Exotic Charmonium-like Spectroscopy @ LHCb

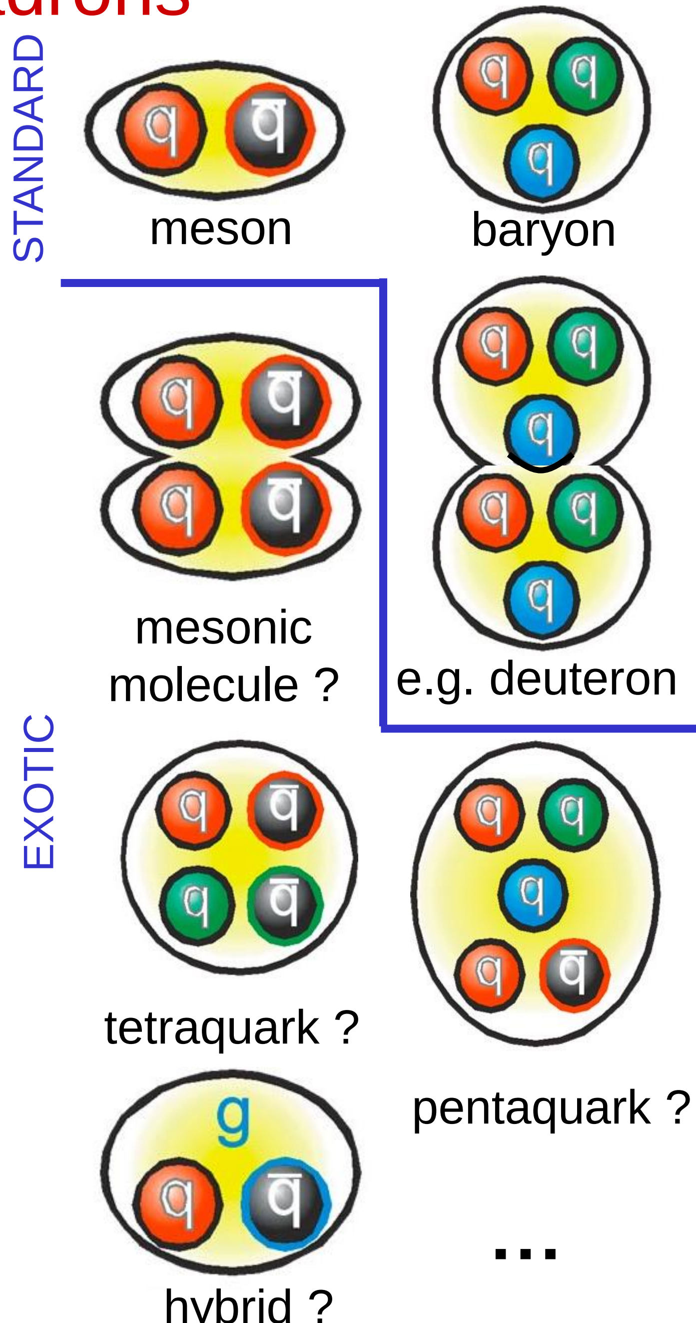
Jozef Chelmonski, 1881

Tomasz Skwarnicki

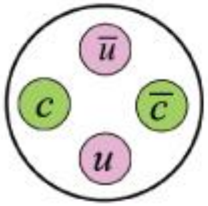
On behalf of the LHCb collaboration

Standard and Exotic Hadrons

- Longstanding dispute in light meson spectroscopy if exotic states exist (too many scalar states?)
- No convincing experimental proofs for existence of elusive pentaquarks
- Recent discoveries in heavy quark states have revived hopes for conclusive proofs for existence of exotic mesons



X(3872)



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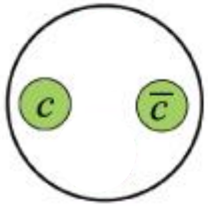

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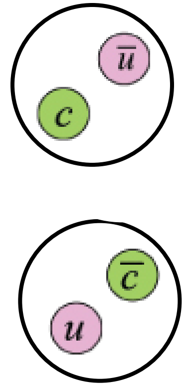
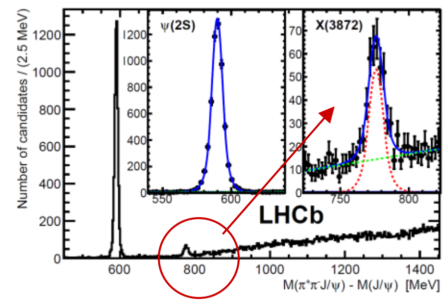


Exotic tetraquark
$\overline{D}^0 D^{*0}$ molecule
hybrid
…

Standard charmonium

Standard $\overline{D}^0 D^{*0}$ threshold cusp

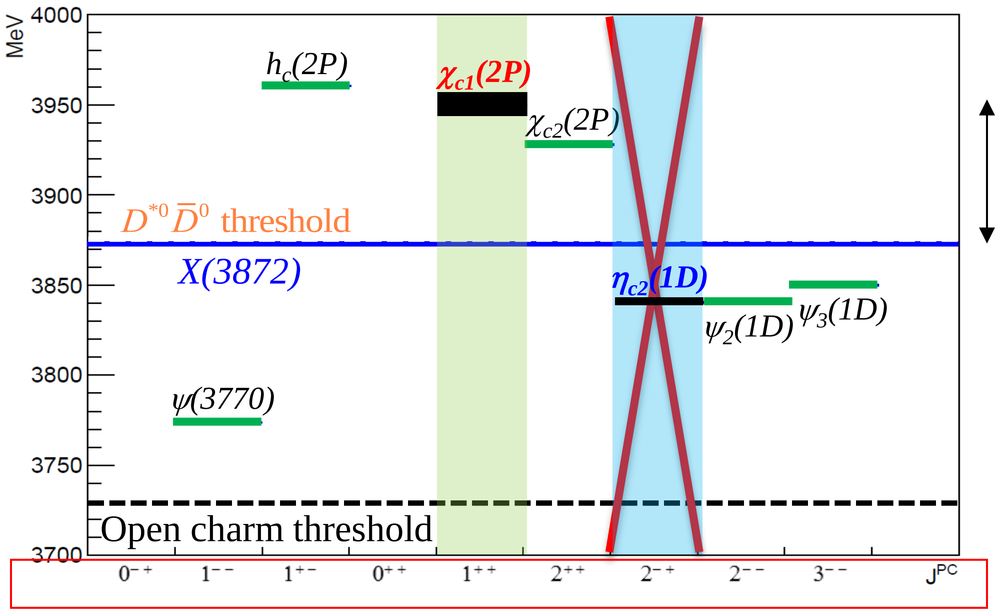
- Discovered by Belle in $B^+ \to X(3872) K^+$, $X(3872) \to J/\psi\, \pi^+\pi^-$ in 2003, also observed by CDF, D0, BaBar, LHCb and CMS
- Last year, using $B^+ \to X(3872) K^+$, $X(3872) \to J/\psi\, \pi^+\pi^-$ data LHCb determined J^{PC} to be 1^{++}



1 fb^{-1}

$\eta_{c2}(1^1D_{2-+})$ is now ruled out!

