Hadron Spectroscopy

Vincent MATHIEU

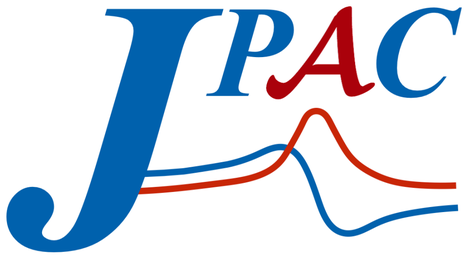
U. Barcelona

Joint Physics Analysis Center

J-Future Meeting

Messina February 2022

UNIVERSITAT DE BARCELONA



Joint Physics Analysis Center

Joint Physics Analysis Center

Miguel Albaladejo
CSIC-Valencia

Lukasz Bibrzycki
Pedagogical University of Kracow

Cesar Fernández Ramírez
National Autonomous University of Mexico

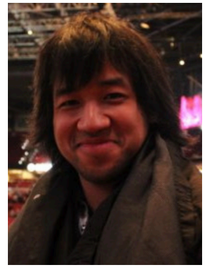
Astrid Hiller Blin
Jefferson Lab

Mikhail Mikasenko
TU Munich

Alessandro Pilloni
U. Messina

Adam Szczepaniak
Indiana University

Daniel Winney
Indiana University



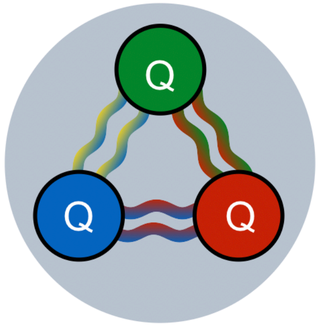
Lawrence Ng
Florida State University

Arkaitz Rodas
College of William and Mary

Robert Perry
National Chiao-Tung University

Ordinary and Exotic Hadrons

Ordinary baryons:

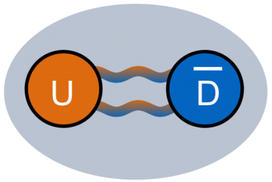


proton stable

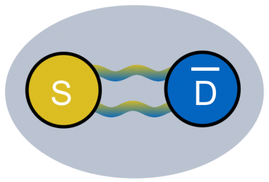
neutron $\tau \sim 10^{3} s$

baryon Λ $\tau \sim 10^{-10} s$

Ordinary mesons



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



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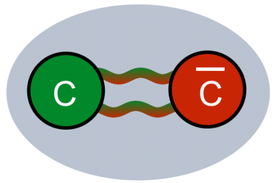

J/ψ $\tau \sim 10^{-20} s$

Ordinary and Exotic Hadrons

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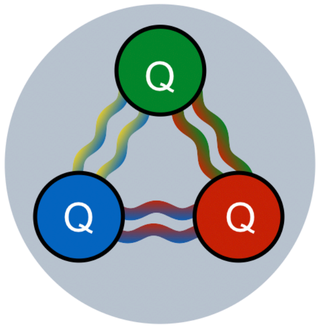

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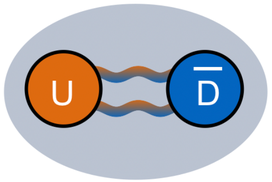

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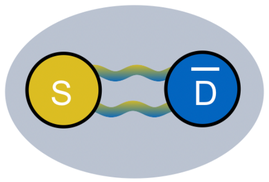

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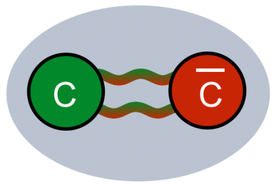

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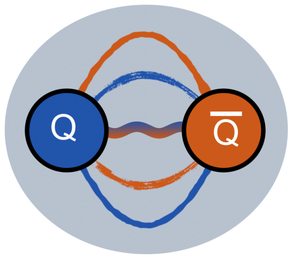
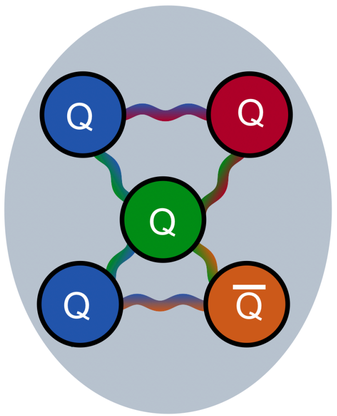
Exotic matter

hybrid mesons

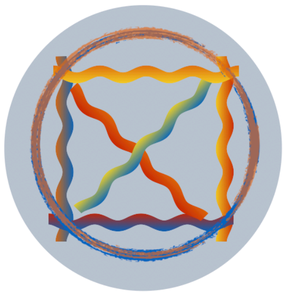


tetraquarks

pentaquarks

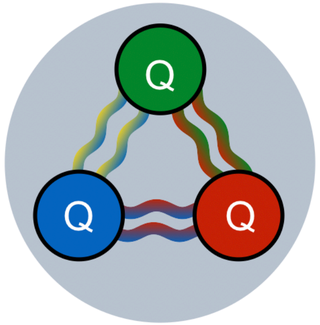


glueballs



Baryons and Mesons

Ordinary baryons:



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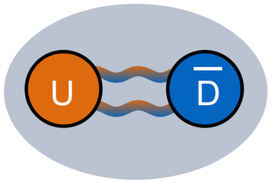
uuu baryon Δ $\tau \sim 10^{-24}\ s$

Ordinary mesons



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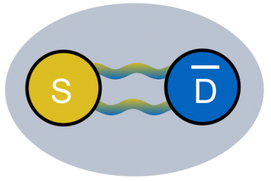

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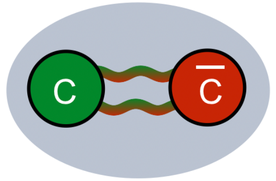
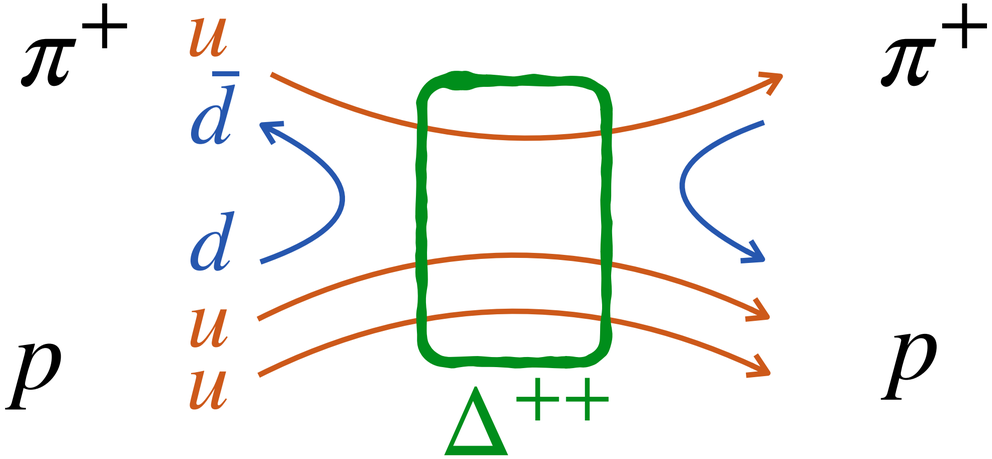
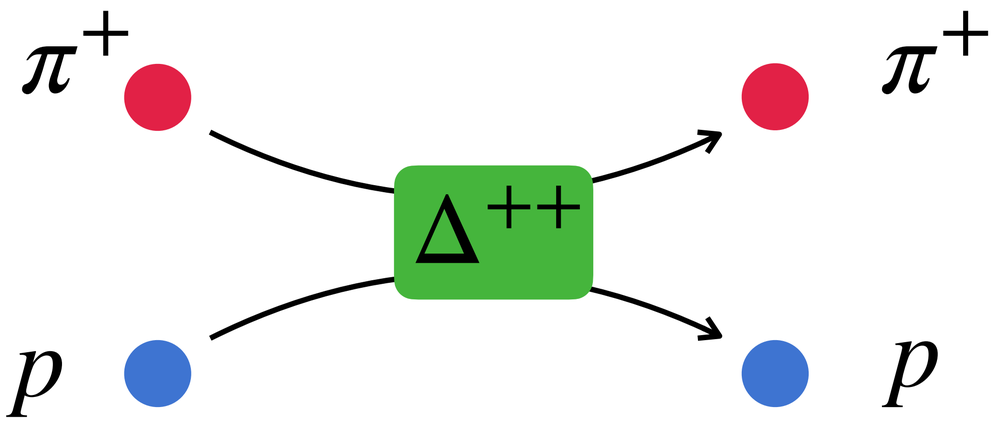


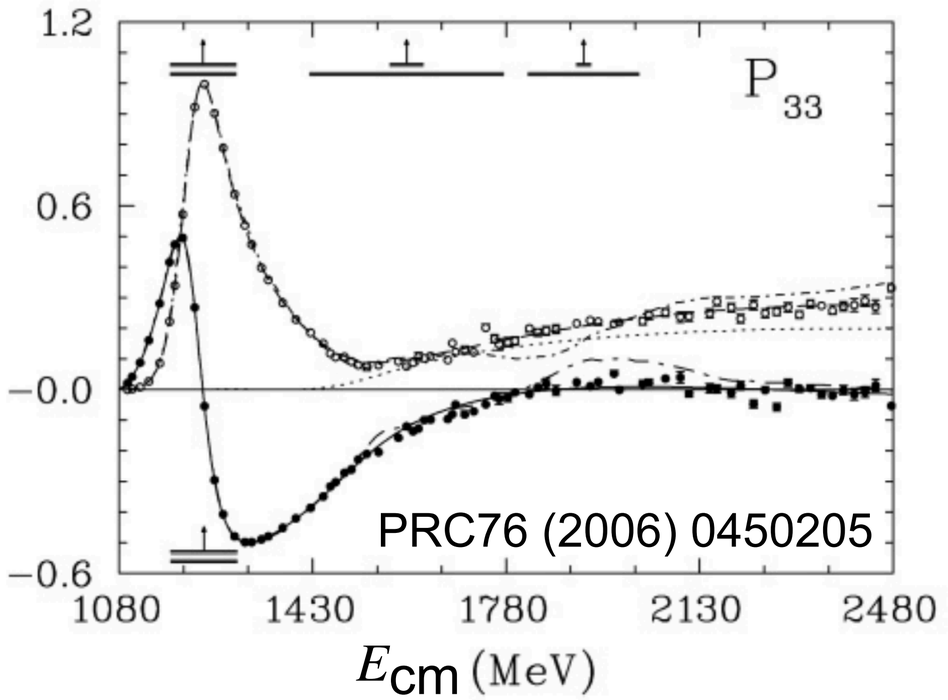
J/ψ $\tau \sim 10^{-20} s$

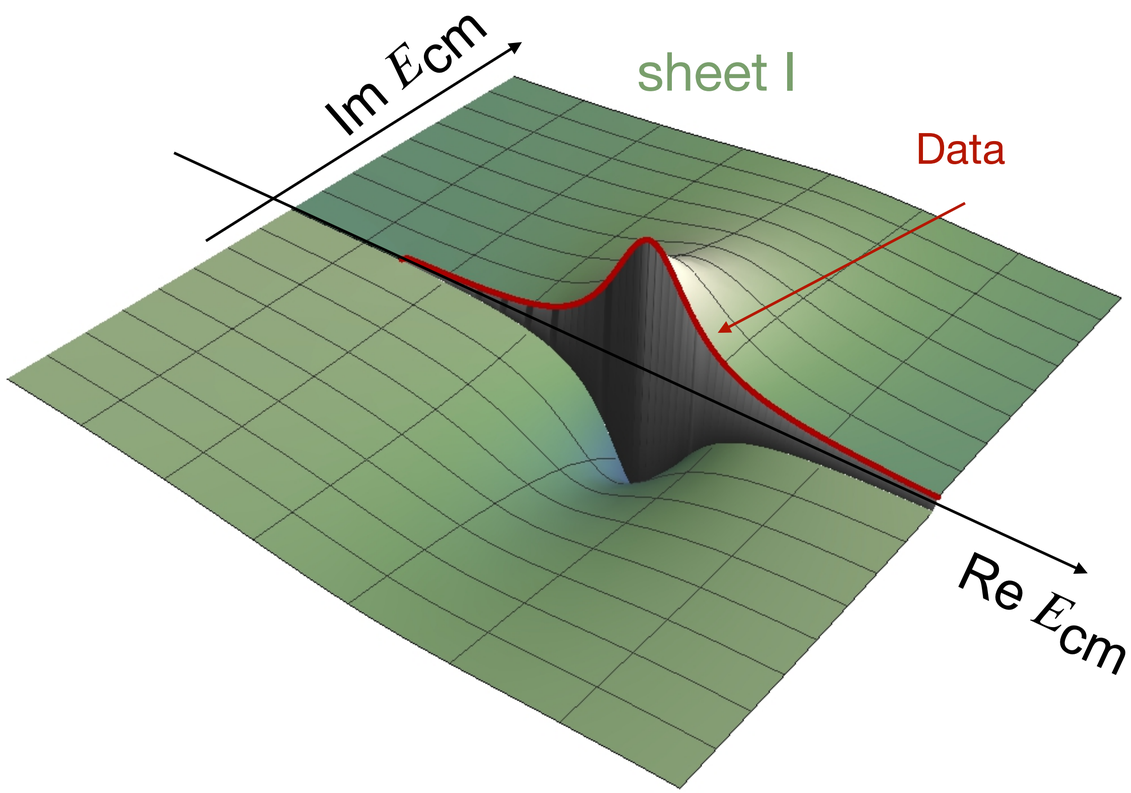
$$\pi^{+} p \to \Delta^{++} \to \pi^{+} p$$



What's a resonance?







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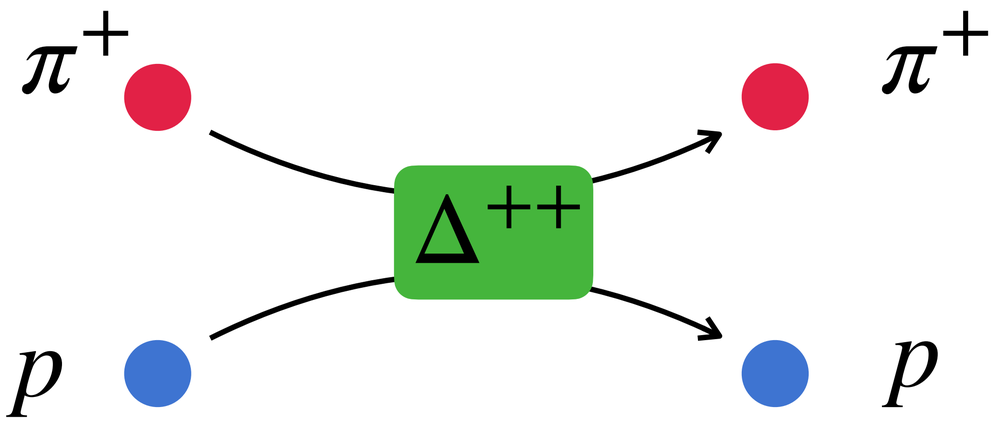
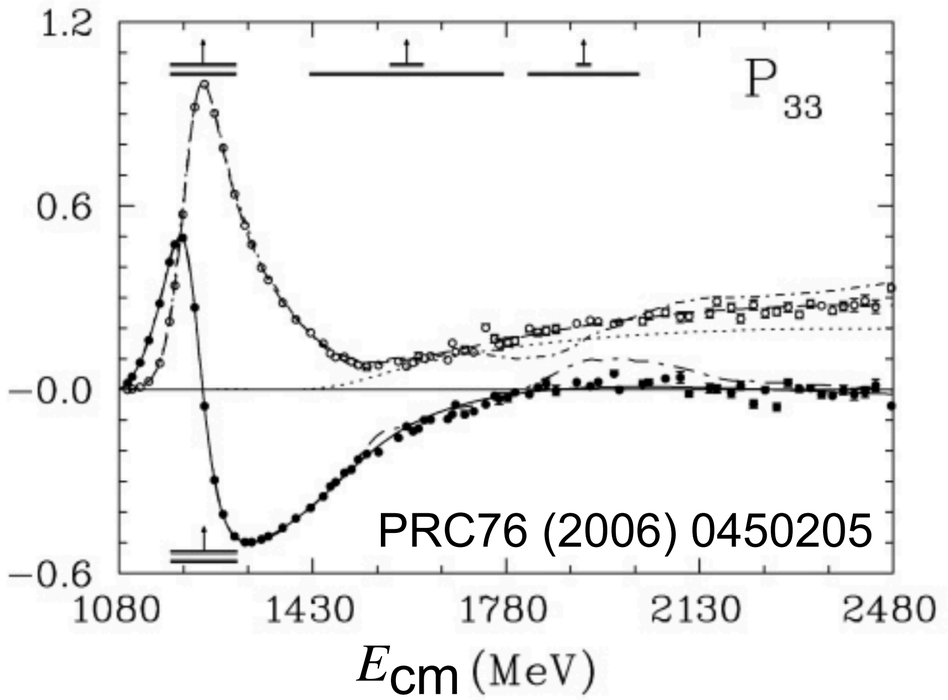
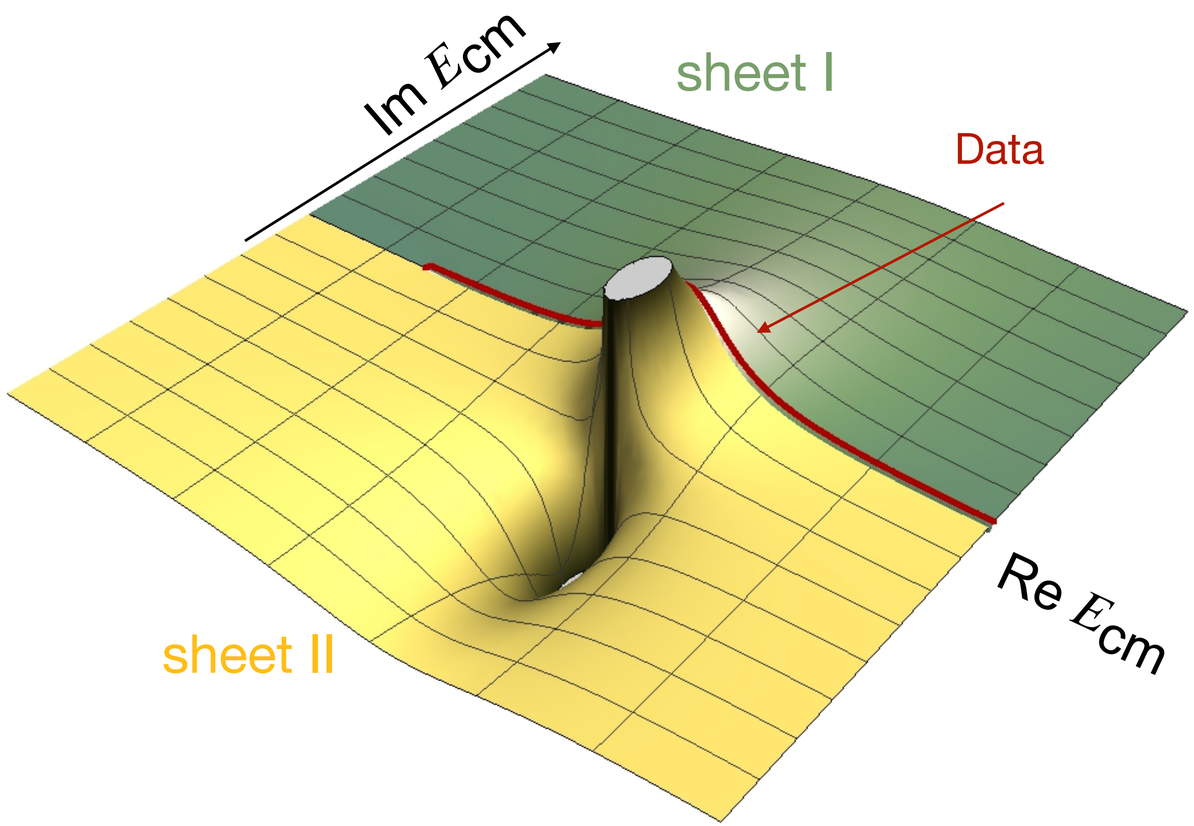
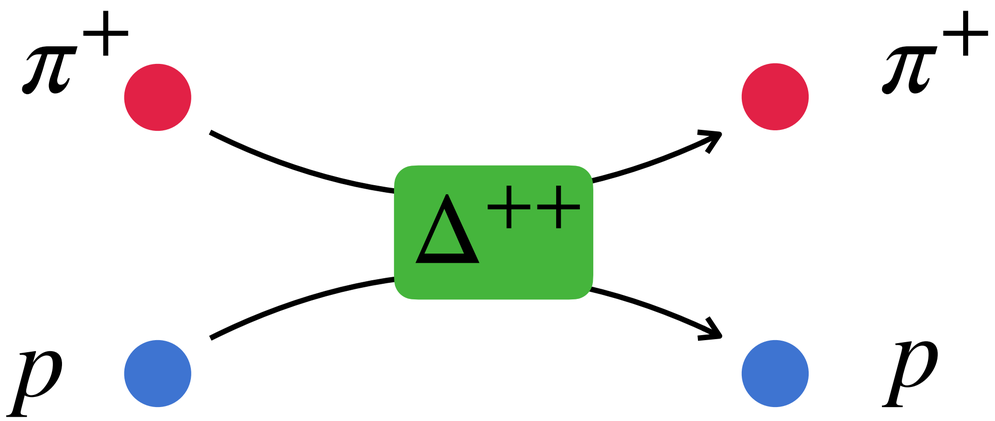


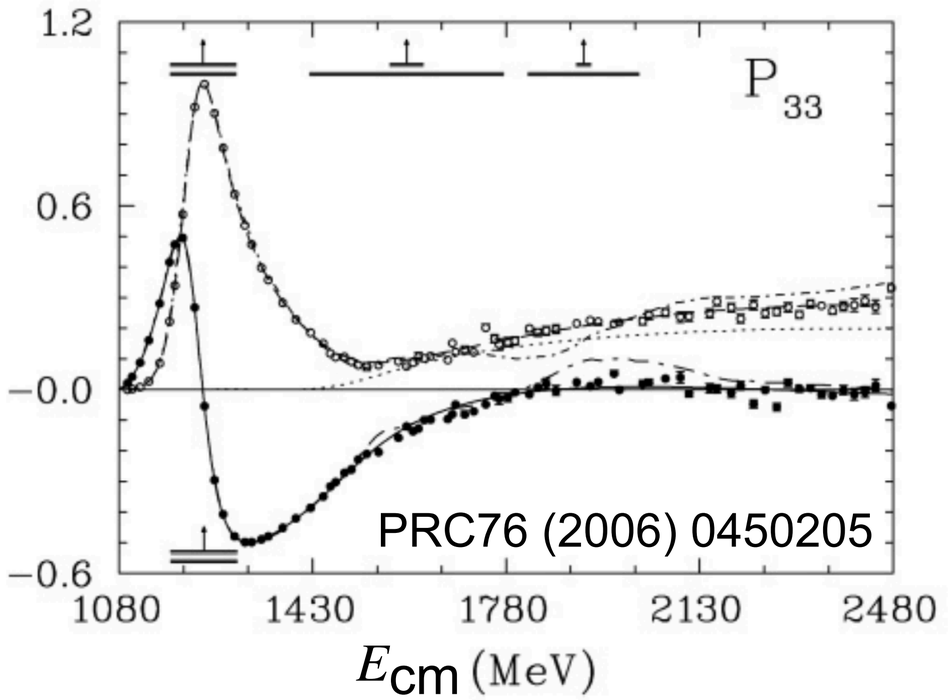


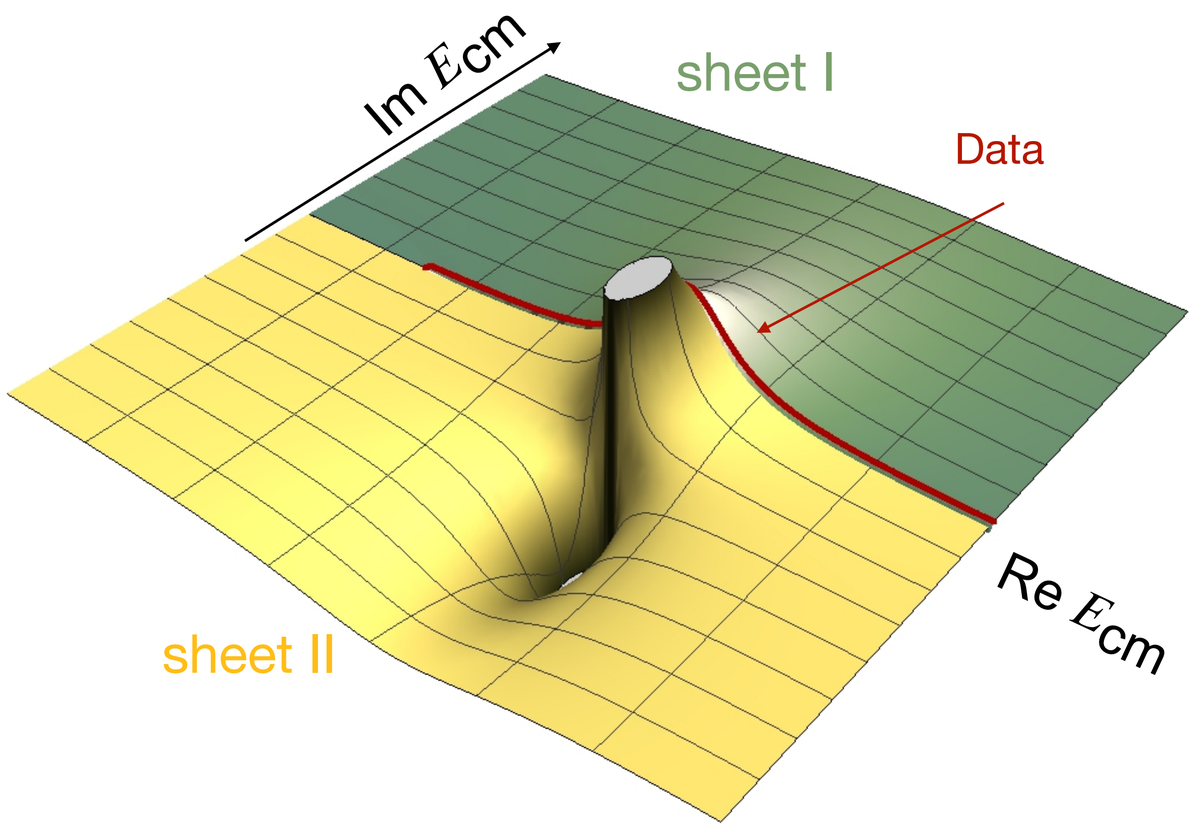


Resonances are poles of the scattering amplitude

What's a resonance?







