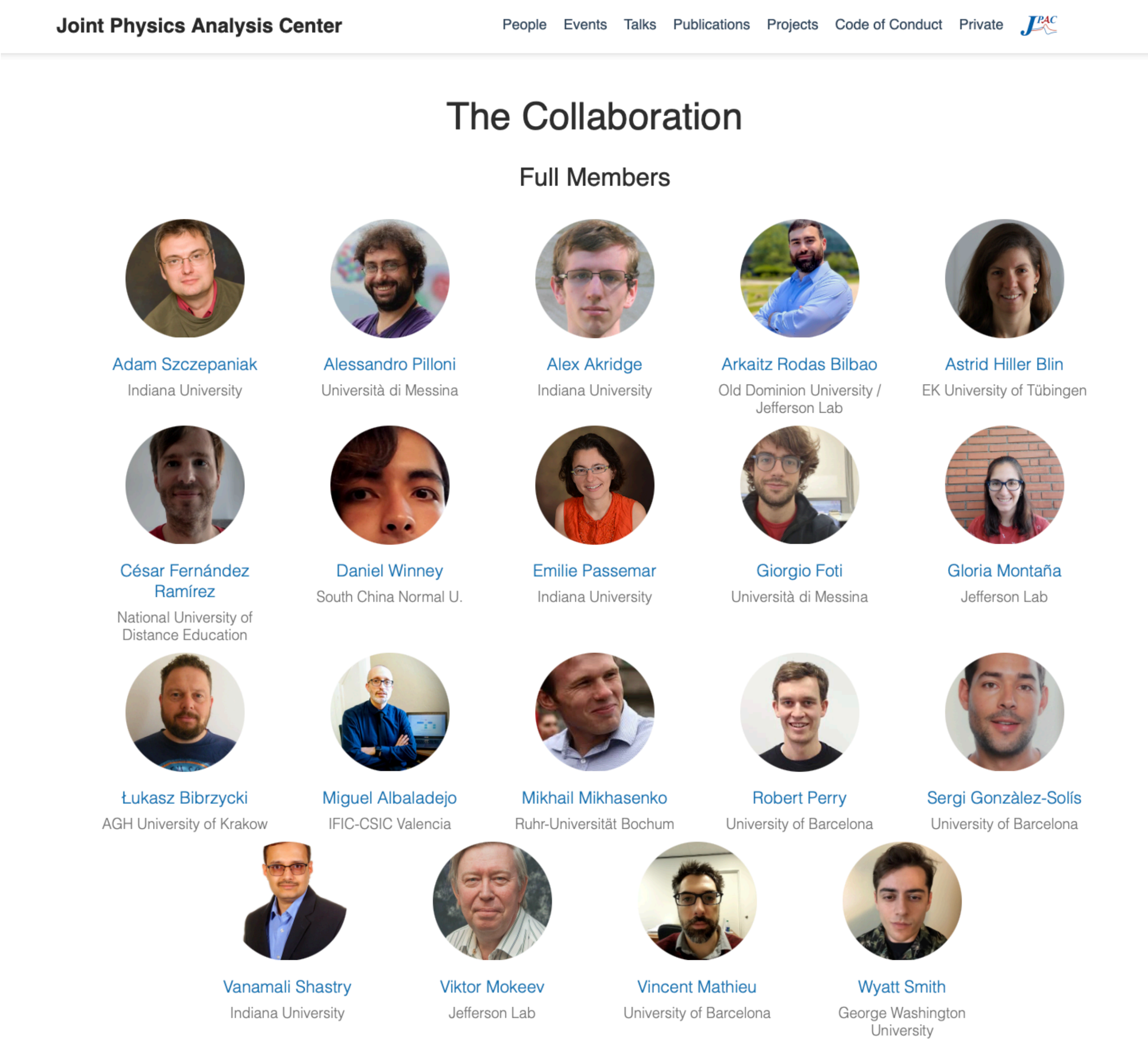
Light Exotic Meson Phenomenology

Adam Szczepaniak (IU/JLab)

- A brief history
- Recent progress and future expectations
- Importance of experiment-theory interactions

JPAC

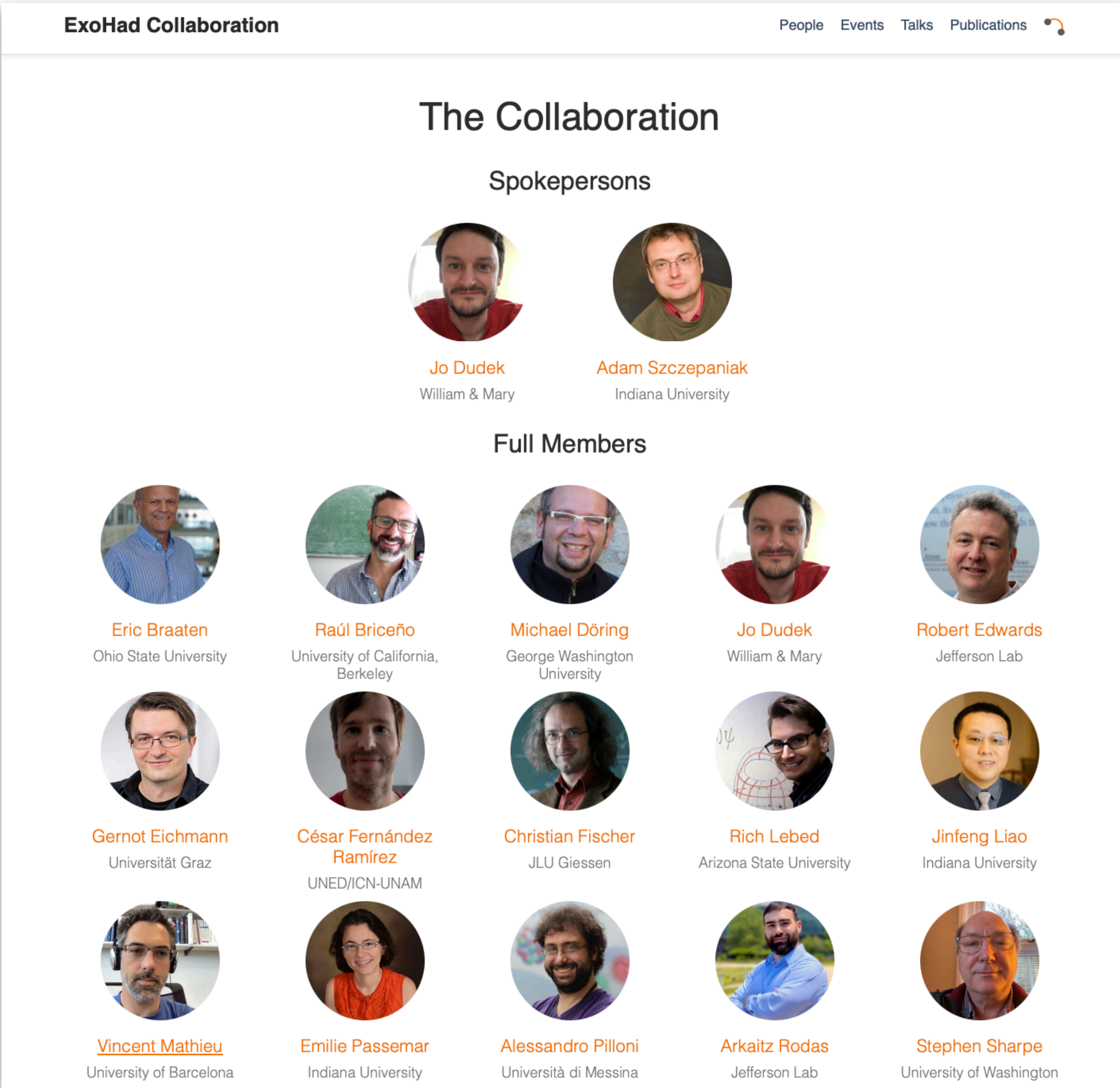
EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

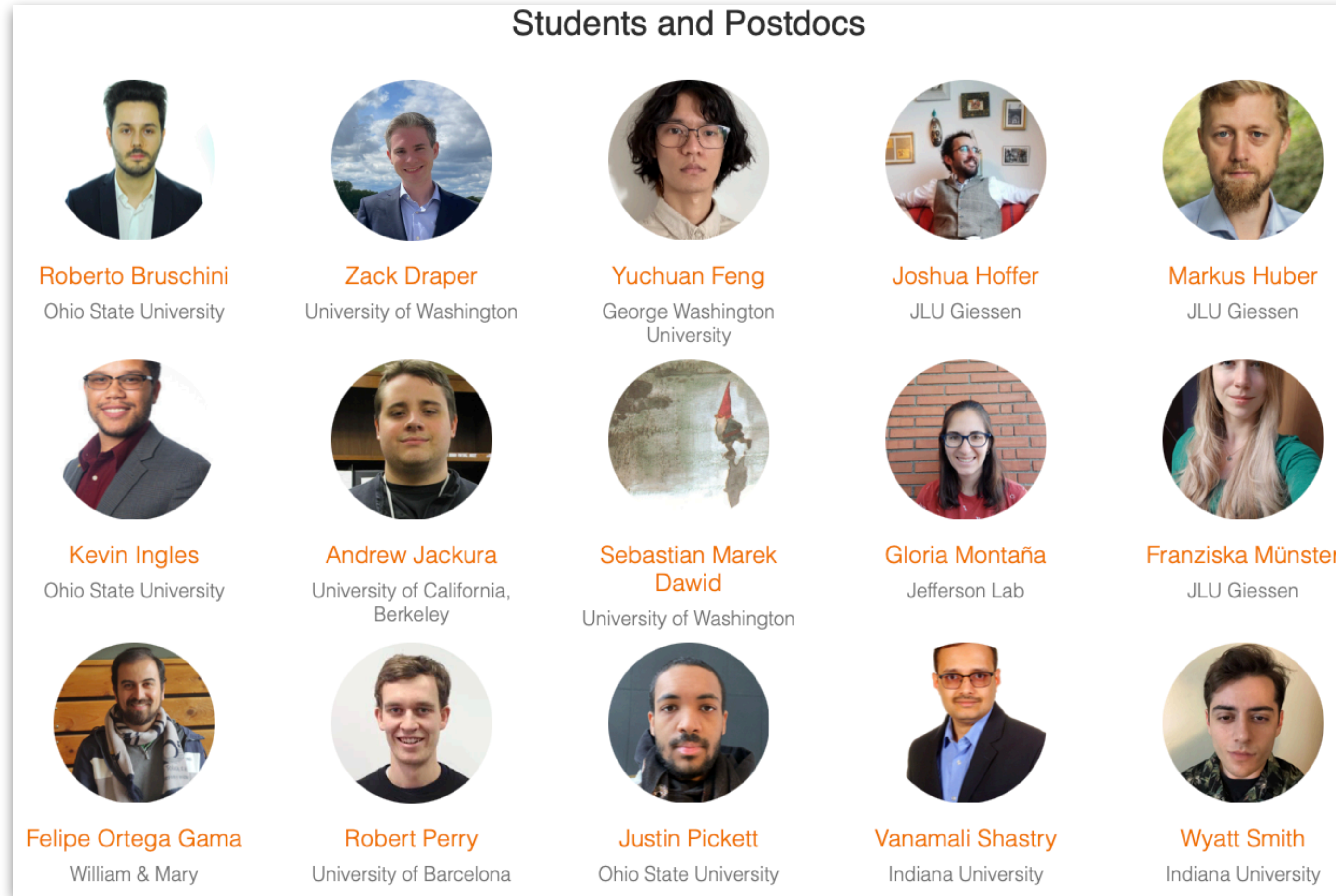


- Since 2013 developing experiment-theory collaboration to analyze and interpret date from hadrons spectroscopy experiments (JLab, COMPASS, BES-III, LHCb, FAIR,..)

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

https://www.exohad.org/people/



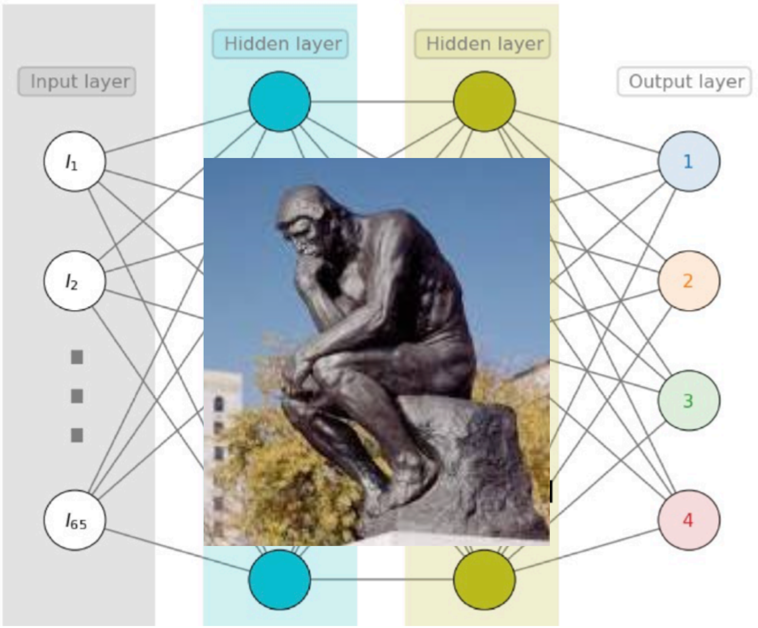


- Lattice Predicting exotic and non-exotic states
- Reaction theory /analysis : extracting exotic states form the dates
- Models : interpretation

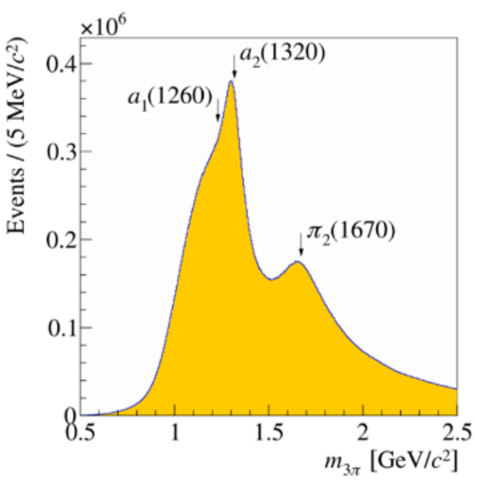
ExoHad
Exotic Hadrons Topical Collaboration

