Exploring Alternate Interpretations of the Pentaquark Candidate Observed by LHCb

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Introduction

What is the Pentaquark?

- The pentaquark (Θ +) is a particle consisting of five quarks (four quarks and one antiquark), whereas protons and neutrons consist of three quarks, and mesons only two.
- Pentaquarks were first predicted in 1964, however weren't (potentially) discovered until 2015, despite the rise of reported discoveries of pentaquark states in the early 2000's.

How Are Particles Like the Pentaquark Discovered? $m = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2)}$

- Particle Accelerators like the Large Hadron Collider at CERN
  - Magnets, tracking devices, calorimeters, particle-identification detectors
  - It is the combination of these techniques that allow particle physicists to identify particles (only muons, protons, electrons, charged pions, kaons, and photons can be easily identified)

Why we Double-Checked Their Analysis

- It is possible that particles can be misidentified, possibly causing a peak in the data that shouldn't be there.
- We looked into different possible particle identification mistakes that could have been made to see if these mistakes could "fake" a pentaquark. In the process, we followed the same selection criteria as LHCb, including certain cuts on the relative angles between particles.

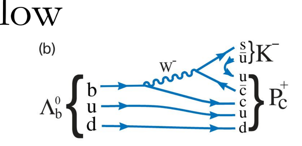
LHCb's Analysis

The decay of the Lambda-baryon $\Lambda_b^0 \to J/\psi + p + K^-$ can occur in one of three possible two-body decays with the following final state decay products: kaon, proton, and J/Ψ which decays into as follows: $J/\psi \to \mu^+ + \mu^-$

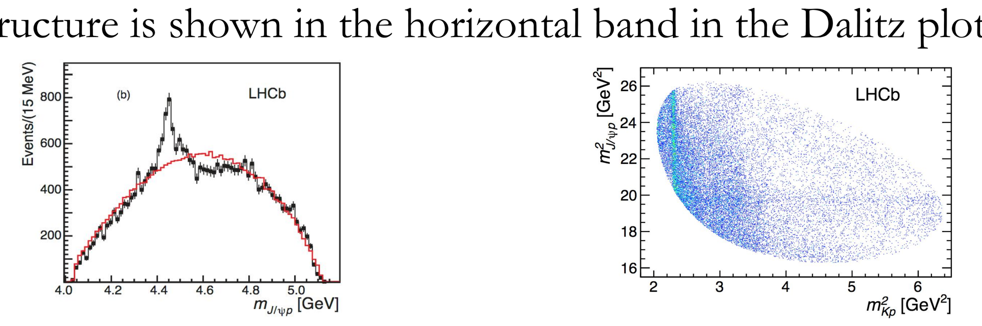
$\Lambda_b^0 \to J/\psi + A$, $A \to p + K^-$ $\Lambda_b^0 \to p + B$, $B \to K^- + J/\psi$ $\boxed{\Lambda_b^0 \to K^- + C,\ C \to p + J/\psi}$

- From the never-before-seen two-body decay that is boxed above, LHCb found J/Ψ proton resonant structures consistent with two pentaquark states with masses 4.38 GeV and 4.45 GeV.
  - LHCb called particle C the pentaquark P_c^+ which decays into a J/Ψ and a proton. They claimed the following decay below

$\Lambda_b^0 \to P_c^+ + K^-$



- The red curve is the expectation from phase space with background subtracted
  - The background takes into account combinations of particles that are not from a Lambda-baryon but happen to have a similar mass.
- The resonant structure is shown in the horizontal band in the Dalitz plot in the bottom right



Our Method

- Identifying particles is not perfect, therefore, it is possible that LHCb was looking at the decay of a different particle.
- Once mistakes are made, the masses of calculated parent particles move around, which can produce convincing results that are actually mistakes.
- We are trying to answer the question: **Are there any mistakes that could have been made to yield the same results as LHCb's analysis?**
- We hypothesize four alternative decays that could be the decay observed by LHCb, three of which are mistaking the original decay product as another particle

$\Lambda_b^0 \to \pi^+ + K^- + p + \mu^- + \nu$ $B^0 \to J/\psi + K^- + \pi^+$

$B_s^0 \to J/\psi + \phi$ $\bar{B}^0 \to J/\psi + K^+ + \pi^-$

Our Analysis

How Did We Generate Data?

