# Quarkonia and quarkonia-like spectroscopy at LHCb

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**on behalf of the LHCb Collaboration**

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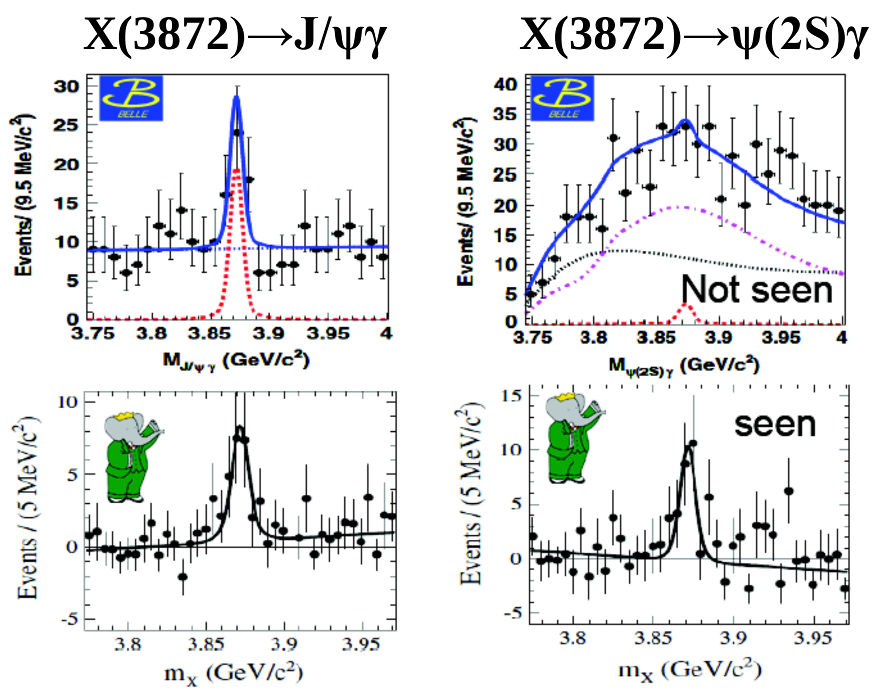
# Introduction

- In recent years, new exotic mesons have been observed by different experiments:
  - $X(3872)$, $X(4140)$, $Z(4430)^-$...
  - $X(3872)$ first assigned to $c\bar{c}$ states but they don't fit standard charmonium model.
- Many models exists, all with limited success.
  - Tetraquark: Tightly bound four quark.
  - Molecular state: Loosely bound mesons with a quark/color exchange (short distance) or pion exchange (large distance).
  - Charmonium hybrids: States with excited gluonic degrees of freedom.
  - Threshold effects: Virtual states at thresholds.