Hadron Spectroscopy Analysis

S-matrix



Tell the story

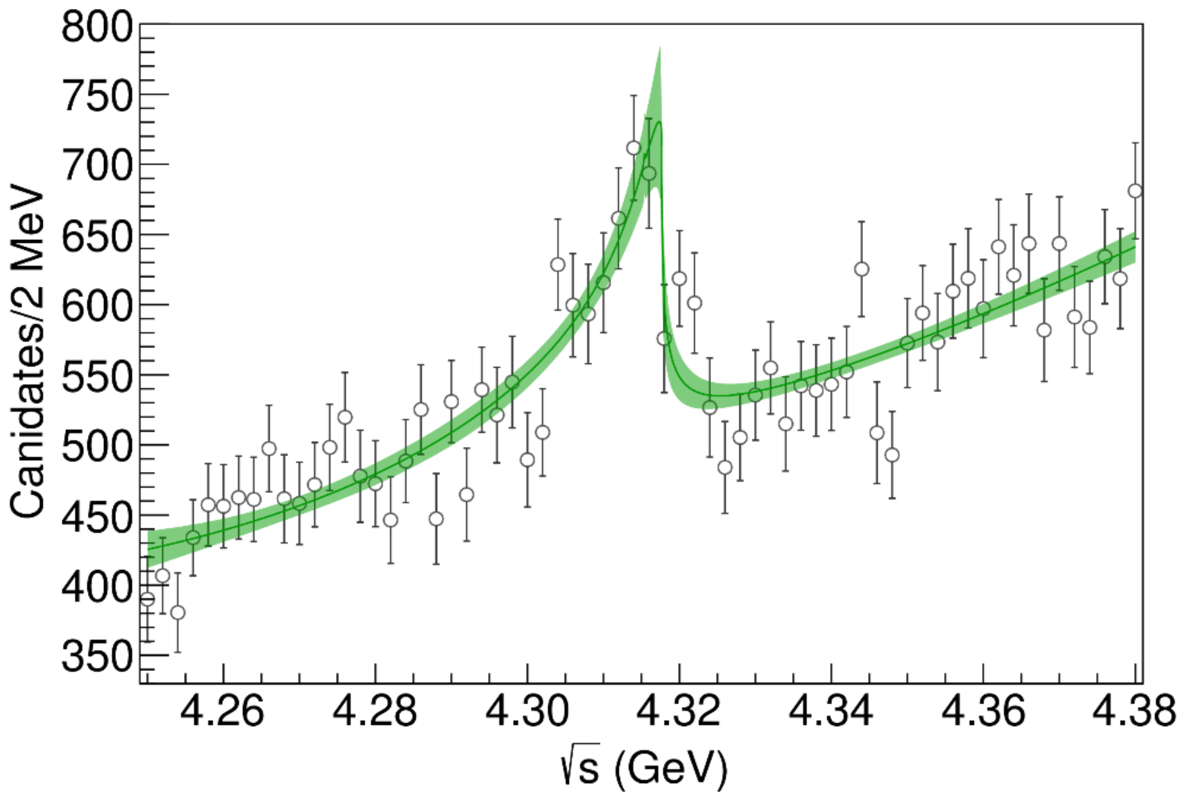


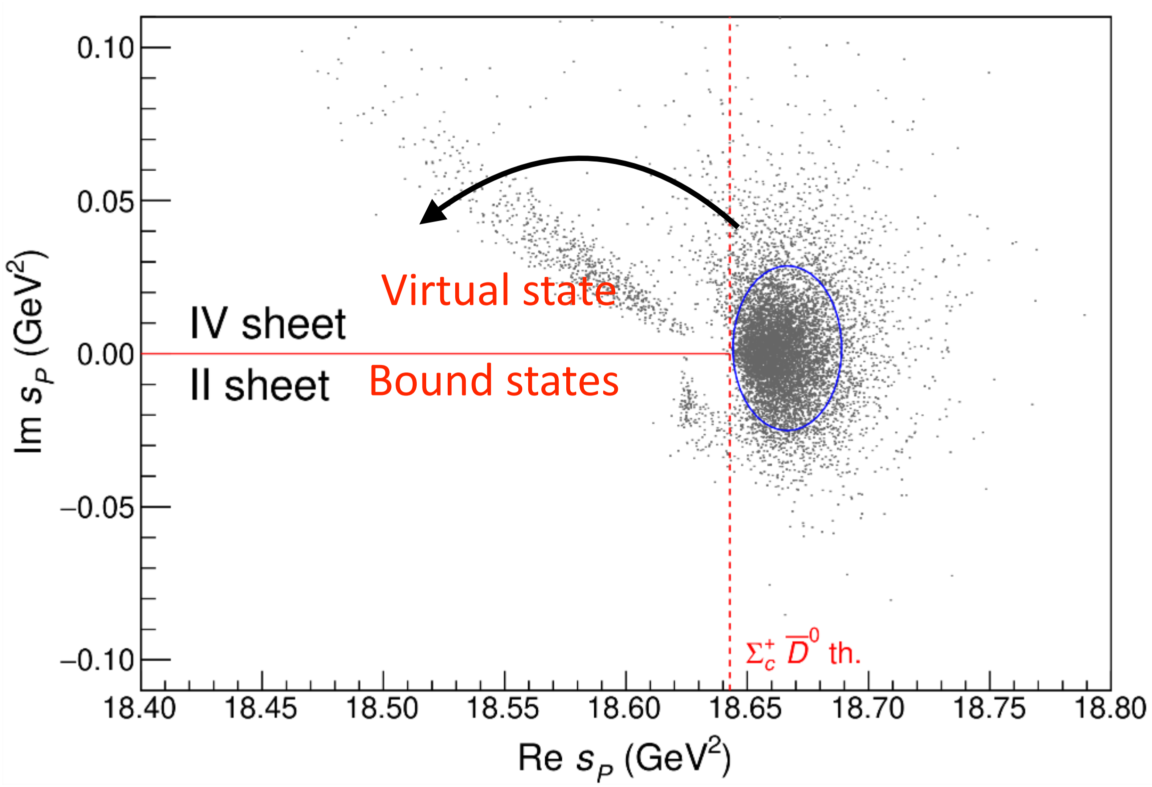
+ LQCD

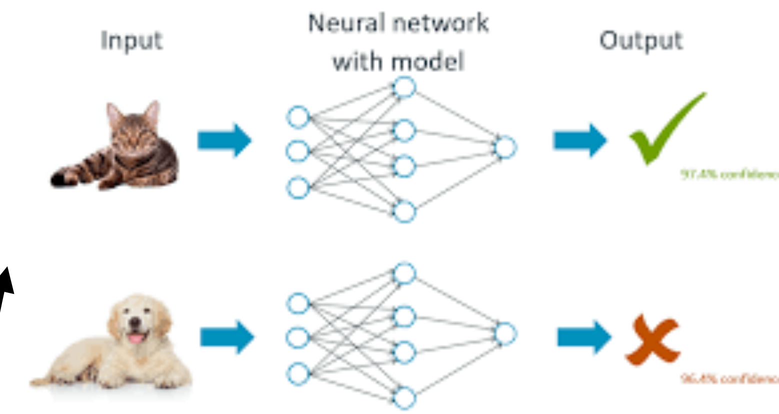
The story includes

- New discoveries e.g. X(3872), $\pi_1(1600)$
- Fundamental parameters : masses, widths (S-matrix singularities
- Interpretations

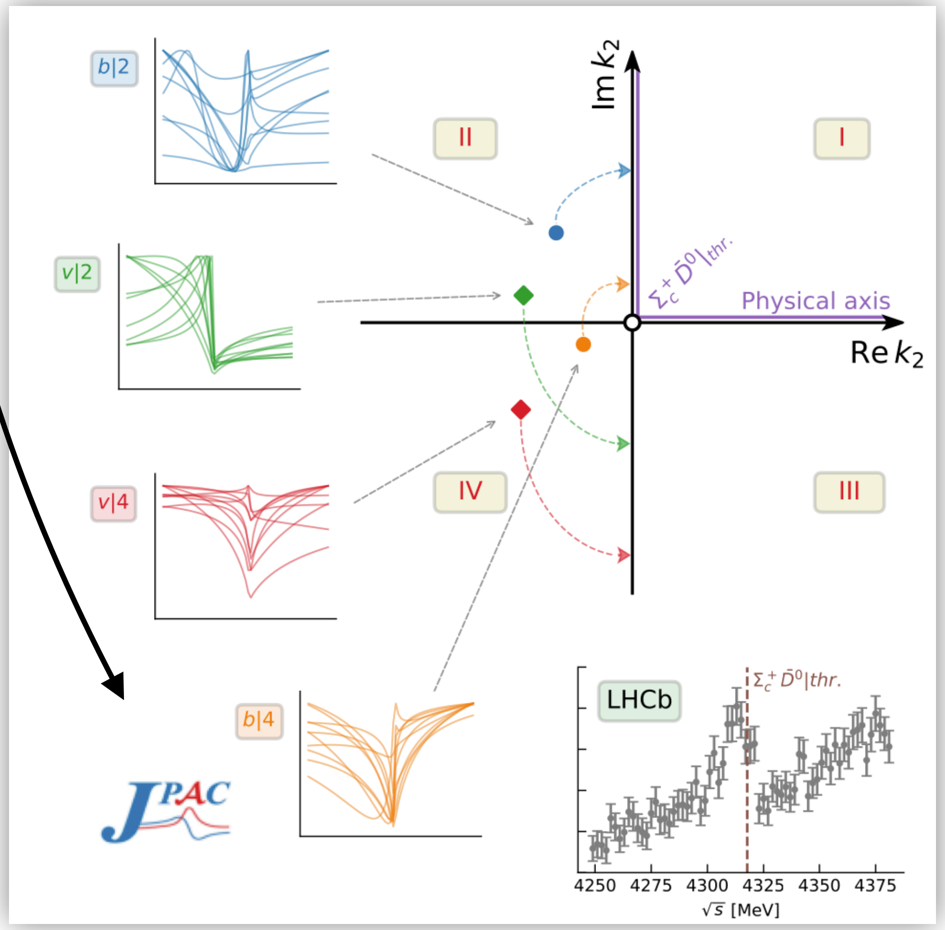
Fitting with conventional methods indicates $P_C(4312)$ does not exits (unbound)



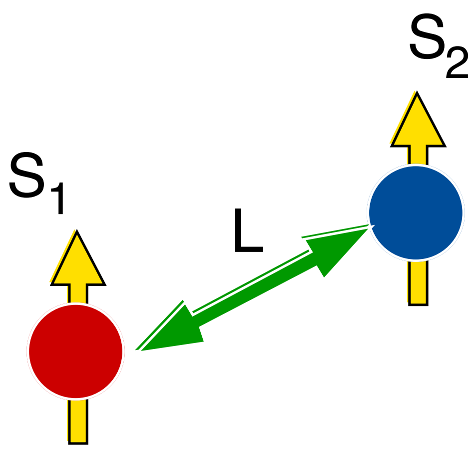




Clarification with Deep learning confirms $P_C(4312)$ is unbound



Light Exotic Hybrid



$S = S_1 + S_2$

$J = L + S$

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

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

π_1

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

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

Characteristic decay patter "S+P"

$$\pi_1 \to b_1\pi$$

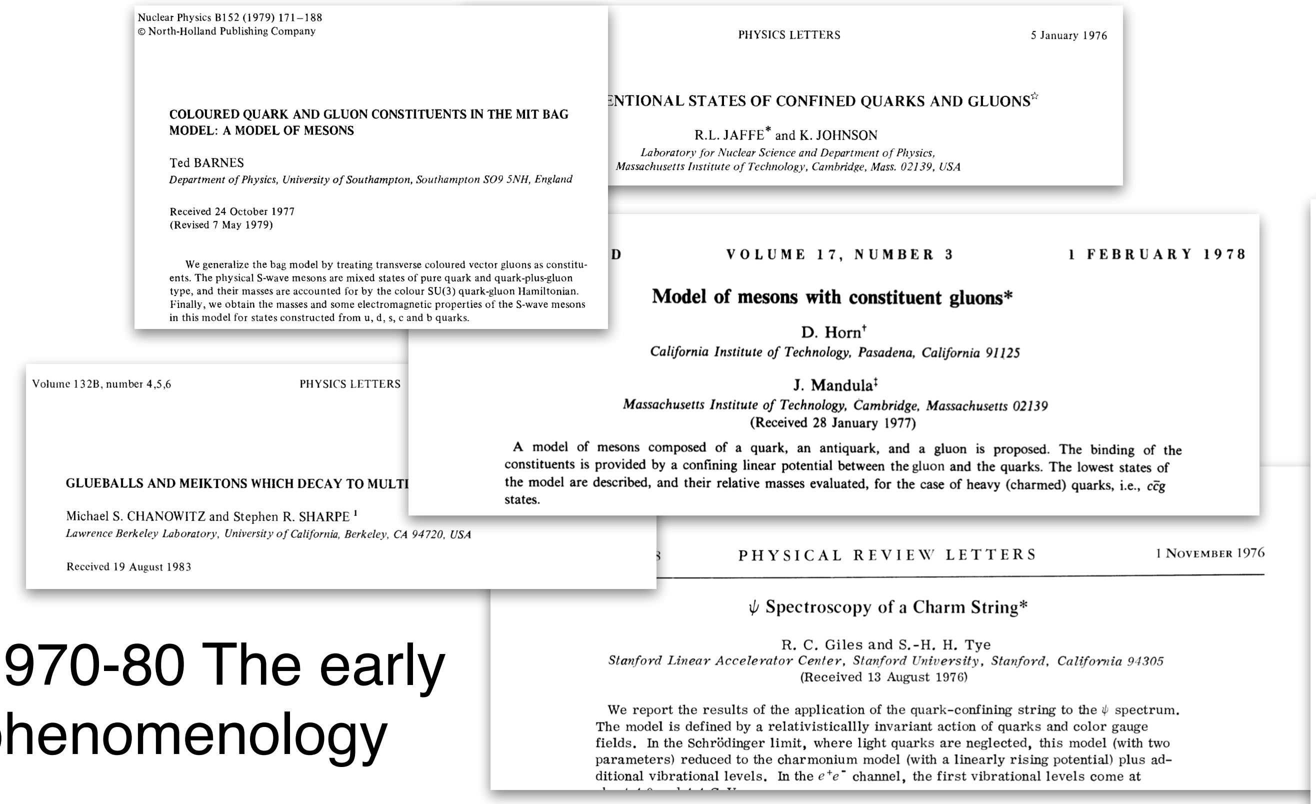
$$\pi_1 \to \rho\pi$$

Golden Channel

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

$$\pi_1 \to \eta\pi$$

Brief history of light hybrids


Nuclear Physics B152 (1979) 171–188
© North-Holland Publishing Company

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 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.

