$B \to D\bar{D}h$ decays: a new (virtual) laboratory for exotic particle searches

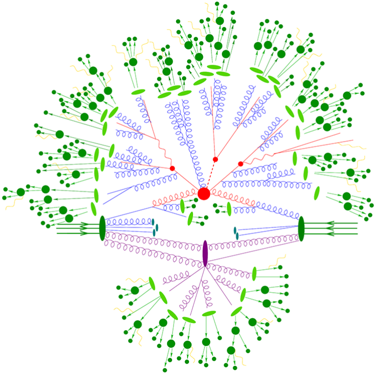
28 04 2021

Dan Johnson (CERN)

CERN

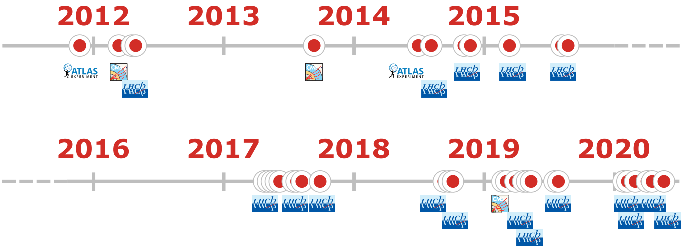
Outline

The mystery of hadronisation



- QCD: successful and predictive. Perturbative at hard scales
- Hadronisation models in lieu of analytical solutions
- Least-well understood aspect of the SM. How to improve?

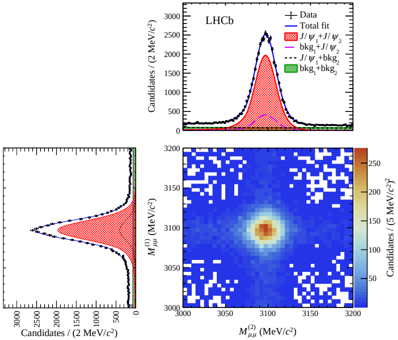
The allure of spectroscopy



- The LHC brought a wealth of new particles: 59 new hadrons
- Great deal of attention: 1,398 citations
- Crucial inputs for hadronisation model-builders

Bump-hunting can get you far...

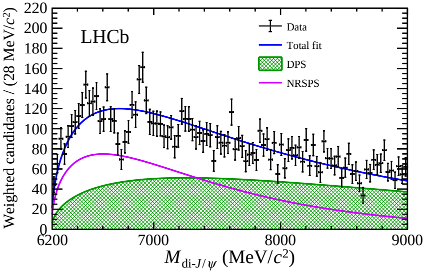
arXiv:2006.16957 LHCb combines $J/\psi \to \mu^+\mu^-$ pairs:



- Striking correlated production, signal: $33,570 \pm 230$
- Double parton scattering background has a lower $p_T^{J/\psi\, J/\psi}$: apply threshold cut or bin in this quantity

Bump-hunting can get you far...

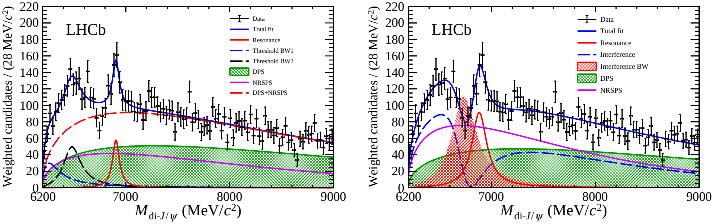
Constrain J/ψ masses and point J/ψ's back to shared vertex



- Obvious narrow feature at 6.9 GeV/c^2
- Broader component between 6.2 and 6.8 GeV/c^2
- Overall distribution inconsistent with NRSPS+DPS at 3.4σ

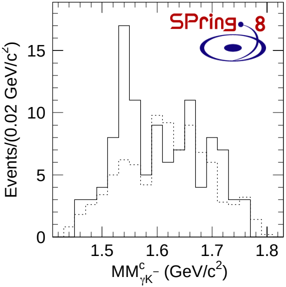
Bump-hunting can get you far...

Constrain J/ψ masses and point J/ψ's back to shared vertex



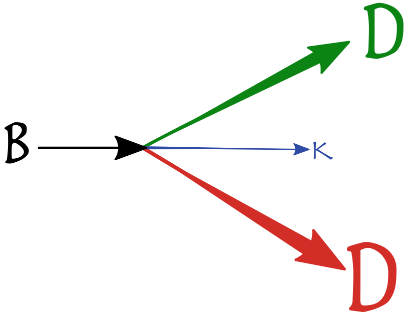
- Model 1: two on-threshold BW shapes, and narrow $X(6900)$
- Model 2: allow threshold BW and NRSPS components to interfere, and narrow $X(6900)$
- Both the threshold and $X(6900)$ structures significant at $> 5\sigma$
- Interpretation: $T_{cc\bar{c}\bar{c}}$ resonance? Via feed-down? Near-threshold enhancement due to rescattering? J^{PC}?

… but beware the (original) pentaquark!

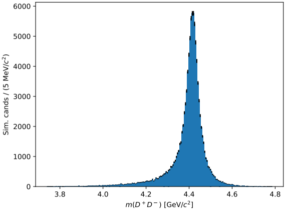


- *uudds̄* state predicted in 1997 arXiv:hep-ph/9703373
- Excess seen in 2003 in $\gamma d \rightarrow K^+ K^- np$ arXiv:hep-ex/0301020
- Bumps 'confirmed' by 9 other experiments
- Un-discovered by CLAS, Belle, …'beautiful' post-mortum: arXiv:1003.1098

The power of exclusive reconstruction



- Fully reconstructed decay
- Much more than a bump-hunt
- Toy $B^+ \to [\psi(4415) \to D^+ D^-] K^+$

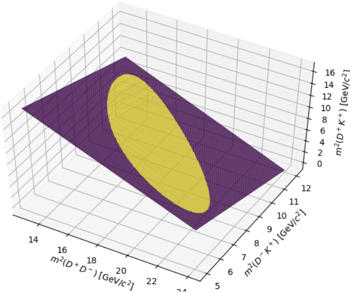


The power of exclusive reconstruction

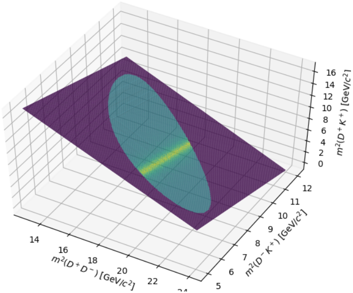
- Conservation of four-momentum in the decay:

$$m_B^2 + 2m_D^2 + m_K^2 = m_{D^+D^-}^2 + m_{D^-K^+}^2 + m_{D^+K^+}^2$$

Toy: phase-space



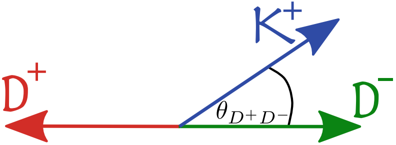
Toy: spin-0



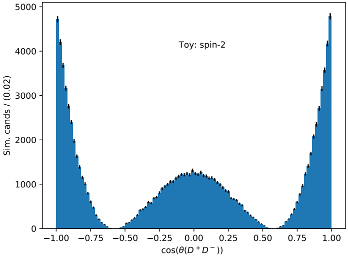
- Two degrees of freedom, within kinematic limits
- Intermediate resonances produce non-uniform structure

