Newly observed $T^{a}_{c\bar{s}0}(2900)^{++/0}$ resonance as a $cu\bar{d}\bar{s}/cd\bar{u}\bar{s}$ tetraquark state

陈 伟

中 山 大 学

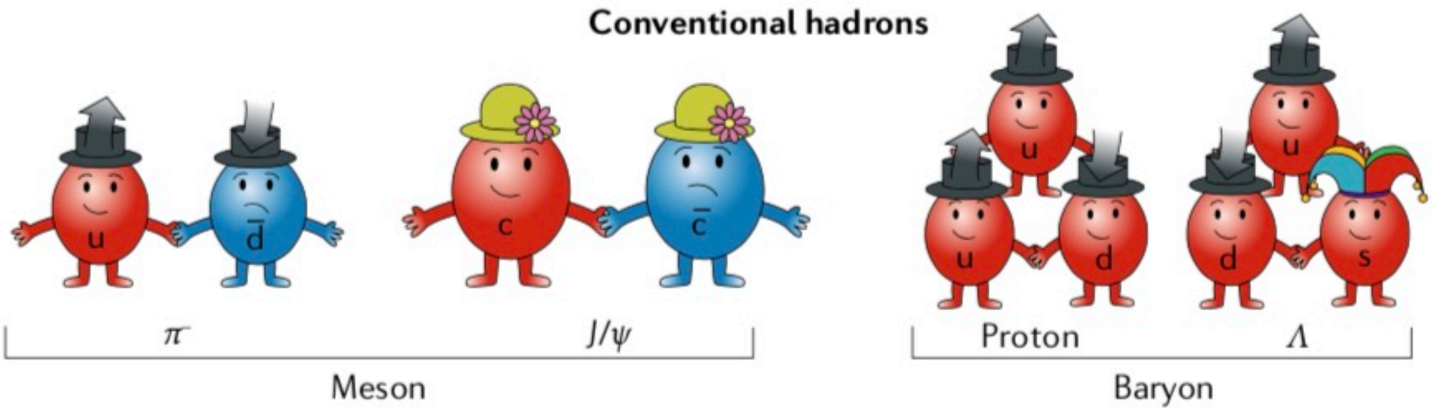
Based on: Wei Chen, Hua-Xing Chen, Xiang Liu, T. G. Steele, Shi-Lin Zhu, Phys. Rev. D95, 114005 (2017)

第四届重味物理与量子色动力学研讨会 长沙

Outline

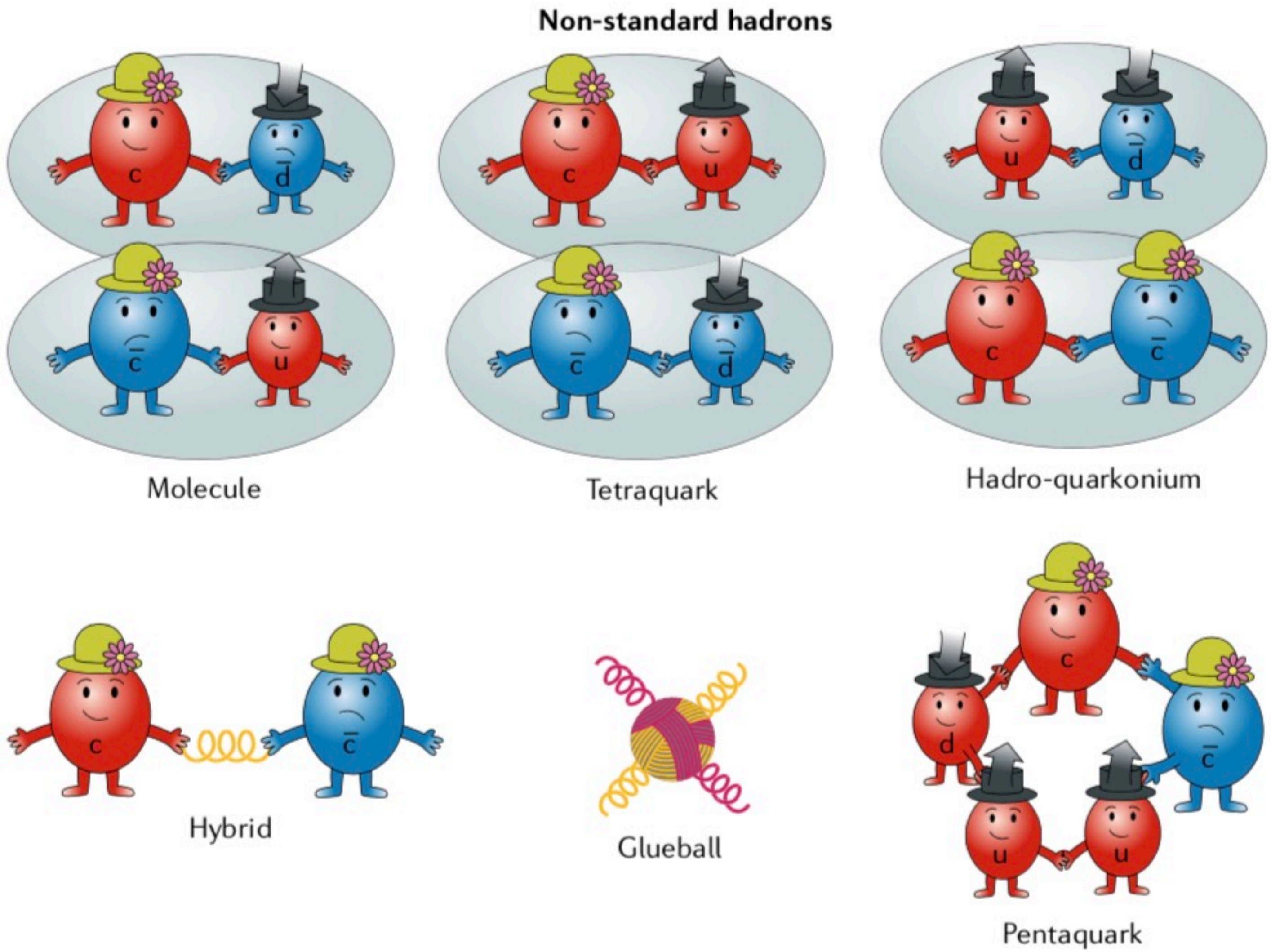
- **Exotic hadrons and fully open-flavor tetraquarks**
- **Method of the QCD sum rules**
- **Mass predictions of $cu\bar{d}\bar{s}$ and $cd\bar{u}\bar{s}$ tetraquarks**
- **Summary**

