HEAVY QUARK SPECTROSCOPY AT LHCB

Daniel Johnson *on behalf of the LHCb collaboration*

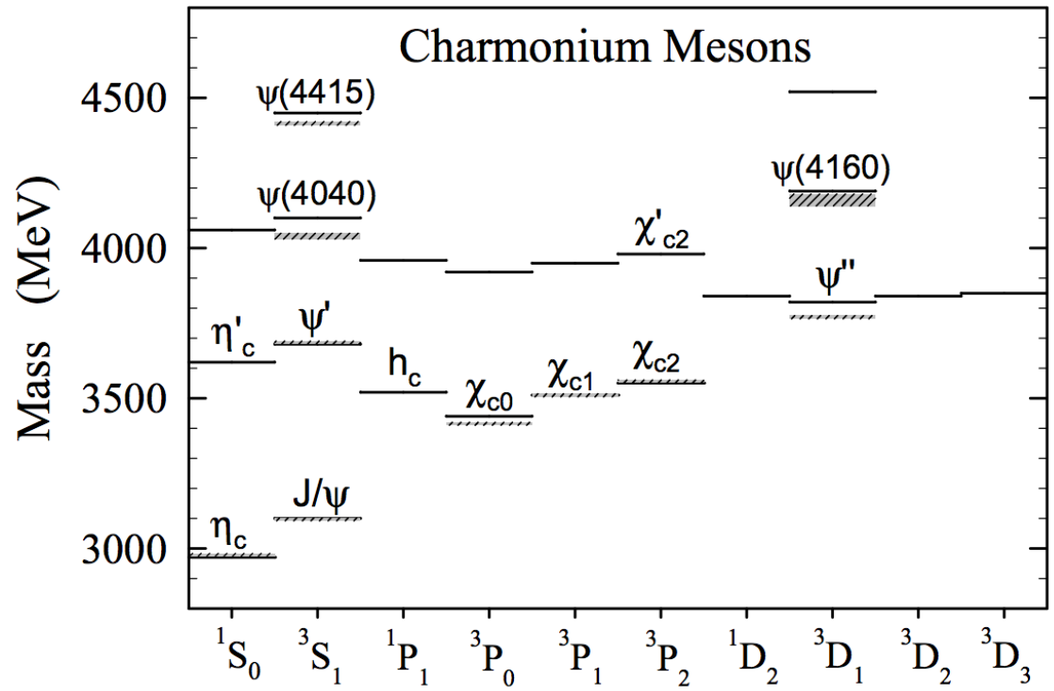
Les Rencontres de Physique de La Vallée d'Aoste
La Thuile, March 6-12, 2016

The charmonium spectrum

- $m_c \approx 1.5\ GeV/c^2 > \Lambda_{QCD} \Rightarrow c\bar{c}$ bound states described with simple potential
  - approximately coulomb-potential (single gluon exchange)
  - linearly increasing potential (confinement)

- Below $D\bar{D}$ threshold:
  - observed states quite well-modelled

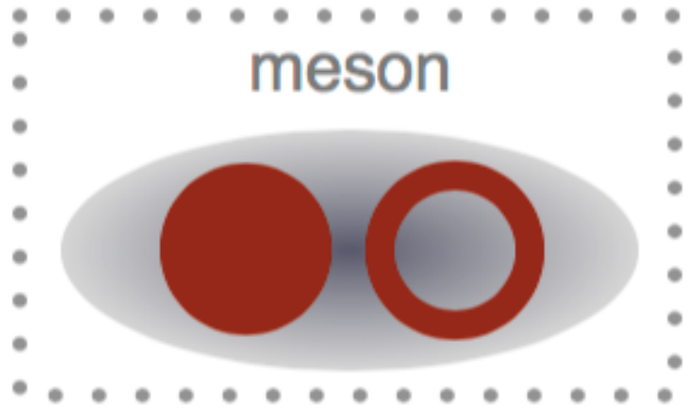
- Above $D\bar{D}$ threshold:
  - only a few predicted states observed
  - assignments of many in question
  - "X,Y,Z" (not simple $q\bar{q}$) states observed

