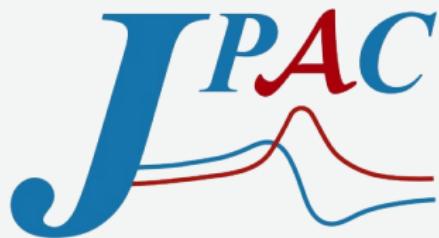


# Need for amplitude analysis in the discovery of new hadrons

*Snowmass*



Arkaitz Rodas

# Joint Physics analysis center

Full-time members



Misha



Cesar



Daniel



Viktor



Sergi



Alessandro



Lukasz



Astrid



Vincent



Adam



Miguel



Akaitz



Robert

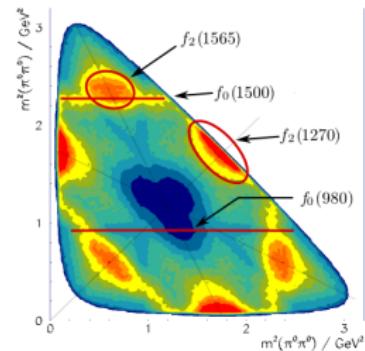


Jorge

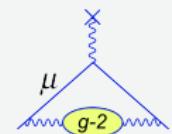
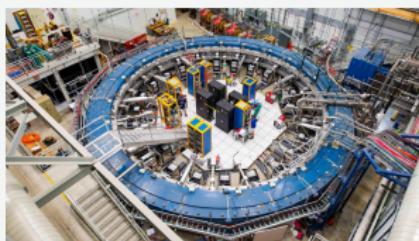


## DOE Long Range Plan

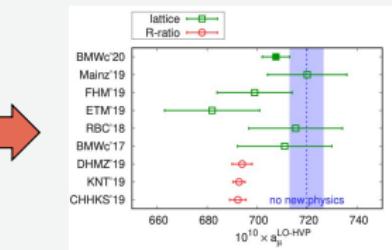
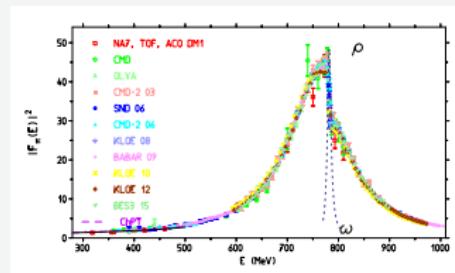
- Ordinary theory → build experiment → describe it!!
- QCD → Known theory → cannot solve it
- “ ... hadron spectroscopy illuminates the QCD interaction that binds quarks.”



## Looking for the beyond?



- $\sigma(e^+e^- \rightarrow \text{all}) \sim$



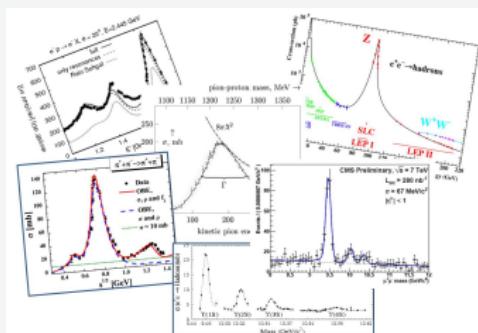
- Physics beyond what's known:

1. Muon magnetic moment  $\rightarrow (g-2)_\mu$
2. Nucleons mass dependence?  $\rightarrow \sigma_{\pi N}$
3. Rare B decays