Quark model and **exotic hadrons**



- **Quark model** is established to classify hadrons: mesons ($q\bar{q}$) and baryons (qqq).
- Hadrons with exotic quantum numbers are exotic hadron states.
- **QCD** may allow for hadrons which lie outside the naive quark model. Hadron structures are more complicated in **QCD**: $N_{\text{quarks}} \neq 2, 3$.
- $SU(3)_c$ **gauge symmetry**: $(N_q - N_{\bar{q}})$ is divisible by 3, plus any number N_g of valence gluons can form a color singlet.

Exotic hadron configurations



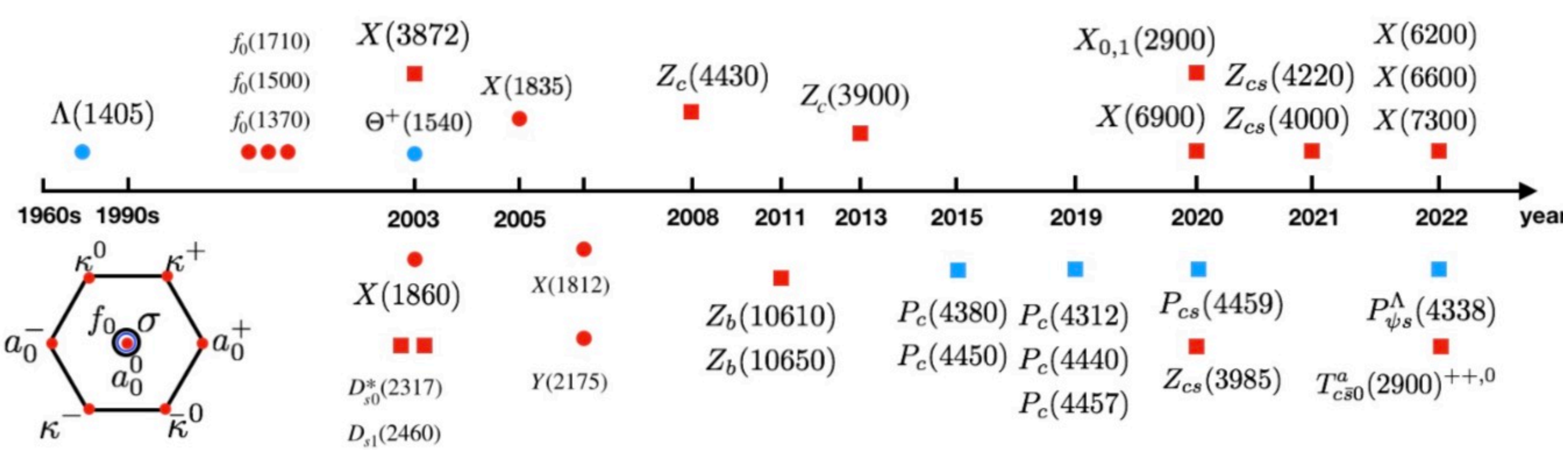
Searching for exotica

Light hadron sector:

- **Dibaryon** candidates: Deuteron, H states, $d^*(2380)$.
- **Hybrid** candidates: $\pi_1(1400)$, $\pi_1(1600)$ and $\pi_1(2015)$ (dispute).
- **Glueball** candidates: $a_0(980)$ and $f_0(980)$, **odderon** (C-odd gluonic compound).
- **Multiquarks** candidates: light scalar mesons (tetraquark candidates); $\Theta^+(1540)$.

