Recent highlights from the LHCb experiment

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On behalf of the LHCb collaboration

Science and Technology Facilities Council

Arnau Brossa Gonzalo (1993-2024)

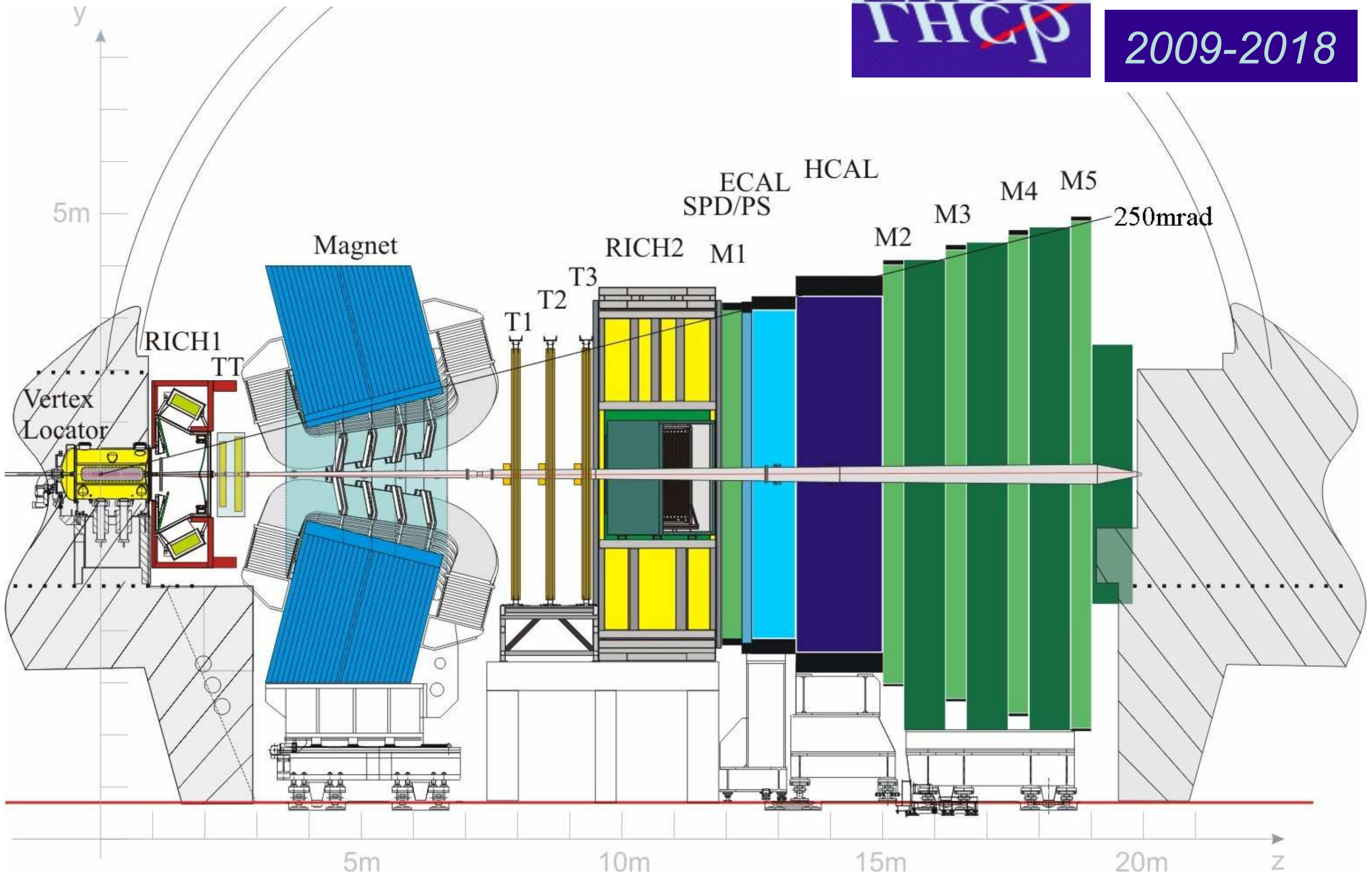
The LHCb experiment

- Designed to study weak decays of heavy hadrons
  - Excellent track and vertex resolution provides high purity samples (>90%) easily for fully reconstructed decays

- Heavy hadrons decay into almost infinite final states
  - Study those decay products in a quasi-background free environment

Original

2009-2018

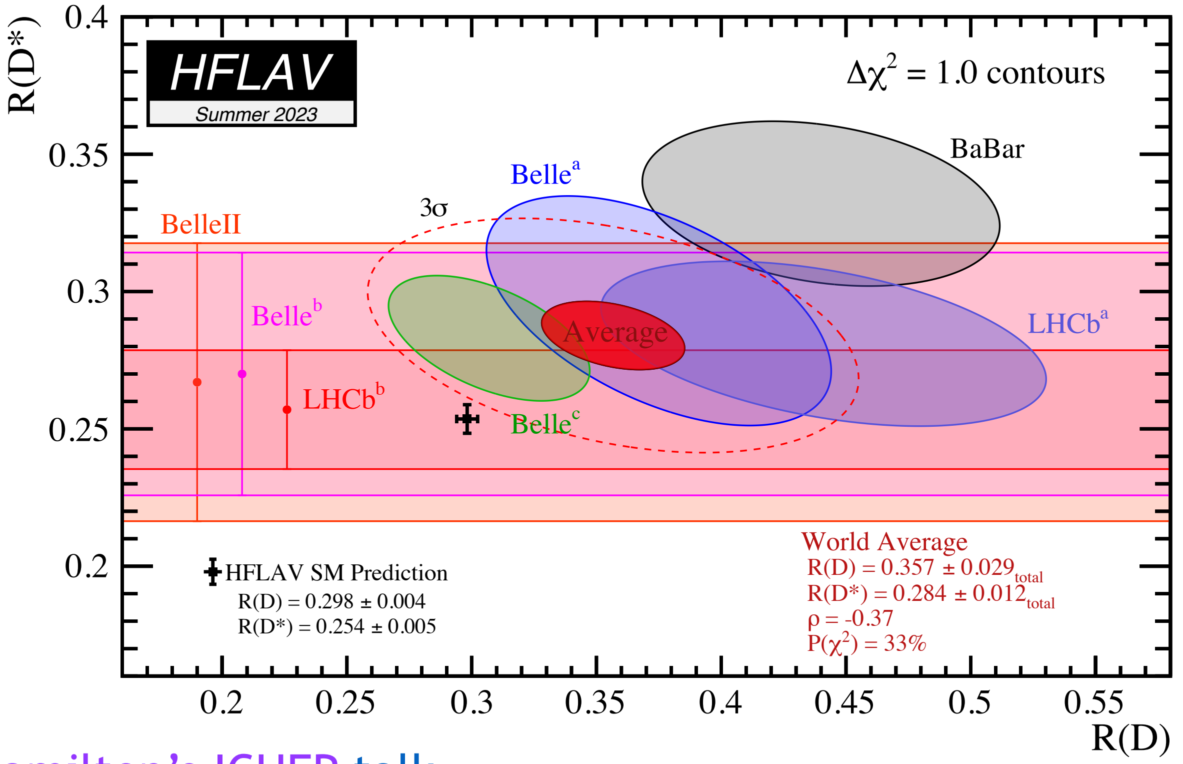


Lepton flavour universality

- Anomalies seen in ratios of decay rates of semi—leptonic decays
  - For beauty hadron decays

$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\mu^-\bar{\nu}_\mu)} \qquad R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\mu^-\bar{\nu}_\mu)}$$

- Measurements from BaBar, Belle(II) and LHCb
  - Approximately 3 sigma tension with the SM prediction



- Need new results!

For more details see P. M. Hamilton's ICHEP talk

Latest on $R(D^+)$ and $R(D^{*+})$

- Latest LHCb result focuses on $R(D^+)$ and $R(D^{*+})$
  - Dataset from 2015+2016

- Processes included

$$B \to D^+ \mu^- \nu_\mu$$

$$B \to D^+ \tau^- (\to \mu^- \bar{\nu}_\mu \nu_\tau)\, \nu_\tau$$

$$B \to D^{*+} (\to D^+ \pi^0)\, \mu^- \nu_\mu$$

$$B \to D^{*+} (\to D^+ \pi^0)\, \tau^- (\to \mu^- \bar{\nu}_\mu \nu_\tau)\, \nu_\tau$$

The reconstructed final state is always $D^+ \mu^-$!

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- Latest LHCb result focuses on $R(D^+)$ and $R(D^{*+})$
  - Dataset from 2015+2016

- Processes included

$$B \to D^+ \mu^- \not{\nu}_\mu$$

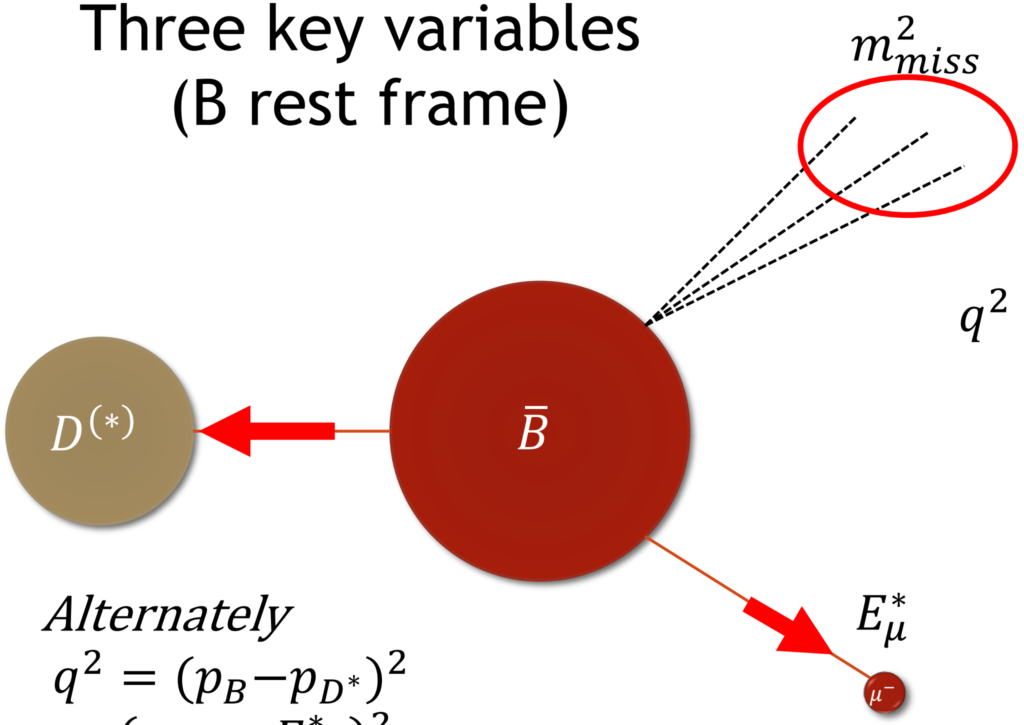
$$B \to D^+ \tau^- (\to \mu^- \not{\bar{\nu}}_\mu \not{\nu}_\tau) \not{\nu}_\tau$$

$$B \to D^{*+} (\to D^+ \not{\pi}^0) \mu^- \not{\nu}_\mu$$

$$B \to D^{*+} (\to D^+ \not{\pi}^0) \tau^- (\to \mu^- \not{\bar{\nu}}_\mu \not{\nu}_\tau) \not{\nu}_\tau$$

The reconstructed final state is always $D^+\mu^-$!

Three key variables (B rest frame)

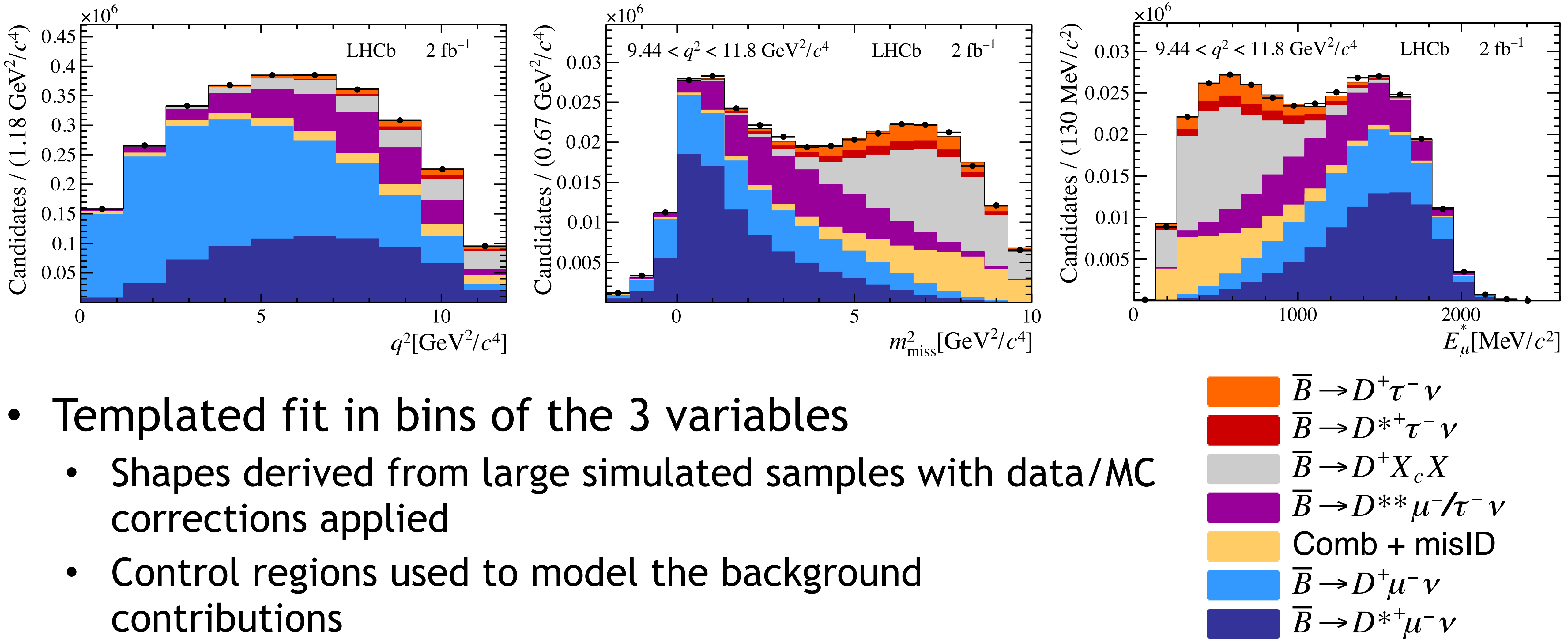


$$q^2 = (p_\ell + p_\nu)^2 = m^2_{W^*}$$

Alternately

$$q^2 = (p_B - p_{D^*})^2 = (m_B - E^*_{D^*})^2$$

Latest on $R(D^+)$ and $R(D^{*+})$



- Templated fit in bins of the 3 variables
  - Shapes derived from large simulated samples with data/MC corrections applied
  - Control regions used to model the background contributions

