Charm Spectroscopy at LHCb

Results and Future Plans

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on behalf of the LHCb Collaboration

CERN

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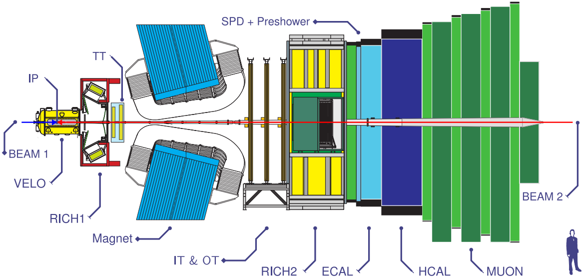
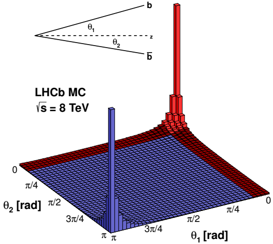
The LHCb Experiment
Precision Beauty and Charm Physics

- *LHCb* is a single-arm ($2 < \eta < 5$) spectrometer at the LHC
  - *CP* violation measurements, rare decays, heavy flavor production
  - Exploits the correlated production of $b\bar{b}$ pairs in the LHC environment

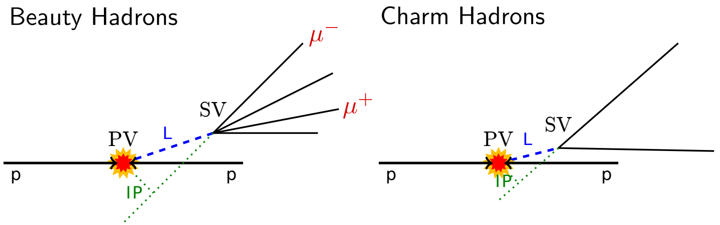




- Time-dependent analyses require good time resolution: $\sim 40\,\mathrm{fs}$ (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID (RICH)
- Rare decays and extremely small asymmetries require pure data samples with high (and controlled) signal efficiency (Trigger)

Charm Production at LHCb
Prompt Charm and Charm from Beauty

- Beauty and charm hadron typical decay topologies:



- $\mathrm{B}^{\pm}$ mass $\sim$5.28 GeV, daughter p_{T} O(1 GeV)
- $\tau \sim 1.6$ ps, Flight distance ~ 1 cm
- Important signature: Detached muons from $\mathrm{B} \to \mathrm{J}/\psi X$, $\mathrm{J}/\psi \to \mu\mu$

- D^0 mass $\sim$1.86 GeV, appreciable daughter p_{T}
- $\tau \sim 0.4$ ps, Flight distance ~ 4 mm
- Also produced as 'secondary' charm from B decays.

Charm Production at LHCb

Prompt Charm and Charm from Beauty

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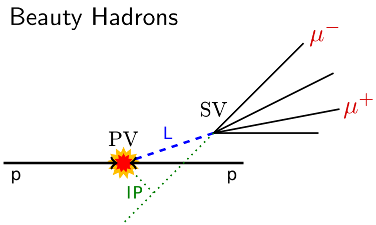

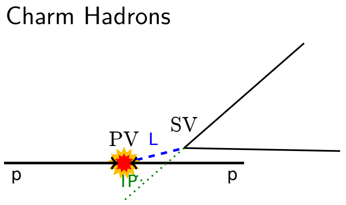

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Trigger Strategy:

- Inclusive triggering on displaced vertices with high-p_{T} tracks and muons
- Exclusive triggering for anything else (Prompt Charm)

Open-Charm Spectroscopy

D_J Mesons in two-body Decays

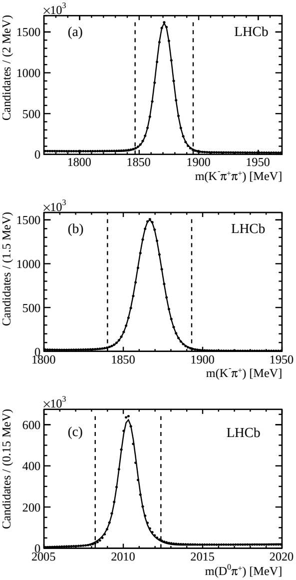
Selection of Prompt Charm – JHEP09(2013)145

- Data set: $1\,fb^{-1}$ at $\sqrt{s} = 7$ TeV
- Prompt D^+, D^0 and D^* yields:

$\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$	$15.1 \cdot 10^6$
$\mathrm{D}^0 \to \mathrm{K}^-\pi^+$	$20.4 \cdot 10^6$
$\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$	$6.4 \cdot 10^6$