The power of exclusive reconstruction

- Strong X$\rightarrow$ $2P$ decay: resonances have $J^P = 0^+, 1^-, 2^+, \ldots$
- Resonance spin dictates angular structure



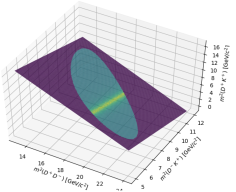
- Resonance (e.g. 2^+) decaying to D^+D^-: intuitive $\theta_{D^+D^-}$ shape



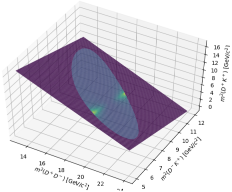
The power of exclusive reconstruction

- Spin-dependent helicity-angle maps onto phase-space plane

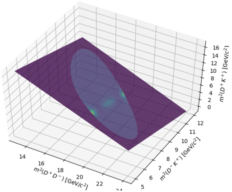
Toy: spin-0



Toy: spin-1



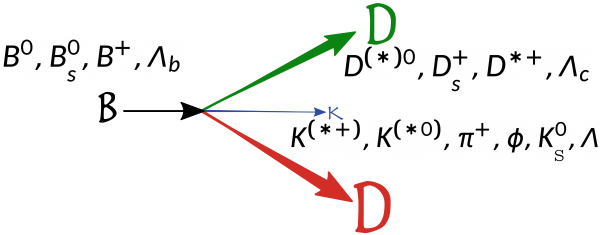
Toy: spin-2



- We'll always project onto one pair of these axes: 'Dalitz plot'

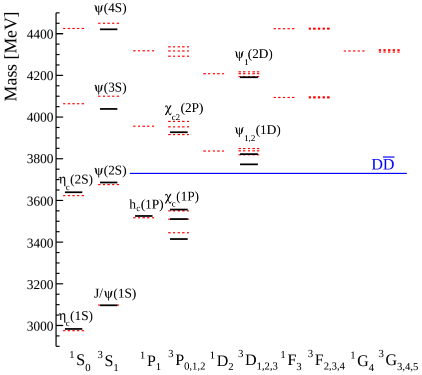
What do we mean by $B \longrightarrow D\bar{D}h$?

- Huge family of topologically similar decays



- Abundantly produced at LHC
- Efficient hadronic trigger
- Very clean topology
- Resonant structure explored for only three of the decays

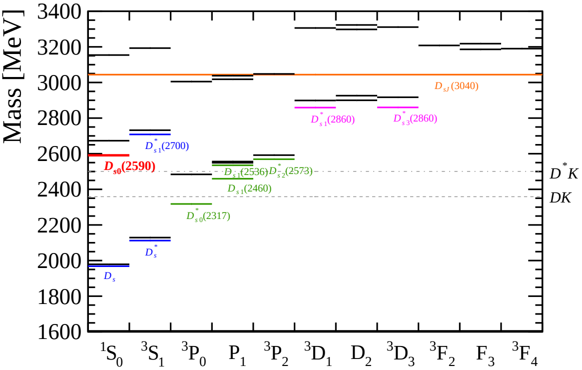
Relevance: the charmonium spectrum



arXiv:1708.04012

- Recent success probing with open-charm pairs arXiv:1903.12240
- Many states remain to be observed
- Sensitivity via $B \to \{D^+D^-, D^0\bar{D}^0, D_s^+D_s^-, \Lambda_c^+\Lambda_c^-\}K$

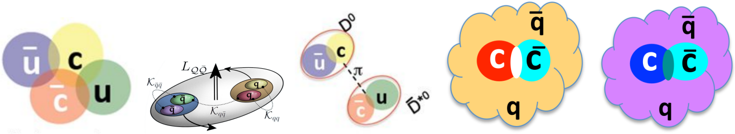
Relevance: the charm-strange spectrum



arXiv:2011.09112

- Solid progress through $B \to Dhh$ amplitude analyses arXiv:1407.7574
- Large samples anticipated for many $B \to \overline{D}D^0K^+$ decays

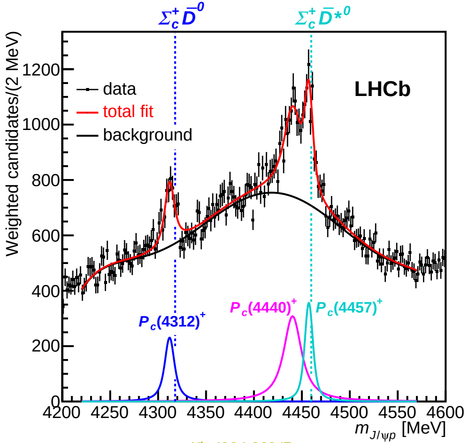
Relevance: charmonium-like exotica



arXiv:1708.04012, arXiv:1605.05954

- Lots of exotic candidates with varying degrees of mystery...
- ... many models to describe them! More experiment needed
- Illucidate open questions e.g. $\chi_{c1}(3872)$ internal composition
  - Study production, lineshape, etc in $B^+ \longrightarrow D^{*0}\overline{D}^0 K^+$ decays
- Study the charged charmonium-like states e.g. Z_c^+
  - Search in $B \longrightarrow D^{*+}\overline{D}^{(*)0} K$ decays

Relevance: pentaquarks

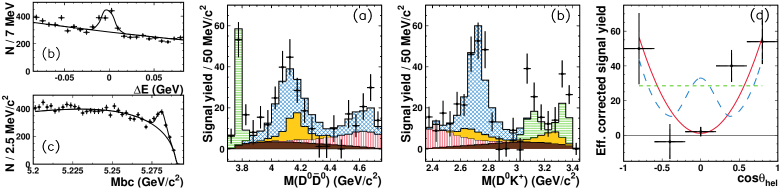


arXiv:1904.03947

- Pentaquarks only seen in $\Lambda_b \to J/\psi\, pK$ decays
  - Same $c\bar{c}uud$ quark content in $\Lambda_b \to \Lambda_c^+ \bar{D}^0 K$ decays

Experimental success elsewhere: Belle

- $B^+ \to D^0 \bar{D}^0 K^+$: pioneering 2008 paper, 414 fb^{-1} e^+e^- 0707.3491

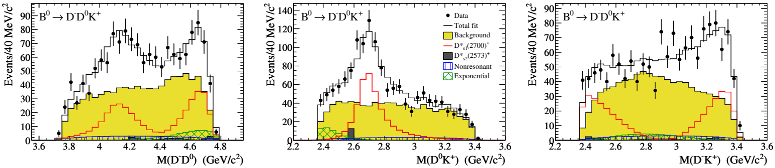


- Clear observation of $D_{s1}(2700)^+ \to D^0 K^+$ resonance
- Strong evidence for its $J^P = 1^-$ character
- Signal of 399 ± 40 candidates
- Fighting an irreducible continuum background of similar size