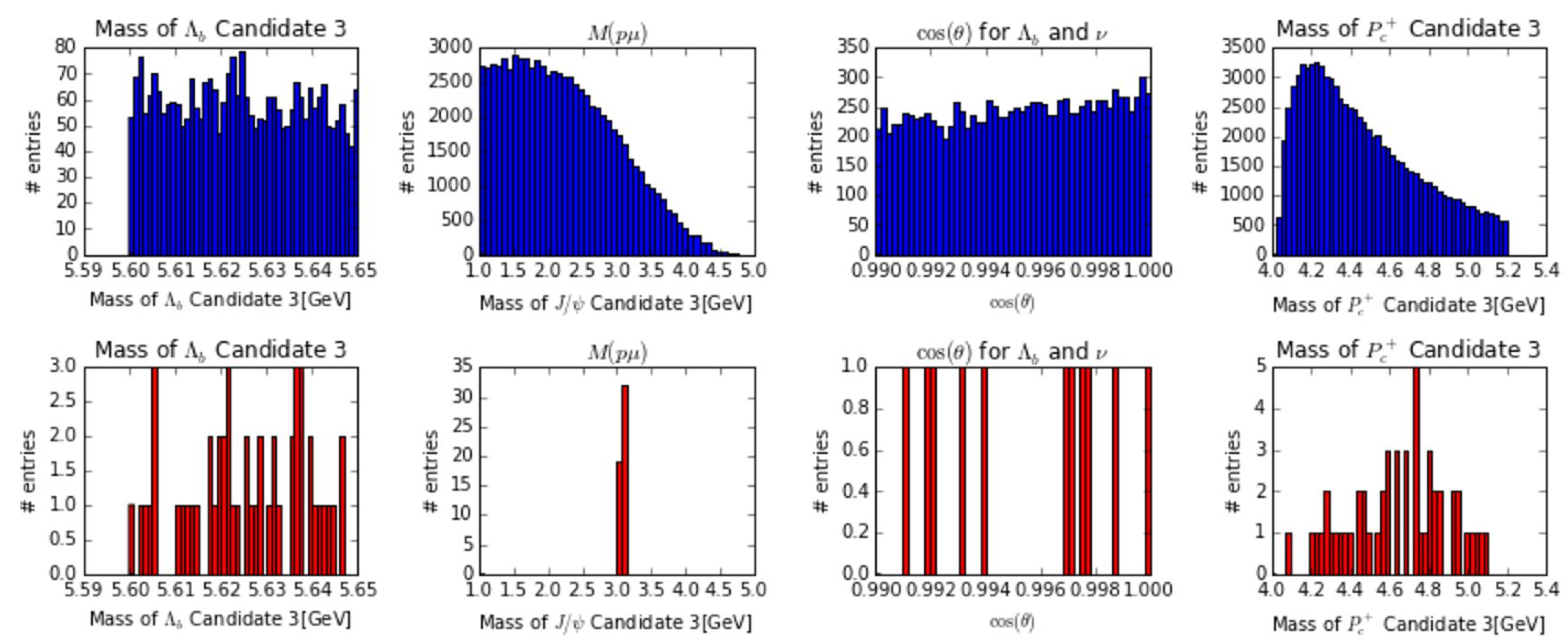
- Since we don't have access to LHCb's data, we generated 100k fake collisions using Monte Carlo techniques.
- We verified the generated data by calculating the masses of particles and matching them with the assumed decays.

