Exotic Charmonium-like Spectroscopy at LHCb
$X(3872)^0$
$Z(4430)^{\pm}$

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On behalf of the LHCb collaboration

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Outline

- $X(3872)^0$
  - Determination of quantum numbers [PRL 110, 222001 (2013)]
  - Evidence for the decay $X(3872) \rightarrow \psi(2S)\,\gamma$ [arXiv:1404.0275]

- $Z(4430)^{\pm}$ [arXiv:1404.1903, accepted by PRL]
  - Improved measurement of mass and width
  - Determination of quantum numbers
  - Observation of its resonant character

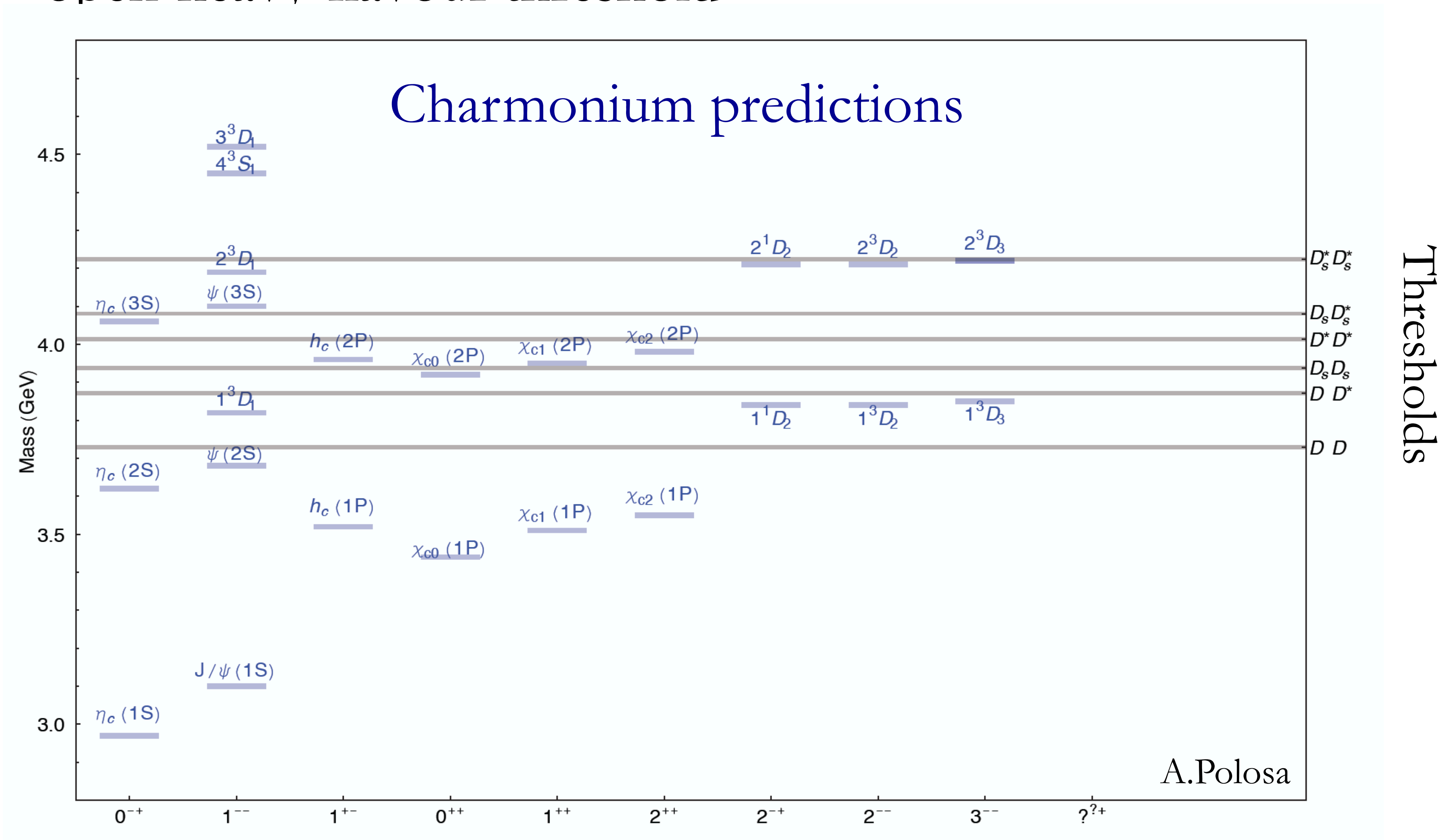
Standard & exotic hadrons

- In the naïve quark model mesons are $q\bar{q}$ states and baryons qqq states
- A large number of states that do not fit in the conventional picture (XYZ) found in the last years
  - Many unexpected neutral states, several charged ones
- A compelling unified description has not yet emerged

Conventional quarkonium? Hybrid? Tetraquark? Molecule? . . .

