Xth Rencontres du Vietnam

Flavour Physics Conference

Heavy flavor spectroscopy and production at LHCb

Victor Egorychev

On behalf of the LHCb collaboration

Outline

Heavy flavor spectroscopy

- ✓ X(3872) state in $B^+ \to \psi(2S)\gamma K^+$ decays
- ✓ $Z(4430)^-$ state in $B^0 \to \psi(2S) K^+ \pi^-$ decays
- ✓ Search for $f_0(980)$ in $B^0 \to J/\psi \pi^+ \pi^-$ decays

Heavy flavor production

- ✓ kinematic dependences of the relative production rates f_{Λ_b} / f_d
- ✓ Production of χ_b(1P,2P,3P) states

X(3872) state

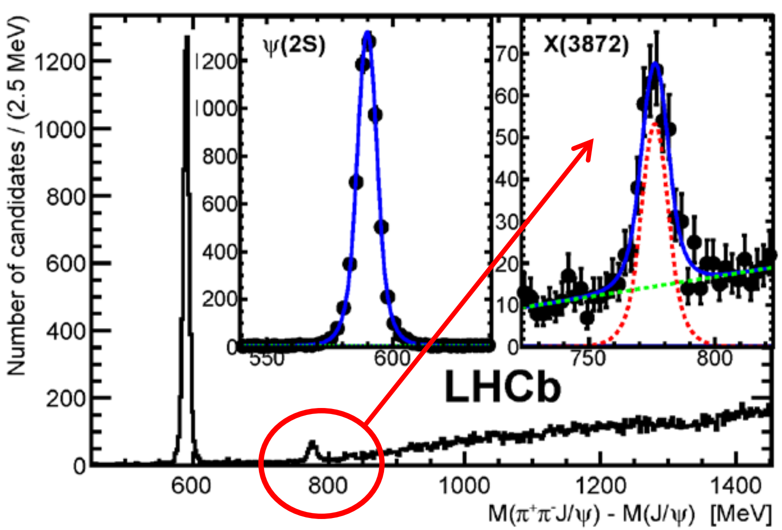
X(3872) discovered by Belle in 2003, also observed by CDF, D0, BaBar, LHCb and CMS

- Exotic particle X(3872)
  - discovered in $X(3872) \to J/\psi\pi^+\pi^-$ decay mode
  - $M = 3871.68 \pm 0.17$ MeV/c^2
    $M \simeq M(D^0) + M(D^{*0})$
  - $\Gamma < 1.2$ MeV/c^2
  - $J^{PC} = 1^{++}$ by LHCb using $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$

- Nature is still unclear, possible interpretations:
  - D^0D^{*0} molecula
  - conventional $\chi_{c1}(2P)$
  - tetraquark
  - …
  - and their mixtures

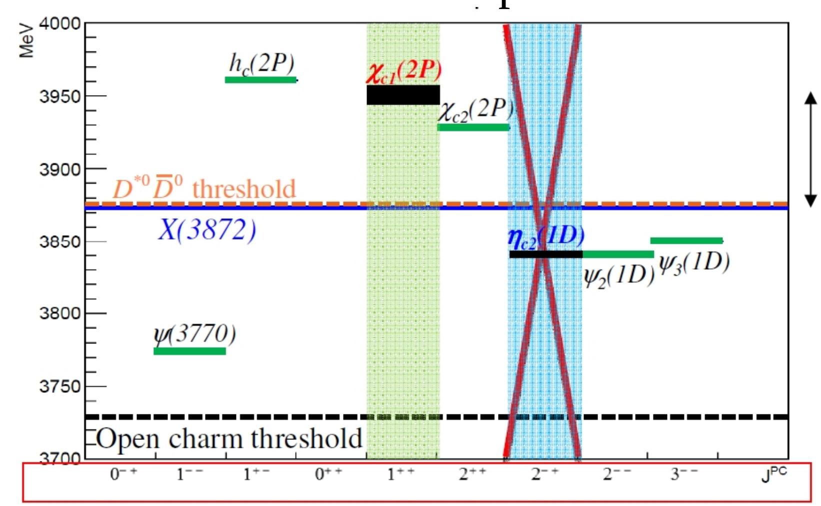
LHCb,
PRL 110 (2013) 222001

$\mathcal{L} \sim 1.0$ fb^{-1}



$\eta_{c2}(1^1D_2)$ is now ruled out
$\chi_{c1}(2^3P_1)$ possible but disfavored by mass

charmonium spectrum



Radiative decay of X(3872)

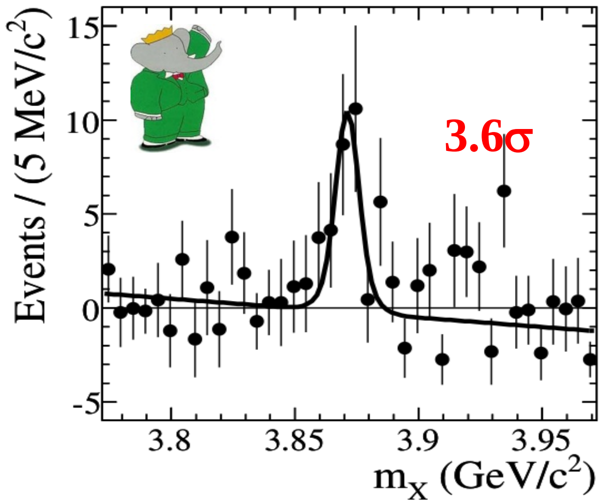
$X(3872)\to\psi(2S)\gamma$ decay allows to better understand the nature of X(3872)

Predictions for the ratio $$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J/\psi\,\gamma)}$$

Model	Prediction
charmonium, $\chi_{c1}(2P)$	1.2 – 15
molecula, DD*	$(3-4)\times10^{-3}$
mixture $\chi_{c1}(2P)$ + DD*	0.5 – 5

LHCb-PAPER-2014-008, Nucl.Phys B 886 (2014) 665

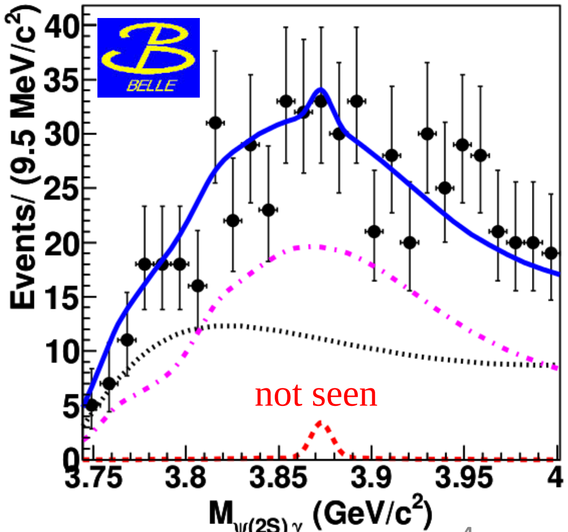
PRL 102 (2009) 132001



BaBar vs Belle descripancy

events		significance	
$\psi(2S)\gamma$	$J/\psi\gamma$	$\psi(2S)\gamma$	$J/\psi\gamma$
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