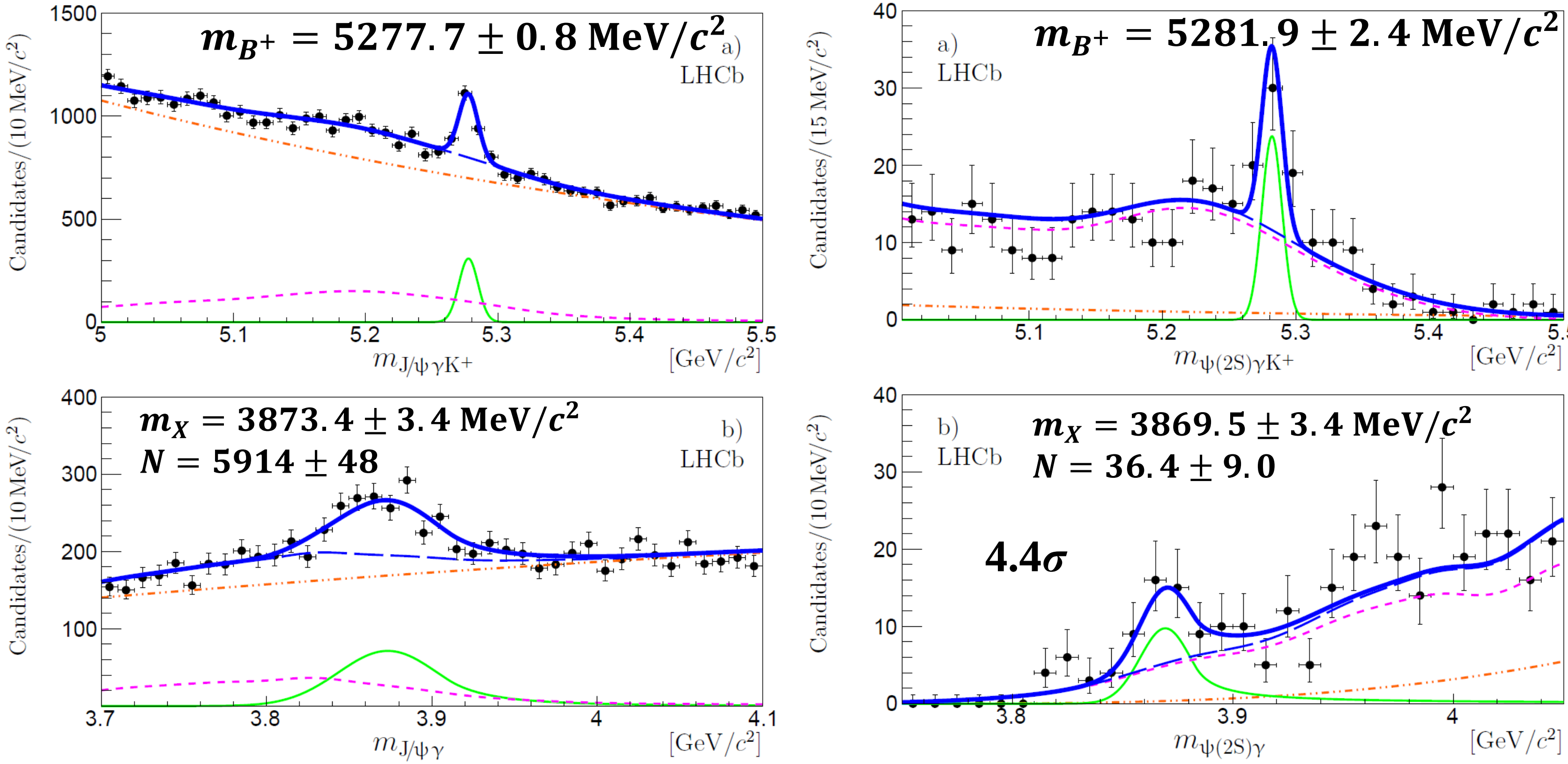
# $X(3872) \to \psi(2S)\gamma$ decay

- **Predictions for $B(X(3872)\to\psi(2S)\gamma)/B(X(3872)\to J/\psi\gamma)$ vary widely in different models.**
  - **$c\bar{c}$ ($2^3P_1$) interpretation: ~ 1.2-15.** **Phys.Rev.D79:094004,2009; Phys. Rev. D85 (2012) 114002**
  - **In molecular picture: ~ $3\times10^{-3}$.** **arXiv:1401.4431**
  - **mixture of $c\bar{c}$ and $DD^*$: 0.5-5.** **Phys. Rev. D85 (2012) 114002; Phys. Rev. D73 (2006) 014014**
- **BaBar observed the $X(3872) \to \psi(2S)\gamma$ decay in $B^+\to X(3872)K^+$ decays and measured the ratio.** **[Phys. Rev. Lett. 102 (2009) 132001]**
- **In 2011 Belle hadn't observed the $X(3872) \to \psi(2S)\gamma$ decay and set a limit.** **[Phys. Rev. Lett. 107 (2011) 091803]**
- **Can be tested by a hadron collider.**



# 2D mass fit

- Combinatorial bkg.
- Peaking bkg. $\left\{ \begin{array}{l} B^+ \to J/\psi(K^{*+} \to K^+(\pi^0 \to \gamma\gamma)) \text{ one } \gamma \text{ missing for } J/\psi\gamma \\ B^+ \to \psi(2S)K^+ + \text{x with random } \gamma \text{ for } \psi(2S)\gamma \end{array} \right.$
- Signal





