Recent Results in Exotic Hadron Spectroscopy at the LHCb Experiment

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- Exotic hadron naming convention. [arXiv:2206.15233]

- First observation of a doubly charged tetraquark and its neutral partner.
[LHCb-PAPER-2022-026][LHCb-PAPER-2022-027]

- Observation of a resonant structure near the $D_s^+ D_s^-$ threshold. [LHCb-PAPER-2022-018]
[LHCb-PAPER-2022-019]

- Observation of a $J/\psi \Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \to J/\psi \Lambda \overline{p}$.
[LHCb-PAPER-2022-031]

Motivation

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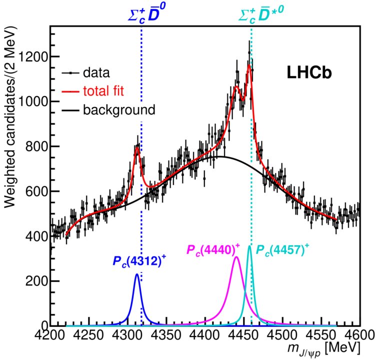
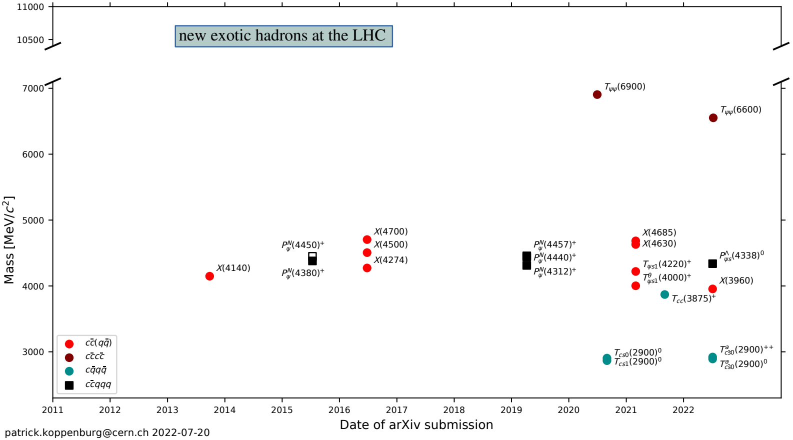
- Exotic hadrons are ones which have greater than 3 valence quarks (tetraquarks, pentaquarks, hexaquarks...).
- Proposed in Gell–Mann's quark model paper (Phys. Lett.(**8**) 3 (1964)).
- Observation of an exotic hadron – $\chi_{c1}(3872)$ by BELLE in 2003 in $J/\psi\pi\pi$ mass spectrum. (PRL (**91**), 262001 (2003)).
- First observation of a pentaquark was by LHCb in 2015 in $J/\psi p$ mass spectrum. (PRL (**115**), 072001 (2015), PRL (**122**), 222001 (2019)).

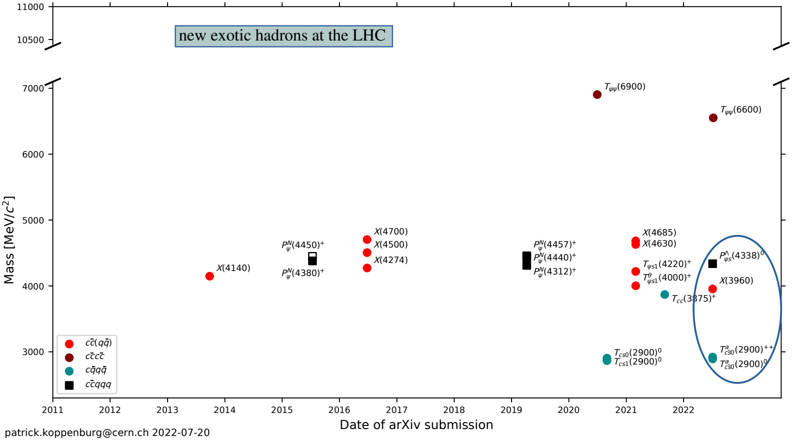
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest



So far, ATLAS, CMS and LHCb have discovered 67 new hadronic states of which 20+ are exotic – all but 2 discovered at LHCb (Plot Source).