Lepton flavour universality

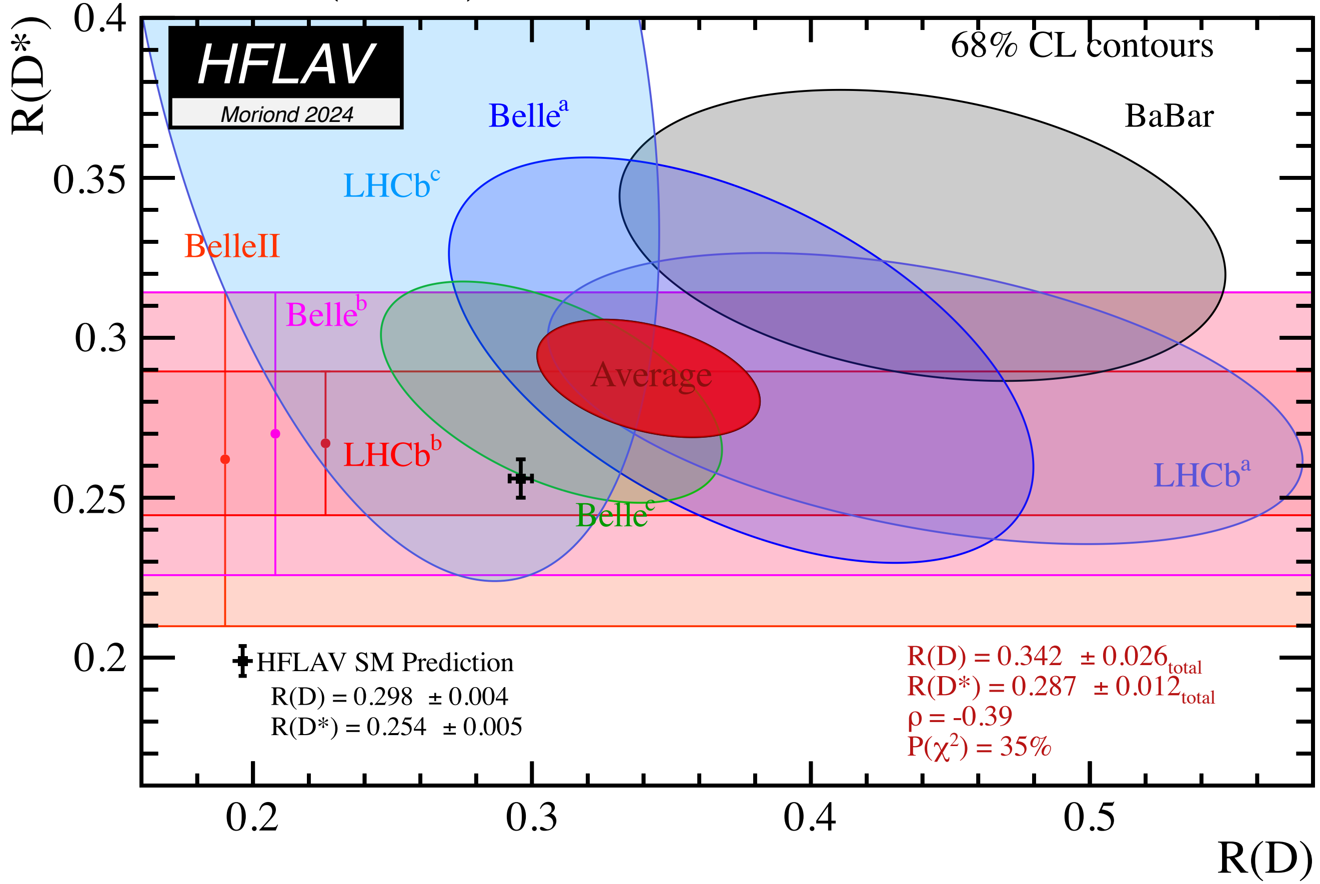
- Tension remains around 3σ
  - Results complimentary to those using D^0 mesons

$$R(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$R(D^*) = 0.281 \pm 0.018 \pm 0.023$$

- Work in progress
  - Lots more to come from Run 1&2
  - Full Run2 updates
  - Angular analyses
  - New modes from LHCb

$$B^- \to \rho^0 \mu^- \bar{\nu}_\mu \qquad \Lambda \to p \mu^- \bar{\nu}_\mu$$
$$B_c^- \to D^0 \mu^- \bar{\nu}_\mu$$

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$



Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

- Electronic version is the famous mode
  - Investigate the discrepancies seen in the muonic mode with electrons
  - Previous results from Belle for this channel
- Angular distributions
  - F_L longitudinal polarisation
  - θ_l angle between electron (dielectron r.f.) and dielectron (B r.f.)
  - θ_K angle between kaon (K* r.f.) and K* meson (B r.f.)
  - ϕ angle between the dielectron and K* decay planes

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-FL)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\tfrac{4}{3}A_{\rm FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

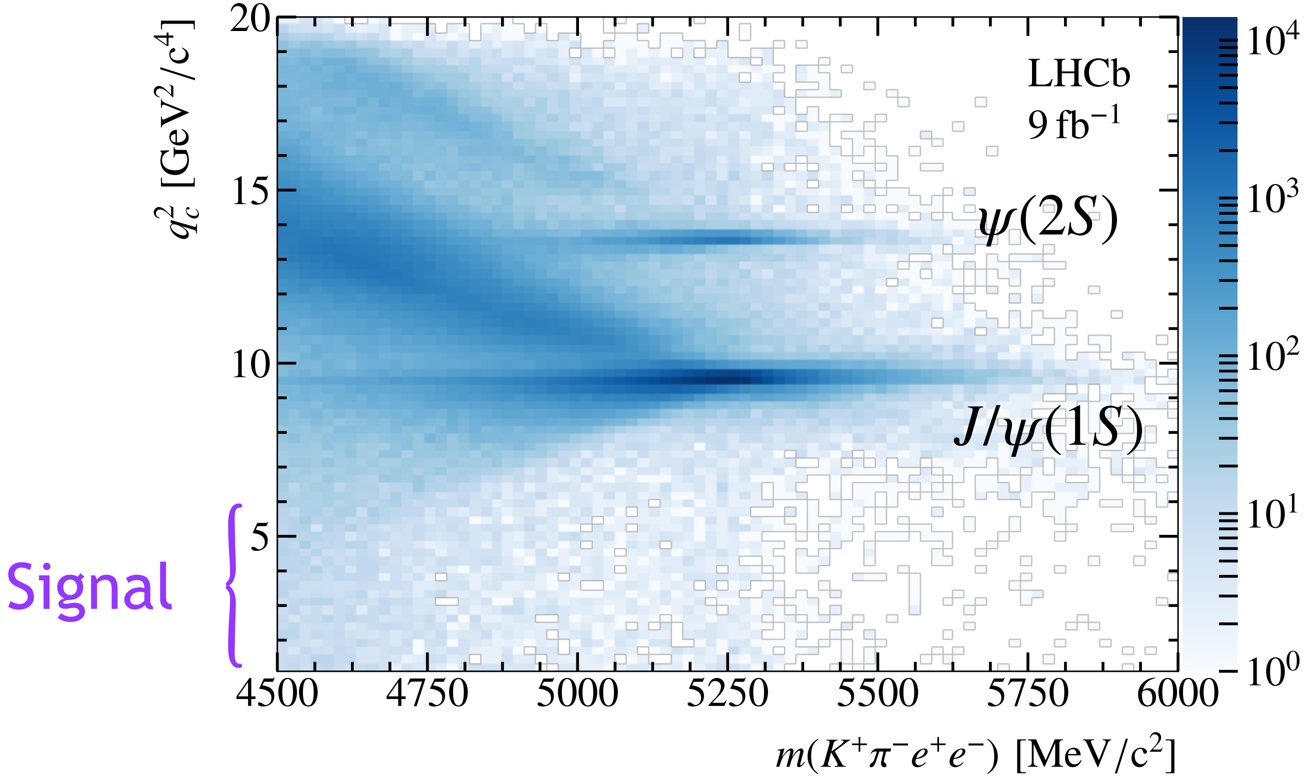
For more details see R. Silva Coutinho's ICHEP talk

Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

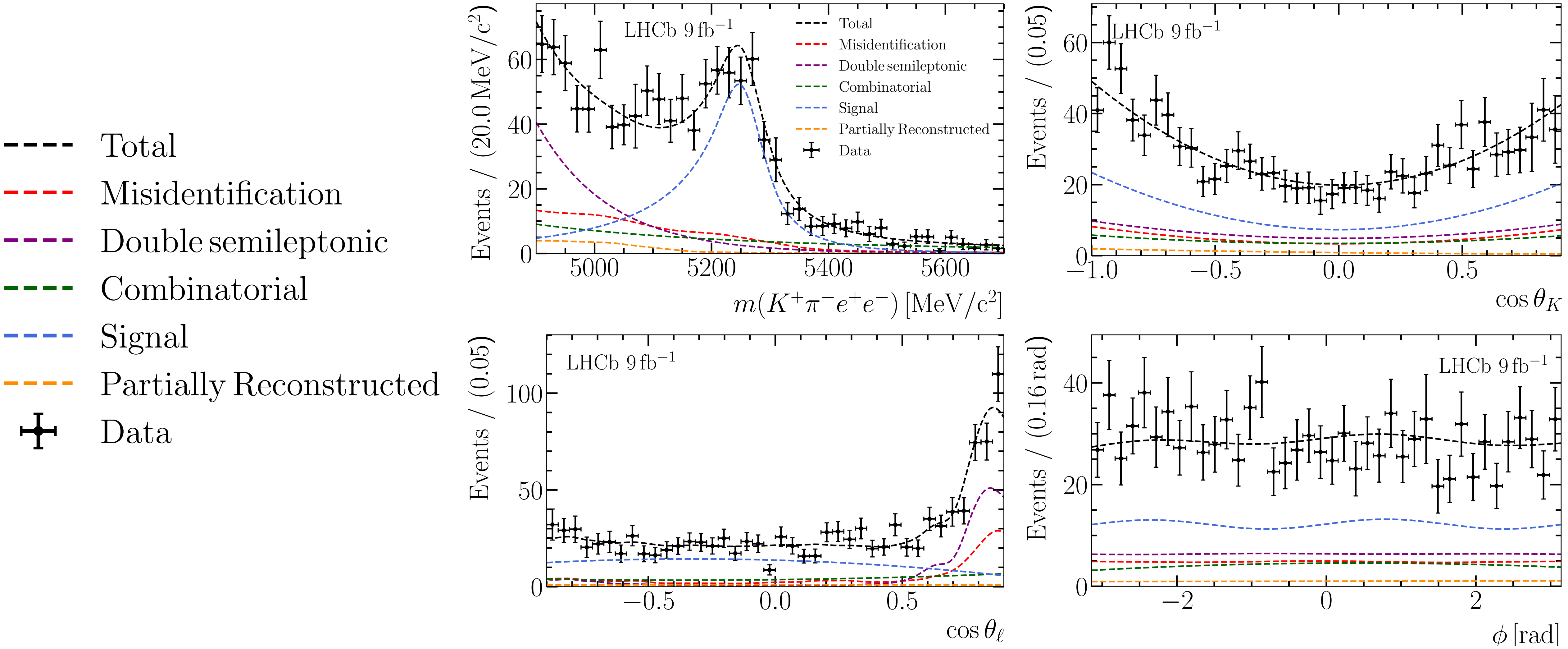
- Use kinematic refit to improve resolution
  - Fix B mass to the measured value
  - Constrain the momentum vector to point to primary vertex

- Define signal region
  - Default 1.1 – 6.0 GeV^2/c^4
  - Extended 1.1 – 7.0 GeV^2/c^4

- Perform fit to B mass distribution and decay angles



Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays



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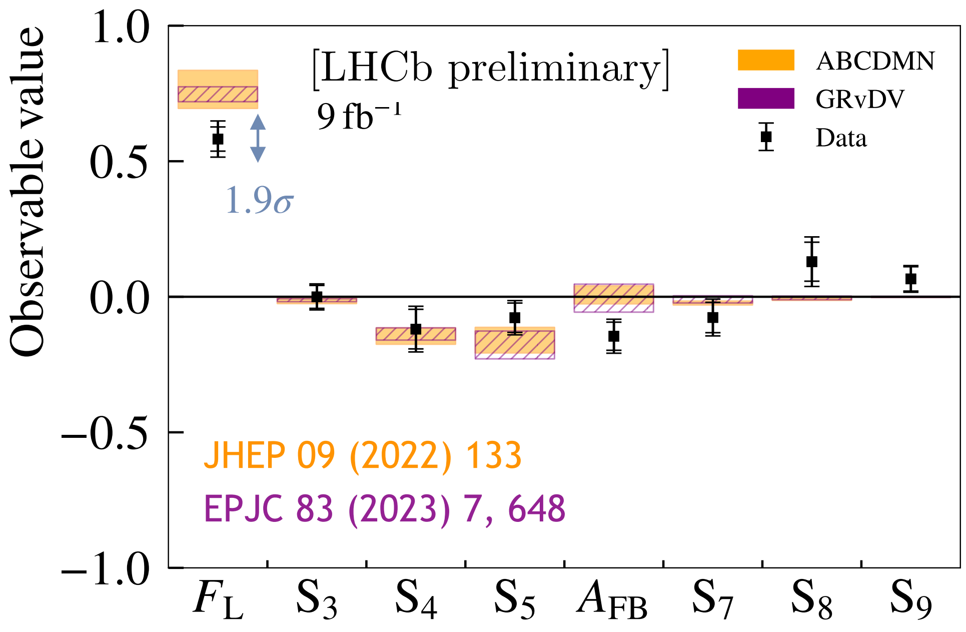
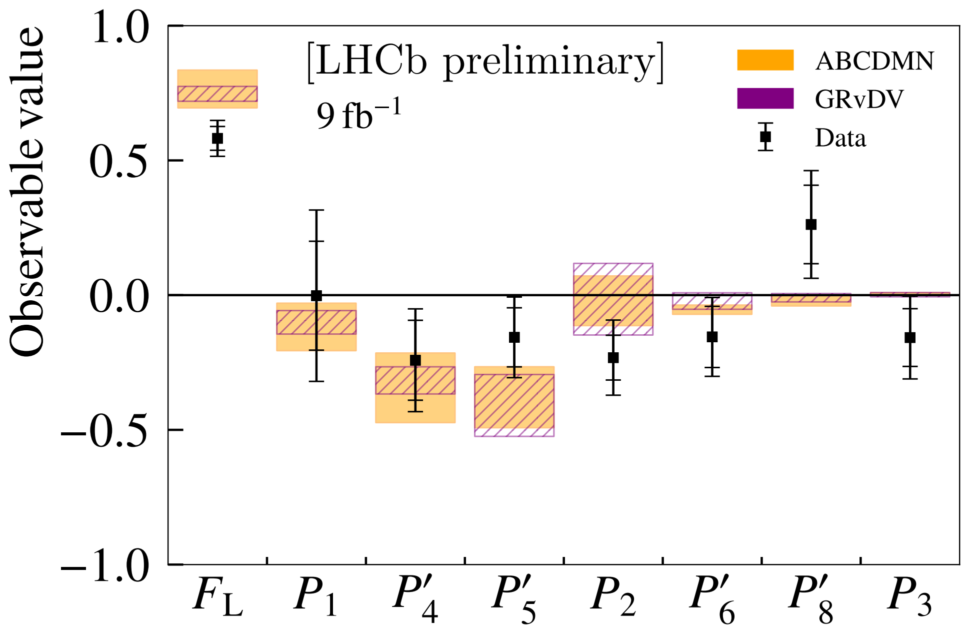




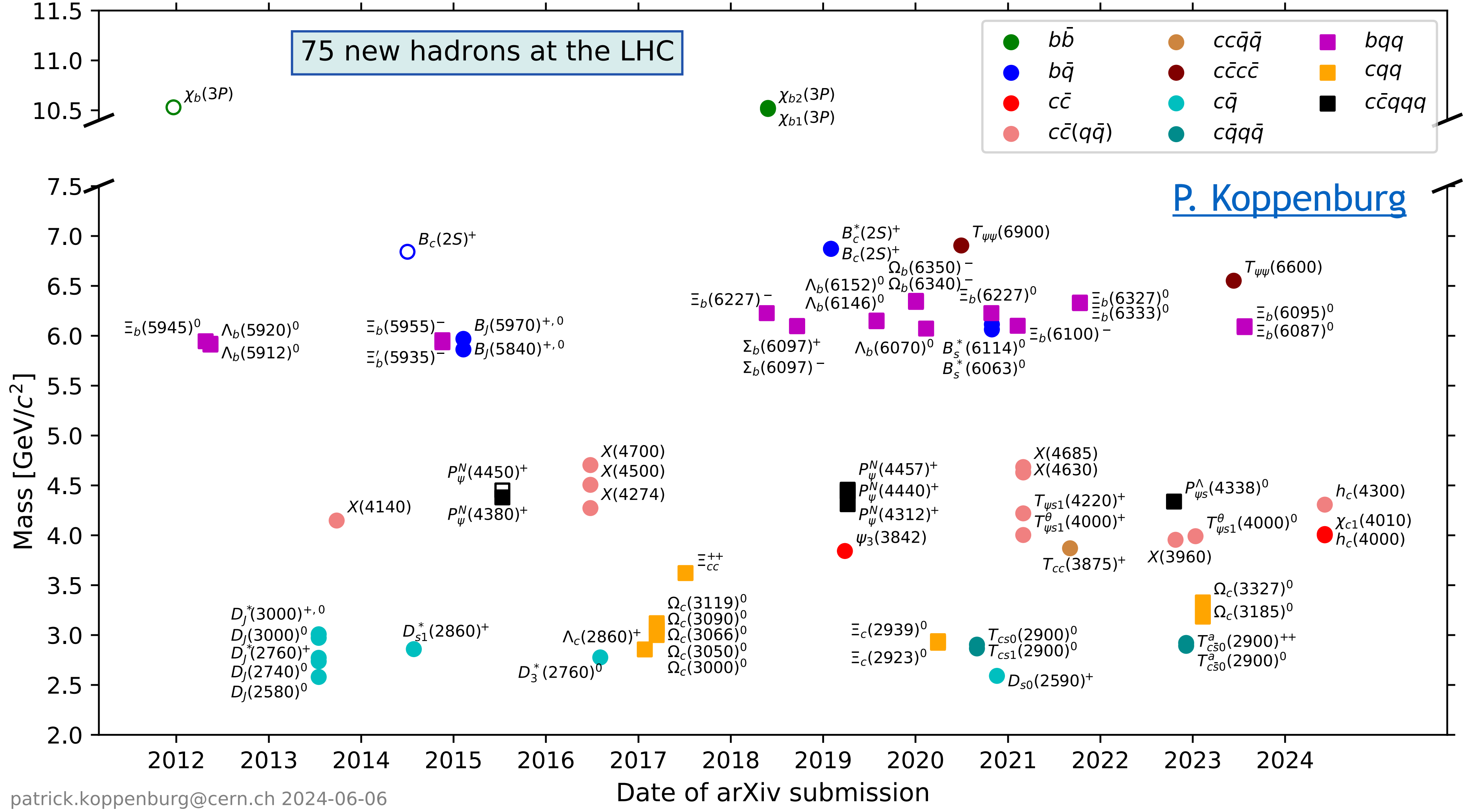
$$P_1 = \frac{2S_3}{(1-F_L)},$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)},$$
$$P_3 = \frac{-S_9}{(1-F_L)},$$
$$P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Good agreement with the SM