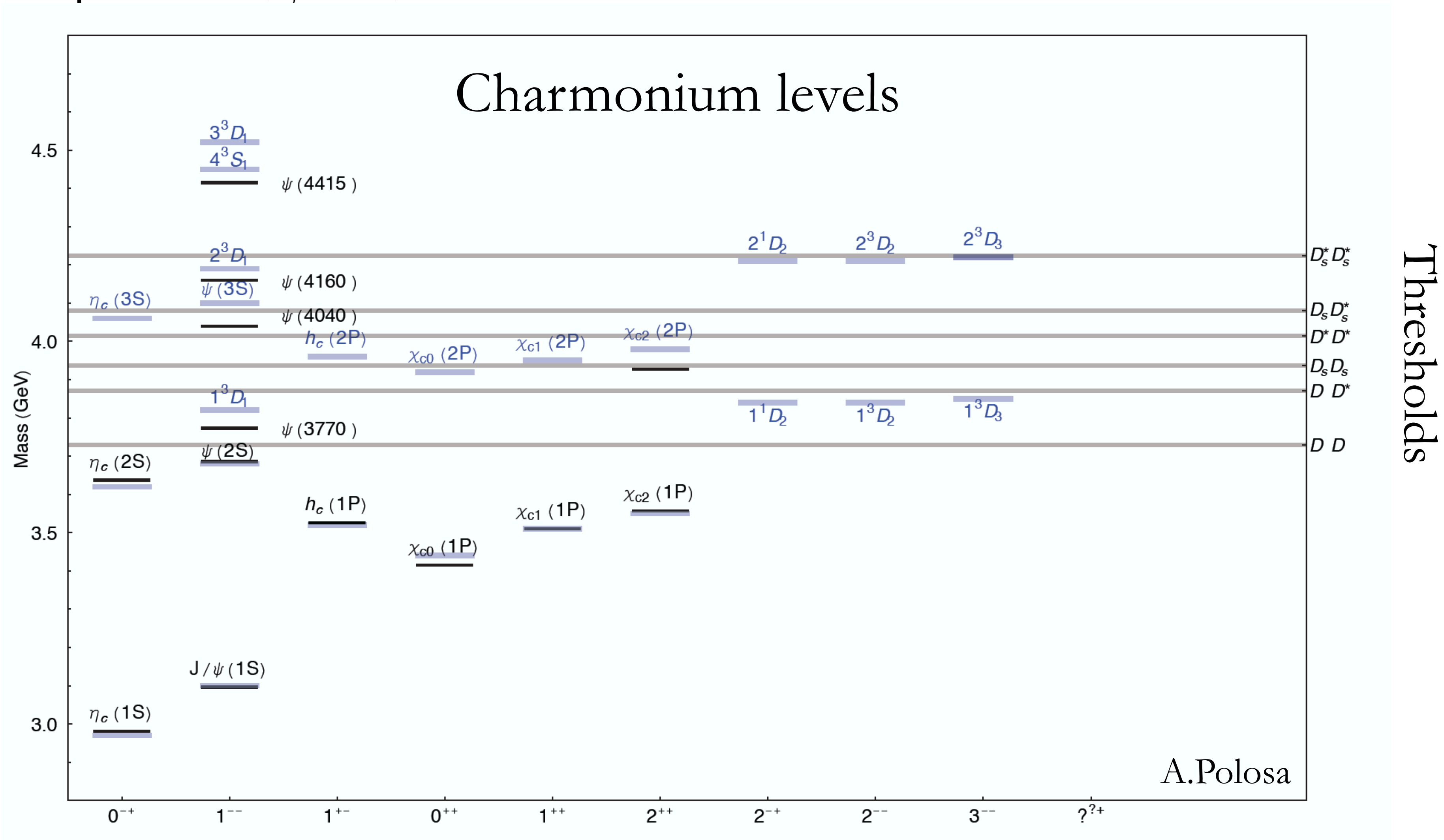
Conventional Quarkonium

- Well motivated models provide successful predictions **below** open-heavy-flavour threshold



Conventional Quarkonium

- Well motivated models provide successful predictions **below** open-heavy-flavour threshold



X(3872), the enduring exotic

- Observed at Belle a decade ago in the mode $J/\psi\pi^+\pi^-$, confirmed by CDF, D0, BaBar, CMS and LHCb
- Mass extremely close to nearest open charm threshold
  - $m_{X(3872)} = 3871.68 \pm 0.17$ MeV while $m_{D^0} + m_{D^{*0}} = 3871.85 \pm 0.20$ MeV
  - If molecule, binding energy only 0.17 ± 0.26 MeV!
- It decays with isospin symmetry violation

$$\frac{B(X \to J/\psi\ \rho)}{B(X \to J/\psi\ \omega)} \approx 1$$

compatible with a $\bar{D}^0 D^{0*}$ molecular interpretation

  - In fact $\bar{D}^0 D^{0*}$ is a superposition of isospin 0,1 as the $D^{*+}D^-$ threshold is ~8 MeV away

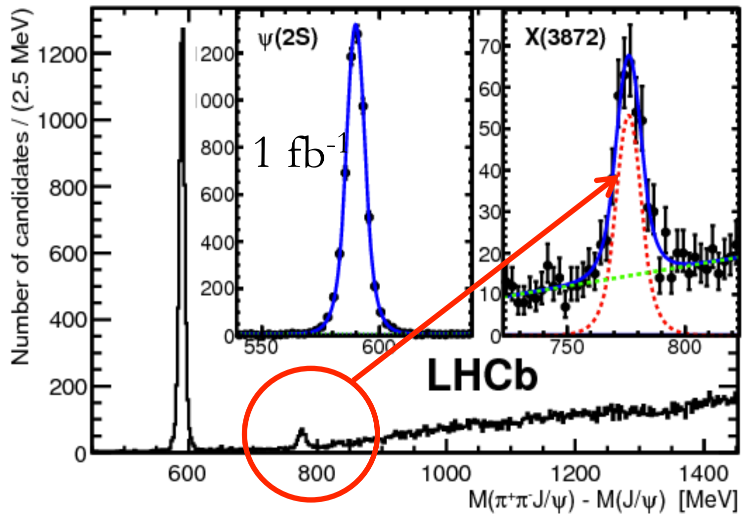
Determination of the X(3872) quantum numbers

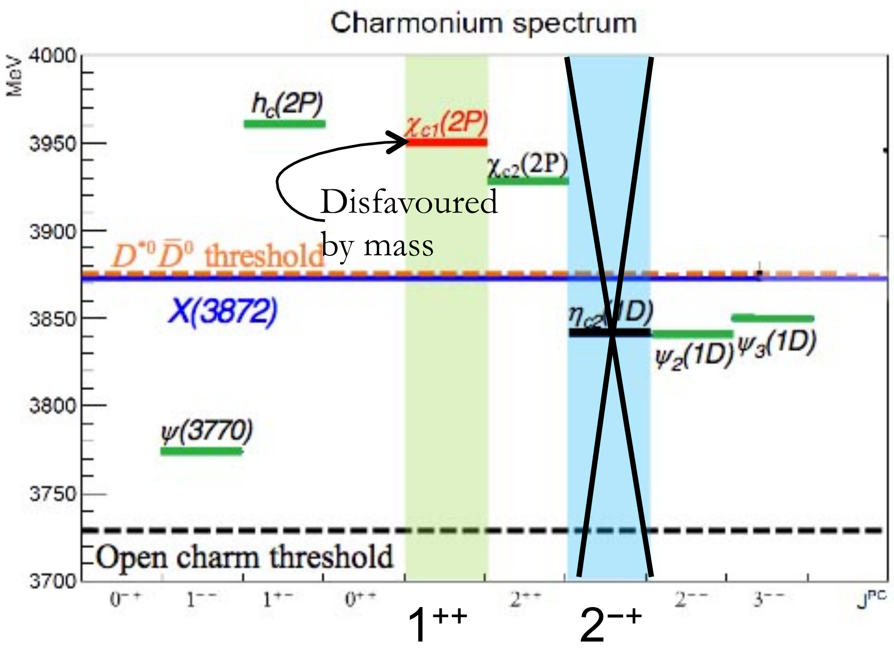
- CDF measurement [PRL 98 132002] excluded all J^{PC} except 2^{-+} and 1^{++}
- LHCb measurement [PRL 110, 222001 (2013)]:

