Exotic Meson Phenomenology

Adam Szczepaniak (IU/JLab)

- Light exotics, Heavy exotics, production and decay characteristics : Towards a complete understanding of the hybrids

JPAC

EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

The Collaboration

Full Members

Adam Szczepaniak — Indiana University
Alessandro Pilloni — Università di Messina
Alex Akridge — Indiana University
Arkaitz Rodas Bilbao — Old Dominion University / Jefferson Lab
Astrid Hiller Blin — EK University of Tübingen

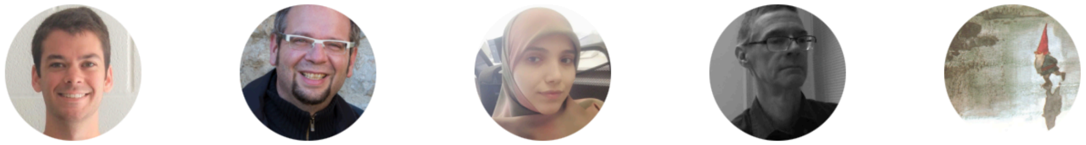
César Fernández Ramírez — National University of Distance Education
Daniel Winney — South China Normal U.
Emilie Passemar — Indiana University
Giorgio Foti — Università di Messina
Gloria Montaña — Jefferson Lab

Łukasz Bibrzycki — AGH University of Krakow
Miguel Albaladejo — IFIC-CSIC Valencia
Mikhail Mikhasenko — Ruhr-Universität Bochum
Robert Perry — University of Barcelona
Sergi Gonzàlez-Solís — University of Barcelona

Vanamali Shastry — Indiana University
Viktor Mokeev — Jefferson Lab
Vincent Mathieu — University of Barcelona
Wyatt Smith — George Washington University

Affiliated Members

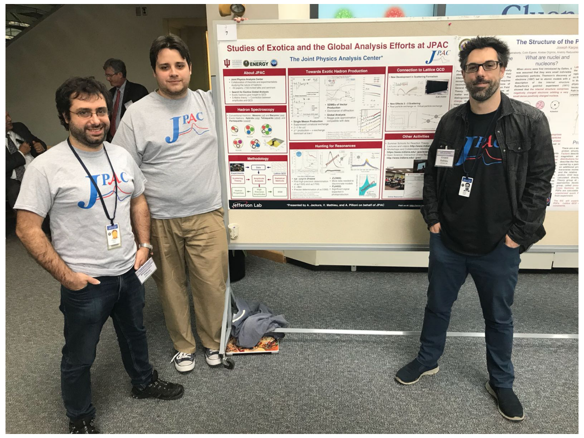
Andrew Jackura — William & Mary
Derek Glazier — University of Glasgow
Geoffrey Fox — University of Virginia
Igor Danilkin — JG University Mainz
Jorge A. Silva-Castro — ICN-UNAM

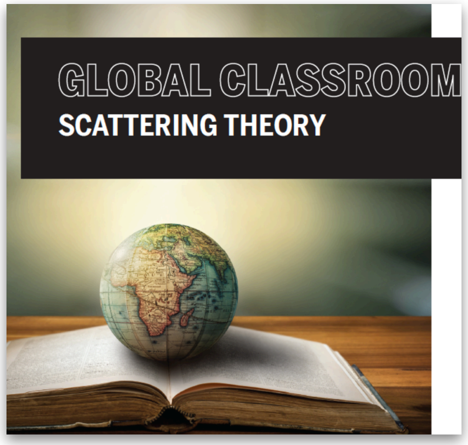


Kevin Quirion — Indiana University
Michael Döring — George Washington University
Nadine Hammoud — INP Krakow
Ron Workman — George Washington University
Sebastian Marek Dawid — University of Washington

JPAC 10+ y

- co-organized over 30 international conferences, including its own "Future Directions in Spectroscopy Analysis" series, summer schools, graduate courses, published over 200 papers





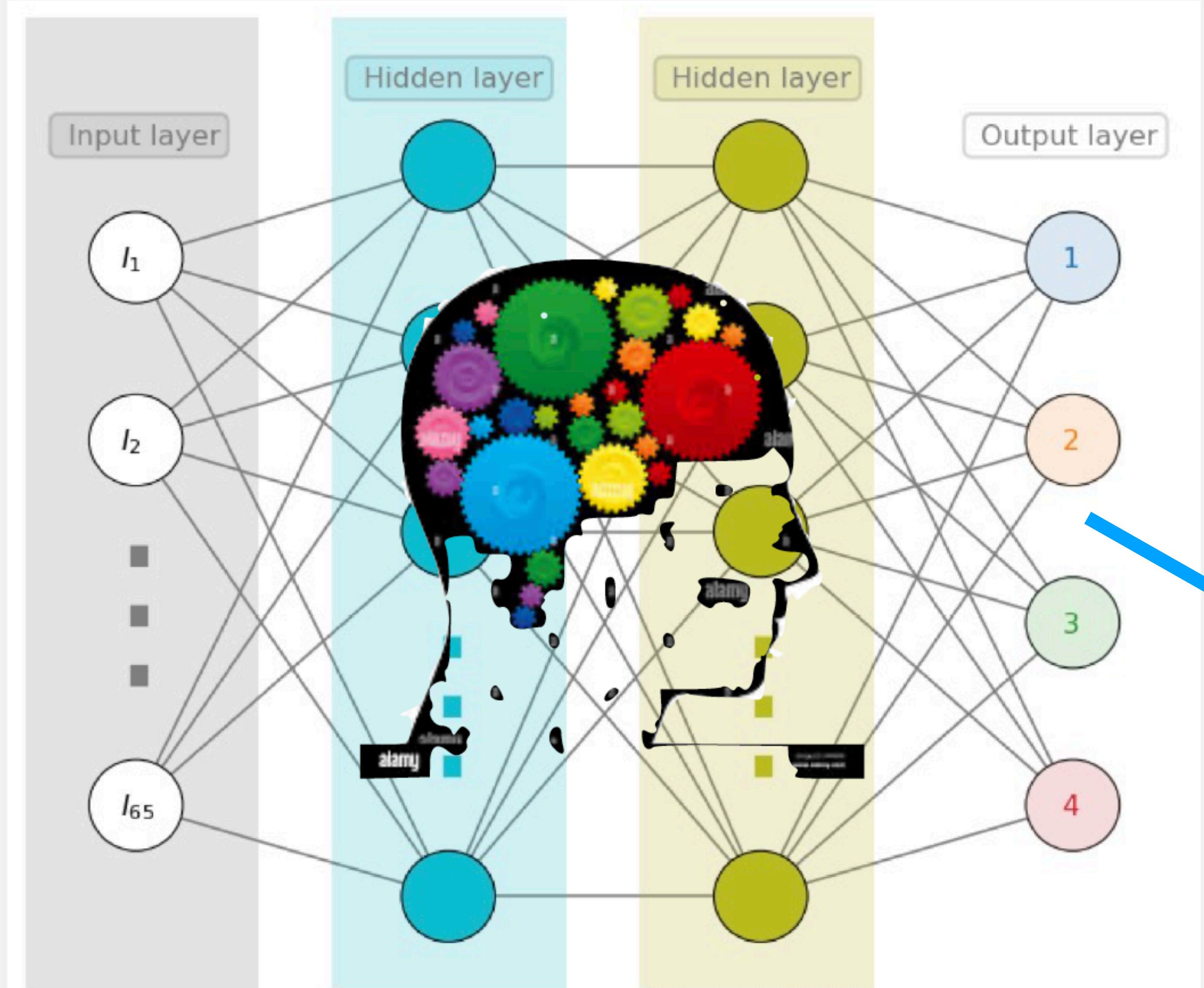
- JPAC's priority is to provide an intellectually stimulating environment and create carrier opportunities for its members

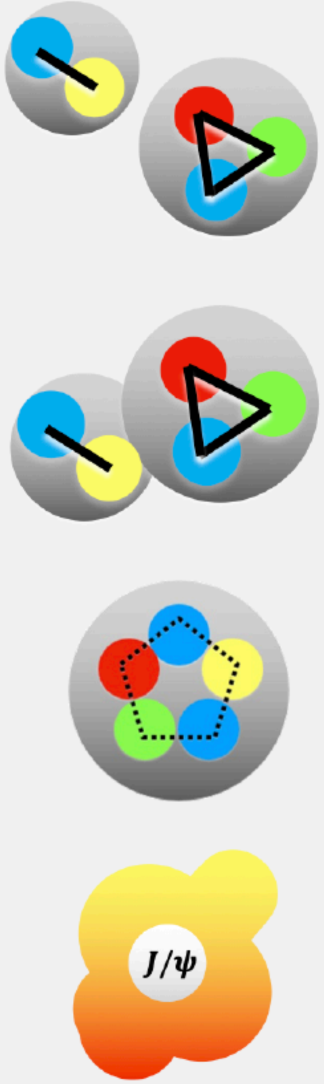
- We adopted a horizontal management structure, decisions made by consensus with shared responsibilities and benefits (e.g. publication policy)

Holy Grail: AI as a tool for physics discovery

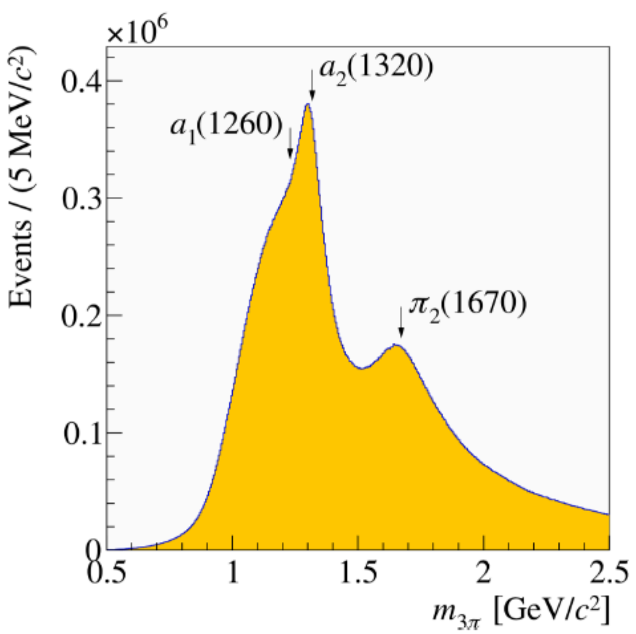
Learn (S-matrix)