arXiv:1404.0275

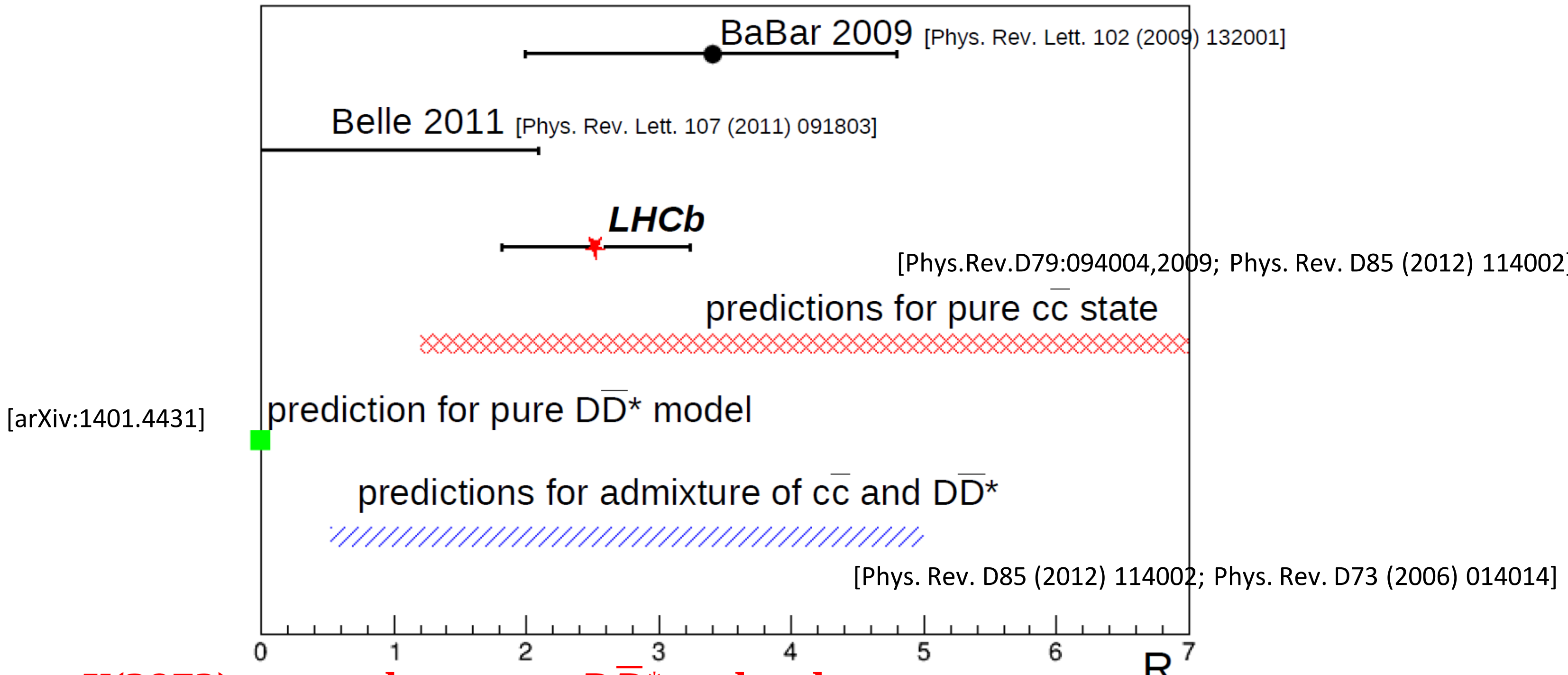
# Systematic uncertainties

| Source | Uncertainty [%] |
|---|---|
| $X(3872) \to J/\psi\,\gamma$ yield determination | 6 |
| $X(3872) \to \psi(2S)\gamma$ yield determination | 7 |
| Photon reconstruction | 6 |
| $B^+$ kinematics | 3 |
| Selection criteria | 2 |
| Trigger | 1 |
| $\mathcal{B}(J/\psi \to e^+e^-)/\mathcal{B}(\psi(2S) \to e^+e^-)$ | 2 |
| Simulation sample size | 1 |
| Sum in quadrature | 12 |

# Results and comparison

- **An evidence for $X(3872)\to\psi(2S)\gamma$ in $B^+\to X(3872)K^+$ decay with significance of 4.4$\sigma$ is obtained**