  $B^+ \rightarrow X(3872)K$

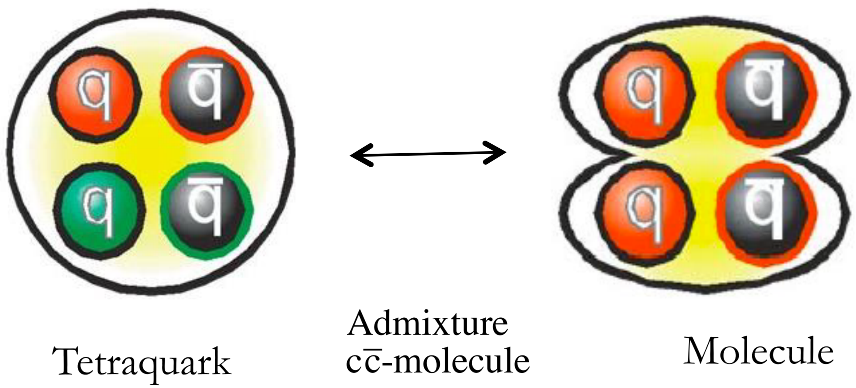
  $\quad \hookrightarrow J/\psi\pi^+\pi^-$

- Established $J^{PC} = 1^{++}$





- $J^{PC} = 1^{++}$ disfavours convential charmonium
- Favours exotic interpretation



Radiative decays of X(3872)

- Measurement of $R_{\psi\gamma} = \frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872) \to J/\psi\gamma)}$
  as a constraint on charmonium content of X(3872)
- $B(X(3872) \to \psi(2S)\gamma)$ expected very small for pure molecule
- Could be enhanced for an admixture of $D^0\overline{D}^{0*}$ molecule and charmonium
- Relative large $B(X(3872) \to \psi(2S)\gamma)$ measured by BaBar
  - $R_{\psi\gamma}$=3.4±1.4 [PRL102 (2009) 132001]
  - Generally inconsistent with a pure molecular interpretation

Radiative decays of X(3872)

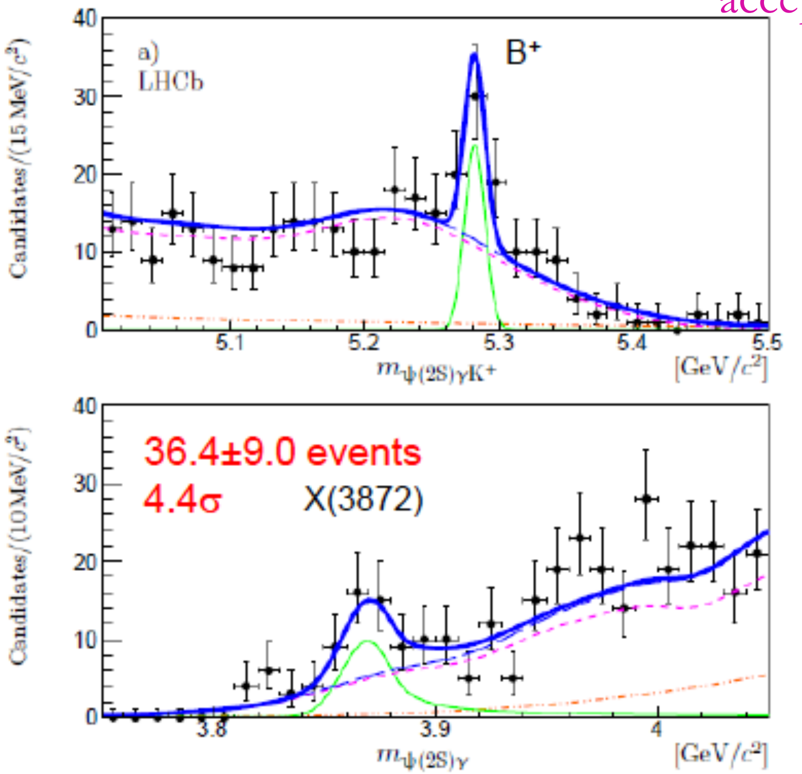
LHCb 3 fb^{-1}

[arXiv:1404.0275]

