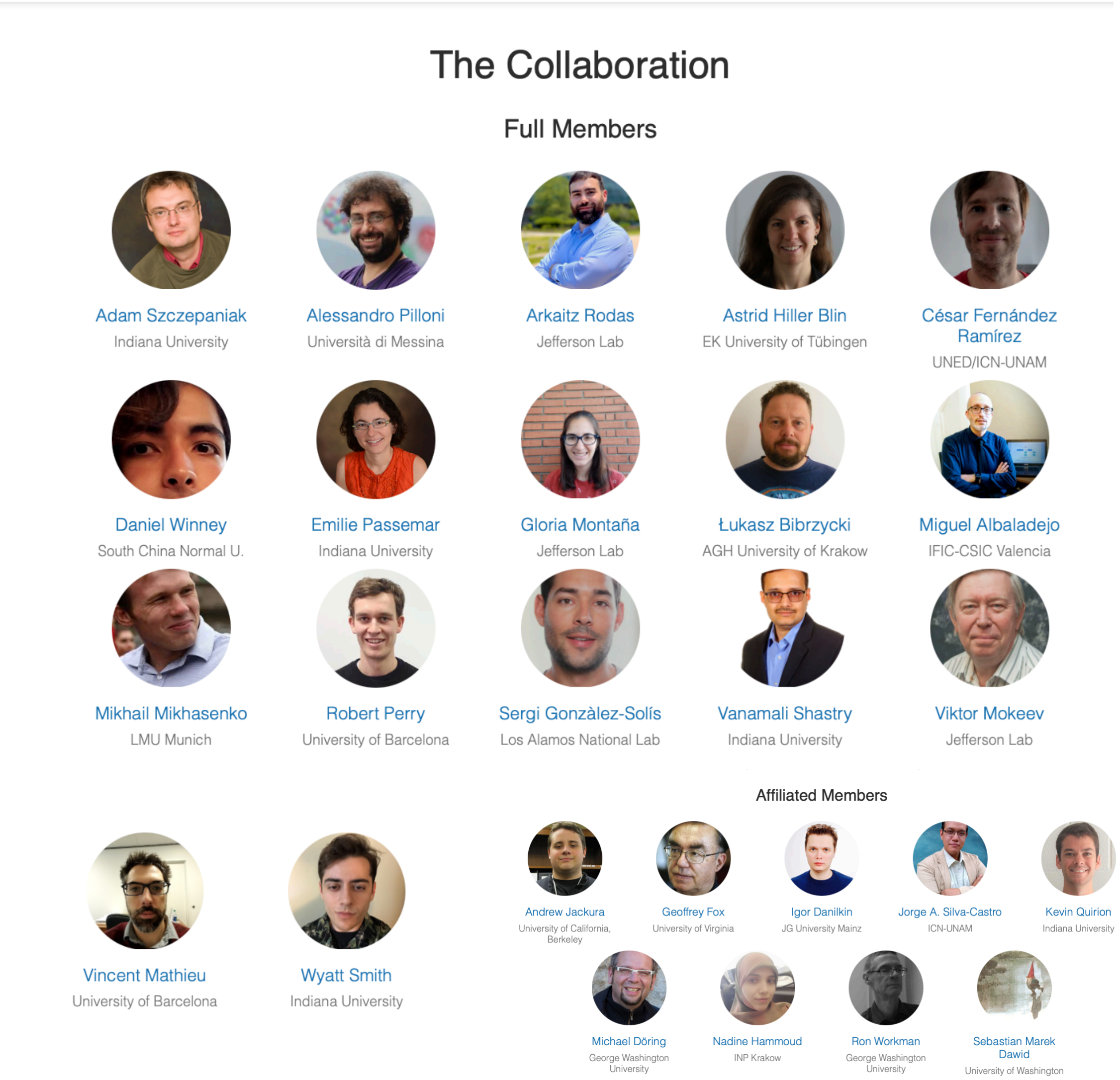
J/ψ and XYZP photo production

Adam Szczepaniak (IU/JLab)

- Quarkonium near threshold possibly relevant for extracting novel nucleon properties (mass radius, gravitational form factors, etc.)
- Signal channel also contains hidden-charm pentaquark candidates seen at LHCb.
- Abundance of new data coming from Jefferson Lab on energy and angular dependence of x-section.
- New window onto the nature of the XYZ states.

JPAC

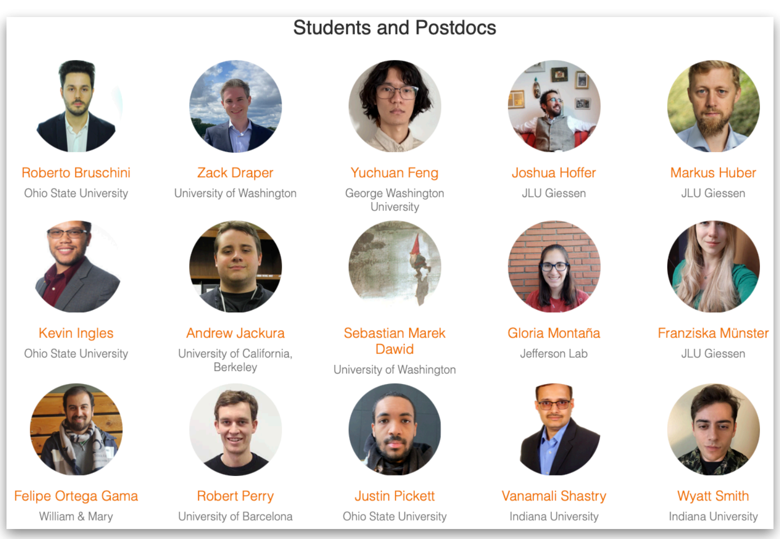
EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

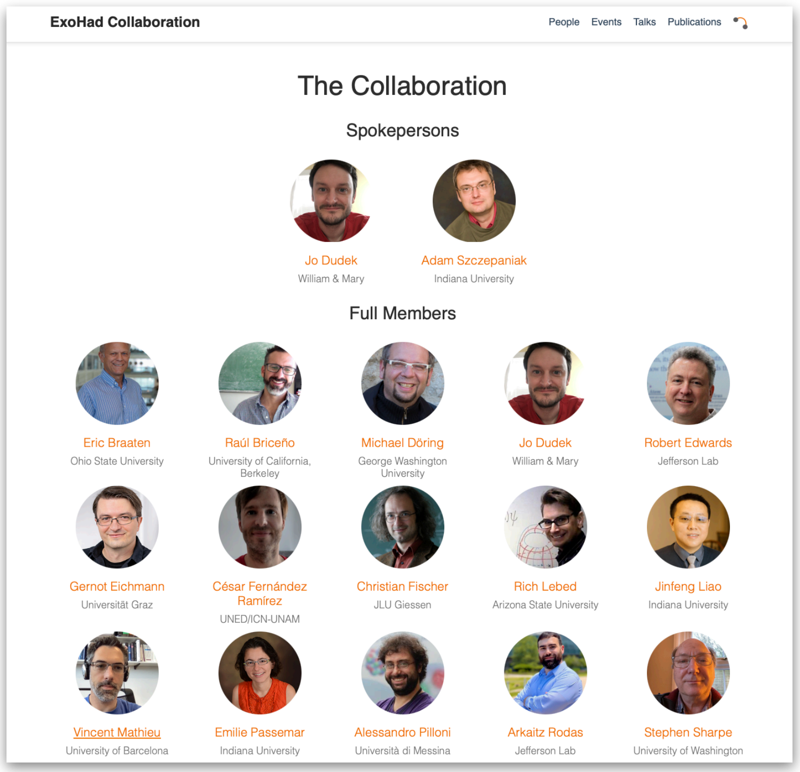


- Established in 2013 to develop theory and phenomenology in support of experimental program at JLab12.
- JPAC served as a liaison between many theoretical and experimental analysis efforts BaBar,BESIII,COMPASS,EIC, LHCb,JLab
- Over 40 researchers have been associated with JPAC.

- Focus on light exotic hybrids
  — predicting their properties from lattice QCD
  — extracting meson resonances from experimental data
  — interpreting both the experiment and theoretical results

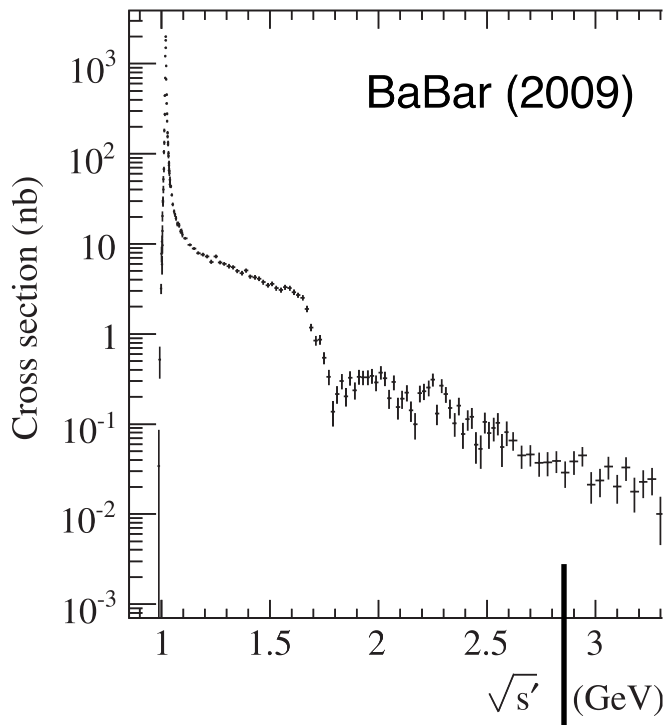
EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