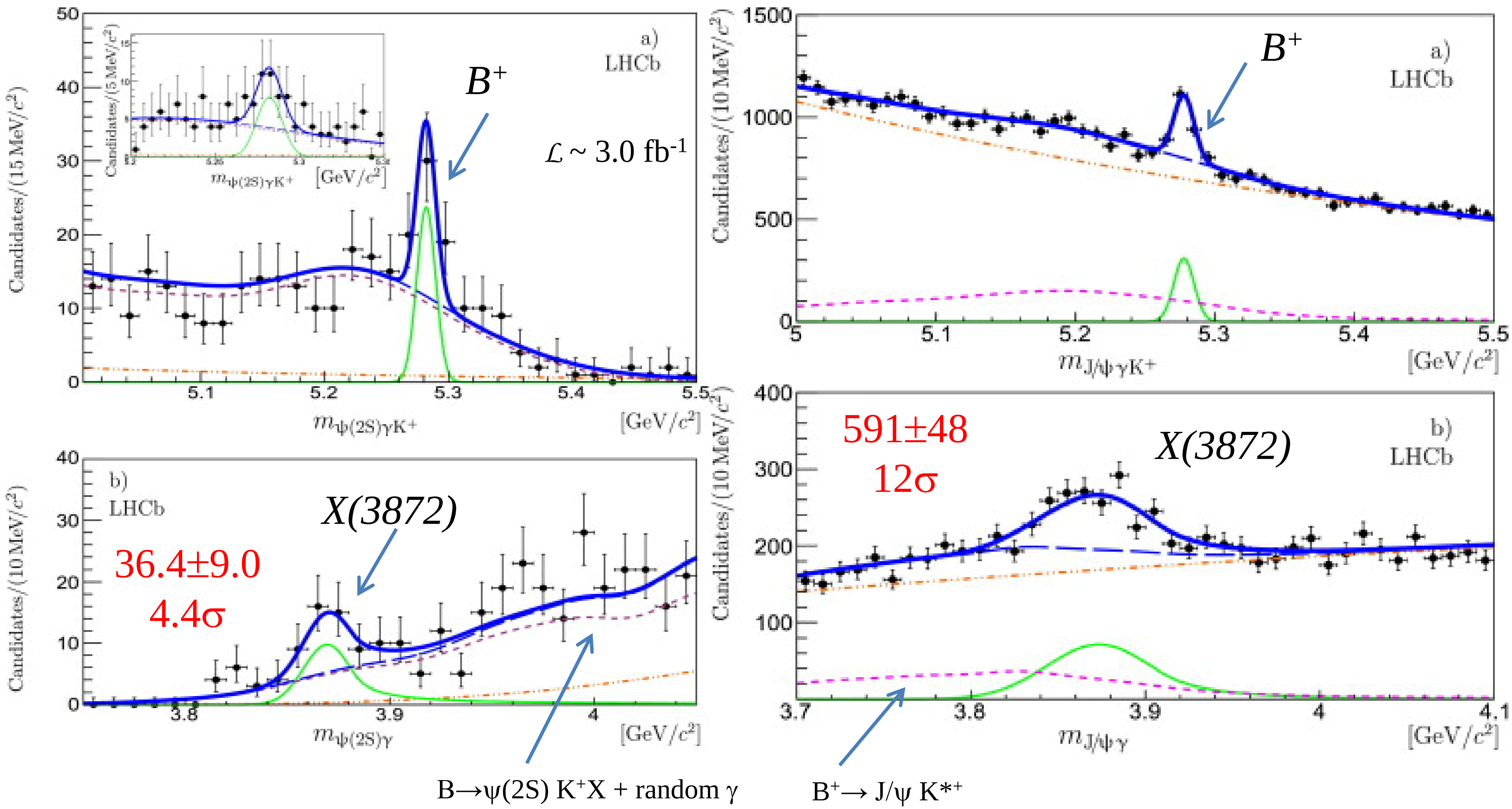
PRL 107 (2011) 091803



Radiative decay of X(3872) in LHCb

Projections of 2D fit to $M(\psi\gamma K^+)$ vs $M(\psi\gamma)$

$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \psi(2S)\gamma$ | $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi\,\gamma$



Projections of the 2D fit to $M(\psi(2S)\gamma\ K)$ and $M(\psi(2S)\gamma\ )$

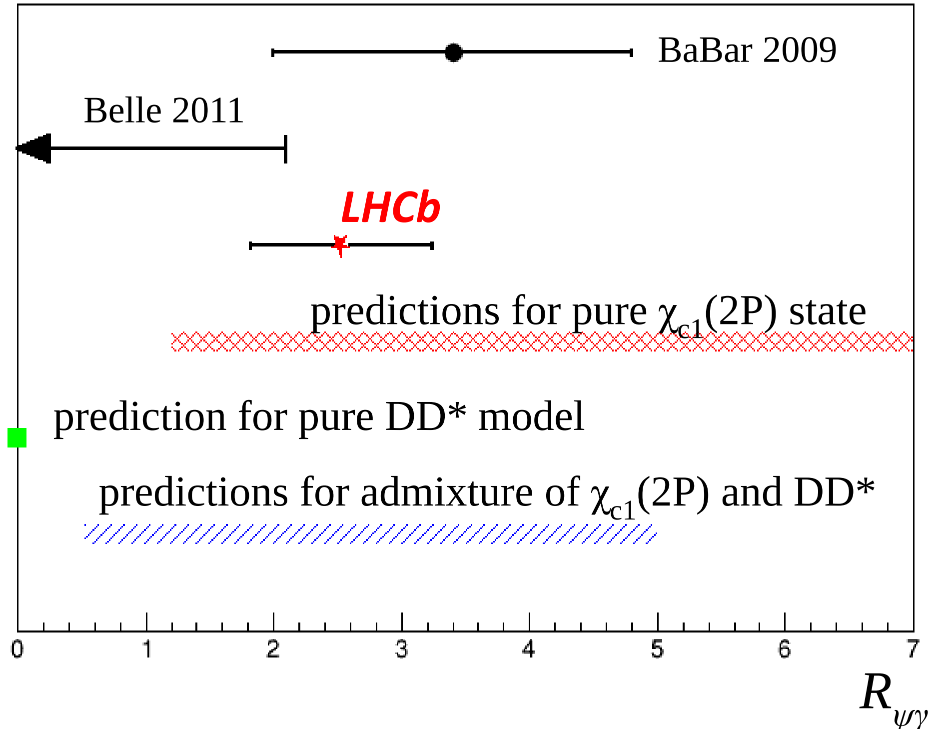
The significance was estimated with simplified simulation

LHCb-PAPER-2014-008, Nucl.Phys B 886 (2014) 665

Radiative decay of X(3872) in LHCb

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

(stat) (syst)



	events		significance	
	$\psi(2S)\gamma$	$J/\psi\gamma$	$\psi(2S)\gamma$	$J/\psi\gamma$
BaBar	25.4±7.3	23.0±6.4	3.6σ	3.5σ
Belle	$5.0^{+11.9}_{-11.0}$	$30.0^{+8.2}_{-7.4}$	0.4σ	4.9σ
LHCb	36.4±9.0	591±48	4.4σ	12σ

LHCb-PAPER-2014-008, Nucl.Phys B 886 (2014) 665

✓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 D^0D^{*0} molecule

$Z(4430)^-$

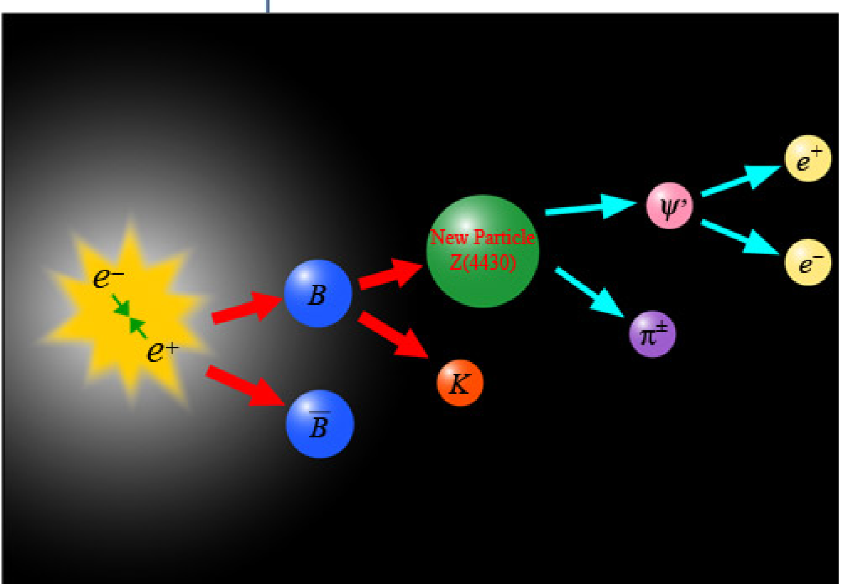
Phys. Rev.Lett. 100 (2008) 142001

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

The observation could be interpreted as the first evidence for the existence of mesons beyond the traditional quark-anti-quark model

