Observation of a new excited D_s^+ state in $B^0 \to D^+ D^- K^+ \pi^-$ decays

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陈 晨(Chen Chen)

Center for High Energy Physics, Tsinghua University

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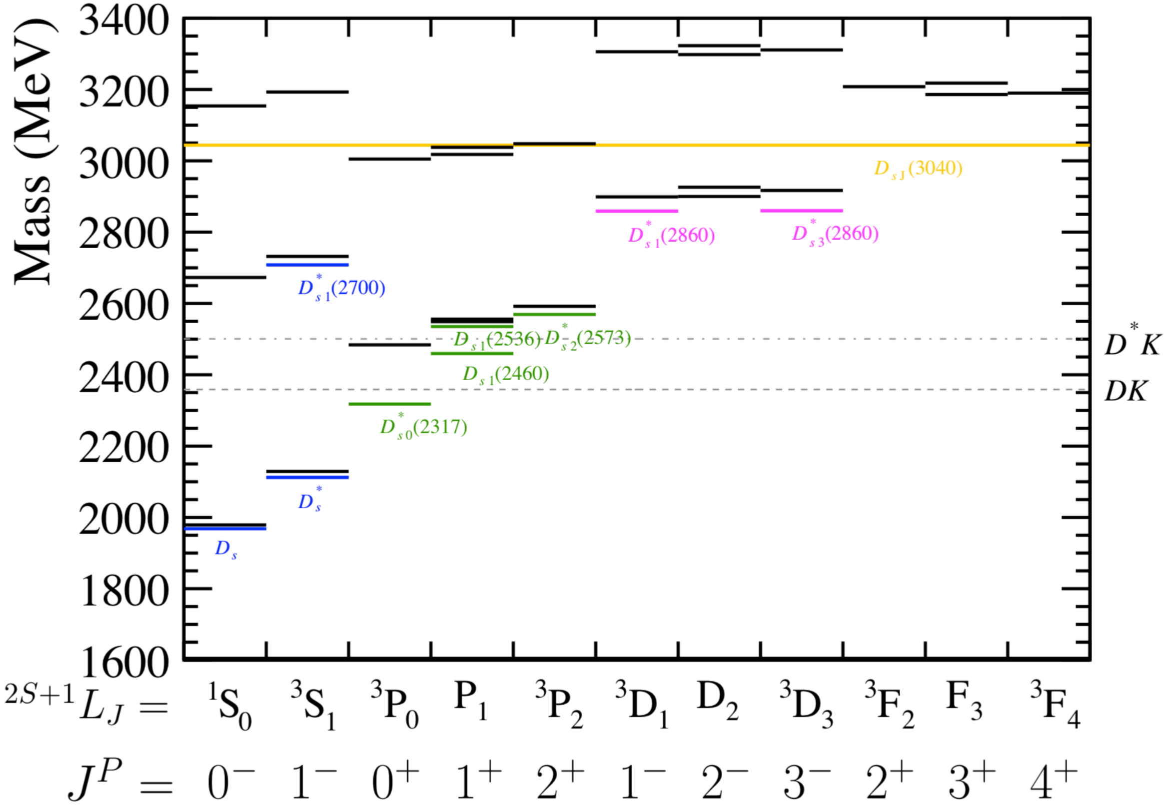
D_s^+ spectroscopy: overview

- Abundant structures, providing an ideal place for theory testing based on QCD
- 10 states experimentally established
  - Nine with spin parity determined
  - $D_{sJ}(3040)^+$ with unknown spin parity, but likely to be a $2P$ state
  - $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ masses much smaller than predicted, not understood yet
  - More experimental input is essential to solve the issues
- Still 6 states missing below 3.1 GeV
  - The 2^1S_0 state is expected to be the lightest



- Theoretical predictions from Phys. Rev. D93 (2016) 034035
- Experimental values from PDG

Motivation for $B^0 \to D^+D^-K^+\pi^-$

- Study of B-decays provides excellent potential for new D_s states searches
  - $D_{s1}^*(2700)$ is seen in $B \to D\bar{D}K$ decays [Phys.Rev.Lett.100(2008)092001, Phys. Rev. D91 (2015) 052002]
  - $D_{s1}^*(2860)$ and $D_{s3}^*(2860)$ are seen in $B_s^0 \to \bar{D}^0K^-\pi^+$ [Phys. Rev. Lett. 113 (2014) 162001, Phys. Rev. D90 (2014) 072003]
  - The analyses so far only focused on DK pair
    - Can only access states with natural spin-parity ($J^P = 0^+, 1^-, 2^+, etc$)

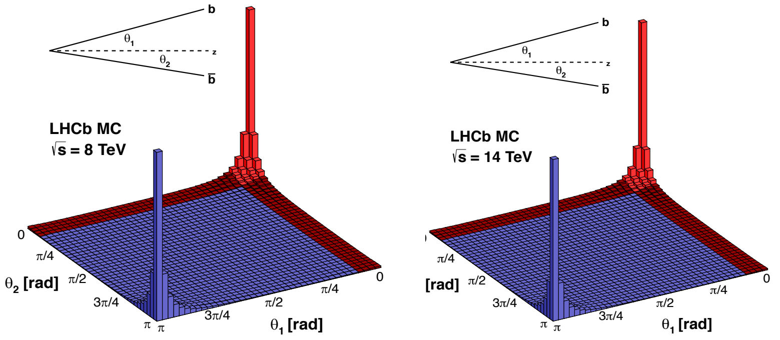
- $D^{*0}K^+$ and $D^{*+}K^0$ final states
  - Can access all the spin-parity
  - But have low reconstruction efficiency of neutral particles at LHCb