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

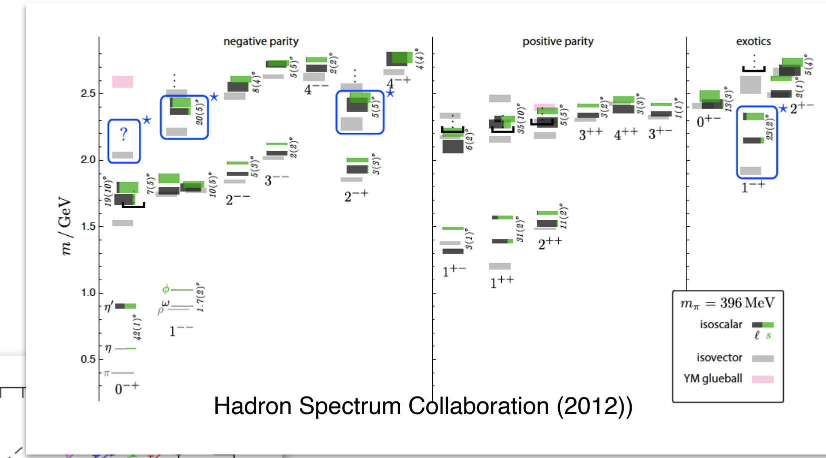
PHYSICAL REVIEW LETTERS 1 November 1976

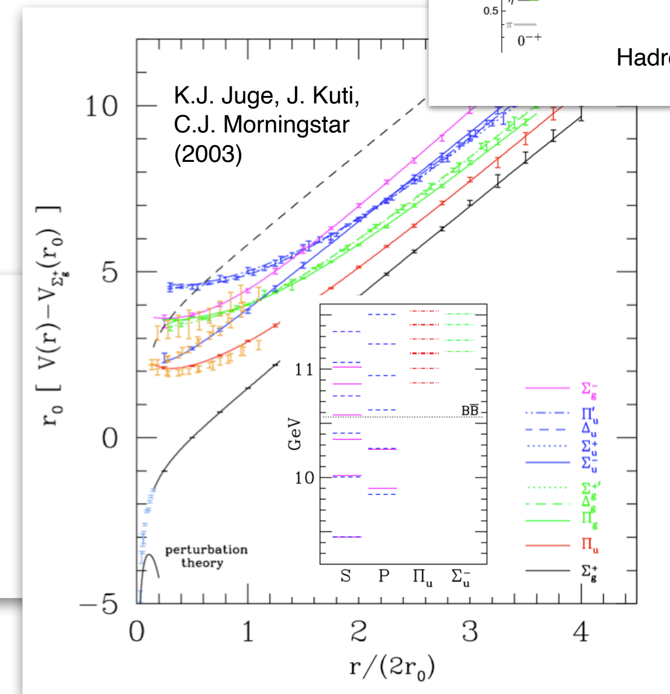
ψ Spectroscopy of a Charm String*

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

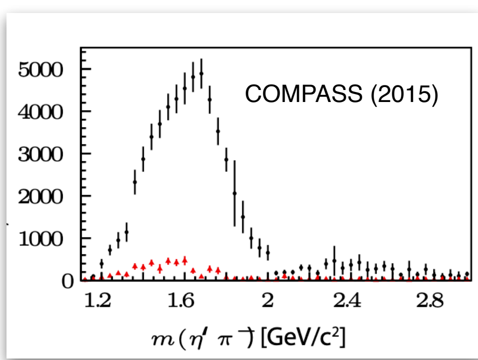
We report the results of the application of the quark-confining string to the ψ spectrum. The model is defined by a relativistically invariant action of quarks and color gauge fields. In the Schrödinger limit, where light quarks are neglected, this model (with two parameters) reduced to the charmonium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

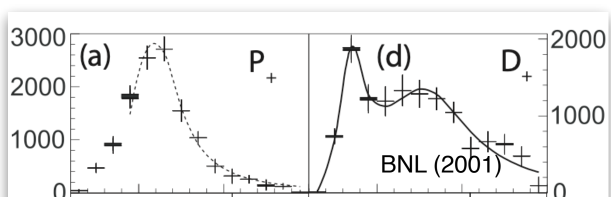
- 1970-80 The early phenomenology

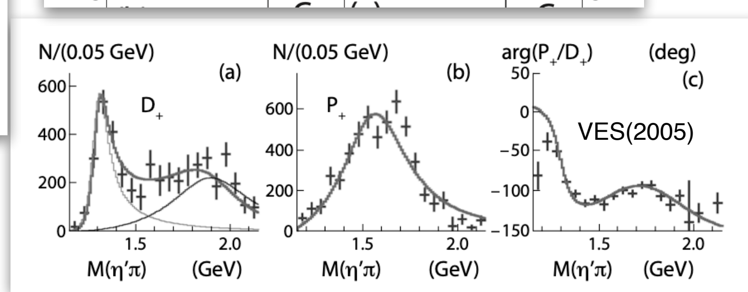




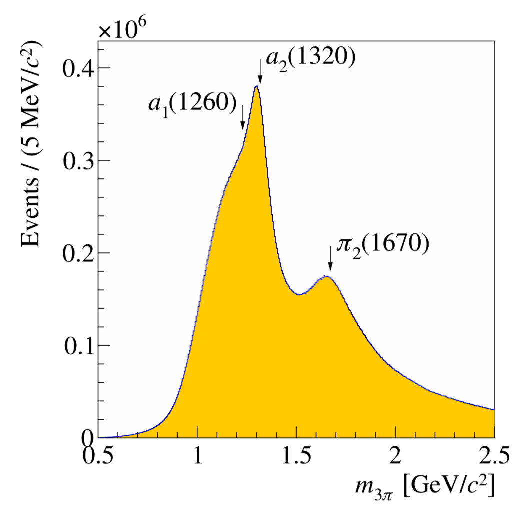
- 2000-2010 The early lattice studies

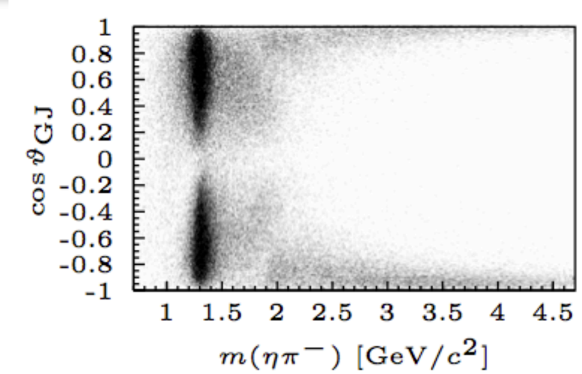






- ’2000-2010 The early data

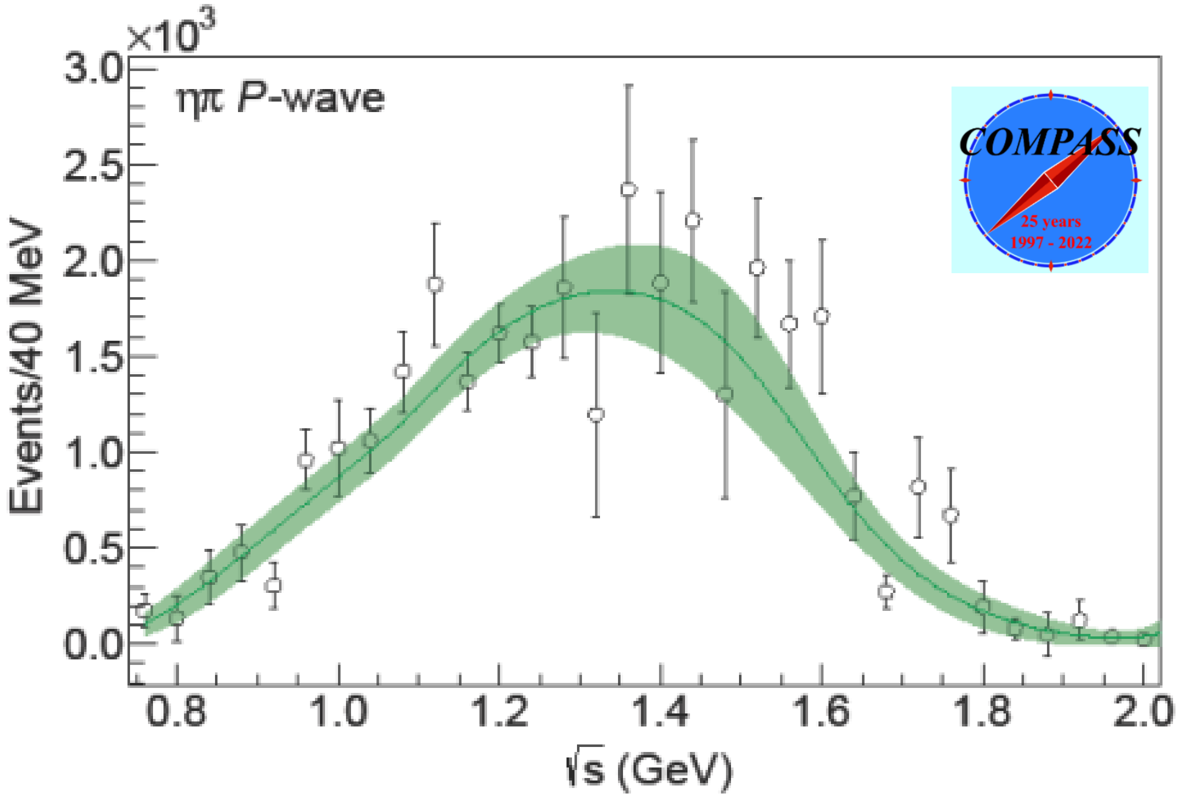


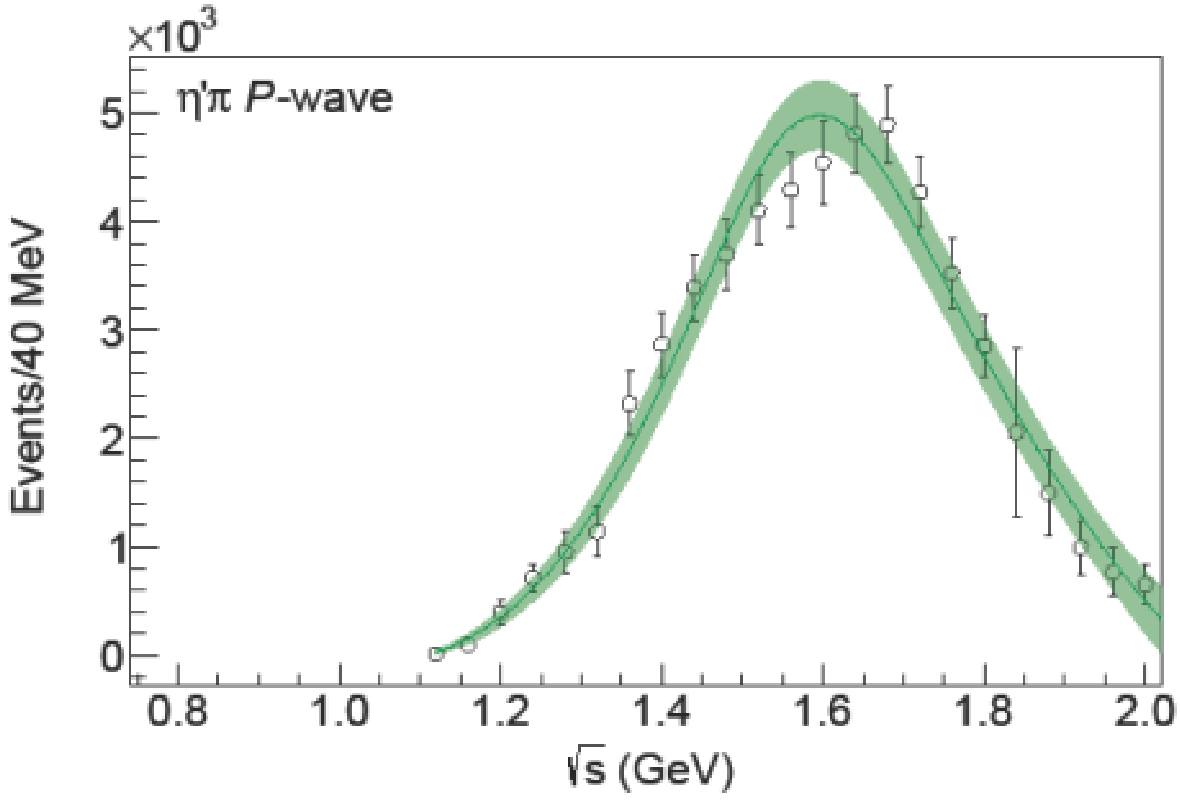


- > 2015 high precision data and high precision analysis, LQCD

Canonical interpretation : Breit-Wigner

$$\frac{1}{M_1^2 - iM_1\Gamma_1 - s} \qquad \frac{1}{M_2^2 - iM_2\Gamma_2 - s}$$





$$M_1 < M_2$$

in $\eta\pi$

Two π_1's (PDG 2022) ?

$\pi_1(1400)$

$I^G(J^{PC}) = 1^-(1^{-+})$

Coupled channel analyses favor the existence of only one broad 1^{-+} isovector state consistent with $\pi_1(1600)$ in the 1400–1600 MeV region. See the review on "Spectroscopy of Light Meson Resonances." See also $\pi_1(1600)$.

$\pi_1(1400)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s})$.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$(1405 \pm 4^{+15}_{-18}) - i\,(314 \pm 14^{+18}_{-69})$ OUR ESTIMATE				
$(1405 \pm 4^{+15}_{-18}) - i\,(314 \pm 14^{+18}_{-69})$	ALBRECHT	20	RVUE	$\bar{p}p \to \pi^0\pi^0\eta$

in $\eta'\pi, \rho\pi, ..$

$\pi_1(1600)$

$I^G(J^{PC}) = 1^-(1^{-+})$

See the review on "Spectroscopy of Light Meson Resonances" and a note in PDG 06, Journal of Physics **G33** 1 (2006).

$\pi_1(1600)$ T-Matrix Pole $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s})$.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$(1480–1680) - i\,(150–300)$ OUR ESTIMATE				
$(1623 \pm 47^{+24}_{-75}) - i\,(228 \pm 44^{+72}_{-88})$	[1] KOPF	21	RVUE	0.9 $p\bar{p} \to \pi^0\pi^0\eta$, $\pi^0\eta\eta$, $\pi^0K^+K^-$ and 191 $\pi^-p \to \pi^-\pi^-\pi^+p$
$(1564 \pm 24 \pm 86) - i\,(246 \pm 27 \pm 51)$	[2] RODAS	19	RVUE	191 $\pi^-p \to \eta^{(\prime)}\pi^-p$

VES

E852

COMPASS

Crystal Barel

One π_1 (PDG 2024)

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$
For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

PDGID:M111 JSON INSPIRE

$\pi_1(1400)$ $I^G(J^{PC}) = 1^-(1^{-+})$

Coupled channel analyses favor the existence of only one broad 1^{-+} isovector state consistent with $\pi_1(1600)$ in the 1400 — 1600 MeV region. See the review on "Spectroscopy of Light Meson Resonances". See also $\pi_1(1600)$.