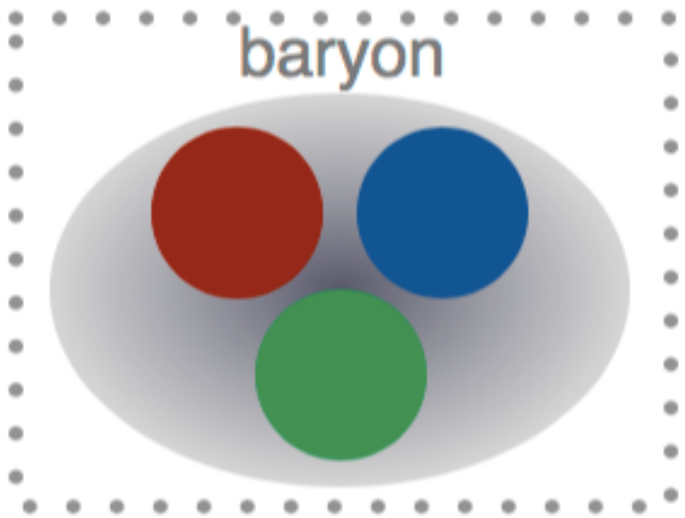


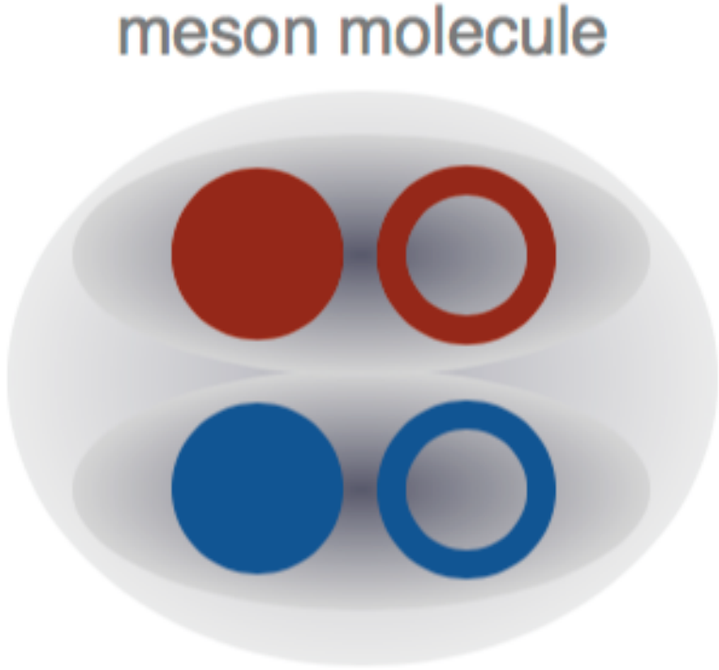
ARNPS. 58 51
arXiv:0801.3867

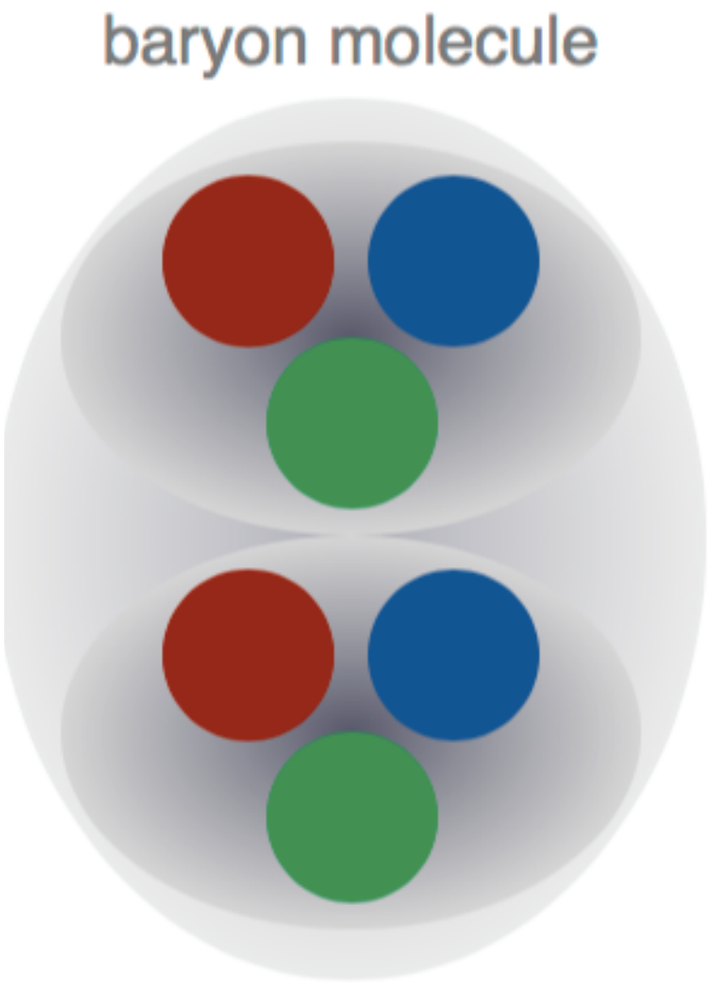
Hadronisation of heavy quarks

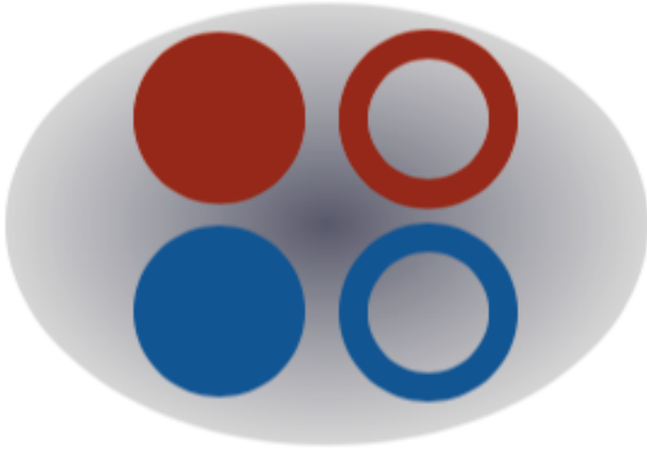
interpreting exotic multi-quark states

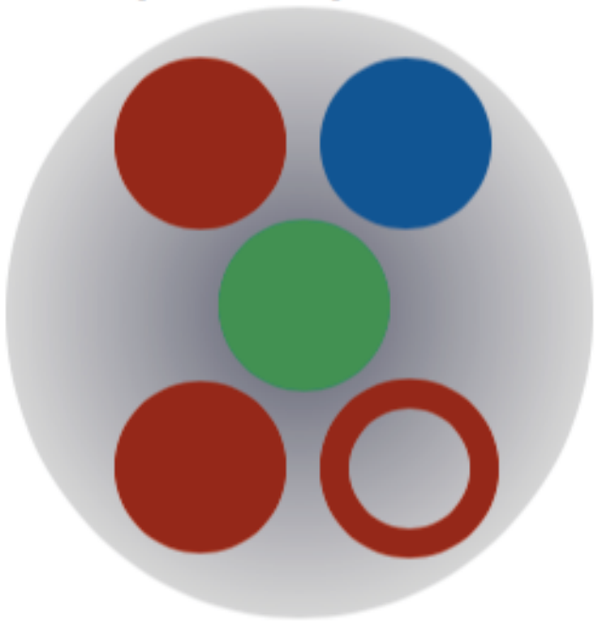


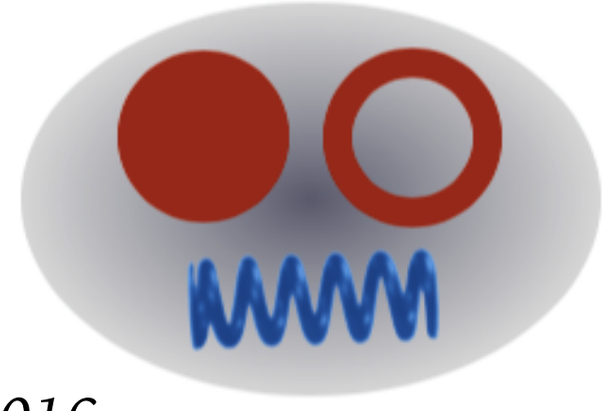










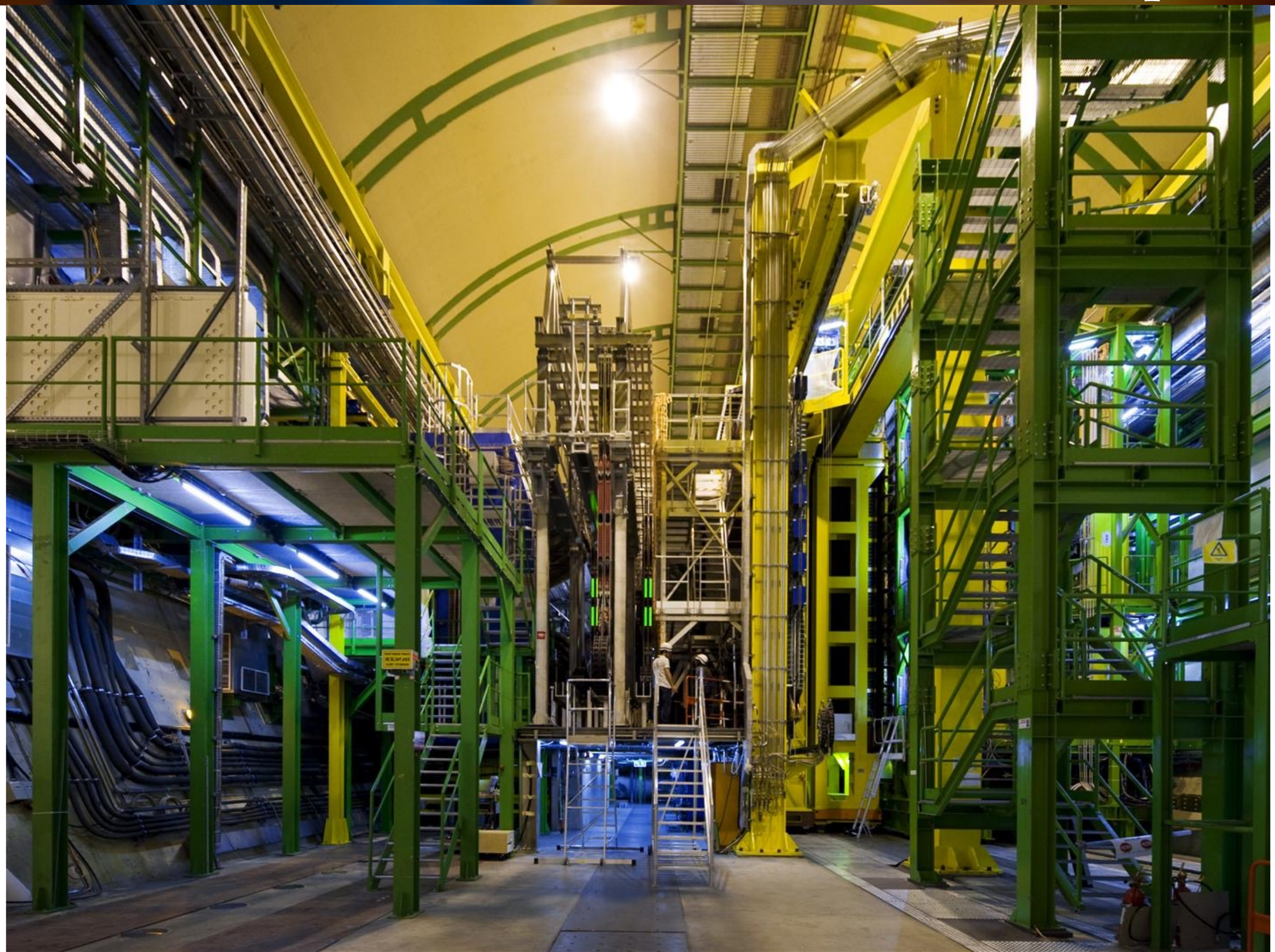


Overview

1. Probing $X(3872)$ composition
2. Studying the $Z(4430)$
3. *Pentaquark* observation

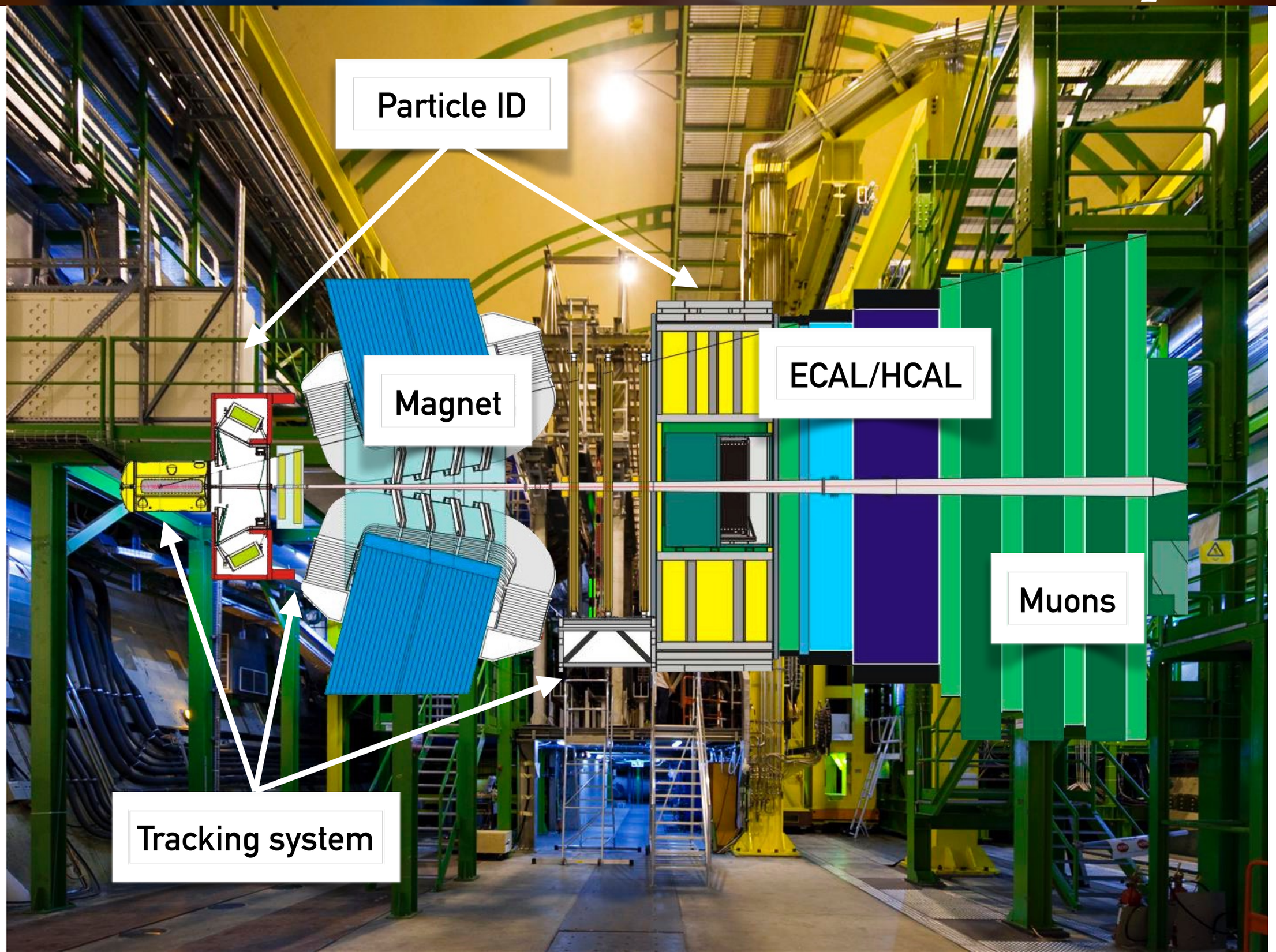
A spectroscopy toolkit

the LHCb experiment



A spectroscopy toolkit

the LHCb experiment

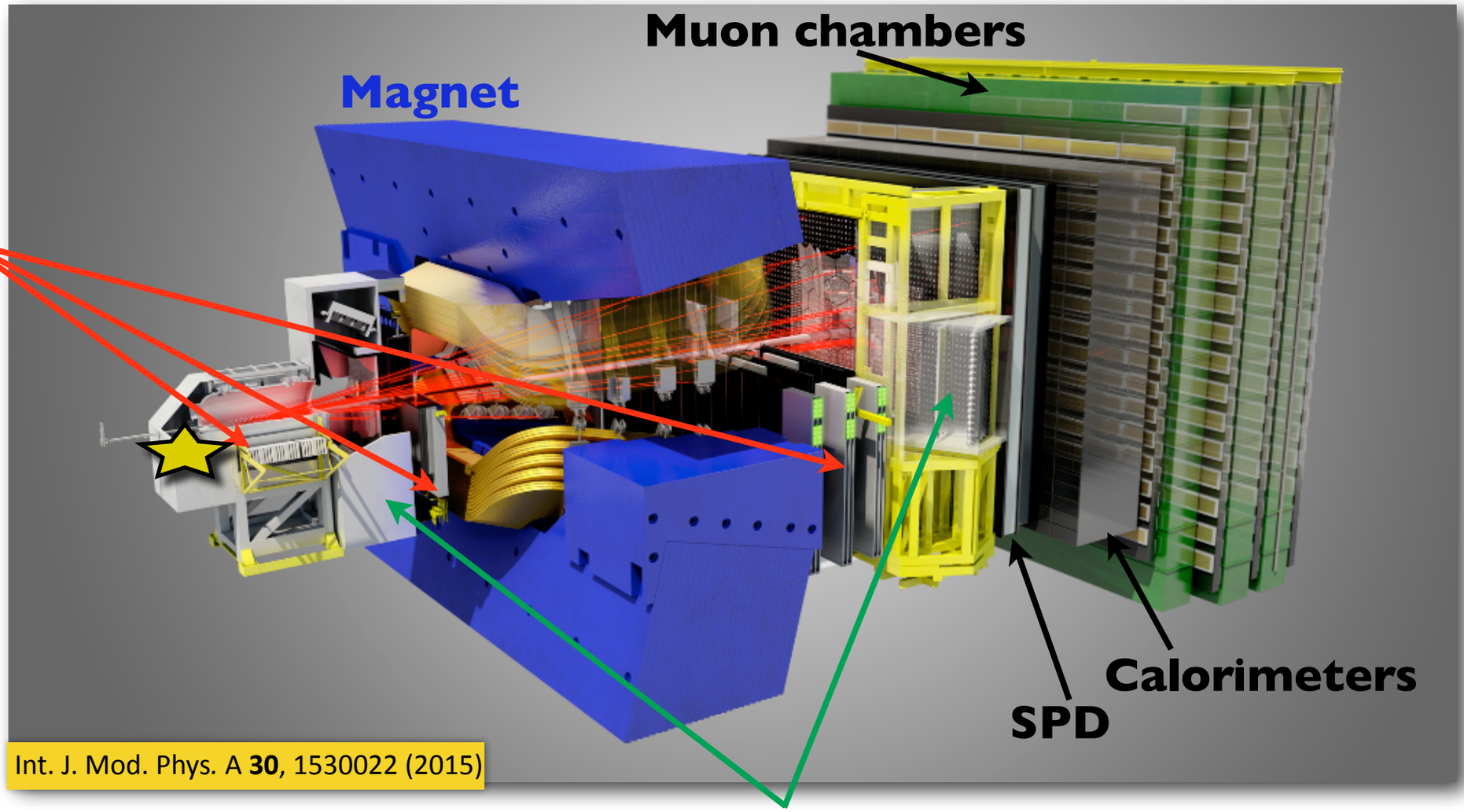


A spectroscopy toolkit

the LHCb experiment

Vertex Locator and tracking system:
B and D vertex positions and track momenta

IP resolution: 20μm



Int. J. Mod. Phys. A **30**, 1530022 (2015)

RICH detectors:
K/π separation

- Efficient hadronic trigger through Run 1 (2011-2012)
  - LHC: *pp* bunch-crossings [11 MHz]
  - Hardware: HCAL, muon information [1 MHz]
  - Software (1/2): 1 track with p_T>1.7 GeV/c [O(10) kHz]
  - Software (2/2): topological (displaced vertex) [O(1) kHz]

