

Photoproduction of Mesons

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University of Barcelona

Joint Physics Analysis Center
Exotic Hadron Topical Collaboration

CLAS collaboration Meeting
Paris March 2023

ExoHAD
EXOTIC HADRONS TOPICAL COLLABORATION

JPAC *Joint
Physics
Analysis
Center*



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BARCELONA





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TU Munich



Alessandro Pilloni
U. Messina



Adam Szczepaniak
Indiana University



Daniel Winney
South China Normal
University



Lawrence Ng
Florida State
University



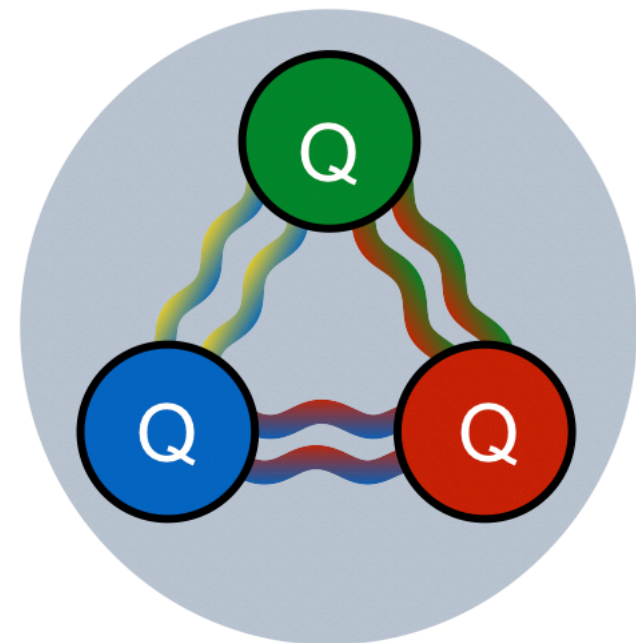
Arkaitz Rodas
JLab



Robert Perry
University of
Barcelona

Ordinary and Exotic Hadrons

Ordinary baryons



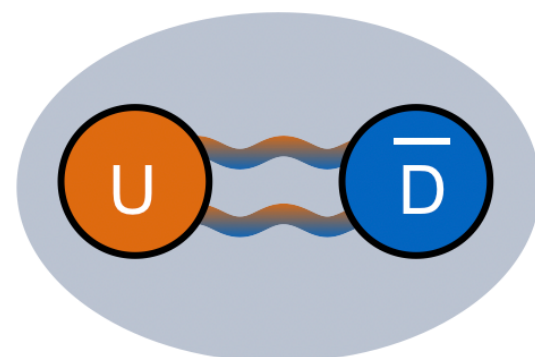
proton stable

neutron $\tau \sim 10^3 s$

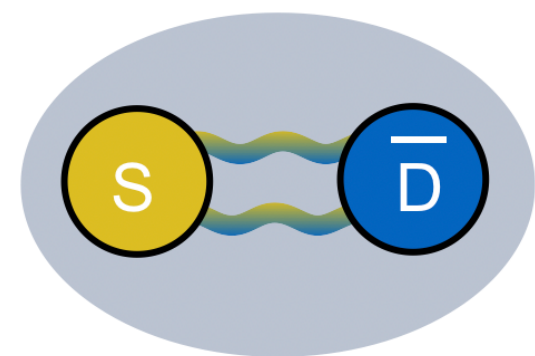
baryon Λ $\tau \sim 10^{-10} s$

Q U A R K S	UP mass 2,3 MeV/c ² charge $\frac{2}{3}$ spin $\frac{1}{2}$ 	CHARM 1,275 GeV/c ² $\frac{2}{3}$ $\frac{1}{2}$ 	TOP 173,07 GeV/c ² $\frac{2}{3}$ $\frac{1}{2}$
	DOWN 4,8 MeV/c ² $-\frac{1}{3}$ $\frac{1}{2}$ 	STRANGE 95 MeV/c ² $-\frac{1}{3}$ $\frac{1}{2}$ 	BOTTOM 4,18 GeV/c ² $-\frac{1}{3}$ $\frac{1}{2}$

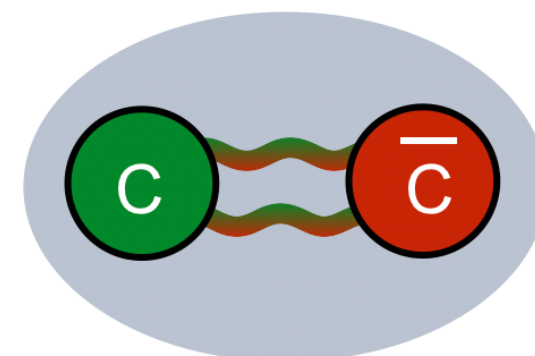
Ordinary mesons



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



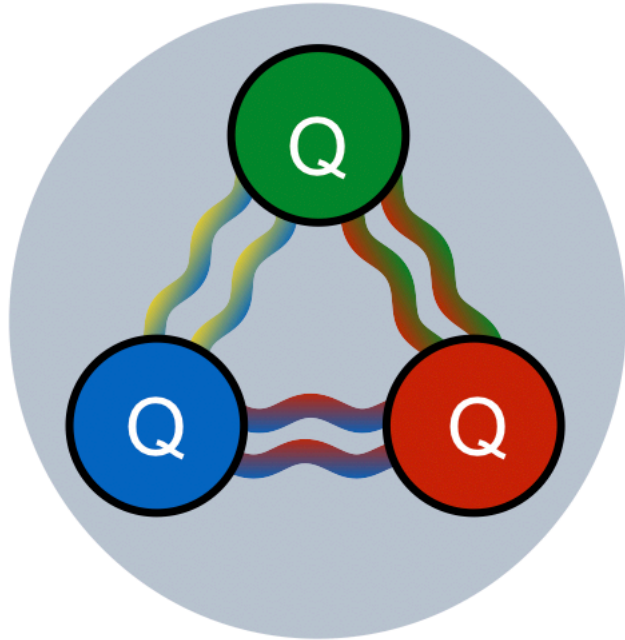
kaon $\tau \sim 10^{-8} s$



J/ψ $\tau \sim 10^{-20} s$

Ordinary and Exotic Hadrons

Ordinary baryons



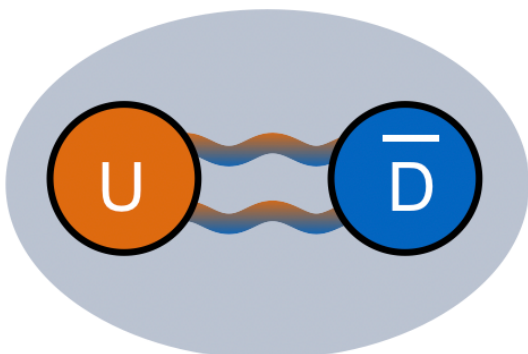
proton stable

neutron $\tau \sim 10^3 s$

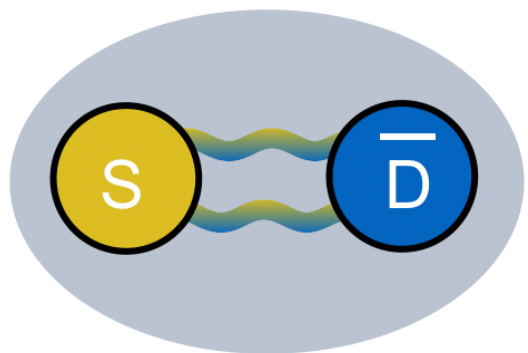
baryon Λ $\tau \sim 10^{-10} s$

QUARKS	UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 	CHARM 1,275 GeV/c ² 2/3 1/2 	TOP 173,07 GeV/c ² 2/3 1/2
	DOWN 4,8 MeV/c ² -1/3 1/2 	STRANGE 95 MeV/c ² -1/3 1/2 	BOTTOM 4,18 GeV/c ² -1/3 1/2

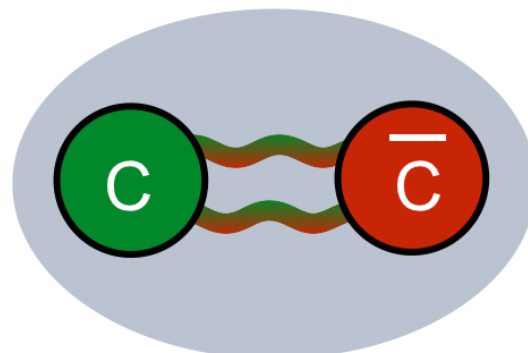
Ordinary mesons



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



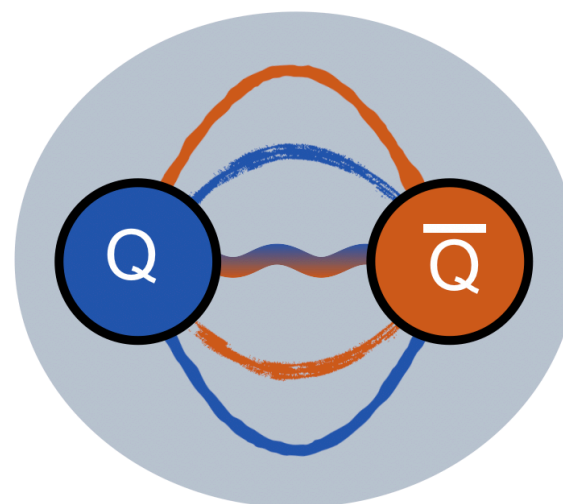
kaon $\tau \sim 10^{-8} s$



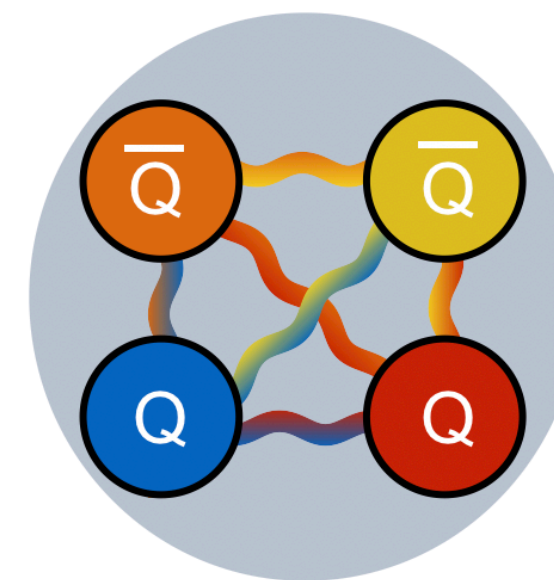
J/ψ $\tau \sim 10^{-20} s$

Exotic matter

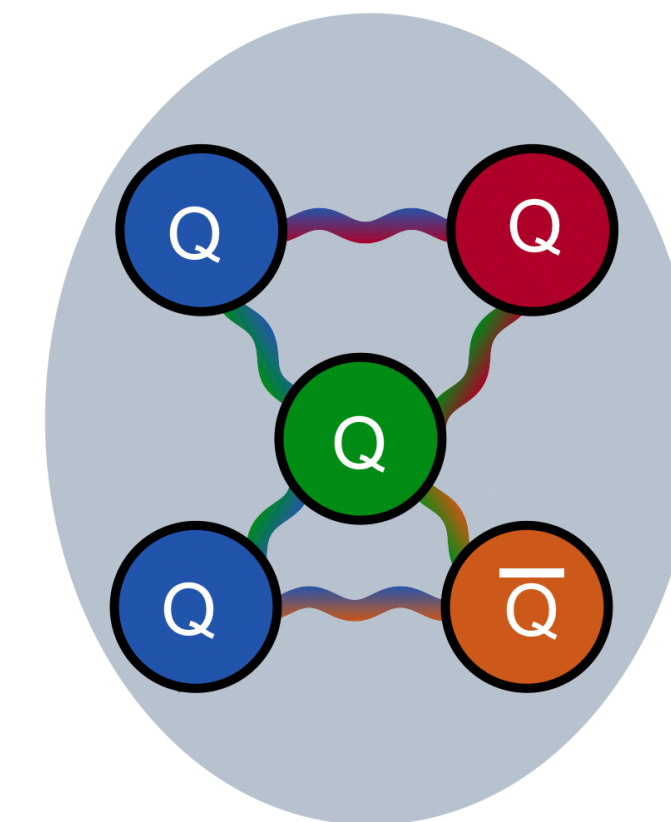
hybrid mesons



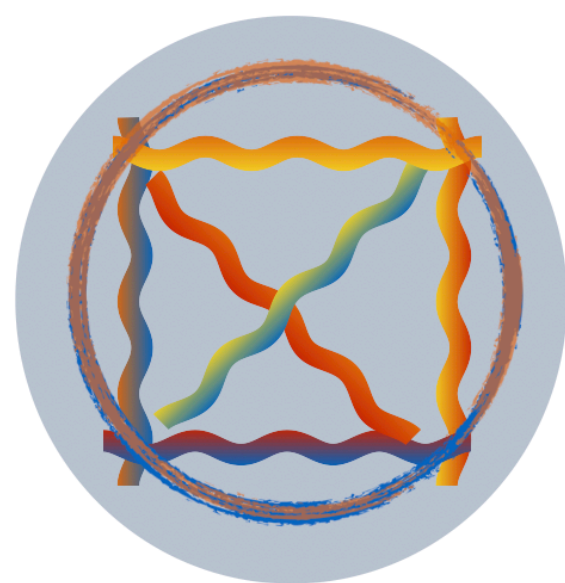
tetraquarks



pentaquarks

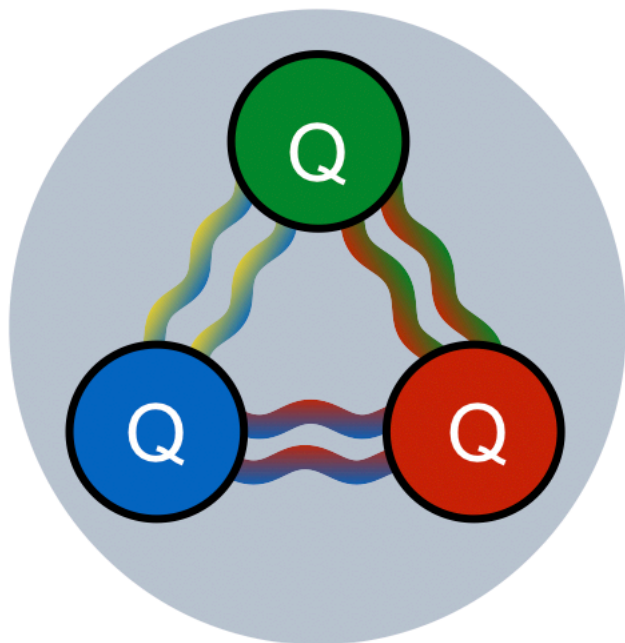


glueballs



Ordinary and Exotic Hadrons

Ordinary baryons



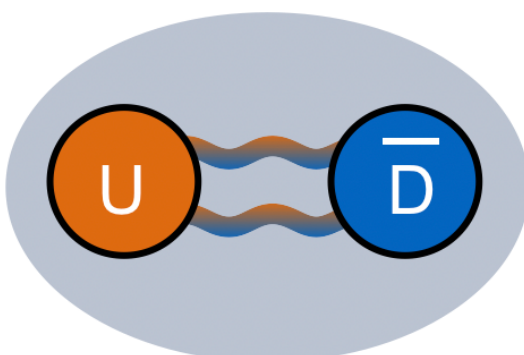
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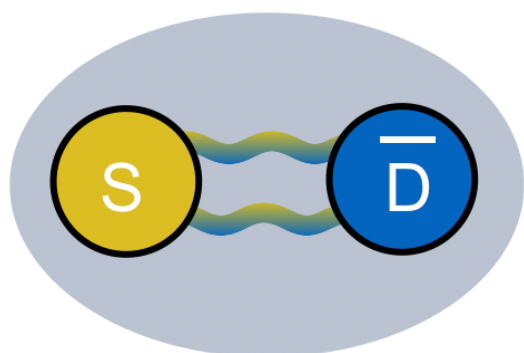
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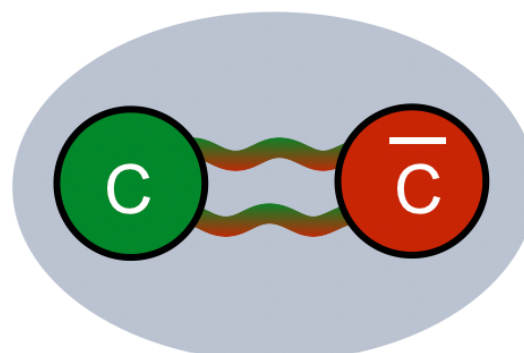
Ordinary mesons



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



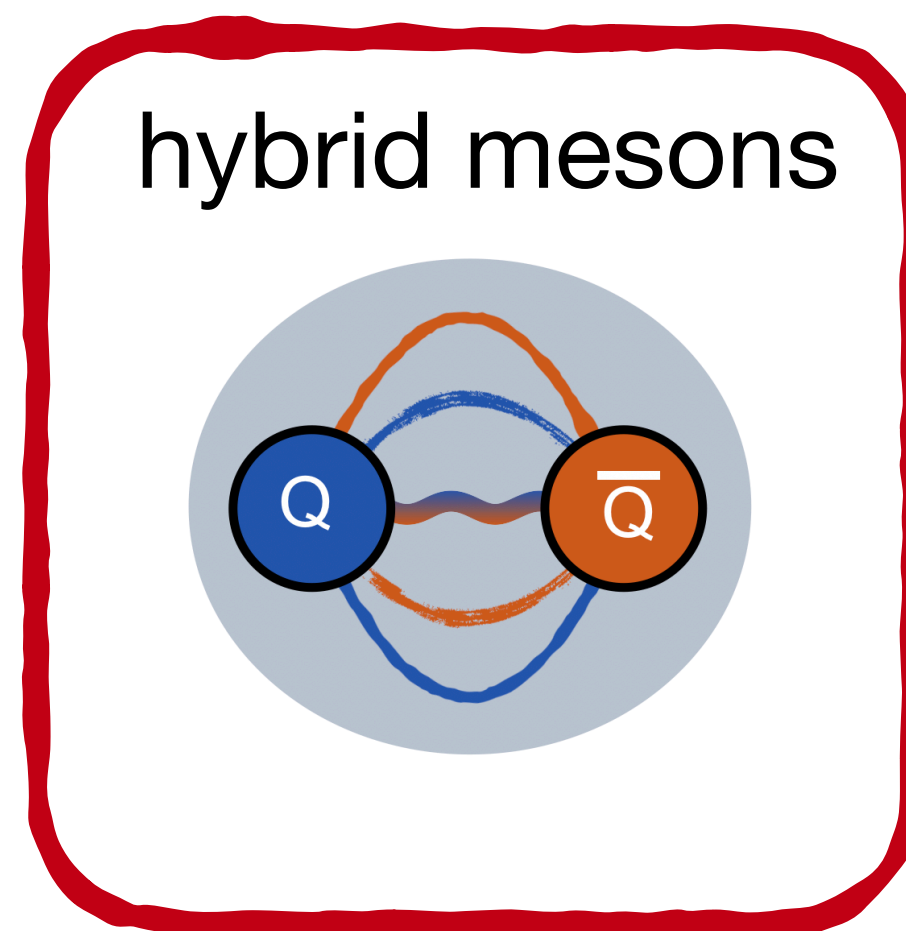
kaon $\tau \sim 10^{-8} s$



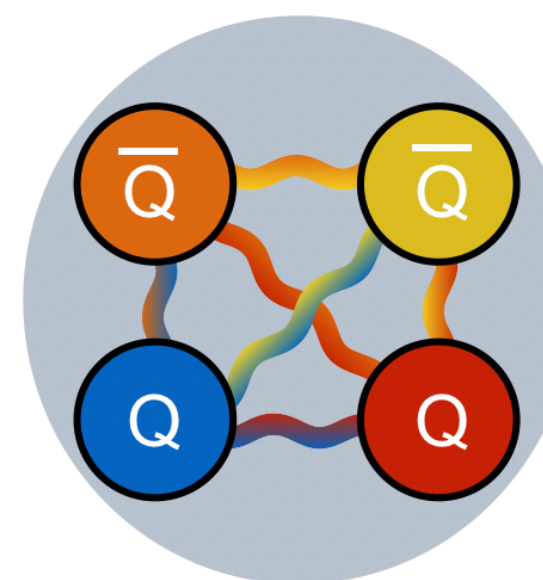
J/ψ $\tau \sim 10^{-20} s$

Exotic matter

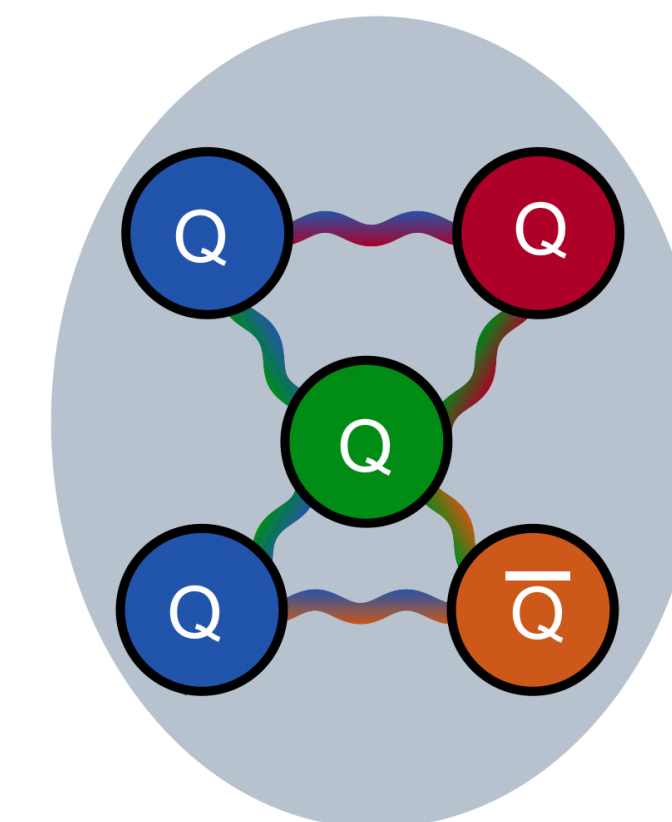
hybrid mesons



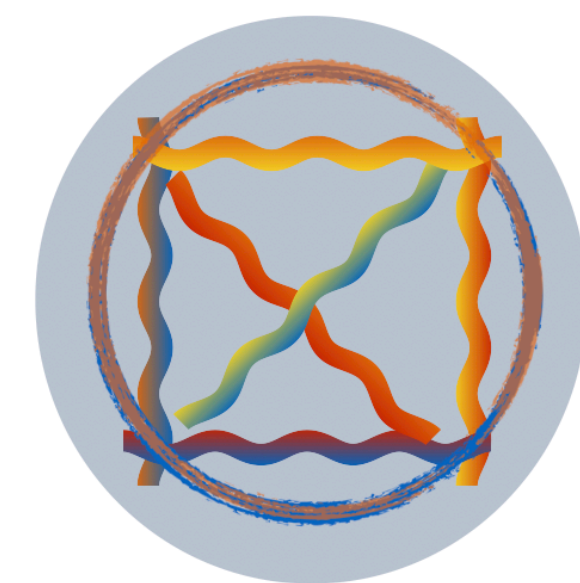
tetraquarks



pentaquarks

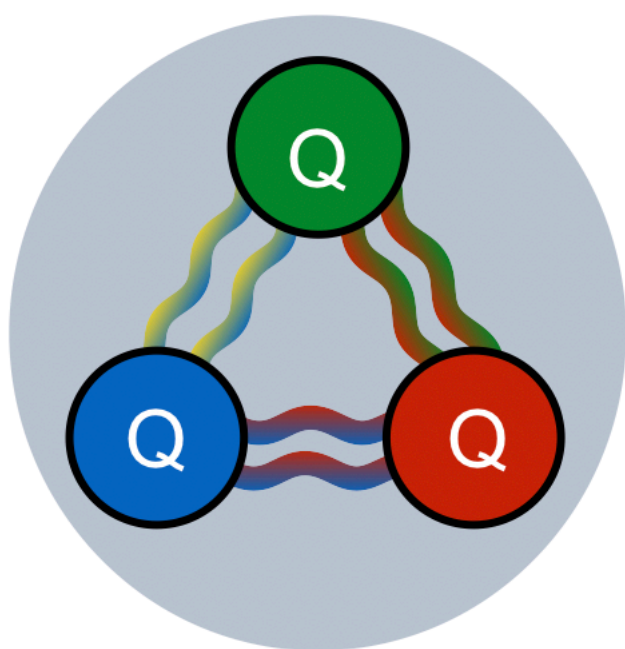


glueballs



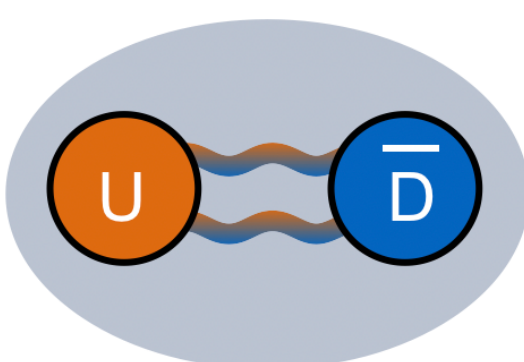
Baryons and Mesons

Ordinary baryons:

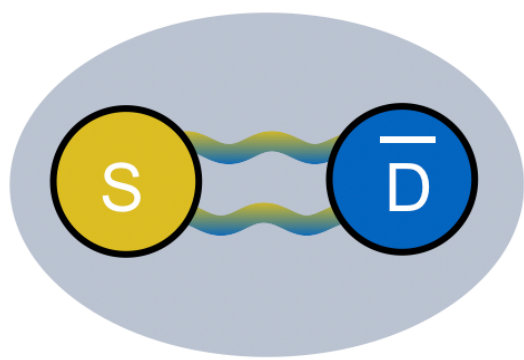


- uud proton stable
- udd neutron $\tau \sim 10^3 s$
- uds baryon Λ $\tau \sim 10^{-10} s$
- uuu baryon Δ $\tau \sim 10^{-24} s$

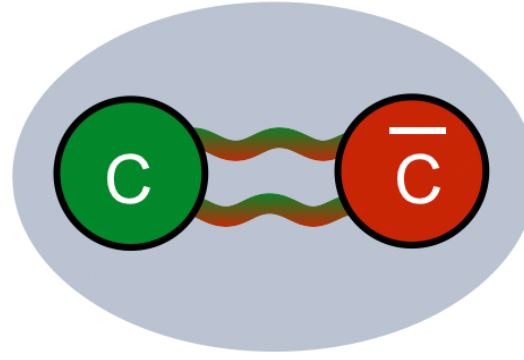
Ordinary mesons



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



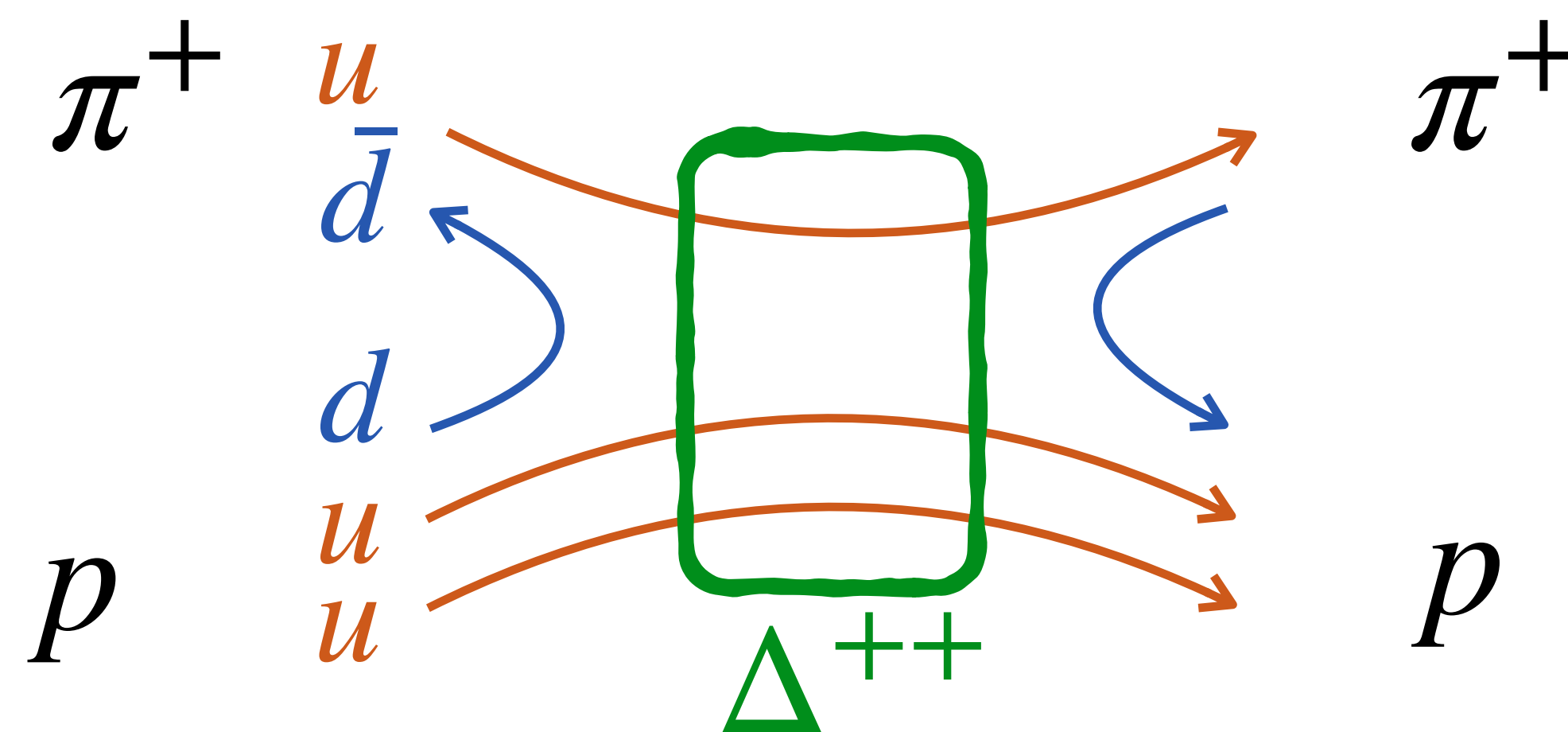
kaon $\tau \sim 10^{-8} s$



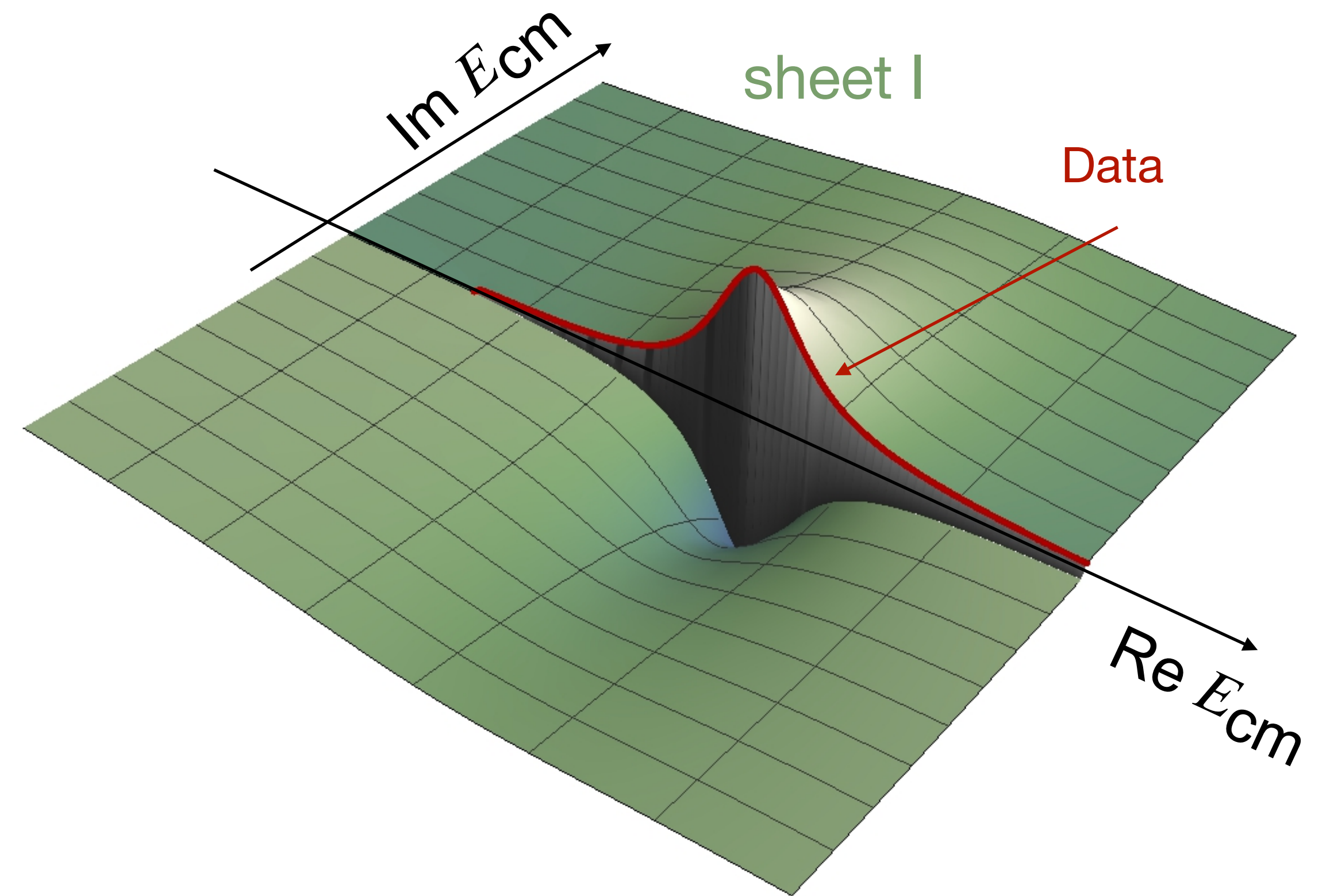
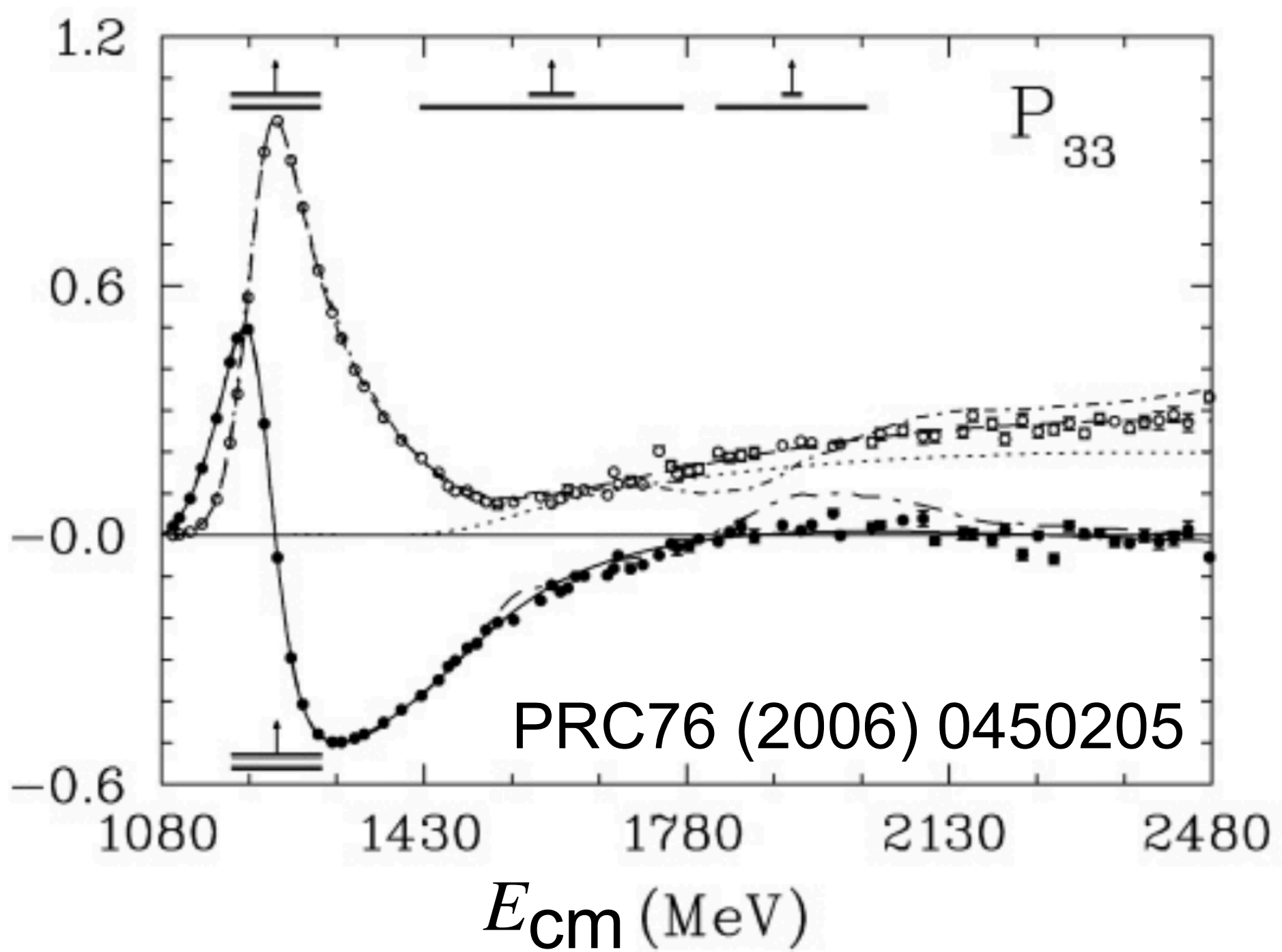
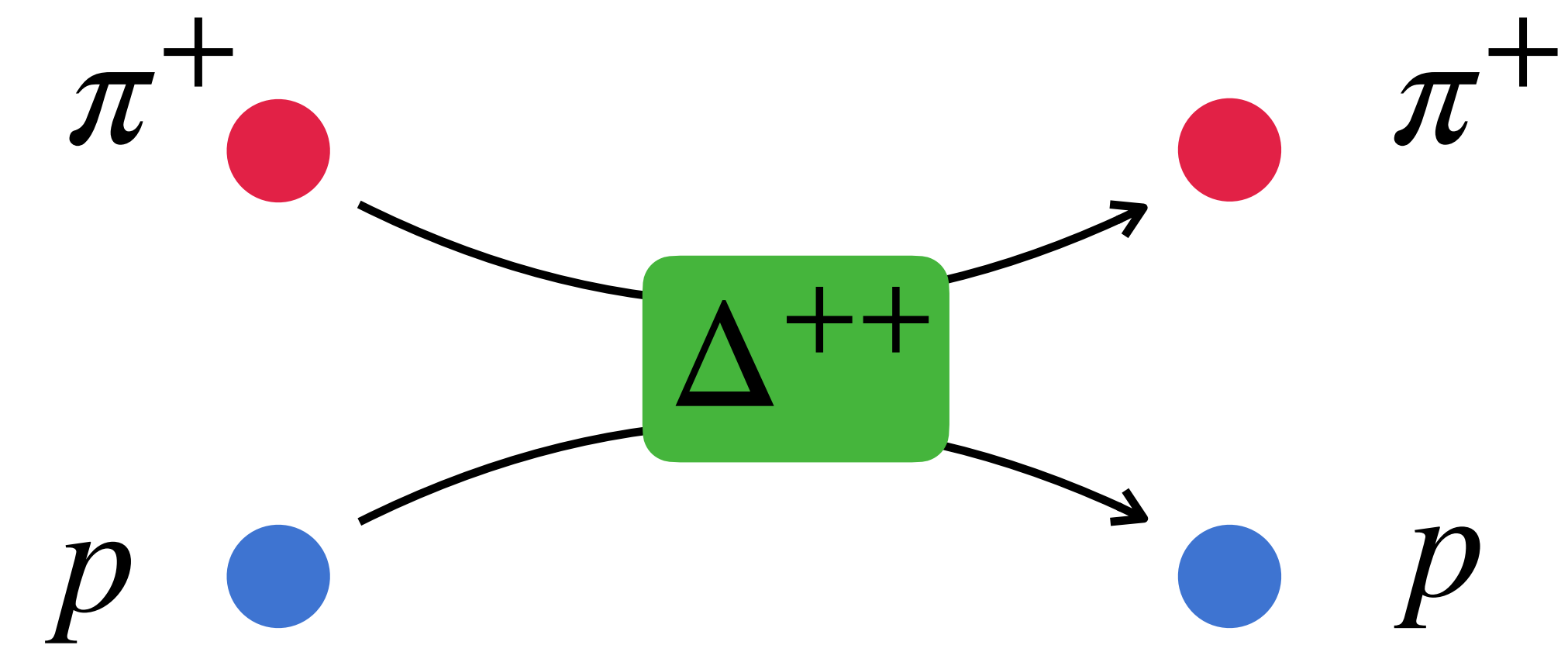
J/ψ $\tau \sim 10^{-20} s$

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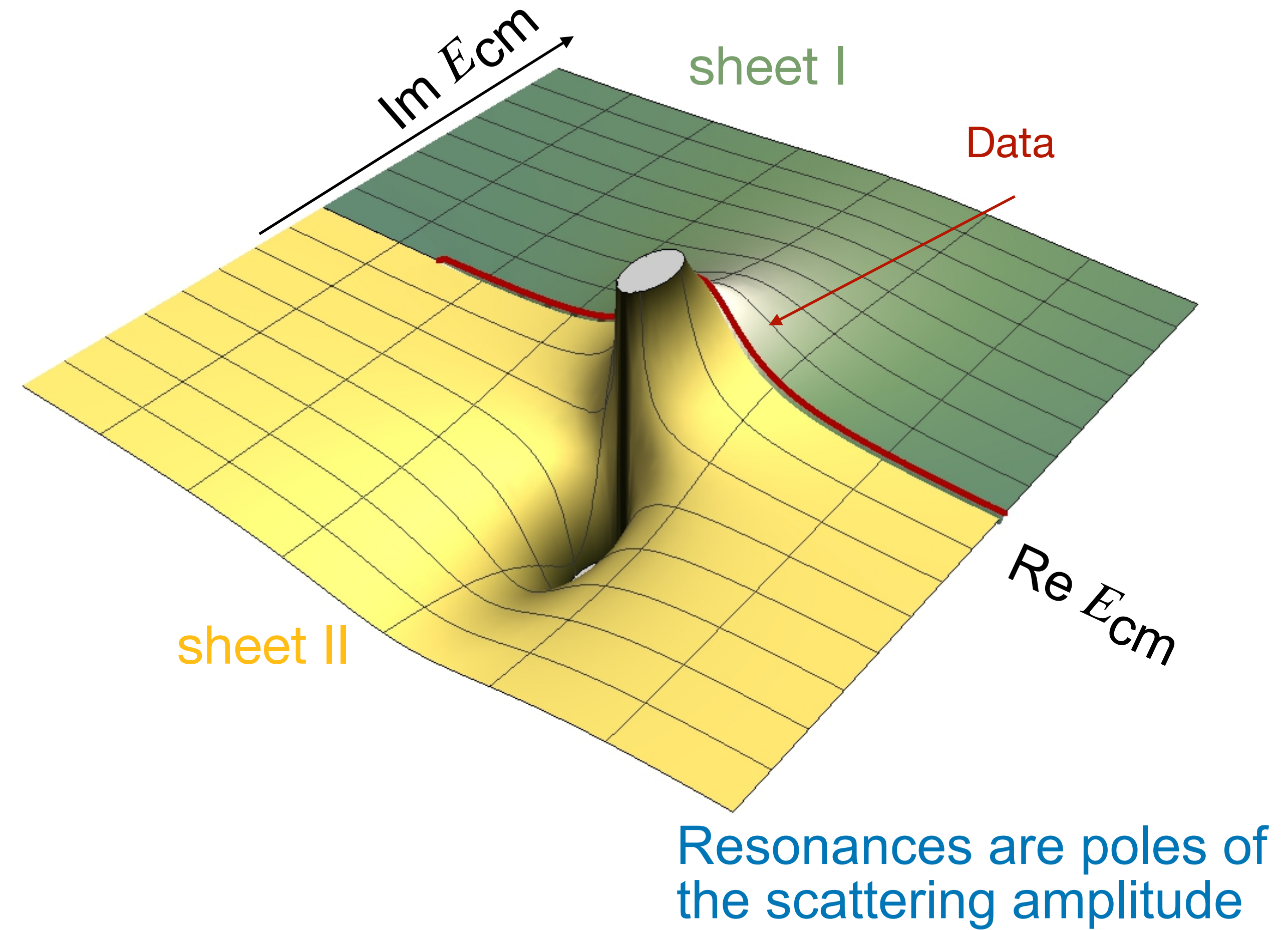
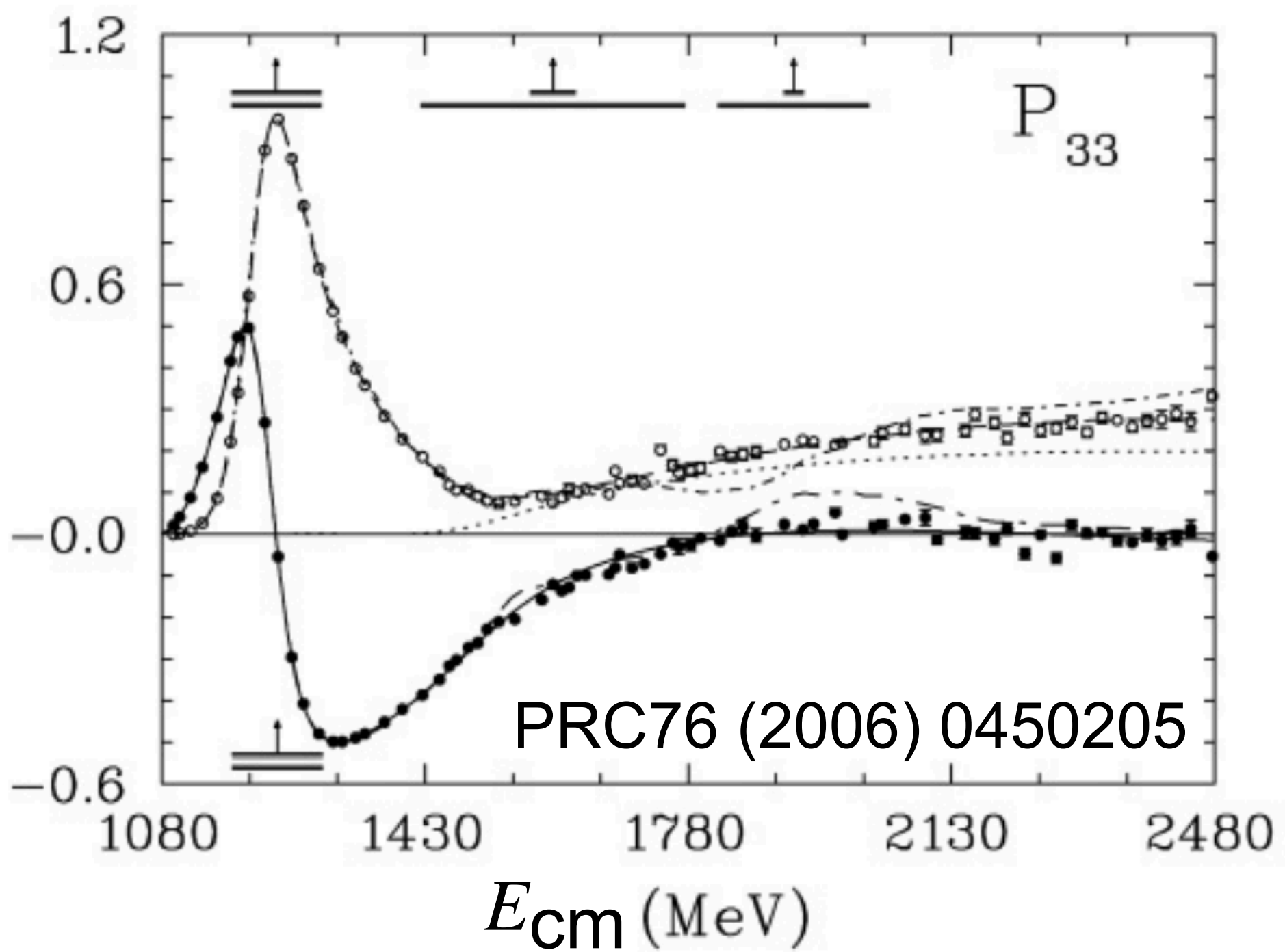
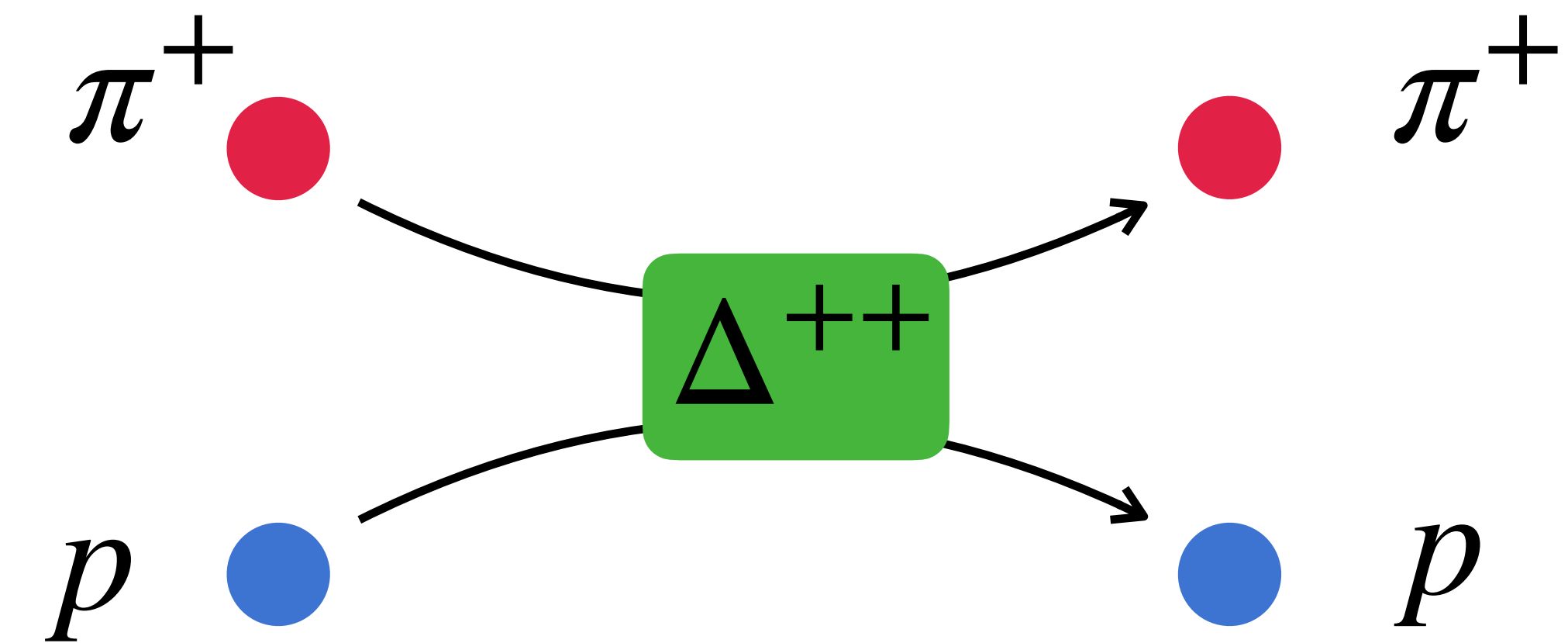
$$\pi^+ p \rightarrow \Delta^{++} \rightarrow \pi^+ p$$