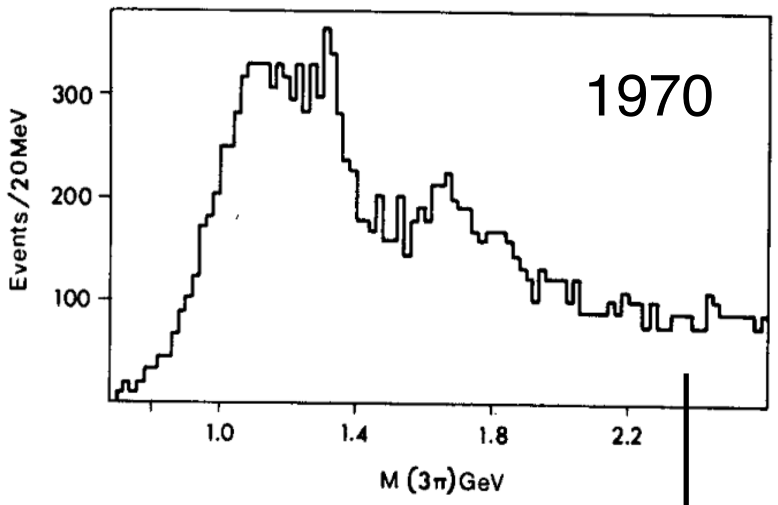


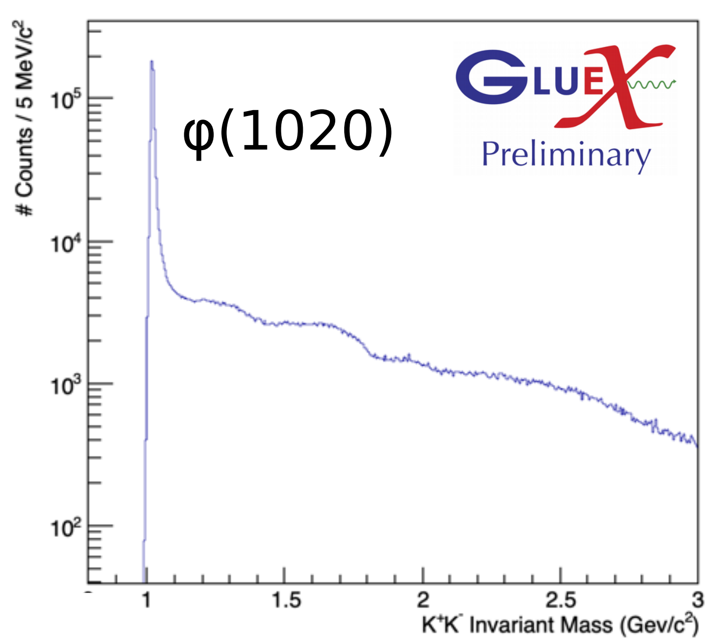


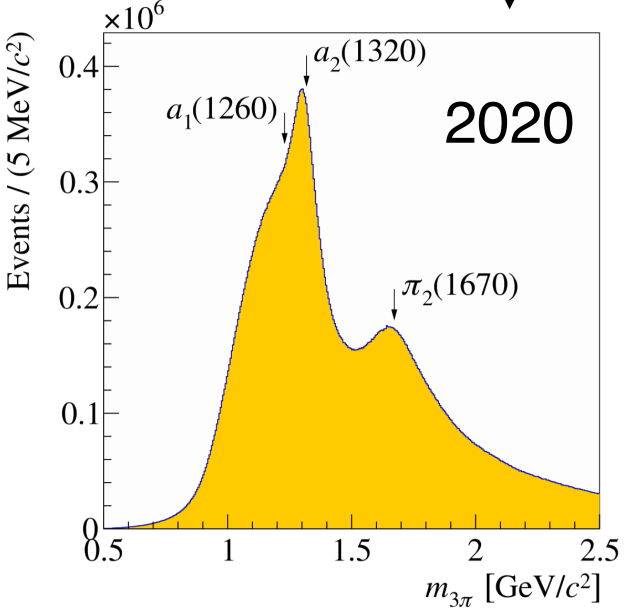
Exp and Theory are working together

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



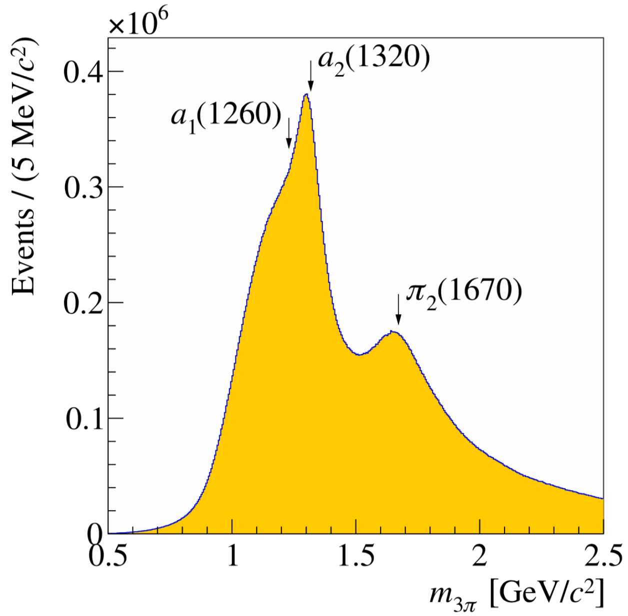




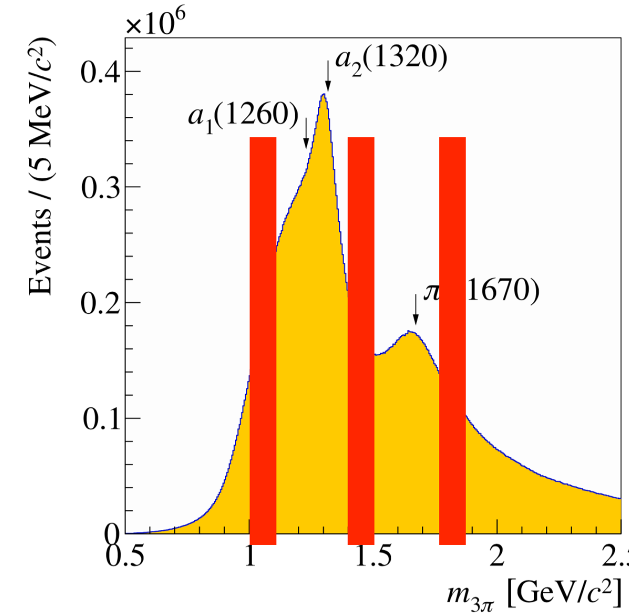


Similar spectra expected from CLAS12

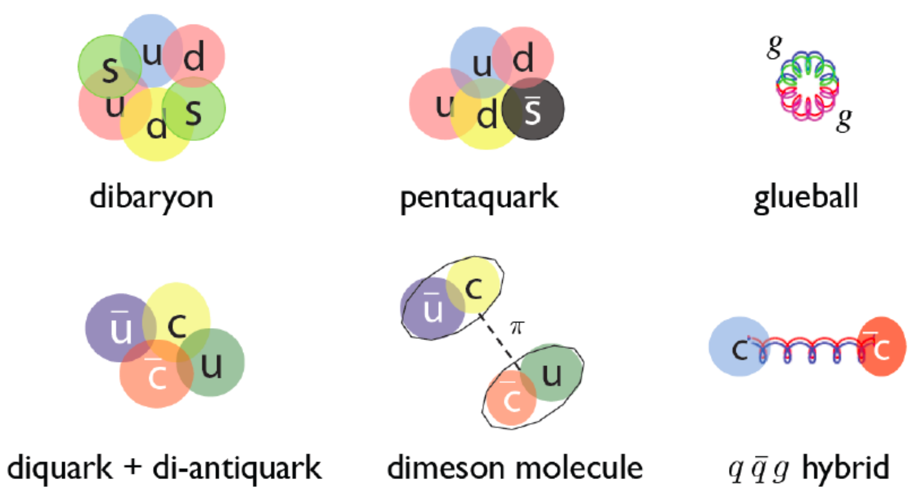
Model independent analysis

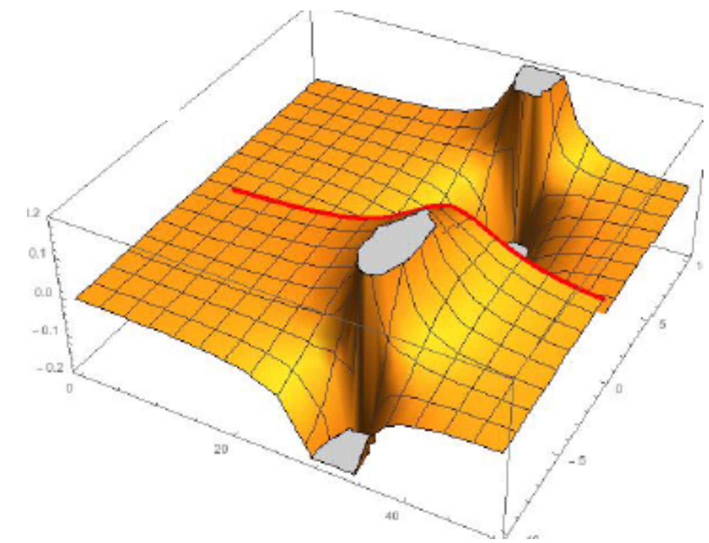


Nature: real axes



QCD

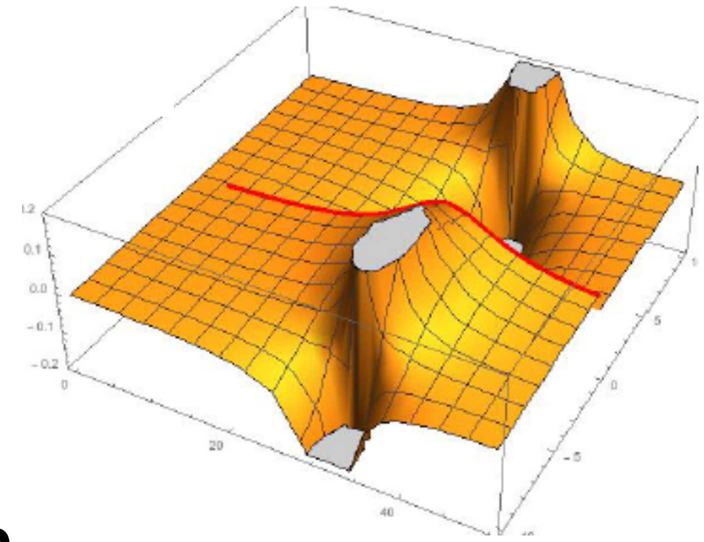




Models

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

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

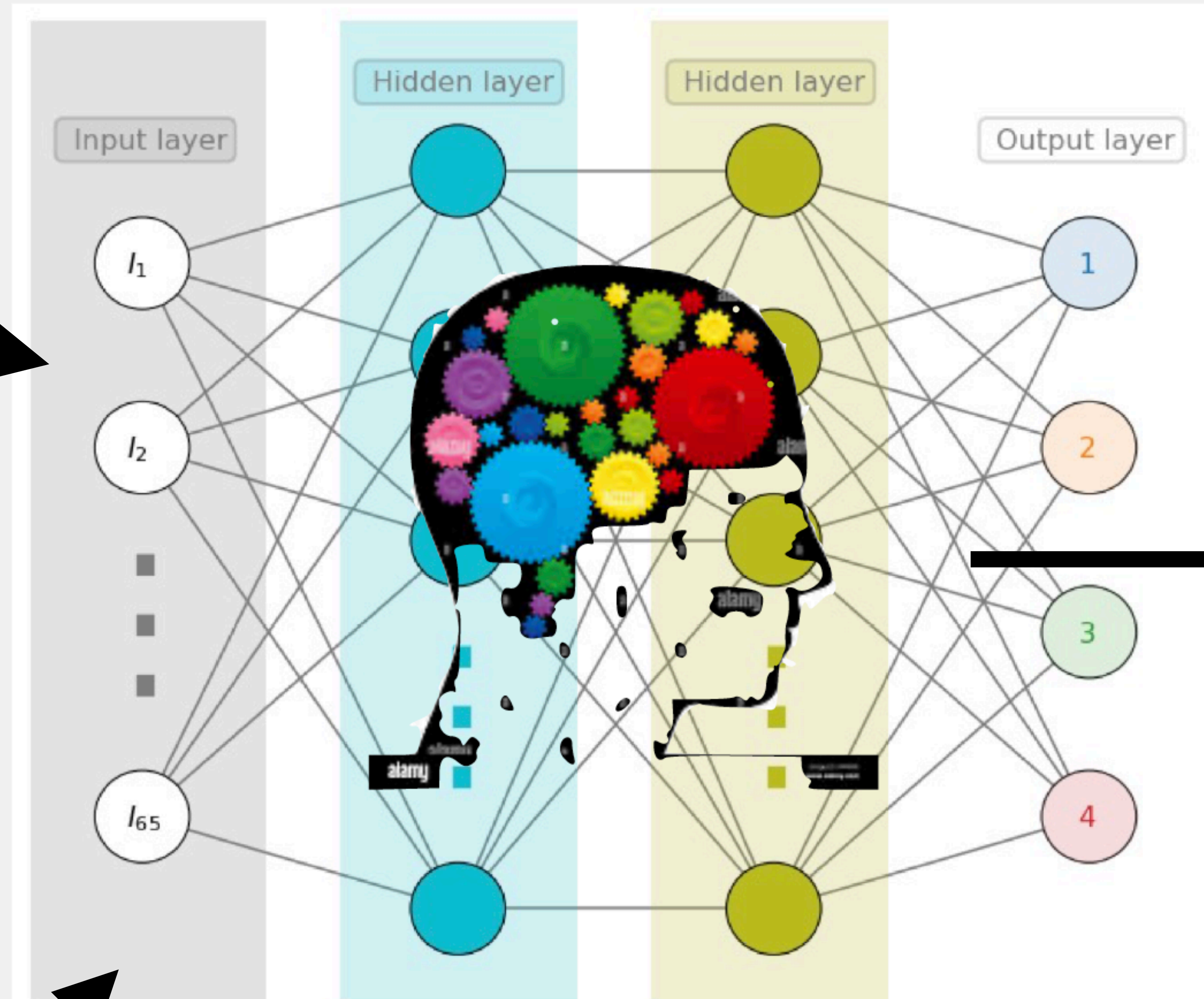
3. Physical sheet singularities are given by unitarity

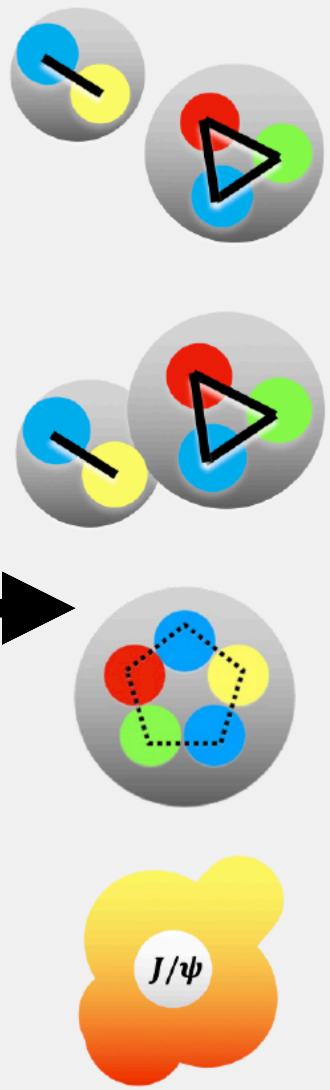
4. Unphysical sheet singularities need to be parametrized in order to test microscopic models

Holy Grail: AI as a tool for physics discovery

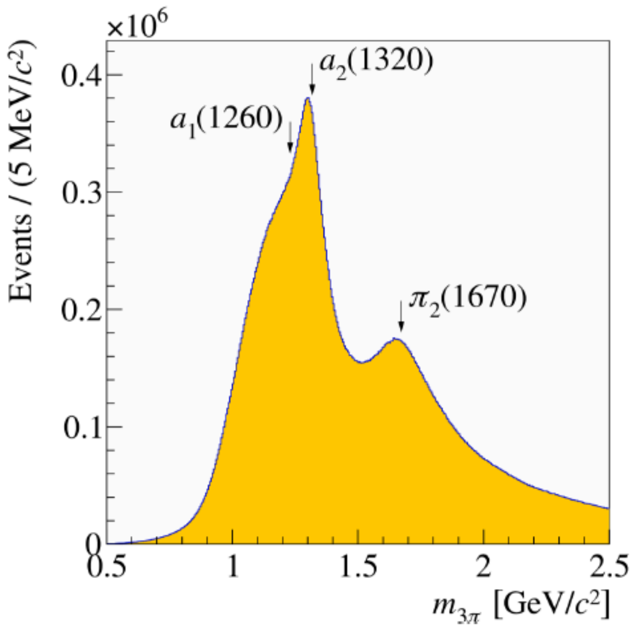
Learn (S-matrix)

