

Recent Progress in Hadron Spectrscopy

Vincent MATHIEU

U. Barcelona

Joint Physics Analysis Center

JLab User Group Meeting

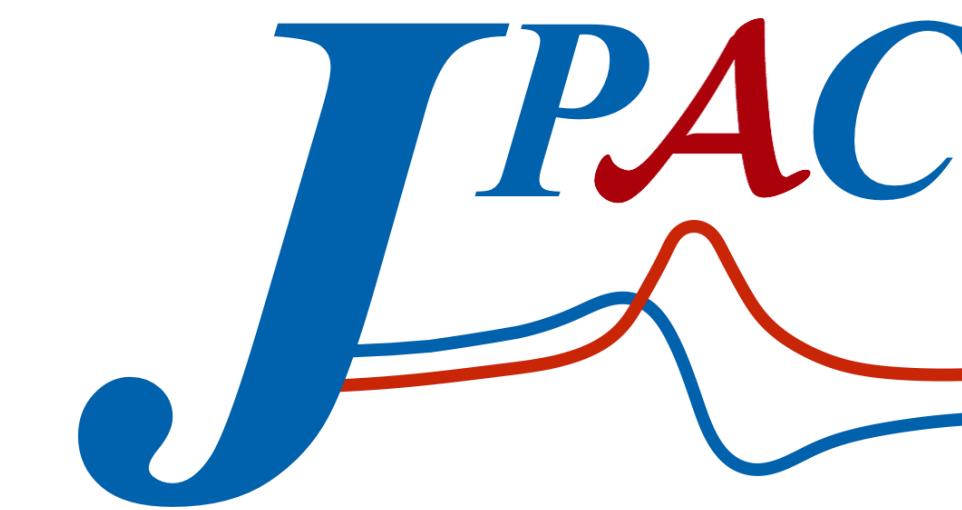
JLab June 2022



UNIVERSITAT DE
BARCELONA

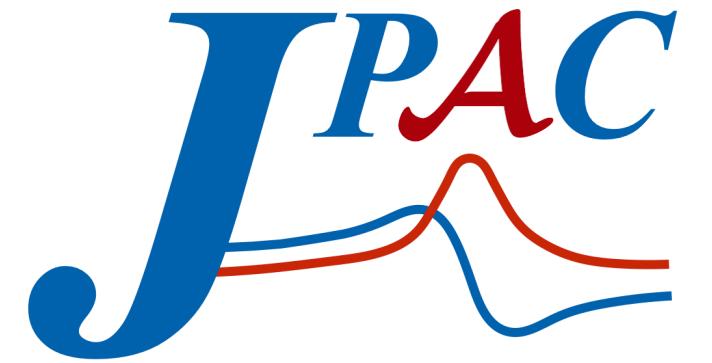


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DE MAEZTU



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Center*

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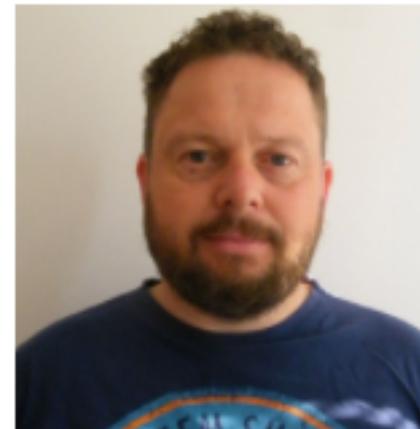
Miguel Albaladejo
CSIC-Valencia



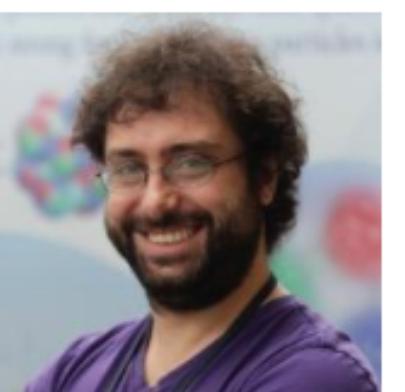
Mikhail Mikasenko
TU Munich



Lawrence Ng
Florida State
University



Lukasz Bibrzycki
Pedagogical University of
Kracow



Alessandro Pilloni
U. Messina



Arkaitz Rodas
College of
William and Mary



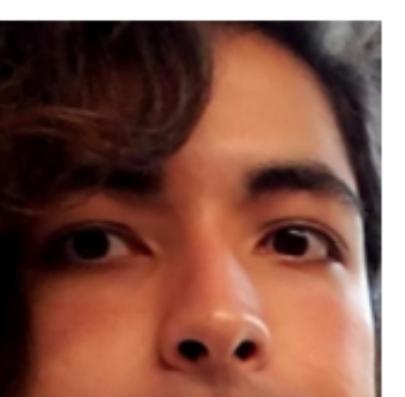
Cesar Fernández Ramírez
National Autonomous
University of Mexico



Adam Szczepaniak
Indiana University



Astrid Hiller Blin
Tübingen University



Daniel Winney
South China Normal
University



Robert Perry
National Chiao-Tung
University

Outline

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: $P_c(4312)^+$

Analysis of LHCb results

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

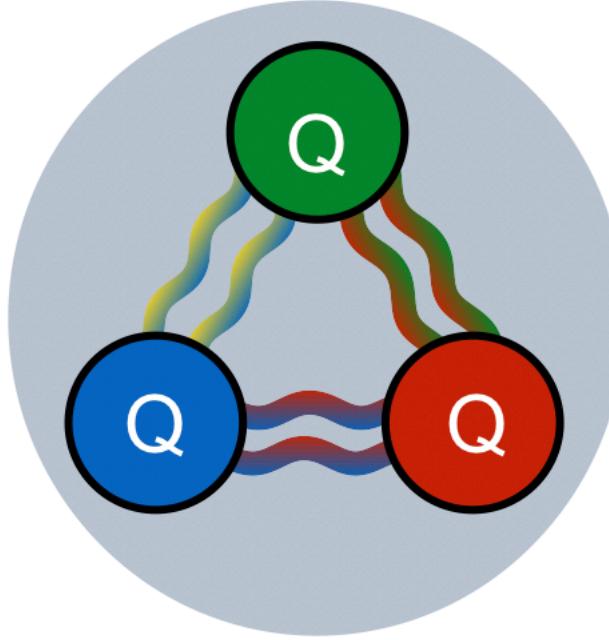
Heavy exotic mesons: $X(3872), Z_c(3900)^+$

Model prediction for EIC

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

Ordinary and Exotic Hadrons

Ordinary baryons:



proton

stable

neutron

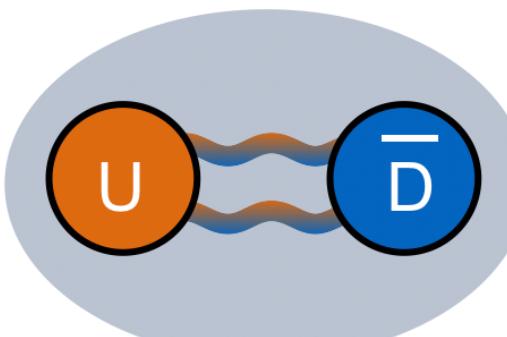
$\tau \sim 10^3 s$

baryon Λ

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

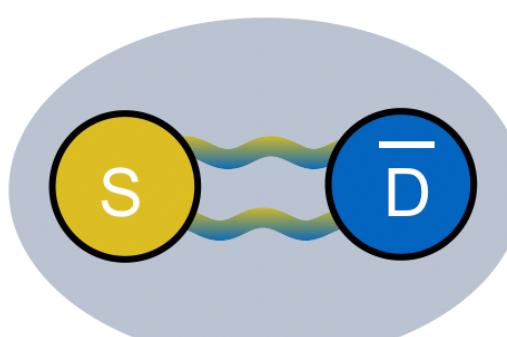


Ordinary mesons



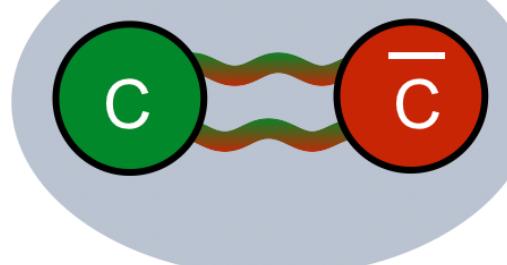
pion

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



kaon

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

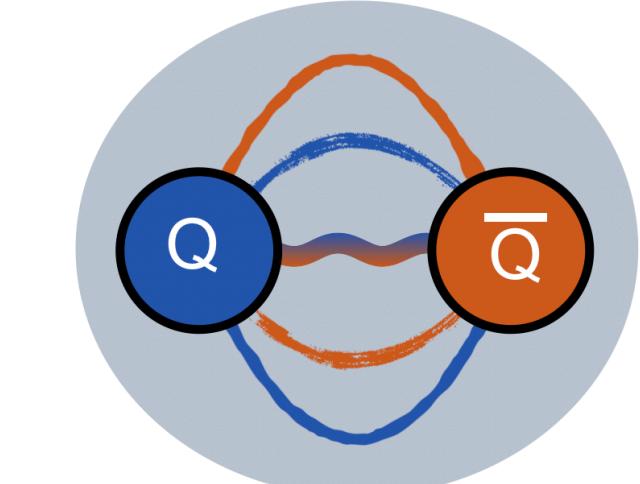


J/ψ

$\tau \sim 10^{-20} s$

Exotic matter

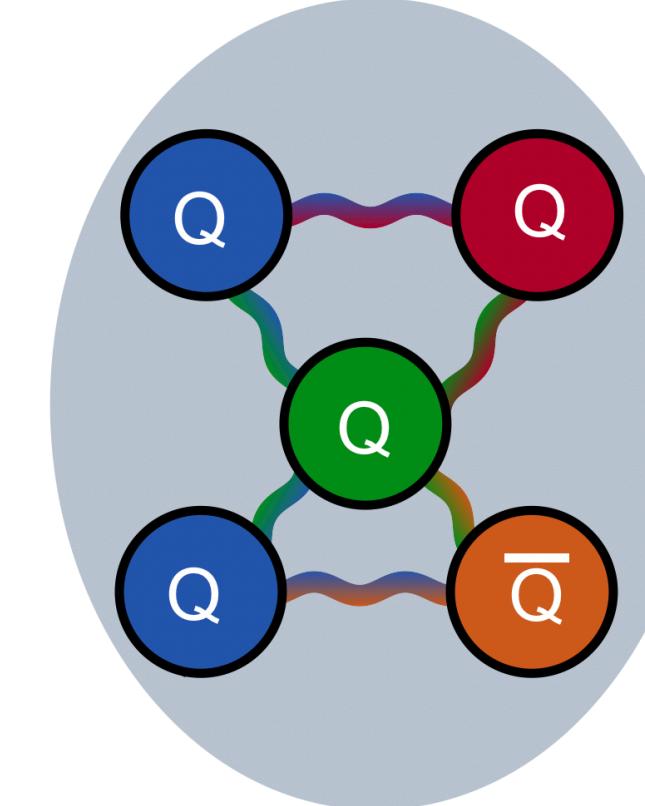
hybrid mesons



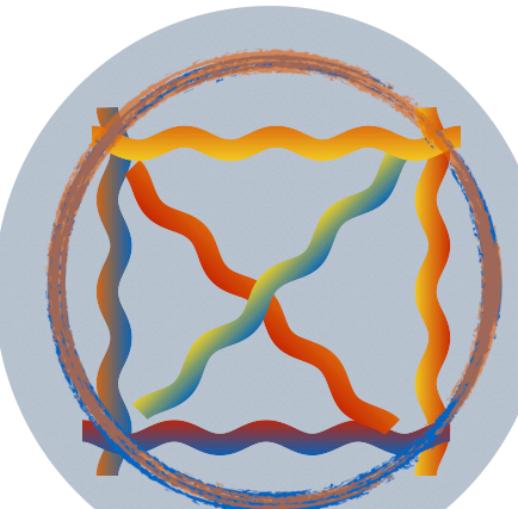
tetraquarks



pentaquarks

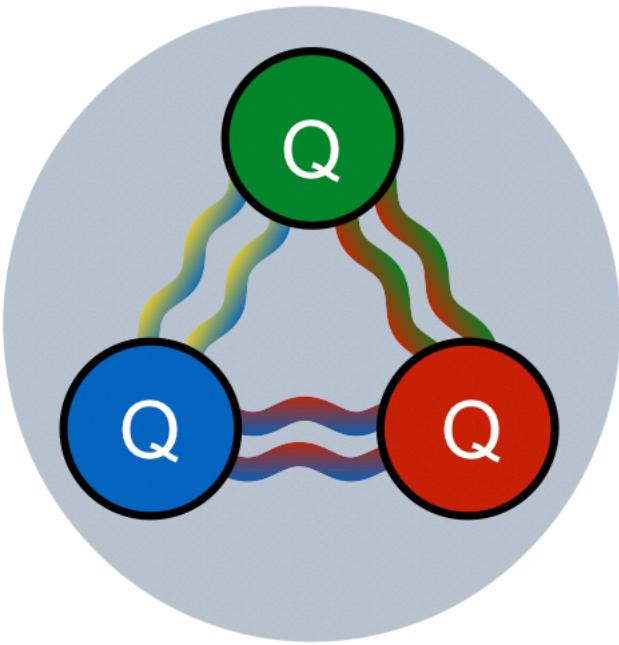


glueballs



Baryons and Mesons

Ordinary baryons:



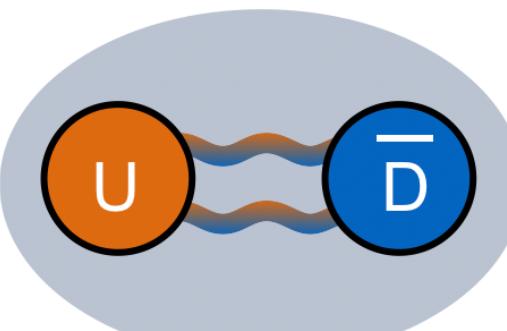
uud proton stable

udd neutron $\tau \sim 10^3 s$

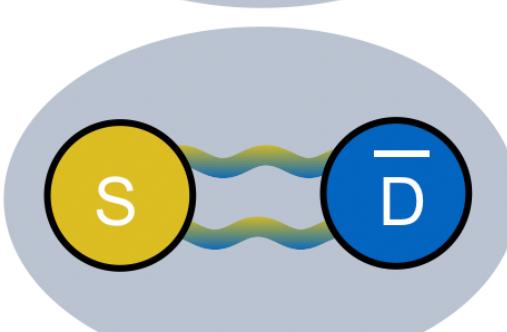
uds baryon Λ $\tau \sim 10^{-10} s$

uuu baryon Δ $\tau \sim 10^{-24} s$

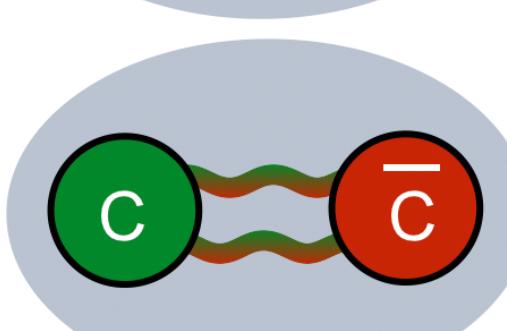
Ordinary mesons



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



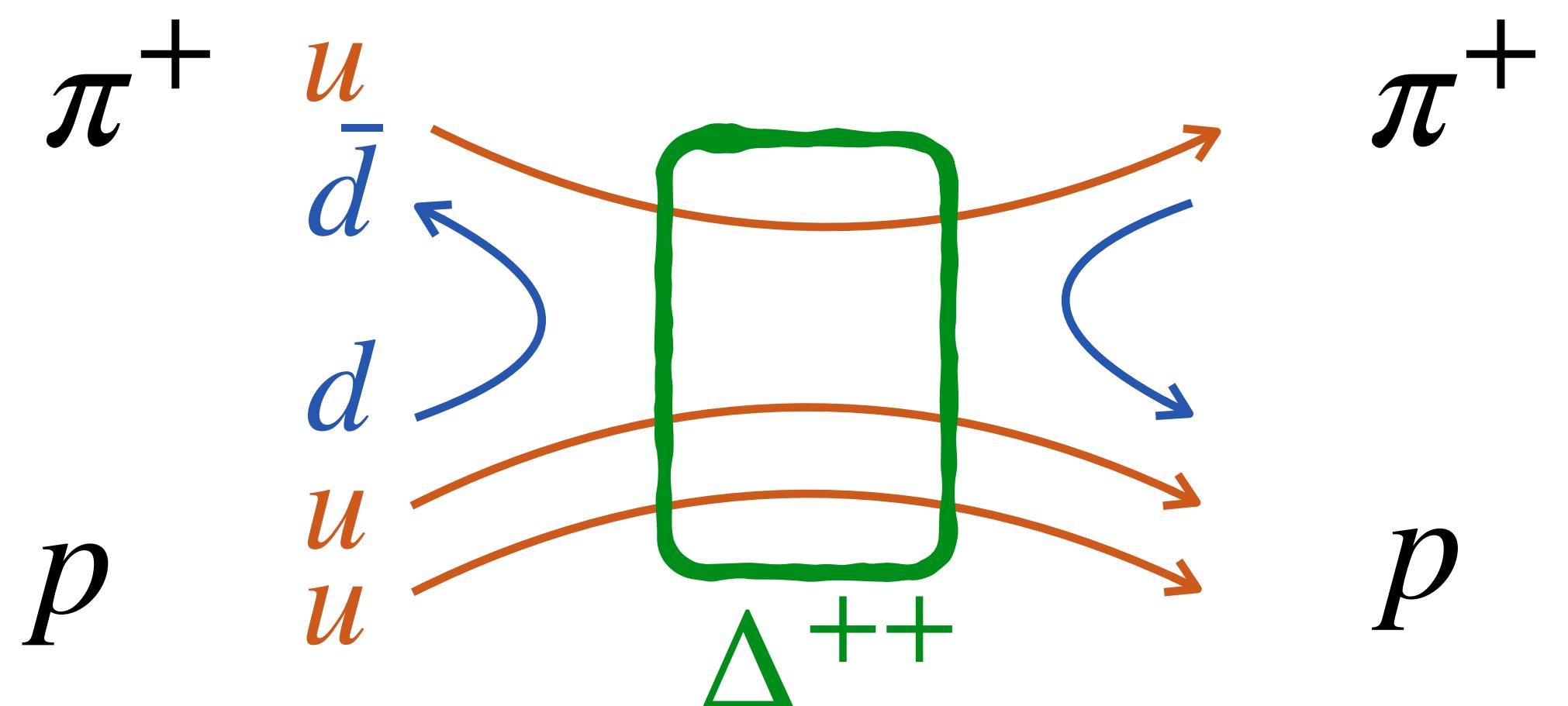
kaon $\tau \sim 10^{-8} s$



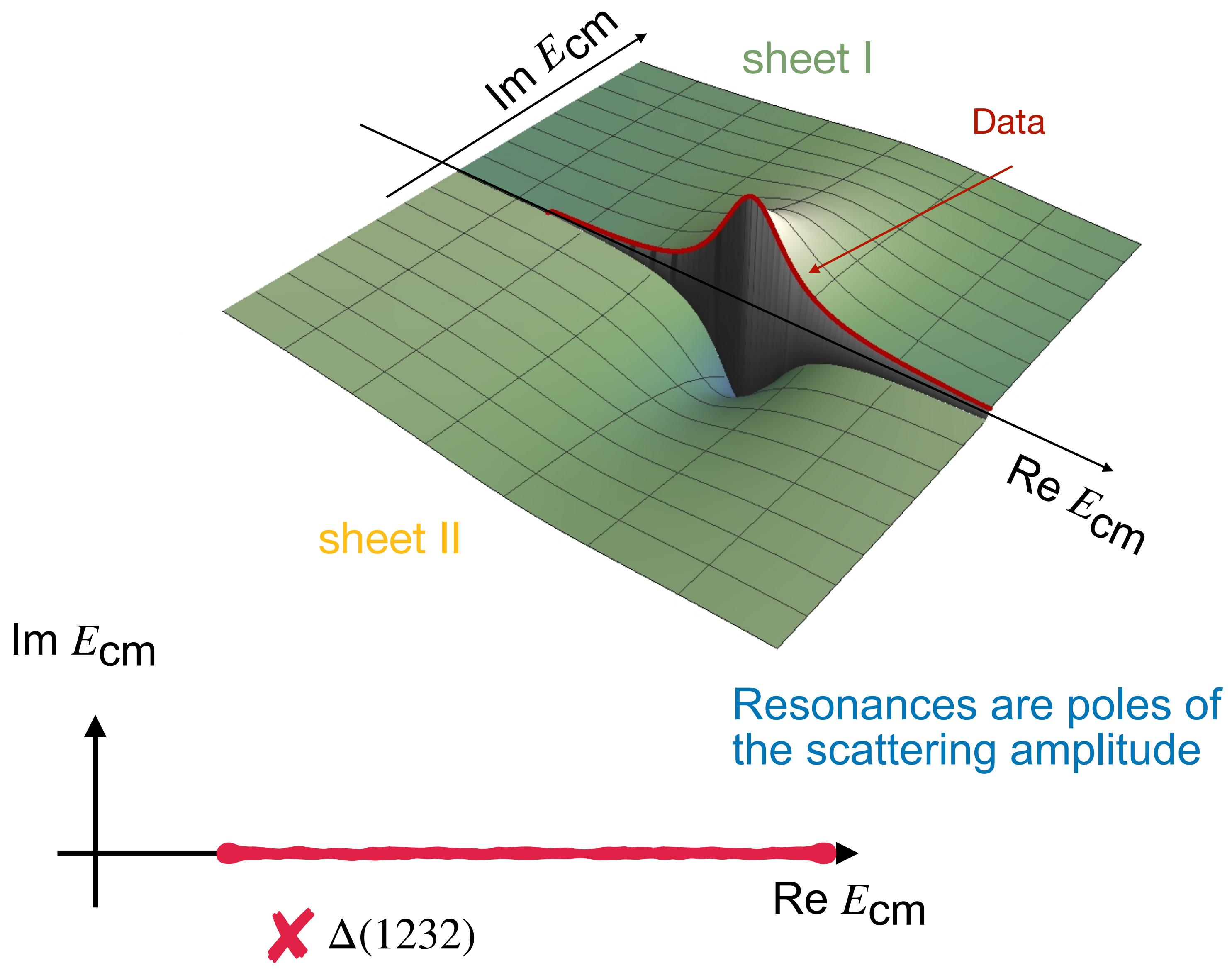
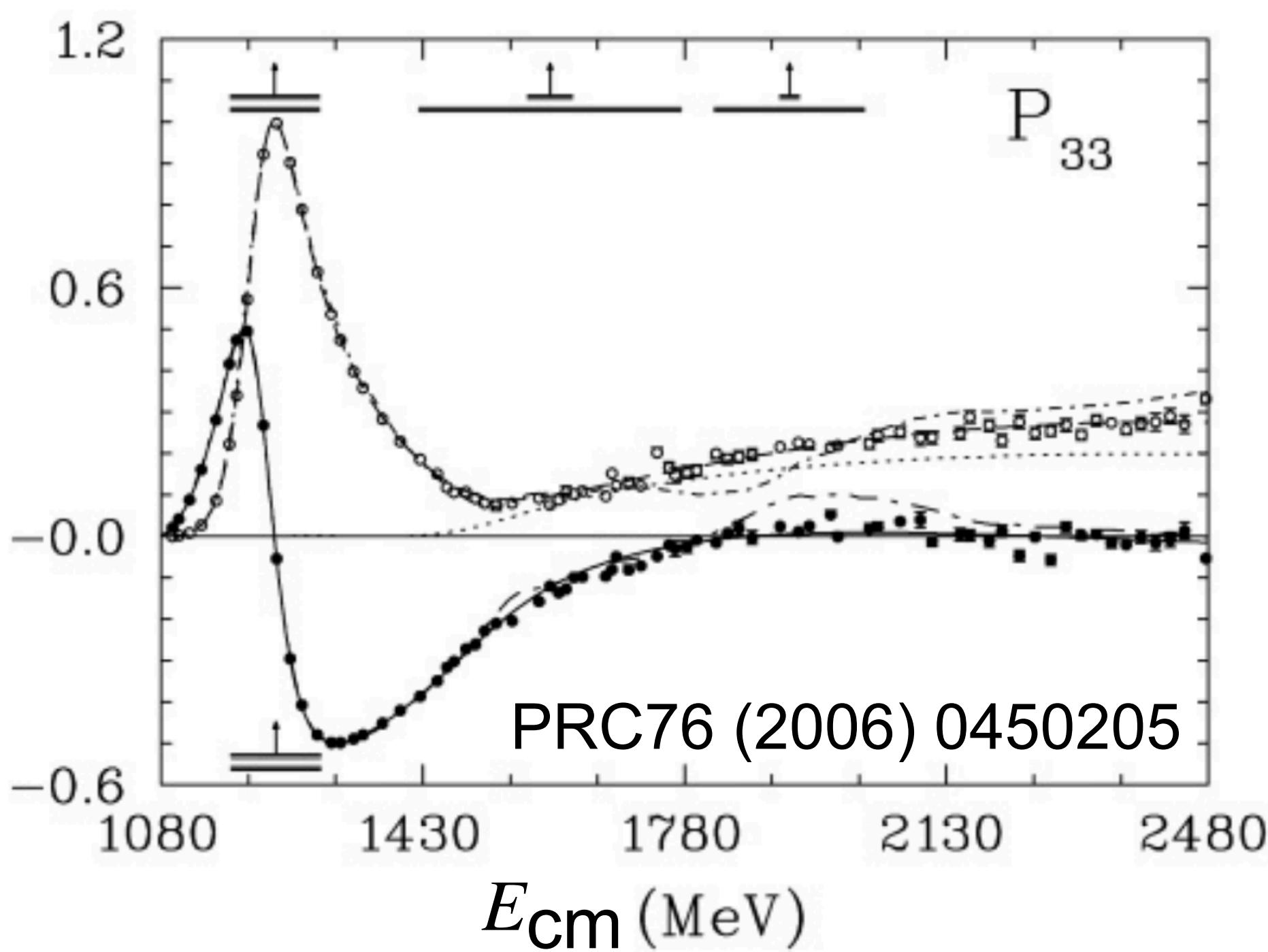
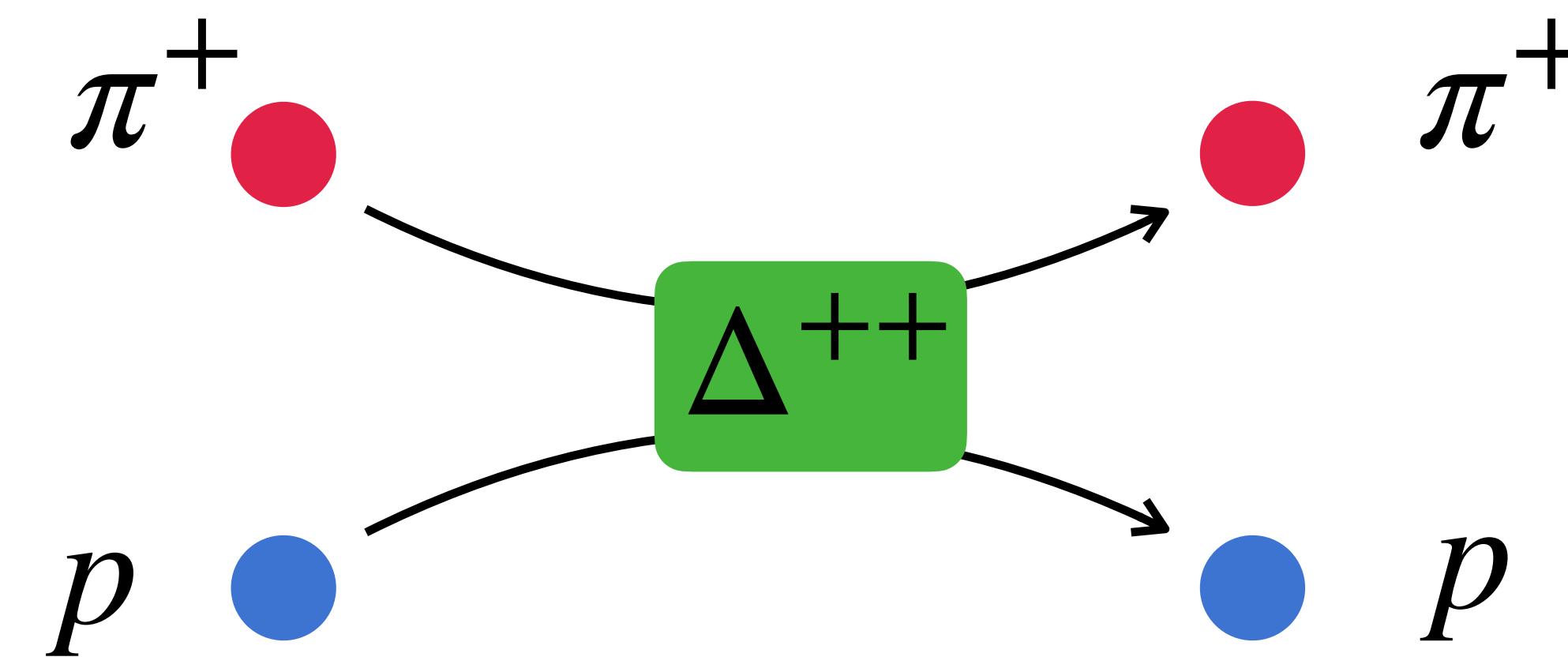
J/ψ $\tau \sim 10^{-20} s$



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

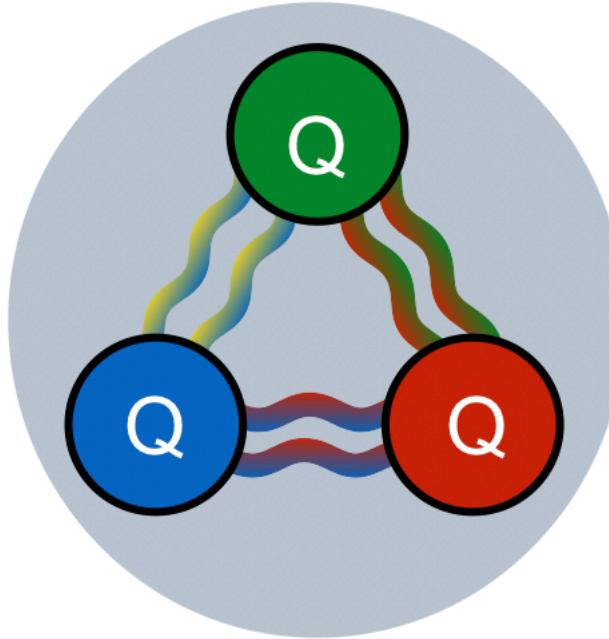


What's a resonance?



