The discussion of D_s family

Jia-jun Wu (UCAS)

Collaborator: Ruhui Ni (UCAS), Xianhui Zhong(HUNNA)

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华南师范大学

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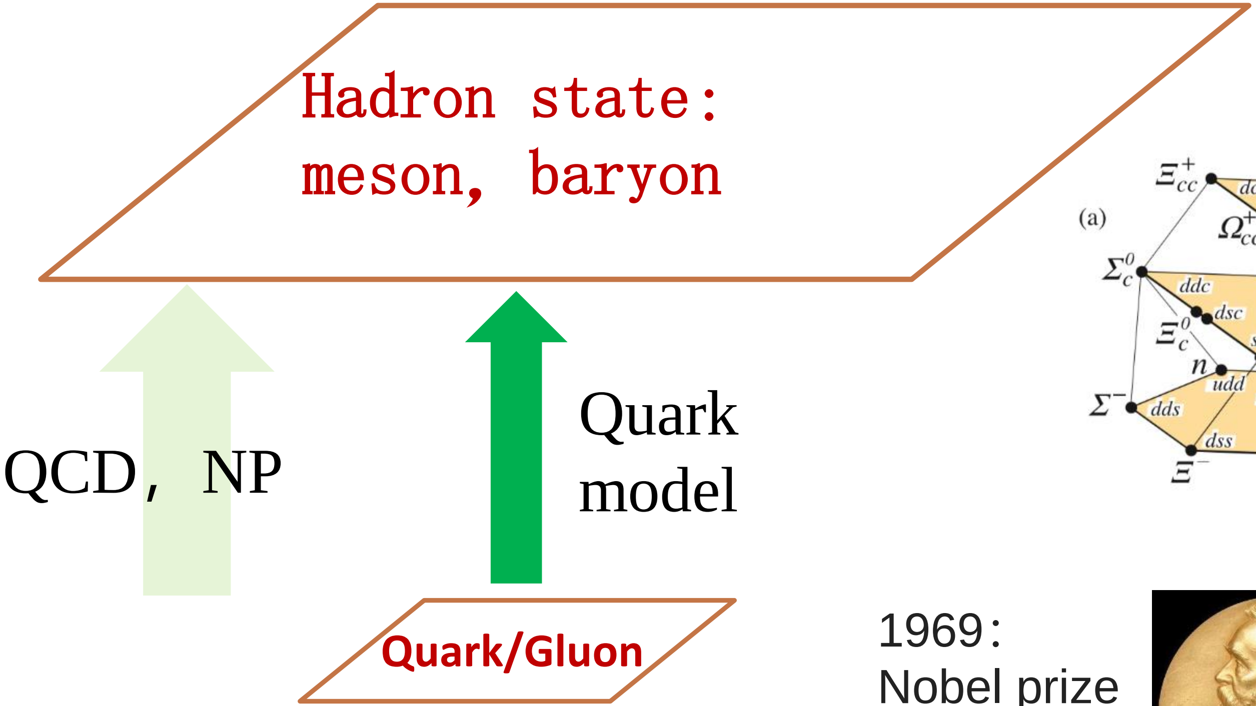
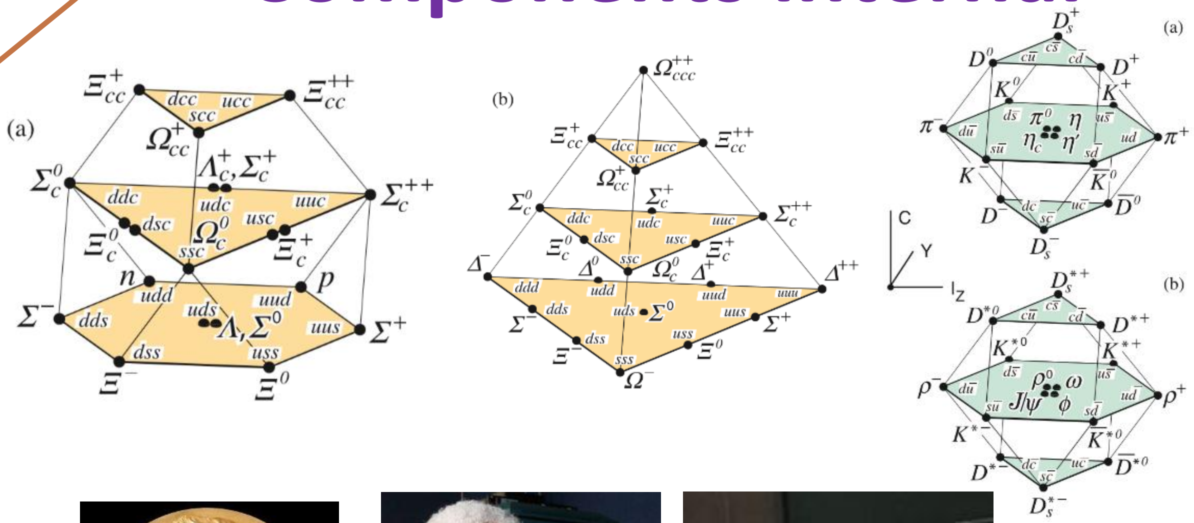
Outline

- Background： Bare state + Coupled channel
- Unquenched quark model for heavy-light mesons
- Family of D_s
- Summary