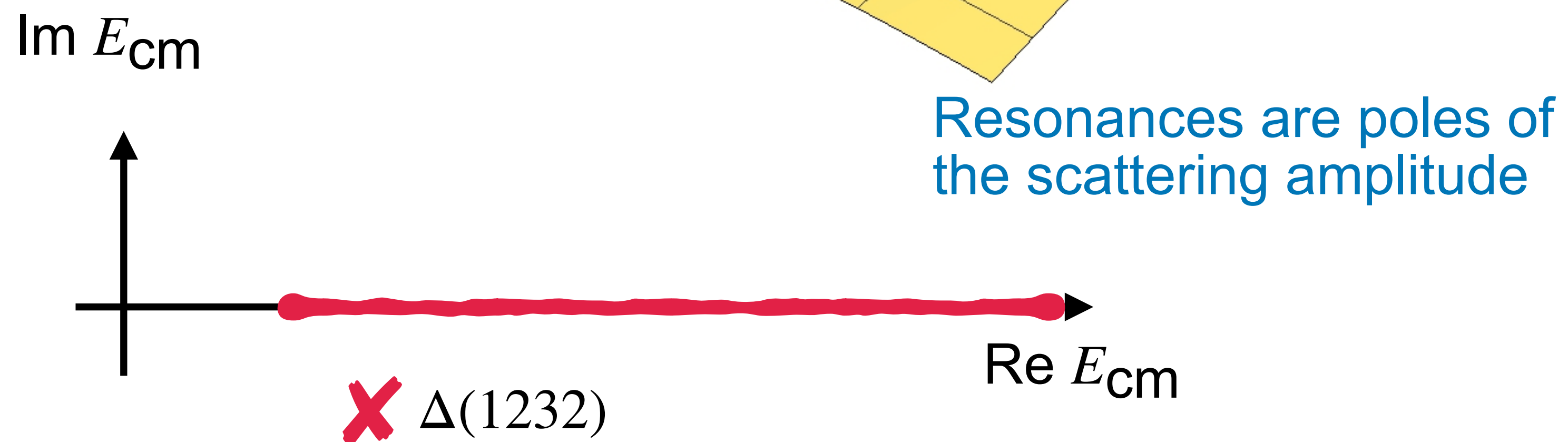
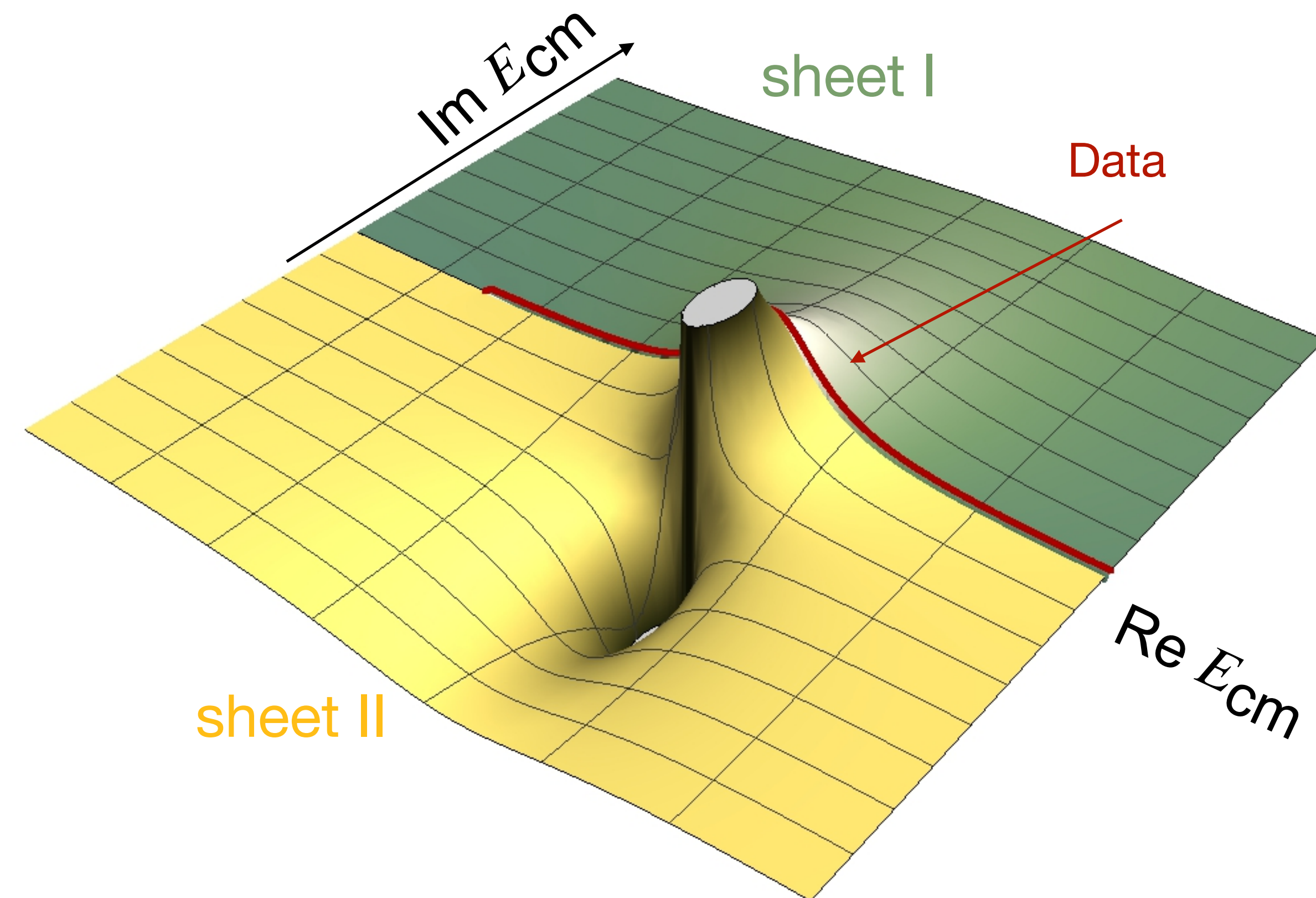
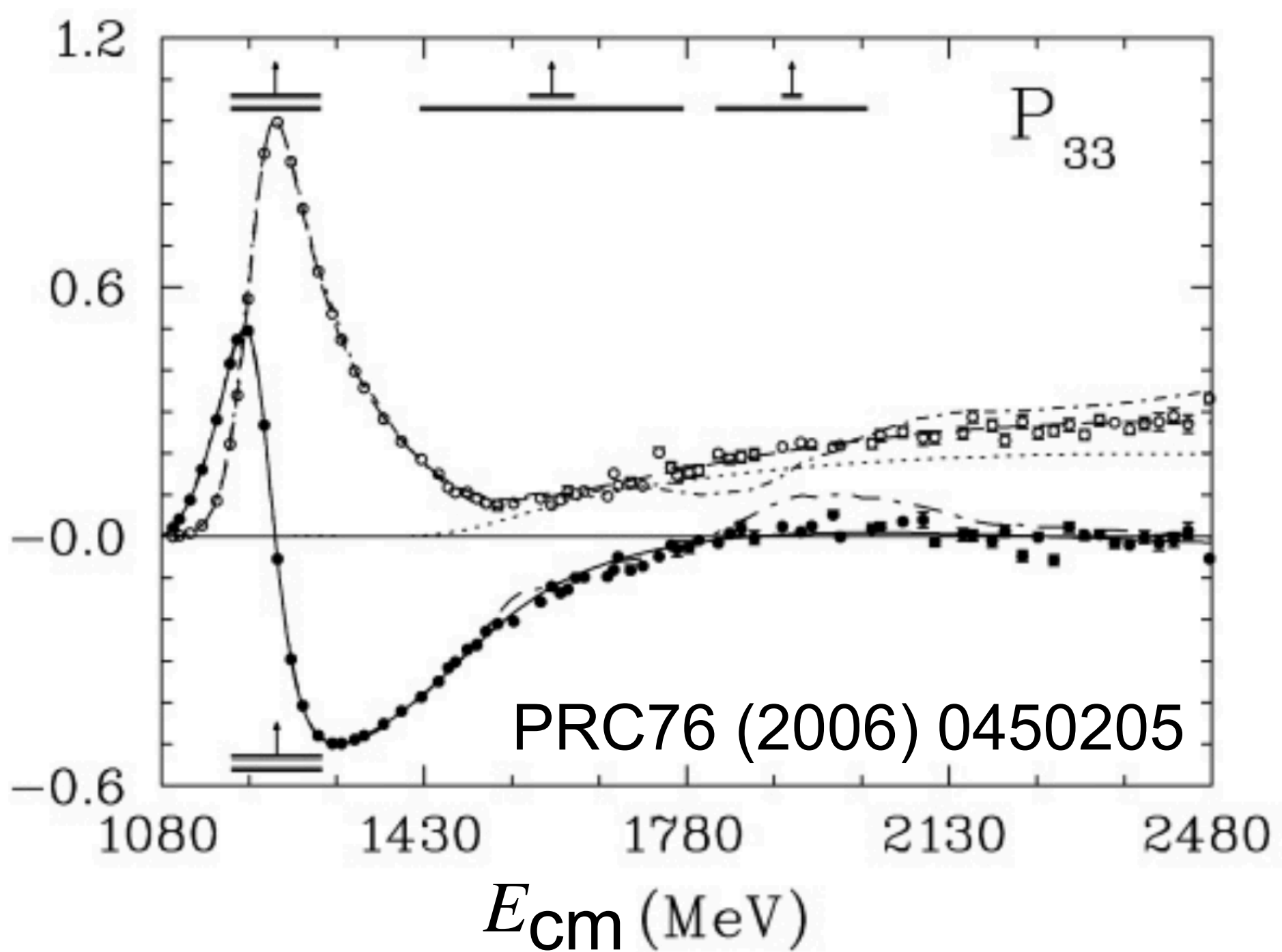
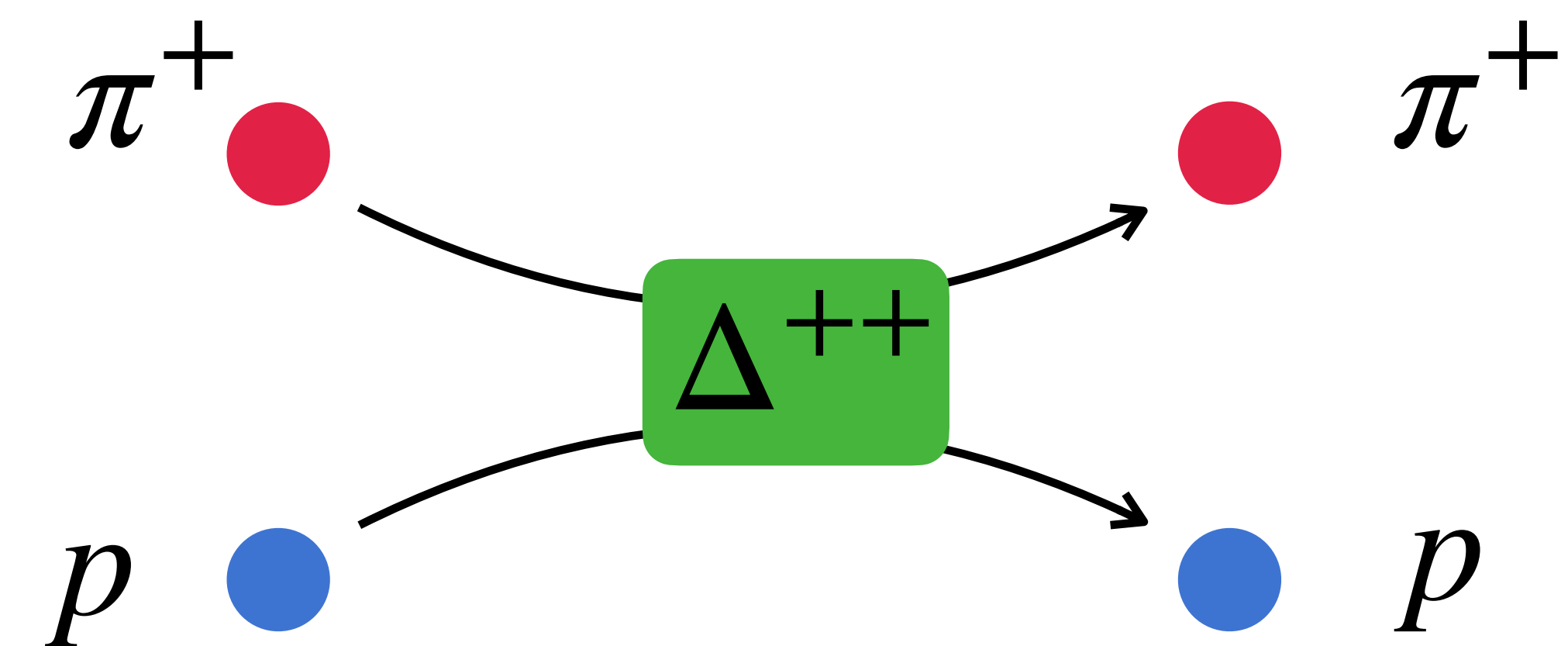
What's a resonance?



What's a resonance?

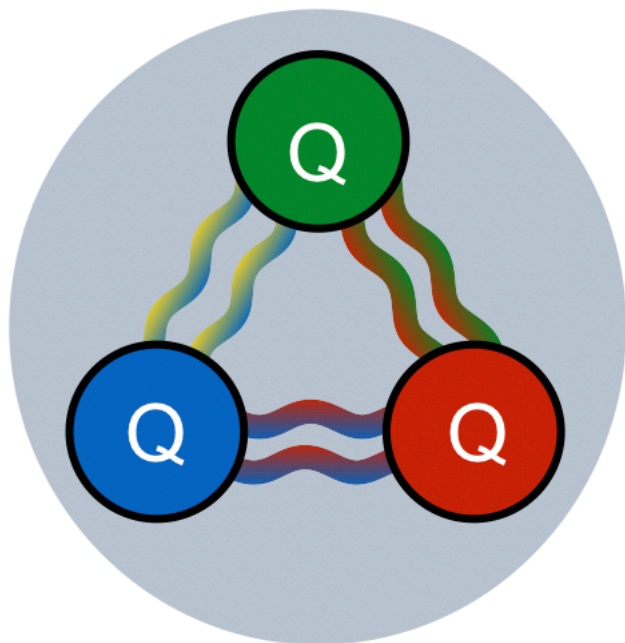


What's a resonance?



Ordinary and Exotic Hadrons

Ordinary baryons:



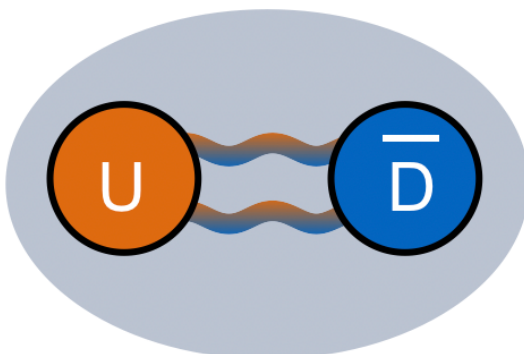
proton stable

neutron $\tau \sim 10^3 s$

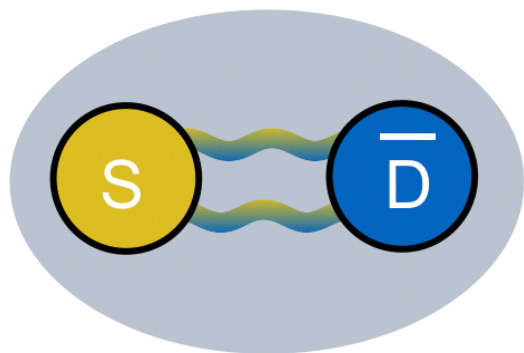
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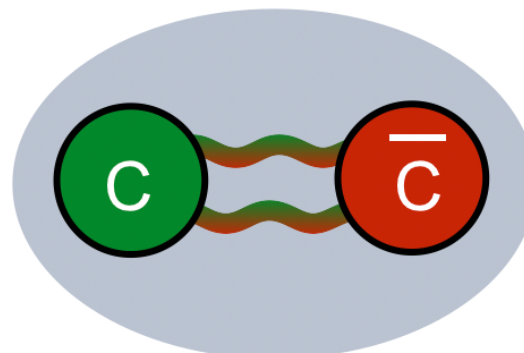
Ordinary mesons



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

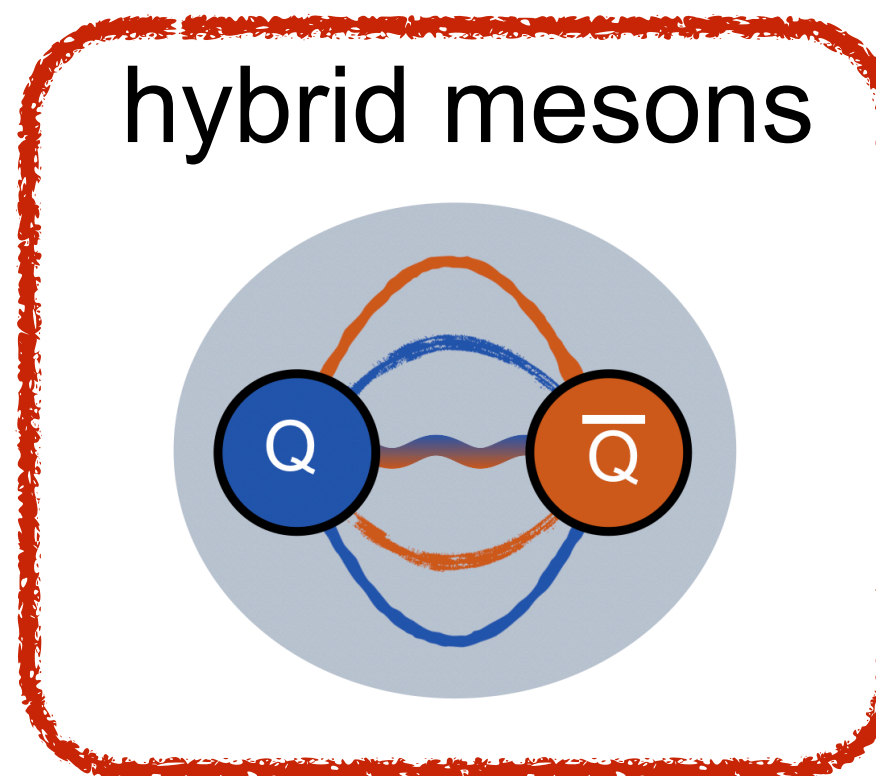


kaon $\tau \sim 10^{-8} s$



J/ψ $\tau \sim 10^{-20} s$

Exotic matter

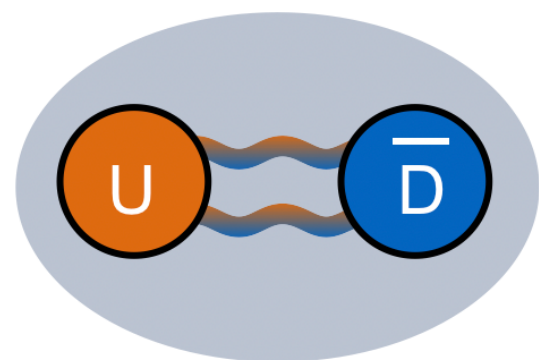


Meson with excited gluon field

Gluon field may carry quantum numbers

Quantum Numbers

Ordinary mesons



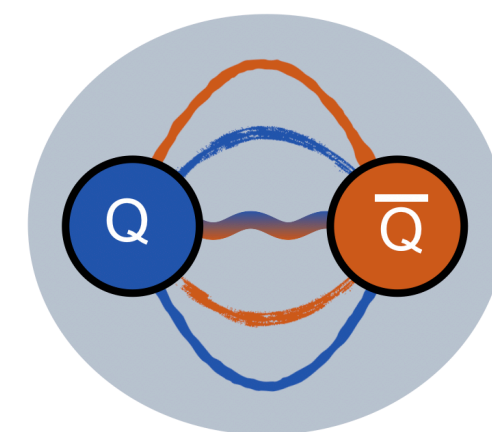
$$\vec{J} = \vec{L} \oplus \vec{S}$$

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

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

0^{--}	0^{-+}	0^{+-}	0^{++}
1^{--}	1^{-+}	1^{+-}	1^{++}
2^{--}	2^{-+}	2^{+-}	2^{++}
3^{--}	3^{-+}	3^{+-}	3^{++}
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Exotic mesons



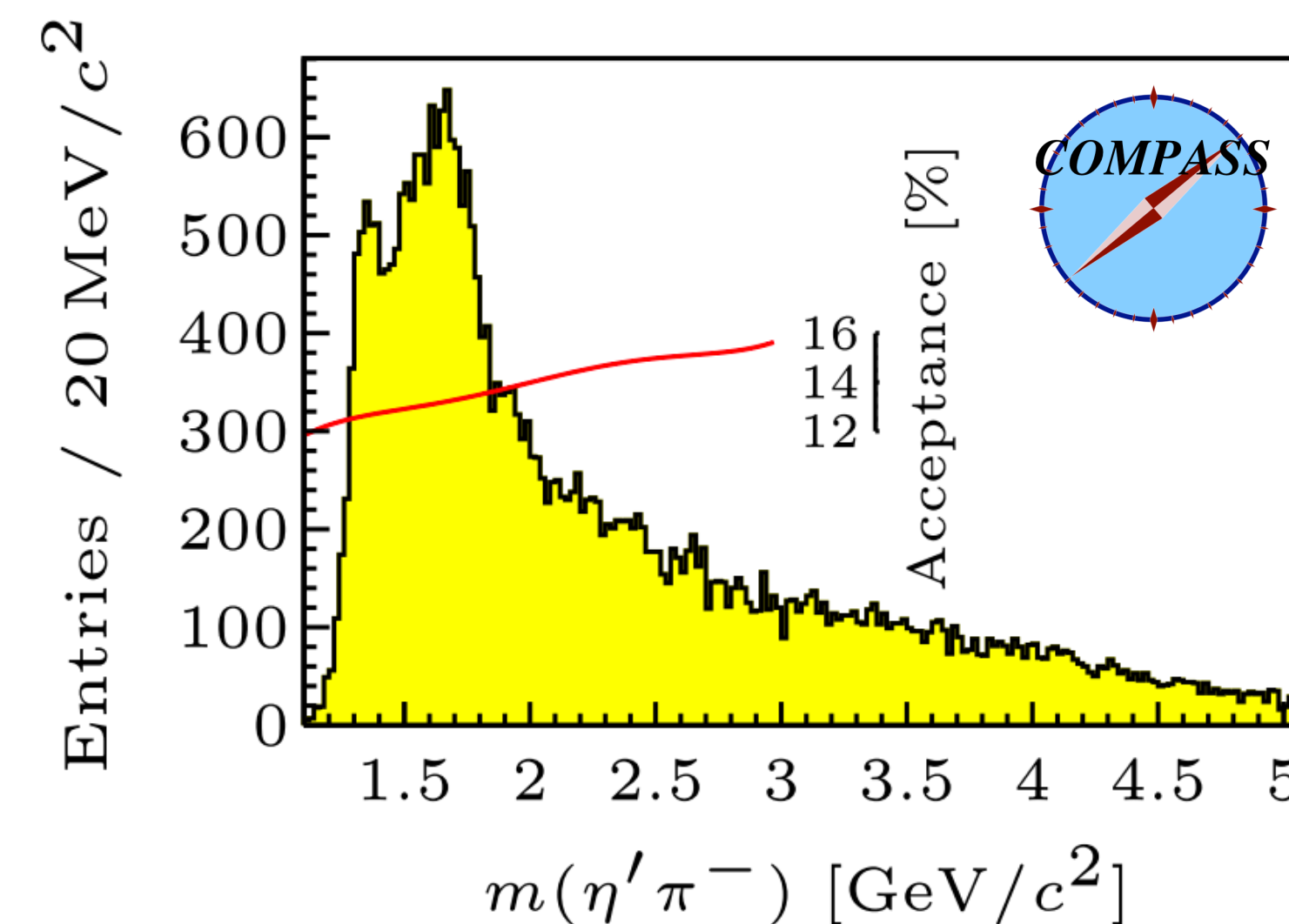
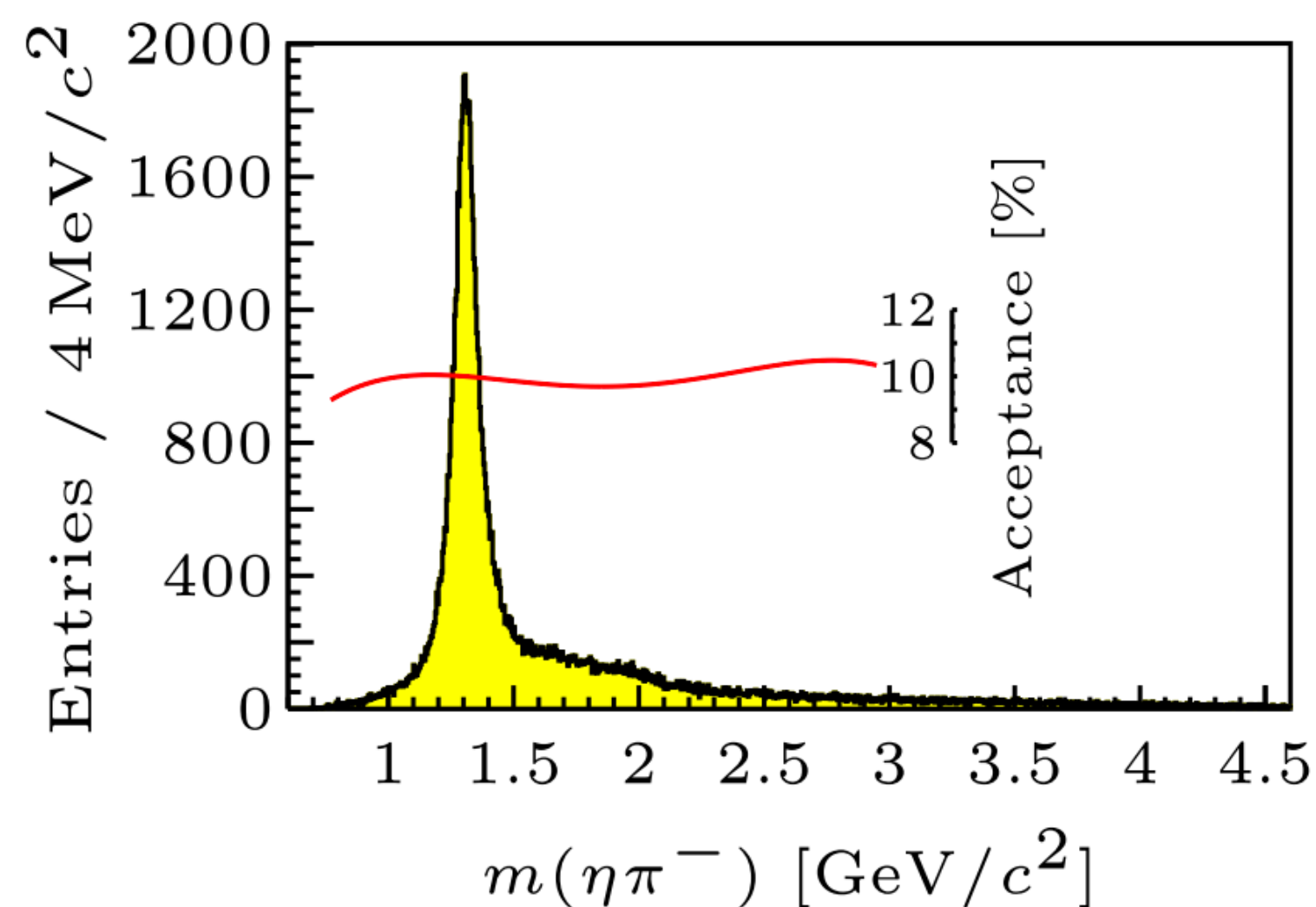
The lightest is π_1

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

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

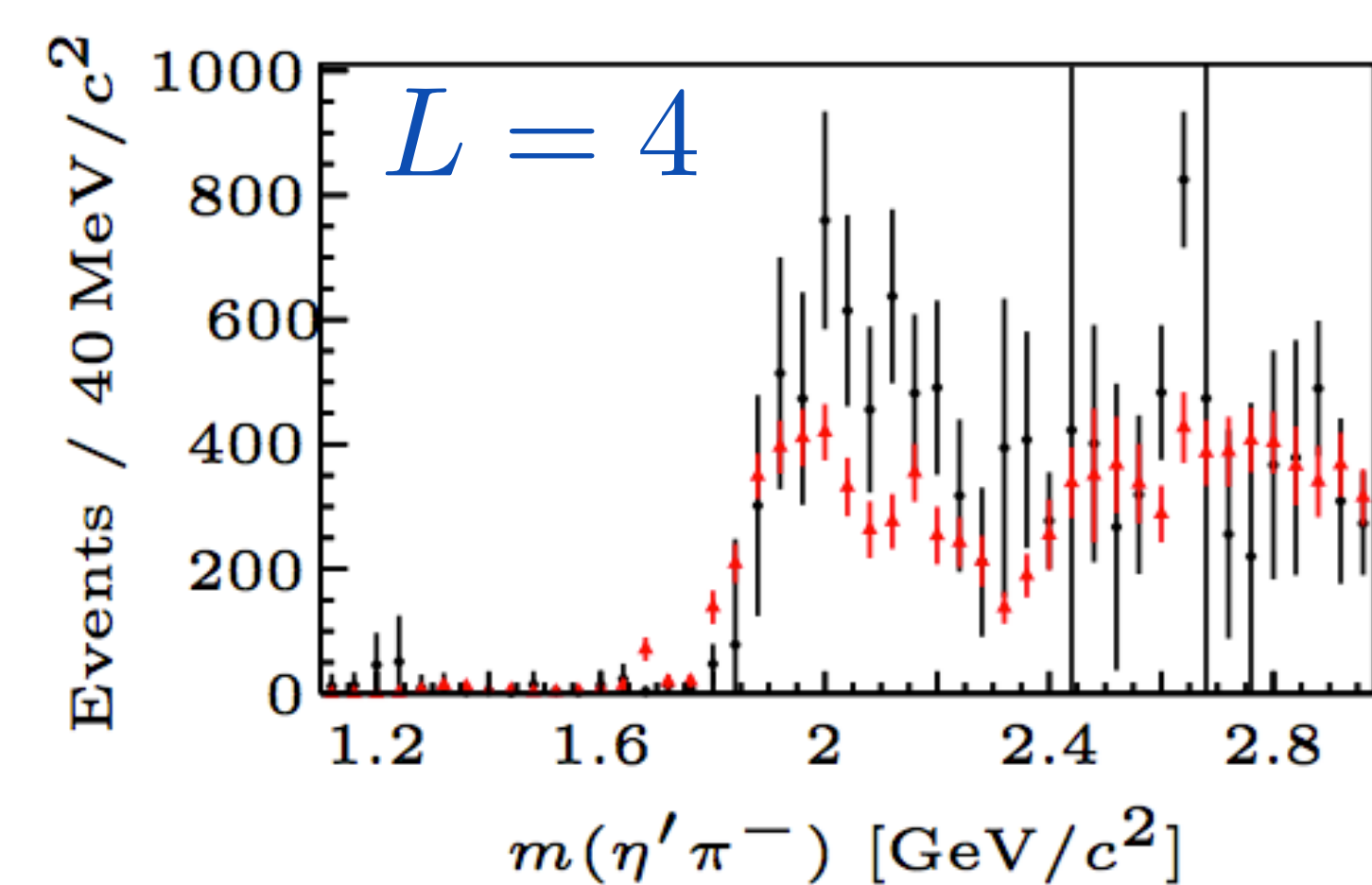
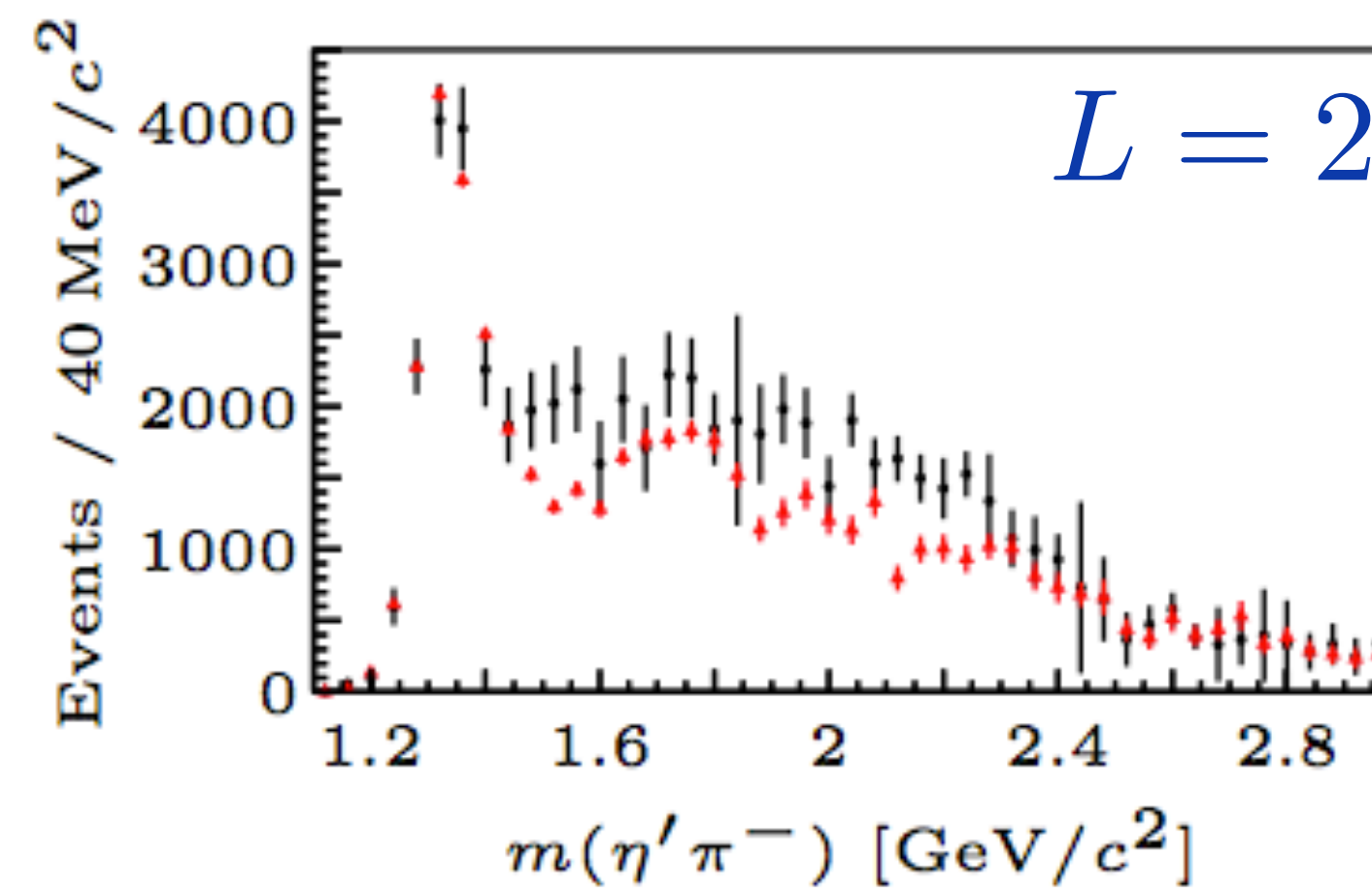
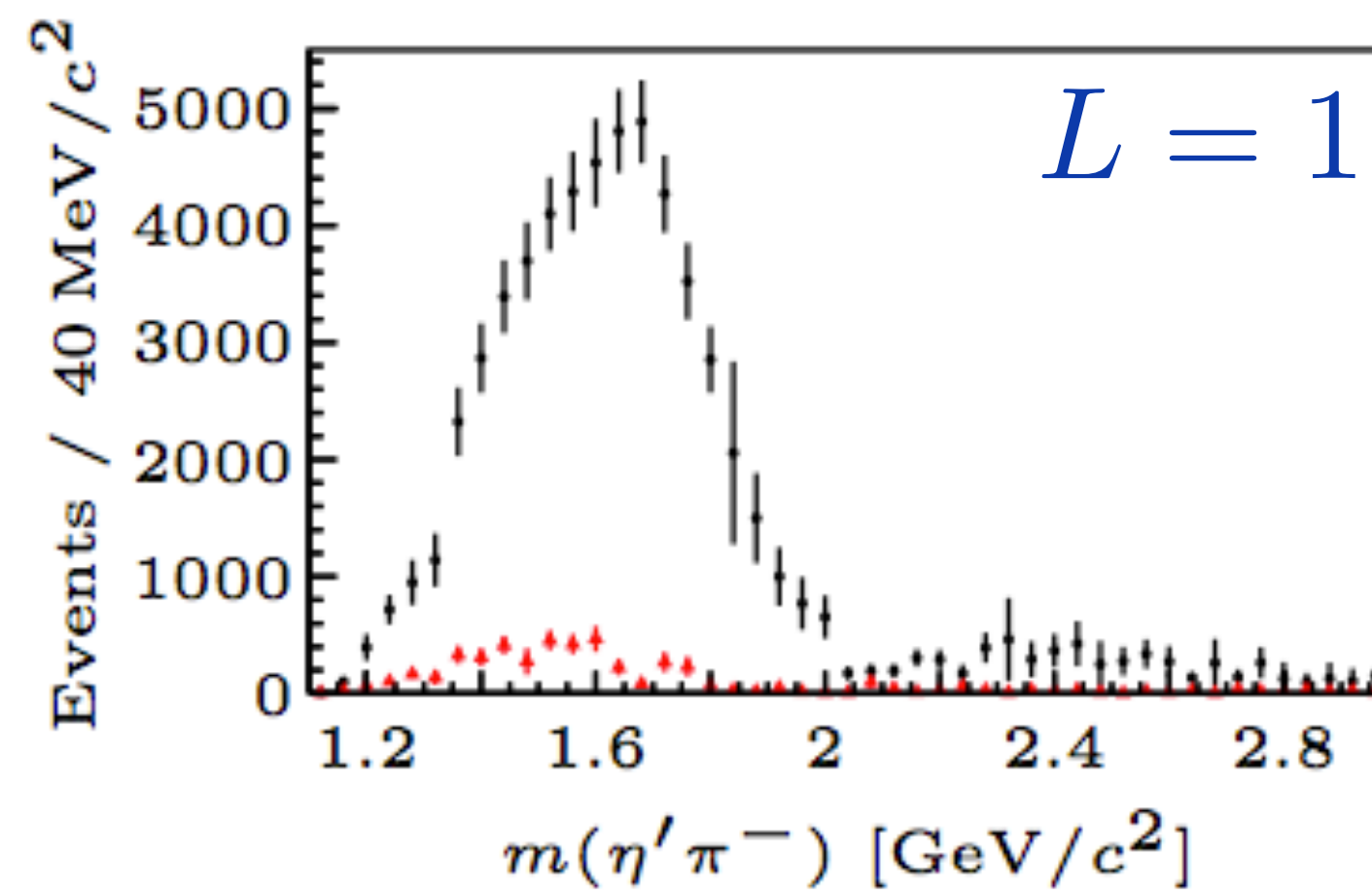
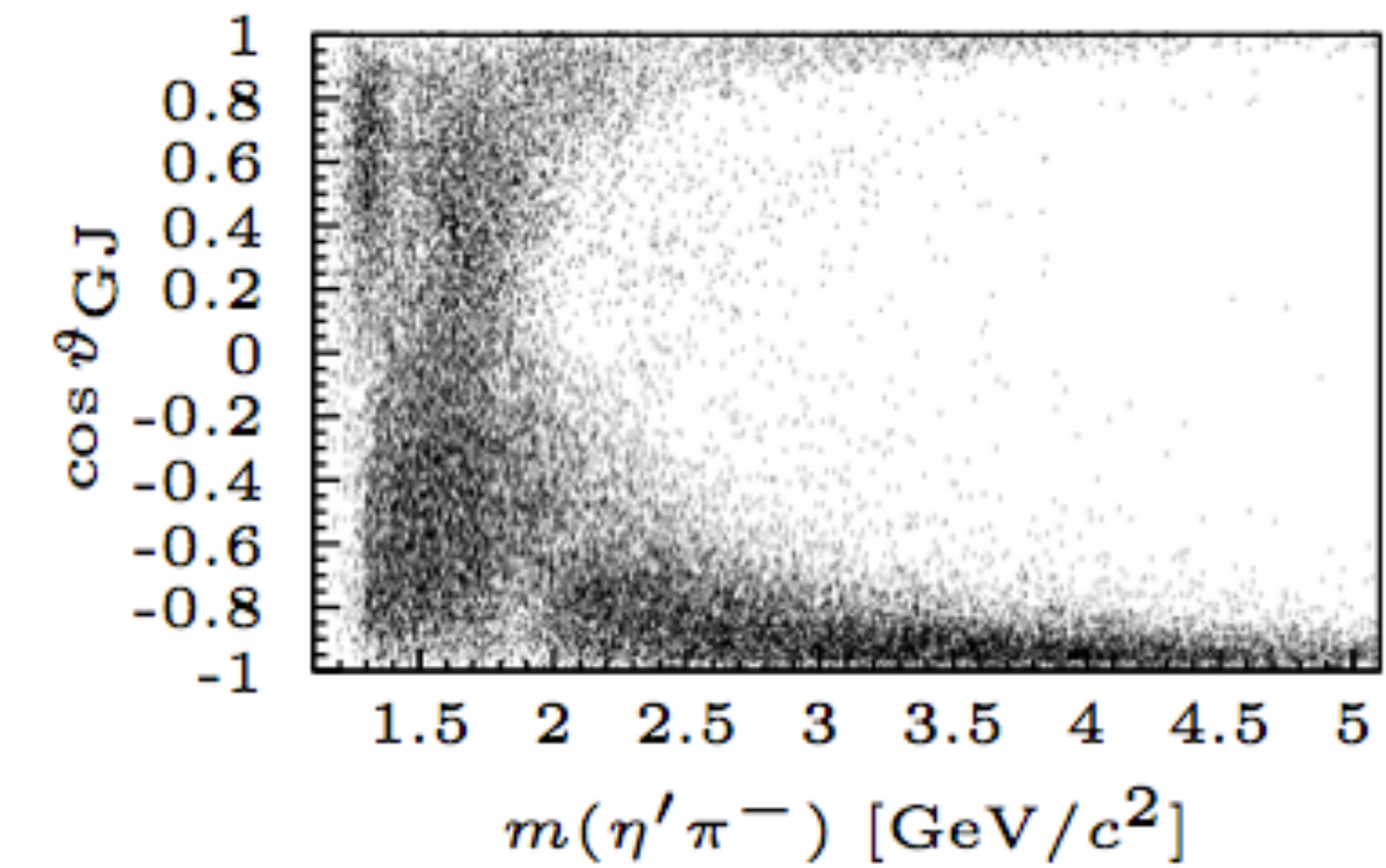
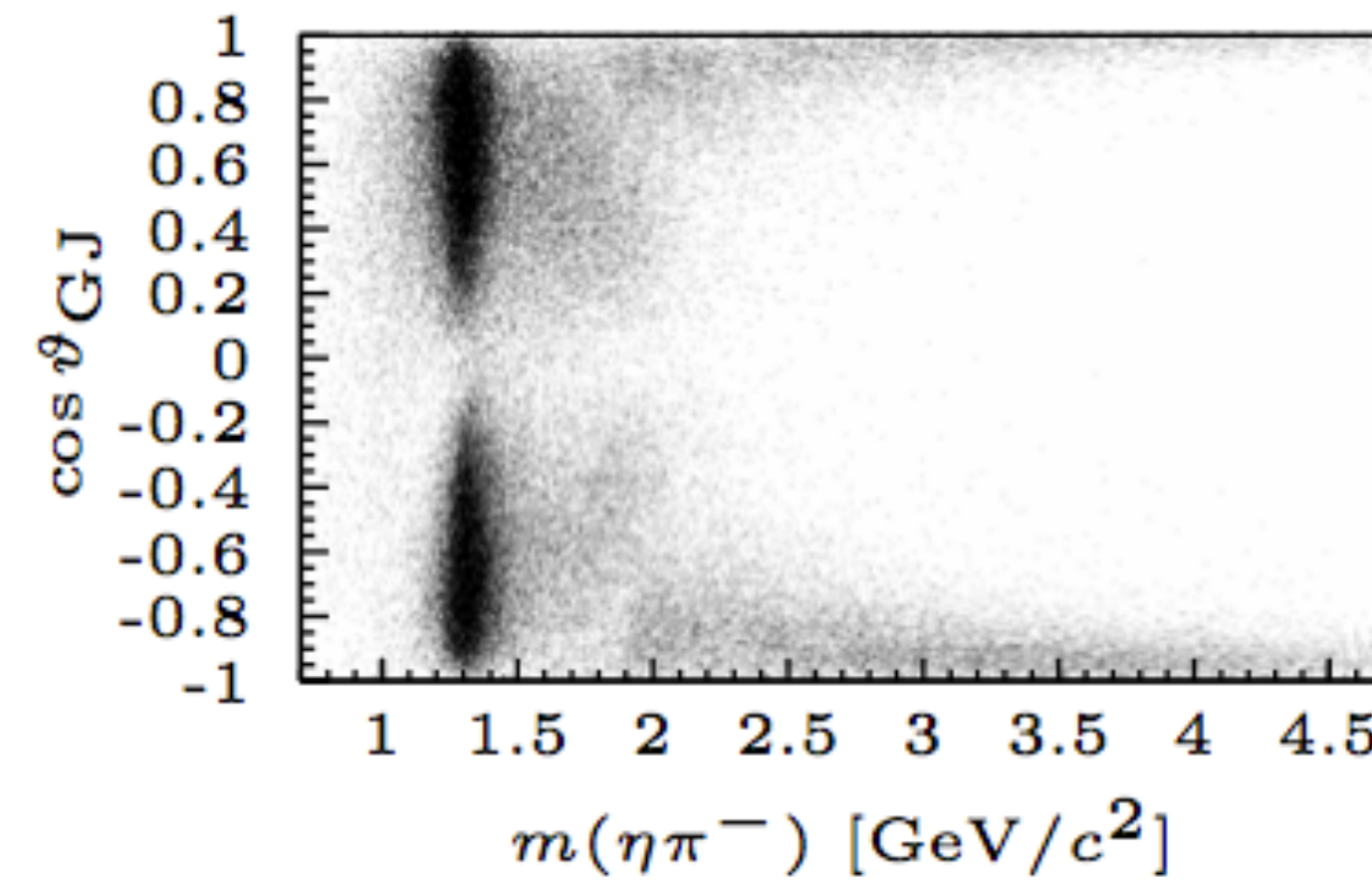
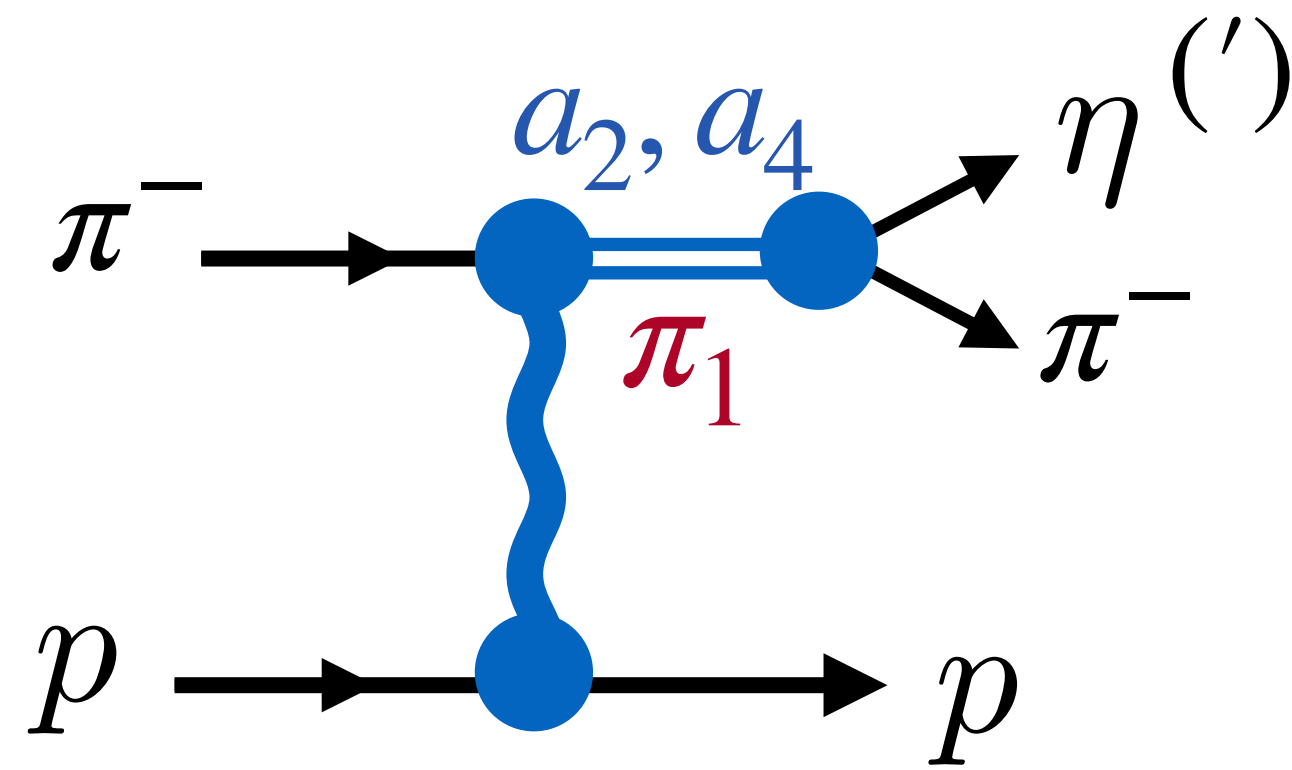
Decay mode

$$\pi_1 \rightarrow \eta\pi, \eta'\pi$$



Partial Waves Expansion

COMPASS PLB740 (2015)