Heavy hadron sector: breakthough in multiquarks!

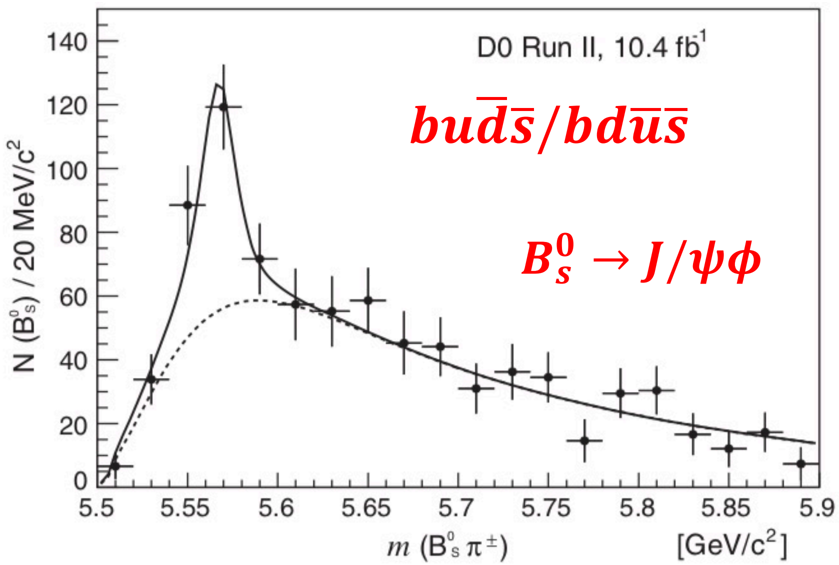
- **XYZ states**: candidates of molecules, tetraquarks, hybrids...
- **Hidden-charm pentaquark states**: $P_c(4312), P_c(4440), P_c(4457), P_{cs}(4459), P^{\Lambda}_{\psi s}(4338)$
- **Fully-charm tetraquark** candidates: $X(6900), X(6200), X(6600), X(7200)$
- **Fully open-flavor tetraquarks** candidates: $X(5568), X_0(2900), X_1(2900)$, $T^a_{c\bar{s}0}(2900)^{++,0}$



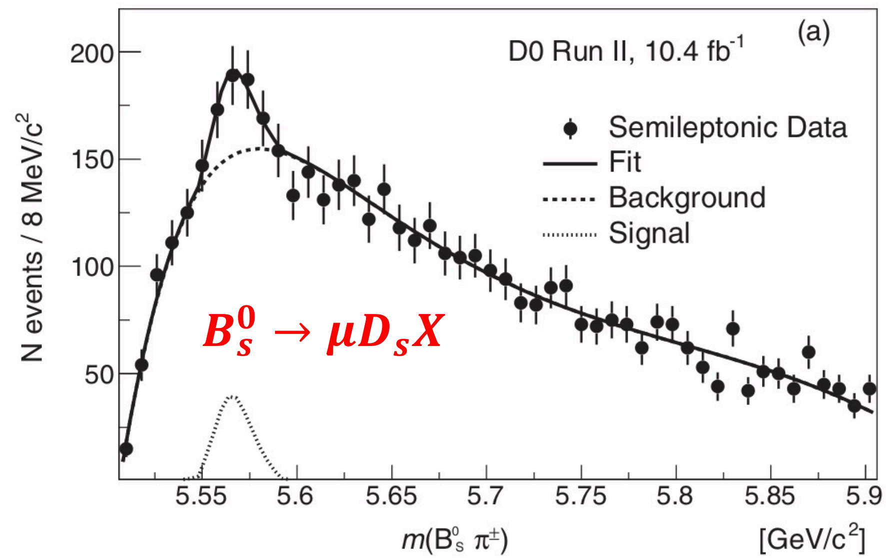
Fully open-flavor tetraquarks

D0 reported the X(5568) in $B_s^0\pi^\pm$ ($bu\bar{d}\bar{s}/bd\bar{u}\bar{s}$) final states in 2016, and confirmed it later in the B_s^0 semileptonic decay process.

