Exotic tetraquarks at LHCb

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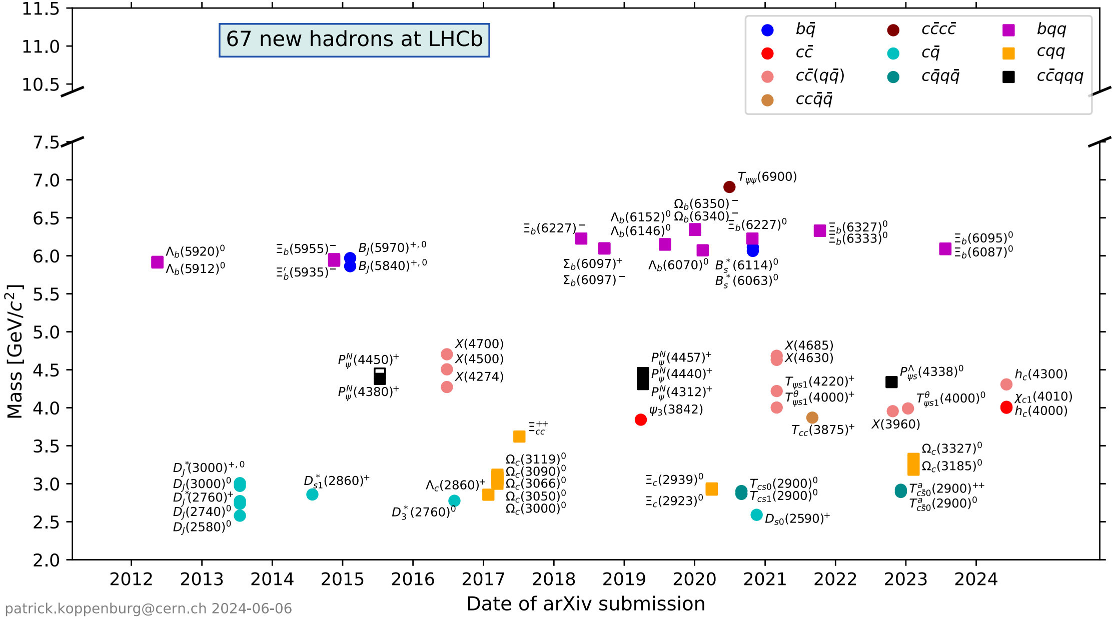
On behalf of the LHCb collaboration

The spectroscopy programme at LHCb



Conventional heavy-hadron spectroscopy

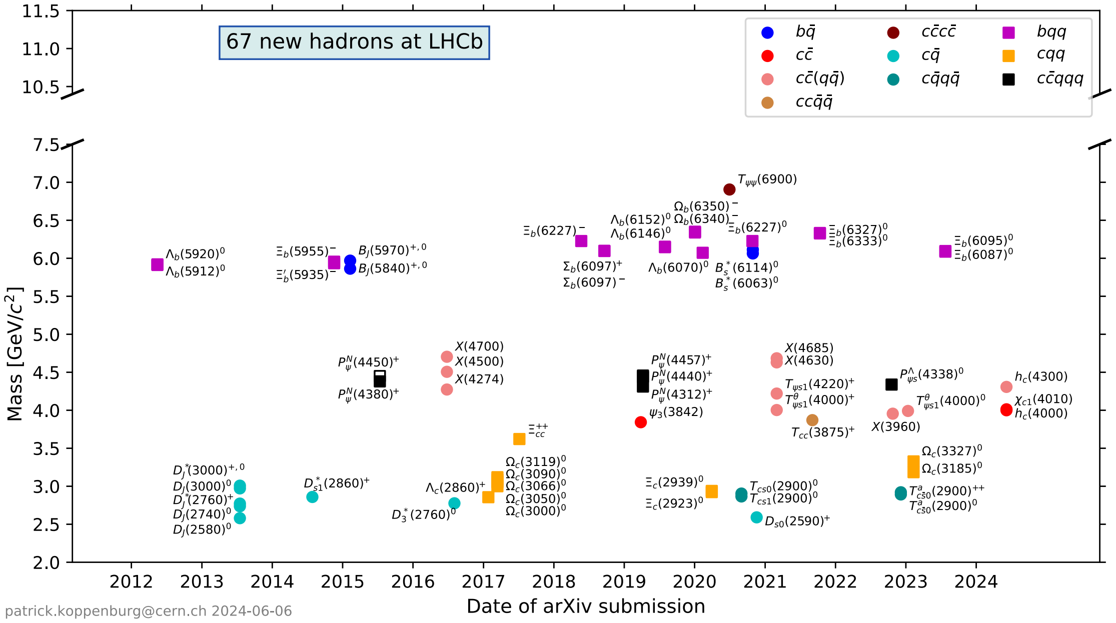
- Excited open-flavour mesons
- Excited conventional charmonia
- Excited heavy baryons

Exotic heavy-hadron spectroscopy

- 23 new exotic states discovered
- Charged, $c\bar{c}$, $cc\bar{c}\bar{c}$, open flavour
- Pentaquark candidates
- Search for unexpected contributions

NB: naming scheme is evolving following a suggestion from LHCb which was partially accepted in the 2024 PDG edition

The spectroscopy programme at LHCb



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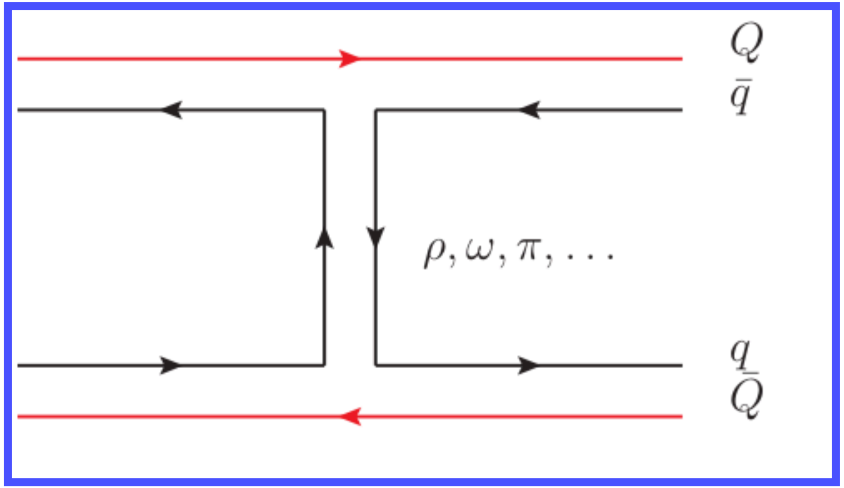
Today: focus on the most recent results on tetraquark states

