华中师范大学粒子物理研究所论坛（IOPP Forum）,2020.11.25

北京航空航天大學
BEIHANG UNIVERSITY


# 自然界存在新的类原子核物质形态么？


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1309.4743

1707.03802

1805.08330

1809.01059

1906.11995

1909.09021

2008.13014

# Contents

- **Motivation: new types of clusters of color singlets in addition to atomic nuclei—as a nontrivial test of the molecule picture**
- **Ds0*(2317) and Ds1(2460) as DK/D*K molecules: theory & lattice**
- **An explicit study of the DDK** system: **$R^{++}$(4140)**
- **K*(4307) as excited K* with hidden charm**
- **Summary and outlook**

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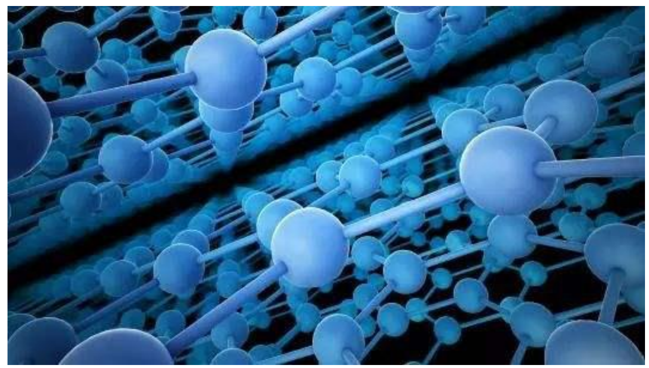
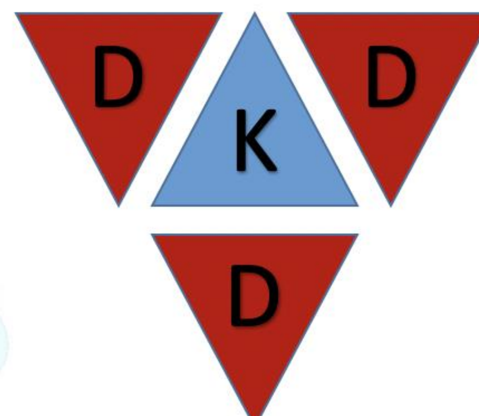
# Frontiers of Physics

**New Energy**

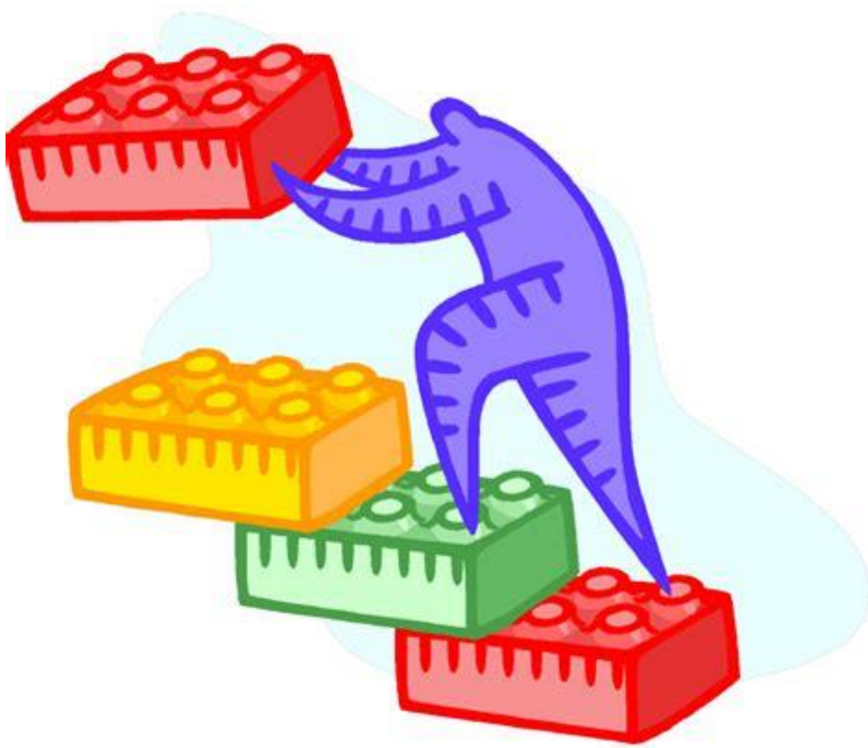
**New Material**

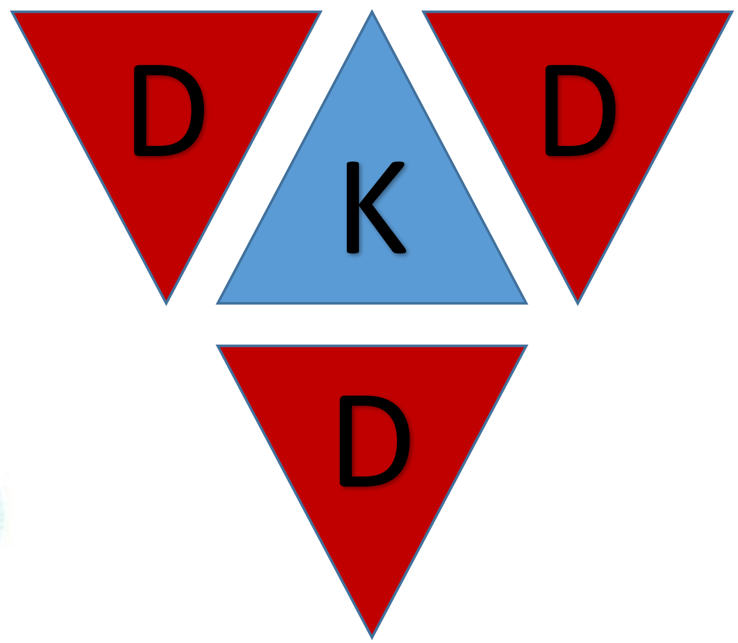


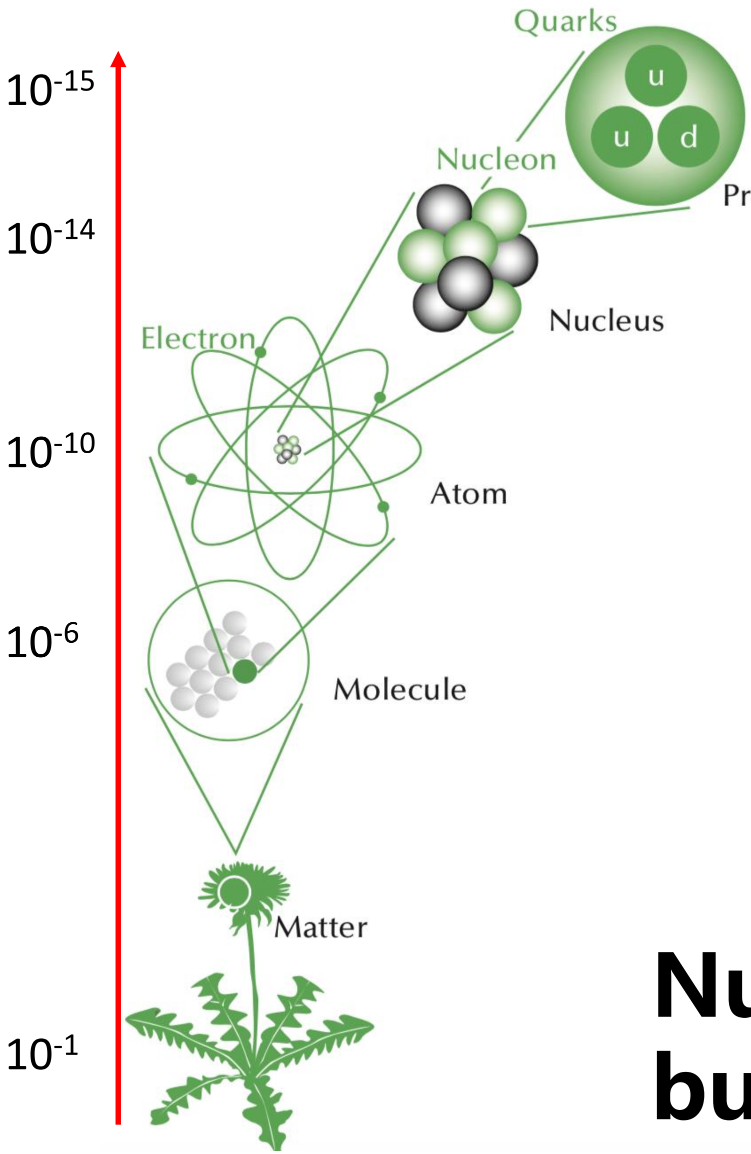
**New Matter**



**Build** **new forms** **of bosonic matter from D & K mesons**








## IUPAC Periodic Table of the Elements

Key: atomic number / Symbol / name / conventional atomic weight / standard atomic weight

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H hydrogen 1.008 [1.0078, 1.0082] | | | | | | | | | | | | | | | | | 2 He helium 4.0026 |
| 3 Li lithium 6.94 [6.938, 6.997] | 4 Be beryllium 9.0122 | | | | | | | | | | | 5 B boron 10.81 [10.806, 10.821] | 6 C carbon 12.011 [12.009, 12.012] | 7 N nitrogen 14.007 [14.006, 14.008] | 8 O oxygen 15.999 [15.999, 16.000] | 9 F fluorine 18.998 | 10 Ne neon 20.180 |
| 11 Na sodium 22.990 | 12 Mg magnesium 24.305 [24.304, 24.307] | | | | | | | | | | | 13 Al aluminium 26.982 | 14 Si silicon 28.085 [28.084, 28.086] | 15 P phosphorus 30.974 | 16 S sulfur 32.06 [32.059, 32.076] | 17 Cl chlorine 35.45 [35.446, 35.457] | 18 Ar argon 39.95 [39.792, 39.963] |
| 19 K potassium 39.098 | 20 Ca calcium 40.078(4) | 21 Sc scandium 44.956 | 22 Ti titanium 47.867 | 23 V vanadium 50.942 | 24 Cr chromium 51.996 | 25 Mn manganese 54.938 | 26 Fe iron 55.845(2) | 27 Co cobalt 58.933 | 28 Ni nickel 58.693 | 29 Cu copper 63.546(3) | 30 Zn zinc 65.38(2) | 31 Ga gallium 69.723 | 32 Ge germanium 72.630(8) | 33 As arsenic 74.922 | 34 Se selenium 78.971(8) | 35 Br bromine 79.904 [79.901, 79.907] | 36 Kr krypton 83.798(2) |
| 37 Rb rubidium 85.468 | 38 Sr strontium 87.62 | 39 Y yttrium 88.906 | 40 Zr zirconium 91.224(2) | 41 Nb niobium 92.906 | 42 Mo molybdenum 95.95 | 43 Tc technetium | 44 Ru ruthenium 101.07(2) | 45 Rh rhodium 102.91 | 46 Pd palladium 106.42 | 47 Ag silver 107.87 | 48 Cd cadmium 112.41 | 49 In indium 114.82 | 50 Sn tin 118.71 | 51 Sb antimony 121.76 | 52 Te tellurium 127.60(3) | 53 I iodine 126.90 | 54 Xe xenon 131.29 |
| 55 Cs caesium 132.91 | 56 Ba barium 137.33 | 57-71 lanthanoids | 72 Hf hafnium 178.49(2) | 73 Ta tantalum 180.95 | 74 W tungsten 183.84 | 75 Re rhenium 186.21 | 76 Os osmium 190.23(3) | 77 Ir iridium 192.22 | 78 Pt platinum 195.08 | 79 Au gold 196.97 | 80 Hg mercury 200.59 | 81 Tl thallium 204.38 [204.38, 204.39] | 82 Pb lead 207.2 | 83 Bi bismuth 208.98 | 84 Po polonium | 85 At astatine | 86 Rn radon |
| 87 Fr francium | 88 Ra radium | 89-103 actinoids | 104 Rf rutherfordium | 105 Db dubnium | 106 Sg seaborgium | 107 Bh bohrium | 108 Hs hassium | 109 Mt meitnerium | 110 Ds darmstadtium | 111 Rg roentgenium | 112 Cn copernicium | 113 Nh nihonium | 114 Fl flerovium | 115 Mc moscovium | 116 Lv livermorium | 117 Ts tennessine | 118 Og oganesson |
| | | | 57 La lanthanum 138.91 | 58 Ce cerium 140.12 | 59 Pr praseodymium 140.91 | 60 Nd neodymium 144.24 | 61 Pm promethium | 62 Sm samarium 150.36(2) | 63 Eu europium 151.96 | 64 Gd gadolinium 157.25(3) | 65 Tb terbium 158.93 | 66 Dy dysprosium 162.50 | 67 Ho holmium 164.93 | 68 Er erbium 167.26 | 69 Tm thulium 168.93 | 70 Yb ytterbium 173.05 | 71 Lu lutetium 174.97 |
| | | | 89 Ac actinium | 90 Th thorium 232.04 | 91 Pa protactinium 231.04 | 92 U uranium 238.03 | 93 Np neptunium | 94 Pu plutonium | 95 Am americium | 96 Cm curium | 97 Bk berkelium | 98 Cf californium | 99 Es einsteinium | 100 Fm fermium | 101 Md mendelevium | 102 No nobelium | 103 Lr lawrencium |

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

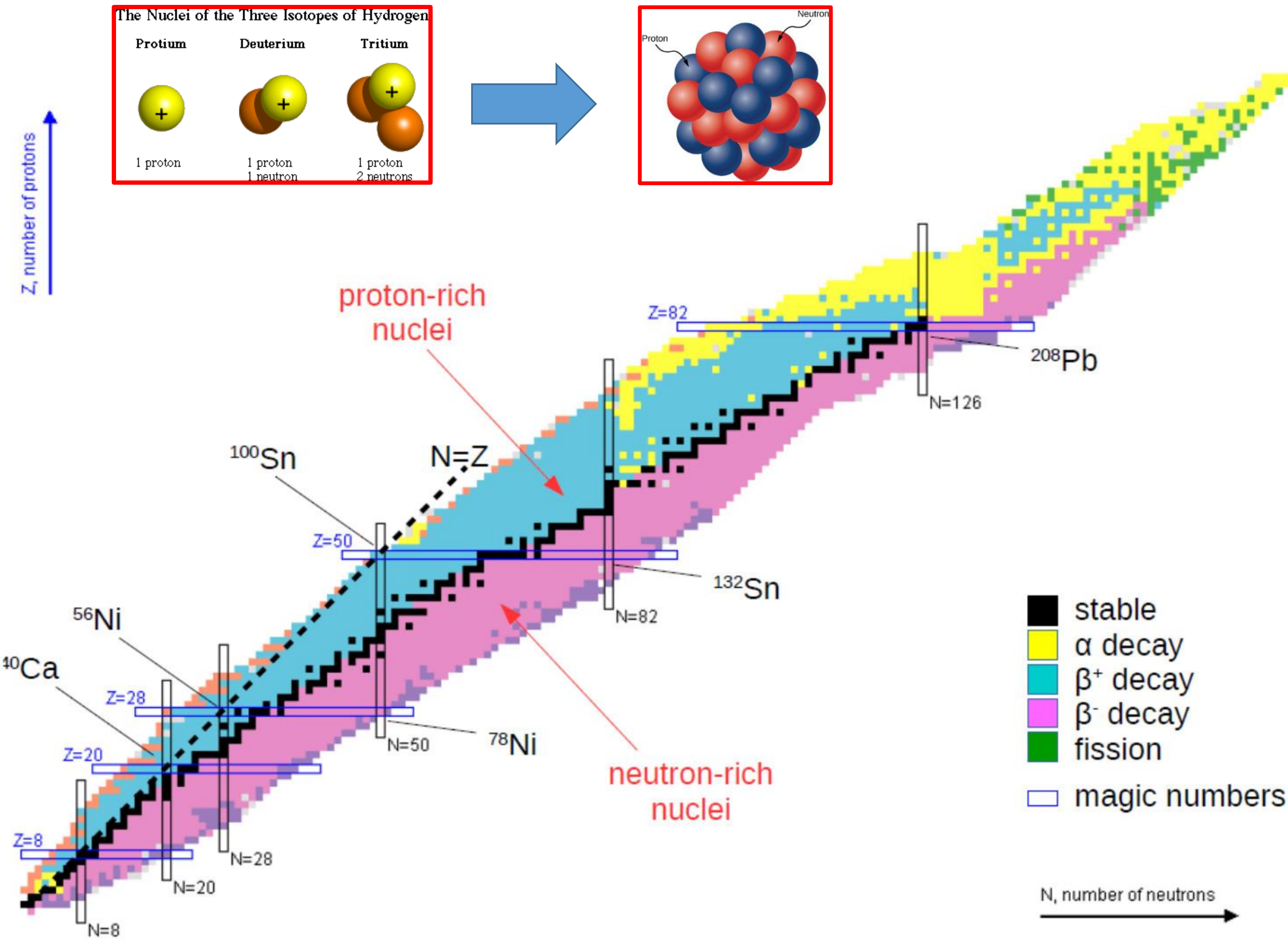
For notes and updates to this table, see www.iupac.org. This version is dated 1 December 2018.



