

Challenges in Hadron Spectroscopy

Vincent MATHIEU

ICC & U. Barcelona

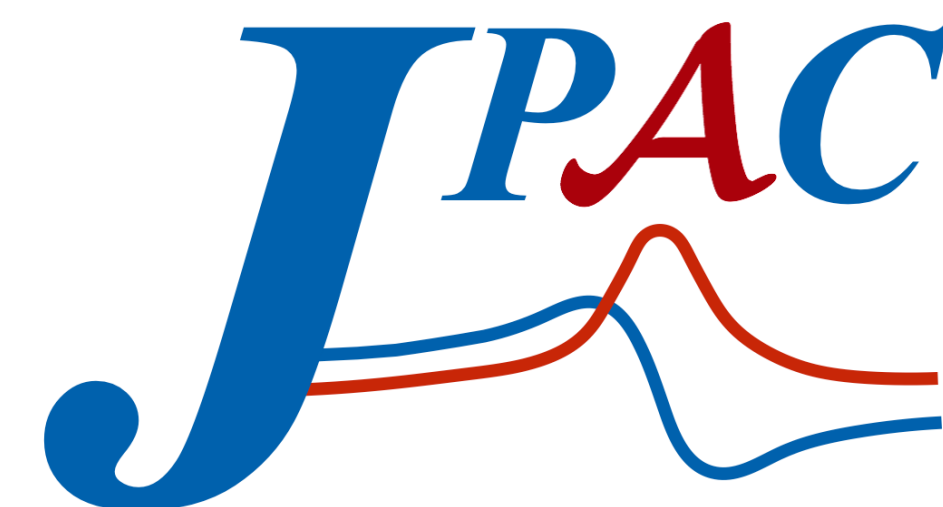
Joint Physics Analysis Center

ICCUB Winter Meeting

February 2022



UNIVERSITAT DE
BARCELONA



*Joint
Physics
Analysis
Center*

Joint Physics Analysis Center



Miguel Albaladejo
CSIC-Valencia



Lukasz Bibrzycki
Pedagogical University of
Kracow



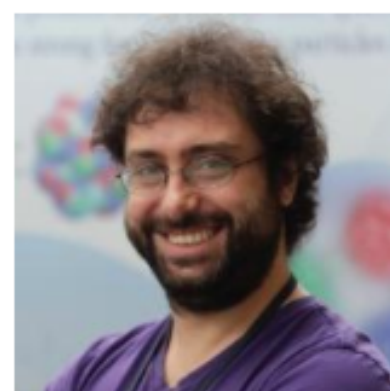
Cesar Fernández Ramírez
National Autonomous
University of Mexico



Astrid Hiller Blin
Jefferson Lab



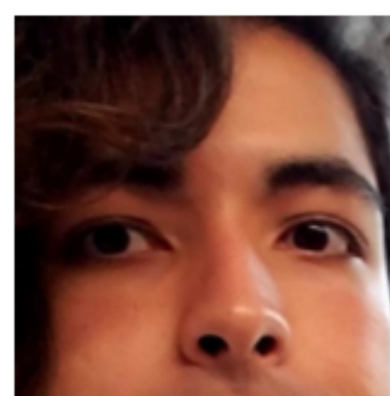
Mikhail Mikasenko
TU Munich



Alessandro Pilloni
U. Messina



Adam Szczepaniak
Indiana University



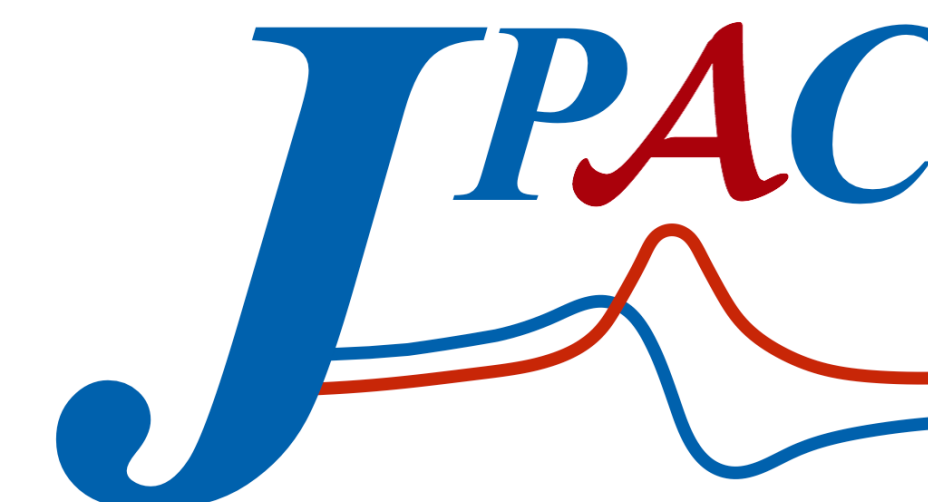
Daniel Winney
Indiana University



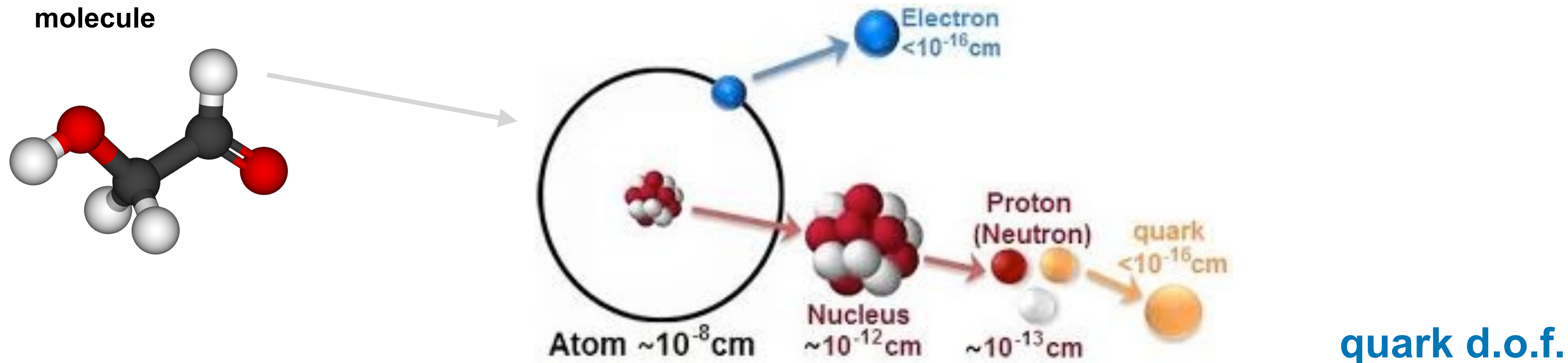
Lawrence Ng
Florida State
University



Arkaitz Rodas
College of
William and Mary



Degrees of Freedom in Hadronic Physics



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

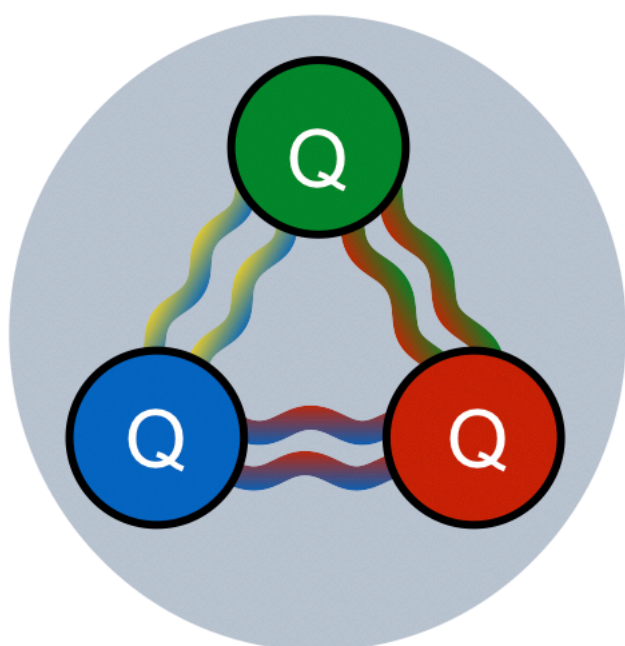
gluon d.o.f.
(force)

interaction

quark d.o.f.
(matter)

Ordinary and Exotic Hadrons

Ordinary baryons:

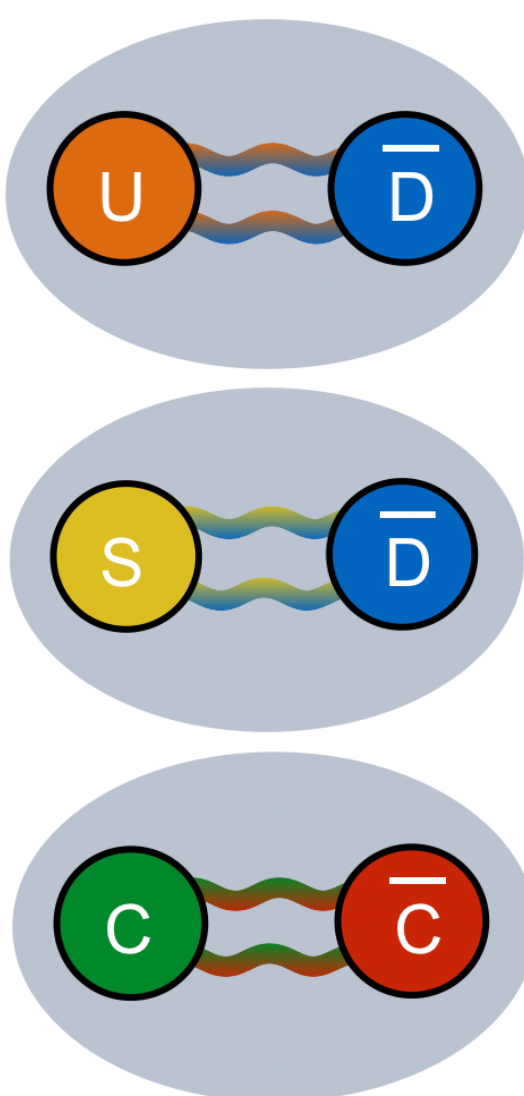


- proton stable
- neutron $\tau \sim 10^3 s$
- baryon Λ $\tau \sim 10^{-10} s$

QUARKS

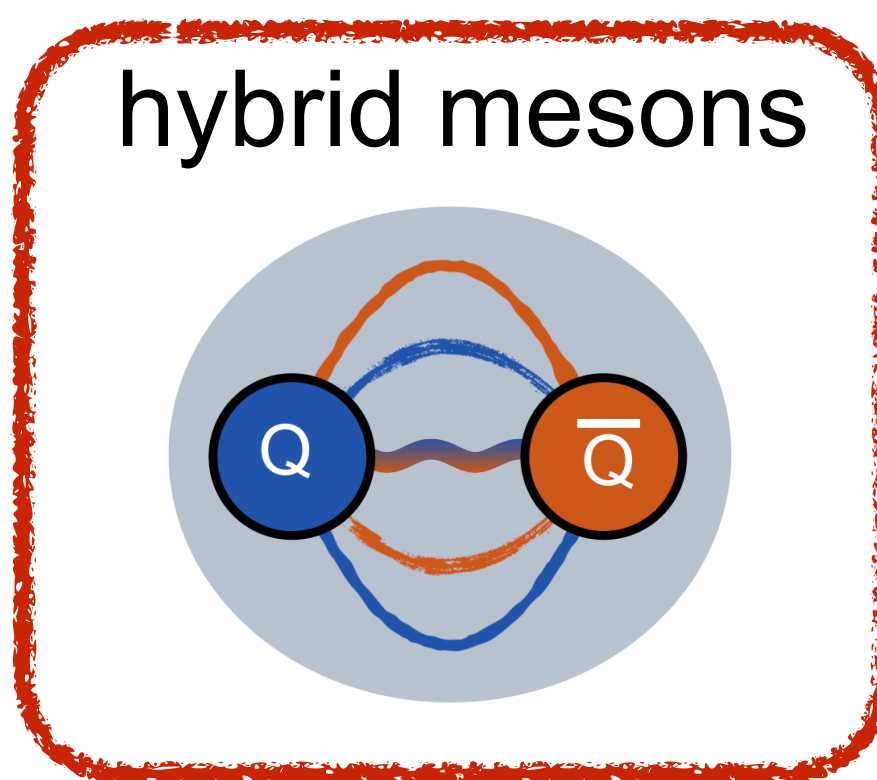
UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 	CHARM 1,275 GeV/c ² 2/3 1/2 	TOP 173,07 GeV/c ² 2/3 1/2
DOWN 4,8 MeV/c ² -1/3 1/2 	STRANGE 95 MeV/c ² -1/3 1/2 	BOTTOM 4,18 GeV/c ² -1/3 1/2

Ordinary mesons

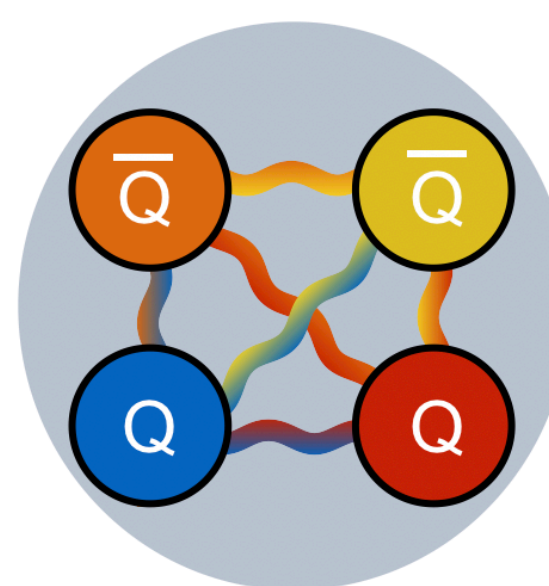


- pion $\tau \sim 10^{-8} s$
- kaon $\tau \sim 10^{-8} s$
- J/ψ $\tau \sim 10^{-20} s$

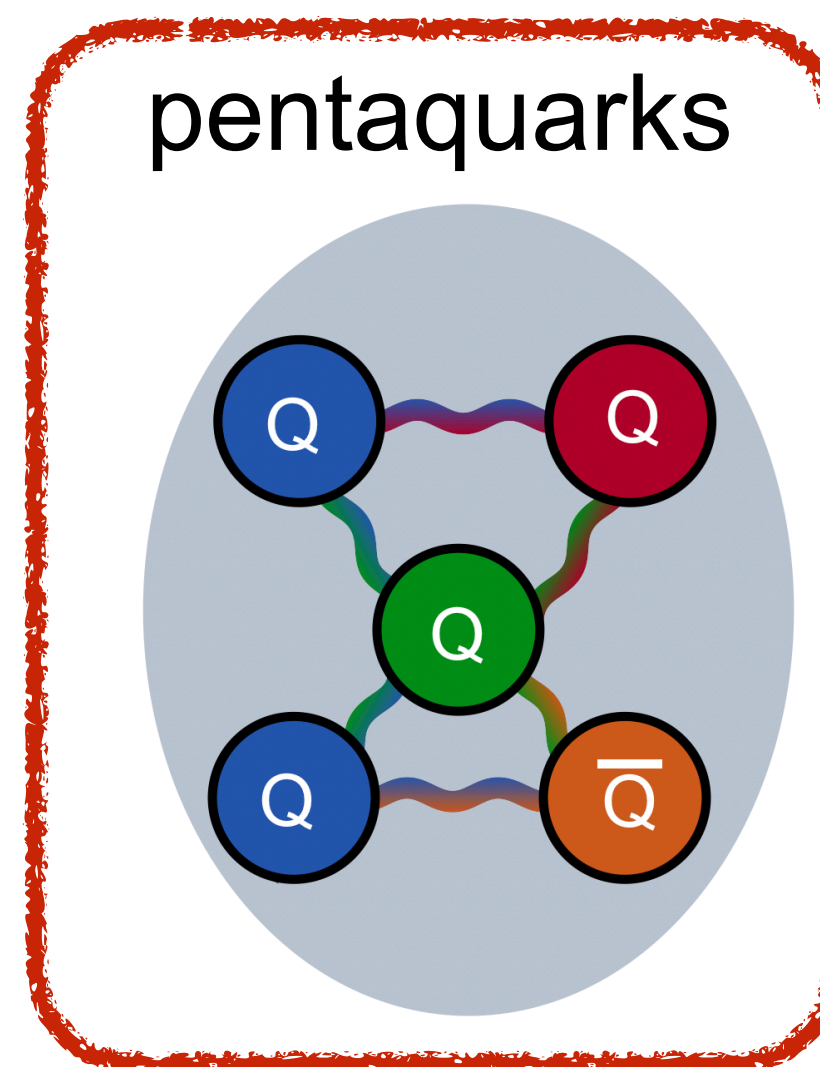
Exotic matter



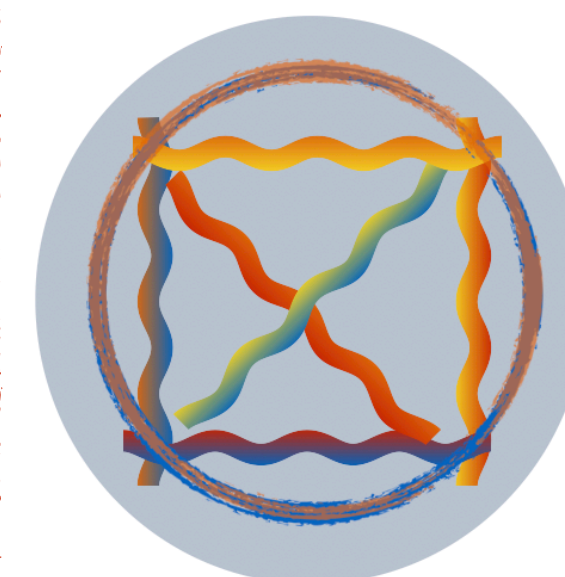
tetraquarks



pentaquarks

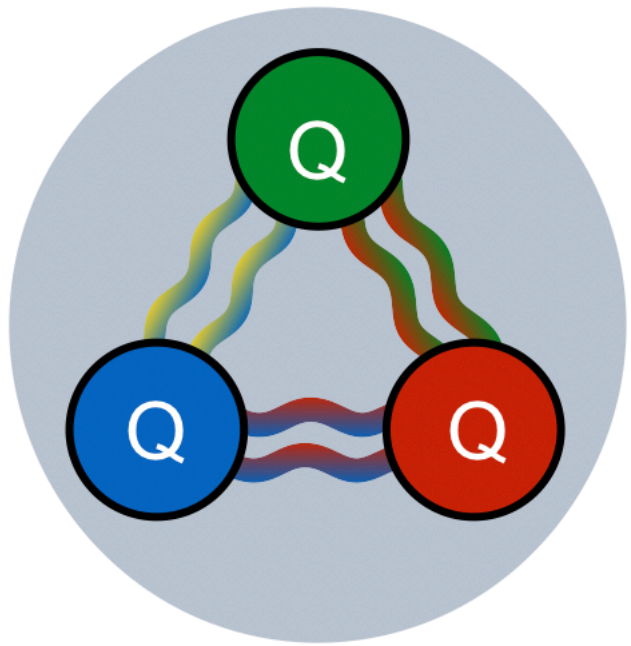


glueballs



Baryons and Mesons

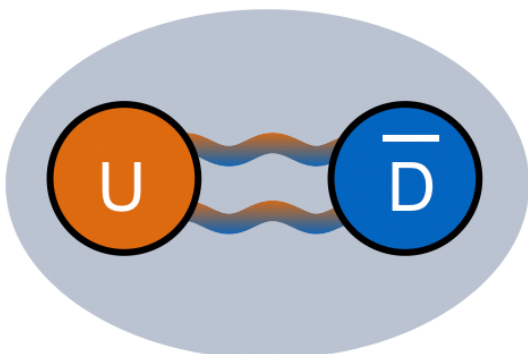
Ordinary baryons:



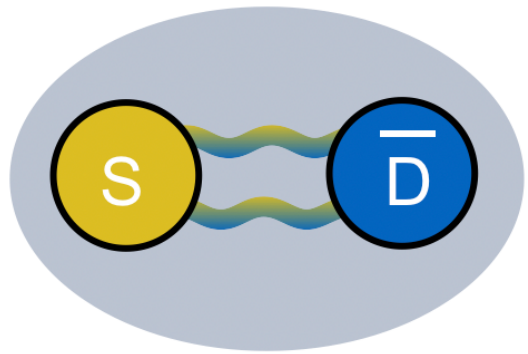
- uud proton stable
- udd neutron $\tau \sim 10^3 s$
- uds baryon Λ $\tau \sim 10^{-10} s$
- uuu baryon Δ $\tau \sim 10^{-24} s$