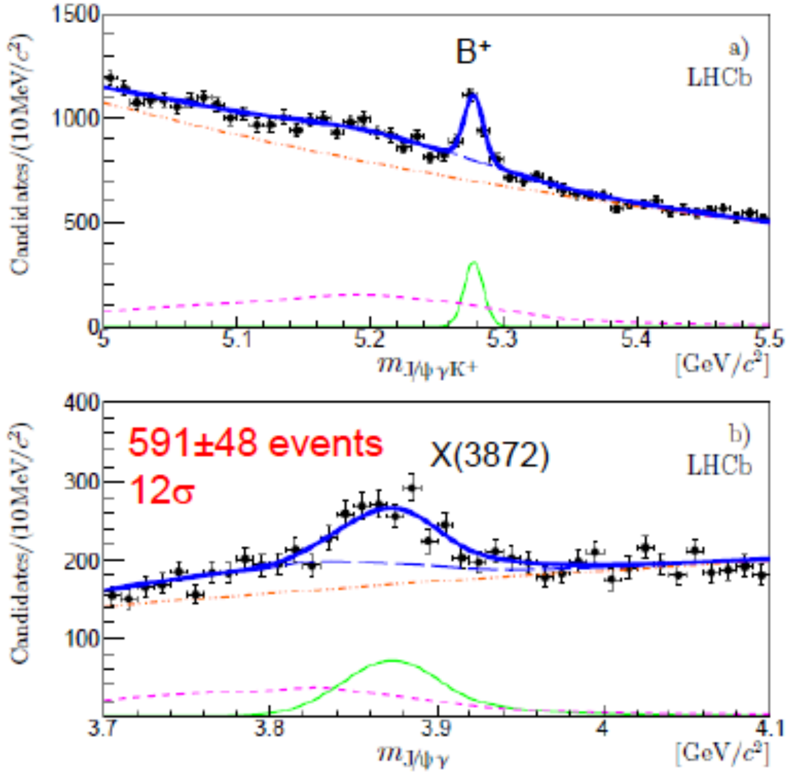
accepted by NPB

Projections of 2D fit to $m_{\psi K^+}$ vs $m_{\psi\gamma}$

$B^+ \to X(3872) K^+$, $X(3872) \to \psi(2S)\gamma$



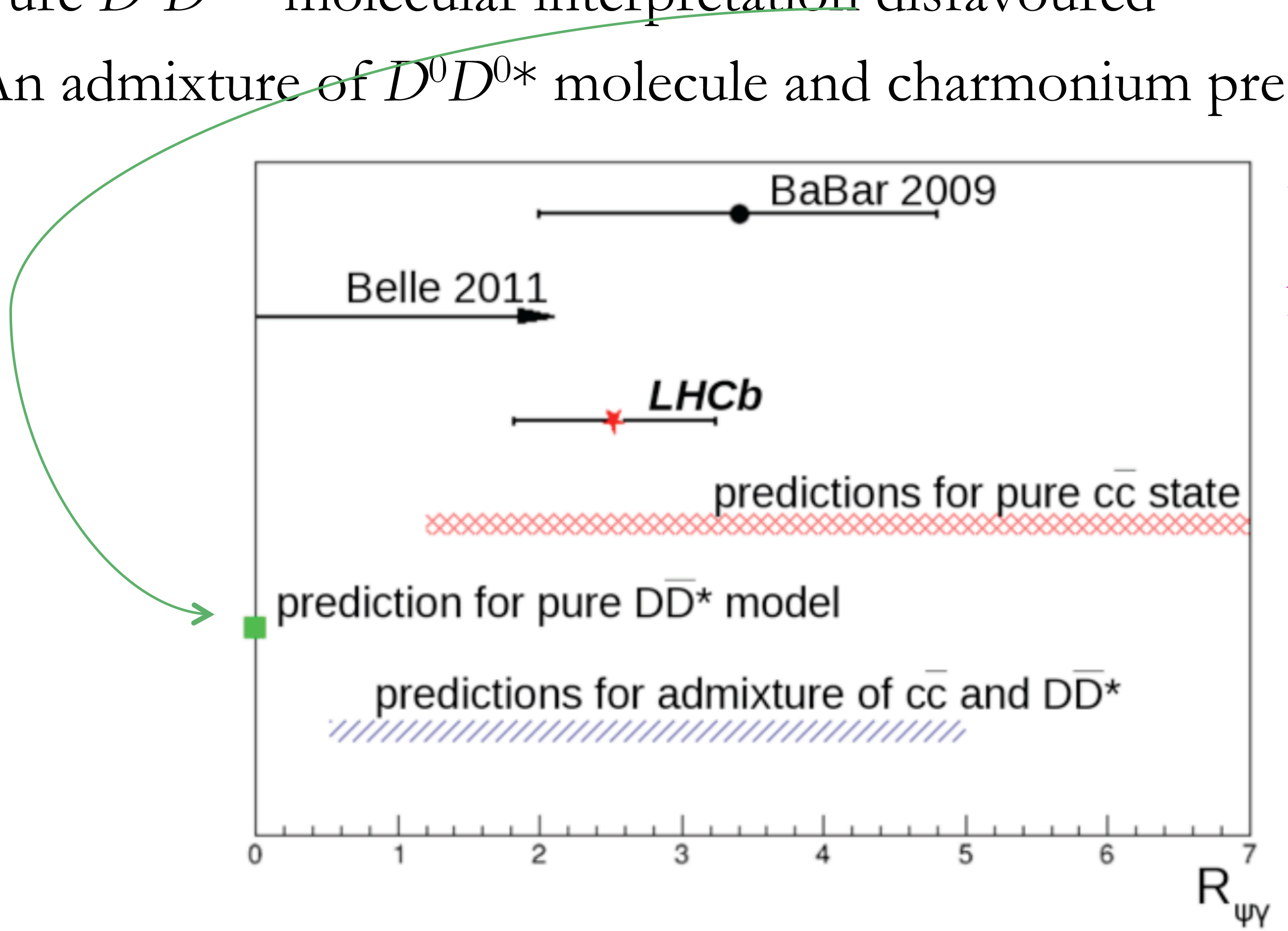
$B^+ \to X(3872) K^+$, $X(3872) \to J/\psi\gamma$



- The most significant evidence for X(3872)→ ψ(2S) γ to date!
- $\varepsilon_{J/\psi} / \varepsilon_{\psi(2S)} \sim 5$ due to the different photon spectra

Radiative decays of X(3872)

- $R_{\psi\gamma} = \frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872) \to J/\psi\ \gamma)} = 2.46 \pm 0.64 \pm 0.29$
- Pure $\bar{D}^0 D^{0*}$ molecular interpretation disfavoured
- An admixture of $D^0 D^{0*}$ molecule and charmonium preferred



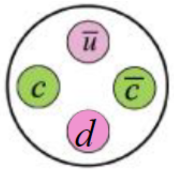
PRL 102, 132001 (2009)

PRL 107, 091803 (2011)

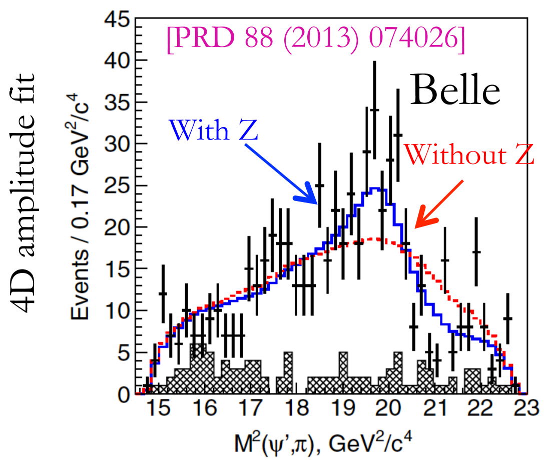
arXiv:1404.0275
accepted by NPB

Z(4430)$^{\pm}$

- $Z(4430)^- \rightarrow \psi(2S)\pi^-$ observed by Belle in $B^0 \rightarrow \psi(2S)K^+\pi^-$ [PRL 100 (2008) 142001] [PRD 80 (2009) 031104(R)]
- Charmonium-like charged state of special interest
  - Minimal quark structure $c\bar{c}u\bar{d}$ → tetraquark with hidden charm
  - Manifestly exotic