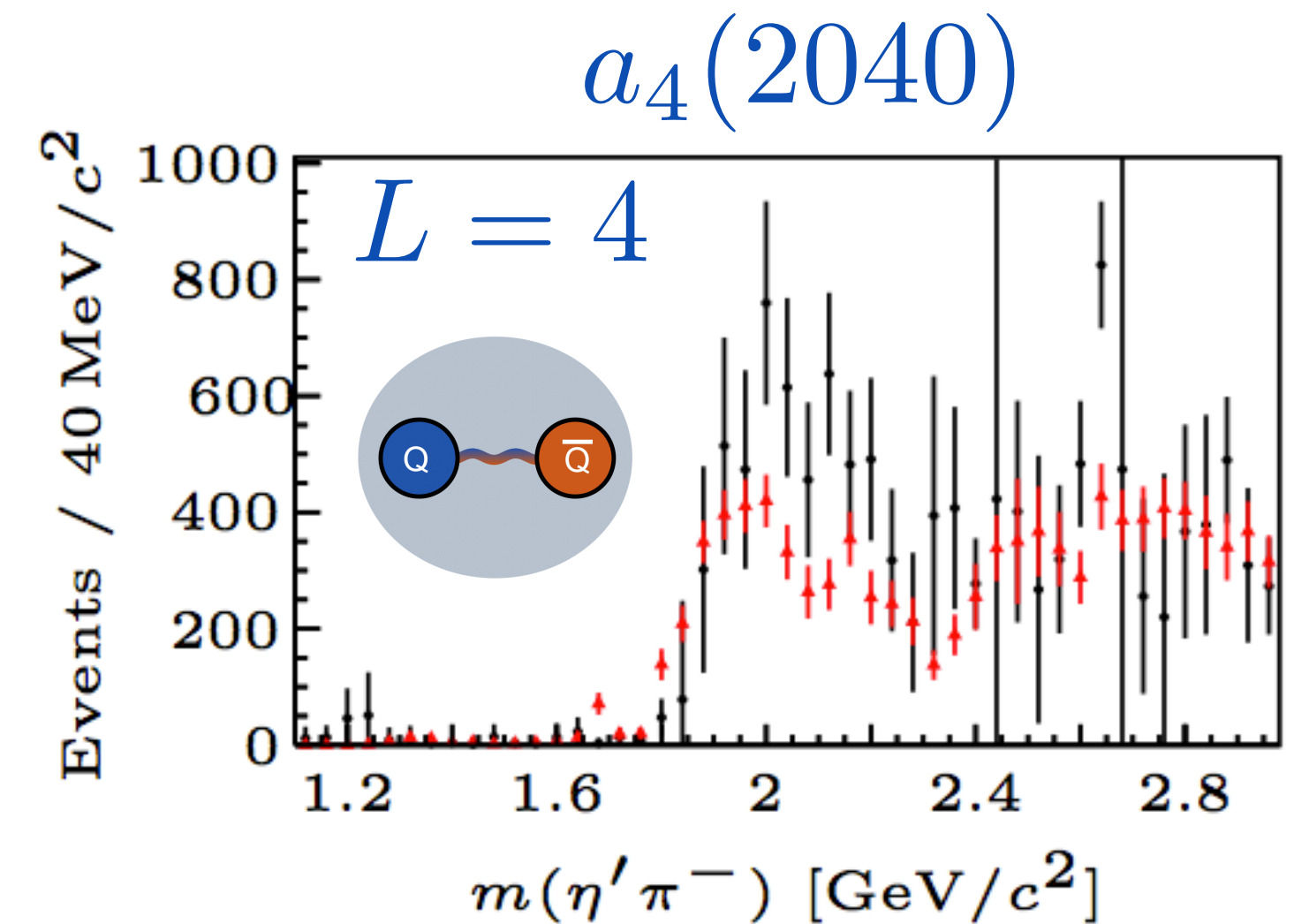
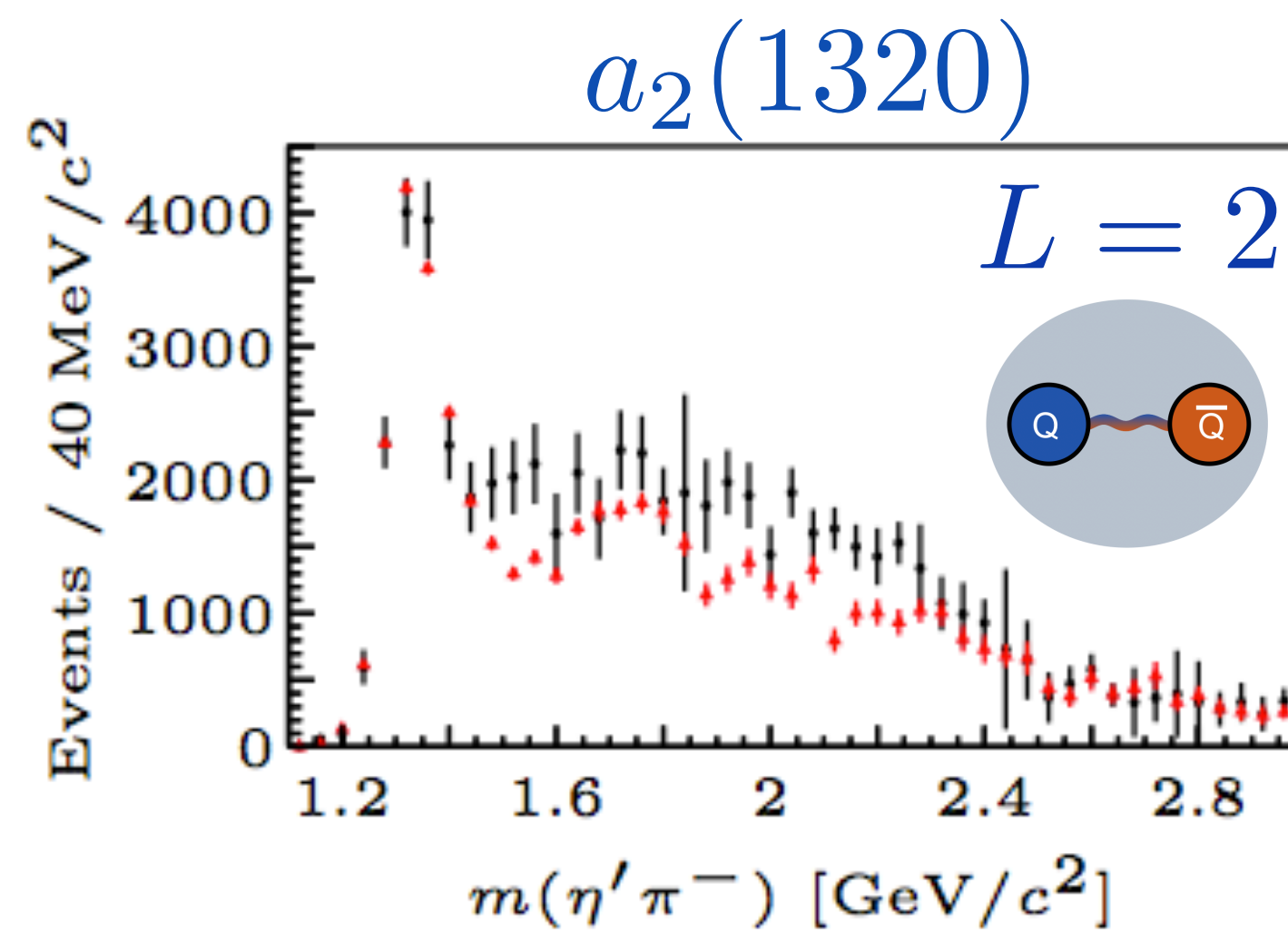
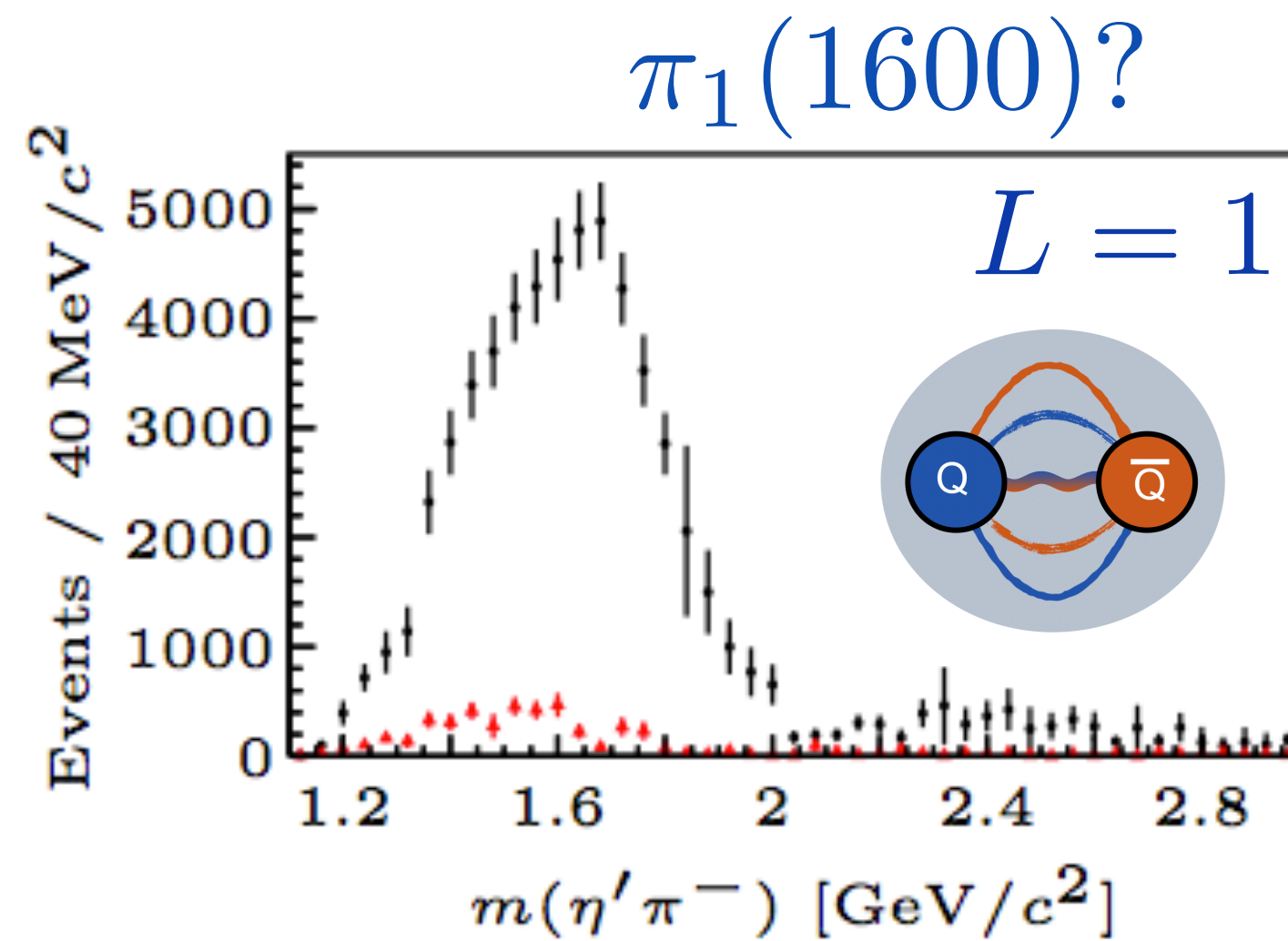
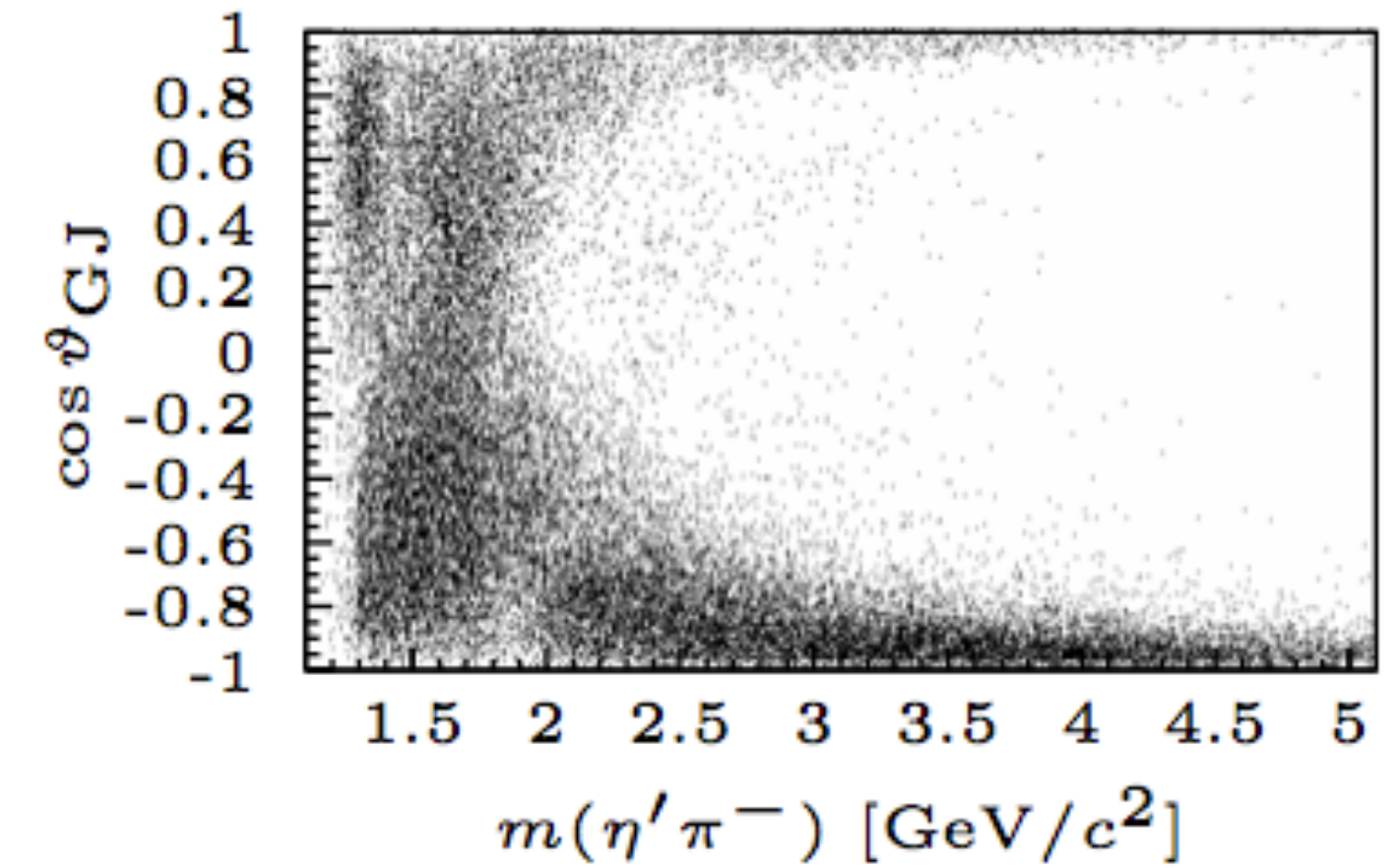
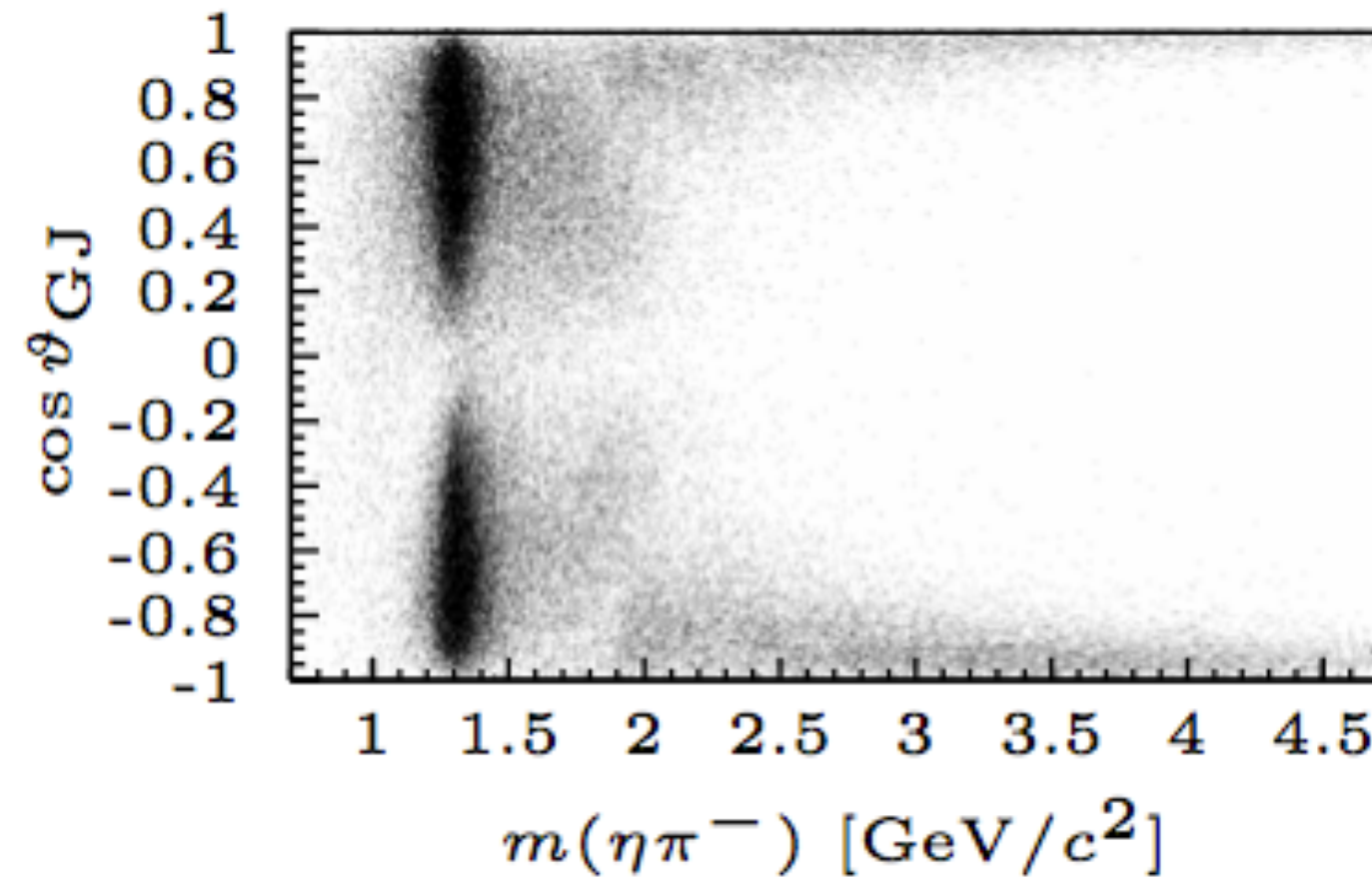
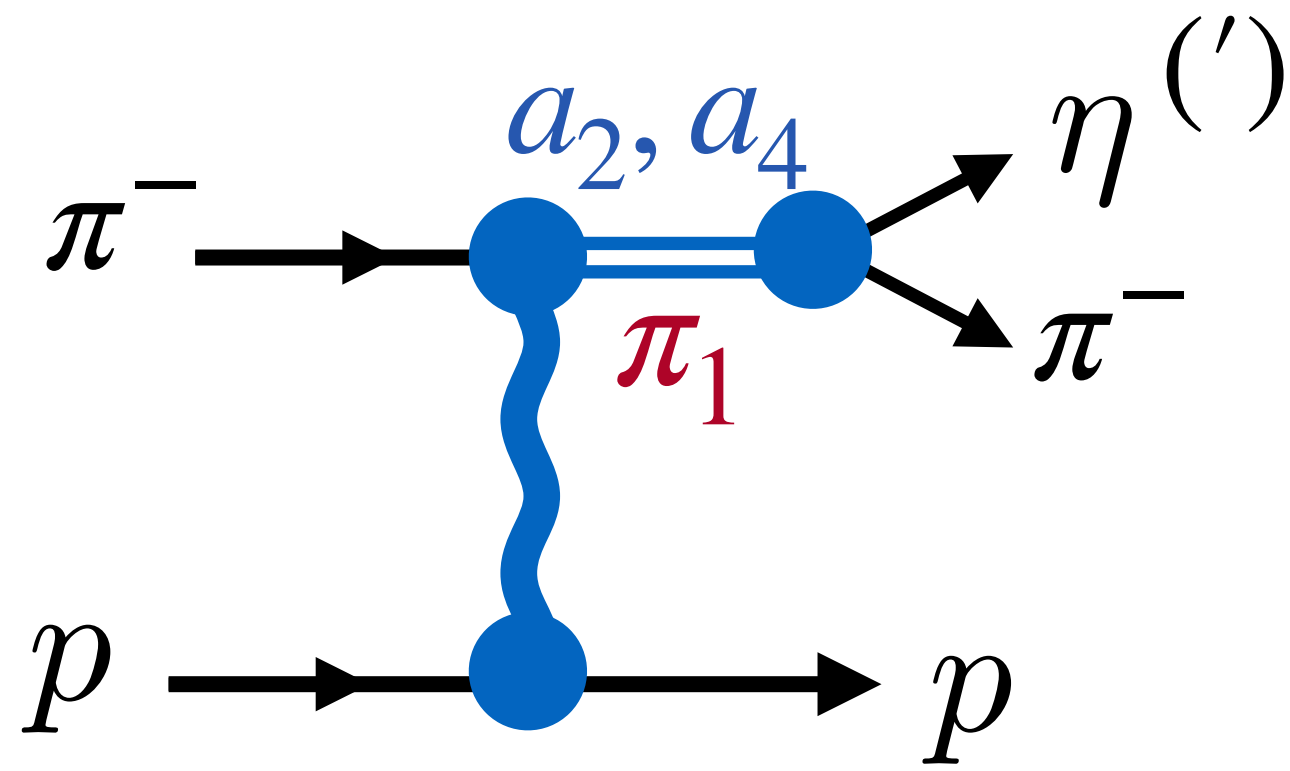


Resonance in angular mom. $L = 1$?

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

Partial Waves Expansion

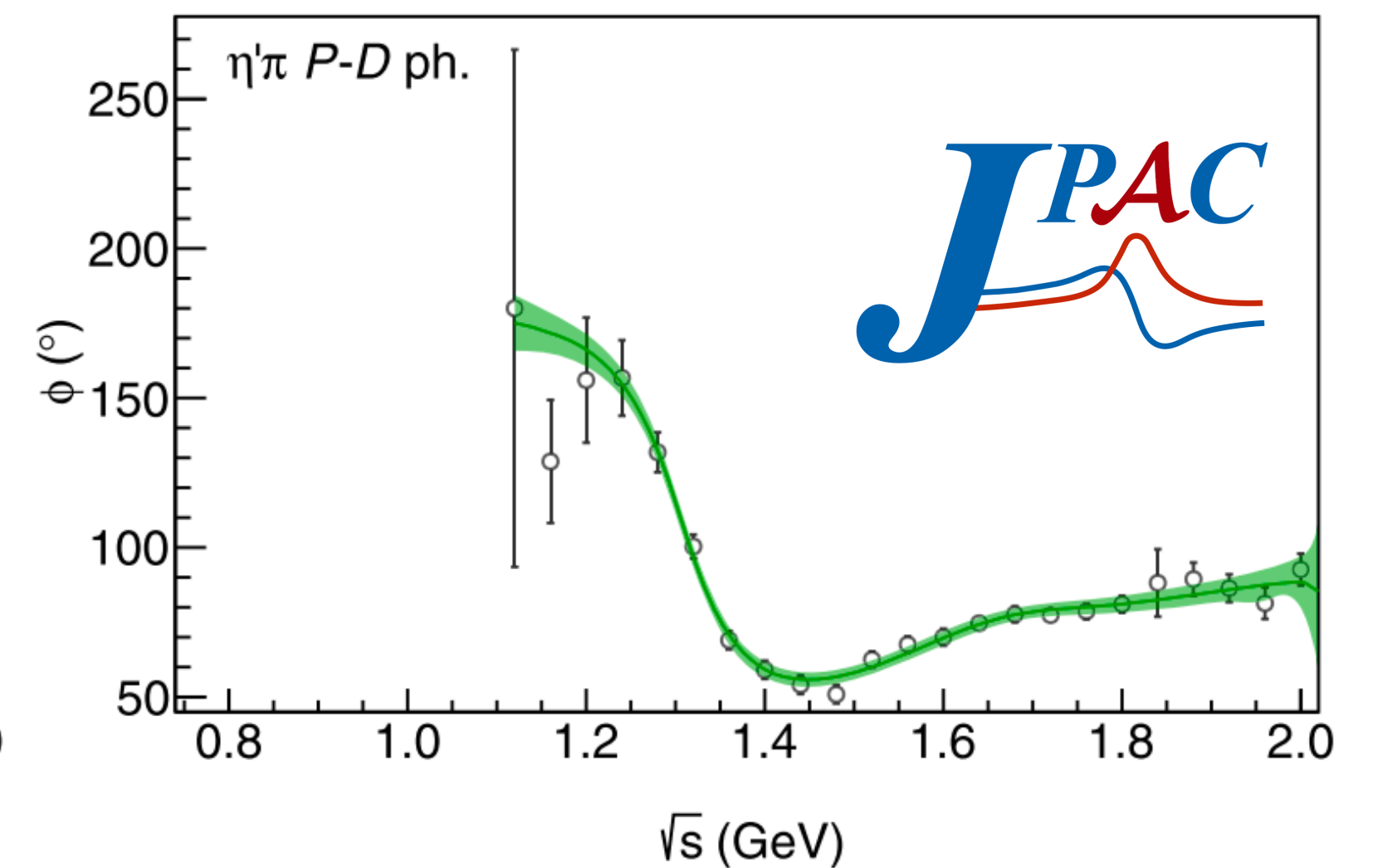
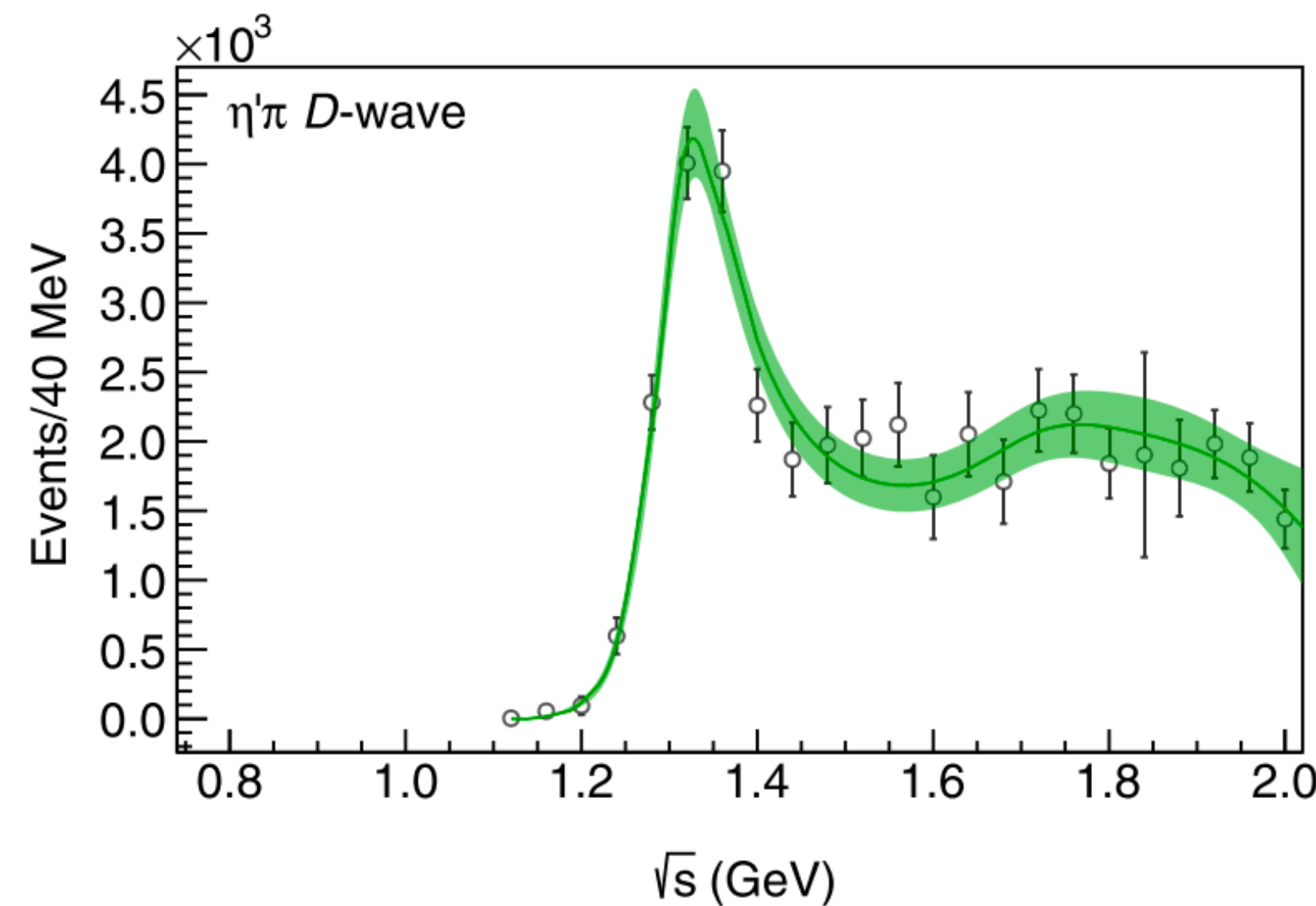
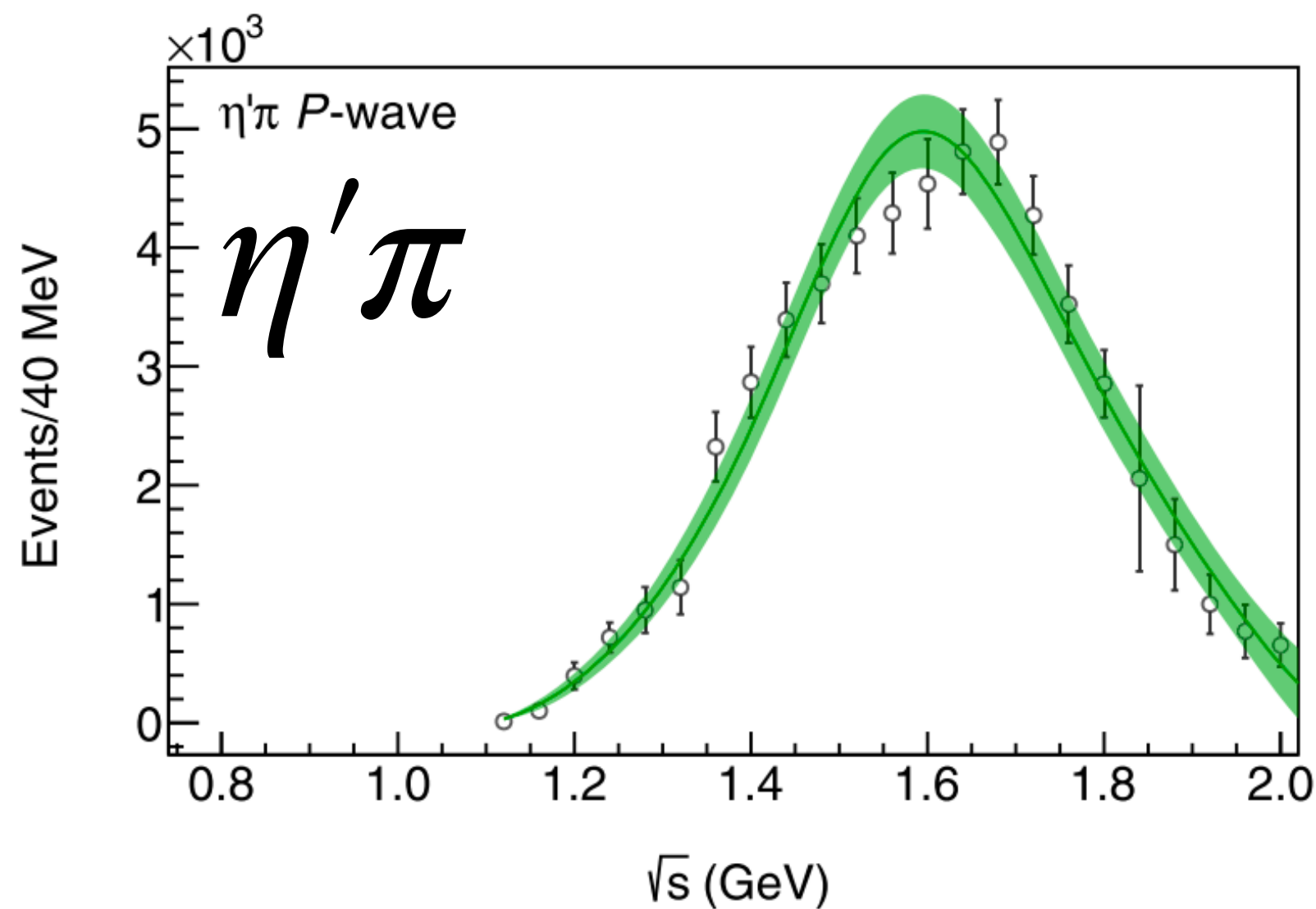
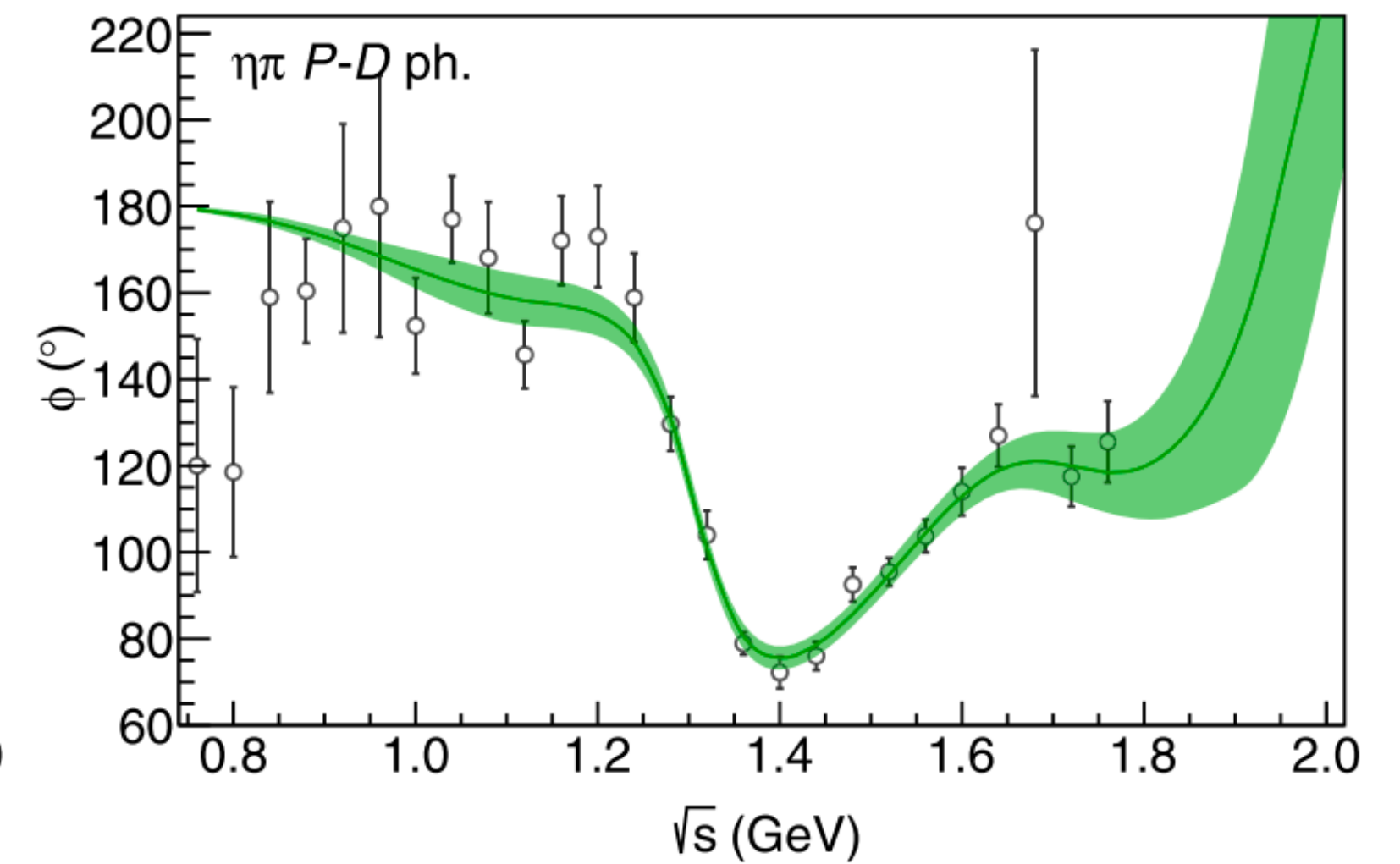
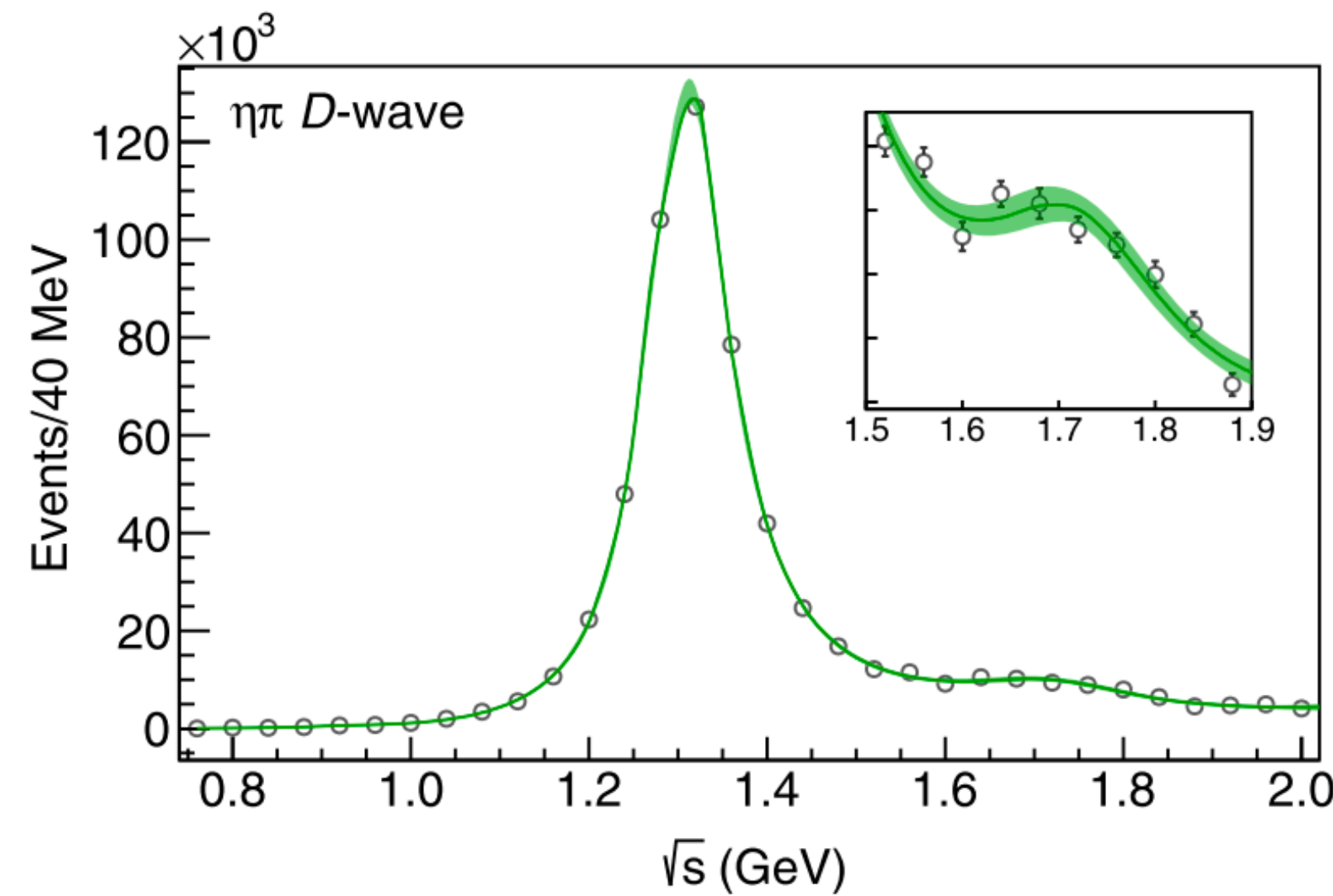
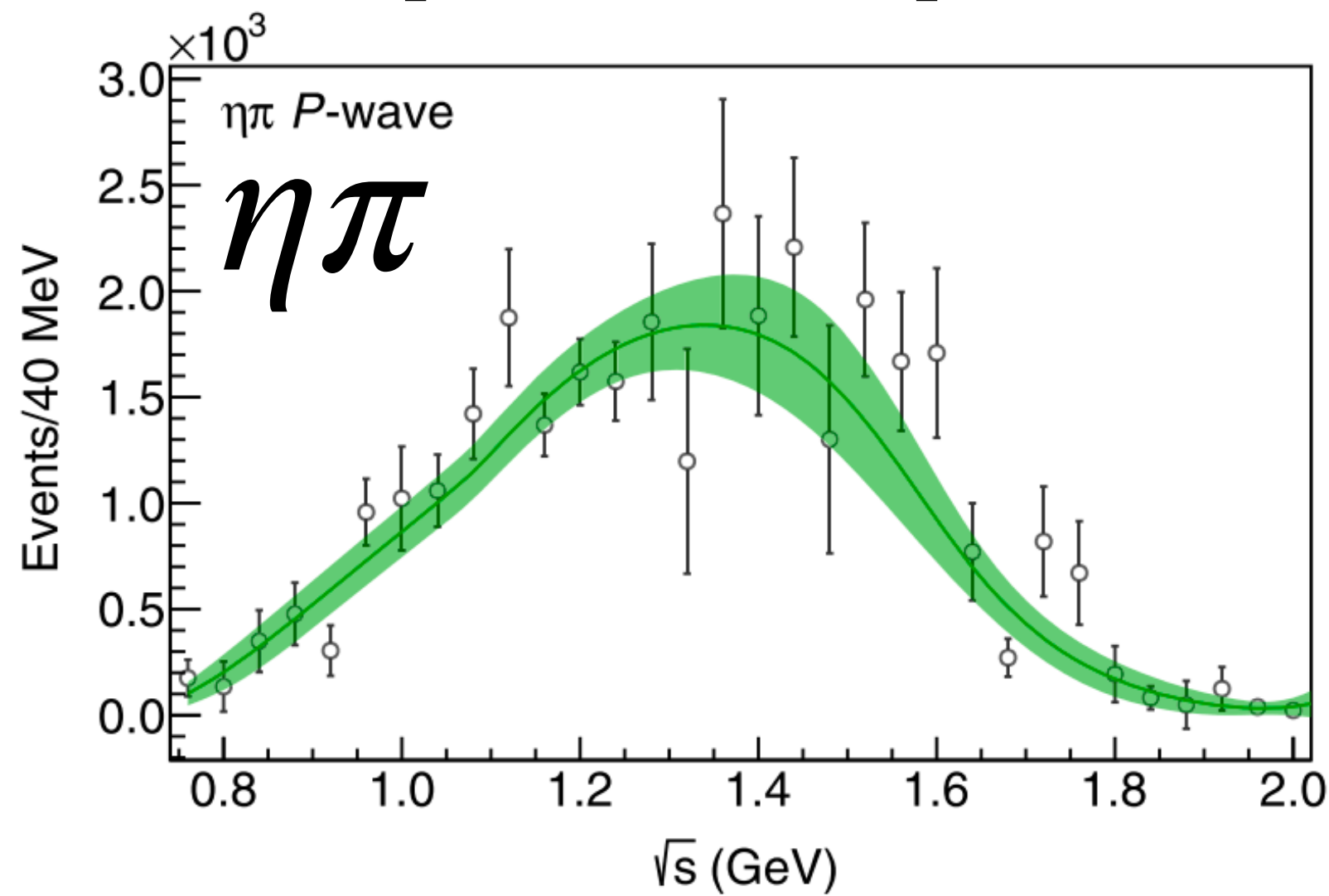
COMPASS PLB740 (2015)



Resonance in angular mom. $L = 1$?

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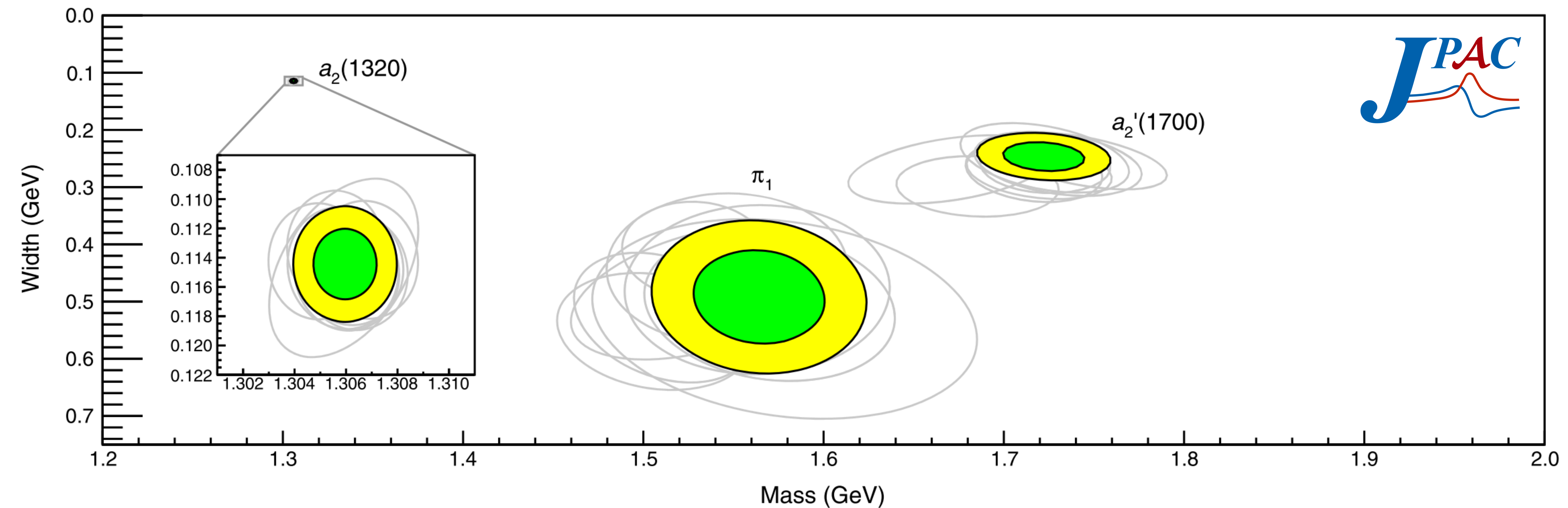
$\pi_1(1400)$ vs $\pi_1(1600)$



The exotic π_1 pole location

Rodas et al (JPAC) PRL122 (2019) 042002

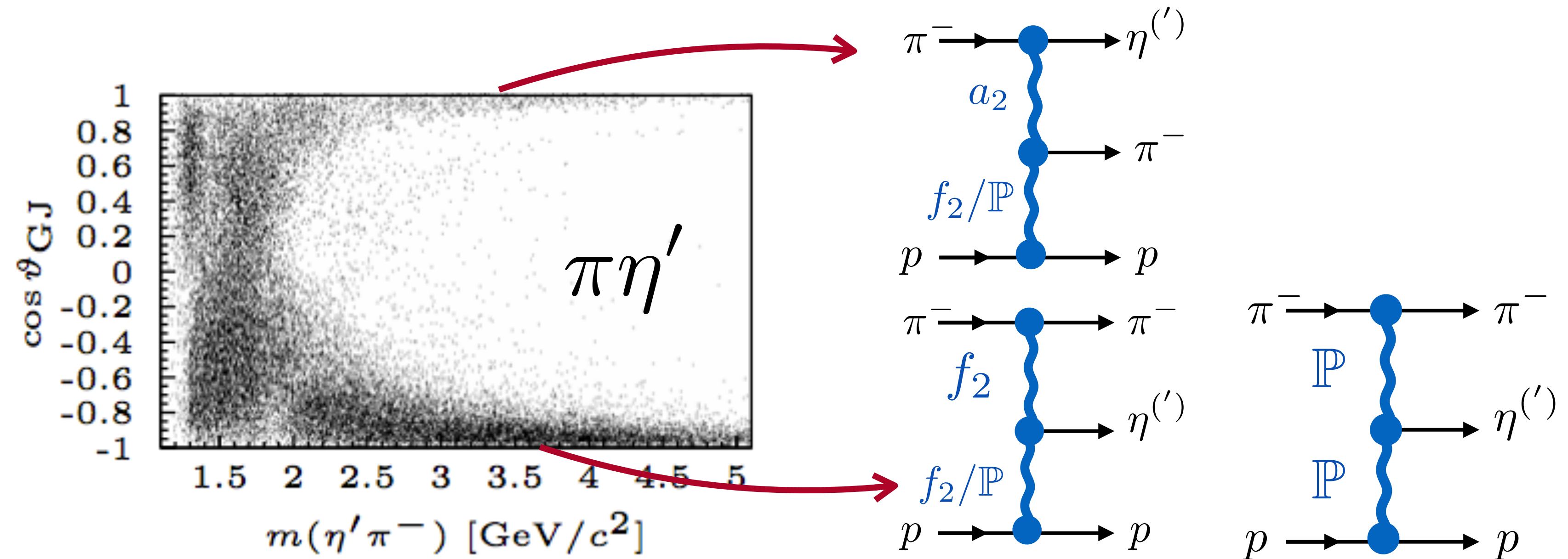
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$



More on the exotic π_1

Bibrzycki et al (JPAC), EPJC81 (2021) 647

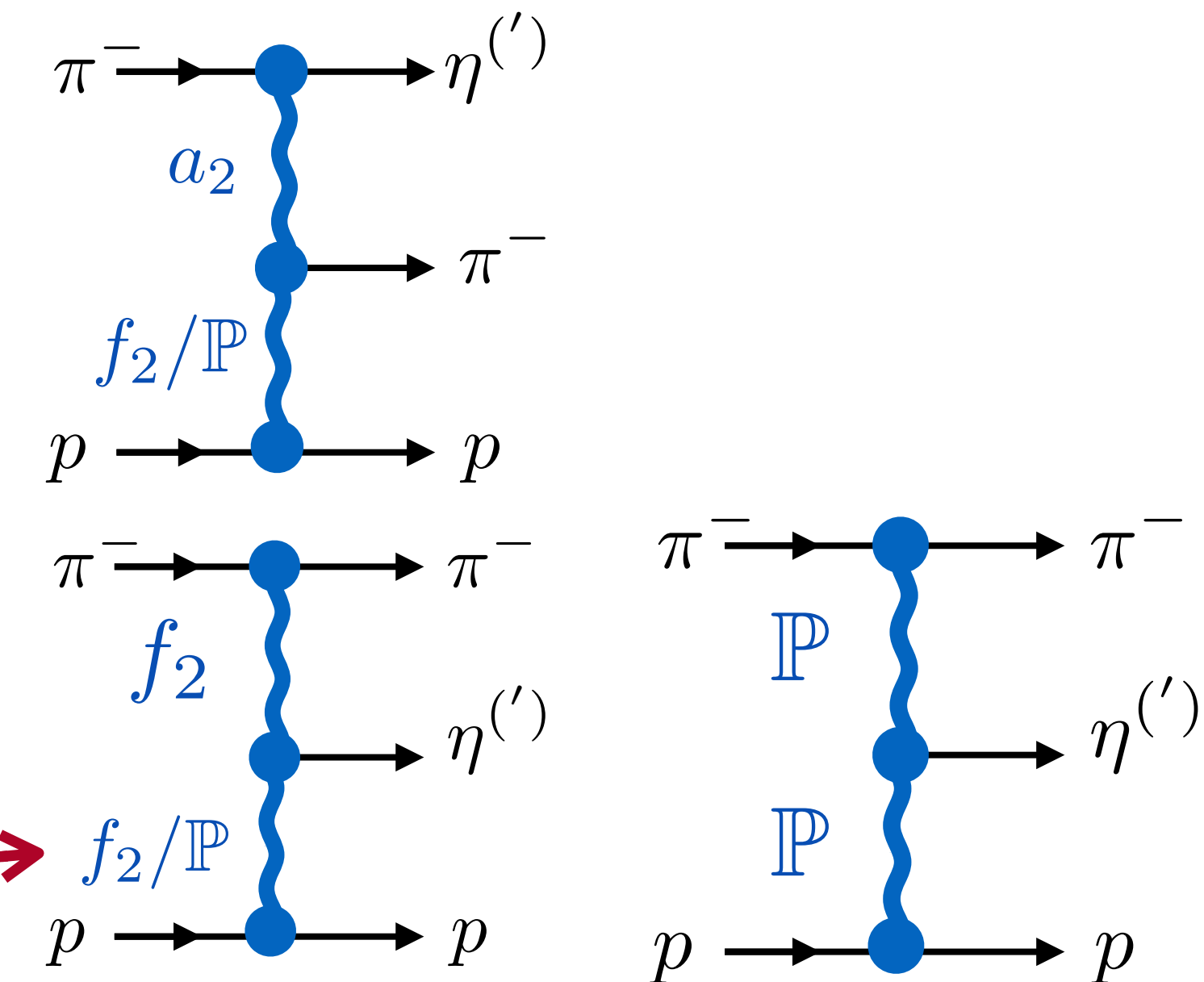
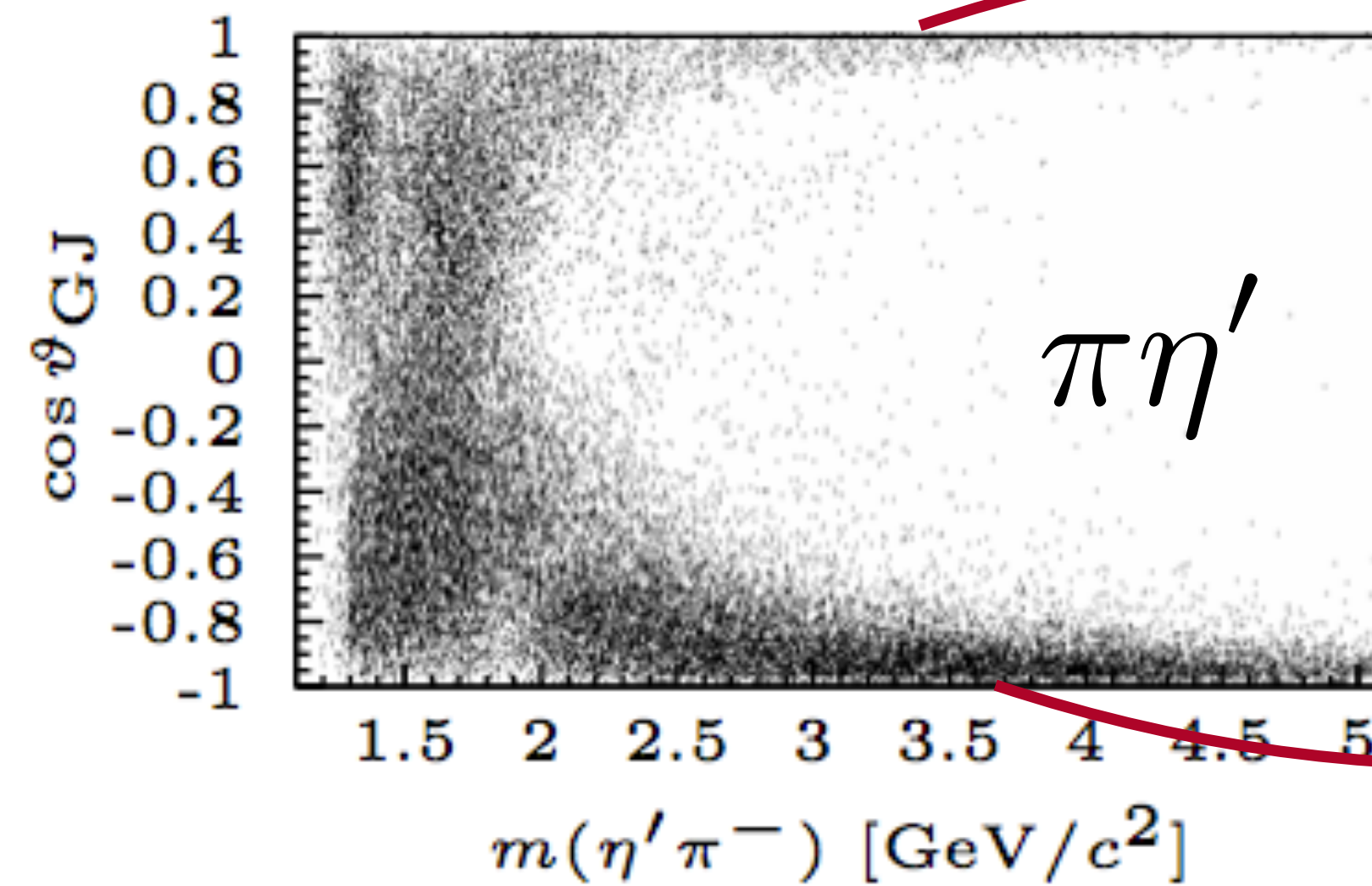
Forward-backward
asymmetry related to
the existence of (exotic)
P-wave



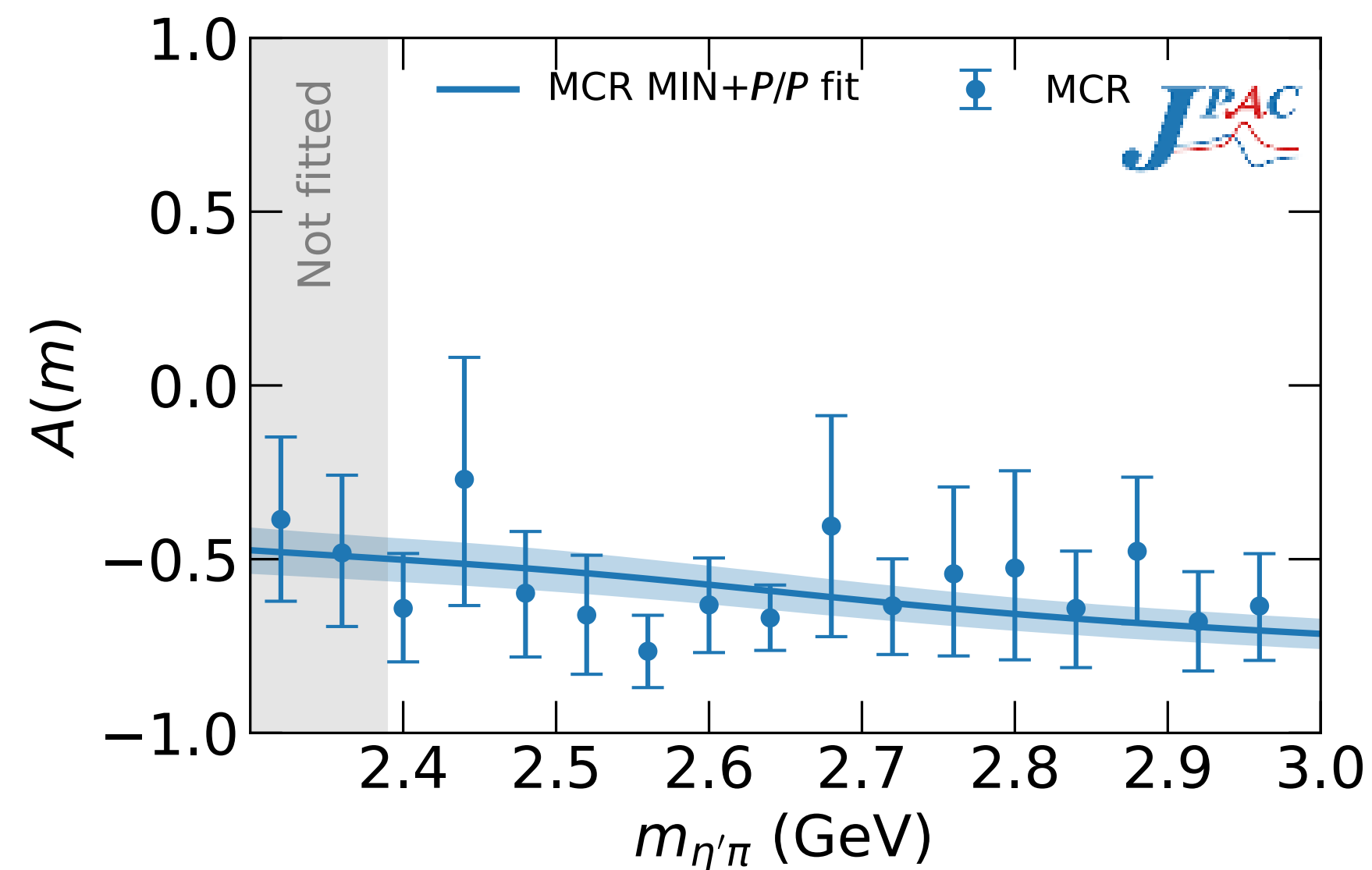
More on the exotic π_1

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Forward-backward asymmetry related to the existence of (exotic) P-wave



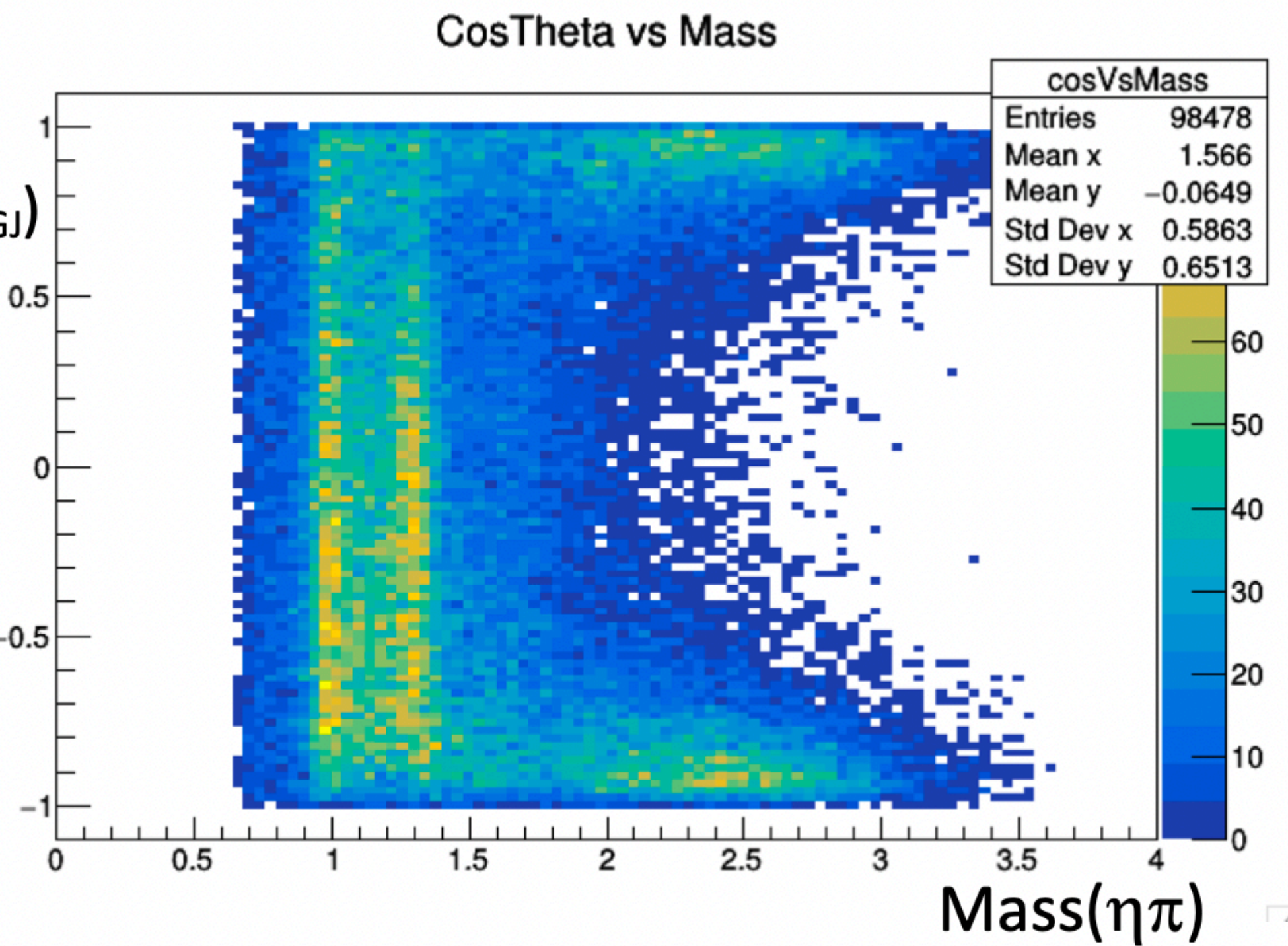
$$\frac{\text{forward} - \text{backward}}{\text{forward} + \text{backward}} =$$



Asymmetry originating mainly from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from $(\mathbb{P}, \mathbb{P})$ in $\eta' \pi$