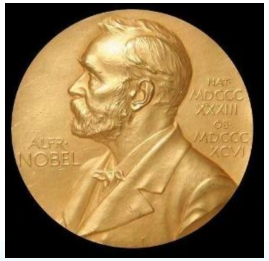
Background： Quark Model

Hadron spectroscopy---Components internal

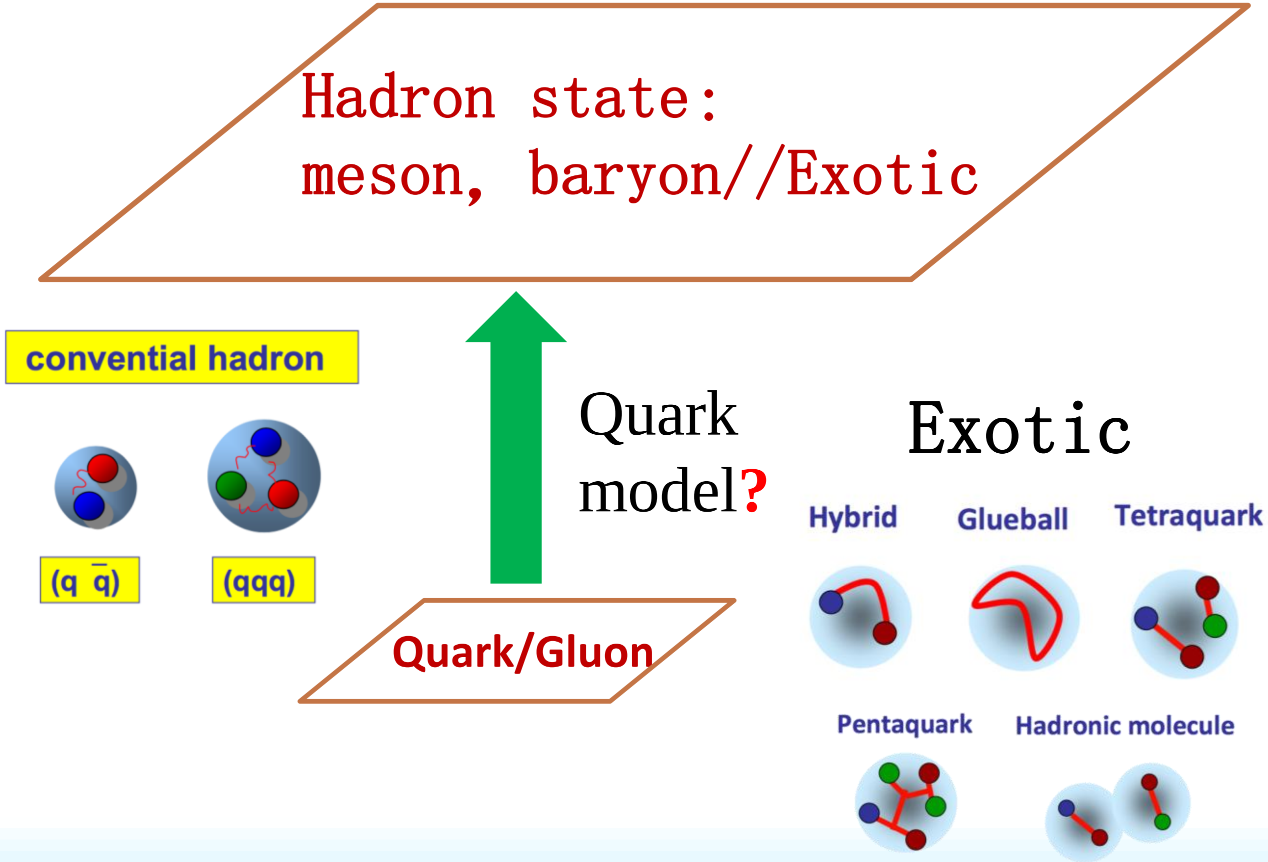


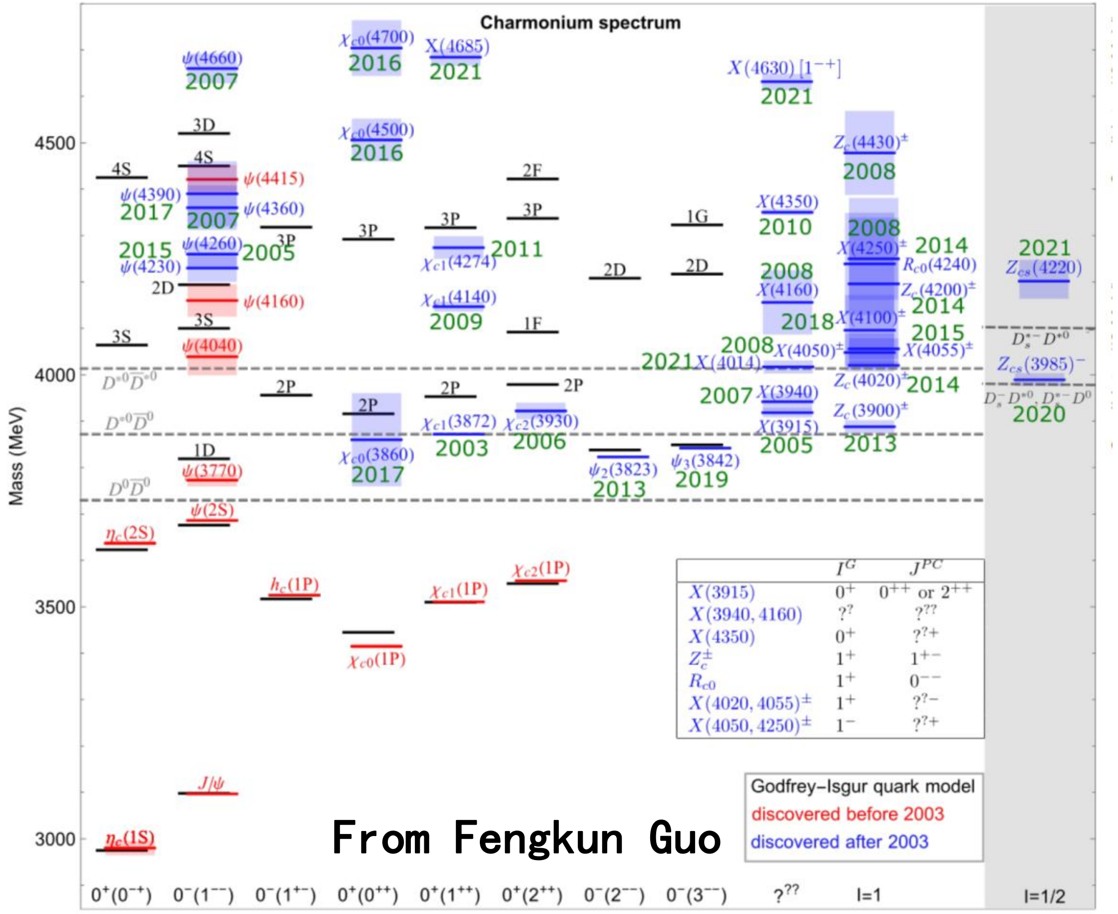


1969：
Nobel prize

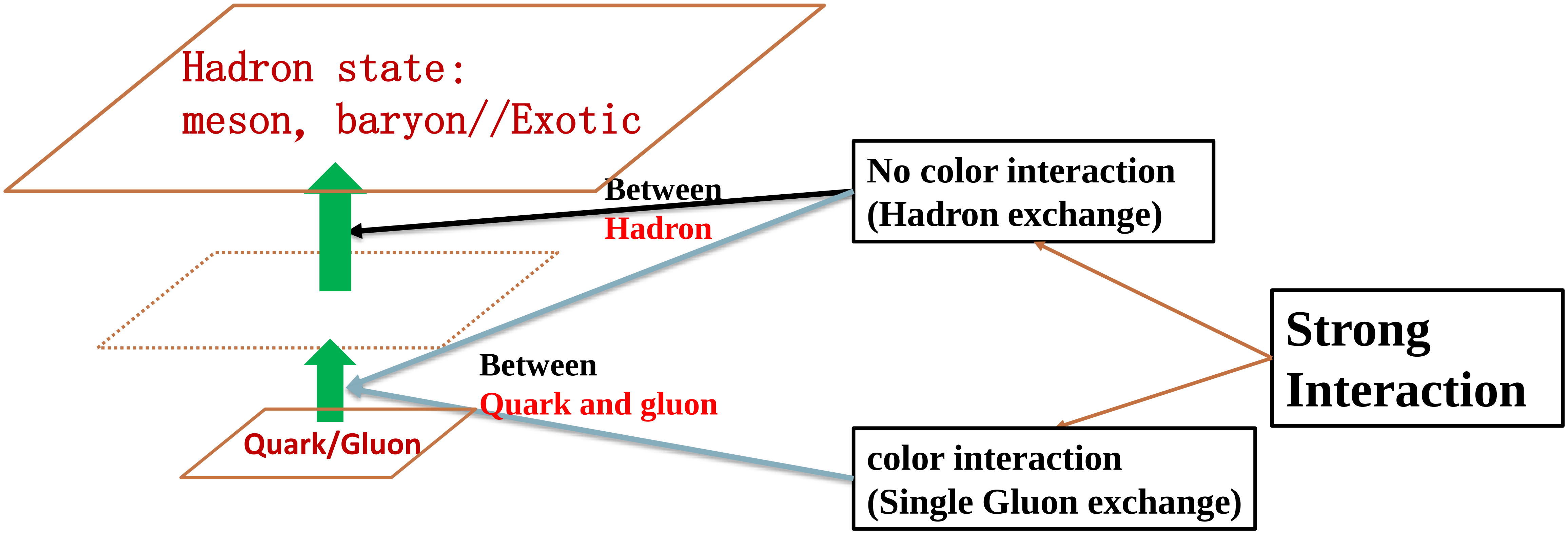


Background： Beyond Quark Model

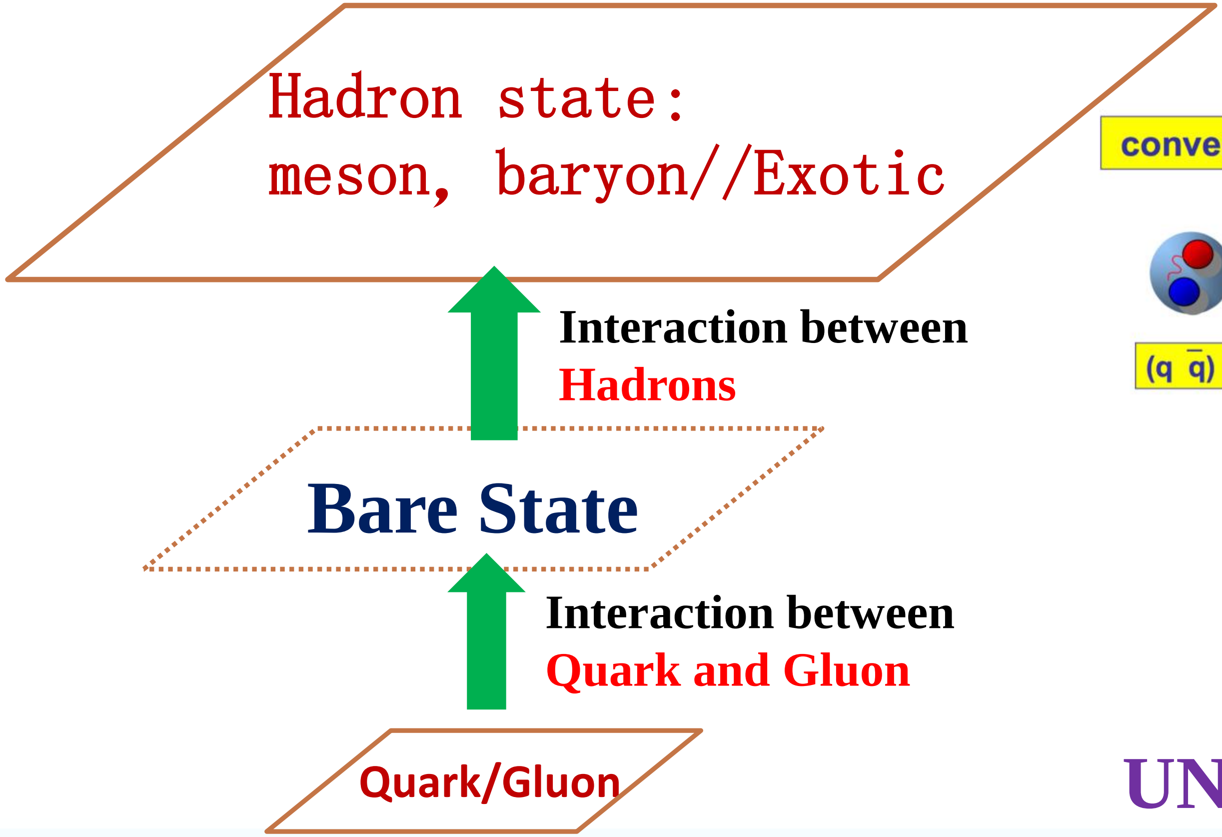




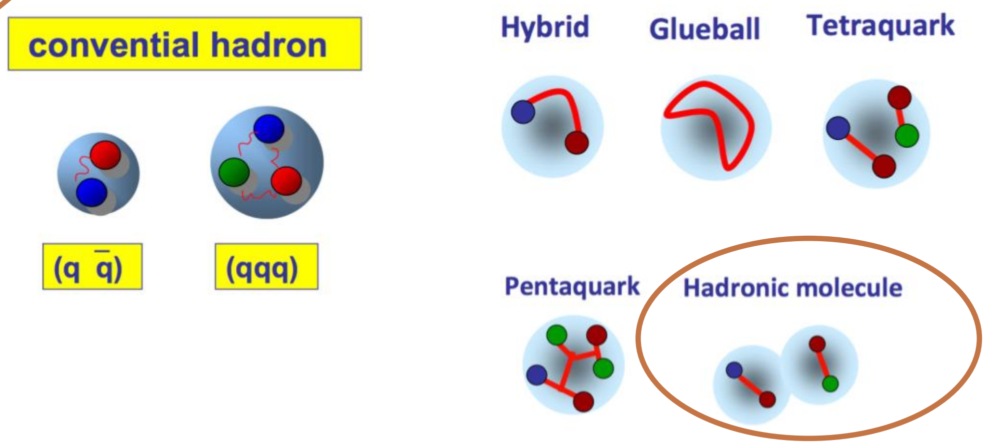
Background： Strong Interaction



