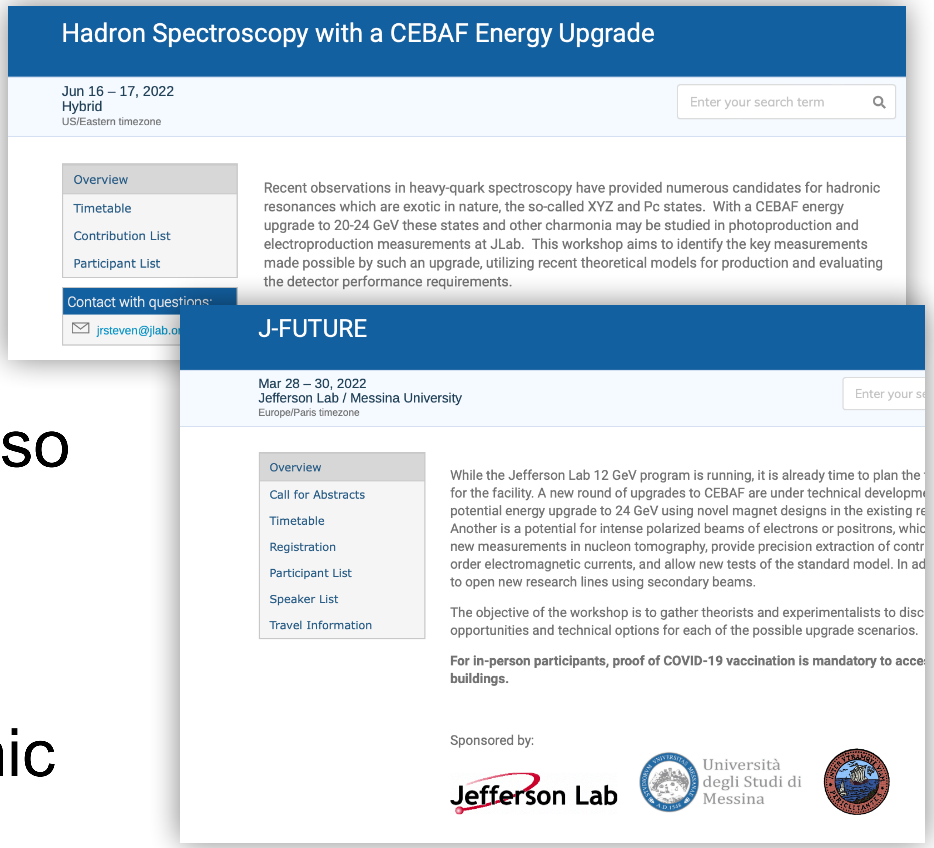
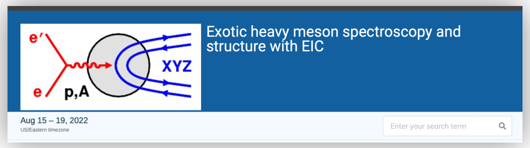
Charmonium Photo-production

Adam Szczepaniak (IU/JLab)



- It's new: no XYZ state has been uncontroversially seen so far. Scarce consistency between various production mechanisms

- Potentially free from re-scattering effects that could mimic resonances in multi-body decays (e.g. triangles)



- The framework is (relatively) clean from a theory point of view

- The local probe (photon) offers another way of exploring nature of the states

  - Several workshops over the past 18months to explore opportunities for XYZP physics with photon/electron beams.

  - This talk: expectations, simulation results and some recent results

JPAC

Happy 10y anniversary JPAC'ers


Misha


Cesar


Daniel


Viktor


Sergi

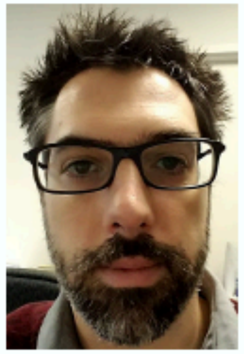

Jorge


Kevin


Alessandro


Lukasz


Astrid


Vincent


Wyatt


Adam

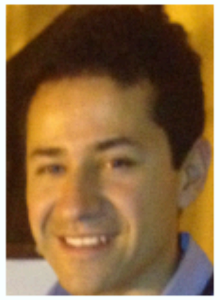

Gloria


Miguel


Andrew


Emilie

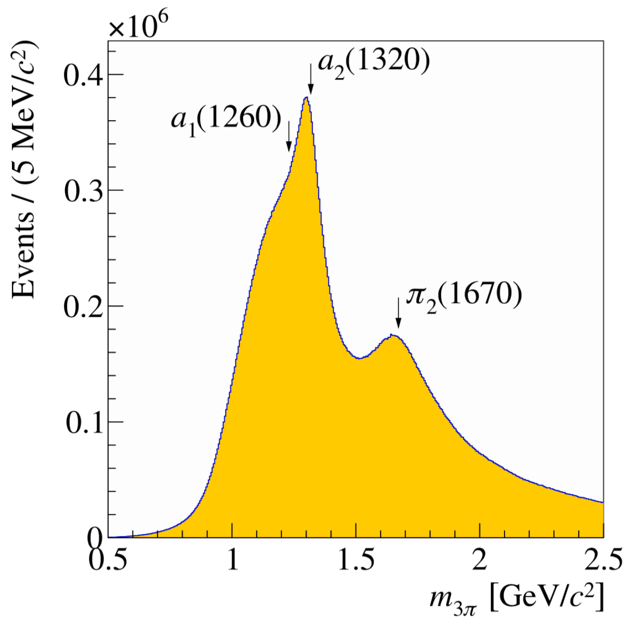

Akaitz


Emmanuel

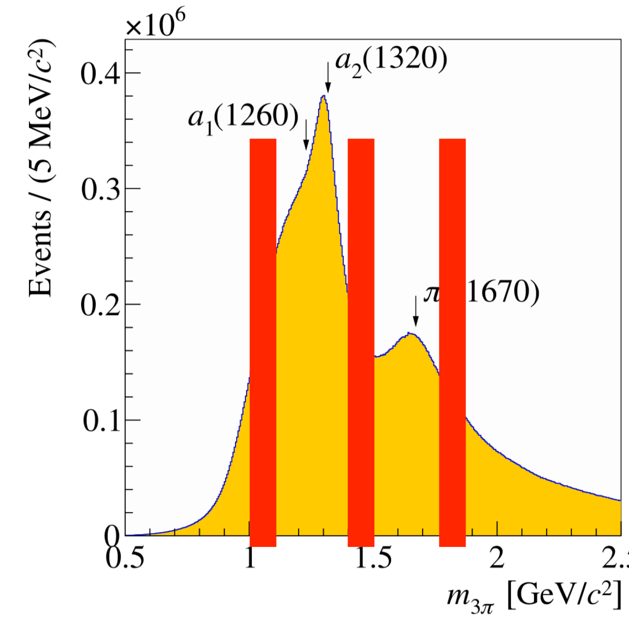

Robert


Sebastian

Amplitude analysis: let the data decide the physics



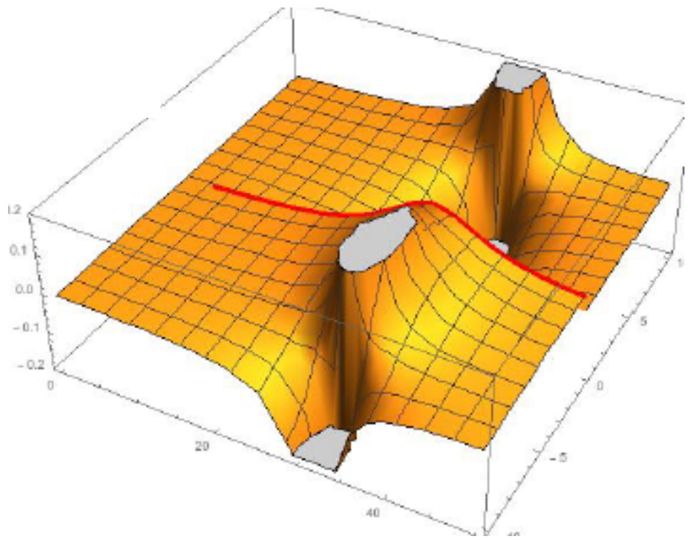
Nature: real axes



QCD

??

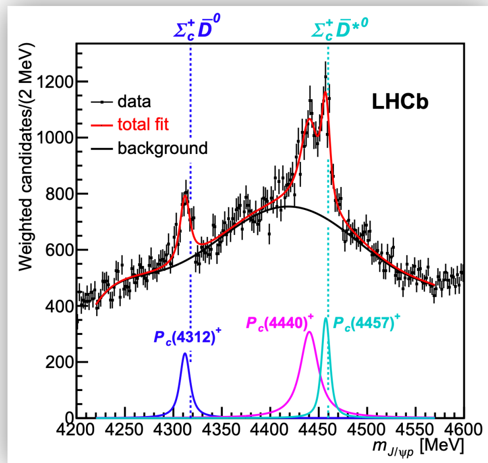
??

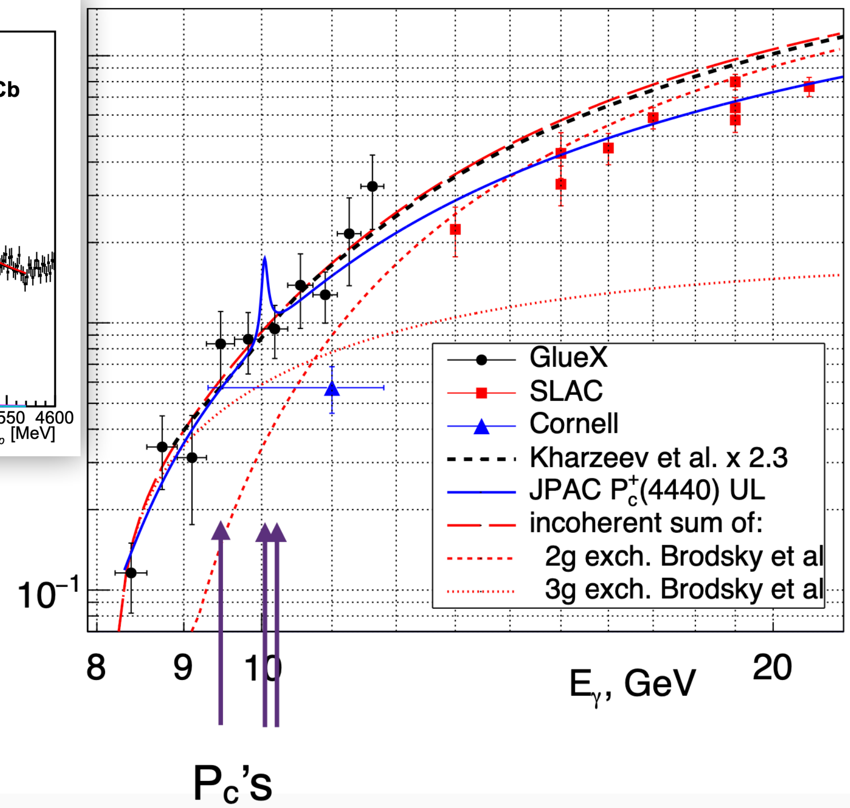


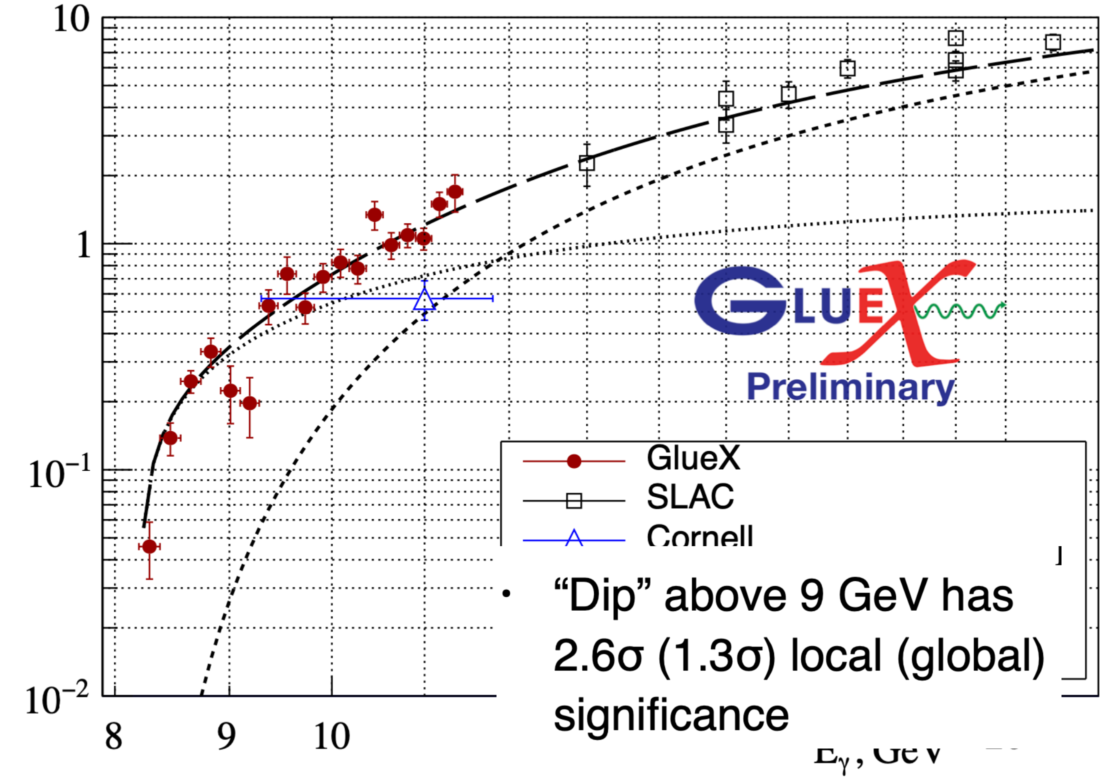
Physical interpretation: complex planes

Pc , X's, Z's ….