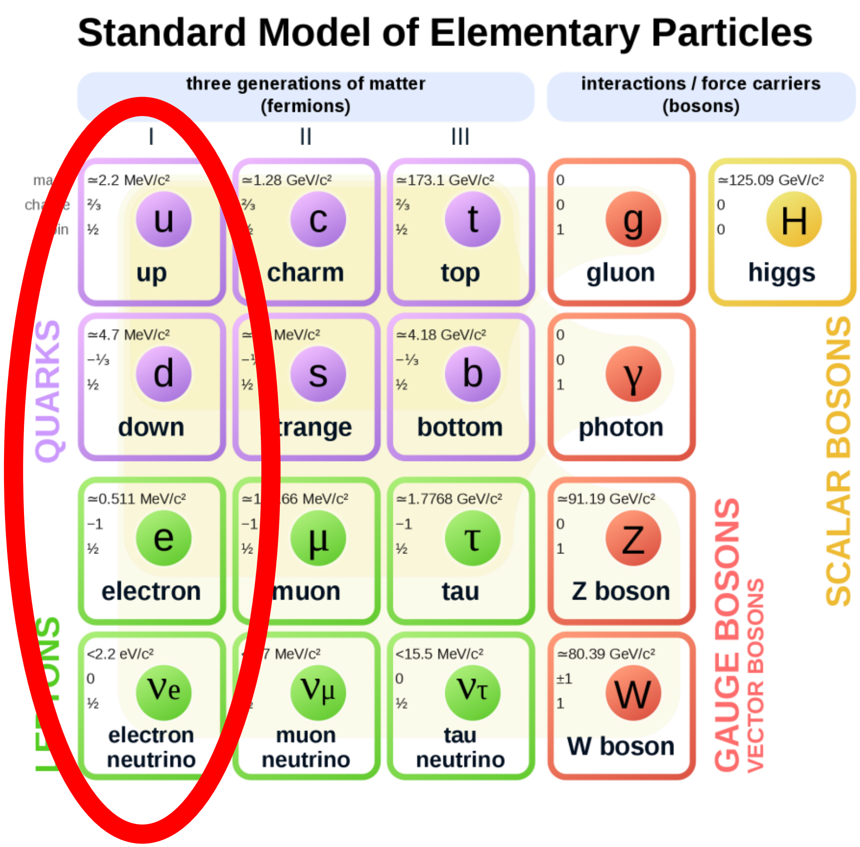
United Nations Educational, Scientific and Cultural Organization

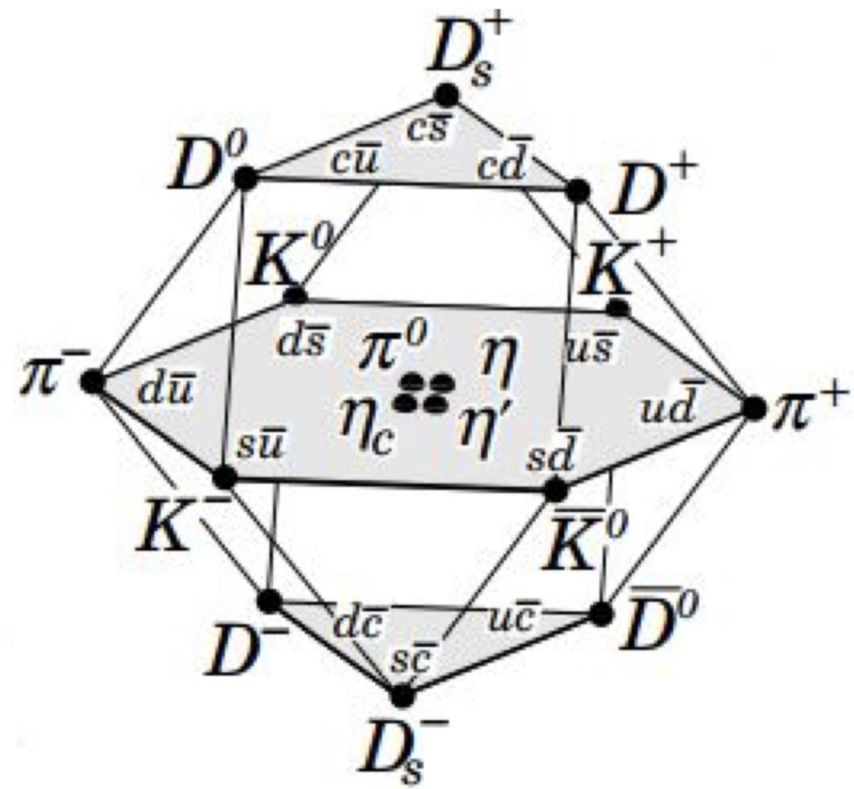
2019 IYPT International Year of the Periodic Table of Chemical Elements

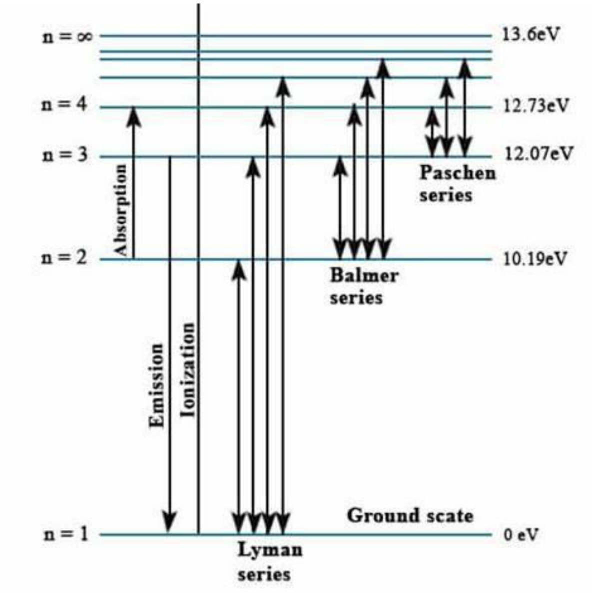
# Nucleons are the essential building blocks of Matter!


The Nuclei of the Three Isotopes of Hydrogen
Protium
Deuterium
Tritium
1 proton
1 proton
1 neutron
1 proton
2 neutrons
Neutron
Proton
Z, number of protons
proton-rich
nuclei
N=Z
100Sn
Z=82
208Pb
N=126
Z=50
132Sn
N=82
56Ni
40Ca
Z=28
Z=20
Z=8
78Ni
N=50
N=28
N=20
N=8
neutron-rich
nuclei
stable
α decay
β+ decay
β- decay
fission
magic numbers
N, number of neutrons

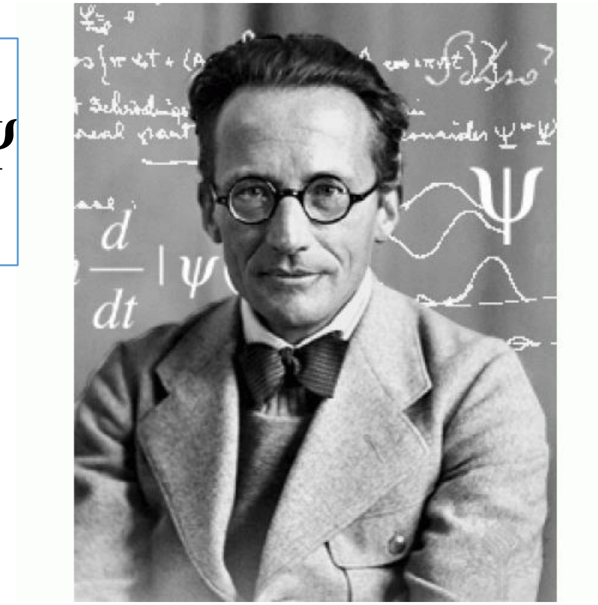
# What are D & K  mesons?



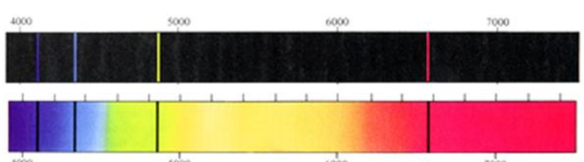






$$\left(\frac{\hat{p}^2}{2\mu} + V\right)\Psi = E\Psi$$



$$V = -\frac{e^2}{4\pi\epsilon_0 r^2}$$

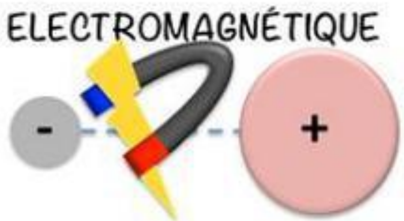



# Schroedinger equation & Hadrogen spectrum

# Strong interaction is much harder

F= $\frac{kq_1q_2}{r^2}$

F=$q\vec{v} \times \vec{B}$

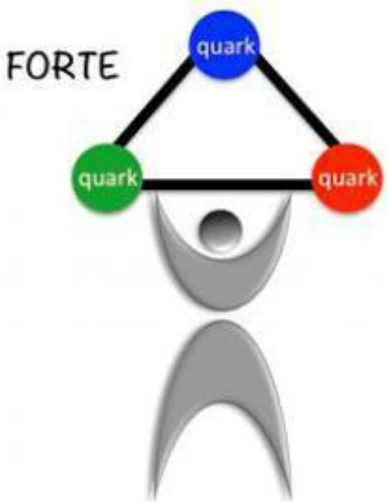


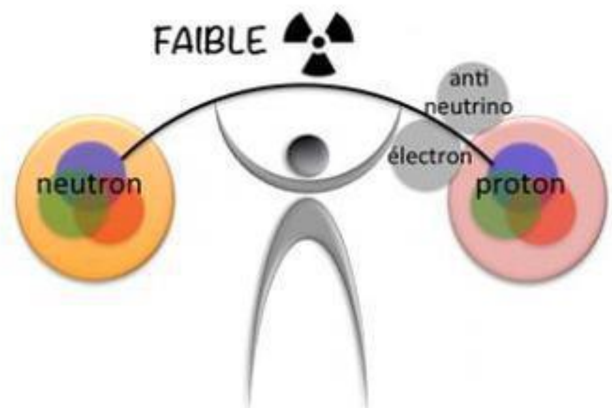


F= $\frac{Gm_1m_2}{r^2}$

F=..............

....




F=$G_F$

# One of the most difficult problems

in the history of mankind

**SCIENTIFIC AMERICAN,** September 1953

## What Holds the Nucleus Together?

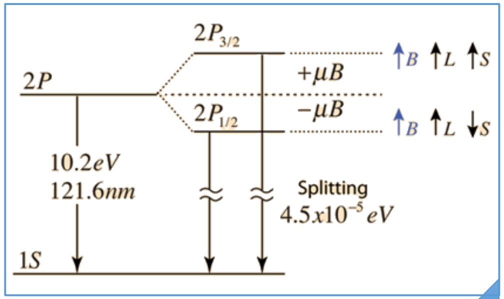
**by Hans A. Bethe**

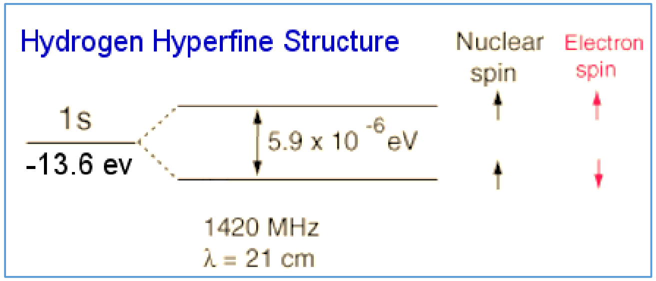
**In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem – probably more man-hours than have been given to any other scientific question in the history of mankind.**

Hans Bethe
Nobel Prize in Physics
1967

高精度协变手征核力—北航

# Why spectroscopy—Atomic




$$\frac{1}{\lambda_{\text{vac}}} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

**Rydberg formula**

**Fine structure**

**Hyperfine structure**

Johannes Rydberg

Niels Henrik David Bohr

Edward W. Morley

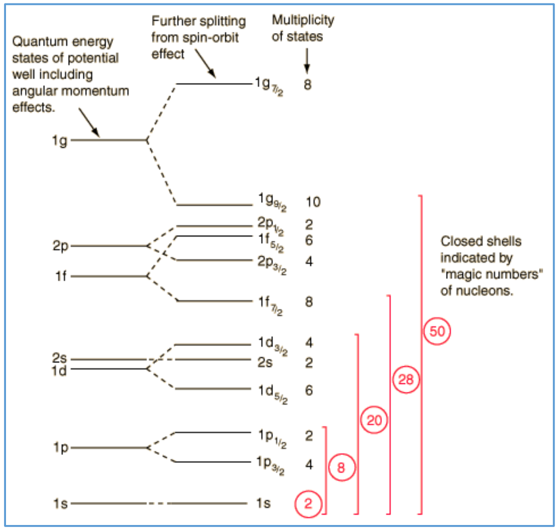
Arnold Sommerfeld

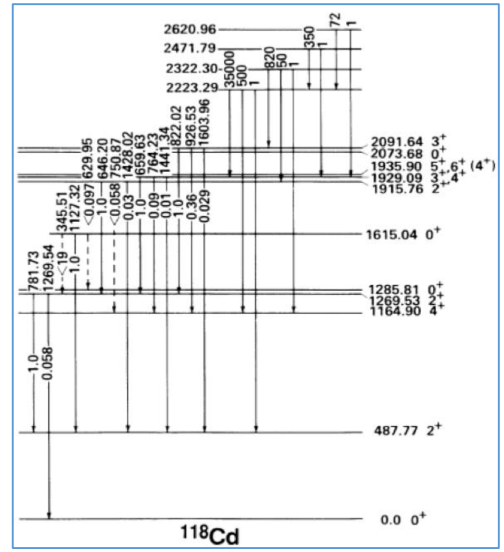
Albert Abraham Michelson

Wolfgang Pauli

# Why spectroscopy—Nuclear

**Single particle motion**

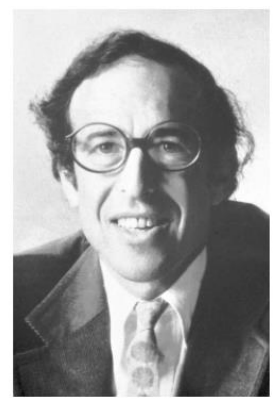



**Collective motion**





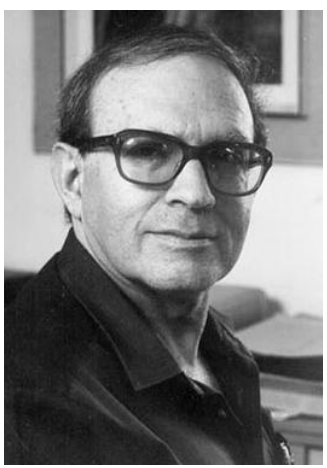



Eugene Paul Wigner Maria Goeppert Mayer J. Hans D. Jensen Aage Niels Bohr, Ben Roy Mottelson Leo James Rainwater

