Exotic quarkonium-like resonances at LHCb

Results and prospects

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Outline

1. The LHCb detector
2. $\mathrm{X}(3872) \to \gamma\psi(2S)$
3. $Z(4430)^+$ confirmation
4. Light meson spectroscopy
5. Conclusions

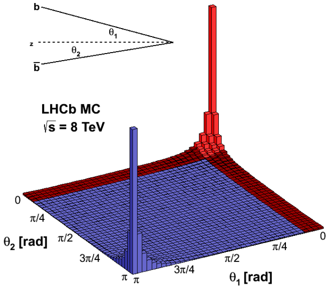
The LHC environment

During most of 2012 run, LHC collided protons at 8 TeV with an average instantaneous luminosity of $4 \times 10^{32} cm^{-2} s^{-1}$ and 11 MHz of bunch crossing.

- Inelastic cross section $\sim 60\,\mathrm{mb}$
- $\sigma(\mathrm{pp} \rightarrow \mathrm{b\bar{b}}X) = (284 \pm 20(\mathrm{stat}) \pm 49(\mathrm{syst}))\ \mu\mathrm{b}$ [PLB 694, 209]
- $\Longrightarrow\ \sim 10^6\ \mathrm{B\bar{B}}$ produced per second
- $\sigma(\mathrm{pp} \rightarrow \mathrm{c\bar{c}}X)$ is about 20 times higher. [Nucl.Phys. B871 (2013) 1-20]

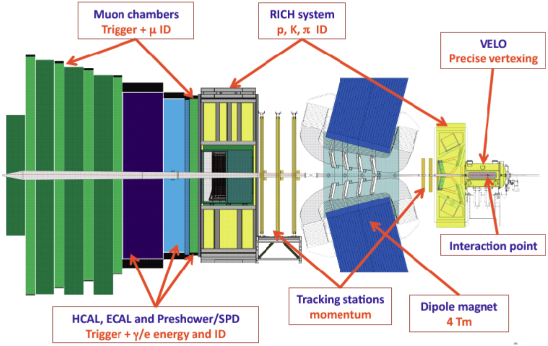
At the LHC energy, the $\mathrm{b\bar{b}}$ pairs are produced preferentially at forward (backward) directions.

- Optimal solution for flavour physics is a forward detector: LHCb



The LHCb detector

LHCb experiment was designed to perform high precision flavor physics measurements at the LHC.



- **Single-arm design.** Covering the range $2 < \eta < 5$, LHCb can exploit the dominant heavy flavour production mechanism at the LHC
- **Good particle identification.** Excellent muon identification and good separation of π, K and p over (2 - 100) GeV.
- **Good vertexing and tracking.** Precise primary and secondary vertex reconstruction. Excellent momentum, IP and proper time resolution.
- **Dataset.** 1 + 2 fb^{-1} aquired in 2011 + 2012 runs

Quarkonia status

In QCD-motivated models, quarkonia states are basically described as $q\bar{q}$ pairs bound by a short-distance potential approximately Coulombic (single-gluon exchange) plus a linearly increasing confining potential at large separations.

- All charmonium states below the $D\bar{D}$ mass threshold have been observed.
- Charmonium states above the $D\bar{D}$ or $D\bar{D}^*$ mass threshold can decay into $D\bar{D}$ and $D\bar{D}^*$ final states.
- Many predicted states still not observed.
- Similar situation in the Beauty sector.

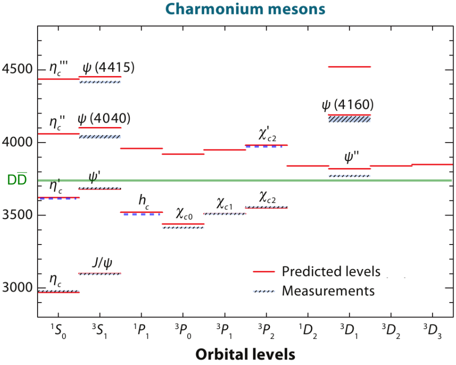


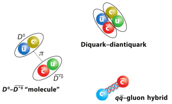
Figure from [Annu.Rev.Nucl. Part. Sci. 2008. 58:51–73]

XYZ states

Many new states have been observed at Charm, B-factories and Tevatron

- Masses lying on the limits of the quarkonia spectrum
- Observed many different production mechanisms: ISR, e^+e^-, $\gamma\gamma$ and B decays.
- The measured masses do not correspond to the predicted values for conventional quarkonia.
- The properties do not fit very well to the quarkonia picture.