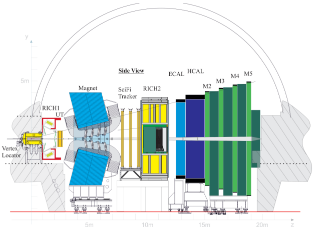


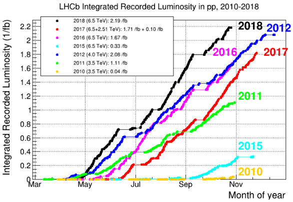
So far, ATLAS, CMS and LHCb have discovered 67 new hadronic states of which 20+ are exotic – all but 2 discovered at LHCb. To be discussed in this talk. (Plot Source)



Why LHCb?

- Largest heavy–flavour dataset collected – 9 fb^{-1} with Run 1+2.
- Largest production cross–sections of b and c hadrons.
- Specialised trigger for hadronic decays.





- Two Ring Imaging CHerenkov (RICH) detectors allow excellent PID.
- VErtex LOcator (VELO) and tracking stations allow precise tracking of particles.

Exotic Hadron Naming Convention

- Many new exotic hadrons do not fit into the current PDG naming convention.
- Even these have flaws however:
  - P_c for a $c\bar{c}uud$ pentaquark – how would we label an open–charm pentaquark state? [LHCb-PAPER-2019-014]
  - $Z_{cs}(4000)$ and $Z_{cs}(4220)$ labelled as Z, with I=1/2 – Z should only be used when I=1. [LHCb-PAPER-2020-044]
- More exotic hadrons to come from LHC experiments as well as others (Belle II *etc.*) drives the need for an updated naming scheme.
- It should be backwards compatible with our current convention.
- Should be formulaic and as simple as possible.
- Should be somewhat futureproof - we may find 6/7 (and so on) quark states in the future, we should be prepared to give them appropriate names.

- Any state with less than 4 quarks will remain unchanged.
- Use T for tetraquarks and P for pentaquarks.
- Superscript will indicate isospin, parity and G–parity.

T states
zero net *S*, *C*, *B*

(P, G)	$I = 0$	$I = 1$
$(-,-)$	ω	π
$(-,+)$	η	ρ
$(+,+)$	f	b
$(+,-)$	h	a

T states
non-zero net *S*, *C*, *B*

(P)	$I = 0$	$I = \frac{1}{2}$	$I = 1$
$(-)$	η	τ	π
$(+)$	f	θ	a

P states

$I = 0$	$I = \frac{1}{2}$	$I = 1$	$I = \frac{3}{2}$
Λ	N	Σ	Δ

- Subscript Υ, ψ and ϕ indicate hidden beauty, charm and strangeness. If more than one needed then they should be in order of mass.
- For open flavour states, *b*, *c* or *s* can be used.
- For T states the spin J should be added as a subscript. For P states, spin–parity should follow the name.

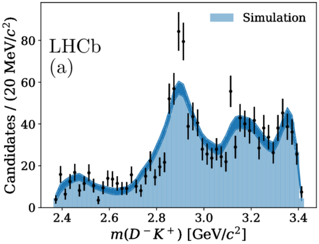
Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^{\theta}_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_{\psi}(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^{\Lambda}_{\psi s}(4459)^0$