$\pi_1(1600)$ T-Matrix Pole $\sqrt{s}$

Note that $\Gamma = -2\,\mathrm{Im}(\sqrt{s})$.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$(1480 - 1680) - i(150 - 300)$ OUR ESTIMATE				
$(1623 \pm 47^{+24}_{-75}) - i(228 \pm 44^{+72}_{-88})$	[1] KOPF	2021	RVUE	0.9 $p\bar{p} \to \pi^0\pi^0\eta, \pi^0\eta\eta, \pi^0K^+K^-$ and 191 $\pi^- p \to \pi^-\pi^-\pi^+ p$
$(1564 \pm 24 \pm 86) - i(246 \pm 27 \pm 51)$	[2] RODAS	2019	RVUE	191 $\pi^- p \to \eta^{(\prime)}\pi^- p$
• • We do not use the following data for averages, fits, limits, etc. • •				
$(1405 \pm 4^{+15}_{-18}) - i(314 \pm 14^{+18}_{-69})$	[3] ALBRECHT	2020	RVUE	$\bar{p}p \to \pi^0\pi^0\eta$

Crystal Barrel + COMPASS ←

Crystal Barrel ← $p\bar{p} \to \eta\pi^0\pi^0$

[1] From T-matrix pole based on combined fit of Crystal Barrel and $\pi\pi$ scattering data (ALBRECHT 2020), and COMPASS data (ADOLPH 2015), using a coupled-channel model of $\eta\pi$, $\eta'\pi$ and $K\bar{K}$ systems.

[2] The coupled-channel analysis of both the $\eta\pi$ and $\eta'\pi$ systems using ADOLPH 2015 data.

[3] Superseded by KOPF 2021.

References

$\pi_1(1600)$ $I^G(J^{PC}) = 1^-(1^{-+})$

See the review on "Spectroscopy of Light Meson Resonances."
Mass (T-Matrix Pole $\sqrt{s}$) = (1480–1680) − i (150–300) MeV
Mass (Breit-Wigner, $\eta\pi$ mode) = 1354 ± 25 MeV (S = 1.8)
Mass (Breit-Wigner, non-$\eta\pi$ mode) = 1645^{+40}_{-17} MeV (S = 1.3)
Full width (Breit-Wigner, $\eta\pi$ mode) = 330 ± 35 MeV
Full width (Breit-Wigner, non-$\eta\pi$ mode) = 370^{+50}_{-60} MeV

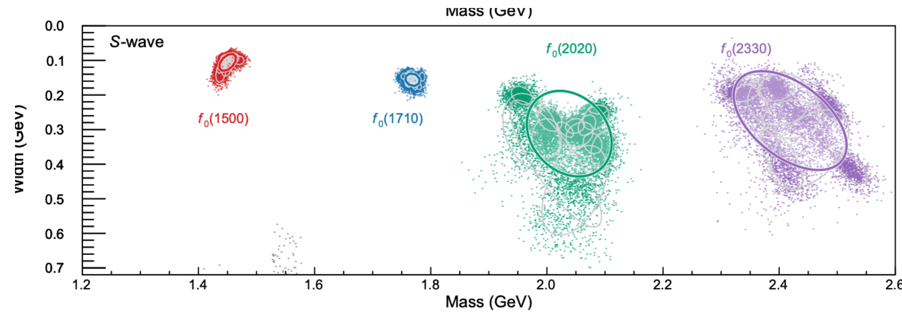
$\pi_1(1600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi\pi$	seen	795
$\rho^0\pi^-$	seen	631
$f_2(1270)\pi^-$	not seen	304
$b_1(1235)\pi$	seen	343
$\eta'(958)\pi^-$	seen	532
$\eta\pi$	seen	725
$f_1(1285)\pi$	seen	300

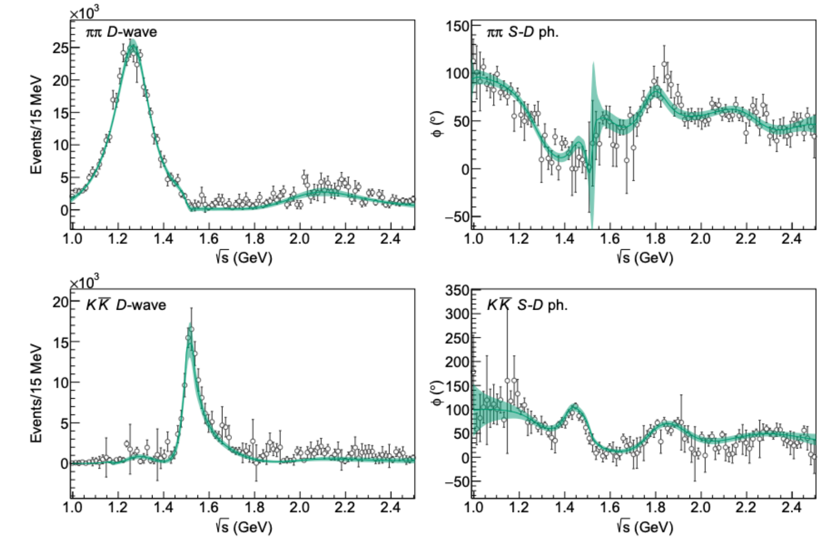
Observation of $\pi_1(1600)$ in $\chi_{c1} \to \eta'\pi^+\pi^-$

Beijing Liu (Wednesday)

BESIII has lot's of $J/\psi's$

$$J\psi \to \gamma\pi\pi, K\bar{K}$$

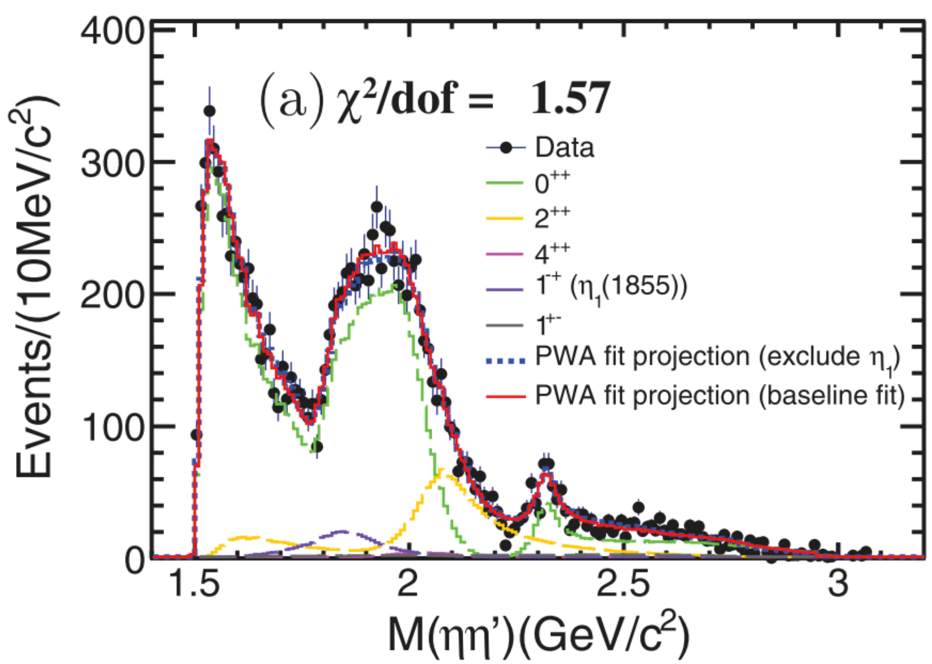


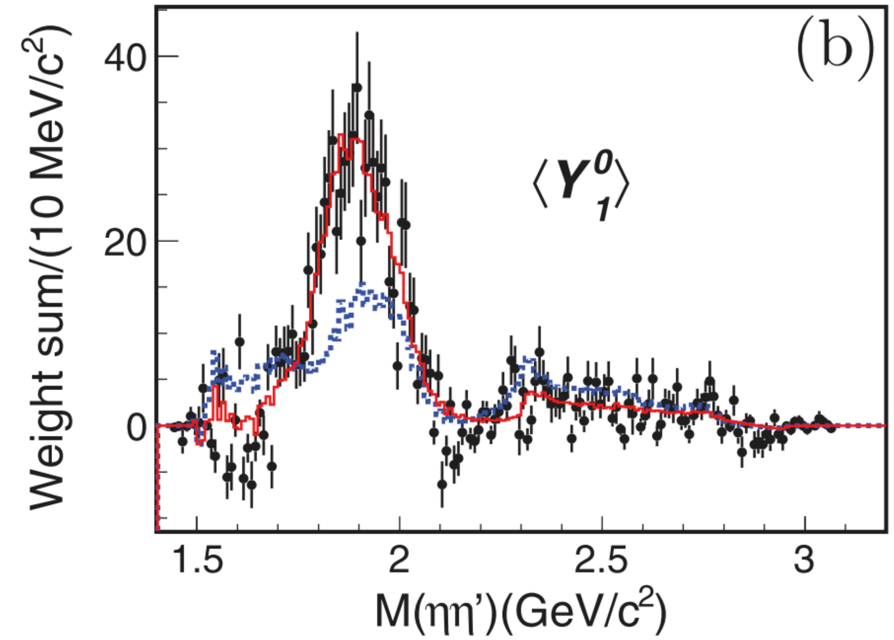


Iso-scalar $J^{PC} = 1^{-+}$

$$J\psi \to \gamma\eta\eta'$$

$$Y_1 \sim P \times (S, D)$$





Uniqueness of JLab/COMPASS for spectroscopy

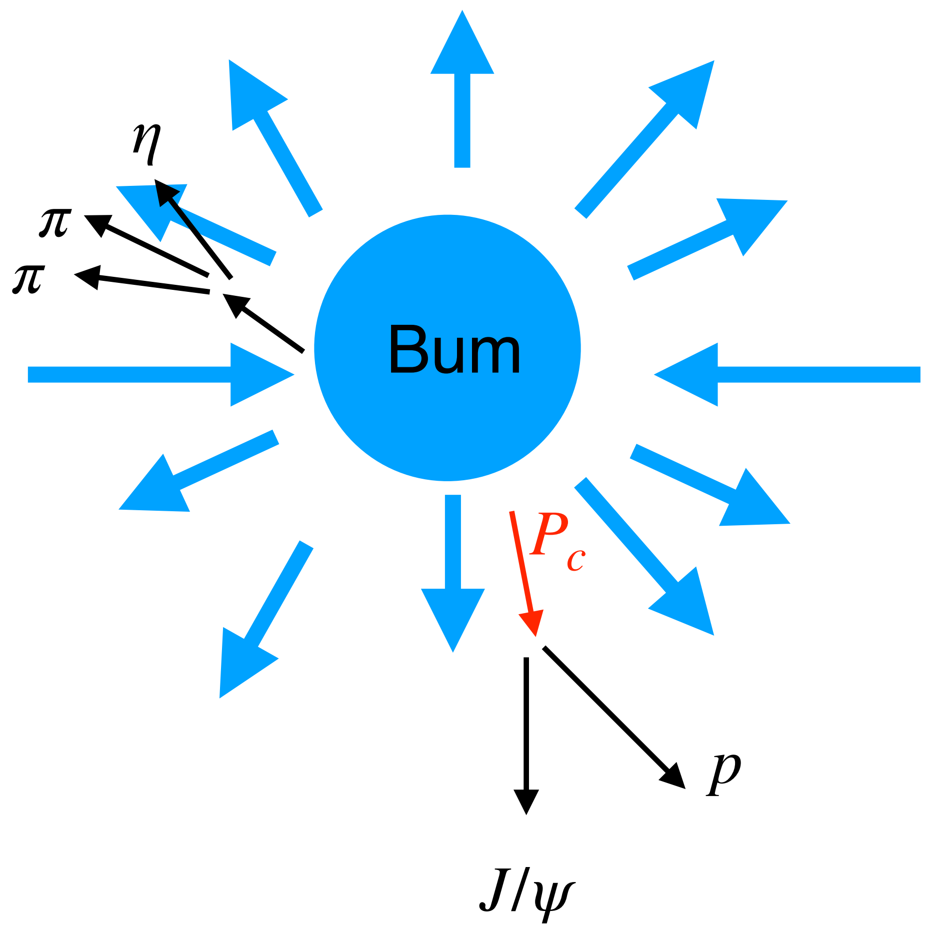
Majority of hadron exotics spotted in colliders.
Very few were seen in more then one setting

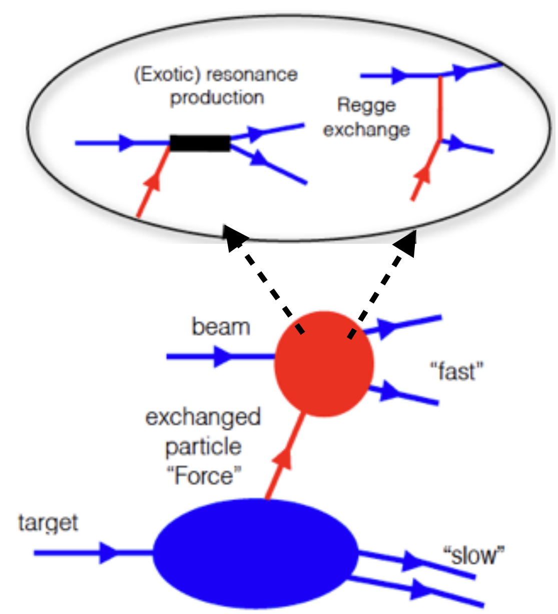
Theory of Production : not quite there !!

Fixed target with well tuned E_γ :

High luminosity
Full exclusivity
Low multiplicity
Significant rapidity gap enables to separate beam from target fragmentation Resonances can be well separated from kinematic effects

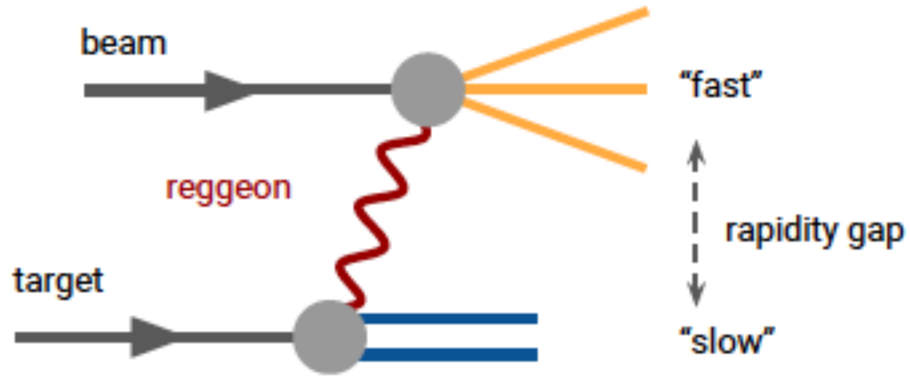
Theory of Production well understood (Regge Theory) !!