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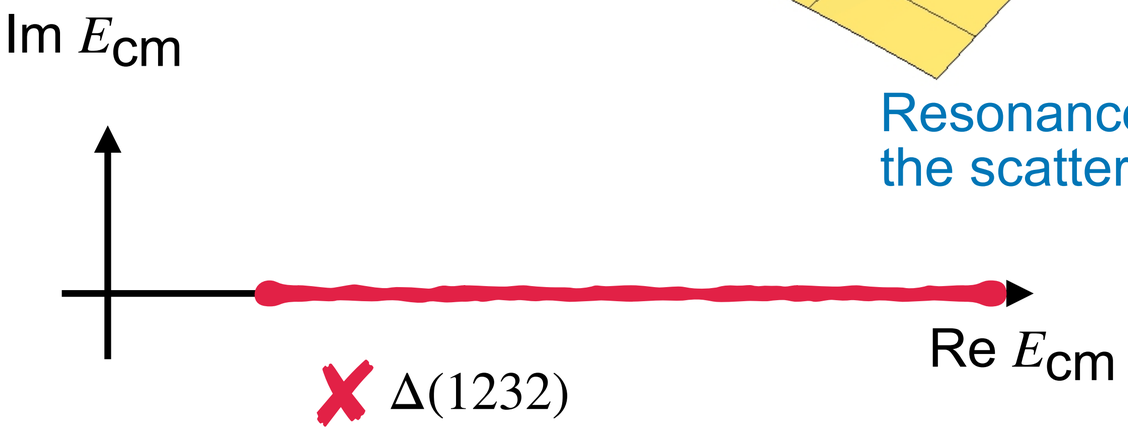

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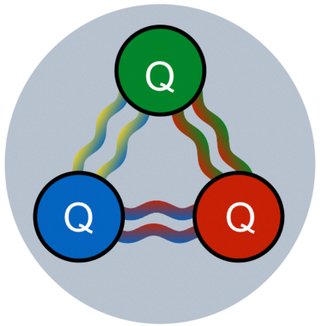

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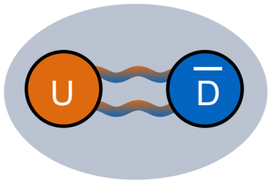

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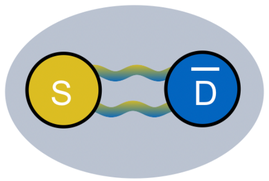

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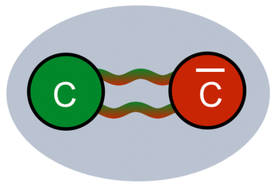

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Exotic matter

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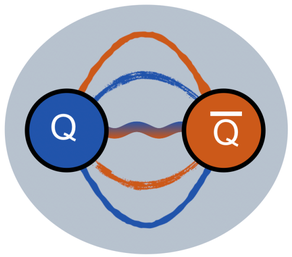
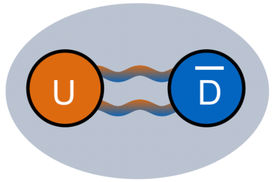


Meson with excited gluon field

Gluon field may carry quantum numbers

Quantum Numbers

Ordinary mesons



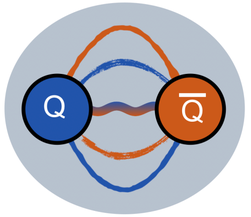
$$\vec{J} = \vec{L} \oplus \vec{S}$$

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

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

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

Exotic mesons



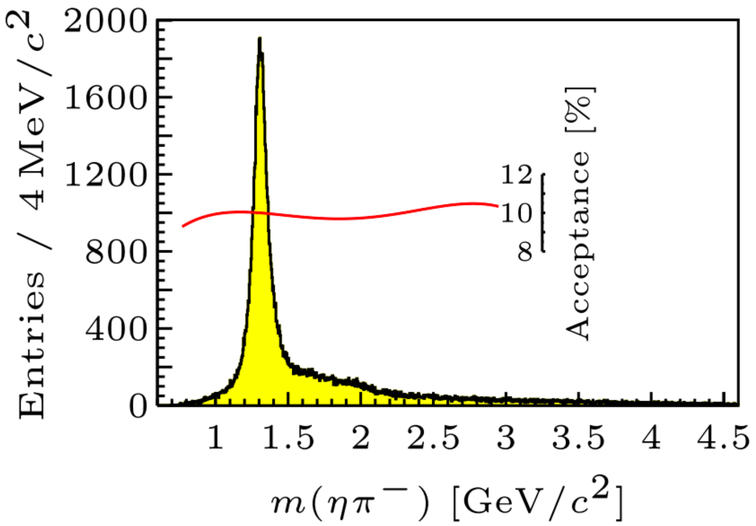
The lightest is π_1

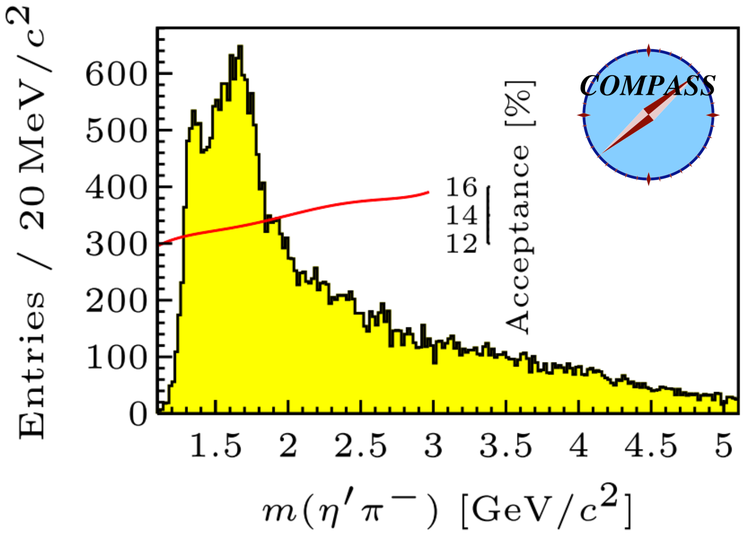
$$J^{PC} = 1^{-+}$$

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

Decay mode

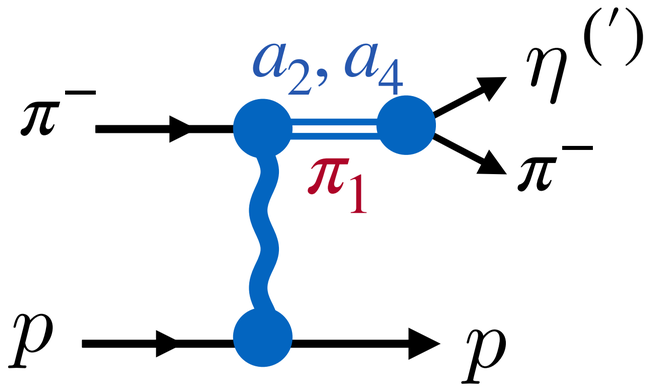
$$\pi_1 \to \eta\pi, \eta'\pi$$

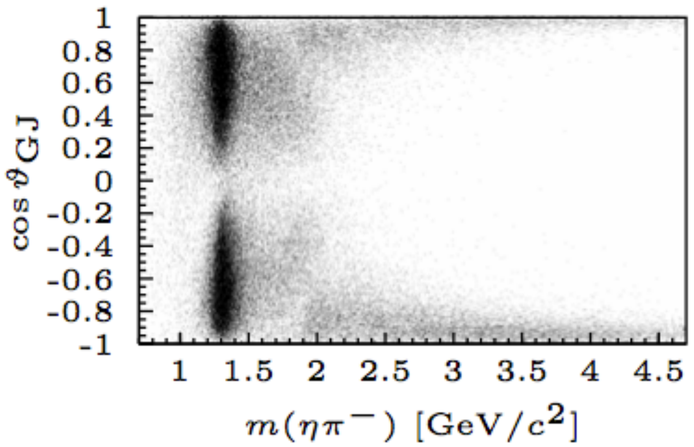


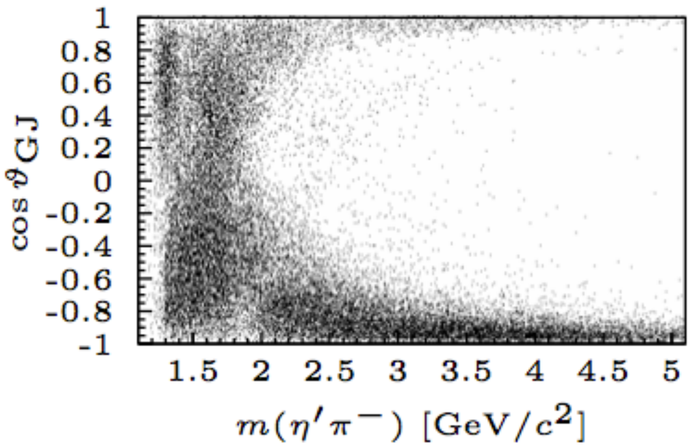


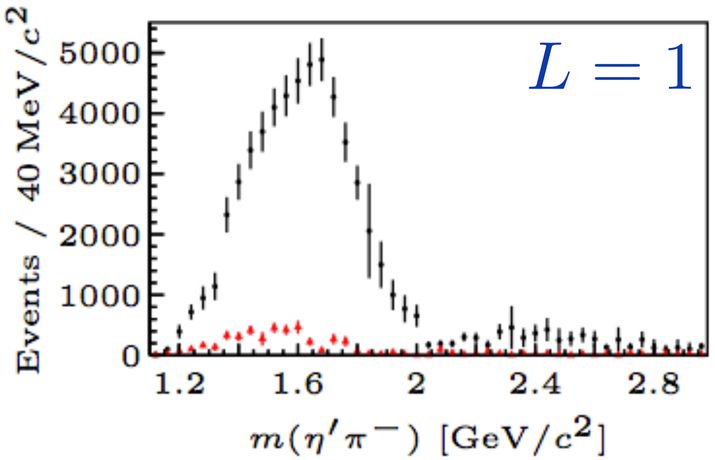
Partial Waves Expansion

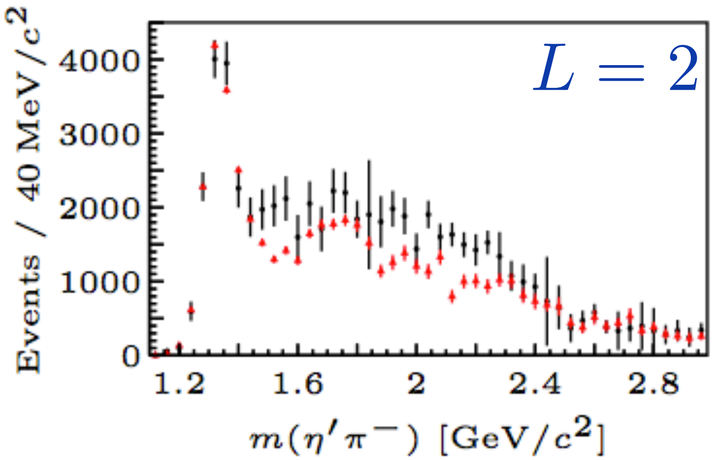
COMPASS PLB740 (2015)

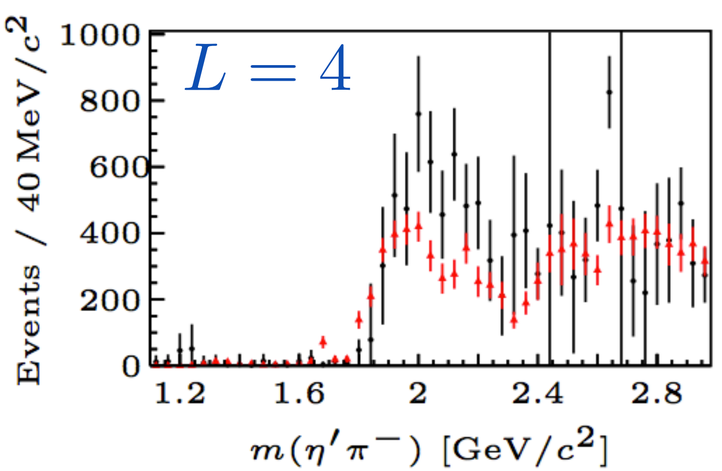












Resonance in angular mom. L = 1 ?

black: $\pi\eta'$

red: $\pi\eta$ (scaled)

Partial Waves Expansion

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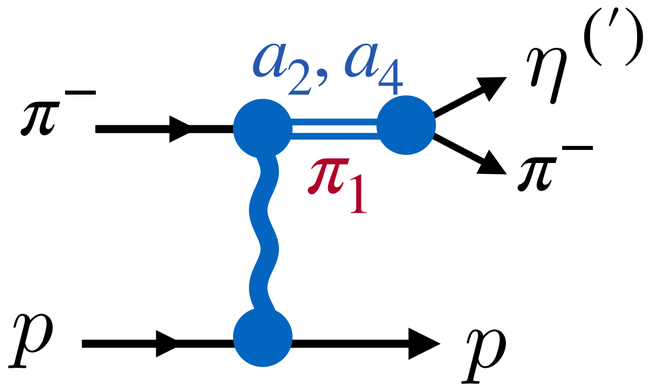
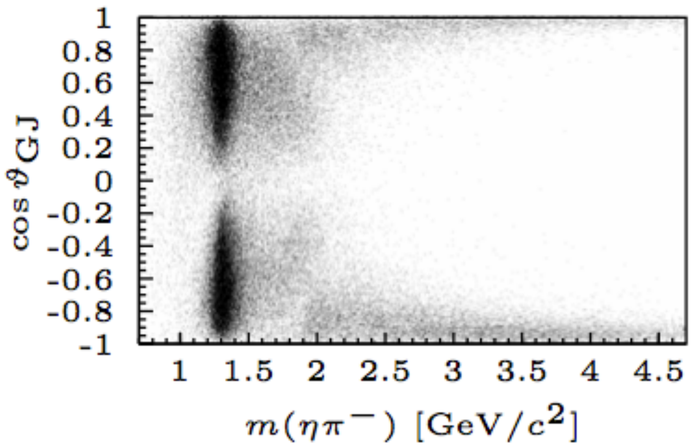
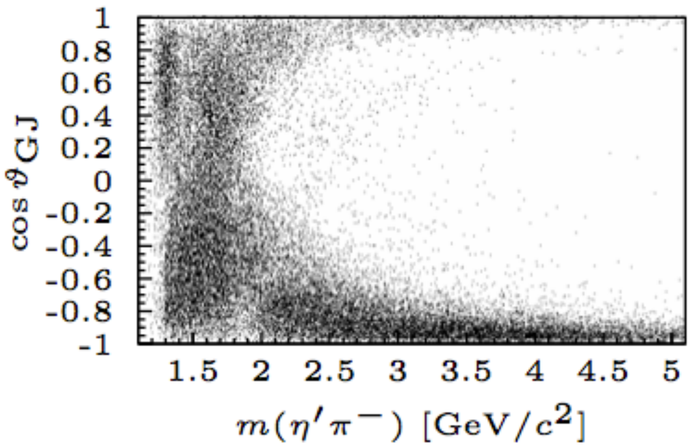
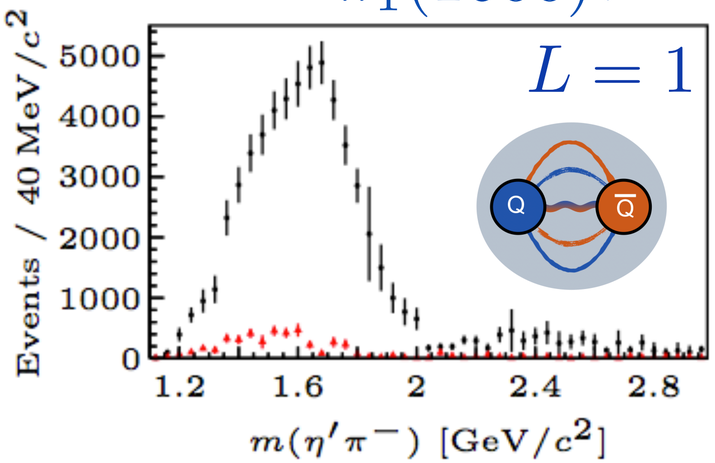


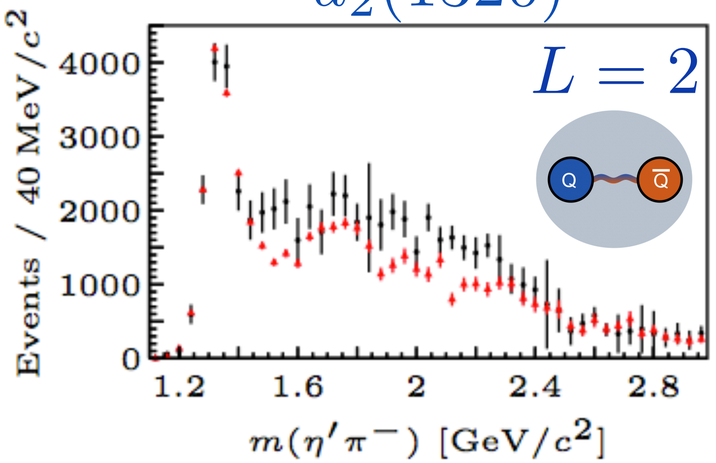




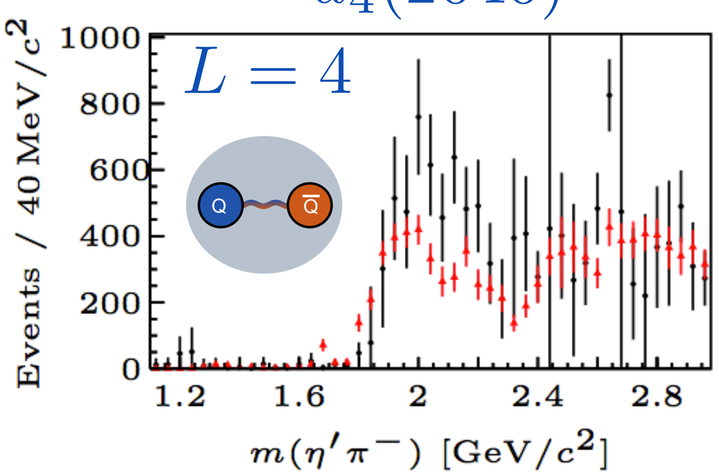
$\pi_1(1600)$?



$a_2(1320)$



$a_4(2040)$



Resonance in angular mom. L = 1 ?

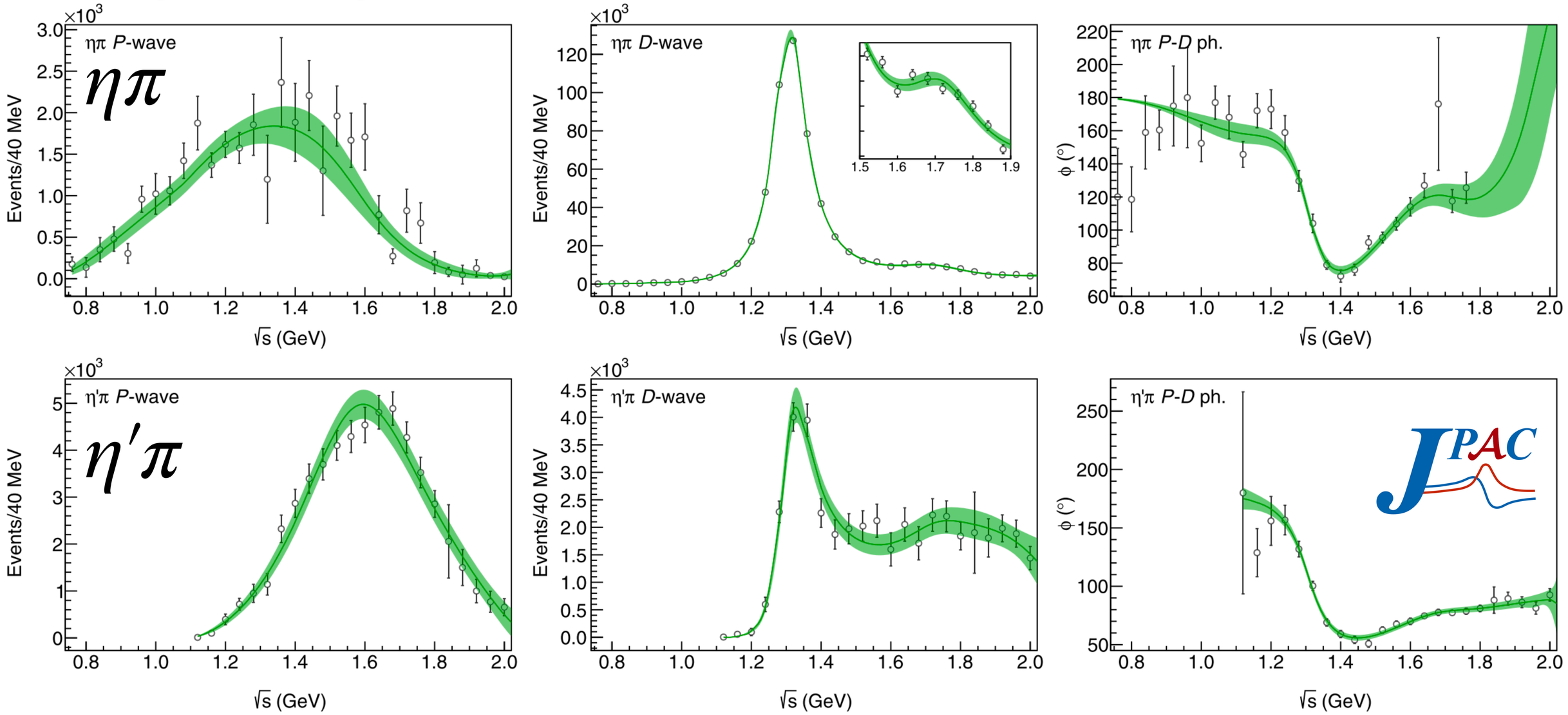
black: $\pi\eta'$

red: $\pi\eta$ (scaled)