Minimal quark content	Potential decay channel(s)	$I^{(G)}$, $J^{P(C)}$	Proposed name
$bc\bar{u}\bar{d}$	$B^- D^{*+}$	$I = 0$, $J^P = 1^+$	$T^f_{bc1}(\mathrm{mass})^0$
$b\bar{c}\bar{u}d$	$B^- D^{*-}$	$I = 1$, $J^P = 1^+$	$T^a_{b\bar{c}1}(\mathrm{mass})^{--}$
$bb\bar{u}\bar{d}$	$B^-\pi^- D^+$, $\bar{B}^0 J/\psi K^-$	$I = 0$, $J^P = 1^+$	$T^f_{bb1}(\mathrm{mass})^-$
$c\bar{c}b\bar{d}$	$J/\psi \bar{B}^0$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^{\theta}_{\psi b1}(\mathrm{mass})^0$
$b\bar{b}uud$	Υp	$I = \frac{1}{2}$	$P^N_{\Upsilon}(\mathrm{mass})^+$
$b\bar{c}uud$	$B_c^- p$	$I = \frac{1}{2}$	$P^N_{b\bar{c}}(\mathrm{mass})^0$
$b\bar{u}cds$	$B^- \Xi_c^0$	$I = 1$	$P^{\Sigma}_{bcs}(\mathrm{mass})^-$
$c\bar{d}cus$	$D^+ \Xi_c^+$	$I = 1$	$P^{\Sigma}_{ccs}(\mathrm{mass})^{++}$
$c\bar{c}cud$	$J/\psi \Lambda_c^+$	$I = 0$	$P^{\Lambda}_{\psi c}(\mathrm{mass})^+$
$c\bar{c}cus$	$J/\psi \Xi_c^+$	$I = \frac{1}{2}$	$P^N_{\psi cs}(\mathrm{mass})^+$

- Slightly alters some already existing states.
- Can be applied for a wide range of potential future states.
- All analyses discussed today use this new convention (see slide 4).

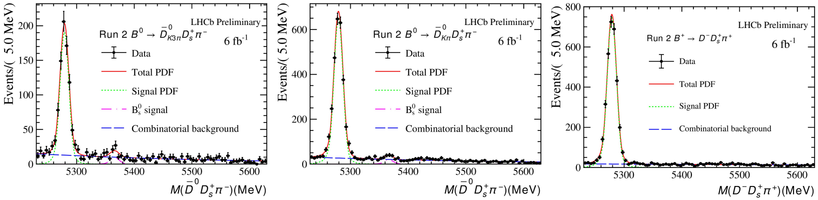
First observation of a doubly charged tetraquark and its neutral partner

- $T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$ ($cs\overline{u}\overline{d}$) previously found by LHCb in D^-K^+ mass spectrum – PRL 125, 242001(2020).



- Possibility to look for isospin partners in $D_s^+\pi^+$ ($c\bar{s}u\overline{d}$) or $D_s^+\pi^-$ ($c\overline{s}\overline{u}d$) final states?
- Can help to determine whether or not D_{sJ} states have some tetraquark component as has been theorised – PRL 90, 242001(2003).

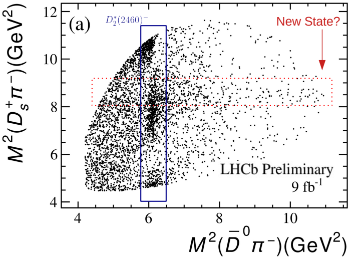
- $B^0 \to \bar{D}^0 D_s^+ \pi^-$, $B^+ \to D^- D_s^+ \pi^+$
- Uses full LHCb Run 1+2 dataset ($9\,\text{fb}^{-1}$).
- Applying loose mass and PID cuts already gives a hint of signal, multivariate analysis improves further.



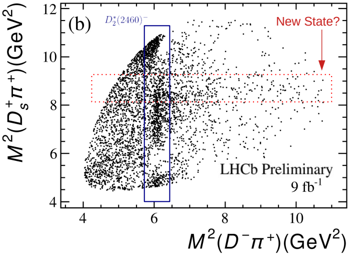
Signal yields:

- B^0 – 4172 ± 131 with 90% purity.
- B^+ – 3921 ± 89 with 89% purity.

- Dalitz plots show similar features – isospin related decay channels.



$B^0 \to \bar{D}^0 D_s^+ \pi^-$



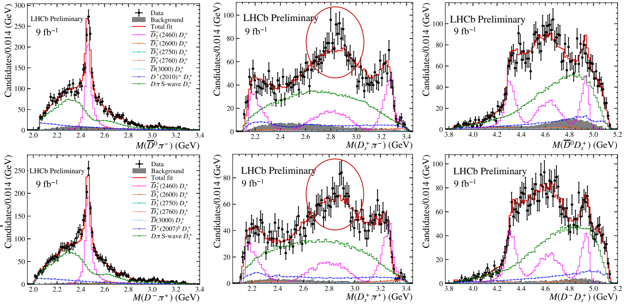
$B^+ \to D^- D_s^+ \pi^+$

- Similarity allows for simultaneous fit in amplitude analysis.

