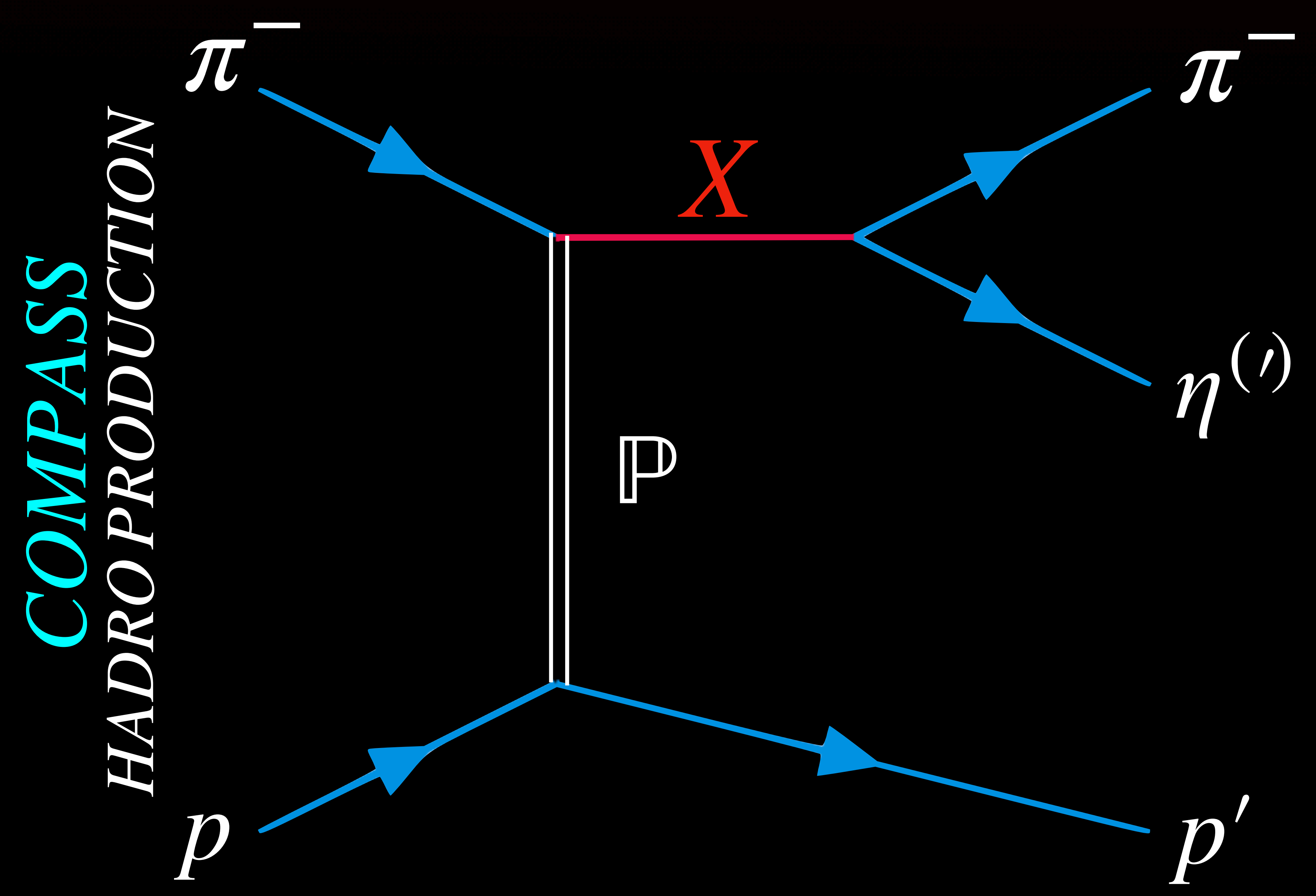




A. Woss et al. [Hadron Spectrum Collab], Phys. Rev. D 103, 054502 (2021)

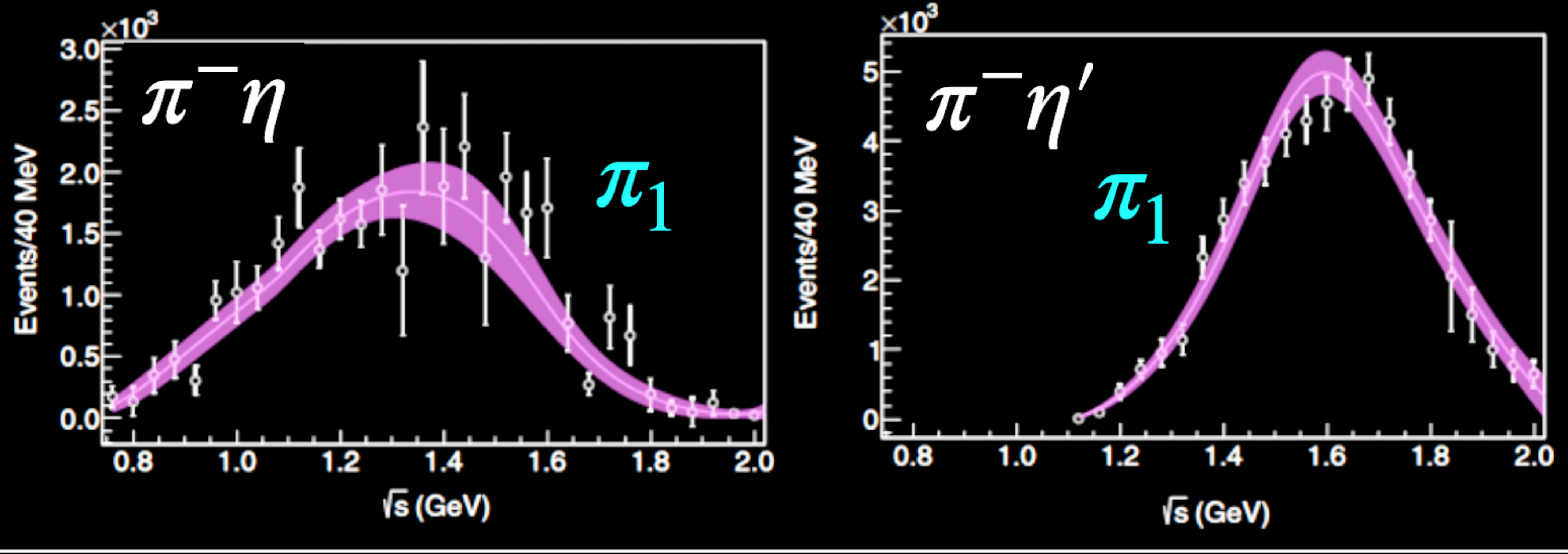
- **Based on upper limit π_1 cross section $\omega\pi\pi$**
  - **first photo-produced upper limit cross sections of spin exotic candidate**
- **Projection of $\pi_1 \rightarrow \eta^{(\prime)}\pi^0$ upper limit**
  - **uses strong a_2 signal measurements as a reference**

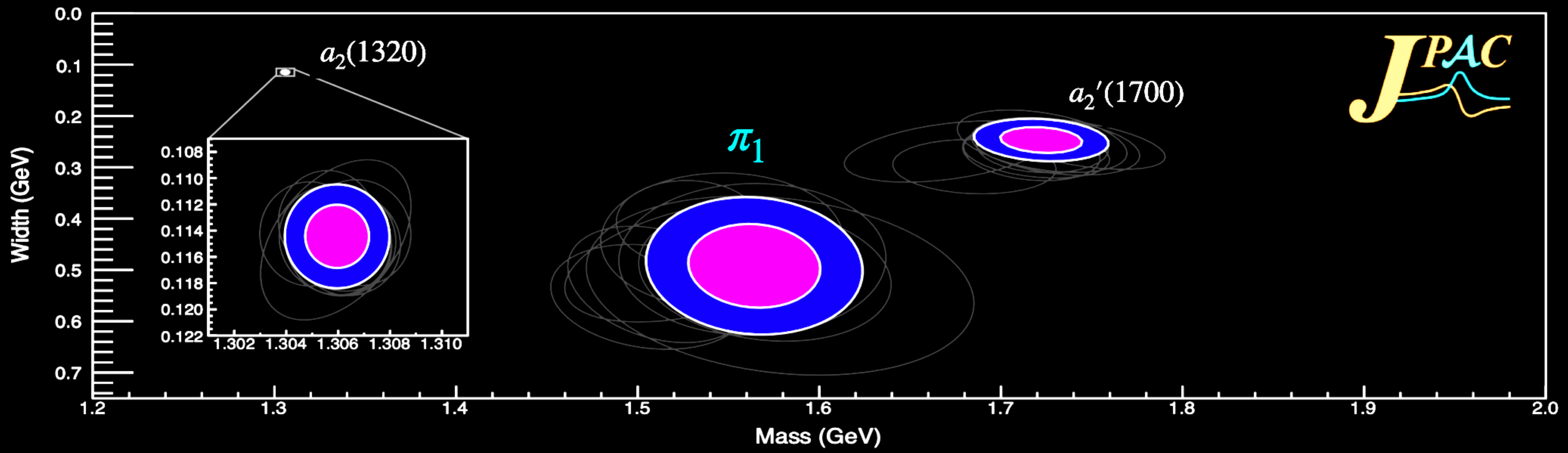
Further overview: A. Austregesilo — Tues. 9:40 am



- **JPAC analysis utilizing COMPASS data**
  - extended with $\bar{p}p$ data

    B.Kopf et.al. Eur. Phys. J. C 81, 1056 (2021)
- **Coupled channel fit to both $\eta^{(\prime)}\pi$ systems**
  - also described the dominate a_2 meson