$$S = T\left[\exp\left(-i\int_{-\infty}^{\infty} dt H'_I(t)\right)\right]$$





Apply to data



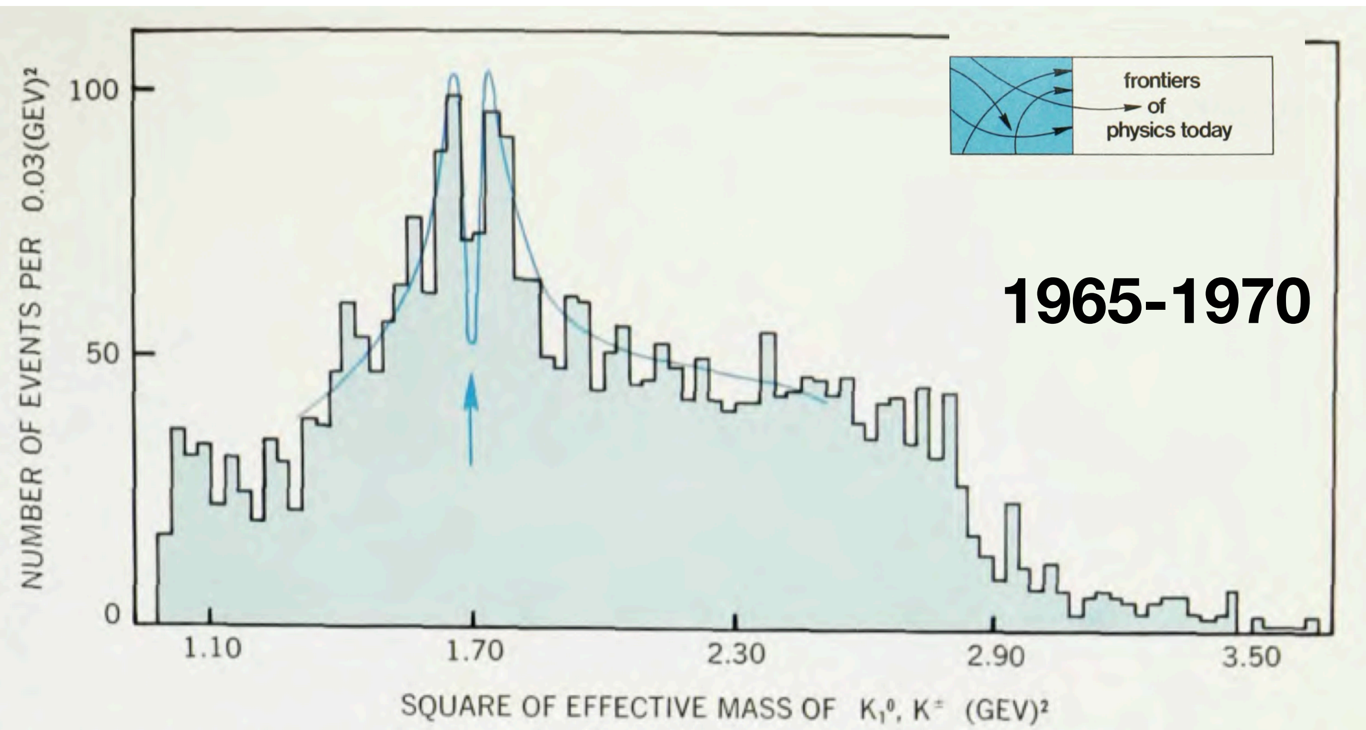
Tell the story

Importance of high quality data

$$\pi^- + p \rightarrow X^- + p$$

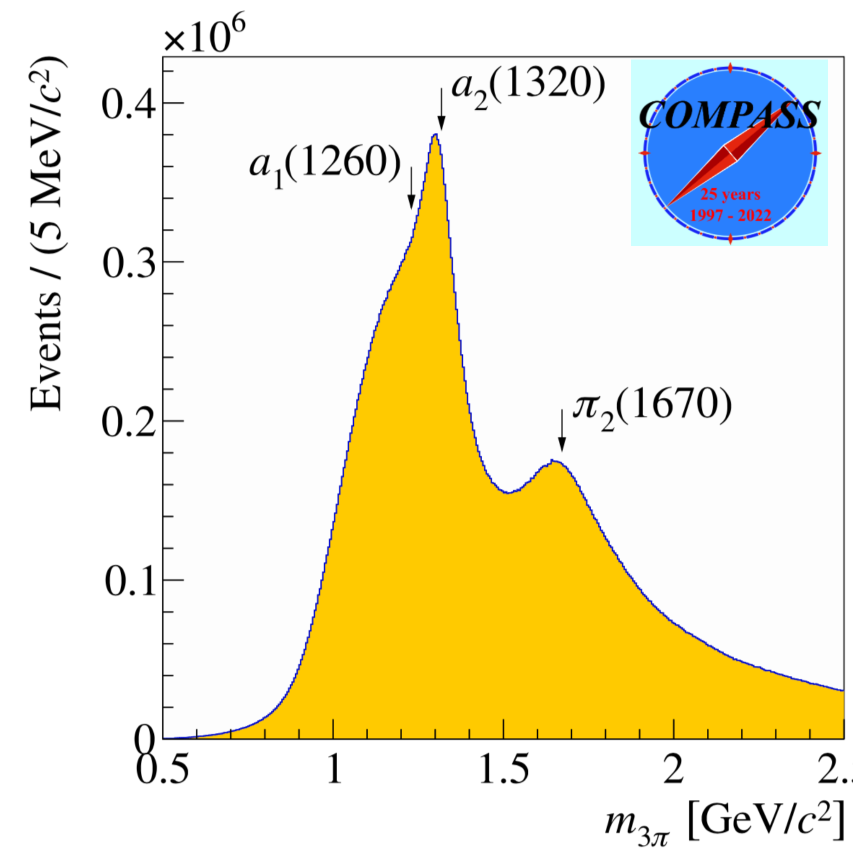
The puzzle of the A2 meson

The A2 may be two distinct but similar particles or a single object of an entirely new type. Either way, it has experimentalists arguing and theorists confused.



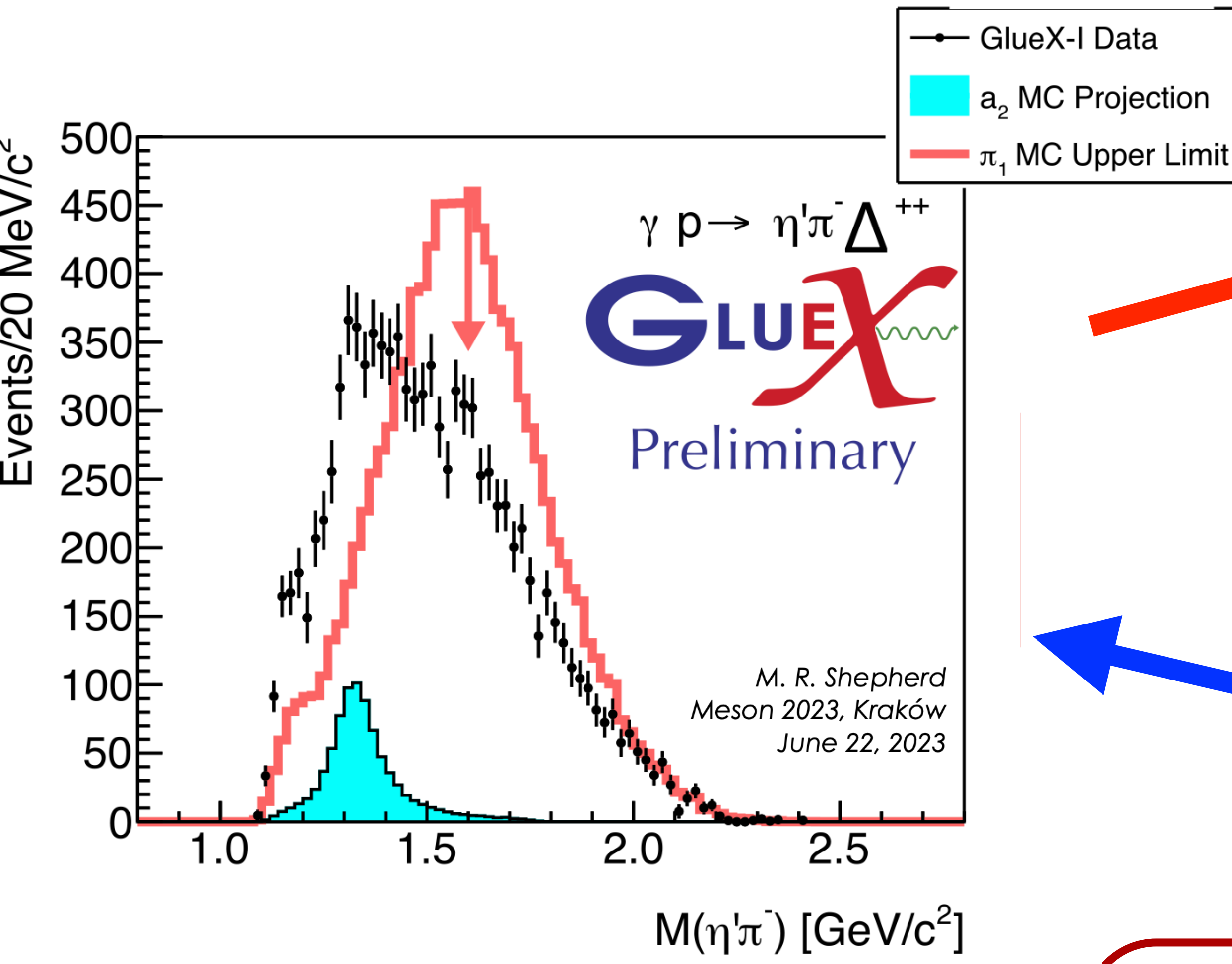
Proton–antiproton annihilation shows evidence for a split A2. The dip at the A2 (mass)², shown by the colored arrow, in the $K_1^0K^+$ effective mass spectrum indicates that the A2 splitting is independent of the production reaction. The data were taken by a CERN-College de France-Liverpool bubble-chamber group. *Figure 5*

vs

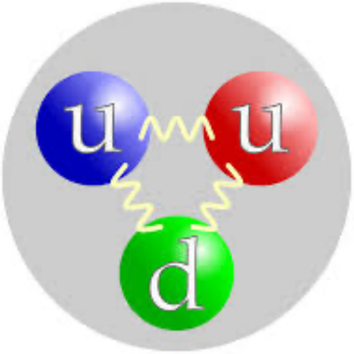


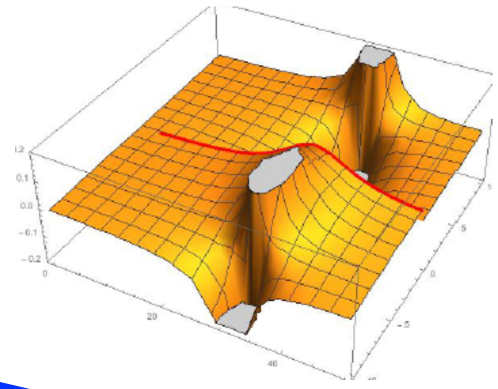
Similar spectra from GlueX and CLAS12

Theory Models

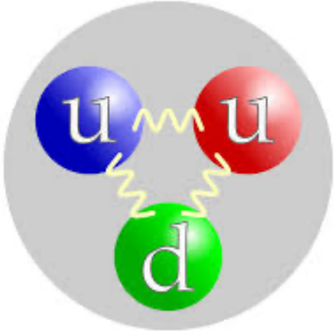


Make S-matrix theory rooted hypotheses : minimal bias



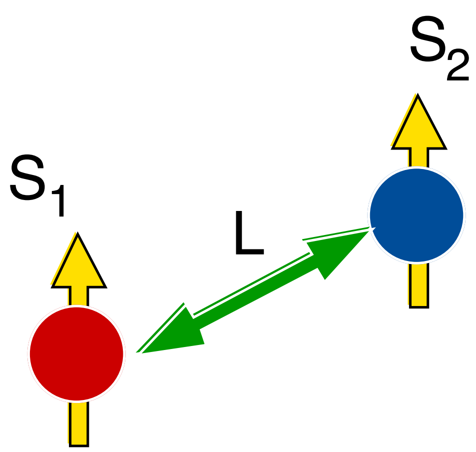


It all goes through analytical reaction amplitudes



Make models and compare with data: difficult to avoid bias

Applications : Light Exotic Hybrid



$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

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

Determine J^{PC} through Partial Wave Analysis

Mesons with $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$: Exotic Quantum Numbers

π_1

Expected to have very similar properties to ordinary $Q\bar{Q}$ mesons

Brief history of light hybrids

Nuclear Physics B152 (1979) 171–188
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COLOURED QUARK AND GLUON CONSTITUENTS IN THE MIT BAG MODEL: A MODEL OF MESONS

Ted BARNES
Department of Physics, University of Southampton, Southampton SO9 5NH, England

Received 24 October 1977
(Revised 7 May 1979)

We generalize the bag model by treating transverse coloured vector gluons as constituents. The physical S-wave mesons are mixed states of pure quark and quark-plus-gluon type, and their masses are accounted for by the colour SU(3) quark-gluon Hamiltonian. Finally, we obtain the masses and some electromagnetic properties of the S-wave mesons in this model for states constructed from u, d, s, c and b quarks.

PHYSICS LETTERS 5 January 1976

…ENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

R.L. JAFFE* and K. JOHNSON
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Mass. 02139, USA

Volume 132B, number 4,5,6 PHYSICS LETTERS

GLUEBALLS AND MEIKTONS WHICH DECAY TO MULTI…

Michael S. CHANOWITZ and Stephen R. SHARPE [1]
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Received 19 August 1983

VOLUME 17, NUMBER 3 1 FEBRUARY 1978

Model of mesons with constituent gluons*

D. Horn†
California Institute of Technology, Pasadena, California 91125

J. Mandula‡
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 28 January 1977)

A model of mesons composed of a quark, an antiquark, and a gluon is proposed. The binding of the constituents is provided by a confining linear potential between the gluon and the quarks. The lowest states of the model are described, and their relative masses evaluated, for the case of heavy (charmed) quarks, i.e., $c\bar{c}g$ states.

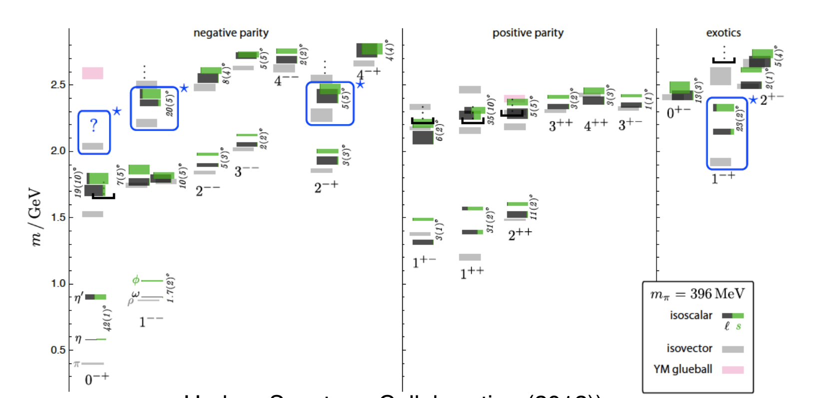
PHYSICAL REVIEW LETTERS 1 November 1976

ψ Spectroscopy of a Charm String*

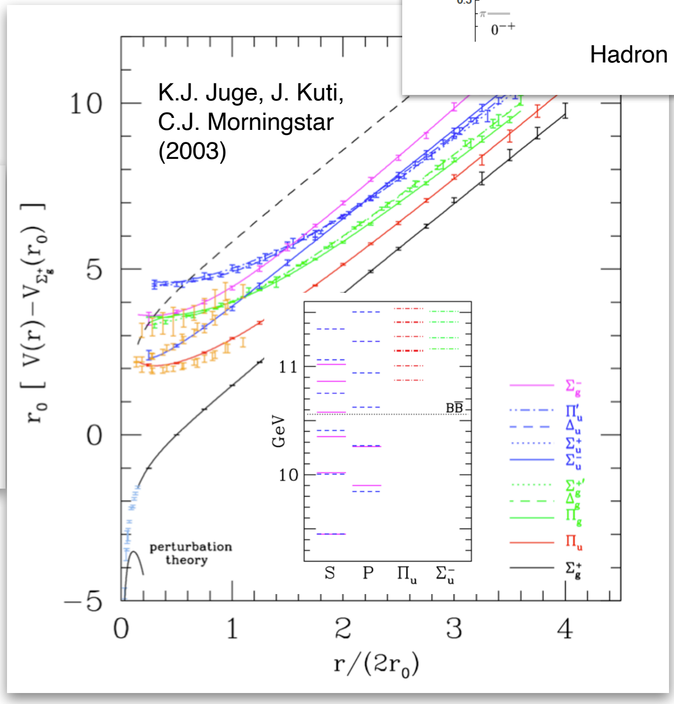
R. C. Giles and S.-H. H. Tye
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 13 August 1976)

