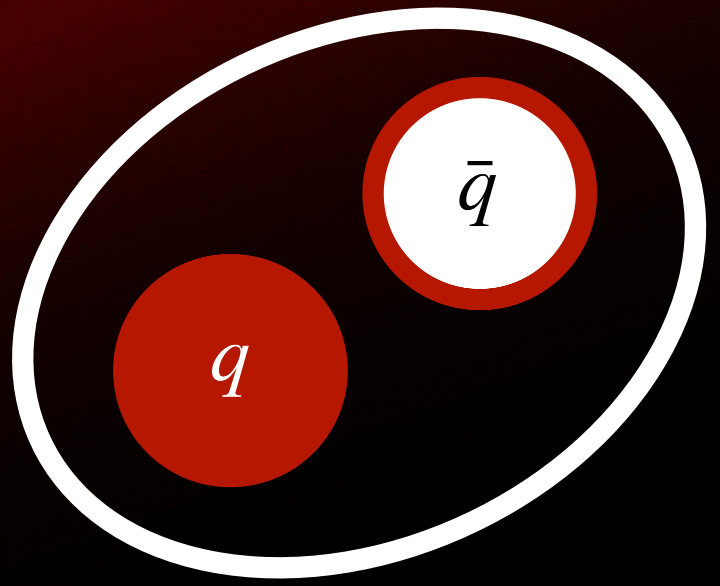
Analyzing $\pi^0\eta$ and $\pi^0\eta'$ systems in the search for exotic hybrid mesons at GlueX

CFNS-CTEQ Summer School—Stony Brook University

The Physics of the Electron-Ion Collider

Zachary Baldwin, June 16, 2023
for the GlueX Collaboration and
Carnegie Mellon University

Meson



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

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

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

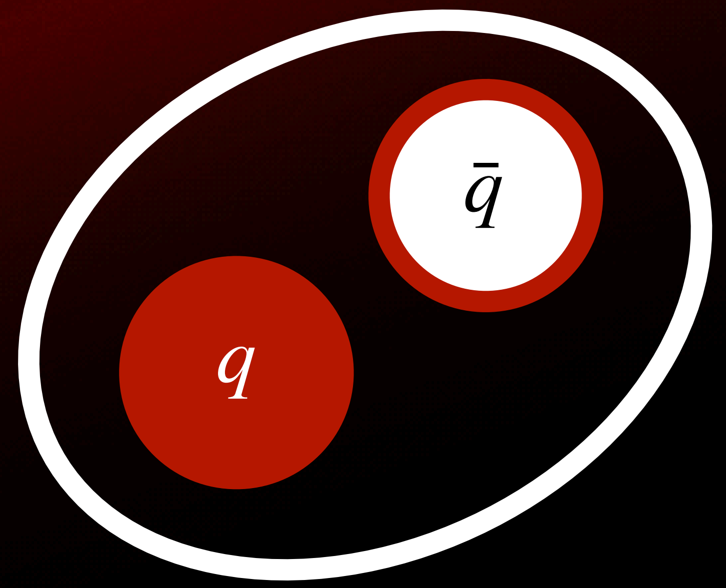
L is the relative orbital angular momentum of the q and $\bar{q}$

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^{--}

Meson



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			1	1	1^{++}	2	1	2^{--}
			1	1	2^{++}	2	1	3^{--}

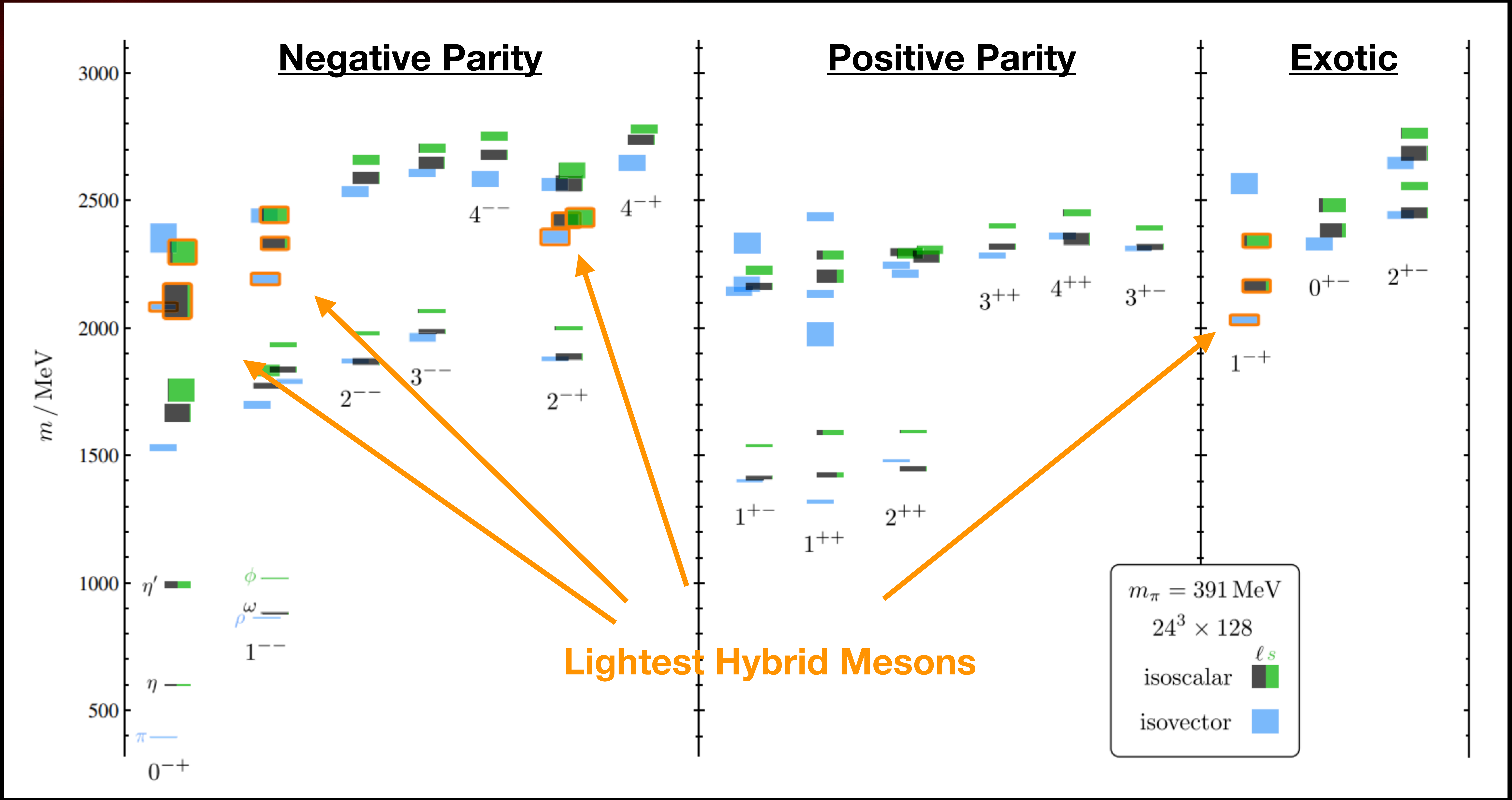
Forbidden J^{PC} quantum numbers

0^{--} 0^{+-} 1^{-+} 2^{+-}

Discovering forbidden quantum numbers would be immediate evidence of a non-$q\bar{q}$ state (i.e. new QCD states)

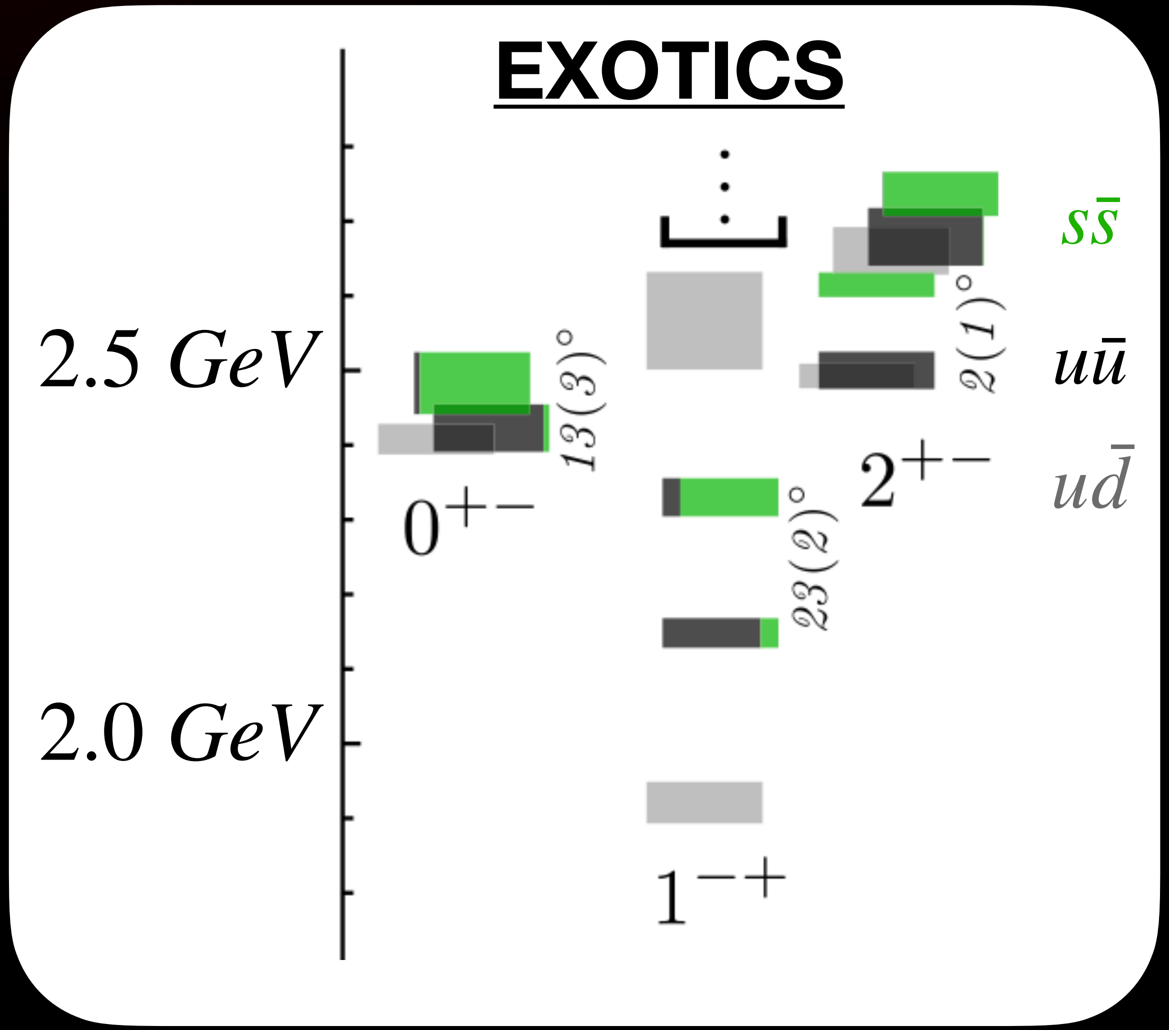
The goal of GlueX is to map the spectrum of light hybrid mesons and potentially find evidence of these new QCD states

Dudek,Edwards,Guo, and Thomas,PRD88,094505(2013)



What predictions show the best exotic quantum number hybrid ?

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



Phys. Rev. D83, 111502 (2011)

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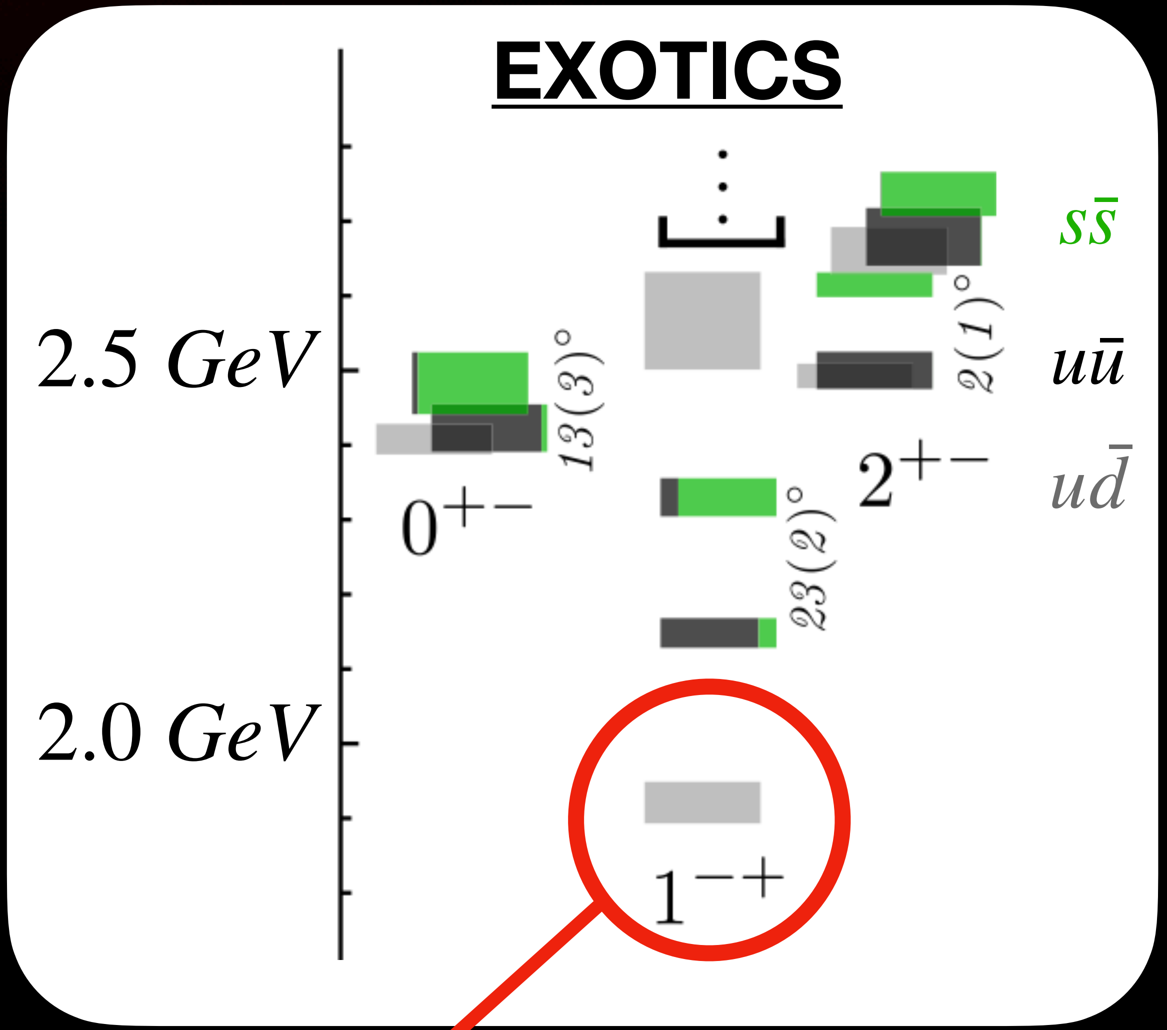

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π_1 → $\pi_1(1400) \longrightarrow \boxed{\pi\eta}$

π_1 → $\pi_1(1600) \longrightarrow \boxed{\pi\eta'}$

Multiple experiments have looked for resonances in the P-wave:

E852, Crystal Barrel, CLEO, etc.