GlueX: PRL 123, 072001 (2019)

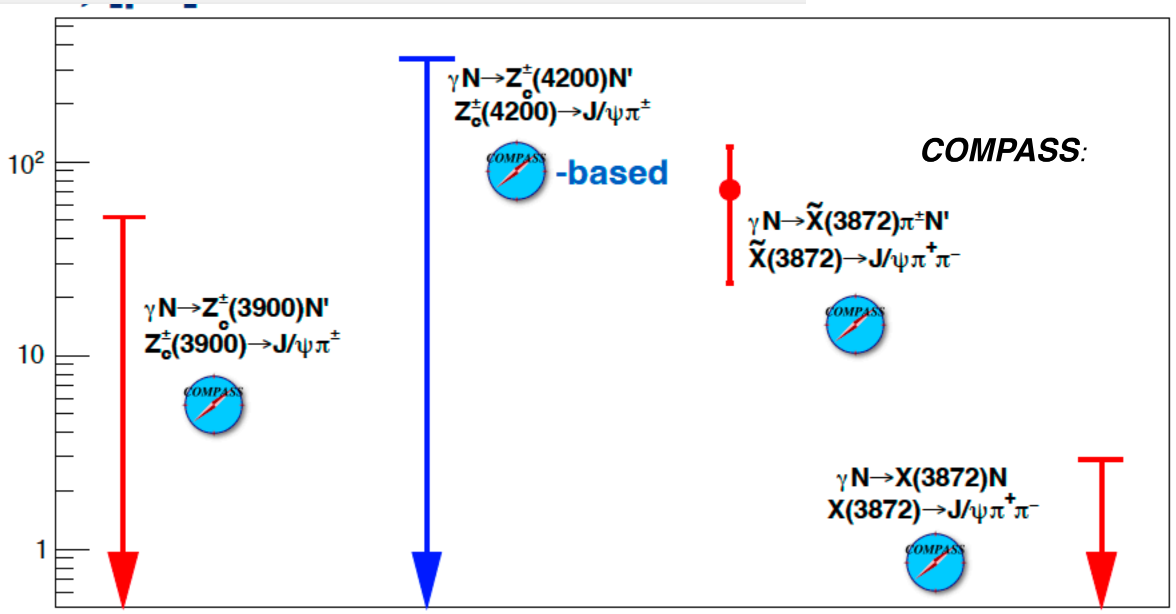






- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance

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



Phys.Lett. B742 (2015) 330

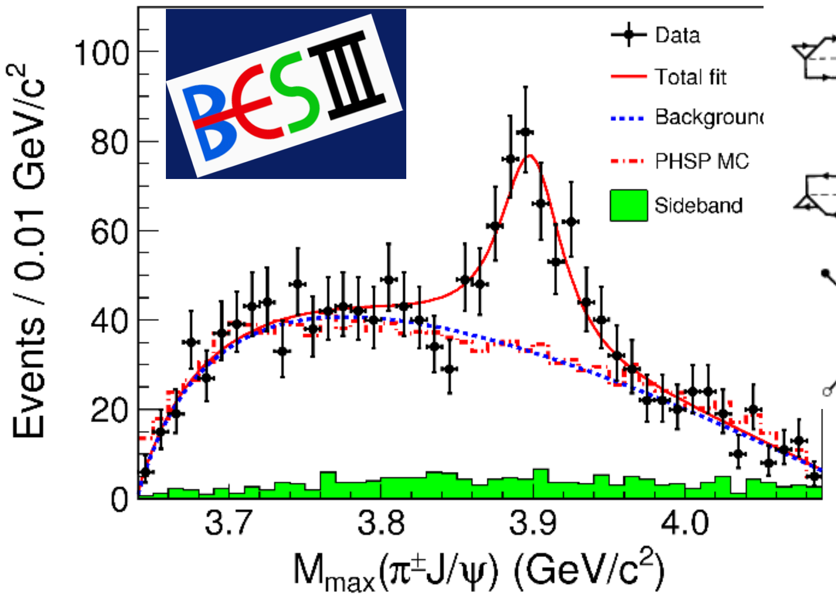
Phys.Rev. D92 (2015) 094017

Phys.Lett. B783 (2018) 334

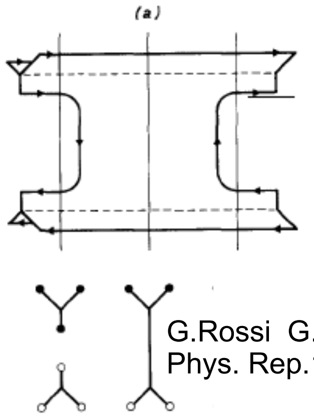
- So far more questions then answers

What are the Z's?

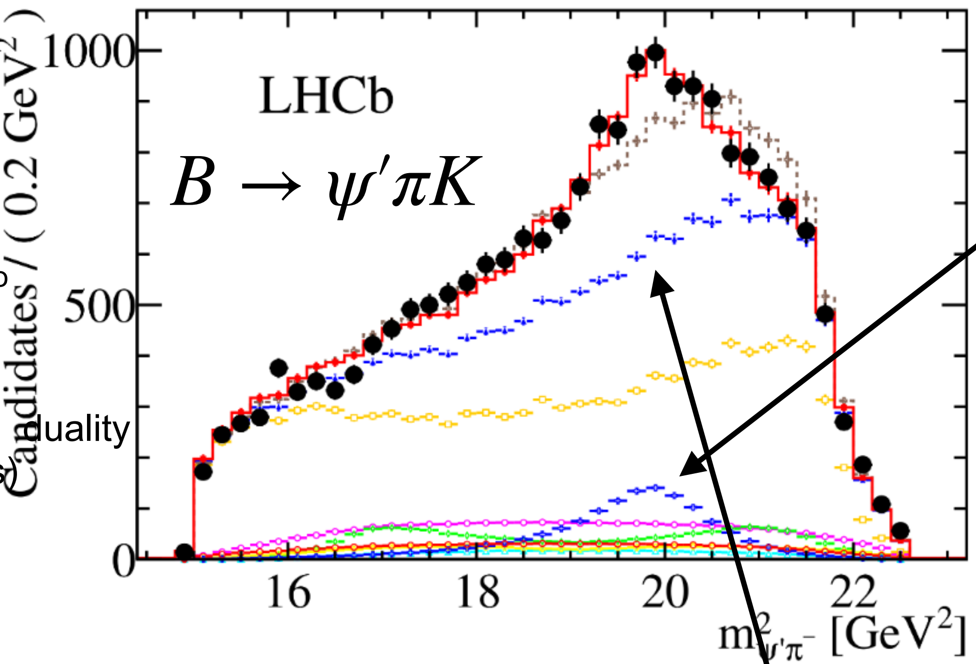
Are the Z's true resonances or kinematic effects



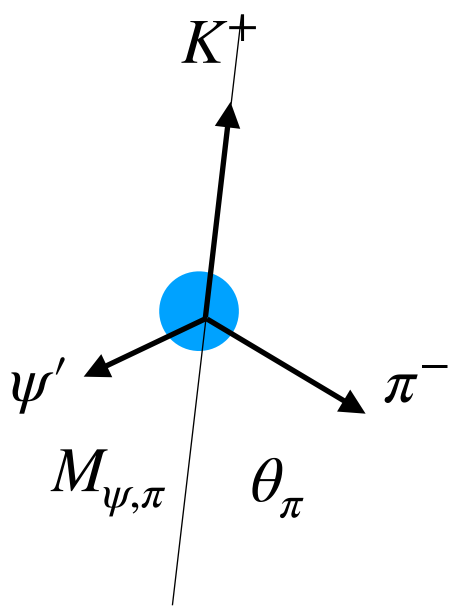
$e^+e^- \to Y \to J/\psi\pi^+\pi^-$



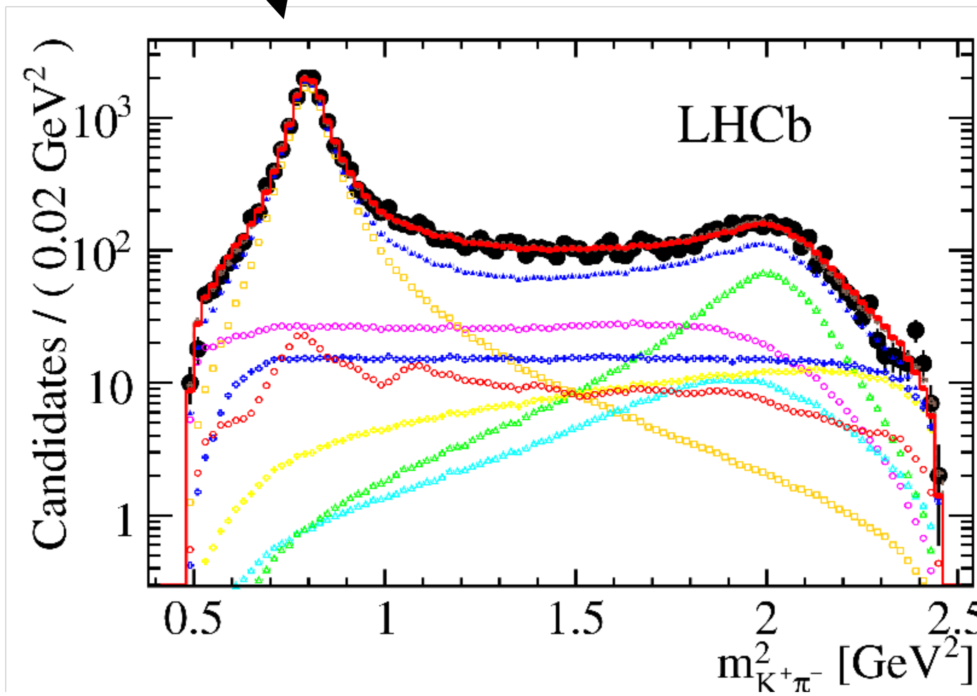
Muti quark states and duality (large-N$_c$, QCD strings)



Kinematic effects from K* decays ?