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





Apply to data



Tell the story

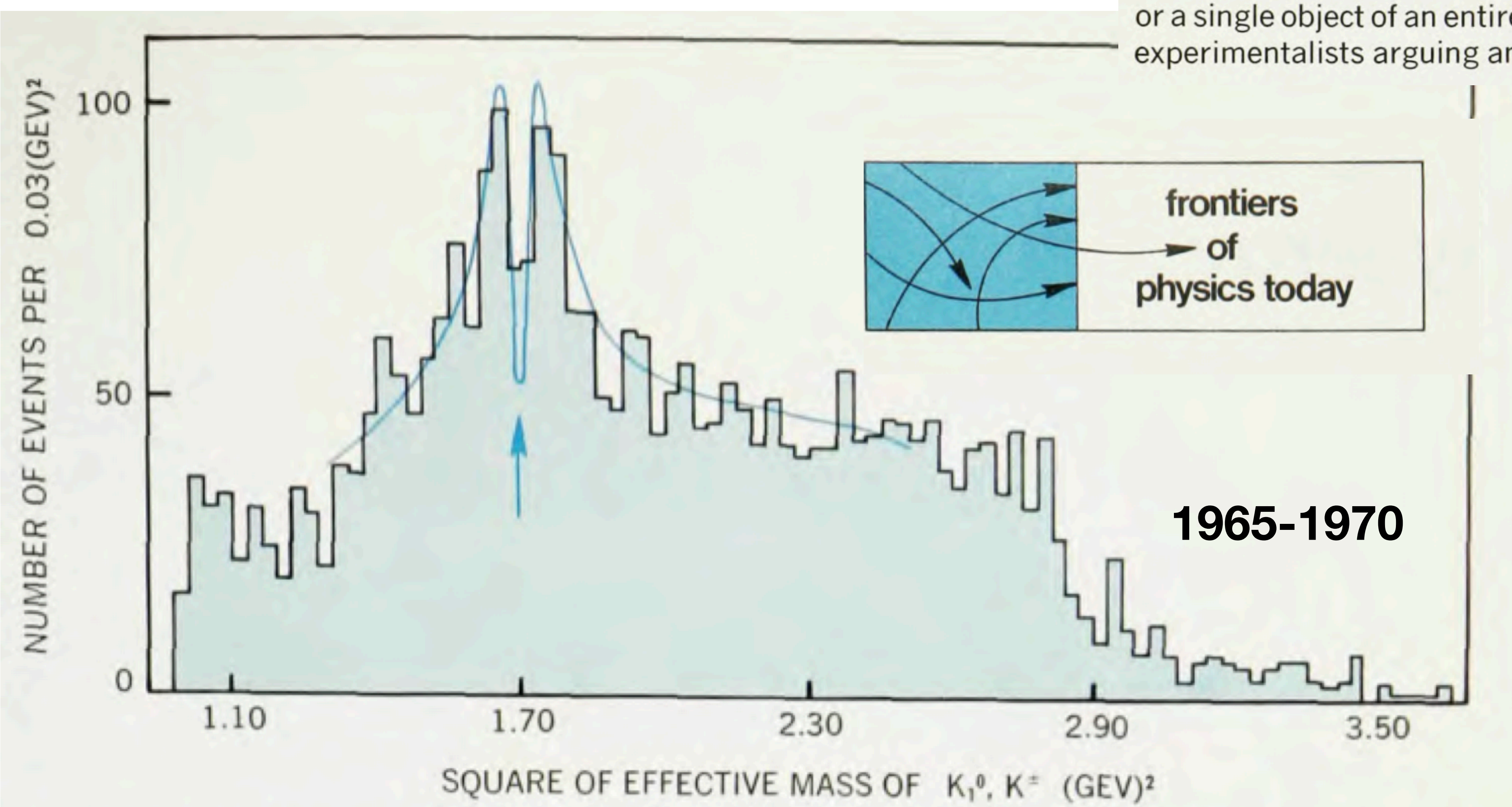
“Deep learning exotic hadrons” L.Ng et al. (JPAC) Phys.Rev.D 105 (2022) 9, L091501

Importance of high quality data : split a2

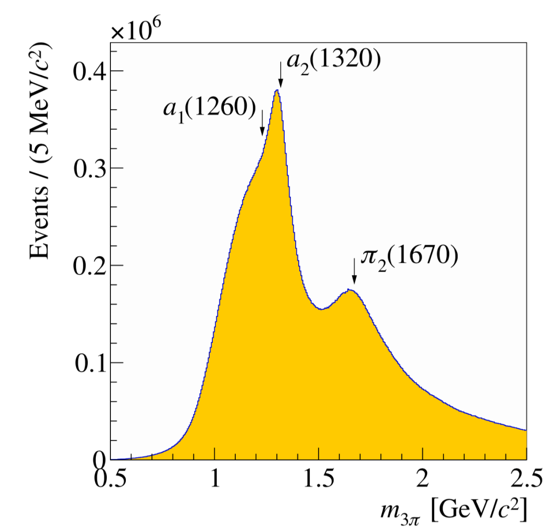
$$\pi^- + p \rightarrow X^- + p$$

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.

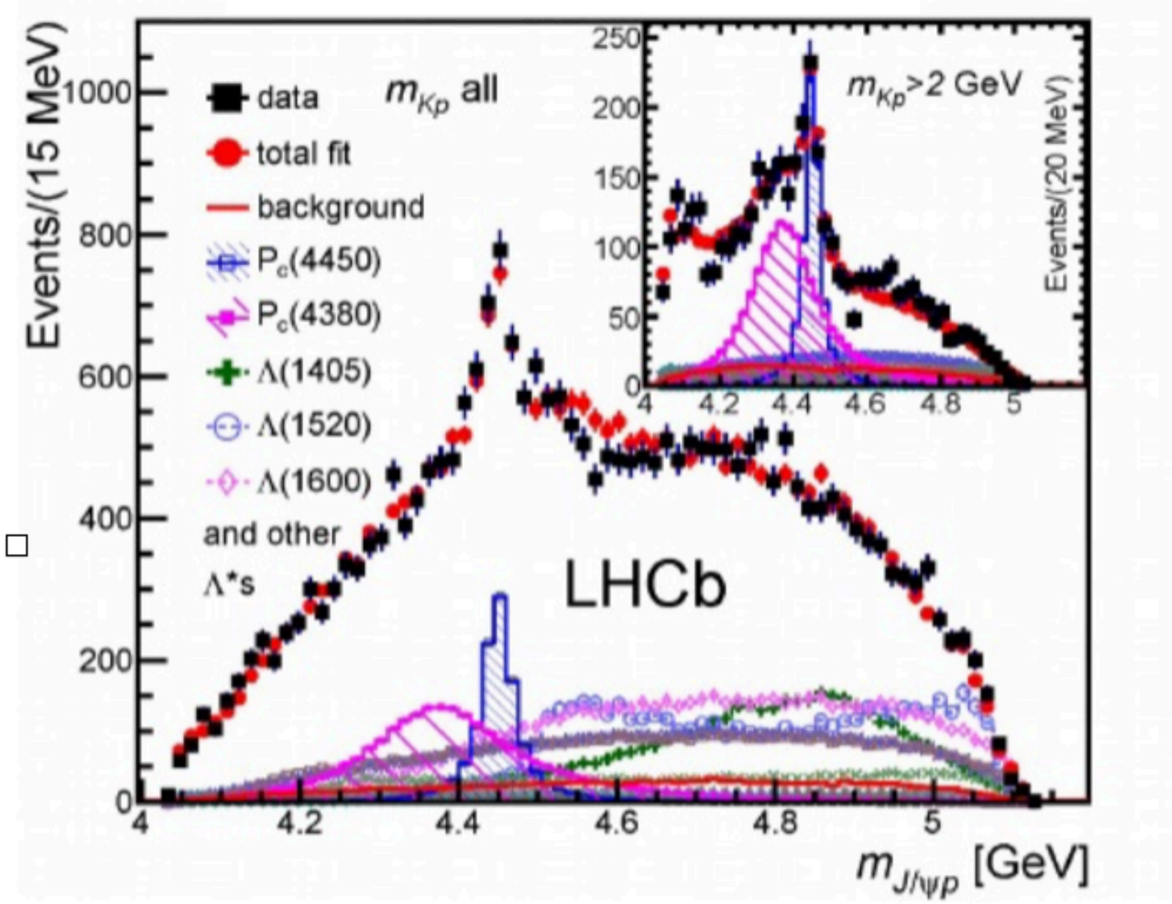


Proton–antiproton annihilation shows evidence for a split A2. The dip at the A2 (mass)², shown by the colored arrow, in the $K_1^0K^+$ effective mass spectrum indicates that the A2 splitting is independent of the production reaction. The data were taken by a CERN-College de France-Liverpool bubble-chamber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

