在底强子衰变过程中研究四夸克态$T_{c\bar{s}}(2900)$

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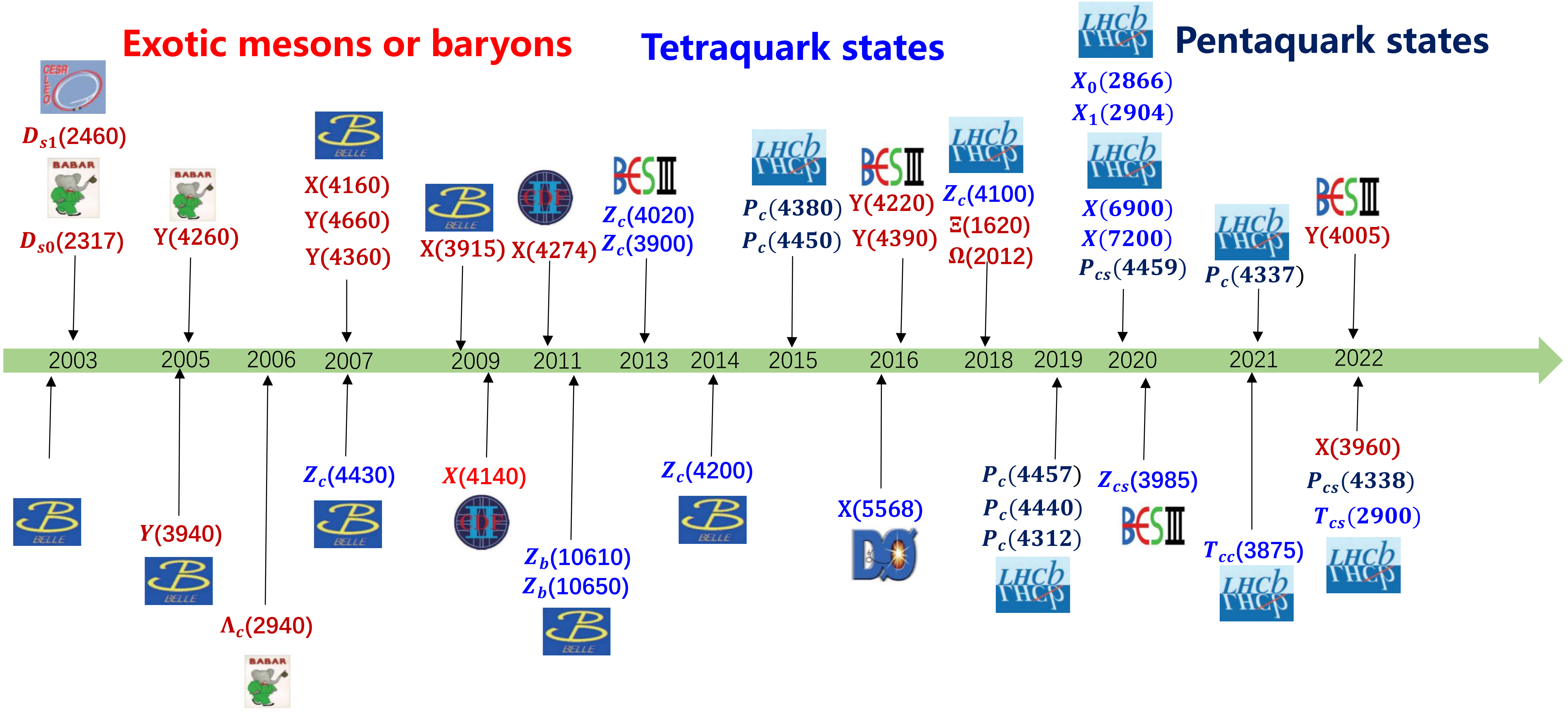
2023年12月18日 @HFCPV-2023

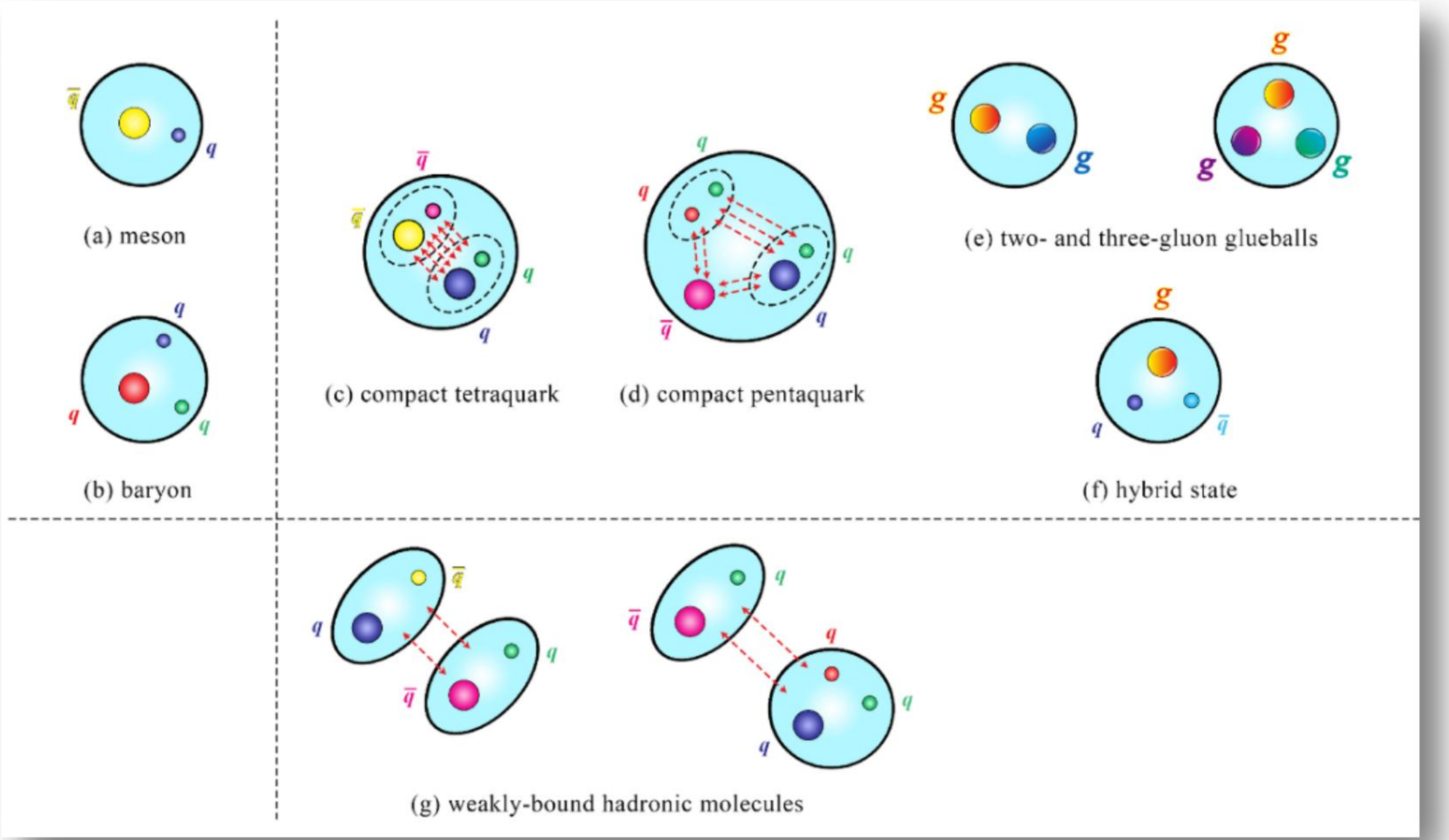
PRD08 (2023) 074006
2305.09436
2306.16101
2310.11139