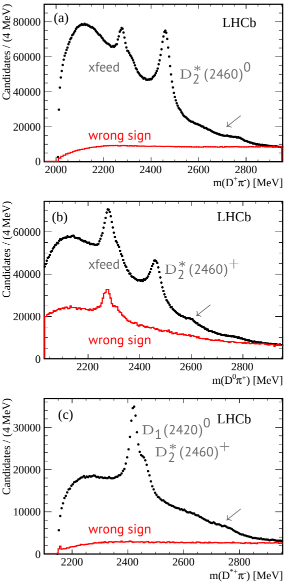
- Recalculate $m(\mathrm{D}\,\pi)$
  $m(\mathrm{D}^0\pi) = m(\mathrm{K}^-\pi^+\pi^+) - m(\mathrm{K}^-\pi^+) + m_{\mathrm{D}^0}$
- Combined with additional π^+
- $p_t(\mathrm{D}^{(*)}\pi) > 7.5$GeV
- Yields:

$\mathrm{D}^+\pi^+$	$7.9 \cdot 10^6$
$\mathrm{D}^0\pi^+$	$7.5 \cdot 10^6$
$\mathrm{D}^{*+}\pi^+$	$2.1 \cdot 10^6$



$D^{(*)}\pi$ Raw Spectra

JHEP09(2013)145



$D^+\pi^-$

- Strong $D_2^*(2460)^0$ signal
- Partially reconstructed cross-feed from $D_1(2420)^0 or D_2^*(2460)^0 \to \pi^- D^{*+}$
- weak structures around 2600 and 2750 MeV

$D^0\pi^+$

- Strong $D_2^*(2460)^+$ signal
- Partially reconstructed cross-feed from $D_1(2420)^+ or D_2^*(2460)^+ \to \pi^+ D^{*0}$
- Wrong sign cross-feed: $D_1(2420)^0 or D_2^*(2460)^0 \to \pi^- D^{*+} (\to D^0\pi^+)$
- weak structures around 2600 and 2750 MeV

$D^{*+}\pi^-$ both natural / unnatural parity

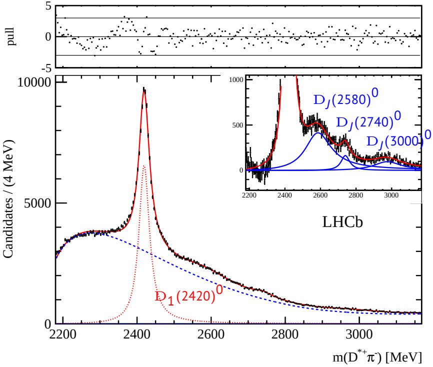
- $D_1(2420)^0$ and $D_2^*(2460)^0$ signals
- Broad structures around 2500 and 2800 MeV

$D^{*+}\pi^-$ Fits

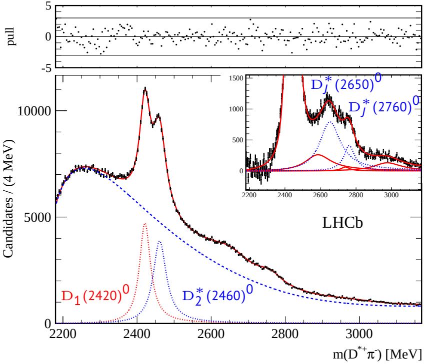
Natural and Unnatural Parity Enriched Samples – JHEP09(2013)145

- Natural / unnatural parity differs in the helicity angle distribution (angle between π^+ and π^- in $D^*\pi$ rest frame)
- Natural: $\propto \sin^2\theta_H = 1 - \cos^2\theta_H$ Unnatural: $\propto (1 + h\cos^2\theta_H)$

$\cos\theta_H > 0.75$
(enhanced unnatural parity)



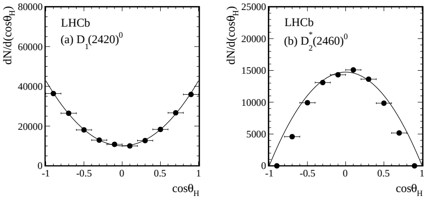
$\cos\theta_H < 0.5$
(natural parity)