- $D^+K^+\pi^-$ is an ideal final state to access all the spin-parity
  - Especially when $K^+\pi^-$ mass is restricted below $K^*(890)$, states with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-, etc$) are possible with masses above 2.5 GeV
  - Provide opportunities to search for such states

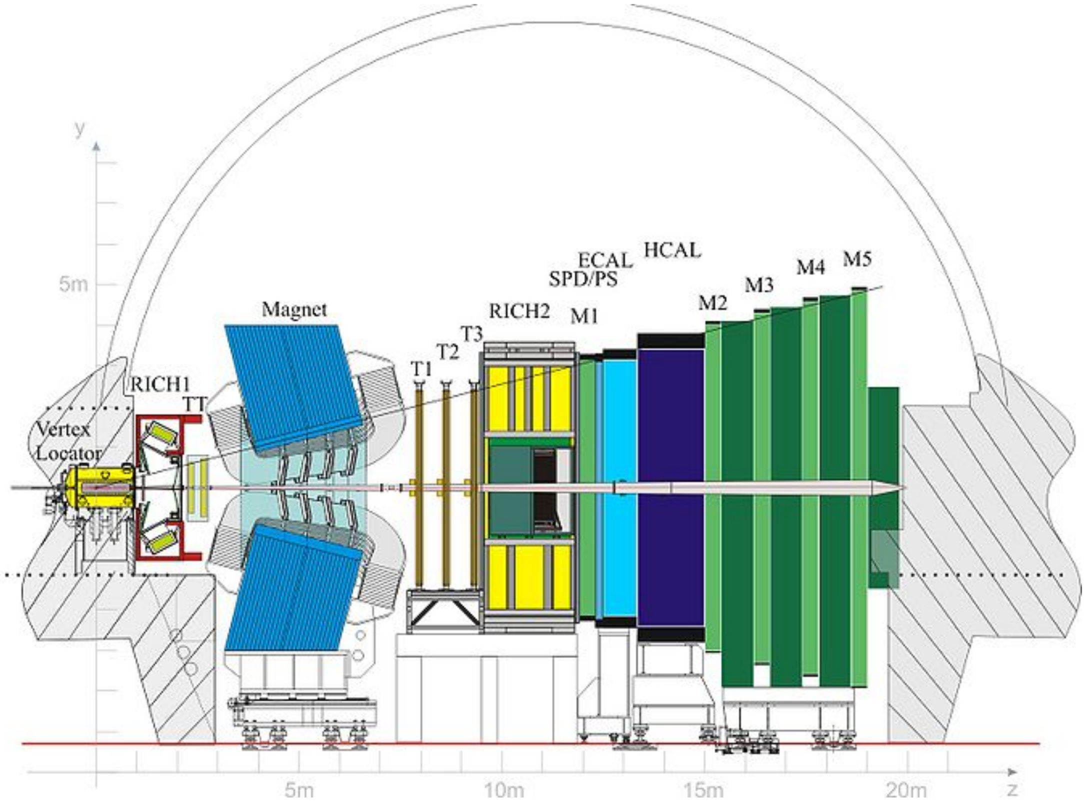
LHCb detector

JINST 3 (2008) S08005   Int.J.Mod.Phys. A30 (2015) 1530022

- Single-arm $(2 < \eta < 5)$ spectrometer, designed for precision flavour measurements
  - Excellent vertex, IP and decay-time resolution
    - $\sigma(\mathrm{IP}) \approx 20\ \mu\mathrm{m}$ for high-p_T tracks
    - $\sigma(\tau) \approx 45\ \mathrm{fs}$ for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$ decays
  - Good momentum resolution
    - $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0{,}200)\mathrm{GeV}$
    - $\sigma(m_B) \approx 24\ \mathrm{MeV}$ for two-body decays
  - Hadron and Muon identification
    - $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to $100\ \mathrm{GeV}$



$2 < \eta < 5$ range: $\sim 25\%\ b\bar{b}$ pairs in LHCb acceptance



Dataset and selections

- 2016-2018 data collected by the LHCb detector. $\mathcal{L} = 5.4\ \mathrm{fb}^{-1}$

- $B^0 \to D^+D^-K^+\pi^-$ with $D^\pm$ reconstructed using $D^+ \to K^-\pi^+\pi^+$
  - $m(K^+\pi^-) < 0.75\ \mathrm{GeV}$

- Cut-based selection is applied
  - Particle-identification for final tracks
  - Good track and vertex fit quality
  - Significant flying distance of B^0
  - Significant displacement between B^0 and $D^\pm$ vertices
    - Suppress contributions from B^0 decays with only one or no $D^\pm$