November 13, 2007

High Energy Accelerator Research Organization (KEK)



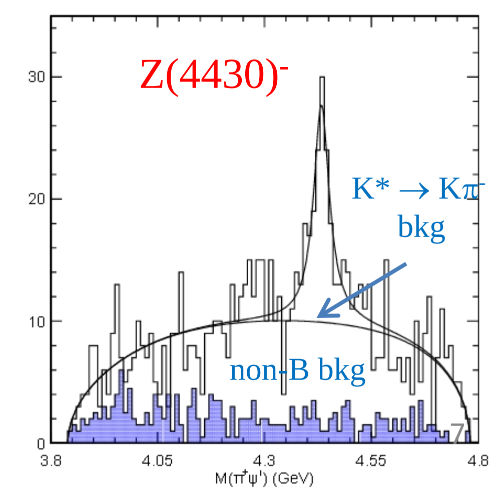
1D M($\pi^{\pm}\psi(2S)$) mass fit

K* veto region

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

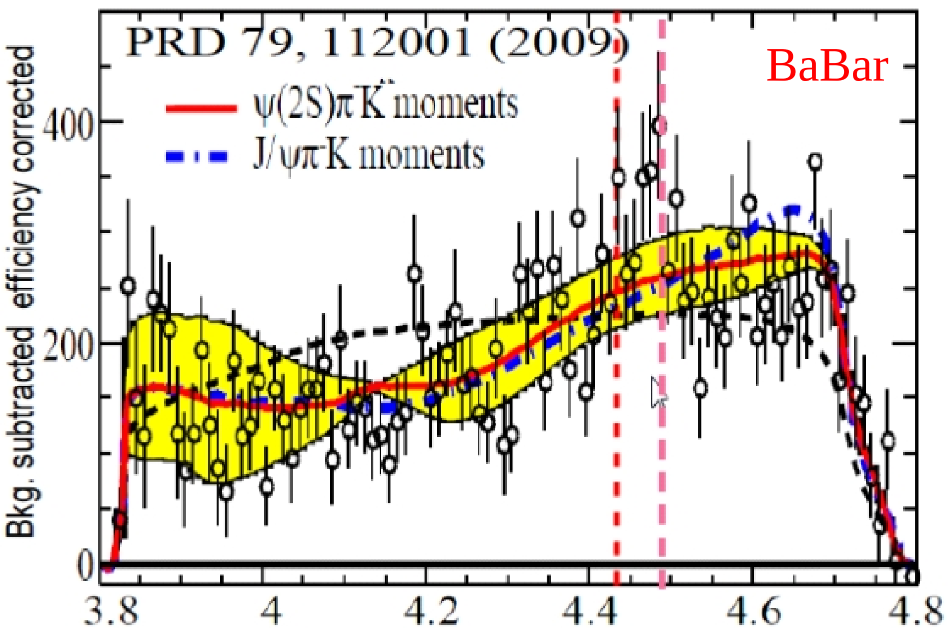
$\Gamma(Z) = 45\ ^{+18}_{-13}\ ^{+30}_{-13}$ MeV

significance 6.5σ



Z(4430)$^-$ in BaBar and Belle

Harmonic moments of K*s (2D)
reflected to M($\pi^{\pm}\psi(2S)$)

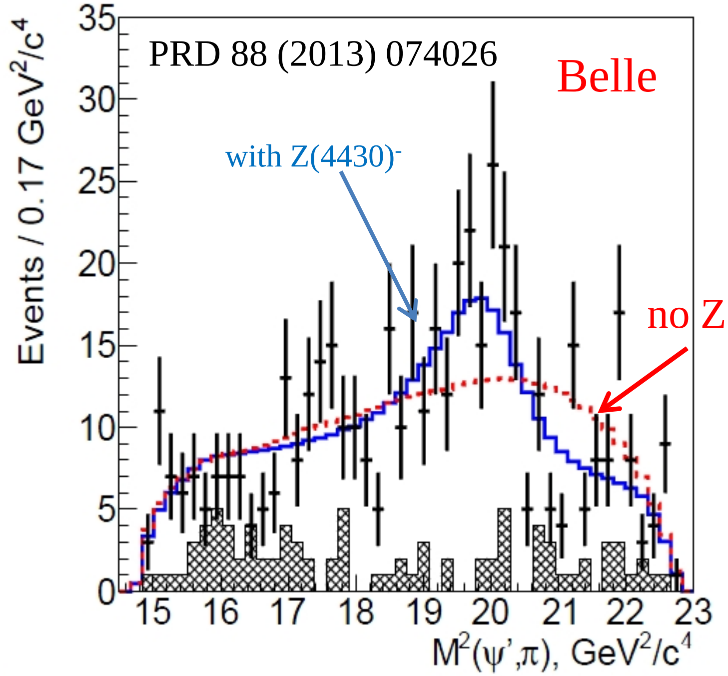


M($\pi^{\pm}\psi(2S)$) GeV Belle 1D

Belle 4D

4D amplitude fit

K* veto region



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

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

Did not numerically contradict the Belle results

$BR(B^0 \to Z^- K^+) \times BR(Z^- \to \pi^- \psi(2S)) < 3.1 \times 10^{-5}$

Model dependent approach to $K^* \to K\pi$ backgrounds

$J^P = 1^+$ prefered by > 3.4 σ

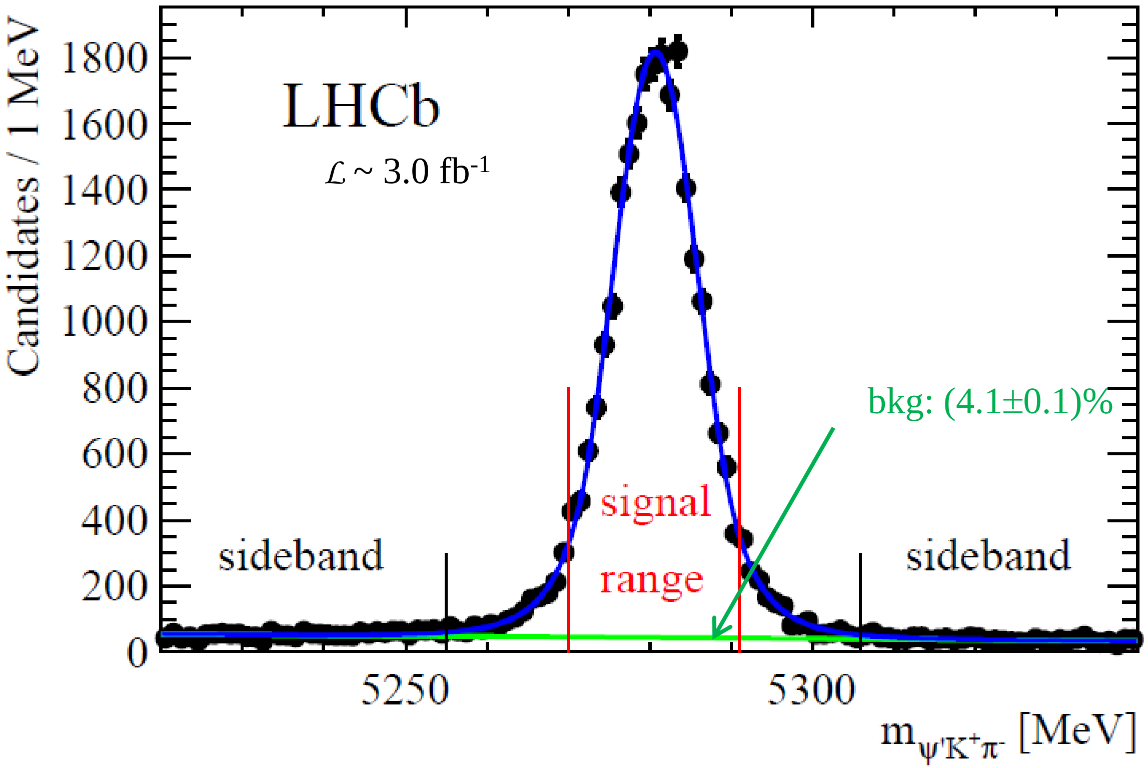
$$M(Z) = 4485\ ^{+22}_{-22}\ ^{+28}_{-11}\ \text{MeV}$$

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

significance 6.4σ (5.6 σ with sys.)