Resonance Parameters and Naturality

JHEP09(2013)145

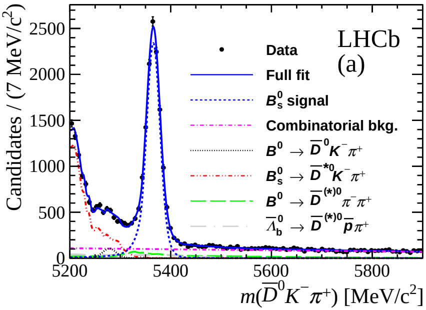
- Extract yields in bins of θ_H
- Fit angular distribution
- Precise measurement of $\mathrm{D}_1(2420)^0$ and $\mathrm{D}_2^*(2460)^+$ parameters
- 2 additional natural parity states
- 3 additional unnatural parity states

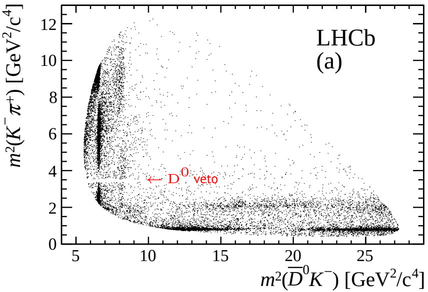


Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Significance (σ)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50.7 \pm 2.2 \pm 2.3$	24.5
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60.3 \pm 3.1 \pm 3.4$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7.7 \pm 1.1 \pm 1.2$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.5 ± 1.1	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675.0 \pm 9.0 \pm 1.3$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55.8 \pm 1.3 \pm 10.0$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	17.6 ± 1.1	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341.6 \pm 22.0 \pm 2.0$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20.1 \pm 2.2 \pm 1.0$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	7.6 ± 1.2	6.6

B candidates

- $B_s^0 \to \overline{D}^0(\to K^+\pi^-)K^+\pi^-$
- Multivariate Selection (Kinematics and PID)
- $B_s^0 \to \bar{D}^0 K^+ \pi^-$ yield: $11\,302 \pm 159$
- Background contributions $\sim 10\%$





Amplitude Model

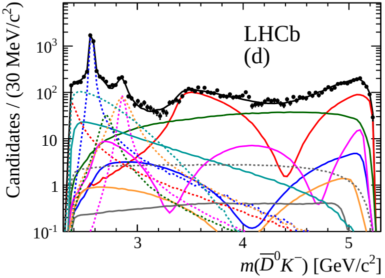
Unbinned extended loglikelihood fit of isobar model amplitudes

- Isobar-model amplitude
- Zemach tensor formalism
- Blatt-Weisskopf barrier factors with $r_{BW} = 4.0\text{GeV}^{-1}$
- Relativistic Breit-Wigner resonances
- LASS parameterisation for $K\pi$ S-wave
- Non-resonant contribution $R(m^2) = e^{-\alpha m^2}$
- Background distributions over the DP: 7.4% combinatorial (B_s^0 sideband), 2.8% $\bar{\Lambda}_b \to \overline{D}^{(*)0}\overline{p}\pi^+$ (MC), 2.3% $B^0 \to \overline{D}^{(*)0}\pi^+\pi^-$(MC)

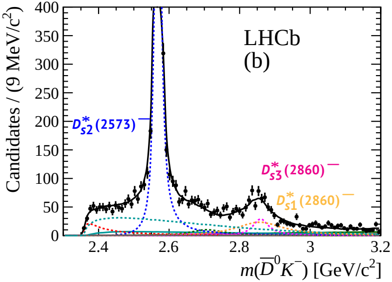
Resonance	Spin	M (MeV/c^2)	Γ
$\bar{K}^*(892)^0$	1	895.81	47.4
$\bar{K}^*(1410)^0$	1	1414	232
$\bar{K}_0^*(1430)^0$	0	LASS	
$\bar{K}_2^*(1430)^0$	2	1432	109
$\bar{K}^*(1680)^0$	1	1717	322
$\bar{K}_0^*(1950)^0$	0	1945	201
$D_{s2}^*(2573)^-$	2	floating	
$D_{s1}^*(2700)^-$	1	2709	117
$D_{sJ}^*(2860)^-$	1	floating	
$D_{sJ}^*(2860)^-$	3	floating	
Nonresonant			
Virtual:			
D_{sv}^{*-}	1	2112.3	1.9
$D_{sv}^*(2317)^-$	0	2317.8	3.8
B_v^{*+}	1	5325.2	0