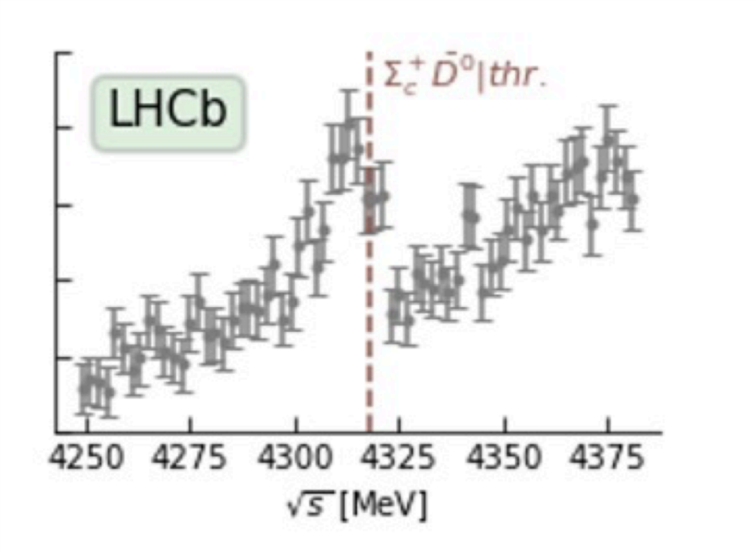


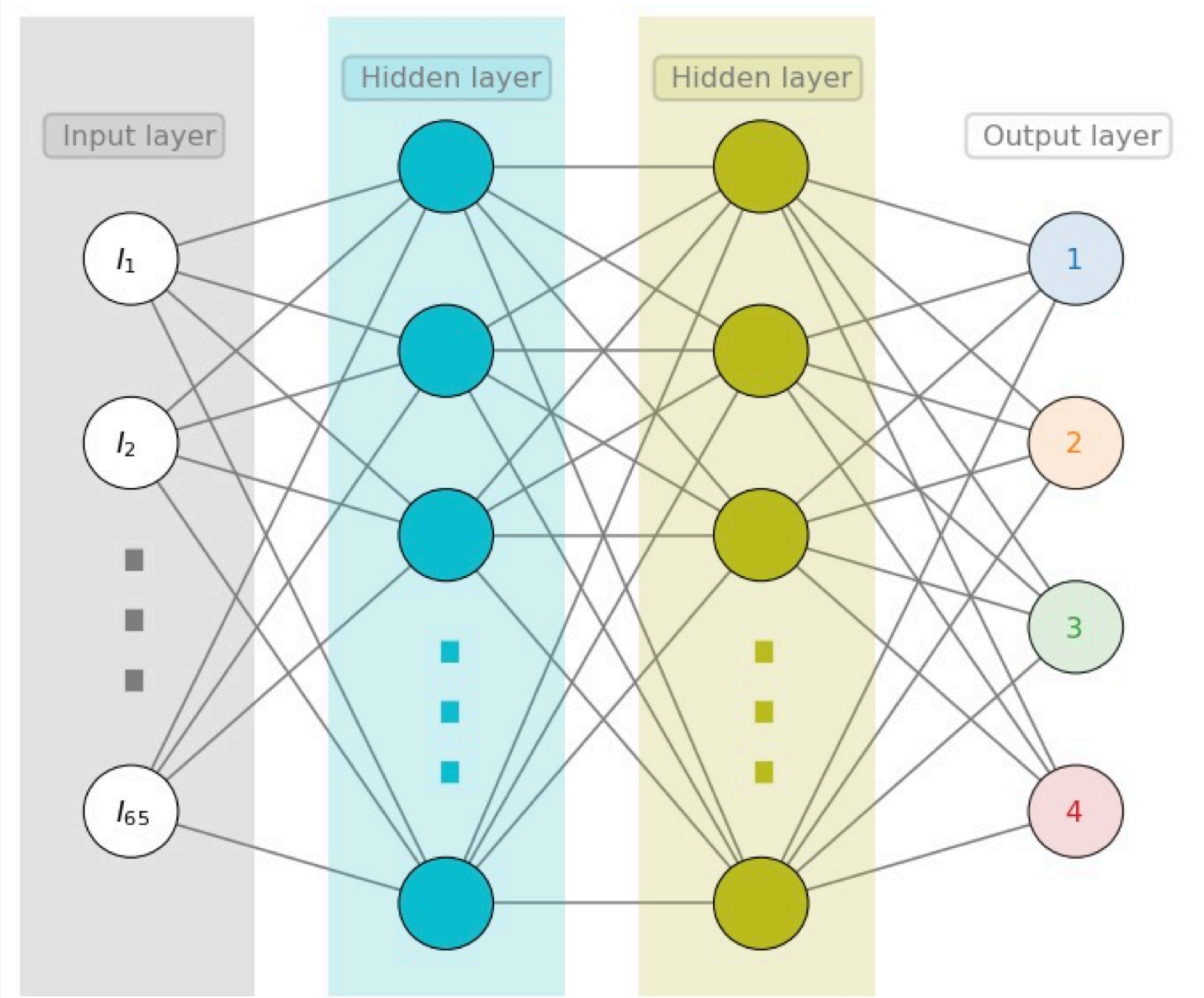
$$B \to \psi'\pi^-K^+$$
$$\nearrow K^{*0}\psi' \to \pi^-K^+\psi'$$
$$\searrow Z^-K^+ \to \psi'\pi^-K^+$$