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

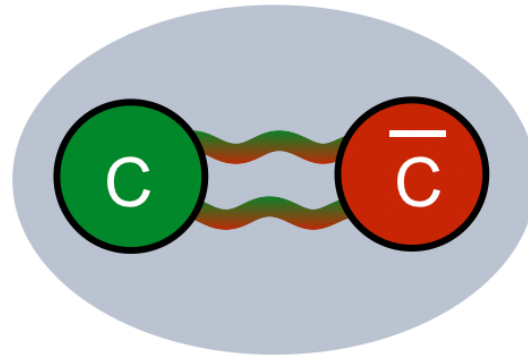
Ordinary mesons



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

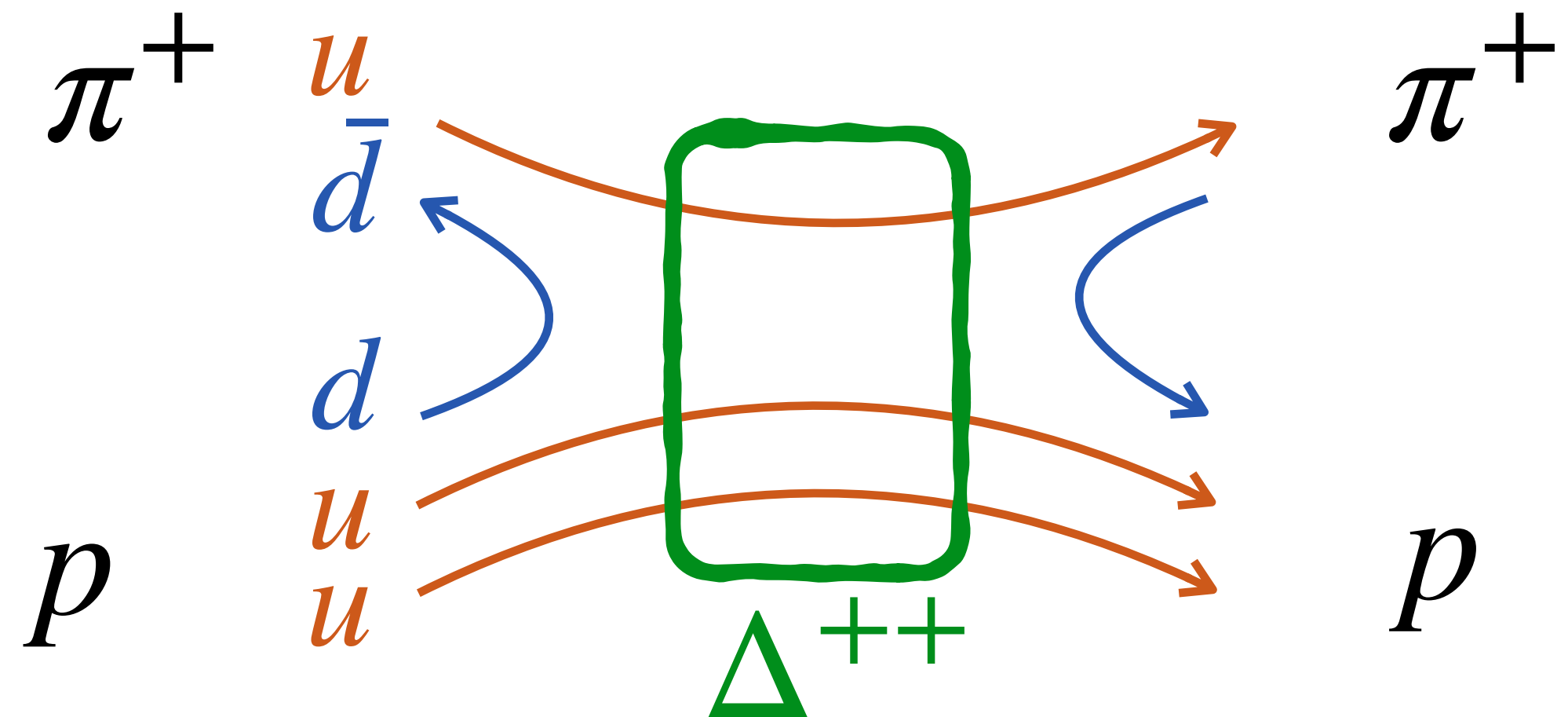


kaon $\tau \sim 10^{-8} s$

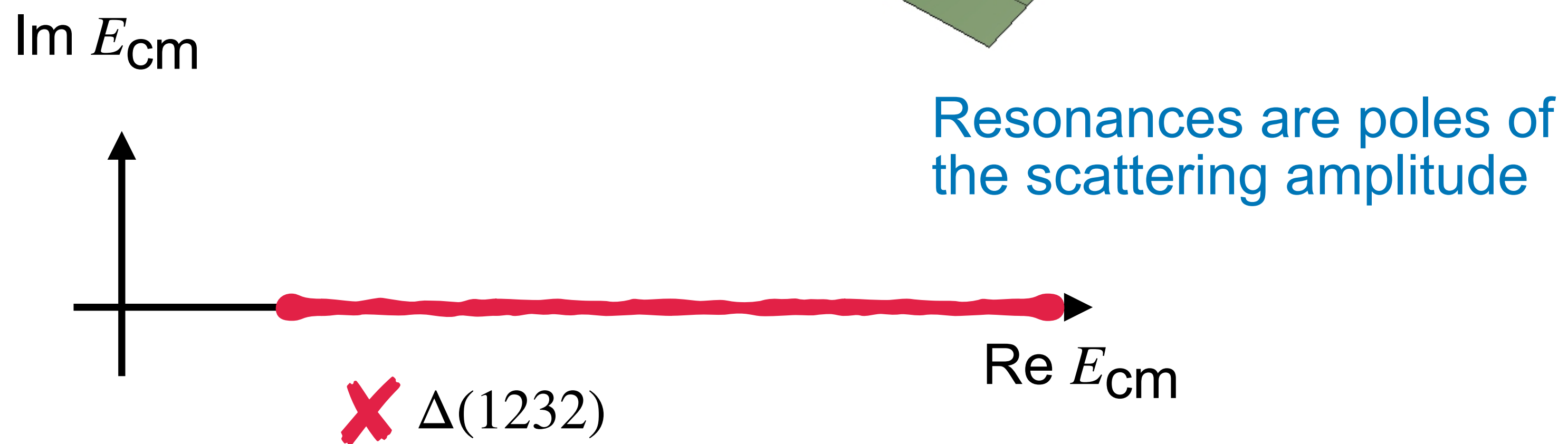
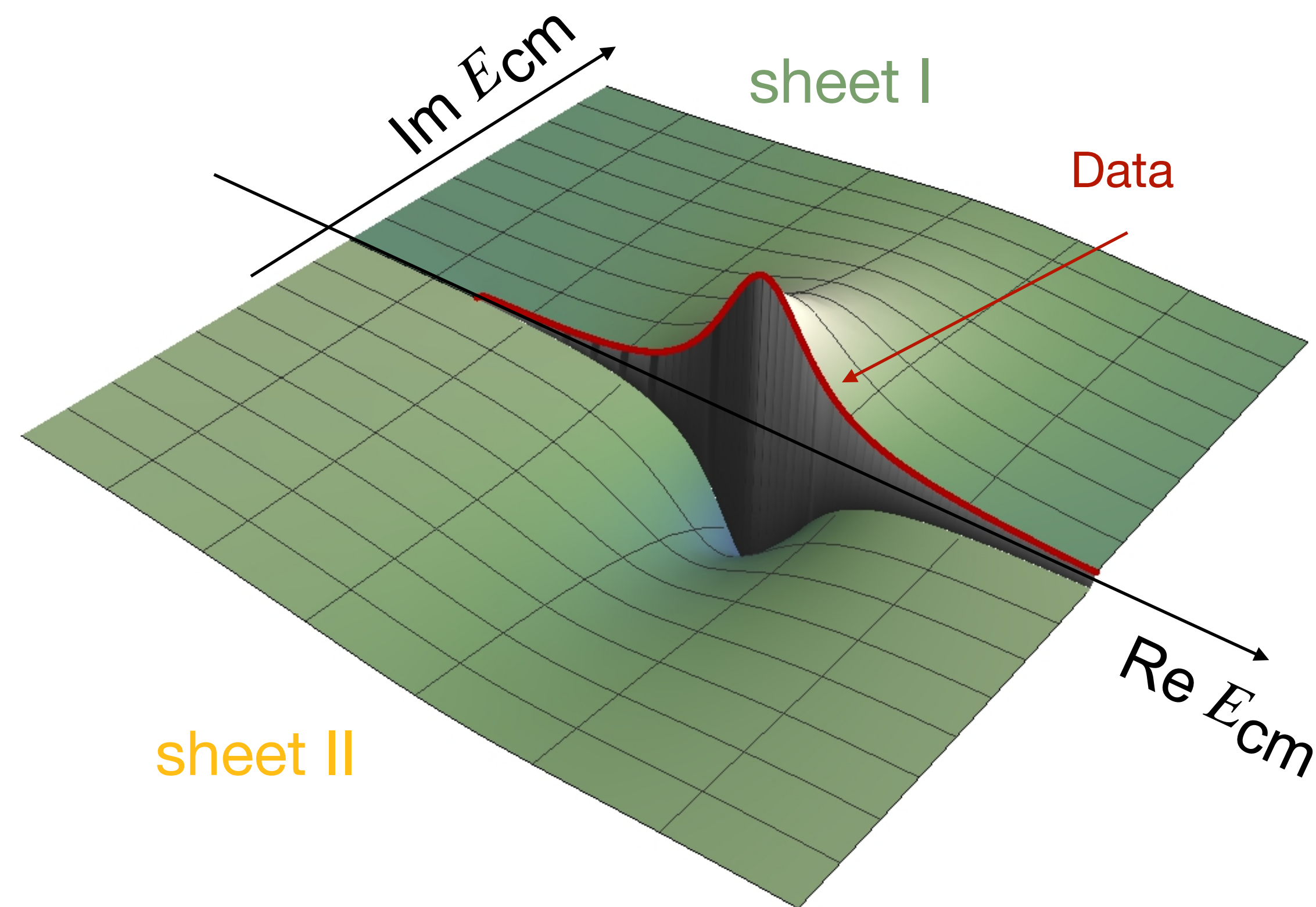
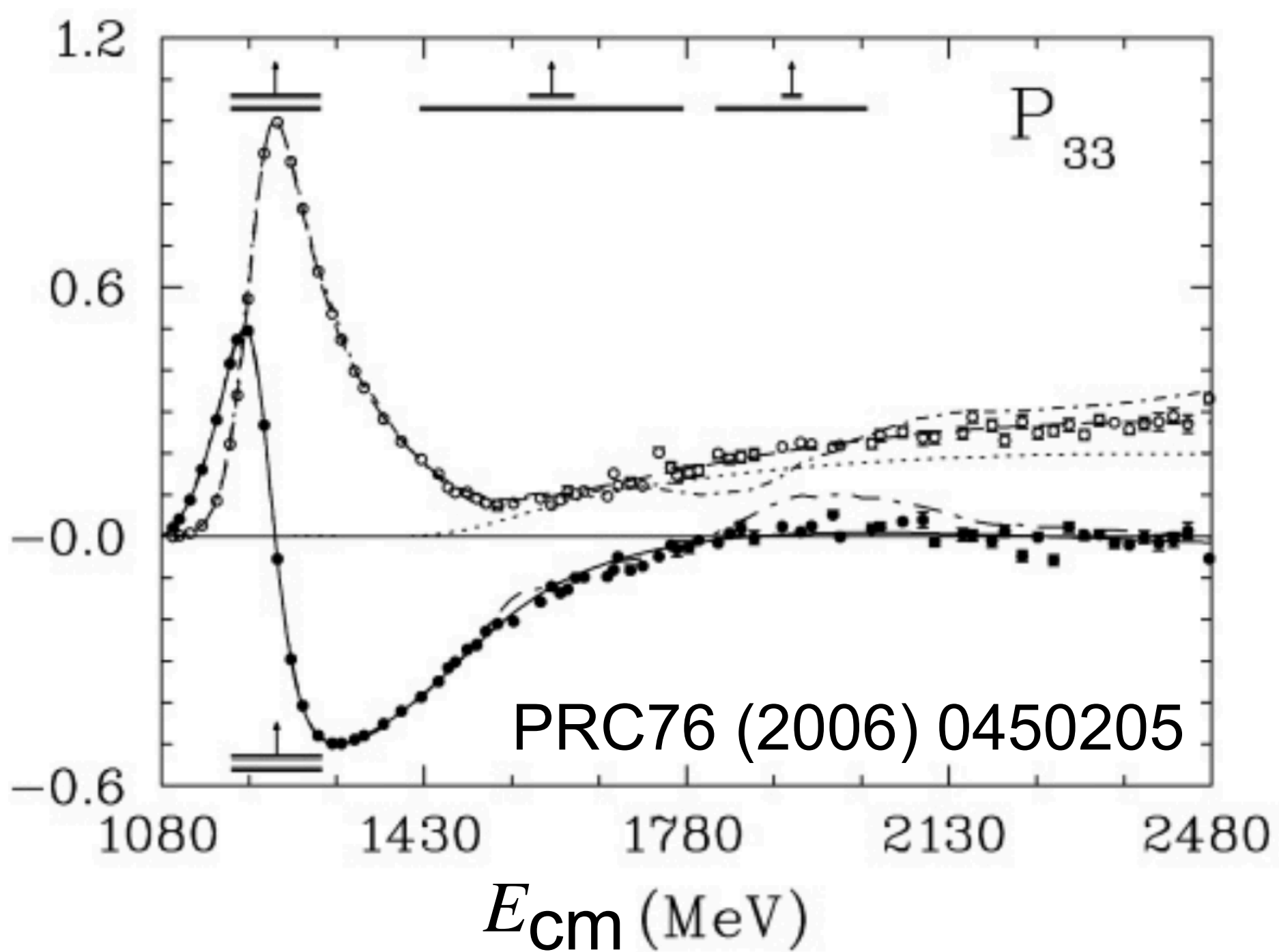
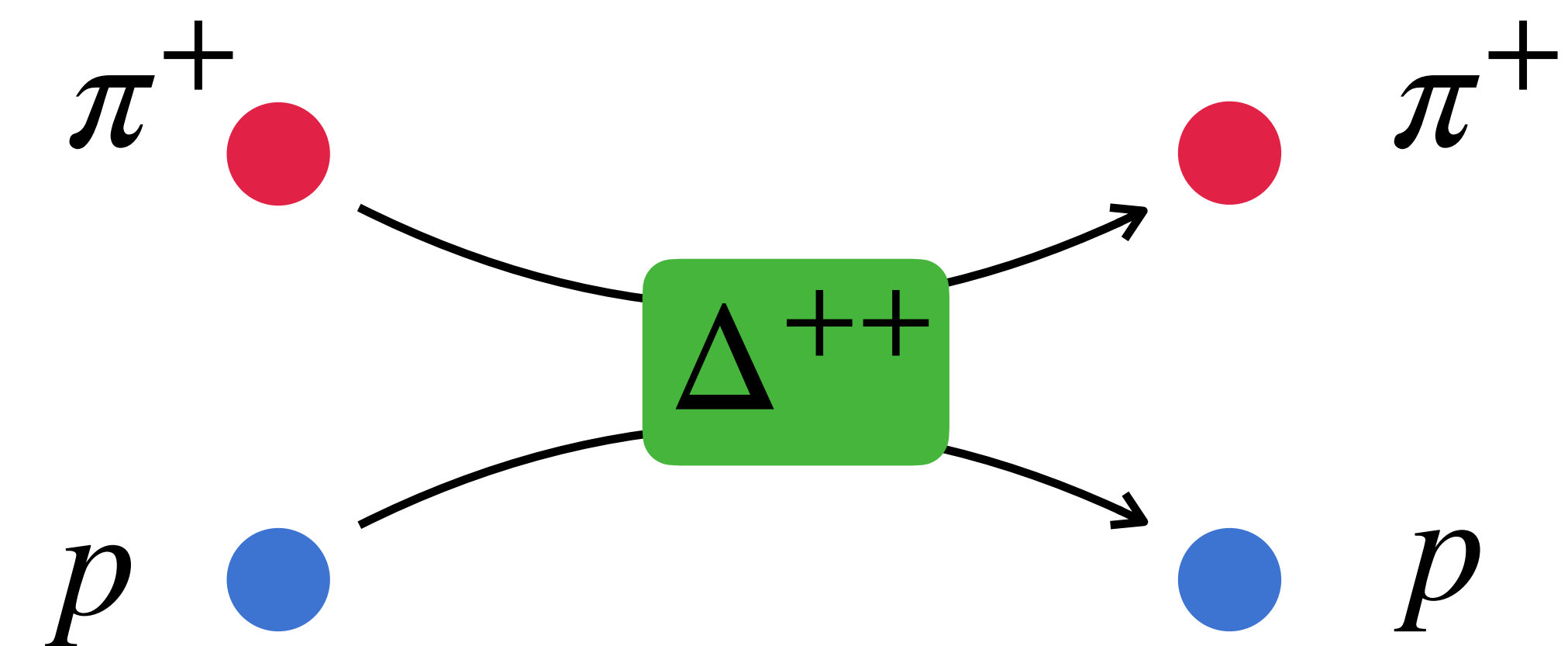


J/ψ $\tau \sim 10^{-20} s$

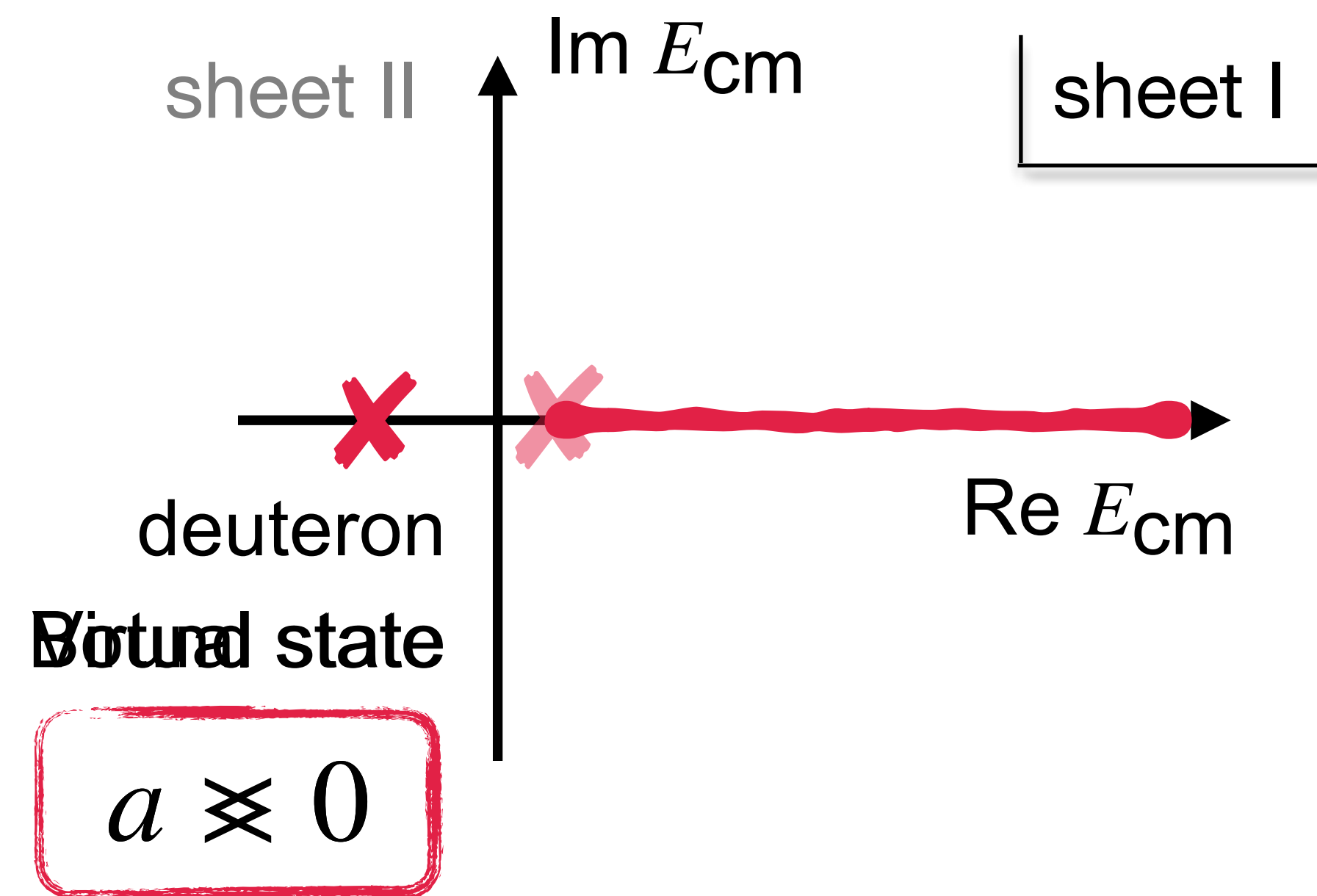
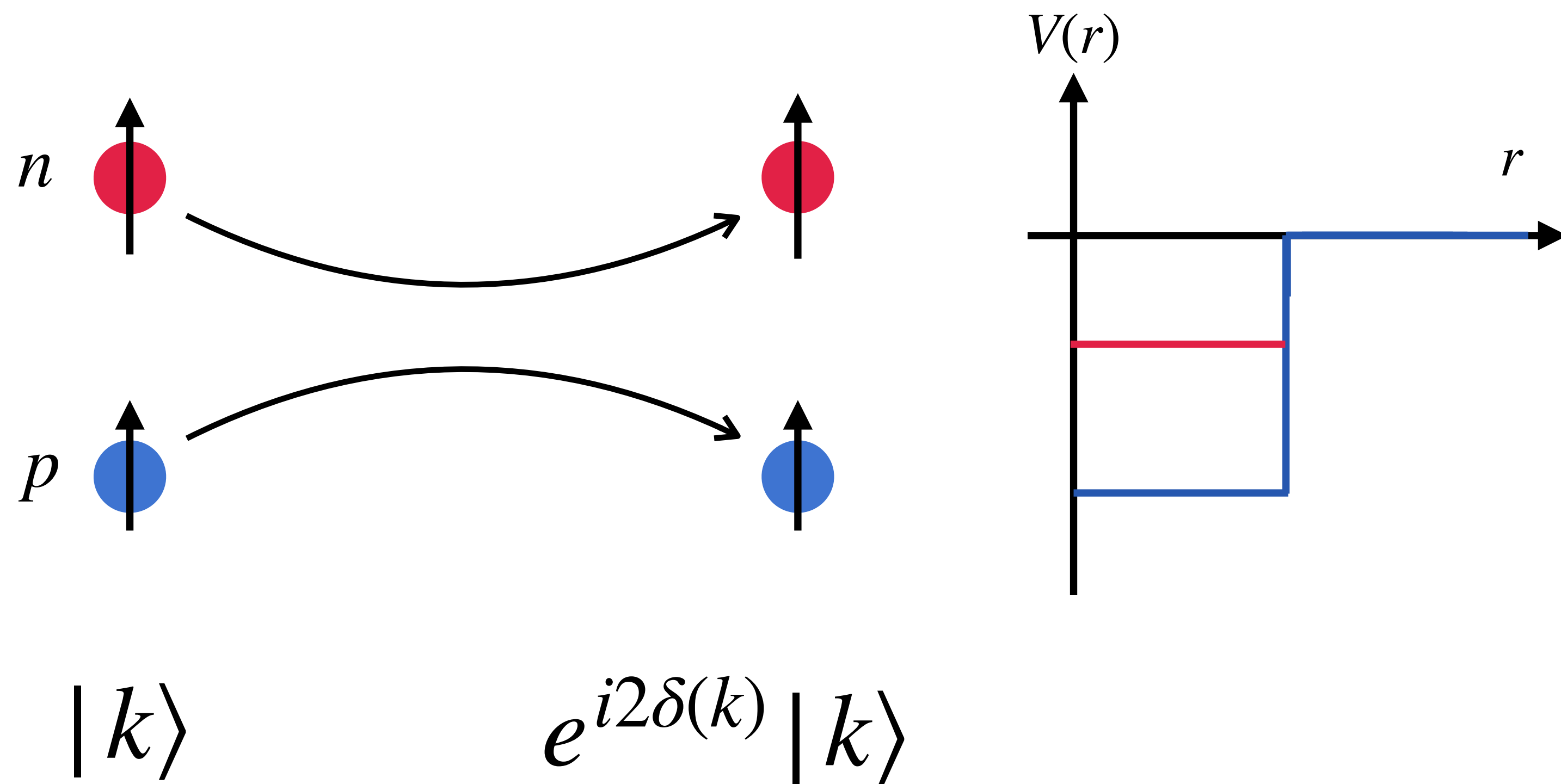
$$\pi^+ p \rightarrow \Delta^{+++} \rightarrow \pi^+ p$$



What's a resonance?



Bound state vs virtual state

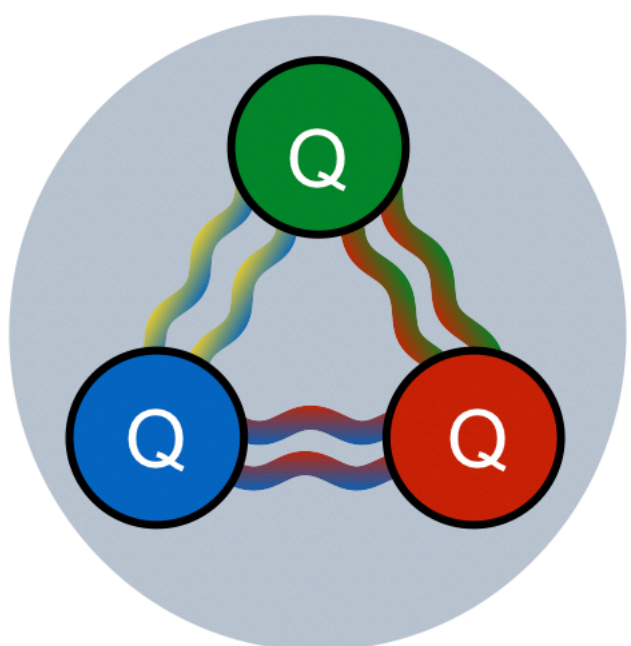


Scattering length $a = \lim_{k \rightarrow 0} \frac{1}{k} \tan \delta(k)$

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

Ordinary and Exotic Hadrons

Ordinary baryons:

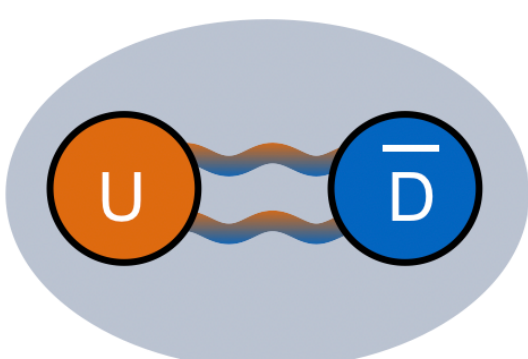


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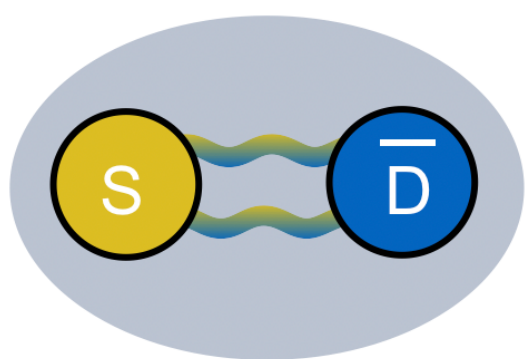
QUARKS

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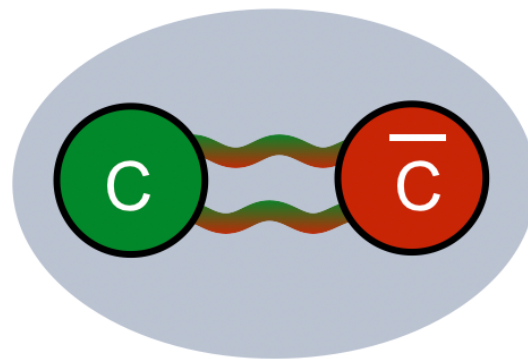
Ordinary mesons