PRL117, 022003 (2016)



PRL117, 022003 (2017)

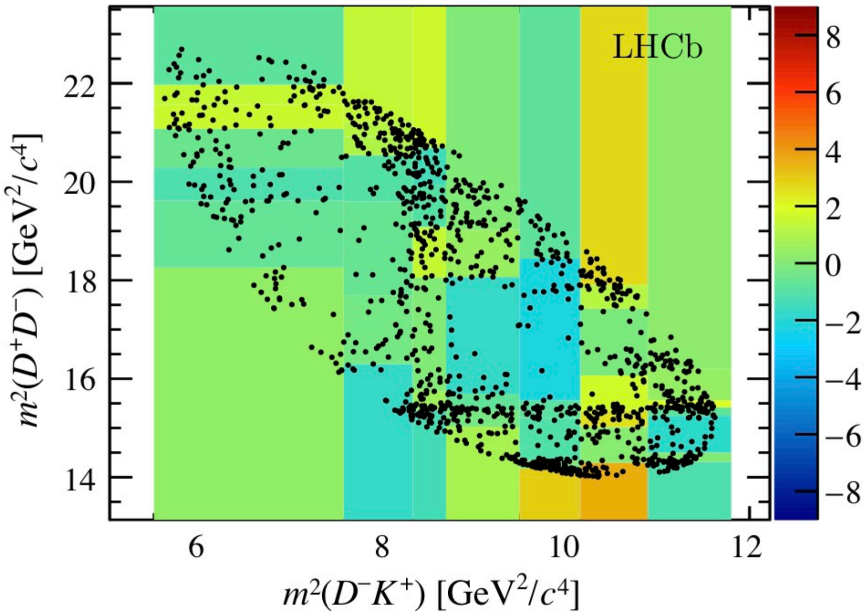


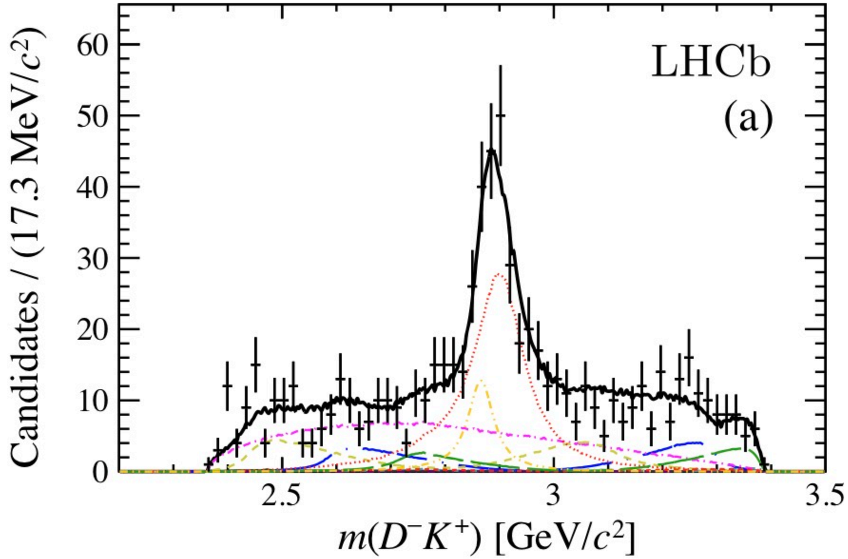
Not confirmed by CDF, LHCb and CMS!

$X_0(2900)$ and $X_1(2900)$

LHCb reported $X_0(2900)$ and $X_1(2900)$ in the D^-K^+ channel in 2020 with spin-0 and spin-1, respectivley.

PRD102,112003(2020); PRL125, 242001 (2020)