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

EXOTIC

COMPASS

Combined analysis for both $\pi\eta$ and $\pi\eta'$

$$\pi^- p \to n\pi^-\eta^{(\prime)}$$

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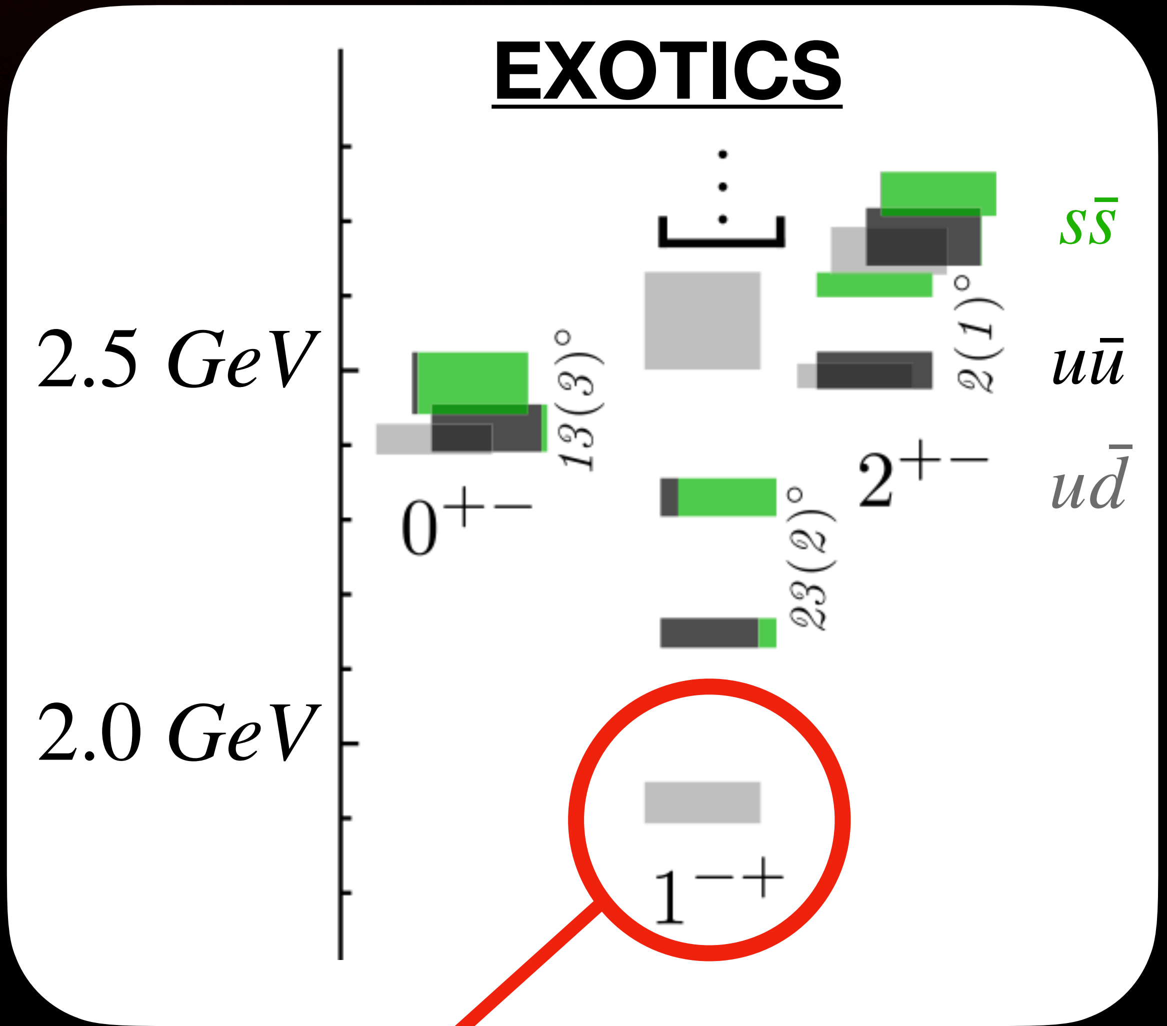

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$\pi_1 \rightarrow \pi_1(1400) \rightarrow \pi\eta$

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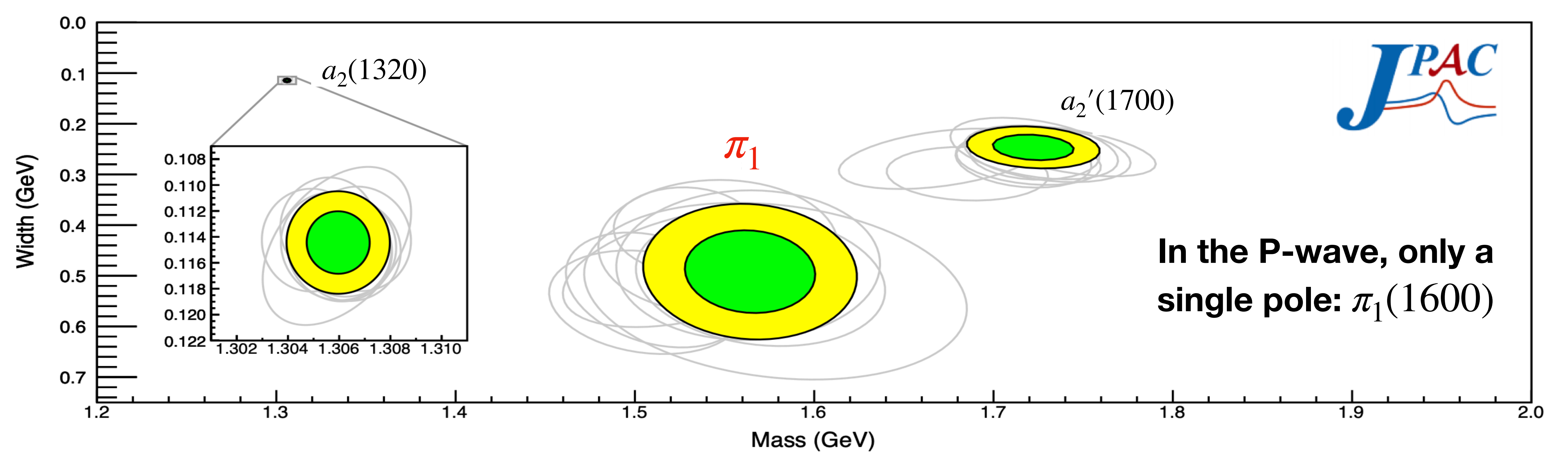

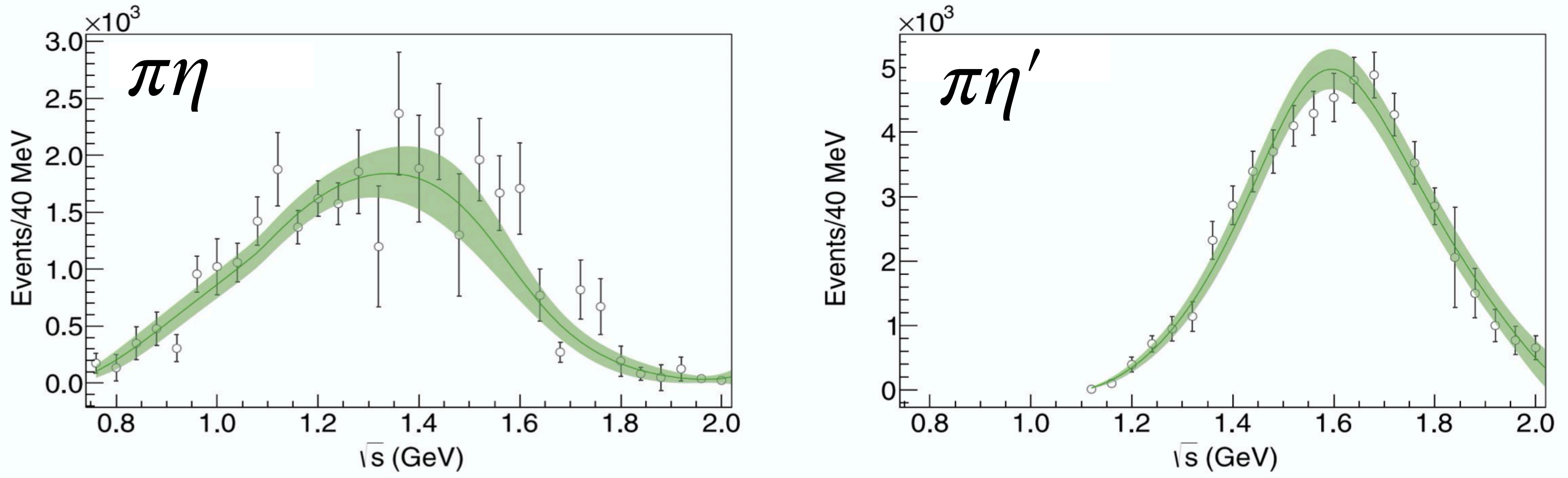

A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

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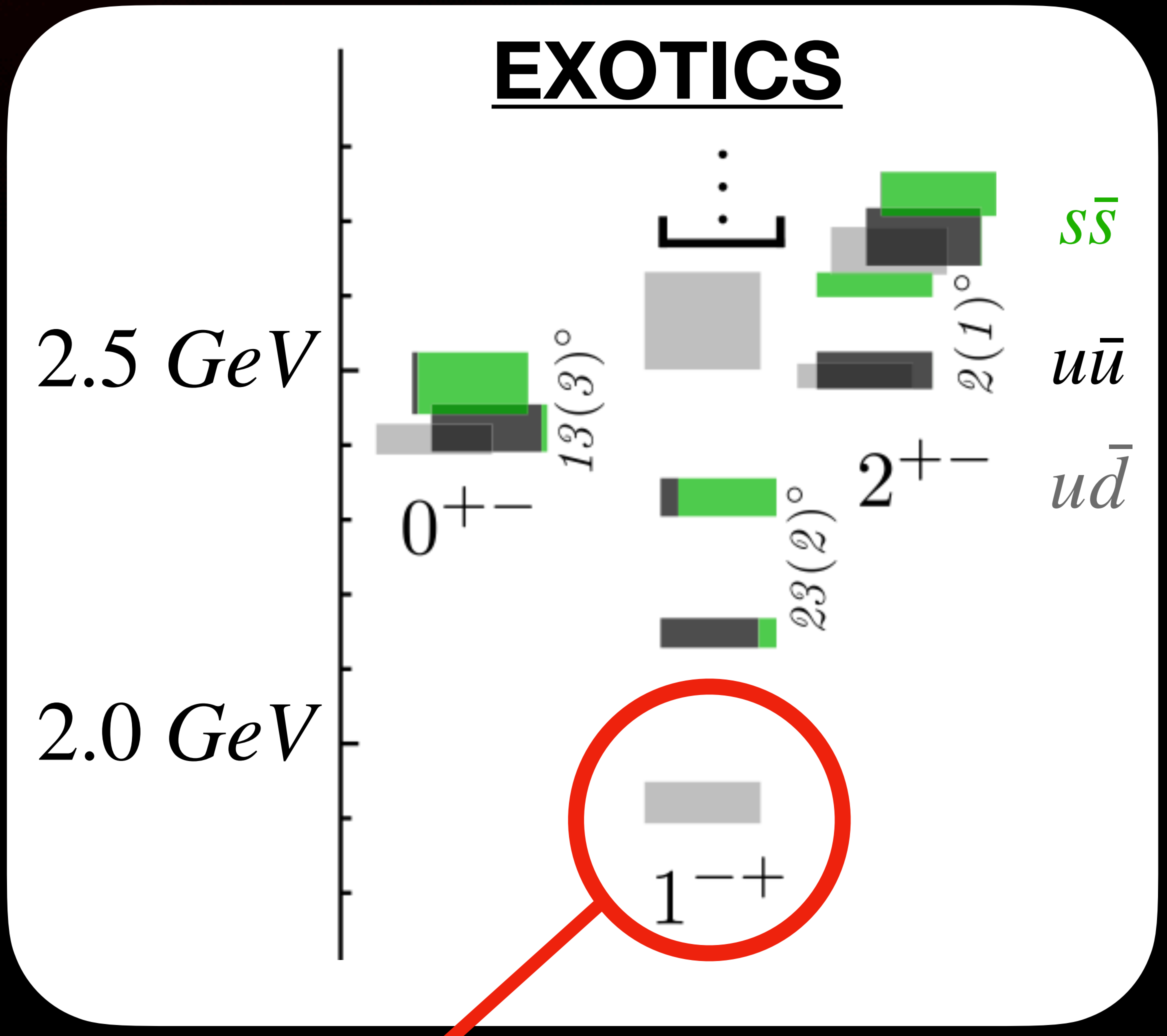

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π_1: $\pi_1(1400) \to \boxed{\pi\eta}$, $\pi_1(1600) \to \boxed{\pi\eta'}$

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L	S	P	D	F	$\cdots$
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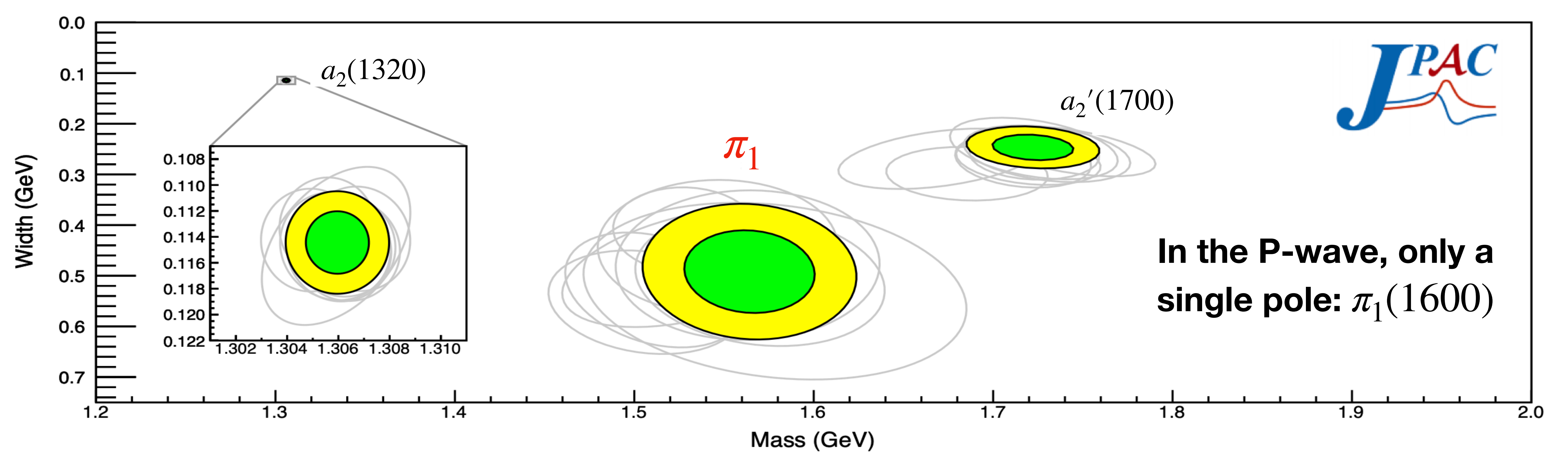

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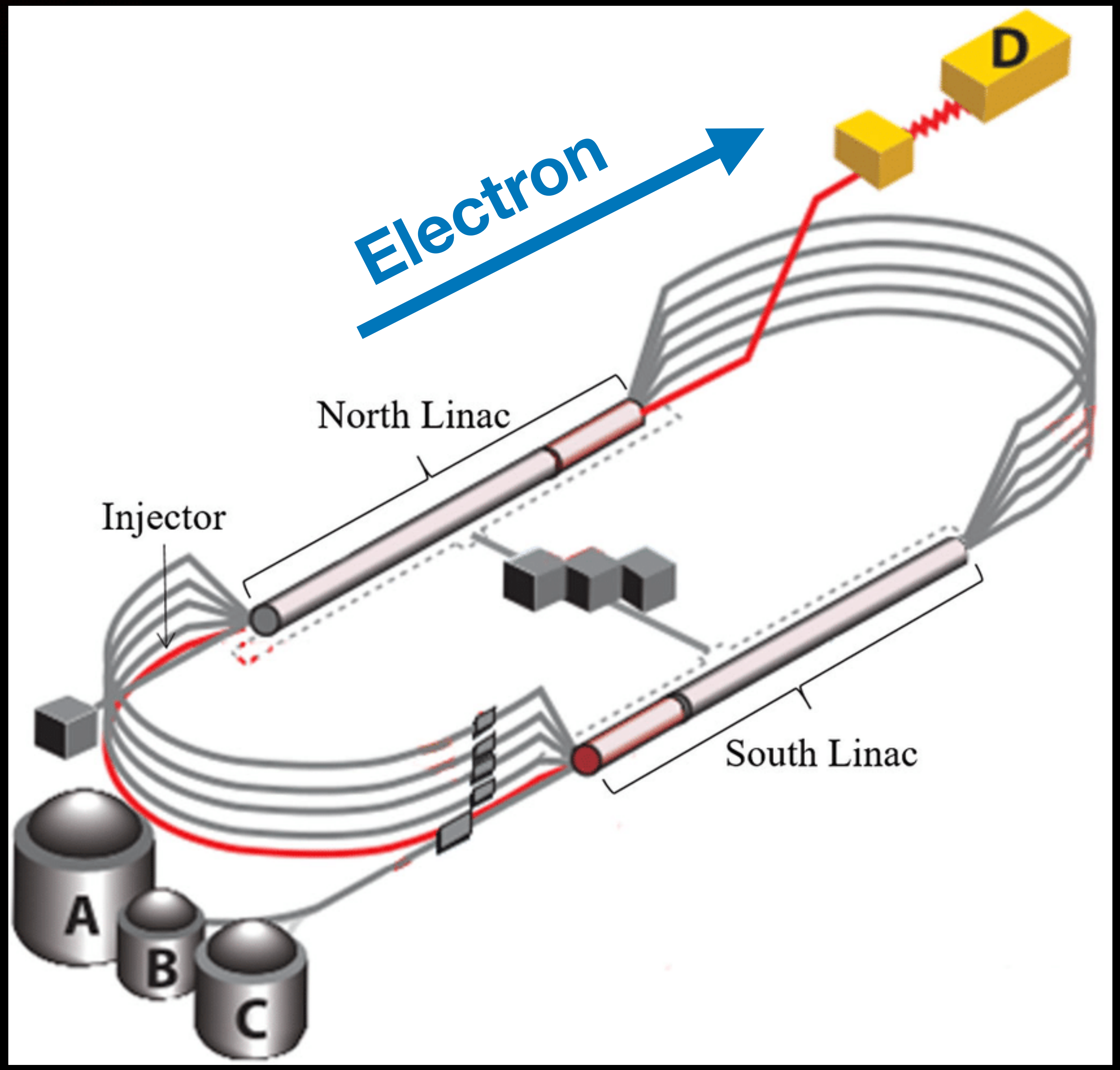
Lattice QCD, although powerful, only provides limited information.

No information is provided about what production mechanism is the best, how often the particle is produced, which decay mode is more prominent, etc.