Exotic states

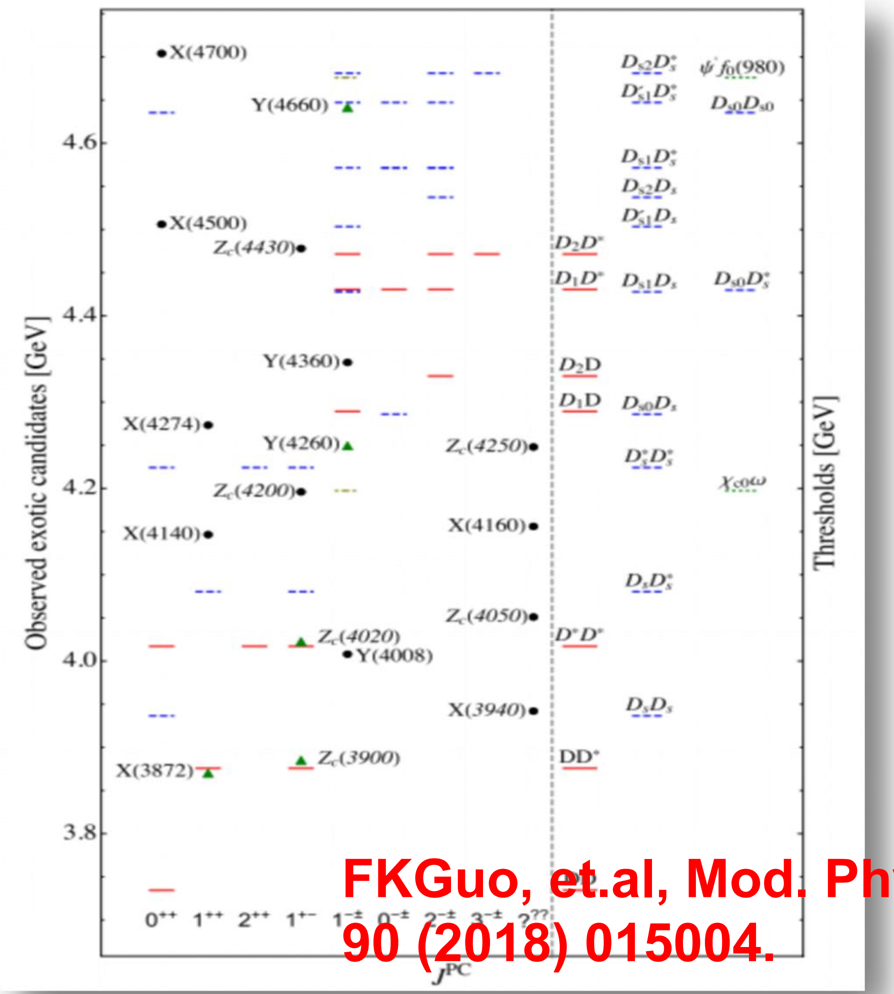
From Li-Sheng Geng



Exotic states

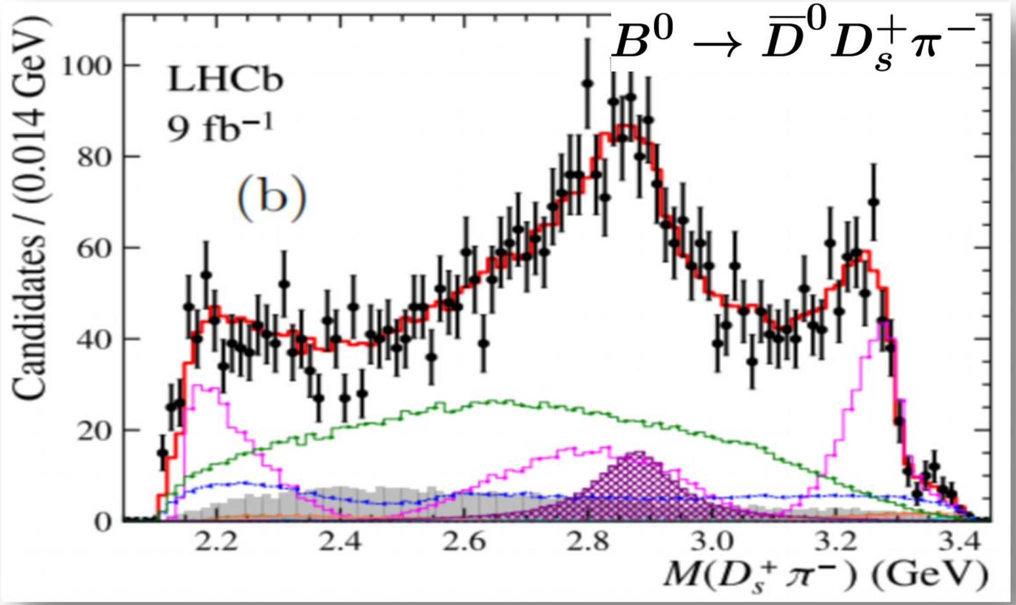


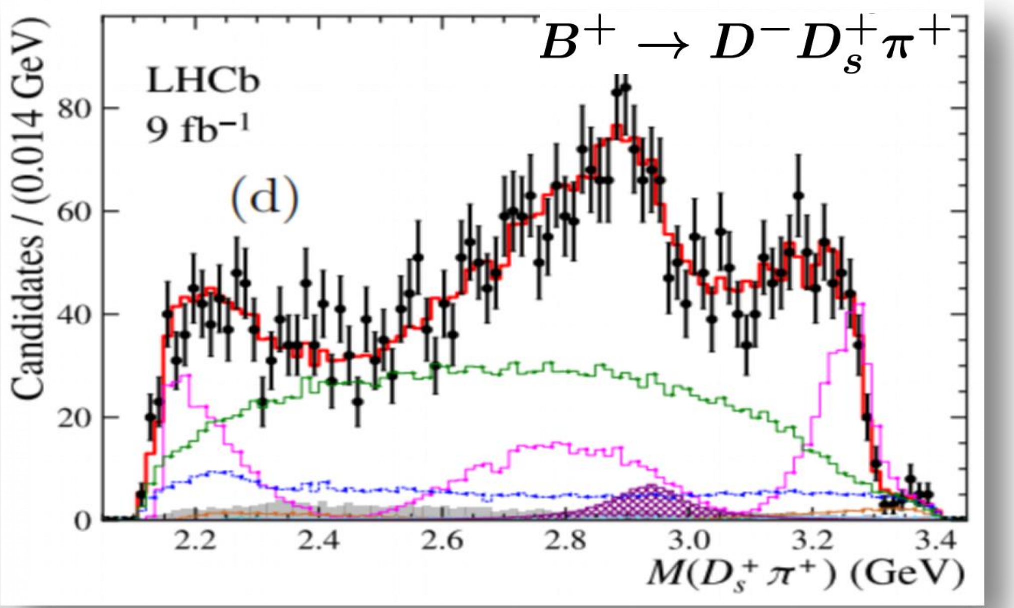
HXChen, YRLiu, et. al, Rep. Prog. Phys. 86 (2023) 026201



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

LHCb measurements





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

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

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

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

Theoretical explanations

◻Molecular state

PRD108 (2023) 094008, 2309.02191, EPJC83 (2023)769,
PRD108 (2023) 074006, 2305.14430, PRD107 (2023) 094019,
PRD106 (2022) 114032

◻Compact tetraqurk

IJMPA38 (2023) 2350056 2310.13354, 2302.01167

Symmetry 2023, 15, 695

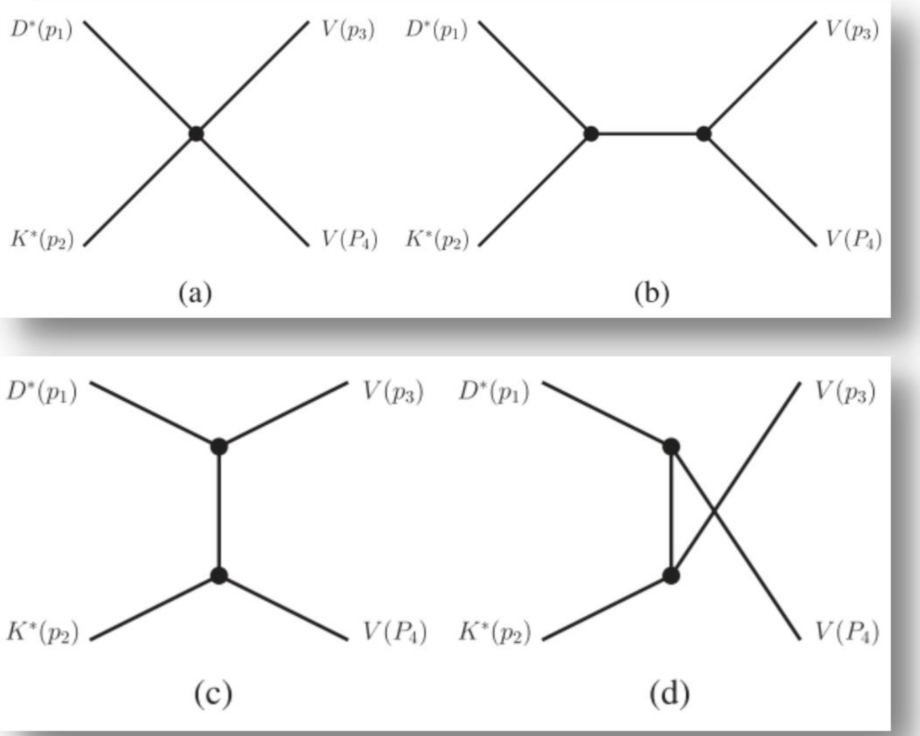
◻Threshold effects

PRD107 (2023) 056015

Local Hidden symmetry formalism

□The interaction between vectors PRD108, 074006 (2023)

M. Bando, PRL54, 1215 (1985), Phys. Rep. 164, 217 (1988).



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

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

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

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

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

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 positions

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.