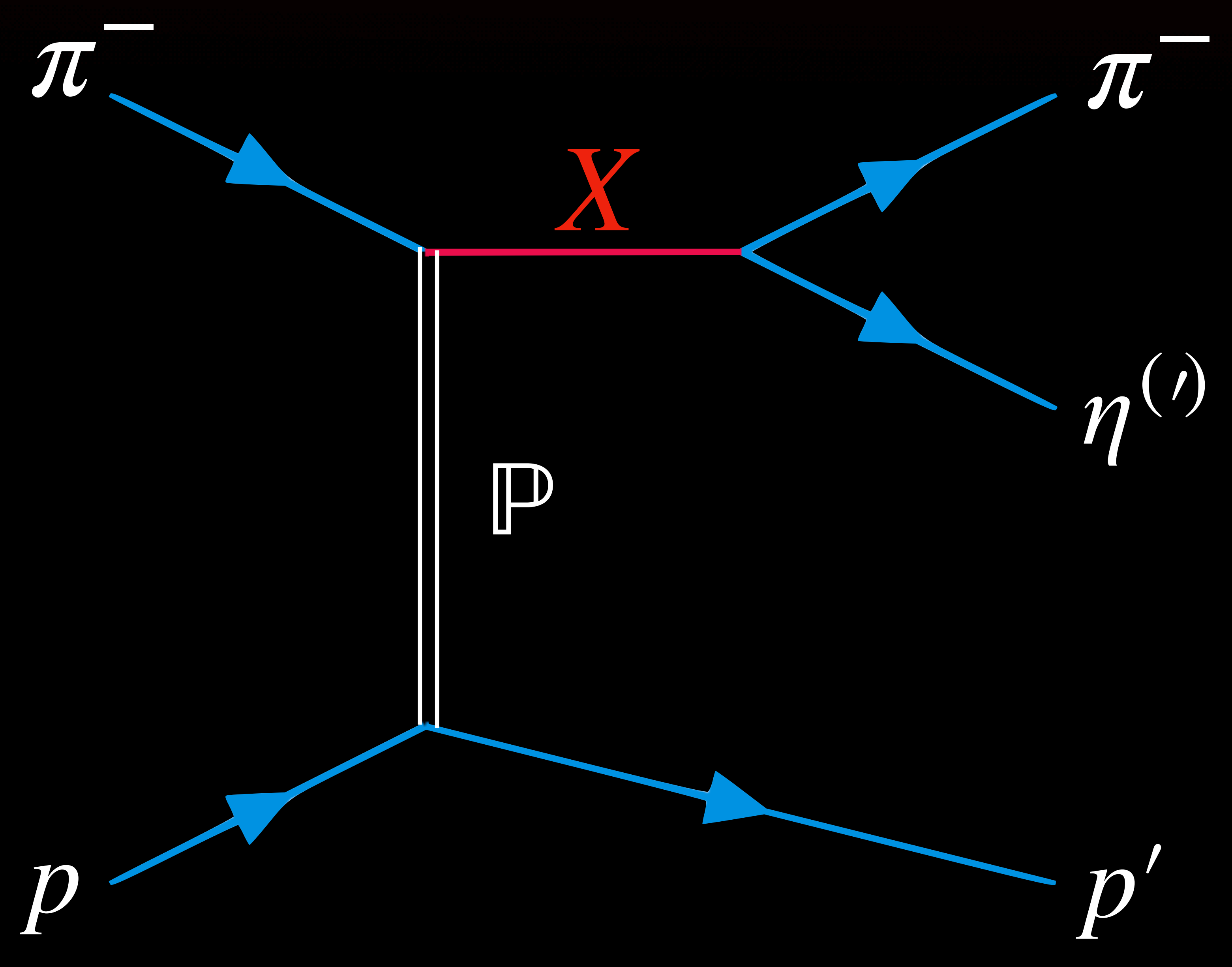


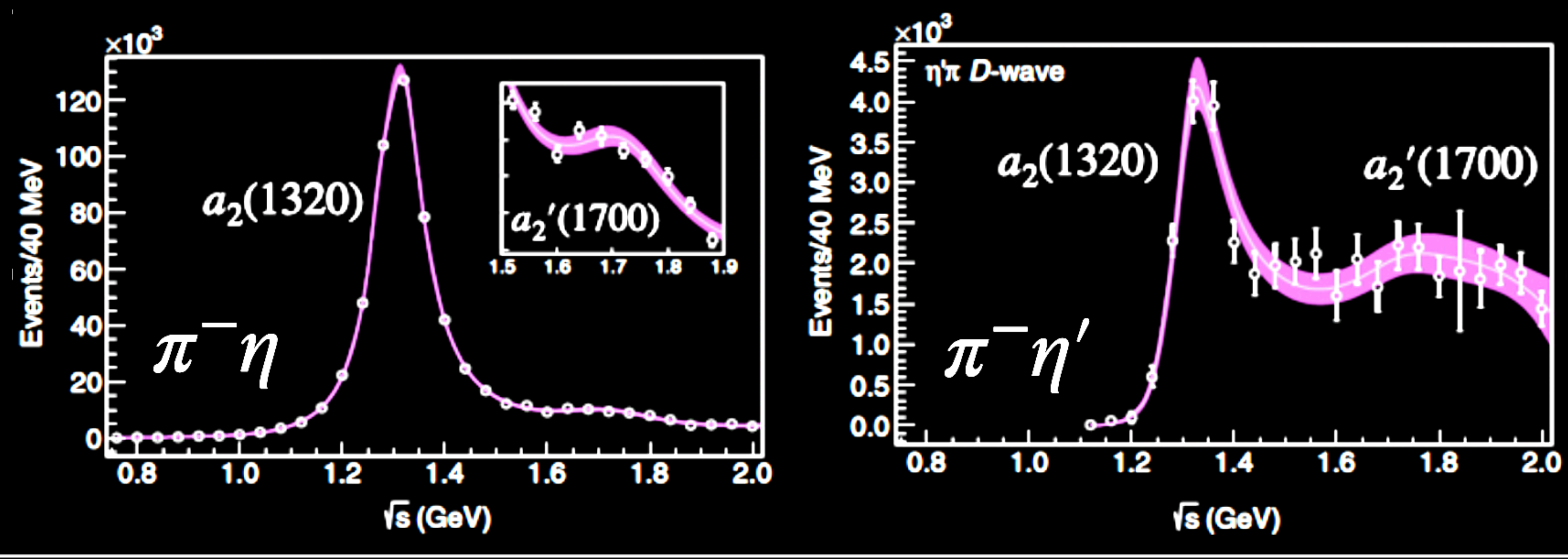


A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

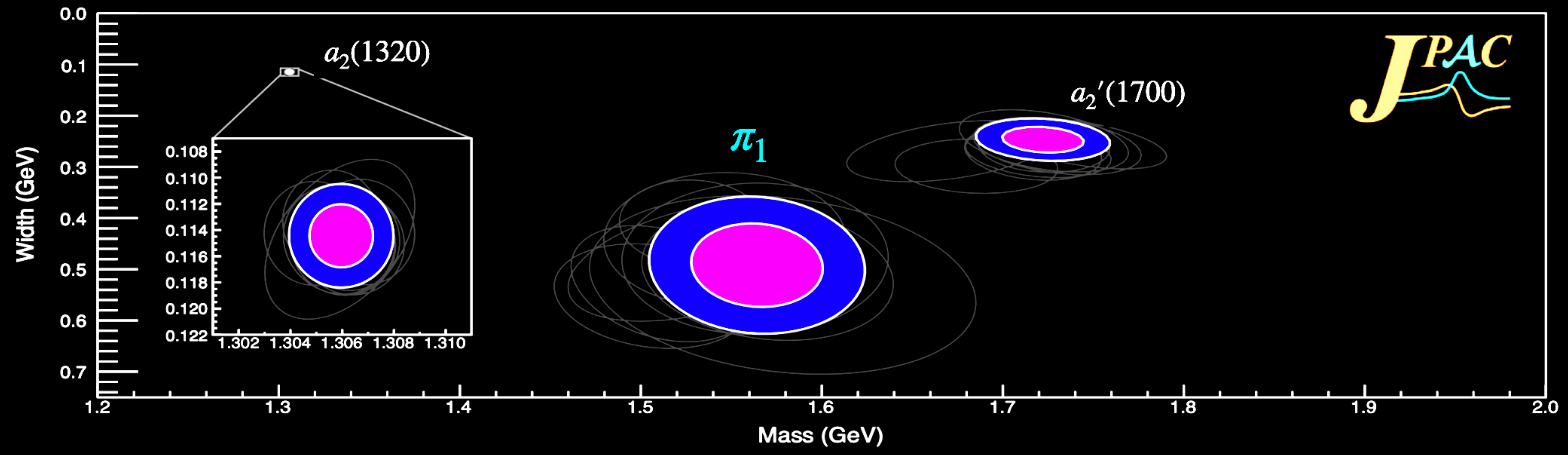
- **JPAC analysis utilizing COMPASS data**
  - extended with $\bar{p}p$ data
    B.Kopf et.al. Eur. Phys. J. C 81, 1056 (2021)
- **Coupled channel fit to both $\eta^{(\prime)}\pi$ systems**
  - also described the dominate a_2 meson

COMPASS
HADRO PRODUCTION





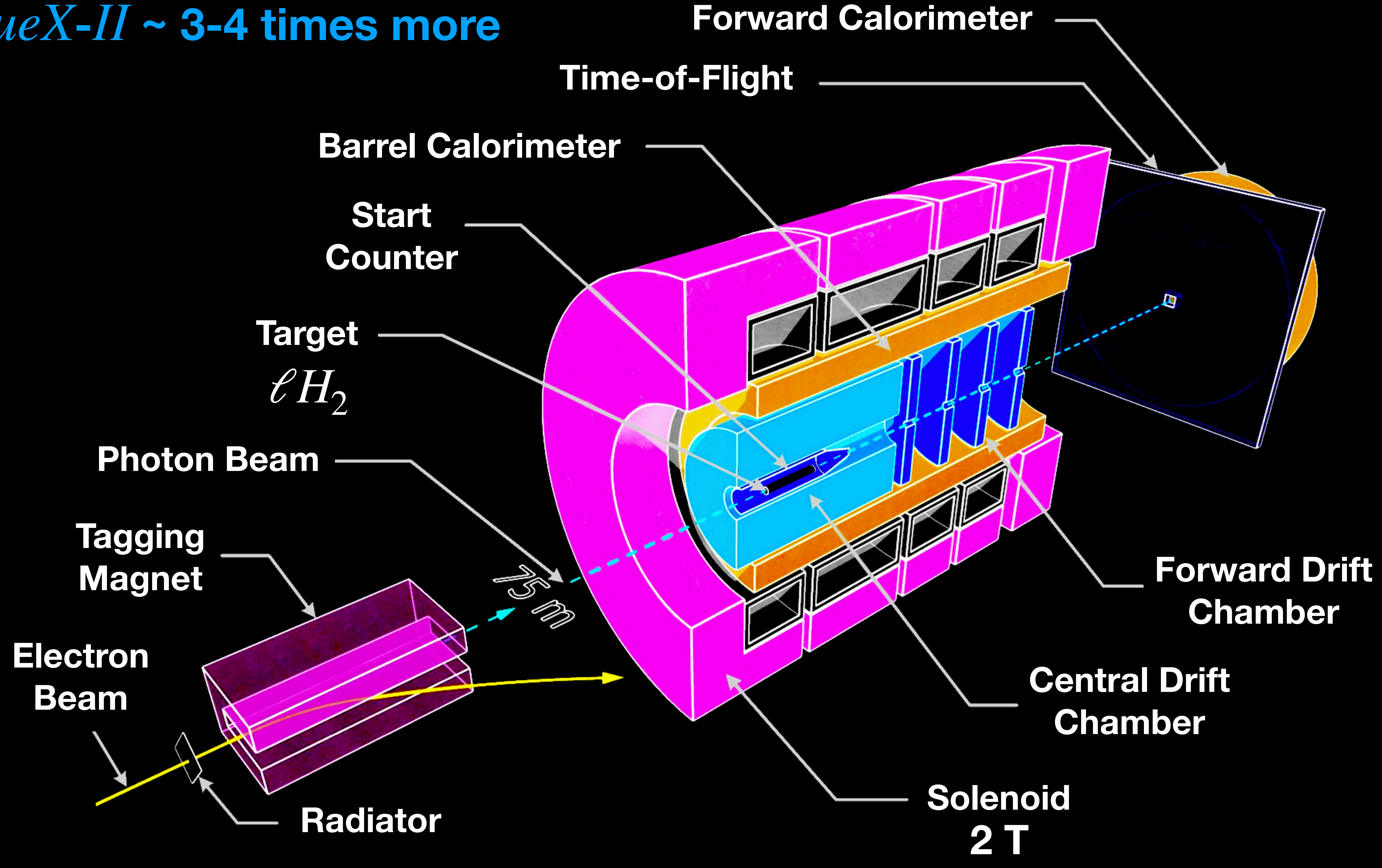
Use dominant $a_2(1320)$ as ***reference signal*** for the π_1 exotic hybrid search