The main goal of the GlueX experiment is understand the underlying nature of confinement within QCD by mapping the spectrum of light quark states

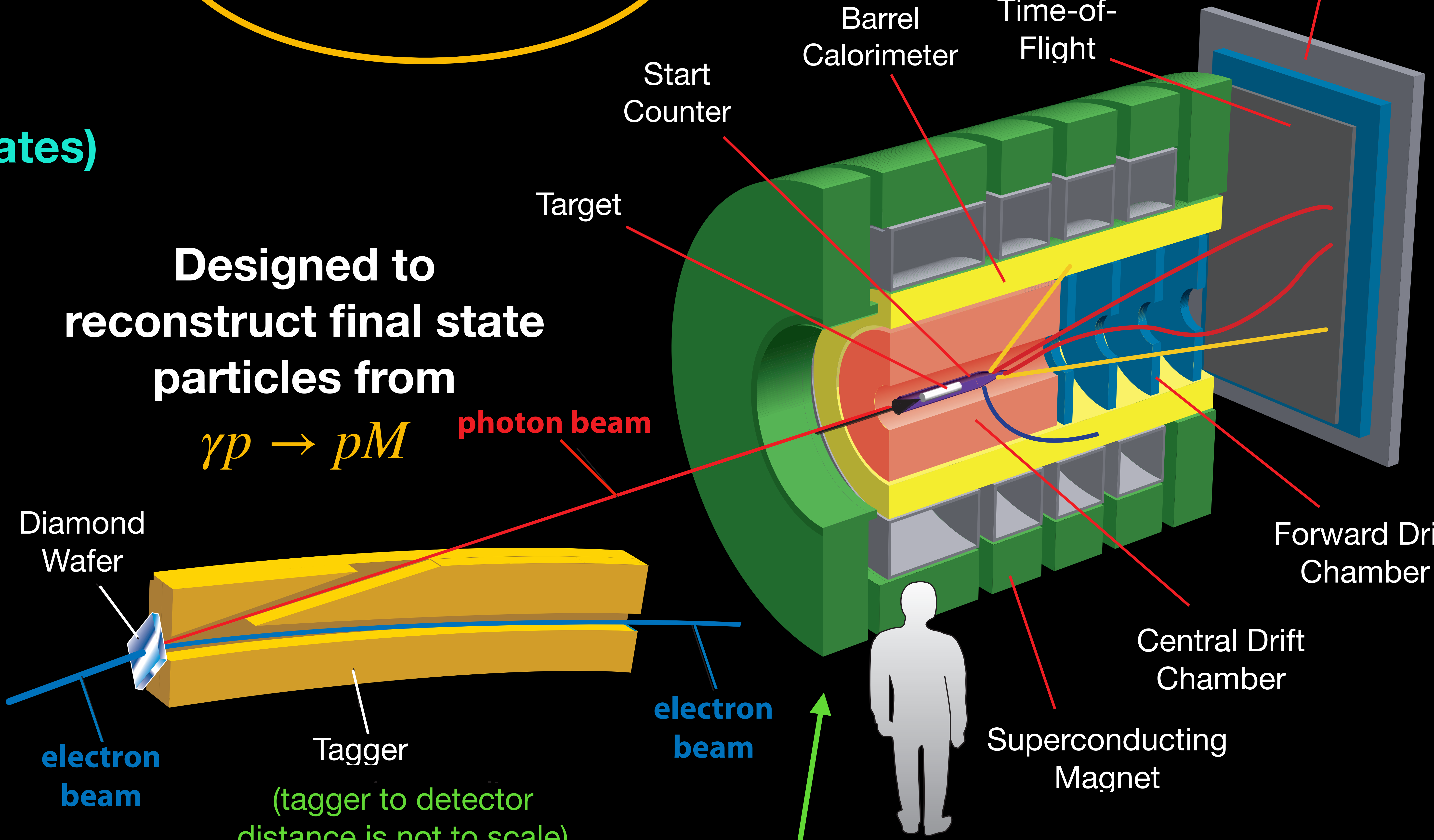
With an emphasis on searching for evidence of a non-$q\bar{q}$ state (i.e. new QCD states)

Gluonic Excitation



Designed to reconstruct final state particles from

$$\gamma p \rightarrow pM$$



- **Solenoid magnet operates at max 2 T magnetic field strength**

$$\gamma p \to \pi^0 \eta p$$
$\pi^0\pi^+\pi^-$
$\gamma\gamma$
$\gamma\gamma$
$\to \boxed{4\gamma\pi^+\pi^-}$

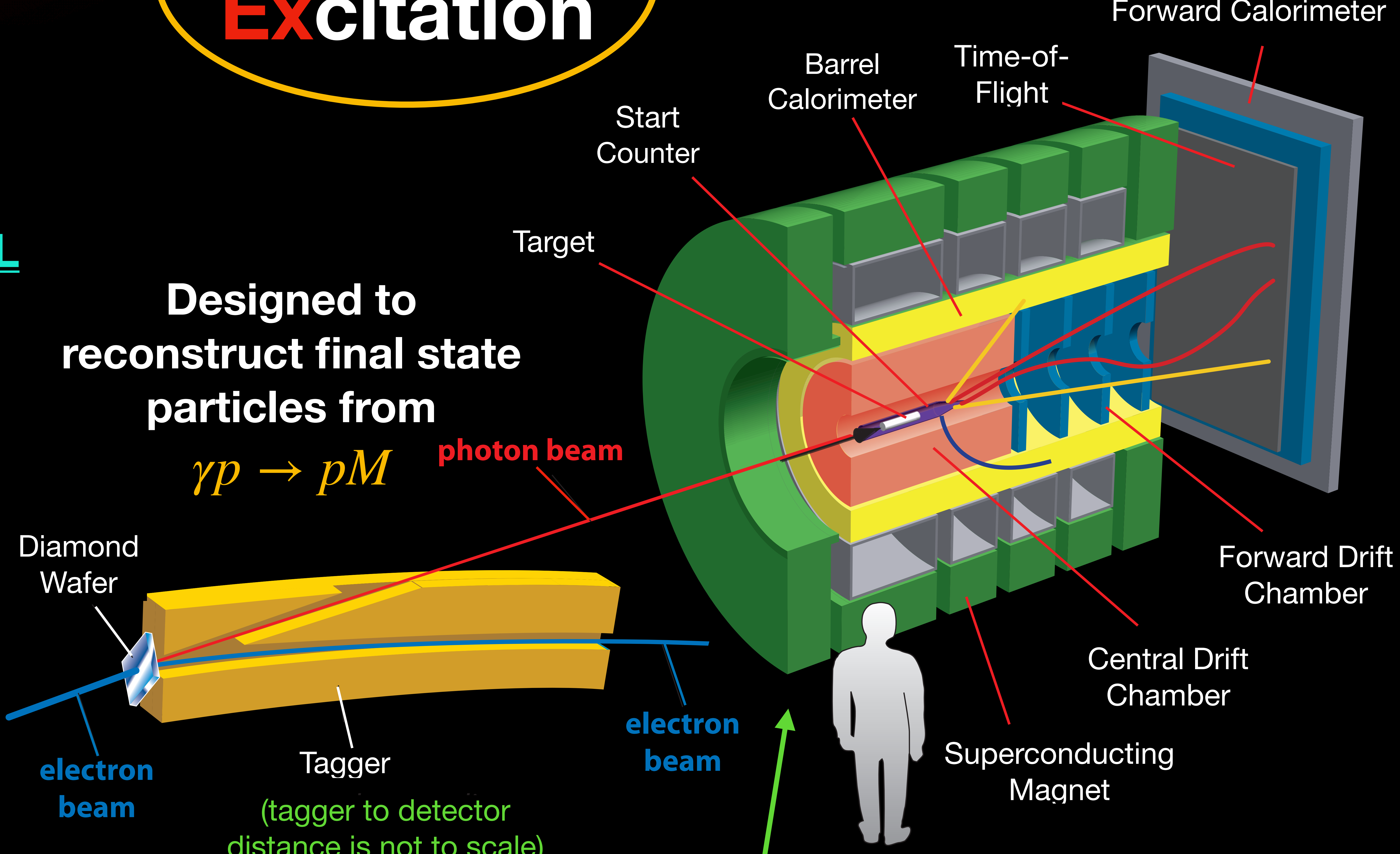
SAME FINAL STATE

$$\gamma p \to \pi^0 \eta' p$$
$\eta\pi^+\pi^-$
$\gamma\gamma$
$\gamma\gamma$
$\to \boxed{4\gamma\pi^+\pi^-}$

$$BR(\pi^0 \to 2\gamma) = (98.823 \pm 0.034)\,\%$$
$$BR(\eta \to \pi^0\pi^+\pi^-) = (22.98 \pm 0.2)\,\%$$
$$BR(\eta' \to \eta\pi^+\pi^-) = (42.9 \pm 0.7)\,\%$$

Gluonic Excitation

Designed to reconstruct final state particles from
$\gamma p \to pM$



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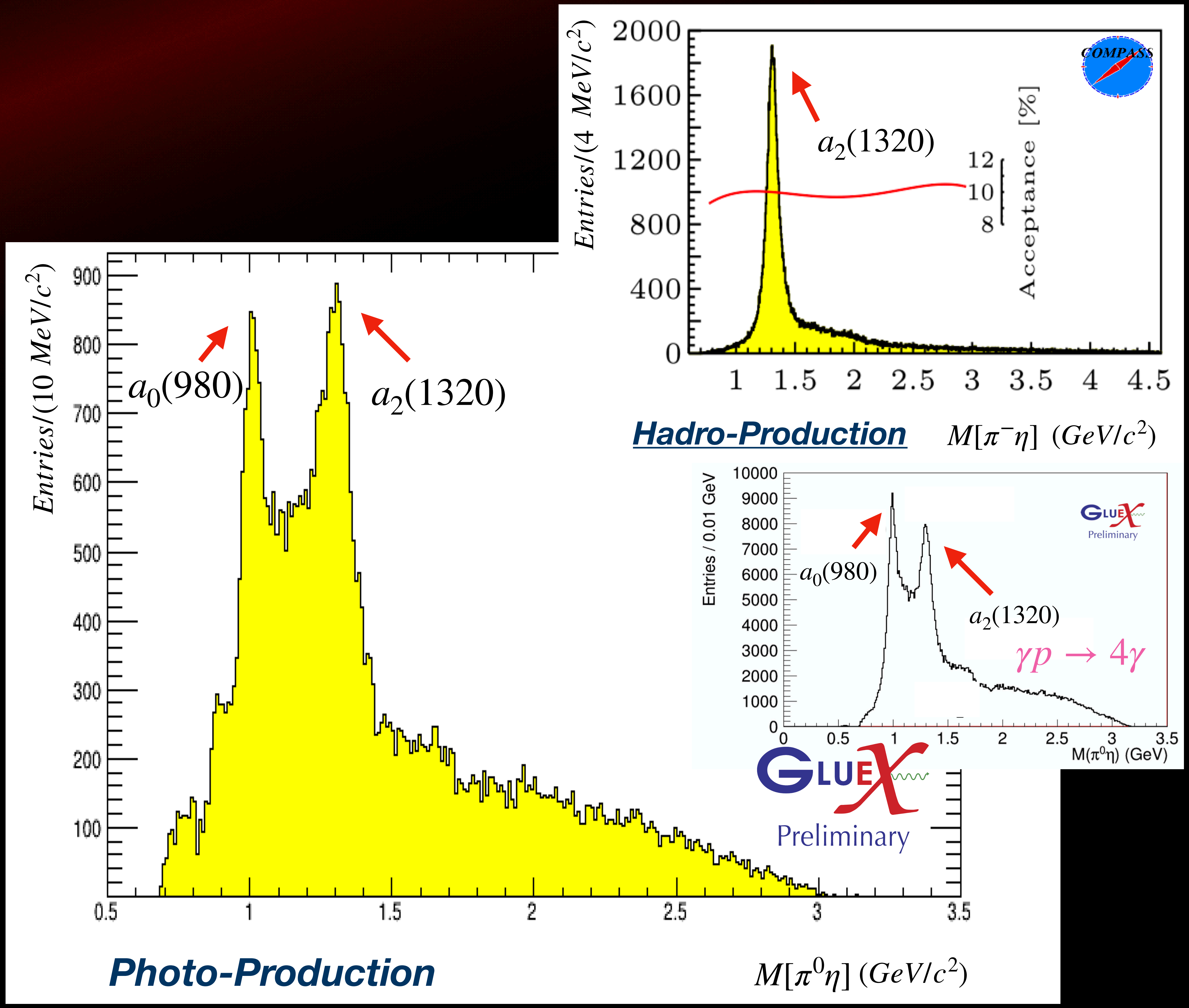

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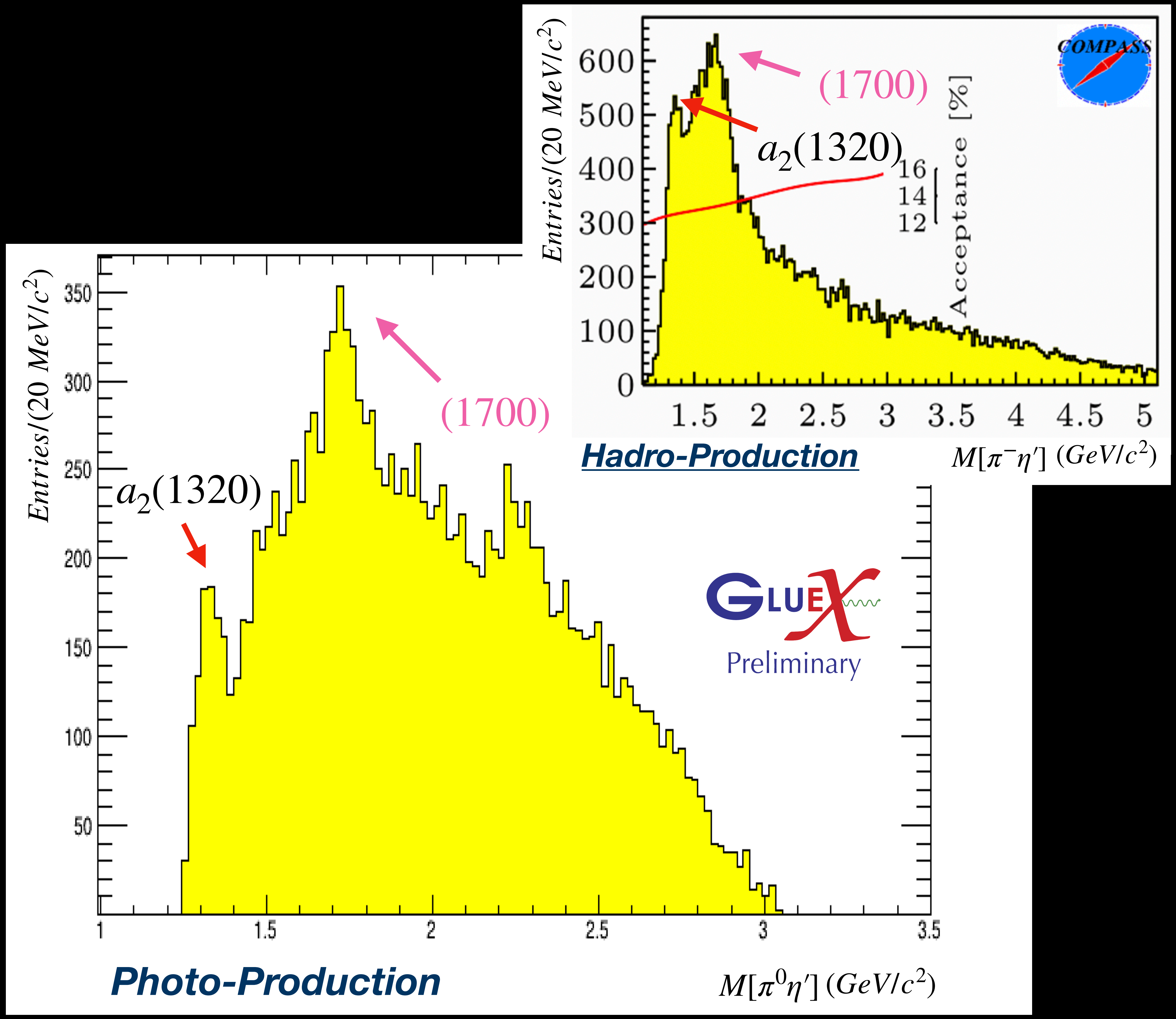