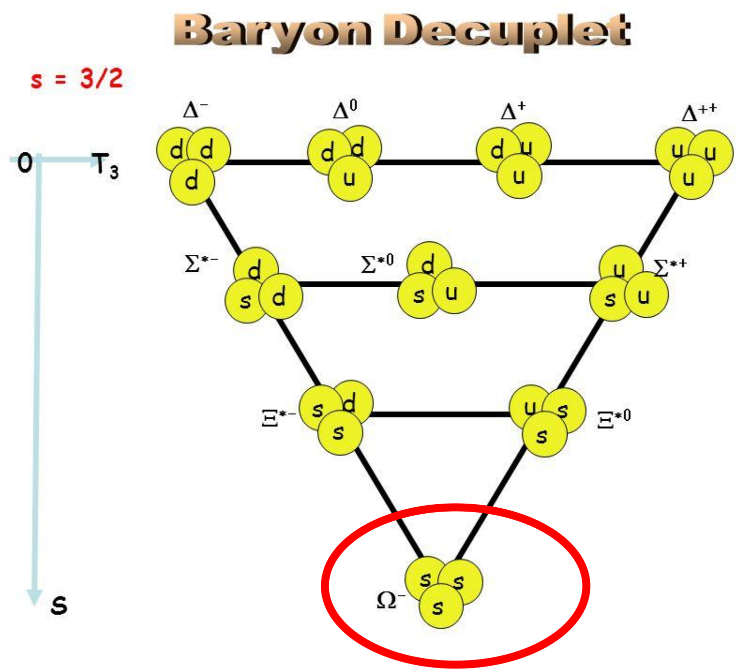
# Hadron spectroscopy—QM—QCD

*Put an end to the then chaotic situation*

Murray Gell-Mann



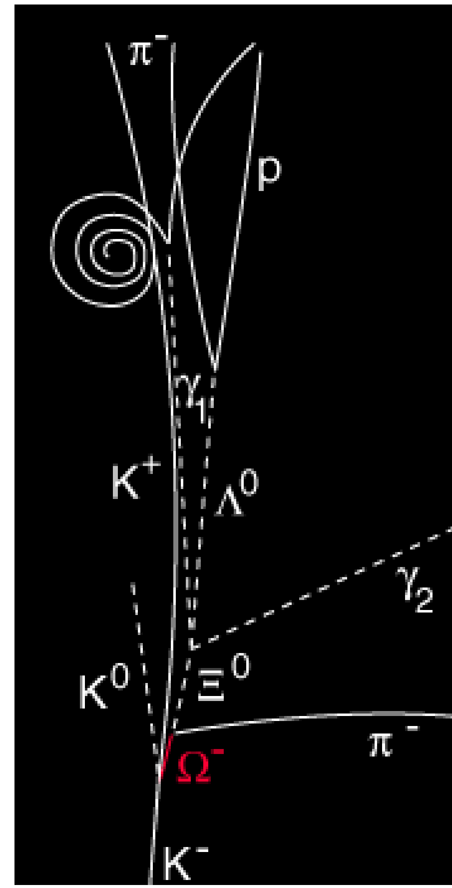
Yuval Ne'eman.




Eightfold way-1961

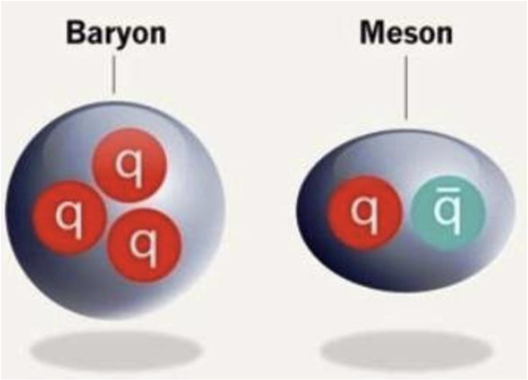
Quark model-1964

QCD/SM



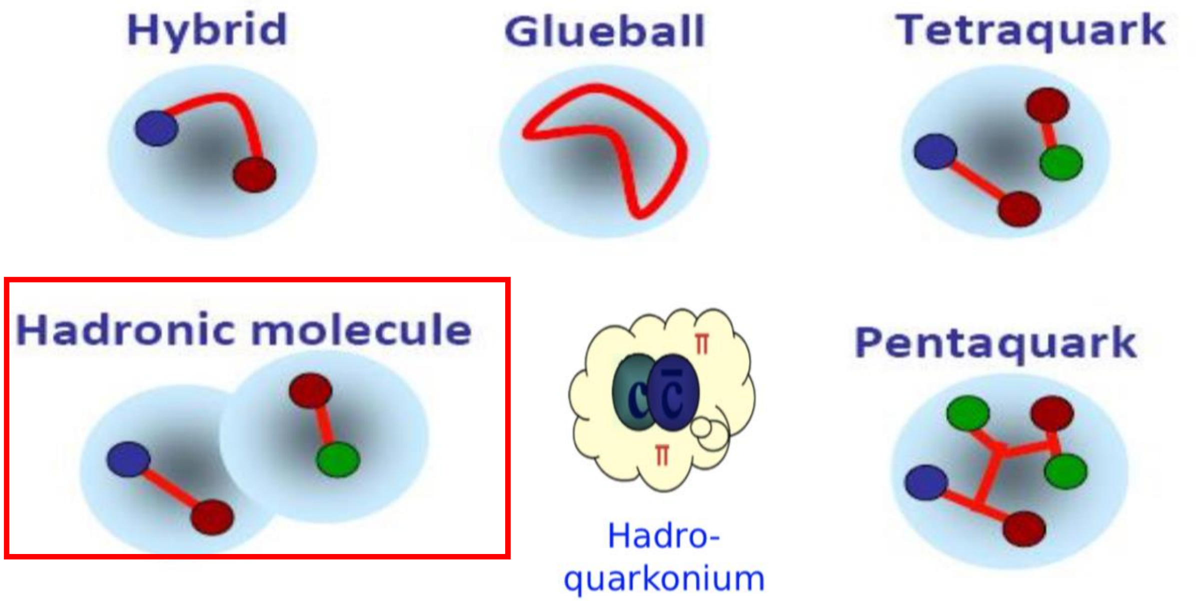

V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964)

# Beyond QM



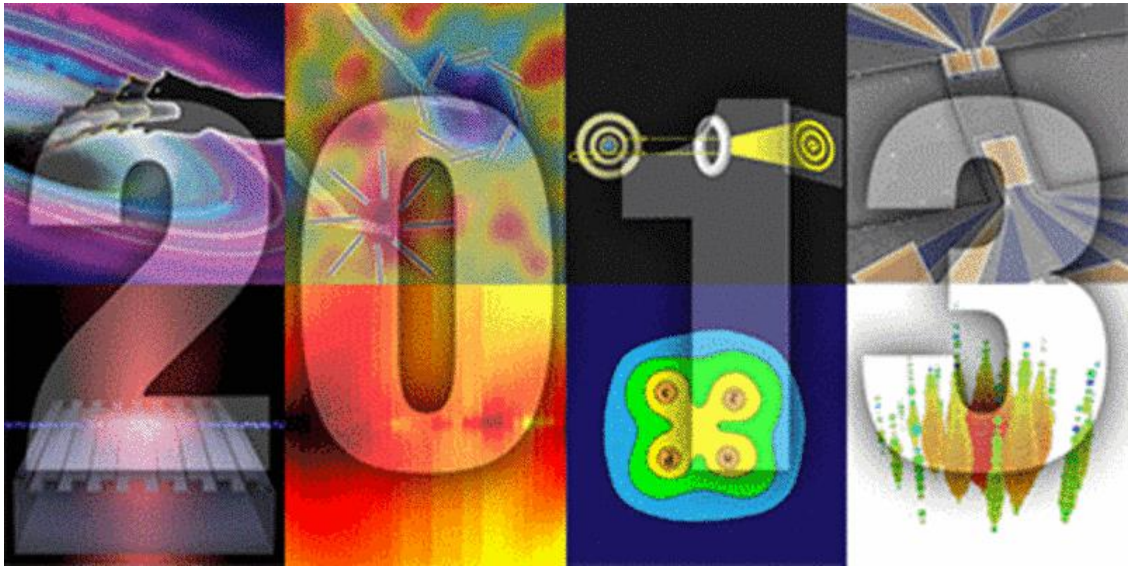

In the **naïve quark model**

In principle, QCD **allows**



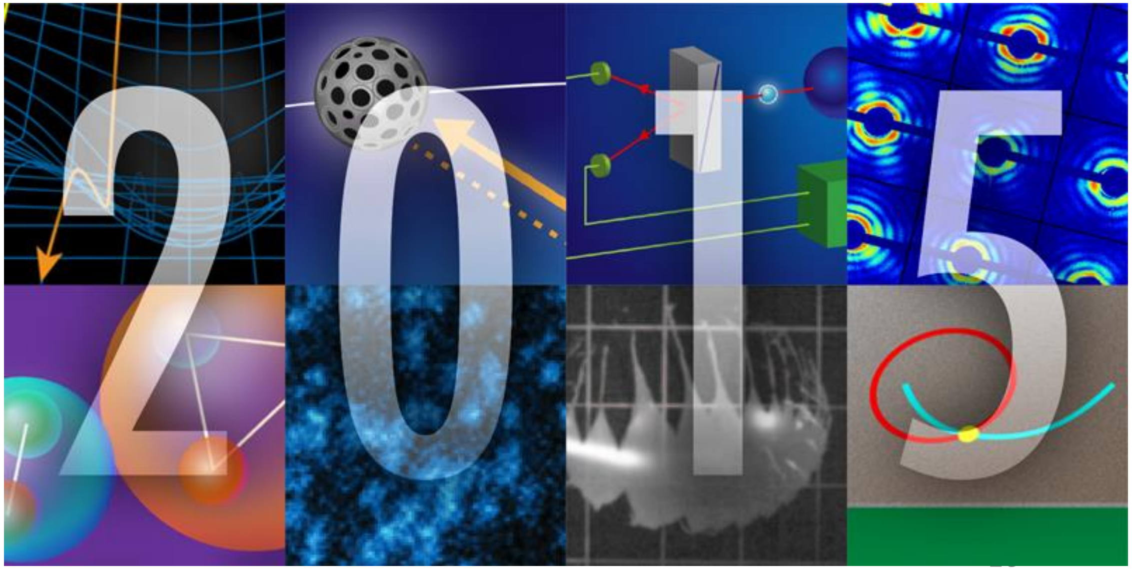
# Highlights of the year

the research covered in Physics that **really made waves in and beyond the physics community.**

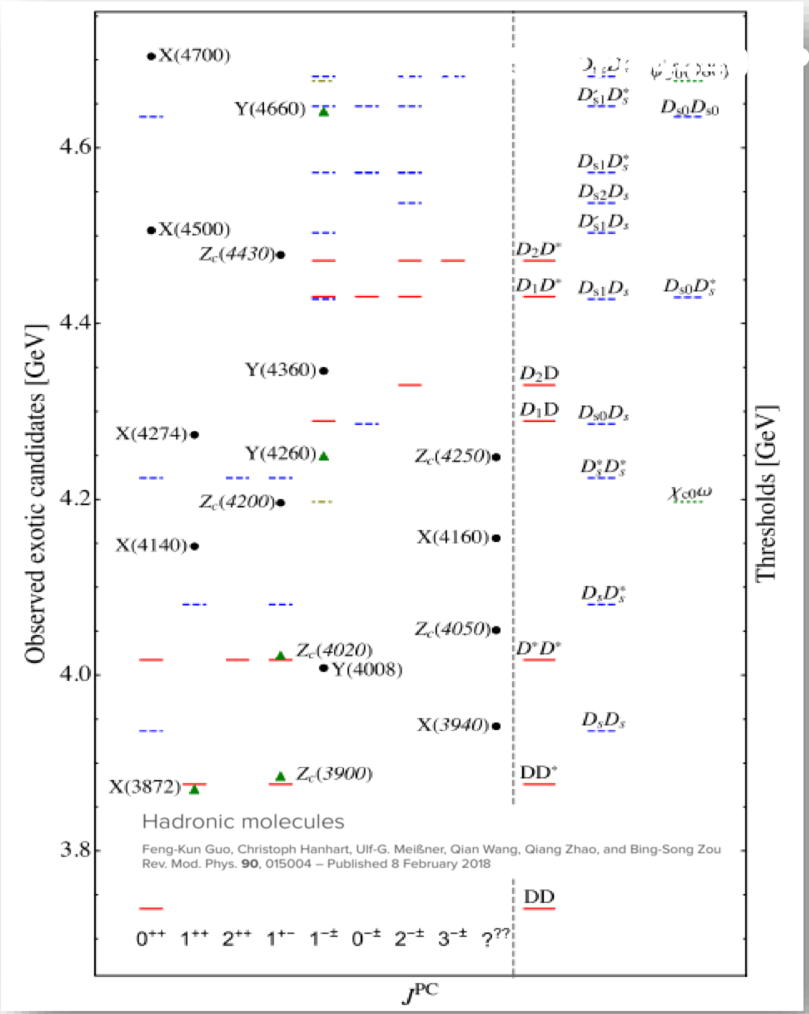


**Four-Quark Matter/BESIII**

**Particle High Five/LHCb**

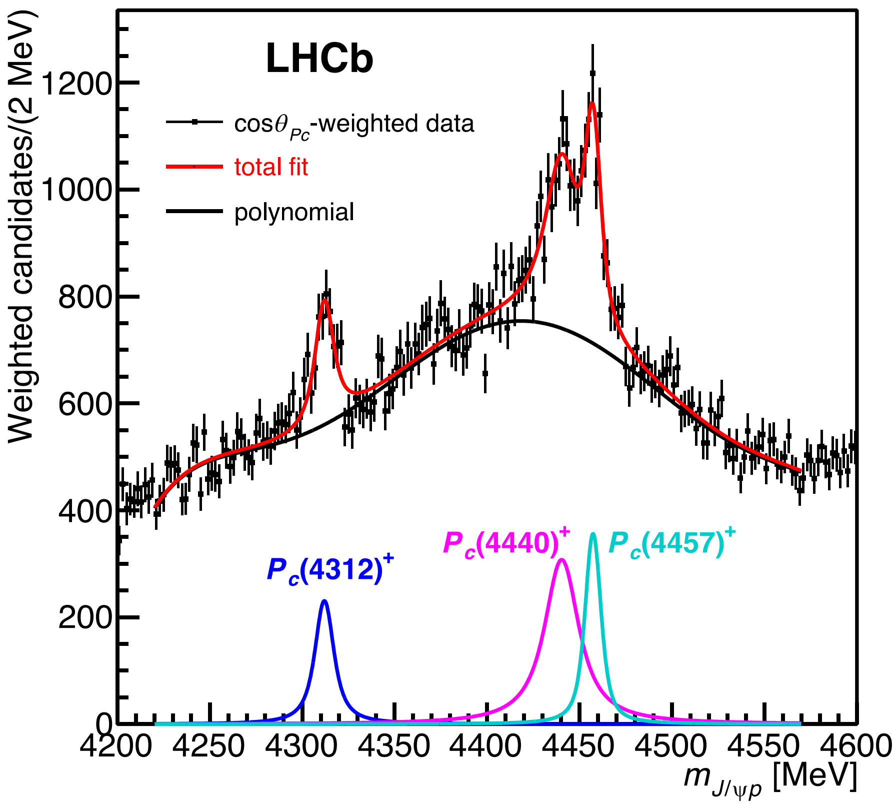


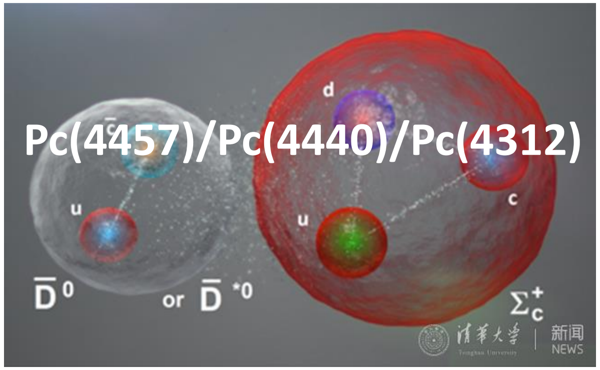
# Most of them close to thresholds

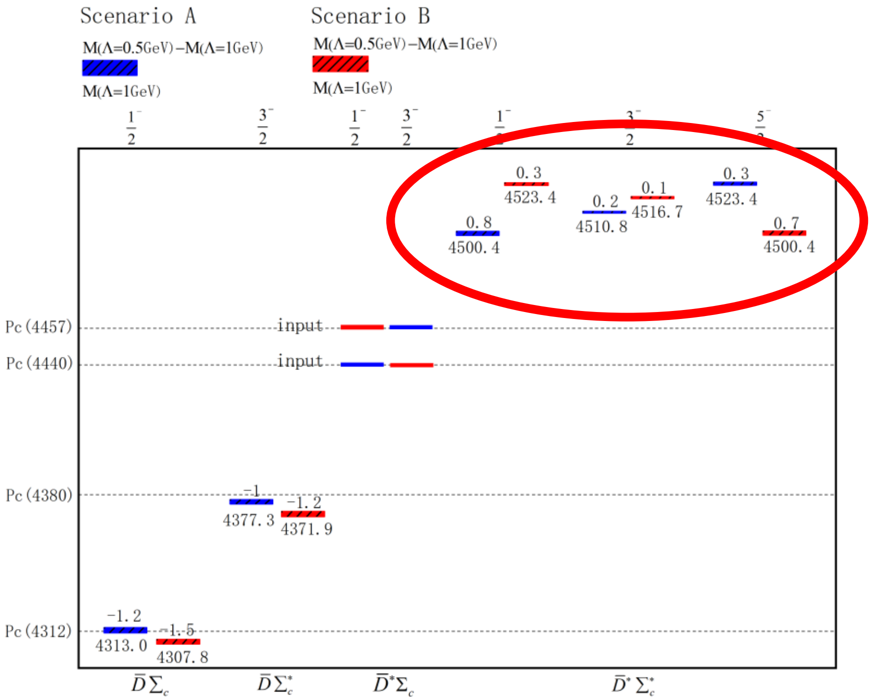



*Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, Bing-Song Zou. Rev.Mod.Phys. 90 (2018) 015004.*