Backgrounds

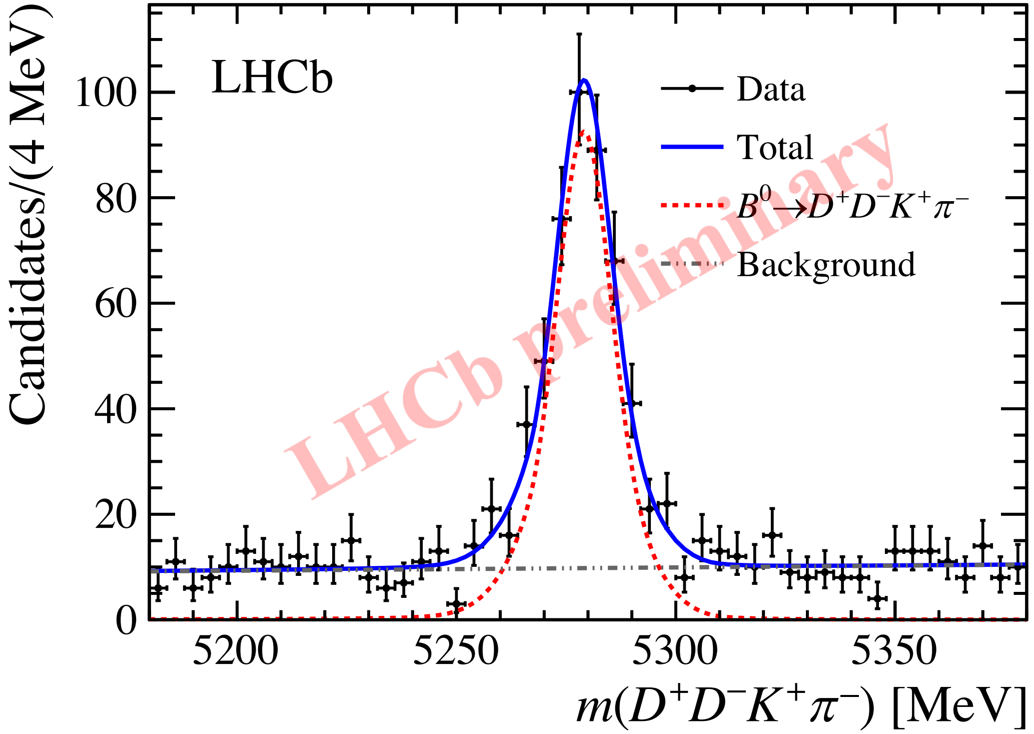
- Backgrounds from final-track misidentifications (K or π) are Cabibbo-suppressed
  - Except $B_s^0 \to D^+D^-K^+K^-$, but it is suppressed by the ratio of fragmentation fractions f_s/f_d
  - Lack of expected contributions of charm or charm-strange resonances

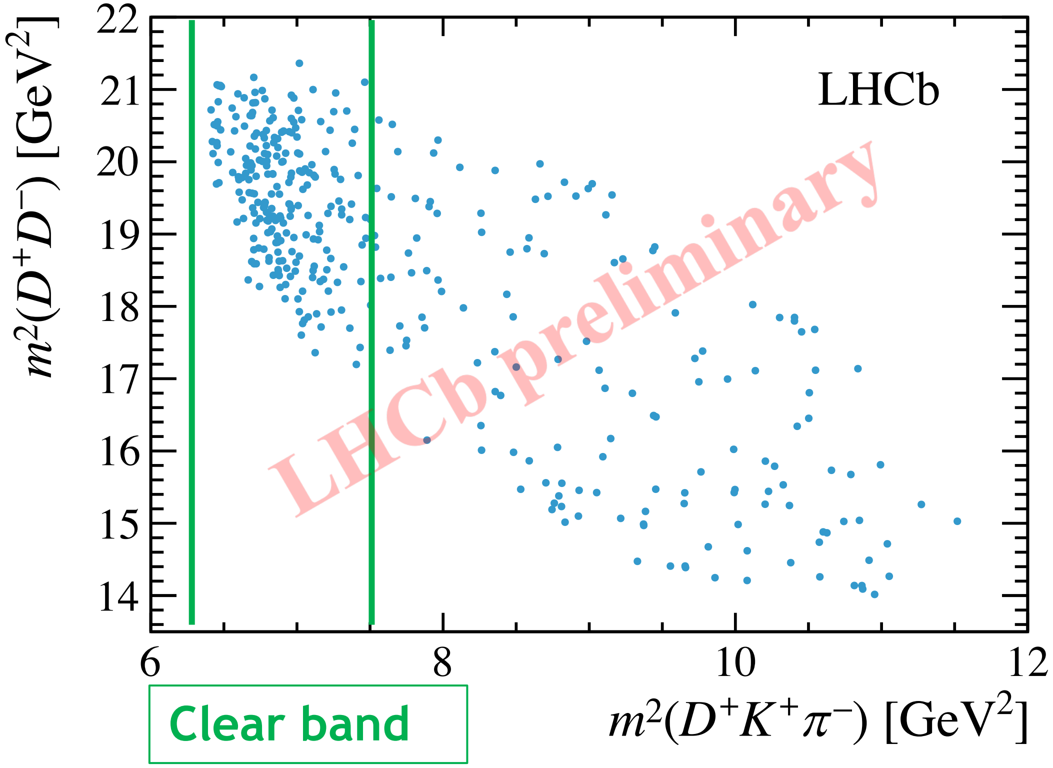
- Partially reconstructed backgrounds: $D^{*+} \to D^+\pi^0/\gamma$
  - $D^{*+} \to D^+\pi^0$: shift out of the B^0 mass window (5280 ± 100 MeV)
  - $D^{*+} \to D^+\gamma$: could have a tail in the B^0 mass window , but is suppressed by its low branching fraction, $\mathcal{B}(D^* \to D^+\gamma) = (1.6 \pm 0.4)\%$

- Therefore, only combinatorial background needs to be considered

B^0 mass fit

- An unbinned maximum-likelihood method
- Fit model
  - Signal: A sum of two Crystal Ball function with a common mean and opposite-side tails
  - Background: An exponential function
- Signal yield: 444 ± 27





Amplitude analysis

$$\mathcal{M} = \sum_k \mathcal{H}^{D_{sk}} \, d_{0,0}^{J_{D_{sk}}}(\theta_{D_s}) \, p^{L_{B^0}} \, F_{L_{B^0}}(p\,R) \, q^{L_{D_{sk}}} \, F_{L_{D_{sk}}}(q\,R) \, \mathrm{BW}(m_{K^+\pi^-}) \, \mathrm{BW}_{D_{sk}}(m_{D^+K^+\pi^-})$$

