Precision Meson Spectroscopy

Adam Szczepaniak (IU/JLab)

- Predicting (exotic)meson resonances and their properties from lattice QCD
- Reliably extracting meson resonance and their production and decay properties from experimental data
- Interpreting both the experiment and theoretical results

The Collaboration

Full Members

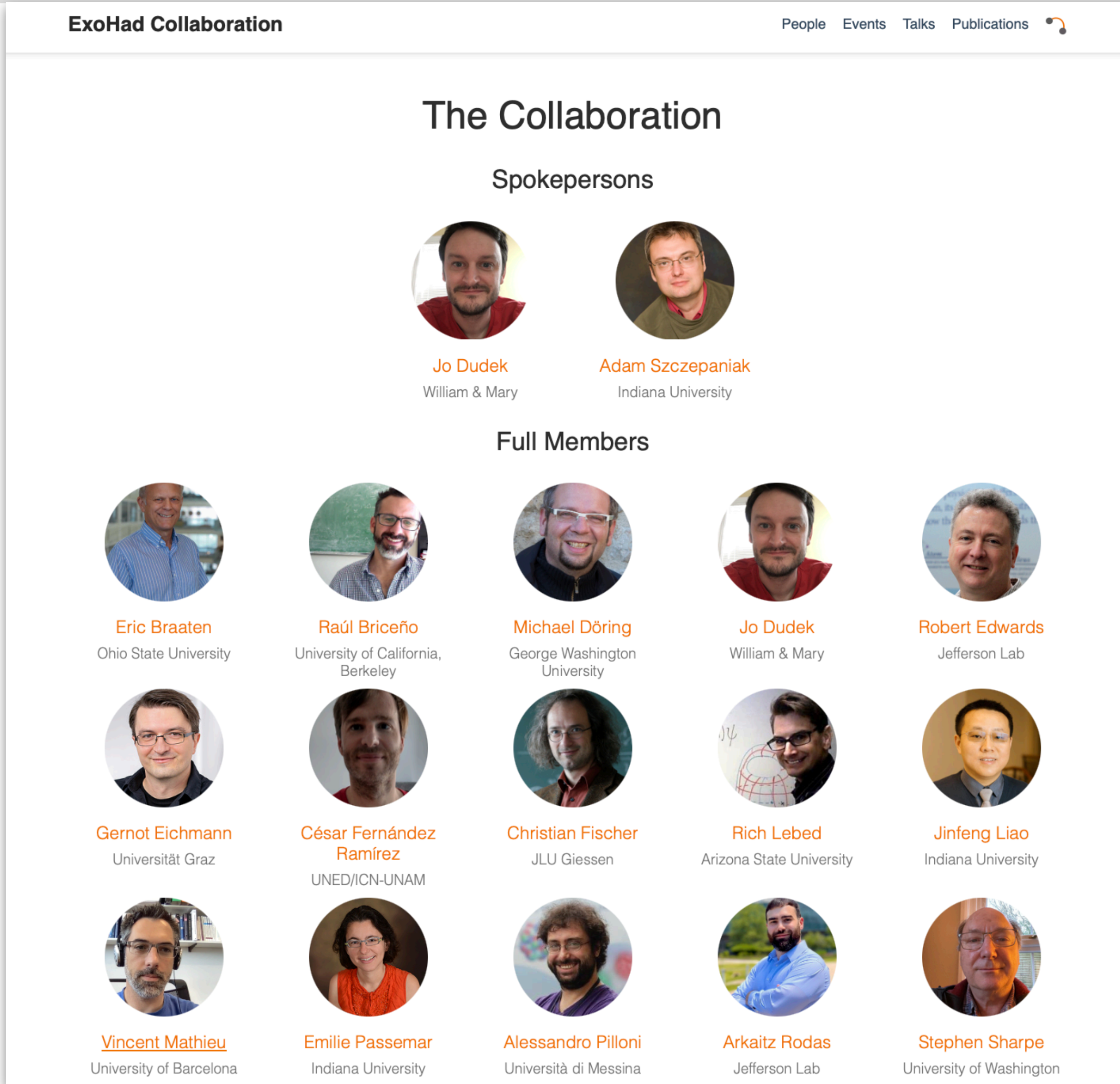
- Adam Szczepaniak — Indiana University
- Alessandro Pilloni — Università di Messina
- Arkaitz Rodas — Jefferson Lab
- Astrid Hiller Blin — EK University of Tübingen
- César Fernández Ramírez — UNED/ICN-UNAM
- Daniel Winney — South China Normal U.
- Emilie Passemar — Indiana University
- Gloria Montaña — Jefferson Lab
- Łukasz Bibrzycki — AGH University of Krakow
- Miguel Albaladejo — IFIC-CSIC Valencia
- Mikhail Mikhasenko — LMU Munich
- Robert Perry — University of Barcelona
- Sergi Gonzàlez-Solís — Los Alamos National Lab
- Vanamali Shastry — Indiana University
- Viktor Mokeev — Jefferson Lab
- Vincent Mathieu — University of Barcelona
- Wyatt Smith — Indiana University

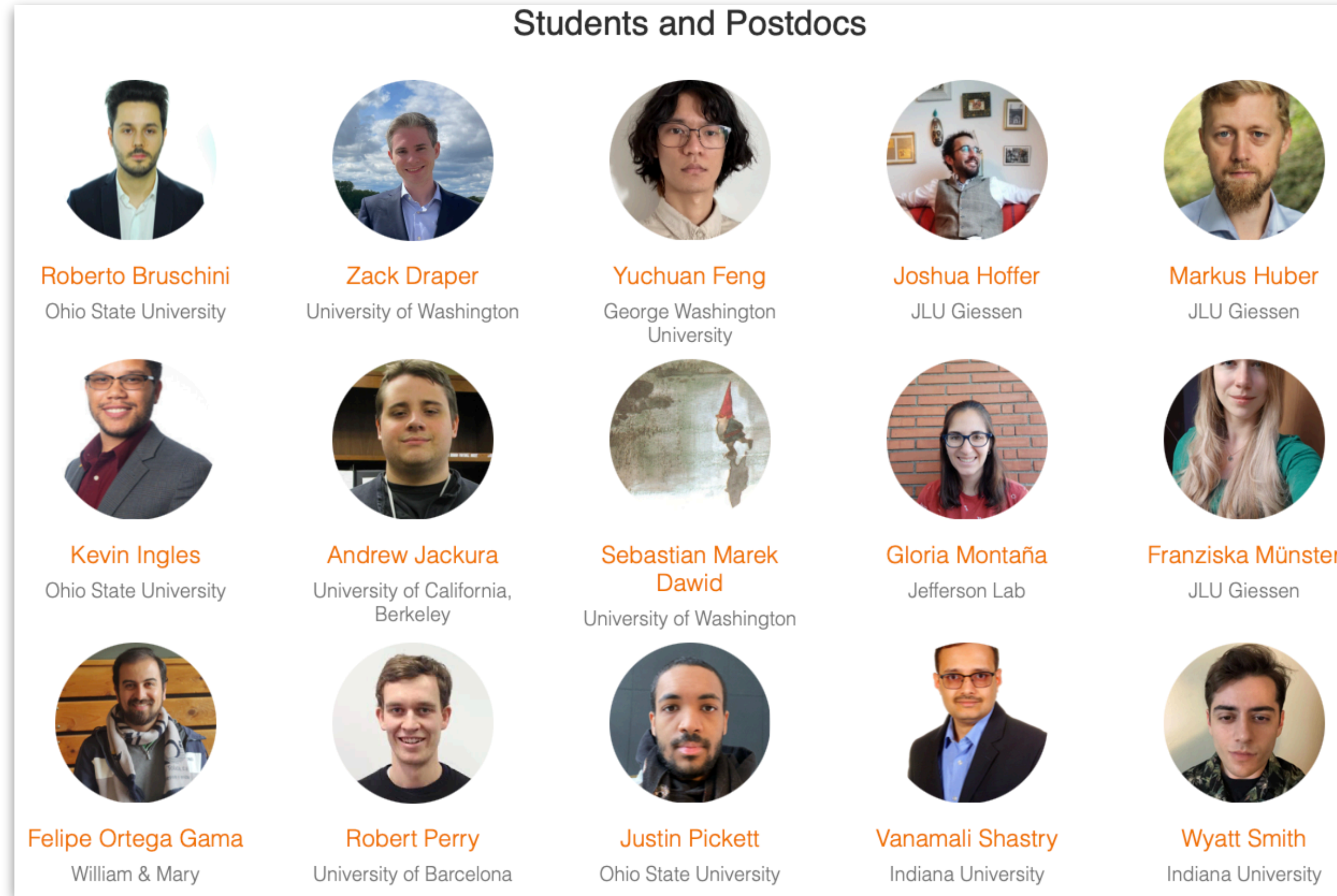
Affiliated Members

- Andrew Jackura — University of California, Berkeley
- 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

- Established in 2013 to develop theory and phenomenology in support of experimental program at JLab12.
- JPAC served as a liaison between many theoretical and experimental analysis efforts BaBar,BESIII,COMPASS,EIC, LHCb,JLab
- Over 40 researchers have been associated with JPAC.
- Tuesday's JPAC meetings have run continuously for the past 10 years

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





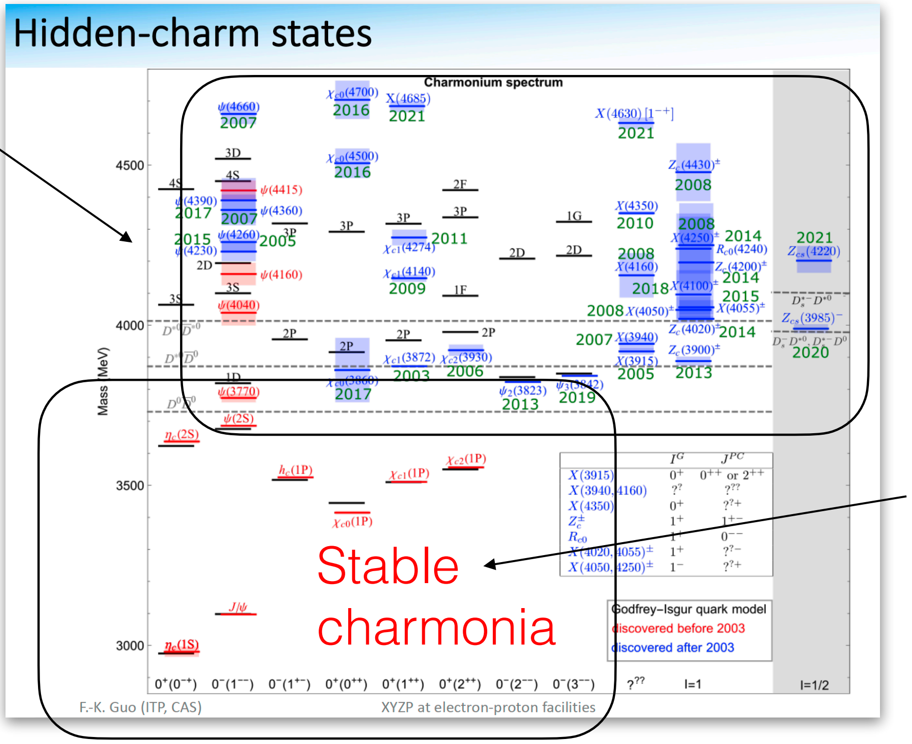
ExoHad

Exotic Hadrons Topical Collaboration

What's ahead for hadron spectroscopy ?

- Can we achieve the level of understanding of hadrons comparable to that of other emergent phenomena ?
- What's the origin and range of validity of the quark model.
- How to investigate the fundamental properties of QCD e.g. confinement ("observables" other than linear trajectories ?)
- Are there more "nuclei" in the "hadronic landscape"

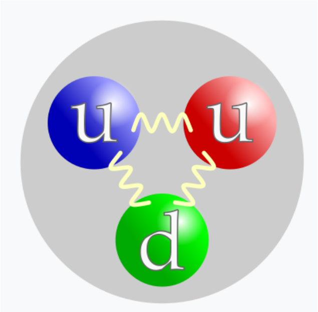
Terra incognita



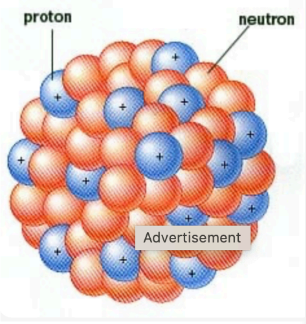
F-K.Guo

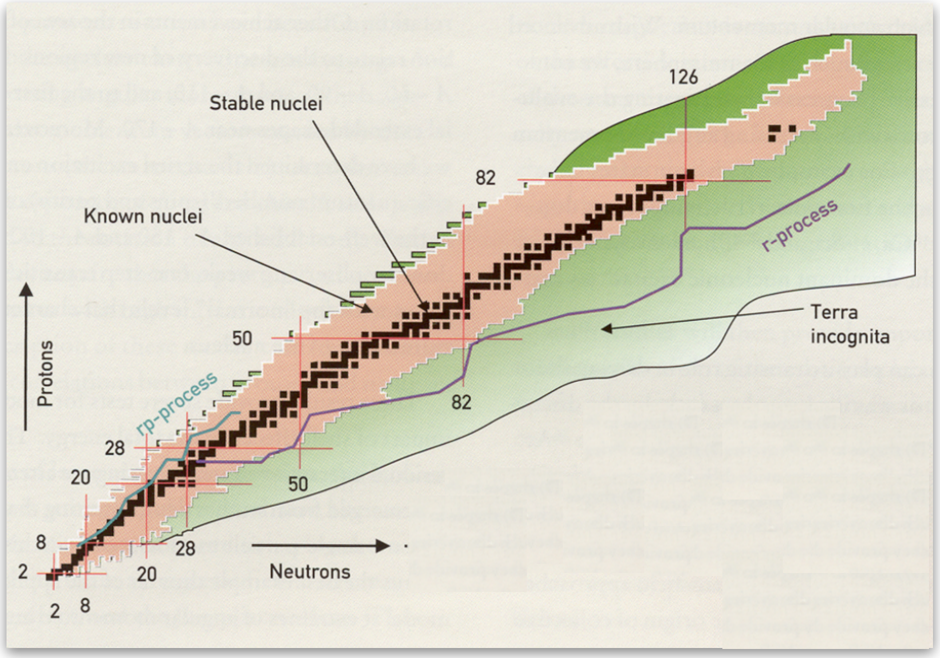
D.Dean, Physics Today 60, 11, 48 (2007)

Hadrons



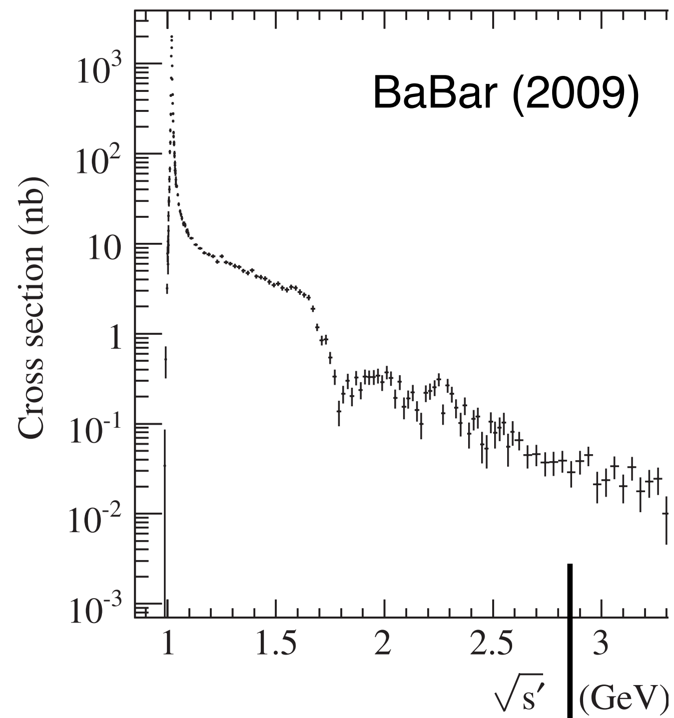
Nuclei

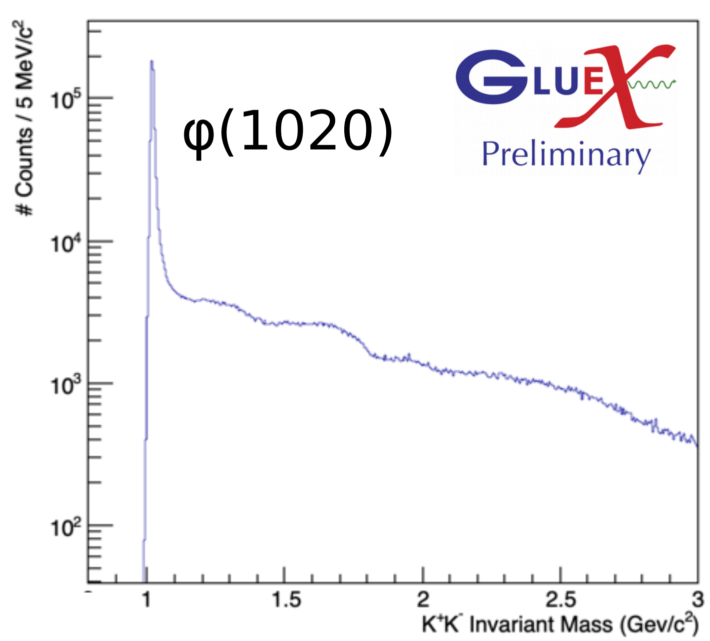


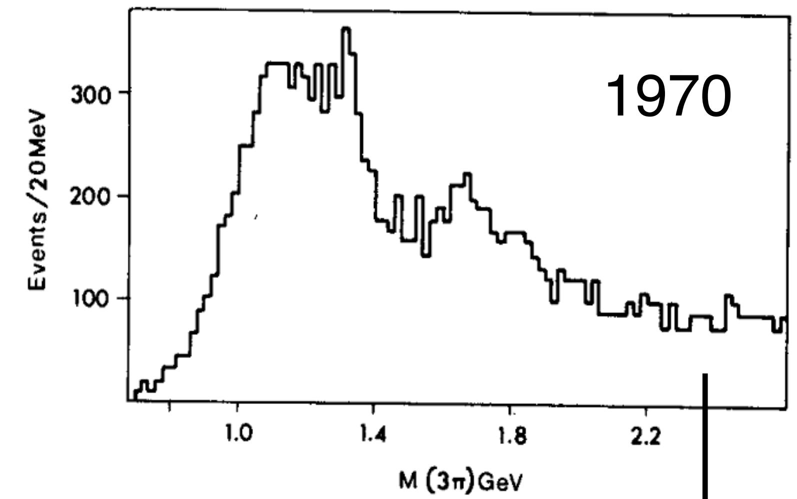


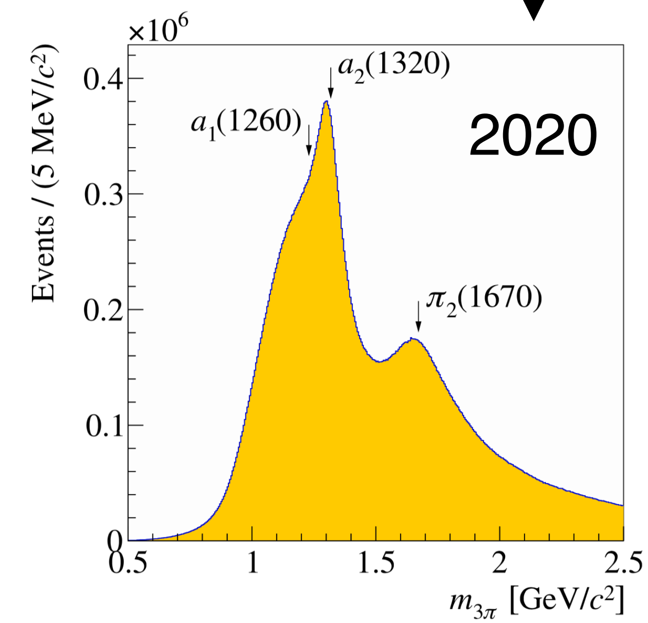
Exp and Theory are working together

- Over the past 50 years data has improved dramatically
- It allows model independent analysis



