

Exotic hadron spectroscopy at Heidelberg

FSP meeting - Rostock

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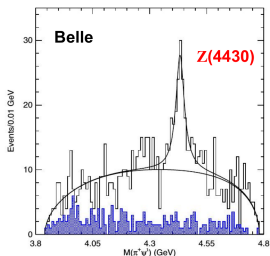


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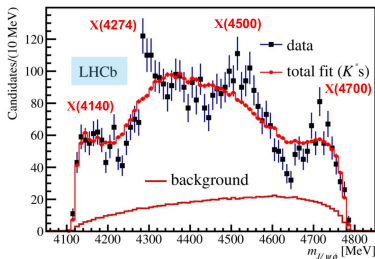


What are exotic states?

We keep finding exotic candidates... especially in charm...



PRL100, 142001(2008)



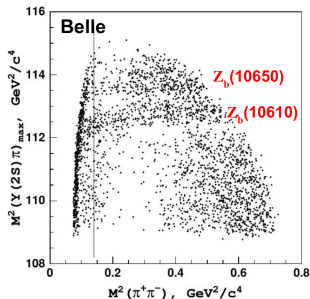
PRL118, 022003(2017)

$Z^+(4430)$ **charged**, hidden-charmonium tetraquark at Belle in $B^0 \rightarrow \psi(2S)\pi^+K^-$ decays. See J. Grabowski's talk

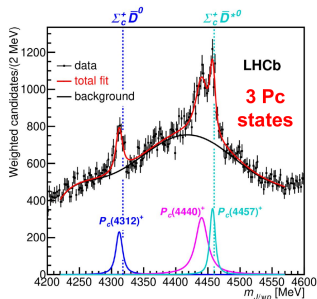
Four X state tetraquarks in $J/\psi\phi$ at LHCb - minimal quark content $cs\bar{c}\bar{s}$ (no u/d light quark)

What are exotic states?

We keep finding exotic candidates... especially in charm...



PRL108,122001(2012)



PRL122, 222001(2019)

Z_b bottomonium tetraquarks with $b\bar{b}u\bar{d}$ decaying to epsilon resonances at Belle

P_c state pentaquarks in $J/\psi p$ with minimal quark content $c\bar{c}uud$ at LHCb

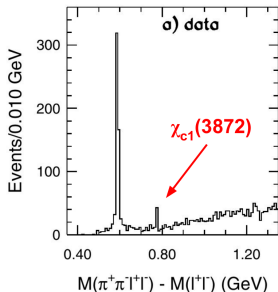
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- 1 How to search for exotic states
- 2 The LHCb pentaquarks
- 3 How to determine the nature of the pentaquarks?

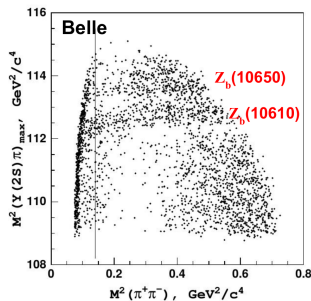
Enhancements in mass distributions or on the Dalitz plot

Short lived exotic states appear as resonances in decays

- Exotic resonances can be seen as enhancements in mass distributions or on the Dalitz plot



$\chi_{c1}(3872)$ in $B \rightarrow K(\pi^+\pi^- J/\psi)$ decays



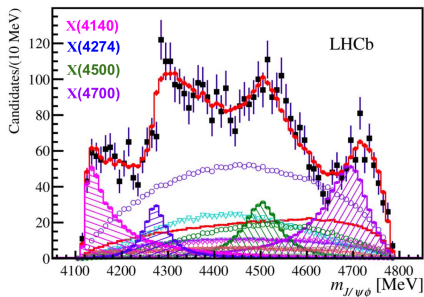
Z_b states in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$

- Pros: Easy measurement of mass/width of states - Breit Wigner model
- Cons: Kinematic effects such as re-scatterings can fake 'bumps'

A full amplitude analysis

Exotic resonances interfere with known resonances creating complex phasespace distributions

- A full amplitude analysis can determine mass/width and quantum numbers (J^P) of exotic states

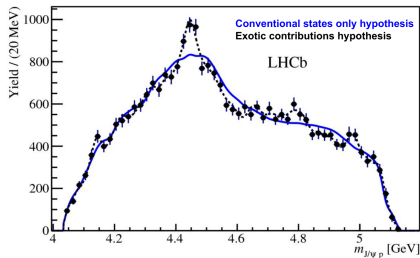


- Pros: Can determine all properties of a new state
- Cons: **Model dependent** - requires the most assumptions about other states and is the most complex of procedures

Model independent approaches

Exotic resonances in a moments analysis contribute at orders greater than that achieved by conventional states

- Model independent approaches can evaluate the null-hypothesis that only conventional states are needed to describe the data