Exotic hadrons as multiquark states

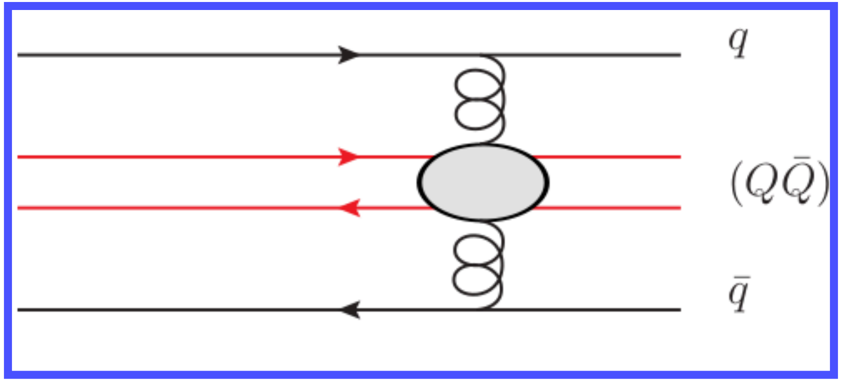
Mesonic/baryonic molecule

- Low binding energy, narrow states
- Orbital excitations suppressed
- Independently decaying components
- Mass close to two-body thresholds



Compact tetraquark/pentaquark

- Tightly bound states
- Large prompt production at high p_T
- Rich isospin splitting
- Charged isospin partners predicted



[Phys. Rep. 668 (2017) 1-97], [arXiv:1905.13156]

Hidden and explicit heavy exotics

Hidden exotics

- Minimal quark content "mimics" regular hadronic structure
- $[c\bar{c}u\bar{u}]$, $\left[c\bar{c}d\bar{d}\right]$…
- Careful study needed
- Establish quantum numbers
- Measure production cross-section
- Unusual mass and/or width

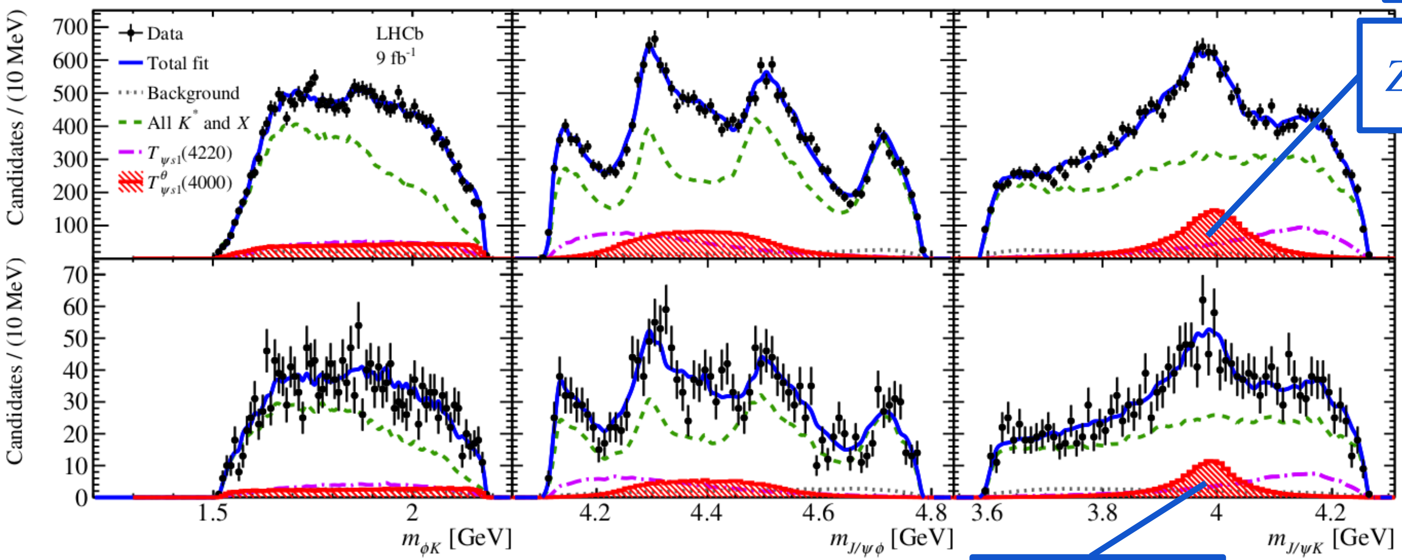
Explicit exotics

- Minimal quark content shows up as manifestly exotic
- "Charged quarkonia" such as Z_c^+, Z_b^+ with $\left[c\bar{c}u\bar{d}\right]$ or $\left[b\bar{b}u\bar{d}\right]$
- Open-flavour tetraquarks: $\left[c\bar{s}u\bar{d}\right]$
- Doubly charm tetraquarks: $\left[c\bar{u}c\bar{d}\right]$
- Fully charm tetraquarks: $[cc\bar{c}\bar{c}]$
- Pentaquarks: $\left[c\bar{c}uud\right]$, $\left[c\bar{c}uds\right]$…

HIDDEN TETRAQUARKS

Neutral isospin partner of the $Z_{cs}(4000)^+$ (aka $T_{c\bar{c}\bar{s}1}(4000)^+$)

Minimal quark content
$[c\bar{c}u\bar{s}]$

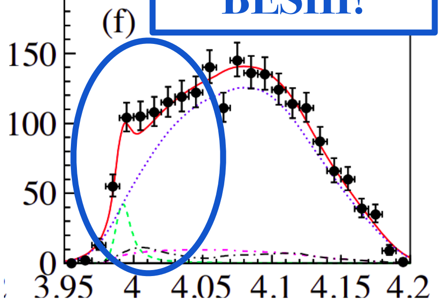


$B^+ \to J/\psi \phi K^+$

$B^0 \to J/\psi \phi K^0_s$

- Search for an isospin partner of the $Z_{cs}(4000)^+$ in the isospin-conjugate decay channel $B^+ \to J/\psi \phi K^+$
- Amplitude model includes 9 excited K^* states and the 9 already observed exotics
- Evidence for a new state at 4σ significance!
- Mass difference $\Delta M = 12^{+11+6}_{-10-4}$ MeV is consistent with isospin partners

Also seen by BESIII!