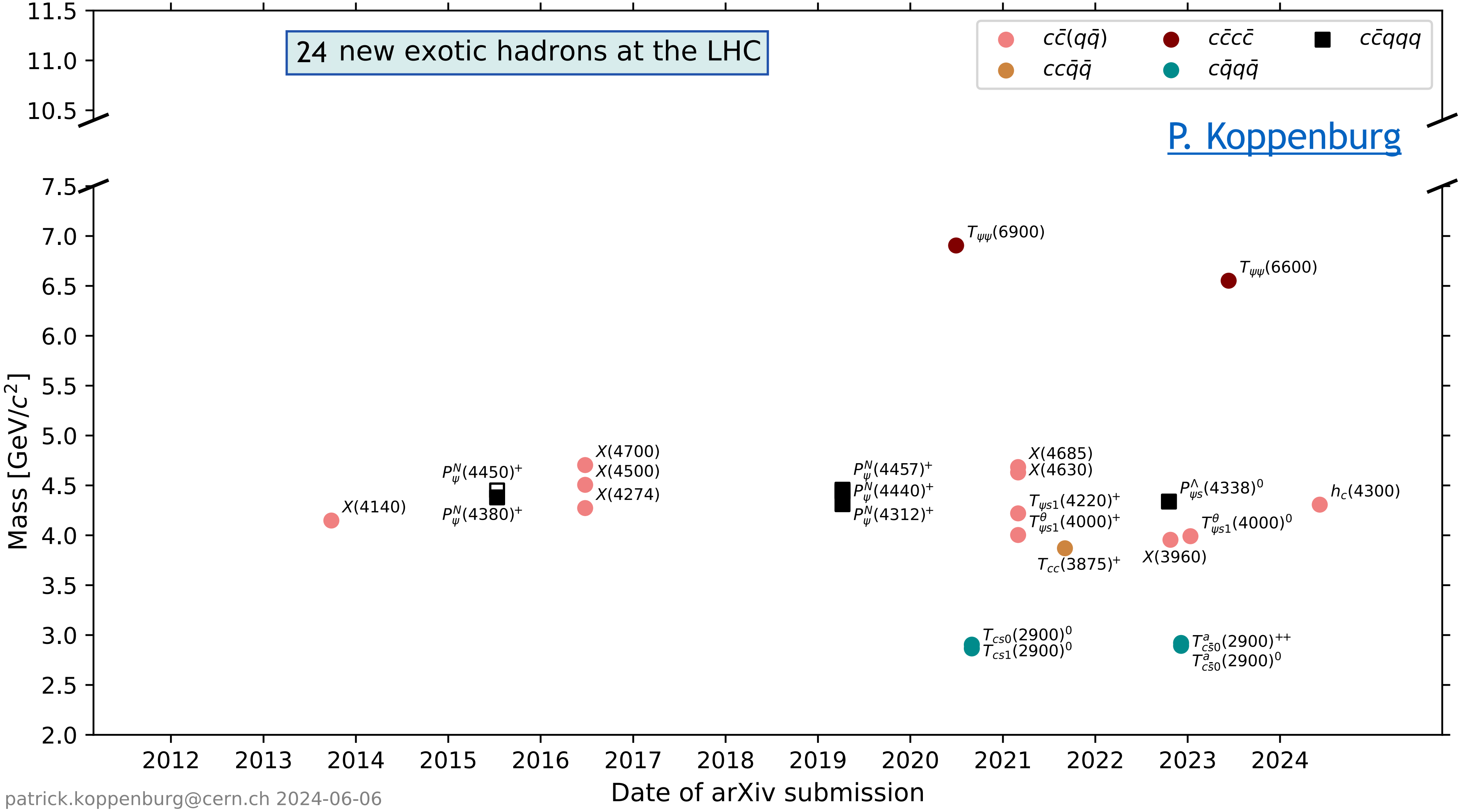
$1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$

F_L	$0.582 \pm 0.045 \pm 0.050$			A_{FB}	$-0.146 \pm 0.052 \pm 0.035$	P_2	$-0.232 \pm 0.083 \pm 0.112$
S_3	$-0.000 \pm 0.042 \pm 0.023$	P_1	$-0.002 \pm 0.202 \pm 0.246$	S_7	$-0.077 \pm 0.056 \pm 0.038$	P'_6	$-0.155 \pm 0.114 \pm 0.092$
S_4	$-0.119 \pm 0.073 \pm 0.042$	P'_4	$-0.242 \pm 0.148 \pm 0.120$	S_8	$0.129 \pm 0.072 \pm 0.056$	P'_8	$0.262 \pm 0.146 \pm 0.137$
S_5	$-0.077 \pm 0.054 \pm 0.033$	P'_5	$-0.157 \pm 0.110 \pm 0.102$	S_9	$0.066 \pm 0.045 \pm 0.020$	P_3	$-0.157 \pm 0.107 \pm 0.110$

Spectroscopy - Introduction



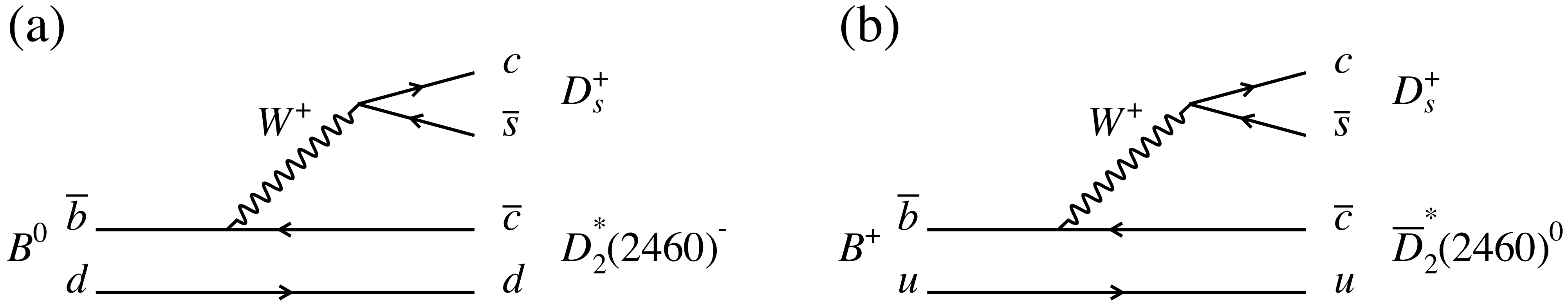
Introduction



Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Decays of B mesons to double charm final states now very popular
  - Following the discovery of new particles in $B^+ \to D^+ D^- K^+$ decays

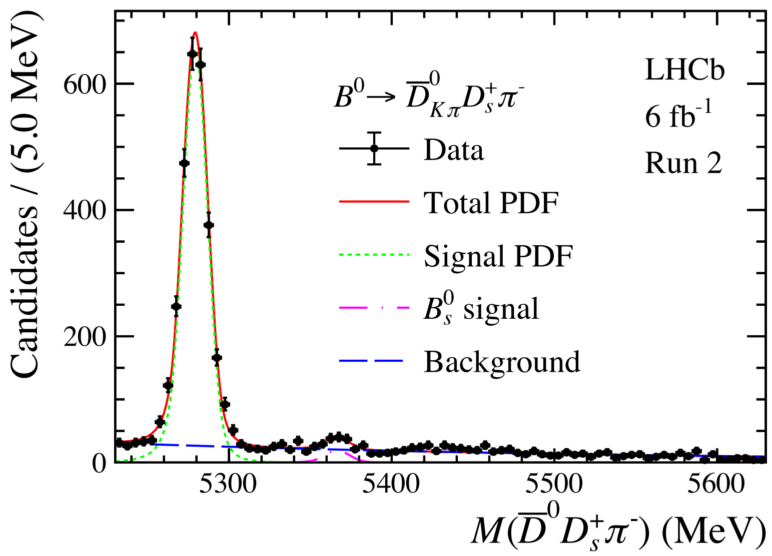
- Isospin partner decays analysed together
  - Expect standard excited charm mesons in the $\overline{D}^0 \pi^-$ and $D^- \pi^+$ channels
  - Anything else would likely be an exotic candidate

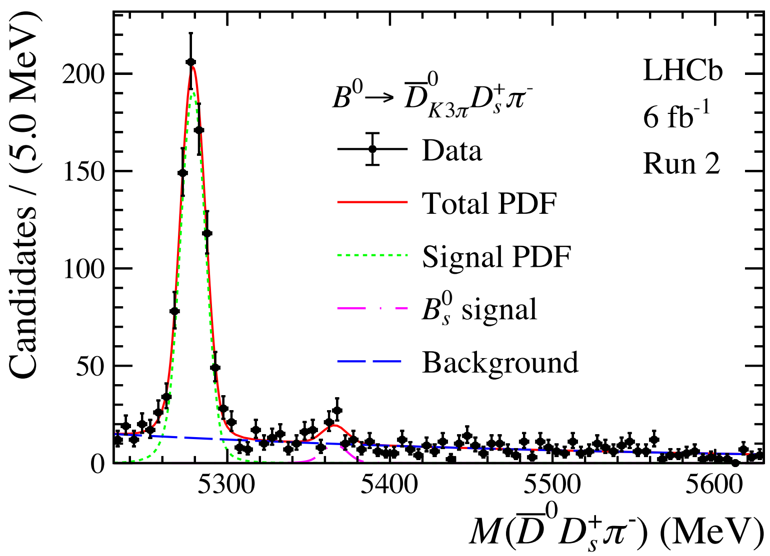


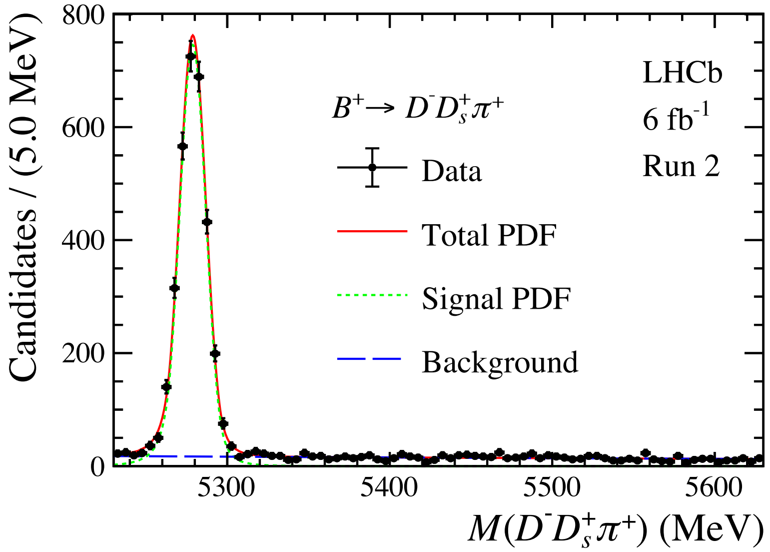
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Firstly need to measure the yields before doing the amplitude fit
  - Separate fits for the three decay modes and split between Run 1 and Run 2
  - Double Crystal Ball functions for the signal (Gaussian core + tails)
  - Exponential function for the combinatorial background

Run 2 fits







Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

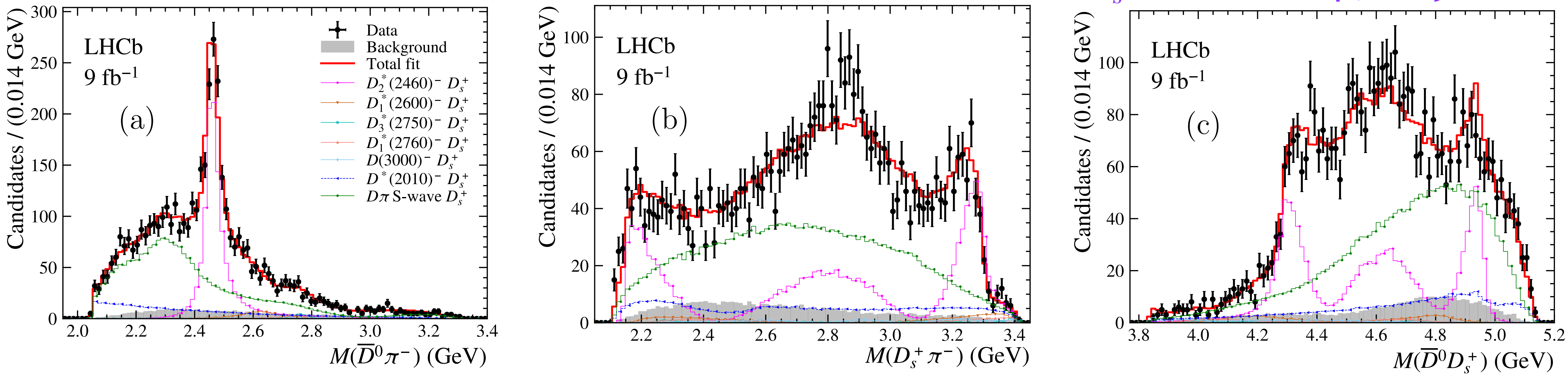
- Now need to perform an amplitude analysis
  - Take just the candidates from the signal regions and fix the yields
  - Include amplitudes for every sub-process that may contribute, starting with known/standard resonances

	Resonance	J^P	Mass (GeV)	Width (GeV)	Comments
	$\overline{D}^*(2007)^0$	1^-	2.00685 ± 0.00005	$< 2.1 \times 10^{-3}$	Width set to be 0.1 MeV
	$D^*(2010)^-$	1^-	2.01026 ± 0.00005	$(8.34 \pm 0.18) \times 10^{-5}$	
*	$\overline{D}_0^*(2300)$	0^+	2.343 ± 0.010	0.229 ± 0.016	#
	$\overline{D}_2^*(2460)$	2^+	2.4611 ± 0.0007	0.0473 ± 0.0008	#
	$\overline{D}_1^*(2600)^0$	1^-	2.627 ± 0.010	0.141 ± 0.023	#
	$\overline{D}_3^*(2750)$	3^-	2.7631 ± 0.0032	0.066 ± 0.005	#
	$\overline{D}_1^*(2760)^0$	1^-	2.781 ± 0.022	0.177 ± 0.040	#
	$\overline{D}_J^*(3000)^0$	??	3.214 ± 0.060	0.186 ± 0.080	# $J^P = 4^+$ is assumed

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Projections from the fit with the list of known excited charm mesons
  - Full $B^0 \to \overline{D}^0 D_s^+ \pi^-$ dataset combining D decays and run periods
  - Good fit to data in the $\overline{D}^0\pi^-$ projection (left)
  - Some possible deficiencies in the $D_s^+\pi^-$ projection (centre)

$B^+ \to D^- D_s^+ \pi^+$ in backup, very similar



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Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