$B_s^0 \to \overline{D}^0 K^+ \pi^-$ Fit Results

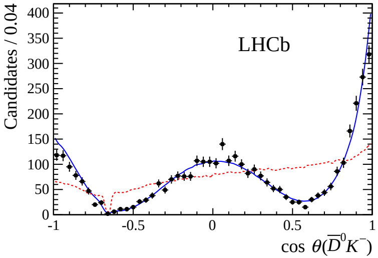
↪ arXiv:1407.7712v2



Resonance	Mass / Width (MeV/c^2)
$D_{s2}^*(2573)^-$	$m = 2568.39 \pm 0.29 \pm 0.19 \pm 0.18$
	$\Gamma = 16.9 \pm 0.5 \pm 0.4 \pm 0.4$
$D_{s1}^*(2860)^-$	$m = 2859 \pm 12 \pm 6 \pm 23$
	$\Gamma = 159 \pm 23 \pm 27 \pm 72$
$D_{s3}^*(2860)^-$	$m = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0$
	$\Gamma = 53 \pm 7 \pm 4 \pm 6$



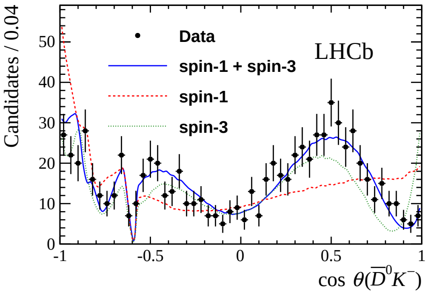
- Spin-assignment of the $D_{s2}^*(2573)^-$:



The $\overline{D}^0 K^-$ System around 2860 MeV/c^2

Evidence for a Spin 3 Resonance

$m(\overline{D}^0 K^-) \in [2.77, 2.91]$ GeV/c^2

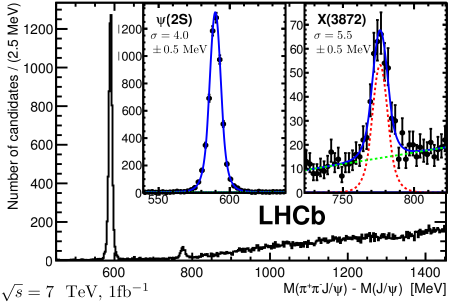


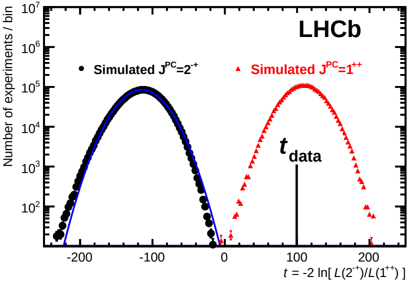
Spin hypothesis	ΔNLL	$\sqrt{2\Delta NLL}$
1+3	0	—
0	141.0	16.8
0+1	113.2	15.0
0+2	155.1	17.6
0+3	105.1	14.5
1	156.8	17.7
1+2	138.6	16.6
2	287.9	24.0
2	365.5	27.0
2+3	131.2	16.2
3	136.5	16.5

- Spin-1+ Spin-3 hypothesis strongly favoured
- First obervation of heavy-flavoured spin-3 resonance
- Could be interpreted as $J^P = 1^-$ and 3^- of the 1D orbital excitations
- Mixture with 2S vector states?

Charmonium-like Exotic States @ LHCb

- $\mathrm{B}^{\pm} \to \mathrm{X}(3872)(\to \mathrm{J}/\psi\pi\pi)\mathrm{K}^{\pm}$ selection calibrated on $\mathrm{B}^{+} \to \psi(2\mathrm{S})\mathrm{K}^{+}$ control channel





Yields:

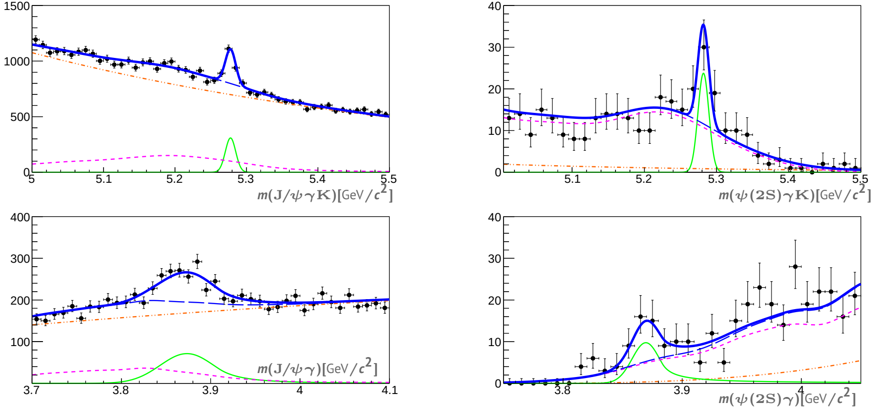
- 5642 ± 76 $\mathrm{B}^{+} \to \psi(2\mathrm{S})\mathrm{K}^{+}$
- 313 ± 26 $\mathrm{B}^{+} \to \mathrm{X}(3872)\mathrm{K}^{+}$