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

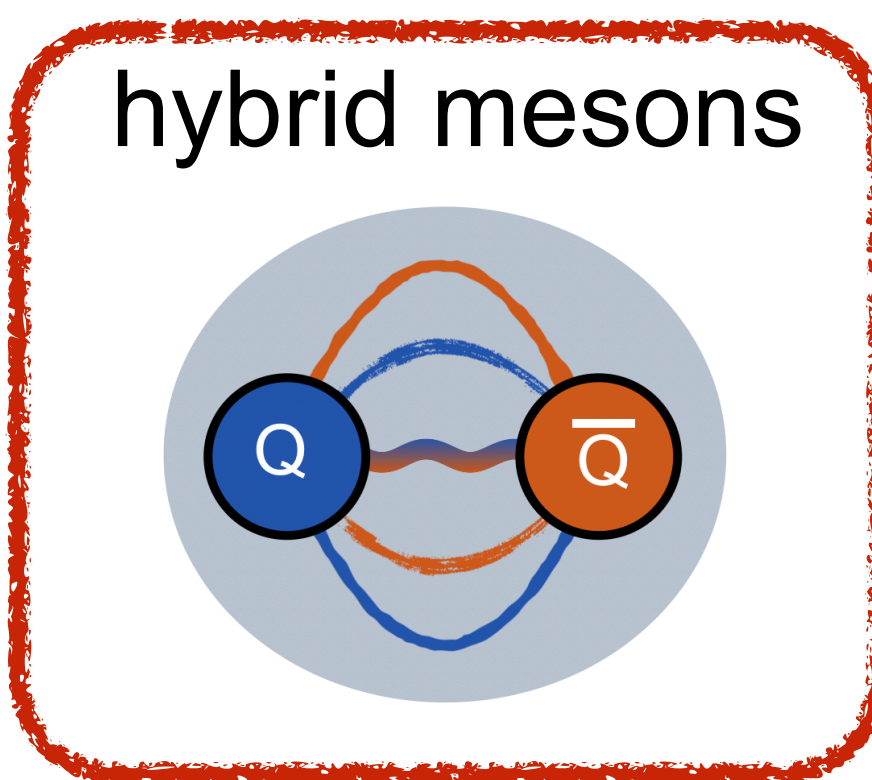


kaon $\tau \sim 10^{-8} s$



J/ψ $\tau \sim 10^{-20} s$

Exotic matter

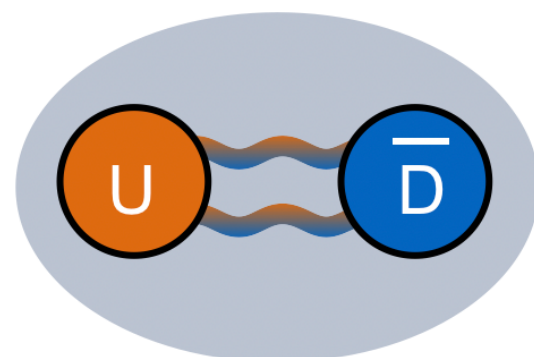


Meson with excited gluon field

Gluon field may carry quantum numbers

Quantum Numbers

Ordinary mesons



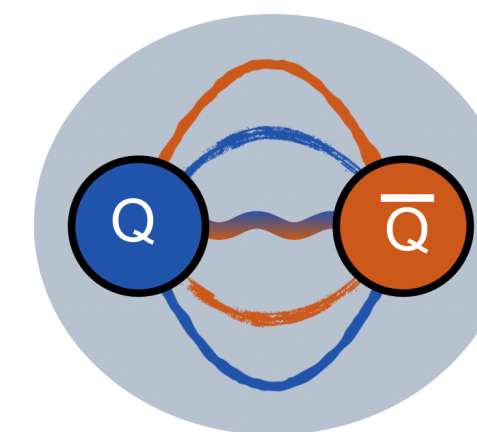
$$\vec{J} = \vec{L} \oplus \vec{S}$$

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

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

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

Exotic mesons



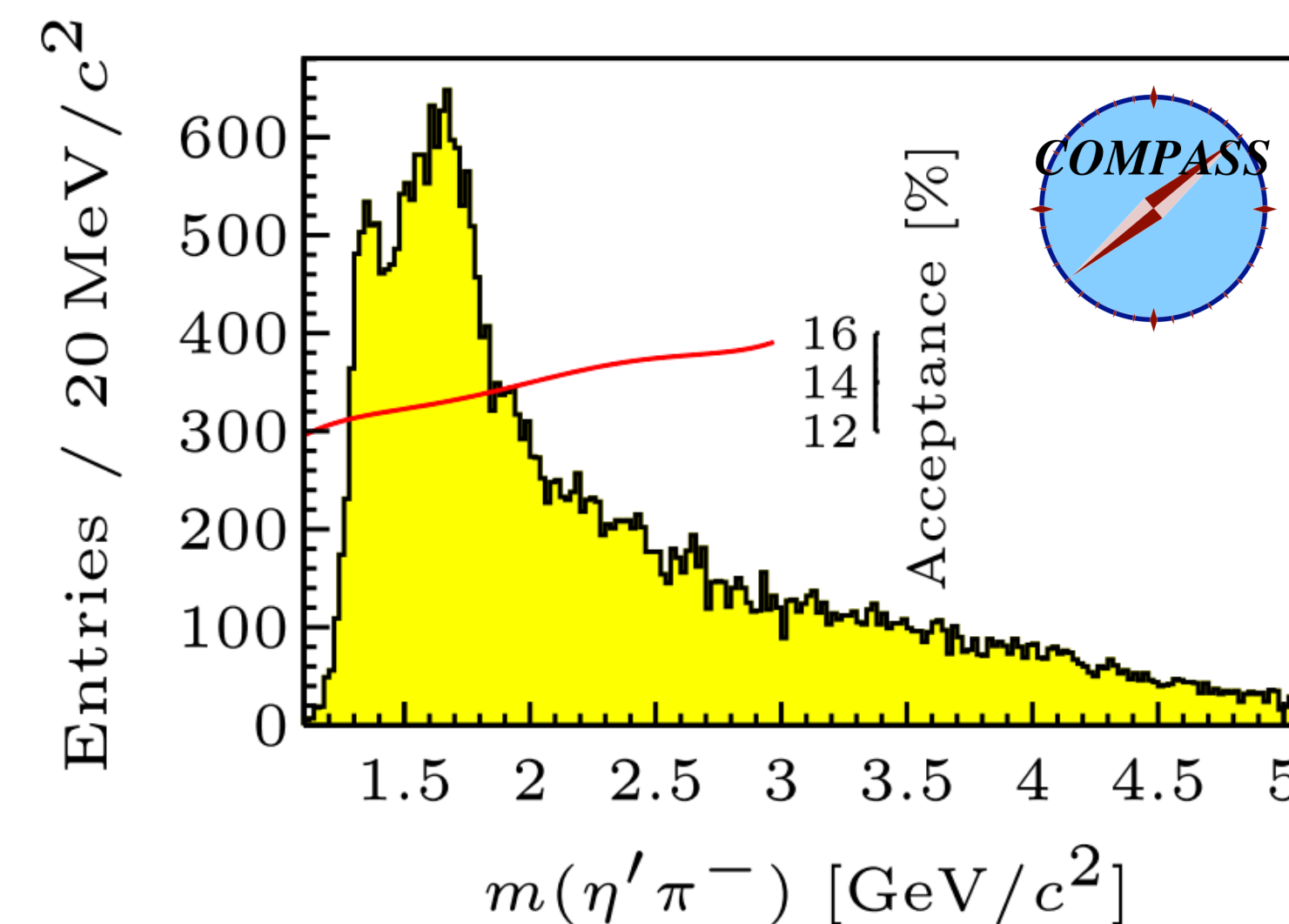
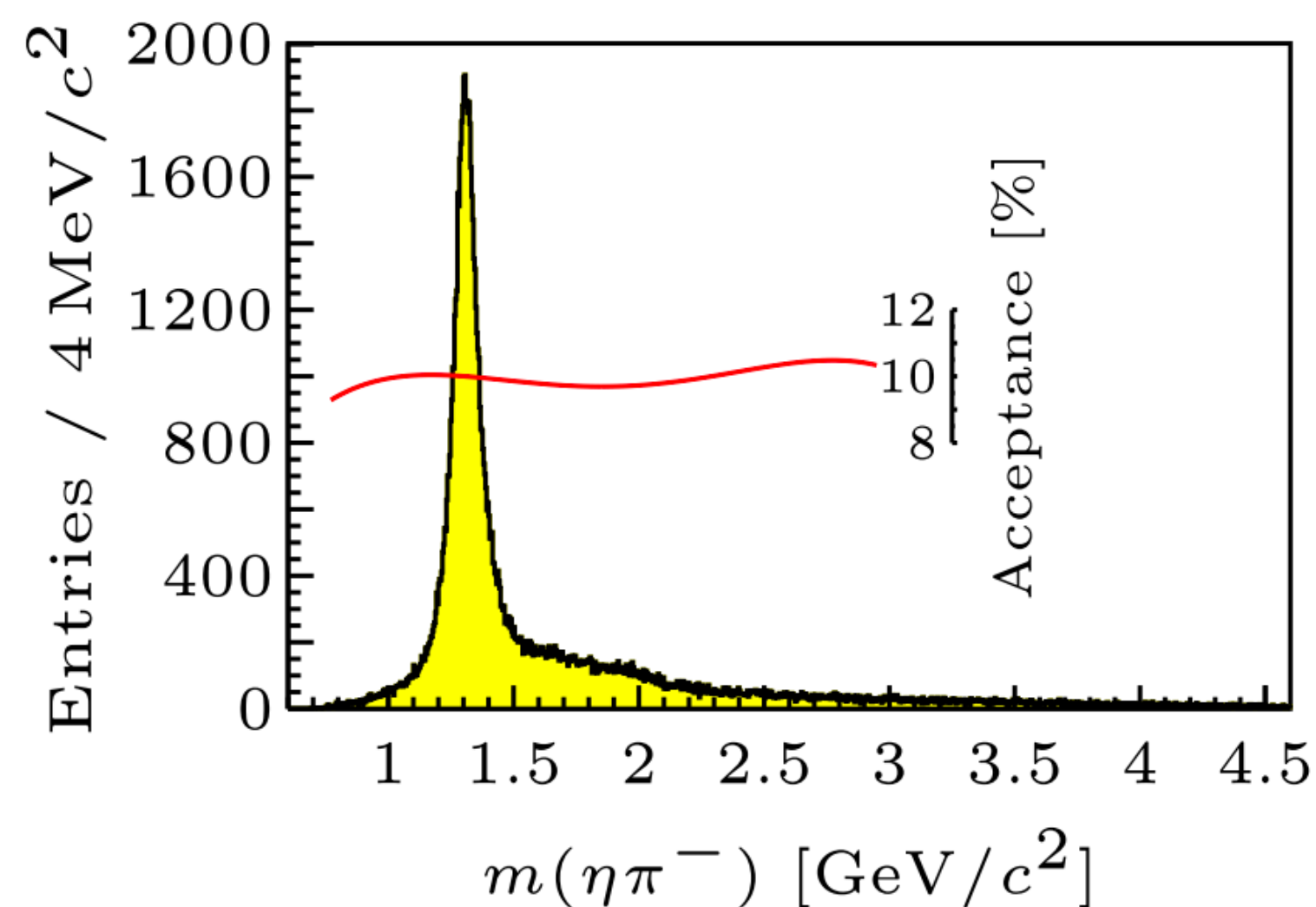
The lightest is π_1

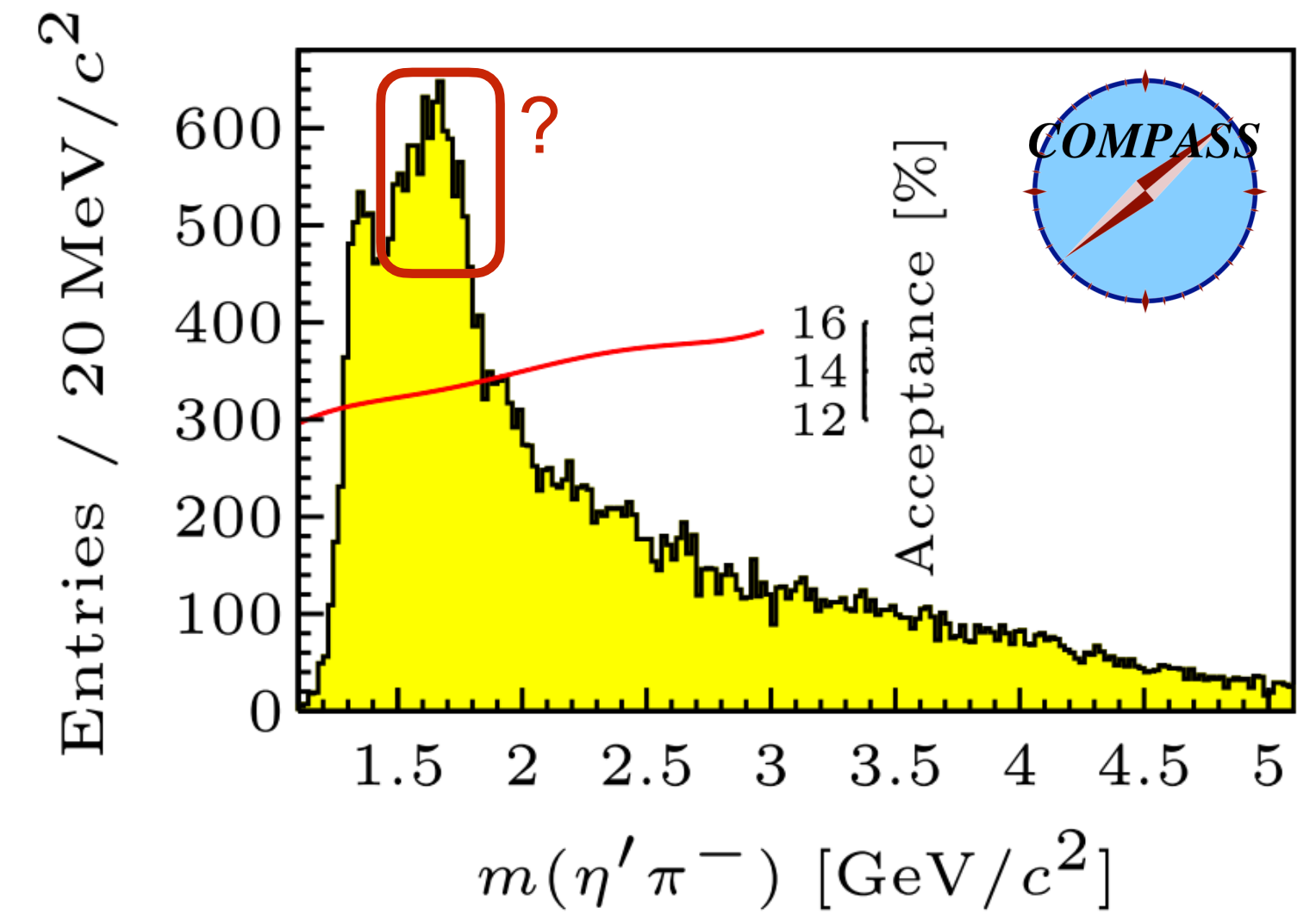
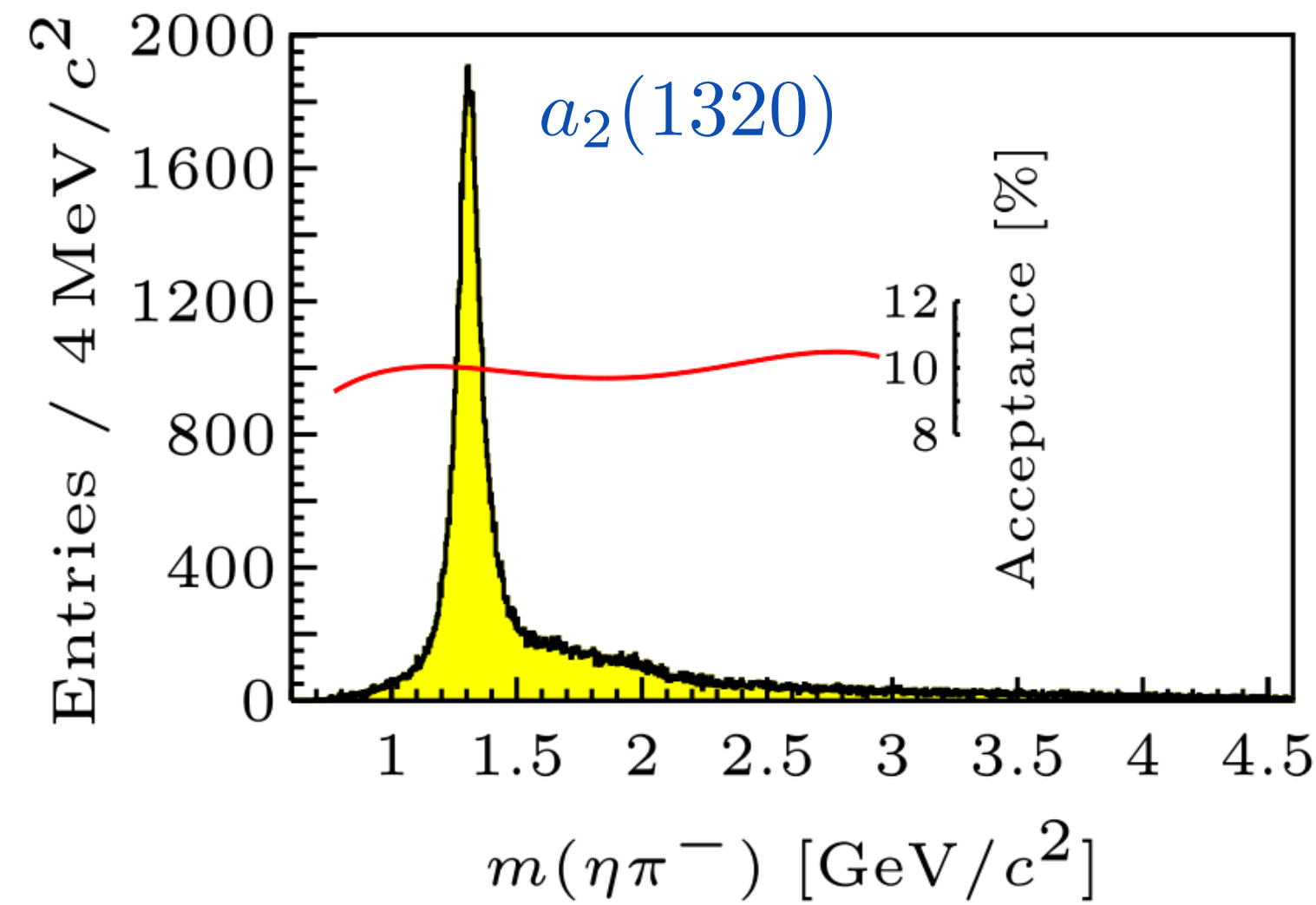
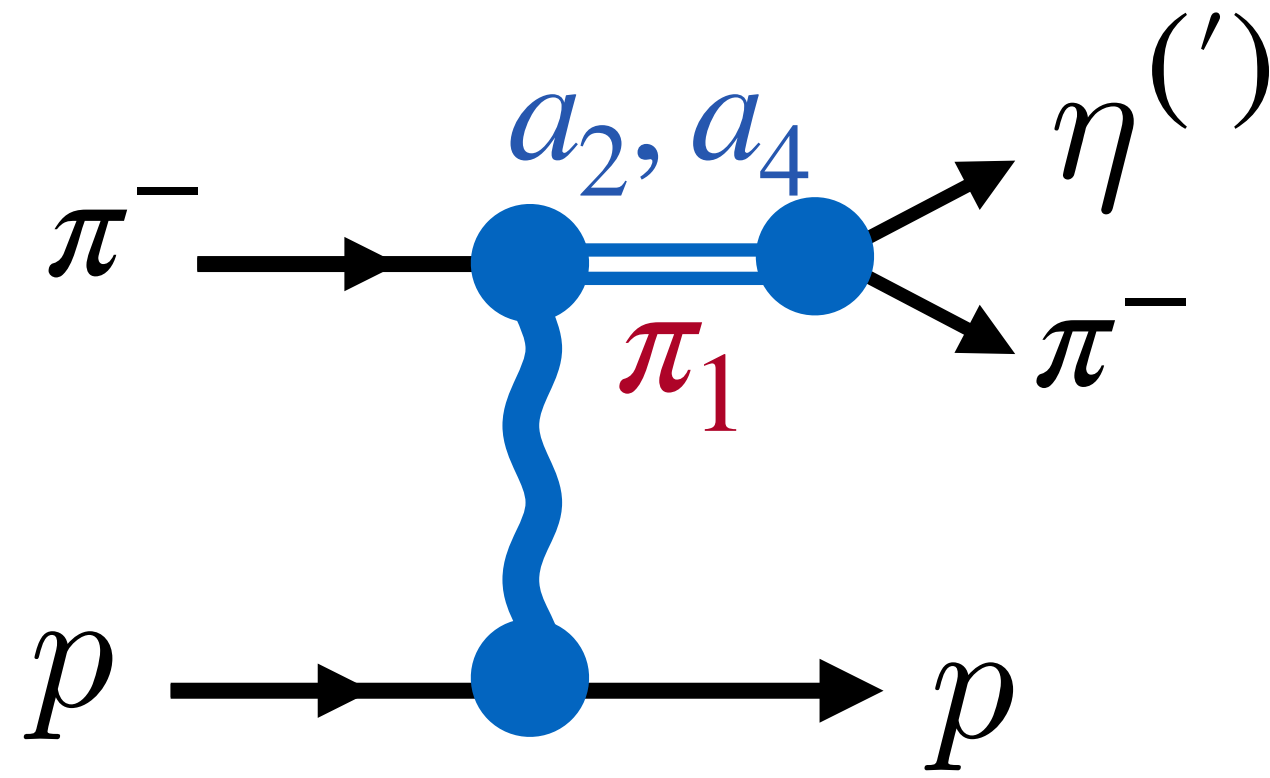
$$J^{PC} = 1^{-+}$$

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

Decay mode

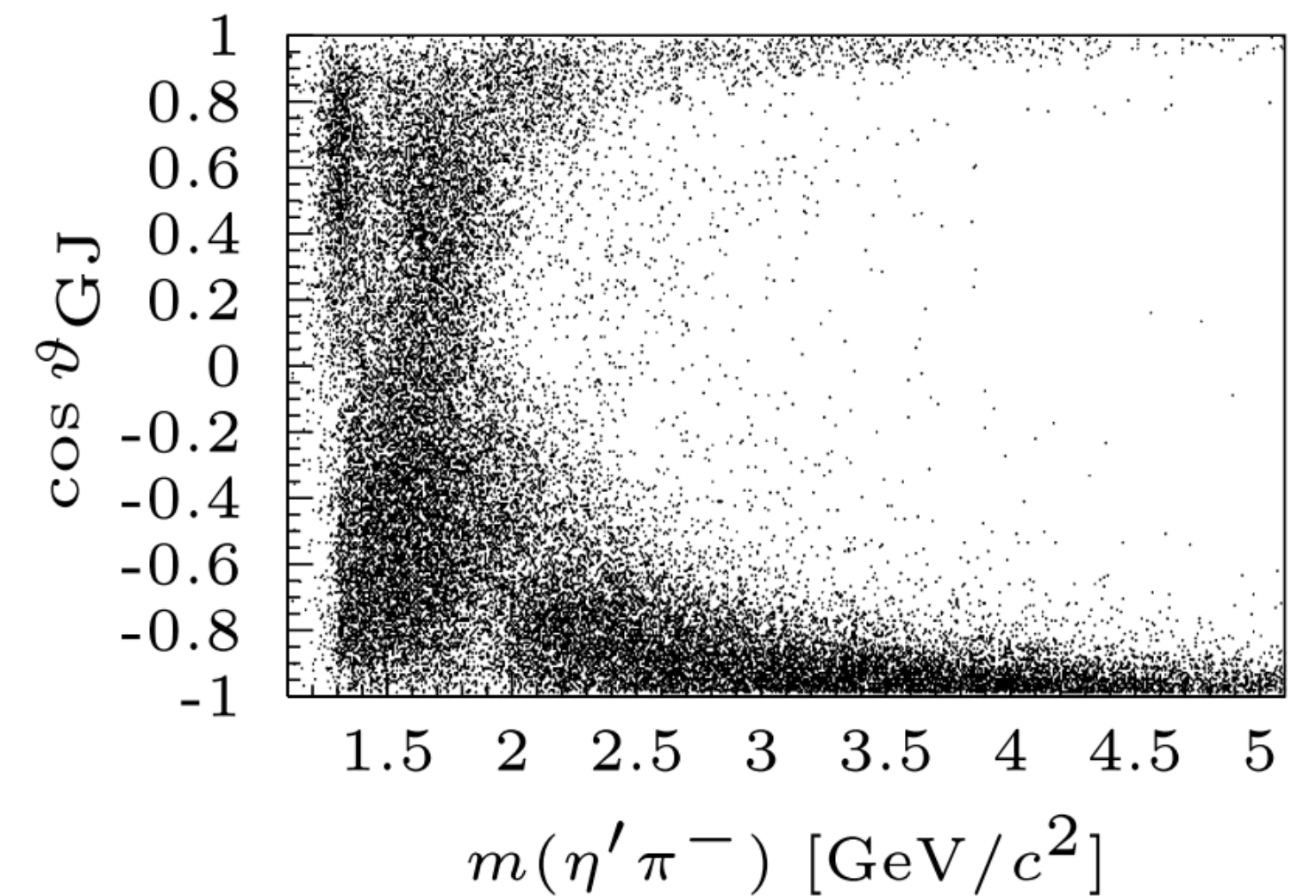
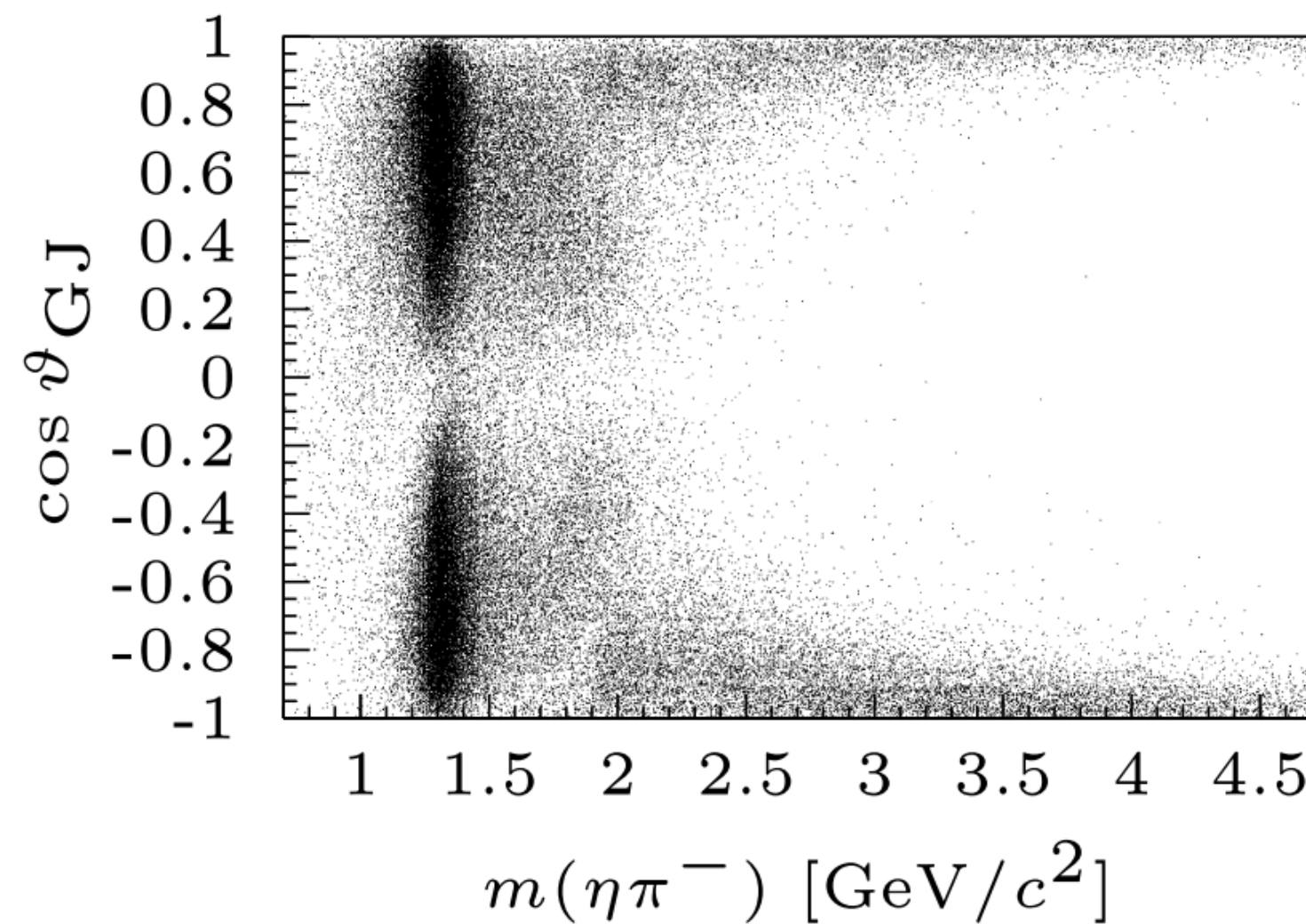
$$\pi_1 \rightarrow \eta\pi, \eta'\pi$$



