LHCb实验上对称性研究

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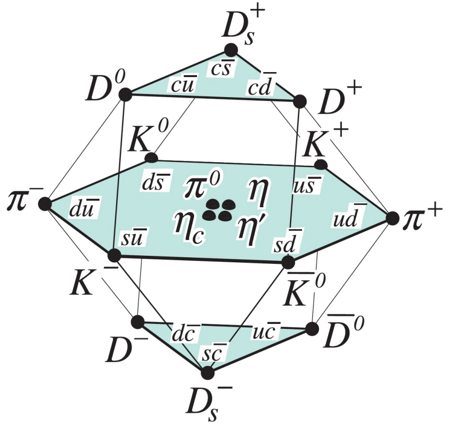
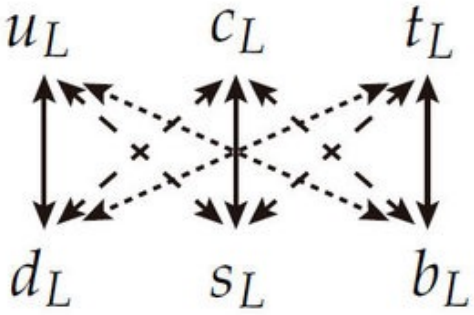
标准模型中的对称性(破坏)

- 规范对称性：$SU(3)_C \times SU(2)_L \times U(1)_Y$



- 味道对称性
  - ➢ QCD： $\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu\partial_\mu\delta_{ab} - g_s\gamma^\mu t^C_{ab}\mathcal{A}^C_\mu - m_q\delta_{ab})\psi_{q,b} - \frac{1}{4}F^A_{\mu\nu}F^{A\,\mu\nu}$

    质量破坏味对称性，但同位旋(isospin)对称性基本保留
  - ➢ EW：破坏U和D对称性，剩余三代味对称性(被质量项破坏)



CKM机制

- P、C、T(CP)对称性
  - ➢ 在电弱作用中分别破坏

$$\mathrm{C}^\dagger \mathcal{L}\left(\gamma^\mu(1-\gamma^5)\right)\mathrm{C} = \mathcal{L}\left(\gamma^\mu(1+\gamma^5)\right)$$
$$\mathrm{P}^\dagger \mathcal{L}\left(\gamma^\mu(1-\gamma^5)\right)\mathrm{P} = \mathcal{L}\left(\gamma^\mu(1+\gamma^5)\right)$$
$$(\mathrm{CP})^\dagger \mathcal{L}(V_{\mathrm{CKM}})(\mathrm{CP}) = \mathcal{L}(V^*_{\mathrm{CKM}})$$

- 手征对称性
- …

对称性是理解标准模型、寻找新物理的有效工具

LHCb实验最近结果

- Observation of the open-charm tetraquark state $T_{cs0}^{*}(2870)^{0}$ in the $B^{-} \to D^{-}D^{0}K_{S}^{0}$ decay, arXiv:2411.19781, 已投稿PRL
- First determination of the spin-parity of the $\Xi_{c}(3055)^{+,0}$ baryons, arXiv:2409.05400, PRL已接受
- Measurement of Λ_{b}^{0}, Λ_{c}^{+} and Λ decay parameters using $\Lambda_{b}^{0} \to \Lambda_{c}^{+}h^{-}$ decays, arXiv:2409.02759, PRL已接受
- Study of Λ_{b}^{0} and Ξ_{b}^{0} decays to $\Lambda h^{+}h'^{-}$ and evidence for CP violation in $\Lambda_{b}^{0} \to \Lambda K^{+}K^{-}$, arXiv:2411.15441, 已投稿PRL

奇特强子态与同位旋对称性

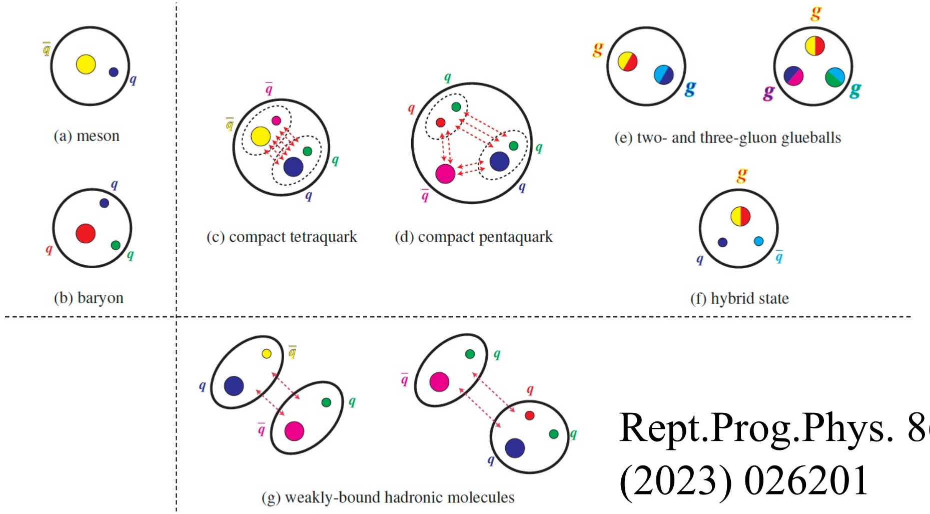
- 奇特强子：超出常规介子、重子的强子结构
  - ➢ 部分态可由运动学效应来解释

  QCD动力学，味道对称性

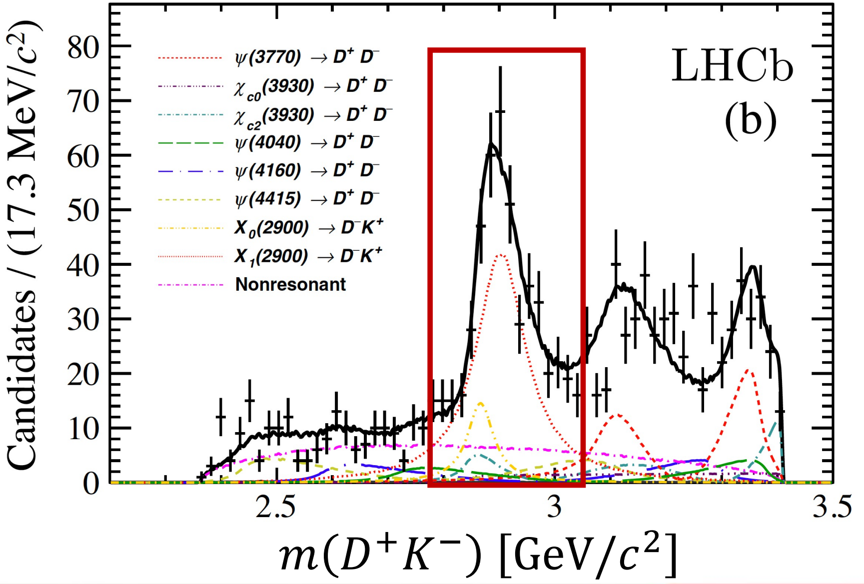
- LHCb实验2019年首次发现显粲四夸克态：

  $T^*_{cs0}(2870)^0$ 和 $T^*_{cs1}(2900)^0$，夸克组分$[cs\bar{u}\bar{d}]$

  产生、衰变模式： $B^- \to D^- T^0_{cs}, T^0_{cs} \to D^+ K^-$



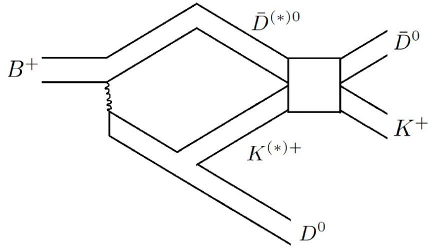
Rept.Prog.Phys. 86 (2023) 026201



PRL125(2020)242001
PRD102(2020)112003

- T^0_{cs}解释为紧致四夸克态、$\bar{D}^* K^*$分子态或运动学效应

Triangle singularity三角图



同位旋要求$T^0_{cs} \to D^+ K^-$和$T^0_{cs} \to D^0 K^0$分支比相等

衰变方式：$[cs\bar{u}\bar{d}] \to (c\bar{d})(\bar{u}s)$，$(c\bar{u})(\bar{d}s)$

PRD103(2021)014004

$B^- \to D^- D^0 K_S^0$衰变中T_{cs}^{*0}研究

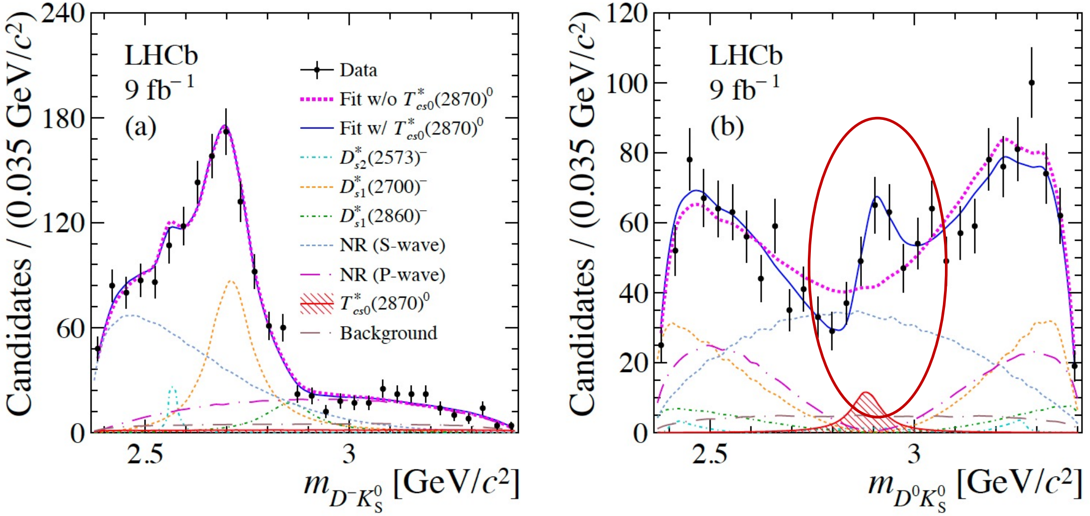
arXiv:2411.19781

- $B^- \to D^- D^0 K_S^0$衰变振幅分析
  - ➤ 由$B^- \to D_{sJ}^{*-} D^0$成分主导
  - ➤ $T_{cs0}^* \to D^0 K_S^0$ 显著性5.3σ
  - ➤ $T_{cs1}^* \to D^0 K_S^0$不显著 $(< 2\sigma)$