Many theoretical interpretations in discussion:



- conventional quarkonia;
- tetra-quarks states;
- meson-molecules;
- hybrid mesons;
- threshold effects;

The table should be updated to include some new states: Z_b^+, $Z_c(3900)^+$ ...

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}\bar{D}^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$
				$e^+e^- \to e^+e^-(\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (...)$
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$

[Eur.Phys.J.C71:1534,2011]

X(3872)

The X(3872) exotic-meson was discovered in 2003 by the Belle collaboration in $\mathrm{B} \to \mathrm{KX}(3872)$ with $\mathrm{X}(3872) \to J/\psi\pi^+\pi^-$.

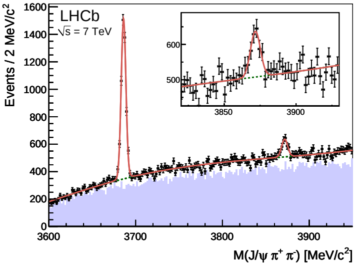
- Its existence was immediately confirmed by BaBar,CDF, DØ collaborations.
- Quantum numbers previously constrained to 1^{++} or 2^{-+}, were measured by LHCb as 1^{++}.
- Clear signature on the $\mathrm{X}(3872) \to J/\psi\pi^+\pi^-$ mode. $\pi^+\pi^-$ mass spectrum well studied.
- Mass known to 0.2 MeV and width < 1.2 MeV. [Eur. Phys. J. C 72 (2012) 1972]

$J/\psi\,\pi^+\pi^-$ inclusive reconstruction.

Mass measurement using the first 34 pb^{-1}

The nature of the X(3872) remains uncertain:

- Conventional charmonium $\chi_{c1}(2^3P_1)$.(very unlikely)
- Mesonic molecular state: $D^{*0}\bar{D}^0$ bound state.
- Tetraquark (diquark-anti-diquark).



Evidence of $X(3872) \to \psi(2S)\gamma$ at LHCb

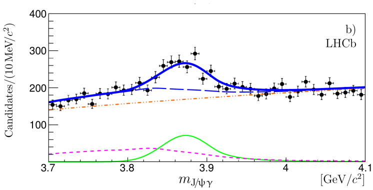
arXiv:1404.0275 (to appear in Nucl. Phys. B)

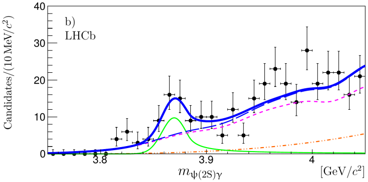
Radiative decays of the $X(3872)$ provide a valuable opportunity to understand its nature.

- The $X(3872)$ C-parity has been determined studying the $X(3872) \to \gamma J/\psi$ decay.
- $R_{\psi\gamma} = \frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J/\psi\,\gamma)}$ can give information about the internal structure of $X(3872)$.

- Analysis performed using 3 fb^{-1} collected in 2011 and 2012.
- Observed 4.4σ evidence of $X(3872) \to \psi(2S)\gamma$ in $B^+ \to K^+X(3872)$ decays.