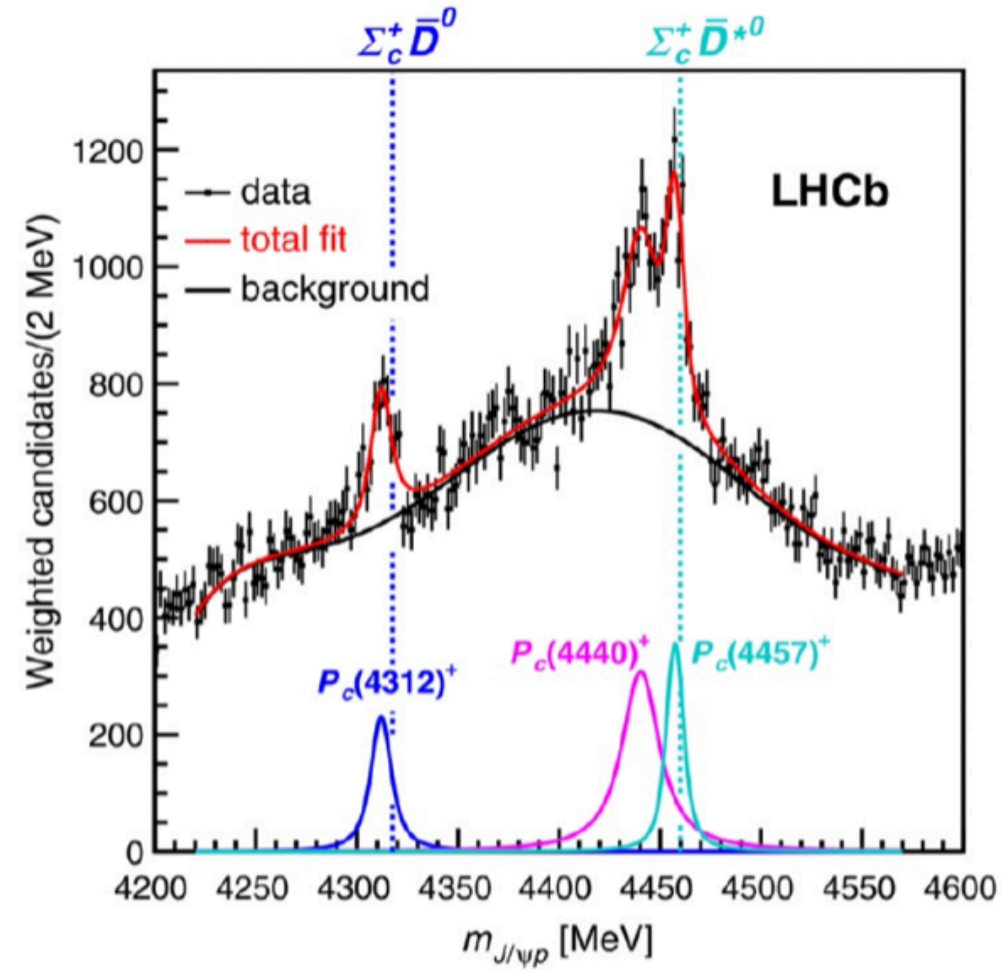


split Pc

LHCb, Run 1, 2015



LHCb, Run 1+Run 2, 2019

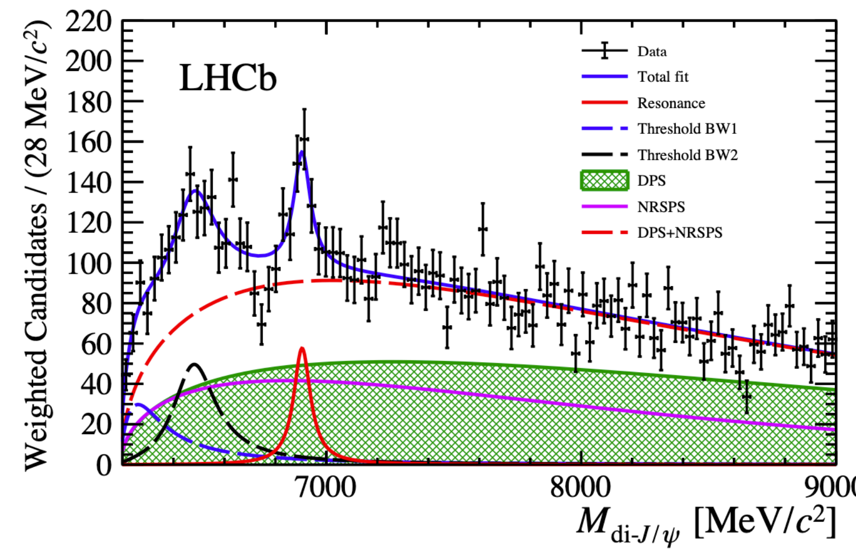


$$P_c(4450) \rightarrow P_c(4440) + P_c(4457)$$

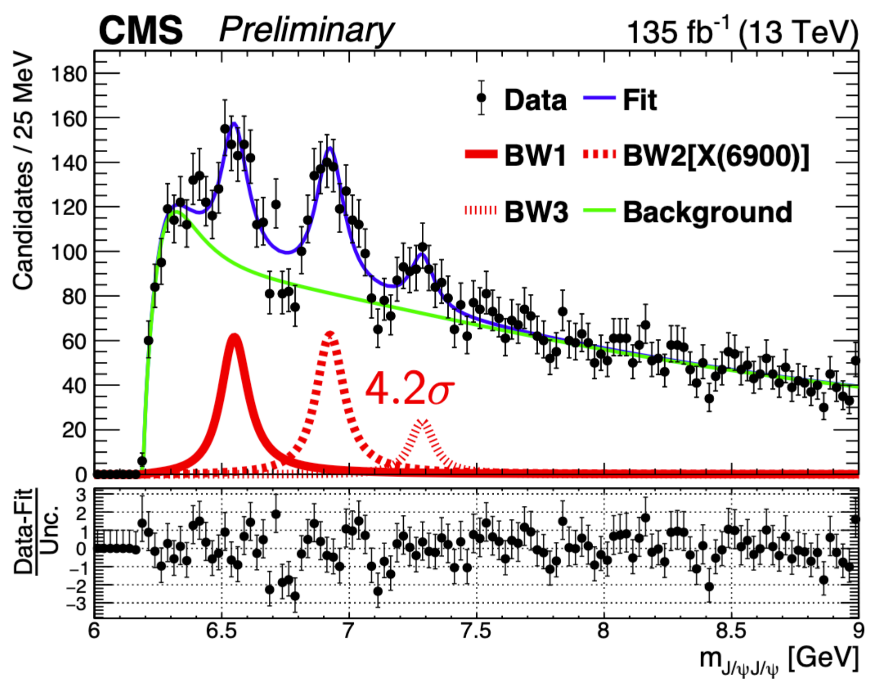
XYZP's : real or not ?

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

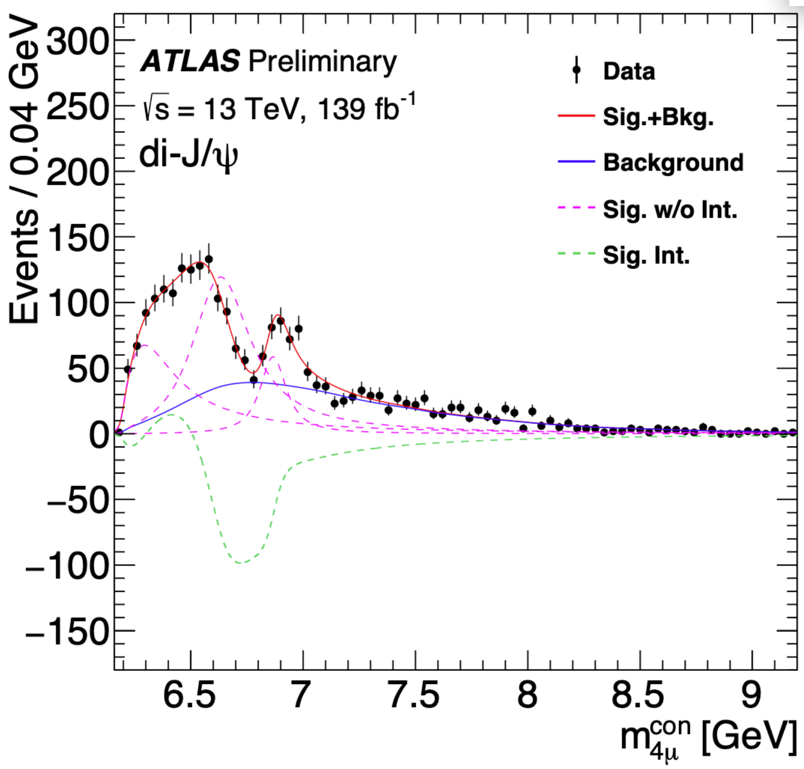
- $T_{\psi\psi}$ or X(6900) a ψ resonance $(cc\bar{c}\bar{c})$?



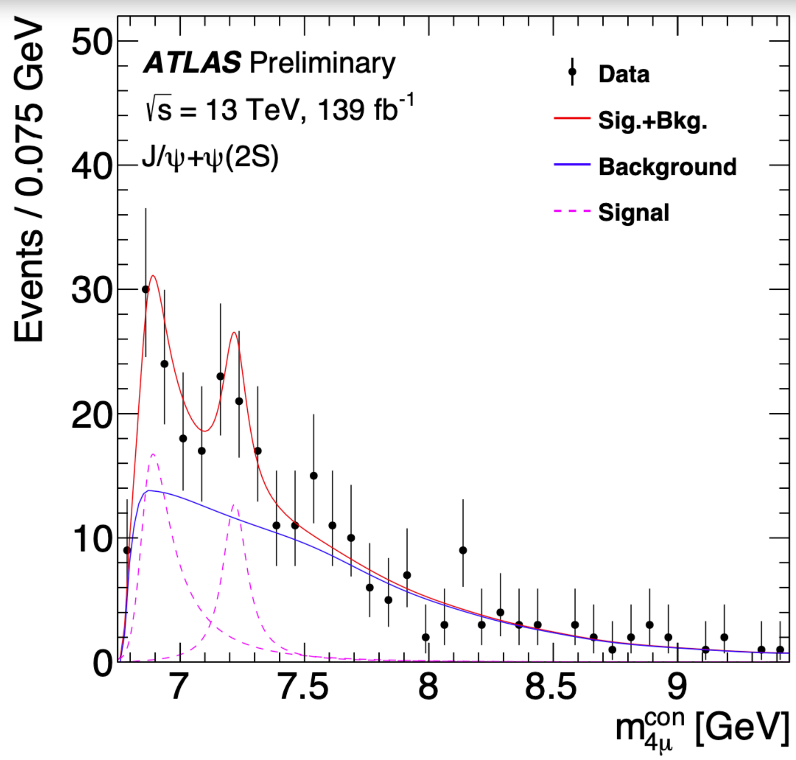
[LHCb, Sci.Bull. 65 (2020) 23, 1983-1993]



[CMS-PAS-BPH-21-003]



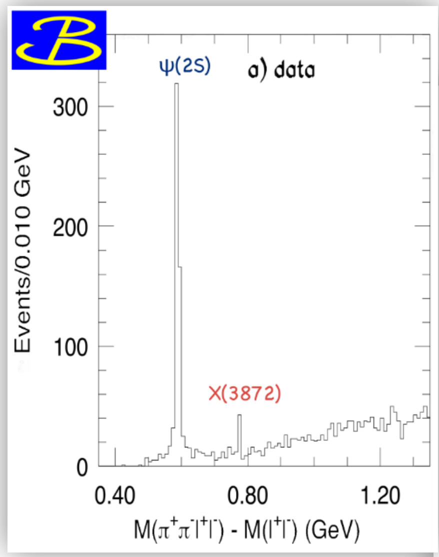
[ATLAS-CONF-2022-040]

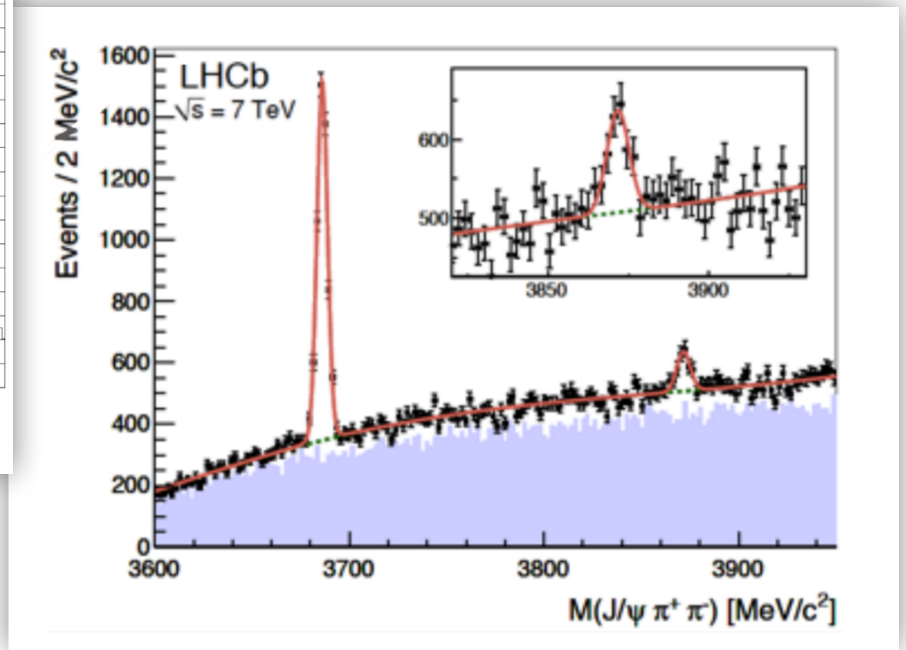


[ATLAS-CONF-2022-040]

XYZP’s : real or not ?

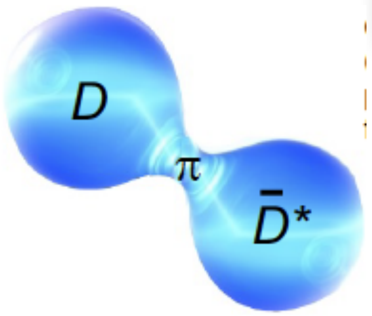
$X(3872)$ $(\chi_{c1}(3872))$

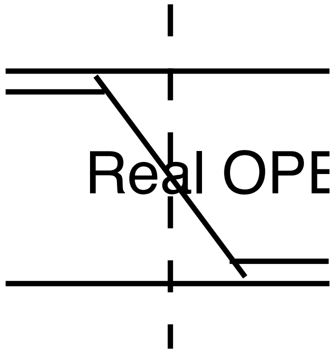


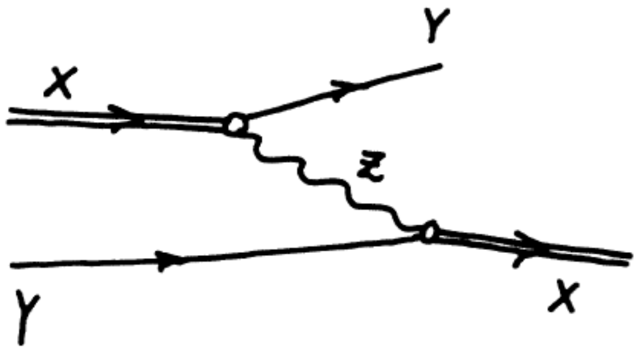


REMARK ON ENERGY PEAKS IN MESON SYSTEMS

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.



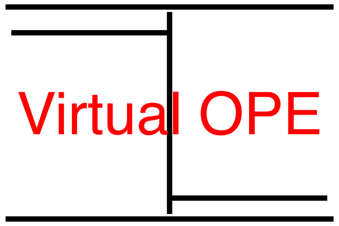




Very close to $D\bar{D}^*$ threshold

Is X(3872) a molecule ?