- Amplitude constructed using helicity formulism
- Three components in the $D^+K^+\pi^-$ system considered
  - 0^- non-resonant (NR) component: constant lineshape
  - 1^+ $D_{s1}(2536)^+$ state: Relativistic Breit-Wigner (RBW) amplitude
  - A new state. Three spin parity hypotheses will be tested: $J^P = 0^-, 1^+, 2^-$. RBW amplitude
- $K^+\pi^-$ mass lineshape modelled by the 0^+ $K_0^*(700)^0$ state: RBW amplitude
- Width parameterization
  - $K_0^*(700)^0$: Two-body mass-dependent width
  - $D_{s1}(2536)^+$: A constant width because it's very narrow
  - The new state:

$$\Gamma^{D_{sJ}^+}(m_{D^+K^+\pi^-}) = \underbrace{\Gamma^{D_{sJ}^+\to D^*K}(m_{D^+K^+\pi^-})}_{\text{Two-body mass-dependent width}} + \underbrace{\Gamma^{D_{sJ}^+\to DK\pi}(m_{D^+K^+\pi^-})}_{\text{A constant width}}$$

Amplitude fit

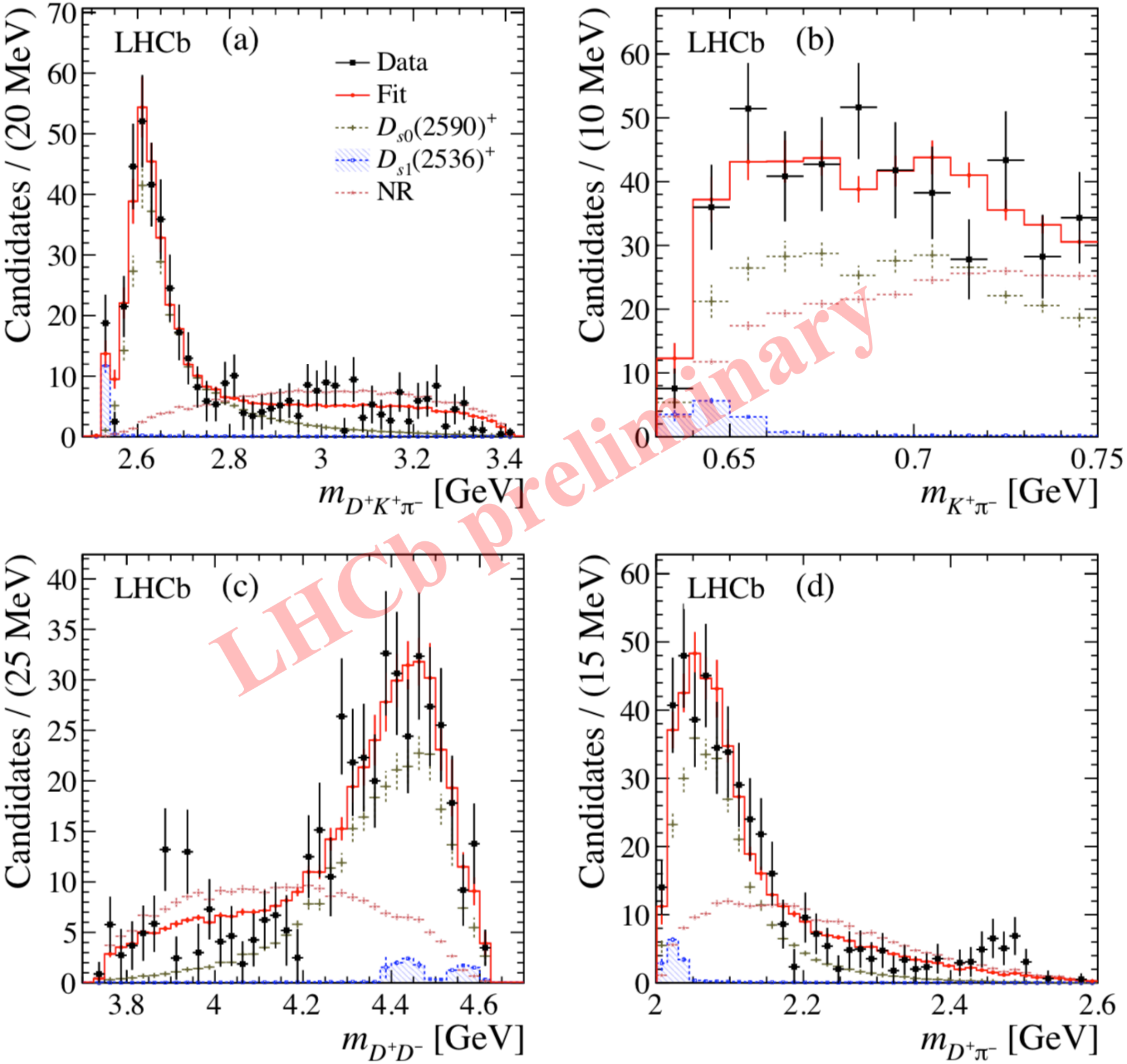
- Combinatorial background statistically subtracted using sPlot method
- Fit parameters
  - Helicity couplings
  - BW mass and width, and width fraction of the new D_s^+ state $r = \Gamma_0^{D_{sJ}^+ \to DK\pi} / \Gamma_0^{D_{sJ}^+}$
- $J^P = 0^-$ leads to the best fit
  - $J^P = 1^+$ and 2^- are rejected by at least 15σ
  - The null hypothesis without the new D_s^+ state is rejected by at least 20σ