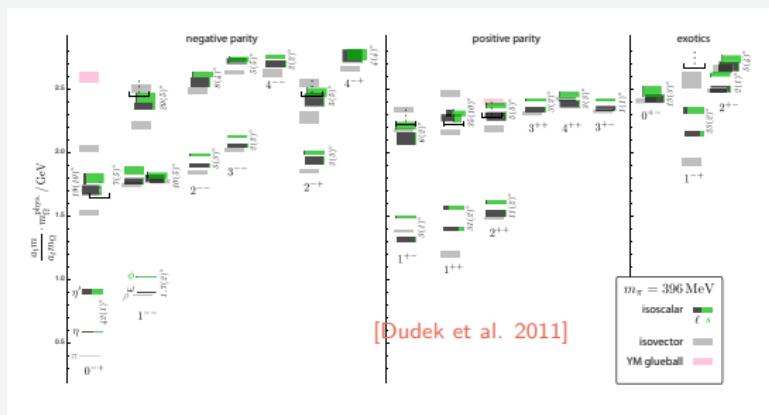
## ■ "Simple" analyses

$$t_\ell(s) = \frac{m\Gamma}{(s - m_R^2)^2 - im\Gamma}$$

Isolated, elastic, narrow



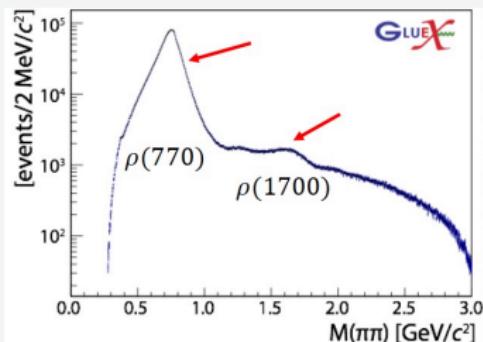
## ■ Lattice too      This plot → Not exactly QCD



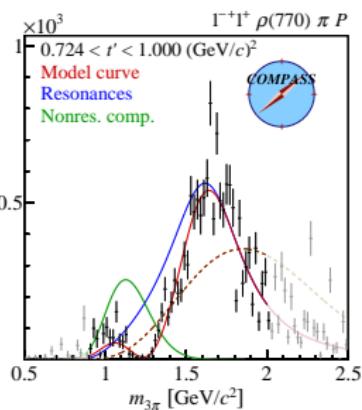
## Recent status

- Lots of modern data  $\longleftrightarrow$  simplistic models?
- Future experiments  $\longleftrightarrow$  Theory in place?
- Lattice QCD  $\longleftrightarrow$  Role of amplitudes?
- Accessing new phenomena  $\longleftrightarrow$  Toolkit?

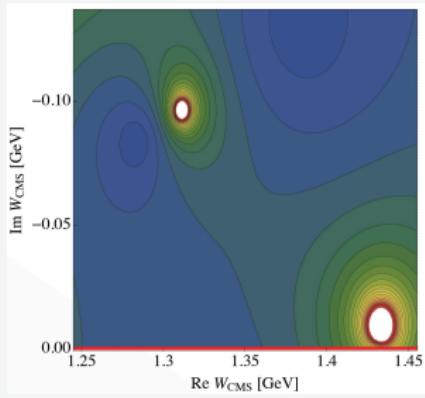
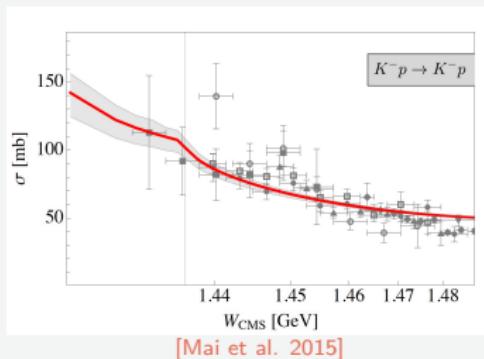
## ■ More complicated hadrons??