Charmonium spectrum



$\chi_{c1}(2^3P_{1++})$ possible but disfavored by mass

LHCb-PAPER-2013-001

PRL 110 (2013) 222001

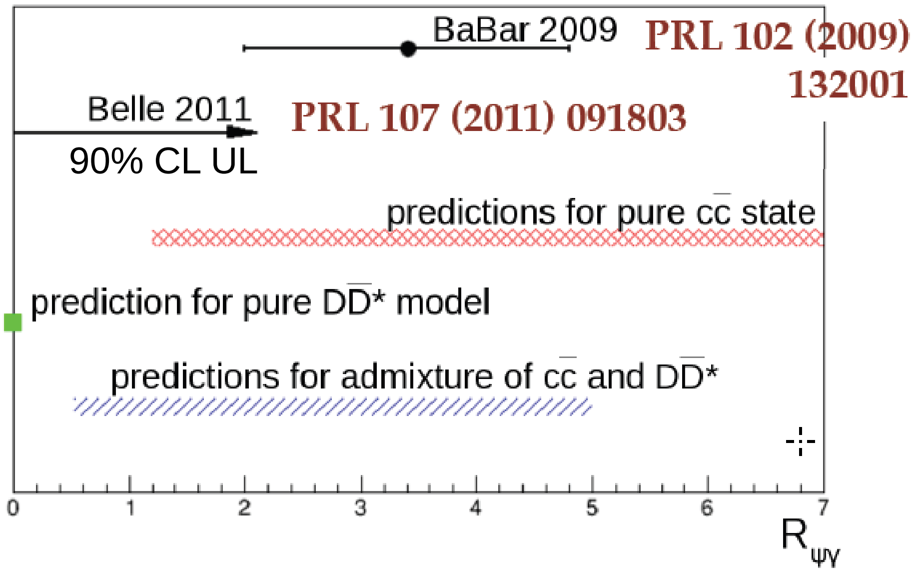
- Makes pure charmonium state interpretation rather unlikely

Radiative decays of X(3872)

- Measurement of
  $R_{\psi\gamma}$=BR(X(3872)→ψ(2S)γ)/BR(X(3872)→J/ψγ)
  a good probe for internal structure of X(3872)

Signal events: B⁺→X(3872)K⁺, X(3872)→ψ(2S)γ, J/ψγ		Signal significance: ψ(2S)γ, J/ψγ
25.4 ± 7.3,	23.0 ± 6.4	3.6σ, 3.5σ
$5.0^{+11.9}_{-11.0}$,	$30.0^{+8.2}_{-7.4}$	0.4σ, 4.9σ

efficiency(ψ(2S)γ) / efficiency(J/ψγ) ~ 1



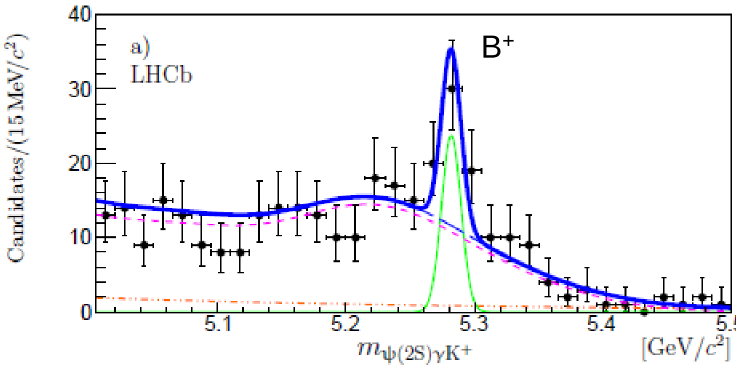
- Previous measurements by BaBar and Belle barely consistent and favoring the opposite conclusions

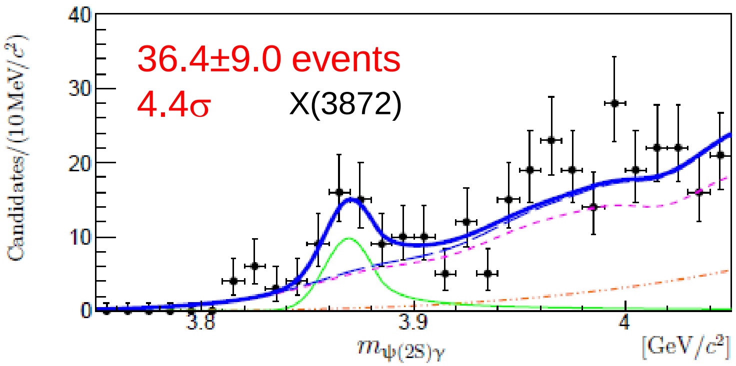
Radiative decays of X(3872) in LHCb

LHCb-PAPER-2014-008 arXiv:1404.0275 **Apr. 1, 2014** new

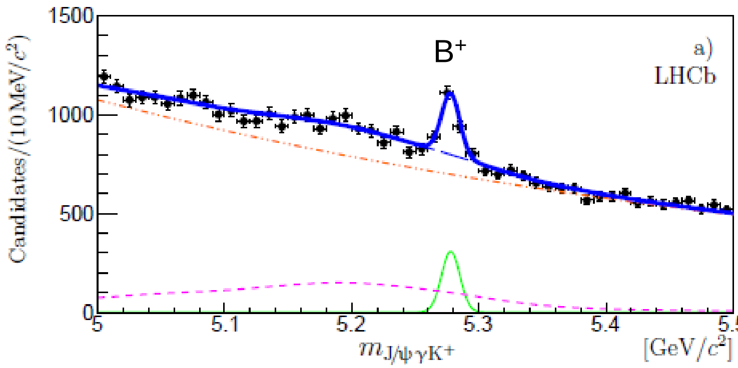
Projections of 2D fit to $m_{\psi\gamma K+}$ vs $m_{\psi\gamma}$

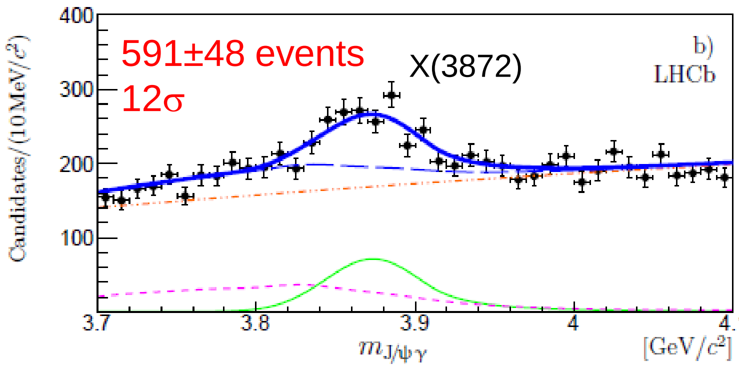
$B^+ \to X(3872)K^+$,
$X(3872) \to \psi(2S)\gamma$





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



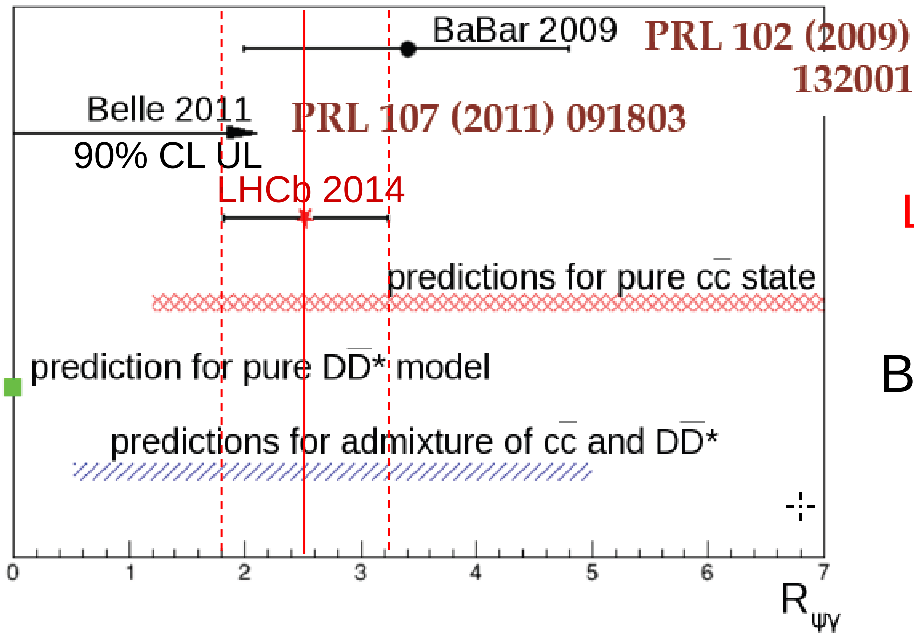


The most significant evidence for $X(3872) \to \psi(2S)\gamma$ to date!

efficiency($\psi(2S)\gamma$) / efficiency($J/\psi\gamma$) ~ 0.2

Detecting soft photons at hadronic collider is hard.