Background： Bare state + Coupled channel

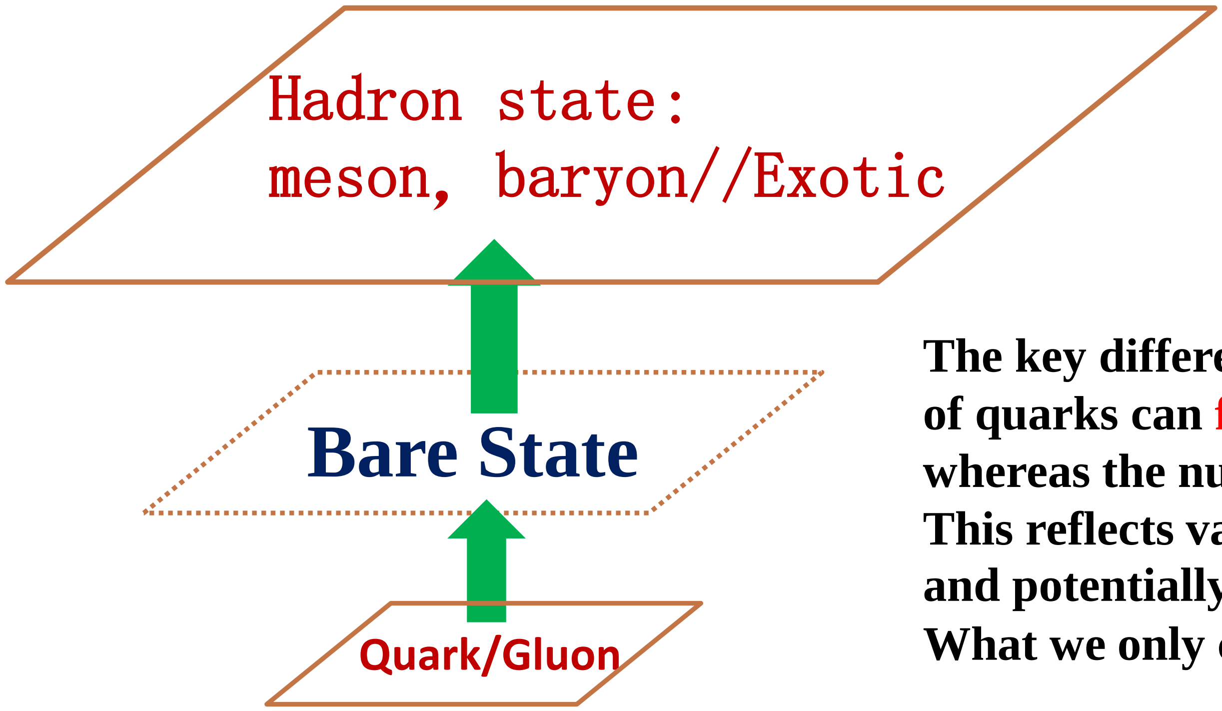


Exotic



UNQUENCHED quark model

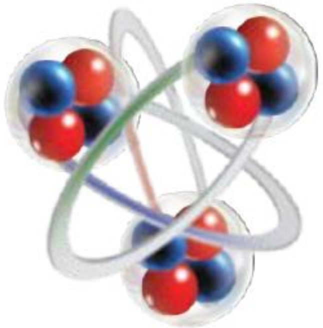
Background：Strong-Spectrum-Reaction



Nuclear Physics：

12C <= 6 p & 6 n

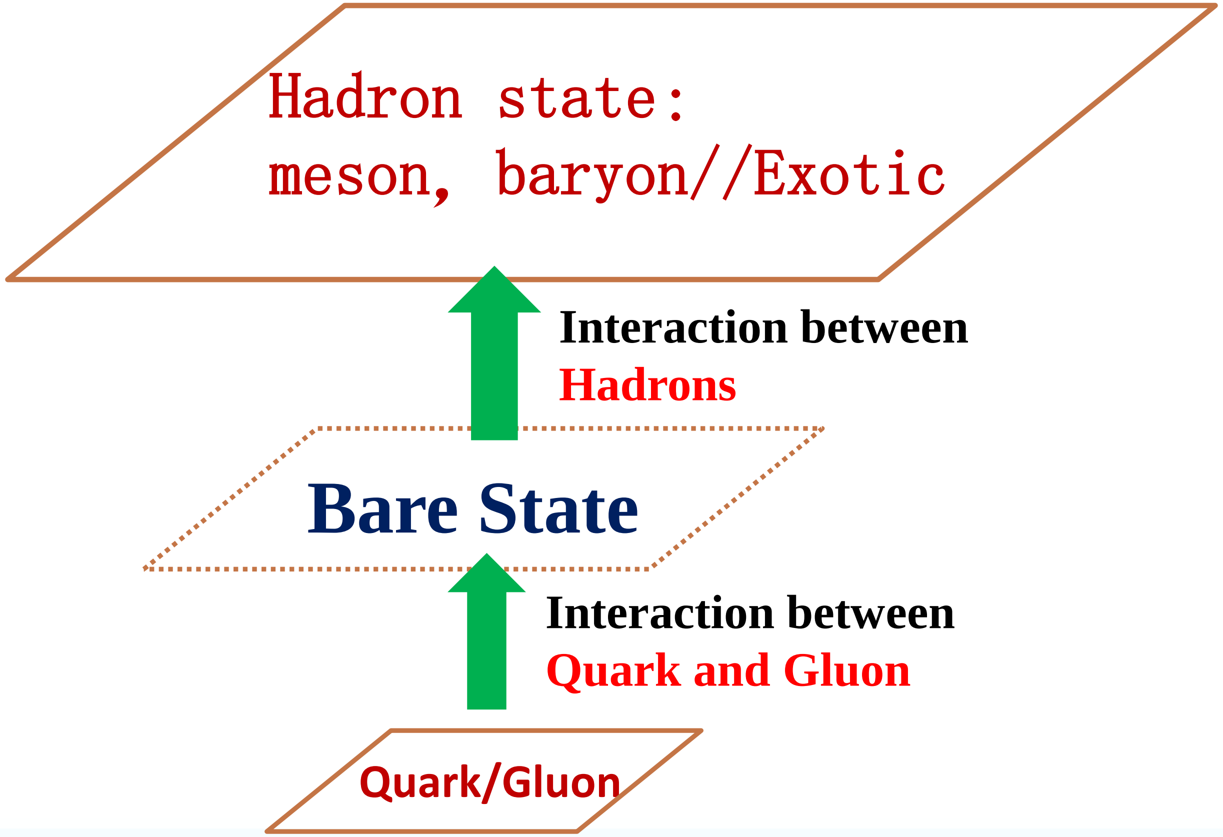
<= 3 α Cluster



The key difference from Hadronic and Atomic system: the number of quarks can fluctuate (only quark quantum numbers conserved), whereas the number of nucleons is fixed.