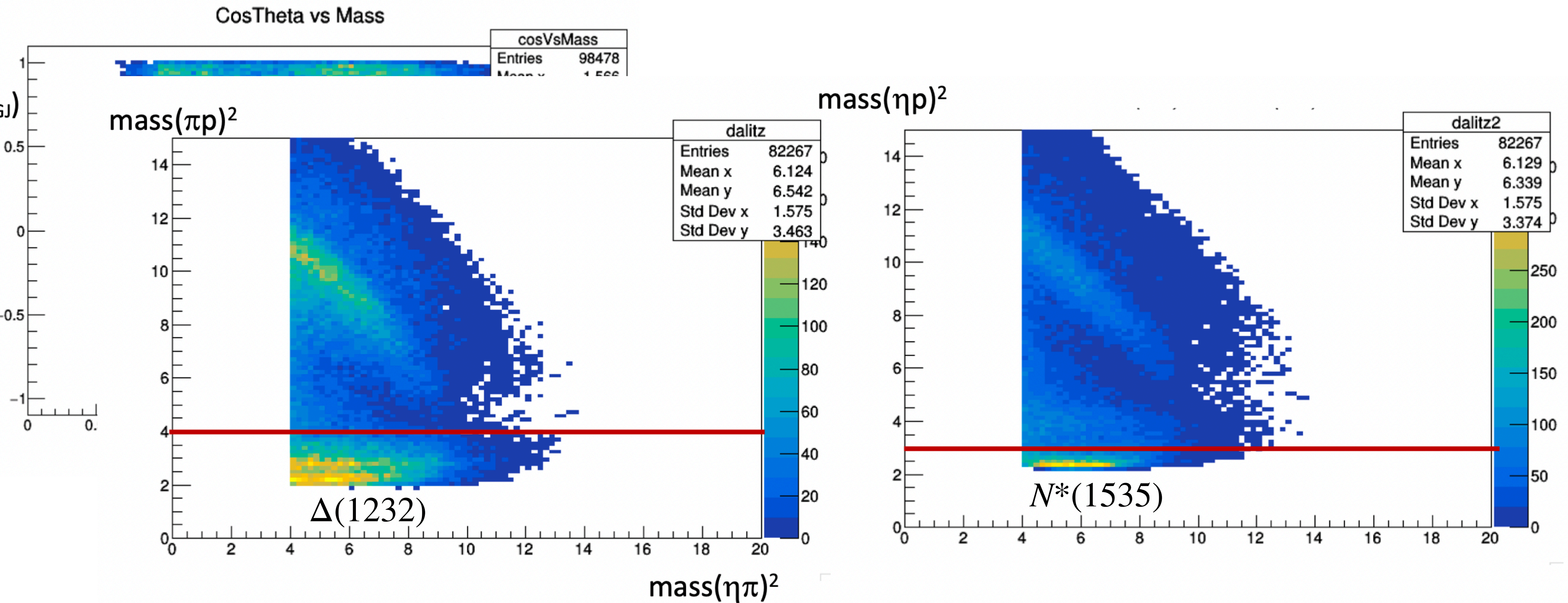
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



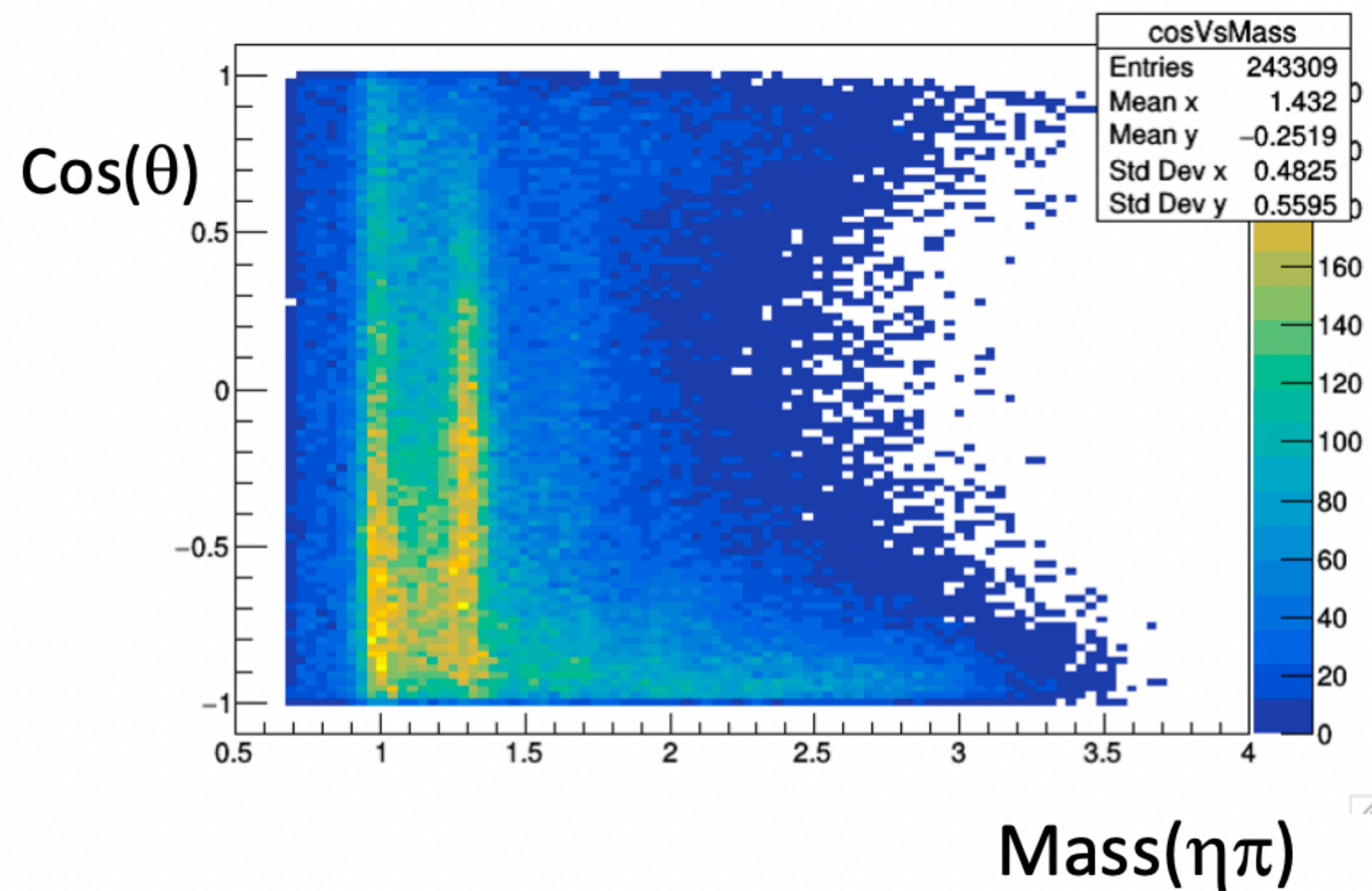
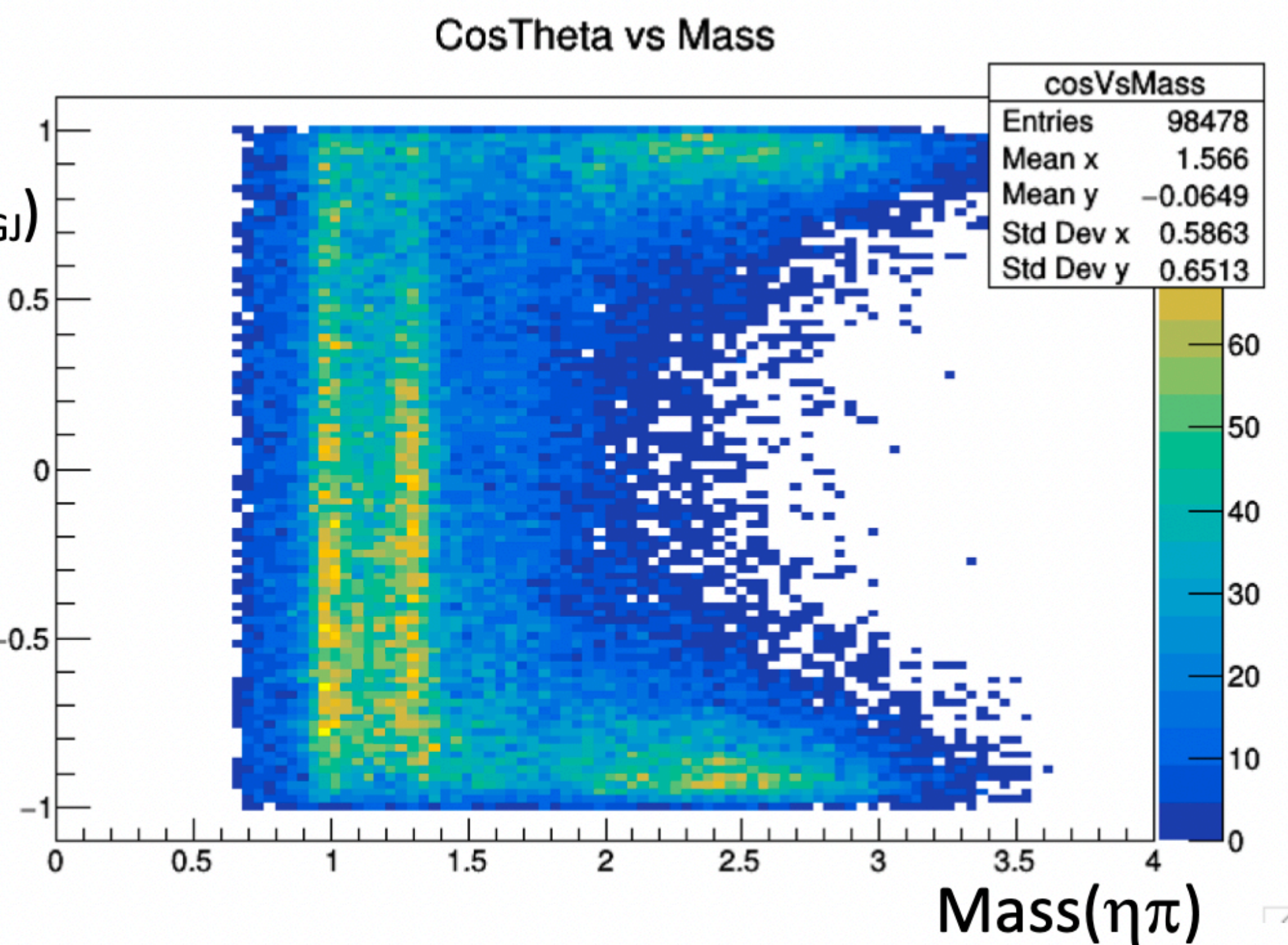
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti

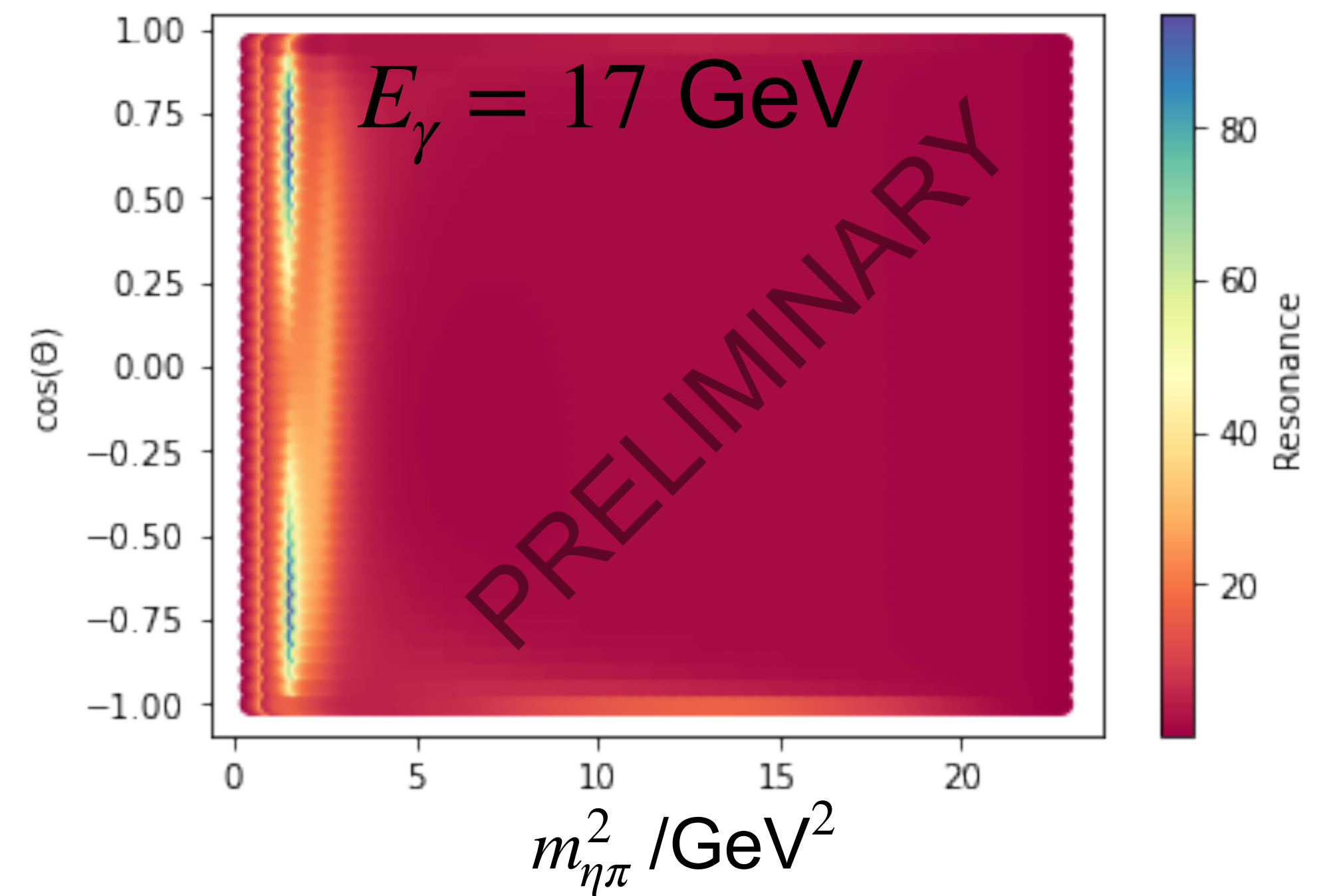
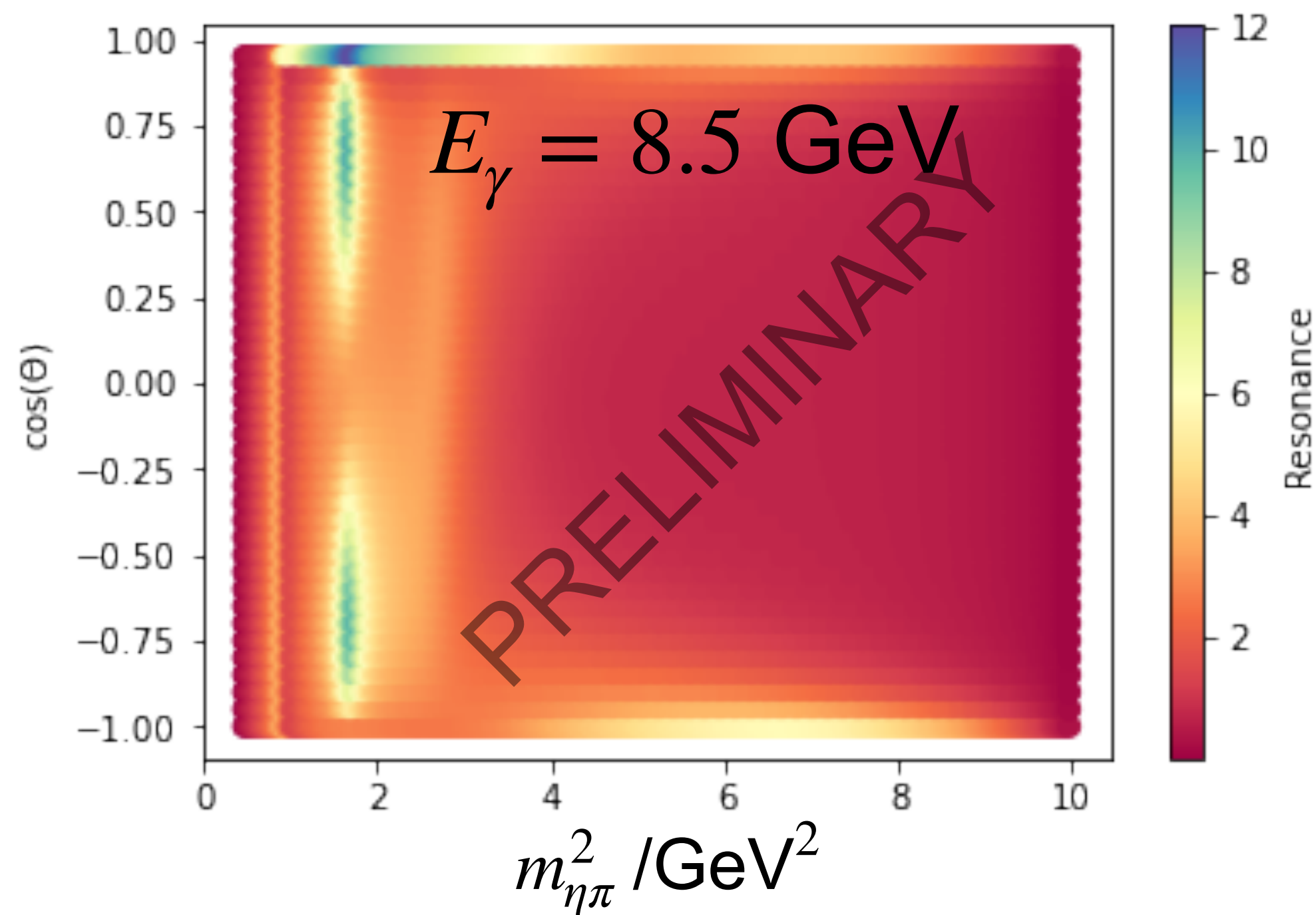


Baryon resonances contaminate the high mass $\eta\pi$

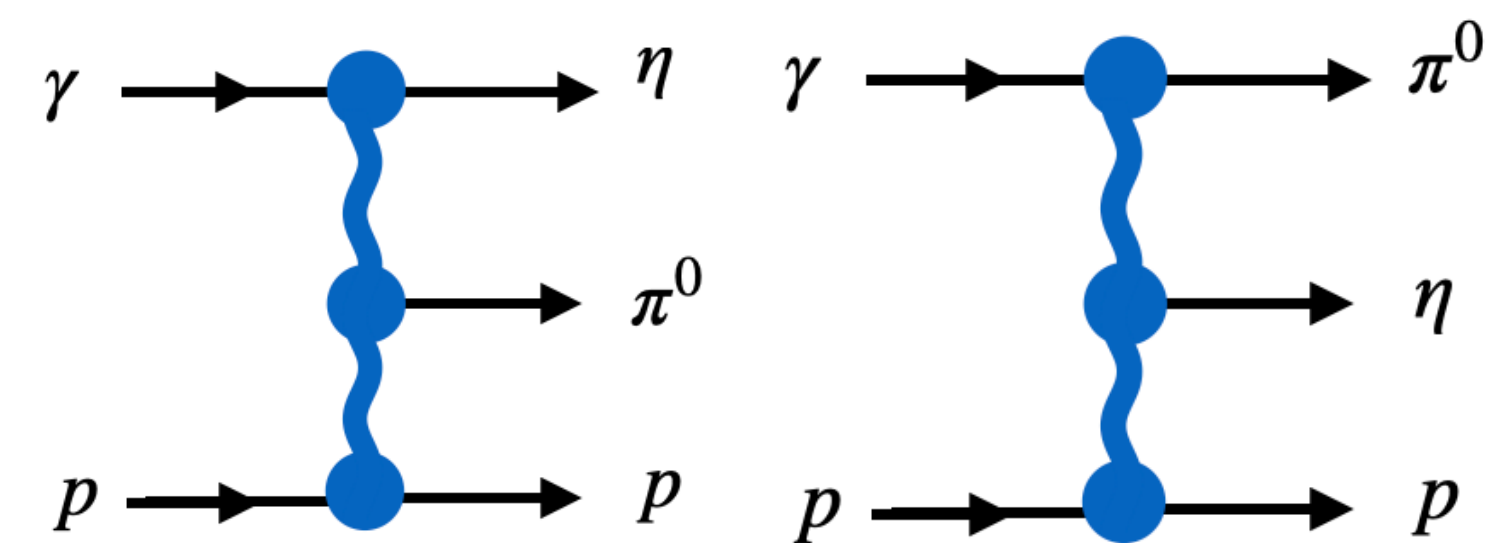
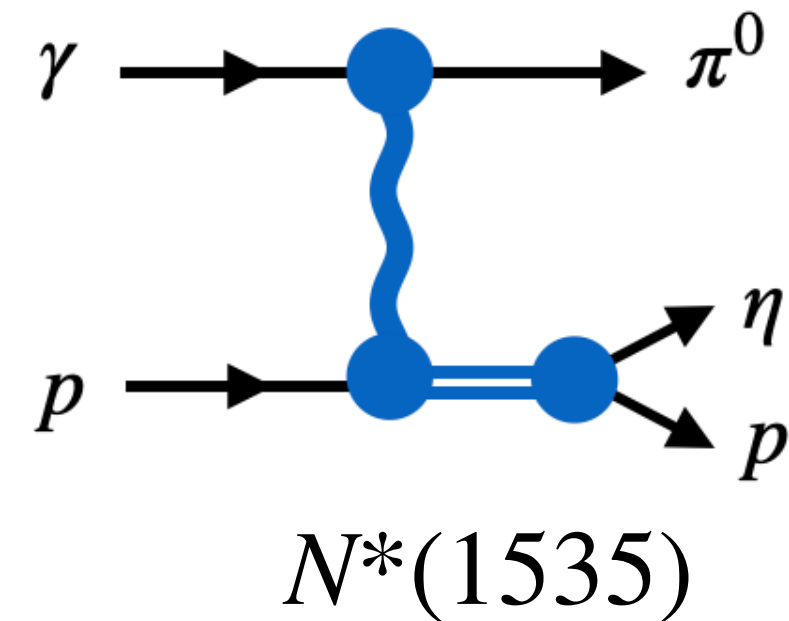
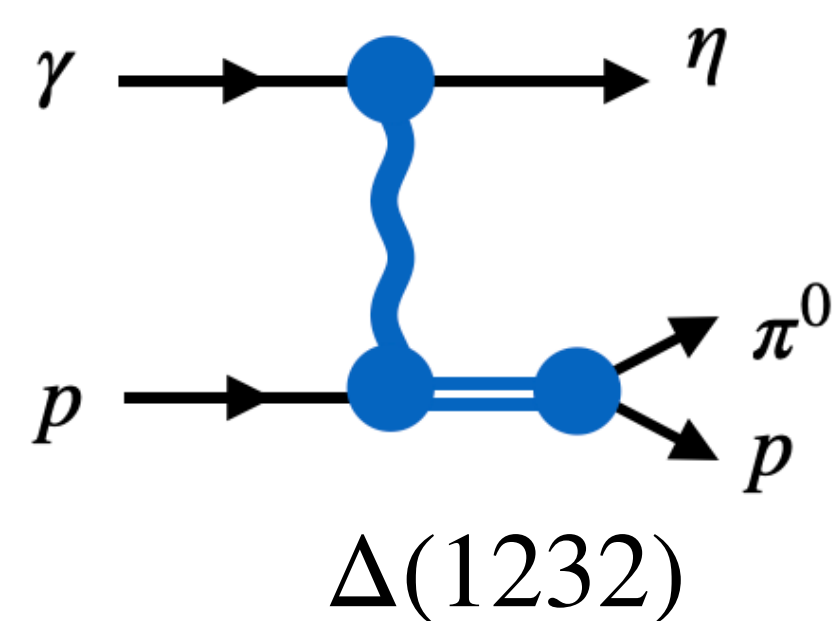
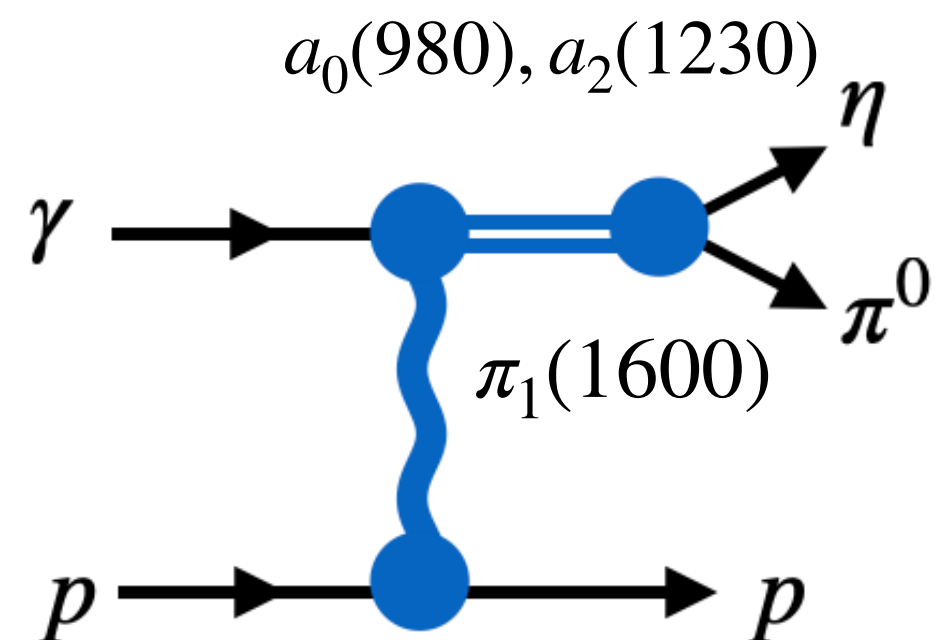
Less baryon contamination when the energy increases

$\eta\pi^0$ Photoproduction@GlueX

In collaboration with E. Llanos

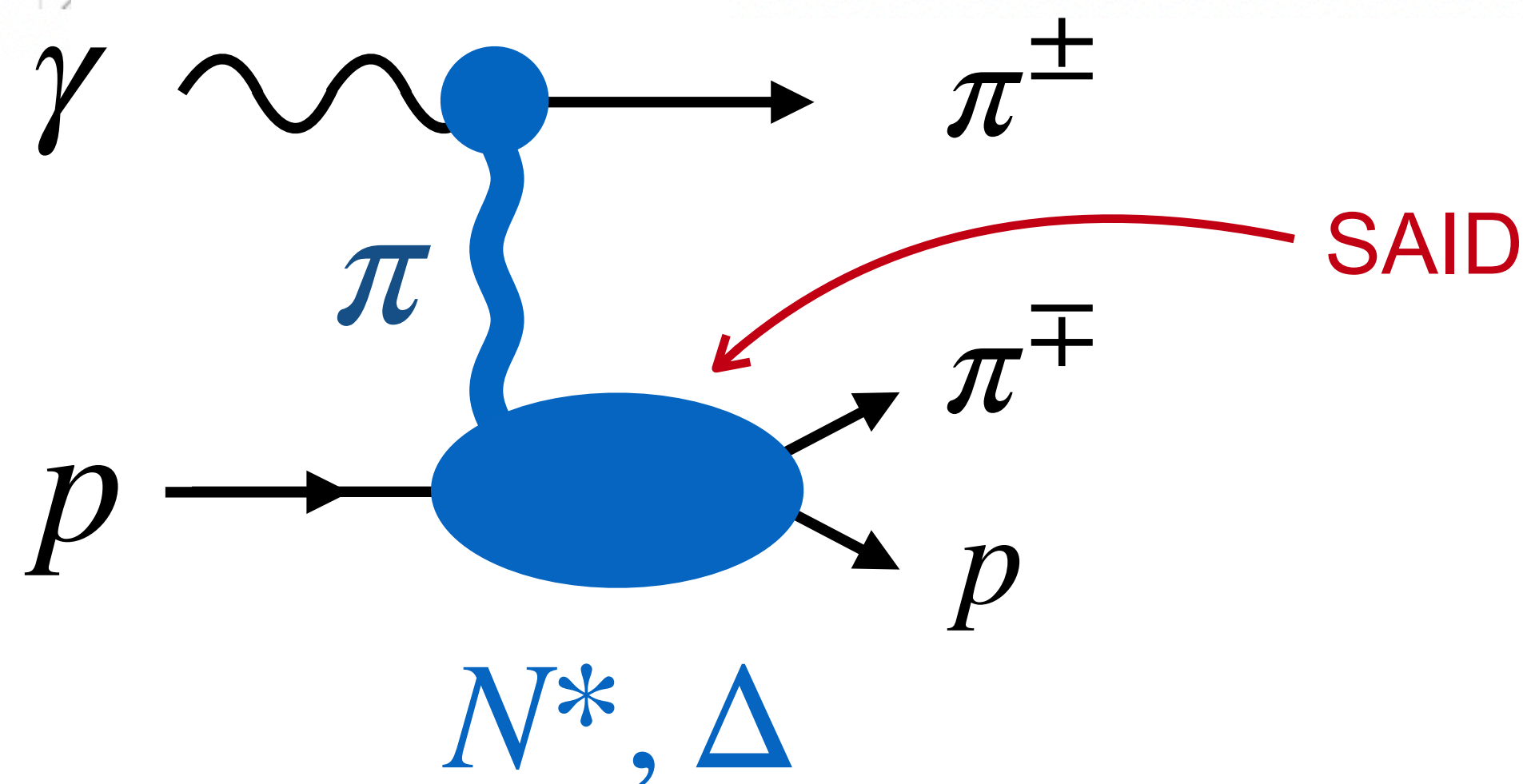
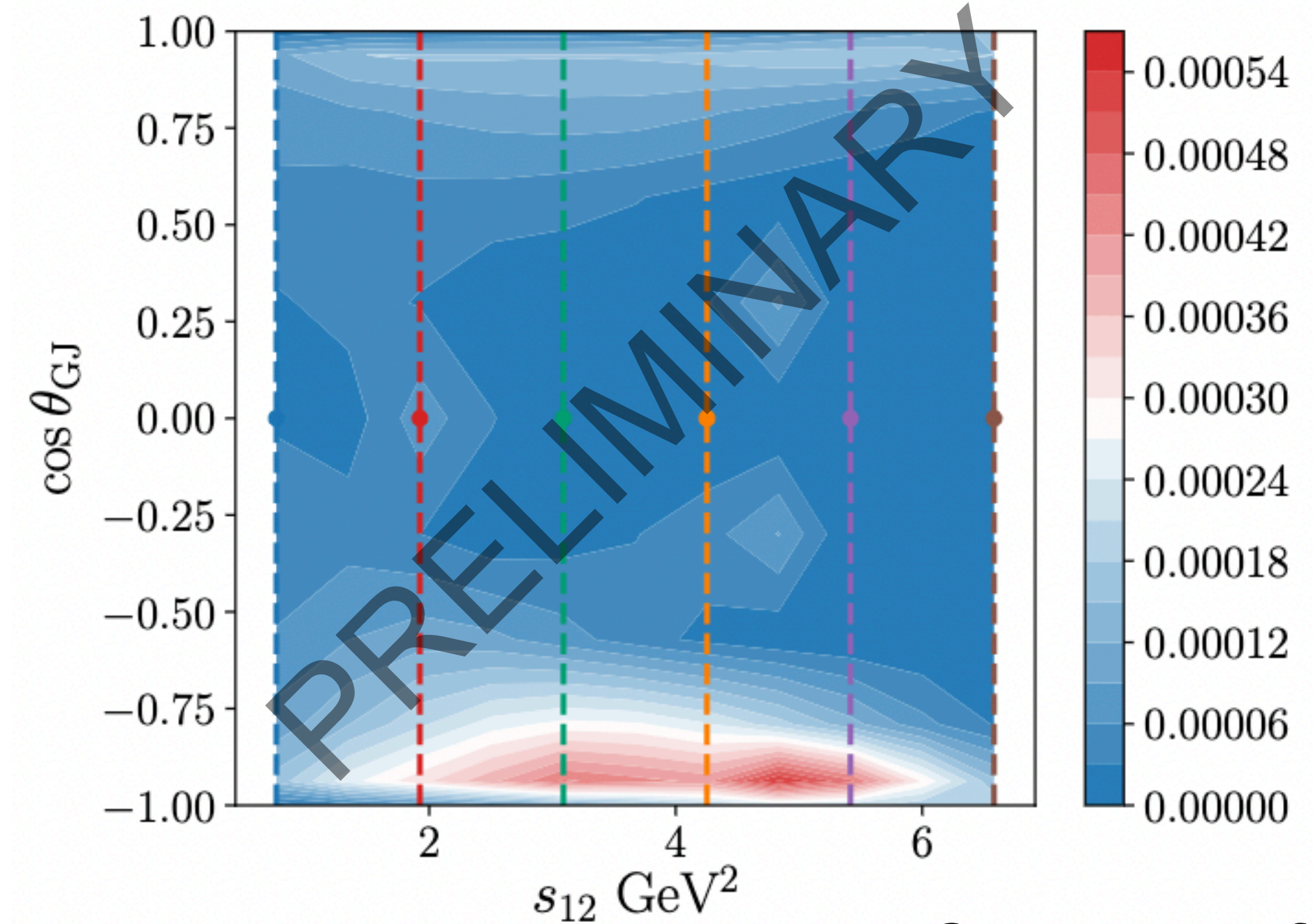
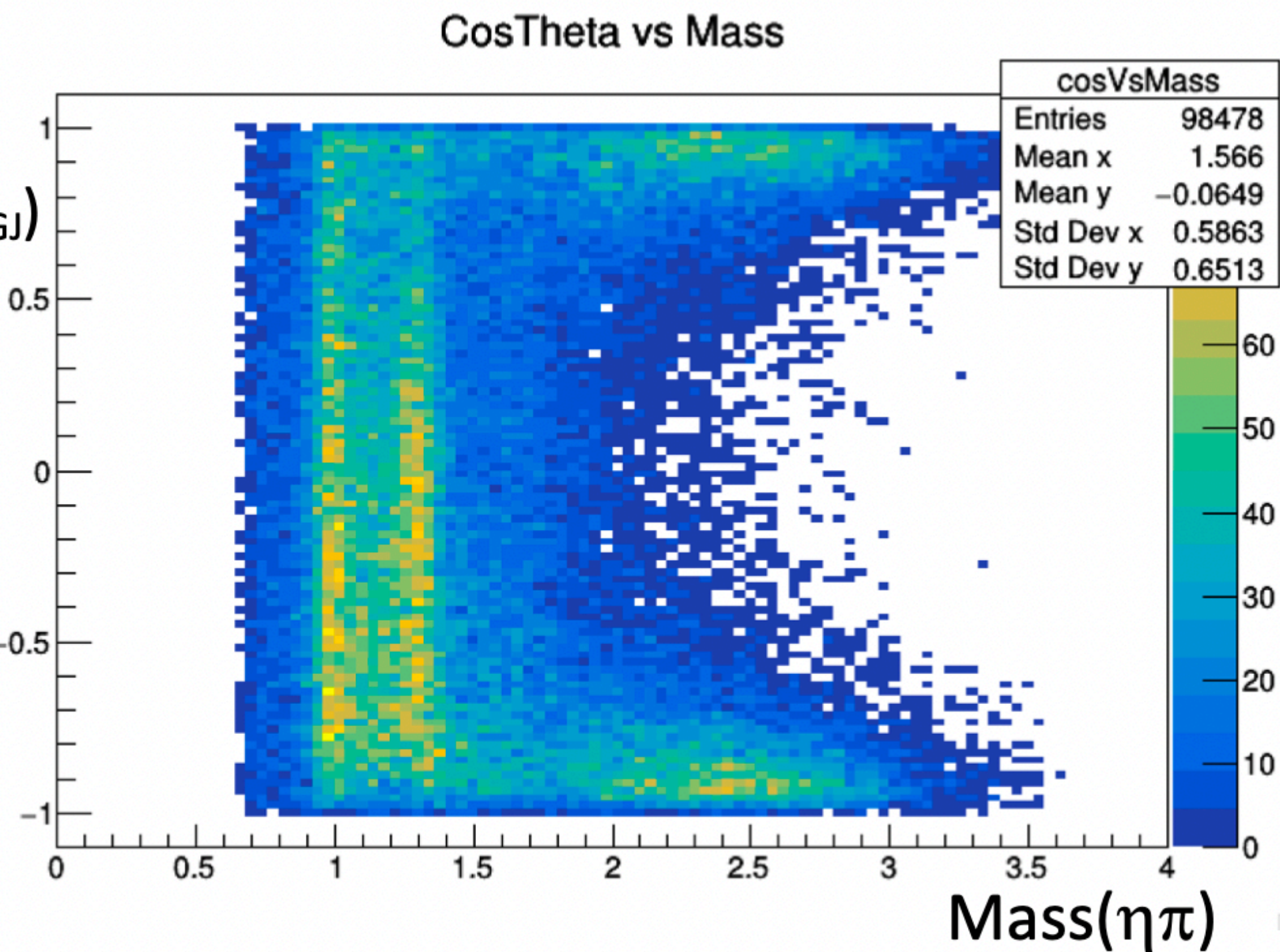


Simple model (all external particles = scalar) including:



$\eta\pi^0$ Photoproduction@GlueX

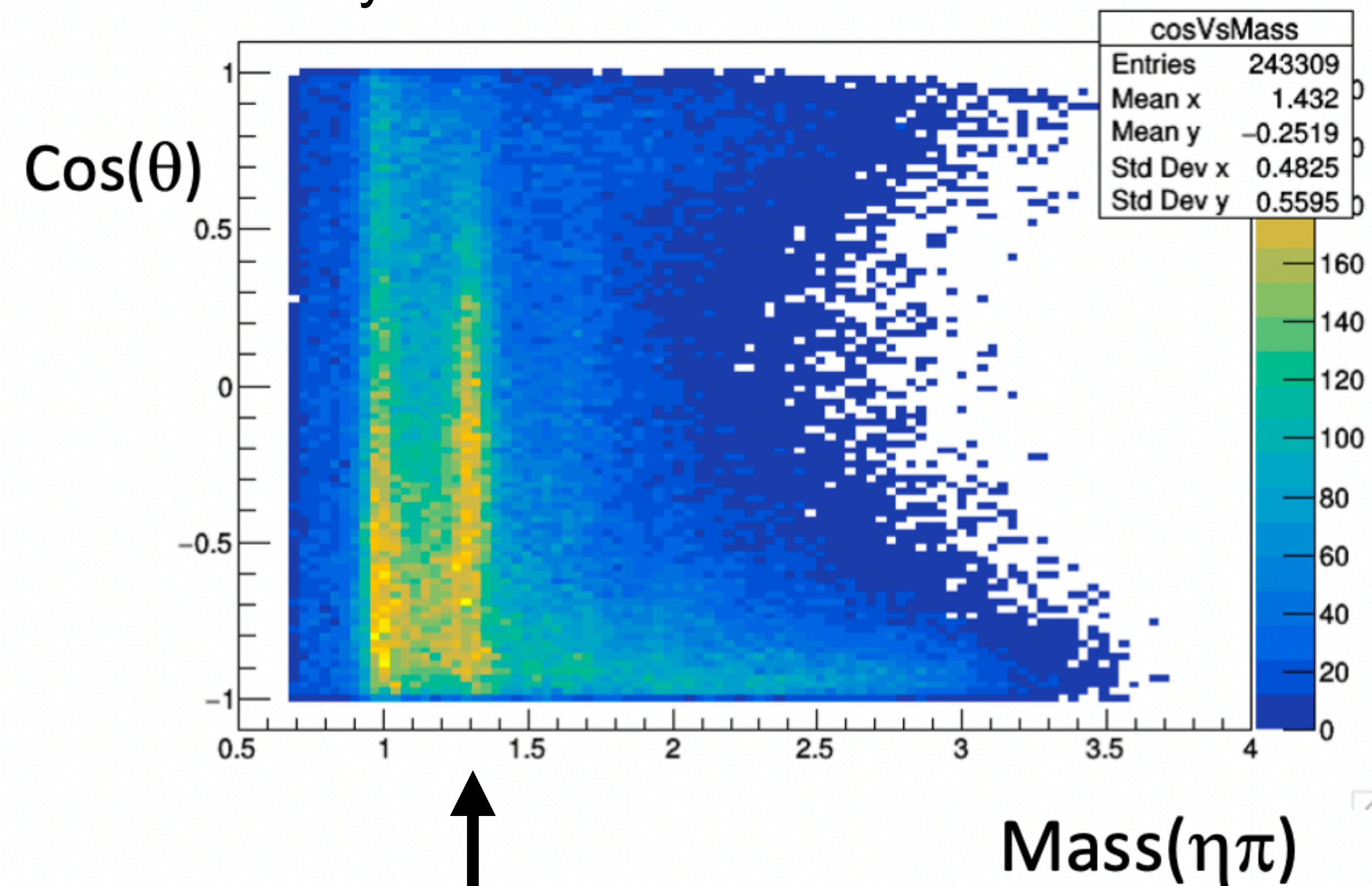
In collaboration with R. Barsotti



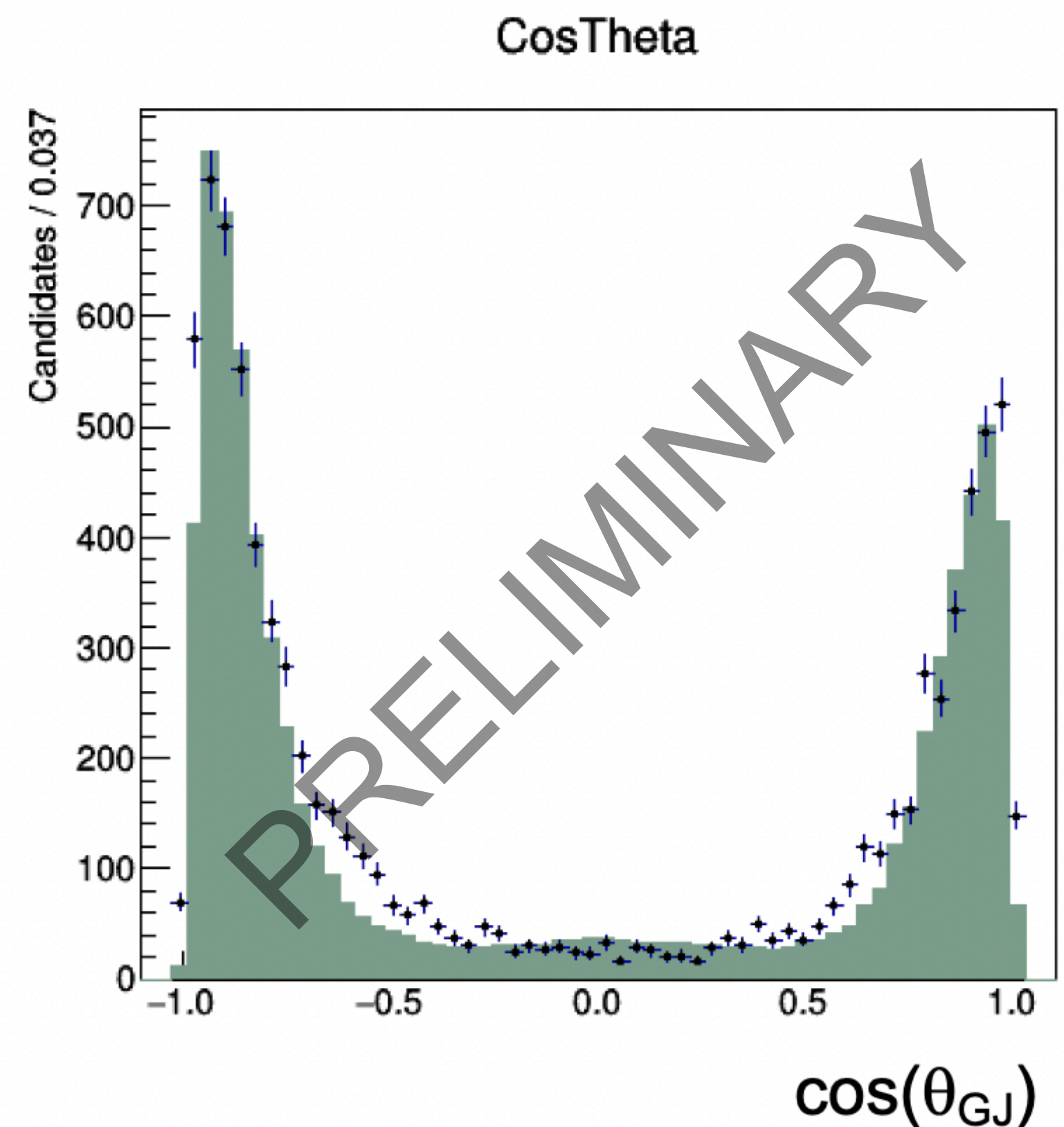
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti

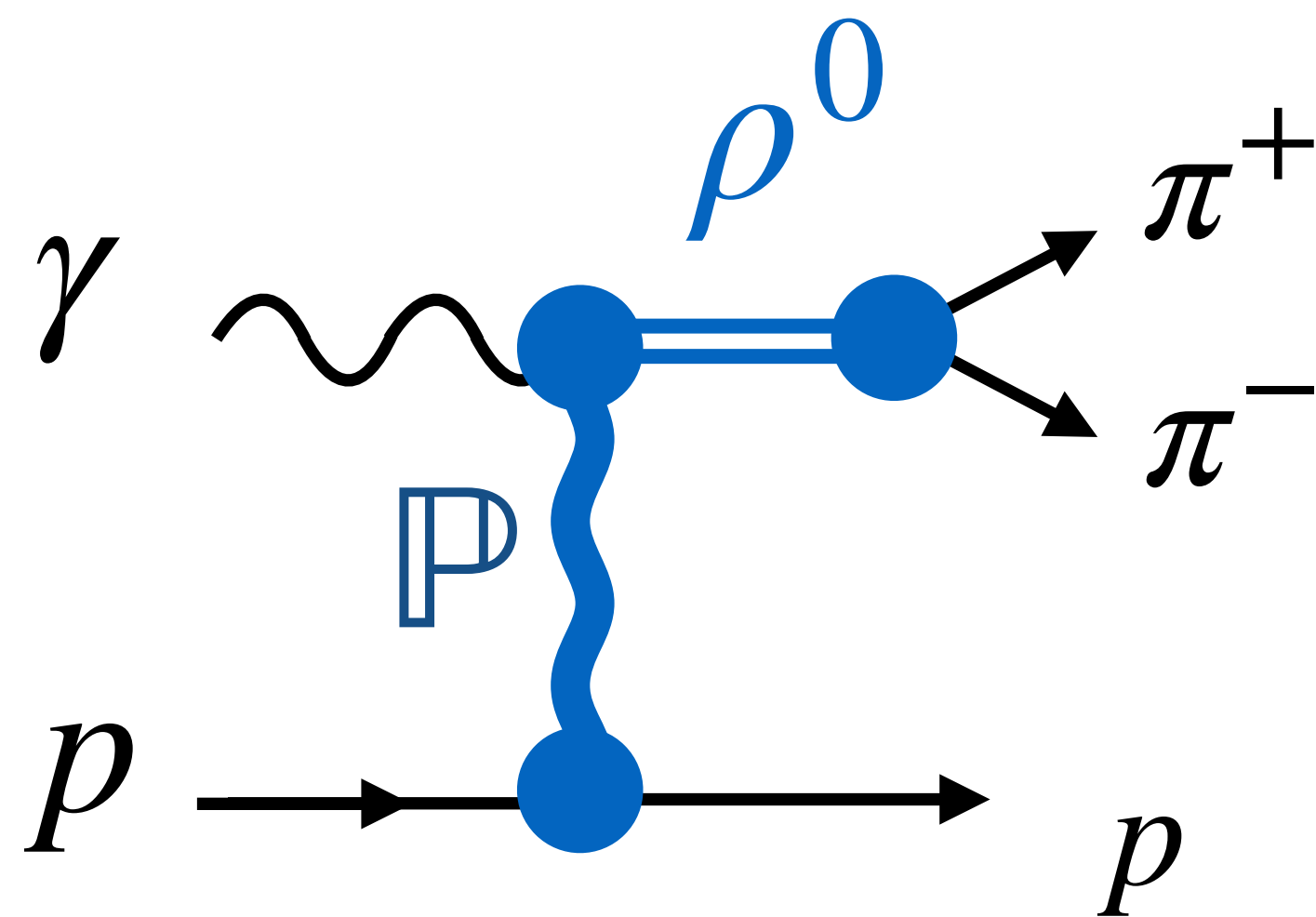
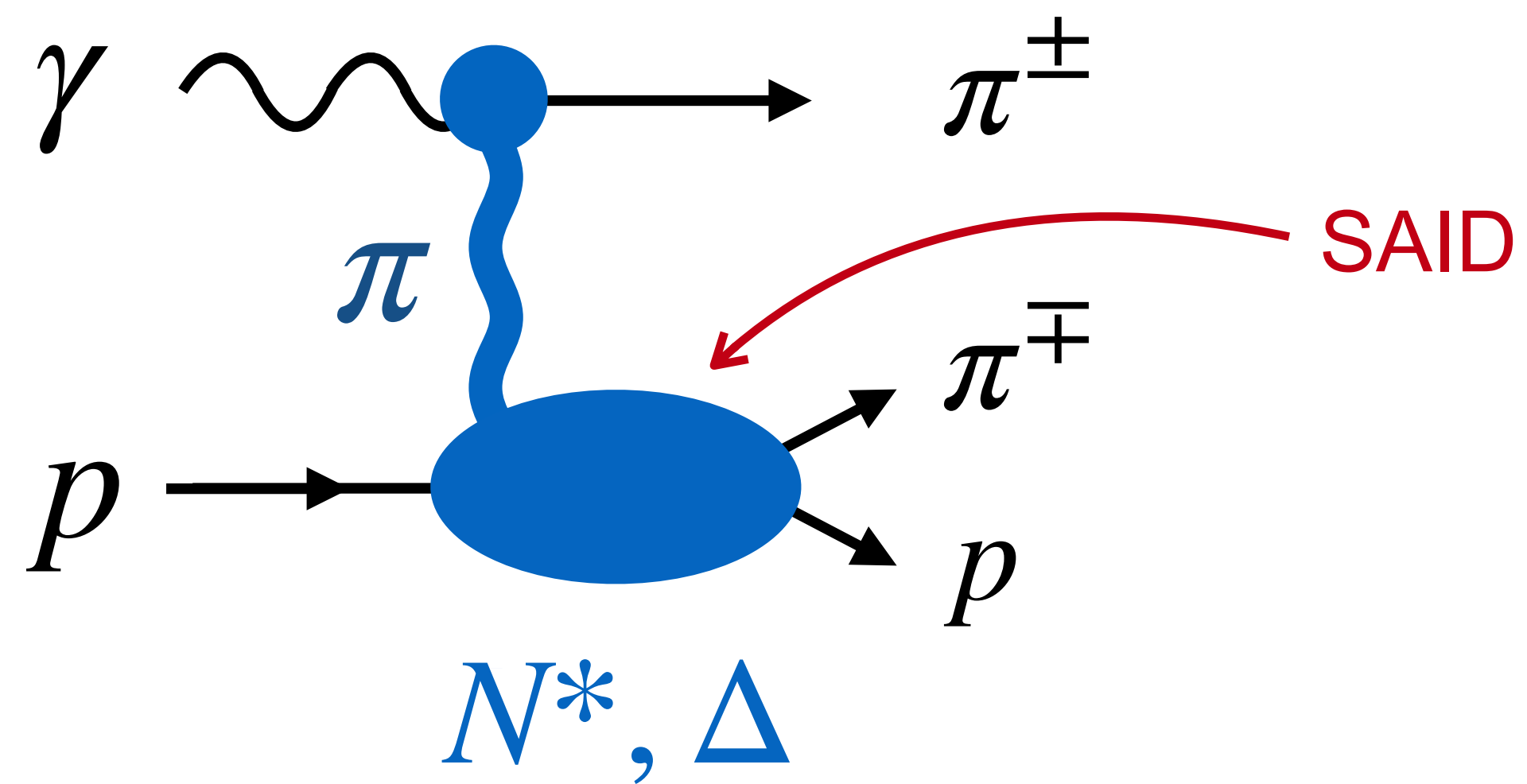
Baryons have been 'cut out'