与$B^- \to D^- D^+ K^-$衰变对比：

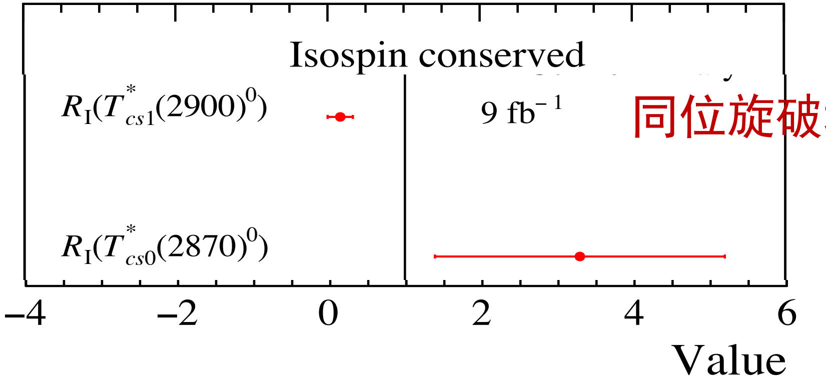
$$\mathrm{FF}[B^- \to D^- T_{cs0}^*(\to D^+ K^-)] \approx 5.6\%$$

$$\mathrm{FF}[B^- \to D^- T_{cs1}^*(\to D^+ K^-)] \approx 31\%$$



- 同位旋检验: $R_I(T_{csJ}^{*0}) \equiv \frac{\Gamma(T_{csJ}^{*0} \to D^0 \bar{K}^0)}{\Gamma(T_{csJ}^{*0} \to D^+ K^-)} \approx 1$ (同位旋对称)

$I = 0$或1



同位旋破坏！

- 理论预期

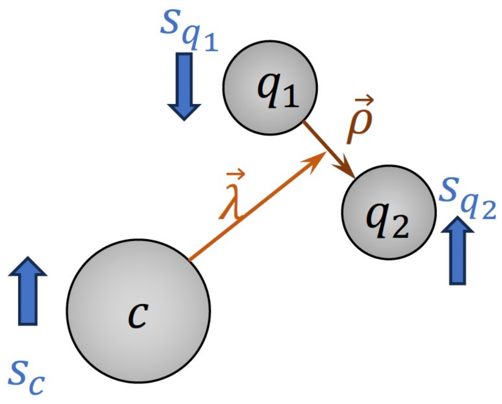
T_{cs}^{*0}结构	$R_I(T_{cs}^{*0})$
Triangle, QE	0
Triangle, OPE	$\frac{1}{4}$
Triangle, EFT	$\frac{1}{4}\left(1 - \frac{C_0}{C_1}\right)^2$
Resonance, $I = 0$	1
Resonance, $I = 1$	1
Resonance, I mixed	$\tan^2\left(\theta \pm \frac{\pi}{4}\right)$ (*)

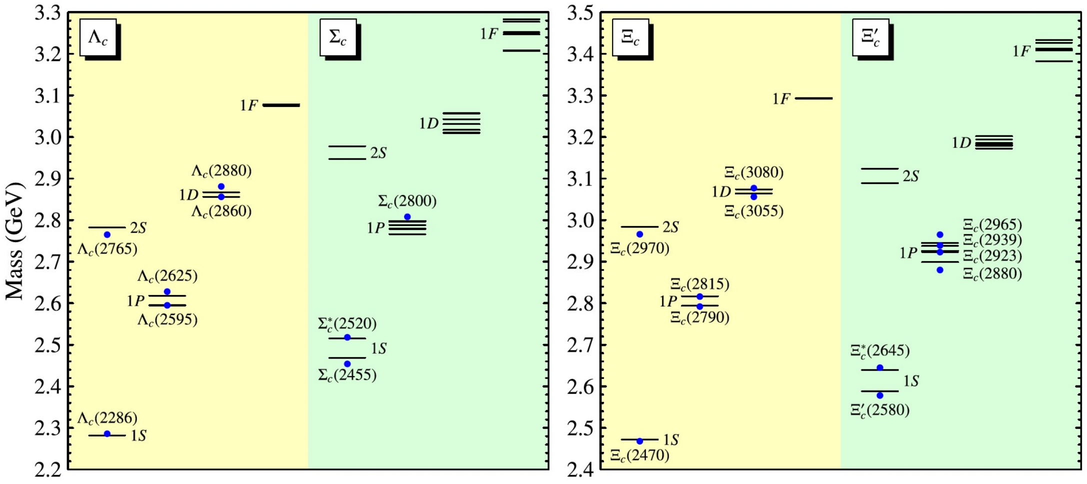
PRD103(2021) 014004

θ:同位旋混合参数

重子谱学

- 单重味重子为研究重子色禁闭机制提供丰富的实验信息
- 分类： 轻夸克味道对称性 (6_F, $\bar{3}_F$)；轨道/径向激发 (λ-模， ρ-模)





PRD108 (2023) 034002

	J^P (nL)	Experimental values [3]	RQM [223]	NQM [224]	NQM [225]	NQM [309]
Λ_c	$1/2^+$ $(1S)$	2286.46 ± 0.14	2286	2268	2285	2286
Ξ_c	$1/2^+$ $(1S)$	$2467.94^{+0.17}_{-0.20}$	2476	2466	–	2470
Σ_c	$1/2^+$ $(1S)$	2452.9 ± 0.4	2443	2455	2460	2456
Σ^*_c	$3/2^+$ $(1S)$	2517.5 ± 2.3	2519	2519	2523	2515
Ξ'_c	$1/2^+$ $(1S)$	2578.4 ± 0.5	2579	2594	–	2579
Ξ^*_c	$3/2^+$ $(1S)$	$2645.56^{+0.24}_{-0.30}$	2649	2649	–	2649
Ω_c	$1/2^+$ $(1S)$	2695.2 ± 1.7	2698	2718	2731	–
Ω^*_c	$3/2^+$ $(1S)$	2765.9 ± 2.0	2768	2776	2779	–
Λ_c	$1/2^-$ $(1P)$	$\Lambda_c(2595) = 2592.25 \pm 0.28$	2598	2625	2628	2614
Λ_c	$3/2^-$ $(1P)$	$\Lambda_c(2625) = 2628.11 \pm 0.19$	2627	2636	2630	2639
Ξ_c	$1/2^-$ $(1P)$	$\Xi_c(2790) = 2792.4 \pm 0.5$	2792	2773	–	2793
Ξ_c	$3/2^-$ $(1P)$	$\Xi_c(2815) = 2816.74^{+0.20}_{-0.23}$	2819	2783	–	2820
Σ_c	$1/2^-$ $(1P)$	–	2713	2748	2802	2702
Σ_c	$1/2^-$ $(1P)$	$\Sigma_c(2800) = 2792^{+14}_{-5}$	2799	2768	2826	2765
Σ_c	$3/2^-$ $(1P)$		2773	2763	2807	2785
Σ_c	$3/2^-$ $(1P)$		2798	2776	2837	2798
Σ_c	$5/2^-$ $(1P)$		2789	2790	2839	2790
Ξ'_c	$1/2^-$ $(1P)$	–	2854	2855	–	2839
Ξ'_c	$1/2^-$ $(1P)$	$\Xi_c(2923) = 2923.04 \pm 0.35$ [304]	2936	–	–	2900
Ξ'_c	$3/2^-$ $(1P)$	$\Xi_c(2939) = 2938.55 \pm 0.30$ [304]	2912	2866	–	2921
Ξ'_c	$3/2^-$ $(1P)$	$\Xi_c(2965) = 2964.88 \pm 0.33$ [304]	2935	–	–	2932
Ξ'_c	$5/2^-$ $(1P)$	–	2929	2895	–	2927
Ω_c	$1/2^-$ $(1P)$	–	2966	2977	3030	–
Ω_c	$1/2^-$ $(1P)$	$\Omega_c(3000) = 3000.41 \pm 0.22$	3055	2990	3048	–
Ω_c	$3/2^-$ $(1P)$	$\Omega_c(3050) = 3050.20 \pm 0.13$	3029	2986	3033	–
Ω_c	$3/2^-$ $(1P)$	$\Omega_c(3066) = 3065.46 \pm 0.28$	3054	2994	3056	–
Ω_c	$5/2^-$ $(1P)$	$\Omega_c(3090) = 3090.0 \pm 0.5$	3051	3014	3057	–
Λ_c	$1/2^+$ $(2S)$	$\Lambda_c(2765) = 2766.6 \pm 2.4$	2769	2791	2857	2772
Ξ_c	$1/2^+$ $(2S)$	$\Xi_c(2970) = 2966.34^{+0.17}_{-1.00}$	2959	–	–	2940
Σ_c	$1/2^+$ $(2S)$	–	2901	2958	3029	2850
Σ_c	$3/2^+$ $(2S)$	–	2936	2995	3065	2876
Ξ'_c	$1/2^+$ $(2S)$	–	2983	–	–	2977
Ξ'_c	$3/2^+$ $(2S)$	–	3026	3012	–	3007
Ω_c	$1/2^+$ $(2S)$	$\Omega_c(3119) = 3119.1 \pm 1.0$	3088	3152	3227	–
Ω_c	$3/2^+$ $(2S)$		3123	3190	3257	–
Λ_c	$3/2^+$ $(1D)$	$\Lambda_c(2860) = 2856.1^{+2.3}_{-5.9}$	2874	2887	2920	2843
Λ_c	$5/2^+$ $(1D)$	$\Lambda_c(2880) = 2881.63 \pm 0.24$	2880	2887	2922	2851
Ξ_c	$3/2^+$ $(1D)$	$\Xi_c(3055) = 3055.9 \pm 0.4$	3059	–	–	3033
Ξ_c	$5/2^+$ $(1D)$	$\Xi_c(3080) = 3077.2 \pm 0.4$	3076	3004	–	3040
Σ_c	$1/2^+$ $(1D)$	–	3041	–	3103	2949
Σ_c	$3/2^+$ $(1D)$	–	3040	–	3094	2952
Σ_c	$3/2^+$ $(1D)$	–	3043	–	–	2964
Σ_c	$5/2^+$ $(1D)$	–	3023	3003	3099	2942
Σ_c	$5/2^+$ $(1D)$	–	3038	3010	3114	2962
Σ_c	$7/2^+$ $(1D)$	–	3013	3015	–	2943
Ξ'_c	$1/2^+$ $(1D)$	–	3163	–	–	3075
Ξ'_c	$3/2^+$ $(1D)$	–	3160	–	–	3081
Ξ'_c	$3/2^+$ $(1D)$	–	3167	–	–	3089
Ξ'_c	$5/2^+$ $(1D)$	–	3153	3080	–	3077
Ξ'_c	$5/2^+$ $(1D)$	–	3166	–	–	3091
Ξ'_c	$7/2^+$ $(1D)$	–	3147	3094	–	3078
Ω_c	$1/2^+$ $(1D)$	–	3287	–	3292	–
Ω_c	$3/2^+$ $(1D)$	–	3282	–	3285	–
Ω_c	$3/2^+$ $(1D)$	–	3298	–	–	–
Ω_c	$5/2^+$ $(1D)$	–	3286	3196	3288	–
Ω_c	$5/2^+$ $(1D)$	–	3297	3203	3299	–
Ω_c	$7/2^+$ $(1D)$	–	3283	3206	–	–