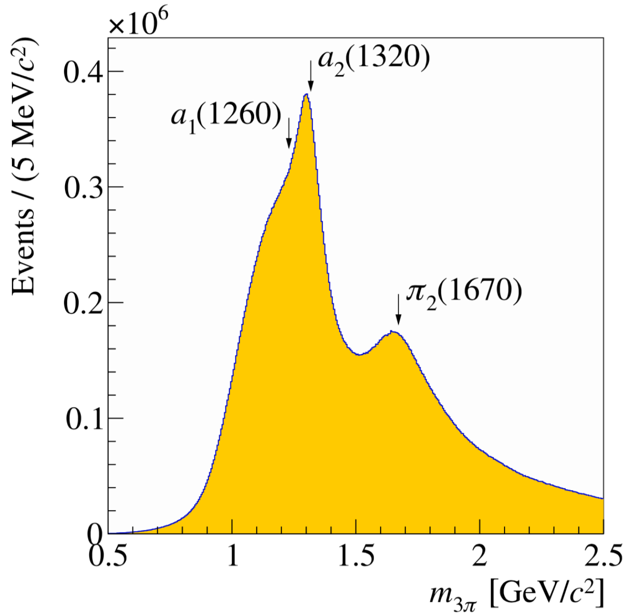




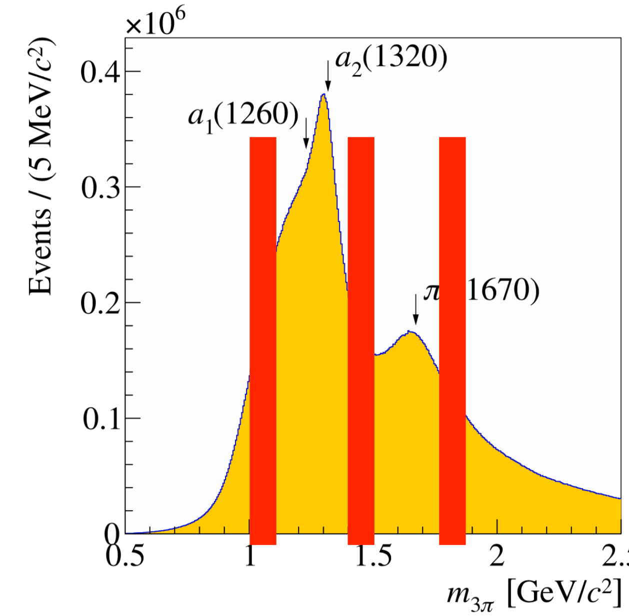


Similar spectra expected from CLAS12

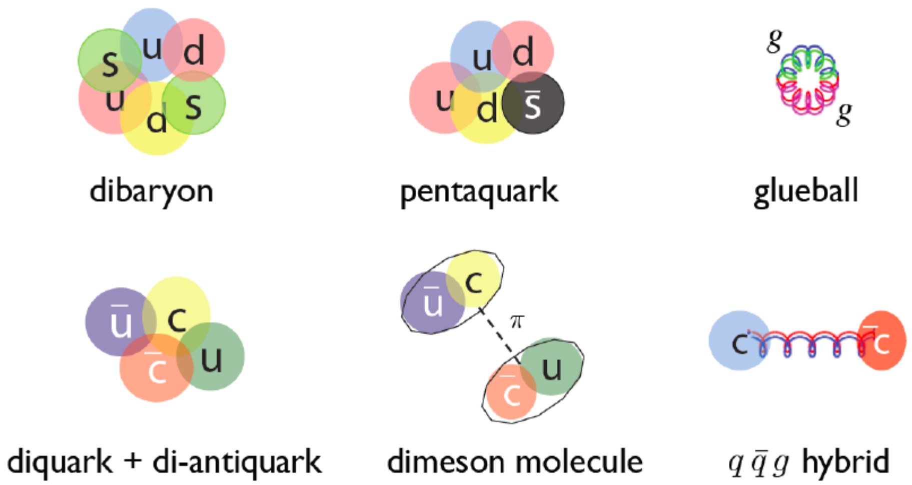
Model independent analysis

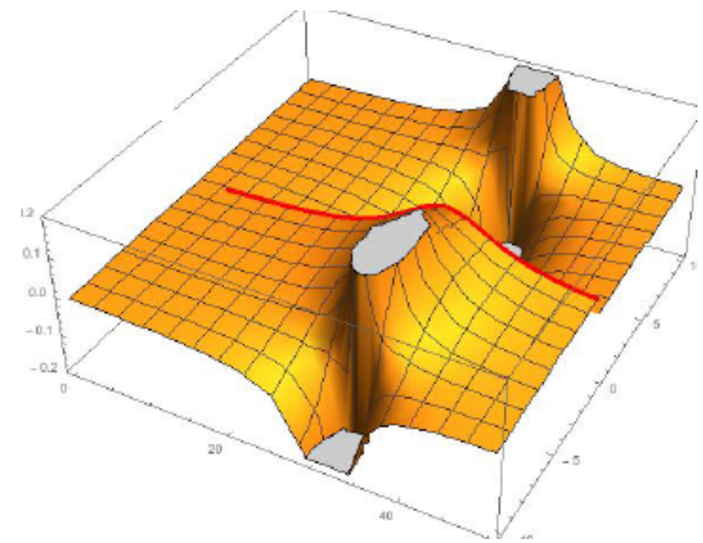


Nature: real axes



QCD

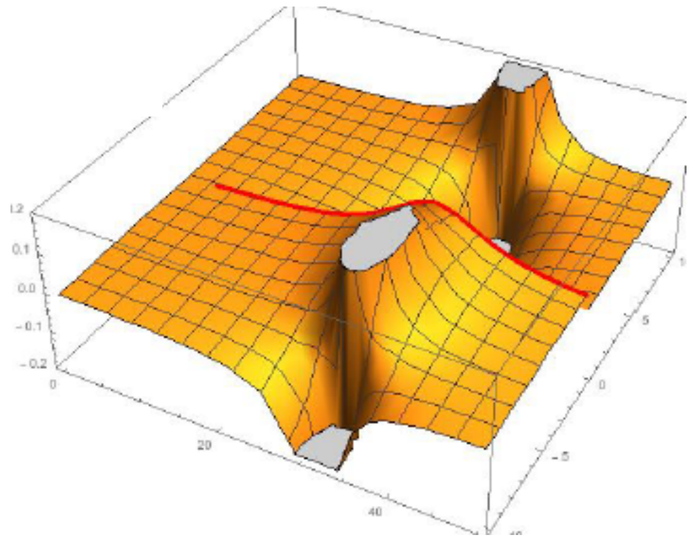




Models

Model independent (based on S-matrix principles)

Amplitude analysis



1. Amplitudes are analytical functions of $s_1, \cdots t_1, \cdots$

2. Partial wave amplitudes are analytical functions angular momentum

$$f_l(s) = f(l, s)$$

3. Physical sheet singularities are given by unitarity

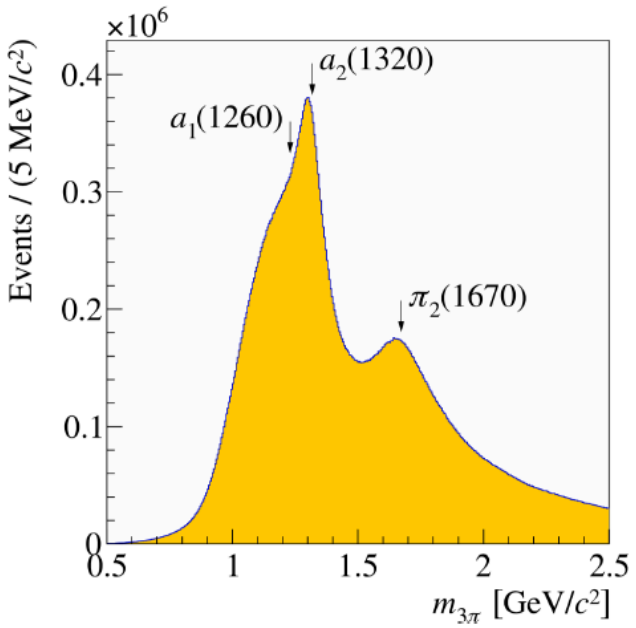
4. Unphysical sheet singularities need to be parametrized in order to test microscopic models

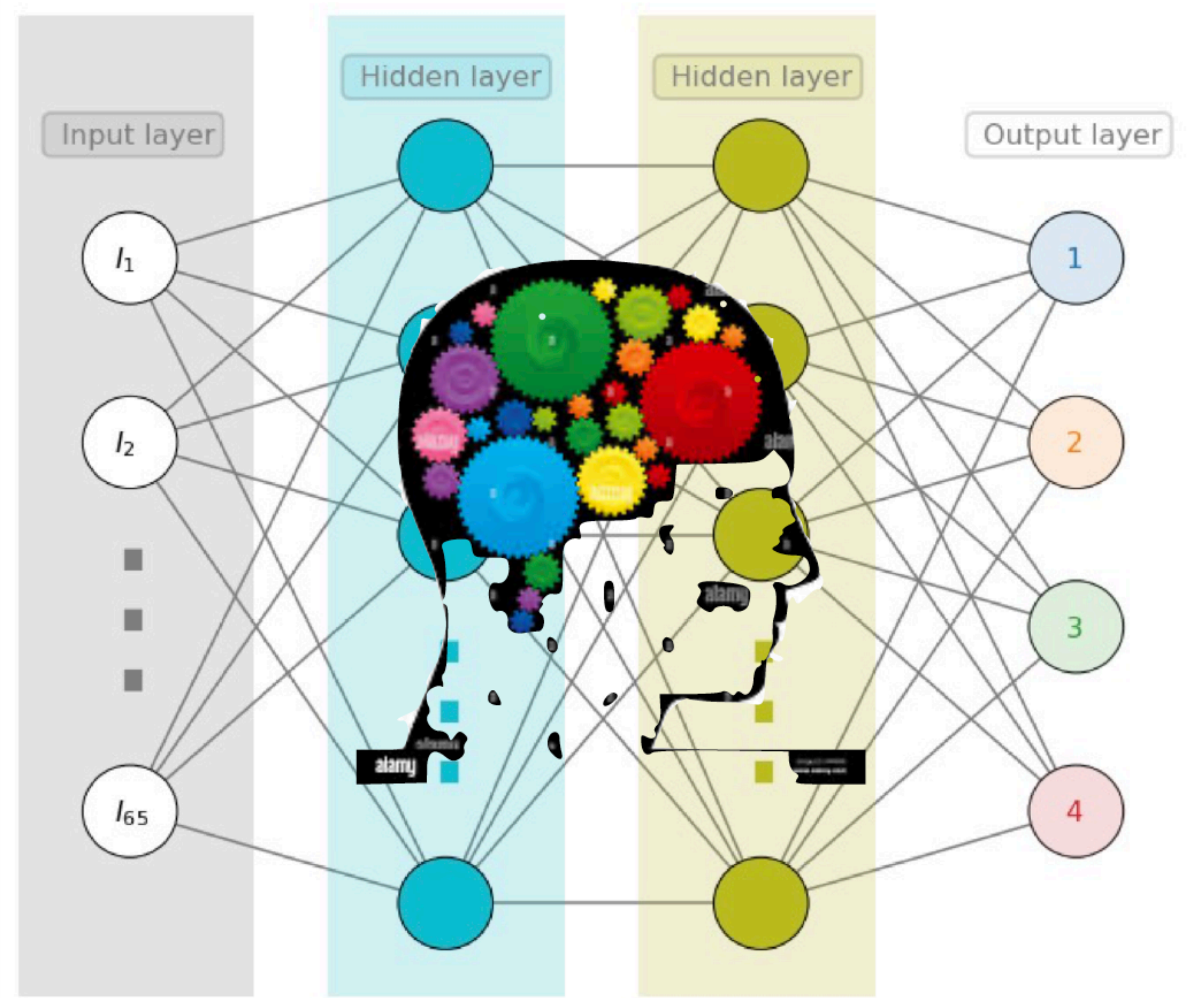
Holy Grail: AI as a tool for physics discovery

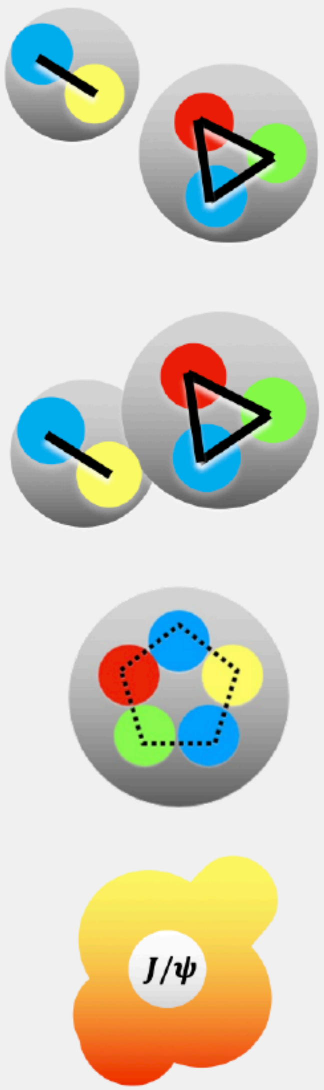
Learn (S-matrix)

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

Apply to data







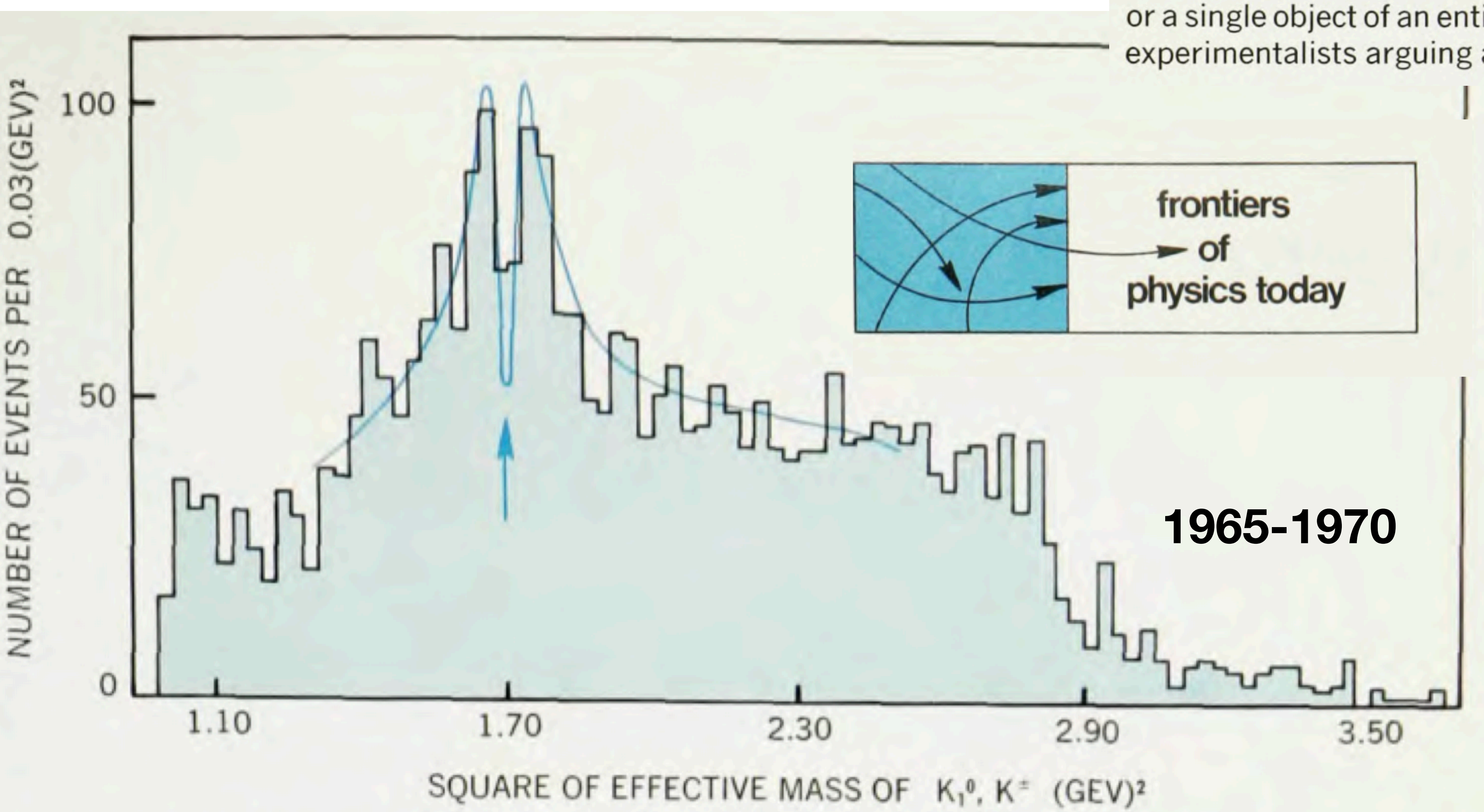
Tell the story

Importance of high quality data : split a2

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

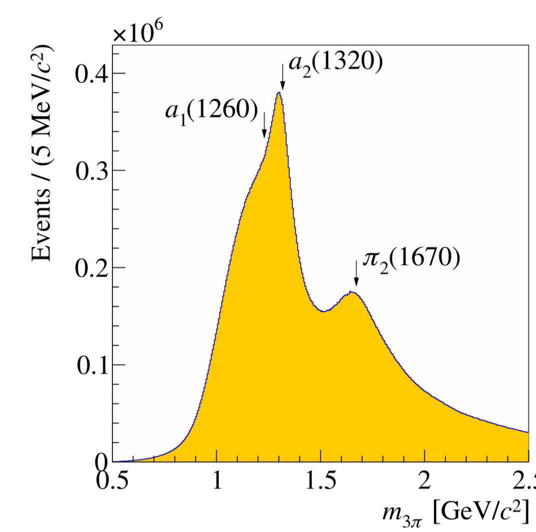
The puzzle of the A2 meson

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.