# Fine structure in Pc

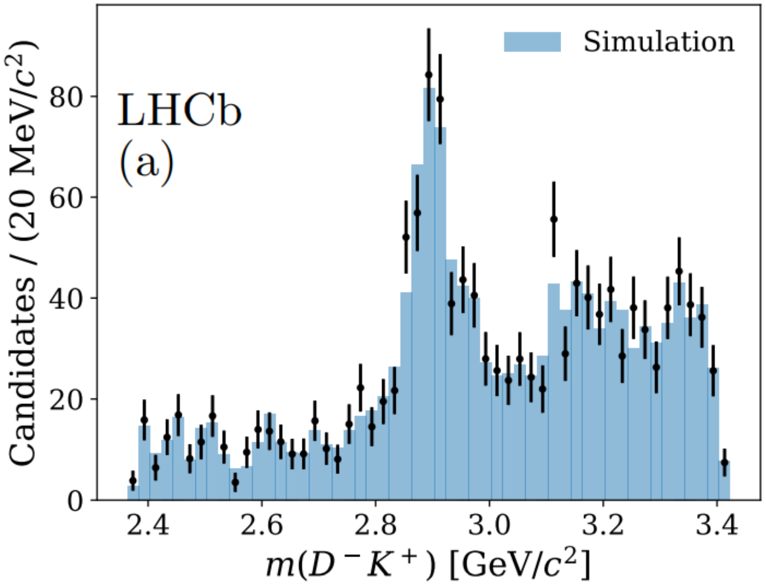


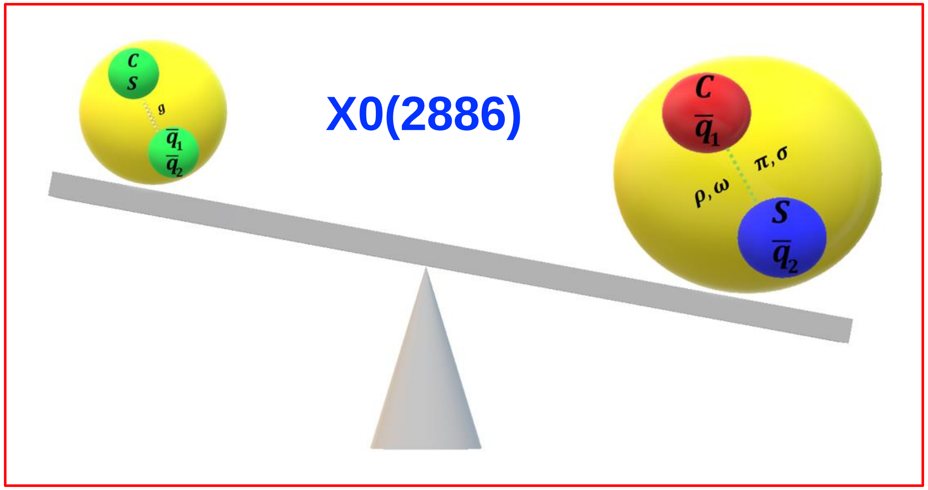




*Phys.Rev.Lett.* 122 (2019) 242001

# Another new state

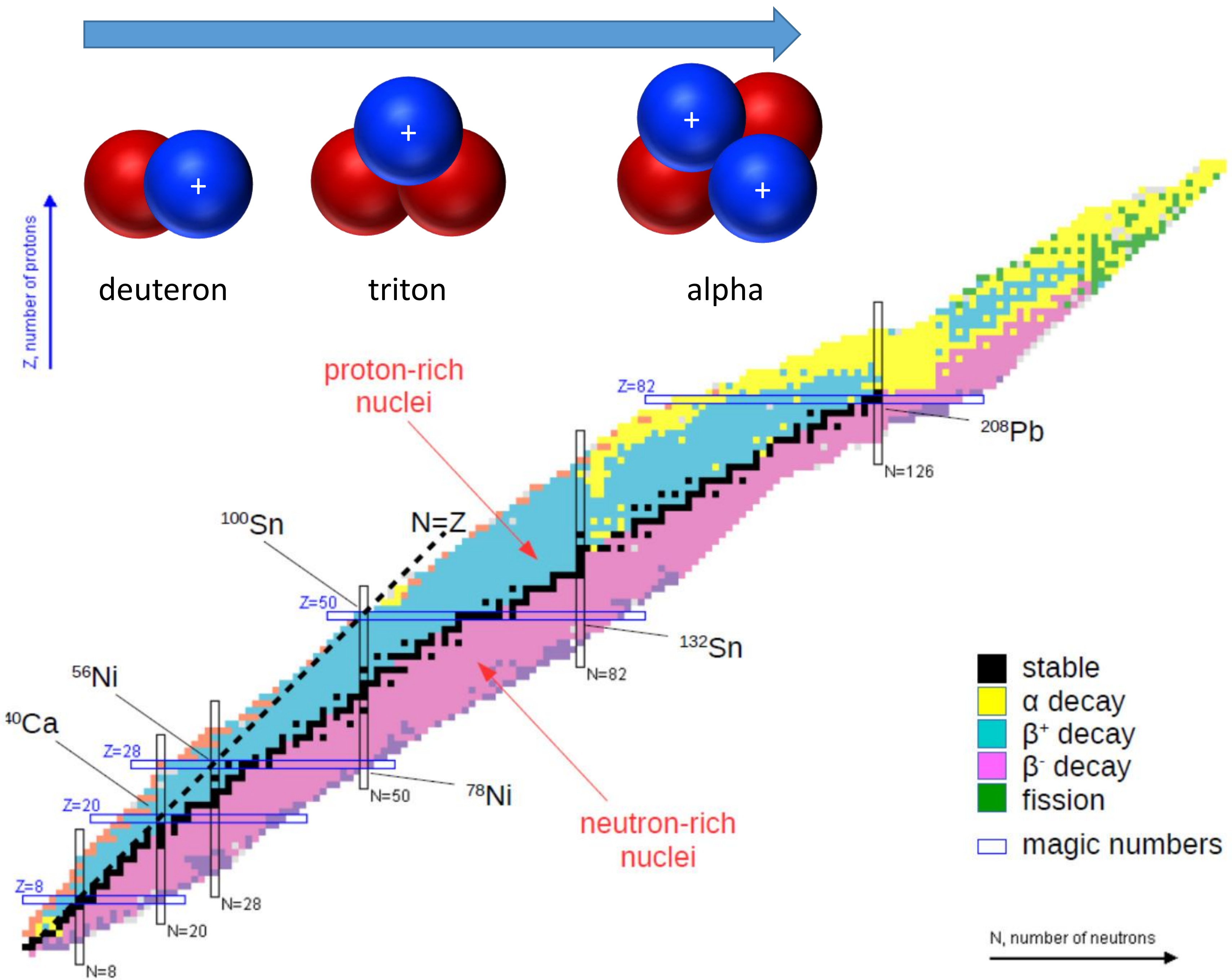



2009.00025

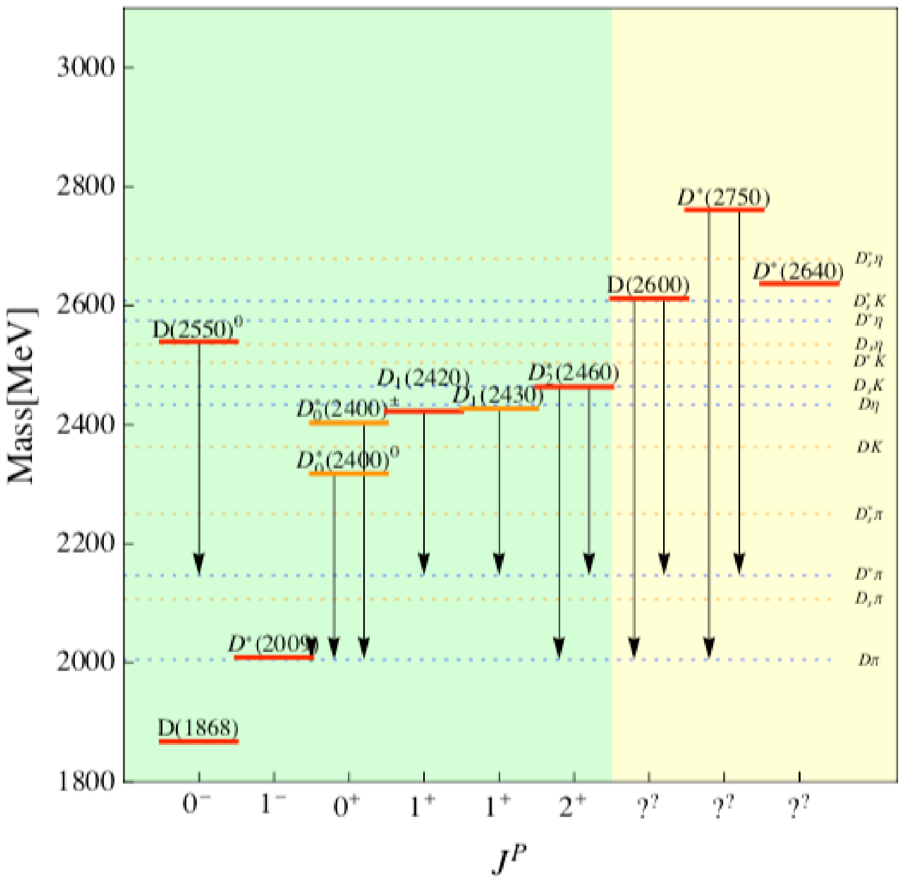


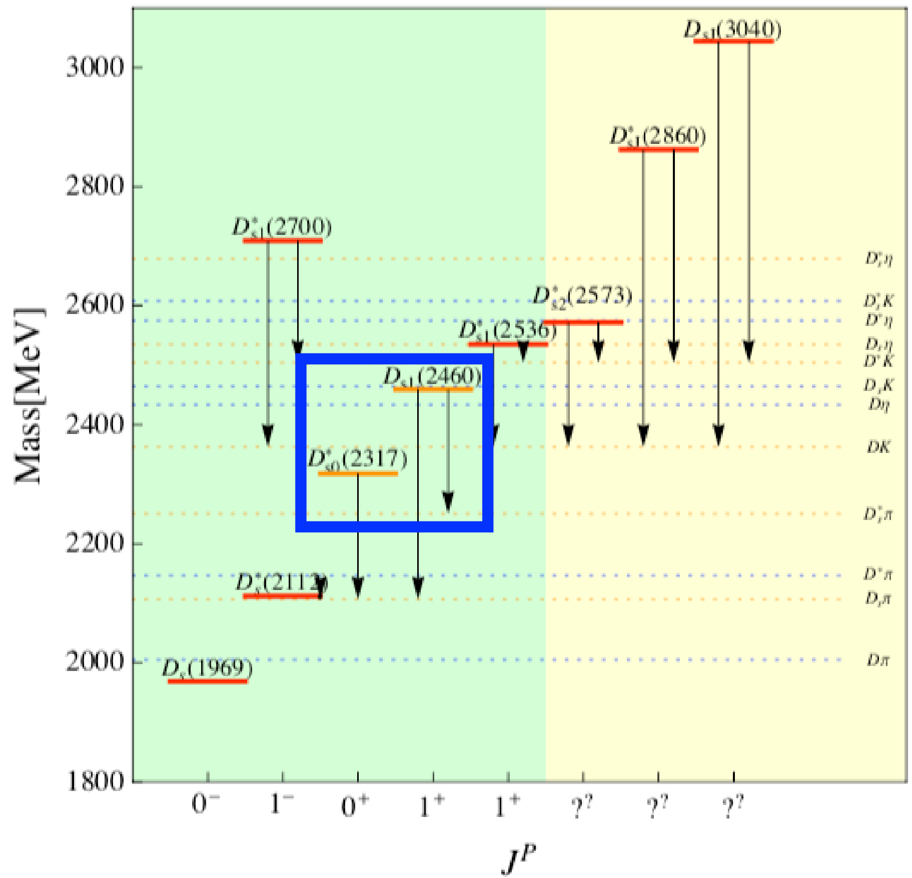

2008.07389, PRD rapid communication

# How to check the molecular picture? our naïve answer—go to many body


deuteron
triton
alpha
Z, number of protons
proton-rich nuclei
neutron-rich nuclei
N=Z
Z=82
Z=50
Z=28
Z=20
Z=8
N=126
N=82
N=50
N=28
N=20
N=8
208Pb
132Sn
100Sn
56Ni
78Ni
40Ca
stable
α decay
β+ decay
β- decay
fission
magic numbers
N, number of neutrons