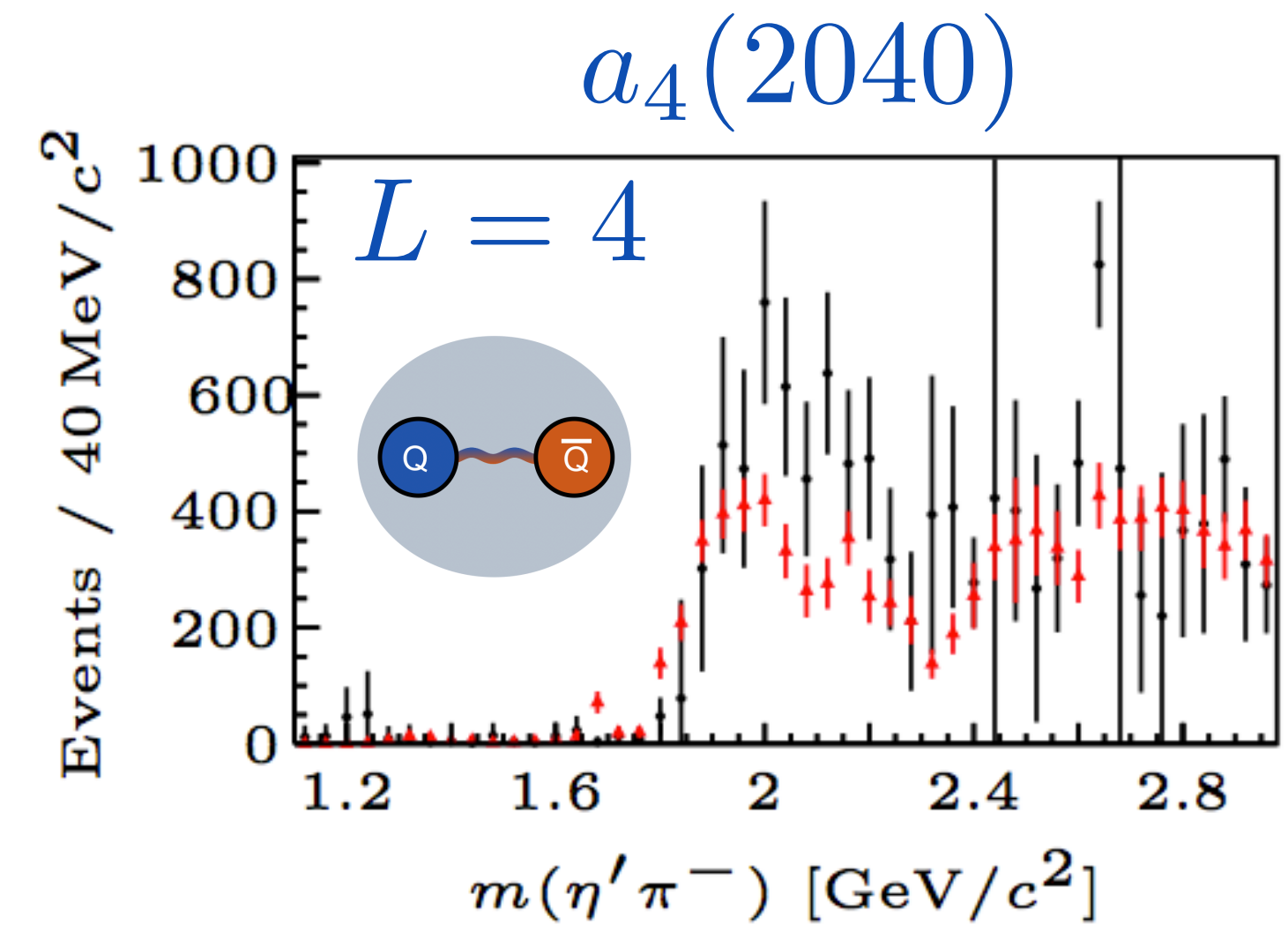
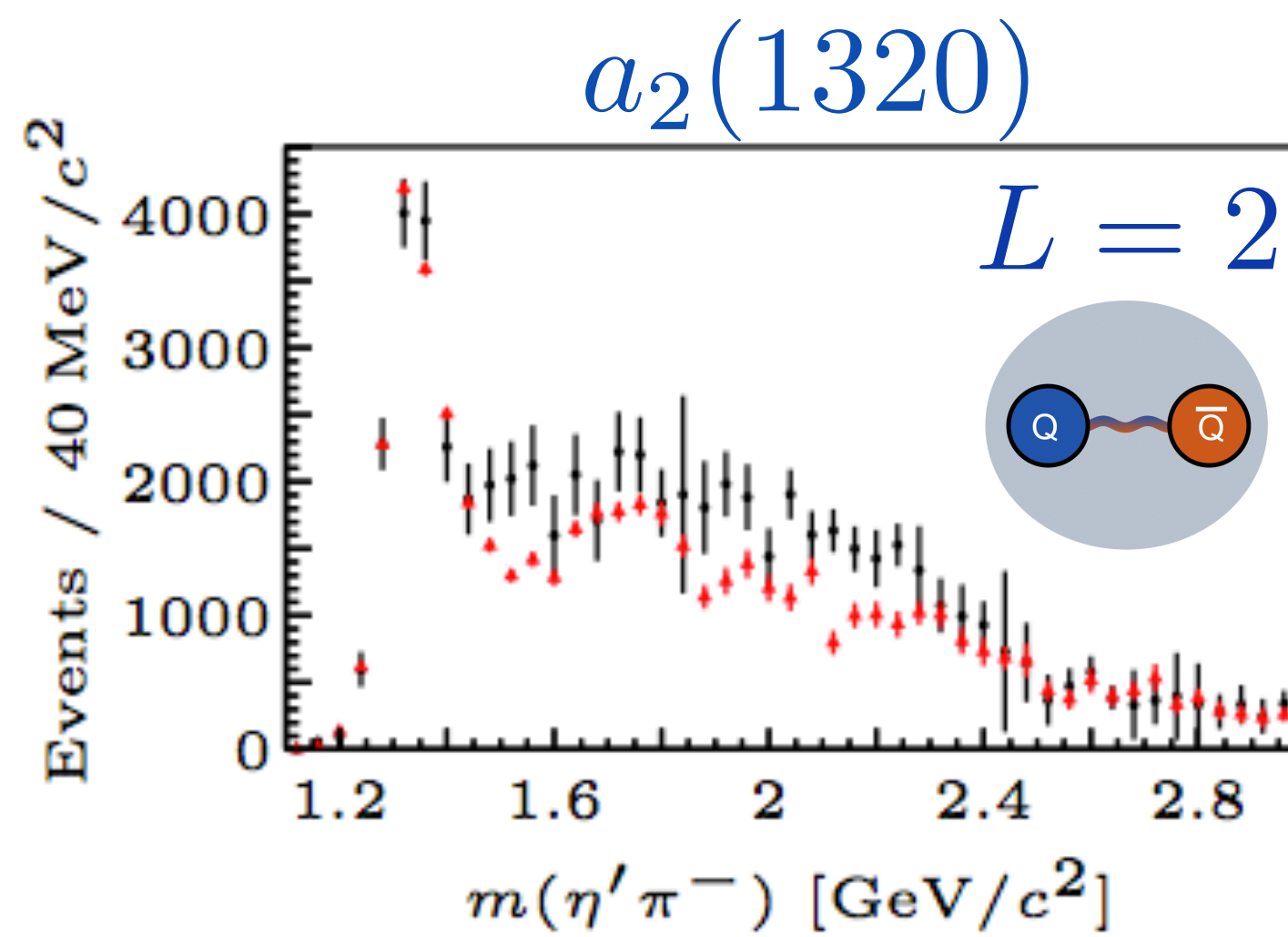
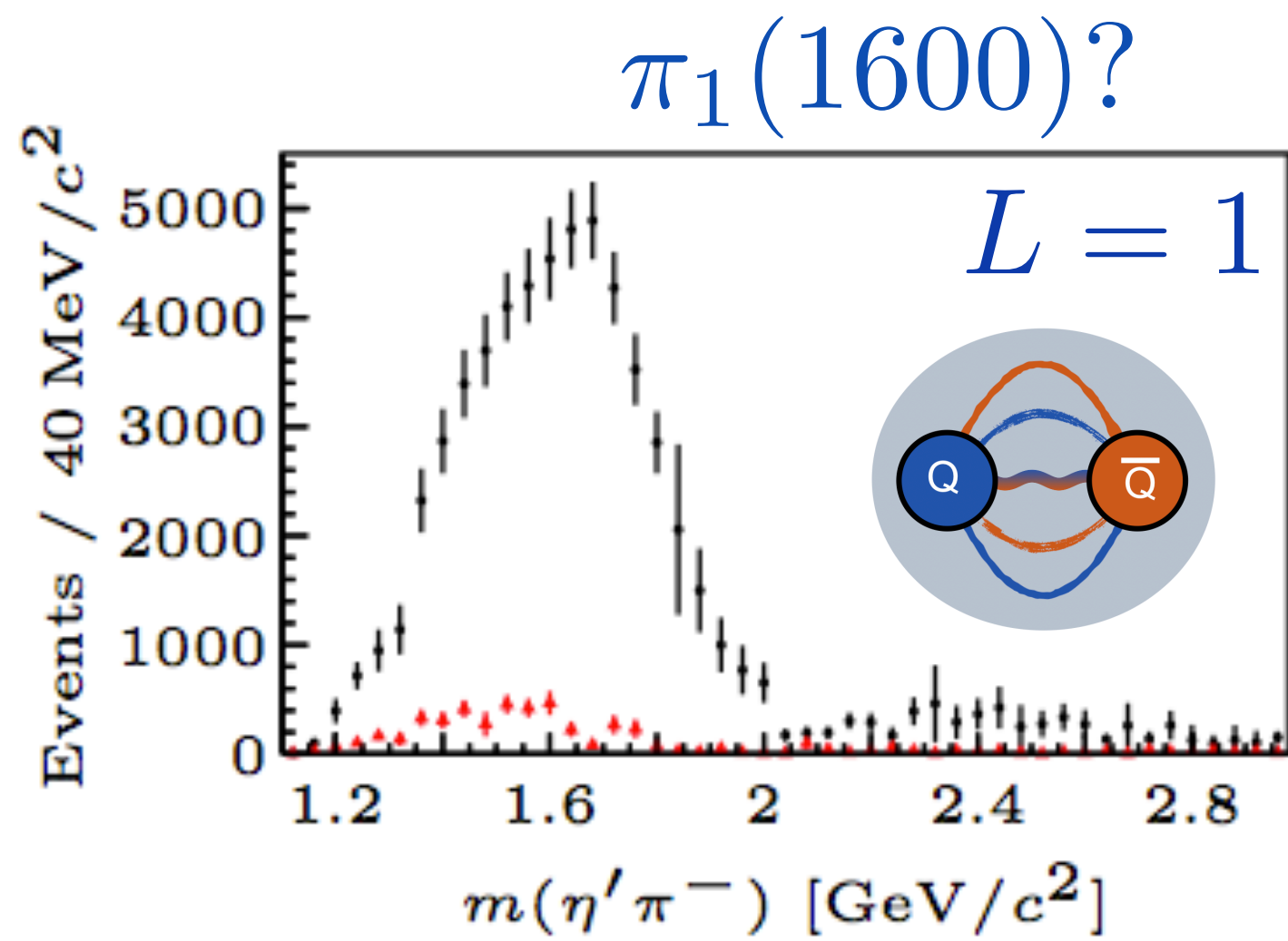
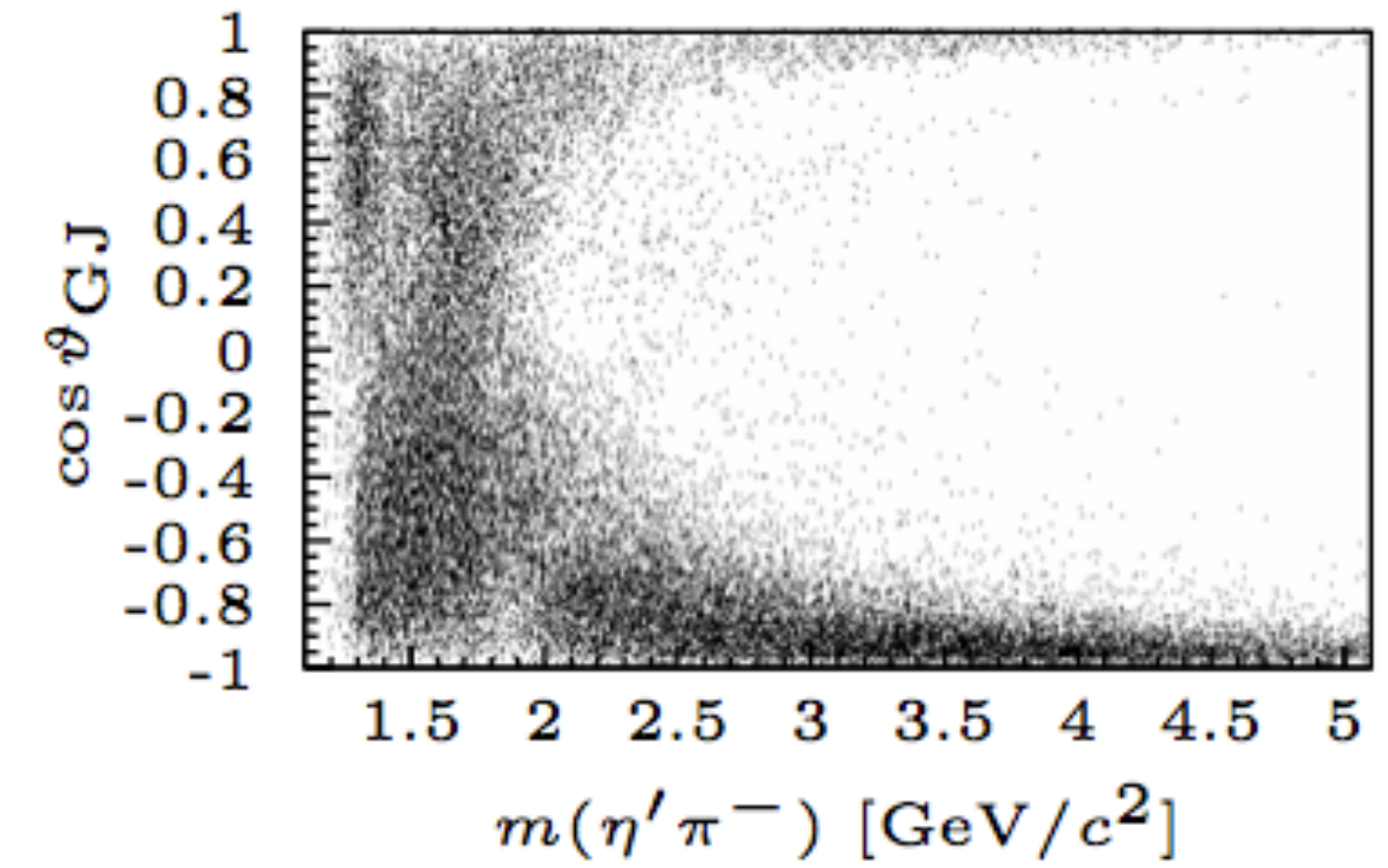
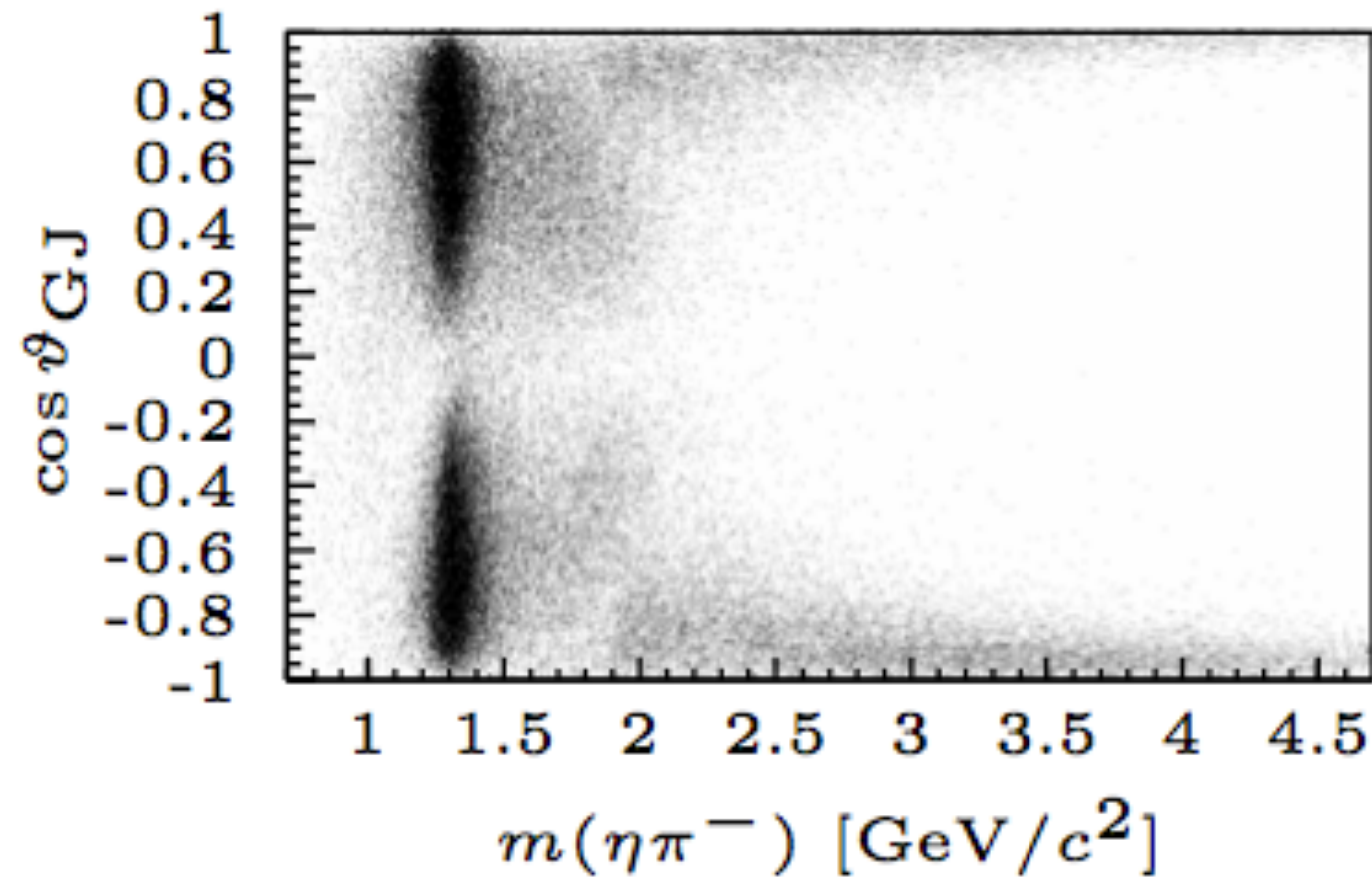
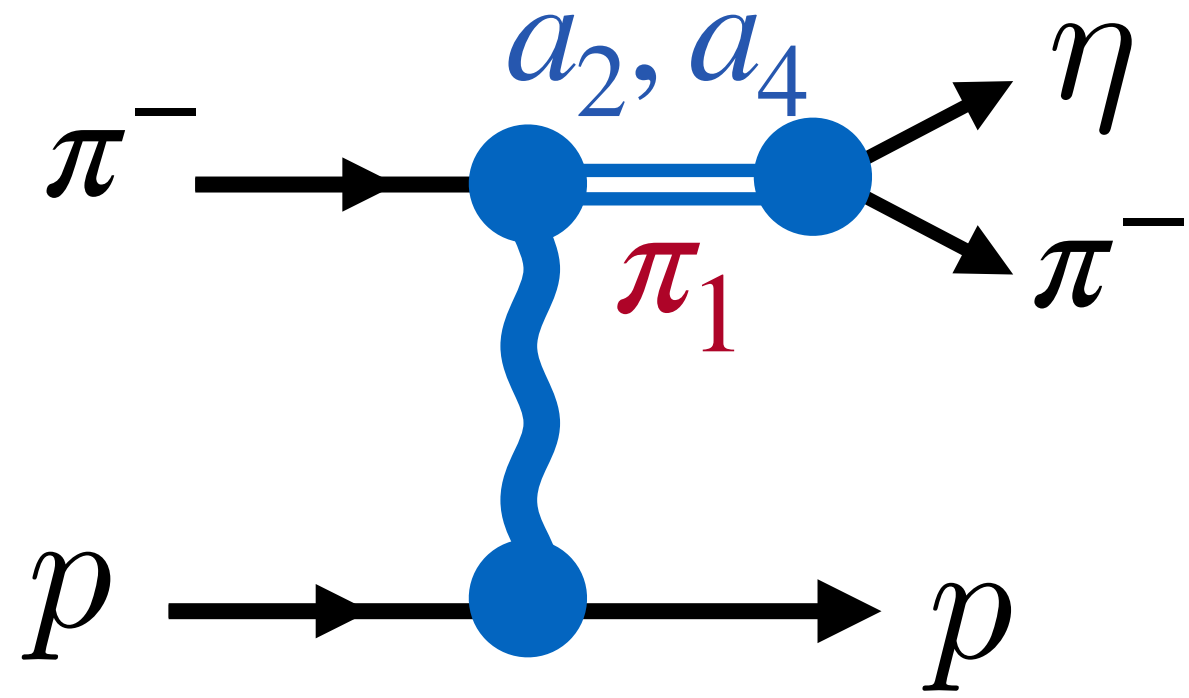