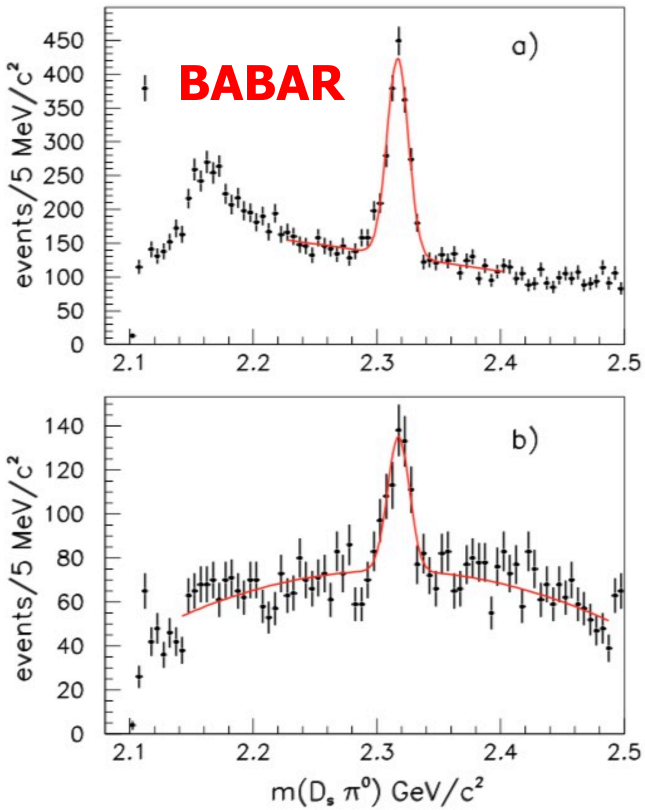




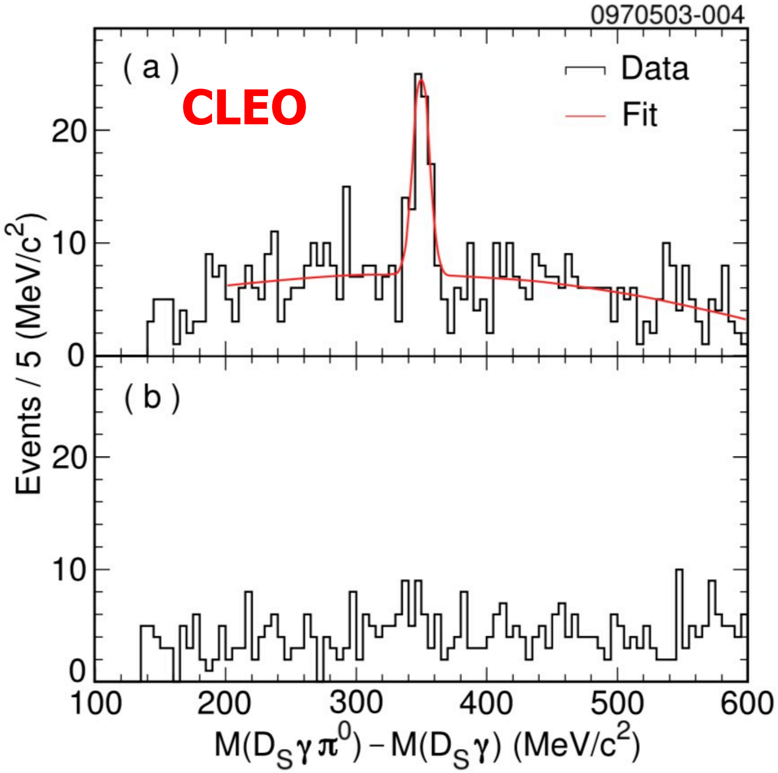
They are candidates for $cs\bar{u}\bar{d}$ states with four different flavors!

$D_{s0}^{*}(2317)$ and $D_{s1}(2460)$

PRL90, 242001 (2003)



PRD68, 032002 (2003)

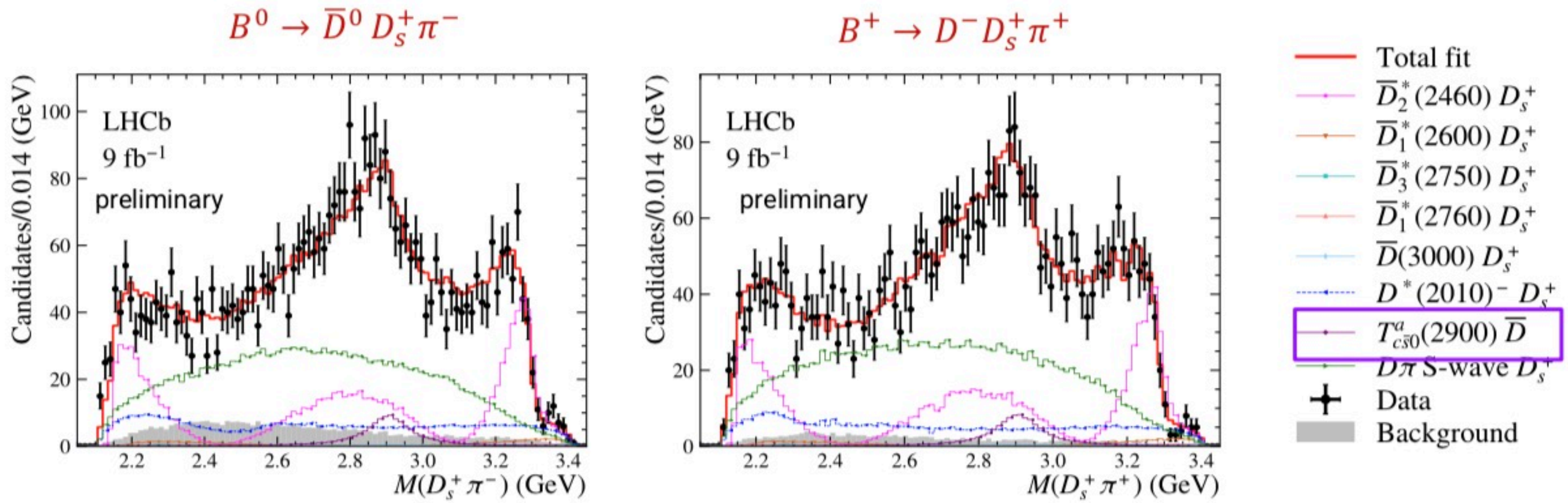


Are they $c\bar{s}$ mesons or $cu\bar{u}\bar{s}$ tetraquarks?