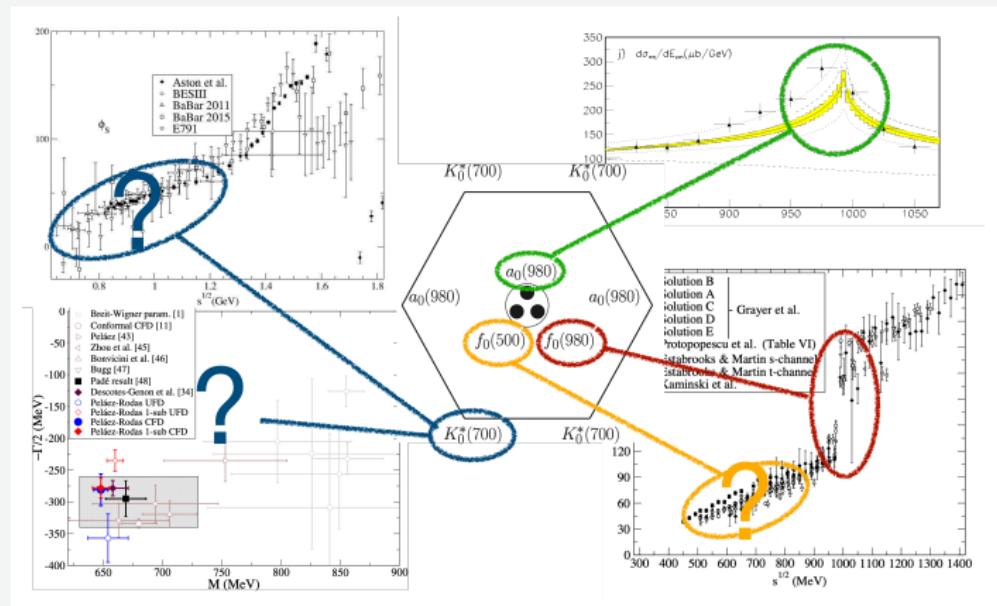
## 3-body effects



## ■ Multi-pole structures??

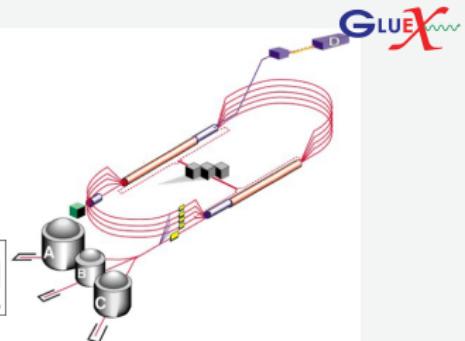


- $f_0(500)/\sigma d_\sigma < 4 \text{ fm} \rightarrow \text{final products}$
- Weak  $\pi, K, \eta$  decay  $\tau_{\pi^+} \sim 2 \times 10^{-8} \text{ s} \rightarrow \sim \text{meters}$



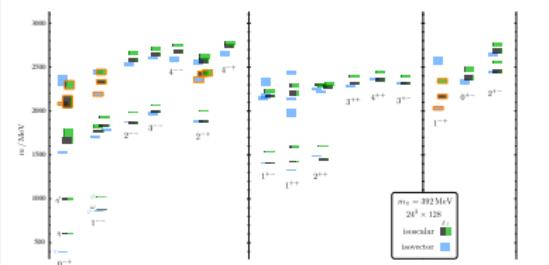
- Now this is complicated!!
- Model to describe this?

## ■ EXPERIMENT



## ■ LATTICE QCD

had spec



### Amplitude analyses: $S$ -matrix

- Unitary  $\rightarrow$  final states
- Symmetries  $\rightarrow$  flavor symmetry
- First-principles  $\rightarrow$  basic requirements



### Observables

# Theory support for spectroscopy

## Amplitude analyses: 3-body

- FF, decays → KT eqs.
- Learning more → X(3872)
- New challenges → a1(1260)
- Lattice QCD



## Ellaborated resonance studies

- Model-independent extractions??
- Broad objects →  $\sigma/f_0(500)$ ,  $\kappa/K_0^*(700)$ ,  $\pi_1(1600)$
- Near-threshold resonances →  $f_0(980)$ ,  $P_c(4312)^+$



## New techniques: ML / AI

- Complementary information on their nature →  $P_c(4312)^+$ ,  $Z_c(3900)$

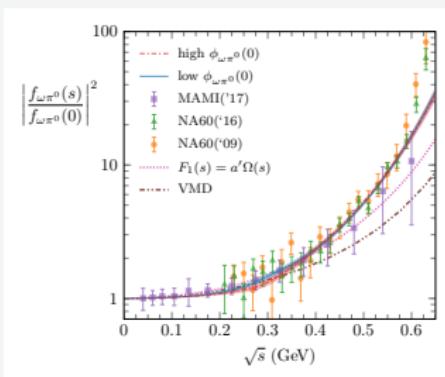


Experiment and theory bound together!!