$a_2(1320)$



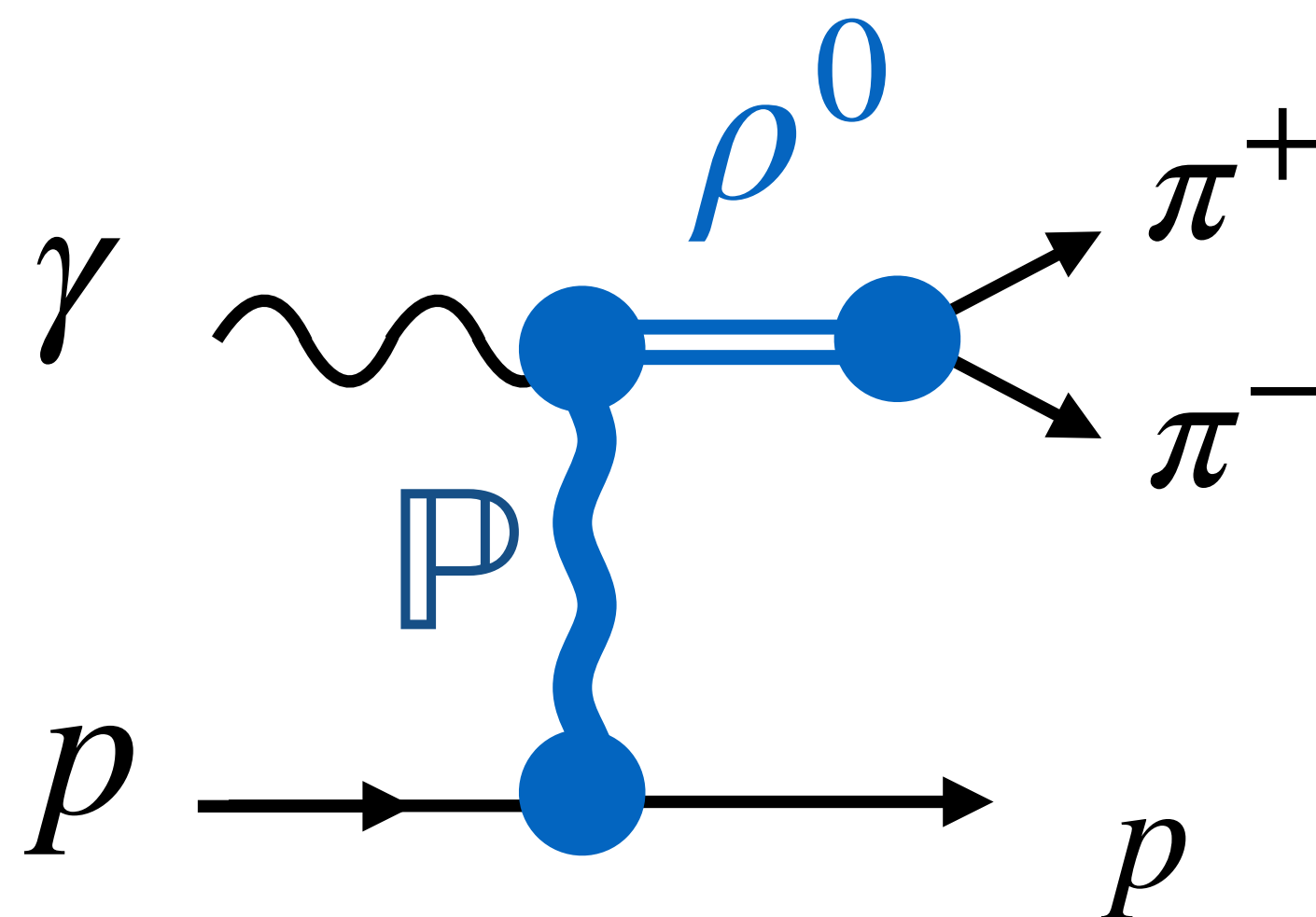
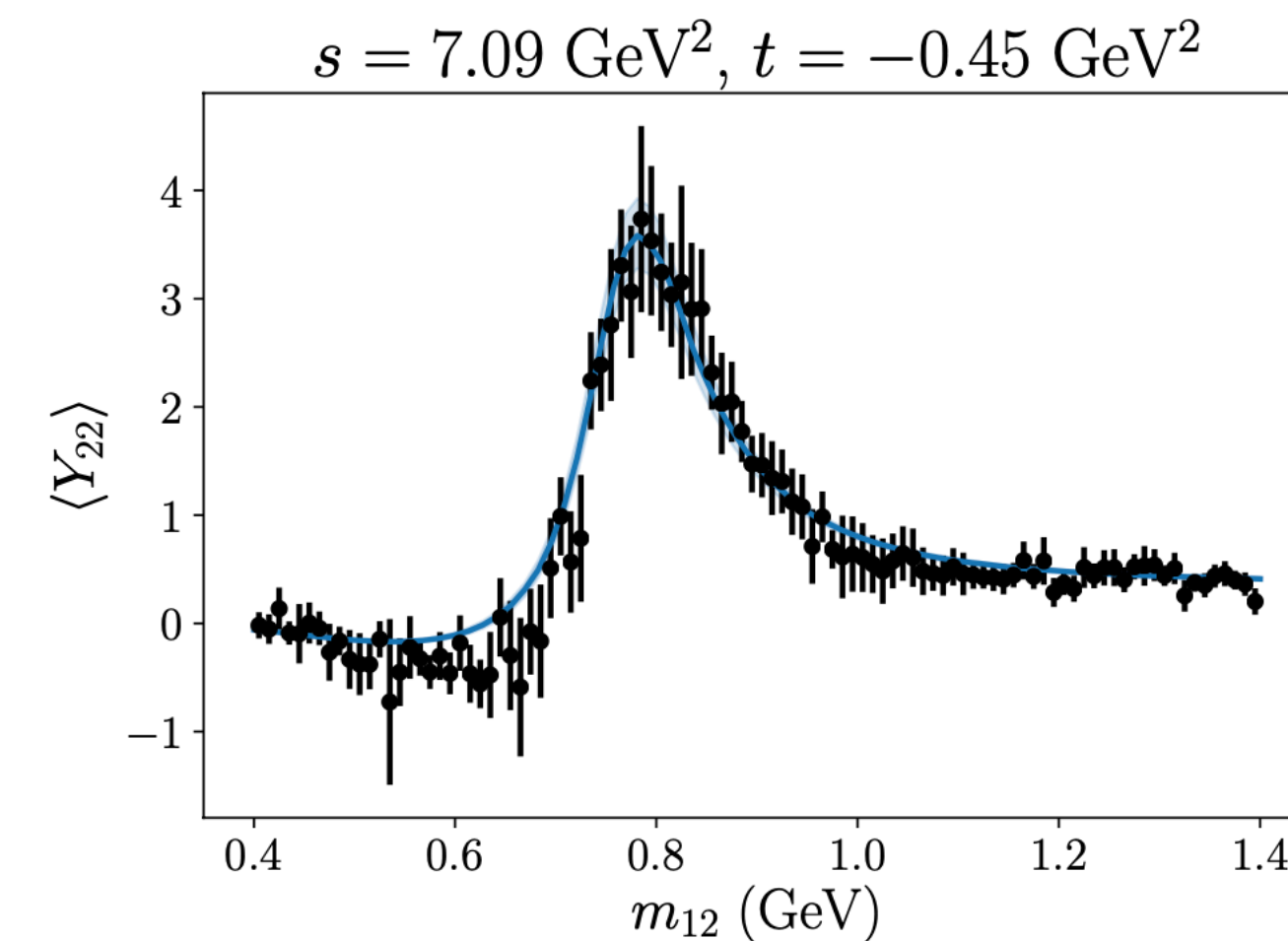
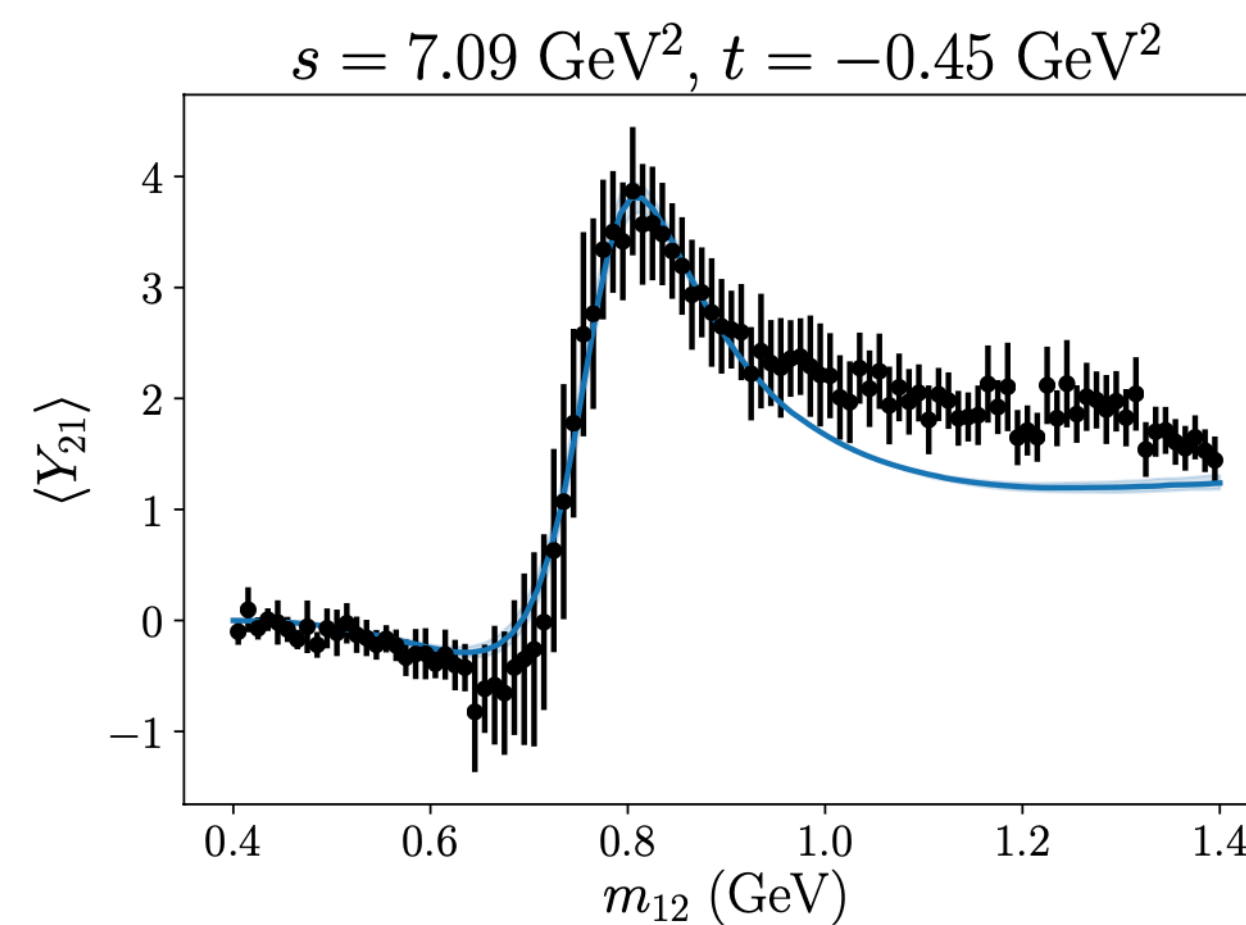
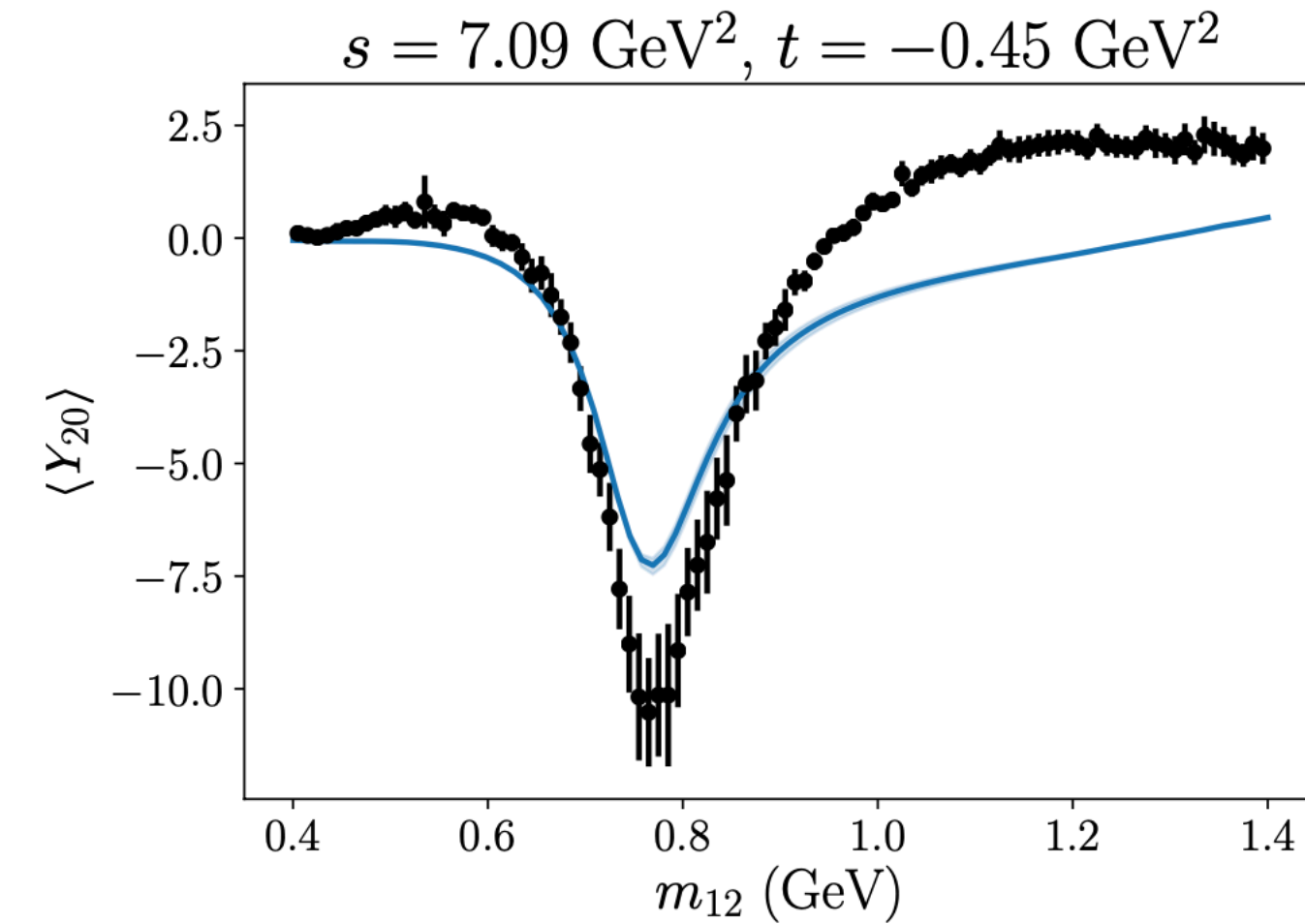
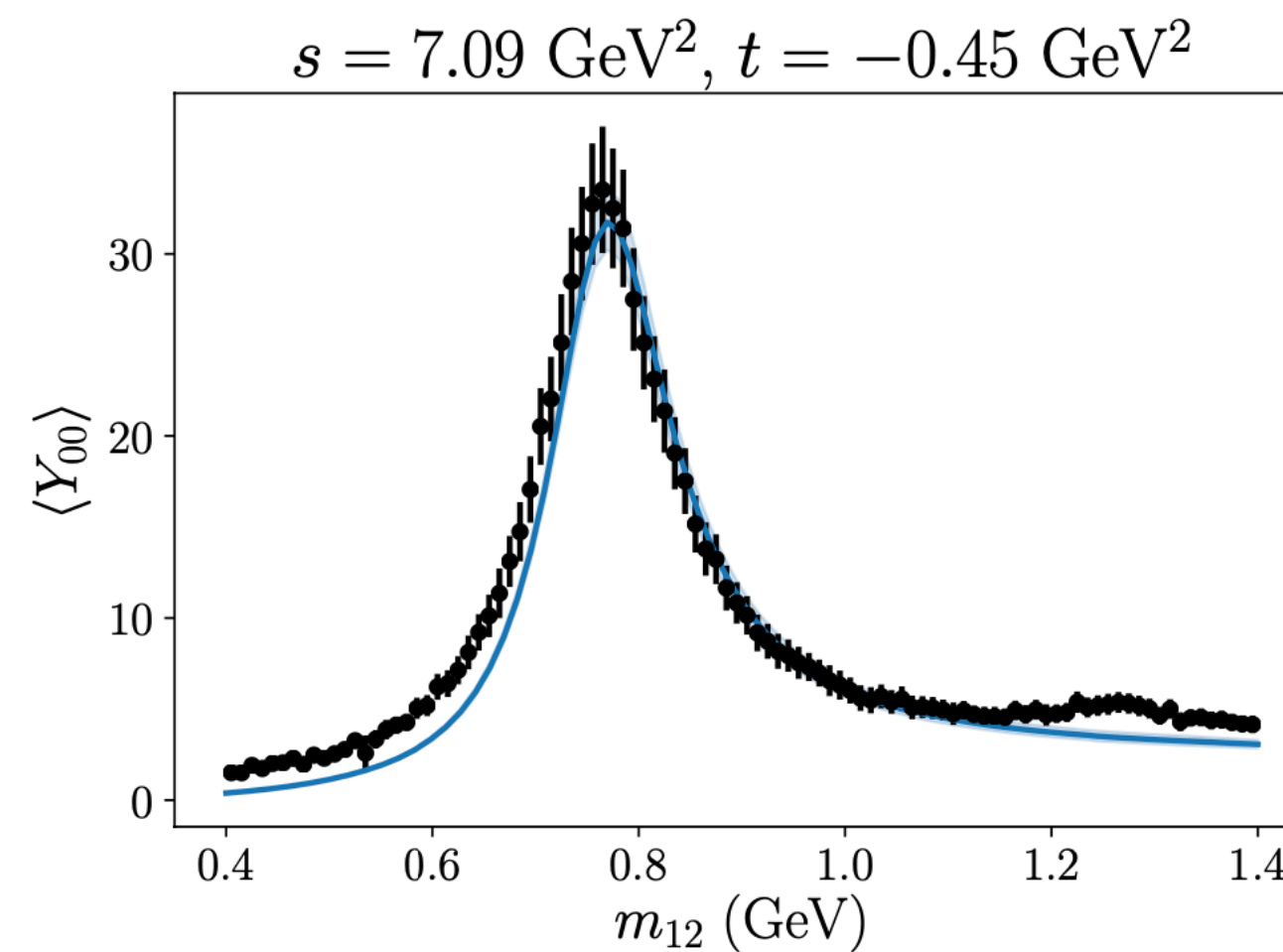
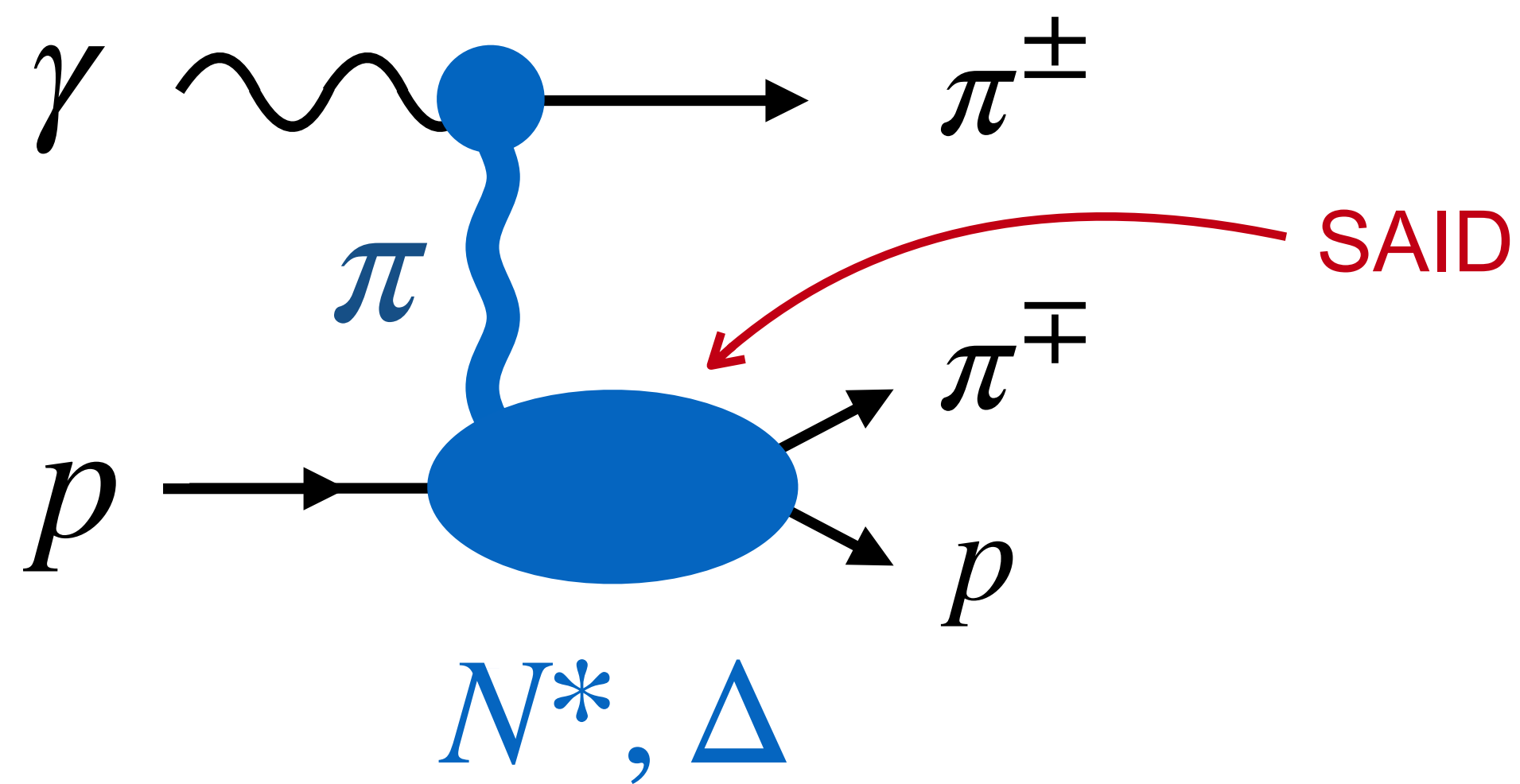
Double regge with Uniform background



R. Perry et al (JPAC) in preparation

(Deck + ρ) model for $\pi\pi$

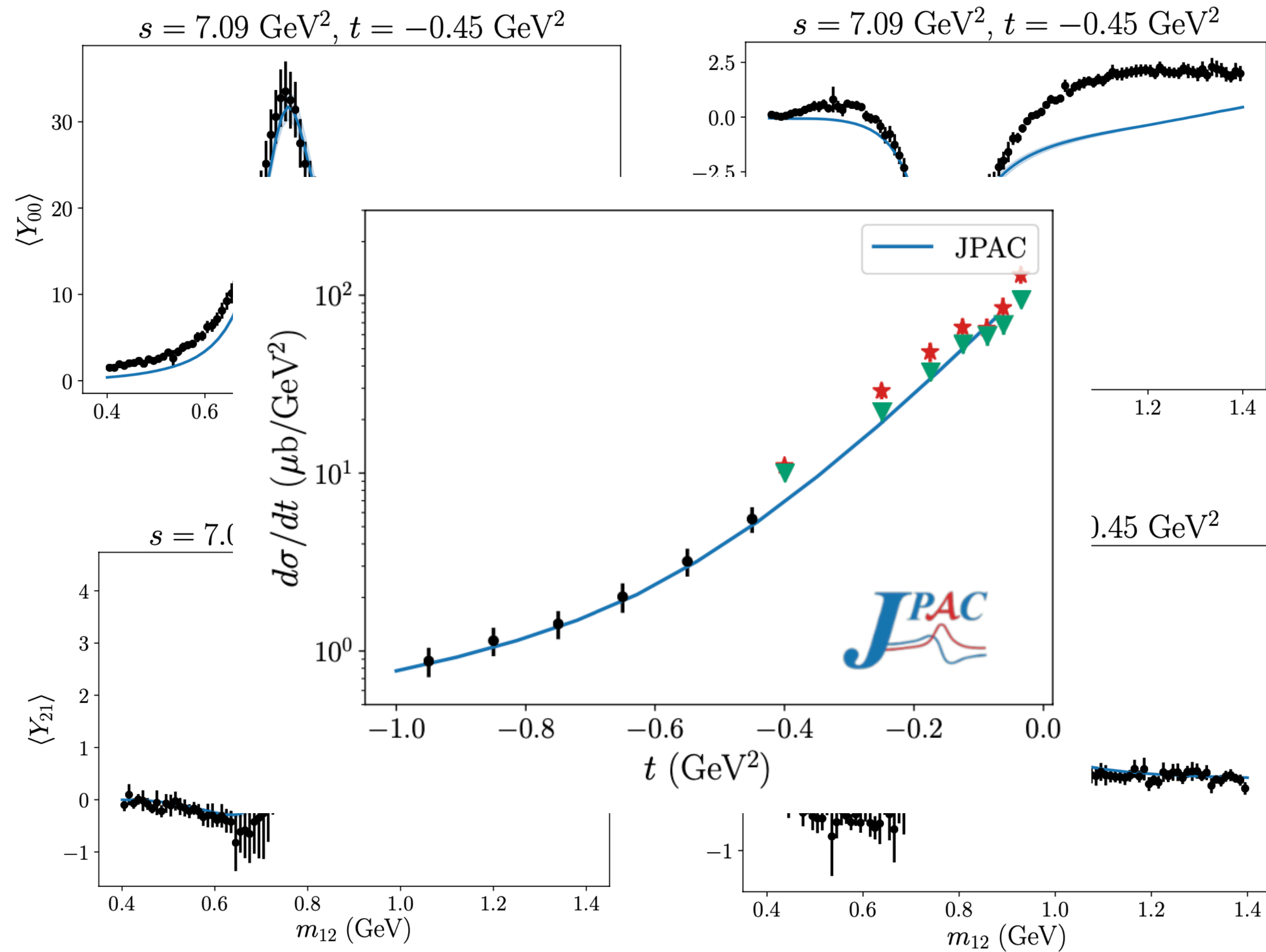
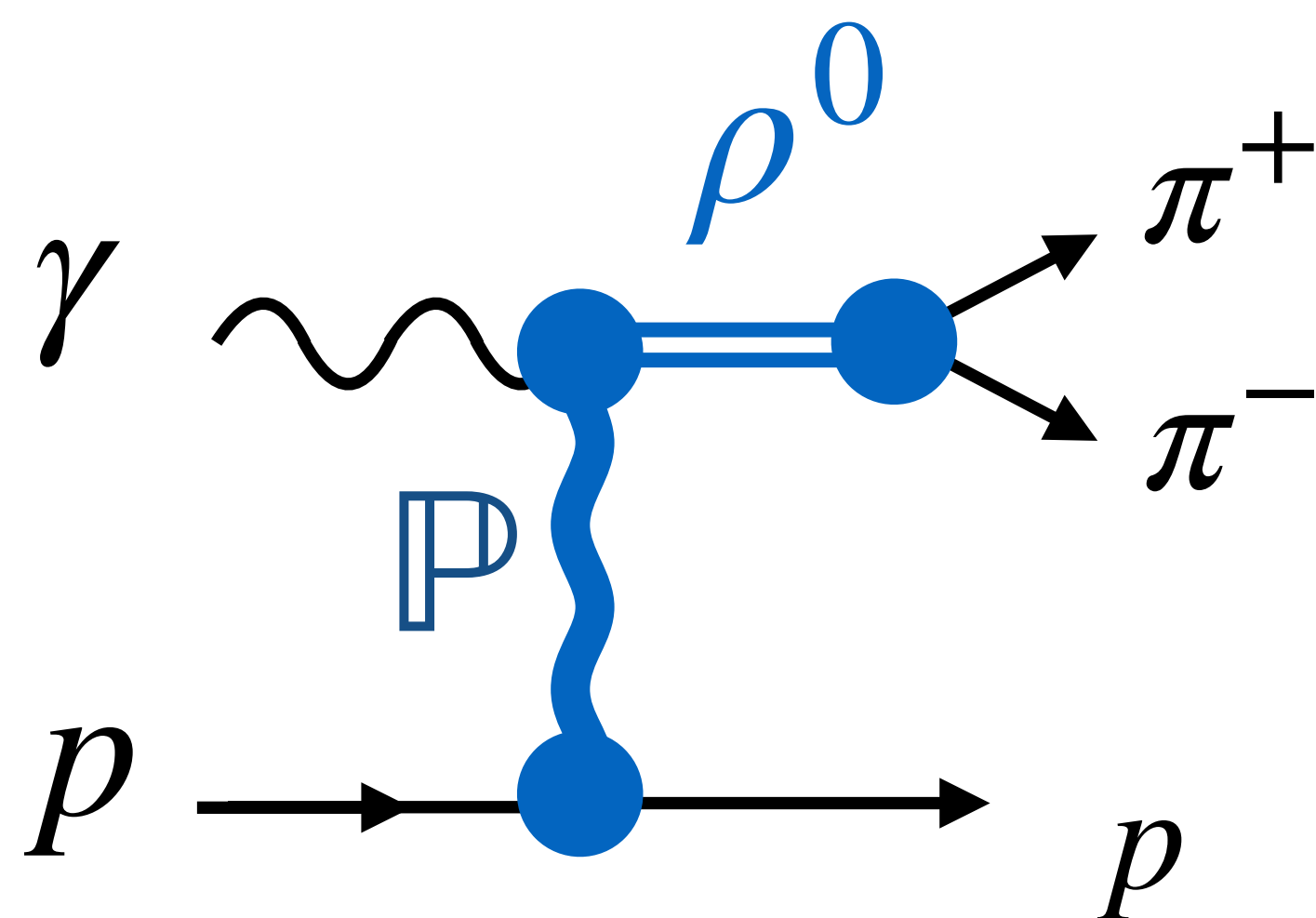
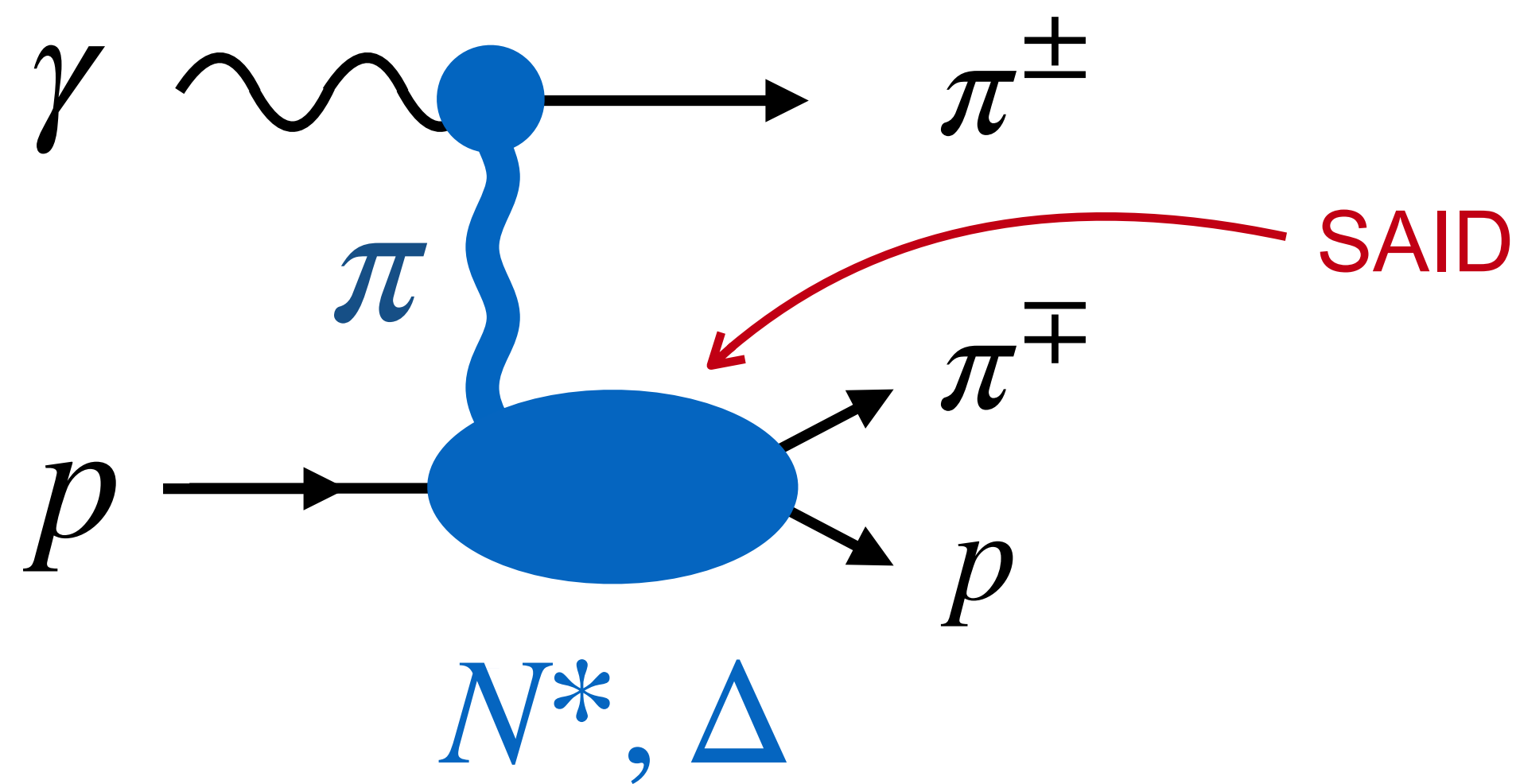
CLAS PRD80 (2009)



R. Perry et al (JPAC) in preparation

(Deck + ρ) model for $\pi\pi$

CLAS PRD80 (2009)



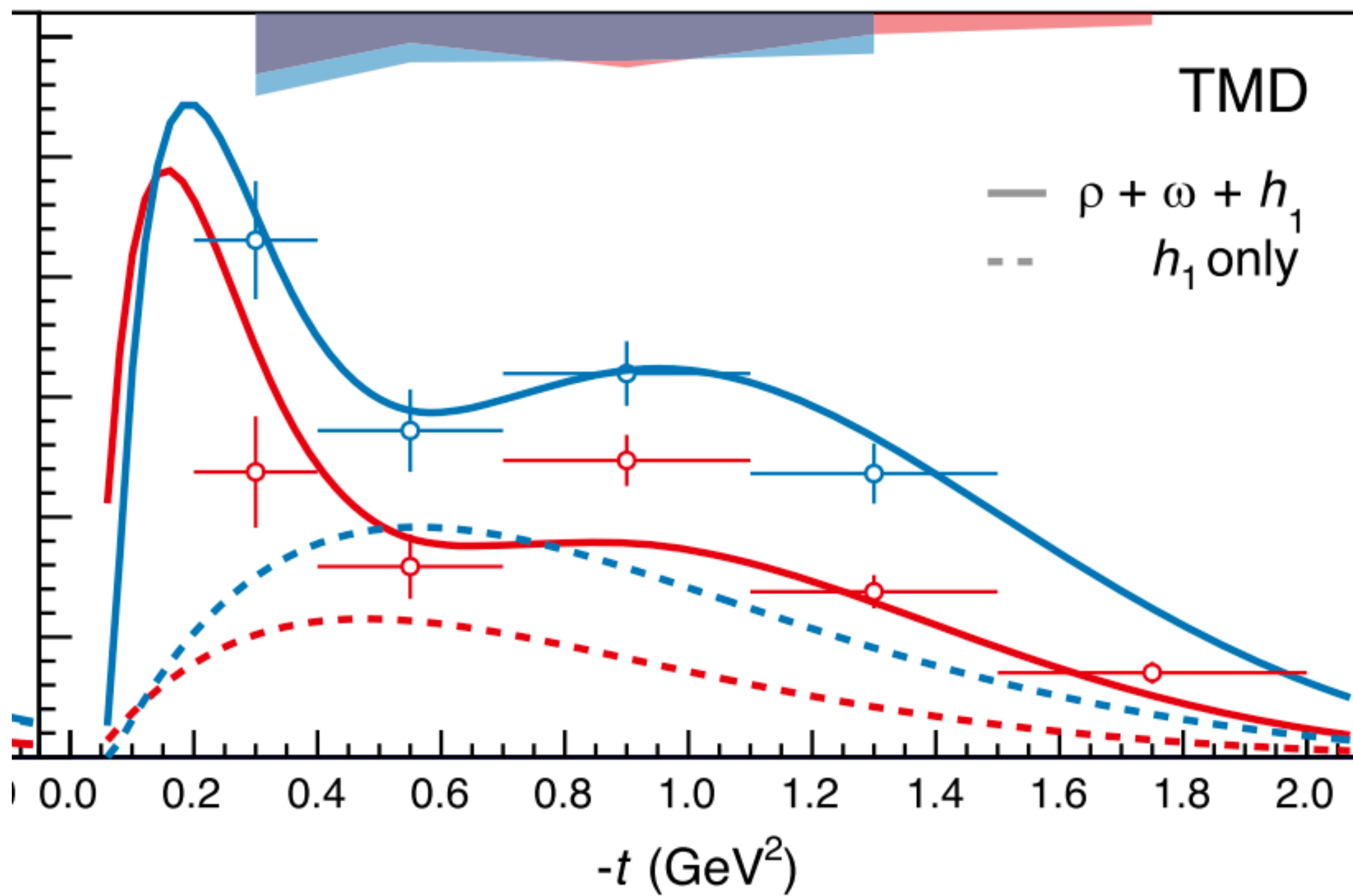
R. Perry et al (JPAC) in preparation

Tensor Meson Photoproduction @CLAS

VM et al (JPAC) PRD102 (2020)

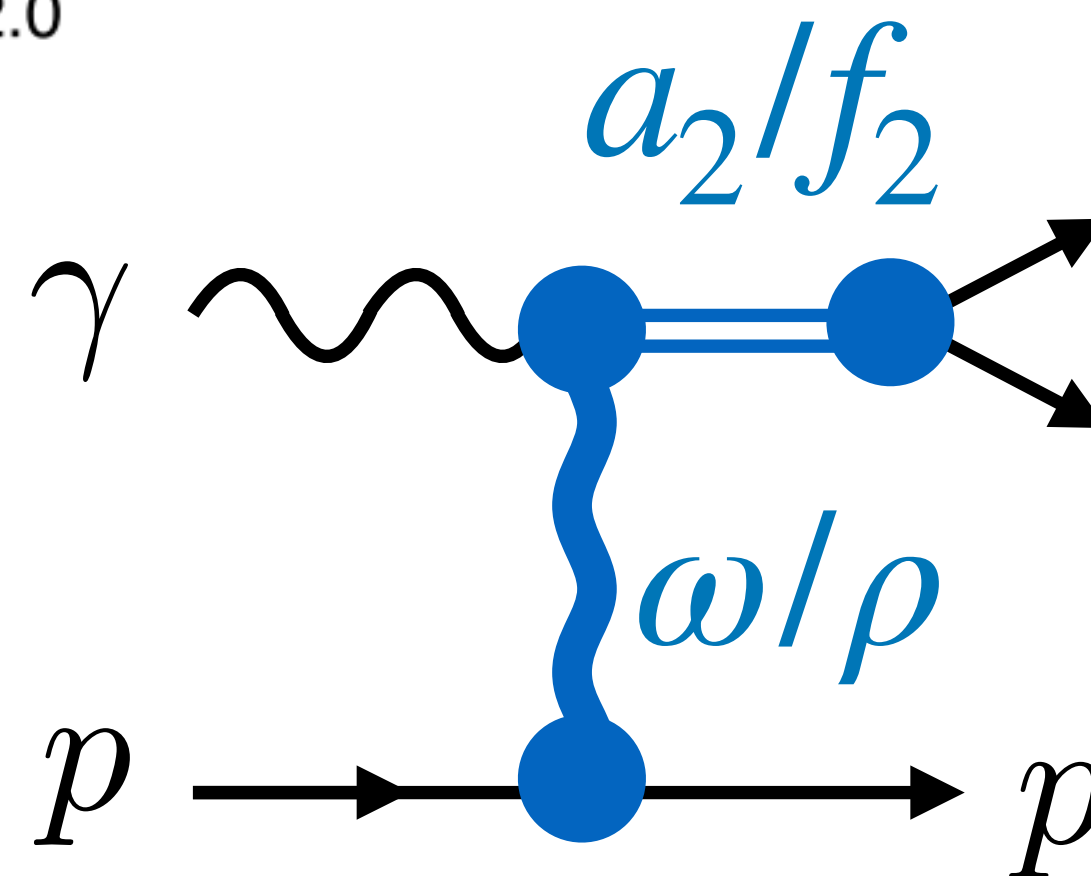
CLAS PRC 102 (2020)

CLAS PRL126 (2021)



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

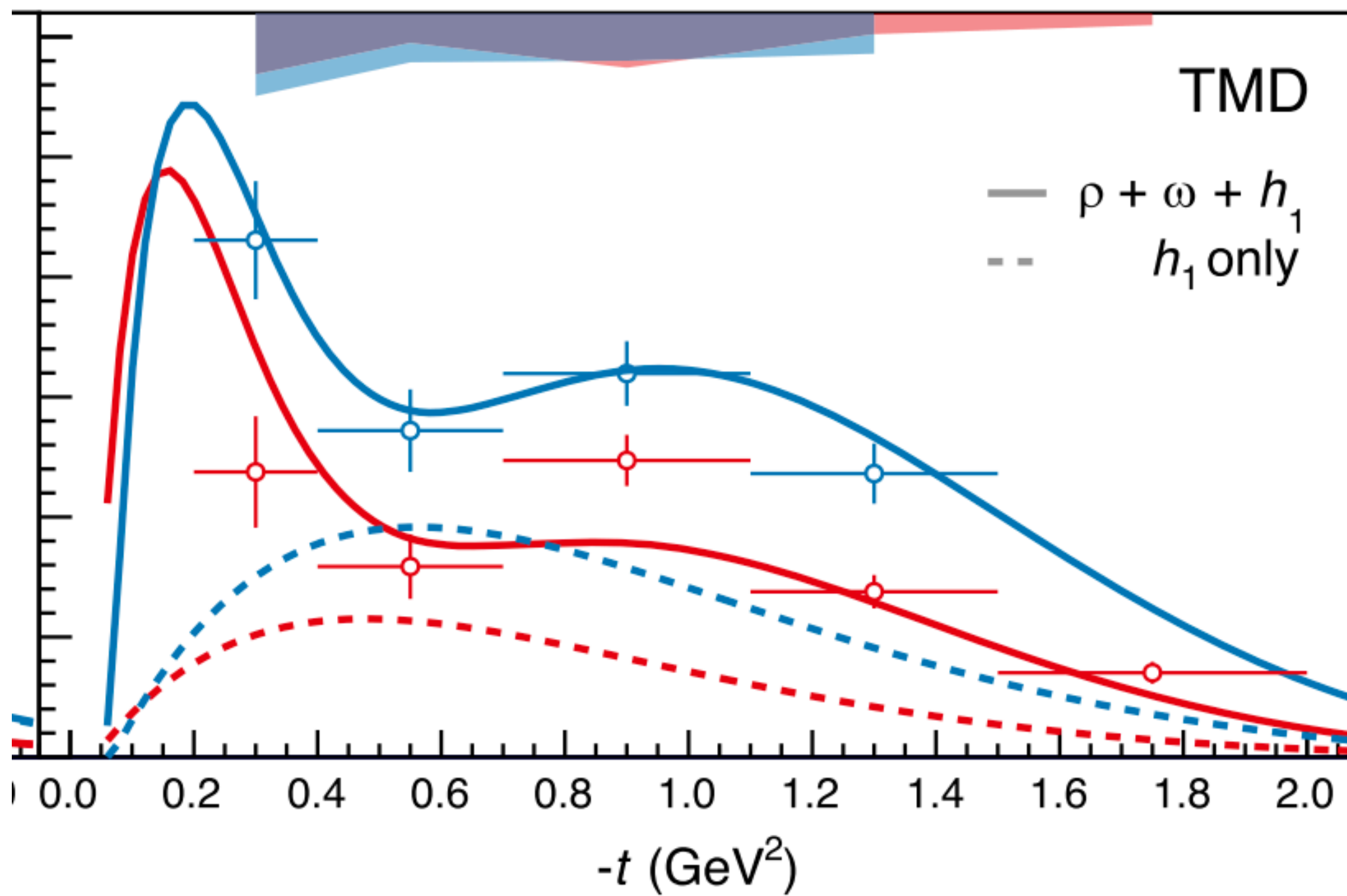
$$\omega + \frac{1}{3}\rho$$



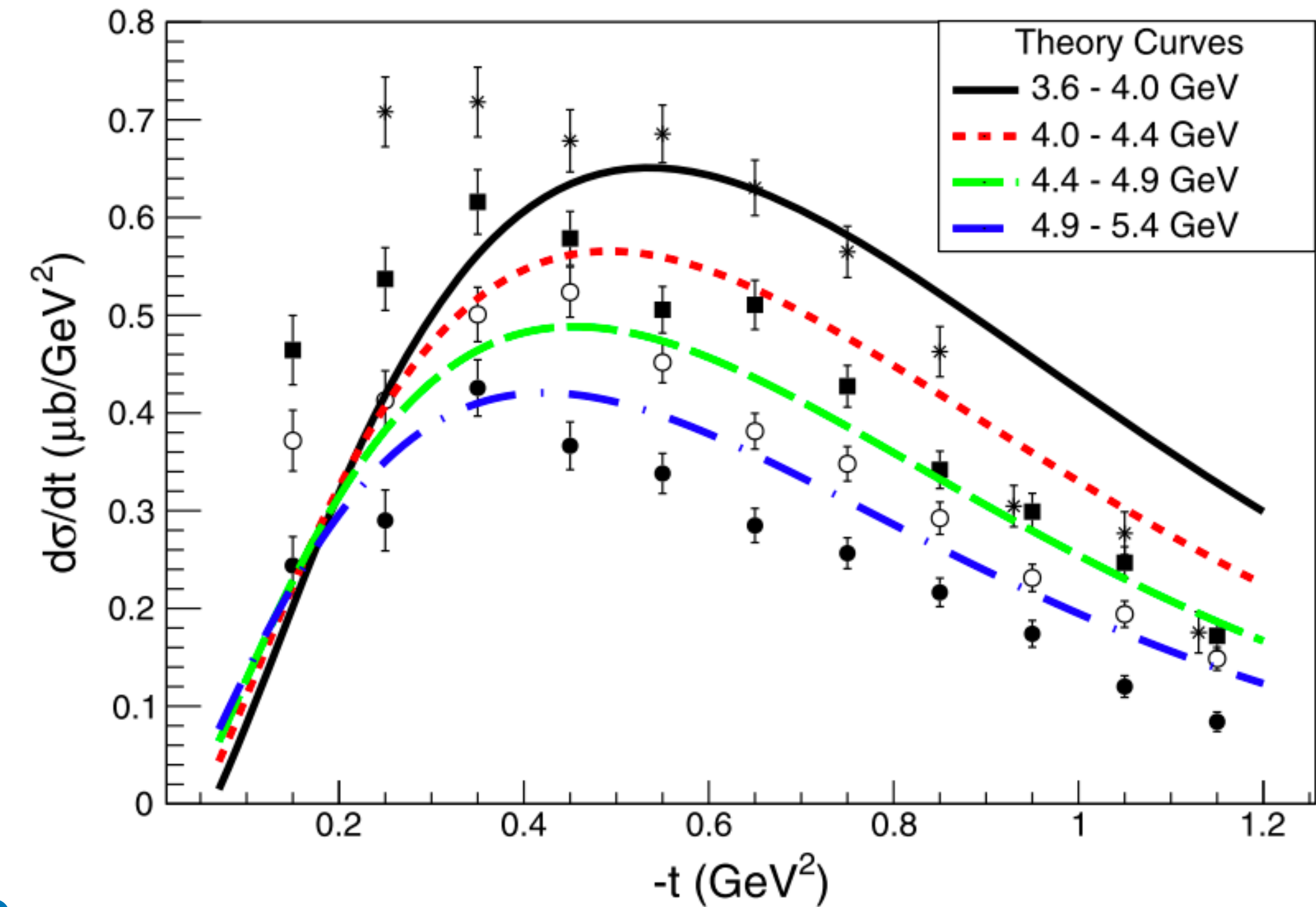
Tensor Meson Photoproduction @CLAS

VM et al (JPAC) PRD102 (2020)

CLAS PRC 102 (2020)

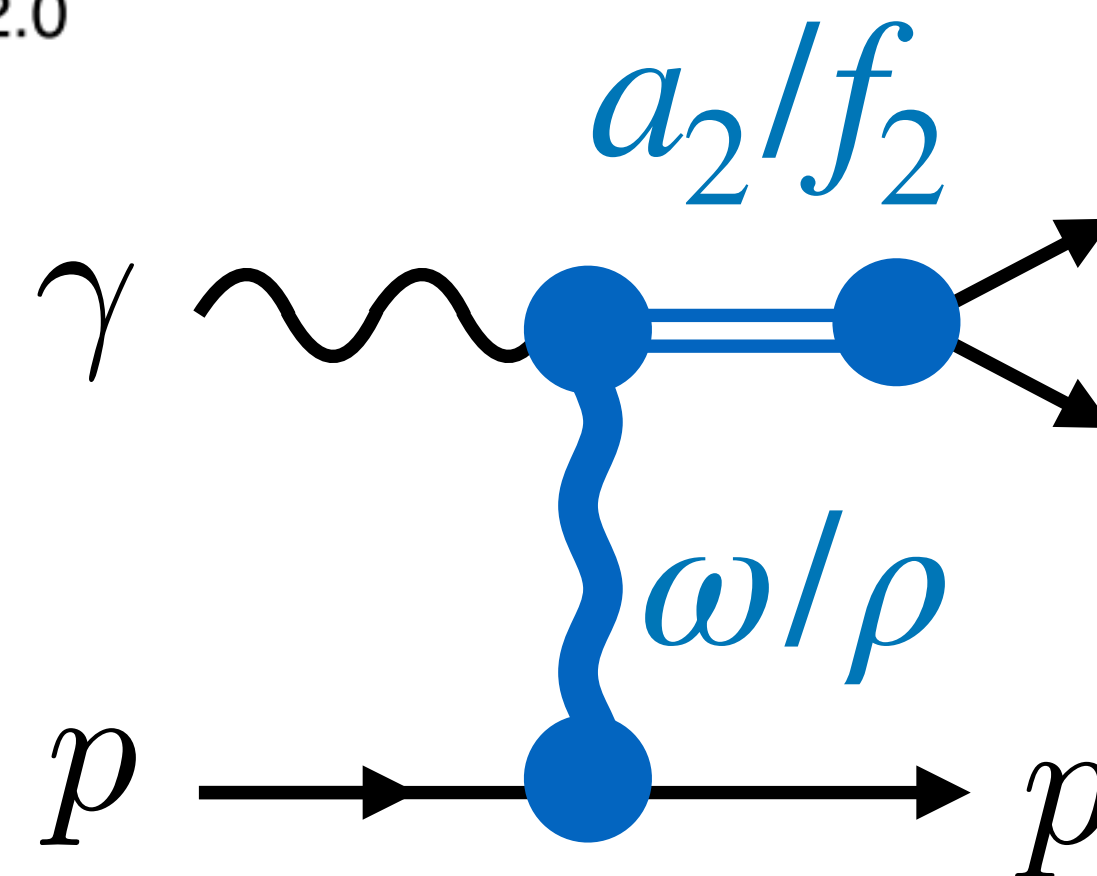


CLAS PRL126 (2021)



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

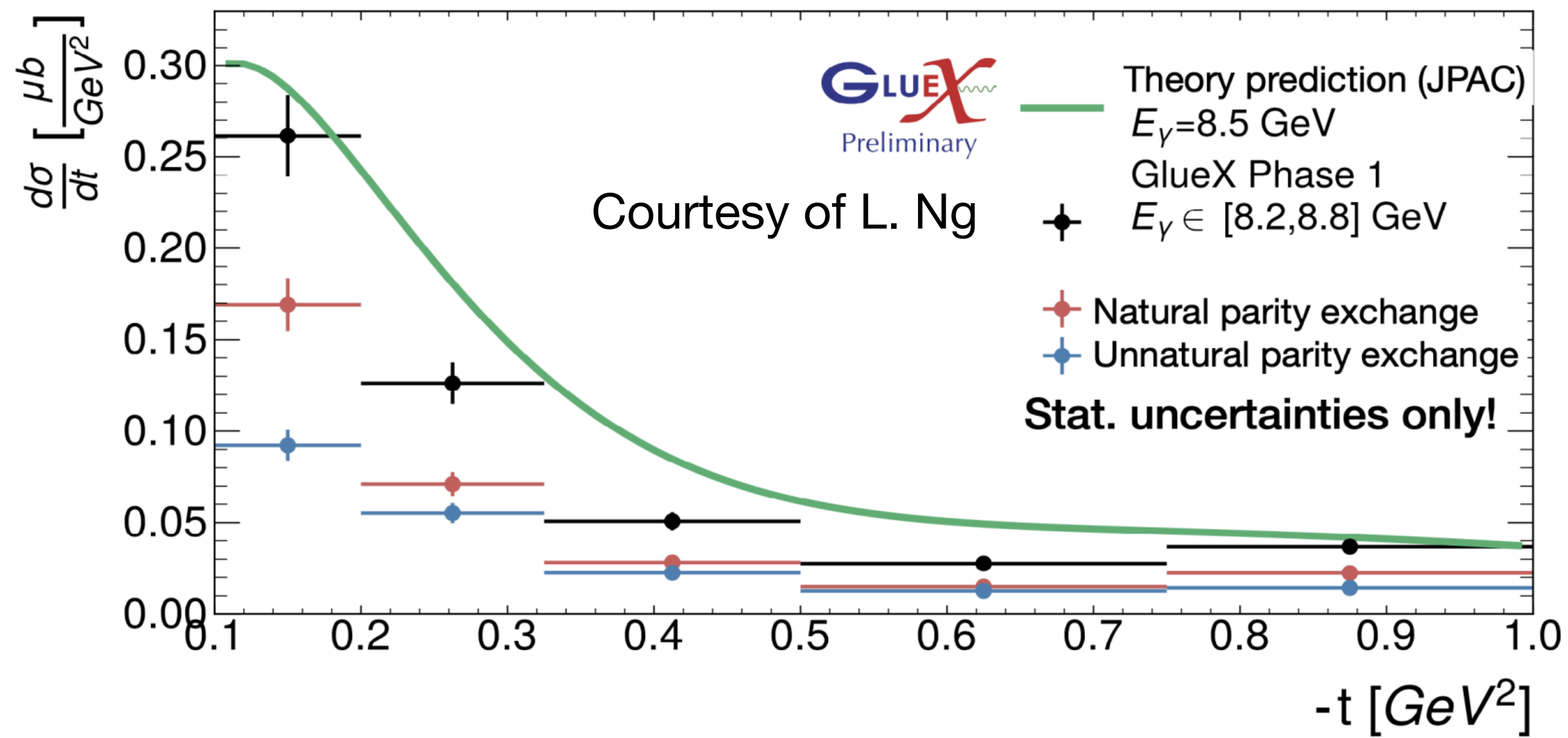
$$\omega + \frac{1}{3}\rho$$



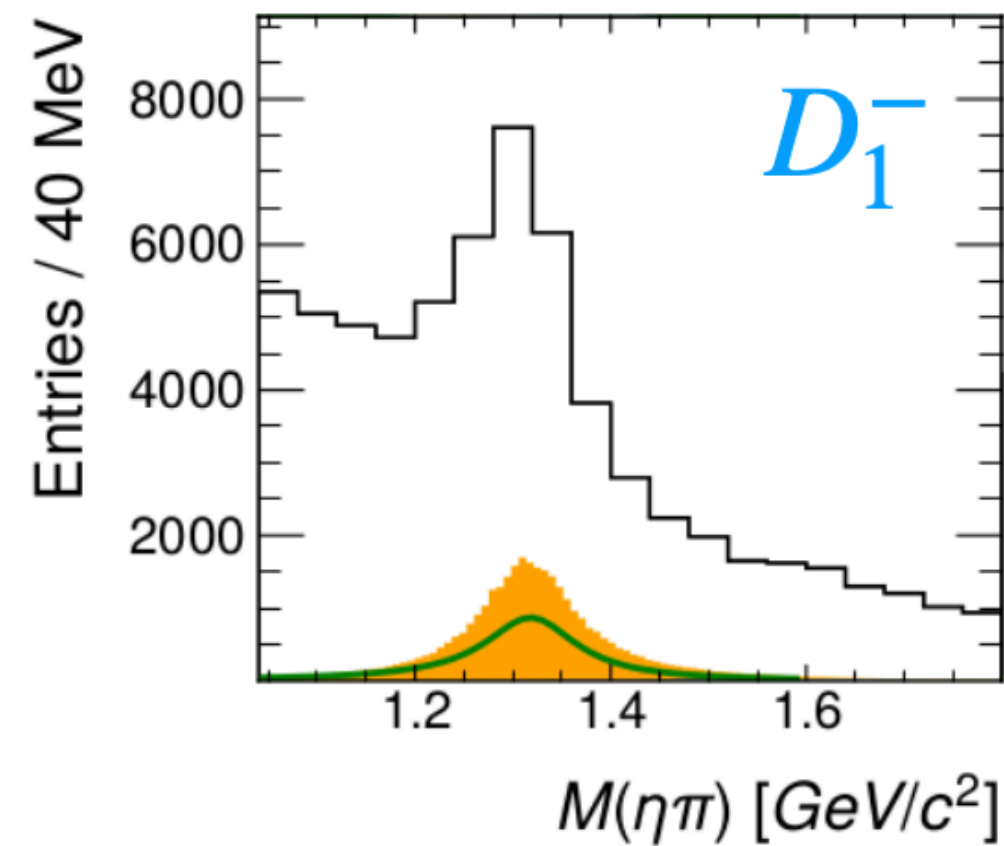
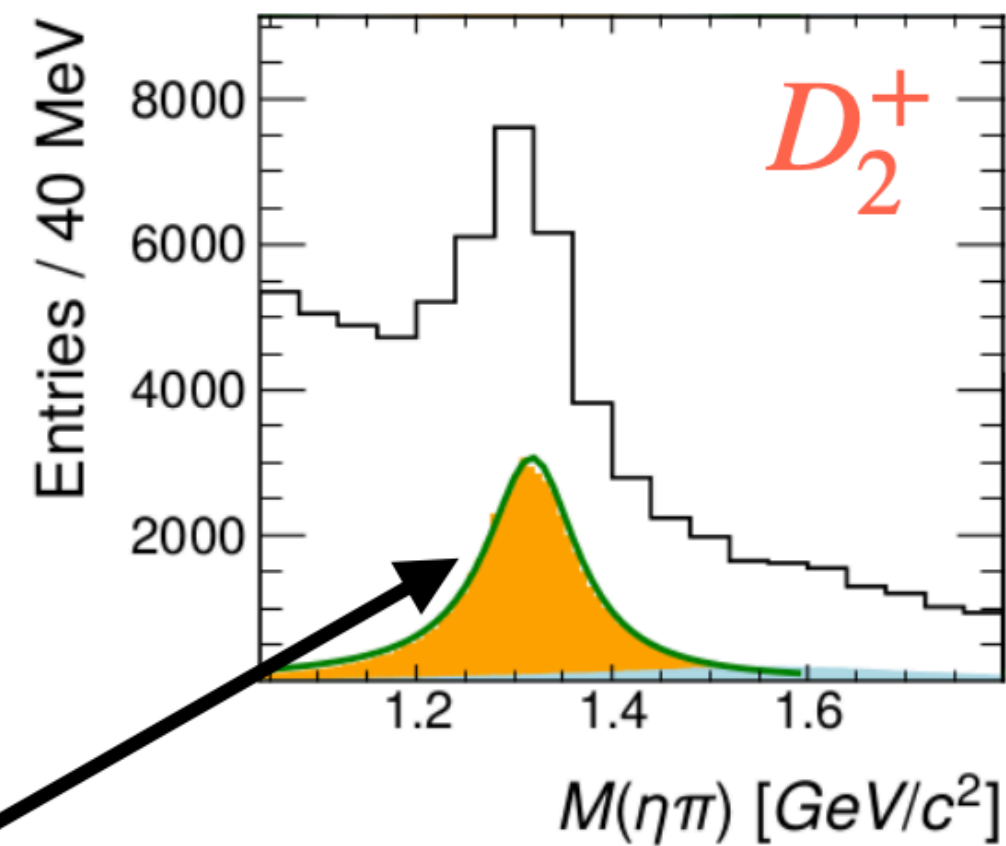
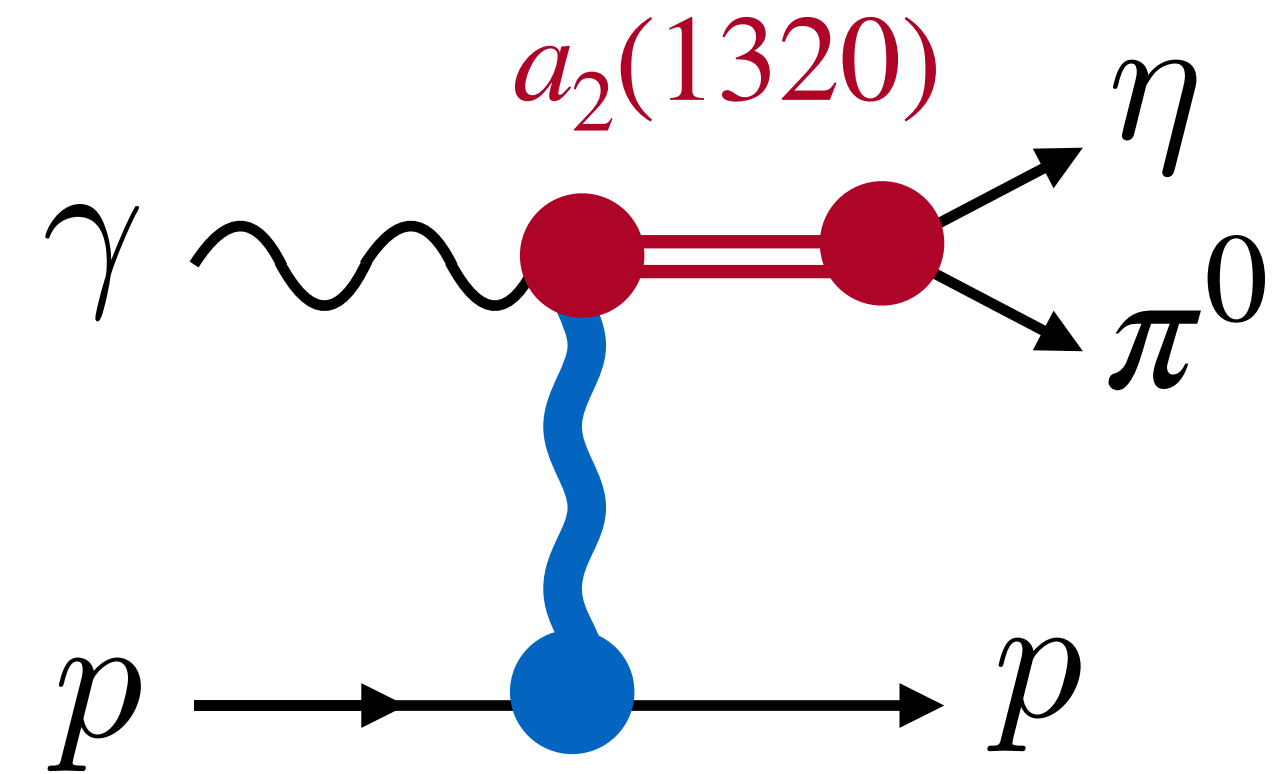
$$\gamma p \rightarrow f_2(1270)p :$$

