Light Exotic Mesons from Pion and Photon Beams

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University of Barcelona

Joint Physics Analysis Center
Exotic Hadron Topical Collaboration

Exotic Hadron Spectroscopy

Durham April 2023

Joint Physics Analysis Center

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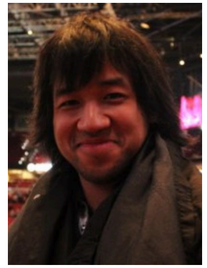
Tübingen University

Mikhail Mikasenko
TU Munich

Alessandro Pilloni
U. Messina

Adam Szczepaniak
Indiana University

Daniel Winney
South China Normal University



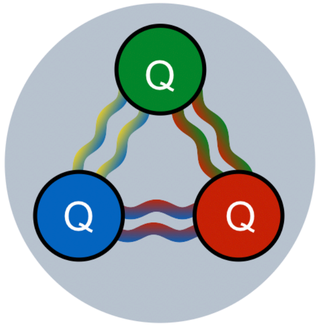
Lawrence Ng
Florida State University

Arkaitz Rodas
JLab

Robert Perry
University of Barcelona

Ordinary and Exotic Hadrons

Ordinary baryons

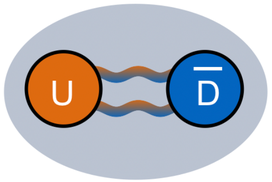


proton stable

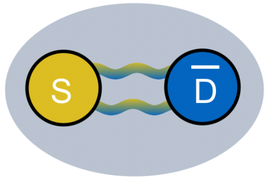
neutron $\tau \sim 10^{3} s$

baryon Λ $\tau \sim 10^{-10} s$

Ordinary mesons



pion $\tau \sim 10^{-8} s$



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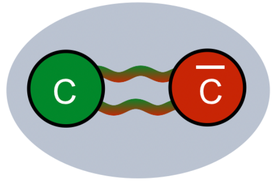

J/ψ $\tau \sim 10^{-20} s$

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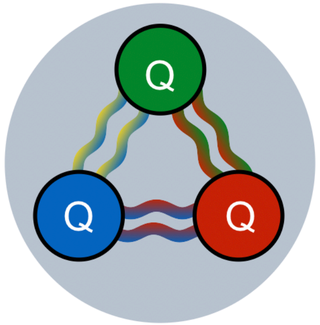

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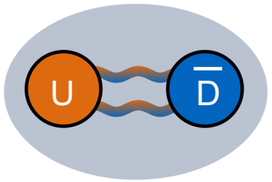

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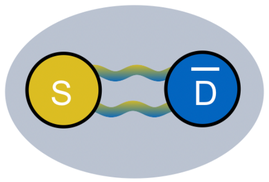

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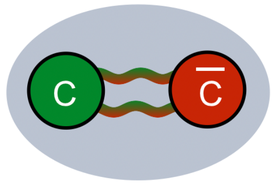

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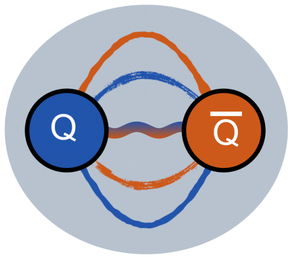
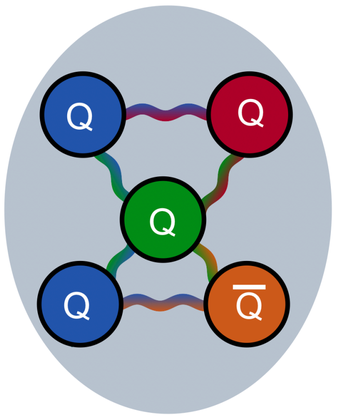
Exotic matter

hybrid mesons

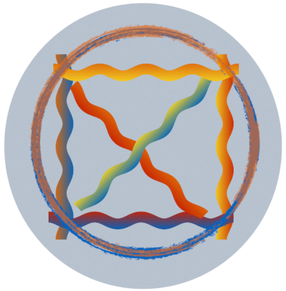


tetraquarks

pentaquarks



glueballs



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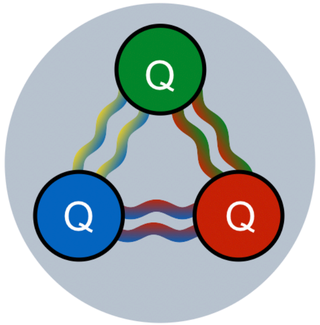

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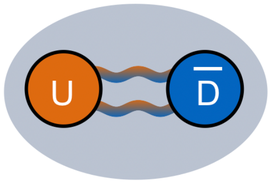

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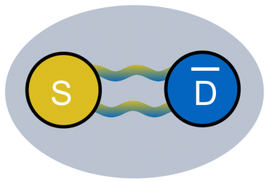

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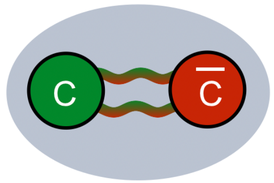

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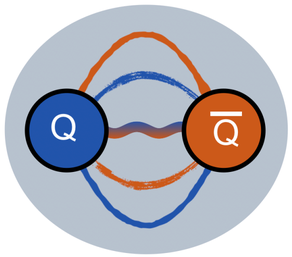

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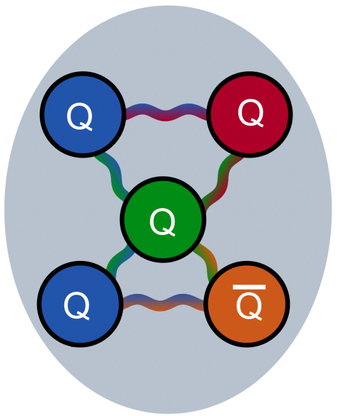

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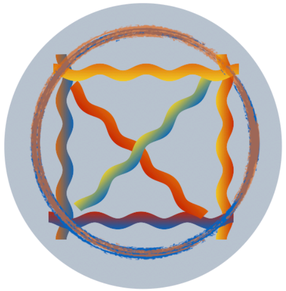
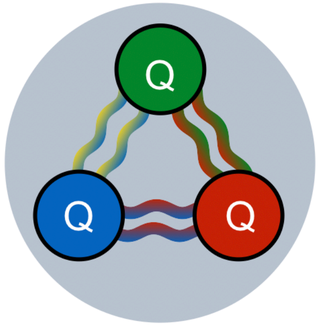


Baryons and Mesons

Ordinary baryons:



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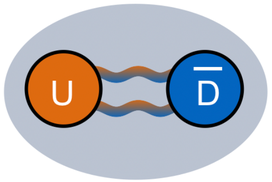
uds baryon Λ $\tau \sim 10^{-10} s$

uuu baryon Δ $\tau \sim 10^{-24}\ s$

Ordinary mesons



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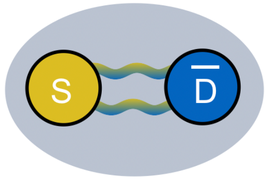

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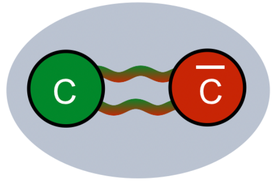
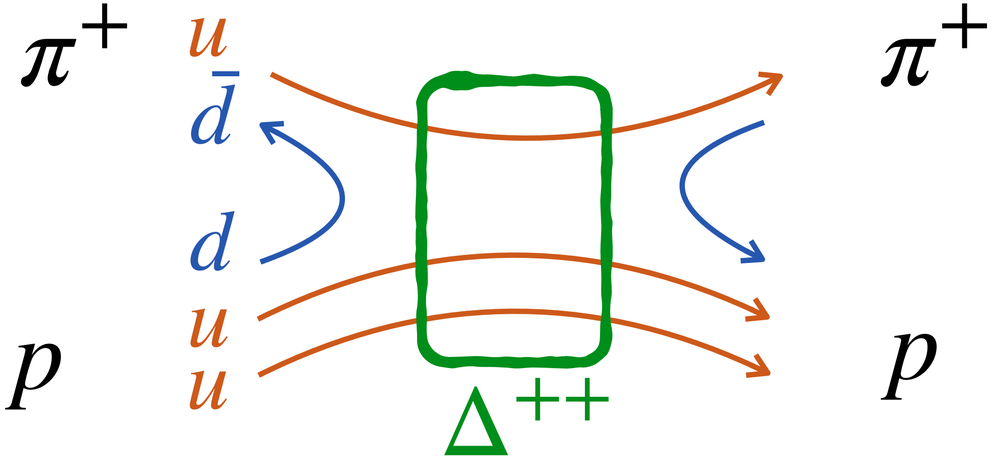
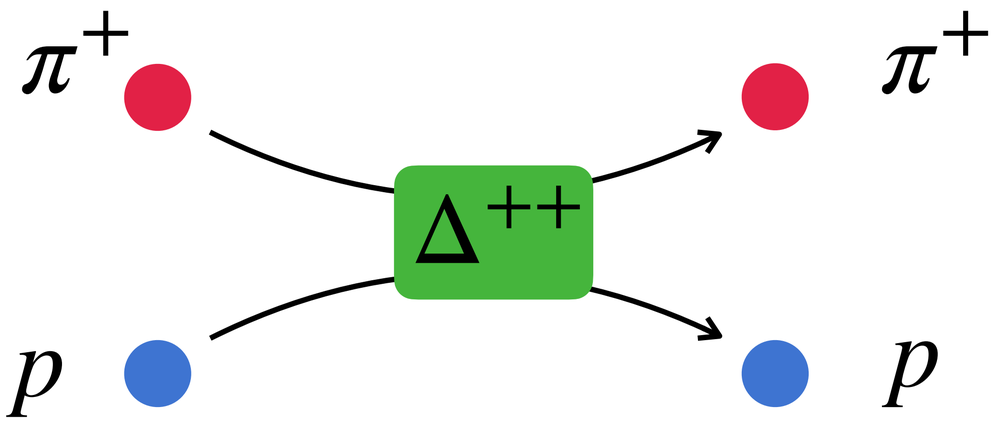


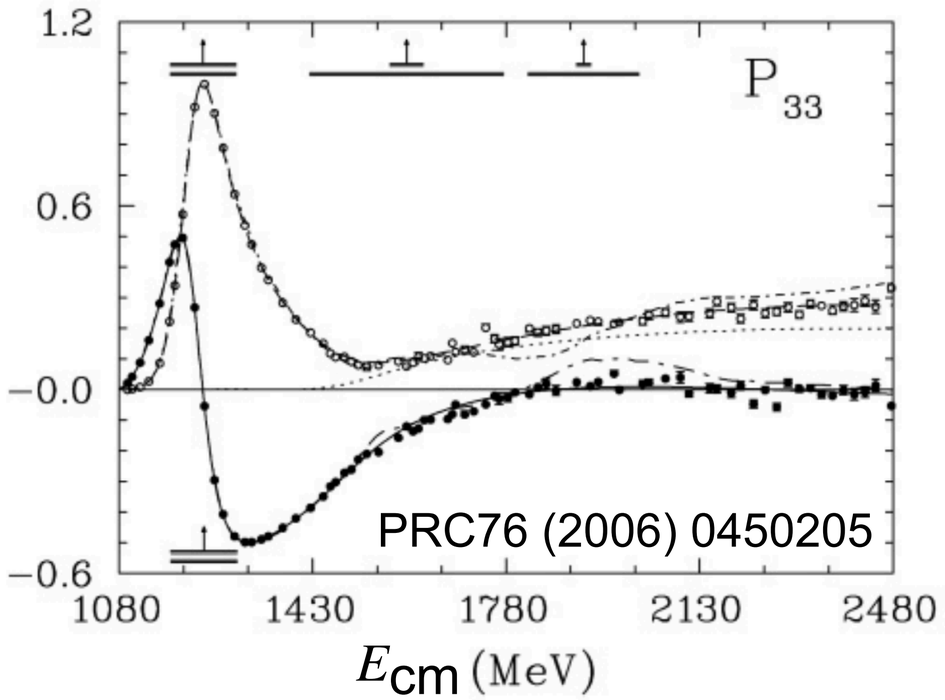
J/ψ $\tau \sim 10^{-20} s$

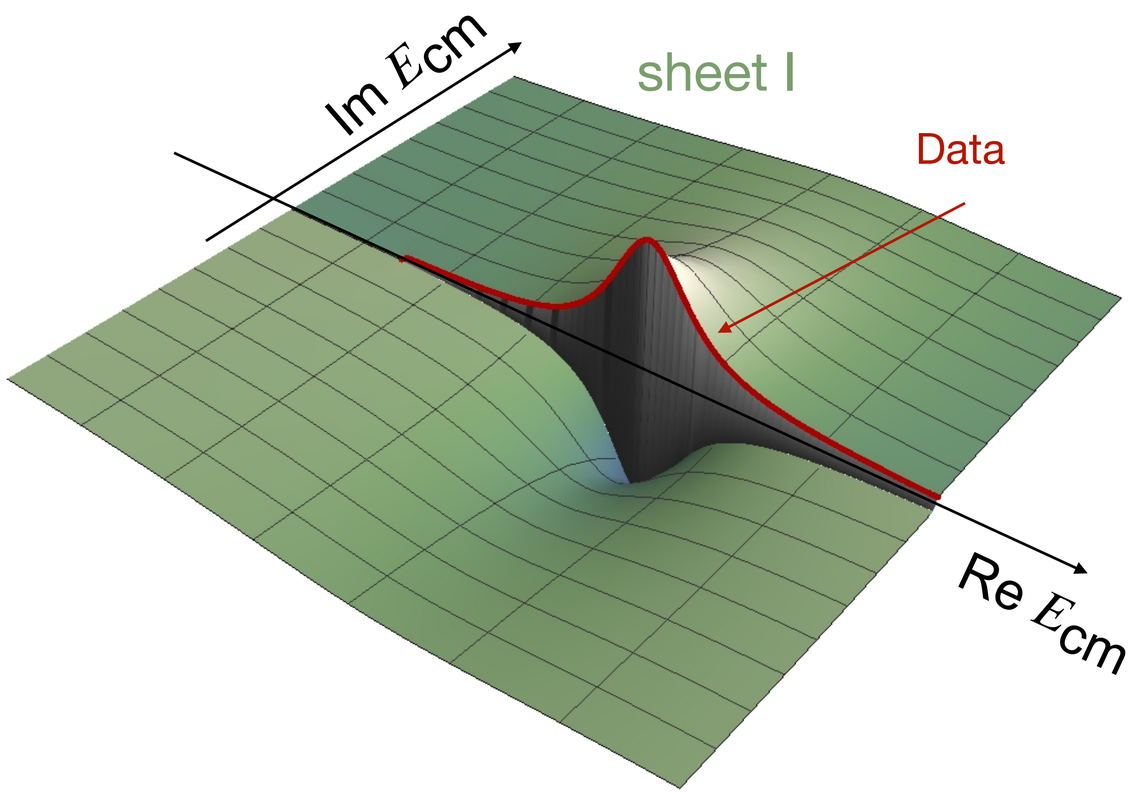
$$\pi^{+} p \to \Delta^{++} \to \pi^{+} p$$



What's a resonance?







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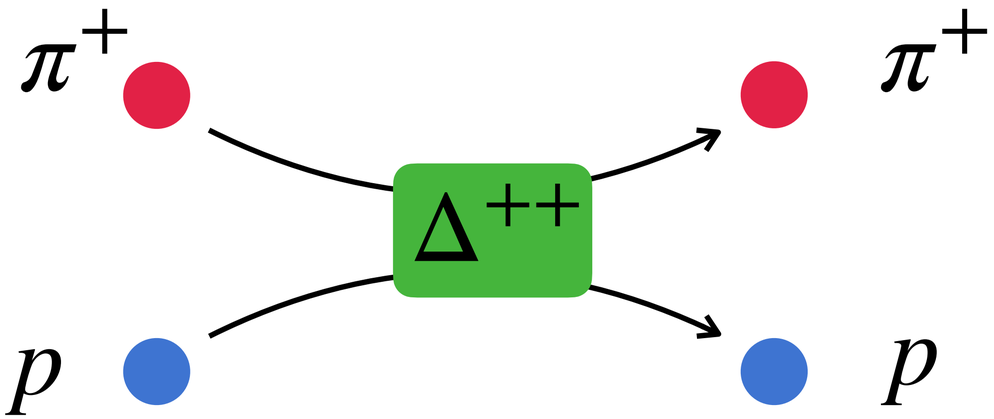

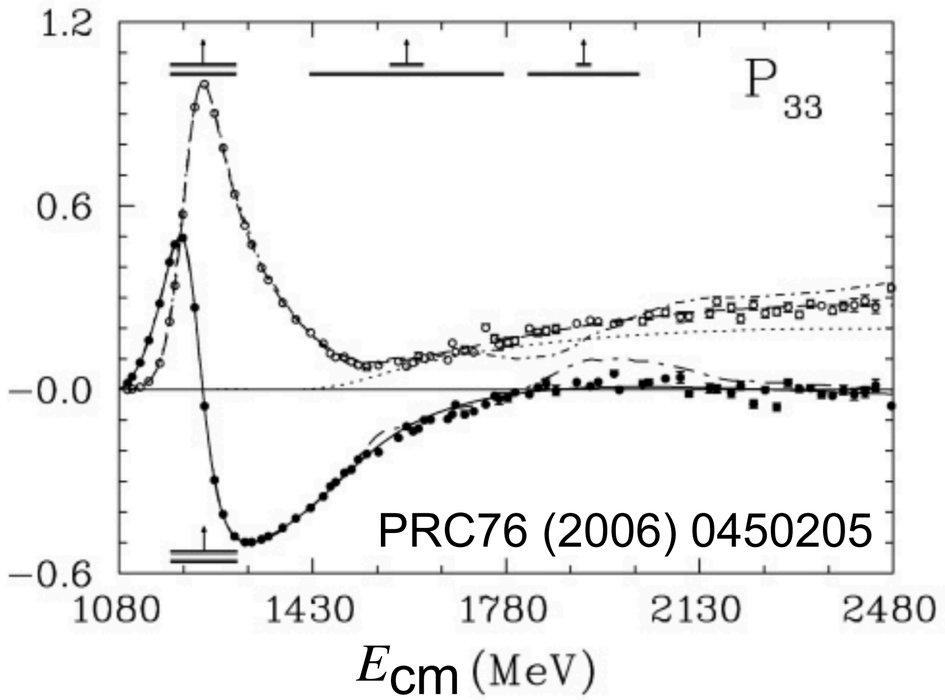

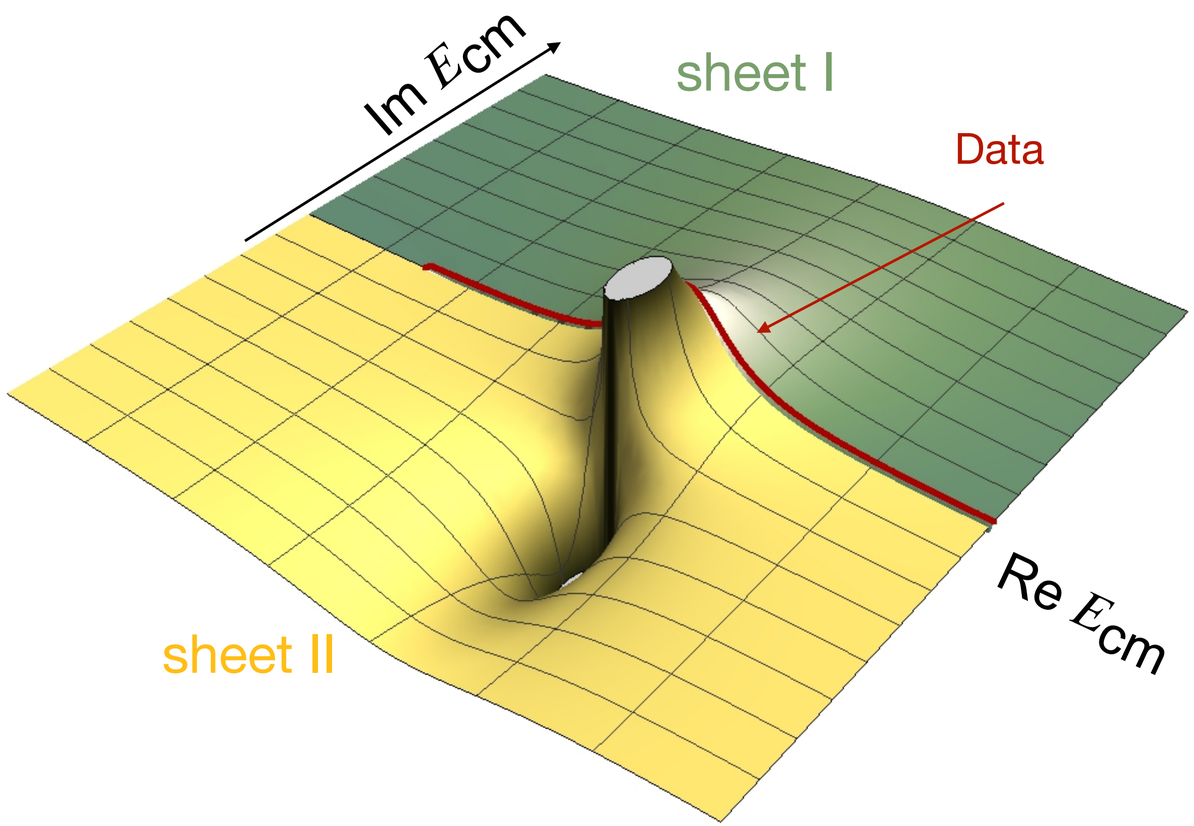

Resonances are poles of the scattering amplitude

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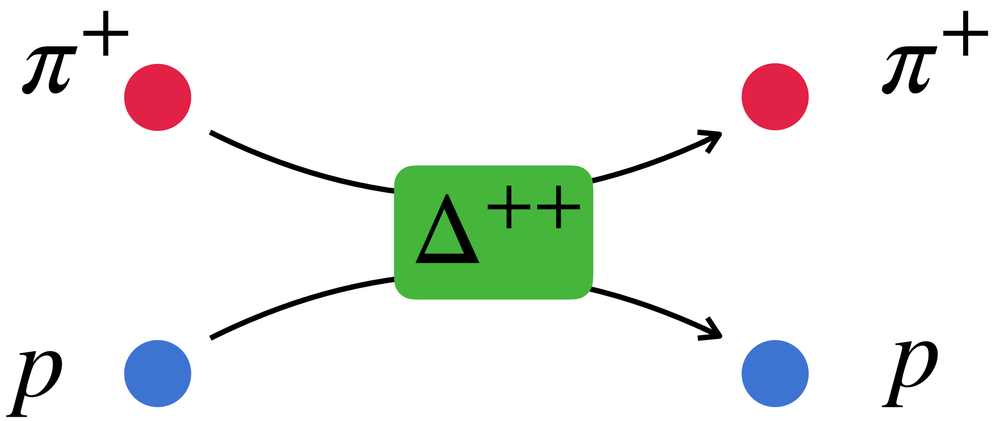

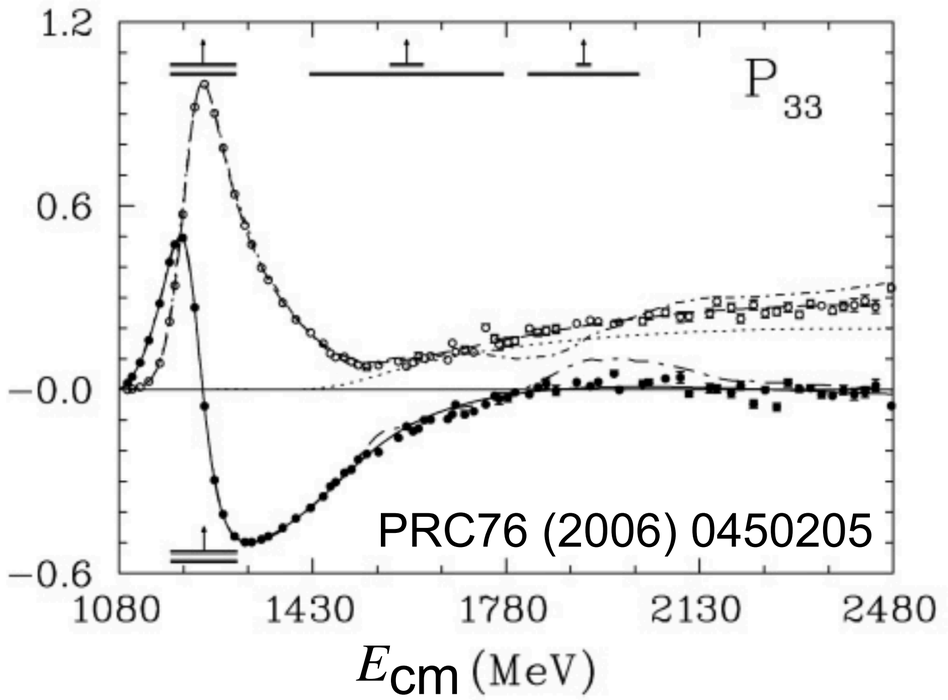

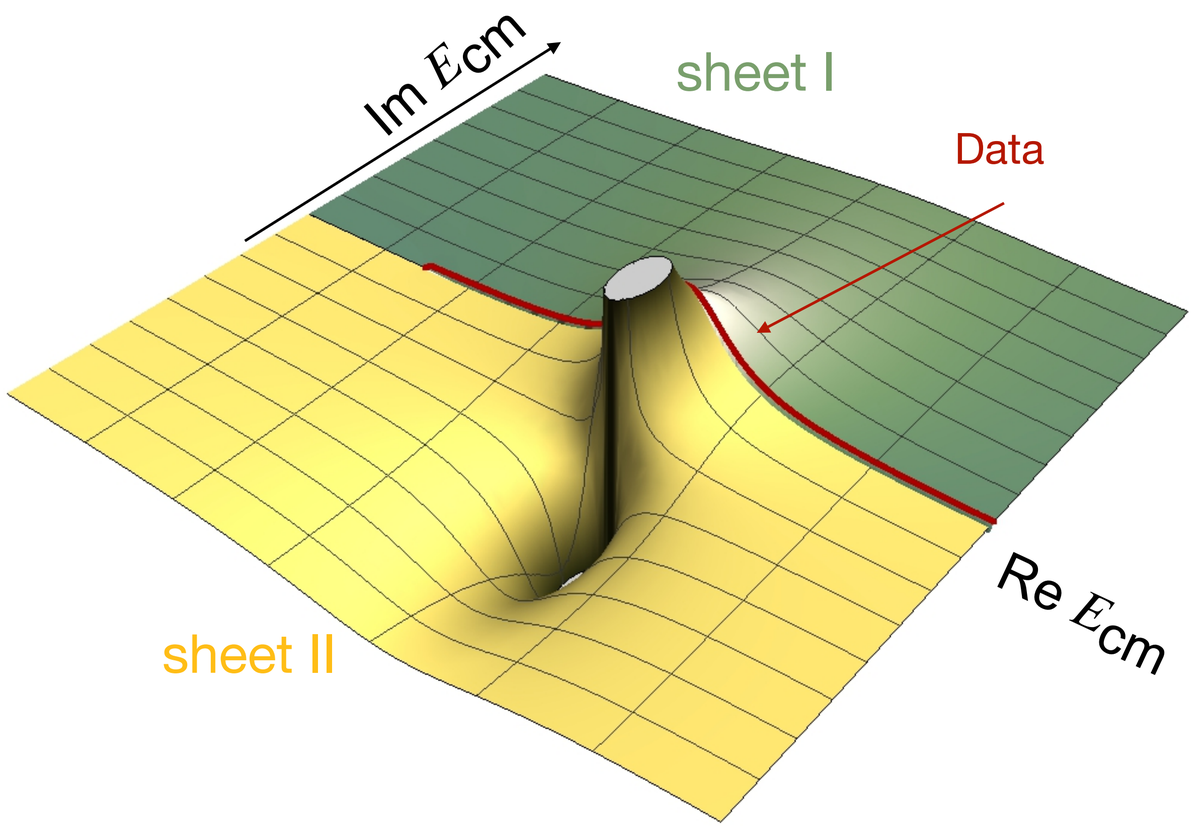

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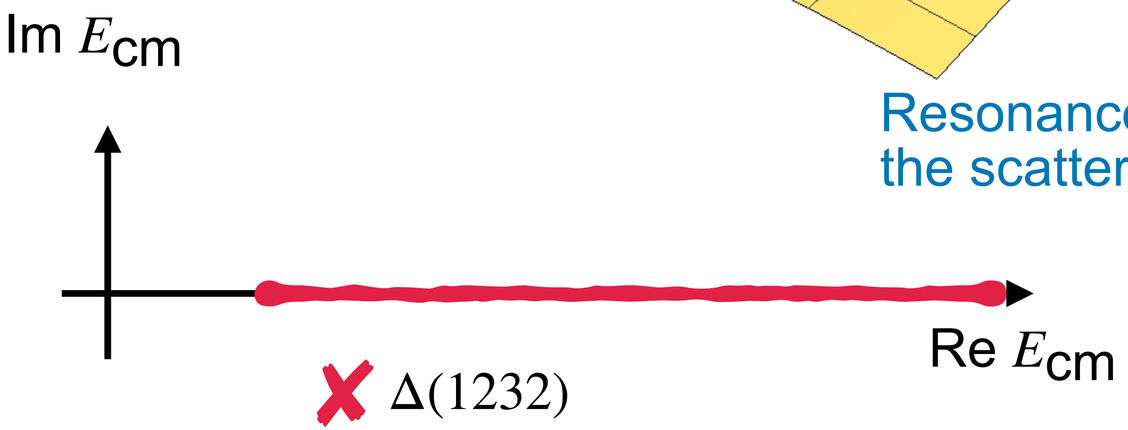