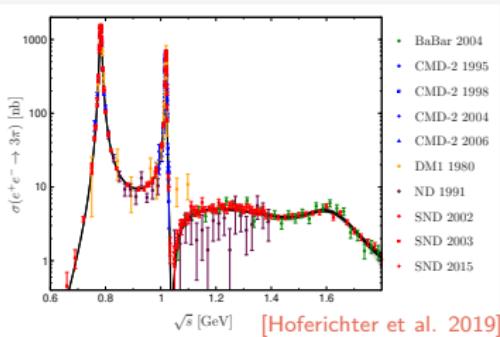
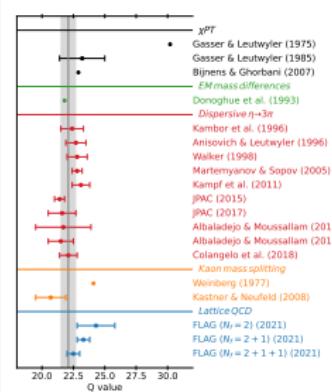
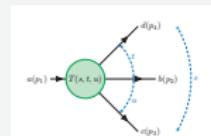
# Amplitude Formalism: Khuri-Treiman

## Studying 3 particle decays

- $F(s, t, u) \simeq F(s) + F(t) + F(u)$
- $\omega \rightarrow 3\pi \rightarrow$  transition form factor  
[Albaladejo et al. 2020]

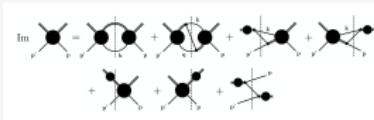


- $\eta \rightarrow 3\pi \rightarrow Q^2 = \frac{m_s^2 - (m_d^2 + m_u^2)/4}{m_d^2 - m_u^2}$
- $\gamma^* \rightarrow 3\pi \rightarrow (g-2)_\mu$  HVP and Hlbl

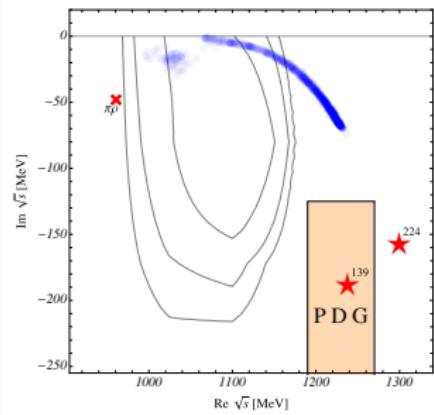
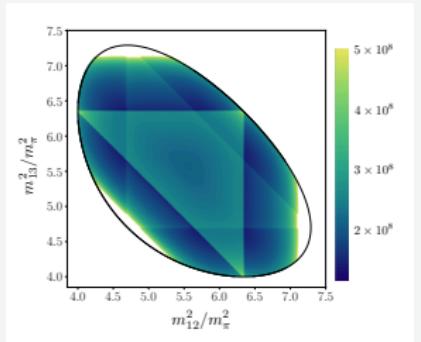
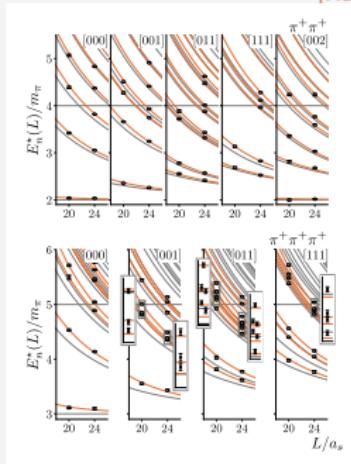


## Amplitude Formalism: 3 body

- From lattice QCD  $\rightarrow 3\pi \rightarrow$  Formalism is ready



[Hansen et al. 2021]



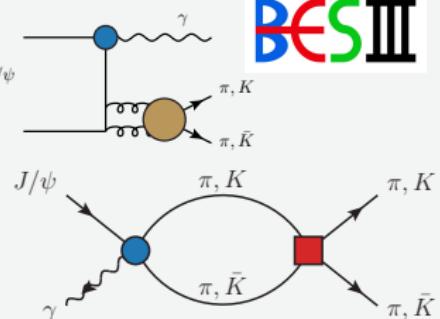
[Sadasivan et al. 2022]