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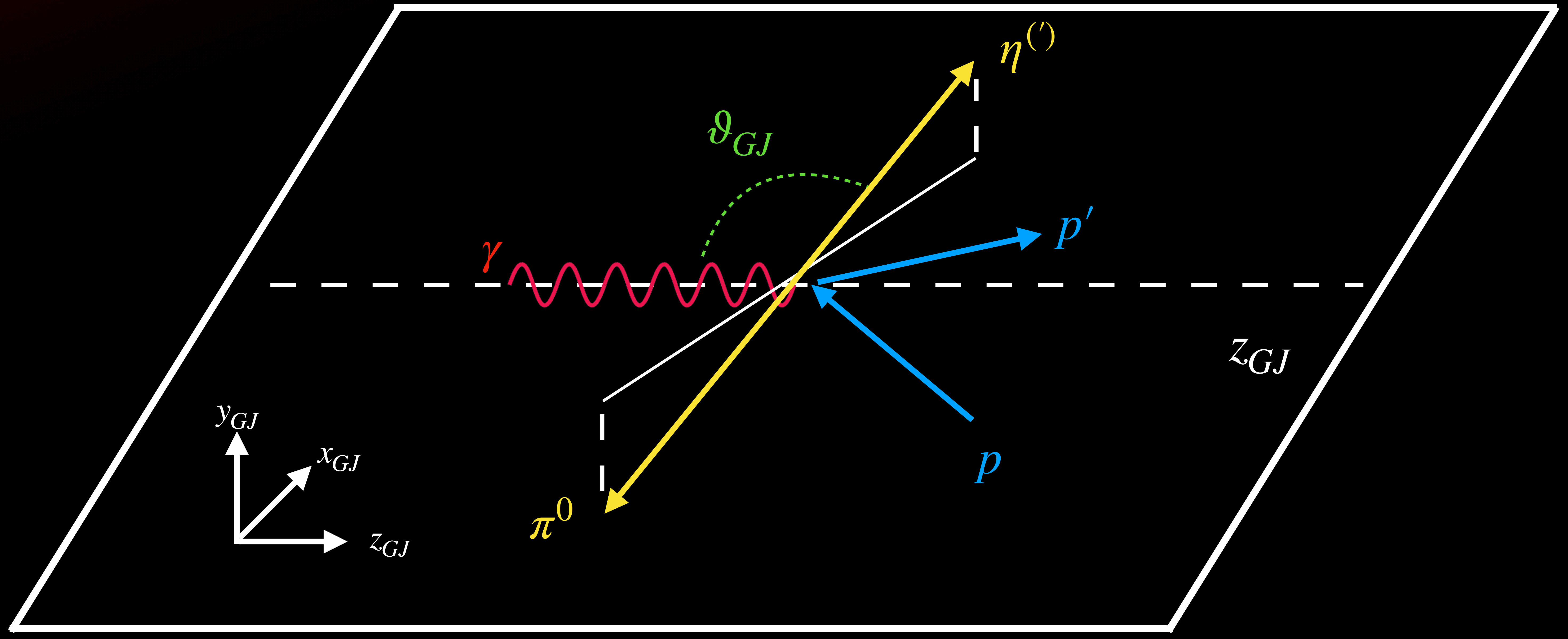
Gottfried-Jackson



Gottfried-Jackson viewed in the center of mass of the $\pi^0\eta^{(\prime)}$ system

Z_{GJ} is taken as the direction of the incident photon

ϑ_{GJ} is the angle between the directions of $\eta^{(\prime)}$ and the incident γ

Angular Distributions

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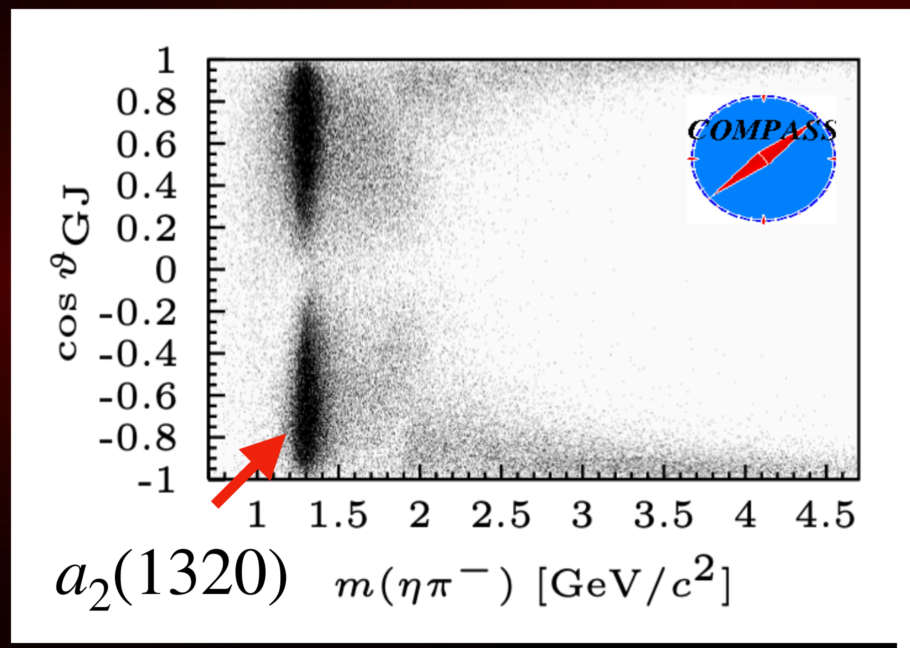
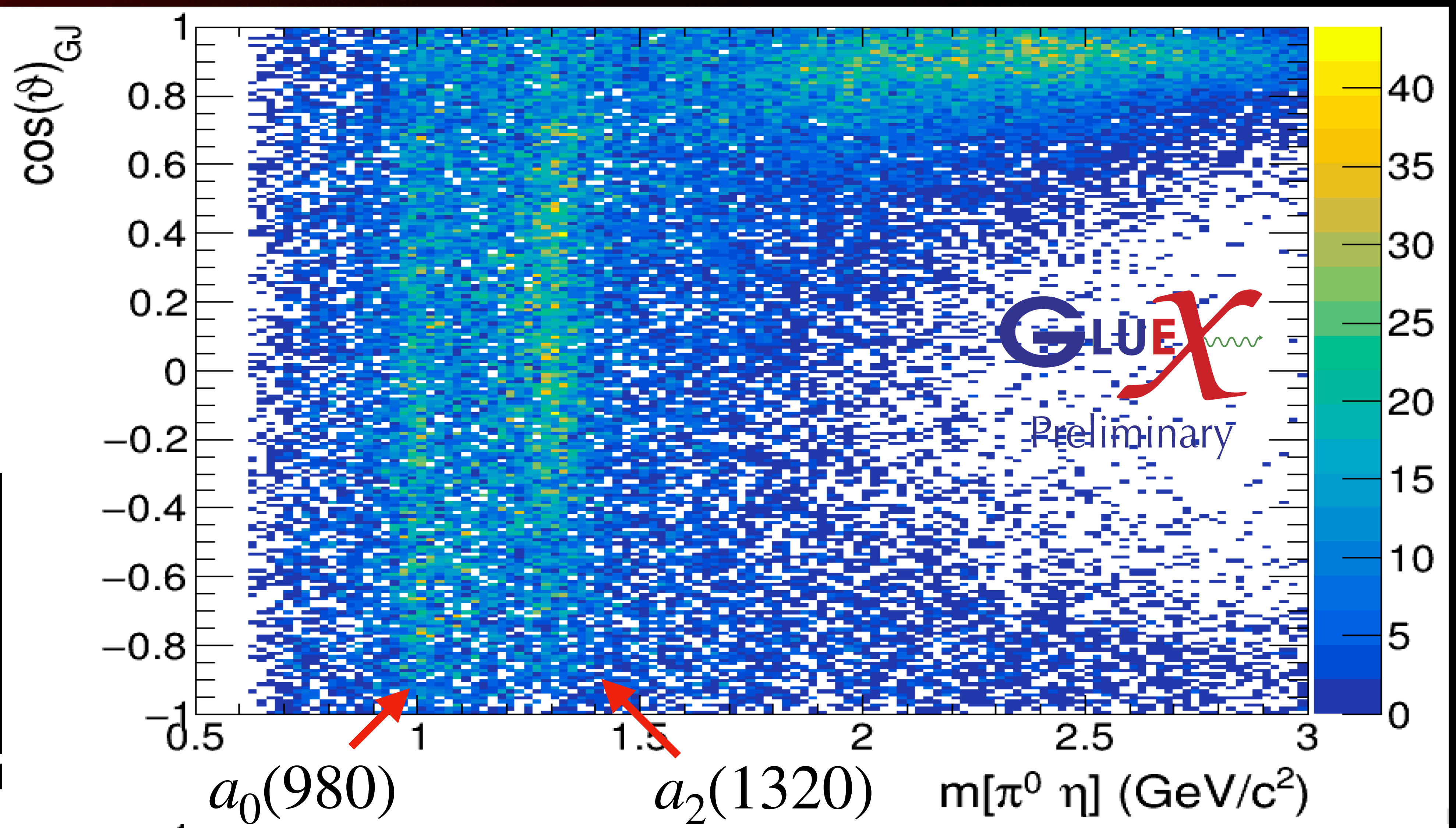
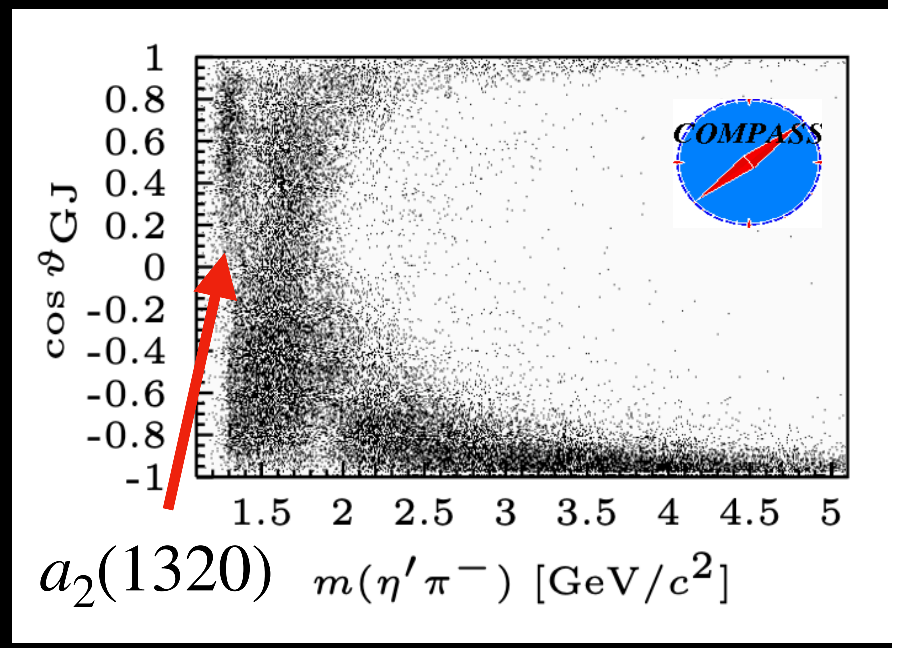
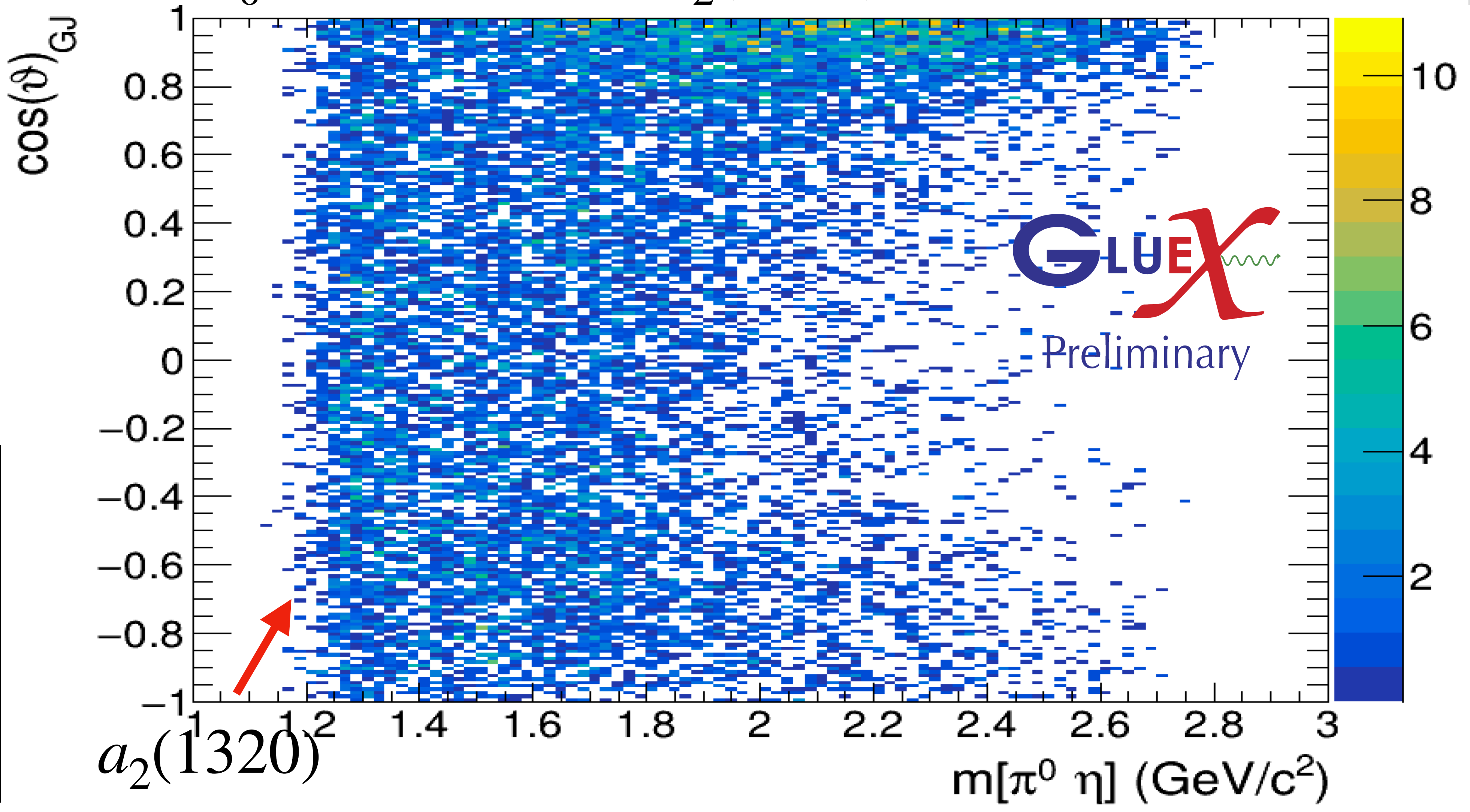




$\pi^0\eta$ system





$\pi^0\eta'$ system

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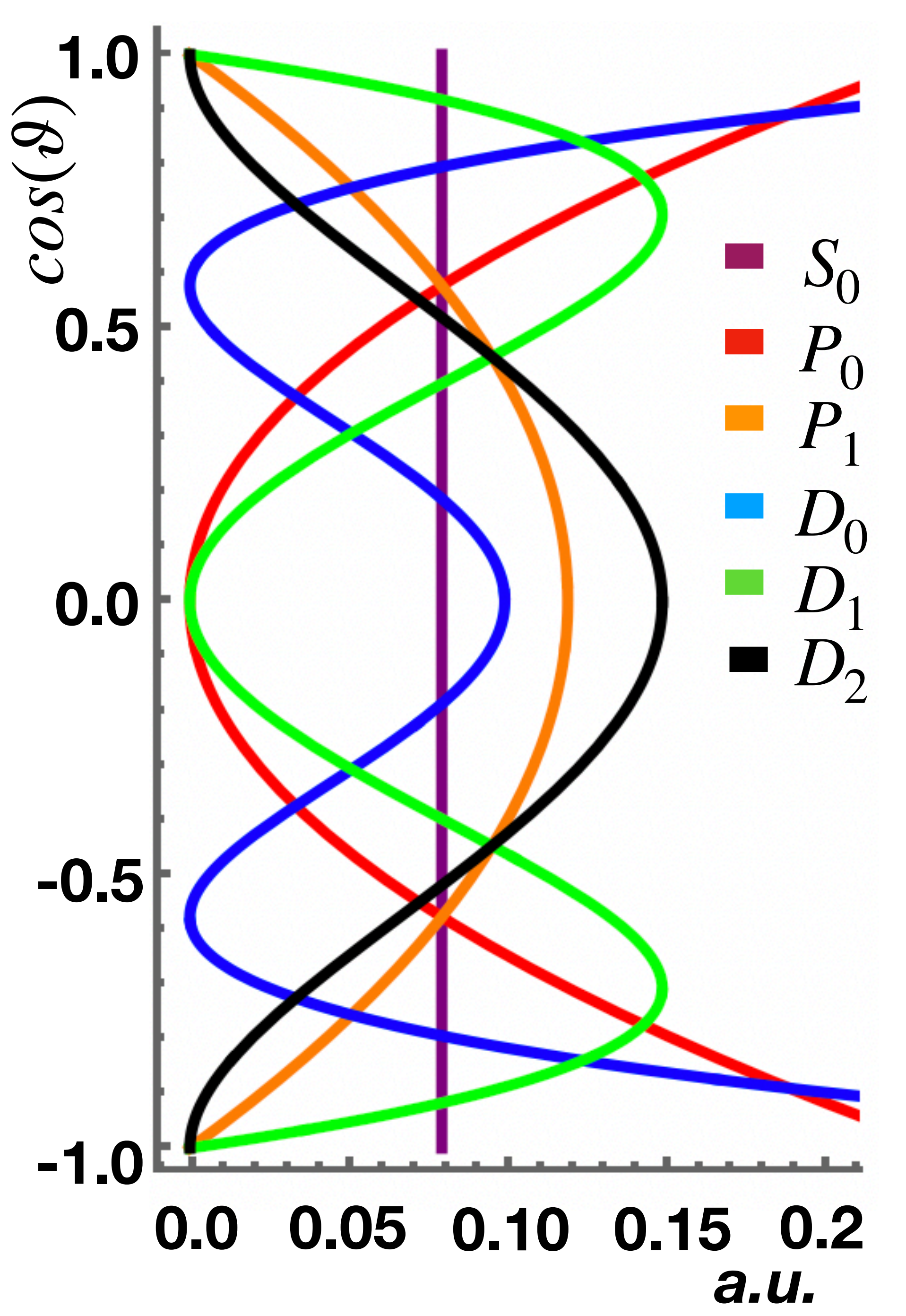
$\cos(\vartheta_{GJ}) \approx 1$