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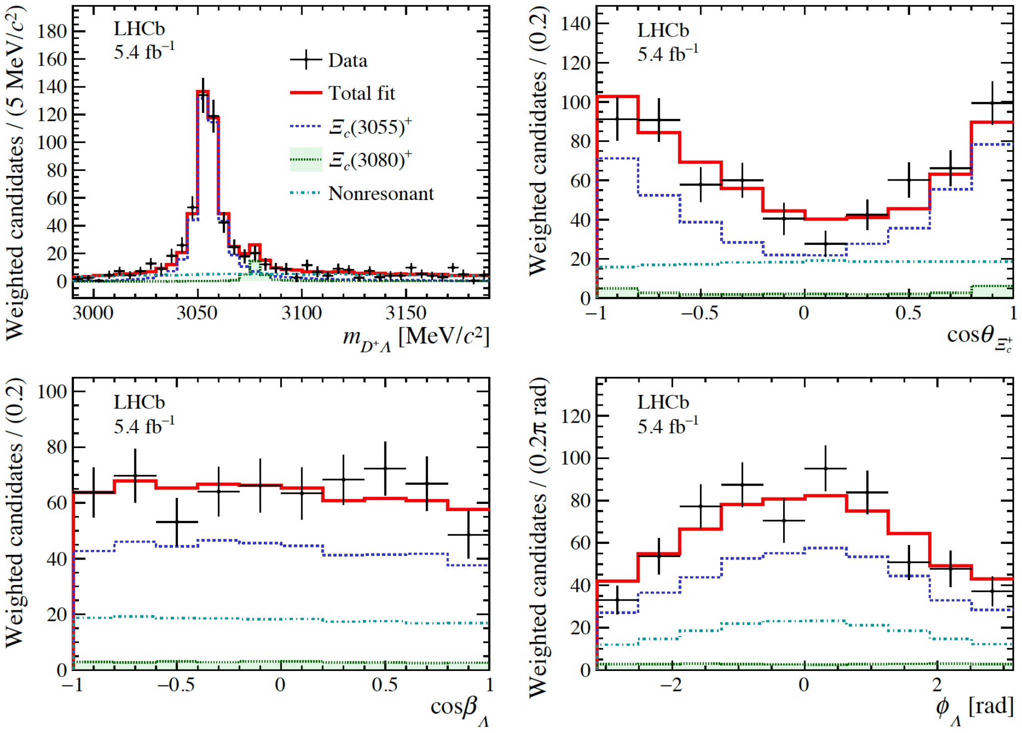
- 不同理论模型计算和解释差异较大，需要实验信息甄别
  - ➢ 新态(3 GeV质量区)、量子数测量、产生、衰变模式等

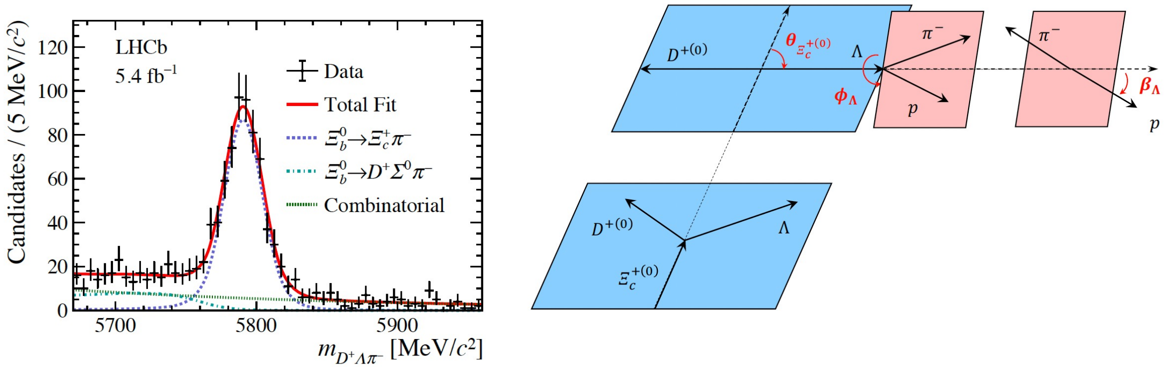
$\Xi_c(3055)^{+,0}$自旋-宇称测量

arXiv:2411.19781

- 首次发现$\Xi_b^{0,+} \to \Xi_c(3055)^{+,0}\pi^-$衰变，用来测量$\Xi_c(3055)^{+,0}$自旋宇称 J^P
  - ➢ $\Xi_c(3055)^{+,0} \to D^{+,0}\Lambda(\to p\pi^-)$

定出 $J^P = 3/2^+$

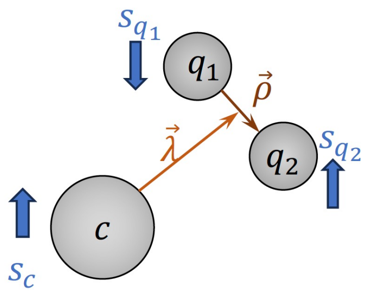




- 前、后向不对称性$\alpha \equiv \frac{|H_+|^2-|H_-|^2}{|H_+|^2+|H_-|^2}$

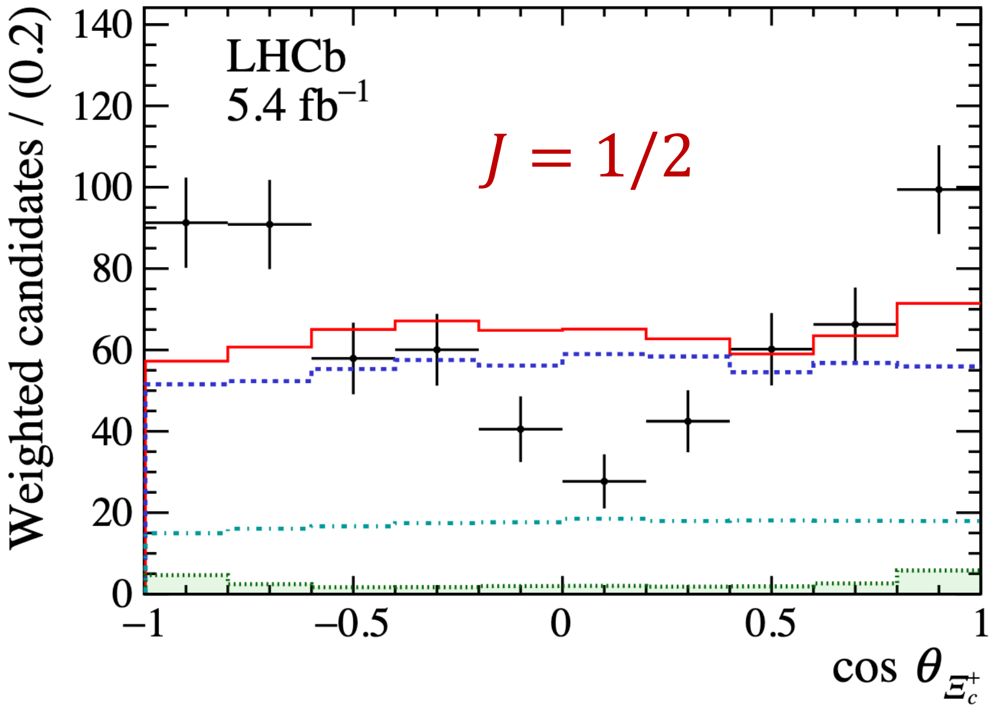
Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
α	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$