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

$a_2(1320)$ Photoproduction @GlueX



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



JPAC model for tensor photoproduction

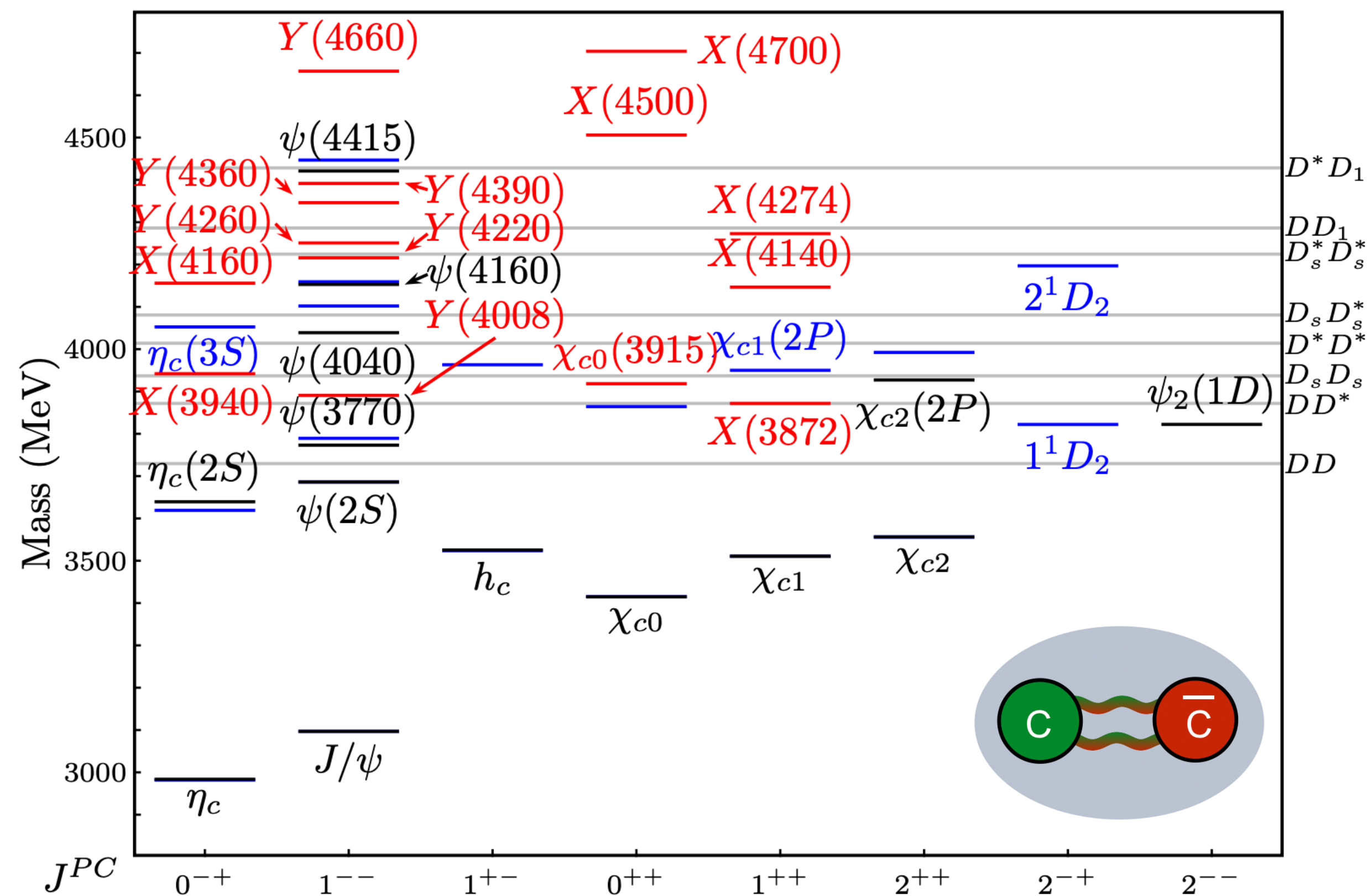
Extraction of the cross-section

Extraction of all D-waves components

Black: $c\bar{c}$ predicted and observed

Blue: $c\bar{c}$ predicted but not observed

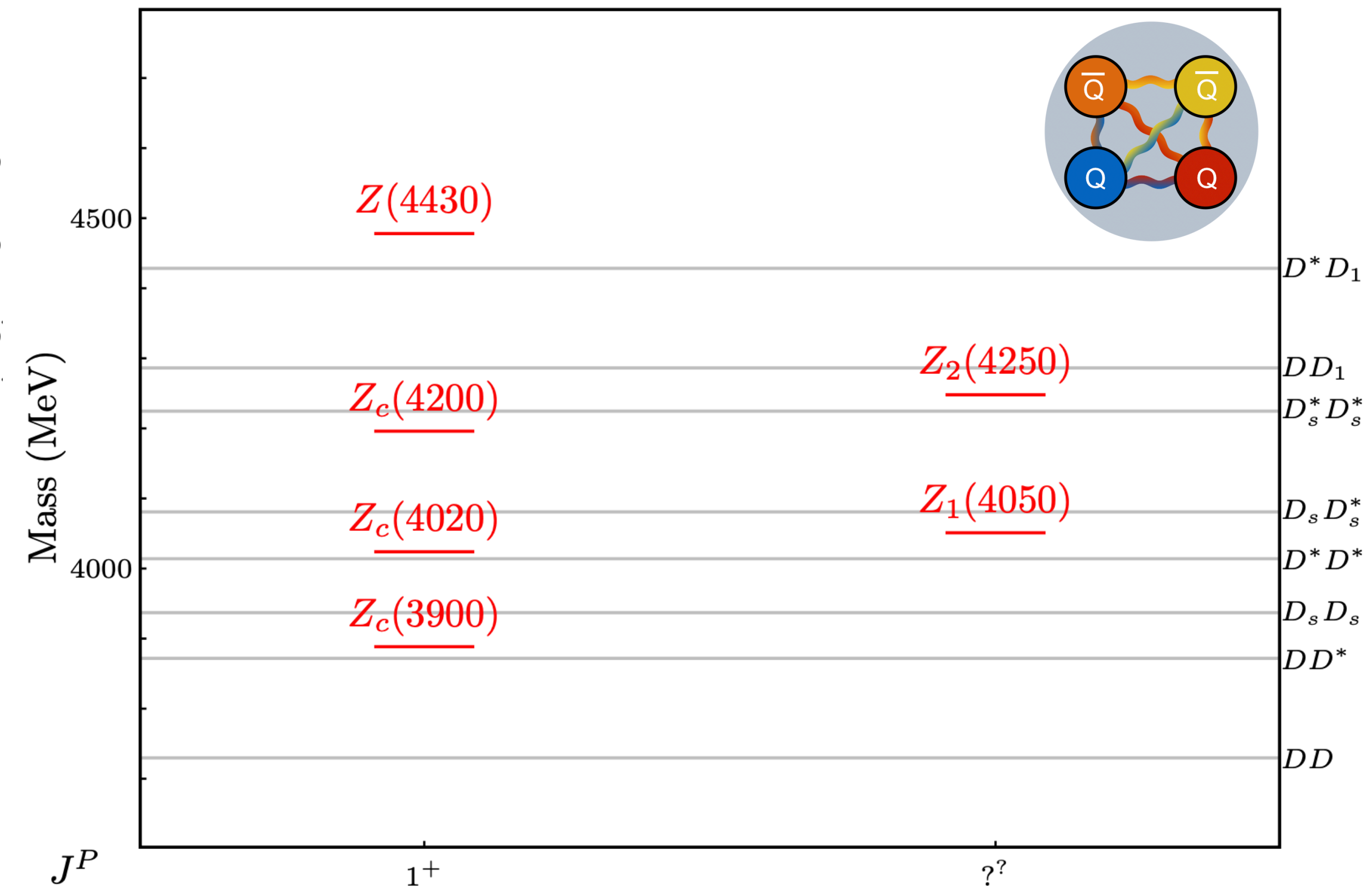
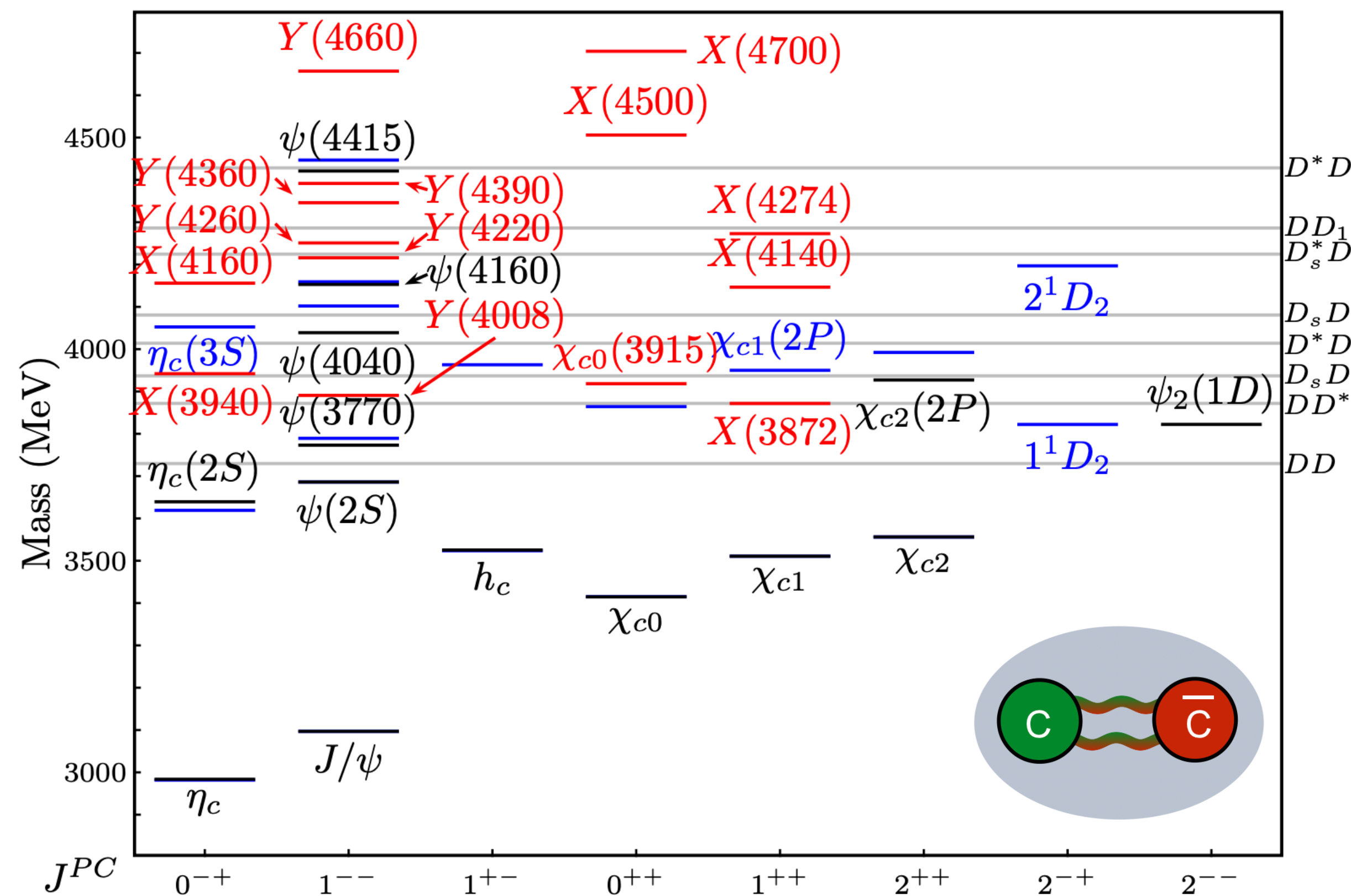
Red: exotic candidates



Black: $c\bar{c}$ predicted and observed

Blue: $c\bar{c}$ predicted but not observed

Red: exotic candidates



$X(3872)$

Discovered in B decays by Belle

$$B \rightarrow KX(3872) \rightarrow K(J/\psi\pi\pi)$$

Quantum numbers 1^{++} (more likely)

Strong isospin violation

$$\frac{X(3872) \rightarrow J/\psi\omega}{X(3872) \rightarrow J/\psi\rho} = 0.8 \pm 0.3$$

Very close to DD^* threshold

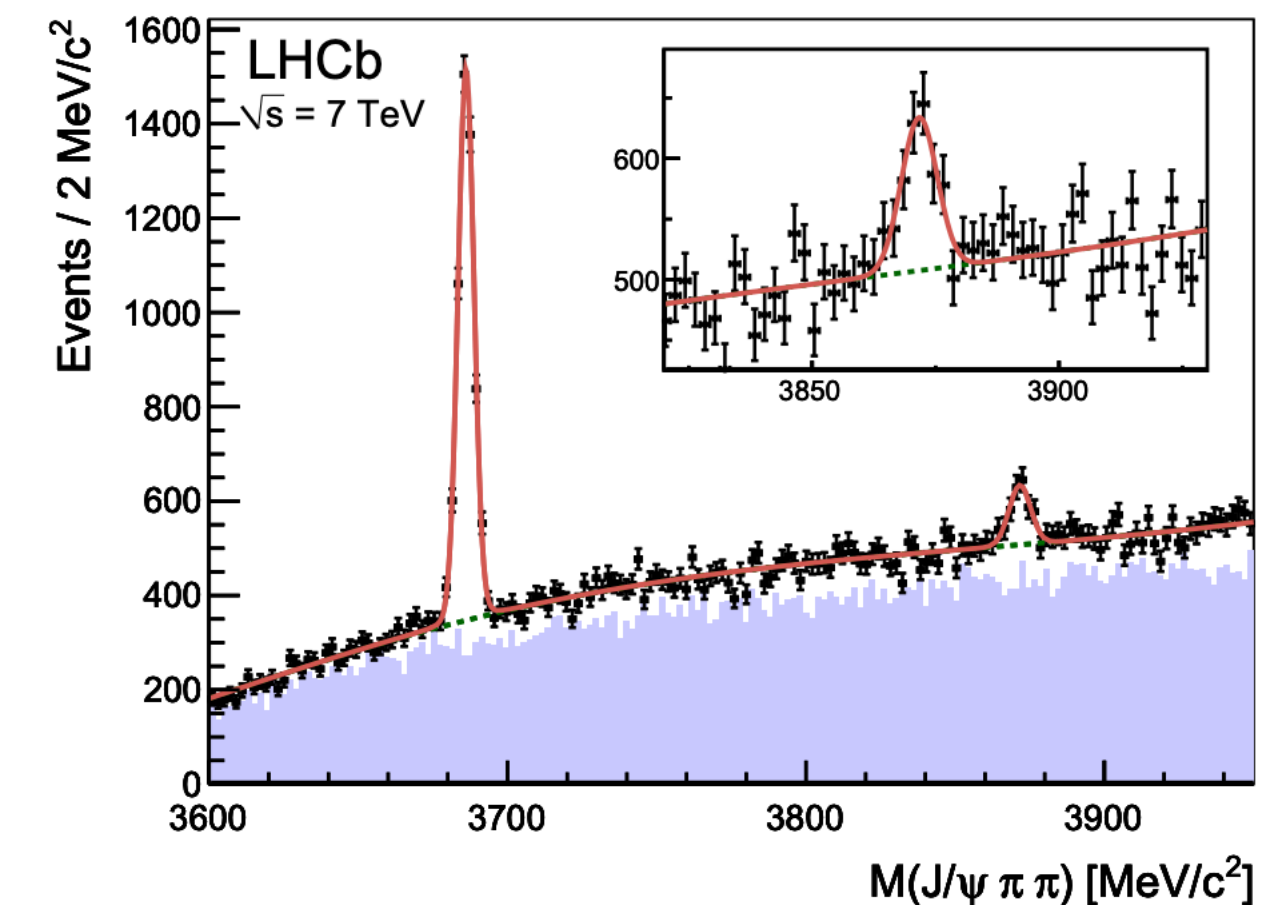
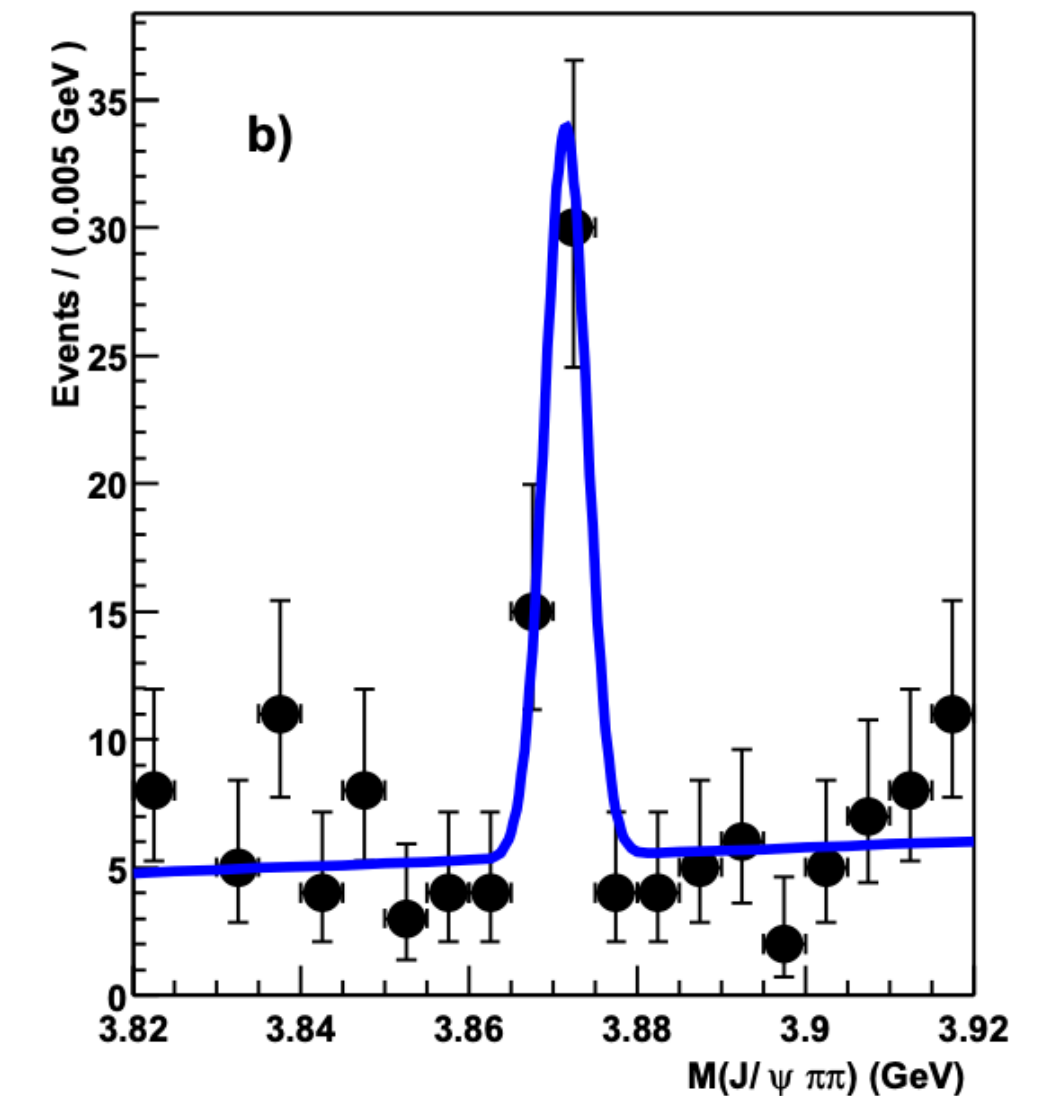
$$M_X - M_{DD^*} = -3 \pm 192 \text{ keV}$$

Observations by independent collaborations

$$pp \rightarrow X(3872) + \text{anything}$$
$$X(3872) \rightarrow J/\psi\pi\pi$$

Challenging interpretation

Belle PRL91 (2003) 262001



LHCb EPJC72 (2012) 1972

$Z_c(3900)^+$

Discovered in e^+e^- interactions by BESIII

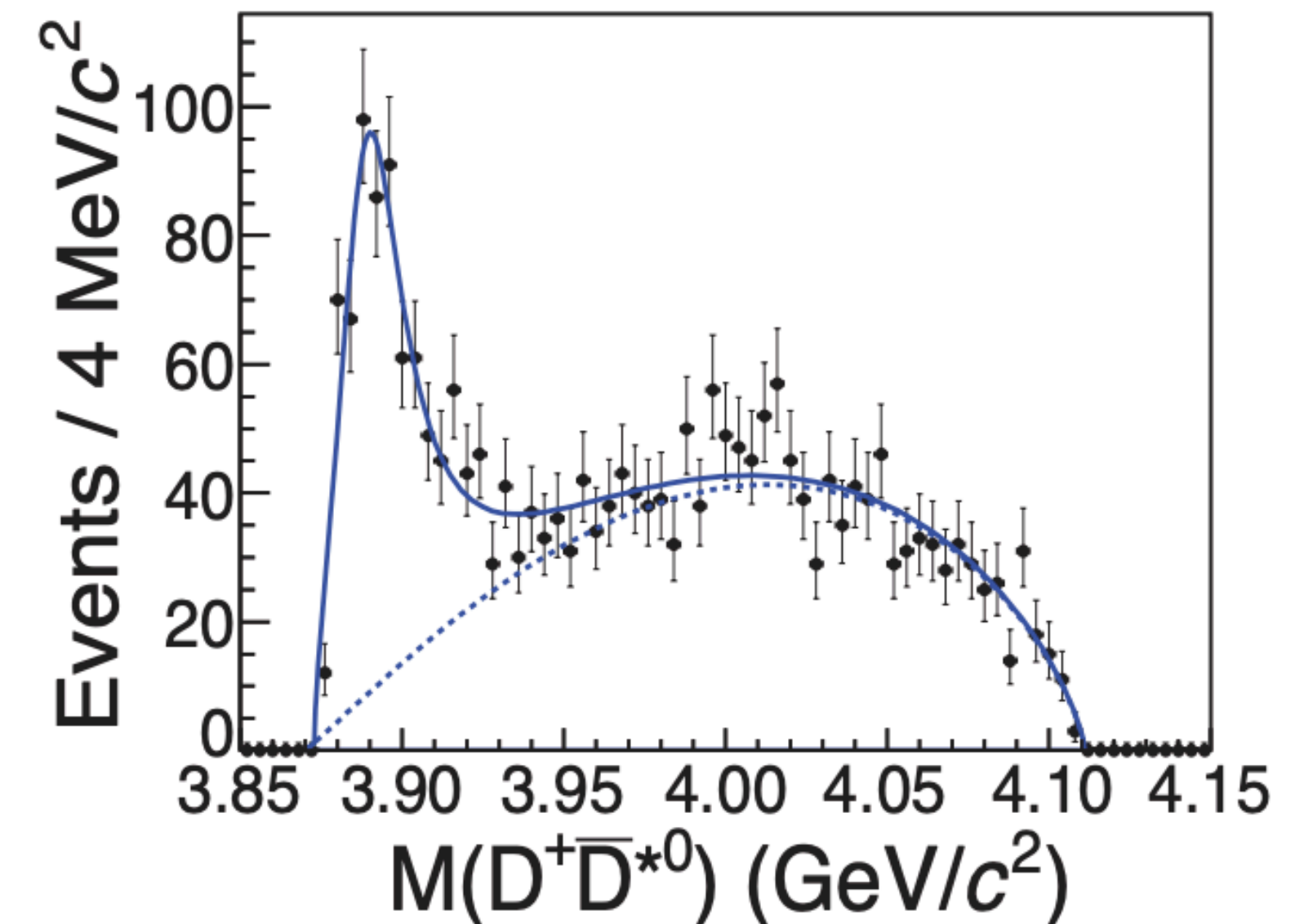
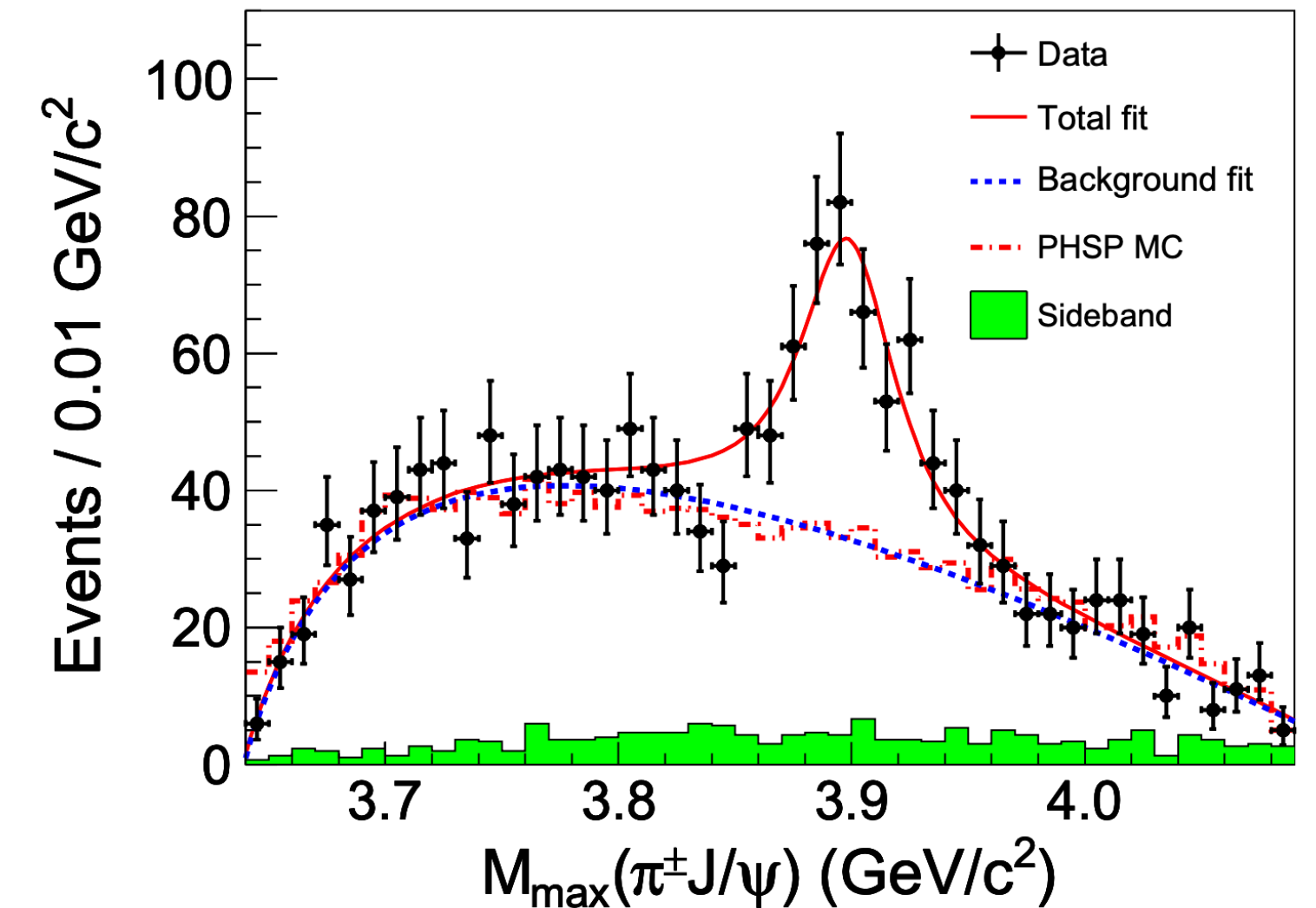
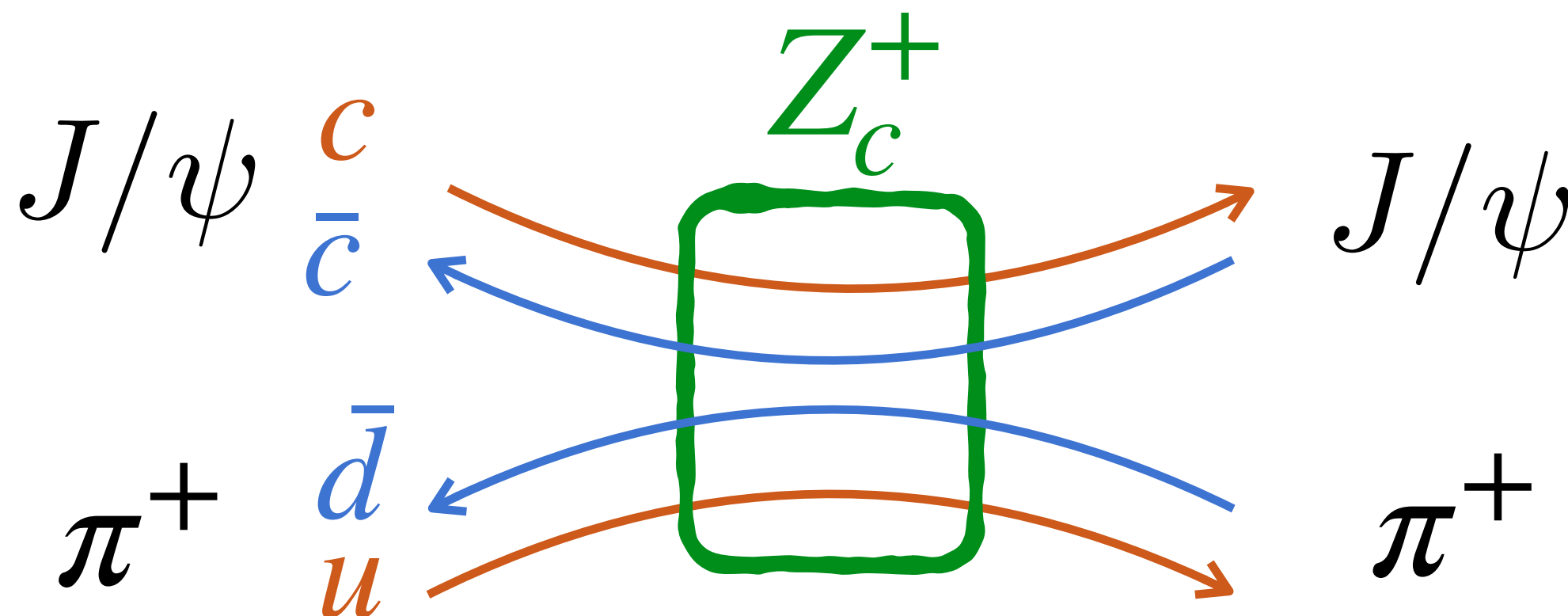
$$e^+e^- \rightarrow \pi^- Z_c(3900)^+$$

$$\rightarrow J/\psi \pi^+ \quad \text{BESIII PRL110 (2013)}$$

$$\rightarrow (D\bar{D}^*)^+ \quad \text{BESIII PRL112 (2014)}$$

Quantum numbers 1^{+-} (more likely)

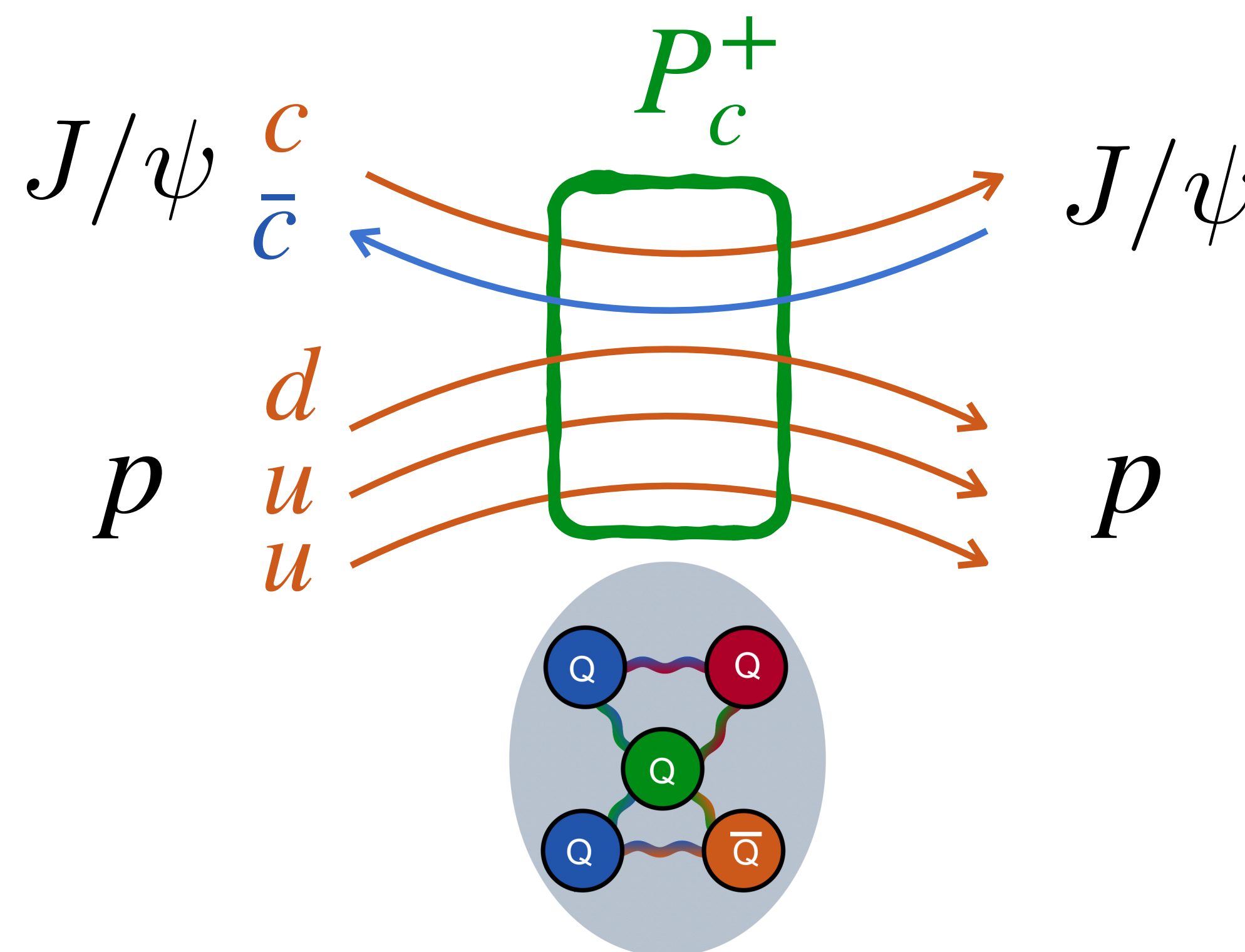
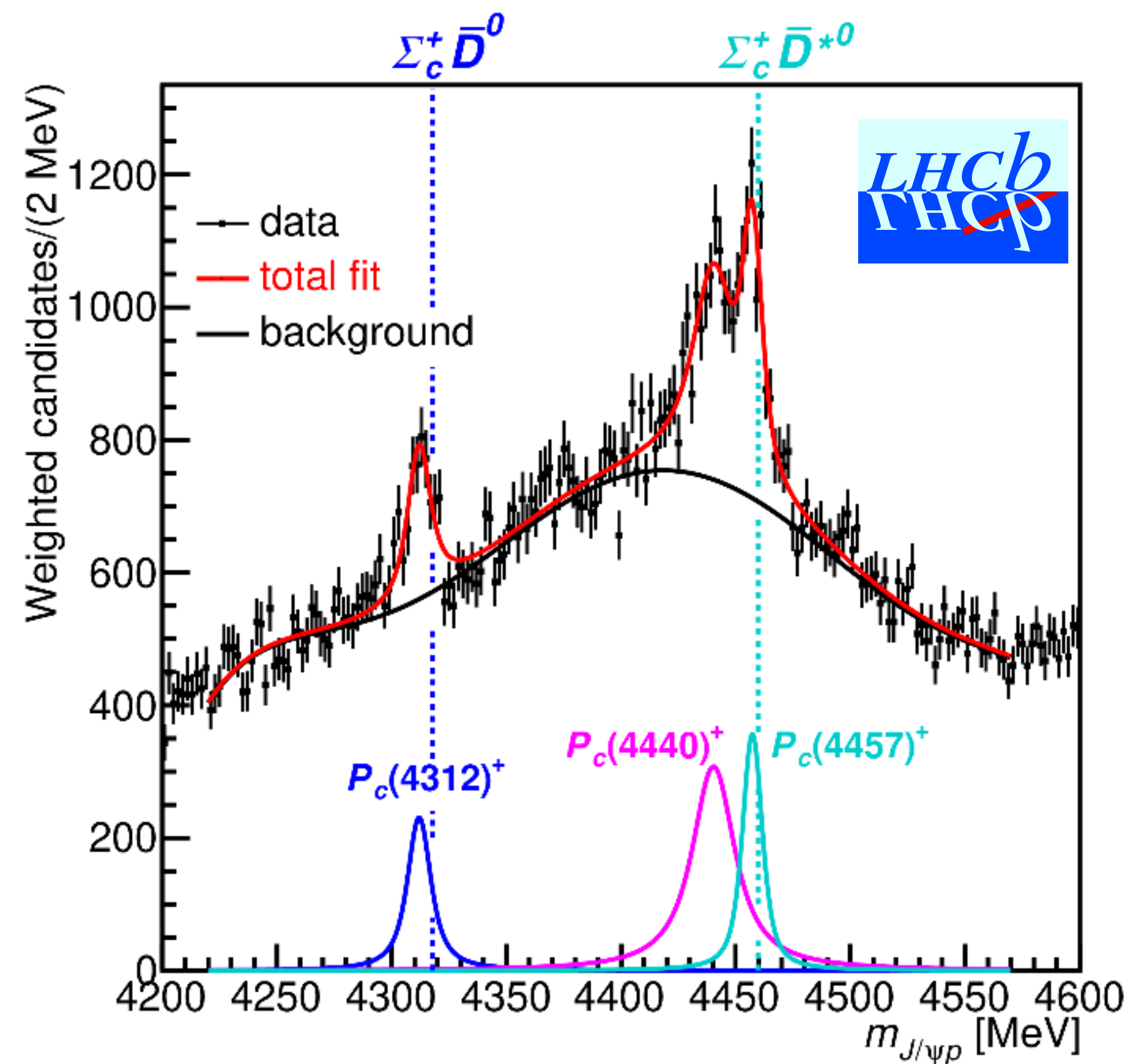
Need at least
4 quarks



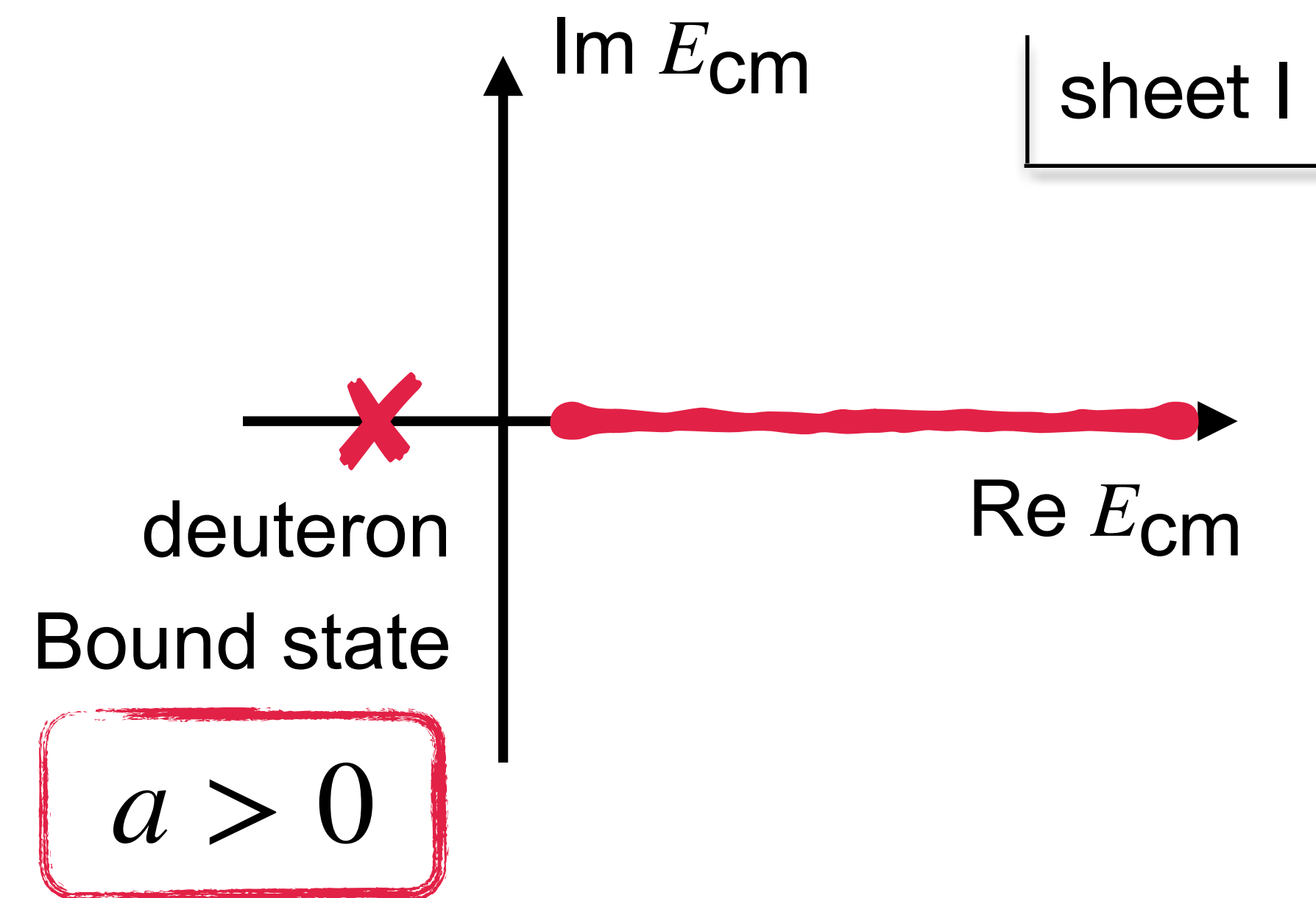
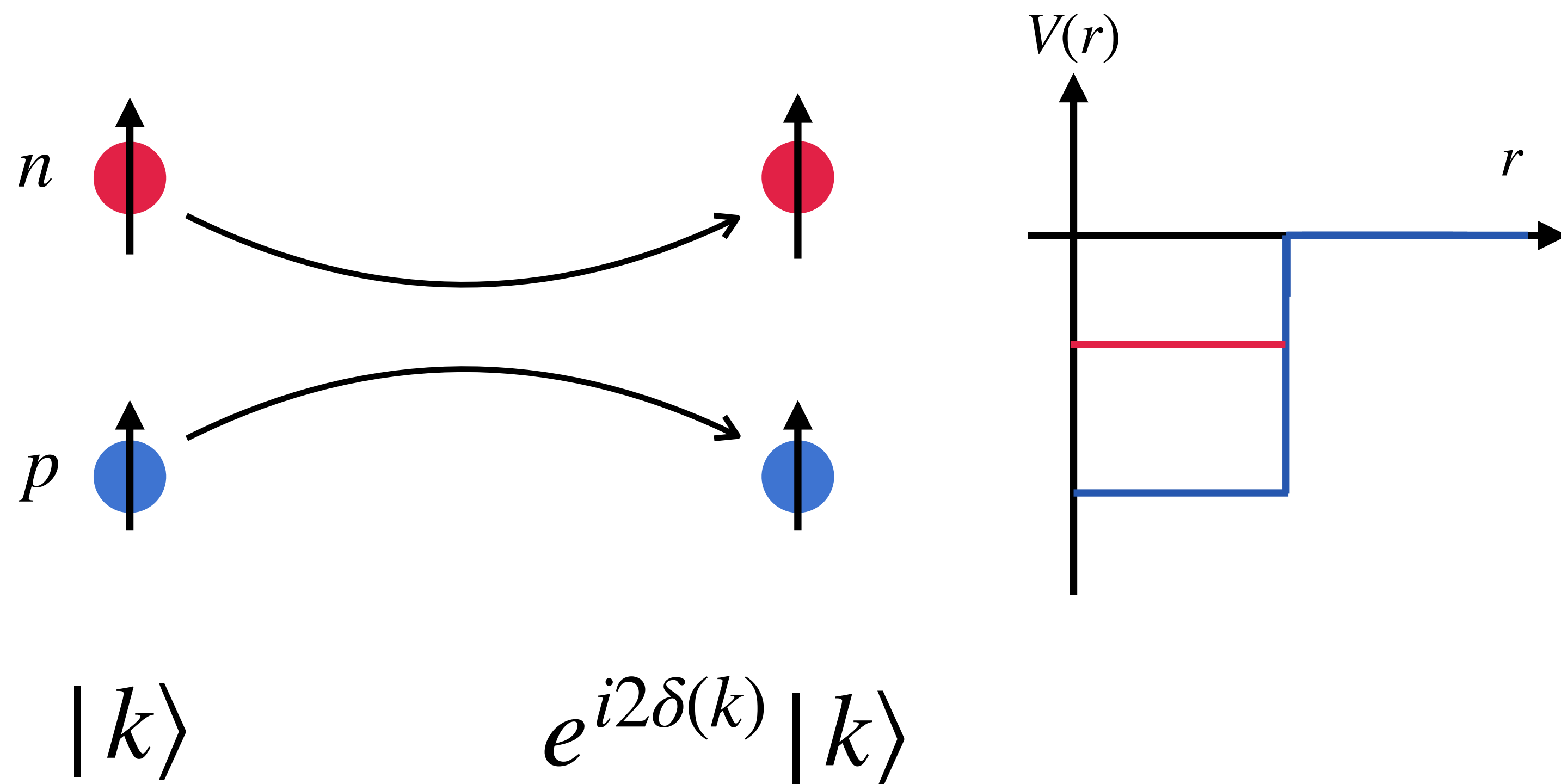
$$\Lambda_b \rightarrow K^- (J/\psi p)$$

unexplained excess of events in $J/\psi p$ spectrum

Cannot be qqq baryon



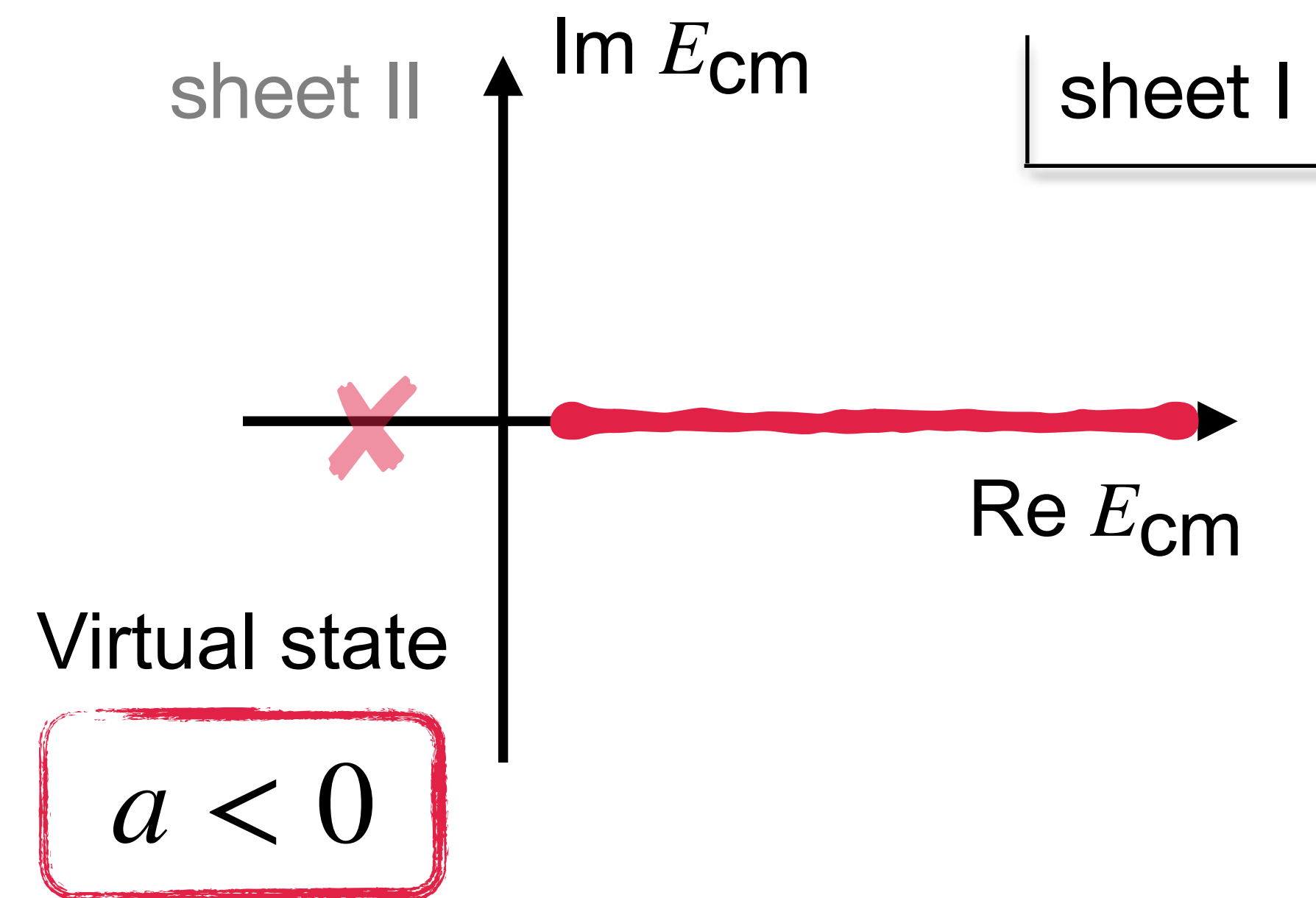
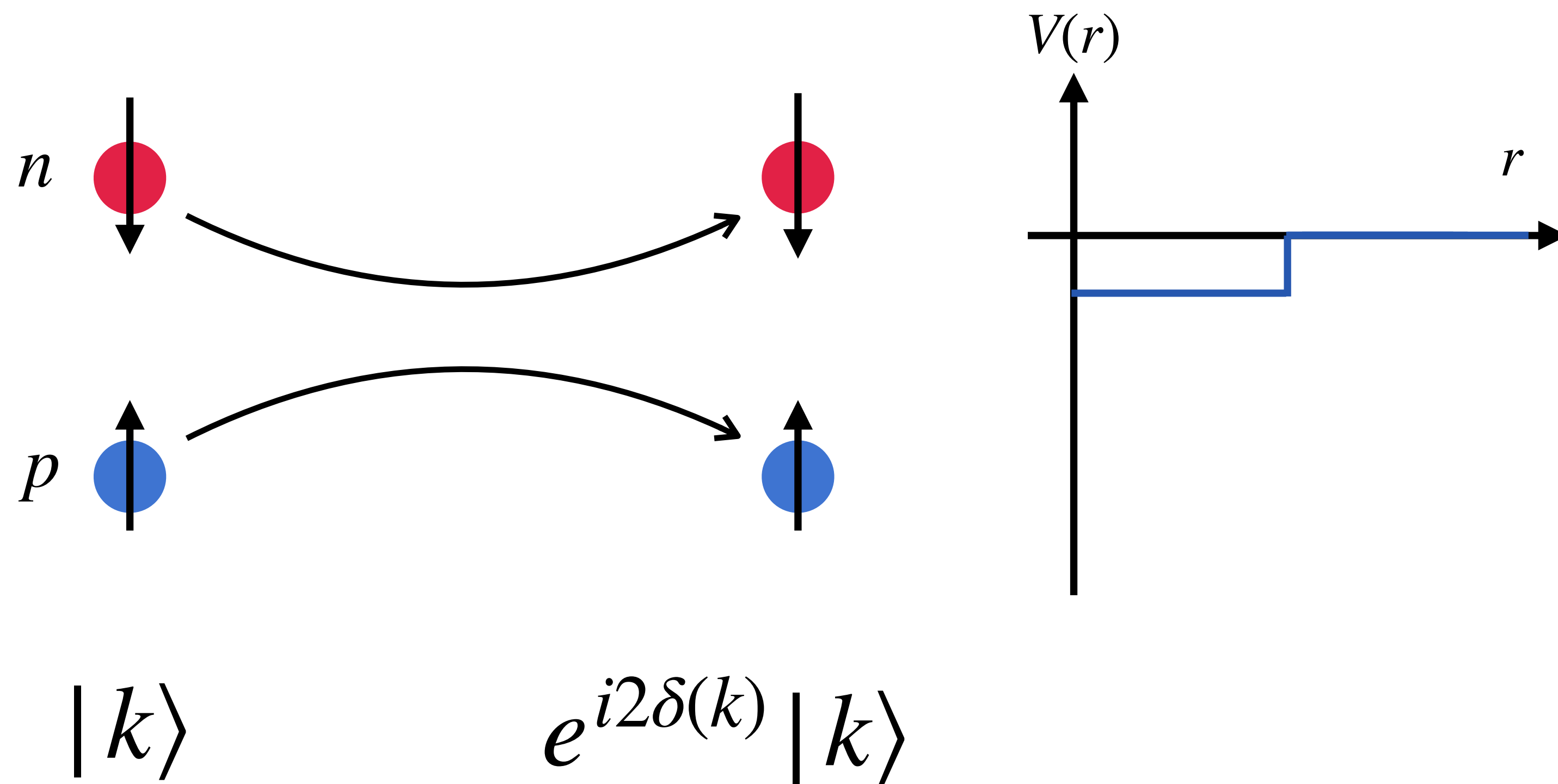
Bound state vs virtual state



