在底强子衰变过程中研究开味四夸克态$T_{c\bar{s}}$

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第五届粒子物理天问论坛

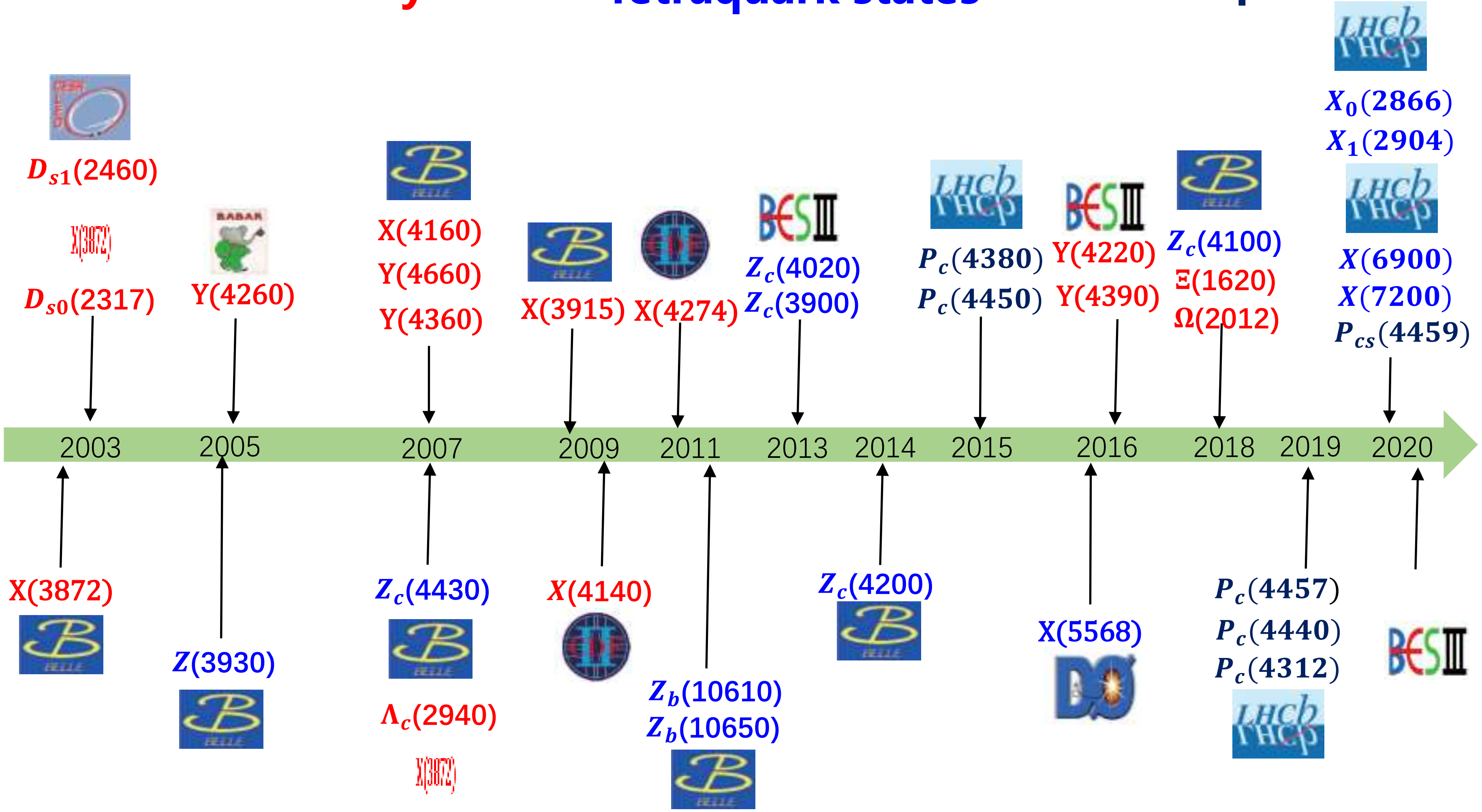
2023年11月10-12日

PRD08 (2023) 074006
2305.09436
2306.16101
2310.11139

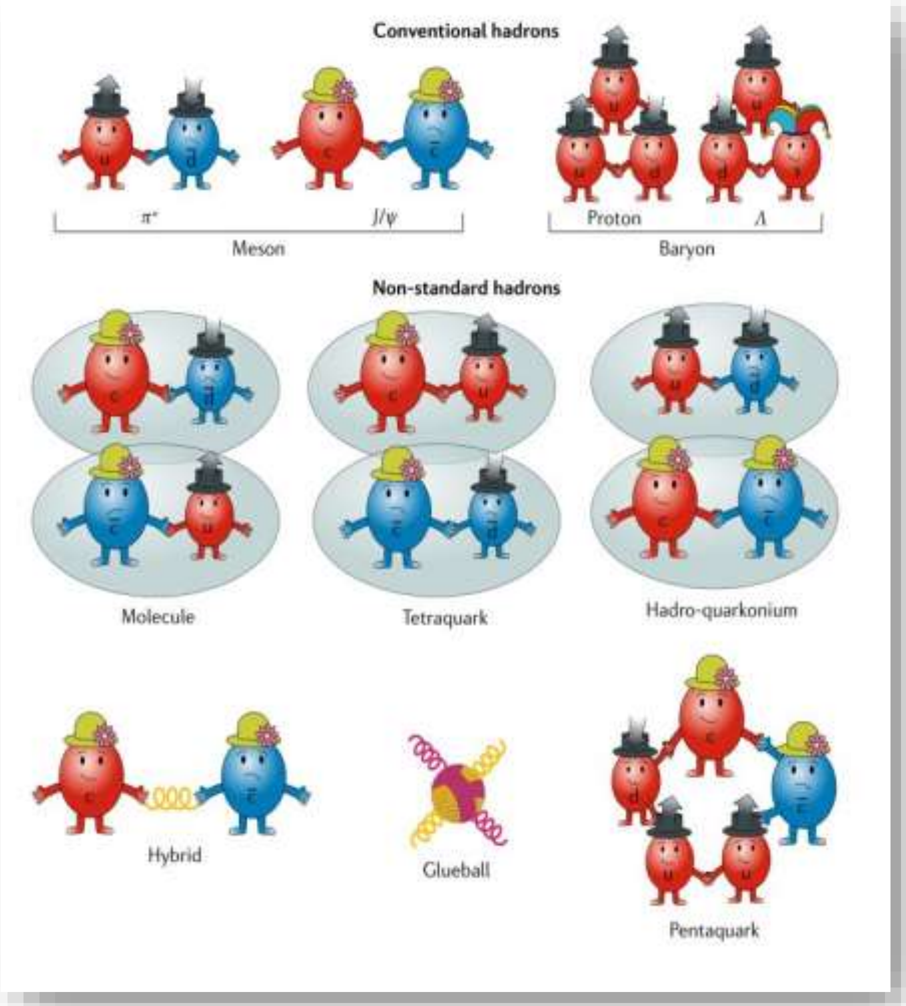
Exotic states

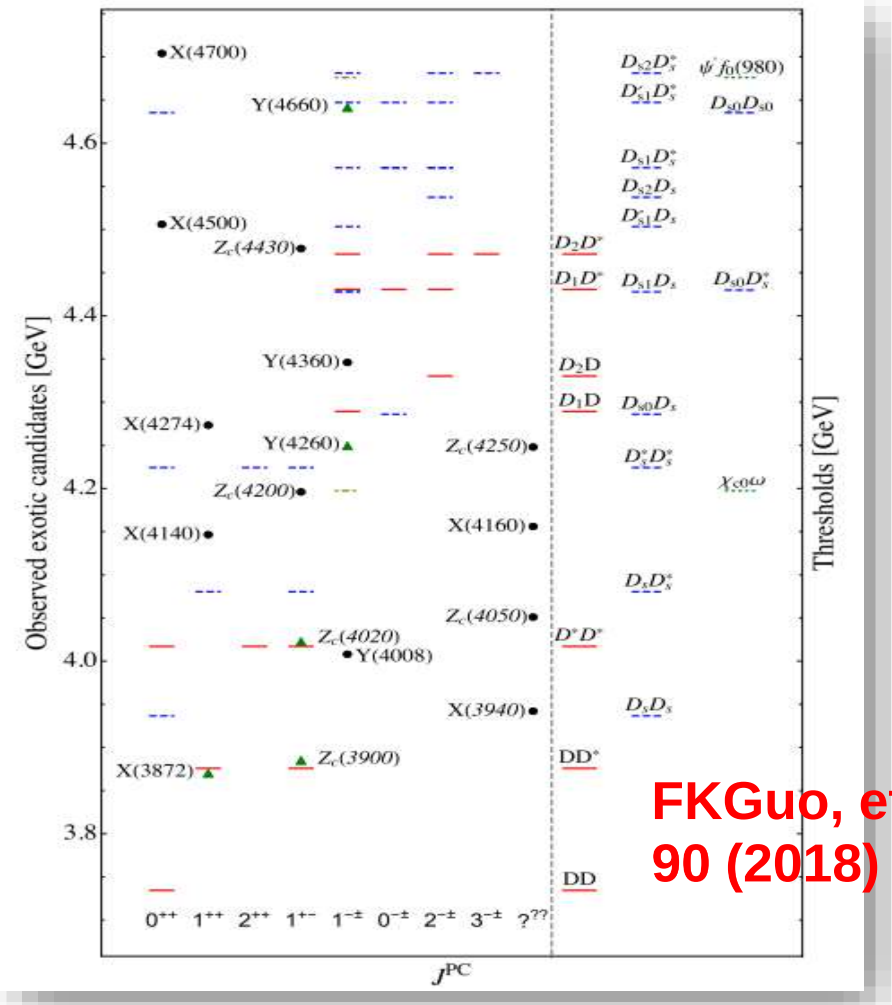
耿立升老师报告

Exotic mesons or baryons **Tetraquark states** **Pentaquark states**



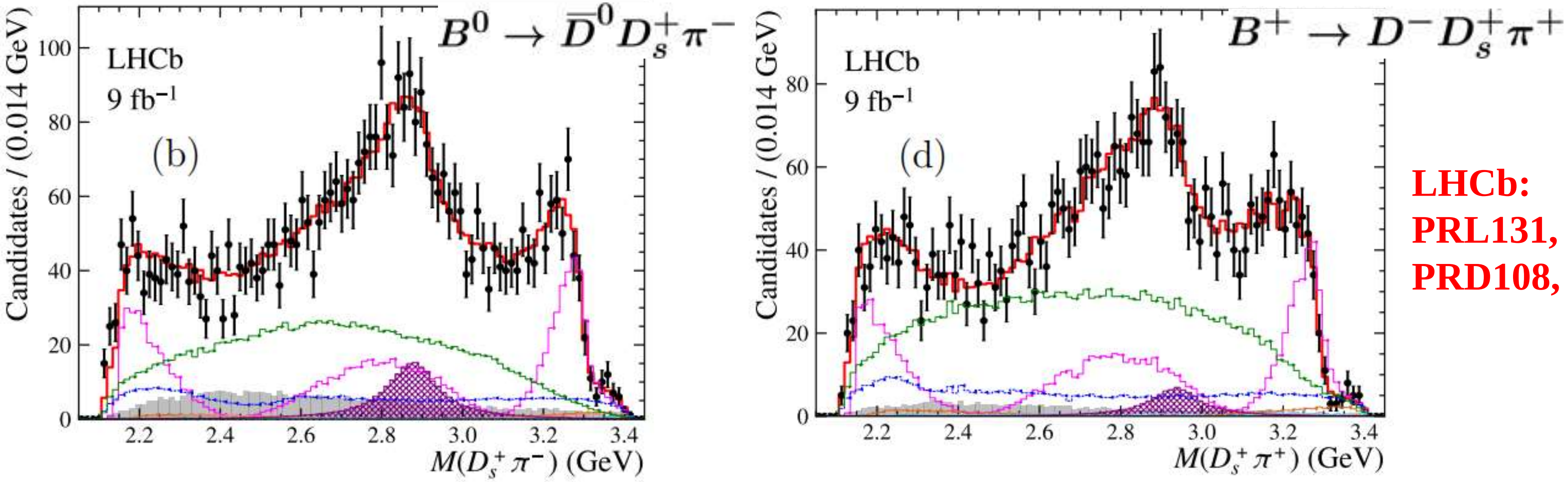
Hadrons





FKGuo, et.al, Mod. Phys 90 (2018) 015004.

LHCb measurements



LHCb:
PRL131, 041902 (2023)
PRD108, 012017 (2023)

$$m_{T_{c\bar{s}0}(2900)^0} = (2892 \pm 14 \pm 15)\ \text{MeV},$$
$$\Gamma_{T_{c\bar{s}0}(2900)^0} = (119 \pm 26 \pm 13)\ \text{MeV},$$

$$m_{T_{c\bar{s}0}(2900)^{++}} = (2921 \pm 17 \pm 20)\ \text{MeV},$$
$$\Gamma_{T_{c\bar{s}0}(2900)^{++}} = (137 \pm 32 \pm 17)\ \text{MeV},$$

$$m_{T_{c\bar{s}0}(2900)} = (2908 \pm 11 \pm 20)\ \text{MeV},$$
$$\Gamma_{T_{c\bar{s}0}(2900)} = (136 \pm 23 \pm 13)\ \text{MeV}.$$

Theoretical explanations

- **Molecular state**

  Phys.Rev.D 108 (2023) 9, 094008, 2309.02191, Eur.Phys.J.C 83 (2023) 8, 769, Phys.Rev.D 108 (2023) 7, 074006, 2305.14430, Phys.Rev.D 107 (2023) 9, 094019, Phys.Rev.D 106 (2022) 11, 114032

- **Compact tetraqurk**

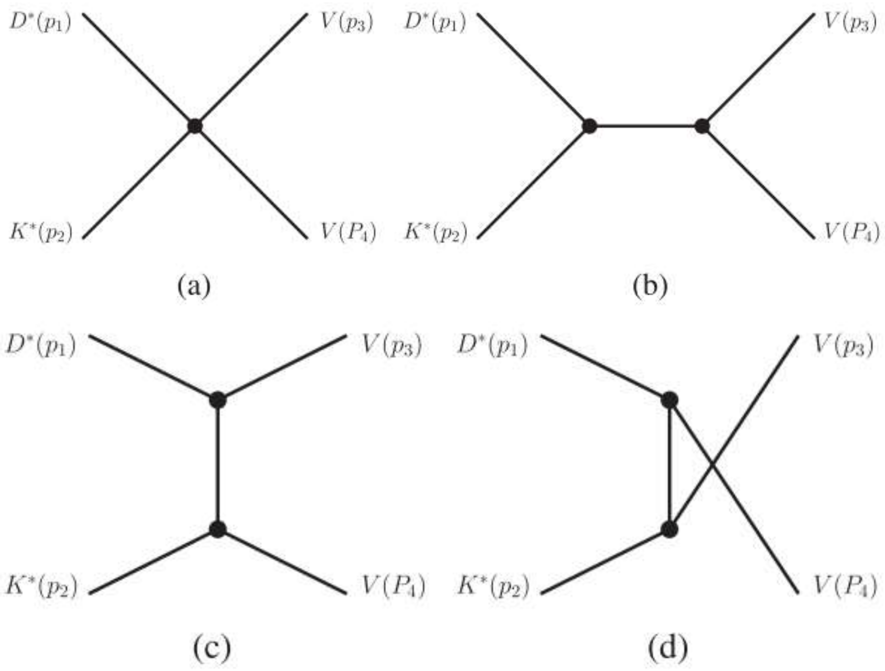
  Int.J.Mod.Phys.A 38 (2023) 11, 2350056 2310.13354, 2302.01167

- **Threshold effects**

  2211.01302

Hidden local symmetry formalism

- **The interaction between vectors** PRD108, 074006 (2023)



$$\mathcal{L} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle,$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu],$$

$$V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu .$$

$$\mathcal{L}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle.$$

$$\mathcal{L}^{(3V)} = ig\langle V^\nu \partial_\mu V_\nu V^\mu - \partial_\nu V_\mu V^\mu V^\nu\rangle$$