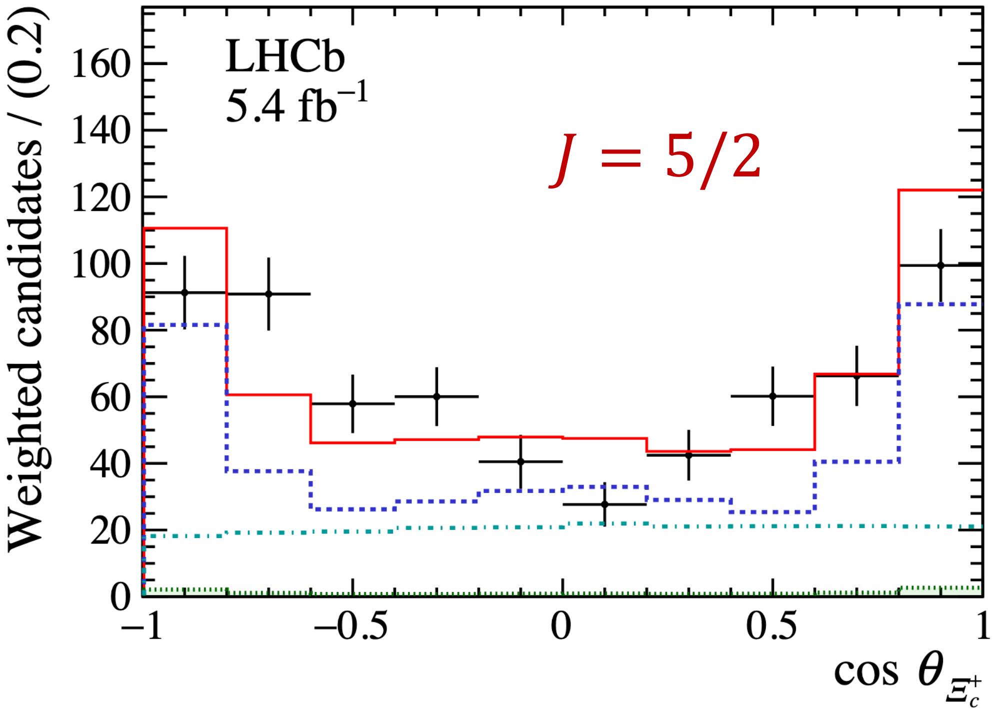
$\Xi_c(3055)$与λ-模D-波激发的$\bar{3}_F$态相符



$\Xi_c(3055)^{+,0}$自旋-宇称测量

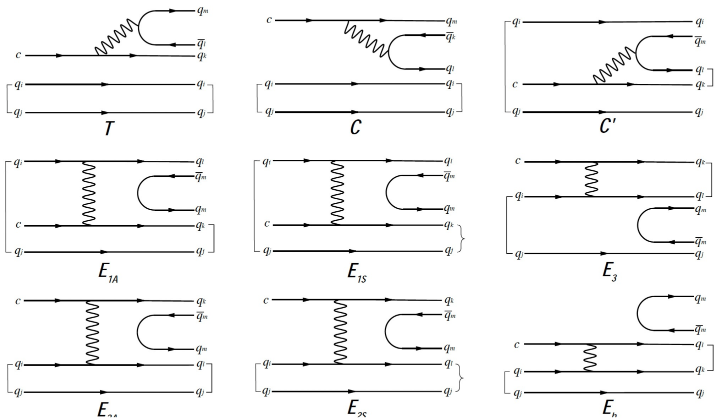
- 备择假设





重子弱衰变与宇称破坏

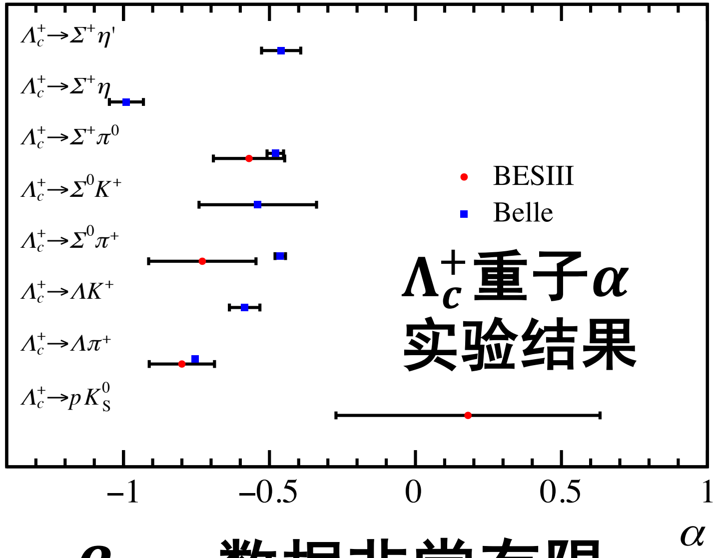
- 丰富衰变模式，帮助理解标准模型强、弱动力学
- 非微扰效应往往较大，对精确计算带来挑战
- $\mathcal{B}(1/2^+) \to \mathcal{B}(1/2^+)P(0^-)$衰变包含宇称破坏$s$-波和宇称守恒的$p$-波　　例：$\Lambda \to p\pi^-$



衰变率：$\Gamma \propto |s|^2 + |p|^2$

李-杨衰变参数：

$$\alpha \equiv \frac{2\Re(s^*p)}{|s|^2+|p|^2},\quad \beta \equiv \frac{2\Im(s^*p)}{|s|^2+|p|^2},\quad \gamma \equiv \frac{|s|^2-|p|^2}{|s|^2+|p|^2}$$



提取强、弱相位差，为研究动力学提供更全面的信息

BESIII基于$e^+e^- \to \mathcal{B}\bar{\mathcal{B}}$对极化、P、CP破坏做出重要测量

Nature Phys. 15 (2019) 631

β、γ数据非常有限

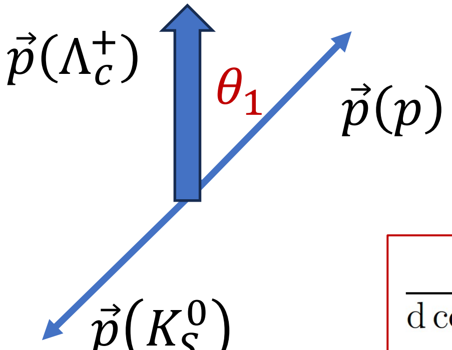
$\Lambda_b^0 \to \Lambda_c^+ h^-$衰变参数测量

arXiv:2409.02759

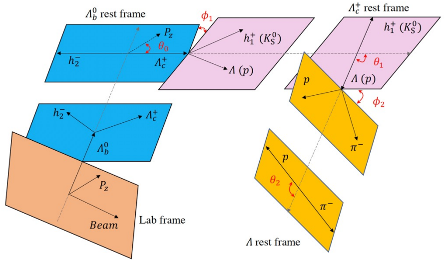
- 六个$\mathcal{B} \to \mathcal{B}P$衰变： $\Lambda_b^0 \to \Lambda_c^+ h^-$， $\Lambda_c^+ \to \Lambda h^+$， $\Lambda_c^+ \to p K_S^0$， $\Lambda \to p\pi^-$ $(h = \pi, K)$

$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h^-$

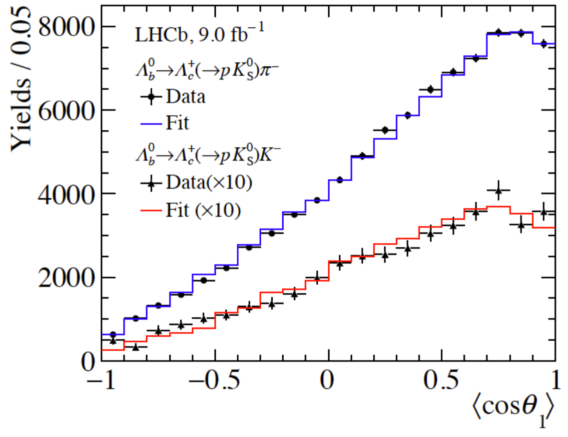
$$\frac{d\Gamma}{d\cos\theta_1} \propto 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1$$

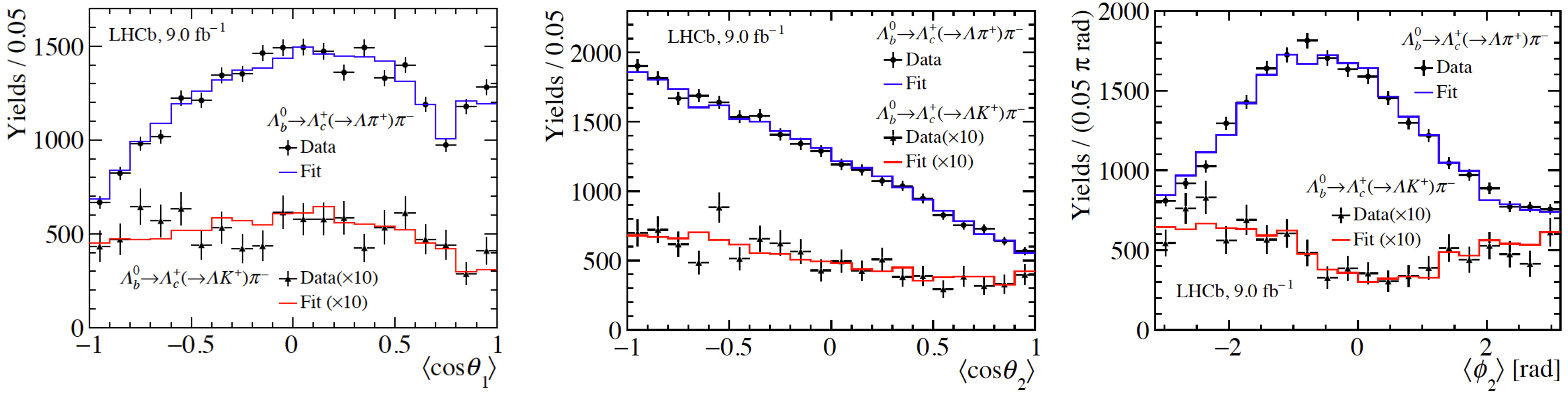


$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h^+)h^-$



$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi_2} \propto (1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + \alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_2 + \alpha_{\Lambda_b^0}\alpha_\Lambda\cos\theta_1\cos\theta_2 - \alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\sin\phi_2)$$





Λ_b^0衰变参数

arXiv:2409.02759

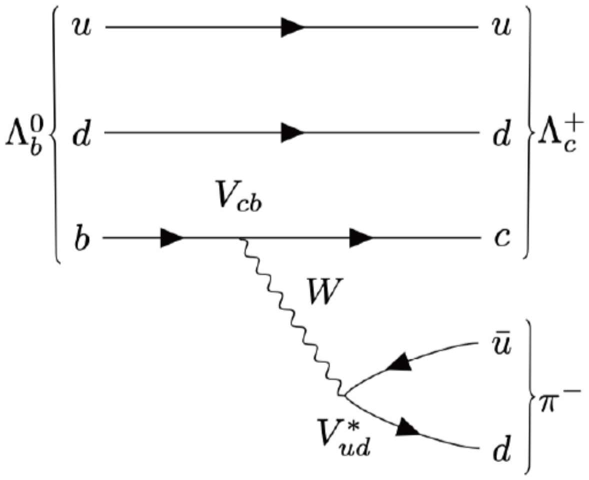
- 首次测量$\Lambda_b^0 \to \Lambda_c^+ h^-$衰变参数$\alpha \approx -1$，标准模型$V-A$形式

Decay	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	$\Lambda_b^0 \to \Lambda_c^+ K^-$
α	$-1.010 \pm 0.011 \pm 0.003$	$-0.933 \pm 0.042 \pm 0.014$
$\bar{\alpha}$	$0.996 \pm 0.011 \pm 0.003$	$0.995 \pm 0.036 \pm 0.013$
$\langle \alpha \rangle$	$-1.003 \pm 0.008 \pm 0.005$	$-0.964 \pm 0.028 \pm 0.015$
A_α	$0.007 \pm 0.008 \pm 0.005$	$-0.032 \pm 0.029 \pm 0.006$

无显著CP破坏

- 与模型预期相符，衰变由W^-外发射过程主导(可因子化)

Mode	This work	[88]	[13][a]	[86,87][a]	[89]	[16]	[78]	[80][a]
$\alpha(\Lambda_b \to \Lambda_c \pi)$	−99.2	−100	−99	−99	⋯	−99.9	−99.8	−99.9
$\alpha(\Lambda_b \to \Lambda_c K)$	−98.2	⋯	⋯	⋯	⋯	−100	−100	−99.9



Λ_c^+衰变参数

arXiv:2409.02759

- α与已有结果精度相当；β,γ精度大大改进

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$	$\Lambda_c^+ \to pK_S^0$
α	$-0.782 \pm 0.009 \pm 0.004$	$-0.569 \pm 0.059 \pm 0.028$	$-0.744 \pm 0.012 \pm 0.009$
$\bar{\alpha}$	$0.787 \pm 0.009 \pm 0.003$	$0.464 \pm 0.058 \pm 0.017$	$0.765 \pm 0.012 \pm 0.007$
$\langle\alpha\rangle$	$-0.785 \pm 0.006 \pm 0.003$	$-0.516 \pm 0.041 \pm 0.021$	$-0.754 \pm 0.008 \pm 0.006$
A_α	$-0.003 \pm 0.008 \pm 0.002$	$0.102 \pm 0.080 \pm 0.023$	$-0.014 \pm 0.011 \pm 0.008$

