Exotic states at LHCb

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1 What are exotic states?

- We are very familiar with the well established colour-neutral $q\bar{q}$ mesons and qqq baryons
- States such as $qqqq\bar{q}$ (pentaquark), $qq\bar{q}\bar{q}$ (tetraquark) are allowed and even postulated in Gell-Mann's and Zweig's original quark model papers (1964)
- We refer to any hadron that does not follow $q\bar{q}/qqq$ as exotic
- LHCb is in a unique position to search for exotic contributions in decays of all b hadrons

What principle means that hadrons have to be colour-neutral?

2 A few key concepts

- A 3-body pseudoscalar decay $X \to 123$ can be completely described by 2 independent variables m_{12} and m_{23}
- A Dalitz plot is a 2D scatter graph of these 2 independent variables showing the resonant substructure of the decay
- Dalitz plots can show the resonances (amplitude components/decay paths) present in a decay, resonances' spin and interference between resonances
- The interference between resonances creates a complex phasespace distribution and gives us access to the amplitude component phases
- Amplitude analyses (sometimes in many dimensions) fit the resulting phasespace distribution to decompose the total amplitude of a decay into amplitude components, A_i, each weighted by a complex coefficient, a_i

$$A_{\text{TOT}} = \sum_i a_i A_i$$

$$A_i = \text{Angular term} \times \text{Form factors} \times \text{Lineshape}$$

Angular term conserves angular momentum - involves quantum numbers J^P of resonance
Form factors account for spatial extent of particles
Lineshape - often a Breit Wigner - appropriate if the resonance is narrow/well separated - involves mass/width of resonance

Compare the form of the Breit Wigner lineshape to the propagator for an unstable particle to understand where it comes from.

3 How to search for exotic states

- Short lived exotic states appear as resonances in decays and can be seen as enhancements in mass distributions or on the Dalitz plot
- Exotic resonances interfere with known resonances creating complex phasespace distributions - a full amplitude analysis is required to untangle these contributions and determine mass/width AND quantum numbers (J^P) of exotic states
- Model independent approaches can tell you if something beyond conventional states are required to model the data

List the pros and cons of searching for exotics using mass distributions/Dalitz plots, full amplitude analyses and model independent approaches.
Show that a resonance that decays into 2 mesons with quantum numbers 1^{-+} must be exotic

4 Brief history of exotic states

- Exotics were first observed in the charm sector
- The charmonium spectrum is very well predicted by theory. The conventional states are well separated and narrow

The light sector (u and d quarks) is very crowded and states are broad. Why does this make it difficult to search for exotic states in the light sector?

5 Pentaquarks - false starts

- Claims of pentaquark states ($qqqq\bar{q}$) go back to the 70s with kaon-nucleon scattering experiments
- Despite several experiments claiming to have observed the $\Theta^+(1540)$ pentaquark with $> 4\sigma$ significance the PDG rescinded its 3-star status due to selection cuts biasing the data and high statistics datasets seeing no evidence for the state

Convince yourself that a resonance with $S = 1$ that decays strongly must have quark content $qqqq\bar{s}$.
How do we know if a particle decays strongly? Hint: B mesons decay weakly, find the width of a B meson. Why do B mesons seemingly have width in the mass distributions?

6 Pentaquarks at LHCb

- LHCb performed a full amplitutde analysis of the decay $\Lambda_b^0 \to J/\psi p K^-$ in 2015 using 3 fb^{-1} data
- Considering the 2 decay paths, the conventional $\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to pK^-$ and the exotic $\Lambda_b^0 \to P_c^+ K^-, P_c^+ \to J/\psi p$, the 6D phasespace was fit
- The conventional Λ^* states could not describe structures in $m_{J/\psi}p$
- Two pentaquark states were needed at 9σ and 12σ significance. One of these was very broad
- The need for contributions beyond conventional states was confirmed at $> 9\sigma$ using a model independent method

Slide 47 shows the conventional resonances that were used to try and fit the data. There are 14 of them. Why are there many more than 14 amplitude components in the fit? Hint: Λ_b^0 has spin 1/2, $\Lambda(1405)$ has spin 1/2, J/ψ has spin 1.

- Using run 2 data with 9x the statistics of run 1, a structure at 4312 MeV became evident and the narrower previous pentaquark state was resolved into 2 even narrower structures
- Due to the narrow width of these structures a 1D mass fit could be used to determine masses and widths
- We cannot know the quantum numbers of these new states without a full amplitude analysis
- We cannot comment on the presence of the previous broad pentaquark

If a state is very narrow why is it unlikely to be a reflection or an interference effect from conventional states?

- There are many interpretations of the pentaquark states including molecular models and kinematic effects (ie. not resonant sates at all)

7 How to determine the nature of the pentaquarks?

- Apart from determining the quantum numbers we can learn more about the nature of the pentaquarks thorough studying their production, decays to other final states and looking for other members of a possible multiplet

If we do not observe the pentaquark states decaying to other final states what would you conclude about their nature? (There is not really an accepted answer here, its just interesting to think about :))