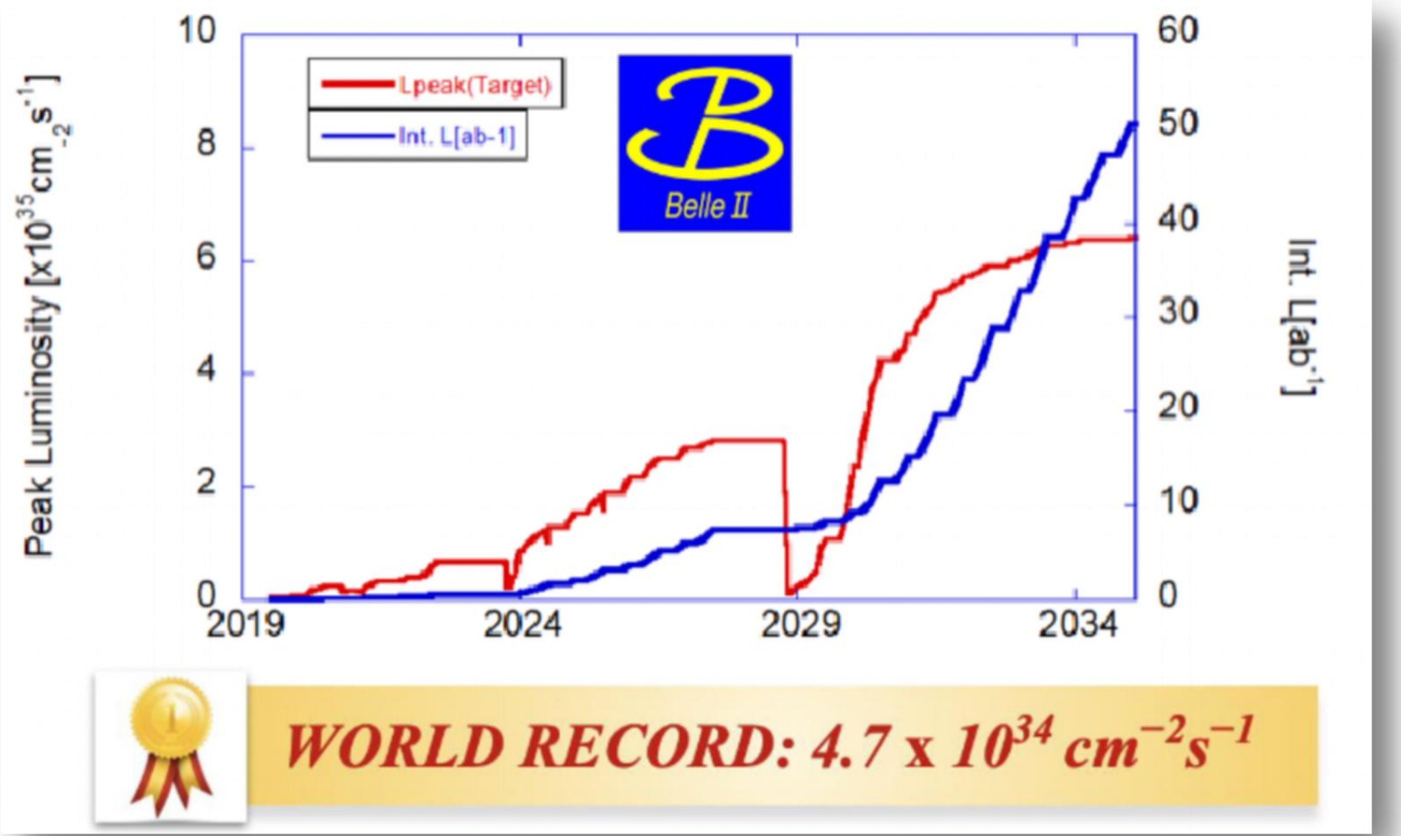
RS	α	$\sqrt{s}_{\text{pole}}$ [MeV]	$\lvert g_{D^*K^*}\rvert$ [MeV]	$\lvert g_{D_s^*\rho}\rvert$ [MeV]
$\{1,1\}$	$-1.65 \sim -1.60$	$2885 \sim 2887$	$5531 \sim 2198$	$5379 \sim 2082$
$\{2,1\}$	$-1.60 \sim -1.55$	$2887 \sim 2885$	$1755 \sim 8202$	$1650 \sim 7348$
$\{1,2\}$	$-1.39 \sim -1.35$	$2885 \sim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

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	$\sqrt{s}_{\text{pole}}$ [MeV]	α	$\sqrt{s}_{\text{pole}}$ [MeV]
$\{1,1\}$	$-1.65 \sim -1.61$	$2886 \sim 2887$	$-1.31 \sim -1.28$	$2780 \sim 2806$
$\{2,1\}$	$-1.61 \sim -1.55$	$2887 \sim 2883$	$\cdots$	$\cdots$
$\{1,2\}$	$-1.39 \sim -1.36$	$2886 \sim 2887$	$\cdots$	$\cdots$
$\{2,2\}$	$-1.36 \sim -1.28$	$2887 \sim 2885$	$\cdots$	$\cdots$

b-hadrons

□Belle/Belle II &LHCb

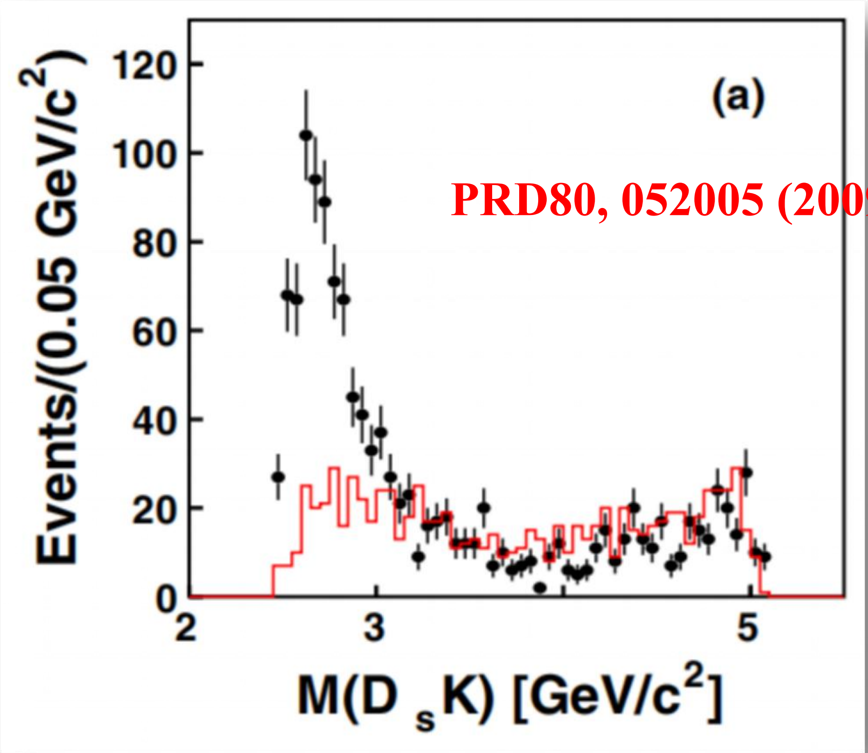


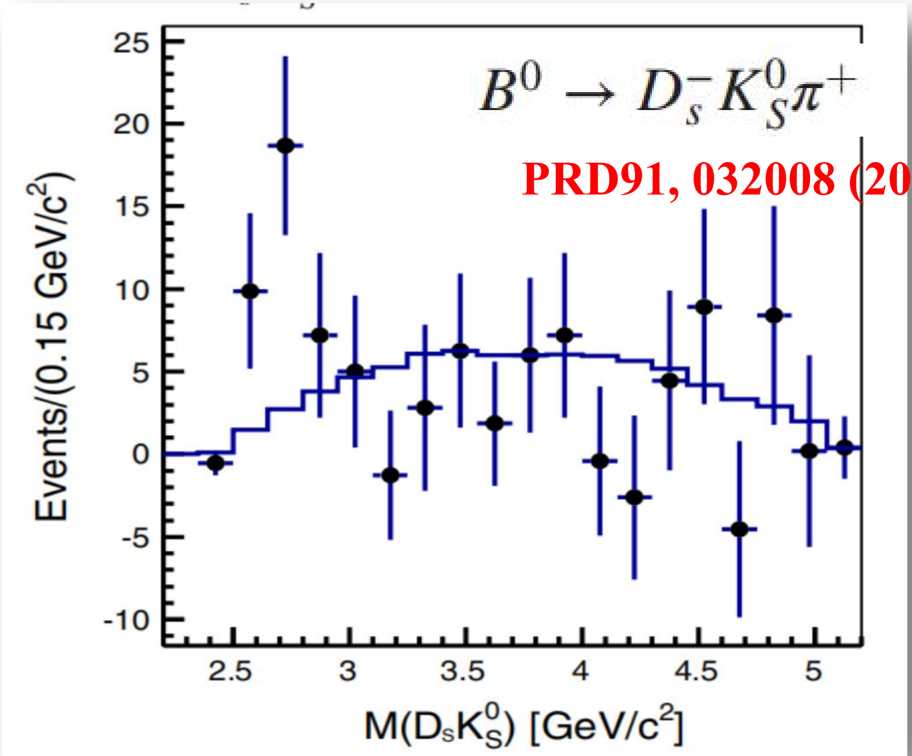
- ✓ Collected ~424 fb-1 around Y(4S) until now
- ✓ LS1 starts in summer 2022 to fully install the pixel detector and accelerator machine study
- ✓ Operation will be resumed around the end of 2023

from the slide of CPShen

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

- **Belle:**



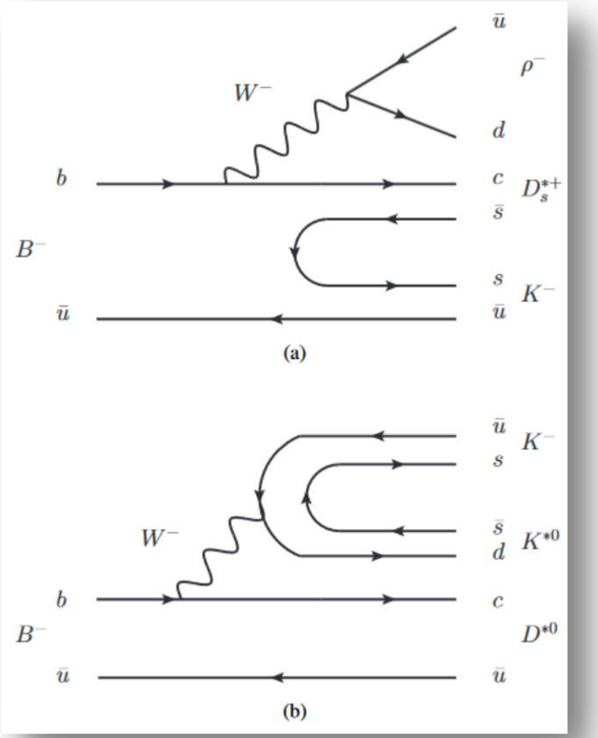


$$\mathcal{B}(B^+ \to D_s^- K^+ \pi^+) = (1.71^{+0.08}_{-0.07}(\text{stat})^{+0.20}_{-0.20}(\text{syst}) \pm 0.15(\mathcal{B}_{\text{int}})) \times 10^{-4},$$