无显著CP破坏

- 检验理论模型，不可因子化贡献显著

α参数理论预言

Decay	Körner	Xu	Cheng		Ivanov
	CCQM	Pole	CA	Pole	CCQM
$\Lambda_c^+ \to \Lambda\pi^+$	-0.70	-0.67	-0.99	-0.95	-0.95
$\Lambda_c^+ \to p\bar{K}^0$	-1.0	0.51	-0.90	-0.49	-0.97

- 提取相位

$\beta(\Lambda_c^+ \to \Lambda\pi^+) = -0.06^{+0.58+0.05}_{-0.47-0.06}$

$\gamma(\Lambda_c^+ \to \Lambda\pi^+) = -0.60^{+0.96+0.17}_{-0.05-0.03}$

[PRD 100 (2019) 072004]

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ (rad)	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$ (rad)	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$

螺旋度振幅相位差

改善模型

Hadronic Weak Decays of Charmed Baryons in the Topological Diagrammatic Approach: An Update

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Abstract

There exist two distinct ways in realizing the approximate SU(3) flavor symmetry of QCD to describe the two-body nonleptonic decays of charmed baryons: the irreducible SU(3) approach (IRA) and the topological diagram approach (TDA). The TDA has the advantage that it is more intuitive, graphic and easier to implement model calculations. We perform a global fit to the currently available data of two-body charmed baryon decays within the framework of the TDA and IRA. The number of the minimum set of tensor invariants in the IRA and the topological amplitudes in the TDA is the same, namely, five in the tree-induced amplitudes and four in the penguin amplitudes. Since we employ the new LHCb measurements to fix the sign ambiguity of the decay parameters β and γ, the fit results for the magnitudes of S- and P-wave amplitudes and their phase shift $\delta_P-\delta_S$ in both the TDA and IRA are more trustworthy than our previous analyses with uncertainties substantially improved. These results can be tested in the near future. The perspective of having direct CP violation in the charmed baryon sector at the per mille level is briefly discussed.

arXiv:2410.04675

$$\alpha \equiv \frac{2\Re(s^*p)}{|s|^2+|p|^2}$$

Channel	$10^2\mathcal{B}$	α	$\delta_P-\delta_S$
$\Lambda_c^+\to\Lambda^0\pi^+$	1.31 ± 0.05	-0.76 ± 0.01	-2.92 ± 0.29
$\Lambda_c^+\to\Sigma^0\pi^+$	1.26 ± 0.05	-0.48 ± 0.02	2.08 ± 0.04
$\Lambda_c^+\to\Sigma^+\pi^0$	1.27 ± 0.05	-0.48 ± 0.02	2.08 ± 1.15
$\Lambda_c^+\to\Sigma^+\eta$	0.33 ± 0.04	-0.93 ± 0.05	-2.80 ± 0.16
$\Lambda_c^+\to\Sigma^+\eta'$	0.39 ± 0.11	-0.45 ± 0.07	-4.25 ± 0.08
$\Lambda_c^+\to\Xi^0K^+$	0.41 ± 0.03	-0.16 ± 0.13	-2.15 ± 0.65

arXiv:2401.15926

Channel	$10^2\mathcal{B}$	α	$\delta_P-\delta_S$
$\Lambda_c^+\to\Lambda^0\pi^+$	1.30 ± 0.05	-0.76 ± 0.01	2.67 ± 0.02
	1.30 ± 0.04	-0.76 ± 0.01	2.67 ± 0.02
$\Lambda_c^+\to\Sigma^0\pi^+$	1.24 ± 0.05	-0.47 ± 0.01	2.54 ± 0.14
	1.24 ± 0.05	-0.47 ± 0.01	2.53 ± 0.14
$\Lambda_c^+\to\Sigma^+\pi^0$	1.25 ± 0.05	-0.47 ± 0.01	2.54 ± 0.14
	1.25 ± 0.05	-0.47 ± 0.01	2.53 ± 0.44
$\Lambda_c^+\to\Sigma^+\eta$	0.33 ± 0.04	-0.90 ± 0.04	-2.99 ± 0.13
	0.33 ± 0.04	-0.89 ± 0.04	-3.06 ± 0.13
$\Lambda_c^+\to\Sigma^+\eta'$	0.18 ± 0.03	-0.44 ± 0.07	2.05 ± 0.10
	0.17 ± 0.04	-0.44 ± 0.07	2.03 ± 0.08
$\Lambda_c^+\to\Xi^0K^+$	0.33 ± 0.03	-0.08 ± 0.11	-1.65 ± 0.12
	0.33 ± 0.03	-0.07 ± 0.11	-1.64 ± 0.11

arXiv:2410.04675

底重子衰变中的CP破坏

- CP破坏已发现于奇异、粲介子系统；在底介子中广泛存在，可具有较大数值

1964
K_L 衰变的CP 破坏
Cronin和Fitch

1973
CKM机制
小林诚和益川敏英

1991, 2001
奇异介子直接CP破坏
KTeV, NA48

2001
B^0 含时CP破坏
BaBar, Belle

2004
B^0 直接CP破坏
BaBar 和Belle

2012
B^+直接CP破坏
LHCb

2013
B_s^0 直接CP破坏
LHCb

2019
D^0 衰变中的CP破坏
LHCb

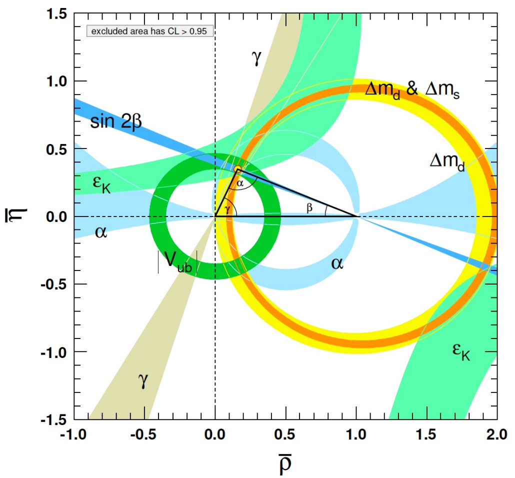
2020
B_s^0 含时CP破坏
LHCb

CP破坏研究
重要进展

与CKM机制相符

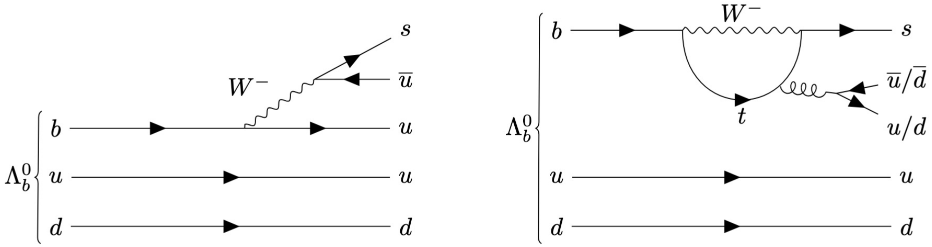
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM矩阵全局拟合



- 底重子与介子夸克动力学"相同"：树图和圈图干涉预期导致CP破坏，但实验尚未发现重子中的CP破坏（$\sim\mathcal{O}(1\%)$）

Puzzle，多分波CP相消？ [于福升, arXiv:2409.02821]



重子CP破坏是全面检验标准模型的关键组成部分

$\Lambda_b^0 \to \Lambda K^+ K^-$ CP破坏迹象

arXiv:2411.15441

- 选择多个衰变道，寻找Λ_b^0等底重子中的CP破坏; 非粲衰变最具优势

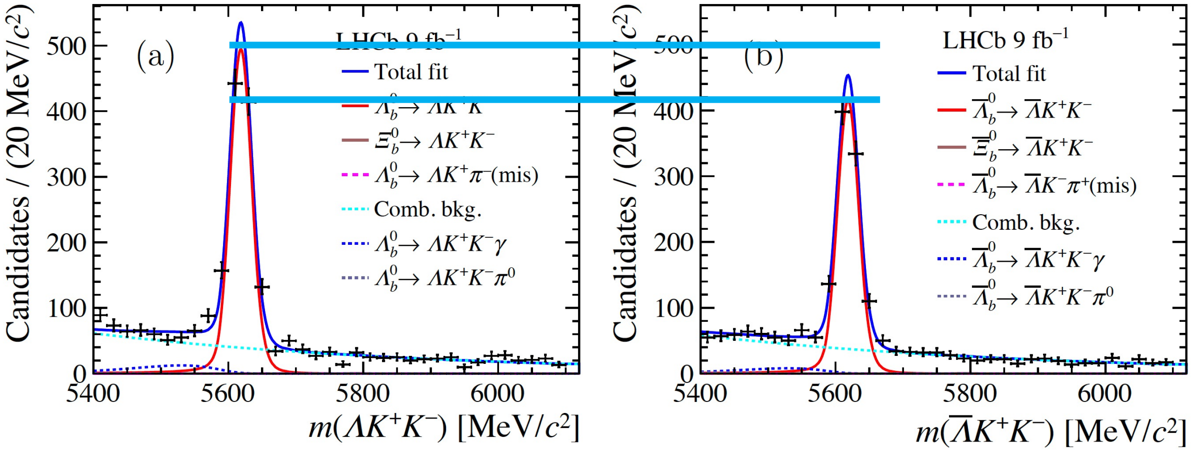
$\Lambda_b^0 \to ph^-, \Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h^-$, $\Lambda_b^0/\Xi_b^0 \to ph^-\pi^0$, $\Lambda_b^0 \to pK_S^0 h^-$, $\Lambda_b^0 \to ph^-h^+h^- \ldots$ $h = \pi, K$

已公开最新结果 预计< 1年公开新结果

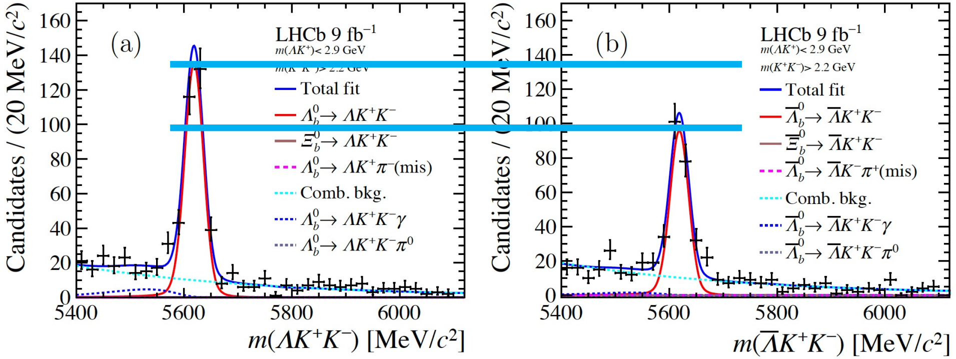
- 首次于$\Lambda_b^0 \to \Lambda K^+ K^-$发现CP破坏迹象(3.1$\sigma$)