We report the results of the application of the quark-confining string to the ψ spectrum. The model is defined by a relativistically invariant action of quarks and color gauge fields. In the Schrödinger limit, where light quarks are neglected, this model (with two parameters) reduced to the charmonium model (with a linearly rising potential) has additional vibrational levels. In the e^+e^- channel, the first vibrational levels come at …

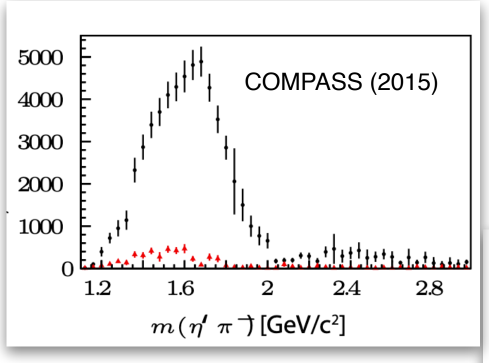
- 1970-80 The early phenomenology

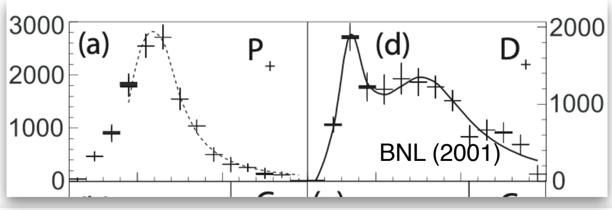


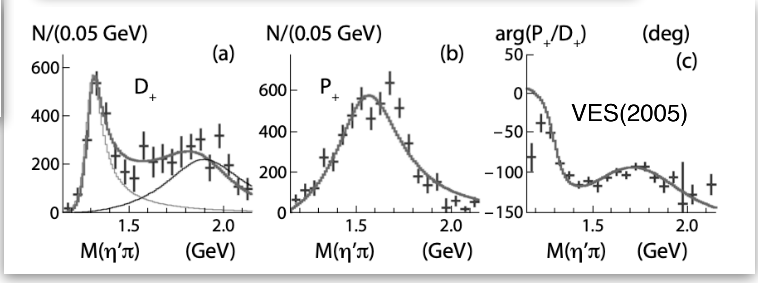
Hadron Spectrum Collaboration (2012))



- 2000-2010 The early lattice studies

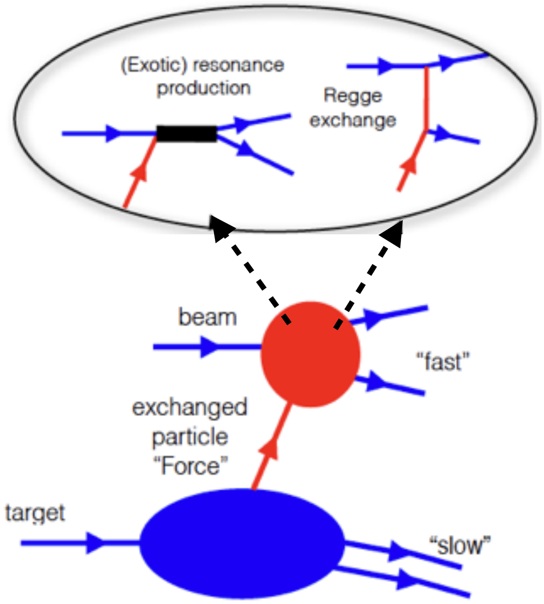






- '2000-2010 The early data

- New perspectives : GlueX,CLAS, COMPAS, JPAC…

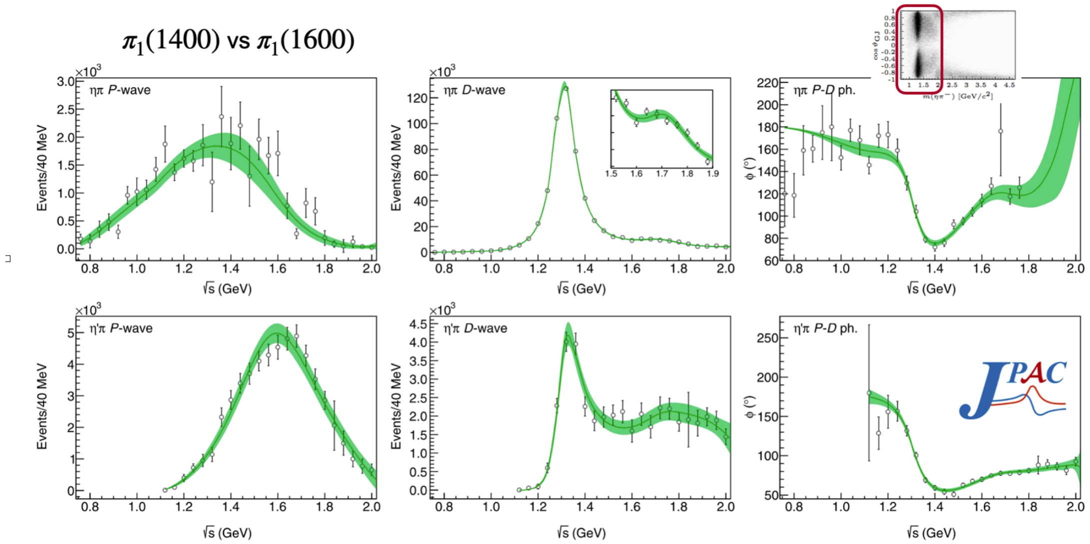


$\eta^{(\prime)}\pi$ resonances from COMPASS data

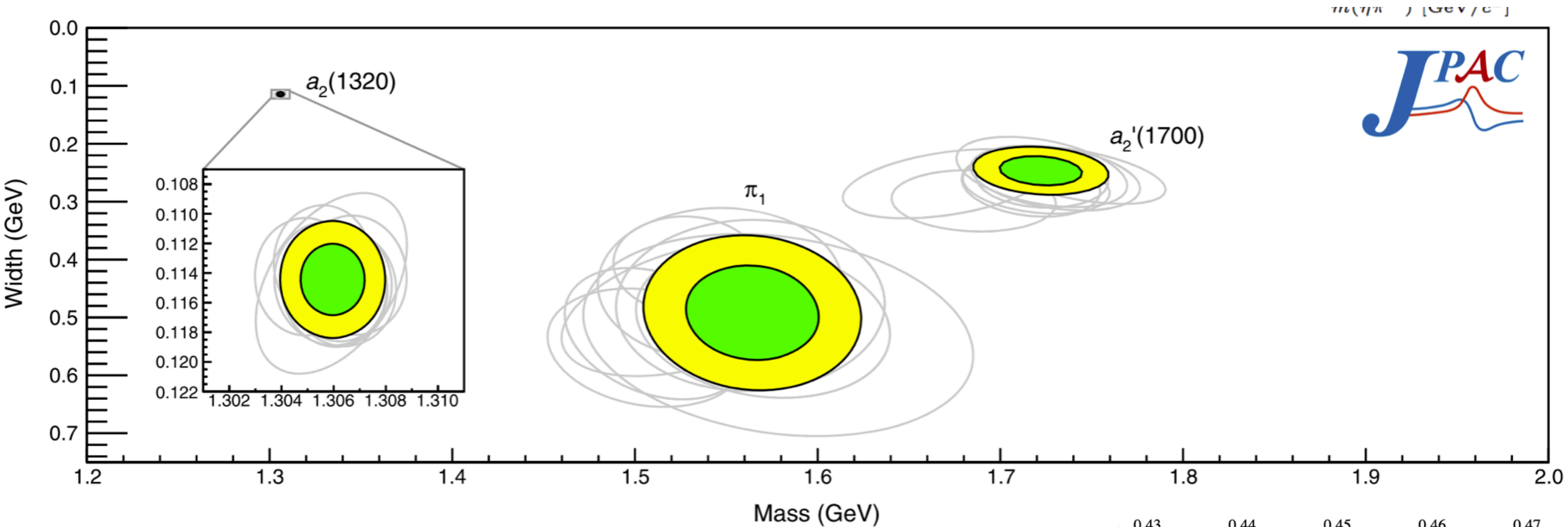
$J^{PC} = 1^{-+}$ Outside valance quark model

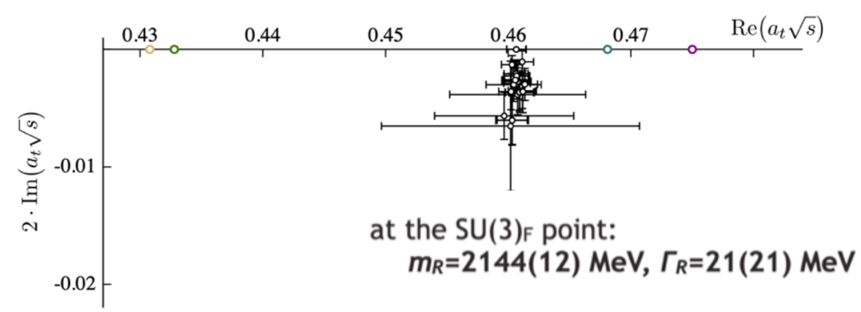
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

[A.Rodas, et al (JAPC) PRL (2019)]



[C.Adolph, et all COMPASS, Phys.Lett.B 740 (2015) 303]





A.Woss et al. PRD 103 (2021) 5, 054502

generates for a π_1 at 1564 MeV:

Γ_{TOT} ~ 140-600 MeV

$\Gamma(\pi\eta) \lesssim 1$ MeV

$\Gamma(\pi\eta') \lesssim 20$ MeV

$\Gamma(\pi\rho) \lesssim 12$ MeV

$\Gamma(\pi b_1)$ ~ 140-530 MeV

INDIANA UNIVERSITY

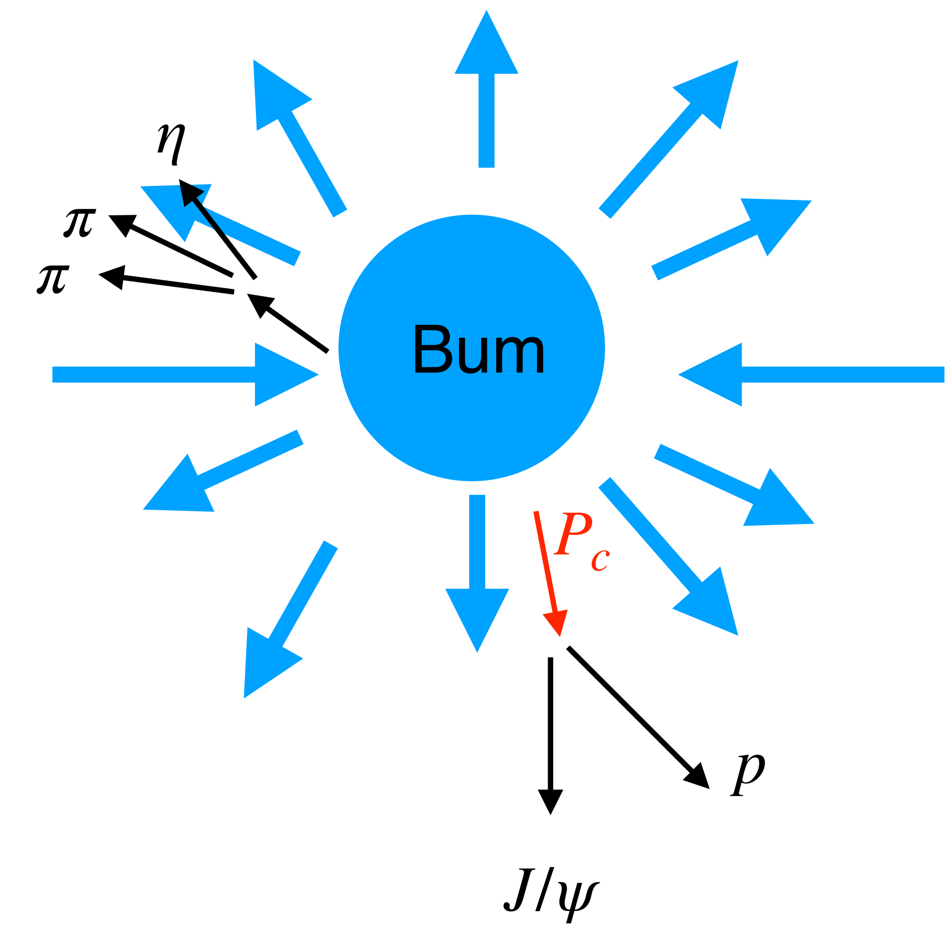
Jefferson Lab

Uniqueness of JLab for spectroscopy

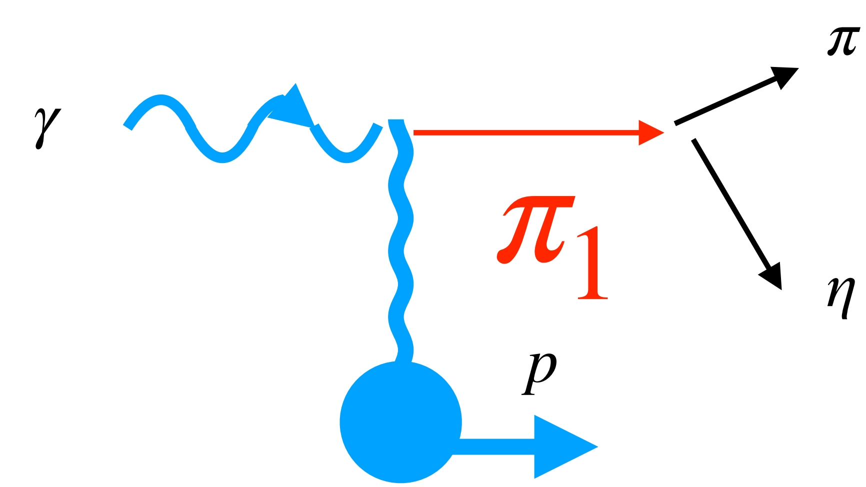
Majority of hadron exotics spotted in colliders.
Very few were seen in more then one setting