Experimental success elsewhere: BaBar

- BaBar added a second channel, 429 fb^{-1} e^+e^-

$B^0 \to D^- D^0 K^+$ 1412.6751

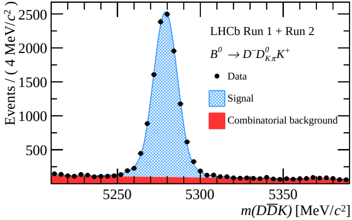


- Signal of 567 ± 51 candidates
- Dominated by $D_{s1}(2700)^+ \to D^0 K^+$ (67% of model)
- Smaller ‘exponential’ component (10%)
- Again, challenging $\sim 60\%$ continuum background

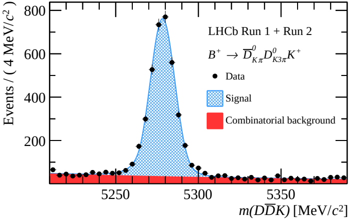
An unprecedented dataset

- LHCb has:
  - high-statistics: order of magnitude improvement
  - high-purity: order of magnitude reduction in background
- (see recent LHCb branching fraction measurement: 2005.10264)

$B^0 \longrightarrow D^- D^0 K^+$



$B^+ \longrightarrow \bar{D}^0 D^0_{K3\pi} K^+$



A simple study?

- $B^{\pm} \to D^{+}D^{-}K^{\pm}$ interesting for charmonia; conventional resonances only expected in the $D^{+}D^{-}$ channel
- Amplitude analysis should be an 'easy' study of charmonia...

Surprising phase-space structure!

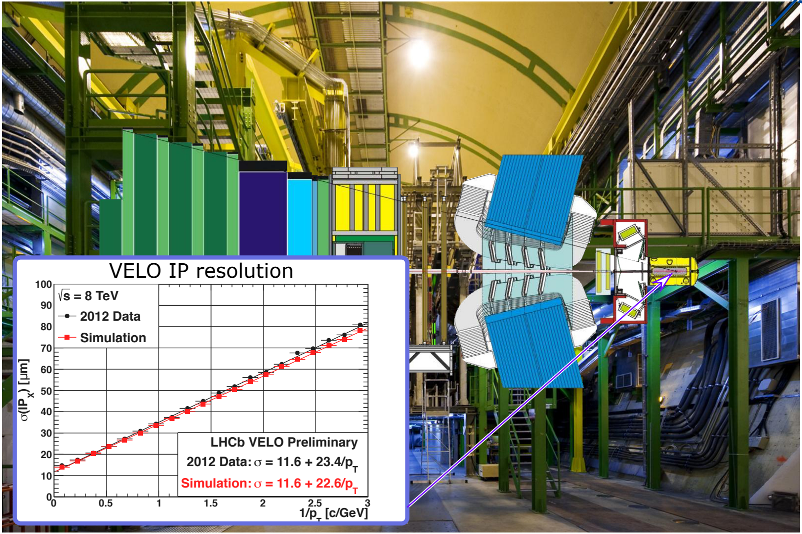
- Paper 1: model-independent study of resonant structure in $B^{+} \to D^{+}D^{-}K^{+}$ decays
- Paper 2: amplitude analysis of the $B^{+} \to D^{+}D^{-}K^{+}$ decay

Outline

LHCb detector

1412.6352

LHCb detector



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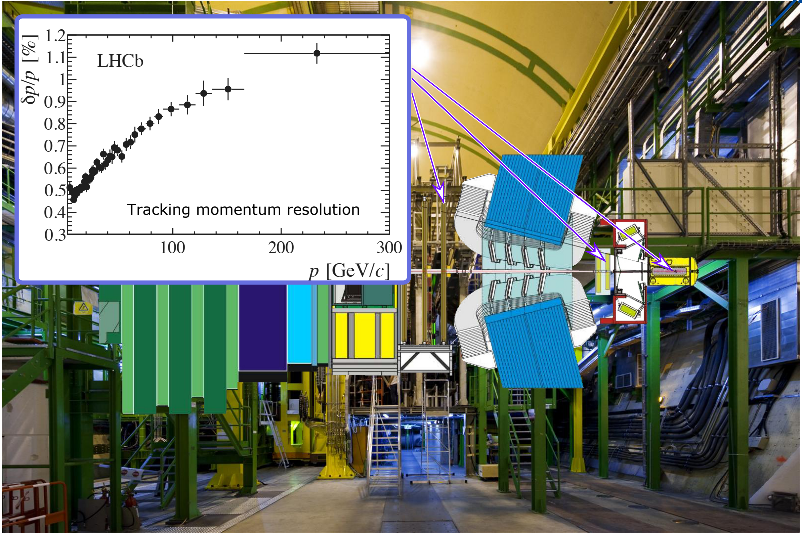
LHCb detector



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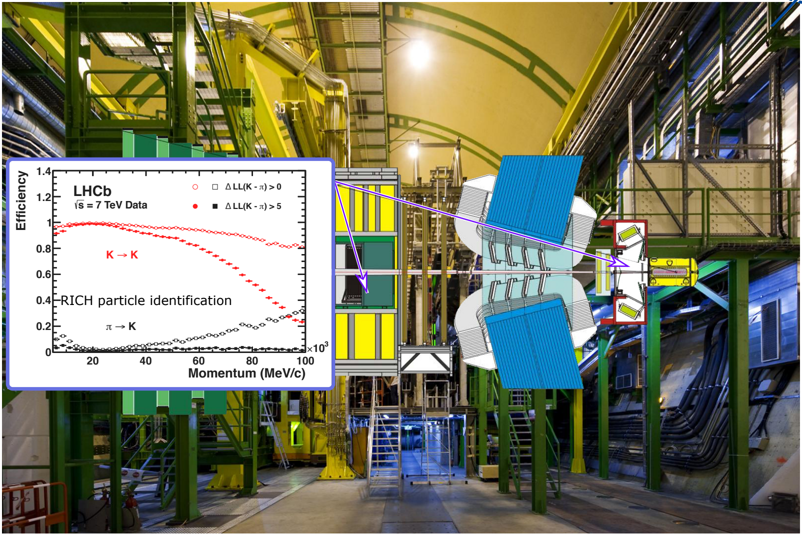
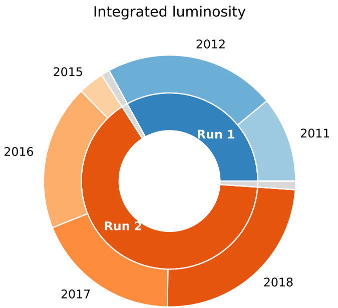
LHCb detector