This reflects vacuum fluctuations involving quark-antiquark pairs and potentially glueballs as well.
What we only can define is the lowest number of constitute quark.

UNQUENCHED quark model

Background： Bare state + Coupled channel

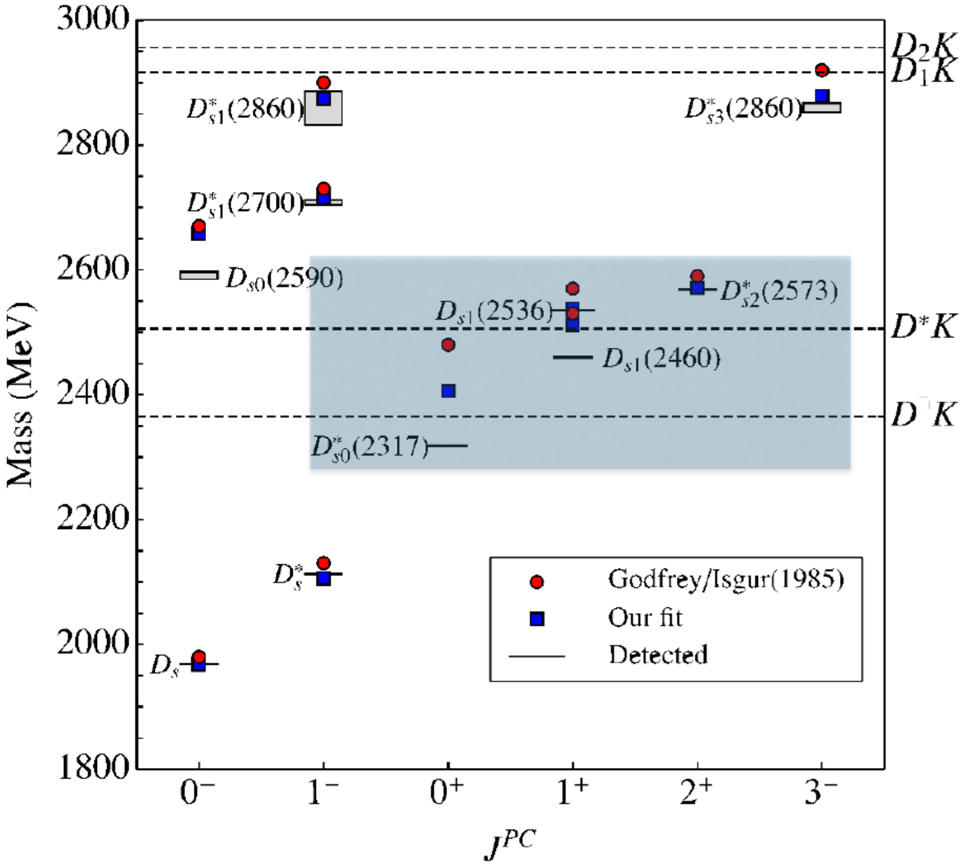


Bare state(Single) + multi-hadron

The number of hadrons is **not conserved**!