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$



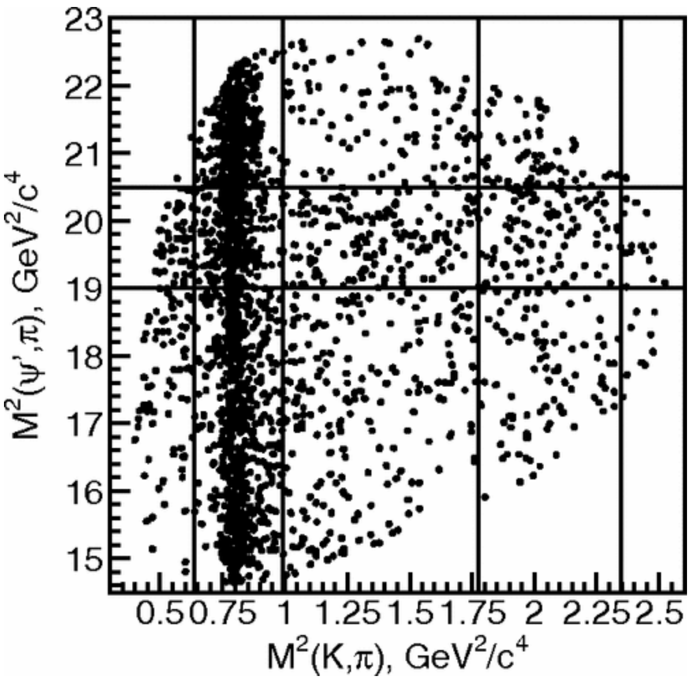

**$X(3872)$ cannot be a pure $D\bar{D}^*$ molecule**

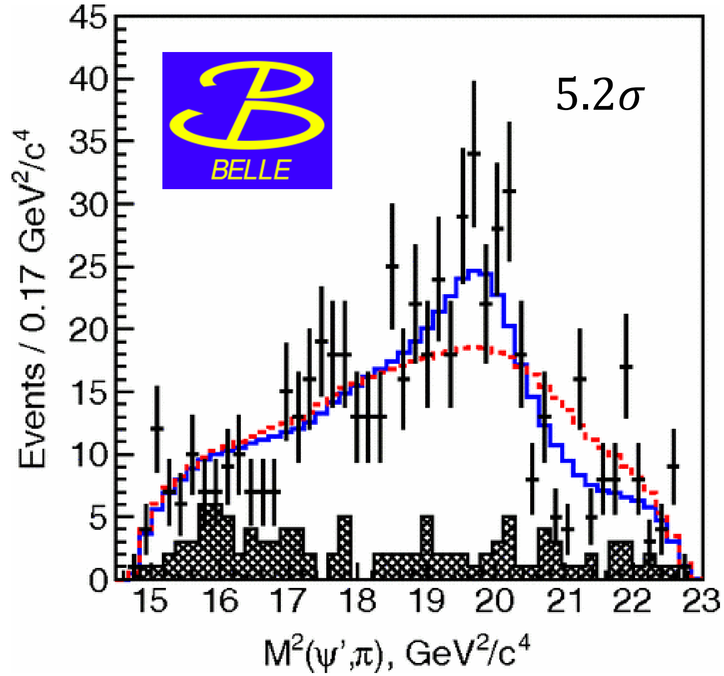
# The puzzle of Z(4430)⁻

- $Z(4430)^{-} \to \psi(2S)\pi^{-}$ observed by Belle in sample of $B^{0} \to \psi(2S)K^{+}\pi^{-}$
- Not confirmed by BaBar (Not excluded, either).

PRD88 (2013) 074026
PRD79 (2009) 112001

- Charged state, not described by quark model, $c\bar{c}u\bar{d}$?
- 4D amplitude fit required to disentangle the many interfering resonances in this system.