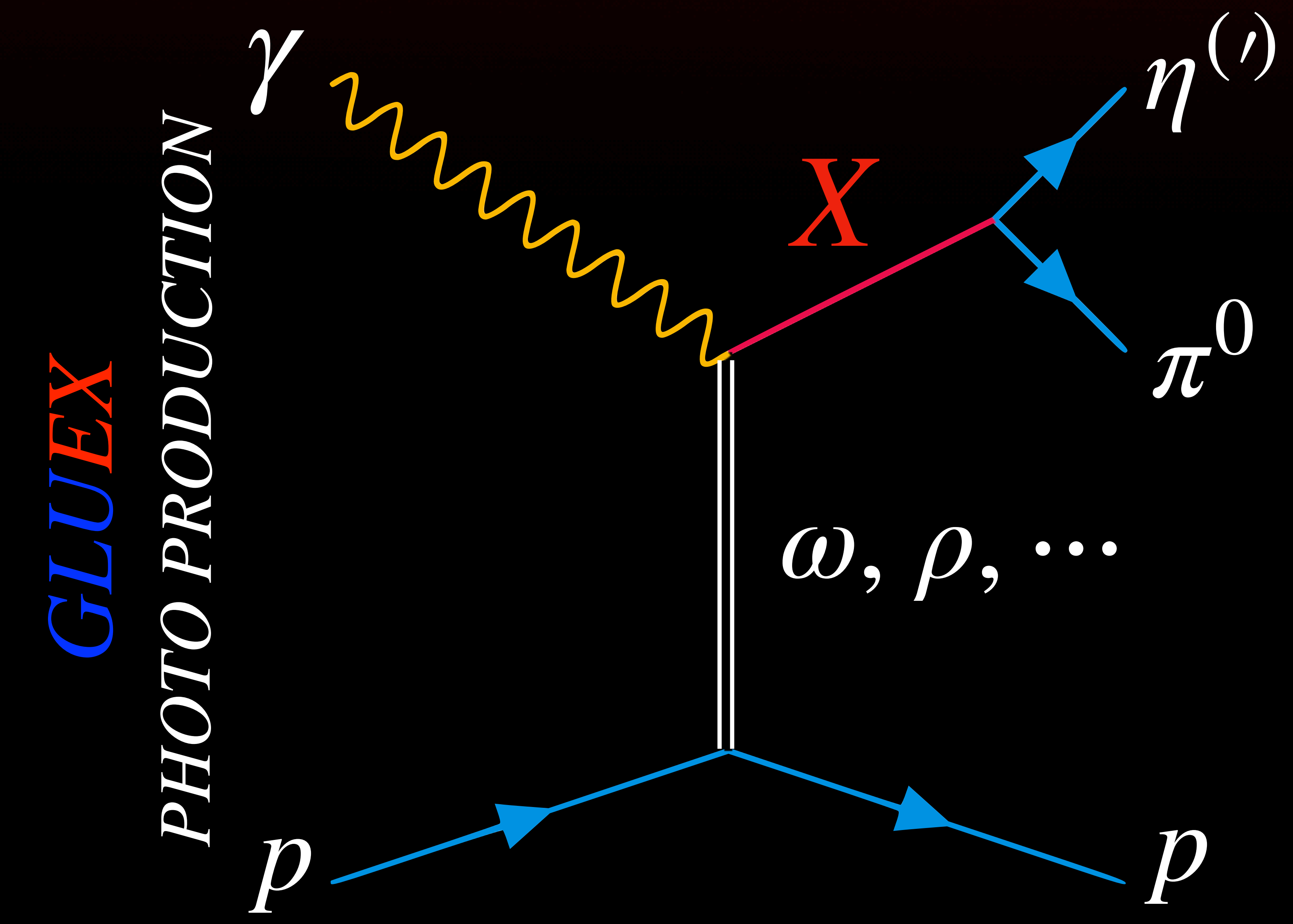
A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

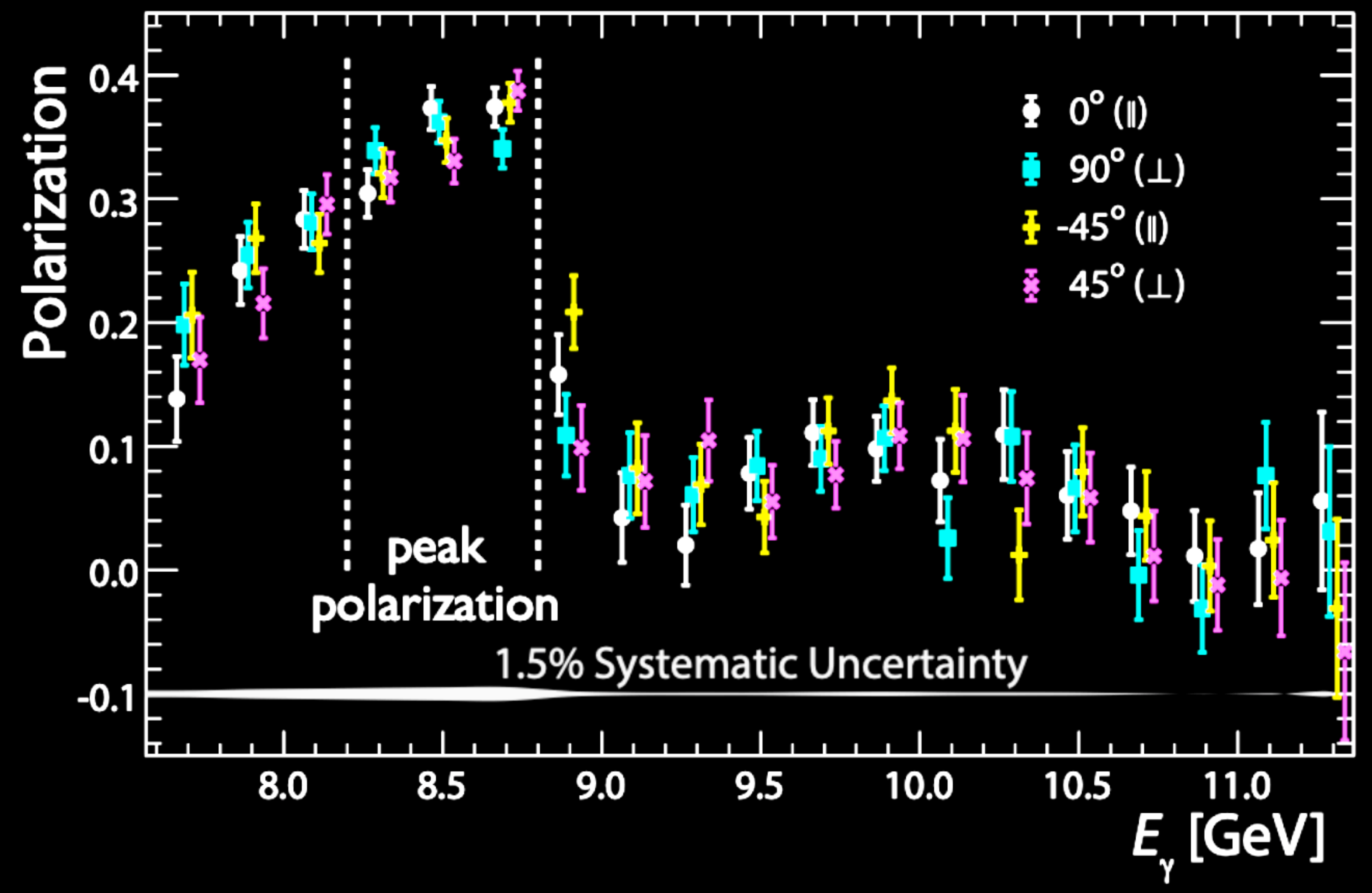
Experiment Details

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



S. Adhikari et al., NIM A 987, 164807 (2021)



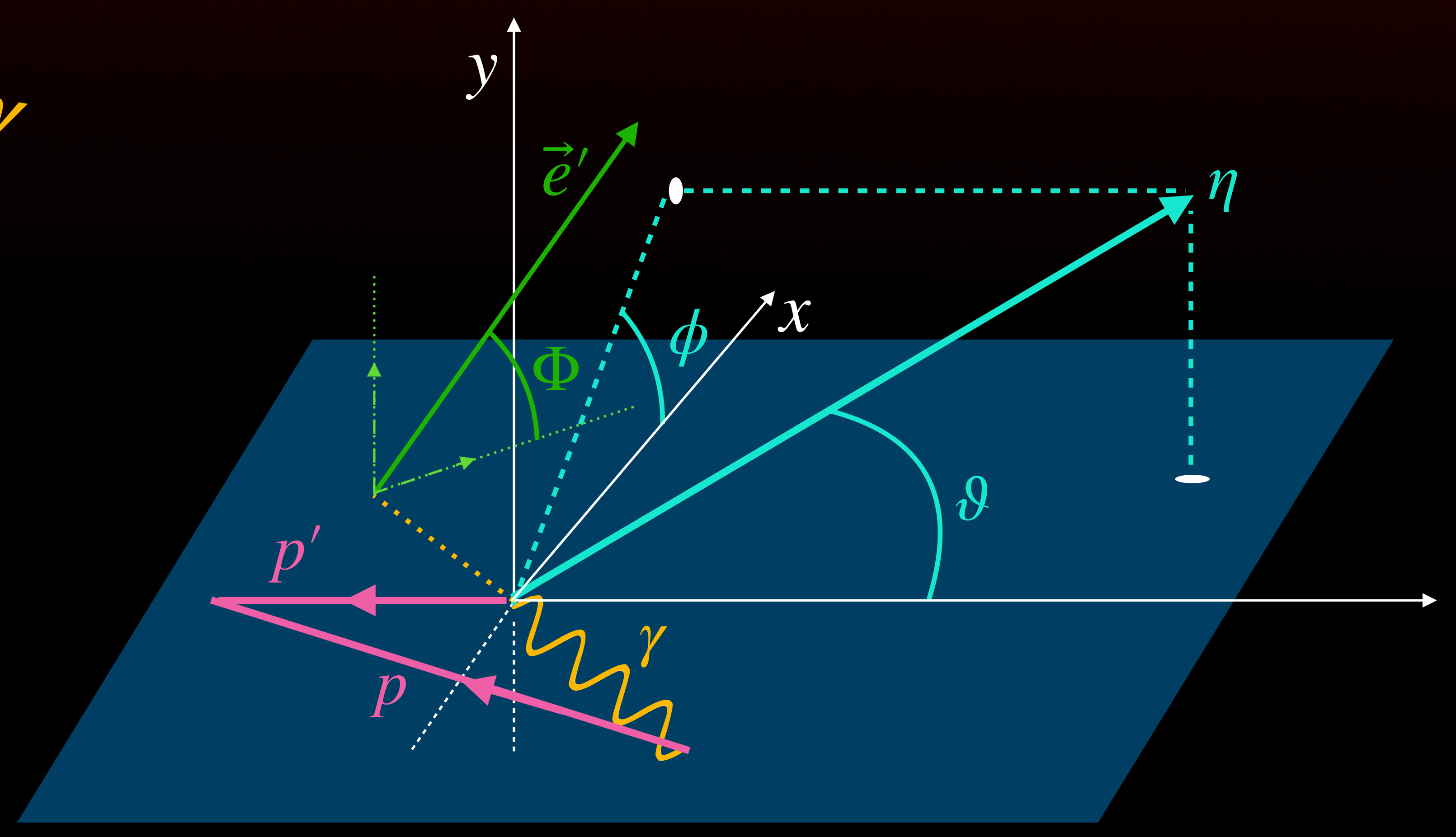


$$\mathcal{I}(\Omega, \Phi) = \sum_{\alpha=0}^{3} \mathcal{I}_\alpha(\Omega) P_\gamma^\alpha(\Phi)$$

