$B \to DDh$ studies and prospects at the LHCb experiment

Yi Jiang (蒋艺)
University of Chinese Academy of Sciences
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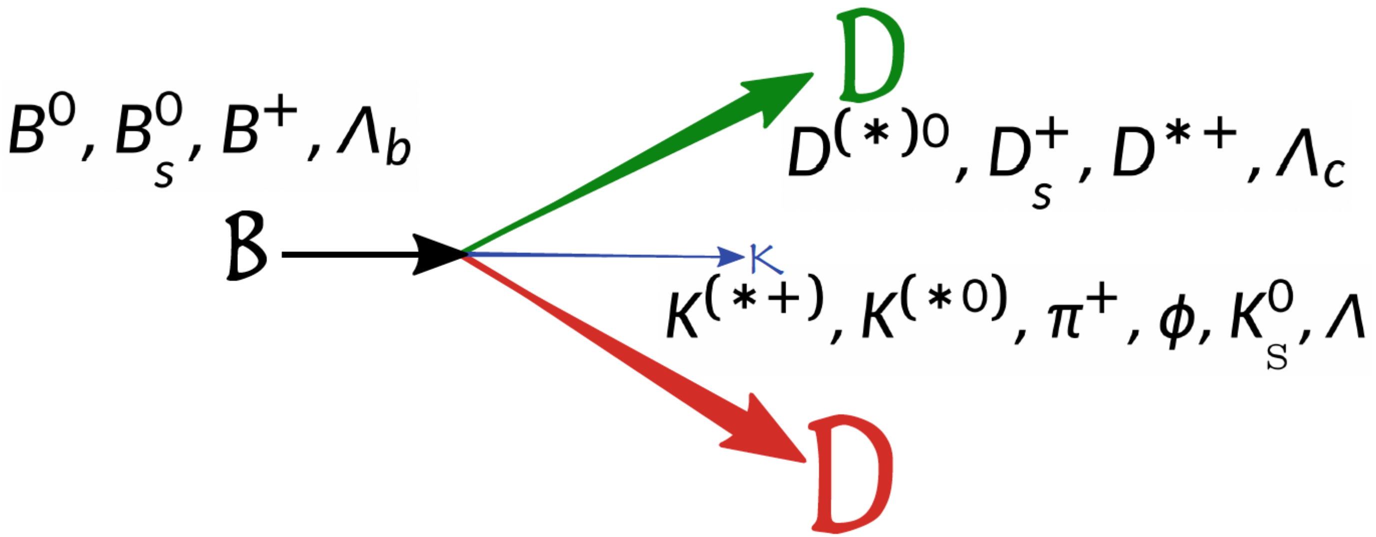
(On behalf of the LHCb collaboration)

Outline

- Introduction
- Observation of $X_{0,1}(2900)$ in $B^+ \to D^+ D^- K^+$ decays
  - Model independent moments analysis
  - Model dependent amplitude analysis
- Observation of $D_s(2590)$ in $B^0 \to D^- D^+ K^+ \pi^-$ decays.
- Future prospects
- Analysis tool: TF-PWA
- Summary

Introduction

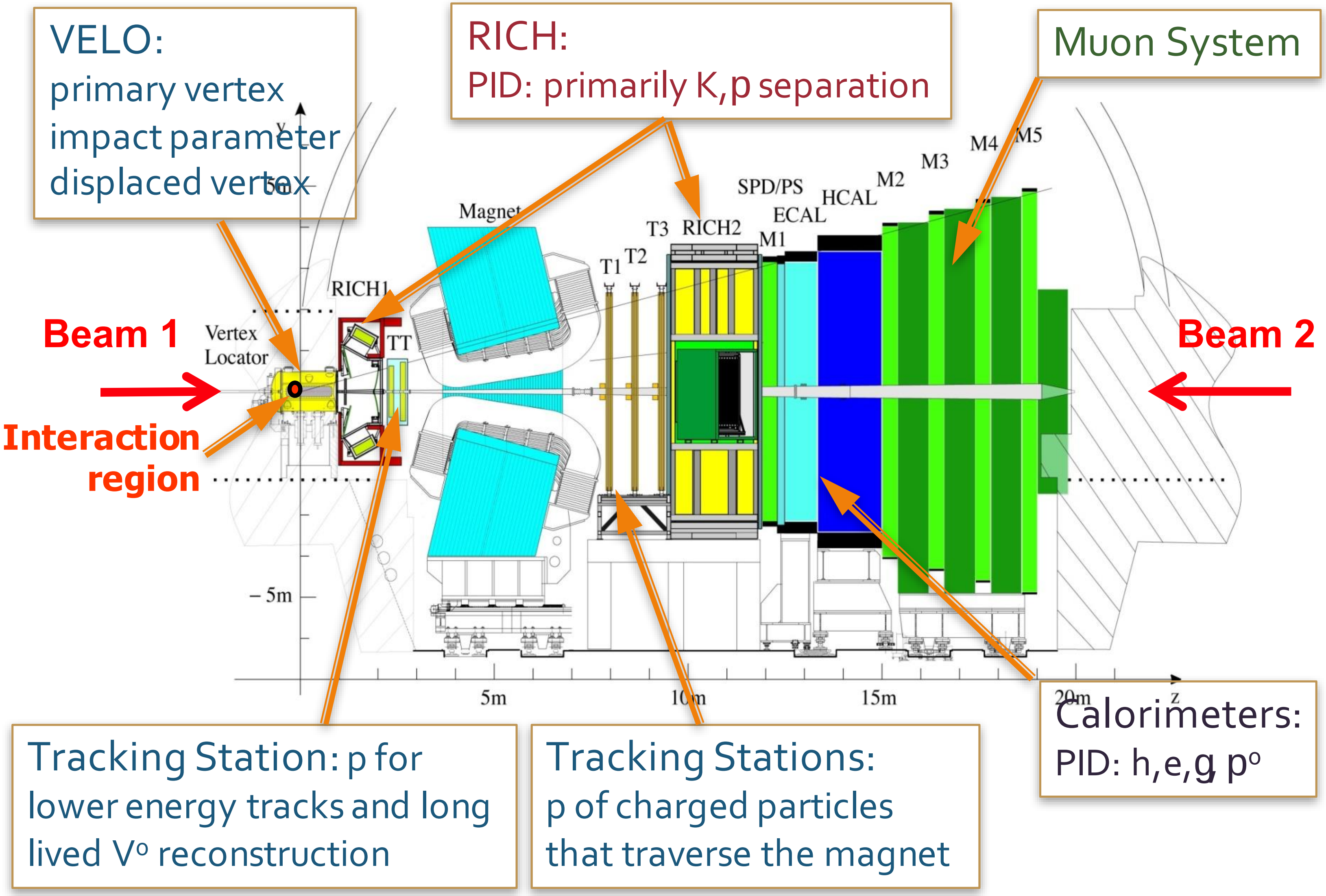
- $B \to DDh$ **Decays involved**



- **Charmonium(-like) spectrum from** $D^{(*)}\overline{D}^{(*)}, D^{(*)}\Lambda_c^-, \Lambda_c^+\Lambda_c^-$ **etc.**
- D_s, D^+, D^0, Λ_c **excited states from** $D^{(*)}K(\pi)^{(*)}, K(\pi)^{(*)}\Lambda_c$ **etc.**
- **Exotic structures from** $D^{(*)}K(\pi)^{(*)}, K(\pi)^{(*)}\Lambda_c$ **etc**

Understanding how particles are formed (from quarks)

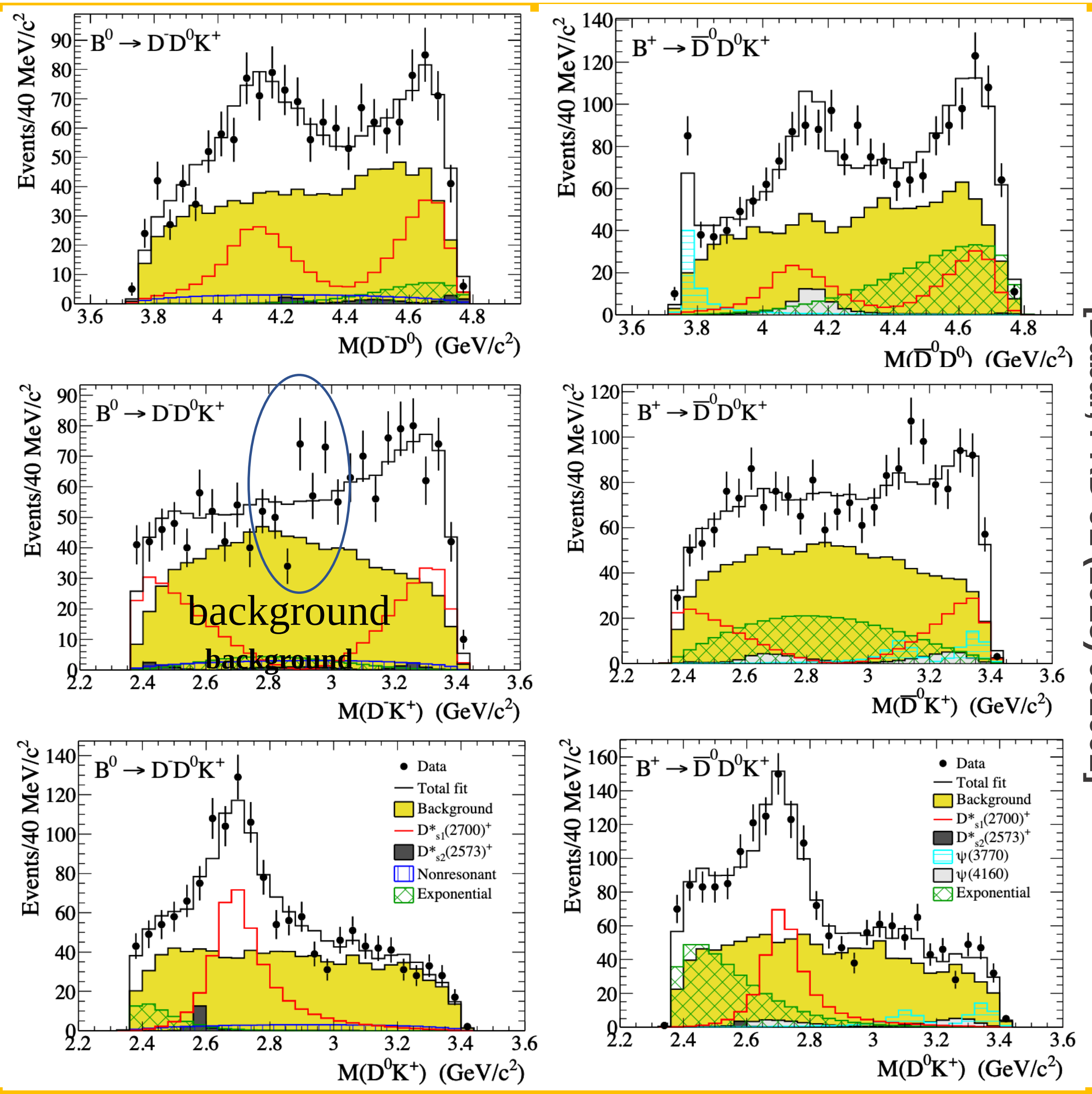
LHCb detector



Why $B \to D\bar{D}h$ decays

- Not yet well explored
  - Belle used $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ and determined the spin of $D_{s1}^*(2700)^+$ **[Belle, PRL 100 (2008) 092001]**
  - About 800 signals, huge background, purity is only 40%
  - No $B^+ \to D^+ D^- K^+$ analysis before
- LHCb provides
  - High statistics
  - Smaller background