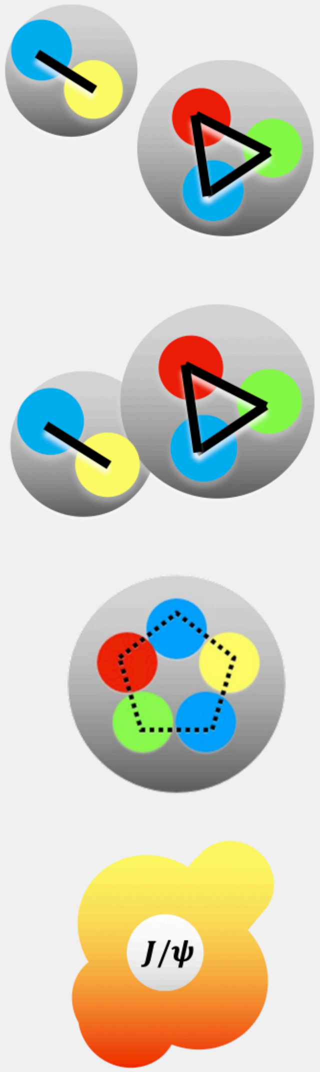


Need for complete amplitude analysis

Holy Grail: AI as a tool for physics discovery



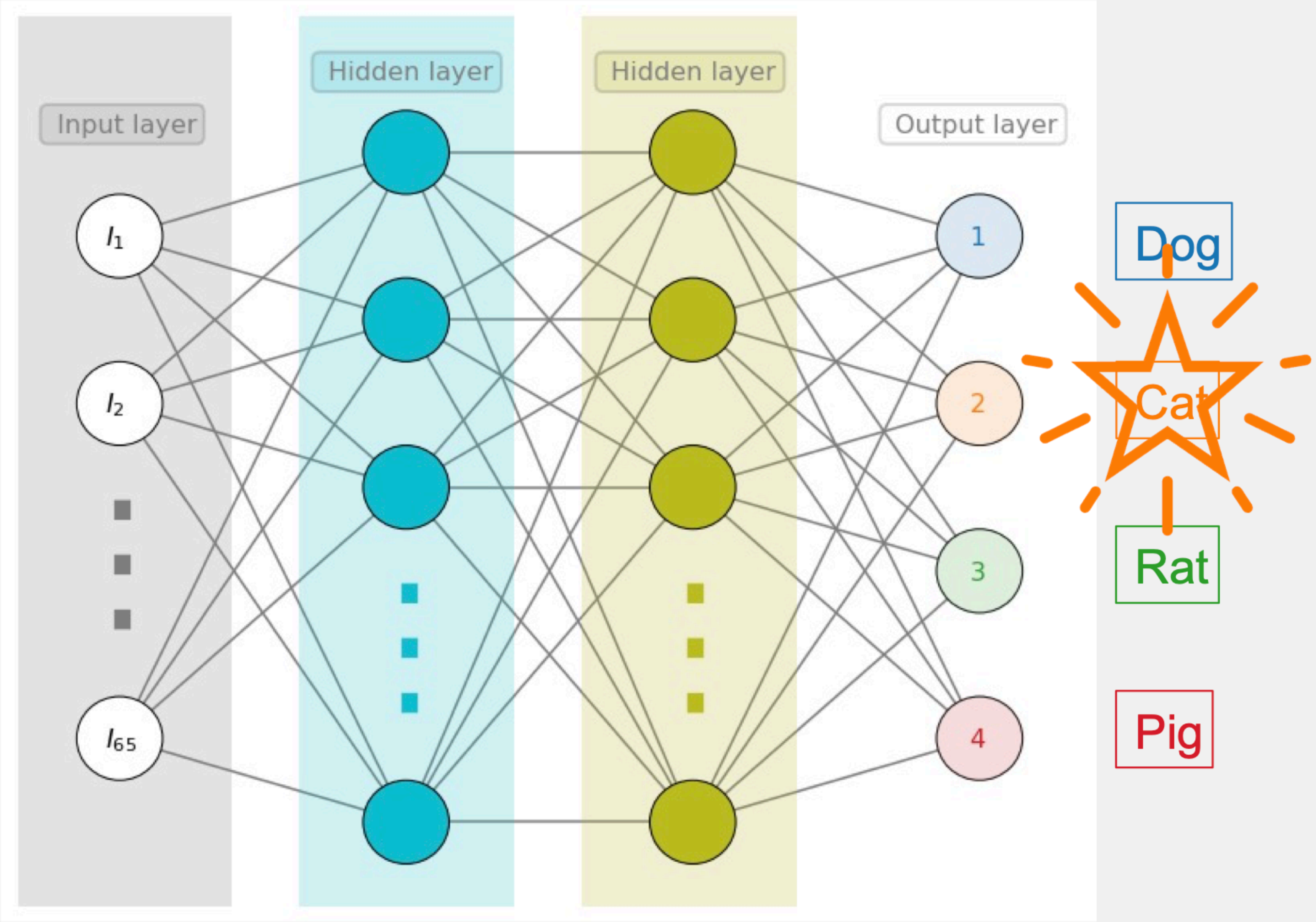




“Deep Learning of Exotic Hadrons” L.Ng. (JPAC) Phys.Rev.D 105 (2022) 9, L091501

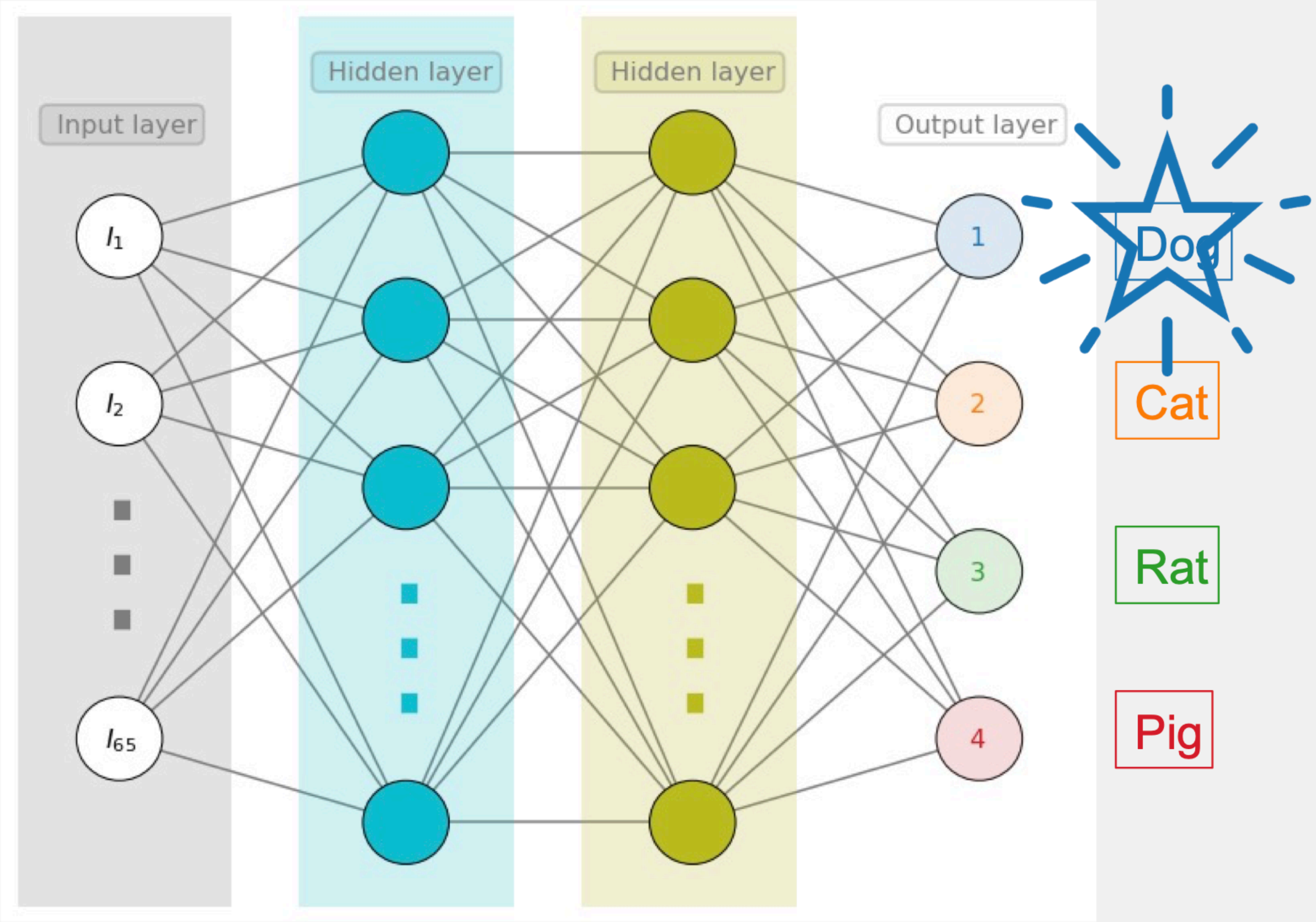
Neural networks as classifiers

Training



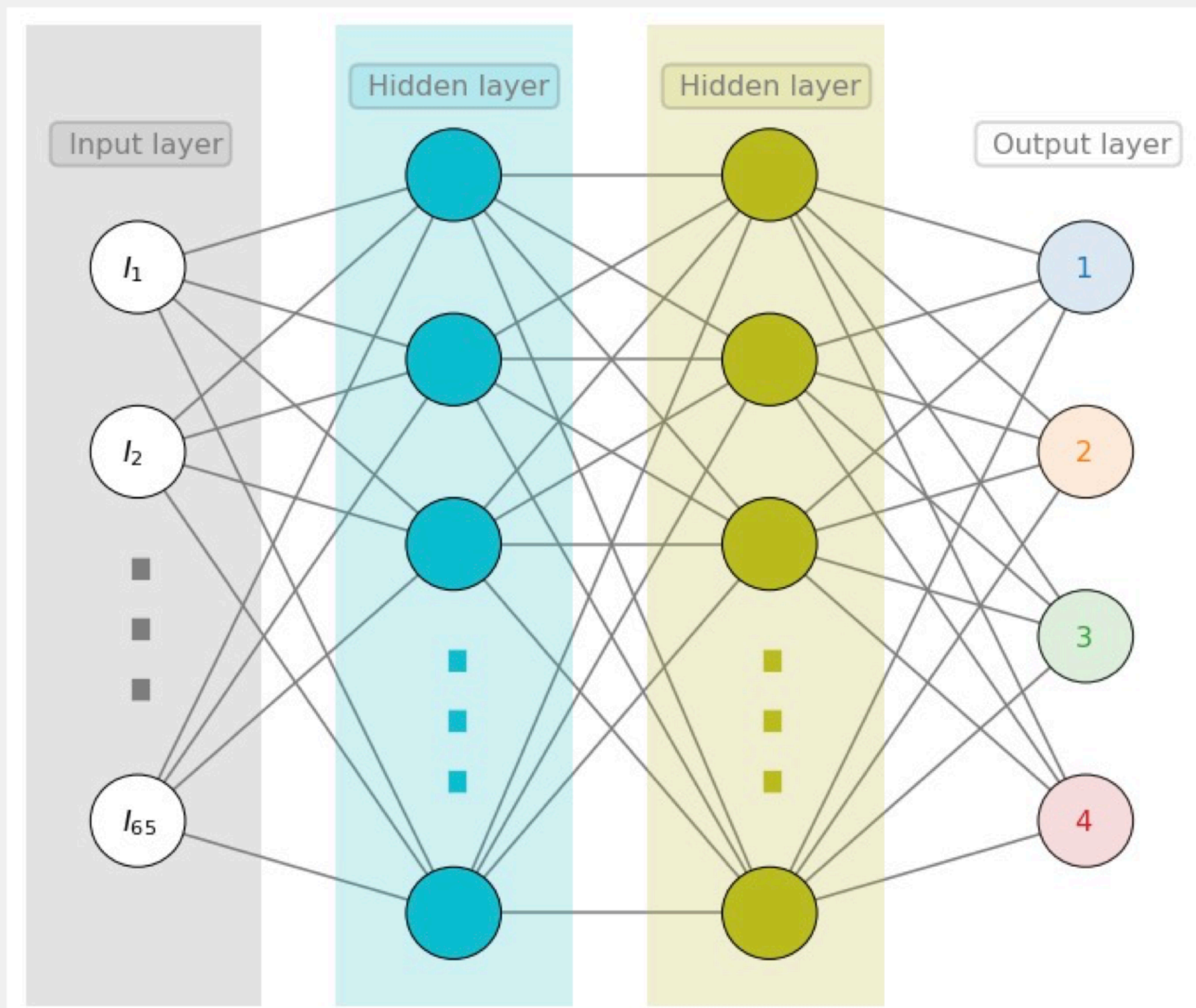
Neural networks as classifiers

Training



Neural networks as classifiers

New picture



Dog	3%
Cat	96.8%
Rat	0.1%
Pig	0.1%

Disclaimer: Made up percentages

Explainability

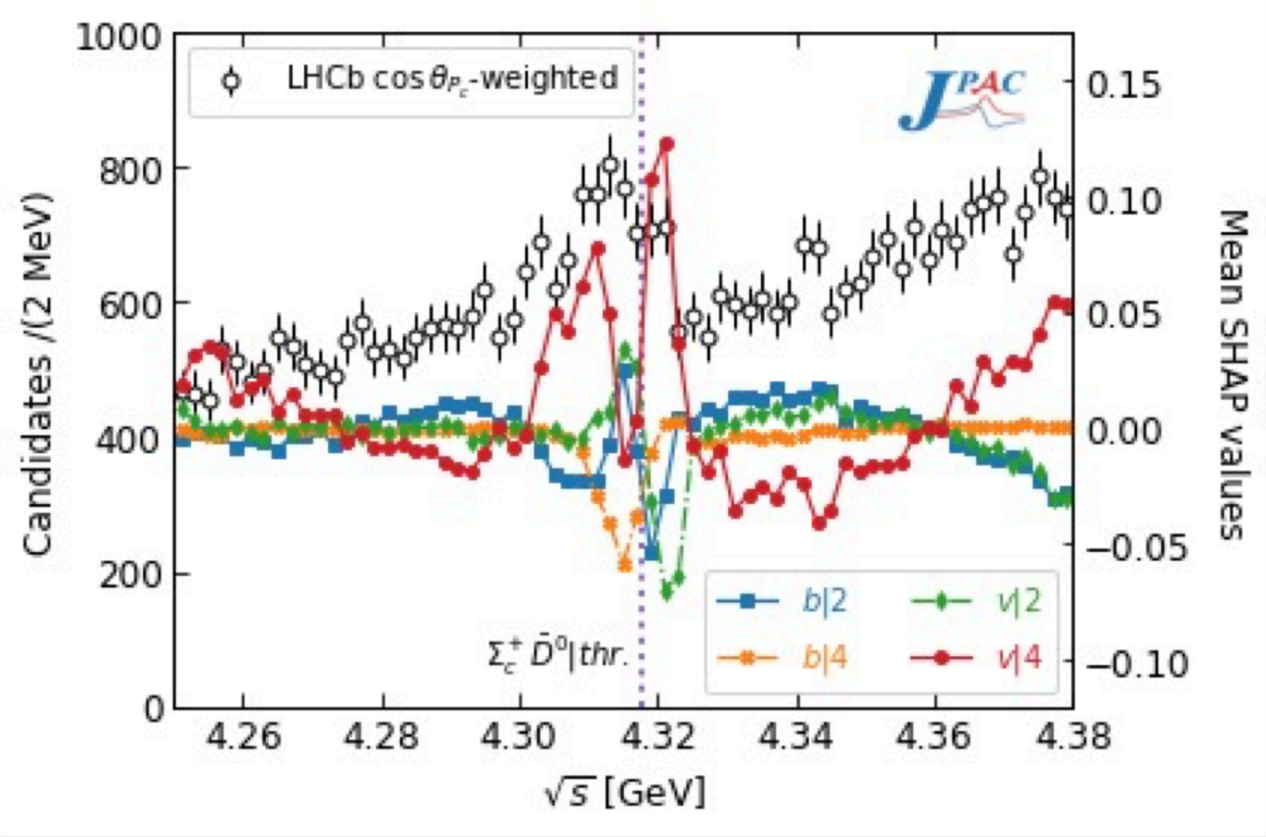
SHAP values

- *SHapley Additive exPlanations*

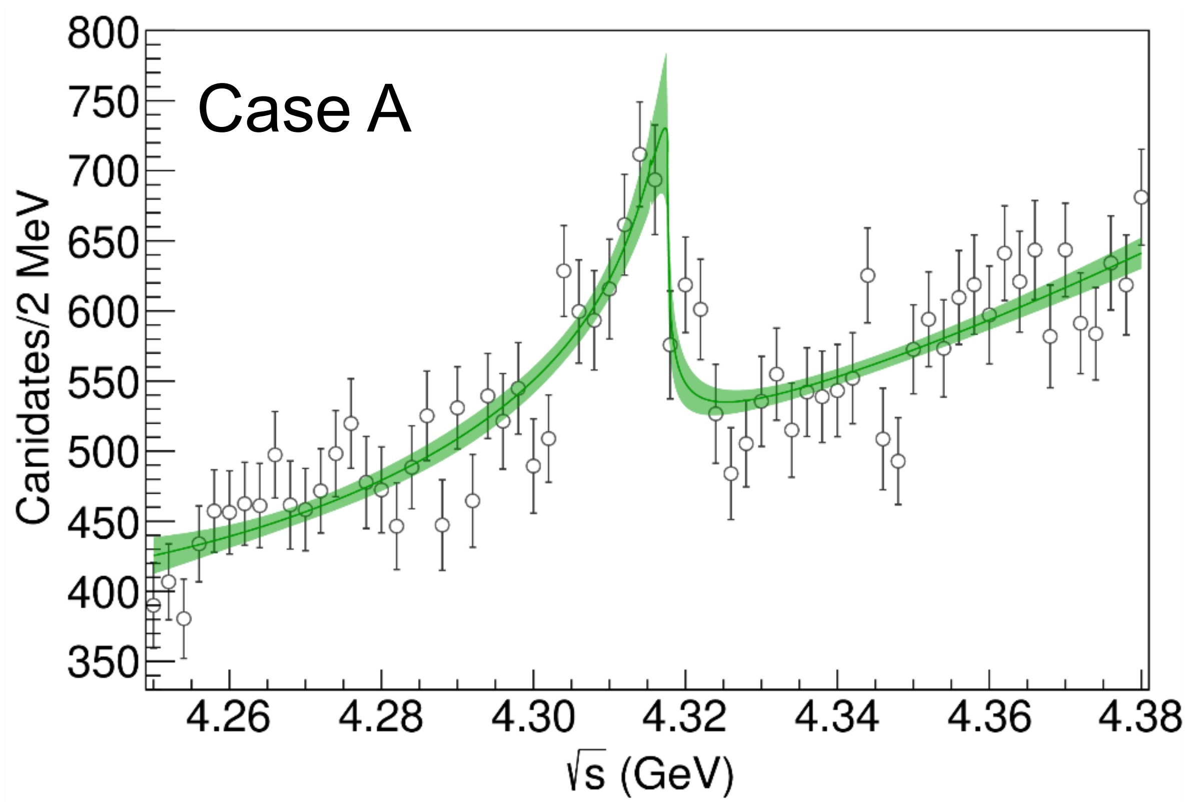
Inherited from game theory

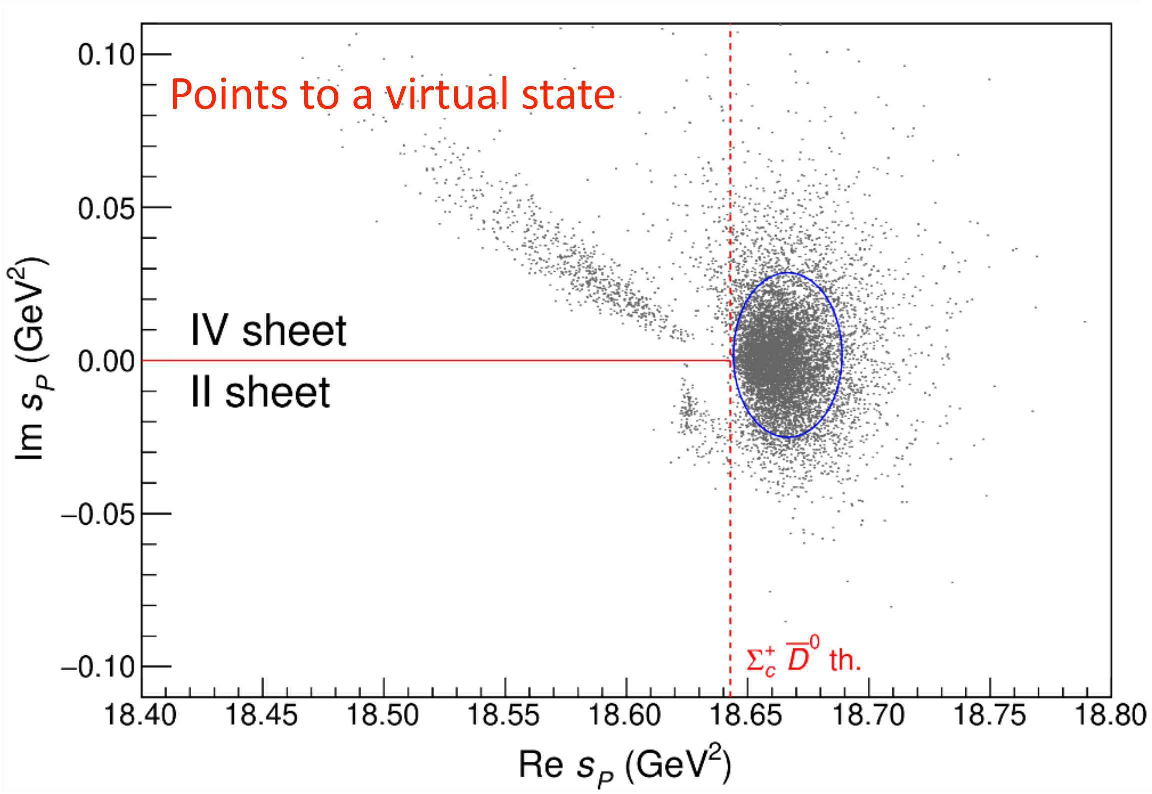
Application

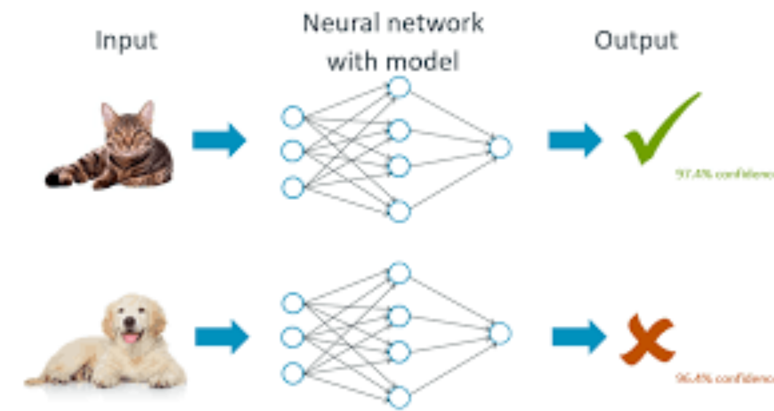