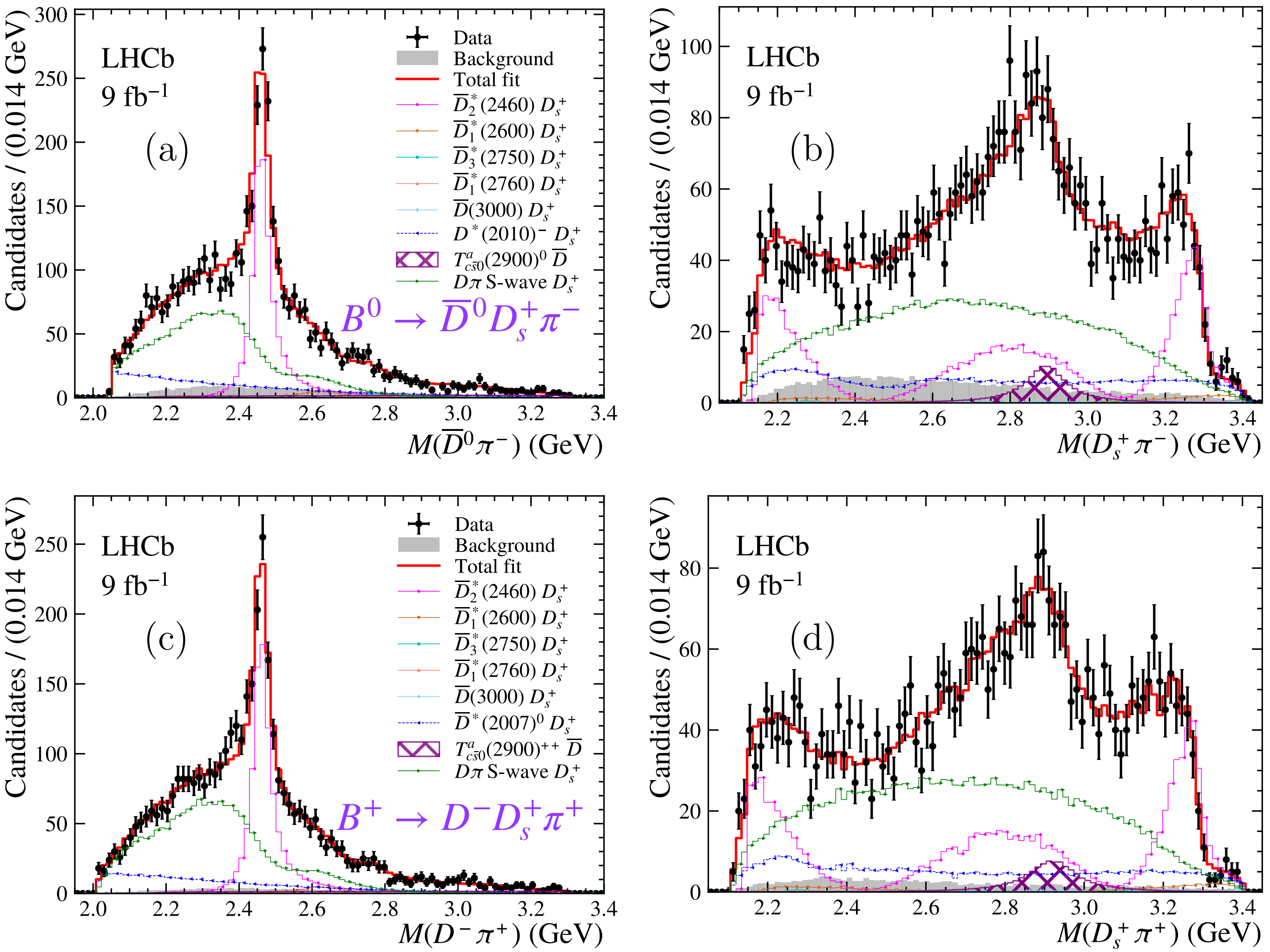
- Perform a simultaneous fit
  - Assuming isospin symmetry to relate the two states

$$T^a_{c\bar{s}0}(2900)^0 : M = (2.892 \pm 0.014 \pm 0.015)\,\text{GeV}, \quad \Gamma = (0.119 \pm 0.026 \pm 0.013)\,\text{GeV},$$

Observed with 8σ significance

$$T^a_{c\bar{s}0}(2900)^{++} : M = (2.921 \pm 0.017 \pm 0.020)\,\text{GeV}, \quad \Gamma = (0.137 \pm 0.032 \pm 0.017)\,\text{GeV},$$

Observed with 6.5σ significance



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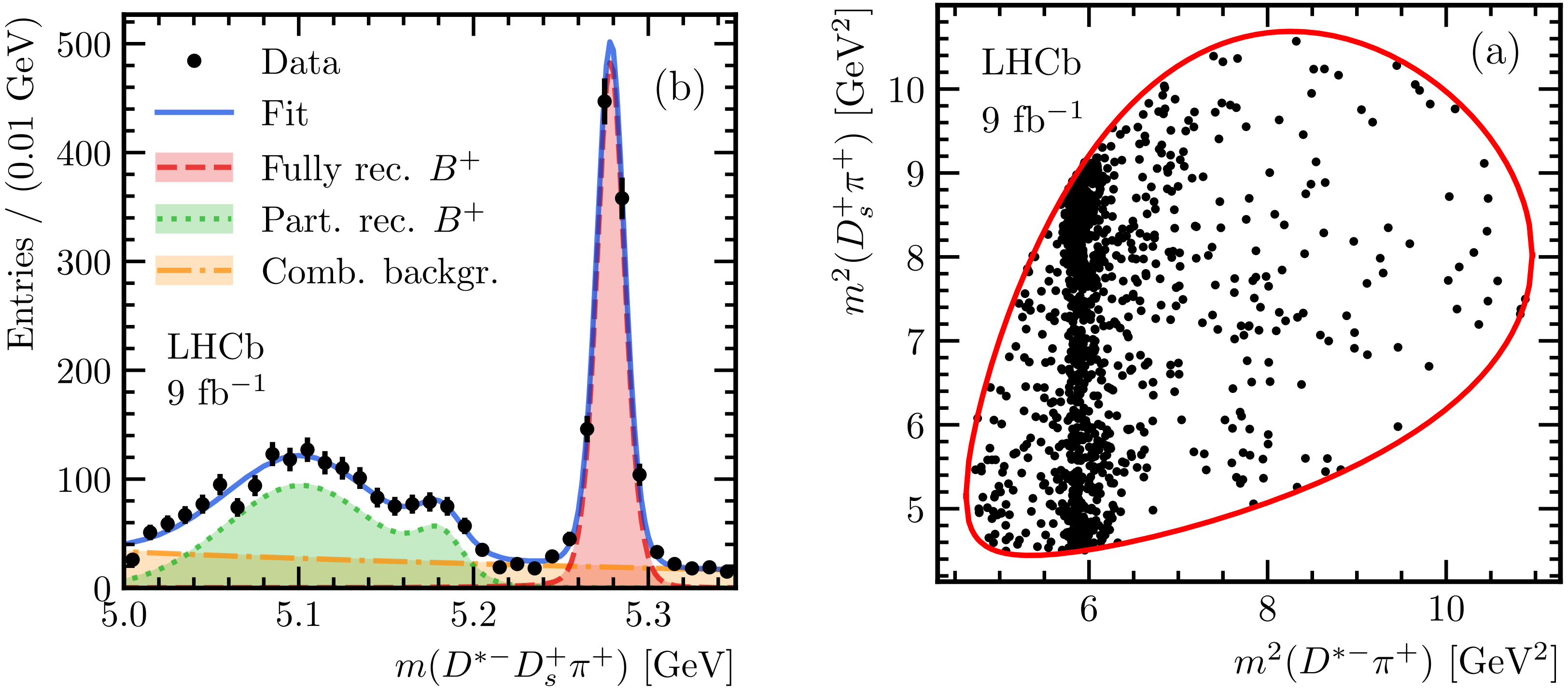
Amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$ decays

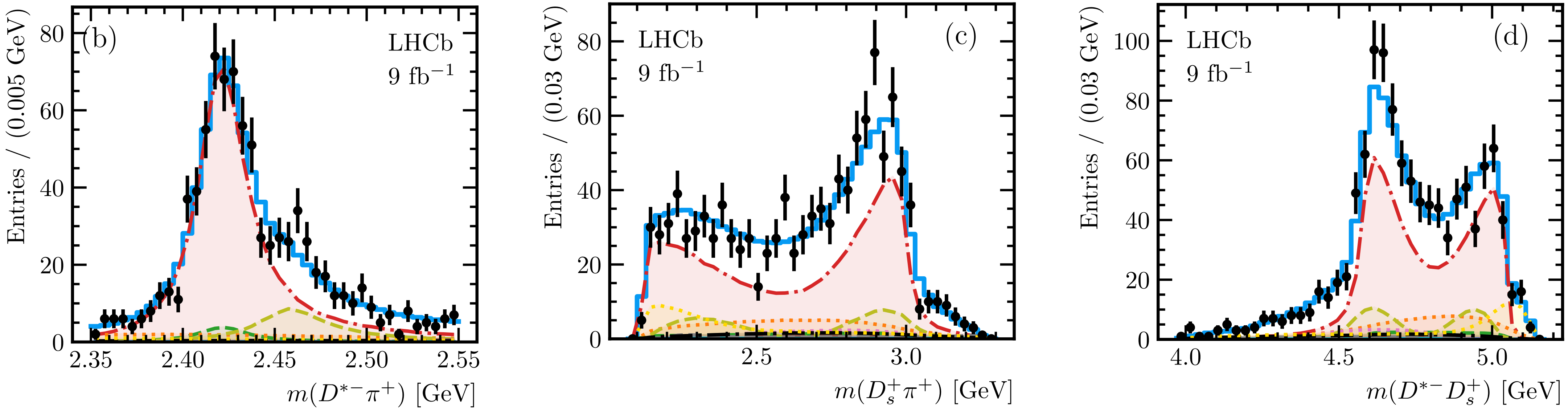
- Very recent paper from LHCb
  - Do we see the $T_{c\bar{s}0}(2900)^{++}$ state?
  - About 850 events in the signal region, analysis strategy ~as before



arXiv:2405.00098 [hep-ex]

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

- Very recent paper from LHCb
  - Do we see the $T_{c\bar{s}0}(2900)^{++}$ state?
  - Region of interest dominated by reflections from $D_1(2420), D_1(2430)$ states
  - No evidence for the tetraquark with this limited data set
  - Fit fraction for $T_{c\bar{s}0}(2900)^{++} < 2.3\,\%\ (90\,\%\ \mathrm{CL})$



Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Again motivated by tetraquark observations in $B^+ \to D^+ D^- K^+$ decays
  - Interest to study this family of tetraquarks further!

- Simultaneous analysis of the two final states
  - Expect charmonium(-like) contributions to be equal in both (C conservation)

- Use the full Run 1 + Run 2 data sample from LHCb
  - Find 1636 ± 43 decays in $B^+ \to D^{*+} D^- K^+$ sample
  - Find 1772 ± 44 decays in $B^+ \to D^{*-} D^+ K^+$ sample
  - Purity in both modes around 95%

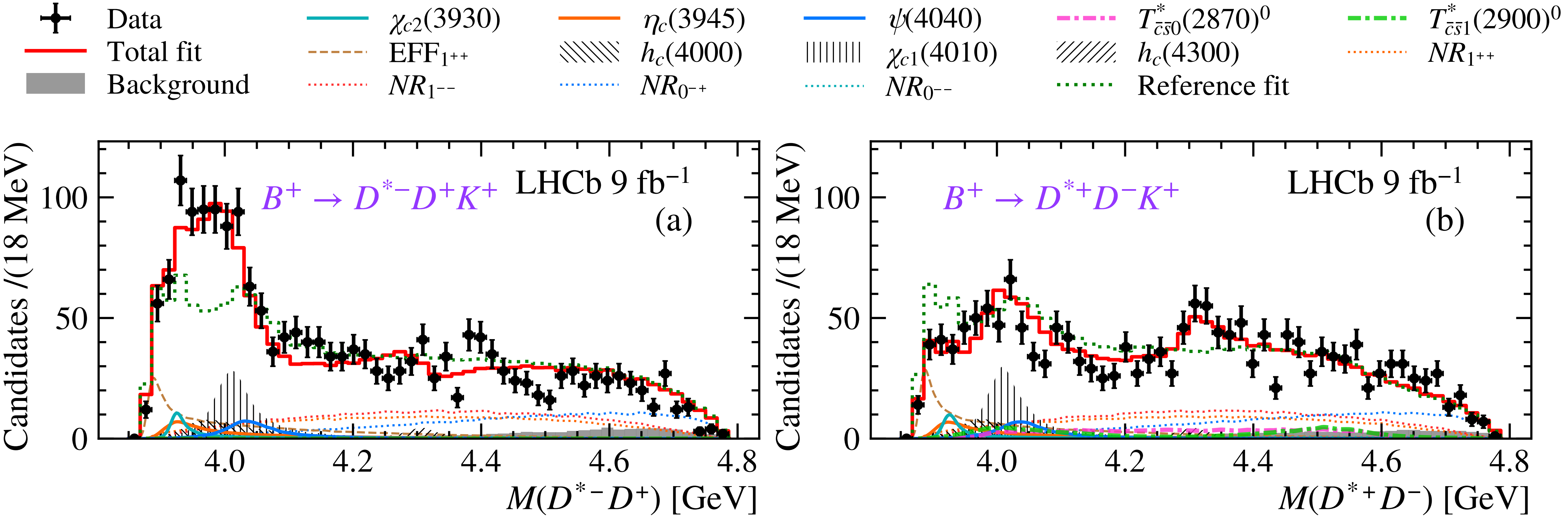
Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Baseline model
  - New charmonium(-like) states
  - Tetraquarks seen in one channel
  - $T_{c\bar{s}0}(2870)^0$ forbidden in $B^+ \to D^{*-} D^+ K^+$ and the spin-1 state not seen

Component	$J^{P(C)}$	Fit fraction [%] $B^+ \to D^{*+} D^- K^+$	Fit fraction [%] $B^+ \to D^{*-} D^+ K^+$	Branching fraction $[10^{-4}]$
$\mathrm{EFF}_{1^{++}}$	1^{++}	$10.9\,^{+2.3}_{-1.2}\,^{+1.6}_{-2.1}$	$9.9\,^{+2.1}_{-1.0}\,^{+1.4}_{-1.9}$	$0.74\,^{+0.16}_{-0.08}\,^{+0.11}_{-0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4\,^{+0.5}_{-1.0}\,^{+1.9}_{-0.7}$	$3.1\,^{+0.5}_{-0.9}\,^{+1.7}_{-0.6}$	$0.23\,^{+0.04}_{-0.07}\,^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)\,^{\dagger}$	2^{++}	$1.8\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.2}$	$1.7\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.1}$	$0.12\,^{+0.03}_{-0.03}\,^{+0.04}_{-0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1\,^{+1.0}_{-0.8}\,^{+1.5}_{-0.8}$	$4.6\,^{+0.9}_{-0.7}\,^{+1.4}_{-0.7}$	$0.35\,^{+0.07}_{-0.05}\,^{+0.10}_{-0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1\,^{+1.6}_{-0.9}\,^{+1.3}_{-1.6}$	$9.1\,^{+1.4}_{-0.8}\,^{+1.2}_{-1.4}$	$0.69\,^{+0.11}_{-0.06}\,^{+0.09}_{-0.11} \pm 0.06$
$\psi(4040)\,^{\dagger}$	1^{--}	$2.8\,^{+0.5}_{-0.4}\,^{+0.5}_{-0.5}$	$2.6\,^{+0.5}_{-0.4}\,^{+0.4}_{-0.5}$	$0.19\,^{+0.04}_{-0.03}\,^{+0.03}_{-0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$1.1\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$0.08\,^{+0.01}_{-0.03}\,^{+0.02}_{-0.01} \pm 0.01$
$T^*_{c\bar{s}0}(2870)^0\,^{\dagger}$	0^+	$6.5\,^{+0.9}_{-1.2}\,^{+1.3}_{-1.6}$	–	$0.45\,^{+0.06}_{-0.08}\,^{+0.09}_{-0.10} \pm 0.04$
$T^*_{c\bar{s}1}(2900)^0\,^{\dagger}$	1^-	$5.5\,^{+1.1}_{-1.5}\,^{+2.4}_{-1.6}$	–	$0.38\,^{+0.07}_{-0.10}\,^{+0.16}_{-0.11} \pm 0.03$
$\mathrm{NR}_{1^{--}}(D^{*\mp} D^{\pm})$	1^{--}	$20.4\,^{+2.3}_{-0.6}\,^{+2.1}_{-2.6}$	$18.5\,^{+2.1}_{-0.5}\,^{+1.9}_{-2.3}$	$1.39\,^{+0.16}_{-0.04}\,^{+0.14}_{-0.17} \pm 0.12$
$\mathrm{NR}_{0^{--}}(D^{*\mp} D^{\pm})$	0^{--}	$1.2\,^{+0.6}_{-0.1}\,^{+0.7}_{-0.6}$	$1.1\,^{+0.6}_{-0.1}\,^{+0.6}_{-0.5}$	$0.08\,^{+0.04}_{-0.01}\,^{+0.05}_{-0.04} \pm 0.01$
$\mathrm{NR}_{1^{++}}(D^{*\mp} D^{\pm})$	1^{++}	$17.8\,^{+1.9}_{-1.4}\,^{+3.6}_{-2.6}$	$16.1\,^{+1.7}_{-1.3}\,^{+3.3}_{-2.3}$	$1.21\,^{+0.13}_{-0.10}\,^{+0.24}_{-0.17} \pm 0.11$
$\mathrm{NR}_{0^{-+}}(D^{*\mp} D^{\pm})$	0^{-+}	$15.9\,^{+3.3}_{-1.2}\,^{+3.3}_{-3.3}$	$14.5\,^{+3.0}_{-1.1}\,^{+3.0}_{-3.0}$	$1.09\,^{+0.23}_{-0.08}\,^{+0.22}_{-0.23} \pm 0.09$