Ordinary and Exotic Hadrons

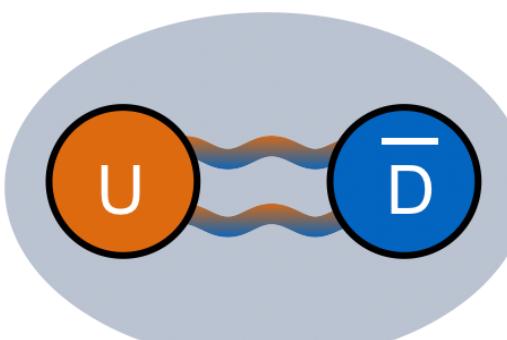
Ordinary baryons:



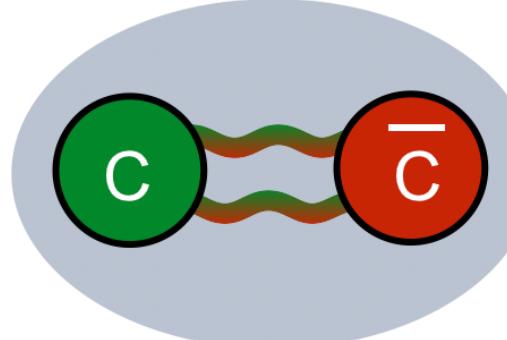
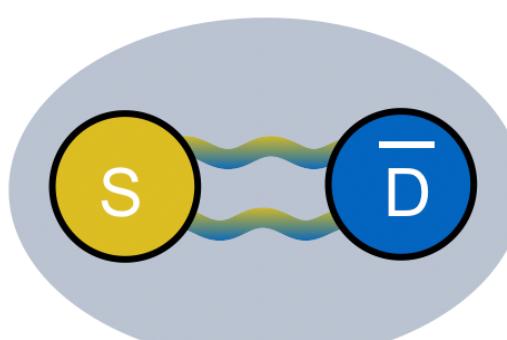
proton	stable
neutron	$\tau \sim 10^3 s$
baryon Λ	$\tau \sim 10^{-10} s$



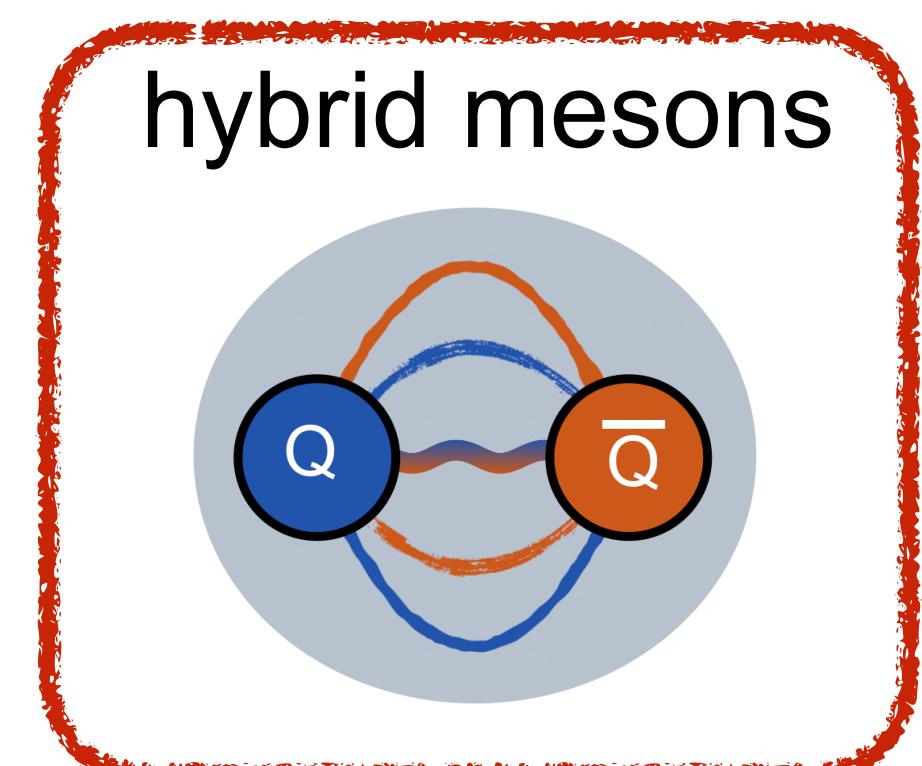
Ordinary mesons



pion	$\tau \sim 10^{-8} s$
kaon	$\tau \sim 10^{-8} s$
J/ψ	$\tau \sim 10^{-20} s$



Exotic matter

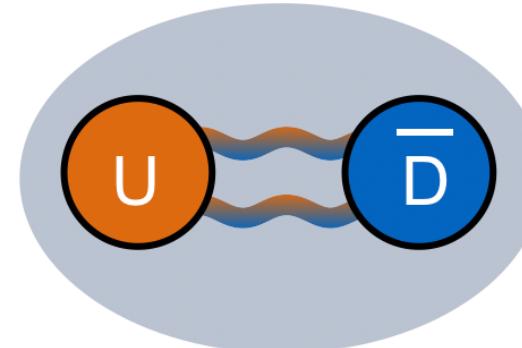


Meson with excited gluon field

Gluon field may carry quantum numbers

Quantum Numbers

Ordinary mesons



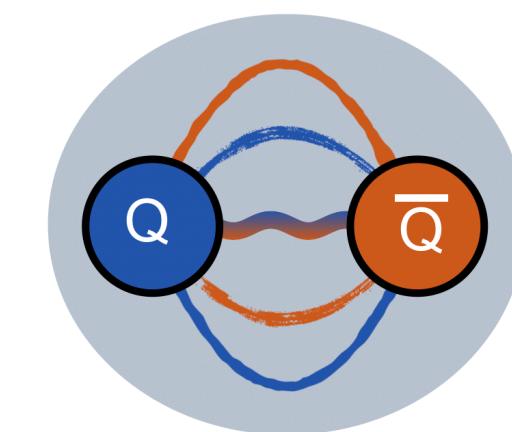
$$\vec{J} = \vec{L} \oplus \vec{S}$$

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

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

0^{--}	0^{-+}	0^{+-}	0^{++}
1^{--}	1^{-+}	1^{+-}	1^{++}
2^{--}	2^{-+}	2^{+-}	2^{++}
3^{--}	3^{-+}	3^{+-}	3^{++}
•	•	•	•
•	•	•	•
•	•	•	•

Exotic mesons

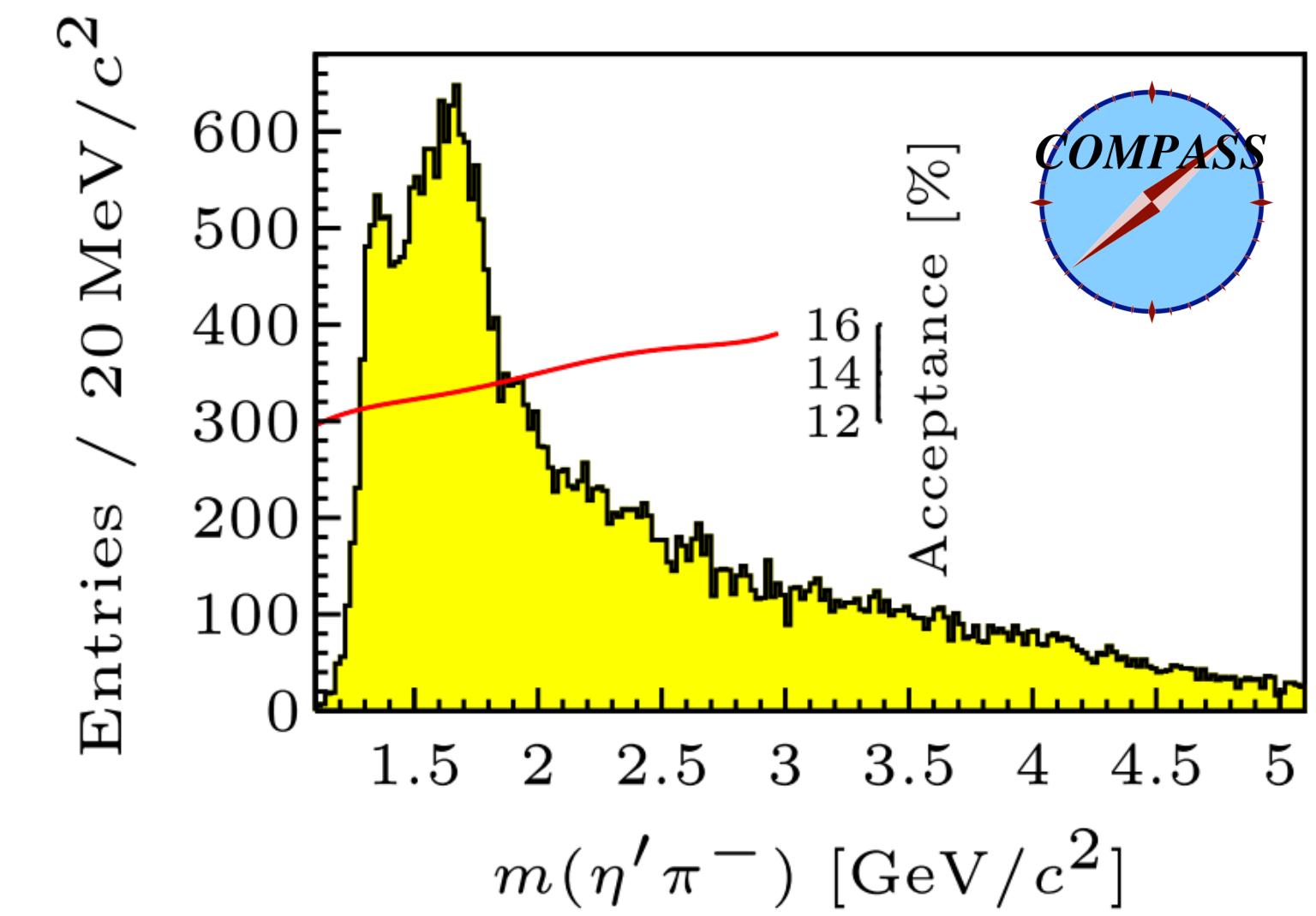
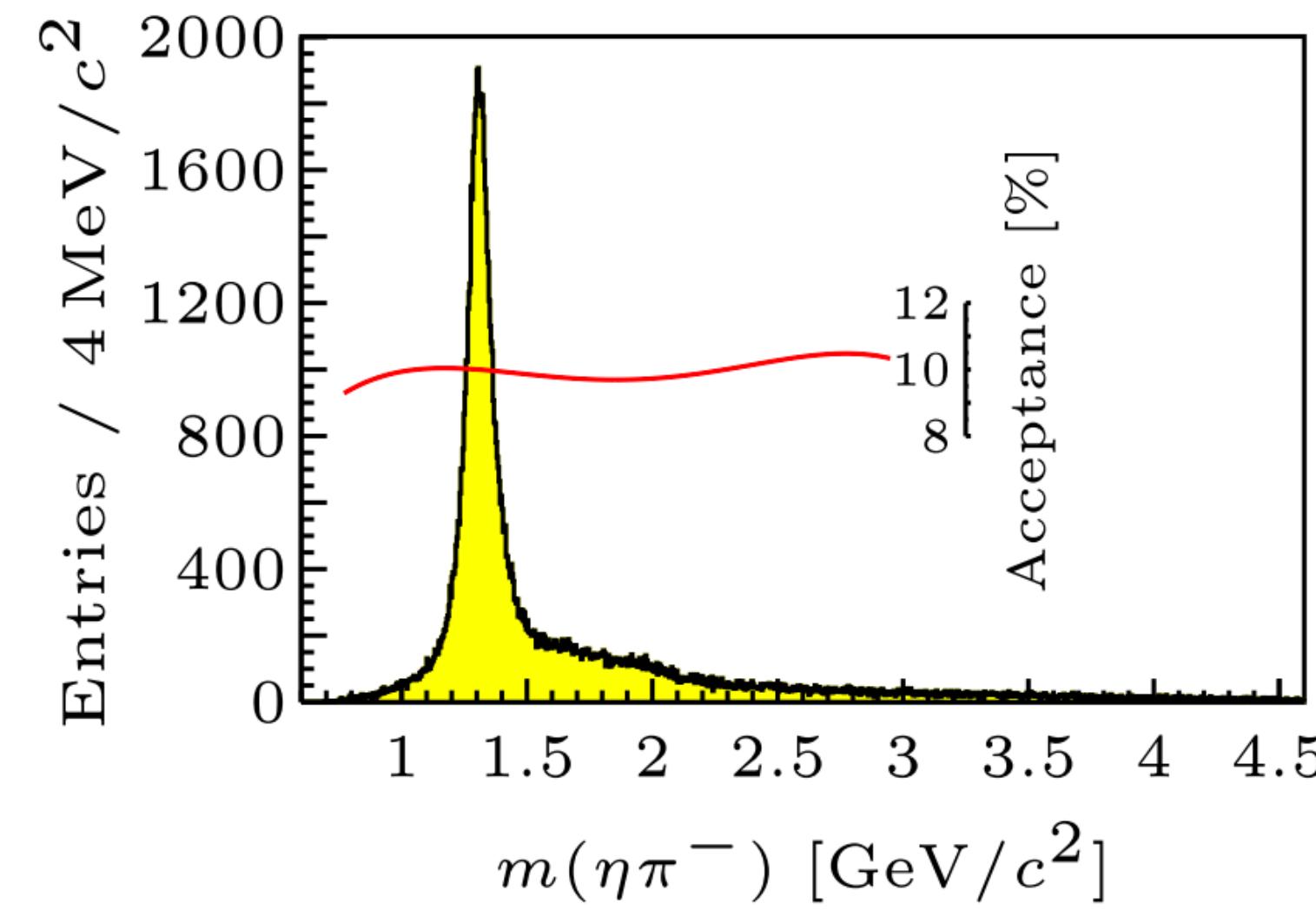


$$J^{PC} = 1^{-+}$$

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

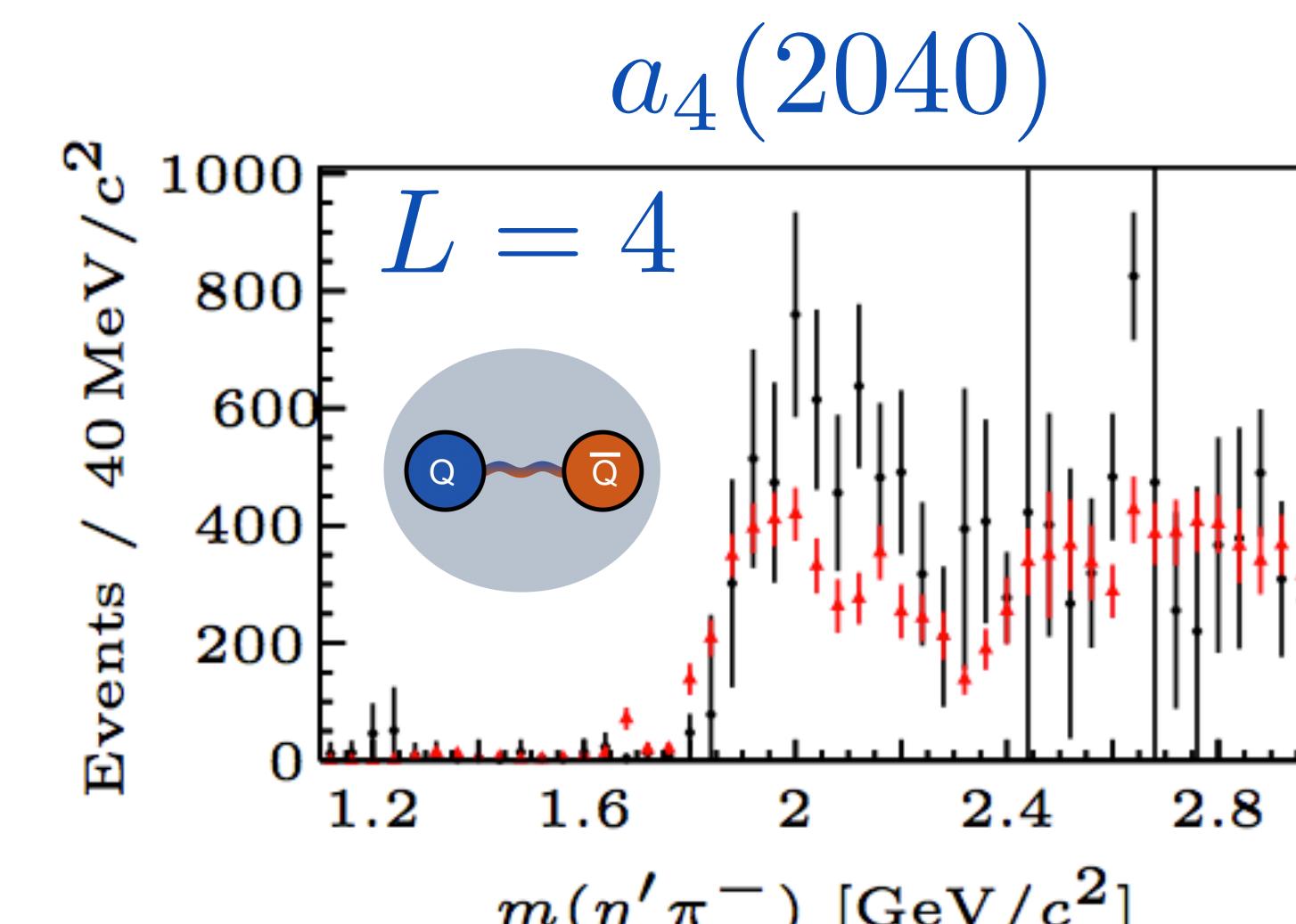
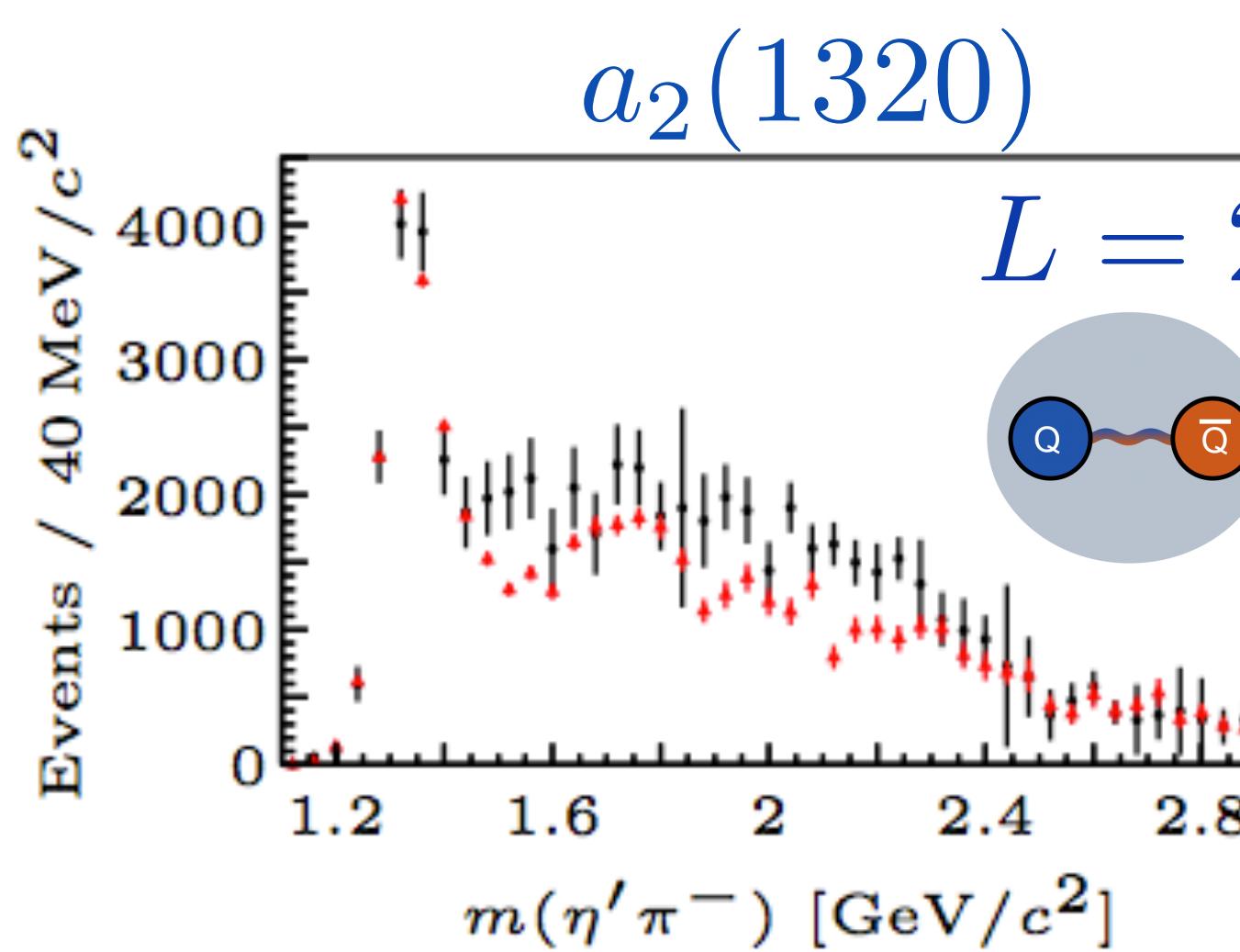
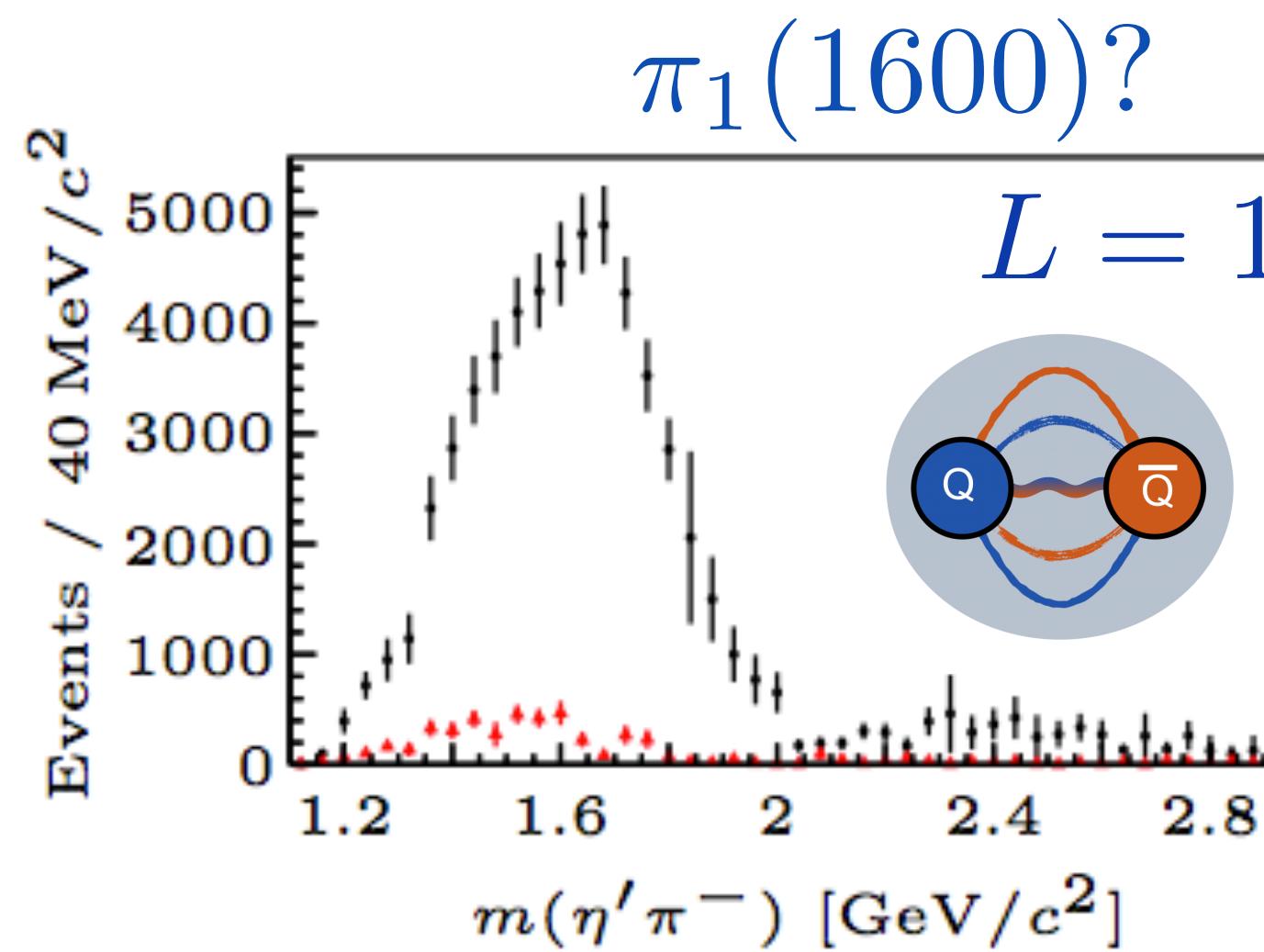
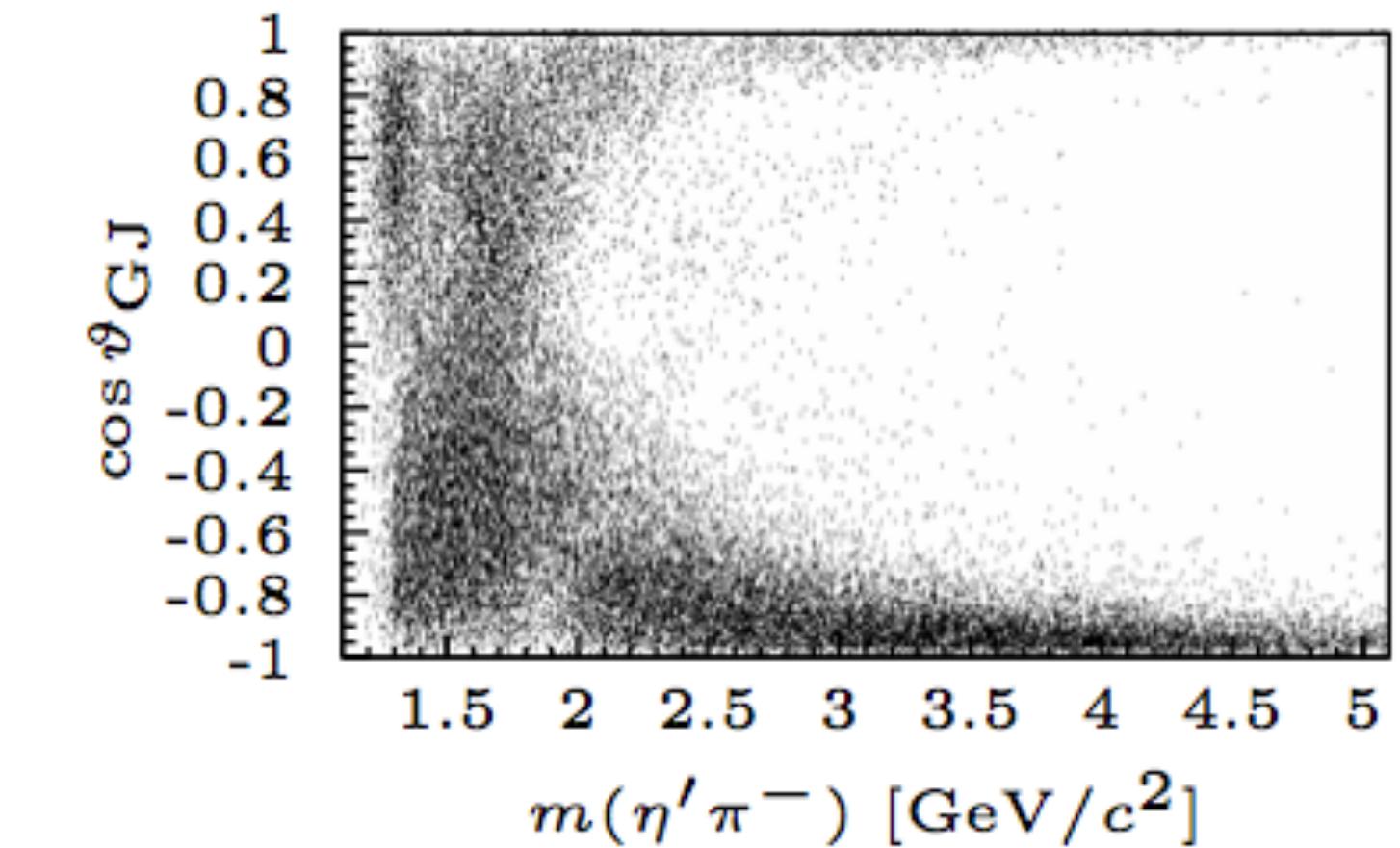
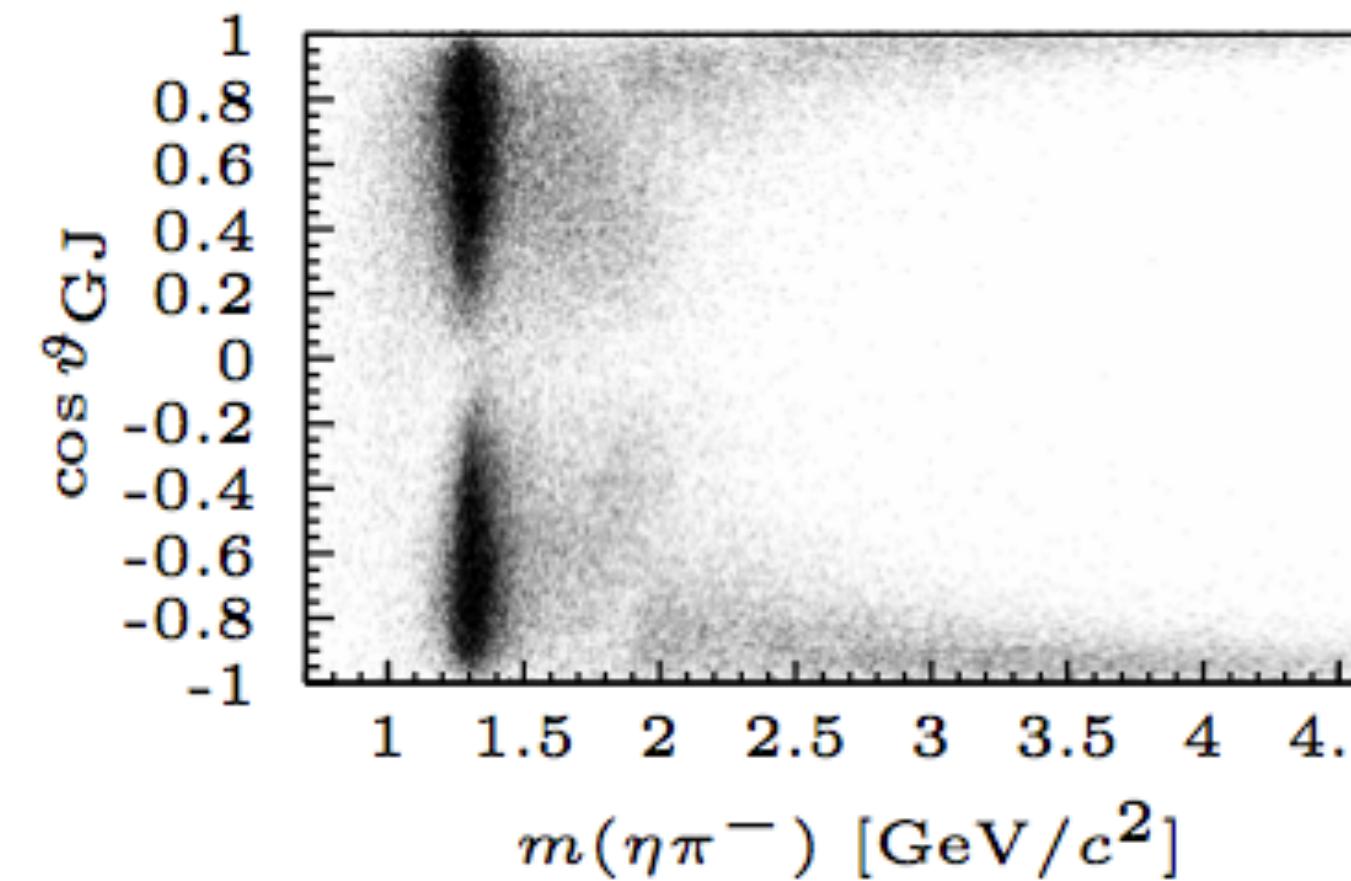
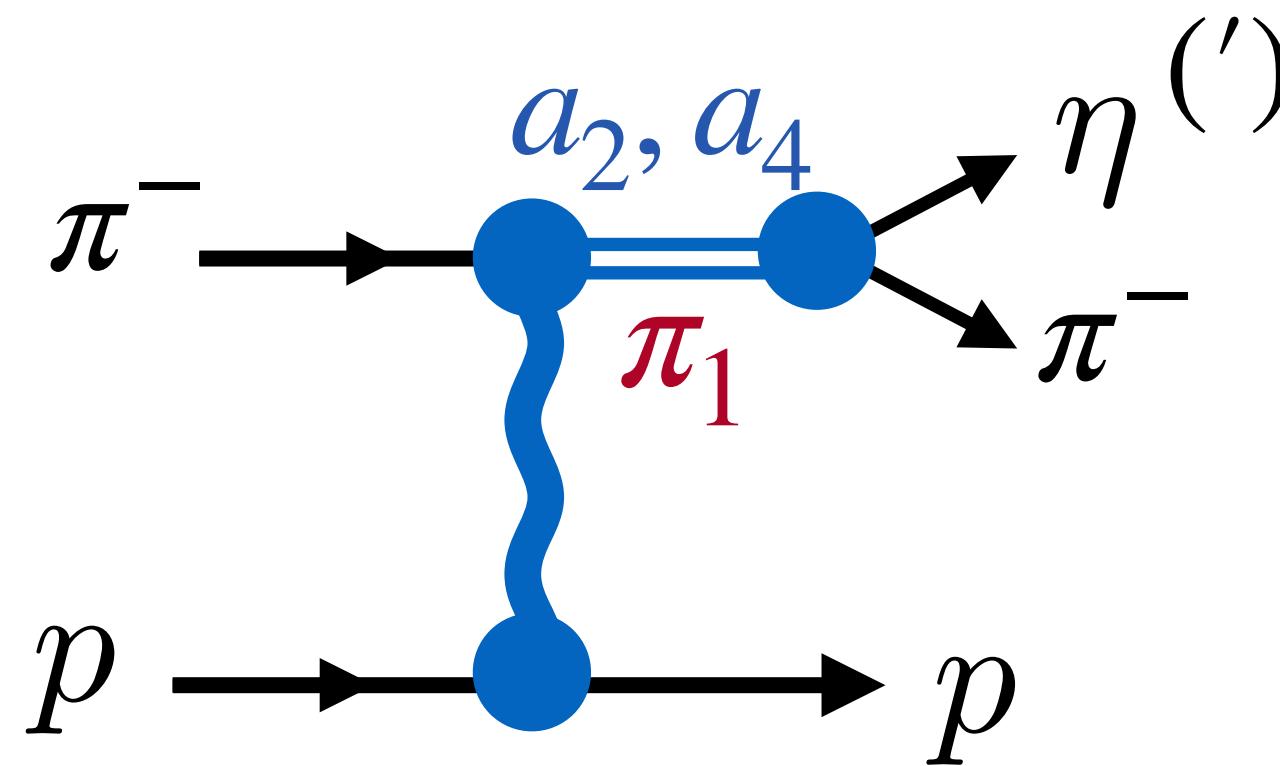
$$\pi_1 \rightarrow \eta\pi, \eta'\pi$$