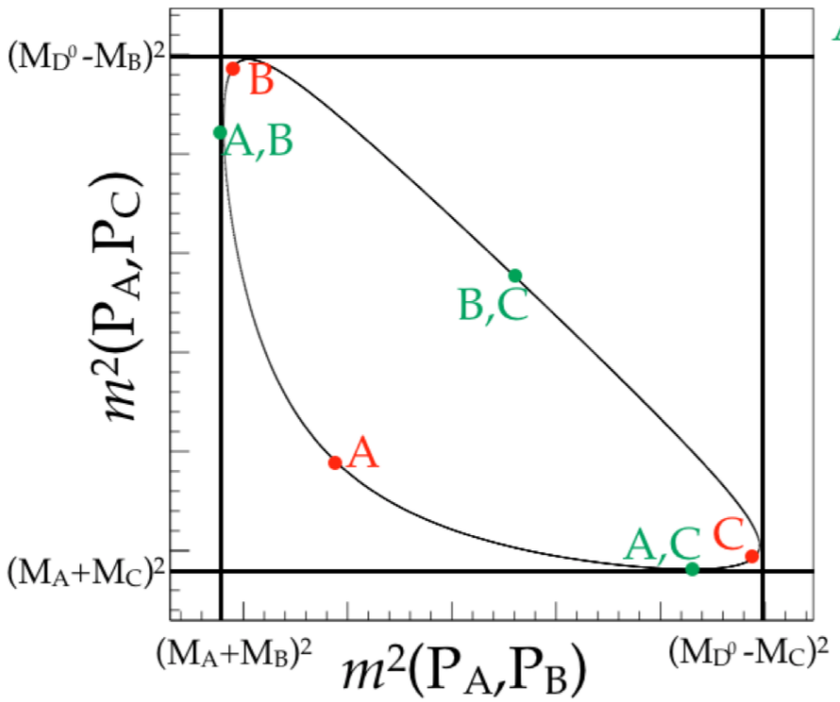
$\Delta\mathcal{L}^{-1}/\mathcal{L}^{-1}$: 1.7% (2011) and 1.2% (2012)
$\mathcal{L}^{-1}$ = 3.0 fb^{-1}

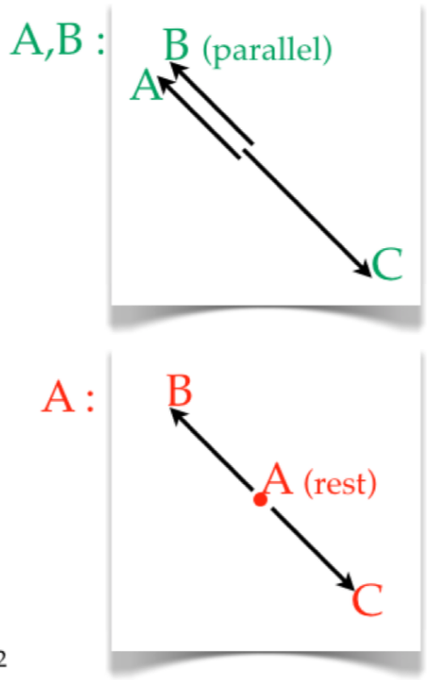
JINST 9 P12005

A spectroscopy toolkit

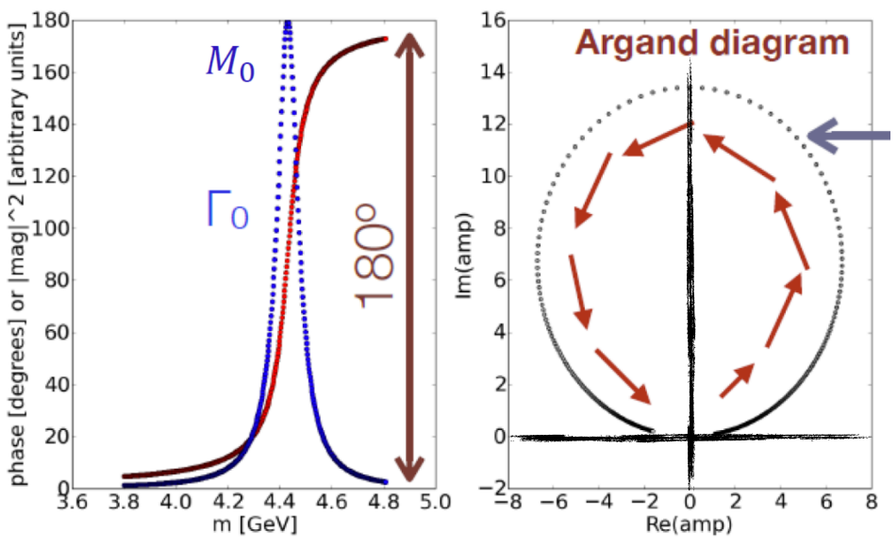
3-body decays

- *For spin-0 → 3 spin-0 (A,B,C)*
  - *2 degrees of freedom*
  - *Visualise e.g. $m^2(A,B) : m^2(A,C)$*
  - *Uniform non-resonant population*

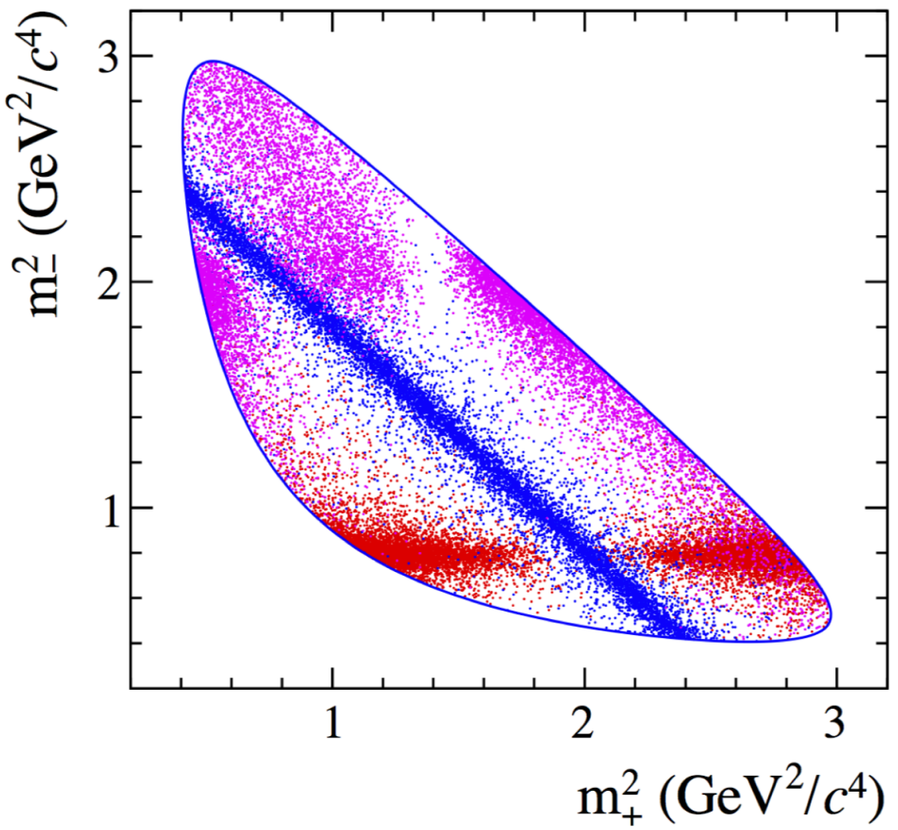




- *New resonances*
  - *Study phase-motion 'model-independently'*



Breit-Wigner "phase rotation"



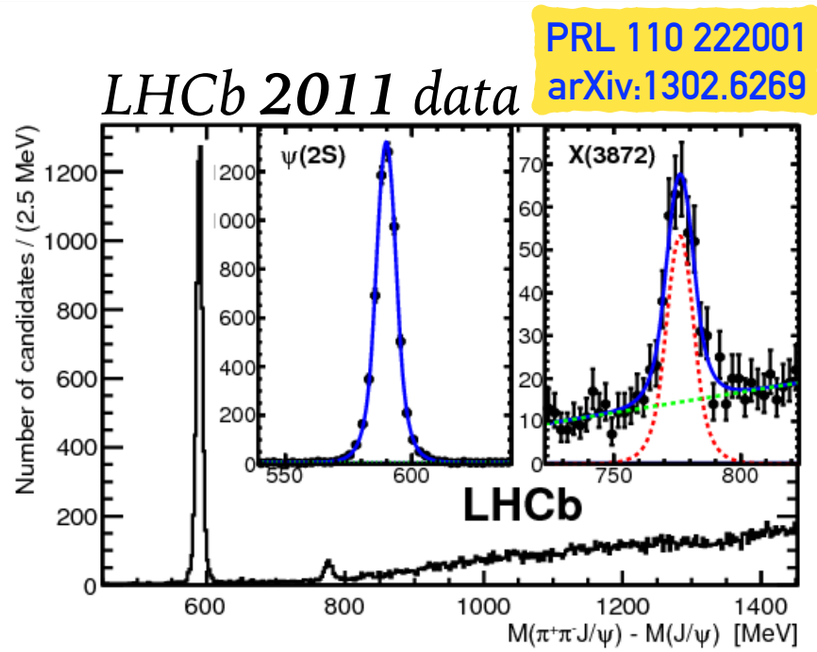
Overview

1. Probing $X(3872)$ composition
2. Studying the $Z(4430)$
3. Pentaquark observation

Probing X(3872) composition

Introduction

- *First observed by Belle in 2003* PRL 91 262001 hep-ex/0309032
  - $B \to K(X \to J/\psi\, \pi^+\pi^-)$
  - *mass 3872 MeV/c^2, very narrow width O(MeV)*
  - *seen at 7 experiments*



- *Conventional charmonium?*
  - $X \to J/\psi\, \rho/\omega$ *decays violate isospin*
  - $c\bar{c}$ *not expected to have large branching fraction to* $(J/\psi\, \rho)$

- *Alternative interpretation?*
  - ***molecule:*** *Intriguing mass* $\approx m(D^0) + m(D^{*0})$ PLB 598 197 hep-ph/0406080
  - ***tetraquark:*** *Expect a second state separated by* $\sim 8 MeV/c^2$ PRD 71 014028 hep-ph/0412098
  - ***hybrid $c\bar{c}g$, vector glueball… or admixture of the above***

PLB 605 306 hep-ph/0410264 PLB 612 1 hep-ph/0411122 PRD 80 056002 arXiv:0907.2683

Probing X(3872) composition

Quantum number determination

- *CDF: $J^{PC} = \{1^{++}$ or $2^{-+}\}$*
  - *angular analysis of $X(3872) \to J/\psi\,\pi^+\pi^-$ (2,300 inclusively reco'd)*

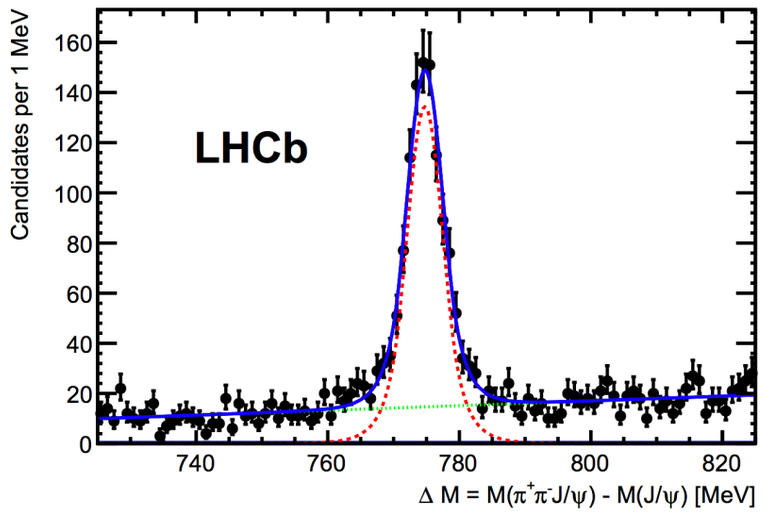
PRL 98 132002
hep-ex/0612053

- *LHCb: $J^{PC} = 1^{++}$ ($1fb^{-1}$)*
  - *5D angular analysis of 300 $B^+ \to K^+X(3872)$ candidates*
  - *assumes lowest angular momentum for $J/\psi\pi\pi$ system*
    - *reasonable given low $X \to J/\psi\pi\pi$ Q-value*
    - *could be violated by unconventional internal X structure*

PRL 110 222001
arXiv:1302.6269

- *LHCb: $J^{PC} = 1^{++}$ ($3fb^{-1}$)*
  - *5D analysis of $B^+ \to K^+(X(3872) \to \rho J/\psi)$: 1000 candidates*
  - *fit allowing for any value of L (up to J=4)*