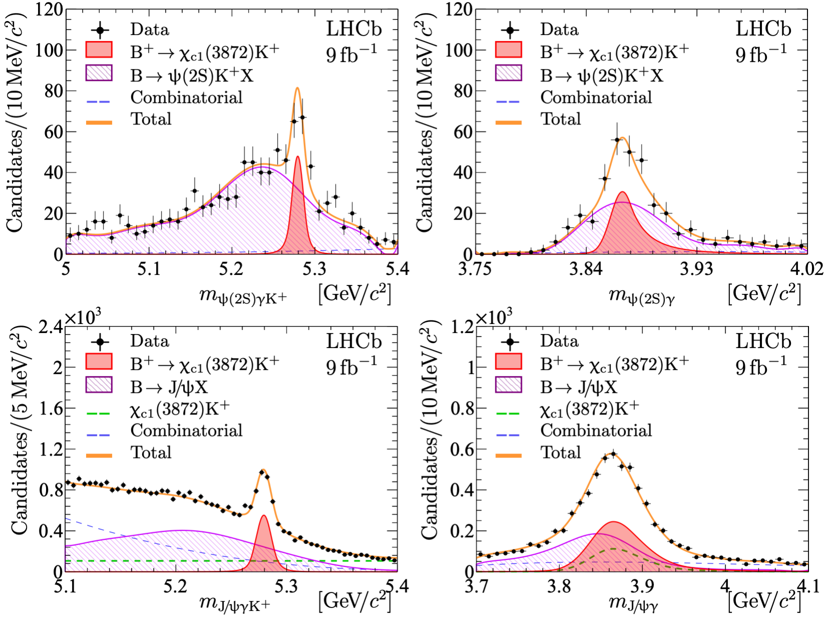


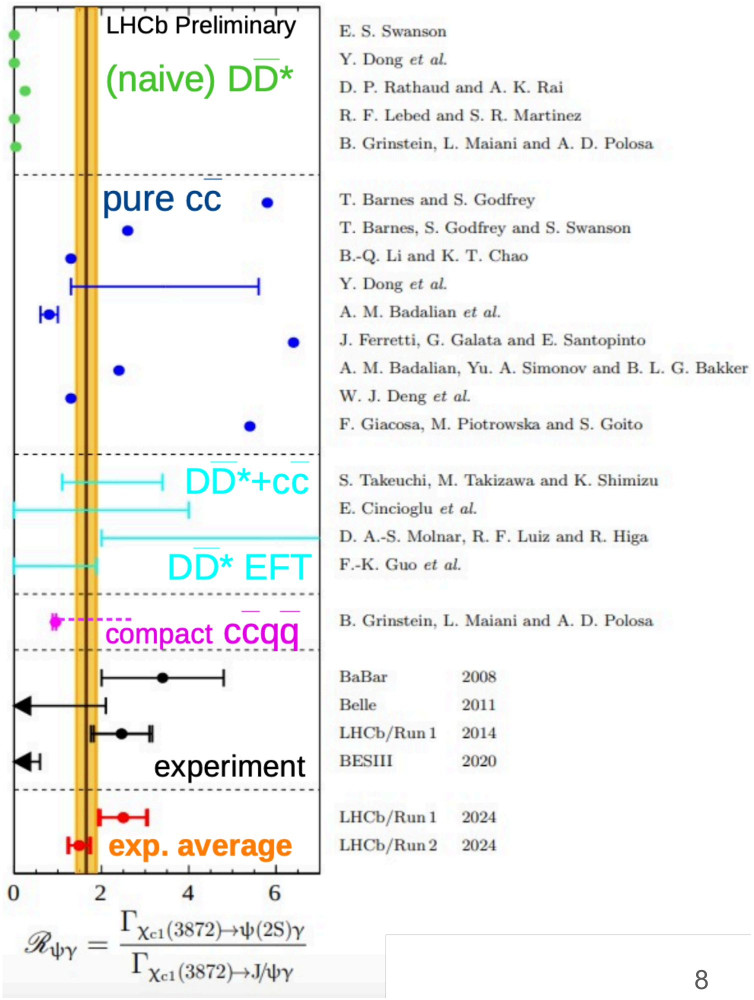
[PRL 127 (2021) 082001], [PRL 131 (2023) 13901]

Radiative decays of the $\chi_{c1}(3872)$

Measurement of the ratio $\mathscr{R}_{\psi\gamma} = \dfrac{\mathscr{B}\left(B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)\, K^+\right)}{\mathscr{B}\left(B^+ \to (\chi_{c1}(3872) \to J/\psi\gamma)\, K^+\right)}$

First observation of the $\chi_{c1}(3872) \to \psi(2S)\gamma$ decay (6σ)





$\mathscr{R}_{\psi\gamma} = \dfrac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$

