The open-charm exotic hadrons $X_0(2900)$ and $X_1(2900)$

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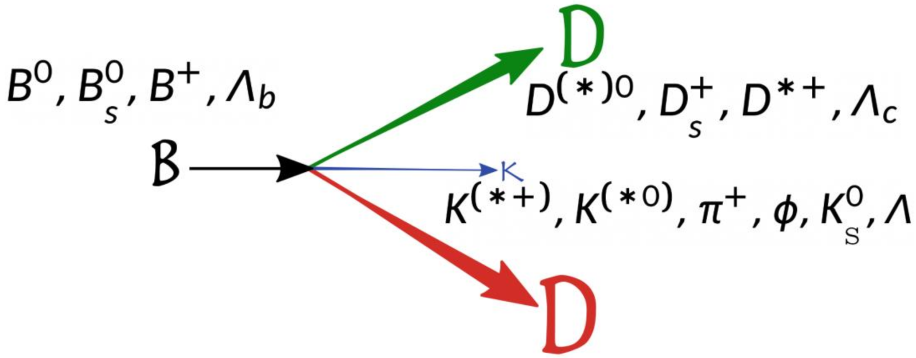
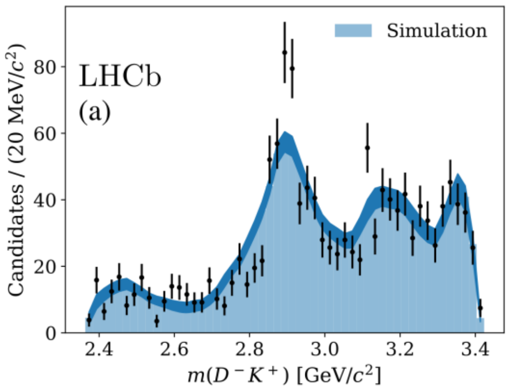
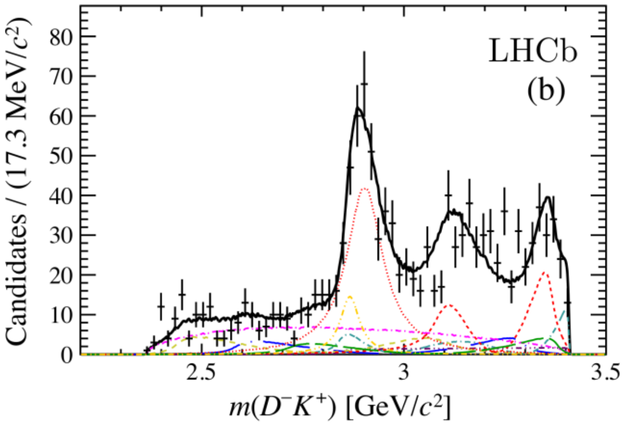


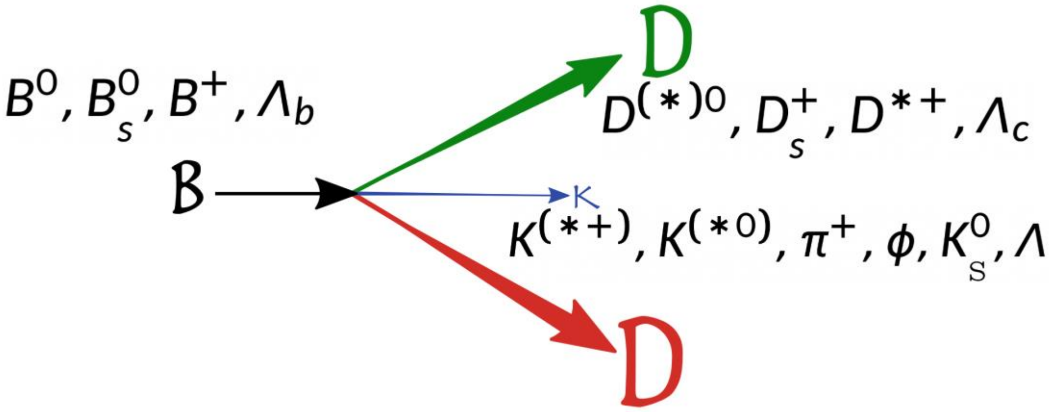




The $B \to DDh$ decays

The $B \to DDh$ decays

- The $B \to DDh$ decays involve huge family of **topologically similar decays.**



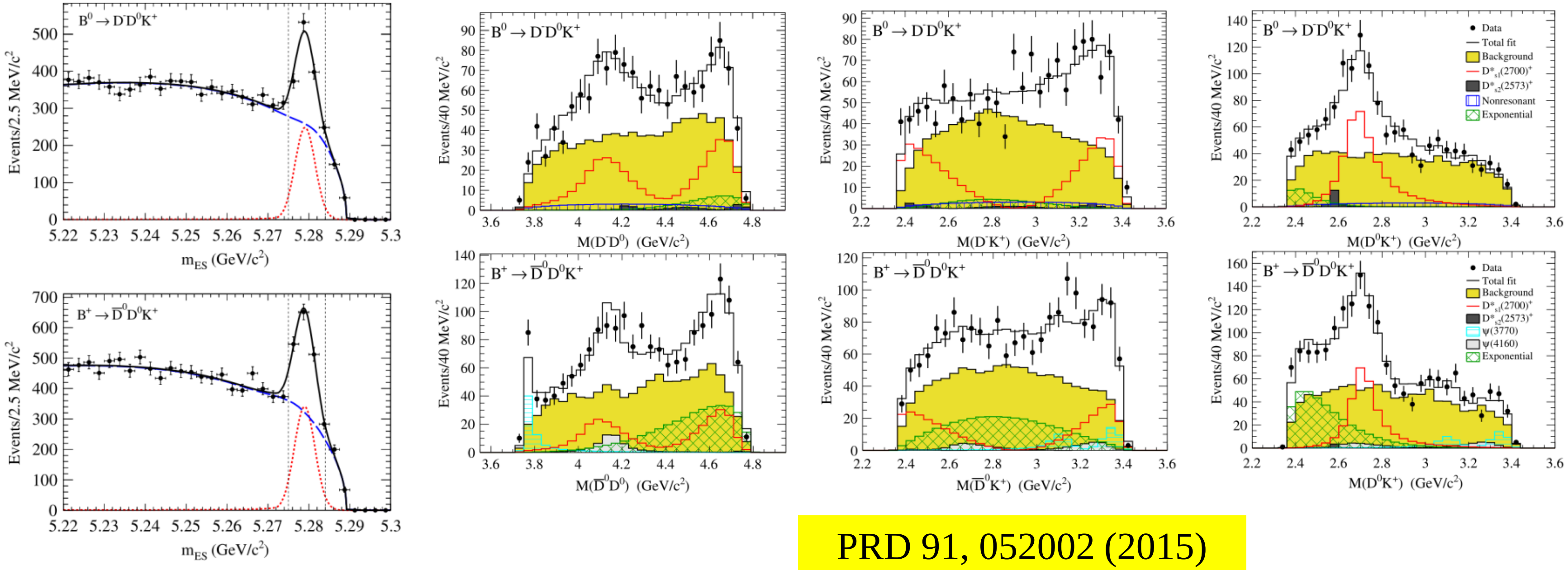
- Many intermediate states include:
  - Charmonium(-like) states ($D^{(*)}\overline{D}^{(*)}$, $\Lambda_c^+\Lambda_c^-$, etc.)
  - D_{sJ}, Λ_c^{*+}, Σ_c^* spectroscopy ($D^{(*)0}K^+, \Lambda_c^{(*)-}\pi^+$, etc.)
  - Exotic states ($D^{(*)0}D^{(*)-}$, $D^{(*)0}\Lambda_c^-$, D^-K^+, etc.)
- **Powerful** exclusive decays for **hadron spectroscopy** studies.