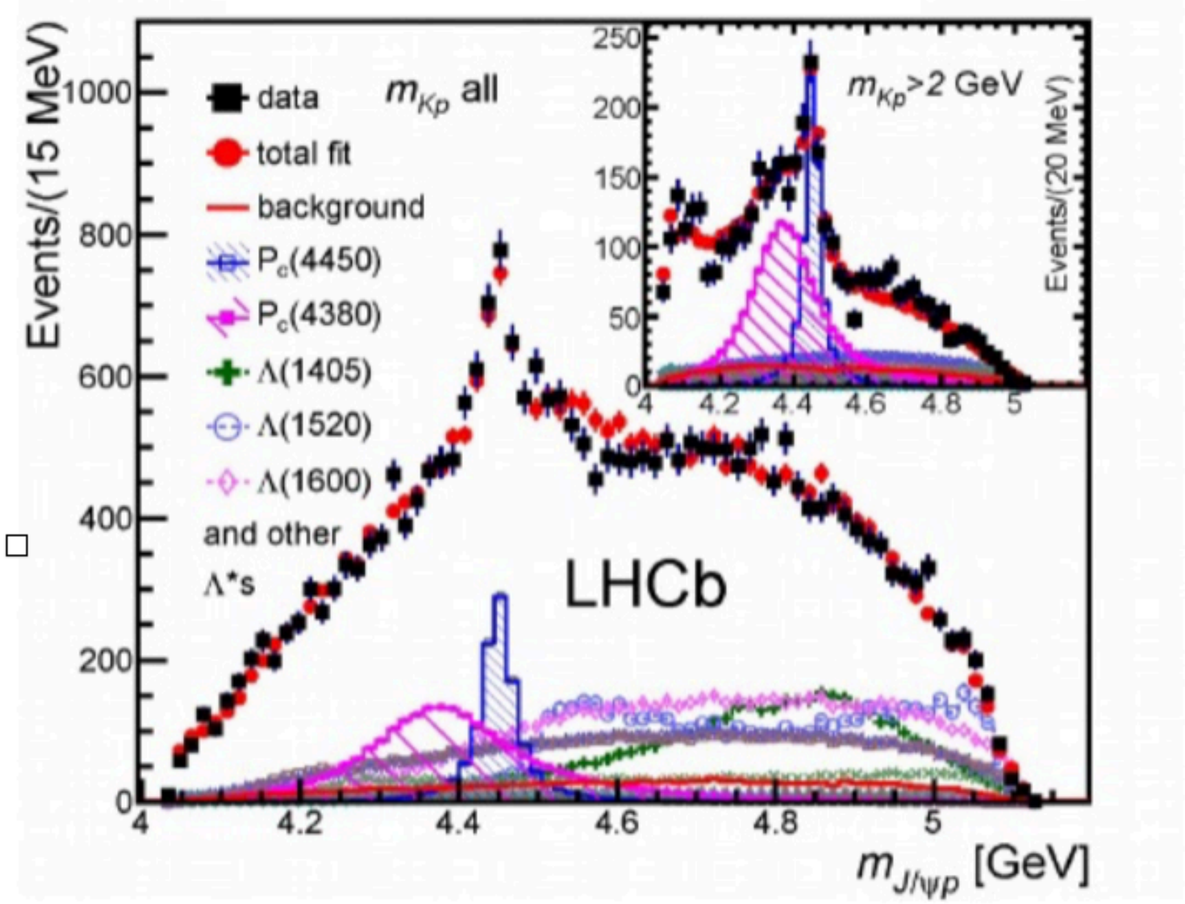
Proton–antiproton annihilation shows evidence for a split A2. The dip at the A2 (mass)², shown by the colored arrow, in the $K_1^0K^+$ effective mass spectrum indicates that the A2 splitting is independent of the production reaction. The data were taken by a CERN-College de France-Liverpool bubble-chamber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

1965-1970

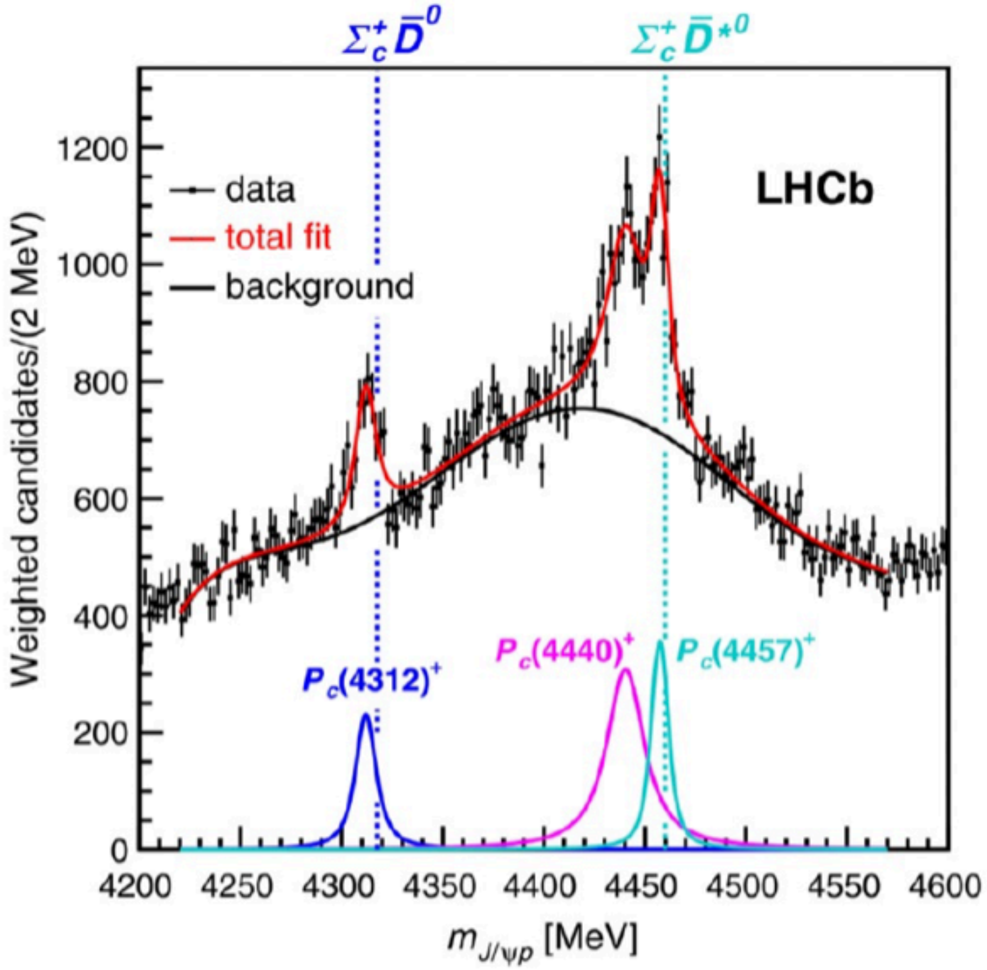


split Pc

LHCb, Run 1, 2015



LHCb, Run 1+Run 2, 2019

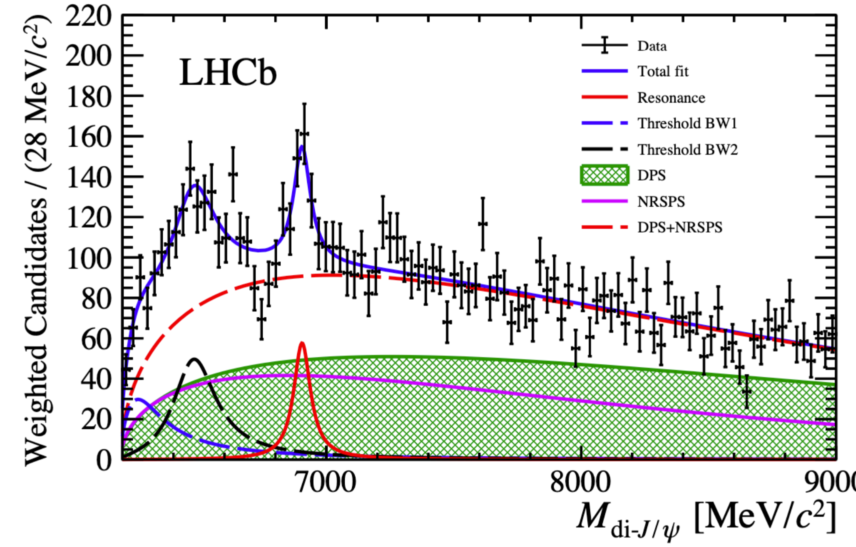


$$P_c(4450) \rightarrow P_c(4440) + P_c(4457)$$

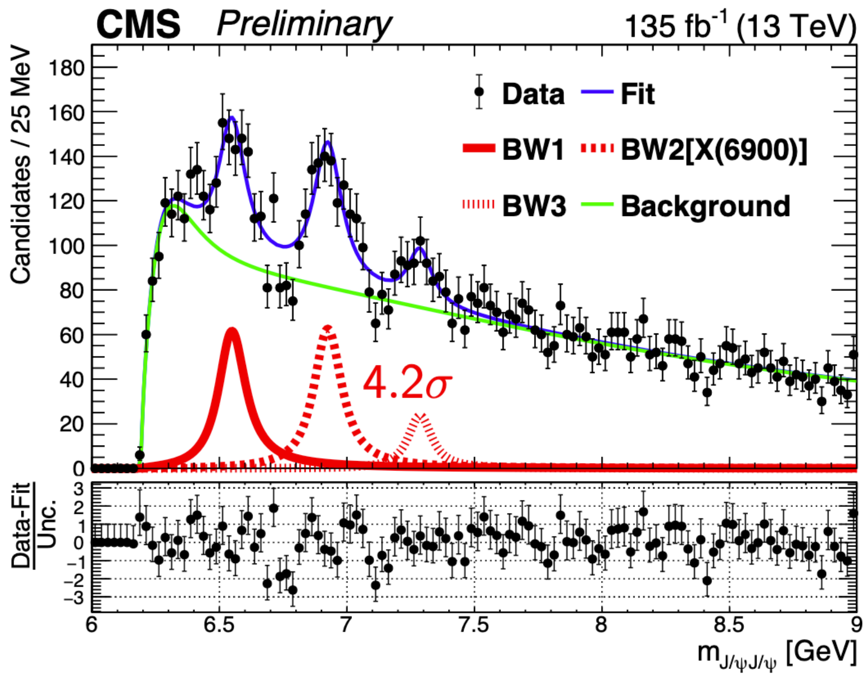
XYZP's : real or not ?

Many XYZ's are unconfirmed but some appear more "real" then other

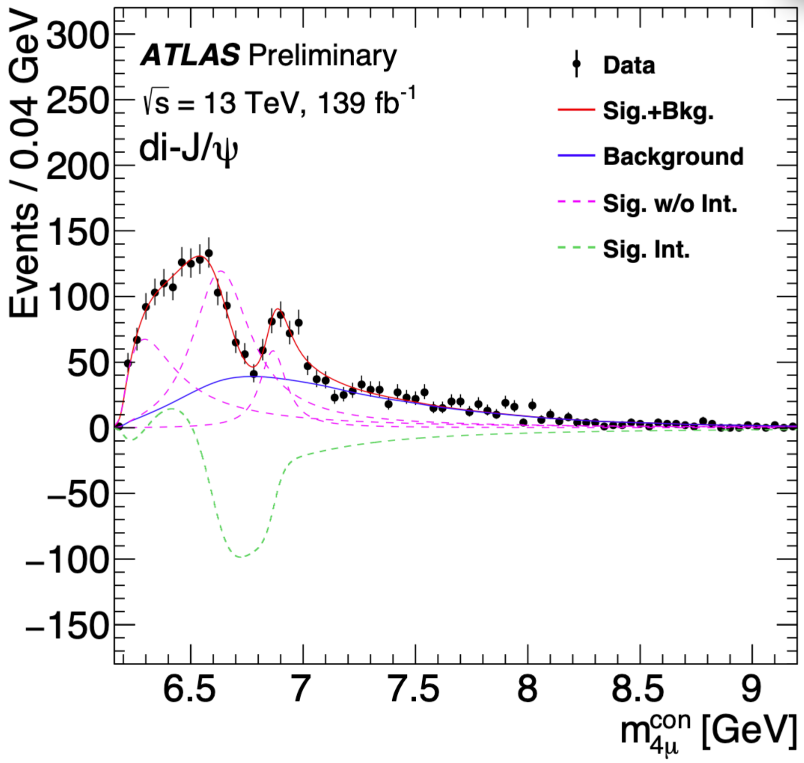
- $T_{\psi\psi}$ or X(6900) a $\psi\psi$ resonance $(cc\bar{c}\bar{c})$?



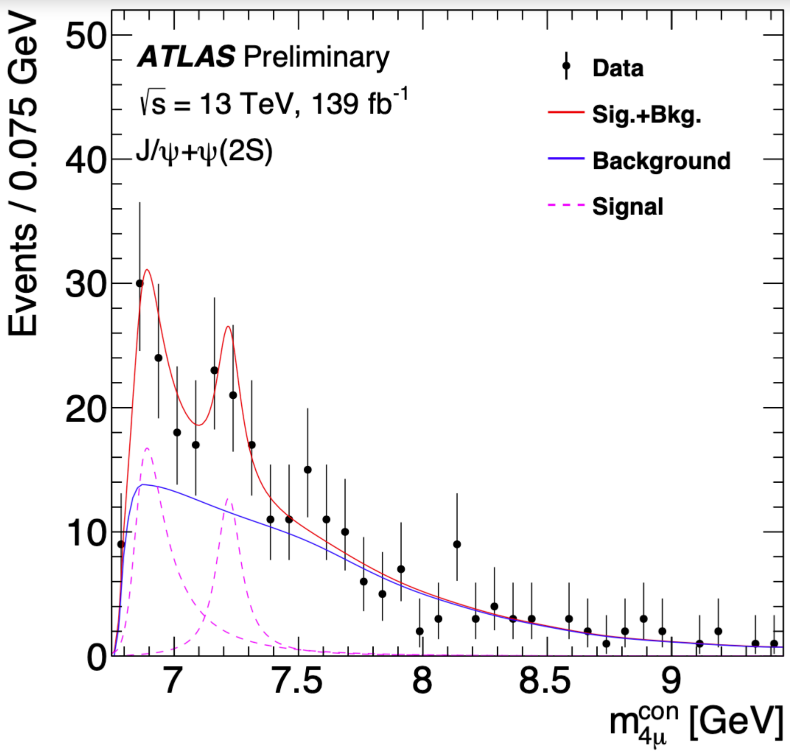
[LHCb, Sci.Bull. 65 (2020) 23, 1983-1993]



[CMS-PAS-BPH-21-003]

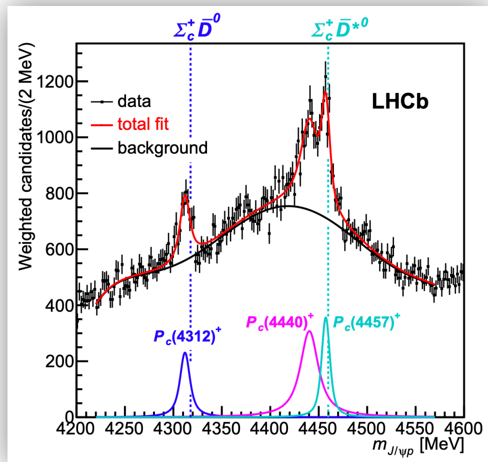


[ATLAS-CONF-2022-040]

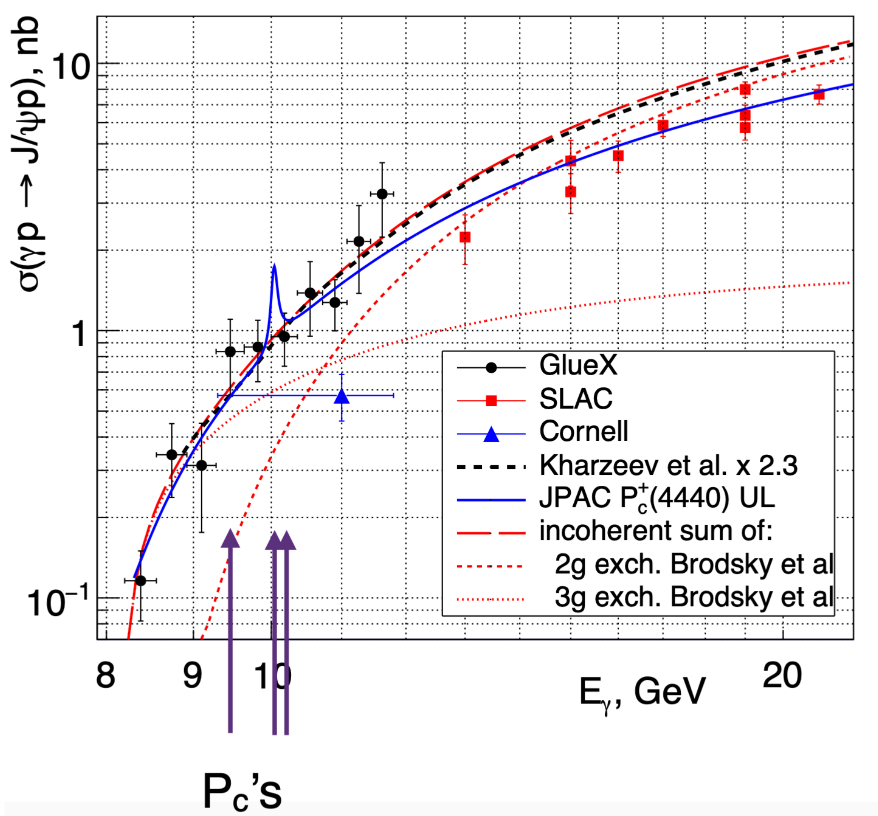


[ATLAS-CONF-2022-040]

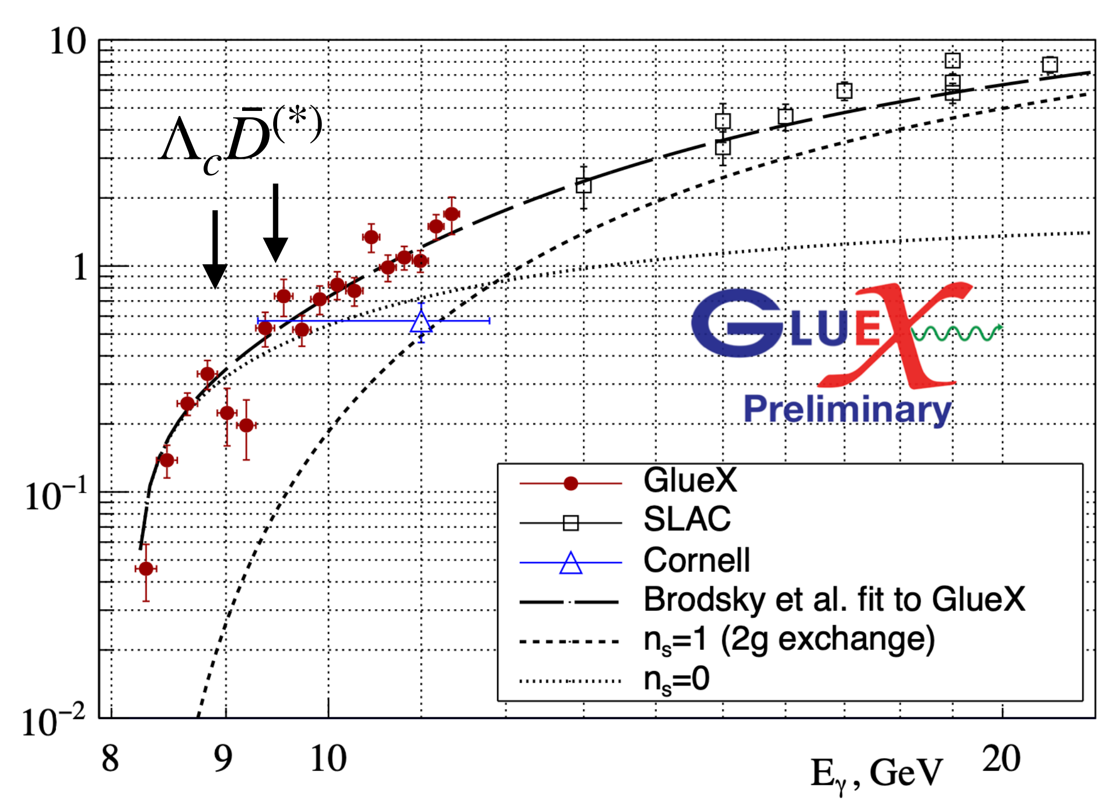
XYZP's : real or not ?