# Next best two-body molecule candidates

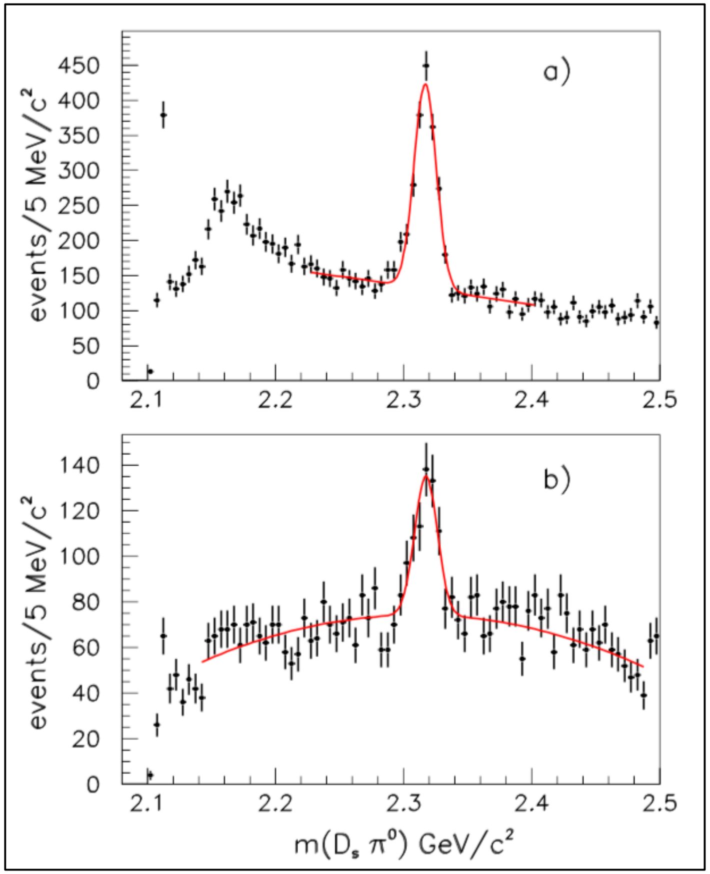



**Ds0*(2317)** **Ds1(2460)**

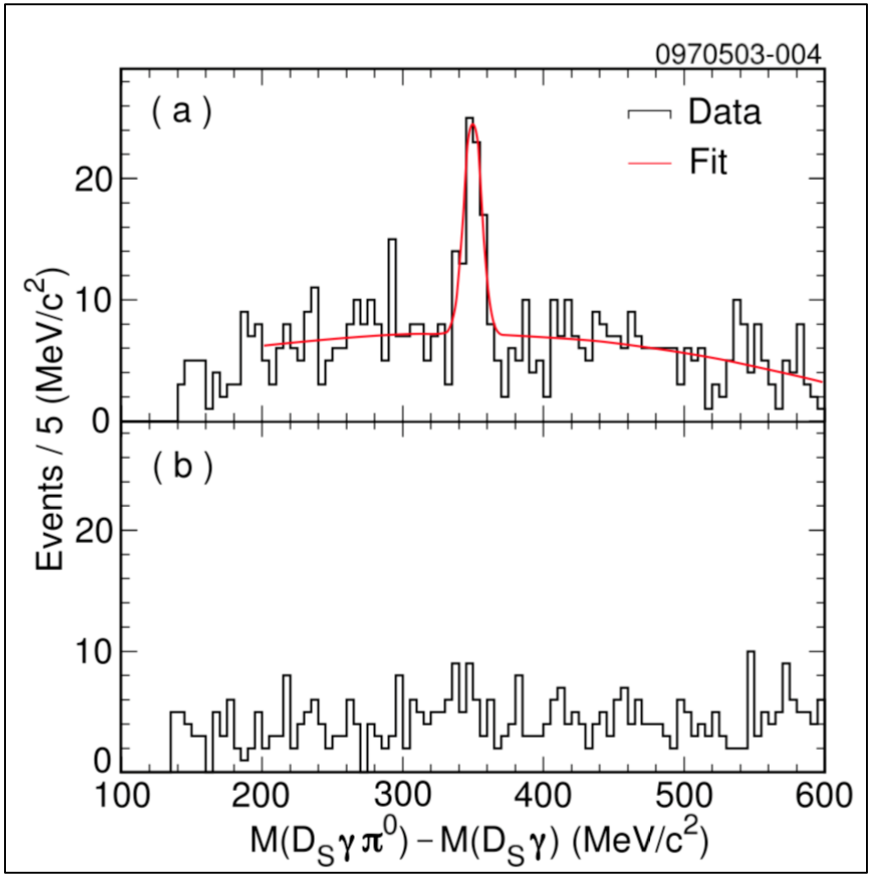
# Discovery channels

**Ds0*(2317)**




BaBar PRL90,242001(2003)

**Ds1(2460)**




CLEO PRD68,032002(2003)

# What are special about these two states

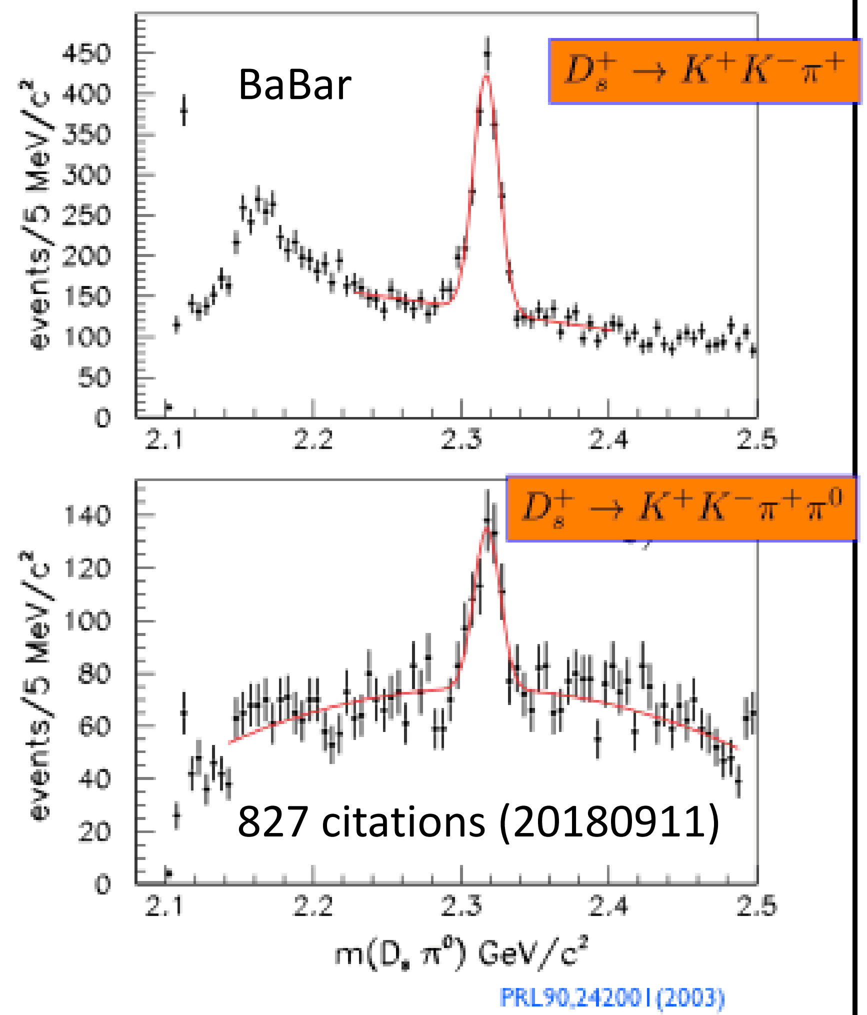
- $\mathbf{D^*_{s0}(2317), D_{s1}(2460)}$

- 160/70 MeV lower than quark model predictions--difficult to be understood as conventional csbar states.

- “Dynamically generated” from strong DK interaction
  - ✓ E. E. Kolomeitsev 2004,
  - ✓ F. K. Guo 2006,
  - ✓ D. Gamermann 2007

$$m_{D_{s1}(2460)} - m_{D^*_{s0}(2317)} \approx m_{D^*} - m_D$$

$\mathbf{M = 2317.8 \pm 0.6}$ and $\mathbf{\Gamma < 3.8}$ MeV






*Feng-Kun Guo,* EPJ Web of Conferences **202**, 02001 (2019)

# Contents

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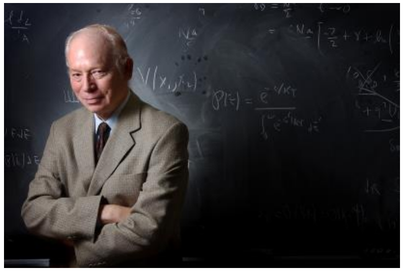
- **Ds0*(2317) and Ds1(2460) as DK/D*K molecules: theory&lattice**
- **An explicit study of the DDK** system: **$R^{++}$(4140)**
- **K*(4307) as excited K*  with hidden charm**
- **Summary and outlook**

1309.4743

# UChPT in Bethe-Salpeter equation



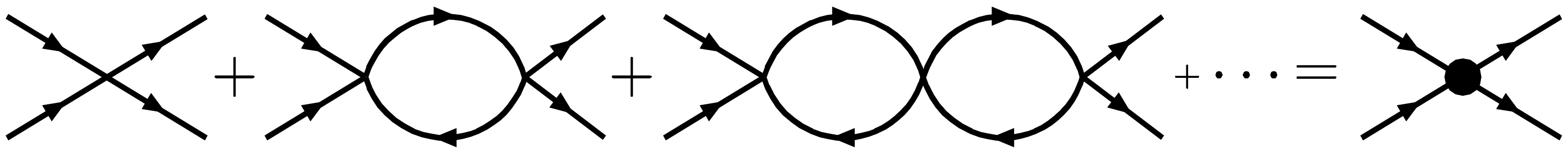
- Model independent DK interaction from ChPT

$$\mathcal{V}_{\rm WT}(P(p_1)\phi(p_2)\to P(p_3)\phi(p_4)) = \frac{1}{4f_0^2}\mathcal{C}_{\rm LO}\,(s-u)$$

Weinberg-Tomazawa

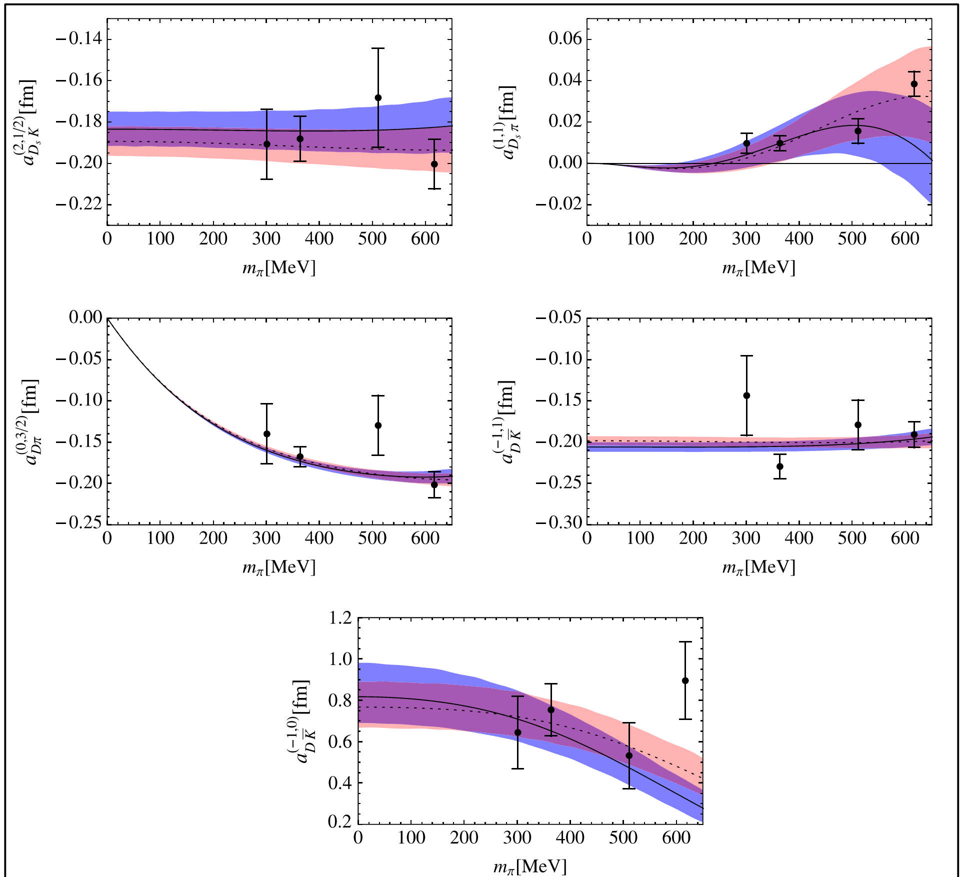
$$\begin{aligned}\mathcal{V}_{\rm NLO}(P(p_1)\phi(p_2)\to P(p_3)\phi(p_4)) = &-\frac{8}{f_0^2}C_{24}\left(c_2\,p_2\cdot p_4-\frac{c_4}{m_P^2}\left(p_1\cdot p_4\;p_2\cdot p_3+p_1\cdot p_2\;p_3\cdot p_4\right)\right)\\ &-\frac{4}{f_0^2}\mathcal{C}_{35}\left(c_3\,p_2\cdot p_4-\frac{c_5}{m_P^2}\left(p_1\cdot p_4\;p_2\cdot p_3+p_1\cdot p_2\;p_3\cdot p_4\right)\right)\\ &-\frac{4}{f_0^2}\mathcal{C}_6\,\frac{c_6}{m_P^2}\left(p_1\cdot p_4\;p_2\cdot p_3-p_1\cdot p_2\;p_3\cdot p_4\right)\\ &-\frac{8}{f_0^2}\mathcal{C}_0\,c_0+\frac{4}{f_0^2}\mathcal{C}_1\,c_1\,, \qquad (11)\end{aligned}$$

- Resumed in the Bethe-Salpeter equation (two-body elastic unitarity)

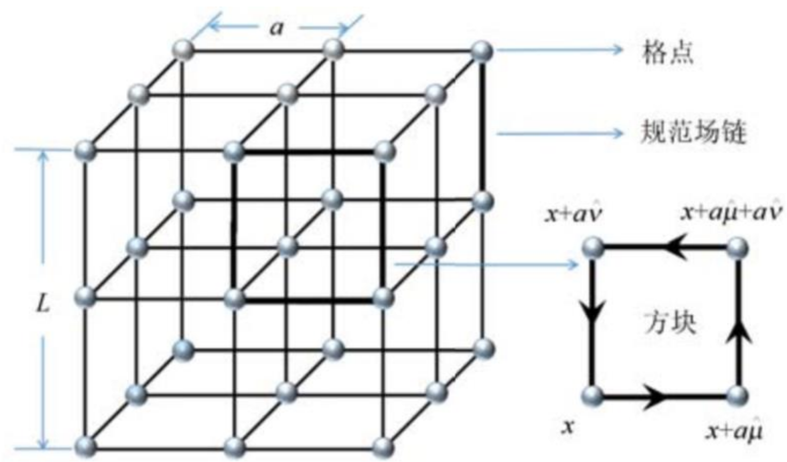


1309.4743

# Fixing the LECs using latest LQCD* data




- NLO ChPT kernel: 5 LECs
- A quite good description of the 20 Lattice **scattering lengths of pseudoscalar mesons and D mesons （I=0 DK excluded）** can be achieved.



1309.4743

# Ds0 and Ds1 dynamically generated

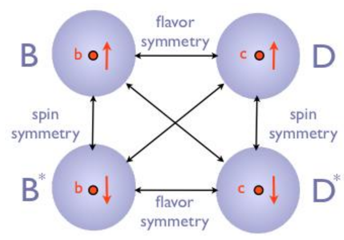
- **Charm sector**

"Post-diction"

$\mathbf{D^*_{s0}(2317),\ D_{s1}(2460)}$

TABLE V. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of charm mesons dynamically generated in the HQS UChPT.

| $(S, I)$ | $J^P = 0^+$ | $J^P = 1^+$ |
|---|---|---|
| (1, 0) | $2317 \pm 10$ | $2457 \pm 17$ |
| (0, 1/2) | $(2105 \pm 4) - i(103 \pm 7)$ | $(2248 \pm 6) - i(106 \pm 13)$ |




- **Bottom Sector**

TABLE VI. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of bottom mesons dynamically generated in the HQS UChPT.

| $(S, I)$ | $J^P = 0^+$ | $J^P = 1^+$ |
|---|---|---|
| (1, 0) | $5726 \pm 28$ | $5778 \pm 26$ |
| (0, 1/2) | $(5537 \pm 14) - i(118 \pm 22)$ | $(5586 \pm 16) - i(124 \pm 25)$ |

1309.4743

# Predicted Bs0 and Bs1 states

Physics Letters B 750 (2015) 17–21

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

## Predicting positive parity $B_s$ mesons from lattice QCD

CrossMark

C.B. Lang [a], Daniel Mohler [b,*], Sasa Prelovsek [c,d], R.M. Woloshyn [e]

[a] Institute of Physics, University of Graz, A-8010 Graz, Austria
[b] Fermi National Accelerator Laboratory, Batavia, IL 60510-5011, USA
[c] Department of Physics, University of Ljubljana, 1000 Ljubljana, Slovenia
[d] Jozef Stefan Institute, 1000 Ljubljana, Slovenia
[e] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada

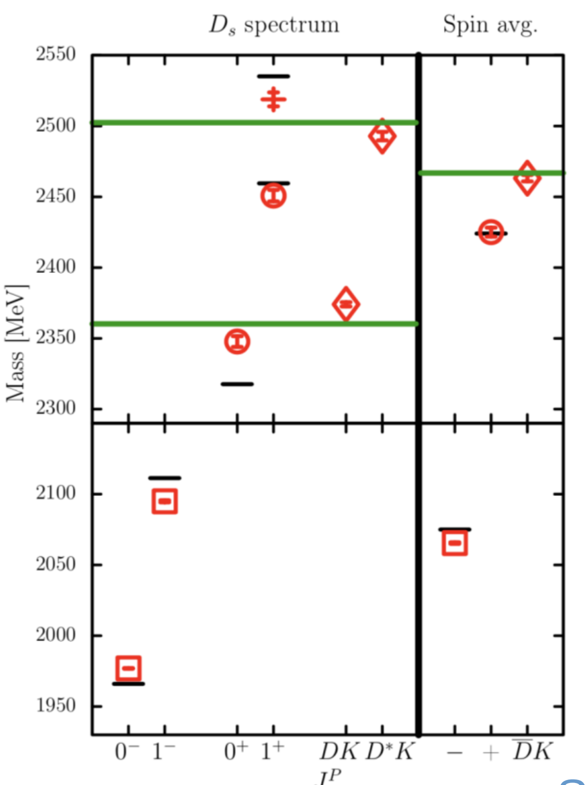
**Table 5**
Comparison of masses from this work to results from various model based calculations; all masses in MeV.

| $J^P$ | $0^+$ | $1^+$ |
|---|---|---|
| Covariant (U)ChPT [24] | 5726(28) | 5778(26) |
| NLO UHMChPT [19] | 5696(20)(30) | 5742(20)(30) |
| LO UChPT [17,18] | 5725(39) | 5778(7) |
| LO $\chi$-SU(3) [16] | 5643 | 5690 |
| HQET + ChPT [20] | 5706.6(1.2) | 5765.6(1.2) |
| Bardeen, Eichten, Hill [15] | 5718(35) | 5765(35) |
| rel. quark model [5] | 5804 | 5842 |
| rel. quark model [22] | 5833 | 5865 |
| rel. quark model [23] | 5830 | 5858 |
| HPQCD [30] | 5752(16)(5)(25) | 5806(15)(5)(25) |
| this work | 5713(11)(19) | 5750(17)(19) |

In agreement with lQCD

# More support from recent lQCD studies

- G.K.C. Cheung et al., arXiv:2008.06432[hep-lat].
- G. S. Bali et al., arXiv:1706.01247 [hep-lat].
- C. B. Lang et al., arXiv:1403.8103 [hep-lat].
- D. Mohler et al., arXiv:1308.3175 [hep-lat].