$$= ig\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle.$$

unitarized amplitude

- **unitarized amplitude**

$$T^{(IJ)}(s) = [1 - V^{(IJ)}(s)G(s)]^{-1}V^{(IJ)}(s),$$

$$V^{(IJ)}_{\ell S;\bar{\ell}\bar{S}}(s) = \frac{Y^0_{\bar{\ell}}(\hat{\mathbf{z}})}{2J+1}\sum_{\sigma_1,\sigma_2,\bar{\sigma}_1,\bar{\sigma}_2,m}\int d\hat{\mathbf{p}}'' Y^m_{\ell}(\mathbf{p}'')^*(\sigma_1\sigma_2 M|s_1 s_2 S)$$
$$\times (mM\bar{M}|\ell SJ)(\bar{\sigma}_1\bar{\sigma}_2\bar{M}|\bar{s}_1\bar{s}_2\bar{S})(0\bar{M}\bar{M}|\bar{\ell}\bar{S}J)$$
$$\times \mathcal{A}^{(I)}(p_1,p_2,p_3,p_4;\epsilon_1,\epsilon_2,\epsilon_3^*,\epsilon_4^*), \qquad (12)$$

$$\mathrm{Det}(s) = \det[1 - V(s)G(s)].$$

$$g_i g_j = \lim_{s\to s_0}(s-s_0)T_{ij}(s).$$

$$G(s) = i\int\frac{d^4q}{(2\pi)^4}\frac{1}{q^2-m_1^2+i\epsilon}\frac{1}{(q-P)^2-m_2^2+i\epsilon},$$

$$G(s) = \frac{1}{16\pi^2}\left[\alpha(\mu) + \log\frac{m_1^2}{\mu^2} + \frac{m_2^2-m_1^2+s}{2s}\log\frac{m_2^2}{m_1^2}\right.$$
$$+\frac{q_{\rm cm}}{\sqrt{s}}\left(\log\frac{s-m_2^2+m_1^2+2q_{\rm cm}\sqrt{s}}{-s+m_2^2-m_1^2+2q_{\rm cm}\sqrt{s}}\right.$$
$$\left.\left.+\log\frac{s+m_2^2-m_1^2+2q_{\rm cm}\sqrt{s}}{-s-m_2^2+m_1^2+2q_{\rm cm}\sqrt{s}}\right)\right],$$

$$G^{II}(s) = G^{I}(s) + i\frac{q_{\rm cm}}{4\pi\sqrt{s}}$$

Pole position

TABLE II. The pole positions and effective couplings evaluated for $I = 1$, $J = 0$ on different RSs with $\mu = 1500$ MeV. The threshold of $D_s^*\rho$ is 2887 MeV.

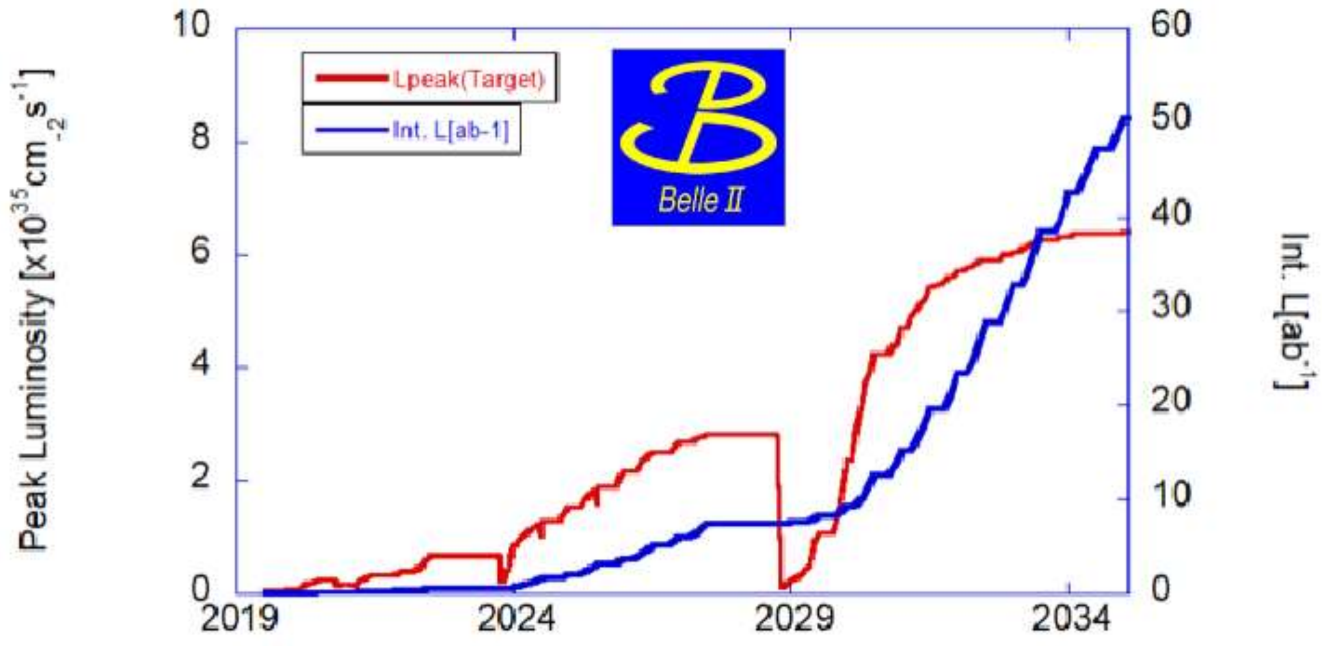
RS	α	$\sqrt{s_{\rm pole}}$ [MeV]	$\lvert g_{D^*K^*}\rvert$ [MeV]	$\lvert g_{D_s^*\rho}\rvert$ [MeV]
$\{1,1\}$	$-1.65 \sim -1.60$	$2885 \sim 2887$	$5531 \sim 2198$	$5379 \sim 2082$
$\{2,1\}$	$-1.60 \sim -1.55$	$2887 \sim 2885$	$1755 \sim 8202$	$1650 \sim 7348$
$\{1,2\}$	$-1.39 \sim -1.35$	$2885 \sim 2887$	$6587 \sim 1625$	$7886 \sim 1865$
$\{2,2\}$	$-1.35 \sim -1.28$	$2887 \sim 2885$	$1415 \sim 4202$	$1613 \sim 4672$