- $J^{PC} = 1^{++}$ compatible
- $J^{PC} = 2^{-+}$ rejected at $> 8\sigma$

Radiative Decays of the X(3872)

Testing molecular models ↪ arXiv:1404.0275 submitted to Nucl.Phys.B

$\mathrm{B} \to \mathrm{X}(3872)\mathrm{K} \to \mathrm{J}/\psi\gamma\mathrm{K}$ $\mathrm{B} \to \mathrm{X}(3872)\mathrm{K} \to \psi(2\mathrm{S})\gamma\mathrm{K}$



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

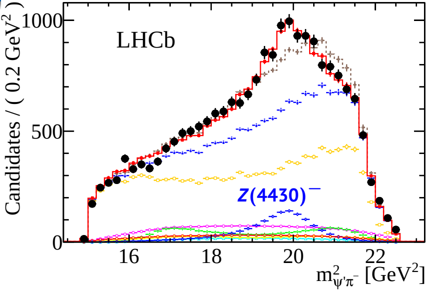
- Does not support the pure $D\bar{D}^*$ molecule interpretation

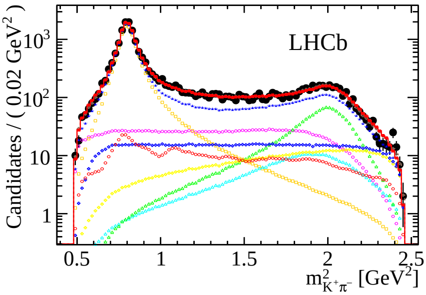
Resonant Nature of the $Z(4430)^-$

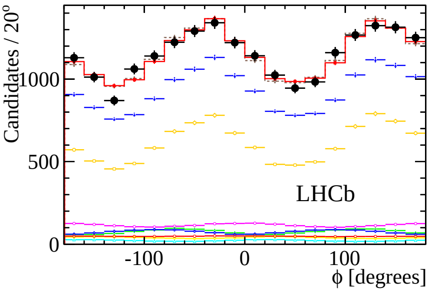
$3\ fb^{-1}$ data set — PRL 112, 222002 (2014)

$$B \to K^+ \underbrace{\pi^- \psi(2S)}(\to \mu\mu)$$

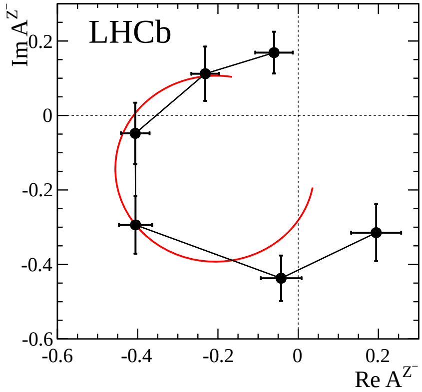
- $25\,176 \pm 174$ candidates
- 4D amplitude fit
- $J^P = 1^+$ established
- $m_{Z(4430)} = 4475 \pm 7^{+15}_{-25}$ MeV
- $\Gamma_{Z(4430)} = 172 \pm 13^{+37}_{-34}$ MeV







- Replace the Breit-Wigner amplitude in the model with a piecewise constant, complex function *A* in 6 bins of $m(\pi^-\psi(2S))$



- Argand plot: amplitude in complex plane
- Circular shape corresponds to resonant phase motion (anti-clockwise)
- Model amplitude (Breit-Wigner) overlaid
- Note: Offset in phase from reference amplitude(s)

Outlook to Run II

Run II Scenario

- $\sqrt{s} = 13$ TeV expectations:
  - $\sim 15\%$ increase of $\sigma_{\text{inel}}(LHCb) \sim 70mb$
  - $\sim 20\%$ increase in multiplicity (per collision)
  - $\sim 60\%$ increase of $\sigma_b(LHCb)$
  - $\sim 10\%$ of all events will contain charm
- Bunch spacing 25ns, 2250 bunches (2012: 50ns, 1260 bunches, $\mu = 1.7$)
- Target Luminosity (levelled): $\mathcal{L} = 4 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Scheduled integrated luminosity Run II: $5.5 \pm 1\,\mathrm{fb}^{-1}$
- We plan on roughly trippling our data set until 2018
- Trigger resources doubled to cope with increased fraction of useful events

Go Small and Fast – TurboStream

Analysis on Online Reconstructed Particles

With Run II we start to enter a regime where signal rates become a challenge for computing