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays



Discrepancies covered by model systematics

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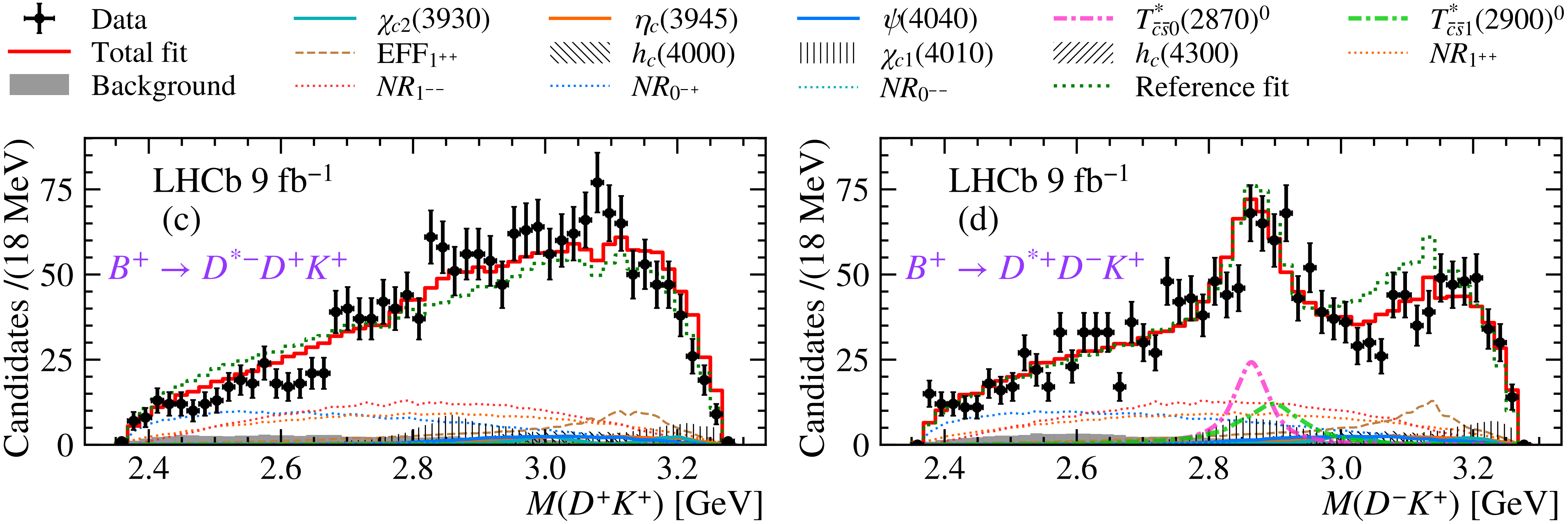

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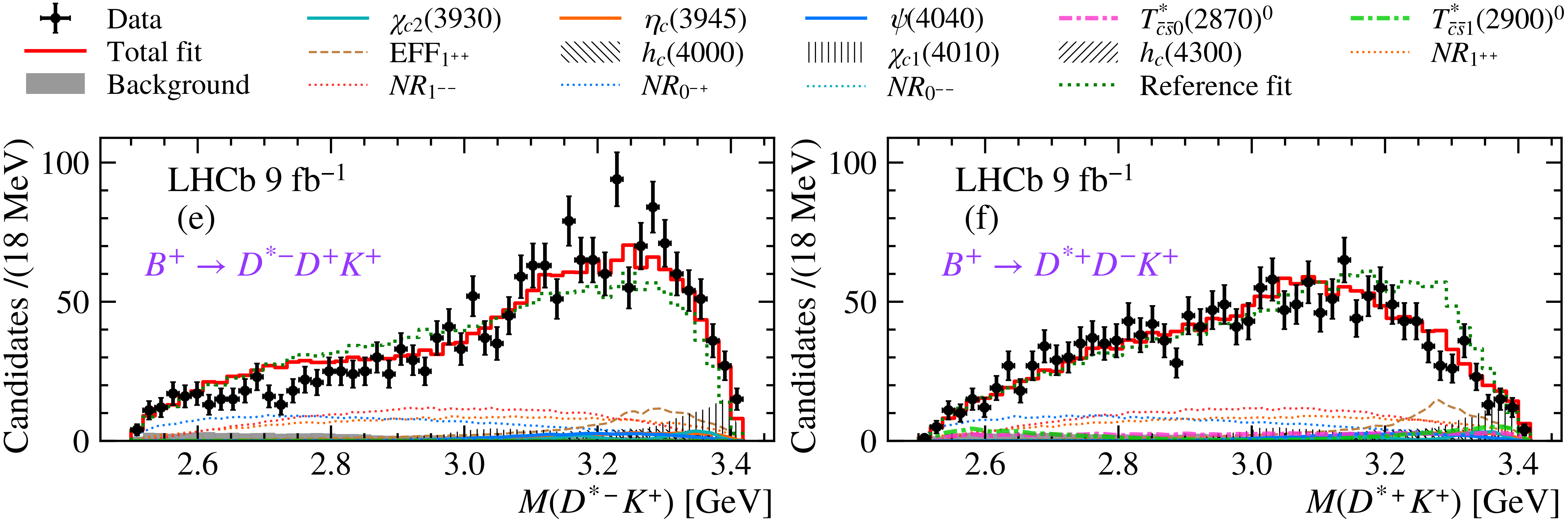


Discrepancies covered by model systematics

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays
  - Tetraquark candidates in fair agreement with previous results
  - Seems to be a difference in the ratio of the two states in this final state

Property	This work	Previous work	
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7	11σ
$T^*_{\bar{c}\bar{s}0}(2870)^0$ 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	9.1σ
$T^*_{\bar{c}\bar{s}1}(2900)^0$ 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	

	$\eta_c(3945)$	$h_c(4000)$	$\chi_{c1}(4010)$	and $h_c(4300)$
Consistent with X(3940) seen by Belle	10σ	9.1σ	16σ	6.4σ
	0^{-+}	1^{+-}	1^{++}	1^{+-}

Looking forwards - my two cents

- We need to understand the structure of exotic particles
  - With four and five quark states, how are the quarks arranged?

- Discovering them pseudo-randomly is a good start…
  - Perhaps it is time for a more focused, systematic, approach
  - Focus on related states and look for any more possible partners e.g.

$T_{cs0}(2900)^0$

$T_{cs1}(2900)^0$

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

$T^a_{c\bar{s}0}(2900)^0$ $c\bar{s}\bar{u}d$

$T^a_{c\bar{s}0}(2900)^{++}$ $c\bar{s}u\bar{d}$

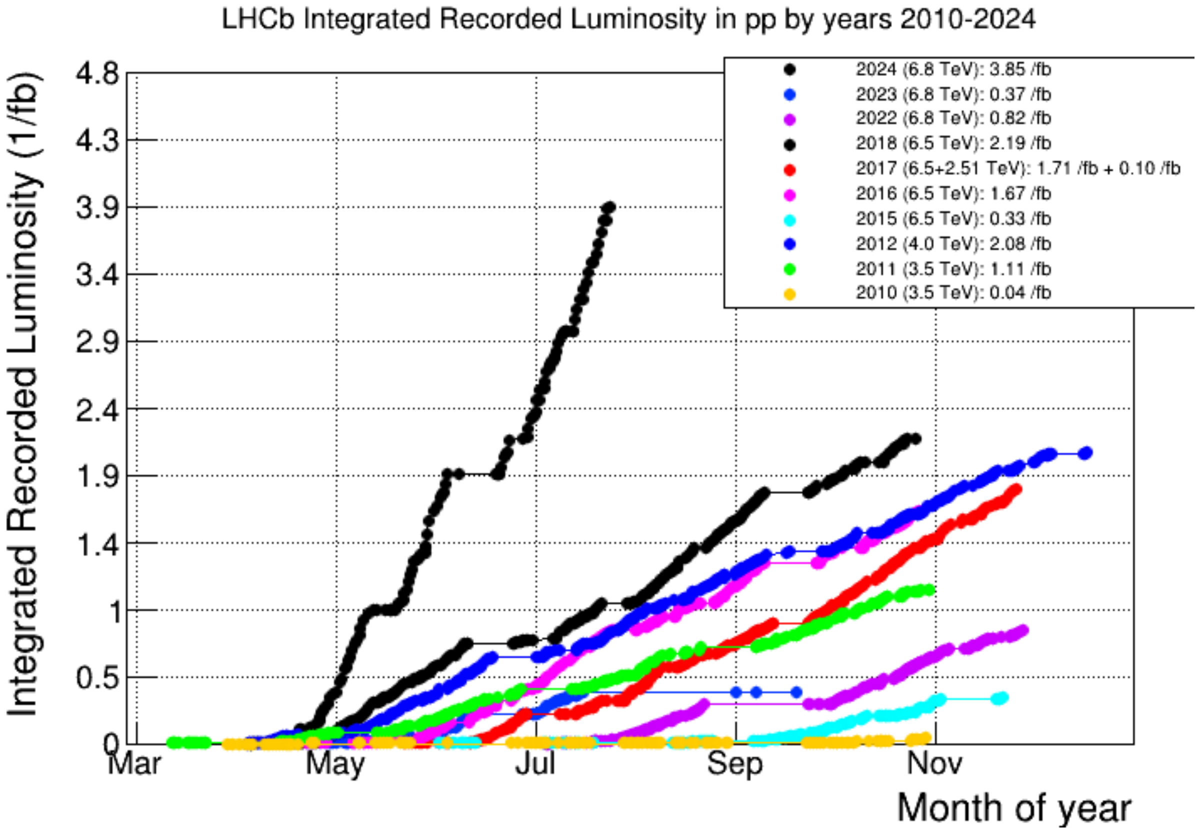
- Make sure we focus equally on final states they do not decay to

LHCb Upgrade - Run 3

- Data pouring in as we speak at point 8!
  - Effect of the upgrade is clear to see!
  - Already collected about twice as much data as our previous record year
- Detector performing well
  - Removal of hardware trigger gives and extra factor of ~2 improvement for hadronic decays
- Lots to look forward to!

Upgrade I

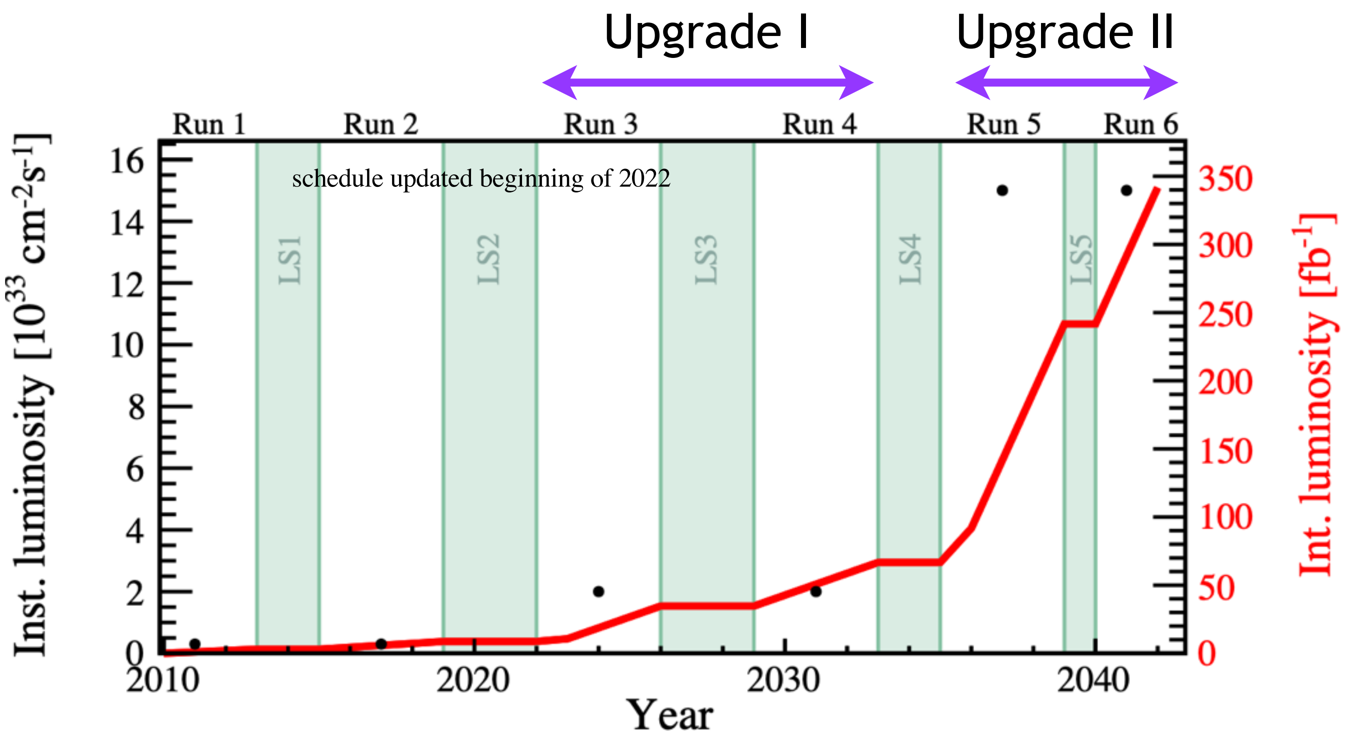
2022-2032



LHCb Upgrade II

- LHCb physics programme not limited by the LHC
  - Ambitious future upgrades plan

Upgrade II
2033-



- Peak luminosity - $1.5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$
- Integrated luminosity ~ $300\,\mathrm{fb^{-1}}$
  - For Run 5 + 6
- Full new detector required!
- Install during LS4
- Smaller detector consolidation and enhancements during LS3

Summary

- Lots of exciting results still coming in from the Run 1 and 2 data set
  - Only a small selection of topics covered today

- Exploitation of Run 3 data for physics analysis to ramp up
  - Data coming in at an unprecedented rate for LHCb

- Reminder of the annual LHCb implications workshop
  - The 2024 addition will be Wednesday 23rd - Friday 25th October
  - Theorists welcome!

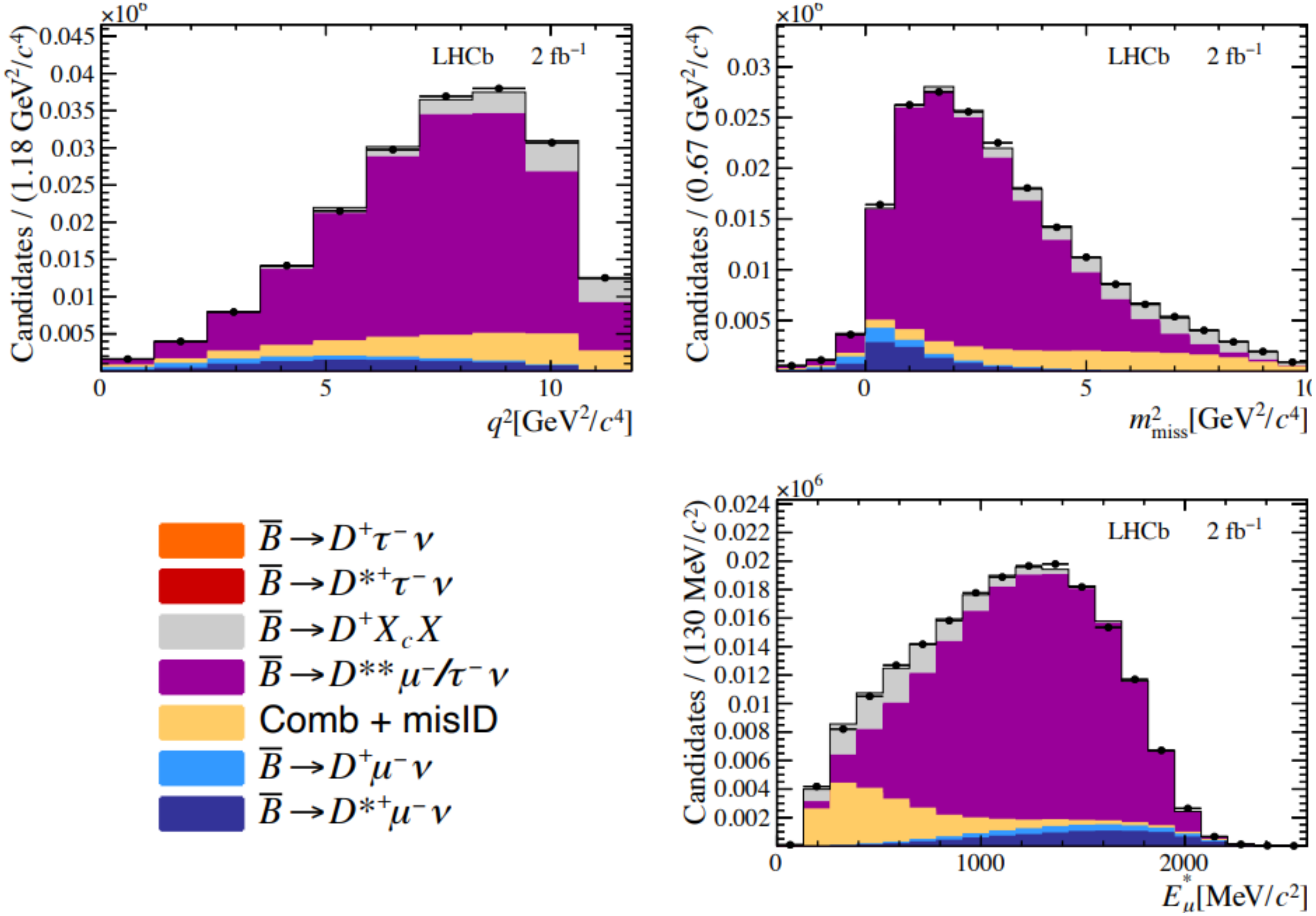
Unfortunately I can only attend the conference today, so please find me at lunch or coffee if you have any additional comments/questions or requests!