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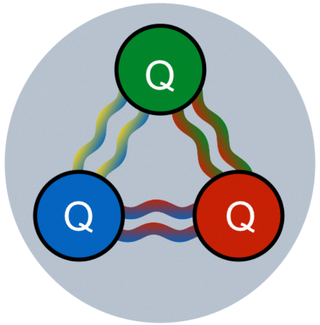

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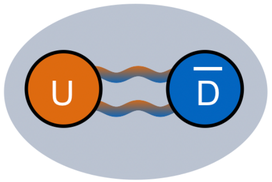

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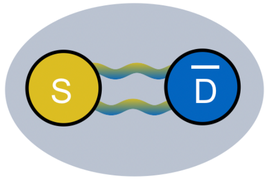

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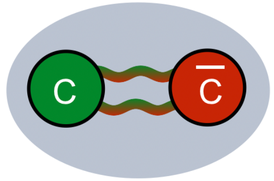

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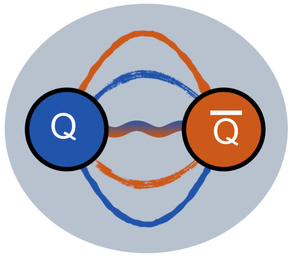
Exotic matter

hybrid mesons

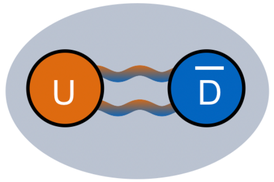


Meson with excited gluon field

Gluon field may carry quantum numbers

Quantum Numbers

Ordinary mesons



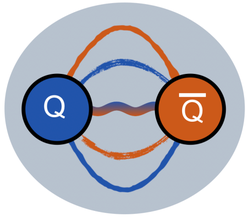
$$\vec{J} = \vec{L} \oplus \vec{S}$$

$$P = -(-1)^L$$

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

$$\begin{array}{cccc} 0^{--} & 0^{-+} & 0^{+-} & 0^{++} \\ 1^{--} & 1^{-+} & 1^{+-} & 1^{++} \\ 2^{--} & 2^{-+} & 2^{+-} & 2^{++} \\ 3^{--} & 3^{-+} & 3^{+-} & 3^{++} \\ \vdots & \vdots & \vdots & \vdots \end{array}$$

Exotic mesons



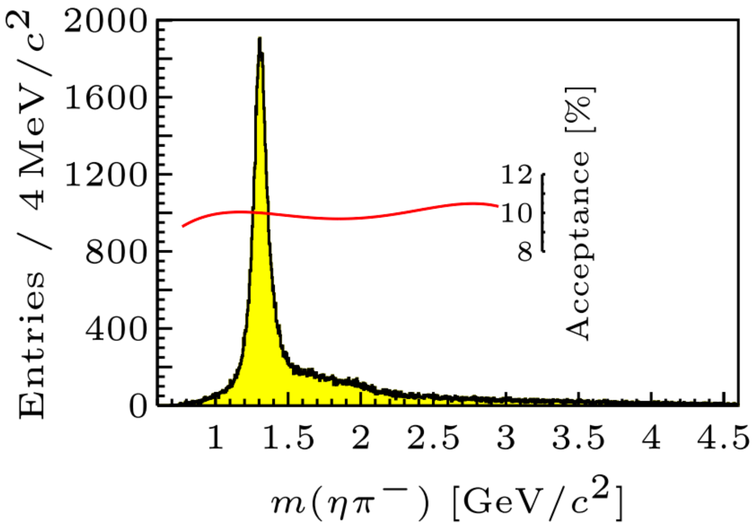
The lightest is π_1

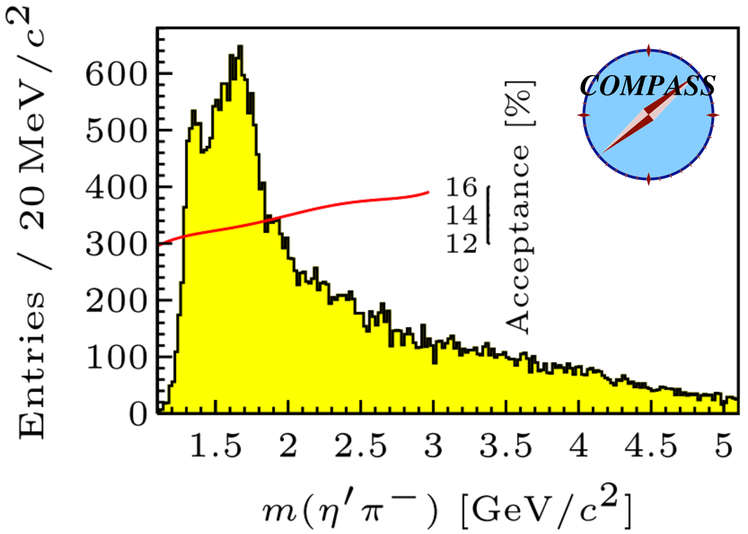
$$J^{PC} = 1^{-+}$$

$$1^{-+} = \left(0^{-+} \otimes 0^{-+}\right)_{P\text{-wave}}$$

Decay mode

$$\pi_1 \to \eta\pi, \eta'\pi$$





Partial Waves Expansion

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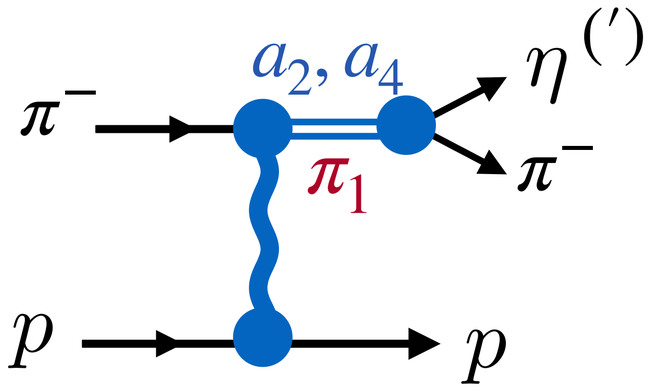
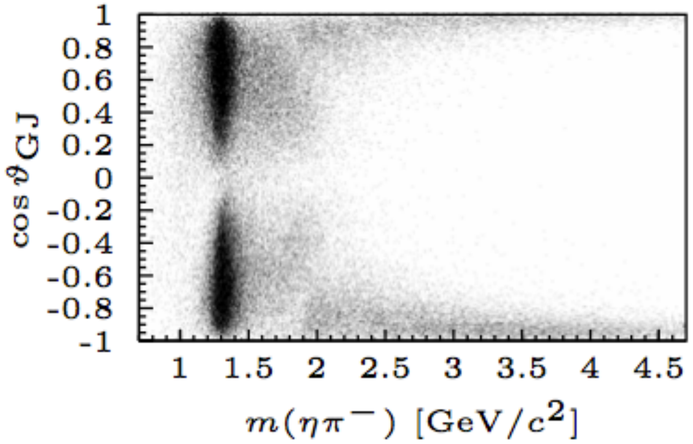
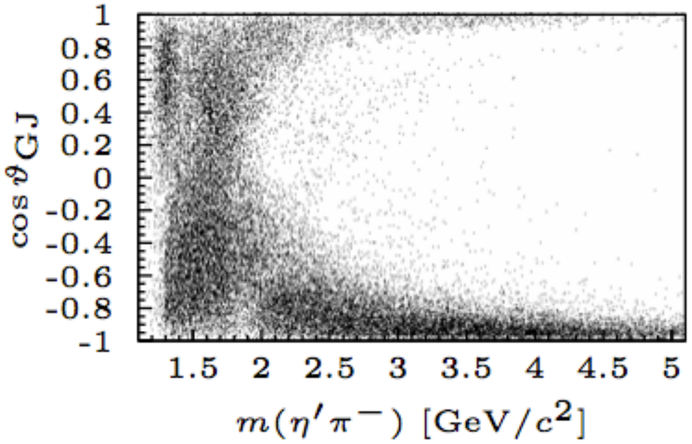
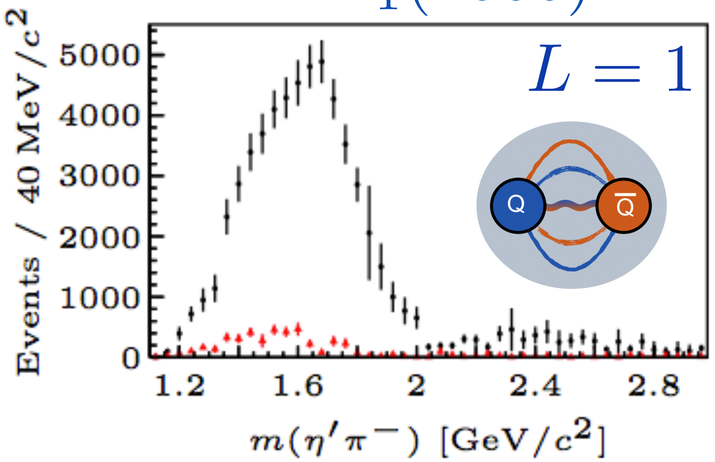


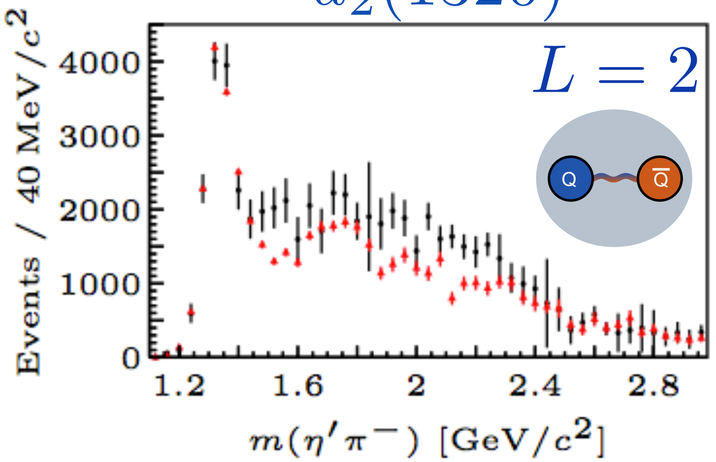




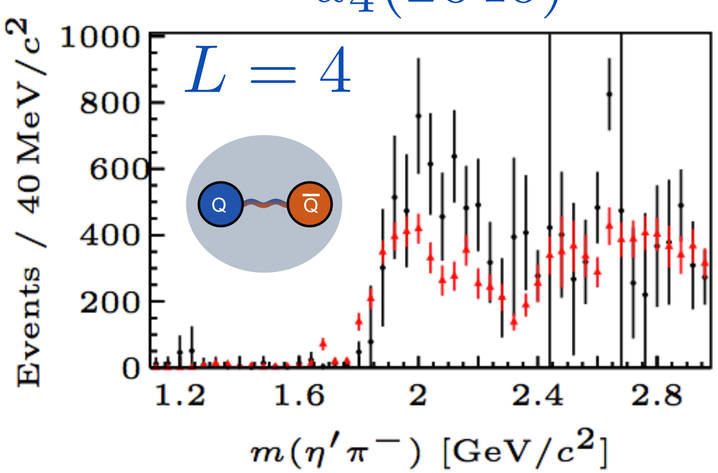
$\pi_1(1600)$?



$a_2(1320)$



$a_4(2040)$



Resonance in angular mom. L = 1 ?

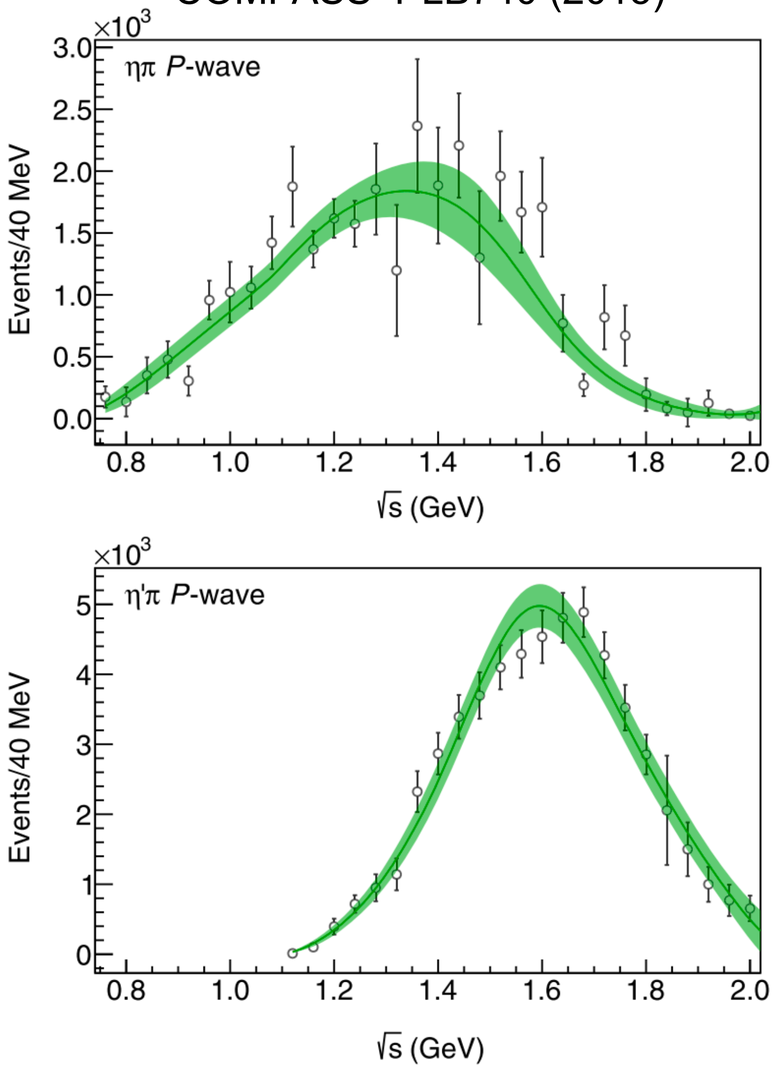
black: $\pi\eta'$

red: $\pi\eta$ (scaled)

$\pi_1(1400)$ vs $\pi_1(1600)$

More refs. on https://pdg.lbl.gov/

COMPASS PLB740 (2015)



$\pi_1(1400)$ vs $\pi_1(1600)$

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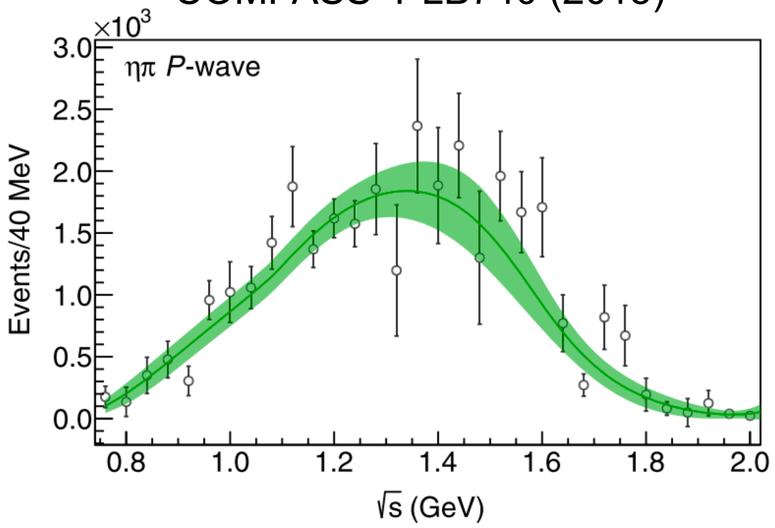
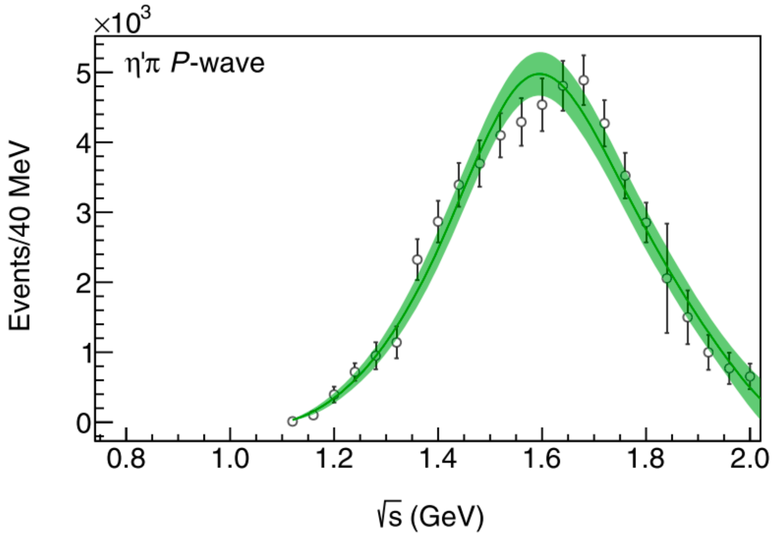
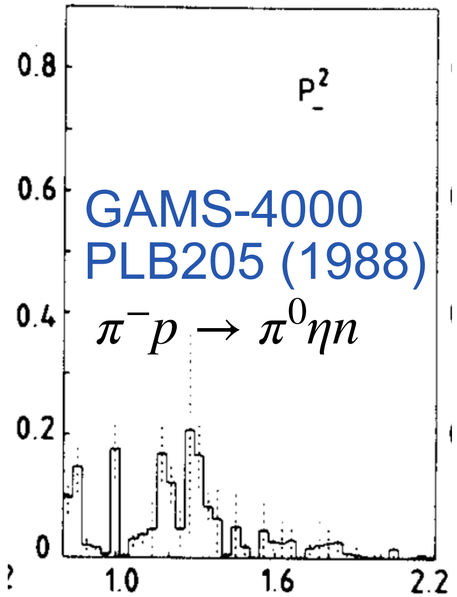
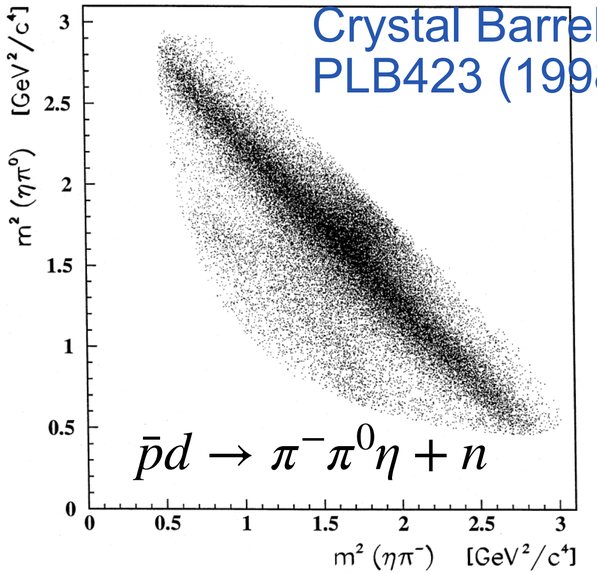






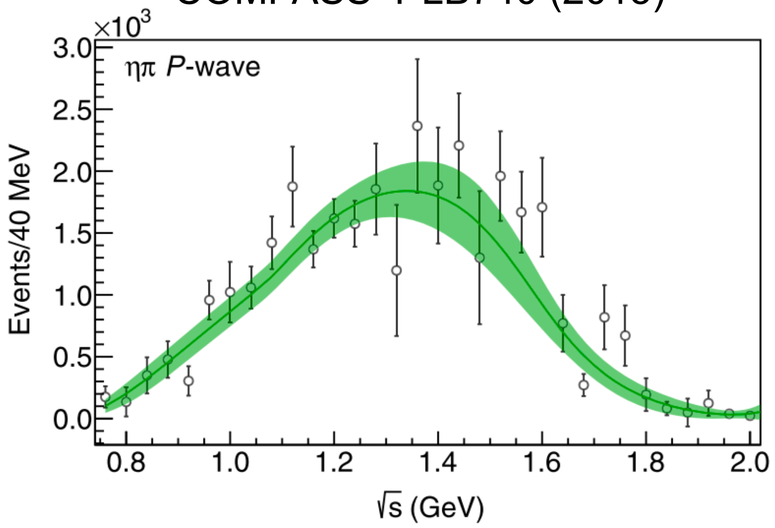
Mass ~ 1400 MeV

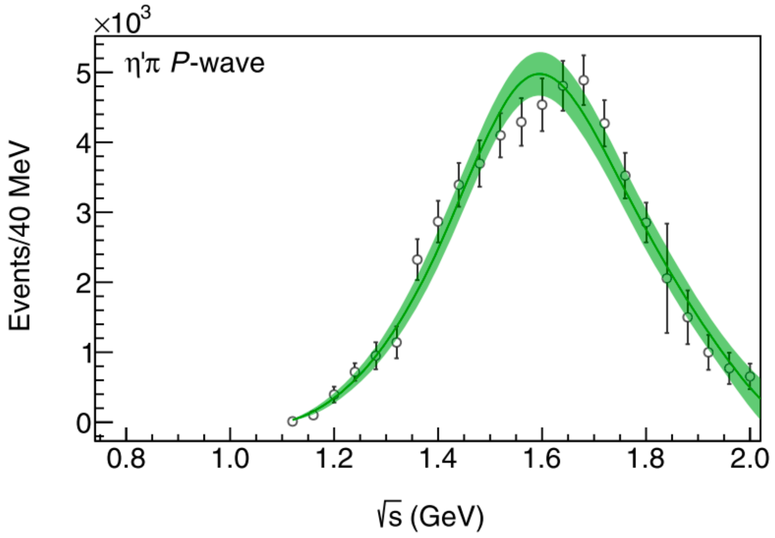


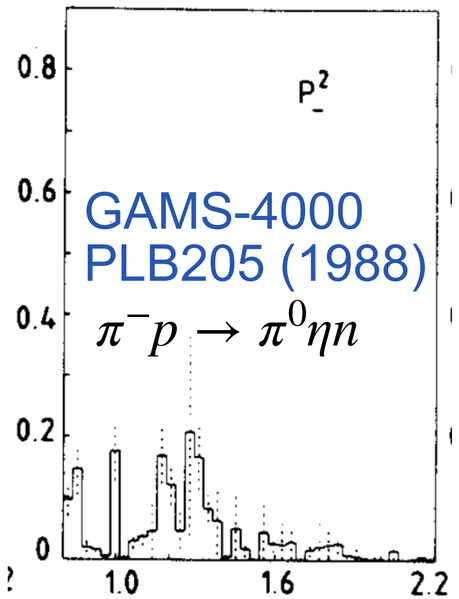
$\pi_1(1400)$ vs $\pi_1(1600)$

More refs. on https://pdg.lbl.gov/

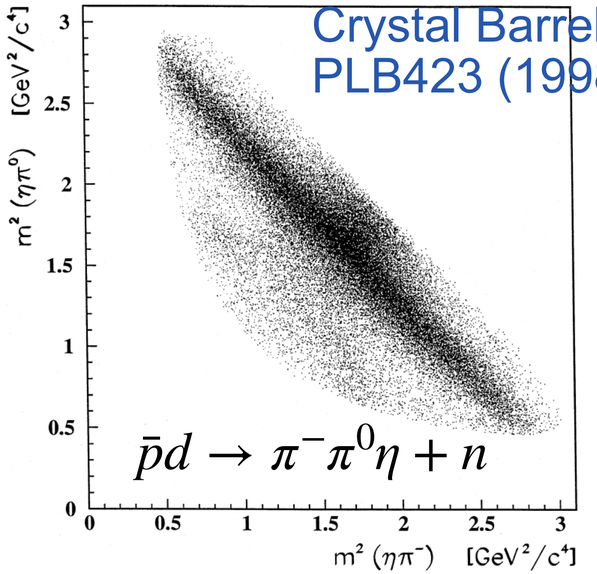
COMPASS PLB740 (2015)

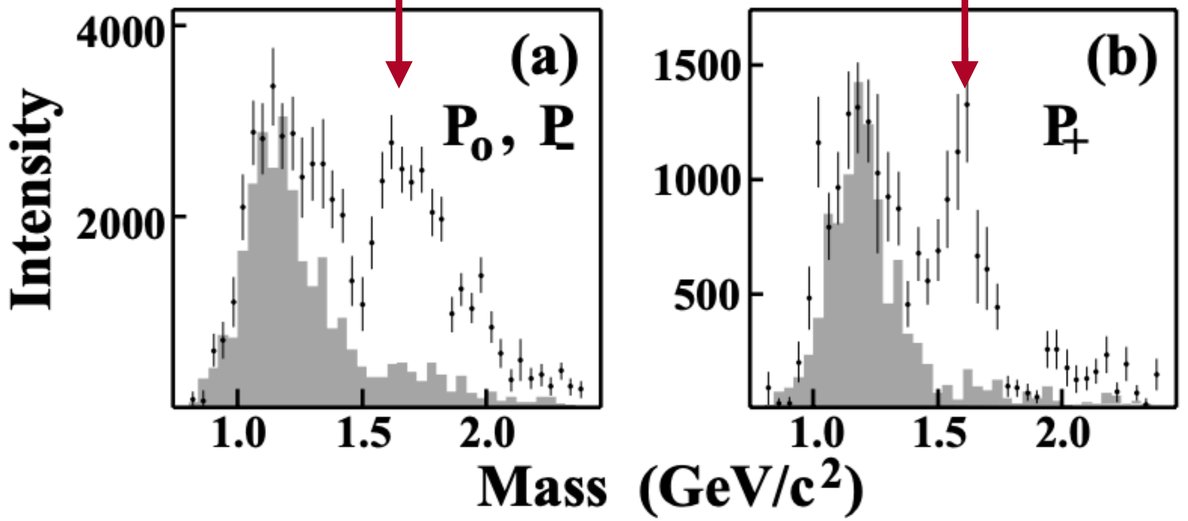






Mass ~ 1400 MeV





E852 PRL81 (1998)