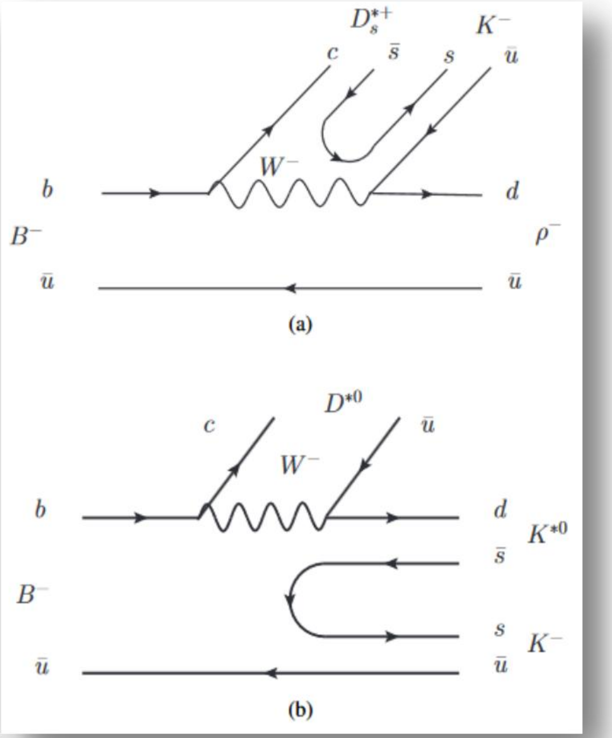
$$\mathcal{B}(B^0 \to D_s^- K_S^0 \pi^+) = [0.47 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})] \times 10^{-4}$$

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

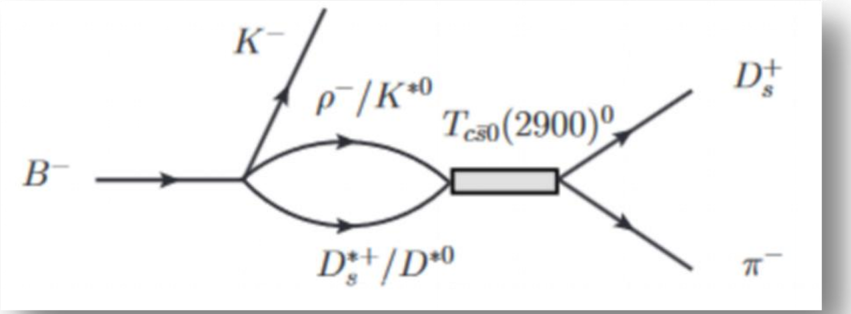
□Mechanisms



(a)
(b)



(a)
(b)



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

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

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

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

Coupling constants

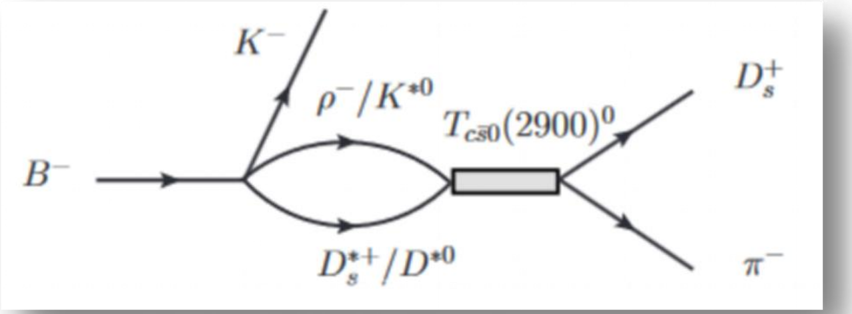
☐Transition amplitudes

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

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

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

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



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

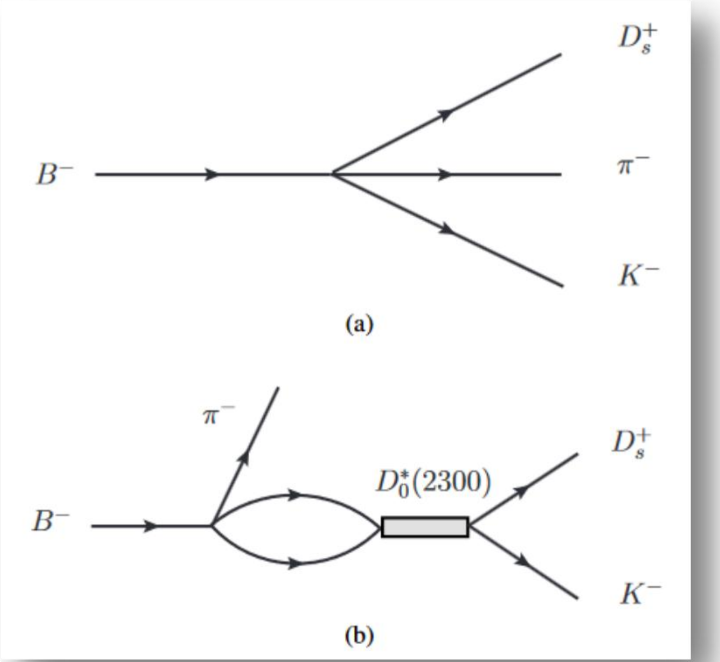
$$\Gamma_{T^0_{c\bar{s}0}\to D_s^+\pi^-} = \frac{1}{8\pi}\frac{1}{m^2_{T^0_{c\bar{s}0}}}|g_{T^0_{c\bar{s}0},D_s^+\pi^-}|^2|\vec{q}_{\pi^-}|, \qquad \Gamma_{T^0_{c\bar{s}0}\to D_s^+\pi^-} = 4.45\ \text{MeV}$$

DYChen: PRD107, 034018 (2023)

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

D(2300)-D_sK interaction

- **Mechanisms**



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

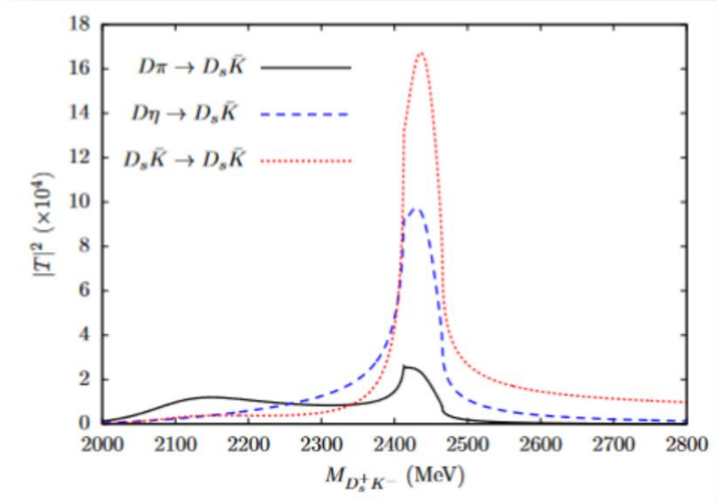
Phys. Rev. D 102, 096020 (2020)
Phys. Rev. D 87014508 (2013)

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

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

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

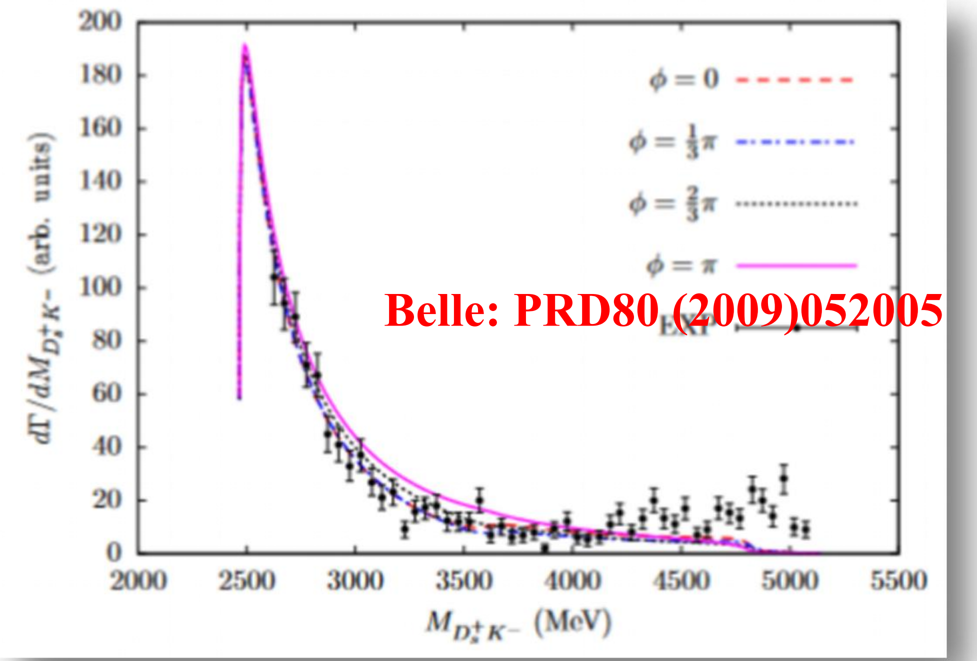
$$|\mathcal{T}^{\rm total}|^2 = |\mathcal{T}^{T^0_{c\bar{s}0}}e^{i\phi} + \mathcal{T}^{D_0^*(2300)}|^2,$$