**"DK components substantial"**

FIG. 12. On the left, our final results for the lower lying $D_s$ spectrum as detailed in Table VII. The short horizontal black lines indicate the corrected experimental values (see Section II) while the green horizontal lines give the positions of the $DK$ and $D^*K$ non-interacting thresholds. Our lattice results for the finite volume thresholds are labelled $DK$ and $D^*K$, respectively. The errors indicated are statistical only. On the right, the negative parity spin-averaged $1S$ mass $m_- = \frac{1}{4}(m_{0^-} + 3m_{1^-})$ is shown and denoted $-$, while the same spin-average of the positive parity $0^+$ and $1^+$ states is labelled with $+$ and the weighted average of the threshold is labelled as $\overline{DK}$.

See as well Miguel Albaladejo et al. arXiv:1805.07104

# Further tests of the DK interaction

- **Experiments, theory, and lattice QCD all show that** $DK$ or $D^*K$ interaction is strong enough to form Ds0*(2317) or Ds1(2460)
- A natural question is: if we add one more $D(\bar{D})$ or $D^*(\overline{D^*})$, can they form molecules of three hadrons?
- This seems to be a rather straightforward and naive question, but remains unexplored until quite recently

# Contents

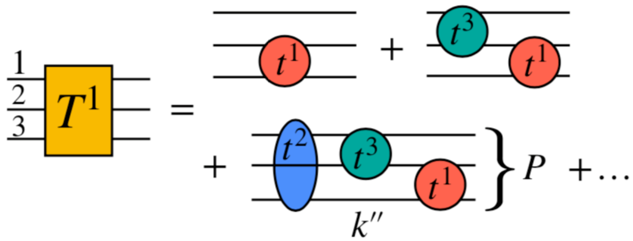
- **Motivation: new types of clusters of color singlets in addition to nuclei—as a nontrivial test of the molecule picture**
- **Ds0*(2317) and Ds1(2460) as DK/D*K molecules**
- **An explicit study of the DDK** system: **$R^{++}$(4140)**
- **K*(4307) as excited K* with hidden charm**
- **Summary and outlook**

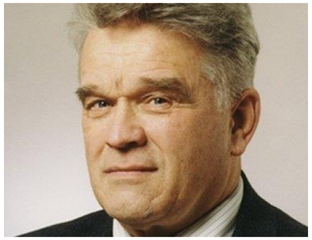
[1809.01059](1809.01059)

# An explicit three-body study of DDK

- **Coupled-three-channel problem:** $\mathrm{D}(\mathrm{DK} - D_s\pi - D_s\eta)$
- **Three-body scattering matrix (Faddeev)**

$$T = \sum_{i=1}^{3} T^i$$



$$T^i = t^i \delta^3(\vec{k}_i' - \vec{k}_i) + \sum_{j\neq i=1}^{3} T_R^{ij}, \quad i = 1, 2, 3,$$

$$T_R^{ij} = t^i g^{ij} t^j + t^i \left[ G^{iji} T_R^{ji} + G^{ijk} T_R^{jk} \right],$$

***A. Martínez Torres****, K. P. Khemchandani, and E. Oset PRC* ***77****, 042203(R)*

*A****. Martinez Torres****, K.P. Khemchandani,* ***LSG****, M. Napsuciale, E. Oset, PRD78 (2008) 074031*

# Two-body inputs

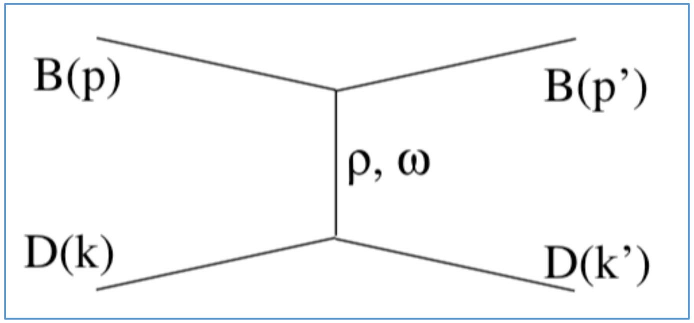
- **DK: leading order UChPT** $DK$, $D_s\eta$ and $D_s\pi$

$$V_{ij} = -\frac{C_{ij}}{4f^2}(s-u)$$

$a(\mu) = -1.846, \mu = 1000\ MeV \Rightarrow$
Pole=2318 MeV

*F.-K. Guo, P.-N. Shen, H.-C. Chiang, R.-G. Ping, and B.-S. Zou, PL B641, 278 (2006).*

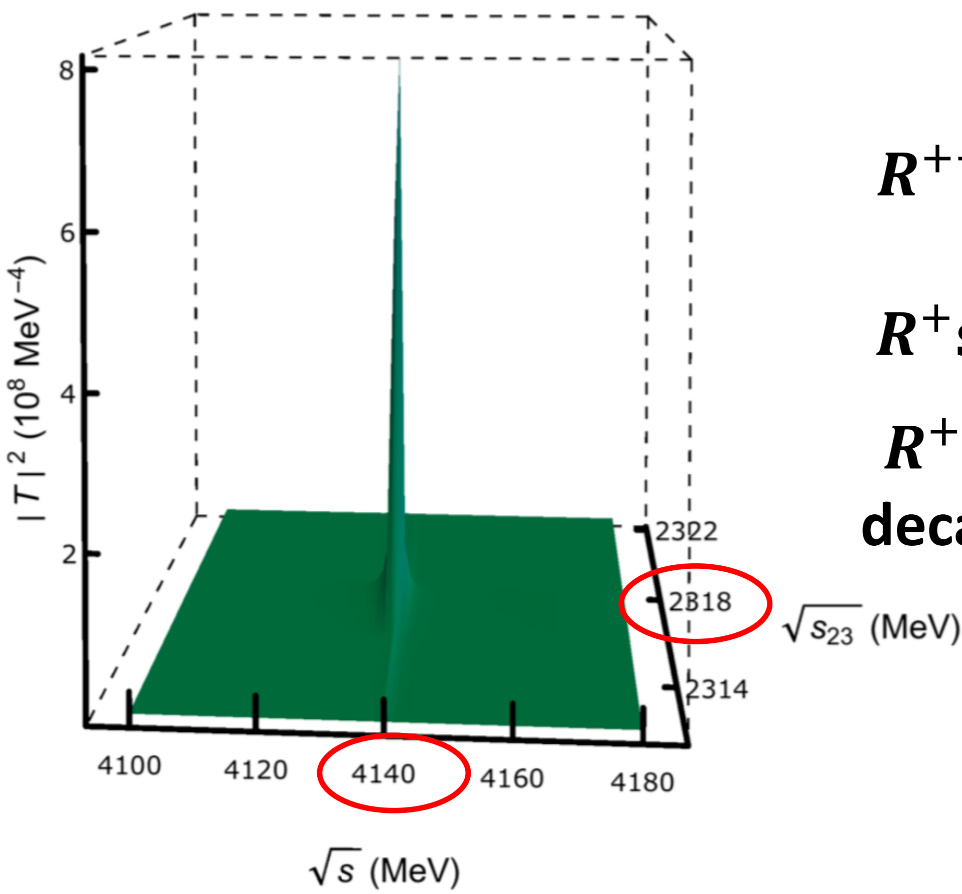
- **DD(Ds): local hidden gauge theory**




$a(\mu) = -1.3 \sim -1.5, \mu = 1500\ MeV \Leftarrow$ fixed from $D\bar{D}/D\overline{D^*}$--X(3700）/X(3872)

*S. Sakai, L. Roca, and E. Oset, PRD96, 054023 (2017).*

# Three-body amplitudes



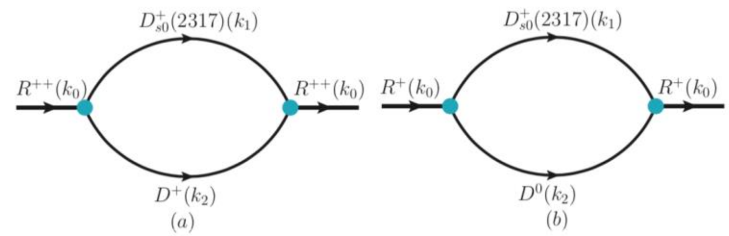

$$R^{++} = (I, I_{23}) = (\frac{1}{2}, 0)$$

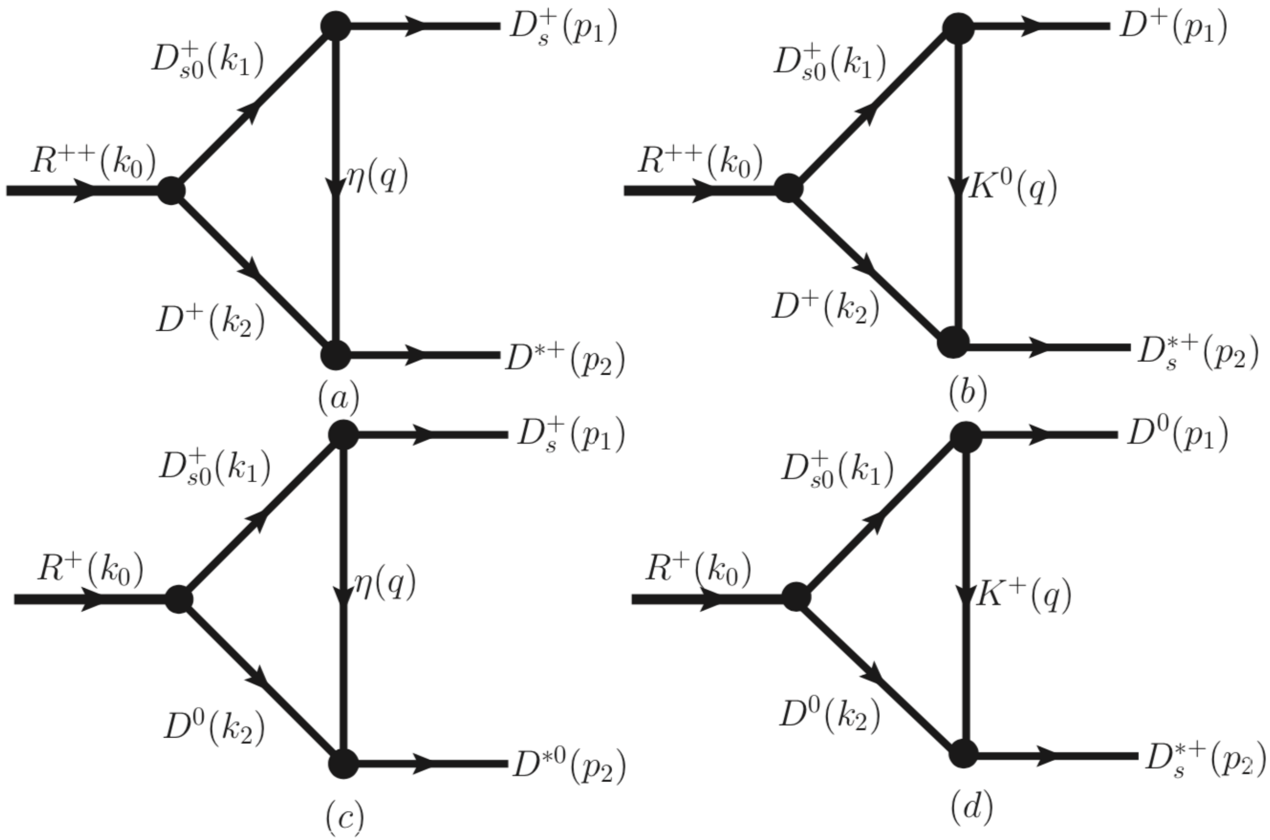
$R^{+}$ should also exist

$R^{++}$ is a bound state, but can decay strongly

[1909.09021](1909.09021)