Linearly polarized γ

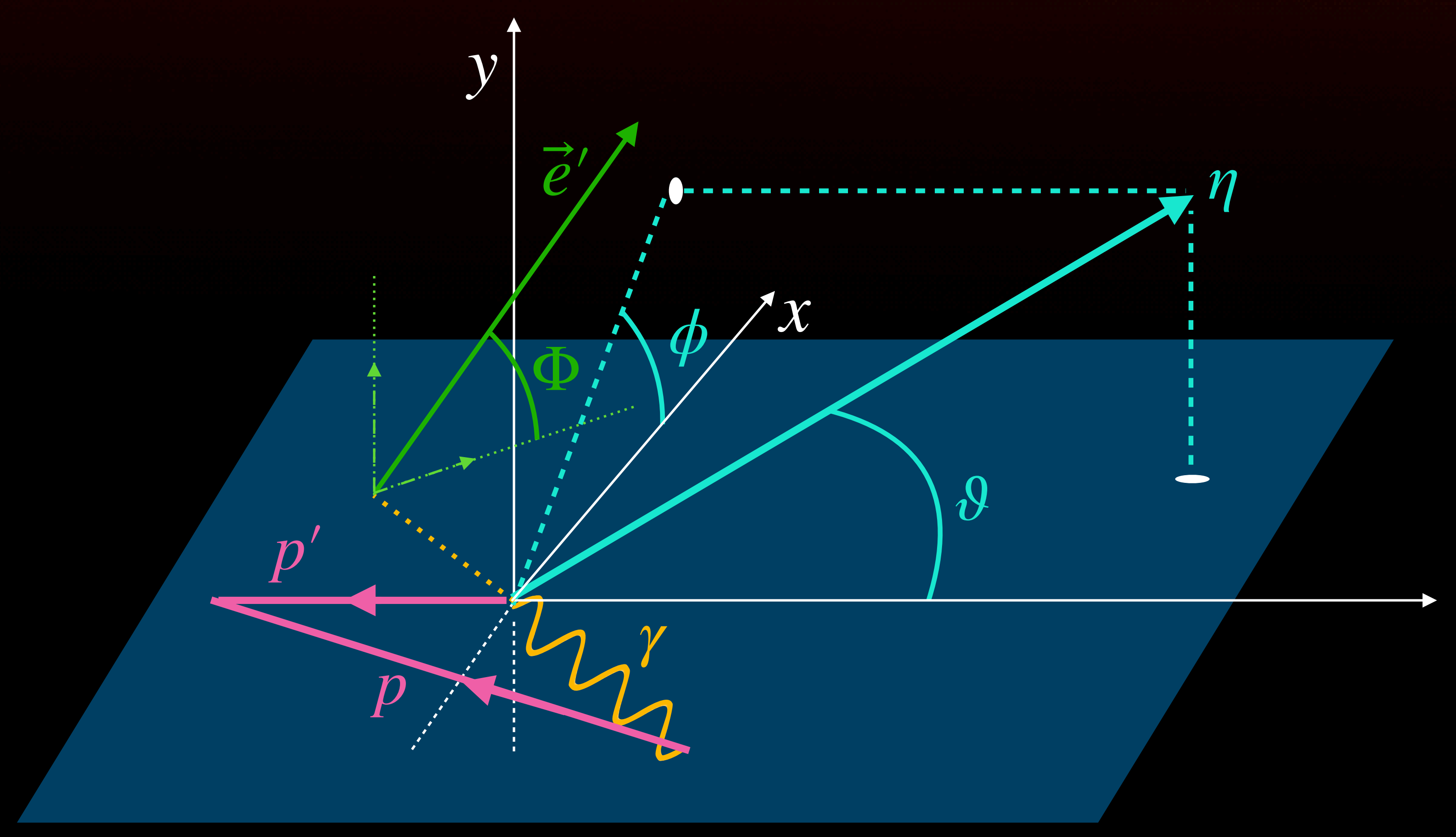
$$P_\gamma^\alpha(\Phi) = (1, -P_\gamma \cos(2\Phi), -P_\gamma \sin(2\Phi), 0)$$

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



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

- Describes all two-psuedoscalar 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



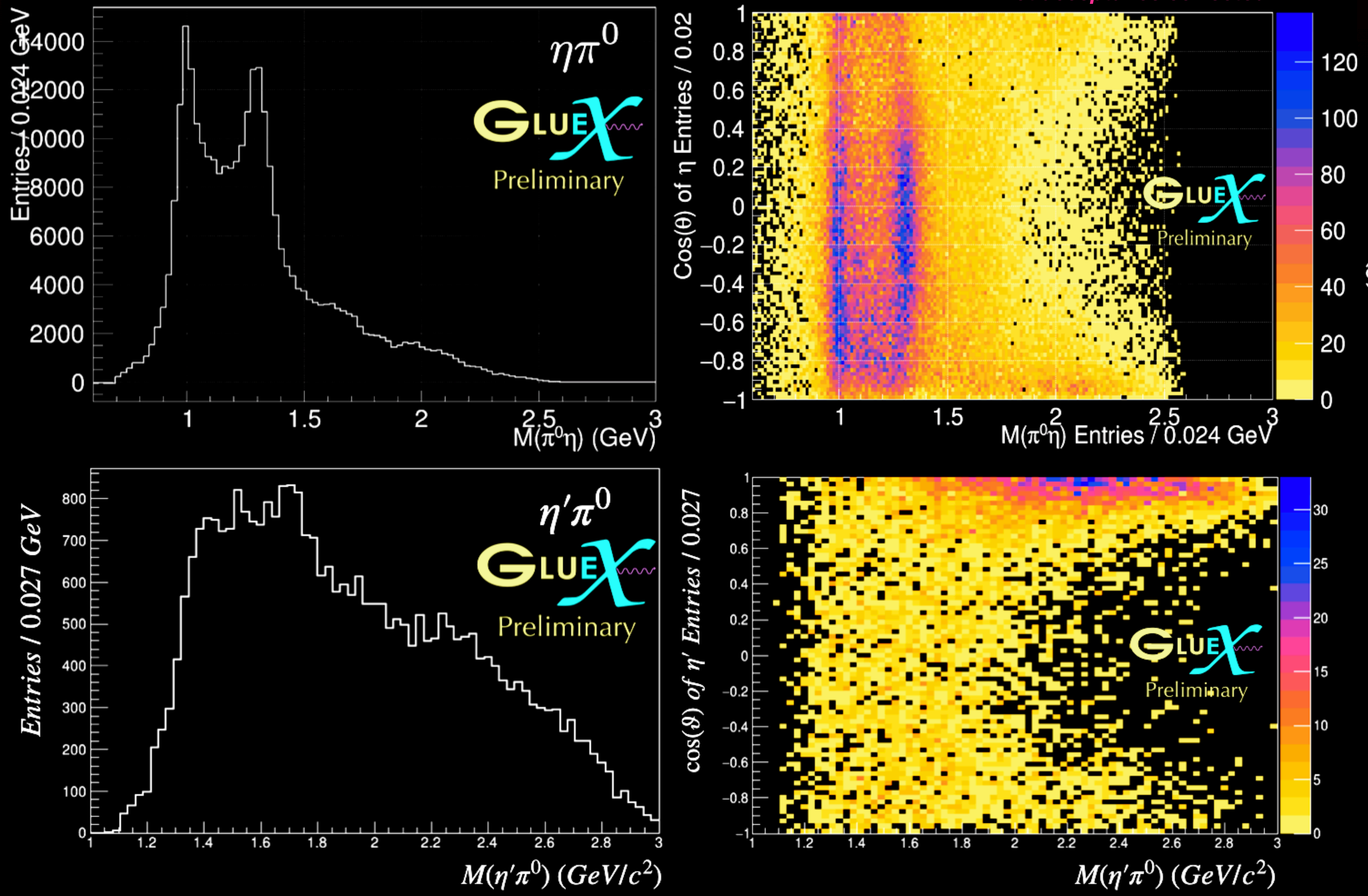
V. Mathieu et al. [JPAC], PRD 100, 054017 (2019)

- Reflectivity corresponds to exchange being natural ($+1$) and unnatural (-1) parity
- 4x more amplitudes than hadro-production

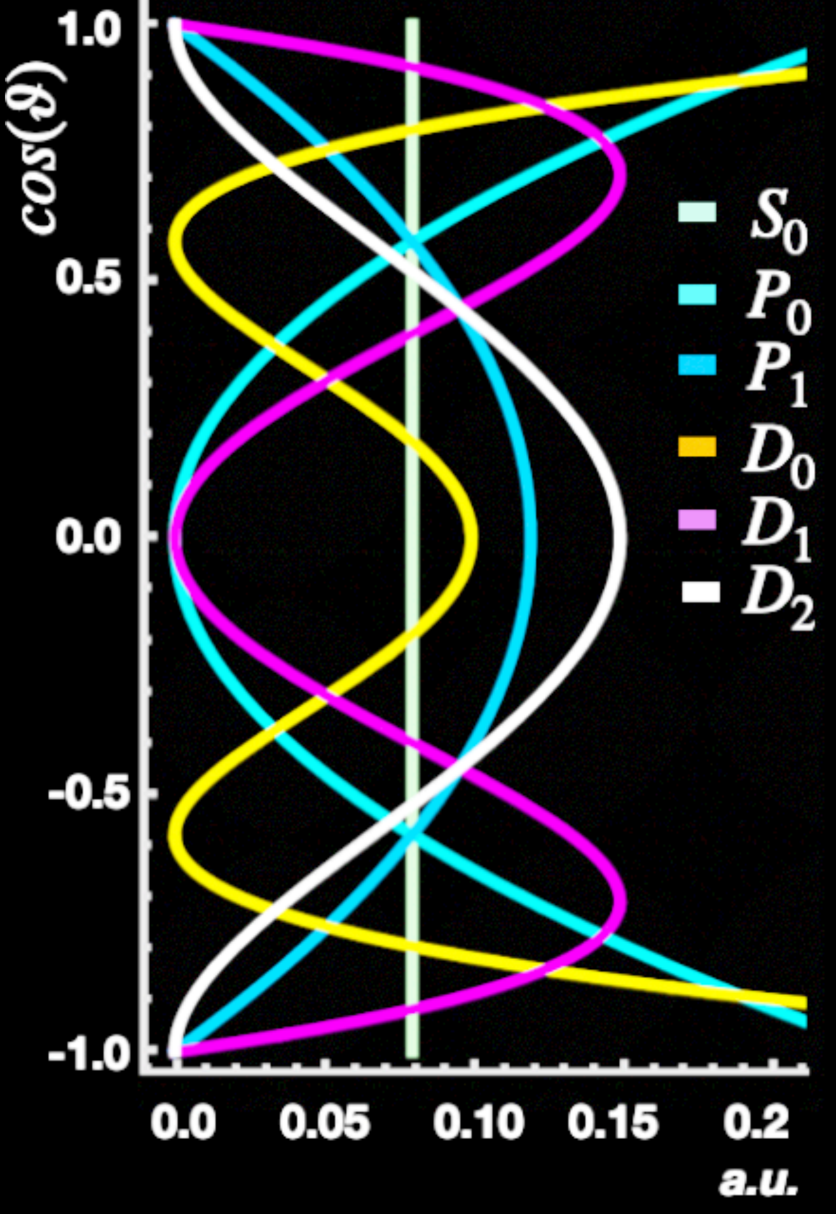
$$\Rightarrow \mathcal{I}(\Omega, \Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma)\left|\sum_{l,m} [l]_m^{(-)} \mathcal{Re}[Z_l^m(\Omega,\Phi)]\right|^2 + (1-P_\gamma)\left|\sum_{l,m} [l]_m^{(+)} \mathcal{Im}[Z_l^m(\Omega,\Phi)]\right|^2 +$$