TABLE III. The pole positions evaluated in the sectors of $I = 1$, $J = 1$ and $I = 1$, $J = 2$ on the different RSs with $-1.65 < \alpha < -1.55$ and $-1.39 < \alpha < -1.28$. The "—" indicates that no pole is found. In the present work, we only consider the energy region safe from the left-hand cut, i.e., $\sqrt{s} > 2780$ MeV.

	$I = 1,\ J = 1$		$I = 1,\ J = 2$	
RS	α	$\sqrt{s_{\rm pole}}$ [MeV]	α	$\sqrt{s_{\rm pole}}$ [MeV]
$\{1,1\}$	$-1.65 \sim -1.61$	$2886 \sim 2887$	$-1.31 \sim -1.28$	$2780 \sim 2806$
$\{2,1\}$	$-1.61 \sim -1.55$	$2887 \sim 2883$	$\cdots$	$\cdots$
$\{1,2\}$	$-1.39 \sim -1.36$	$2886 \sim 2887$	$\cdots$	$\cdots$
$\{2,2\}$	$-1.36 \sim -1.28$	$2887 \sim 2885$	$\cdots$	$\cdots$

底重子

- **Belle/Belle II &LHCb**

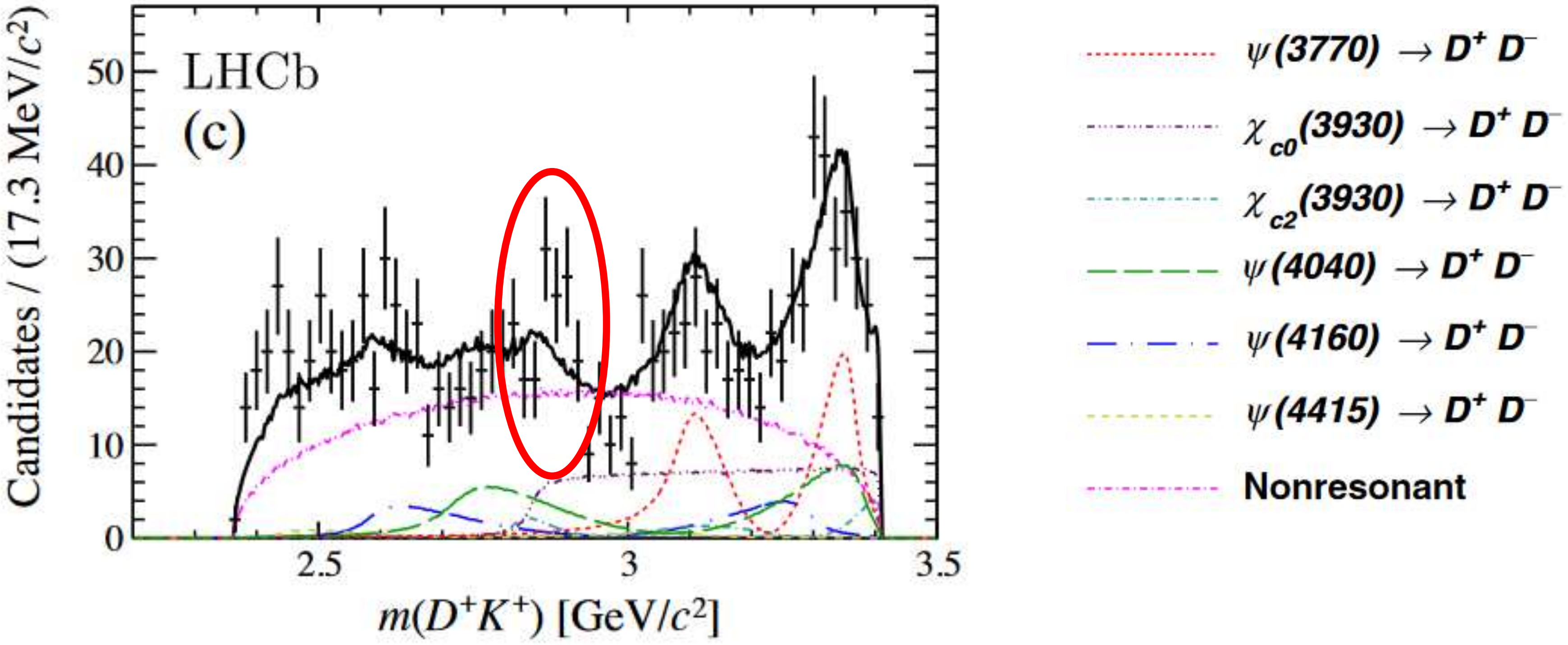


•Collected ~424 fb-1 around Y(4S) until now
•LS1 starts in summer 2022 to fully install the pixel detector and accelerator machine study
•Operation will be resumed around the end of 2023

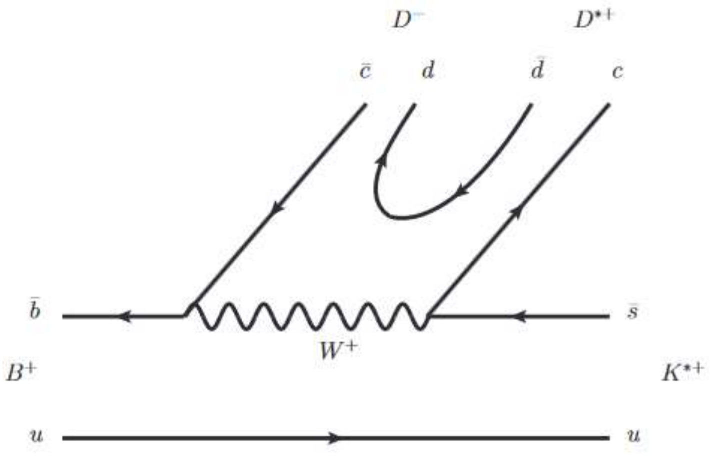
from the slide of CPShen

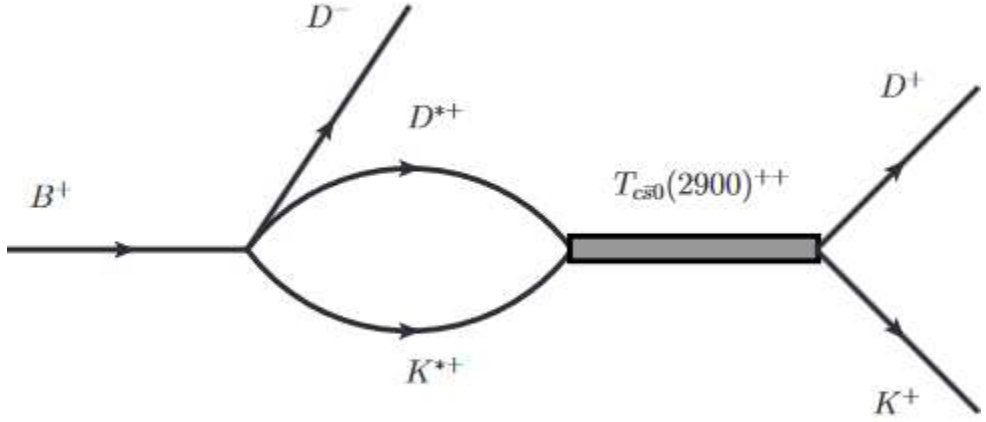
$B^+ \to K^+ D^+ D^-$

- **LHCb:** PRD102, 112003 (2020)



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





$$
\begin{aligned}
\mathcal{V}^{(0)} &= \frac{1}{3}\epsilon_l(D^{*+})\epsilon_l(K^{*+})\delta_{ij}, \\
\mathcal{V}^{(1)} &= \frac{1}{2}\left[\epsilon_i(D^{*+})\epsilon_j(K^{*+}) - \epsilon_j(D^{*+})\epsilon_i(K^{*+})\right], \\
\mathcal{V}^{(2)} &= \frac{1}{2}\left[\epsilon_i(D^{*+})\epsilon_j(K^{*+}) + \epsilon_j(D^{*+})\epsilon_i(K^{*+})\right] \\
&\quad -\frac{1}{3}\epsilon_l(D^{*+})\epsilon_l(K^{*+})\delta_{ij}.
\end{aligned}
$$

$$
\begin{aligned}
-it_{2a} &= -iC_1\epsilon_\alpha(D^{*+})\epsilon_\beta(K^{*+})\delta^{\alpha\beta}G_{D^*K^*}(M_{\rm inv}(D^+K^+)) \\
&\quad \times\frac{1}{3}\epsilon_l^*(D^{*+})\epsilon_l^*(K^{*+})\delta_{ij}g_{T^{++}_{c\bar{s}0}D^*K^*} \\
&= -iC_1\delta_{ij}G_{D^*K^*}(M_{\rm inv}(D^+K^+))g_{T^{++}_{c\bar{s}0}D^*K^*}, \\
-it_{2b} &= -iC_1\delta_{ij}G_{D^*K^*}\left(M_{\rm inv}(D^+K^+)\right) \\
&\quad \times\frac{g_{T^{++}_{c\bar{s}0}D^*K^*}\,g_{T^{++}_{c\bar{s}0}DK}}{M^2_{\rm inv}(D^+K^+) - m^2_{T^{++}_{c\bar{s}0}} + im_{T^{++}_{c\bar{s}0}}\Gamma_{T^{++}_{c\bar{s}0}}},
\end{aligned}
$$