Low Energy Fit of $L = 1,2$

Rodas et al (JPAC) PRL122 (2019) 042002

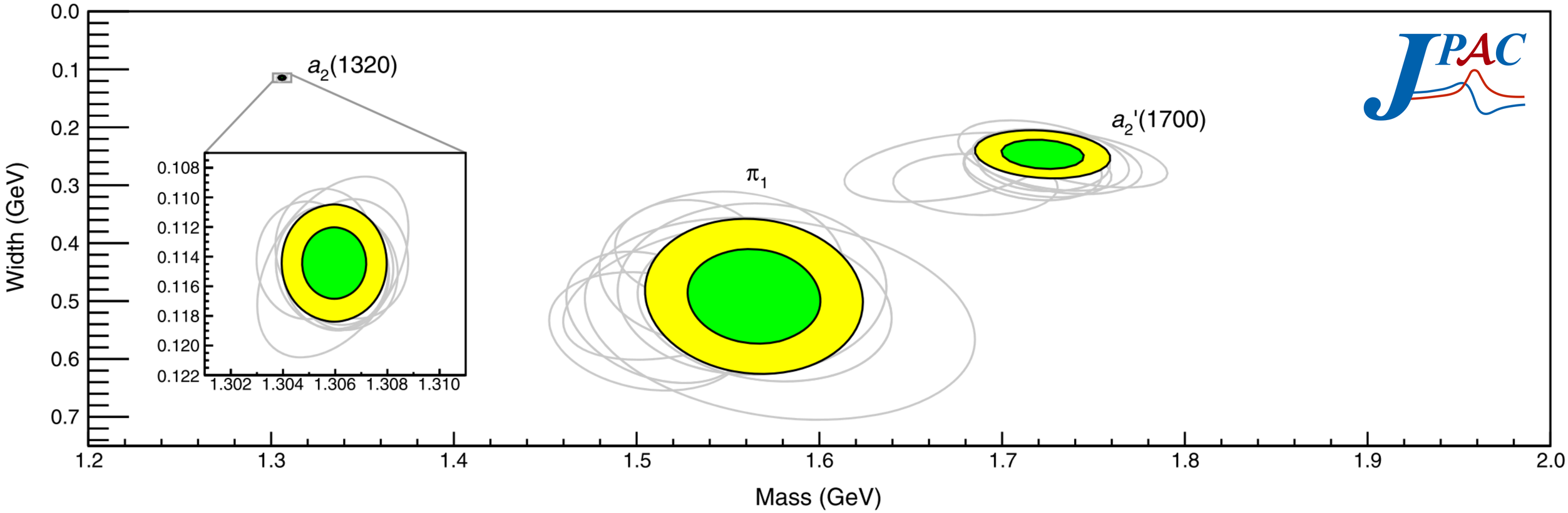
$\pi_1(1400)$ vs $\pi_1(1600)$



The exotic π_1 pole location

Rodas et al (JPAC) PRL122 (2019) 042002

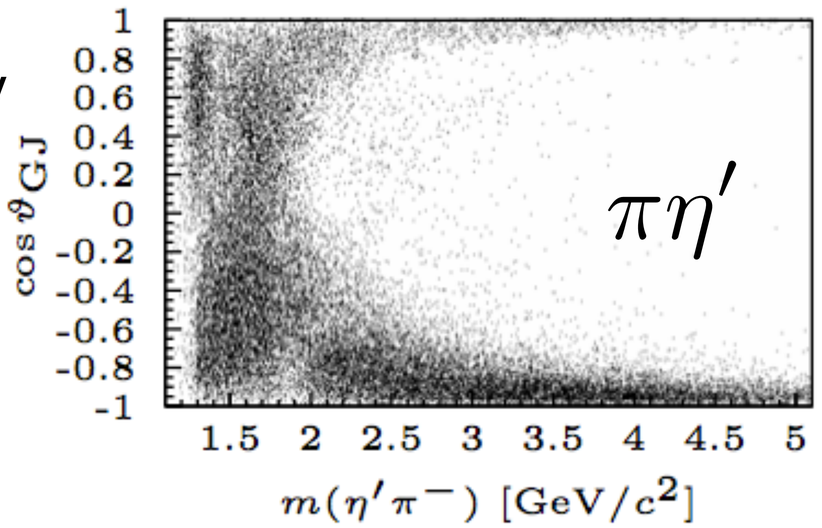
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

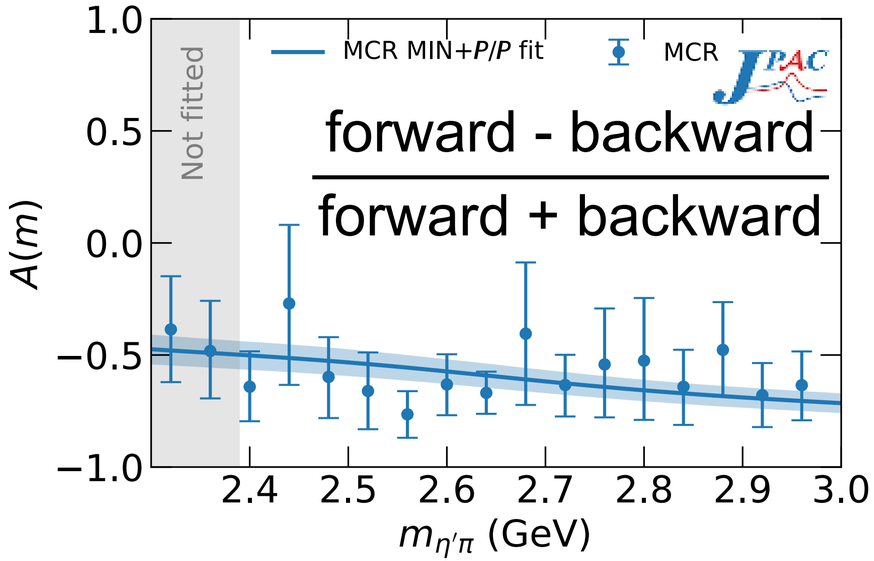


More on the exotic π_1

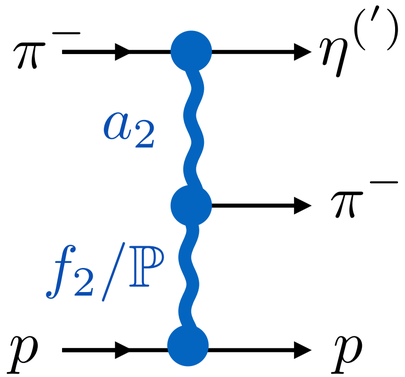
Bibrzycki et al (JPAC), EPJC81 (2021) 647

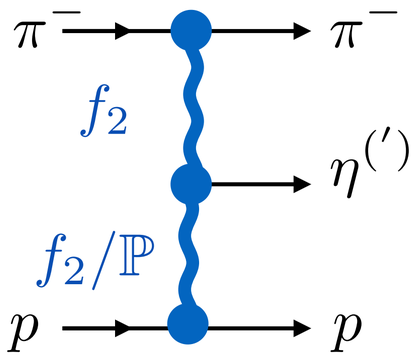
Forward-backward asymmetry related to the existence of (exotic) P-wave

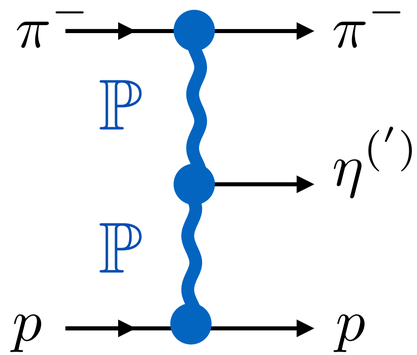




Asymmetry originating mainly from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from $(\mathbb{P}, \mathbb{P})$ in $\eta'\pi$

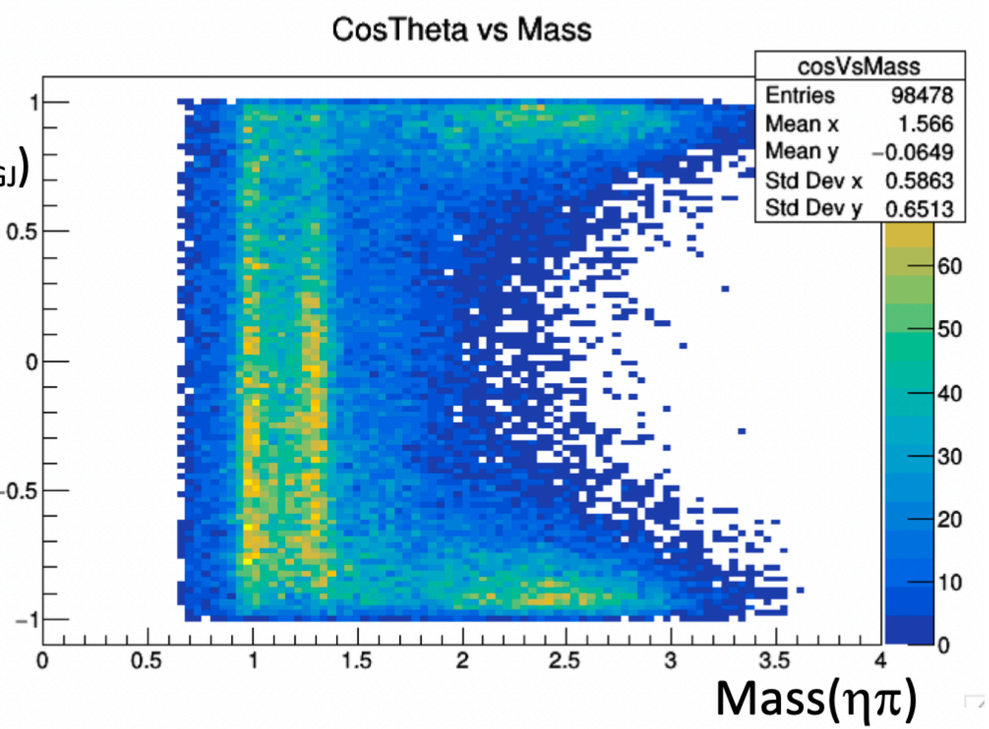






$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



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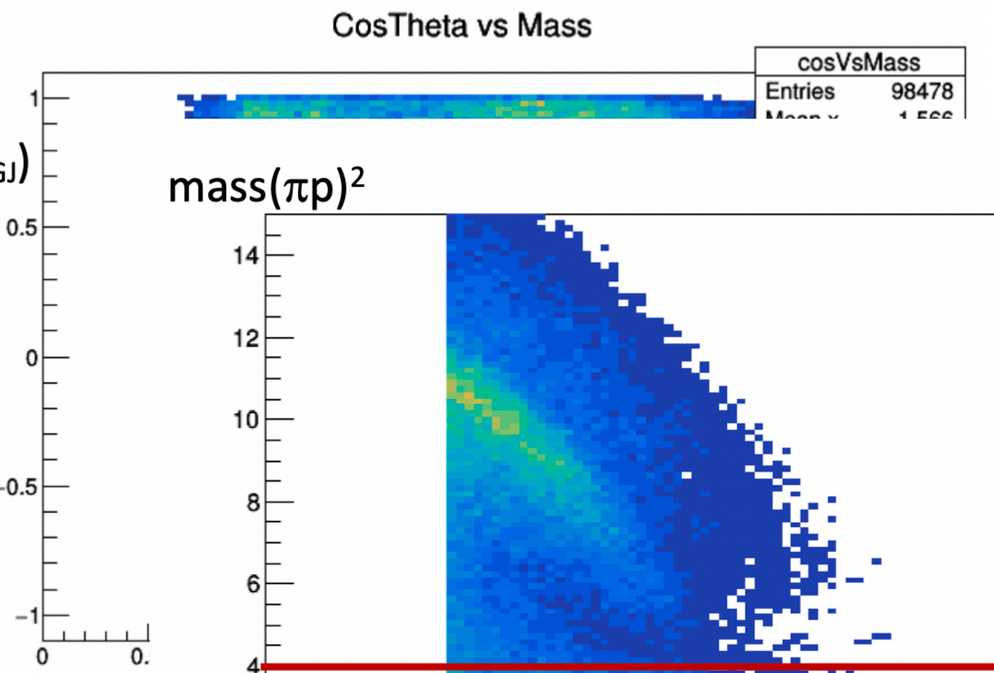

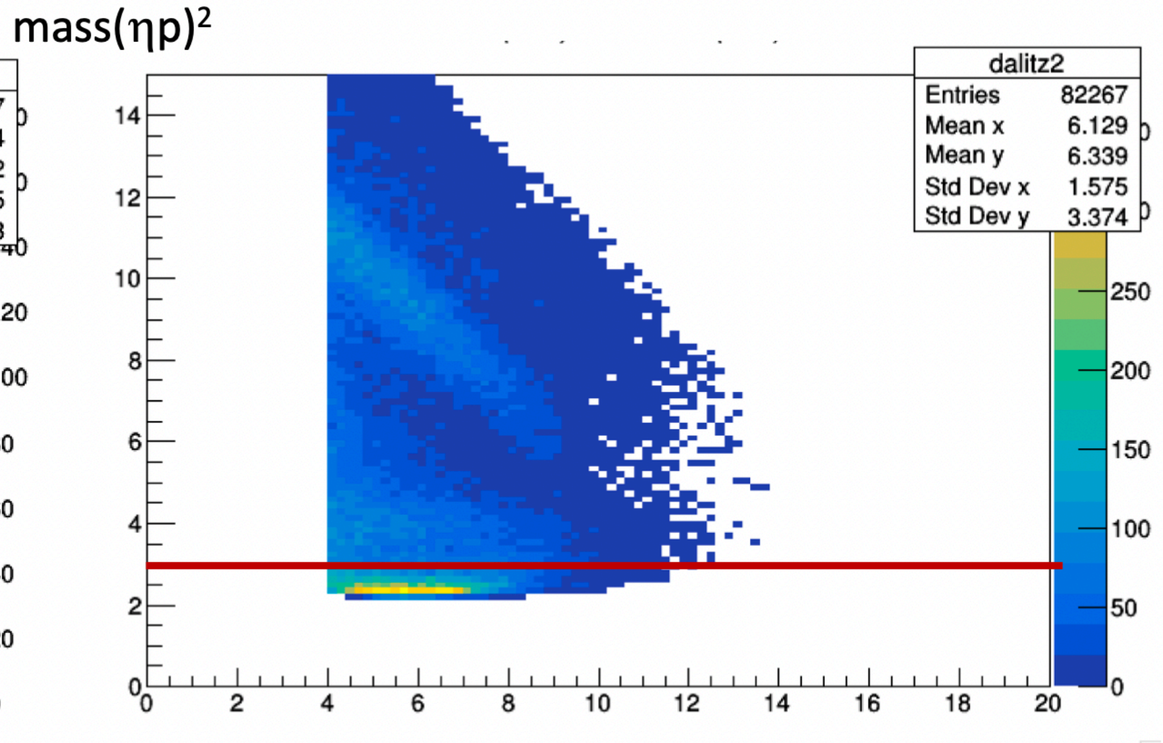

$\eta\pi^0$ Photoproduction@GlueX

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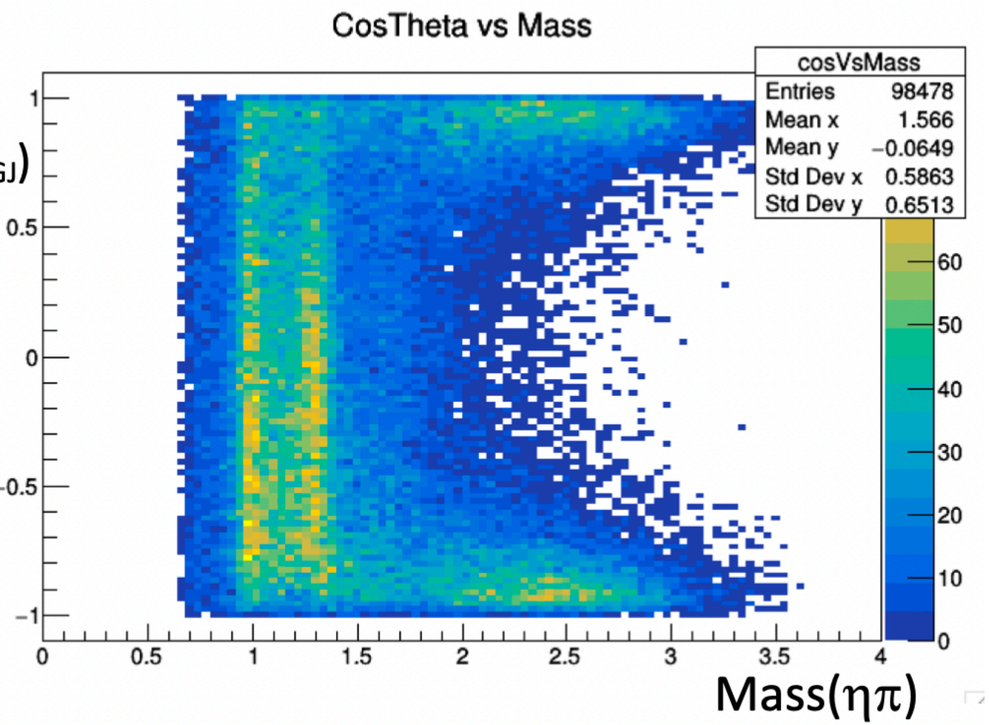
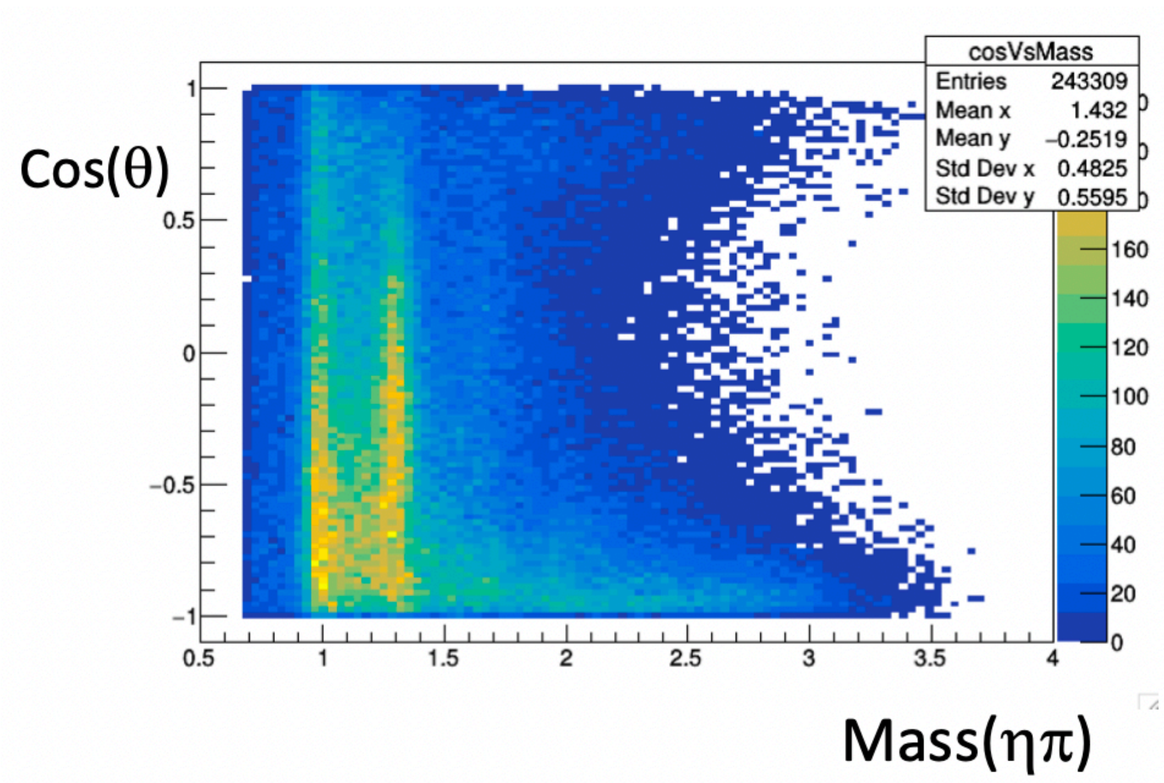


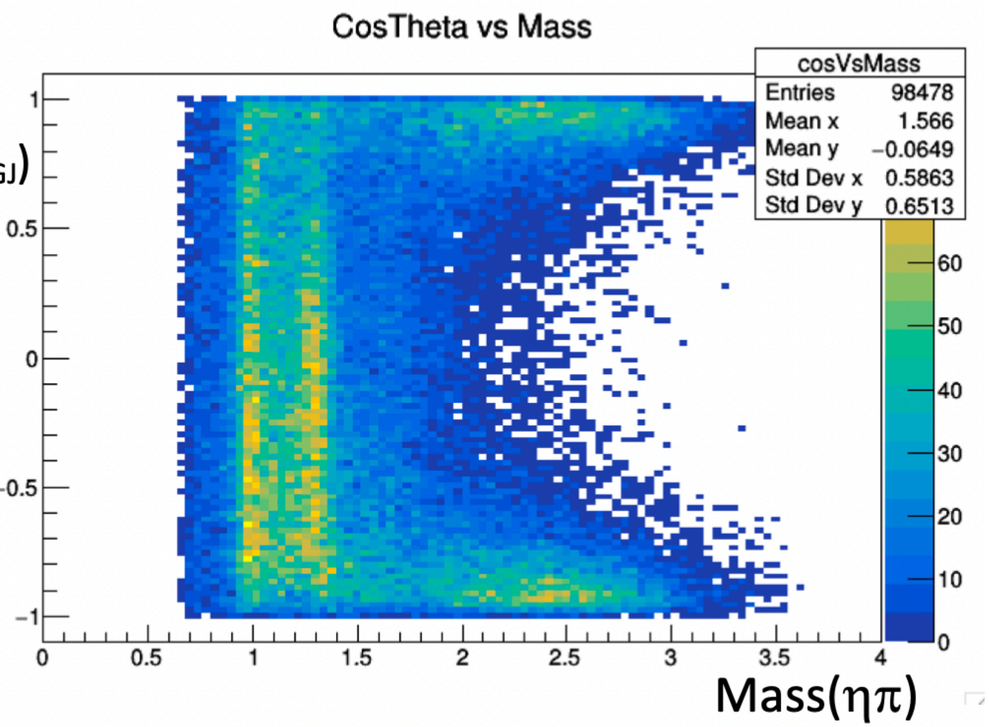


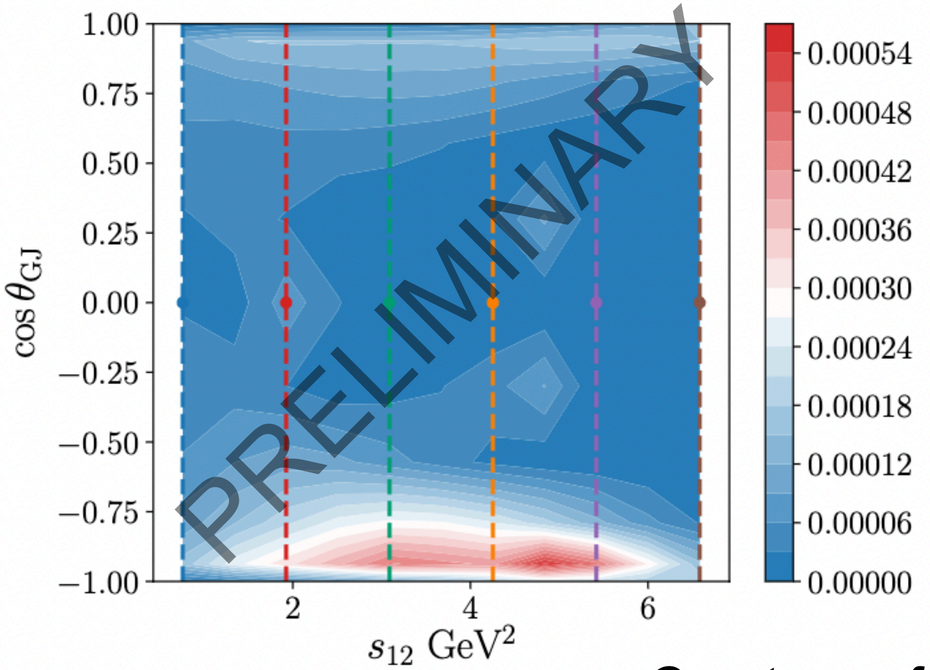
Baryon resonances contaminate the high mass $\eta\pi$