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

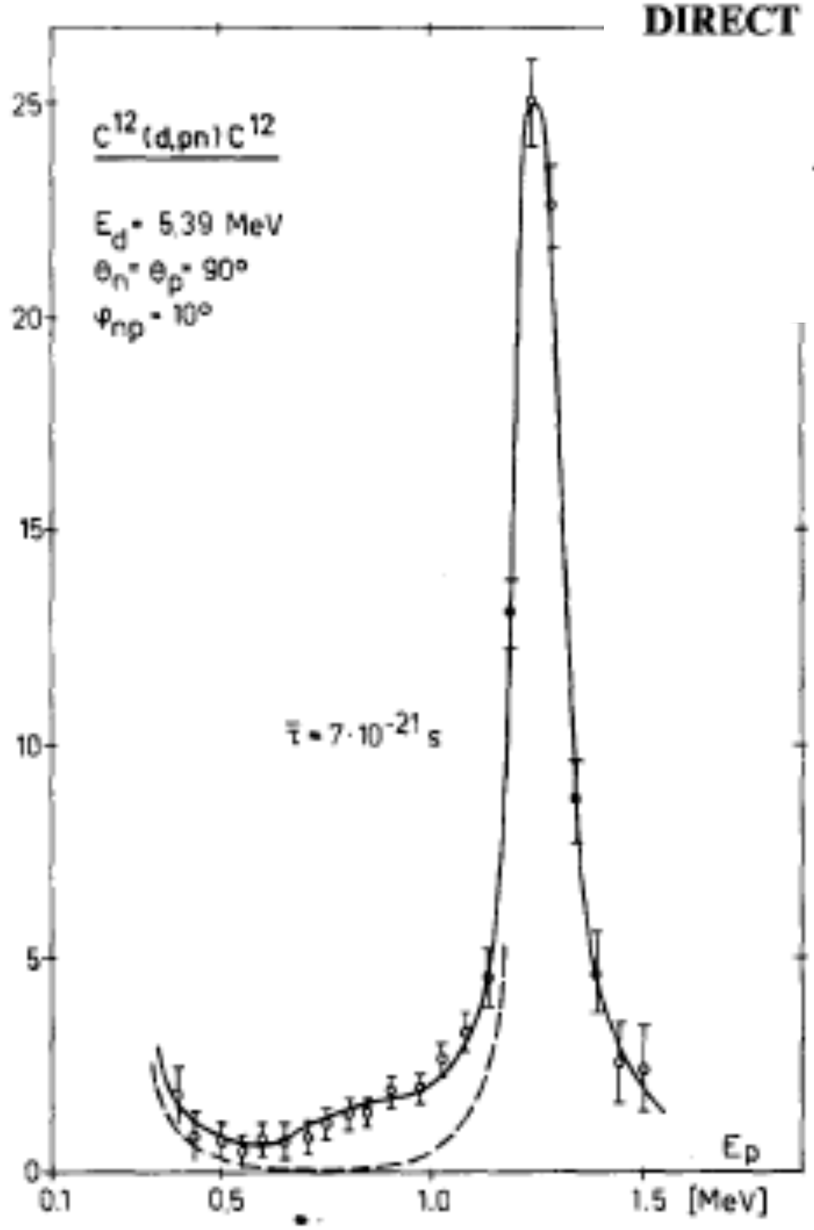


Even Virtual OPE exchange is tricky

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

Attractive = Attractive + Repulsive

Need to understand Production !

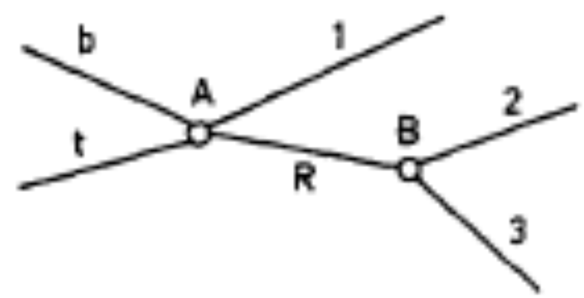


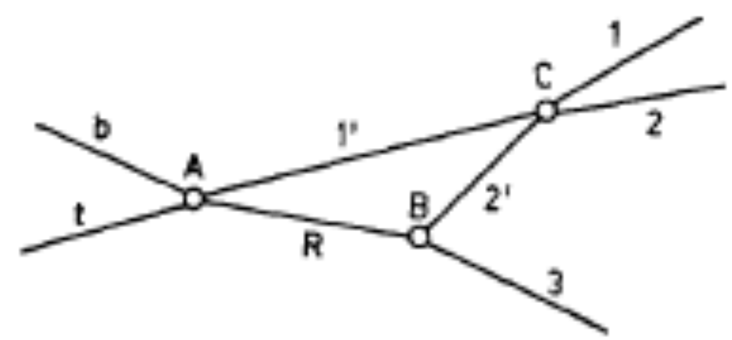
DIRECT DETERMINATION OF A SHORT NUCLEAR LIFETIME ($\approx 10^{-20}$ s) BY THE PROXIMITY SCATTERING METHOD

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

Received 4 February 1966

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



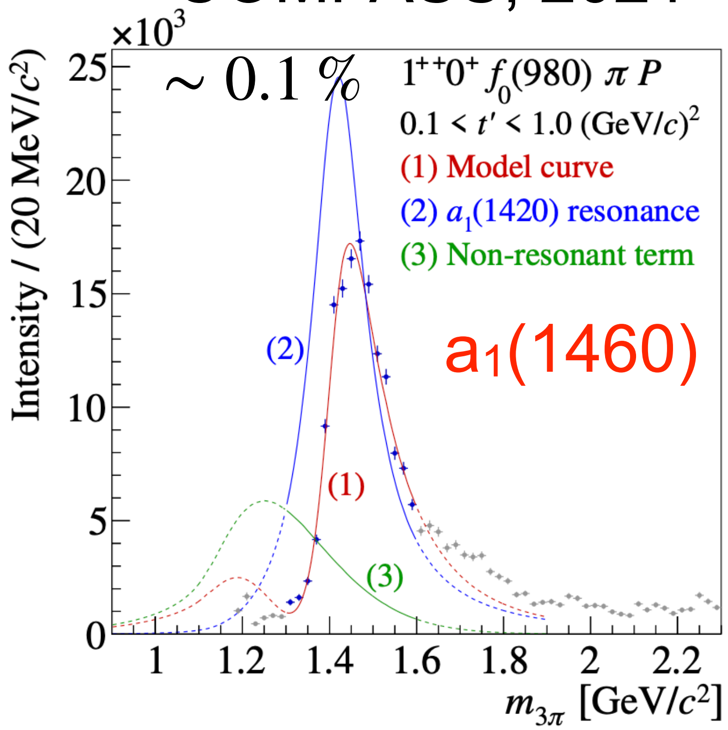


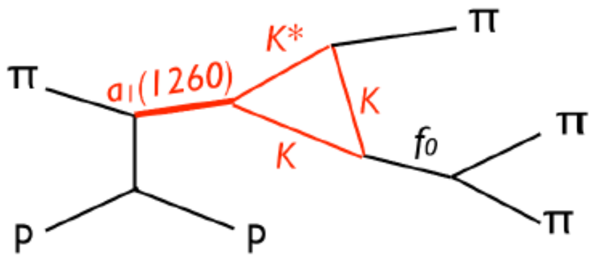
$$b+t \to 1+R, \qquad \text{with } Q\text{-value } Q_1 \qquad [d+{}^{12}C \to n+{}^{13}N^*, \qquad Q_1 = -3.82\ \text{MeV}],$$