- **Coupling constants**

$$g^2_{T^{++}_{c\bar{s}0},D^*K^*} = 16\pi(m_{D^*} + m_{K^*})^2\tilde{\lambda}^2\sqrt{\frac{2\Delta E}{\mu}},$$

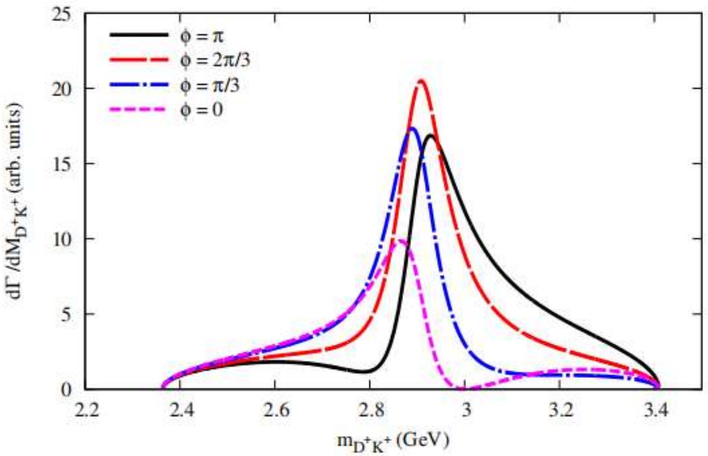
$\lambda = 1$ gives the probability to find the molecular component in the physical states

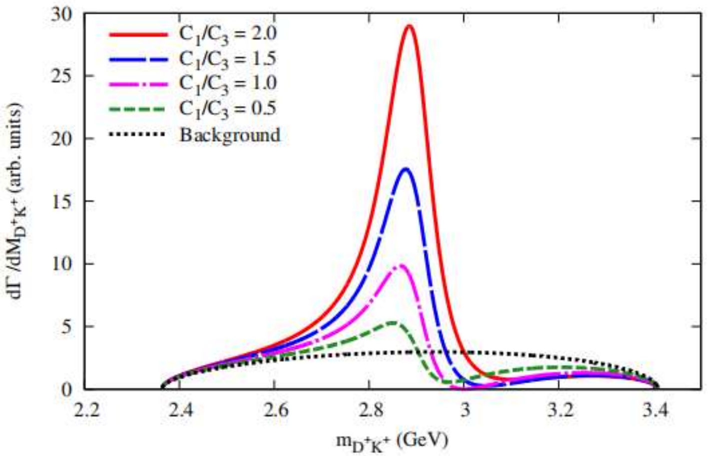
S. Weinberg, PR137, B672 (1965)
Baru, PLB 586, 53-61 (2004)

$$\Gamma_{T^{++}_{c\bar{s}0}} = \frac{1}{8\pi}\frac{1}{m^2_{T^{++}_{c\bar{s}0}}}|g_{T^{++}_{c\bar{s}0},DK}|^2|\vec{q}_{K^+}|,$$

85MeV, DYChen: PRD107 (2023) 034018

$$\frac{d\Gamma}{dM_{\rm inv}(D^+K^+)} = \frac{1}{(2\pi)^3}\frac{1}{4m^2_{B^+}}p_{D^-}\tilde{p}_{K^+}\sum|t_{2b} + C_3e^{i\phi}|^2,$$





Results

- **Branching fraction ~13%**

$$B^+ \to D^- T_{c\bar{s}0}(2900)^{++} \to K^+ D^+ D^-$$

- **Other process**

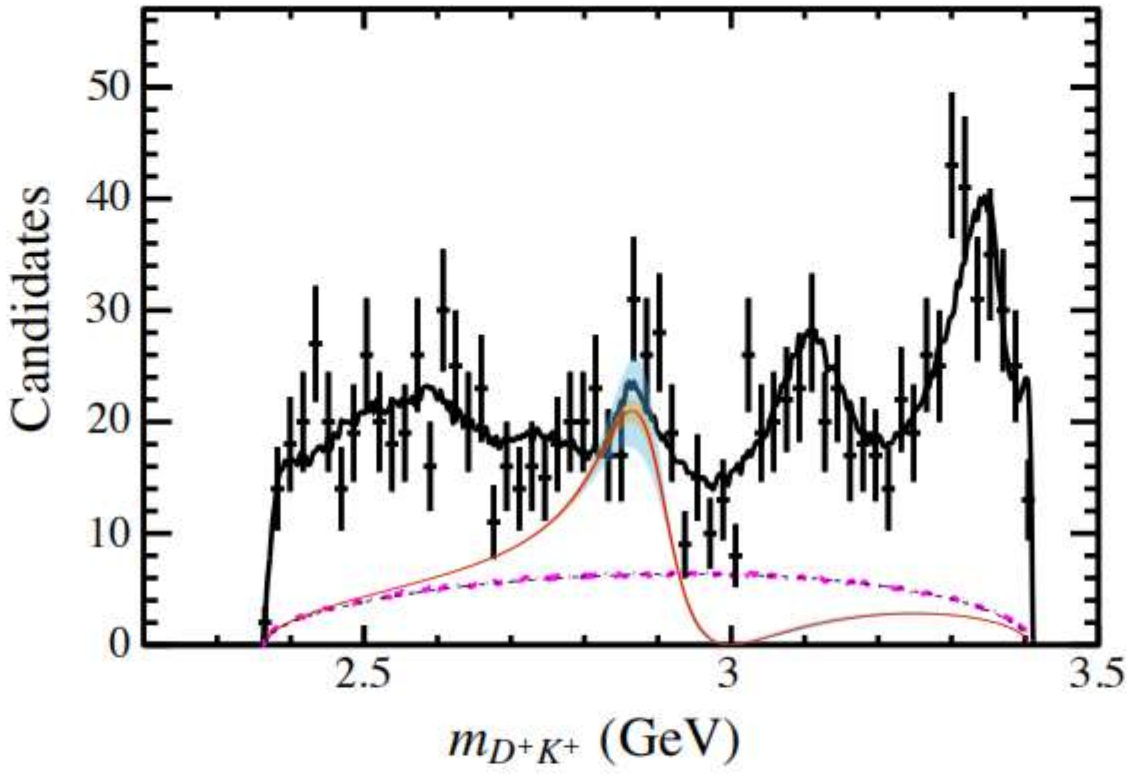
$$B^0 \to D^- D^0 K^+$$

$$(1.07 \pm 0.07 \pm 0.09) \times 10^{-3}$$

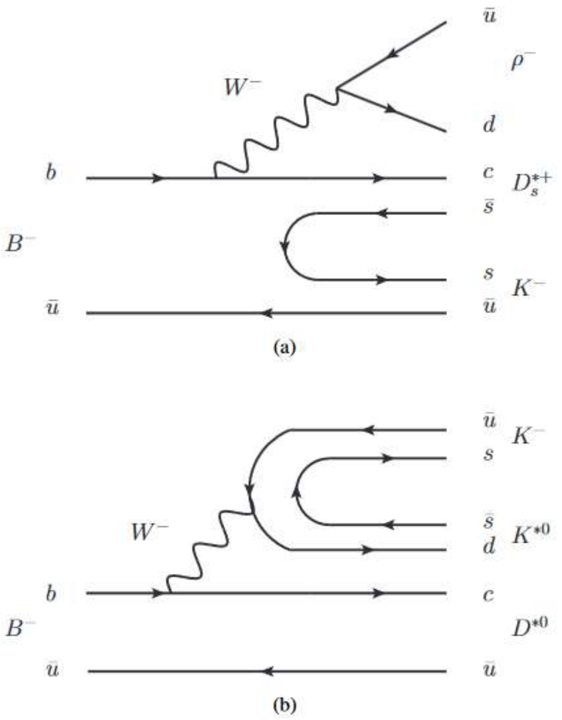
$$B^0 \to D^- D^+ K^0$$

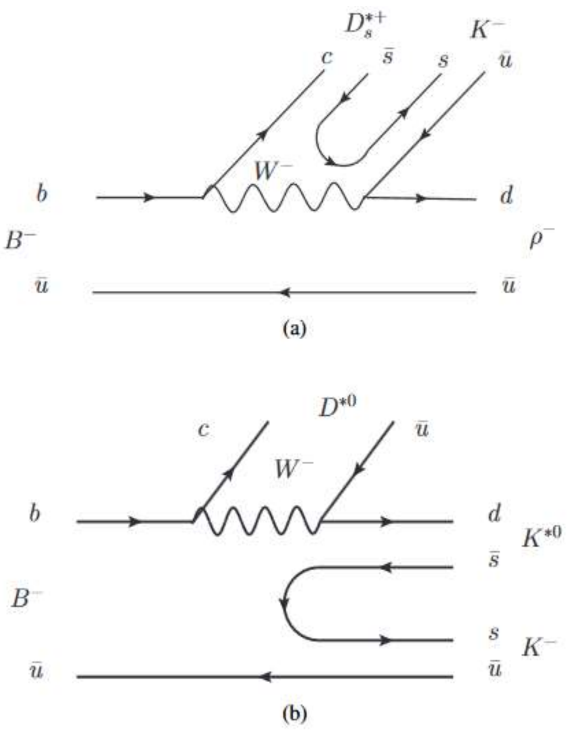
$$(0.75 \pm 0.12 \pm 0.12) \times 10^{-3}$$

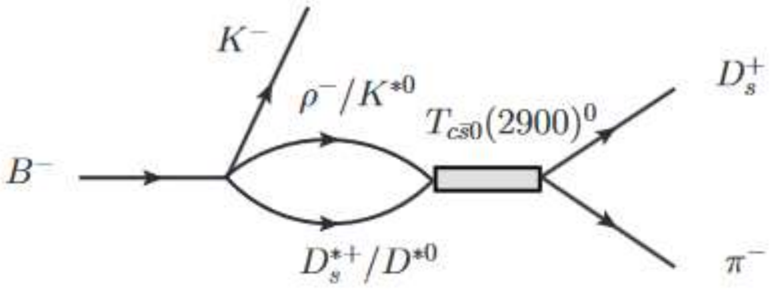
BaBar: PRD 68, 092001(2003)



