第十届XYZ研讨会

如何系统计算分子态贡献和传统夸克模型贡献

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University of Chinese Academy of Sciences

目录

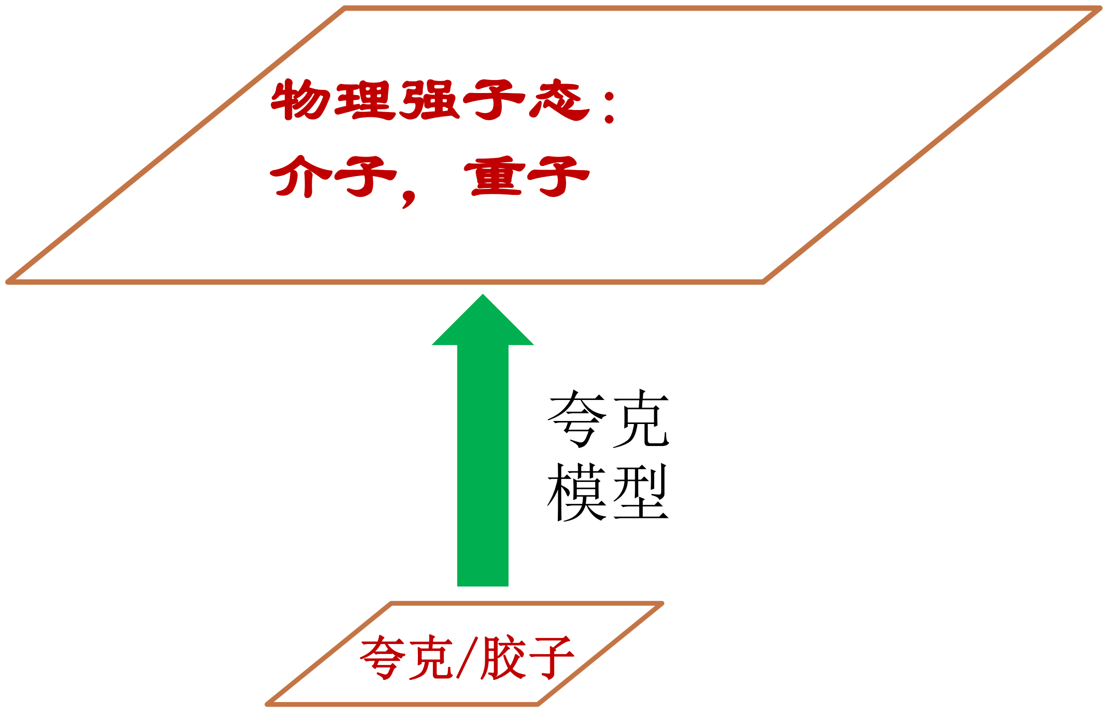
- 动机
- HEFT方案
- 从Tcc 到 X(3872)
- 总结和展望

动机

强子谱？强子结构——

—强子内部的成分？

动机



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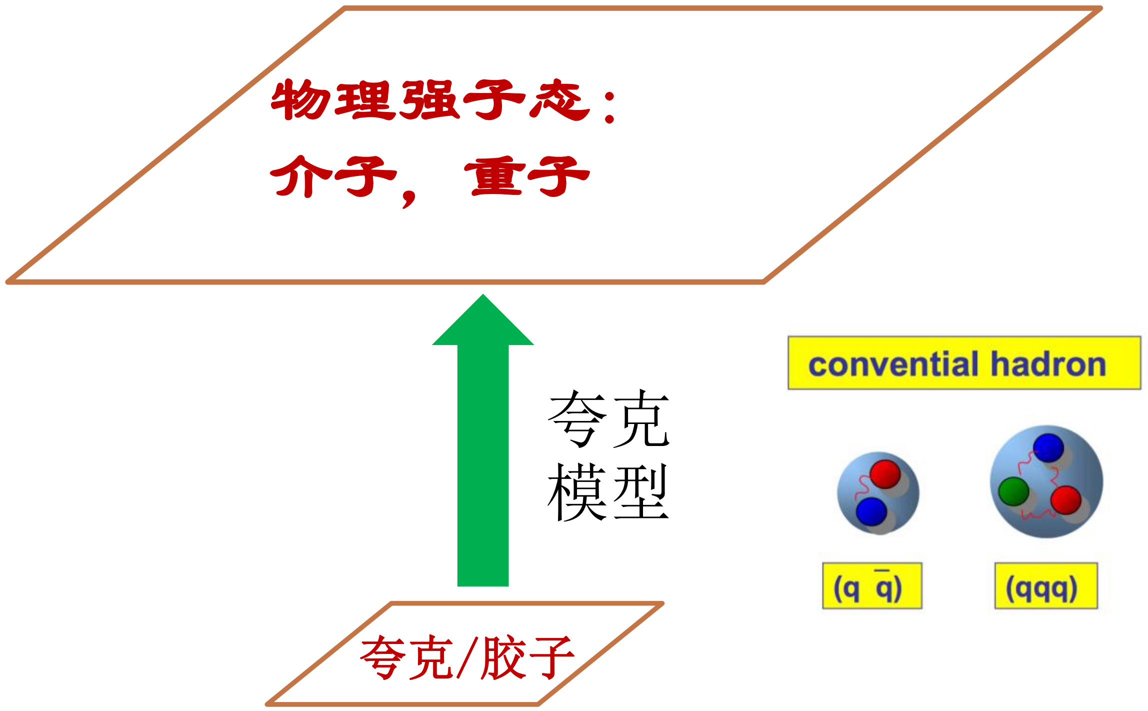

强子谱？强子结构---强子内部的成分？

UNQUENCHED quark model
非淬火夸克模型

动机

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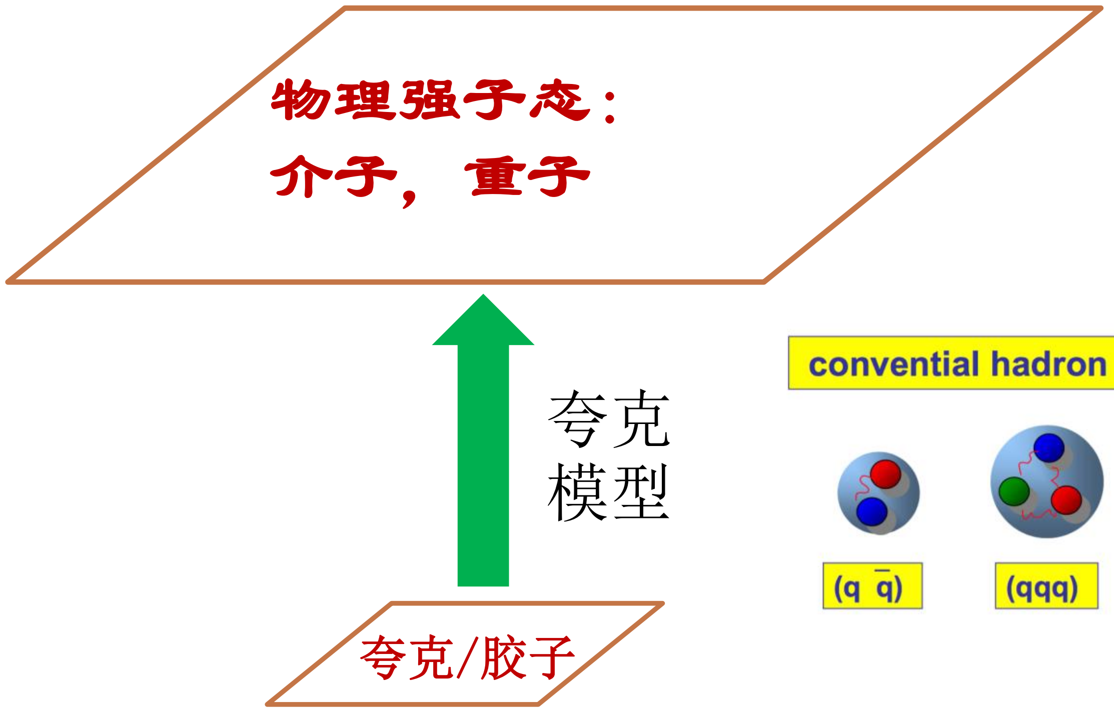
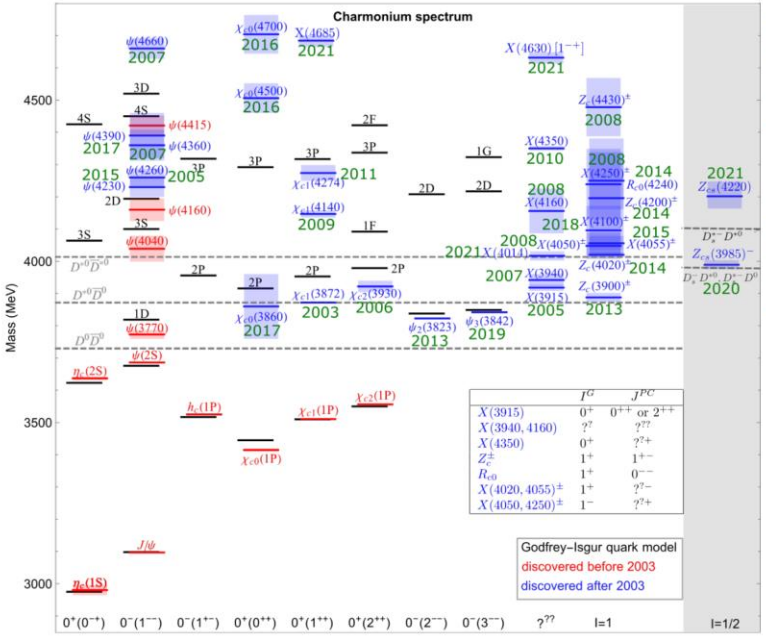


convential hadron

(q q̄) (qqq)



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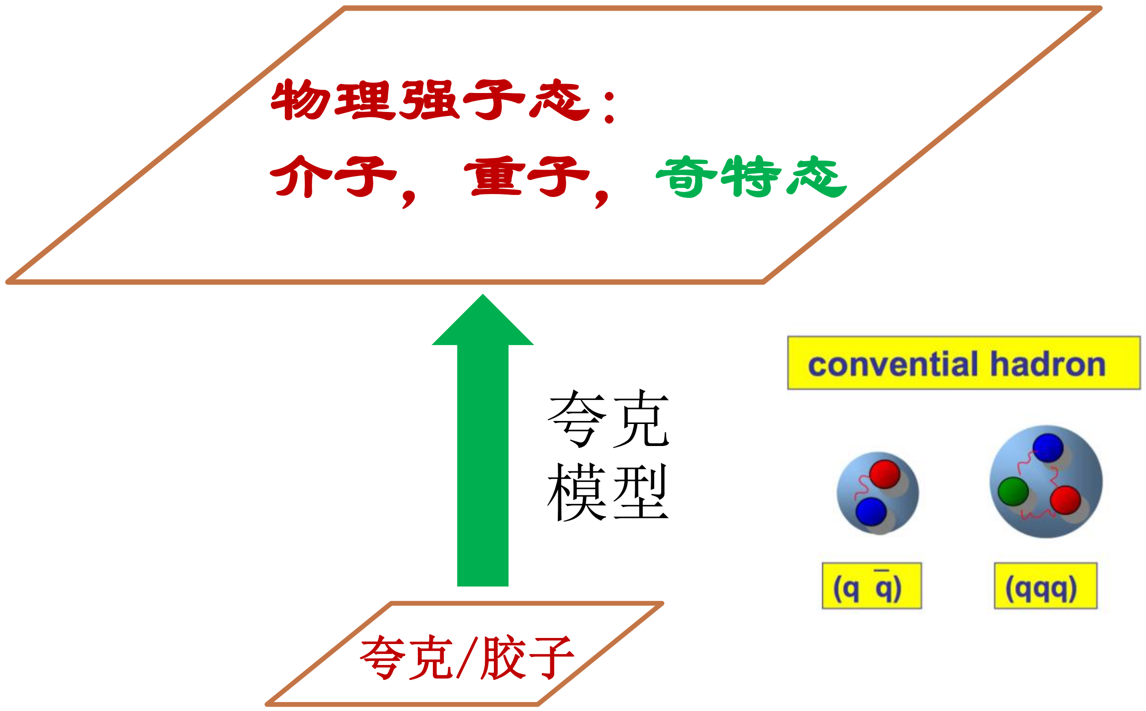