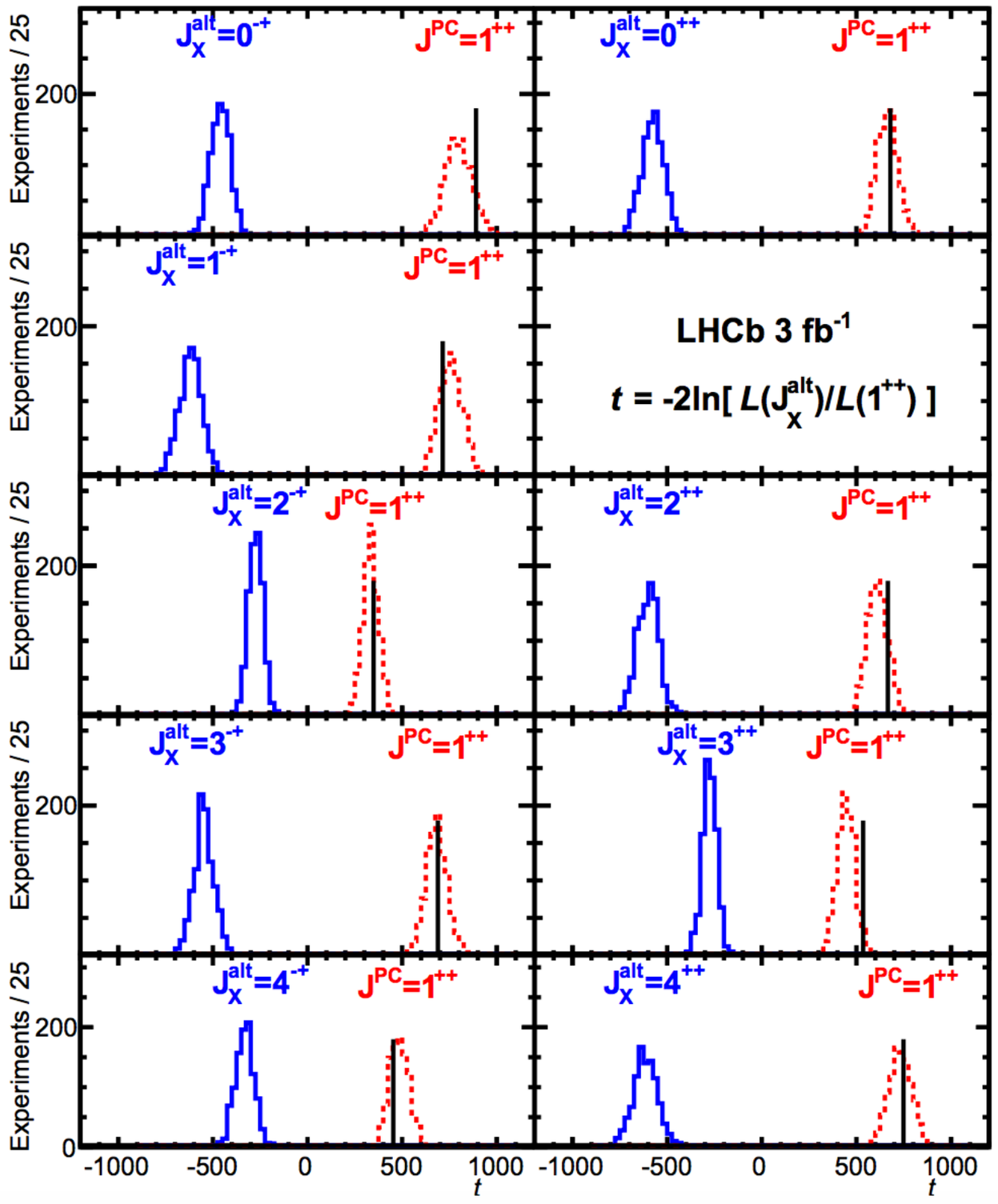
PRD 92 011102
arXiv:1504.06339



Probing X(3872) composition

Quantum number determination

- *Fit the data for different J^{PC}*
  - *minimum log-likelihood fit*
  - *X(3872) L,S values encoded in the helicity couplings via "B_{LS}"*
- *Likelihood-ratio for alt. J^{PC}*
  - *1^{++} consistent and preferred*
  - *simulate test statistic…*
  - *… alternatives excluded at >16s.d.*
- *Limit on D-wave*
  - *$J^{PC}=1^{++}$: L,S = 0,1; 2,1; 2,2*
  - *D-wave fraction < 4% @ 95% C.L.*
- *Implications*
  - *large S-wave suggests compact state*
  - *D-wave favours extended structure*



$$t \equiv -2\ln[\mathcal{L}(J_X^{\rm alt})/\mathcal{L}(1^{++})]$$

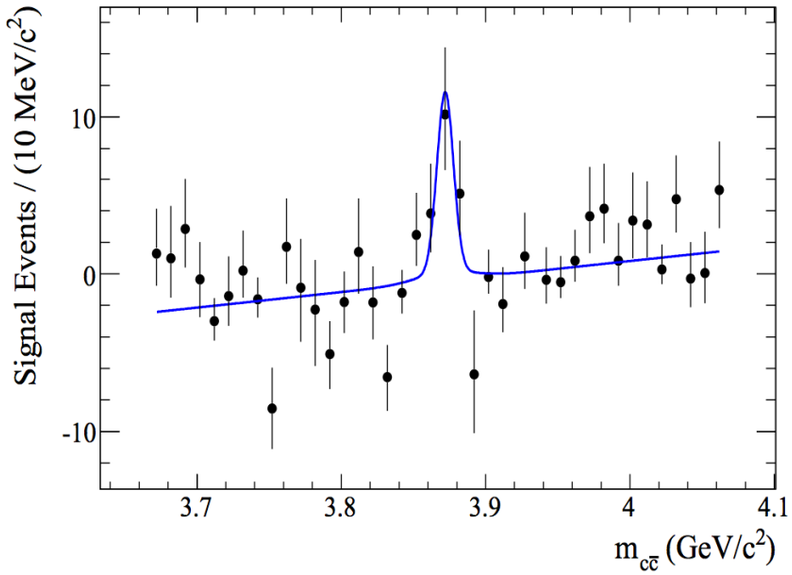
Probing X(3872) composition

Radiative decays

- *Radiative transitions are a sensitive probe of exotic structure*
  - *E-M transitions amongst charmonium states well-defined*
  - *potential models provide precise predictions*

- *Searching for $X(3872) \to J/\psi\,\gamma$*
  - *evidence from BaBar in 2006: 19 candidates*
  - *constrained C-parity to be even*

PRD 74 071101
hep-ex/0607050

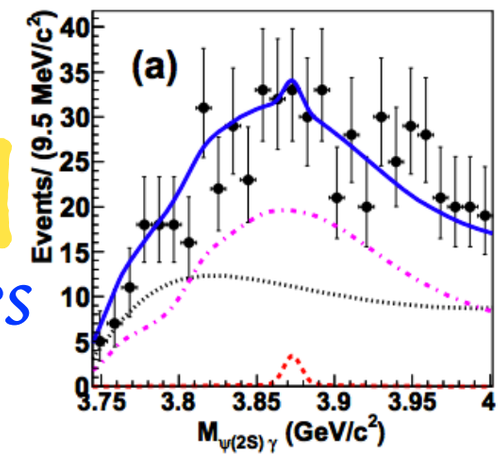


- *Ratio $R_{\psi\gamma}$: $X(3872) \to \psi(2S)\,\gamma$ to $X(3872) \to J/\psi\gamma$ constrains models*
  - *molecule*: $R_{\psi\gamma} \sim$ ***0.003***
  - *charmonium*: $R_{\psi\gamma} \sim$ ***1.2 - 15***
  - *admixture*: $R_{\psi\gamma} \sim$ ***0.5 - 5***

PRD 79 0940004
arXiv:1401.4431
PRD 85 114002

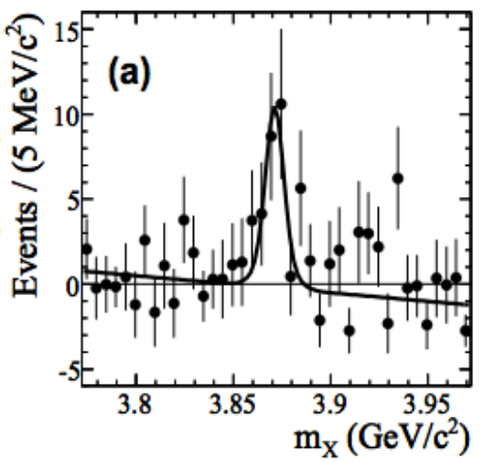
Belle: $R_{\psi\gamma} < 1.2$@90%

PRL 107 091803
arXiv:1105.0177



BaBar: $R_{\psi\gamma}$ 3.4 ± 1.4

PRL 102 132001
arXiv:0809.0042



$\psi(2S)\,\gamma$ *searches*

Probing X(3872) composition

Radiative decays

- *LHCb: 3fb^{-1}*
  - *search for $B^+ \to K^+ (X \to \psi\gamma)$*
  - *600 $X \to J/\psi\gamma$, 40 $X \to \psi(2S)\gamma$*

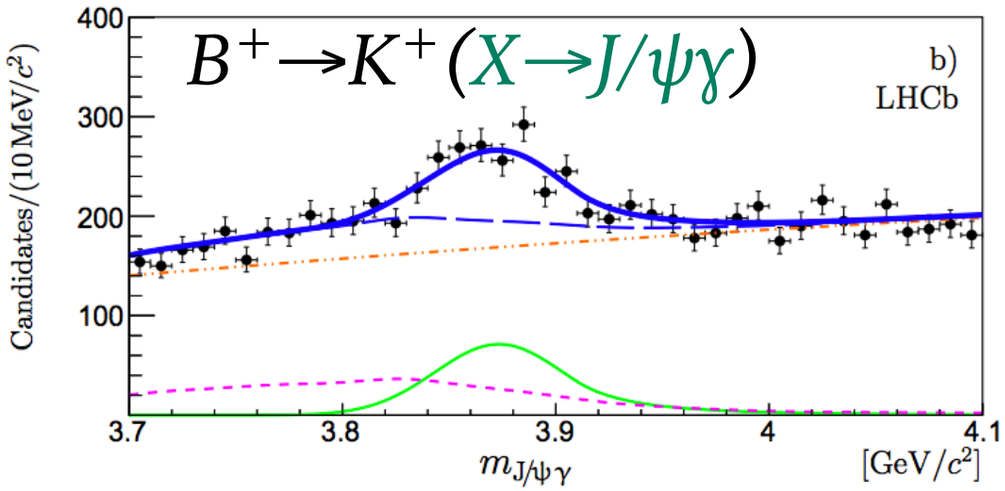
- *Measure:*

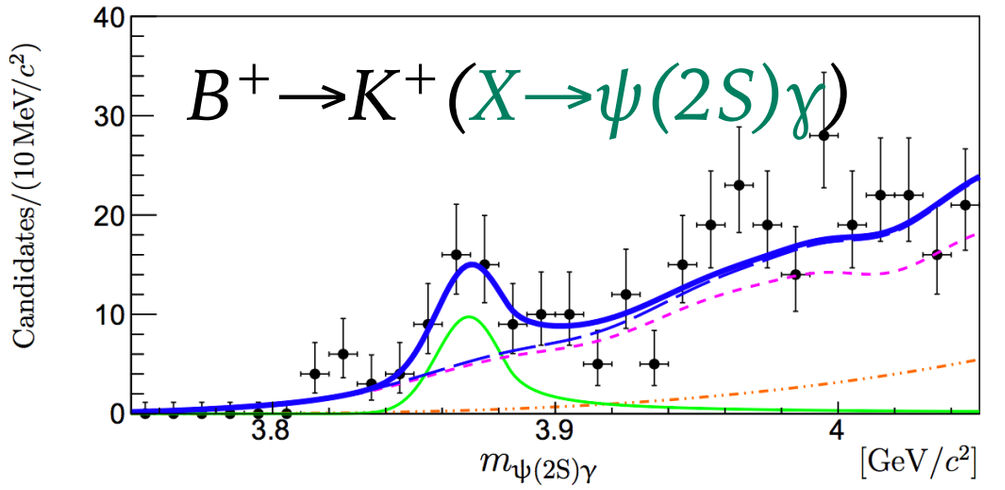
$$R_{\psi\gamma} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi(2S)}} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)},$$

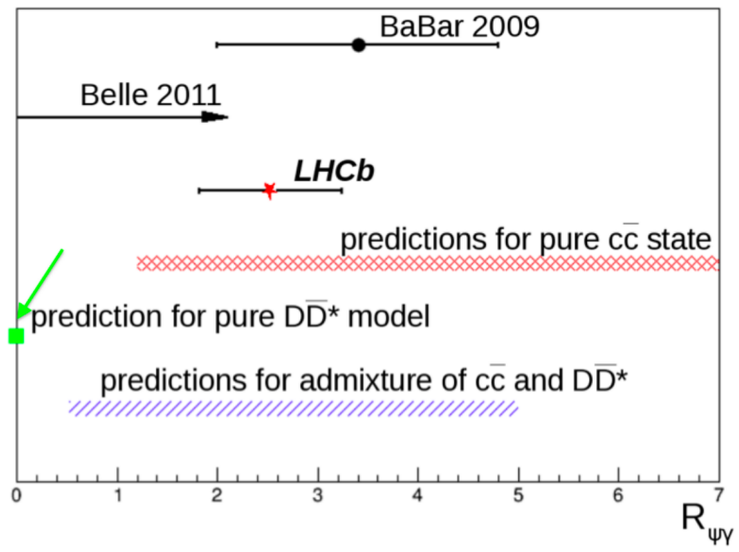
  - *main uncertainties:*
    - *fit model*
    - *photon reconstruction*