Coupled channel

Non-Perturbative Hamiltonian Framework



V contain various parameters

HEFT ➔ NPHF

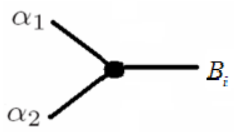
$$H = H_0 + H_I$$

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

$|B_i>$ bare state， bare mass m_i

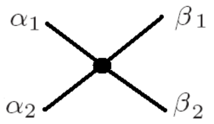
$|\alpha(k_\alpha)>$ non-interaction channels

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



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

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



Yang, Wang, Wu, Oka, Zhu, PRL128(2022),112001

Unquenched quark model for heavy-light mesons

$$\begin{pmatrix} \mathcal{H}_0 & \mathcal{H}_I \\ \mathcal{H}_I & \mathcal{H}_c \end{pmatrix} \begin{pmatrix} c_A(M)|A\rangle \\ \sum_{BC}\int c_{BC}(\boldsymbol{q},M)d^3\boldsymbol{q}|BC,\boldsymbol{q}\rangle \end{pmatrix} = M \begin{pmatrix} c_A(M)|A\rangle \\ \sum_{BC}\int c_{BC}(\boldsymbol{q},M)d^3\boldsymbol{q}|BC,\boldsymbol{q}\rangle \end{pmatrix}$$

$\mathcal{H}_0$ » OGE Potential

$$\mathcal{H}_0 = \sqrt{\boldsymbol{p}_1^2 + m_q^2} + \sqrt{\boldsymbol{p}_2^2 + m_{\bar{q}}^2} + V_0(r) + V_{sd}(r)$$

$$V_0(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br + C_0$$

$$V_{\rm sd}(r) = \frac{32\pi\alpha_s(r)\sigma^3 e^{-\sigma^2 r^2}}{9\sqrt{\pi^3}\,\tilde{m}_1 m_2}\boldsymbol{S}_1\cdot\boldsymbol{S}_2 + \frac{4}{3}\frac{\alpha_s(r)}{\tilde{m}_1 m_2}\frac{1}{r^3}S_{12} + H_{LS},$$

$$H_{LS} = H_{\rm sym} + H_{\rm anti},$$

$$H_{\rm sym} = \frac{\boldsymbol{S}_+\cdot\boldsymbol{L}}{2}\left[\left(\frac{1}{2\tilde{m}_1^2} + \frac{1}{2m_2^2}\right)G(r) + \frac{8\alpha_s(r)}{3\tilde{m}_1 m_2 r^3}\right],$$

$$H_{\rm anti} = \frac{\boldsymbol{S}_-\cdot\boldsymbol{L}}{2}\left(\frac{1}{2\tilde{m}_1^2} - \frac{1}{2m_2^2}\right)G(r),$$

$\mathcal{H}_I$ » Chiral quark model

$$\mathcal{L}_{Pqq} = \sum_j \frac{1}{f_m}\bar{\psi}_j\gamma_\mu^j\gamma_5^j\psi_j\vec{\tau}\cdot\partial^\mu\vec{\phi}_m$$

$$\mathcal{H}_I^{NR} = g\sum\left[-\left(1+\frac{\omega_m}{4\mu_a}\right)\boldsymbol{\sigma}_j\cdot\boldsymbol{q} + \frac{\omega_m}{2\mu_a}\boldsymbol{\sigma}_j\cdot\boldsymbol{p}_j\right]\hat{I}_j\phi_m$$

the leading nonrelativistic operator

$$\mathcal{H}_I^{RC} = \frac{g}{32\mu_q^2}\sum_j[-m_{\mathbb{P}}^2(\boldsymbol{\sigma}_j\cdot\boldsymbol{q}) - 2\boldsymbol{\sigma}_j\cdot(\boldsymbol{q}-2\boldsymbol{p}_j)\times(\boldsymbol{q}\times\boldsymbol{p}_j)]\hat{I}_j\phi_m$$

the relativistic correction terms kept up to order 1/m2

$\mathcal{H}_c$ » $\sqrt{m_B^2 + \boldsymbol{q}^2} + \sqrt{m_C^2 + \boldsymbol{q}^2}$

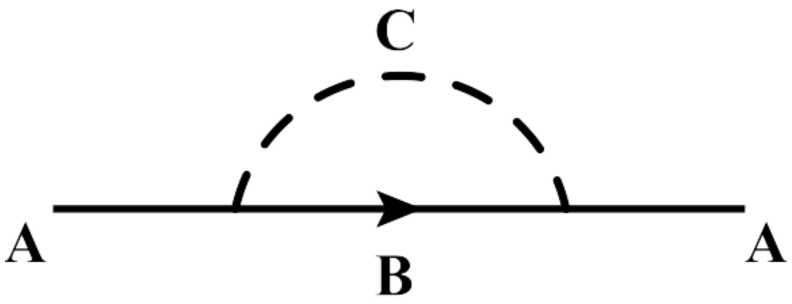
Ni, Wu, Zhong, PRD109, 116006(2024)
Ni, Li, Zhong, PRD105 056006 (2022),
Zhong, Zhao, PRD78 014029 (2008),

Unquenched quark model for heavy-light mesons

$$M = M_A + g(M)$$

$$\mathrm{Re}\ g(M) \equiv \Delta M(M) = \sum_{BC} \mathcal{P} \int_0^\infty \frac{\overline{|\mathcal{M}_{A\to BC}(\boldsymbol{q})|^2}}{M - E_{BC}} q^2 dq,$$

$$\mathrm{Im}\ g(M) = -\sum_{BC} \pi \frac{|\boldsymbol{q}|E_B E_C}{E_{BC}} |\mathcal{M}_{A\to BC}(\boldsymbol{q})|^2 \Big|_{M_i = E_{BC}}$$



$$\langle BC, \boldsymbol{q}|\mathcal{H}_I|A\rangle \to \langle BC, \boldsymbol{q}|\mathcal{H}_I e^{-\boldsymbol{q}^2/(2\Lambda^2)}|A\rangle$$

M.R.Pennington and D.J.Wilson, Decay channels and charmonium mass-shifts, PRD 76 077502 (2007)

$$\Delta\Pi_n(s, s_0) \equiv \Pi_n(s) - \Pi_n(s_0) = \frac{(s - s_0)}{\pi} \int_{s_n}^\infty ds' \frac{\mathrm{Im}\Pi_n(s')}{(s' - s)\ (s' - s_0)} . \quad (3)$$