    (Significance calculation is based on an empirical method [Phys. Rev. Lett. 115 (2015) 072001, Phys. Rev. D95 (2017) 012002])
- r could not be determined from the current dataset, so instead is fixed to 0.5
  - BW parameters vary a lot for different r, but the pole position is stable
    - Understood as that pole is a physical characteristic of a resonance, but BW parameters depend on width parameterizations and processes
  - Only the pole mass and width are reported

$D_{s0}(2590)^+$

LHCb preliminary: $m_R = 2591 \pm 6 \pm 7\ \mathrm{MeV}, \ \Gamma_R = 89 \pm 16 \pm 12\ \mathrm{MeV}$

Mass projections from the fit for $J^P = 0^-$

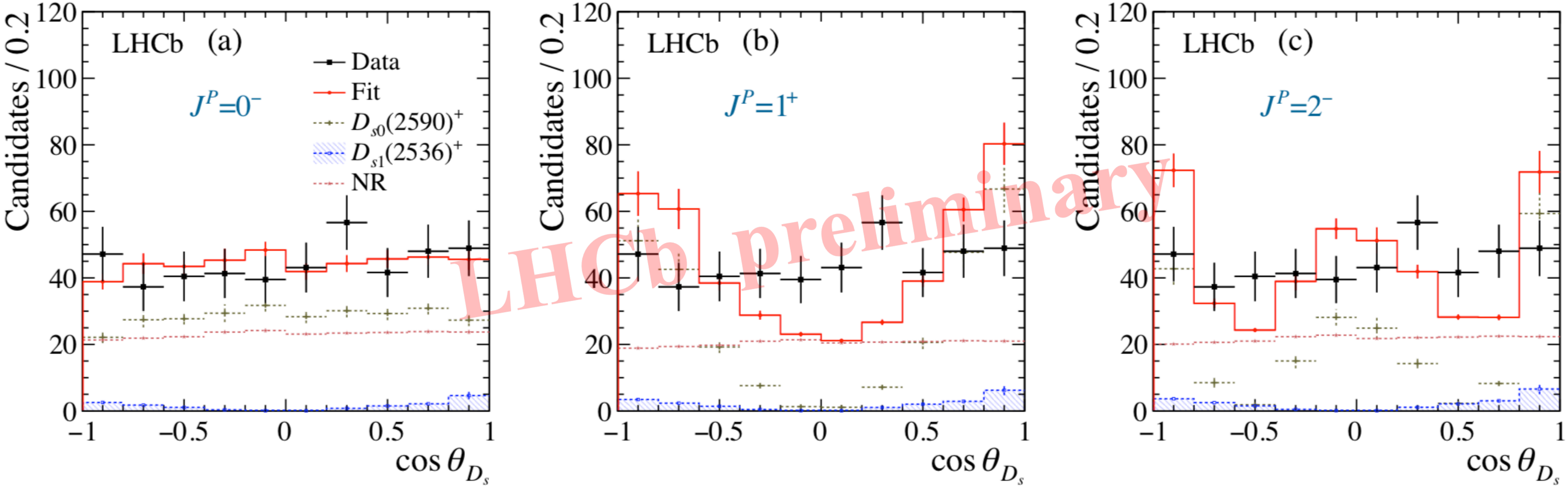


- No D^+D^- resonant contribution is seen

- The peak in the $D^+\pi^-$ mass at about 2.45GeV could be from the $D_2^*(2460)^+$ contribution
  - Handled in systematic study