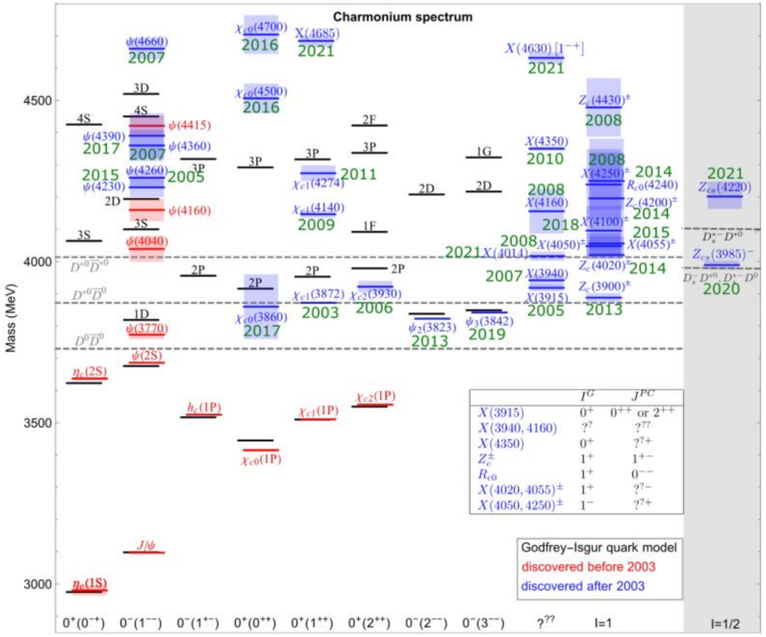

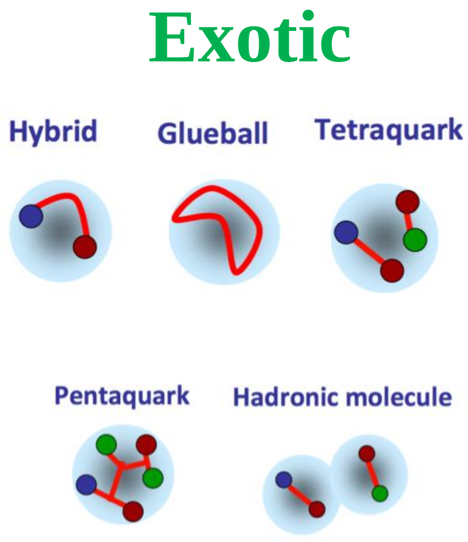

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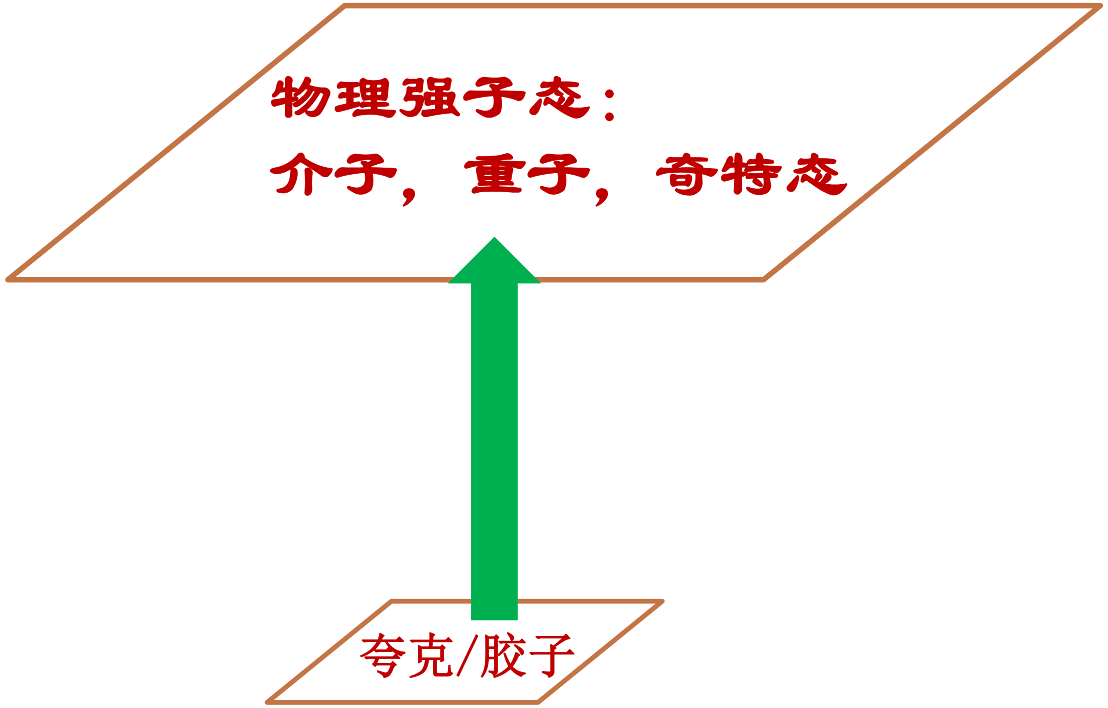

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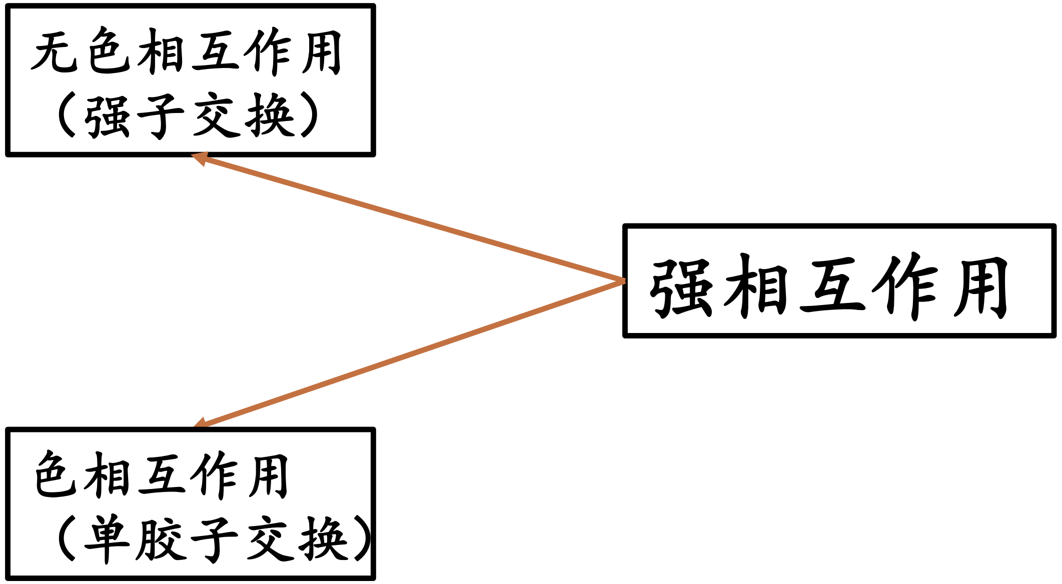

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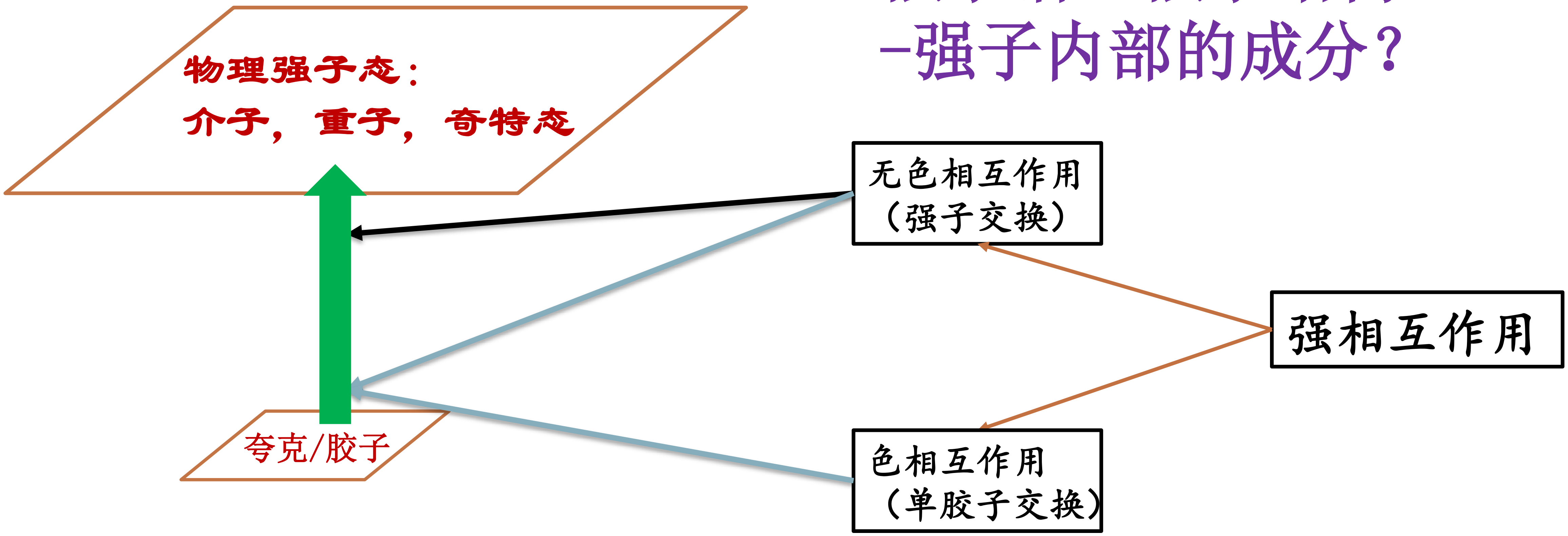

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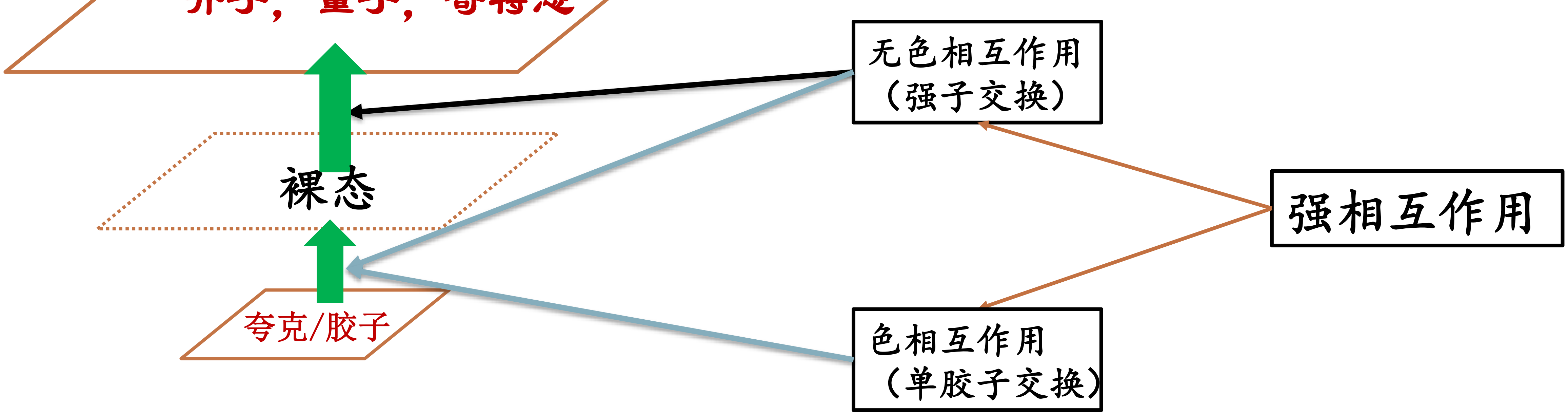

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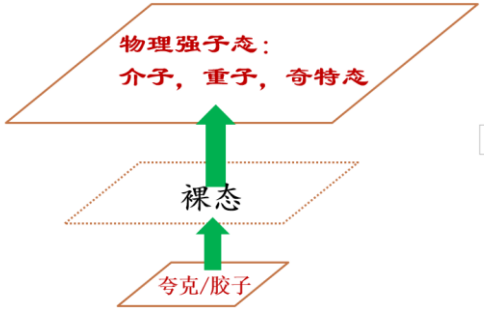
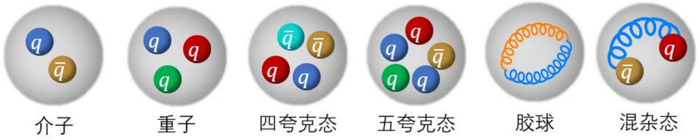
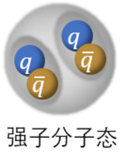


相互作用的完整性：
- 夸克胶子层次
- 强子层次

传统夸克模型贡献



强子：
- 夸克胶子层次：单强子态
- 强子层次：多强子态



耦合道模型

分子态贡献

能够系统描述强子的较为完整的框架

能够描述一系列强子，不是一个两个

HEFT介绍

$$H = H_0 + H_I$$

$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_\alpha)\rangle \left[\sqrt{m_{\alpha 1}^2 + k_\alpha^2} + \sqrt{m_{\alpha 2}^2 + k_\alpha^2}\right] \langle \alpha(k_\alpha)|$$