- *Allows to determine how a given feature in the input layer (in our case an experimental datapoint) impacts the decision made by the NN in the output layer (the classes)*

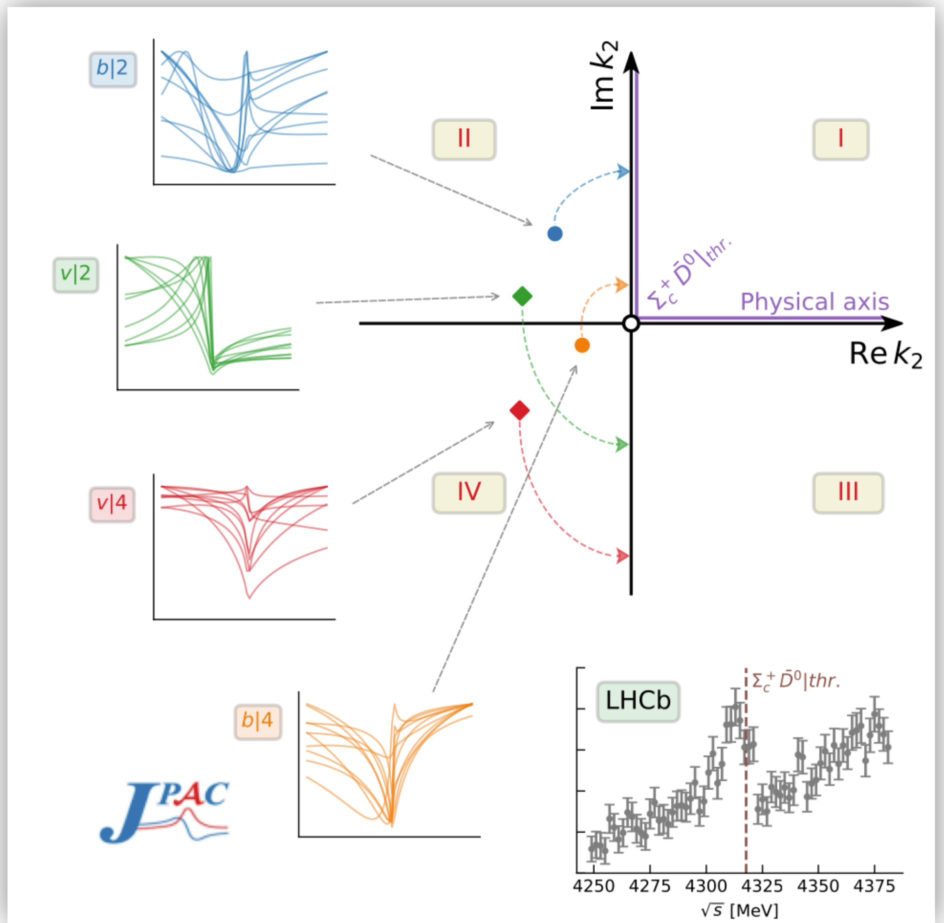


AI/ML in spectroscopy



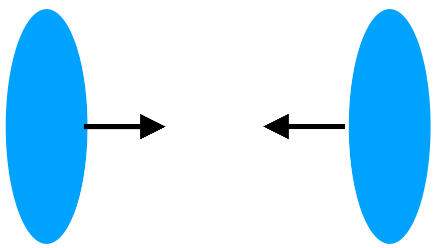




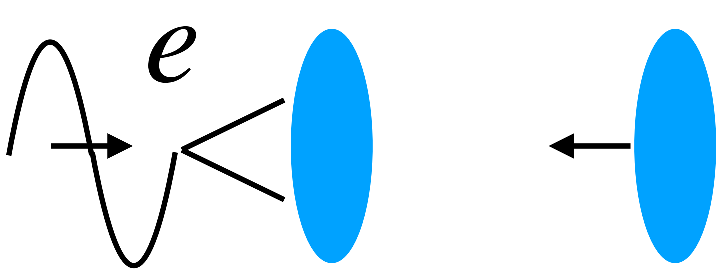


Simple remarks about cross sections

$$\sigma_{a+b \to c+b} \sim \pi R_{eff}^2$$

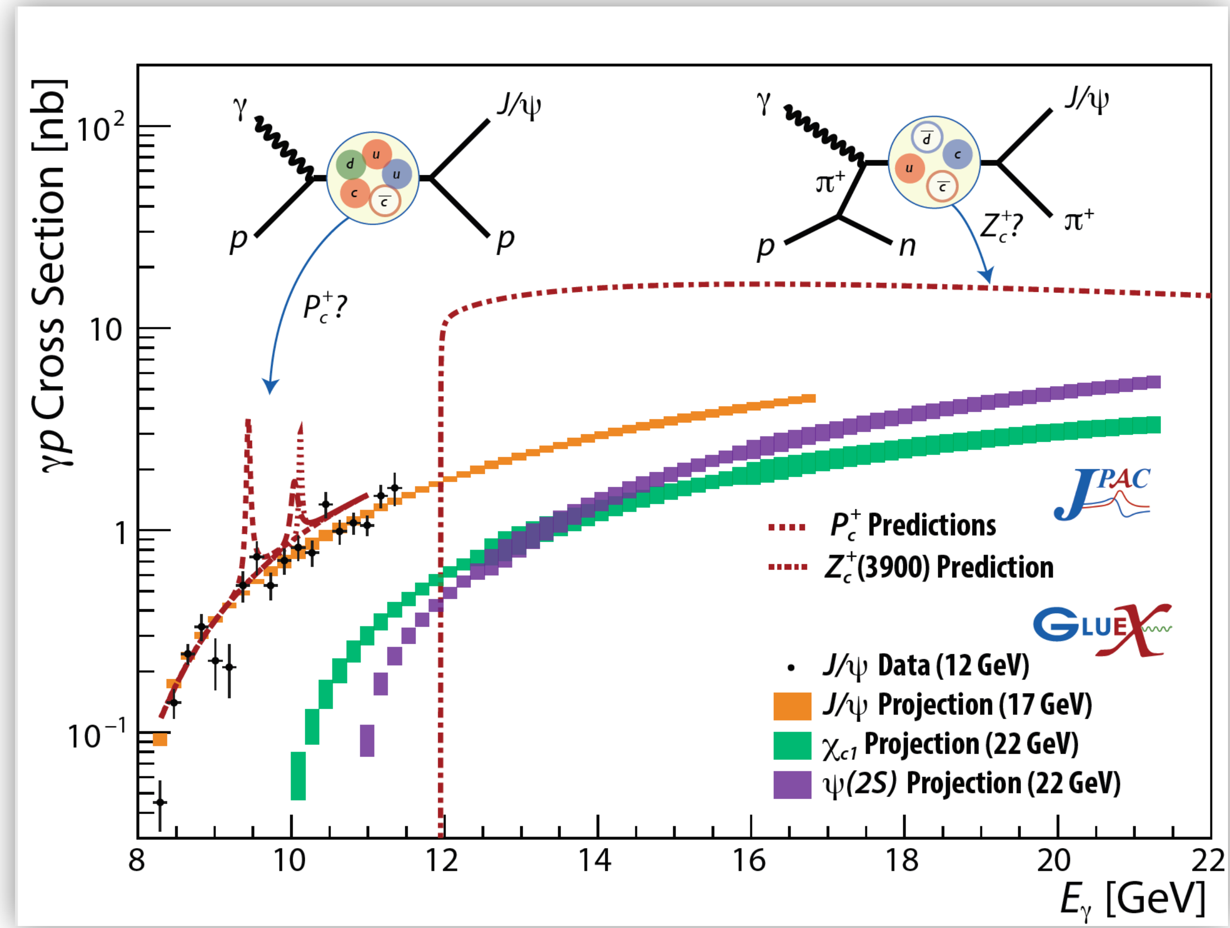


$(1 - 100)\ mb$



$(0.1 - 10)\ mb$

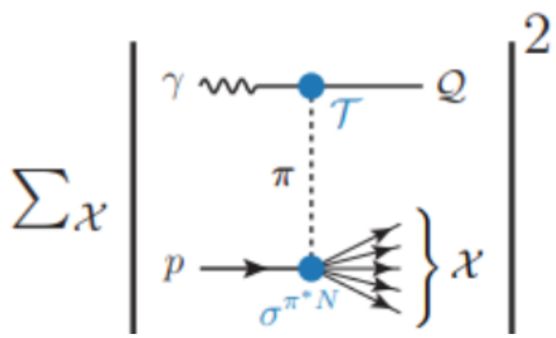
- XYZ production cross section ~ 1 mb
- XYZ detection = production x branching ratio



courtesy of M.Shepherd

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

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



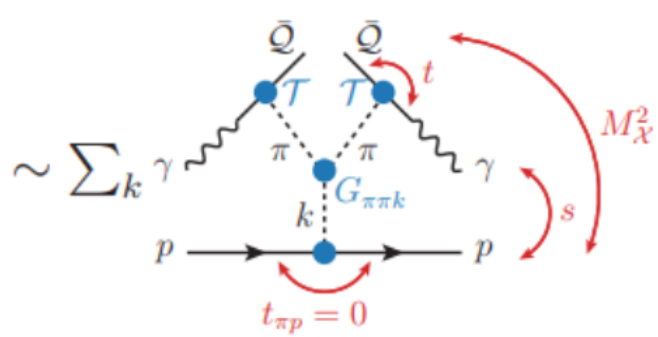


TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100(GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1};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