$\cos\theta_{D_s}$ projection from the fit

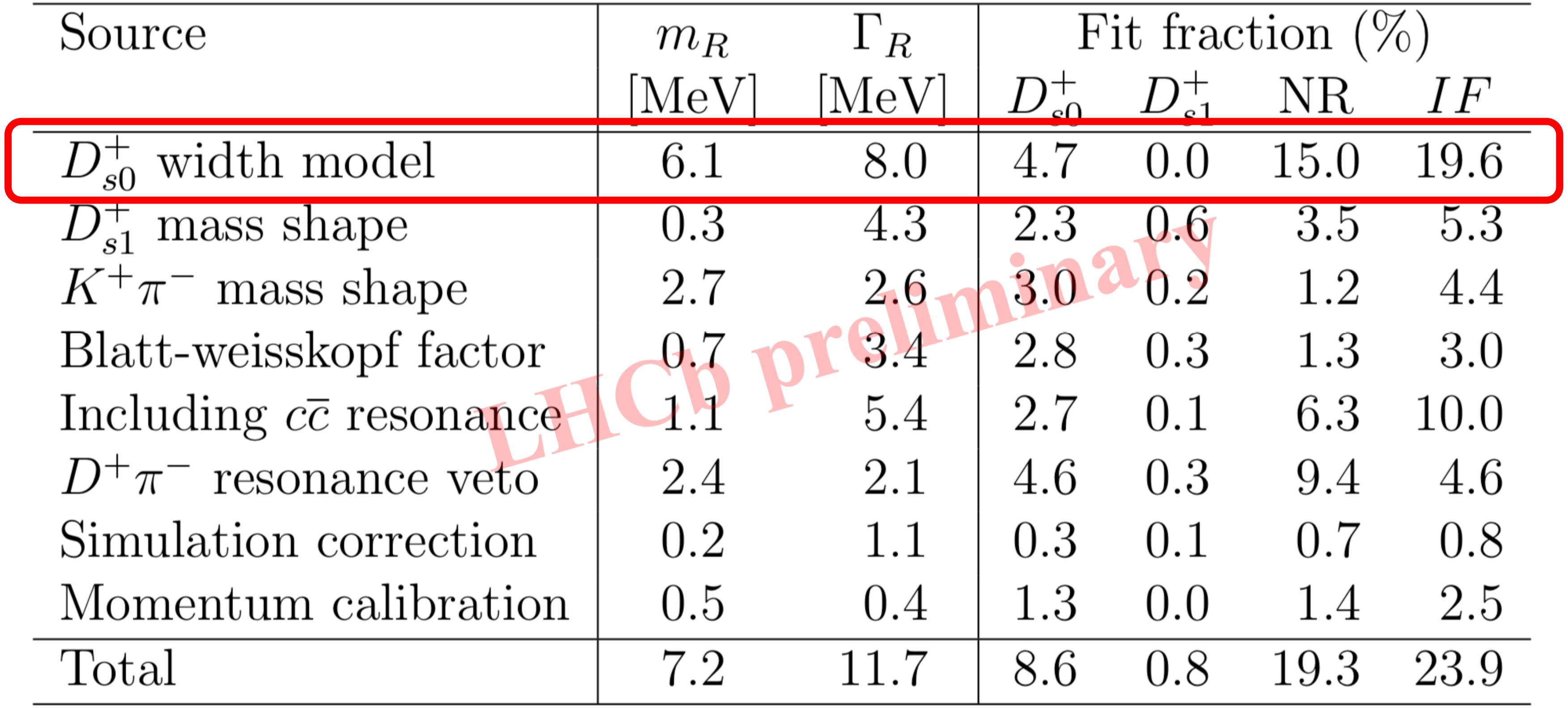
- $\cos\theta_{D_s}$-behavior is described by the Wigner d-matrix, $d^J_{0,0}(\cos\theta_{D_s})$, thus
  - $J^P = 0^-$: $|M|^2 \sim$ a constant function of $\cos\theta_{D_s}$
  - $J^P = 1^+$: $|M|^2 \sim$ a second-order polynomial of $\cos\theta_{D_s}$
  - $J^P = 2^-$: $|M|^2 \sim$ a fourth-order polynomial of $\cos\theta_{D_s}$
- $J^P = 0^-$ is clearly seen to be the most consistent with data



Fit fractions

	Fit fraction (%)
$D_{s0}(2590)^+$	63 ± 9 (stat) $\pm$ 9 (syst)
$D_{s1}(2536)^+$	3.9 ± 1.4 (stat) $\pm$ 0.8 (syst)
NR	51 ± 11 (stat) $\pm$ 19 (syst)
D_{s0}^+-NR	-18 ± 18 (stat) $\pm$ 24 (syst)

Systematic uncertainties



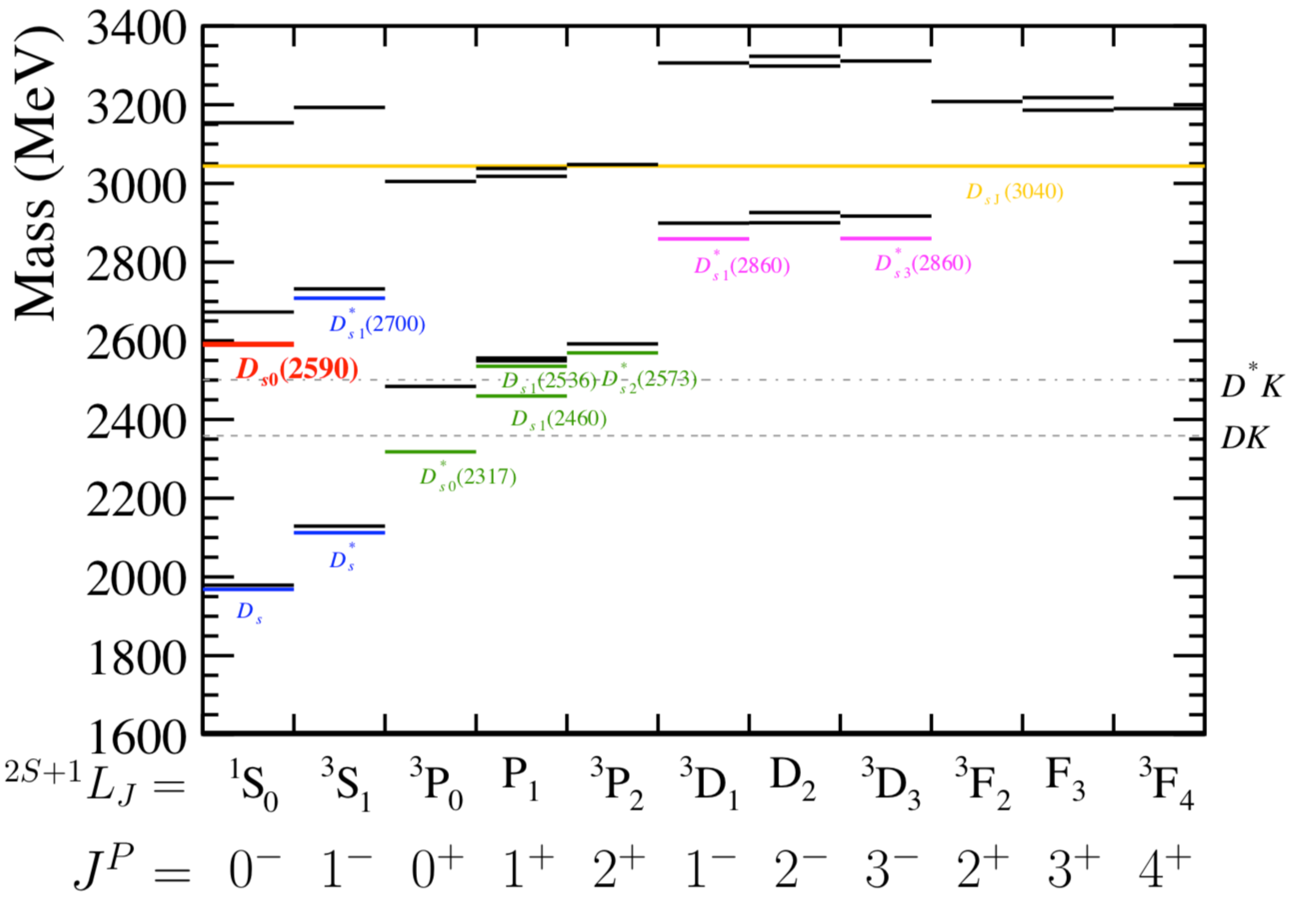
Source	m_R [MeV]	Γ_R [MeV]	Fit fraction (%)			
			D_{s0}^+	D_{s1}^+	NR	IF
D_{s0}^+ width model	6.1	8.0	4.7	0.0	15.0	19.6
D_{s1}^+ mass shape	0.3	4.3	2.3	0.6	3.5	5.3
$K^+\pi^-$ mass shape	2.7	2.6	3.0	0.2	1.2	4.4
Blatt-weisskopf factor	0.7	3.4	2.8	0.3	1.3	3.0
Including $c\bar{c}$ resonance	1.1	5.4	2.7	0.1	6.3	10.0
$D^+\pi^-$ resonance veto	2.4	2.1	4.6	0.3	9.4	4.6
Simulation correction	0.2	1.1	0.3	0.1	0.7	0.8
Momentum calibration	0.5	0.4	1.3	0.0	1.4	2.5
Total	7.2	11.7	8.6	0.8	19.3	23.9