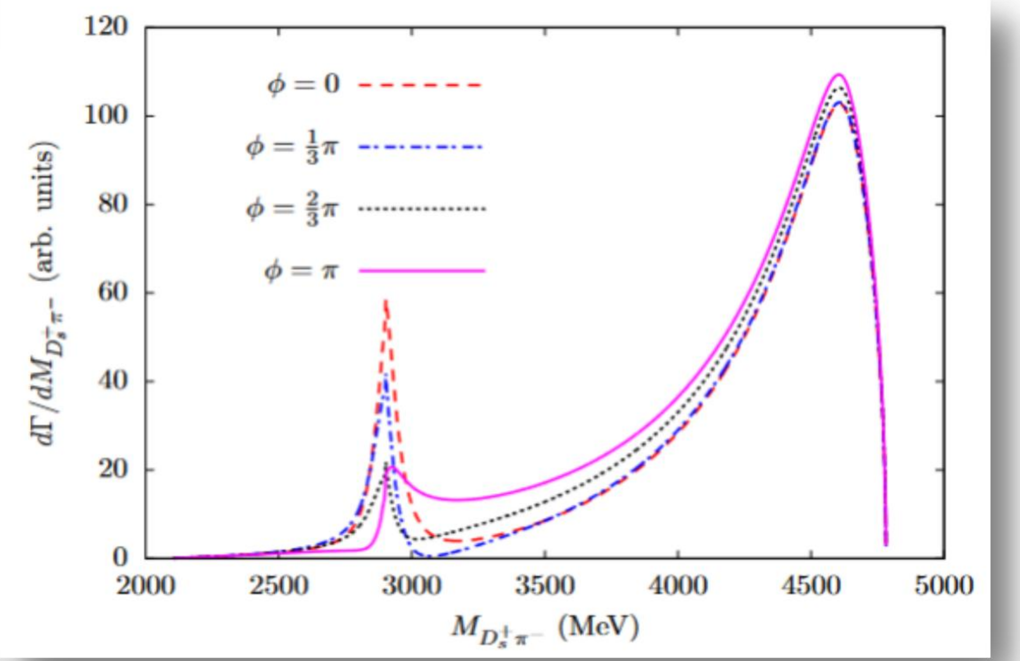


$$\frac{d^2\Gamma}{dM_{D_s^+K^-}dM_{D_s^+\pi^-}} = \frac{1}{(2\pi)^3}\frac{2M_{D_s^+K^-}2M_{D_s^+\pi^-}}{32M_{B^-}^3}|\mathcal{T}^{\rm total}|^2,$$

Results

□Mass distributions

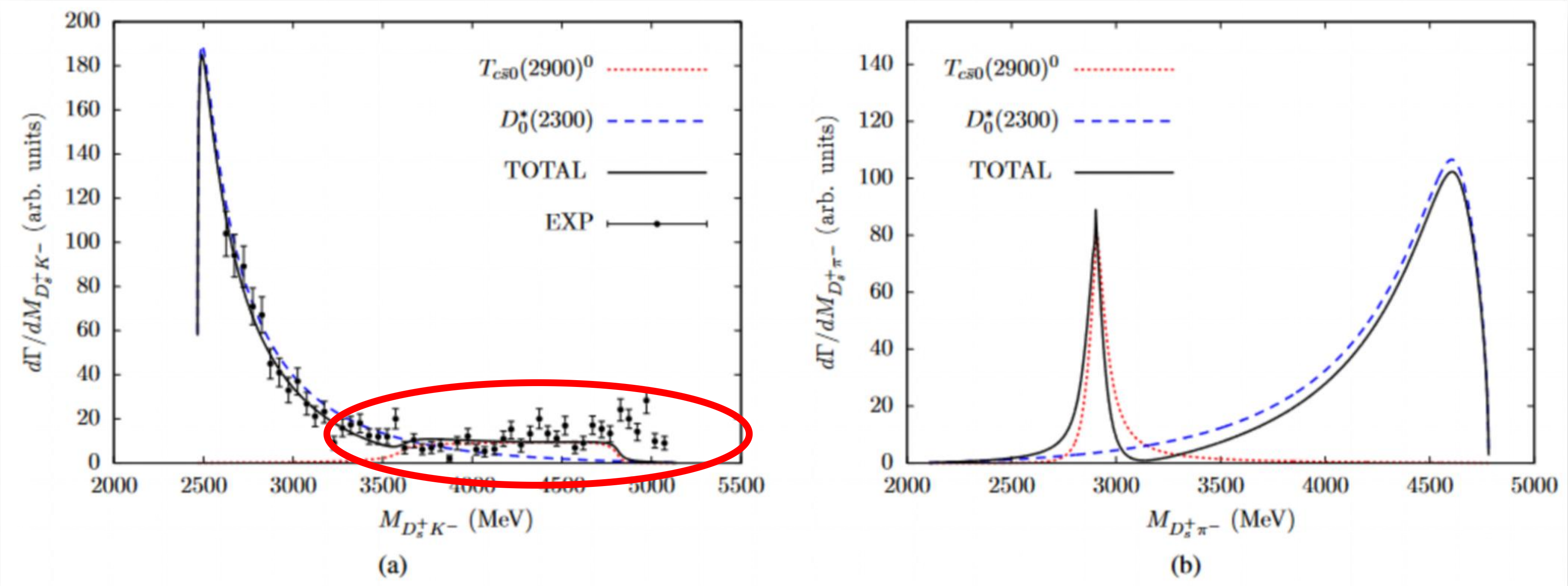




$$\left|\mathcal{T}^{\rm total}\right|^2 = \left|\mathcal{T}^{T^0_{c\bar{s}0}} e^{i\phi} + \mathcal{T}^{D_0^*(2300)}\right|^2,$$

Results with fitted parameters

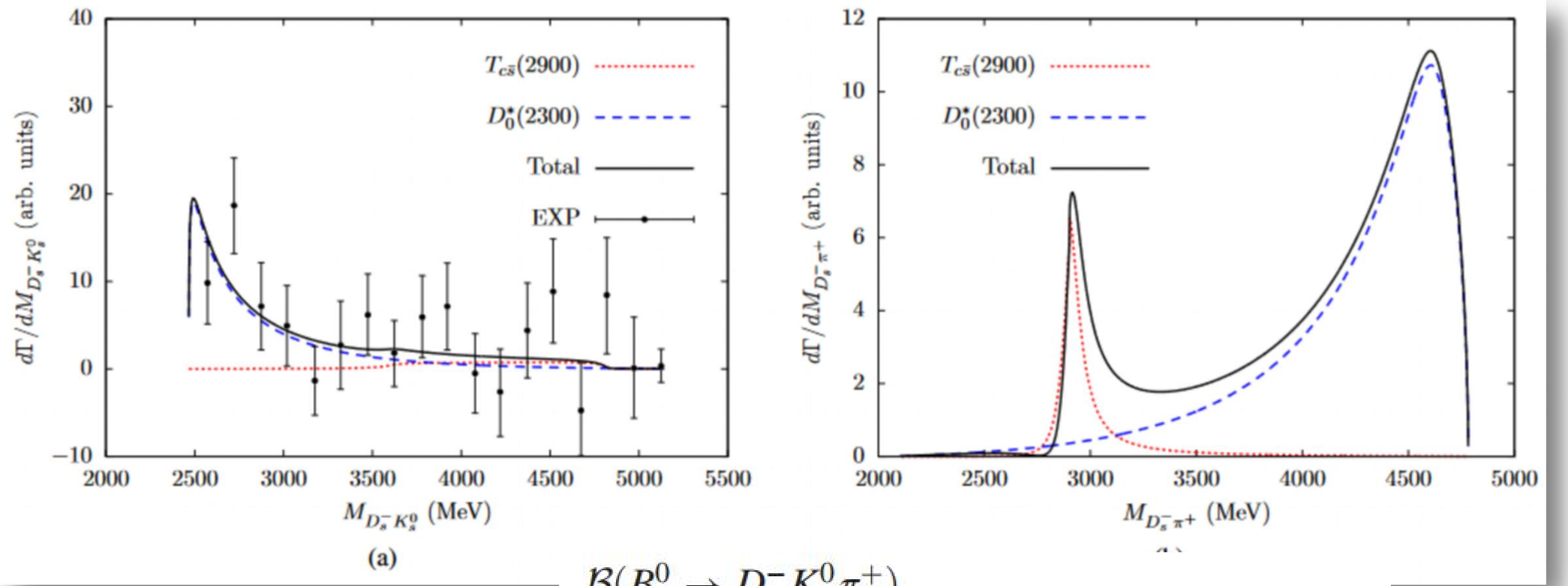
□Fitted results



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

Results-Fitted parameters

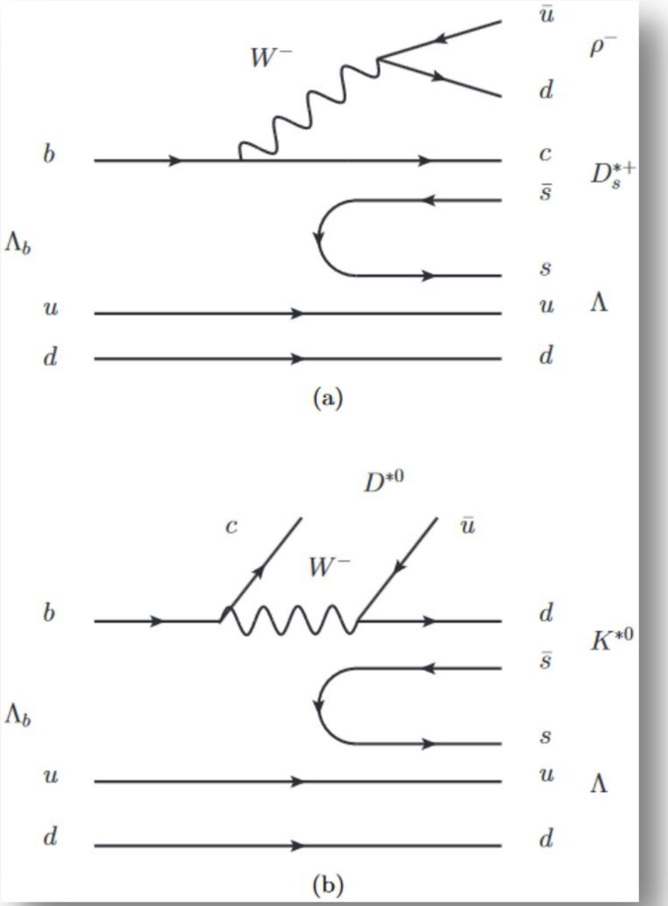
□Belle: $B^0 \to D_s^- K_S^0 \pi^+$, PRD91, 032008(2015)