- *$R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29$* NPB 886 665 arXiv:1404.0275
  - *compatible with B-factories but more precise*
  - *contradicts pure-molecule predictions*

  - ***X(3872) is charmonium(+molecule)?***







Overview

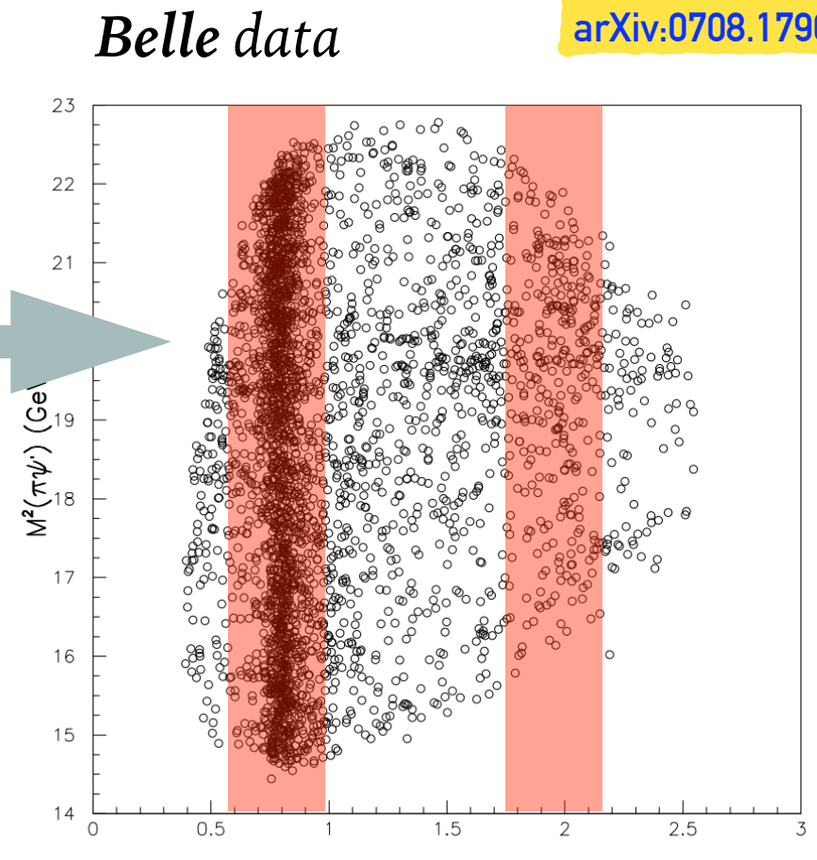
1. Probing X(3872) composition
2. Studying the Z(4430)
3. Pentaquark observation

Studying the Z(4430)

Introduction

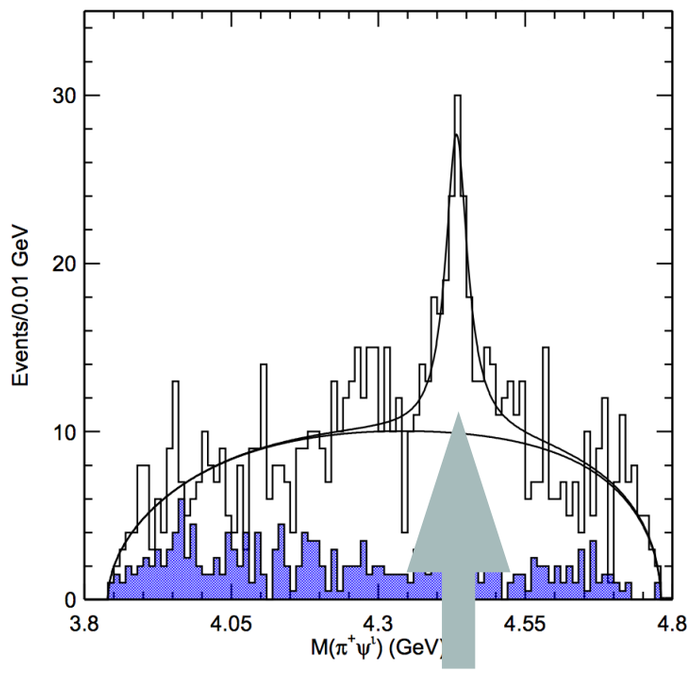
- *First observed by Belle in 2008*
  - $B \to K(Z \to \psi(2S)\,\pi^-)$ *and* $B \to K(Z \to J/\psi\,\pi^-)$
  - *mass 4433 MeV/c², width O(50 MeV)*
  - *charged; minimal* $c\bar{c}u\bar{d}$ *content*
  - *narrow; unlikely to be Kπ reflection*
  - *not yet confirmed elsewhere*

PRL 100 142001
arXiv:0708.1790



PRD 76 114002
arXiv:0708.3496

- *Alternative interpretation?*
  - ***S-wave threshold:*** $mass \approx m(D^*) + m(\bar{D}_1(2420))$
  - ***molecular:*** $D^* D_1(2420)$ arXiv:0908.1734
  - ***diquark-diantiquark:*** $[cu][\bar{c}\bar{d}]$ *excitation* NJPhys 10 073004
  - *and more…* ***or admixture of the above***

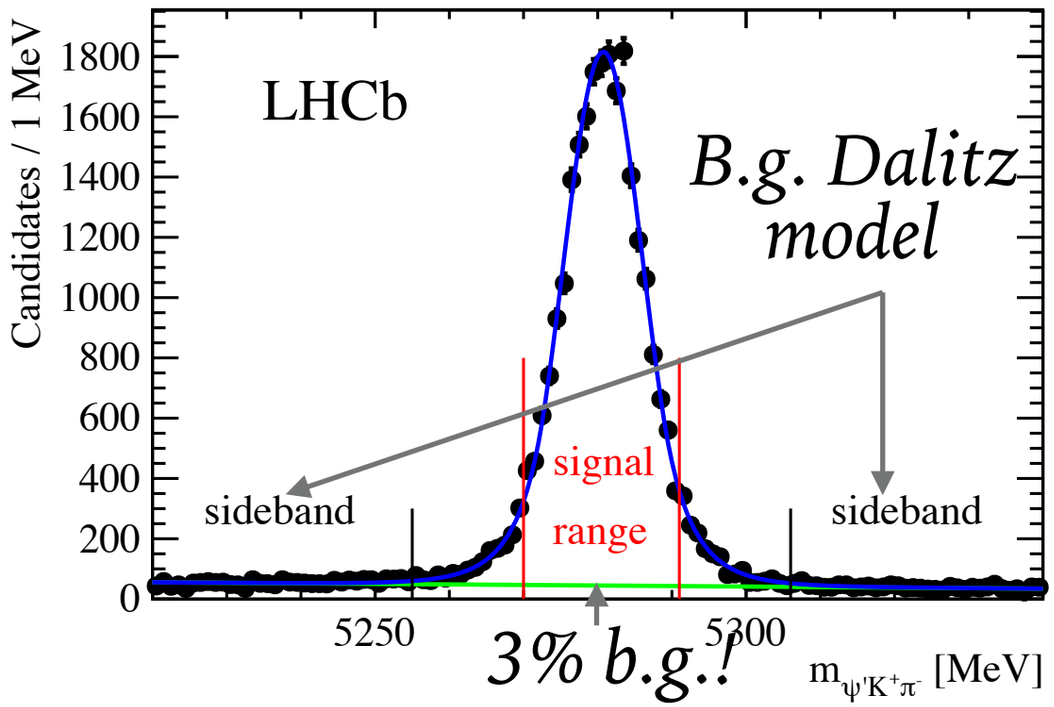


Studying the Z(4430)

LHCb analysis

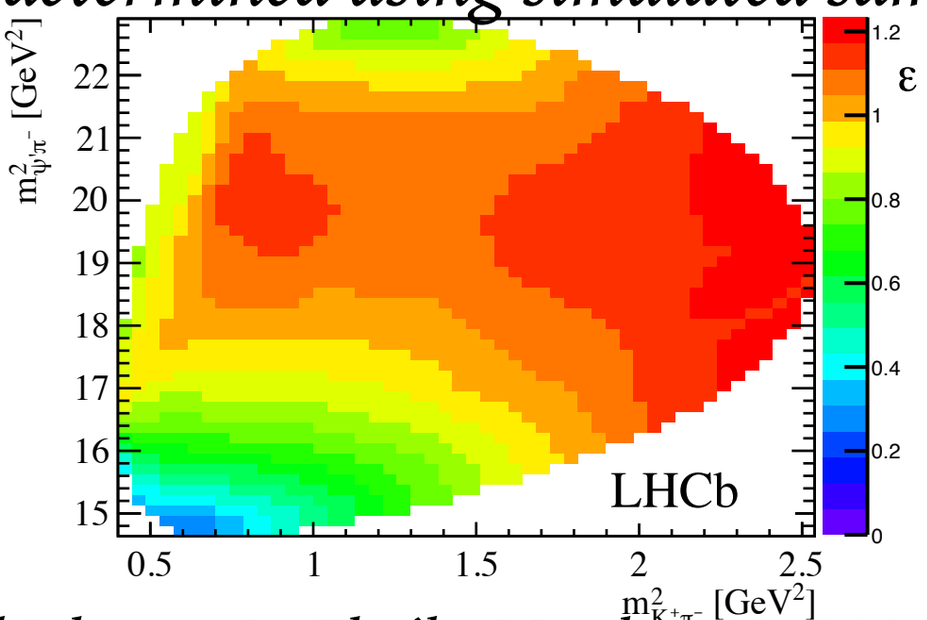
PRL 112 222002
arXiv:1404.1903

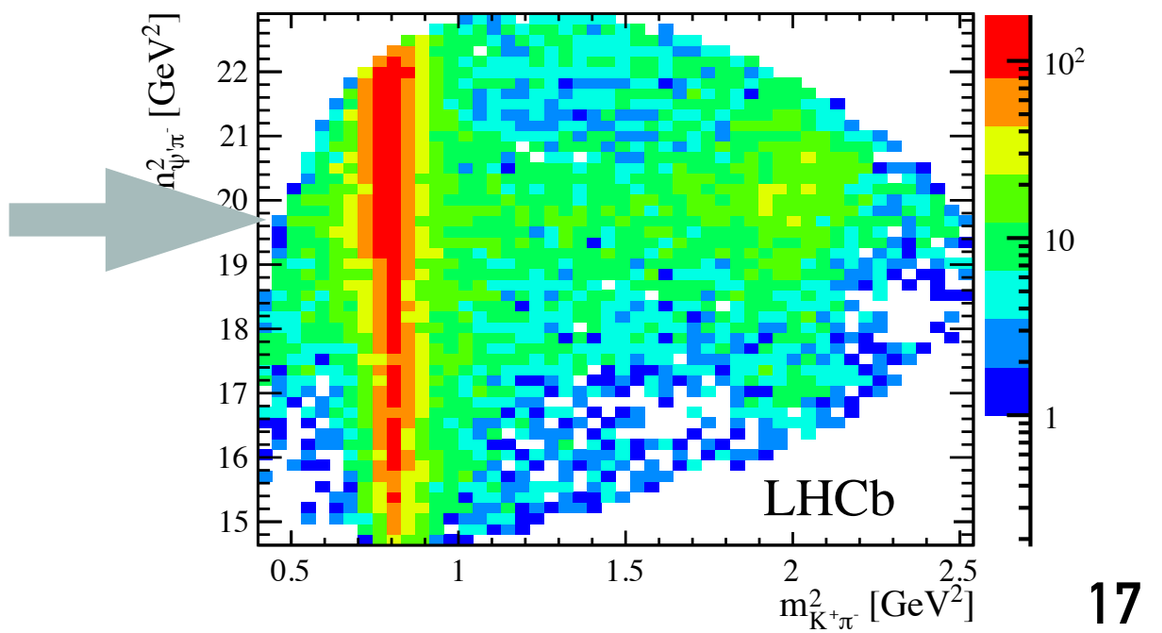
- *LHCb study: $3fb^{-1}$*
  - *10 times larger data sample than previous Z(4430) study*
  - *25,000 $B^+ \to K^+\psi(2S)\pi^-$ candidates*



- *Two analysis approaches*
  - *mod. indep.: Kπ Legendre moments*
  - *mod. dep.: 4D amplitude fit*