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

$0.1 < -t < 0.3$

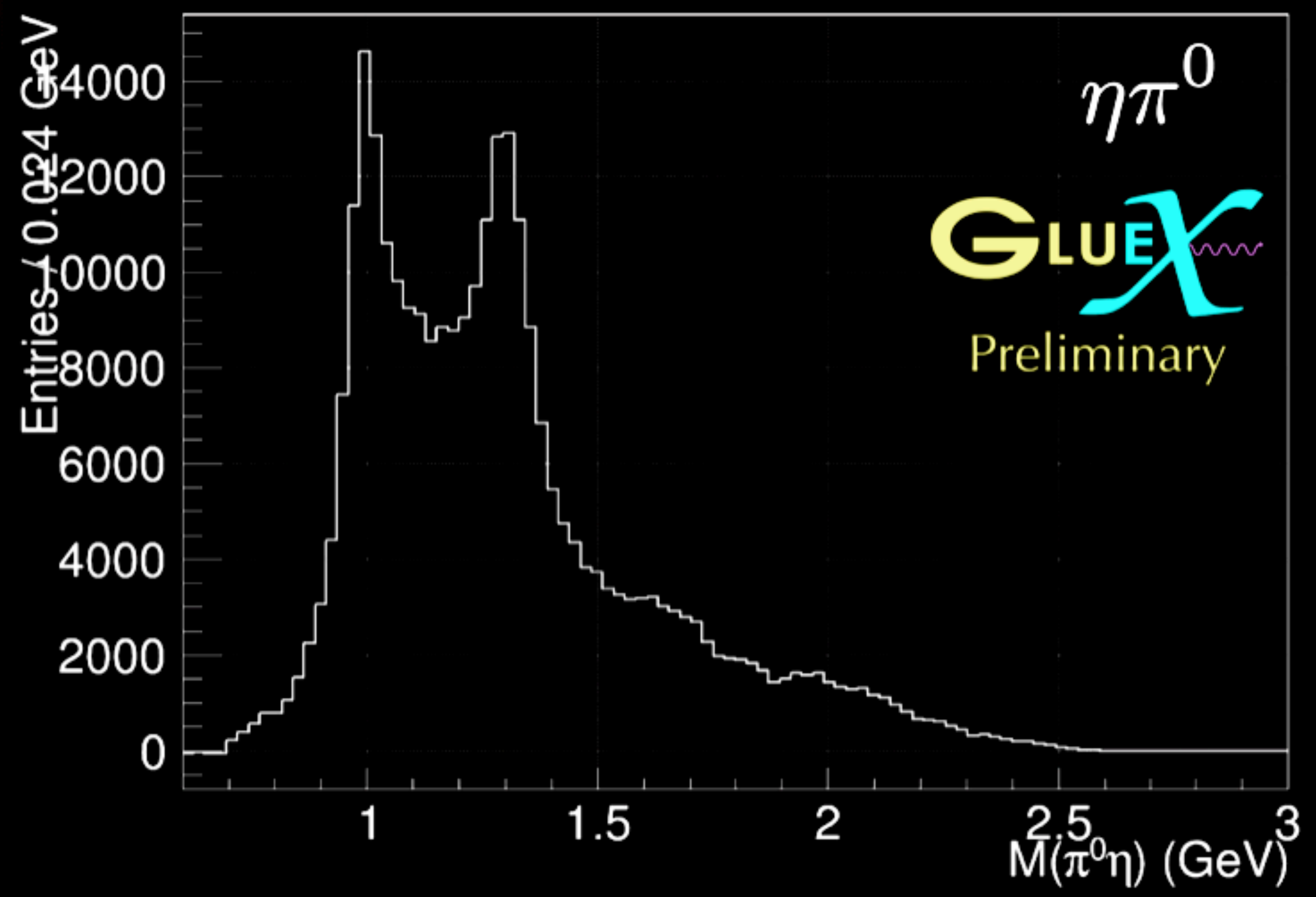


- **Neutral decay modes**
  - $\eta\pi^0 \to 4\gamma$
  - $\eta'\pi^0 \to 4\gamma\pi^+\pi^-$

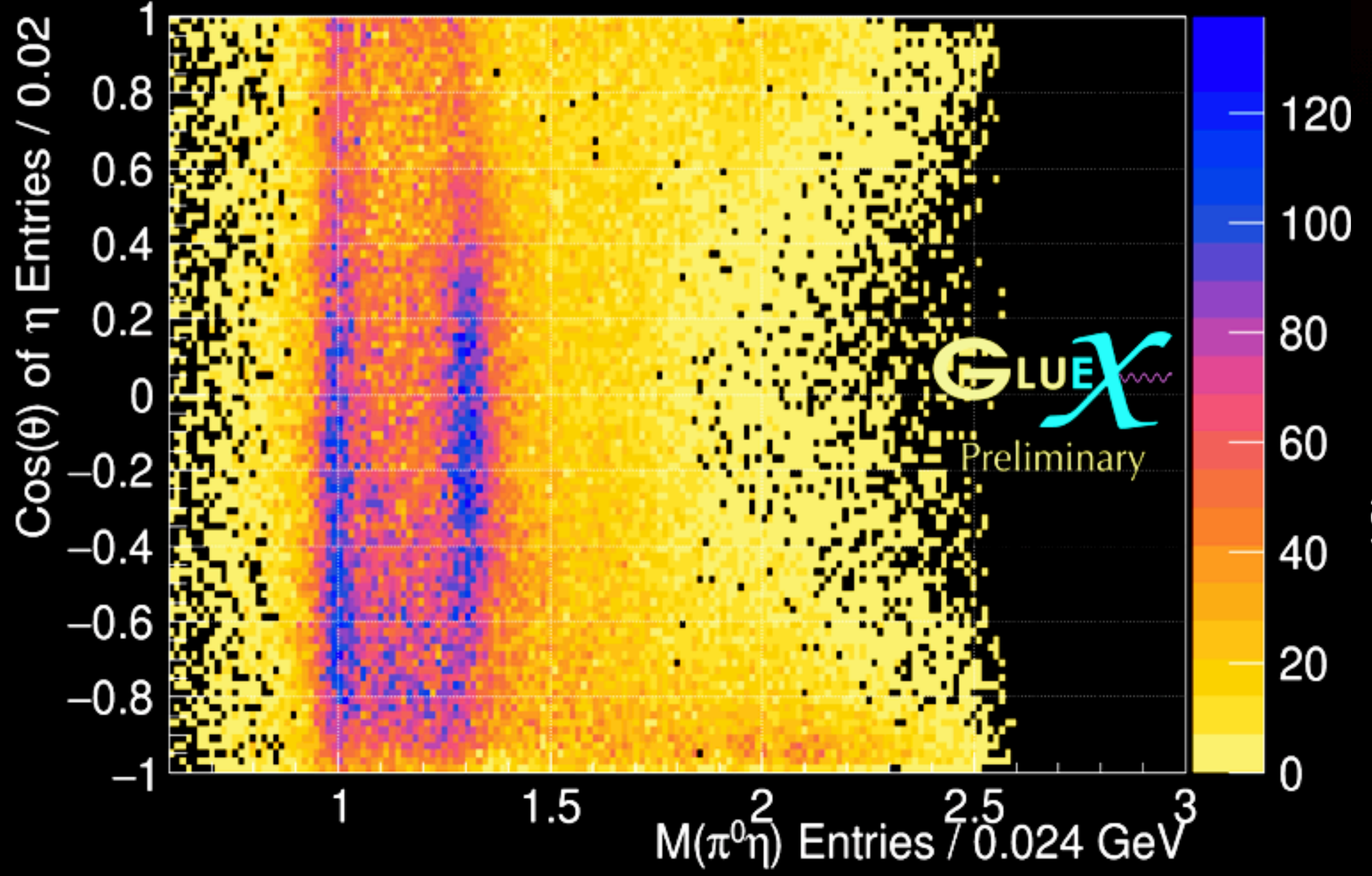


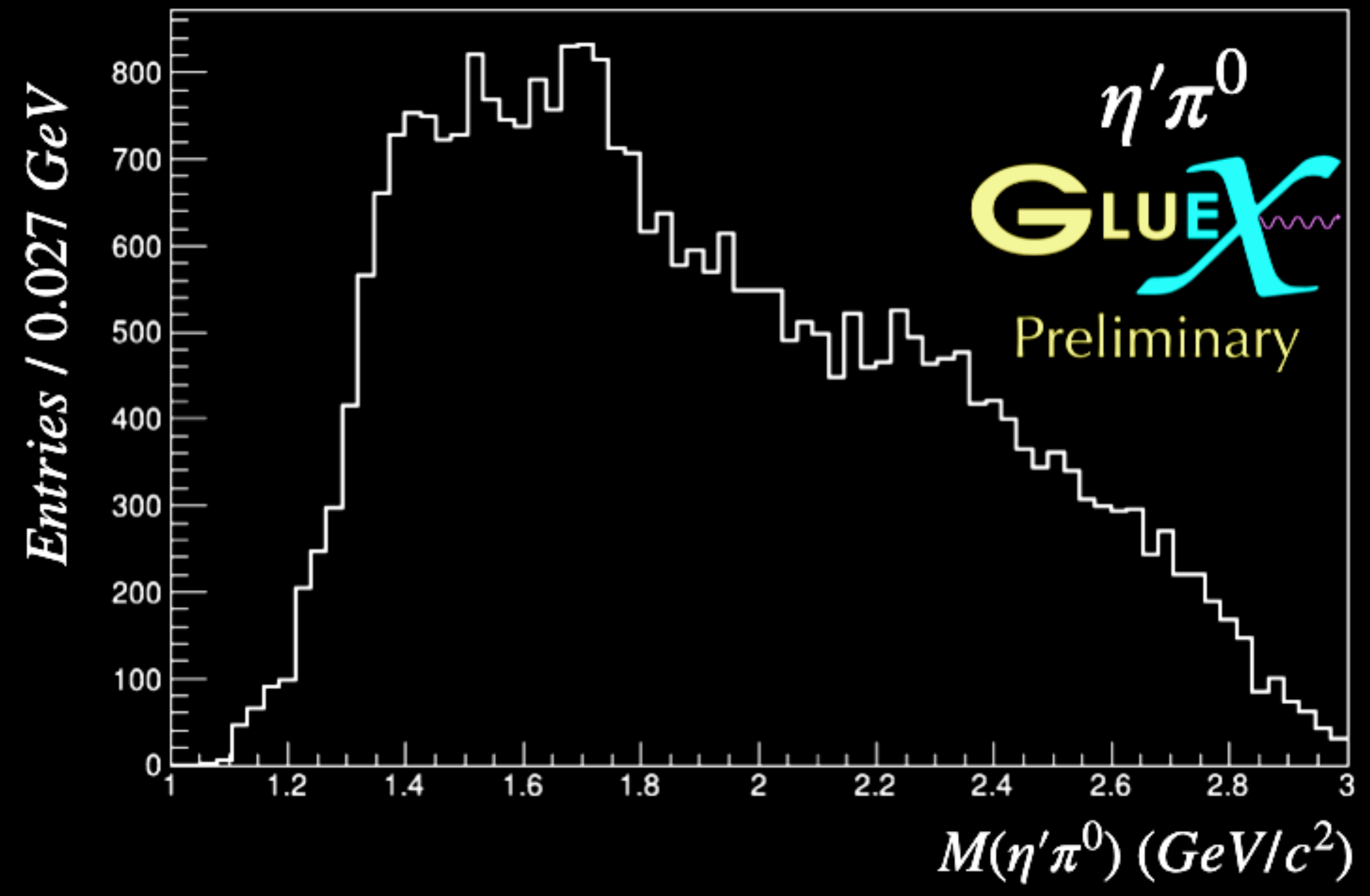
- **Charged decay modes also being analyzed …**
  - $\eta^{(\prime)}\pi^-\Delta^{++}$ | $\Delta^{++} \to \pi^+ p$, $\eta' \to \eta\pi^+\pi^-$