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

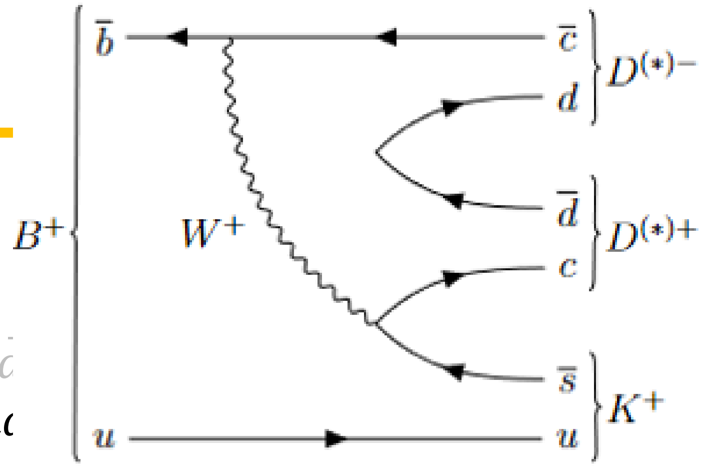


[Babar, PRD 91 (2015) 052002]

$$X_{0,1}(2900)$$

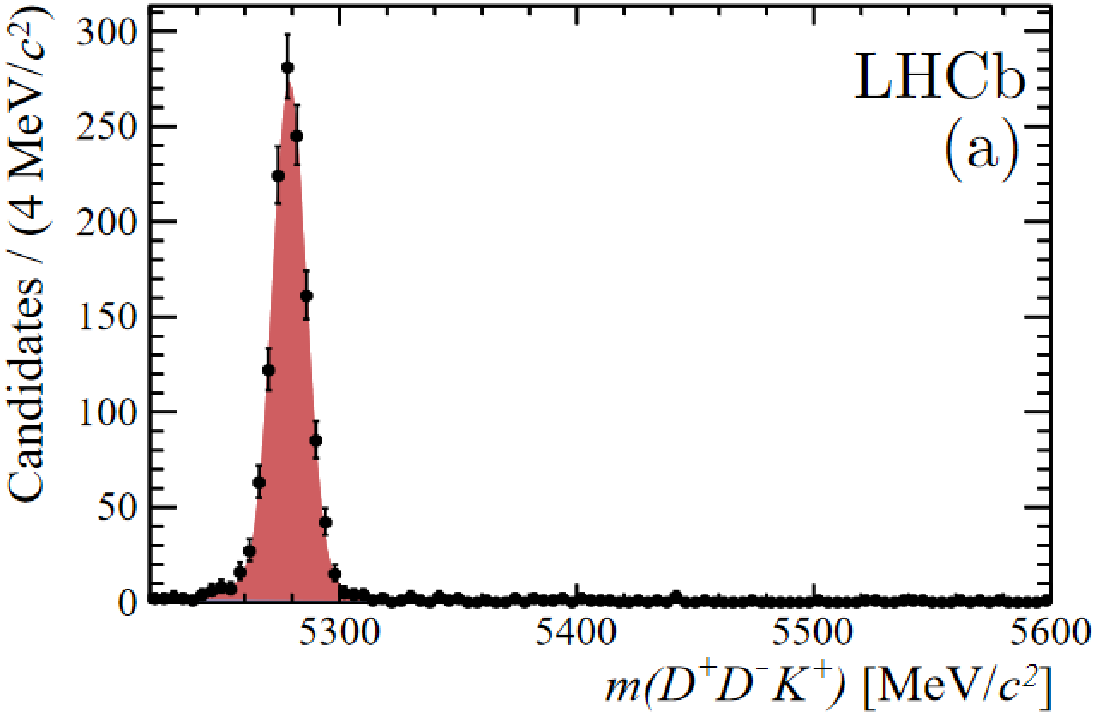
6

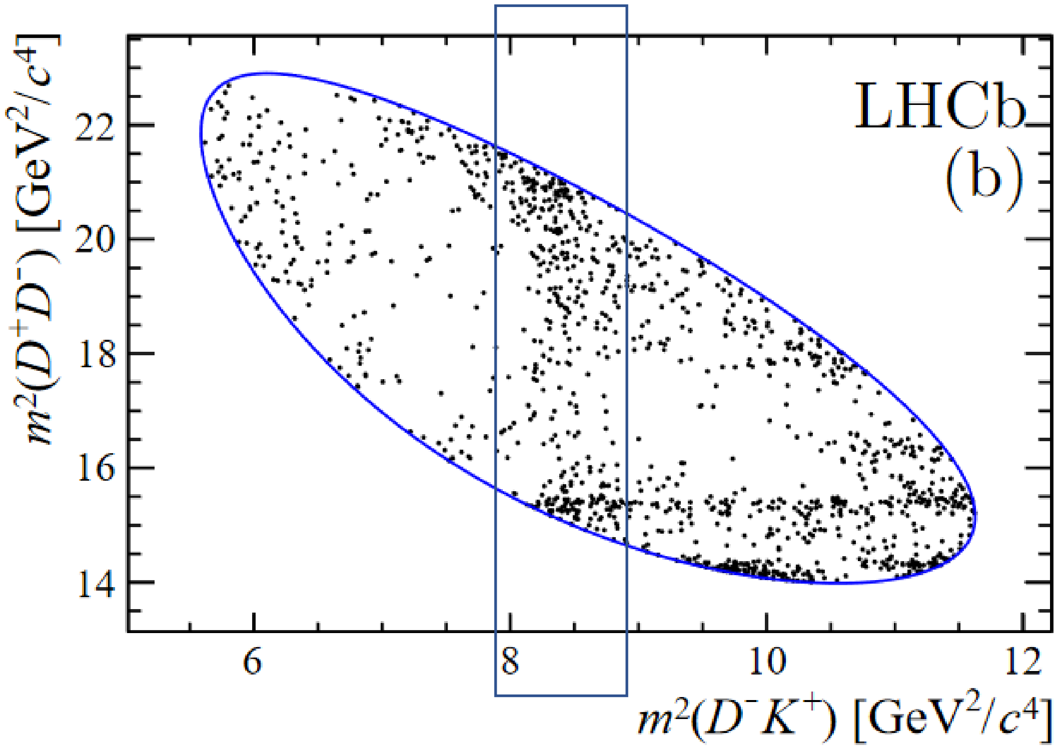
Dataset for $B^+ \to D^+ D^- K^+$



- Data purity > 99.5%, signals yields ~ 1.3k
- Some structures in $\mathrm{m}(D^- K^+) = 2.8 \sim 3.0\ \mathrm{GeV}/c^2$

$D^- D^+: c\bar{c}d\bar{d}$
$D^- K^+: \bar{c}\bar{s}u$
$D^+ K^+: c\bar{s}u$



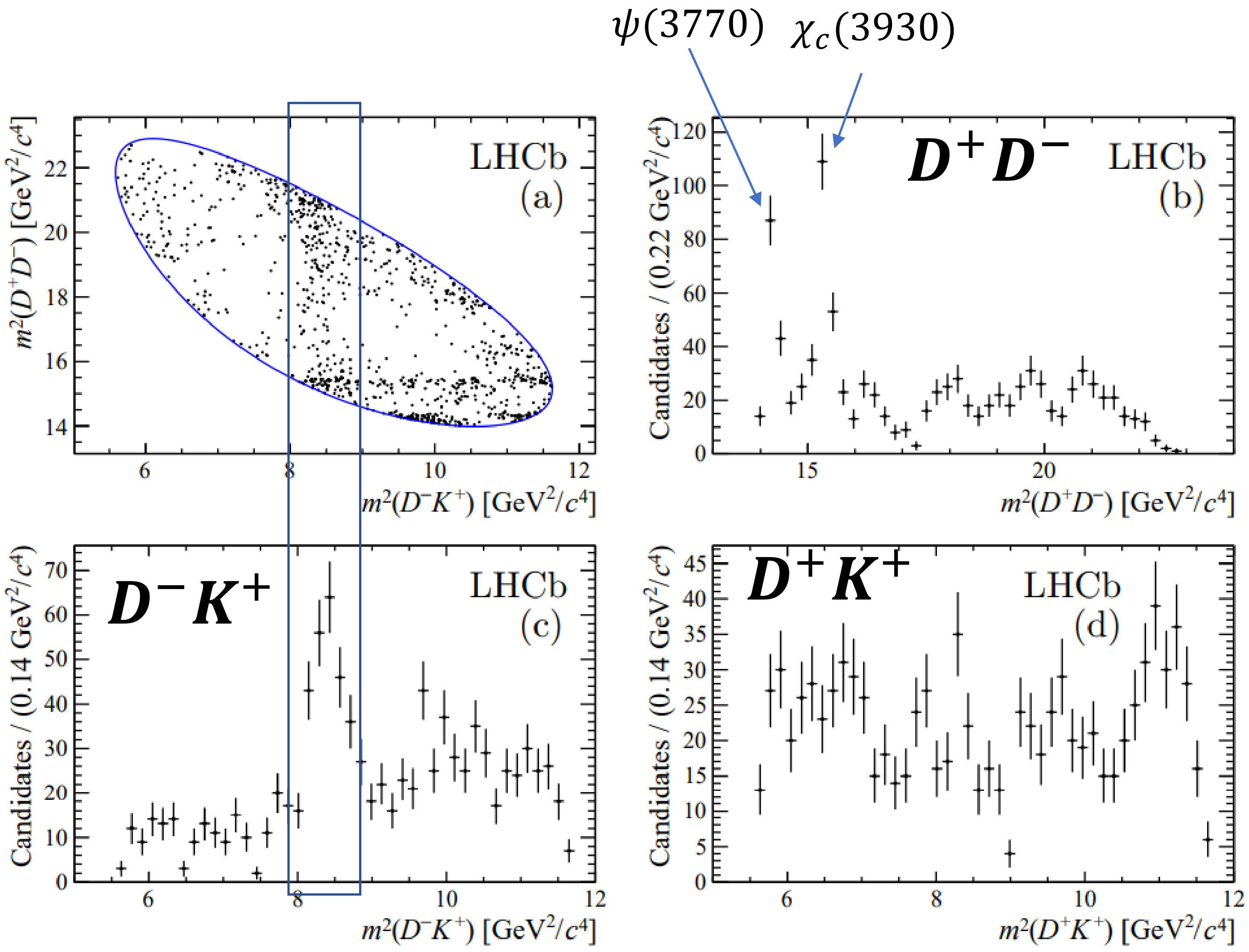


[PRD 102 (2020) 112003]

X(2900)?

1D projections

- Clear $\psi(3770), \chi_c(3930)$ in D^+D^- spectrum
- Peaking structures in D^-K^+ spectrum close to 8.5 GeV^2/c^4
- Reflection? or exotics?



[PRD 102 (2020) 112003]

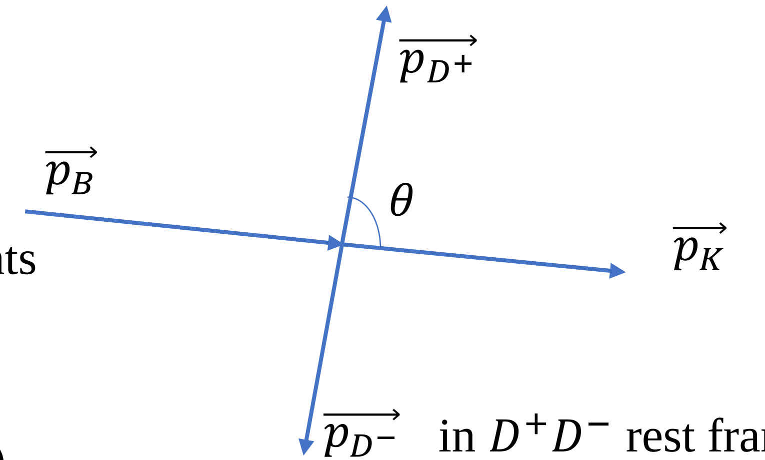
Model independent moments analysis [PRL 125 (2020) 242001]

- Assert only D^+D^- resonances
- Dividing D^+D^- into different mass bins, expand angular distribution by Legendre polynomials
- For each bin the k-th unnormalized moment:

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

$h_l(D^+D^-) = \cos\theta$

w_l is corrected weights for each events



in D^+D^- rest frame

- The full probability distribution:

$$\mathcal{P}\left(m_j(D^+D^-), h(D^+, D^-)\middle|H\right) = \mathcal{P}\left(m_j(D^+D^-)\right)\mathcal{P}(h(D^+D^-|H, m_j(D^+D^-))$$

$$\mathcal{P}\left(m_j(D^+D^-)\right) = \mathcal{N}\sum_{l=0}^{N_j^{\text{Data}}} w_l$$

$$\mathcal{P}\left(h(D^+D^-)\middle|H, m_j(D^+, D^-)\right) = 1 + \frac{2}{\sum_{l=0}^{N_j^{Data}} w_l}\sum_{k=1}^{k_{\max}}\left\langle Y_k^j\right\rangle P_k(h(D^+D^-))$$

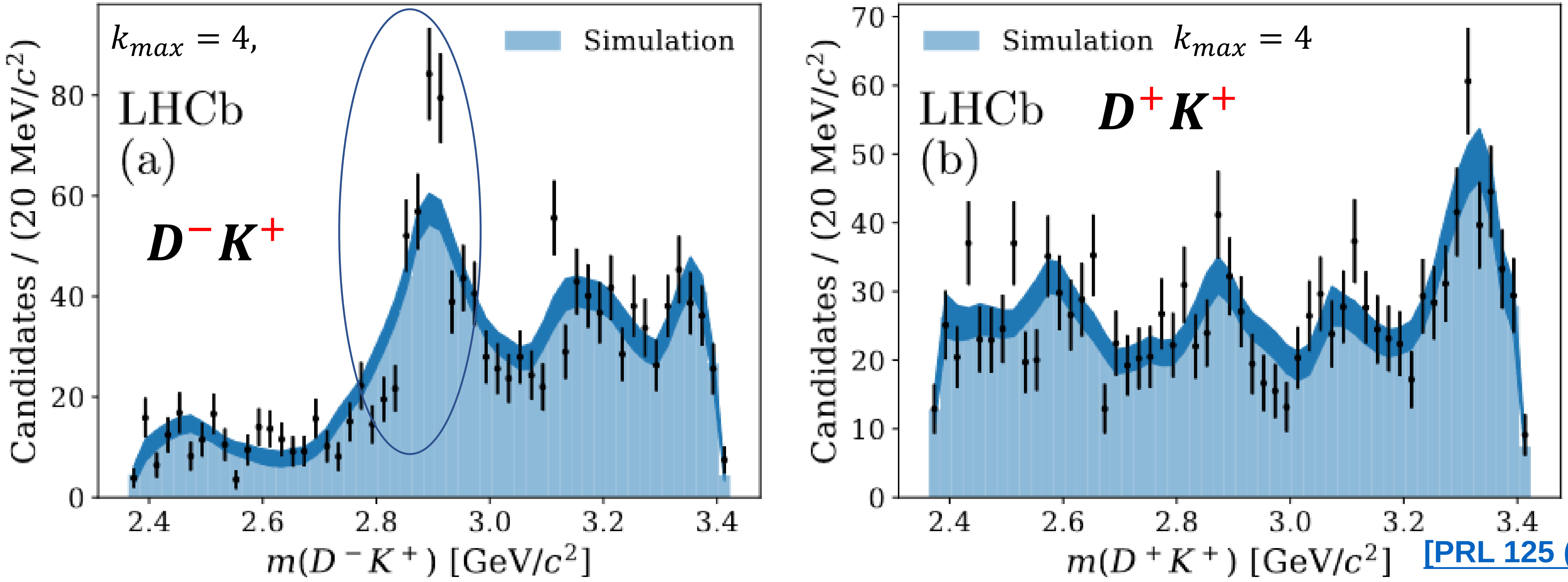
The limit of sum give a truncation of high spins contribution.