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







$$\tilde{\mathcal{T}} = Q(C+1)\vec{\epsilon}(V_1)\cdot\vec{\epsilon}(V_2),$$

$$Q^2 \approx \frac{\Gamma_{B^-}\mathcal{B}(B^- \to D^{*0}K^{*0}K^-)}{\int \frac{3}{(2\pi)^3}\frac{(C+1)^2}{4M_{B^-}^2} p_{K^*}\tilde{p}_K dM_{\rm inv}(D^{*0}K^{*0})}.$$

$$\mathcal{B}(B^- \to D^{*0}K^{*0}K^-) = (1.5 \pm 0.4)\times 10^{-3}$$

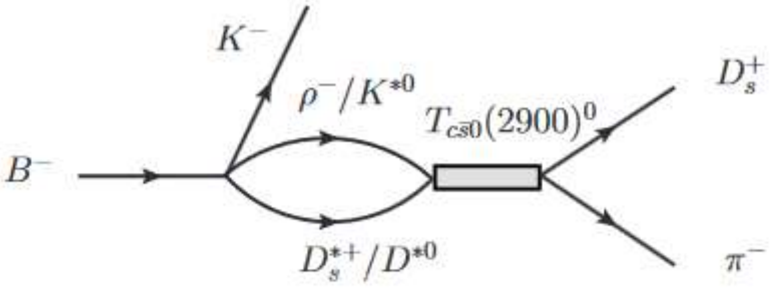
$$\begin{aligned}\mathcal{T}^{T^0_{c\bar{s}0}} = {} & Q\vec{\epsilon}(V_1)\cdot\vec{\epsilon}(V_2) \\ & \times(C+1)\Big[G_{\rho^- D_s^{*+}} t_{\rho^- D_s^{*+}\to D_s^+\pi^-} \\ & + G_{D^{*0}K^{*0}} t_{D^{*0}K^{*0}\to D_s^+\pi^-}\Big],\end{aligned}$$

Couplings

$$t_{\rho^- D_s^{*+}\to D_s^+\pi^-} = \frac{g_{T^0_{c\bar{s}0},\rho^- D_s^{*+}}\, g_{T^0_{c\bar{s}0},D_s^+\pi^-}}{M^2_{D_s^+\pi^-} - m^2_{T^0_{c\bar{s}0}} + i m_{T^0_{c\bar{s}0}}\Gamma_{T^0_{c\bar{s}0}}},$$

$$t_{D^{*0}K^{*0}\to D_s^+\pi^-} = \frac{g_{T^0_{c\bar{s}0},D^{*0}K^{*0}}\, g_{T^0_{c\bar{s}0},D_s^+\pi^-}}{M^2_{D_s^+\pi^-} - m^2_{T^0_{c\bar{s}0}} + i m_{T^0_{c\bar{s}0}}\Gamma_{T^0_{c\bar{s}0}}},$$

$$g^2_{T^0_{c\bar{s}0},D^*K^*} = 16\pi(m_{D^*} + m_{K^*})^2\tilde{\lambda}^2\sqrt{\frac{2\Delta E}{\mu}},$$



$$\Gamma_{T^0_{c\bar{s}0}\to\rho^- D_s^{*+}} = \frac{3}{8\pi}\frac{1}{m^2_{T^0_{c\bar{s}0}}}|g_{T^0_{c\bar{s}0},\rho^- D_s^{*+}}|^2|\vec{q}_\rho|, \qquad \Gamma_{T^0_{c\bar{s}0}\to\rho^- D_s^{*+}} = 4.13$$

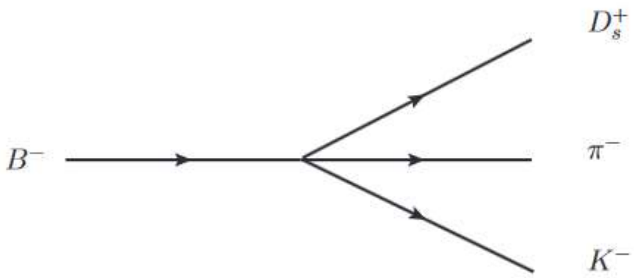
$$\Gamma_{T^0_{c\bar{s}0}\to D_s^+\pi^-} = \frac{1}{8\pi}\frac{1}{m^2_{T^0_{c\bar{s}0}}}|g_{T^0_{c\bar{s}0},D_s^+\pi^-}|^2|\vec{q}_{\pi^-}|, \qquad \Gamma_{T^0_{c\bar{s}0}\to D_s^+\pi^-} = 4.45\ \text{MeV}$$

$\lambda = 1$ gives the probability to find the molecular component in the physical states

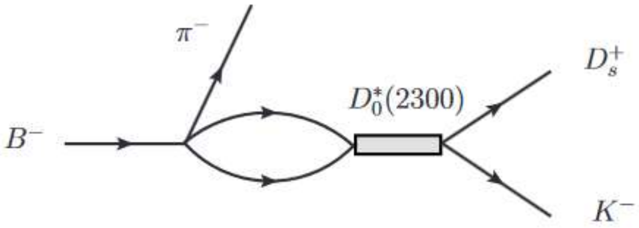
S. Weinberg, PR137, B672 (1965)
Baru, PLB 586, 53-61 (2004)

DYChen: PRD107, 034018 (2023)

D(2300)



(a)



(b)

$$T = [1 - VG]^{-1} V.$$

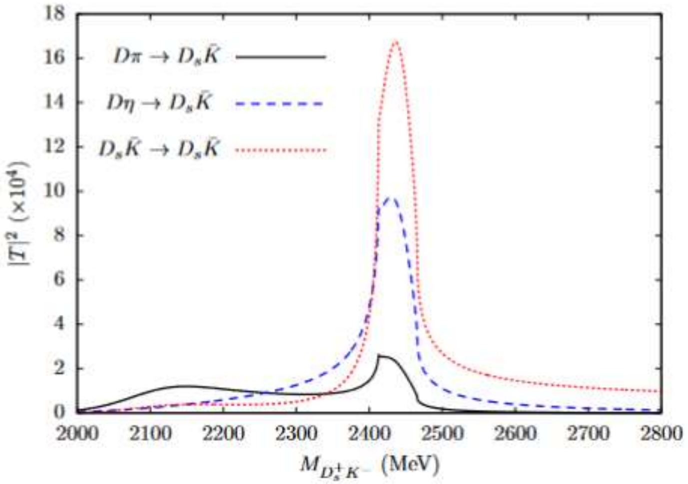
$$\mathcal{T}^{D_0^*(2300)} = Q'(C+1)(h_{D_s\bar{K}} + \sum_i h_i G_i t_{i\to D_s\bar{K}}) = \mathcal{T}^{\text{tree}} + \mathcal{T}^{S},$$

$$\mathcal{B}(B^- \to D_s^+ K^- \pi^-) = (1.80 \pm 0.22) \times 10^{-4}$$

$$\Gamma_{B^-}\mathcal{B}(B^- \to D_s^+ K^- \pi^-) = Q'^2 \int \frac{1}{(2\pi)^3} \frac{(C+1)^2}{4M_{B^-}^2} p_\pi \tilde{p}_K \times |h_{D_s\bar{K}} + \sum_i h_i G_i t_{i\to D_s\bar{K}}|^2 dM_{\text{inv}}(D_s^+ K^-).$$

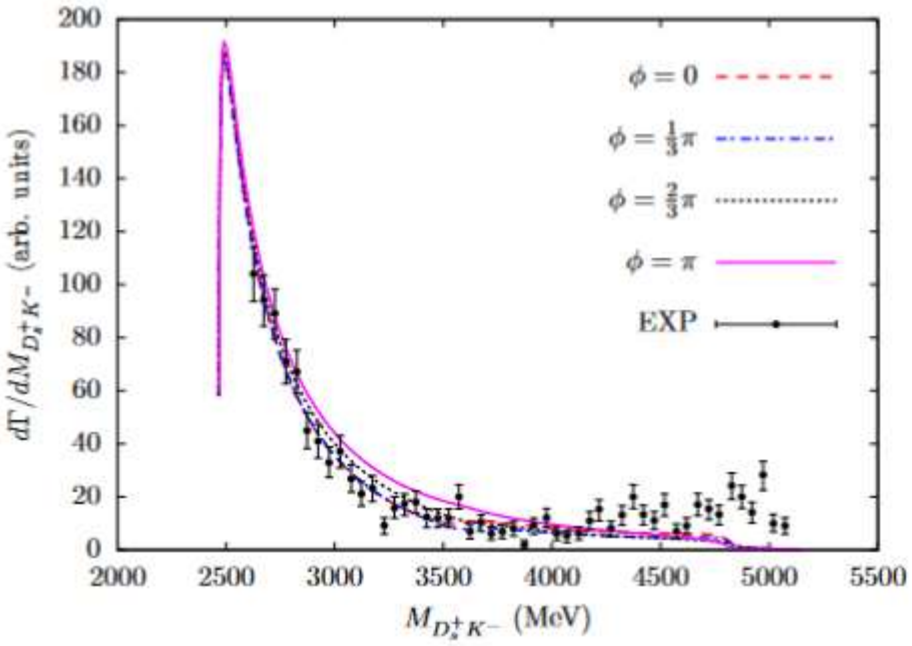
$$\left|\mathcal{T}^{\text{total}}\right|^2 = \left|\mathcal{T}^{T^0_{c\bar{s}0}} e^{i\phi} + \mathcal{T}^{D_0^*(2300)}\right|^2,$$