$Z(4430)^-$ state in LHCb

LHCb-PAPER-2014-014
arXiv: 1404.1903



$B^0 \rightarrow \psi(2S)\ K^+\pi^-,\ \psi(2S) \rightarrow \mu^+\mu^-$

LHCb: 25176±174
Belle: 2010±50
BaBar: 2021±53

bkg in Belle 7.8%

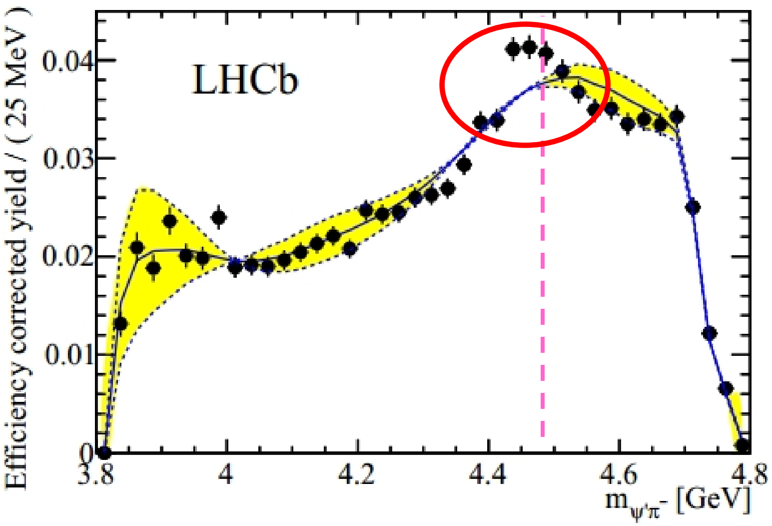
An order of magnitude larger signal statistics than in Belle or BaBar thanks to hadronic production of b-quarks at LHC

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

Z(4430)$^-$ state in LHCb

LHCb uses both approaches

LHCb-PAPER-2014-014
arXiv: 1404.1903



Moments analysis

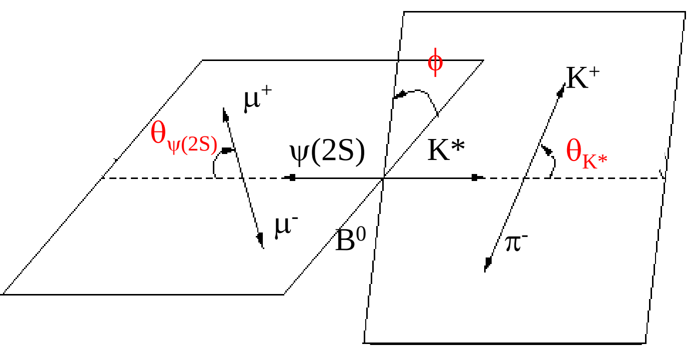
No assumptions about K* contributions except for the maximal J

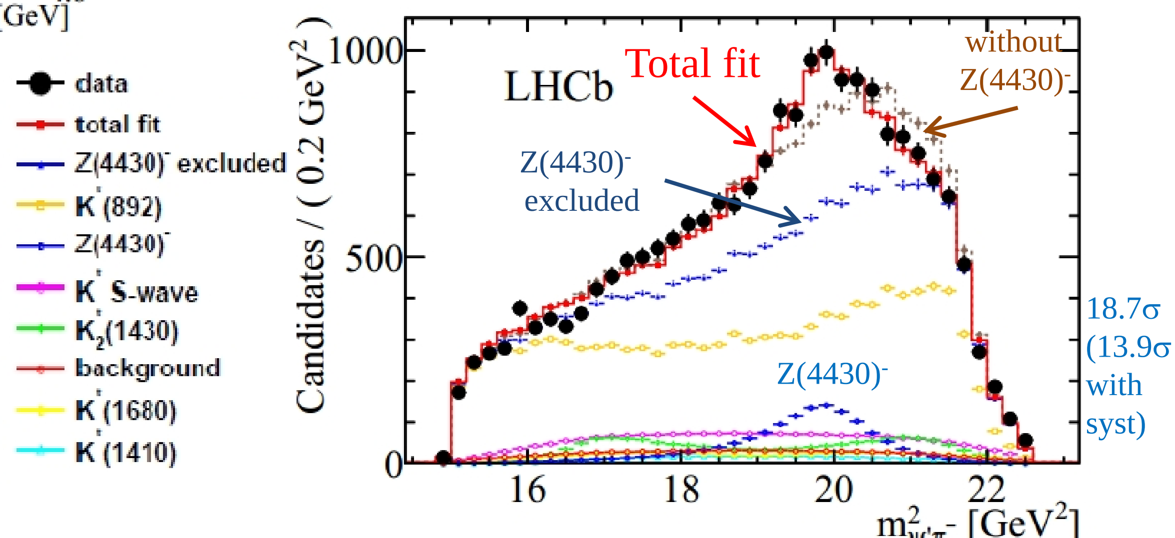
K* reflection do not describe the Z(4430)$^-$ region

This approach does not allow to define Z(4430)$^-$ parameters

4D fit method

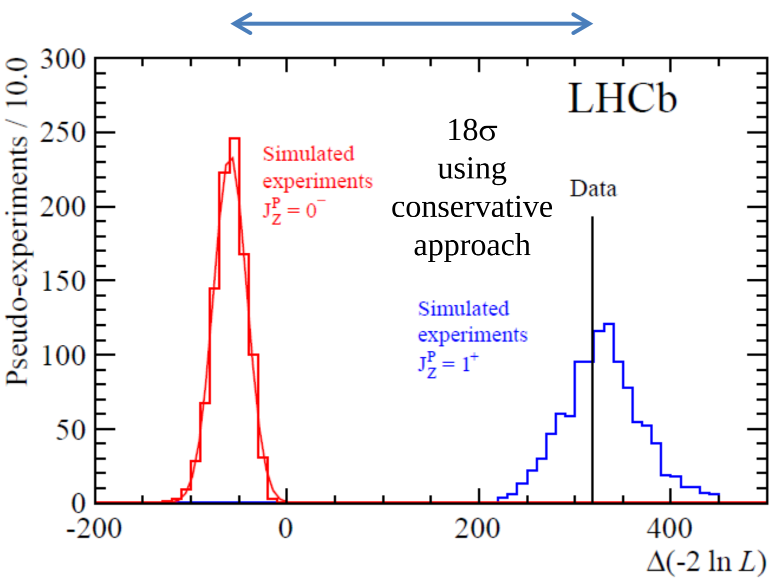
4D model dependent amplitude analysis





The χ^2 p-value < 2 x10^{-6} (Z excluded)
The χ^2 p-value = 12% (with Z(4430)$^-$)

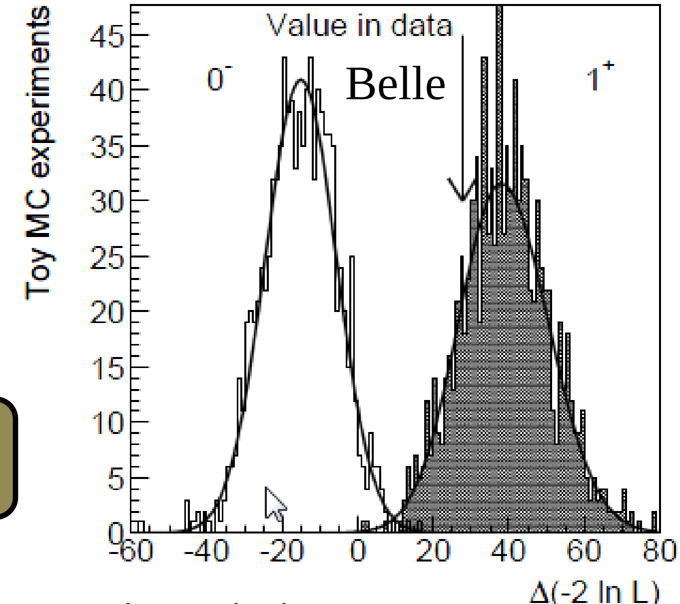
$Z(4430)^-$ parameters in LHCb



spin parity

Likelihood-ratio test to discriminate between 0^- and 1^+ hypotheses

LHCb-PAPER-2014-014
arXiv: 1404.1903



Excellent consistency

	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+26}_{-46-35}
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0+4.3}_{-3.5-2.3}$
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)