- *Efficiency*
  - *determined using simulated samples*



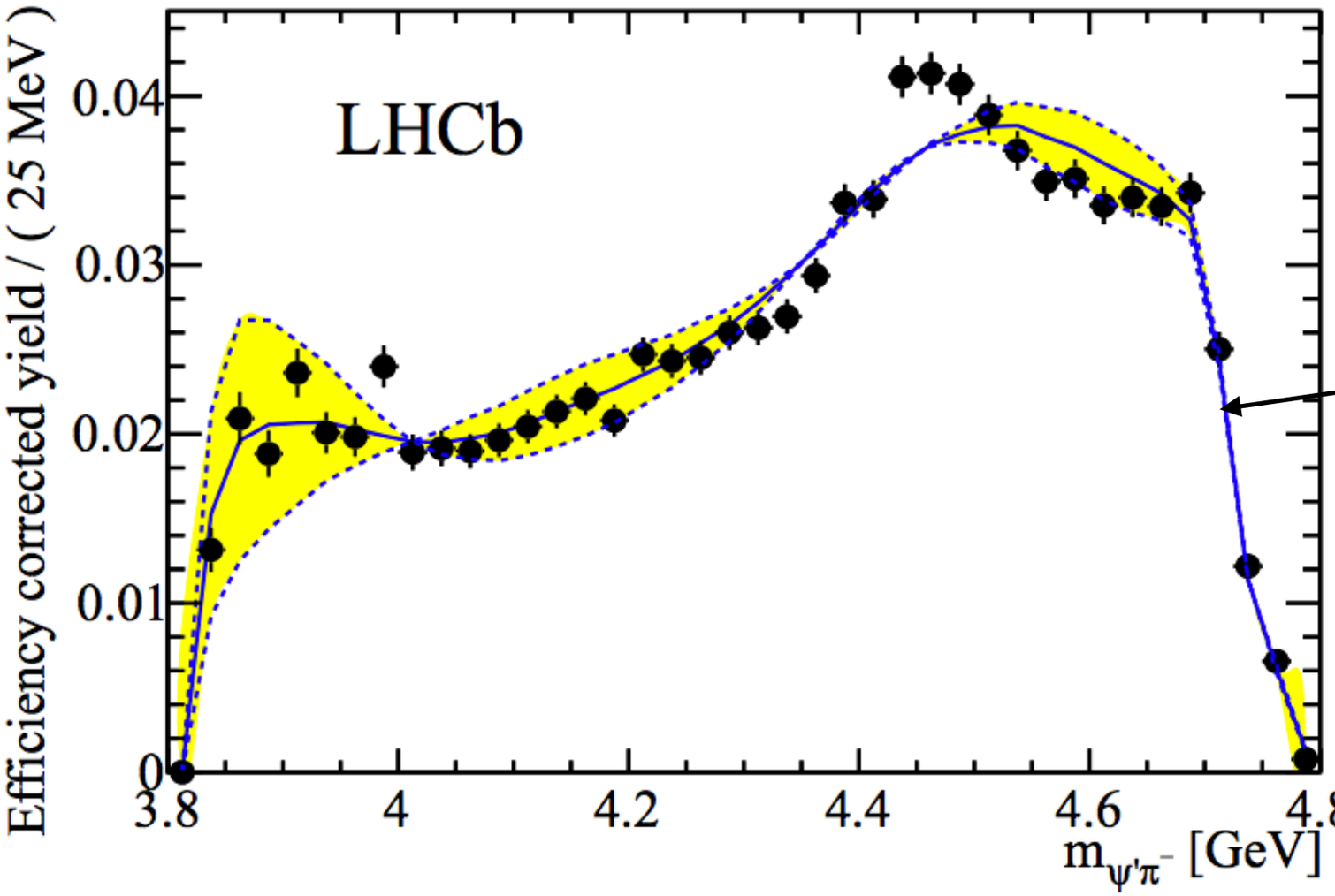


Studying the Z(4430)

PRL 112 222002
arXiv:1404.1903

Moments analysis

- *Can the Z(4430) be explained by K* reflections?*
  - *sideband subtract and efficiency correct $B^+ \to K^+\psi(2S)\pi^-$ sample*
  - *project $m_{K\pi}$ angular structure using Legendre moments of $\cos\theta_{K^*}$*
  - *reflect moments into $m_{\psi\pi^-}$ using weighted $B^+ \to K^+\psi(2S)\pi^-$ simulation*



Data
efficiency corrected, background subtracted

Projection
of $\cos(\theta_{K^*})$ moments, up to order 4.
Yellow band: correlated statistical uncertainty)

- *K* reflections provide inadequate description of the Z(4430) region*

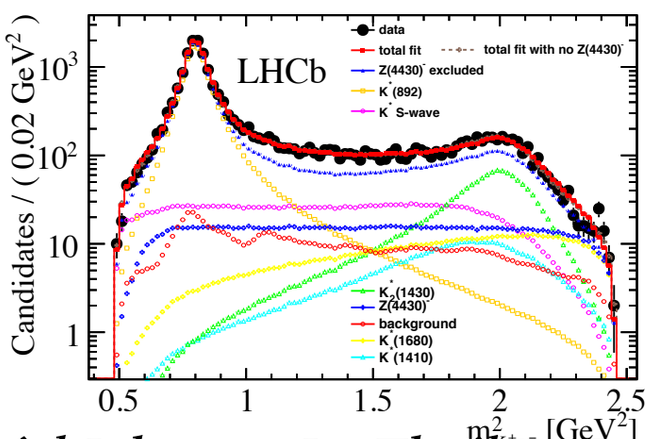
Studying the Z(4430)

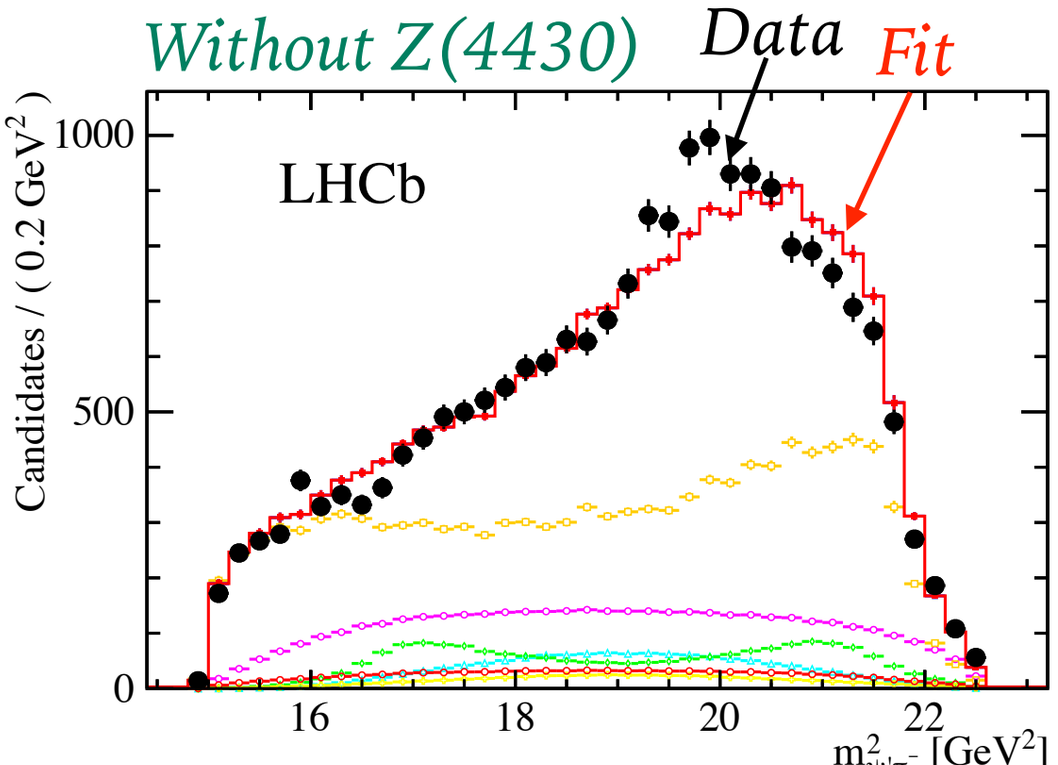
PRL 112 222002
arXiv:1404.1903

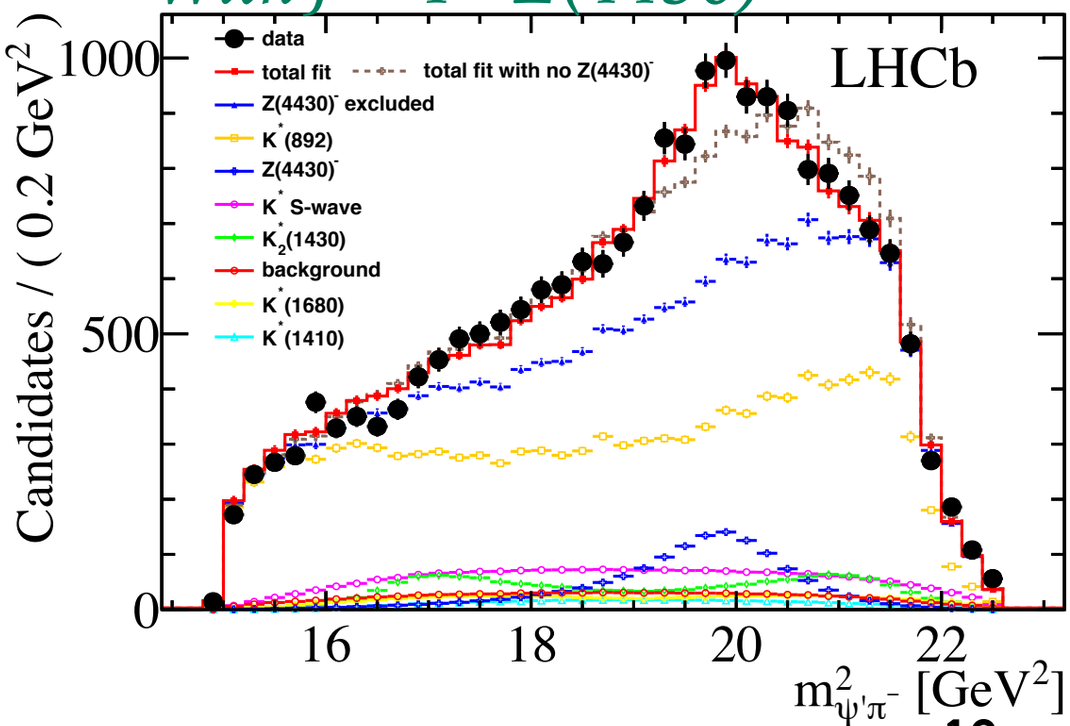
Amplitude analysis

- *Amplitude model*
  - *isobar formalism*
  - *consider all known neutral K^{*0} resonances*
    - *$K^{*0}(800)$ up to $K^*_3(1780)$*
    - *fix all masses and widths…*
    - *except $K^*(892)$ & $K^*_2(1430)$ widths…*
    - *and $K^*(800)$ mass and width*
  - *non-resonant term included, $J=0$*
  - *alternative model with LASS parameterisation*

- *Structure*
  - *clearly not described by K* reflections*
  - *deficiencies emphasised in the "K* veto" region*
  - *well described by a $J^P=1^+$ $Z(4430)$*





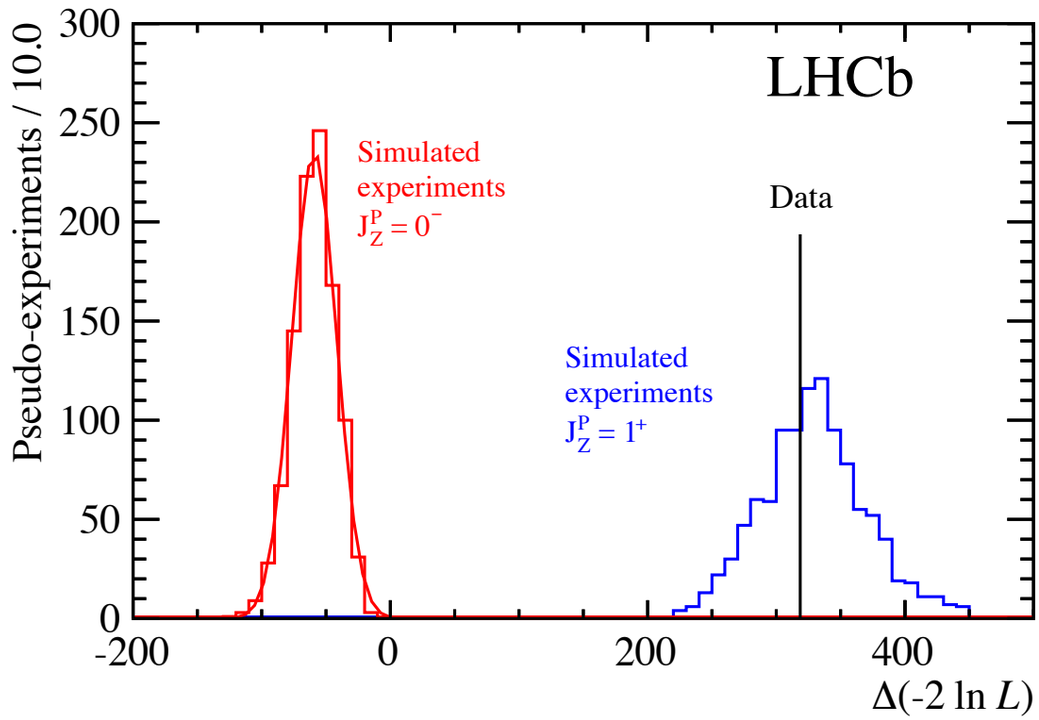


Studying the Z(4430)