Forward $\eta^{(\prime)}$ Particles



$\cos(\vartheta_{GJ}) \approx -1$

Backward $\eta^{(\prime)}$ Particles

$$I(\Omega,\Phi) = 2\kappa \sum_k \left\{ (1-P_\gamma) \left| \sum_{l,m} [l]^{(-)}_{m;k} \mathcal{R}\mathcal{E}[Z^m_l(\Omega,\Phi)] \right|^2 + (1-P_\gamma) \left| \sum_{l,m} [l]^{(+)}_{m;k} \mathcal{I}\mathcal{M}[Z^m_l(\Omega,\Phi)] \right|^2 + \right.$$
$$\left. (1+P_\gamma) \left| \sum_{l,m} [l]^{(+)}_{m;k} \mathcal{R}\mathcal{E}[Z^m_l(\Omega,\Phi)] \right|^2 (1+P_\gamma) \left| \sum_{l,m} [l]^{(-)}_{m;k} \mathcal{I}\mathcal{M}[Z^m_l(\Omega,\Phi)] \right|^2 \right\}$$

Described by
$\Omega = \theta, \phi$
(in GJ or HX frame)

Fit $[l]^{(\pm)}_{m;k}$ to the data
- $m =^- l, \ldots, ^+ l$
- $(\pm)$ = reflectivity

$$Z^m_l(\Omega,\Phi) = Y^m_l(\Omega) e^{(-i\phi)}$$

Joint Physics Analysis Center

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

Event based maximum likelihood fitting procedure
(ability to acceptance correct)

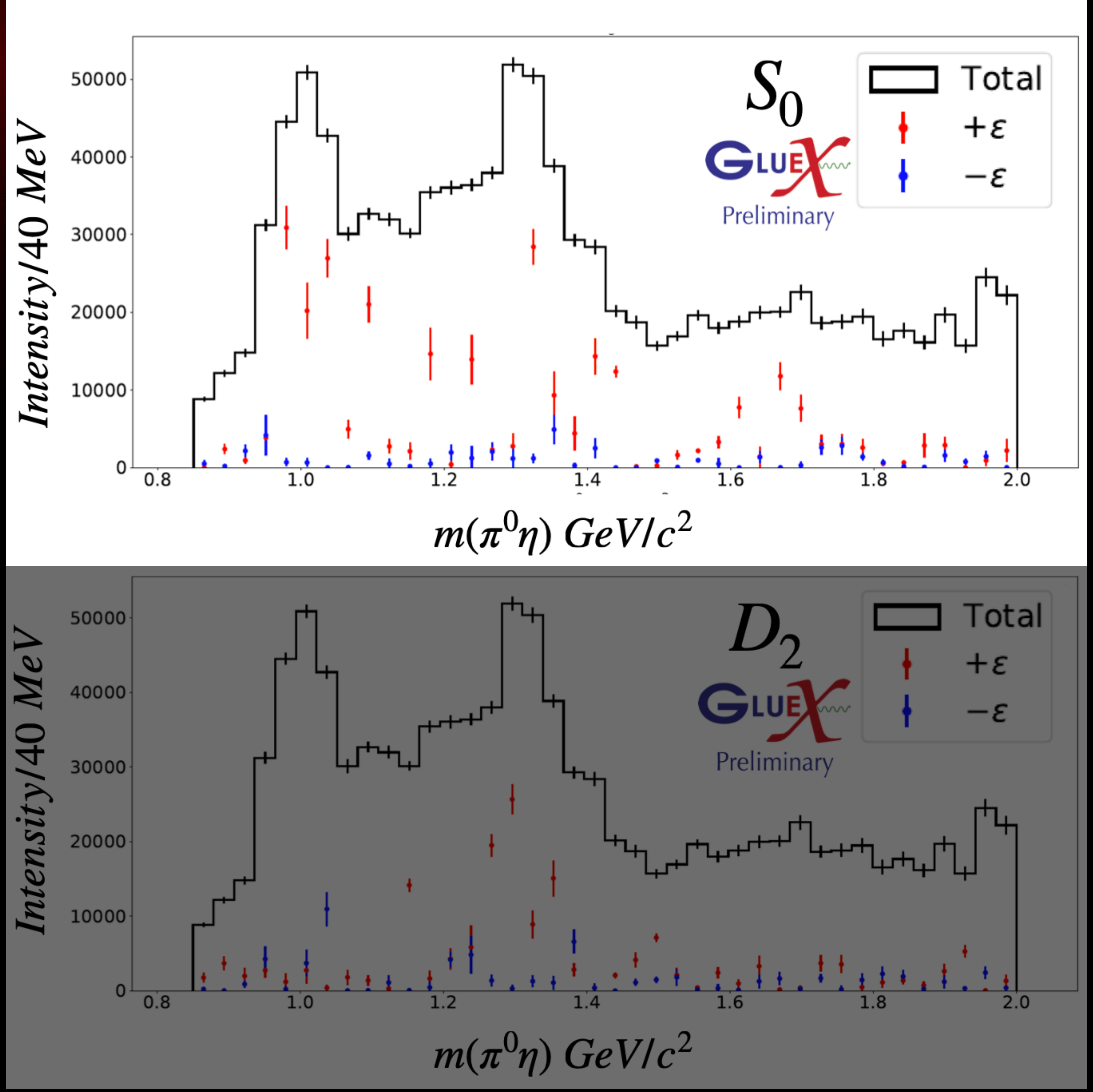
Divide in bins of mass to perform each fit
(don't require dependence on energy)

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

Φ → btw the polarization and production plane

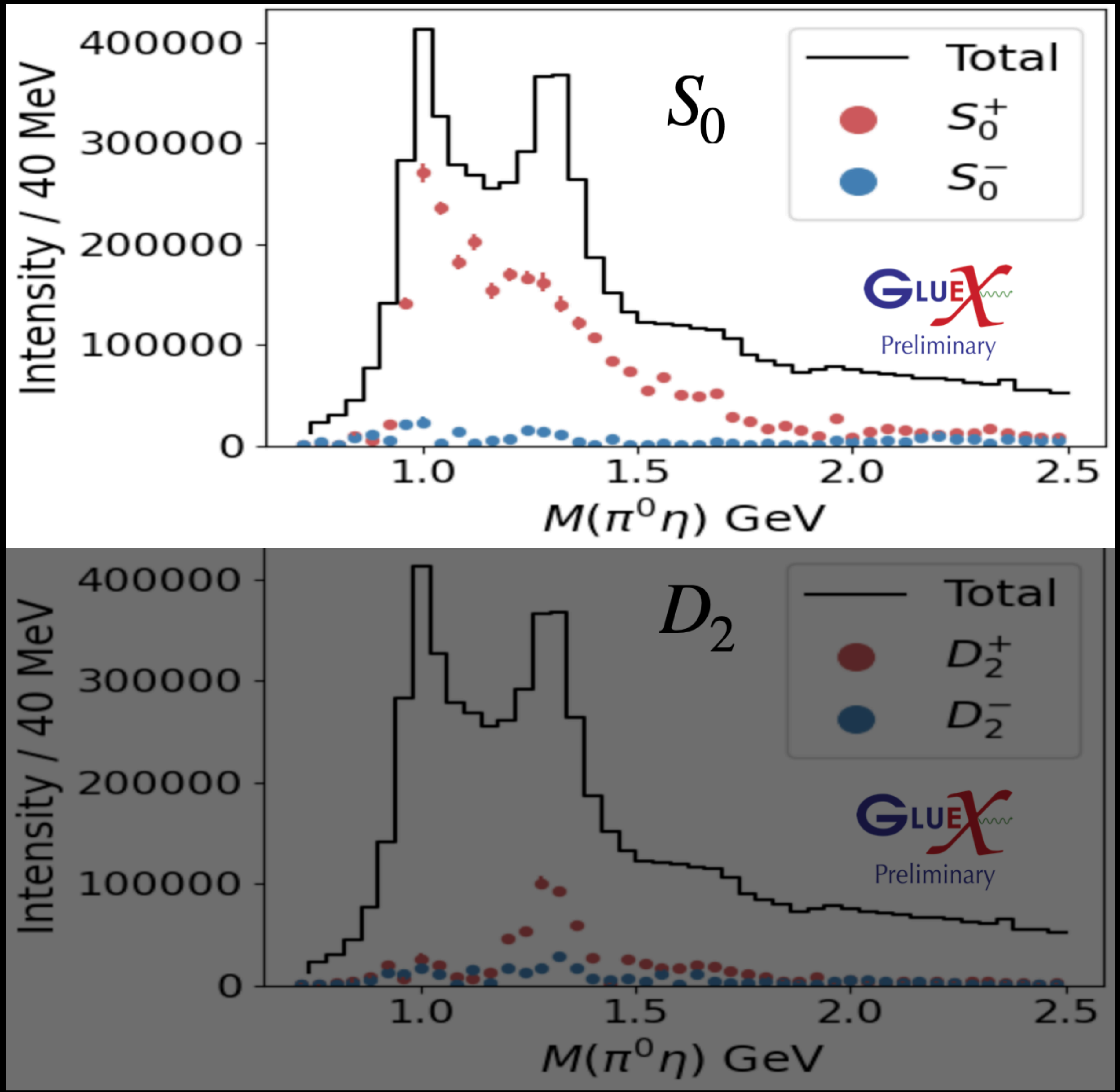
$\gamma p \rightarrow 4\gamma\pi^+\pi^-$

$\gamma p \rightarrow 4\gamma$



Different final state particles, backgrounds, acceptances, etc.

still many similarities btw decay modes



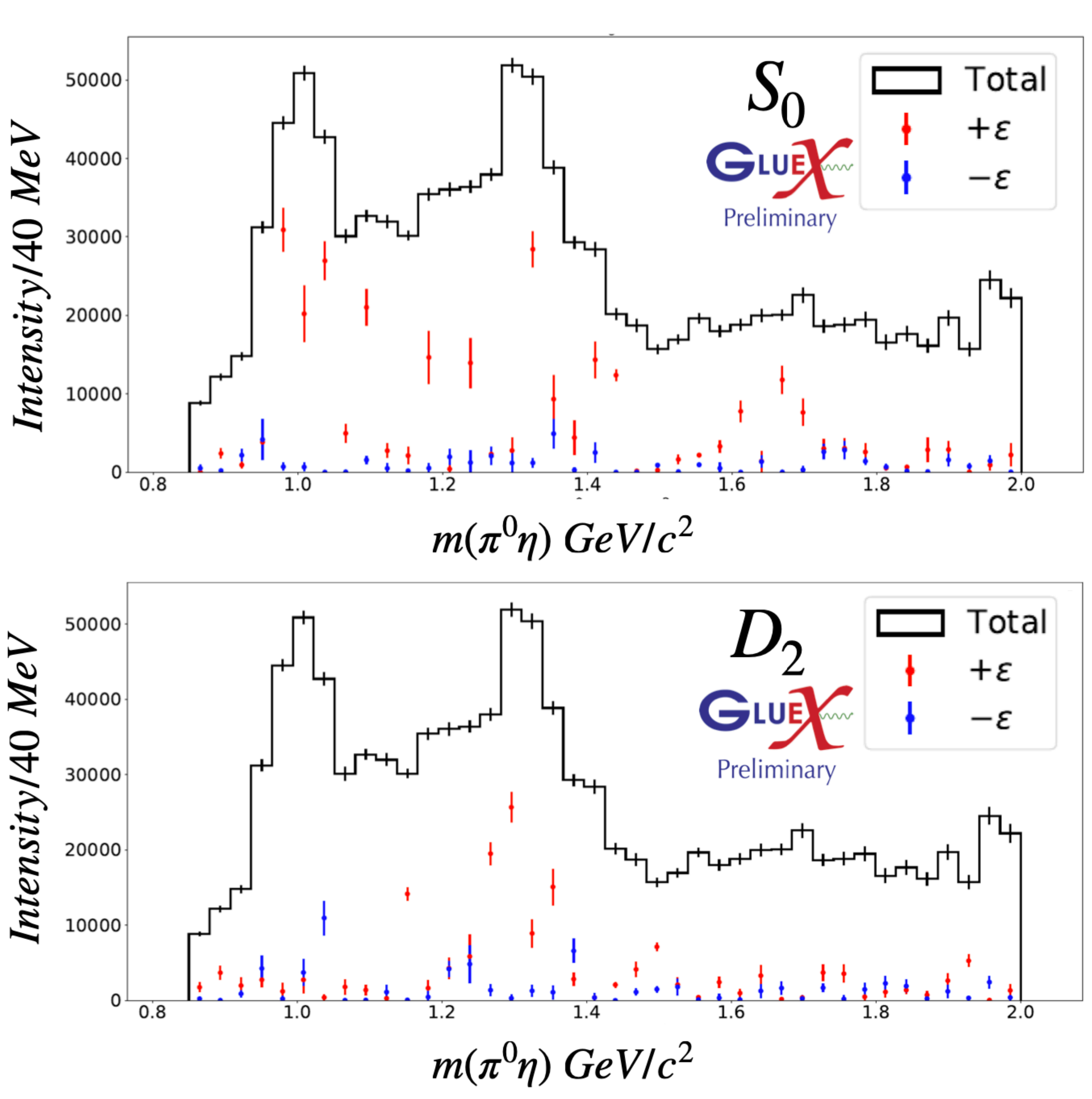
Mass Independent Fits

$0.1 < -t < 0.3$

TMD Model $\rightarrow L_m^\epsilon = S_0^\pm, D_{-1}^-, D_0^\pm, D_1^\pm, D_2^+$

$\gamma p \rightarrow 4\gamma\pi^+\pi^-$

$\gamma p \rightarrow 4\gamma$



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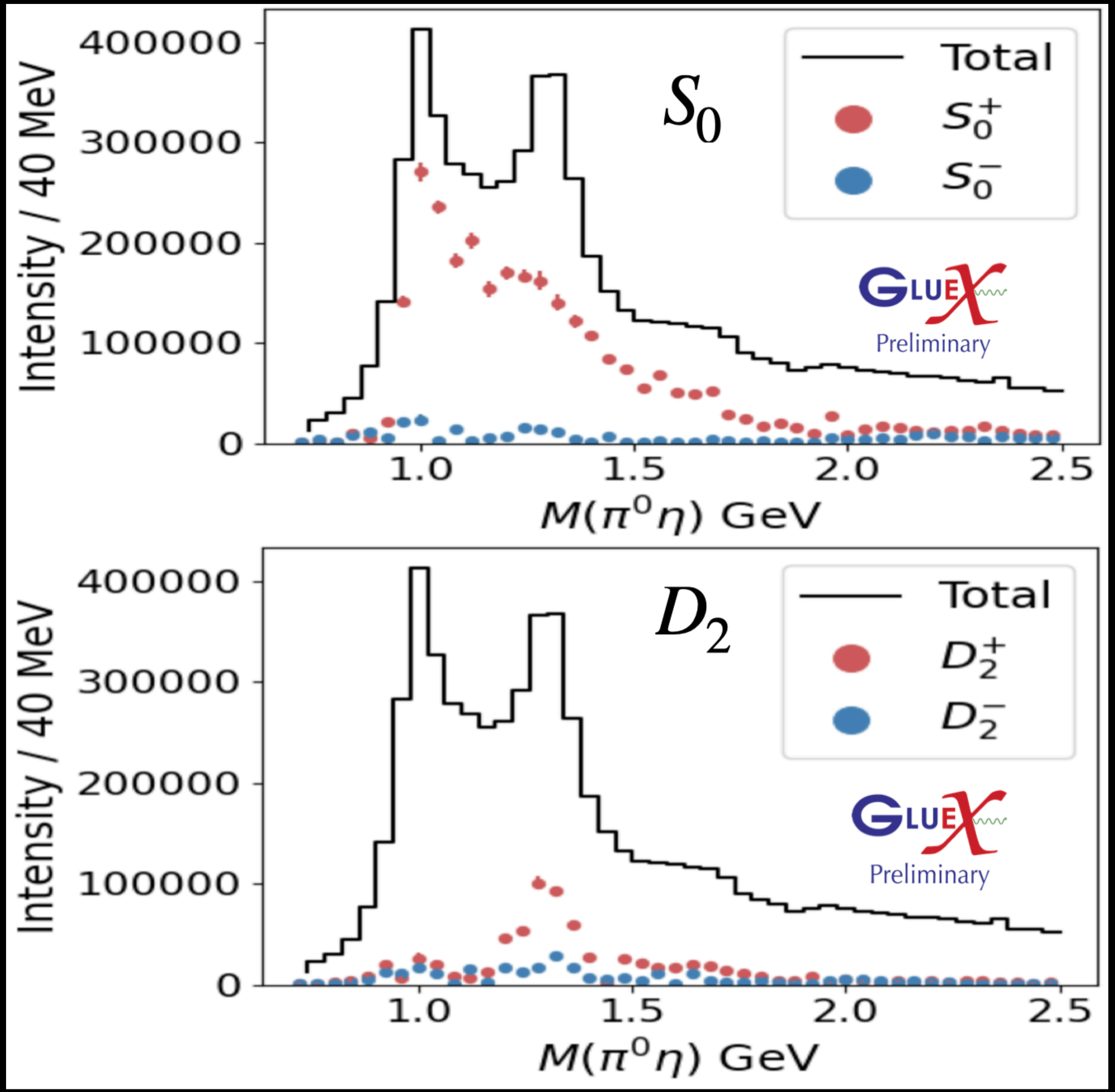