The $B \to DDh$ decays

- **Several $B \to DDh$ branching fractions have been measured.**
- Amplitude analyses of **only two decays** have been performed from **Belle** and **BaBar**:
  - $B^0 \to D^- D^0 K^+$, $B^+ \to \bar{D}^0 D^0 K^+$
  - $400 - 800$ signals with ~ 40% purity.
- Could be improved by LHCb collaboration!

PRL 100, 092001 (2008)

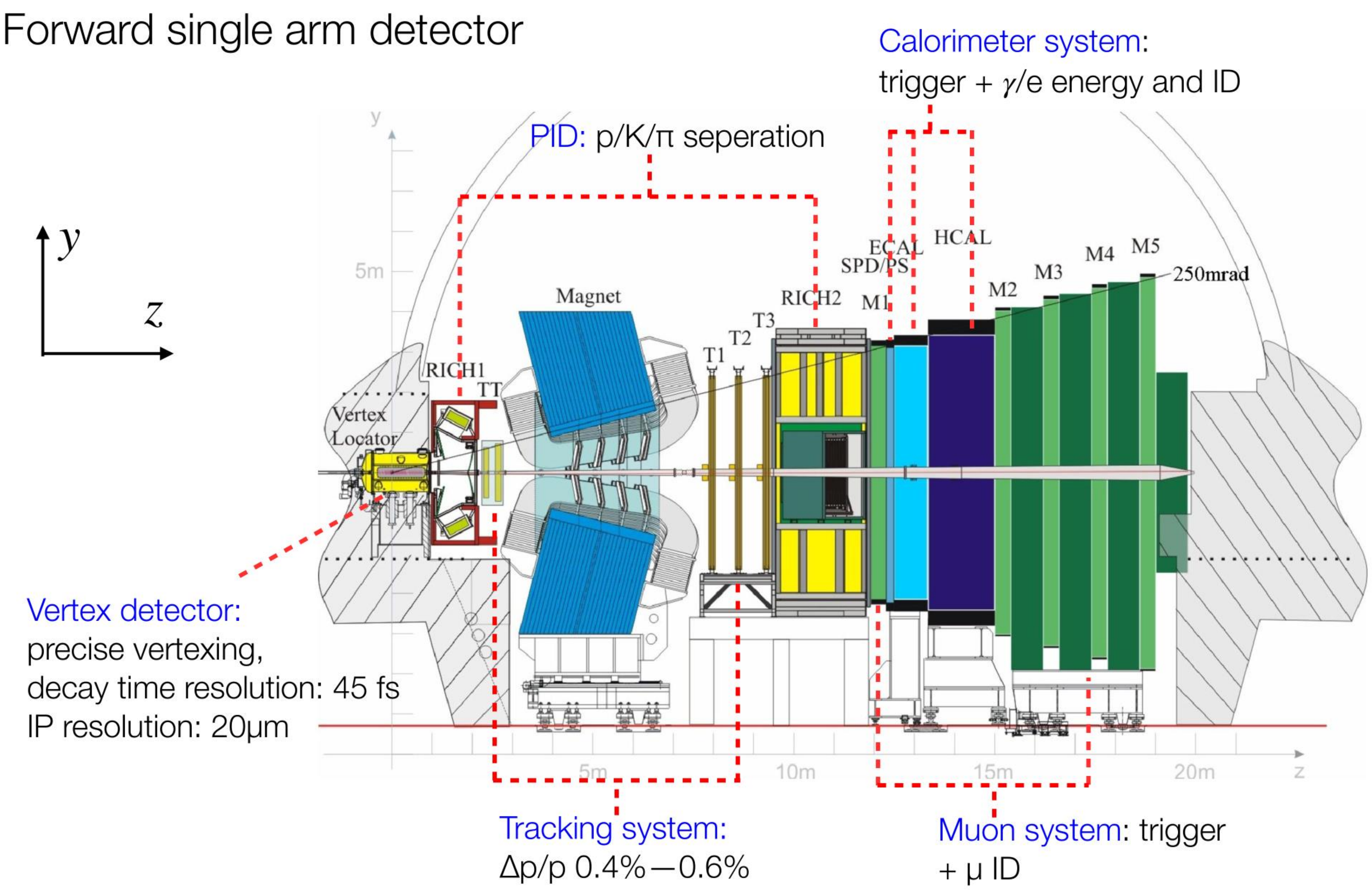
PRD 91, 052002 (2015)



PRD 91, 052002 (2015)