Peripheral production

Peripheral Production : Regge poles (+ corrections)



- Factorization

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

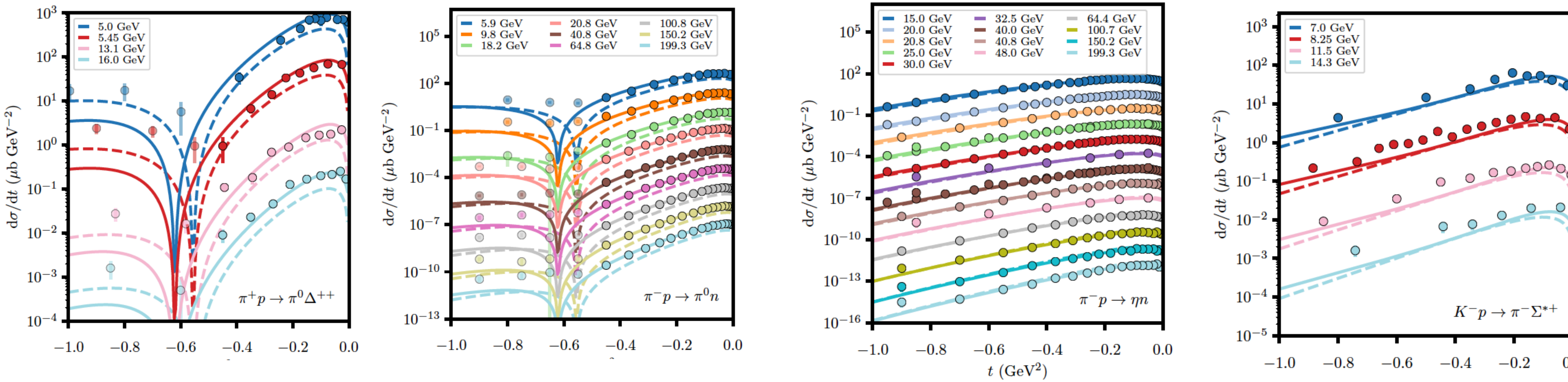
- Shrinkage of the forward peak $\quad G(s,t) \sim exp(b\log(s)t)$

- 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

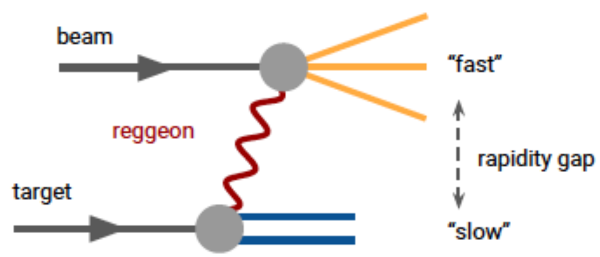
Global Regge pole of CEX (no P no π)

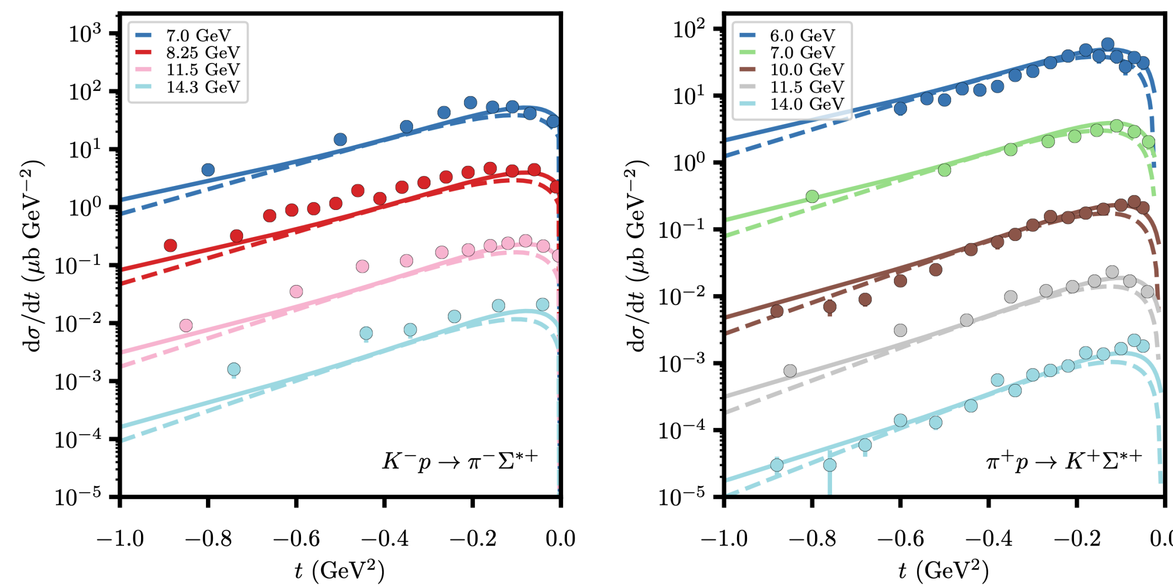


"ρ" exchange dip at

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

"a_2" exchange





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

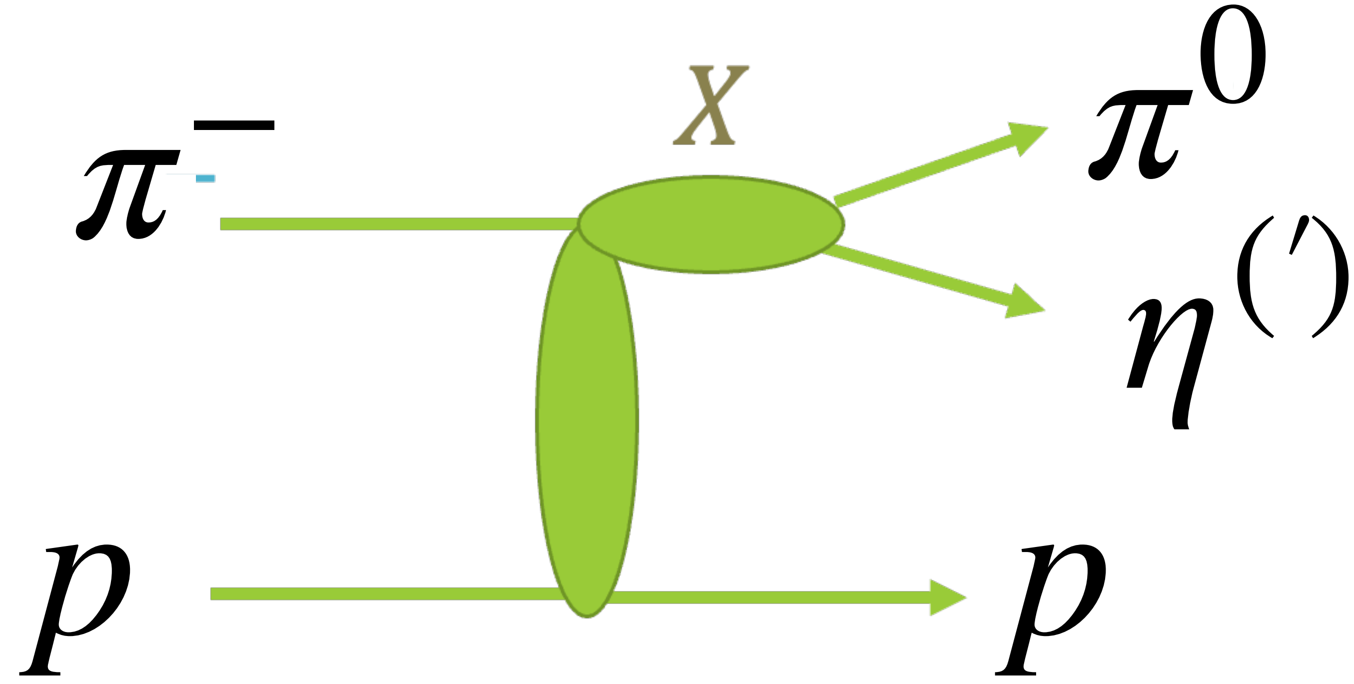
Regge poles well describe peripheral production at CEBAF energies….