## Resonance studies

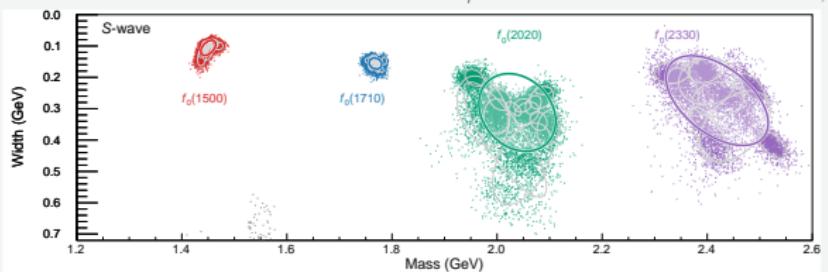
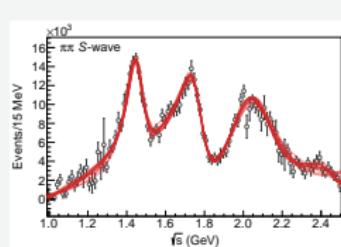
[Rodas et al. 2022]

- Isoscalar ( $0^{++}$ ) Glueball production

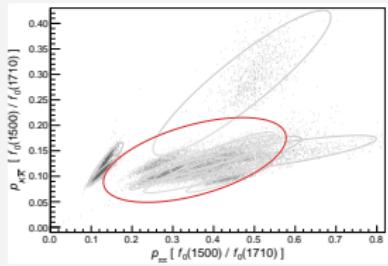
$a(s)$



- $S$ -matrix principles  $\Rightarrow Im a(s) = \rho(s) t^*(s) a(s)$



- Production  $P(f_0(1710))/P(f_0(1500)) \gg 1$
- Suggests  $f_0(1710)$  predominant Glueball

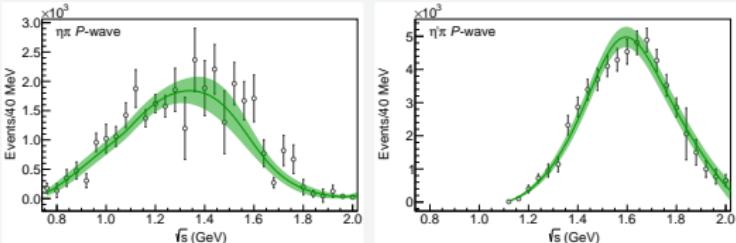


## Resonance studies

[Rodas et al. 2019]



- $\pi_1(1400)$  vs  $\pi_1(1600)$
- One hybrid meson  $\pi_1(1600)$



- Experiment+pheno  
+lattice QCD agree

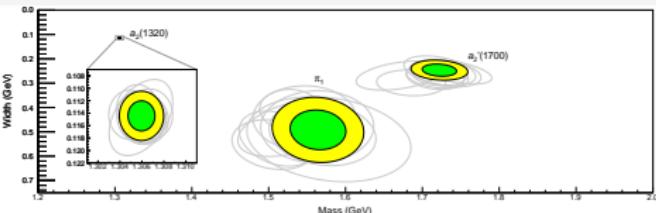
Confirmed by recent exp. and lat works

[Woss et al. 2020]

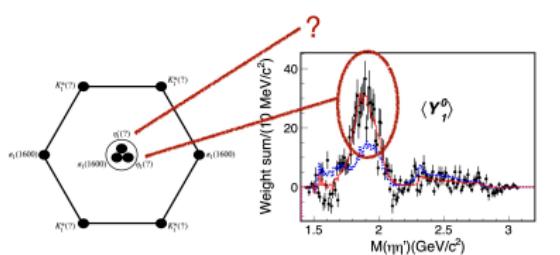
[Kopf et al. 2019]

- BESIII partner?