Radiative decays of X(3872) in LHCb



	Signal events: $B^+\to X(3872)K^+$, $X(3872)\to\psi(2S)\gamma$, $J/\psi\gamma$		Signal significance: $\psi(2S)\gamma$, $J/\psi\gamma$
	25.4 ± 7.3,	23.0 ± 6.4	3.6σ, 3.5σ
	$5.0^{+11.9}_{-11.0}$,	$30.0^{+8.2}_{-7.4}$	0.4σ, 4.9σ
LHCb	36.4 ± 9.0,	591.0 ± 48.0	4.4σ, 12σ

$BR(X(3872)\to\psi(2S)\gamma)/BR(X(3872)\to J/\psi\gamma)$
$= 2.48\pm0.64\pm0.29$

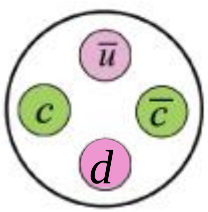
- The LHCb results are consistent with, but more precise than, the BaBar and Belle results
- The results are not consistent with the expectations for pure molecular X(3872)
- X(3872) is likely a mixture of a $\chi_{c1}(2^3P_{1^{++}})$ charmonium state and of $\overline{D^0}D^{*0}$ molecule or cusp

Z(4430)$^-$ discovery and its importance

Phys.Rev.Lett. 100, 142001 (2008)

Observation of a resonance-like structure in the $\pi^{\pm}\psi'$ mass distribution in exclusive $B \to K\pi^{\pm}\psi'$ decays

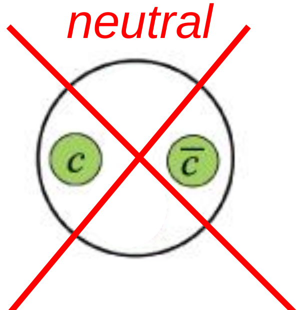
charged



Exotic
tetraquark
molecule
hybrid
…

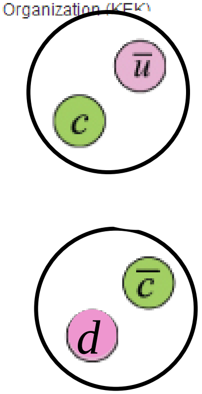
or

neutral



Standard
charmonium

or



Standard
$\bar{D}^{*}$-D_1^{*0}
threshold
cusp

$Z(4430)^-$ previous measurements

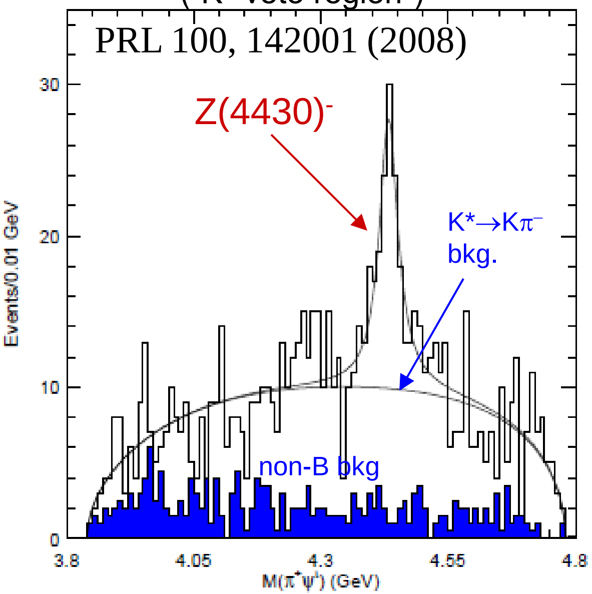
[$\psi' \equiv \psi(2S)$]

$B \to \psi' \pi^- K$ (Z^-: $\psi'\pi^-$; K^*: $\pi^- K$)

Belle 2008

1D $M(\psi'\pi^-)$ mass fit

("K* veto region")



$M(Z) = 4433 \pm 4 \pm 2$ MeV

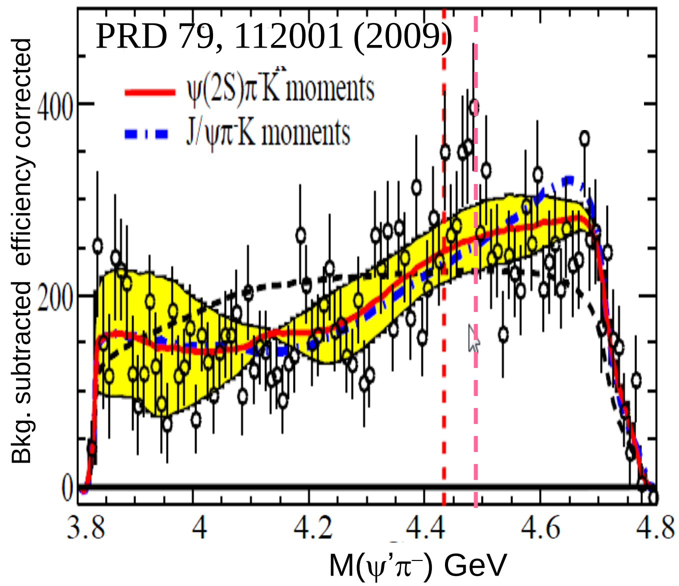
$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

significance 6.5σ

Ad hoc assumption about the $K^* \to K\pi^-$ background shape.

BaBar 2009

Harmonic moments of K*s (2D) reflected to $M(\psi'\pi^-)$



BaBar did not confirm $Z(4430)^-$ in B sample comparable to Belle.

Did not numerically contradict the Belle results.

Almost **model independent** approach to $K^* \to K\pi^-$ backgrounds.

Belle 2013

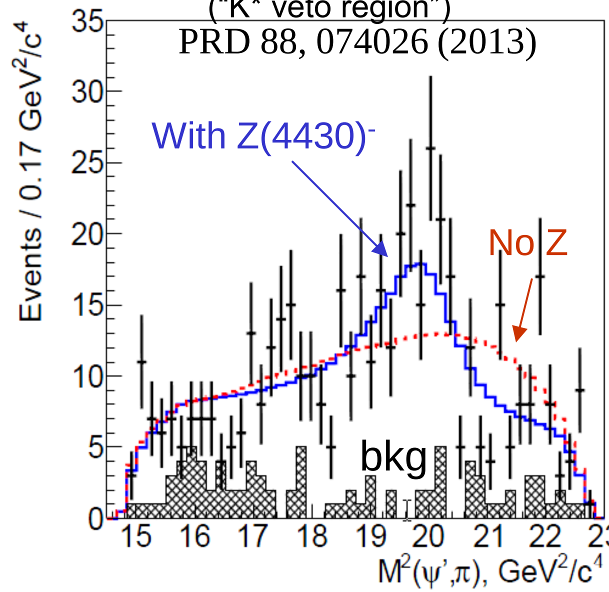
(2D amplitude fit in 2009)

4D amplitude fit

(subsample with $\psi' \to l^+ l^-$)

0.996 GeV/c² < M(K,π) < 1.332 GeV/c²

("K* veto region")



$M(Z) = 4485^{+22}_{-22}{}^{+28}_{-11}$ MeV

$\Gamma(Z) = 200^{+41}_{-46}{}^{+26}_{-35}$ MeV

6.4σ (5.6σ with sys.)