Back up

Latest on $R(D^{+})$ and $R(D^{*+})$

Control region with an additional charged pion added

Sample enriched with excited charm meson contributions

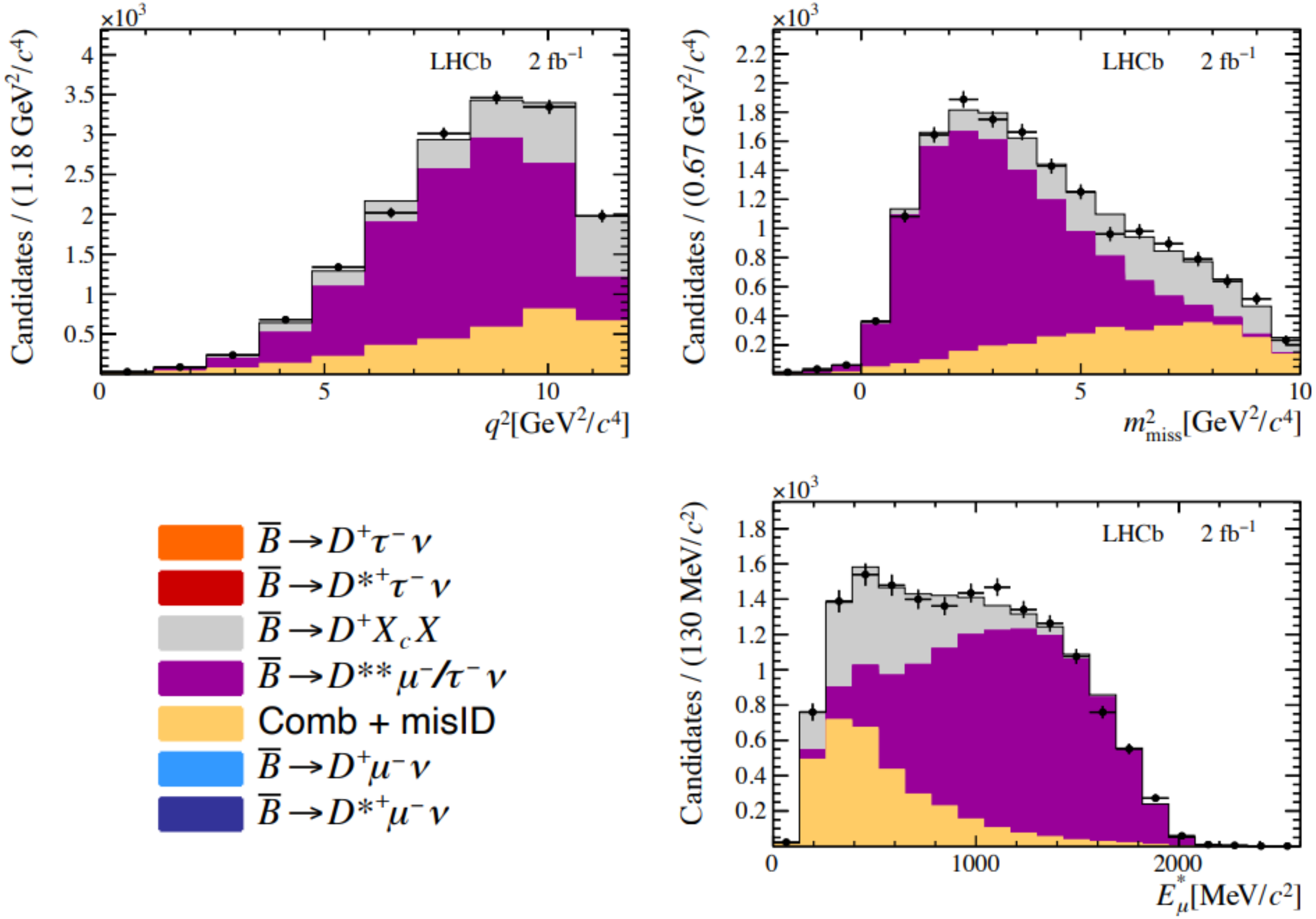


arXiv:2406.03387 [hep-ex]

Latest on $R(D^+)$ and $R(D^{*+})$

Control region with two additional charged pion added (opposite sign)

Sample enriched with higher excited charm meson contributions

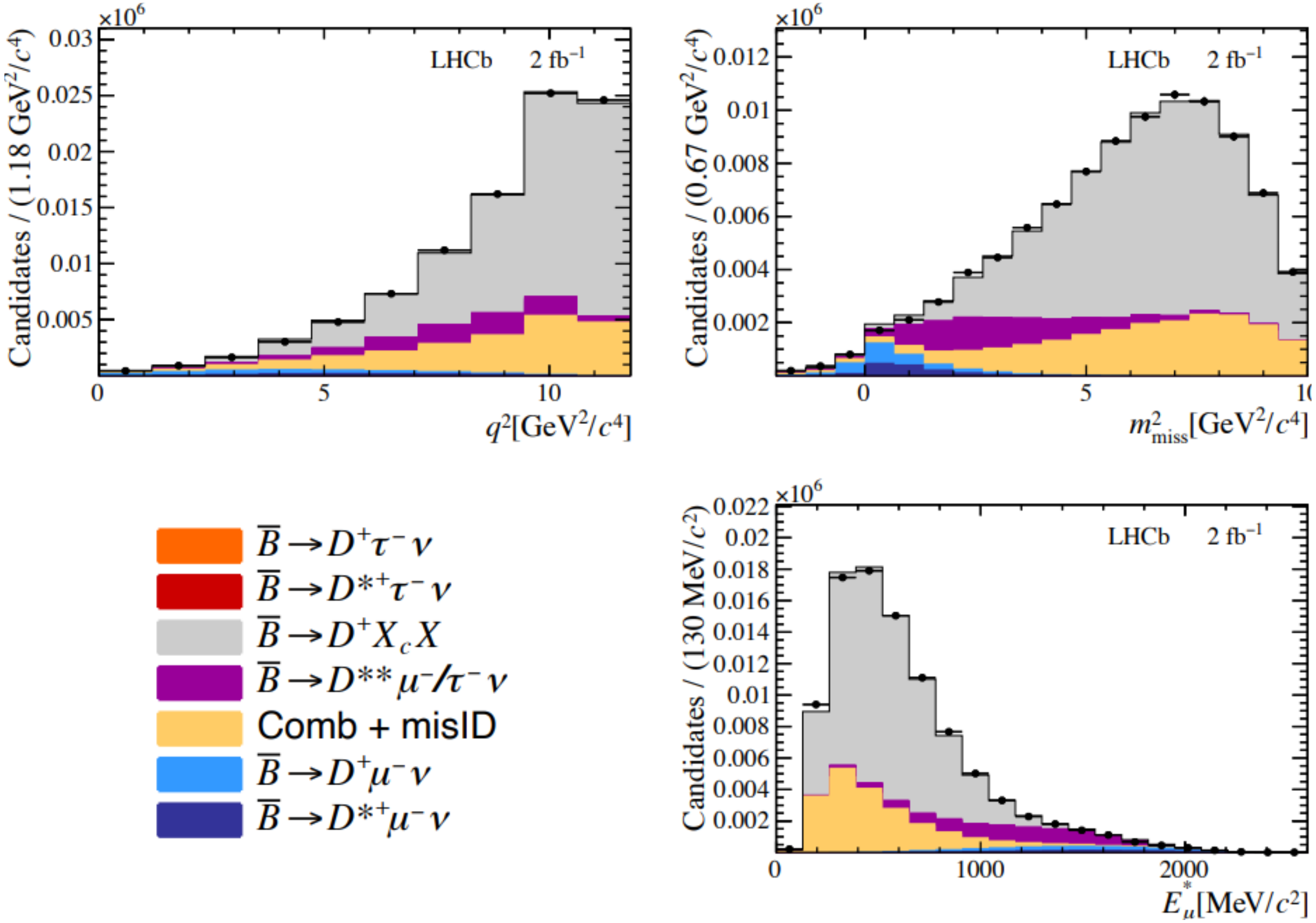


arXiv:2406.03387 [hep-ex]

Latest on $R(D^+)$ and $R(D^{*+})$

Control region with at least one additional charged kaon added

Sample enriched with double charm background contributions



Latest on $R(D^+)$ and $R(D^{*+})$

- Control of systematic uncertainties crucial with such large samples
  - Dataset from 2015+2016

- Largest sources
  - Form factors
  - Background fractions

Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

- Finally we get

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$

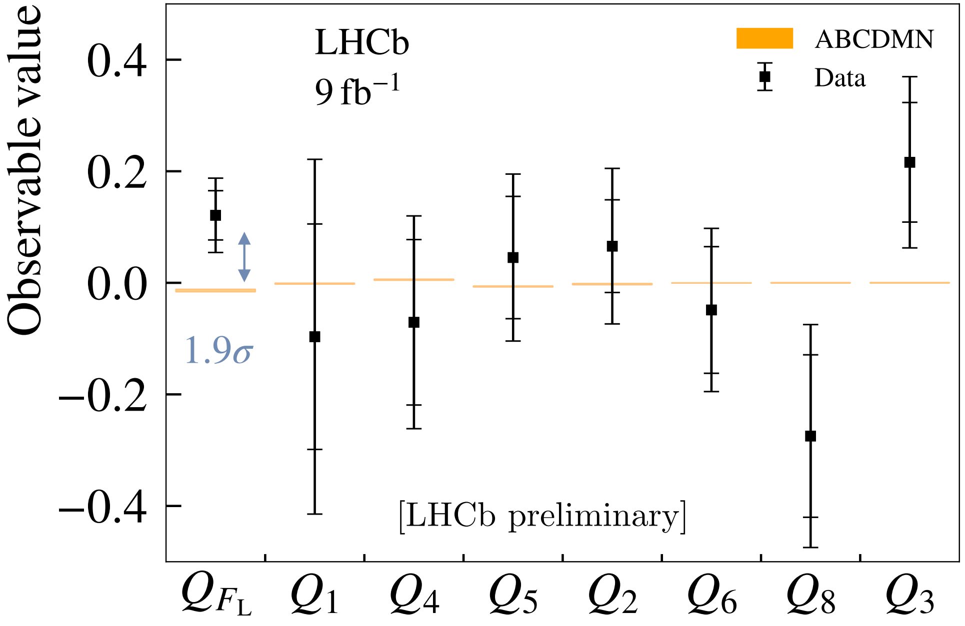
Results from D^0 decays PRL 131, 111802 (2023)

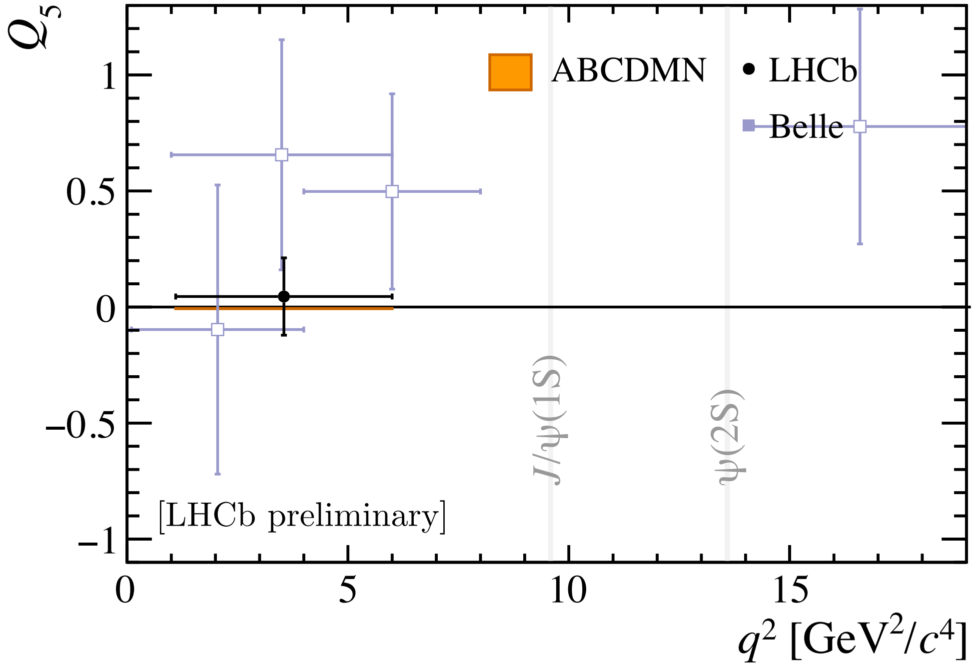
$$R(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$R(D^*) = 0.281 \pm 0.018 \pm 0.023$$

Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

- Compare each variable with the muon results PRL 132 (2024) 131801
  - Consistent with lepton flavour universality