LHCb: $T^a_{c\bar{s}0}(2900)^{++}$ **and** $T^a_{c\bar{s}0}(2900)^0$

From Norella and Chen's slides

Fit with additional $T^a_{c\bar{s}0}(2900)^{++/0} \to D_s^+\pi^{+/-}$



- Significance: $> 9\sigma$

Evaluated using pseudo-experiment

- Spin-parity: 0^+ over other spin-parity by at least 7.5σ

- Mass and width

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV}$$

Fully open-flavor tetraquark candidates

- **$X(5568)$:** $B_s^0\pi^\pm$ $(bu\bar{d}\bar{s})$. Its existence is not confirmed!
- **$X_{0/1}(2900)$:** $D^-K^+(cs\bar{u}\bar{d})$ with four different flavors of valence quarks. Hadron molecules or compact tetraquarks?
- **$D_{s0}^*(2317)$ and $D_{s1}(2460)$:** $D_s^{(*)+}\pi^0$ $(c\bar{s}$ or $cu\bar{u}\bar{s}?)$
- **$T_{c\bar{s}0}^a(2900)^{++,0}$:** $D_s^+\pi^+(cu\bar{d}\bar{s})$ and $D_s^+\pi^-(cd\bar{u}\bar{s})$ with $\mathrm{I}(J^P)=1(0^+)$. **The doubly-charged meson must be exotic!** It is a very good candidates for $cu\bar{d}\bar{s}$ compact tetraquark.
- Our previous prediction on the existence of $T_{c\bar{s}0}^a(2900)^{++,0}$.

QCD sum rules

- Study two-point correlation function of current $J_\mu(x)$ with the same quantum numbers with hadron state:

$$\Pi_{\mu\nu}(q^2) = i \int d^4x e^{iq\cdot x} \langle \Omega | T[J_\mu(x) J_\nu^\dagger(0)] | \Omega \rangle$$

- Classify states $|X\rangle$ by coupling to current $\langle \Omega | J_\mu(x) | X \rangle \neq 0$
- Currents are probes of spectrum and might not overlap with state
- Hadron level: described by the dispersion relation

$$\Pi(q^2) \; = \; \frac{(q^2)^N}{\pi} \int \frac{\mathrm{Im}\Pi(s)}{s^N(s - q^2 - i\epsilon)} ds + \sum_{n=0}^{N-1} b_n (q^2)^n,$$

QCD sum rules

- Quark-gluon level: evaluated via operator product expansion(OPE)

$$\rho(s) = \rho^{pert}(s) + \rho^{\langle\bar{q}q\rangle}(s) + \rho^{\langle GG\rangle}(s) + \rho^{\langle\bar{q}q\rangle^2}(s) + \rho^{\langle\bar{q}g_s\sigma\cdot Gq\rangle}(s) + \ldots,$$

- Apply Borel transform to correlation functions
- Quark-hadron duality: Laplace Sum Rules with QCD spectral function

$$\mathcal{L}_k\left(s_0, M_B^2\right) = \int_{4m_Q^2}^{s_0} ds e^{-s/M_B^2} \rho(s) s^k = f_X^2 m_X^{2k} e^{-m_X^2/M_B^2},$$

- Predict Hadron mass via:

$$m_X\left(s_0, M_B^2\right) = \sqrt{\frac{\mathcal{L}_1\left(s_0, M_B^2\right)}{\mathcal{L}_0\left(s_0, M_B^2\right)}}.$$

Fully open-flavor tetraquark currents:

Considering only S-wave diquarks

$$
\begin{aligned}
J_1 &= q_{1a}^T C\gamma_5 q_{2b}(\bar{q}_{3a}\gamma_5 C\bar{Q}_b^T - \bar{q}_{3b}\gamma_5 C\bar{Q}_a^T), & J^P &= 0^+, \\
J_2 &= q_{1a}^T C\gamma_\mu q_{2b}(\bar{q}_{3a}\gamma^\mu C\bar{Q}_b^T - \bar{q}_{3b}\gamma^\mu C\bar{Q}_a^T), & J^P &= 0^+, \\
J_{3\mu} &= q_{1a}^T C\gamma_5 q_{2b}(\bar{q}_{3a}\gamma_\mu C\bar{Q}_b^T - \bar{q}_{3b}\gamma_\mu C\bar{Q}_a^T), & J^P &= 0^-, 1^+, \\
J_{4\mu} &= q_{1a}^T C\gamma_\mu q_{2b}(\bar{q}_{3a}\gamma_5 C\bar{Q}_b^T - \bar{q}_{3b}\gamma_5 C\bar{Q}_a^T), & J^P &= 0^-, 1^+, \\
J_{5\mu\nu} &= q_{1a}^T C\gamma_\mu q_{2b}(\bar{q}_{3a}\gamma_\nu C\bar{Q}_b^T - \bar{q}_{3b}\gamma_\nu C\bar{Q}_a^T), & J^P &= 0^+, 1^-, \\
&\quad 2^+(\mathrm{S}); 1^-, 1^+(\mathrm{A}); 0^+(\mathrm{T}), & & (1)
\end{aligned}
$$

$$
\langle 0|J|X\rangle = f_S,
$$

$$
\langle 0|J_\mu|X\rangle = f_V\epsilon_\mu + f_S q_\mu,
$$

$$
\begin{aligned}
&\langle 0|J_{\mu\nu}|X\rangle \\
&\quad = f_{0T} g_{\mu\nu} + f_{0S} q_\mu q_\nu \qquad (J^P = 0^+) \\
&\qquad + f_{1S}^-(\epsilon_\mu q_\nu + \epsilon_\nu q_\mu) + f_{1A}^-(\epsilon_\mu q_\nu - \epsilon_\nu q_\mu) \\
&\qquad + f_{1A}^+ \epsilon^{\mu\nu\rho\sigma}\epsilon_\rho q_\sigma \qquad (J^P = 1^+) \\
&\qquad + f_{2S}\epsilon_{\mu\nu} \qquad (J^P = 2^+),
\end{aligned}
$$