Then

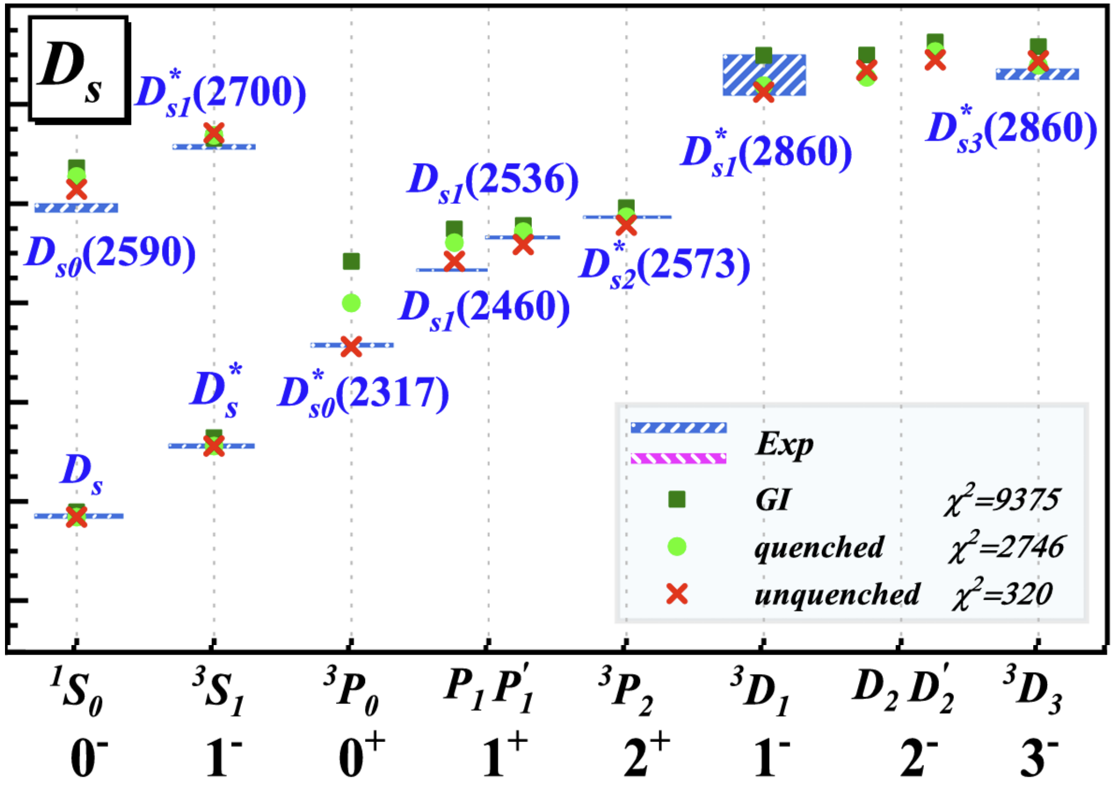
$$\sum_{n=1} \Delta\Pi_n(s, s_0) = \mathcal{M}^2(s) - \mathcal{M}^2_{charmonium} \equiv \Delta\mathcal{M}^2(s) . \quad (4)$$

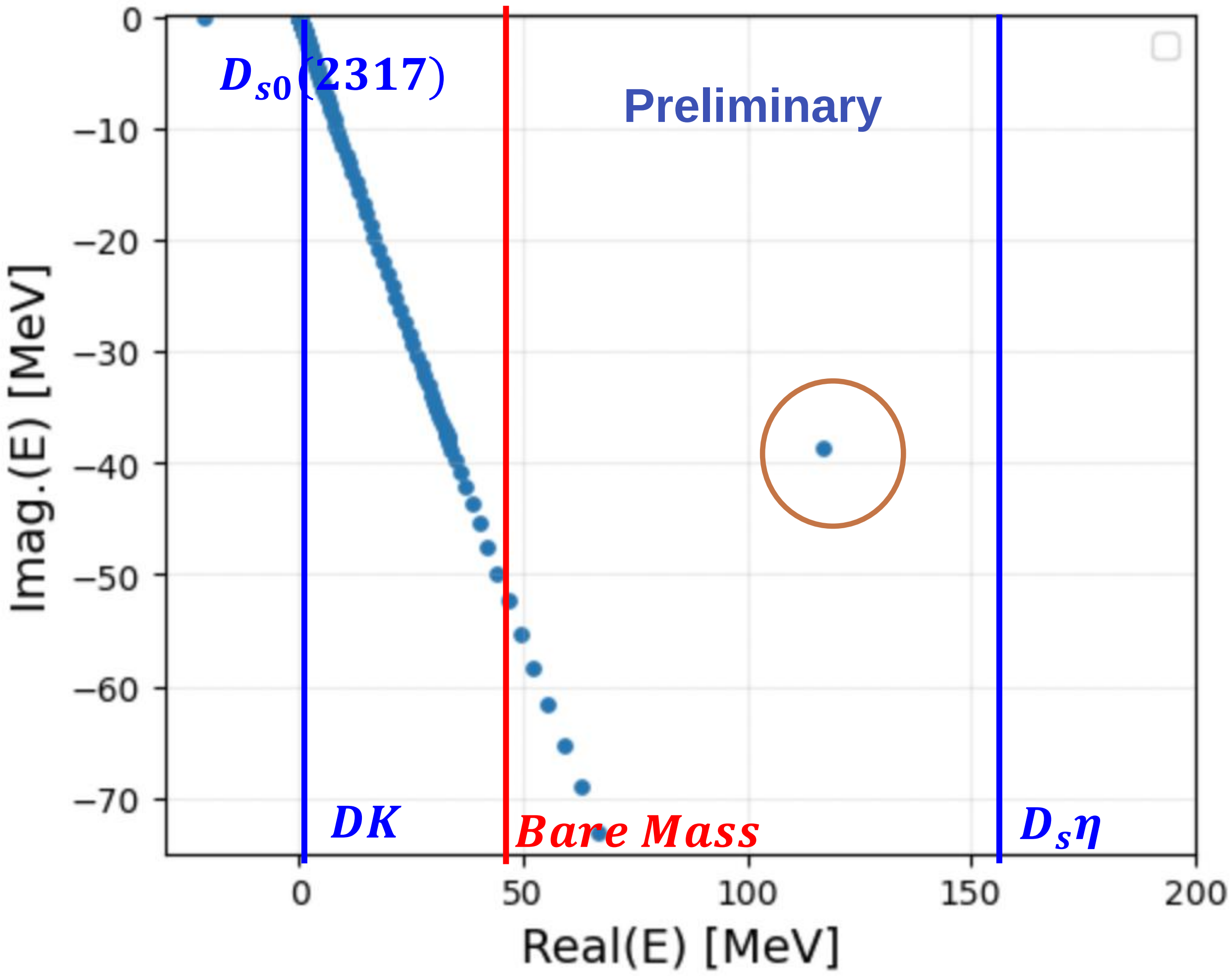
Key Question: How to choose coupled channel ?

One only need consider the OZI-allowed two-body hadronic channels with mass thresholds below or just above the bare |A⟩ states.