190 GeV beam,
Only natural exchanges
No scalar, $M \geq 1$

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



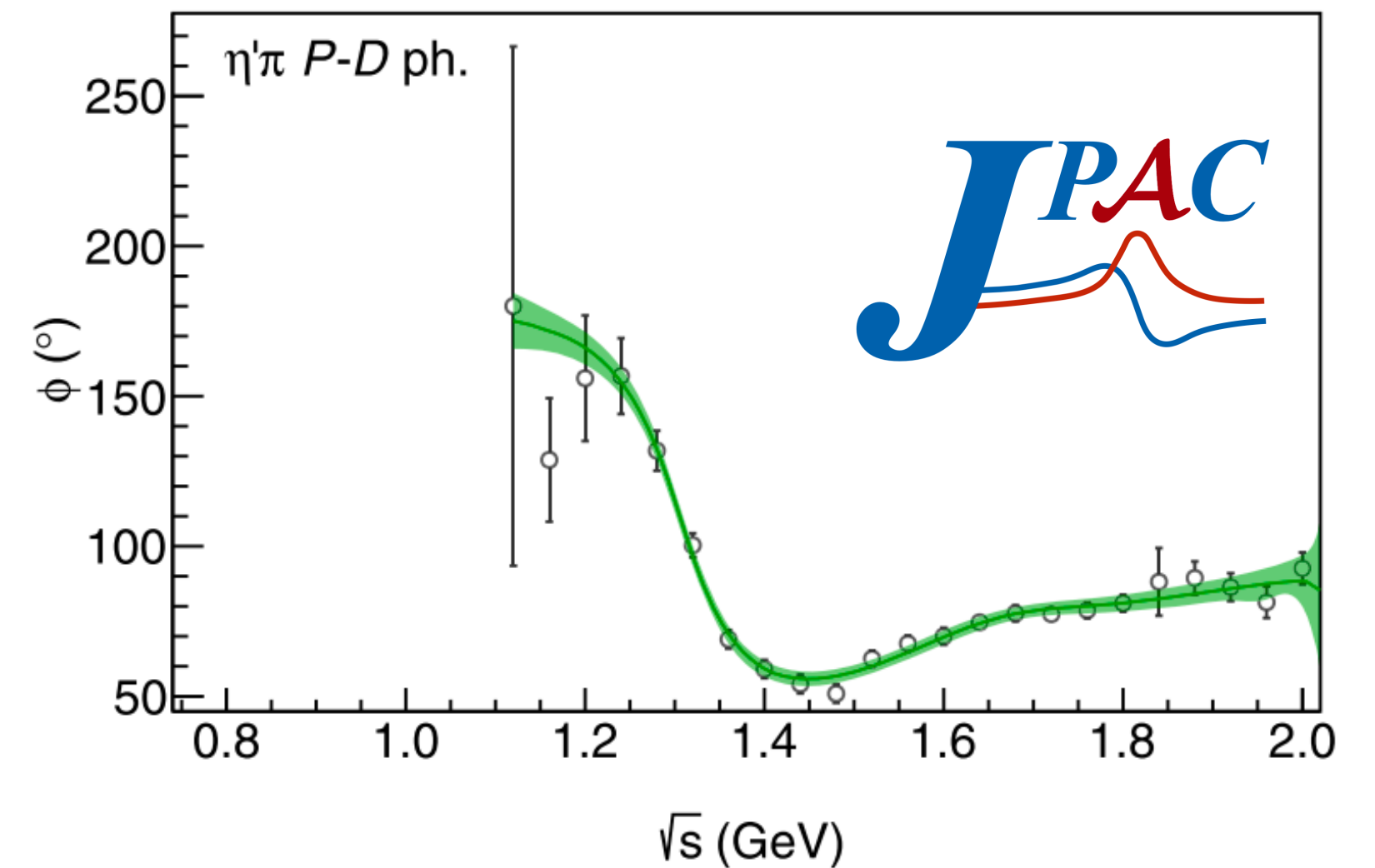
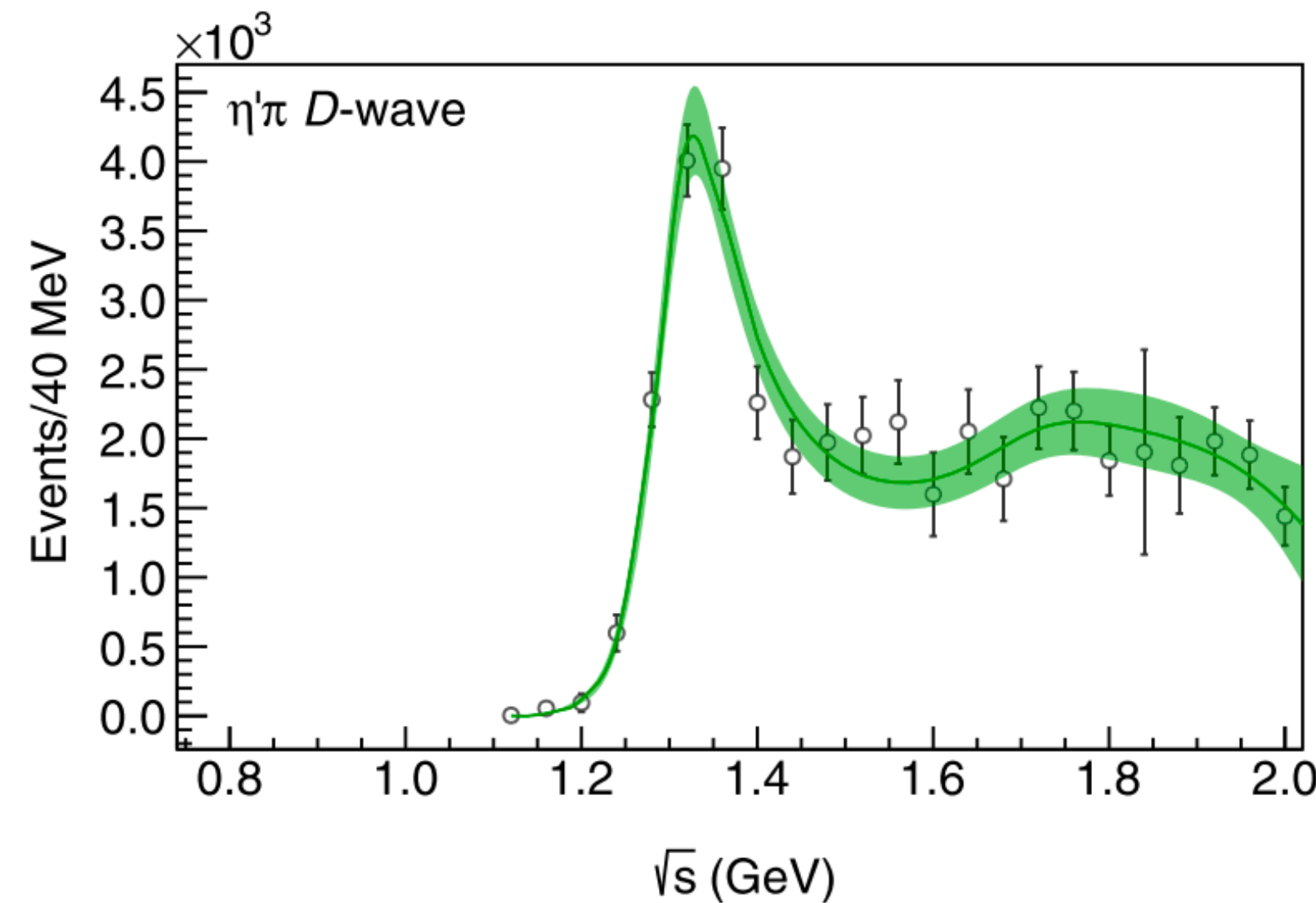
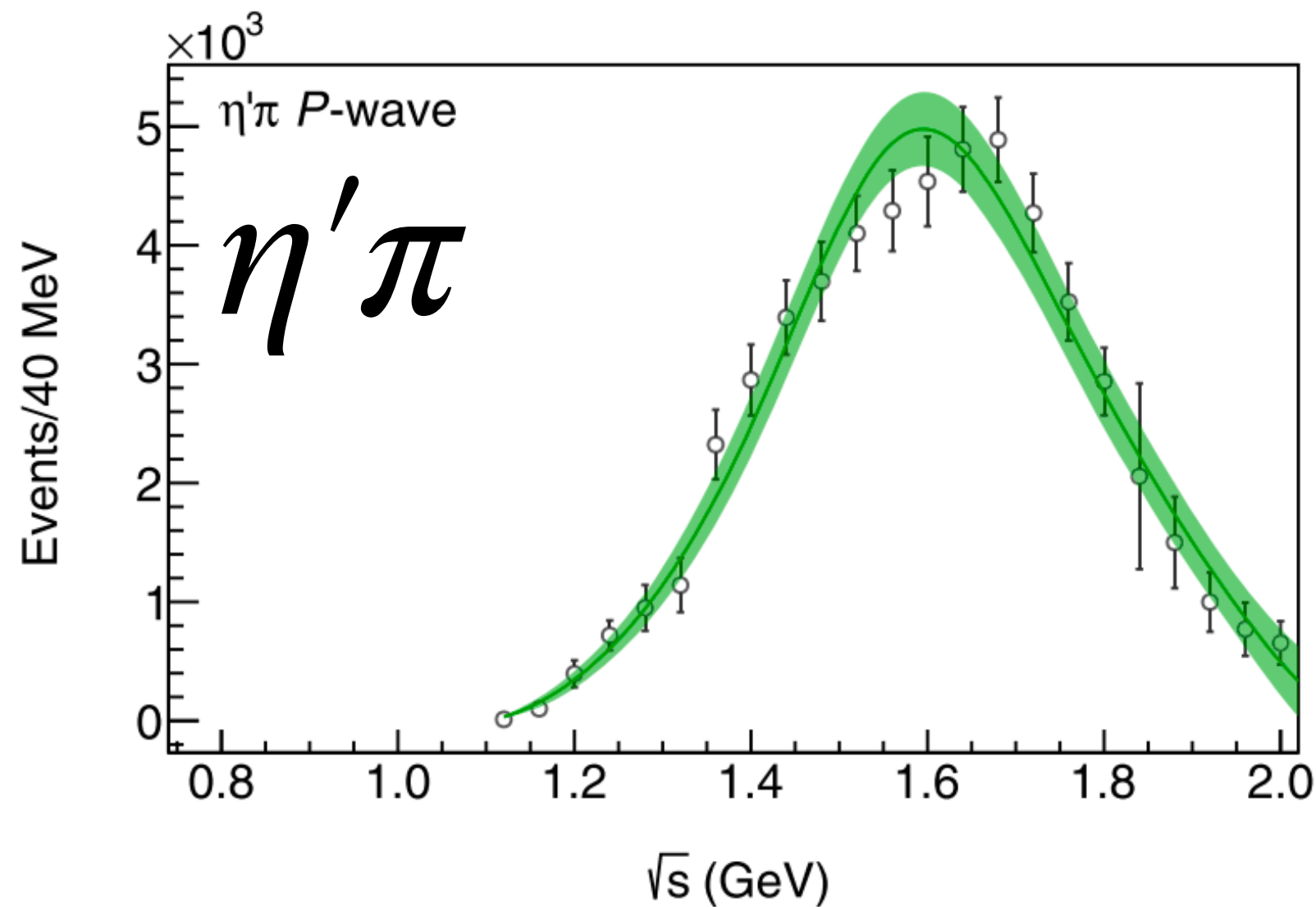
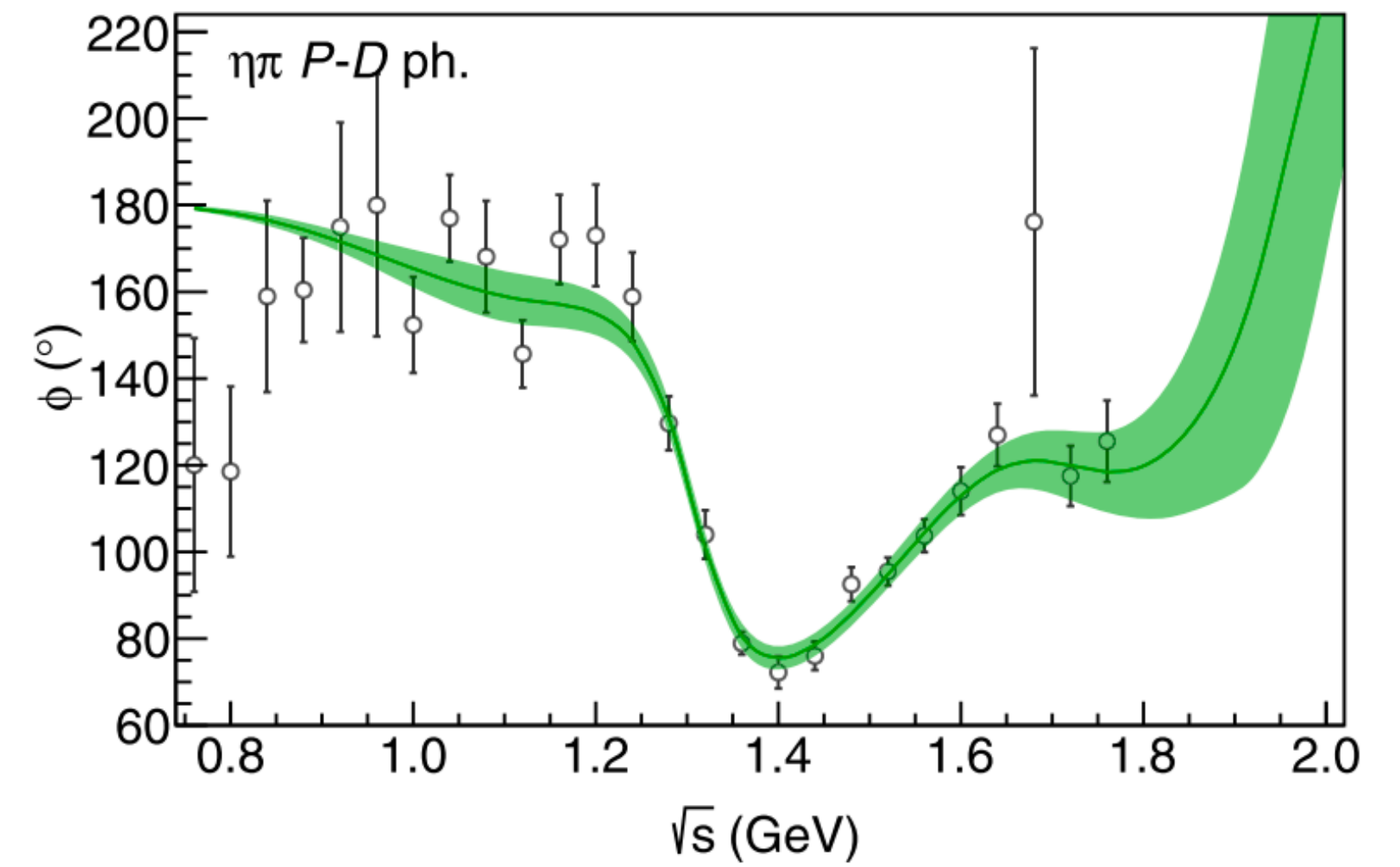
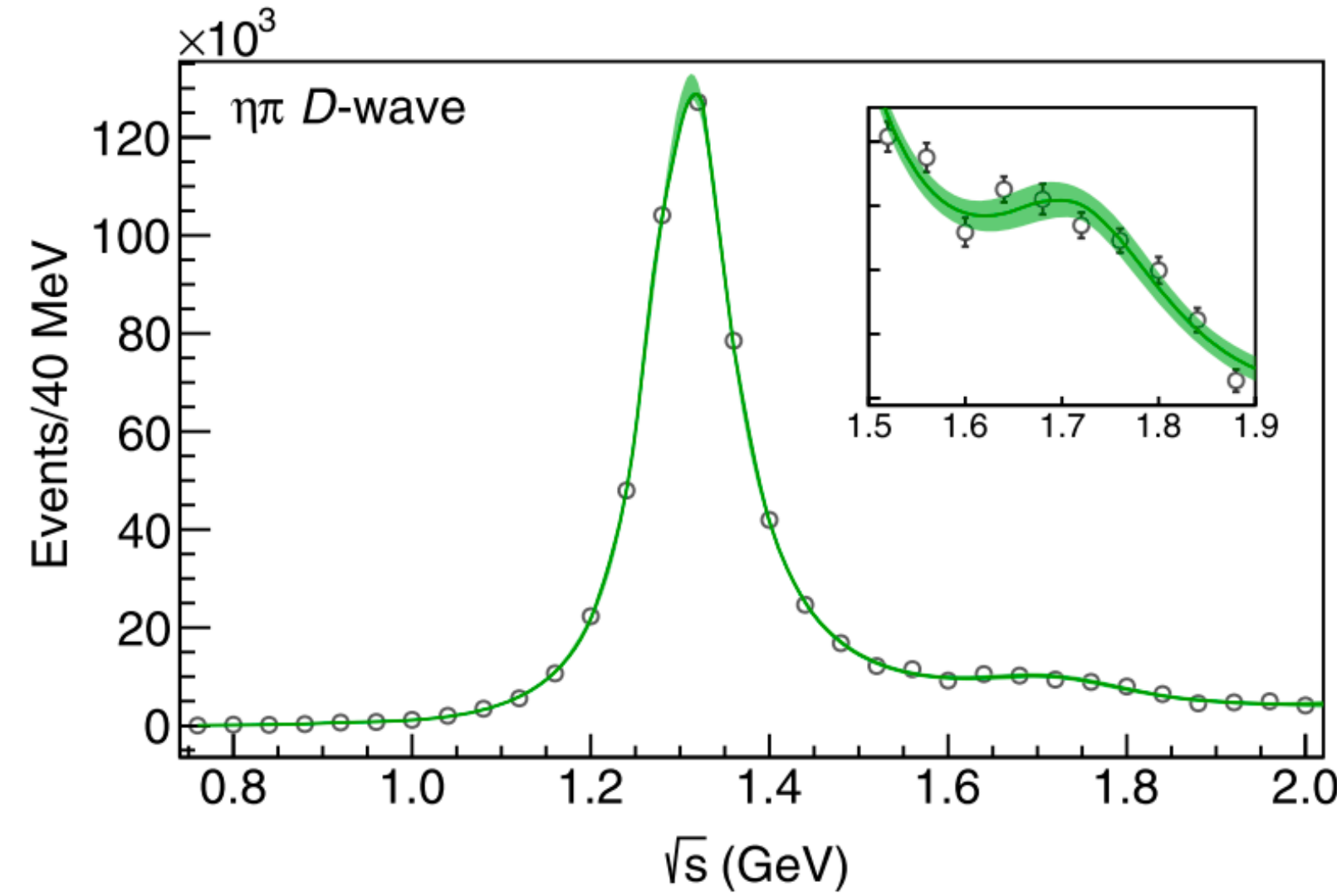
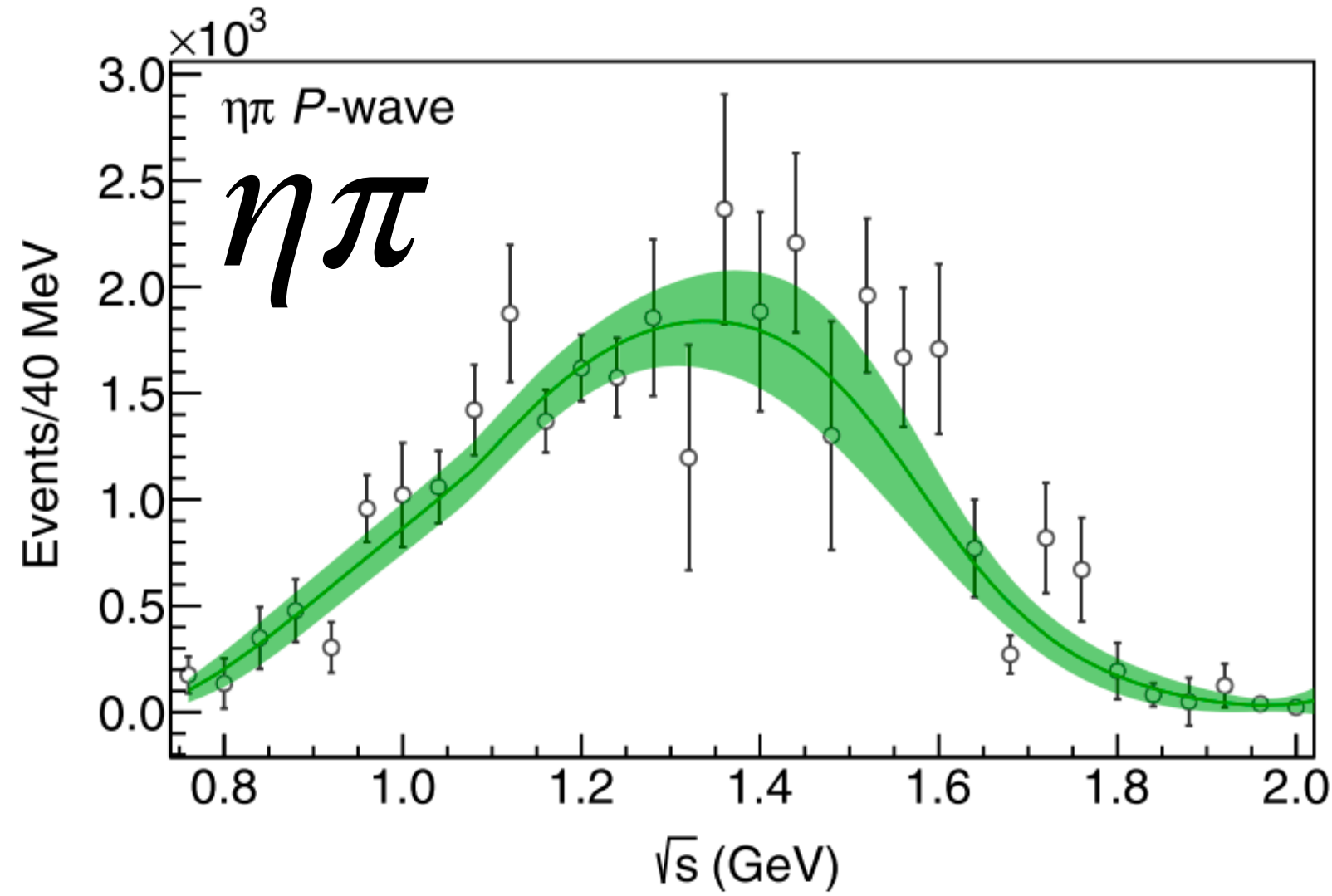
Partial Waves Expansion



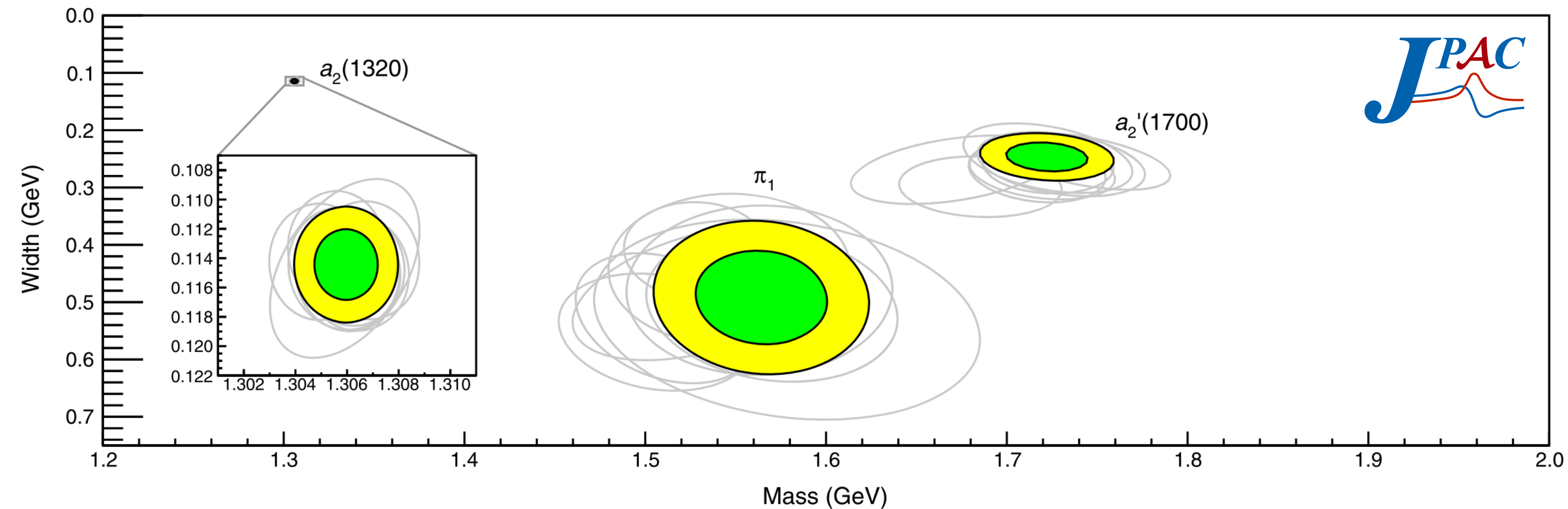
Resonance in angular mom. $L = 1$?

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

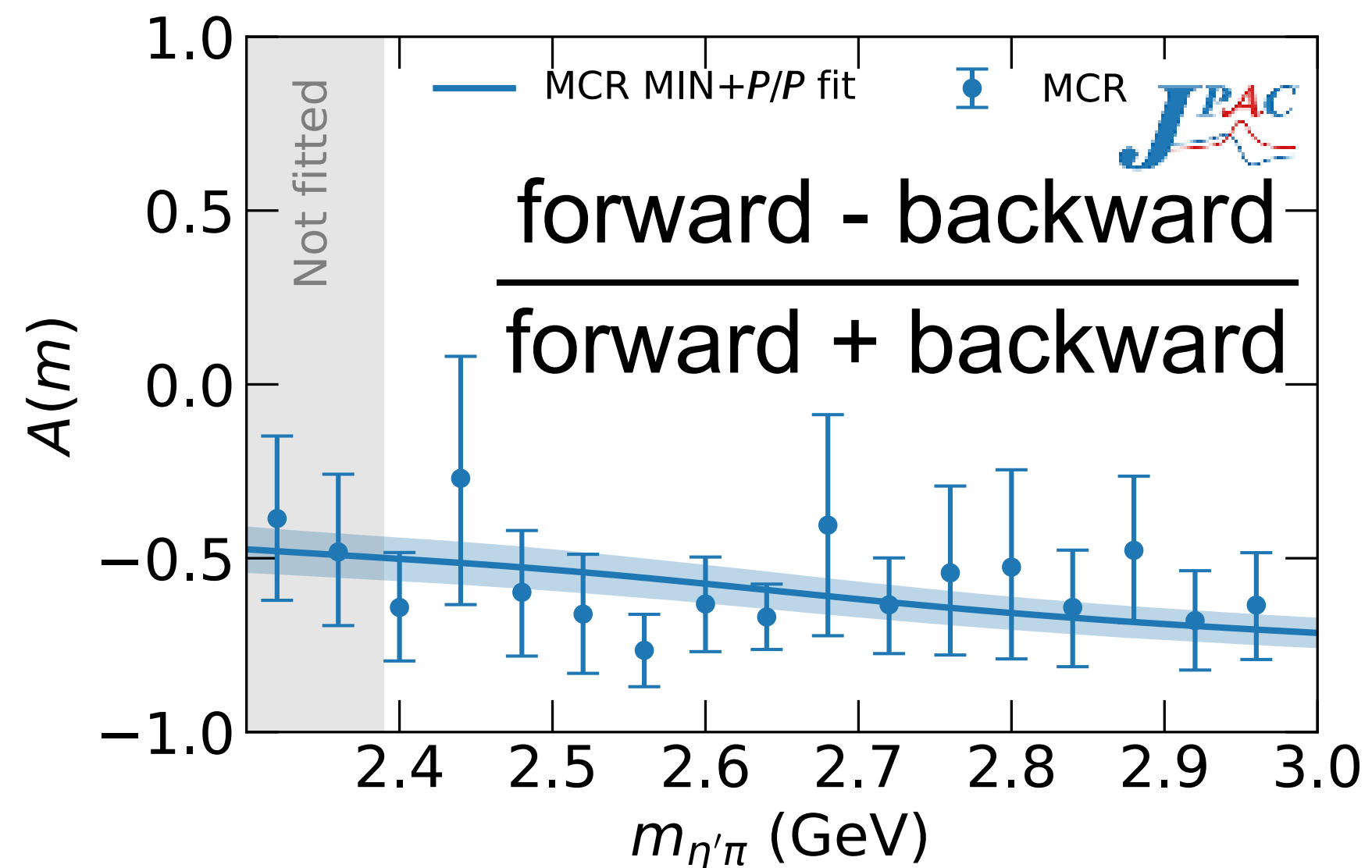
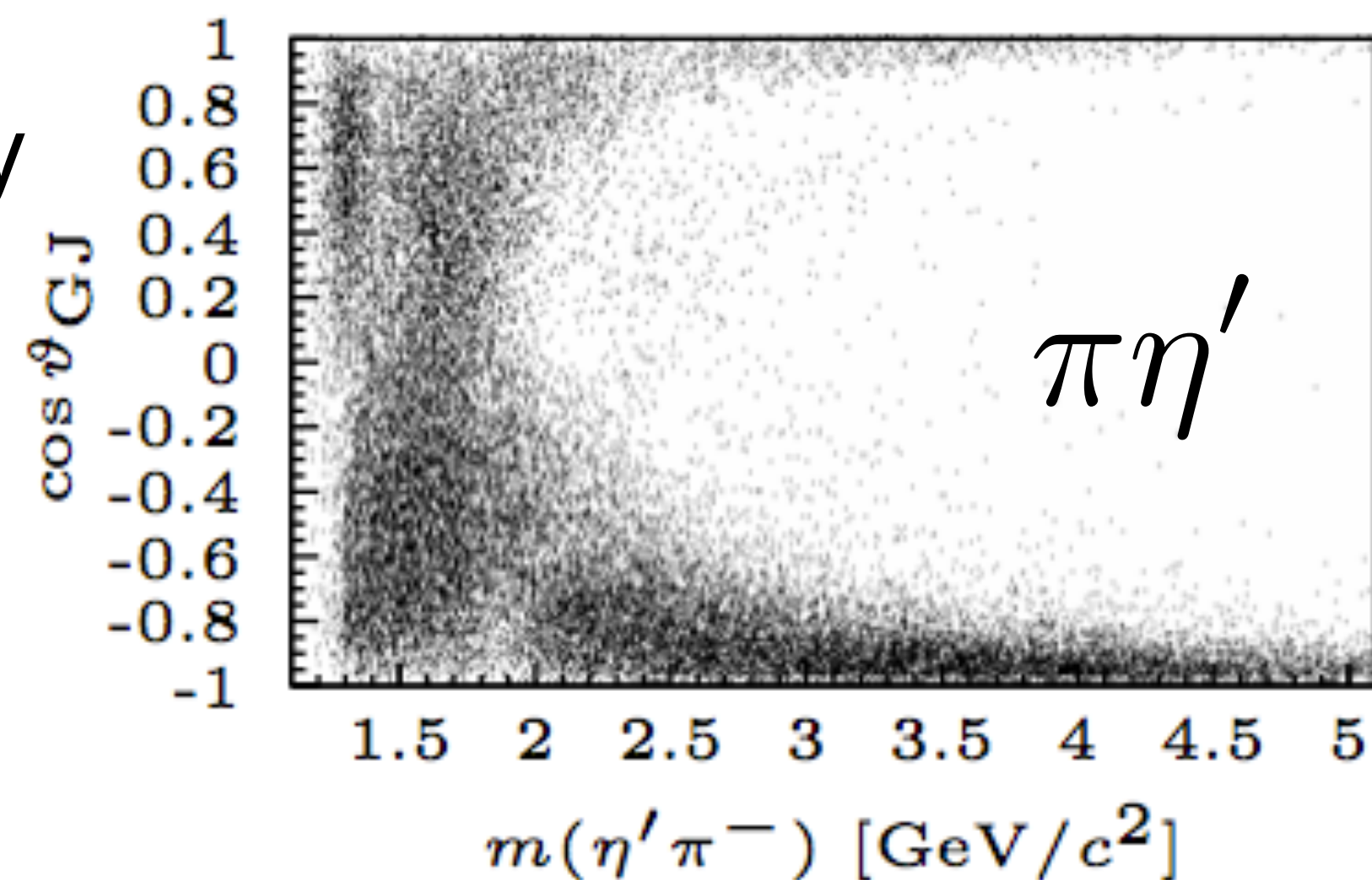
$\pi_1(1400)$ vs $\pi_1(1600)$