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

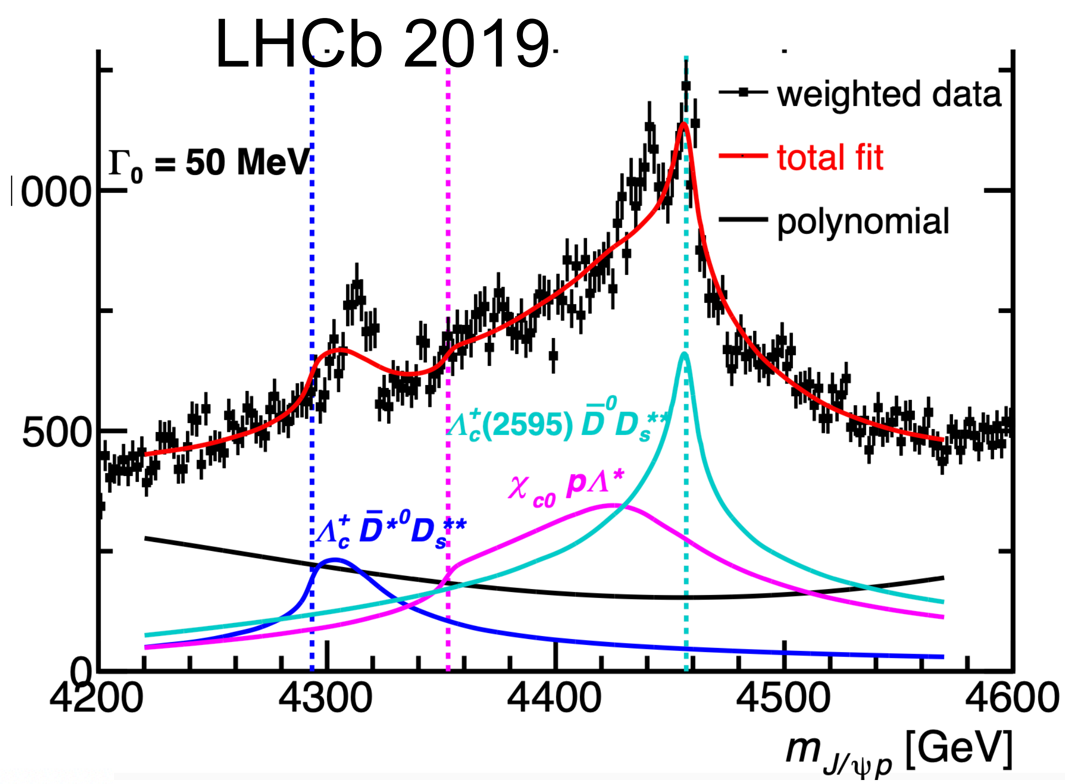
Triangles are everywhere

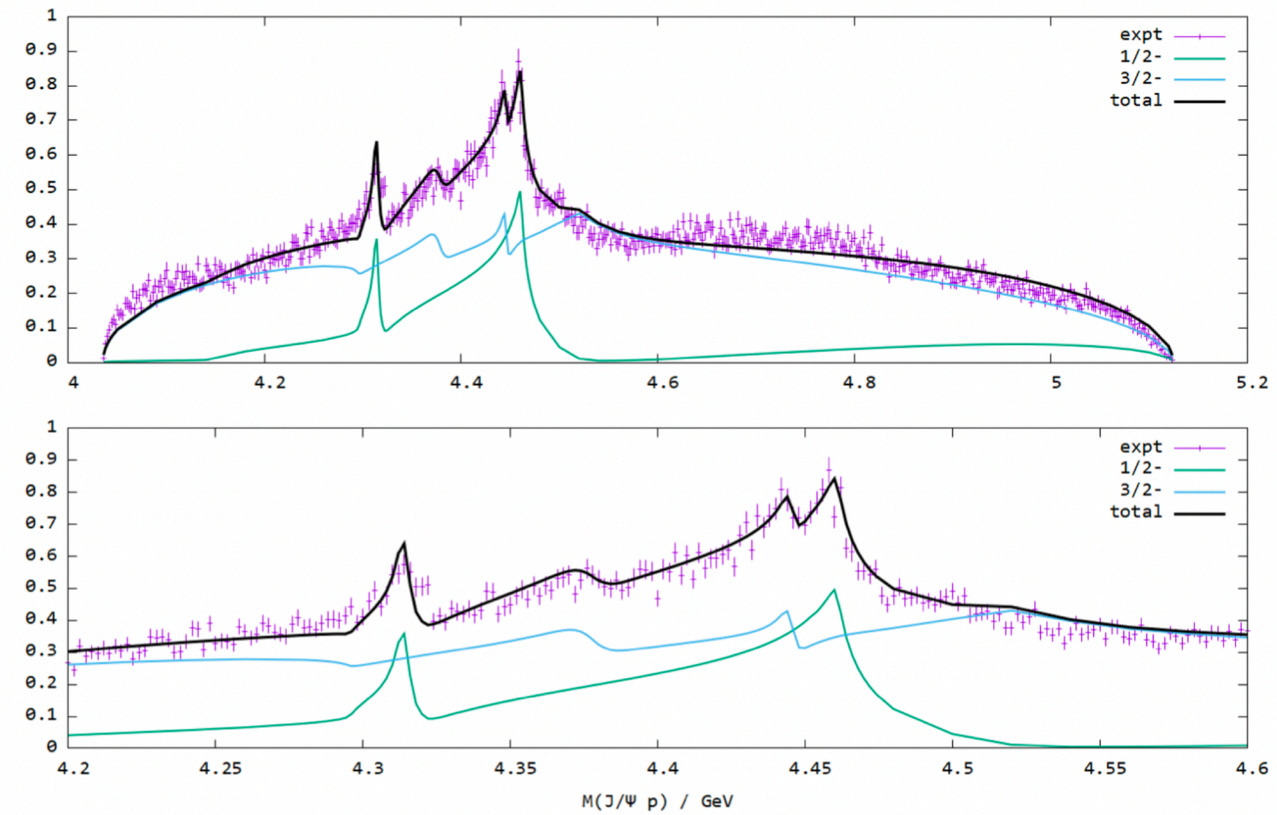
COMPASS, 2021





LHCb 2019

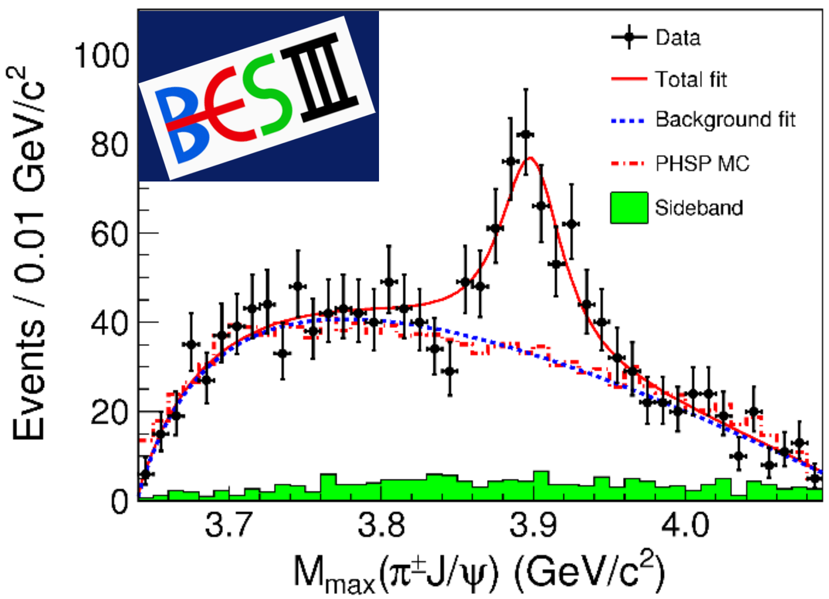




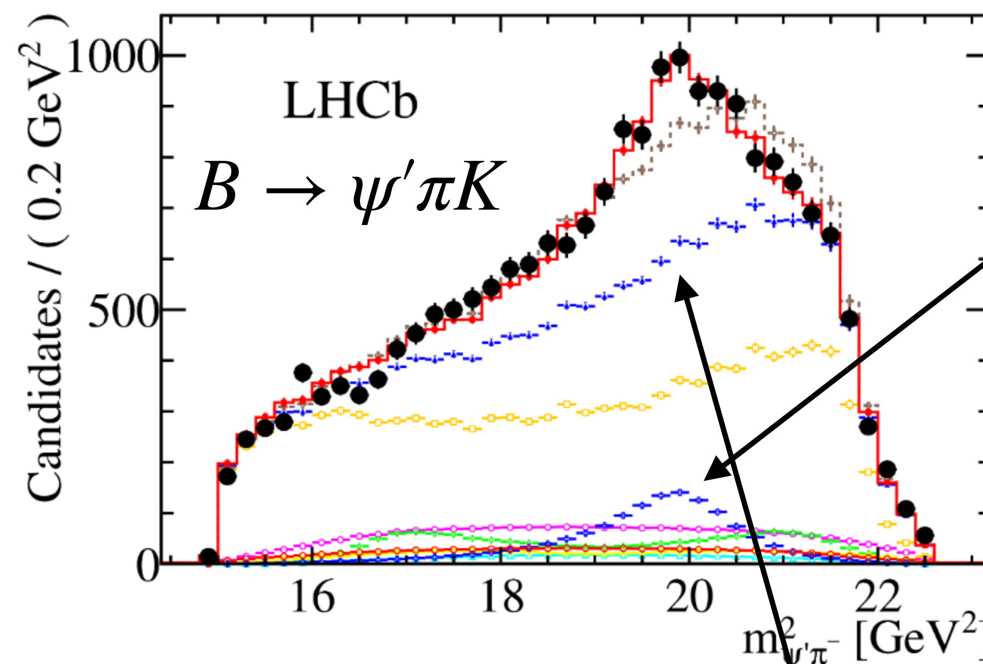
Burns, Swanson

Kinematic reflections

Are the Z's true resonances or kinematic effects

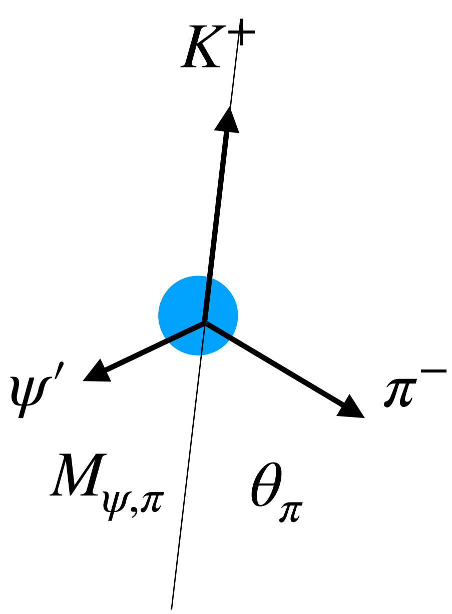


$e^+e^- \to Y \to J/\psi\pi^+\pi^-$



Z(4430)

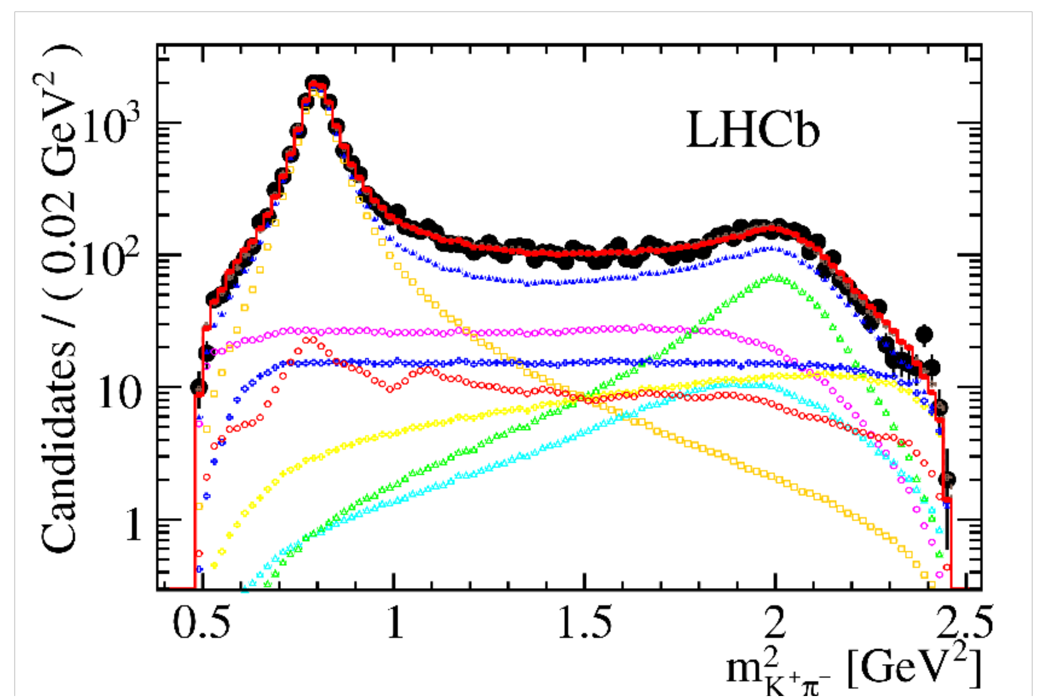
Kinematic effects from K* decays ?



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

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

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



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

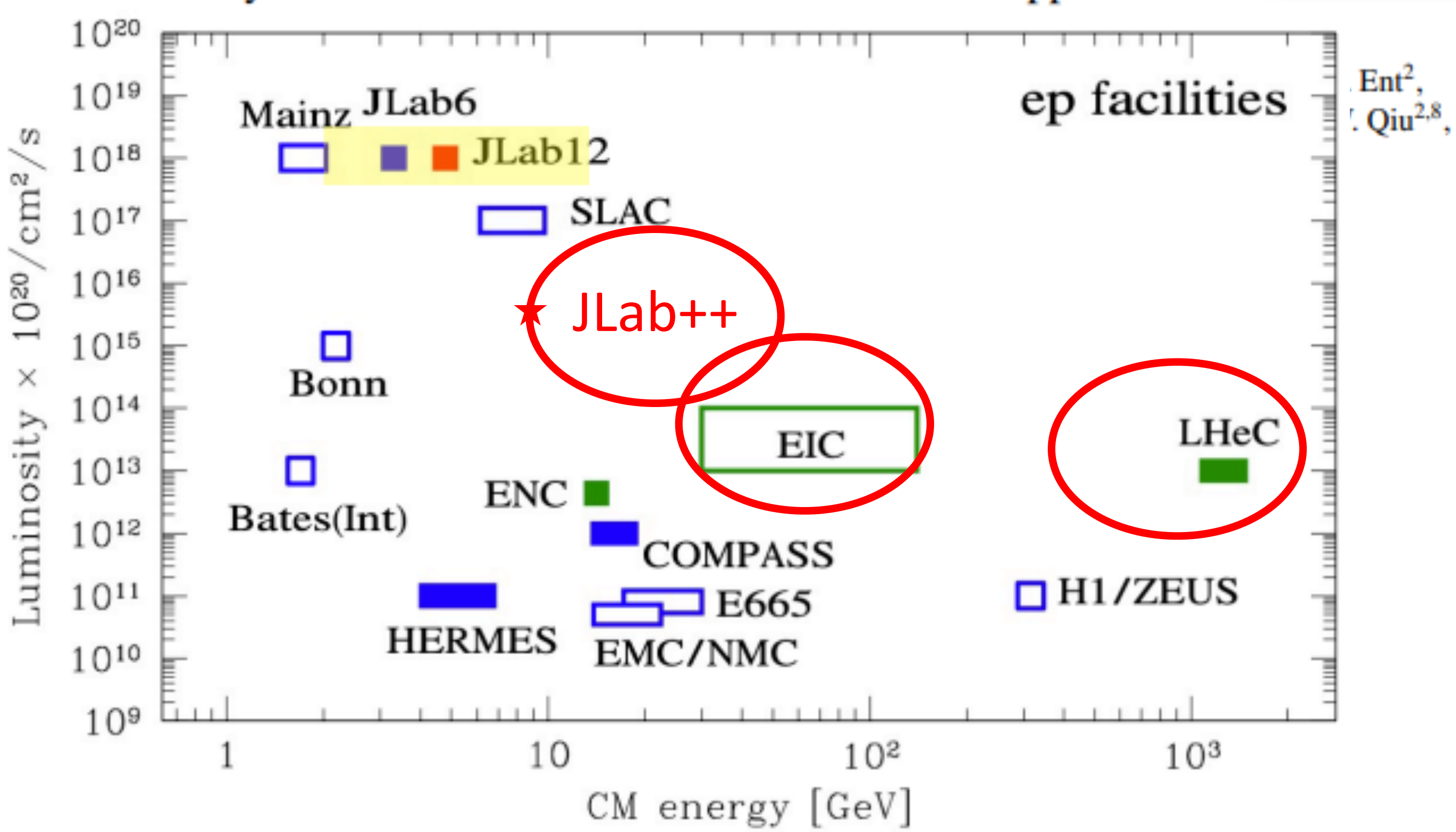
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Hadron Spectroscopy in Photoproduction

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

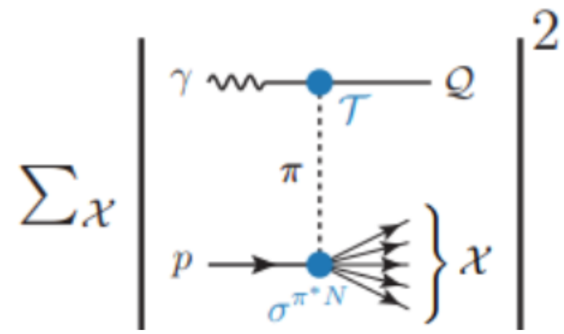


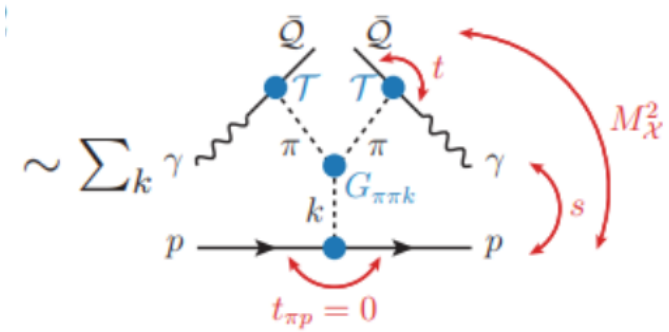
EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production

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

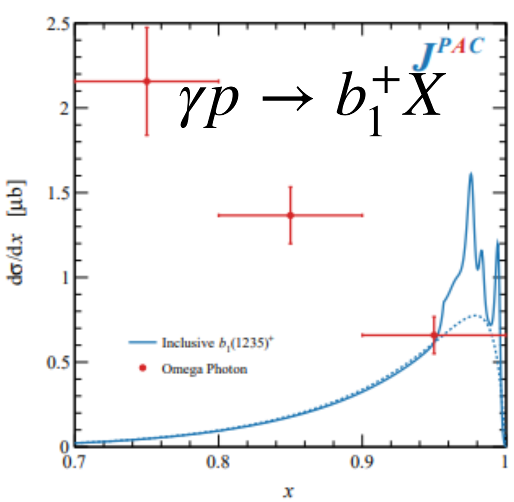
TABLE I. Estimates of yields for day of data taking at CLAS24 assuming a zero-angle electron detector