Evidence for non-conventional states in $\Lambda_b^0 \rightarrow J/\psi p K^-$

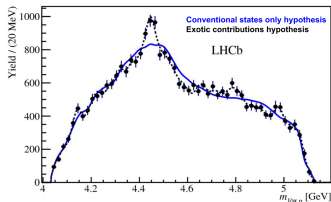
- Pros: Model independent - only require knowledge of the spins of conventional states
- Cons: Can only tell you that 'something' beyond the simple conventional state interpretation is required. Could be a kinematic effects

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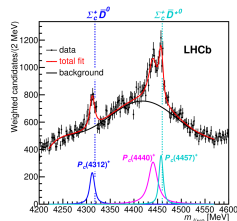
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The LHCb Pentaquarks

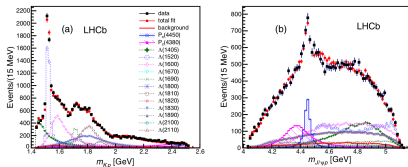
LHCb has used all three to conclude there are exotics in $\Lambda_b^0 \rightarrow J/\psi p K^- \dots$



2016 model independent analysis



2019 fit to 1D invariant mass distributions

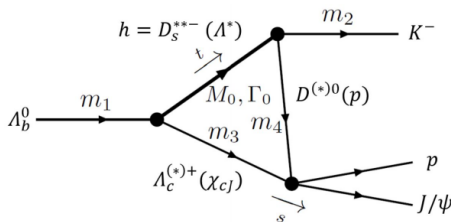


2015 full amplitude analysis

How to interpret these... some ideas...

The LHCb Pentaquarks

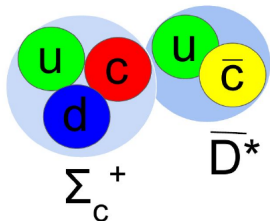
Re-scattering effects - triangle diagrams



- $P_c(4457)$ peaks at $\Lambda_c^+(2595)\bar{D}^0$ threshold - $D_{s1}(2860)$ excited strange hadron suitable candidate to be exchanged in triangle
- Purely kinematical effect - P_c not a resonant state
- Some investigations into this in PRL122, 222001 (2019)

The LHCb Pentaquarks

Molecular Model - bound state of baryon and meson

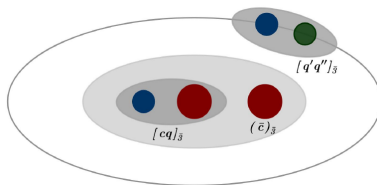


- Three P_c states **very close to $\Sigma_c \bar{D}$ thresholds**
- Molecular models can predict multiplet of states eg. molecular + HQSS predicts 7 bound states, three of which correspond to the observed P_c states

$P_c(4312)$	$P_c(4440)$	$P_c(4457)$
$\Sigma_c^+ \bar{D}^0$	$\Sigma_c^+ \bar{D}^{*0}$	$\Sigma_c^+ \bar{D}^{*0}$
$1/2^-$	$1/2^-$	$3/2^-$
Molecular + HQSS model. arxiv:1904.01296		

The LHCb Pentaquarks

Compact di-quark model



Tri-quark + light di-quark = colour singlet pentaquark

$P_c(4312)$	$P_c(4440)$	$P_c(4457)$
$\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 0$ $3/2^-$	$\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 1$ $3/2^+$	$\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 1$ $5/2^+$

arxiv:1904.00446

J^{PC} of $P_c(4312)$ disagrees with all molecular models

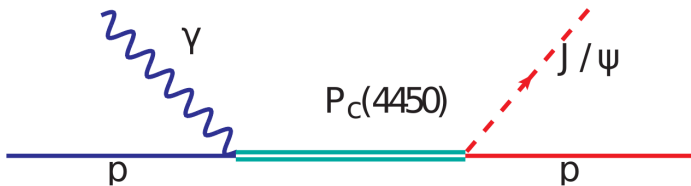
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Production

Look for the P_c states in other production mechanisms

- JLAB can search for P_c states in J/ψ photoproduction
- Observation of the P_c states here **would exclude the P_c being a result of kinematical effects** such as triangle singularities

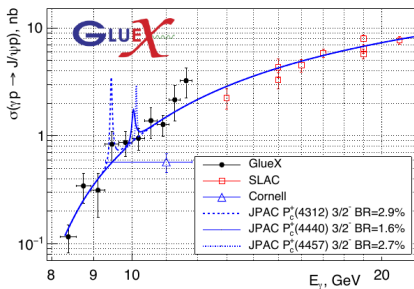


See [JLAB talk](#) for more experimental details

Presented at Hadron 2019

J/ψ @ GlueX: Search for P_c states

PRL 123, 072001 (2019): Editor's Suggestion!



- No evidence of P_c states!
- Model-dependent upper limits at 90% CL (assuming J^P=3/2⁻):
 - Br(P_c(4312) → J/ψ p) < 4.6%
 - Br(P_c(4440) → J/ψ p) < 2.3%
 - Br(P_c(4457) → J/ψ p) < 3.8% [ULs scale as (2J+1)]
- Disfavors hadrocharmonium and some molecular models. P_c's could preferentially couple to other channels?
 - Need consistent picture with Λ_b decays.