Parameter		Decay mode $X(3872) \to J/\psi\gamma$	$X(3872) \to \psi(2S)\gamma$
m_{B^+}	$[\text{MeV}/c^2]$	5277.7 ± 0.8	5281.9 ± 2.4
$m_{X(3872)}$	$[\text{MeV}/c^2]$	3873.4 ± 3.4	3869.5 ± 3.4
N_ψ		591 ± 48	36.4 ± 9.0



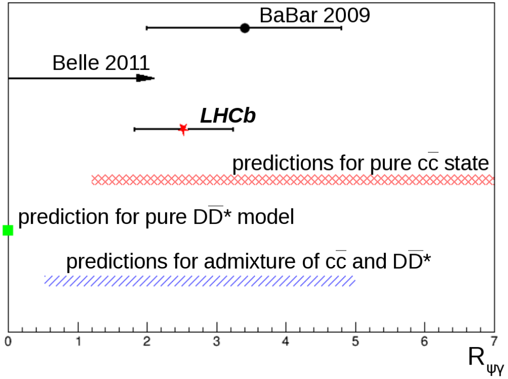


Evidence of $X(3872) \to \psi(2S)\gamma$ at LHCb

arXiv:1404.0275 (to appear in Nucl. Phys. B)

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

- These results disfavours $D^{*0}\bar{D}^0$ molecule hypothesis

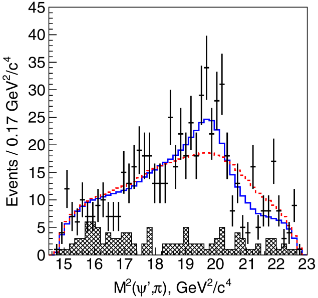


$Z(4430)^+ \to \psi(2S)\pi^+$

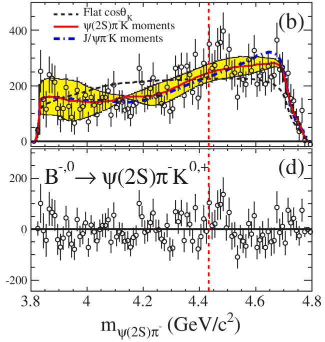
- Charged charmonium like state reported by Belle in $B^0 \to \psi(2S)K^+\pi^-$ decays [Phys.Rev.D88:074026]
- Searched and not confirmed or excluded by BaBar [Phys.Rev.D79:112001]
- Can not be understood as conventional meson ($q\bar{q}$).
- Minimum quark content: $c\bar{c}u\bar{d}$
- No corresponding structure observed in $B^0 \to J/\psi\, K^+\pi^-$

$Z(4430)^+$ at Belle. $K^*(892)^0$ and $K_2^*(1432)$ vetoed.

With $Z(4430)^+$ and No $Z(4430)^+$



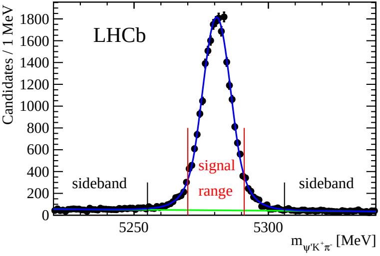
$Z(4430)^+$ at BaBar. Legendre polynomials approach.



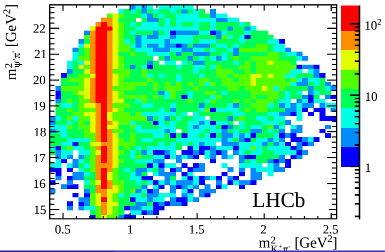
Confirmation of $Z(4430)^+$ at LHCb

Phys. Rev. Lett. 112, 222002 (2014)

- Sample with >25.000 $B^0 \to K^+\pi^-\psi(2S)$ signal candidates,
- Analysis performed using two different approaches:
  - Model dependent. Four-dimensional amplitude fit (a la Belle).
  - Model independent. An analysis based on the Legendre polynomial moments extracted from the $K\pi$ system (a la BaBar)
- Background from sidebands. Estimated 4% of combinatorial background in the signal region.
- Four-dimensional efficiency calculated using complete simulation of the detector



background subtracted Dalitz plot



$Z(4430)^+$ at LHCb: model independent analysis

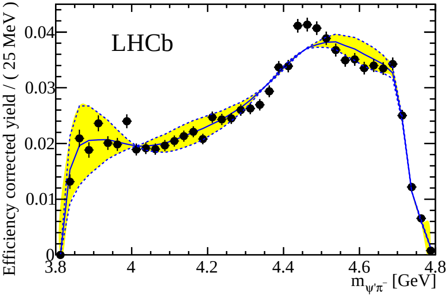
Phys. Rev. Lett. 112, 222002 (2014)