"K/K^*" exchange

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

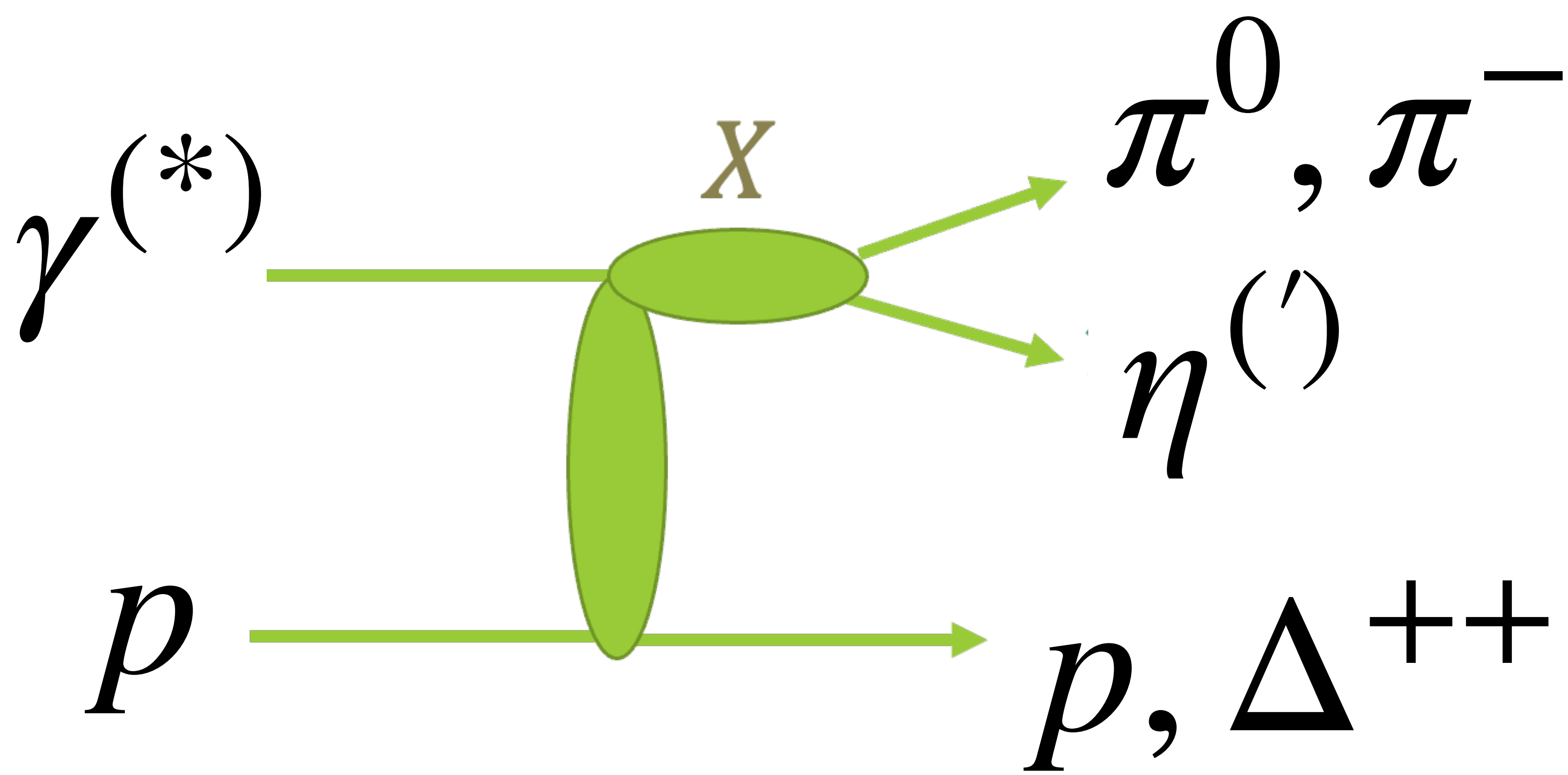
COMPASS vs GlueX/CLAS12

$E_L \sim 200\ GeV$



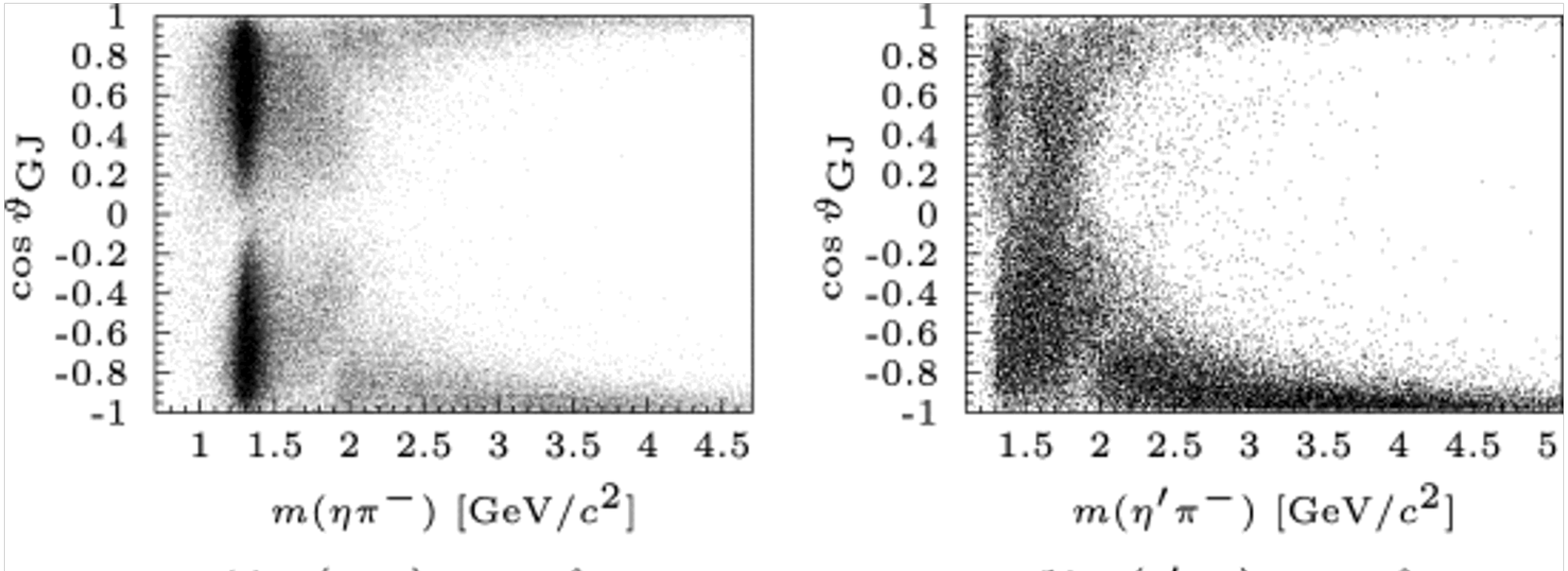
$E_L \sim 10\ GeV$

γ Is polarized

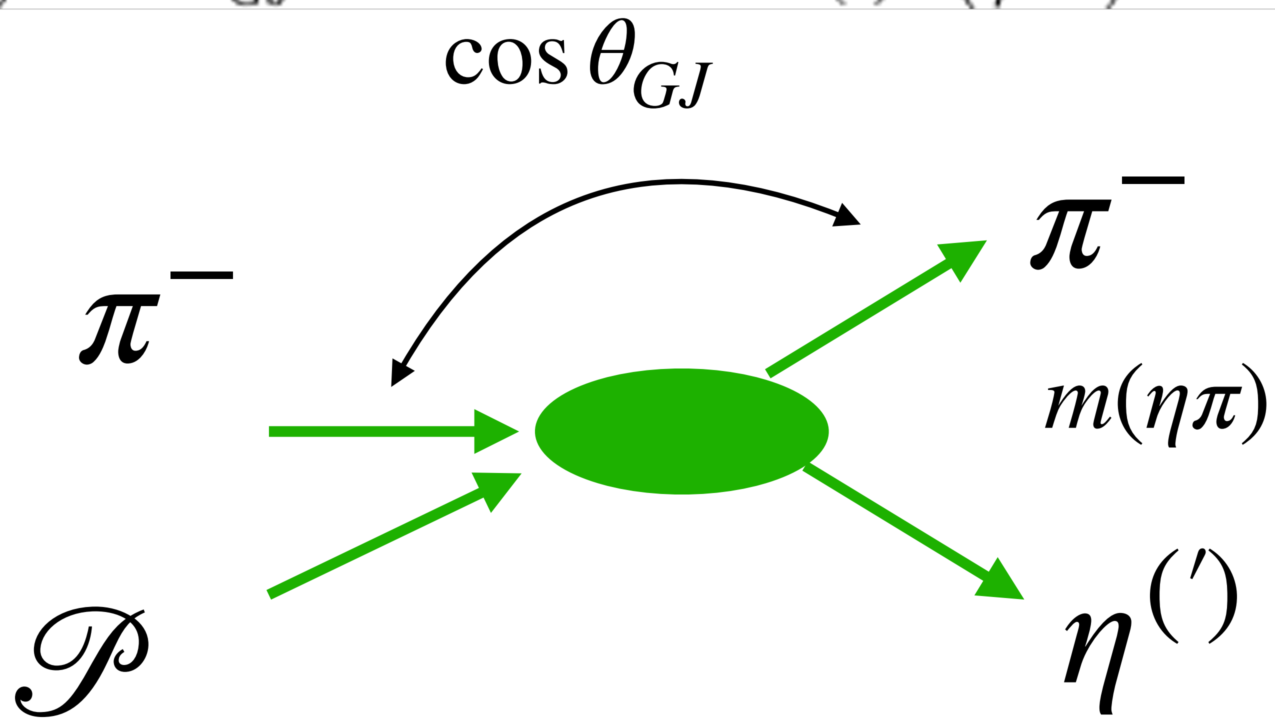


COMPASS plot

COMPASS, Phys. Lett. B 740 (2015) 303 [Erratum: 811 (2020) 135913]

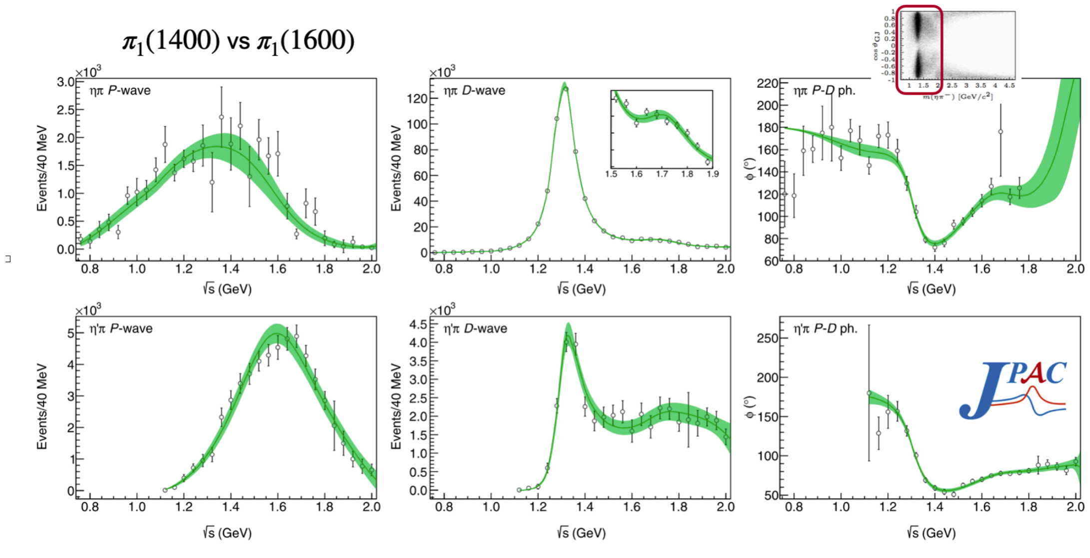


(a) $m(\eta\pi^-)$ vs. $\cos\vartheta_{GJ}$ (b) $m(\eta'\pi^-)$ vs. $\cos\vartheta_{GJ}$



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

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



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

Poles	Mass (MeV)	Width (MeV)
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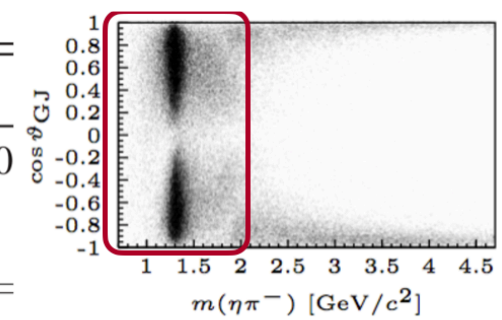
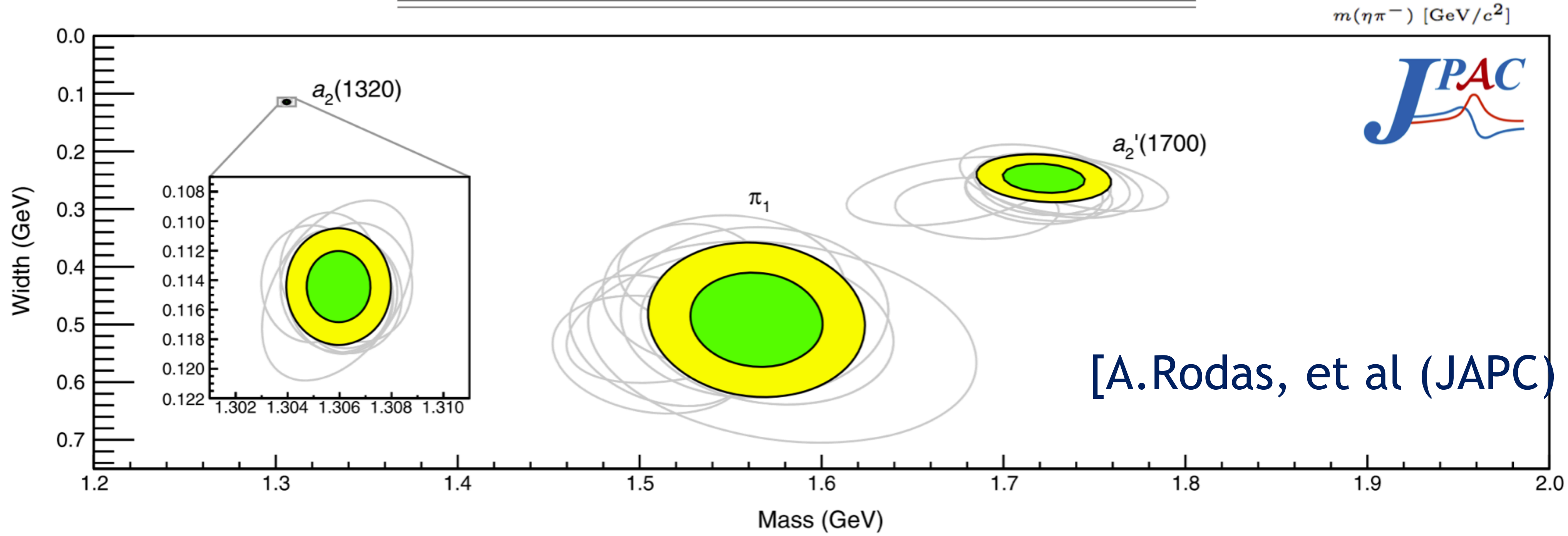
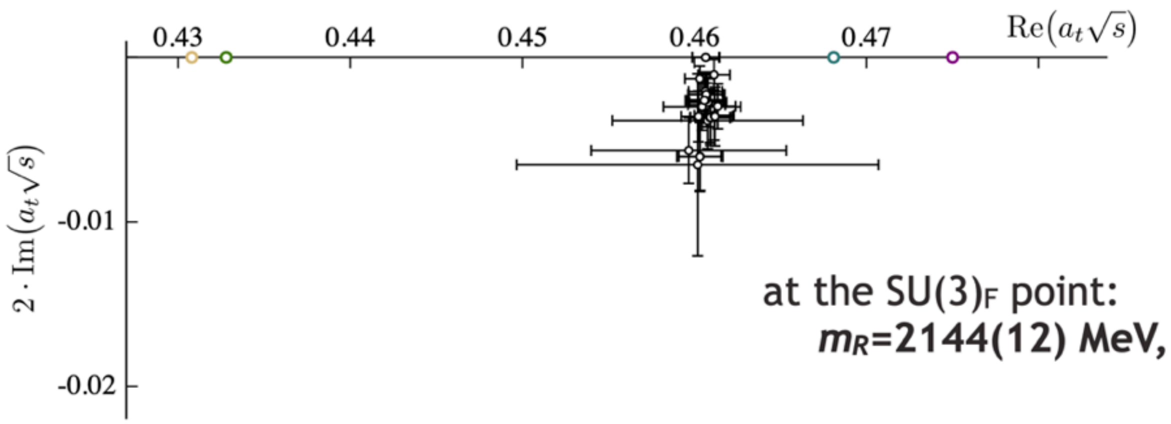




[A.Rodas, et al (JAPC) PRL (2019)]

and from lattice



at the SU(3)$_F$ point:
m_R=2144(12) MeV, Γ

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

Extrapolated to physical point

generates for a π_1 at 1564 MeV:

Γ_{TOT} ~ **140-600 MeV**

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

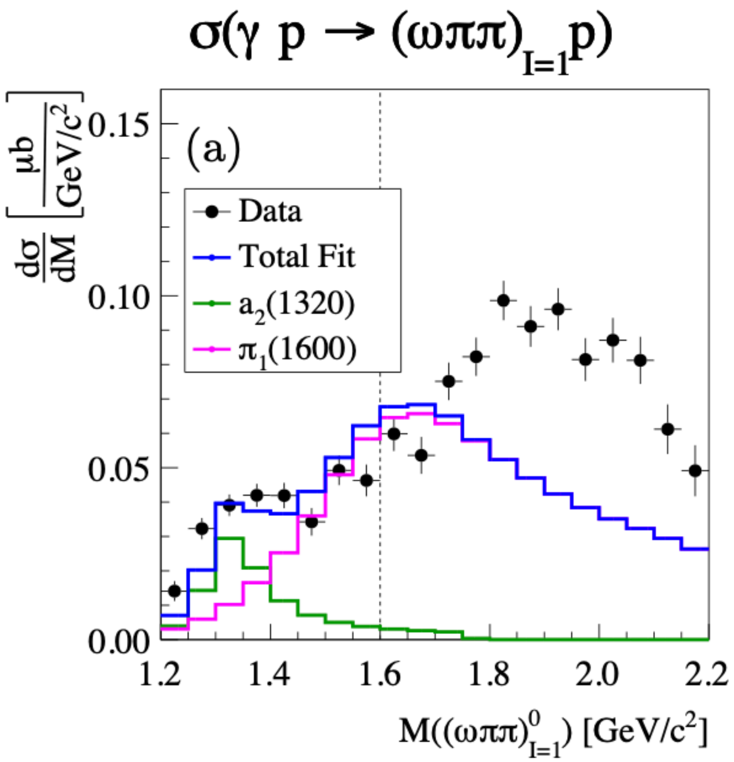
$\Gamma(\pi\eta') \lesssim$ 20 MeV

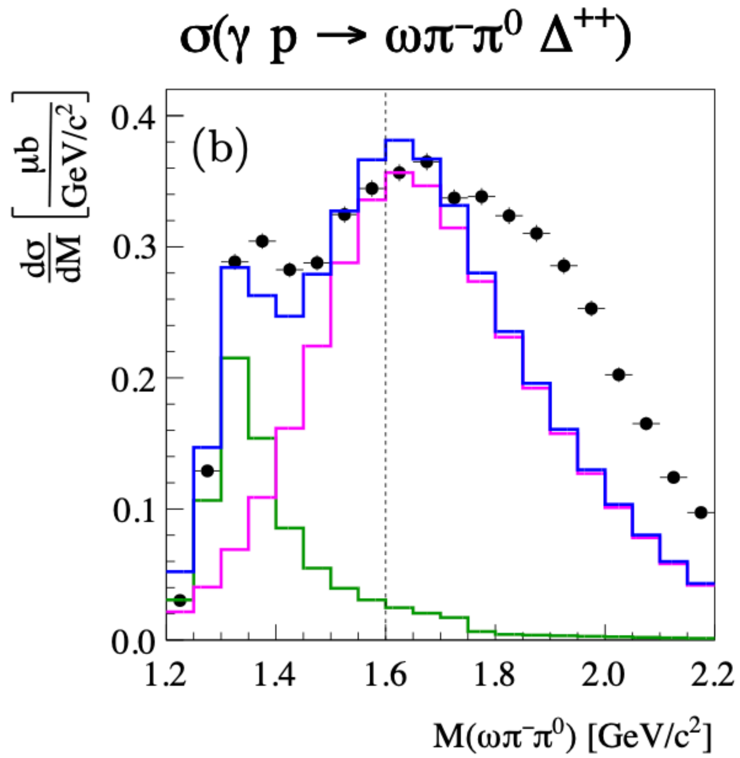
$\Gamma(\pi\rho) \lesssim$ 12 MeV

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

As expected from old models

and in the future from GlueX



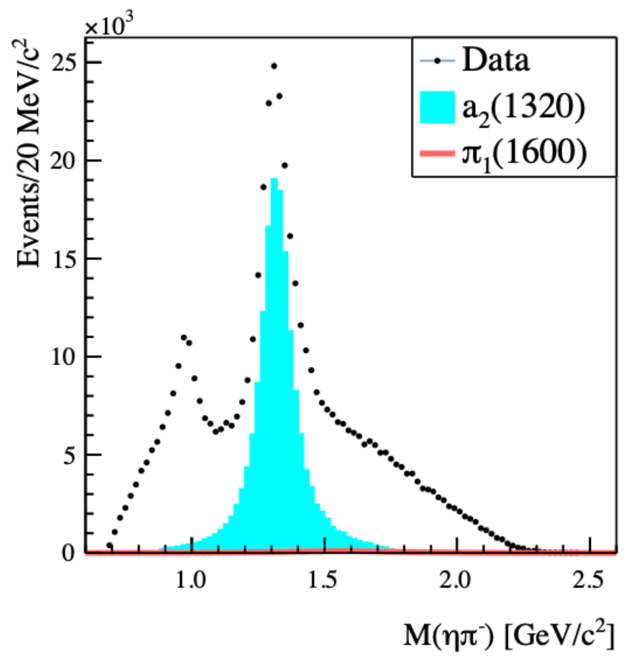


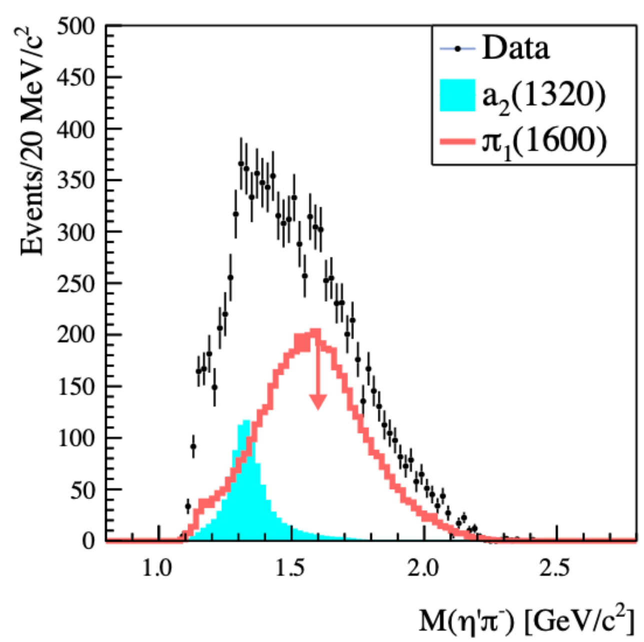
$$\sigma(\gamma p \to \pi_1^-(1600)\Delta^{++}) < 627nb$$