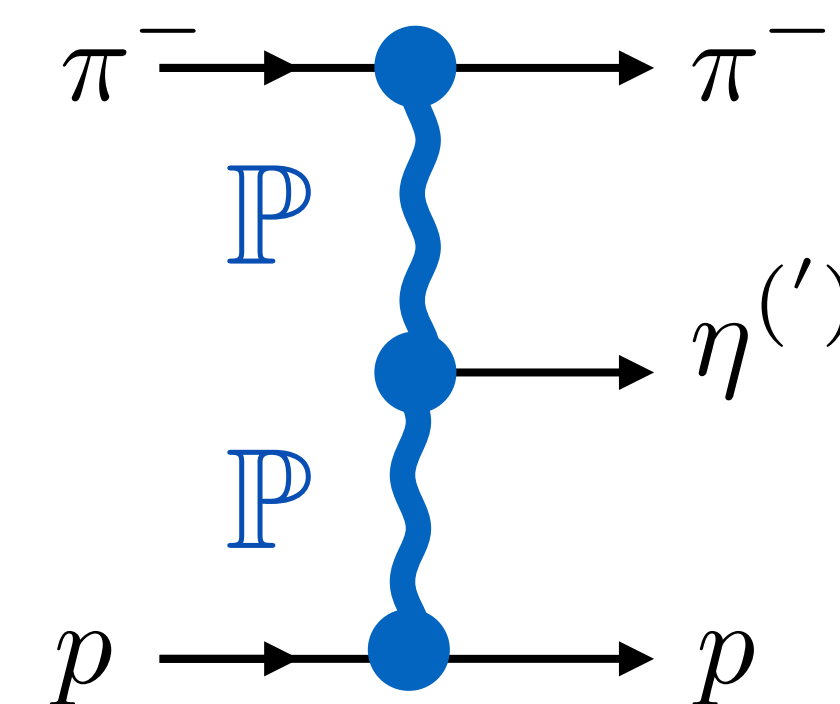
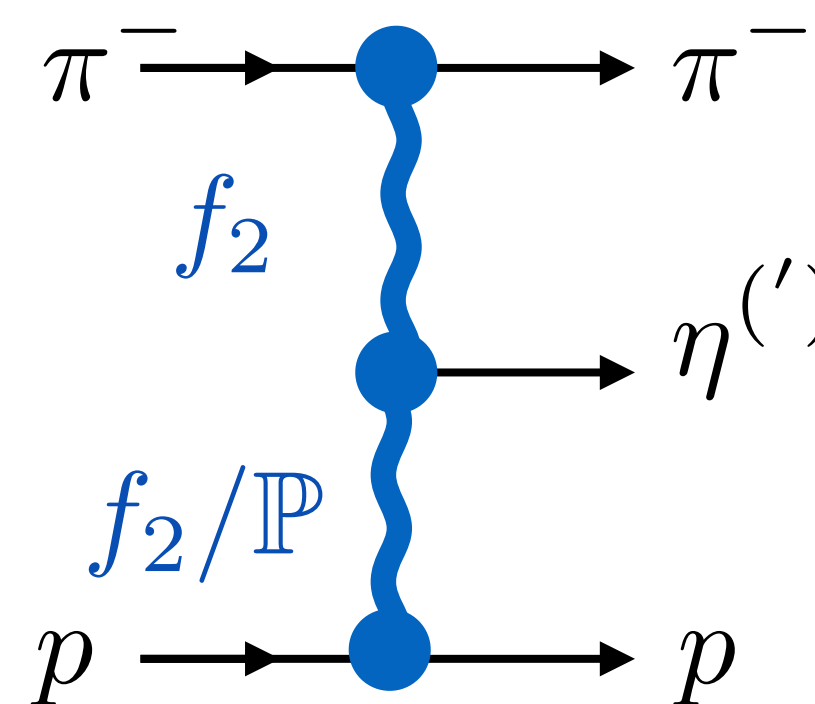
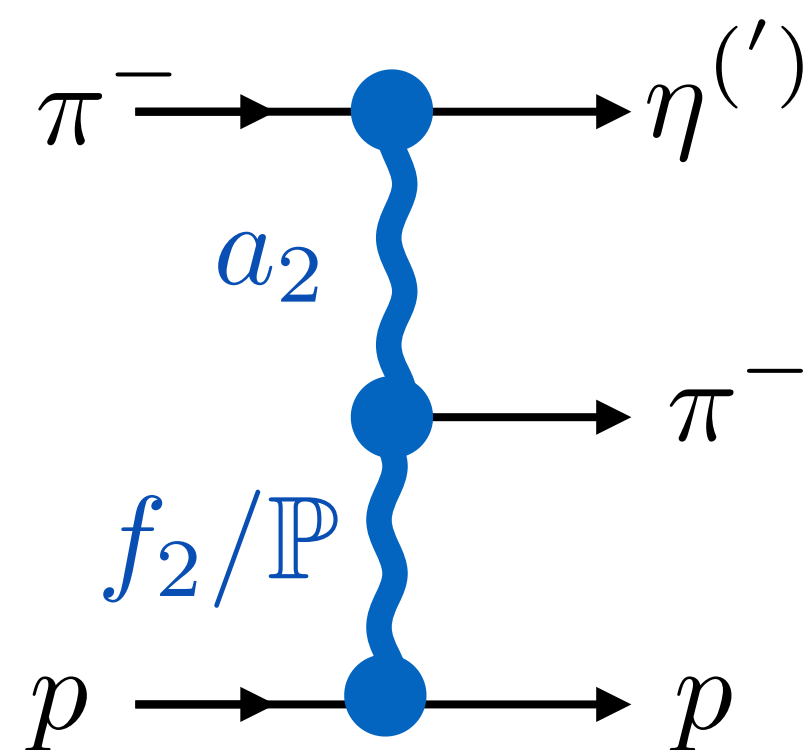
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$



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



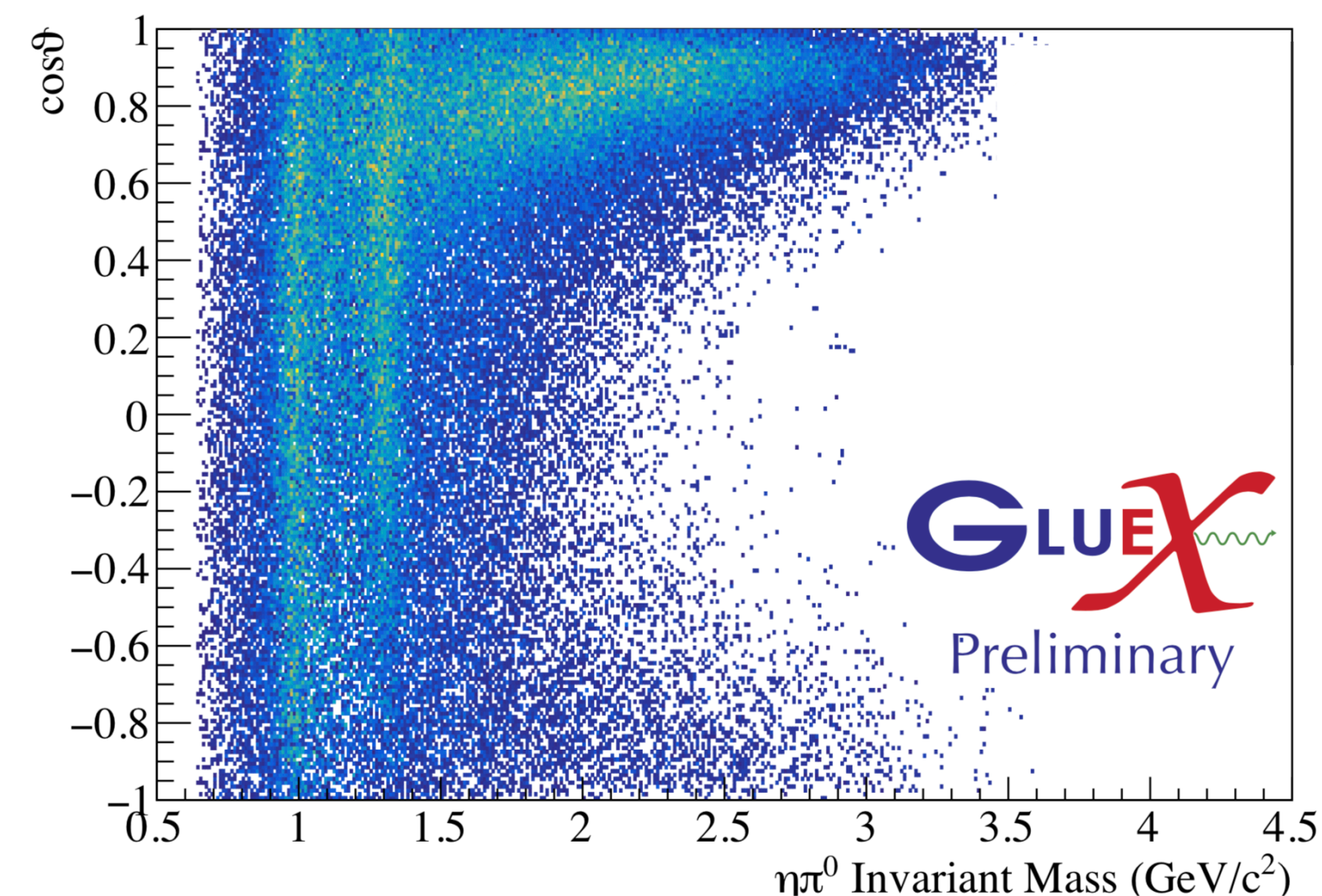
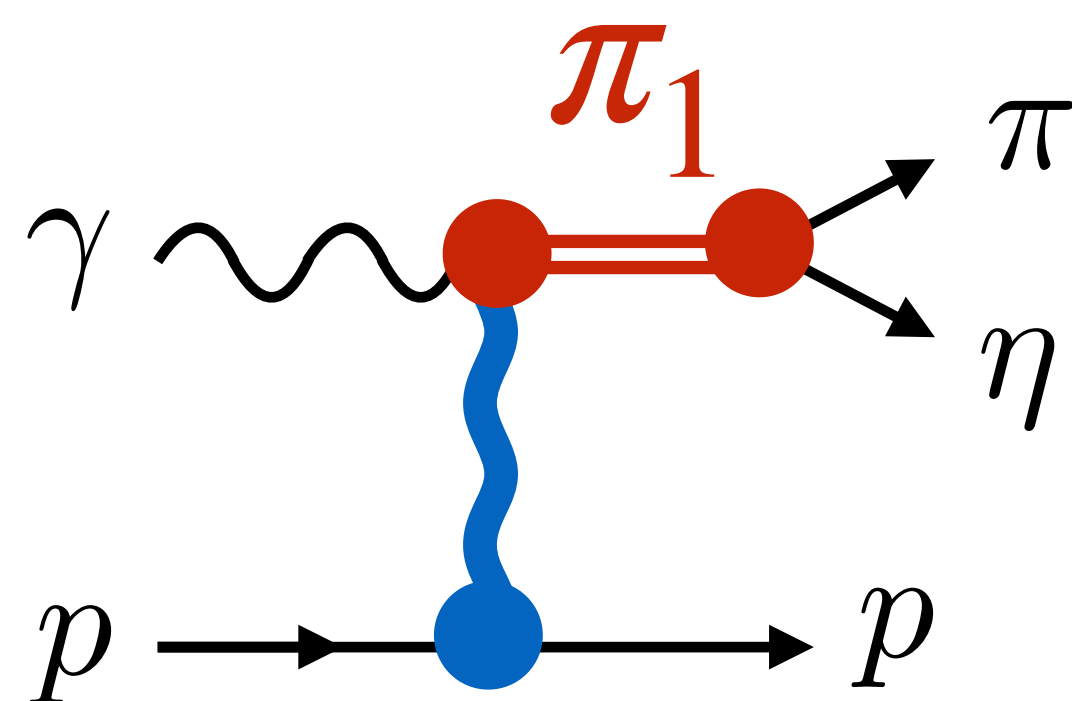
Asymmetry originating mainly from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from (\mathbb{P}, \mathbb{P}) in $\eta'\pi$



More on the exotic π_1

New data from the
GlueX experiments @JLab

Ongoing analyses

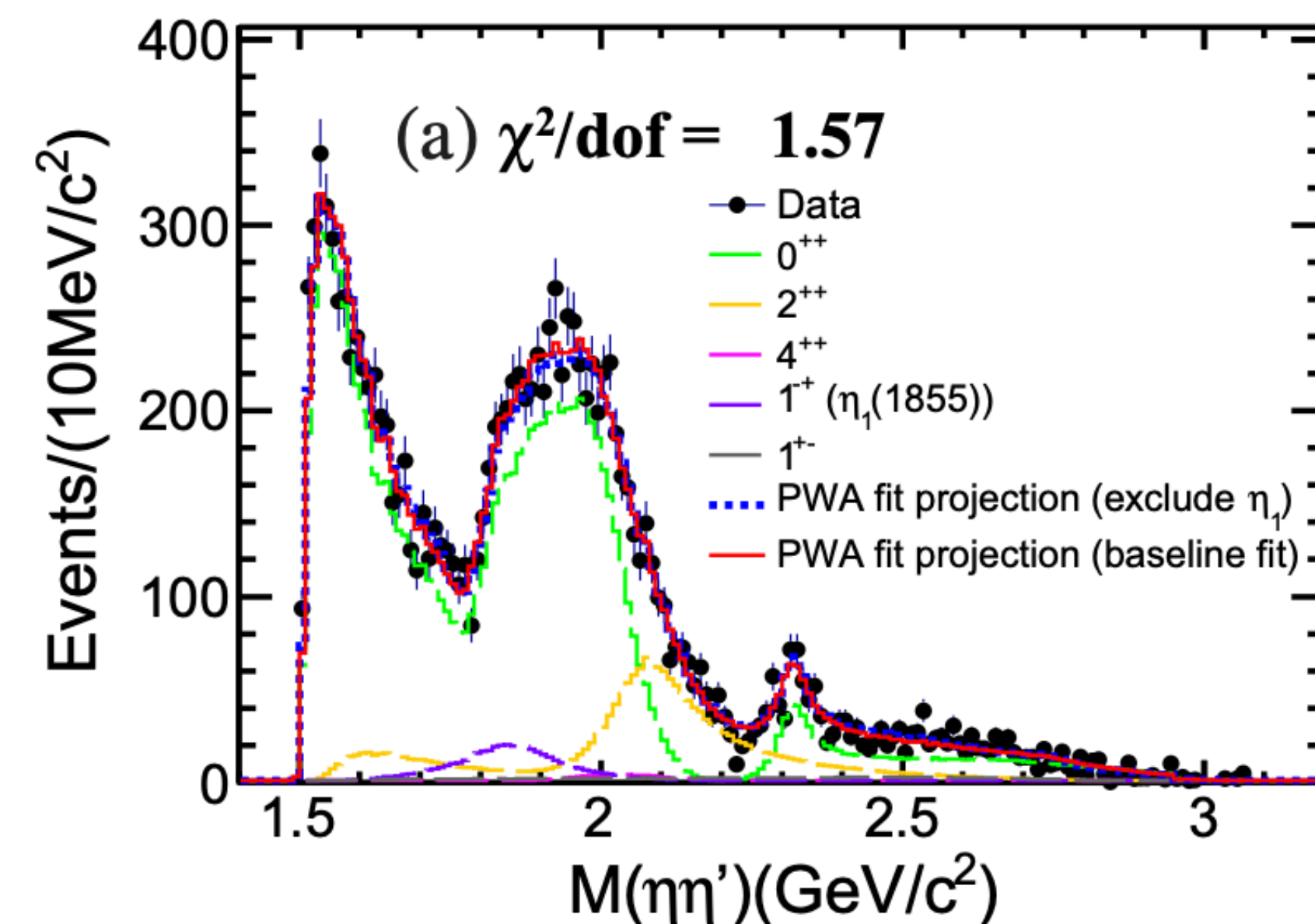
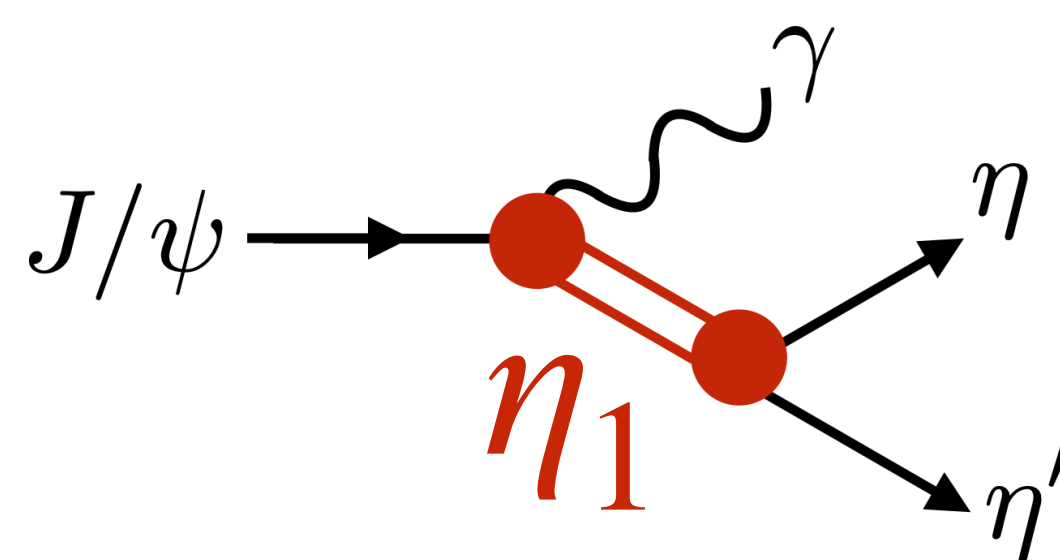


Brand new isoscalar partner
from BESIII

BESIII, arXiv:2202.00621



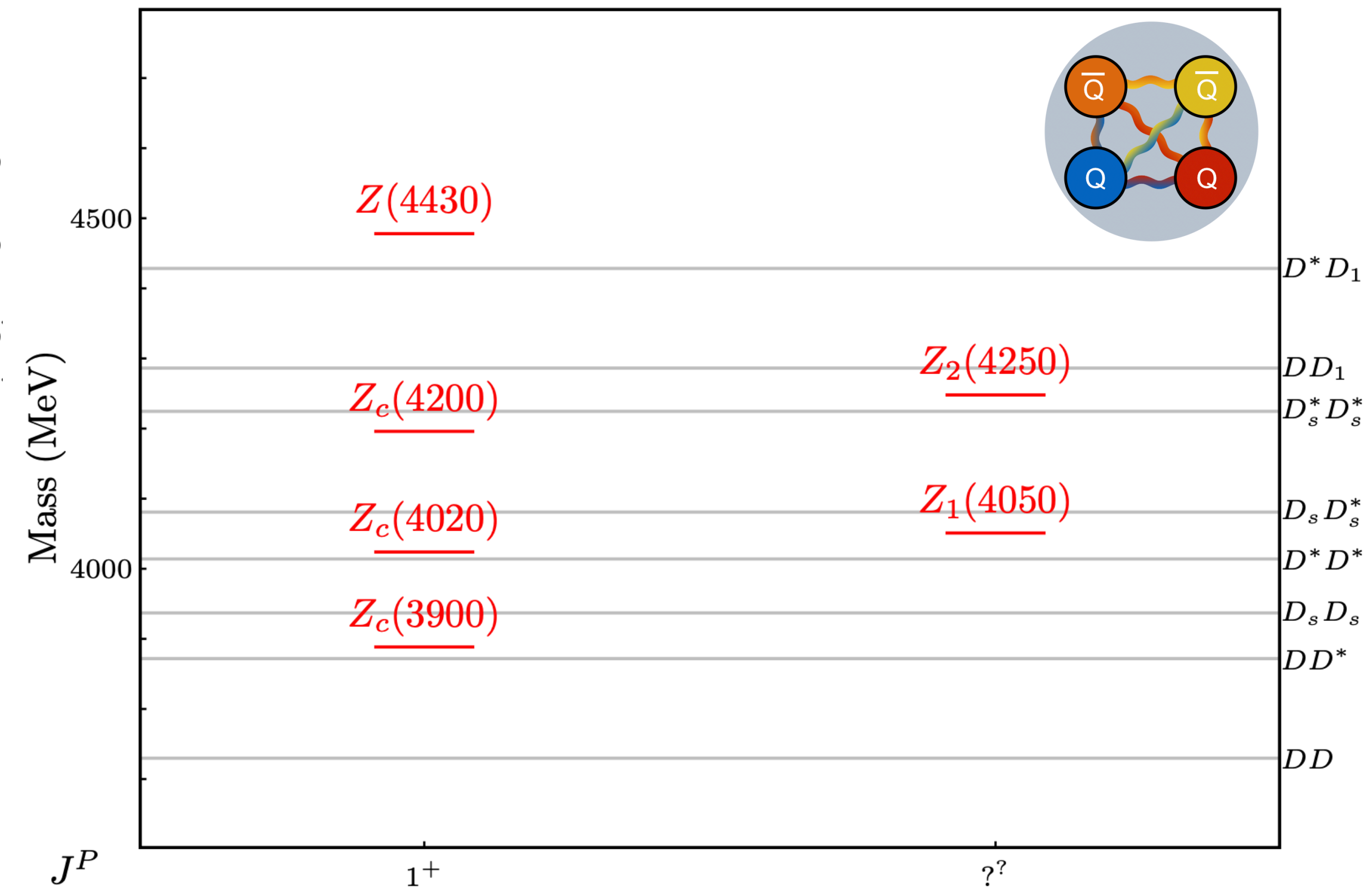
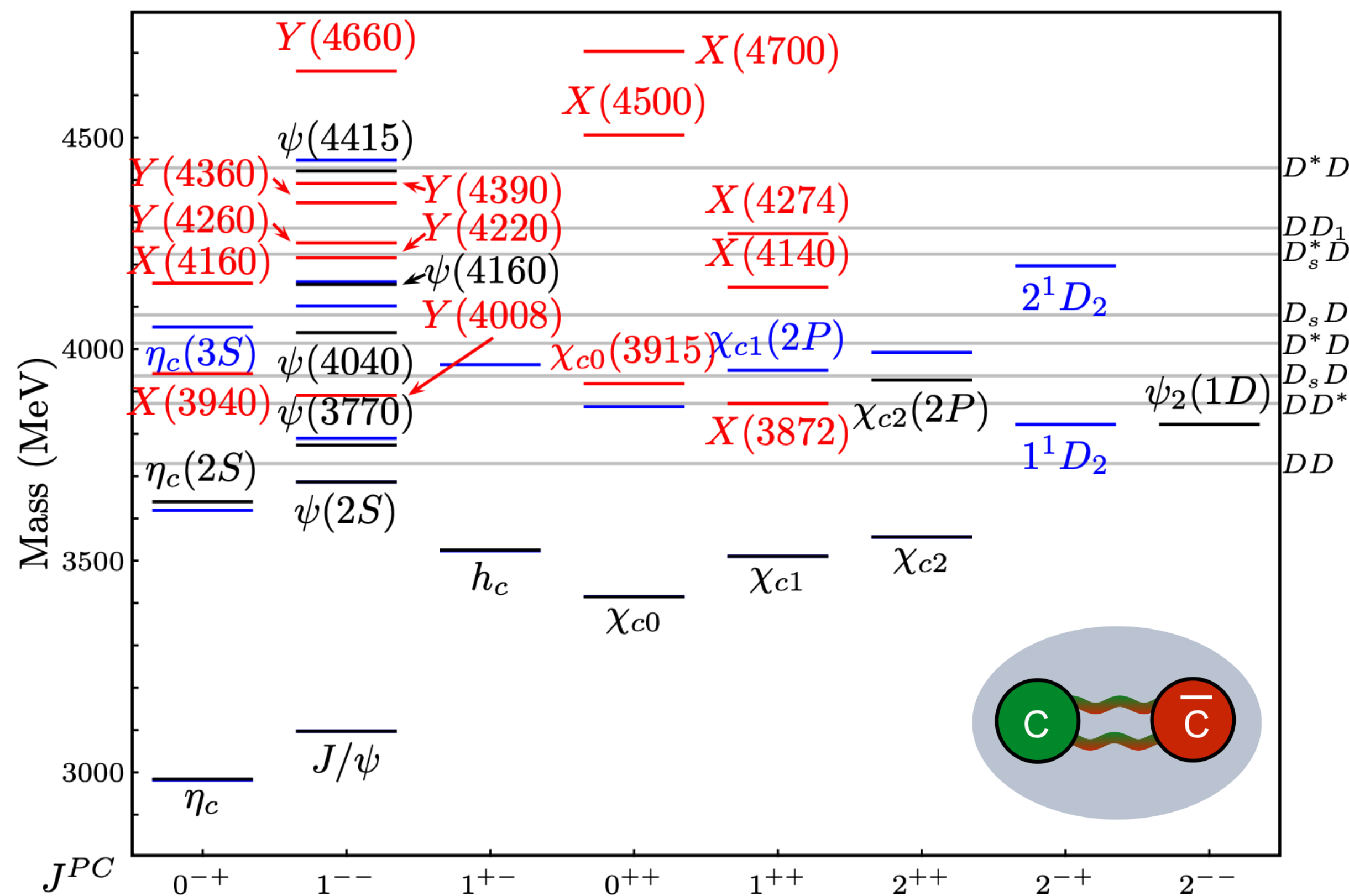
Needs confirmation