Scattering length $a = \lim_{k \rightarrow 0} \frac{1}{k} \tan \delta(k)$

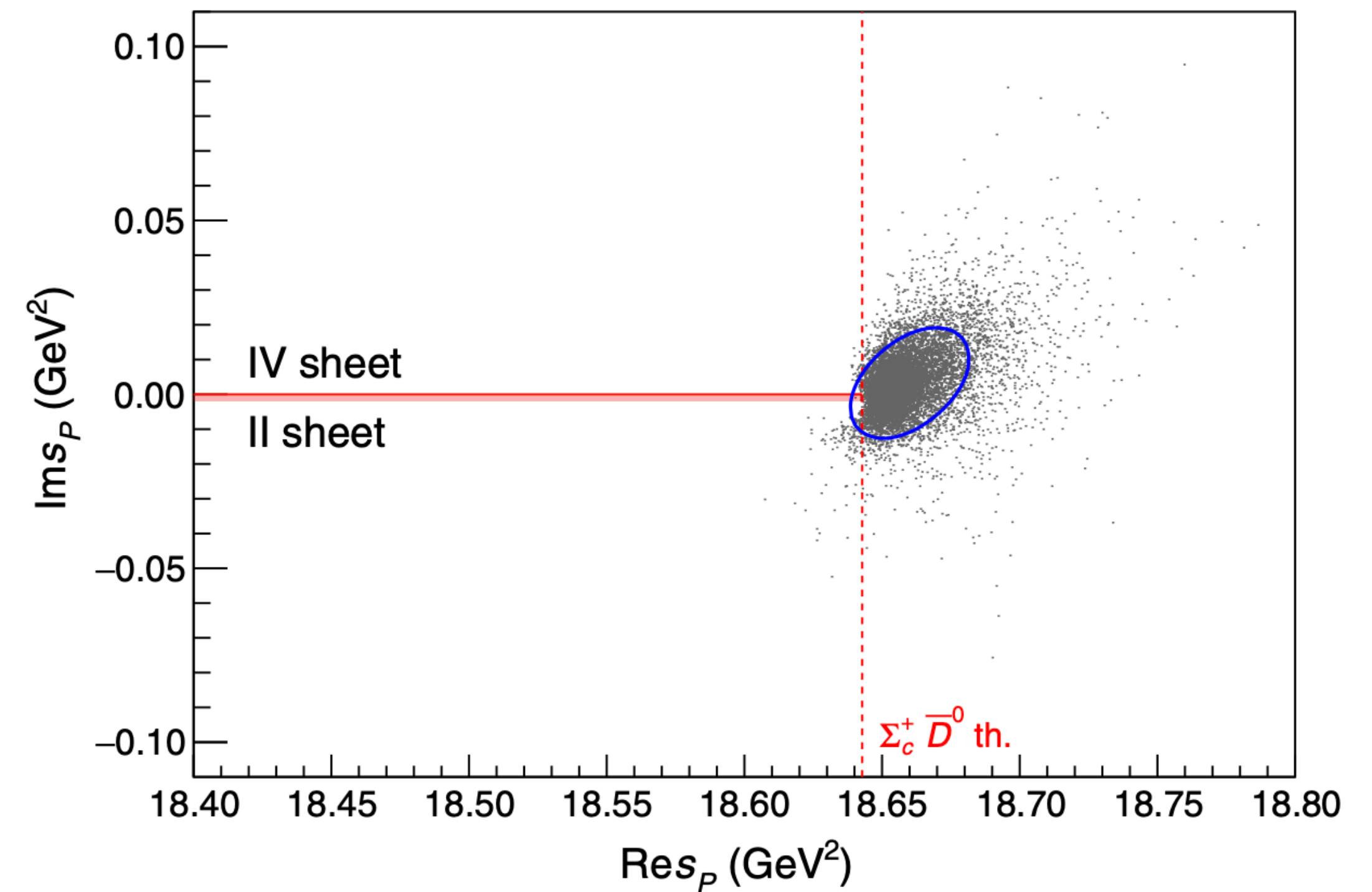
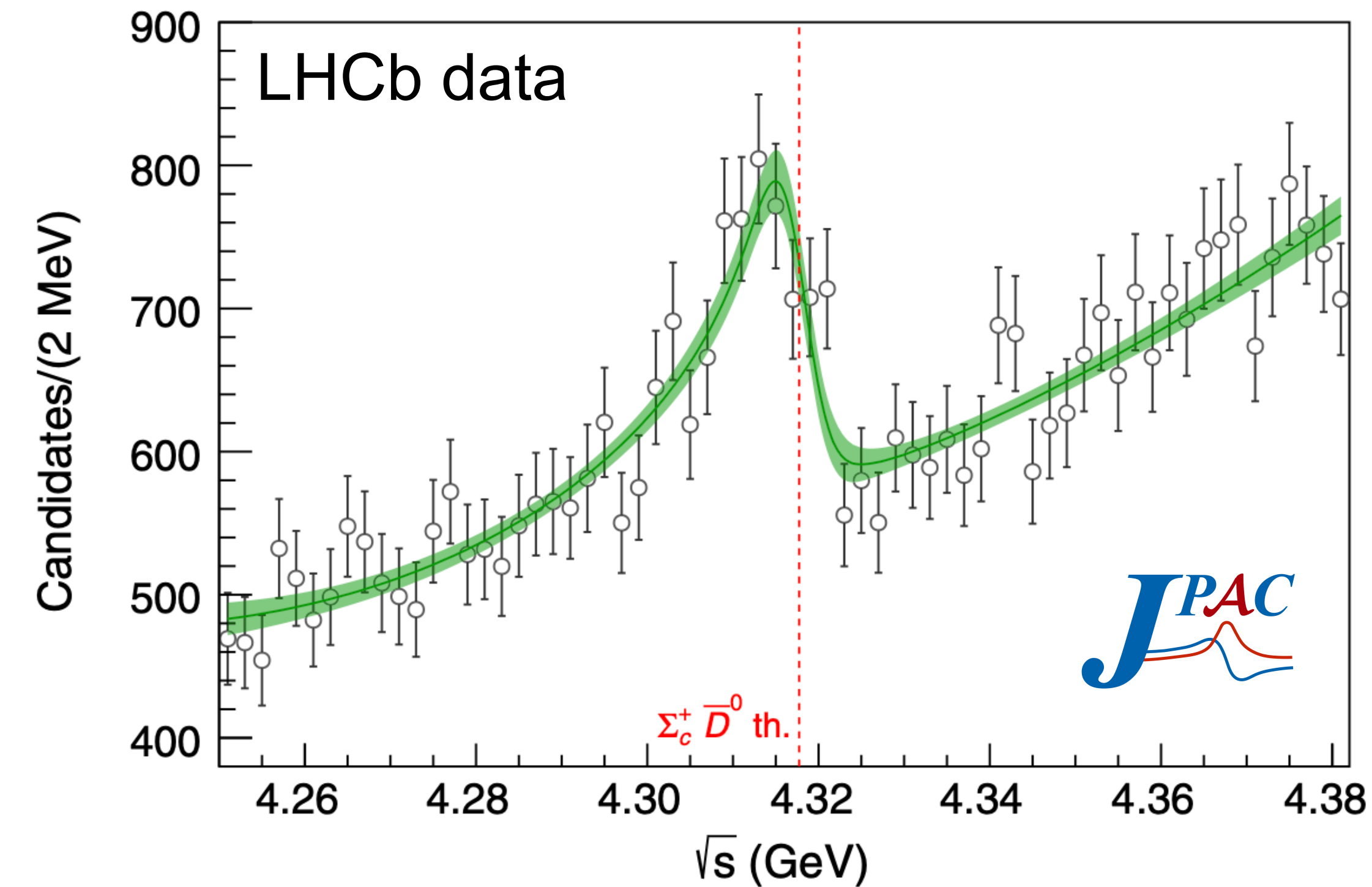
Cross section $\sigma = 4\pi a^2$

Bound state vs virtual state



Scattering length $a = \lim_{k \rightarrow 0} \frac{1}{k} \tan \delta(k)$

Cross section $\sigma = 4\pi a^2$

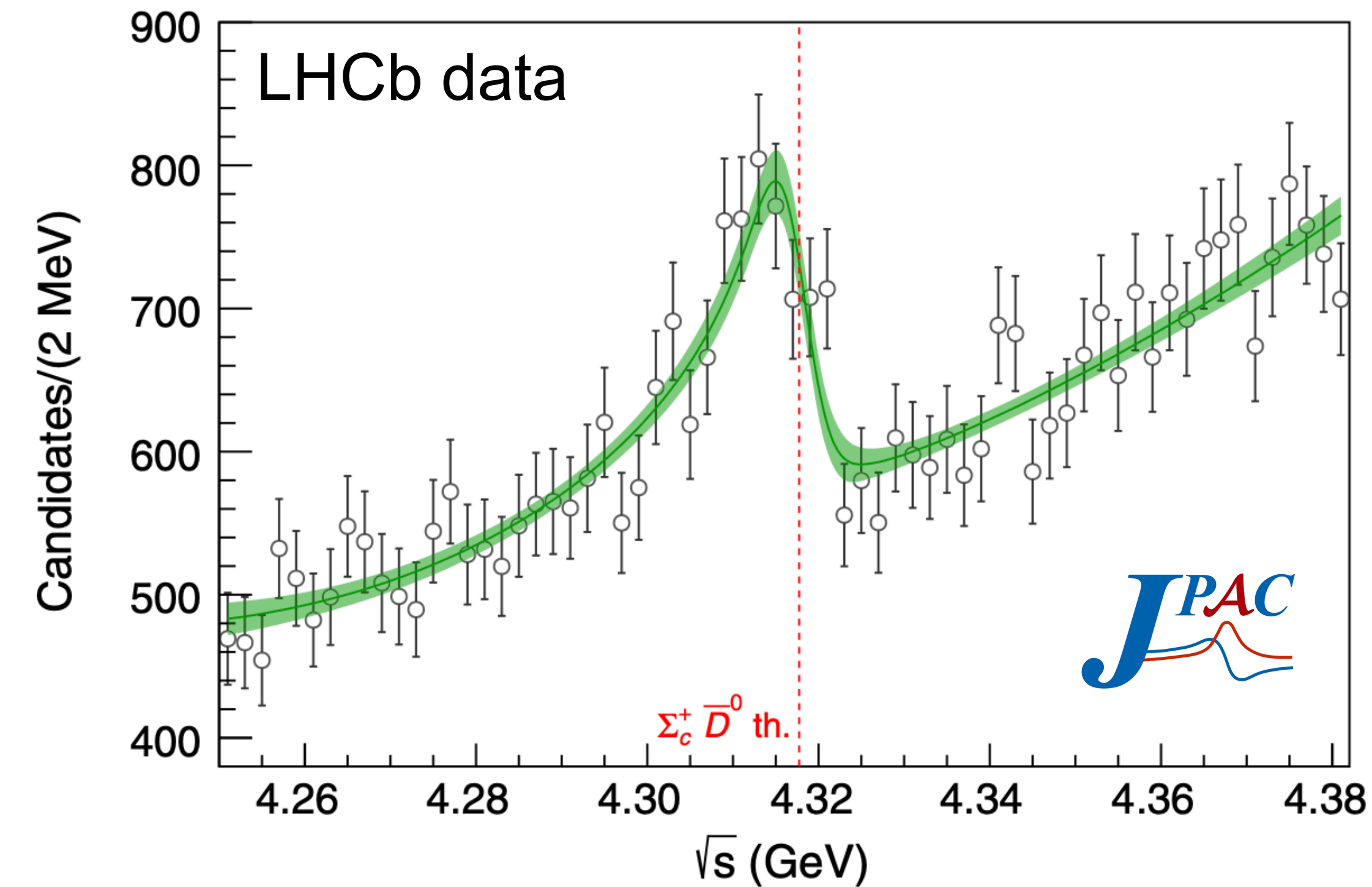


Bootstrap: generate 10k data

When $J/\psi p$ decouples, pole moves to the real axis on the

Physical sheet - positive scattering length - bound state

Unphysical sheet - negative scattering length - virtual state

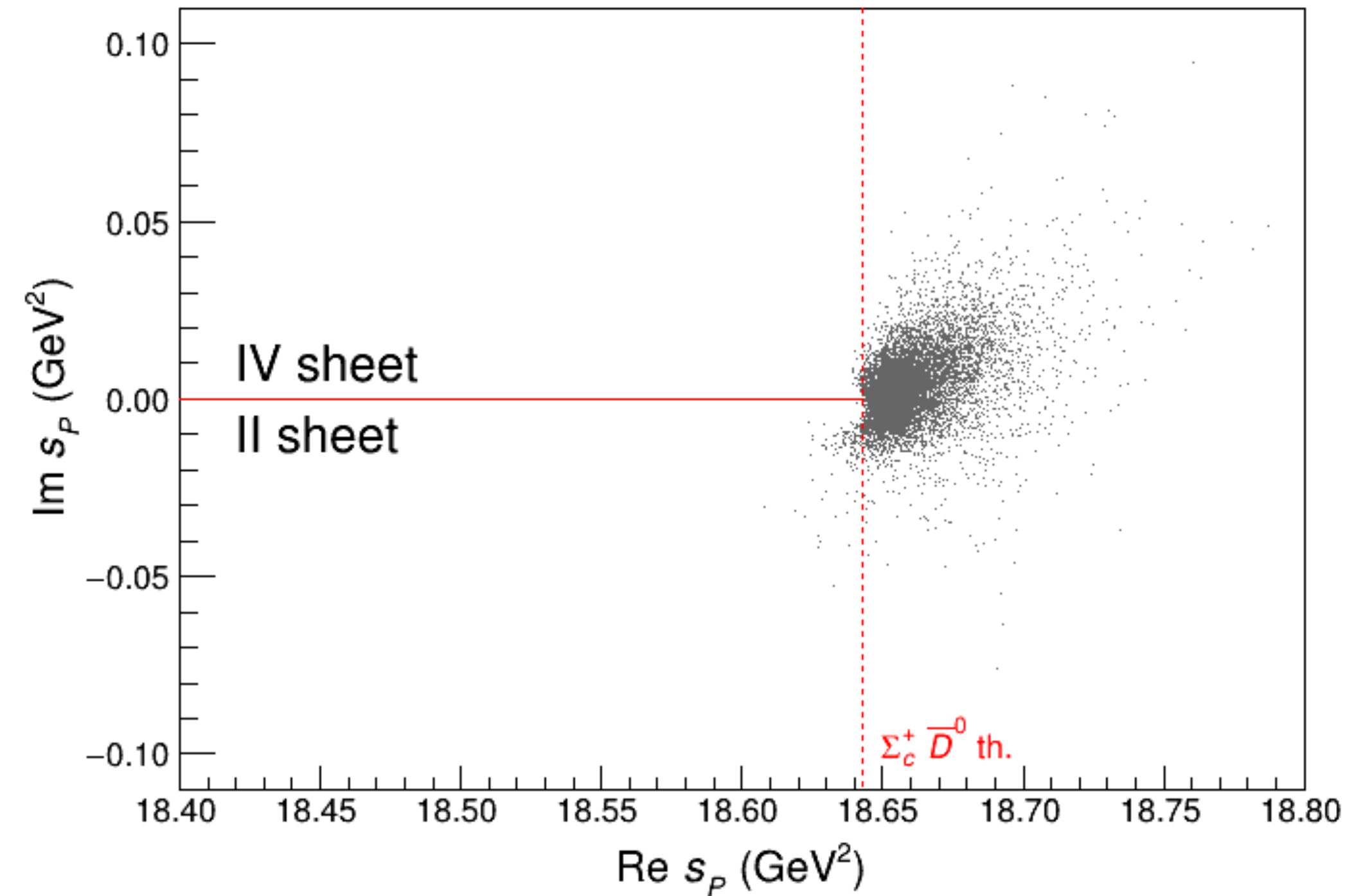
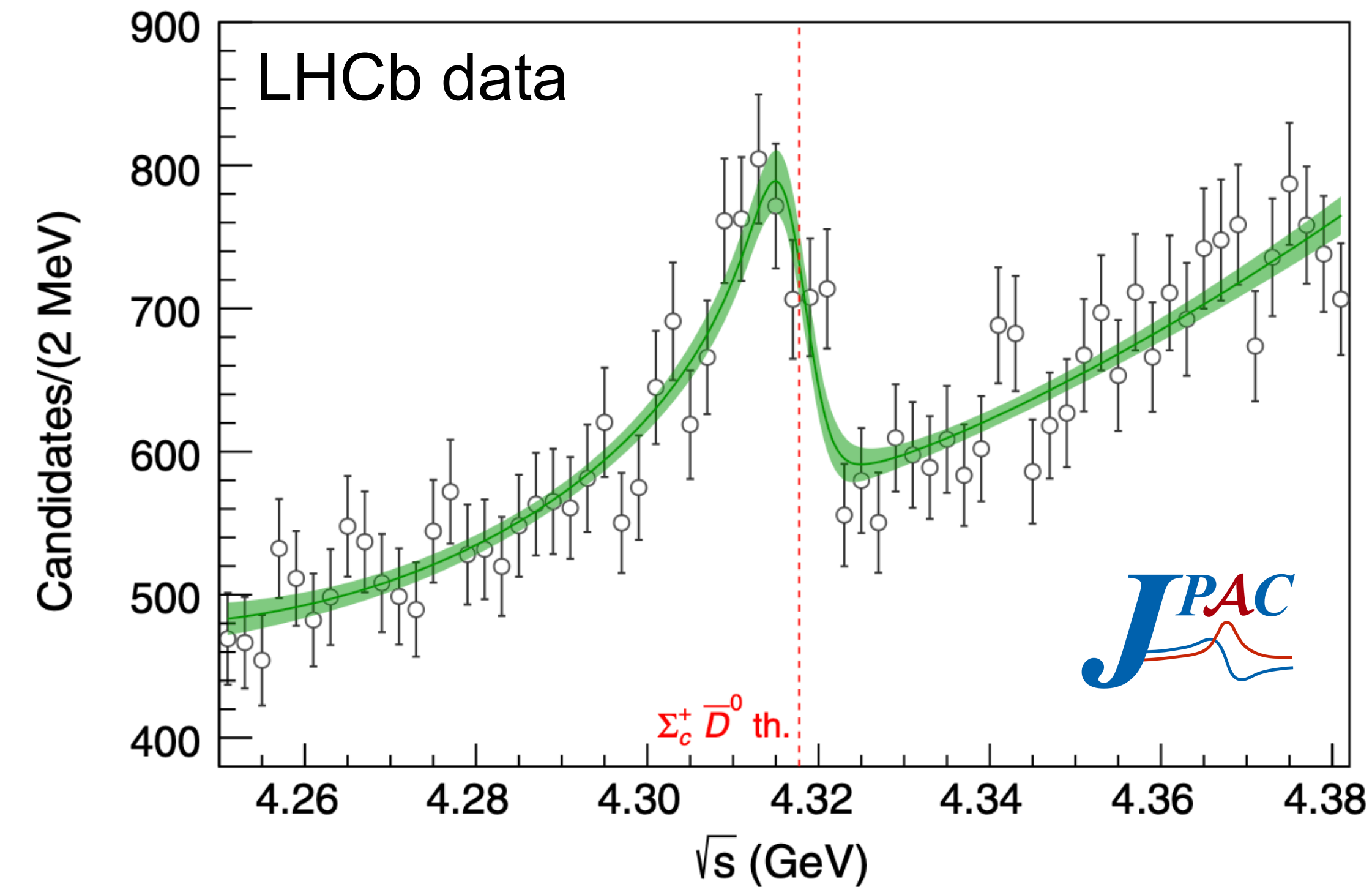


Bootstrap: generate 10k data

When $J/\psi p$ decouples, pole moves to the real axis on the

Physical sheet - positive scattering length - bound state

Unphysical sheet - negative scattering length - virtual state

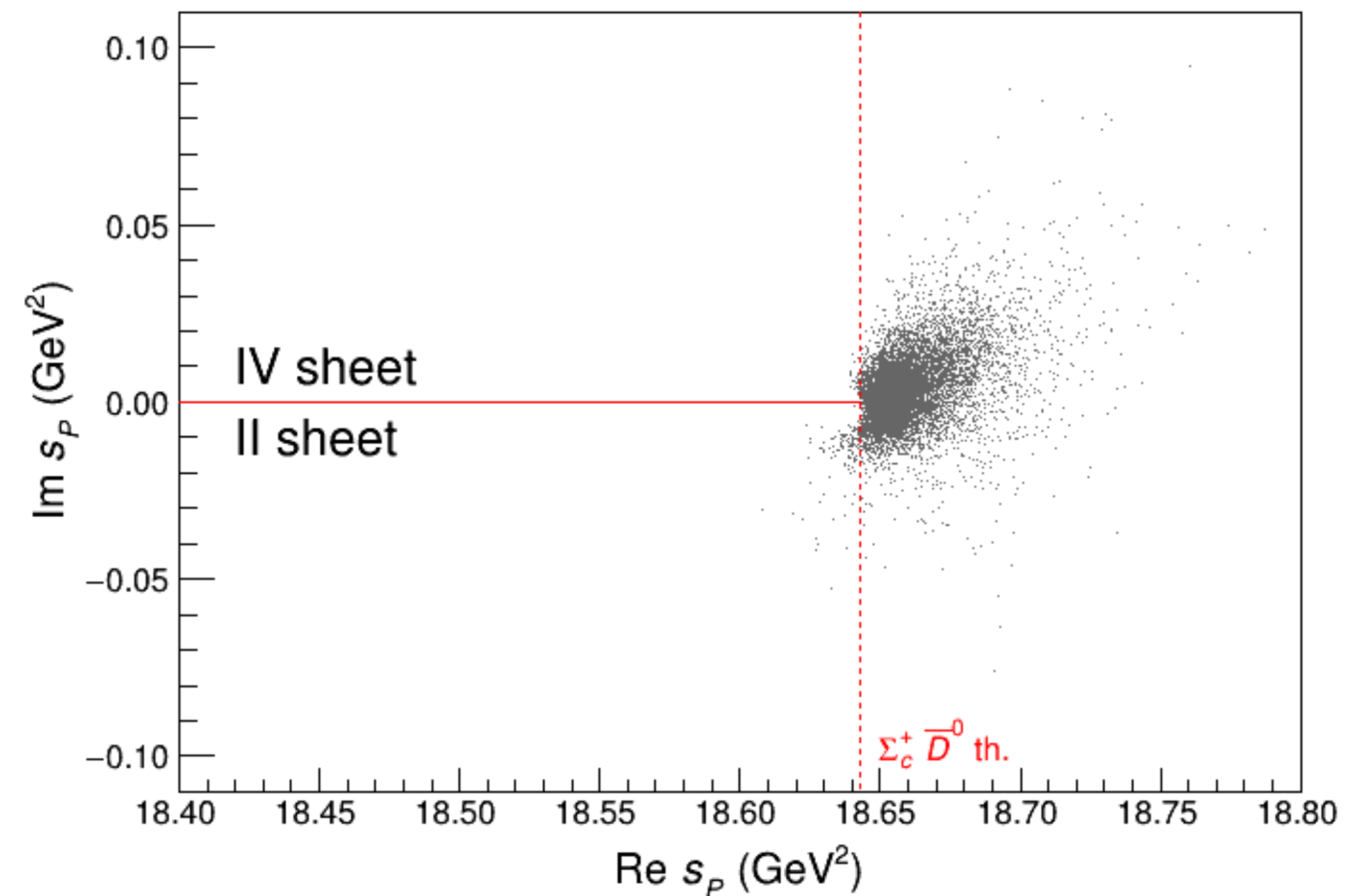
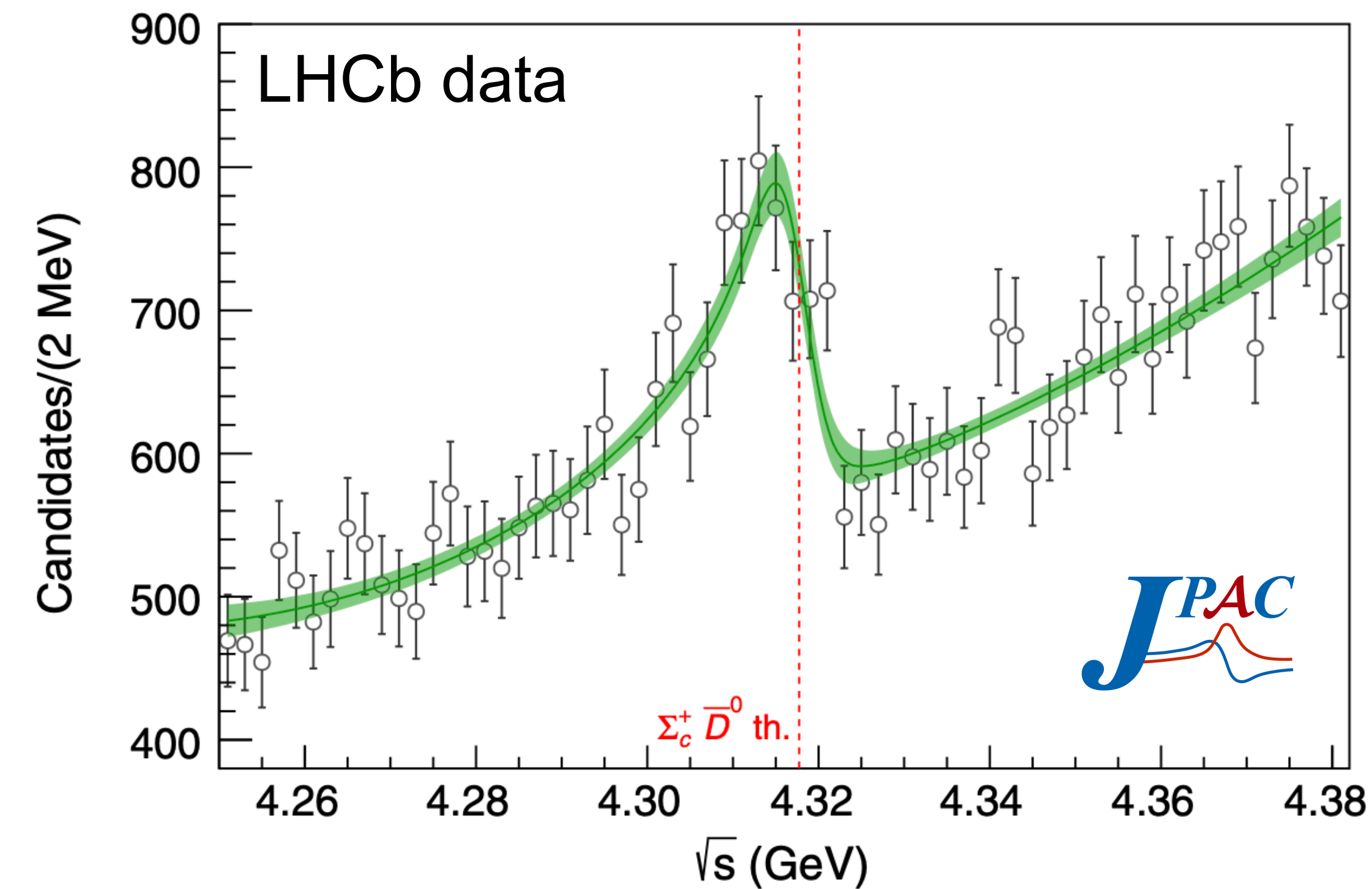


Bootstrap: generate 10k data

When $J/\psi p$ decouples, pole moves to the real axis on the

Physical sheet - positive scattering length - bound state

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Bootstrap: generate 10k data

When $J/\psi p$ decouples, pole moves to the real axis on the

Physical sheet - positive scattering length - bound state

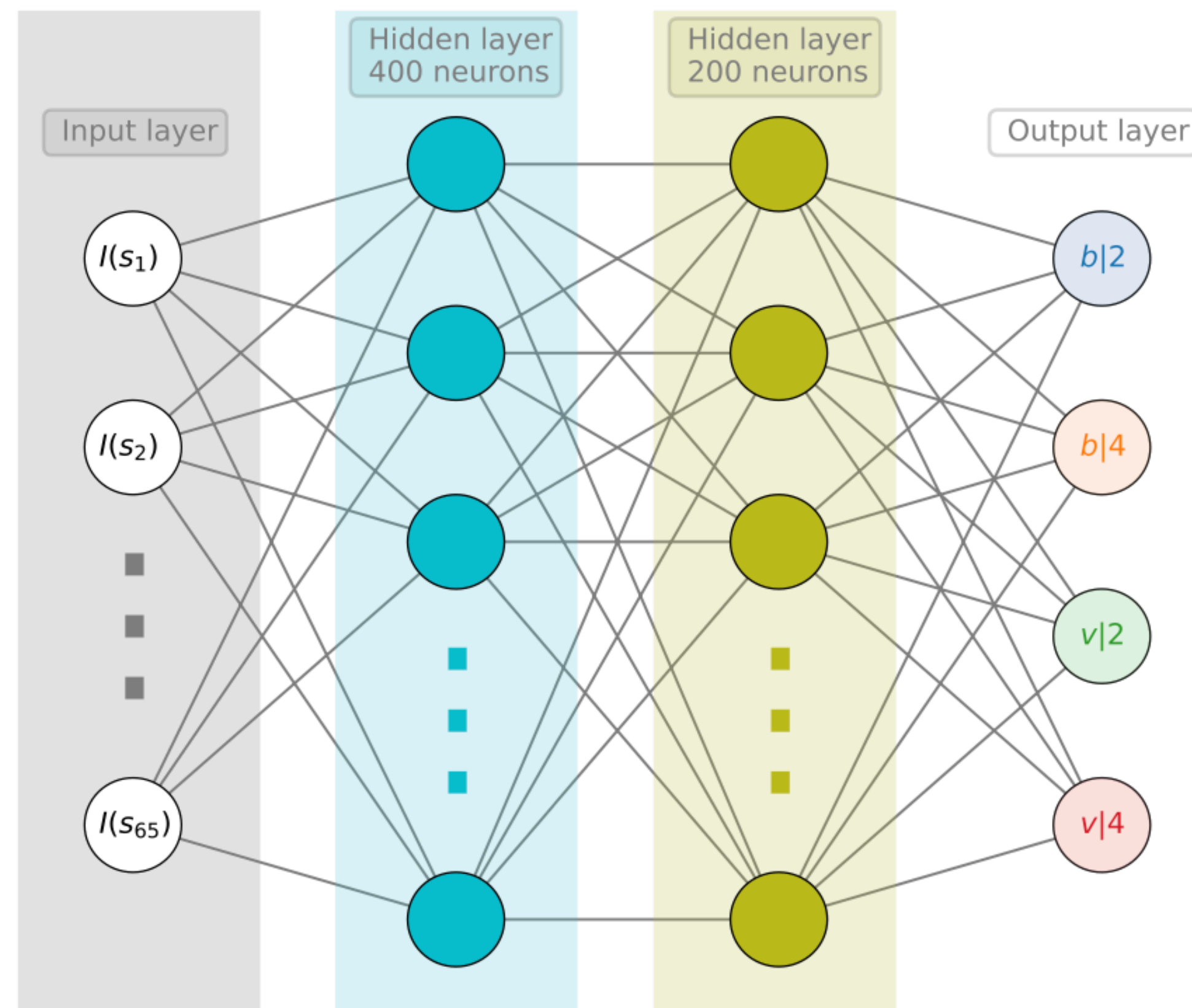
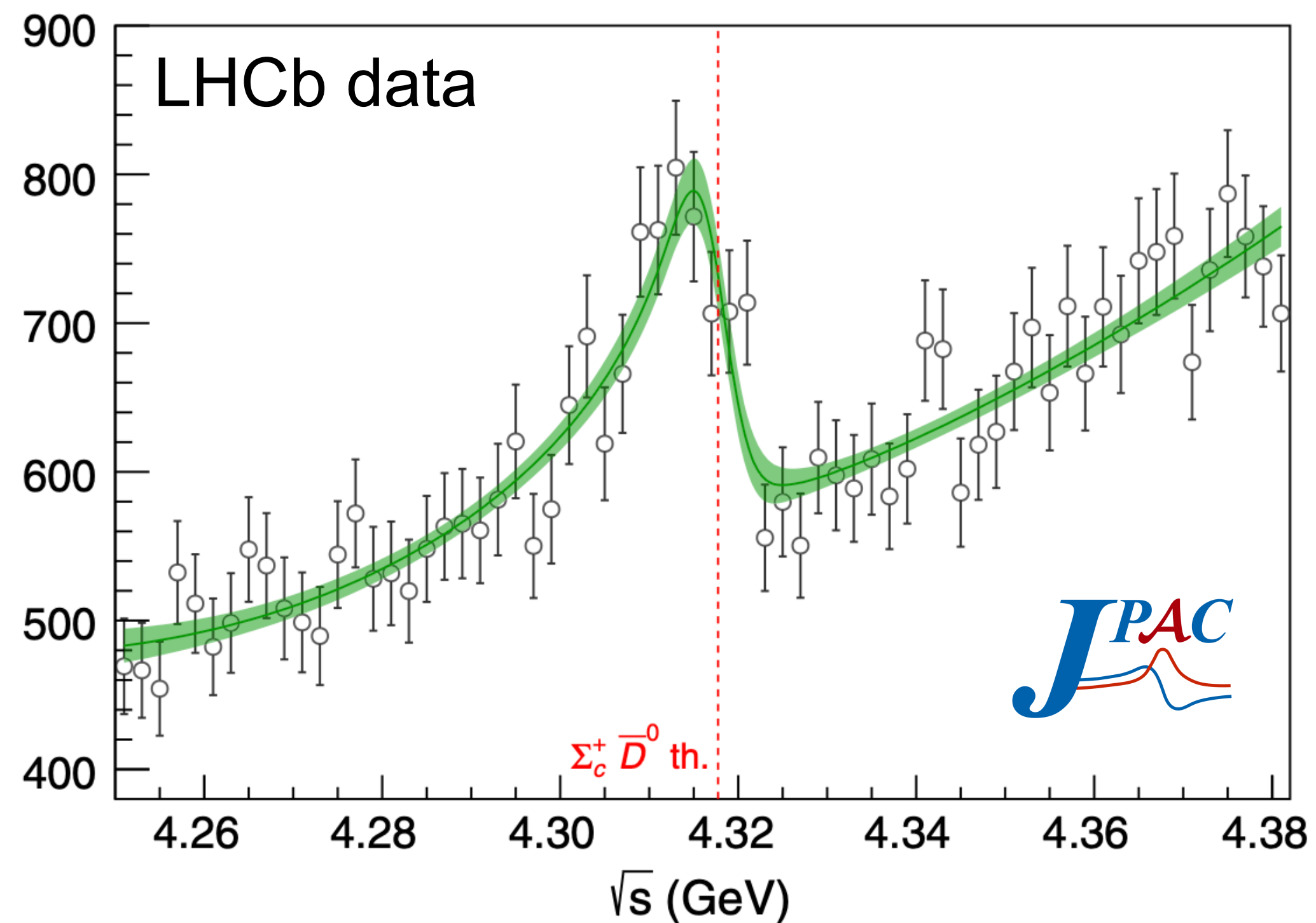
0.7 %

Unphysical sheet - negative scattering length - virtual state

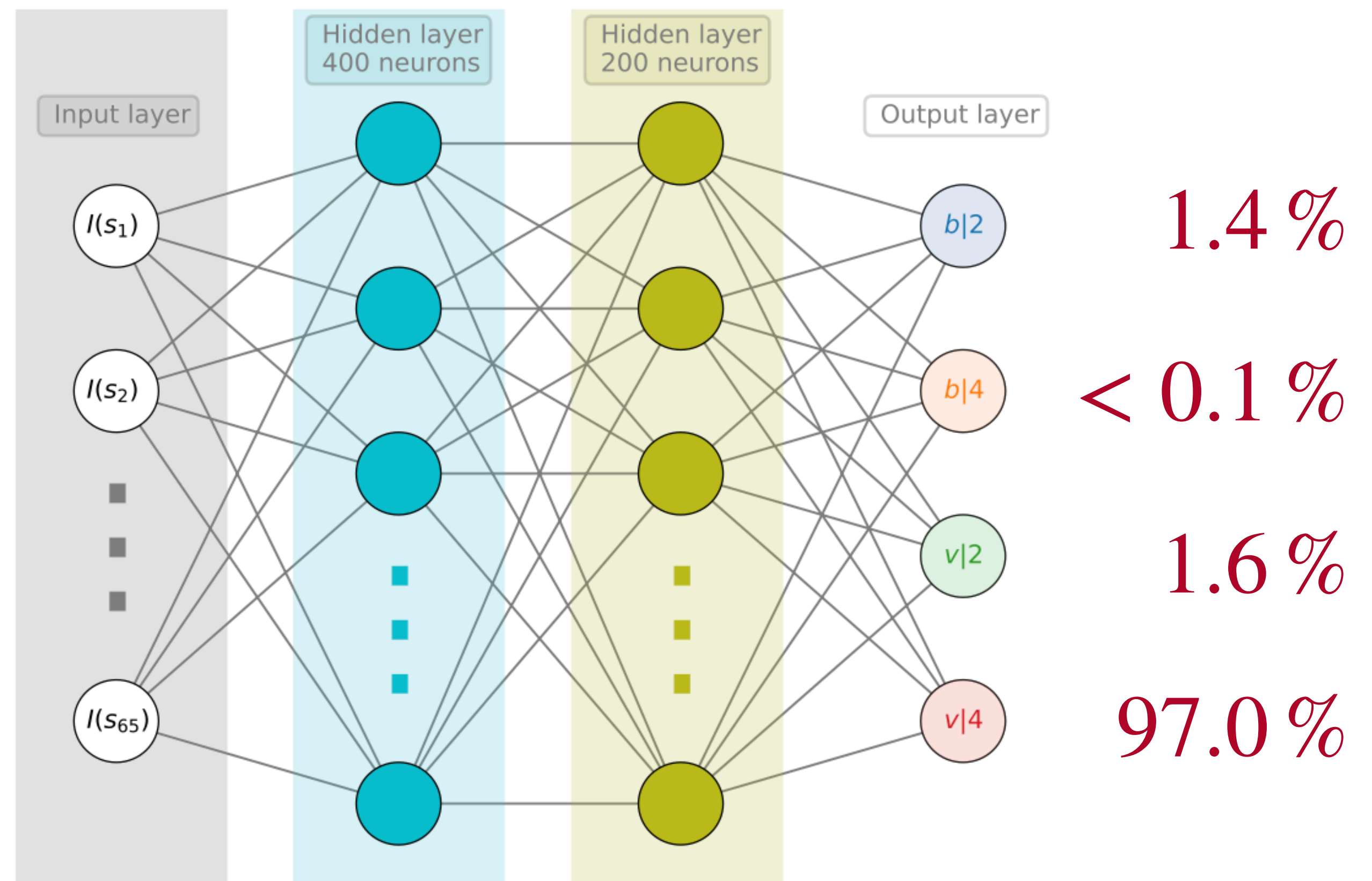
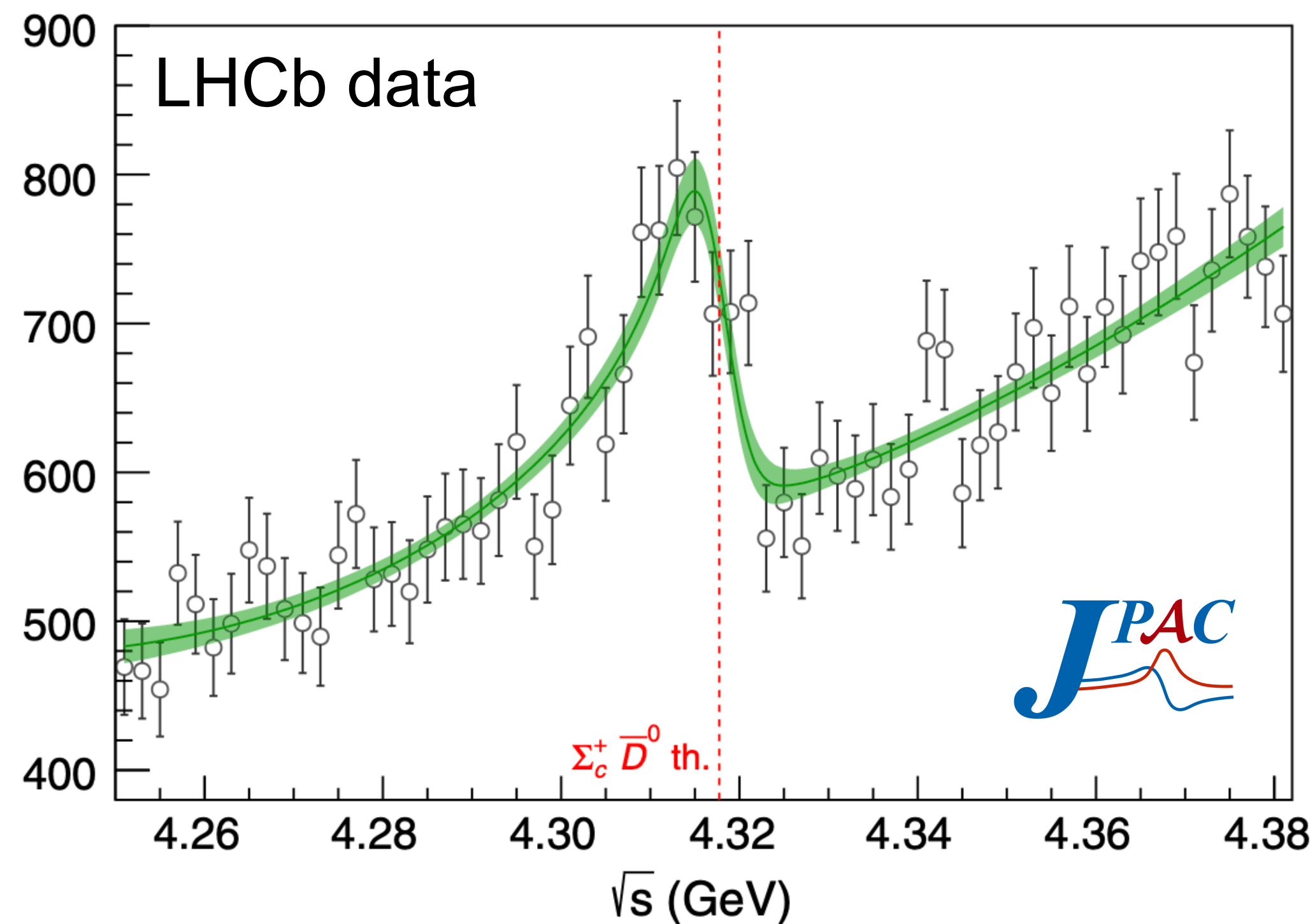
99.3 %

Virtual state in the $\Sigma_c^+ \bar{D}^0$ channel

Deep neural network trained with 4 types of amplitudes



Deep neural network trained with 4 types of amplitudes



Direct production of P_c^+ ?