Confirmed Lambda-Baryon Decay

- The graphs below represent one of the four possible particle misidentification mistakes that could have been made for the decay $\Lambda_b^0 \to \pi^+ + K^- + p + \mu^- + \nu$ The neutrino rarely interact with matter and so is not detected.
- We assume that a proton is misidentified as a postitive muon and a pion is misidentified as a proton.

Actual Decay:
Mistakes: $\Lambda_b^0 \to p + \pi^+ + K^- + \mu^-$
$\Lambda_b^0 \to \mu^+ + p + K^- + \mu^-$

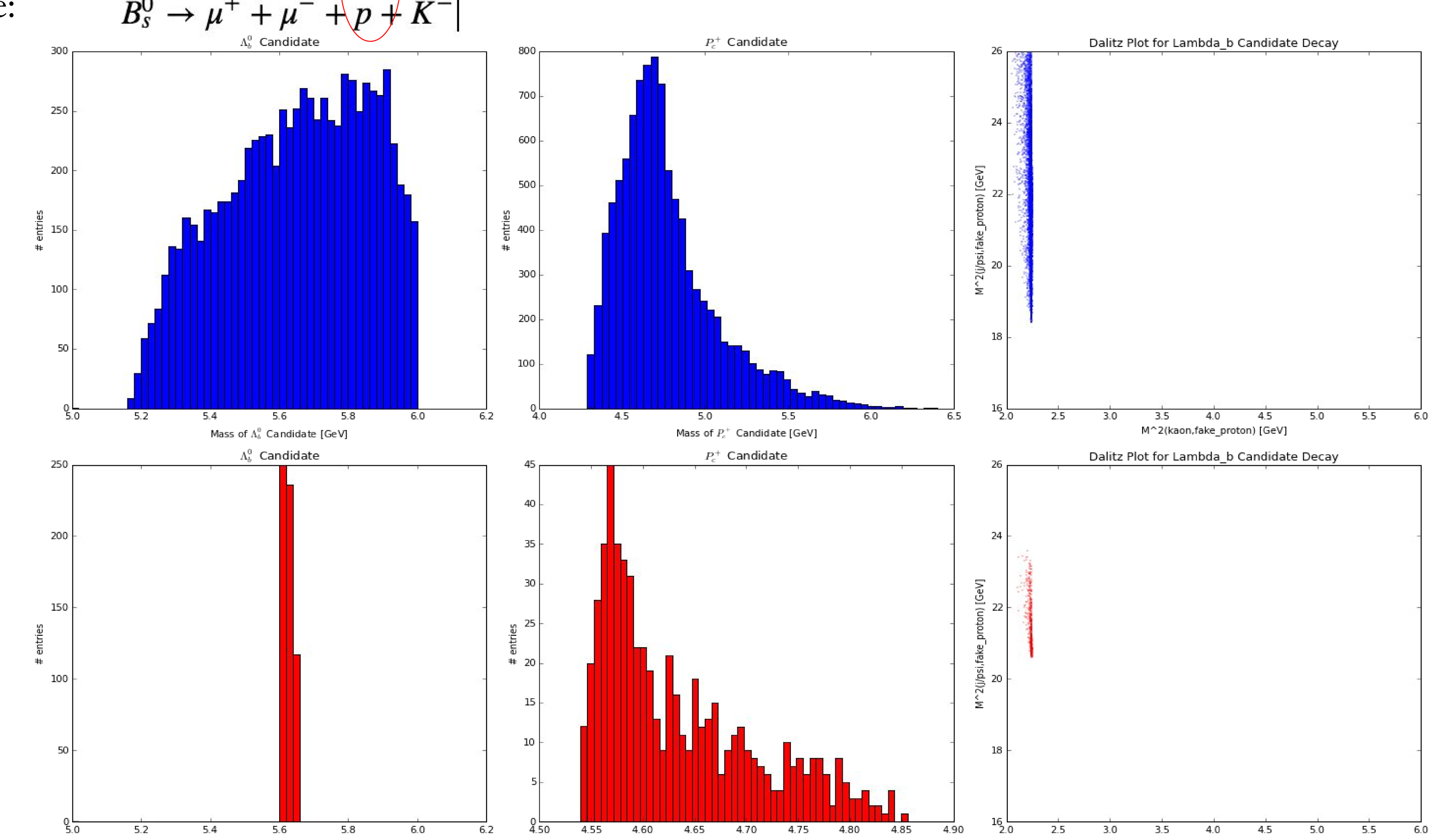
- The blue histograms represent different quantities of interest, without imposing any selection criteria.
- The red histograms show candidates that pass LHCb's selection criteria: a J/Ψ mass of 3.096 GeV $\pm$ 0.048, a Lambda-baryon mass of 5.6 GeV-5.65 GeV, and cos(Θ)>0.99, where Θ is the angle between the neutrino and the Lambda-baryon candidate.
- Two of the four possible decays were eliminated because the mistake would not have produced a fake J/Ψ mass consistent with the actual mass of 3.096 GeV.