GlueX: PRL 123, 072001 (2019)



- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance
- Full GlueX-I data yields 2270 ± 58 J/ψ's

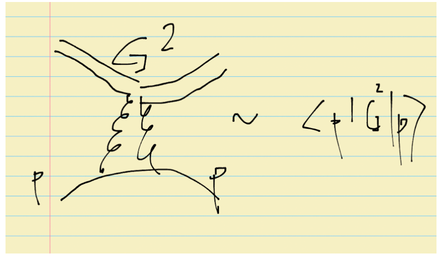


Threshold effects ? Du et al, EPJC 80, 1053 (2020)

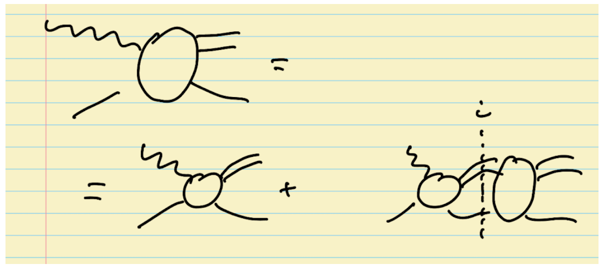
J/ψ photo production

J/ψ-007 [Nature 615 (2023) 7954, 813-816]   GlueX [arXiv:2304.03845]

- Two (distinct) approaches:
  - t-channel partial waves ← $l_{max} \leq 2$ — mass radius, gravitational form factors, etc.
  - s-channel partial waves ← s-channel thresholds



Kharzeev et al. (1999), Brodsky et al (2001) Ji et al.Guo et al. (2021) Z, Mamo, Zahed, (2020)



Du et al [Eur. Phys. J. C 80 (2020) 1053]

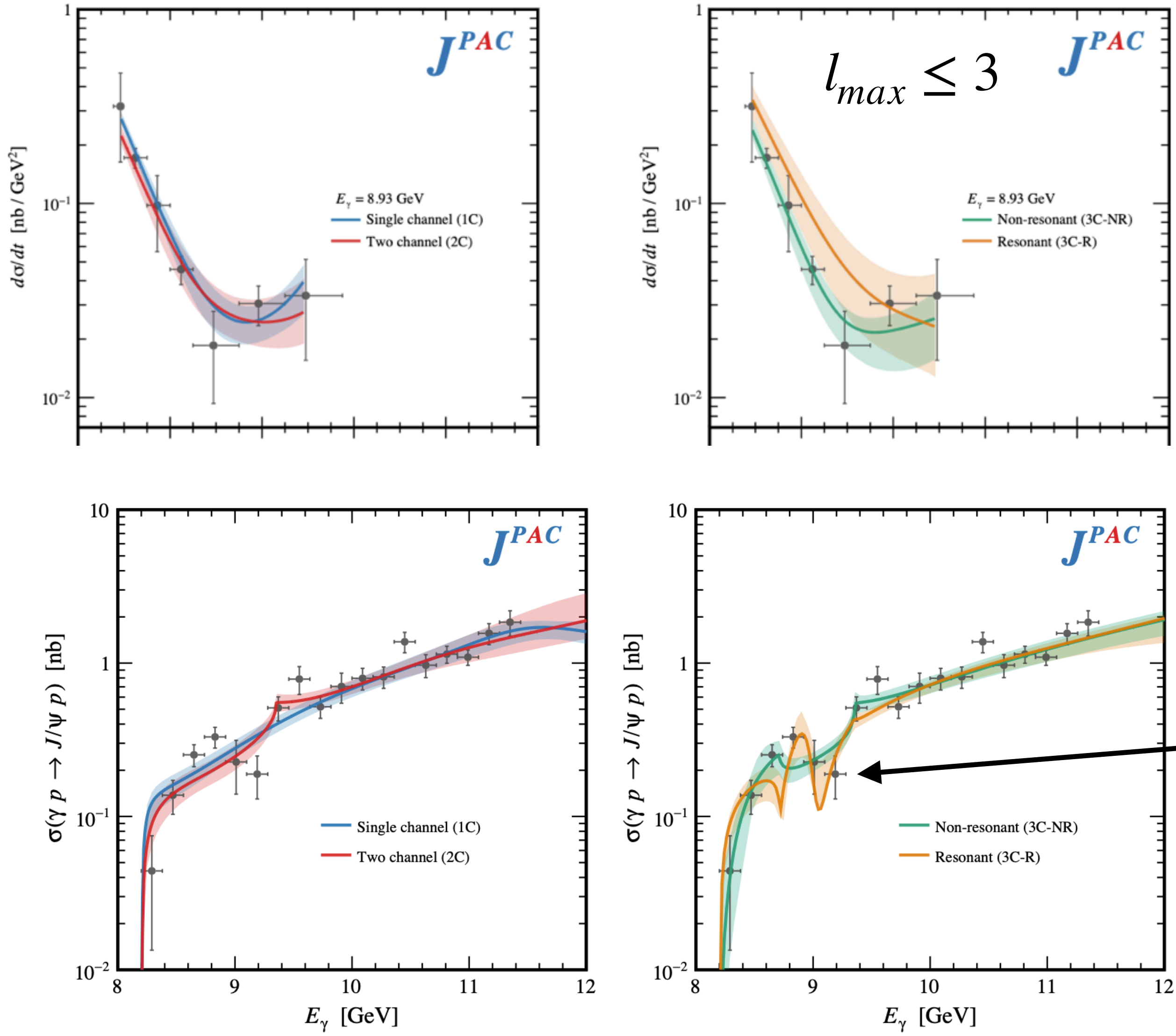
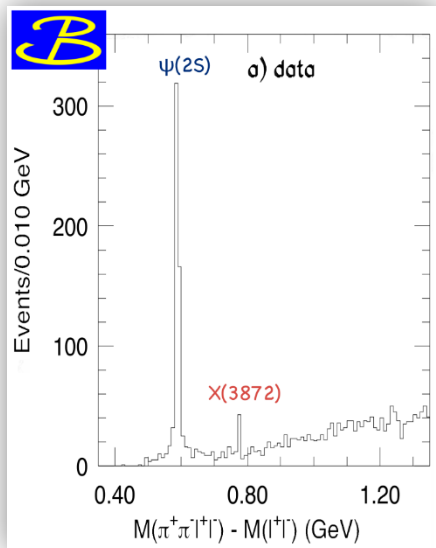


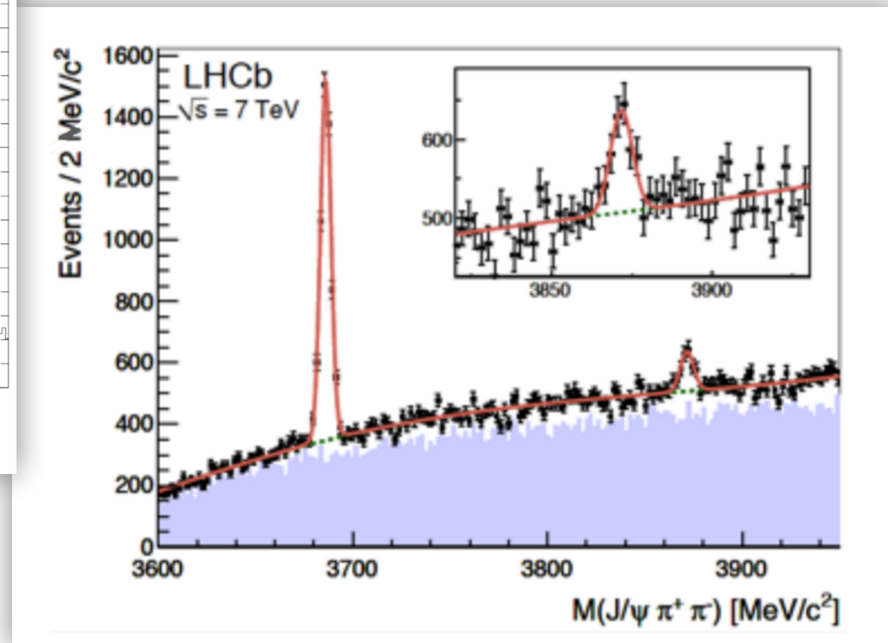
FIG. 1: Fit results for the integrated cross section compared to GlueX data from [37]. Bands correspond to 1σ uncertainties from bootstrap analysis.

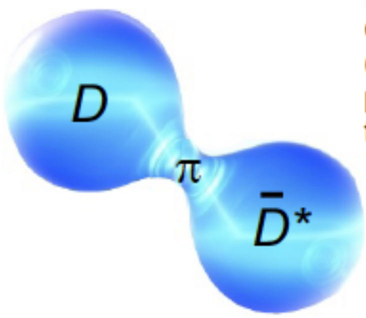
Consistent with Pc(4312)

XYZP's : real or not ?

$X(3872)\ (\chi_{c1}(3872))$

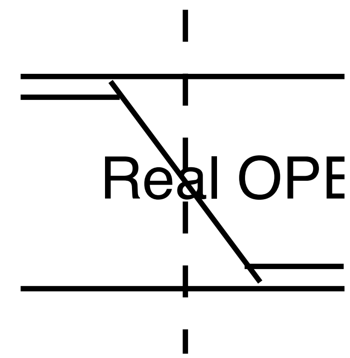


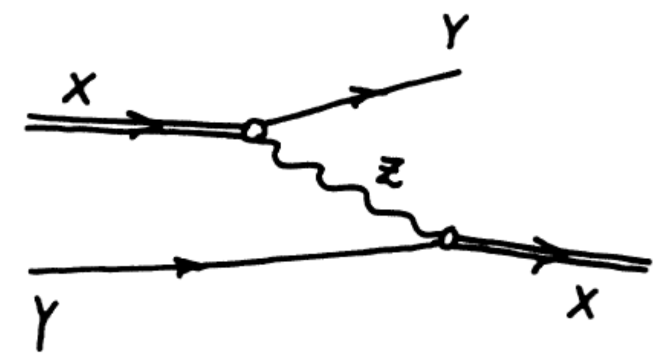




REMARK ON ENERGY PEAKS IN MESON SYSTEMS

If the width of particle X is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical s causes the peaking effect to which we refer as an (X, Y, Z) peak.

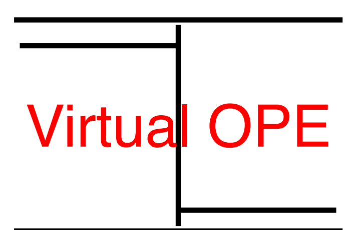




Very close to $D\bar{D}^*$ threshold

Is X(3872) a molecule ?