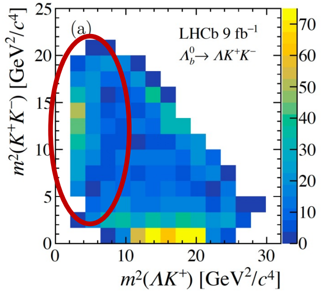
$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+ K^-\right) = 0.083 \pm 0.023 \pm 0.016$$

$\Lambda_b^0 \to \Lambda K^+ K^-$ $\qquad$ $\overline{\Lambda}_b^0 \to \overline{\Lambda} K^+ K^-$



其中的CP破坏由$\Lambda_b^0 \to N^{*+}(\Lambda K^+)K^-$主导



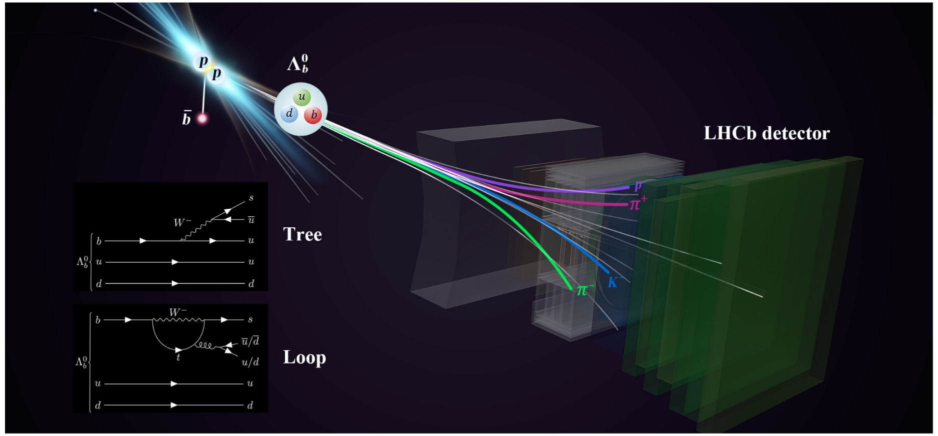


$\Lambda_b^0 \to N^{*+}(p\pi^+\pi^-)K^-$衰变具有更大统计量，灵敏度更高

总结

- 对称性为研究强子动力学，检验标准模型提供了独特视角
  - $B^- \to D^- D^0 K_S^0$衰变发现$T_{cs0}^*(2870)^0$，但无$T_{cs1}^*(2900)^0$ 迹象， arXiv:2411.19781
  - 首次确定$\Xi_c(3055)^{+,0}$ $J^P = 3/2^+$量子数，确认其激发模式，arXiv:2409.05400
  - 精确测量Λ_b^0, Λ_c^+ 和 Λ 衰变的宇称破坏参数及其CP破坏， arXiv:2409.02759
  - $\Lambda_b^0 \to \Lambda K^+ K^-$衰变首次发现重子CP破坏迹象，arXiv:2411.15441

CP破坏、稀有衰变、轻子味普适性(反常)、重味强子态等引领LHCb实验味物理研究



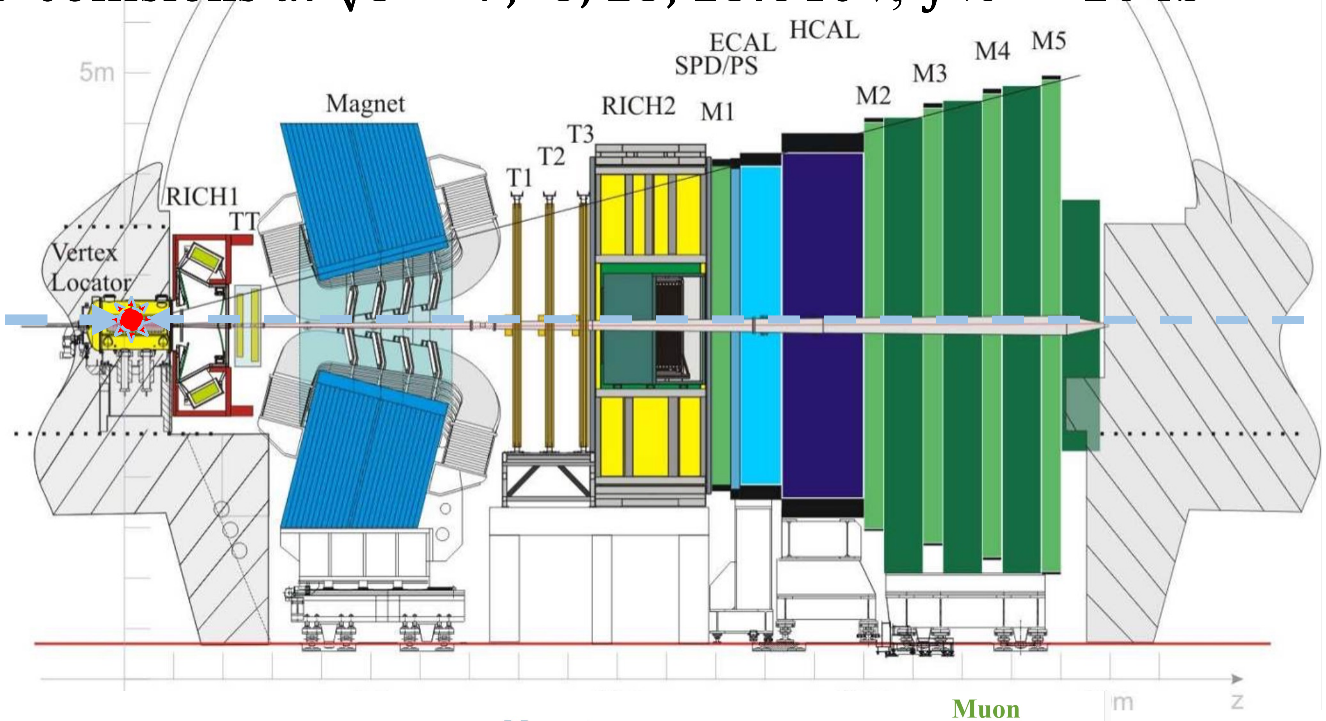
LHCb

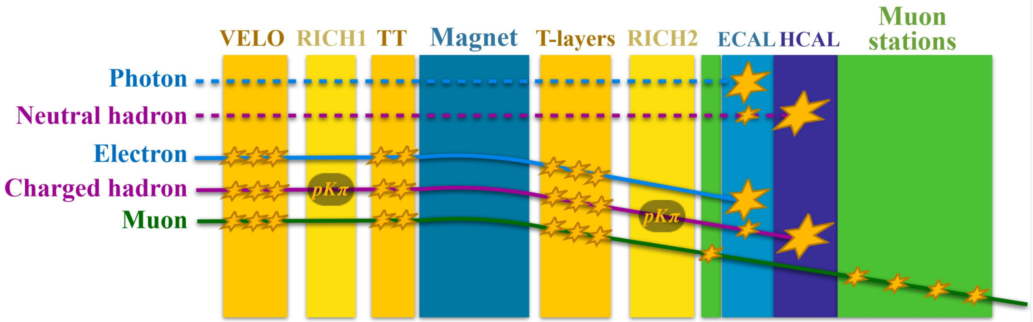
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Dedicated flavor experiment at CERN for b, c hadrons
- pp collisions at $\sqrt{s} = 7,\ 8, 13, 13.6\text{TeV}$, $\int \mathcal{L} = 10\ \text{fb}^{-1}$

$\sigma(b\bar{b}, 13\ \text{TeV}) \approx 0.5\ \mu\text{b}$

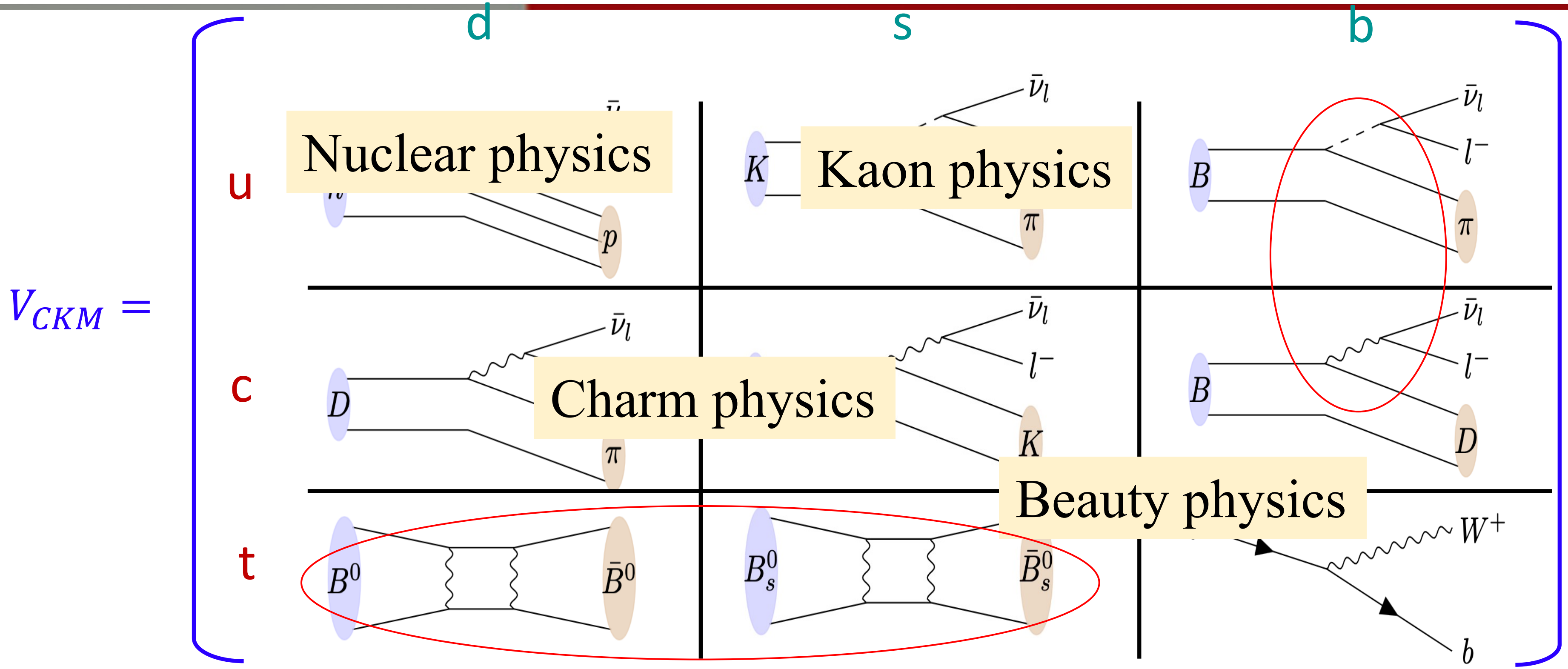
$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$