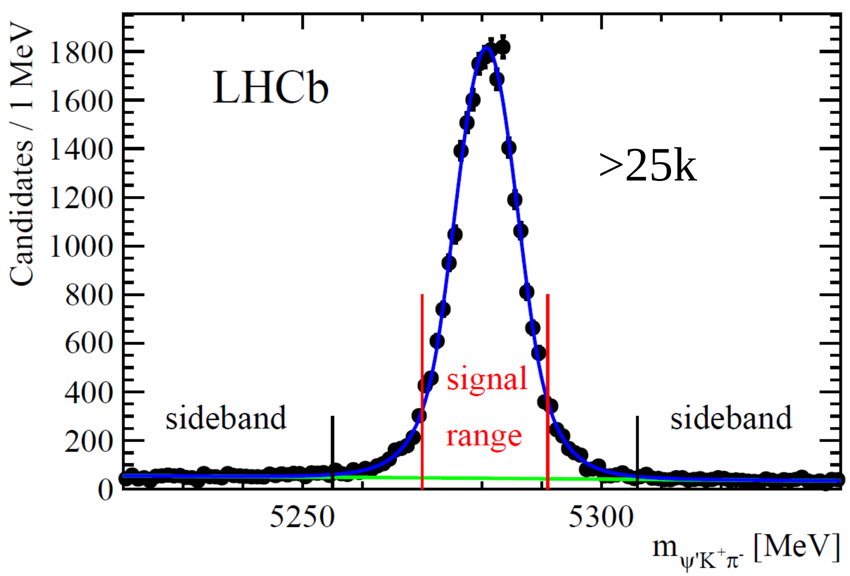


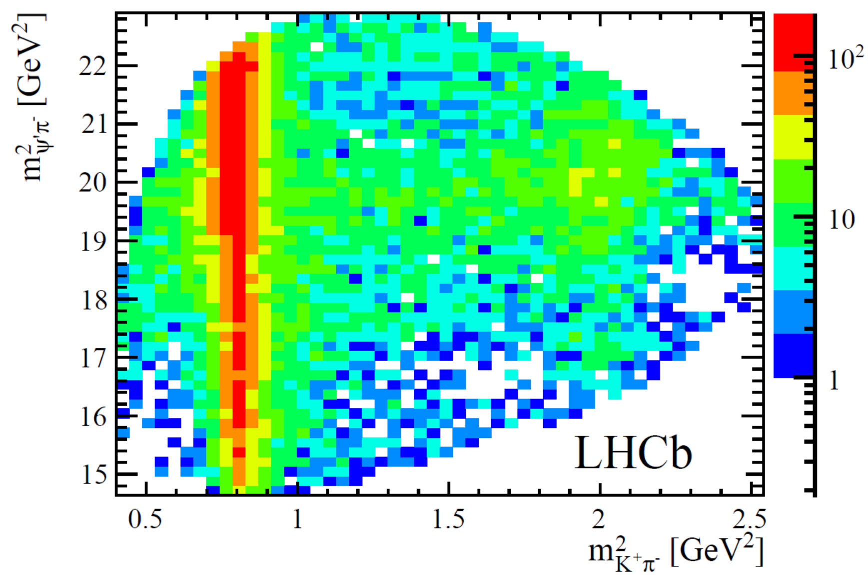



# Z(4430)$^-$ at LHCb

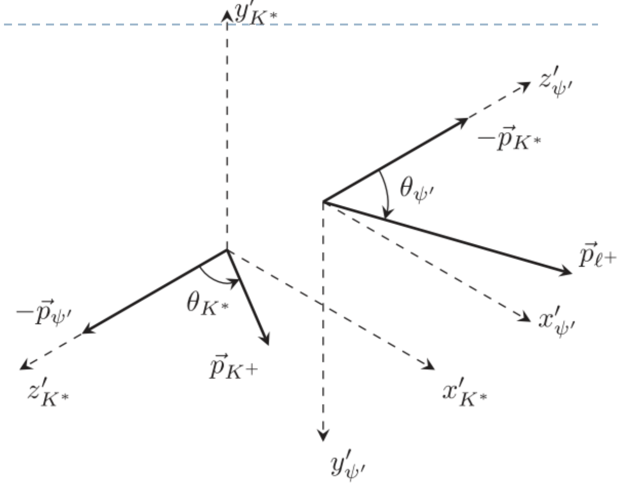
- **>25k $B^0 \to \psi(2S)K^+\pi^-$ candidates, factor 10 more than BaBar/Belle**
- **Perform two separate analyses**
  - **Model independent (BaBar) using harmonic moments of $K^*$ decay angle**
  - **Model dependent (Belle) using 4D amplitude fit**
- **Background from sidebands**