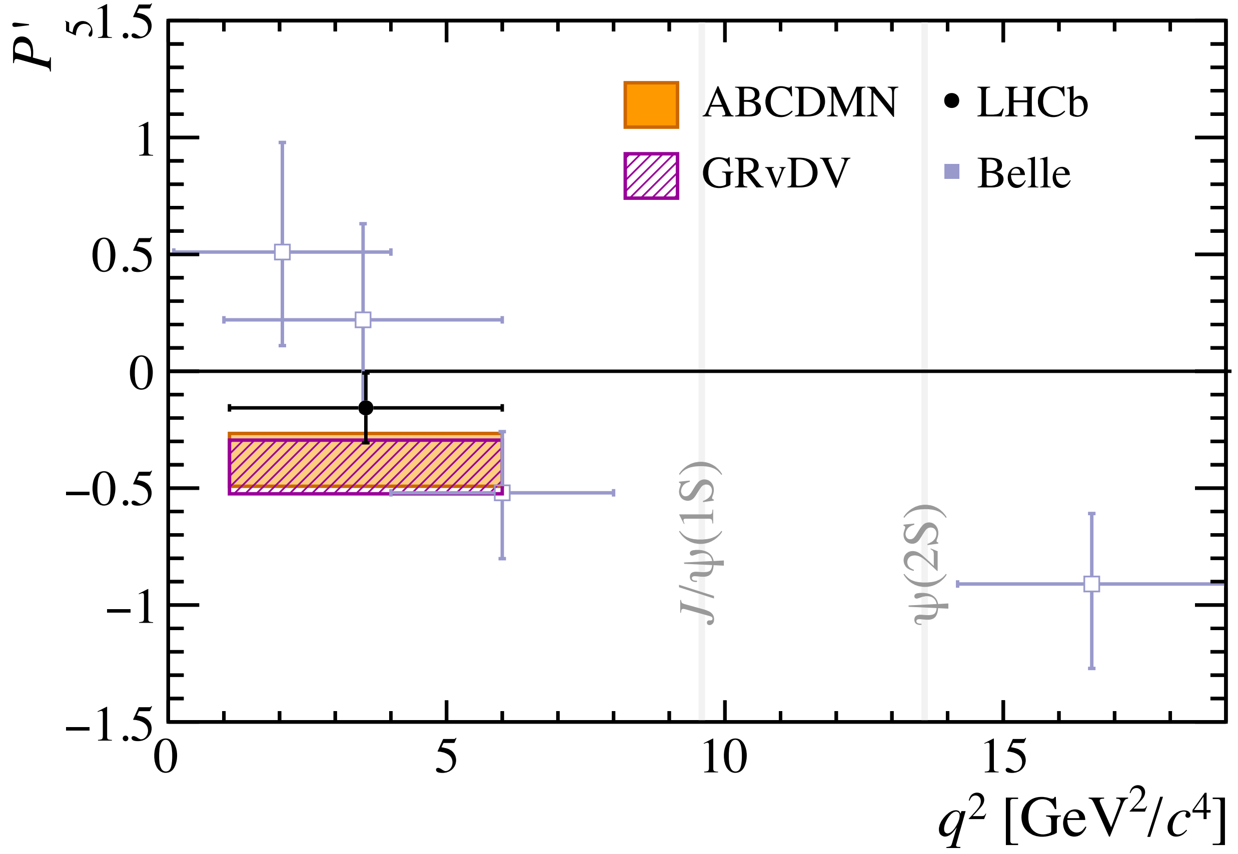
$$Q_i = P_i^{(\mu)} - P_i^{(e)}$$

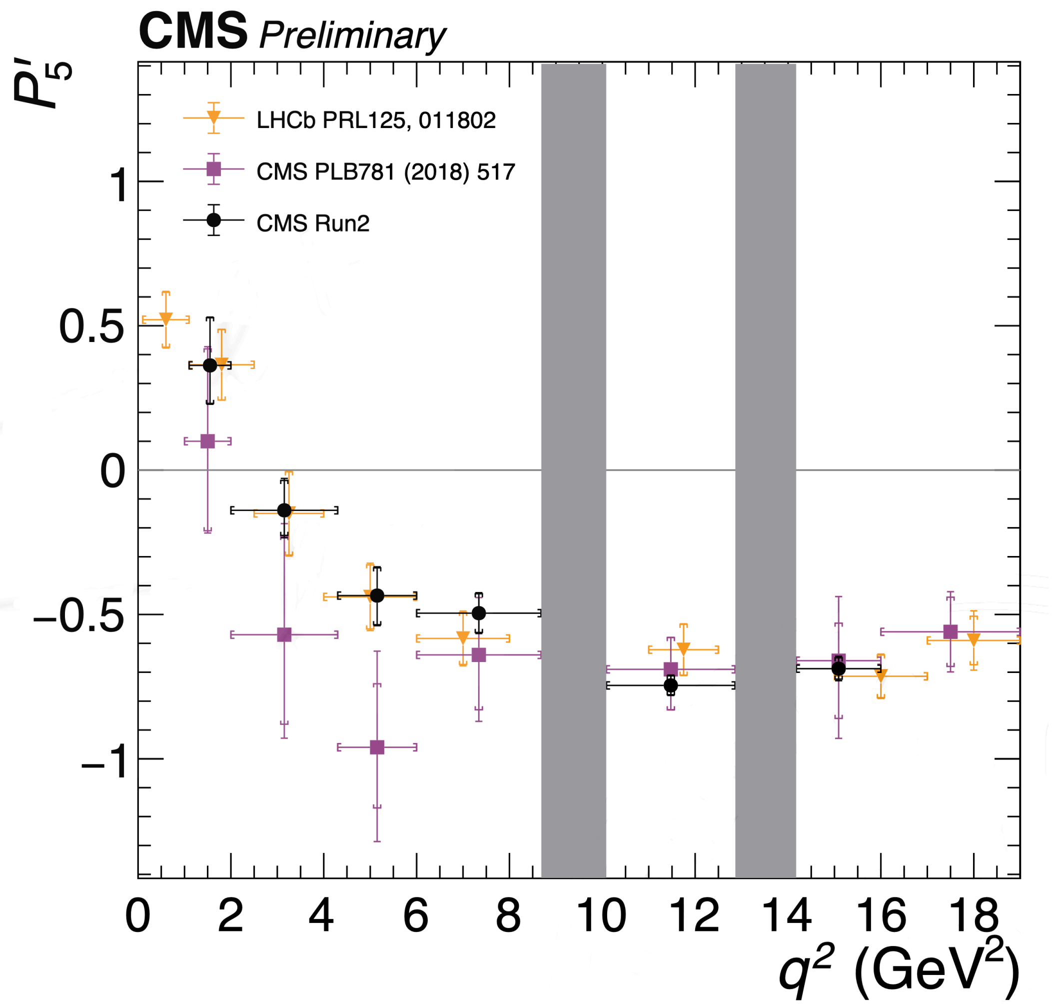




Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

- Same pattern as the muonic decays





Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Three data samples initially
  - $B^0 \to \overline{D}^0 D_s^+ \pi^-$ with $\overline{D}^0 \to K^+ \pi^-$
  - $B^0 \to \overline{D}^0 D_s^+ \pi^-$ with $\overline{D}^0 \to K^+ \pi^- \pi^+ \pi^-$
  - $B^+ \to D^- D_s^+ \pi^+$ with $D^- \to K^+ \pi^- \pi^-$

  } $D_s^+ \to K^+ K^- \pi^+$

- Analysis uses the full Run 1 + Run 2 data sample of 9fb^{-1}

- Standard selections
  - Combinatorial background suppressed using a BDT (boosted decision tree)
  - Non-charm background surpassed with flight distance cuts

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

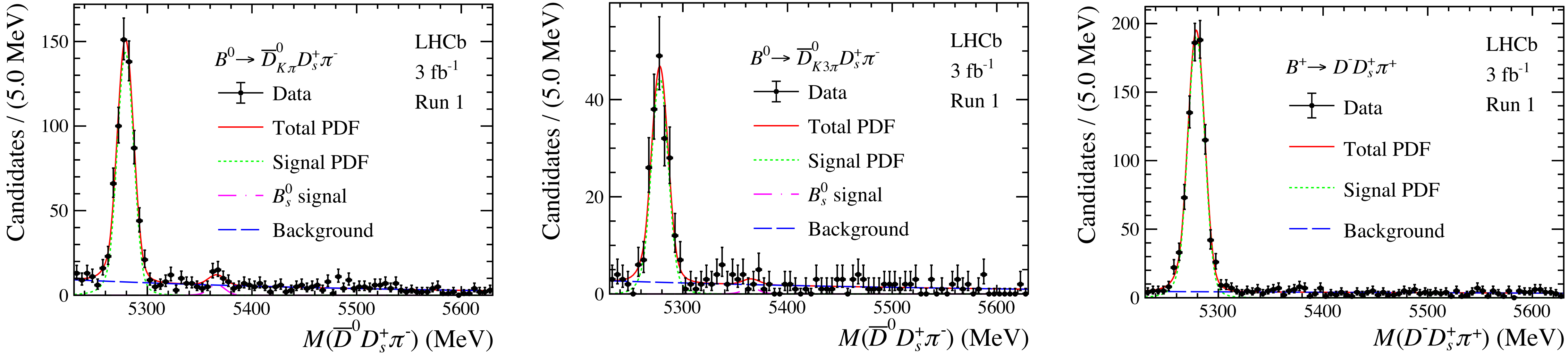
- Decays of B mesons to double charm final states now very popular
  - Following the discovery of new particles in $B^+ \to D^+ D^- K^+$ decays

- Isospin partner decays analysed together
  - Expect standard excited charm mesons in the $\overline{D}^0 \pi^-$ and $D^- \pi^+$ channels
  - Anything else would likely be an exotic candidate
    - E.g. Z_{cs} tetraquark candidates seen to decay to $\overline{D}^* D_s^+, \overline{D} D_s^{*+}$ and $J/\psi K$
    - Motivation to search in the $D_s^+ \pi^-$ and $D_s^+ \pi^+$ from theory side in analogy to $T_{cs(0,1)}(2900)^0$ candidates in the $D^- K^+$ system

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Firstly need to measure the yields before doing the amplitude fit
  - Separate fits for the three decay modes and split between Run 1 and Run 2
  - Double Crystal Ball functions for the signal (Gaussian core + tails)
  - Exponential function for the combinatorial background

Run 1 fits



Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Fit results
  - Full results in the backup slides
  - Focus here on the yields in the signal region of $\pm 20\,\mathrm{MeV}/c^2$ around the B mass
    - Corresponds to about 2.5-3 times the mass resolution

Decay	Parameter	Run 1	Run 2
$B^0 \to \overline{D}^0_{K\pi} D_s^+ \pi^-$	Signal yield	564 ± 26	2534 ± 55
	Total candidates	633	2753
	Purity	89.1%	92.1%
$B^0 \to \overline{D}^0_{K3\pi} D_s^+ \pi^-$	Signal yields	177 ± 14	734 ± 31
	Total candidates	199	835
	Purity	88.9%	87.9%
$B^+ \to D^- D_s^+ \pi^+$	Signal yield	766 ± 29	2984 ± 57
	Total candidates	797	3143
	Purity	96.1%	94.9%

~4k signal candidates per channel

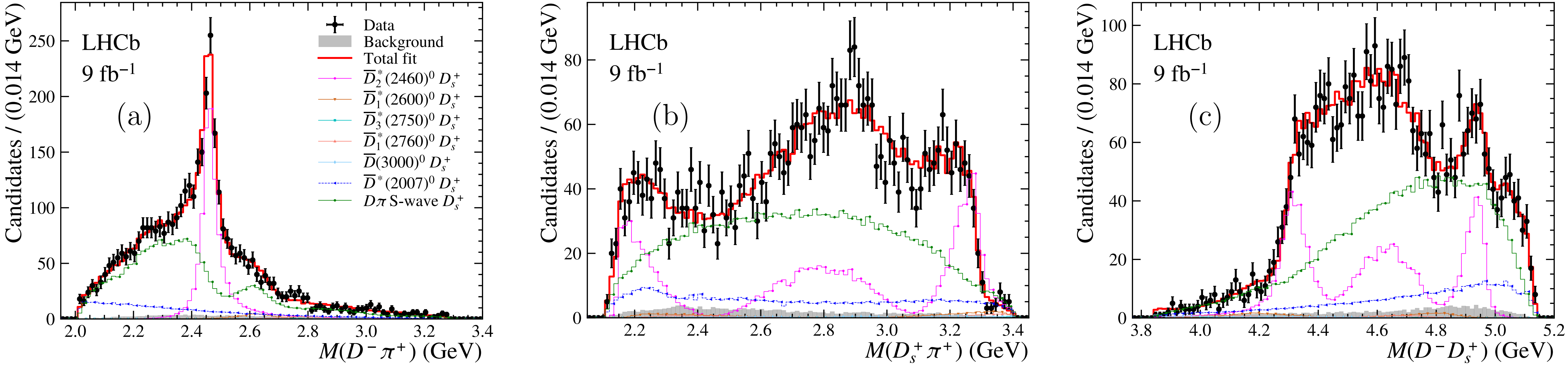
Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

Decay	Parameter	Run 1	Run 2
$B^0 \to \overline{D}^0_{K\pi} D_s^+ \pi^-$	Signal yield	587 ± 27	2641 ± 57
	B_s^0 signal	25.3 ± 8.3	77 ± 15
	Background yield	421 ± 26	1440 ± 49
	Mean (MeV)	5279.12 ± 0.38	5279.16 ± 0.18
	Width (MeV)	7.89 ± 0.35	7.73 ± 0.17
	Exponential slope	$-(3.08 \pm 0.52) \times 10^{-3}$	$-(2.98 \pm 0.29) \times 10^{-3}$
$B^0 \to \overline{D}^0_{K3\pi} D_s^+ \pi^-$	Signal yield	185 ± 15	759 ± 32
	B_s^0 signal	4.9 ± 4.6	38 ± 11
	Background yield	136 ± 14	692 ± 33
	Mean (MeV)	5277.98 ± 0.70	5278.79 ± 0.34
	Width (MeV)	8.01 ± 0.59	7.72 ± 0.33
	Exponential slope	$-(2.56 \pm 0.90) \times 10^{-3}$	$-(3.03 \pm 0.41) \times 10^{-3}$
$B^+ \to D^- D_s^+ \pi^+$	Signal yield	798 ± 30	3123 ± 59
	Background yield	311 ± 21	1201 ± 40
	Mean (MeV)	5278.88 ± 0.33	5278.74 ± 0.16
	Width (MeV)	8.08 ± 0.30	8.05 ± 0.14
	Exponential slope	$-(0.82 \pm 0.61) \times 10^{-3}$	$-(0.90 \pm 0.31) \times 10^{-3}$

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Projections from the fit with the list of known excited charm mesons
  - Full $B^+ \to D^- D_s^+ \pi^+$ dataset combining D decays and run periods
  - Good fit to data in the $D^-\pi^+$ projection (left)
  - Some possible deficiencies in the $D_s^+\pi^+$ projection (centre)

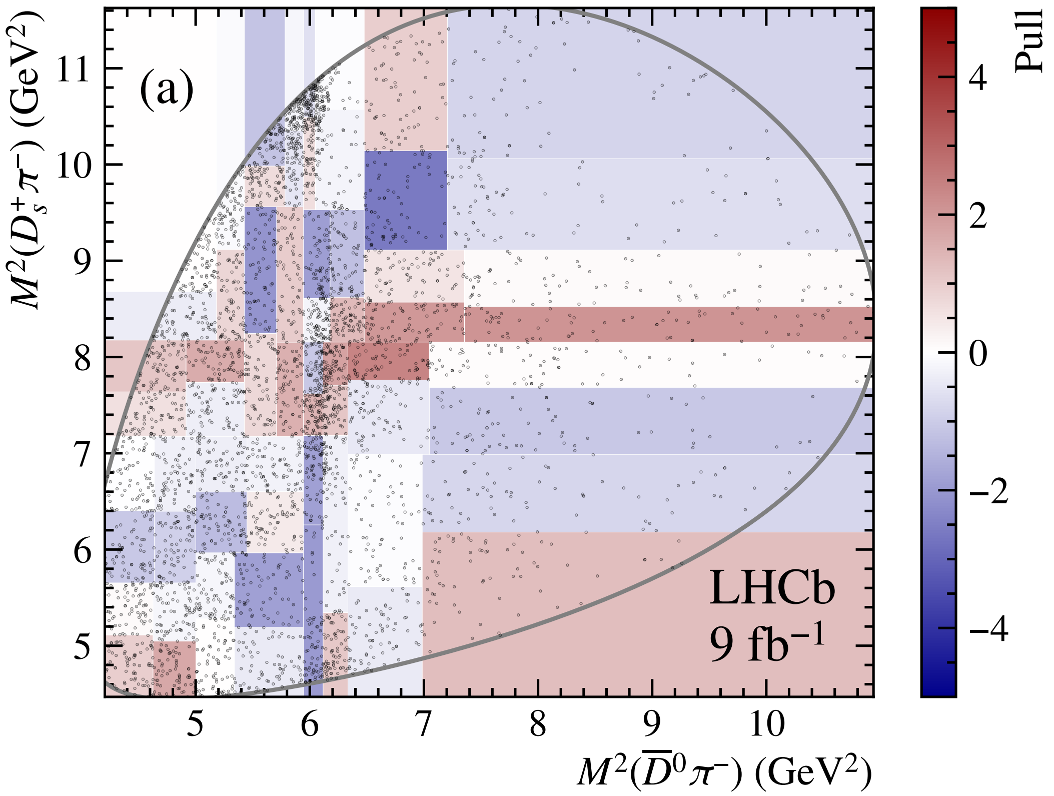


Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

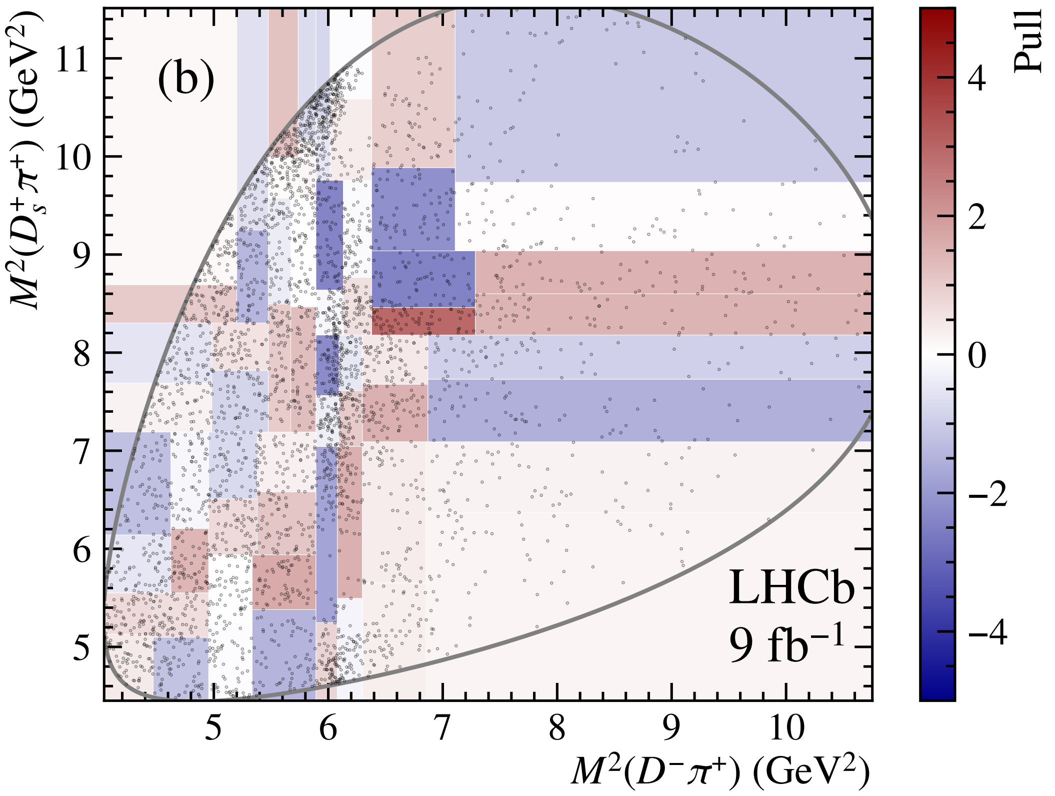
Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Have a look at the fit quality