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

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

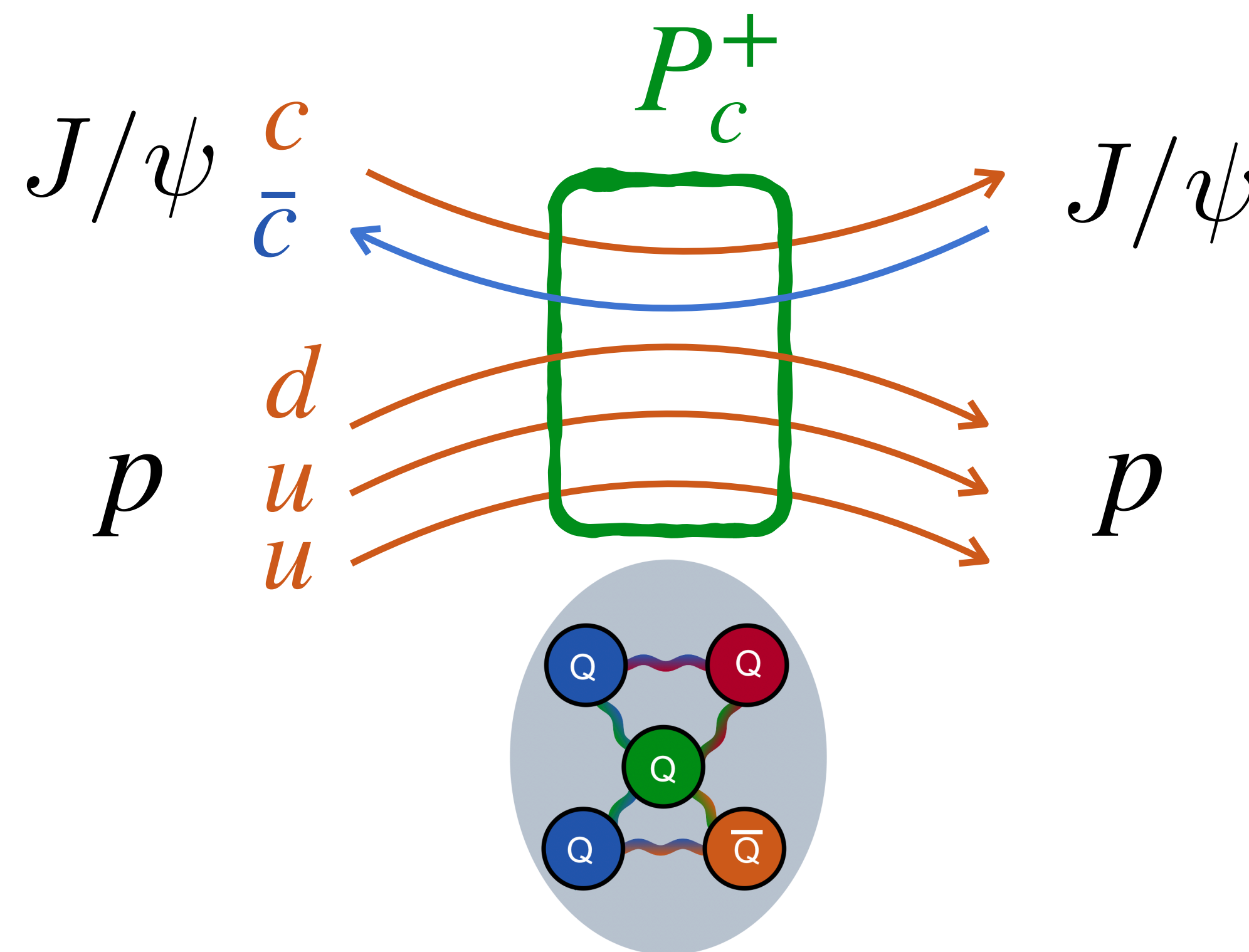
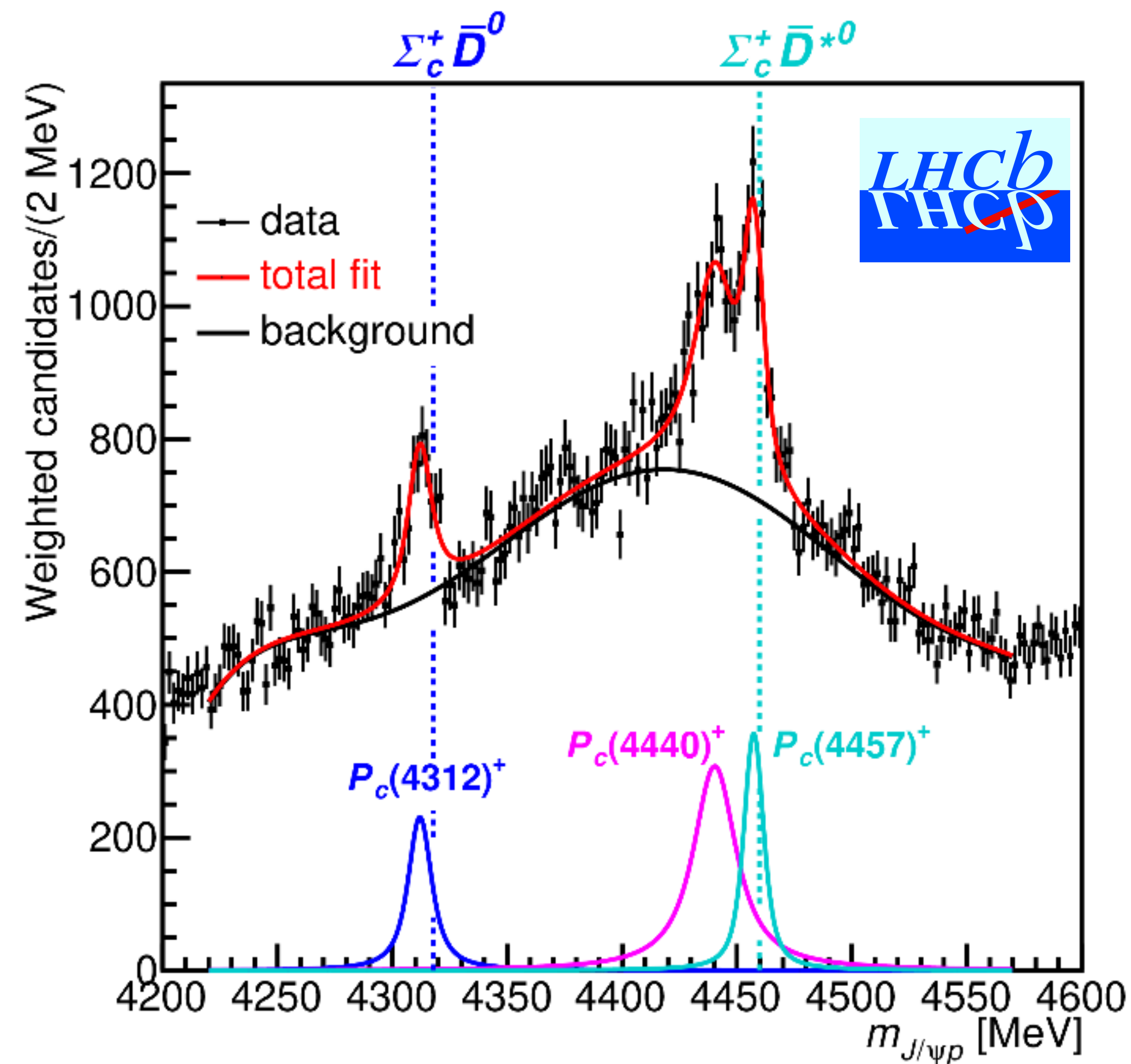
Red: exotic candidates

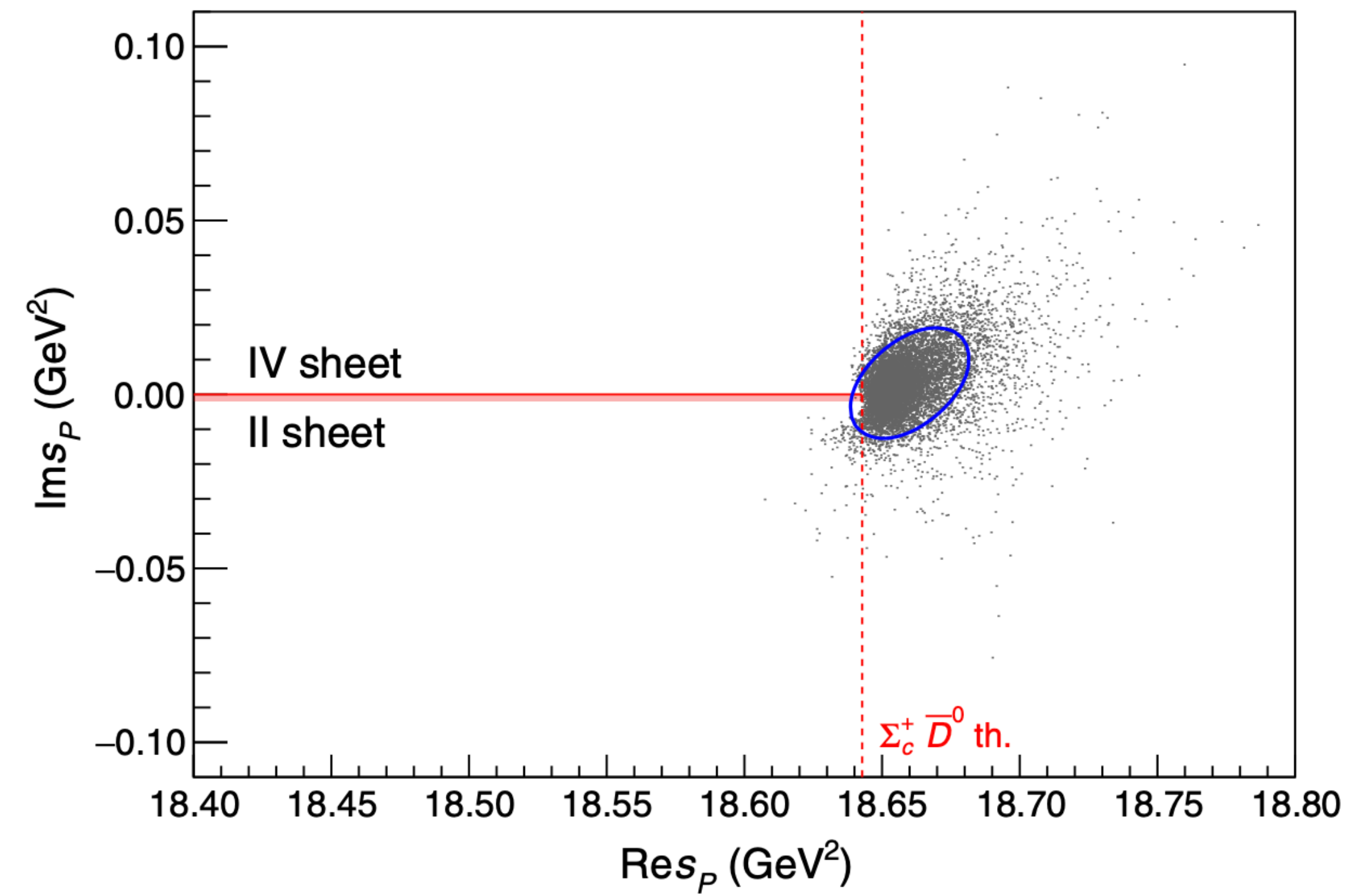
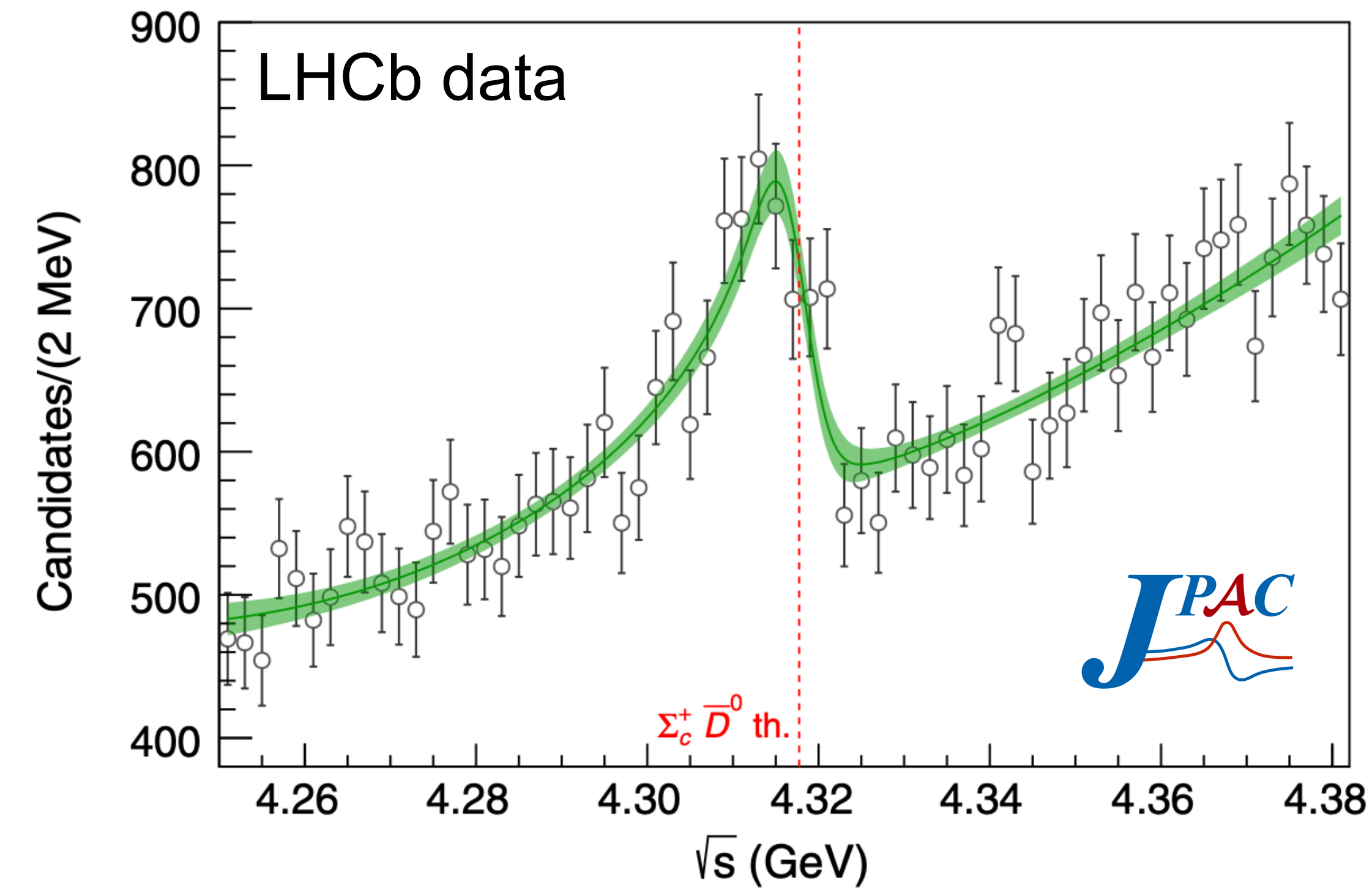


$$\Lambda_b \rightarrow K^- (J/\psi p)$$

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

Cannot be qqq baryon



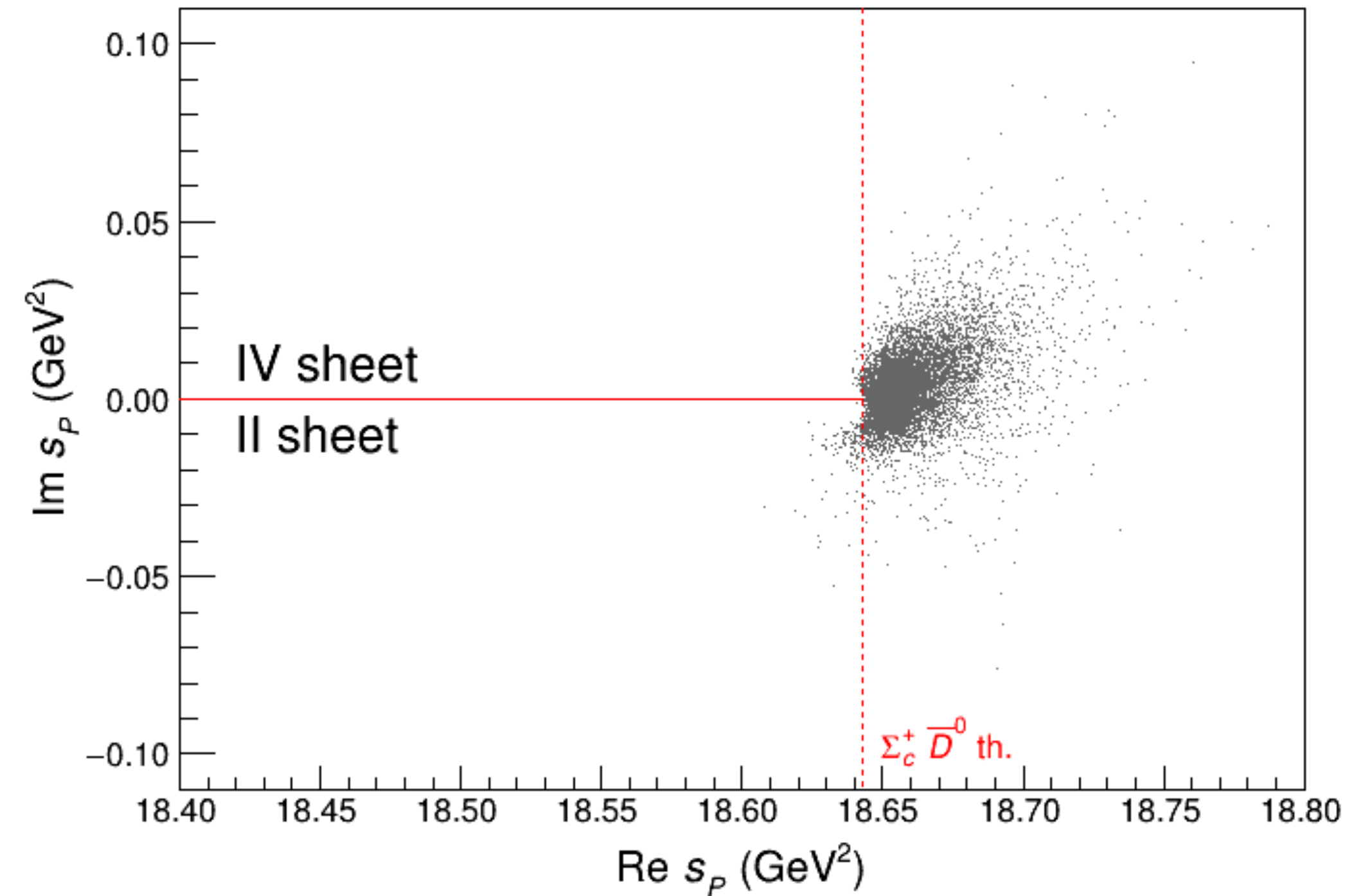
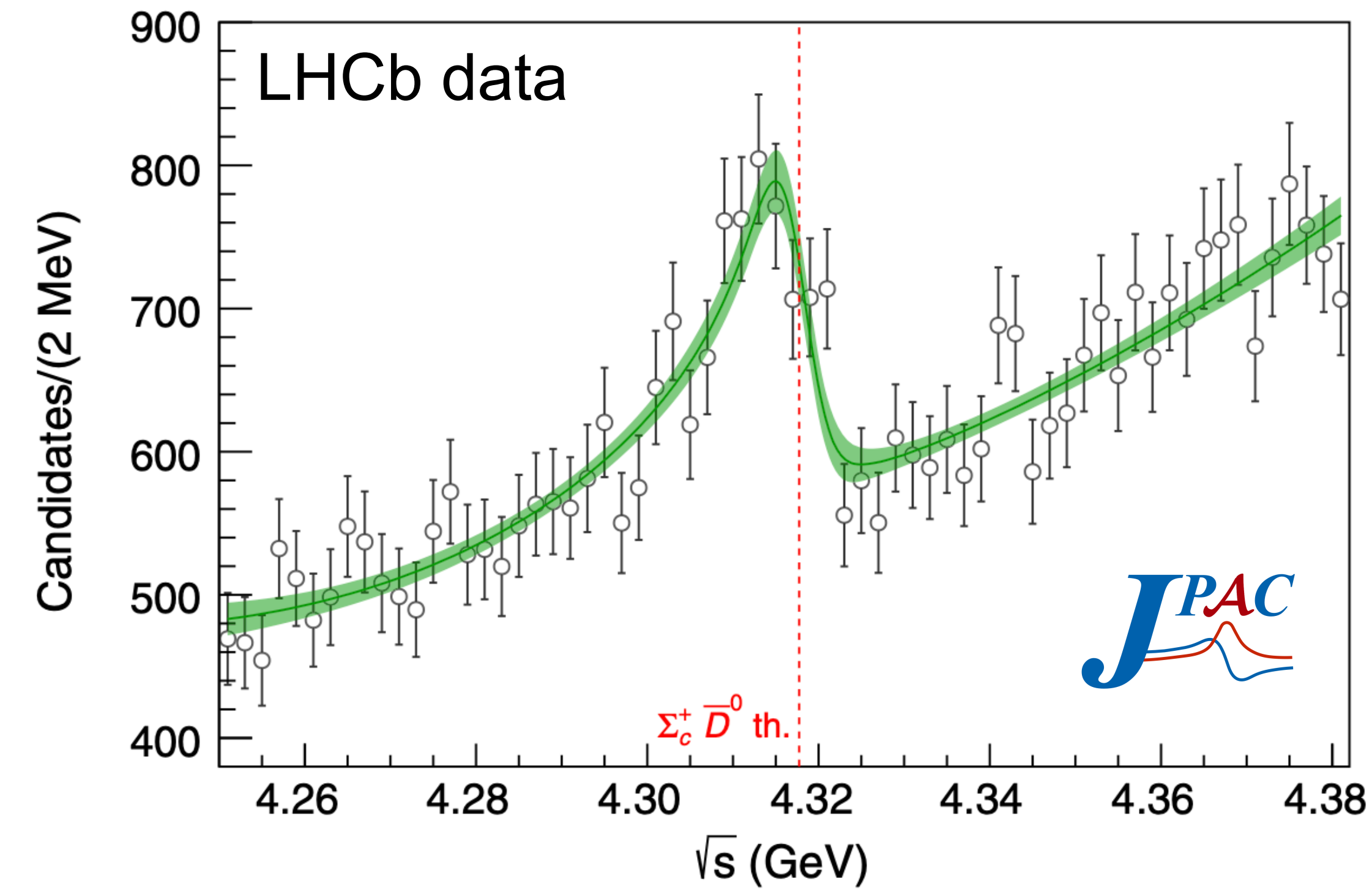


Bootstrap: generate 10k data

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

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

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

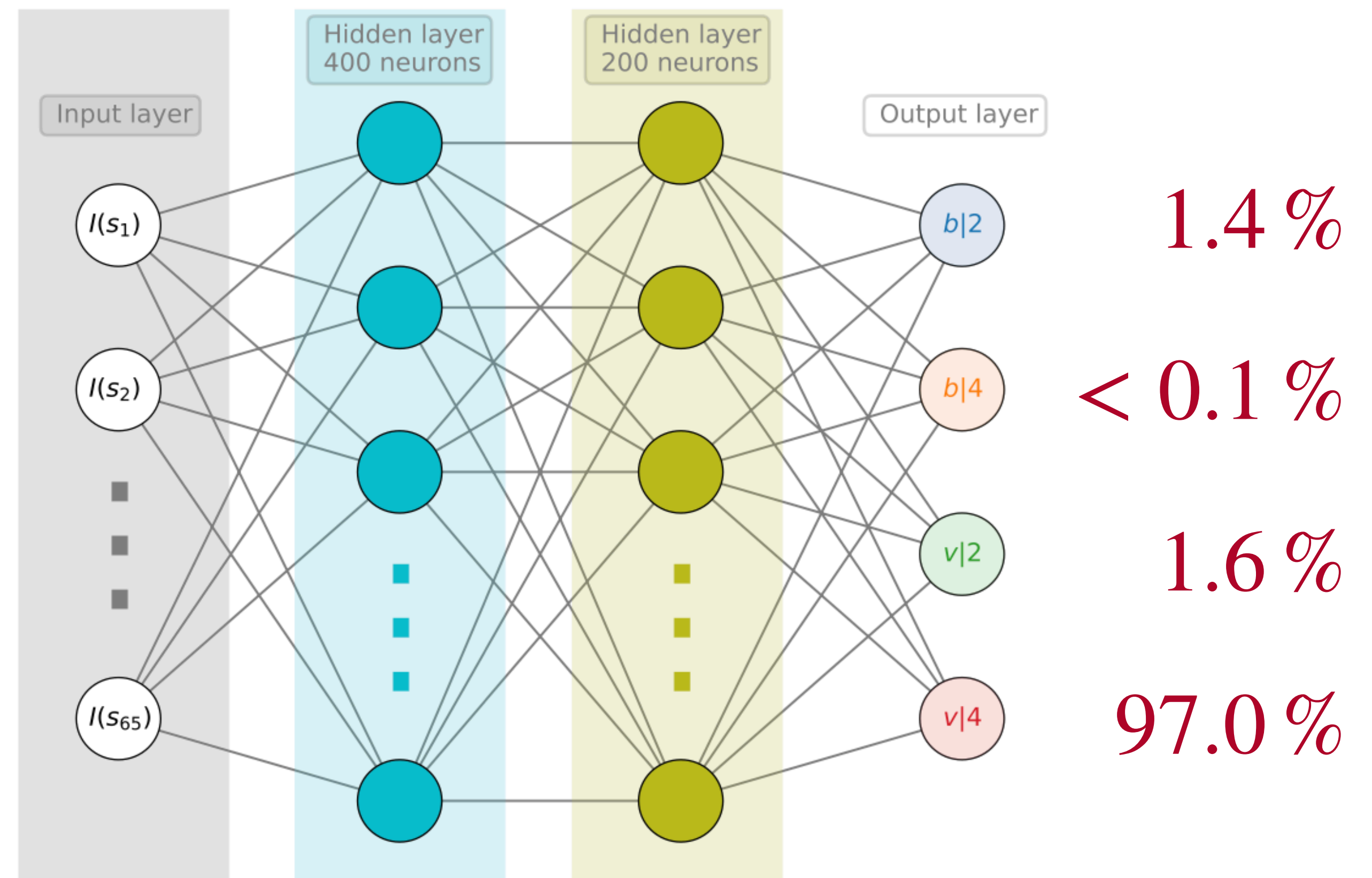
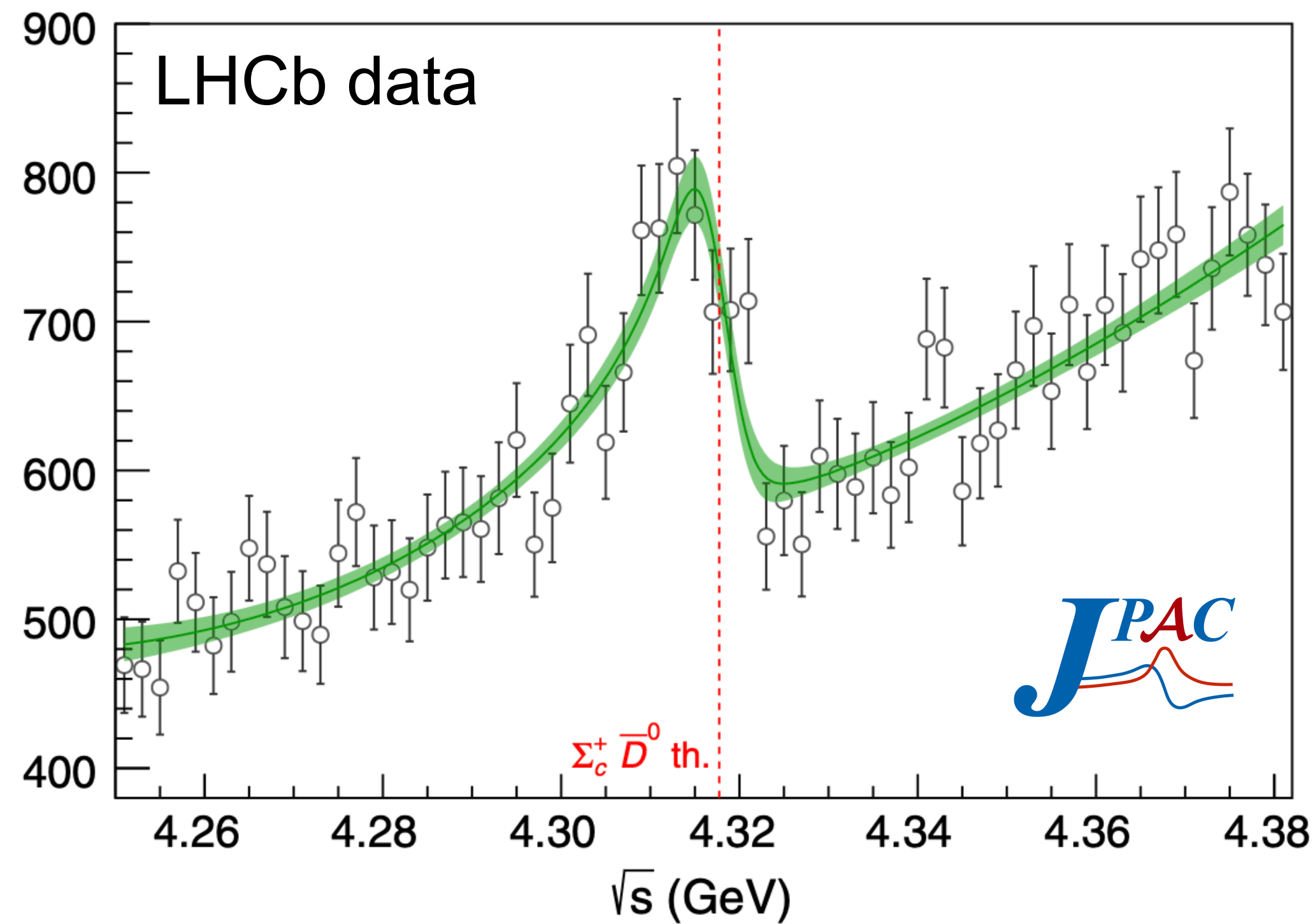
Physical sheet - positive scattering length - bound state

0.7 %

Unphysical sheet - negative scattering length - virtual state

99.3 %

Deep neural network trained with 4 types of amplitudes



Direct production of P_c^+ ?