The LHCb detector

Forward single arm detector

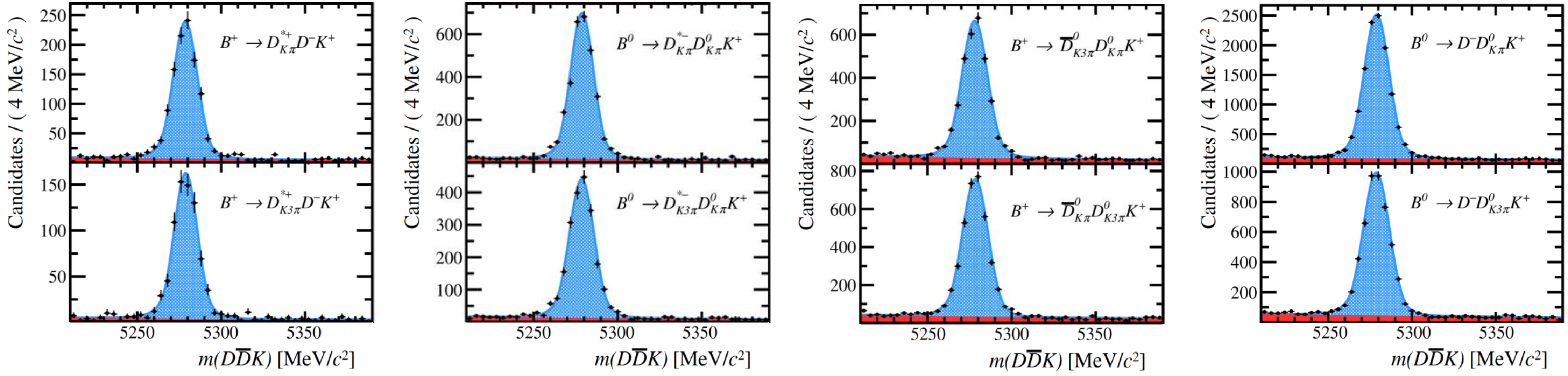


The $B \to DDh$ decays

- **$B \to DDh$ branching fractions measurements in LHCb:**
  - Measurement of the branching fractions for $B \to D^{*}DK$ decays.
  - First observation of the decay $B \to D^0\overline{D}^0K^+\pi^-$.
- **High statistic & High purity unprecedented datasets**
- **Ideal $B \to DDh$ data samples for amplitude analyses.**

JHEP 12 (2020) 139

PRD 102, 051102 (2020)



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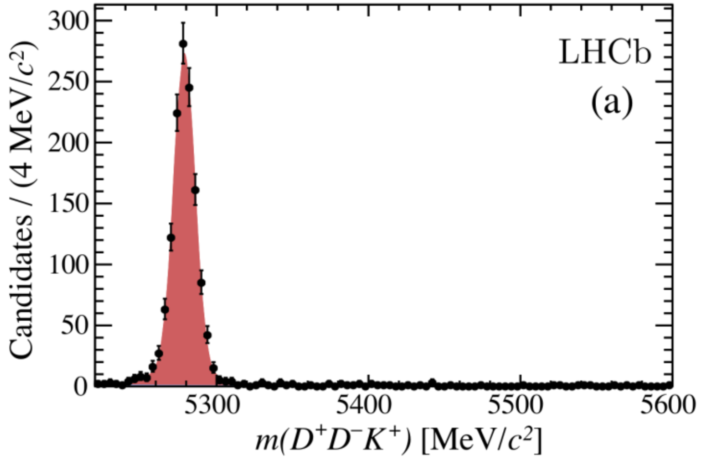
Model-independent analysis of $B^+ \to D^+ D^- K^+$ decay

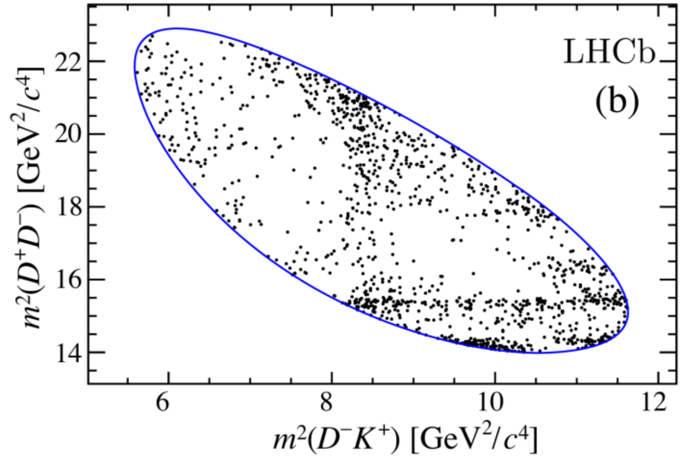
- **Why $B^+ \to D^+D^-K^+$?**
  - Haven't been explored yet.
  - Only the charmonium states (D^+D^-) are expected.

- **Dataset**
  - Full LHCb Run 1 and Run 2 pp collision datasets (9 fb^{-1}).
  - Reconstructed through $B^+ \to [K^-\pi^+\pi^+]_{D^+}[K^+\pi^-\pi^-]_{D^-}K^+$.
  - Uniform BDT with topological and PID variables.

- **Signal yields**
  - **1260 candidates** with in $\pm 20\ \text{MeV}/c^2$ of known B^+ mass.
  - **99.5% purity!**