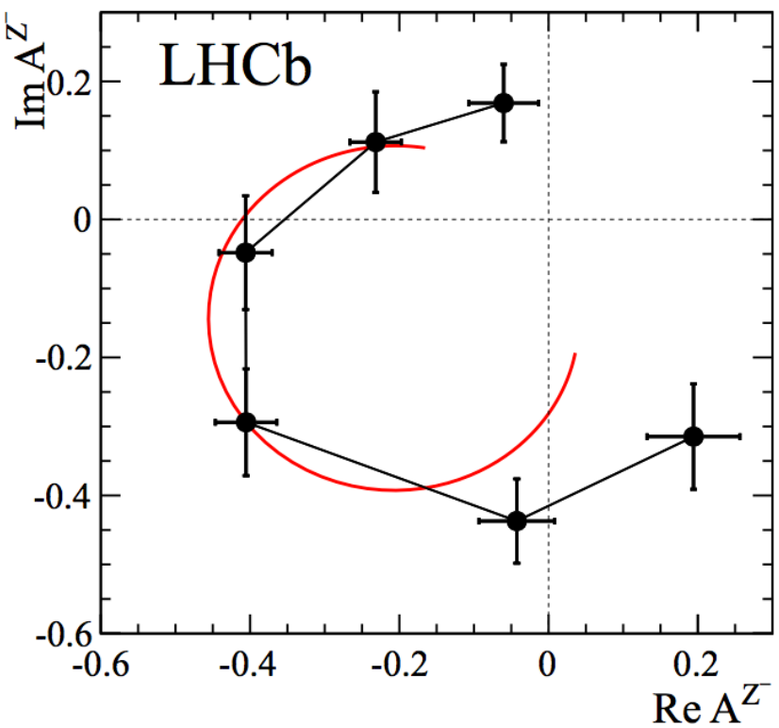
PRL 112 222002
arXiv:1404.1903

Amplitude analysis

- *Z(4430) resonance J^P*
  - *compare delta-log likelihood J^P 1^+ vs 0^-*
  - *pseudoexperiments using data-fit with either*
  - *strongly exclude 0^- hypothesis $\gg 5\sigma$*



- *Z(4430) resonance character*
  - *additional fit where represent Z amplitude with complex parameters in 6 $m_{\psi\pi^-}$ bins*
  - *plot resulting Argand diagram*
  - *phase rotation as expected for Breit-Wigner resonance*

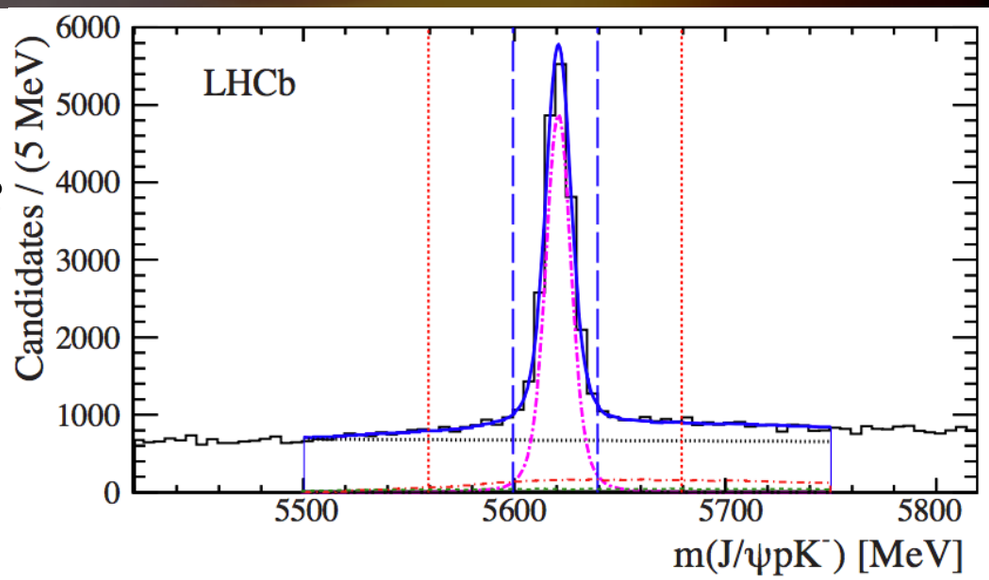


Overview

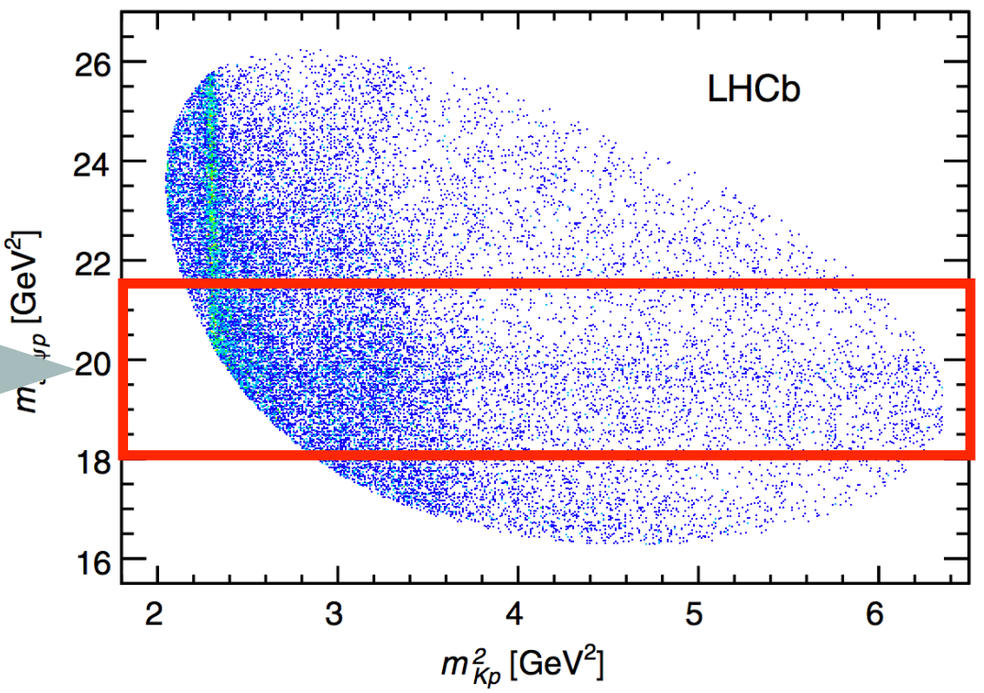
1. Probing X(3872) composition
2. Studying the Z(4430)
3. Pentaquark observation

Introduction

- $\Lambda_b \to J/\psi p K$ PRL 111 102003 arXiv:1307.2476
  - LHCb $1fb^{-1}$ used to measure precisely Λ_b lifetime
  - 15,600 $\Lambda_b \to J/\psi p K$ candidates



- *Update to* $3fb^{-1}$ PRL 115 072001 arXiv:1507.03414
  - 26,000 candidates; 5% background
  - standard selection; peaking b.g. removed
  - unexpected peak in $m(J/\psi p)$

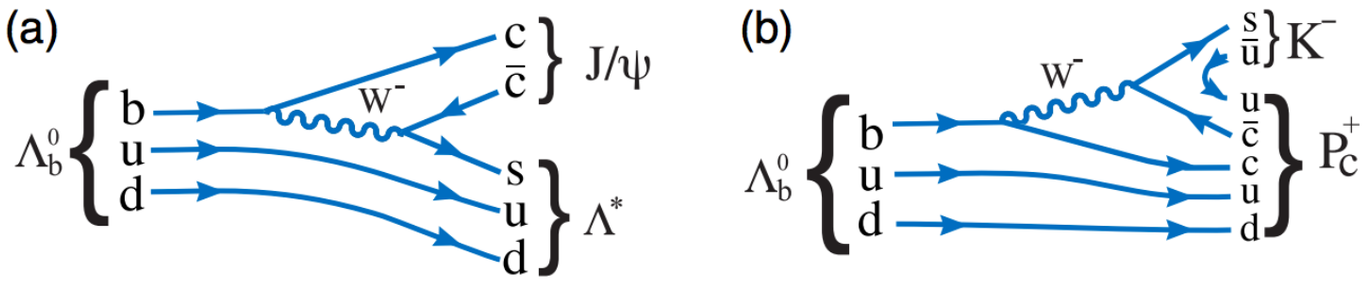


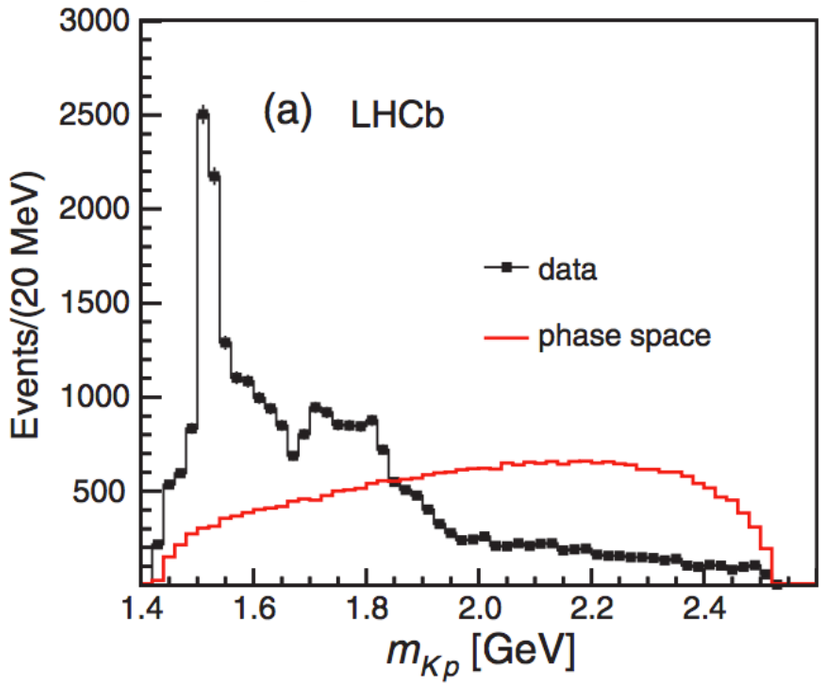
Pentaquarks

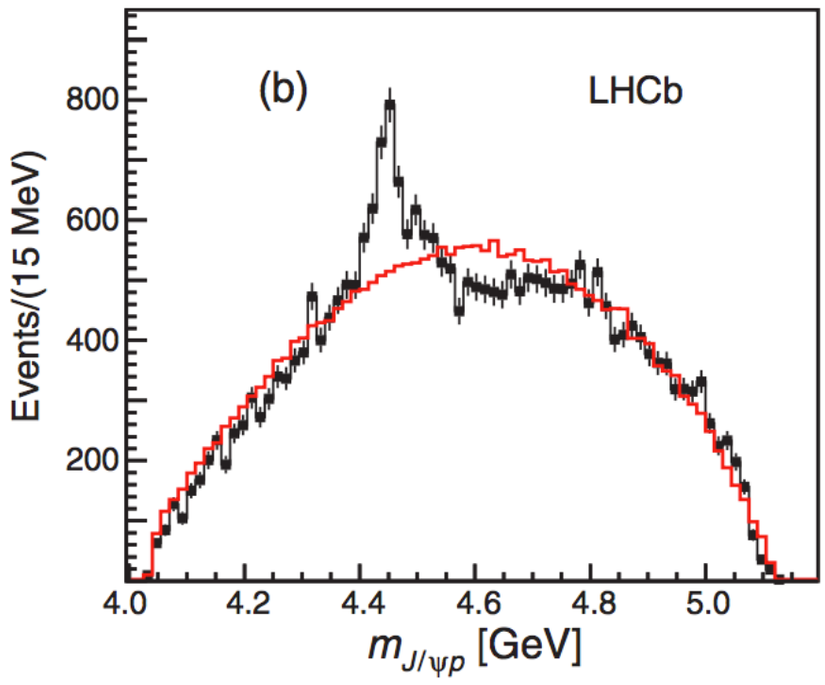
PRL 115 072001
arXiv:1507.03414

Unexpected structure

- *Resonant structure*
  - *expect Λ* resonances to dominate*
  - *$J/\psi p$ resonance must have $c\bar{c}uud$*
  - *sharp structure appears…*