$0.1 < -t < 0.3$

TMD Model $\rightarrow L_m^{\epsilon} = S_0^{\pm}, D_{-1}^{-}, D_0^{\pm}, D_1^{\pm}, D_2^{+}$

Summary

- Resonances can be seen for: $a_0(980)$, $a_2(1320)$ as well for possible higher resonances
- First look at mass independent partial wave analysis $\gamma p \to \eta\pi^0 p$
- Comparison between different decay modes looks similar

Future Work

- Continue Monte Carlo simulations to further understand detector acceptance and resonance regions
- Further collaborate with theory group to understand properties of both $\eta^{(\prime)}\pi^0$ systems
- Perform mass dependent partial wave analysis

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

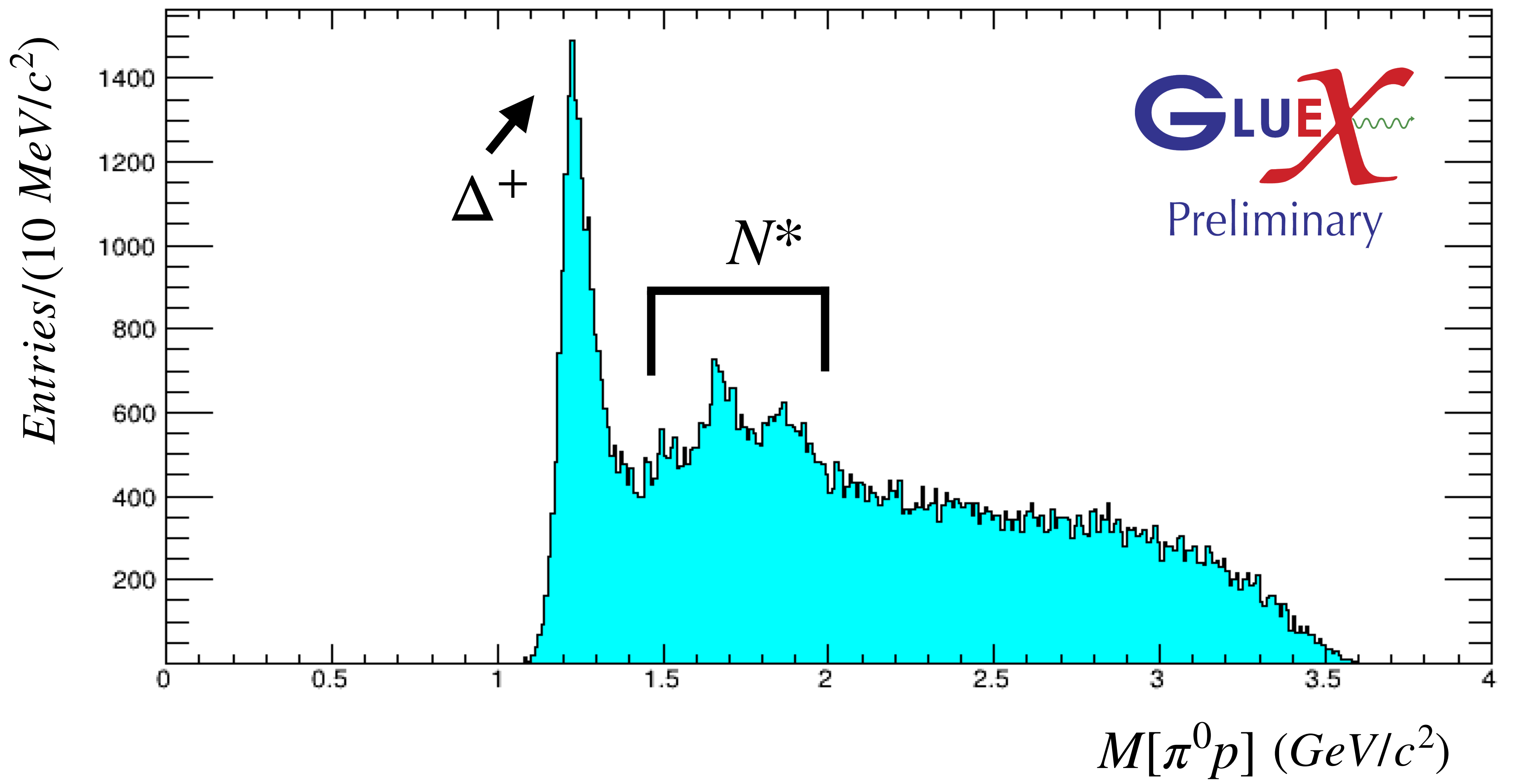
BACKUP SLIDES

Major contributions to background involves Δ^+ baryons and multiple N* states

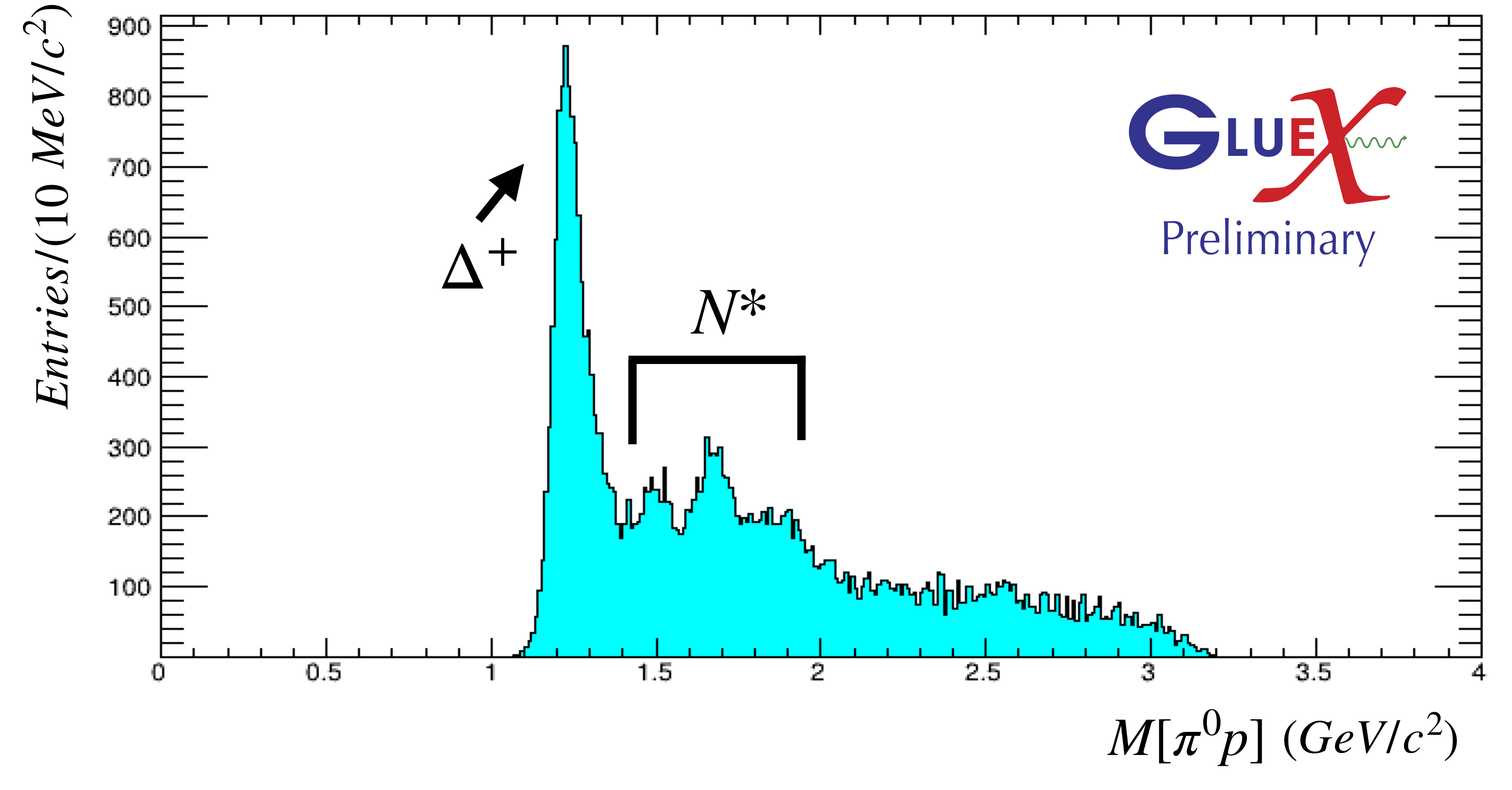
Removal of the Δ^+ is relatively simple, but this is not the case for the $N*$ region

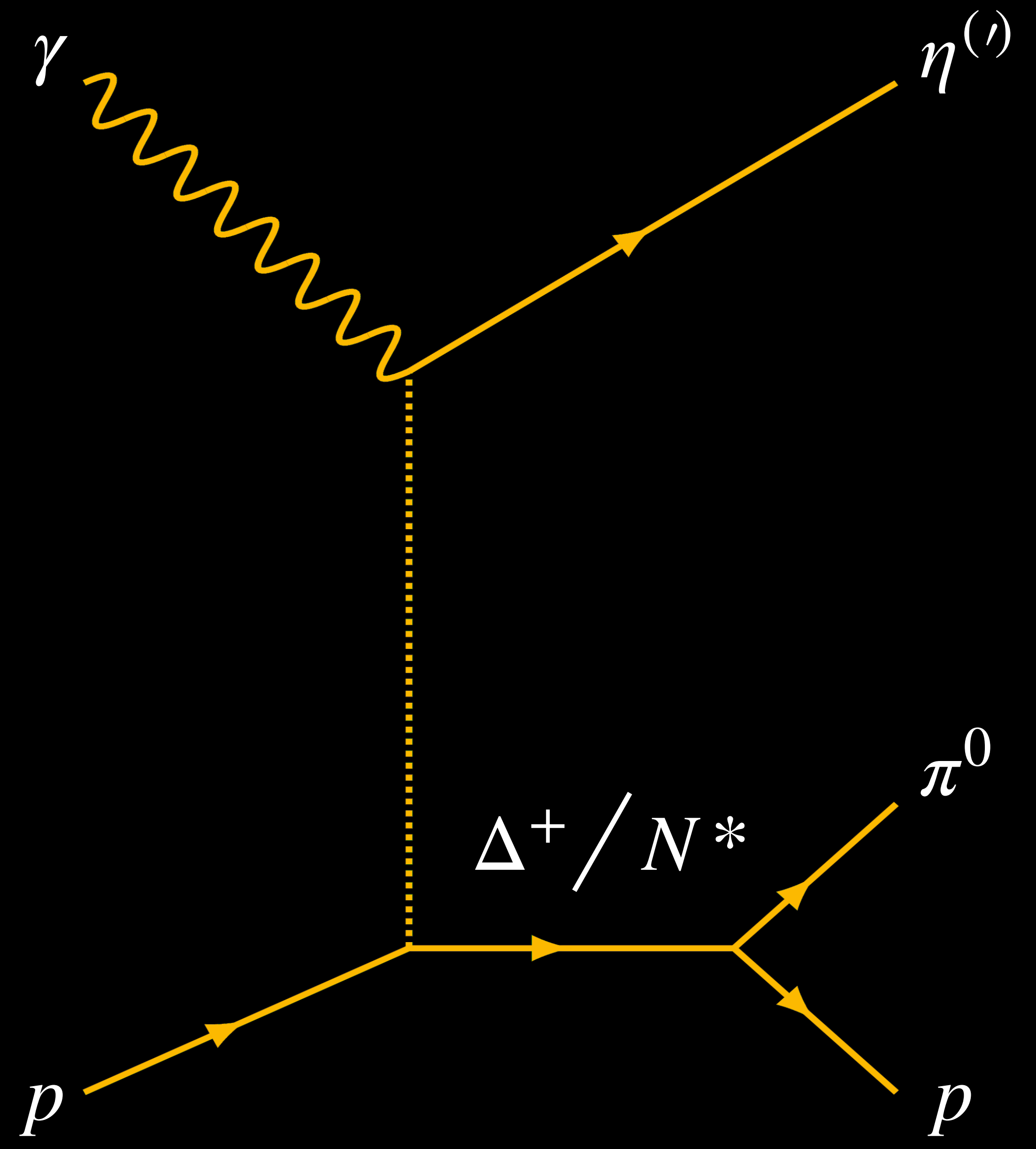
Is there a clear way to reject each $N*$?

$\pi^0\eta$ system

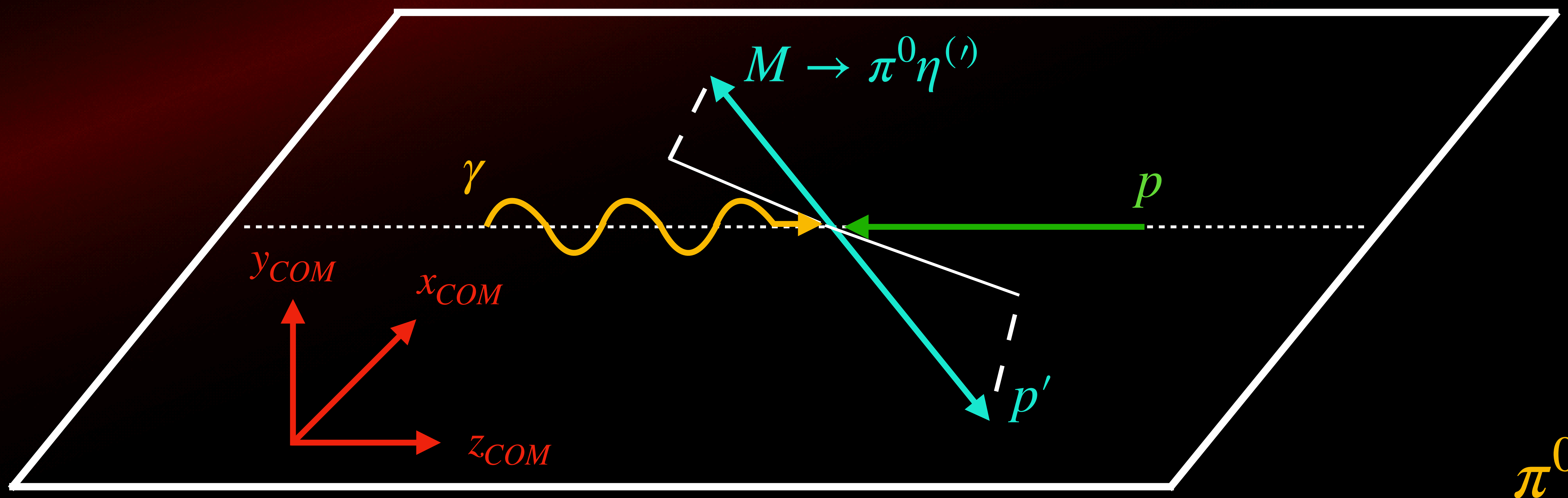


$\pi^0\eta'$ system





Center Of Mass



By looking in the center of mass frame, it becomes apparent that the baryon contributions will tend to go backwards in θ_{π^0}

Studies still on-going, so only the removal of the Δ^+ structure is shown going forward

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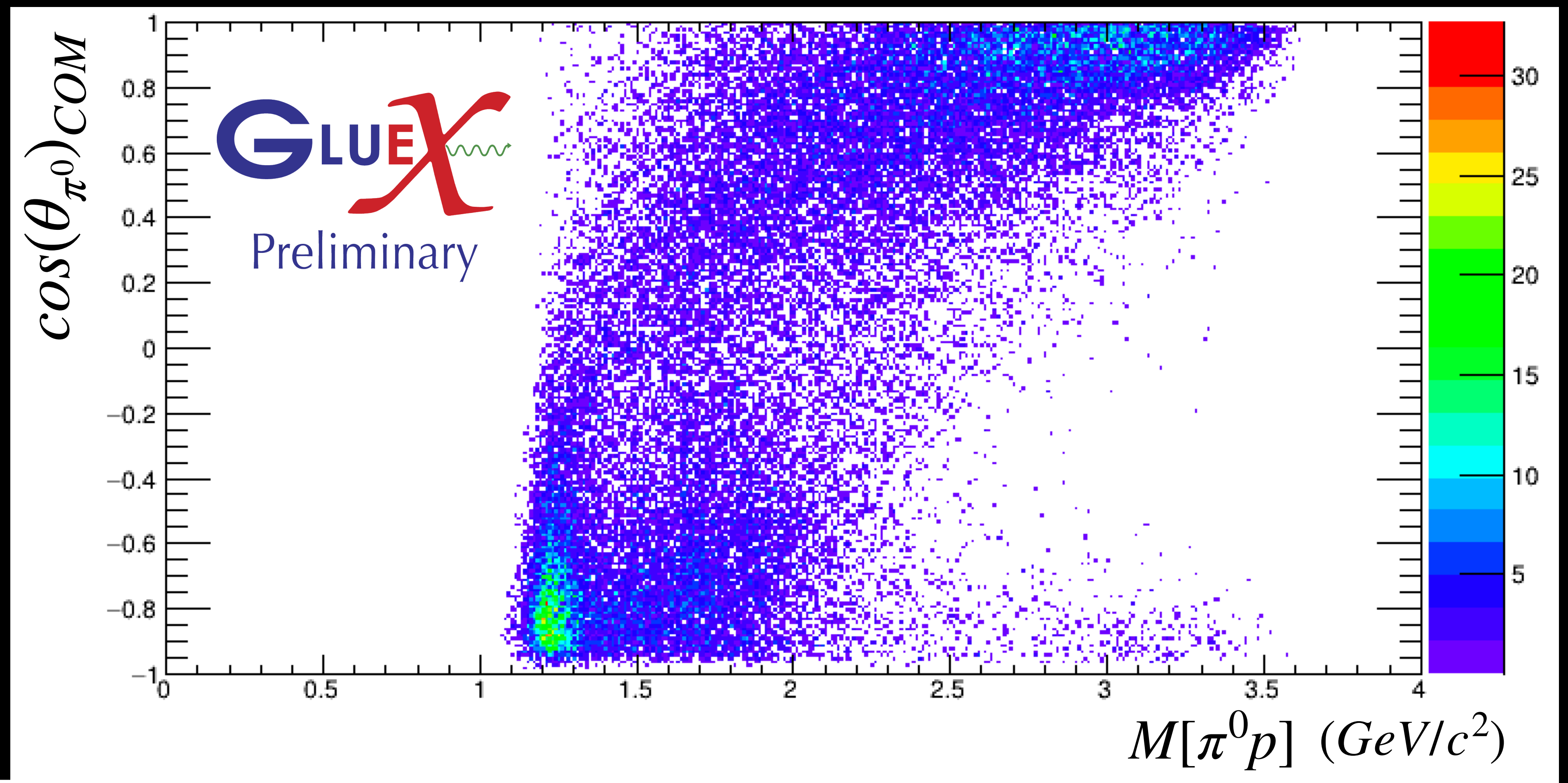
$\pi^0\eta$ system