- Project it in $m(DK)$ to check its discrepancy

Projection in DK spectrum

- Considering up to spin 2 resonances ($k_{max} = 4$), the significance is 3.9 σ.
- Considering up to spin 3 resonances ($k_{max} = 6$), the significance is 3.7 σ.

- There should be some structures besides D^+D^- resonances.
- Exotics in D^-K^+ ?



[PRL 125 (2020) 242001]

Model dependent amplitude analysis

[PRD 102 (2020) 112003]

Likelihood:

$$\mathcal{L} = \prod_{j=1}^{N_c} \left(N_{\text{sig}}\mathcal{P}_{\text{sig}}(\vec{x}_j) + N_{\text{bg}}\mathcal{P}_{\text{bg}}(\vec{x}_j)\right)$$

signal model + background model

Signal probability density function:

$$\mathcal{P}_{\text{sig}}(\vec{x}) = \frac{1}{\mathcal{N}} \times \epsilon(\vec{x}) \times \left|\mathcal{A}_{\text{sig}}(\vec{x})\right|^2$$

Signal amplitude is the sum of resonant amplitude:

$$\mathcal{A}_{\text{sig}}(\vec{x}) = \sum_{j}^{N} c_j F_j(\vec{x})$$

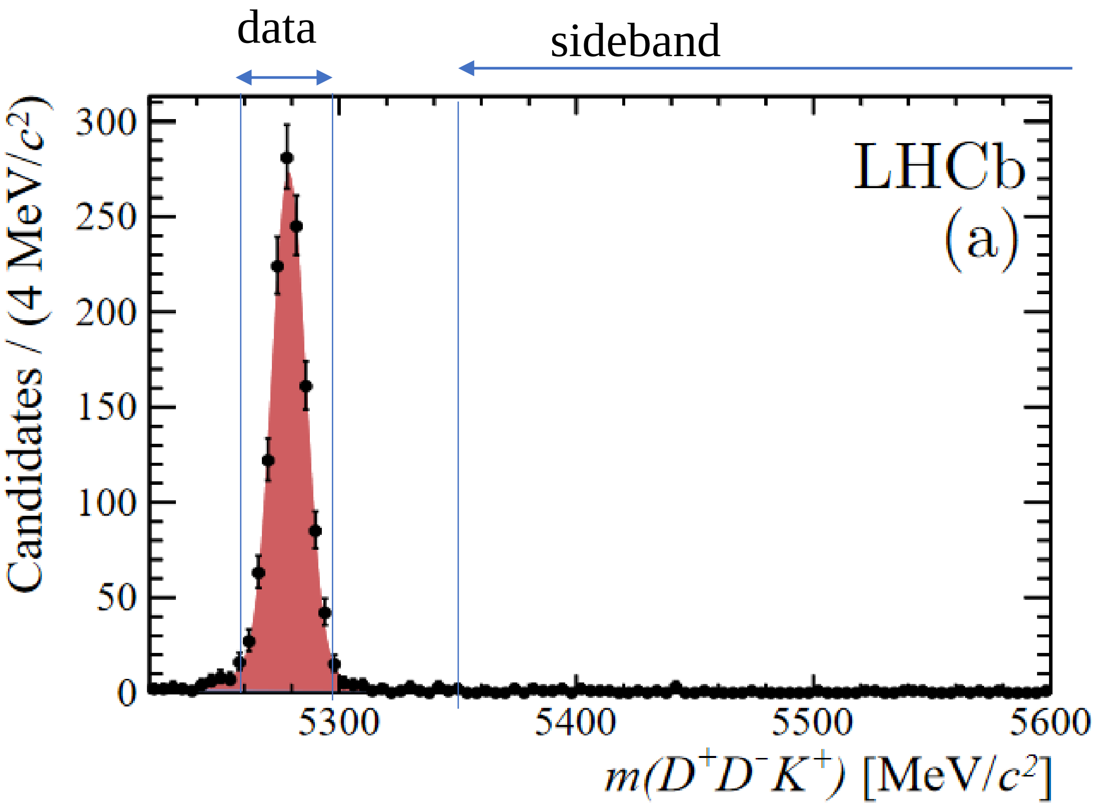
Resonant amplitude:

$$F(\vec{x}) = R\left(m(D^+D^-)\right) \times T(\vec{p},\vec{q}) \times X(|\vec{p}|) \times X(|\vec{q}|)$$

$R(m)$: 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 factor



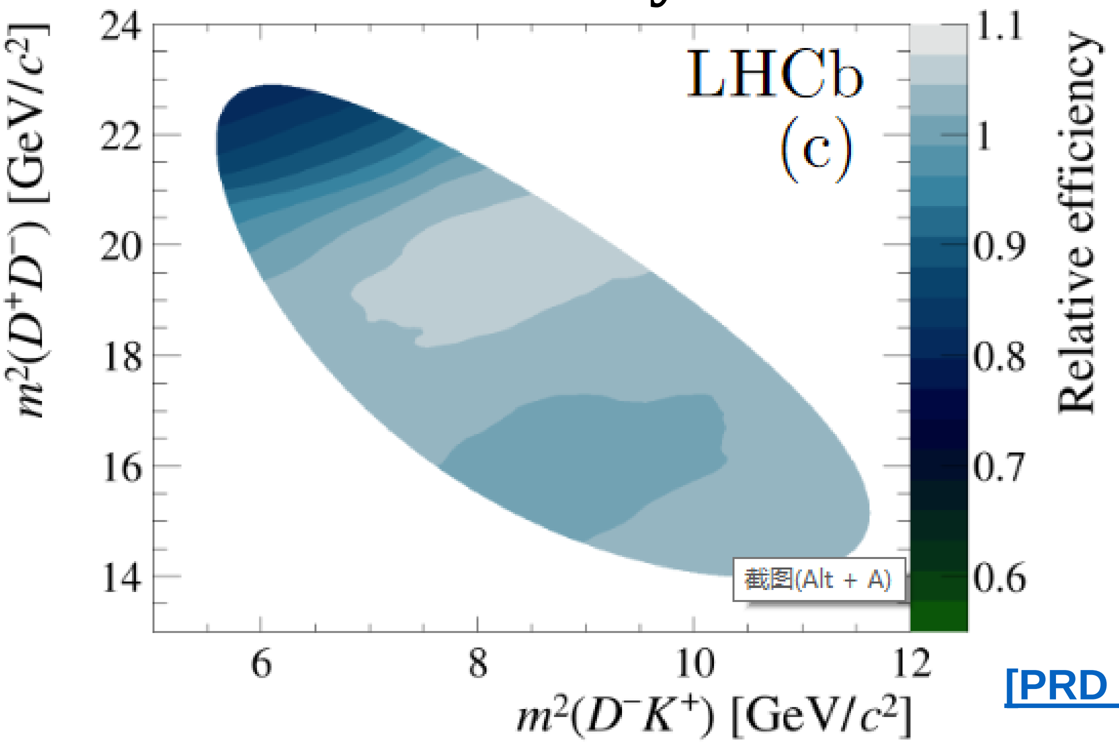
data range : $m_{B^+} \pm 20$ MeV

sideband range : 5.35 ~ 5.69 GeV

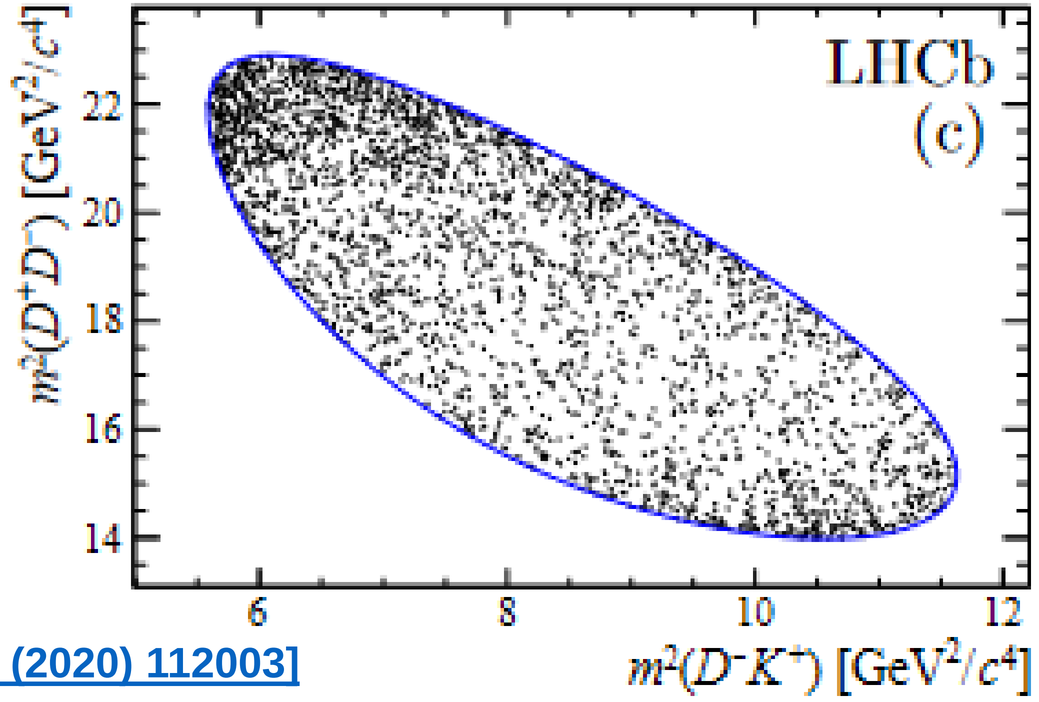
Efficiency and background

- Efficiency function from simulation.
- Background model from sideband with relaxed BDT requirement.

efficiency



sideband as background



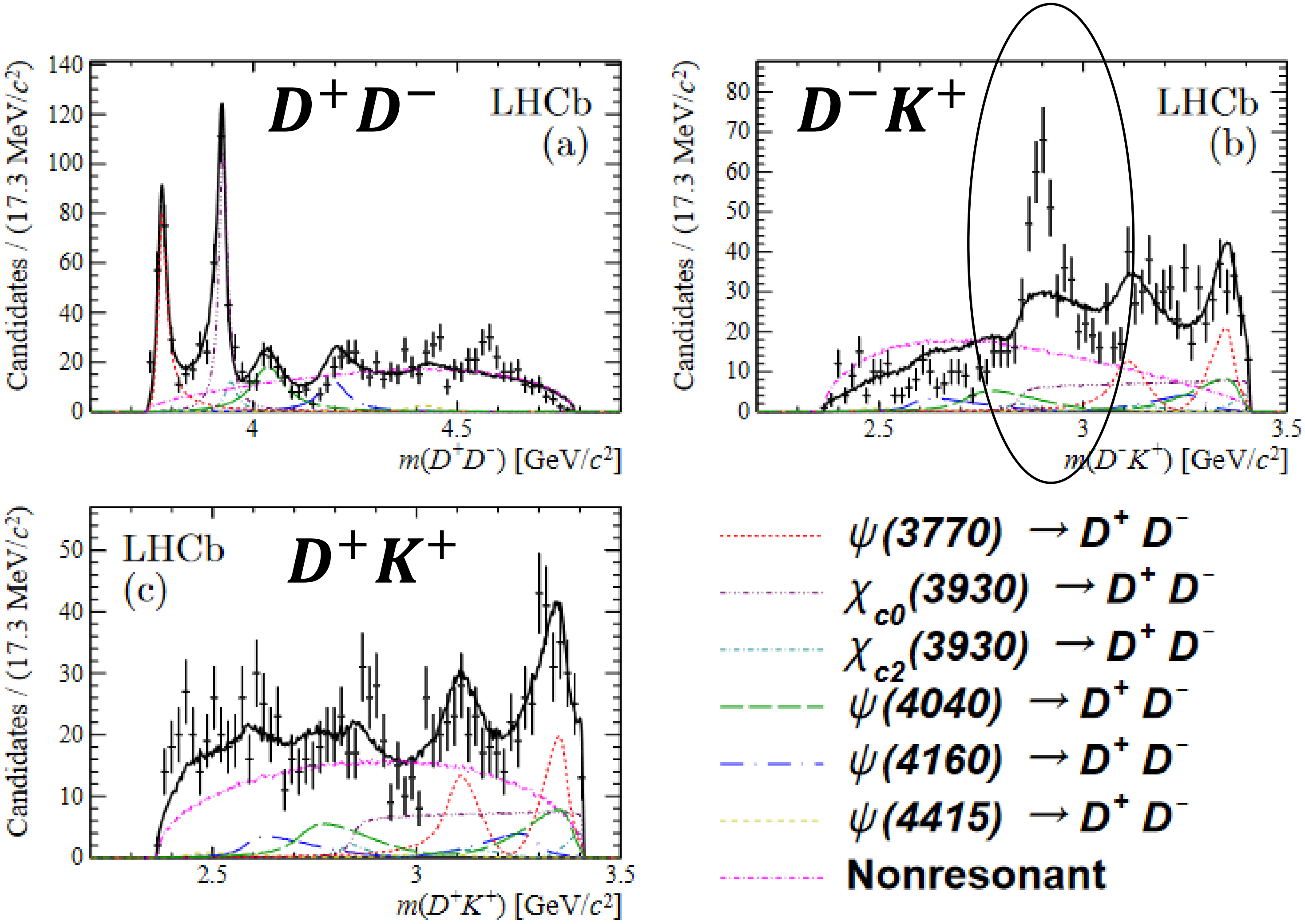
[PRD 102 (2020) 112003]

Without DK resonances

- Fit with only D^+D^- resonances.
- significant discrepancy in m$(D^-K^+) \sim 2.9$ GeV
- new D^-K^+ states?