Family of D_s

NPHF

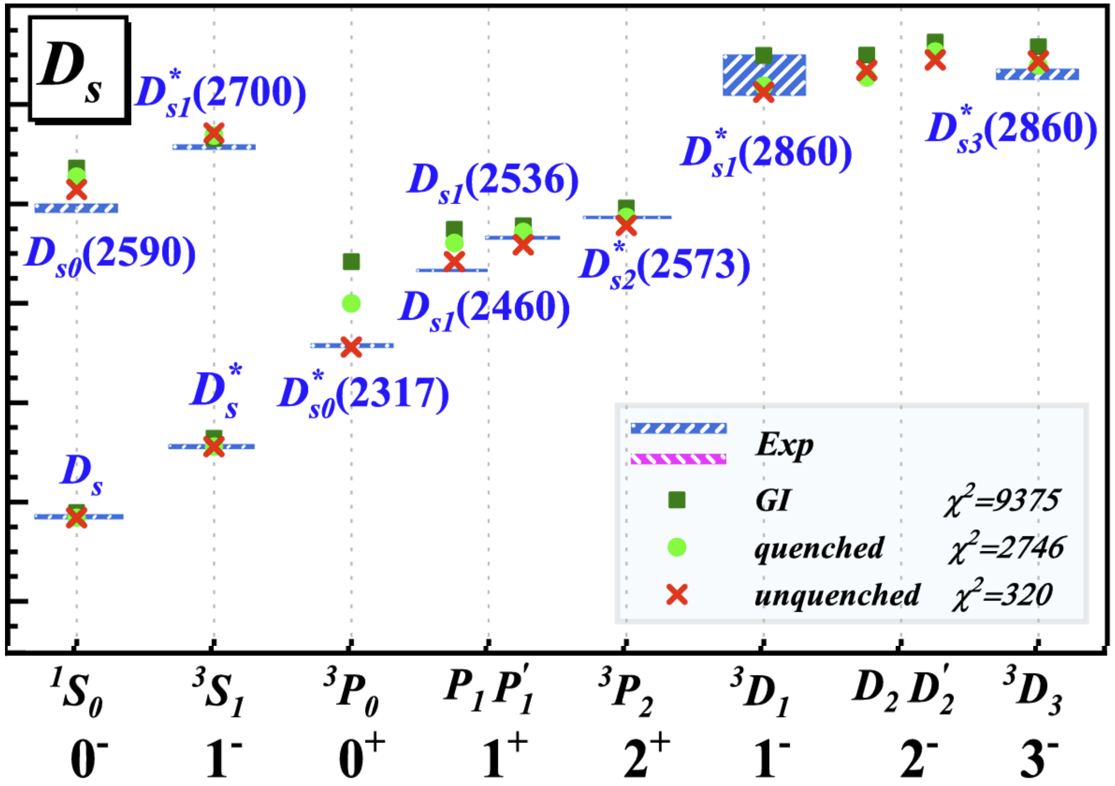


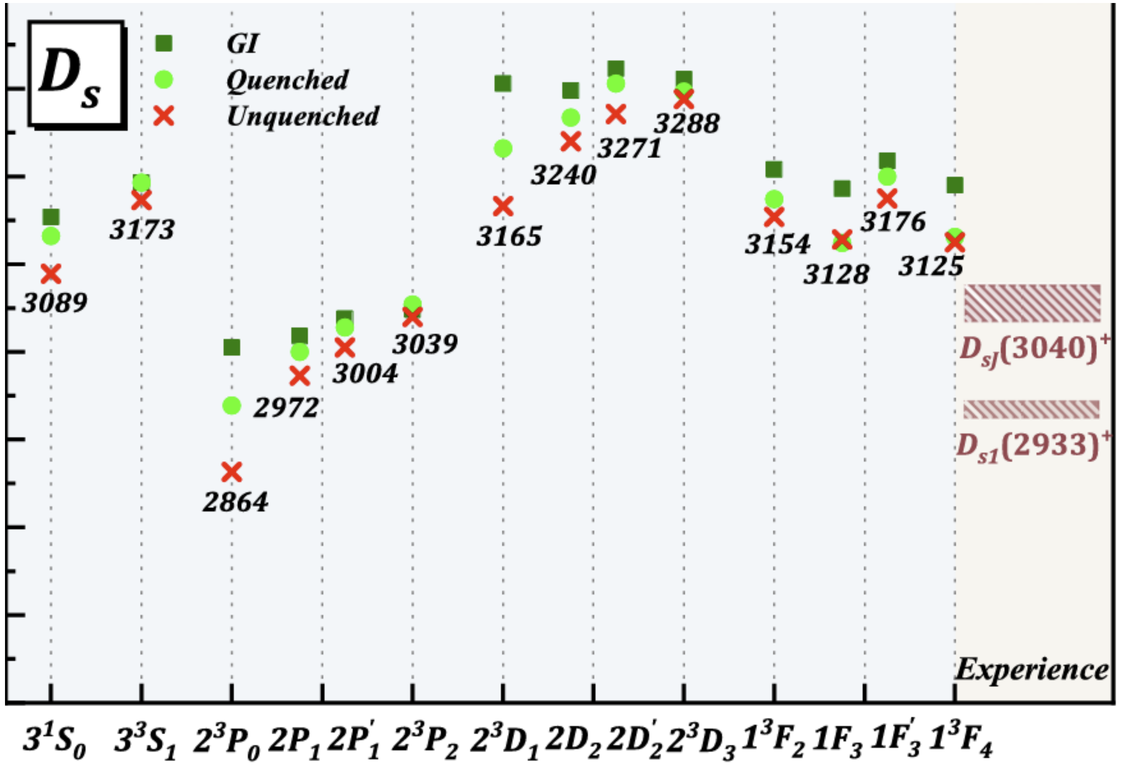


Only one $D_{s0}(2317)$ one state with $J^P = 0^+$ ablow 2700 MeV !

Fitted

Family of D_s

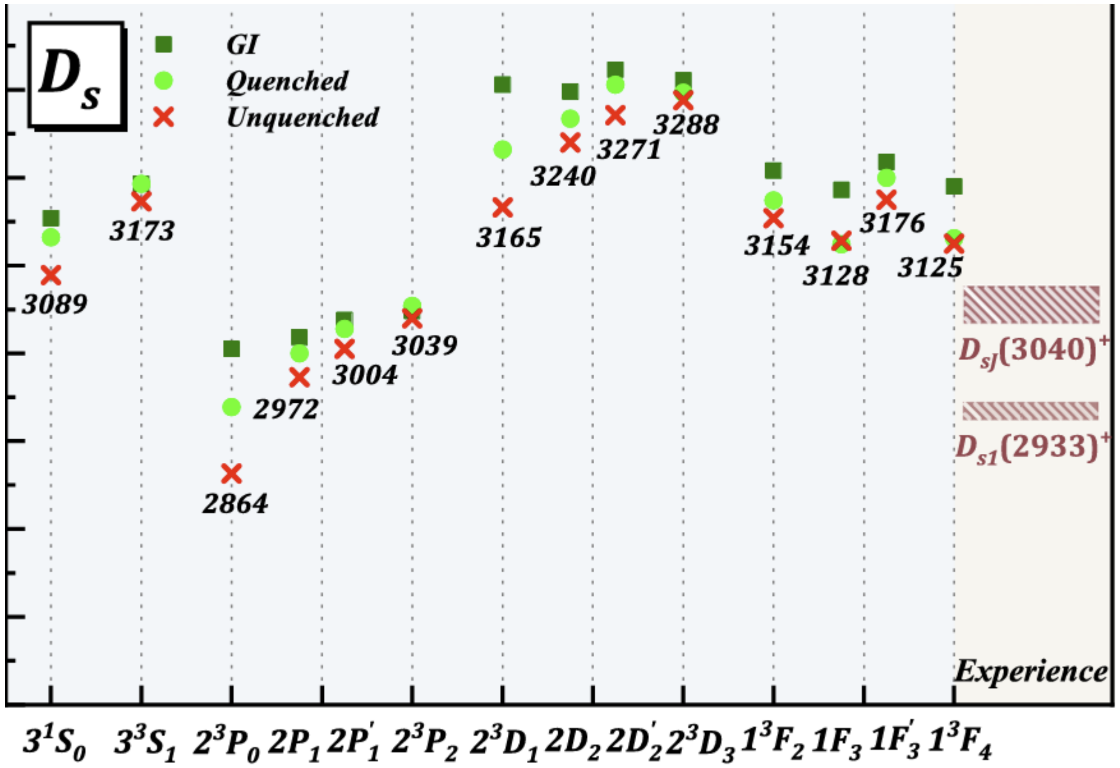




There are so many predicted states !

Fitted **Predicted**

Family of D_s



There are so many predicted states !

Predicted

1^+ 2933^{+6+4}_{-5-3} MeV, 72^{+18+7}_{-12-10} MeV **LHCb arXiv:2604.21257**

$2P_1$ 2972 MeV 92 MeV

Channel	$D_s(2P_1)$ as $D_{s1}(2933)^+$
D^*K	53.7
$D_0^*(2300)K$	0.1
$D_1(2430)K$	1.5
$D_1(2420)K$	4.4×10^{-2}
$D_2^*(2460)K$	–
$D_s^*\eta$	8.7
$D_{s0}^*(2317)\eta$	1.5×10^{-2}
$D_{s1}(2460)\eta$	–
DK^*	15.8
D^*K^*	9.4×10^{-2}
$D_s\phi$	–
Total	79.8

$J^P=?$ **$3044\pm8^{+30}_{-5}$ MeV, $239\pm35^{+46}_{-42}$ MeV**

BaBar, PRD80, 092003 (2009)

$2P_1'$ 3004 MeV 116 MeV

3^1S_0 3089 MeV 160 MeV

$D_s(2^3P_2)(3039)$: $D_2^*(2460)K$ [~ 26%], DK [~ 20%],

$D_s(2^3P_0)(2864)$: DK [~ 88%], $D_s\eta$ [~ 12%].