Decay mode



Partial Waves Expansion

COMPASS PLB740 (2015)



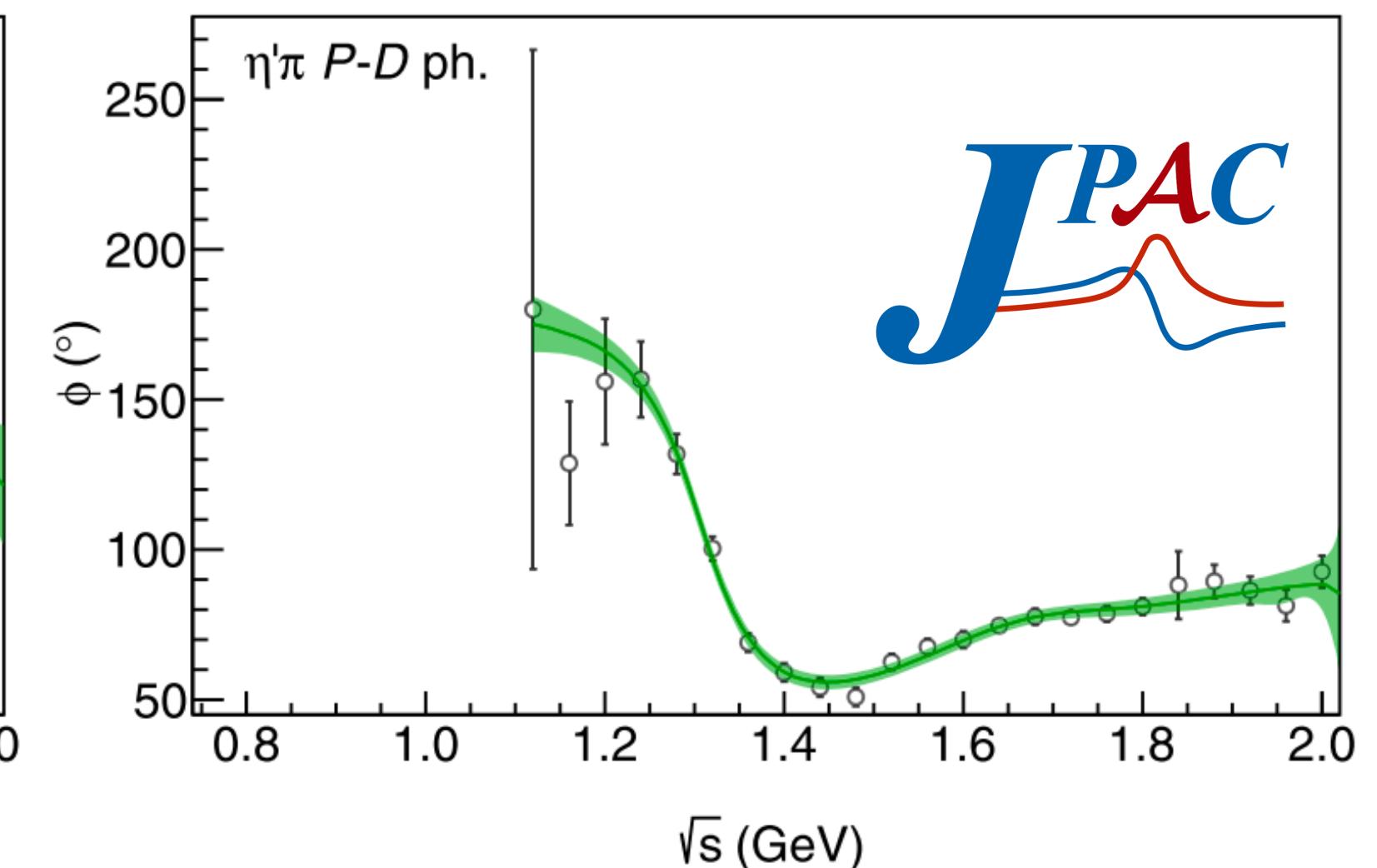
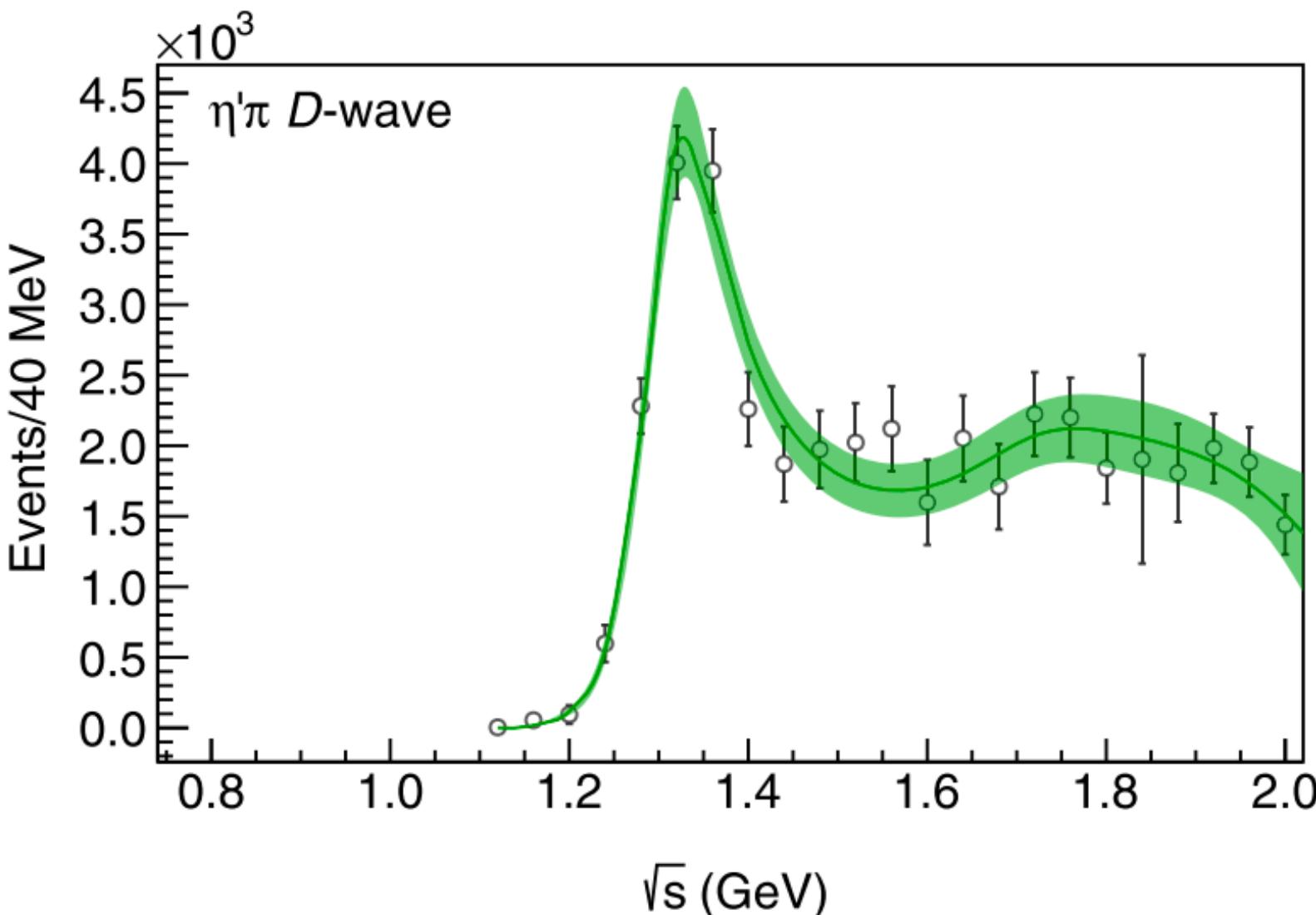
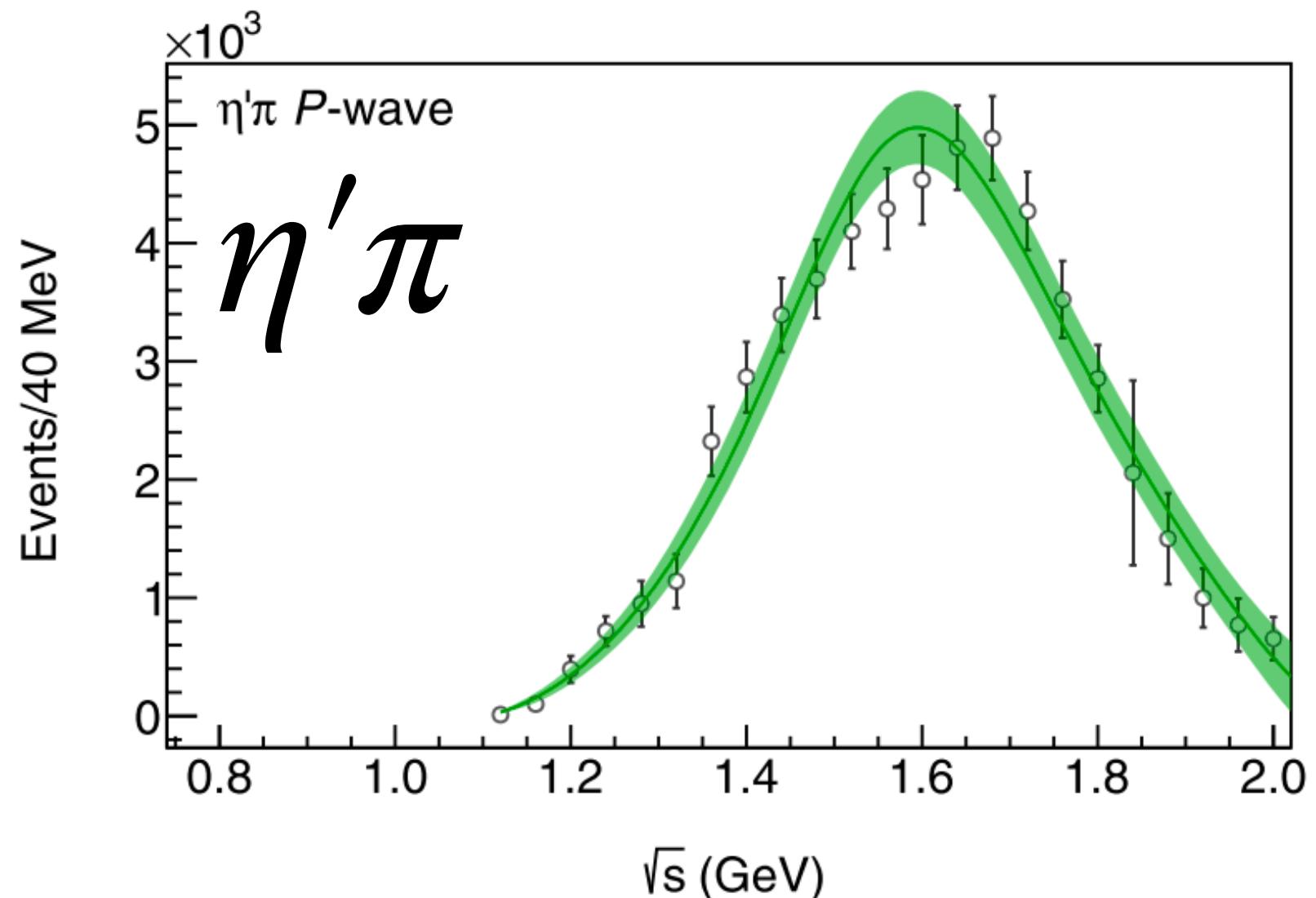
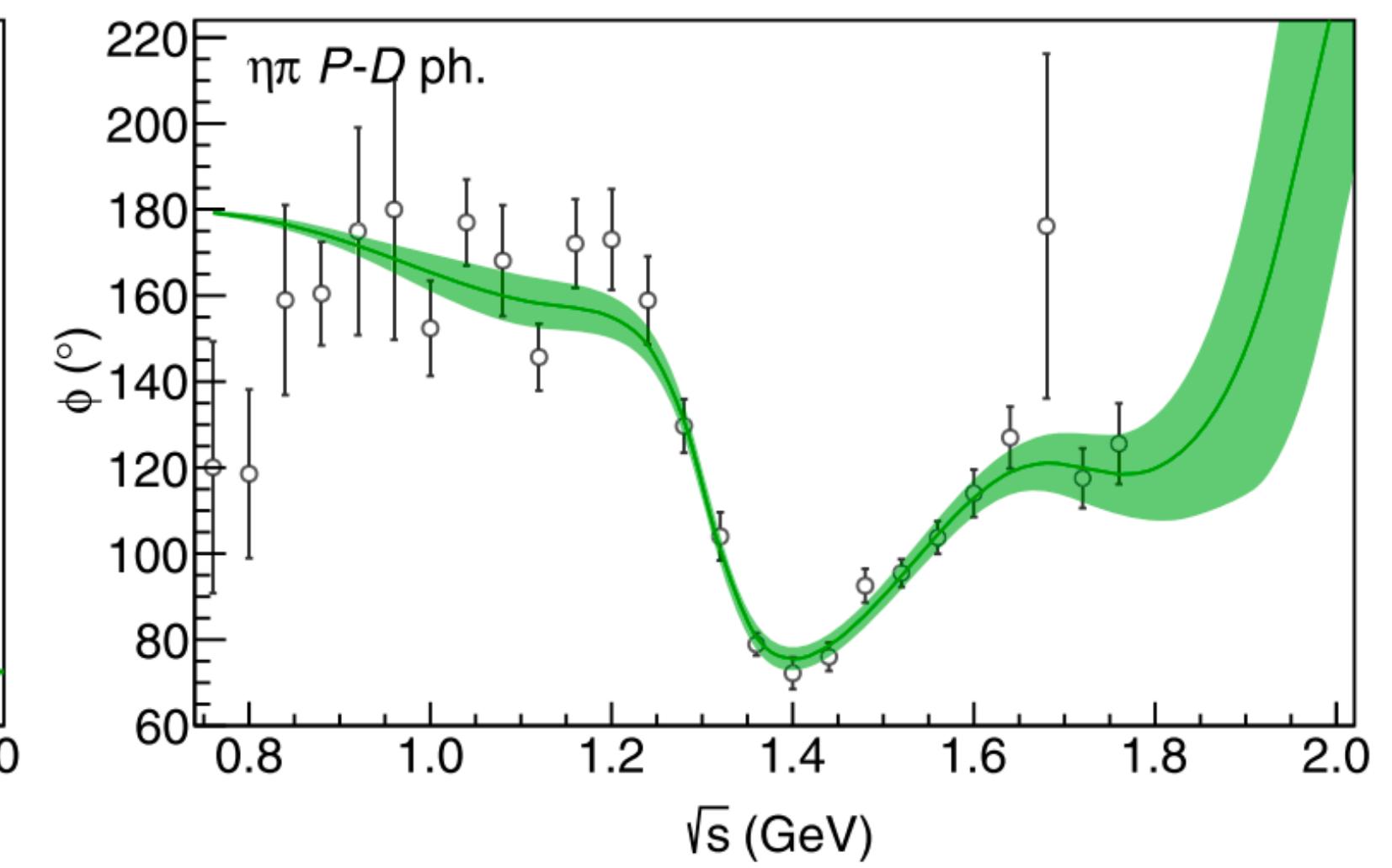
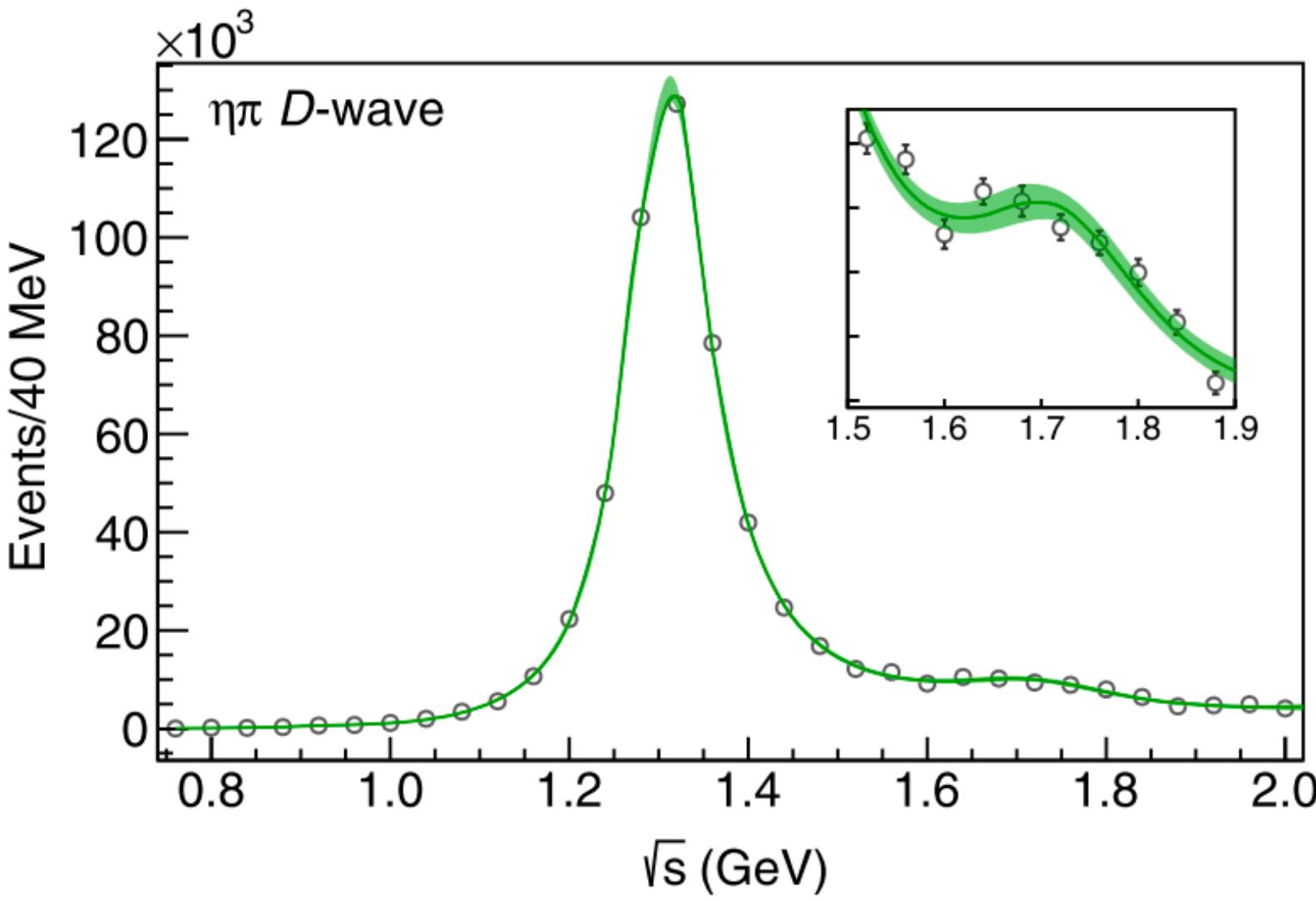
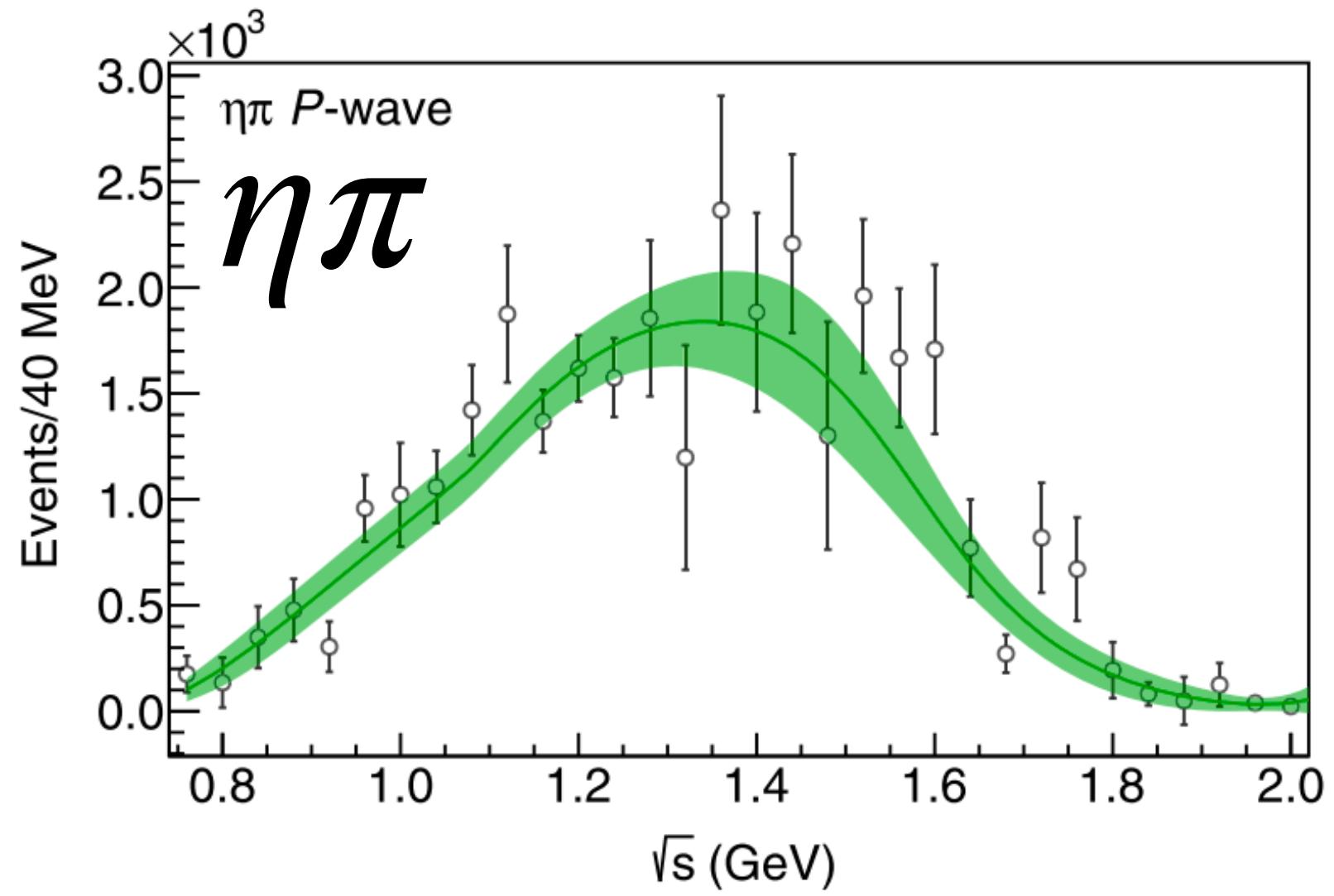
Resonance in angular mom. $L = 1$?