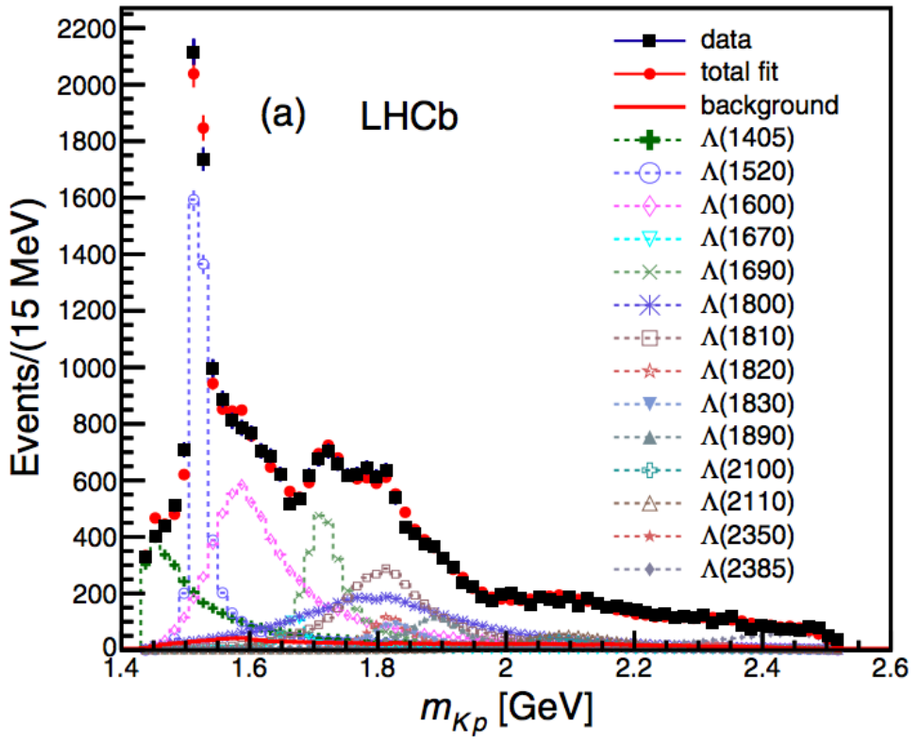


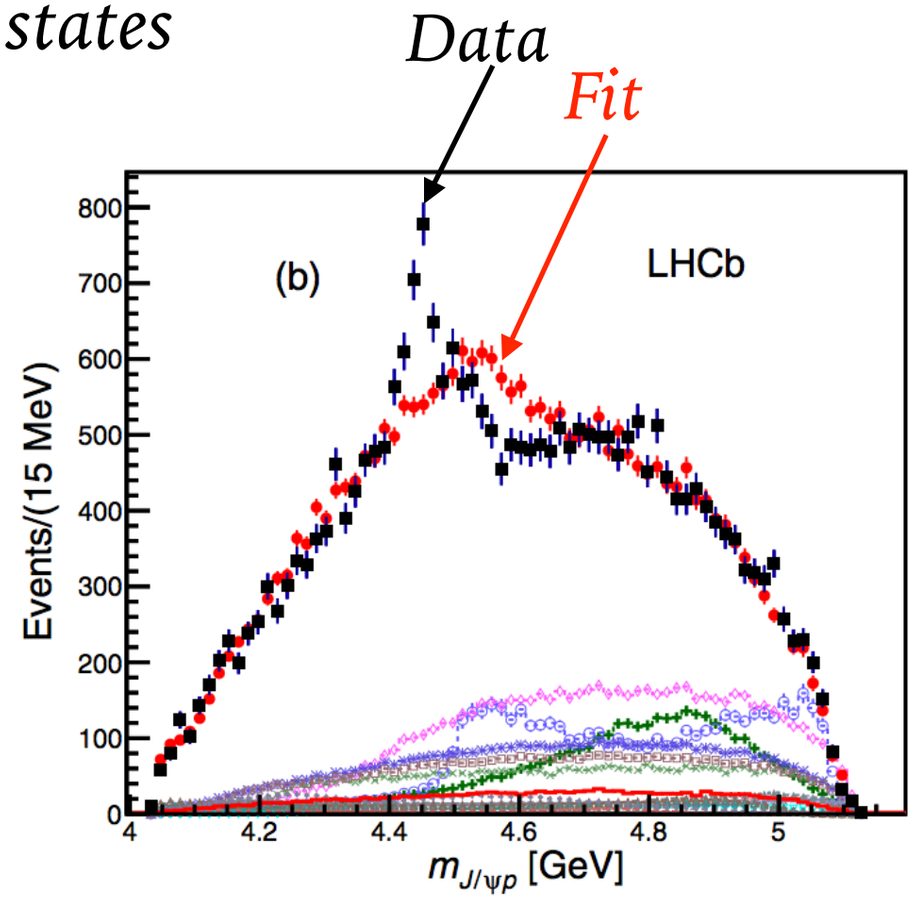


- *Alternative explanations*
  - *efficiencies vary smoothly*
  - *specific veto for $B_s \to J/\psi KK$ and $B^0 \to J/\psi K\pi$*
  - *ghost- and clone-tracks are removed*
  - *is it a Λ* reflection?*

Amplitude analysis

- *LHCb study: 3fb^{-1}*
  - *6D amplitude fit*
  - *amplitude model includes all known Λ* states*
  - *fit without J/ψp states:*





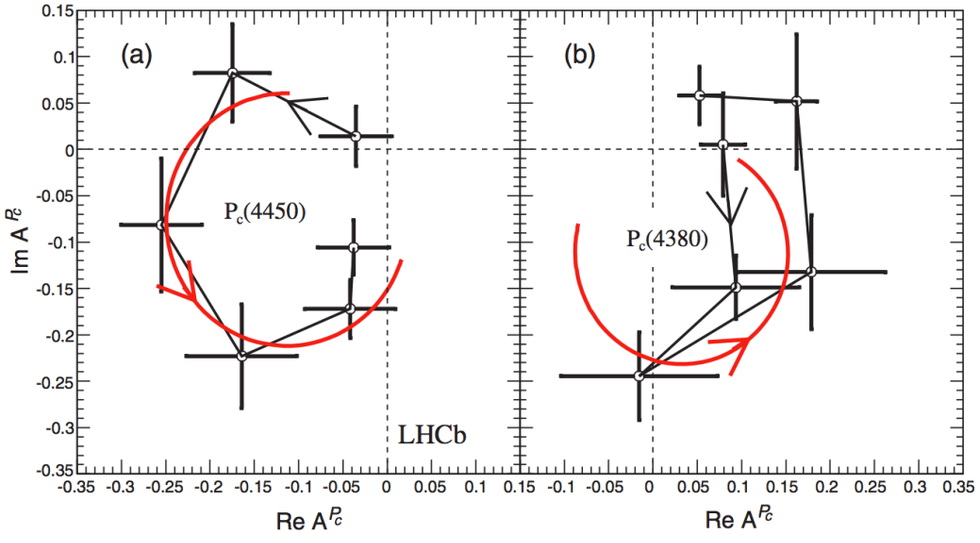
- *Tried:*
  - *floating masses and widths*
  - *adding further Λ states*
  - *adding non-resonant term/Σ**

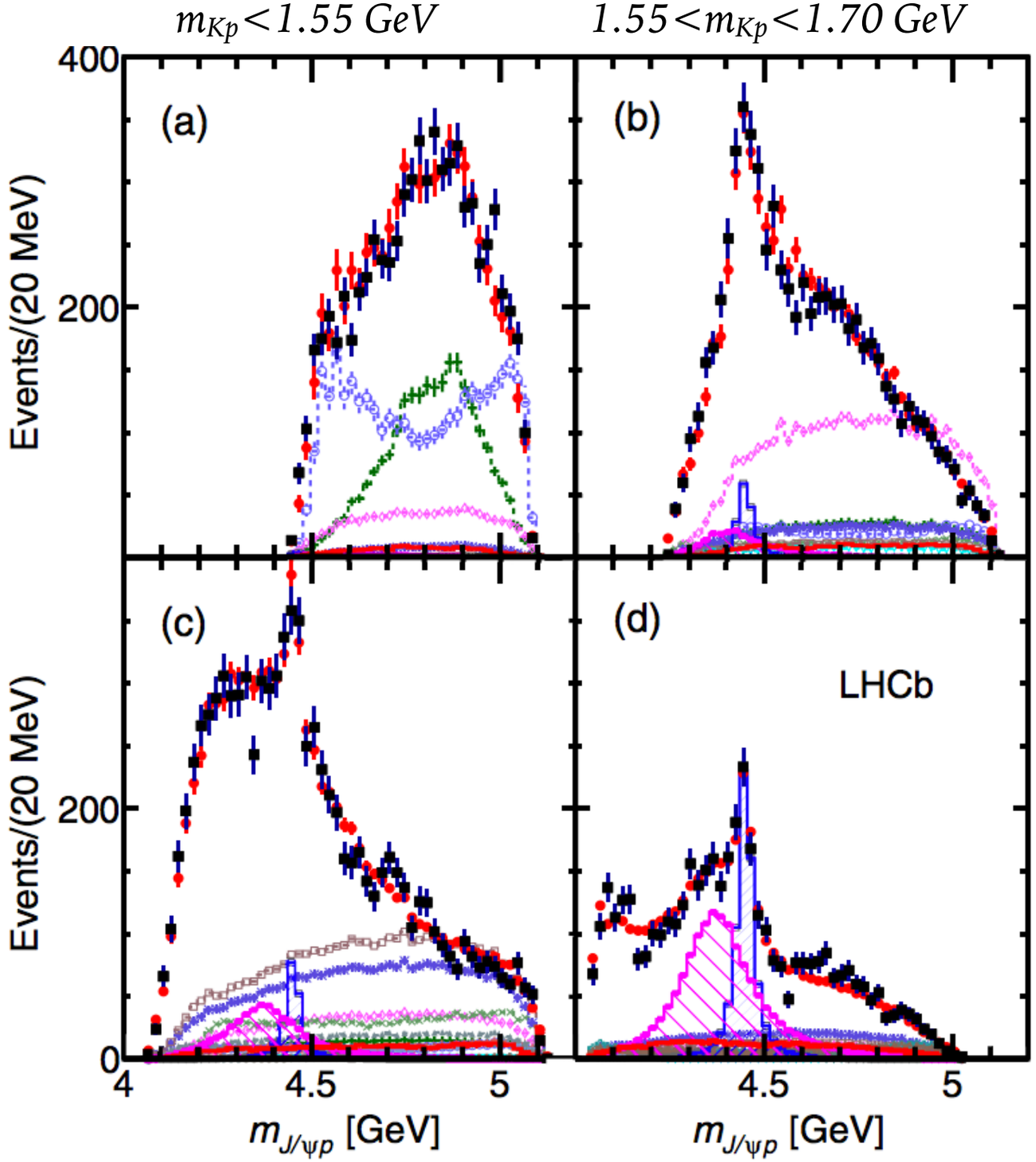
Pentaquarks

LHCb analysis

- *Adding two pentaquarks*
  - *good fit even with reduced Λ* set*
    - *$P_c(4380)$, width 205 MeV/c^2*
    - *$P_c(4450)$, width 40 MeV/c^2*

- *Resonant behaviour*
  - *preference for $J^P = (3/2^-, 5/2^+)$*
  - *phase rotation visible*
  - *more data required to confirm quantum numbers*





Summary:

- *X(3872)*
  - *quantum numbers confirmed 1^{++}*
  - *radiative transition disfavours D*D molecule*
- *Z(4430)*
  - *confirmation of state and resonant behaviour*
  - *quantum number confirmed 1^{+}*
- *Pentaquarks*
  - *two new $c\bar{c}uud$ states observed*
  - *evidence of resonant behaviour*
  - *more data needed to confirm quantum numbers*
- *Run 2 re-starts soon!*