Fit With Only D^* Resonances

$B^0 \to \overline{D}^0 D_s^+ \pi^-$

$B^+ \to D^- D_s^+ \pi^+$



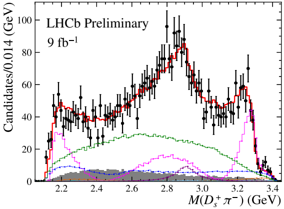
Fit describes data around 2.9 GeV poorly.

What if we add a new state? Denoted $T^a_{c\bar{s}0}(2900)$.

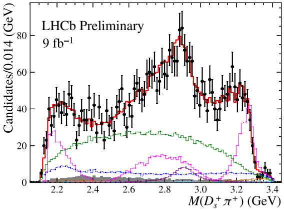
Fit With $T^a_{c\bar{s}0}(2900)$ Component

- Fit greatly improved.
- Significance of states in simultaneous fit – 9.7σ.
- Strong preference for J^P as 0^+ (7.5σ).
- Mass shows good agreement with $T_{csJ}(2900)$ but with differing width.

$$T_{cs0}(2900):\ M = 2.866 \pm 0.007 \pm 0.002\ \text{GeV}/c^2,$$
$$\Gamma = 57 \pm 12 \pm 4\ \text{MeV},$$
$$T^a_{c\bar{s}0}(2900)^0:\ M = 2.892 \pm 0.014 \pm 0.015\,\text{GeV},$$
$$\Gamma = 0.119 \pm 0.026 \pm 0.013\,\text{GeV},$$



$B^0 \to \bar{D}^0 D_s^+ \pi^-$

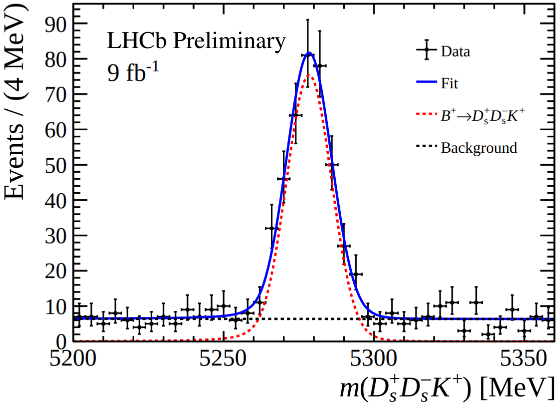


$B^+ \to D^- D_s^+ \pi^+$

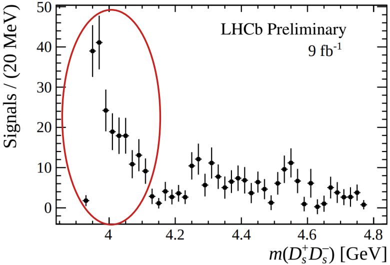
Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

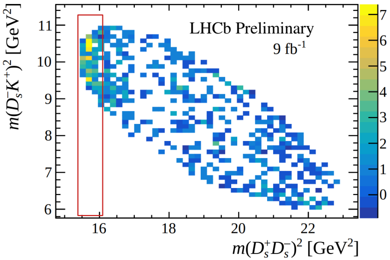
- $B^+ \to D_s^+ D_s^- K^+$ decay has not been previously observed.
- $\chi_{c0}(3930)$ found recently by LHCb in $D^+ D^-$ (PRD.102.112003(2020)). Mass and width close to X(3915)($\to J/\psi\ \omega$). Are they the same state?
- Should have a peak in $D_s^+ D_s^- K^+$ mass spectrum.
- $\mathcal{B}\ (B^+ \to D_s^+ D_s^- K^+)$ allows to estimate partial width of X near threshold – useful for discerning structure (arXiv:1602.08421).
- Can also search for other exotics.

- Uses full LHCb Run 1+2 dataset ($9\,\mathrm{fb}^{-1}$).