Projectors to pick out the invariant functions：

$$P_{0T} = \frac{1}{16} g_{\mu\nu} g_{\rho\sigma} , \qquad \text{for } J^P = 0^+, \text{ T}$$

trace part

$$P_{0S} = T_{\mu\nu} T_{\rho\sigma} , \qquad \text{for } J^P = 0^+, \text{ S}$$

traceless symmetric part

$$P_{0TS} = \frac{1}{4}(T_{\mu\nu} g_{\rho\sigma} + T_{\rho\sigma} g_{\mu\nu}) , \text{ for } J^P = 0^+, \text{ TS}$$

cross term

$$P_{1A} = \left[\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}\right] , \text{ for } J^P = 1^+,$$

$$P^P_{2S} = \frac{1}{2}\left(\eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \frac{2}{3}\eta_{\mu\nu}\eta_{\rho\sigma}\right) , \text{ for } J^P = 2^+, \text{ S}$$

where

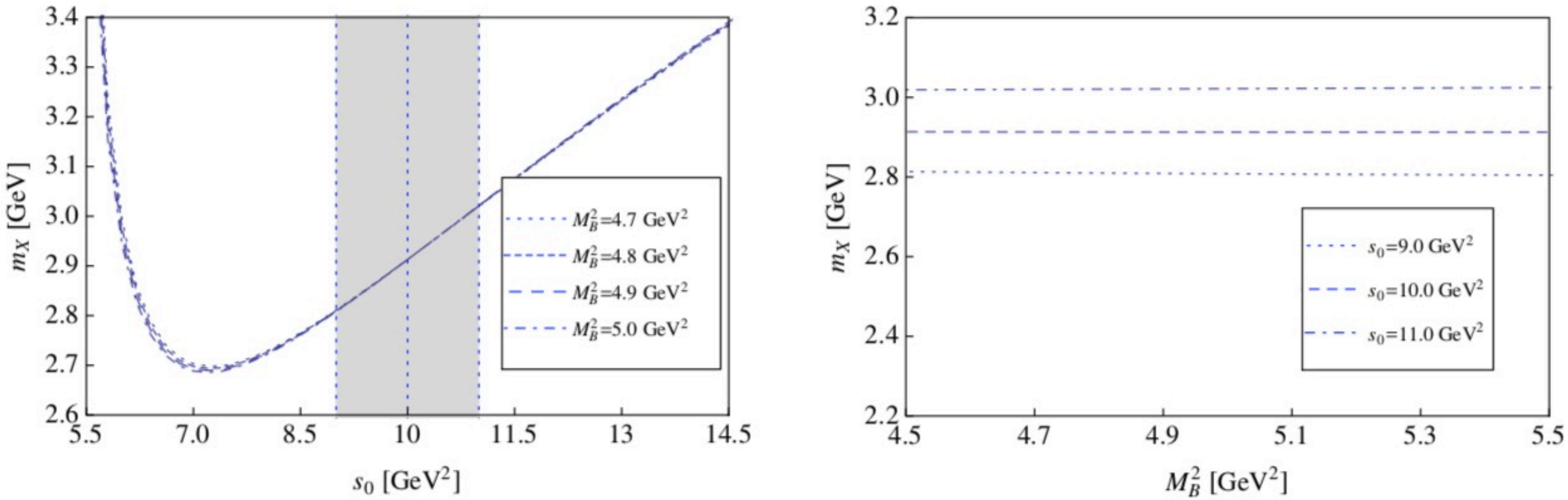
$$\eta_{\mu\nu} = \frac{q_\mu q_\nu}{q^2} - g_{\mu\nu} ,$$

$$T_{\mu\nu} = \frac{q_\mu q_\nu}{q^2} - \frac{1}{4} g_{\mu\nu} ,$$

$$T^{\pm}_{\mu\nu,\rho\sigma} = \left[\frac{q_\mu q_\rho}{q^2}\eta_{\nu\sigma} \pm (\mu \leftrightarrow \nu)\right] \pm (\rho \leftrightarrow \sigma) .$$

$sd\bar{u}\bar{c}$ fully open-flavor tetraquarks:

Wei Chen, Hua-Xing Chen, Xiang Liu, T. G. Steele, Shi-Lin Zhu, Phys. Rev. D95, 114005 (2017)



$J_2(x)$ **with** $J^P = 0^+$

$$M_X = (2.91 \pm 0.14)\ \mathrm{MeV}$$

in excellent agreement with $T^a_{c\bar{s}0}(2900)^{++,0}$!