PDG value	J^P	Mass/MeV	Width/MeV
$\psi(3770)$	1^-	3778.1±0.9	27.2±1.0
$\chi_{c0}(3930)$	0^+	3918.4±1.9	20±5
$\chi_{c2}(3930)$	2^+	3921.9±0.6	36.6±2.1
$\psi(4040)$	1^-	4039±1	80±10
$\psi(4160)$	1^-	4191±5	70±10
$\psi(4415)$	1^-	4421±4	62±20

Constraints with PDG value except $\chi_{c0,2}(3930)$



[PRD 102 (2020) 112003]

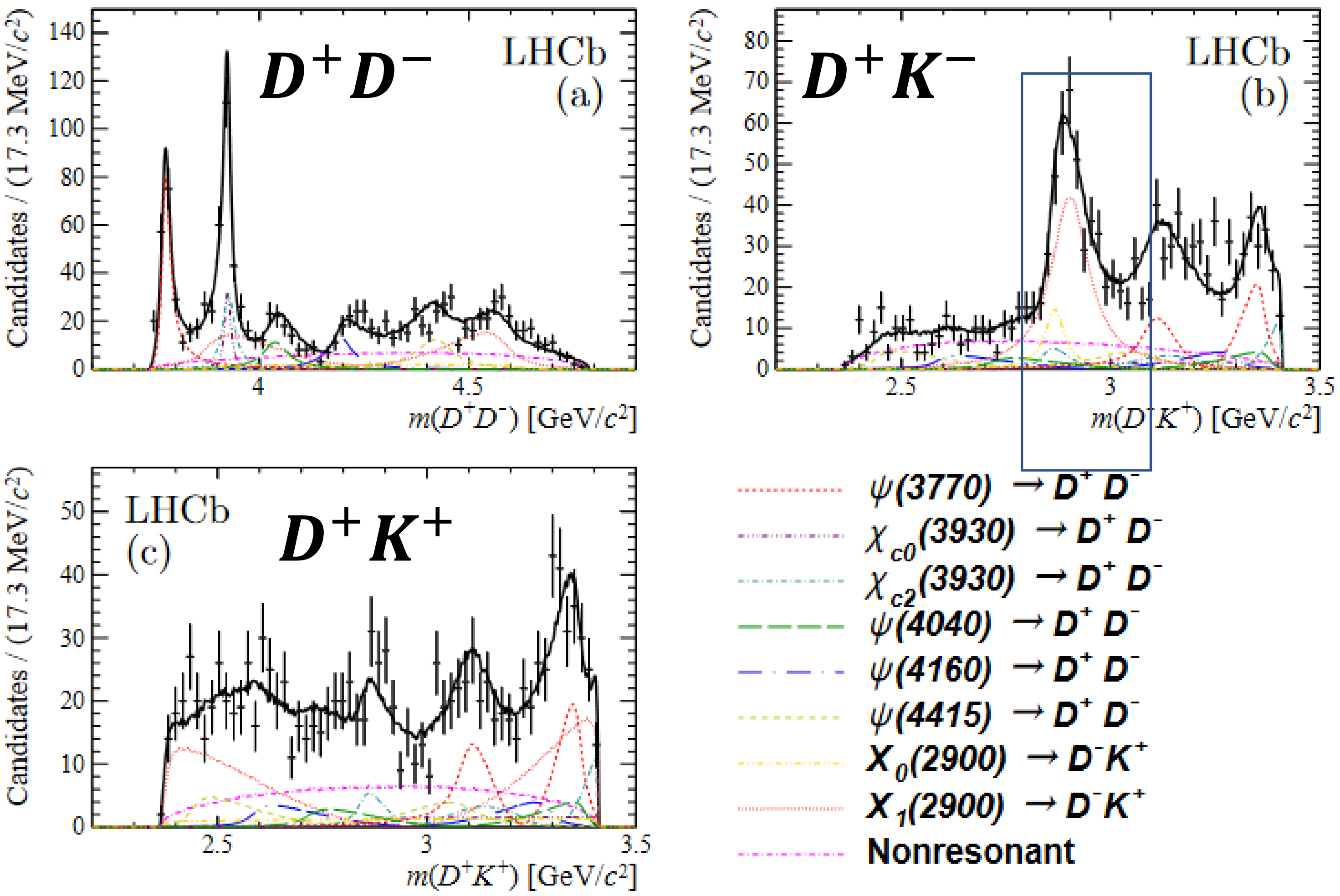
Baseline model

- Two D^-K^+ resonances are needed

0^+ : $X_0(2900)$
$M = 2866 \pm 7 \pm 2\ \mathrm{GeV}/c^2$
$\Gamma = 57 \pm 12 \pm 4\ \ \mathrm{MeV}$
1^- : $X_1(2900)$
$M = 2904 \pm 5 \pm 1\ \mathrm{MeV}/c^2$
$\Gamma = 110 \pm 11 \pm 4\ \mathrm{MeV}$

- Total significance ~ 16σ

- Other models are also tested, but add $0^+, 1^-$ resonances together is the best.



[PRD 102 (2020) 112003]

Nonresonant use D^+K^- S-wave $R(m(D^-K^+)) = e^{-\alpha m^2}$ α =0.08±0.05

$\chi_{c0}(3930), \chi_{c2}(3930)$ structures

Summary of current PDG

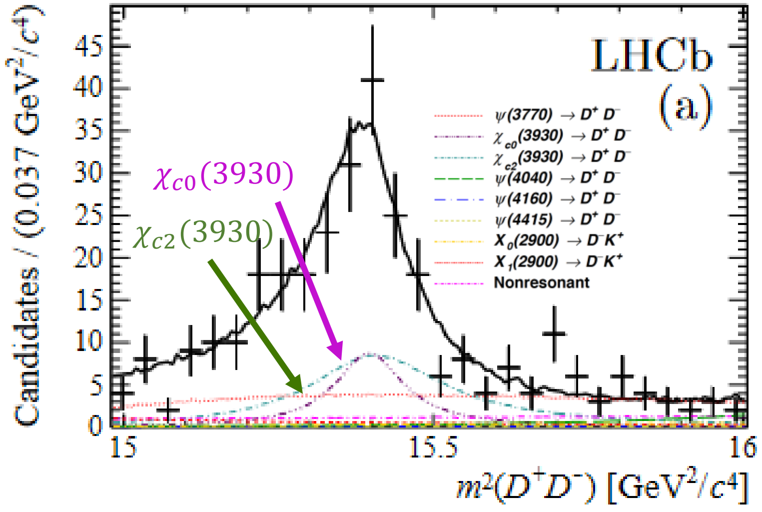
$D_s^+ D_s^-$ threshold: 3936.68 MeV

	J^{PC}	Mass(MeV)	Width(MeV)	Decays
$X(3915)$	$0^{++}/2^{++}$	3918.4 ± 1.9	20 ± 5	$J/\psi\omega, \gamma\gamma$
$\chi_{c2}(3930)$	2^{++}	3922.2 ± 1.0	35.3 ± 2.8	$D\bar{D}, \gamma\gamma$

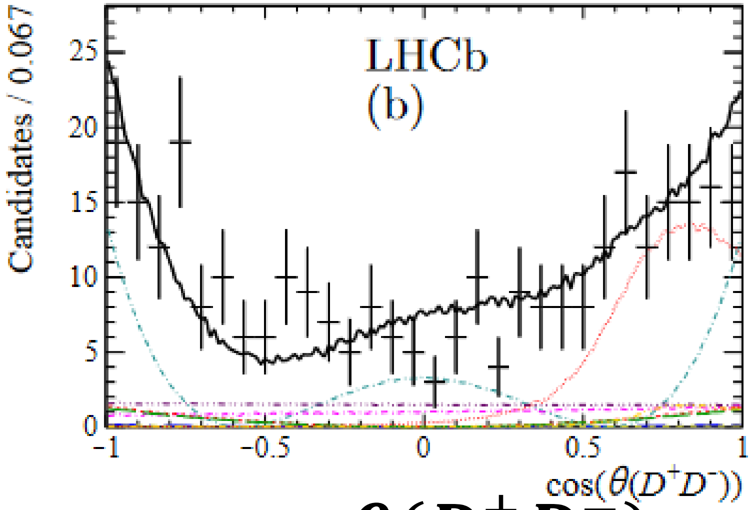
- **This fit**

Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

[PRD 102 (2020) 112003]



$m^2(D^+D^-)$



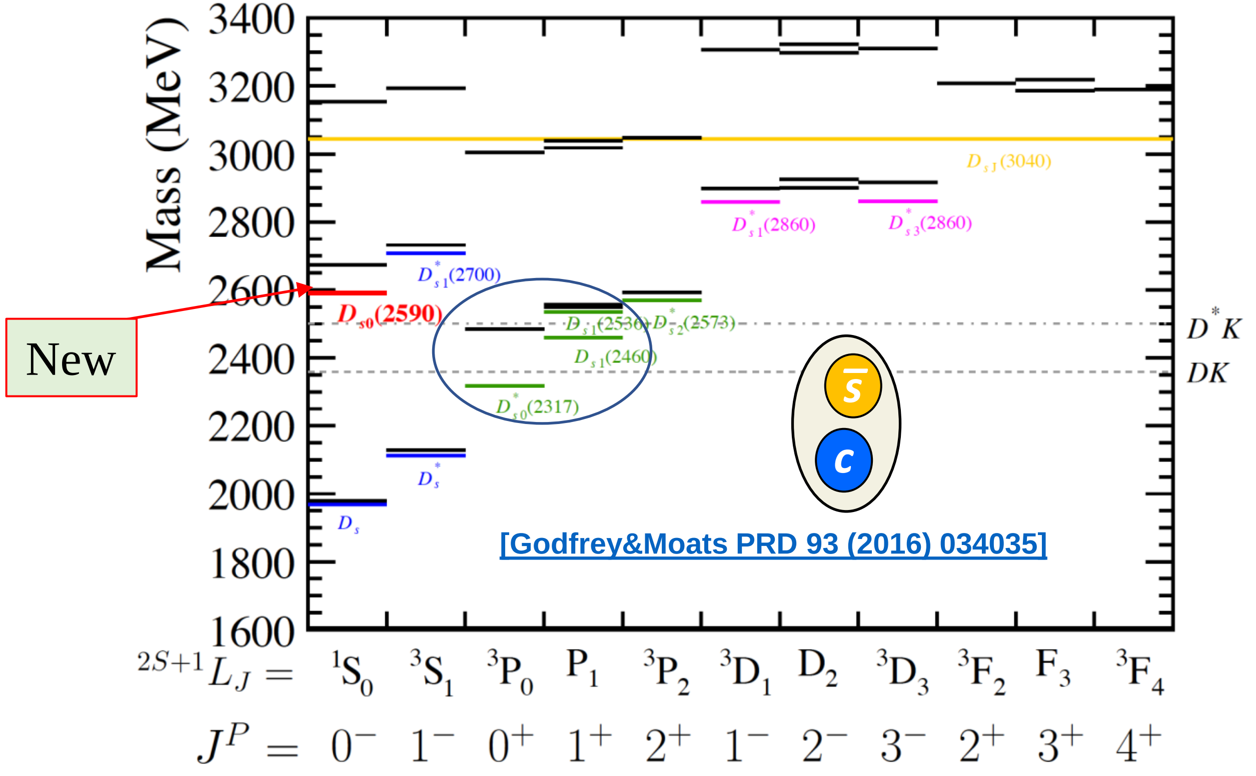
$\cos\theta(D^+D^-)$

- Two resonances seen in DD decays, with J=0 and J=2; lead to rethink of previous results
- It also puts the question whether this spin 0 particle = $X(3915)$?