$\pi^- p \to \pi^+\pi^-\pi^- p$

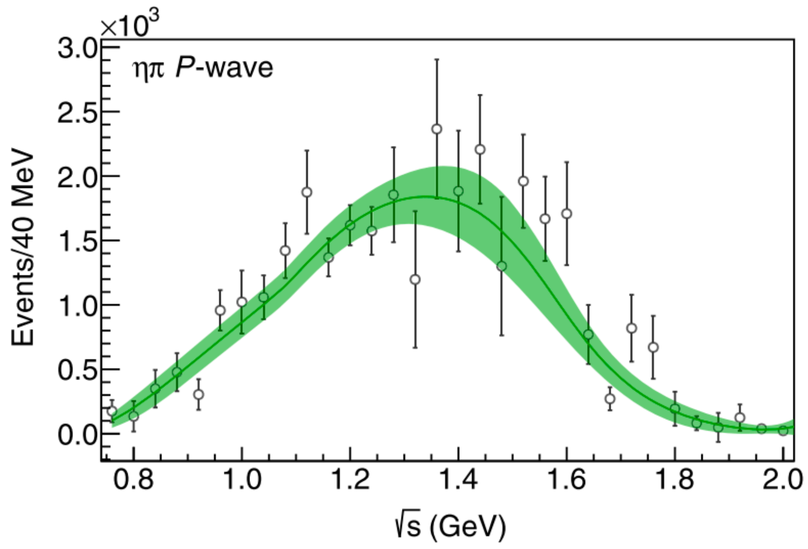
At 18 GeV

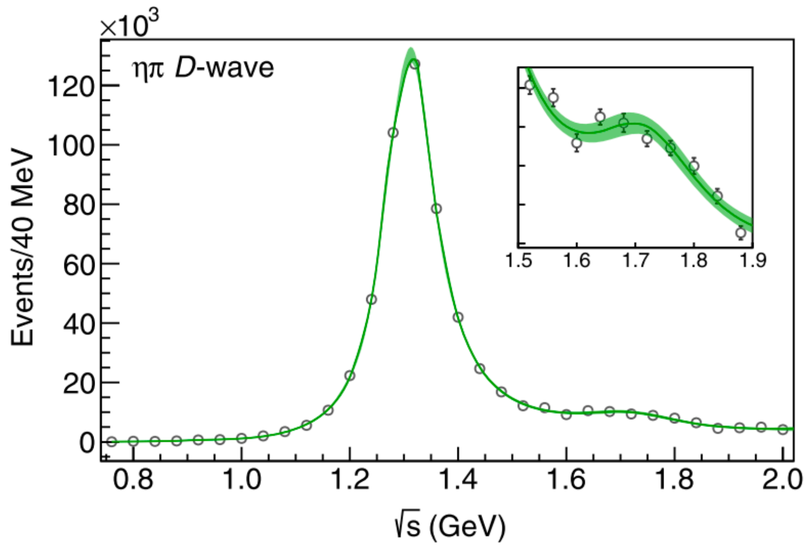
Mass ~ 1600 GeV

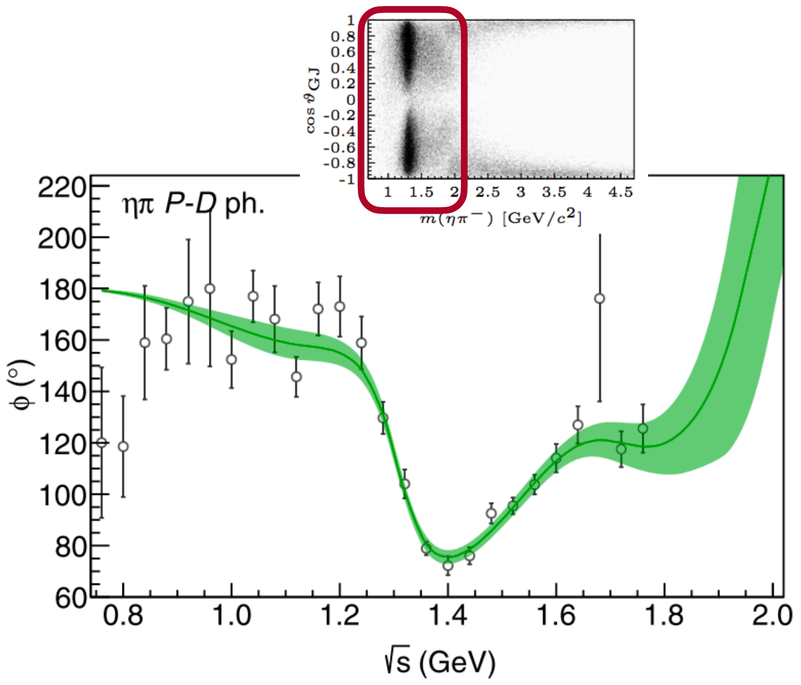
Low Energy Fit of $L = 1,2$

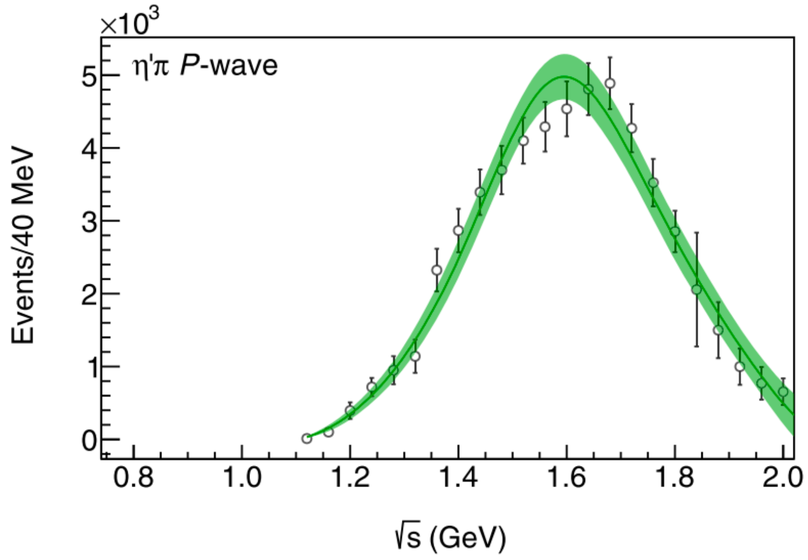
Rodas et al PRL122 (2019)

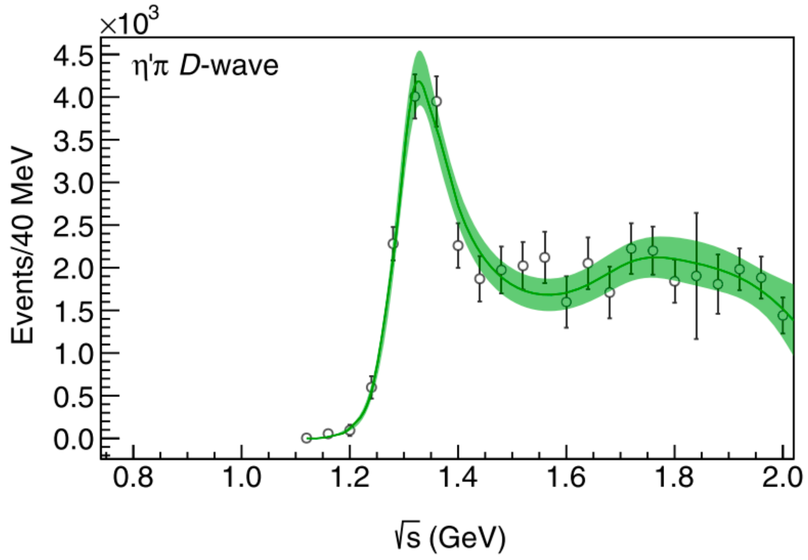
$\pi_1(1400)$ vs $\pi_1(1600)$

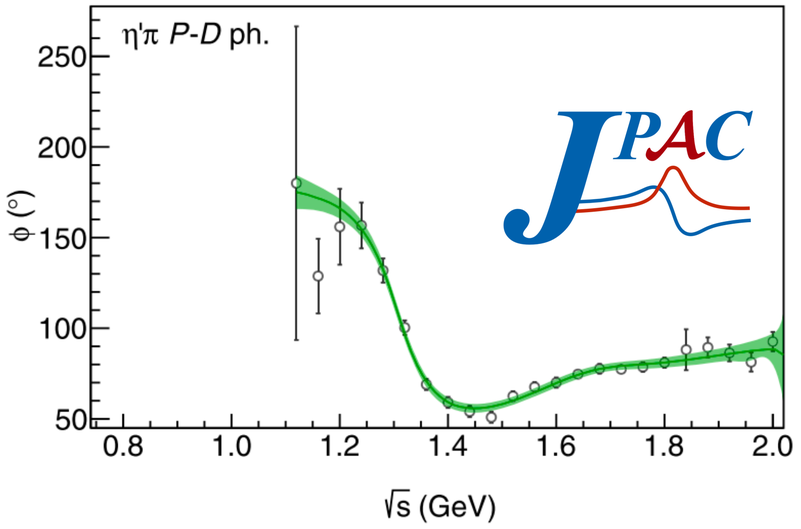








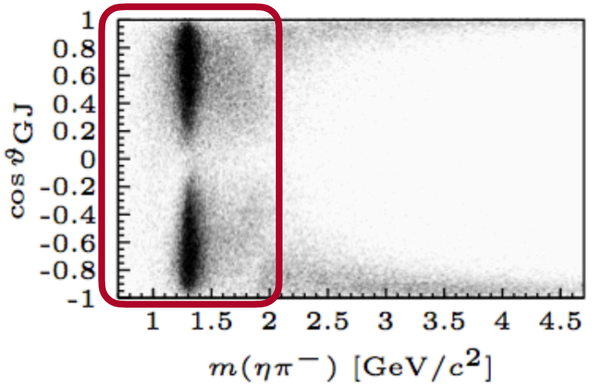


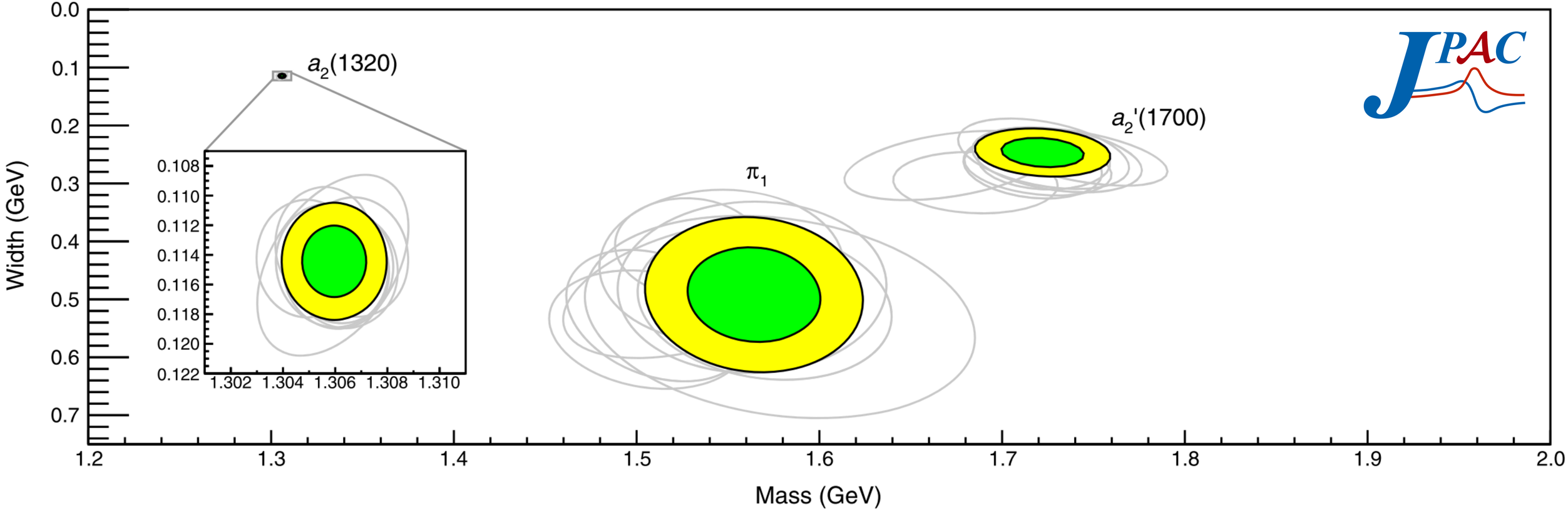


Low Energy Fit of $L = 1,2$

Rodas et al (JPAC) PRL122 (2019)

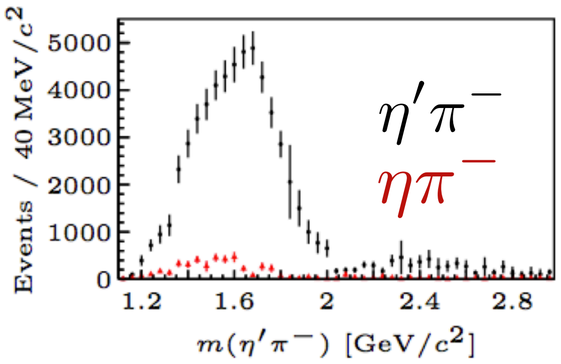
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

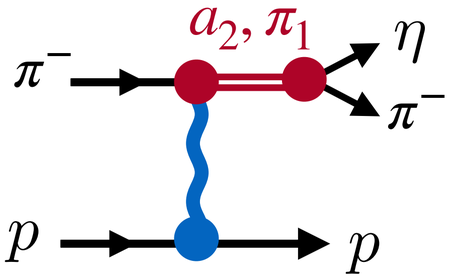


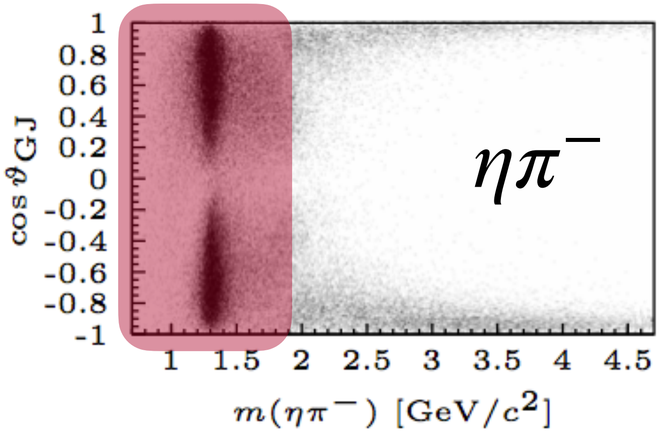


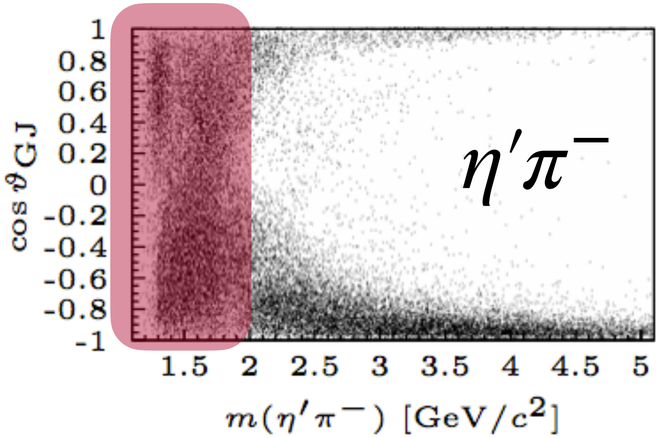
Origin of the Exotic Meson

COMPASS PLB740 (2015)







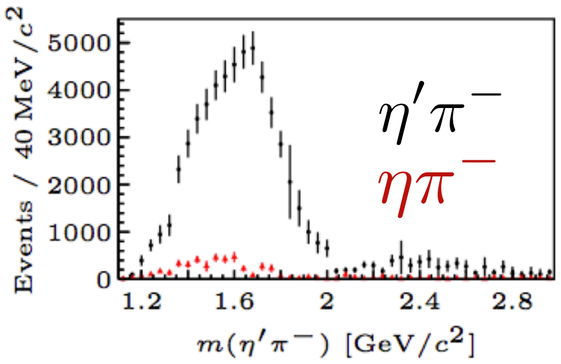


Exotic meson related to
Forward-backward asymmetry

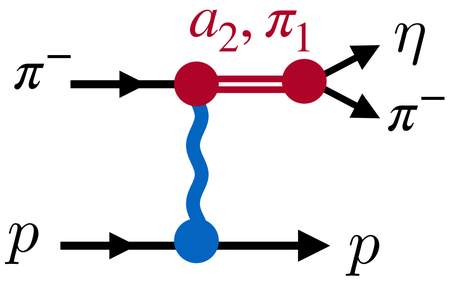
Asymmetry related to
even-odd waves interferences

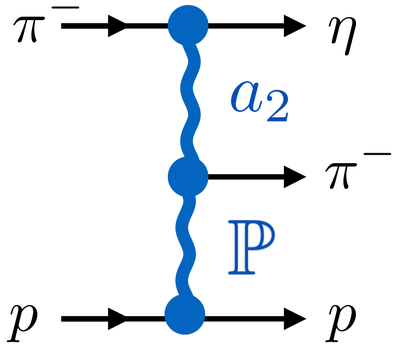
Origin of the Exotic Meson

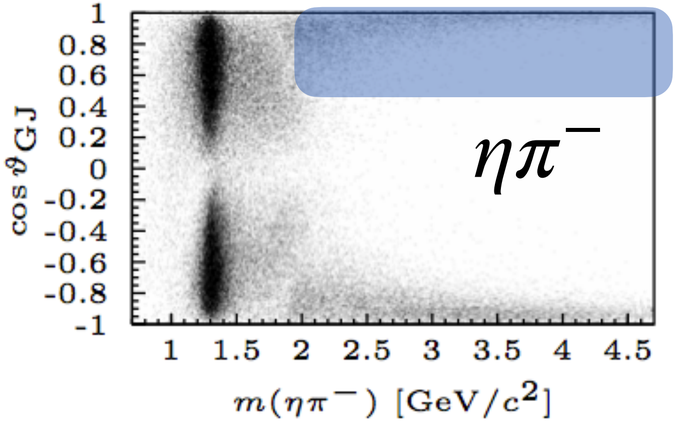
COMPASS PLB740 (2015)

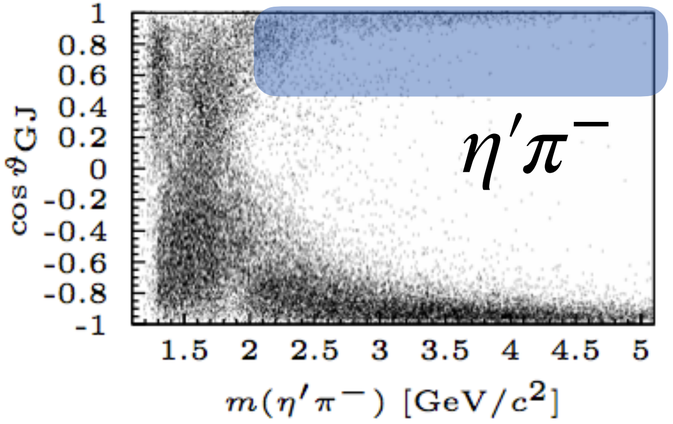


$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward







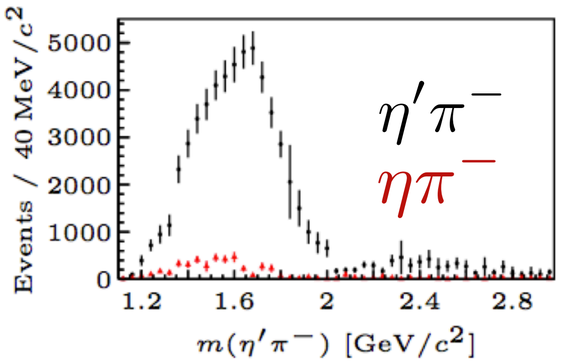


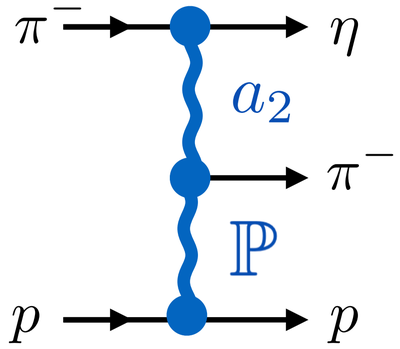
Exotic meson related to
Forward-backward asymmetry

Asymmetry related to
even-odd waves interferences

Origin of the Exotic Meson

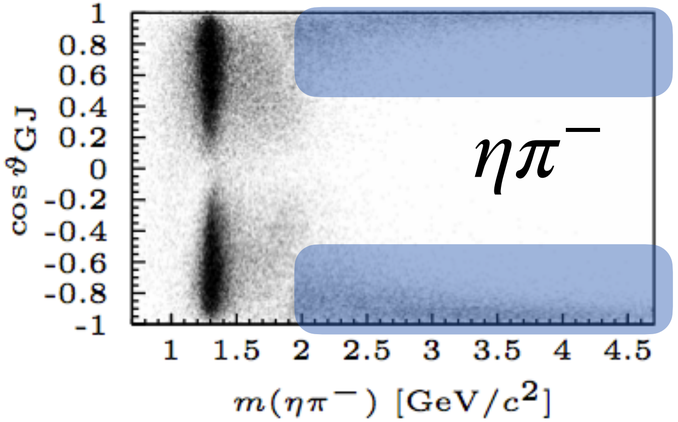
COMPASS PLB740 (2015)

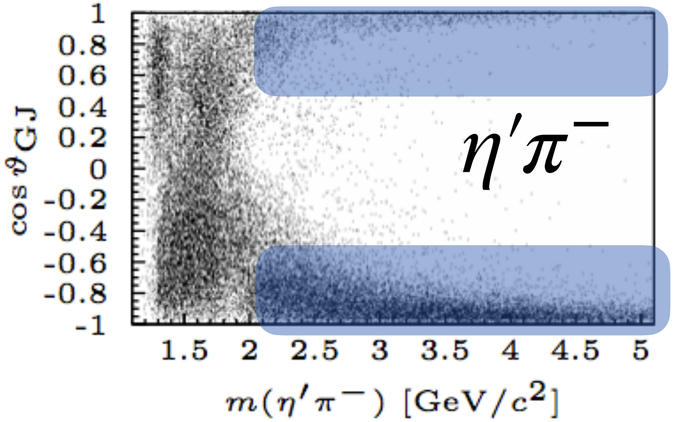




$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward

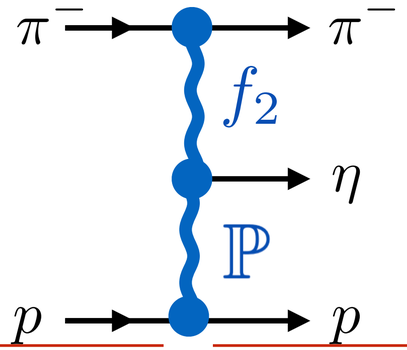
$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward

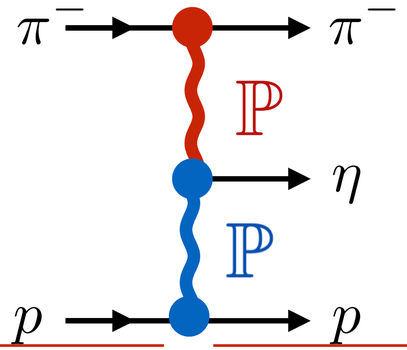




Exotic meson related to
Forward-backward asymmetry

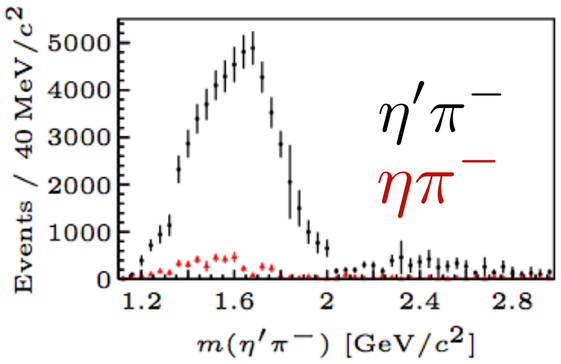
Asymmetry related to
even-odd waves interferences

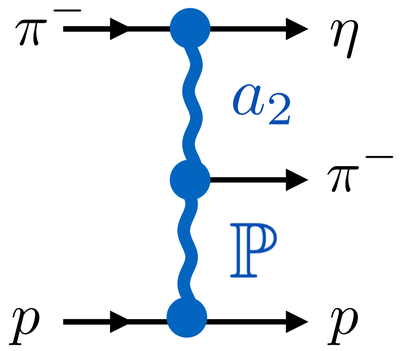




Origin of the Exotic Meson

COMPASS PLB740 (2015)



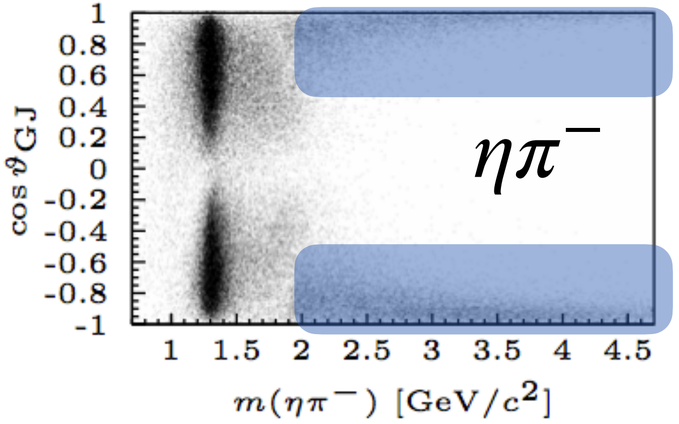


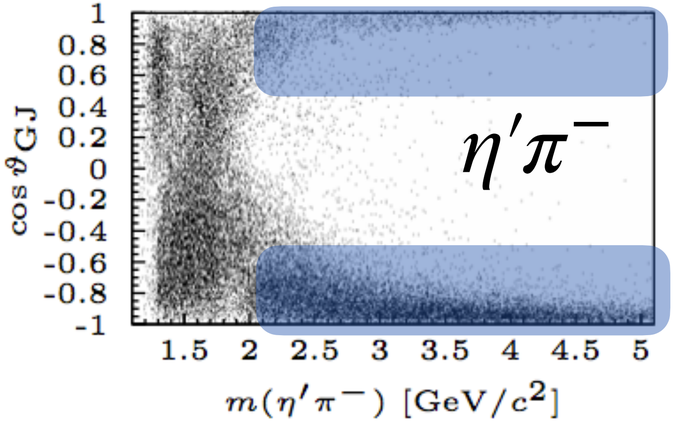
If a2 and f2 diagrams equal and no Pomeron

NO ASYMMETRY and NO π_1

$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward

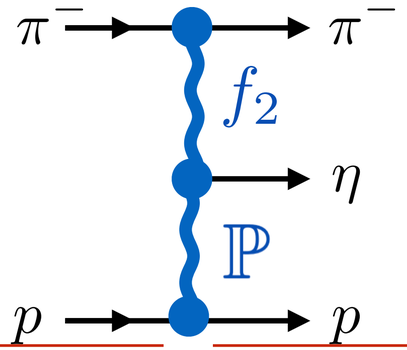
$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward

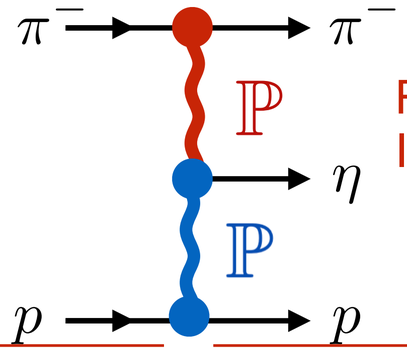




Exotic meson related to Forward-backward asymmetry

Asymmetry related to even-odd waves interferences

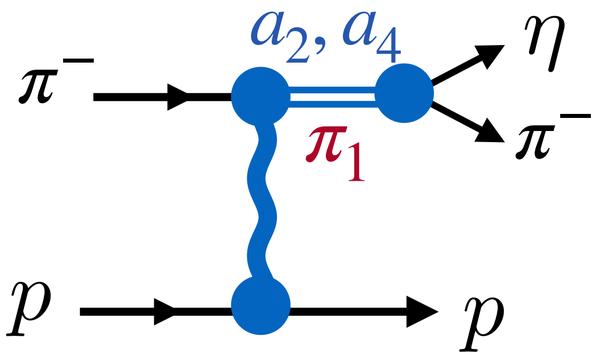


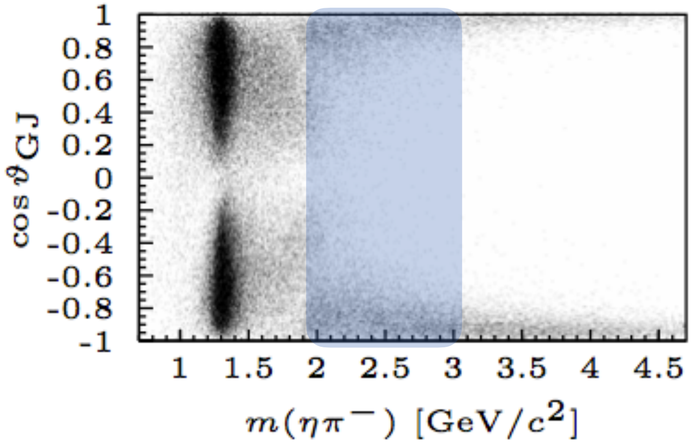


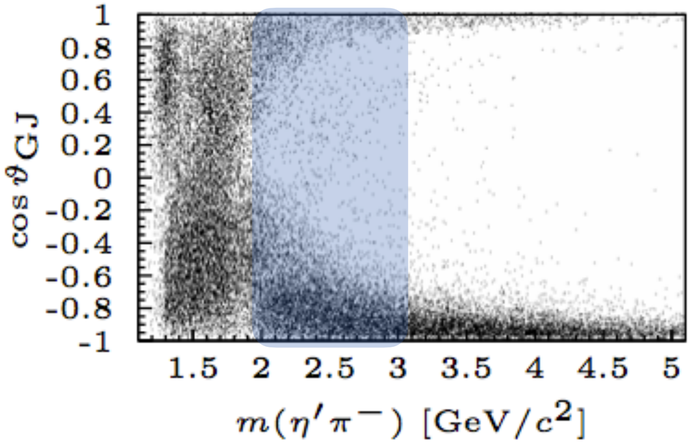
Responsible for asymmetry In eta-Prime - pion?