[Ryan's talk]



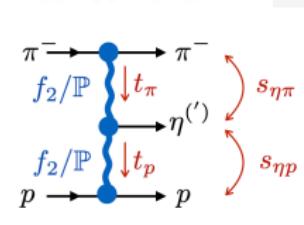
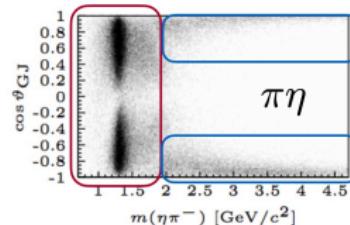
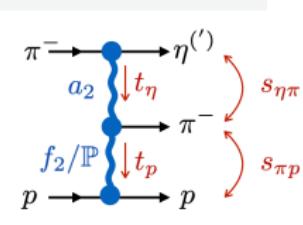
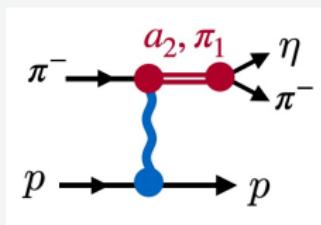
- There should be two!!



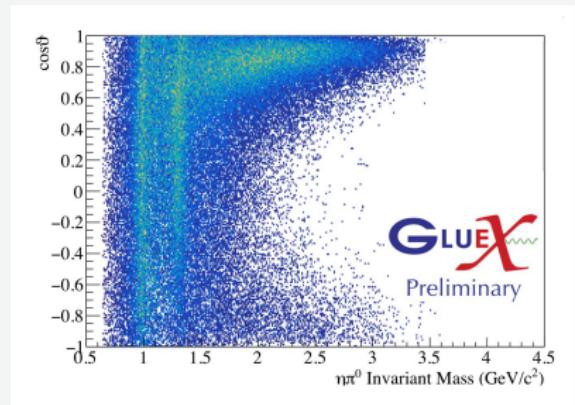
## Resonance studies

[Bibrzycki et al. 2021]

- $\pi_1(1600) \longleftrightarrow$  asymmetry

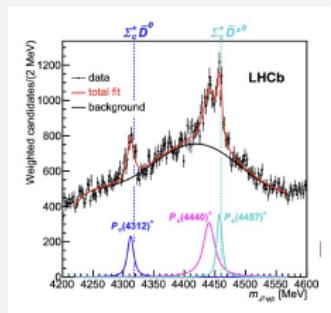
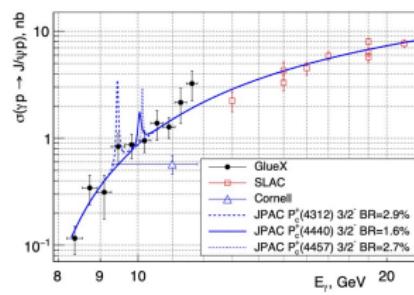


- GlueX  $\rightarrow$  double-Regge exchanges

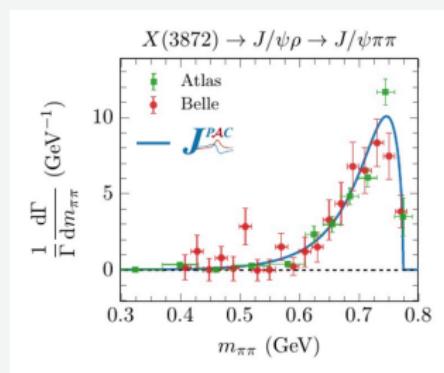
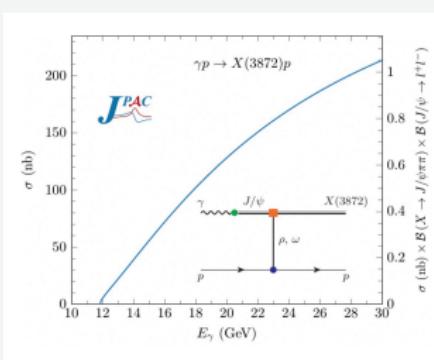


## Resonance studies

- Pentaquark  $\gamma$ -prod



- Compatible with available data!