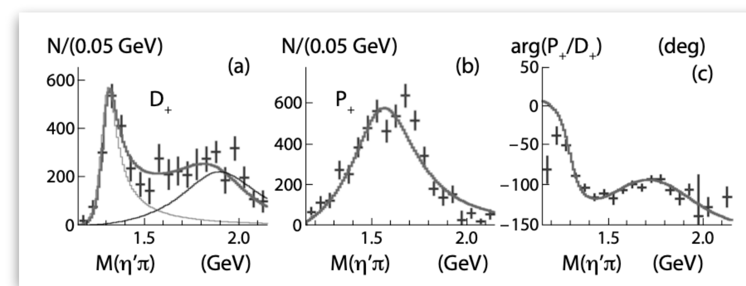
$$\sigma(\gamma p \to \pi_1^0(1600)p) < 177nb$$

F. Afzal et al. (GlueX, 2407.0331 2024)

Convert into expectation for $\to \eta^{(\prime)}\pi p$



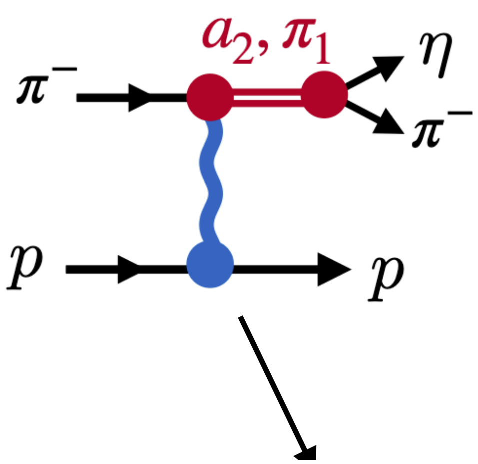




Theory expectations (Swat, AS 2001)

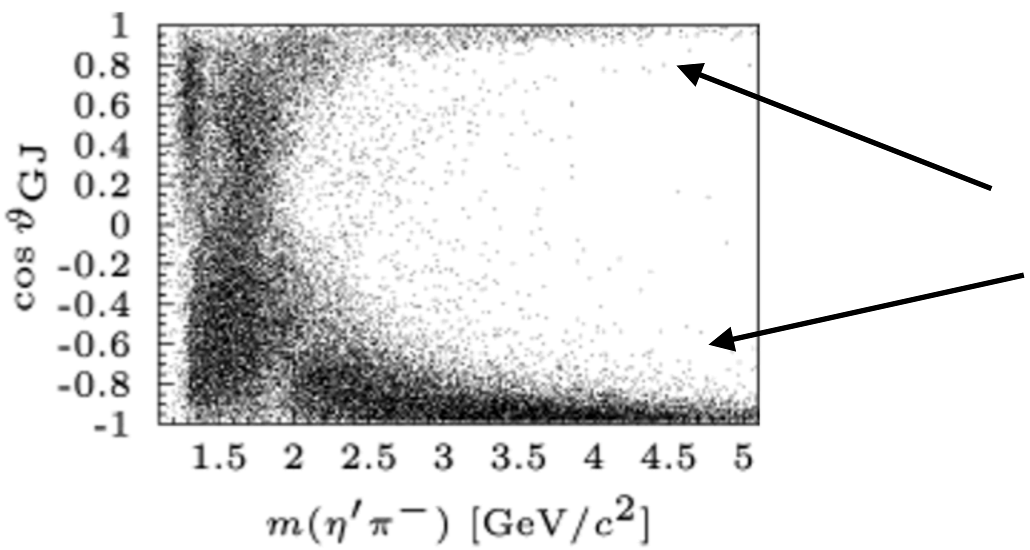
$$\frac{\sigma(\gamma p \to \pi_1^+(1600)n)}{\sigma(\gamma p \to a_2^+(1320)n)} \sim 0.5 - 1$$

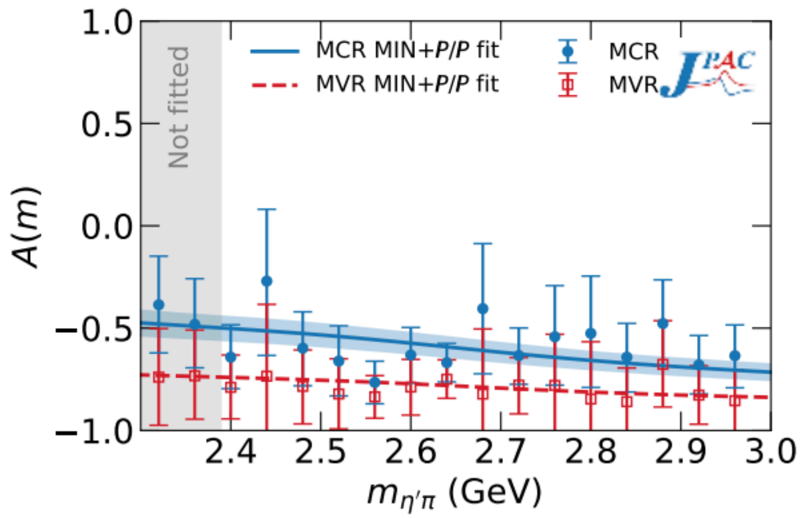
Single vs Double Regge region

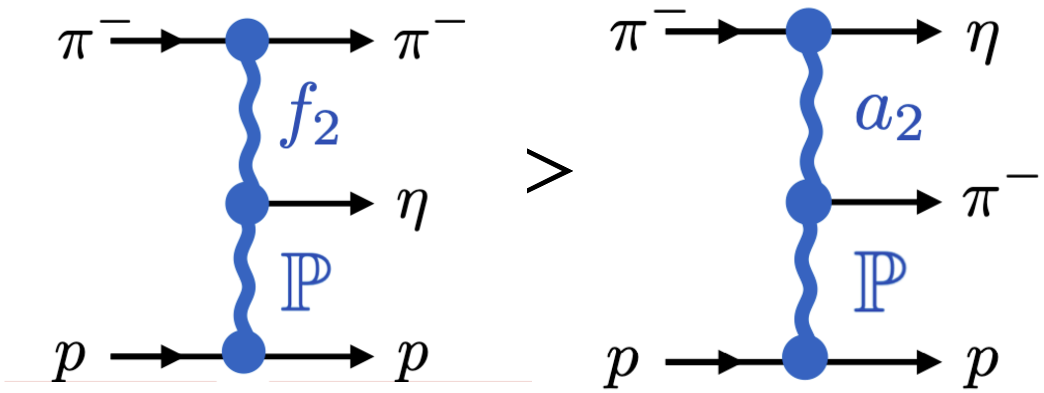


$$A(m) = \frac{F - B}{F + B}$$

L.Bibrzycki, et al. (JPAC) EPJ 2021)





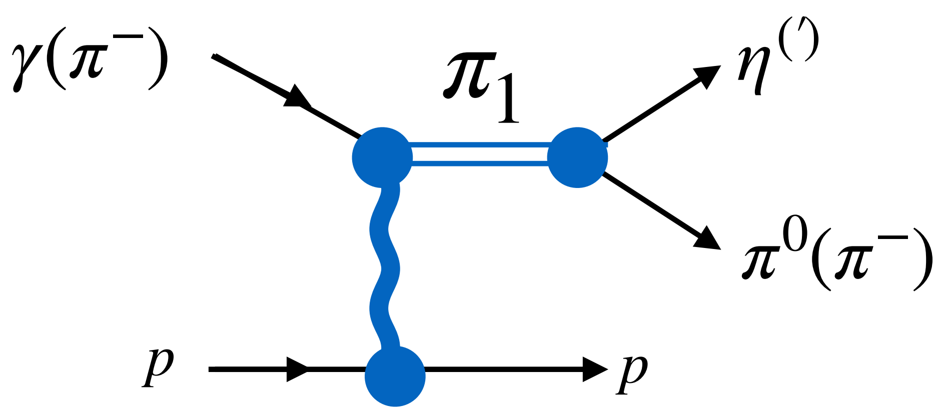


Significant P-wave:

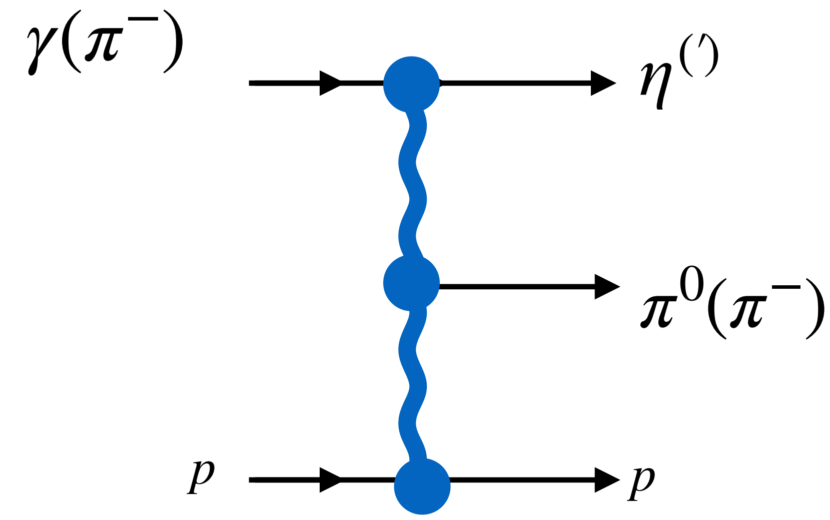
- At low mass = π_1
- At high mass breakdowns of exchange degeneracy
- What is π_1 dual to (e.g. Veneziano duality)
- Need to connect the two regimes -> Dispersion relations for 2-3

~5 x more data from COMPASS currently being analyzed

Dispersion relations for 2-3 process



Dispersion relations , Finite Energy Sum Rules, etc

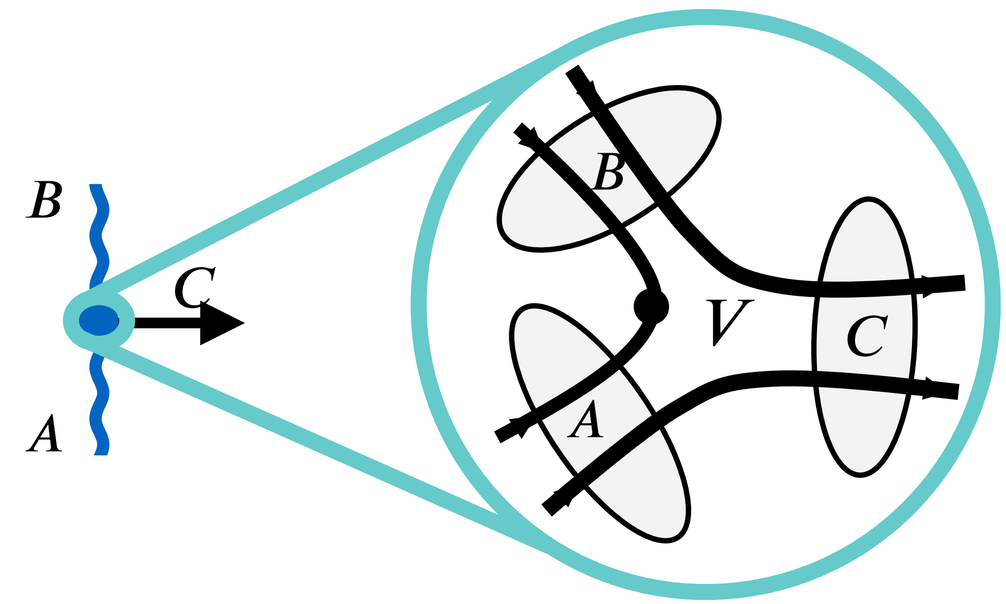


GlueX/(COMPAS) analysis in progress

Existing models of the Double Regge exchange suffer from pathologies (infinite narrow resonances)

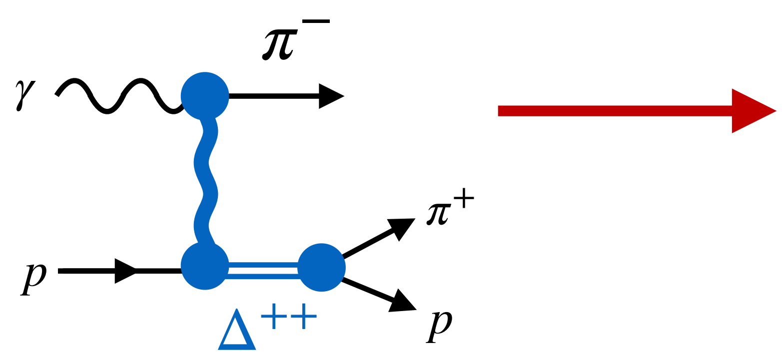
We have "understood" how to construct DR amplitudes without such pathologies