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

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

□Mechanisms



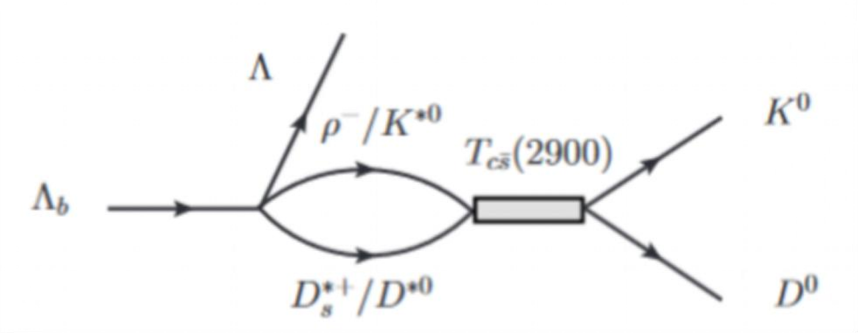
$$|\Lambda_b\rangle = \frac{1}{\sqrt{2}} b\,(ud - du)$$
$$\Rightarrow W^- c \frac{1}{\sqrt{2}} (ud - du)$$
$$\Rightarrow \bar{u}dc\,(\bar{s}s) \frac{1}{\sqrt{2}} (ud - du)$$
$$\Rightarrow \rho^- c\,(\bar{s}s) \frac{1}{\sqrt{2}} (ud - du)$$
$$\Rightarrow \rho^- D_s^{*+} \frac{1}{\sqrt{2}} s\,(ud - du)$$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

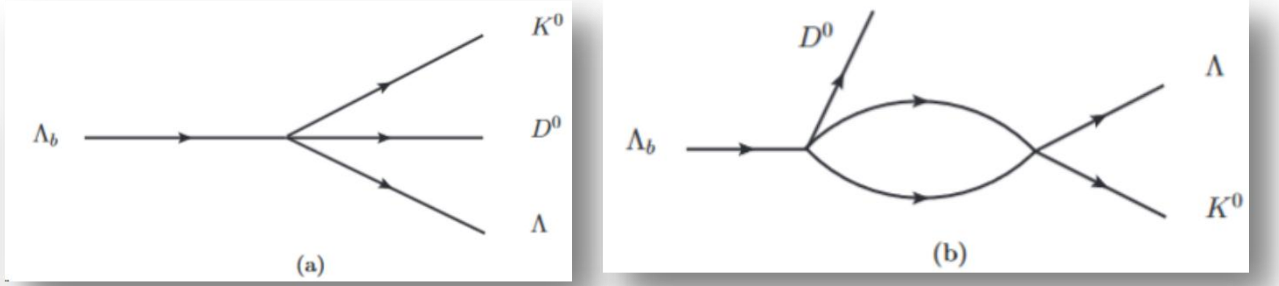
$$|\Lambda_b\rangle = \frac{1}{\sqrt{2}} b\,(ud - du)$$
$$\Rightarrow cW^- \frac{1}{\sqrt{2}} (ud - du)$$
$$\Rightarrow c\bar{u}d\,(\bar{s}s) \frac{1}{\sqrt{2}} (ud - du)$$
$$\Rightarrow -\sqrt{\frac{2}{3}} D^{*0} K^{*0} \Lambda.$$

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

Formalism

- **Final state interaction**





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

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

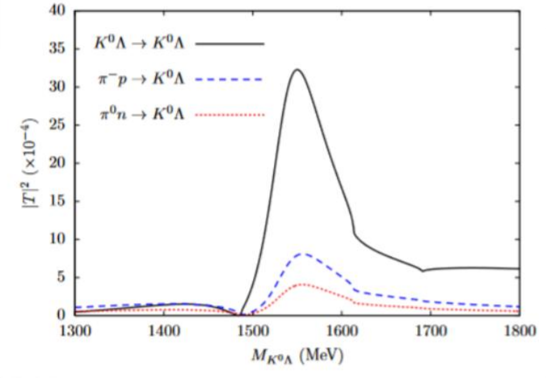
$$t_{D^{*0}K^{*0} \to D^0 K^0} = \frac{g_{T_{c\bar{s}},D^{*0}K^{*0}}\, g_{T_{c\bar{s}},D^0 K^0}}{M^2_{D^0 K^0} - m^2_{T_{c\bar{s}}} + i m_{T_{c\bar{s}}} \Gamma_{T_{c\bar{s}}}},$$

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

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

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

Inone Oset, PRC65, 035204 (2002)

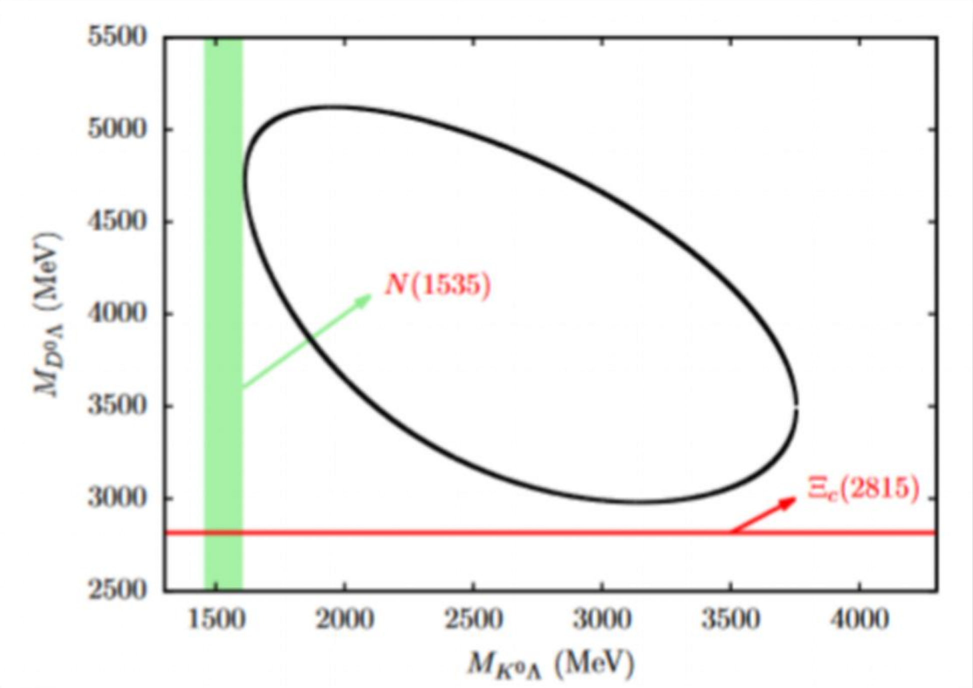


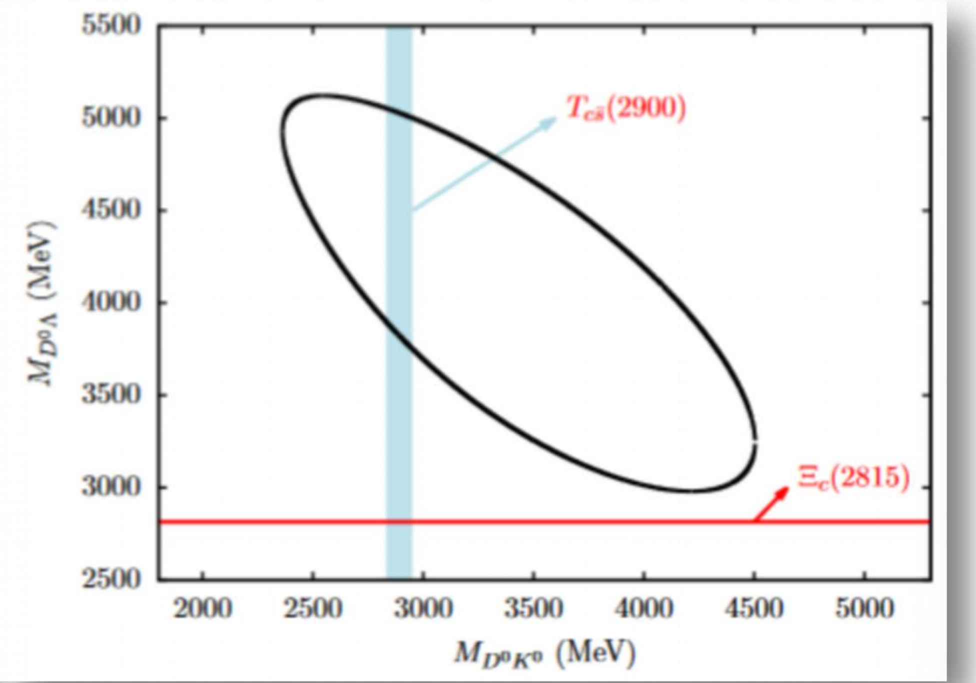
$$\frac{d^2\Gamma}{dM_{K^0\Lambda} dM_{D^0 K^0}} = \frac{1}{(2\pi)^3} \frac{2M_{K^0\Lambda} 2M_{D^0 K^0}}{32 M^3_{\Lambda_b}} |\mathcal{T}^{\rm Total}|^2,$$