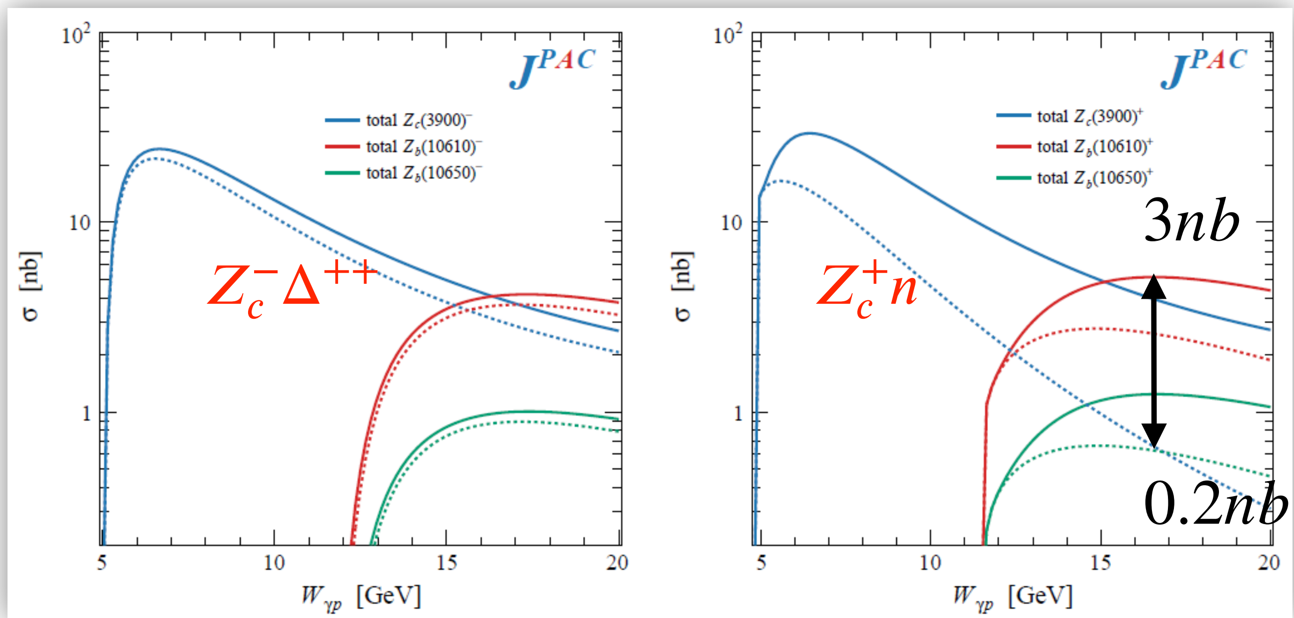
TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100 (GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1};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

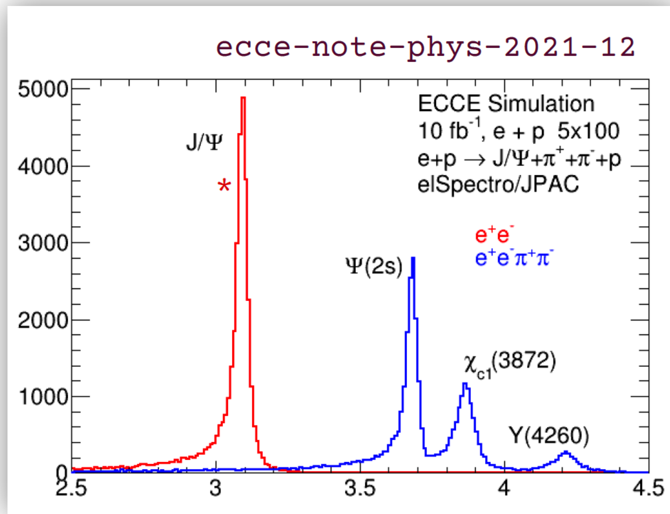
Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$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

https://github.com/dwinney/jpacPhoto

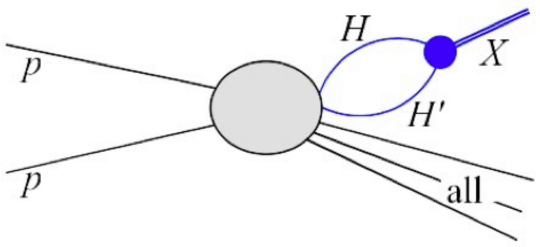






• Production at EIC

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)

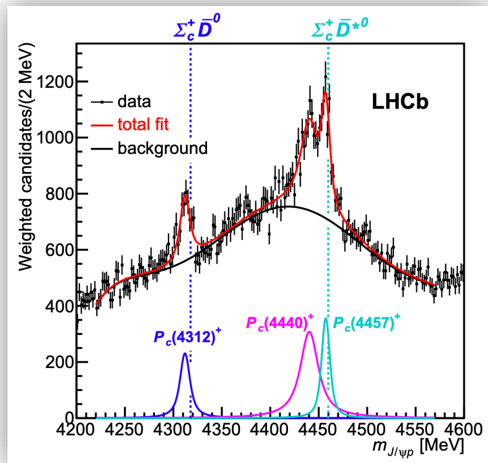
Albaladejo, FKG, Hanhart et al., CPC41(2017)121001

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

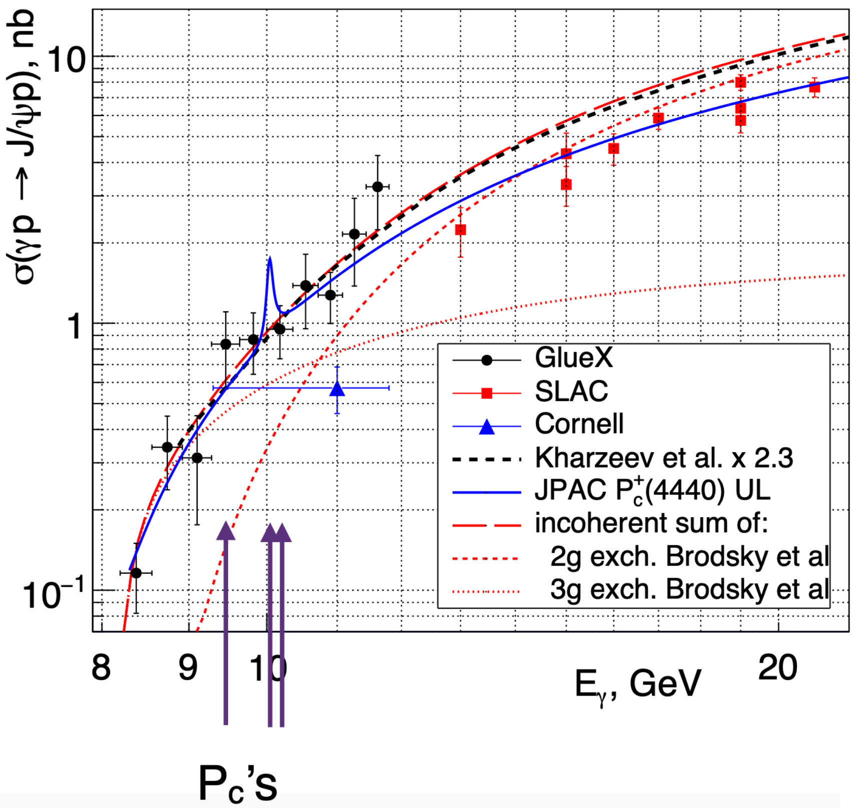
	Constituents	$I, J^{P(C)}$	EicC	EIC
$X(3872)$	$D\bar{D}^*$	$0, 1^{++}$	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	$1, 1^{+-}$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	$1/2, 1^+$	19(69)	250(900)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2, 1/2^-$	0.8(4.1)	15(73)
$P_{cs}(4338)$	$\Xi_c\bar{D}$	$0, 1/2^-$	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

XYZP's : real or not ?

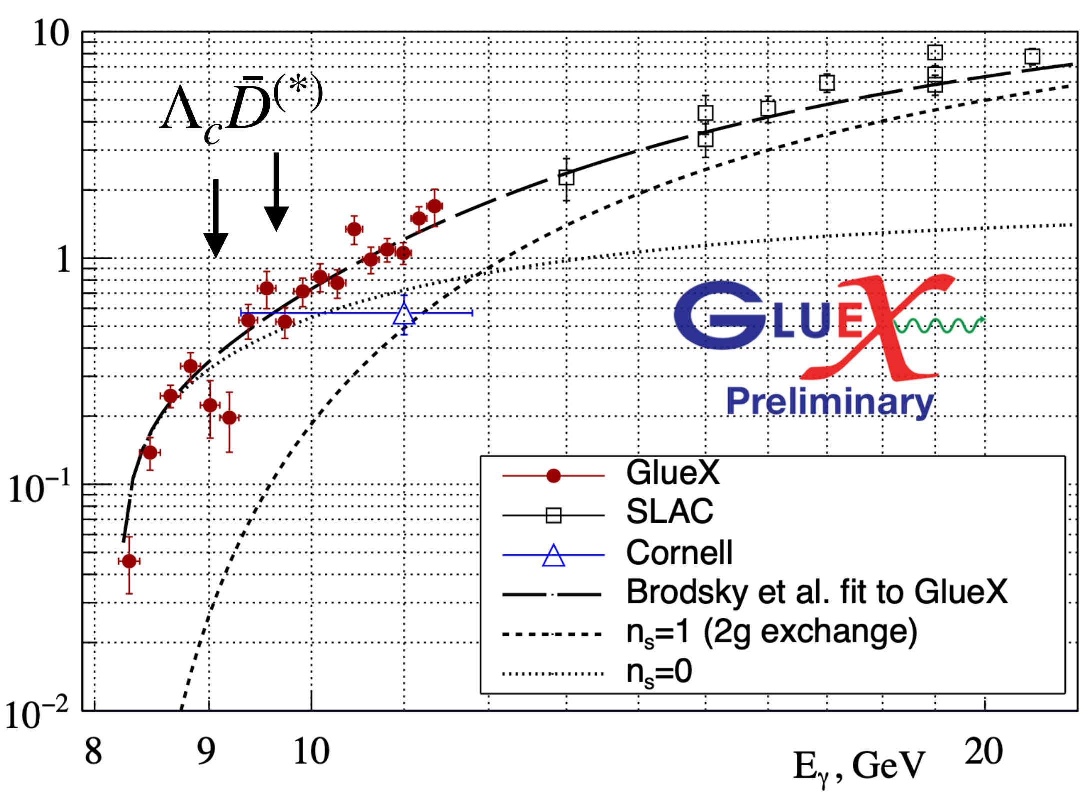


GlueX: PRL 123, 072001 (2019)

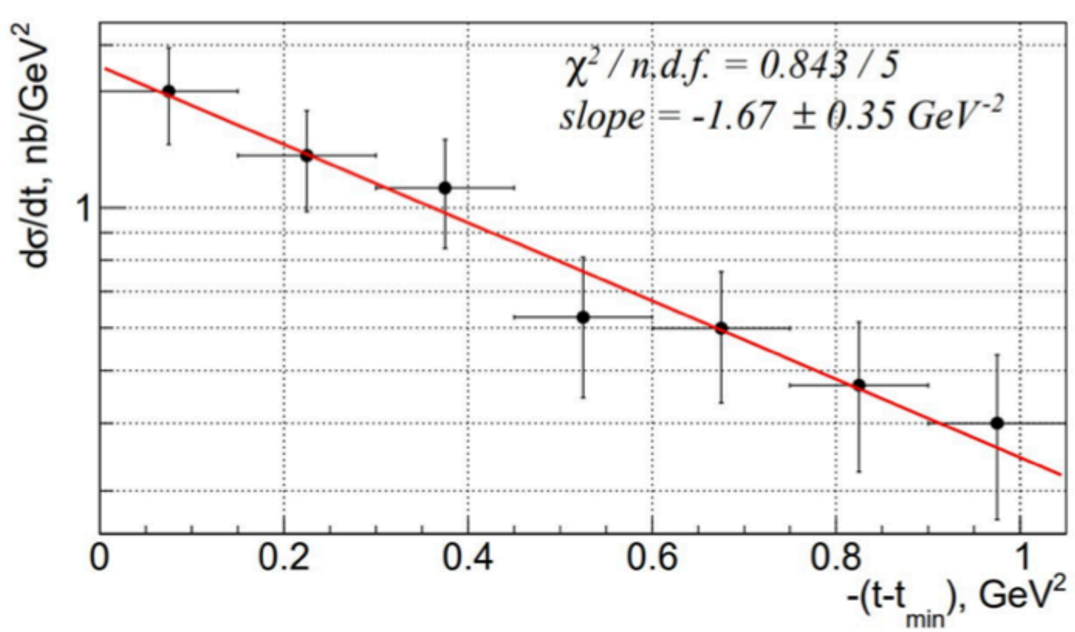


- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance
- Full GlueX-I data yields 2270 ± 58 J/ψ's

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



Confirmation of **gluon dominated dynamics**? **… but**



GlueX [Phys.Rev.Lett. 123 (2019) 7, 072001]

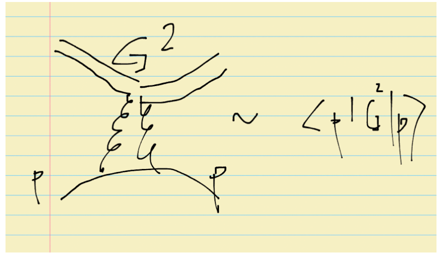
J/ψ photo production

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

- Two (distinct) approaches:
  - t-channel partial waves

$$A(s,t) = \sum_l f_l(t) P_l(z_t) \longleftarrow l_{max} \leq 2$$

mass radius, gravitational form factors, etc.