[arXiv:2406.17006], submitted to JHEP

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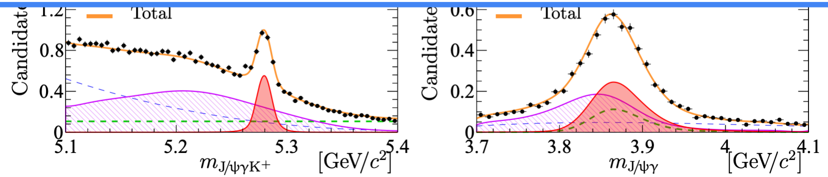
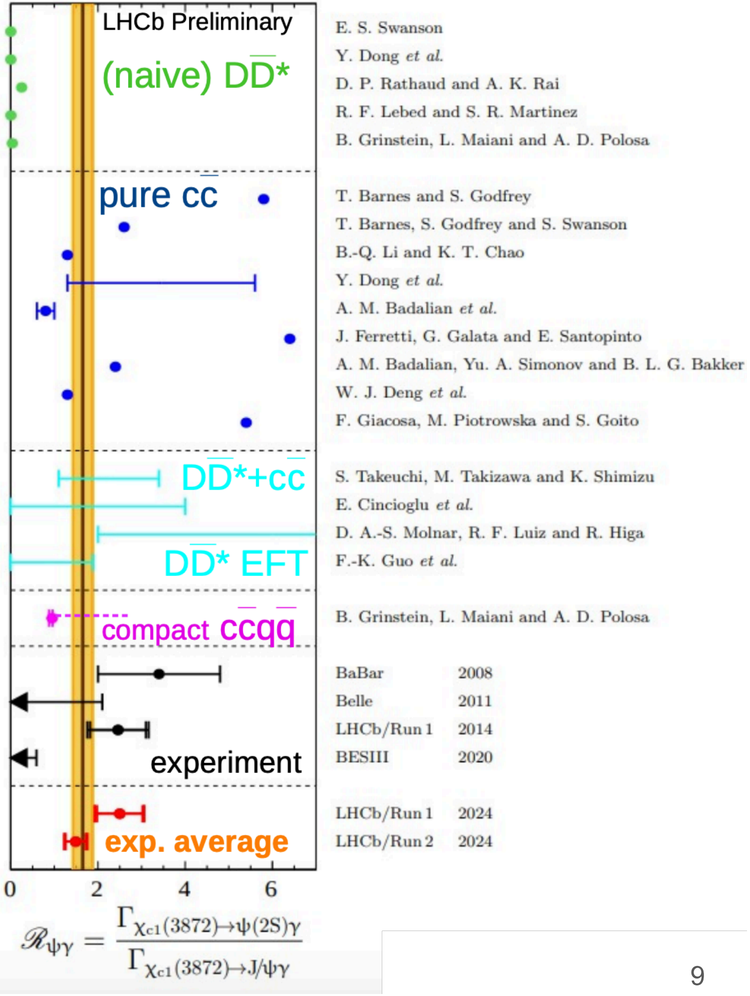
First observation of the $\chi_{c1}(3872) \to \psi(2S)\gamma$ decay (6σ)

$$\mathscr{R}_{\psi\gamma}^{\text{Run 1}} = 2.50 \pm 0.52^{+0.20}_{-0.23} \pm 0.06$$
$$\mathscr{R}_{\psi\gamma}^{\text{Run 2}} = 1.49 \pm 0.23^{+0.13}_{-0.12} \pm 0.03$$

$$\mathscr{R}_{\psi\gamma}^{\text{Comb}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

Strong indication of a sizeable compact component





[arXiv:2406.17006], submitted to JHEP

CHARGED AND OPEN-FLAVOUR TETRAQUARKS

The first open-charm tetraquarks: X(2900)

Minimal quark content
$[\bar{c}d\bar{s}u]$

Amplitude analysis of the $B^+ \to D^+D^-K^+$ channel shows discrepancies

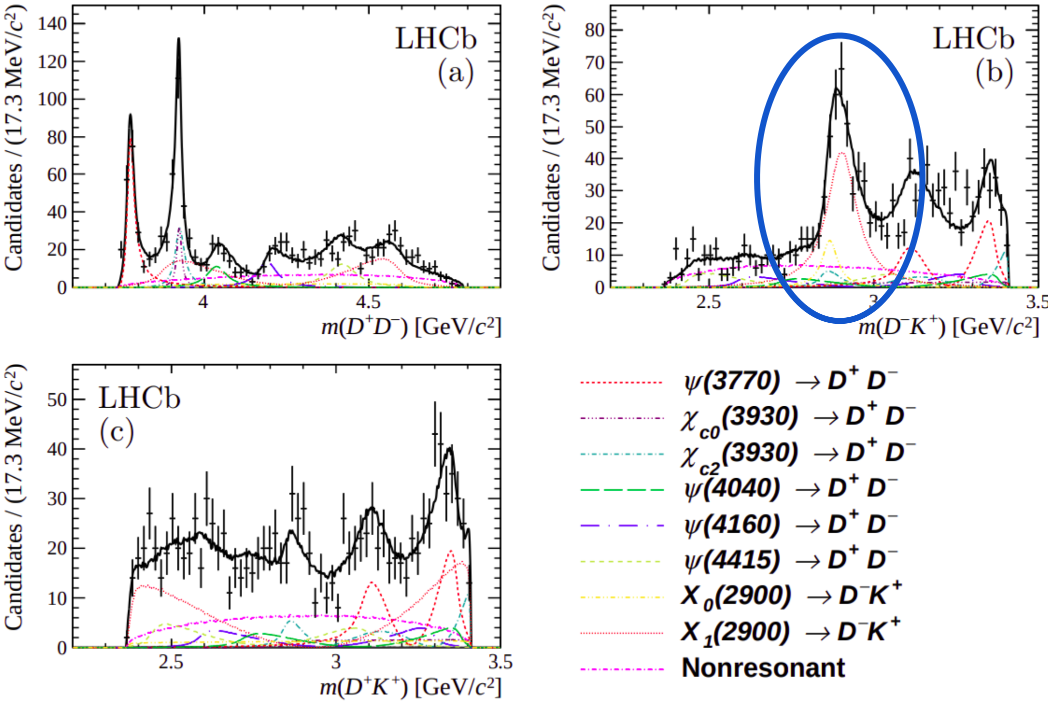
Known excited charmonia cannot explain the mass spectrum

No conventional resonance is expected in the D^-K^+ final state

Two new states are needed to describe the data!

