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

Support for amplitude analyses
1 Motivation

DOE Long Range Plan

REACHING FOR THE HORIZON

- Ordinary theory → build experiment → describe it!!

- QCD → Known theory → cannot solve it

- “... hadron spectroscopy illuminates the QCD interaction that binds quarks.”

The Site of the Wright Brothers’ First Airplane Flight

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

Support for amplitude analyses
1 Motivation

Looking for the beyond?

- \( \sigma(e^+e^\rightarrow all) \sim \)

- Physics beyond what’s known:
  1. Muon manetic moment \( \rightarrow (g-2)_\mu \)
  2. Nucleons mass dependance? \( \rightarrow \sigma_{\pi N} \)
  3. Rare B decays

Support for amplitude analyses

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1 Motivation

- "Simple" analyses

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

Isolated, elastic, narrow

- Lattice too

This plot → Not exactly QCD

[Dudek et al. 2011]
Recent status

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

- More complicated hadrons??

- Multi-pole structures??

3-body effects

[Graph showing data and analysis]

Support for amplitude analyses

[Mai et al. 2015]
- \( f_0(500) / \sigma \, d_\sigma < 4 \) fm \( \rightarrow \) final products

- Weak \( \pi, K, \eta \) decay \( \tau_{\pi^+} \sim 2 \times 10^{-8} \) s \( \rightarrow \sim \) meters

- Now this is complicated!!

- Model to describe this?
Motivation

- EXPERIMENT

- LATTICE QCD

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 $\rightarrow$ KT eqs.
- Learning more $\rightarrow$ X(3872)
- New challenges $\rightarrow$ a1(1260)
- Lattice QCD

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

## New techniques: ML / AI
- Complementary information on their nature $\rightarrow$ $P_c(4312)^+$, $Z_c(3900)$

**Experiment and theory bound together!!**
Amplitude Formalism: Khuri-Treiman

Studying 3 particle decays

- \( F(s, t, u) \approx F(s) + F(t) + F(u) \)
- \( \omega \rightarrow 3\pi \rightarrow \text{transition form factor} \) [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

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Amplitude Formalism: 3 body

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

[Hansen et al. 2021]

- Including resonances $\rightarrow a_1(1260)$ extraction
- Future: $X(3872)$
- Far Future: $4\pi$ analyses $\rightarrow$ Glueballs

[Sadasivan et al. 2022]

Support for amplitude analyses A. Rodas
Resonance studies

- 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

Support for amplitude analyses
Resonance studies

- $$\pi_1(1400)$$ 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?

- There should be two!!
Resonance studies

- $\pi_1(1600) \leftrightarrow$ asymmetry

- **GlueX** $\rightarrow$ double-Regge exchanges

[Bibrzycki et al. 2021]
Resonance studies

- Pentaquark $\gamma$-prod

- Compatible with available data!

- Future facilities $\rightarrow$ XYZ at EIC/JLab ??

[Justin’s talk]
AI for Exotic searches

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

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

[Ng et al. 2021]
Prospects

- 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