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

ΛD interaction

☐Dalitz plots



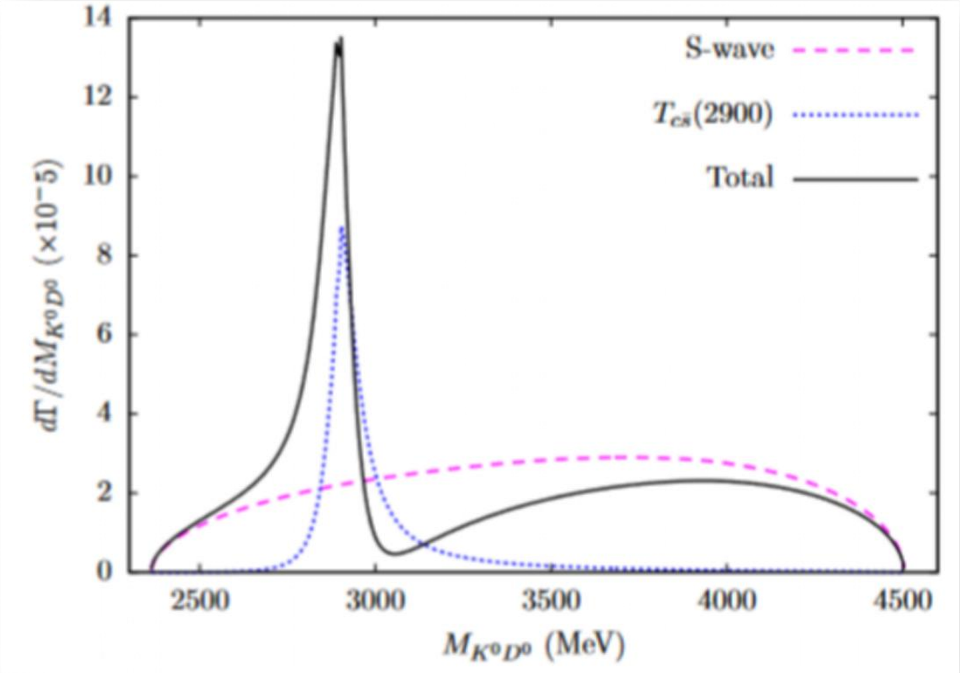


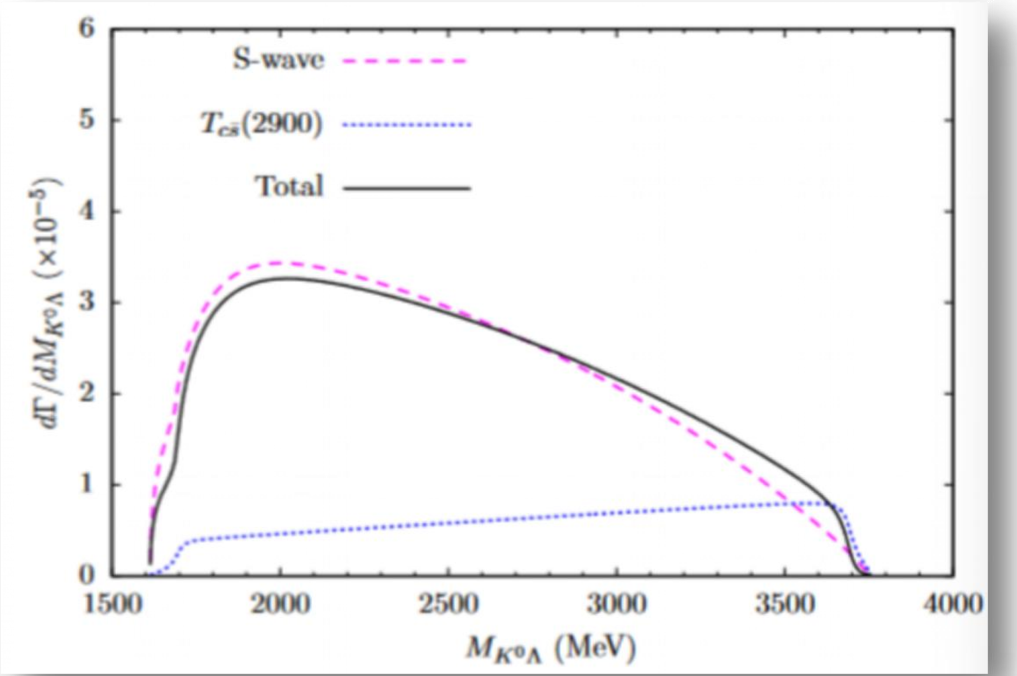
Contribution from ΛD interaction is neglected!

PRD 85 (2012), 114032

Results

□Mass distributions





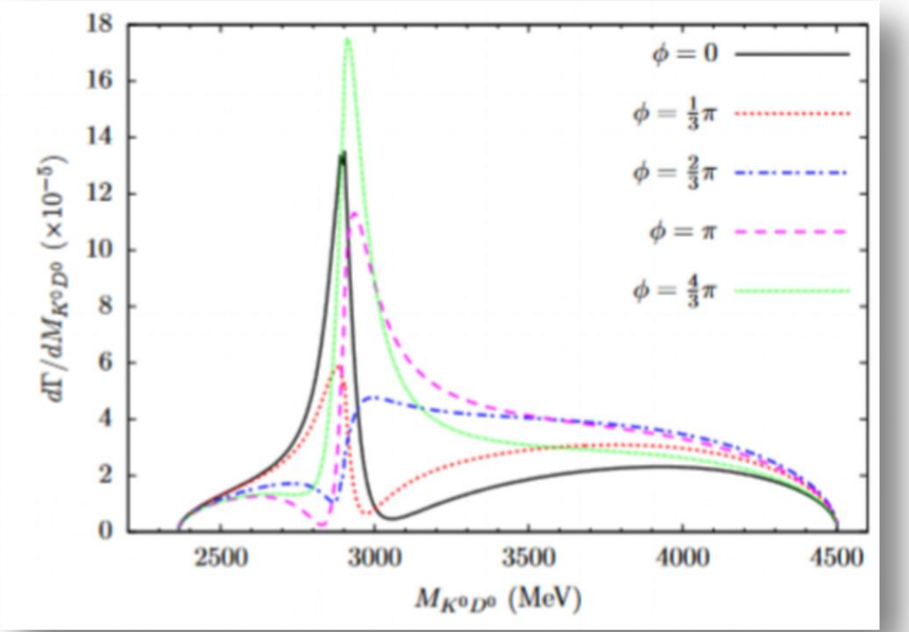
$$\mathcal{T}^{T_{c\bar{s}}} = -\sqrt{\frac{2}{3}} V_P \left[C \times G_{D_s^{*+}\rho^-} t_{D_s^{*+}\rho^- \to D^0 K^0} + G_{D^{*0}K^{*0}} t_{D^{*0}K^{*0} \to D^0 K^0} \right],$$

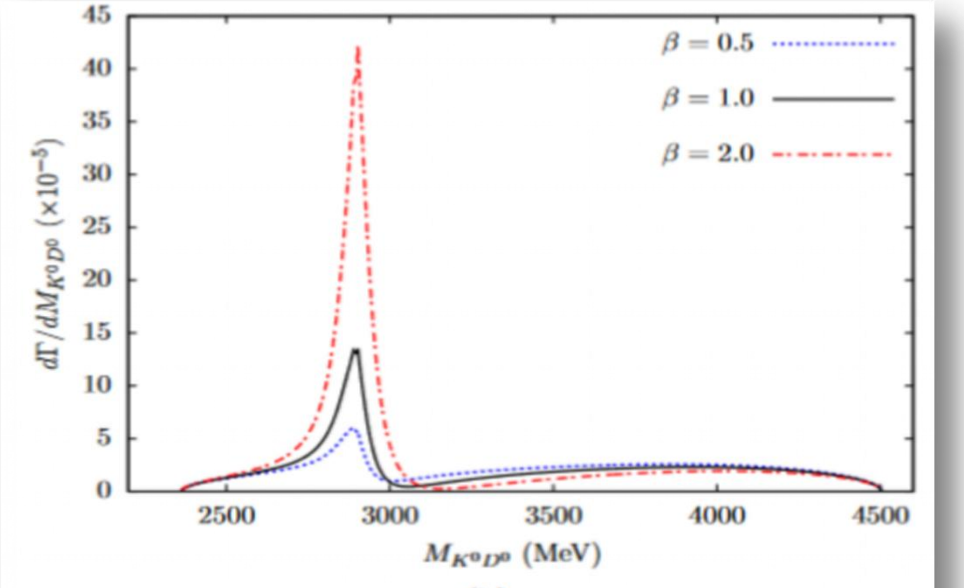
$$\mathcal{T}^{S-wave} = V_{P'} (h_{K^0\Lambda} + \sum h_i \tilde{G}_i t_{i \to K^0\Lambda}),$$

$$V_P = V_{P'},$$

Results

□Interference





(b)

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

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

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 $T_{c\bar{s}}(2900)$.
- 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!

Backup

Hidden local symmetry

VOLUME 54, NUMBER 12 PHYSICAL REVIEW LETTERS 25 MARCH 1985

Is the ρ Meson a Dynamical Gauge Boson of Hidden Local Symmetry?