$J^P = 1^+$ preferred by $>3.4\sigma$

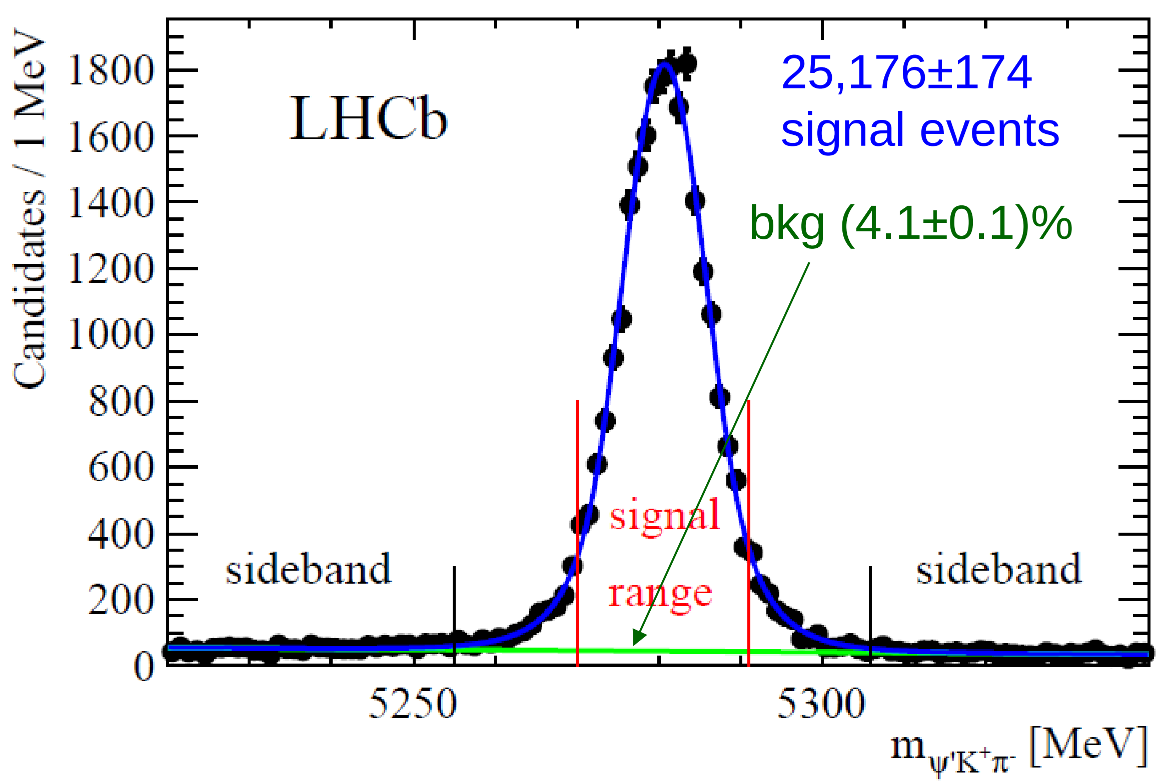
Model dependent approach to $K^* \to K\pi^-$ backgrounds. Higher statistical sensitivity.

Z(4430)$^-$ in LHCb

LHCb-PAPER-2014-014 arXiv:1404.1903 **Apr. 7, 2014**

new

- $B^0 \to \psi' K^+ \pi^-$, $\psi' \to \mu^+ \mu^-$ (3 fb^{-1})



vs
Belle: 2,010±50
BaBar: 2,021±53

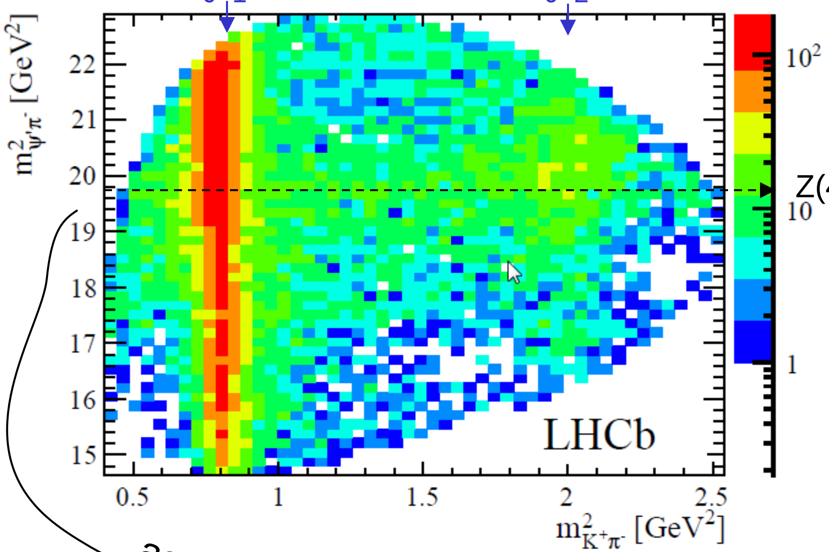
vs. bkg in Belle: 7.8%

An order of magnitude larger signal statistics than in Belle or BaBar thanks to hadronic production of b-quarks at LHC.

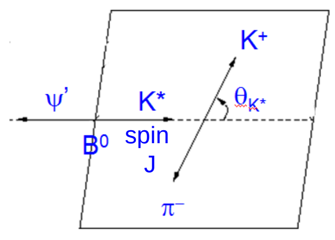
Even smaller non-B background than at the e^+e^- experiments thanks to excellent performance of the LHCb detector (vertexing, PID)

Z(4430)$^-$ in LHCb: 2D model independent analysis (a la BaBar)

K*(892) J=1 Dalitz plot K^*_2(1430) J=2



"Rectangular Dalitz plot"



⇨ $\cos(\theta_{K^*})$ vs. $m_{K+\pi-}$ ⇨

Decompose into Legendre moments

$$< P_l^U >= \sum_{i=1}^{N_{data}} \frac{1}{\varepsilon_i} P_l(\cos\theta_{K^* i})$$

vs. $m_{K+\pi-}$

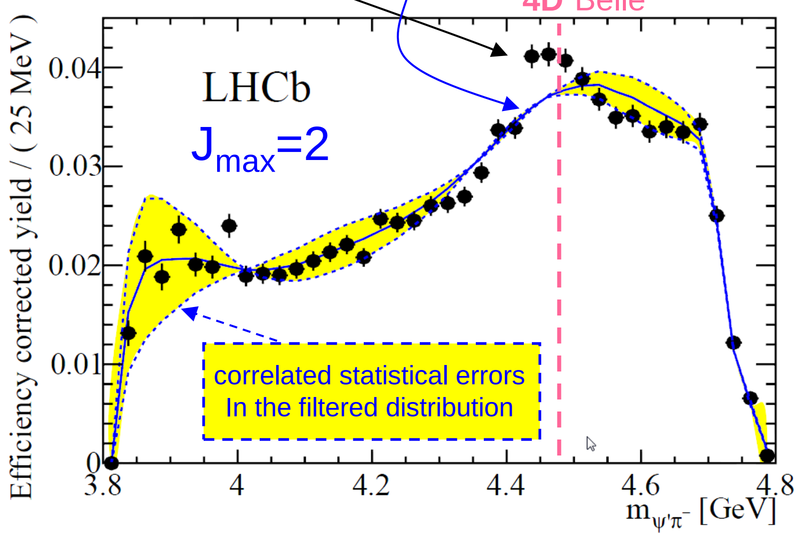
⇩

Pass only moments with l not more than J_{max}/2

⇦ "K* J_{max} filtered" $\cos(\theta_{K^*})$ vs. $m_{K+\pi-}$ ⇦ "K* J_{max} filtered" Dalitz plot