Less baryon contamination when the energy increases

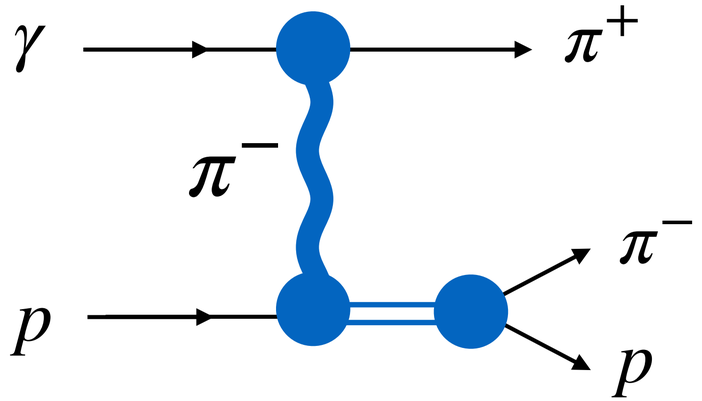
$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



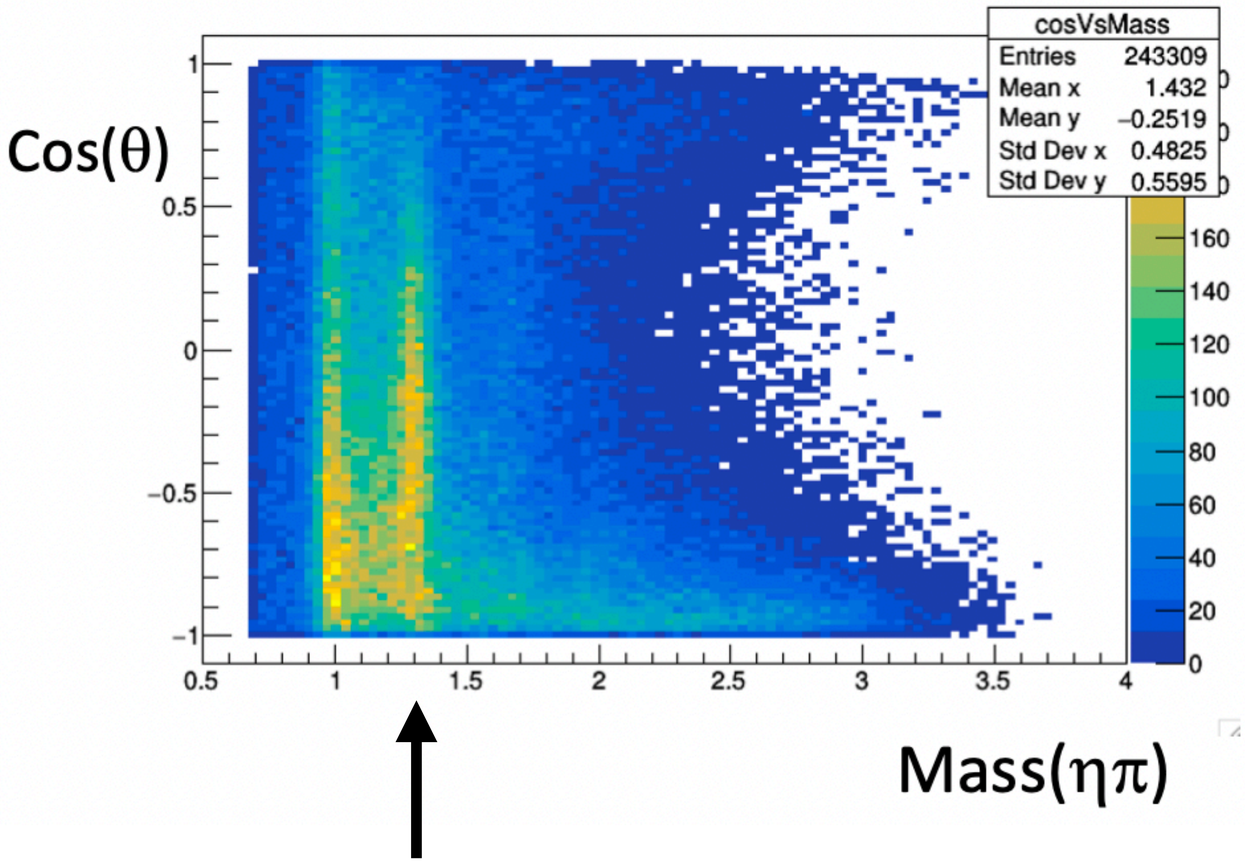


Courtesy of R. Perry

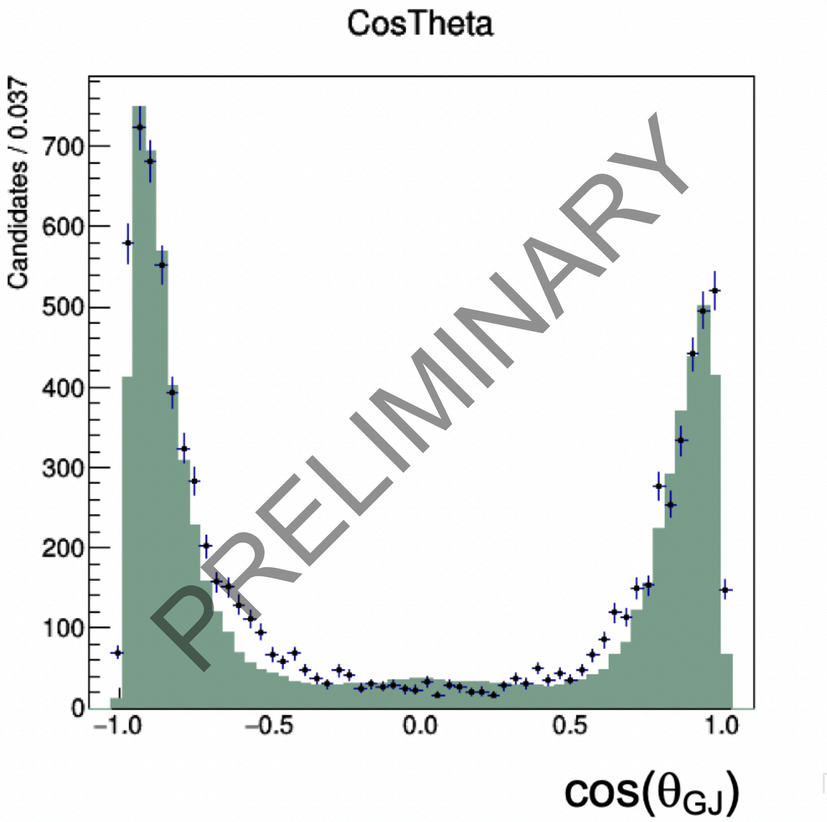


$\eta\pi^0$ Photoproduction@GlueX

In collaboration with R. Barsotti



$a_2(1320)$

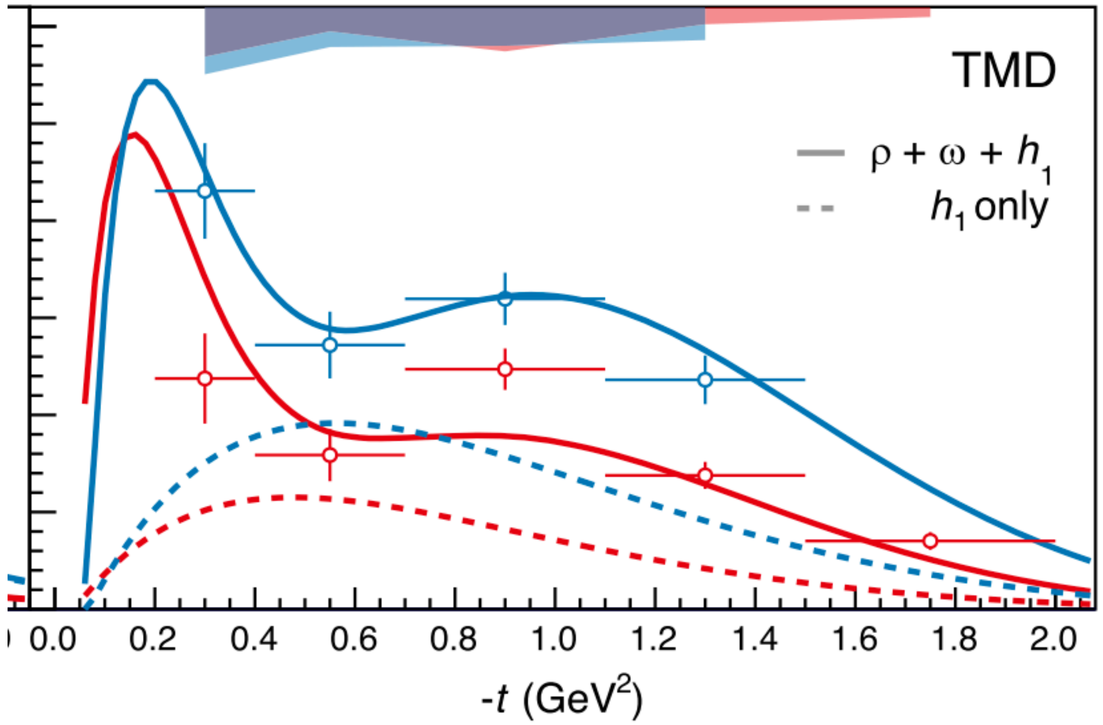


Double regge with Uniform background

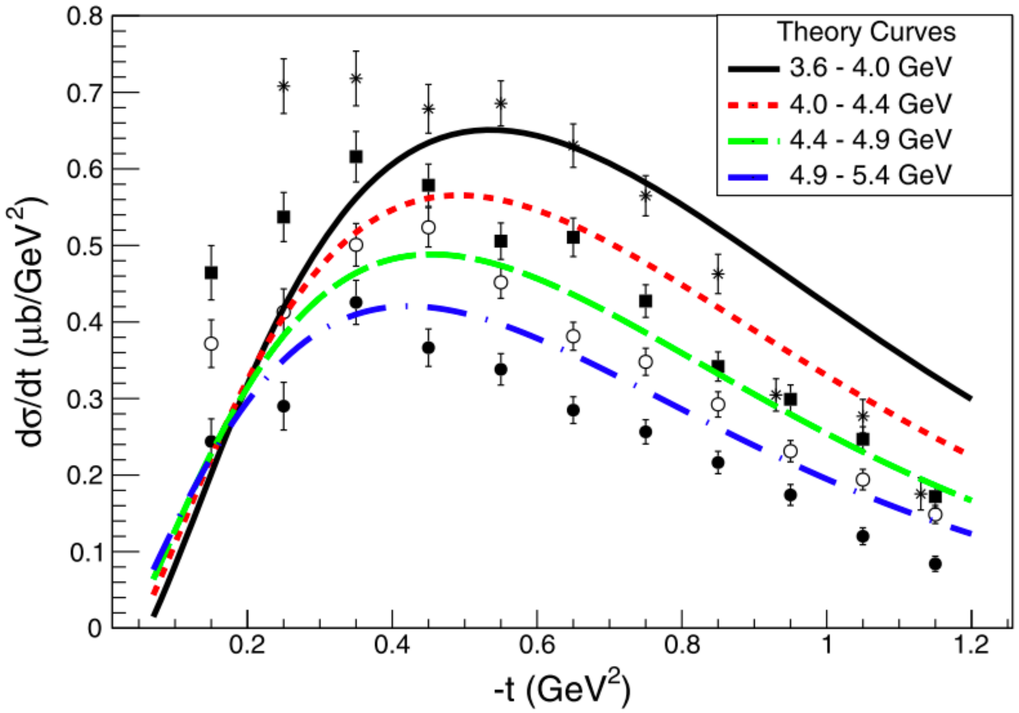
Tensor Meson Photoproduction @CLAS

Mathieu et al PRD102 (2020)

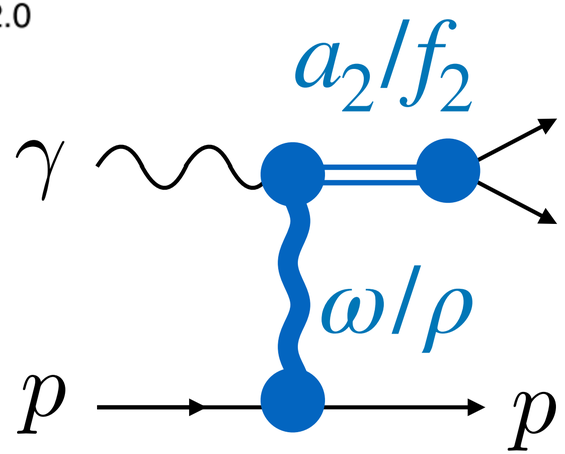
CLAS PRC 102 (2020)



CLAS PRL126 (2021)



$$\gamma p \to a_2(1320)p : \quad \omega + \frac{1}{3}\rho$$



$$\gamma p \to f_2(1270)p : \quad \rho + \frac{1}{3}\omega$$

$a_2(1320)$ Photoproduction @GlueX

In collaboration with L. Ng

PRELIMINARY

PRELIMINARY

PRELIMINARY

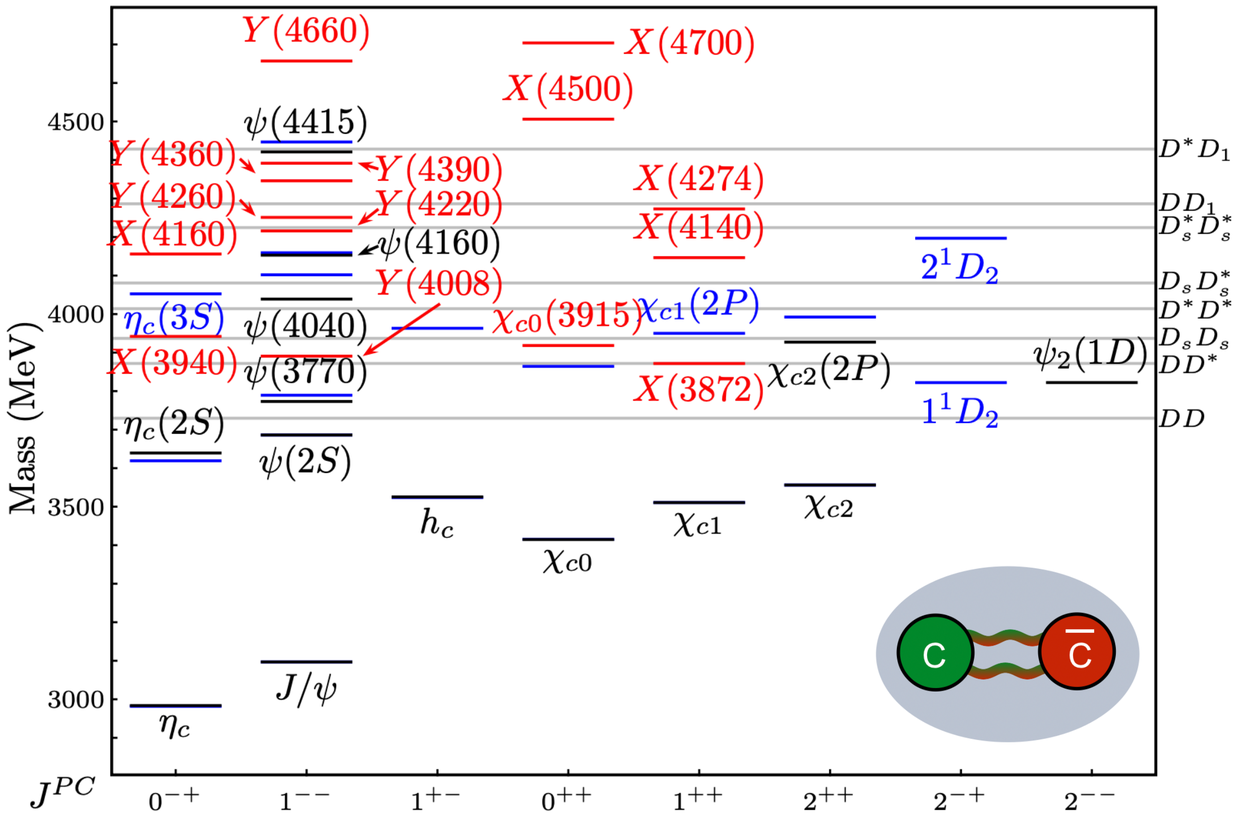
Exp. status of XYZ

Esposito, Pilloni, Polosa Phys Rep 668 (2017) 1

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

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

Red: exotic candidates



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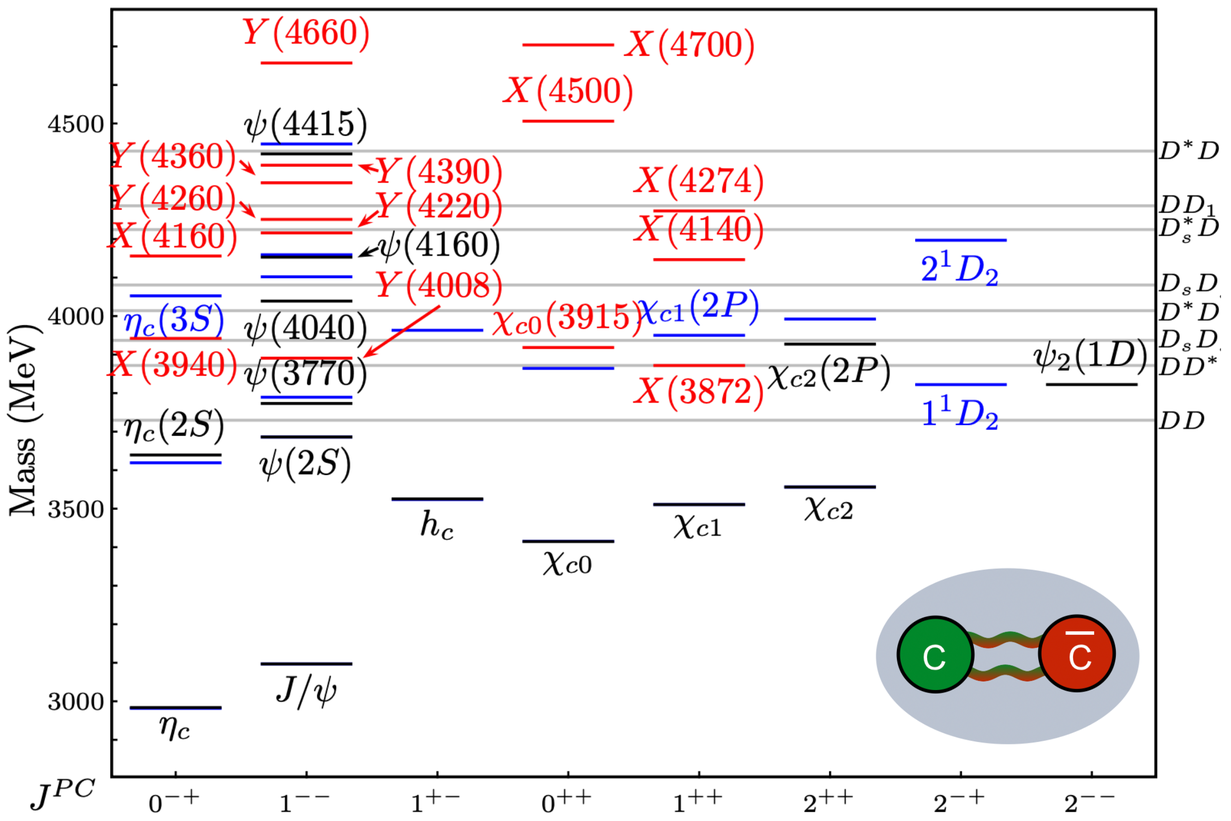
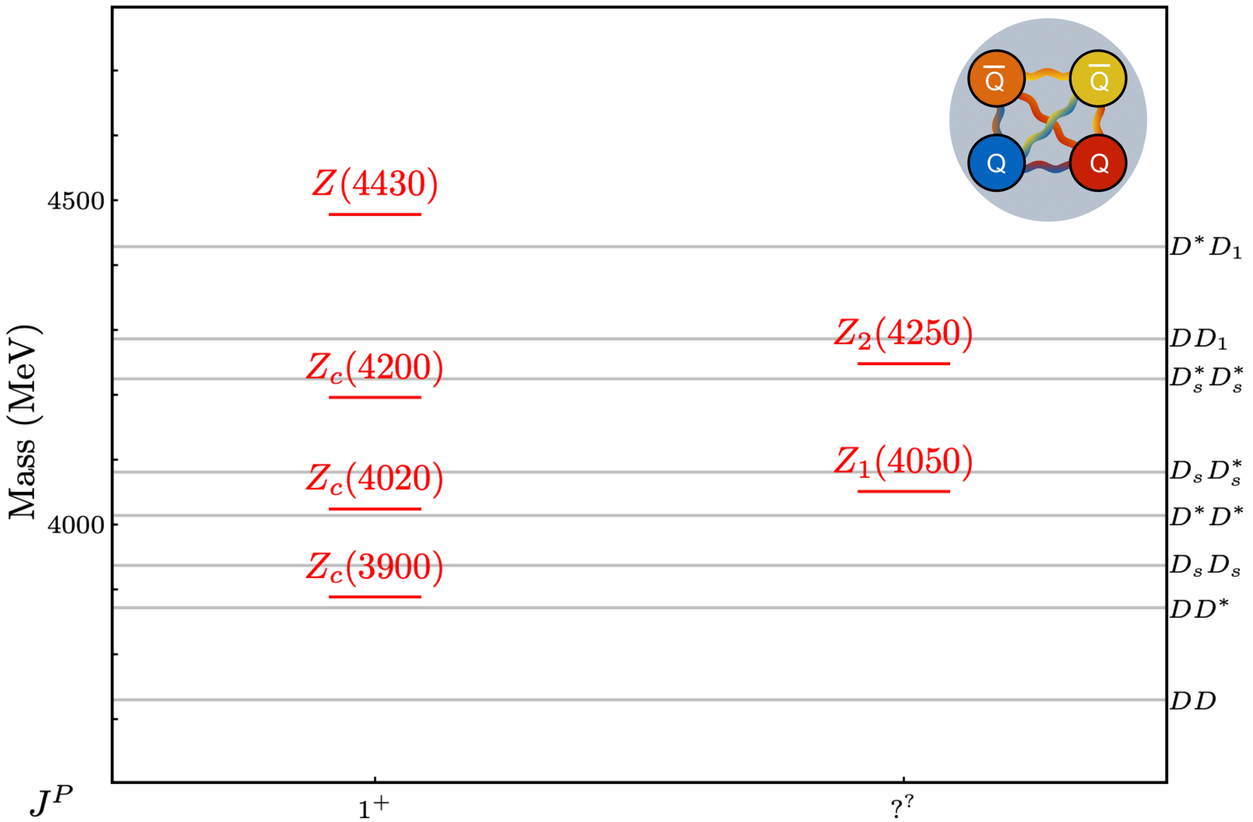
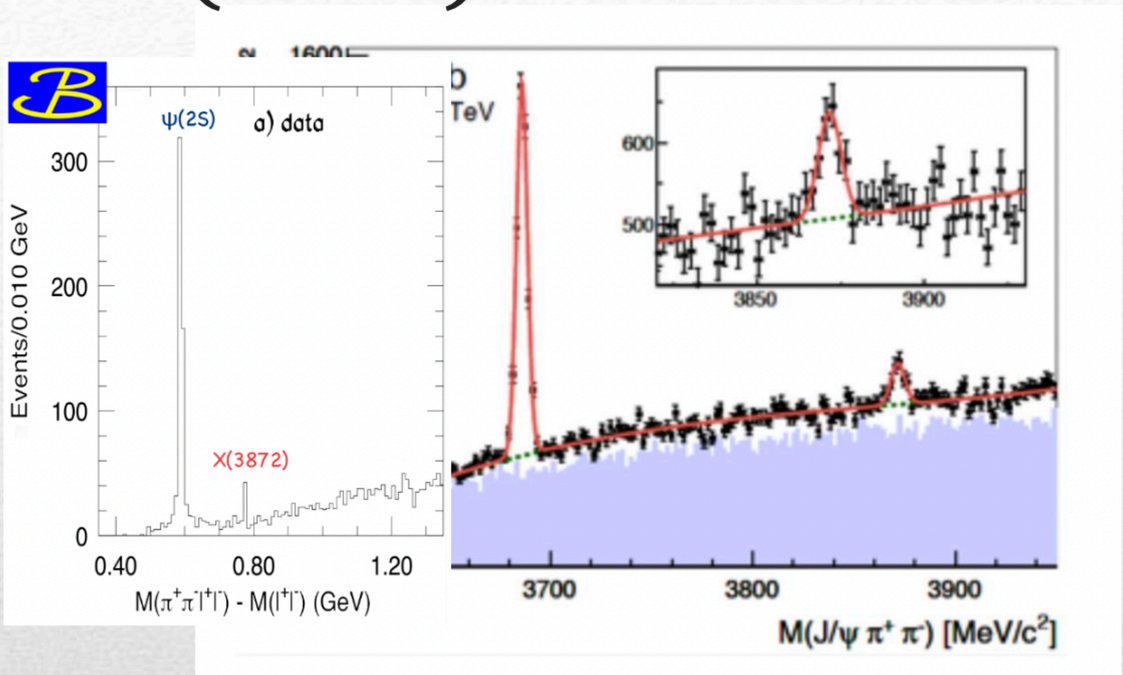