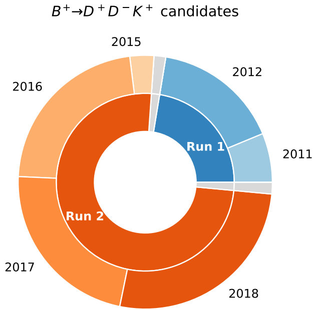


1412.6352

Full Run 1 + Run 2 pp datasets (9 fb^{-1})

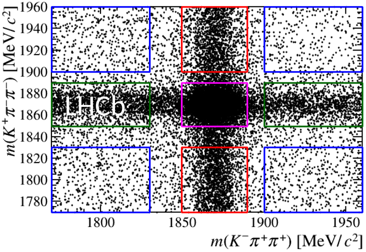
- Reconstruct $B^+ \to [K^-\pi^+\pi^+]_{D^+}[K^+\pi^-\pi^-]_{D^-}K^+$
- Efficient hardware (and subsequent software) trigger
- UniformBDT 1305.7248 with topological and PID variables
- Optimise `(significance × purity)`





Specific backgrounds

- Suppress peaking backgrounds producing the same final state:
  - Veto sharp inv. mass peaks for disconnected pairs of f.s. particles
  - Inspect $B^{\pm}$ peak in D^{+} and D^{-} sidebands, and cut on $D^{\pm}$ FD



Charmless

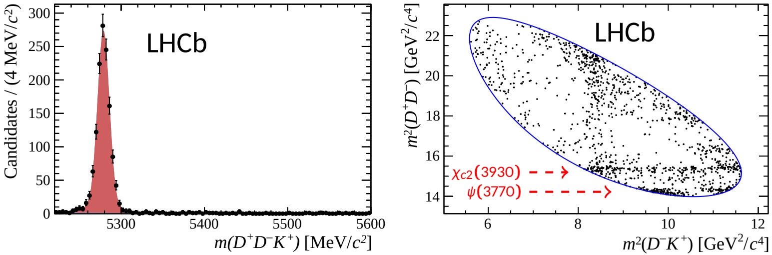
Single charm

Remove with F.D. cuts; typical 20% efficiency cost

- Negligible residual peaking background
- No dangerous partially-reconstructed backgrounds

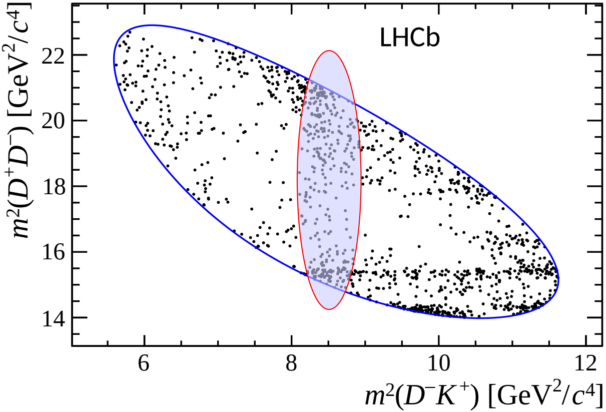
Resonant structure, paper 1,2: $B^+ \to D^+ D^- K^+$

- Published in September, full Run 1+2 2009.00025, 2009.00026



- 1,260 candidates enter the $B^\pm$ mass window for Dalitz plot study
- Purity > 99.5%!
- Only expected resonances in one channel ($D^+ D^-$)

Sneak-peak: the phasespace structure



What is that???

Outline

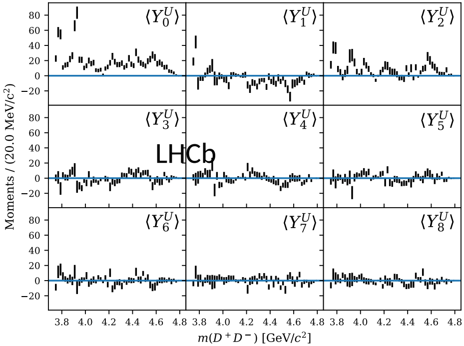
Model-independent analysis approach

- Can $D^+D^-K^+$ phsp be described by D^+D^- partial-waves only?
- Resonances only expected in a single channel: 'simple'
- Method used in $B^0 \to \psi(2S)K^+\pi^-$ 1510.01951,
  $B^0 \to J/\psi K^+\pi^-$ 1901.05745,
  $\Lambda_b \to J/\psi pK^-$ 1604.05708, CERN-THESIS-2016-086.

Procedure

1. Capture D^+D^- angular structure using orthonormal basis of Legendre polynomials in $h(D^+D^-) = \cos(\theta(D^+D^-))$:

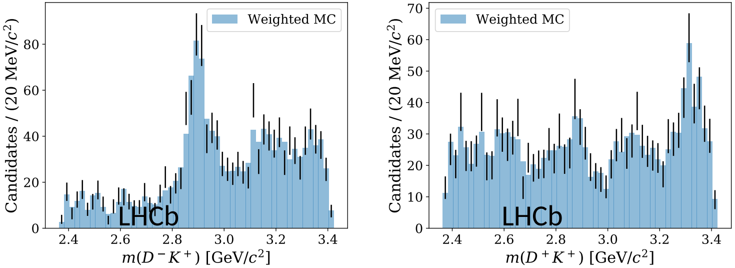
$$\langle Y_k^{U,j} \rangle = \sum_{l=1}^{N_j^{\mathrm{Data}}} w_l P_k\left(h_l(D^+D^-)\right) \qquad (1)$$



Procedure

2. Apply weights to MC to visualise resulting $m(D^+K^-)$ shape:

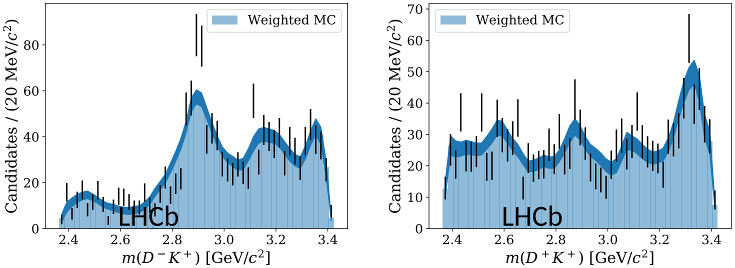
$$\eta_i = \frac{2}{N_j^{\mathrm{Sim}}} \times \sum_{k=0}^{k_{\max}} \langle Y_k^{U,j} \rangle P_k \left(h(D^+D^-) \right) \quad (2)$$



- Obviously high $k_{\max}$ allows to describe nearly everything

Procedure

3. Truncate the expansion: up to spin-2 ⟶ up to $k_{\max} = 4$:

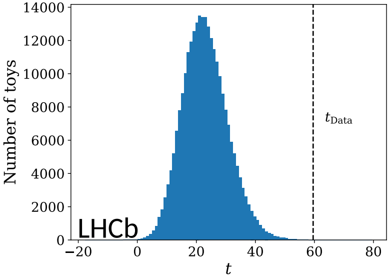


- Bootstrap to propagate uncertainty on moments $\langle Y_k^{U,j} \rangle$
- Clear problem describing the D^+K^- spectrum