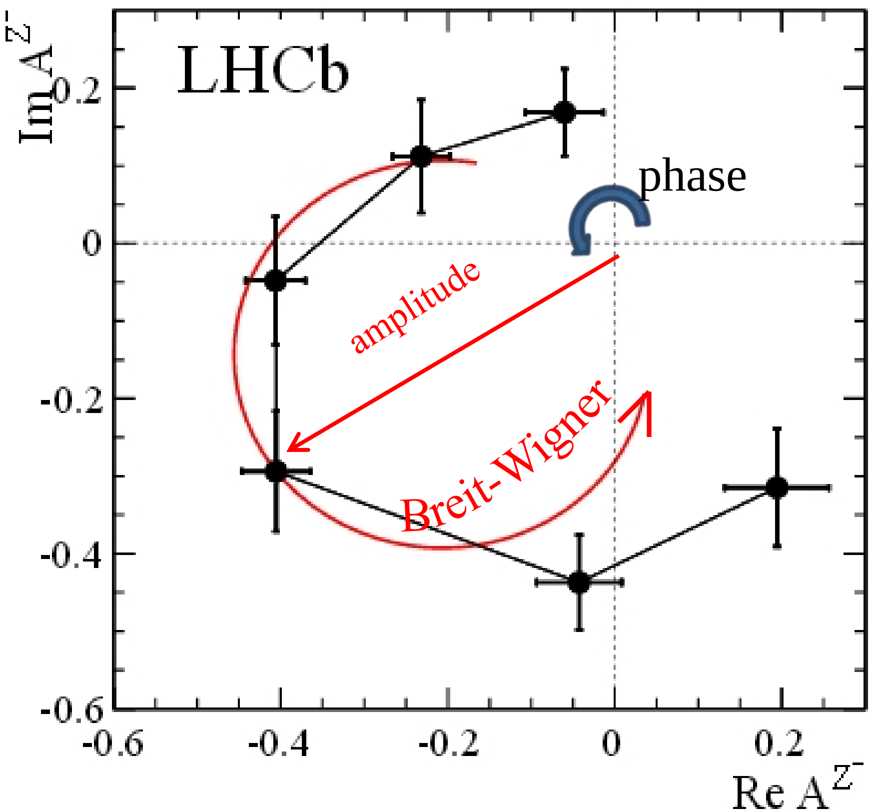
Including systematic variations

	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

$Z(4430)^-$ in LHCb

Argand diagram



Replace the Breit-Wigner amplitude for $Z(4430)^-$ by 6 independent amplitudes in $M^2(\psi(2S)\ \pi^-)$ bins in its peak region

Observe a fast change of phase crossing maximum of magnitude

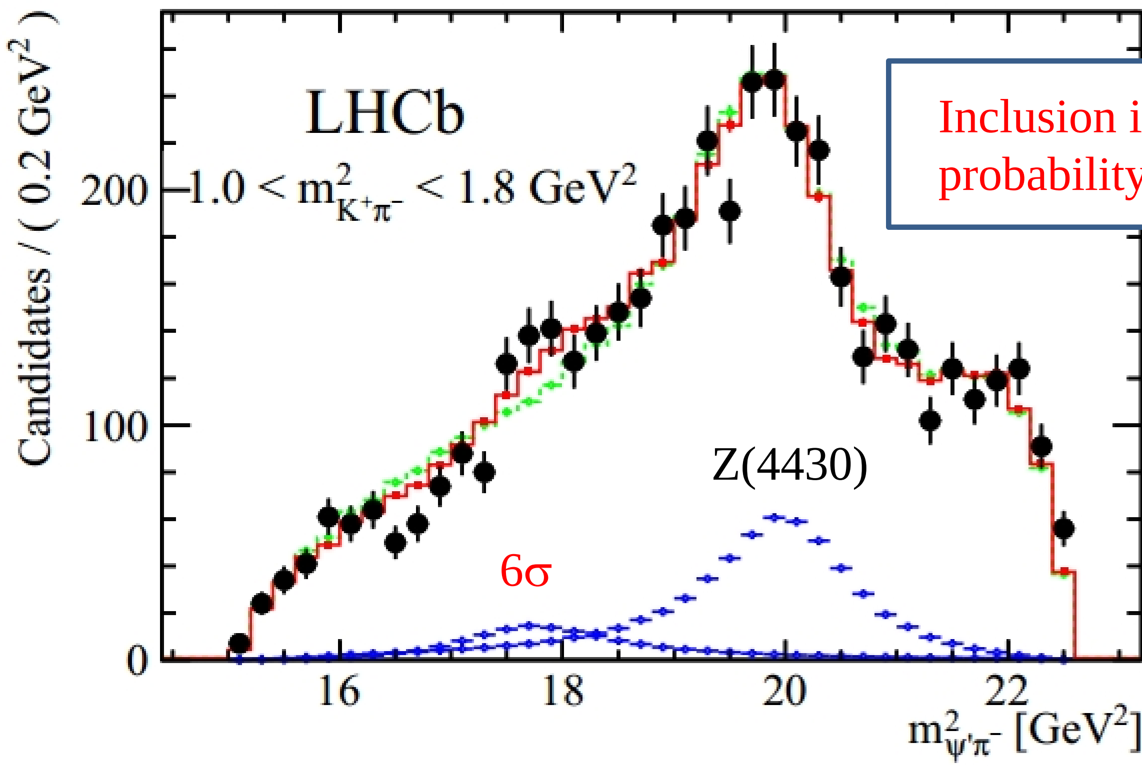
Expected behaviour for a resonance

LHCb-PAPER-2014-014
arXiv: 1404.1903

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

More than one $Z(4430)^- \to \psi(2S)\pi^-$

$K^*(872)$ and $K^*_2(1430)$ veto region



Inclusion increases the fit probability 12% → 26%

0^- state is preferred over $1^-,2^-,2^+$ by 8σ over 1^+ by 1σ

LHCb-PAPER-2014-014
arXiv: 1404.1903

One more Z resonance may be included

Argand diagram studies are inconclusive

Need more data to clarify!

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

$\Gamma(Z) = 200 \pm 47 \,^{+108}_{-74}$ MeV

Excitement

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 פיירולאיג'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 ARE NOUWEN • REAGEER

ISNA
خبرگزاری دانشجویان ایران، ایسنا
Iranian Students' News Agency

تاکنون کشف ذره (4430)Z 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

Spectroscopy in light quark sector

Scalar mesons in general (particular $f_0(980)$) are not well understood
Recently, LHCb observed two channels $B_s \to J/\psi\ f_0(980)$ and $B_d \to J/\psi\ f_0(500)$
Many possibilities: $q\bar{q}$, $q\bar{q}q\bar{q}$, mixtures…

When $f_0(500)$ and $f_0(980)$ are considered as $q\bar{q}$ states there is the possibility of their being mixtures of light and strange quarks

mixing angle

$$\begin{aligned} |f_0(980)\rangle &= \cos\varphi_m |s\bar{s}\rangle + \sin\varphi_m |n\bar{n}\rangle \\ |f_0(500)\rangle &= -\sin\varphi_m |s\bar{s}\rangle + \cos\varphi_m |n\bar{n}\rangle, \\ \text{where } |n\bar{n}\rangle &\equiv \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right). \end{aligned}$$

When these states are viewed as $q\bar{q}q\bar{q}$ states the wave functions becomes

$$\begin{aligned} |f_0(980)\rangle &= \frac{1}{\sqrt{2}}\left(|[su][\bar{s}\,\bar{u}]\rangle + |[sd][\bar{s}\bar{d}]\rangle\right) \\ |f_0(500)\rangle &= |[ud][\bar{u}\bar{d}]\rangle. \end{aligned}$$