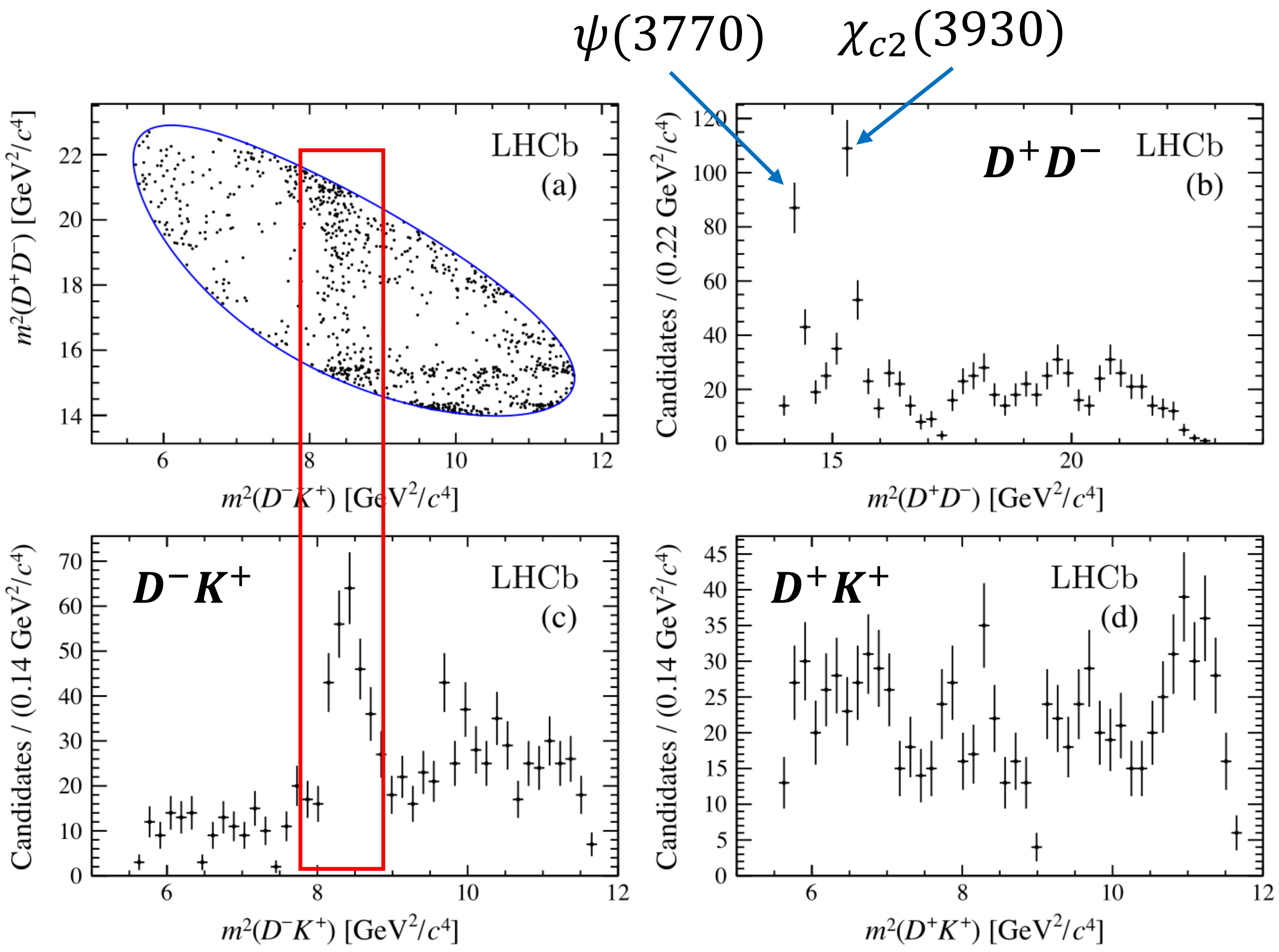
Invariant mass fit



Dalitz distribution

Model-independent analysis

- Clear $\boldsymbol{\psi(3770)}$ and $\boldsymbol{\chi_{c2}(3930)}$ peaks in D^+D^- spectrum.
- Obvious **peaking structures** in D^-K^+ spectrum at 8.5 GeV^2/c^4 (2.9 GeV/c^2).
- Is it a **new exotic state**? Or **reflection** from D^+D^- resonance?



Model-independent analysis

- Decompose the $h(D^+D^-)$ according to the basis of Legendre polynomials:

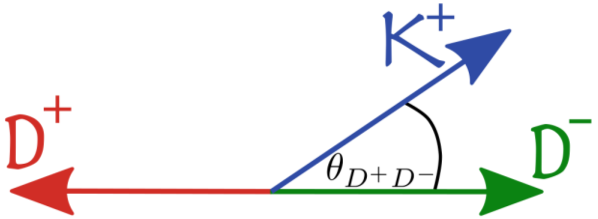
$$P_k[h(D^+D^-)] = \sqrt{\frac{2k+1}{2}} \times 2^k \sum_{r=0}^{k} [h(D^+D^-)]^r \binom{k}{r} \binom{\frac{k+r-1}{2}}{k}$$

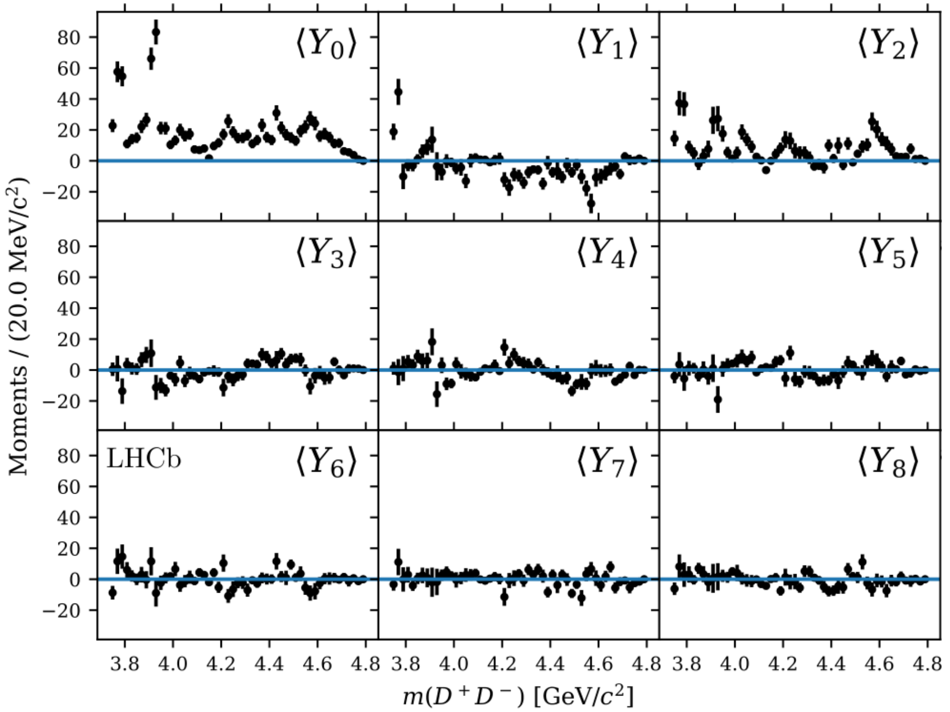
- Divide the $m(D^+D^-)$ into slices, the **coefficient of bin $\boldsymbol{j}$** weighted by **order-$\boldsymbol{k}$** Legendre polynomial can be expressed as:

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

- The $\langle \boldsymbol{Y_k} \rangle$ with $\boldsymbol{k = 2J_{\max}}$ could account for the contribution of the charmonium resonances with spin up to $J_{\max}$.

$$\boldsymbol{h(D^+D^-) = cos(\theta_{D^+D^-})}$$



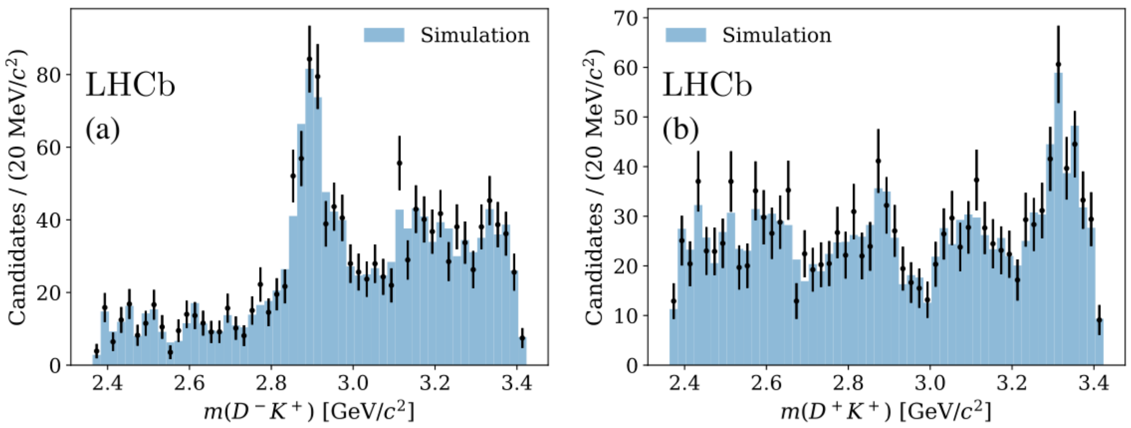


Distributions of unnormalized moments $\left\langle Y_k^j \right\rangle$

- Phase space MC samples are generated, and weighted by:

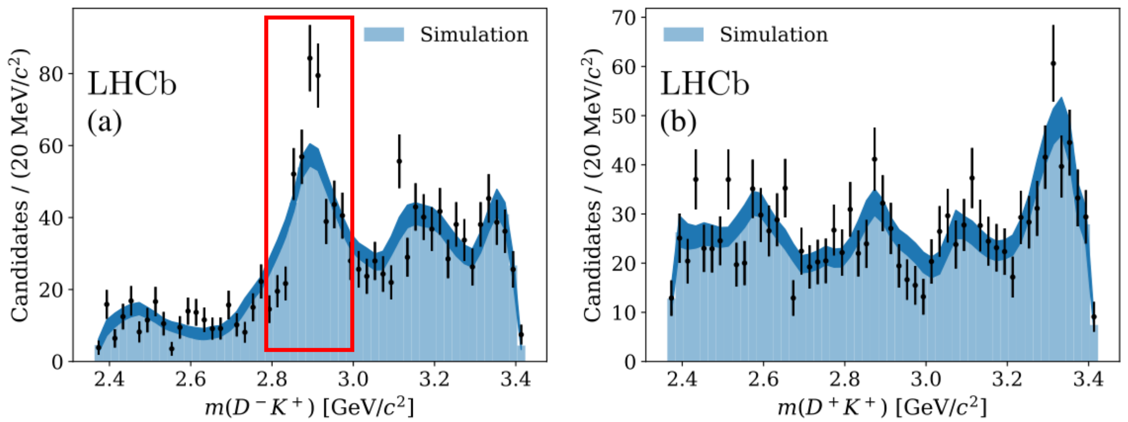
$$\eta_i = \frac{2}{N_j^{Sim}} \times \sum_{k=0}^{k_{\text{max}}} \left\langle Y_k^j \right\rangle P_k[h_i(D^+D^-)]$$

then project to $m(D^-K^+)$ and $m(D^-K^+)$ spectra.



$\boldsymbol{k_{\text{max}} = 29}$

- $m(D^-K^+)$ could be well described with **high k_{max}**.
- **Clear deviation** on $m(D^-K^+)$ spectrum around 2.9 GeV/c^2 with $\boldsymbol{k_{\text{max}} = 4}$ ($J_{\text{max}} = 2$).
- The **significance** of disagreement is estimated to be $\boldsymbol{3.9\sigma}$ with $\boldsymbol{k_{max} = 4}$ and $\boldsymbol{3.7\sigma}$ with $\boldsymbol{k_{max} = 6}$ by using test statistic.



$\boldsymbol{k_{\text{max}} = 4}$

Indicate a new exotic charm-strange resonance!

Model-dependent analysis of $B^+ \to D^+ D^- K^+$ decay

Model-dependent analysis

- **Based on Laura++ Dalitz plot fitter.**

Gaussian constraints — Signal model — Background model

- **Likelihood:** $$\mathcal{L} = \exp\left[-\sum_c \left(\frac{(p_c-\mu_c)^2}{2\sigma_c^2}\right)\right] \times \prod_{j=1}^{N_c}\left(N_{sig}\mathcal{P}_{sig}(\vec{x}_j) + N_{bg}\mathcal{P}_{bg}(\vec{x}_j)\right)$$

- **Signal PDF:** $$\mathcal{P}_{sig}(\vec{x}) = \frac{1}{\mathcal{N}} \times \epsilon_{\text{total}}(\vec{x}) \times \left|\mathcal{A}_{sig}(\vec{x})\right|^2$$

- **Signal Amplitude:** $$\mathcal{A}_{sig}(\vec{x}) = \sum_{j=1}^{N} c_j F_j(\vec{x})$$

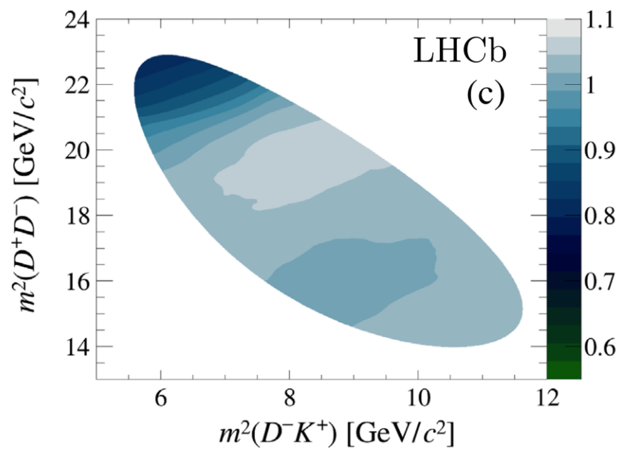
- **Resonant Amplitude:** $$F_j(\vec{x}) = R\left(m(D^+D^-)\right) \times T(\vec{p},\vec{q}) \times X(\vec{p}) \times X(\vec{q})$$
  - $R\left(m(D^+D^-)\right)$: Relativistic Breit-Wigner function.
  - $T(\vec{p},\vec{q})$: Angular factor – non-relativistic Zemach tensor formalism.
  - $X(\vec{p}), X(\vec{q})$: Blatt-Weisskopf barrier factors.

Efficiency & Background

- **Efficiency maps:**

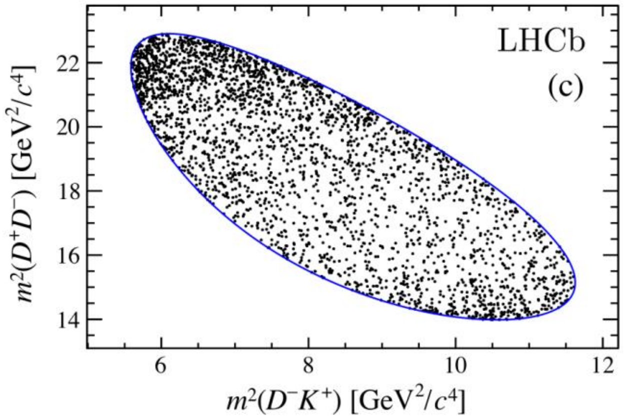
$$\epsilon_{\mathbf{total}}(\vec{x}) = \epsilon_{\mathbf{offline|reco}}(\vec{x}) \times \epsilon_{\mathbf{reco|trig}}(\vec{x}) \times \epsilon_{\mathbf{trig|gemo}}(\vec{x}) \times \epsilon_{\mathbf{gemo}}(\vec{x}).$$

  - Extracted from simulated samples with data-driven method to correct data-MC difference.
  - Run 1 and Run 2 datasets are fitted simultaneously with corresponding efficiency map.



