Quarkonia and Quarkonia-like spectroscopy at LHCb

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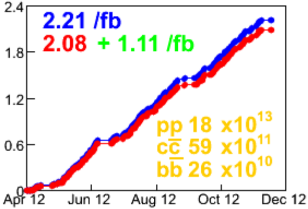
Introduction

- Over the past decade a number of heavy states decaying into quarkonia have been observed at colliders
- There is some uncertainty as to their composition and in some cases controversy as to their existence



- LHCb is in an ideal position to study these states
  - Large b, c production cross-sections at LHC,
  - Excellent particle ID performance: High purity final states involving hadrons, muons
  - Precise vertexing and momentum resolution: B decays to quarkonia easily isolated
  - Flexible, efficient software trigger
- For measurements of more conventional onia at LHCb see Maddalena's talk in WG2 this afternoon

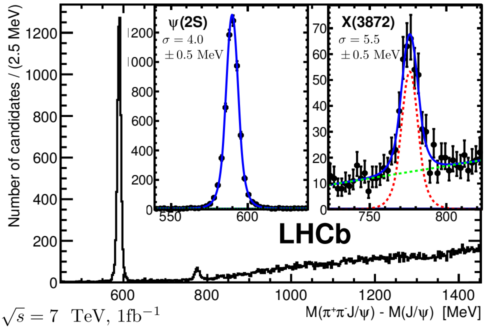
X(3872)

$X(3872) \to J/\psi\pi^+\pi^-$

- Since its discovery a decade ago by Belle [PRL 91 262001] in $B^\pm \to J/\psi\pi\pi K^\pm$ the $X(3872)$ has been studied at a number of experiments including LHCb:
  - Production cross-section and mass measurement with 34.7pb^{-1}: [EPJ C72, 1972 (2012)]
- The existence of the $X(3872)$ is now beyond doubt, but structure is still unclear:
  - Mass and decay mode disfavor $c\bar{c}$ state. Quantum number measurements needed to confirm!
  - C-parity of $X(3872)$ known to be positive as $X(3872) \to J/\psi\gamma$ observed by Belle [PRL 107 091803], *BABAR* [PRD 74 071101(R)]
  - CDF helicity angle measurement [PRL 98 132002] of inclusive $X(3872)$ excluded all J^{PC} except:
    - $J^{PC} = 2^{-+}$: Nearest in mass to $\eta_c\left(1^1D_2\right)$
    - $J^{PC} = 1^{++}$: Exotic: $D^0\, D^*$ molecule, Tetra-quark
  - *BABAR* analysis of $X(3872) \to \omega J/\psi$ prefers 2^{-+} but does not exclude 1^{++} [PRD 82, 011101(R)]

X(3872) Quantum numbers

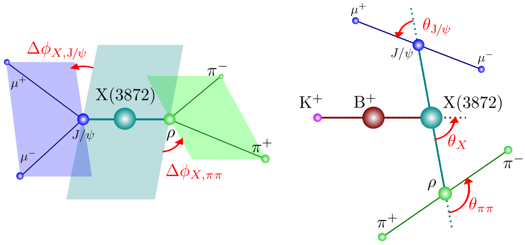
- LHCb analysis of quantum numbers in $B^{\pm} \to X(3872)K^{\pm}$, 1 fb^{-1} @ 7 TeV: arXiv:1302.6269
- $B^{+} \to \psi(2S)K^{+}$ control channel used for systematic studies, signal shape determination
- Selection uses kinematic likelihood ratio determined from simulated $B^{+} \to \psi(2S)K^{+}$ and $B^{\pm}$ sidebands to enhance background rejection



- 5642 ± 76 $B^{+} \to \psi(2S)K^{+}$
- 313 ± 26 $B^{+} \to X(3872)K^{+}$
- Largest sample of $B^{\pm} \to X(3872)K^{\pm}$ decays to-date