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

Low Energy Fit of $L = 1,2$

Rodas et al (JPAC) PRL122 (2019) 042002

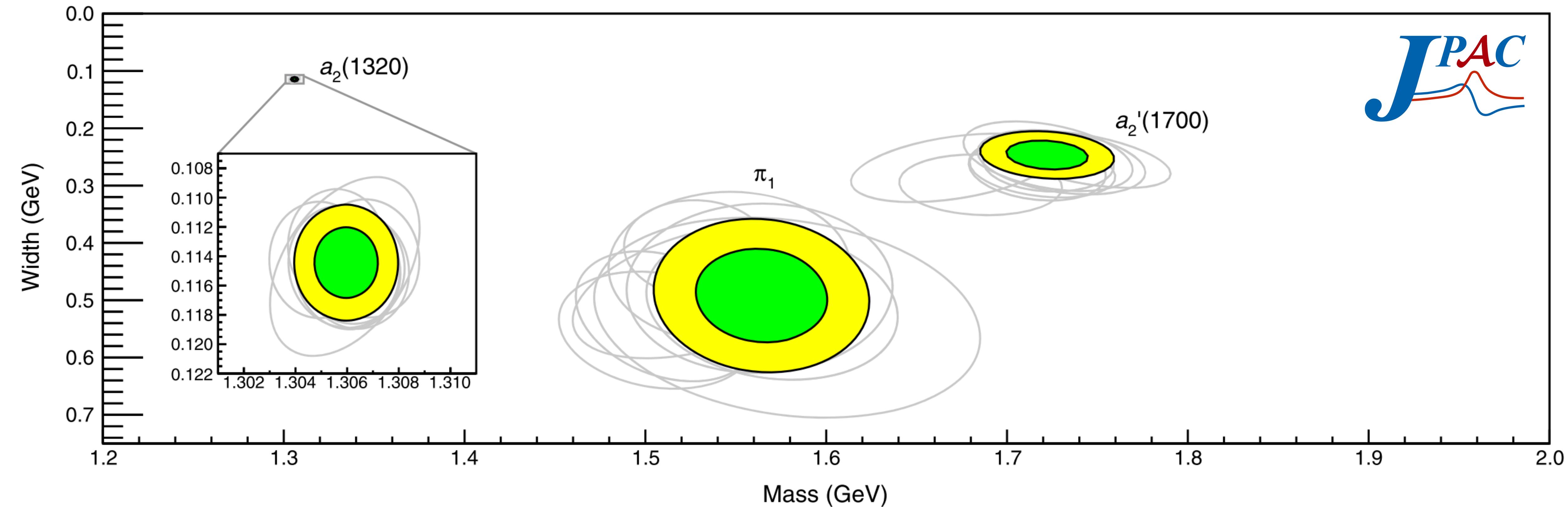
$\pi_1(1400)$ vs $\pi_1(1600)$



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	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

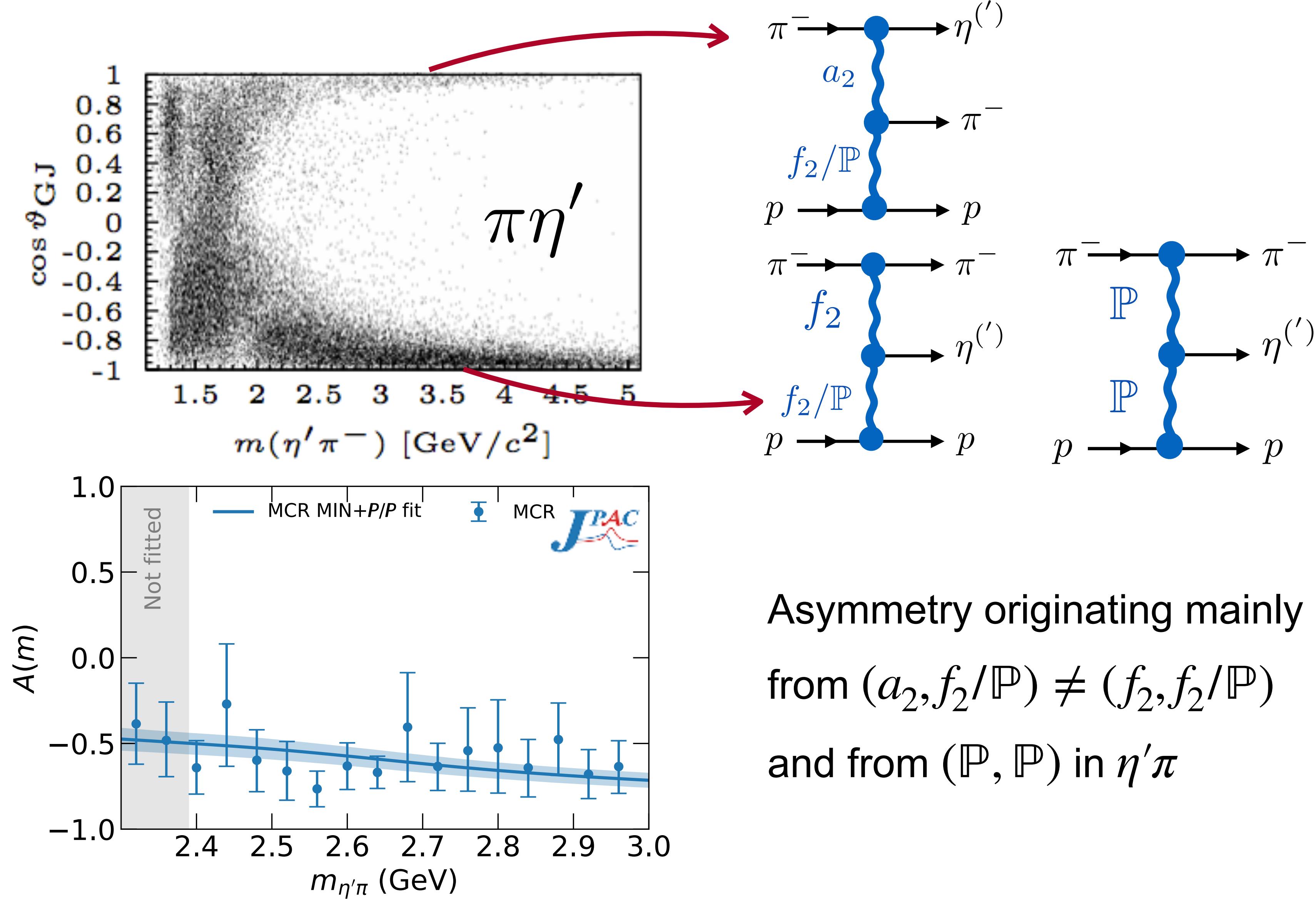


More on the exotic π_1

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

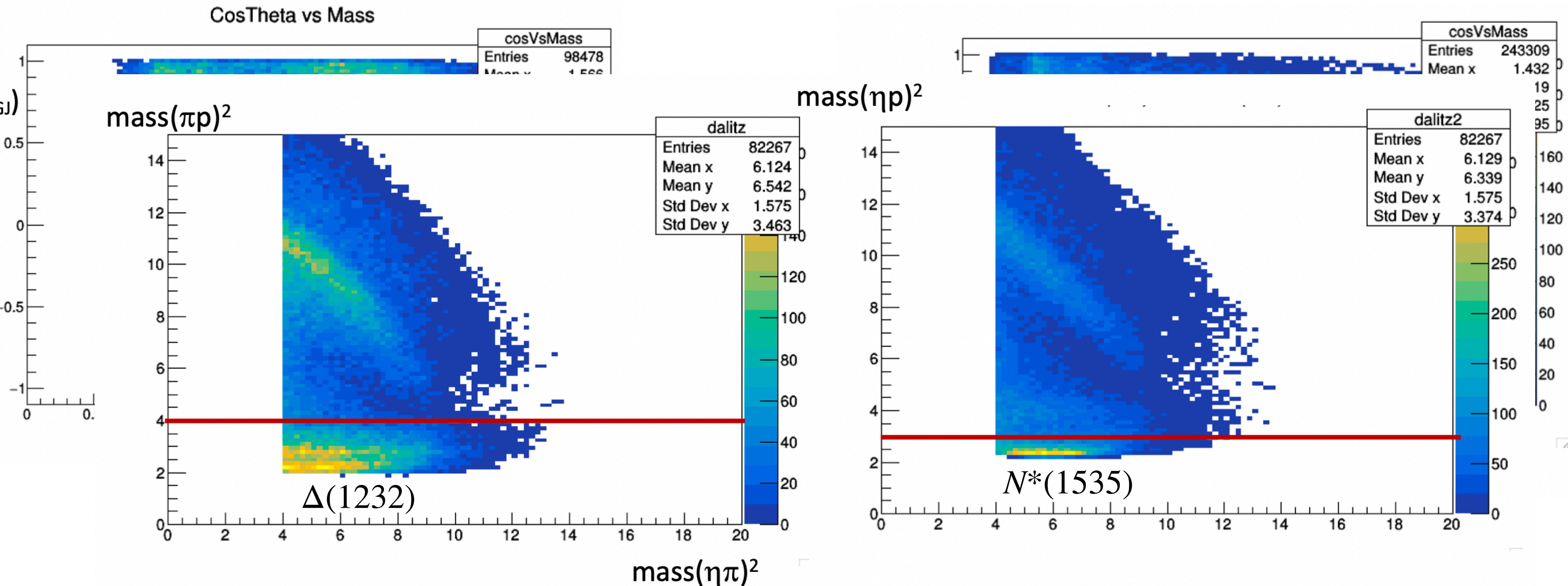
Forward-backward asymmetry related to the existence of (exotic) P-wave

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



$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti

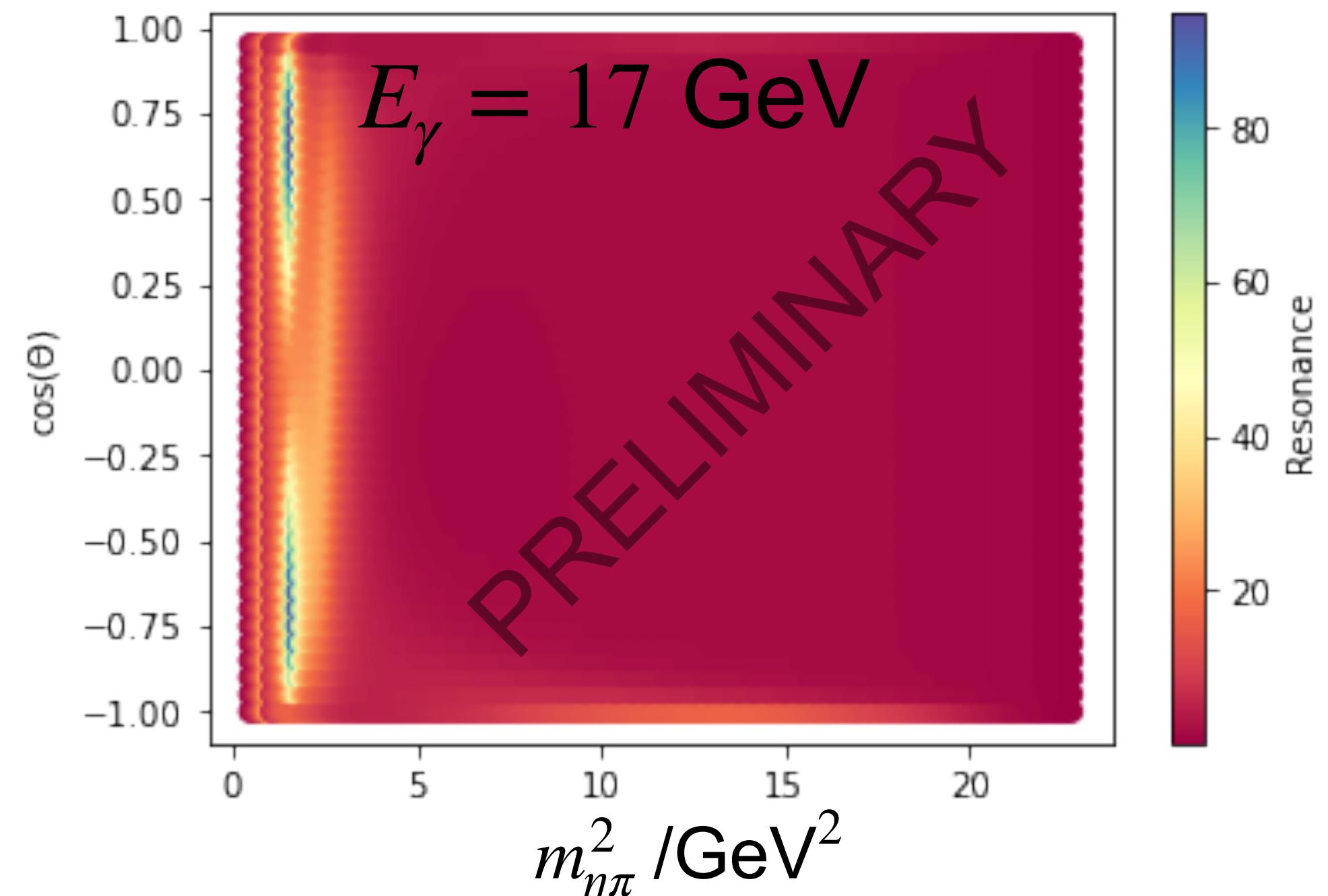
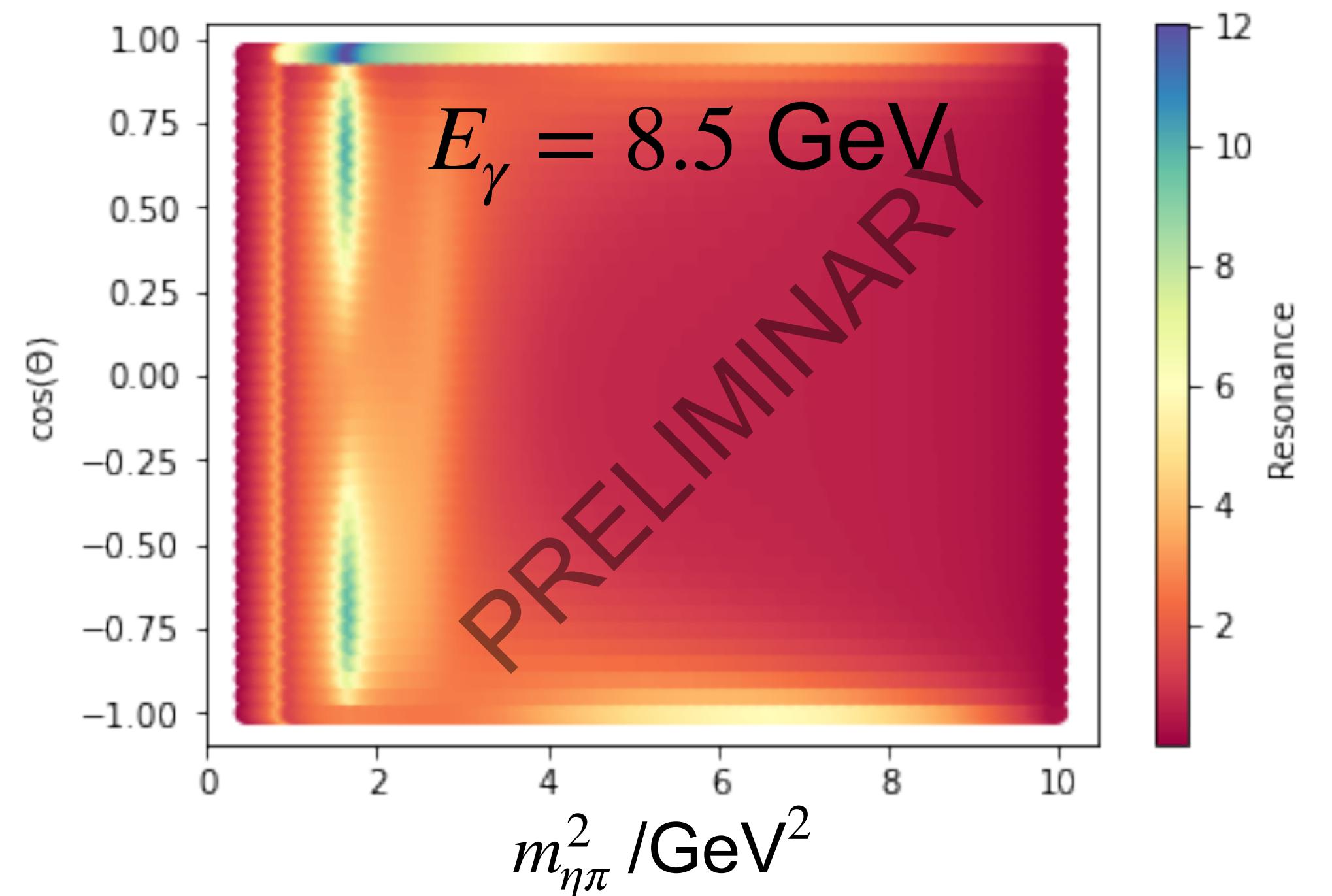


Baryon resonances contaminate the high mass $\eta\pi$

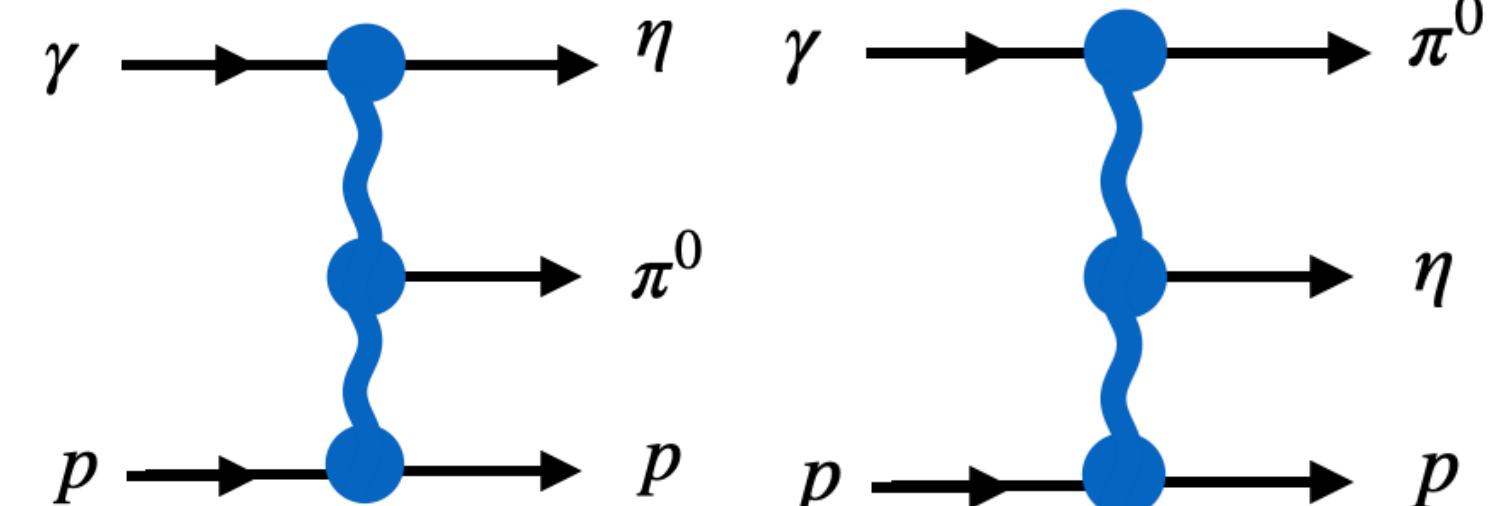
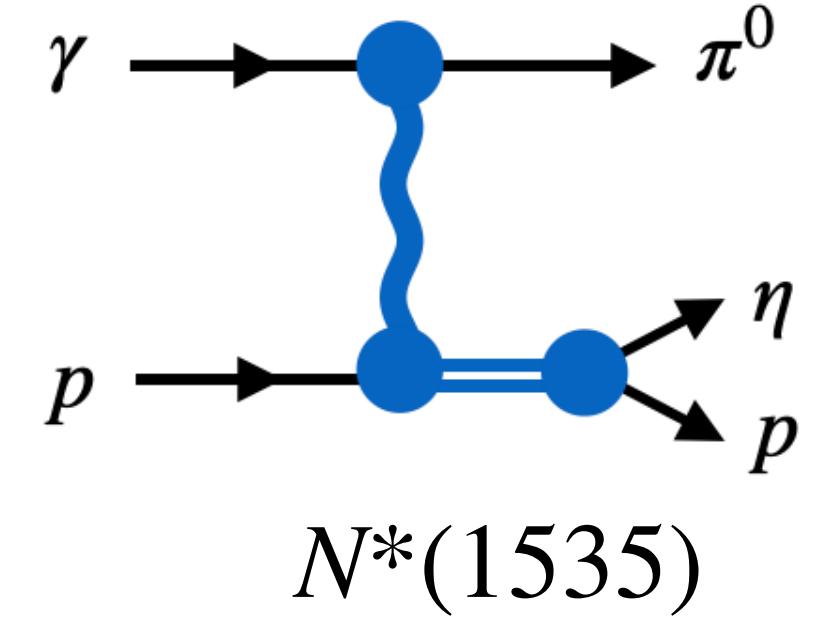
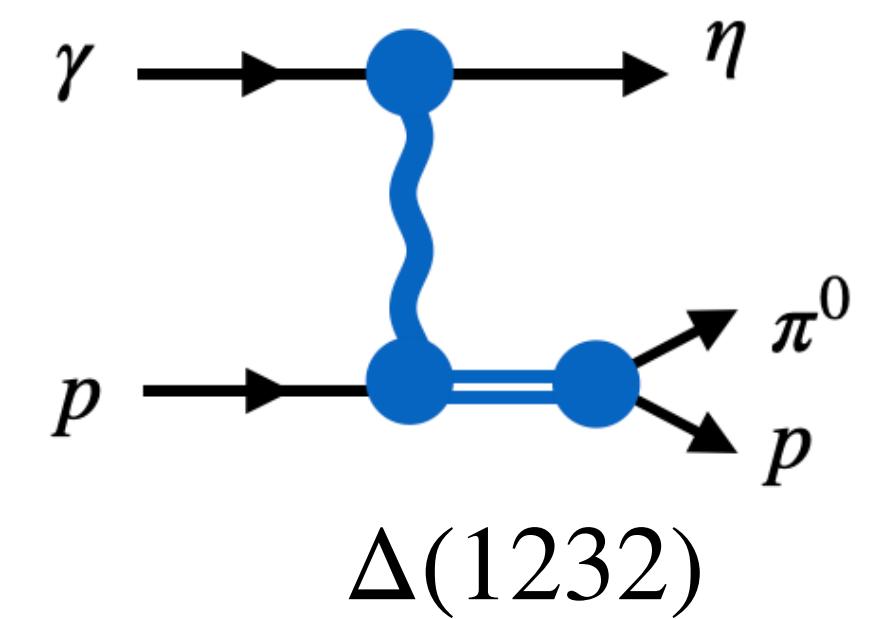
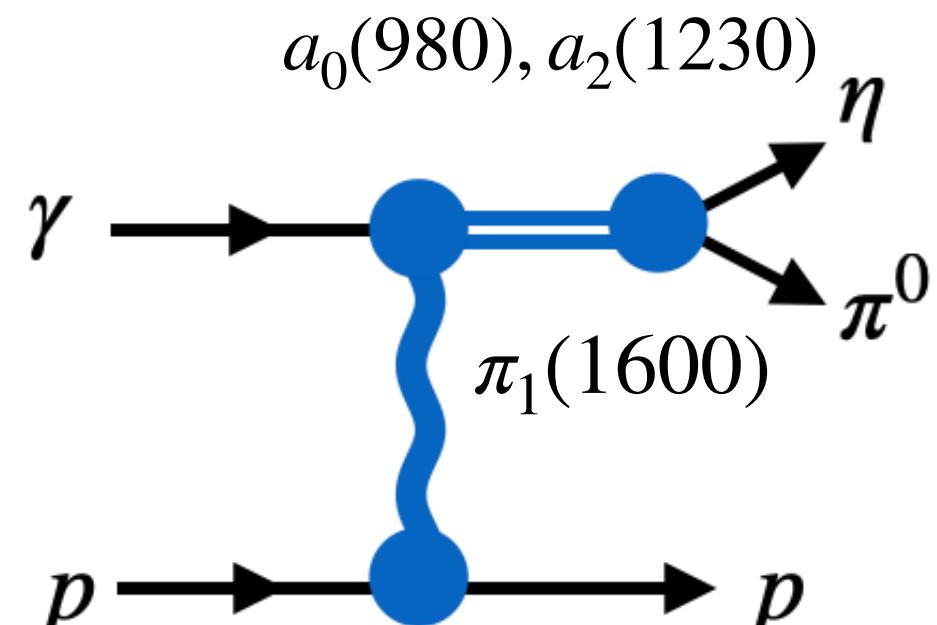
Less baryon contamination when the energy increases