$X(3872)$



- Discovered in
  $B \to K\, X \to K\, J/\psi\, \pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X \to J/\psi\ \omega)}{\Gamma(X \to J/\psi\ \rho)} \sim 0.8 \pm 0.3$
- Mass prediction not compatible with $\chi_{c1}(2P)$

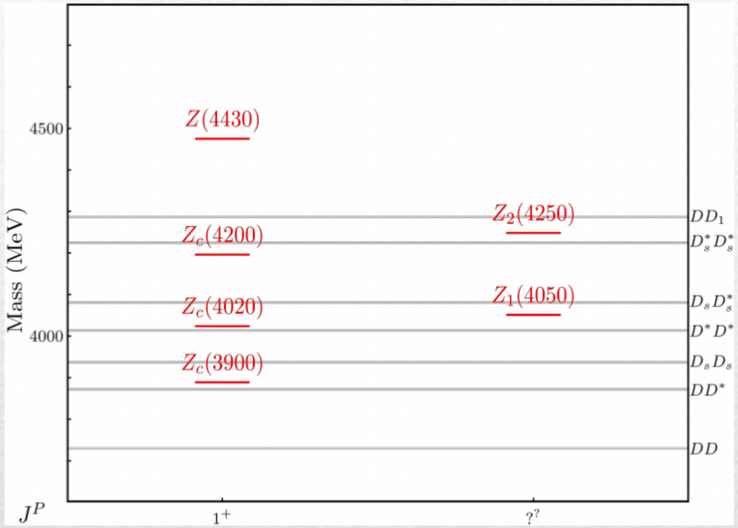
Sizeable prompt production at hadron colliders, $\sim 5\%$ of $\psi(2S)$

$\sigma_{PR} \times B(X \to J/\psi\pi\pi) = (1.06 \pm 0.11 \pm 0.15)$ nb @CMS

$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma = 1.19 \pm 0.19$ MeV

Charged Z states: $Z_c(3900), Z_c'(4020)$

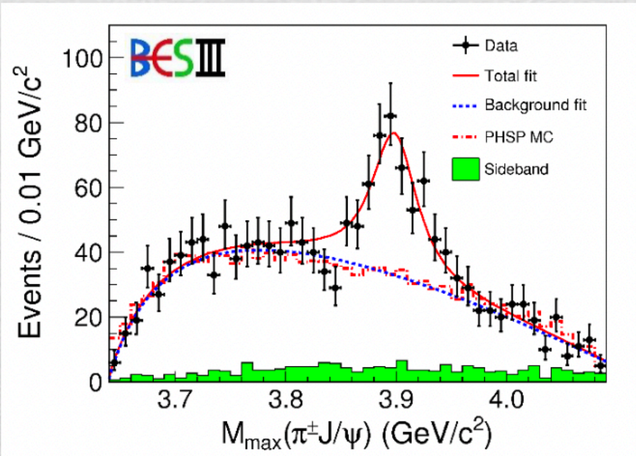
Charged quarkonium-like resonances have been found, **4q needed**

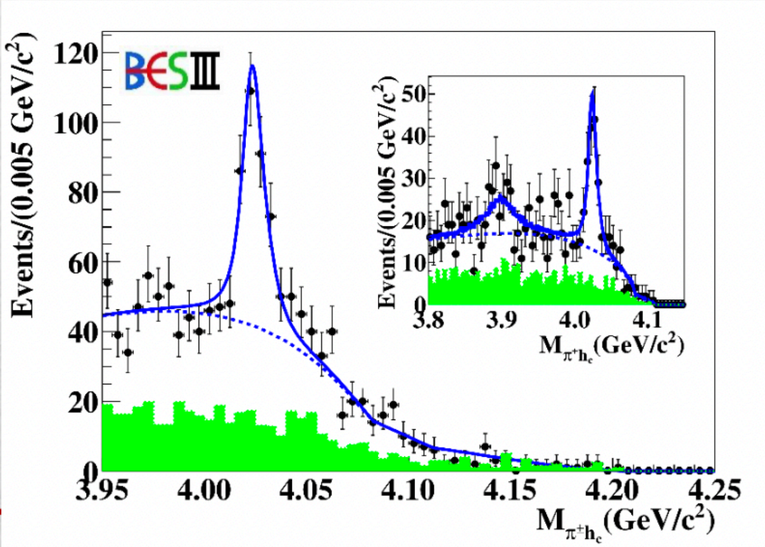


Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV

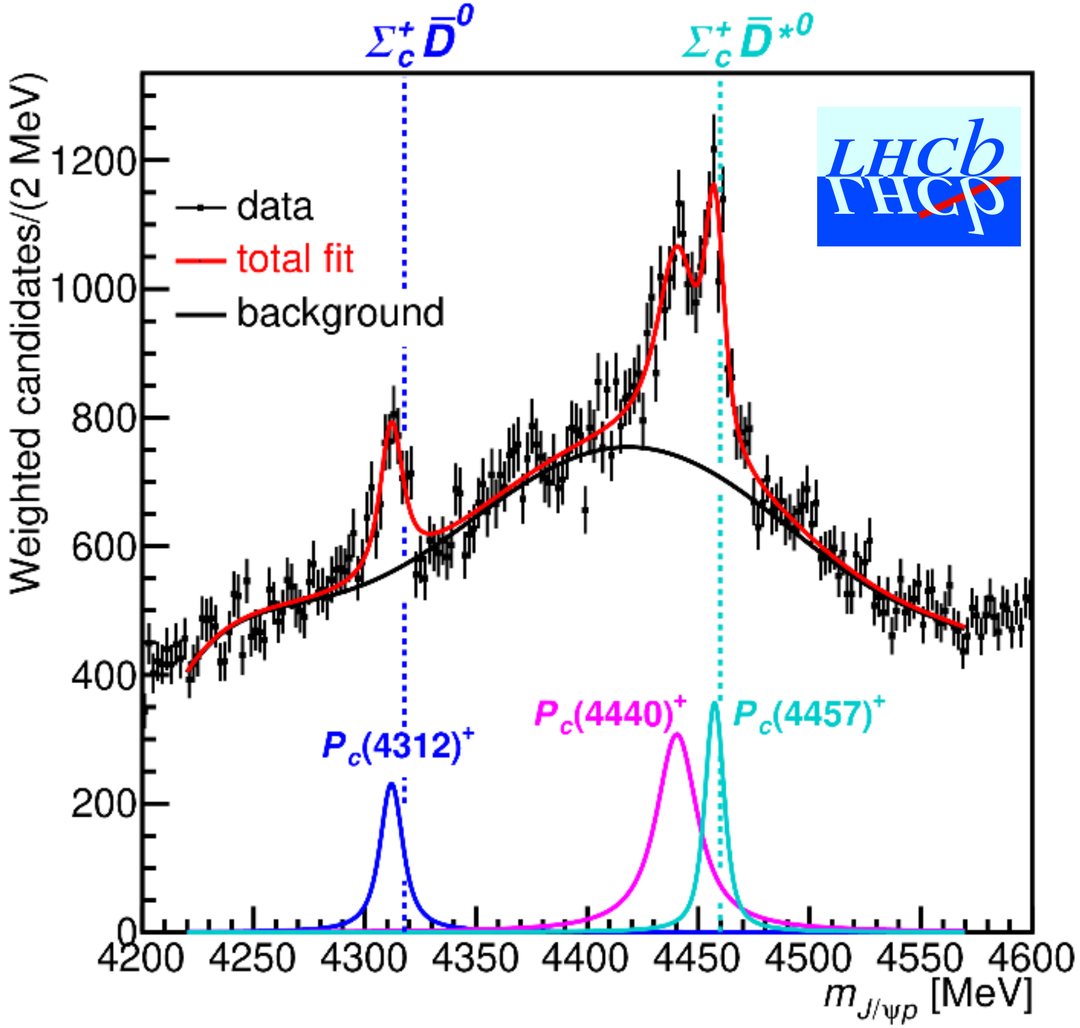




Pentaquarks candidates from LHCb

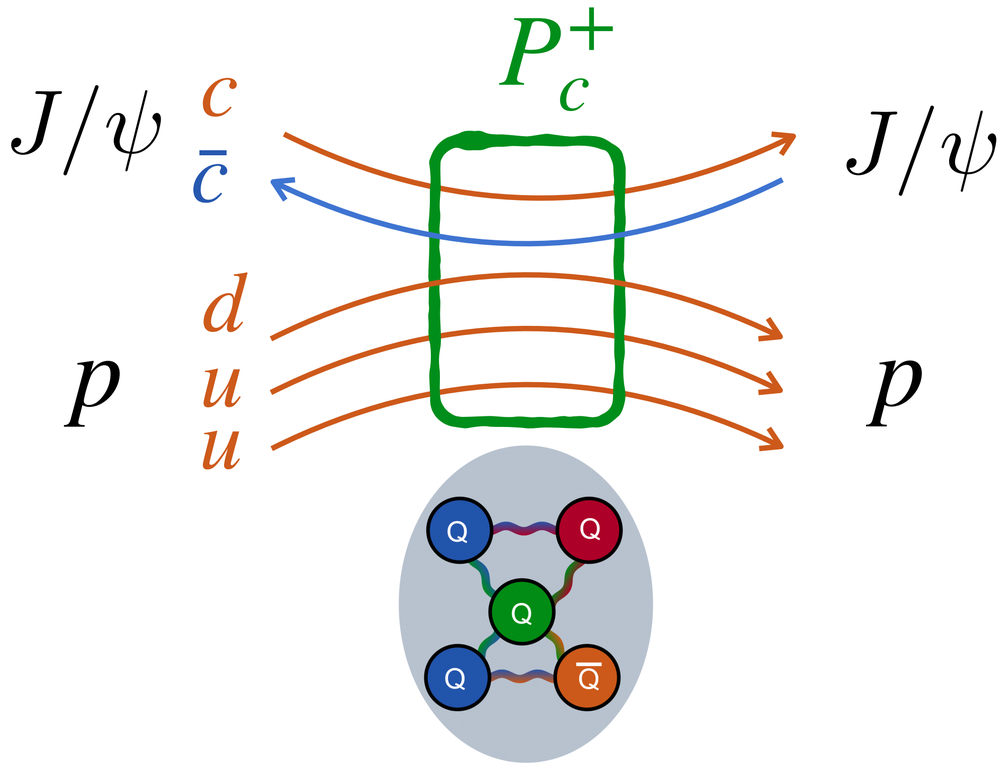
LHCb, PRL122 (2019) 222001

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



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

Cannot be qqq baryon



Direct production of P_c^+?

GlueX, PRL23 (2019) 072001 Data

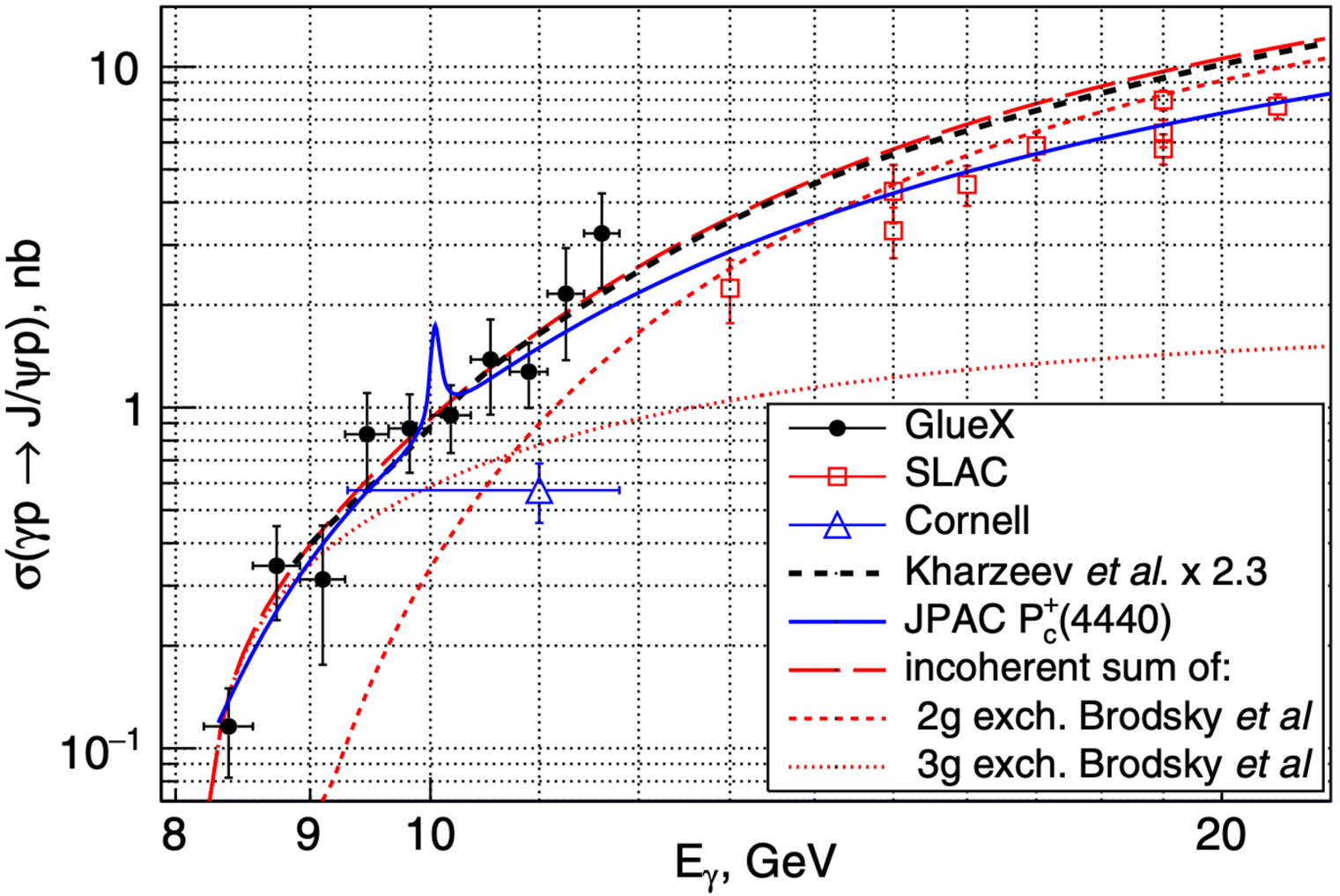
Hiller-Blin et al (JPAC), PRD94 (2016) 034002 Model