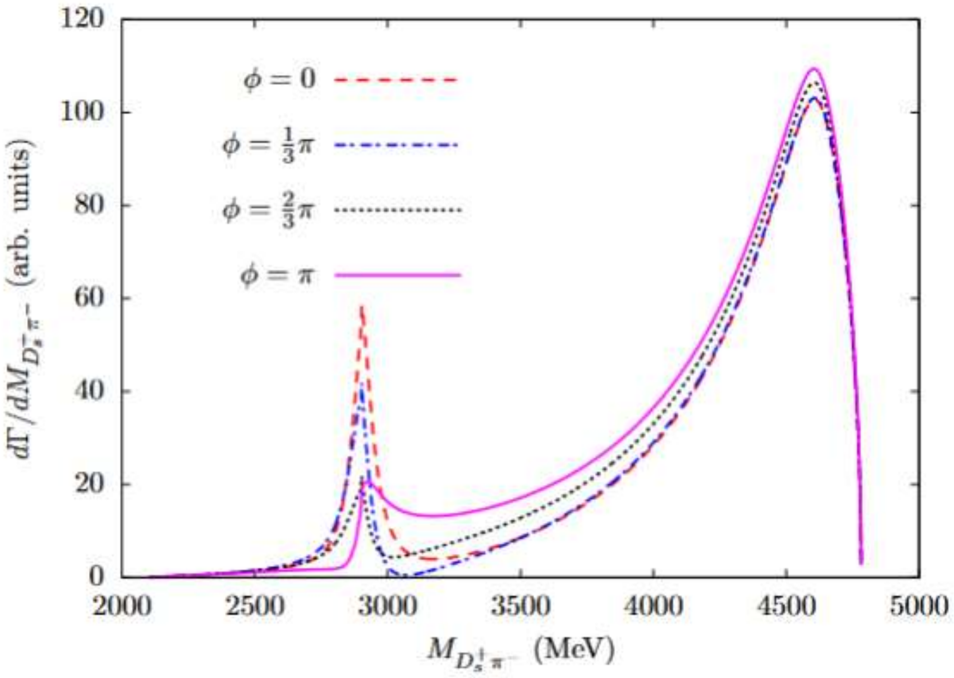
$$\frac{d^2\Gamma}{dM_{D_s^+K^-}\,dM_{D_s^+\pi^-}} = \frac{1}{(2\pi)^3}\frac{2M_{D_s^+K^-}\,2M_{D_s^+\pi^-}}{32M_{B^-}^3}|\mathcal{T}^{\text{total}}$$



Phys. Rev. D 102, 096020 (2020)
Phys. Rev. D 87014508 (2013)

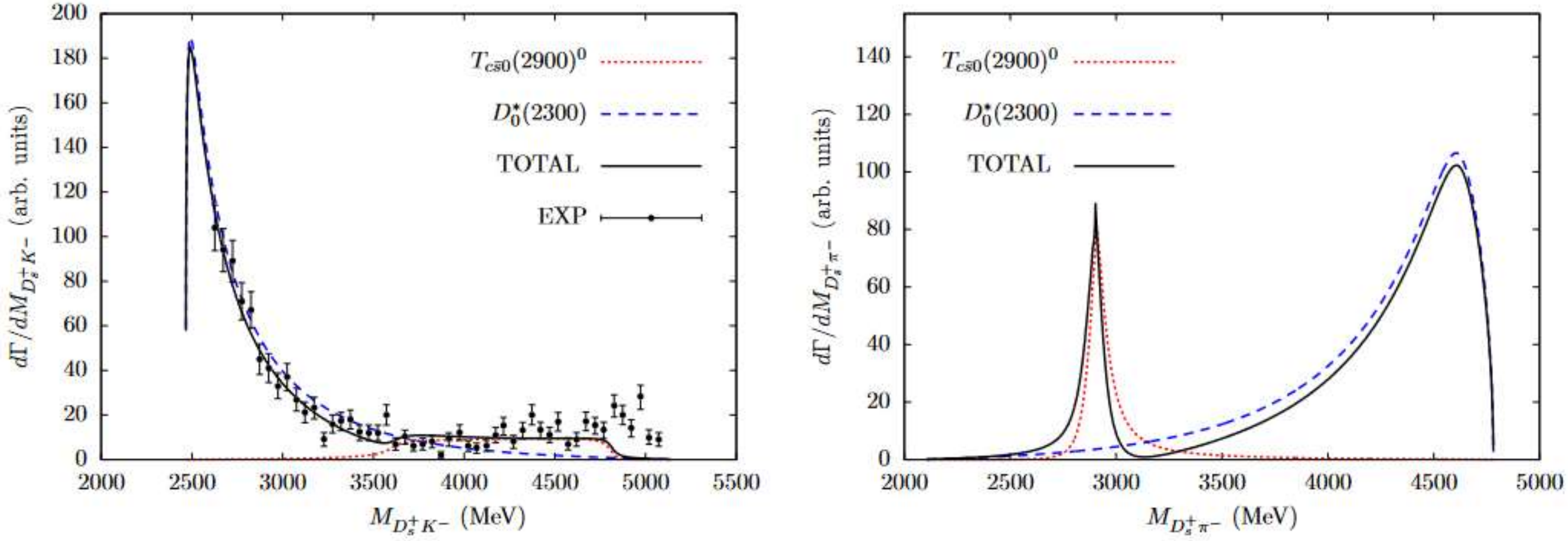
Results





Belle: PRD80 (2009)052005

Results

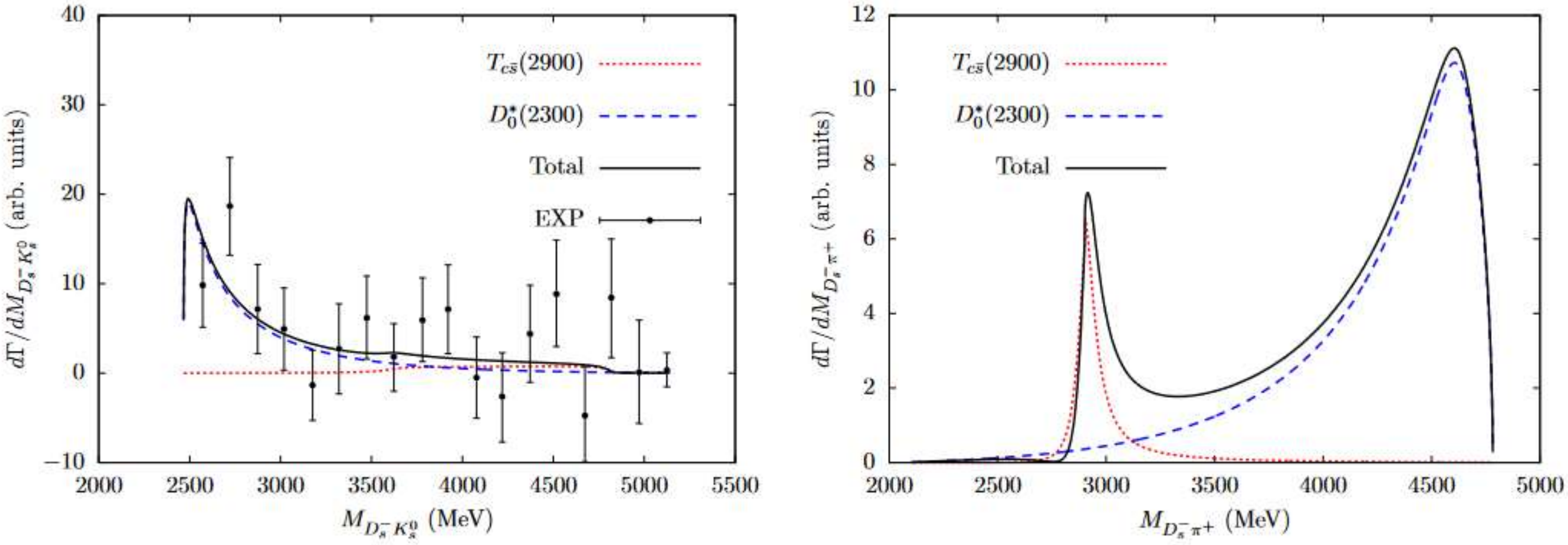


(a) (b)

$$\Gamma_{T^0_{c\bar{s}0}\to D_s^+\pi^-} = 10.45\ \text{MeV and}\ \phi = 0.35\pi,$$

Results

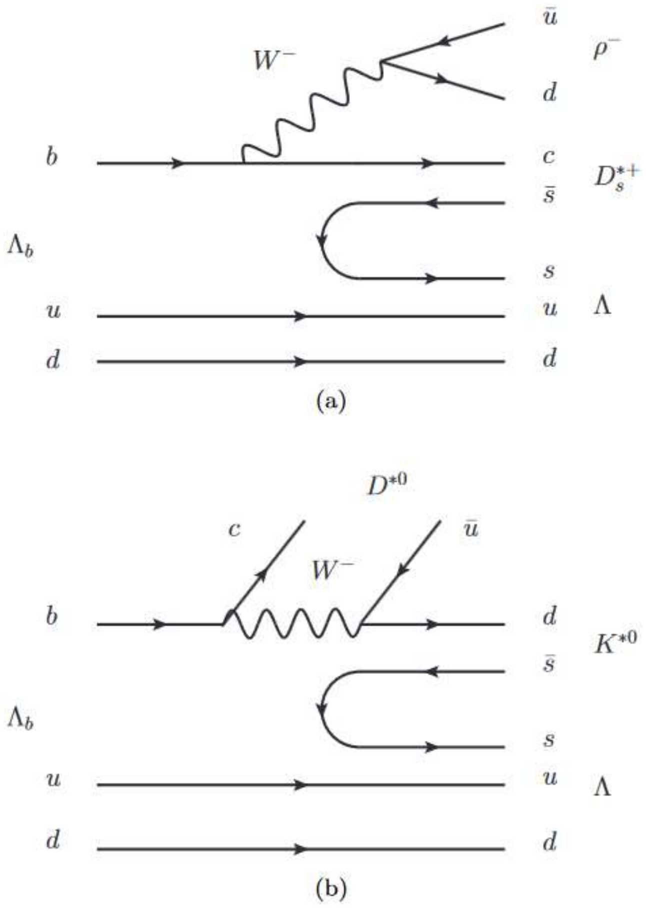
- **Belle:** $B^0 \to D_s^- K_s^0 \pi^+$, PRD91, 032008(2015)



(a)

$$\mathcal{B}(B^0 \to D_s^- K_S^0 \pi^+)$$
$$= [0.47 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})] \times 10^{-4}$$