The main goal is to check if the structures in the $m_{\psi(2S)\pi}$ spectrum can be explained as reflections of the resonance activity in the $K\pi$ system.

- No assumptions on the K^* resonances. Only its maximum J is restricted.
- Angular structure of the $K\pi$ system is extracted using Legendre polynomial moments.
- The moments are used in toy Monte Carlo simulation to predict the expected $m_{\psi(2S)\pi}$ spectrum.
- $m_{\psi(2S)\pi}$ spectrum can not be explained in terms of moments corresponding to resonances with $J <= 2$.

Amplitude fit is necessary for:

- Determine the K^* resonant structure of the $K\pi$ system.
- Determine the $Z(4430)^+$ parameters (mass, width, spin etc).



$Z(4430)^+$ at LHCb: amplitude fit

Phys. Rev. Lett. 112, 222002 (2014)

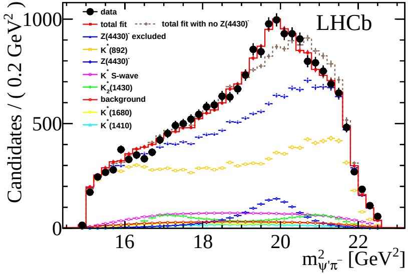
- Fitted parameters:

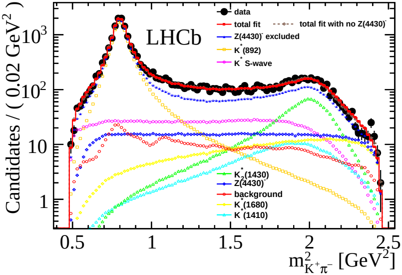
$$M_{Z(4430)^+} = 4475 \pm 7^{+15}_{-25}\,\mathrm{MeV}/c^2, \Gamma_{Z(4430)^+} = 172 \pm 13^{+37}_{-34}\,\mathrm{MeV}/c^2$$

$$f_{Z(4430)^+} = (5.9 \pm 0.9^{+1.5}_{-3.3})\%$$

.

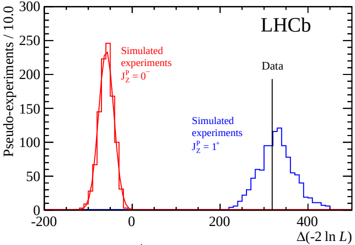
- Significance: $\Delta(-2lnL) > 13.9\sigma$





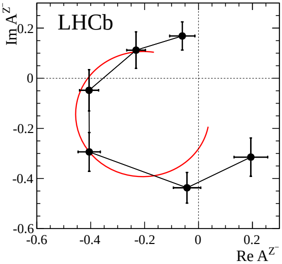
$Z(4430)^+$: resonance character and spin determination

Phys. Rev. Lett. 112, 222002 (2014)



- $J^P = 1^+$ assignment favoured.
- Other J^P assignments are rulled out with large significance: $> 9\sigma$

- $Z(4430)^+$ amplitude is described by 6 independent complex numbers instead of a Breit-Wigner
- Observe a fast change of phase crossing maximum of magnitude.
- Expected behaviour for a resonance.