Procedure

4. Construct PDF in $m(D^+K^-)$ to build a test-statistic:

$$t = -2 \sum_{l=1}^{N^{\mathrm{Data}}} s_l \log \left(\frac{\mathscr{P}\left(m_l(D^-K^+)|H_0\right)/I_{H_0}}{\mathscr{P}\left(m_l(D^-K^+)|H_1\right)/I_{H_1}} \right) \tag{3}$$



- Ensemble of toys using $k_{\max} = 4$; bootstrap efficiency models
- Evaluate t. t_{Data} discrepant at level of 3.9σ

Outline

1. Introduction

2. Datasets

3. Model-independent analysis [arXiv:2009.00025] (published PRL)

4. Amplitude analysis [arXiv:2009.00026] (published PRD)

5. Reaction

6. Conclusion

Formalism

Used the Laura++ Dalitz plot fitter[1711.09854] to maximise

$$\mathscr{L} = \exp\left[-\sum_{c}\left(\frac{(p_c-\mu_c)^2}{2\sigma_c^2}\right)\right]\prod_{j=1}^{N_c}\left(N_{\rm sig}\mathscr{P}_{\rm sig}(\vec{x}_j) + N_{\rm bg}\mathscr{P}_{\rm bg}(\vec{x}_j)\right)$$

with signal PDF,

$$\mathscr{P}_{\rm sig}(\vec{x}) = \frac{1}{\mathscr{N}} \times \epsilon_{\rm total}(\vec{x}) \times |\mathscr{A}_{\rm sig}(\vec{x})|^2$$

and isobar construction for signal amplitude:

$$\mathscr{A}_{\rm sig}(\vec{x}) = \sum_{j=1}^{N} c_j F_j(\vec{x})$$

Formalism

For a resonance in the $D^+ D^-$ channel, the amplitude is

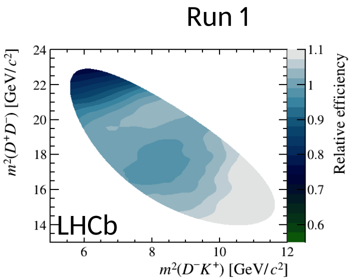
$$F(\vec{x}) = R\left(m(D^+D^-)\right) \times T(\vec{p}, \vec{q}) \times X(|\vec{p}|) \times X(|\vec{q}|)\,, \qquad (4)$$

- R: relativistic Breit-Wigner for all resonances
- T: angular factor - non-relativistic Zemach tensor formalism
- X: Blatt-Weisskopf barrier factors

Efficiency variations

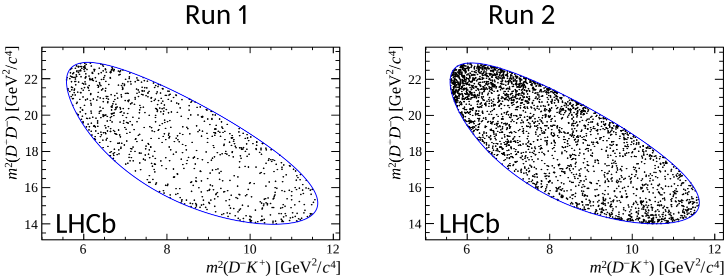
$$\epsilon_{\text{total}}(\vec{x}) = \epsilon_{\text{offline|reco}}(\vec{x}) \times \epsilon_{\text{reco|trig}}(\vec{x}) \times \epsilon_{\text{trig|geom}}(\vec{x}) \times \epsilon_{\text{geom}}(\vec{x})\,.$$

- Main variations at trigger, reconstruction, and stripping stages
- Uniform BDT achieves flat acceptance, as expected



Tiny background component

- Use $5.35\,\mathrm{GeV}/c^2 < m(D^+D^-K^+) < 5.69\,\mathrm{GeV}/c^2$, relaxing BDT
- Dalitz plots in the sidebands:



Signal model ingredients (1/2)

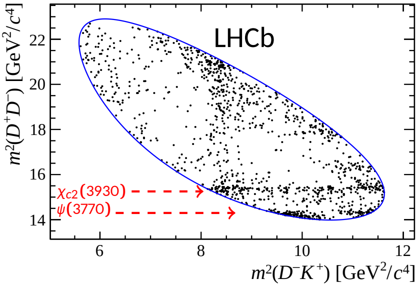
Expect natural J^P (→pseudoscalars) and suppressed high-spin

Partial wave (J^{PC})	Resonance	Mass (MeV/c^2)	Width (MeV/c^2)
S wave (0^{++})	$\chi_{c0}(3860)$	3862 ± 39	201 ± 139
	$X(3915)$	3918.4 ± 1.9	20 ± 5
	Possible nonresonant contributions		
P wave (1^{--})	$\psi(3770)$	3778.1 ± 0.9	27.2 ± 1.0
	$\psi(4040)$	4039 ± 1	80 ± 10
	$\psi(4160)$	4191 ± 5	70 ± 10
	$\psi(4260)$	4230 ± 8	55 ± 19
	$\psi(4415)$	4421 ± 4	62 ± 20
D wave (2^{++})	$\chi_{c2}(3930)$	3921.9 ± 0.6	36.6 ± 2.1
F wave (3^{--})	$X(3842)$	$3842.71 \pm 0.16 \pm 0.12$	$2.79 \pm 0.51 \pm 0.35$

- Most values taken from PDG
- $m(\psi(3770))$ and $\{m, \sigma\}(\chi_{c2}(3930), X(3842))$ from 1903.12240

Fit procedure

- Refit decay, constraining $B^{\pm}$ & $D^{\pm}$ masses: $\sigma(D^{+}D^{-})$ improves from $\mathcal{O}(10\,\mathrm{MeV}/c^2)$ to $\mathcal{O}(2\,\mathrm{MeV}/c^2)$: neglect resolution
- Fit Run 1 and Run 2 data simultaneously, with separate efficiency, bg models and purity
- Minimisation repeated 100 times, randomising coefficients
- $\chi^2/ndof_{\mathrm{effective}}$ computed with adaptive binning scheme

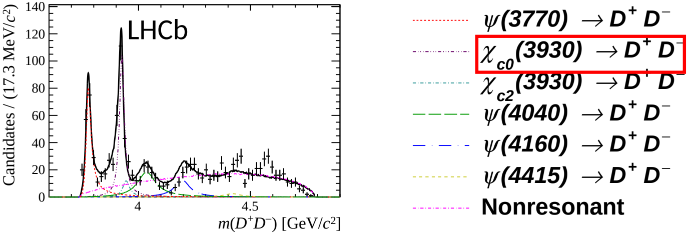


Fit procedure

- Always include $\psi(3770)$ and $\chi_{c2}(3930)$: clearly visible
- Further components included if significantly reduce NLL
- Complex coefficients vary for all except $\psi(3770)$
- Vary m & σ; constrain $\psi(3770)/\psi(4040)/\psi(4160)/\psi(4415)$
- Better fit adding '$\chi_{c0}(3930)$'; no constraint on $\chi_{cJ}(3930)$ m, σ
- Tried various nonresonant lineshapes (uniform, exponential, polynomial, cubic spline) with spin-0,1