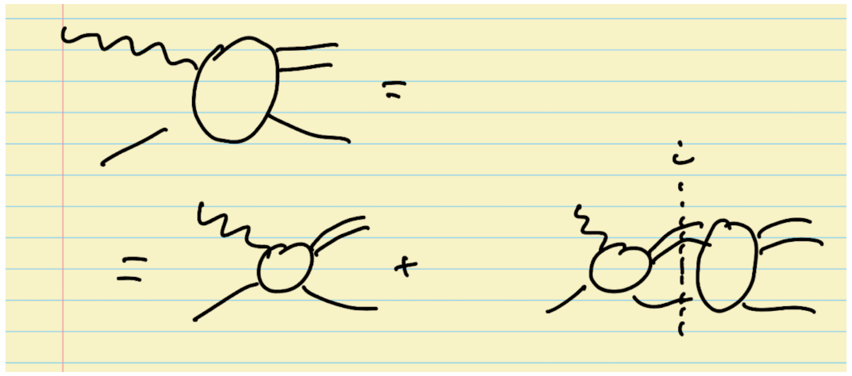
Kharzeev et al. (1999), Brodsky et al (2001) Ji et al.Guo et al. (2021) Z, Mamo Zahed, (2020)

smooth s-dependence

  - s-channel partial waves

$$A(s,t) = \sum_l f_l(s) P_l(z_s) \longleftarrow l_{max} \leq 3$$

s-channel thresholds



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

Fit results/conclusions

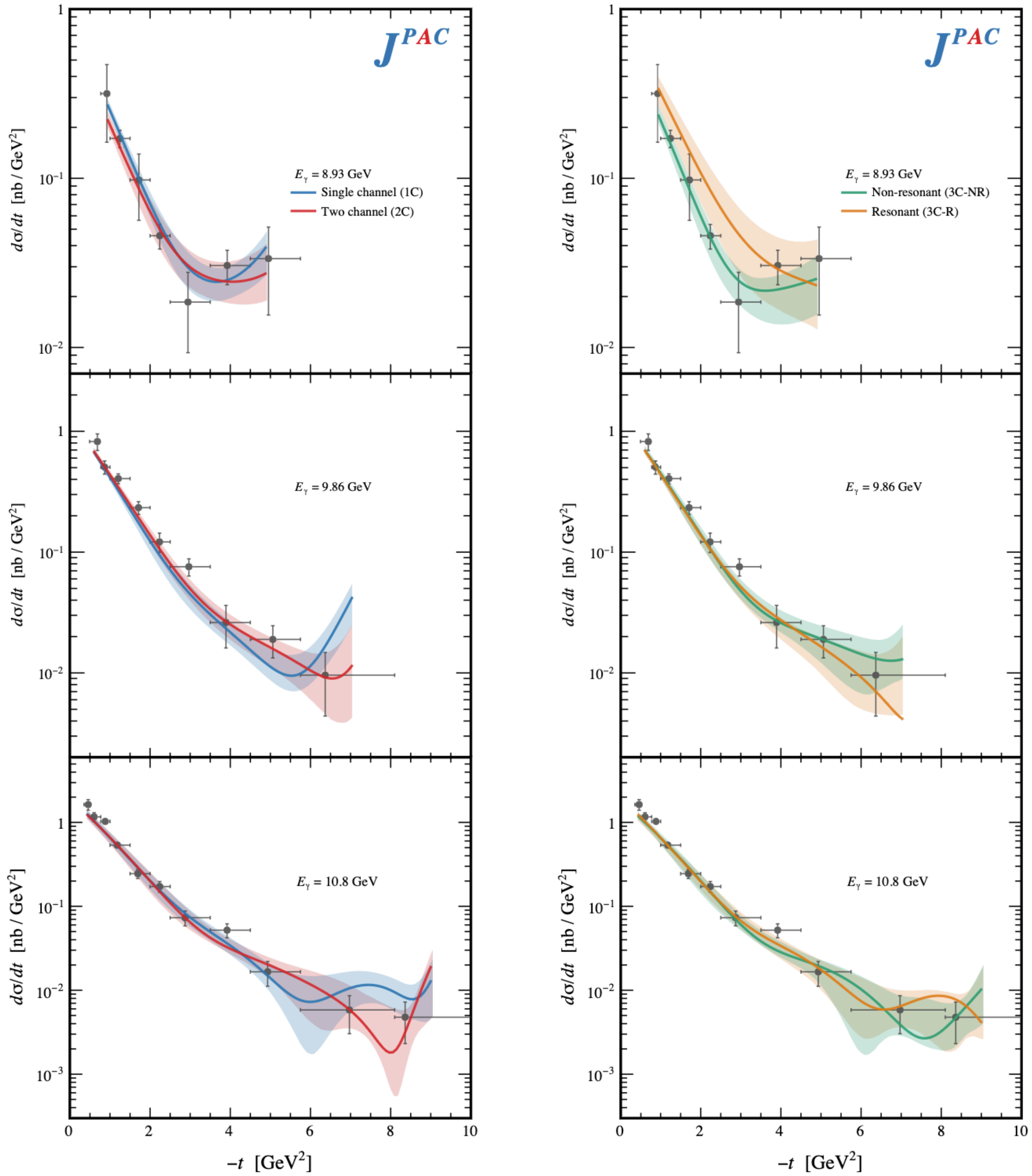


FIG. 2: Fit results for the differential cross section compared to GlueX data from [37]. The bands correspond to the 1σ uncertainties from the bootstrap analysis.

- "Exponential" behavior from the few lowest partial waves

$$l_{max} \leq 3$$

- The expected hierarchy of partial waves S>P>D>F with the flattening at larger-t accounted for by p.w interferences

Fit results/conclusions

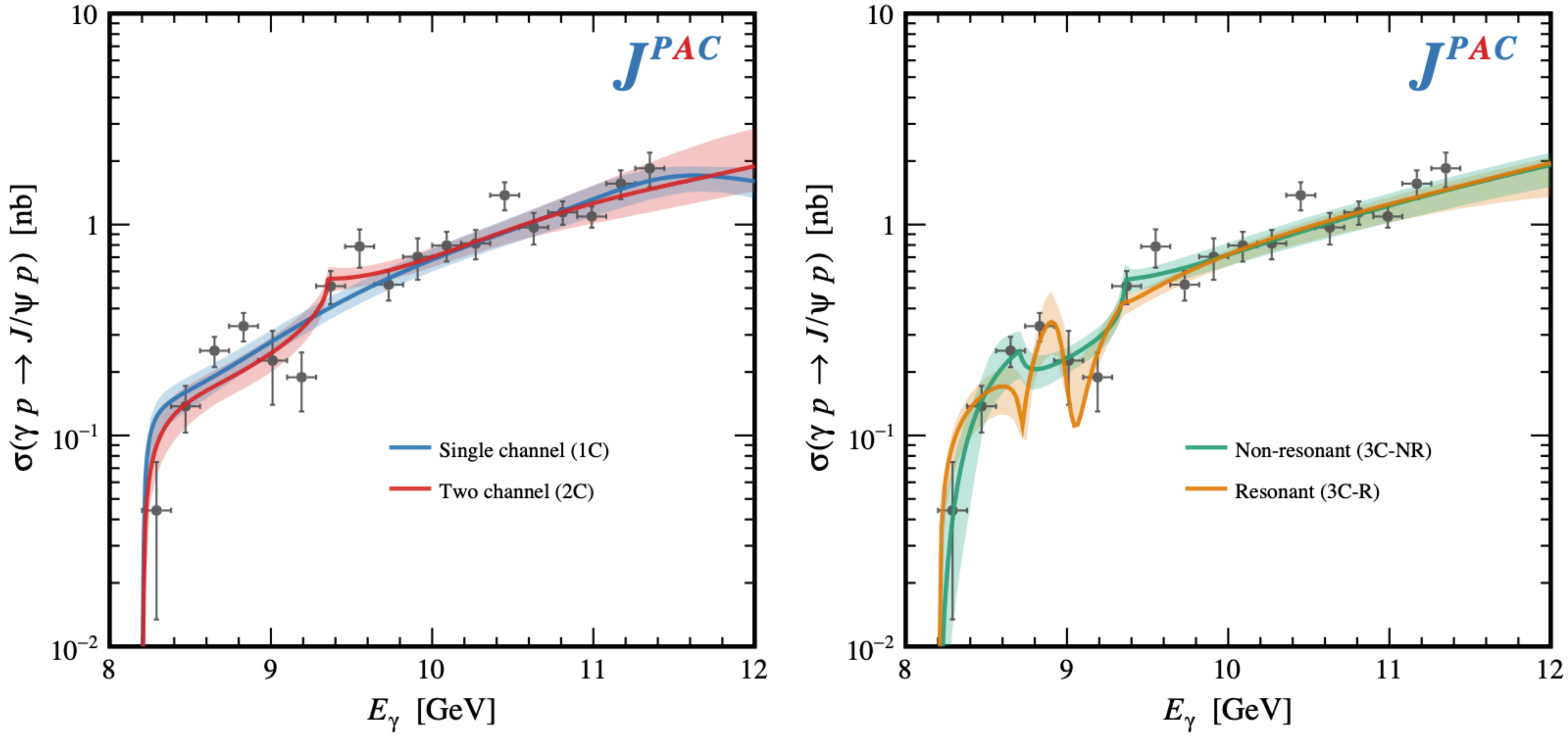
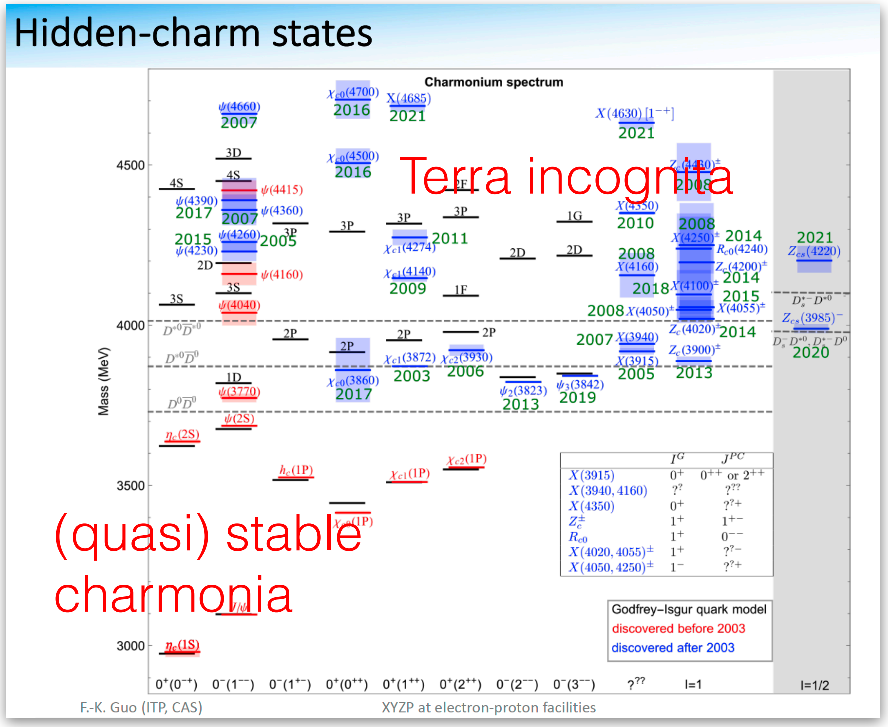


FIG. 1: Fit results for the integrated cross section compared to GlueX data from [37]. Bands correspond to 1σ uncertainties from bootstrap analysis.

- Elastic $\psi p \to \psi p$ scattering length $a_S \sim O(0.1 fm)$ found incompatible with VMD expectations (albeit with large errors)
- Inclusion of open charm reduces the discrepancy
- Fits also suggests relevance of open charm production and compatible with pentaquark production
- Need more precise data, including open charm production

Summary

- Discoveries of XYZP phenomena show there is a large “hadronic landscape” yet to be discovered (also in the light flavor sector).
- Properly constrained S-matrix amplitude analysis can determine if these “exotic” states are real (e.g. true partial wave poles) or something else (e.g. kinematic artifacts).
- At JLab++(EIC) yields are expected to be comparable to colliders at ~10^{34} (higher luminosity, lower energy) and triggers optimized for charmonium final states;
- Direct (photo) production needed for confirmation particularly true for the Z’s which so far seen only in 3body final states. Null results are as important as observations !
- In a decade we will have a very different view of hadrons compared to that proposed by Gell-Mann and Zweig.



F-K.Guo

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