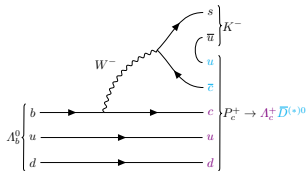
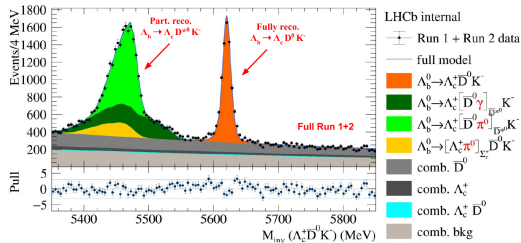


A.N. Hiller Blin, et al., PRD 94, 034002 (2016).

Decays to other final states

Look for the P_c states in other final states

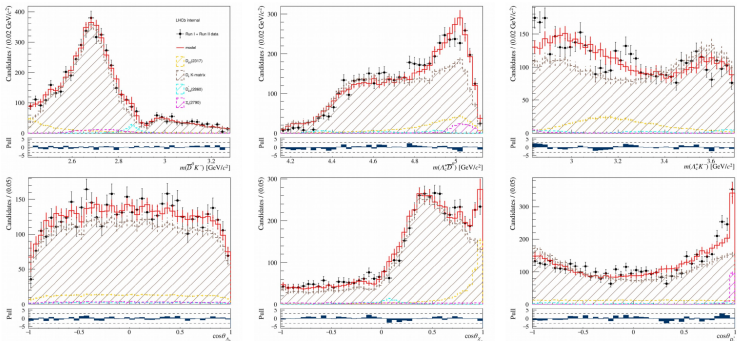
- Multitude of possible channels in which P_c states could be observed with models of the P_c states **predicting their couplings**
- Some models predict higher couplings of the P_c states to $\Lambda_c^+ D^{(*)0}$ in the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ D^{(*)0} K^-$ than the discovery channel
- HD is using these channels to discriminate between models of P_c



Decays to other final states

For the fully reconstructed final state $\Lambda_b^0 \rightarrow \Lambda_c^+ D^0 K^-$ amplitude analysis performed using **TensorFlow based amplitude fitter TOAST** Trademark of A. Piucci including K-matrix formalism

- Conventional states used to fit 6D phasespace, addition of P_c states does not improve fit quality. No evidence for presence of P_c states in this channel

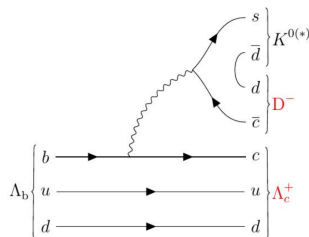
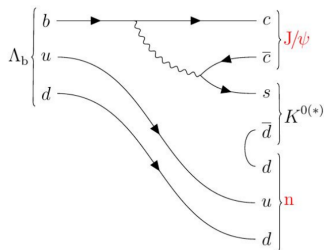


*Amplitude analysis of partially reconstructed channel $\Lambda_b^0 \rightarrow \Lambda_c^+ D^{*0} K^-$ presents more challenges and is ongoing*

Search for other members of the multiplet

Look for the rest of the P_c multiplet

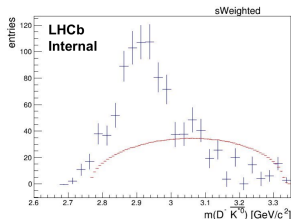
- Each model yields a **different multiplet of states**
- Potential neutral isospin partners ($c\bar{c}udd$) of P_c ?
- The obvious $P_c \rightarrow J/\psi n$ channel is not reconstructible at LHCb
- HD is using $\Lambda_b^0 \rightarrow \Lambda_c^+ D^- \bar{K}^{*0}$ channel where $P_c \rightarrow \Lambda_c^+ D^-$ to search for neutral P_c state



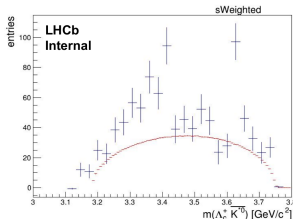
Search for other members of the multiplet

The $K^{\bar{*}0}$ complicates the decay channel - presence of $K\pi$ S-wave and another 2 final state particles

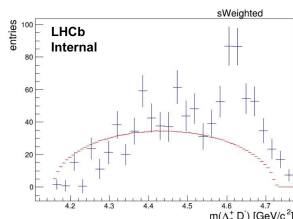
- Invariant mass projections of selected $\Lambda_b^0 \rightarrow \Lambda_c^+ D^- K^{\bar{*}0}$ events compared to phasespace



D_s contributions



High mass Ξ_c^+ states



Pentaquark projection

- Peak in $\Lambda_c^+ D^-$ likely a reflection of the Ξ_c^+ state
- Amplitude analysis using TOAST in preparation

Conclusions

Exotic hadron spectroscopy is developing fast both in experiment and theory!

The Heidelberg spectroscopy group is looking at the most meaningful decay channels to determine the nature of the P_c states

