## Amplitude Analysis: Physics and Tools

Matthew Shepherd Indiana University (CLEO Collaboration)

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- <u>Physics</u>
  - Light quark spectroscopy in charm decay
  - Study both production and decay of light systems
  - Shed light on the mysterious 1.0-2.5 GeV region
  - Motivate with recent CLEO and BES results
- <u>Tools</u>
  - Need amplitude analysis (or PWA) tools to extract the physics -fitting mass distributions doesn't work
  - Large data sets and complicated physics models demand significant computing resources
  - Discuss an experiment-independent analysis framework that is currently under development



# The Charm System

- <u>A laboratory for light quark physics</u>
- Running on the Ψ' provides clean access to a variety of states with different quantum numbers which decay into light hadrons through cc annihilation.
  - Decays are typically low-multiplicity which permits exclusive reconstruction and makes analyzing substructure possible.
  - Annihilation provides a "glue-rich" environment.



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## **Glueball Physics**

- A popular picture: three  $f_0(0^{++})$  states,  $f_0(1370)$ ,  $f_0(1500)$ , and  $f_0(1710)$ , where two are expected
- Much experimental progress: CBAR, WA102, BES, and others
- Are all experimental data consistent with a single picture?
  - need extensive cross checks in a variety of production and decay modes
  - need to better understand properties of states themselves, masses, widths branching fractions
- What about f<sub>0</sub>(1790)?

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- Naively unexpected results for f<sub>0</sub>(1370)
- In addition,  $J/\psi \rightarrow \omega f_0(1710)$ seems  $\geq J/\psi \rightarrow \phi f_0(1710)$
- Understanding production is critical!

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 $f_0$ 

#### Probing Gluon Dynamics

 Results on f<sub>0</sub> production in J/ψ decay are interesting... suggestive of large OZI violating effects in J/ψ decay? ....glueball mixing? (Close and Zhao, PRD 71, 094002)



 Yes! Use the factorization scheme proposed by Q. Zhao (PRD 72, 074001)



r = relative strength of doubly-OZI to singly-OZI suppressed transition amplitudes

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## $\chi_{cJ} \rightarrow \eta^{(\prime)}\eta^{(\prime)}$





- Update of previous CLEO analysis on 3M ψ' (PRD 75, 071101(R)(2007))
- Explores the role of DOZI production in pseudoscalars

**CLEO** Preliminary

B.F. (x10 <sup>-3</sup> )	<b>X</b> c0	<b>X</b> c2
ηη	3.18±0.13±0.18±0.16	0.51±0.05±0.03±0.03
η'η	<0.25 (90% CL)	<0.05 (90% CL)
η'η'	2. 2±0. 3±0.  ±0.	0.06±0.03±0.004±0.004 < 0.10 (90%CL)

Errors: (stat.)  $\pm$  (syst.)  $\pm$  (B( $\psi' \rightarrow \gamma \chi_{cJ}$ ))

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Data suggest small if any contribution for DOZI decays in the pseudoscalar channel.

What we would really like to probe are the scalars. This can be done through channels like  $\chi_{c0,2} \rightarrow f_0 f_0$  or  $\chi_{c2} \rightarrow f_2 f_0$ These analyses are significantly more complicated.



#### Hadronic X<sub>c</sub> Decay

- f<sub>2</sub> and f<sub>0</sub> are most accessible in two-pseudoscalar channels like ππ and KK: *four-hadron final* states are key
- Clean separation of the three χ<sub>c</sub> states guarantees initial state quantum numbers
- Access to a variety of final states and isospin combinations is very helpful
- Rich physics potential relies on ability to analyze substructure



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- Substructure in m and KK channels.
- Sensitivity to resonance properties and new resonances in the 1-3 GeV range
- Simultaneous analysis of multiple channels allows one to disentangle "physics backgrounds"
- But analysis is more complicated than just these histograms...



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- Examination of Kπ combinations shows strong K<sup>\*</sup> production also which will reflect into other mass projections
- Kππ resonances also present
- Need a full amplitude analysis to pull out physics
- First work done by BES on  $\chi_{c0} \rightarrow K^+ K^- \pi^+ \pi^-$ (PRD 72, 092002)