- ✓ Excellent vertexing
  $\sigma_\tau \sim 45$ fs
- ✓ Hadron PID
  $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- ✓ Precise momentum measurement
  $\delta m_{B \to K\pi} / m_B \sim 0.005$

Quark mixing matrix

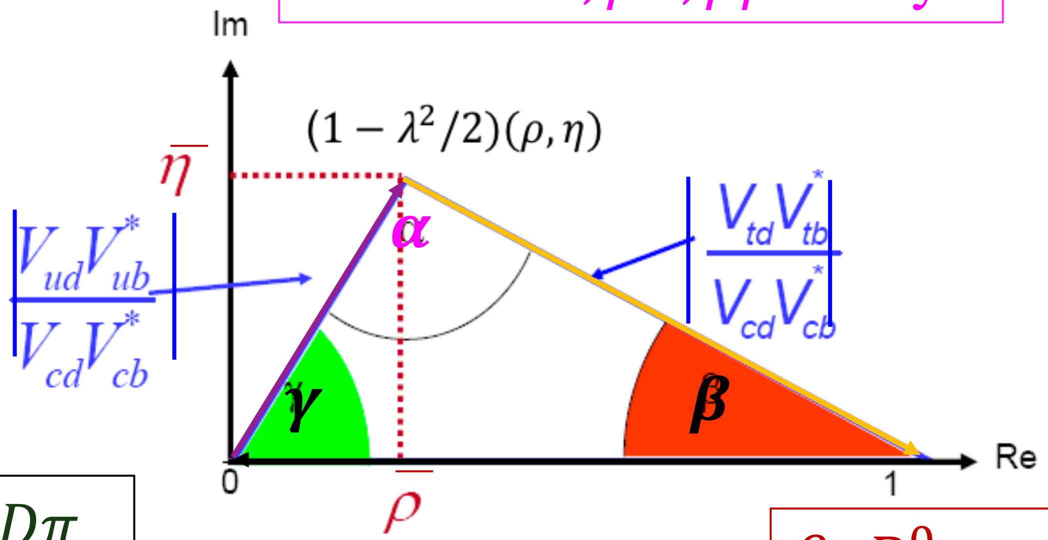


Complementarity between beauty and charm factories

Three angles of the Unitarity triangle

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

α: $B \to \pi\pi, \rho\pi, \rho\rho$ decays



γ: CPV in $B \to DK,\ D\pi$ decays

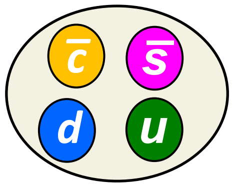
β: $B^0 \to \psi K_{S/L}$ decays, golden channel

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \qquad \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\approx \arg V_{ub}^* \qquad \approx \pi - \alpha - \beta \qquad \approx V_{td}^*$$

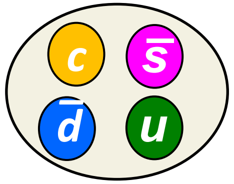
Study of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

2020



$\to D^- K^+$

2023



$\to D_s^+ \pi^\pm$

2024

$B^+ \to D^{*-} D_s^+ \pi^+$
No obvious exotics

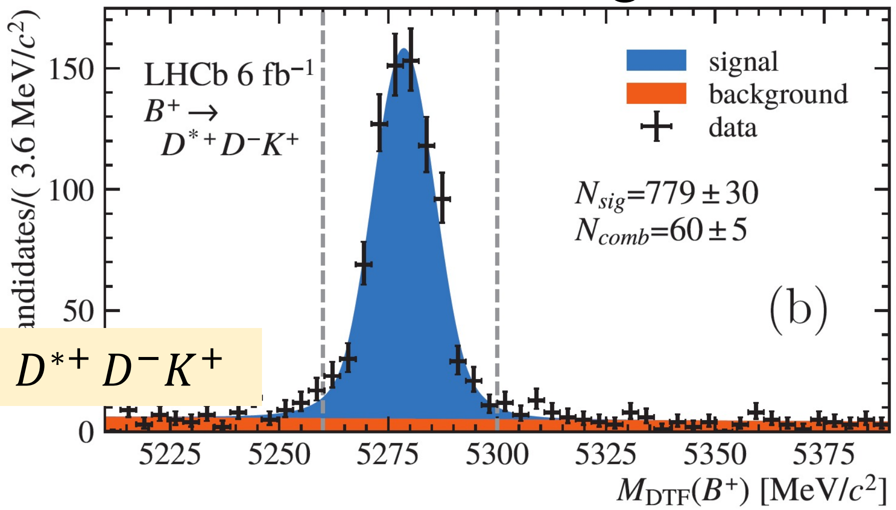
2024

$B^+ \to D^{*\pm} D^{\mp} K^+$

PRL33 (2024) 131902

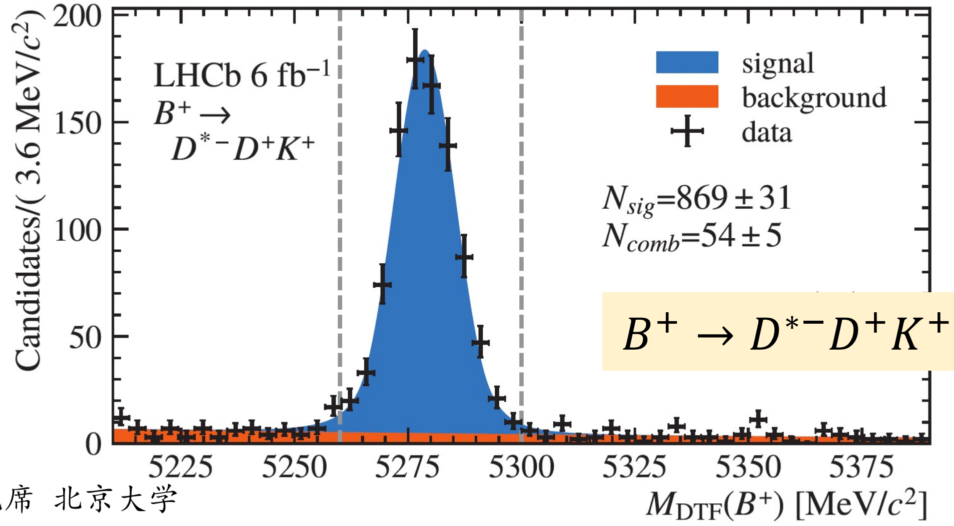
$B^+ \to D^{*\pm} D^{\mp} K^+$ topology similar to $B^+ \to D^- D^+ K^+$ decays