actual distribution

4D Belle



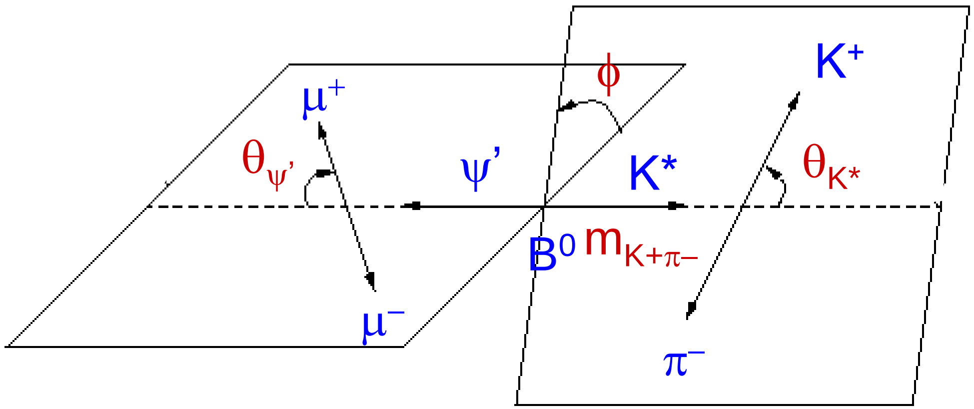
Excess of events over the K* J_{max}=2 filtered distribution in the Z(4430)$^-$ region is apparent !

This method cannot be used to determine Z(4430)$^-$ parameters because **Z(4430)$^-$ contributes** to the K* J_{max} filtered distribution **in an unpredictable way** due to unknown Z - K*s interferences

⇩

use of amplitude analysis is unavoidable for characterization of Z(4430)$^-$

Z(4430)⁻ in LHCb: 4D model dependent amplitude analysis (a la Belle)



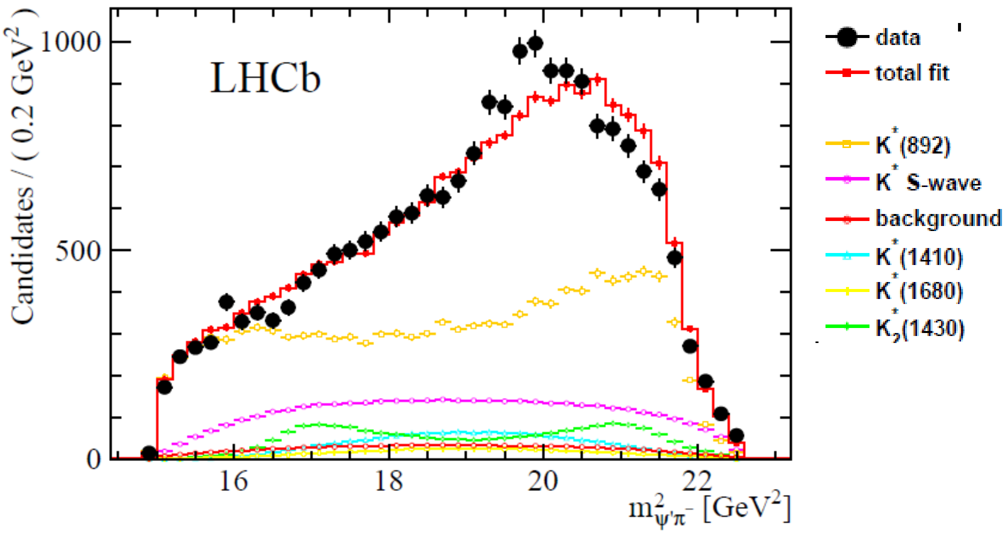
(or $m_{K^+\pi^-}{}^2$, $m_{\psi'\pi^-}{}^2$)

Z(4430)⁻ amplitude parameterized in different angles derivable from the angles in the K* decay chain

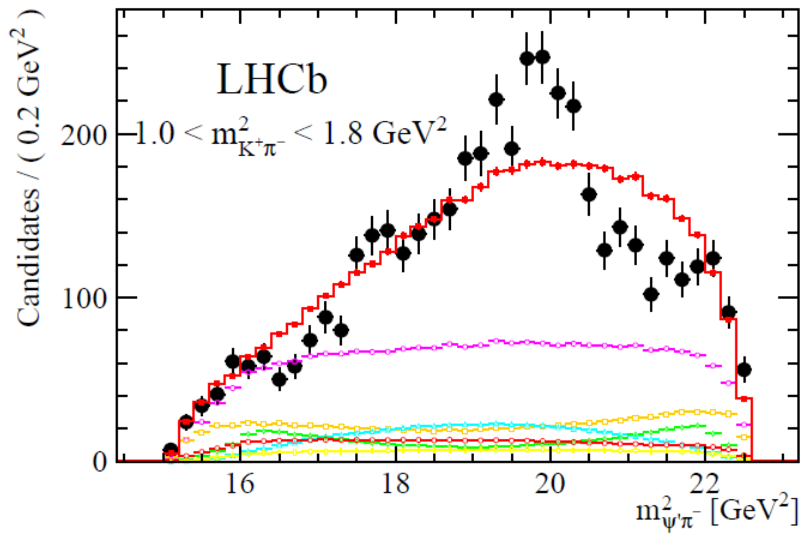
- Amplitude model:
  - Construct decay matrix elements as a sum of quasi-two-body $B^0 \to \psi' K^{*0}$ and $B^0 \to Z^- K^+$ components.
  - Each resonance represented as Breit-Wigner amplitude (“Isobar model”) and J dependent angular terms.
  - Allow all known $K^{*0} \to K^+\pi^-$ resonances with $J \leq 3$ (higher J states are above the kinematic K* mass limit and suppressed by orbital angular momentum barrier in the B^0 decay) with masses and widths constrained to the PDG values; fit their complex helicity amplitudes.
  - Two different J=0 (“S-wave”) parameterizations (Isobar and LASS).
  - Study K* model dependence for systematic errors.
- Fit method:
  - Use two different methods of implementing efficiency corrections and of non-B^0 background parameterization.
  - Perform unbinned maximum likelihood fit of free model parameters to the 4D data.
  - Discriminate between various amplitude models using the likelihood ratio test:
    - $\Delta(-2\ln L)$ is a test statistic
    - generate and fit pseudo-experiment to predict probability density distribution under each amplitude hypothesis
  - Also evaluate goodness-of-fit by calculating a χ^2 value between the data and the fit using adaptive 4D binning.

Amplitude fits without Z(4430)$^-$

("all data")



("K* veto region")