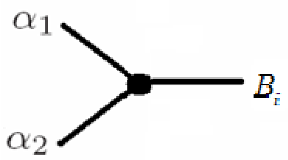
$|B_i>$ bare state， bare mass m_i ⟷ 夸克胶子层次的相互作用

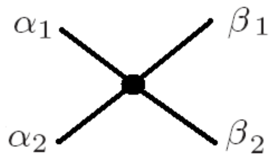
$|\alpha(k_\alpha)>$ non-interaction channels ⟷ 强子层次相互作用

$$H_I = \hat{g} + \hat{v}$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_\alpha)\rangle g_{i,\alpha}^{+} \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_\alpha)| \right]$$

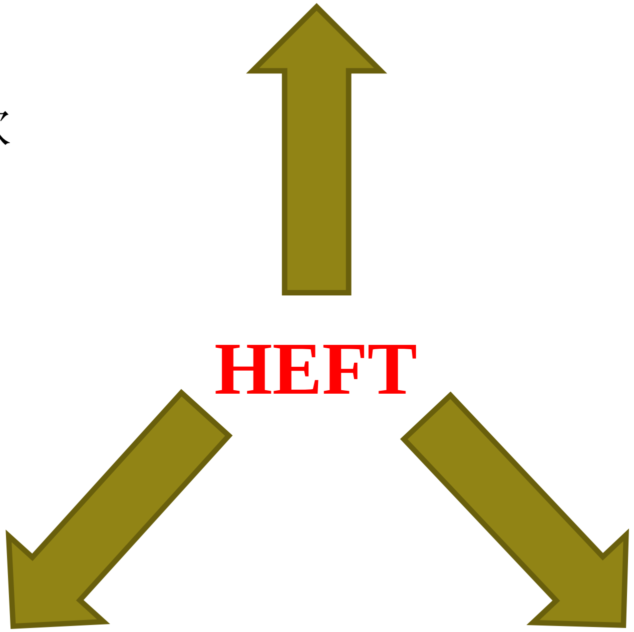
$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_\alpha)\rangle v_{\alpha,\beta} \langle \beta(k_\beta)|$$





共振态

（质量，宽度，极点位置，耦合强度）



HEFT

T 矩阵

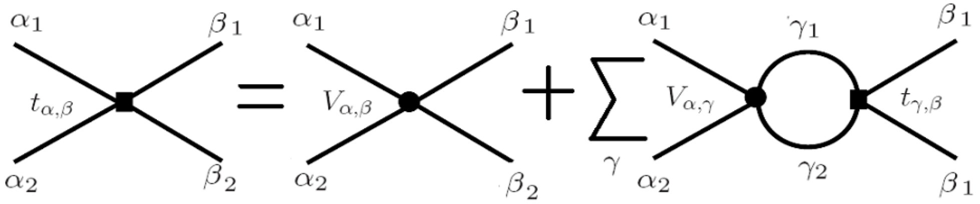
（相移，

非弹系数）

格点能谱

HEFT介绍

$$T_{\alpha\beta}(k_\alpha, k_\beta, E) = V_{\alpha\beta}(k_\alpha, k_\beta) + \sum_\gamma \int k_\gamma{}^2 dk_\gamma \frac{V_{\alpha\gamma}(k_\alpha, k_\gamma) T_{\gamma\beta}(k_\gamma, k_\beta, E)}{E - \sqrt{m_{\gamma 1}^2 + k_\gamma^2} - \sqrt{m_{\gamma 2}^2 + k_\gamma^2} + i\varepsilon}$$



HEFT介绍

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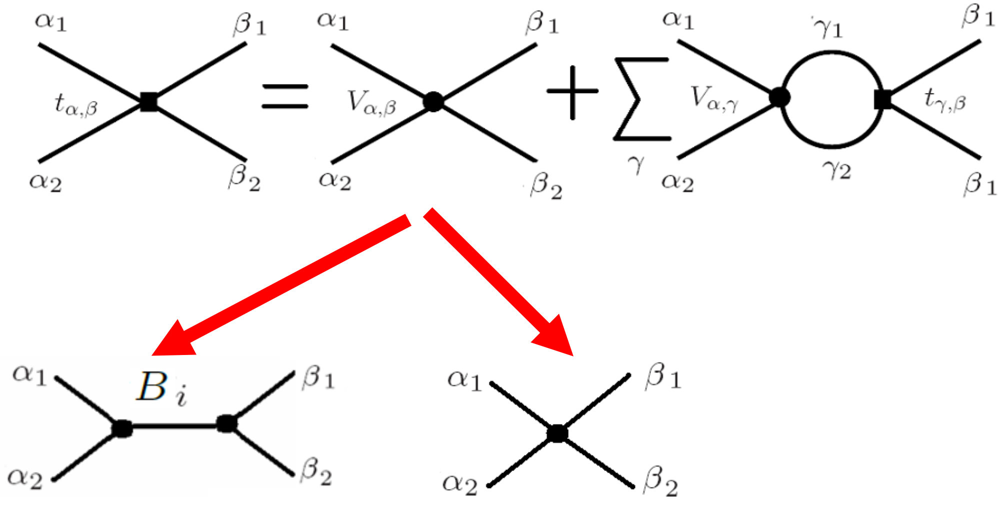

$$G_\alpha^{B*}\frac{1}{E-m_B}G_\beta^B$$

$$V_{\alpha,\beta}$$

$$G_{MN}^B(k) = \frac{g_{MN}^B}{m_M}\frac{k}{\sqrt{\omega_M(k)}}u(k).$$

$$v_{\alpha\beta}(k,k')=v_{\alpha\beta}f_\alpha(k)f_\beta(k')$$

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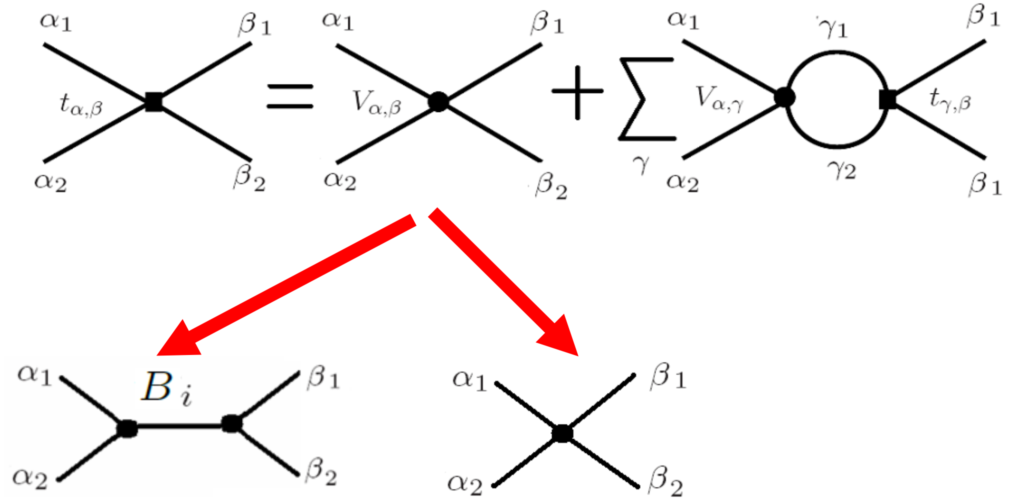
$$T_{\alpha\beta}\left(k,k';E\right)=t_{\alpha\beta}\left(k,k';E\right)+T_{\alpha\beta}^{bare}\left(k,k';E\right)$$



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$$G_{MN}^B(k) = \frac{g_{MN}^B}{m_M}\frac{k}{\sqrt{\omega_M(k)}}u(k). \qquad v_{\alpha\beta}\left(k,k'\right)=v_{\alpha\beta}f_\alpha(k)f_\beta(k')$$

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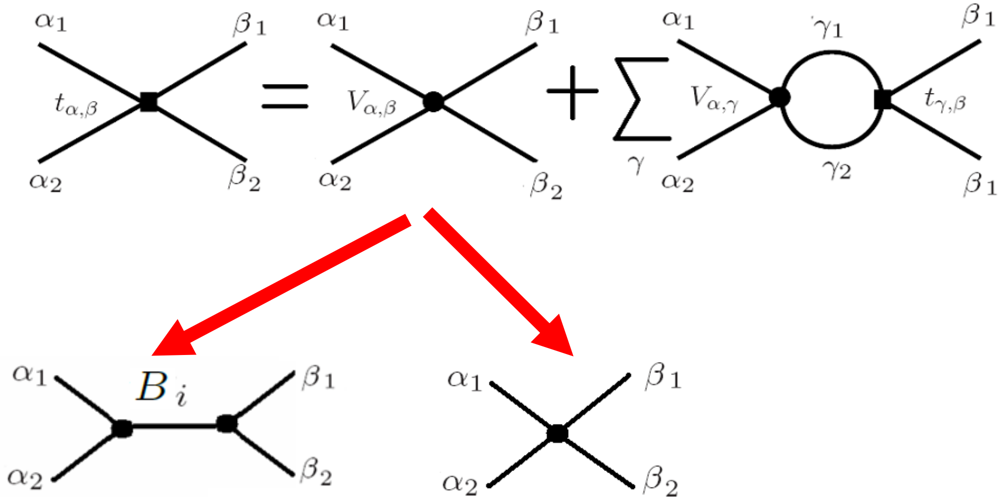

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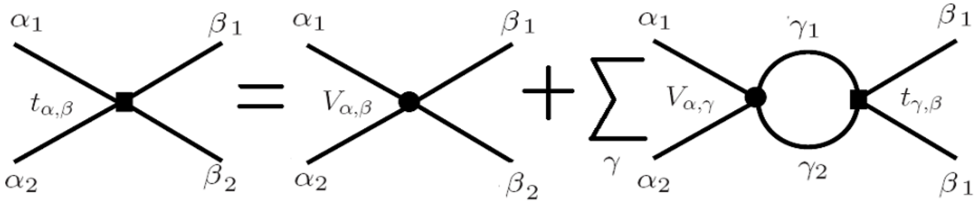

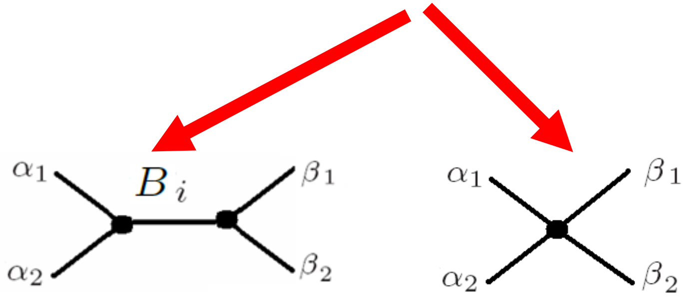

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HEFT介绍

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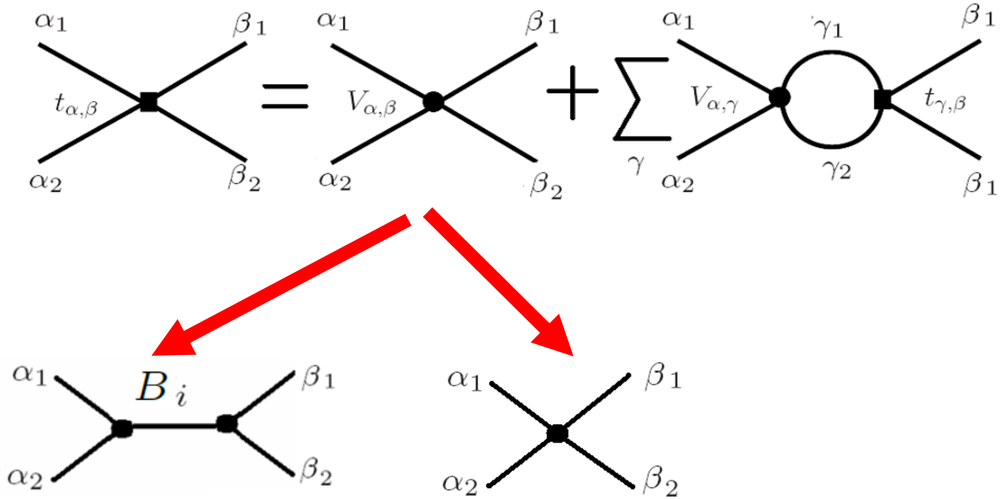