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



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

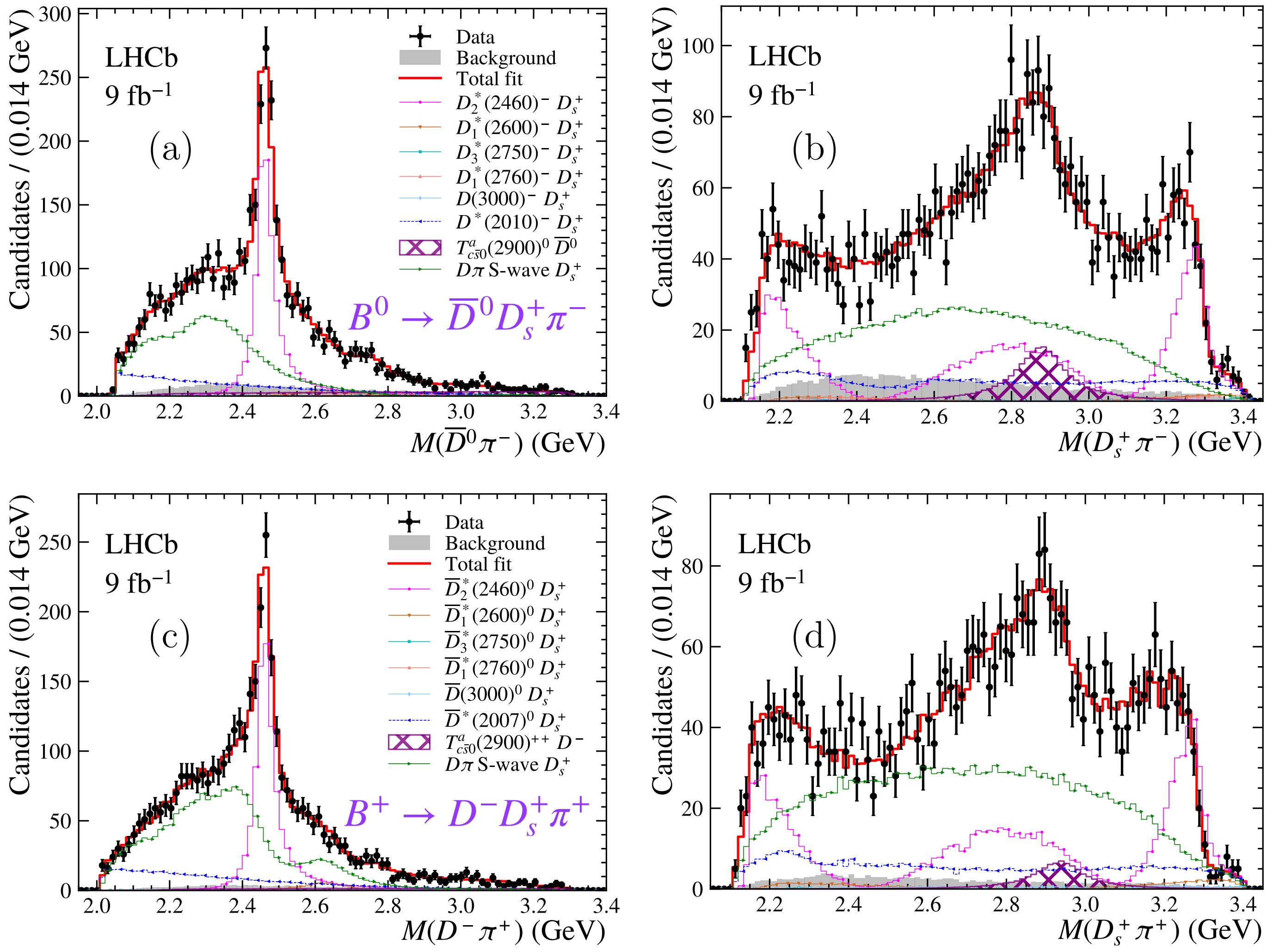


Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

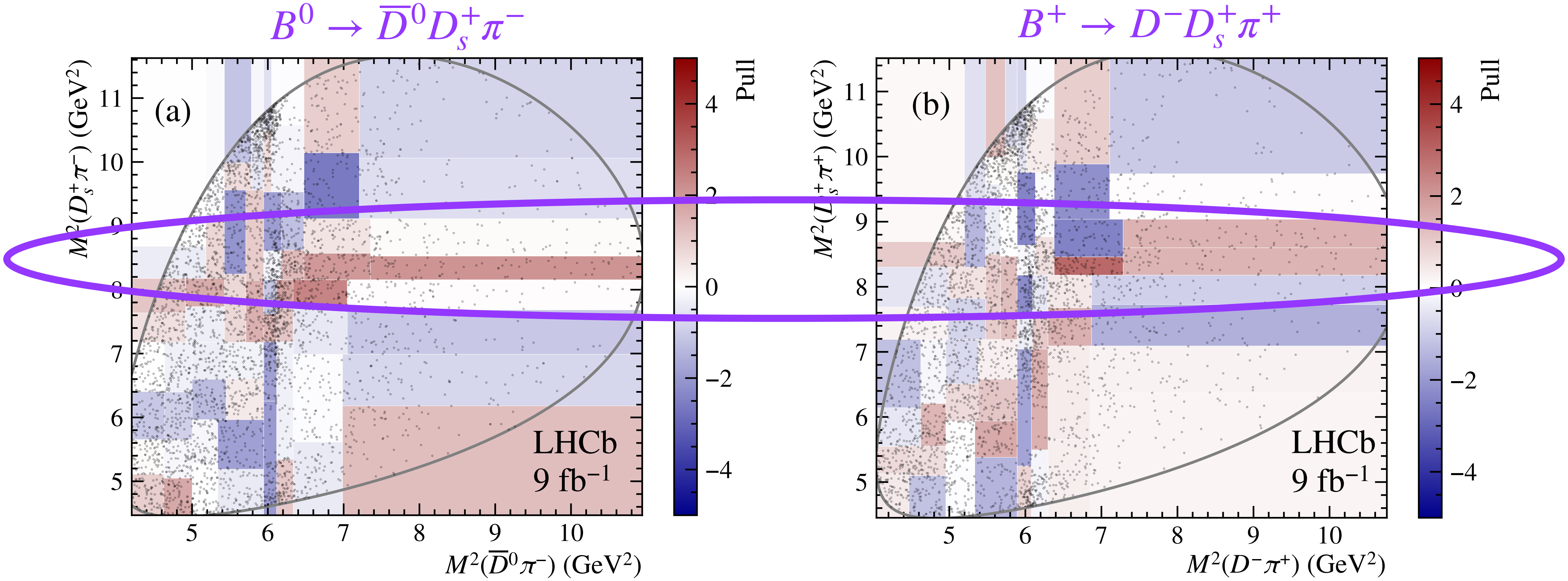
- Since the problem seems to be in the $D_s^+\pi$ projections
  - Try adding one state per decay mode
  - No relation between them assumed
  - Float mass, width and spin

- Both data sets prefer a spin-0 resonance at $2900\,\mathrm{MeV}/c^2$



Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

- Have a look at the fit quality
  - Quite a bit of strong colour in the area flagged previously



Phys. Rev. D108 (2023) 012017, Phys. Rev. Lett. 131 (2023) 041902

Study of the $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

- Study resonant structures in $B^+ \to D^{*+} D^- K^+, B^+ \to D^{*-} D^+ K^+$ decays

This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9, 10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC} = ?^{?-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 4025.5\,^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$	$\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0 = 3953$	$\Gamma_0 = 165$
$h_c(4300)$	$J^{PC} = 1^{+-}$			$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

$\eta_c(3945)$, $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$

$\eta_c(3945)$	$h_c(4000)$	$\chi_{c1}(4010)$	$h_c(4300)$
10σ	9.1σ	16σ	6.4σ
0^{-+}	1^{+-}	1^{++}	1^{+-}

arXiv:2406.03156 [hep-ex]

Looking forwards - my two cents

- We need to understand the structure of exotic particles
  - With four and five quark states, how are the quarks arranged?

- Discovering them pseudo-randomly is a good start…
  - Perh…
  - Focu…

The $T^{\theta}_{\psi s1}(4X00)$ family could be another starting point

$T_{cs1}(2900)^0$ $cs\bar{u}\bar{d}$

$T^{a}_{c\bar{s}0}(2900)^{++}$ $c\bar{s}u\bar{d}$

- Make sure we focus equally on final states they do not decay to

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

- Try to learn more about this famous state by studying these decay modes
  - Aim to measure the ratio of branching fractions

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma(\chi_{c1}(3872) \to \psi(2S)\gamma)}{\Gamma(\chi_{c1}(3872) \to J/\psi\gamma)}$$

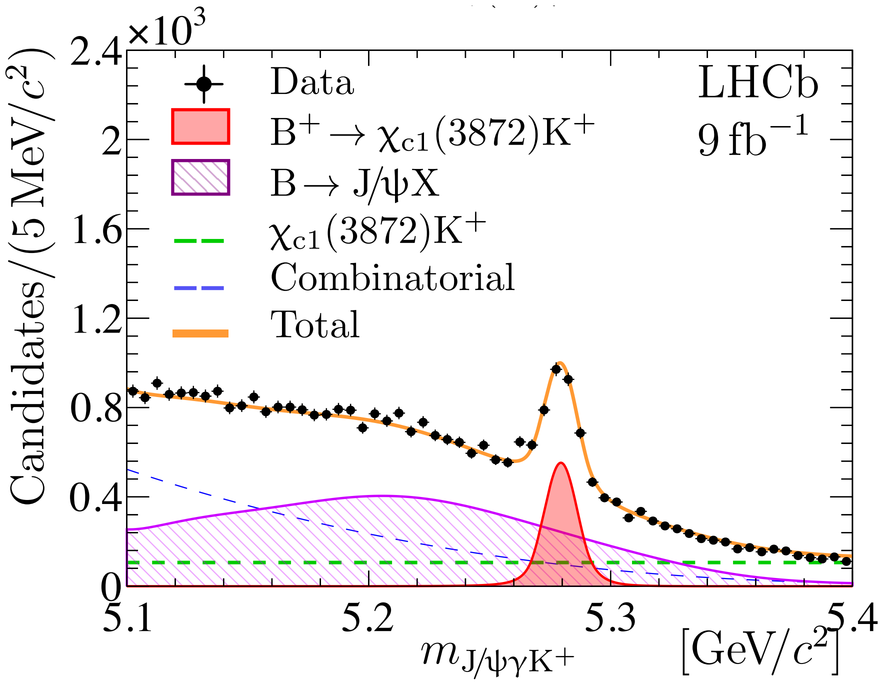
  - Predictions vary strongly depending on the nature of the $\chi_{c1}(3872)$ state

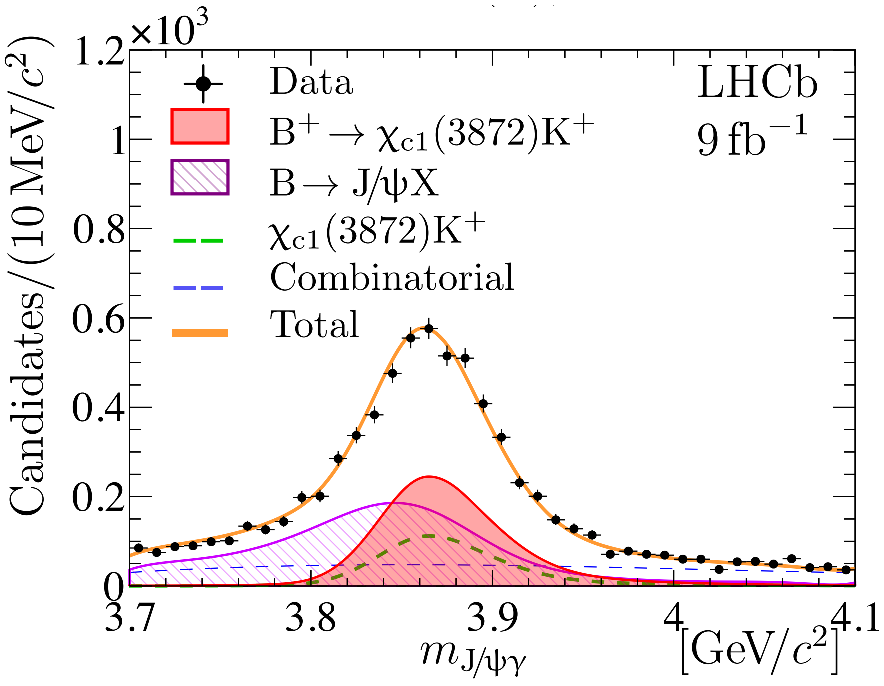
- Experimental history
  - BaBar measured $\mathcal{R}_{\psi\gamma} = 3.4 \pm 1.4$
  - LHCb measured $\mathcal{R}_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29$
  - Belle and BESIII found no significant signal for $\chi_{c1}(3872) \to \psi(2S)\gamma$

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

- In the latest LHCb measurement we determine

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma(B^+ \to [\chi_{c1}(3872) \to \psi(2S)\gamma]K^+)}{\Gamma(B^+ \to [\chi_{c1}(3872) \to J/\psi\gamma]K^+)}$$





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

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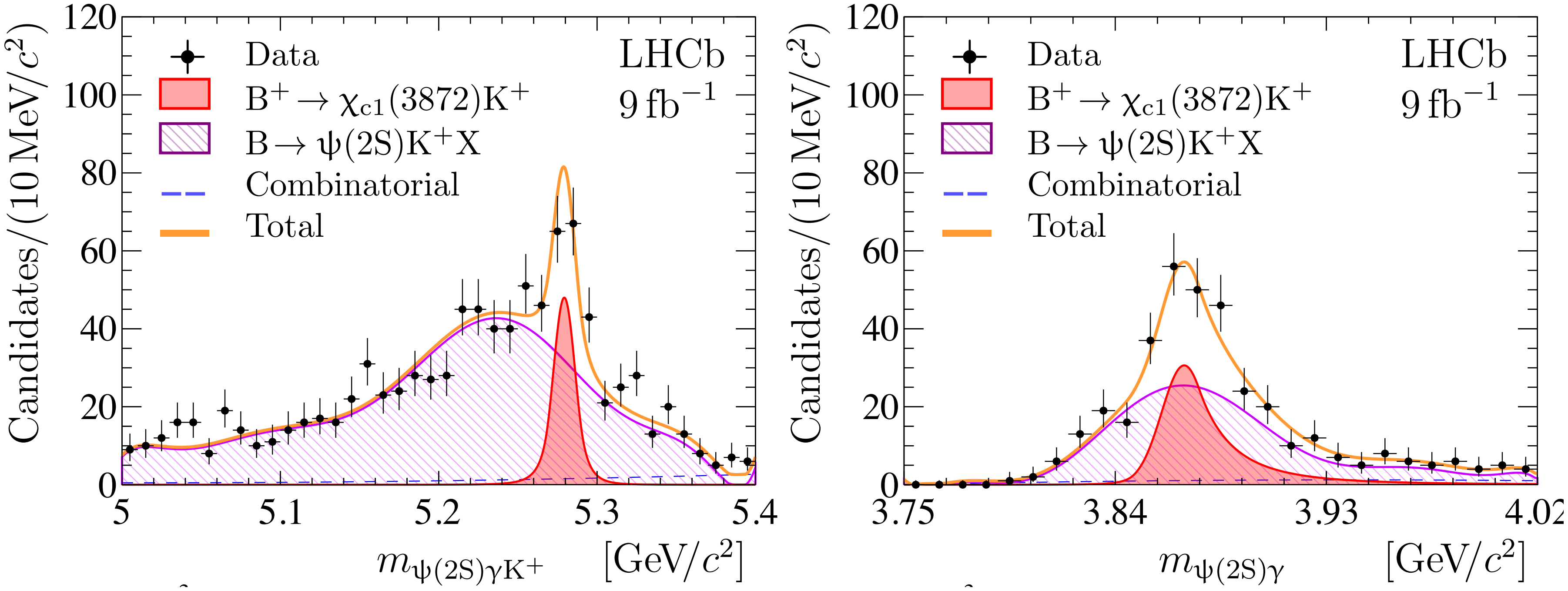

arXiv:2406.17006 [hep-ex]

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

- Summary of yield from the mass fits

Parameter		Data-taking period Run 1	Run 2
$\psi(2S)\gamma K^+$		5.3σ	6.7σ
$N_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}$		40 ± 8	63 ± 10
$N_{B\to\psi(2S)K^+X}$		567 ± 24	885 ± 29
N_{comb}		55 ± 17	132 ± 19
$J/\psi\gamma K^+$			
$N_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}$	$[10^3]$	0.43 ± 0.03	1.69 ± 0.05
$N_{B\to J/\psi X}$	$[10^3]$	3.61 ± 0.11	18.72 ± 0.26
$N_{\chi_{c1}(3872)K^+}$	$[10^3]$	1.18 ± 0.06	5.53 ± 0.23
N_{comb}	$[10^3]$	4.05 ± 0.11	17.46 ± 0.21

Stat only

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

- Summary of results by year

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

  - Averaged (BLUE method) to give

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

  - Inconsistent with an upper limit from BESIII
  - Inconsistent with many predictions using DD* molecular models

LHCb Upgrade II

- Complete new detector required
  - Vertexing: Pixel detector with timing
  - Hadron PID: RICH with timing and better resolution, TORCH for low momentum tracks
  - Tracking: New magnet stations and pixel mighty tracker
  - Calorimeter: Better resolution and timing information
  - Muon system: New technologies for high occupancy regions

Upgrade II
2033-

FTDR