$\eta\pi^0$ Photoproduction@GlueX

In collaboration with E. Llanos

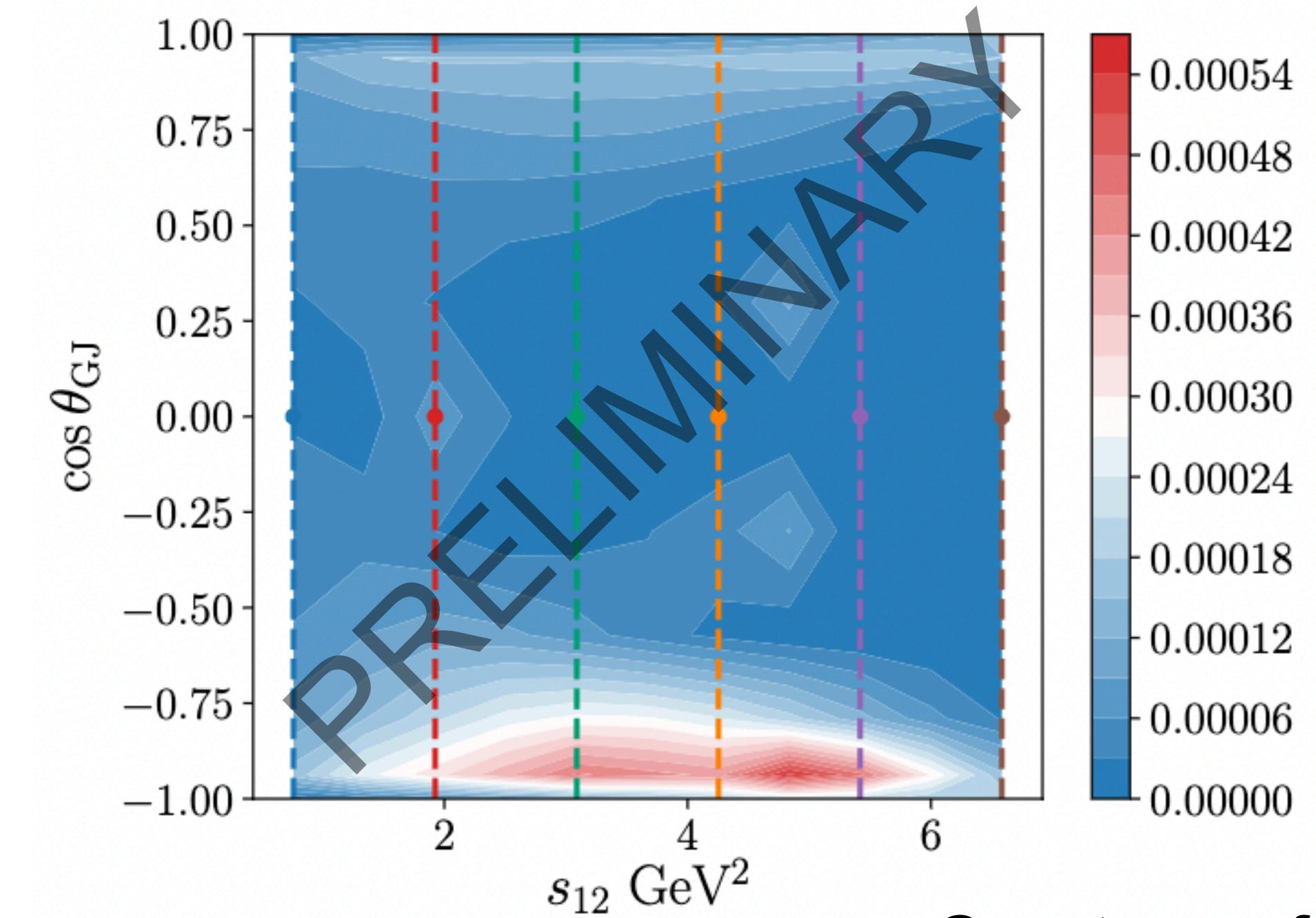
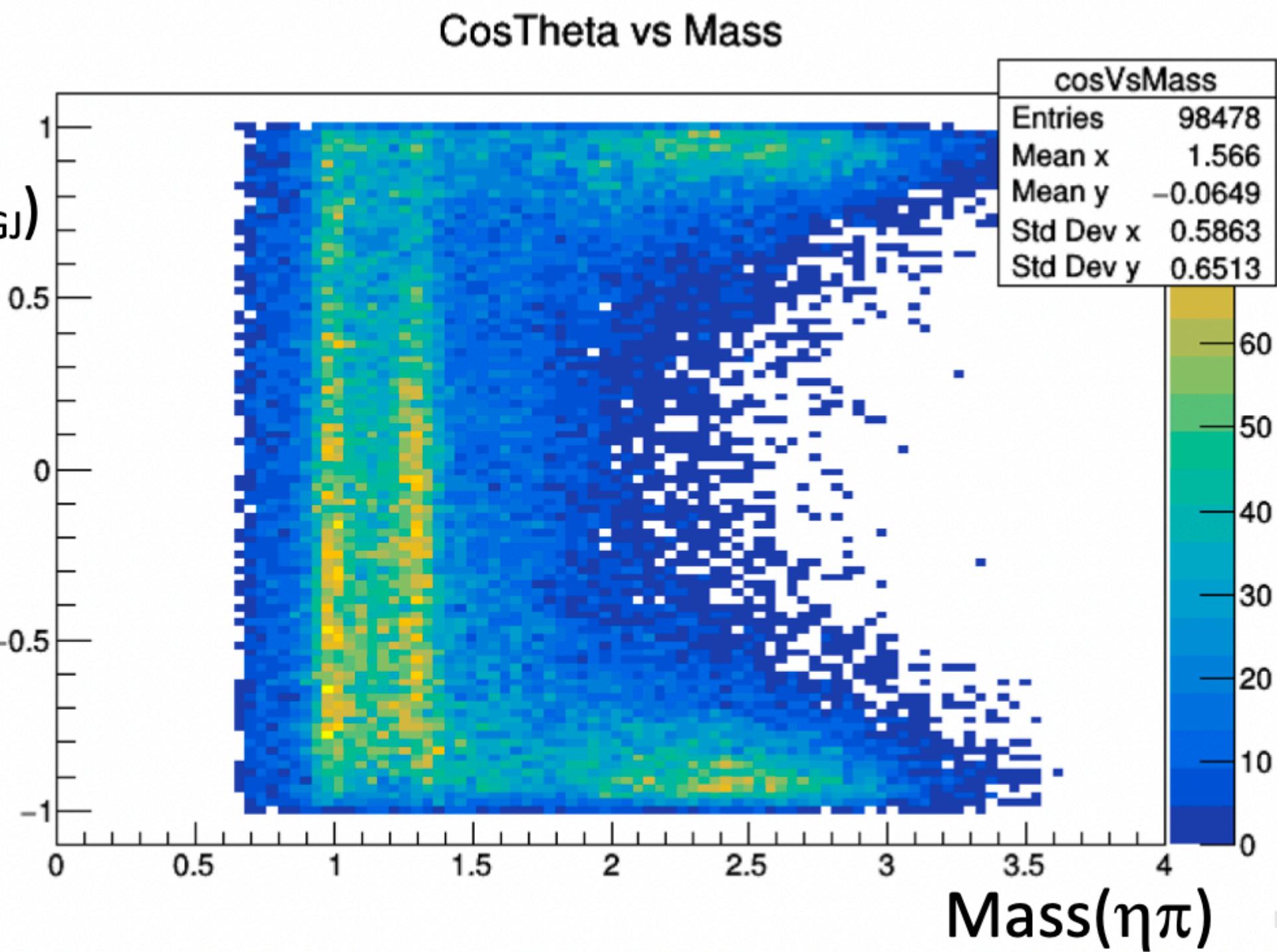


Simple model (all external particles = scalar) including:

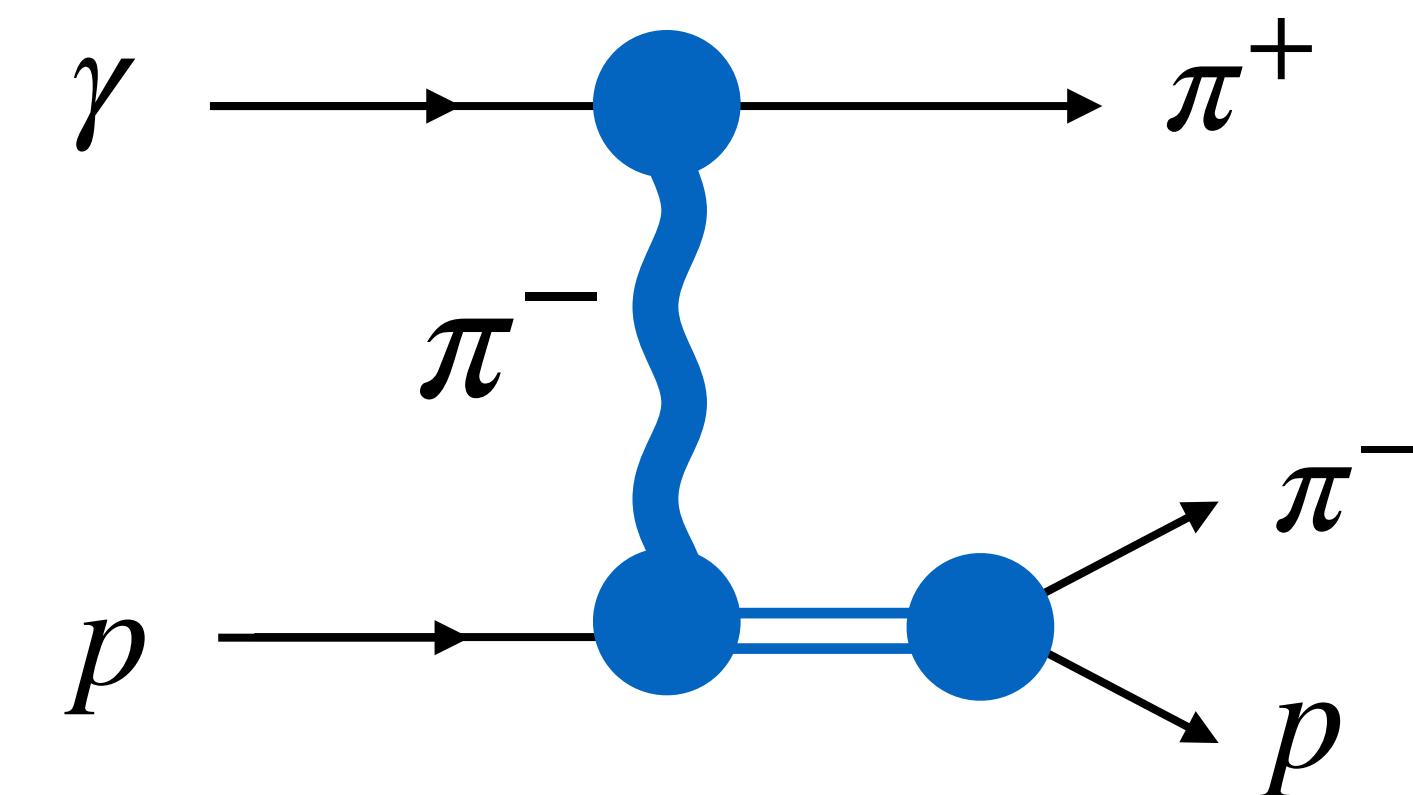


$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



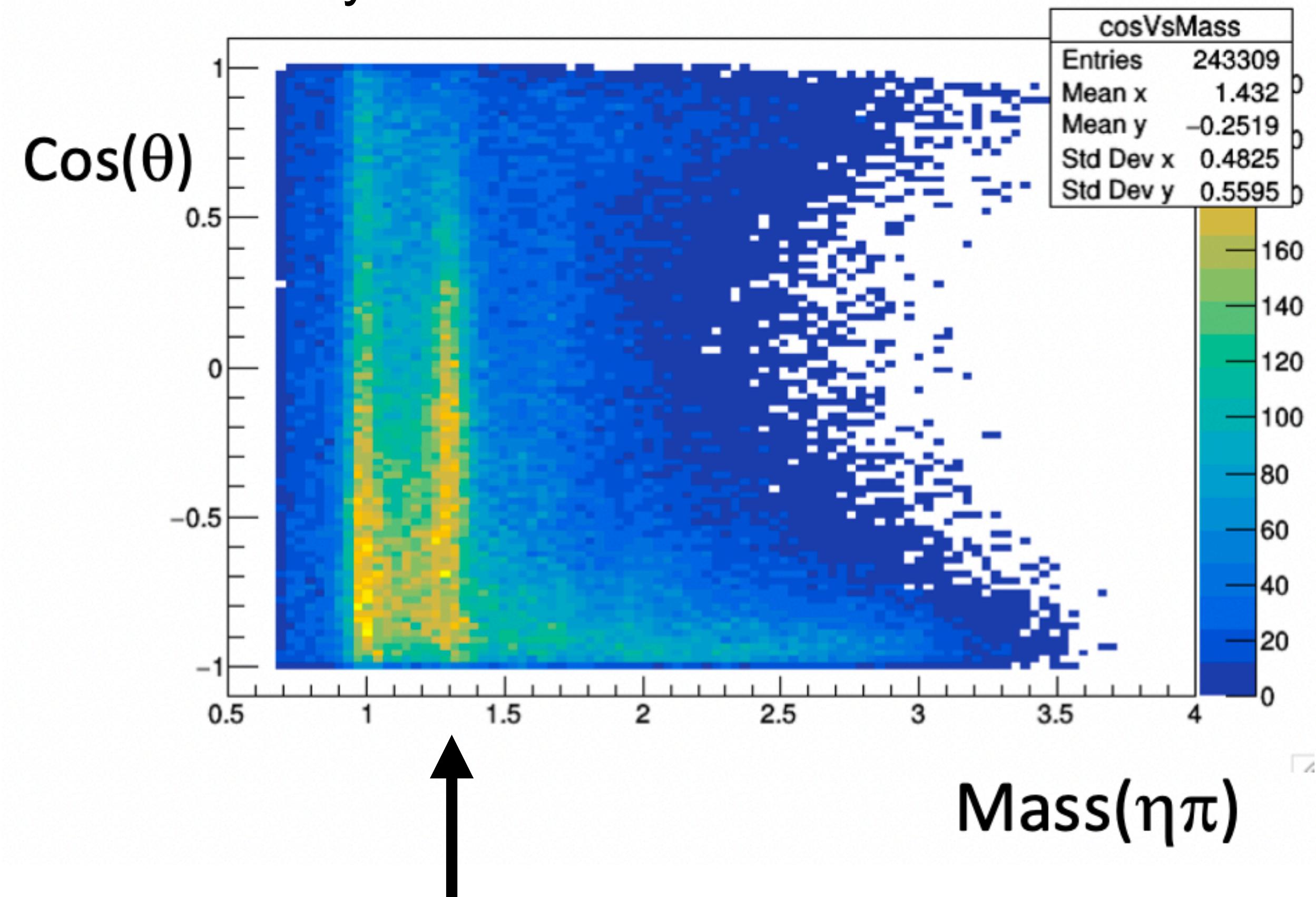
Courtesy of R. Perry



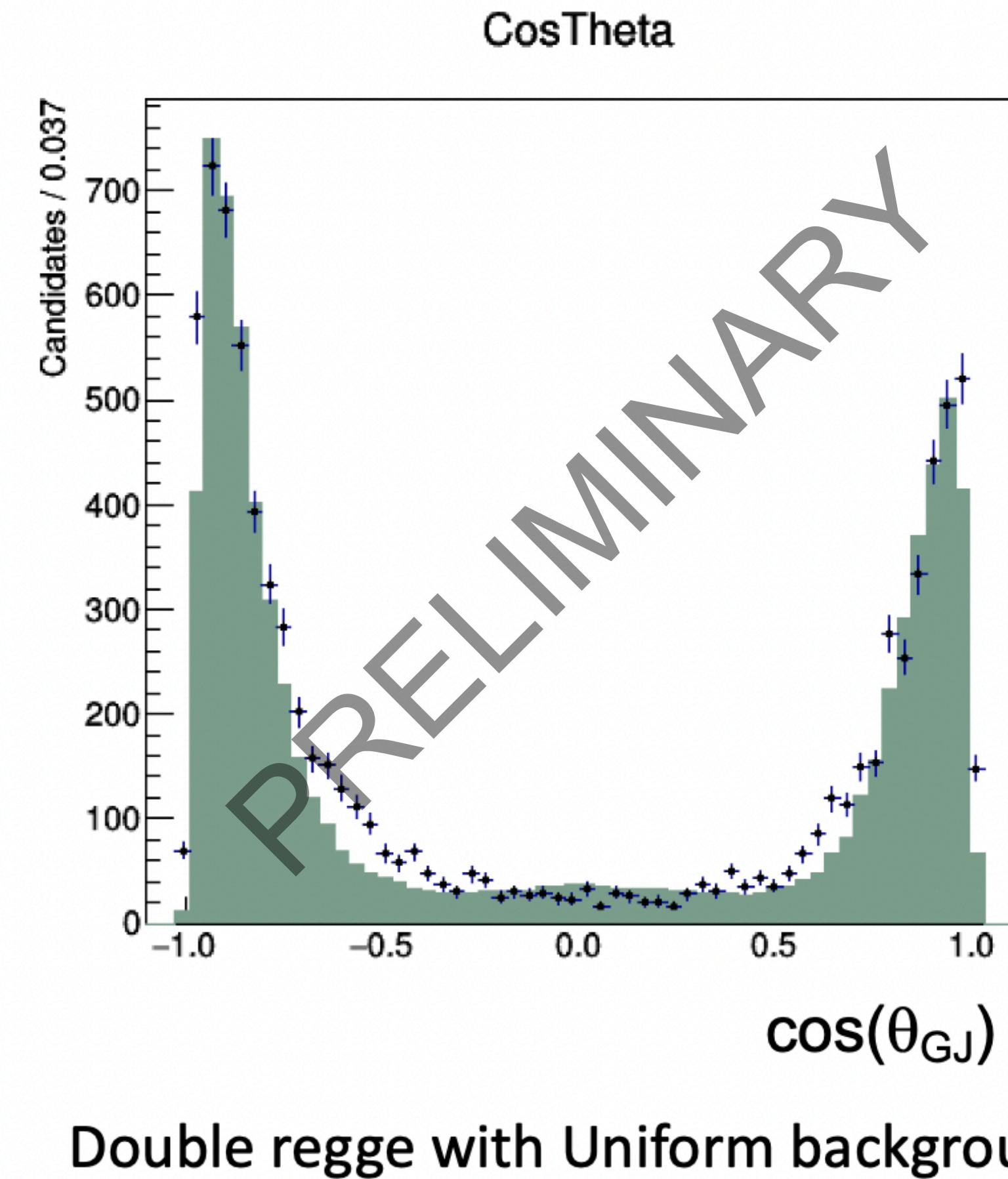
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti

Baryons have been ‘cut out’



$a_2(1320)$

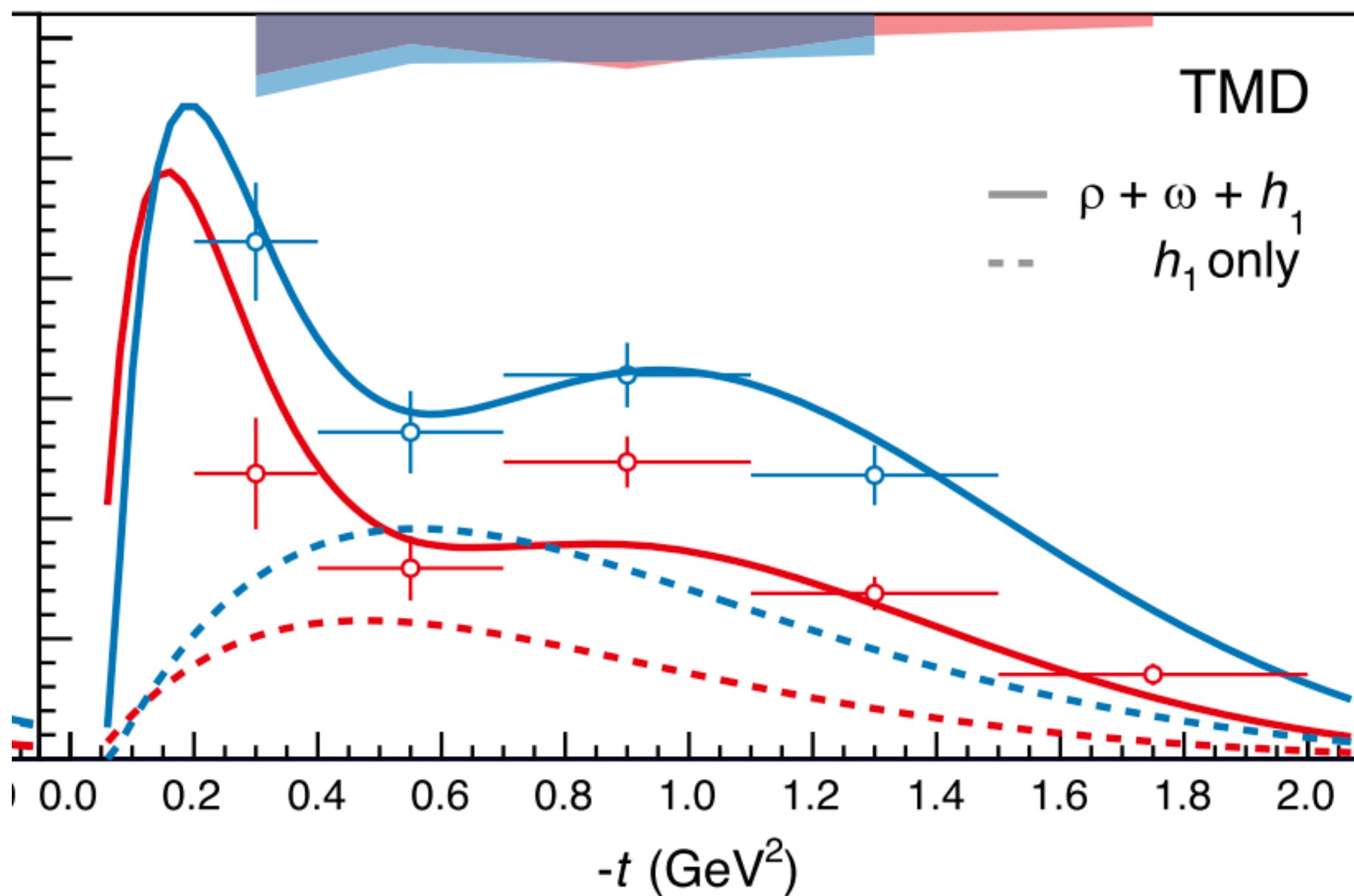


Double regge with Uniform background

Tensor Meson Photoproduction @CLAS

VM et al (JPAC) PRD102 (2020)

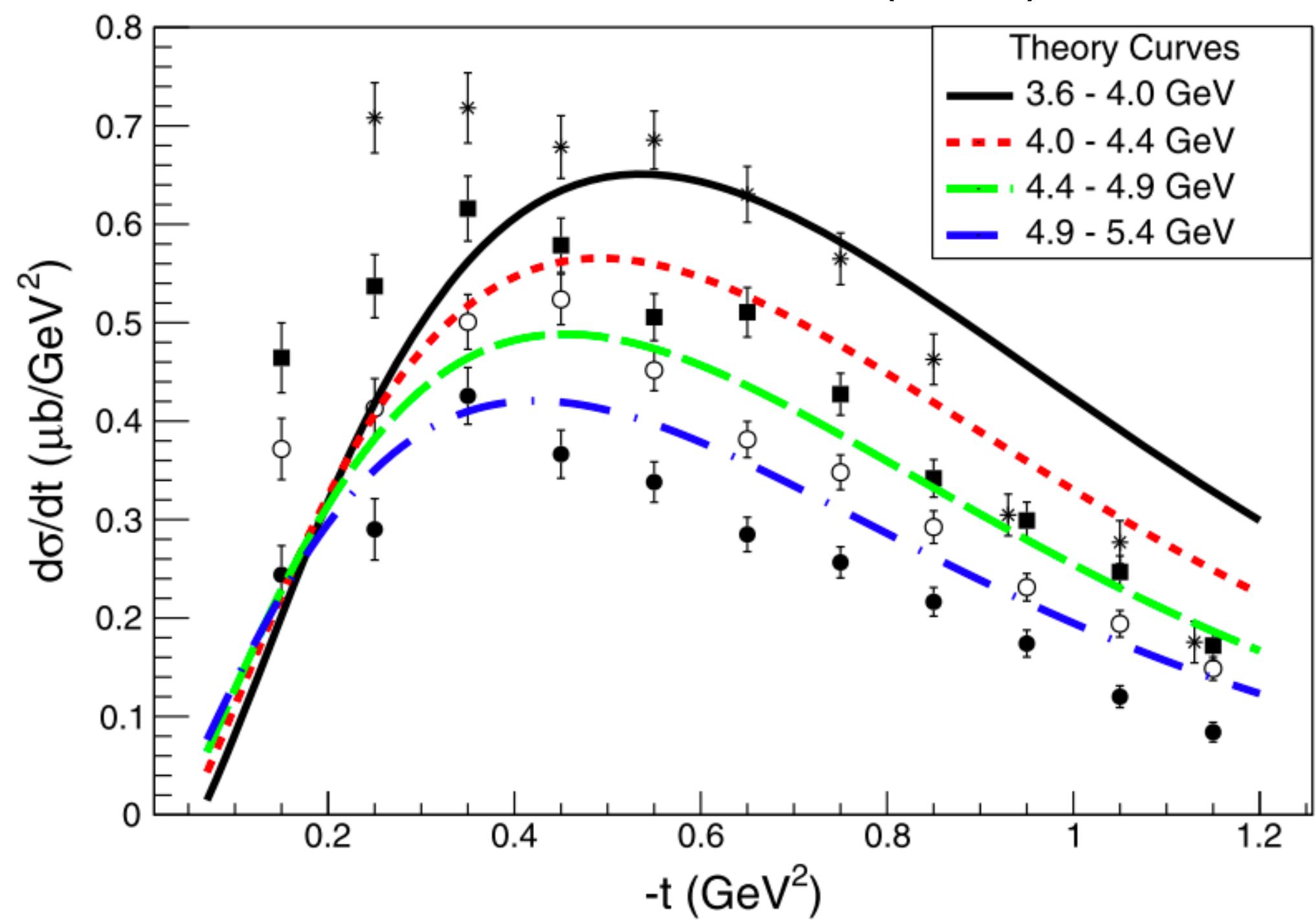
CLAS PRC 102 (2020)