$$M_{X(3872)} - M_{D^0} - M_{\bar{D}^{*0}}$$
$$= -0.01 \pm 0.14 MeV$$

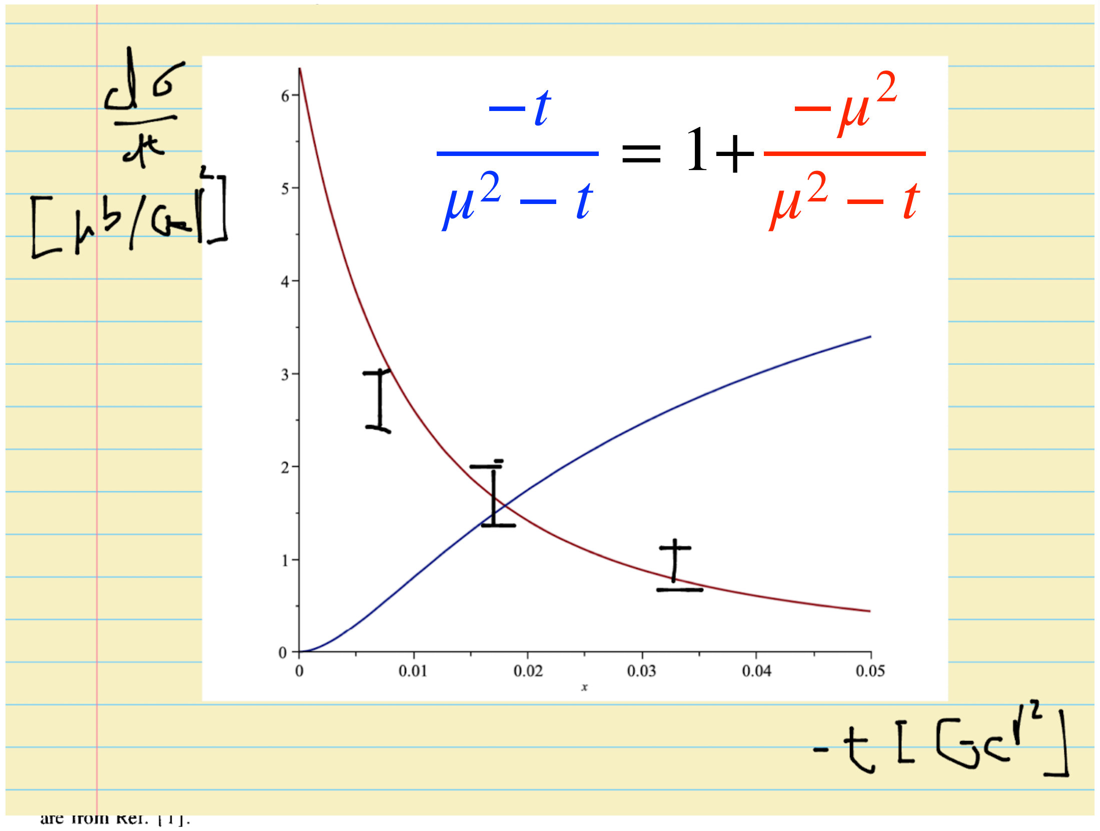


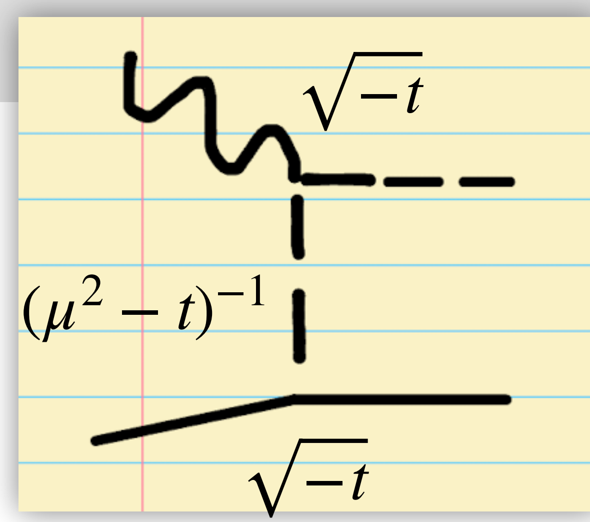
Even Virtual OPE exchange is tricky

$$-\frac{\vec{q}^2}{\mu^2+\vec{q}^2} = -1 + \frac{\mu^2}{\mu^2+\vec{q}^2}$$

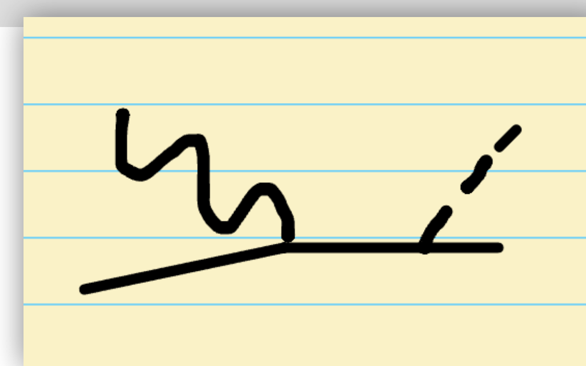
Attractive = Attractive + Repulsive

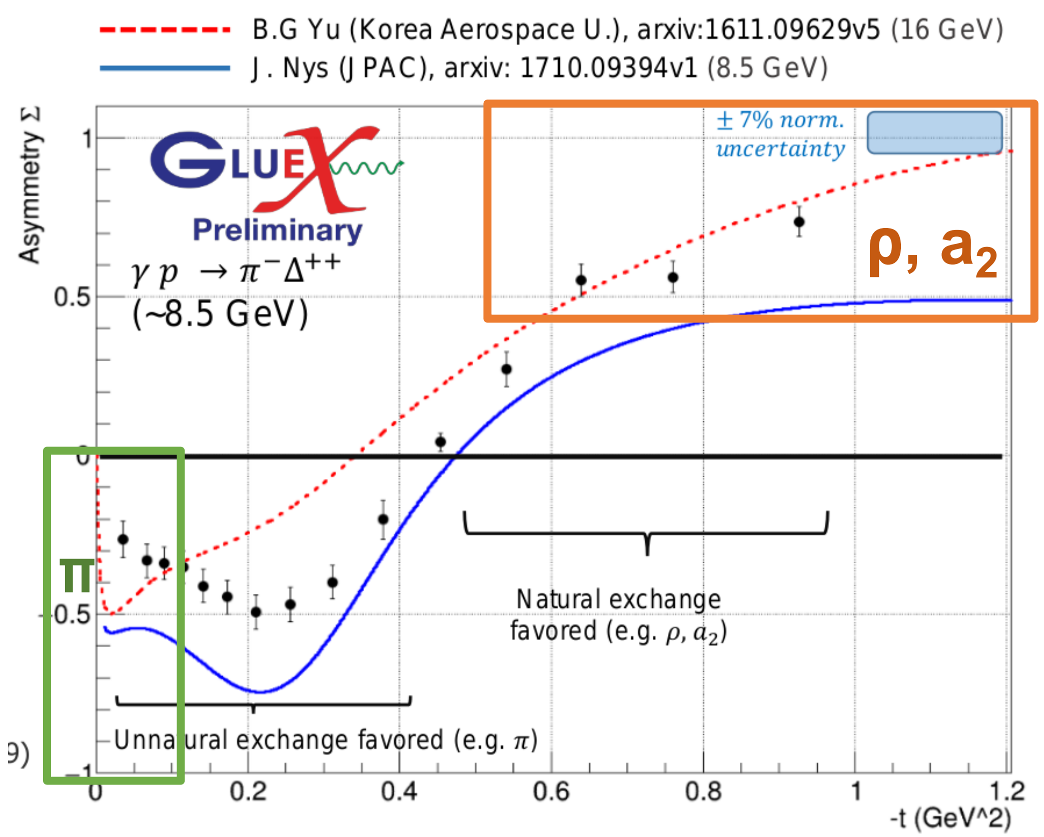
Pion exchange





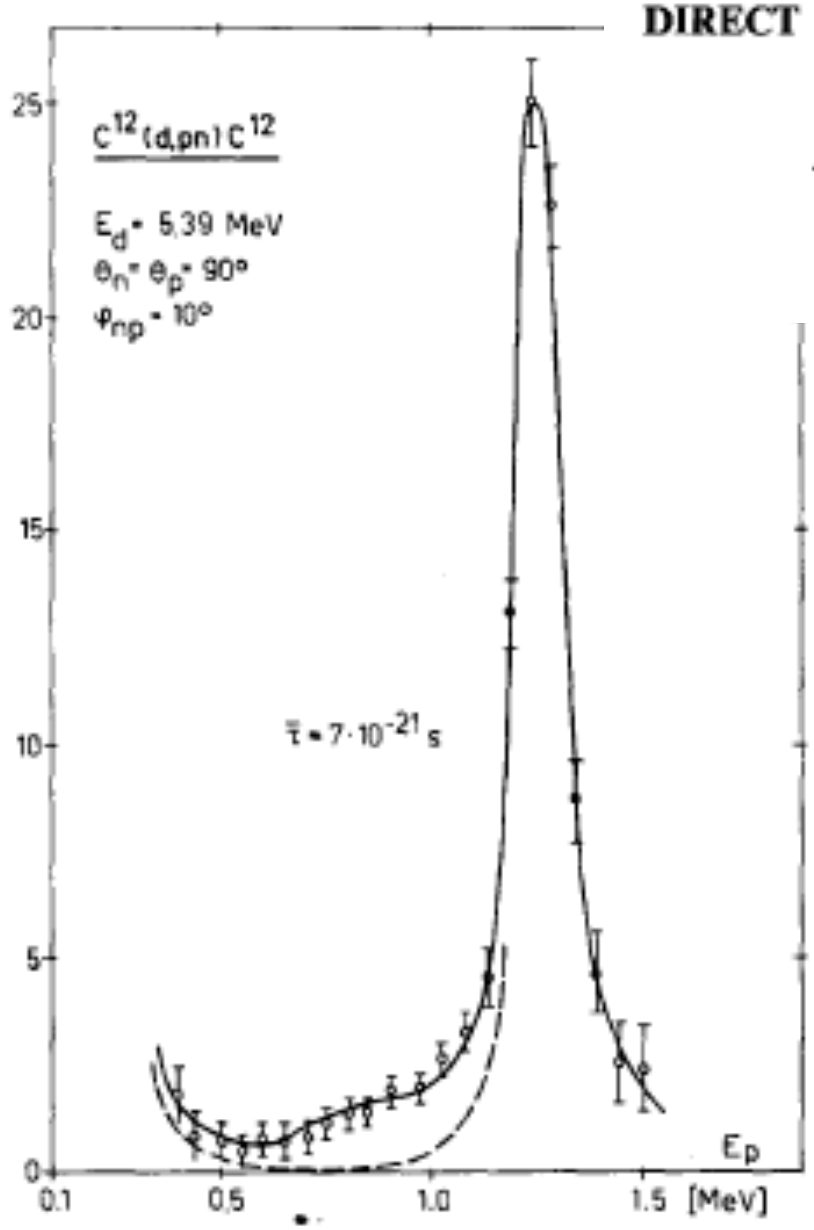
Vs





- Pion exchnage in photo-production is frame dependent
- Interesting phenomena: eg. elementary vs Regge pole, role of absorption, cuts, conspiracy between pion and nucleon poles etc.
- Photo-production is the “cleanest” probe of OPE. How does OPE at high energy compares to OPE in at low energies, or heavy quark EFT’s ?

Need to understand Production !

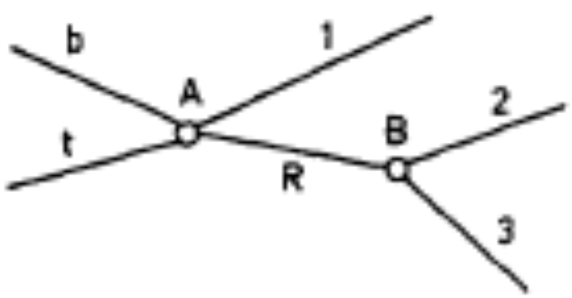


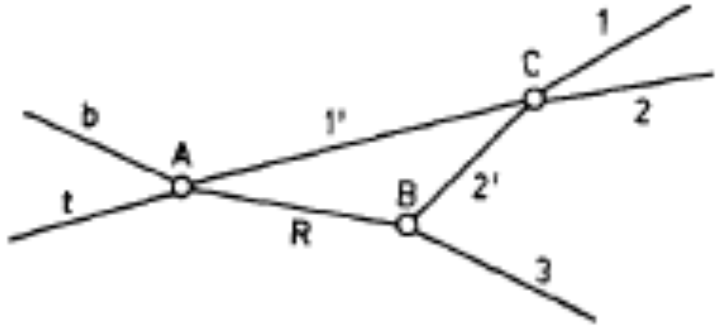
DIRECT DETERMINATION OF A SHORT NUCLEAR LIFETIME ($\approx 10^{-20}$ s) BY THE PROXIMITY SCATTERING METHOD

J. LANG, R. MÜLLER, W. WÖLFLI, R. BÖSCH and P. MARMIER
Laboratorium für Kernphysik, Eidg. Techn. Hochschule, Zürich †

Received 4 February 1966

$$b+t \rightarrow 1+2+3 \qquad [d+{}^{12}C \rightarrow n+p+{}^{12}C],$$



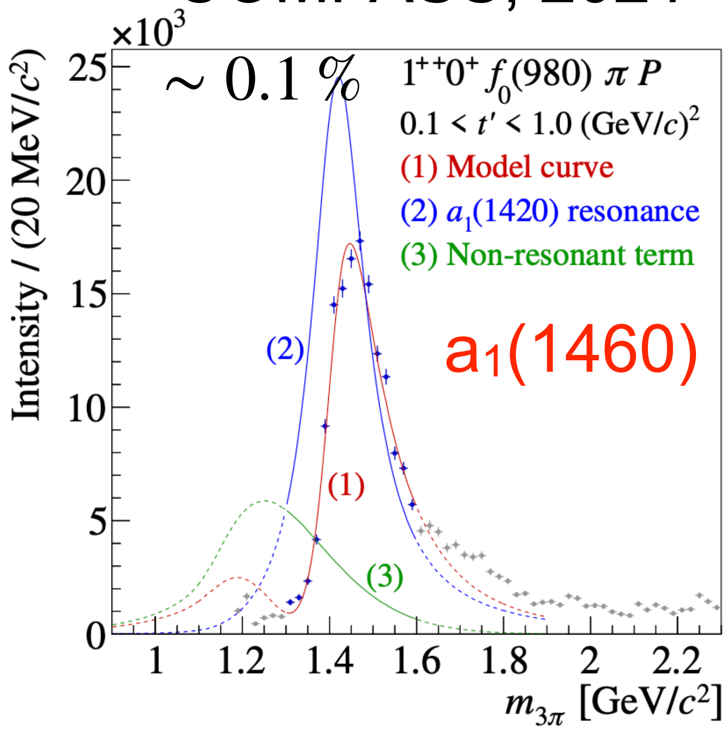


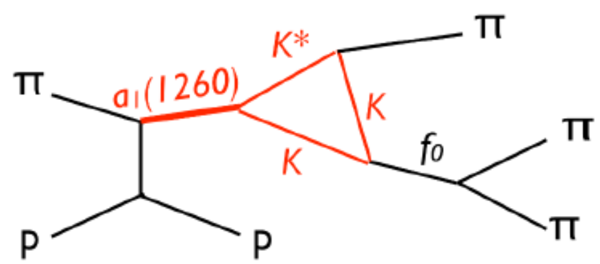
$$b+t \rightarrow 1+R, \quad \text{with } Q\text{-value } Q_1 \quad [d+{}^{12}C \rightarrow n+{}^{13}N^*, \quad Q_1 = -3.82 \text{ MeV}],$$

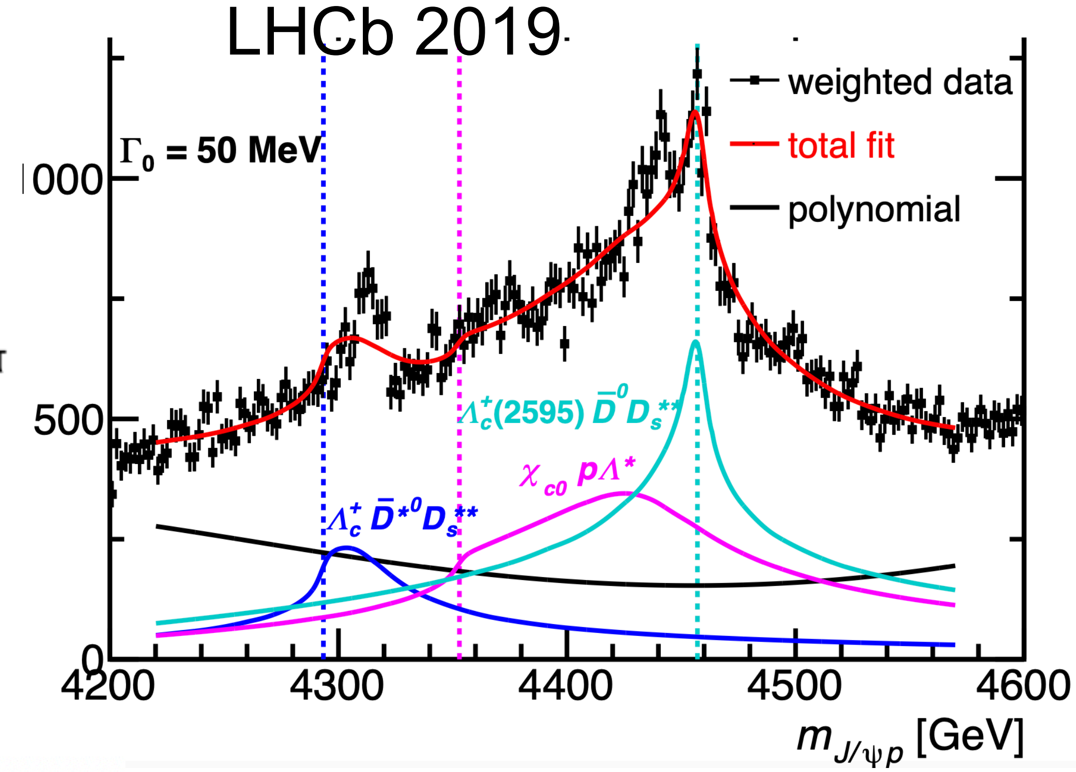
$$R \rightarrow 2+3 \quad \text{with } Q\text{-value } Q_2 \quad [{}^{13}N^* \rightarrow p+{}^{12}C, \quad Q_2 = 1.59 \text{ MeV}],$$

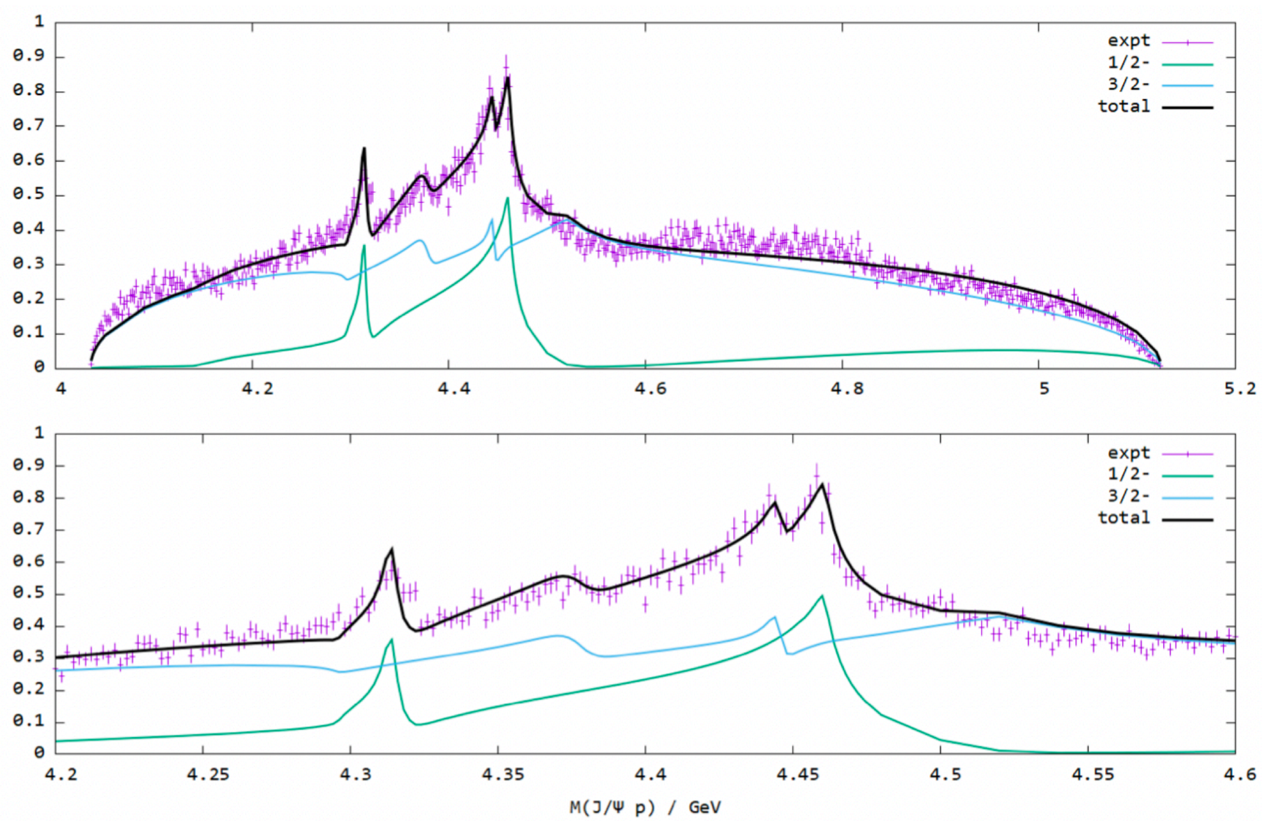
Triangles are everywhere

COMPASS, 2021





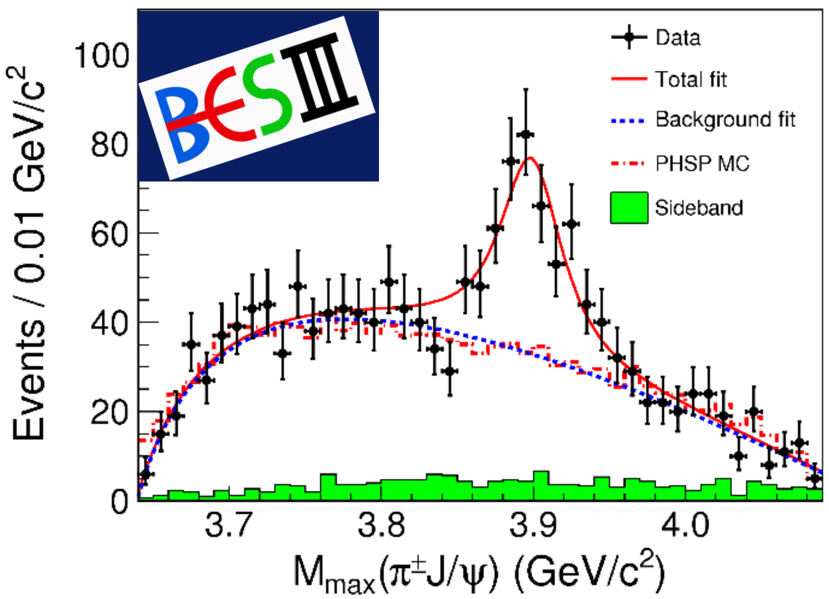




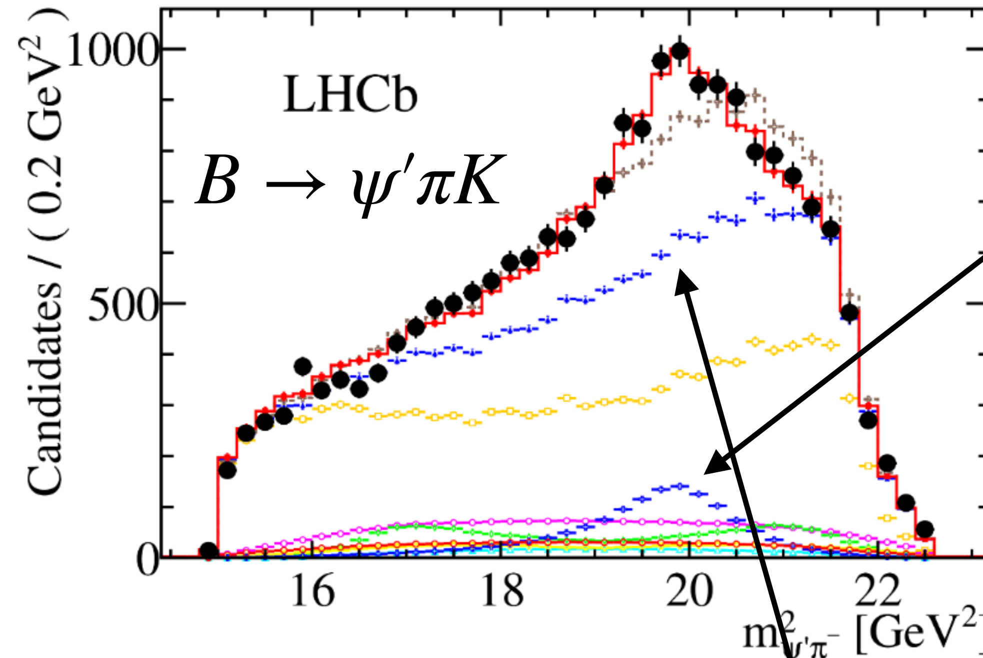
Burns, Swanson

Kinematic reflections

Are the Z's true resonances or kinematic effects

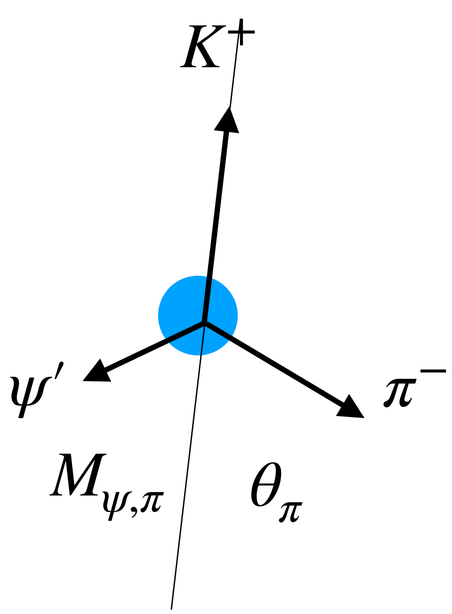


$e^+e^- \to Y \to J/\psi\pi^+\pi^-$



Z(4430)