D_{s0}^+: $D_{s0}(2950)^+$
D_{s1}^+: $D_{s1}(2536)^+$
IF : D_{s0}-NR interference

Conclusion

- $B^0 \to D^+D^-K^+\pi^-$ decays reconstructed using LHCb dataset with $\mathcal{L} = 5.4\ \mathrm{fb}^{-1}$
- A new D_s^+ resonance observed in the $D^+K^+\pi^-$ system with high significance
  - $\boldsymbol{m_R = 2591 \pm 6 \pm 7\ \mathrm{MeV}}$
  - $\boldsymbol{\Gamma_R = 89 \pm 16 \pm 12\ \mathrm{MeV}}$
  - $\boldsymbol{J^P = 0^-}$

- Fit fractions of the three D_s^+ components measured
- The new state is a strong candidate to be the missing $D_s(2^1S_0)^+$ state, the radial excitation of the D_s^+ meson

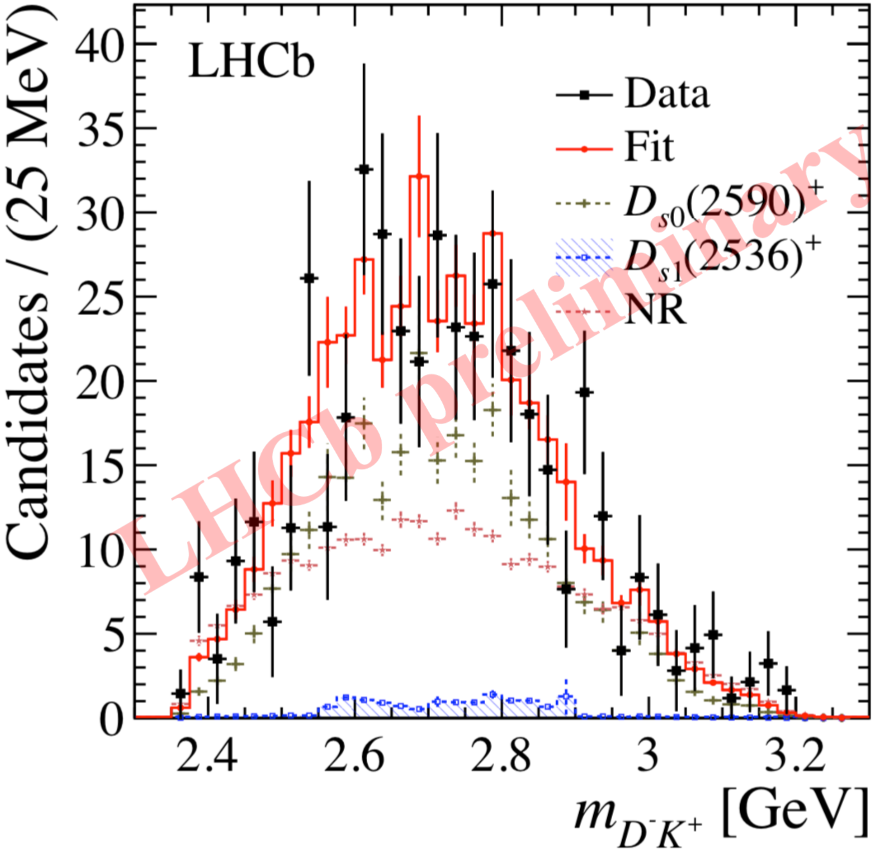


Thanks for your attention!