GlueX, PRL23 (2019) 072001

Data

Hiller-Blin et al (JPAC), PRD94 (2016) 034002

Model

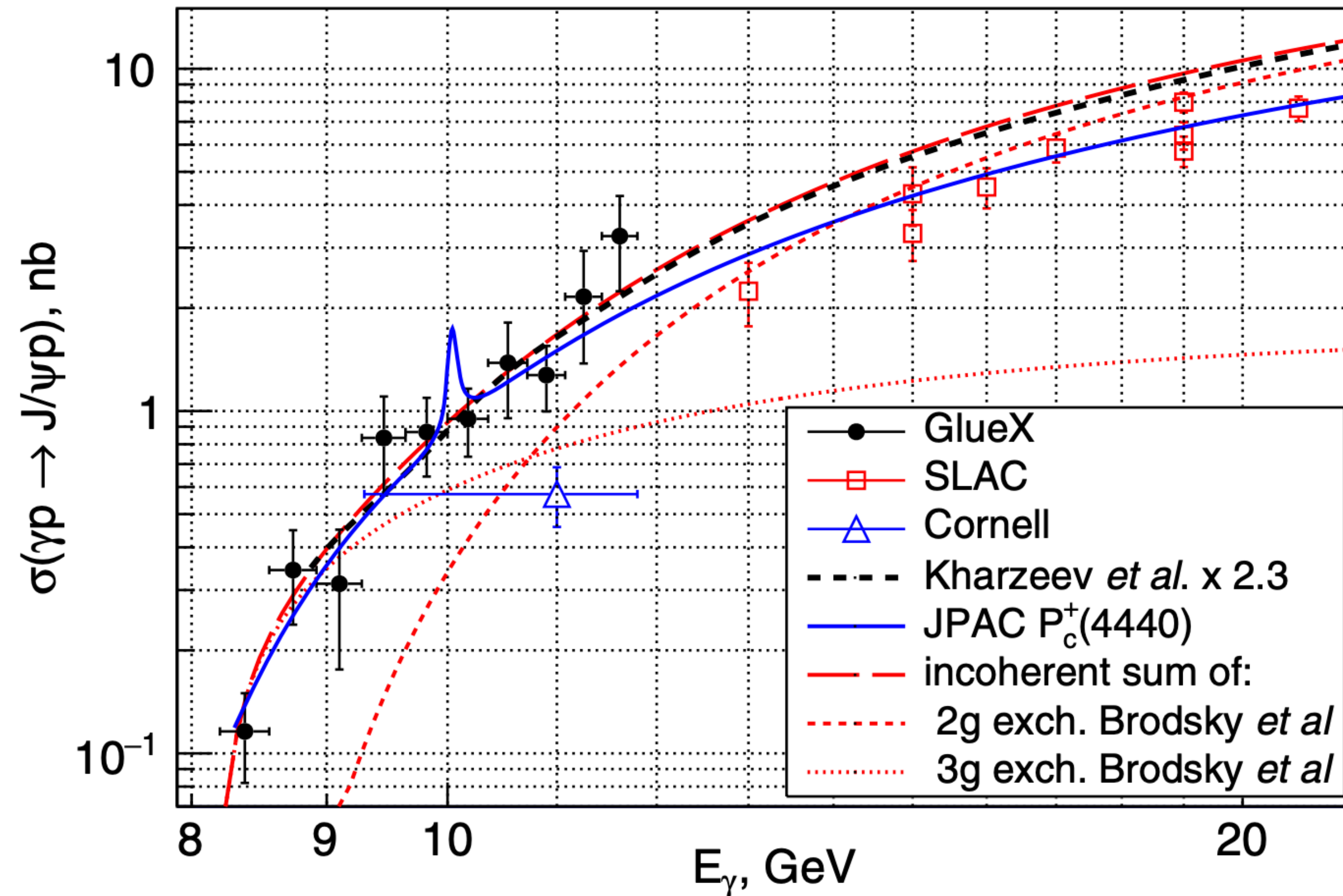
P_c^+ in 3-body decay

$\Lambda_b \rightarrow K^- (J/\psi p)$

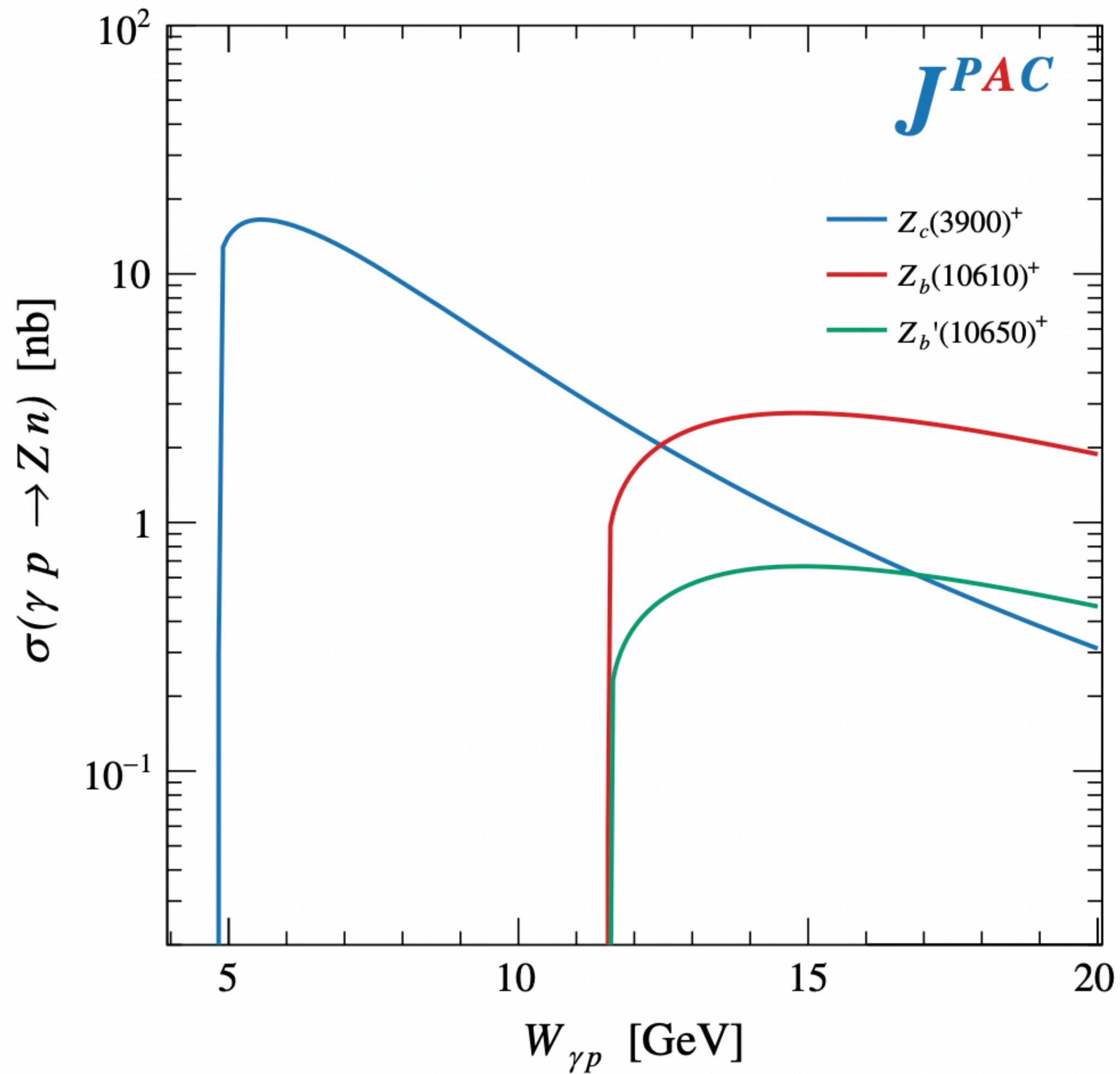


Photoproduction of P_c^+

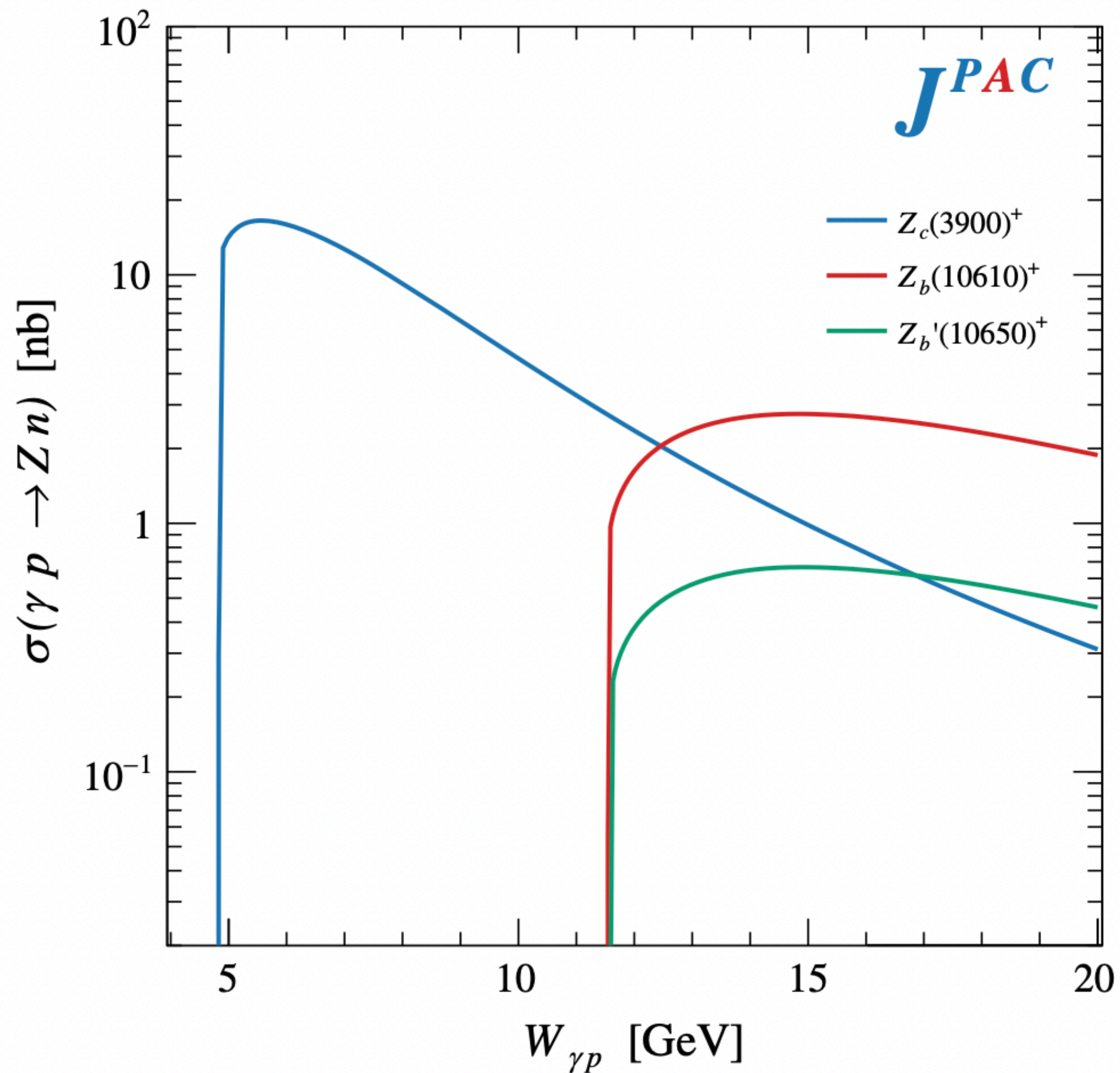
$\gamma p \rightarrow J/\psi p$



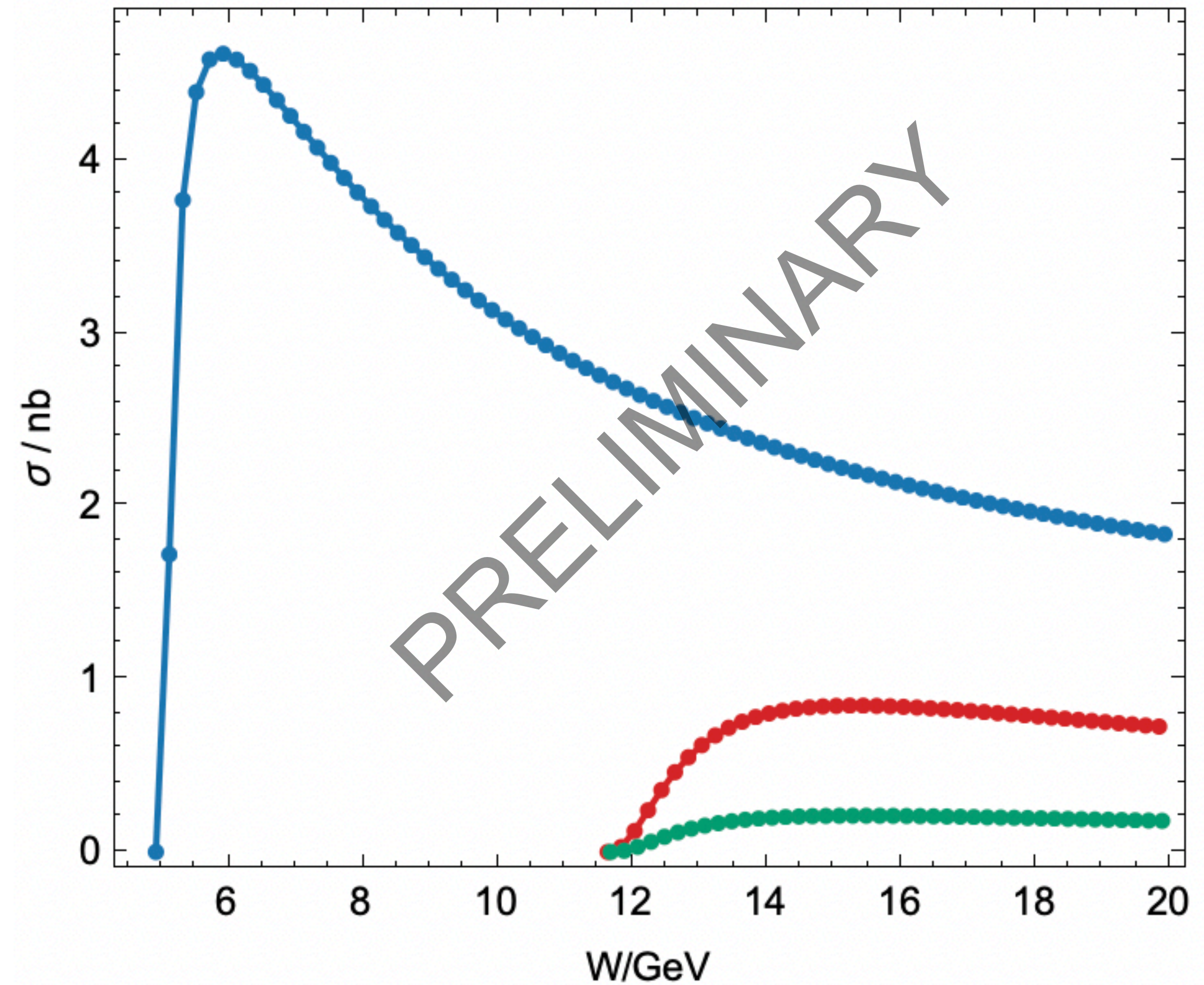
$$\gamma p \rightarrow Z^+ n$$

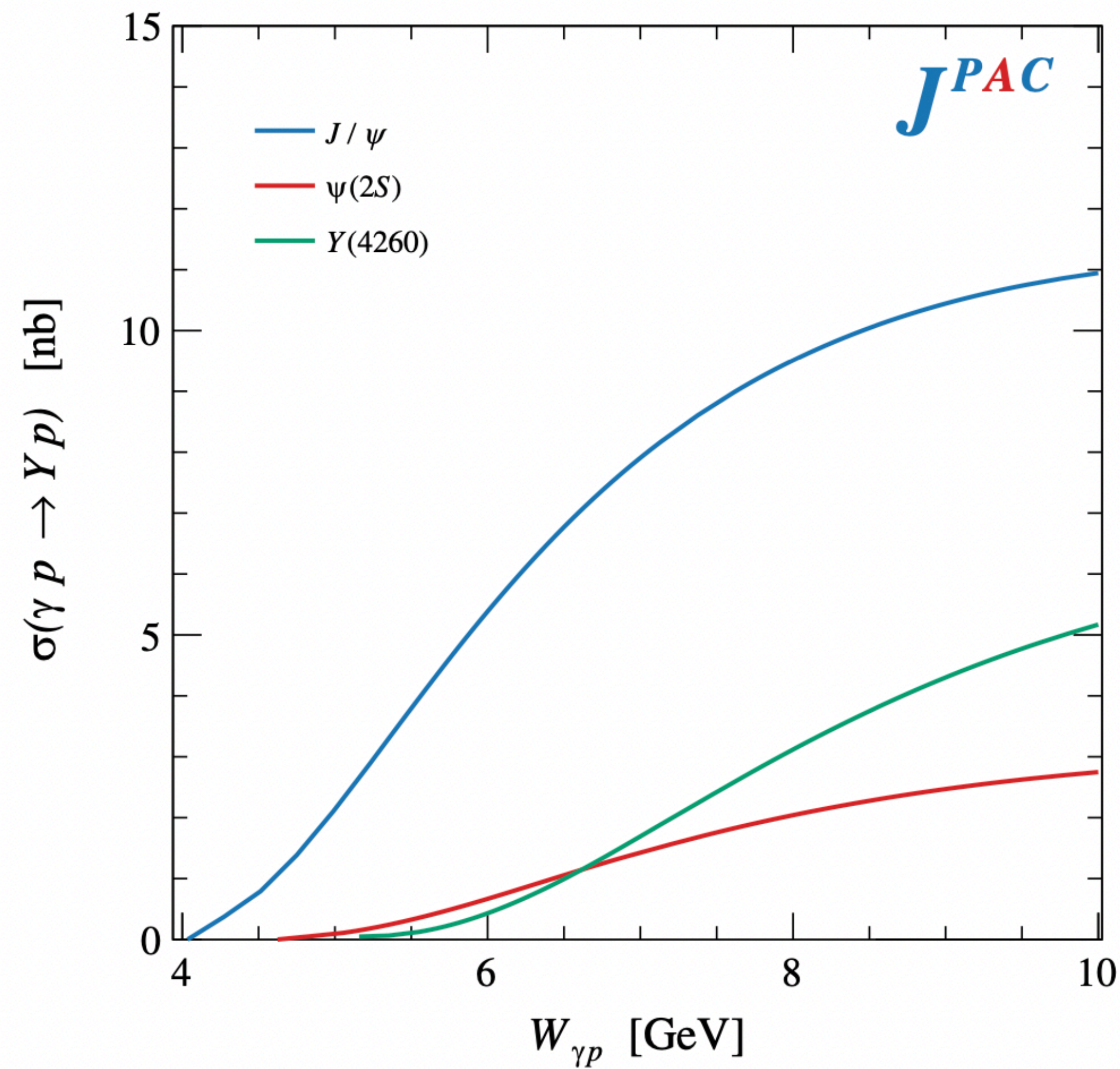
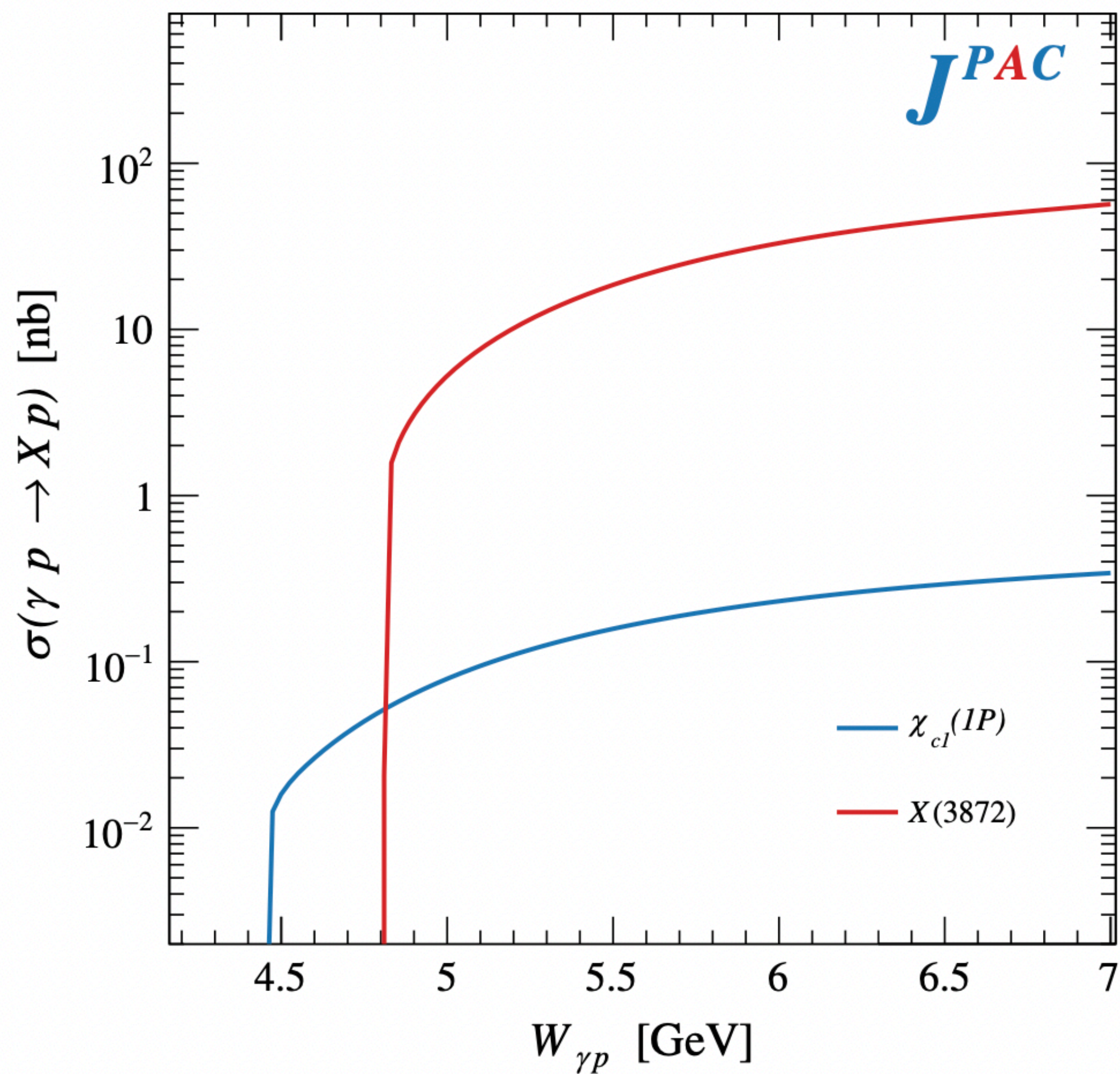


$$\gamma p \rightarrow Z^+ n$$



$$\gamma p \rightarrow Z^+ X \quad M_X \geq m_p + m_\pi$$





Summary

Light exotic mesons: $\pi_1(1600)$

Analyses of resonance region
and double Regge region

COMPASS: $\pi^- p \rightarrow \pi^- \eta^{(\prime)} p$

GlueX: $\gamma p \rightarrow \pi^0 \eta p$

Heavy exotic baryons: $P_c(4372)$

Analysis of LHCb results

LHCb: $\Lambda_b \rightarrow K^- J/\psi p$

Heavy exotic mesons: $X(3872), Z_c(3600)^+$

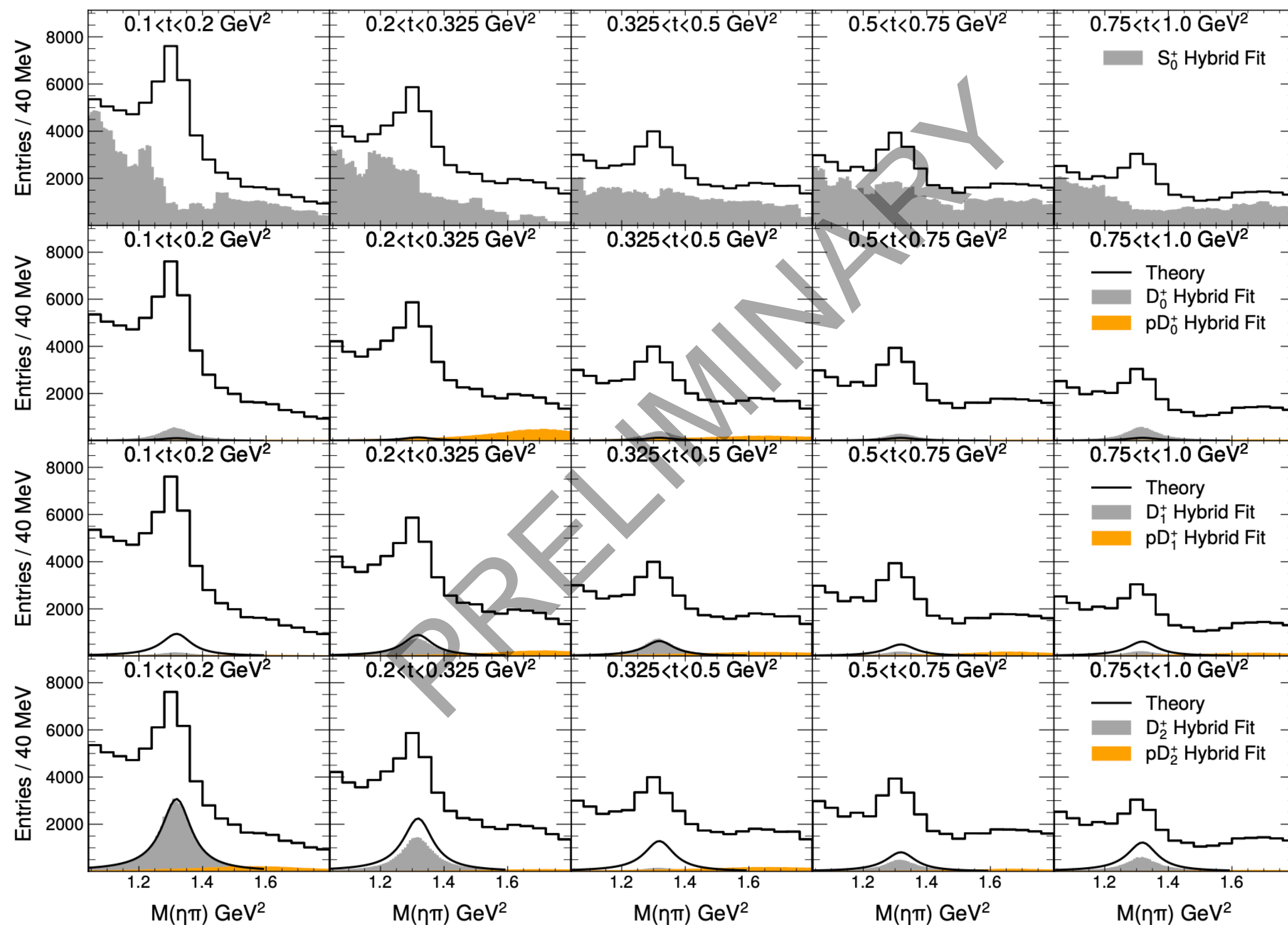
Model prediction for EIC

EIC: $\gamma p \rightarrow X p, Z p$

Backup Slides

$a_2(1320)$ Photoproduction @GlueX

In collaboration with L. Ng and M. Albrecht

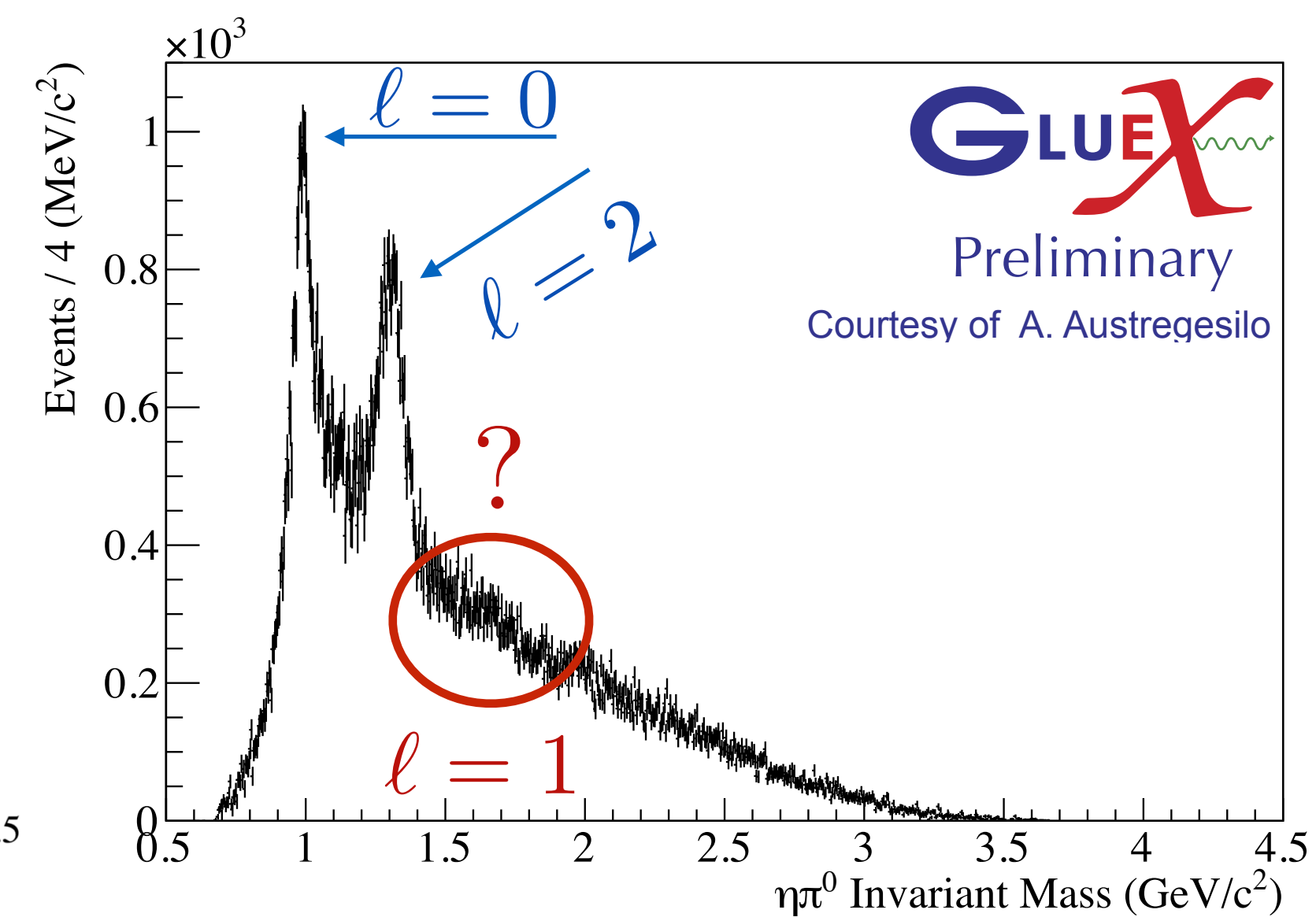
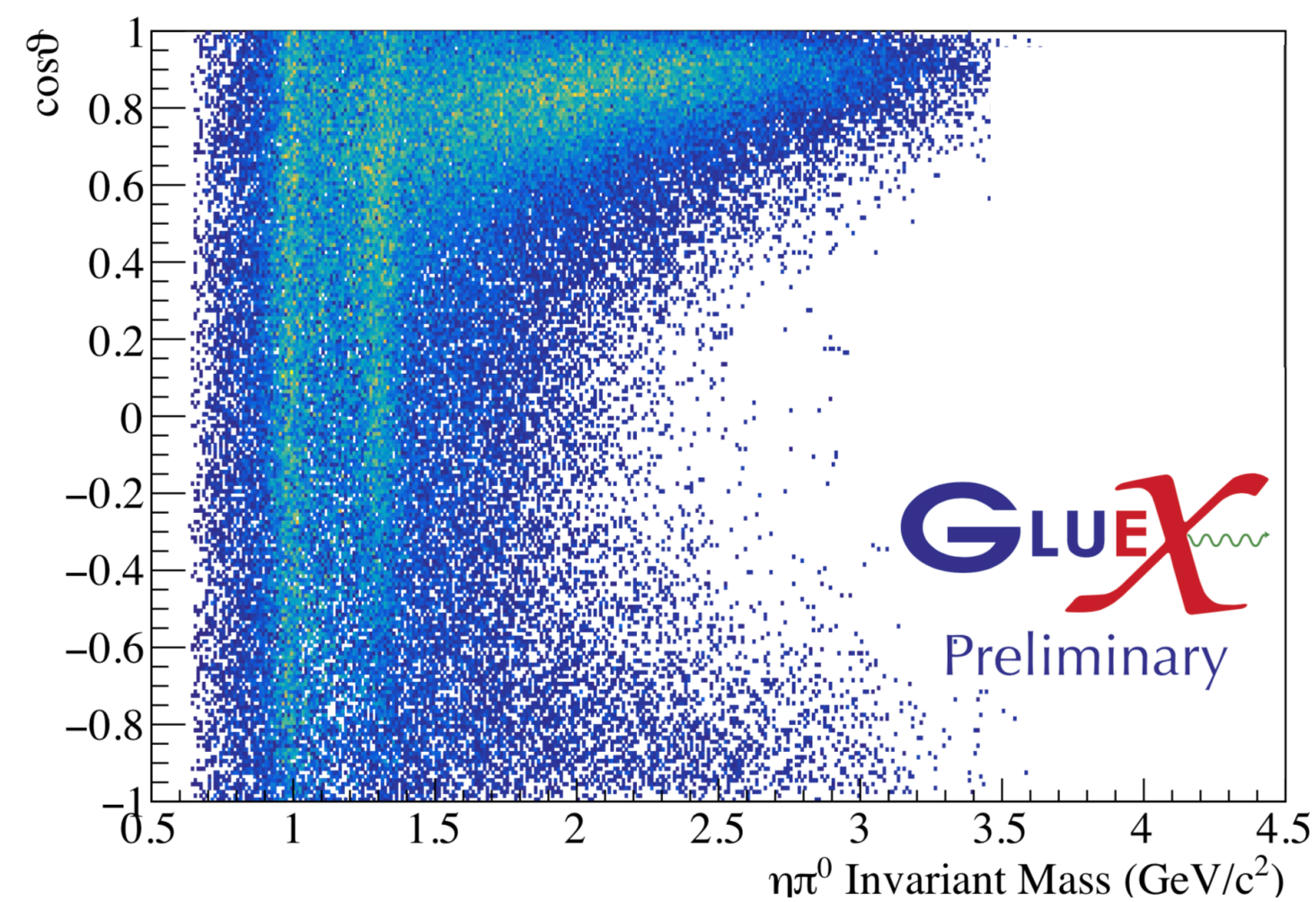
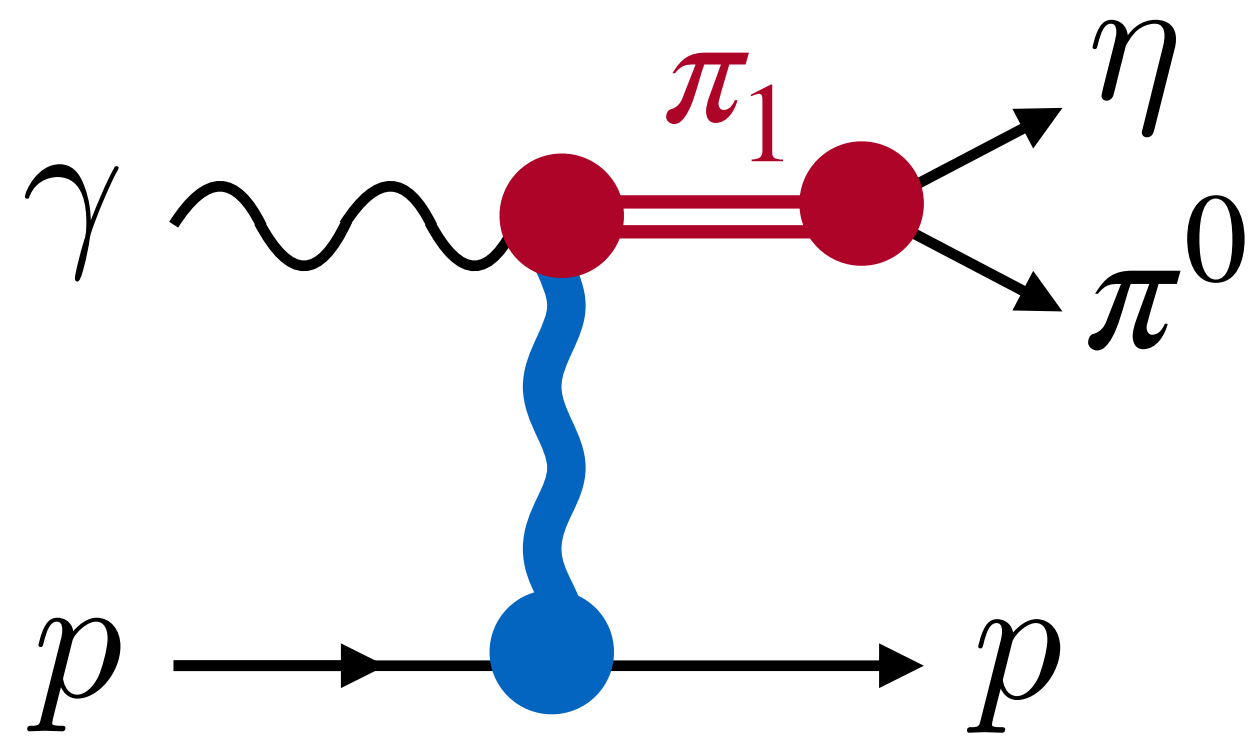


Extraction of $a_2(1320)$ production amplitudes from GlueX data

Reasonable agreement with model predictions from VM et al (JPAC) PRD102 (2020)

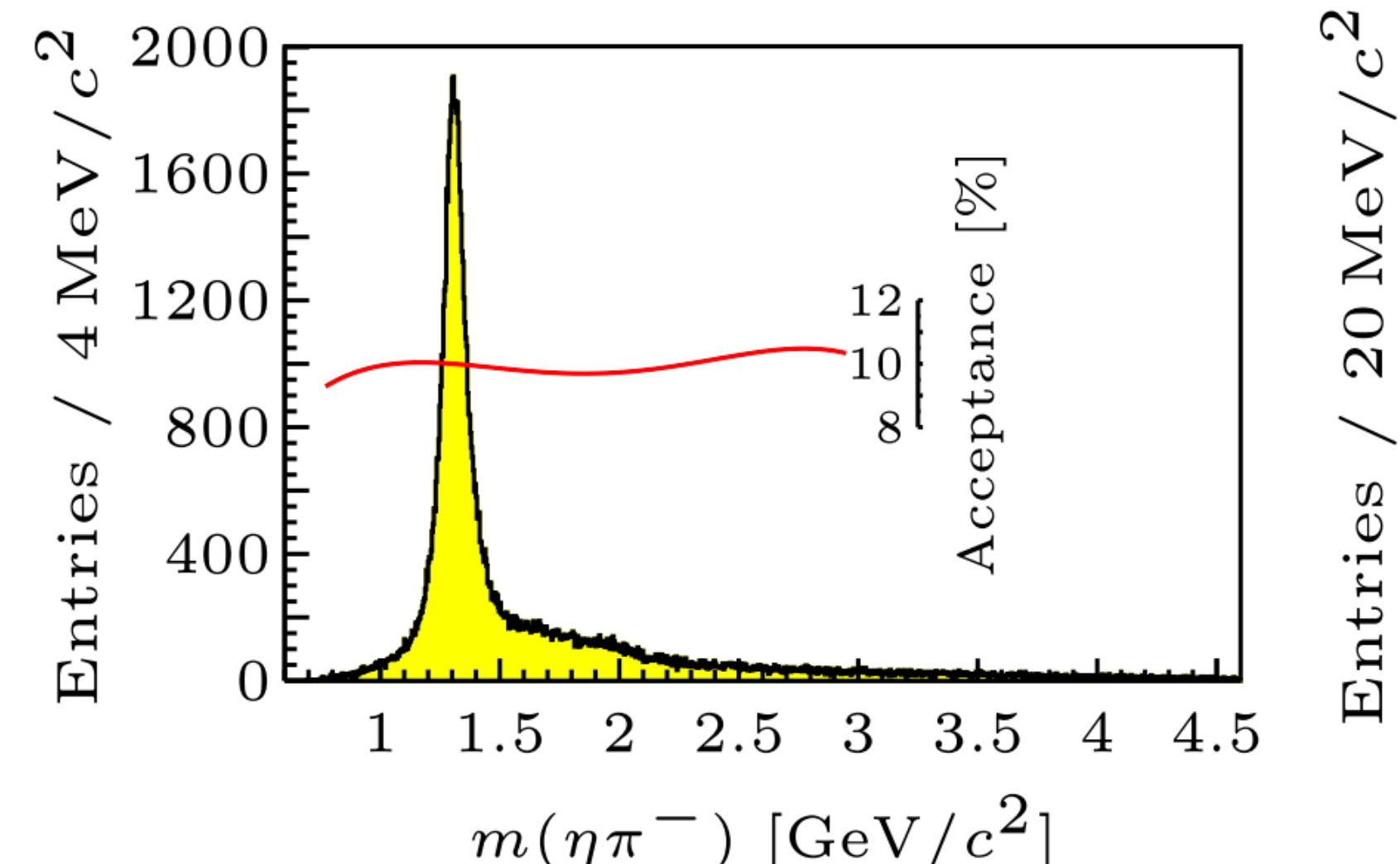
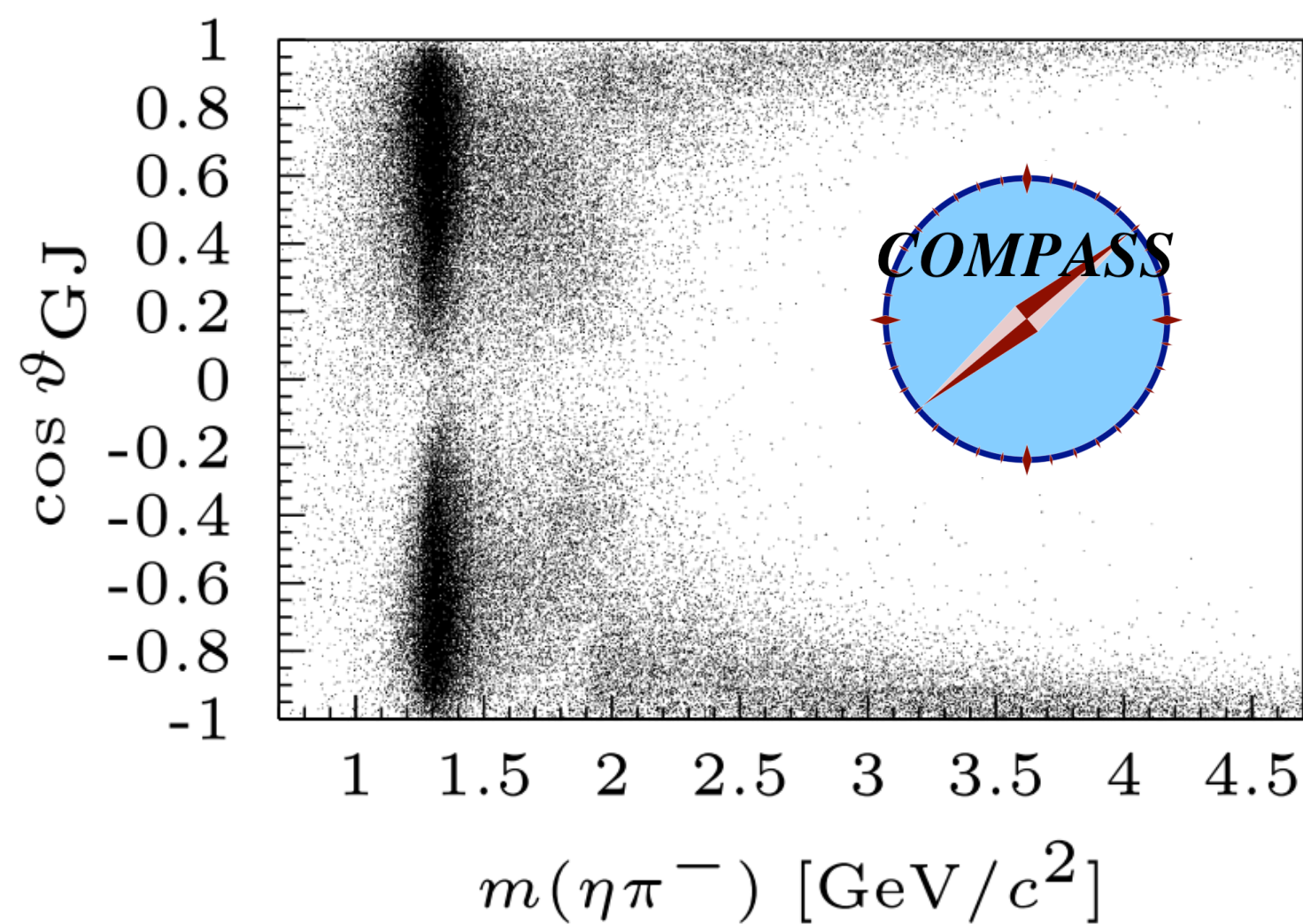
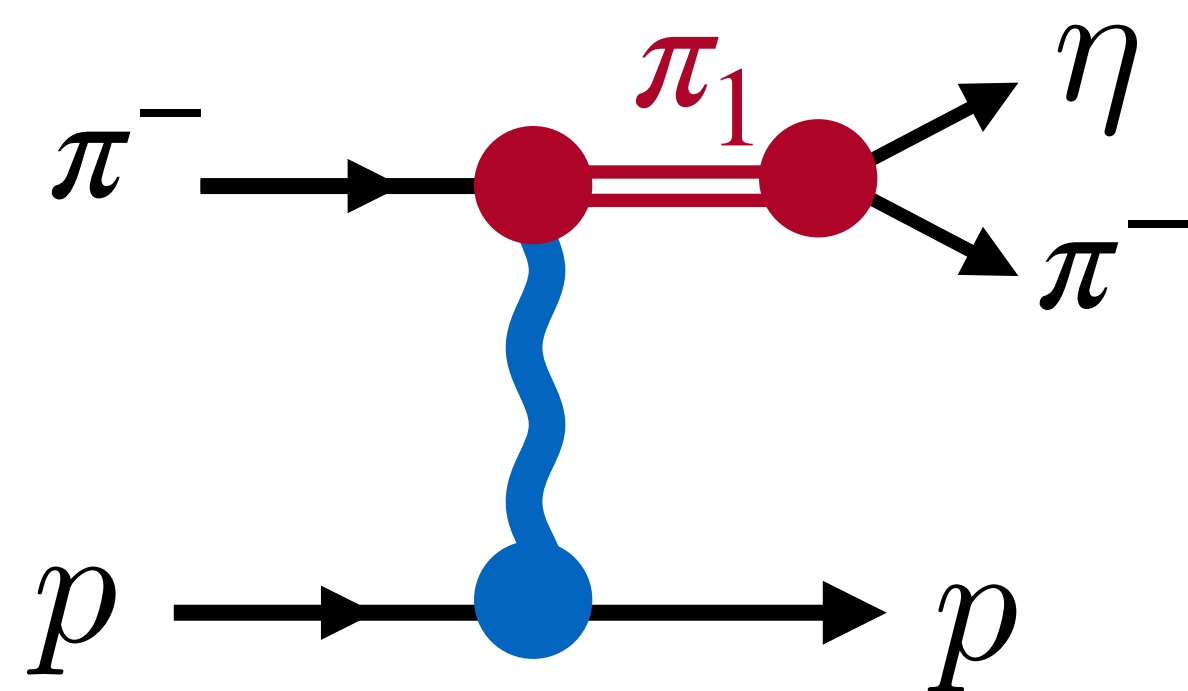
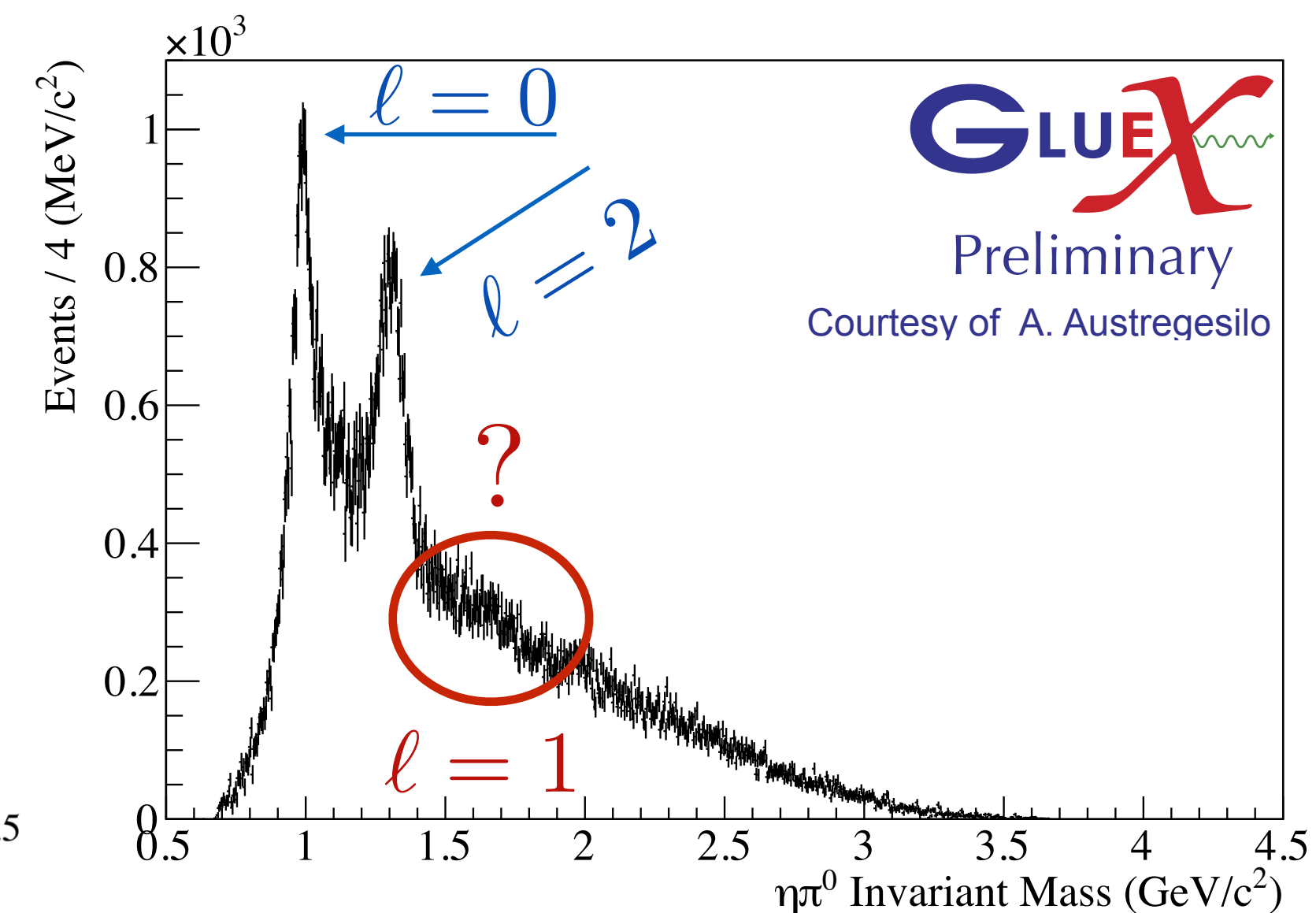
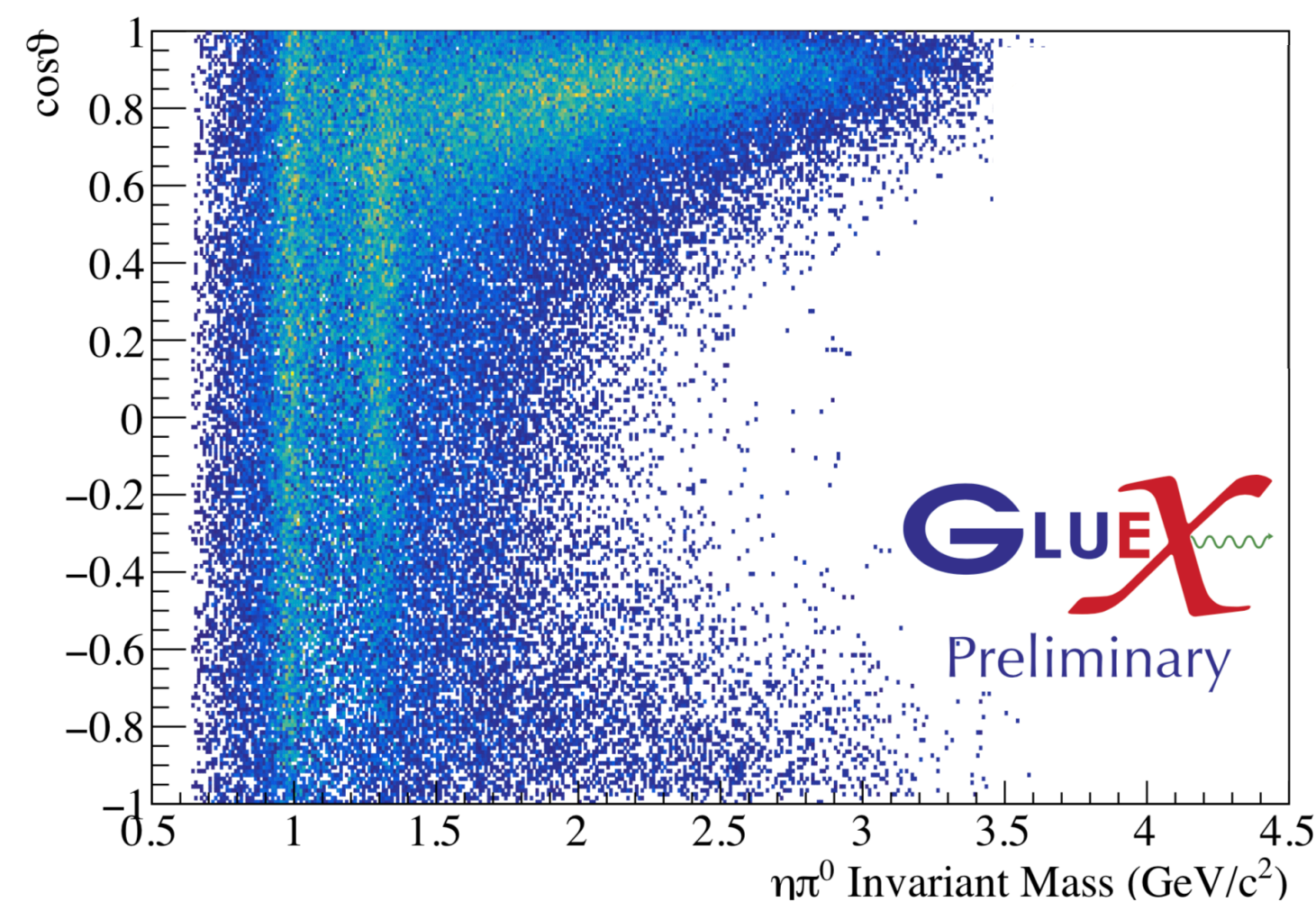
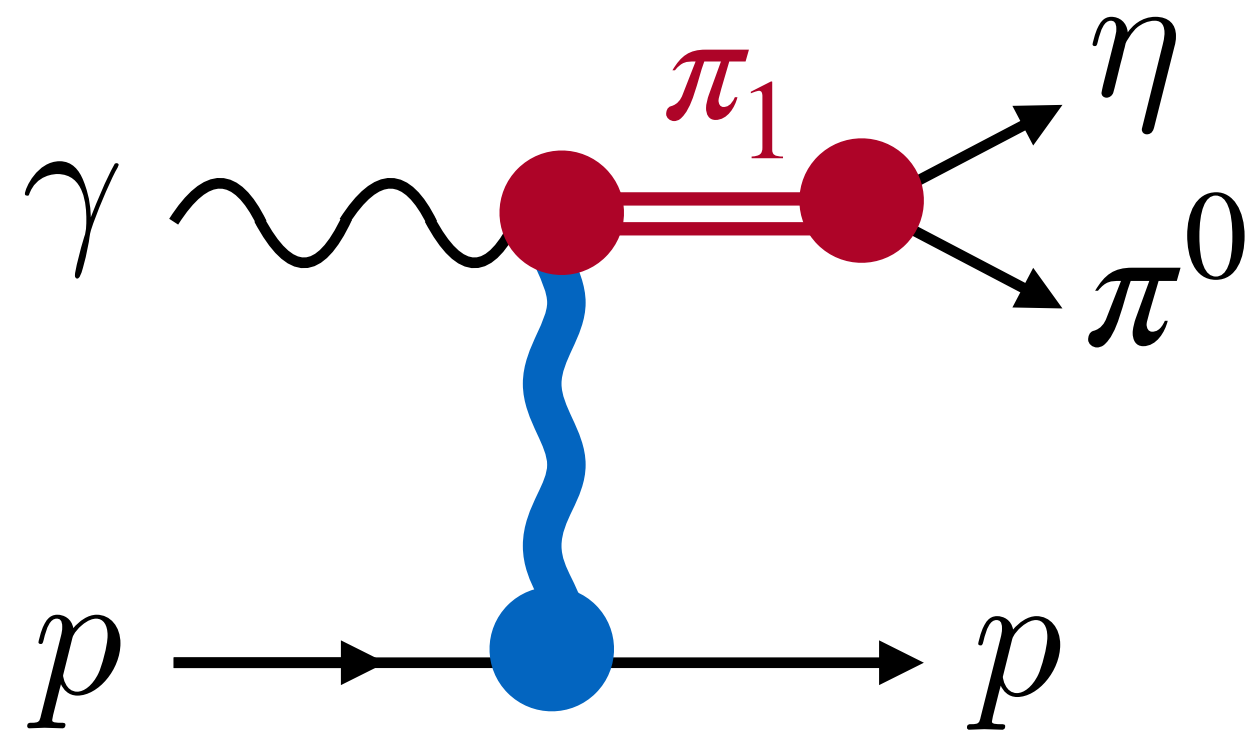
Ongoing extraction of $a_2(1320)$ cross-section

Hybrid Mesons @GlueX and @COMPASS



COMPASS PLB740 (2015)

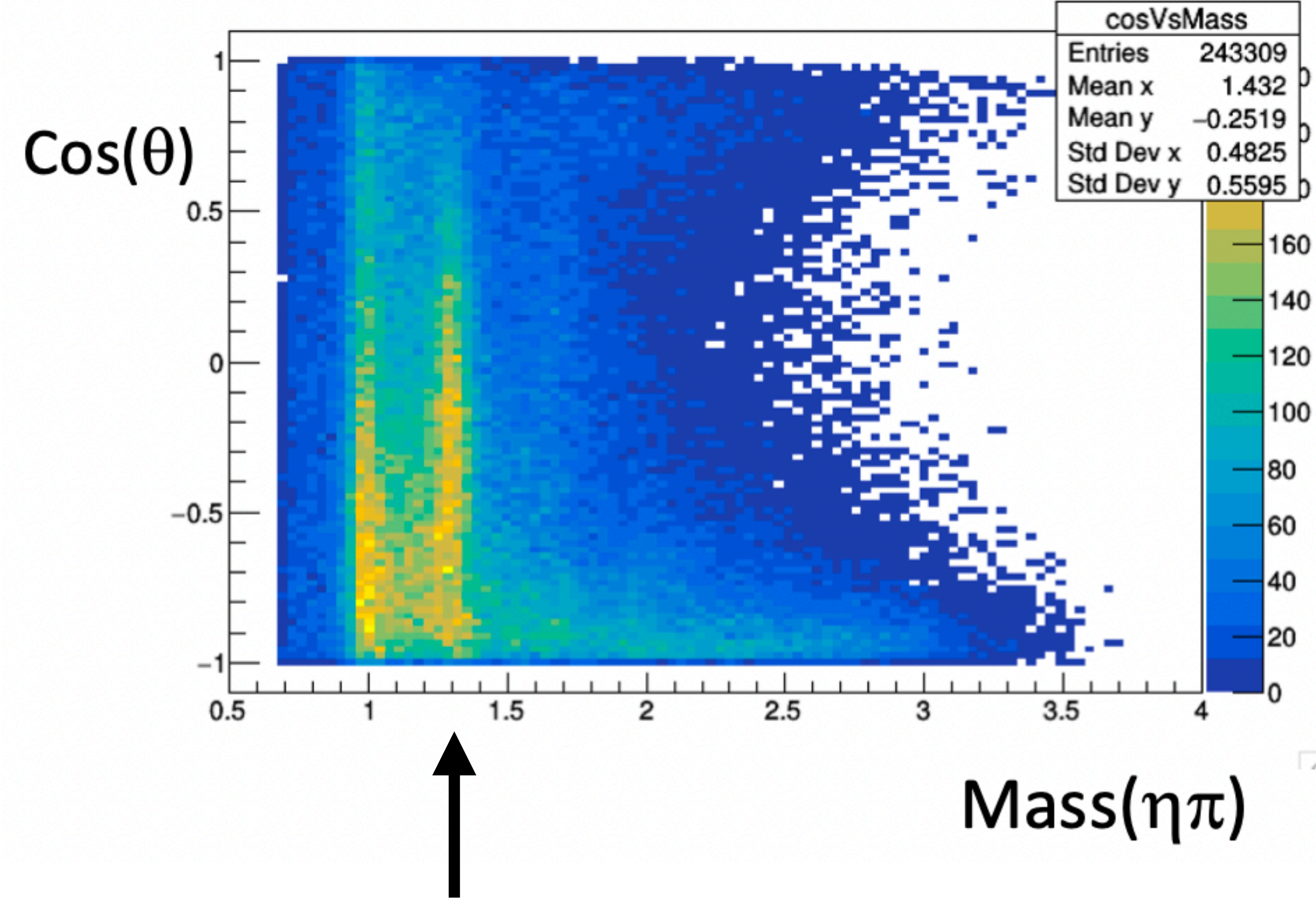
Hybrid Mesons @GlueX and @COMPASS



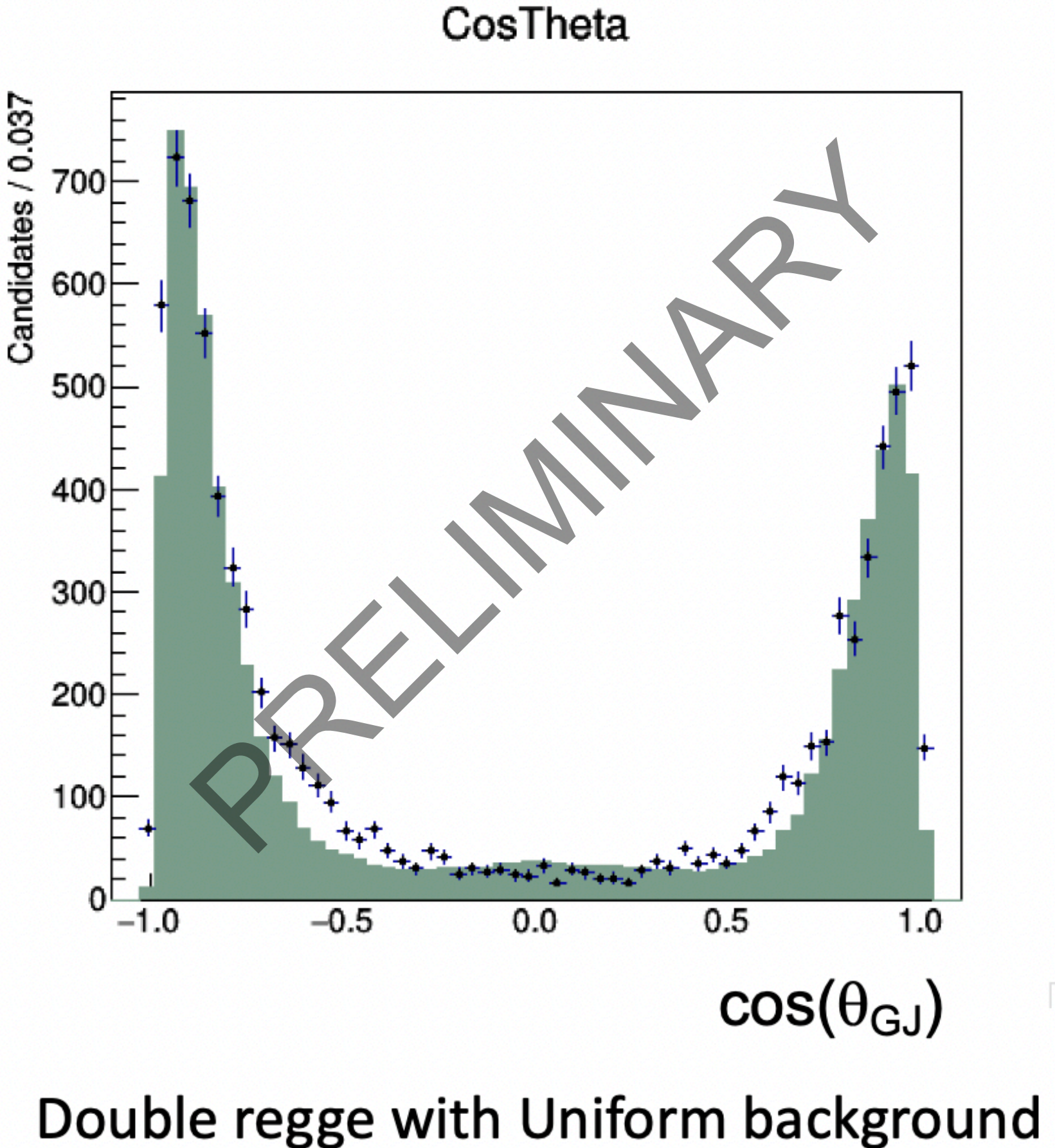
COMPASS PLB740 (2015)

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>