Observable:

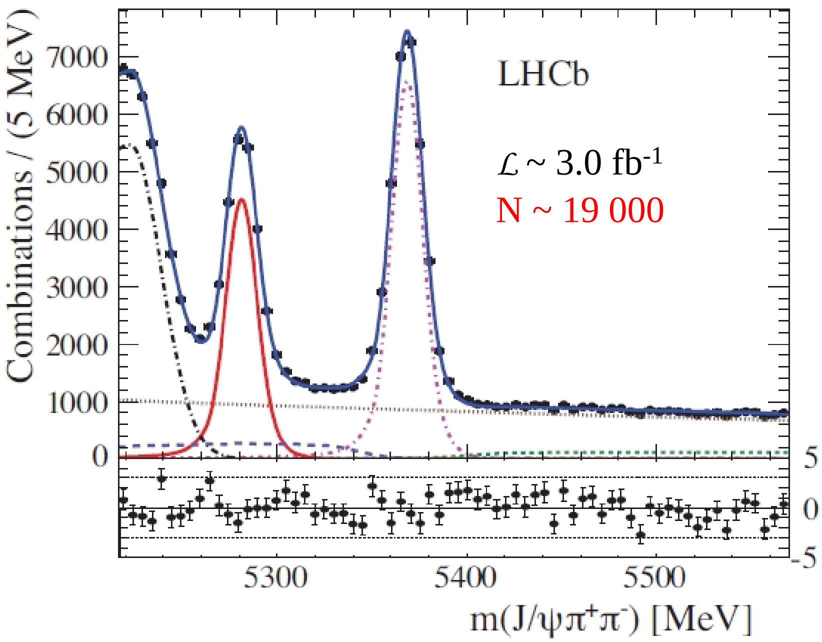
phase space factors

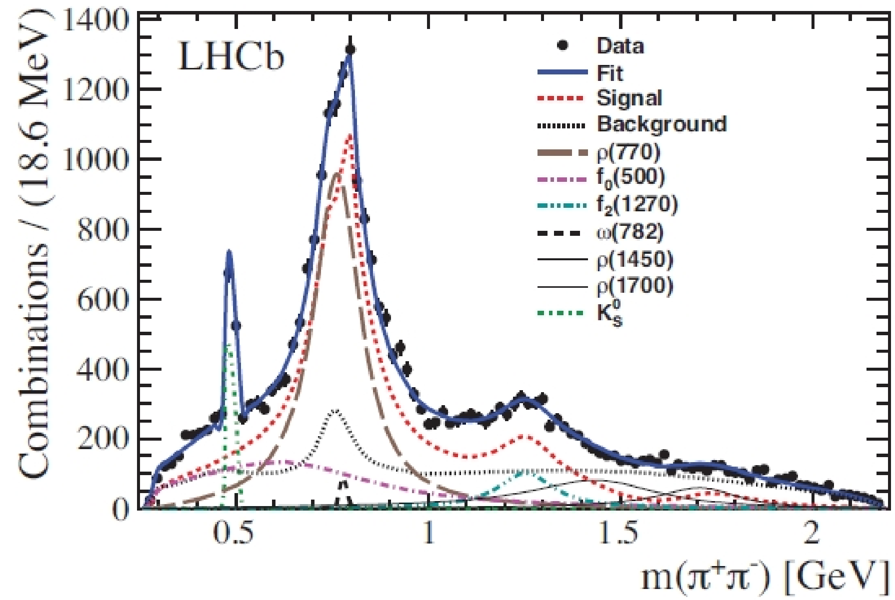
$$\tan^2\varphi_m \equiv r_\sigma^f = \frac{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(980)\right)}{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(500)\right)} \frac{\Phi(500)}{\Phi(980)},$$

for pure tetraquark states ~1/2

PRL 111 (2013) 062001

Amplitude analysis $B_d \to J/\psi\pi^+\pi^-$





Branching fractions for each channel

R	$\mathcal{B}(\overline{B}^0 \to J/\psi\, R, R \to \pi^+\pi^-)$
$\rho(770)$	$(2.50 \pm 0.10^{+0.18}_{-0.15}) \times 10^{-5}$
$f_0(500)$	$(8.8 \pm 0.5^{+1.1}_{-1.5}) \times 10^{-6}$
$f_2(1270)$	$(3.0 \pm 0.3^{+0.2}_{-0.3}) \times 10^{-6}$
$\omega(782)$	$(2.7^{+0.8+0.7}_{-0.6-0.5}) \times 10^{-7}$
$\rho(1450)$	$(4.6 \pm 1.1 \pm 1.9) \times 10^{-6}$
$\rho(1700)$	$(2.0 \pm 0.5 \pm 1.2) \times 10^{-6}$

Similar to the $Z(4430)^-$: 4D analysis
No evidence for $J/\psi\pi^+$
Best fit model does not require $f_0(980)$ component

$$\tan^2\varphi_m \equiv r_\sigma^f = \left(1.1^{+1.2+6.0}_{-0.7-0.7}\right) \times 10^{-2} < 0.098 \text{ at } 90\% \text{ C.L}$$

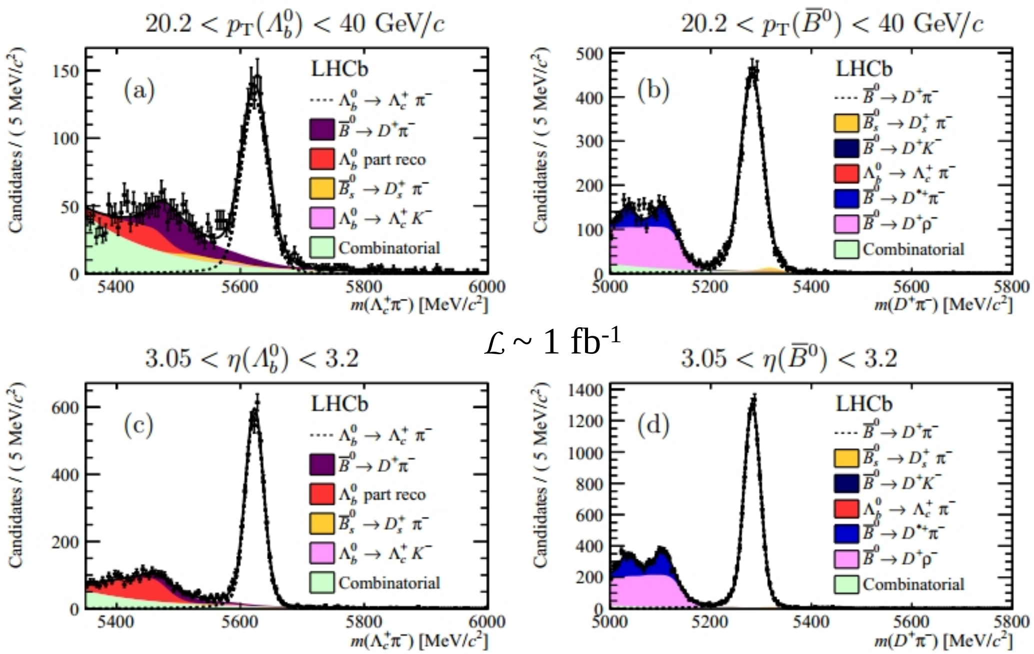
The measured upper limit on r^f_σ deviates from the tetraquark prediction (1/2) by 8σ

LHCb-PAPER-2014-012
arXiv 1404.5673

Λ_b production

The relative production rates of beauty hadrons are described by the fragmentation fractions f_u, f_d, f_s, f_c, and f_{Λ_b} which describe the probability that a b quark fragments into a B_q or a Λ_b

The kinematic dependences of the relative production rates f_{Λ_b}/f_d of Λ_b baryons and B_d mesons are measured using $\Lambda_b \to \Lambda_c \pi^+$ and $B_d \to D^+\pi^-$ decays