- Not confirmed by BaBar with model independent analysis [PRD 79 (2009) 112001]
  - $\psi(2S)\,\pi^-$ mass distribution well-described by reflections of $K\pi^-$ states without invoking exotic resonances, however Belle results not ruled out
- Belle's latest full amplitude analysis constrains Z(4430)$^{\pm}$ quantum numbers
  - $J^P=1^+$ hypothesis favoured (>3.4 σ)
  - $M_Z = 4485^{+22+28}_{-22-11}\,\mathrm{MeV}/c^2$
  - $\Gamma = 200^{+41+26}_{-46-35}\,\mathrm{MeV}$

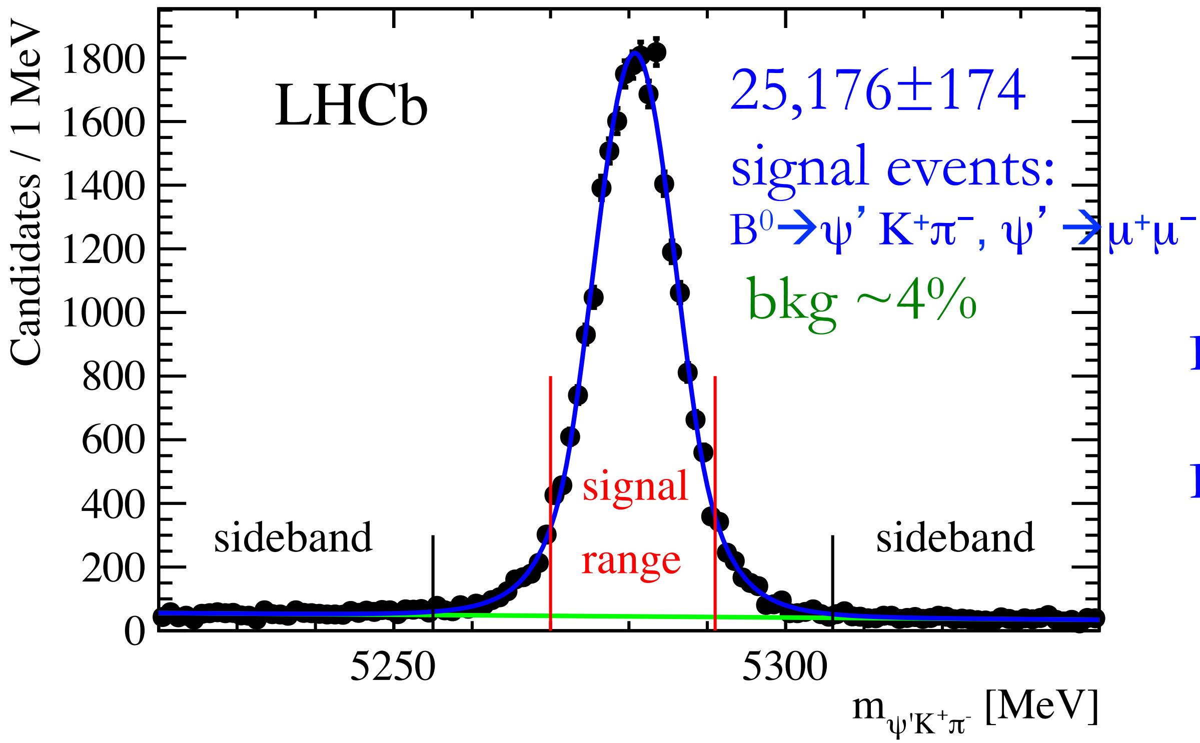


$m^2(\psi(2S)\pi^-)$ with $K^*(892)$, $K^*_2(1430)$ veto

Z(4430)$^{\pm}$ in LHCb

- $B^0 \rightarrow \psi' K^+\pi^-$, $\psi' \rightarrow \mu^+\mu^-$ (3 fb^{-1}) [ψ' =ψ(2S)]

[arXiv:1404.1903]



Belle: 2010±50 signal events

bkg ~8%

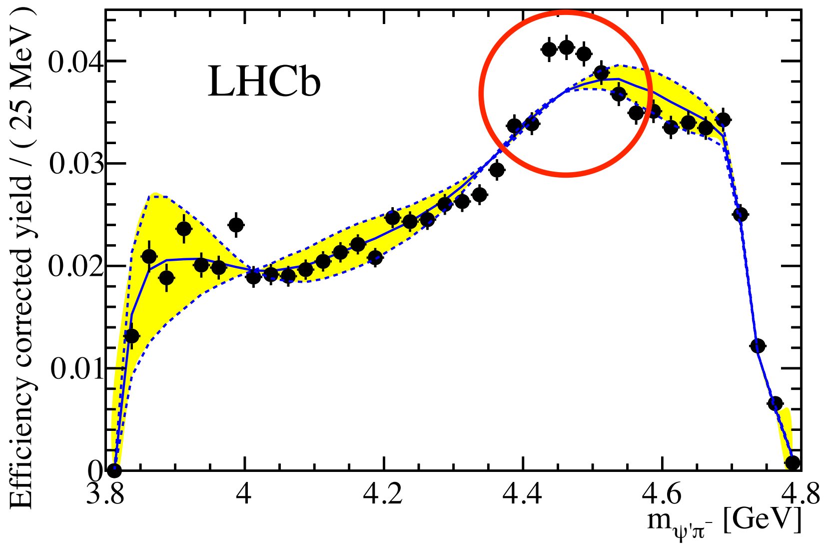
BaBar: 2021±53

- An order of magnitude larger signal statistics than in Belle or BaBar (larger x-section)
- Smaller non-B background in hostile LHC environment (vertexing, PID)!