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

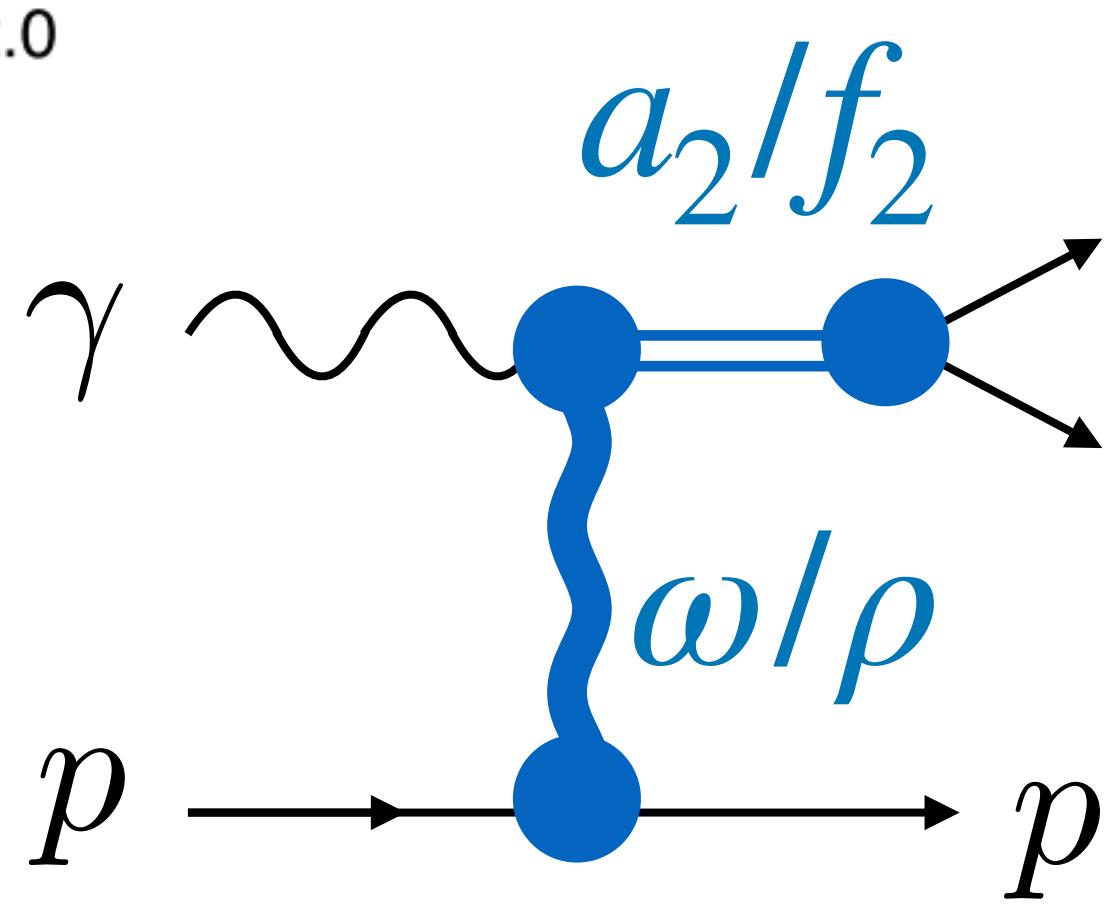
$$\omega + \frac{1}{3}\rho$$

CLAS PRL126 (2021)



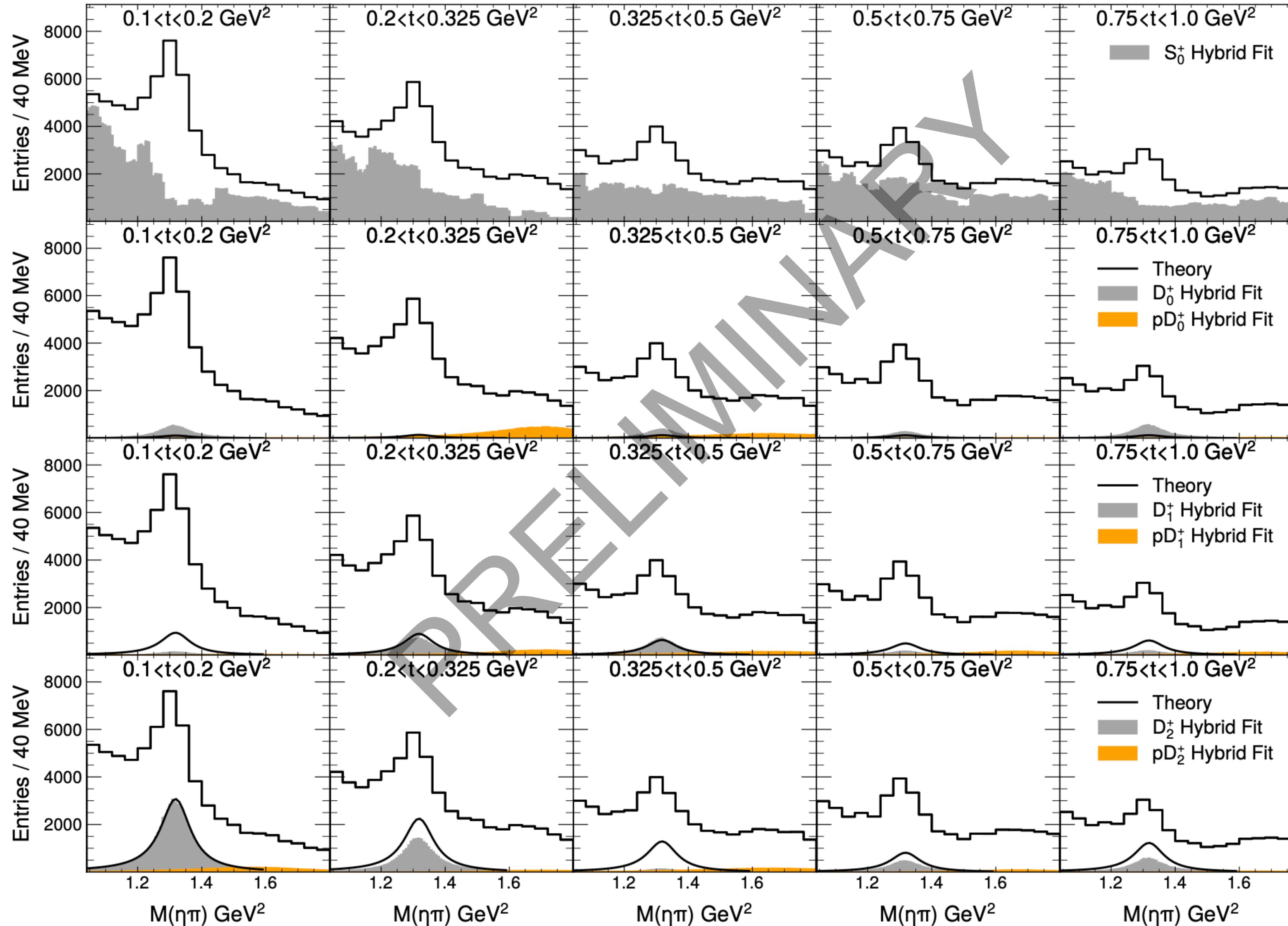
$\gamma p \rightarrow f_2(1270)p :$

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



$a_2(1320)$ Photoproduction @GlueX

In collaboration with L. Ng and M. Albrecht



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

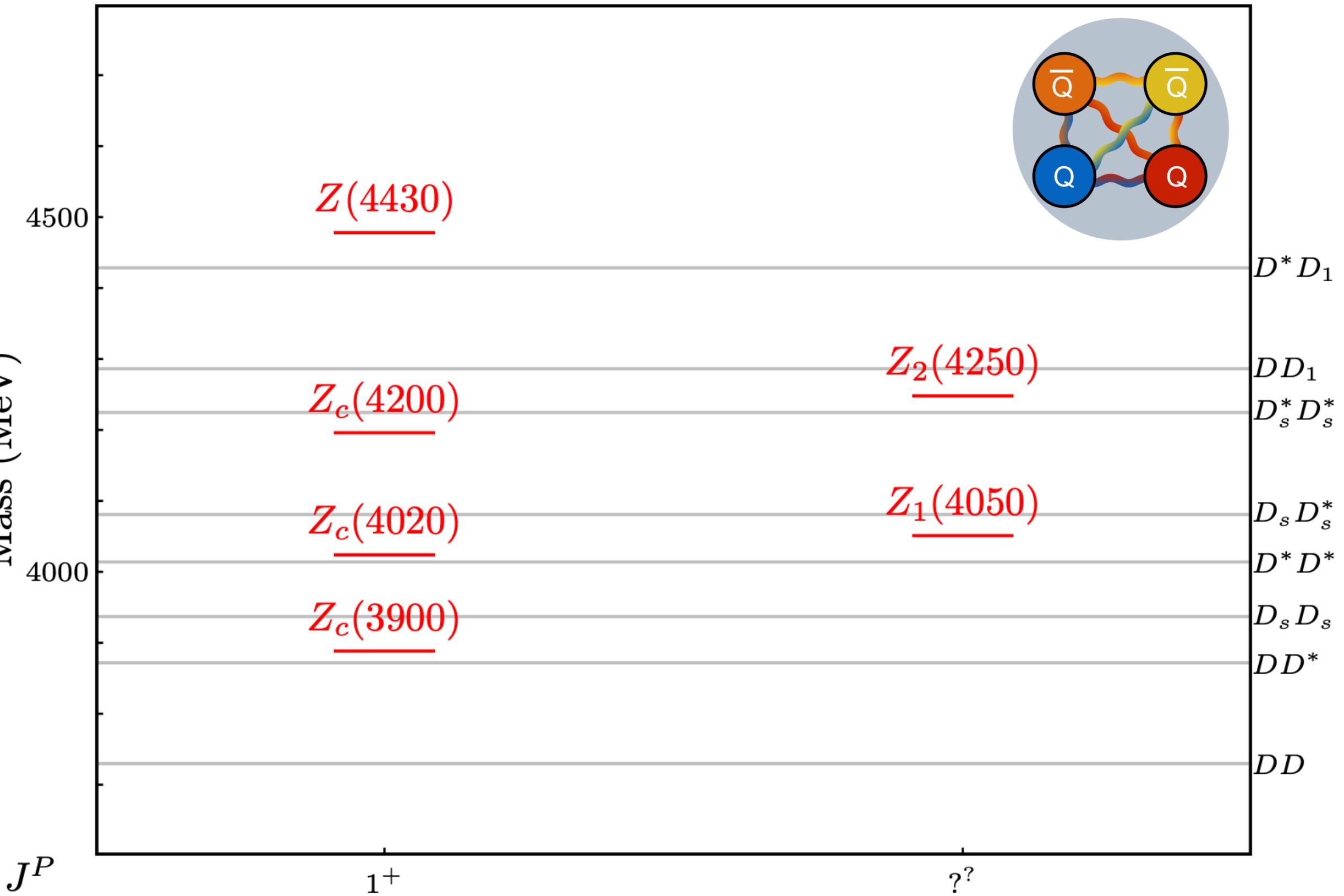
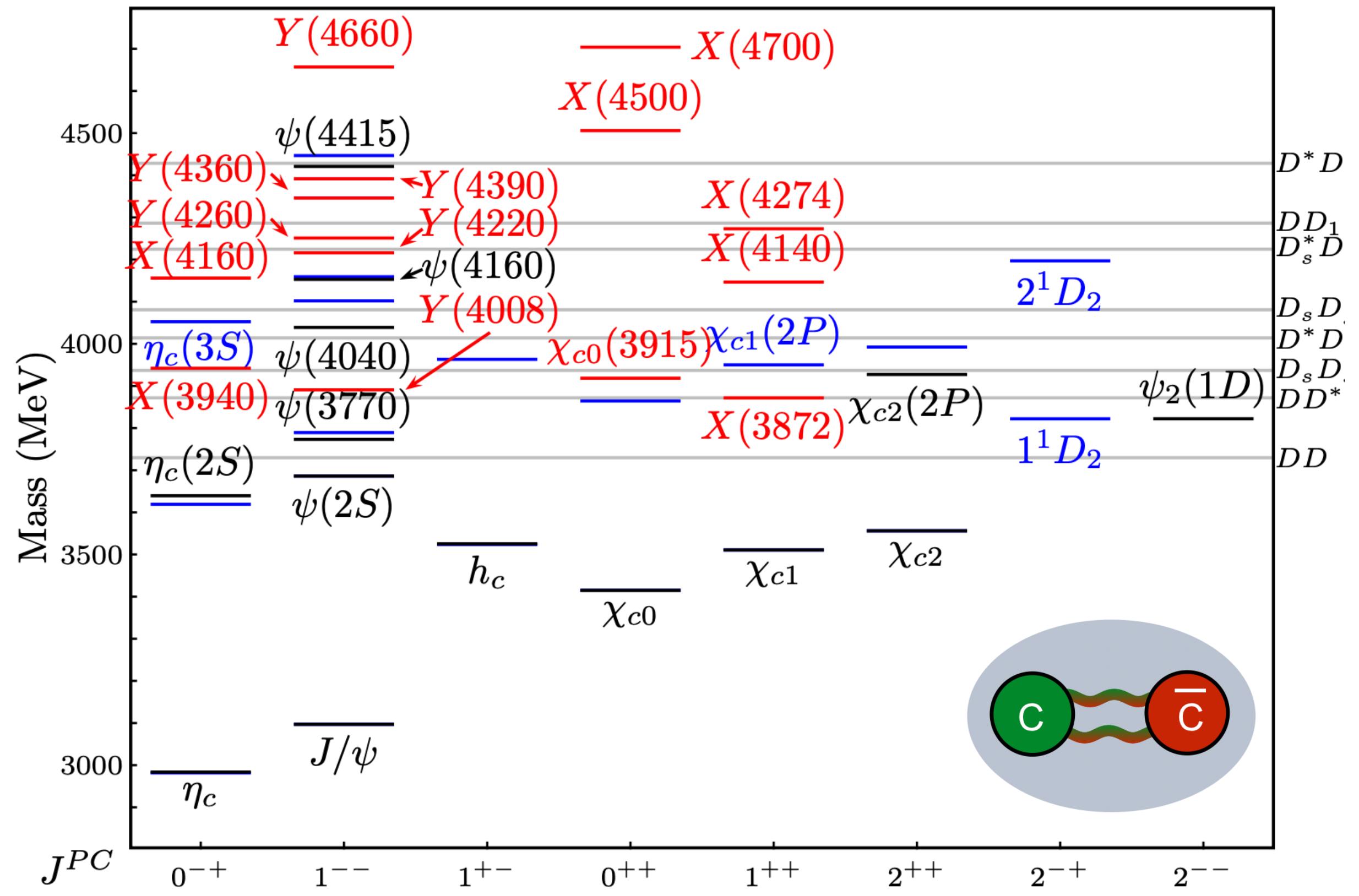
Reasonable agreement with model predictions from VM et al (JPAC) PRD102 (2020)

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

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

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

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

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

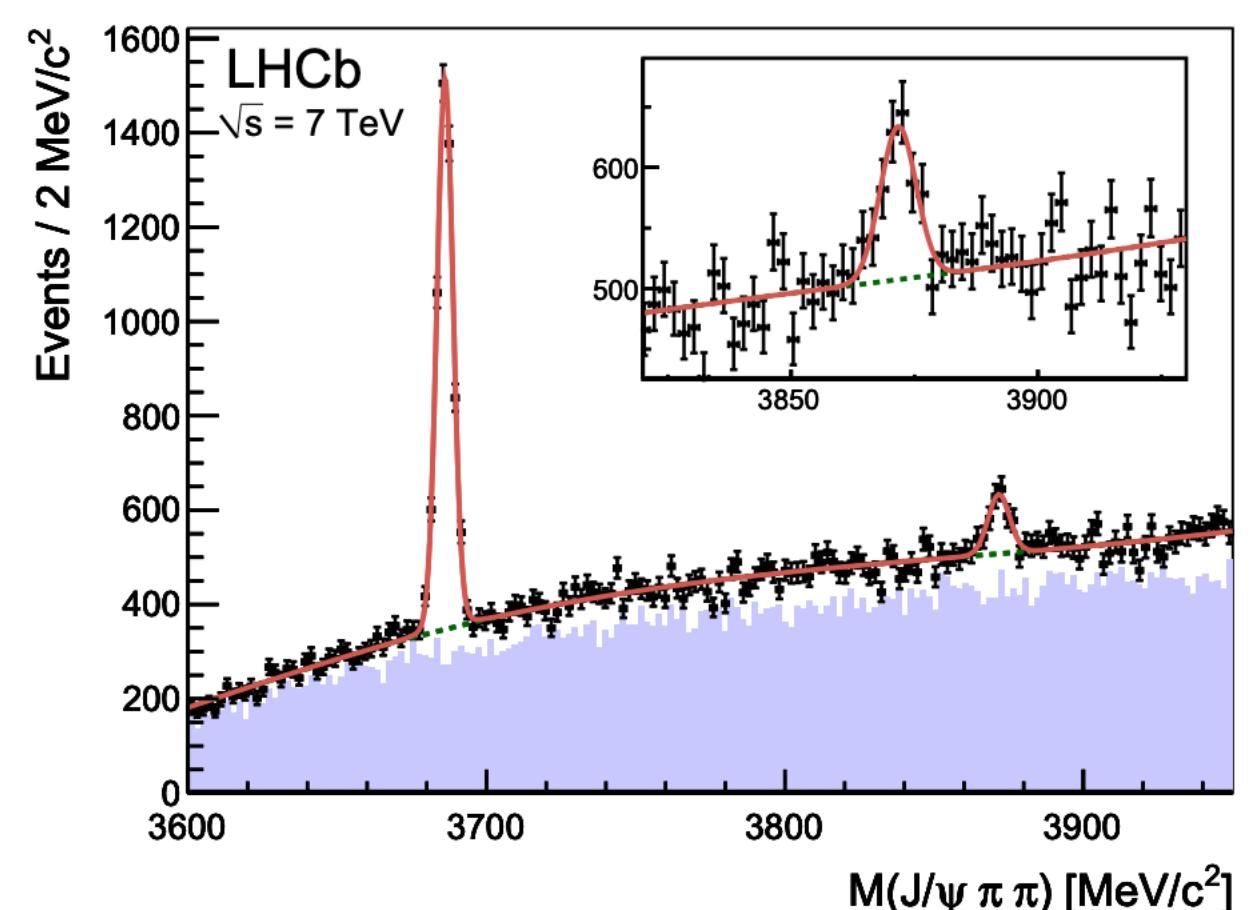
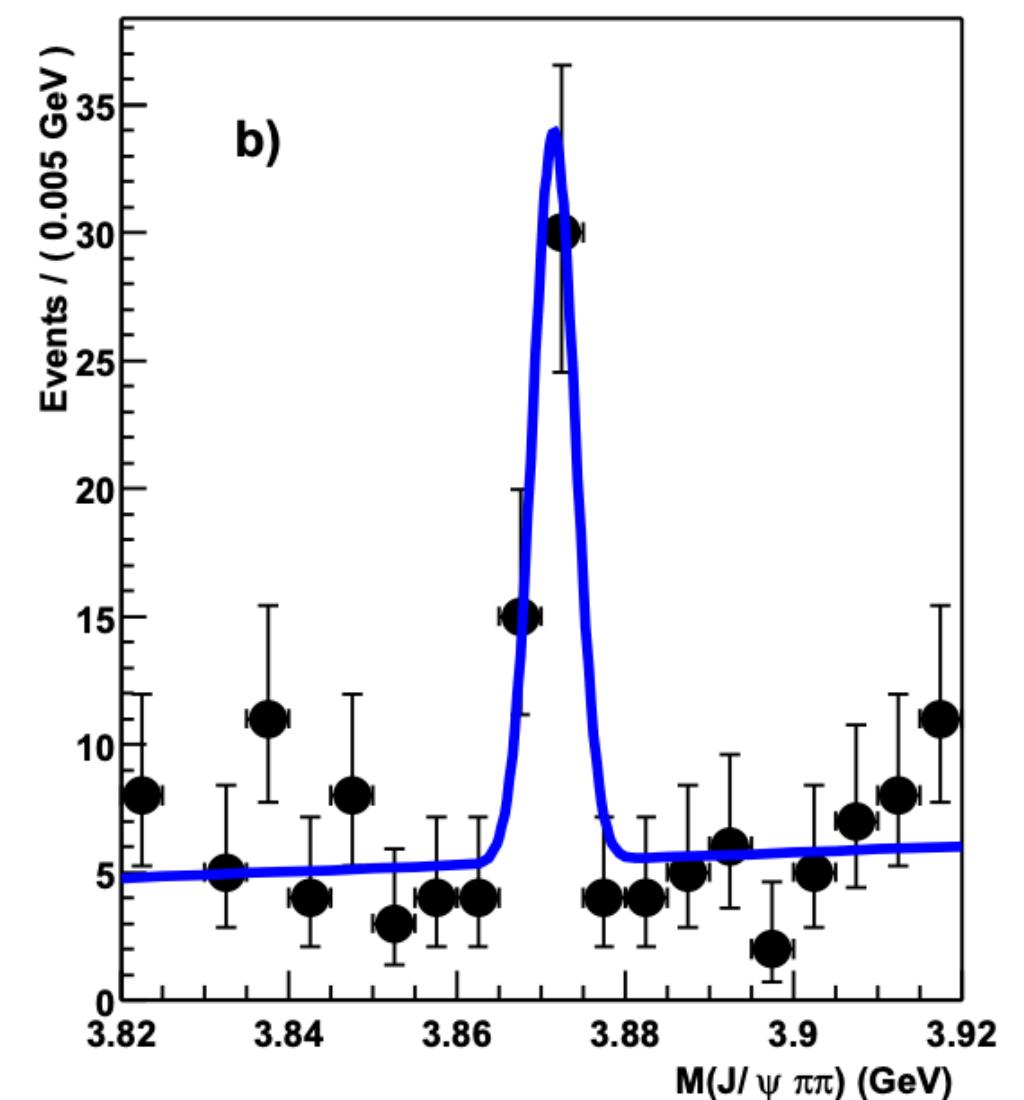
Observations by
independent collaborations

$$pp \rightarrow X(3872) + \text{anything}$$

$$X(3872) \rightarrow J/\psi \pi\pi$$

Challenging interpretation

Belle PRL91 (2003) 262001



LHCb EPJC72 (2012) 1972

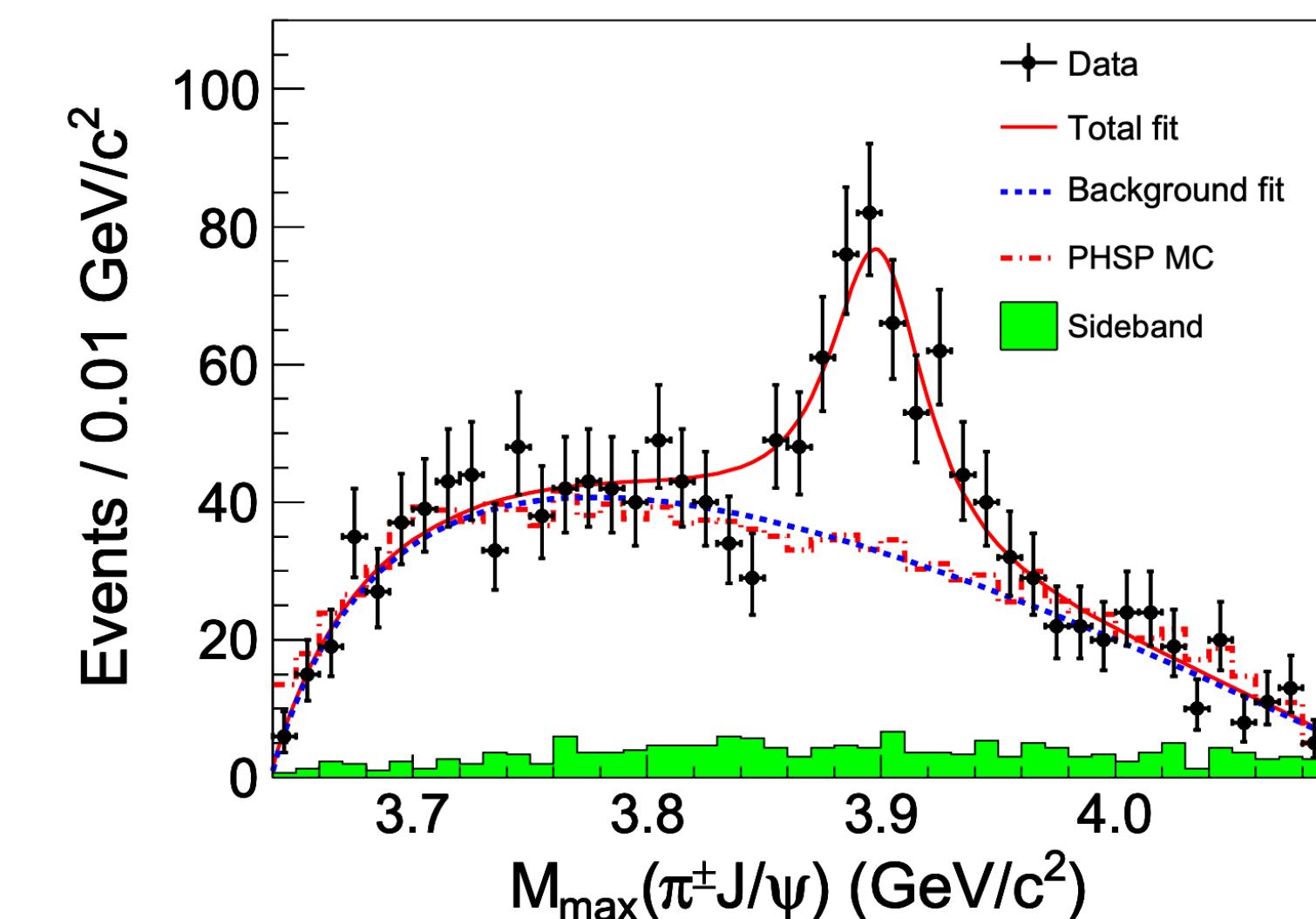
$Z_c(3900)^+$

Discovered in e^+e^- interactions by BESIII

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

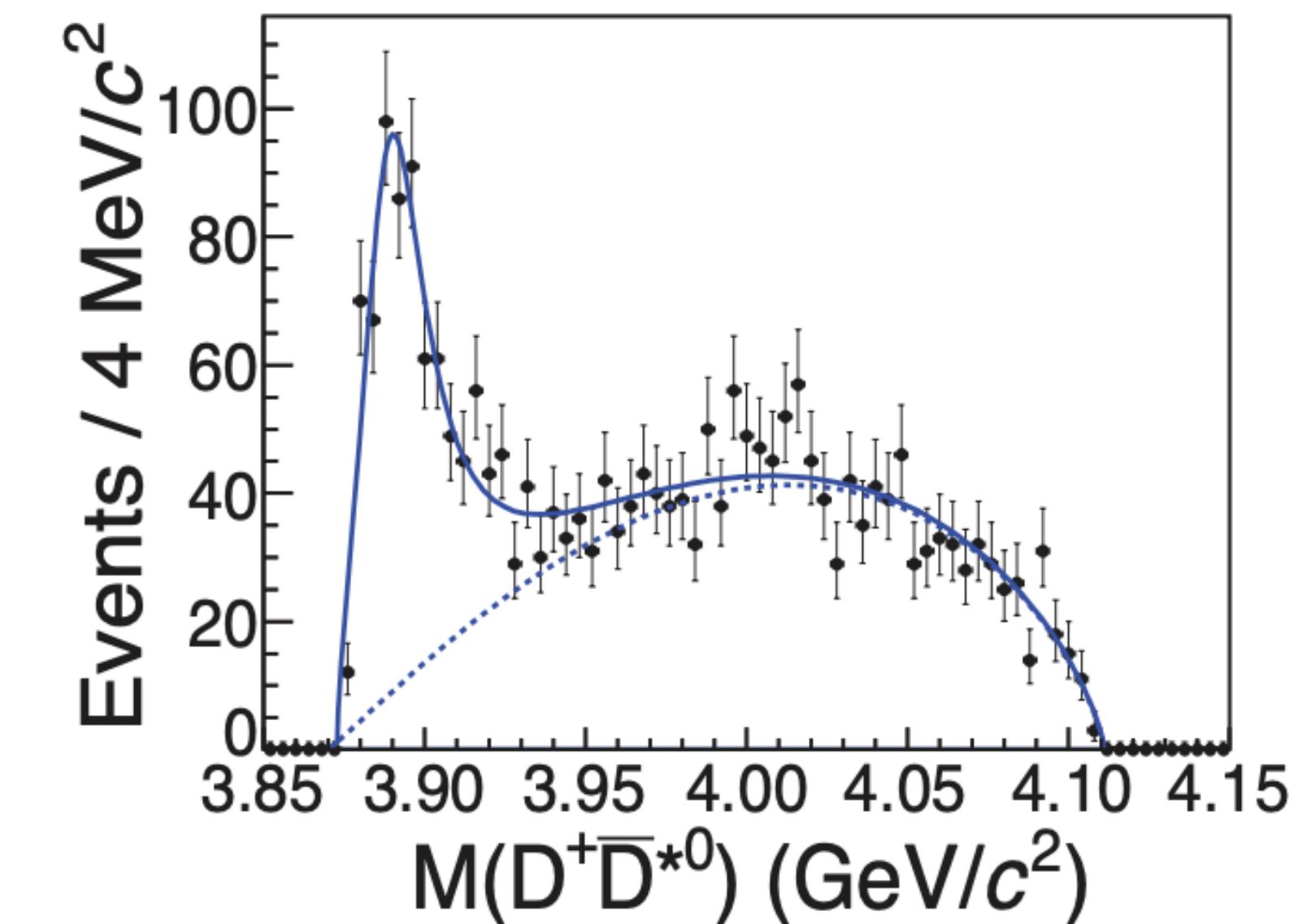
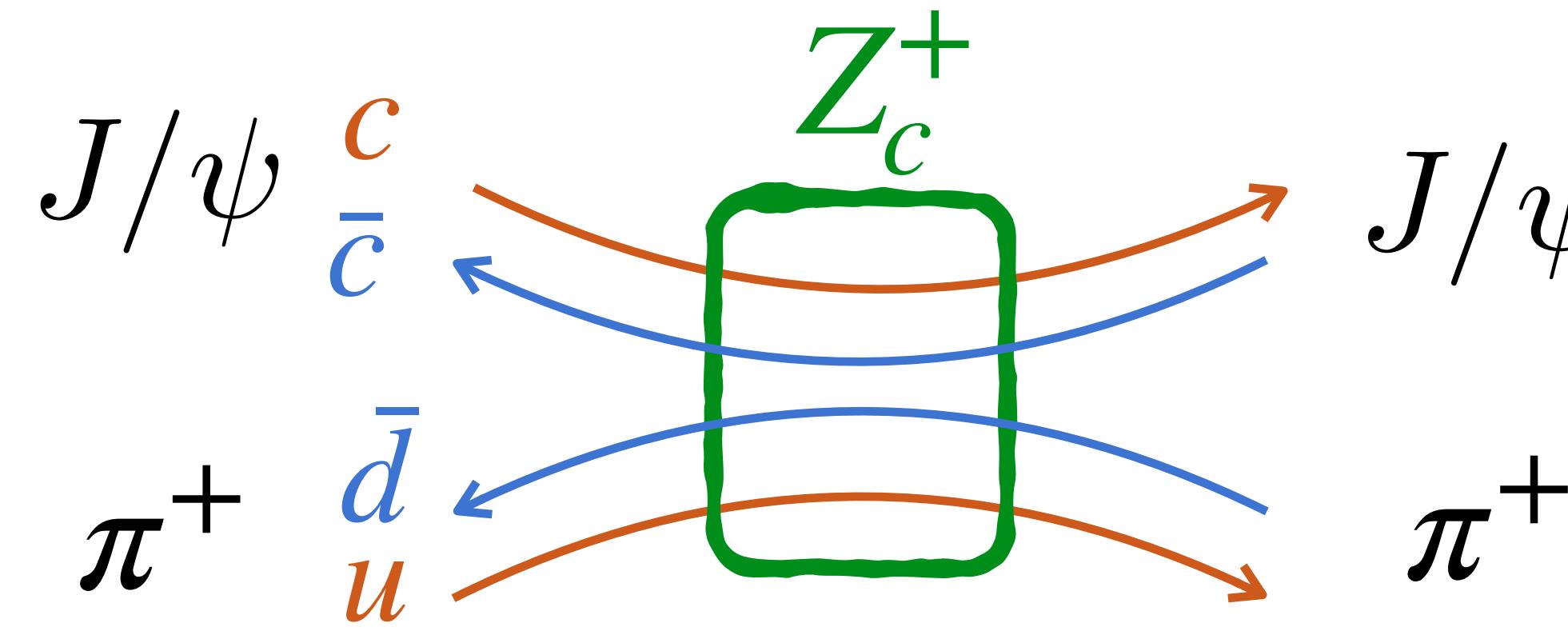
$\rightarrow J/\psi \pi^+$ BESIII PRL110 (2013)