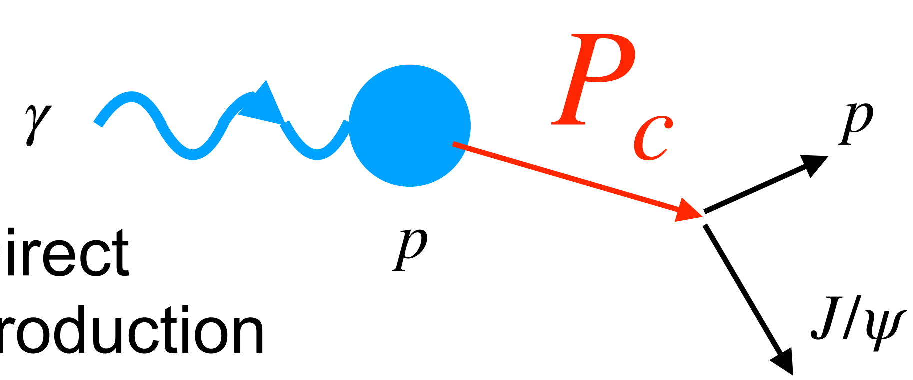
Fixed target with well tuned E_γ :

Full exclusivity
Low multiplicity
Direct production and peripheral production are calculable
Resonances can be well separated from kinematic effects
Significant rapidity gap enables to separate beam from target fragmentation



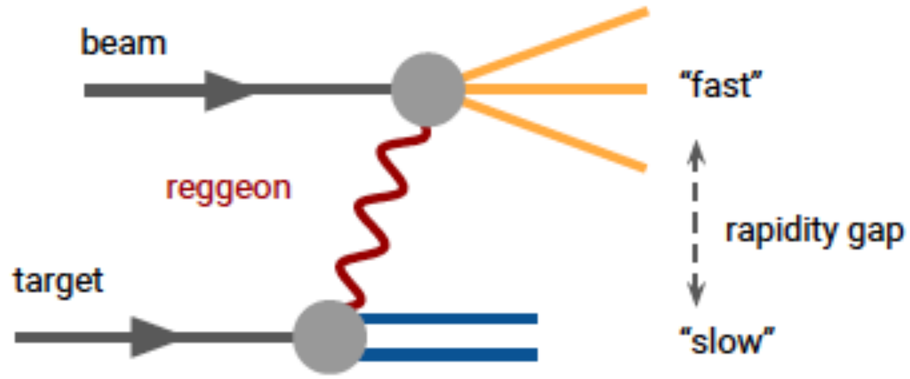
Peripheral production





Direct production

Peripheral Production : Regge poles (+ corrections)



- Factorization

$$A_{\lambda_i}(s,t) = \beta^{Top}_{\lambda_1,\lambda_{\bar{3}}}(t)\beta^{Bottom}_{\lambda_1,\lambda_{\bar{4}}}(t)G(s,t)$$

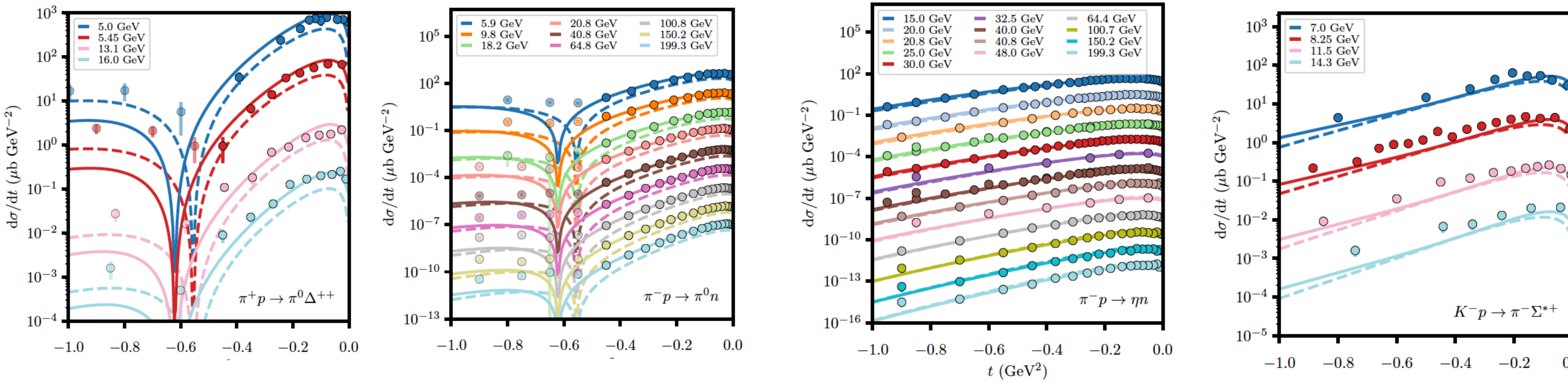
- Shrinkage of the forward peak $\quad G(s,t) \sim exp(b\log(s)t)$

- Phases constrained by unitarity

- Residues (β's) related to observables e.g. $\quad \beta^2(\gamma b_1, R_\pi) \sim \Gamma(b_1 \to \gamma\pi)$

- Corrections O(1/log(s)) can be formalized within an EFT

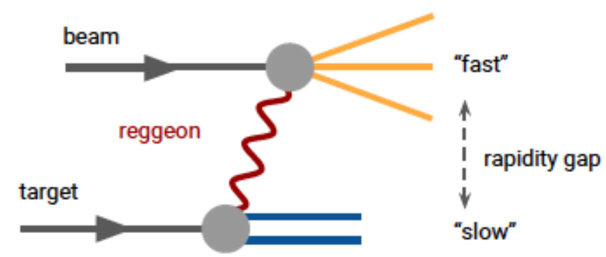
Global Regge pole of CEX (no P no π)

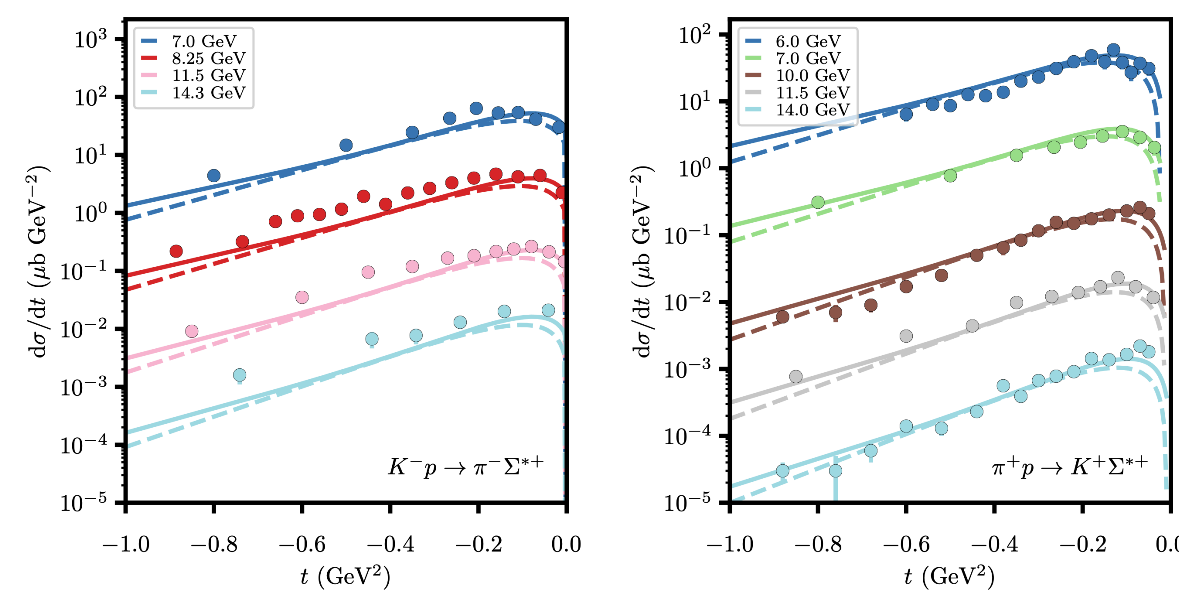


"ρ" exchange dip at

$(t \sim -0.5 GeV^2)$

"a_2" exchange





(a) $K^- p \to \pi^- \Sigma^{*+}$

(b) $\pi^+ p \to K^+ \Sigma^{*+}$

Regge poles well describe peripheral production at CEBAF energies….

"K/K^*" exchange

Data =1271 points, N_{par} = 6 SU(3) couplings, 1 mixing angle, 2 exp. slopes)   *J.Nys et al. (JPAC) 2018*

Systematic analysis of the π_1 at JLab

1 We know π_1 decay characteristics (mostly done)

Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
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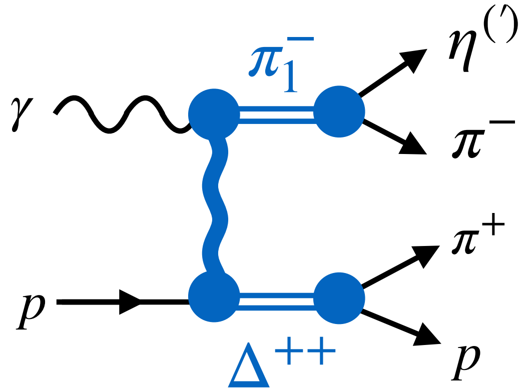
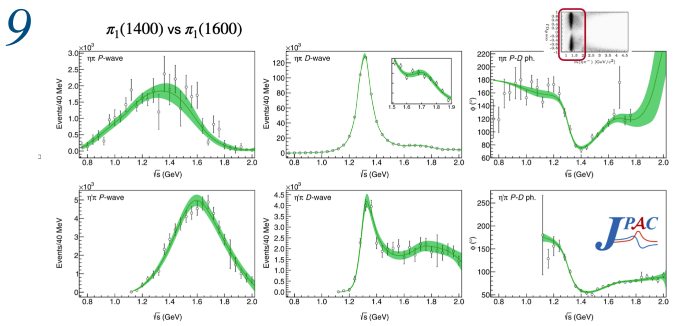
A.Rodas et al. (JPAC) 2019

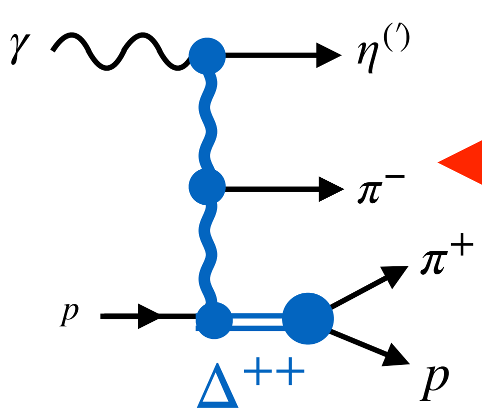
	thr./MeV	$\lvert c_i^{\text{phys}} \rvert$/MeV	Γ_i/MeV
$\eta\pi$	688	$0 \to 43$	$0 \to 1$
$\rho\pi$	910	$0 \to 203$	$0 \to 20$
$\eta'\pi$	1098	$0 \to 173$	$0 \to 12$
$b_1\pi$	1375	$799 \to 1559$	$139 \to 529$
$K^*\bar{K}$	1386	$0 \to 87$	$0 \to 2$
$f_1(1285)\pi$	1425	$0 \to 363$	$0 \to 24$
$\rho\omega\{^1P_1\}$	1552	$\lesssim 19$	$\lesssim 0.03$
$\rho\omega\{^3P_1\}$	1552	$\lesssim 32$	$\lesssim 0.09$
$\rho\omega\{^5P_1\}$	1552	$\lesssim 19$	$\lesssim 0.03$
$f_1(1420)\pi$	1560	$0 \to 245$	$0 \to 2$
			$\Gamma = \sum_i \Gamma_i = 139 \to 590$

A.Voss et al. (HadSpec) 2021

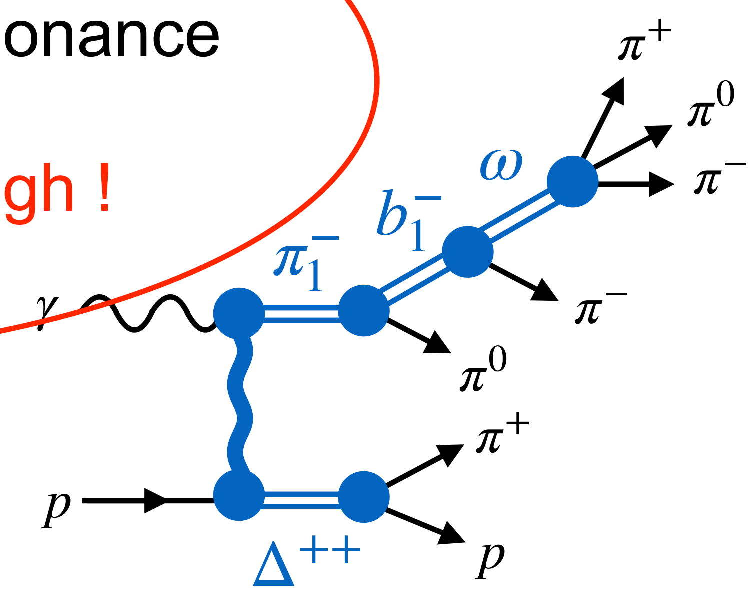




2. We need to know how π_1 is produced (single Regge) (in progress)

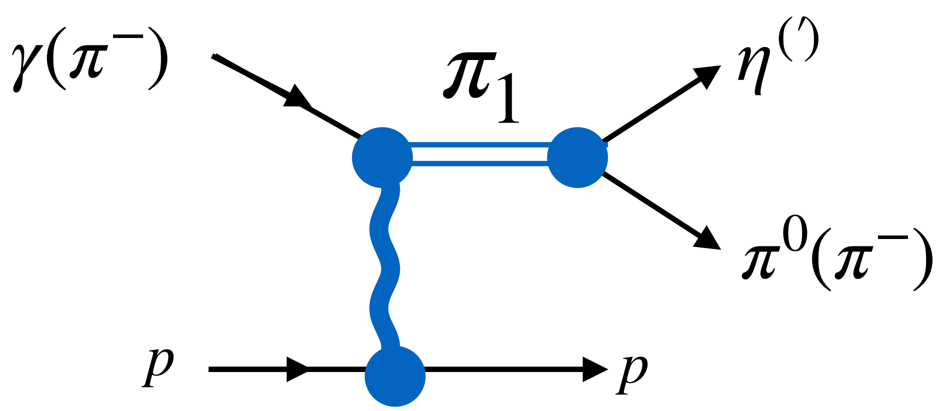


3.Use data outside the resonance region Double Regge to constrain resonance parameters
(In progress) Major breakthrough !