Partial Waves Expansion

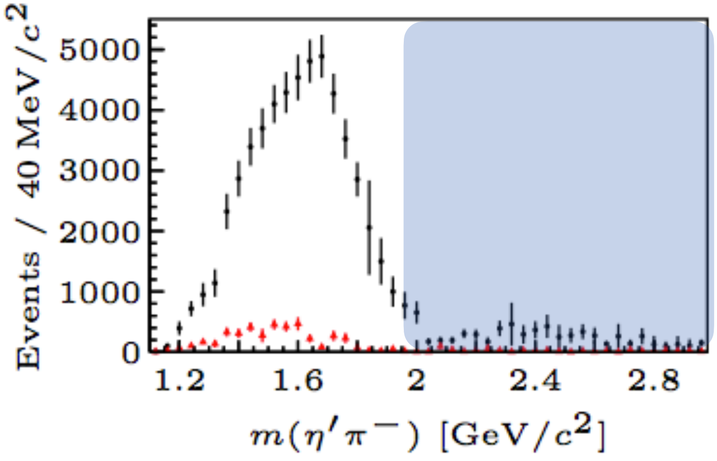
COMPASS PLB740 (2015)



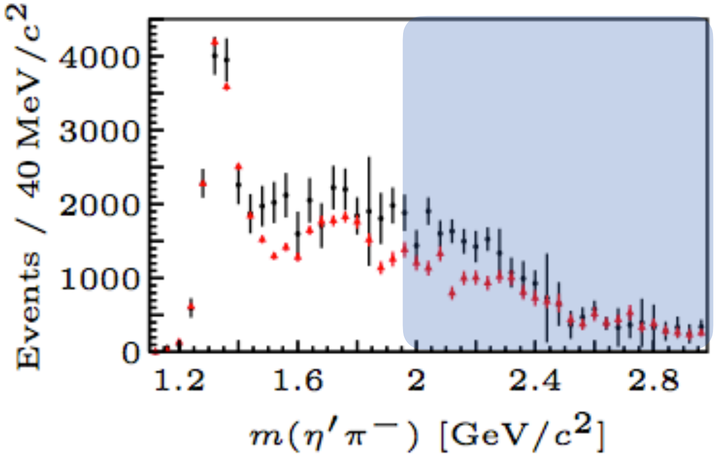




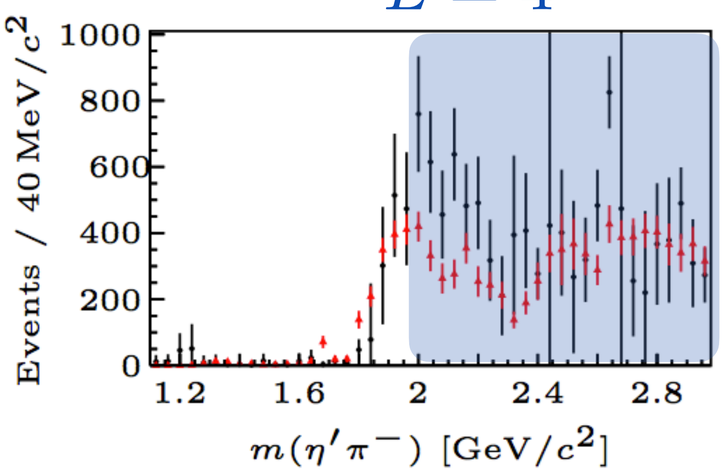
$L = 1$



$L = 2$



$L = 4$

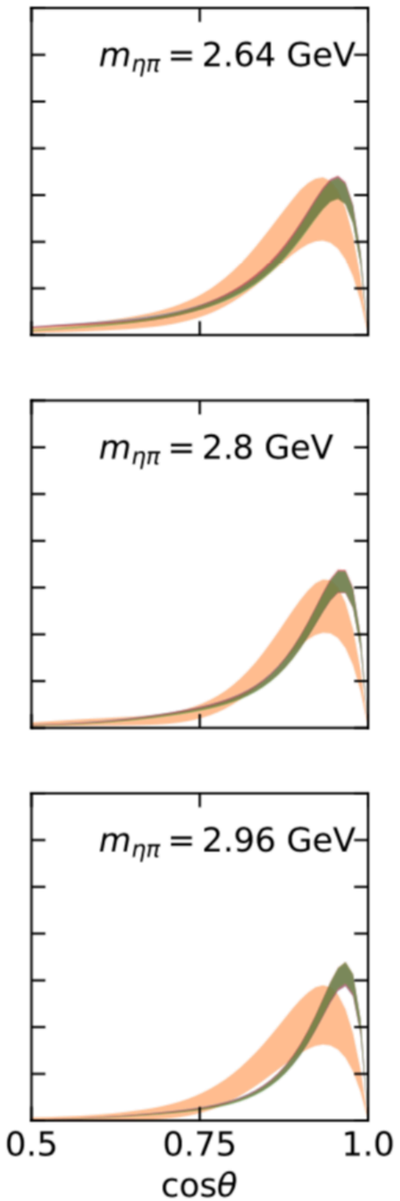


Resonance in angular mom. L = 1 ?

black: $\pi\eta'$ red: $\pi\eta$ (scaled)

Eta-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

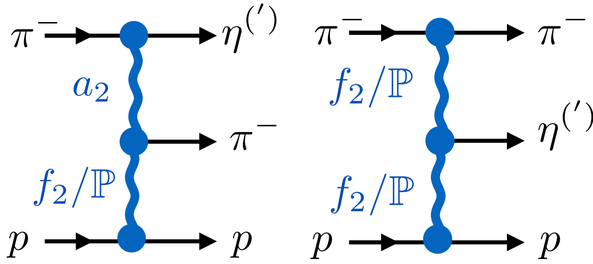
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

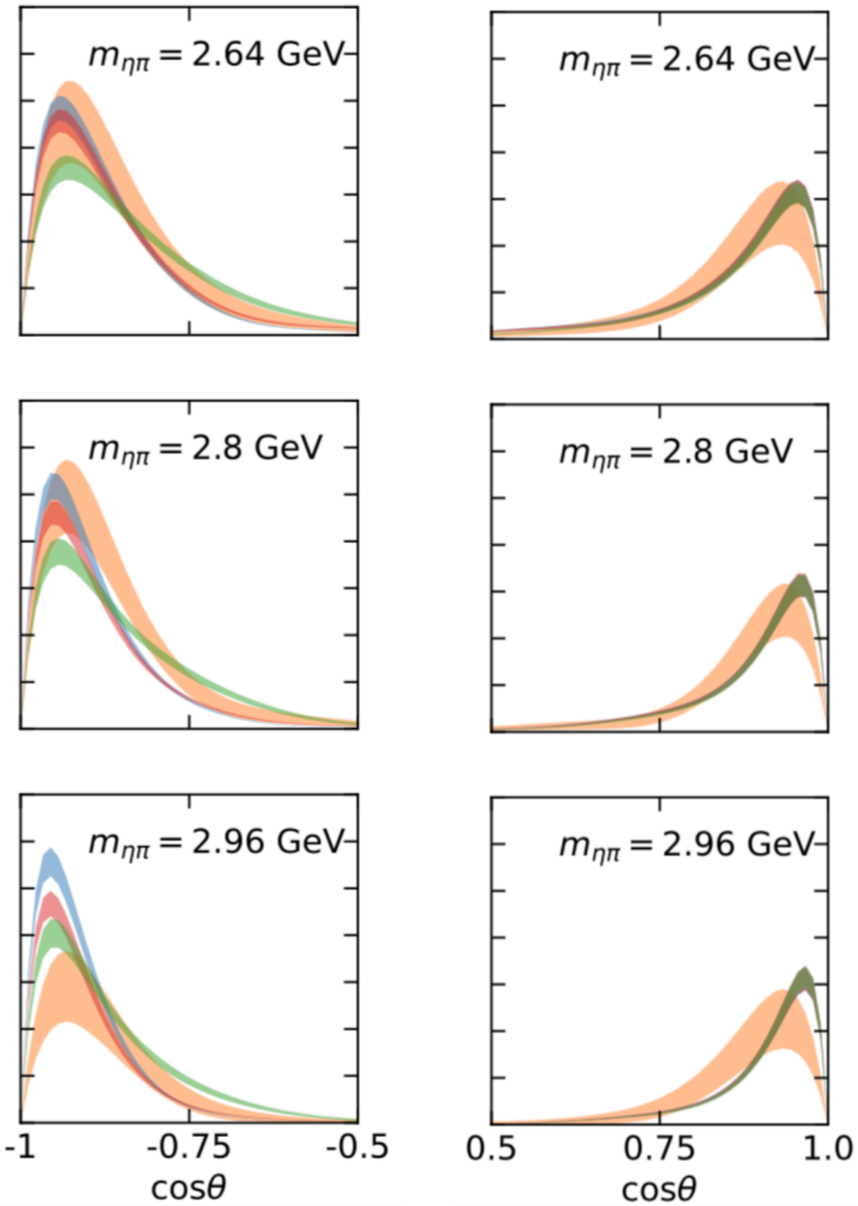
Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

6 diagrams total



Eta-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



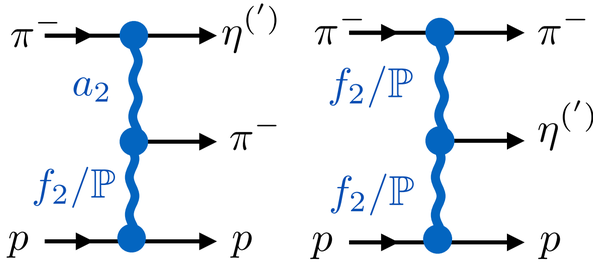
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total

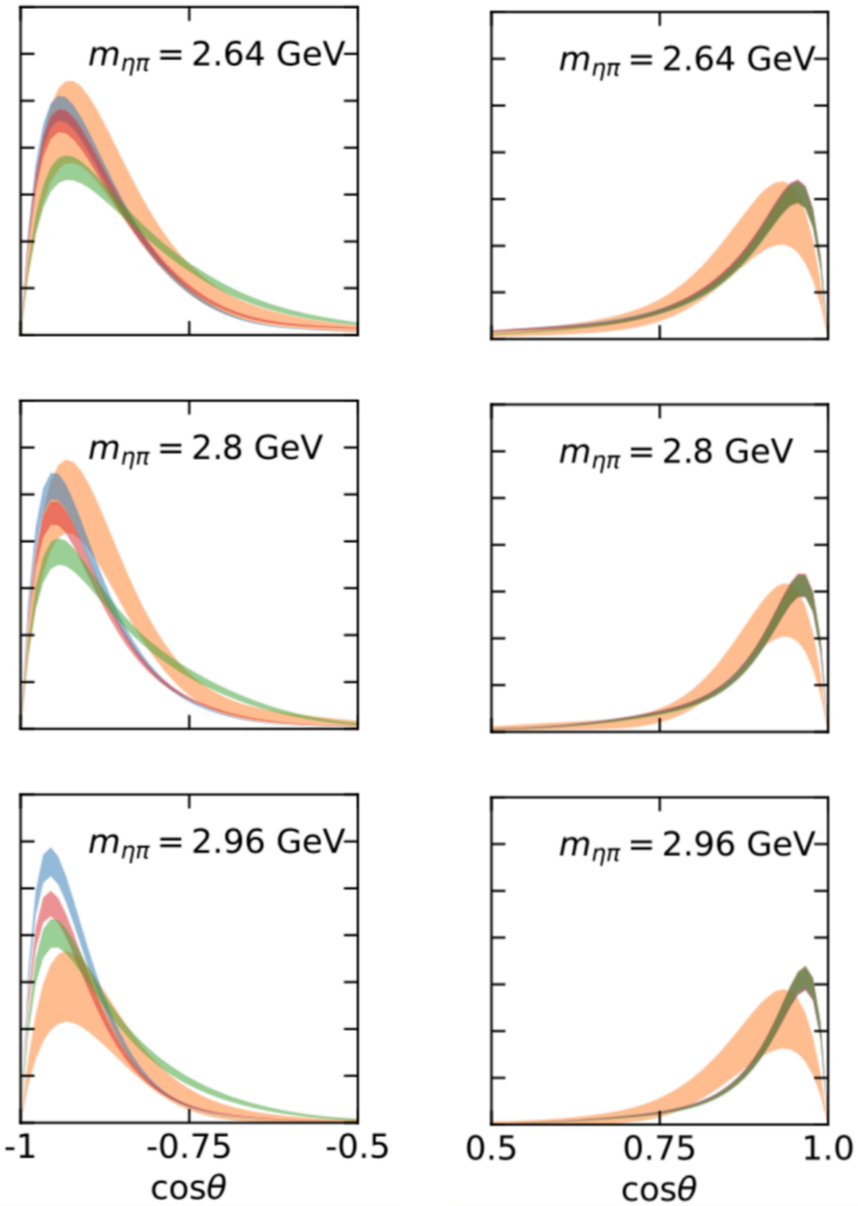


Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and either $(f_2, \mathbb{P})$ or $(\mathbb{P}, \mathbb{P})$

Eta-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



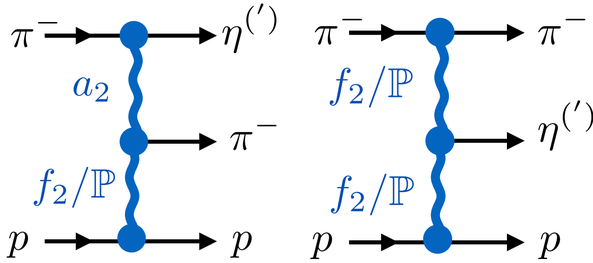
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total



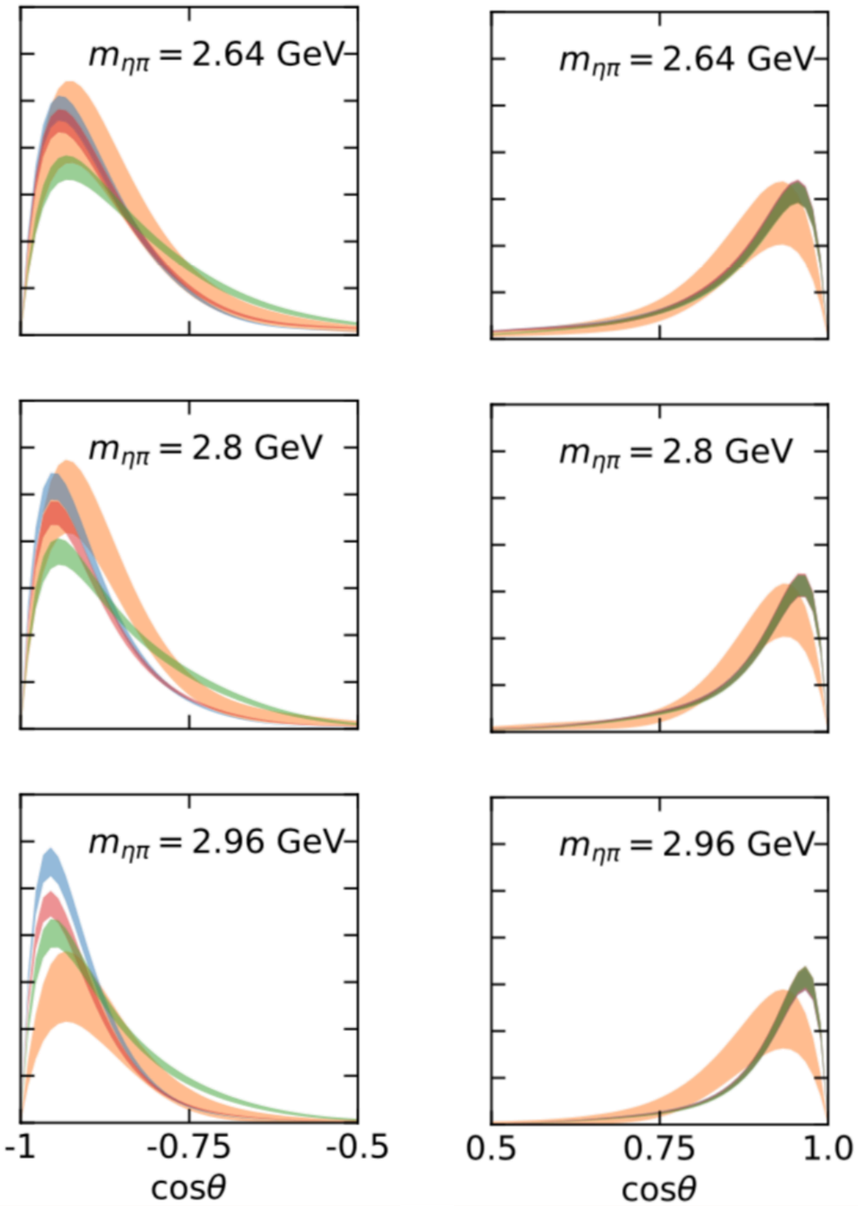
Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and either $(f_2, \mathbb{P})$ or $(\mathbb{P}, \mathbb{P})$

$(a_2, \mathbb{P})$	0.40 ± 0.04
(a_2, f_2)	3.4 ± 0.4
$(f_2, \mathbb{P})$	-0.30 ± 0.05
(f_2, f_2)	-6.6 ± 0.7

Eta-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



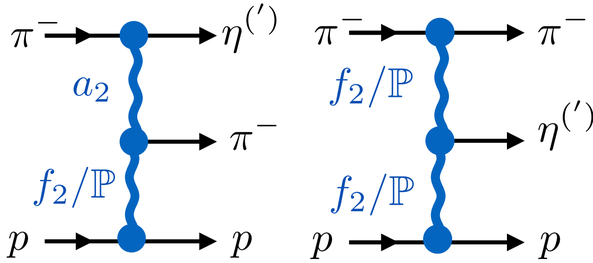
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total



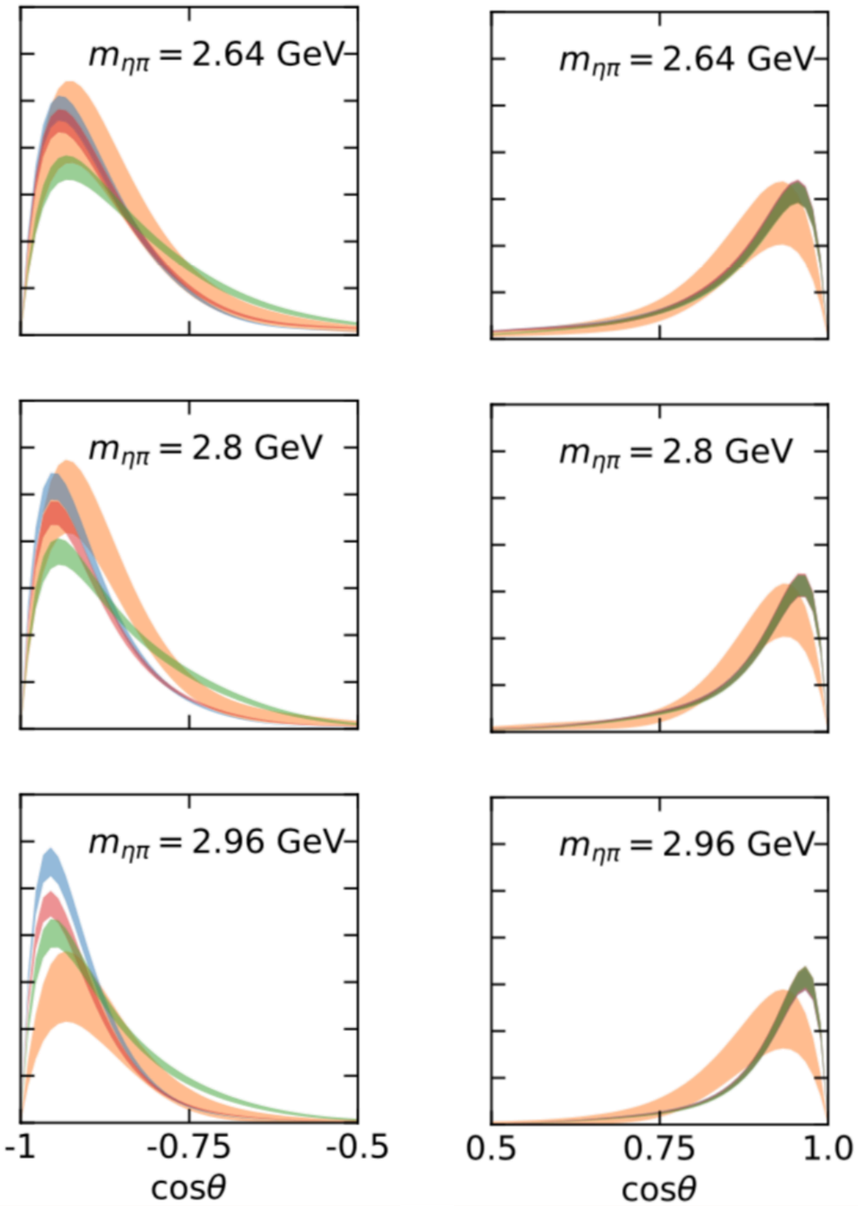
Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and either $(f_2, \mathbb{P})$ or $(\mathbb{P}, \mathbb{P})$

$(a_2, \mathbb{P})$	0.40 ± 0.04
(a_2, f_2)	3.4 ± 0.4
$(f_2, \mathbb{P})$	-0.30 ± 0.05
(f_2, f_2)	-6.6 ± 0.7

Eta-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



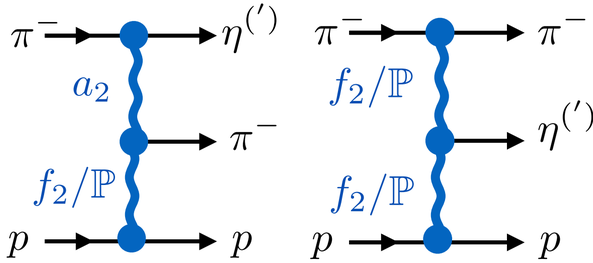
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total



Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and either $(f_2, \mathbb{P})$ or $(\mathbb{P}, \mathbb{P})$

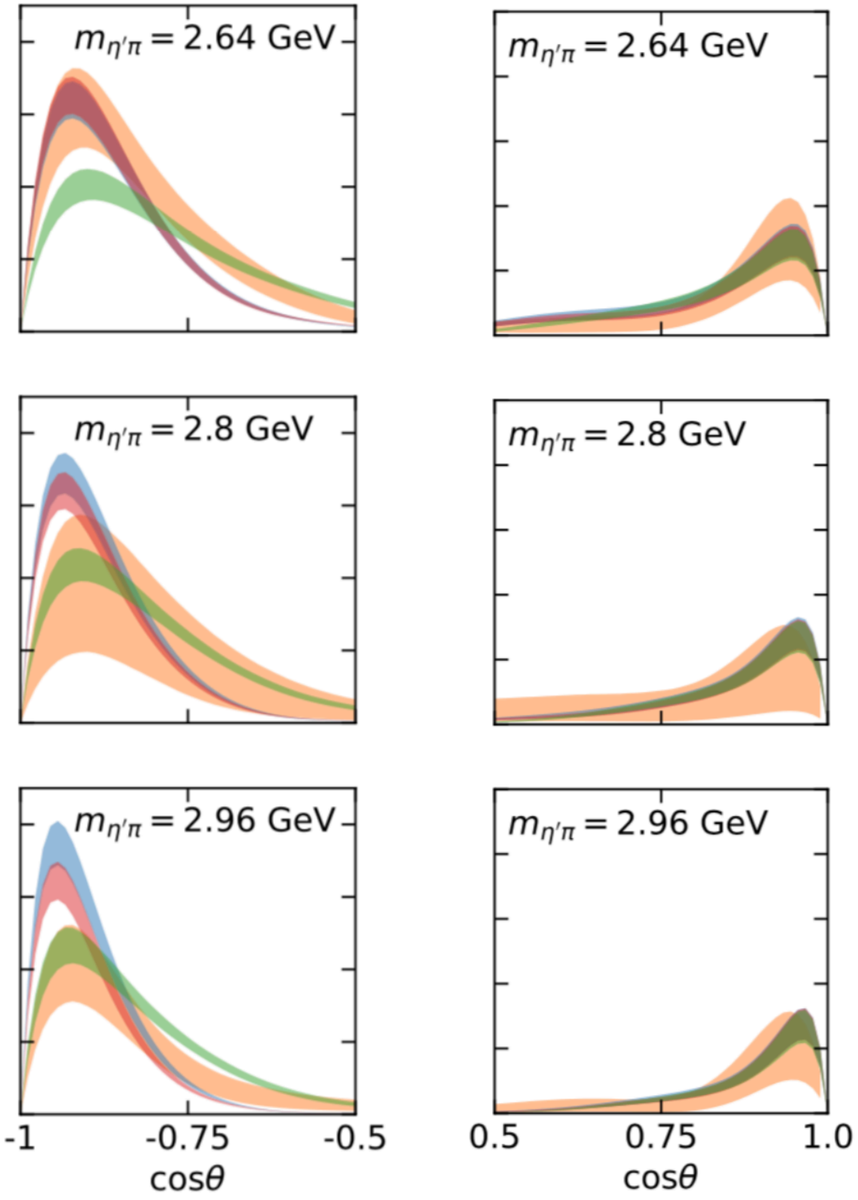
$(a_2, \mathbb{P})$	0.40 ± 0.04
(a_2, f_2)	3.4 ± 0.4
$(f_2, \mathbb{P})$	-0.30 ± 0.05
(f_2, f_2)	-6.6 ± 0.7