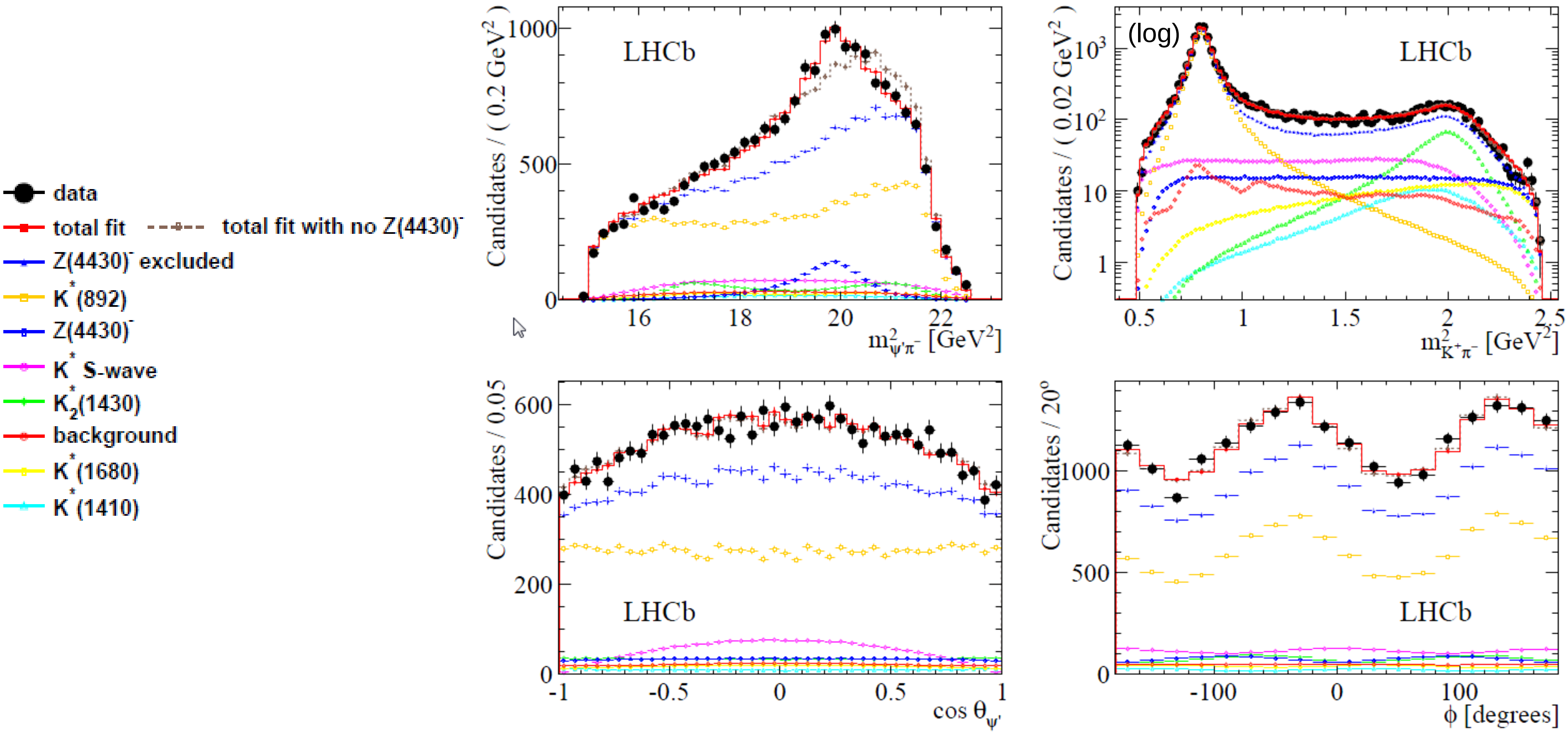


- The χ^2 p-value < $2\text{x}10^{-6}$

⇩

- The data cannot be adequately described with the J ≤ 3 K* contributions alone

Amplitude fits with $J^P=1^+$ $Z(4430)^-$ ("all data")

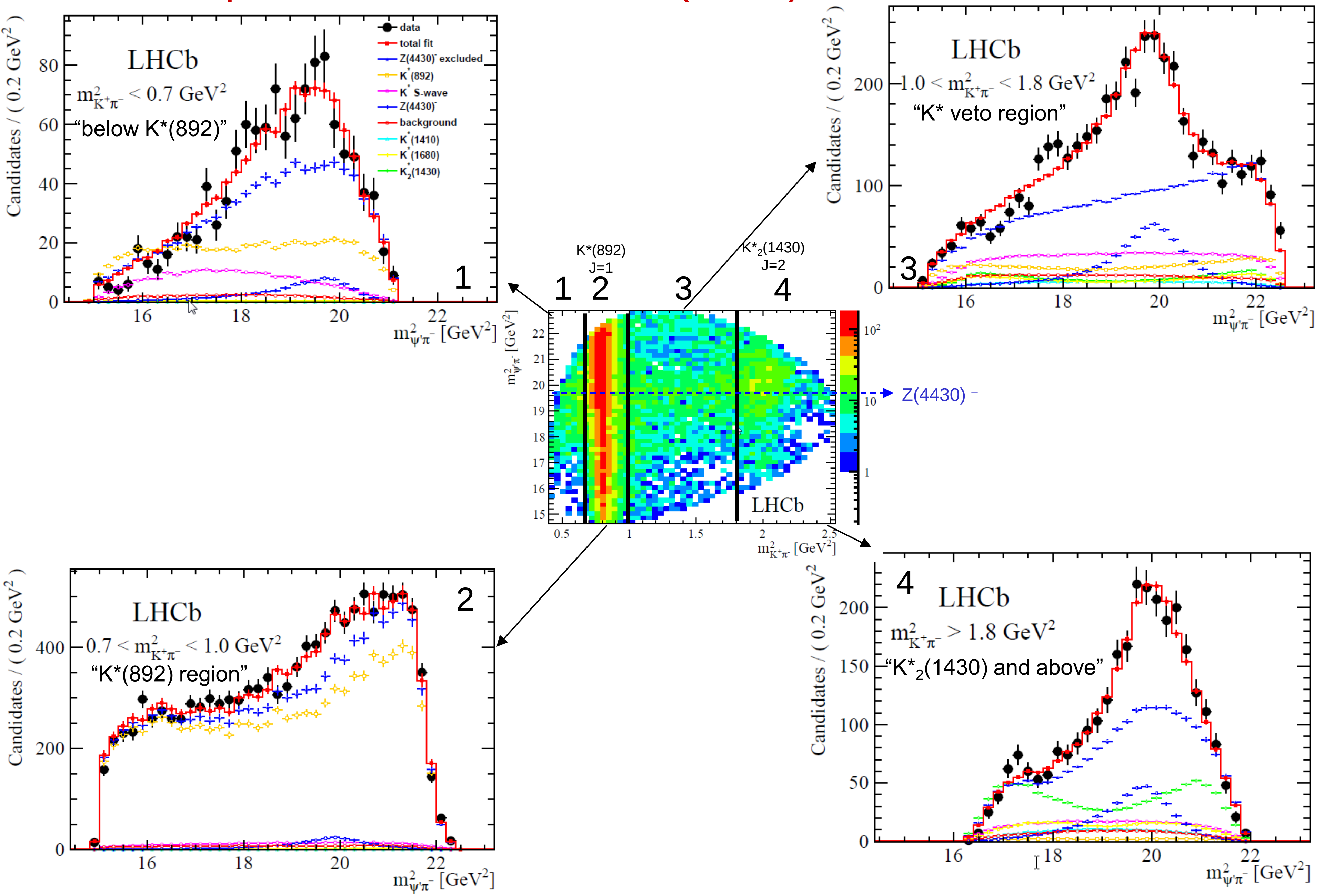


- The χ^2 p-value = 12%

⇩

- The data are well described when $J^P=1^+$ $Z(4430)^-$ is included in the fit
- $Z(4430)^-$ significances from $\Delta(-2\ln L)$ is 18.7σ (13.9σ with systematic variations)

Amplitude fits with $J^P=1^+$ $Z(4430)^-$



Z(4430)$^-$ parameters: LHCb vs Belle

	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interferences)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	
Significance	$> 13.9\sigma$	$> 5.2\sigma$

(new large systematic effect included by LHCb)