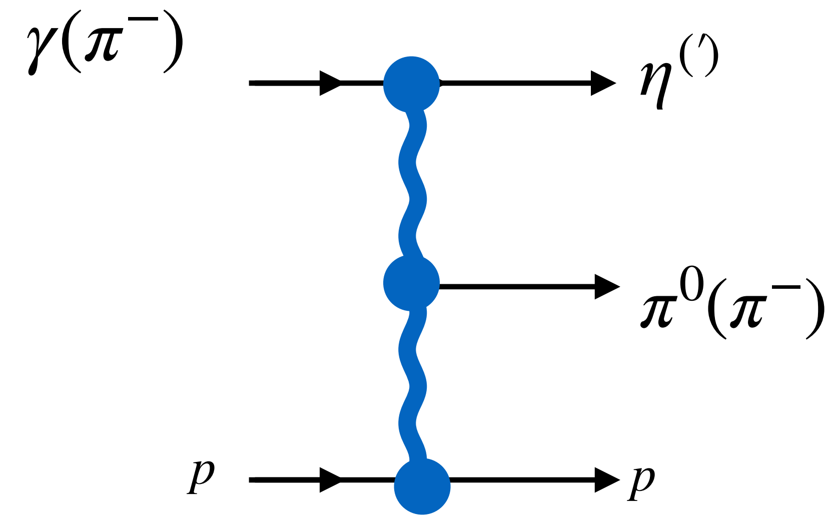


4.Extend to include other channels
(in progress)

Dispersion relations for 2-3 process

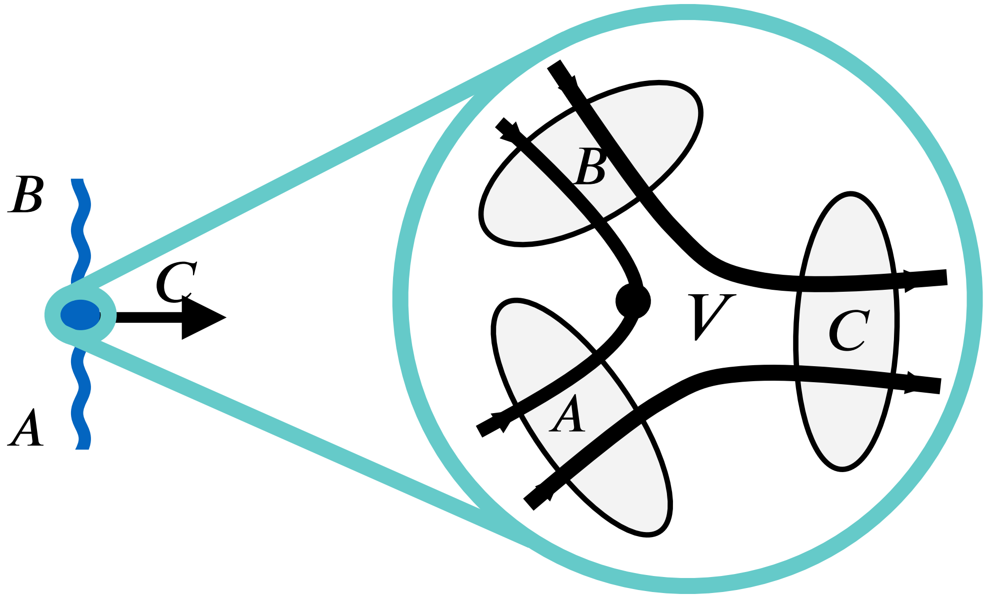


Dispersion relations , Finite Energy Sum Rules, etc



GlueX/(COMPAS) analysis in progress

The existing models of the Double Regge exchange suffer from pathologies (infinite narrow resonances) We have “understood” how to construct DR amplitudes without such pathologies



Enables comparison with microscopic models and lattice

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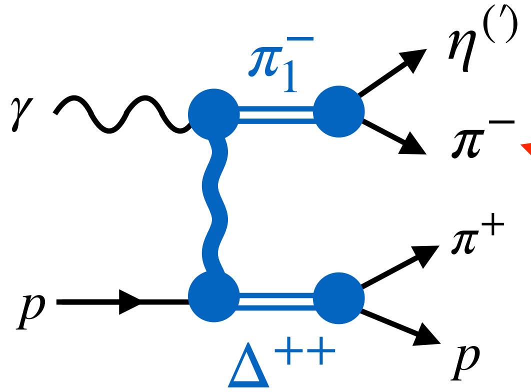

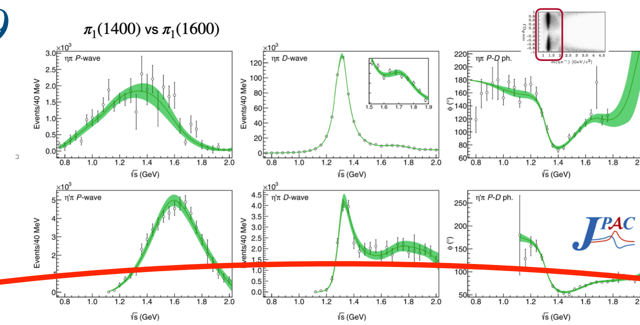

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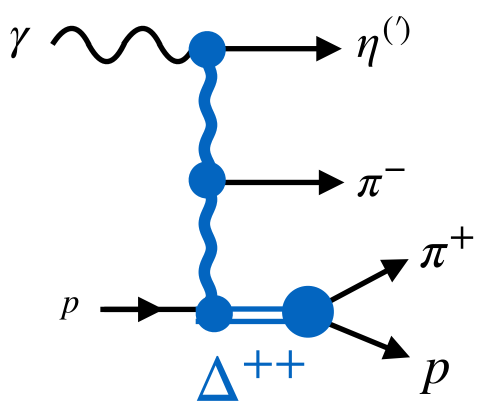

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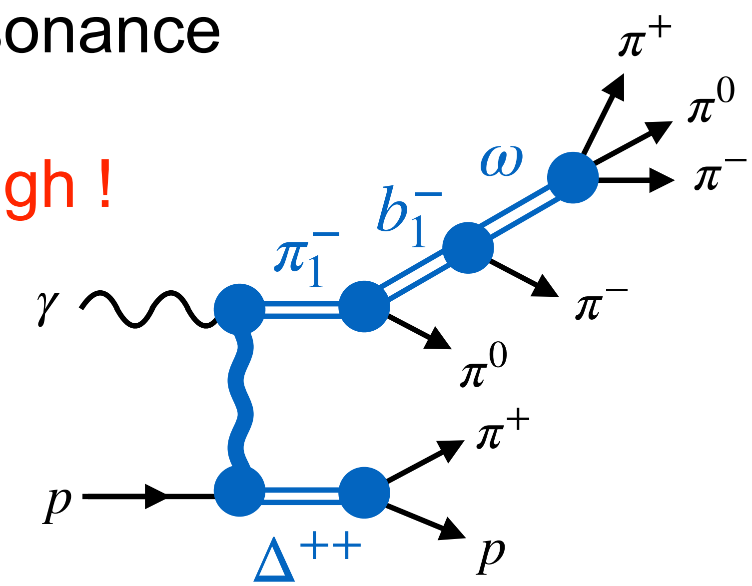
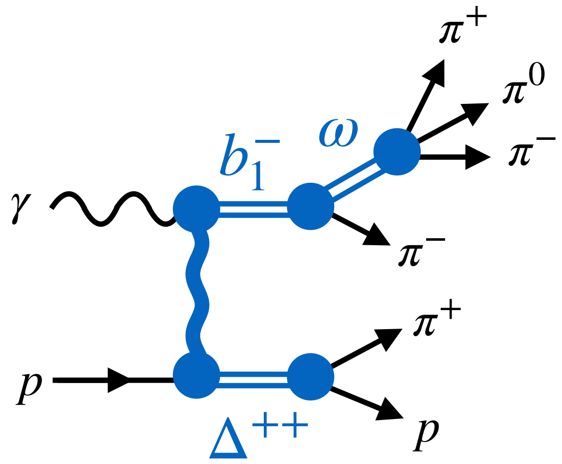


Resonance production via single Regge exchange

Main exotic decay is $\pi_1 \to b_1\pi$

Need first to understand b_1 photoproduction

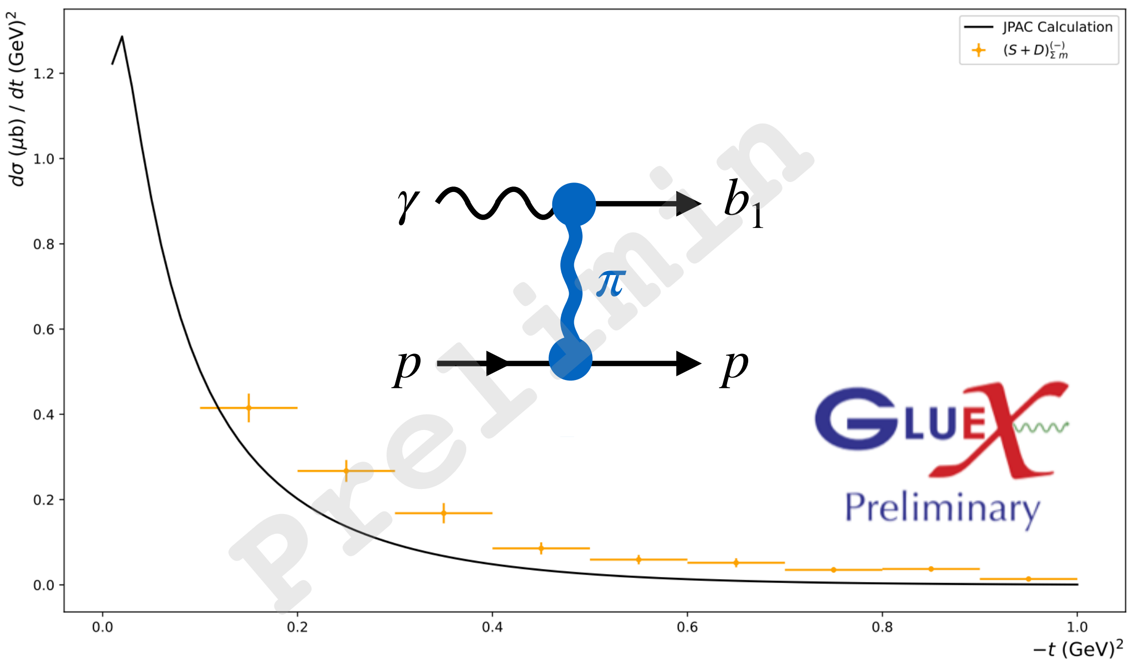


$\gamma p \to b_1^- \Delta^{++}$ $\gamma p \to b_1^0 p$

Model/Decay chain:

$$A_{\lambda_\gamma,\lambda_1,\lambda_2} = \sum_{\Lambda=-1}^{1} \sum_{\lambda_\Delta=-\frac{3}{2}}^{\frac{3}{2}} V_{\lambda_\gamma,\Lambda;\lambda_1,\lambda_\Delta}(s,t) \sum_{\lambda=-1}^{1} F_\lambda D^{J*}_{\Lambda,\lambda}(\Omega_\omega) Y^1_\lambda(\Omega_H) G \tilde{F}_{\lambda_2} D^{\frac{3}{2}*}_{\lambda_\Delta,\lambda_2}(\Omega_p)$$

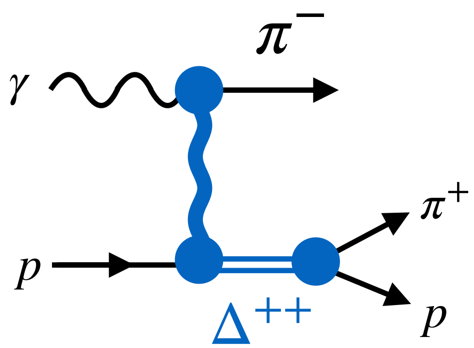
In the neutral channel $\gamma p \to b_1^0 p$
GlueX PWA shows (very) small contribution from unnatural exchange compares to natural (?)