- $X_0(2900)$ aka $T^*_{cs0}(2870)^0$
- $X_1(2900)$ aka $T^*_{cs1}(2900)^0$

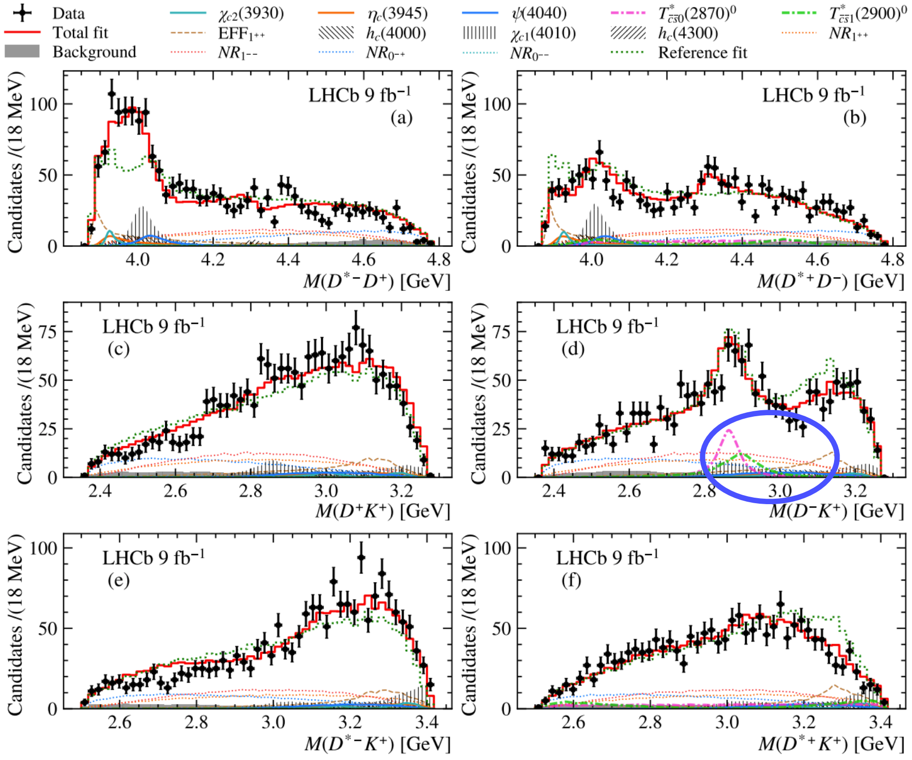
First observation of an exotic state without heavy quark-antiquark



[PRD 102 (2020) 112003]

Amplitude analysis of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

Minimal quark content
$[\bar{c}d\bar{s}u]$



Confirmation of the states previously observed in the $B^+ \to D^+ D^- K^+$ channel. Fit fractions:

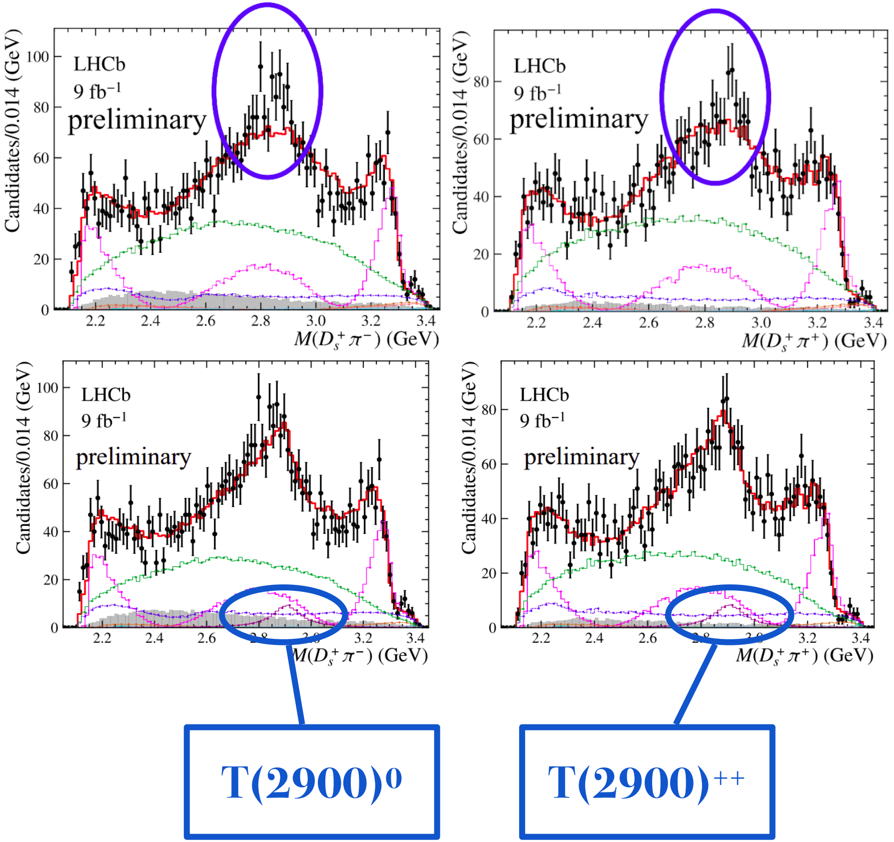
- $\sim$6% each for $T^{*0}_{cs\{0,1\}} \to D^- K^+$
- < 1.5 % for $T^*_{cs1}(2900)^0 \to D^{*-} K^+$ (95% CL)
- < 3.3 % for $T^*_{cs0}(2900)^{++} \to D^+ K^+$ (95% CL)

Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

[arXiv:2406.03156], submitted to PRL

Amplitude analysis of $B \to DD_s\pi$ decays

Minimal quark content
$[c\bar{s}d\bar{u}]$, $[c\bar{s}u\bar{d}]$



Joint amplitude analysis linked through isospin symmetry

- $B^+ \to D^- D_s^+ \pi^+$ (left)
- $B^0 \to \bar{D}^0 D_s^+ \pi^-$ (right)

Two new exotic states necessary to describe the resonant structure (one per channel)

- $T^*_{c\bar{s}0}(2900)^0$
- $T^*_{c\bar{s}0}(2900)^{++}$
- Quantum numbers $J^P = 0^+$