P_c^+ in 3-body decay

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

Photoproduction of P_c^+

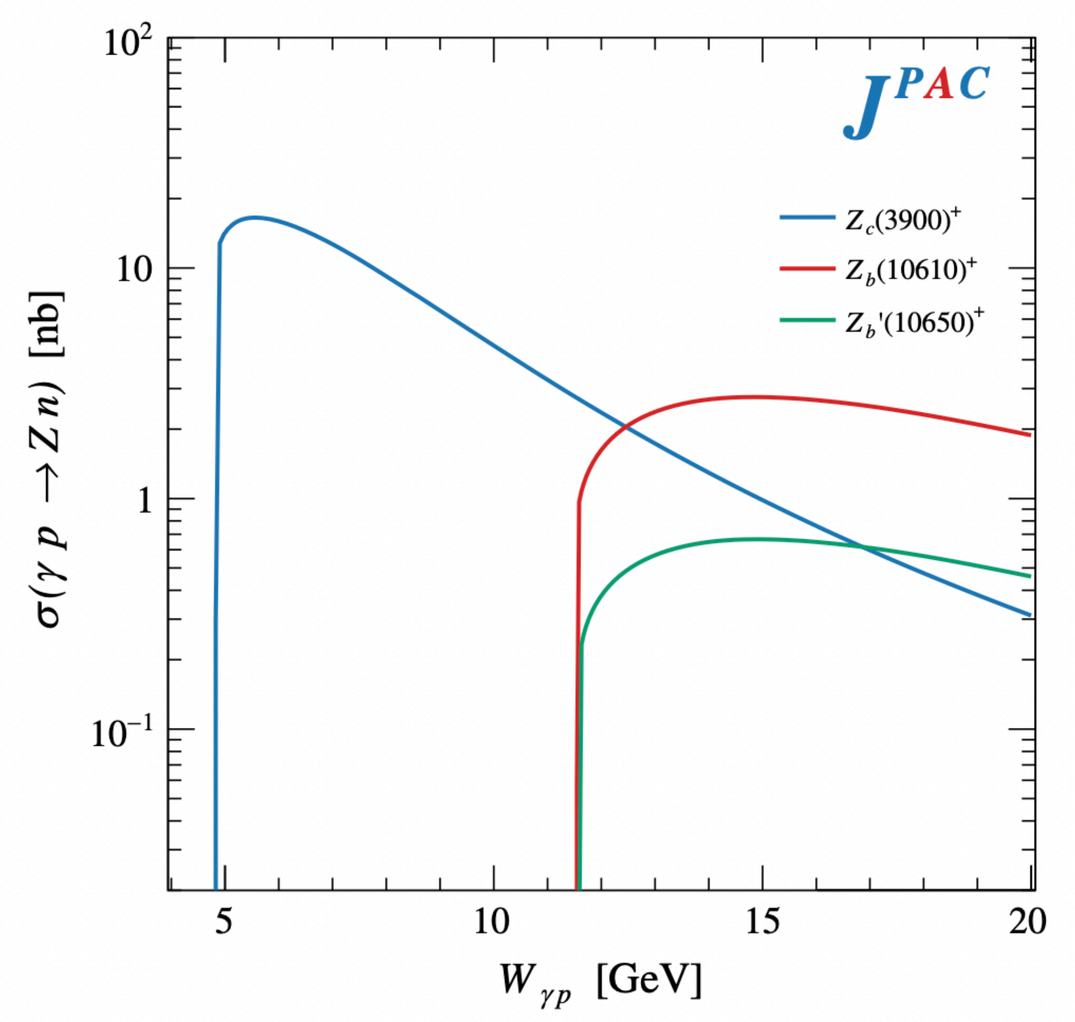
$$\gamma p \to J/\psi\, p$$



Exclusive XYZ Production @EIC

JPAC, PRD102 (2020) 114010

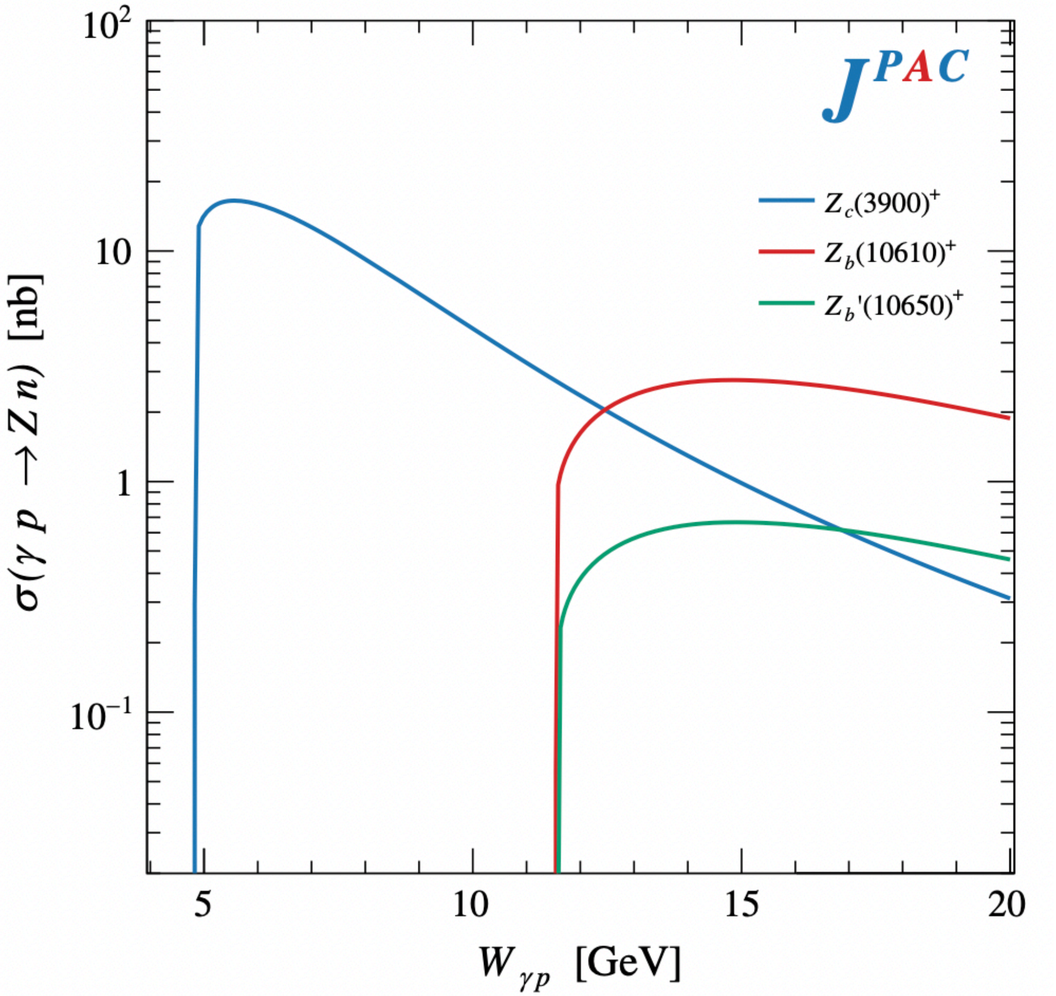
$$\gamma p \to Z^+ n$$



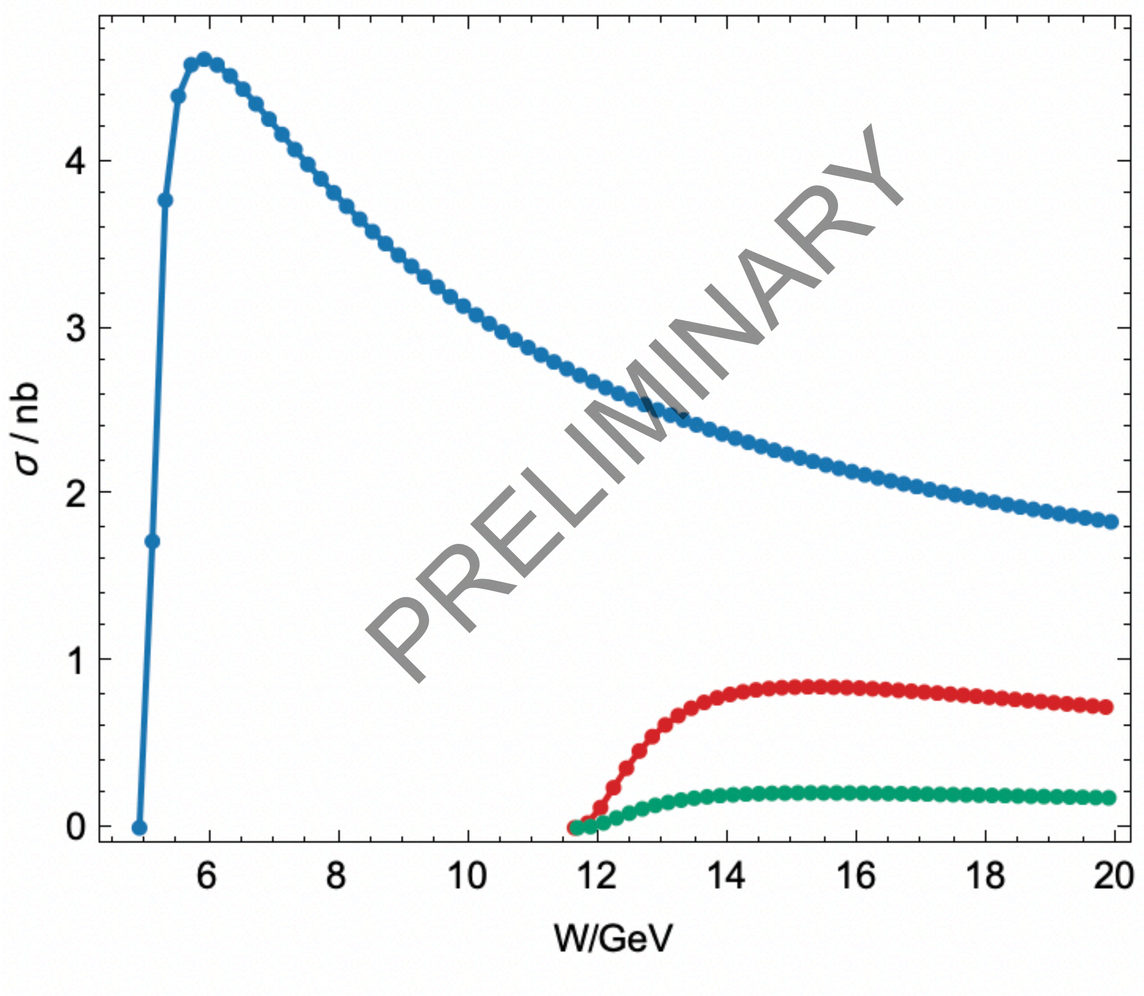
Exclusive XYZ Production @EIC

JPAC, PRD102 (2020) 114010

$\gamma p \to Z^+ n$



$\gamma p \to Z^+ X \qquad M_X \geq m_p + m_\pi$



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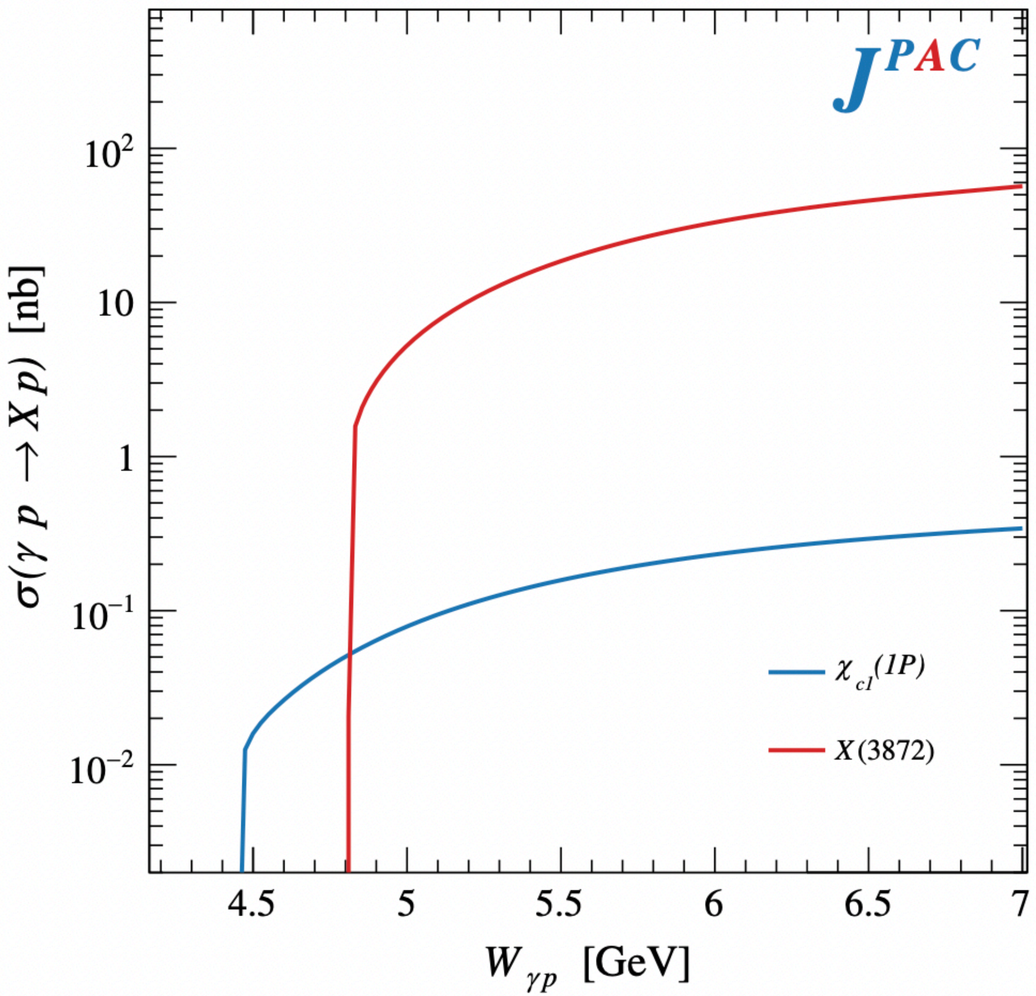
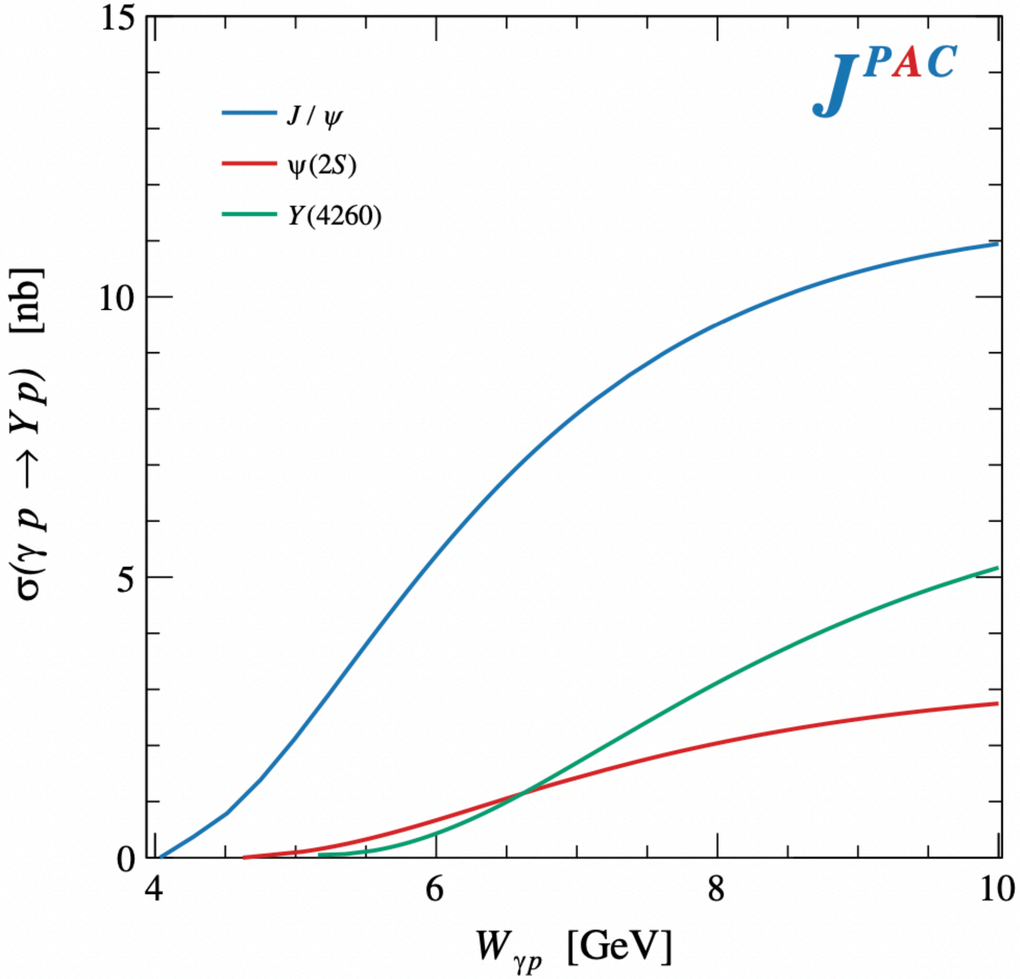
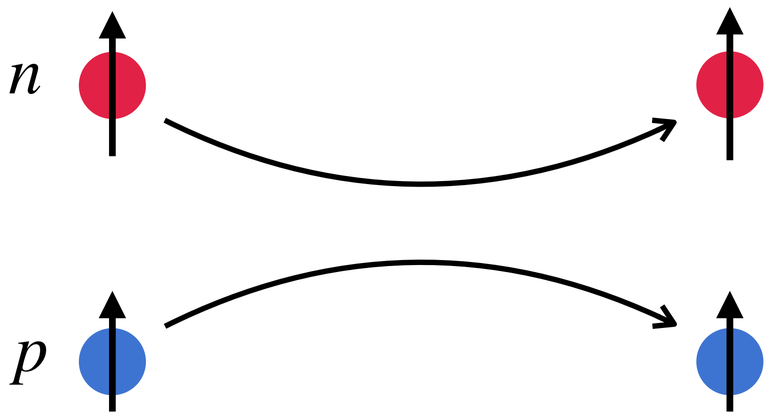
JPAC, PRD102 (2020) 114010

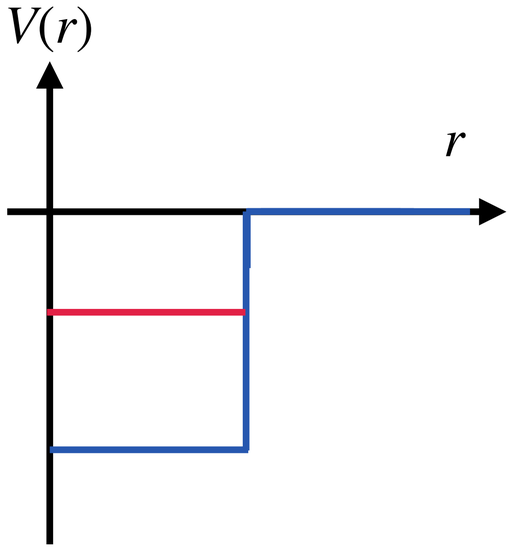


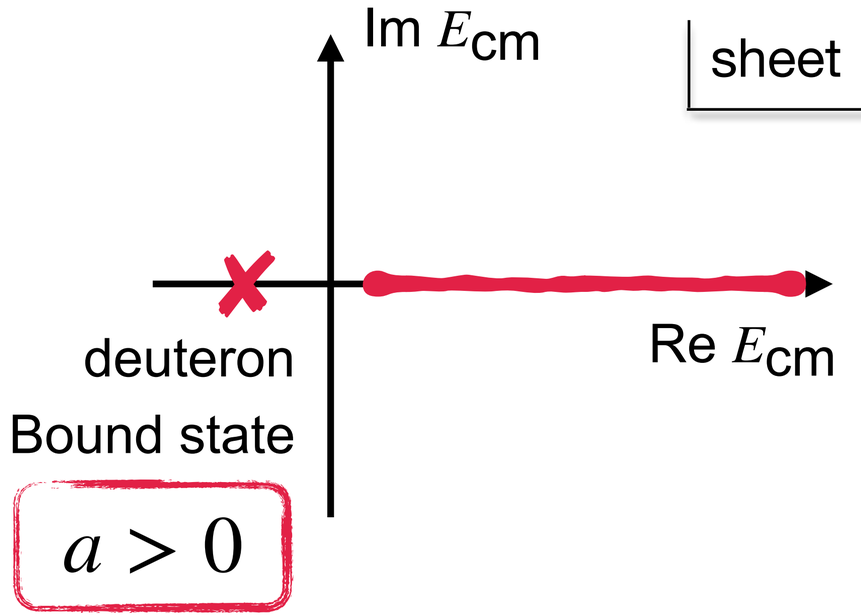


Backup Slides

Bound state vs virtual state





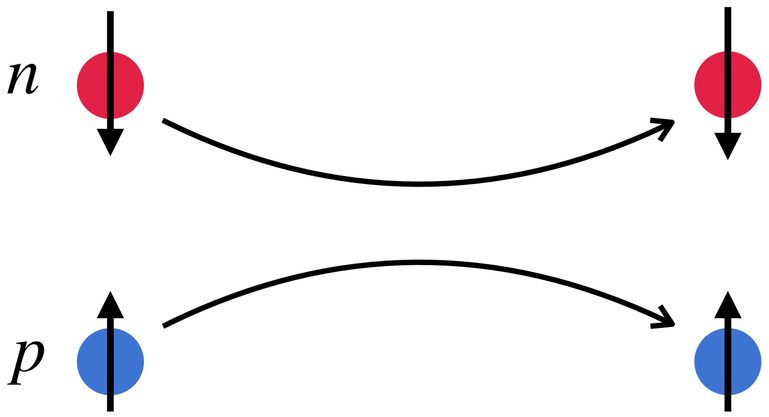


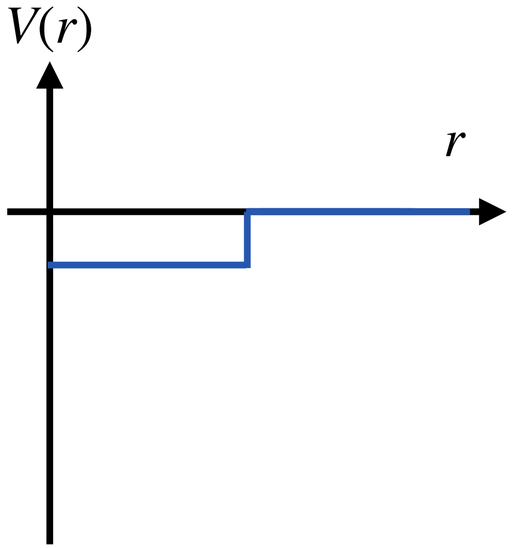
$$|k\rangle \qquad e^{i2\delta(k)}|k\rangle$$

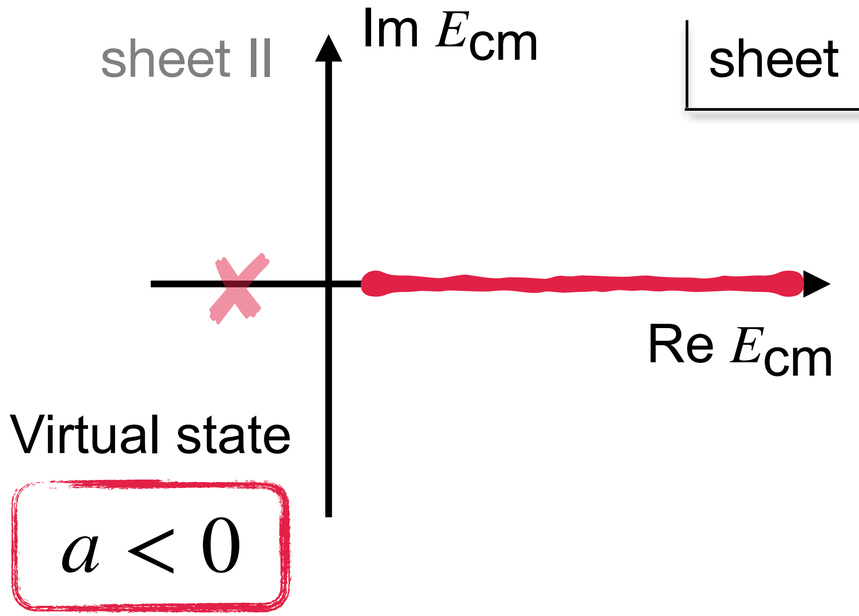
Scattering length $$a = \lim_{k\to 0} \frac{1}{k} \tan\delta(k)$$

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

Bound state vs virtual state







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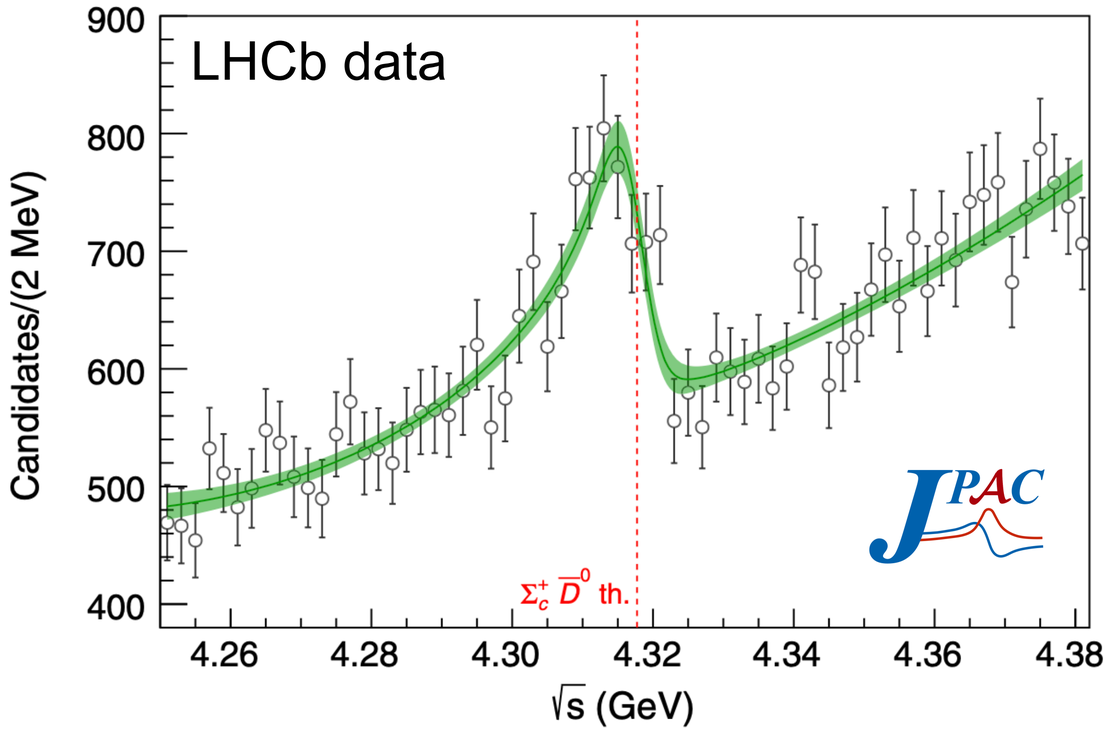
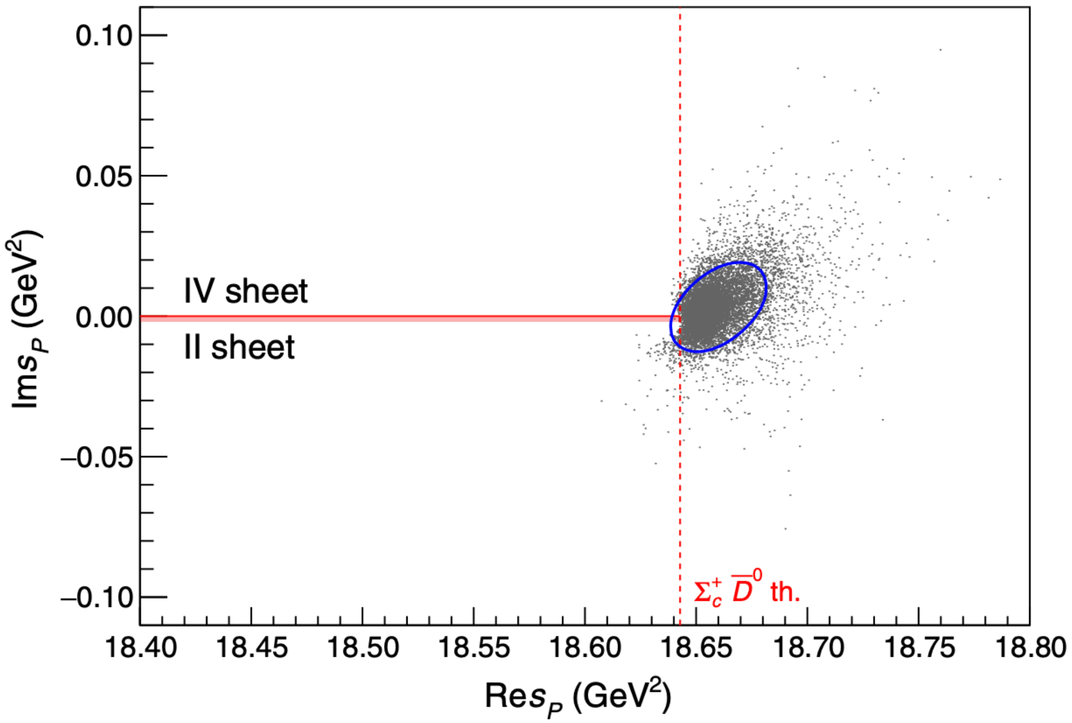
$P_c(4312)^+$ analysis

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





Bootstrap: generate 10k data

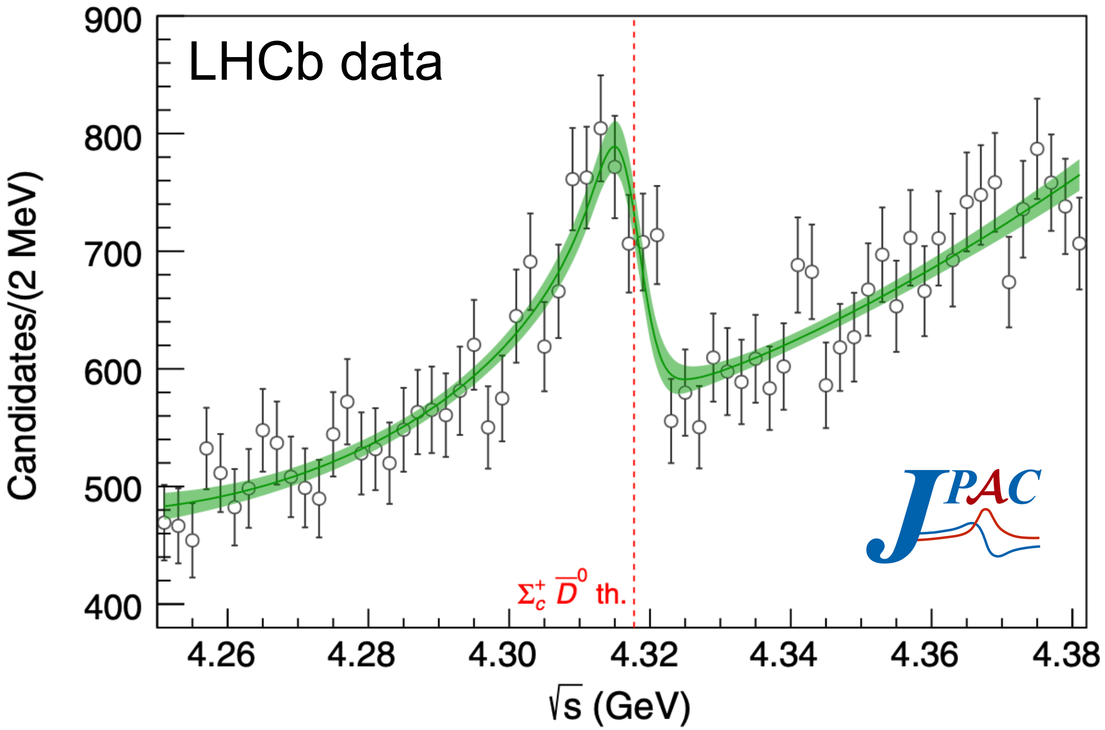
When $J\psi p$ decouples, pole moves to the real axis on the

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



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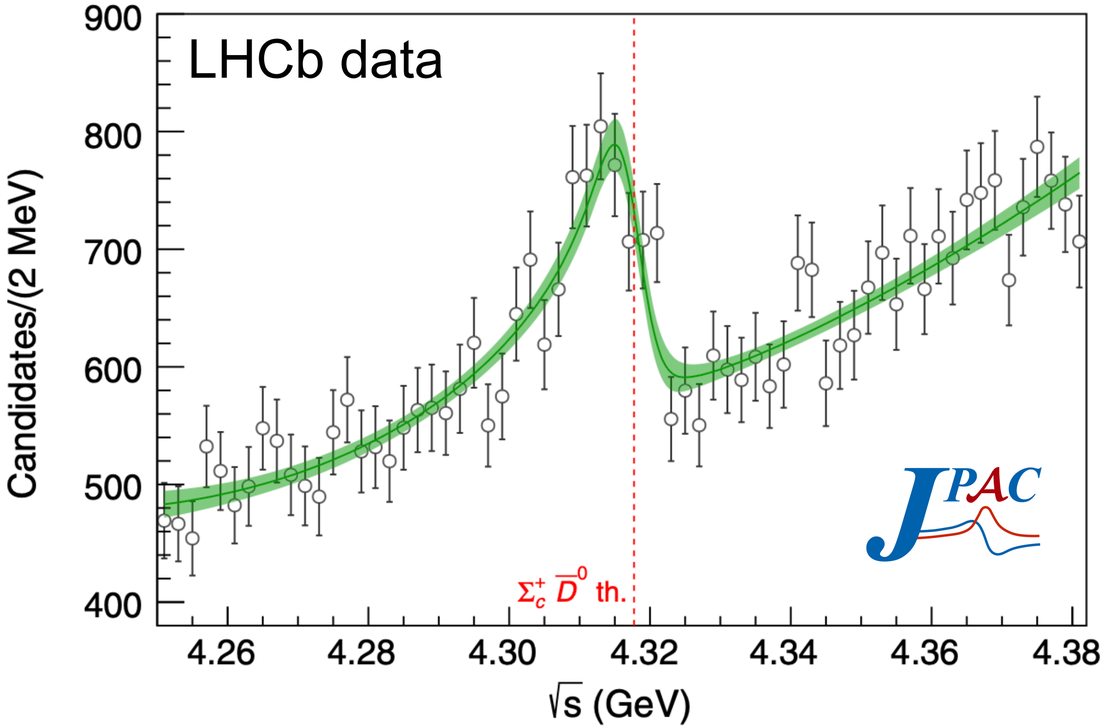