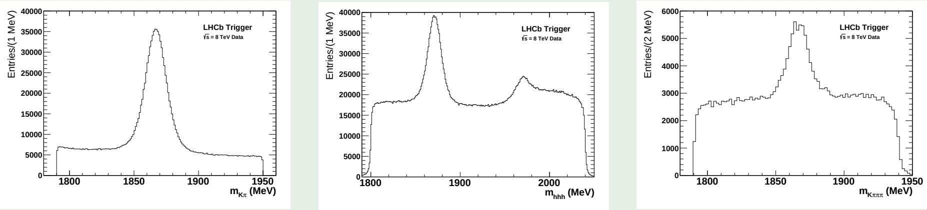
- Example: Cabibbo favoured Charm decays (Spectroscopy!)
- Prompt Charm analyses rely on exclusive triggers
  - Exclusive charm rate 2012: 2.5 kHz
  - Expect a factor ~ 2 for 2015
  - For exclusively triggered modes offline cannot add new particles

Perform analysis on online reconstructed particles

- Only save the particles found by the trigger $\rightarrow$ TurboStream
- very small event size allows larger rate to be pushed to offline at same bandwidth
- No offline reconstruction
- Completely rely on quality of online tracking/PID
- Proof of concept in Run II; Essential tool for Run III and beyond

2012: Online, exclusive D-samples (No PID!)

$D^0 \to K\pi$ $D_{(s)} \to hhh$ $D^0 \to K\pi\pi\pi$



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Outlook: Planned Analyses

Open Charm Spectroscopy:

- Continue $\mathrm{D}^{(*)}\pi$ spectroscopy
- Search for new D_{sJ} resonances in $\mathrm{D}^{*}\mathrm{K}$
- Charmed Baryons in $\mathrm{D}\ \mathrm{p}$
- Λ_c decays
- Decays of Λ_b to charmed baryons
- Search for doubly charmed baryons JHEP12(2013)090 first result

Hidden Charm, Exotics:

- Study the $\mathrm{D}^{(*)}\overline{\mathrm{D}}^{(*)}$ system in B-decays
- Study the $\mathrm{D_s}\overline{\mathrm{D}}^{(*)}_{(s)}$ system
- $X(4140), X(4300) \to \mathrm{J}/\psi\phi$ in $\mathrm{B} \to \mathrm{J}/\psi\phi\mathrm{K}$
- $Z \to \mathrm{J}/\psi\pi$ in $\mathrm{B} \to \mathrm{J}/\psi\pi\mathrm{K}$
- Search for $\mathrm{J}/\psi\eta(')$ or $\mathrm{J}/\psi\omega$
- Use B^0_s as source of charmed mesons e.g. $\mathrm{B}^0_\mathrm{s} \to \mathrm{D}\overline{\mathrm{D}}\phi$
- Look for exotics in Cabibbo suppressed decays e.g. $\mathrm{B} \to \psi(2\mathrm{S})\pi\pi$

Summary

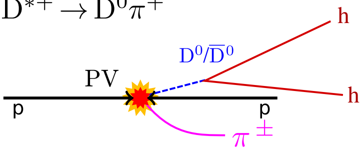
- Both prompt charm as well as charm from B-decays studied
- LHCb has performed several first observations, precision measurements and searches
  - Open charm spectroscopy
  - Charmonium-like exotics
  - Charmed baryons

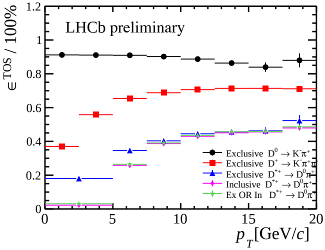
- Already the present data set can be further explored
- Run II: triple statistics $\rightarrow$ advanced amplitude analysis techniques, multiparticle final states

Stay Tuned!

Supporting Material

$D^{*+} \rightarrow D^0\pi^+$



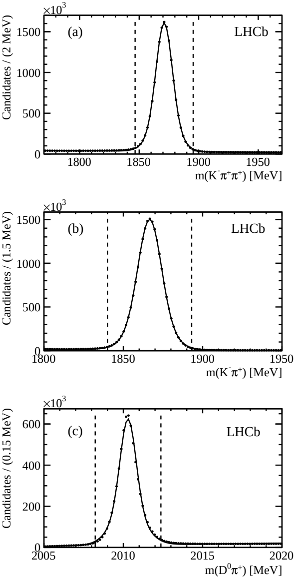


- Full track reconstruction available in the High Level Trigger
- 600 kHz of $c\bar{c}$ in 2012: Easy to swamp the output bandwidth unless exclusive selections are used
  - Exception: $D^* \rightarrow D^0\pi$ inclusive trigger uses $M(D^*) - M(D^0)$ to reduce the rate
  - D^0 exclusively reconstructed in $K\,K$, $\pi\,\pi$, $K\,\pi$, $\pi\,K$ final states, any in mass window are kept
- Cabbibo favored $D^0 \rightarrow K^-\pi^+$ is ~ 300 times more abundant than Doubly cabbibo suppressed $D^0 \rightarrow K^+\pi^-$