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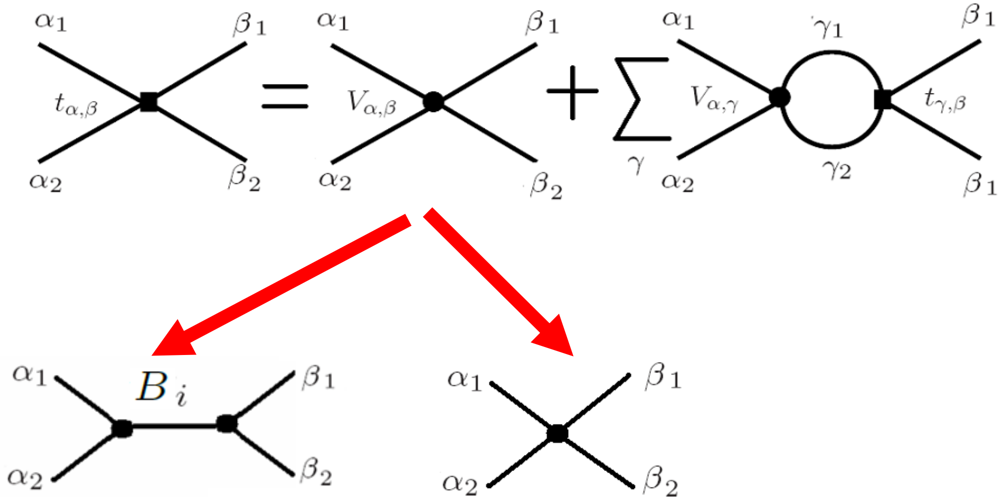

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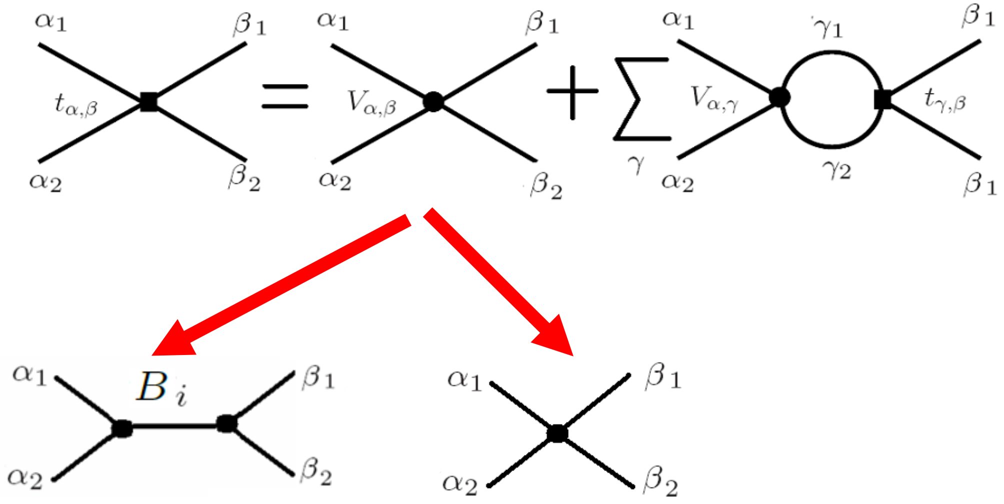
$$A^{-1}_{BB'}(E)=\delta_{BB'}(E-m_B)-\bar{\Sigma}_{BB'}(E)$$

$$\bar{\Sigma}_{BB'}(E)=\Sigma_{BB'}(E)+\Sigma^I_{BB'}(E) \qquad \Sigma_{BB'}(E)=\sum_\gamma\int dqq^2\frac{G^B_\gamma(q)G^{B'\,*}_\gamma(q)}{E-\omega_\gamma(k)+i\epsilon}$$

$$\Sigma^{\rm I}_{BB'}(E)=\sum_{\alpha,\beta}\bar{g}^B_{f,\alpha}(E)\tilde{t}_{\alpha\beta}(E)g^{B'}_{f,\beta}(E)$$

HEFT介绍

$$T_{\alpha\beta}(k_\alpha,k_\beta,E)=V_{\alpha\beta}(k_\alpha,k_\beta)+\sum_\gamma\int k_\gamma^{\ 2}dk_\gamma\frac{V_{\alpha\gamma}(k_\alpha,k_\gamma)T_{\gamma\beta}(k_\gamma,k_\beta,E)}{E-\sqrt{m_{\gamma1}^2+k_\gamma^2}-\sqrt{m_{\gamma2}^2+k_\gamma^2}+i\varepsilon}$$



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$$T_{\alpha\beta}^{\mathrm{bare}}(k,k';E)=\bar{\mathcal{G}}_\alpha^{B\dagger}(k;E)A_{BB'}(E)\mathcal{G}_\beta^{B'}(k';E)$$

$$\mathcal{G}_\alpha^B(k;E)=G_\alpha^B+\sum_\gamma f_\alpha(k)\tilde{t}_{\alpha\gamma}(E)g_{f,\gamma}^B(E) \qquad g_{f,\gamma}^B(E)=\int dqq^2\frac{f_\gamma(q)G_\gamma^B(q)}{E-\omega_\gamma(q)+i\epsilon}$$

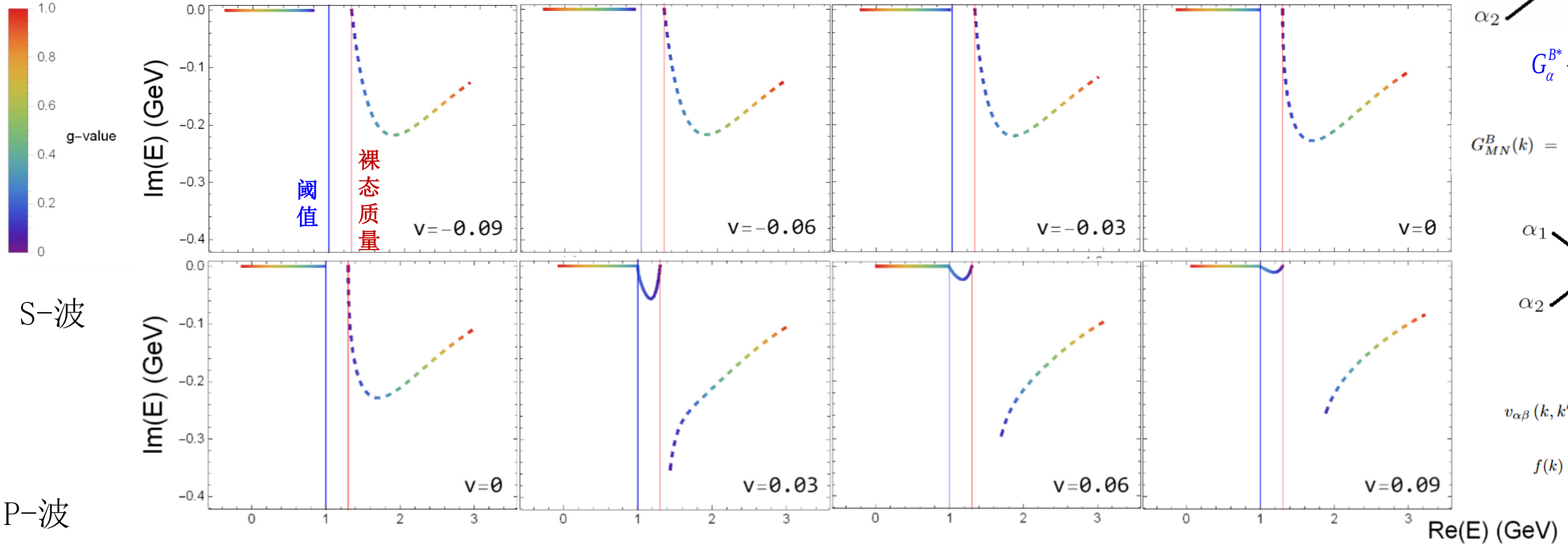
$$\bar{\mathcal{G}}_\alpha^B(k;E)=G_\alpha^{B*}+\sum_\gamma \bar{g}_{f,\gamma}^B(E)\tilde{t}_{\gamma\alpha}(E)f_\alpha(k) \qquad \bar{g}_{f,\gamma}^B(E)=\int dqq^2\frac{f_\gamma(q)G_\gamma^{B*}(q)}{E-\omega_\gamma(q)+i\epsilon}$$

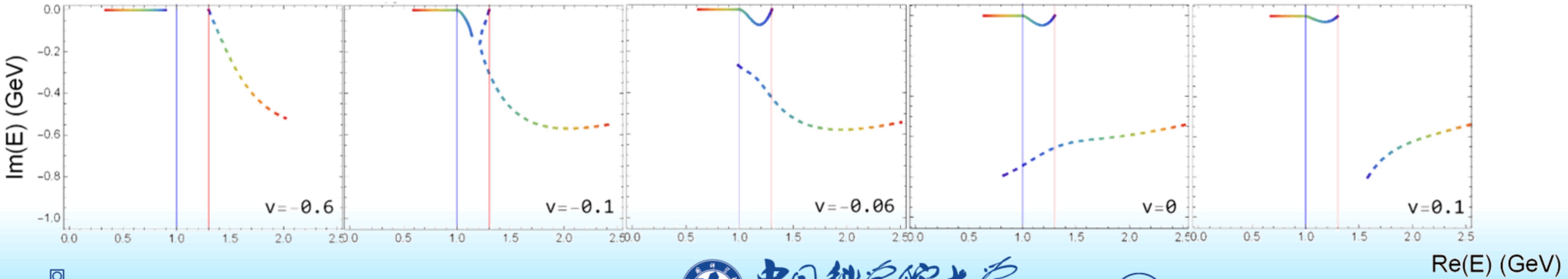
$$A_{BB'}^{-1}(E)=\delta_{BB'}(E-m_B)-\bar{\Sigma}_{BB'}(E) \qquad \mathbf{det}[A^{-1}]=0$$

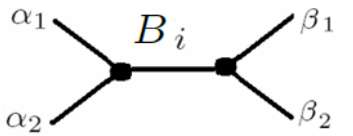
$$\bar{\Sigma}_{BB'}(E)=\Sigma_{BB'}(E)+\Sigma_{BB'}^I(E) \qquad \Sigma_{BB'}(E)=\sum_\gamma\int dqq^2\frac{G_\gamma^B(q)G_\gamma^{B'*}(q)}{E-\omega_\gamma(k)+i\epsilon}$$

$$\Sigma_{BB'}^{\mathrm{I}}(E)=\sum_{\alpha,\beta}\bar{g}_{f,\alpha}^B(E)\tilde{t}_{\alpha\beta}(E)g_{f,\beta}^{B'}(E)$$

HEFT介绍----奇点的轨迹（初步）

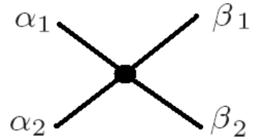






$$G_\alpha^{B*}\frac{1}{E-m_B}G_\beta^B$$

$$G^B_{MN}(k) = \frac{g^B_{MN}}{m_M}\frac{k}{\sqrt{\omega_M(k)}}u(k).$$



$$v_{\alpha,\beta}$$

$$v_{\alpha\beta}(k,k') = v_{\alpha\beta} f_\alpha(k) f_\beta(k')$$

$$f(k) = \frac{1}{m_M^2}\frac{k}{\omega_M(k)}u(k)$$

Tcc-X(3872)

$$H = H_0 + H_I$$

$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_\alpha)\rangle \left[\sqrt{m_{\alpha 1}^2 + k_\alpha^2} + \sqrt{m_{\alpha 2}^2 + k_\alpha^2} \right] \langle \alpha(k_\alpha)|$$

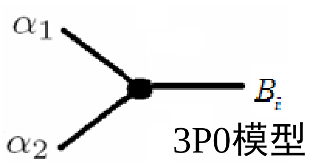
|Bᵢ> bare state， bare mass mᵢ ⟷ 夸克胶子层次的相互作用

$|\alpha(k_\alpha)\rangle$ non-interaction channels ⟷ 强子层次相互作用

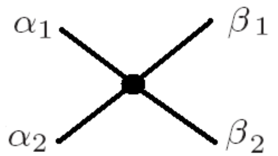
$$H_I = \hat{g} + \hat{v}$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_\alpha)\rangle g_{i,\alpha}^{+} \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_\alpha)| \right]$$

$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_\alpha)\rangle v_{\alpha,\beta} \langle \beta(k_\beta)|$$



3P0模型，利用从夸克模型中得到的裸态波函数。



单玻色子交换 OBE

共振态

（质量，宽度，极点位置，耦合强度）

HEFT

T 矩阵

（相移，非弹系数）

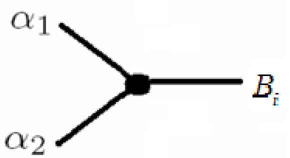
格点能谱

HEFT介绍

$$H = H_0 + H_I = H_0 + g + \hat{v}$$

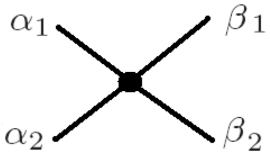
$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_\alpha)\rangle \left[\sqrt{m_{\alpha 1}^2 + k_\alpha^2} + \sqrt{m_{\alpha 2}^2 + k_\alpha^2}\right] \langle \alpha(k_\alpha)|$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_\alpha)\rangle g_{i,\alpha}^{+} \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_\alpha)| \right]$$



3P0模型，利用从夸克模型中得到的裸态波函数。

$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_\alpha)\rangle v_{\alpha,\beta} \langle \beta(k_\beta)|$$