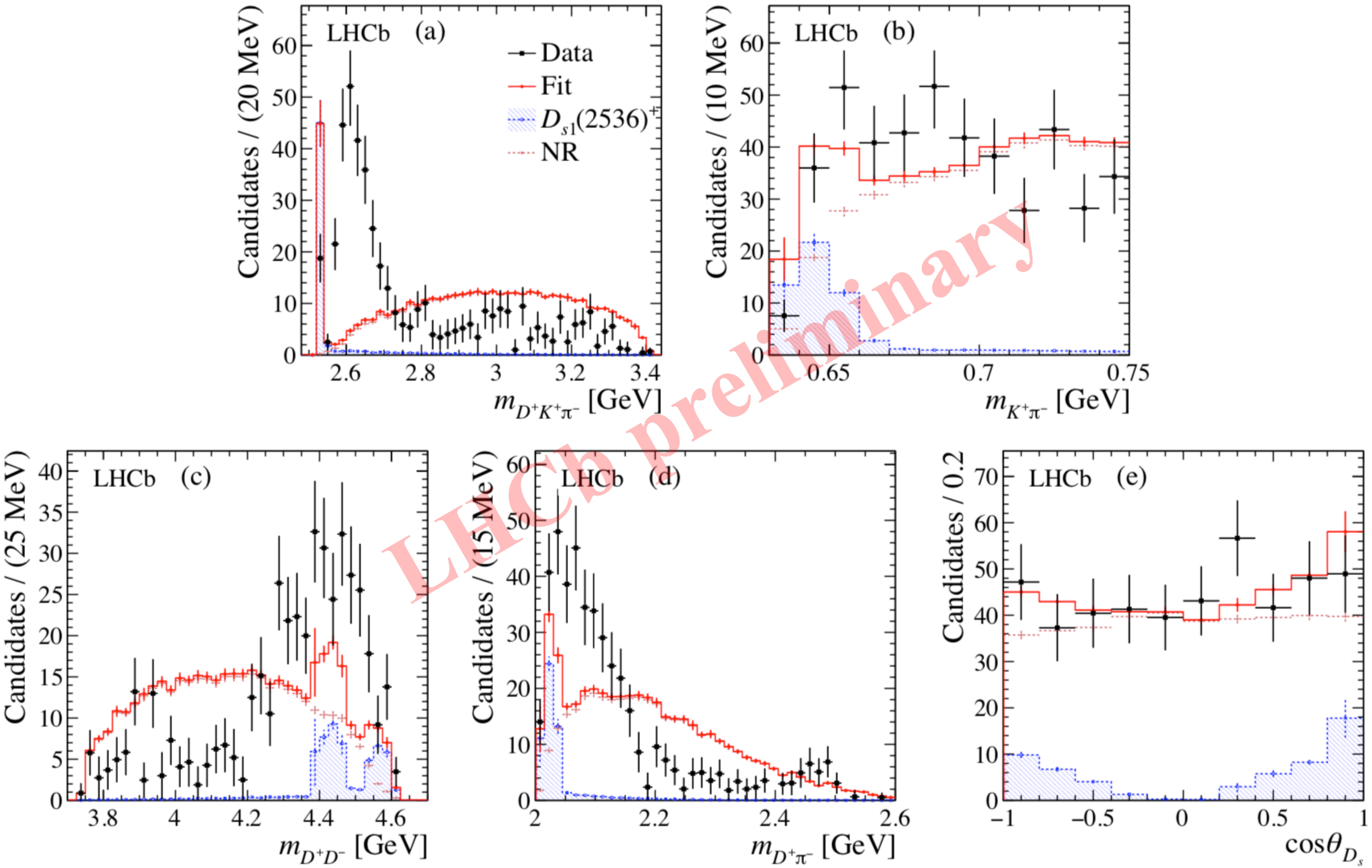
Any comments or questions?

Backup slides

D^-K^+ mass projection



Fit results for the model without the $D_{s0}(2590)^0$ state



Fit fractions

- Fit fraction for a component D_{sj}

$$FF^{D_{sj}} = \frac{\int \left|M^{D_{sj}}\right|^2 \mathrm{d}\Phi}{\int |M^{tot}|^2 \mathrm{d}\Phi}$$

- Interference fraction between two components, D_{si} and D_{sj}

$$IF^{D_{si},D_{sj}} = \frac{2\int M^{D_{si}} \cdot M^{*D_{sj}} \mathrm{d}\Phi}{\int |M^{tot}|^2 \mathrm{d}\Phi}$$

	Fit fraction (%)
$D_{s0}(2590)^+$	63 ± 9 (stat) $\pm$ 9 (syst)
$D_{s1}(2536)^+$	3.9 ± 1.4 (stat) $\pm$ 0.8 (syst)
NR	51 ± 11 (stat) ± 19 (syst)
D_{s0}^+-NR	-18 ± 18 (stat) ± 24 (syst)

Details on systematic uncertainties

- $D_{s0}(2590)^+$ width model
  - Using 3-body formula for the $D_{s0}(2590)^+ \to D^+K^+\pi^-$ partial width instead of constant
  - Varying width fraction r between 0 and 1
- $D_{s1}(2536)^+$ mass shape
  - Uncertainty of the BW parameters
  - Using 2-body width model
- $K^+\pi^-$ mass shape
  - Uncertainty of the $K_0^*(700)^0$ BW parameters
  - Changed to LASS shape
- Blatt-Weisskopf barrier factor
  - Varying it between 1.5 and 4.5 GeV
- Inclusion of possible $c\bar{c}$ resonances
  - Adding $\psi(3770)$ and $\chi_{c2}(3930)$ in the amplitude fit
- Vetoing $D^+\pi^-$ resonance
  - Requiring $m(D^+\pi^-) < 2.4\ \mathrm{GeV}$
- Imperfect corrections on simulated events
- Imperfect momentum calibration
  - Due to limited knowledge of the magnetic field and the detector alignment