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



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

Need at least
4 quarks

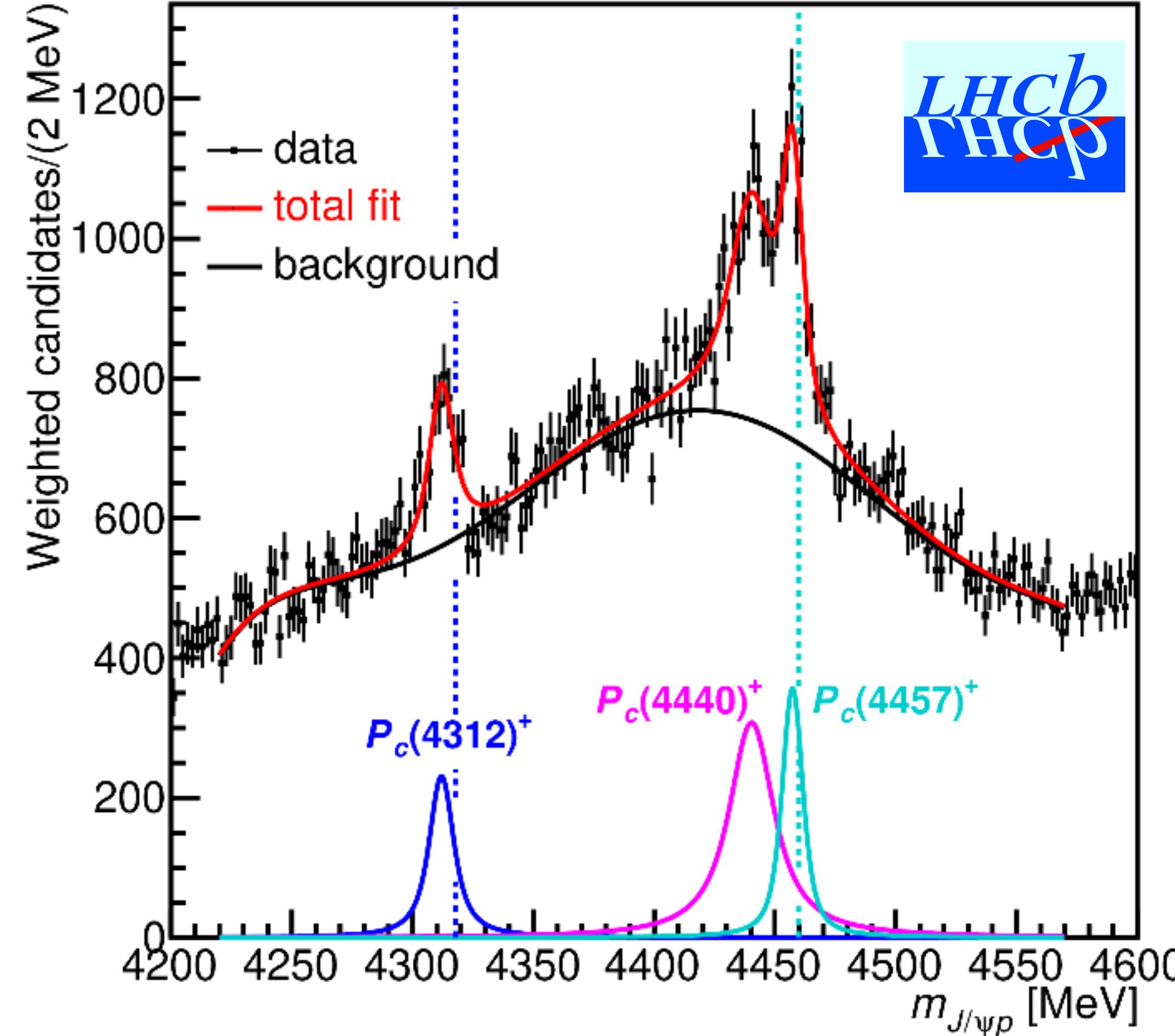


Pentaquarks candidates from LHCb

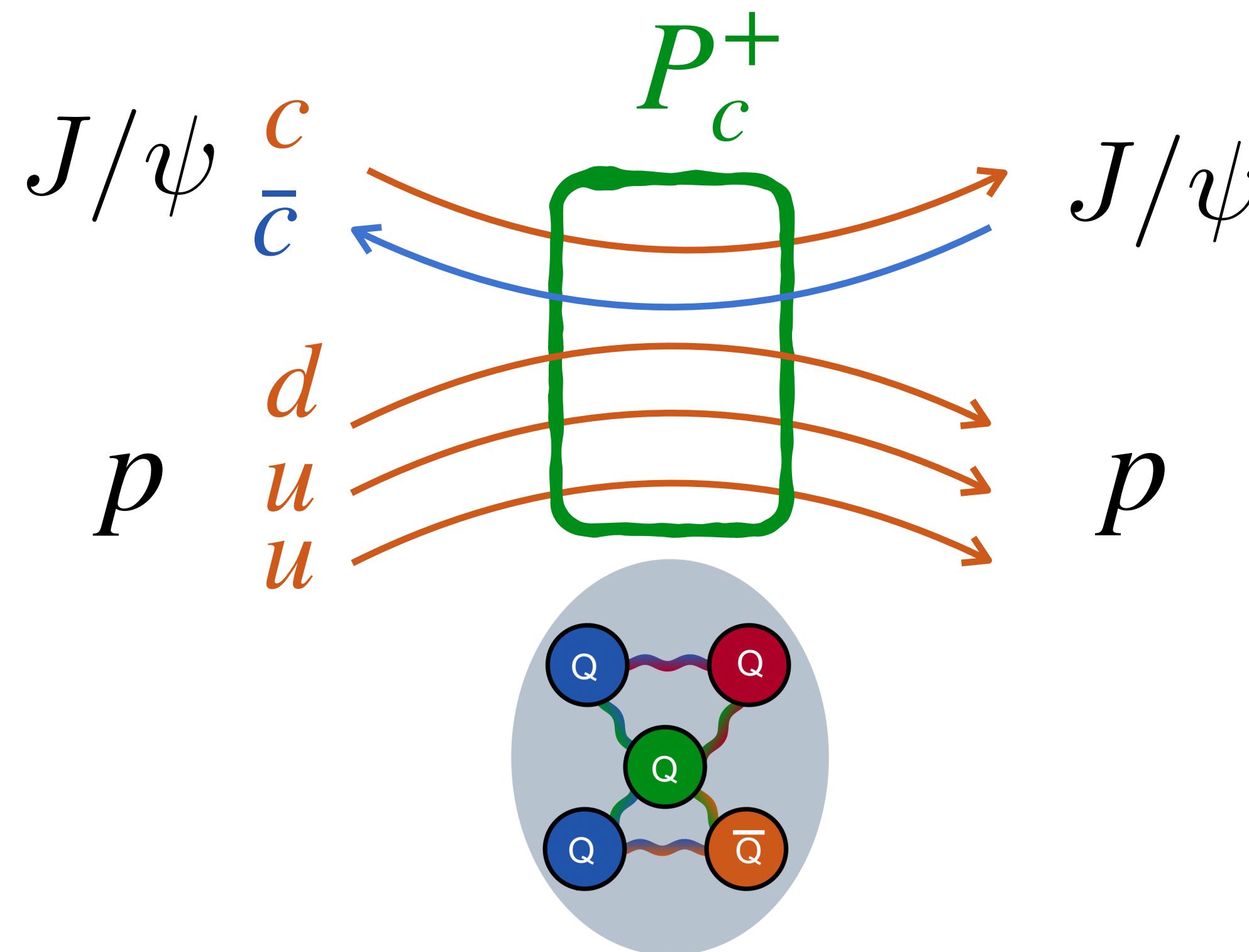
LHCb, PRL122 (2019) 222001

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

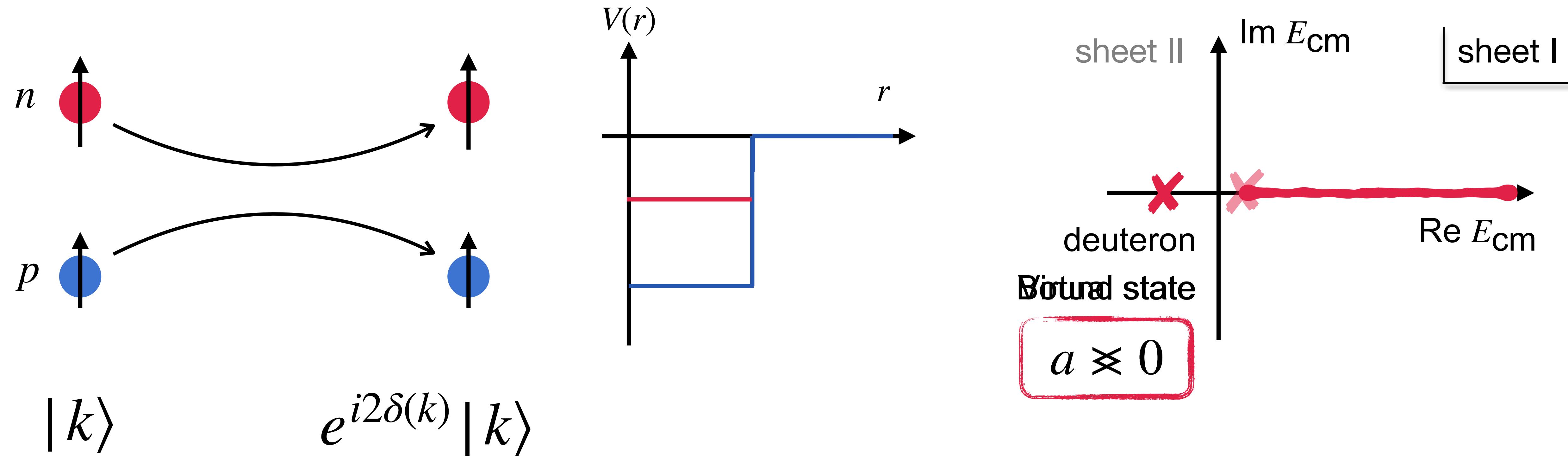
$\Sigma_c^+ \bar{D}^0$ $\Sigma_c^+ \bar{D}^{*0}$



unexplained excess of events in $J/\psi p$ spectrum
Cannot be qqq baryon



Bound state vs virtual state

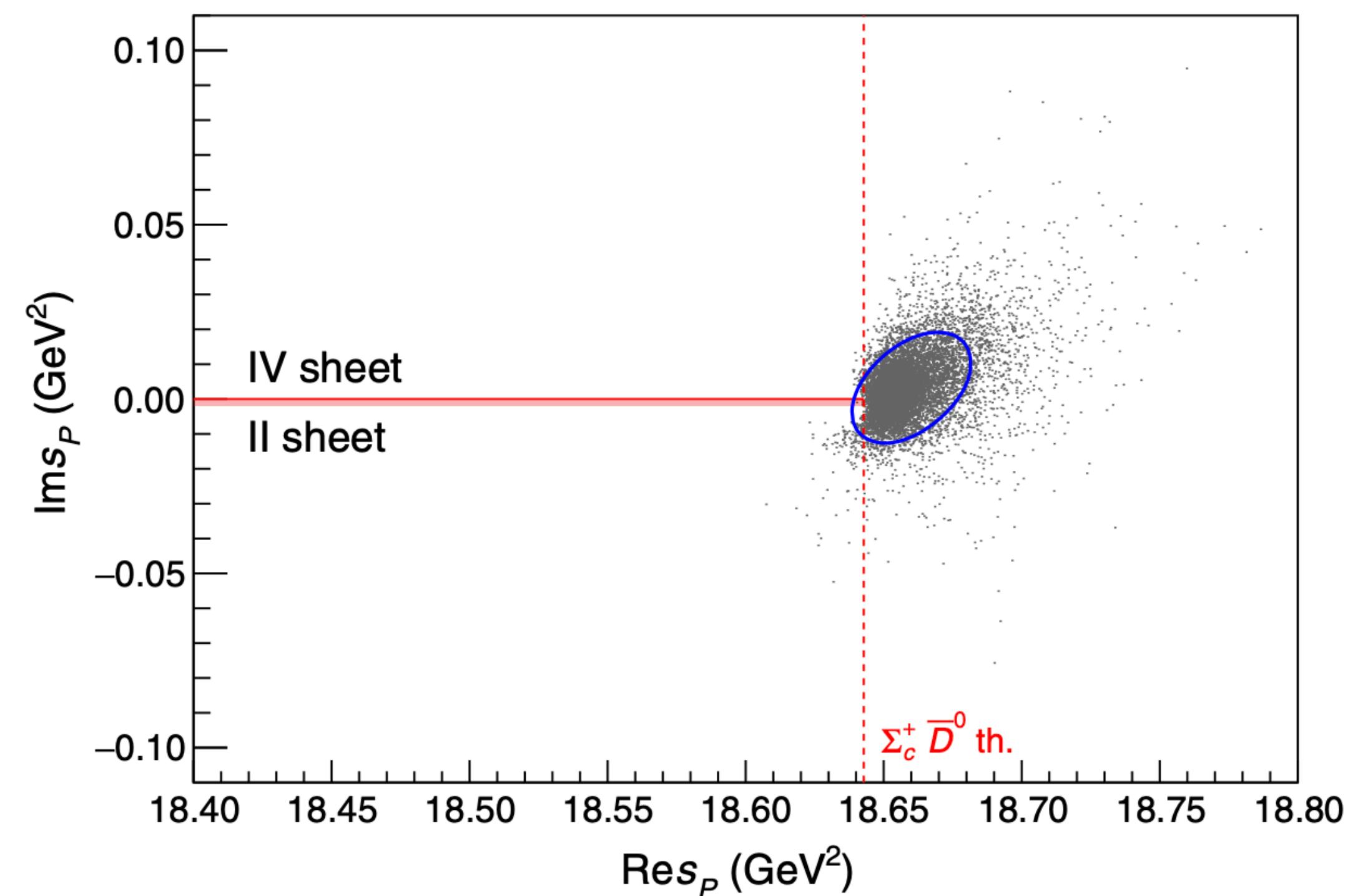
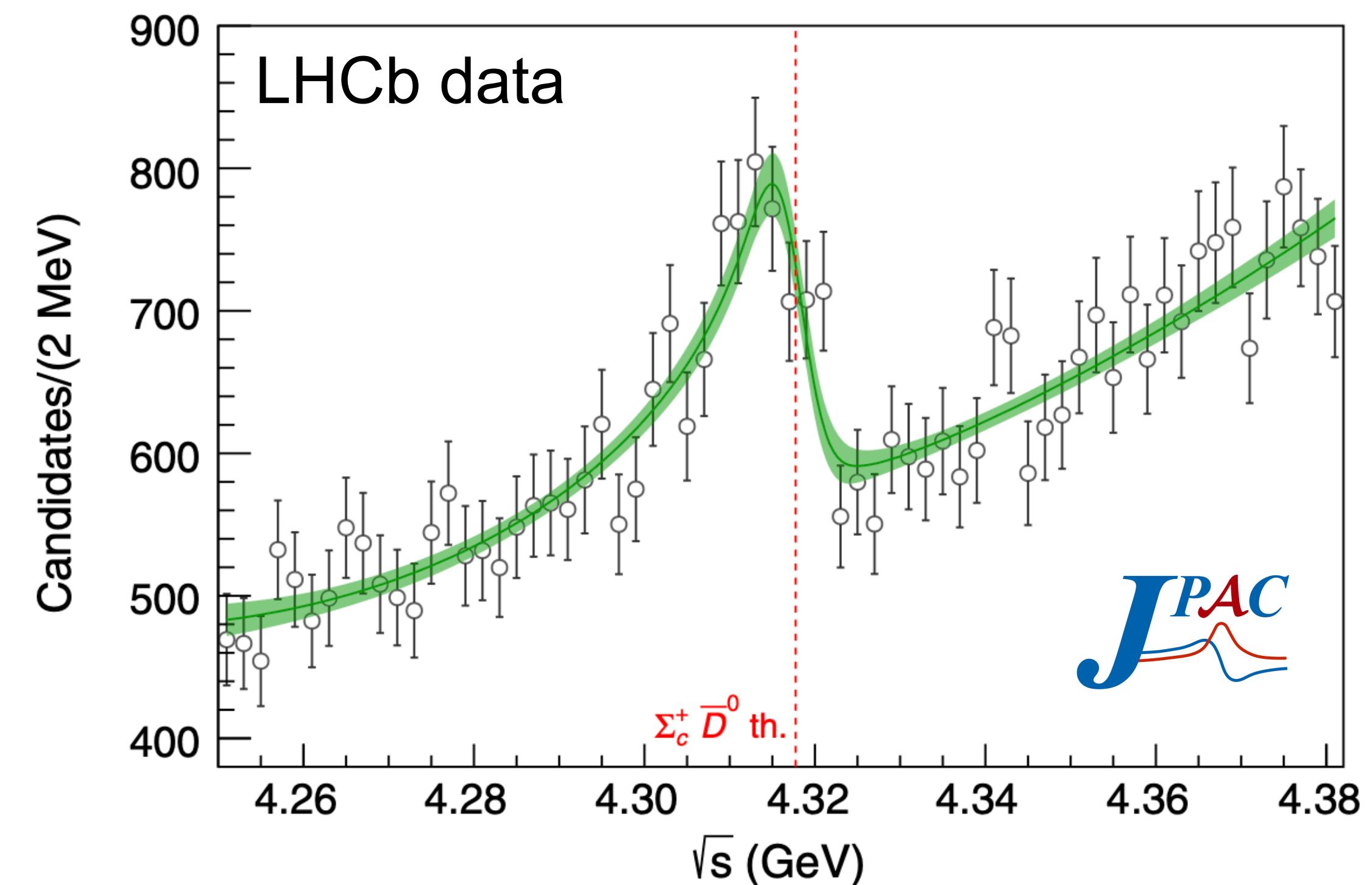


Scattering length

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

Cross section

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



Bootstrap: generate 10k data

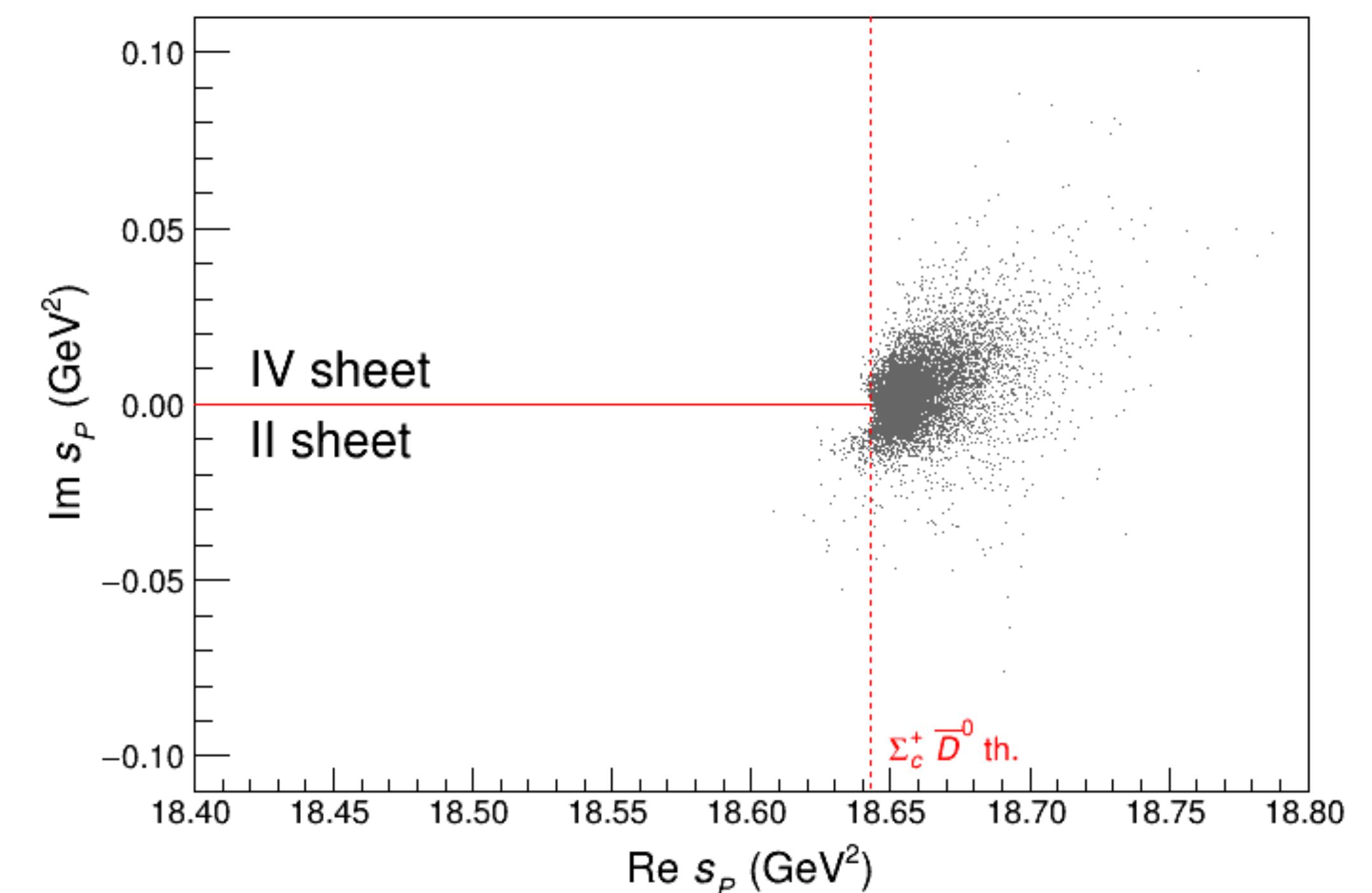
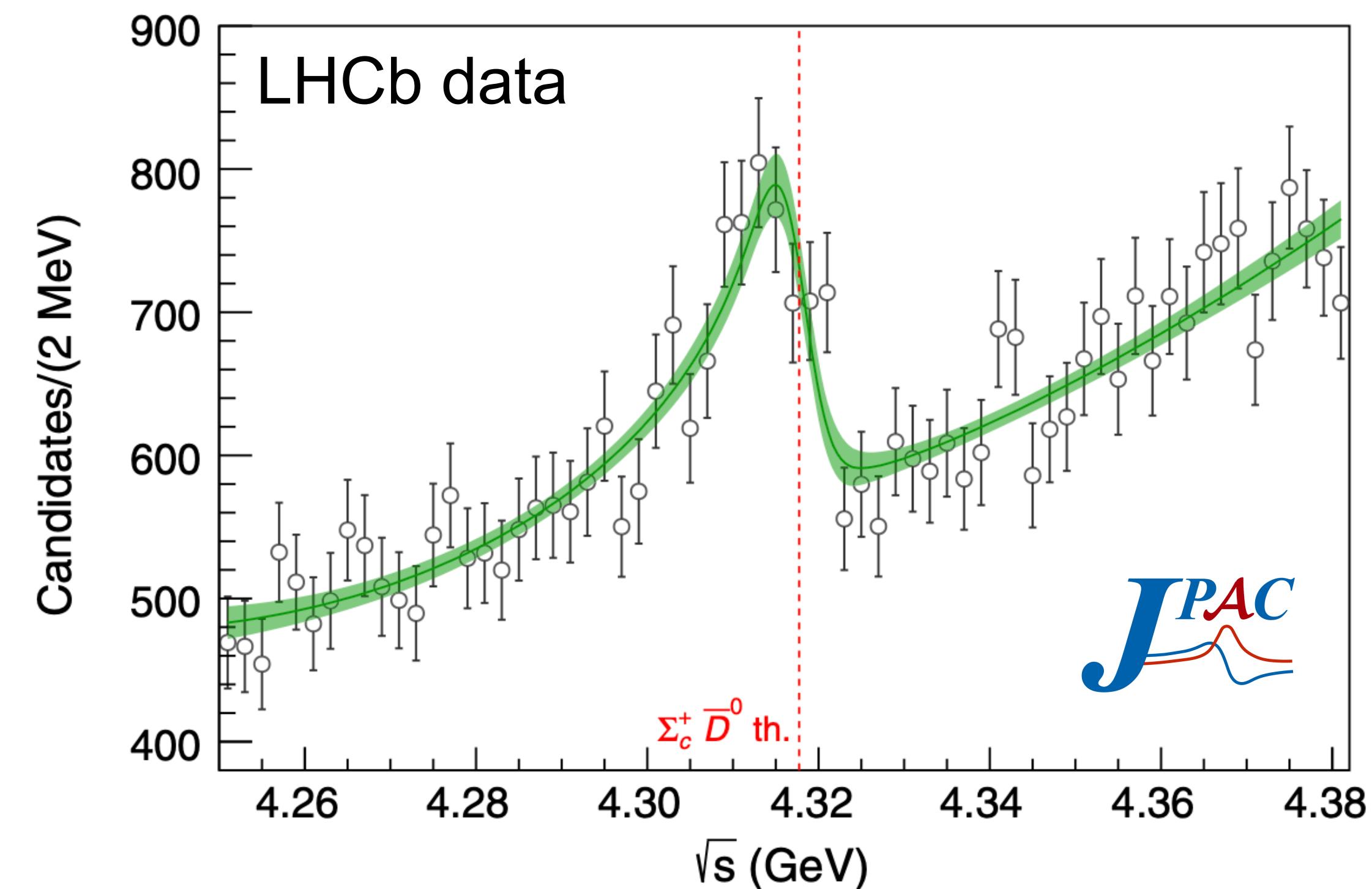
When $J/\psi p$ decouples, pole moves to the real axis on the