Not the same as the $T^*_{cs0}(2870)^0$ observed in $B^+ \to D^+ D^- K^+$ decays

Different quark content: $[c\bar{d}s\bar{u}]$

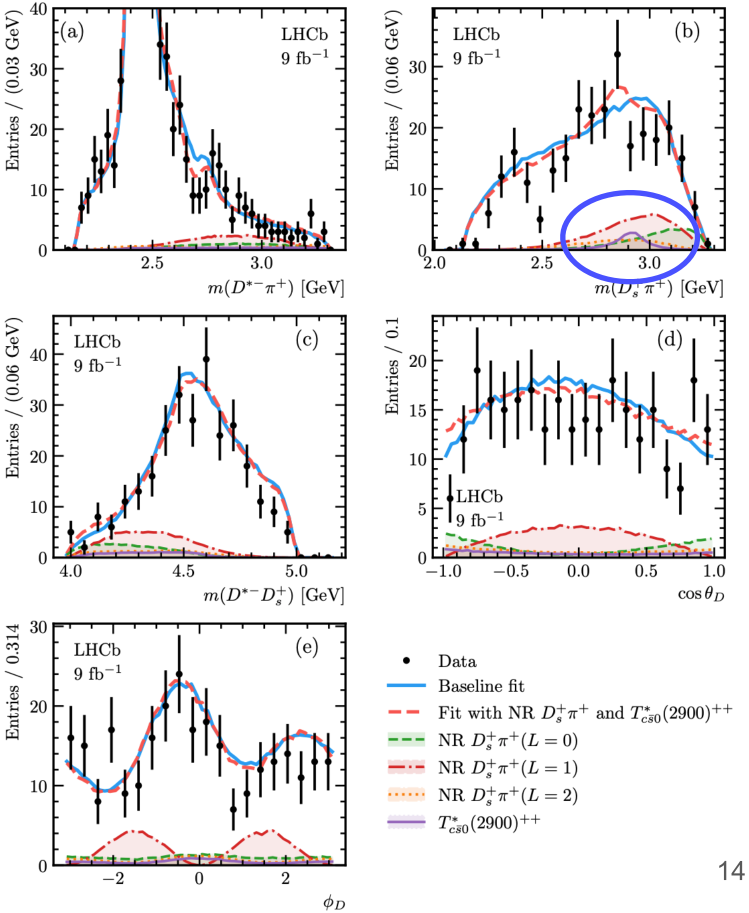
[PRL 131 (2023) 041902], [PRD 102 (2020) 112003]

Amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$ decays

The $T(2900)^{++}$ state has been also searched in $B^+ \to D^{*-} D_s^+ \pi^+$ decays

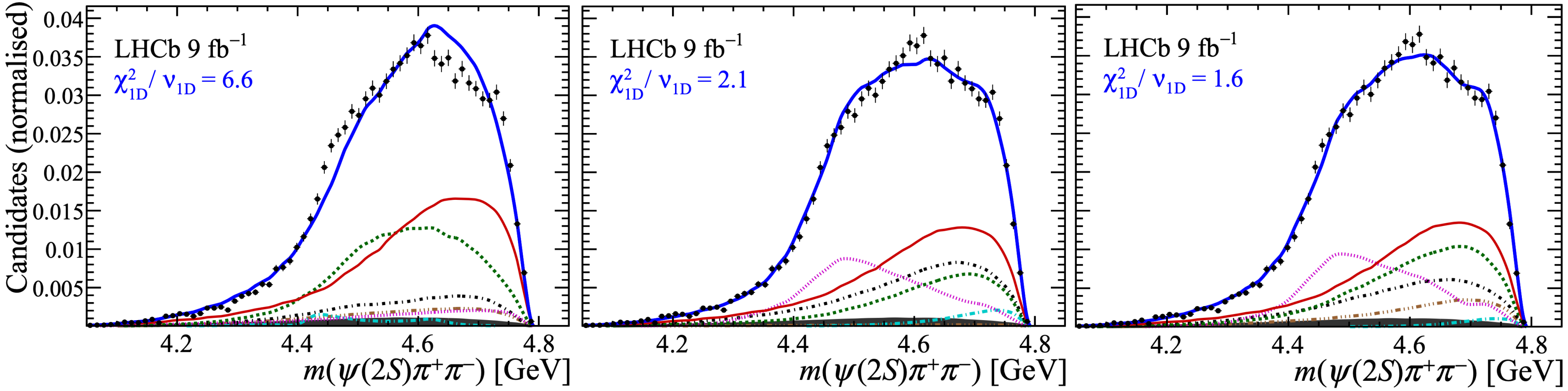
No strong evidence of exotics states contributing to the total decay amplitude

Fit fraction of $T^*_{c\bar{s}0}(2900)^{++} \to D_s^+ \pi^+$ is found to be less than 2.3% at 90% CL



[arXiv:2405.00098], submitted to JHEP

Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decays



8 known excited $K' \to K\pi\pi$ 3 known excited $\psi^* \to \psi(2S)\pi\pi$ No exotic states	6 known excited $K' \to K\pi\pi$ 1 known excited $\psi^* \to \psi(2S)\pi\pi$ 8 "known" $T \to \psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$	6 known excited $K' \to K\pi\pi$ 1 known excited $\psi^* \to \psi(2S)\pi\pi$ 8 "known" $T \to \psi(2S)\pi\pi, \psi(2S)\pi$ or $\psi(2S)K$ 3 new exotic states

$T_{c\bar{c}\bar{s}1}(4600)^0 \to \psi(2S)K\pi$
$T_{c\bar{c}\bar{s}1}(4900)^0 \to \psi(2S)K\pi$
$T^*_{c\bar{c}\bar{s}1}(5200)^0 \to \psi(2S)K\pi$

7D amplitude analysis, using a model-building algorithm to iteratively add contributions to the total amplitude.

Interpretation of results is not straightforward.

Solid groundwork for subsequent investigations into similar decay modes.

[arXiv:2407.12475], submitted to JHEP

CONCLUSIONS AND PROSPECTS

Conclusions and prospects

After more than 20 years, the field of exotic spectroscopy is still mostly an unexplored territory!