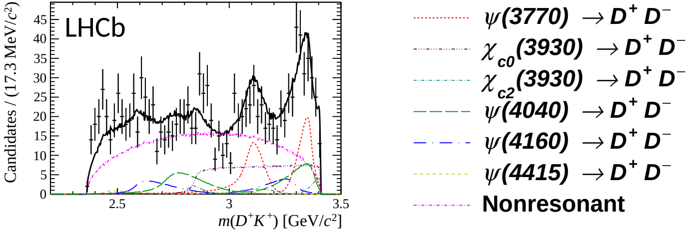
Model excluding D^-K^+ resonances

- $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances
- Nonresonant best described by an exponential S-wave lineshape in the D^-K^+ spectrum



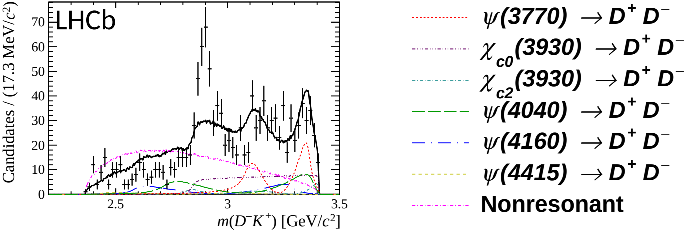
Model excluding D^-K^+ resonances

- $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances
- Reflections model the D^+K^+ spectrum satisfactorily:



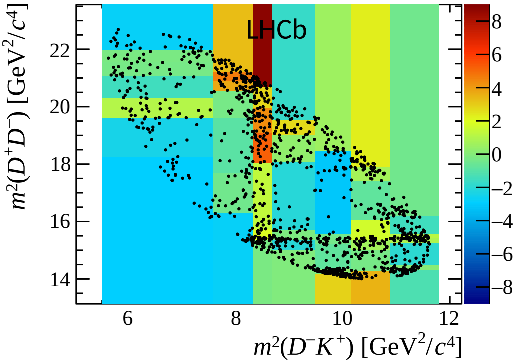
Model excluding $D^- K^+$ resonances

- $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances
- But the description of the $D^- K^+$ spectrum is severely deficient!



Model excluding $D^- K^+$ resonances

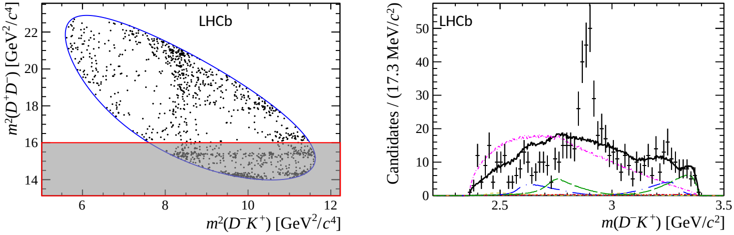
Goodness of fit:



- Largest deviations seen near $m(D^- K^+) \approx 2.9\,\mathrm{GeV}/c^2$

Model excluding $D^{-}K^{+}$ resonances

- Clearer: $m(D^{+}D^{-}) > 4\,\mathrm{GeV}/c^{2}$: cut away low-mass charmonia



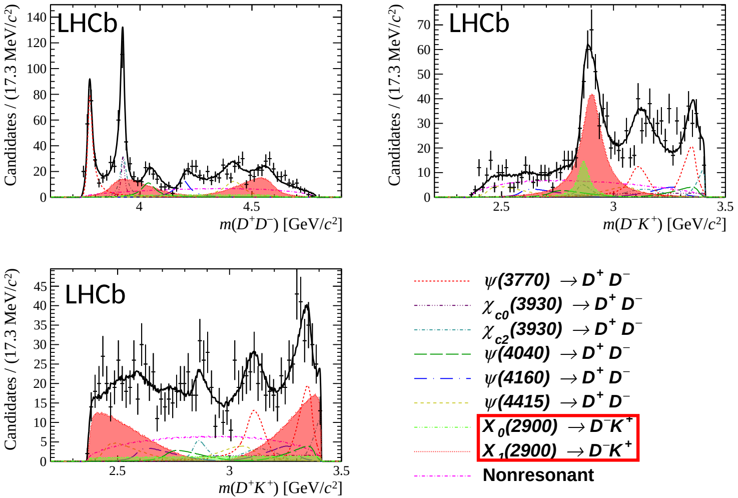
- Bit of a show-stopper

Model including $D^- K^+$ resonances

We had to do something about the $D^- K^+$ channel

- May well need more intricate theoretical study e.g. rescattering effects since suspiciously close to $D^* K^*$ threshold
- Simple approach: new Breit-Wigners (spin-0 **and** spin-1 needed)

Model including $D^{-}K^{+}$ resonances



Model including D^-K^+ resonances

Fit results: coefficients

Resonance	Magnitude	Phase (rad)	Fit fraction (%)
D^+D^- resonances			
$\psi(3770)$	1 (fixed)	0 (fixed)	$14.5 \pm 1.2 \pm 0.8$
$\chi_{c0}(3930)$	$0.506 \pm 0.064 \pm 0.017$	$2.162 \pm 0.184 \pm 0.034$	$3.7 \pm 0.9 \pm 0.2$
$\chi_{c2}(3930)$	$0.703 \pm 0.064 \pm 0.012$	$0.827 \pm 0.170 \pm 0.133$	$7.2 \pm 1.2 \pm 0.3$
$\psi(4040)$	$0.585 \pm 0.078 \pm 0.035$	$1.416 \pm 0.176 \pm 0.084$	$5.0 \pm 1.3 \pm 0.4$
$\psi(4160)$	$0.668 \pm 0.084 \pm 0.052$	$0.898 \pm 0.225 \pm 0.092$	$6.6 \pm 1.5 \pm 1.2$
$\psi(4415)$	$0.797 \pm 0.080 \pm 0.061$	$-1.458 \pm 0.197 \pm 0.091$	$9.2 \pm 1.4 \pm 1.5$
D^-K^+ resonances			
$X_0(2900)$	$0.619 \pm 0.079 \pm 0.025$	$1.091 \pm 0.193 \pm 0.095$	$5.6 \pm 1.4 \pm 0.5$
$X_1(2900)$	$1.449 \pm 0.086 \pm 0.032$	$0.367 \pm 0.102 \pm 0.049$	$30.6 \pm 2.4 \pm 2.1$
Nonresonant	$1.293 \pm 0.088 \pm 0.043$	$-2.410 \pm 0.119 \pm 0.508$	$24.2 \pm 2.2 \pm 0.5$