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#### Physics Recap

- Through hadronic decays of cleanly separated states, I<sup>--</sup>, 0<sup>++</sup>, I<sup>++</sup>, 2<sup>++</sup>, in the charm system we can systematically study light quark systems
  - $\Psi$  data is ideal because it allows tagged access to all of these "initial" states
- Study <u>production</u>:
  - How well do we understand the OZI rule in production? Can production of scalar mesons against "flavor tags" helps us understand the "scalar puzzle"?
- Study <u>decay</u>:
  - Simultaneously fitting multiple channels in isospin space may greatly help in sorting out physics ambiguities in fits.
  - Simultaneously fitting different final states provides sensitivity to relative branching fractions

$$\frac{\mathcal{A}(\boldsymbol{\chi}_{c0} \to f_0 X)[KK\pi\pi]}{\mathcal{A}(\boldsymbol{\chi}_{c0} \to f_0 X)[\pi\pi\pi\pi]} \propto \frac{\mathcal{B}(f_0 \to KK)}{\mathcal{B}(f_0 \to \pi\pi)}$$

• Fitting directly for masses and widths may be the best way to search for new resonances and measure their properties

...we need a comprehensive set of analysis tools to tackle this!



## Amplitude Analysis



- Limitations/Features:
  - CPU intensive unbinned fit is needed to deal with large number of phase space dimensions
  - Decay amplitudes are challenging to write and even more challenging to code
  - To optimize fit, *typically* decay amplitudes do not contain fit parameters. This makes it hard to fit directly for "decay physics" like masses widths of resonances.

#### **Computing Demands**

- In the case of a Dalitz analyses, efficiency can be parametrized as a function of location on the Dalitz plot -- independent of physics or amplitudes
- Parametrizations are no longer useful or possible for large, high-dimension phase space and one uses acceptance weighted integrals of the amplitudes over phase space in the likelihood calculation

single event intensity  

$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!} \prod_{i=1}^n \frac{I(\Omega_i)}{\int \eta(\Omega)I(\Omega)d\Omega}$$
minimize probability normalization

$$-\ln \mathcal{L} \propto -\sum_{i=1}^{n} \ln \left( \sum_{\alpha,\alpha'} V_{\alpha} V_{\alpha'}^* A_{\alpha}(\Omega_i) A_{\alpha'}^*(\Omega_i) \right) + \sum_{\alpha,\alpha'} V_{\alpha} V_{\alpha'}^* \left( \frac{1}{N_{MC}^{Gen}} \sum_{i=1}^{N_{MC}^{Acc}} A_{\alpha}(\Omega_i) A_{\alpha'}^*(\Omega_i) \right)$$

- "Expensive" -- compute numerically using MC, <u>but constant as long as A's aren't</u> <u>changing with each fit iteration</u>. *This limits decay model flexibility*.
- Likelihood calculation is a difference of sums over data and Monte Carlo: ideal for parallel computing

...remove physics limitation (optimization) by using more compute power.

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#### Collaborative Research: Open Access Amplitude Analysis on a Grid

A. R. Dzierba, G. C. Fox, M. R. Shepherd and A. P. Szczepaniak Indiana University, Bloomington, IN C. A. Meyer

C. A. Meyer Carnegie Mellon University, Pittsburgh, PA R. T. Jones University of Connecticut, Storrs, CT J. J. Dudek Old Dominion University, Norfolk, VA



Distributed Data Storage and Compute Elements



- Desire to develop modular analysis package that
  - scales to very large data sets
  - is generally applicable (experiment independent)
  - works for any physics model
  - is distributed: allows anyone to analyze data anywhere
- Development driven by need to analyze massive data set from the GlueX experiment in ~2014
- Start work now -- prototype components on existing data
- Funded by NSF Physics at the Information Frontier program

## Development Status

- About to enter the first year of a three-year development plan
- Build off of existing core tools and knowledge:
  - library of routines developed for writing kinematics in covariant tensor formalism
  - experience with fitting: ability to do CLEO-c fits using "parallelized" code on a cluster of about 100 machines
- Focus on optimization, user interfacing, and grid computing
- Plan for a polished open-source package that is available for general use

#### $\chi_{c0} \rightarrow KK\pi\pi \text{ via}$ $\chi_{c0} \rightarrow K_1^*K; K_1^* \rightarrow K^*\pi; K^* \rightarrow K\pi$

complicated angular structure! Write Lorentz-covariant decay kinematics:

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- The charm system provides a wealth of opportunities for trying to understand the light quark meson spectrum and glueballs.
- To take advantage of these opportunities, we need high statistics data samples in a variety of production and decay modes: large data samples at CLEO-c now even larger at BES III in the future
- <u>Statistics alone is not enough</u> -- one needs a comprehensive suite of amplitude analysis tools to extract the physics and fully probe the spectrum of decay models to understand ambiguities, limitations, etc.
- Work is now underway at CLEO-c and also other experiments to develop analysis machinery to both handle tomorrow's huge data sets and to separate physics from computational challenges -- <u>there are great possibilities for</u> <u>collaboration</u>.
- CLEO-c is an ideal place to do this work, and, in the future, we look forward to the exciting results that will come from BES III!