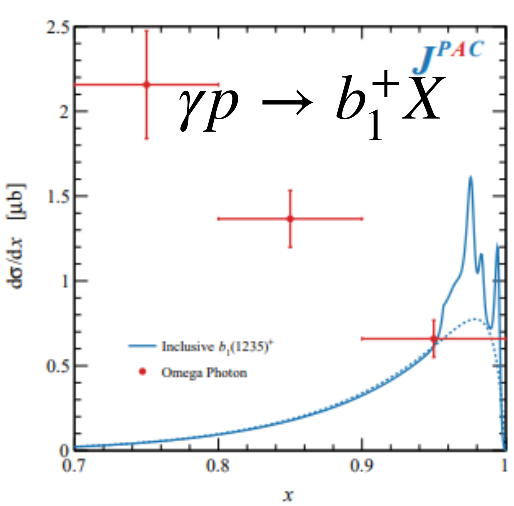
Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$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

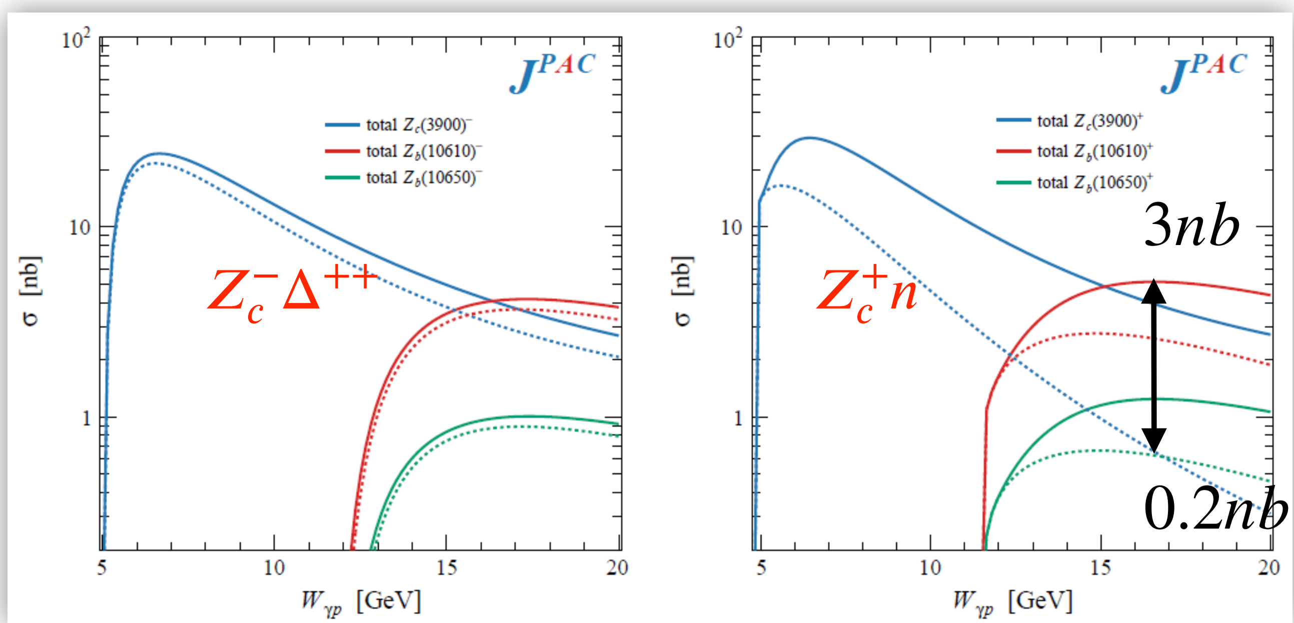
C++ code available online (D. Winney)

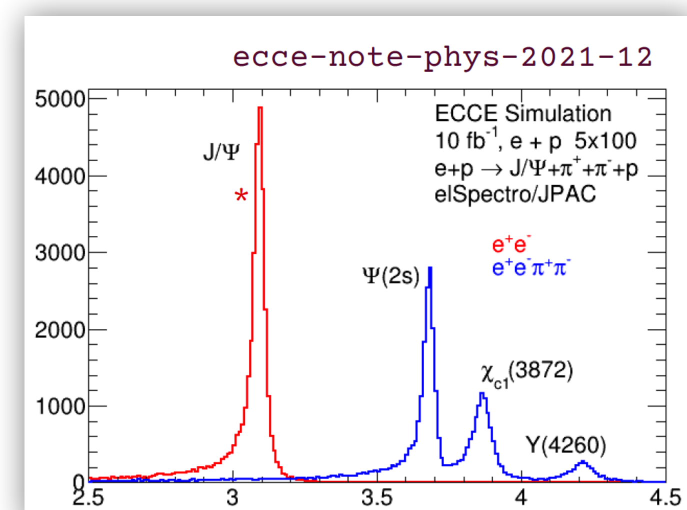
Implementation in simulation with El-Spectro (D. Glazier)

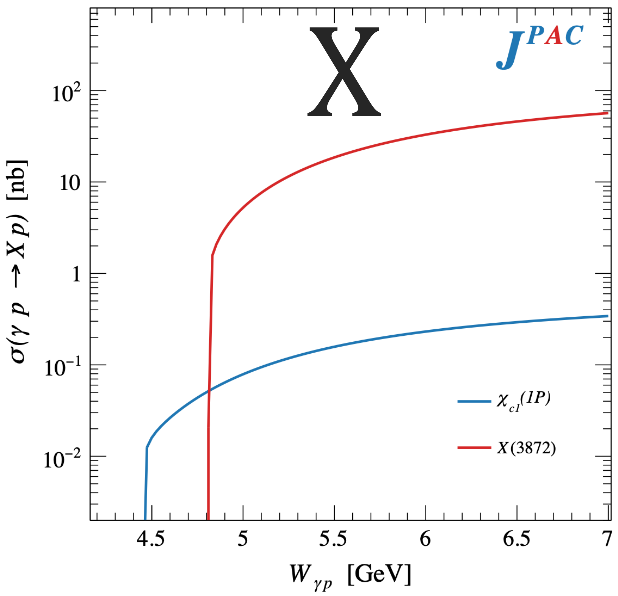
- Couplings from data as much as possible, not relying on the nature of XYZ
- The model is expected to hold in the highest x- bin
- Model underestimates lower bins, conservative estimates

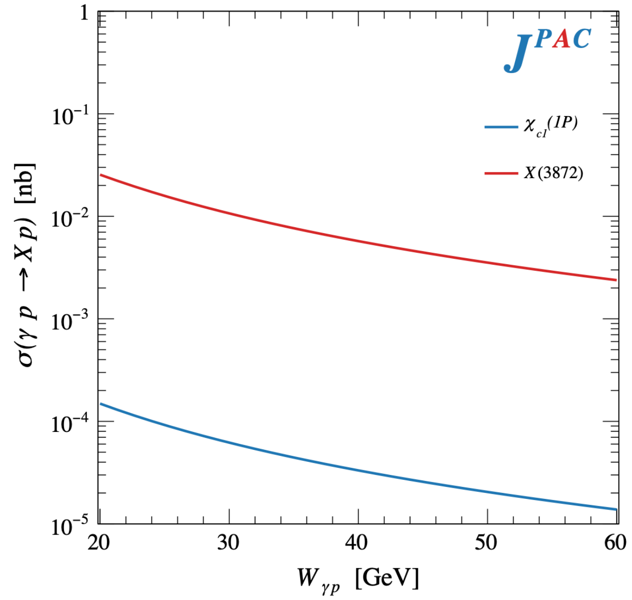
https://github.com/dwinney/jpacPhoto



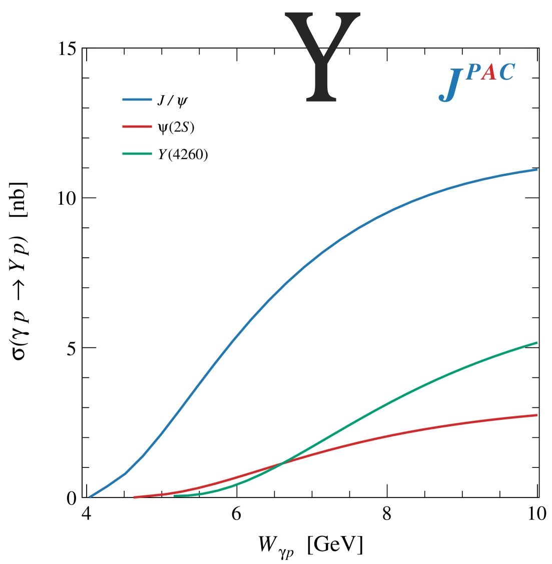


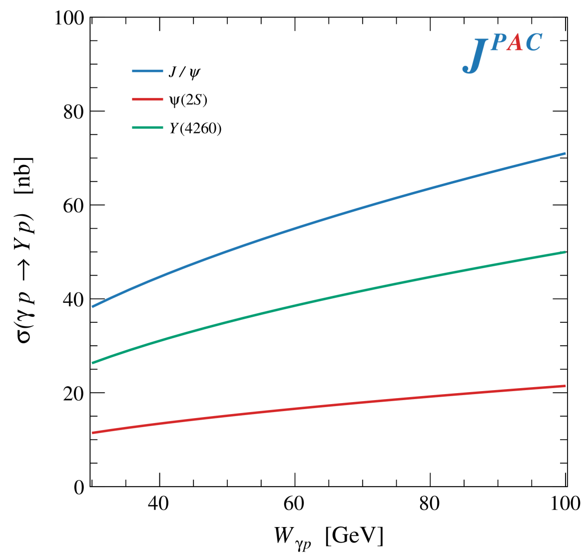




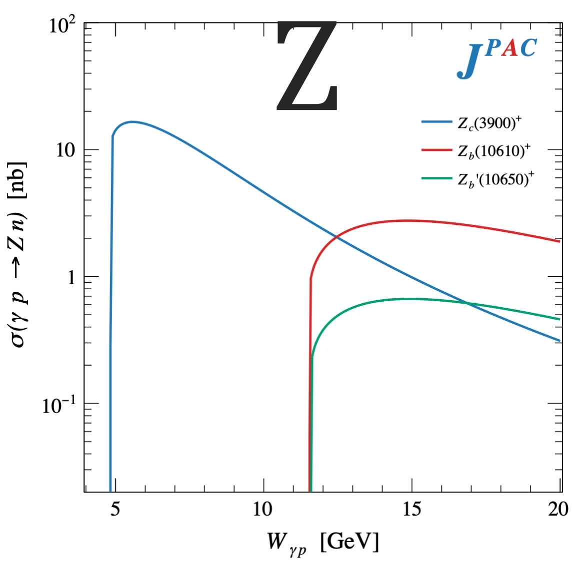


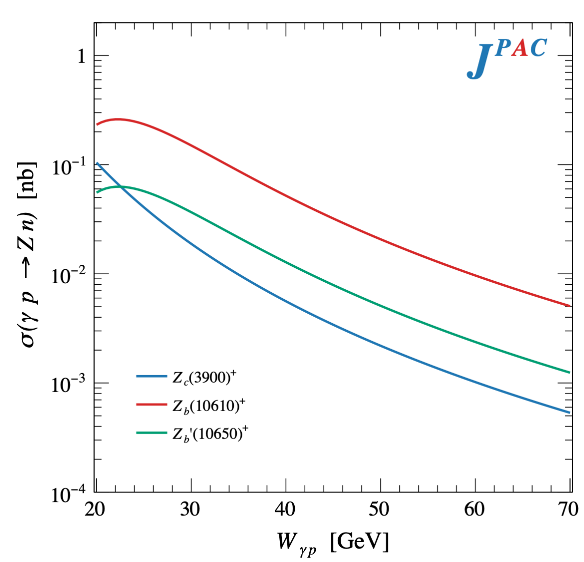
- **ω** and **ρ** exchanges give main contributions:





- Diffractive production, dominated by Pomeron (2-gluon) exchange. Benefits from higher energies at the EIC

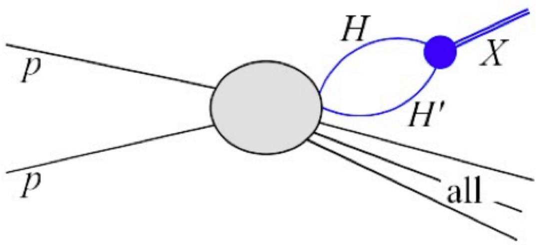




- Focus $Z_c(3900) \to J/\psi\pi$, $Z_b(10610) \to \Upsilon(nS)\pi$, pion is exchange

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 phot-electro/production (reviews)

$XYZP$ 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)

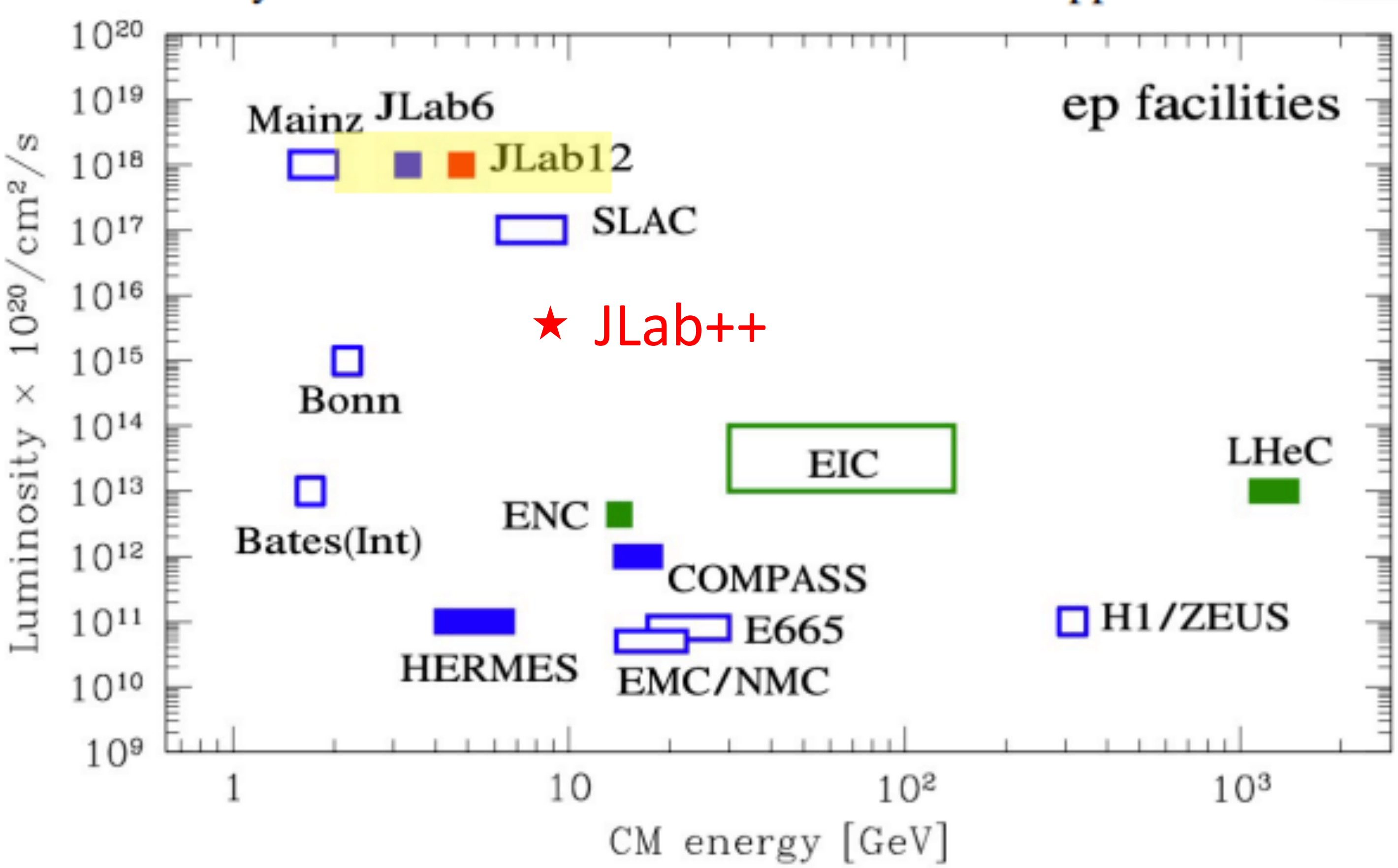
Hadron Spectroscopy in Photoproduction

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

J/ψ photoproduction near threshold

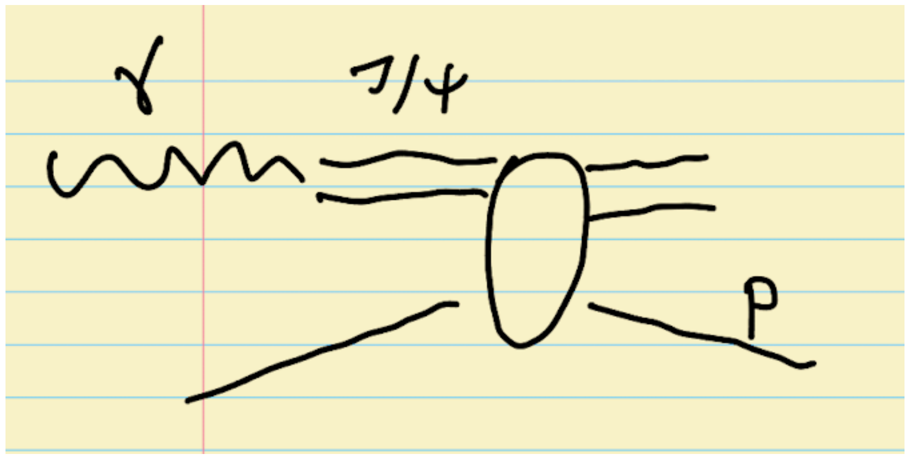
- Heavy vector quarkonium near threshold possibly relevant for extracting unexplored nucleon properties (mass radius, gravitational form factors, etc.)
- Signal channel also contains hidden-charm pentaquark candidates seen at LHCb.
- Abundance of new data coming from Jefferson Lab on energy and angular dependence of x-section.

GlueX [arXiv:2304.03845]

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

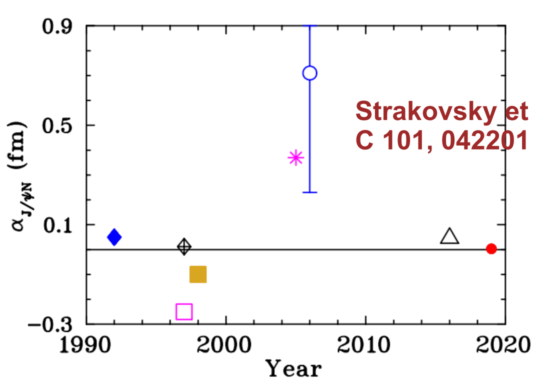
J/ψ near threshold

- VMD (is a specific production model)



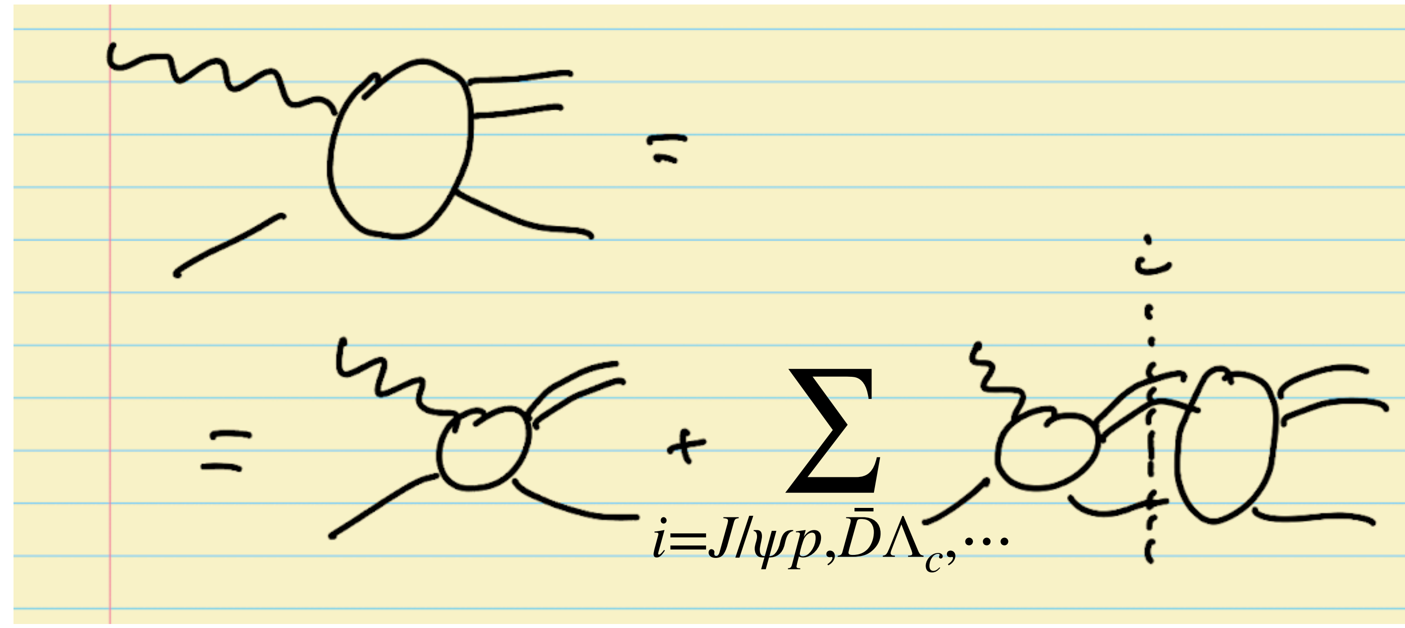
$$T_{\gamma p \to \psi p} \propto \left(\frac{ef}{m_\psi}\right)(8\pi E_{th}) a_S$$

ψp scattering length



Strakovsky et al [Phys. Rev. C 101, 042201 (2020)]

- In general



$$T_{\gamma p \to \psi p} \propto (8\pi E_{th}) r_{\gamma p \psi p}(1 - i a_S k_f + O(k_f^2))$$

Range of $c\bar{c}$ photo-production

x-section @ threshold determines $r_{\gamma p \psi p}$

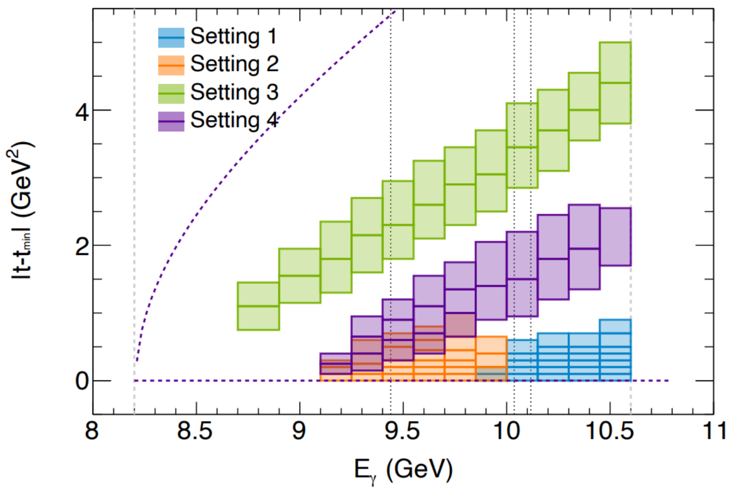
while energy dependents gives a_S

J/ψ photoproduction near threshold

- Fit energy and mom-transfer using s-channel partial waves

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\left(\frac{k_f}{k_i}\right)|T_{\gamma p \to \psi p}(s,\theta)|^2$$

$$T_{\gamma p \to \psi p}(s,\theta) = \sum_{l=0}^{l_{max}} (2l+1) T_l(s) P_l(\theta)$$