单玻色子交换 OBE

问题：两种相互作用怎么办？

a+b=5的解有太多了

以T_{cc}和X(3872)给出方案

共振态

（质量，宽度，极点位置，耦合强度）

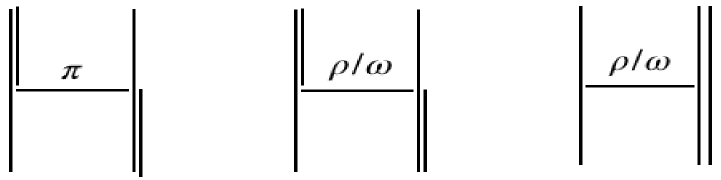
HEFT

T 矩阵（相移，非弹系数）

格点能谱

单玻色子交换势能 DD^* vs $D\bar{D}^*$

D 和 D* 在单玻色子交换势下（OBE）



$$V_\pi = \frac{g^2}{f_\pi^2}\frac{(q\cdot\epsilon_\lambda)\left(q\cdot\epsilon_{\lambda'}^\dagger\right)}{q^2-m_\pi^2},$$

$$V_{\rho/\omega}^u = -2\lambda^2 g_V^2\frac{(\epsilon_{\lambda'}^\dagger\cdot q)(\epsilon_\lambda\cdot q)-q^2\left(\epsilon_\lambda\cdot\epsilon_{\lambda'}^\dagger\right)}{q^2-m_{\rho/\omega}^2},$$

$$V_{\rho/\omega}^t = \frac{\beta^2 g_V^2}{2}\frac{\left(\epsilon_\lambda\cdot\epsilon_{\lambda'}^\dagger\right)}{q^2-m_{\rho/\omega}^2}.$$

PWA 仅仅S波

$$\mathcal{V}(l,l'S,j) = \frac{1}{(2\pi)^3}\sqrt{\frac{1}{2E_D^i 2E_D^f 2E_K^i 2E_K^f}}$$

$$2\pi\int dcos\theta V^v(\vec{p}_f,\vec{p}_i)\left(\frac{\Lambda^2}{\Lambda^2+p_f^2}\right)^2\left(\frac{\Lambda^2}{\Lambda^2+p_i^2}\right)^2$$

- $g = 0.57$ 从$D^* \to D\pi$ 的衰变宽度获得， $\lambda\&\beta$ 是自由参数

重夸克对称性

$D^{(*)}D^{(*)}$

$$H_a^{(Q)} = \frac{1+\not{v}}{2}\left[P_a^{*\mu}\gamma_\mu - P_a\gamma_5\right]$$

$$\bar{H}_a^{(Q)} \equiv \gamma_0 H^{(Q)\dagger}\gamma_0 = \left[P_a^{*\dagger\mu}\gamma_\mu + P_a^\dagger\gamma_5\right]\frac{1+\not{v}}{2}$$

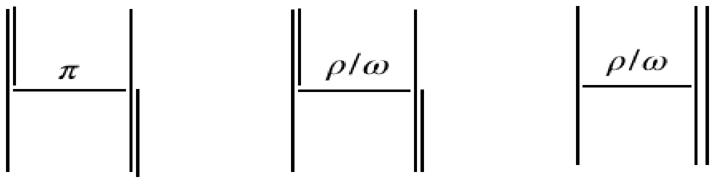
$$P = (D^0, D^+, D_s^+)\ \&P^* = (D^{*0}, D^{*+}, D_s^{*+})$$

$$\mathcal{L}_{MH^{(Q)}H^{(Q)}} = ig\,\mathrm{Tr}\left[H_b^{(Q)}\gamma_\mu\gamma_5 A_{ba}^\mu \bar{H}_a^{(Q)}\right]$$

$$\mathcal{L}_{VH^{(Q)}H^{(Q)}} = i\beta\,\mathrm{Tr}\left[H_b^{(Q)}v_\mu\left(V_{ba}^\mu-\rho_{ba}^\mu\right)\bar{H}_a^{(Q)}\right] + i\lambda\,\mathrm{Tr}\left[H_b^{(Q)}\sigma_{\mu\nu}F^{\mu\nu}(\rho)_{ba}\bar{H}_a^{(Q)}\right]$$

单玻色子交换势能 DD^* vs $D\bar{D}^*$

D 和 D* 在单玻色子交换势下（OBE）



$$V_\pi = \frac{g^2}{f_\pi^2}\frac{(q\cdot\epsilon_\lambda)\left(q\cdot\epsilon^\dagger_{\lambda'}\right)}{q^2-m_\pi^2},$$

$$V^u_{\rho/\omega} = -2\lambda^2 g_V^2 \frac{(\epsilon^\dagger_{\lambda'}\cdot q)(\epsilon_\lambda\cdot q) - q^2\left(\epsilon_\lambda\cdot\epsilon^\dagger_{\lambda'}\right)}{q^2-m^2_{\rho/\omega}},$$

$$V^t_{\rho/\omega} = \frac{\beta^2 g_V^2}{2}\frac{\left(\epsilon_\lambda\cdot\epsilon^\dagger_{\lambda'}\right)}{q^2-m^2_{\rho/\omega}}.$$

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$$H_a^{(\bar{Q})} \equiv C\left(\mathcal{C}H_a^{(Q)}\mathcal{C}^{-1}\right)^T C^{-1} = \left[P^{(\bar{Q})*}_{a\mu}\gamma^\mu - P_a^{(\bar{Q})}\gamma_5\right]\frac{1-\not{v}}{2}$$

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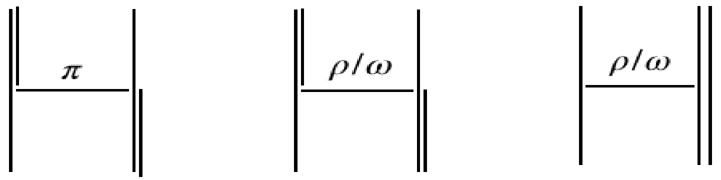
$D^{(*)}\overline{D^{(*)}}$

单玻色子交换势能 DD^* vs $D\bar{D}^*$

D 和 D* 在单玻色子交换势下（OBE）



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	wave function	$I(J^{PC})$	$u-$channel : π	$u-$channel : ρ/ω	$t-$channel : ρ/ω
DD^*	$\frac{1}{\sqrt{2}}(D^+D^{*0}-D^0D^{*+})$	$0(1^+)$ $[T_{cc}^+]$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V^u_\rho-\frac{1}{2}V^u_\omega$	$-\frac{3}{2}V^t_\rho+\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}(D^+D^{*0}+D^0D^{*+})$	$1(1^+)$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V^u_\rho+\frac{1}{2}V^u_\omega$	$\frac{1}{2}V^t_\rho+\frac{1}{2}V^t_\omega$
$D\bar{D}^*$	$\frac{1}{\sqrt{2}}([D^+D^{*-}]+[D^0\bar{D}^{*0}])$	$0(1^{++})[X(3872)]$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V^u_\rho-\frac{1}{2}V^u_\omega$	$-\frac{3}{2}V^t_\rho-\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}([D^+D^{*-}]-[D^0\bar{D}^{*0}])$	$1(1^{++})$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V^u_\rho-\frac{1}{2}V^u_\omega$	$\frac{1}{2}V^t_\rho-\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\}+\{D^0\bar{D}^{*0}\})$	$0(1^{+-})[h_c]$	$-\frac{3}{2}V_\pi$	$\frac{3}{2}V^u_\rho+\frac{1}{2}V^u_\omega$	$-\frac{3}{2}V^t_\rho-\frac{1}{2}V^t_\omega$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\}-\{D^0\bar{D}^{*0}\})$	$1(1^{+-})$ $[Z_c(3900)]$	$\frac{1}{2}V_\pi$	$-\frac{1}{2}V^u_\rho+\frac{1}{2}V^u_\omega$	$\frac{1}{2}V^t_\rho-\frac{1}{2}V^t_\omega$

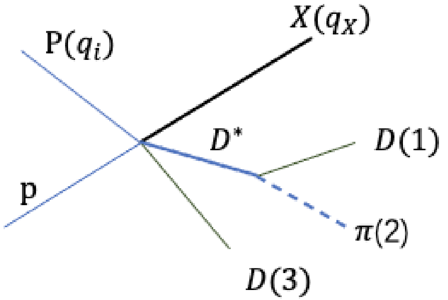
带电和中性粒子的质量不同会导致同位旋破坏，因此在实际计算中我们的态矢量直接使用粒子态而不是同位旋本征态。

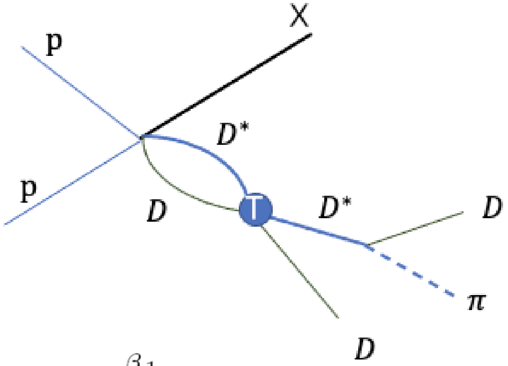
T_{cc} → $DD^*, D\bar{D}^*$ interaction

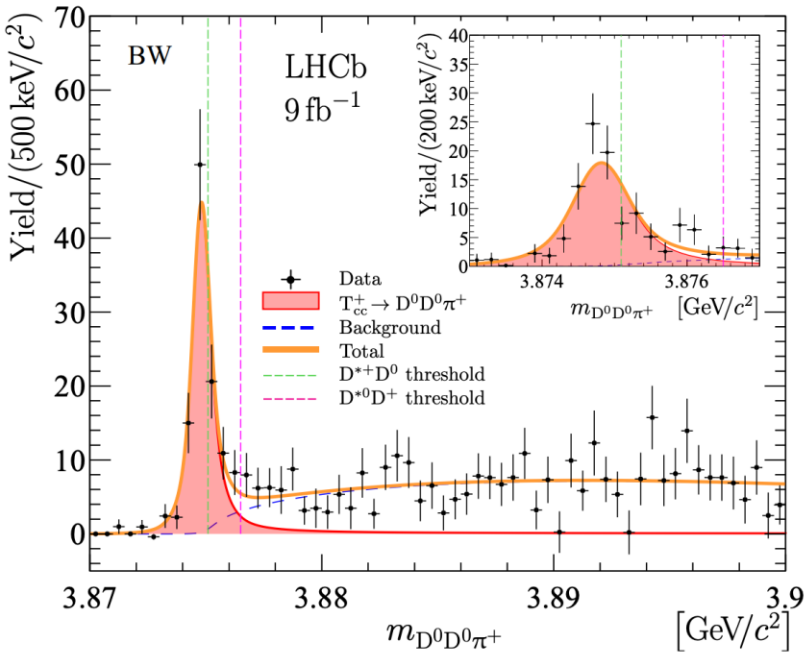
T_{cc}的产生

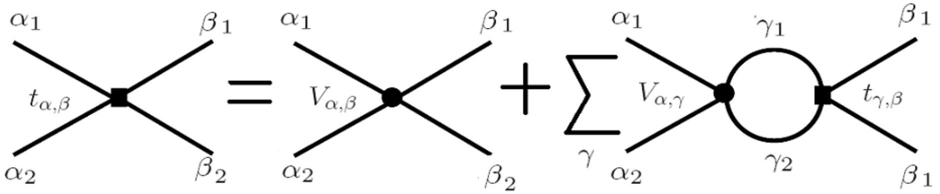
$pp \to X\ D^0 D^0 \pi^+$

p^t









$$t_{\alpha,\beta}(k_\alpha,k_\beta,E)=V_{\alpha,\beta}(k_\alpha,k_\beta)+\sum_\gamma\int k_\gamma{}^2 dk_\gamma \frac{V_{\alpha,\gamma}(k_\alpha,k_\gamma)t_{\gamma,\beta}(k_\gamma,k_\beta,E)}{E-\sqrt{m_{\gamma1}^2+k_\gamma^2}-\sqrt{m_{\gamma2}^2+k_\gamma^2}+i\varepsilon}$$

$$|\mathcal{M}|^2=|a_{pp\to DD^*X}|^2\sum_{\lambda_X}\epsilon_\mu(p_X,\lambda_X)\epsilon^\dagger_{\mu'}(p_X,\lambda_X)\sum_j\mathcal{B}_{j\mu}\mathcal{B}_j^{\dagger\mu'}$$

$$\mathcal{B}_j^\mu(p_{12},p_{23})=g\left\{\frac{-i(p_\pi^\mu-\frac{p_{12}^\mu p_{12}\cdot p_\pi}{m_{D^*}^2})}{p_{12}^2-m_{D^*}^2+im_{D^*}\Gamma_{D^*}}\right\}_j+\sum_{i=1,2}ig\left\{\int dq_{D^*}q_{D^*}^2\frac{d\Omega_{q_{D^*}}}{4\pi}\frac{\sqrt{2w_{D_2}}}{\sqrt{2w_{D^*}}}\frac{\sqrt{2w_{D_{12}^*}}}{\sqrt{2w_D}}\frac{T_{ij}^{J00}(M,|q_{D^*}|,|p_{12}|)}{(M-w_{D^*}^i)-w_D^i+i\epsilon}\frac{\epsilon_a^{*\mu}(w_{D^*},q_{D^*})\epsilon_a(p_{12})\cdot p_\pi}{p_{12}^2-m_{D^*}^2+im_{D^*}\Gamma_{D^*}}\right\}_j+(p_{D_1}\to p_{D_2})$$