arXiv:1404.1903



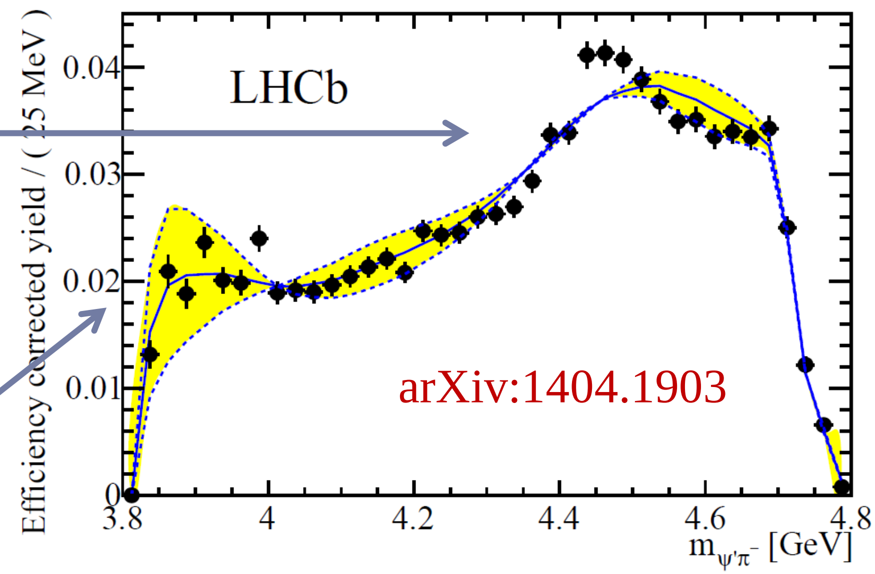



# Model independent approach



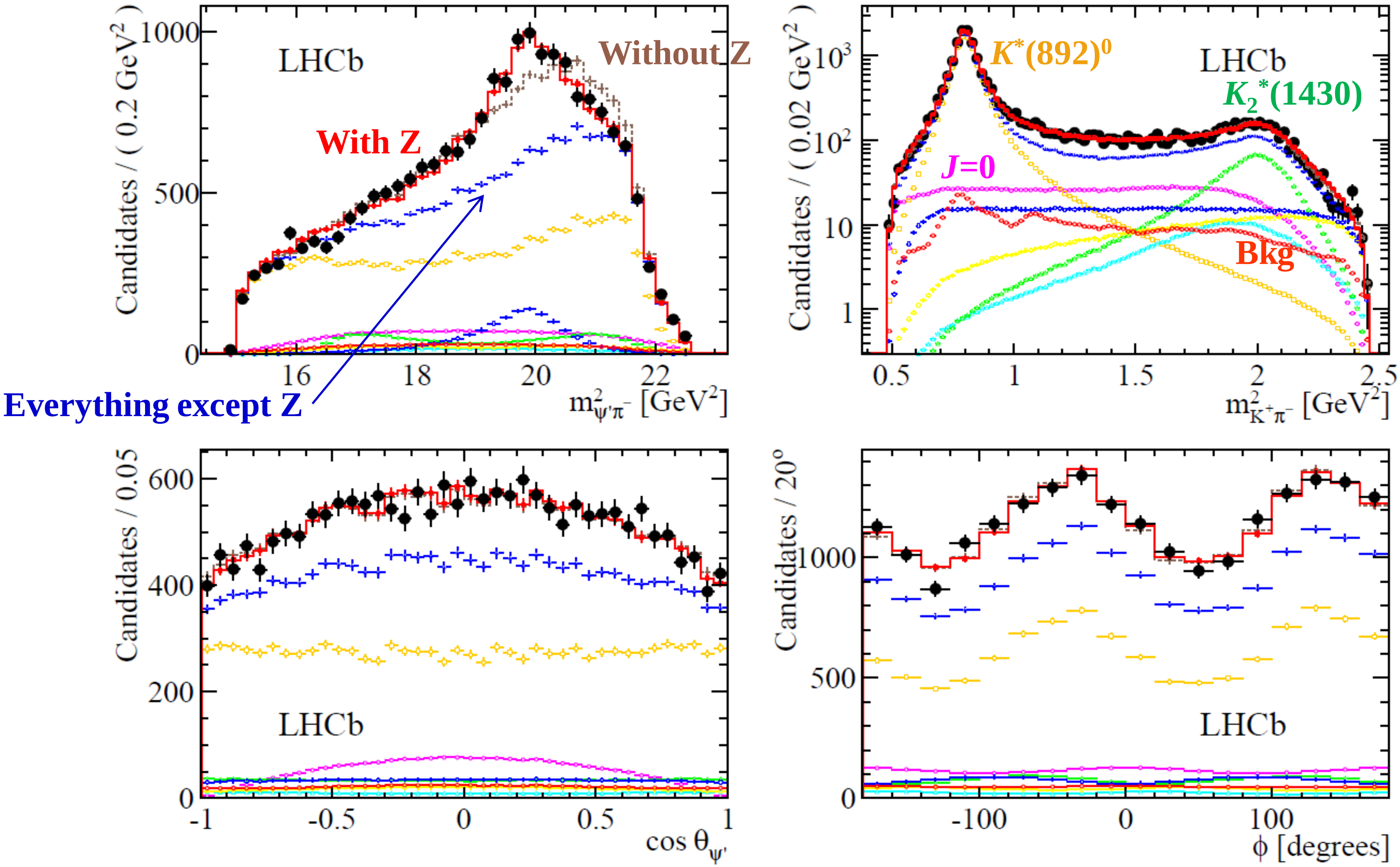

- **No constrain to any combination of known *K* resonances, but restriction on their maximal spin.** PRD88 (2013) 074026
- **Check if $m_{\psi'\pi}$ distribution can be understood in terms of structures caused via angular momentum conservation.**
- **Moments of $K^*$ resonances ($J \leq 2$) are unable to explain observed distribution of $m_{\psi'\pi}$.**
- **Need 4D amplitude fit to determine the $Z(4430)^-$ parameters.**