Asymmetry coming from difference between

(a_2, f_2) and (f_2, f_2)

Eta'-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



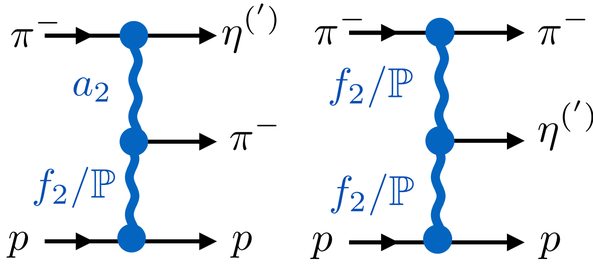
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total

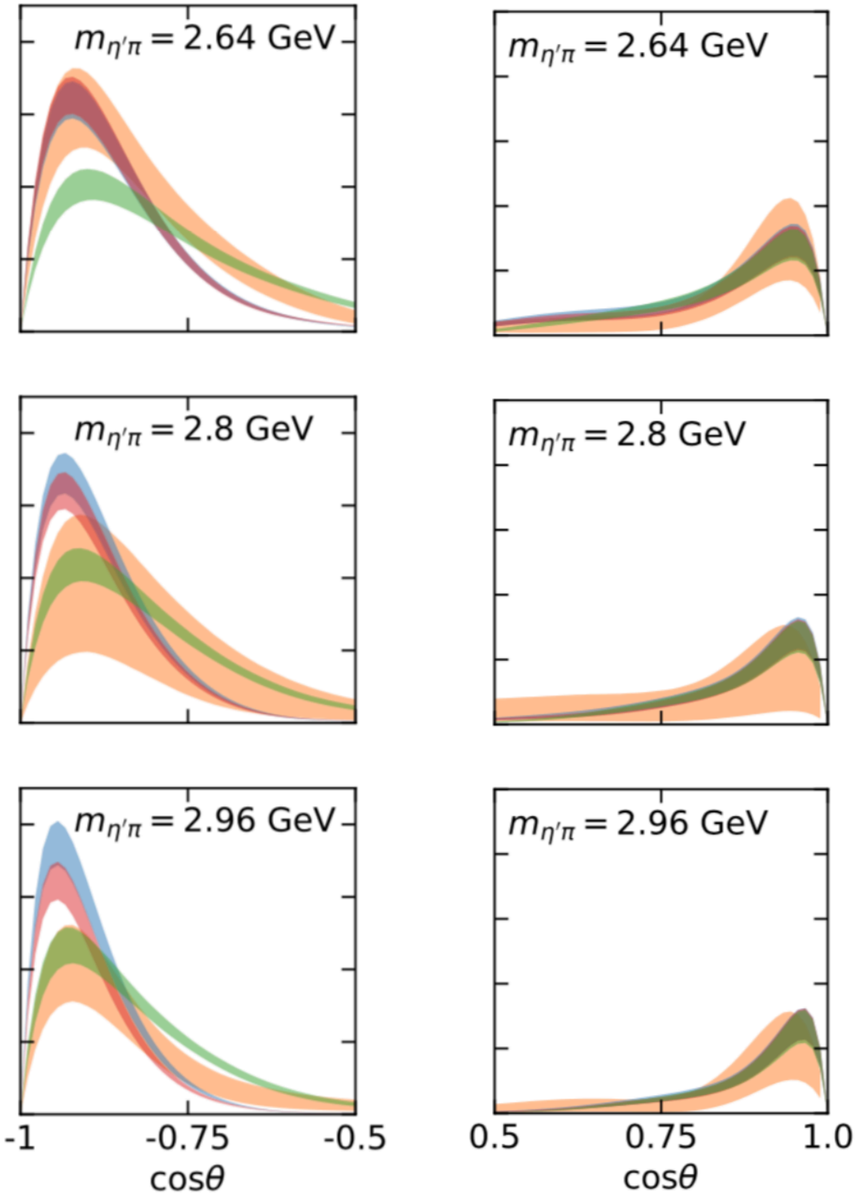


Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and $(\mathbb{P}, \mathbb{P})$

Eta'-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



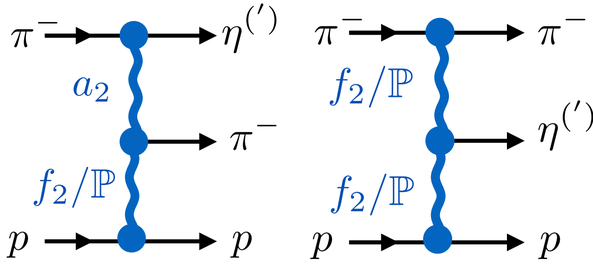
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total



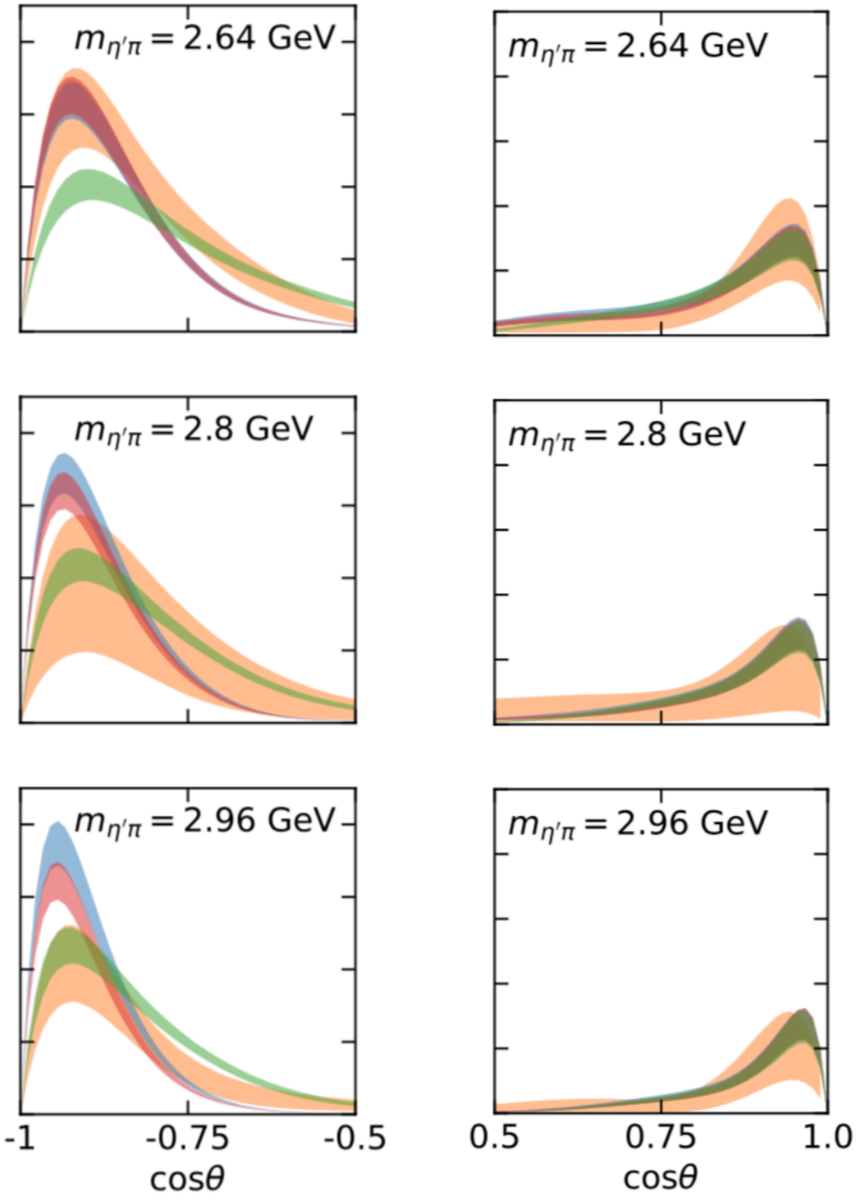
Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and $(\mathbb{P}, \mathbb{P})$

$(a_2, \mathbb{P})$	0.35 ± 0.05
(a_2, f_2)	0.6 ± 0.5
(f_2, f_2)	-7.1 ± 0.6
$(\mathbb{P}, \mathbb{P})$	0.018 ± 0.002

Eta'-Pi results

Bibrzycki et al (JPAC) EPJC81 (2021) 915



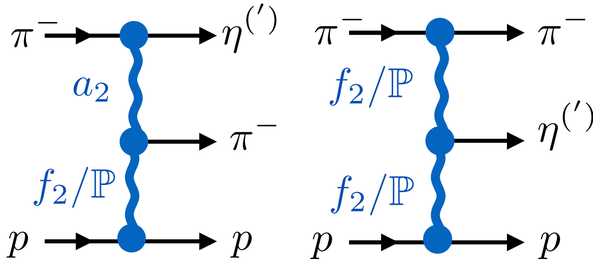
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total



Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and $(\mathbb{P}, \mathbb{P})$

$(a_2, \mathbb{P})$	0.35 ± 0.05
(a_2, f_2)	0.6 ± 0.5
(f_2, f_2)	-7.1 ± 0.6
$(\mathbb{P}, \mathbb{P})$	0.018 ± 0.002

Asymmetry coming from difference between

(a_2, f_2) and (f_2, f_2)

+ contribution from $(\mathbb{P}, \mathbb{P})$

Forward-Backward Asymmetry

Bibrzycki et al (JPAC) EPJC81 (2021) 915

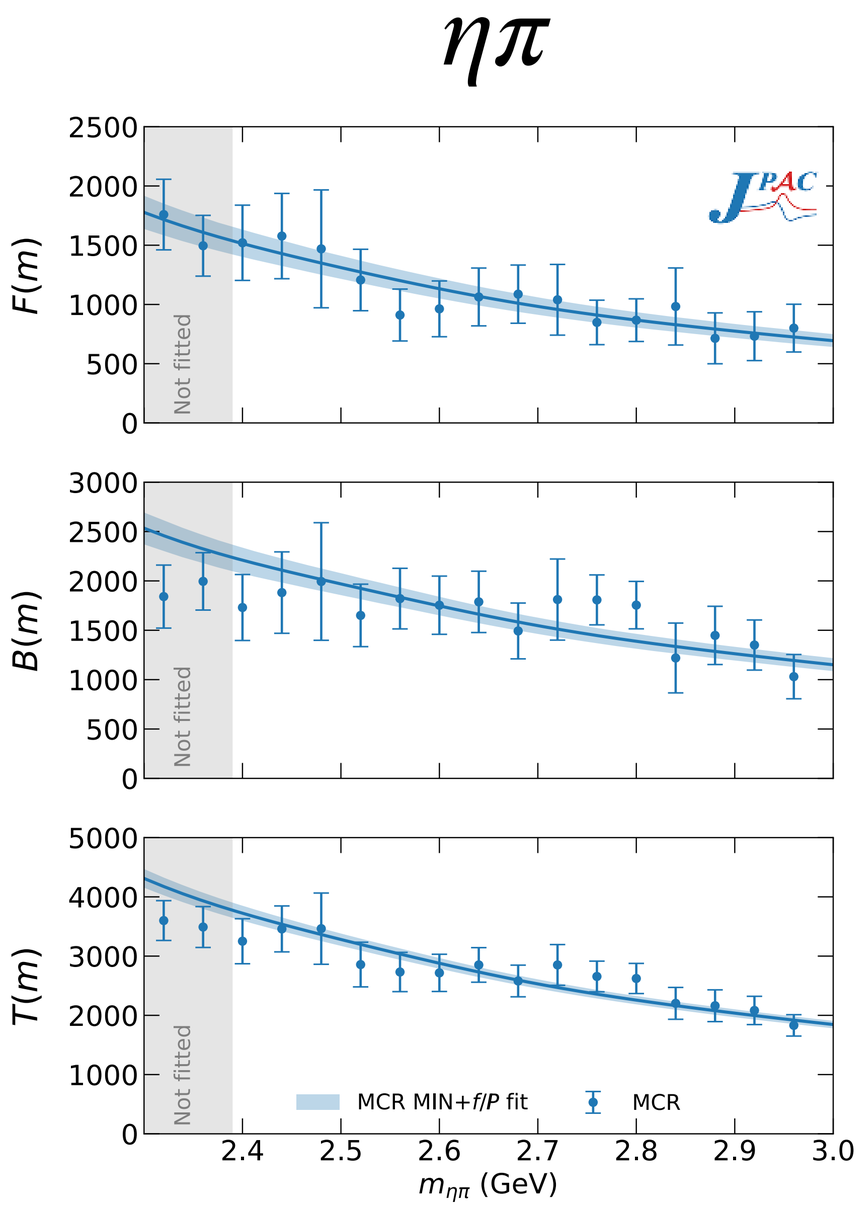
Forward intensity

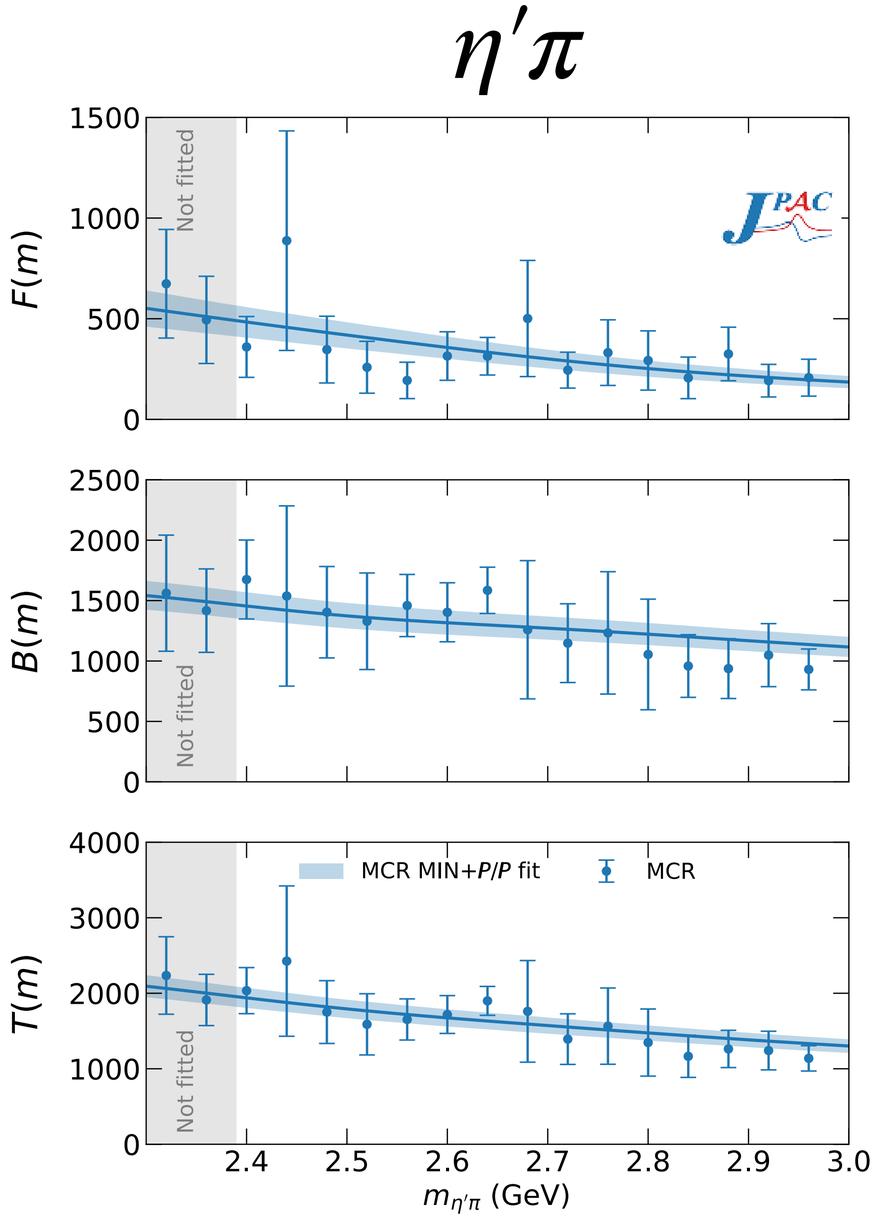
$\cos\theta \geq 0$

Backward intensity

$\cos\theta \leq 0$

Total intensity



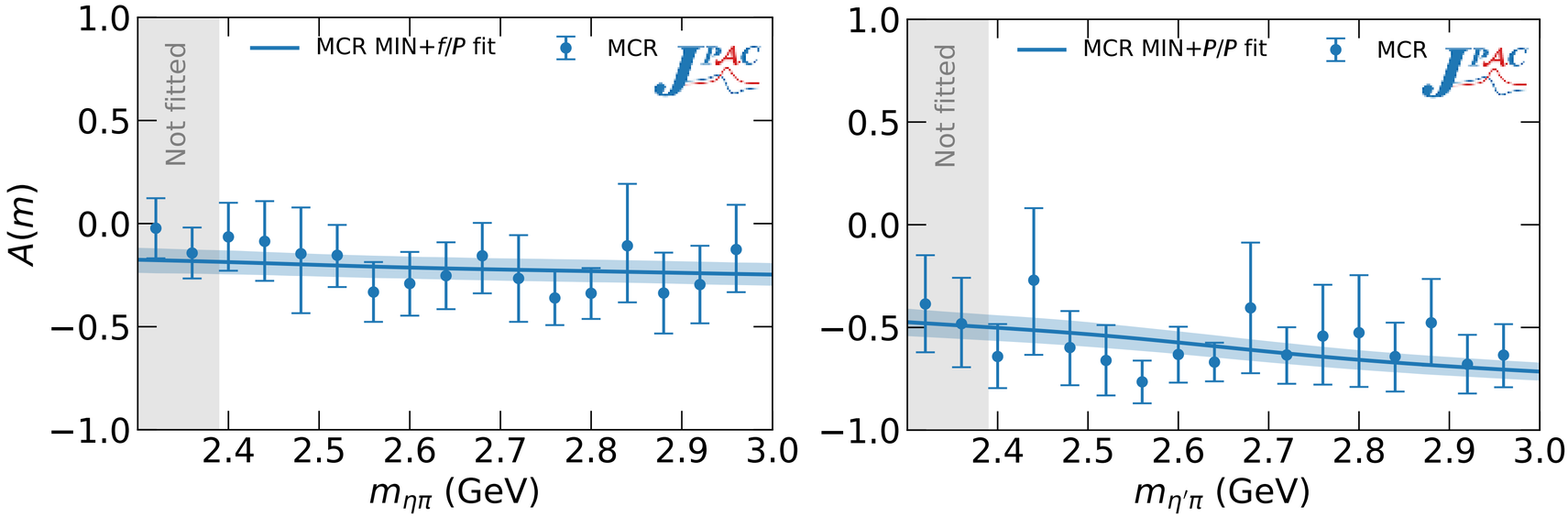


Forward-Backward Asymmetry

Fernández-Ramírez et al arXiv:2104.10646

$$A = \frac{\text{Forward} - \text{Backward}}{\text{Forward} + \text{Backward}}$$

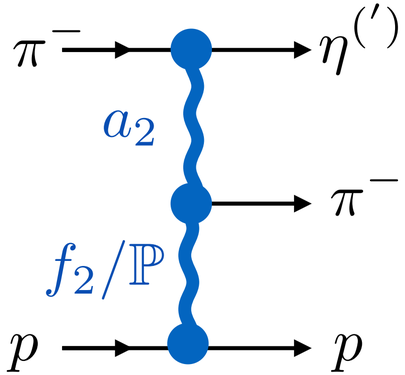
$\eta\pi$ $\qquad$ $\eta'\pi$

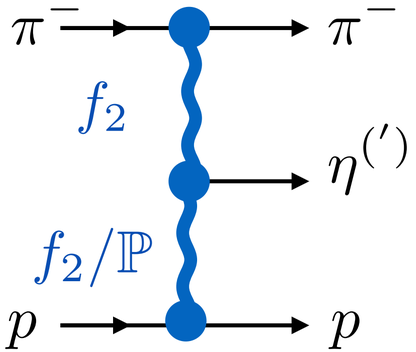


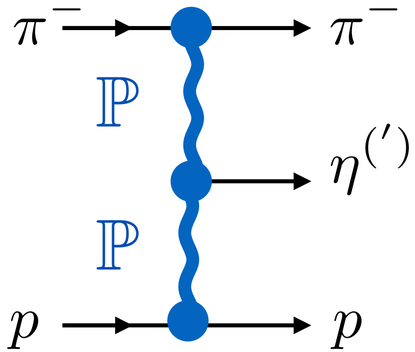
Asymmetry originating mainly

from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$

and from $(\mathbb{P}, \mathbb{P})$ in $\eta'\pi$

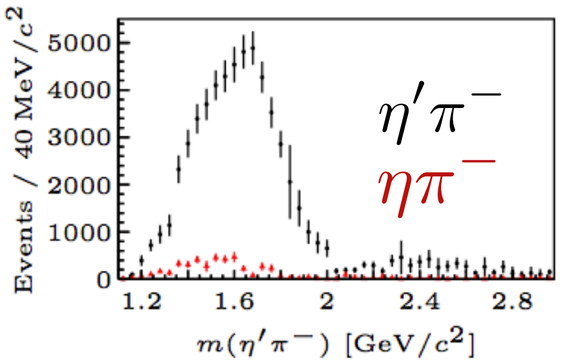


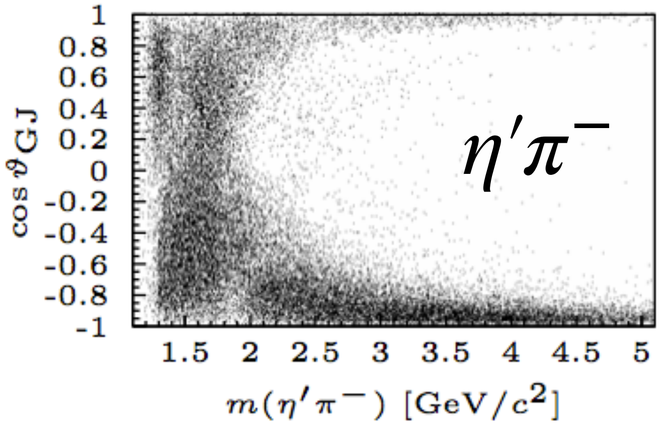


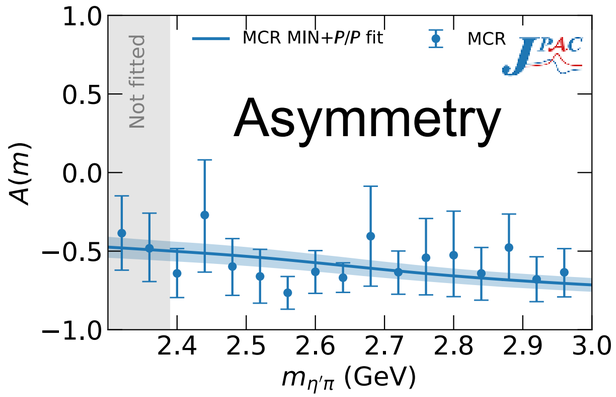


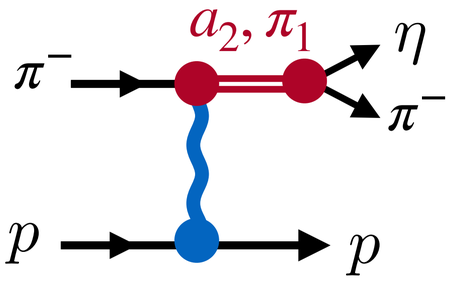
Future Works

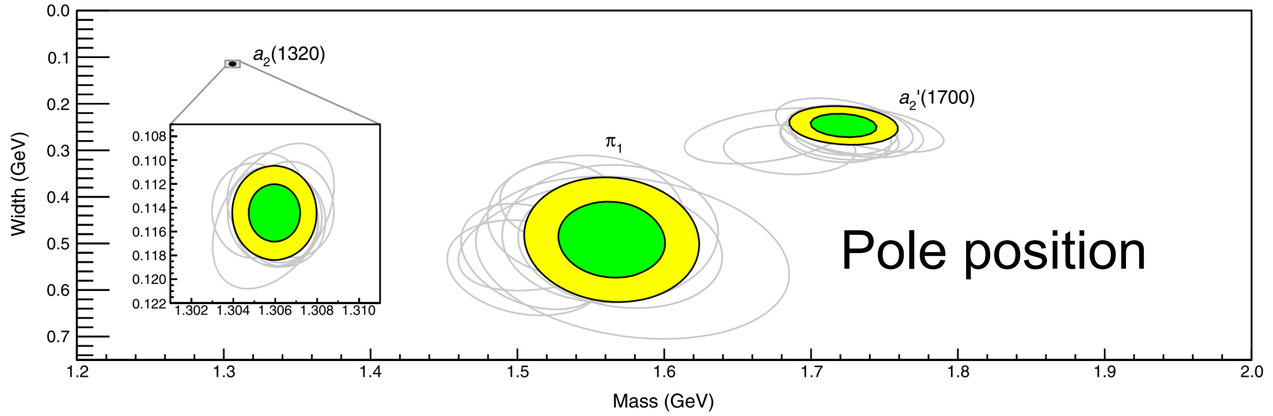
COMPASS PLB740 (2015)







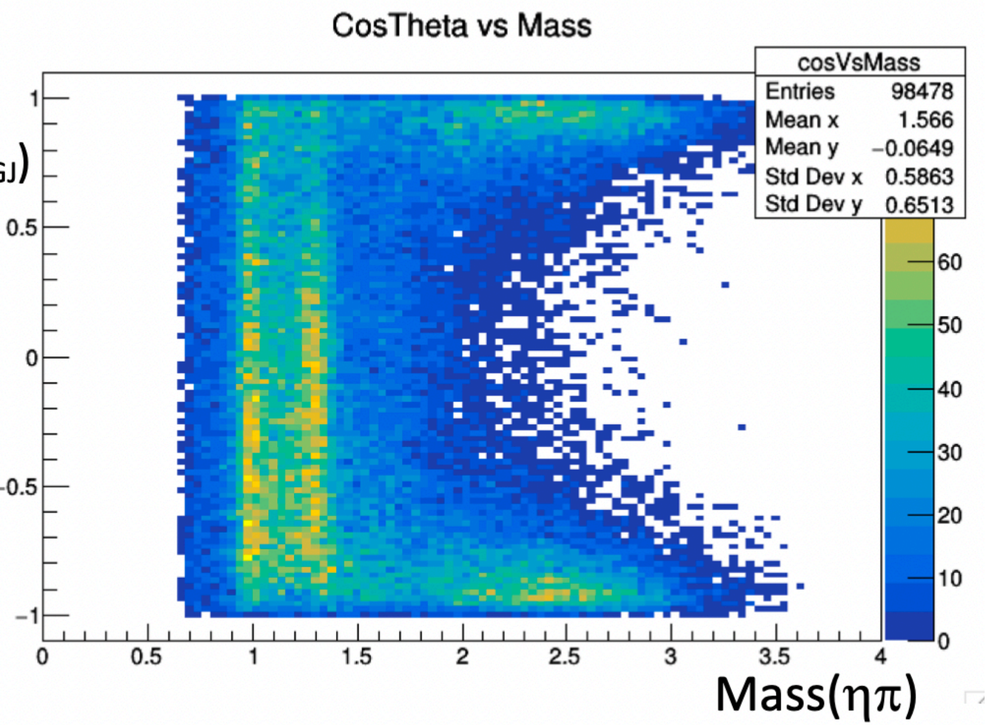




Impose dispersion relations between resonance region and double diffractive region