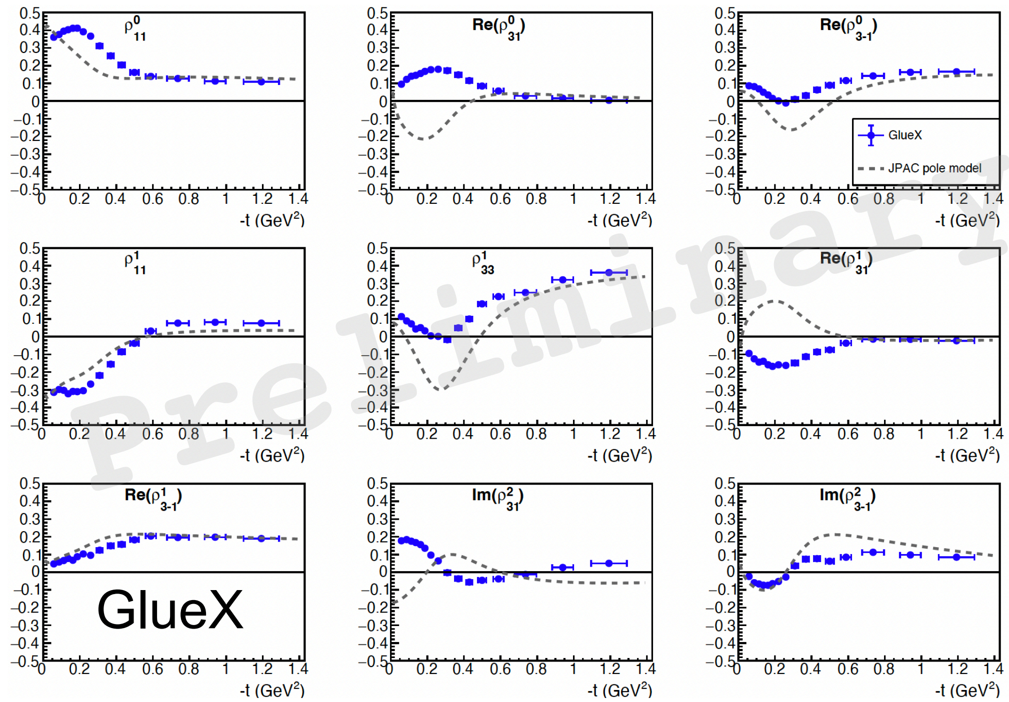


Pion exchange cross-section in agreement (prediction, not fit!) with preliminary data

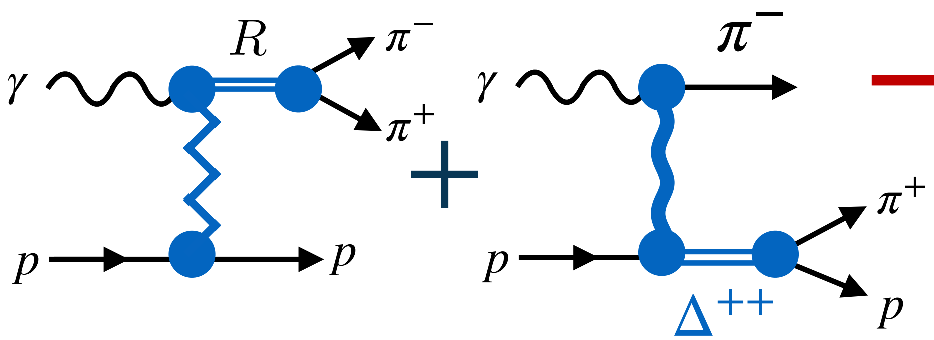
Towards complete understanding of photoproduction

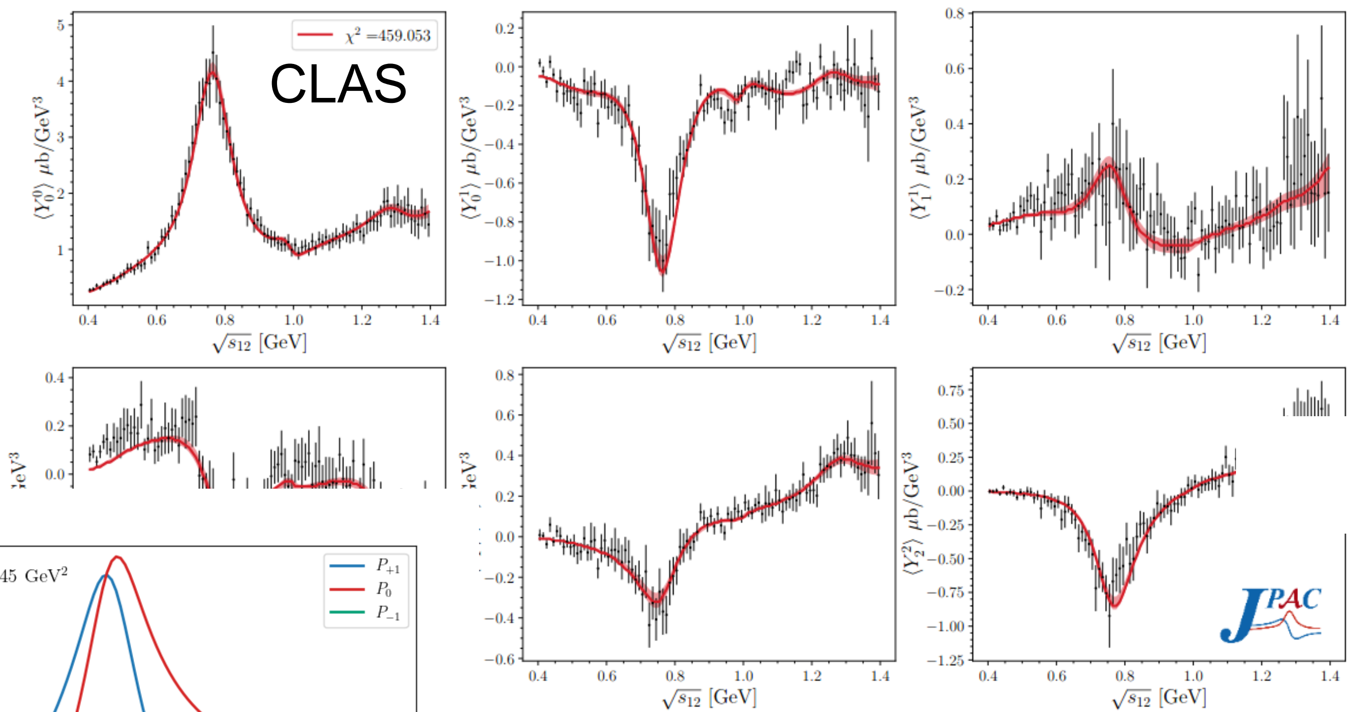
Understanding Δ^{++} production is underway





Two-pion photo production project almost completed (impressive data agreement)

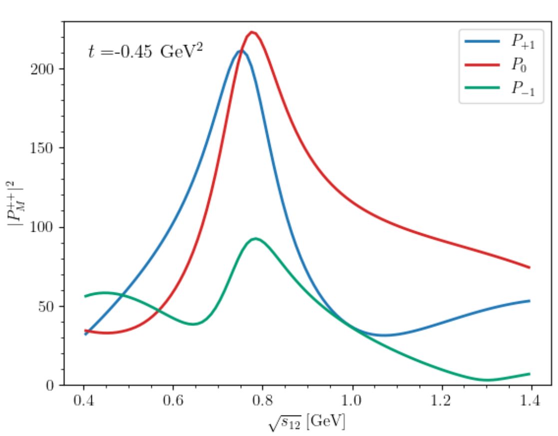




$\rangle$ for $L = 0, 1, 2$ and $M = 0, \ldots L$ for $E_\gamma = 3.7$ GeV and $t = -0.95$ GeV^2.

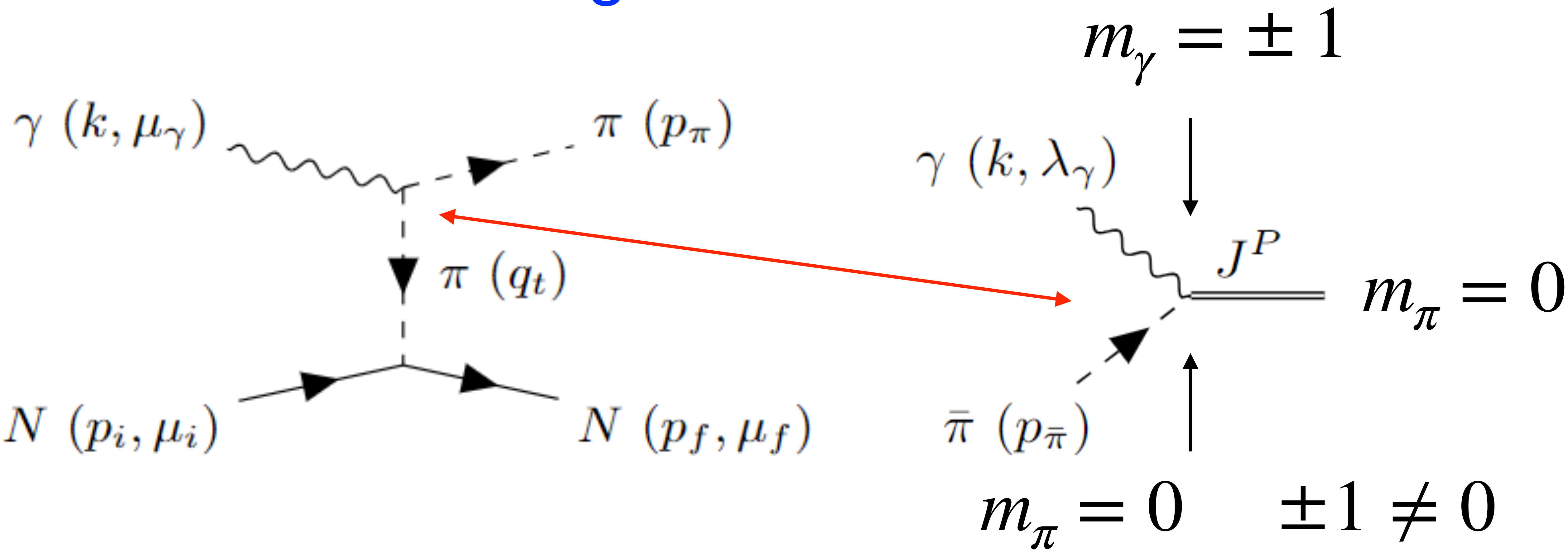
High quality data from CLAS, more expected from CLAS12 and GlueX

Hierarchy of P-waves for various helicities, determined production dynamics that gives rise to other helicity structures for $|t| \approx 0.45$ GeV^2



L.Bibrzycki, et al. (JPAC) 2024

Fun with π exchange

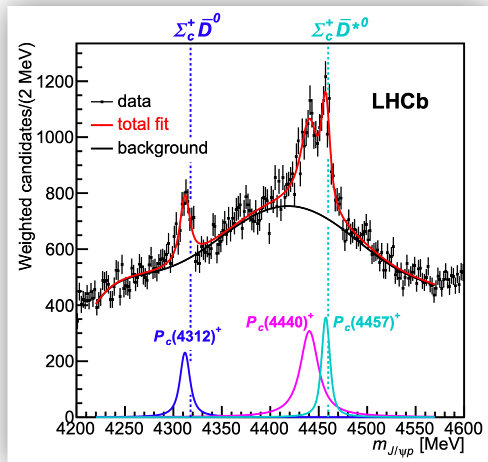


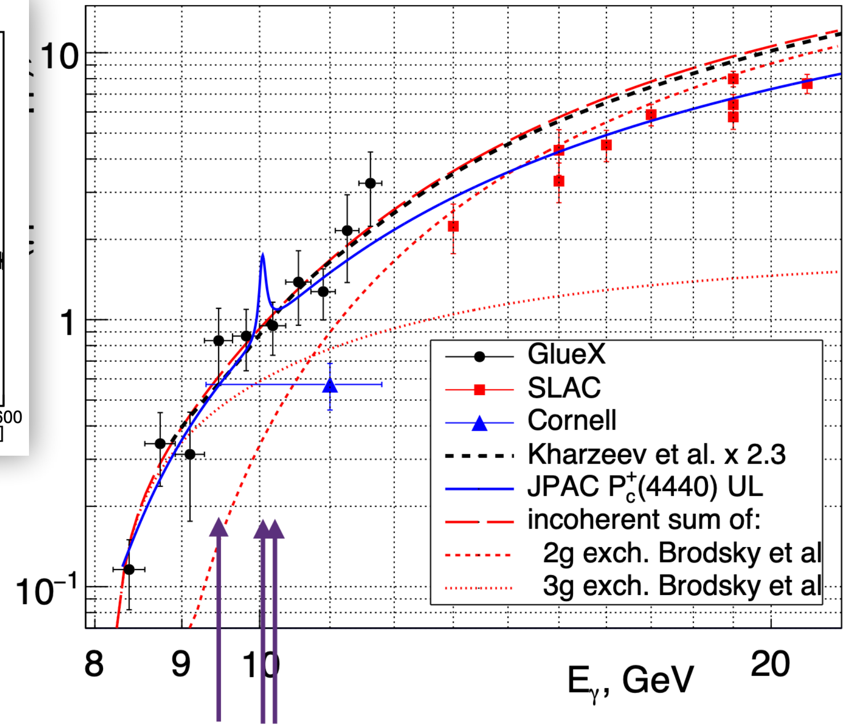
Naively there is no π exchange !