Spectroscopy in light quark sector: $\mathrm{B}^0 \to \mathrm{J}/\psi\, \pi^+\pi^-$

Phys. Rev. D 87, 052001

- The substructure of mesons belonging to the scalar nonet is controversial.
- Many possibilities: $\mathrm{q\bar{q}}$, $\mathrm{q\bar{q}q\bar{q}}$, mixtures etc.
- $\mathrm{q\bar{q}}$ case:

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

- $\mathrm{q\bar{q}q\bar{q}}$ case:

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

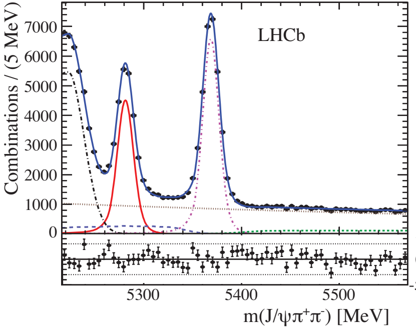
- Observable of interest for both cases:

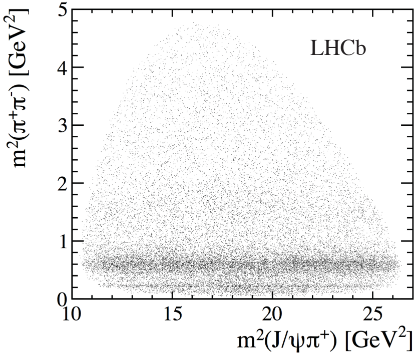
$$\tan^2\varphi_m \equiv r_\sigma^f = \frac{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(980)\right)}{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(500)\right)} \frac{\Phi(500)}{\Phi(980)}$$

- Prediction for tetraquark states: $r_\sigma^f = 1/2$ [PRL 111, 062001 (2013)]

- Approach similar to the $Z(4430)^+$ analysis: 4D matrix element describing π^+ π^- resonances;
- No evidence of $J/\psi\,\pi^+$ resonances
- 19,000 B^0 signal candidates
- Background modelled from sidebands

Signal B^0 candidates in red.

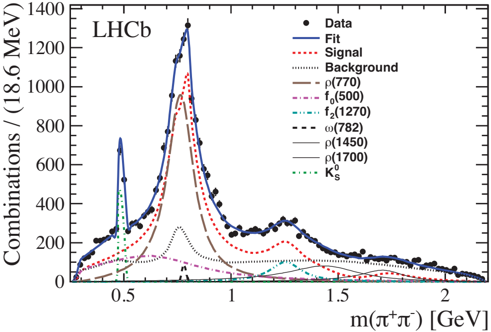




Amplitude analysis of $B^0 \to J/\psi\,\pi^+\pi^-$

Phys. Rev. D 87, 052001

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



- Best fit model shows does not require $f_0(980)$ component.
- Upper limit on the $f_0(500) - f_0(980)$ mixing angle.
- Different from tetraquark prediction (1/2) by $8\,\sigma$

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

Many other results in b and c spectroscopy

Access:

http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php

LHCb Papers

N°	Title	Journal	Code	Submit Date	Lead Group
185	Measurement of the Ξ_b^- and Ω_b^- baryon lifetimes	()	LHCB-PAPER-2014-010	07 May 2014	B2CC
184	Measurement of the resonant and CP components in $\overline{B}^0 \to J/\psi\pi^+\pi^-$ decays	()	LHCB-PAPER-2014-012	05 May 2014	B2CC
183	Observation of the resonant character of the $Z(4430)^-$ state	()	LHCB-PAPER-2014-014	07 Apr 2014	B&Q
182	Evidence for the decay $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$	()	LHCB-PAPER-2014-009	1 Apr 2014	B&Q
181	Evidence for the decay $X(3872) \to \psi(2S)\gamma$	()	LHCB-PAPER-2014-008	1 Apr 2014	B&Q
180	Angular analysis of charged and neutral $B \to K\mu^+\mu^-$ decays	()	LHCB-PAPER-2014-007	31 Mar 2014	RD
179	Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^+$ decays	()	LHCB-PAPER-2014-006	31 Mar 2014	RD
178	Study of beauty hadron decays into pairs of charm hadrons	()	LHCB-PAPER-2014-002	14 Mar 2014	B2OC
177	Measurement of polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$	()	LHCB-PAPER-2014-005	12 Mar 2014	BNoC