**Reflections of $cos\theta_{K^*}$ moments**



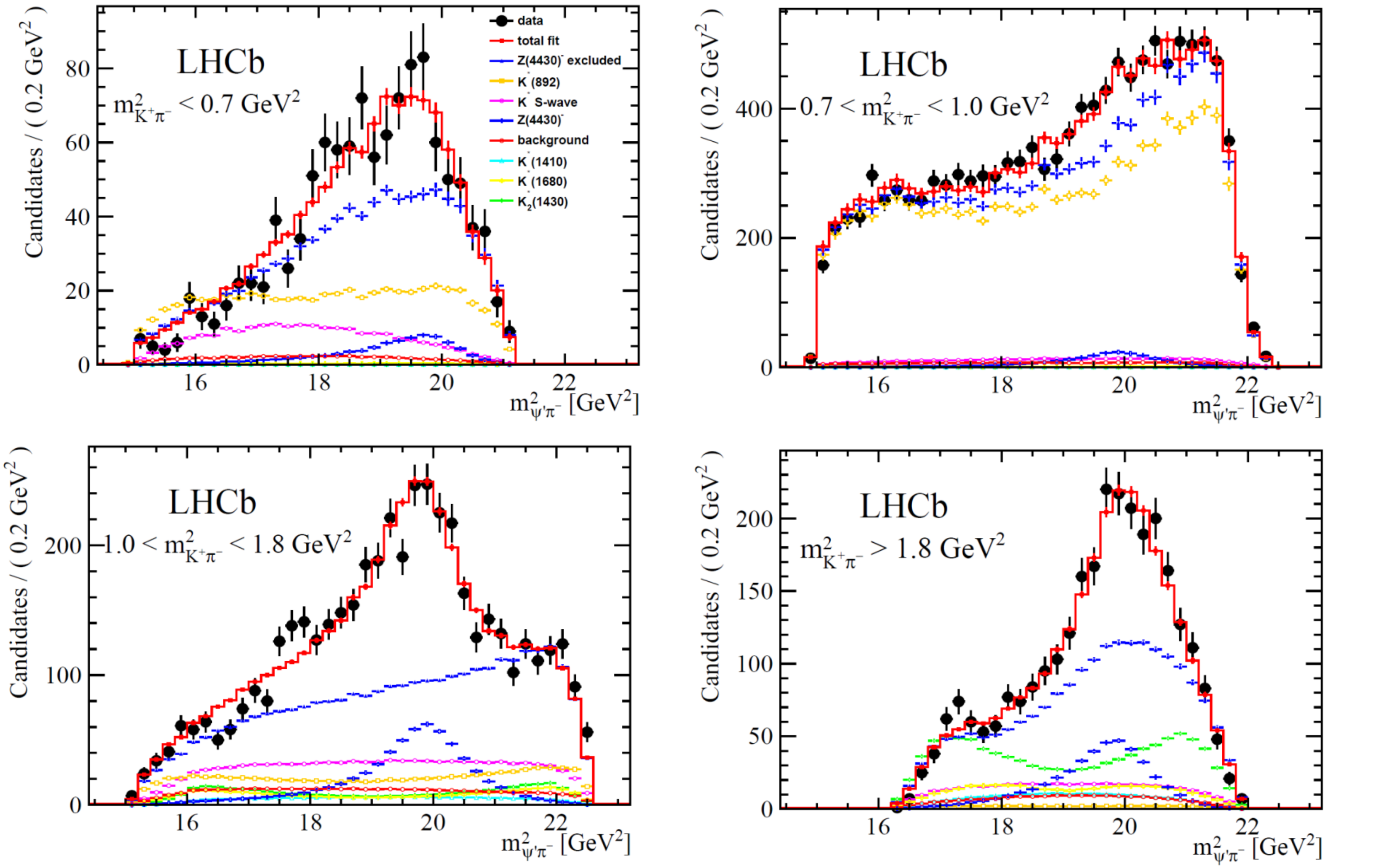
# 4D fit projections

arXiv:1404.1903



# $m_{\psi'\pi}$ in different $m_{K\pi}$ region

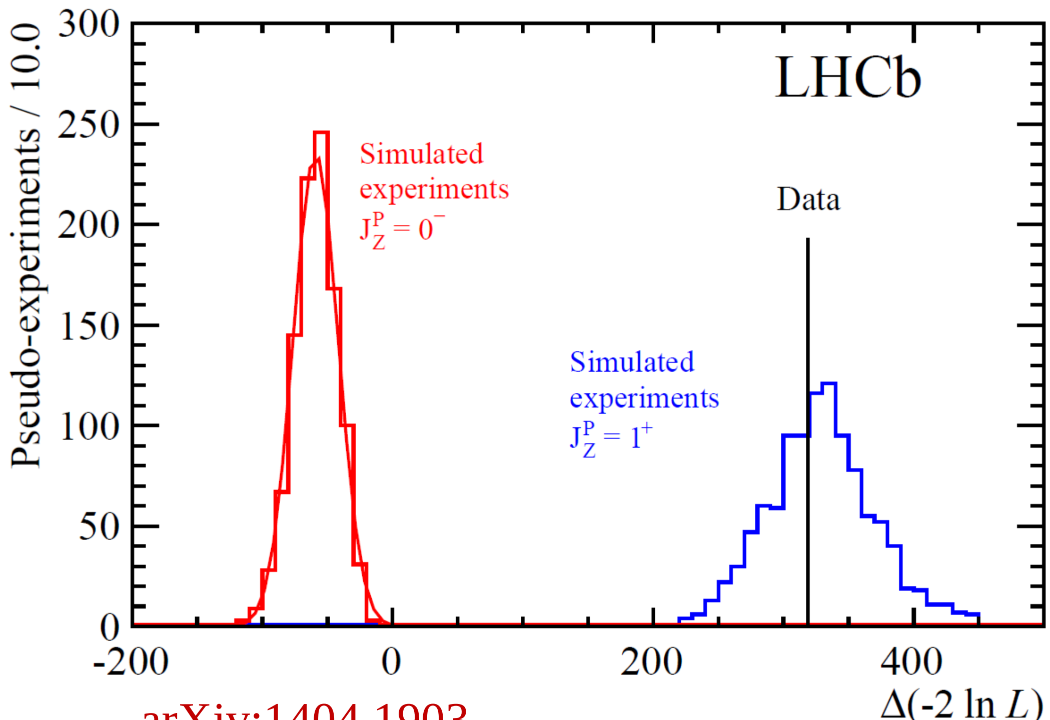
arXiv:1404.1903



# Spin determination

- $J^P = 1^+$ **assignment favoured (confirms Belle)**
- **Rule out other** $J^P$ **with large significance** ($> 9.7\sigma$)