Relatively efficiency map

- **Background modelling.**
  - Using the B^+ sideband samples ($5.35\ \mathrm{GeV}/c^2 < m(D^+D^-K^+) < 5.69\ \mathrm{GeV}/c^2$).
  - Relaxing BDT to increase the sample size.
  - Applying kernel estimation procedure to reduce statistic fluctuations.

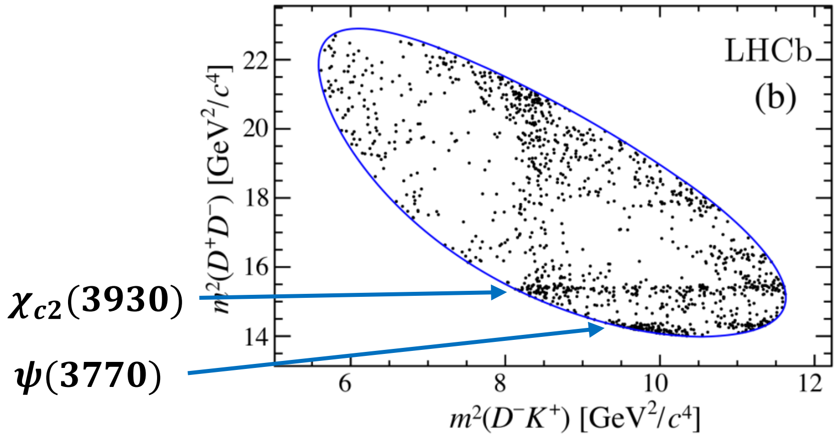


Sideband samples

- **Model content:**
  - MI analysis indicate possible D^-K^+ resonant contributions.
  - First try with only charmonium resonances.
  - Only states with natural J^P ($0^+, 1^-, 2^+$ …) are allowed to decay into D^+D^-.

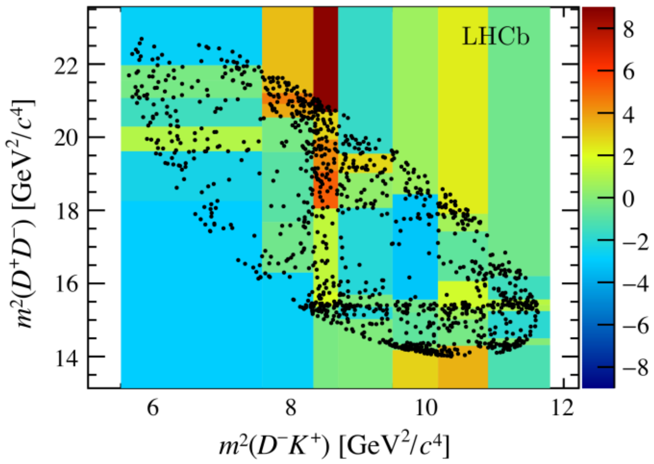
- **Fitting procedure:**
  - Always include $\psi(3770)$ and $\chi_{c2}(3930)$.
  - Include other components if significantly reduce NLL.
  - Constrain m & σ of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$.
  - Add $\chi_{c0}(3930)$, float m & σ of $\chi_{cJ}(3930)$.
  - Try various non-resonant lineshapes (uniform, exponential, polynomial, spline) with spin-0 or 1.

Partial wave (J^{PC})	Resonance	Mass (MeV/c^2)	Width (MeV)
S wave (0^{++})	$\chi_{c0}(3860)$	3862 ± 43	201 ± 145
	$X(3915)$	3918.4 ± 1.9	20 ± 5
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 ± 0.20	2.79 ± 0.62