$\mathcal{L} \sim 1$ fb^{-1}

$N(\Lambda_b) = 44\,859 \pm 229$

$N(B_d) = 106\,197 \pm 344$

LHCb-PAPER-2014-004, arXiv 1405.6842

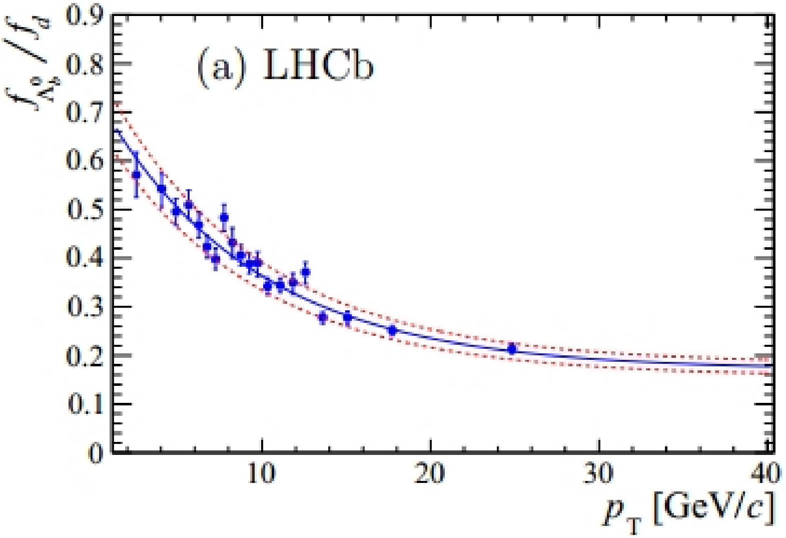
$$\frac{f_{\Lambda_b}}{f_d}(x) = \frac{BR(\overline{B}_d^0 \to D^+\pi^-)}{BR(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \times \frac{BR(D^+ \to K^-\pi^+\pi^+)}{BR(\Lambda_c^+ \to pK^-\pi^+)} \times R(x)$$

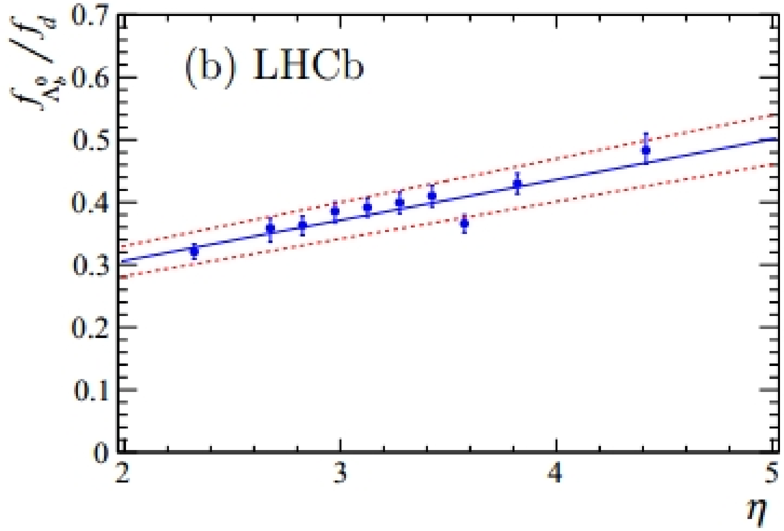
$$R(x) = \frac{N_{\Lambda_b^0 \to \Lambda_c^+\pi^-}(x)}{N_{\overline{B}_d^0 \to D^+\pi^-}(x)} \times \frac{\varepsilon_{\overline{B}_d^0 \to D^+\pi^-}(x)}{\varepsilon_{\Lambda_b^0 \to \Lambda_c^+\pi^-}(x)}$$

Λ_b production

LHCb-PAPER-2014-004,
arXiv 1405.6842

Dependences of f_{Λ_b}/ f_d on the p_T and η of the beauty hadrons





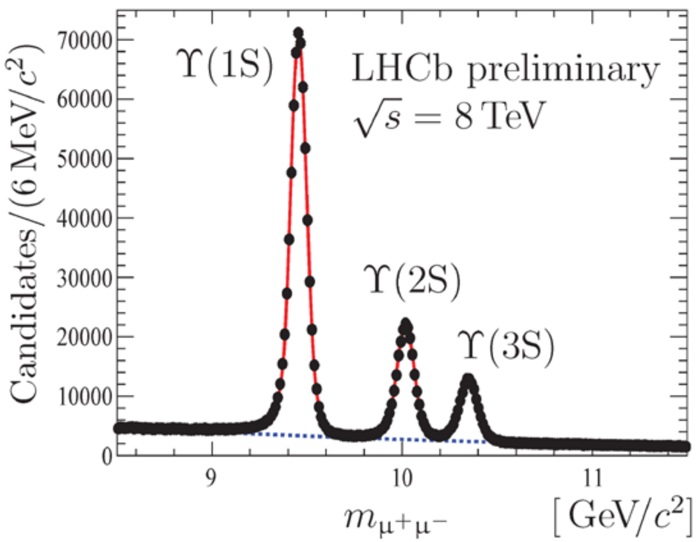
✓The p_T dependence is accurately described by an exponential function

✓The ratio of fragmentation fractions f_{Λ_b}/ f_d decreases by a factor of three in the range $1.5 < p_T < 40$ GeV/c

✓The ratio of fragmentation fractions f_{Λ_b}/ f_d versus η is described by a linear dependence in the range $2 < \eta < 5$