Physical sheet - positive scattering length - bound state

Unphysical sheet - negative scattering length - virtual state

$P_c(4312)^+$ analysis

Fernández-Ramírez et al (JPAC), PRL123 (2019) 092001



Bootstrap: generate 10k data

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

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

Physical sheet - positive scattering length - bound state

0.7 %

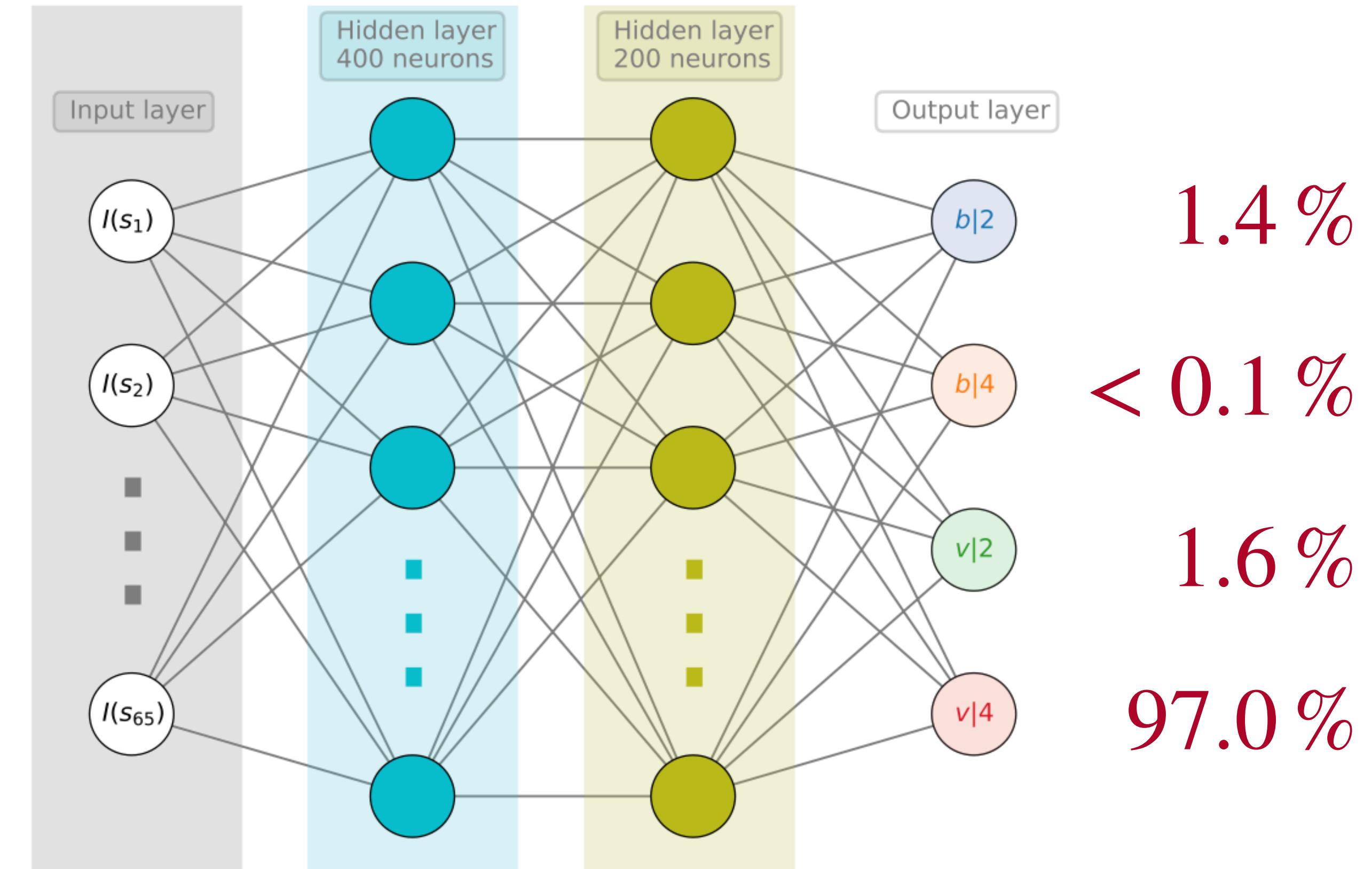
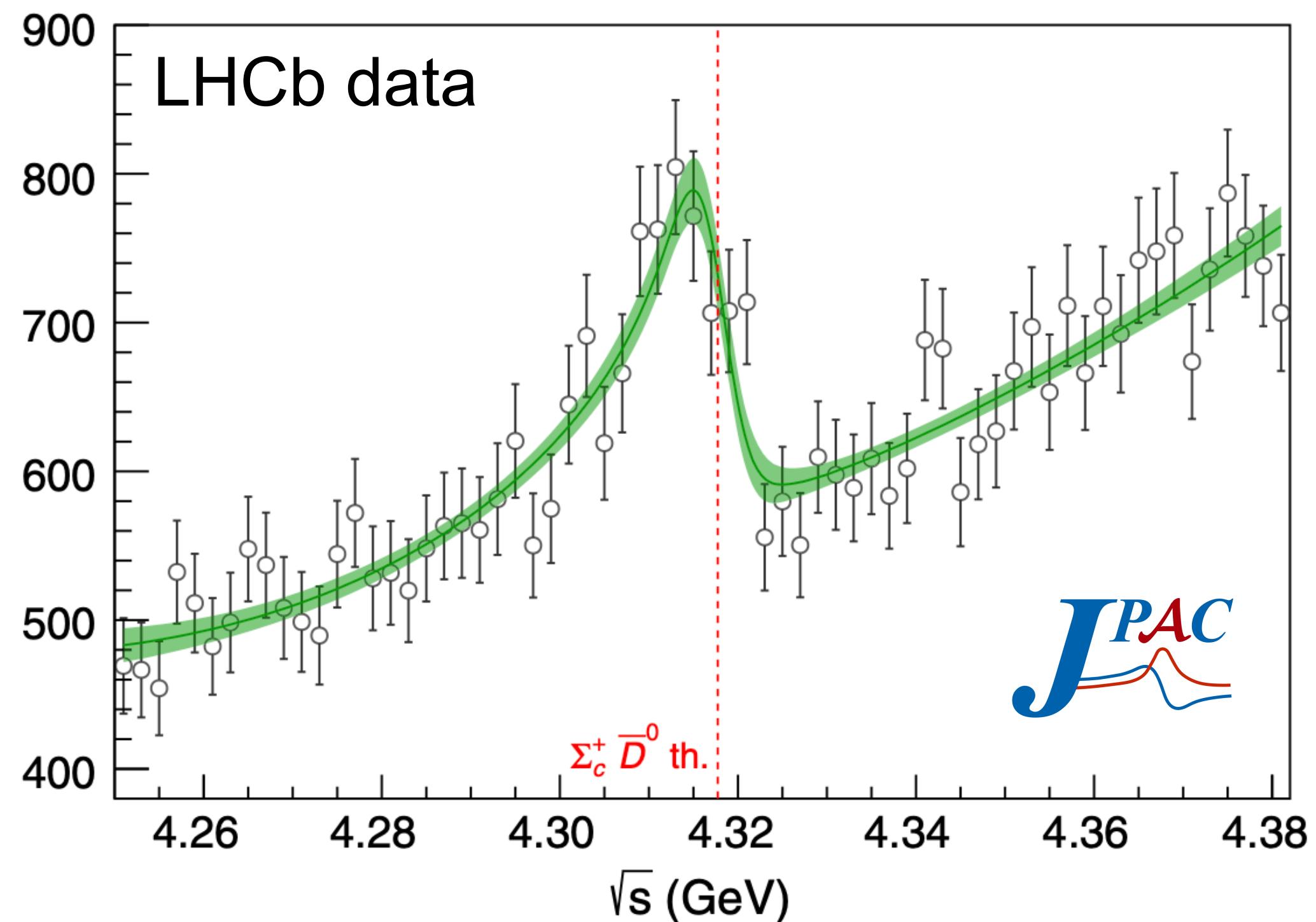
Unphysical sheet - negative scattering length - virtual state

99.3 %

$P_c(4312)^+$ analysis

Ng et al (JPAC), PRD105 (2022) L091501

Deep neural network trained with 4 types of amplitudes

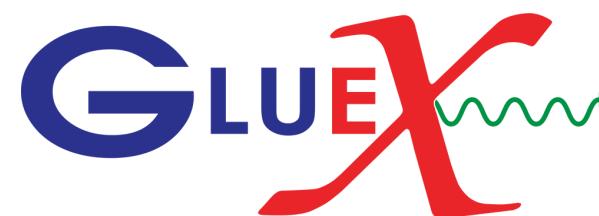


Direct production of P_c^+ ?



P_c^+ in 3-body decay

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



Photoproduction of P_c^+

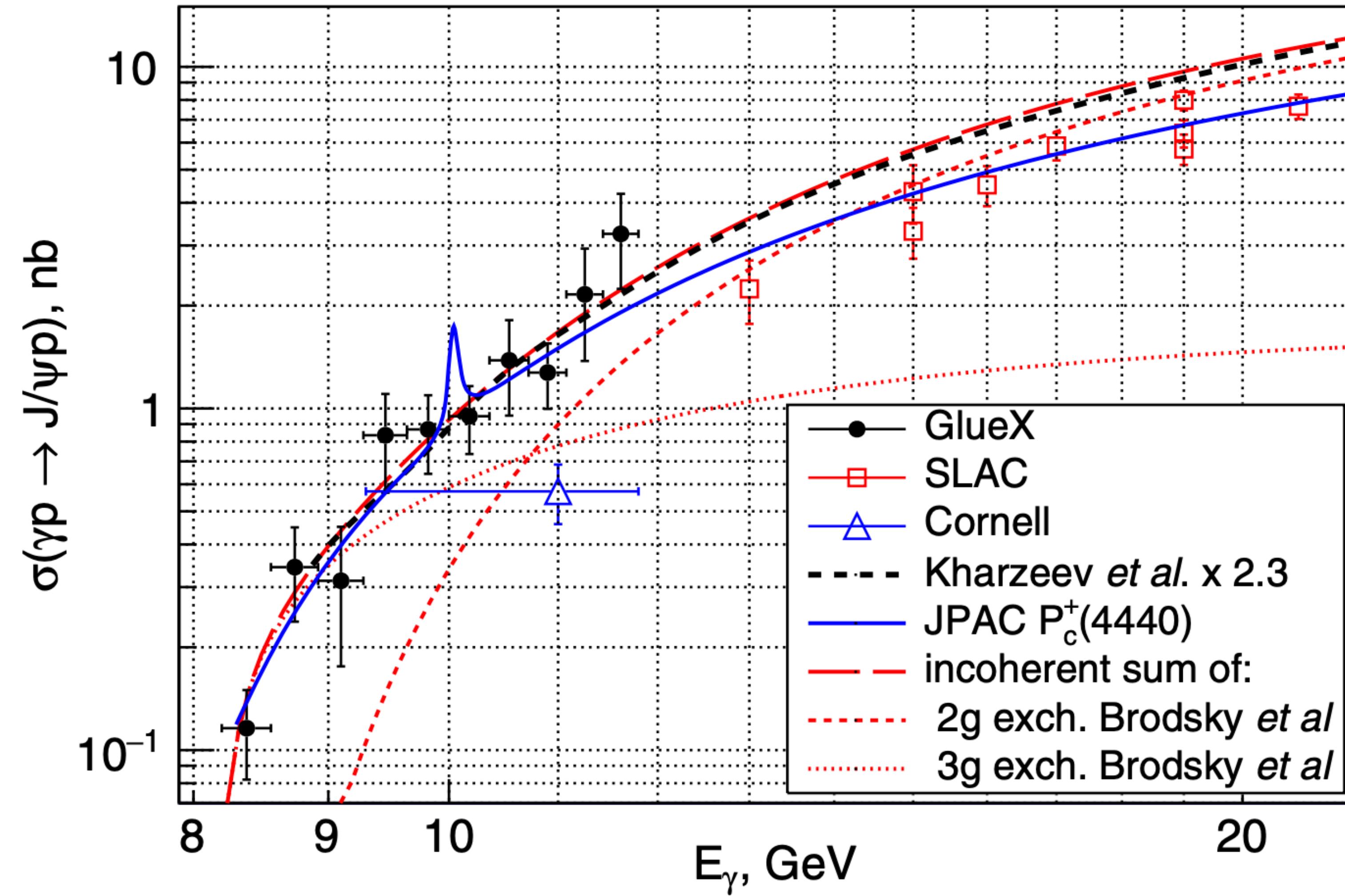
$\gamma p \rightarrow J/\psi p$

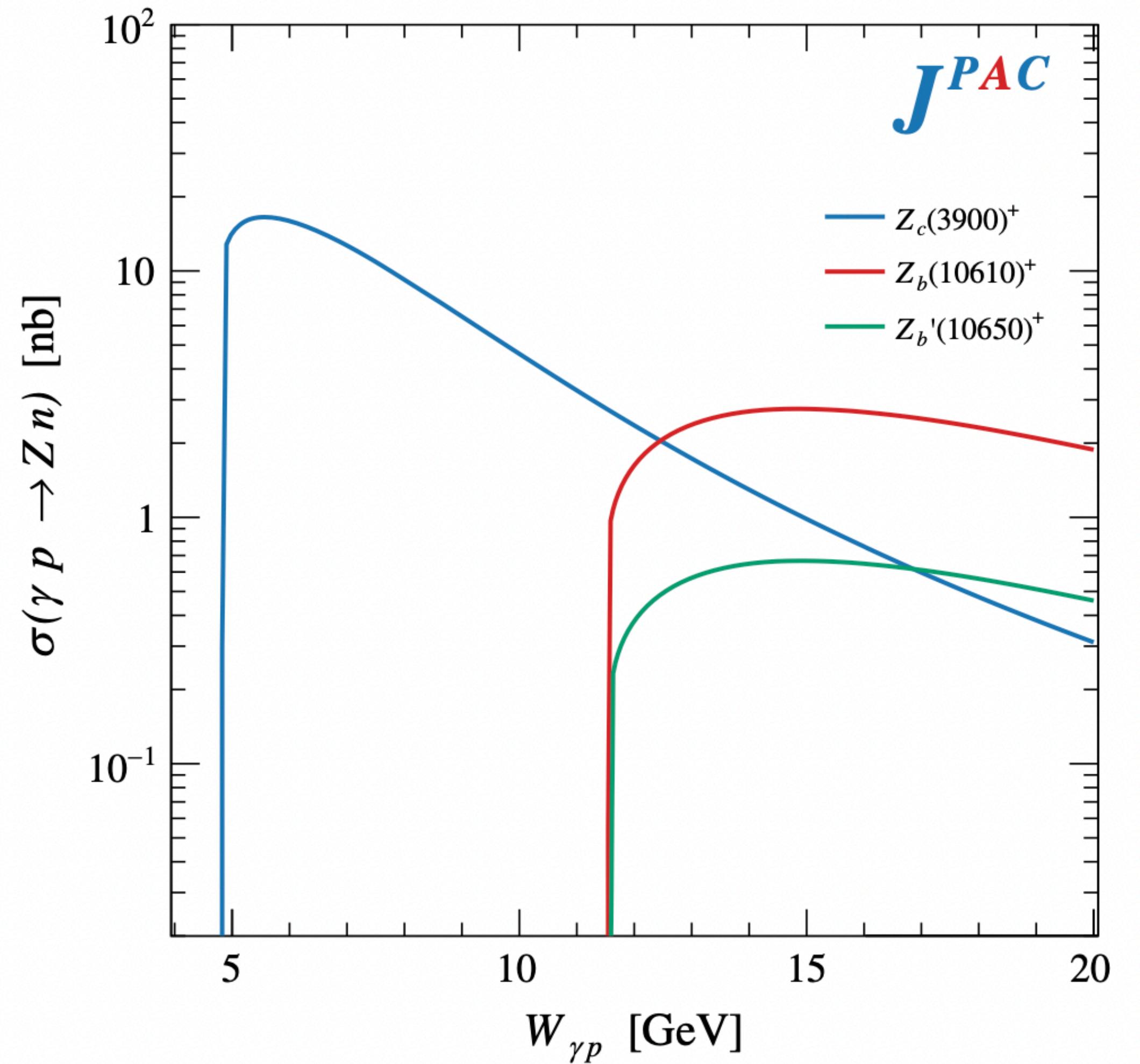
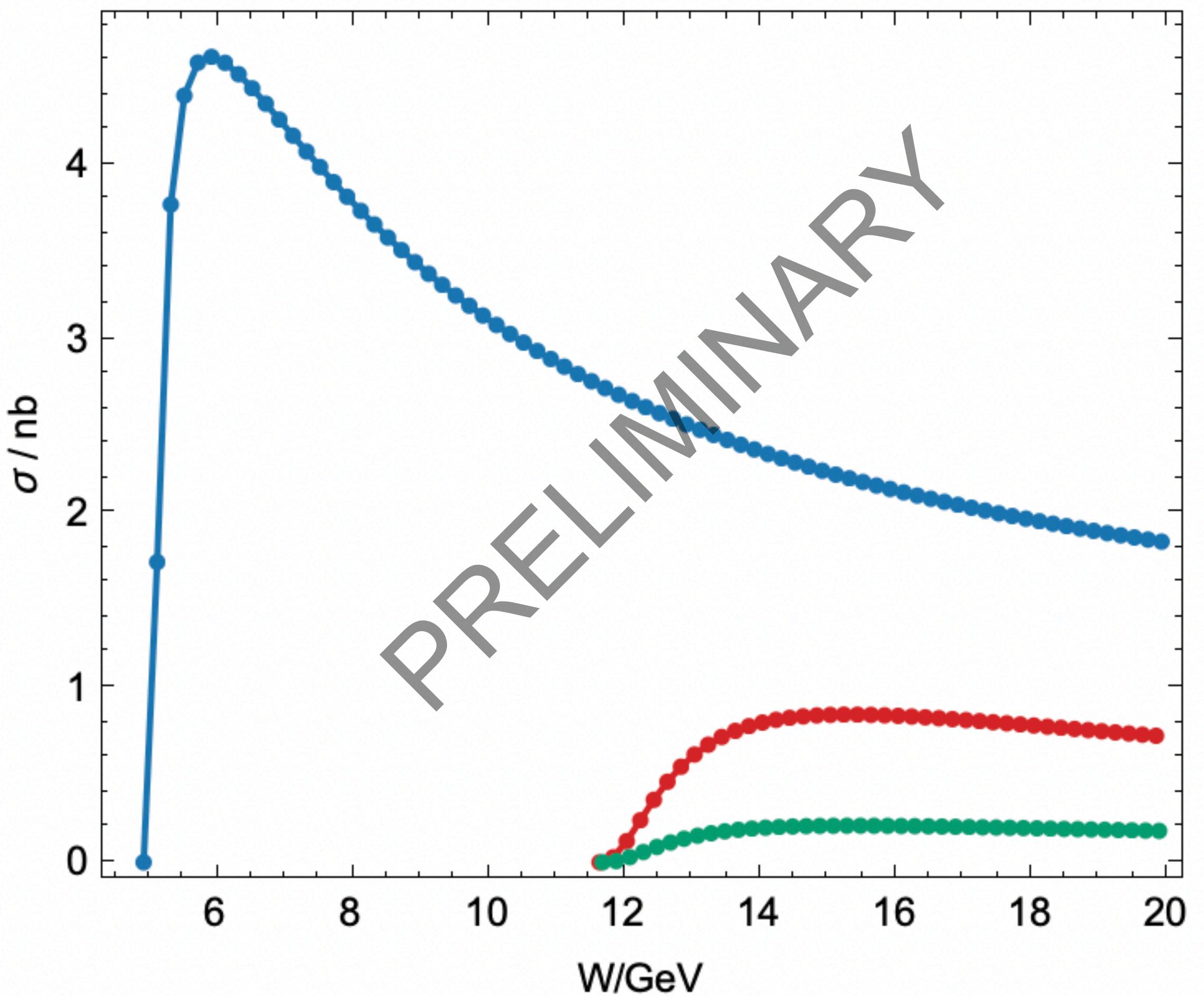
GlueX, PRL23 (2019) 072001

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

Data

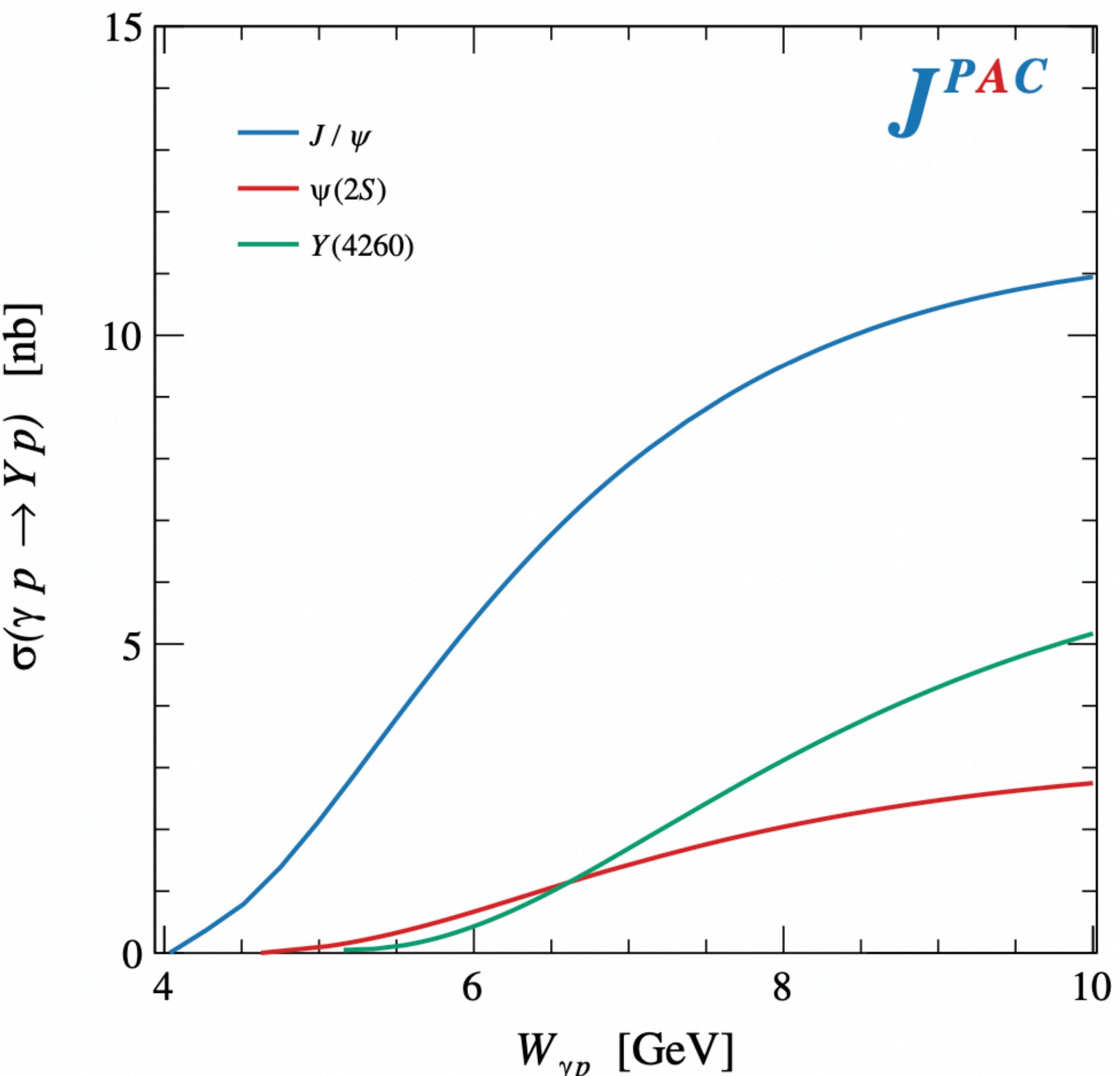
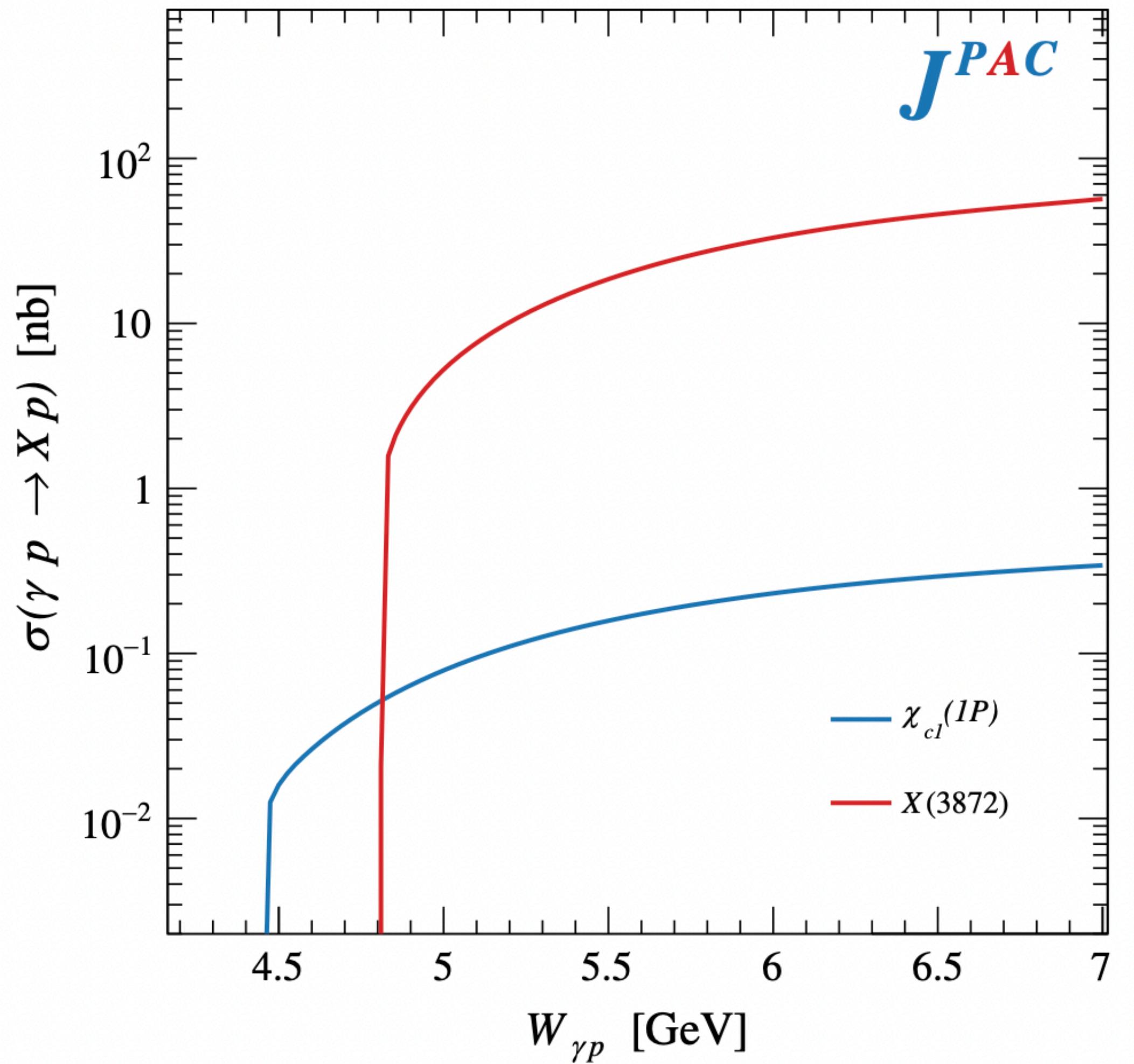
Model



$\gamma p \rightarrow Z^+ n$

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


Exclusive XYZ Production @EIC

JPAC, PRD102 (2020) 114010



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