LHCb analysis I: Model-independent (a la BaBar)

- Check whether one can understand $m_{\psi'\pi^-}$ spectrum in $B^0 \rightarrow \psi' K^+\pi^-$ in terms of reflections of known K^* resonances
  - BaBar's method BaBar: [PRD 79 (2009) 112001]
- No assumption on underlying K^* resonances, only maximal spin restricted
  - Bin data in $K^+\pi^-$ mass and decompose K helicity angle distribution in Legendre polynomial moments
  - $J \leq 2$ as only *S*-, *P*- and *D*-partial waves in $K^+\pi^-$ are significant
- Moments of K* resonances unable to explain observed $m_{\psi'\pi^-}$ distribution

[arXiv:1404.1903]

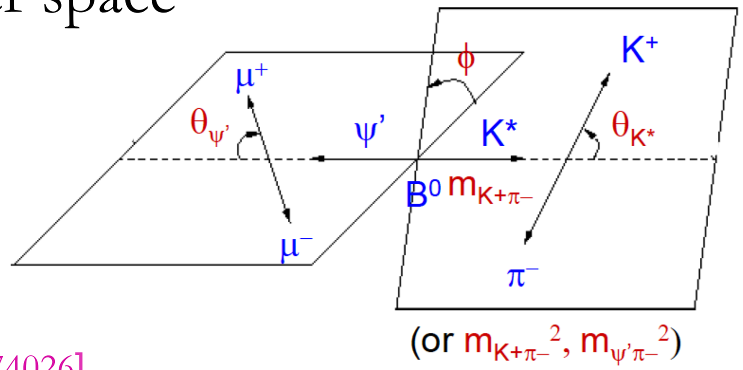


- Need to use amplitude analysis to extract quantitative information about this structure, Z mass, width and spin (properly accounting for interferences)

LHCb analysis II: 4D amplitude (a la Belle)

- Fit a model of $B^0 \rightarrow \psi' K^+\pi^-$ amplitude to the data (with K^*_0 contribution alone and with $Z(4430)^- \rightarrow \psi' \pi^-$)
- Amplitude calculated in 4D parameter space

$$\Phi = (m^2_{K^+\pi^-},\ m^2_{\psi'\pi^-},\ \cos\theta_{\psi'},\ \phi)$$

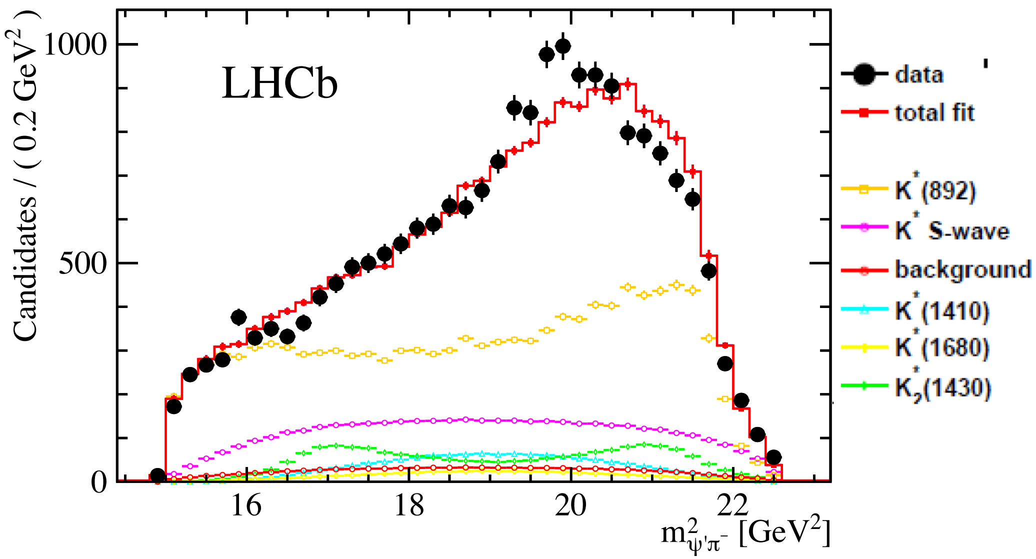


- Amplitude model: Belle: [PRD 88 (2013) 074026]
  - Decay matrix as sum of several two-body decays: $B^0 \rightarrow Z^- K^+$ (signal) and $B^0 \rightarrow \psi' K^*_0$ (background)
  - Each resonance represented as a Breit-Wigner amplitude and J-dependent angular terms
  - All known $K^*_0 \rightarrow K^+\pi^-$ resonances with $J \leq 3$ allowed (within or slightly above kinematic limit of 1593 MeV); fit their complex helicity amplitudes

Amplitude fits without Z(4430)±

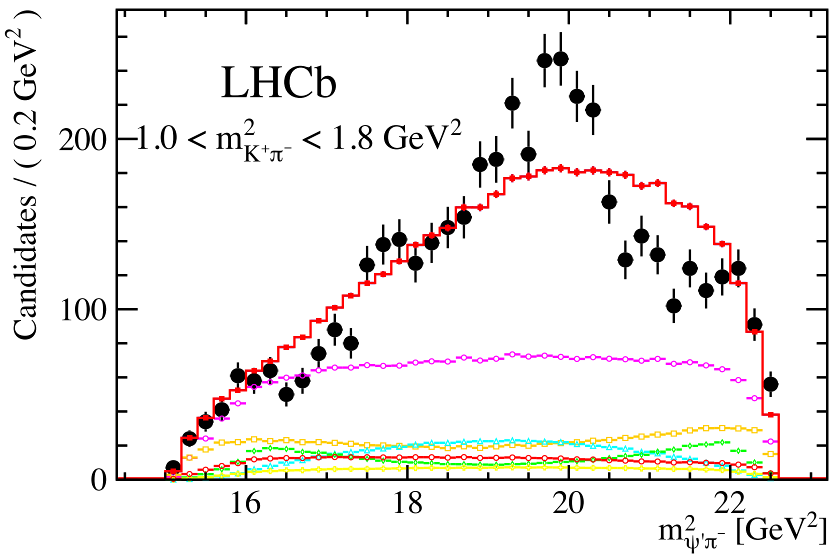
[arXiv:1404.1903]