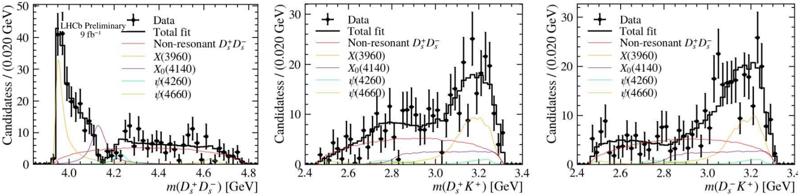
B^+ Yield – 360 ± 22 candidates with 84.4% purity.





- Mass projections show enhancement in $D_s^+ D_s^-$ around 3.6 GeV/c^2. Hint of a new state?
- Amplitude analysis needed.

- Flatte–like formula used for structure at threshold, Breit–Wigner for known resonances.
- Non–Resonant three–body phase space.
- Dip around 4.14 GeV/c^2 modelled by destructive interference with a new X(4140) state.



- K–Matrix model can partially be used to model spectrum, suggests strong coupling of $J/\psi\ \phi \rightarrow D_s^+ D_s^-$.

	Mass (MeV/c^2)	Width (MeV/c^2)	J^{PC}
$\chi_{c0}(3930)$	3921.7 ± 1.8	18.8 ± 3.5	0^{++}
X(3960)	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	0^{++}

- Mass and width are consistent within 2.5σ.
- Coupled channel effects mean mass doesn't need to be same.
  - Coupling to $s\bar{s}$ is suppressed relative to $u\bar{u}$.
  - X$\to D_s^+ D_s^-$ near threshold has much smaller phase space than X$\to D^+ D^-$.
  - $\therefore$ $D^+ D^-$ should have much higher $\mathcal{B}$ than $D_s^+ D_s^-$.
- If we assume $\chi_{c0}(3930)$ and X(3960) are the same state:

$$\frac{\mathcal{B}(X \to D^+ D^-)}{\mathcal{B}(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+ D^- K^+) FF^X_{D^+ D^- K^+}}{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+) FF^X_{D_s^+ D_s^- K^+}}$$

$$= 0.29 \pm 0.09(stat.) \pm 0.10(syst.) \pm 0.08(ext.)$$

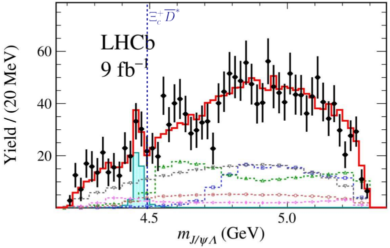
- If X(3960) and χ_{c0}(3930) are same state then cannot be conventional charmonium.
- First observation of $B^+ \to D_s^+ D_s^- K^+$ decay.
- Relative branching fraction measured:

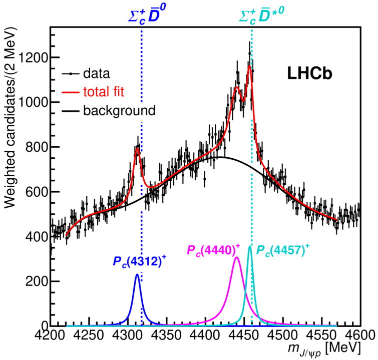
$$\mathcal{R} = \frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033(stat.) \pm 0.027(syst.) \pm 0.034(ext.)$$

- X(3960) observed at high significance (>12σ).
- Favours an exotic ($c\bar{c}s\bar{s}$) state with $J^{PC} = 0^{++}$ (>9σ).
- Evidence of a potentially new X_0(4140) state (<4σ).
- More studies needed.

Observation of a $J/\psi\Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \to J/\psi\Lambda\overline{p}$

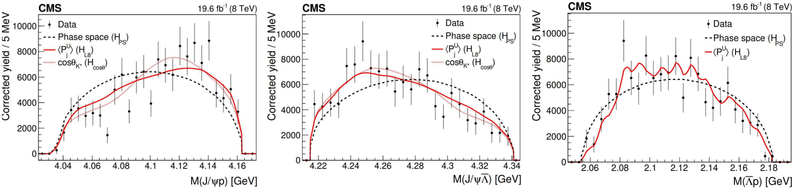
- Pentaquarks seen at LHCb have often been noted to be close to charm–hadron thresholds. (Sci.Bull.66(2021), PRL (**122**), 222001 (2019))
- $B^- \to J/\psi \Lambda \overline{p}$ decay allows to search near thresholds of $\Xi_c D^-$, $\Lambda_c^+ D_s^-$ and $\Lambda_c^+ \overline{D}^0$.