- Total fit fraction: 107%

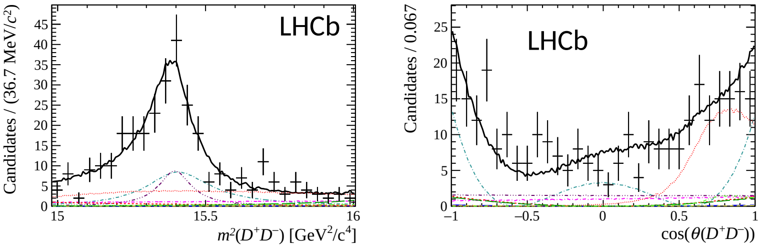
Model including D^-K^+ resonances

Fit results: lineshapes

Resonance	Mass (GeV/c^2)	Width (MeV/c^2)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.8663 \pm 0.0065 \pm 0.0020$	$57.2 \pm 12.2 \pm 4.1$
$X_1(2900)$	$2.9041 \pm 0.0048 \pm 0.0013$	$110.3 \pm 10.7 \pm 4.3$

Model including D^-K^+ resonances

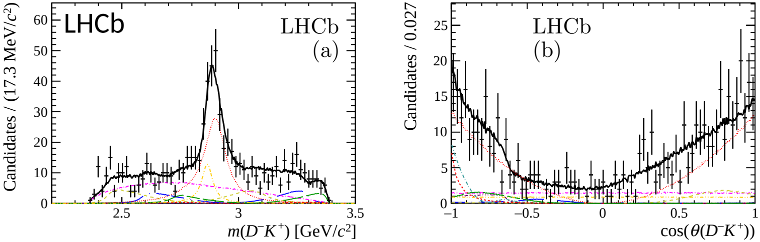
Zoom in on the $\chi_{cJ}(3930)$ ($15\,\mathrm{GeV}/c^2 < m^2(D^+D^-) < 16\,\mathrm{GeV}/c^2$):



- Both a spin-0 and spin-2 component are needed in this region
- Masses are consistent and spin-0 slightly narrower 2002.03311

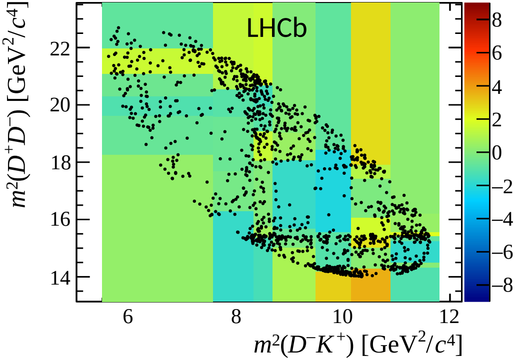
Model including $D^- K^+$ resonances

Focus on the new $D^- K^+$ states ($m(D^+ D^-) > 4\,\mathrm{GeV}/c^2$):



Model including $D^{-}K^{+}$ resonances

Goodness of fit:



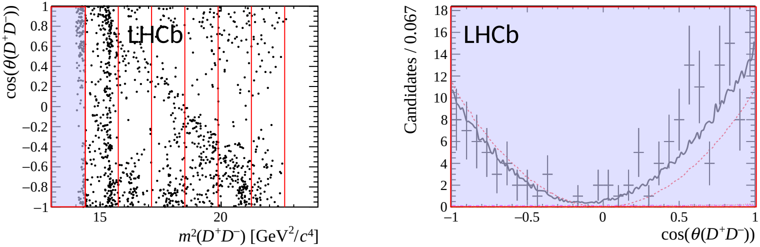
- The χ^2/ndf is 86.1/38.3 = 2.25

Model including $D^{-}K^{+}$ resonances

Main areas of disagreement (1):

$\left(m^2(D^-K^+), m^2(D^+D^-)\right) \sim (10.5\,\mathrm{GeV}^2/c^4, 13.5\,\mathrm{GeV}^2/c^4)$

- Data exhibit large interference between S and P wave at low $m(D^+D^-)$, but fit does not introduce any S wave here:



Model including $D^- K^+$ resonances

Main areas of disagreement (2):

$\left(m^2(D^- K^+), m^2(D^+ D^-)\right) \sim (10.5\,\mathrm{GeV}^2/c^4, 18.5\,\mathrm{GeV}^2/c^4)$

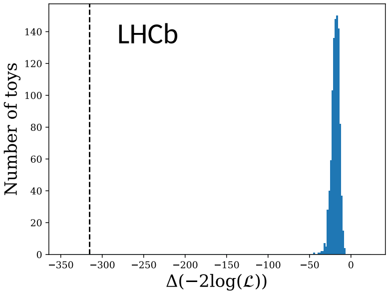
- Seems to originate at low values of $m^2(D^+ K^+)$. No particular disagreement is seen in other projections of this region, and therefore it is not considered a source of concern.

Conclusion

The fit is not perfect but the new features are too narrow or too prominent to be ignored

Significance of new D^-K^+ state

- Generate $\sim$ 1000 toys from data fit with no D^-K^+ components
- Fit with model with and without the new components
- Find difference in NLL for the toy ensemble, and for the data:

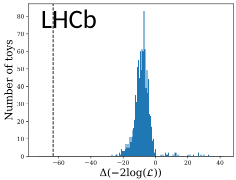


- Overwhelmingly significant, $\gg 5\sigma$

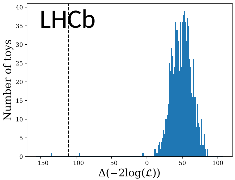
Significance of $\chi_{cJ}(3930)$ spin conclusions

- Generate $\sim$ 1000 toys from data fit with single $\chi_{c0,1,2}$ resonance
- Fit with model with that resonance or with both spin-0 and 2
- Find difference in NLL for the toy ensemble, and for the data:

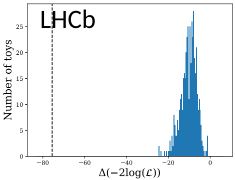
χ_{c0}-only



χ_{c1}-only



χ_{c2}-only



- Strong preference for the spin-0 and spin-2 combination

Systematic uncertainties

Major sources:

- Blatt-Weisskopf radii conventionally set to $4\,\mathrm{GeV}^{-1}$. Vary parent, charmonia, charm-strange radii separately. Dominant effect from the latter two ($\sim 50\%\ \sigma_{\mathrm{stat}}$)
- S wave modelling: introduce 5% uniform NR component in toy ensemble and fit with standard model ($10 \to 80\%\ \sigma_{\mathrm{stat}}$)
- P wave modelling: add $\psi(4320)$ with fixed parameters ($10 \to 100\%\ \sigma_{\mathrm{stat}}$)
- Limited MC statistics: bootstrap efficiency models and repeat fit to data ($\sim 10\%\ \sigma_{\mathrm{stat}}$)
- Hardware trigger modelling in MC: build alternative efficiency map using calibration samples ($\sim 10\%\ \sigma_{\mathrm{stat}}$)