# Two-body decay width

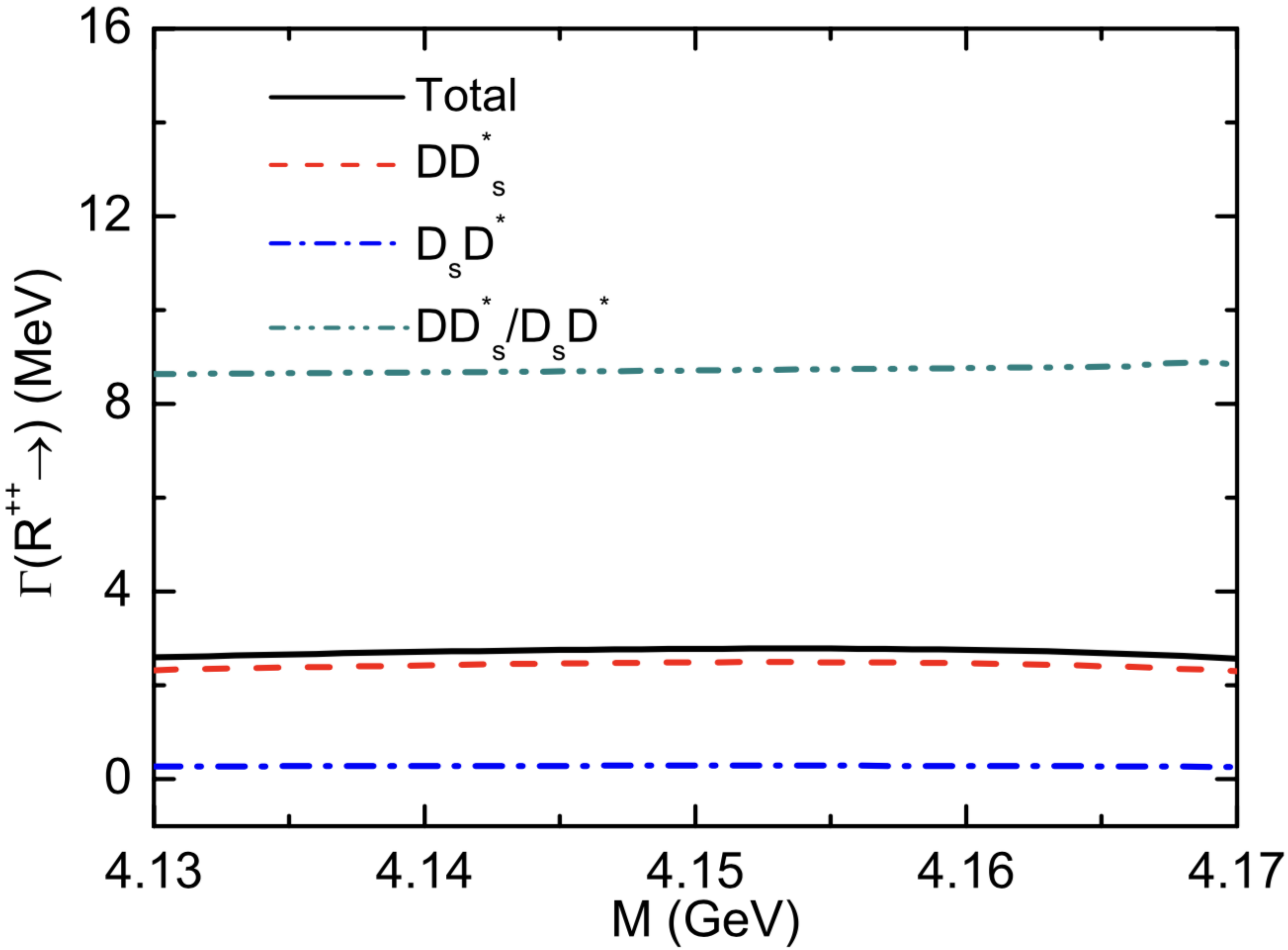


1909.09021

# Two-body decay width

**Kaon-Exchange Dominant**



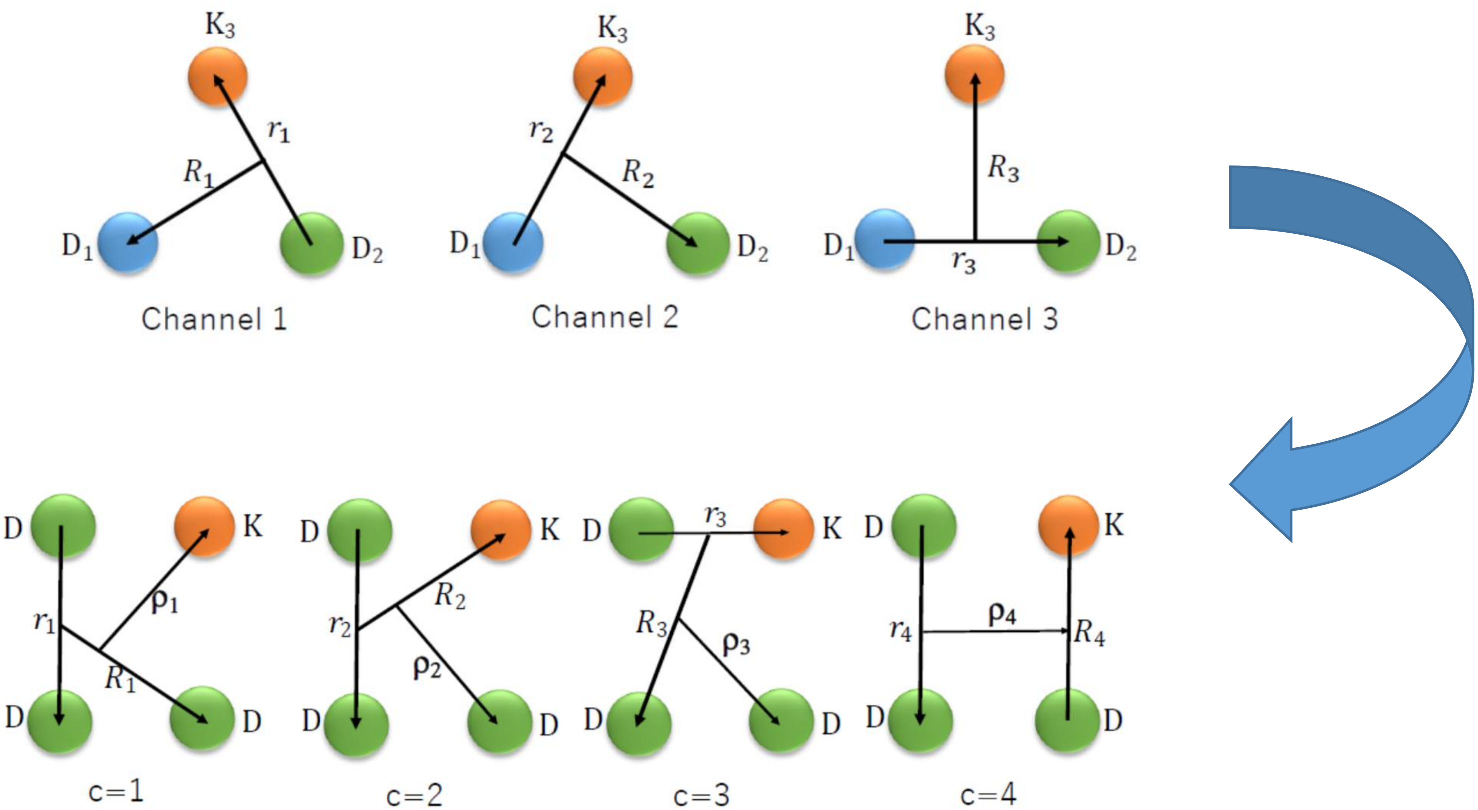
# A DDDK state

1906.11995

1(0⁺)

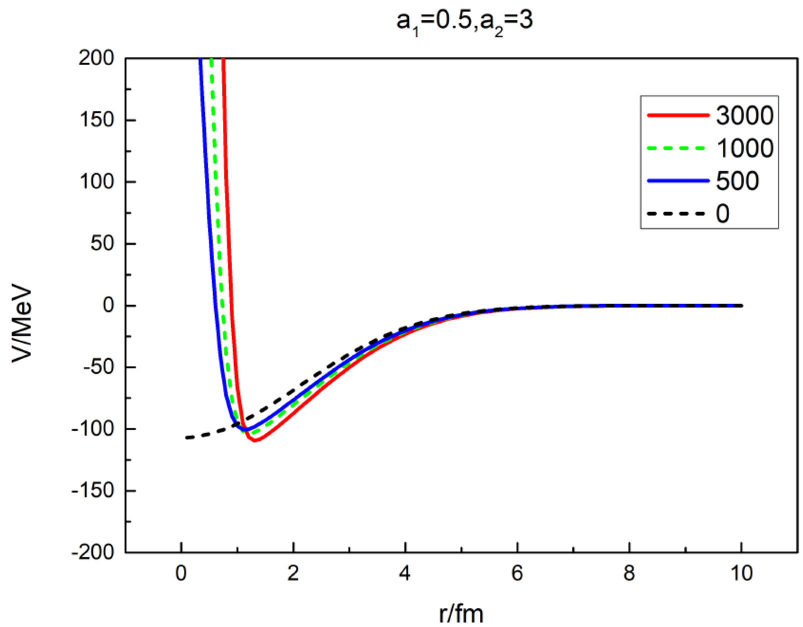
**Gaussian Expansion Method**

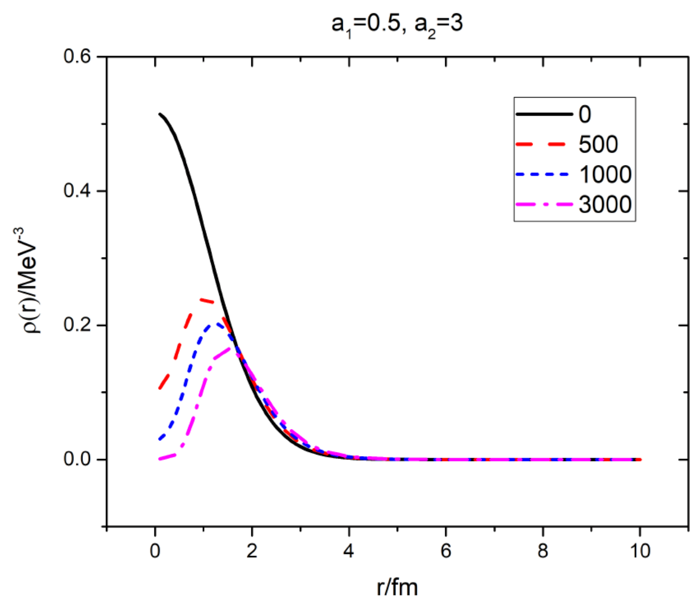
**What if we add one more D?**



# A DDDK state 1(0⁺)

**What if we add one more D? Our study shows that such a state exists as well**




Uncertainties are at **the order of 10-20 MeV**

$$V_{DK}(r) = C_1 e^{-r^2/a_1^2} + C_2 e^{-r^2/a_2^2}$$

| | DK* | DDK | DDDK |
|---|---|---|---|
| Binding | 45 MeV | (67-71) MeV | 91-107 MeV |

# DD interactions play a minor role

1906.11995

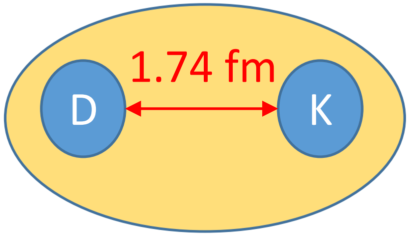
| $\frac{C_S}{\pi R_S^3}$ | $\frac{C(R_c)}{\pi R_c^3}$ | $E_2$ | $E_3$(only $V_{DK}$) | $E_3(V_{DK}+V_{DD})$ | $E_4$(only$V_{DK}$) | $E_4(V_{DK}+V_{DD})$ |
|---|---|---|---|---|---|---|
| | | $R_S = 0.5$fm | | $R_c = 1$fm | | |
| 0 | −320.1 | −45.0 | −65.8 | −71.2 | −89.4 | −106.8 |
| 500 | −455.4 | −45.0 | −65.8 | −70.4 | −89.2 | −103.5 |
| 1000 | −562.6 | −45.0 | −65.7 | −69.7 | −88.8 | −101.4 |
| 3000 | −838.7 | −45.0 | −65.0 | −68.4 | −87.0 | −97.3 |
| | | $R_S = 0.5$fm | | $R_c = 2$fm | | |
| 0 | −149.1 | −45.0 | −66.0 | −68.8, −45.1 | −88.7, −66.3 | −97.6, −70.7 |
| 500 | −178.4 | −45.0 | −65.9 | −68.2, −45.5 | −88.5, −66.7 | −95.5, −70.9 |
| 1000 | −195.0 | −45.0 | −65.8, −45.2 | −67.9, −45.8 | −88.2, −66.9 | −94.5, −71.2 |
| 3000 | −225.9 | −45.0 | −65.3, −45.6 | −67.2, −46.6 | −87.0, −67.0 | −92.6, −71.7 |
| | | $R_S = 0.5$fm | | $R_c = 3$fm | | |
| 0 | −107.0 | −45.0 | −66.2, −47.3 | −68.0, −48.3 | −88.8, −70.2 | −94.4, −74.3 |
| 500 | −119.4 | −45.0 | −66.2, −48.2 | −67.7, −49.3 | −88.7, −71.0 | −93.2, −74.8 |
| 1000 | −125.6 | −45.0 | −66.1, −48.7 | −67.5, −49.8 | −88.4, −71.3 | −92.5, −75.2 |
| 3000 | −136.2 | −45.0 | −65.8, −49.4 | −67.1, −50.7 | −87.6, −71.7 | −91.4, −75.7 |

# Spatial distributions

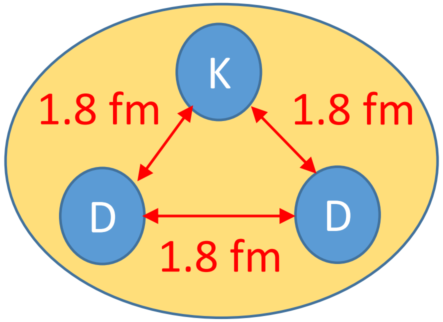
1906.11995

| $\frac{C_S}{\pi R_S^3}$ | $\frac{C(R_c)}{\pi R_c^3}$ | $r_2(DK)$ | $r_3(DK)$ | $r_3(DD)$ | $<T>$ | $<V_{DK}>$ | $<V_{DD}>$ |
|---|---|---|---|---|---|---|---|
| | | | $R_S = 0.5\text{fm}$ $R_c = 1\text{fm}$ | | | | |
| 0 | −320.1 | 1.28 | 1.32 | 1.36 | 124.37 | −189.61 | −5.98 |
| 500 | −455.4 | 1.39 | 1.44 | 1.47 | 99.51 | −164.83 | −5.03 |
| 1000 | −562.6 | 1.46 | 1.53 | 1.54 | 91.43 | −156.67 | −4.51 |
| 3000 | −838.7 | 1.61 | 1.69 | 1.68 | 93.24 | −157.80 | −3.82 |
| | | | $R_S = 0.5\text{fm}$ $R_c = 2\text{fm}$ | | | | |
| 0 | −149.1 | 1.74 | 1.80 | 1.80 | 60.20 | −125.74 | −3.23 |
| 500 | −178.4 | 1.91 | 1.98 | 1.96 | 51.00 | −116.59 | −2.64 |
| 1000 | −195.0 | 1.99 | 2.07 | 2.04 | 50.63 | −116.12 | −2.43 |
| 3000 | −225.9 | 2.13 | 2.22 | 2.15 | 53.61 | −118.59 | −2.24 |
| | | | $R_S = 0.5\text{fm}$ $R_c = 3\text{fm}$ | | | | |
| 0 | −107.0 | 2.13 | 2.19 | 2.17 | 39.49 | −105.35 | −2.13 |
| 500 | −119.4 | 2.31 | 2.38 | 2.34 | 34.80 | −100.73 | −1.77 |
| 1000 | −125.6 | 2.37 | 2.47 | 2.42 | 34.90 | −100.77 | −1.65 |
| 3000 | −136.2 | 2.53 | 2.61 | 2.53 | 36.66 | −102.24 | −1.54 |

Ds0*(2317)




R(4140)



# Contents

- **Motivation: new types of clusters of color singlets in addition to nuclei—as a nontrivial test of the molecule picture**
- **Ds0*(2317) and Ds1(2460) as DK/D*K molecules**
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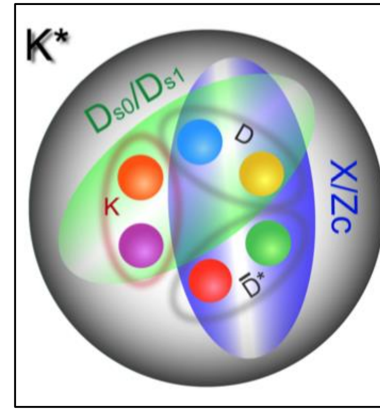
- **K*(4307) as excited K* with hidden charm**
- **Summary and outlook**

# K*(4307)




**Instead of a $D$, what happens if we add a $\overline{D}^*$ to the DK pair**

Physics Letters B 785 (2018) 112–117

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$K^*$ mesons with hidden charm arising from $KX(3872)$ and $KZ_c(3900)$ dynamics

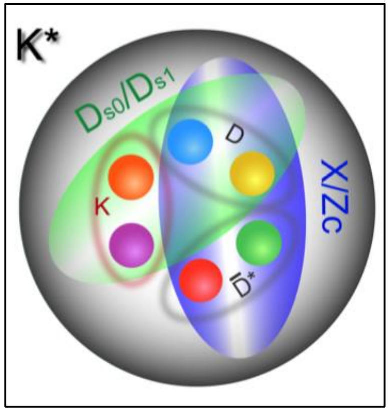
Xiu-Lei Ren [a], Brenda B. Malabarba [b], Li-Sheng Geng [c,d], K.P. Khemchandani [e,c], A. Martínez Torres [b,c,*]

[a] Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[b] Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 São Paulo, São Paulo, Brazil
[c] School of Physics and Nuclear Energy Engineering & Beijing Key Laboratory of Advanced Nuclear Materials and Physics, Beihang University, Beijing 100191, China
[d] Beijing Advanced Innovation Center for Big Date-Based Precision Medicine, Beihang University, Beijing 100191, China
[e] Universidade Federal de São Paulo, C.P. 01302-907, São Paulo, Brazil