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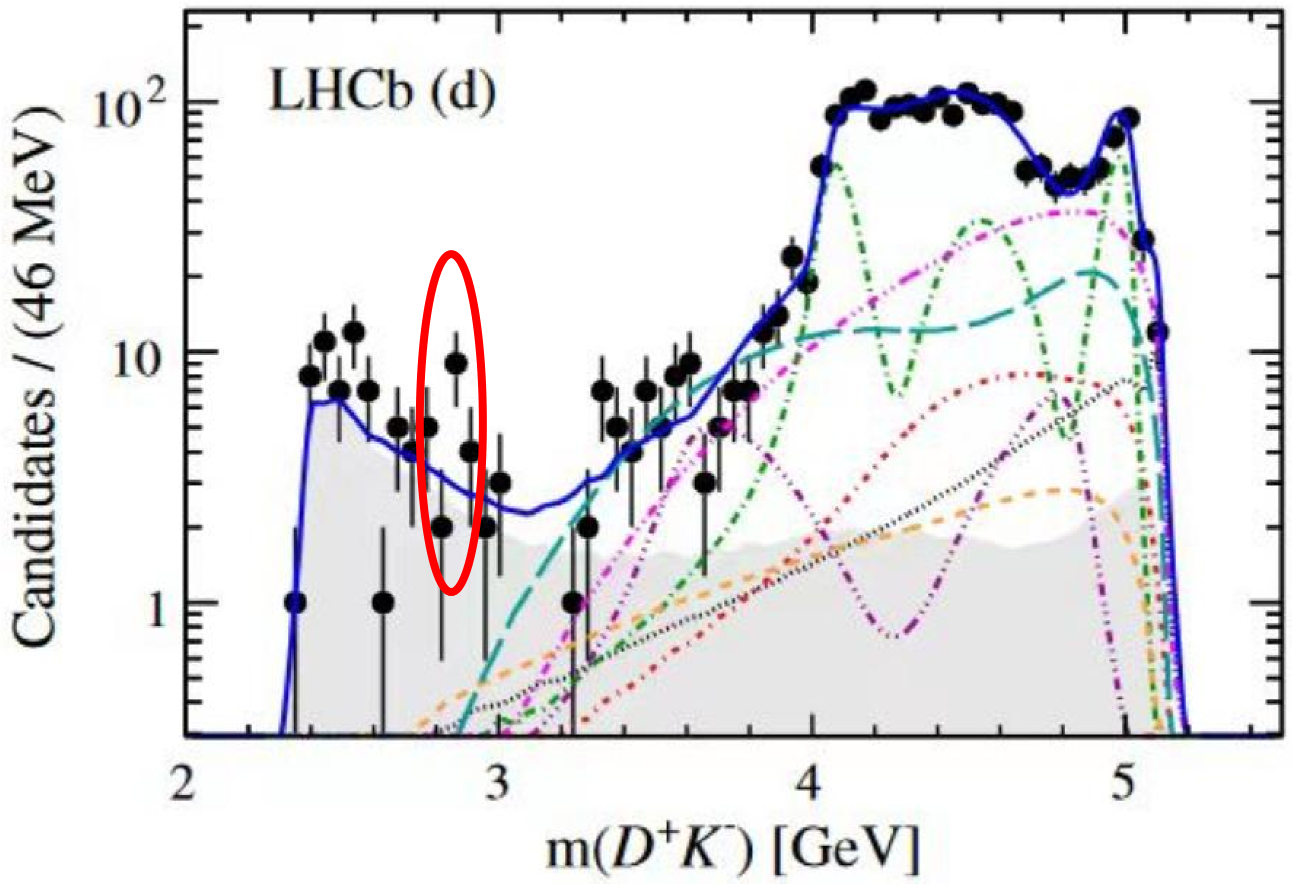
We suggest that the ρ meson is a dynamical gauge boson of a hidden local symmetry in the nonlinear chiral Lagrangian. The origin of the ρ-meson mass is understood as the Higgs mechanism of the hidden local symmetry. The low-energy dynamics of ρ, π, and matter fields, including the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin relation and ρ-coupling universality, is consistently described in this new framework. The electromagnetic interaction can be introduced in a unique manner, which gives a successful explanation of ρ dominance of the photon coupling.

PACS numbers: 14.40.Cs, 11.30.Na, 14.80.Er

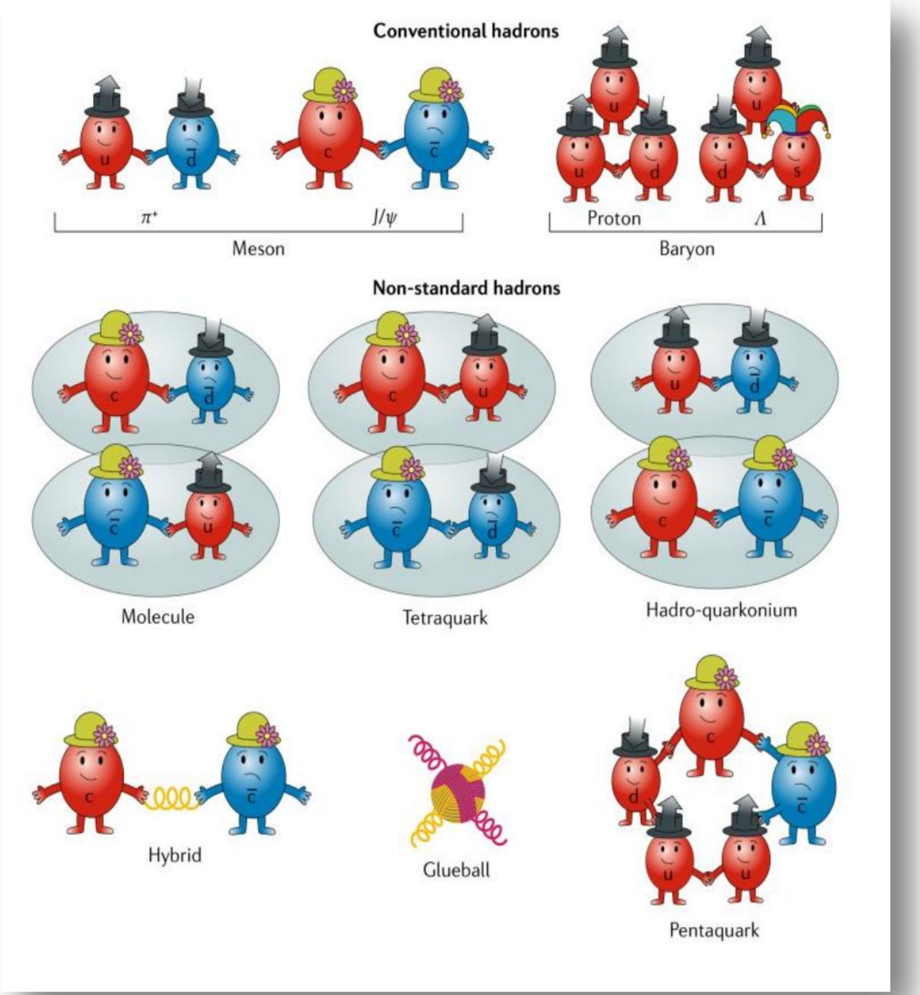
other evidence

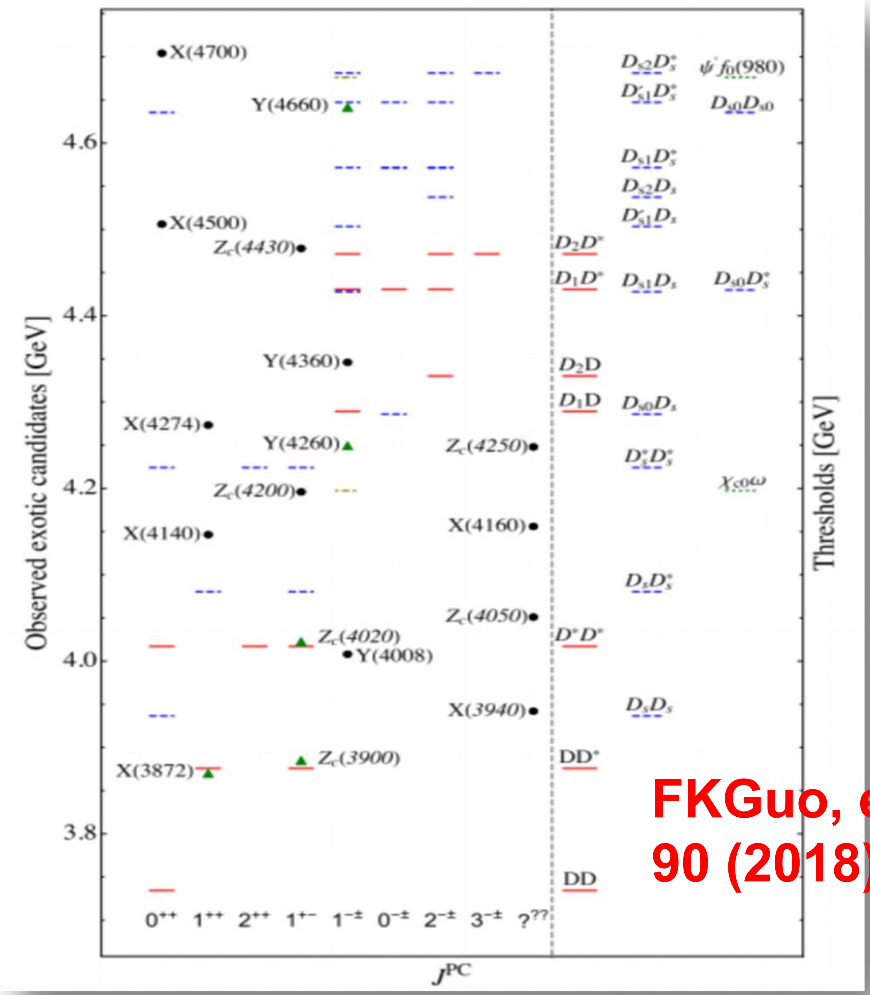
- **LHCb**， PRD91,092002 (2015)

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



Hadrons





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