$D_s(2^3D_1)(3165)$: $D_1(2420)K$ [~ 85%],

$D_s(2D_2)(3240)$: $D_2^*(2460)K$ [~ 76%].

$D_s(2D_2')(3271)$: $D_2^*(2460)K$ [~ 17%].

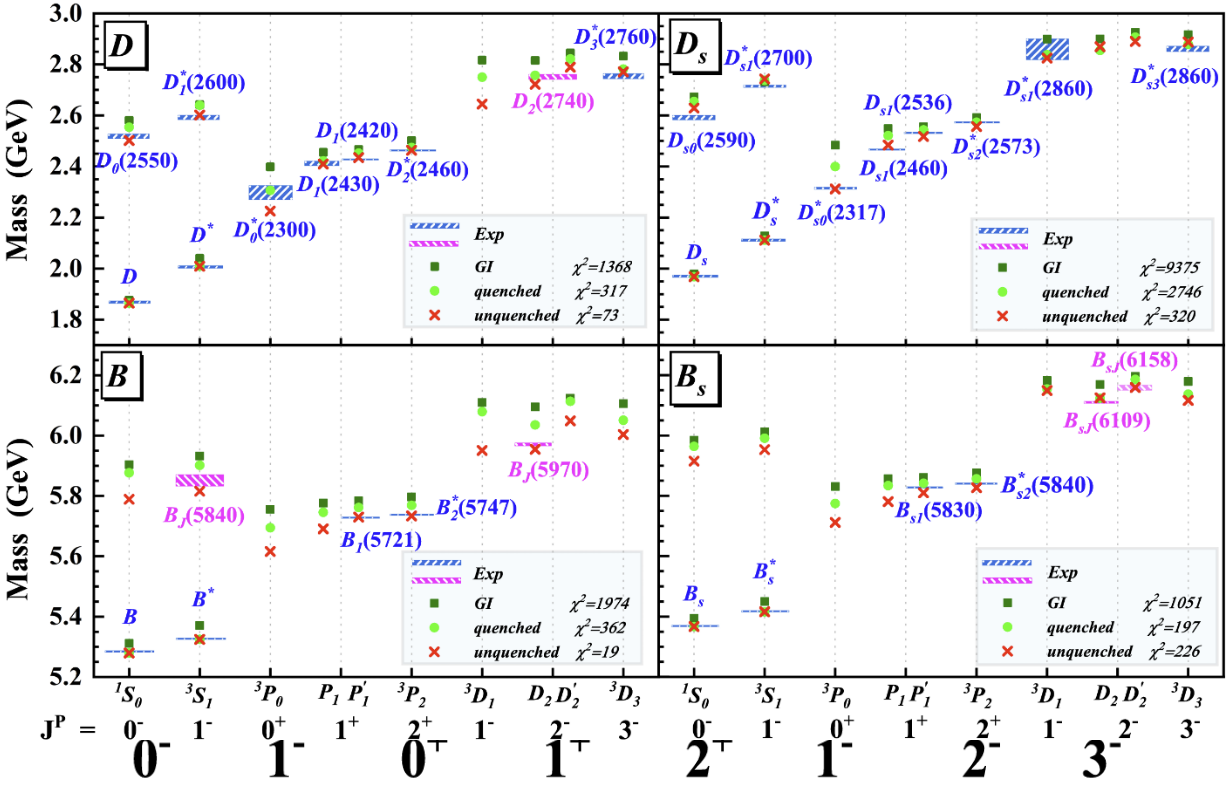
$D_s(1^3F_2)(3154)$: $D_1(2420)K$ [~ 57%],

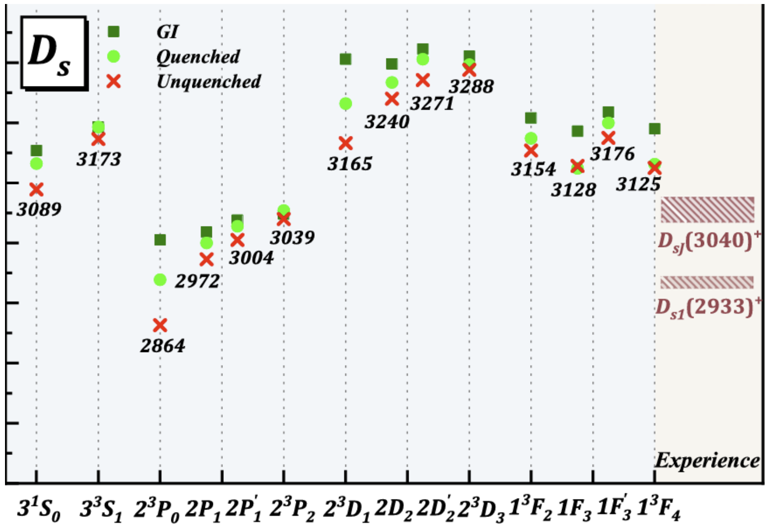
$D_s(1F_3)(3128)$: $D_2^*(2460)K$ [~ 82%],

$D_s(1F_3')(3176)$: D^*K [~ 41%], $D_1(2420)K$ [~ 14%],

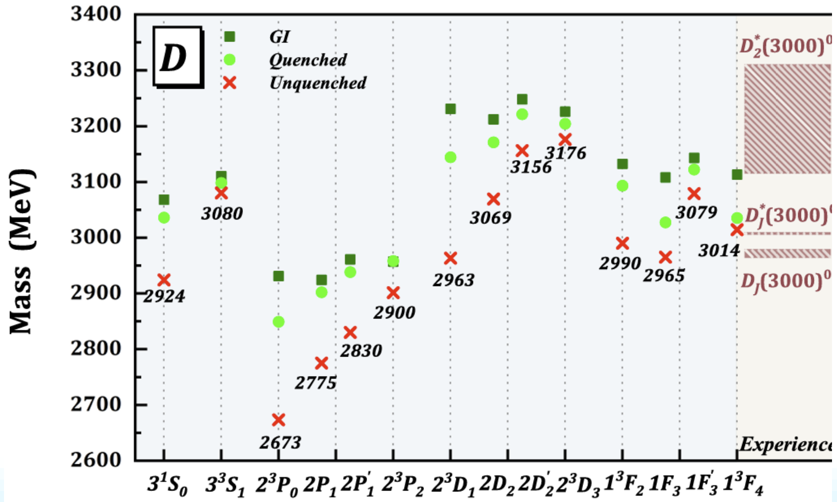
$D_s(1^3F_4)(3125)$: D^*K [~ 31%], $D_1(2430)K$ [~ 26%].

Other D, B, B_s states





Fitted **Predicted**



Summary

- Introduce an unquenched quark model.
- $D_{s0}(2317)$ should need DK channel, while higher state exist or not should be checked to understand how large interaction of $DK \to DK$
- We predict the $D_s(2933)$ as a $2P_1$ state, the predicted mass and width are all similar, and $D_s(3044)$ looks like a 3^1S_0 state.
- We also predicted various high angular momentum D_s states.

THANKS !