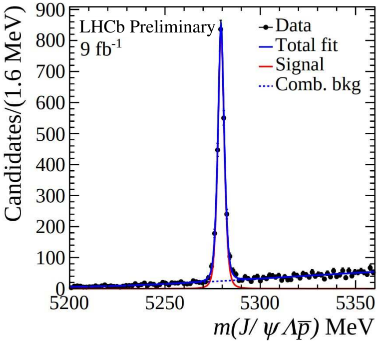
- $P_{\psi s}^{\Lambda}$ candidates have been predicted by theorists – Progr.Phys.41(2021)65–93.

- CMS results with 19.6 fb^{-1} ($\sim$450 events) finds that data are inconsistent with purely phase space contributions. (JHEP12(2019)100)



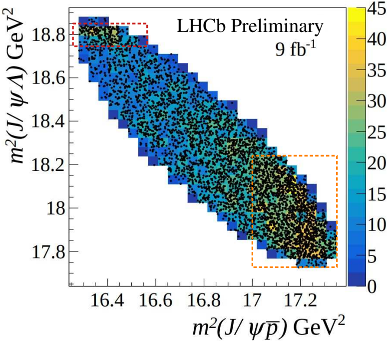
- Data are consistent with K^* contributions.

Uses full LHCb dataset ($9\,\mathrm{fb}^{-1}$).



- Small Q value ($\sim$128 MeV/c^2) – 2 MeV/c^2 resolution.
- Only uses decays where Λ decays in Velo.
- Only uses tracks that go through the entire tracking system.
- Most precise measurement of B^+ mass.
- B^+ yield – 4617 ± 73 with 93% purity.

$$m_{B^+} = 5279.44 \pm 0.05(stat.) \pm 0.07(syst.)\,\mathrm{MeV}/c^2$$



- Narrow structure in $J/\psi\Lambda$.
- Broad structure in $J/\psi p$.
- Reflections from $K^*{}_{2,3,4}$?
- Amplitude analysis needed to determine.

K^* Amplitude Model

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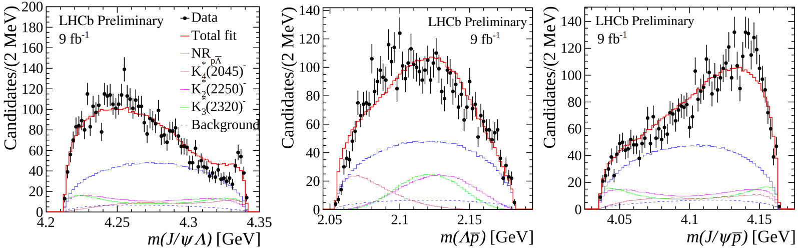
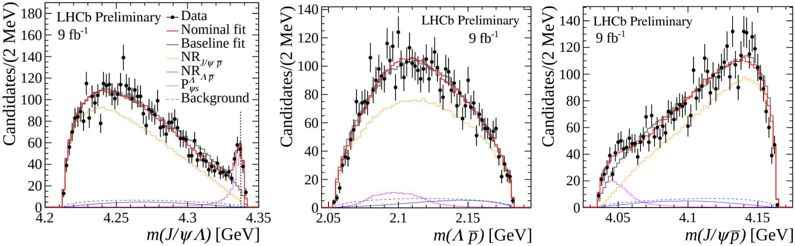
- Try first a model with $K^*_{2,3,4}$ and NR($\overline{p}\Lambda$).
- $K^*_{2,3,4}$ does not peak in phase space – no evidence of contribution to $\overline{p}\Lambda$.