Summary and perspectives

- $\mathrm{X}(3872)$
  - 4.4σ evidence for $\mathrm{X}(3872) \to \psi(2S)\gamma$ in B decays.
  - $R_{\psi\gamma} = \frac{\mathcal{B}(\mathrm{X}(3872)\to\psi(2S)\gamma)}{\mathcal{B}(\mathrm{X}(3872)\to\mathrm{J}/\psi\,\gamma)} = 2.46 \pm 0.64(\mathrm{stat}) \pm 0.29(\mathrm{syst})$ disfavours the molecular hypothesis.
- $Z(4430)^+$
  - Existence confirmation with $> 13.0\sigma$
  - Quantum numbers determination $J^P = 1^+$
  - Resonance behaviour observed.
- Light quark spectroscopy using $\mathrm{B}^0 \to \mathrm{J}/\psi\,\pi^+\pi^-$
  - No evidence for $f_0(980)$ resonance production
  - $f_0(980)$ as a tetraquark state ruled out at $8\,\sigma$

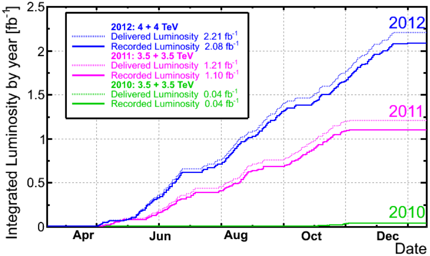
Thanks!

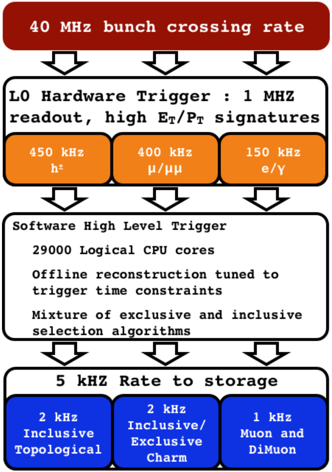
Backup

The LHCb trigger and dataset

Running conditions in most of 2012

- LHC: 20 MHz bunch crossing
- Luminosity: $4.0 \times 10^{32} cm^{-2} s^{-1}$, using luminosity leveling
- Visible interactions rate: 12.0 - 14.0 MHz
- L0 output rate: 950 kHz
- HLT output rate:4.5 kHz
- Event size: 60 kB



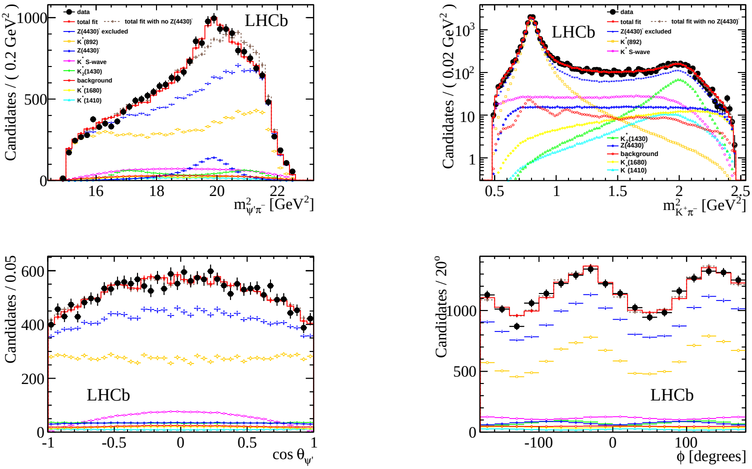


37 pb^{-1} acquired in 2010

1 fb^{-1} acquired in 2011

2 fb^{-1} acquired in 2012

$Z(4430)^+$ at LHCb: amplitude fit



The high-performance, efficiency and flexibility of the trigger associated to the high quality of the event reconstruction, puts the LHCb experiment in very advantageous position to analyse the copious statistics provided by the LHC and perform competitive measurements in heavy flavor physics.