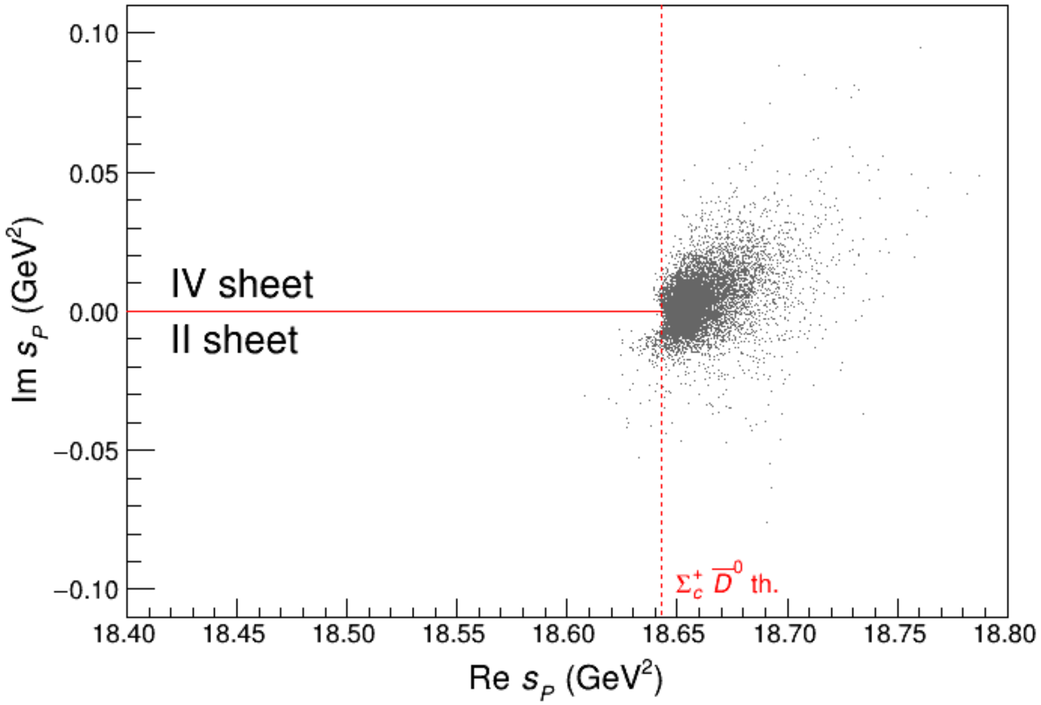

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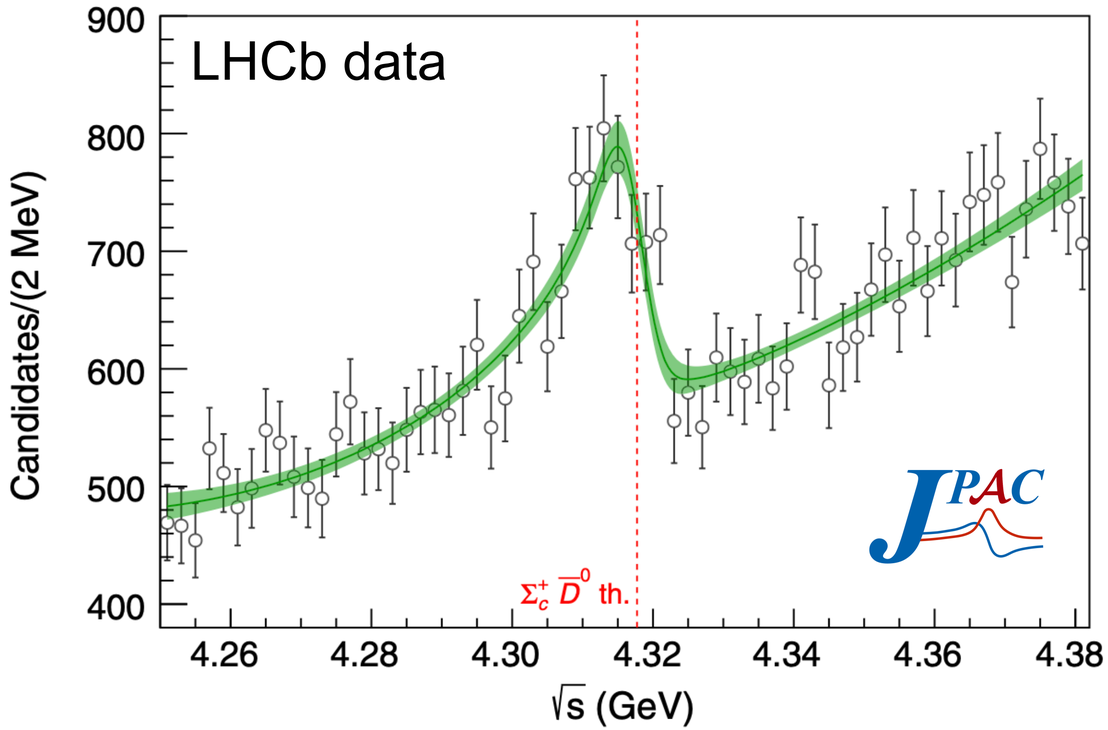
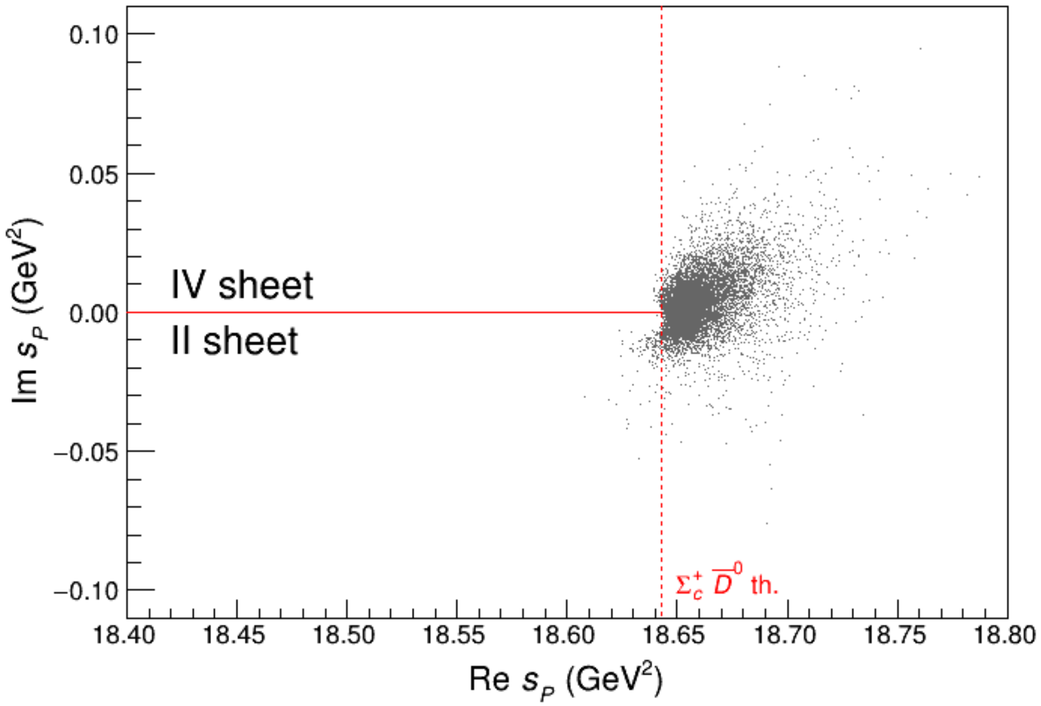




Bootstrap: generate 10k data

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

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

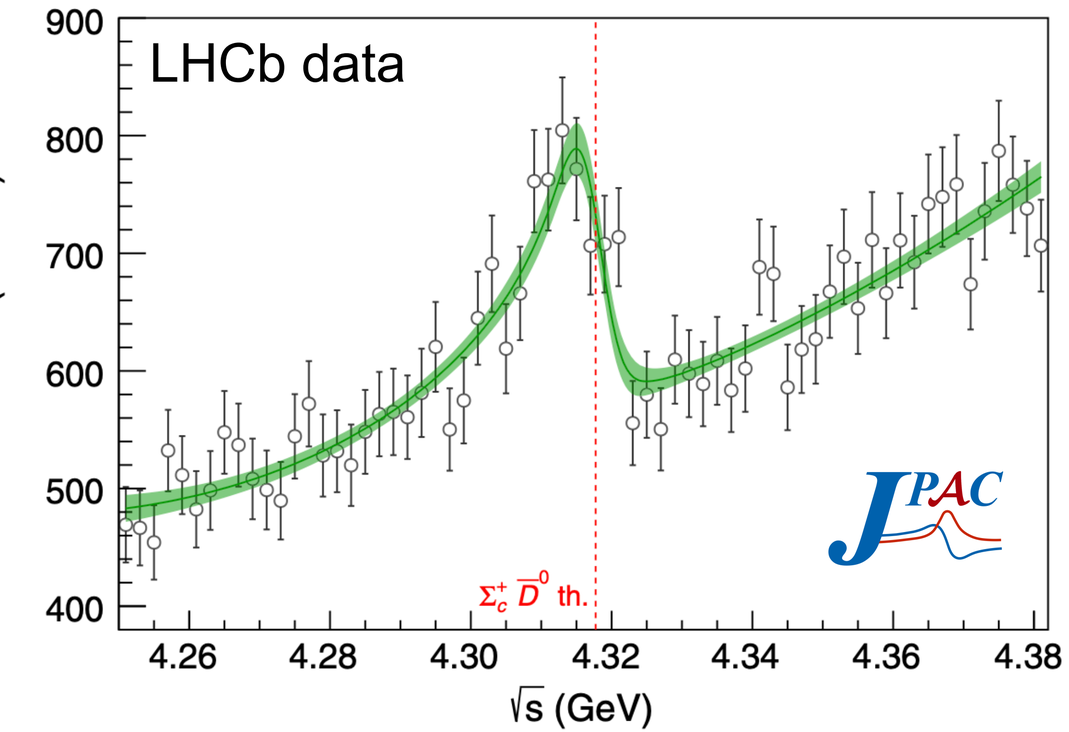
Physical sheet - positive scattering length - bound state 0.7 %

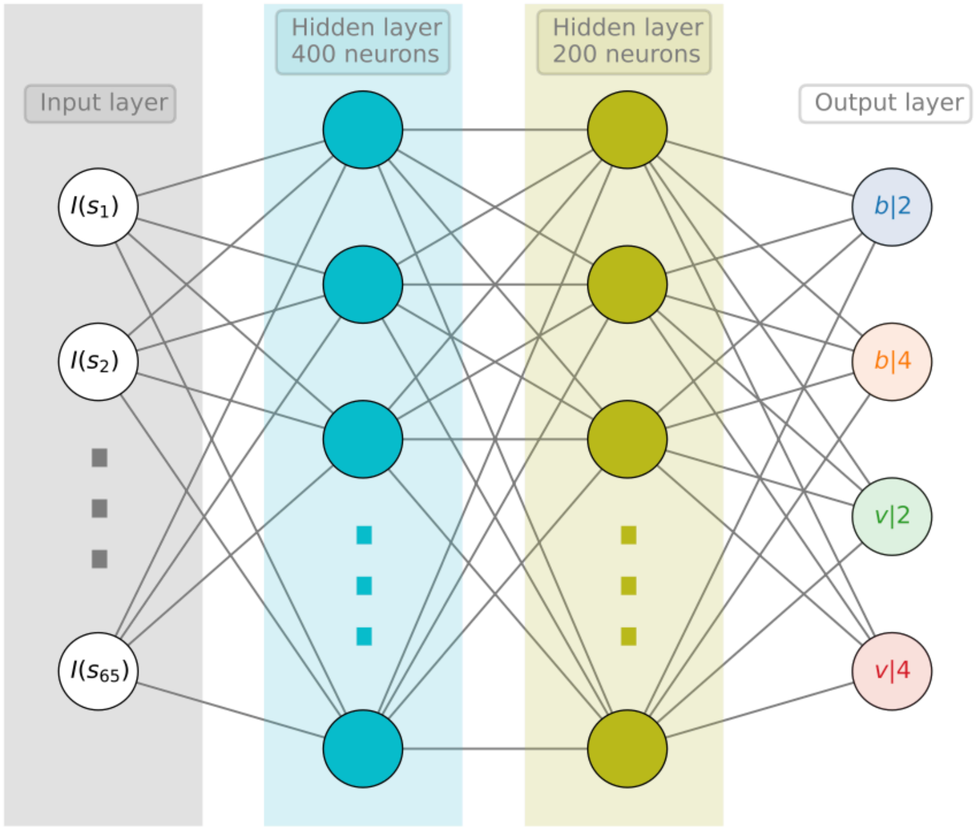
Unphysical sheet - negative scattering length - virtual state 99.3 %

$P_c(4312)^+$ analysis

Ng et al (JPAC), 2110.13742 (submitted to PRL)

Deep neural network trained with 4 types of amplitudes





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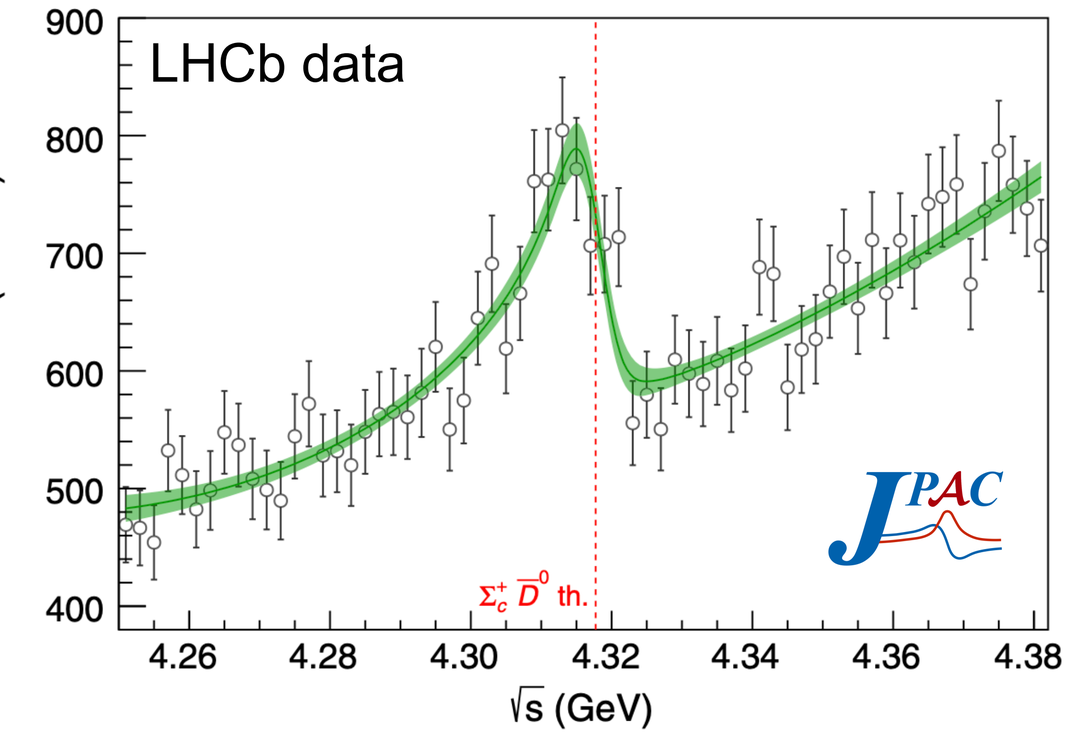
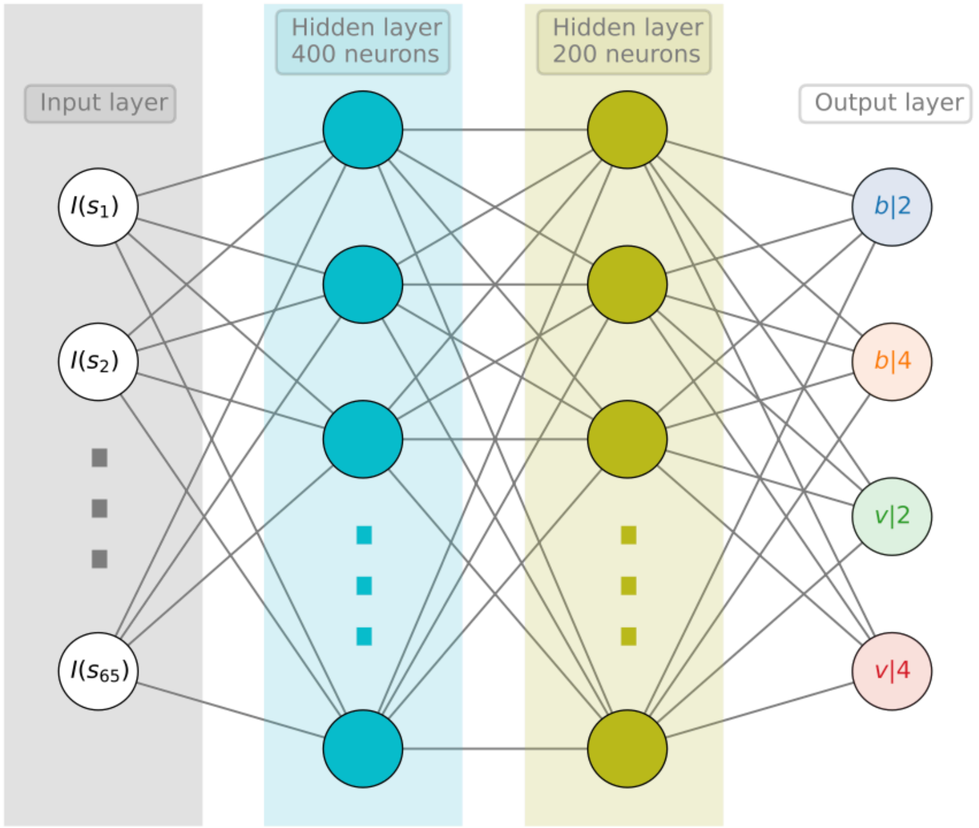
Ng et al (JPAC), 2110.13742 (submitted to PRL)

Deep neural network trained with 4 types of amplitudes





1.4 %

< 0.1 %

1.6 %

97.0 %

Direct production of P_c^+?

P_c^+ in 3-body decay

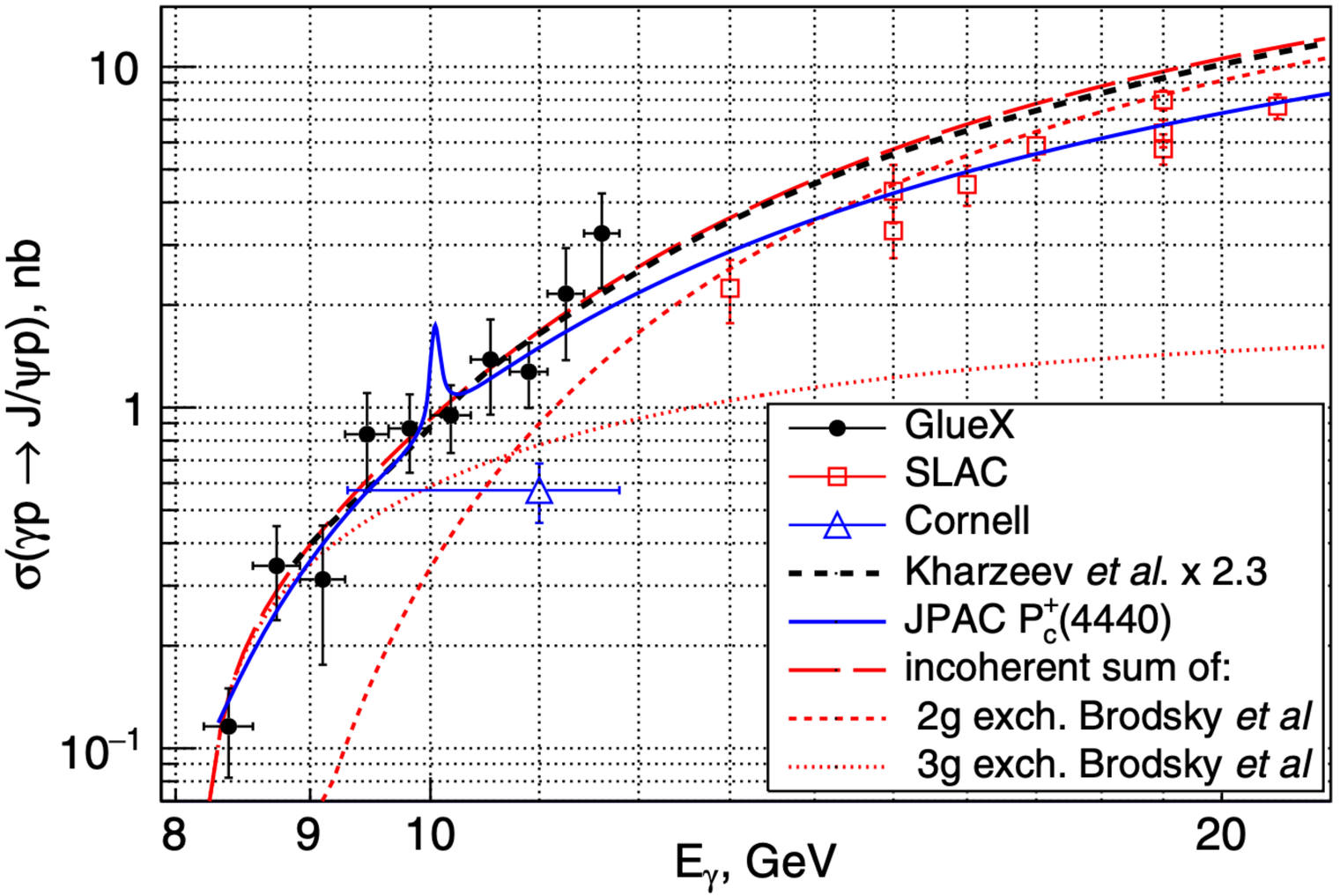
$$\Lambda_b \to K^- (J/\psi\, p)$$

Photoproduction of P_c^+

$$\gamma p \to J/\psi\, p$$

GlueX, PRL23 (2019) 072001 Data

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



SEMINAR ON SCATTERING THEORY AND APPLICATIONS

https://sites.google.com/iu.edu/ssta/

Every Thursday 4pm CEST
From February until end of May

Last Thursday: 50+ participants,

Including 5 ICCUB members

- February 3, Alessandro Pilloni

  Scope of the course: What is scattering, basic S-matrix principles, natural units

- February 10, Adam Szczepaniak

  QFT vs Schrodinger equation: fields, particles and interactions. QM review, fields vs particles

- February 17, Miguel Albaladejo

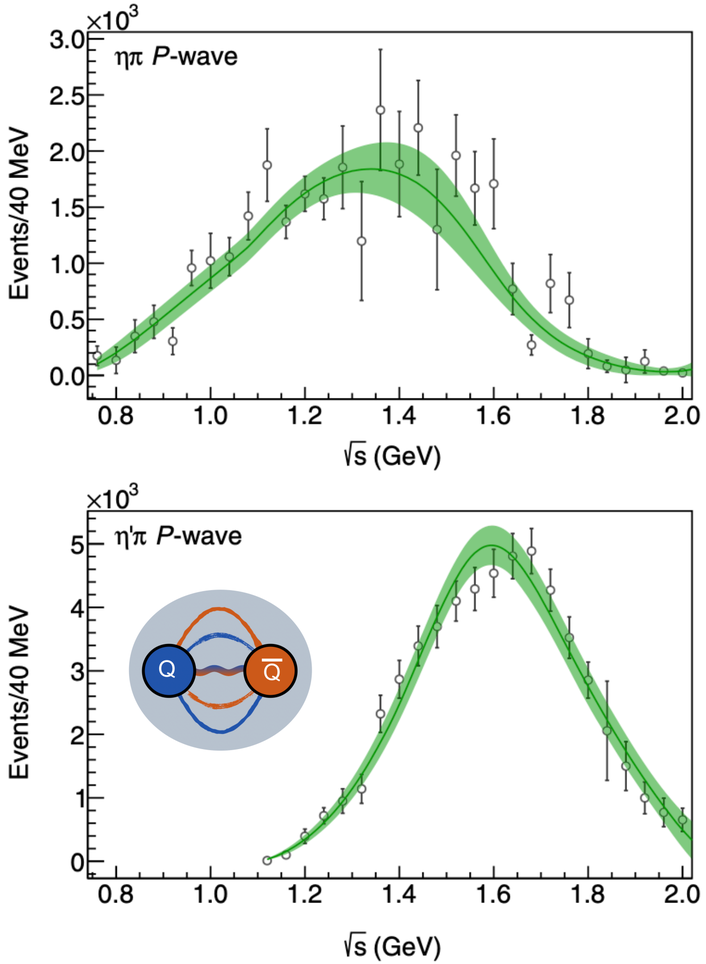
  Lippmann-Schwinger equation, partial waves

- February 24, Adam Szczepaniak

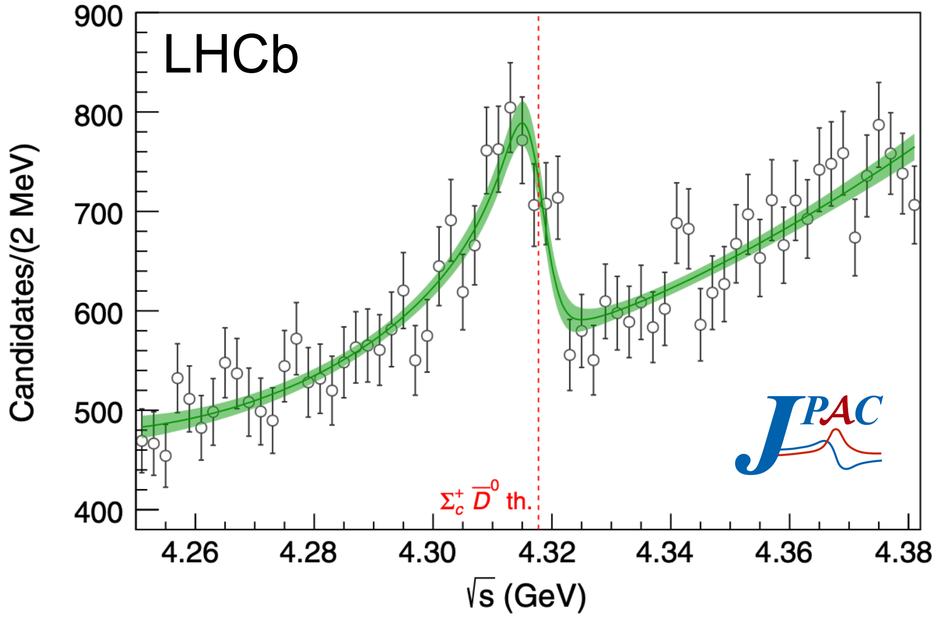
  Examples: Delta-shell, Feshbach resonances

Direct production of P_c^+?