$D_s(2590)$

A new D_s^+ excited state from $B^0 \to D^+ D^- K^+ \pi^-$

- Big puzzle: $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ have much smaller masses than the predictions
- Additional experimental input is helpful

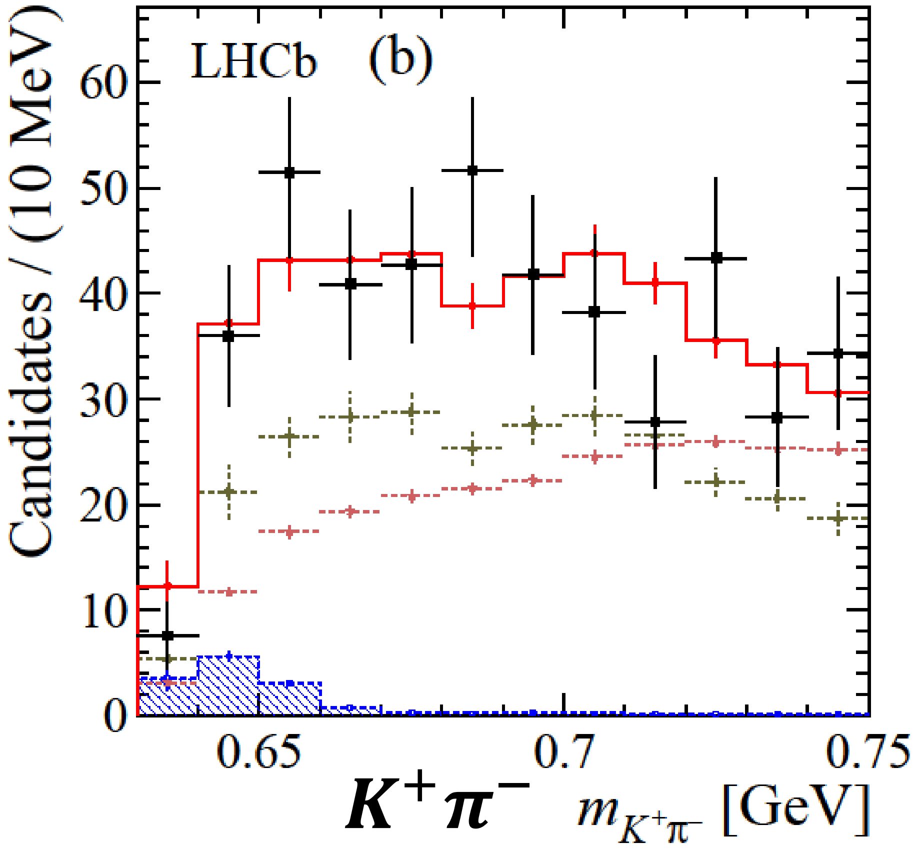


A new D_s^+ excited state from $B^0 \to D^+ D^- K^+ \pi^-$

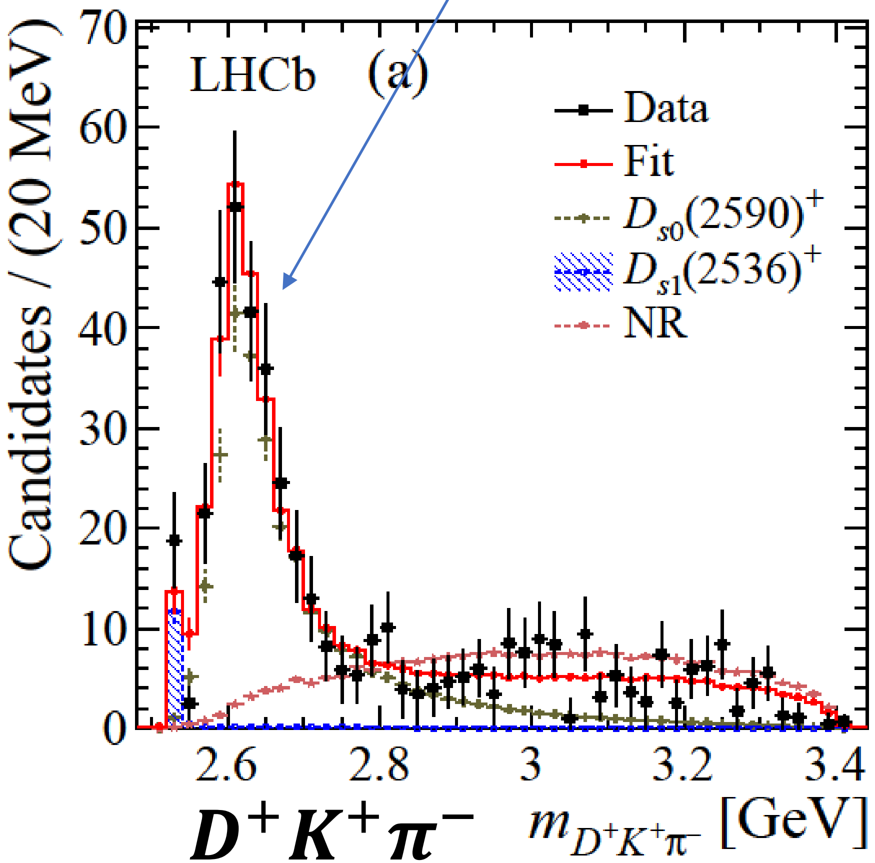
- Use $B^0 \to D^+ D^- K^+ \pi^-$ decays
  - $m(K^+\pi^-) < 0.75$ GeV consistent with S-wave $K^+\pi^-$
  - $D^+ K^+ \pi^-$ invariant mass shows a strong peak and can be described as

$D_s(2590)$
$m_R = 2591 \pm 6 MeV$
$\Gamma_R = 89 \pm 16 MeV$

[PRL 126, 122002 (2021)]



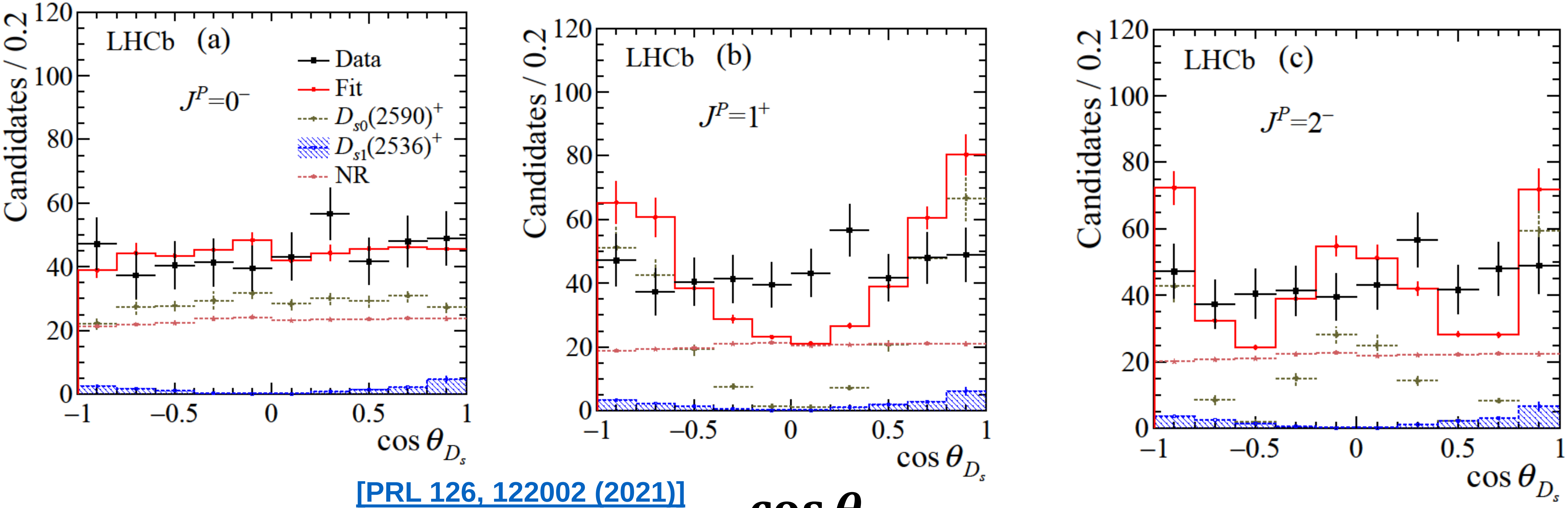
$K^+\pi^-$



$D^+K^+\pi^-$

Spin parity of $D_s(2590)^-$

- Test with different possible spin parities.
- Data prefers $J^P = 0^-$



[PRL 126, 122002 (2021)]

$\cos\theta_{D^*}$

Future prospects

Future possibilities of $B \to D^* D K$

- Branching fraction ratios of 9fb^{-1} data in LHCb are measured

[JHEP 12 (2020) 139]

$$\frac{\mathcal{B}(B^+ \to D^{*-}D^+K^+)}{\mathcal{B}(B^+ \to D^{*+}D^-K^+)} = 0.907 \pm 0.033 \pm 0.014$$

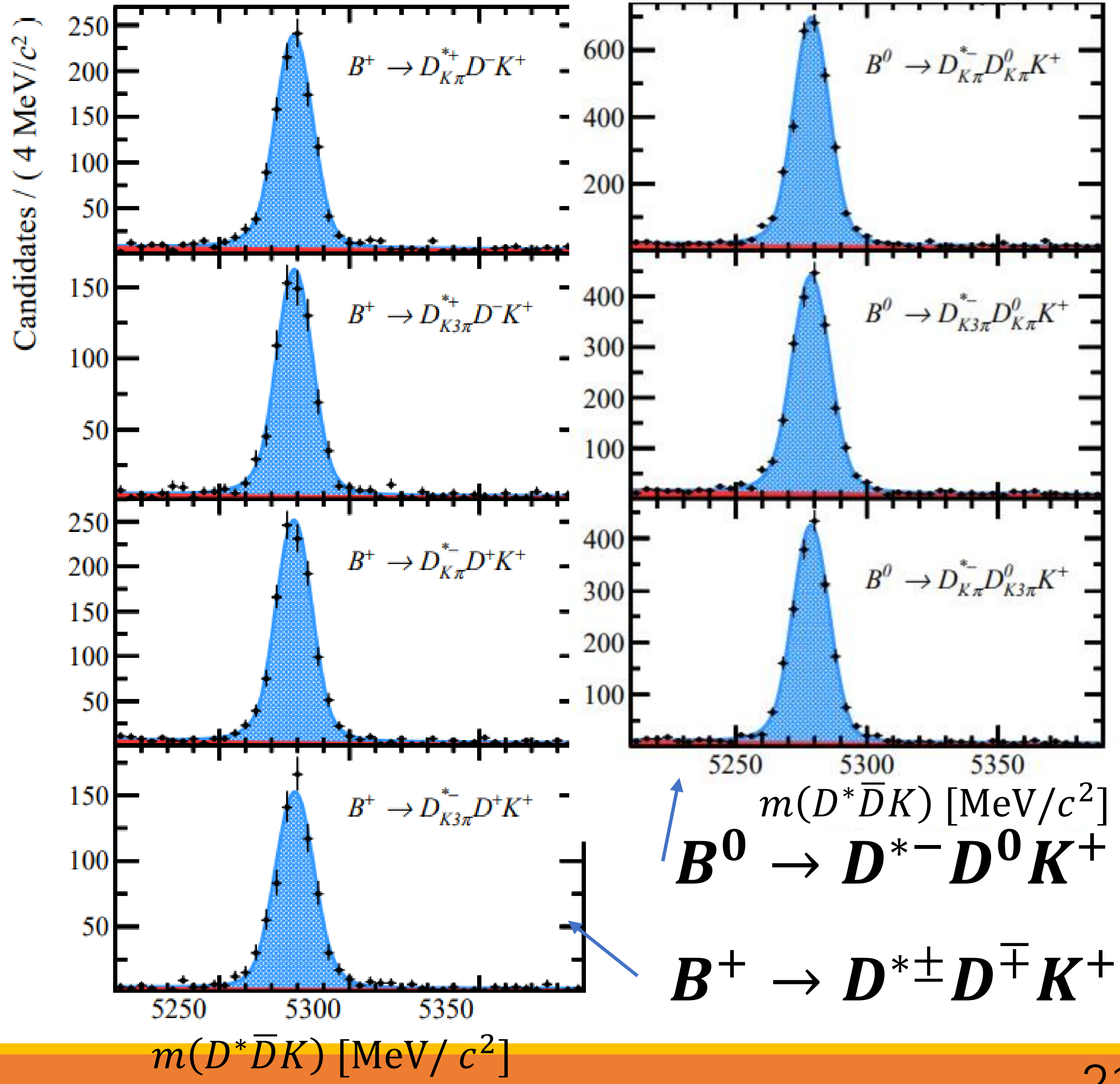
$$\frac{\mathcal{B}(B^+ \to D^{*+}D^-K^+)}{\mathcal{B}(B^+ \to \bar{D}^0D^0K^+)} = 0.517 \pm 0.015 \pm 0.013 \pm 0.011$$

$$\frac{\mathcal{B}(B^+ \to D^{*-}D^+K^+)}{\mathcal{B}(B^+ \to \bar{D}^0D^0K^+)} = 0.577 \pm 0.016 \pm 0.013 \pm 0.013$$

$$\frac{\mathcal{B}(B^0 \to D^{*-}D^0K^+)}{\mathcal{B}(B^0 \to D^-D^0K^+)} = 1.754 \pm 0.028 \pm 0.016 \pm 0.035$$

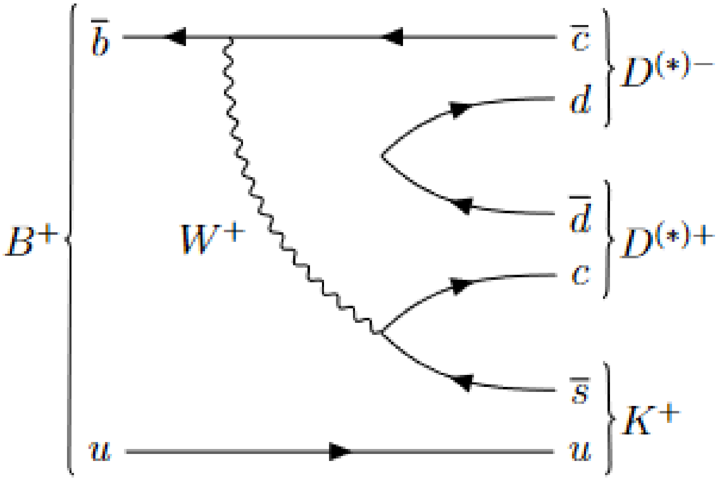
value $\pm$ stat. $\pm$ sys. $\pm$ from D-meson branching ratios

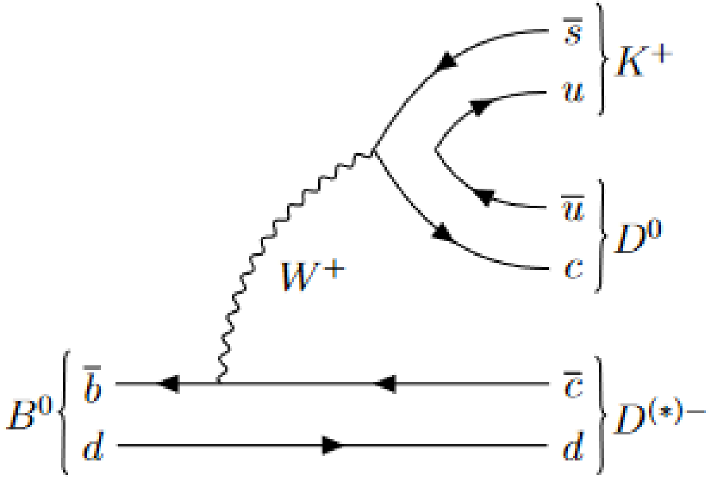
- The dataset is enough for amplitude analysis