D_J Mesons in two-body Decays

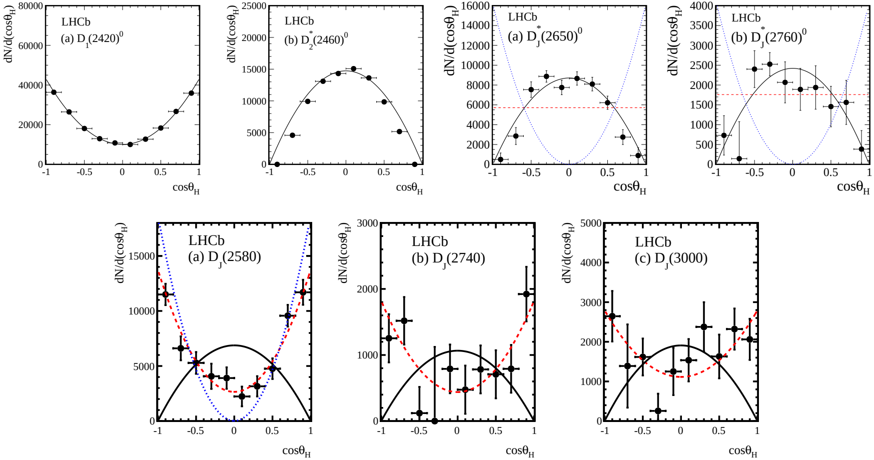
Selection of Prompt Charm

- Data set: $1\,fb^{-1}$ at $\sqrt{s} = 7$ TeV
- Track quality
- $p > 3$ GeV and $p_t > 250\,MeV$ (relaxed for D from D^*)
- Single track impact parameter
- Pointing of D-momentum to PV
- D vertex quality
- $\mathrm{D}\,\pi$ vertex quality $\chi^2/ndf < 8$
- PID requirements
- D and π point to same PV
- Slow pion from $\mathrm{D}^{(*)} \rightarrow$ cut on angle between $\pi^{\pm}$ in $\mathrm{D}^{(*)}\pi$ rest-frame and $\mathrm{D}^{(*)}\pi$-momentum in lab
- Recalculate $m(\mathrm{D}\,\pi)$
  $m(\mathrm{D}^0\pi) = m(\mathrm{K}^-\pi^+\pi^+) - m(\mathrm{K}^-\pi^+) + m_{\mathrm{D}^0}$



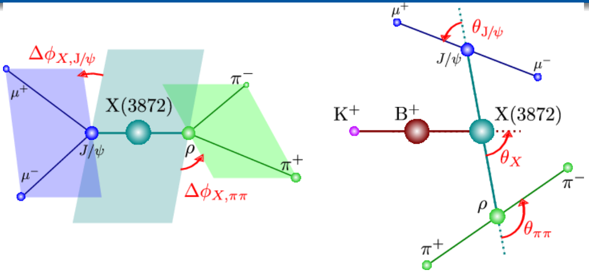
Spin-Parity Analysis of $D^{*+}\pi^{-}$

Extracting yield in resonances in bins of $theta_H$ – JHEP09(2013)145



$X(3872)$ Angular Analysis

Exploit all angular correlations in the B decay → 5*D* decay model



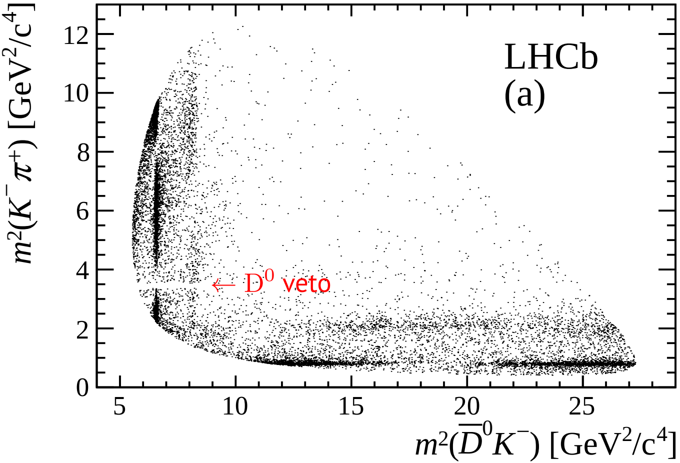
- Only $\pi\pi$ P-wave contribution included
- Decay amplitude constructed in helicity formalism