X(3872) Quantum numbers

- Angular analysis in 5D exploits all angular correlations in the B decay



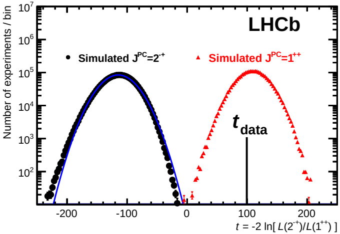
- PDF for each J^{PC} are a function of the matrix element and reconstruction efficieny
- Matrix element contains the angular information in the helicity basis:

$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Big| \sum_{\lambda_{J/\psi},\lambda_{\pi\pi}=-1,0,+1} A_{\lambda_{J/\psi},\lambda_{\pi\pi}} \times D^{J_X}_{0,\,\lambda_{J/\psi}-\lambda_{\pi\pi}}(\phi_X,\theta_X,-\phi_X) \times D^1_{\lambda_{\pi\pi},\,0}(\phi_{\pi\pi},\theta_{\pi\pi},-\phi_{\pi\pi}) \times D^1_{\lambda_{J/\psi},\,\Delta\lambda_\mu}(\phi_{J/\psi},\theta_{J/\psi},-\phi_{J/\psi}) \Big|^2$$

- Helicity couplings $A_{\lambda_{J/\psi},\lambda_{\pi\pi}}$ include complex parameter α for $J^{PC}=2^{-+}$
  No free parameter for $J^{PC}=1^{++}$

X(3872) results

- Test statistic to determine J^{PC}: $t = -2\ln[\mathcal{L}(2^{-+})/\mathcal{L}(1^{++})]$
- Likelihood ratio between fit including complex parameter α and excluding it
  - $t > 0$ implies $J^{PC} = 1^{++}$ favoured
  - $t < 0$ implies $J^{PC} = 2^{-+}$ favoured
- Compared to results of simulated $\mathrm{B}^{\pm} \to \mathrm{X}(3872)\mathrm{K}^{\pm}$ candidates of both hypotheses:



- LHCb result favours $J^{PC} = 1^{++}$
- $J^{PC} = 2^{-+}$ rejected at $> 8\sigma$
- $\Re\mathfrak{e}\{\alpha\} = 0.671 \pm 0.046$
  $\Im\mathfrak{m}\{\alpha\} = 0.280 \pm 0.046$

- α compatible with Belle [$\alpha = (0.64, 0.27)$] PRD 84, 052004
- Also consistent with α in $J^{PC} = 1^{++}$ simulated events

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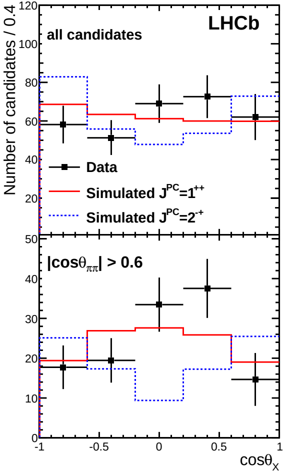
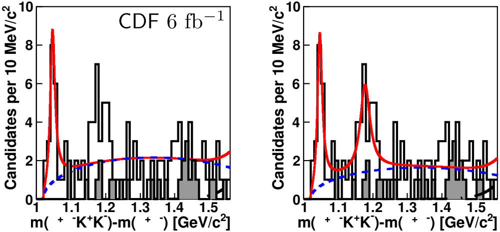
X(3872) angular correlations



- How important are the angular correlations?
- Projections in $\cos\theta_X$ for all background-subtracted signal candidates (top) and background-subtracted signal candidates with $|\cos\theta_{\pi\pi}| > 0.6$ (bottom)
- Little discrimination between $J^{PC} = 1^{++}$ (red), $J^{PC} = 2^{-+}, \alpha = (0.671, 0.280)$ (blue) without using correlations!