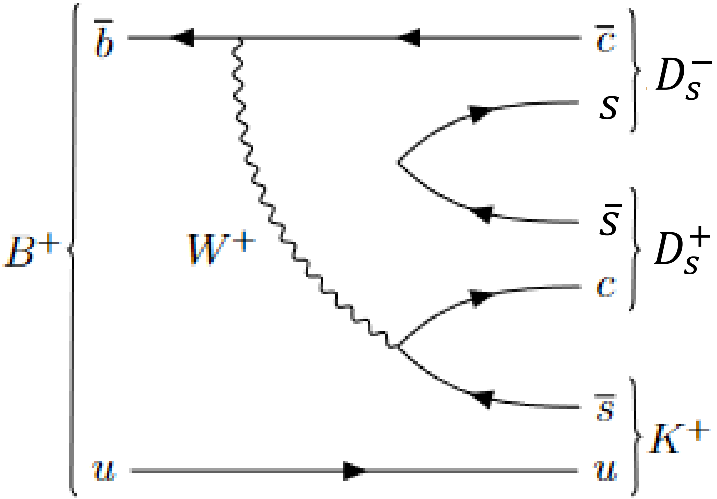


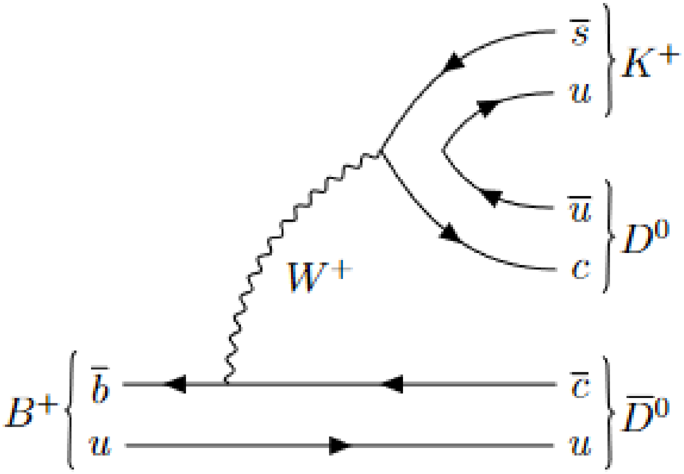
Ongoing analyses

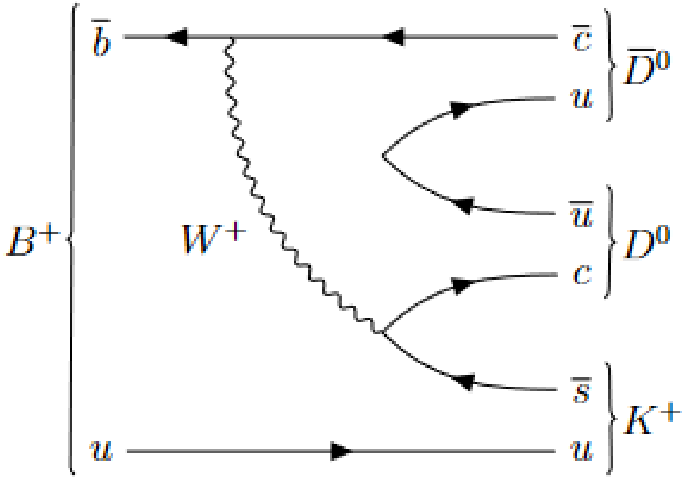
- $B^+ \to D^{*\mp} D^{\pm} K^+$
- $B^0 \to D^{*-} D^0 K^+$
- $B^+ \to D_s^+ D_s^- K^+$
- $B^+ \to D^{*-} D^{*+} K^+$
- $B^+ \to D^- D_s^+ \pi^+$
- …











A general and user-friendly partial wave analysis framework

Hao Cai[1], Chen Chen[5], Yi Jiang[2], Pei-Rong Li[3], Yinrui Liu[2], Xiao-Rui Lyu[2], Rong-Gang Ping[4], Wenbin Qian[2], Mengzhen Wang[5], Zi-Yi Wang[2], Liming Zhang[5],Yang-Heng Zheng[2]

[1]WHU, [2]UCAS, [3]LZU, [4]IHEP, [5]THU

- **Several independent fitters developed previously for dedicated analyses: e.g. $Z(4430)^+$ and pentaquark search, $B^0 \to \overline{D^0}\pi^+\pi^-$ analysis etc.**
- **Joint efforts + experience on previous analyses**

TF-PWA: Partial Wave Analysis with TensorFlow

- Fast
  - GPU based
  - Vectorized calculation
  - Automatic differentiation

    Quasi-Newton Method: scipy.optimize
- General
  - Custom model available
- Easy to use
  - Simple configuration file (example provided)
  - Automatics process
  - All necessary functions implemented

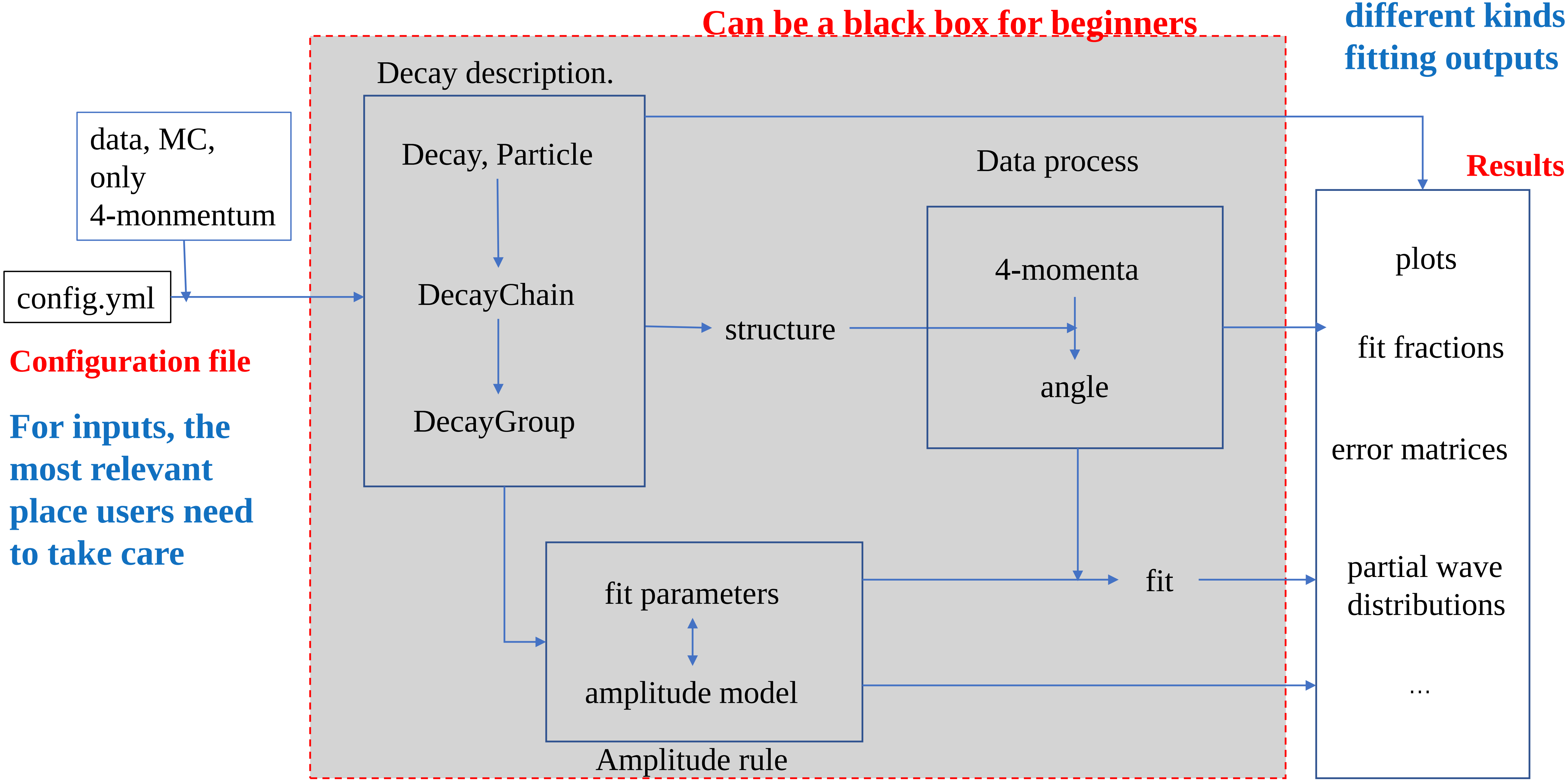
- Open access and well supported

https://github.com/jiangyi15/tf-pwa

Welcome to use it from other experiments

The Framework

Automatic generations of different kinds of fitting outputs



Summary

- $D^- K^+ (\bar{c}\bar{s}ud)$ structures $X_{0,1}(2900)$ are observed in $B^+ \to D^+ D^- K^+$.
  - Model independent analysis shows some structures besides $D^+ D^-$ [PRL 125 (2020) 242001]
  - New $0^+, 1^-$ states describe it most well in the amplitude analysis

  [PRD 102 (2020) 112003]

- A new excited D_s state $D_s(2590)^-$ is observed in $B^0 \to D^+ D^- K^+ \pi^-$.

  [PRL 126, 122002 (2021)]

- Many analyses of $B \to DDh$ decays are ongoing.

- A general and user-friendly partial wave analysis framework has been developed; which can be used in different amplitude analyses, such as $B \to DDh$.

Thank you for your attention.

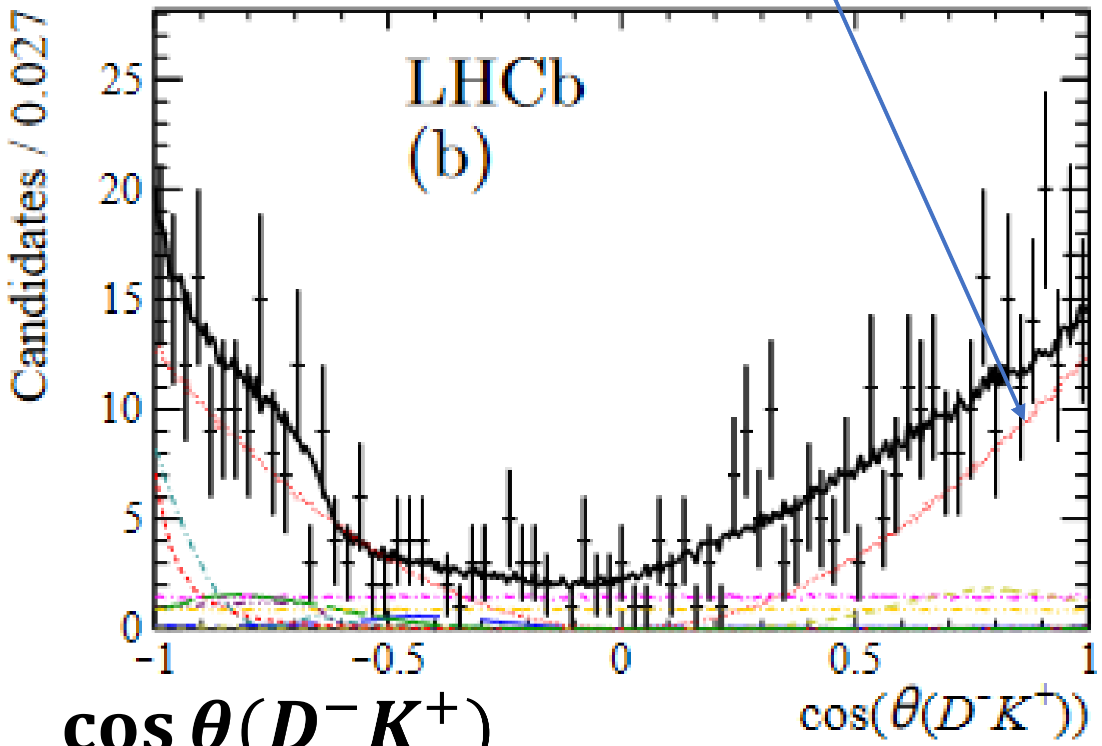
Backup

Spin parity of $X_{0,1}(2900)$

in 2.75 GeV/c^2< $m(D^-K^+)$ < 3.0 GeV/c^2

model	- ln L	significance
Baseline	−3540	16.8σ
No D−K+ resonances	−3382	ref
One D−K+ resonance (spin-0)	−3491	14.2σ
One D−K+ resonance (spin-1)	−3497	14.6σ
One D−K+ resonance (spin-2)	−3463	12.1σ
Two D−K+ resonances (spin-1 + spin-2)	−3536	16.6σ

large contribution of 1^-



$\cos\theta(D^-K^+)$

Fit Fraction

	$\psi(3770)$	$\chi_{c0}(3930)$	$\chi_{c2}(3930)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$	$X_0(2900)$	$X_1(2900)$	**Non resonant**
$\psi(3770)$	14.5±1.2±0.8	-	-	3.7±0.5±0.18	1.7±0.6±0.3	−3.3±0.7±0.6	−0.6±0.2±0.1	−4.6±0.5±0.6	−0.4±0.3±0.5
$\chi_{c0}(3930)$		3.7±0.9±0.2	-	-	-	-	0.1±0.1±0.0	0.5±0.1±0.0	3.2±0.7±1.5
$\chi_{c2}(3930)$			7.2±1.2±0.3	-	-	-	−0.2±0.0±0.1	−1.5±0.2±0.4	0.0±0.0±0.0
$\psi(4040)$				5.0±1.3±0.4	−1.2±1.3±0.1	−0.3±0.7±0.3	0.1±0.1±0.0	−0.6±0.5±0.2	-0.6±0.4±0.5
$\psi(4160)$					6.6±1.5±1.2	-5.1±1.3±0.9	−0.2±0.1±0.0	−2.8±0.5±0.4	−0.2±0.2±0.4
$\psi(4415)$						9.2±1.4±1.5	0.0±0.1±0.1	3.1±0.5±0.2	0.5±0.3±0.4
$X_0(2900)$							5.6±1.4±0.5	-	2.3±1.4±3.0
$X_1(2900)$								30.6±2.4±2.1	-
Non resonant									24.2±2.2±0.5