- Unveil the true nature of X(3872): are the observed exotics molecules, compact states or something else?
- Tetraquarks, pentaquarks and more: do six-quark bound states exist?
- Direct line with open-flavour exotics: the removal of the hardware trigger in LHCb allows studies on fully-hadronic final states starting from Run 3 data
- Increased sensitivity: sensitivity of spectroscopy studies is highly increased due to the higher efficiency of the LHCb topological trigger in Run 3
- Heavyweight championship: the T_{cc} state has been observed, how about T_{bc} and T_{bb} ?
- Production mechanisms: what is the connection between exotics production and event multiplicity? Do all exotics form through coalescence?

More than 30% of the new hadrons discovered at LHC experiments are exotics

Exotic hadrons are not rare!

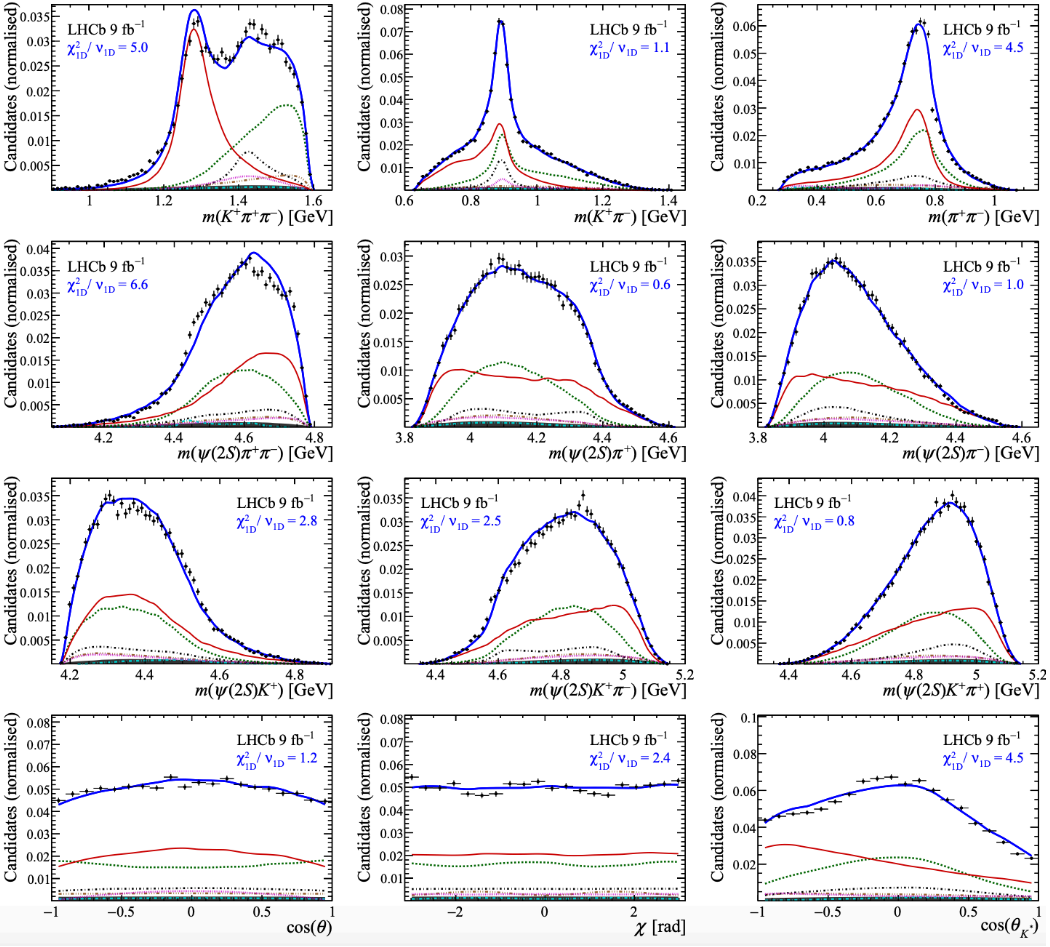
Plenty of new exciting results are guaranteed in the near future!

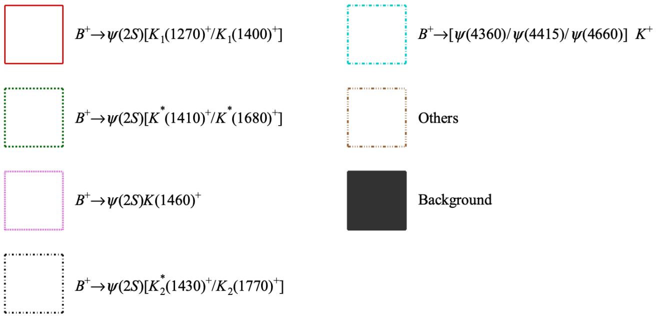
BACKUP

Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decays

Fit projections

6 known excited $K' \to K\pi\pi$
1 known excited $\psi^* \to \psi(2S)\pi\pi$
No exotics





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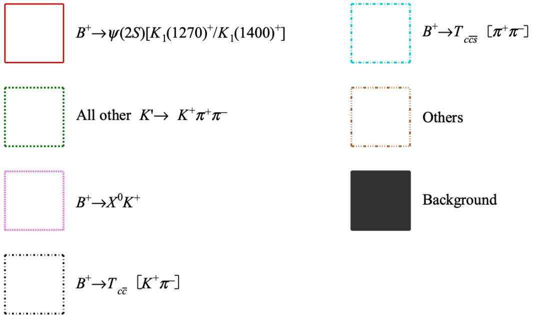