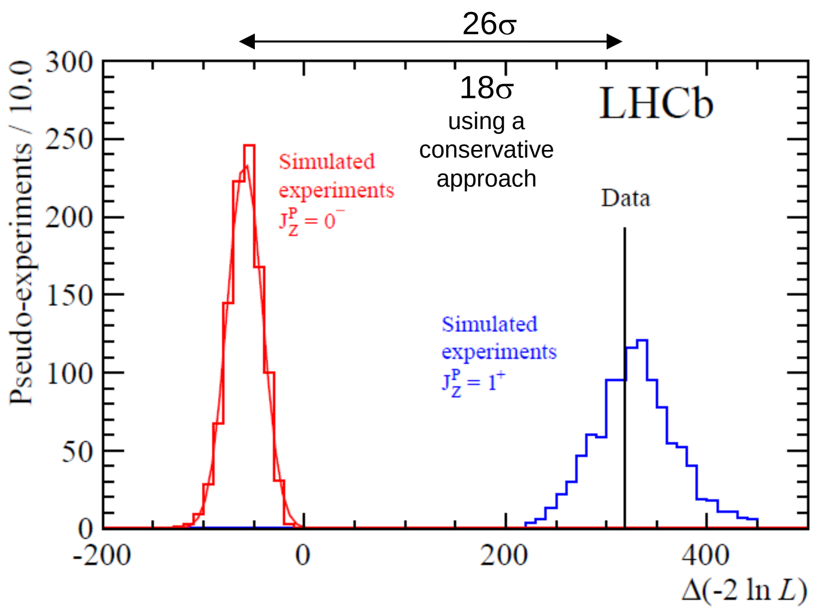
Amplitude fractions [%]
(statistical errors only)

Contribution	LHCb	Belle
S-wave total	10.8 ± 1.3	
NR	0.3 ± 0.8	
$K_0^*(800)$	3.2 ± 2.2	5.8 ± 2.1
$K_0^*(1430)$	3.6 ± 1.1	1.1 ± 1.4
$K^*(892)$	59.1 ± 0.9	63.8 ± 2.6
$K_2^*(1430)$	7.0 ± 0.4	4.5 ± 1.0
$K_1^*(1410)$	1.7 ± 0.8	4.3 ± 2.3
$K_1^*(1680)$	4.0 ± 1.5	4.4 ± 1.9
$Z(4430)^-$	5.9 ± 0.9	$10.3^{+3.0}_{-3.5}$

(not in the default fit $K^*_3(1780)$ 0.5 ± 0.2)

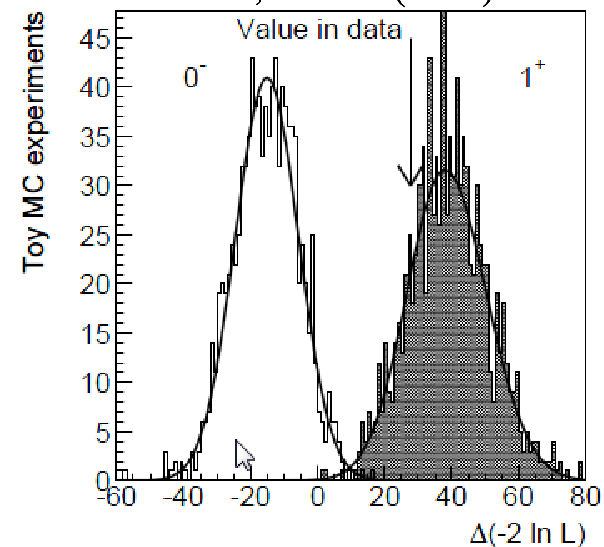
- Overall excellent consistency between LHCb and Belle
- Errors substantially improved

Z(4430)$^-$ spin-parity analysis



Belle

PRD 88, 074026 (2013)

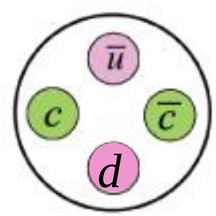


Including systematic variations:

	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

- $J^P=1^+$ now established beyond any doubt

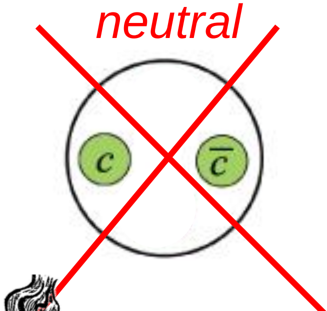
charged



Exotic
tetraquark
molecule
hybrid
…

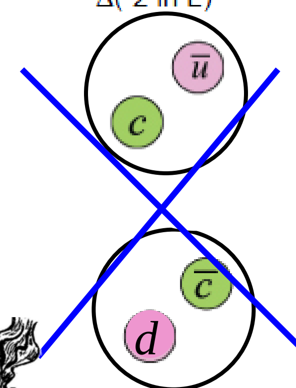
or

neutral



Standard
charmonium

or

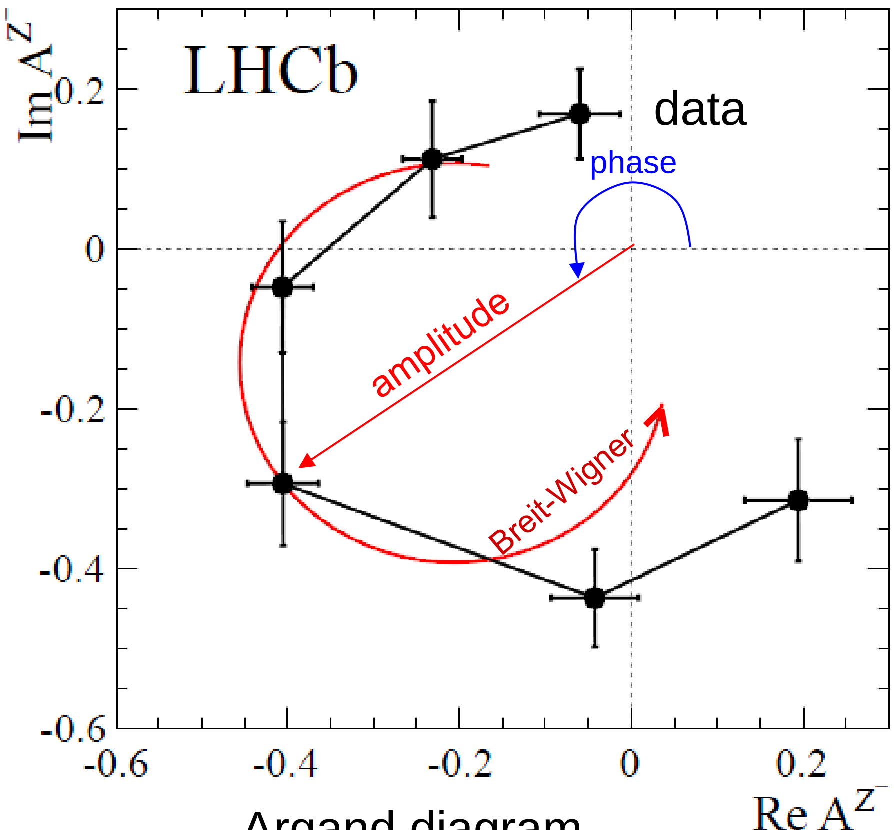


Standard
$\overline{D}^*$-D_1^{*0}
threshold
cusp
$J^P=0^-,1^-,2^-$

The only other confirmed charged four-quark candidate Z(3900)$^-$ observed by BES-III and Belle in 2013 could be a $\overline{D}D^*$ threshold effect

Is Z(4430)⁻ really a particle i.e. a real bound state?

- Does it follow resonant behavior if not forced to it by the amplitude model?
- Replace the Breit-Wigner amplitude for $Z(4430)^-$ by 6 independent amplitudes in $m_{\psi'\pi-}{}^2$ bins in its peak region



Argand diagram

Rapid phase transition at the peak of the amplitude → resonance!

First time ever the resonant character of the four-quark candidate has been demonstrated this way!