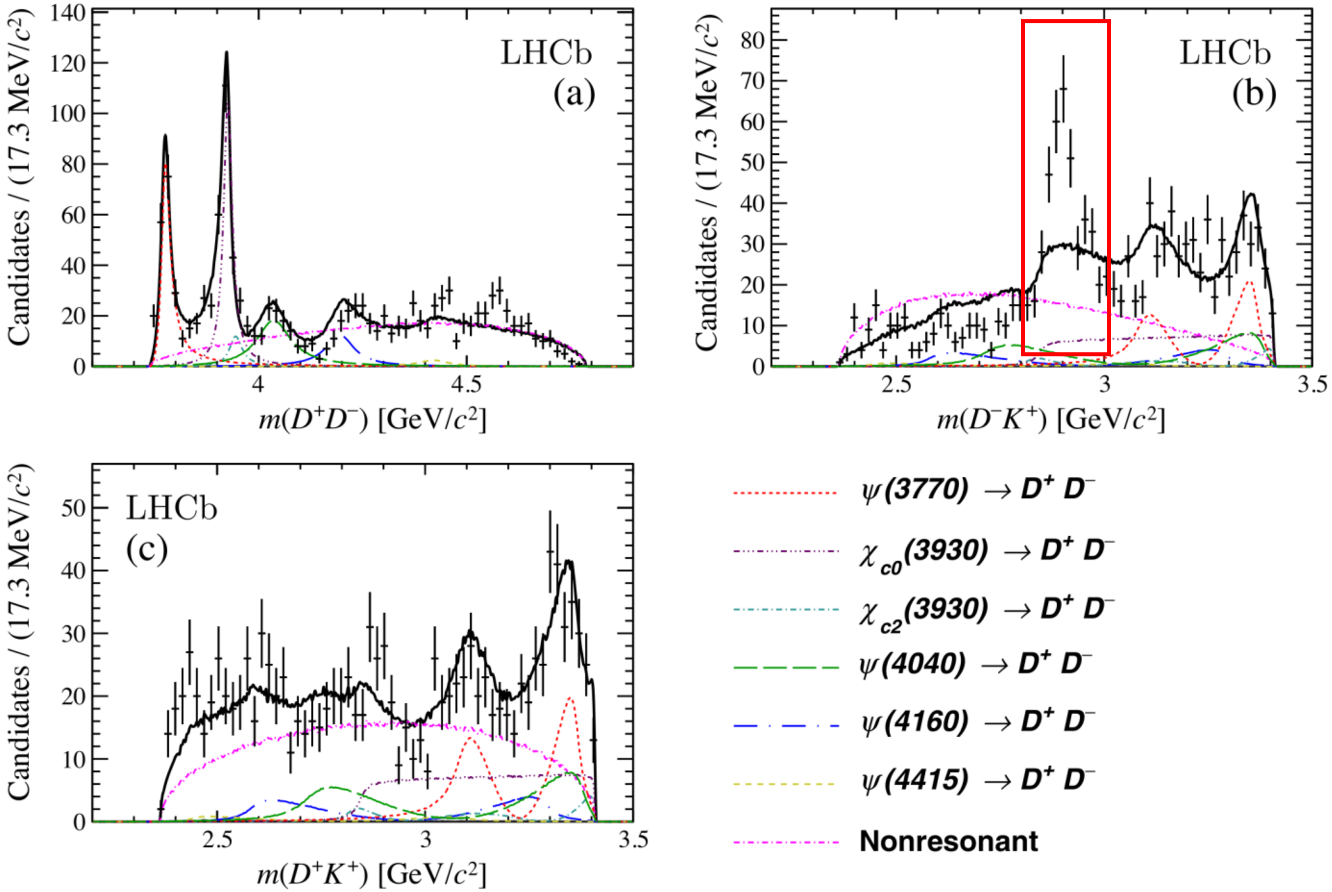


Results without D^-K^+ resonance

- **Results with only D^+D^- resonances:**
  - Including $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonances.
  - $m(D^+D^-)$ and $m(D^+K^+)$ could be well described.
  - **Large deviation on $m(D^-K^+)$ spectrum around $2.9\ \mathrm{GeV}/c^2$.**



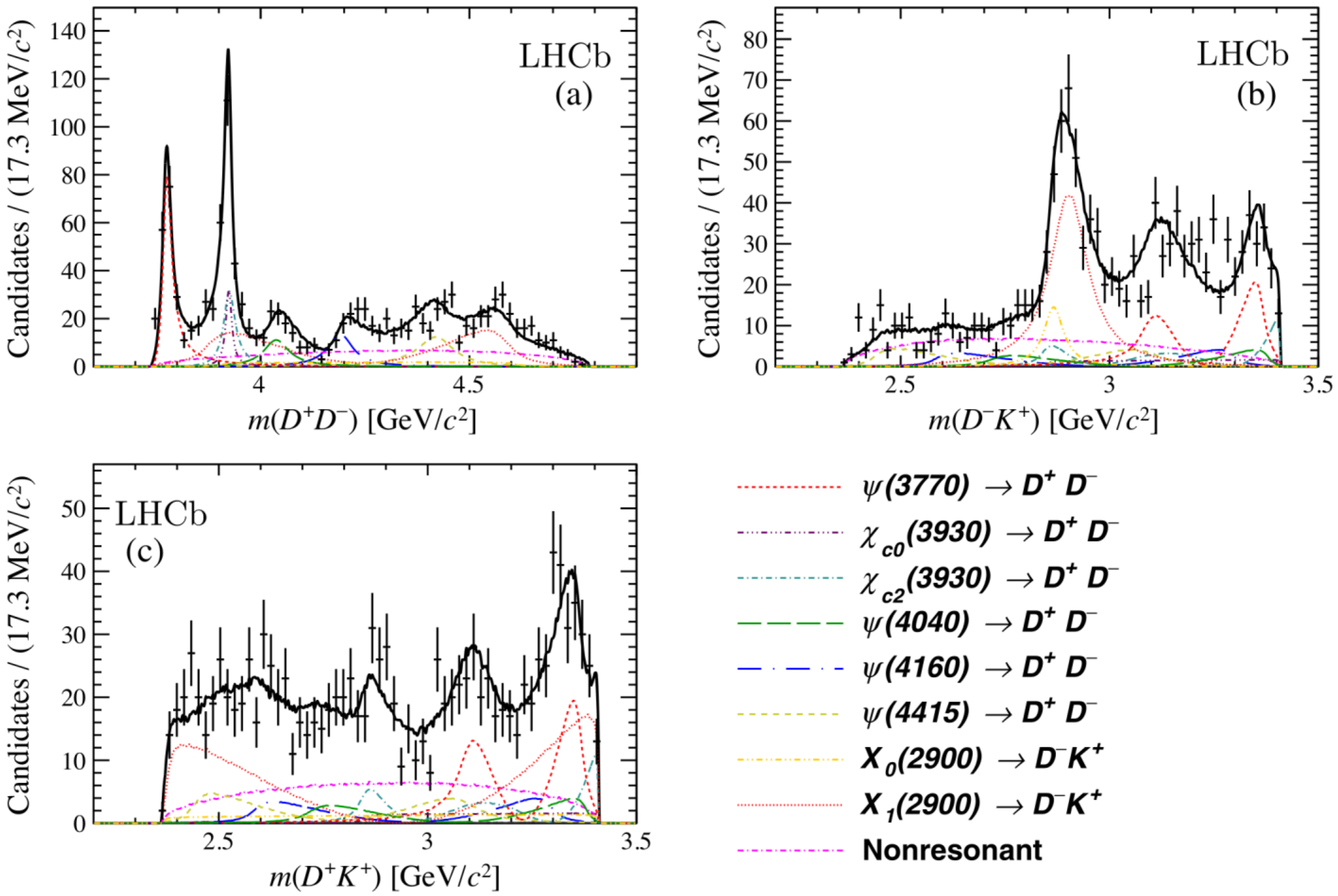
Goodness of fit



Fitting result without D^+K^- reconance

Results with D^-K^+ resonances

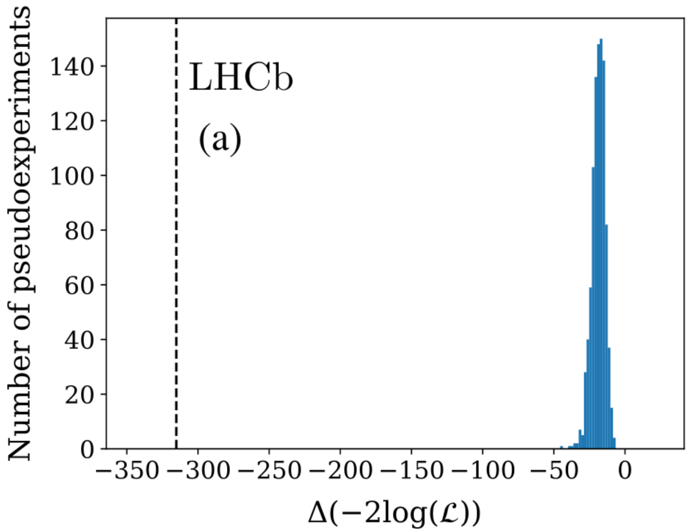
- **Results after add D^-K^+ resonances:**
  - Two D^-K^+ resonances are added:
    - **$X_0(2900), J^P = 0^+$**
      - Mass: $2866 \pm 7 \pm 2$ MeV/c^2
      - Width: $57 \pm 12 \pm 4$ MeV
    - **$X_1(2900), J^P = 1^-$**
      - Mass: $2904 \pm 5 \pm 1$ MeV/c^2
      - Width: $110 \pm 11 \pm 4$ MeV
  - Also test other models, this model gives the best description.