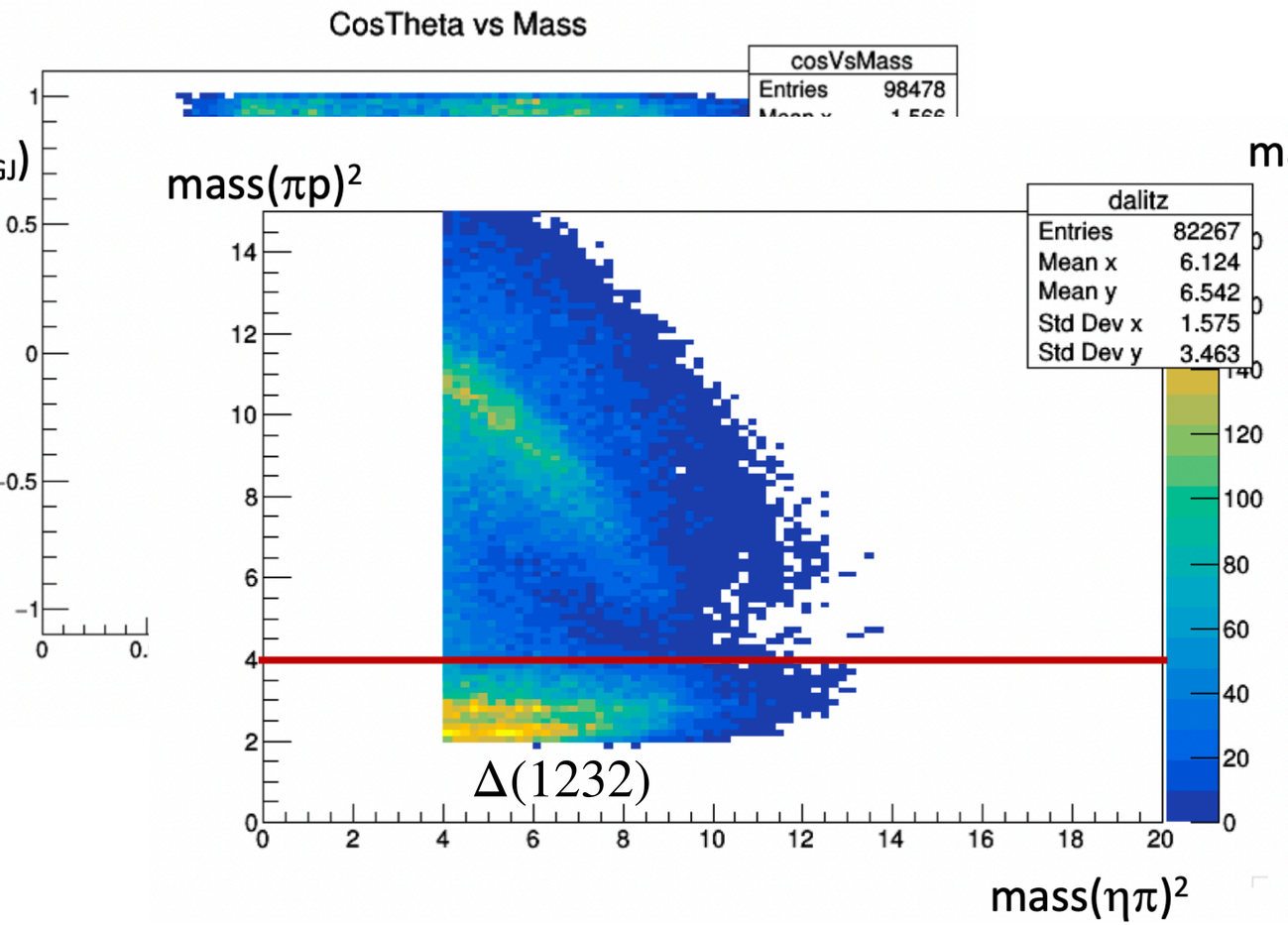
$\eta\pi^0$ Photoproduction@GlueX

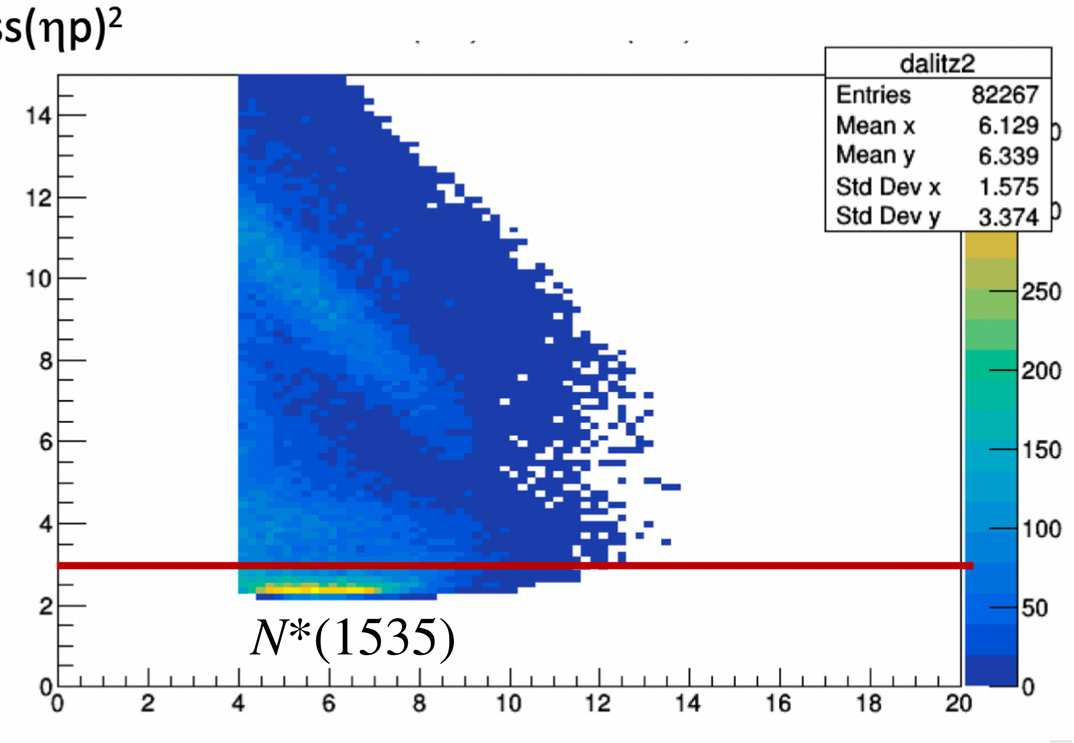
In collaboration with R. Barsotti



$\eta\pi^0$ Photoproduction@GlueX

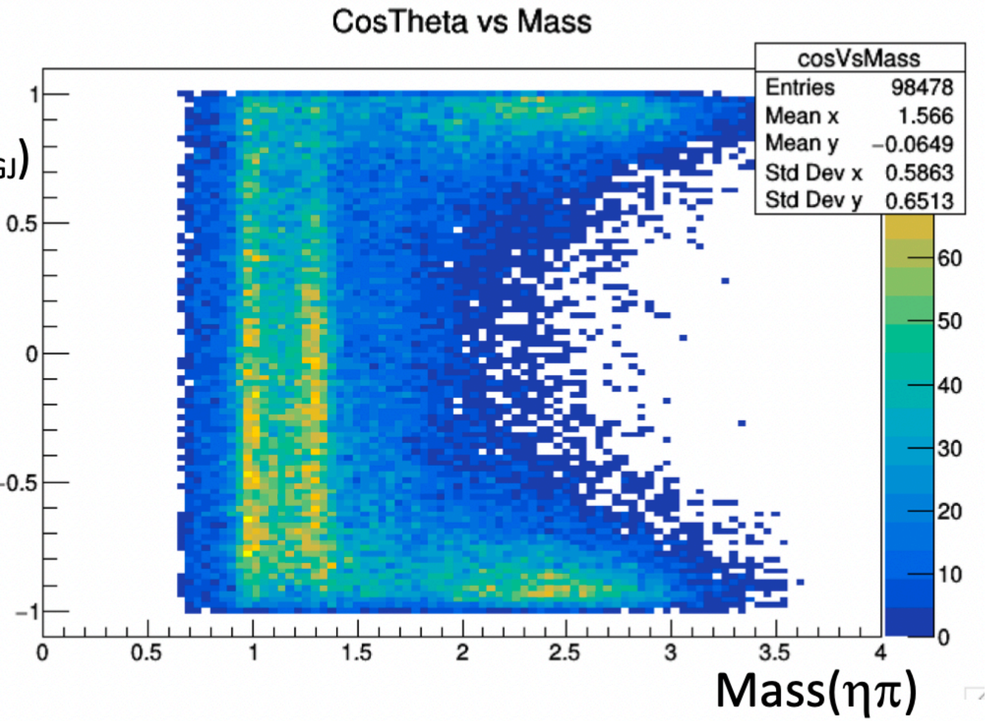
In collaboration with R. Barsotti

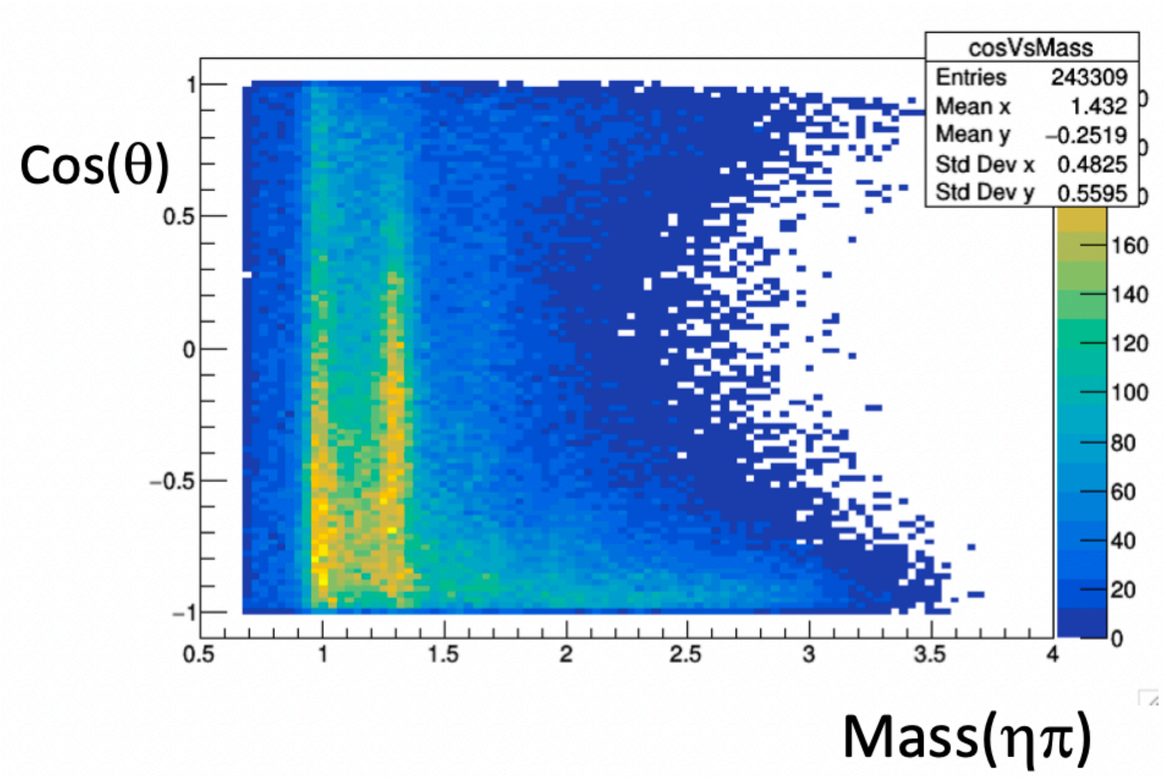




$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



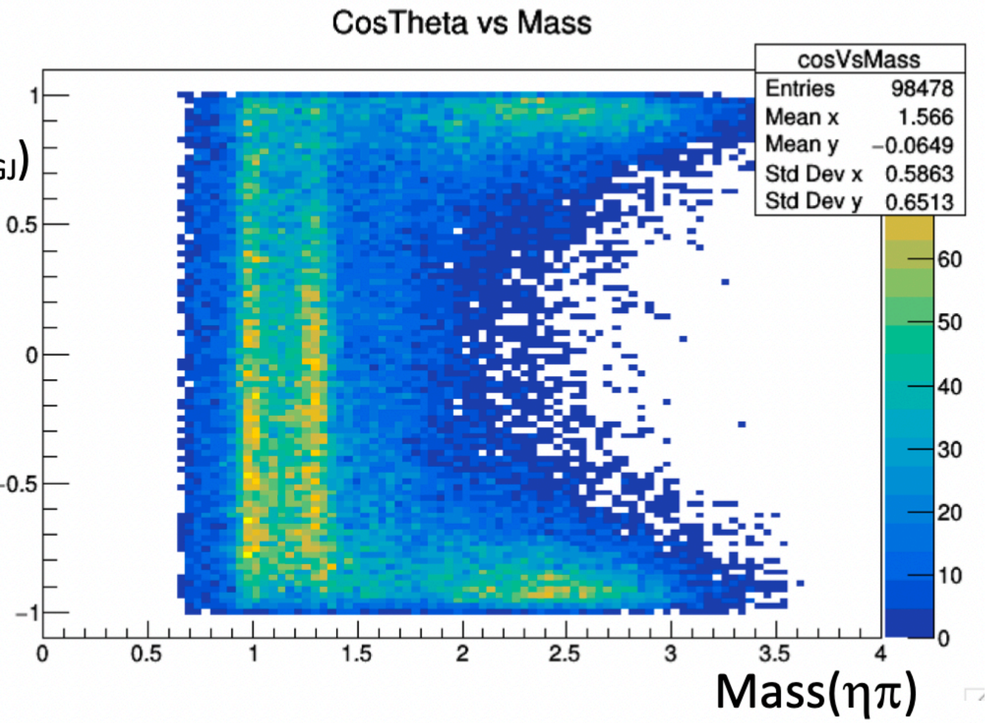


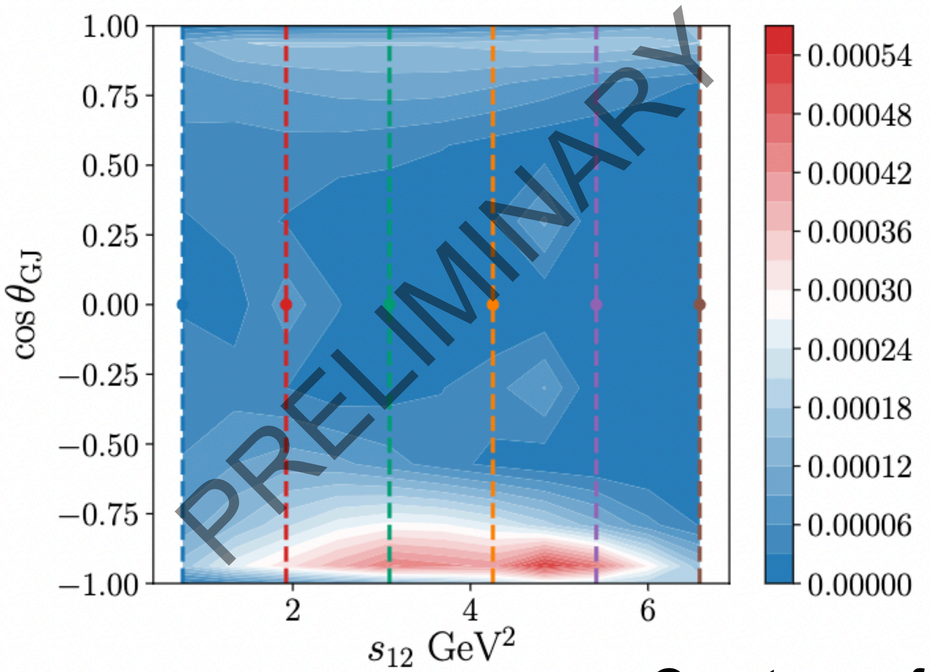
Baryon resonances contaminate the high mass $\eta\pi$

Less baryon contamination when the energy increases

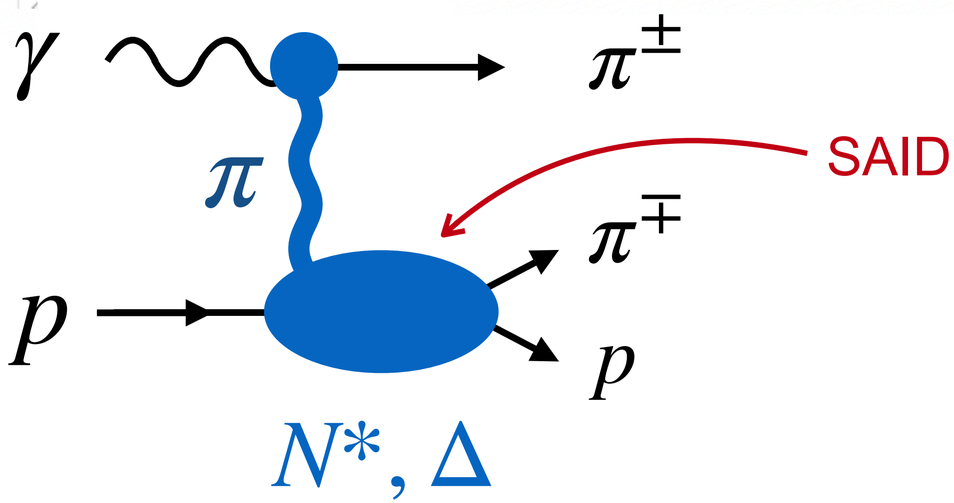
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti





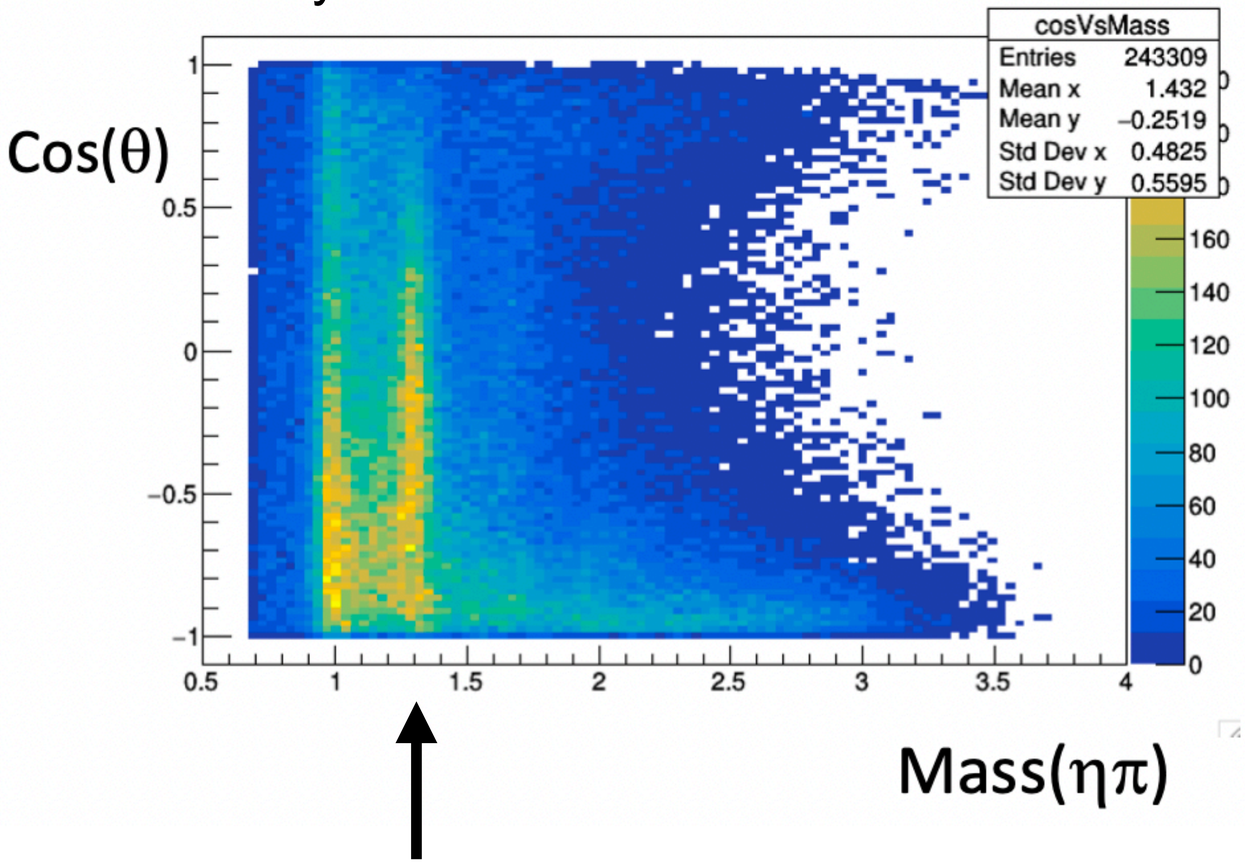
Courtesy of R. Perry



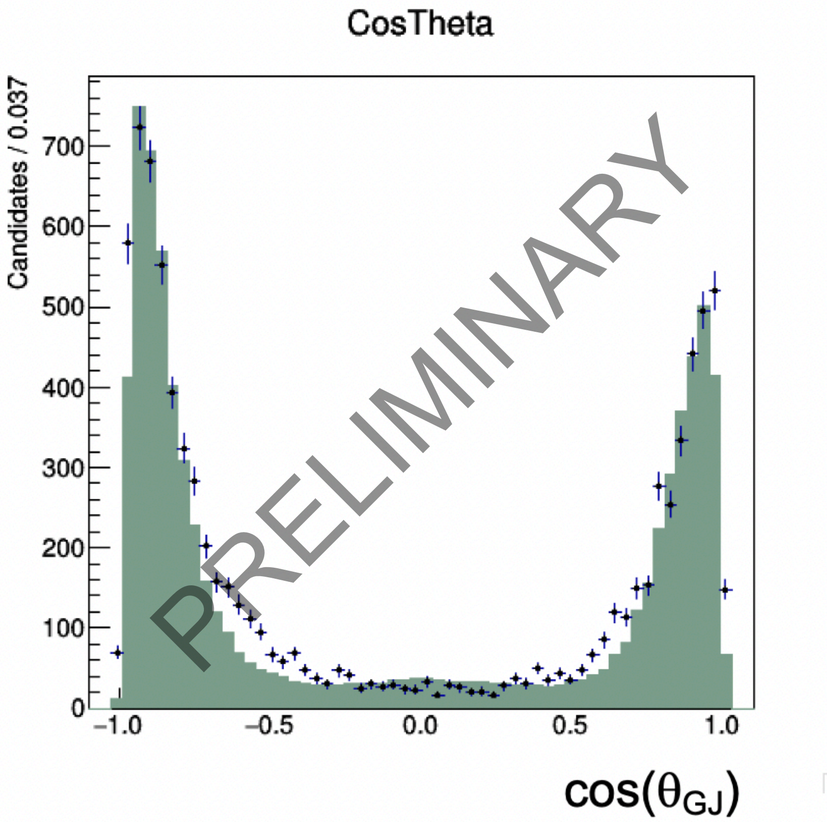
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti

Baryons have been ‘cut out’



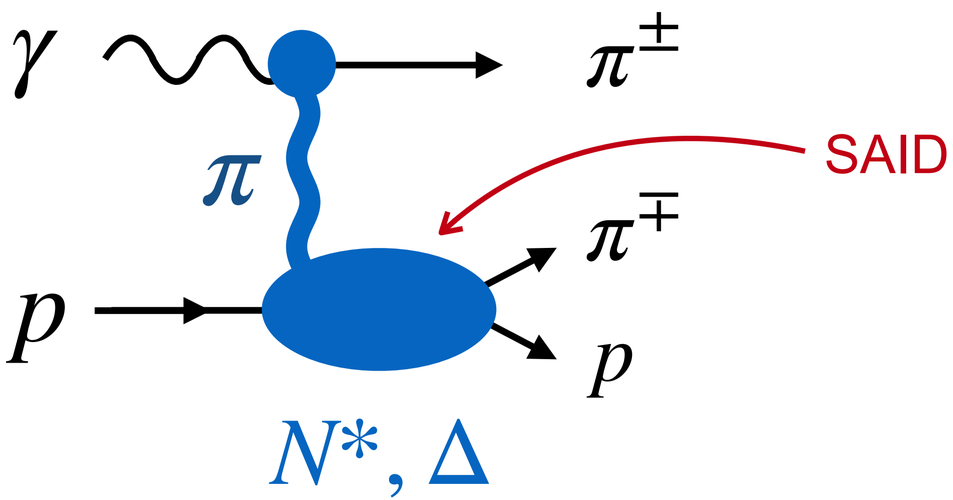
$a_2(1320)$

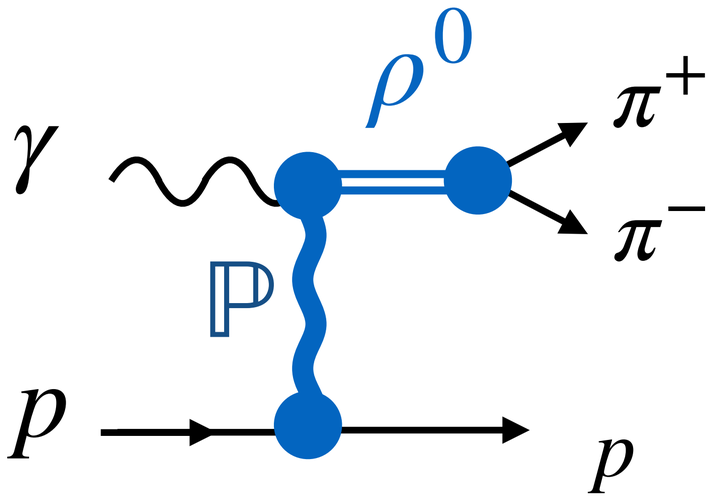


Double regge with Uniform background

(Deck + ρ) model for $\pi\pi$

CLAS PRD80 (2009)