See Gloria Montana talk

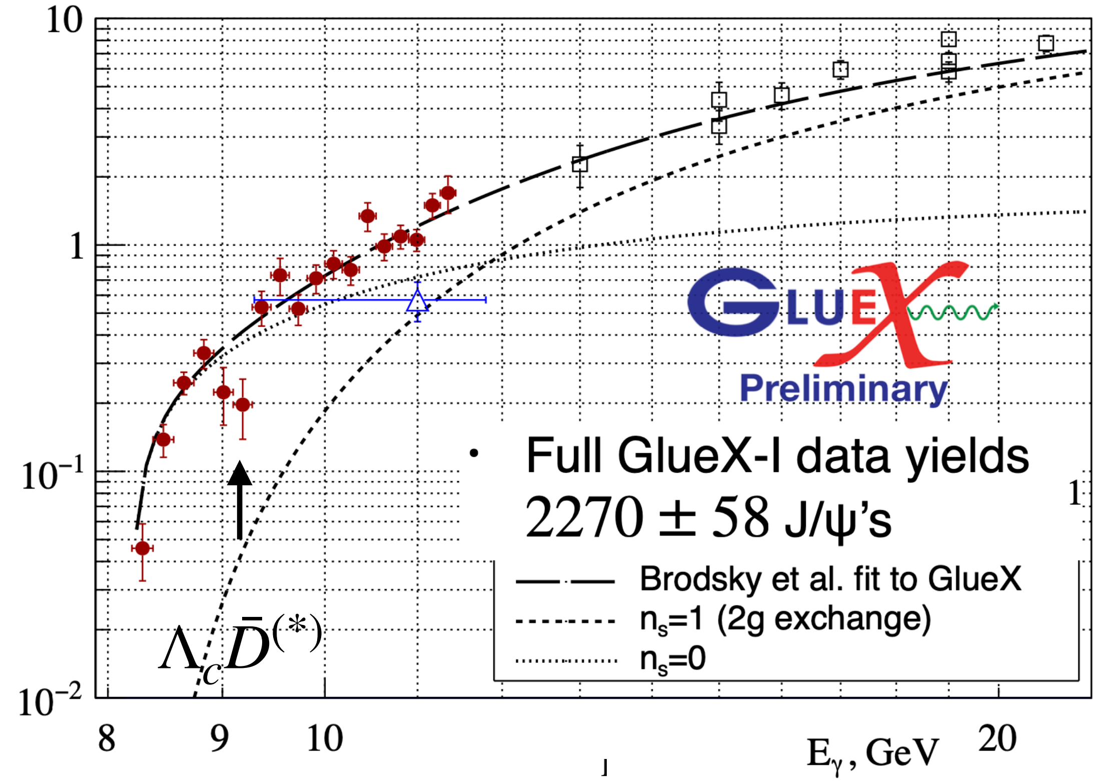
Applications : Heavy quarks

GlueX: PRL 123, 072001 (2019)





P_c's



- Full GlueX-I data yields 2270 ± 58 J/ψ's

- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance

Threshold effects ? Du et al, EPJC 80, 1053 (2020)

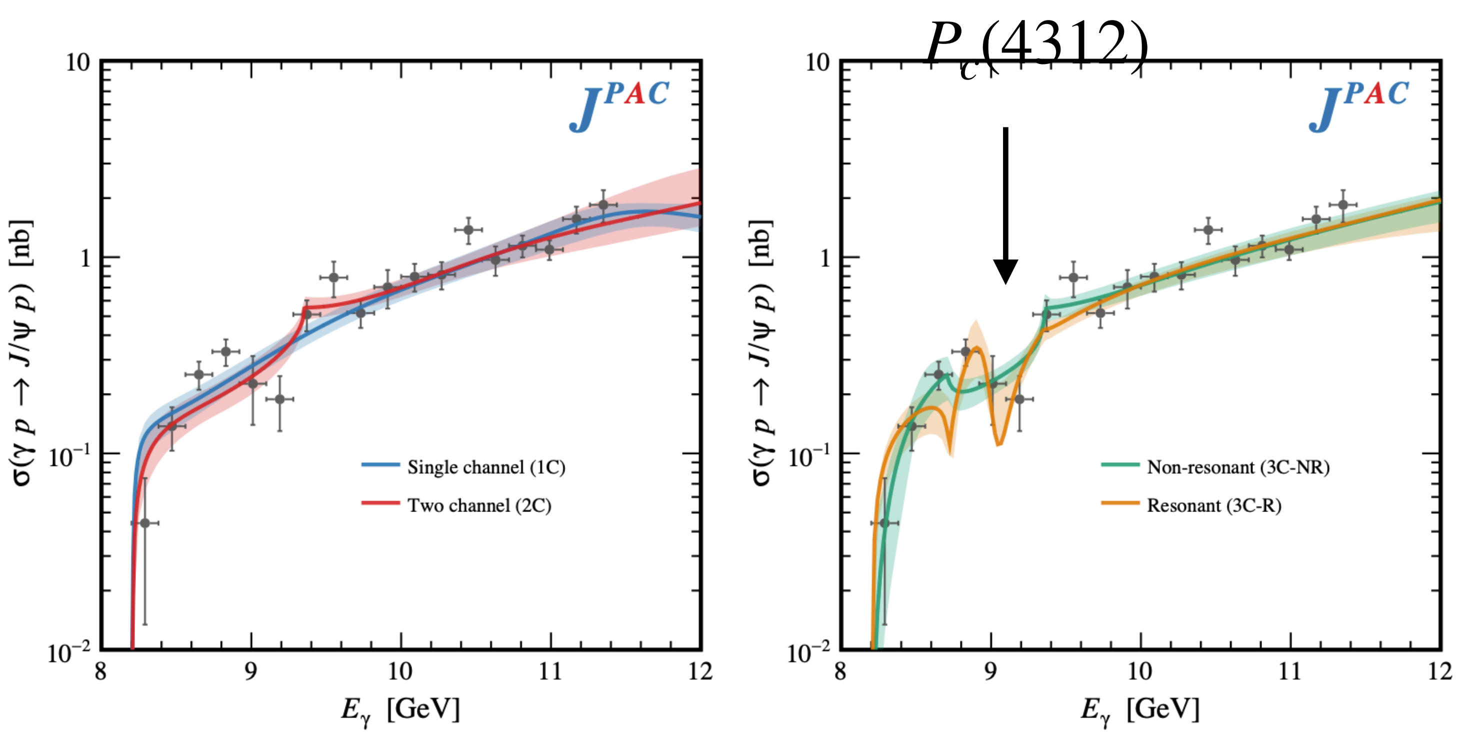


FIG. 1: Fit results for the integrated cross section compared to GlueX data from [37]. Bands correspond to 1σ uncertainties from bootstrap analysis.

D.Winney et al. (JPAC, 2023) Combined analysis of J/ψ 007 and GlueX

Spectroscopy at the future facilities

***XYZP* spectroscopy at a charm photoproduction factory**

M. Albaladejo,[1] M. Battaglieri,[2,3] A. Esposito,[4] C. Fernández-Ramírez,[5]
A. N. Hiller Blin,[1] V. Mathieu,[6] W. Melnitchouk,[1] M. Mikhasenko,[7] V. I. Mokeev,[2]
A. Pilloni,[3,8,*] A. D. Polosa,[9] J.-W. Qiu,[1] A. P. Szczepaniak,[1,10,11] and D. Winney[10,11]

LoI RF7_RF0_120

arXiv:2203.08290

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

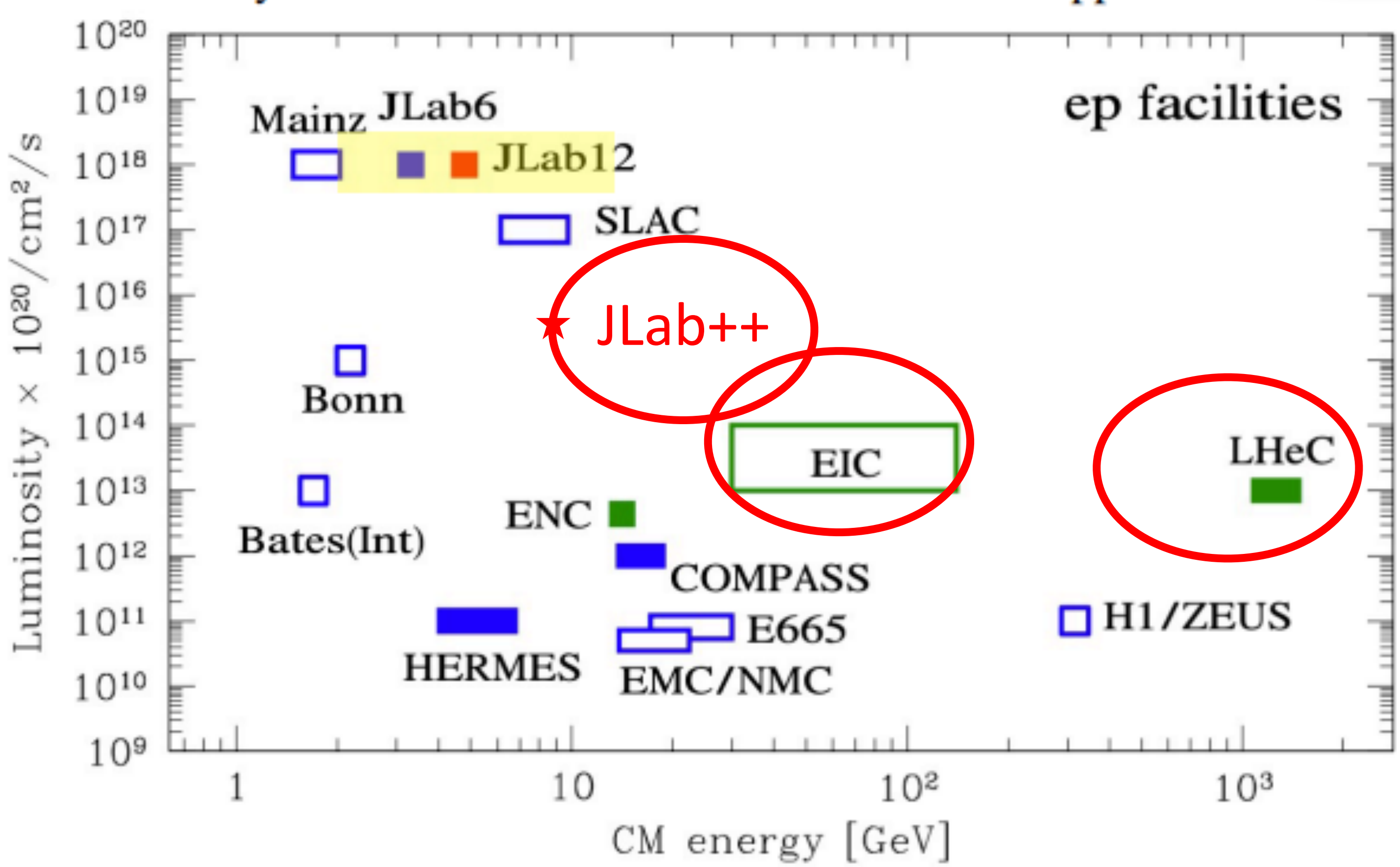
Hadron Spectroscopy in Photoproduction

Miguel Albaladejo[1], Lukasz Bibrzycki[2], Sean Dobbs[3], César Fernández-Ramírez[4,5],
Astrid N. Hiller Blin[6], Vincent Mathieu[7,8], Alessandro Pilloni[9,10], Justin Stevens[11],
Adam P. Szczepaniak[12,13,14], and Daniel Winney[13,14,15,16]

arXiv:2112.00060

Physics with CEBAF at 12 GeV and Future Opportunities

Ent[2],
Qiu[2,8],

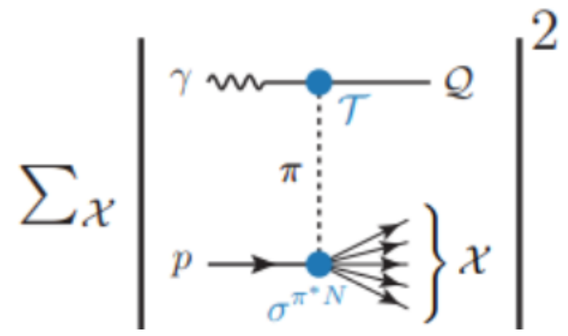


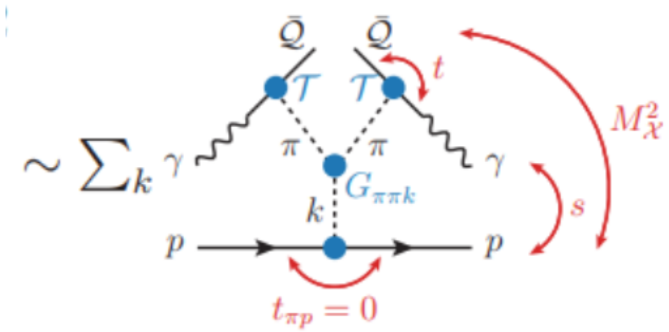
EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production