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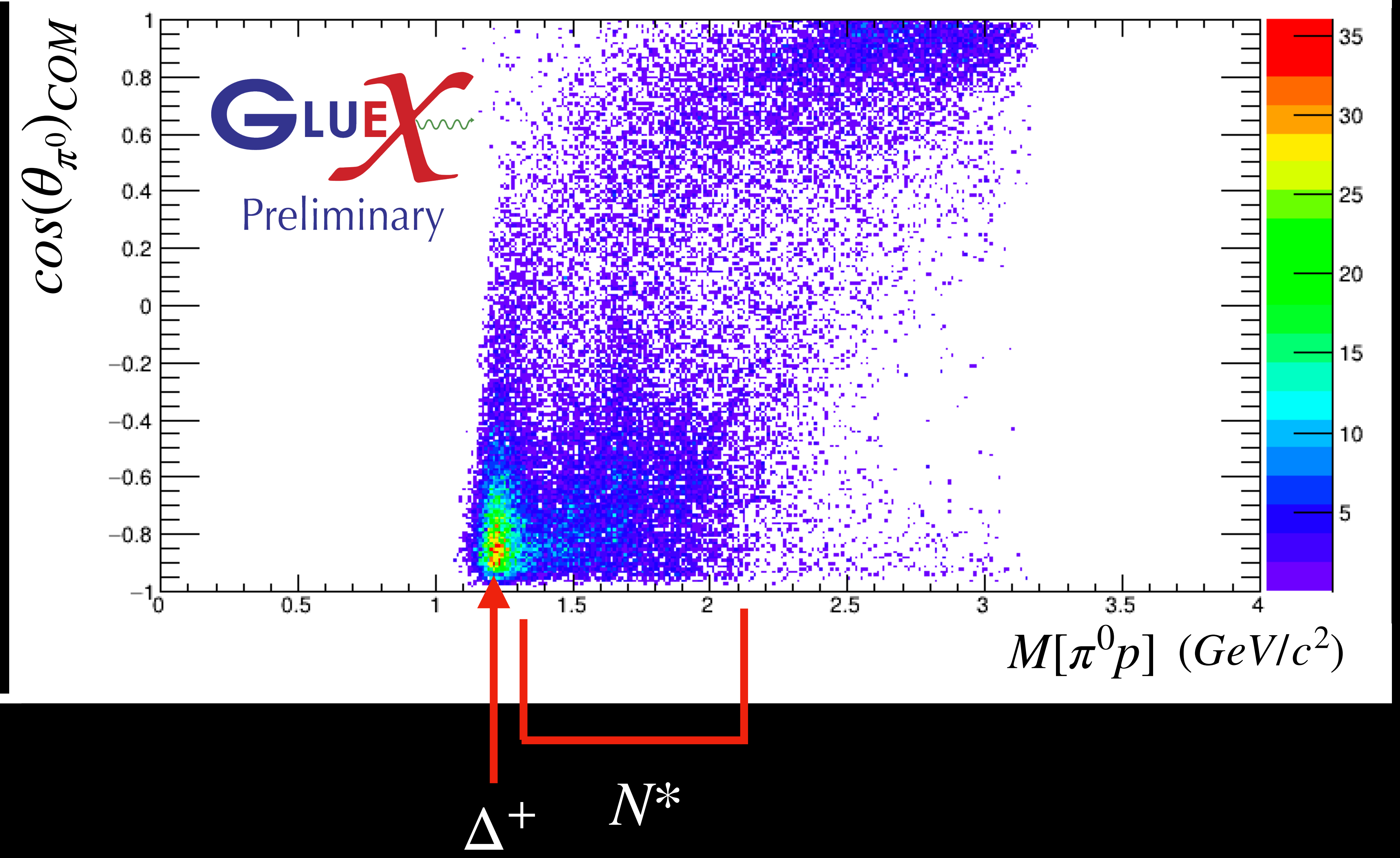

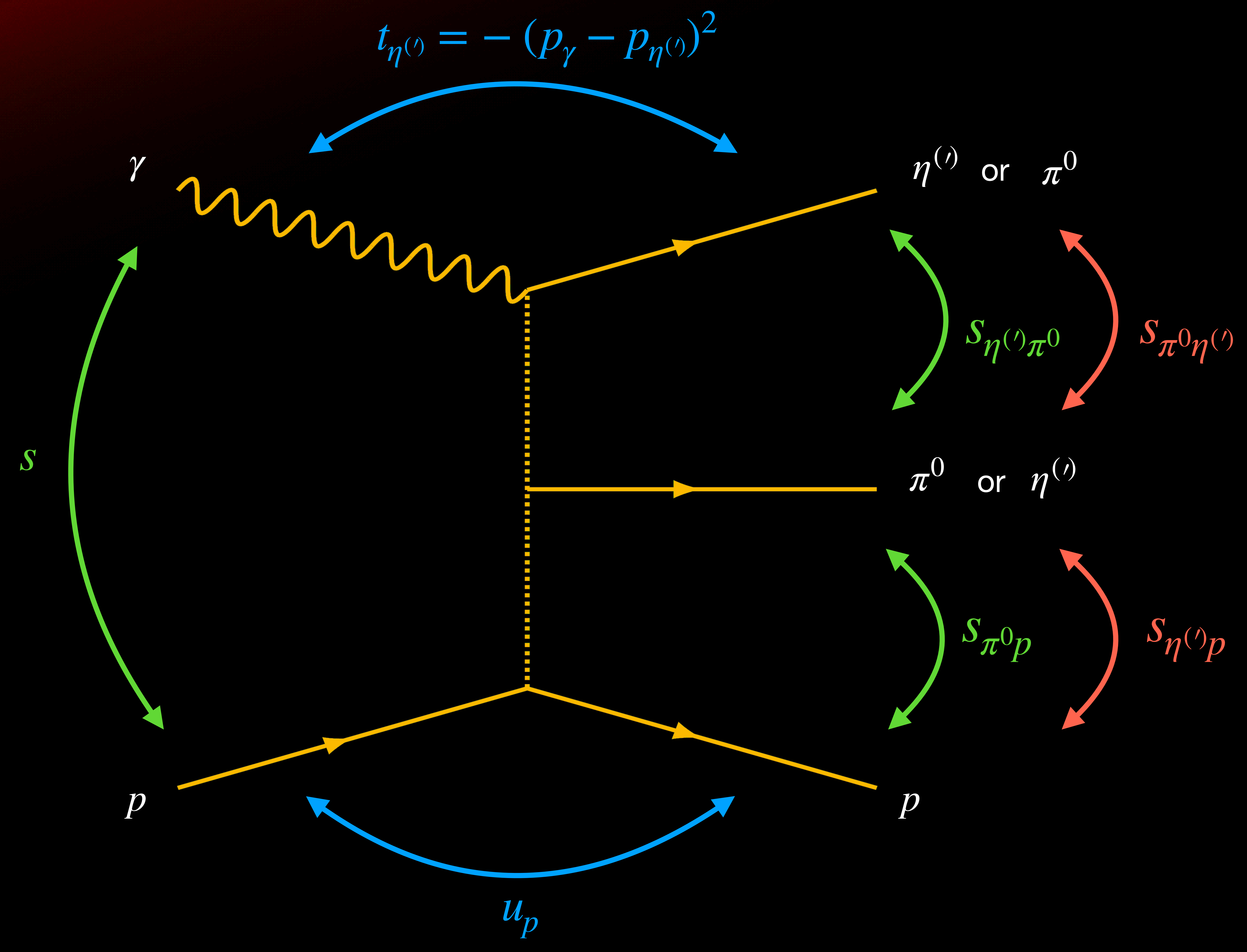

The exotic hybrid signature in $\eta^{(\prime)}\pi$ systems would be observed as odd partial waves, which may be enhanced by other processes

Understanding and modeling this type of exchange is crucial

Closely working with JPAC

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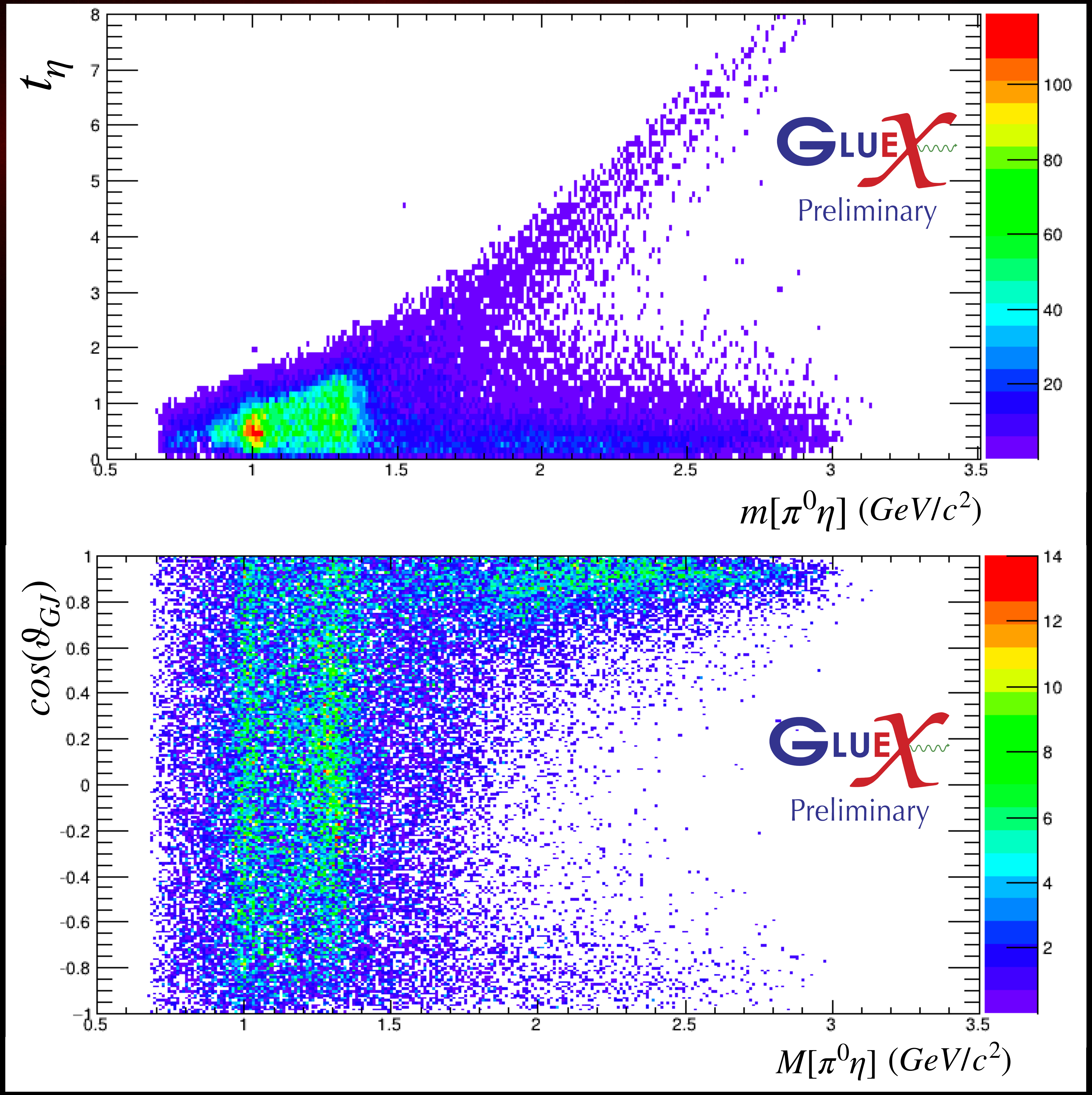
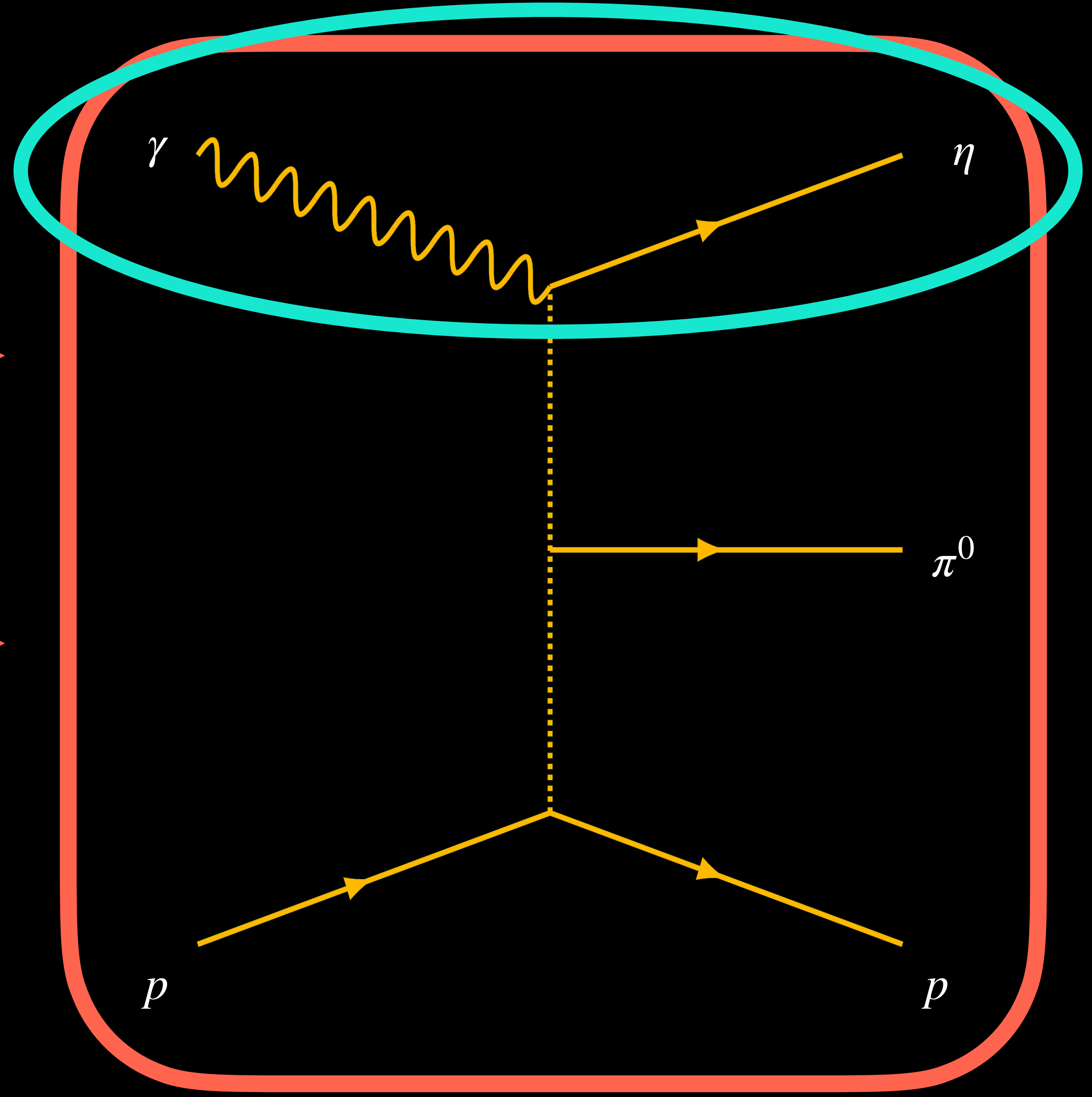