Resonance	Mass (MeV)	Width (MeV)
$K_2(2250)^+(2^-)$	2247 ± 17	180 ± 30
$K_3(2320)^+(3^+)$	2324 ± 24	150 ± 30
$K_4^*(2045)^+(4^+)$	2045 ± 9	198 ± 30

- χ^2/ndf = 123/33.
- K^* model cannot describe data.
- LHCb dataset has more events than CMS.

- Model containing NR($\bar{p}\Lambda$), NR($\bar{p}J/\psi$) and $P_{\psi s}^{\Lambda}$.



- χ^2/ndf = 55.3/39, $\sim$15σ significance.
- Spin $1/2$, with $1/2^+$ preferred, $1/2^-$ rejected at 90% CL.

$$m = 4338.2 \pm 0.7(stat.) \pm 0.4(syst.)\,\mathrm{MeV}/c^2$$

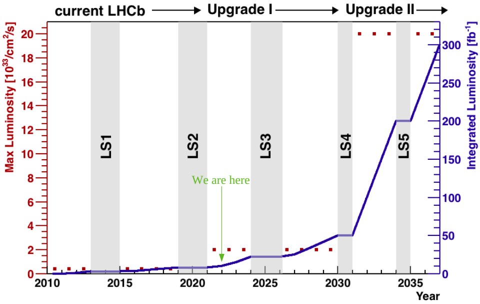
$$\Gamma = 7.0 \pm 1.2(stat.) \pm 1.3(syst.)\,\mathrm{MeV}$$

Some new and interesting results discussed:

- Brief summary of new naming convention.
- Two new tetraquarks $T^{a}_{c\bar{s}0}(2900)^{++/0}$ – first observation of a doubly charged tetraquark.
- One new X structure X(3960) – lots of discussion on its exact structure and distinction from other X states.
- Evidence for $X_0(4140)$.
- One new pentaquark $P^{\Lambda}_{\psi s}(4338)^0$.

But this is not the end for LHCb:

- Run 1+2 results are still to come.
- Run 3+4 dataset will be ~10x larger than current dataset (arXiv:1808.08865).
- Improved trigger means cleaner hadronic events.

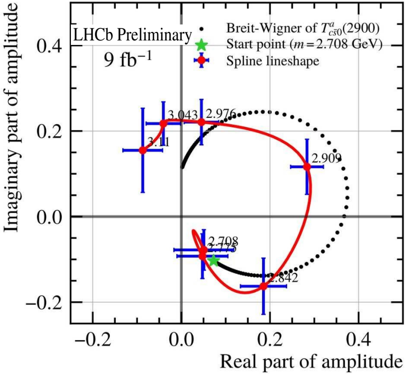


- Stay tuned to LHCb!

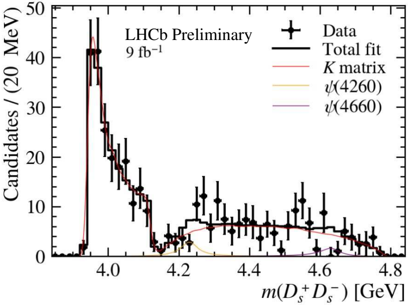
Thanks for listening!

Backup slides

- Spline lineshape is consistent with BW description of resonance.



- The dip around 4.14 GeV/c^2 is near the $J/\psi\phi$ threshold, so can instead be modelled with a K–matrix:



- But leads to large errors in fit parameters.
- Baseline model is preferred.

β_1	-1.2 ± 4.5
f_{11}	0.8 ± 1.2
f_{22}	8.0 ± 5.1

Alternative 1:

- Introducing second $P^{\Lambda}_{\psi s}$ yields $\sim 1.2\sigma$ significance.
- More data needed.
- $\Lambda_c^+ D_s^-$ threshold is $\sim$4255 MeV/c^2.

$$m = 4255 \pm 0.4\,\text{MeV}/c^2, \Gamma = 2.0 \pm 1.1\,\text{MeV}/c^2$$

Alternative 2:

- Use BW to model m($\overline{p}J/\psi$) lineshape.
- Model prefers to use second order polynomial for NR($\overline{p}J/\psi$) rather than BW.
- $-2\Delta log\mathcal{L}$ = 80 w.r.t. nominal fit.