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

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

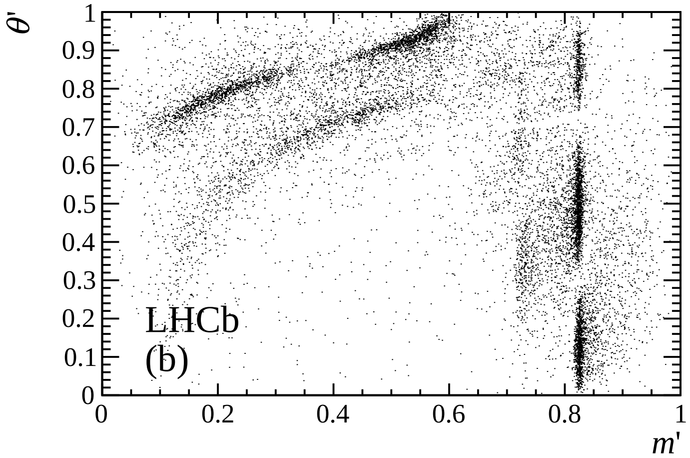
$B_s^0 \to \bar{D}^0 K^+ \pi^-$ Dalitz Plot

Signal region: [5333.75, 5397.25] **MeV**/c^2



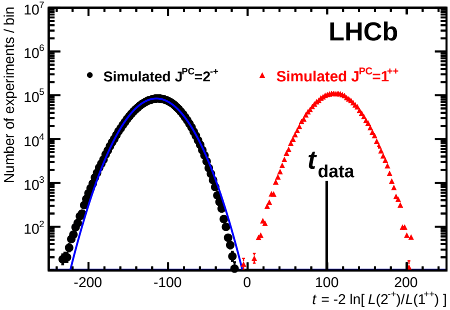
"Square Dalitz Plot"

- $\theta' = \frac{1}{\pi}\theta_H(\overline{\mathrm{D}}^0\mathrm{K}^-)$ helicity angle
- $m' = \frac{1}{\pi}\arccos\left(2\frac{m_{\overline{\mathrm{D}}^0\mathrm{K}^-} - (m_{\overline{\mathrm{D}}^0} + m_{\mathrm{K}^-})}{(m_{\mathrm{B}^0_s} - m_{\pi^+}) - (m_{\overline{\mathrm{D}}^0} + m_{\mathrm{K}^-})} - 1\right)$



LogLikelihood Ratio Test

- Likelihood ratio t
  - $t > 0$ implies $J^{PC} = 1^{++}$ favoured
  - $t < 0$ implies $J^{PC} = 2^{-+}$ favoured
- Compared to results for simulated $\mathrm{B}^{\pm} \to \mathrm{X}(3872)\mathrm{K}^{\pm}$ candidates



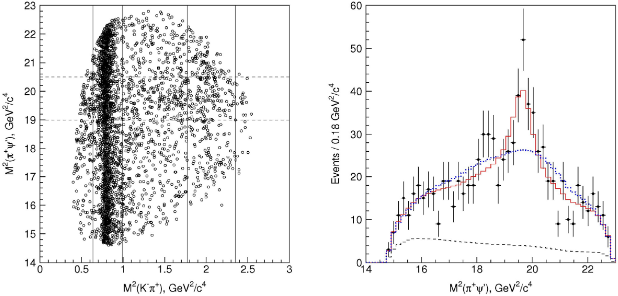
- $J^{PC} = 1^{++}$ compatible
- $J^{PC} = 2^{-+}$ rejected at $> 8\sigma$

- Fitting $J^{PC} = 1^{++}$ simulated events with 2^{-+} model for α yields consistent result

Resonant Nature of the $Z(4430)^-$

- $Z(4430)^-$ has first been claimed by Belle in $\mathrm{B} \to \mathrm{K}(\pi^- \psi(2\mathrm{S}))$
- Minimal quark content: $\mathrm{c}\bar{\mathrm{c}}\mathrm{d}\bar{\mathrm{u}}$
- *BABAR* could explain this through reflections of the $\mathrm{K}\pi$ system (K^*)
- Amplitude analysis by Belle confirms new state (assuming a resonant shape)
- LHCb recently extracts the resonant phase motion of the state

Belle data



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