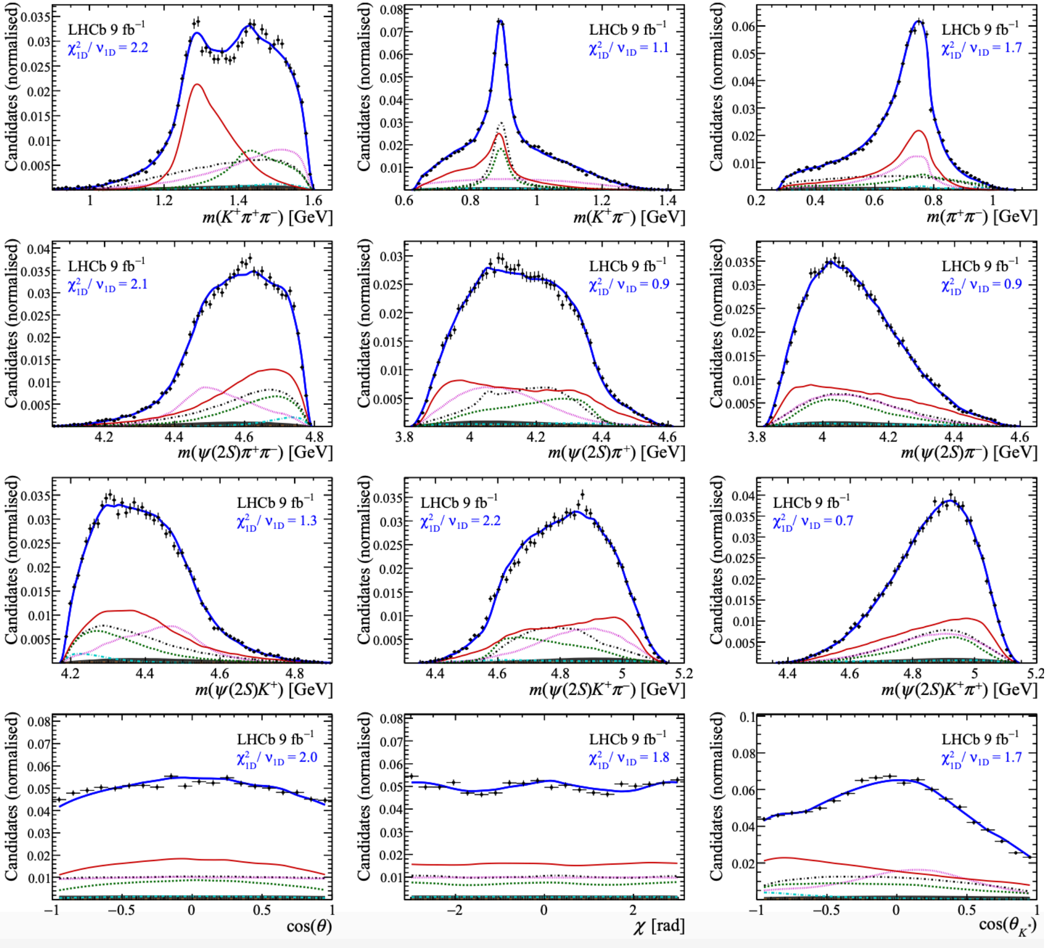

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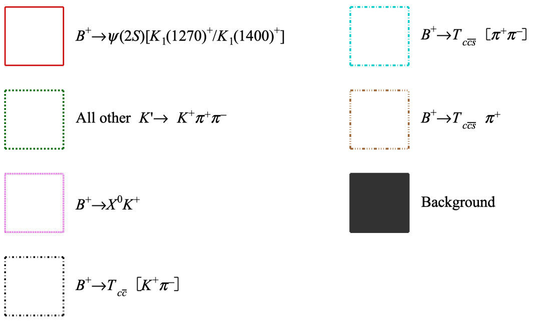
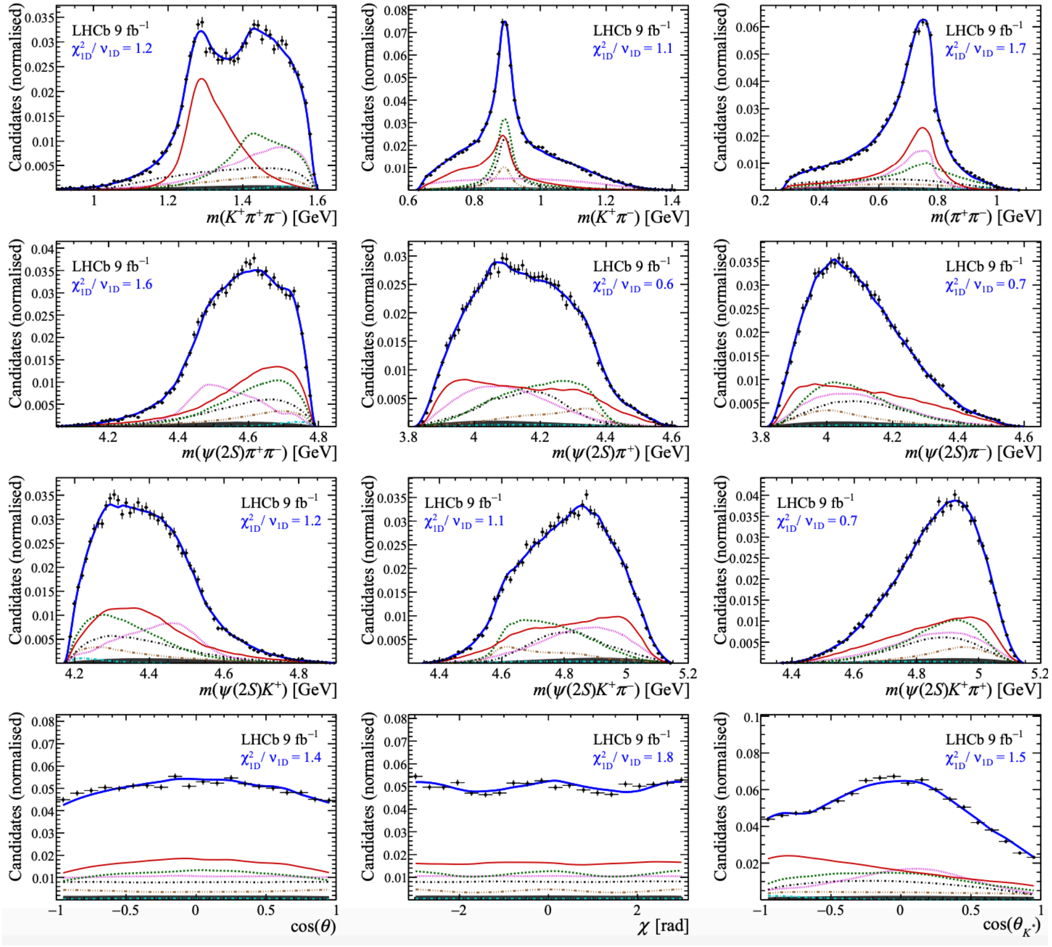
3 new exotic states





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