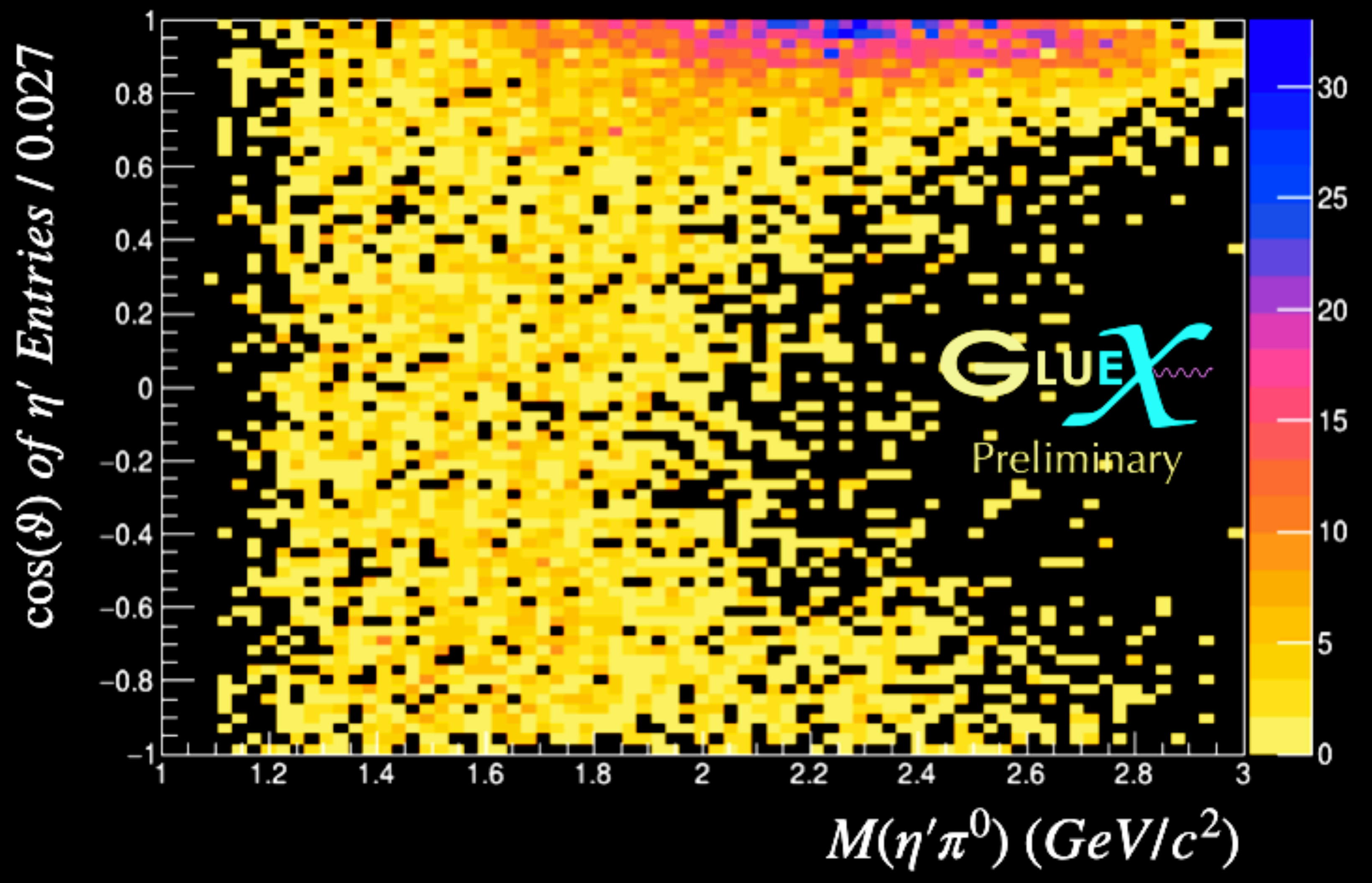
$0.1 < -t < 0.3$



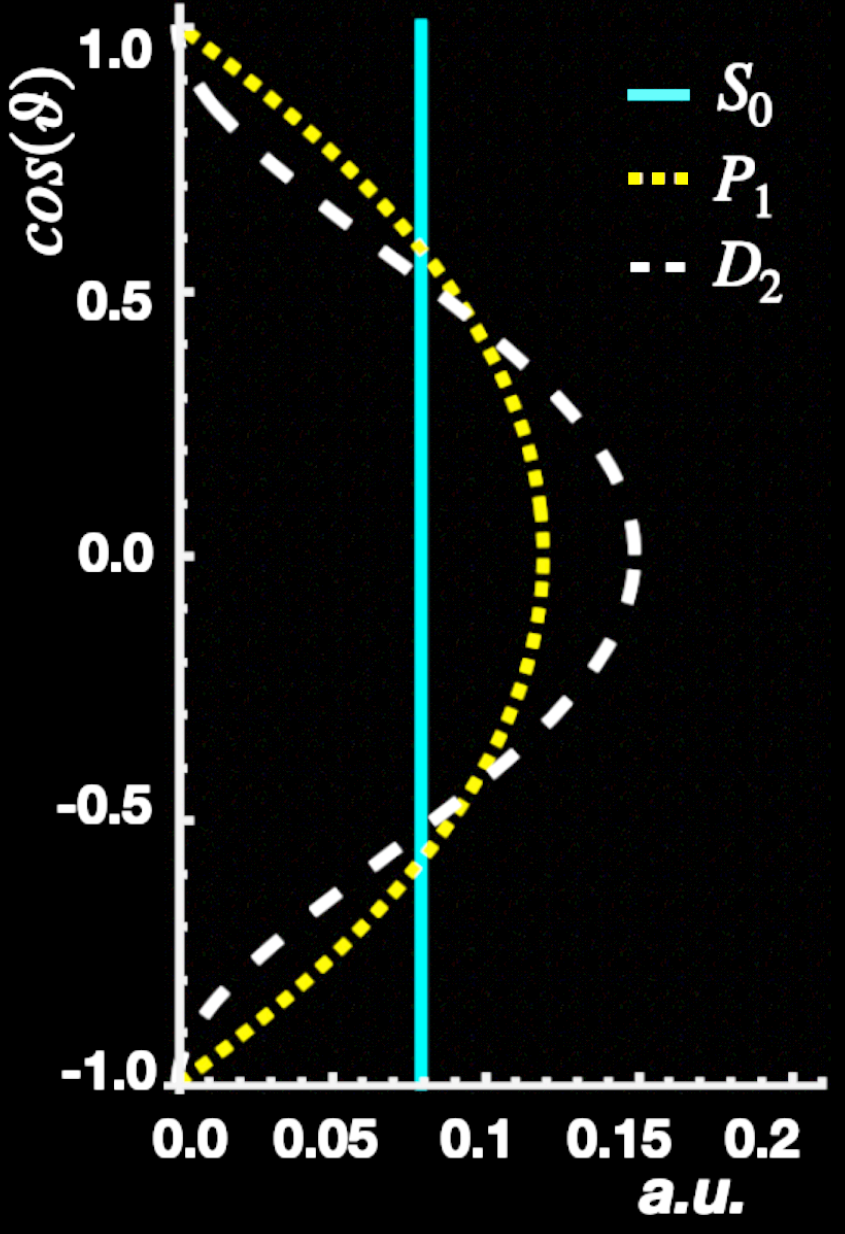
Not acceptance corrected







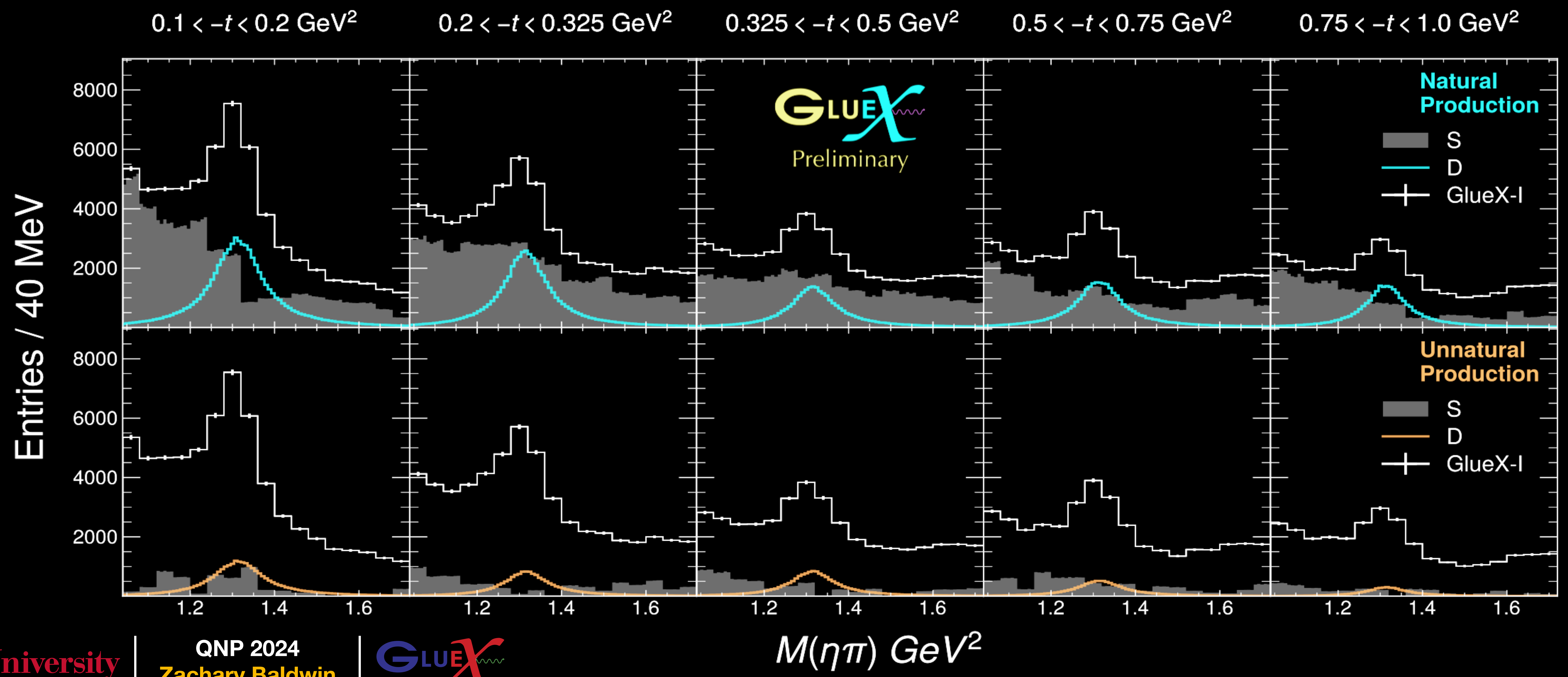
- **Neutral decay modes**
  - $\eta\pi^0 \rightarrow 4\gamma$
  - $\eta'\pi^0 \rightarrow 4\gamma\pi^+\pi^-$