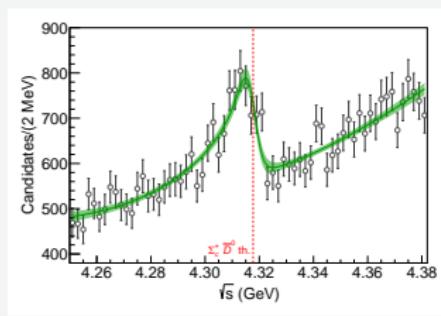
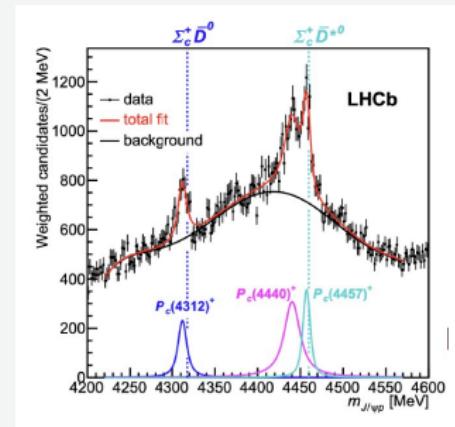
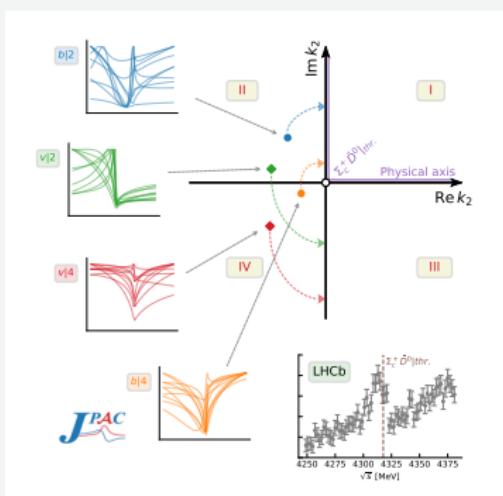


- Future facilities → XYZ at EIC/JLab ??  
[Justin's talk]

# AI for Exotic searches

[Ng et al. 2021]

- ML/AI to help us?
- Main benefit: Unbiased "model" selection



- $P_c(4312)^+ \rightarrow \text{VB state coupling strongly to } \Sigma_c^+ \bar{D}^0$

- Exciting times for spectroscopists!
- Lots of new Experiments and Lattice QCD information

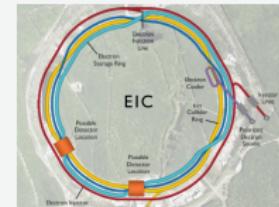


- High precision → Modern reaction techniques
- Exotic hadrons → Coupled channels
- Exotic hadrons → Multi-body states



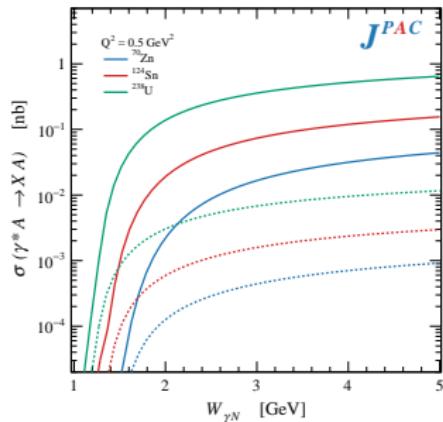
- EM effects → size/structure
- Exotics
- Approaching phys.  $m_\pi$
- Future 3 body analyses

- Crucial next few years!!

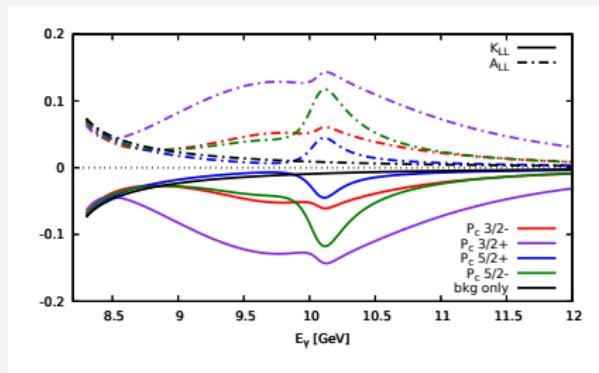


## New experiments

- XYZ at the EIC



- Selecting sensitive observables



- JLab Hall C → new information