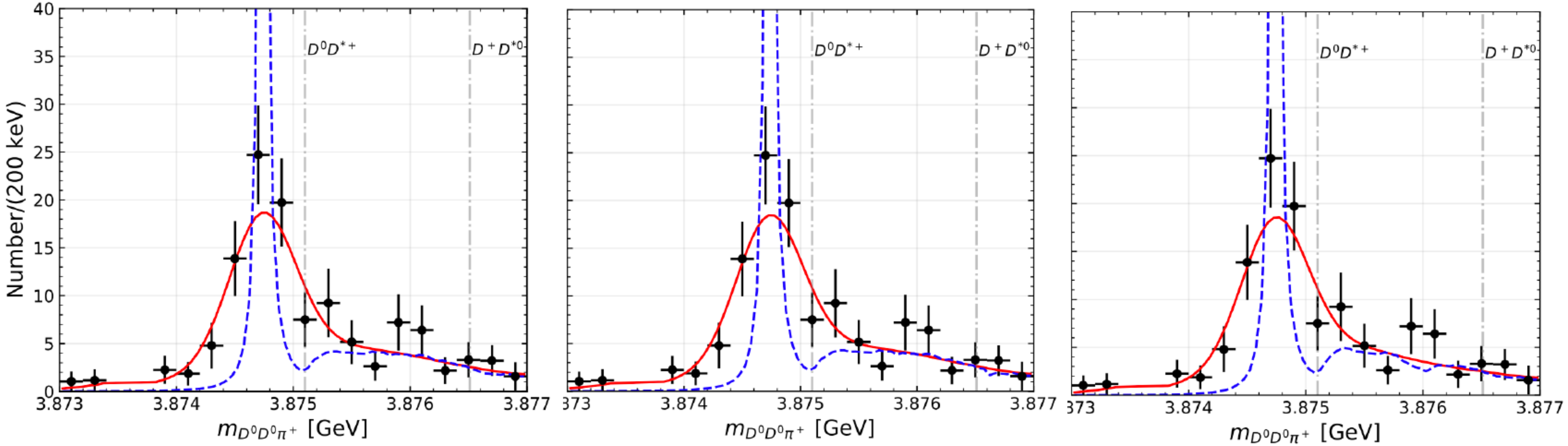
检查阶段参数的稳定性

T_{cc}的产生

$$pp \to X\, D^0 D^0 \pi^+$$

Λ(fixed)	λ（/GeV）	β
0.8 GeV	0.890 ± 0.20	0.810 ± 0.11
1 GeV	0.683 ± 0.025	0.687 ± 0.017
1.2 GeV	0.587±0.21	0.550±0.12
1.17 GeV	0. 56	0. 9

Cheng, et al. PRD 106,016012



Λ (GeV)	BE (keV)	Γ (keV)	$\sqrt{\langle r^2\rangle}$	$I=0$	$I=1$	$P(D^0D^{*+})$	$P(D^+D^{*0})$	$\frac{\mathrm{Res}(D^0D^{*+})}{\mathrm{Res}(D^+D^{*0})}$
0.8	-387.7	67.3	4.8 fm	95.8%	4.2%	70.0%	30.0%	$-1.063+0.001I$
1.0	-393.0	70.4	4.7 fm	95.8%	4.2%	70.0%	30.0%	$-1.055+0.001I$
1.2	-391.6	72.7	4.7 fm	95.7%	4.3%	70.3%	29.7%	$-1.052+0.001I$

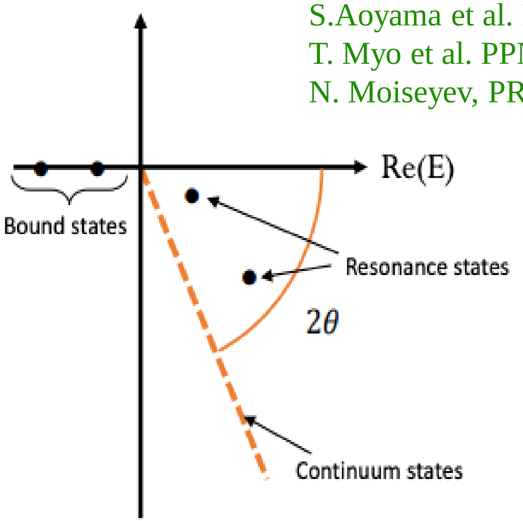
T_{cc}的性质

Complex scaling method

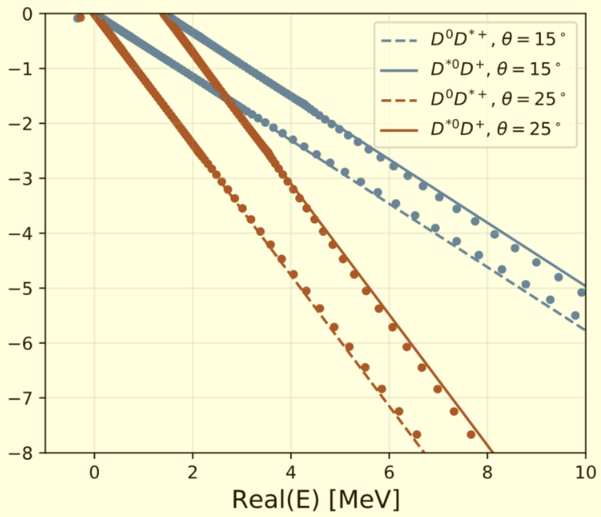
$$\boldsymbol{r} \to \boldsymbol{r}e^{i\theta}, \quad \boldsymbol{q} \to \boldsymbol{q}e^{-i\theta} \qquad H_\theta\Phi_\theta = E_\theta\Phi_\theta,$$

$\overline{D^{*0}}D^0 \,/\, \overline{D^0}D^{*0}$ Coupled-channel effect

$\cdots$ $D^{*-}D^+/D^{*+}D^-$



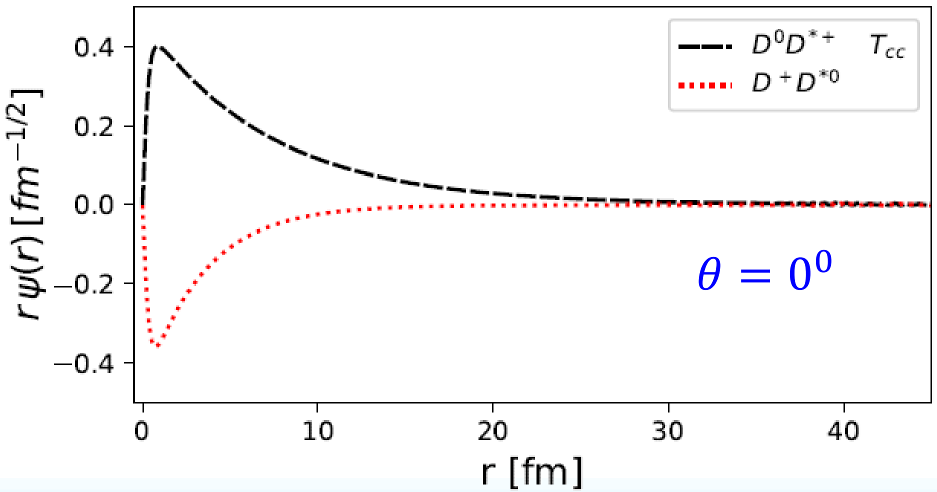
S.Aoyama et al. PTP. 116, 1 (2006).
T. Myo et al. PPNP. 79, 1 (2014)
N. Moiseyev, PR 302, 212 (1998)



- **Bound state: T_{cc}**
  $m_{T_{cc}}$=3874.7 MeV,
  $\Delta E = -393$ keV
  $\Gamma_{T_{cc}} = 70.4$ keV
- $\sqrt{\langle r^2 \rangle} = 4.7\ fm$
- 70.0% $D^{*+}D^0$, 30.0% D^+D^{*0}

95.8%, $DD^*(I=0)$
4.2% $DD^*(I=1)$

Because of mass difference



$$[I=0] = \frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

$$[I=1] = \frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$

问题：两种相互作用怎么办？

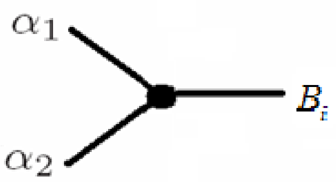
a+b=5的解有太多了

利用T_{cc}限定强子耦合道相互作用再确定 X(3872) 的性质

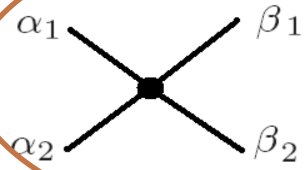
T_{cc} → $DD^*, D\bar{D}^*$ interaction

$c\bar{c}$ state ↓

X(3872)



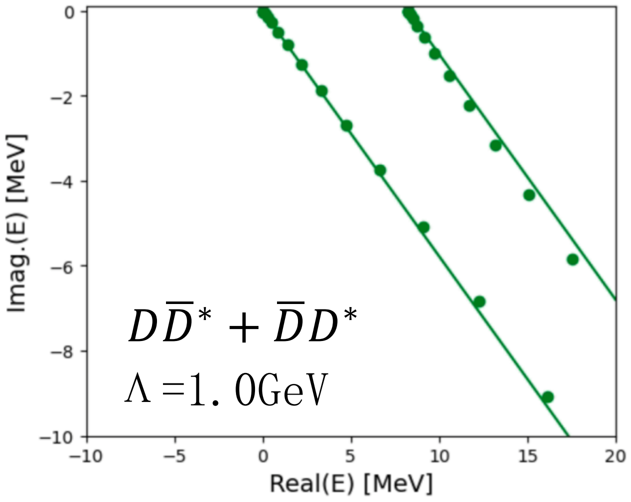
From 3P0 model, and the wavefunction of quark model

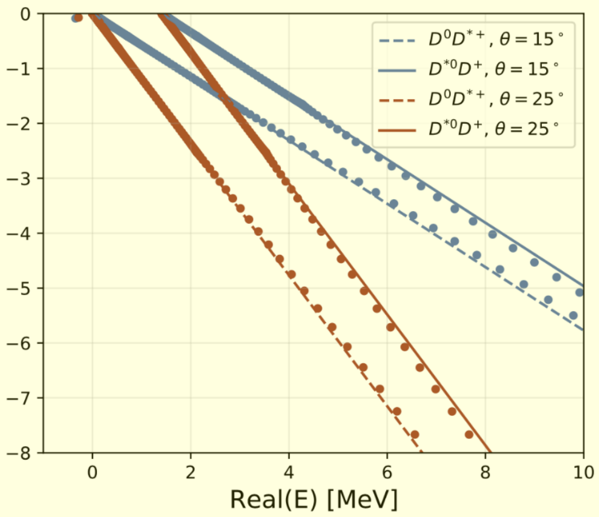


One boson exchange (OBE)

X(3872) 从纯$D\bar{D}^* + \bar{D}D^*$产生

From the interaction of DD^* to obtain the interaction of $D\bar{D}^* + \bar{D}D^*$, check X(3872) exists or not by pure $D\bar{D}^* + \bar{D}D^*$ interaction, without $c\bar{c}$ state.