Outline

1. Introduction
2. Datasets
3. Model-independent analysis [arXiv:2009.00025] (published PRL)
4. Amplitude analysis [arXiv:2009.00026] (published PRD)
5. Reaction
6. Conclusion

$cs\bar{u}\bar{d}$ tetraquark

- 0^+ state an isosinglet compact tetraquark
- Analogy to $bb\bar{u}\bar{d}$ predicted by lattice QCD
- Discussed in 2008.05993, 2008.07145, 2008.07295, 2008.07340

Pro

Successfully explain the 0^+ state

Con

- *(Most) struggle with 1^-*
- *Analogy to $bb\bar{u}\bar{d}$ doubtful (far from threshold)*
- *Accompanied by plethora of additional states (pro?)*

Molecular bound state

- Genuine prediction (2010) for an isoscalar $D^*\overline{K}^*$ 0^+ state
- Prediction in 1005.0335 refined (to get the right mass!) in 2008.11171
- More discussion in 2008.07389, 2008.07782, 2008.06894, 2008.07516, 2008.09516.

Pro

- *Successfully explain the 0^+ state*
- *Diquark-diantiquark picture gives 1^-*

Con

- *(Most) struggle with 1^-*
- *More 1^+, 2^+ states expected*

Rescattering structure from nearby threshold

- Triangle diagram coupling B to DDK final state
- Assume single-pion exchange dominates: only possible between $D^*\overline{K}^*$ (not $D^*\overline{K}$, $D\overline{K}^*$, $D\overline{K}$)
- $D_1(2420)\overline{K} \to D^*\overline{K}^*$ scattering OK. Thresholds at $2.9\ \mathrm{GeV}/c^2$.

Pro

- *Nice connection to suspicious thresholds*
- *Natural explanation of 1^- with $D_1(2420)\overline{K}$ in S wave*
- *Discussed in 2008.07190 and 2008.12838*

Con

- *Only (so far) tested in fit to 1D mass projection*

What next?

Confirmation:

- Does the state reappear in $B^0 \to D^0 D^- K^+$ and $B^+ \to D^- K^+ \pi^+$?

Composition:

- Is the structure also present in $B^+ \to D^+ \bar{D}^0 K^0_S$ (also $cs\bar{u}\bar{d}$)?

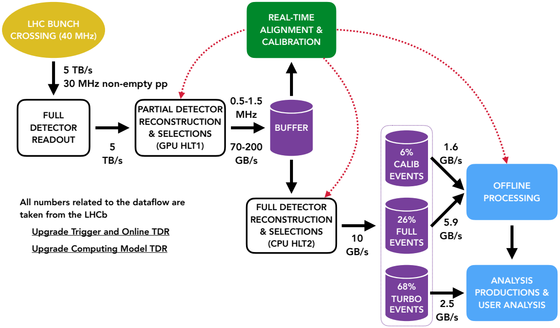
Extension:

- Is it an isosinglet/triplet? Do additional states appear in $B^+ \to D^0 \bar{D}^0 K^+$ $(\bar{c}uu\bar{s})$?
- Is there a 1^+ partner in $B^+ \to D^+ D^{-*} K^+$?

What next?

Run 3

- Major changes to DAQ pipeline

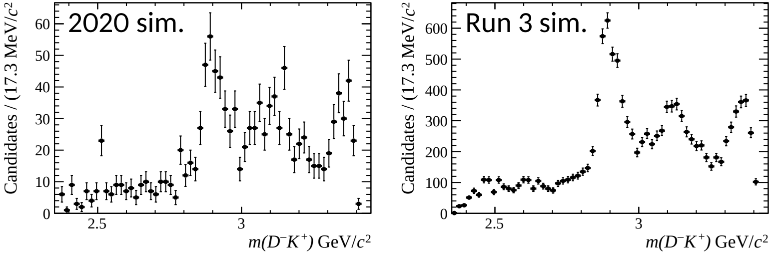


- Consequently improved trigger efficiency
- Run 3 (2021-2023) anticipated to carry an order of magnitude greater statistical weight vis-a-vis Run 1+2.

What next?

SIMULATED projection for Run 1+2 vs Run 3 datasets

- Generate pseudo-experiments from $B^+ \to D^+ D^- K^+$ model



- Radical increase in sensitivity just by middle of this decade

Outline

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2. Datasets

3. Model-independent analysis [arXiv:2009.00025] (published PRL)

4. Amplitude analysis [arXiv:2009.00026] (published PRD)

5. Reaction

6. Conclusion

Summary

- LHCb is a powerhouse for new, exotic particle discovery. We can go far with a simple bump-hunt ($X(6900)$), but even further exploiting a fully-reconstructed decay
- **First** analysis of $D^+D^-K^+$ resonant structure
- **First** model-independent evidence for $D^+D^-K^+$ structure that cannot be accounted for by charmonium resonances
- **First** amplitude model of $D^+D^-K^+$
- Model-dependent **discovery** of exotic structure in D^-K^+
- **Discovery** of contributions from spin-0 and spin-2 components in the region of the existing '$\chi_{c2}(3930)$'

Resonance	Mass (GeV/c^2)	Width (MeV/c^2)	Fit fraction (%)
$\chi_{c0}(3930)$	3.924 ± 0.002	17.4 ± 5.2	3.7 ± 0.9
$\chi_{c2}(3930)$	3.927 ± 0.003	34.2 ± 6.7	7.2 ± 1.2
$X_0(2900)$	2.866 ± 0.007	57.2 ± 12.9	5.6 ± 1.5
$X(2900)$	2.904 ± 0.005	110.3 ± 11.5	30.6 ± 3.2

Outlook

- The tide of LHCb results in $B \to D\overline{D}h$ decays broke in 2020. Did we answer as many questions as we raised?
- We have surely demonstrated
  - high-statistics: $\sim$ order of magnitude wrt B-factories
  - high-purity: order of magnitude reduction in background
- A great deal of work undoubtedly remains ahead
- As models become more detailed / new features emerge, continued theory input will be needed
- Approaching data-taking will provide a step-change in sensitivity

Backup: constraints compared to PDG

Expect natural J^P (→pseudoscalars) and suppressed high-spin

Partial wave (J^{PC})	Resonance	Mass (MeV/c^2)	Width (MeV/c^2)
P wave (1^{--})	$\psi(3770)$ (PDG)	3773.4 ± 0.4	27.2 ± 1.0
	$\psi(3770)$ (1903.12240)	3778.1 ± 0.9	27.2 ± 1.0
D wave (2^{++})	$\chi_{c2}(3930)$ (PDG)	3922.2 ± 1.0	35.3 ± 2.8
	$\chi_{c2}(3930)$ (1903.12240)	3921.9 ± 0.6	36.6 ± 2.1

- Most values taken from PDG
- $m(\psi(3770))$ and $\{m, \sigma\}(\chi_{c2}(3930), X(3842))$ from 1903.12240