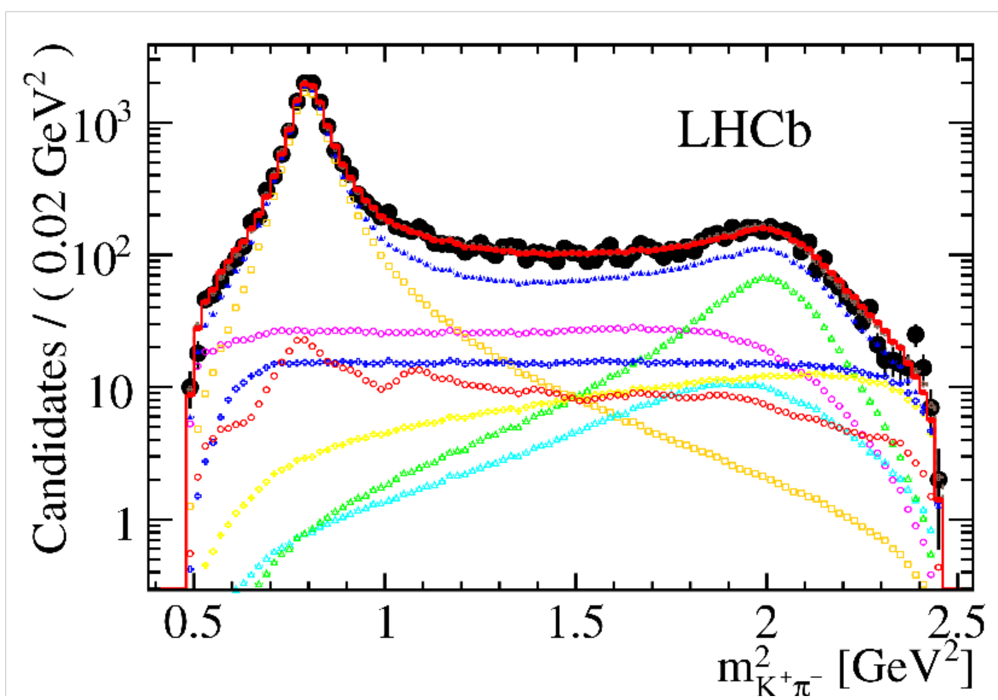
Kinematic effects from K* decays ?



$$B \to \psi'\pi^-K^+$$

$$\nearrow K^{*0}\psi' \to \pi^-K^+\psi'$$

$$\searrow Z^-K^+ \to \psi'\pi^-K^+$$



Understanding production cont.

$XYZP$ 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

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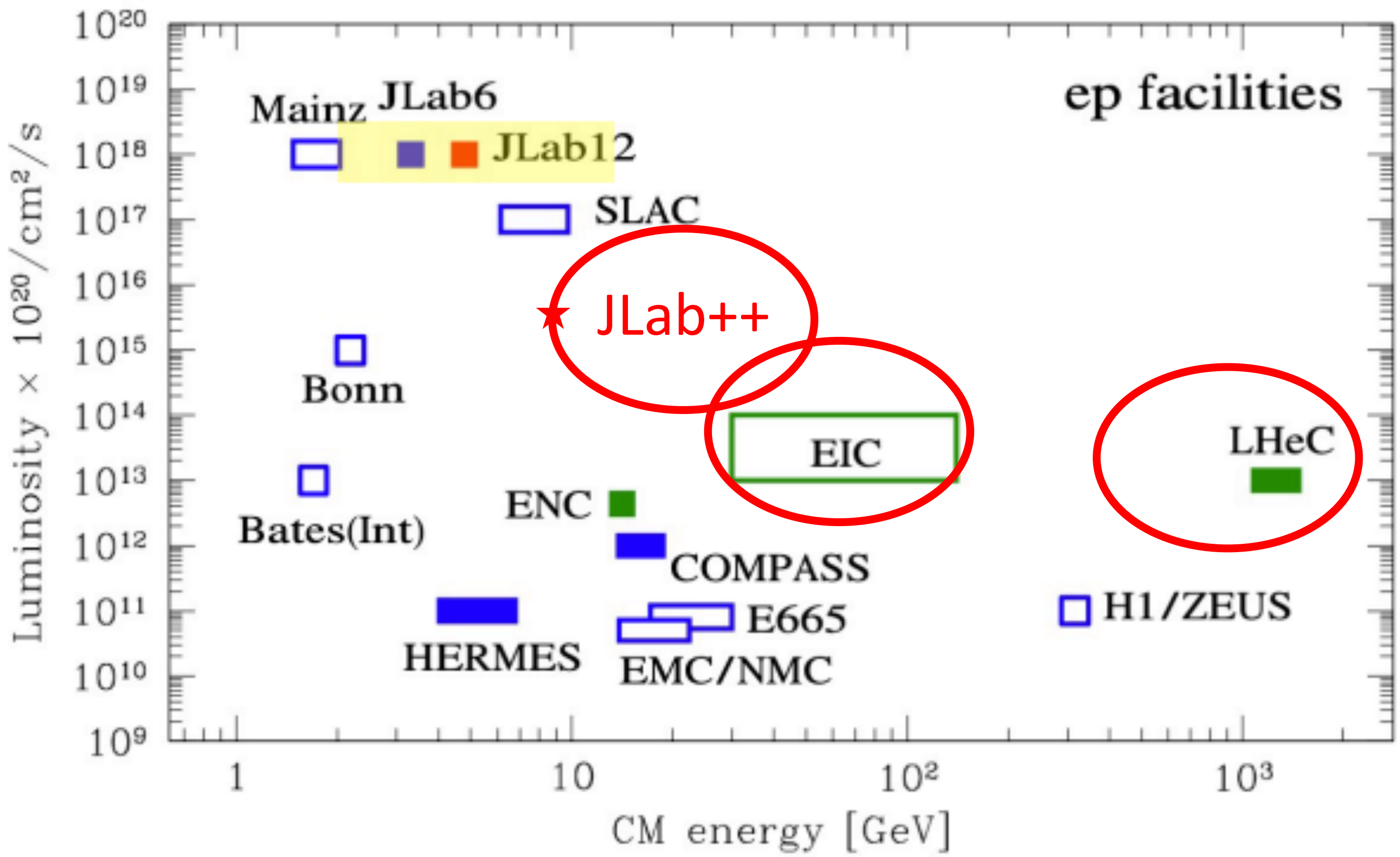
Astrid N. Hiller Blin[6], Vincent Mathieu[7,8], Alessandro Pilloni[9,10], Justin Stevens[11],
Adam P. Szczepaniak[12,13,14], and Daniel Winney[13,14,15,16]

arXiv:2112.00060

Physics with CEBAF at 12 GeV and Future Opportunities

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

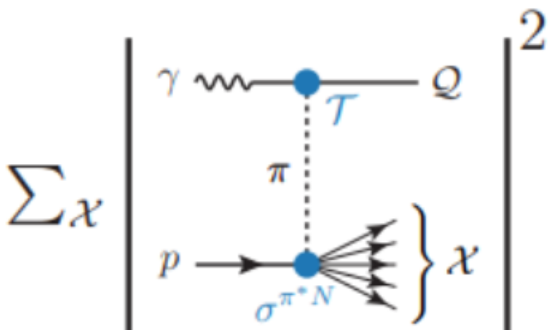


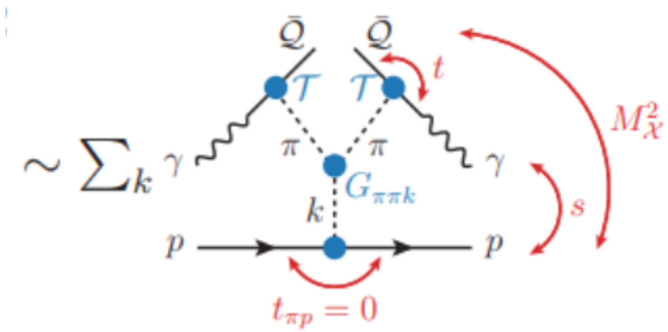
EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production

Spectroscopy at the future facilities

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

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





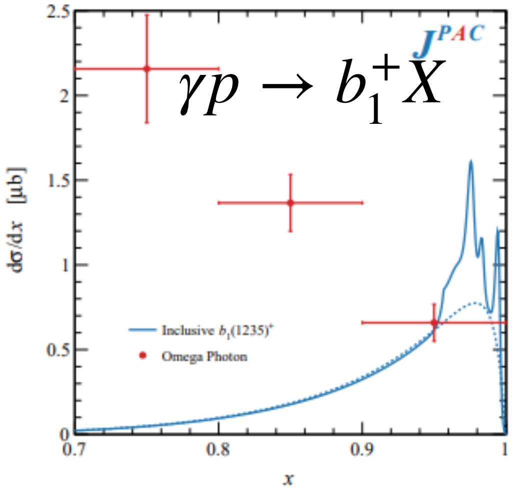
	17 GeV		24 GeV	
	produced	detected	produced	detected
$Z_c(3900)^+$	2.2 k	371	4.2 k	588
$X(3872)$	1.1 k	32	4.2 k	63

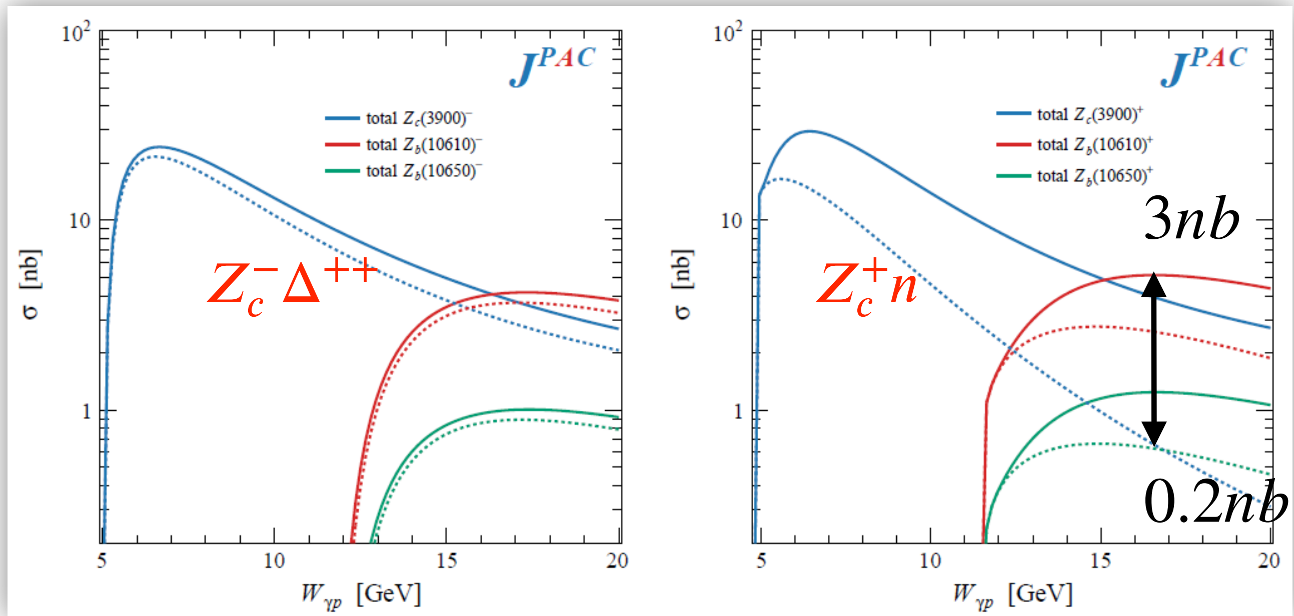
TABLE I. Estimates of yields for day of data taking at CLAS24 assuming a zero-angle electron detector

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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

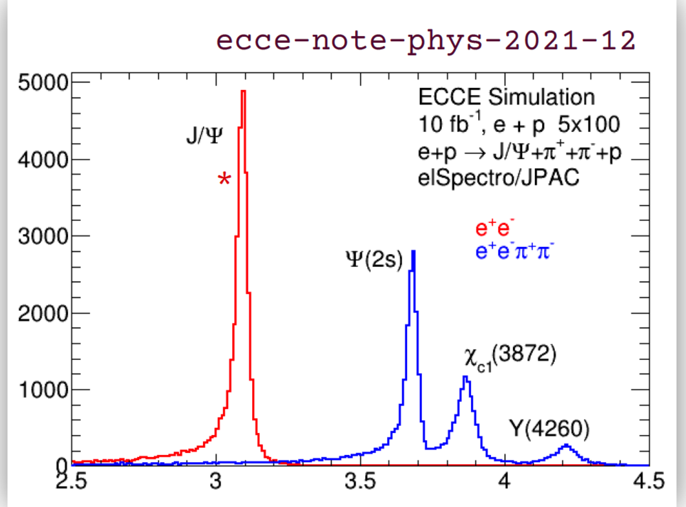
Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\, \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\, \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\, \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\, J/\Psi$	100	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



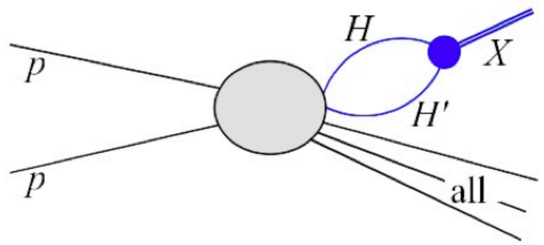


https://github.com/dwinney/jpacPhoto



• Production at EIC

Artoisenet, Braaten, PRD83(2011)014019; FKG, Meißner, W. Wang, Z. Yang, EPJC74(2014)3063



$\sigma(pp/\bar{p} \to X)$ [nb]	Exp.	Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

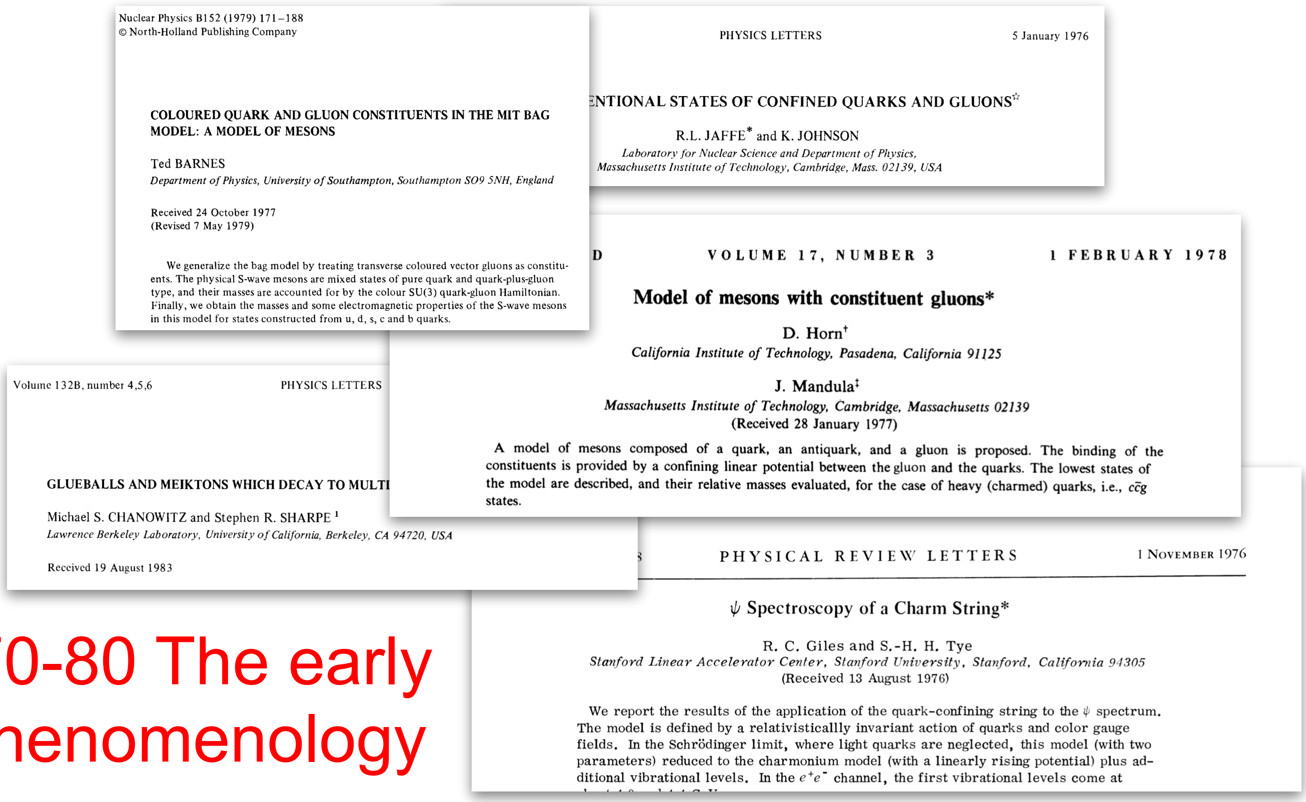
Albaladejo, FKG, Hanhart et al., CPC41(2017)121001

- Order-of-magnitude estimates of the semi-inclusive electro-production of hidden/double-charm hadronic molecules (in units of pb)