- **Dominant S_0 and D_2 contributions**

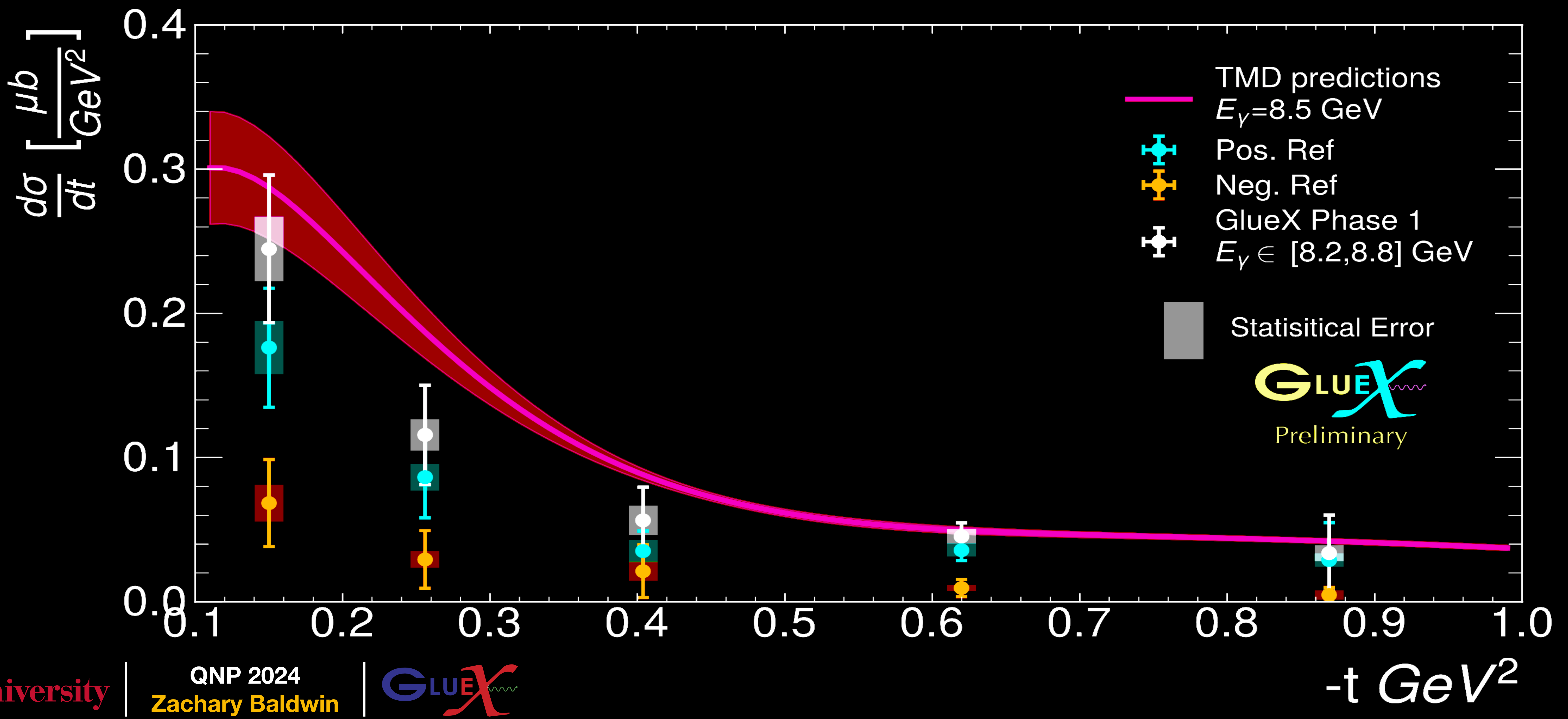
Semi-Mass Independent PWA

- **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**



Semi-Mass Independent PWA

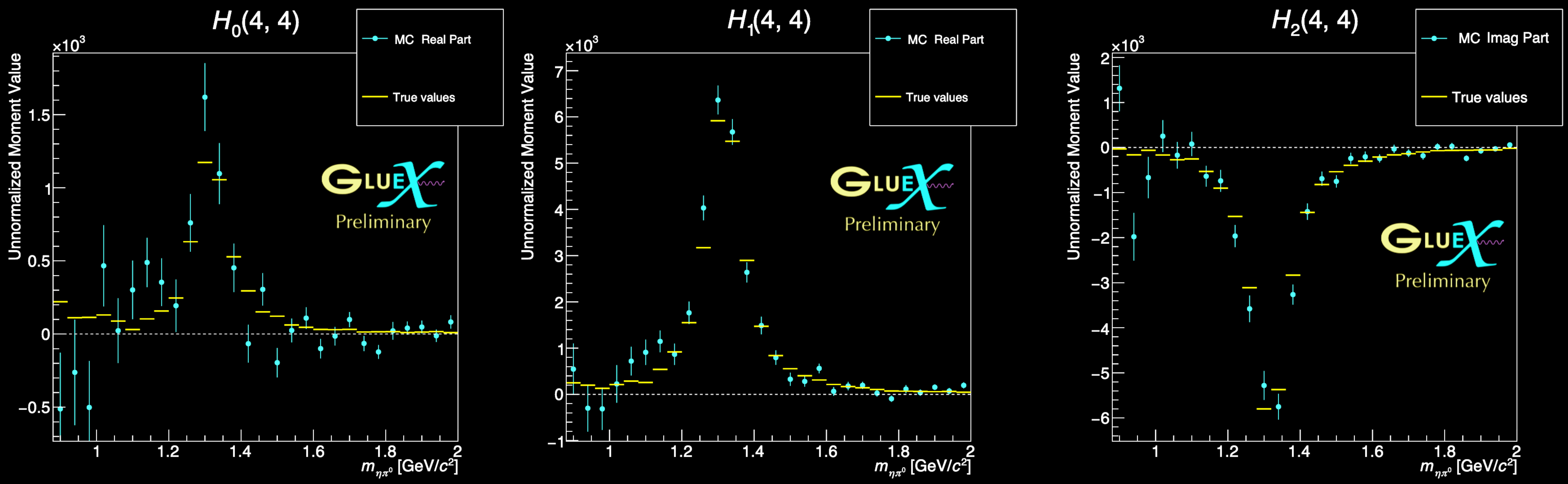
- **Assume $a_2(1320)$ and $a_2(1700)$ are text book Breit-Wigner resonances**
  - share only 1 common phase parameter for each in the D_{waves}
- **S_{wave} contributions more complicated**
  - define *mass independent* piecewise parameterization
- **Decent agreement between JPAC predictions**
  - systematics finalized — Publication in the works!



What can moments provide?

- Decompose angular components into spherical harmonics
  - determine sensitivity to exotic contributions
- No direct access to partial wave amplitudes
  - BUT vice-versa — can calculate moments from partial wave

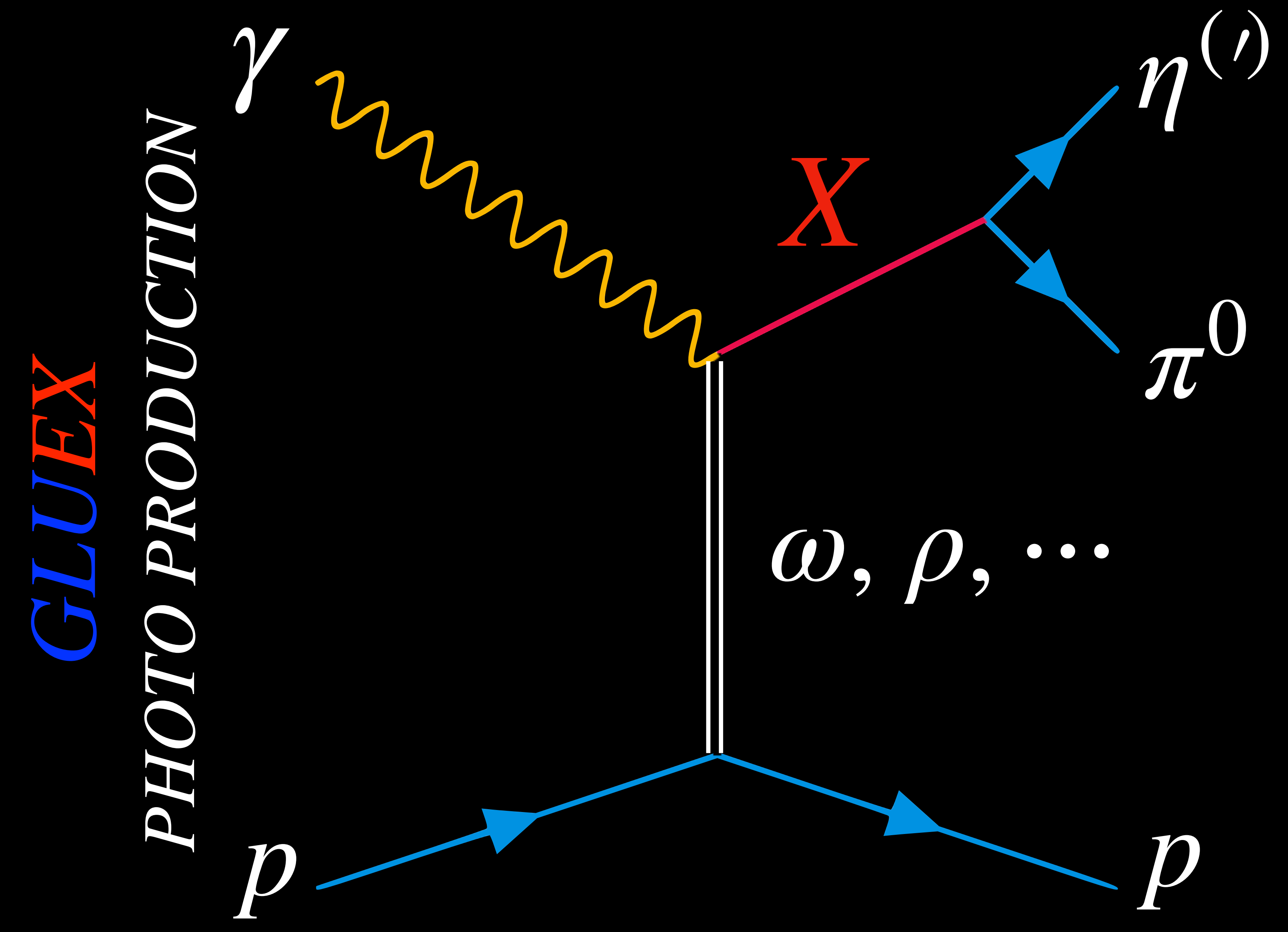
$H_i(4,4)$ contains clear $a_2(1320)$ signal