all data



K* veto region

between two dominant K* resonances, $K^*(892)$ and $K^*_2(1430)$

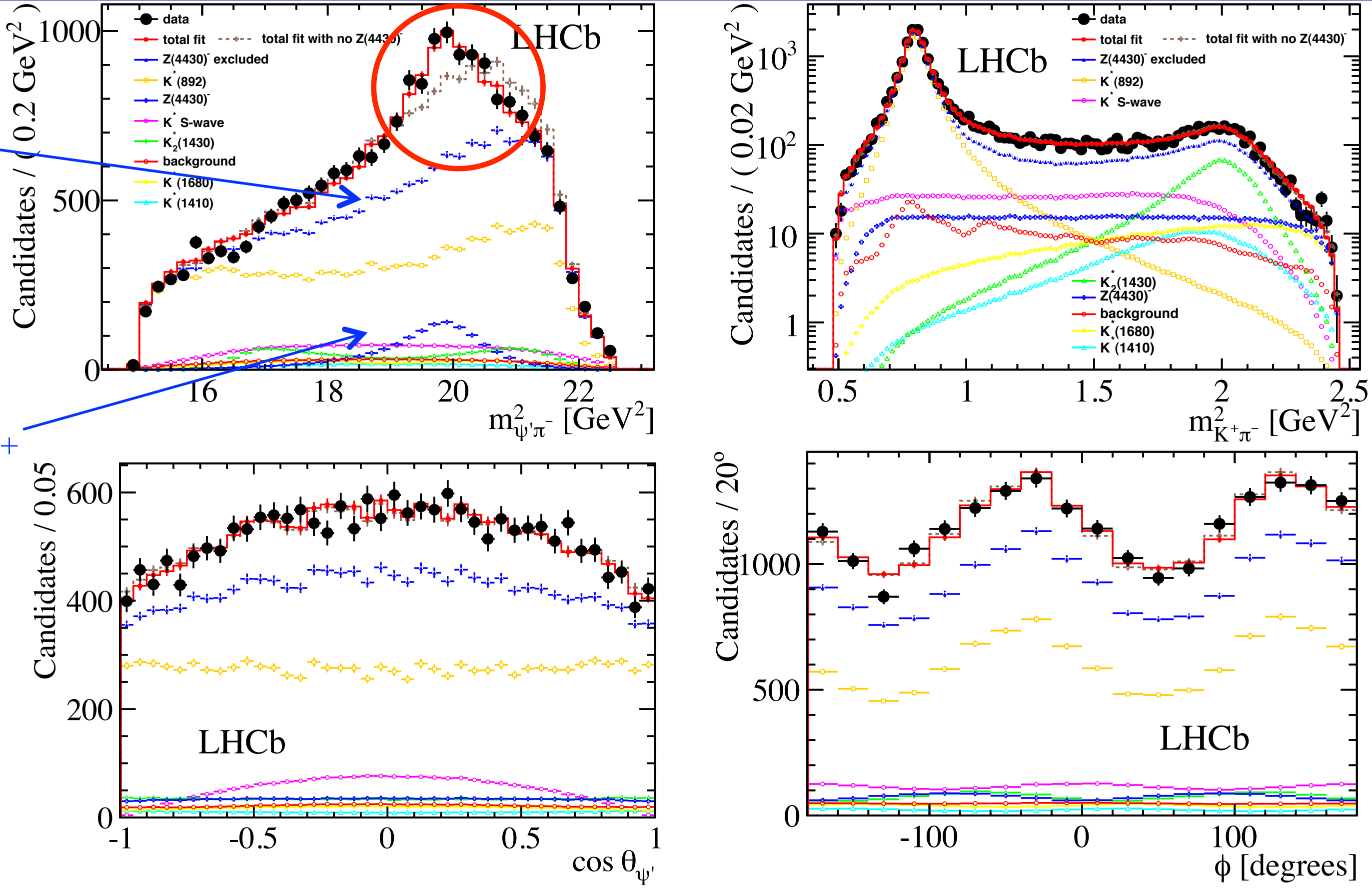


- The χ^2 p-value $\sim 10^{-6}$
- This isn't a reflection !