Hybrid mesons resonance in $\eta\pi$ and $\eta'\pi$



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

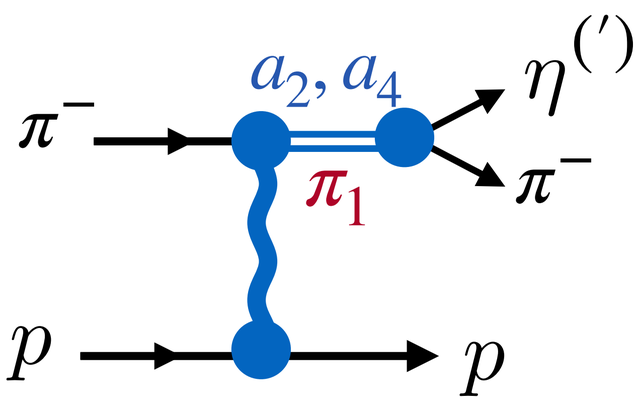


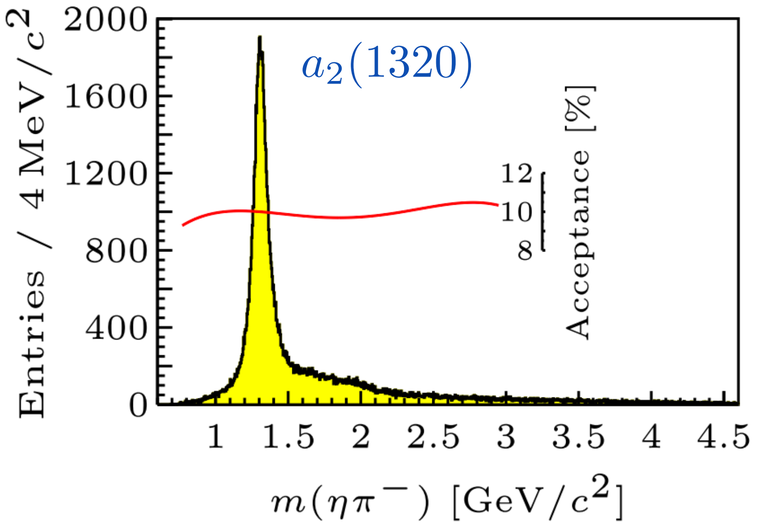
Review

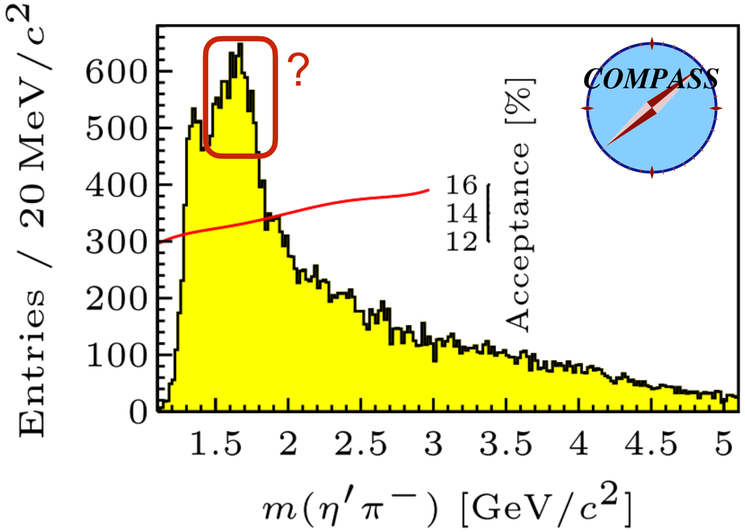
Albaladejo et al (JPAC), arXiv:2112.13436
invited by Progress in Particle and Nuclear Physics

Eta-Pi @COMPASS

COMPASS PLB740 (2015)





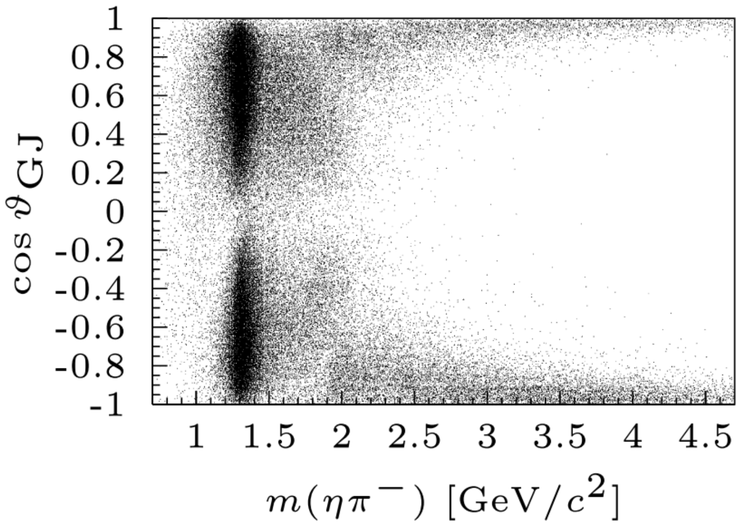


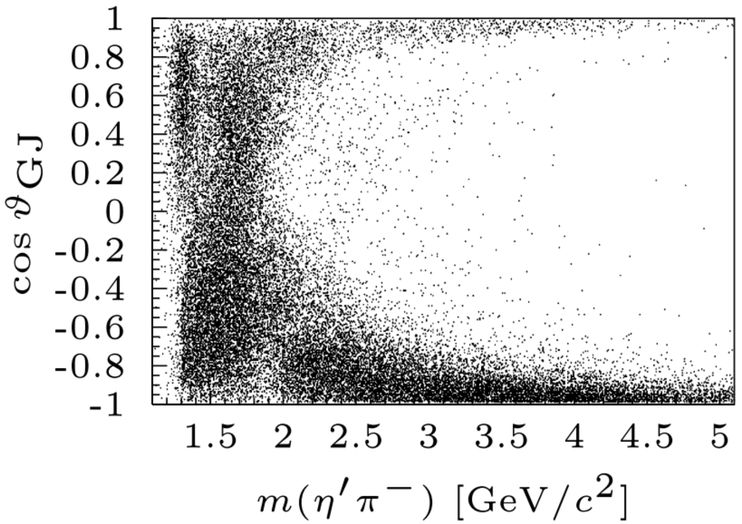
190 GeV beam,

Only natural exchanges

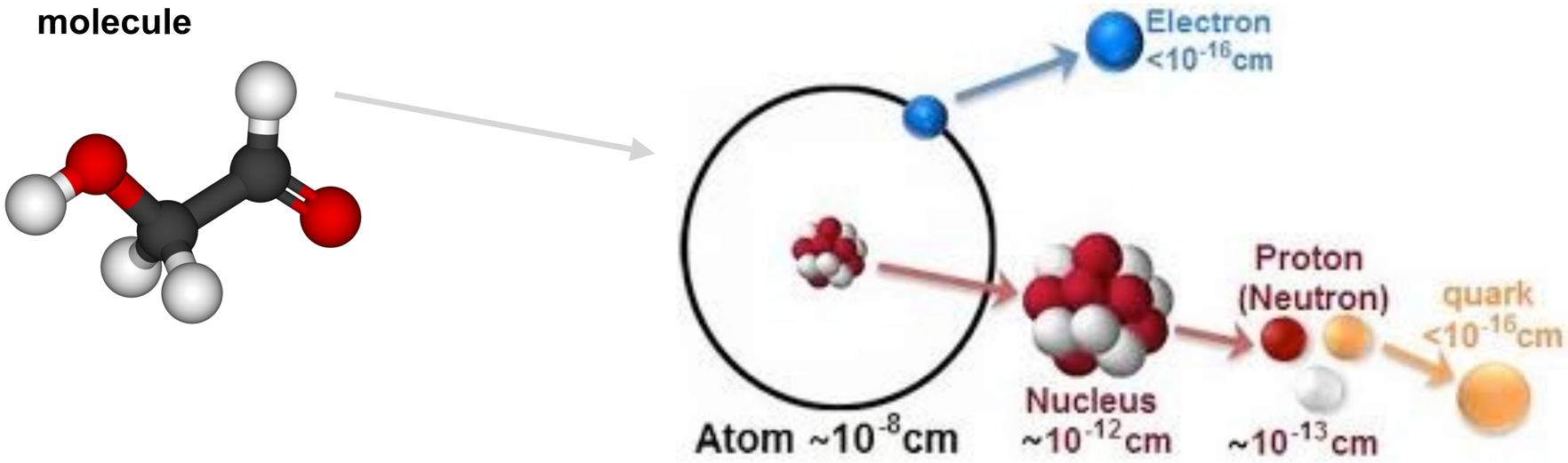
No scalar, $M \geqslant 1$

D-wave $\propto \cos\theta \sin\theta \sin\phi$

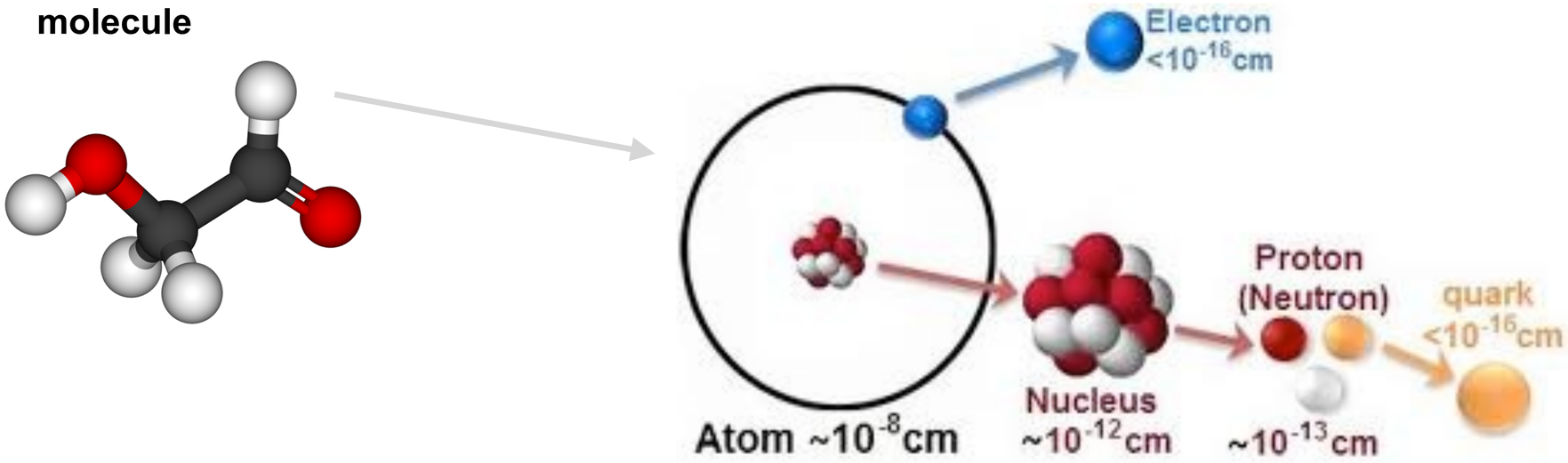




Degrees of Freedom in Hadronic Physics



Degrees of Freedom in Hadronic Physics



$$\mathcal{L}_{QCD} = -\frac{1}{4}\left(\partial \cdot \vec{A} + g\vec{A} \times \vec{A}\right)^2 + \sum_f \bar{q}_f \left(\gamma \cdot \partial - ig\gamma \cdot \vec{A} - m_f\right) q_f$$

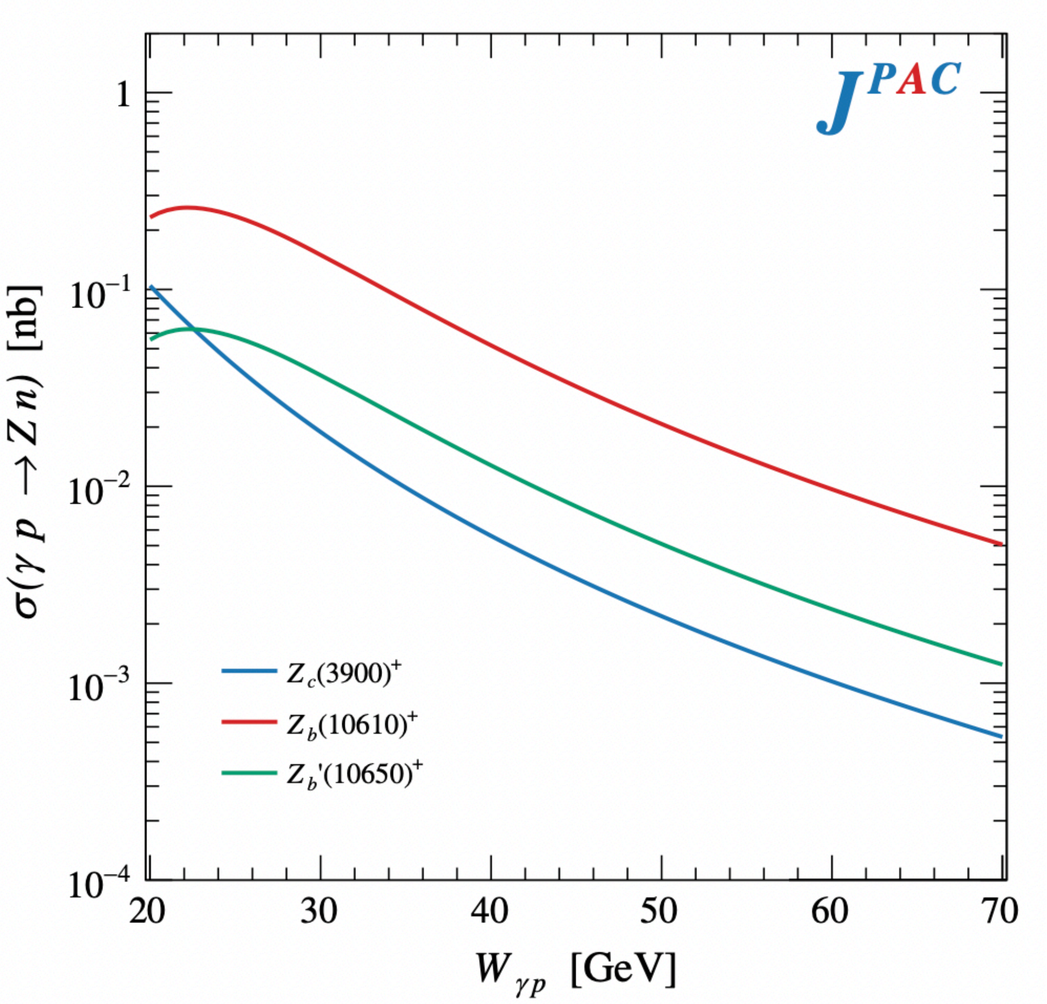
quark d.o.f. (matter)

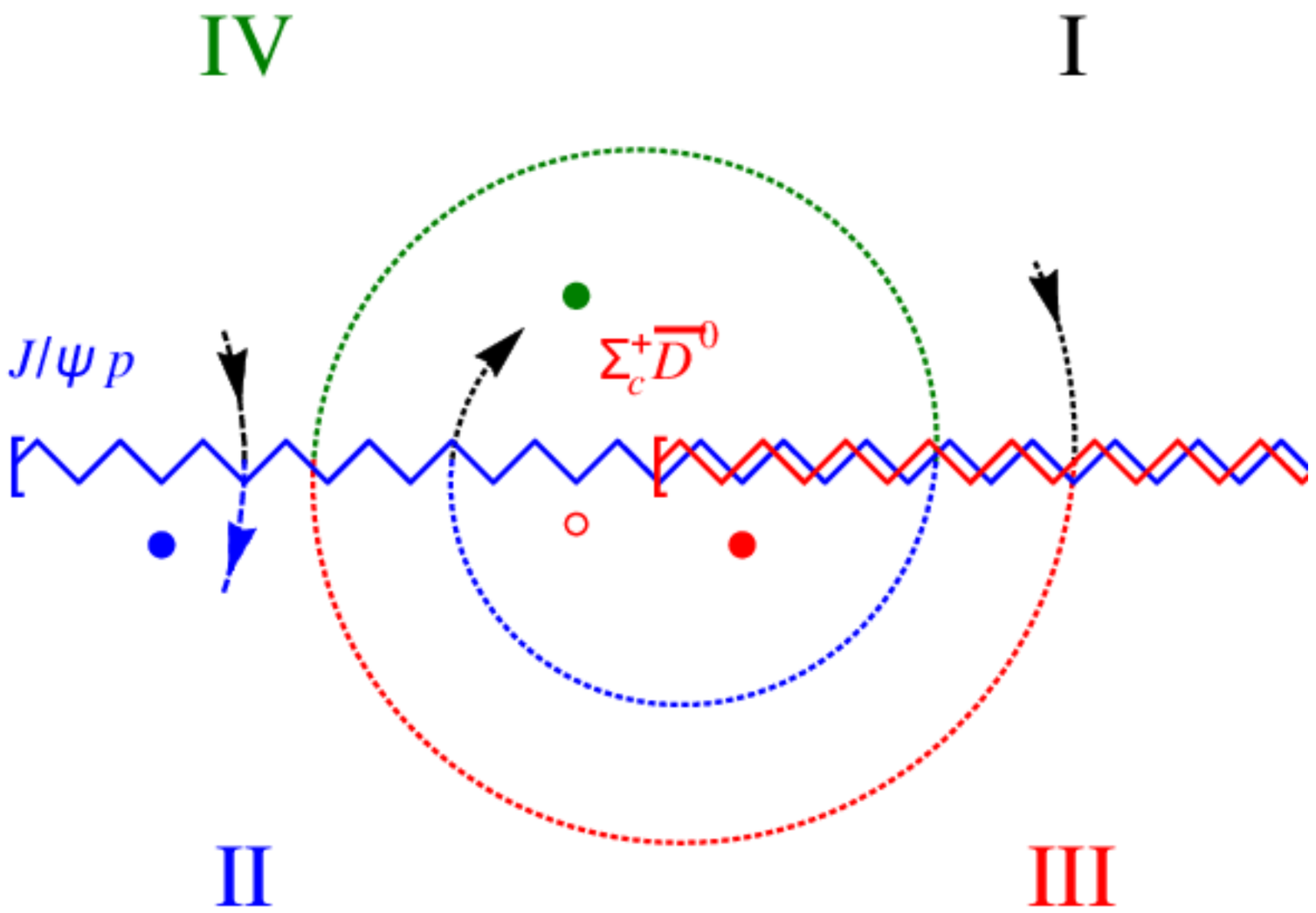
gluon d.o.f. (force)

interaction

Exclusive XYZ Production @EIC

JPAC, PRD102 (2020) 114010




IV
I
$J/\psi\, p$
$\Sigma_c^+ \overline{D}^0$
II
III

Joint Physics Analysis Center

HOME PUBLICATIONS TALKS SCHOOLS LINKS

JPAC acknowledges support from DOE and NSF

NEWS

Photoproduction:

1. High energy model for $\gamma p \to \eta\pi^0 p$ and di-meson moments: $\gamma p \to \eta\pi^0 p$ page
2. High energy model for $\gamma N \to \pi N$ constrained by FESR: $\gamma N \to \pi N$ page
3. High energy model for ρ^0, ω, ϕ spin density matrix elements: $\gamma p \to V p$ page
4. High energy model for η' beam asymmetry photoproduction: $\gamma p \to \eta^{(\prime)} p$ page
5. High energy model for η photoproduction: $\gamma p \to \eta p$ page
6. High energy model for π^0 photoproduction: $\gamma p \to \pi^0 p$ page
7. Model for J/ψ photoproduction $\gamma p \to J/\psi p$: unpolarized observables ; polarized observables

JPAC Joint Physics Analysis Center

Hadroproduction:

1. Pion-nucleon Scattering:
   - Amplitudes $\pi N \to \pi N$ amplitude page
   - Finite energy sum rules $\pi N \to \pi N$ FESR page
2. Kaon-nucleon scattering: $\bar{K} N \to \bar{K} N$ page

Three-body Decay: Isobar decomposition and recoupling coefficients.
Light Meson Decay:

1. η meson into three pions: $\eta \to 3\pi$ page
2. vector meson into three pions: $\omega, \phi \to 3\pi$ page

Heavy Baryon Decay:

1. $\Lambda_b^0 \to J/\psi p K^-$ and the $P_c(4312)^+$: $P_c(4312)^+$ page

www.ceem.indiana.edu/jpac

Started in May 2015
About 100 visits/month
Used by theorists and experimental collaborations

JPAC Website

Joint Physics Analysis Center

Interactive webpage

Codes downloadable

www.ceem.indiana.edu/jpac

Beam energy in the lab frame (target rest frame):

E_γ in GeV 8,50

Vector meson: ω ρ^0 ϕ

Natural exchanges (Pomeron and tensor exchanges): [show/hide]

$\mathbb{P}$ $\beta_{\mathbb{P}}^{\gamma\omega}$: 0,739	$\beta_{\mathbb{P}}^{\gamma\rho}$: 2,506	$\beta_{\mathbb{P}}^{\gamma\phi}$: 0,932
$\beta_1^{\mathbb{P}}$: 0,00	$\beta_2^{\mathbb{P}}$: 0,00	$b_{\mathbb{P}}$: 3,60
$\alpha_0^{\mathbb{P}}$: 1,08	$\alpha_1^{\mathbb{P}}$: 0,20	$\kappa_{\mathbb{P}}$: 0,00

Results

Simulation at Eg = 8.50 GeV
Photoproduction of Rho^0 meson

The x-axis of the plots is -t in GeV^2.
Download the output file (results in helicity and Gottfried-Jackson frames): resultsH.txt , resultsGJ.txt
Download the plots: plotH.png , plotGJ.png