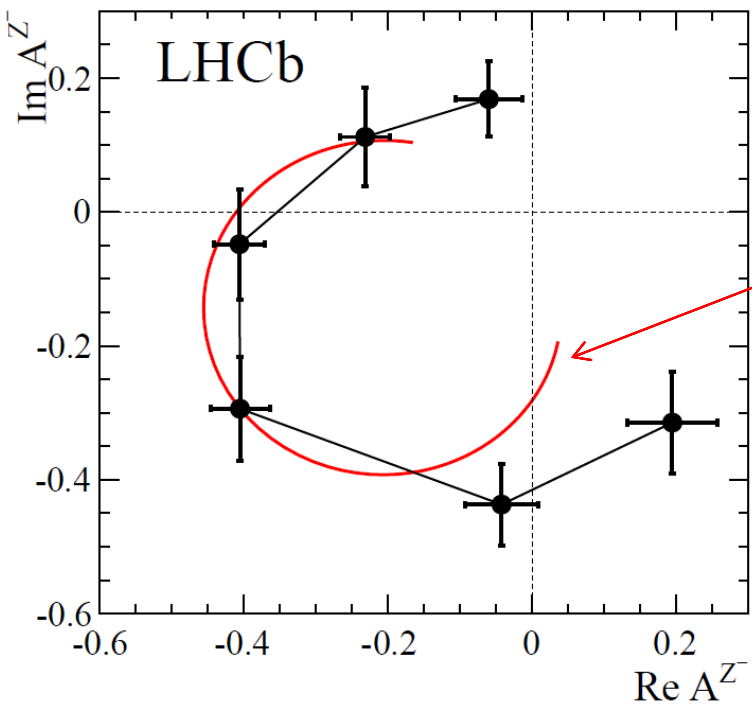
$$\Delta(-2\ln L) = [-2\ln L(0^-)] - [-2\ln L(1^+)]$$




arXiv:1404.1903

# Resonant behaviour

- **Replace BW amplitude with 6 independent complex numbers in Z region.**
- **Observe rapid change of phase near maximum of magnitude → Resonance!**




**BW amplitude with default Z parameters**

arXiv:1404.1903

# Second exotic $Z$?

- **Fit confidence level increases to 26%.**
- **Significance from $\Delta(-2\ln L)$ is $6\sigma$.**
- **Need larger samples to characterise this state.**

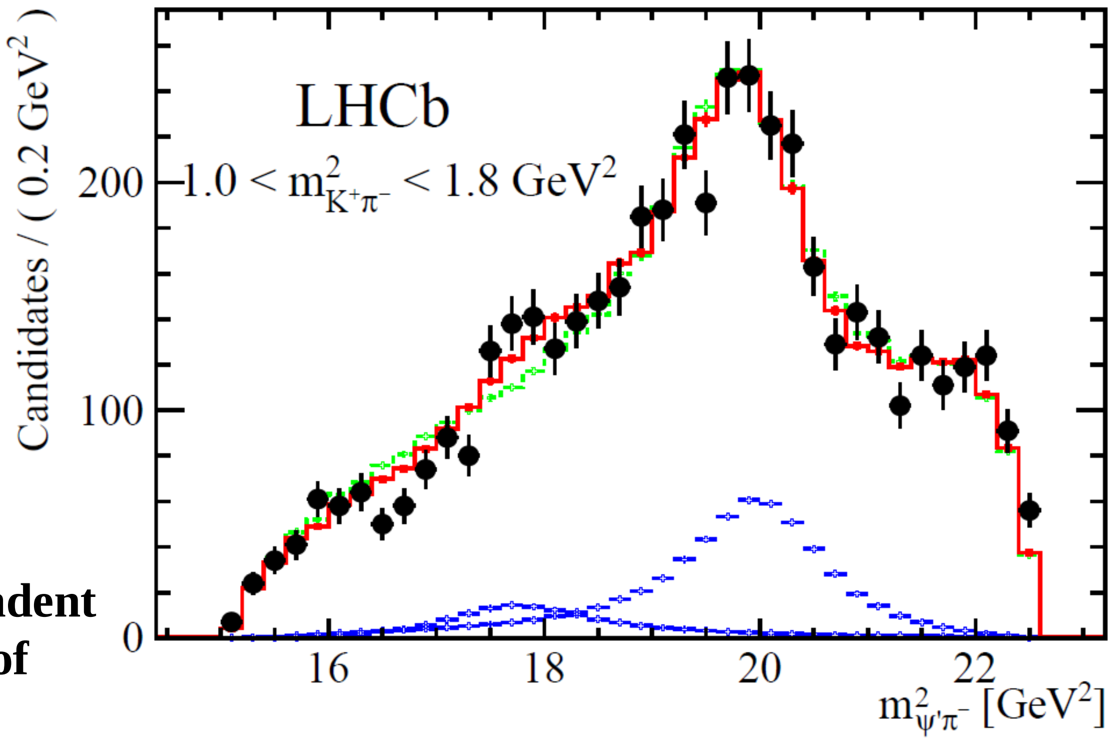
arXiv:1404.1903

$J^P = 0^-$ **assigned**

$M_{Z_0} = 4239 \pm 18^{+45}_{-10}$ **MeV**

$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}$ **MeV**

$f_{Z_0} = 1.6 \pm 0.5^{+1.9}_{-0.4}$ %




**Evidence from model-independent approach, and measurement of phase motion inconclusive.**

# Summary

- **An evidence for $X(3872)\to\psi(2S)\gamma$ in $B^+\to X(3872)K^+$ decay with significance of $4.4\sigma$ is obtained.**
- **Branching ratio measured with respect to $X(3872)\to J/\psi\gamma$, the measured ratio is comparable to BaBar and Belle results.**

arXiv:1404.1903

- **LHCb has confirmed the existence of the $Z(4430)$.**
- $J^P = 1^+$
- **Possible second exotic state around 4240?**