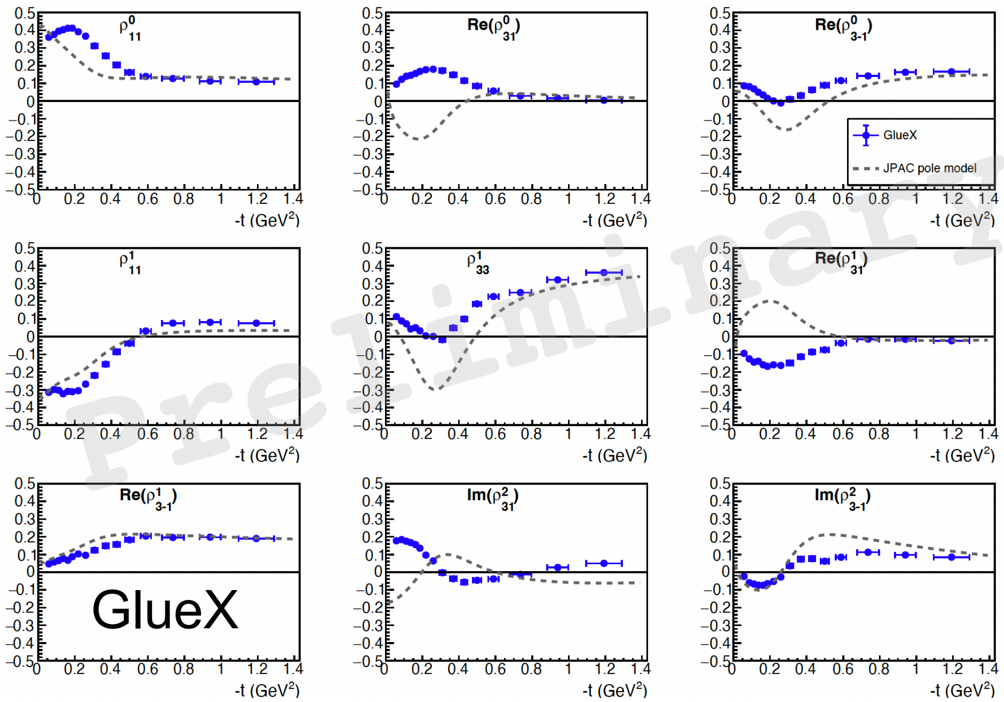
Enables comparison with microscopic models and lattice



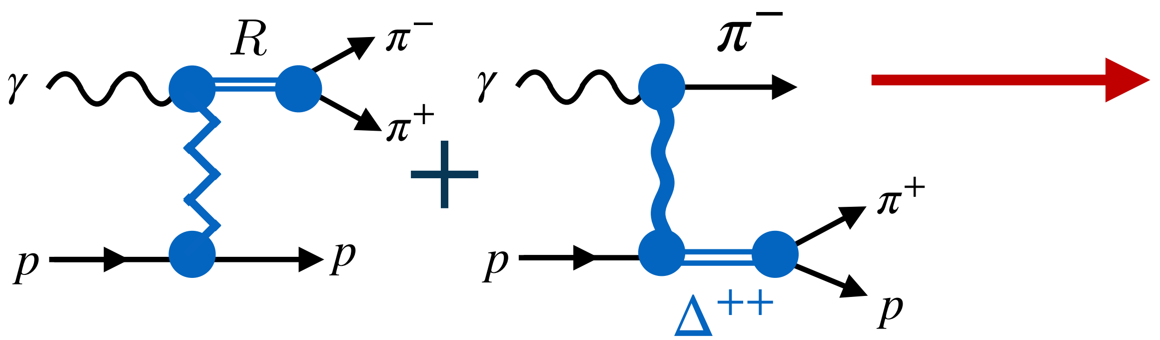
Towards complete understanding of photoproduction

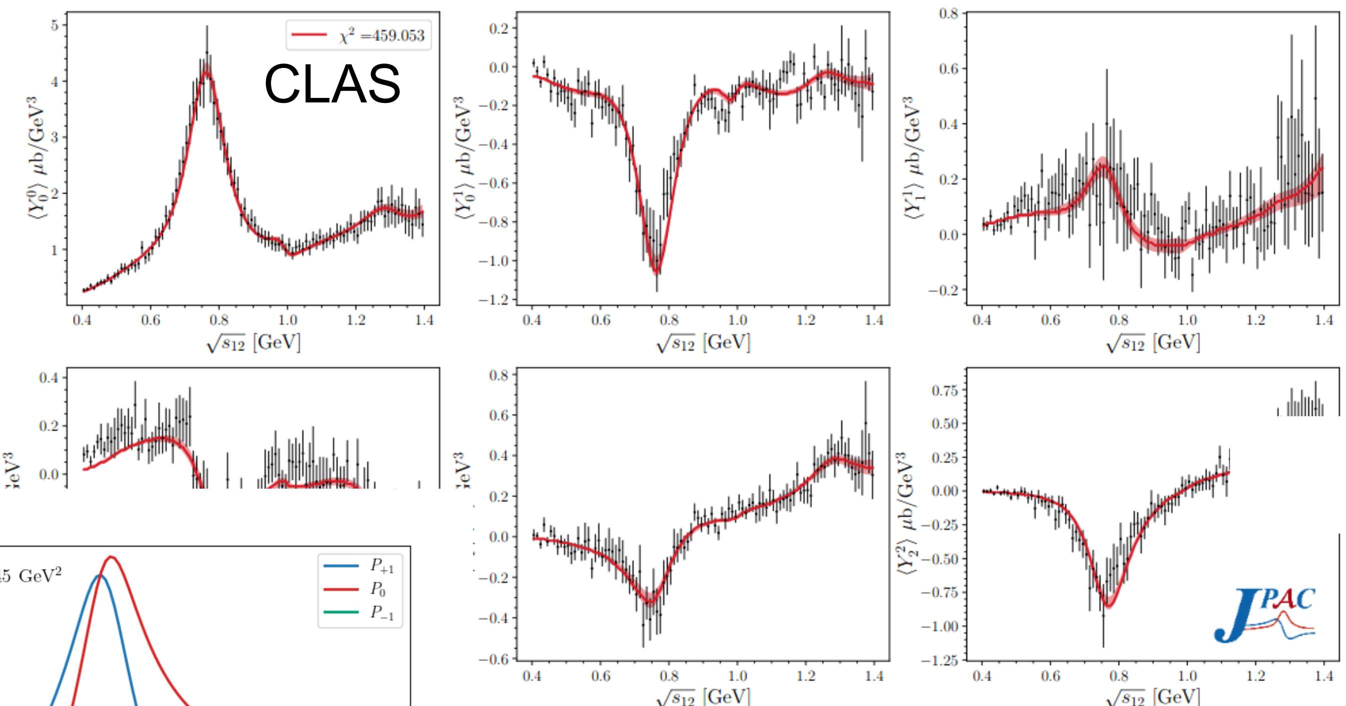
Understanding Δ^{++} production is underway





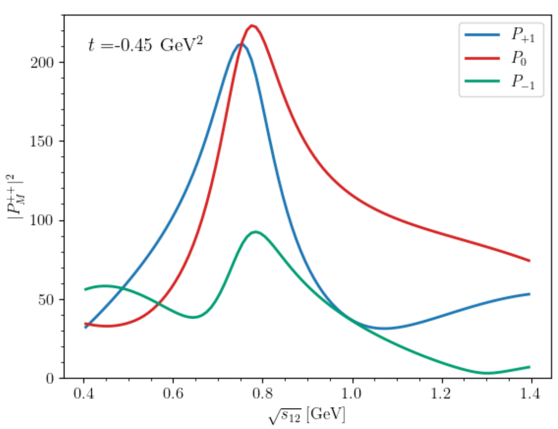
Two-pion photo production project almost completed (impressive data agreement)





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

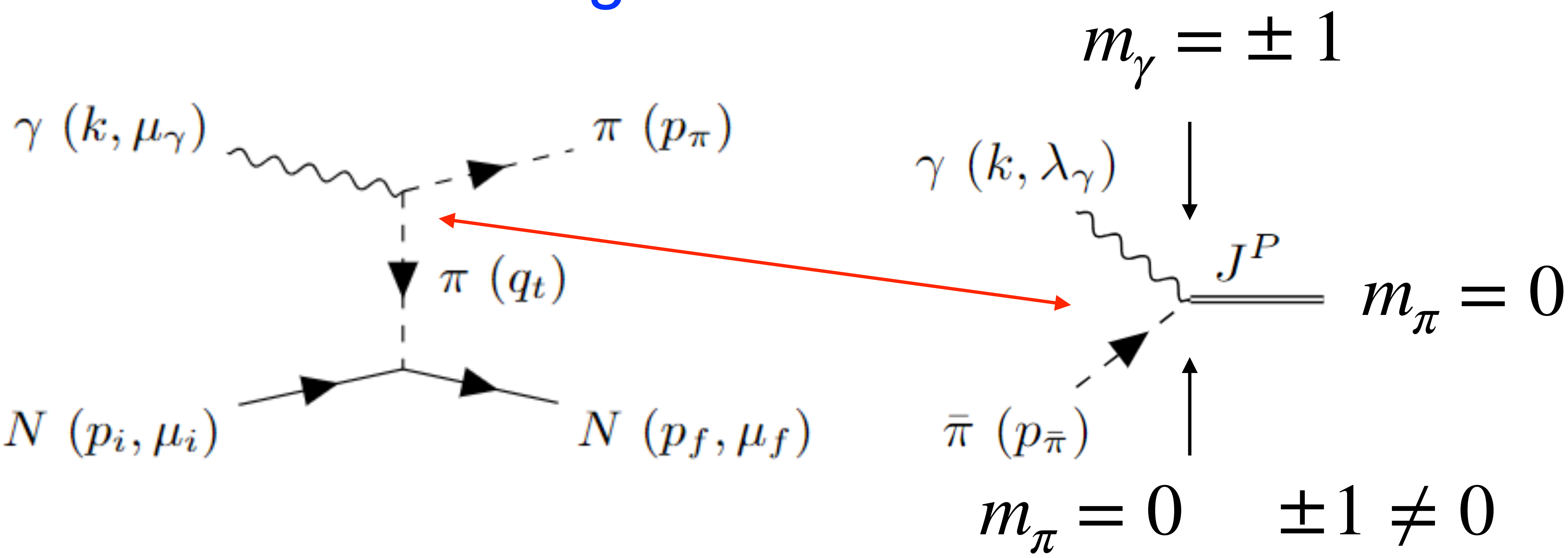
Hierarchy of P-waves for various helicities, determined production dynamics that gives rise to other helicity structures for |t|≈0.45 GeV²



⟩ for $L = 0, 1, 2$ and $M = 0, \ldots L$ for $E_\gamma = 3.7$ GeV and $t = -0.95$ GeV².

L.Bibrzycki, et al. (JPAC) 2024

Fun with π exchange



Naively there is no π exchange !

G.Montana, et al. (JPAC) arXiv:2407.19577

The t-channel has the pion pole and a J=0 pole (current conservation)

$$\frac{1}{J - \alpha_\pi(t)} + \frac{1}{J}$$

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

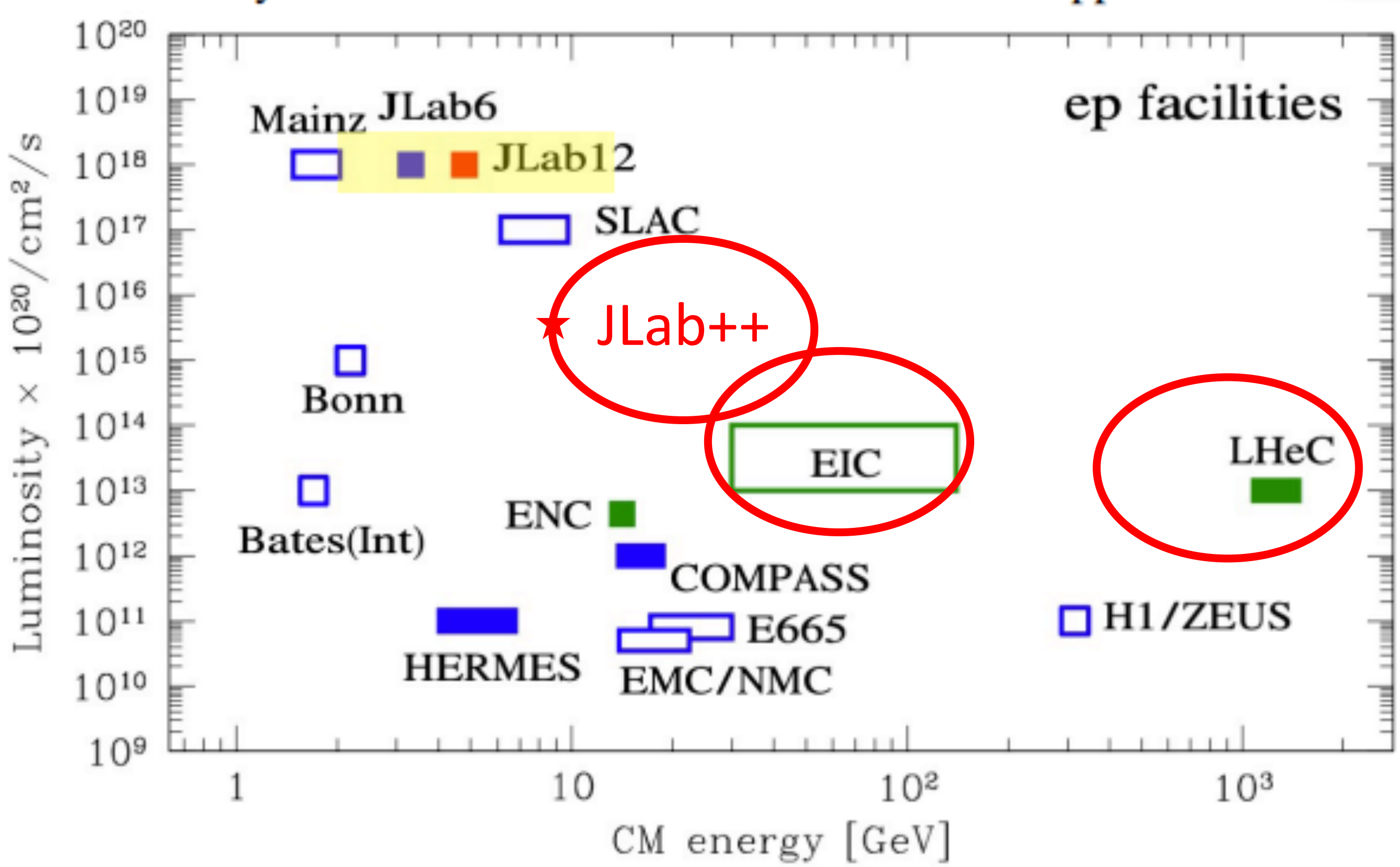
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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/JLab22 explore the complementarity of diffraction, peripheral and/or direct production