Production of χ_b(1P,2P,3P) state

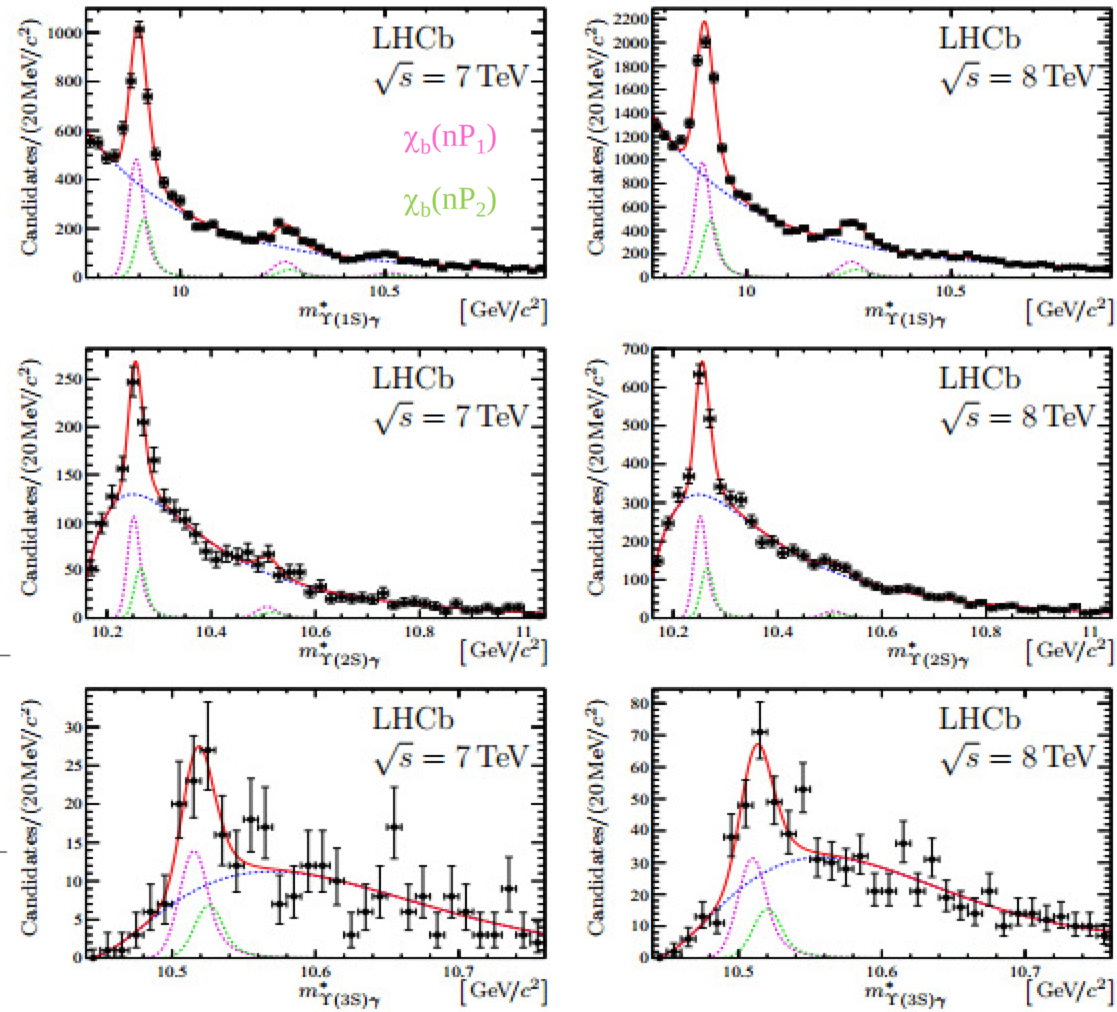
LHCb-PAPER-2014-031



	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$N_{\Upsilon(1S)}$	283 252 ± 592	659 599 ± 906
$N_{\Upsilon(2S)}$	87 541 ± 263	203 277 ± 558
$N_{\Upsilon(3S)}$	50 419 ± 289	115 271 ± 435

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$N_{\chi_b(1P)\to\Upsilon(1S)\gamma}$	1908 ± 71	4608 ± 115
$N_{\chi_b(2P)\to\Upsilon(1S)\gamma}$	390 ± 41	904 ± 68
$N_{\chi_b(3P)\to\Upsilon(1S)\gamma}$	133 ± 31	196 ± 50
$N_{\chi_b(2P)\to\Upsilon(2S)\gamma}$	265 ± 30	660 ± 46
$N_{\chi_b(3P)\to\Upsilon(2S)\gamma}$	48 ± 17	73 ± 26
$N_{\chi_b(3P)\to\Upsilon(3S)\gamma}$	56 ± 12	126 ± 20

LHCb preliminary



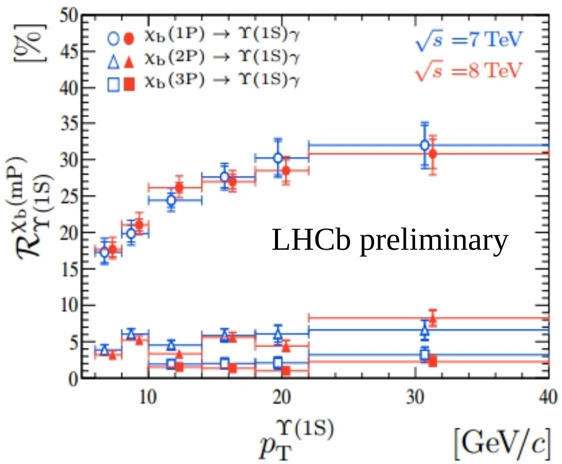
$M\chi_b(3P_1) = 10511.3 \pm 1.7 \pm 2.4$ MeV/c^2 Most precise measurement

$\chi_b(nP)$ to $\Upsilon(n'S)$ feeddown fractions

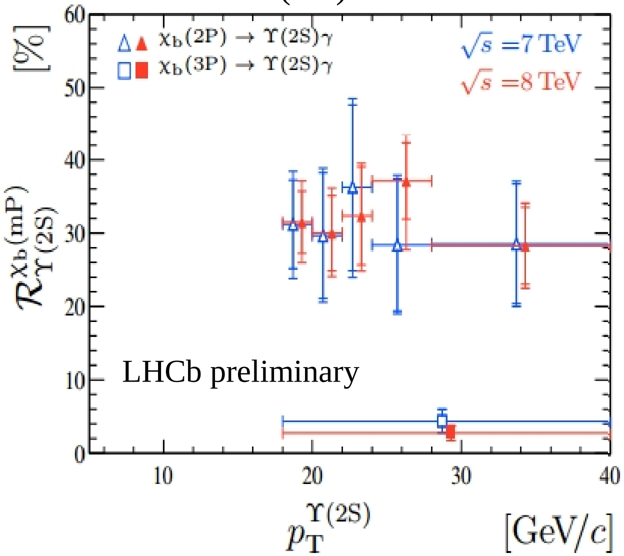
LHCb-PAPER-2014-031

Fraction of Υ mesons originating from χ_b radiative decays

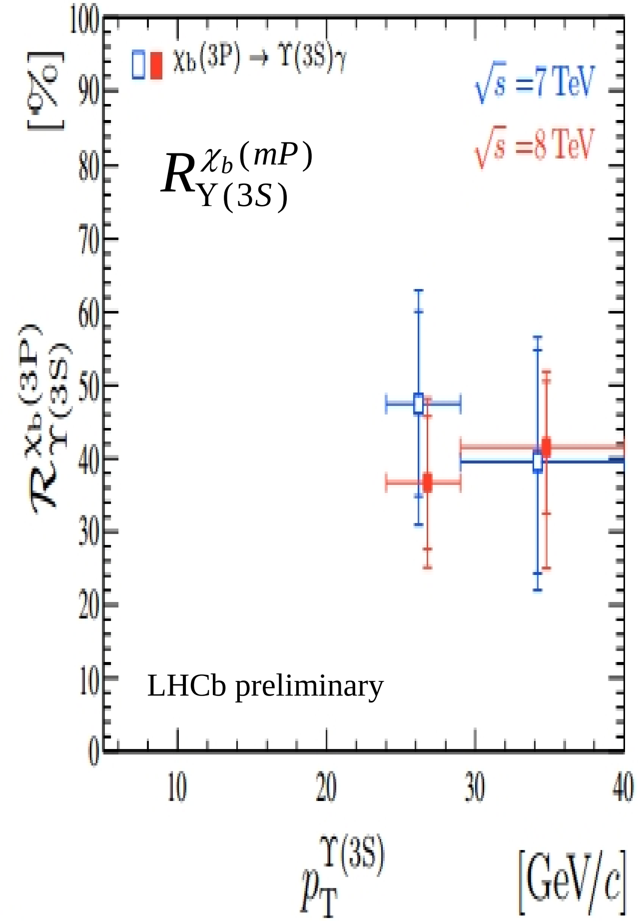
$R^{\chi_b(mP)}_{\Upsilon(1S)}$



$R^{\chi_b(mP)}_{\Upsilon(2S)}$



$R^{\chi_b(mP)}_{\Upsilon(3S)}$



χ_b(3P) to Υ(3S) feed-down has been often neglected when comparing data and theory on Υ(3S)
This measurements demonstrates its importance

The measurement of the Υ(3S) production fraction due to radiative χ_b(3P) decays is performed for the first time

Conclusions

LHCb-PAPER-2014-008,
Nucl.Phys B 886 (2014) 665

✓$X(3872) \rightarrow \psi(2S)\gamma$ decay now established at 4.4 σ

•$BR(X(3872) \rightarrow \psi(2S)\gamma)/BR(X(3872) \rightarrow J/\psi\gamma)$ inconsistent with pure molecular interpretation of X(3872)

✓Existence confirmation of $Z(4430)^-$ with $>13.9\sigma$

LHCb-PAPER-2014-014
arXiv: 1404.1903

- quantum numbers determination $J^P = 1^+$
- resonant behaviour observed
- the charge and spin-party make $Z(4430)^-$ unambiguous four-quark candidate

✓No evidence for $f_0(980)$ in $B_d \rightarrow J/\psi\pi+\pi-$ decays

- resonance production $f_0(980)$ as a tetraquark state ruled out at 8σ

LHCb-PAPER-2014-012
arXiv 1404.5673

✓New interesting results on $\chi_b(3P)$ production rate:

LHCb-PAPER-2014-031

- $\chi_b(3P)$ to $\Upsilon(3S)$ feed-down is large

✓The kinematic dependences of the relative production rates f_{Λ_b}/ f_d of Λ_b baryons and B_d mesons are measured

LHCb-PAPER-2014-004,
arXiv 1405.6842

✓Looking forward for new exciting results!