$\Lambda_b \to K^0 D^0 \Lambda$



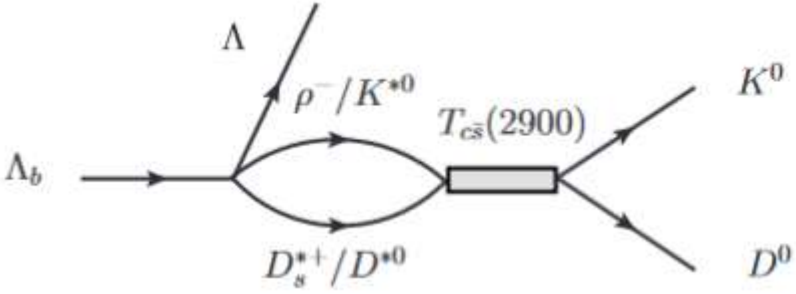
$$
\begin{aligned}
|\Lambda_b\rangle &= \frac{1}{\sqrt{2}} b\,(ud - du) \\
&\Rightarrow W^- c \frac{1}{\sqrt{2}}\,(ud - du) \\
&\Rightarrow \bar{u}dc\,(\bar{s}s)\,\frac{1}{\sqrt{2}}\,(ud - du) \\
&\Rightarrow \rho^- c\,(\bar{s}s)\,\frac{1}{\sqrt{2}}\,(ud - du) \\
&\Rightarrow \rho^- D_s^{*+} \frac{1}{\sqrt{2}} s\,(ud - du) \\
&\Rightarrow -\sqrt{\frac{2}{3}}\rho^- D_s^{*+}\Lambda,
\end{aligned}
$$

$$
\begin{aligned}
|\Lambda_b\rangle &= \frac{1}{\sqrt{2}} b\,(ud - du) \\
&\Rightarrow cW^- \frac{1}{\sqrt{2}}\,(ud - du) \\
&\Rightarrow c\bar{u}d\,(\bar{s}s)\,\frac{1}{\sqrt{2}}\,(ud - du) \\
&\Rightarrow -\sqrt{\frac{2}{3}} D^{*0} K^{*0} \Lambda.
\end{aligned}
$$

$$
\Lambda_b = \frac{1}{\sqrt{2}}\,|b(ud - du)\rangle\,,
$$

$$
\Lambda = \frac{1}{\sqrt{12}}\,|u(ds - sd) + d(su - us) - 2s(ud - du)\rangle
$$

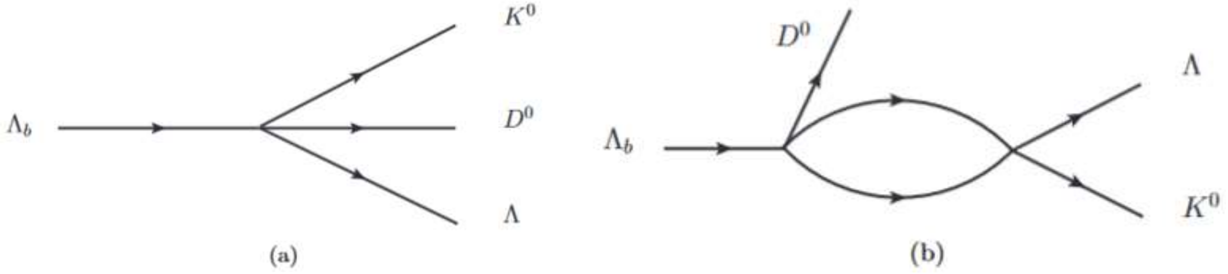
Formalism



$$\mathcal{T}^{T_{c\bar{s}}} = -\sqrt{\frac{2}{3}} V_p \Big[C \times G_{D_s^{*+}\rho^-} t_{D_s^{*+}\rho^- \to D^0K^0} + G_{D^{*0}K^{*0}} t_{D^{*0}K^{*0} \to D^0K^0} \Big],$$

$$t_{D_s^{*+}\rho^- \to D^0K^0} = \frac{g_{T_{c\bar{s}},D_s^{*+}\rho^-}\, g_{T_{c\bar{s}},D^0K^0}}{M^2_{D^0K^0} - m^2_{T_{c\bar{s}}} + i m_{T_{c\bar{s}}} \Gamma_{T_{c\bar{s}}}},$$

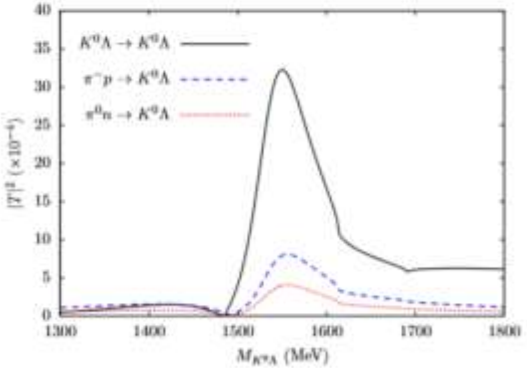
$$t_{D^{*0}K^{*0} \to D^0K^0} = \frac{g_{T_{c\bar{s}},D^{*0}K^{*0}}\, g_{T_{c\bar{s}},D^0K^0}}{M^2_{D^0K^0} - m^2_{T_{c\bar{s}}} + i m_{T_{c\bar{s}}} \Gamma_{T_{c\bar{s}}}},$$



$$|H\rangle = \pi^- p - \frac{1}{\sqrt{2}}\pi^0 n + \frac{1}{\sqrt{3}}\eta n - \sqrt{\frac{2}{3}} K^0\Lambda,$$

$$\mathcal{T}^{S-wave} = V_{p'}\Big(h_{K^0\Lambda} + \sum_i h_i \tilde{G}_i t_{i\to K^0\Lambda}\Big),$$

$$T = [1 - VG]^{-1} V.$$

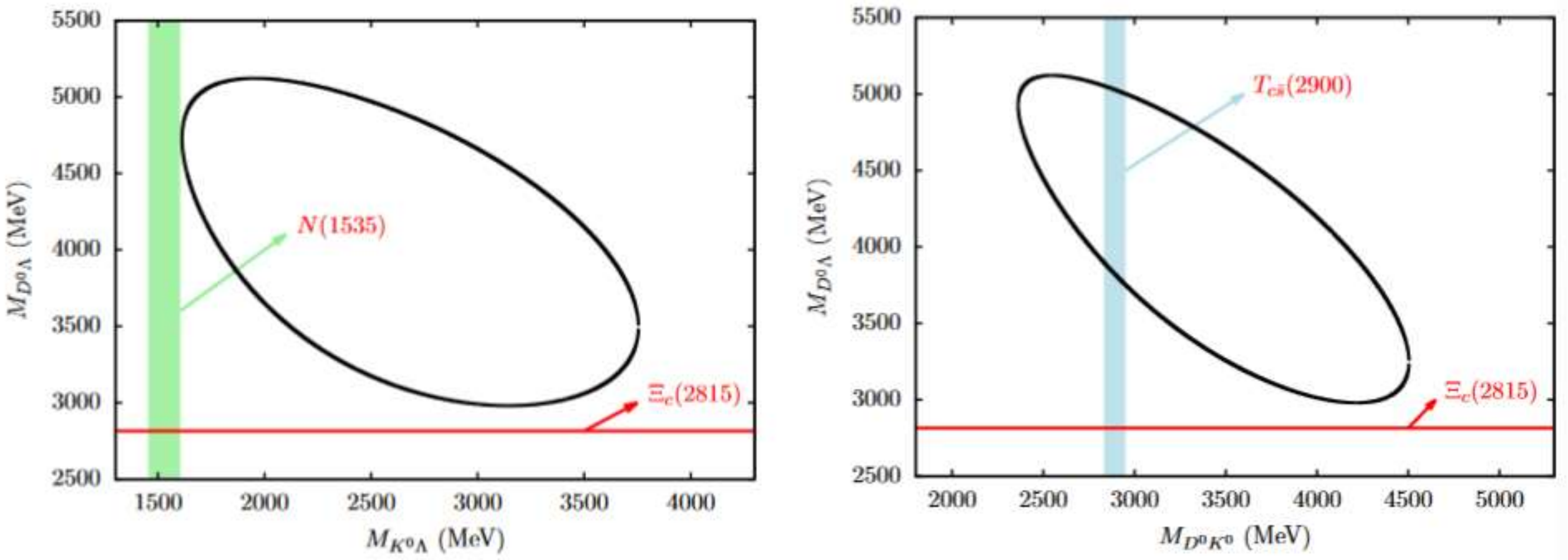


Inone Oset, PRC65, 035204 (2002)

$$\frac{d^2\Gamma}{dM_{K^0\Lambda} dM_{D^0K^0}} = \frac{1}{(2\pi)^3} \frac{2M_{K^0\Lambda} 2M_{D^0K^0}}{32 M^3_{\Lambda_b}} |\mathcal{T}^{\text{Total}}|^2,$$

$$\mathcal{T}^{\text{Total}} = \mathcal{T}^{S-wave} + \mathcal{T}^{T_{c\bar{s}}}.$$