Significance

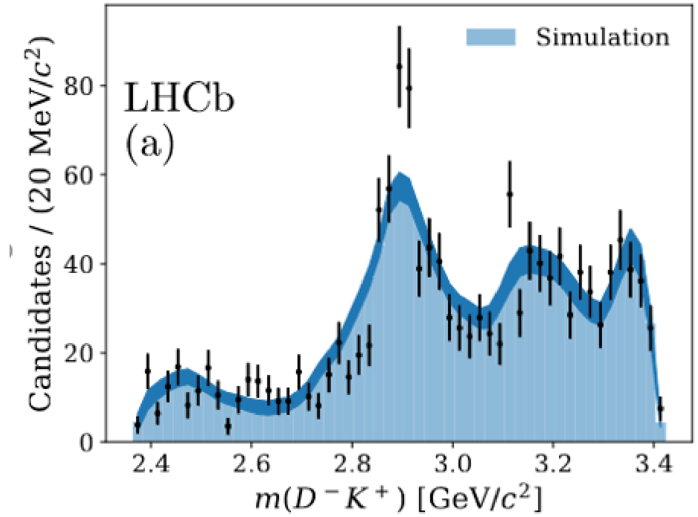
$$t = -2 \sum_{l=1}^{N^{\mathrm{Data}}} s_l \log\left(\frac{\mathcal{P}\left(m_l(D^-K^+)|H_0\right)/I_{H_0}}{\mathcal{P}\left(m_l(D^-K^+)|H_1\right)/I_{H_1}}\right)$$

test model

real model

$\sim\chi^2(N_{ndf})$

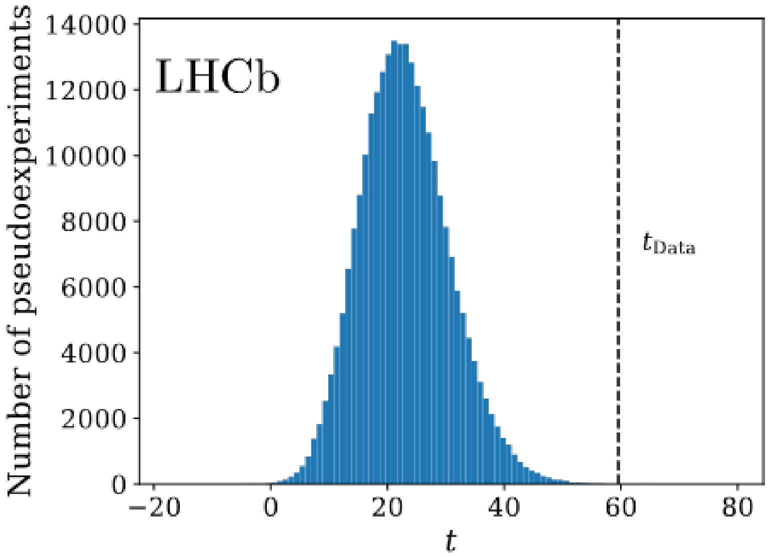
$$I_H = \sum_{l=1}^{N^{\mathrm{Sim}}} \mathcal{P}(m_l(D^-K^+)|H)\epsilon_l \, ,$$



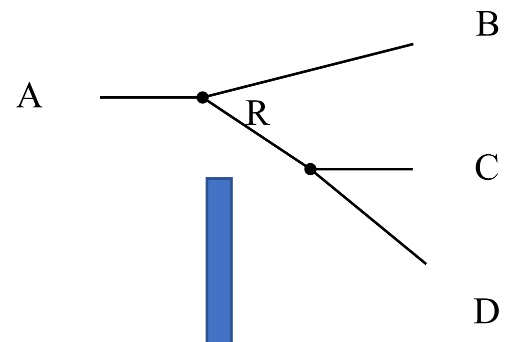
model independent significance

$k_{max} = 4$, spin 2
99.994% , 3.9 σ

$k_{max} = 6$, spin 3
3.7 σ



Helicity formalism



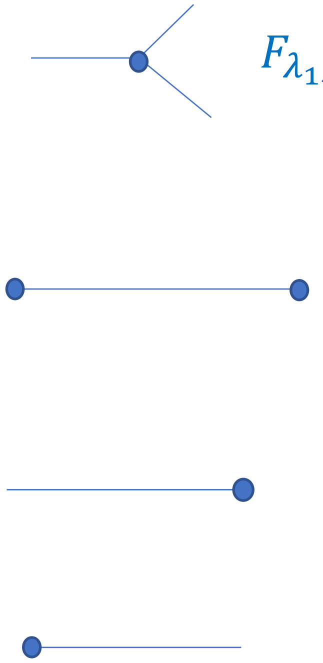
$$A^{R}_{\lambda_A,\lambda'_B,\lambda'_C,\lambda'_D}$$

$$= \sum_{\lambda} F_{\lambda_R\lambda_B} D^{j_A\star}_{\lambda_A,\lambda_R-\lambda_B}(\varphi_1,\theta_1,0) R(M) F_{\lambda_C,\lambda_D} D^{j_R\star}_{\lambda_R,\lambda_C-\lambda_D}(\varphi_2,\theta_2,0)$$

$$D^{j_B\star}_{\lambda_B,\lambda_B'}(\alpha_B,\beta_B,\gamma_B) D^{j_C\star}_{\lambda_C,\lambda_C'}(\alpha_C,\beta_C,\gamma_C) D^{j_D\star}_{\lambda_D,\lambda_D'}(\alpha_D,\beta_D,\gamma_D)$$

$$\frac{d\sigma}{d\Phi} \propto \sum_{\lambda_A} \sum_{\lambda_B,\lambda_C,\lambda_D} \left| \sum_{R} A^{R}_{\lambda_A,\lambda_B,\lambda_C,\lambda_D} \right|^2$$

Feynman rules



Decay: $F_{\lambda_1,\lambda_2} D^{j_0\star}_{\lambda_0,\lambda_1-\lambda_2}(\varphi,\theta,0)$ (Wigner-D matrix)

Particle:

$R(M) = \frac{1}{m_0^2 - M^2 - i m_0 \Gamma}, \cdots$

1

$D^{j_1\star}_{\lambda_1,\lambda_1'}(\alpha,\beta,\gamma)$

probability: $|\mathcal{A}|$^2

Decay Group: $\mathcal{A} = \tilde{A}_1 + \tilde{A}_2 + \cdots$

Decay Chain: $\tilde{A} = A_1 R A_2 \cdots$

Decay: Wigner D-matrix, $A = FD^{*J}\ (\phi,\theta,0)$

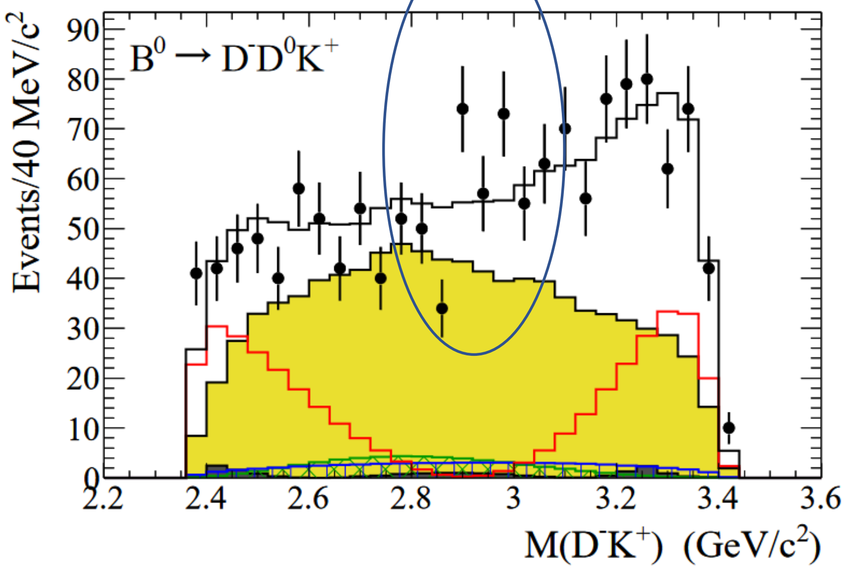
Particle: Breit-Wigner: $R(m)$, user defined