Strange B Meson Decay

- The graphs below represent mistaking a kaon for a proton in the decay $B_s^0 \to J/\psi + \phi$
- The J/Ψ decays as follows: $J/\psi \to \mu^+ + \mu^-$ while the phi meson decays as follows $\phi \to K^+ + K^-$

Actual Decay: $B_s^0 \to \mu^+ + \mu^- + K^+ + K^-$
Mistake: $B_s^0 \to \mu^+ + \mu^- + p + K^-$

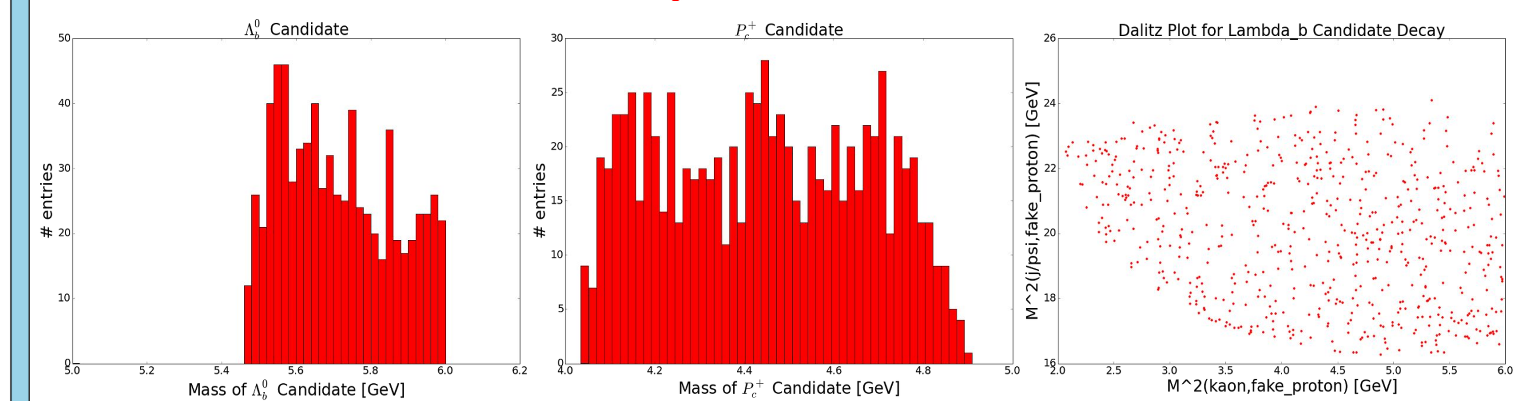


Analysis Continued

Neutral B Meson Decay

- The graphs below represent mistaking a pion for a proton for the following decay $B^0 \to J/\psi + K^- + \pi^+$