Z(4430)⁻ is the first **confirmed unambiguous** four-quark candidate

LHCb confirms existence of exotic hadrons

How CERN's Discovery of Exotic Particles May Affect Astrophysics
by BRIAN KOBERLEIN *on* APRIL 10, 2014

大型强子对撞机捕获到神秘粒子Z（4430）
或许成为物质形式"四夸克态"存在的有力证据

2014/04/13 15:46
LHCb実験を行っている国際研究チームが、4個のクォークが結合した粒子である「Z(4430)⁻」を合成したと発表した。Z(4430) としては、初発見から7年目にしてようやく別の研究チームが存在を立証した事になる。

นักฟิสิกส์ยืนยันพบฮาดรอนสองคว้ากสองแอนตีคว้าก
WRITTEN BY NATTY_SCI ON APRIL 13, 2014. POSTED IN ฟิสิกส์, วิทยาศาสตร์
ล่าสุด เครื่อง LHCb ได้มีการศึกษาอีกครั้งและใช้ข้อมูลอนุภาคจากเครื่องโดยตรงมาวิเคราะห์ แต่นำเอาเทคนิคการวิเคราะห์ของศูนย์ปฏิบัติการวิจัยเบลล์และ BaBar มาใช้ ศาสตราจารย์ชวาร์นิคกี้และทีมงานได้ยืนยันแล้วว่า Z(4430) นั้นมีอยู่จริง และ exotic hadron ก็มีอยู่จริงด้วย

Nowa forma materii: potwierdzono istnienie egzotycznych hadronów
13-04-2014 13:08 TO TRZECI RODZAJ HADRONÓW, DOTYCHCZAS WYRÓŻNIANO BARIONY I MEZONY

confirmada l'existència d'una nova partícula subatòmica

"המובהקות לאותות של Z (4430) מדהימה – לפחות 13.9 סיגמה – דבר המאשר את קיומו של מצב זה" אמר דובר LHCb פיירולואיג'י קמפנה. "ניתוח ה- LHCb חשף את הטבע המהדהד של המבנים הנצפים, והוכיח כי זהו באמת חלקיק, ולא תכונה מיוחדת של הנתונים".

Эксперимент LHCb окончательно доказал реальность экзотического мезона Z(4430)

PISTOLA FUMANTE DI UNA PARTICELLA A QUATTRO QUARK

Objavili čudnú časticu, urýchľovač ju potvrdil

LHCb kinnitas tetrakvargi olemasolu

LHC Beauty Tangkap Z (4430) Mungkin Tetraquark

Mystisk partikel udfordrer fysikernes kvarkmodel

SPIEGEL ONLINE WISSENSCHAFT
Exotisches Teilchen: **Physikern gelingt Nachweis eines Partikels aus vier Quarks**

Các nhà nghiên cứu tại LHC xác nhận sự tồn tại của hạt Tetraquark: tổ hợp tạo thành từ 4 quark
Thảo luận trong 'Khoa học' bắt đầu bởi ndminhduc, 15/4/14.

De LHCb heeft 't bevestigd: er bestaan exotische hadronen
10 APRIL 2014 DOOR ARIE NOUWEN • REAGEER

تاکنون کشف ذره Z(4430) در سال 2007 بشدت جنجال برانگیز بود و فیزیکدانان بر سر موجودیت یا عدم موجودیت آن اختلاف نظر داشتند

تائید کنونی ذره با استفاده از آشکارساز LHCb ماورای هرگونه تردید منطقی موجود است.

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Παρασκευή, 11 Απριλίου 2014

Ο LHCb επιβεβαιώνει την ύπαρξη εξωτικού σωματιδίου, LHCb confirms existence of exotic hadrons

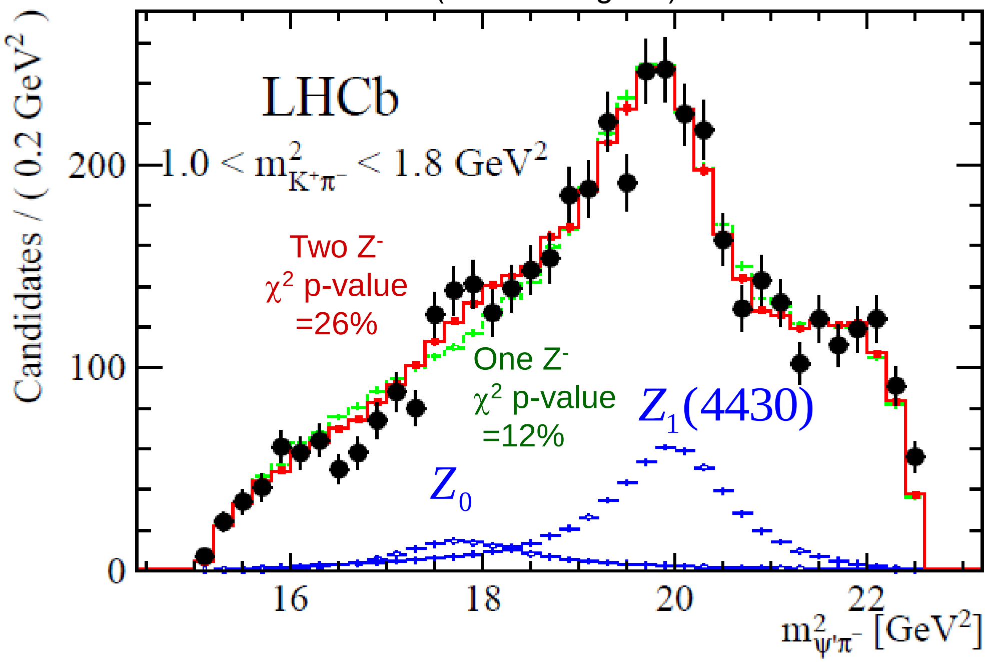
Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers 'Very Exotic Matter' That Challenges Traditional Physics! (Must-See Videos)
Thursday, April 17, 2014 19:57

SAT APR 12, 2014 AT 08:25 PM PDT
Tetra Quark: Not a New Star Trek Character, a New State of Matter.

Natuurkunde & wiskunde
CERN-fysici bevestigen bestaan nieuw exotisch deeltje

More than one $Z^- \to \psi' \pi^-$?

("K* veto region")



- Argand diagram for the Z_0 is inconclusive
- No evidence for the Z_0 in the model independent approach
- Need more data to clarify!

$$M(Z_0) = 4239 \pm 18^{+45}_{-10} \text{ MeV}$$

$$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74} \text{ MeV}$$

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

$$f^I_{Z_0} = 2.4 \pm 1.1^{+1.7}_{-0.2} \text{ \%}$$

6σ significane (with systematics)

$J^P(Z_0) = 0^-$ preferred over $1^-, 2^+, 2^-$ by 8σ

(660 ± 150 MeV wide 1^+ cannot be ruled out)

Summary

- $X(3872)\to\psi(2S)\gamma$ decay now established at 4.4σ level
  - $BR(X(3872)\to\psi(2S)\gamma)/BR(X(3872)\to J/\psi\gamma)$= 2.48±0.64±0.29 inconsistent with pure molecular interpretation of X(3872)
- $Z(4430)^-$ confirmed together with its $J^P=1^+$ assignment with overwhelming significance
  - Mass, width consistent with the recent Belle redetermination
  - Resonant character of Z(4430)- demonstrated with the Argand diagram
    - first time ever for a four-quark candidate
  - Only second charged four-quark candidate observed by two different experiments
  - Unlike for $Z(3900)^-$, its quantum numbers rule out $Z(4430)^-$ as a threshold effect
  - The charge and the spin-parity make $Z(4430)^-$ unambiguous four-quark candidate
  - Confirmation of exotic hadrons may have important implications to astrophysicist (models of neutron stars and haronization phase of the early Universe)
- Much remains to be done for the four-quark states
  - Probing internal structure of the existing candidates ($Z(4430)^-$ in particular) via detection of the new decay modes and new production mechanisms
  - Looking for more candidates
  - Coherent theoretical description