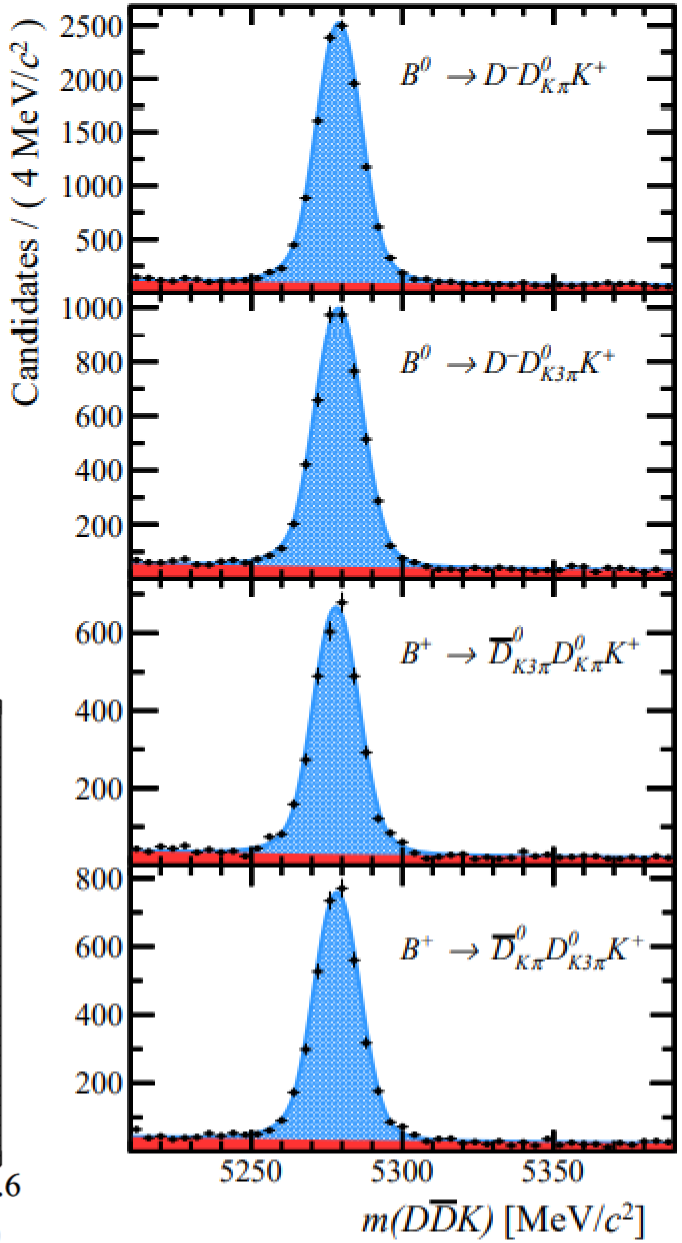
$B \to DDK$

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

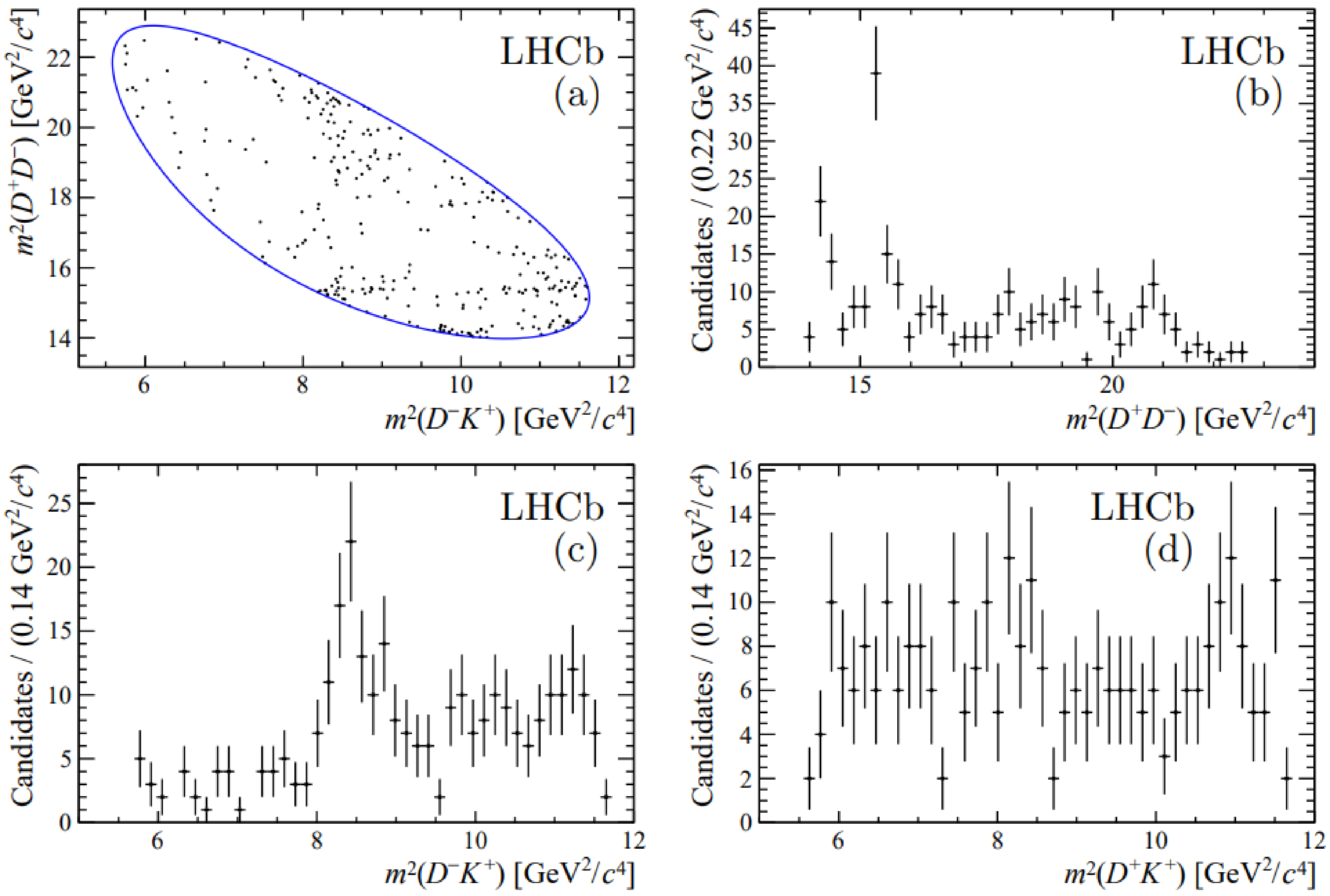
Signal yields	Run 1	Run 2
$B^+ \to D^0_{K\pi}\overline{D}^0_{K3\pi}K^+$	477 ± 24	2564 ± 56
$B^+ \to D^0_{K3\pi}\overline{D}^0_{K\pi}K^+$	622 ± 28	2853 ± 60
$B^0 \to D^-D^0_{K\pi}K^+$	2443 ± 54	9071 ± 104
$B^0 \to D^-D^0_{K3\pi}K^+$	864 ± 32	3867 ± 69

- $X(2900) \to D^-K^+$ in $B^0 \to D^-D^0K^+$?



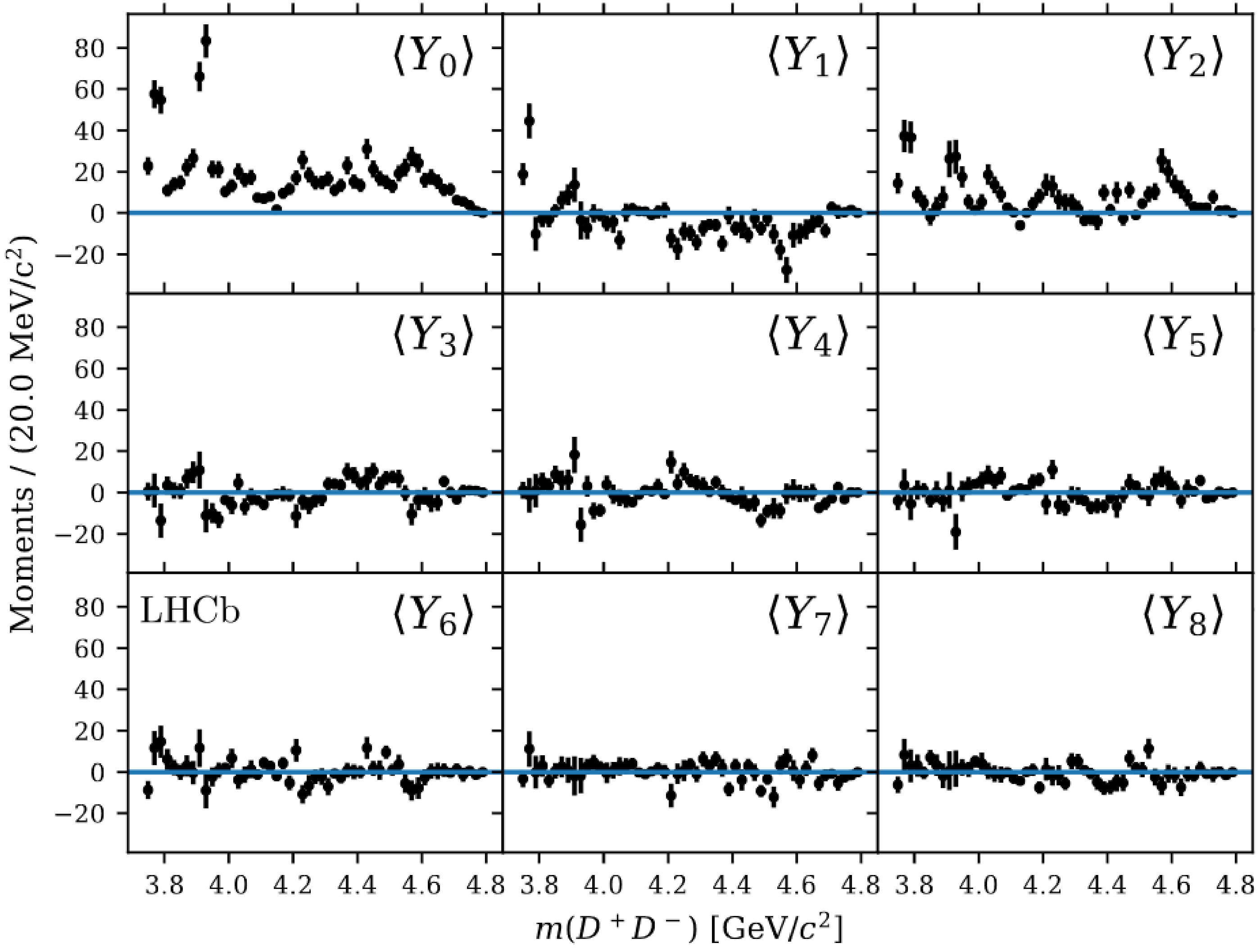


run 1

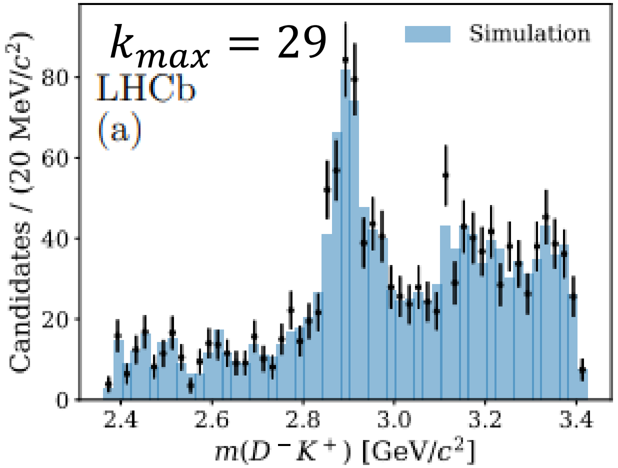


LHCb
(a)
$m^2(D^+D^-)$ [GeV$^2/c^4$]
$m^2(D^-K^+)$ [GeV$^2/c^4$]
LHCb
(b)
Candidates / (0.22 GeV$^2/c^4$)
$m^2(D^+D^-)$ [GeV$^2/c^4$]
LHCb
(c)
Candidates / (0.14 GeV$^2/c^4$)
$m^2(D^-K^+)$ [GeV$^2/c^4$]
LHCb
(d)
Candidates / (0.14 GeV$^2/c^4$)
$m^2(D^+K^+)$ [GeV$^2/c^4$]

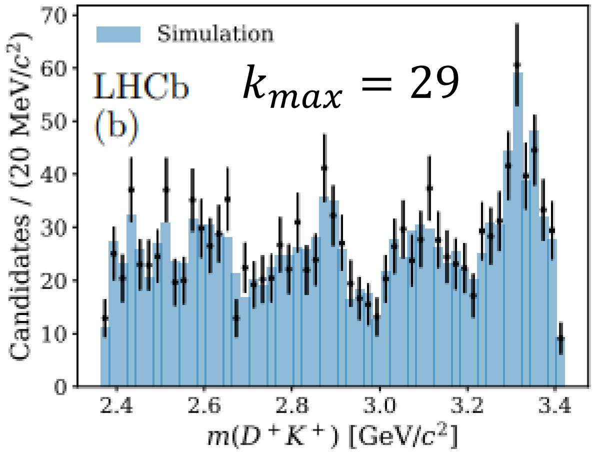
moments



⟨Y_0⟩
⟨Y_1⟩
⟨Y_2⟩
⟨Y_3⟩
⟨Y_4⟩
⟨Y_5⟩
⟨Y_6⟩
⟨Y_7⟩
⟨Y_8⟩
LHCb
Moments / (20.0 MeV/c^2)
$m(D^+D^-)$ [GeV/c^2]



k_{max} = 29
Simulation
LHCb
(a)
Candidates / (20 MeV/c^2)
$m(D^-K^+)$ [GeV/c^2]



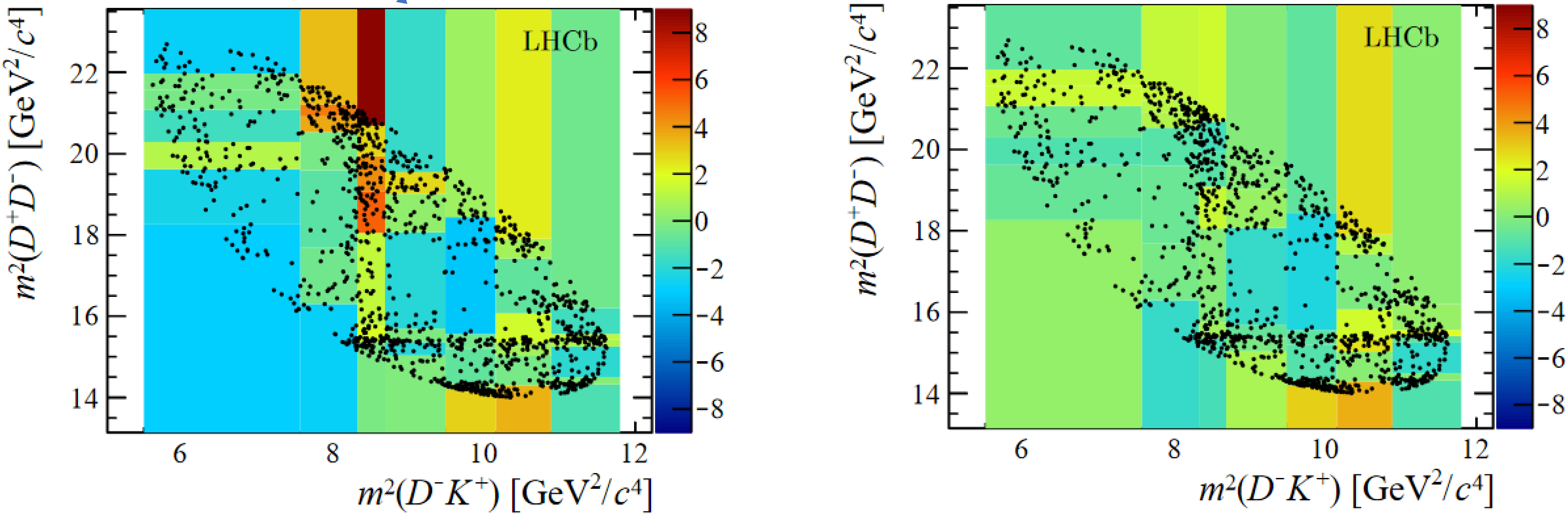
Simulation
LHCb
(b)
k_{max} = 29
Candidates / (20 MeV/c^2)
$m(D^+K^+)$ [GeV/c^2]

2d plot of $\frac{N_{data} - N_{fit}}{\sqrt{N_{fit}}}$

$X(2900)$

without DK

with DK



signal yields

signal yields	Run 1	Run 2
$B^+ \to D^{*+}_{K\pi} D^- K^+$	212 ± 16	869 ± 32
$B^+ \to D^{*+}_{K3\pi} D^- K^+$	116 ± 11	606 ± 26
$B^+ \to D^{*-}_{K\pi} D^+ K^+$	210 ± 15	912 ± 32
$B^+ \to D^{*-}_{K3\pi} D^+ K^+$	153 ± 13	566 ± 25
$B^0 \to D^{*-}_{K\pi} D^0_{K\pi} K^+$	605 ± 26	2409 ± 52
$B^0 \to D^{*-}_{K3\pi} D^0_{K\pi} K^+$	321 ± 20	1706 ± 44
$B^0 \to D^{*-}_{K\pi} D^0_{K3\pi} K^+$	331 ± 20	1544 ± 41

Signal yields	Run 1	Run 2
$B^+ \to D^0_{K\pi} \overline{D}^0_{K3\pi} K^+$	477 ± 24	2564 ± 56
$B^+ \to D^0_{K3\pi} \overline{D}^0_{K\pi} K^+$	622 ± 28	2853 ± 60
$B^0 \to D^- D^0_{K\pi} K^+$	2443 ± 54	9071 ± 104
$B^0 \to D^- D^0_{K3\pi} K^+$	864 ± 32	3867 ± 69