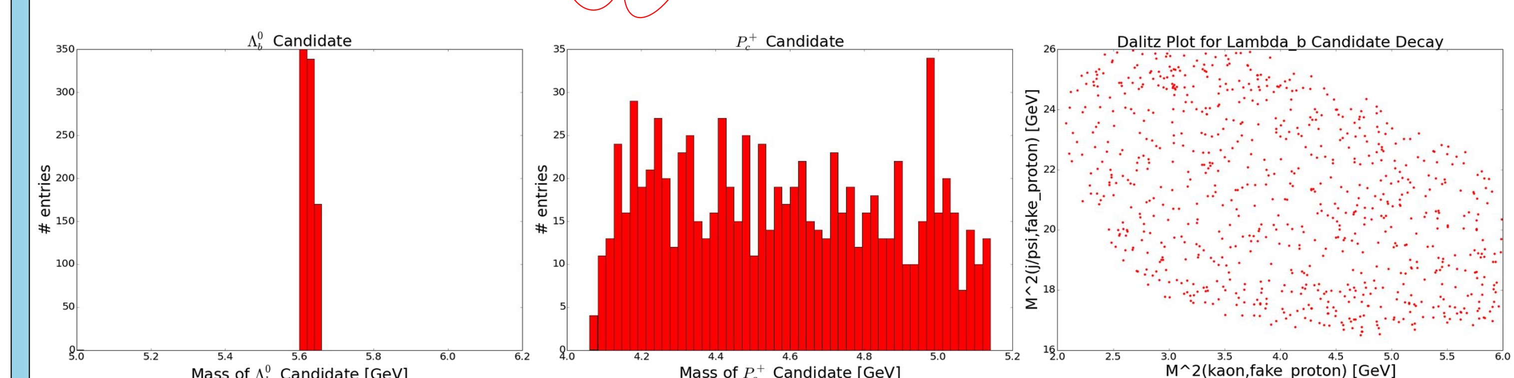
Actual Decay: $B^0 \to J/\psi + K^- + \pi^+$
Mistake: $B^0 \to J/\psi + K^- + p$



Neutral Anti-B Meson Decay

- The graphs below represent mistaking a kaon for a proton and mistaking a pion for a kaon for the following decay $\bar{B}^0 \to J/\psi + K^+ + \pi^-$

Actual Decay: $\bar{B}^0 \to J/\psi + K^+ + \pi^-$
Mistakes: $\bar{B}^0 \to J/\psi + p + K^-$

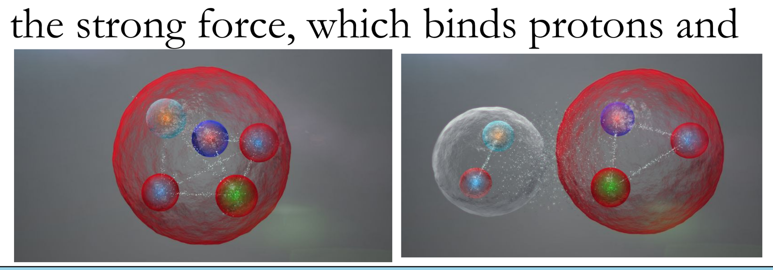


Conclusions

- Our results show that the pentaquark claimed by LHCb is unlikely to be the result of misidentifications of any of the decay modes we studied.
- The particle misidentifications that we tested do not produce peaks consistent with the pentaquark states observed by LHCb.
- Our analysis confirms that LHCb did not make any obvious particle misidentification mistakes, at least for these 3 decay modes.

Future Directions

- The internal structure of the pentaquark is currently unknown.
- All five quarks could be bound together in a spherical system or a meson could be weakly bounded to a proton.
- Pentaquarks can be formed in supernovae explosions or formations of neutron stars.
- Studying these particles can give us insight into how neutron stars are formed as well as information regarding the strong force, which binds protons and neutrons together in nuclei.



References

[1] K.A. Olive et al. Review of Particle Physics. *Chin.Phys.*, C38:090001, 2014.

[2] Roel Aaij et al. Observation of J/ψ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays. *Phys. Rev. Lett.*, 115:072001, 2015.

[3] CERN. http://home.cern/.