- **Bound state: T_{cc}**

$m_{T_{cc}}$=3874.7 MeV,

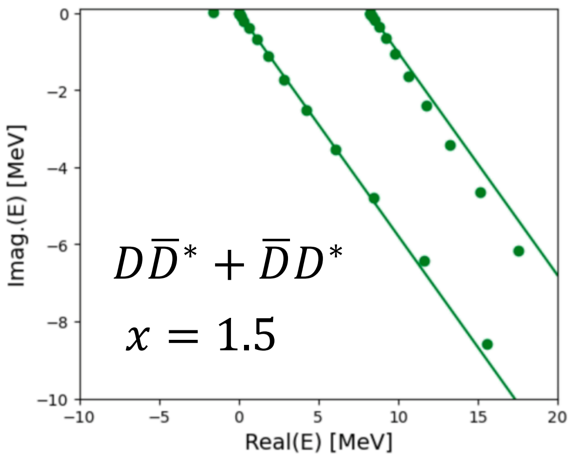
$\Delta E = -393$ keV

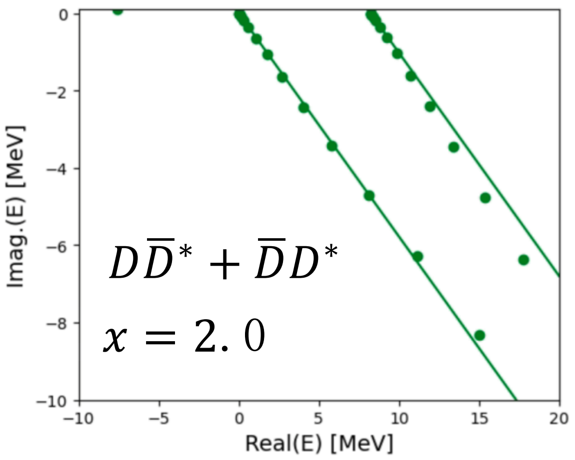
$\Gamma_{T_{cc}} = 70.4$ keV

- $\sqrt{\langle r^2 \rangle} = 4.7\ fm$

- 70.0% $D^{*+}D^0$， 30.0% D^+D^{*0}

$$V'_{\bar{D}^*D} = x * V_{\bar{D}^*D}$$



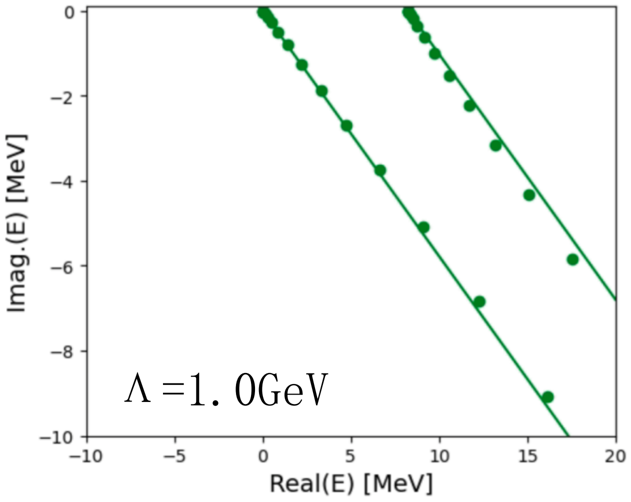


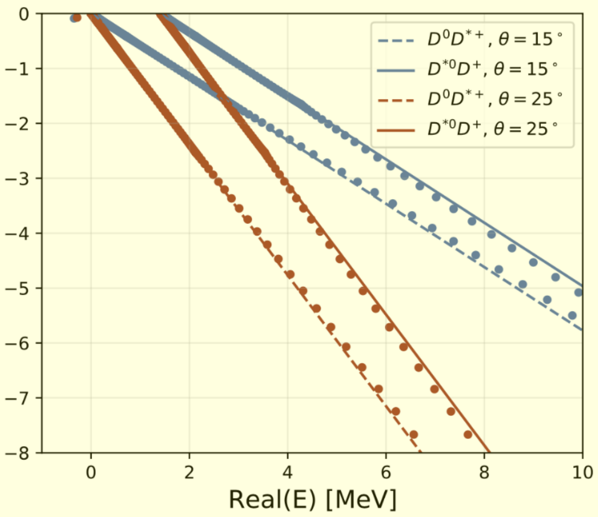
这是一个吸引势，但不足够产生一个束缚态，而只是一个虚态。

3870.0 + 0.26 i MeV

X(3872) 从 $D\bar{D}^* + \bar{D}D^*$和 $c\bar{c}$ 产生

From the interaction of DD^* to obtain the intraction of $D\bar{D}^* + \bar{D}D^*$， check X(3872) exists or not by pure $D\bar{D}^* + \bar{D}D^*$ interaction, without $c\bar{c}$ state.





- **Bound state: T_{cc}**
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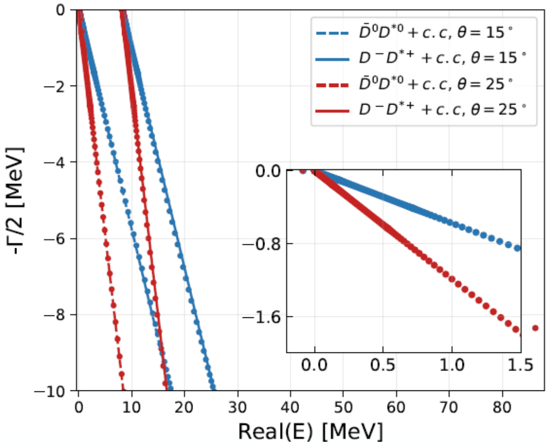
  $\Gamma_{T_{cc}} = 70.4$ keV
- $\sqrt{\langle r^2 \rangle} = 4.7\ fm$
- 70.0% $D^{*+}D^0$， 30.0% D^+D^{*0}

吸引势，但不足够产生一个束缚态

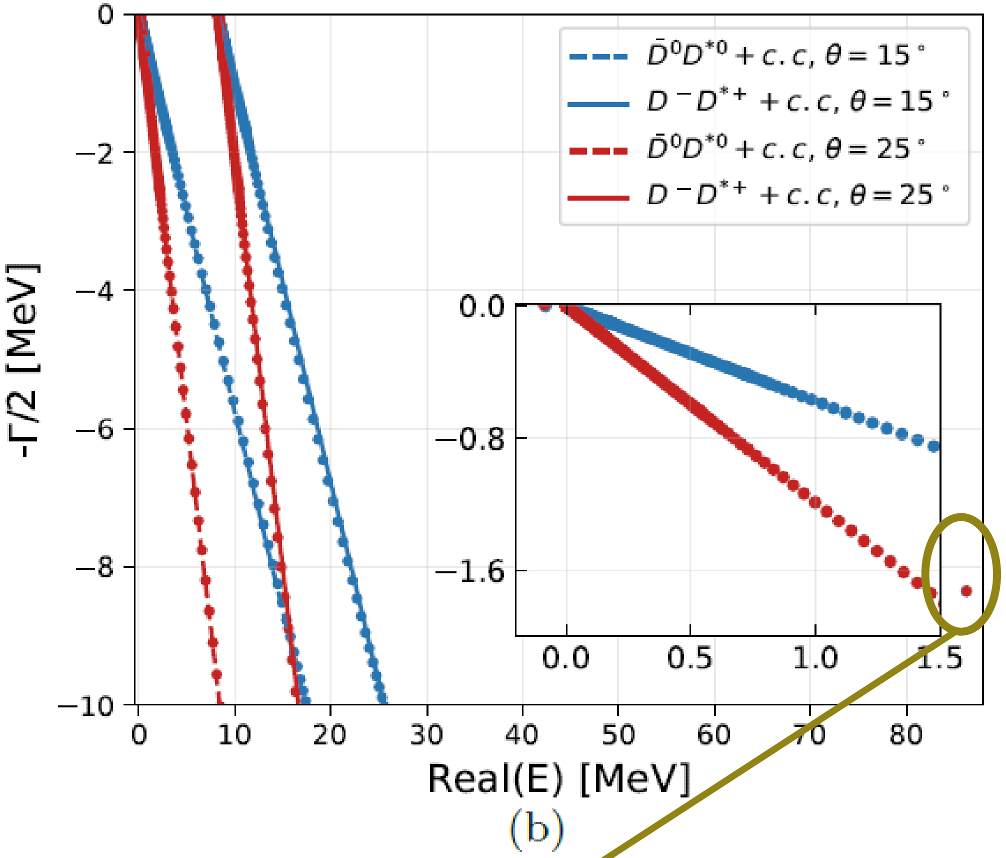
- **传统夸克模型$c\bar{c}$裸态， χc1(2P, 3940) 和其波函数都可以从夸克模型中得到**
- **3P0的耦合参数γ = 4.69 可以从ψ(3770)→ $D\bar{D}$获得。**
- **X(3872) 的研究没有额外的自由参数。**



(b)

- **Bound state for X(3872)**
  $\Delta E = -80.4$ keV
  $\Gamma_{T_{cc}} = 32.5$ keV
- $\sqrt{\langle r^2 \rangle} = 11.2\ fm$
- 94.0% $\bar{D}^{*0}D^0$， 4.8% $D^{*-}D^+$，
  1.2% $c\bar{c}$

预言



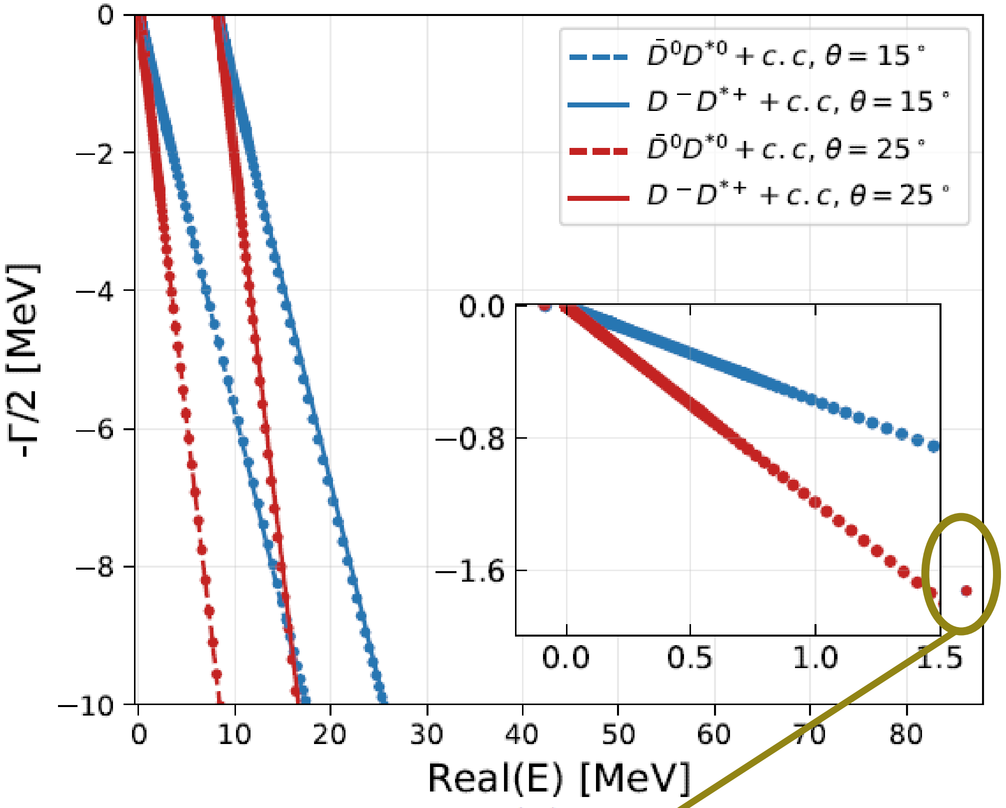
(b)

- χ_{c1}(2p)

  M = 3957.9 MeV $\Gamma_{\chi_{c1(2P)}} = 16.7$ MeV

- Main decay channel： $\bar{D}^*D$

预言



(b)

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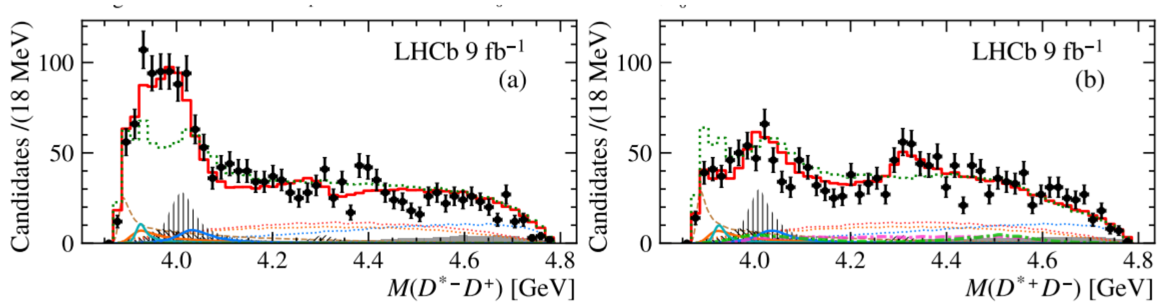
- Main decay channel： $\bar{D}^* D$

Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

LHCb Collaboration 2406.03156

$\chi_{c1}(4010)$ $J^{PC} = 1^{++}$

$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$ $\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$