Fitting result with D^+K^- reconances

Results with D^-K^+ resonances

- **Results after add D^-K^+ resonances:**
  - Determining the significance with pseudo-experiments.
    - Generate 1000 toys from fit with no D^-K^+ components.
    - Fit the toy with model with and without new resonances.
  - **Overwhelmingly significance $\gg 5\sigma$.**



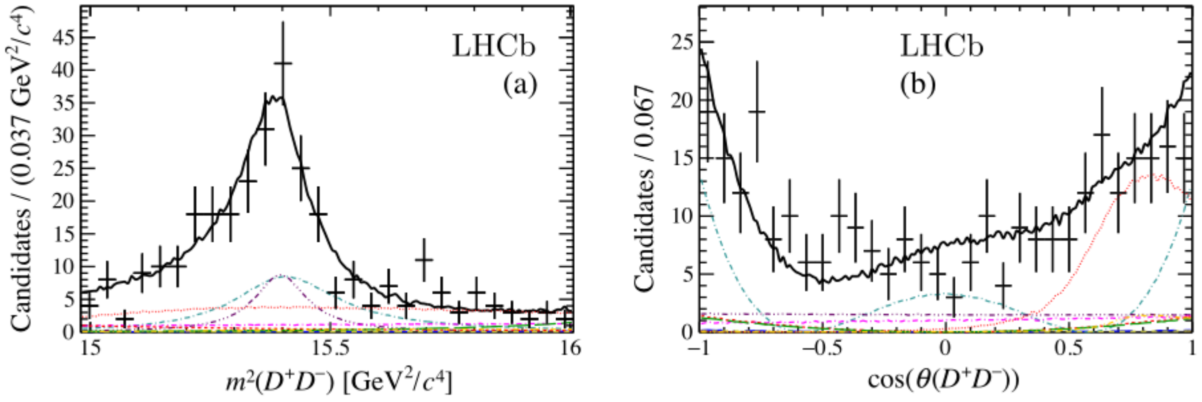
- **Tetraquark candidates with four flavors:**
  - In 2016, D0 collaboration report evidence of a $B_s^0\pi^+$ $(\bar{b}su\bar{d})$ resonance called $X(5568)^+$, but isn't confirmed by other experiments.

PRL 117, 022003 (2016)

  - $X(2900)$ could be confirmed in the other $B \to DDK$ analyses.
  - $X_0(2900)$ and $X_1(2900)$ $(c\bar{s}u\bar{d})$ would be the **first confirmed observation** of tetraquark state with **four different flavors**.

Test $\chi_{cJ}(3930)$

- **In $\chi_{cJ}(3930)$ region:**
  - ➢ Necessary to include both spin-0 and spin-2 components:
    - ☐ $\chi_{c0}(3930), J^P = 0^+$
      - Mass: $3923.8 \pm 1.5 \pm 0.4\ \mathrm{MeV}/c^2$
      - Width: $17.4 \pm 5.1 \pm 0.8$ MeV
    - ☐ $\chi_{c2}(3930), J^P = 2^+$
      - Mass: $3926.8 \pm 2.4 \pm 0.8\ \mathrm{MeV}/c^2$
      - Width: $34.2 \pm 6.6 \pm 1.1$ MeV



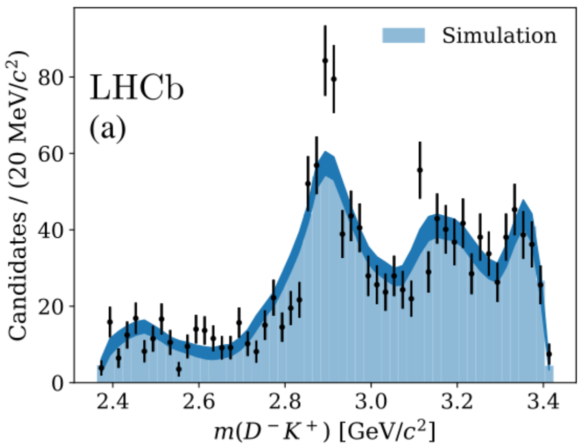
Zoom in on the $\chi_{cJ}(3930)$ ($15\ \mathrm{GeV}^2/c^2 < m^2(D^+D^-) < 16\ \mathrm{GeV}/c^2$)

  - ➢ $\chi_{c2}(3930)$ measured mass not consistent with inclusive study.
    - **Mass:** $3921.9 \pm 0.6 \pm 0.2\ \mathrm{MeV}/c^2$

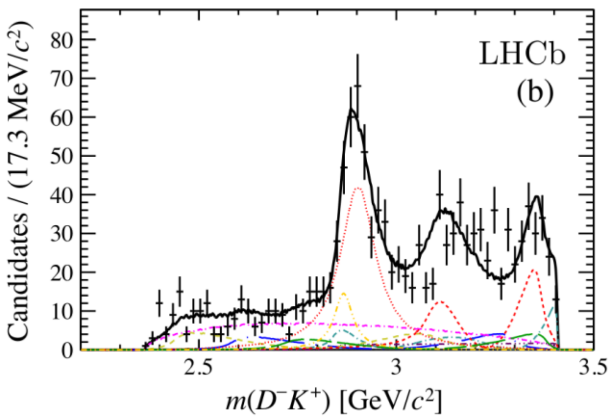
JHEP 07 (2019) 035

  - ➢ Why $\chi_{c0}(3860)$ didn't observe in $B^+ \to D^+D^-K^+$ channel?
  - ➢ **Need more statistic to confirm.**

Conclusion and next step



Model-independent analysis



Amplitude analysis

● Conclusion

- ✓ **Model-independent analysis** indicates possible resonance on D^-K^+ spectrum.
- ✓ With the **amplitude analysis**, two exotic D^-K^+ resonances with spin-0 and spin-1 are observed.
- ✓ Discovery of contributions from spin-0 and spin-2 components in the region of the existing $\chi_{c2}(3930)$.

● Next step

- ➢ Several **ongoing $B \to DDh$ analyses** with LHCb Run 1 and Run 2 datasets.
  - $\boldsymbol{B}$: $B^{0,+}, B_s^0, \Lambda_b^0 \ldots$; $\boldsymbol{D}$: $D^{0,+}, D^{*+}, D_s^+, \Lambda_c^+ \ldots$; $\boldsymbol{h}$: $K^+, \pi^+, p, \Lambda \ldots$
- ➢ LHCb Run 3 data taking will start soon.
  - ✓ 10 times statistic, detail analysis on $B^+ \to D^+D^-K^+$
  - ✓ More potential $B \to DDh$ channels to be explored.