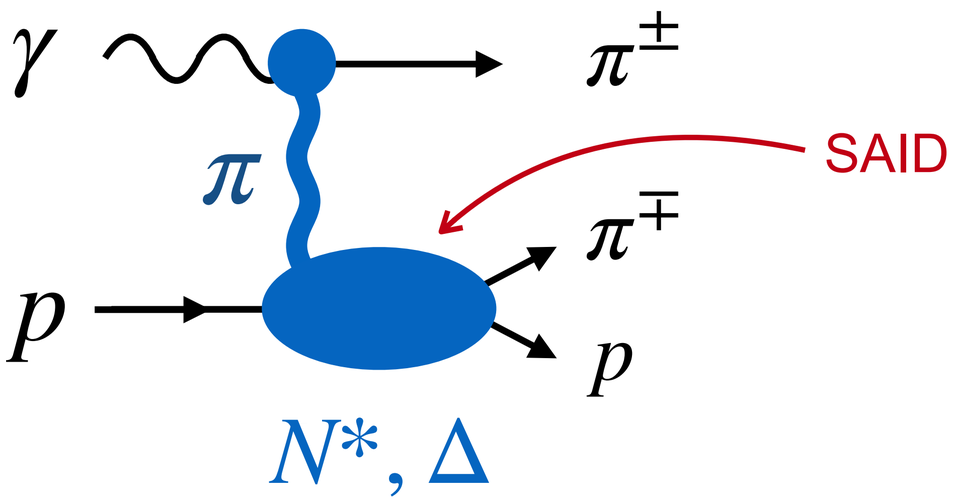


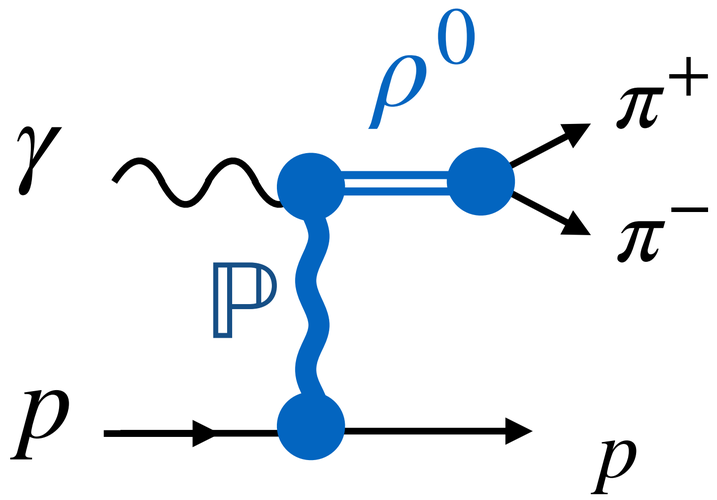


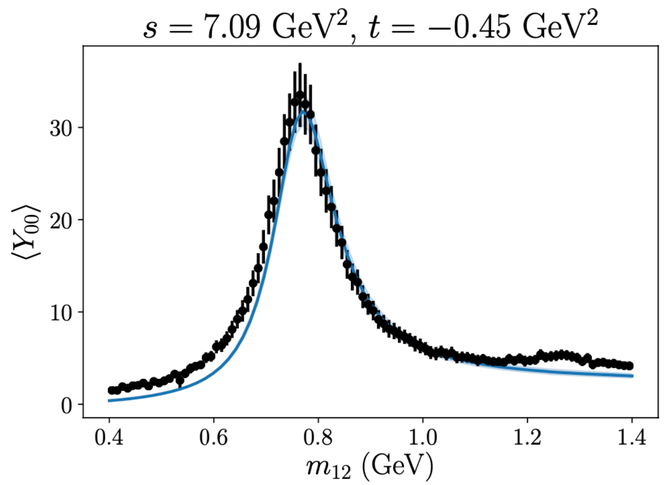
R. Perry et al (JPAC) in preparation

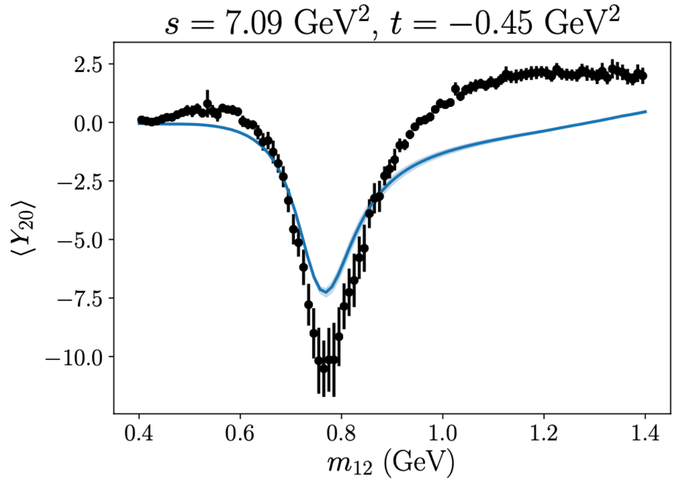
(Deck + ρ) model for $\pi\pi$

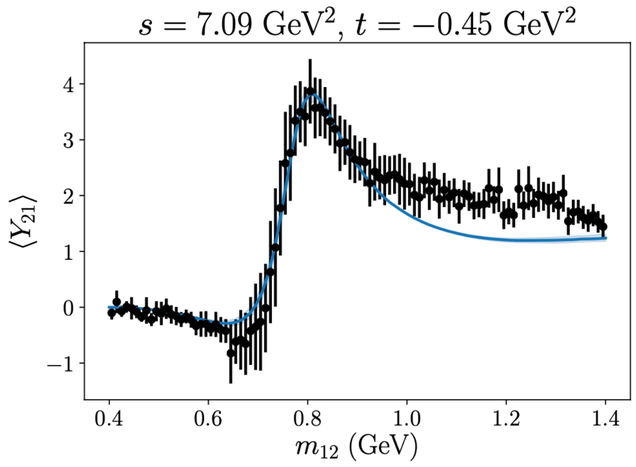
CLAS PRD80 (2009)

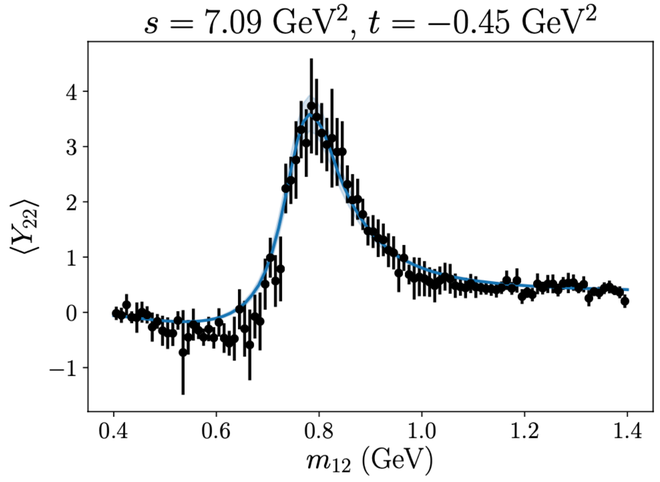








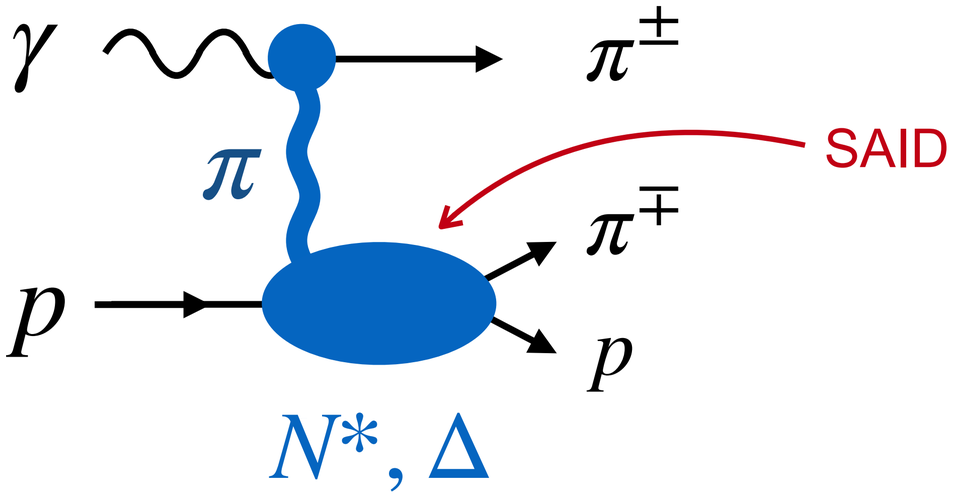


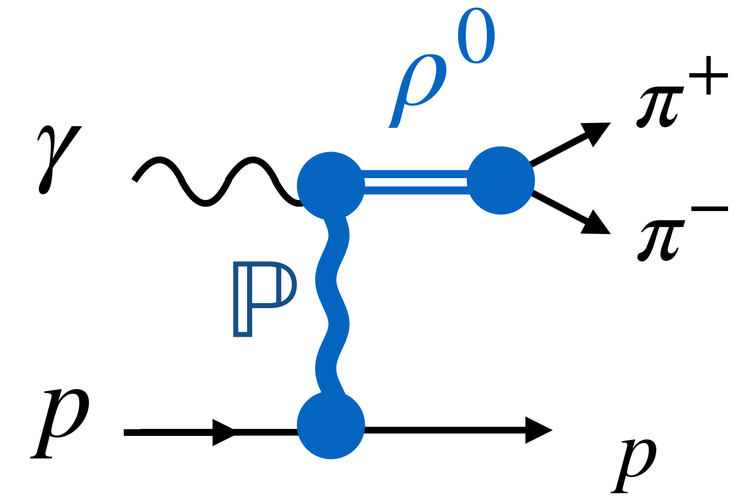


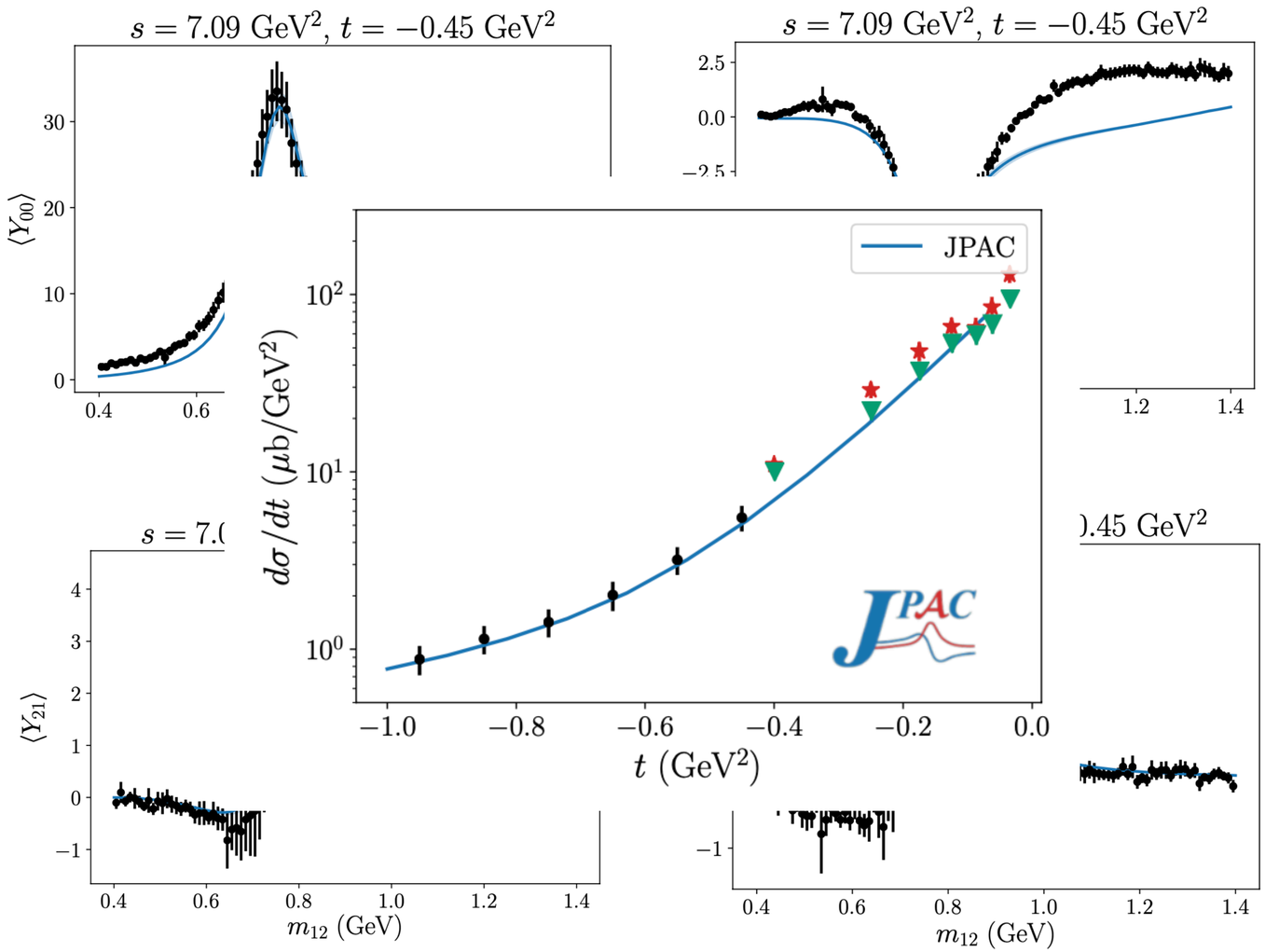
R. Perry et al (JPAC) in preparation

(Deck + ρ) model for $\pi\pi$

CLAS PRD80 (2009)





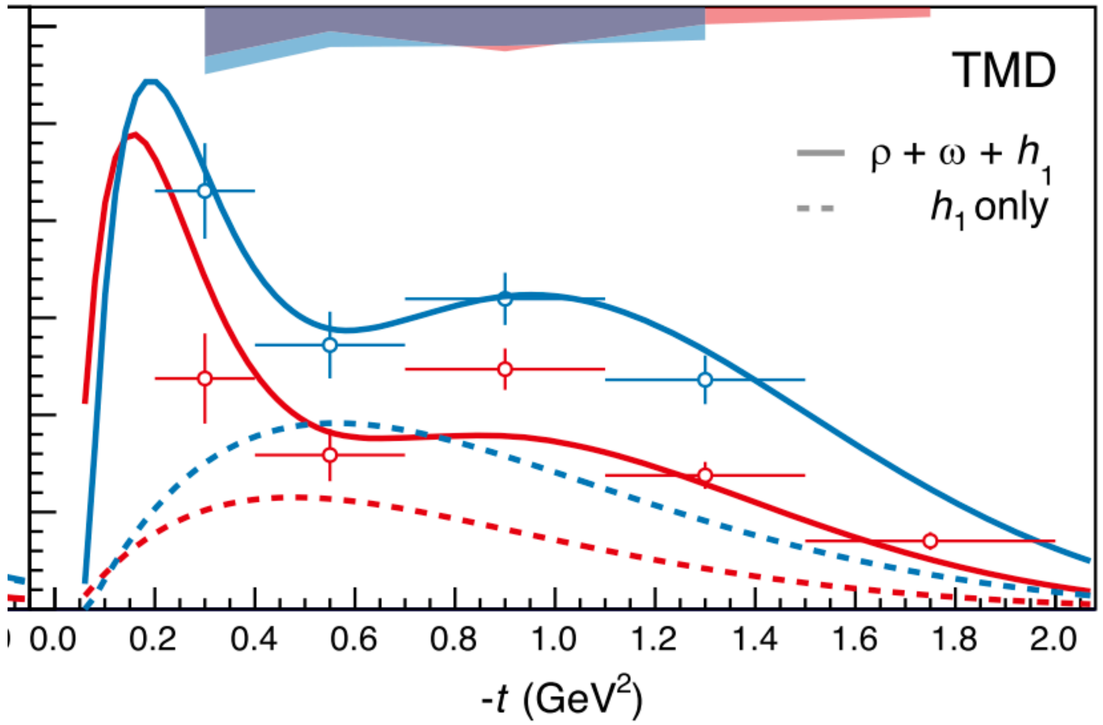


R. Perry et al (JPAC) in preparation

Tensor Meson Photoproduction @CLAS

VM et al (JPAC) PRD102 (2020)

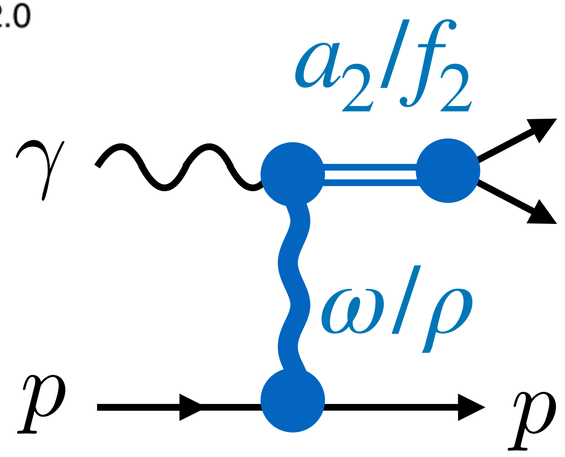
CLAS PRC 102 (2020)



CLAS PRL126 (2021)

$$\gamma p \to a_2(1320) p :$$

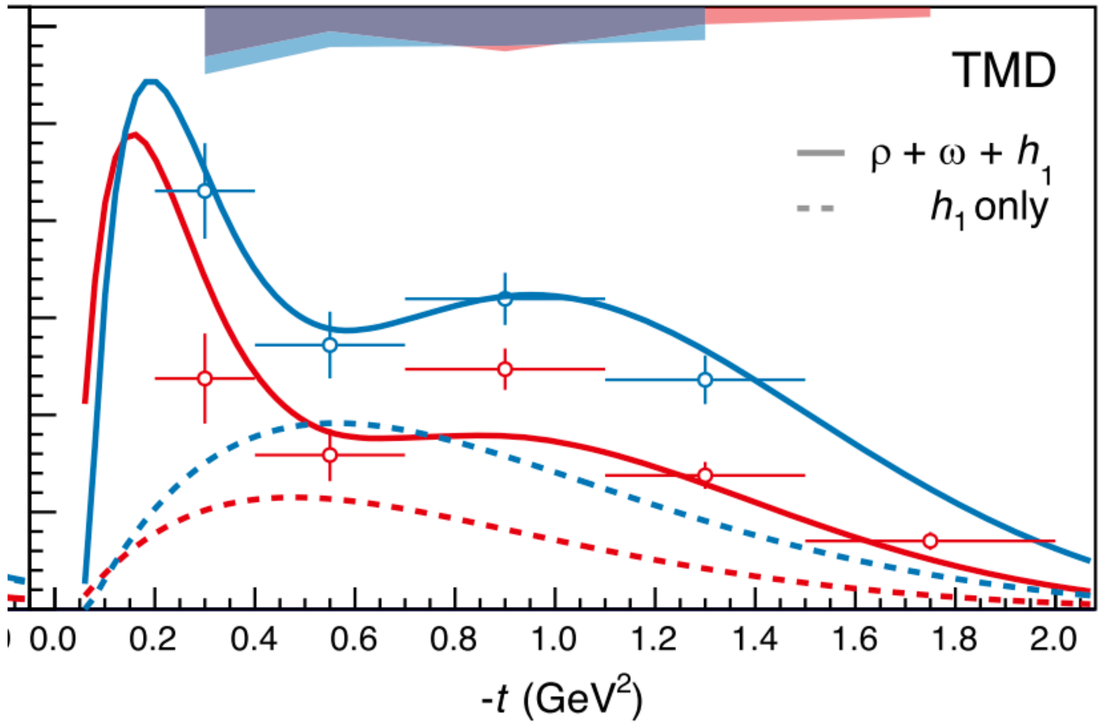
$$\omega + \frac{1}{3}\rho$$



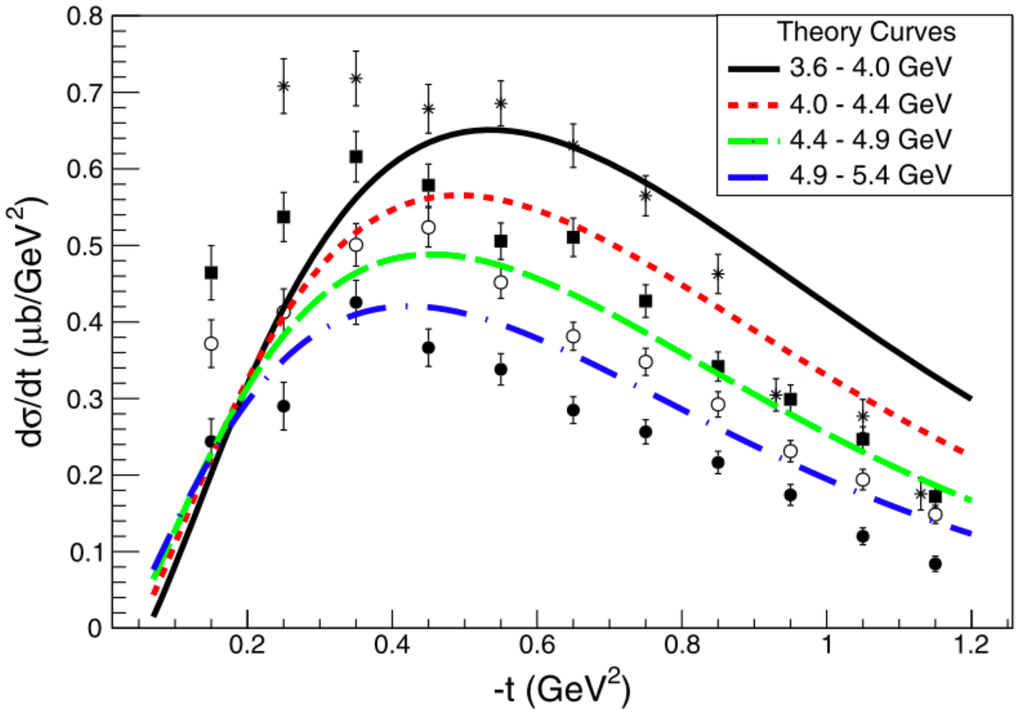
Tensor Meson Photoproduction @CLAS

VM et al (JPAC) PRD102 (2020)

CLAS PRC 102 (2020)

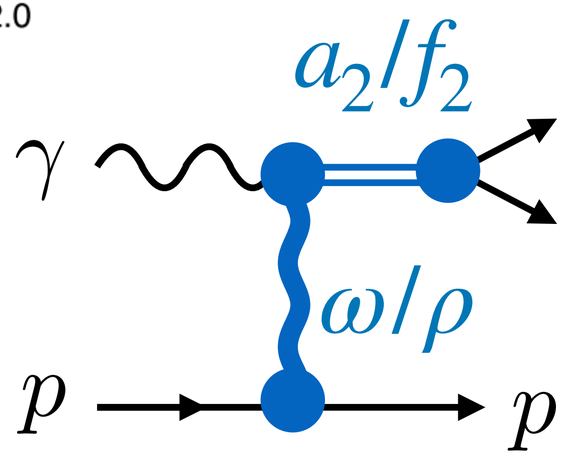


CLAS PRL126 (2021)



$$\gamma p \to a_2(1320)p:$$

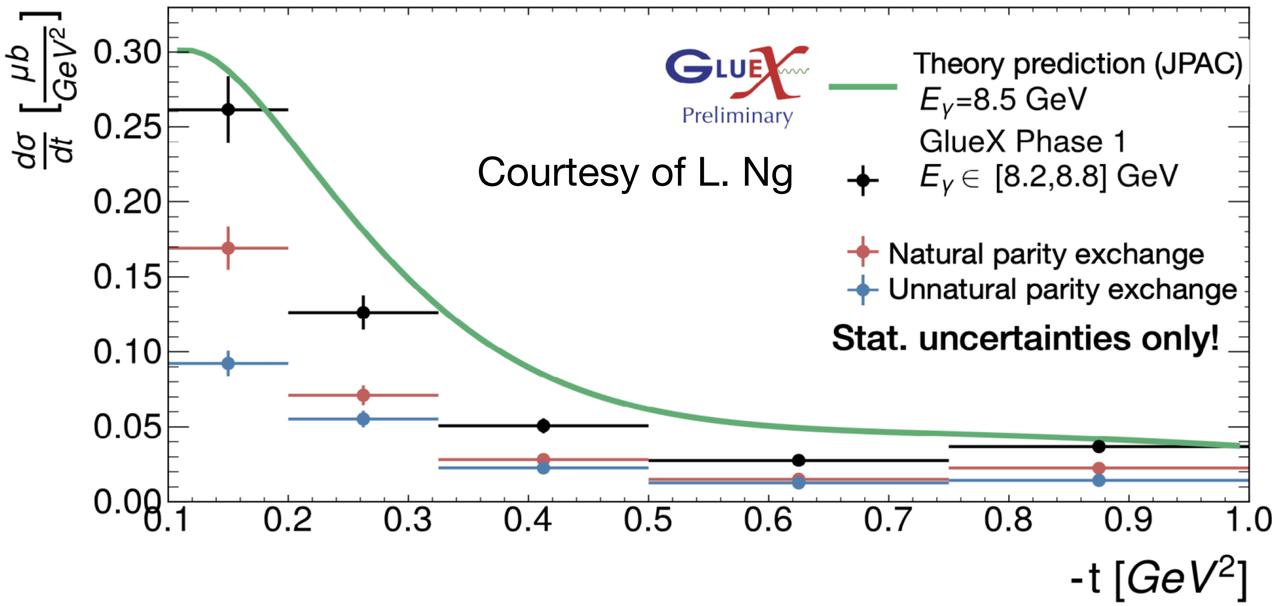
$$\omega + \frac{1}{3}\rho$$

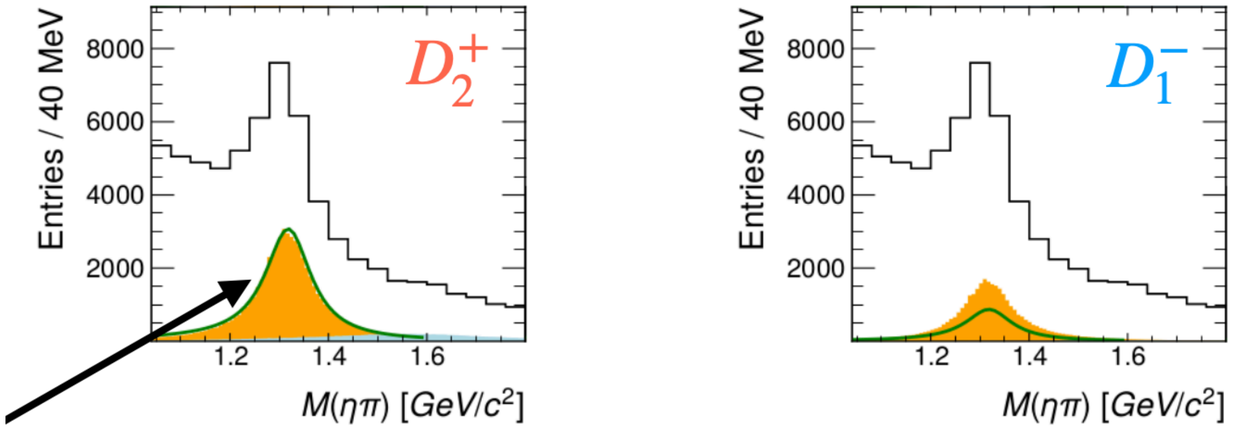


$$\gamma p \to f_2(1270)p:$$

$$\rho + \frac{1}{3}\omega$$

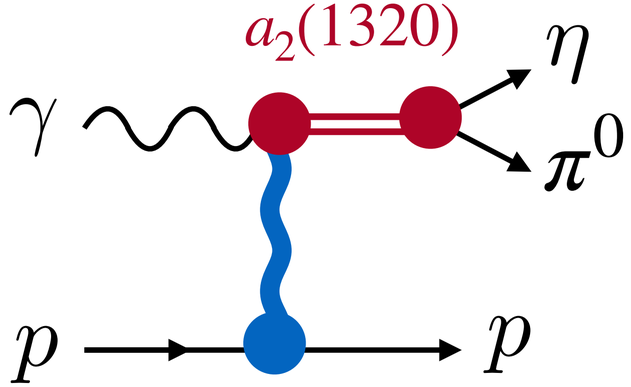
$a_2(1320)$ Photoproduction @GlueX





JPAC model for tensor photoproduction

Strong $a_2(1320)$ signal in $\pi\eta$



Extraction of the cross-section

Extraction of all D-waves components

Strong2020 School in Salamanca

https://diarium.usal.es/strong2020/

September 5th - 14th 2023

Analysis tools for hadron physics (VM, M. Albaladejo)