$sd\bar{u}\bar{c}$ fully open-flavor tetraquarks:

TABLE I. Mass spectrum for the charm-strange $sq\bar{q}\bar{c}$ tetraquark states.

J^{PC}	Currents	$s_0(\text{GeV}^2)$	Borel window (GeV^2)	$m_{X^{cs}}(\text{GeV})$	Type
0^+	J_1	7.5 ± 0.5	3.3–3.6	2.55 ± 0.10	A
	J_2	10.0 ± 0.5	4.7–5.0	2.91 ± 0.14	A
	$J_{5\mu\nu}(\text{T})$	10.0 ± 0.5	2.2–3.1	2.88 ± 0.15	A
	$J_{5\mu\nu}(\text{S})$	12.0 ± 0.5	3.9–4.2	2.53 ± 0.13	B
1^+	$J_{3\mu}$	7.5 ± 0.5	5–3.8	2.55 ± 0.12	A
	$J_{4\mu}$	9.5 ± 0.5	3.2–3.9	2.81 ± 0.13	A
	$J_{5\mu\nu}(\text{A})$	9.5 ± 0.5	3.5–3.8	2.83 ± 0.13	A
2^+	$J_{5\mu\nu}(\text{S})$	10.0 ± 0.5	3.4–4.0	2.91 ± 0.13	A
0^-	$J_{3\mu}$	7.5 ± 0.5	4.0–4.3	2.31 ± 0.09	A
	$J_{4\mu}$	12.0 ± 0.5	3.2–4.1	3.30 ± 0.16	A
1^-	$J_{5\mu\nu}(\text{A})$	13.5 ± 1.0	2.6–3.4	3.35 ± 0.16	C
	$J_{5\mu\nu}(\text{S})$	15.5 ± 1.0	3.2–3.9	3.55 ± 0.18	C

Wei Chen, Hua-Xing Chen, Xiang Liu, T. G. Steele, Shi-Lin Zhu, Phys. Rev. D95, 114005 (2017)

Suggested to search for exotic doubly-charged tetraquarks in $D_s^{(*)}\pi$ final states

PHYSICAL REVIEW D **95**, 114005 (2017)

Open-flavor charm and bottom $sq\bar{q}\bar{Q}$ and $qq\bar{q}\bar{Q}$ tetraquark states

Wei Chen,[1] Hua-Xing Chen,[2,*] Xiang Liu,[3,4,†] T. G. Steele,[1,‡] and Shi-Lin Zhu[5,6,7,§]

We provide comprehensive investigations for the mass spectrum of exotic open-flavor charmed/bottom $sq\bar{q}\bar{c}$, $qq\bar{q}\bar{c}$, $sq\bar{q}\bar{b}$, $qq\bar{q}\bar{b}$ tetraquark states with various spin-parity assignments $J^P = 0^+, 1^+, 2^+$ and $0^-, 1^-$ in the framework of QCD sum rules. In the diquark configuration, we construct the diquark-antidiquark interpolating tetraquark currents using the color-antisymmetric scalar and axial-vector diquark fields. The stable mass sum rules are established in reasonable parameter working ranges, which are used to give reliable mass predictions for these tetraquark states. We obtain the mass spectra for the open-flavor charmed/bottom $sq\bar{q}\,\bar{c}$, $qq\bar{q}\,\bar{c}$, $sq\bar{q}\,\bar{b}$, $qq\bar{q}\,\bar{b}$ tetraquark states with various spin-parity quantum numbers. In addition, we suggest searching for exotic doubly-charged tetraquarks, such as $[sd][\bar{u}\,\bar{c}] \to D_s^{(*)-}\pi^-$ in future experiments at facilities such as BESIII, BelleII, PANDA, LHCb, and CMS, etc.

DOI: 10.1103/PhysRevD.95.114005

Predicted the existence of $T^a_{c\bar{s}0}(2900)^{++,0}$ before their observation!

Summary

- Recently, LHCb reported $T^{a}_{c\bar{s}0}(2900)^{++}$ and $T^{a}_{c\bar{s}0}(2900)^{0}$ in the $\mathrm{D}_s\pi$ final states, containing four different flavored quarks;
- The first observed doubly-charged exotic hadron since 2003;
- We have calculated the masses of the open-flavor $cu\bar{d}\bar{s}$ and $cd\bar{u}\bar{s}$ tetraquarks in 2017, in which one of our results is in excellent agreement with $T^{a}_{c\bar{s}0}(2900)^{++}$ and $T^{a}_{c\bar{s}0}(2900)^{0}$;
- We have suggested to search for doubly-charged tetraquarks in $D_s^{(*)}\pi$ final states;
- It is necessary to reproduce their decay widths in compact tetraquark configuration!

Thank you!