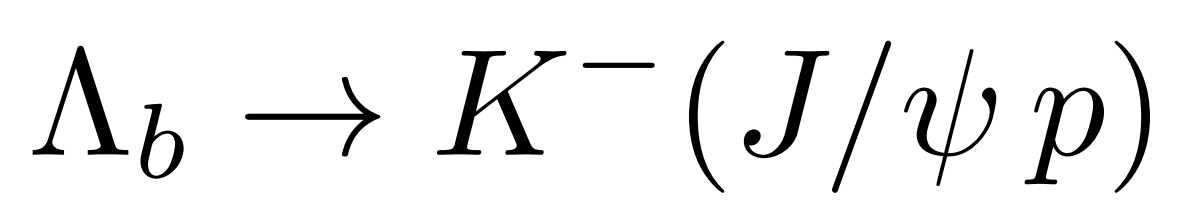
GlueX, PRL23 (2019) 072001

Data

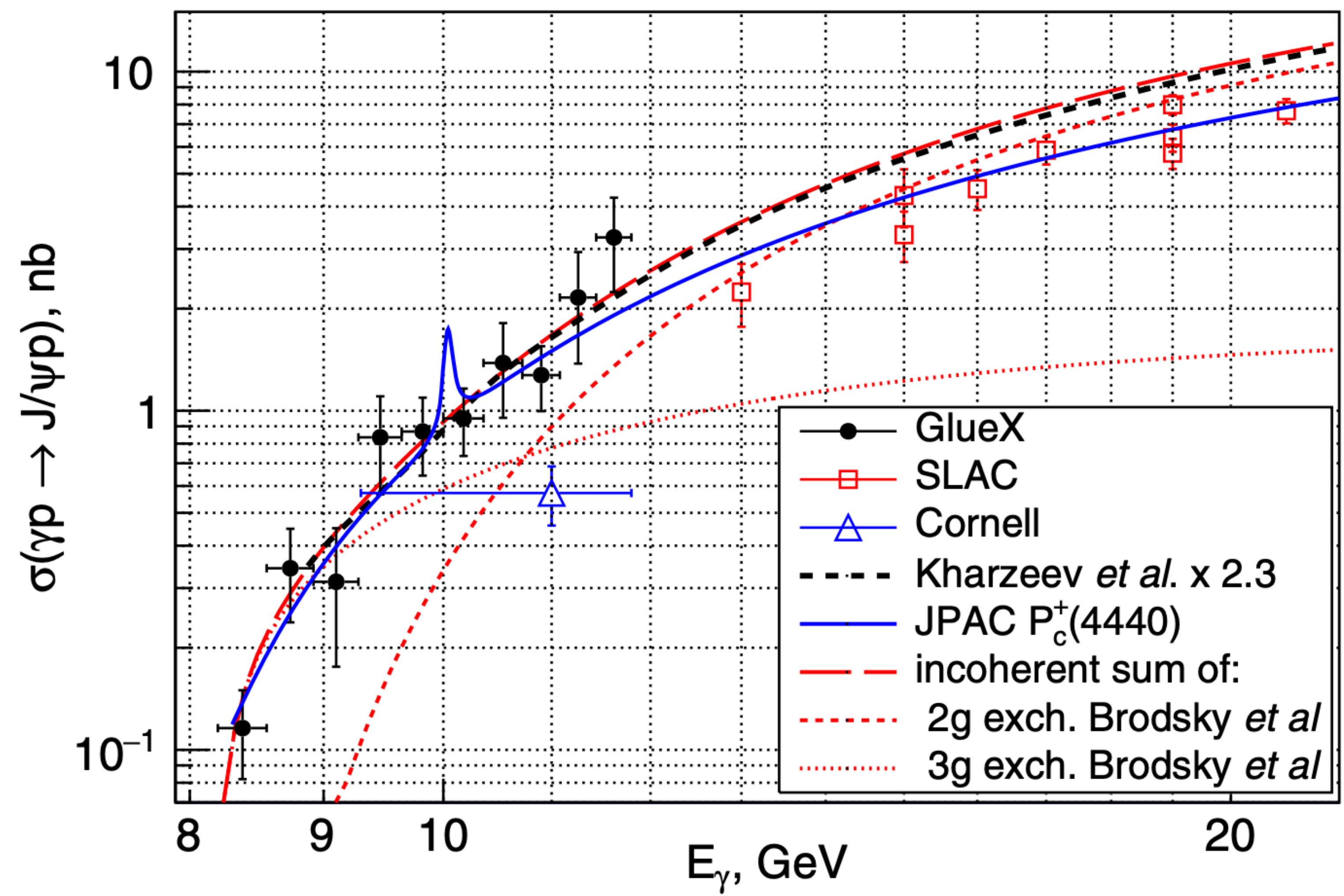
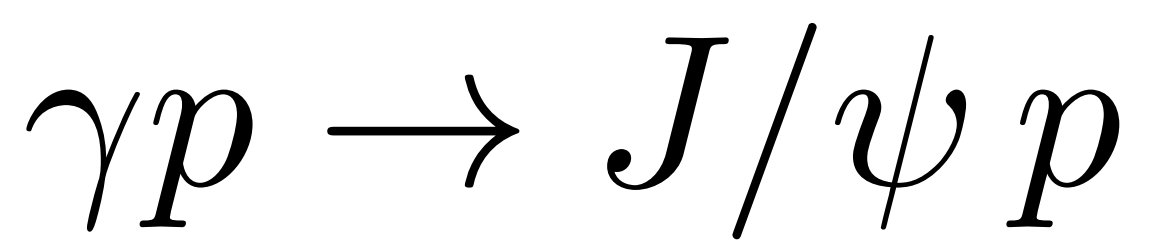
Hiller-Blin et al (JPAC), PRD94 (2016) 034002

Model

P_c^+ in 3-body decay



Photoproduction of P_c^+



SEMINAR ON SCATTERING THEORY AND APPLICATIONS

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

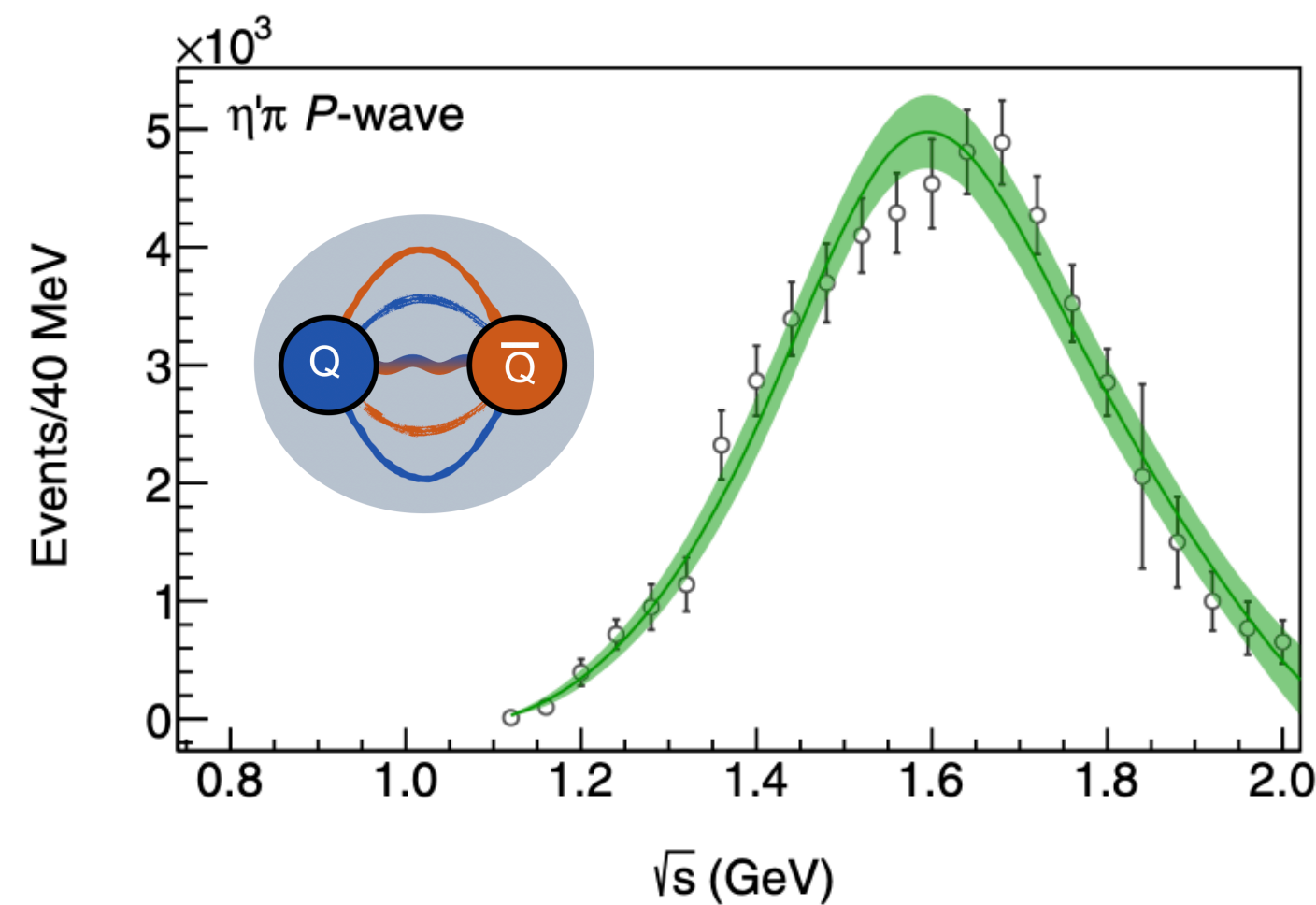
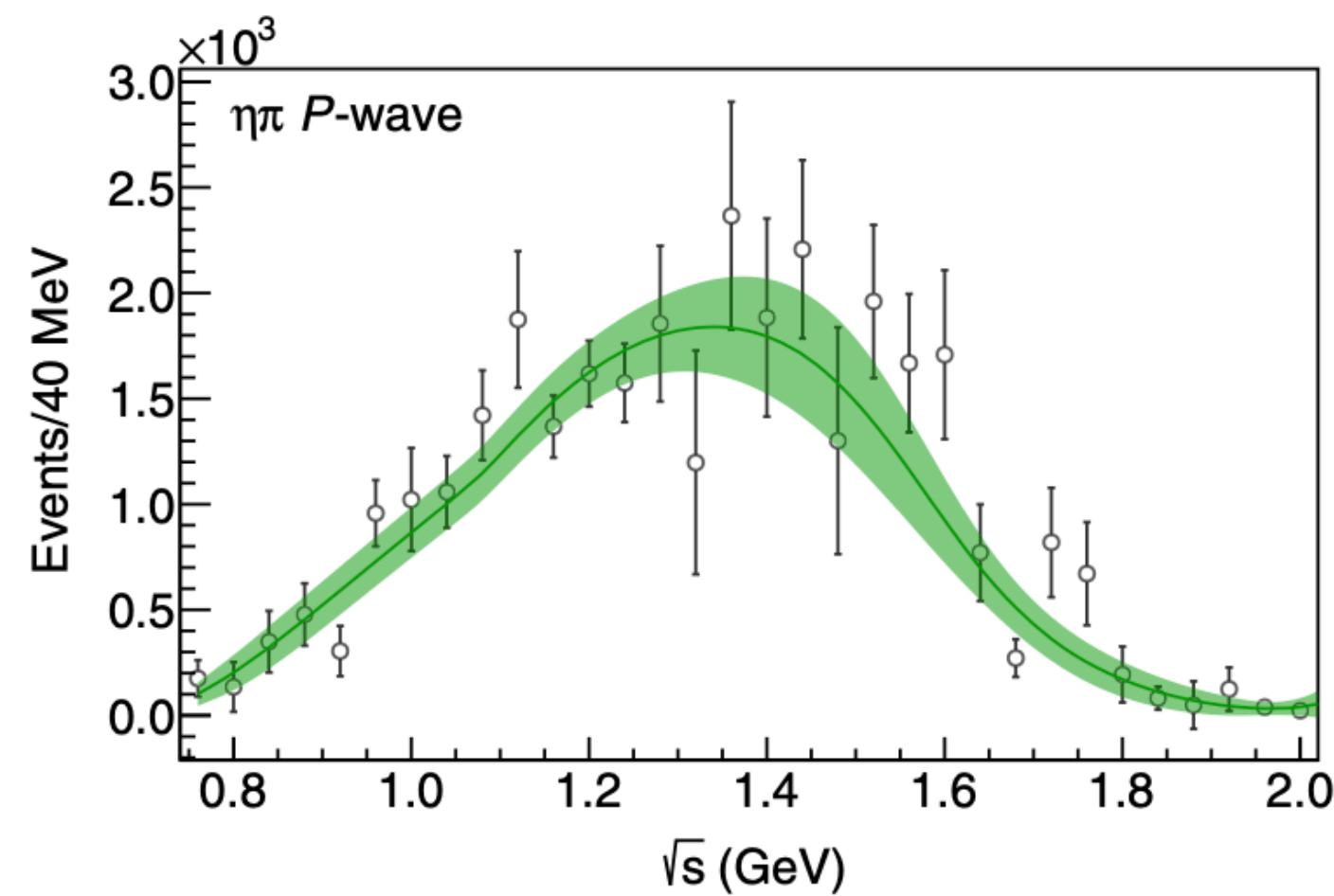
Every Thursday 4pm CEST
From February until end of May

Last Thursday: 50+ participants,
Including 5 ICCUB members

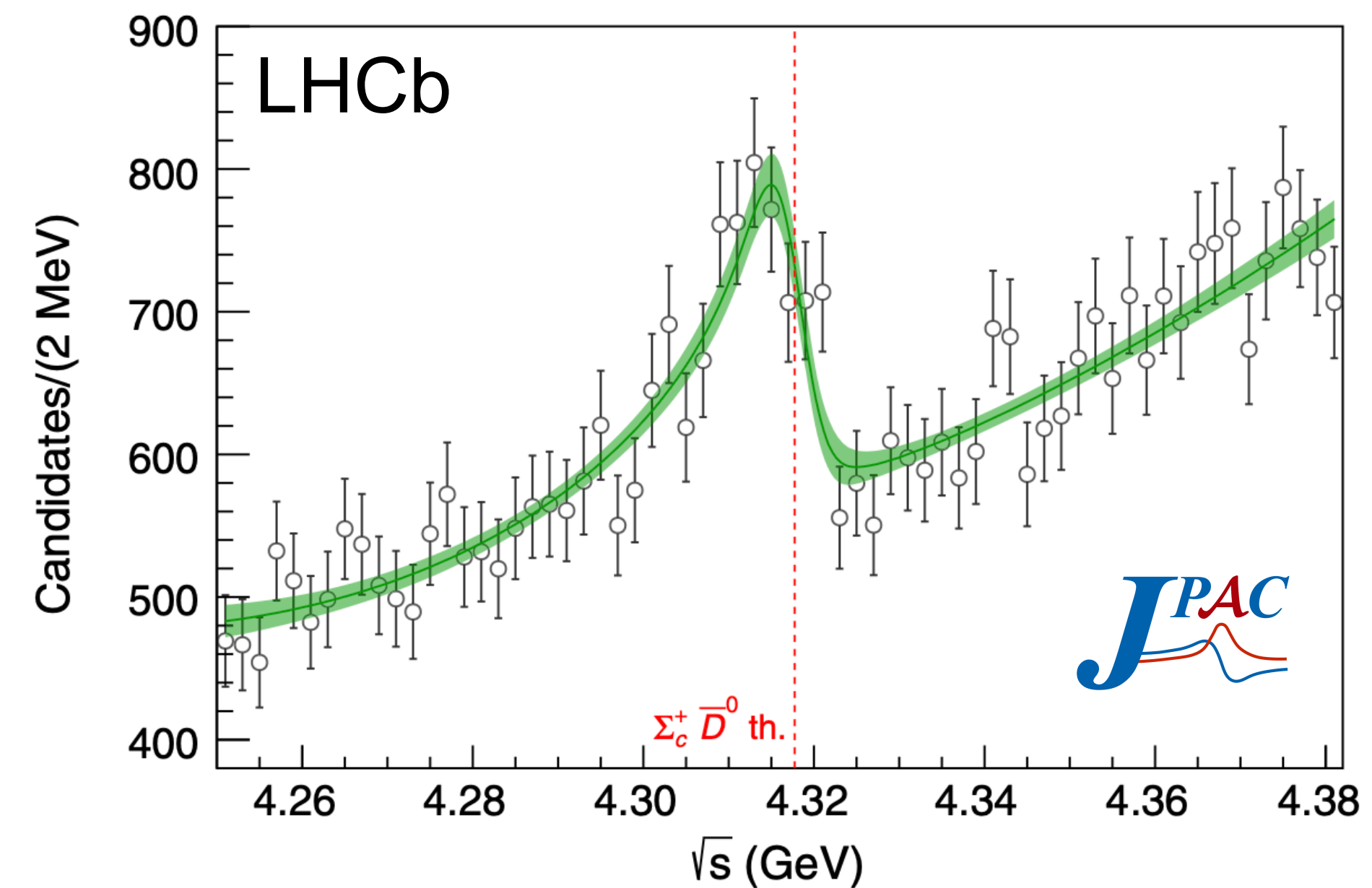
- February 3, Alessandro Pilloni
Scope of the course: What is scattering, basic S-matrix principles, natural units
- February 10, Adam Szczepaniak
QFT vs Schrodinger equation: fields, particles and interactions. QM review, fields vs particles
- February 17, Miguel Albaladejo
Lippmann-Schwinger equation, partial waves
- February 24, Adam Szczepaniak
Examples: Delta-shell, Feshbach resonances

Direct production of P_c^+ ?

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



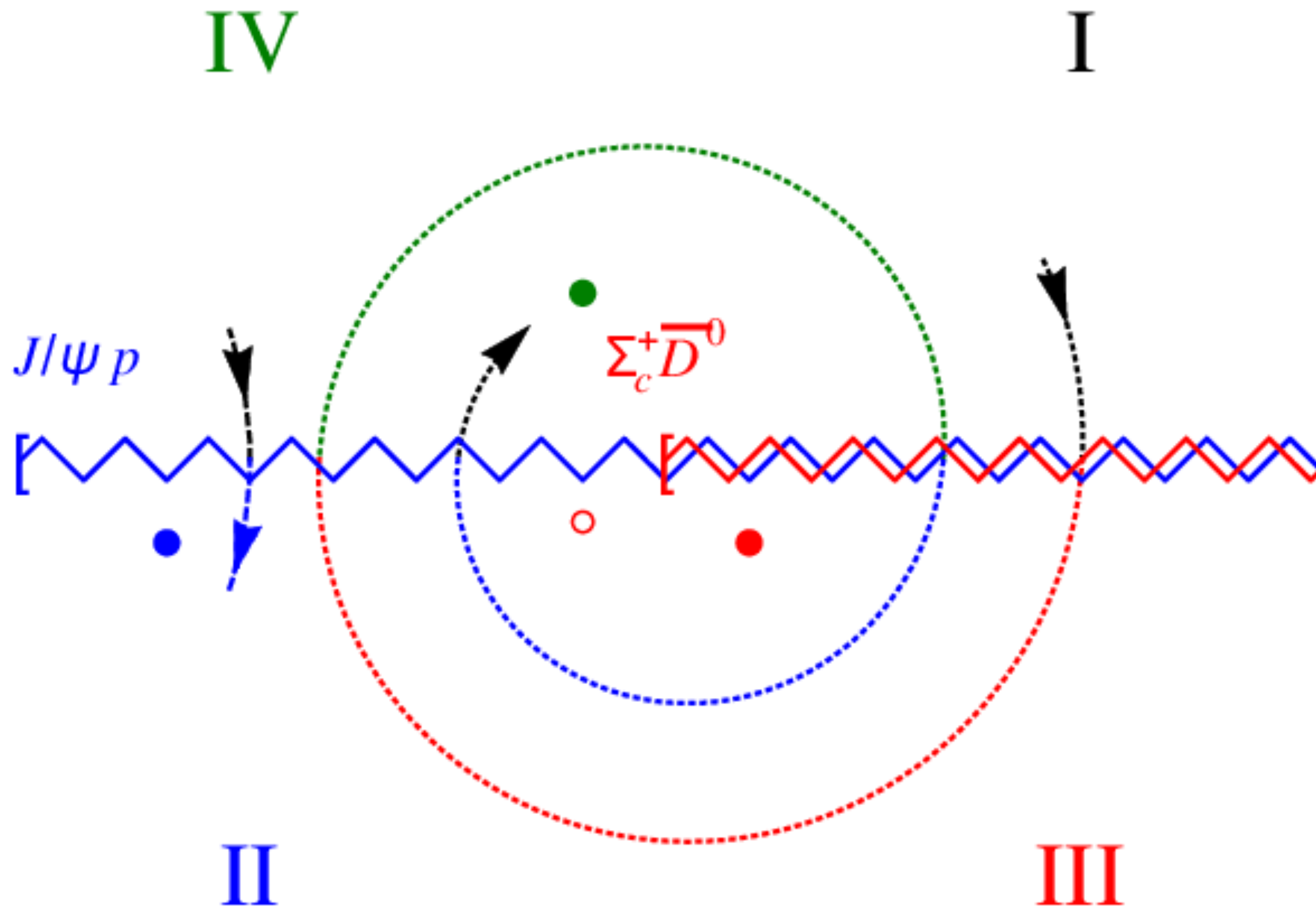
Virtual state in the $\Sigma_c^+ \bar{D}^0$ channel



Review

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

Backup Slides



Joint Physics Analysis Center

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JPAC acknowledges support from DOE and NSF

NEWS

Photoproduction:

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



Hadroproduction:

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

Three-body Decay: Isobar decomposition and recoupling coefficients.

Light Meson Decay:

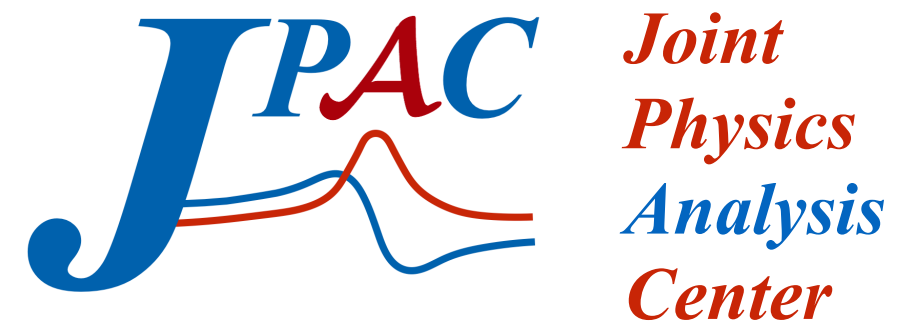
1. η meson into three pions: $\eta \rightarrow 3\pi$ page
2. vector meson into three pions: $\omega, \phi \rightarrow 3\pi$ page

Heavy Baryon Decay:

1. $\Lambda_b^0 \rightarrow J/\psi p K^-$ 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



Interactive webpage
Codes downloadable

www.ceem.indiana.edu/jpac

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

E_γ in GeV

Vector meson: ω ρ^0 ϕ

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

$\beta_P^{\gamma\omega}$: <input type="text" value="0,739"/>	$\beta_P^{\gamma\rho}$: <input type="text" value="2,506"/>	$\beta_P^{\gamma\phi}$: <input type="text" value="0,932"/>
β_1^P : <input type="text" value="0,00"/>	β_2^P : <input type="text" value="0,00"/>	b_P : <input type="text" value="3,60"/>
α_0^P : <input type="text" value="1,08"/>	α_1^P : <input type="text" value="0,20"/>	κ_P : <input type="text" value="0,00"/>

Results

Simulation at $E_g = 8.50$ GeV
Photoproduction of ρ^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](#)