Amplitude fits with Z(4430)±

Everything except Z

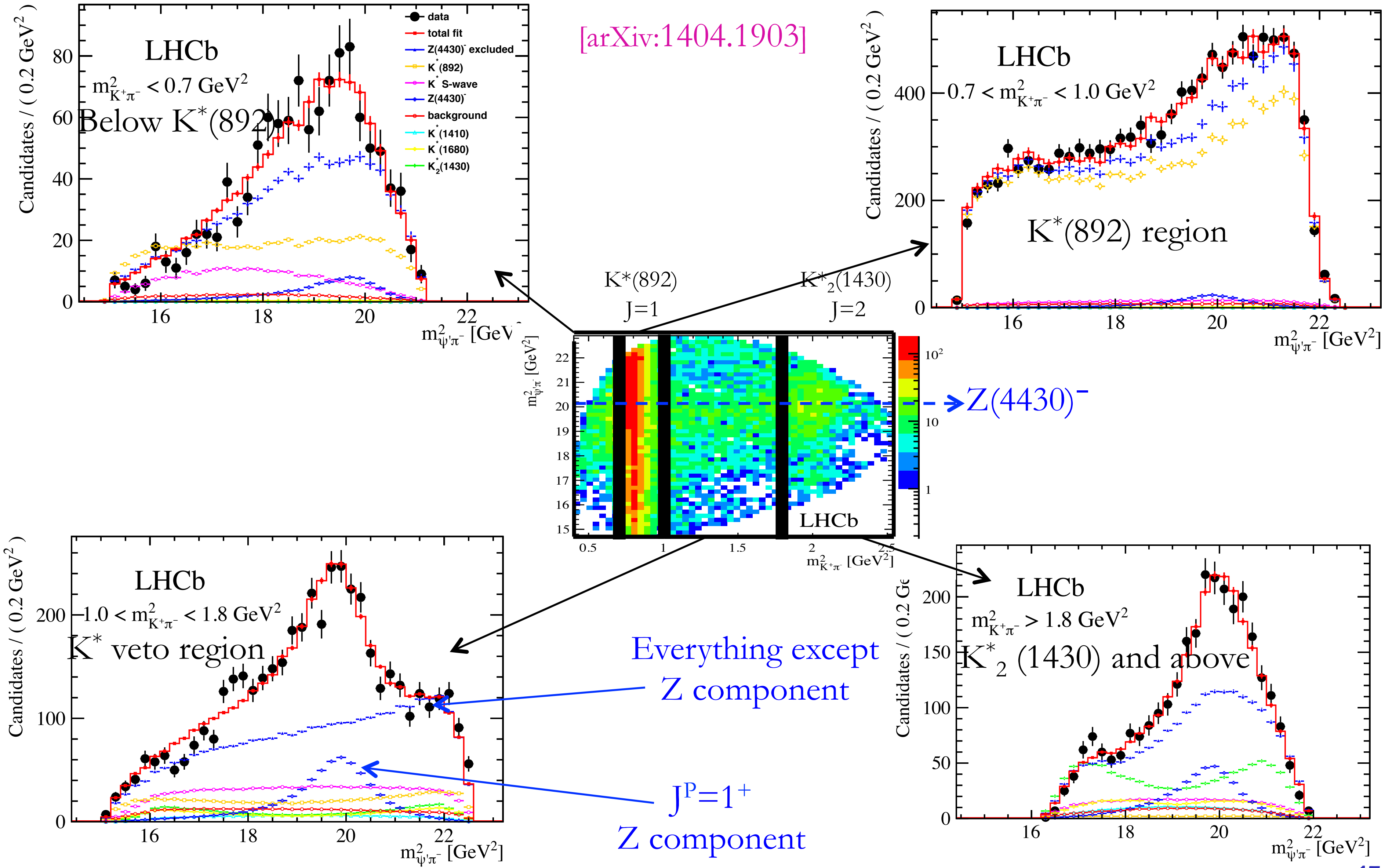
Z with $J^P=1^+$



[arXiv:1404.1903]

- χ^2 p-value =12% →data well described when $J^P=1^+$ Z(4430)→ψ' π included in fit
- Significance > 13.9 σ including systematics (kaon resonances model varied, multiple Kπ S-wave parameterizations, etc)

Dalitz plot slices with J^P=1 Z(4430)$^{\pm}$



Z(4430)± results

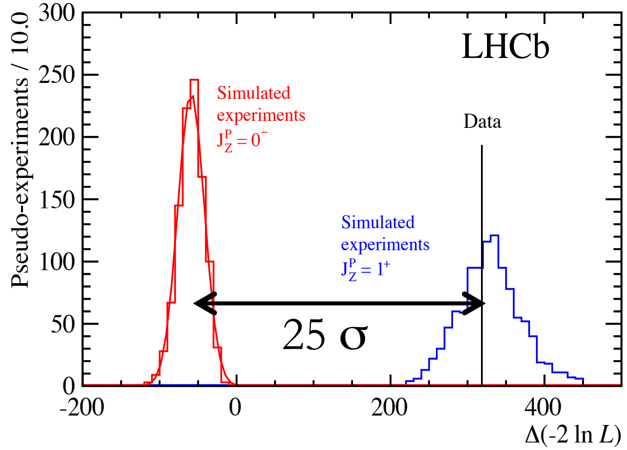
$$M(Z) = 4475 \pm 7^{+15}_{-25}\ \text{MeV}$$
$$\Gamma(Z) = 172 \pm 13^{+37}_{-34}\ \text{MeV}$$
$$f_Z = 5.9 \pm 0.9^{+1.5}_{-3.3}\ \%$$
$$J^P = 1^+\ \text{established}$$

Belle

$$M(Z) = 4485 \pm 22^{+28}_{-11}\ \text{MeV}$$
$$\Gamma(Z) = 200^{+41+26}_{-46-35}\ \text{MeV}$$
$$f_Z = 10.3^{+3.0+4.3}_{-3.5-2.3}$$
$J^P = 1^+$ preferred but 0^- and 1^- not excluded

- Results consistent with Belle and more precise
- Other J^P ruled out with large significance (>9σ after systematics)
- Not consistent with $J^P=0^-, 1^-, 2^-$ threshold effects
- Tetraquark of diquarks [cq] and antidiquarks ?
  [Maiani et al, arXiv:1405.1551]

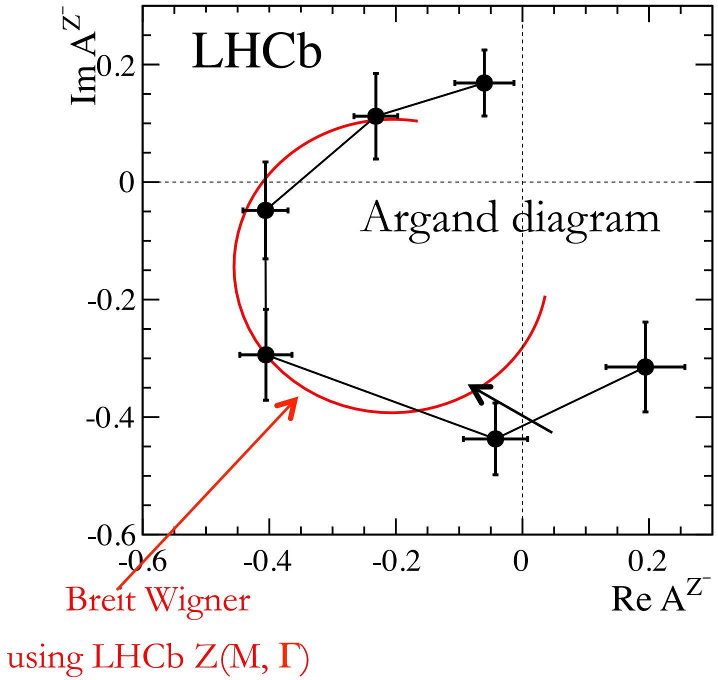
[arXiv:1404.1903]



$Z(4430)^{\pm}$ resonant behaviour

- Is $Z(4430)^{\pm}$ a real bound state?
- Does it follow resonant behavior if not forced by amplitude model?
- Replace Breit Wigner amplitude with 6 independent complex amplitudes in $m_{\psi' \pi^-}$ bins in Z peak region

[arXiv:1404.1903]



- Diagram consistent with rapid phase transition at the peak of the amplitude → resonance!

Summary

- X(3872)^0
  - Quantum numbers determined: $J^{PC} = 1^{++}$
  - X(3872)→ψ(2S) γ decay now established at 4.4σ level
  - Pure $D^0\bar{D}^{0*}$ molecular interpretation disfavoured
- Z(4430)$^\pm$ confirmed together with its $J^P=1^+$ assignment with overwhelming significance
  - Mass, width consistent with the recent Belle analysis and much improved
  - Resonant character of Z(4430)$^\pm$ demonstrated with the Argand diagram
  - Quantum numbers disfavour Z(4430)$^\pm$ as threshold effect
- Much more needed for a unified description of XYZ
  - New decay modes, production mechanism etc