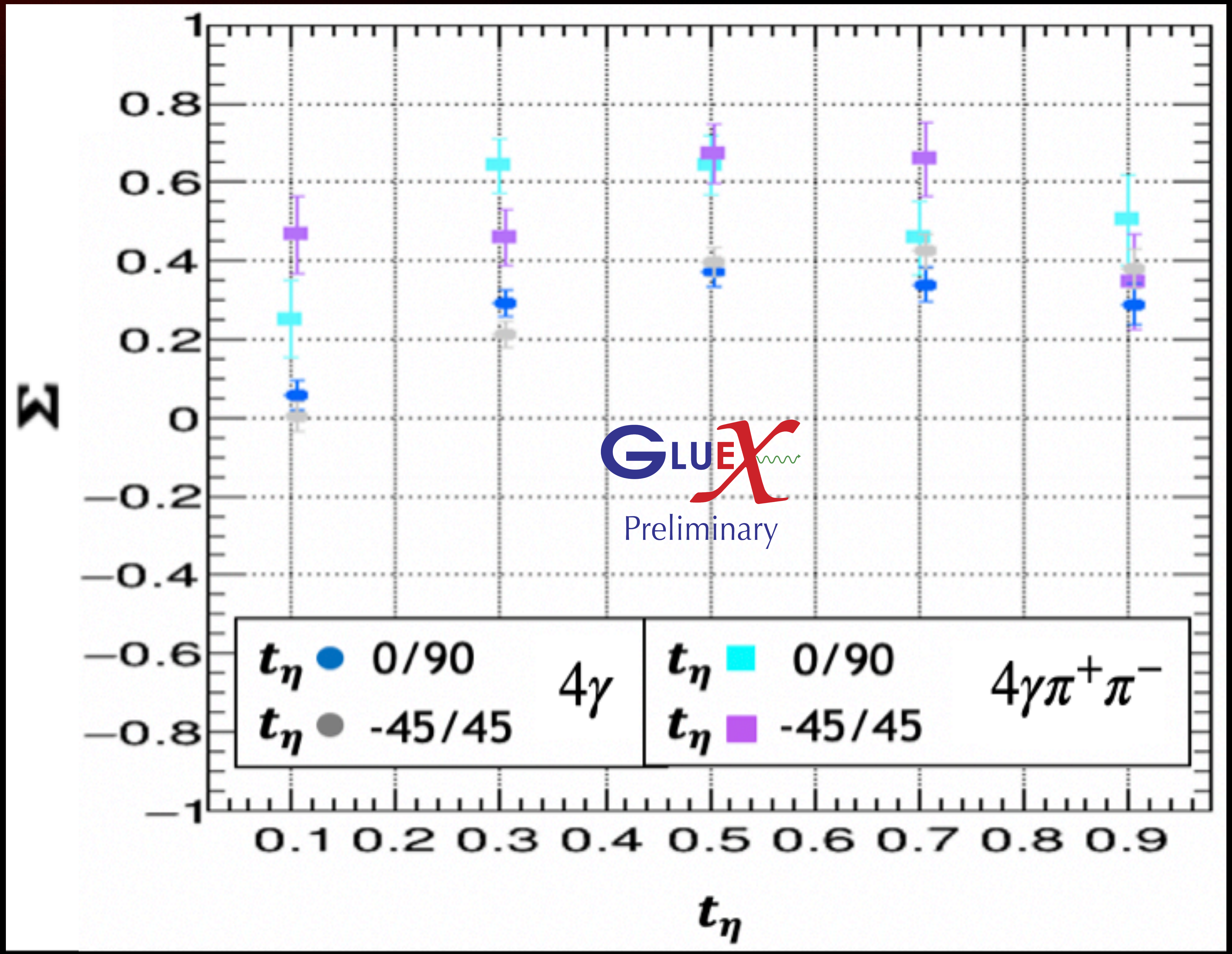
Can study the upper vertex exchange through a beam asymmetry

$t_\eta \approx < 1$
Faster η Particles

$cos(\vartheta_{GJ}) \approx 1$
Forward η Particles



This observable is sensitive to the naturally of the exchange particle



Beam asymmetries for different decays modes will behave the same!

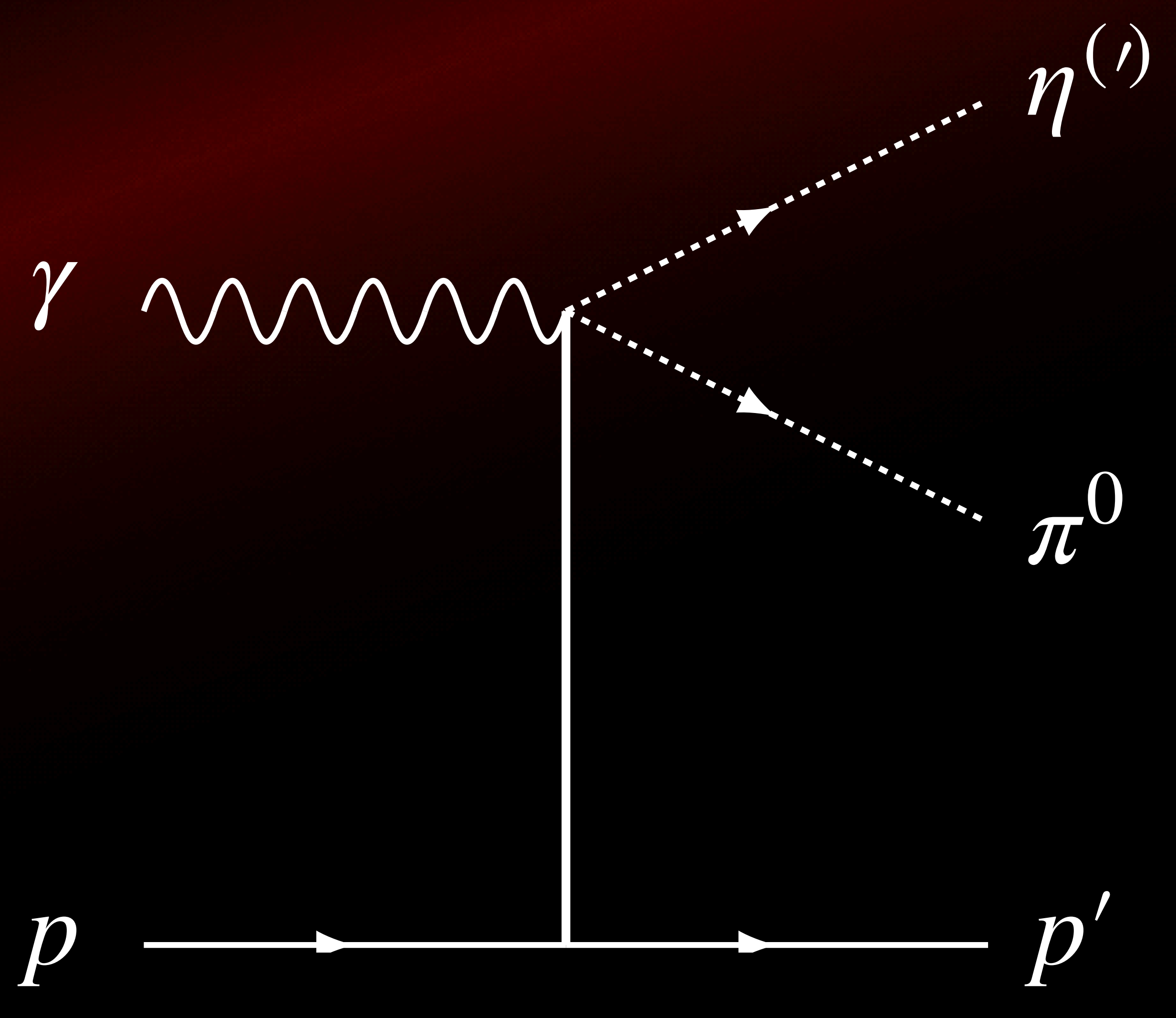
$\gamma p \rightarrow 4\gamma\pi^+\pi^- p$

$\gamma p \rightarrow 4\gamma p$

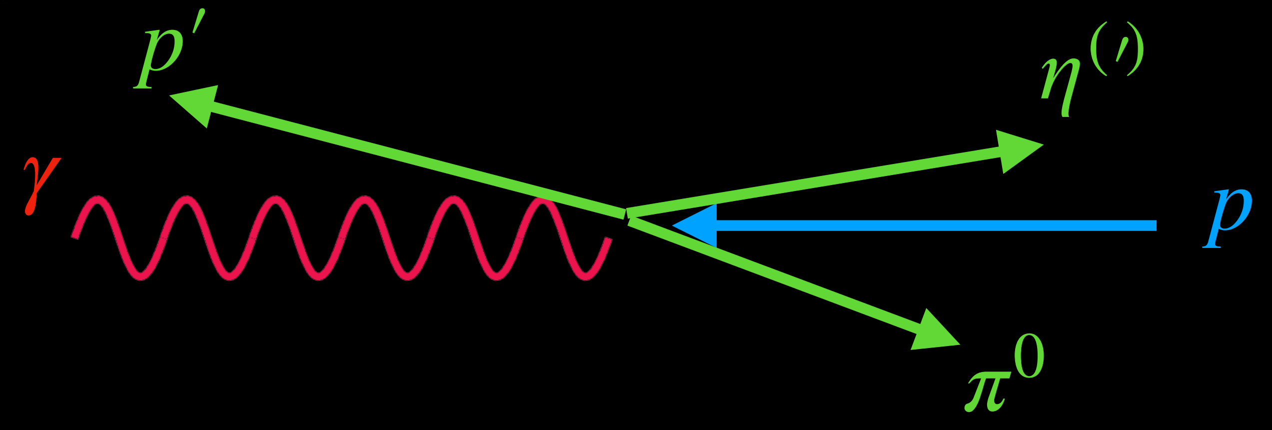
HIGHER Σ FOR $4\gamma\pi^+\pi^-$?

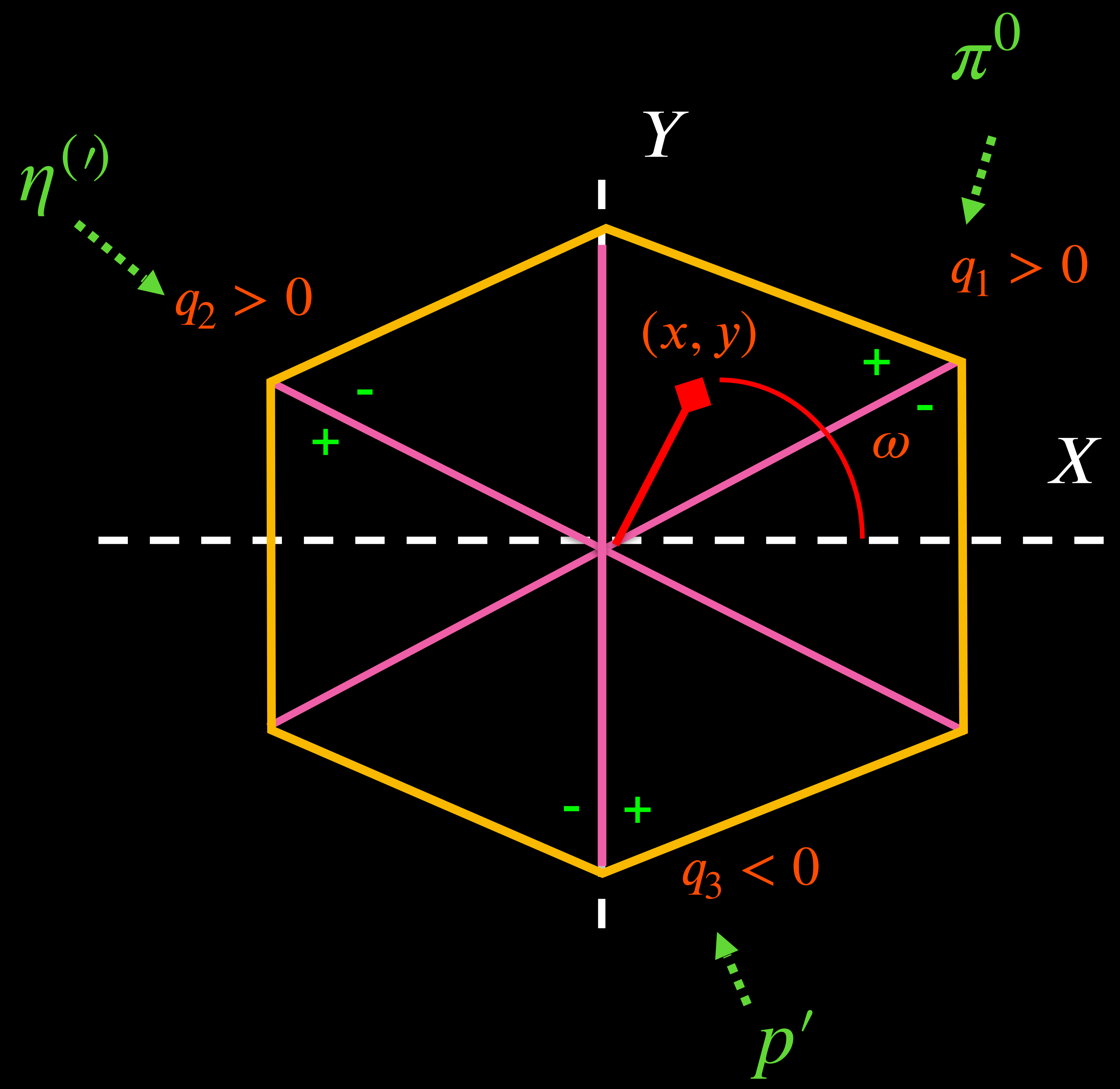
For the more complicated reaction, there seems to be something that we don't understand yet and that's ok!

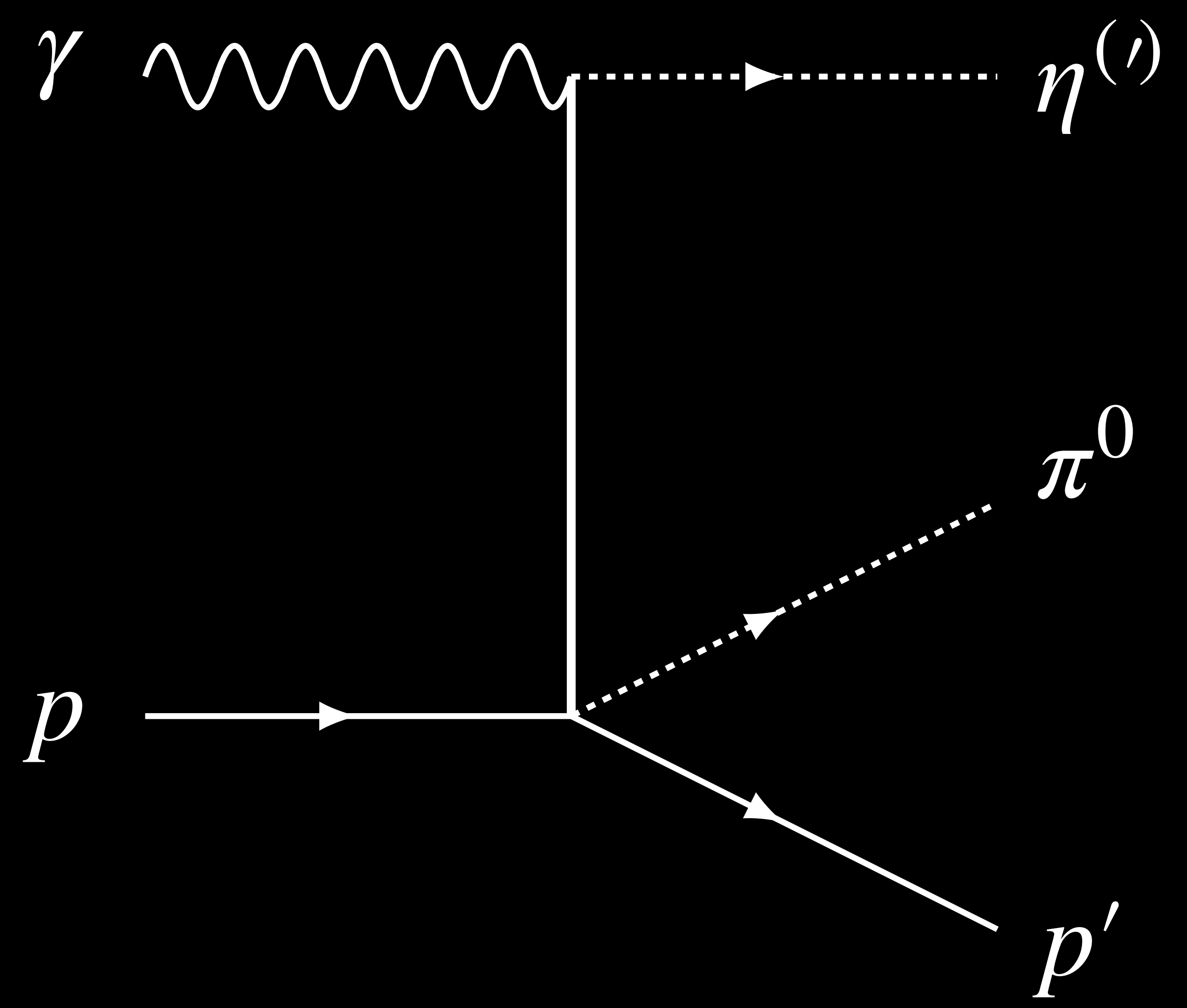
Σ is integrated over multiple variables mentioned previously so in both channels the different acceptances for these variables will ultimately affect their overall contribution



Beam Fragmentation







Target Fragmentation