- Since $T_l(s) \sim (k_i k_f R^2)^l$ convergences requires $(k_i k_f R^2) < 1$

  We find $k_f k_i R^2 \le 1$ for $E_\gamma \sim 20 GeV$

- Determine $r_{\gamma p \psi p}$ and a_S from normalization and energy dependence

  - Generalizations :
    - Coupled channels $\bar{D}^{0(*)}\Lambda_c^+$ Du et al [Eur. Phys. J. C 80 (2020) 1053]
    - Extension of effective Range $K_l(s) = k_f^{2l}(a + bk_f^2 + \cdots)$
    - Statistical analysis

Fit results/conclusions

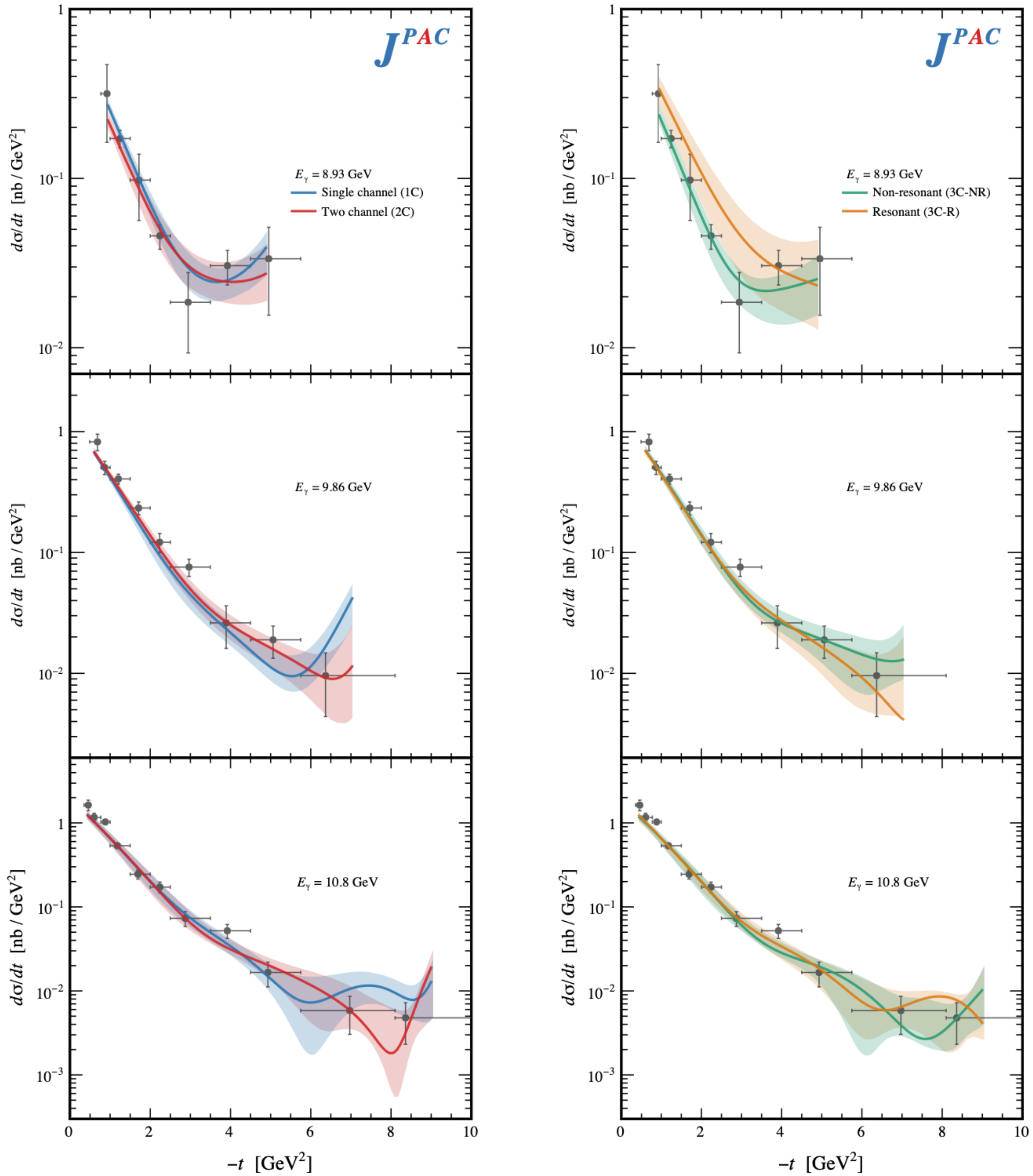


FIG. 2: Fit results for the differential cross section compared to GlueX data from [37]. The bands correspond to the 1σ uncertainties from the bootstrap analysis.

- Angular dependence saturated by the 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

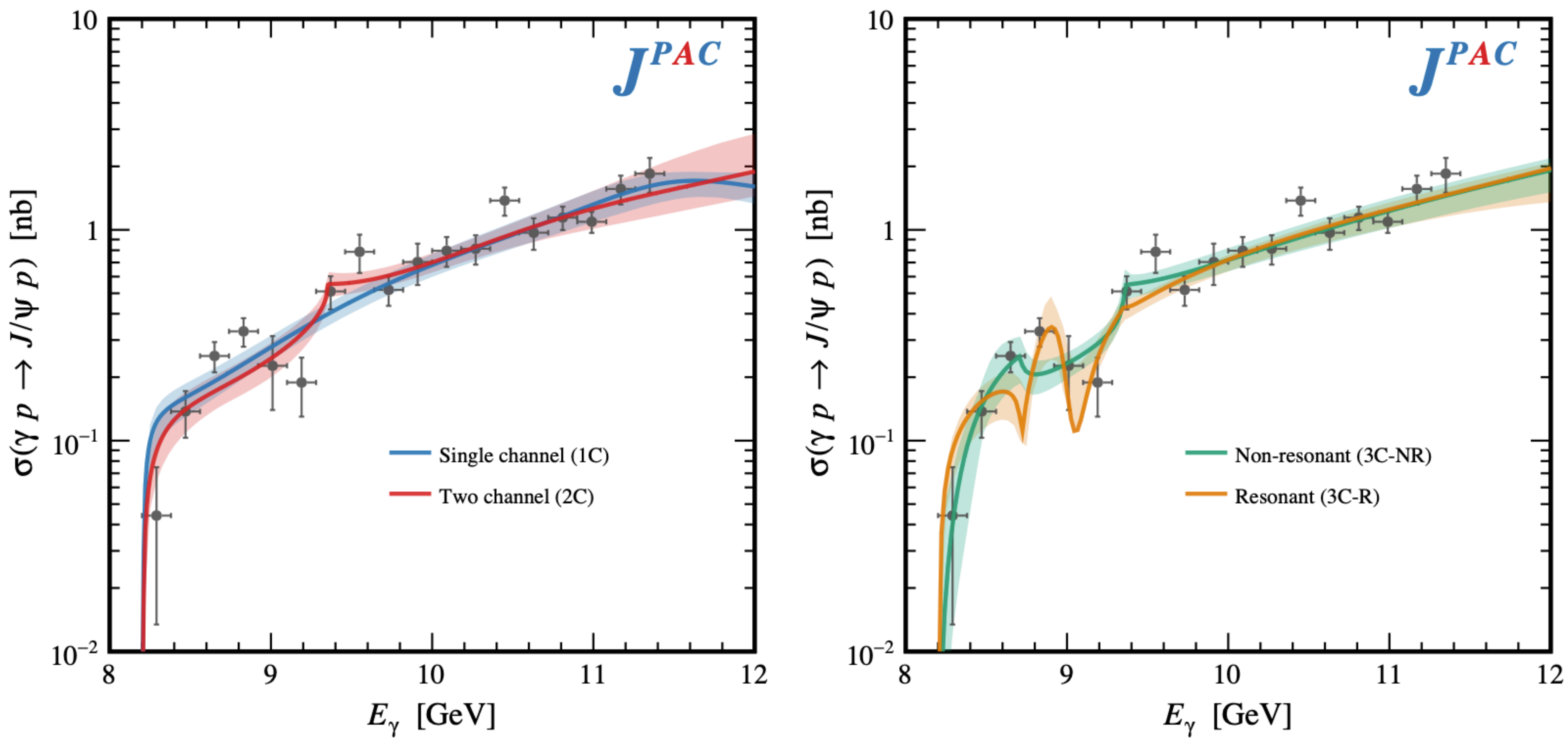
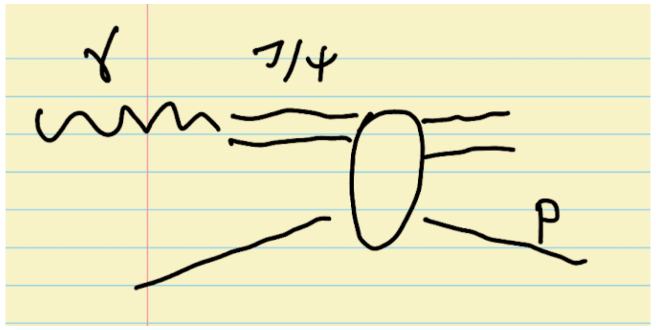


FIG. 1: Fit results for the integrated cross section compared to GlueX data from [37]. Bands correspond to 1σ uncertainties from bootstrap analysis.

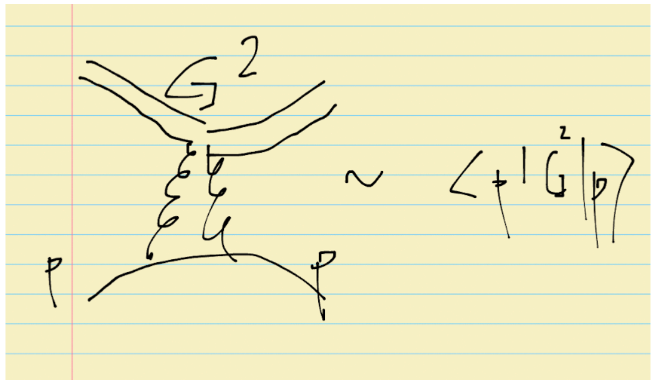
- Elastic $\psi p \to \psi p$ scattering length $a_S \sim O(0.1 fm)$ found incompatible with VMD expectations (albeit with large errors)
- Inclusion of open charm reduces the discrepancy
- Fits also suggests relevance of open charm production and not incompatible with pentaquark production Du et al [Eur. Phys. J. C 80 (2020) 1053]
- Need more precise data, including open charm production

Comments/comparison with popular wisdom



- VMD, GPD, Brodsky at al. : proton is spectator while $c\bar{c}$ is produced only -> $\sigma \sim a^2_{\psi p}$
- $\sigma \sim |n(1 - i a_{\psi p} q + O(q^2))|^2$

- In the residual of ψp, $c\bar{c}$ propagates freely and weakly interacted with the target -> $G_{\alpha_1\alpha_2} D^{\alpha_3} \cdots D G_{\alpha_{n-1},\alpha_n}$



- threshold determines s-channel (in dual models pentaquark proaction is tiny)

- Twist = Dimension - Spin (t-channel) $G_{\mu\alpha}G^{\alpha\nu}$ e.g. 4-2 = 2

  PDF's : fixed twist, all spins = all partial waves (moments of pfd's are essentially t-channel partial waves)

- For $c\bar{c}$ production it often assumed (?) spin ≤ 2 Analytical in s (no physics of open charm)