Spectroscopy at the future facilities

$Z^{+}_{c,b}$ Production @JLab++, EIC

M. Albaladejo et al. [JPAC], PRD (2020)
D.Winney et al. (JPAC)
D.Glazier et al (JPAC)





	17 GeV		24 GeV	
	produced	detected	produced	detected
$Z_c(3900)^+$	2.2 k	371	4.2 k	588
$X(3872)$	1.1 k	32	4.2 k	63

TABLE I. Estimates of yields for day of data taking at CLAS24 assuming a zero-angle electron detector

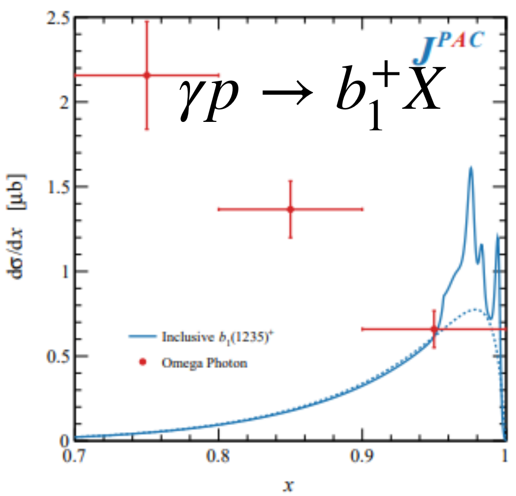
TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100 (GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1}; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

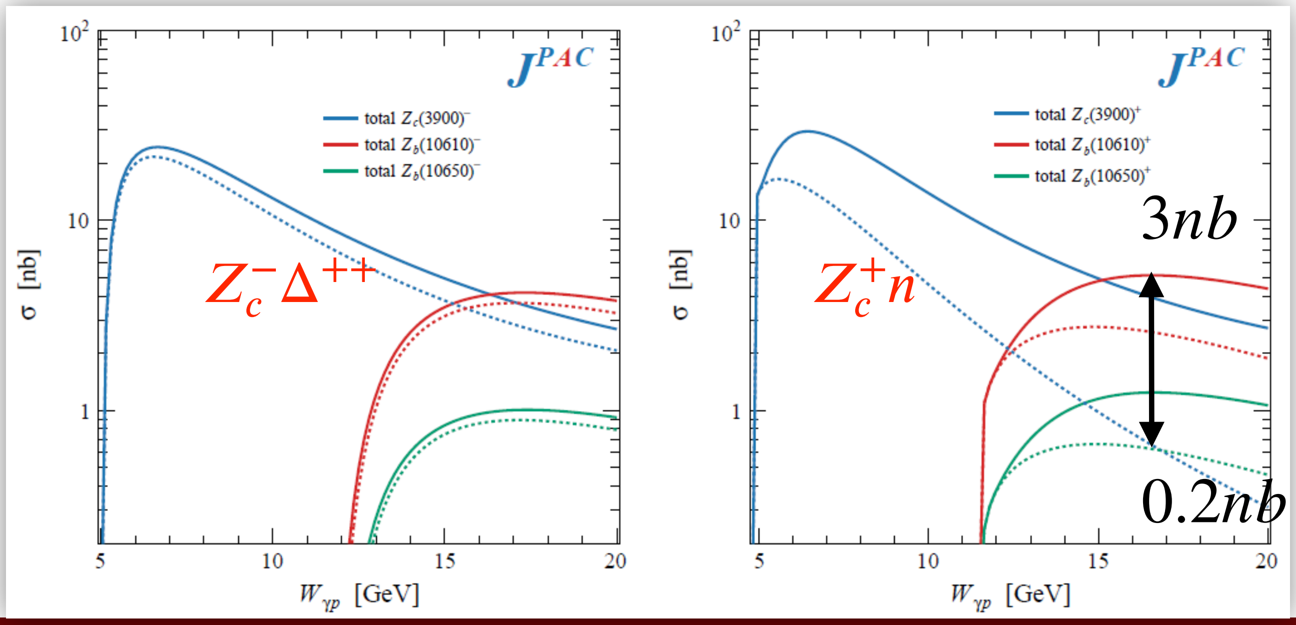
Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\ K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\ \pi^+$	3.6	24

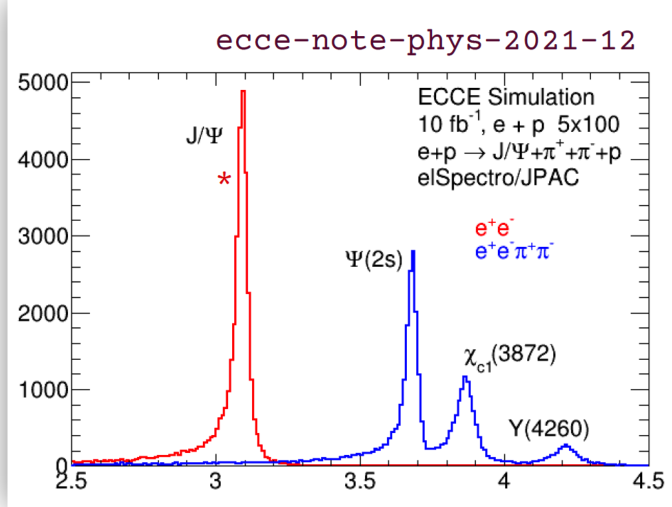
- Couplings from data as much as possible, not relying on the nature of XYZ
- The model is expected to hold in the highest x- bin
- Model underestimates lower bins, conservative estimates

JLab22 ideal for XZ, EIC better for Y's

https://github.com/dwinney/jpacPhoto







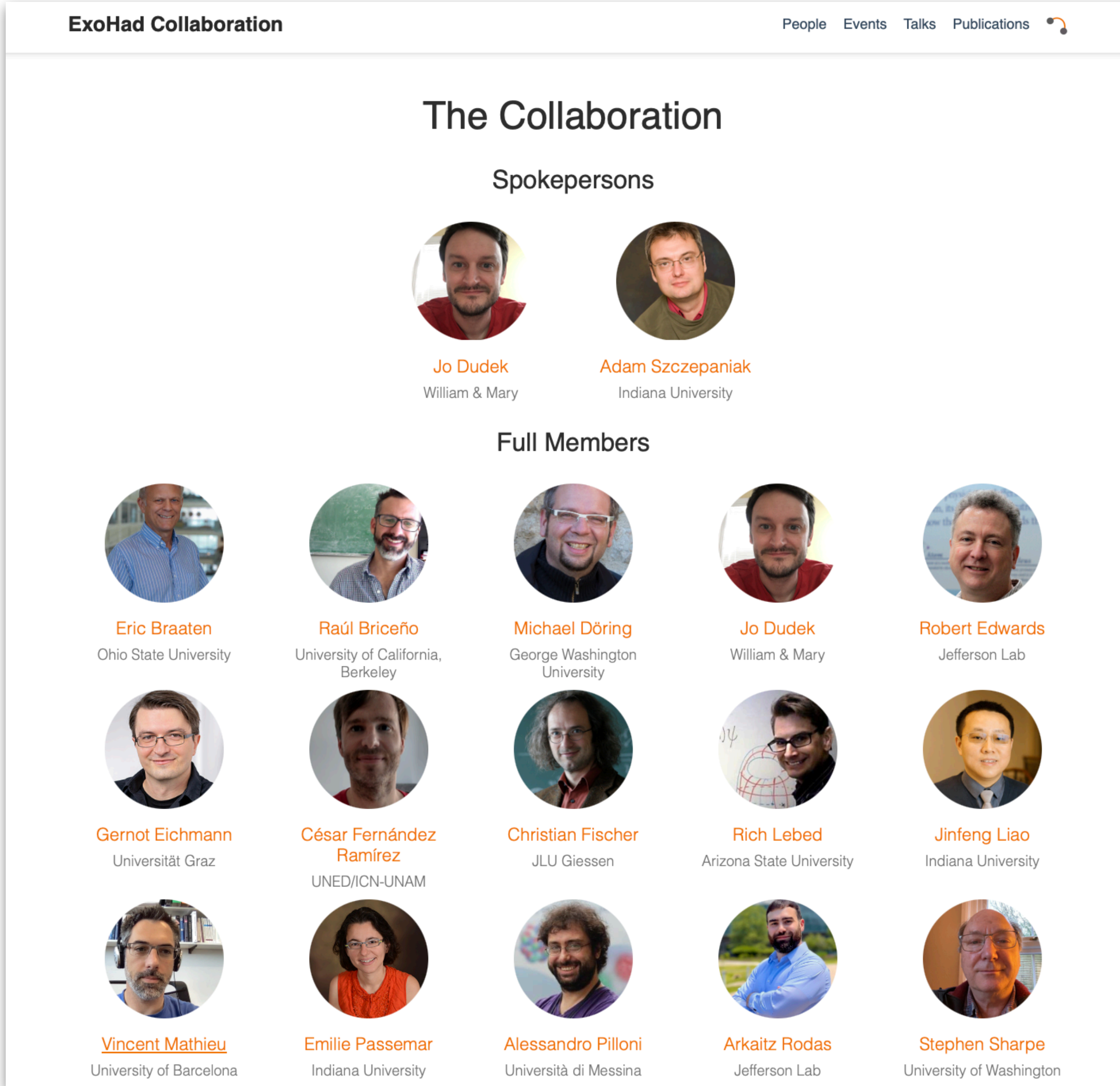
Summary

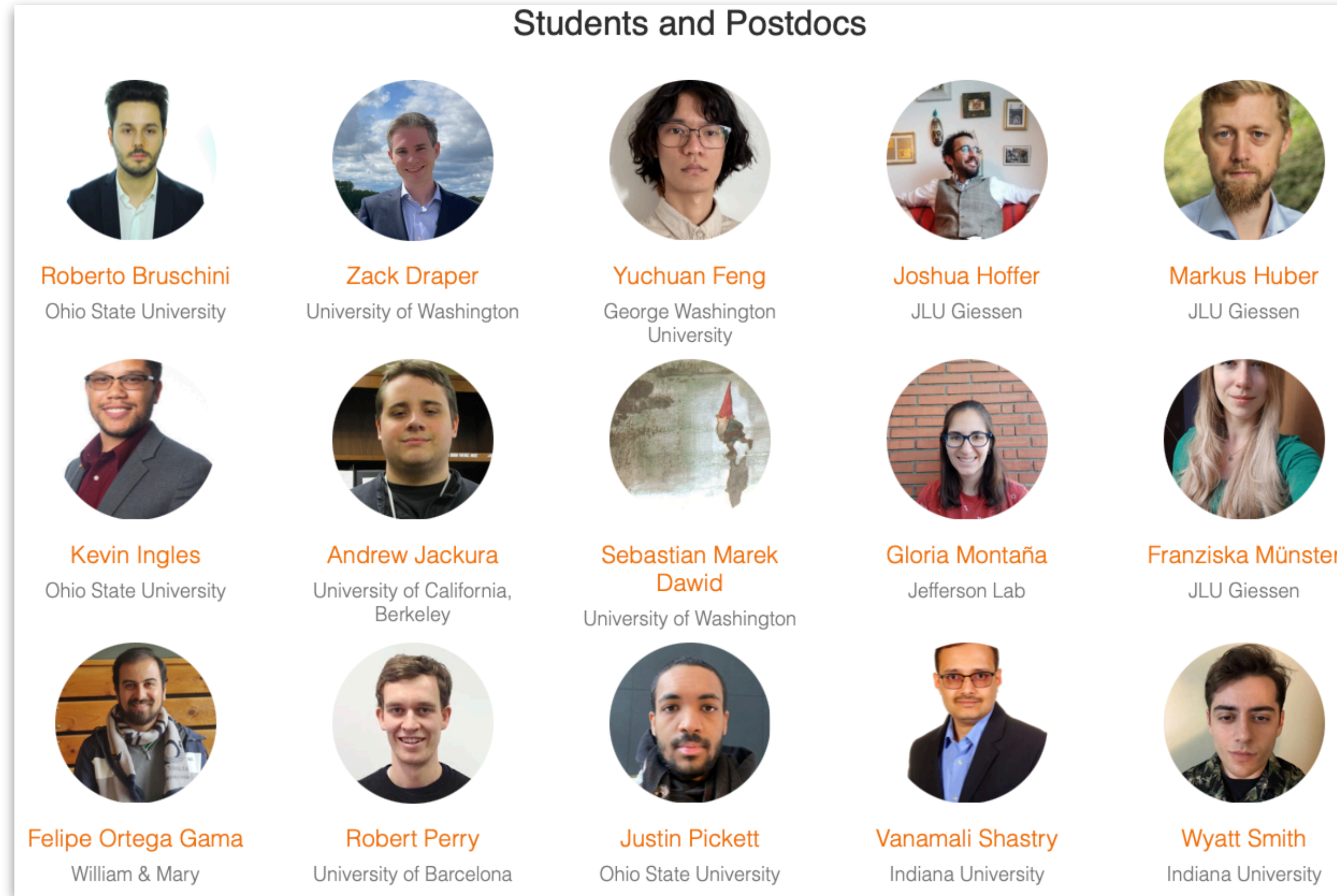
- Observation of new hadrons indicate that there is a large "hadronic landscape" yet to be discovered

- Production of meson resonances in CBAF kinematics (including exotics) well described in terms of an Regge EFT which relates production and decays

- The $\pi_1(1600)$ story is shaping up

- Great prospects for spectroscopy at JLab22 https://www.exohad.org/people/





- **predicting** exotic and non-exotic meson resonances and their properties from lattice QCD;
- reliably **extracting** exotic and non-exotic meson resonances and their production and decay properties from experimental data sets;
- **interpreting** both the experimental and theoretical results.

ExoHad
Exotic Hadrons Topical Collaboration

INDIANA UNIVERSITY
Jefferson Lab