About 1700 signals



$B^+ \to D^{*+} D^- K^+$

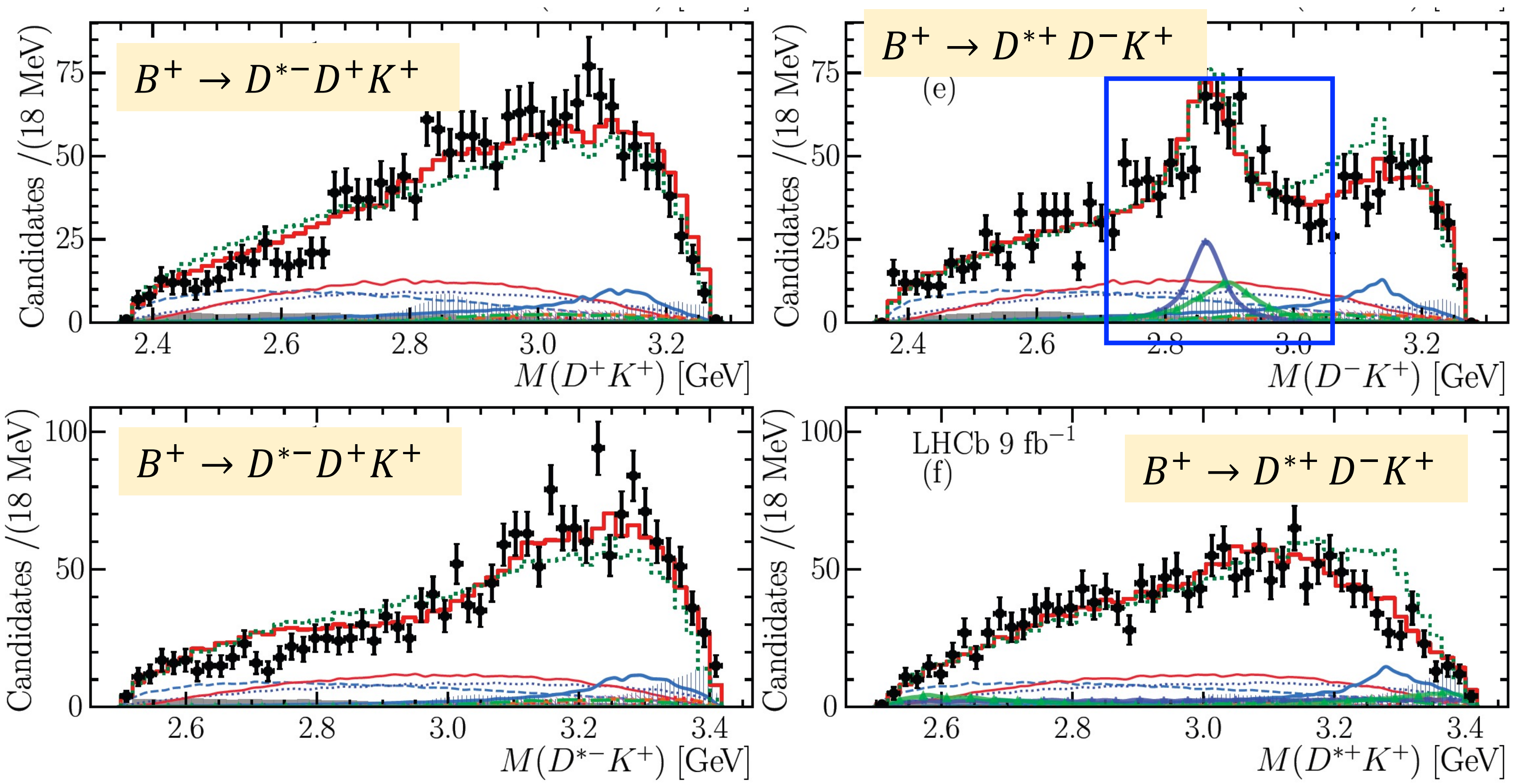
About 1700 signals



$B^+ \to D^{*-} D^+ K^+$

Open charm tetraquarks

arXiv:2406.03156



Statistical significance

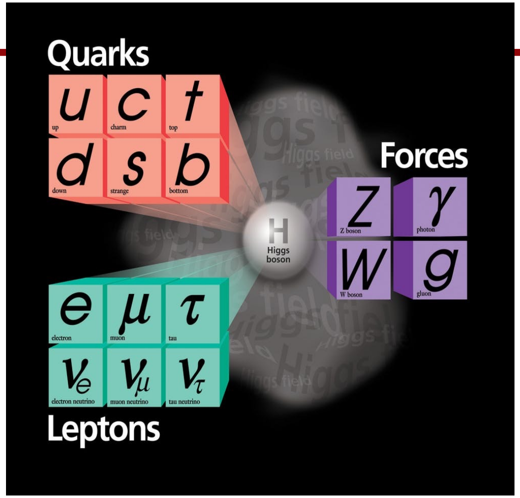
$T^*_{cs0}(2900)^0$: 11σ

$T^*_{cs1}(2900)^0$: 9.2σ

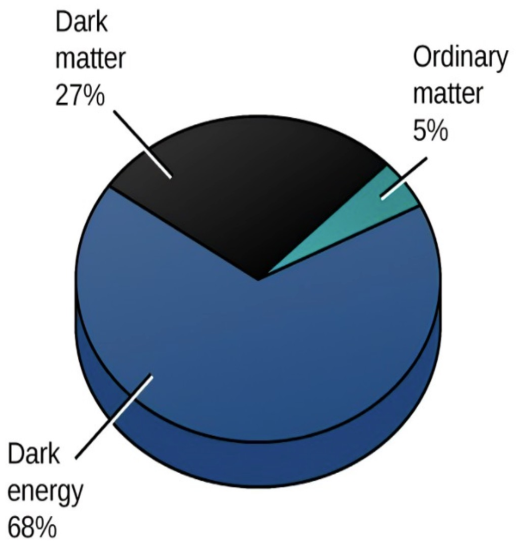
No obvious structure in $D^{*\pm}K^+$ and D^+K^+ spectra

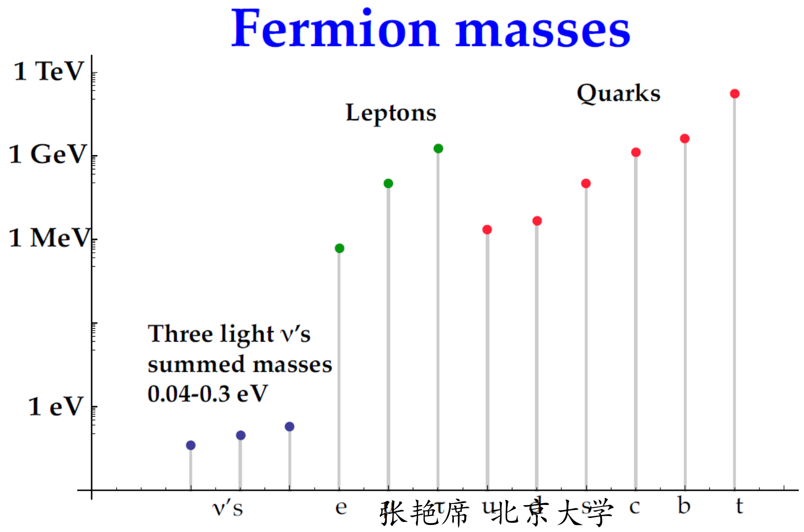
Introduction

- The **Standard Model** (SM): remarkably successful at describing **particles of nature** and **interactions between them**



- But answered questions/observations
  - ➢ Dark matter, dark energy
  - ➢ Baryon Asymmetry in the Universe (BAU): $n_{\mathrm{B}}/n_{\overline{\mathrm{B}}} \gg 1$
  - ➢ Quark/lepton family structure and masses
  - ➢ …





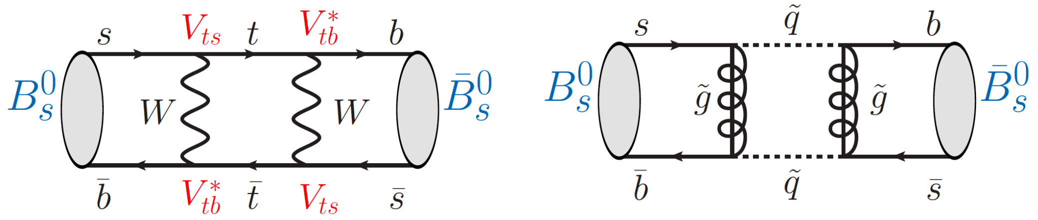
Must there be New Physics (NP)

Flavor physics

- Most SM parameters related to flavor structure

  Yukawa couplings (9), Quark mixing (4), Gauge couplings (3), Higgs potential (2)

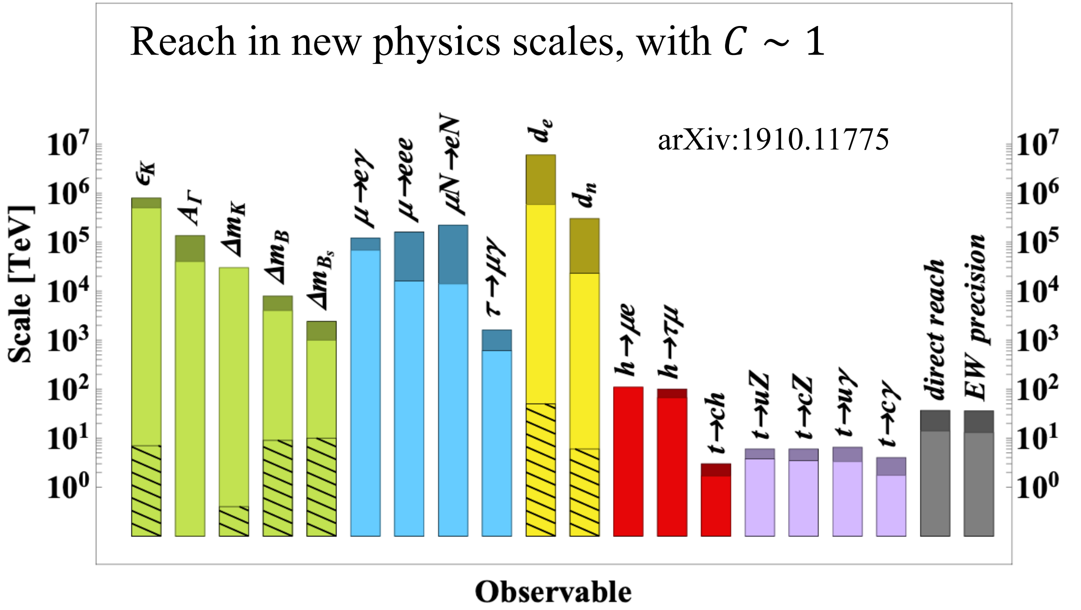
- General idea of flavor physics for NP
  - ➢ Possible new physics enters in (low-energy) quantum loops
  - ➢ Deviations w.r.t SM → possible new physics



Complementary to direct detection of BSM particles/forces, possible to probe energy scales beyond collider energy

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{C_5}{\Lambda_M}\mathscr{O}^{(5)} + \sum_a \frac{C_6^a}{\Lambda^2}\mathscr{O}_a^{(6)} + \cdots$$

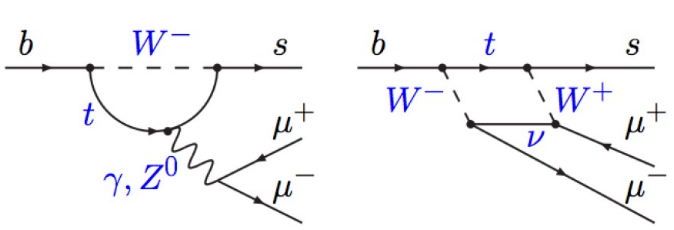
$$\delta_{\rm NP} \sim C_{n+4}/\Lambda^n, \quad \Lambda^n \sim C_{n+4}/\delta_{SM}$$

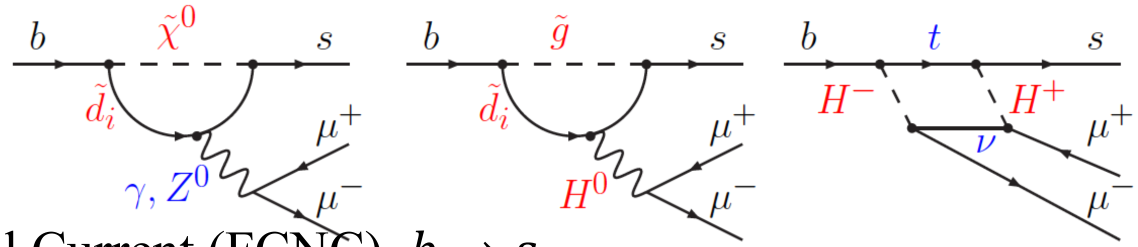


CP violation, mixing, (forbidden) rare decays, lepton flavor universality/violation, EDM…

Quark flavor physics

- SM rare/forbidden decays, may be enhanced/allowed by new physics





E.g.: Flavor Changing Neutral Current (FCNC), $b \to s$…

- Charge conjugation-Parity (CP) violation
  - One of the Sakharov conditions to explain BAU
  - Incorporated in SM by CKM matrix, **quark flavor eigenstates = mixing of mass eigenstates**

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitary matrix
- Four parameters: 3 mixing angle and 1 phase which generates CPV

- Is CKM the only source of CPV? No, CPV from CKM far below that required for BAU

BAU from CKM $J_Y = J_{\rm CP} \frac{(m_t^2 - m_c^2)}{v^2/2} \frac{(m_t^2 - m_u^2)}{v^2/2} \frac{(m_c^2 - m_u^2)}{v^2/2} \frac{(m_b^2 - m_s^2)}{v^2/2} \frac{(m_b^2 - m_d^2)}{v^2/2} \frac{(m_s^2 - m_d^2)}{v^2/2} \simeq \mathcal{O}(10^{-22}) \ll 10^{-10}$