X(3872) Relevant $D\bar{D}^*$ Scattering in $N_f = 2$ Lattice QCD

H. Li, C. Shi, Y. Chen, M. Gong, J. Liang et al

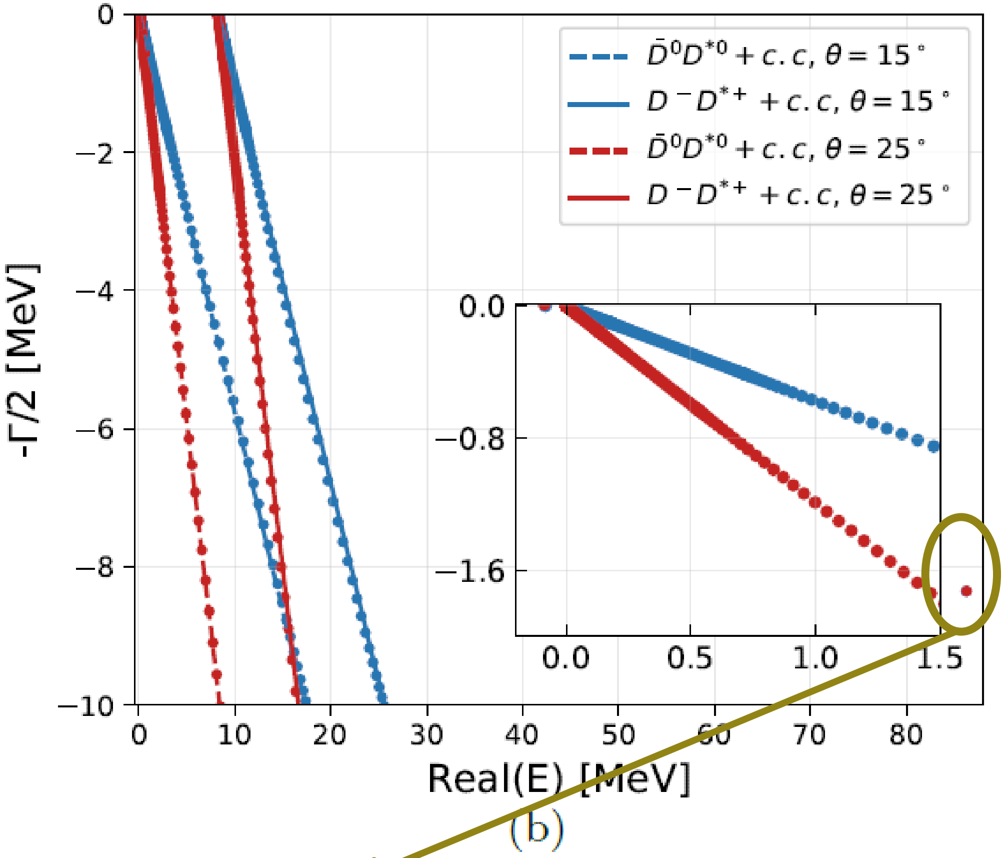
CLQCD 2402.14541

$$t(s) = \frac{K(s)}{1 - K(s) i\rho(s)}$$

$$K(s) = \frac{g}{M^2 - s} + \gamma$$

m_π(MeV)	250(3)	307(2)	362(1)	417(1)
Bound state from $E_{2,3}$				
E_B(MeV)	$-9.7^{+2.1}_{-2.2}$	$-9.7^{+1.9}_{-2.0}$	$-1.3^{+0.6}_{-0.8}$	$\mathbf{-1.3^{+0.8}_{-1.0}}$
BW fit from $E_{3,4}$				
m_R(MeV)	3924(5)	3926(6)	3969(4)	3995(4)
Γ_R(MeV)	63(23)	57(18)	37(13)	57(10)
Bound state pole and residual from $E_{2,3,4}$				
E_B(MeV)	−11(1)	−10(2)	−1.6(7)	−1.7(7)
Resonance pole and residue				
m_R(MeV)	4008(4)	4029(4)	4050(3)	4071(3)
Γ_R(MeV)	60(6)	38(9)	43(8)	50(7)
$Br_{D\bar{D}^*}$(%)	~ 100	~ 100	~ 100	~ 100

预言



	wave function	$I(J^{PC})$	u − channel : π	u − channel : ρ/ω	t − channel : ρ/ω
DD^*	$\frac{1}{\sqrt{2}}(D^+D^{*0} - D^0D^{*+})$	$0(1^+)$ $[T_{cc}^+]$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(D^+D^{*0} + D^0D^{*+})$	$1(1^+)$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
$D\bar{D}^*$	$\frac{1}{\sqrt{2}}([D^+D^{*-}] + [D^0\bar{D}^{*0}])$	$0(1^{++})[X(3872)]$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}([D^+D^{*-}] - [D^0\bar{D}^{*0}])$	$1(1^{++})$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\} + \{D^0\bar{D}^{*0}\})$	$0(1^{+-})[h_c]$	$-\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\} - \{D^0\bar{D}^{*0}\})$	$1(1^{+-})$ $[Z_c(3900)]$	$\frac{1}{2}V_\pi$	$-\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$

	I (J^PC)	Our
DD^*	$0\,(1^+)\,[T_{cc}^+]$	$T_{cc}^+(3874)$
	$1\,(1^+)$	Unstable
$D\bar{D}^*$	$0\,(1^{++})\,[\chi_{c1}]$	X(3872), $\chi_{c1}(3958)$
	$1\,(1^{++})\,[W_{c1}]$	Missing…
	$0\,(1^{+-})\,[h_c]$	$\tilde{X}(3870)$, $h_c(3961)$
	$1\,(1^{+-})\,[Z_c]$	Nopole around 3900

Black, $DD^*/D\bar{D}^*$

Red, $c\bar{c} + D\bar{D}^*$

LHCb 2406.03156

Teng Ji, Dong, Guo, Hanhart, Meißner, 2502.04458

COMPASS, PLB 783,334 (2018)

- **χ_{c1}(2p)**

  M = 3957.9 MeV $\Gamma_{\chi_{c1(2P)}}$ = 16.7 MeV

- Main decay channel： $\bar{D}^* D$

Preliminary results of $X(3872)$ decay

T_{cc} → $DD^*, D\bar{D}^*$ interaction

$c\bar{c}$ state ↓

$X(3872)$ → Detail Study of X(3872), very soon…

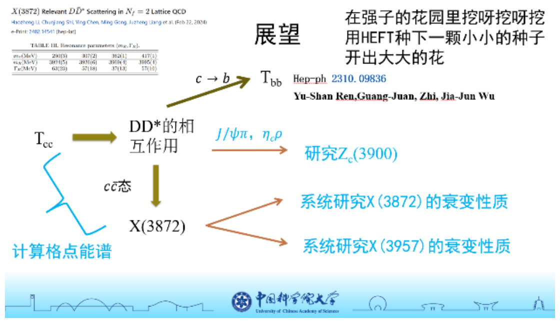
TABLE III. Branching ratio of different channels $\Gamma_i/\Gamma_{\text{total}}$

Decay channels	PDG [60]	Ref. [68]	Ours
$\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$	0.035 ± 0.009	$4.1^{+1.9}_{-1.1}\%$	0.035
$\chi_{c1}(3872) \to \rho^0 J/\psi$	$2.8 \pm 0.7\%$	–	4.1%
$\chi_{c1}(3872) \to \omega J/\psi$	$4.1 \pm 1.4\%$	$4.4^{+2.3}_{-1.3}\%$	13.7%
$\chi_{c1}(3872) \to \pi\pi\pi J/\psi$	not seen	–	6.2%
$\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0$	$45 \pm 21\%$	–	11.4%
$\chi_{c1}(3872) \to \bar{D}^{*0}D^0$	$34 \pm 12\%$	$52.4^{+25.3}_{-14.3}\%$	58.5%
$\chi_{c1}(3872) \to \pi^0\chi_{c2}$	$< 4\%$	–	1.8%
$\chi_{c1}(3872) \to \pi^0\chi_{c1}$	$3.1^{+1.5}_{-1.3}\%$	$3.6^{+2.2}_{-1.6}\%$	2.3%
$\chi_{c1}(3872) \to \pi^0\chi_{c0}$	$< 13\%$	–	1.5%
$\chi_{c1}(3872) \to \gamma D^+D^-$	$< 3.5\%$	–	0.1%
$\chi_{c1}(3872) \to \gamma\bar{D}^0D^0$	$< 6\%$	–	6.4%
$\chi_{c1}(3872) \to \gamma J/\psi$	$(7.8 \pm 2.9) \times 10^{-3}$	$1.1^{+0.6}_{-0.3}\%$	$< 5 \times 10^{-3}$
$\chi_{c1}(3872) \to \gamma\psi(2S)$	possibly seen	$2.4^{+1.3}_{-0.8}\%$	7×10^{-3}

Γ_{total} ~280 keV (LHCb)
Γ_{total} ~380 keV (BESIII)
$\Gamma_{\text{total}} \sim 284$ keV

[68] C. H. Li, C. Z. Yuan, Phys. Rev. D 100, 094003

LHCb, Phys. Rev. D 102 (2020) 9, 092005.
BESIII, Phys. Rev. Lett. 132, 151903.



第六届重味物理和量子色动力学研讨会
2024.04.22 中国海洋大学 青岛

能够系统描述强子的较为完整的框架

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DD^*	$0\,(1^+)\,[T_{cc}^+]$	$T_{cc}^+(3874)$
	$1\,(1^+)$	Unstable
$D\bar{D}^*$	$0\,(1^{++})\,[\chi_{c1}]$	X(3872), $\chi_{c1}(3958)$
	$1\,(1^{++})\,[W_{c1}]$	Missing…
	$0\,(1^{+-})\,[h_c]$	$\tilde{X}(3870)$, $h_c(3961)$
	$1\,(1^{+-})\,[Z_c]$	Nopole around 3900

T_{bb}

Yu-Shan Ren, G.-J. Wang, Z. Yang, J.-J. Wu PRD 110 (2024) 7, 074007

$c \to b$

T_{cc} → DD^*, $D\bar{D}^*$ interaction

G.-J. Wang, Z. Yang, J.-J. Wu, M. Oka, S.-L. Zhu Scib.2024.07.012

$J/\psi\pi$, $\eta_c\rho$ → Study Z_c(3900)

Kang-Yu, G.-J. Wang, Z. Yang, J.-J. Wu PRD 110 (2024) 11, 114029

$c\bar{c}$ state

X(3872)

Study the decay of X(3872), soon…

Study the decay of $\tilde{X}(3870)$, $\chi_{c1}(4010)$, $h_c(3961)$…

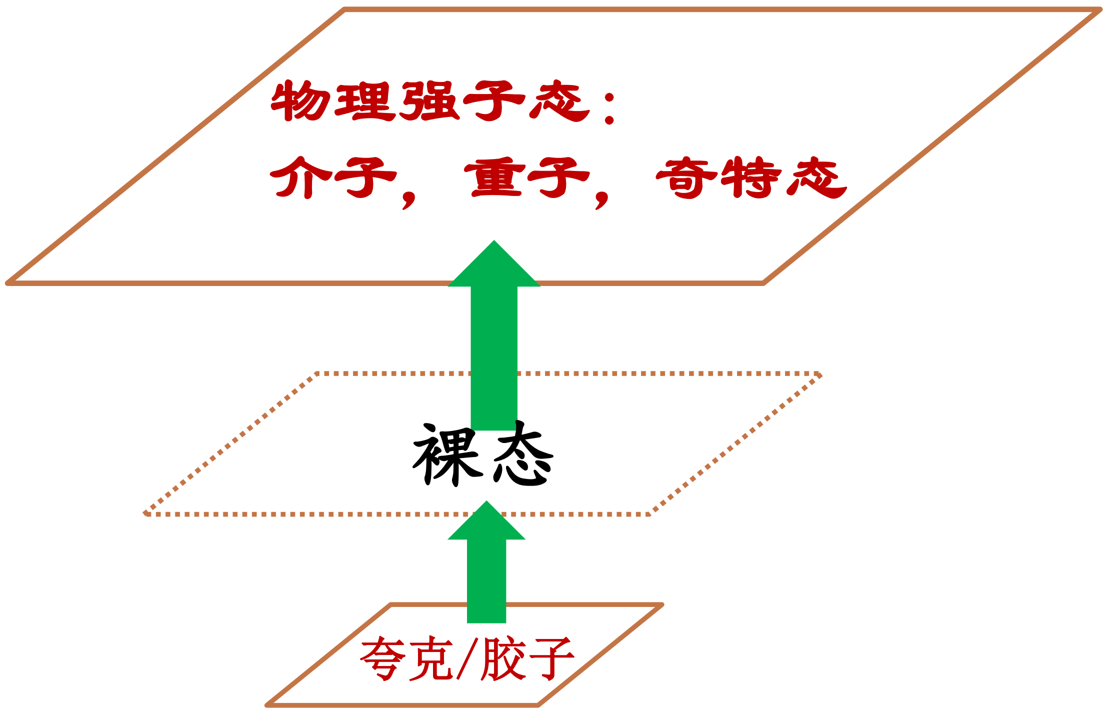
Lattice spectrum,

T_{cc} soon…(Adelaide LQCD)

K. Yu, G.-J.Wang, J.-J. Wu, Z. Yang, 2502.05789 (Accept by JHEP)

小结

- 探讨了裸态和分子态共同作用下产生的极点的轨迹
- 通过Tcc的研究确定DD^*的相互作用
- 由确定的DD^*的相互作用和裸态可以研究X(3872)的性质



谢谢