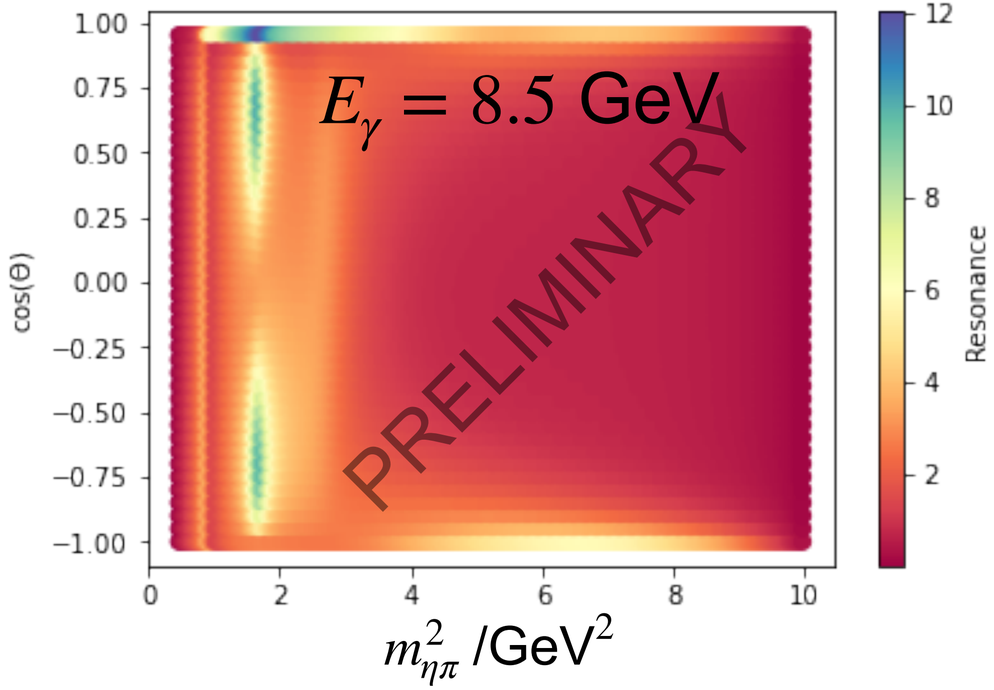
Experimental Methods in Hadron Spectroscopy (A. D'angelo, D. Glazier, L. Lanza, N. Zachariou)

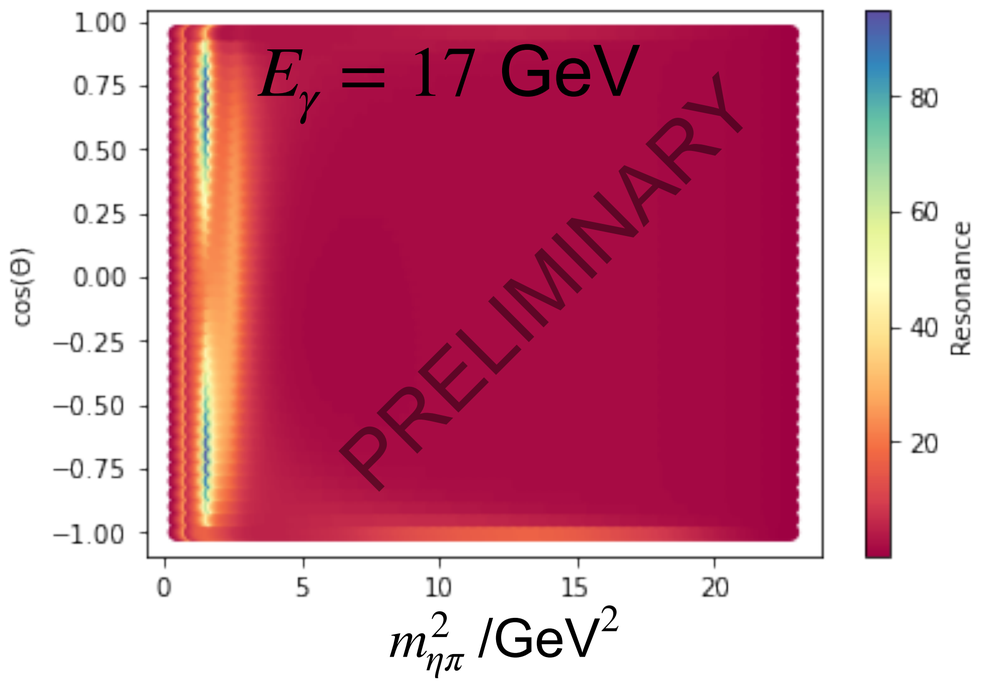
Effective Field Theories of QCD (A. Vairo, J. Ghiglieri)

Backup Slides

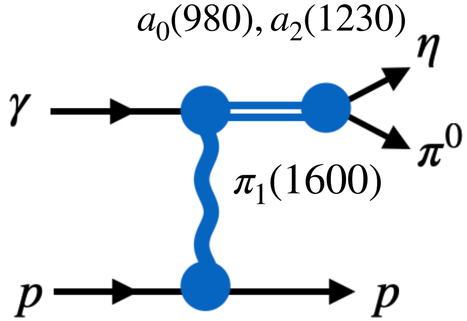
$\eta\pi^0$ Photoproduction@GlueX

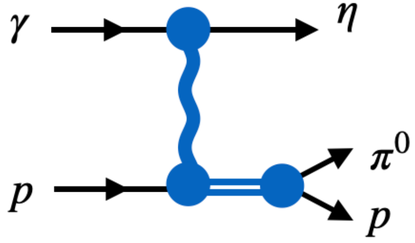
In collaboration with E. Llanos



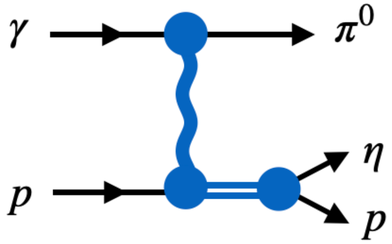


Simple model (all external particles = scalar) including:

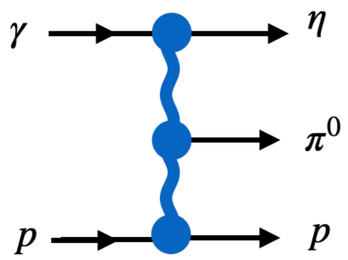


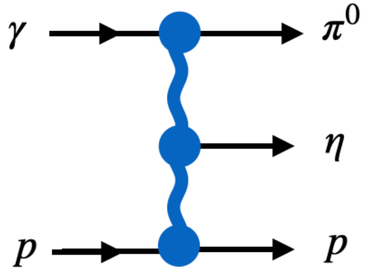


$\Delta(1232)$



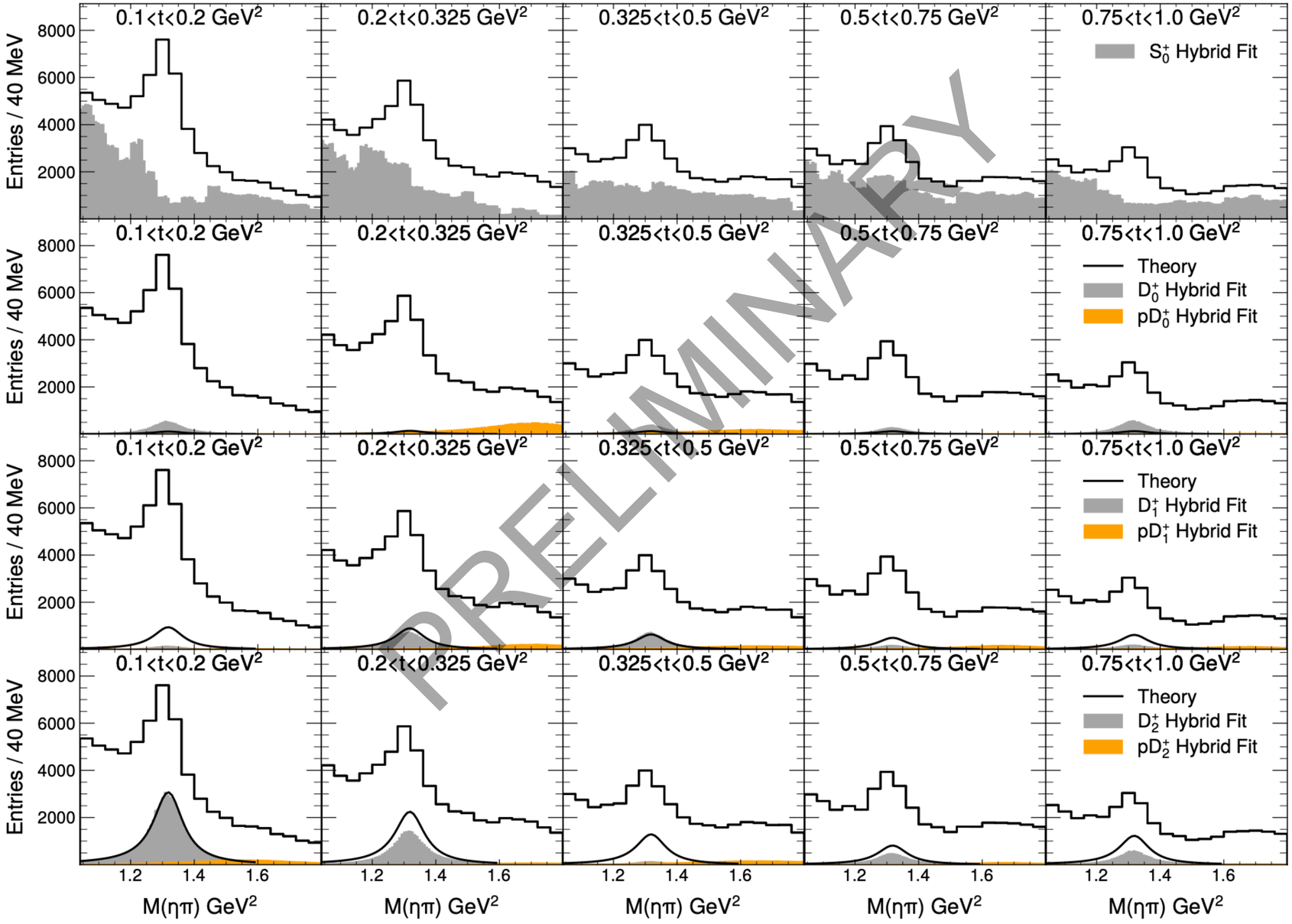
$N^*(1535)$





$a_2(1320)$ Photoproduction @GlueX

In collaboration with L. Ng and M. Albrecht



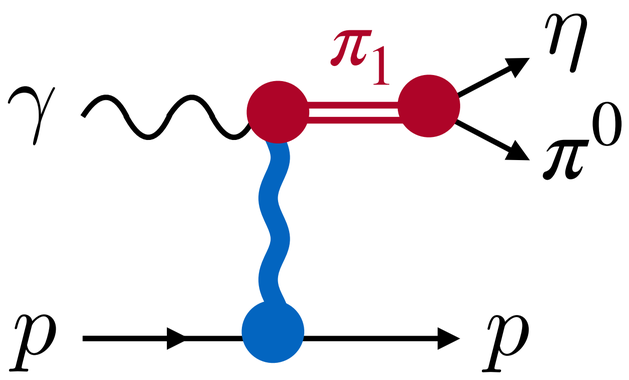
Extraction of $a_2(1320)$ production amplitudes from GlueX data

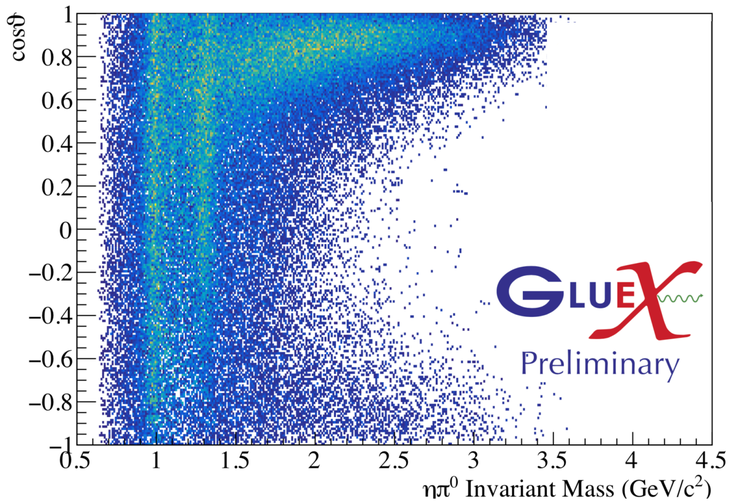
Reasonable agreement with model predictions from

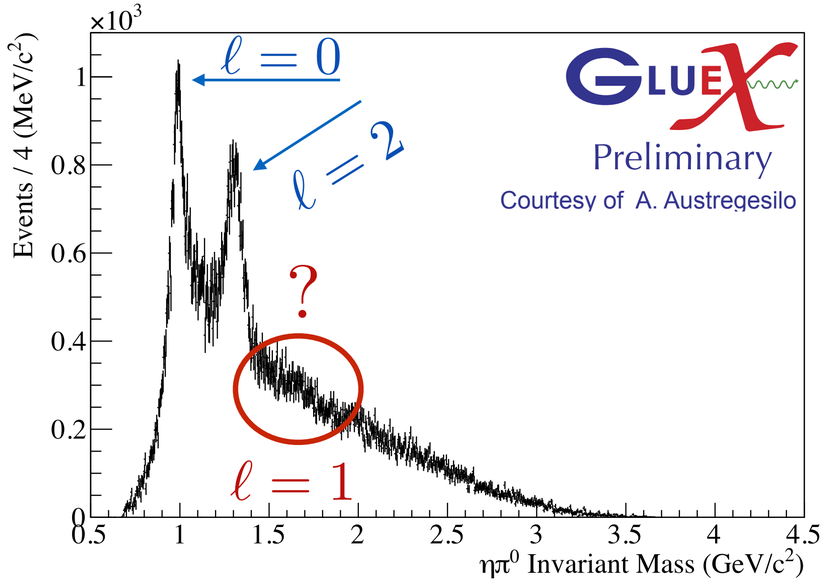
VM et al (JPAC) PRD102 (2020)

Ongoing extraction of $a_2(1320)$ cross-section

Hybrid Mesons @GlueX and @COMPASS

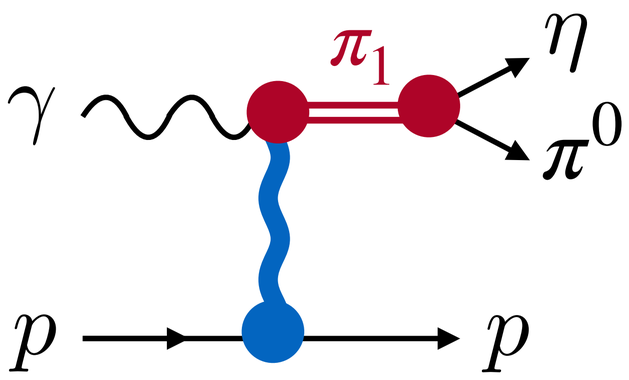


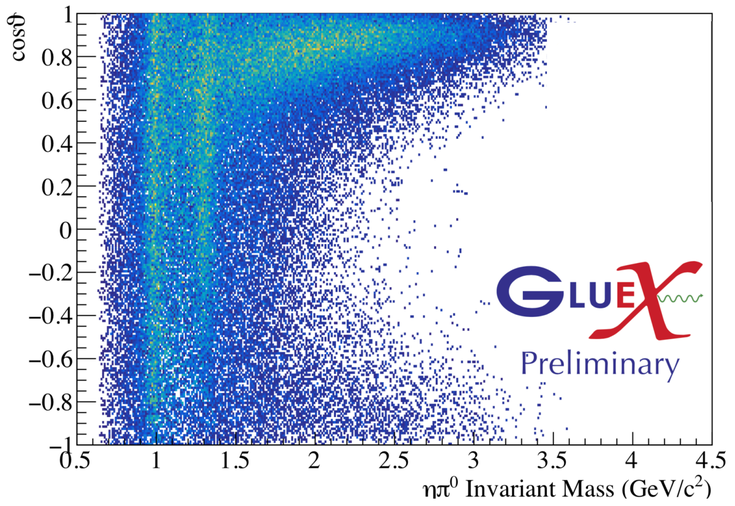


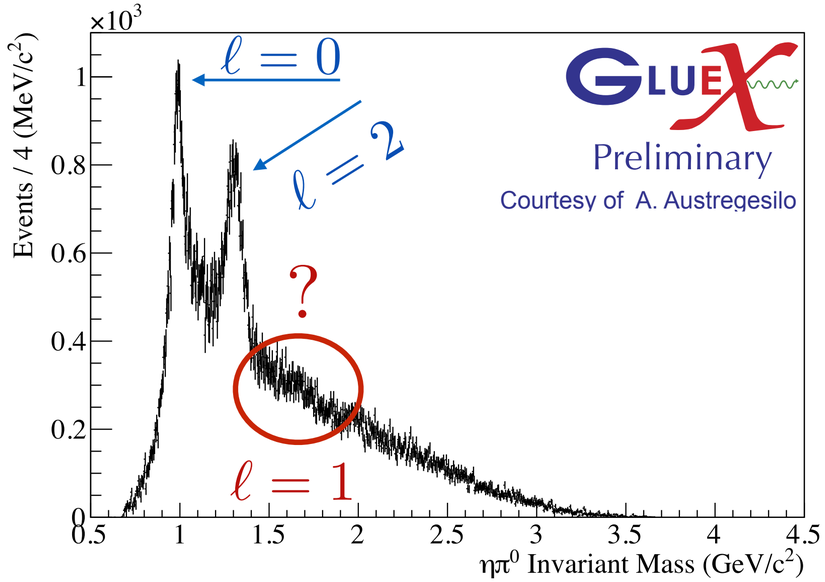


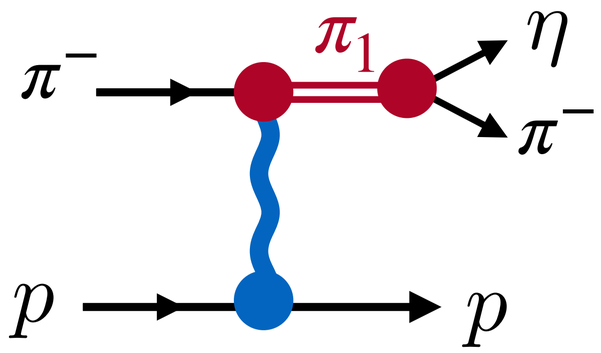
COMPASS PLB740 (2015)

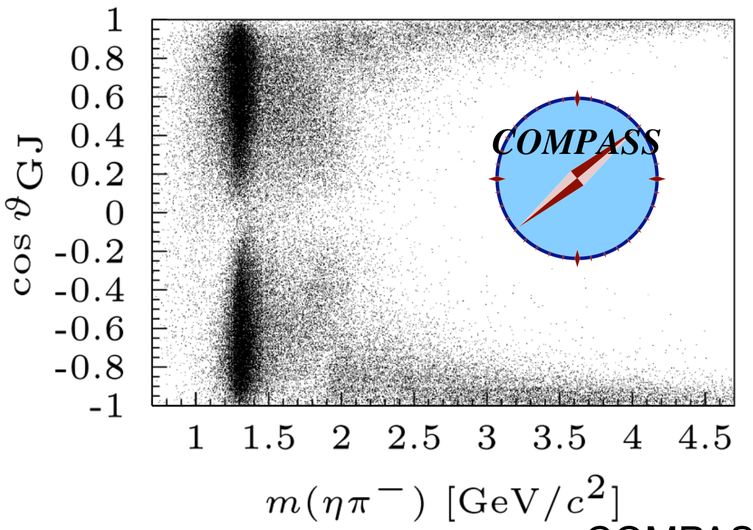
Hybrid Mesons @GlueX and @COMPASS

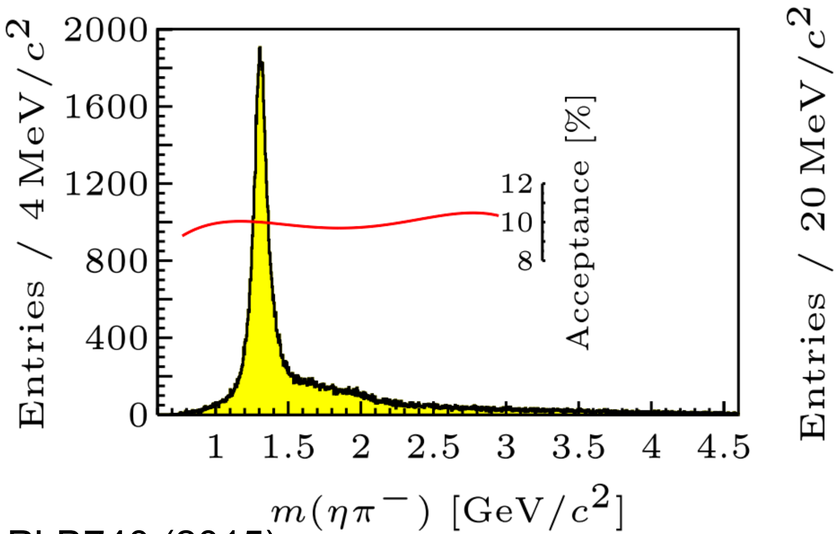








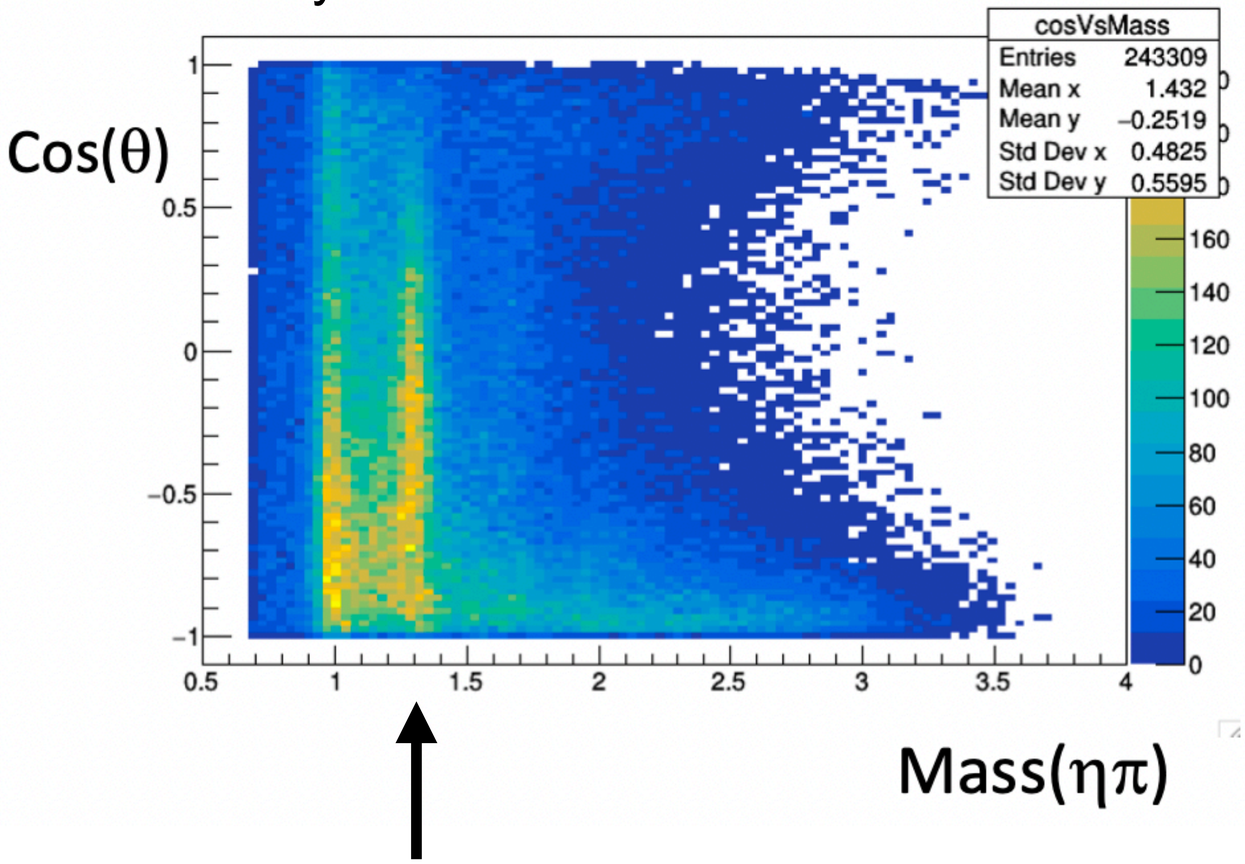




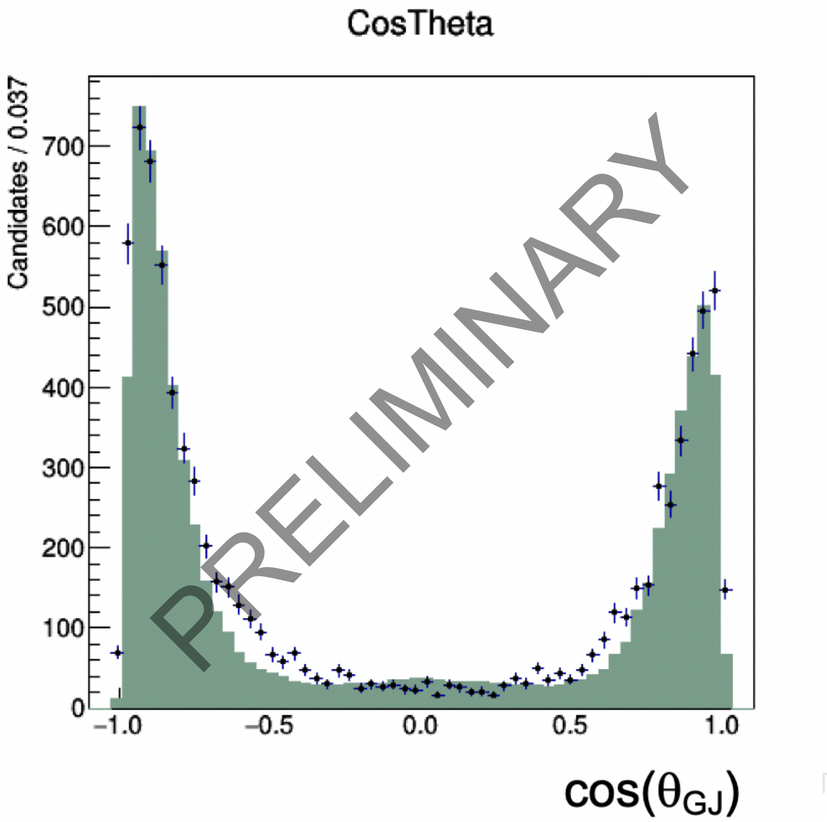
COMPASS PLB740 (2015)

Double Regge $\eta\pi^0$ Photoproduction @GlueX

Baryons have been ‘cut out’



$a_2(1320)$



Double regge with Uniform background

From https://arxiv.org/pdf/1809.06123.pdf