Monte Carlo Input-Output for $\eta^{(\prime)}\pi^0$
— synthetic acceptance applied

Summary

- GlueX has collected large quantity of photoproduced data
  - strong effort to look for *exotic hybrid* π_1 meson in $\eta^{(\prime)}\pi$ systems using partial wave and moment analyses
  - recent results extract a_2 cross sections in multiple channels which will be used as a reference signal — Publication in the works!
  - can analyze production mechanisms using polarization info



Exciting time for exotic hybrid search at GlueX

Future Work

- Further analyze both neutral and charged $\eta^{(\prime)}\pi$
  - extract a_2^- cross section
  - perform cross checks with other decay modes
- Continue strong collaboration with theorists
  - work with JPAC on coupled channel fits

GlueX acknowledges the support of several funding agencies and computing facilities
gluex.org/thanks

BACKUP SLIDES

Cross Section definition

$$N_{produced} = \sigma \mathscr{L}$$

$$\Rightarrow \quad \sigma = \frac{N_{obs}}{\mathscr{B}_{tot}\epsilon_{tot}\mathscr{L}}$$

$\epsilon_{tot} = \epsilon_{tag} \times \epsilon_{non-tag}$

$\mathscr{B}_{tot} = \mathscr{B}_{a_2 \to \pi^0\eta} \times \mathscr{B}_{\eta \to \pi^0\pi^+\pi^-} \times \mathscr{B}_{\pi^0 \to \gamma\gamma}$

(0.145) (0.2302) (0.9882)

$$= \left(\frac{1}{\mathscr{B}_{tot}}\right)\left(\frac{N_{obs}}{\epsilon_{non-tag}}\right)\left(\frac{1}{\epsilon_{tag}\mathscr{L}}\right)$$

- Calculated to be $\approx 107.2\ pb^{-1}$
- AmpTools calculation from "hybrid" fits

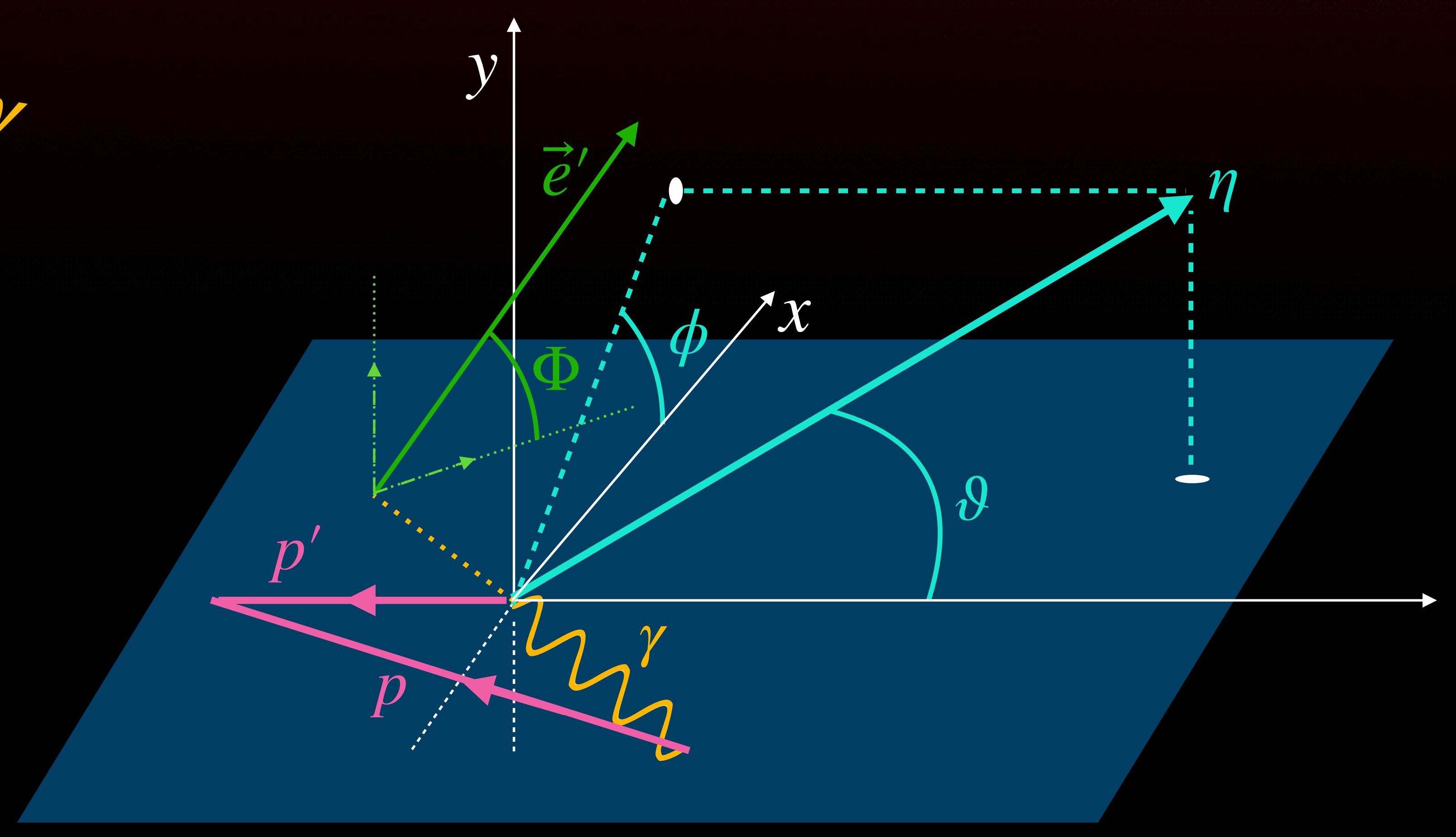
Moment definition

$$\mathcal{I}(\Omega, \Phi) = \sum_{\alpha=0}^{3} \mathcal{I}_\alpha(\Omega) P_\gamma^\alpha(\Phi)$$

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)

Decompose intensity components into spherical harmonics

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

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

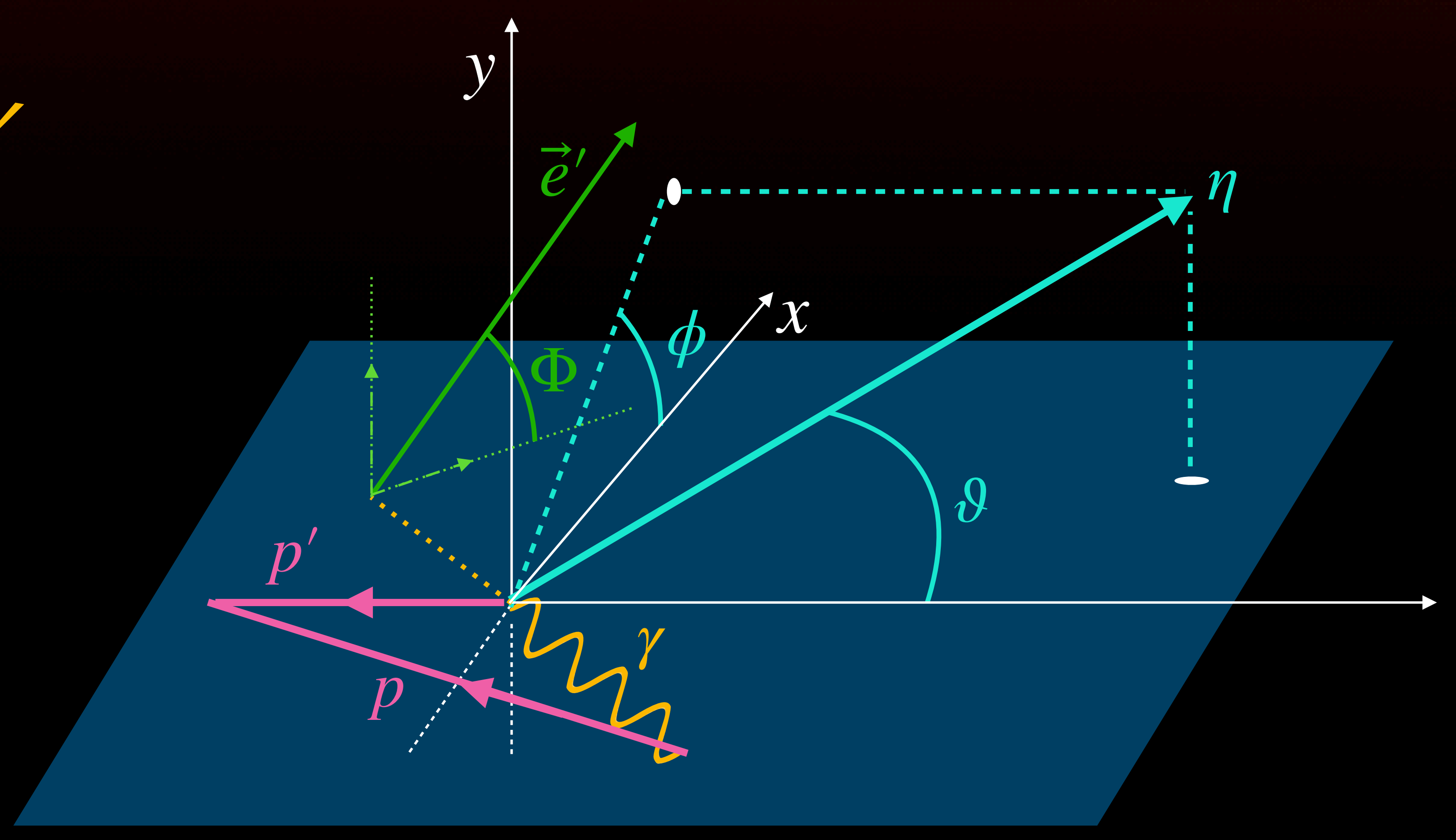
Moment definition

$$\mathcal{I}(\Omega, \Phi) = \sum_{\alpha=0}^{3} \mathcal{I}_\alpha(\Omega) P_\gamma^\alpha(\Phi)$$

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)

Corresponding moments:

$$\mathcal{I}_0(\Omega) \quad \Rightarrow \quad H_0(L, M) = \frac{1}{2\pi} \sqrt{\frac{4\pi}{2L+1}} \int_{4\pi} d\Omega \int_{-\pi}^{\pi} d\Phi \; \mathcal{I}(\Omega, \Phi) \; Y_L^{M*}(\Omega)$$

$$\mathcal{I}_{1,2}(\Omega) \quad \Rightarrow \quad H_{1,2}(L, M) = \frac{1}{\pi P_\gamma} \sqrt{\frac{4\pi}{2L+1}} \int_{4\pi} d\Omega \int_{-\pi}^{\pi} d\Phi \; \mathcal{I}(\Omega, \Phi) \; Y_L^{M*}(\Omega) \times \begin{cases} \cos(2\Phi) \\ \sin(2\Phi) \end{cases}$$