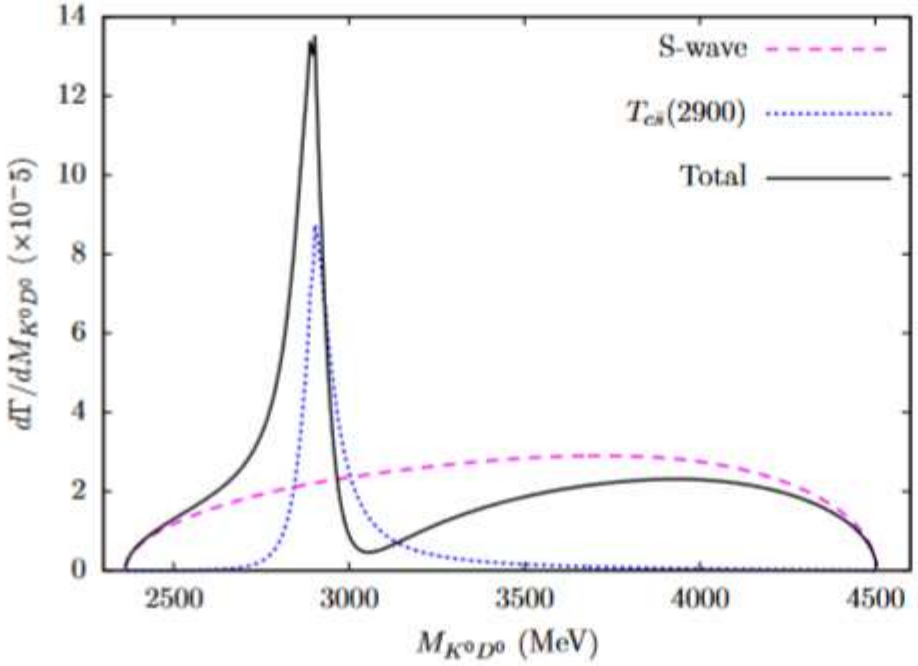
$K\Lambda$ interaction

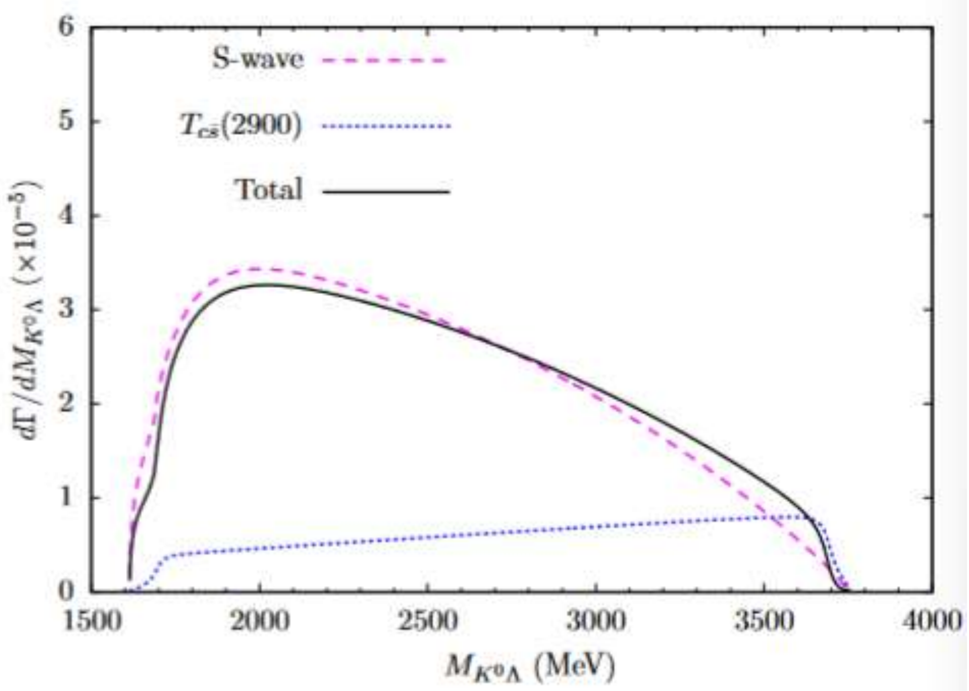


Contribution from $K\Lambda$ interaction is neglected!

PRD 85 (2012), 114032

Results



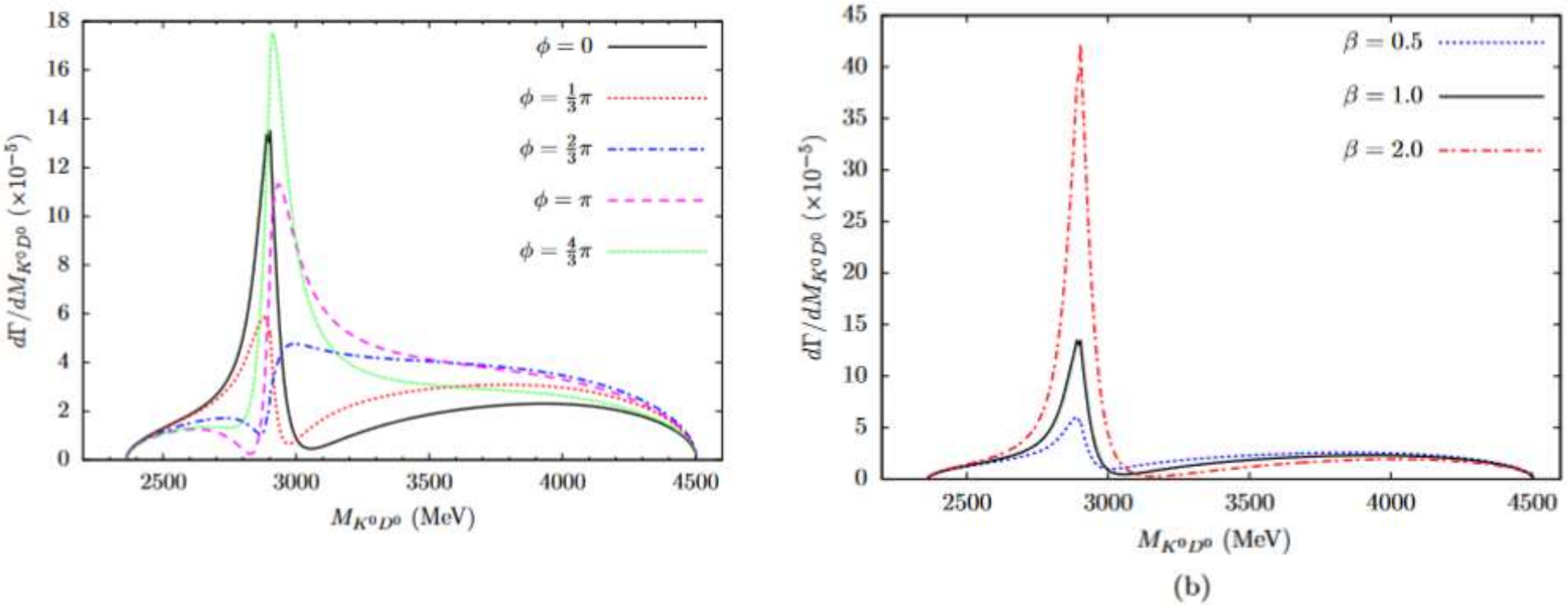


$$\mathcal{T}^{T_{c\bar{s}}} = -\sqrt{\frac{2}{3}} V_p \left[C \times G_{D_s^{*+}\rho^-} t_{D_s^{*+}\rho^- \to D^0 K^0} + G_{D^{*0}K^{*0}} t_{D^{*0}K^{*0} \to D^0 K^0} \right],$$

$$\mathcal{T}^{S-wave} = V_{p'}(h_{K^0\Lambda} + \sum h_i \tilde{G}_i t_{i \to K^0\Lambda}),$$

$$V_p = V_{p'},$$

Results



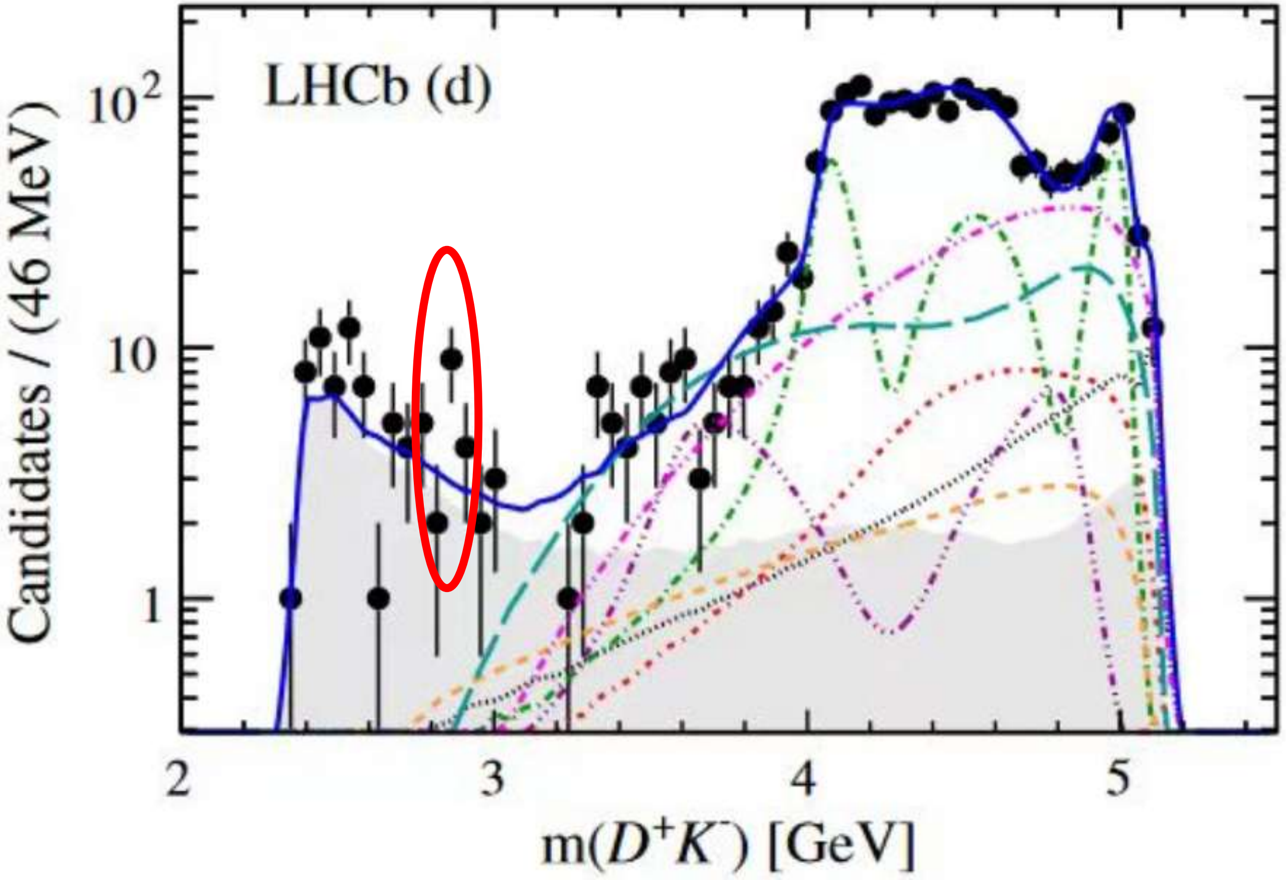
$$\mathcal{T}^{T_{c\bar{s}}} = -\sqrt{\frac{2}{3}} V_p \left[C \times G_{D_s^{*+}\rho^-} t_{D_s^{*+}\rho^- \to D^0 K^0} + G_{D^{*0}K^{*0}} t_{D^{*0}K^{*0} \to D^0 K^0} \right],$$

$$\mathcal{T}^{S-wave} = V_{p'}(h_{K^0\Lambda} + \sum h_i \tilde{G}_i t_{i \to K^0\Lambda}),$$

other evidence

- **LHCb**，PRD91,092002 (2015)

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



Summary

- $T_{c\bar{s}}(2900)$ could be the $D_s^*\rho - D^*K^*$ bound/virtual state.
- The data of $B^+ \to D^+D^-K^+$ shows some hints of the existence $T_{c\bar{s}}(2900)$.
- Evidence is also found in
- We propose to search for $T_{c\bar{s}}(2900)$ in $B^- \to D_sK\pi$ and $\Lambda_b \to KD\Lambda$.

Thank you very much!

致谢：
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