X(4140)

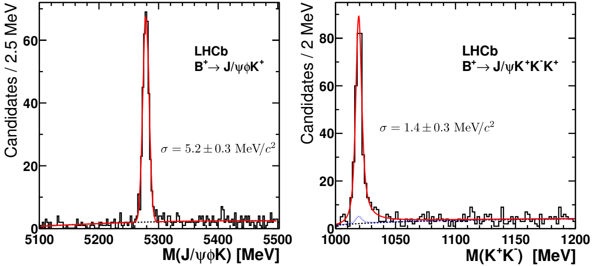
$\mathrm{X}(4140) \to \mathrm{J}/\psi\phi$



- $\mathrm{X}(4140) \to \mathrm{J}/\psi\phi$ observed by CDF in $\mathrm{B}^{\pm} \to \mathrm{J}/\psi\phi\mathrm{K}^{\pm}$ decays:
  - 3.8σ significance in 2.7fb^{-1} [PRL 102 242002], updated to $> 5\sigma$ with 6fb^{-1} arXiv:1101.6058[hep-ex].
  - 115 ± 2 $\mathrm{B}^{\pm} \to \mathrm{J}/\psi\phi\mathrm{K}^{\pm}$ events with 19 ± 6 $\mathrm{X}(4140) \to \mathrm{J}/\psi\phi$ candidates
  - Narrow structure: $15.3^{+10.4}_{-6.1}(\mathrm{stat}) \pm 2.5(\mathrm{syst})$ MeV/c^2 considered unusual for a charmonium state at this mass: Almost certainly exotic
  - In the 6fb^{-1} they also see an additional structure at 4274MeV/c^2 ($> 3\sigma$)
    - $m_1 = 4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV/c^2
    - $m_2 = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV/c^2
  - Belle looked for the $\mathrm{X}(4140)$ in $\gamma\gamma \to \mathrm{J}/\psi\phi$ channel [PRL 104 112004]. Could neither confirm nor refute CDF result

X(4140) at LHCb

- LHCb has searched for the X(4140) with 0.37fb^{-1} in $B^{\pm} \to J/\psi\phi K^{\pm}$ at 7 TeV [PRD 85 091103(R)]
- Selection uses kinematic likelihood ratio determined from phase-space simulated $B^{\pm} \to J/\psi\phi K^{\pm}$ candidates and data sidebands to suppress background, maximises $S/\sqrt{S+B}$



- 346 ± 20 $B^{\pm} \to J/\psi K^{+}K^{-}K^{\pm}$ signal candidates within $M(\phi) \pm 15$ MeV/c^2
- Peaking ϕ background contribution determined from $B^{\pm}$ sidebands
- Extremely pure $B^{\pm} \to J/\psi\phi K^{\pm}$ sample: 14 ± 3 background candidates within 2.5σ of the $B^{\pm}$

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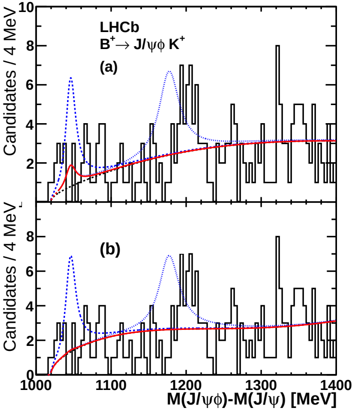
X(4140) results

- Fit to $M(J/\psi\phi) - M(J/\psi)$ for candidates within $M(B^\pm) \pm 2.5\sigma$ and $M(\phi) \pm 15$ MeV$/c^2$ assuming CDF masses and widths
- CDF fits overlaid, scaled to the expected yield in 0.37fb^{-1}: $N(X(4140))_{exp} = 35 \pm 9 \pm 6$, $N(X(4274))_{exp} = 53 \pm 19$