	Constituents	$I, J^{P(C)}$	EicC	EIC
$X(3872)$	$D\bar{D}^*$	$0, 1^{++}$	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	$1, 1^{+-}$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	$1/2, 1^+$	19(69)	250(900)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2, 1/2^-$	0.8(4.1)	15(73)
$P_{cs}(4338)$	$\Xi_c\bar{D}$	$0, 1/2^-$	0.1(1.6)	1.8 (30)
Predicted	$\Lambda_c\bar{\Lambda}_c$	$0, 0^{-+}$	0.3 (3.0)	10 (110)
Predicted	$\Lambda_c\bar{\Sigma}_c$	$1, 0^-$	0.01 (0.12)	0.5 (5.5)
T_{cc}^+	DD^*	$0, 1^+$	0.3×10^{-3} (1.2×10^{-3})	0.1 (0.5)

F-K Guo @ EIC Workshop

Brief history of exotics (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

…NTIONAL 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

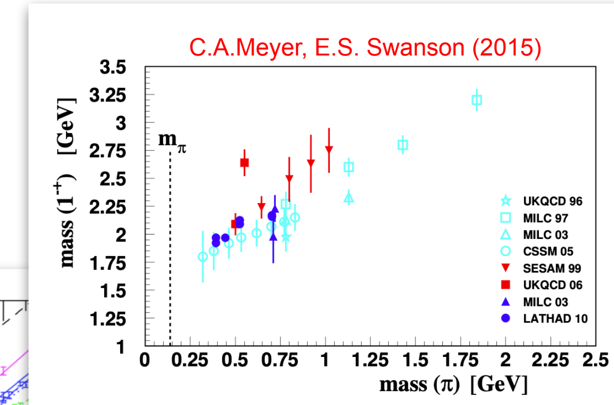
ψ Spectroscopy of a Charm String*

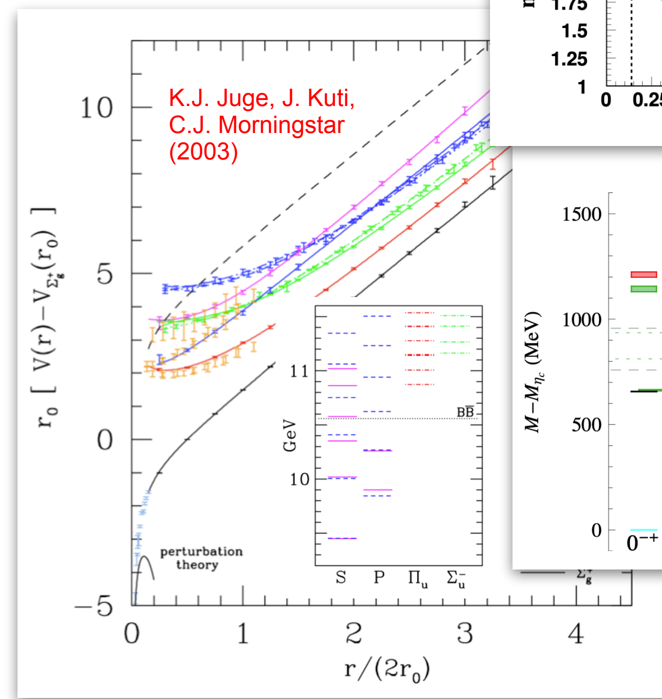
R. C. Giles and S.-H. H. Tye
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 13 August 1976)

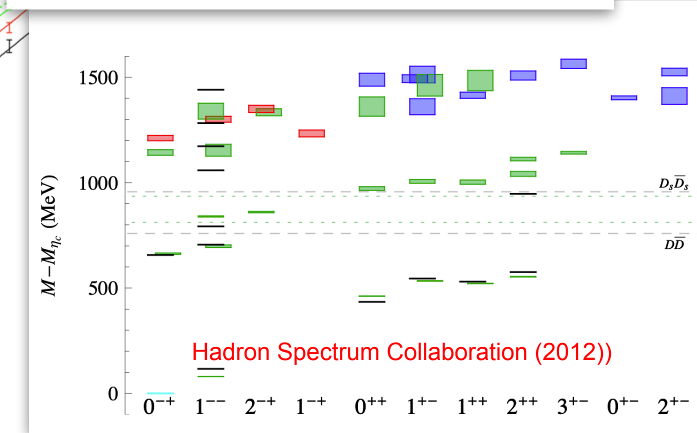
We report the results of the application of the quark-confining string to the ψ spectrum. The model is defined by a relativisticallly invariant action of quarks and color gauge fields. In the Schrödinger limit, where light quarks are neglected, this model (with two parameters) reduced to the charmonium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

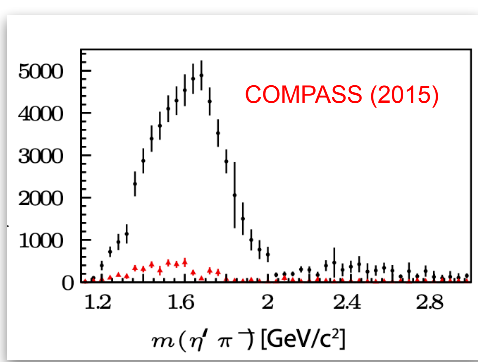
- ’70-80 The early phenomenology

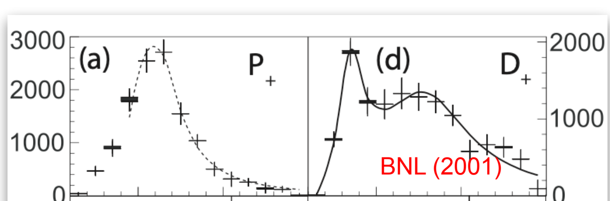
- ’00-10 The early lattice studies

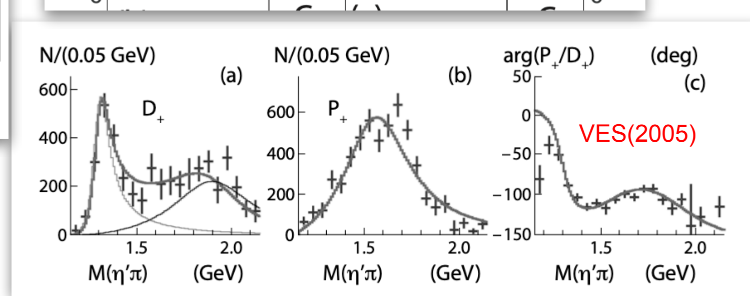






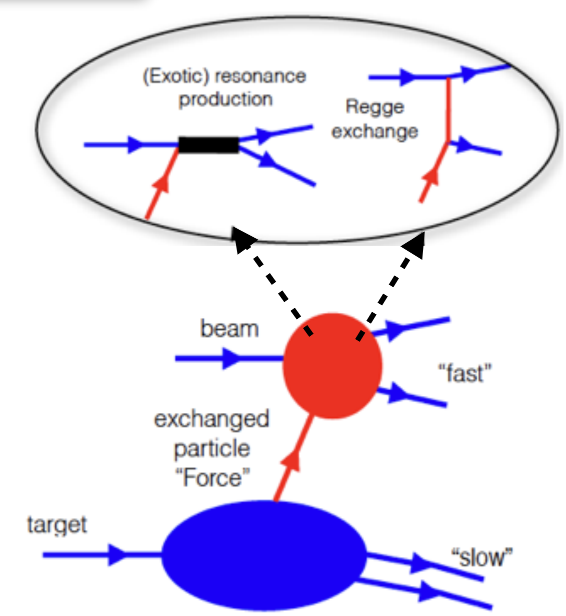






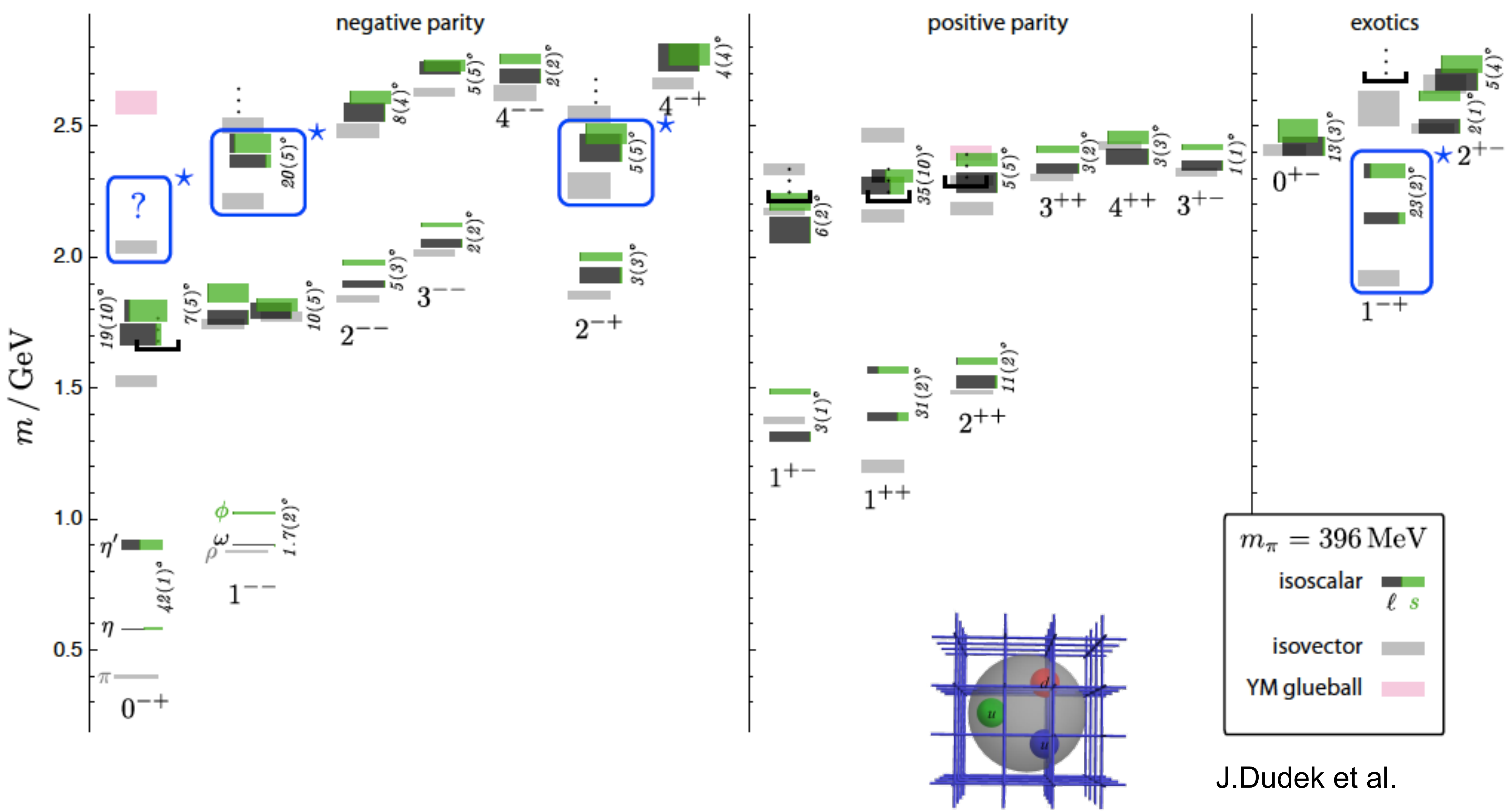
- ’00-10 The early data

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



"Evidence" for Constituent Quarks:Light Quark Hadrons

Spectrum of mesons containing u,d,s quarks from numerical QCD simulations (lattice) resembles spectrum of quark models.



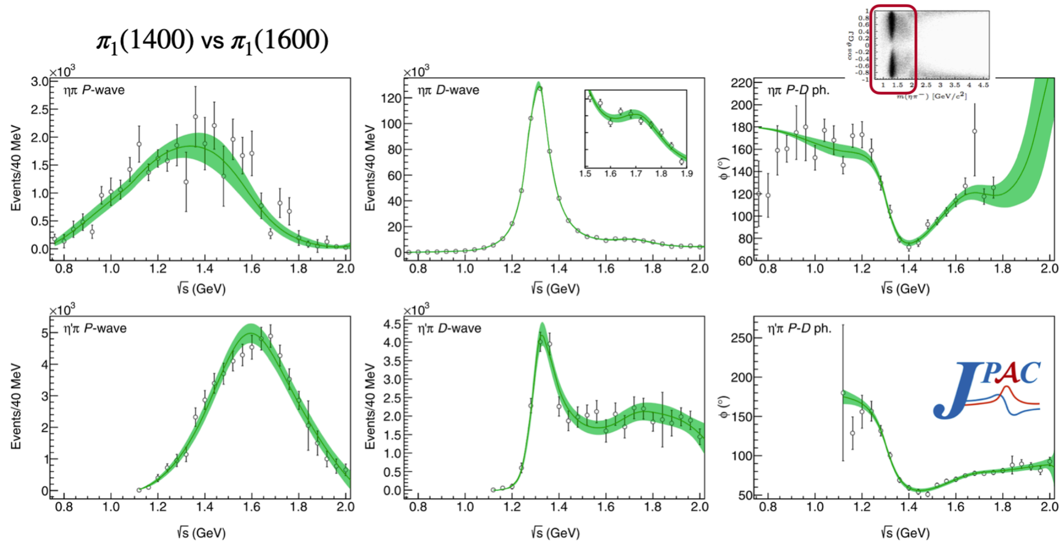
J.Dudek et al.

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

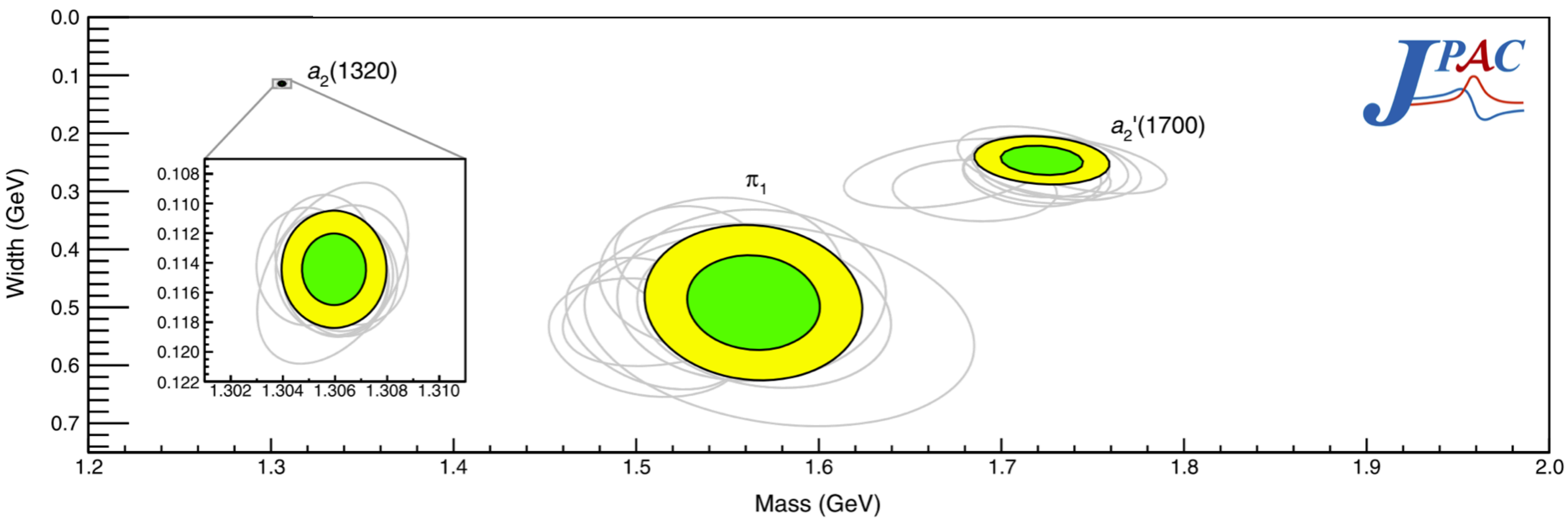
$J^{PC} = 1^{-+}$ Outside valance quark model

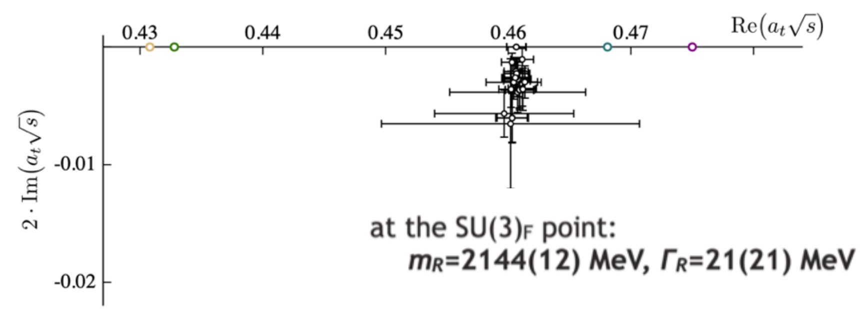
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

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



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





at the SU(3)$_F$ point:
m_R=2144(12) MeV, Γ_R=21(21) MeV

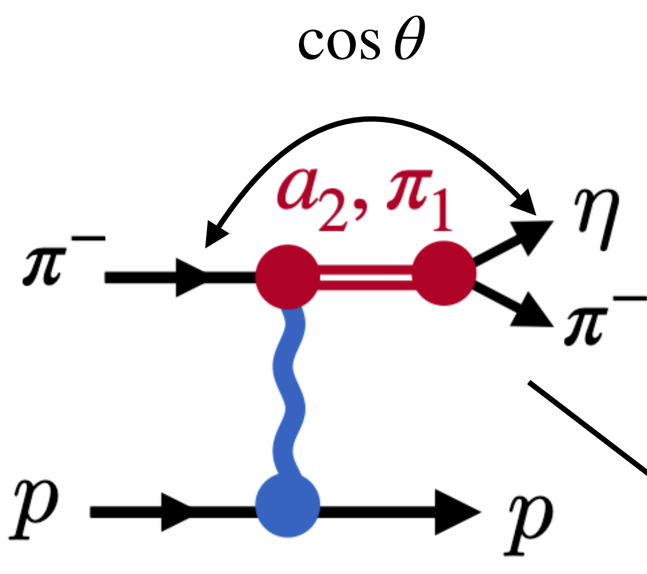
A.Woss et al. PRD 103 (2021) 5, 054502

generates for a π_1 at 1564 MeV:

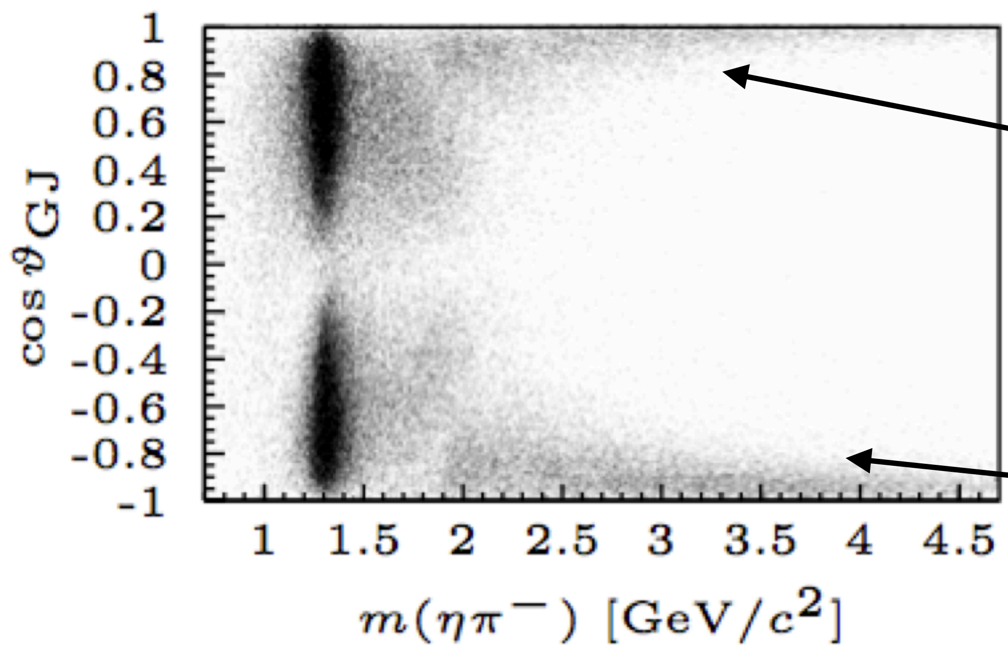
Γ_{TOT} ~ 140-600 MeV

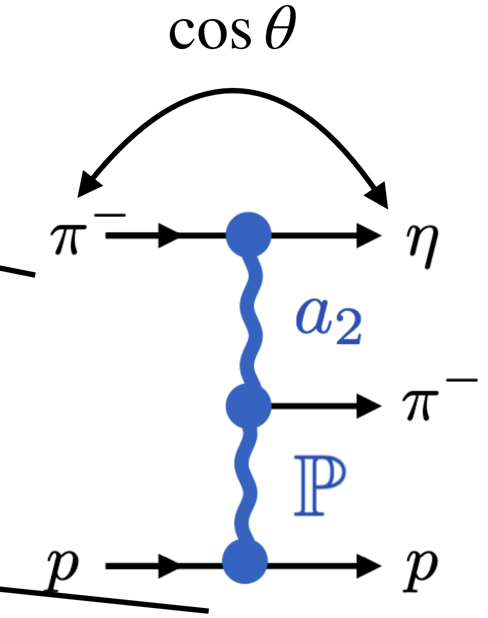
$\Gamma(\pi\eta) \lesssim 1$ MeV
$\Gamma(\pi\eta') \lesssim 20$ MeV
$\Gamma(\pi\rho) \lesssim 12$ MeV
$\Gamma(\pi b_1)$ ~ 140-530 MeV

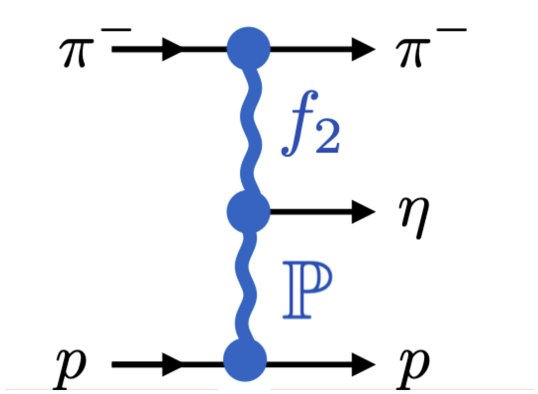
To Resonance or not to Resonate



- Amplitude is analytical in $\cos(\theta)$ when $s_{\eta\pi}$ near a resonance

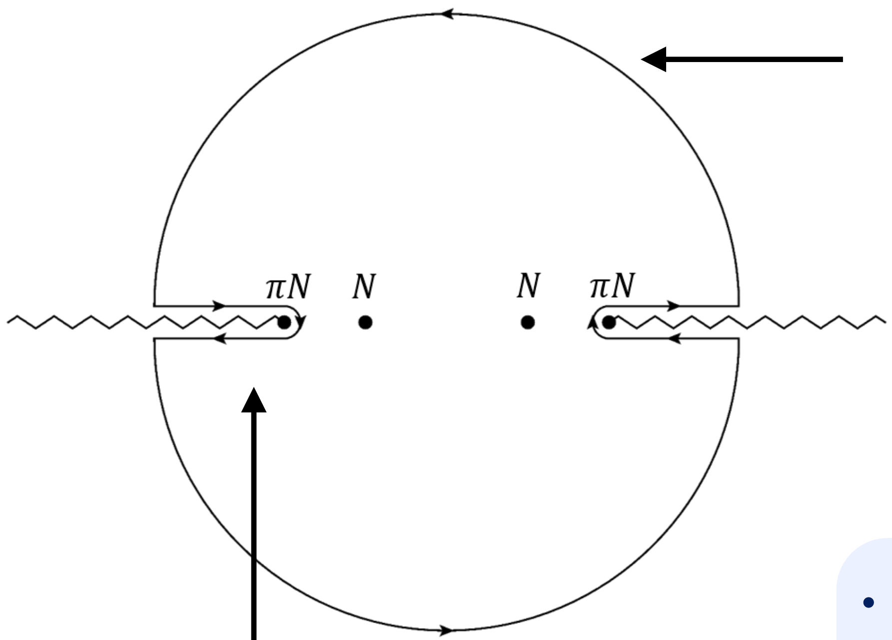


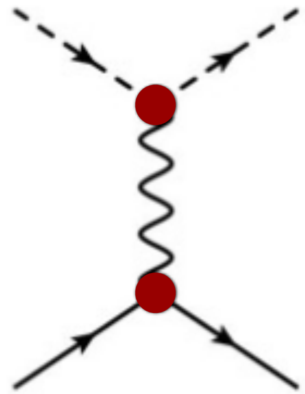


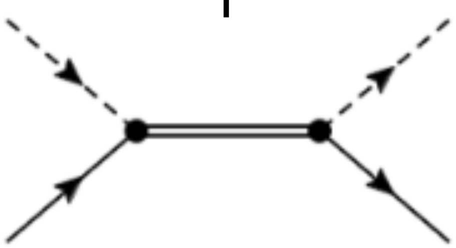


- Singularities of $\cos(\theta)$ exposed for large $s_{\eta\pi}$

Finite Energy Sum Rules





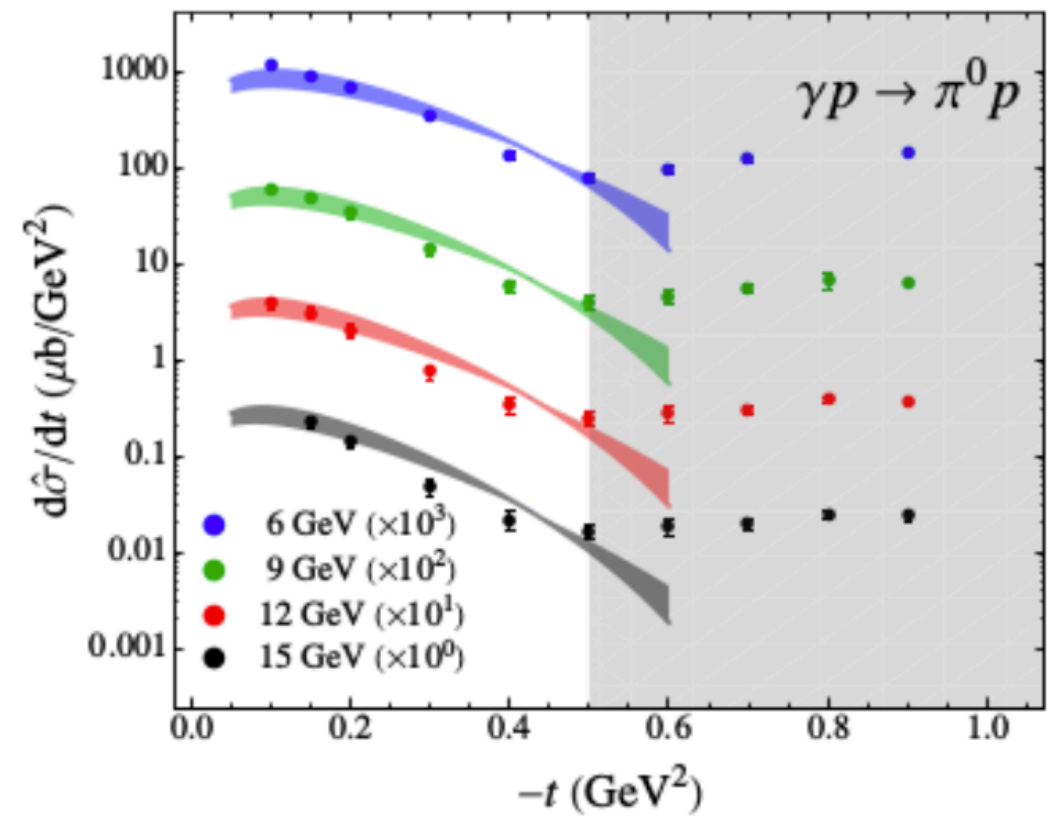


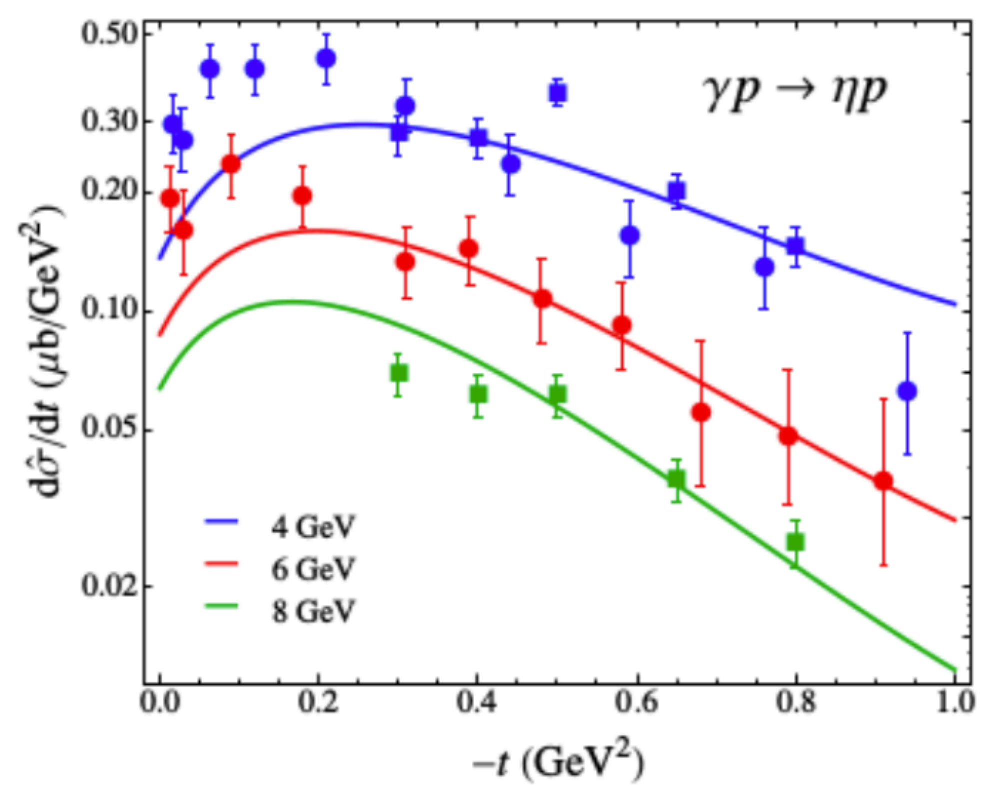
- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

$$A_{\lambda';\lambda\lambda_\gamma}(s,t) = \overline{u}_{\lambda'}(p')\left(\sum_{k=1}^{4} A_k(s,t)M_k\right)u_\lambda(p)$$

$$\int_0^\Lambda \text{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

$$\beta_i(t) = \frac{\alpha(t)+k}{\Lambda^{\alpha(t)+k}}\int_0^\Lambda \text{Im}\ A_i(\nu,t)\nu^k d\nu$$

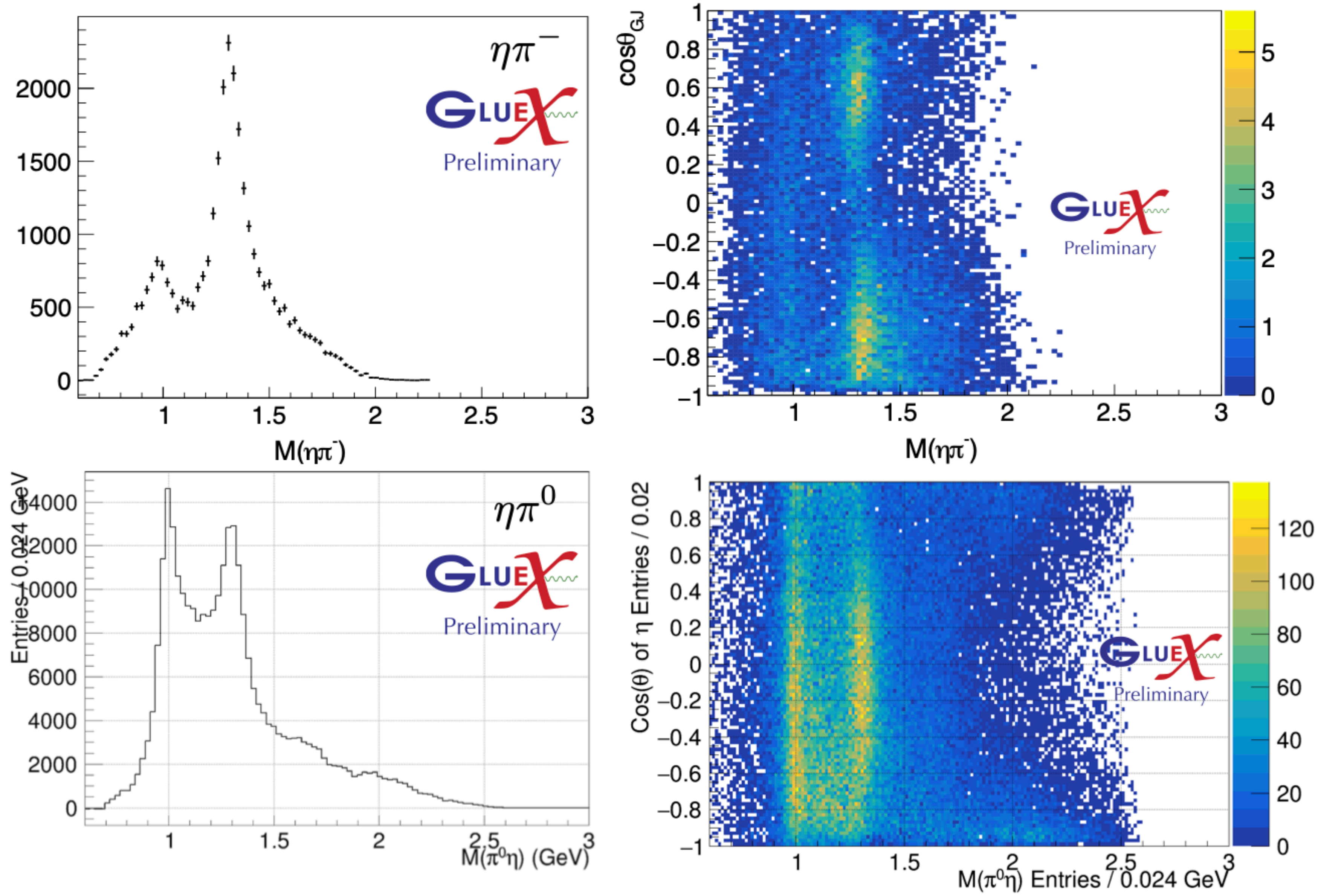




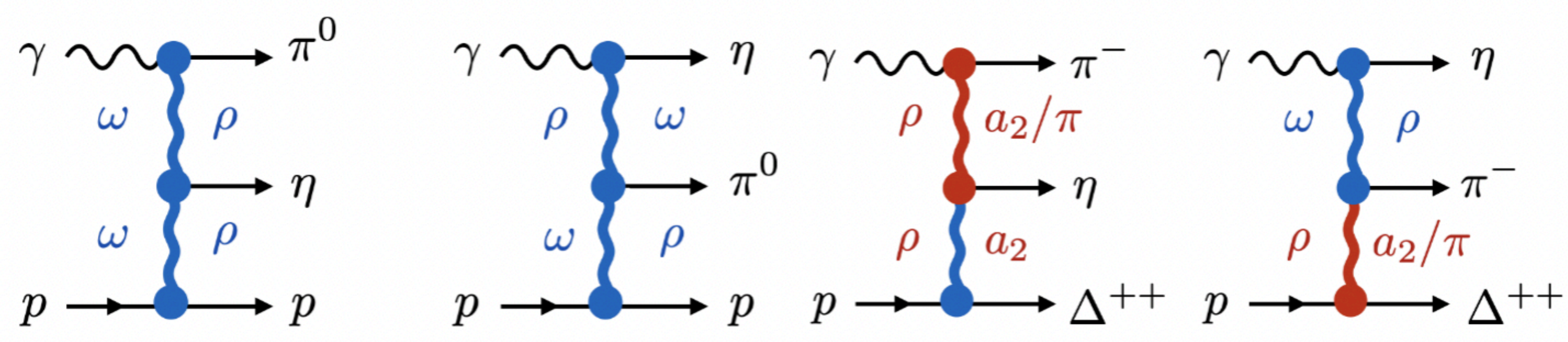
Production of $a_2(1320)^{-,0}$ and $a_0(980)^{-,0}$ at low t

M. R. Shepherd
INT Workshop
March 23, 2023

$0.1 < -t < 0.3$ GeV^2



Double-regge exchange



- Dispersion relations (FESR's) for 2-to-3 more versatile then in 2-to-2 processes (multiple variables to consider)

- Can the middle vertex be tested : (how does QCD affect helicity dependence) ?

- Theory and applications are sparse

De Tarr et al. (), Hoyer, Schimada et al, Bibrzycki at al (JPAC) (..

What's in the future for JPAC/ExoHaD

- Next 5 y : Complete development of the tools and techniques necessary to extract physics results from the GlueX and CLAS experiments.

- Beyond 5y Develop a broad program of XYZP studies relevant to the current measurements at accelerators and the future electron-hadron facilities, including the EIC and the upgraded Jefferson Lab.

- All along Support the growth of the QCD spectroscopy community by investing in the education of next generations.