- Top: Fit assuming 3-body phase-space model: $N(X(4140)) = 6.9 \pm 4.9$ 2.4σ disagreement $N(X(4274)) = 3.4^{+6.5}_{-3.4}$
- Bottom: Fit assuming 3-body phase-space $\times$ quadratic polynomial $N(X(4140)) = 0.6\ (< 7.1)$ 2.7σ disagreement $N(X(4274)) = 0\ (< 10)$
- LHCb does not confirm narrow structure near threshold

$\mathcal{B}(B^\pm \to X(4140)K^\pm) \times \mathcal{B}(X(4140) \to J/\psi\phi)/\mathcal{B}(B^\pm \to J/\psi\phi K^\pm) < 0.07$ @ 90% CL

$\mathcal{B}(B^\pm \to X(4274)K^\pm) \times \mathcal{B}(X(4274) \to J/\psi\phi)/\mathcal{B}(B^\pm \to J/\psi\phi K^\pm) < 0.08$ @ 90% CL

X(4140): A continuing saga

- LHCb measurement left the X(4140) in an uncertain state.
- Since then, CMS has performed a similar analysis in which they find evidence of two structures in the $M(J/\psi\phi) - M(J/\psi)$ spectrum CMS BPH-11-026 (Preliminary)
- See next talk for more details of the CMS result
- This leaves the X(4140) scorecard at 2-2. Will there be a tiebreaker?
- K^* reflections? Multidimensional amplitude and angular analysis needed to say anything conclusive

Summary

- Exotic quarkonia analyses are host to a number of exciting and intriguing results!
- There is much room for theoretical and experimental input
- LHCb is active and competitive in this field
  - LHCb analysis of J^{PC} favors exotic interpretation of $\mathrm{X}(3872)$
  - We do not confirm the CDF observation of a narrow resonance in $\mathrm{X}(4140)$
- Results presented today are on less than a third of the LHCb dataset
- Expect more and updated results in the near future:
  - Amplitude analysis of $\mathrm{B}^{\pm} \to \mathrm{J}/\psi\phi\mathrm{K}^{\pm}$ decays
  - Search for the $\mathrm{Z}(4430)^{+}$ in $\mathrm{Z}(4430)^{+} \to \psi(2\mathrm{S})\pi$ decays as observed by Belle
  - ...and maybe a few more surprises!

Thanks for listening!

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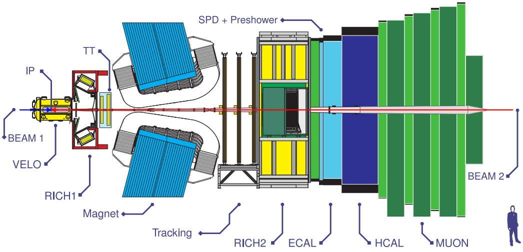
LHCb

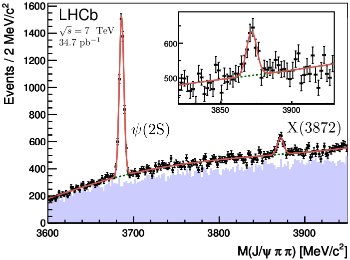
- The LHC is a copious source of beauty in the forward region
- $\mathcal{CP}$-violation measurements are a great way to test the SM…
- …but require precision:
  - Time dependent analyses need good time resolution
  - Flavour tagging needs particle ID
  - High rates and large backgrounds in a pp environment: purity and efficiency needed to reach SM predictions



- LHCb was built *precisely* for this purpose!
  - Single-arm spectrometer on $2 < \eta < 5$
  - Vertex Locator (VELO) for accurate vertexing
  - Ring Imaging Čerenkov (RICH) detectors for $\pi - \mathrm{K}$ discrimination
  - Flexible software trigger to reduce backgrounds and preserve signal

$\mathrm{X}(3872)$ Mass measurement

- 2010 data sample ($34.7\mathrm{pb}^{-1}$) at 7 TeV: EPJ C72, 1972 (2012)
- Inclusive measurement of $\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-$ with $\psi(2S)$ as control channel:



Fit parameter or derived quantity	$\psi(2S)$	$X(3872)$
Number of signal events	3998 ± 83	565 ± 62
Mass m [MeV/c^2]	3686.10 ± 0.06	3871.88 ± 0.48
Resolution σ [MeV/c^2]	2.54 ± 0.06	3.33 ± 0.08
Signal-to-noise ratio in $\pm 3\sigma$ window	1.5	0.15
Number of background events	73094 ± 282	

X(3872) mass results

- Measurement of the mass is important as molecular state hypothesis should have mass below $D^0\, D^*$ threshold = 3871.94 ± 0.32 MeV/c^2

Category	Source of uncertainty	m [MeV/c^2] $\psi(2S)$	m [MeV/c^2] $X(3872)$
Mass fitting	Natural width	–	0.01
	Radiative tail	0.02	0.02
	Resolution	–	0.01
	Background model	0.02	0.02
Momentum calibration	Average momentum scale	0.08	0.10
	η dependence of momentum scale	0.02	0.03
Detector description	Energy loss correction	0.05	0.05
Detector alignment	Track slopes	0.01	0.01
Total		0.10	0.12

- Dominant systematics due to momentum calibration and energy loss corrections
- Result:

$$M_{X(3872)} = 3871.95 \pm 0.48\ \text{(stat)}\ \pm 0.12\ \text{(syst)}\ \text{MeV}/c^2$$

- Still dominated by statistical uncertainty: Can be improved with full dataset!
- Updated WA $M_{X(3872)} = 3871.68 \pm 0.17$ MeV/c^2 is consistent with $D^0 D^*$ threshold.
- If bound particle, binding energy of X(3872) is small: $E_B = 0.16 \pm 0.26$MeV/c^2
- Measurement will benefit from more precise knowledge of D masses.

$\mathrm{X}(3872)$ production cross-section

- 2010 data sample (34.7pb^{-1}) at 7 TeV: EPJ C72, 1972 (2012)
- Measurement of $\mathrm{X}(3872)$ cross-section $\times$ branching fraction
- Same data sample as used for mass measurement
- Fiducial region: $p_{\mathrm{T}} \in [5; 20]$ GeV/c and $y \in [2.5; 4.5]$
- inclusive cross-section assuming $J^{PC} = 1^{++}$

$$\sigma_{\mathrm{X}(3872)} \times \mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-) = \frac{N_{\mathrm{X}(3872)}}{\epsilon_{\mathrm{tot}} \times \mathcal{L}_{\mathrm{int}} \times \mathcal{B}(\mathrm{J}/\psi \to \mu^-\mu^+)}$$

- $N_{\mathrm{X}(3872)}/\epsilon_{\mathrm{tot}}$ is the efficiency corrected yield extracted from fit
- ϵ_{tot} detection efficiency (incl. acceptance, reconstruction, trigger, selection) from Monte-Carlo
- $\mathcal{L}_{\mathrm{int}} = 34.7\ \mathrm{pb}^{-1}$, integrated luminosity of the 2010 dataset used.

X(3872) production cross-section result

- Dominant systematics: Tracking efficiency and background model

Source of uncertainty	σ/σ [%]
$X(3872)$ polarization	2.1
$X(3872)$ decay model	1.0
$X(3872)$ decay width	5.0
Mass resolution	2.5
Background model	6.4
Tracking efficiency	7.4
Track χ^2 cut	2.0
Vertex χ^2 cut	3.0
Muon trigger efficiency	2.9
Hit-multiplicity cuts	3.0
Muon identification	1.1
Pion identification	4.9
Integrated luminosity	3.5
$J/\psi \to \mu^+\mu^-$ branching fraction	1.0
Total	14.2

- Total production cross-section:

$$\sigma_{X(3872)} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 5.4 \pm 1.3\ \text{(stat)}\ \pm 0.4\ \text{(syst) nb}$$

- NRQCD prediction 2.4σ larger: 13.0 ± 2.7 nb [PRD 81 114018]