$D$

1805.08330

# K*(4307)




- **Fixed center approximation (FCA):**

$$K(D\overline{D^*}+\overline{D}D^*)\sim KX(3872)/Zc(3900)$$

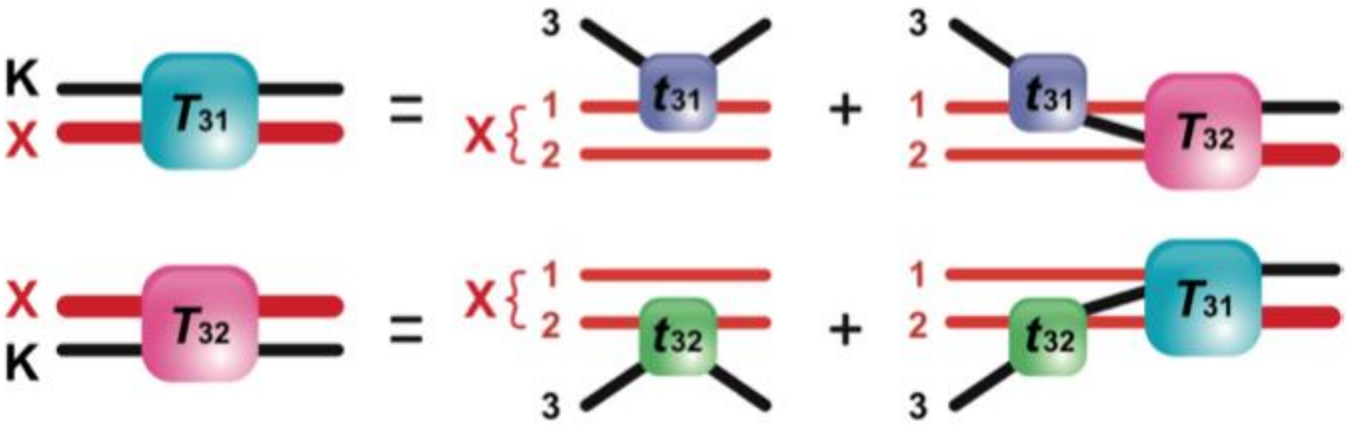
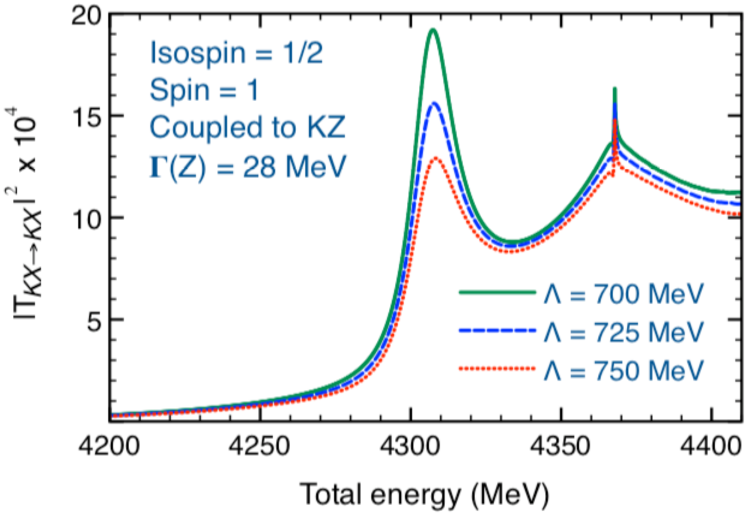
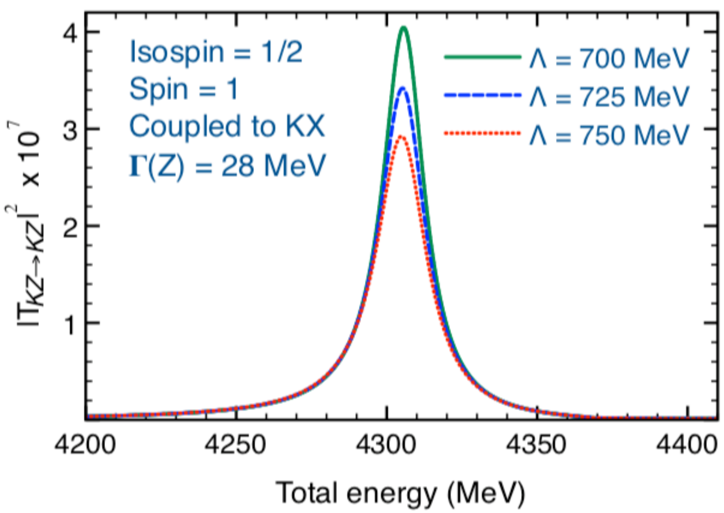
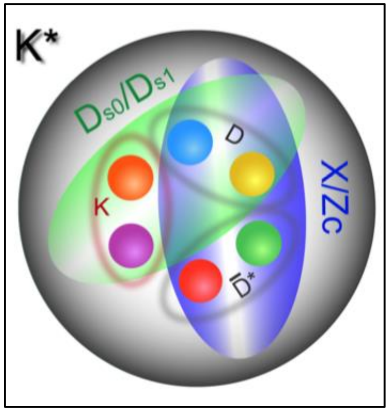



Figure 2: Diagrams showing the scattering of the particle labeled "3" ($K$) on a cluster ($X$) made of particles 1 ($D$) and 2 ($\bar{D}^*$).

# K*(4307)



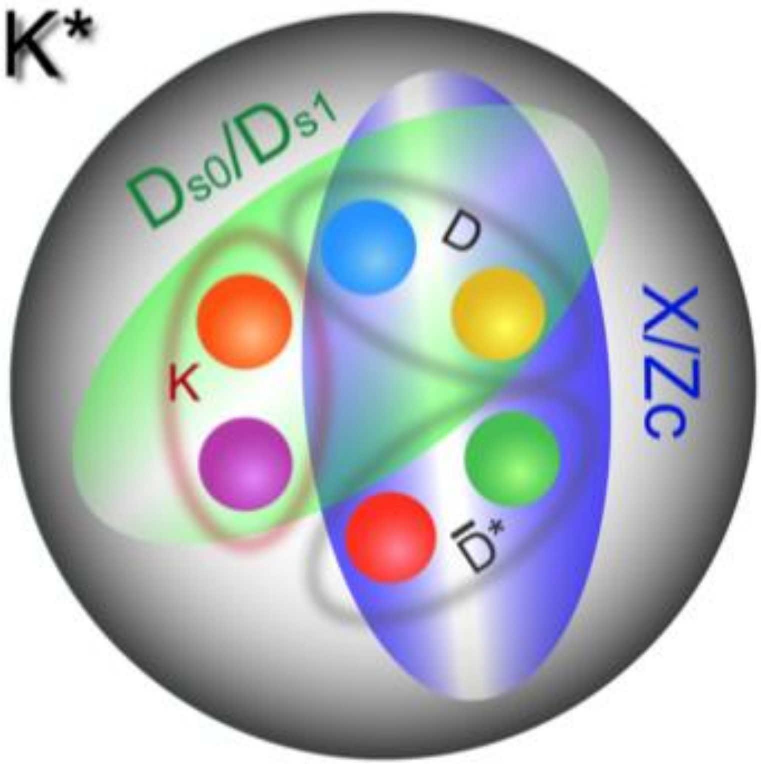



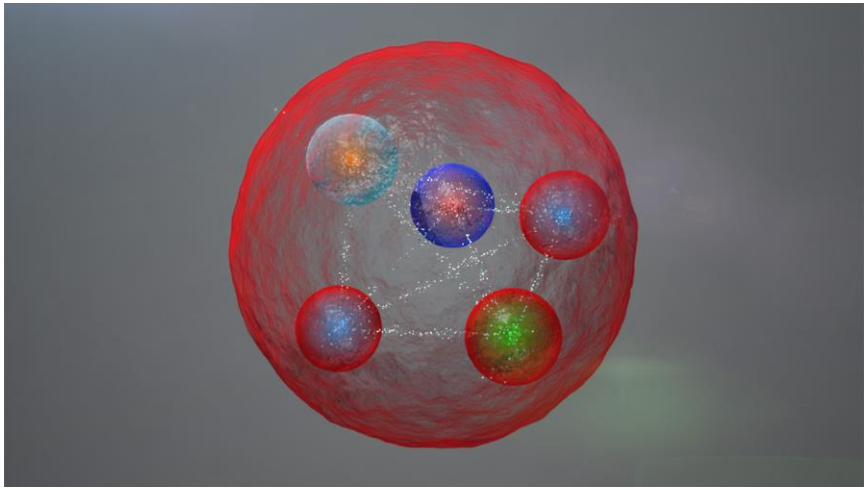




- **Treating KX and KZ as coupled channel systems**
- **A resonance with M=(4307 ± 2) – i(9 ± 2) MeV with $I(J^P) = 1/2(1^-)$**

*In agreement with Li Ma, Qian Wang, Ulf-G. Meißner, 1711.06143, but with completely different dynamics*

# K*(4307)—bosonic counterpart of Pc



**Pentaquark (N*) by LHCb**

*Phys.Rev.Lett. 115 (2015) 072001*

Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV, Jia-Jun Wu, R. Molina, E. Oset, B.S. Zou, 1007.0573

# Analogy between $KD$ and $\bar{\bar{K}}N$

$\mathbf{D_{s0}^*(2317)}$

- DK bound state
- **Dynamically generated**--
  Unitary heavy hadron
  chiral perturbation theory

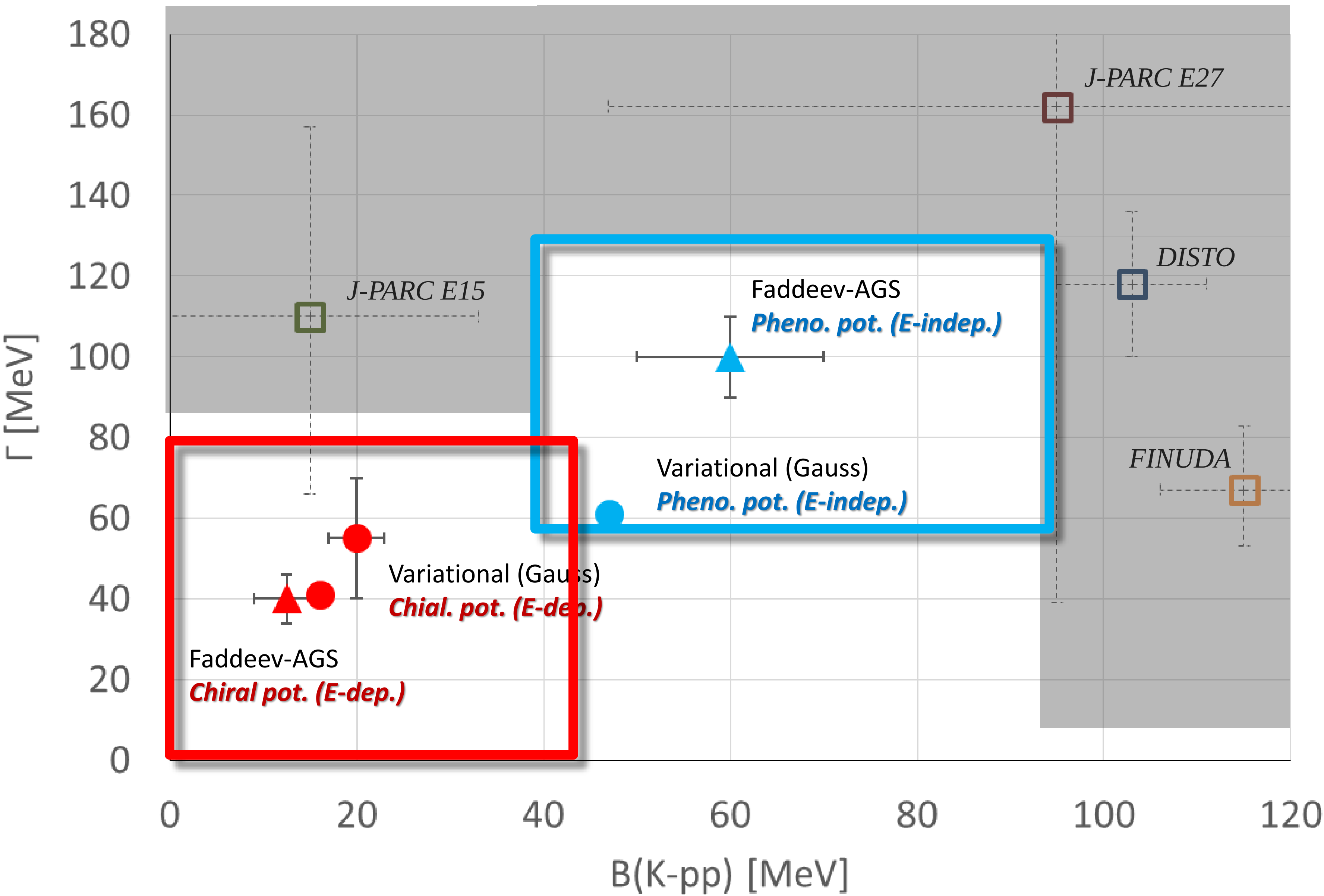
$\boldsymbol{\Lambda(1405)}$

- N-Kbar bound state
- **Dynamically generated**--
  Unitary baryon chiral
  perturbation theory

The interaction between **a kaon and a heavy particle** seems to play an important role

# Current status on "$K^{-}pp$"

A. Dote, Menu2019



# Experimental search by the Belle Collaboration

2008.13341

Search for a doubly-charged $DDK$ bound state in $\Upsilon(1S,2S)$ inclusive decays and via direct production in $e^+e^-$ collisions at $\sqrt{s}$ = 10.520, 10.580, and 10.867 GeV

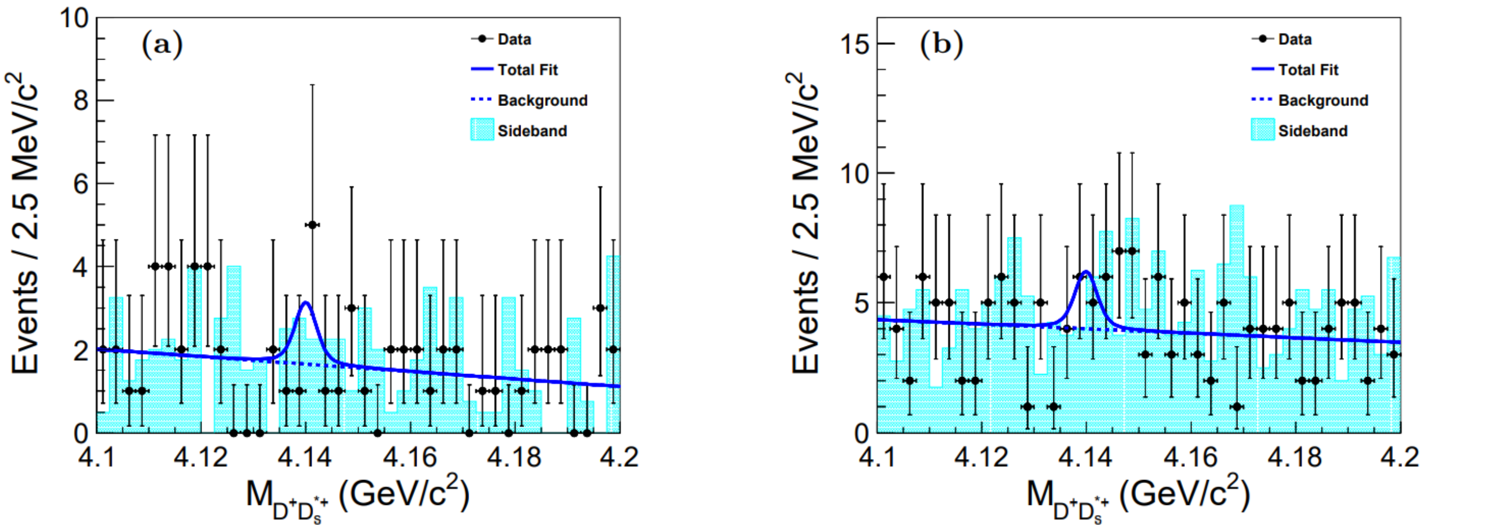



FIG. 4: The invariant-mass spectra of $D^+D_s^{*+}$ in the (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$ data samples. The cyan shaded histograms are from the normalized $M_{D^+}$ and $M_{D_s^{*+}}$ sideband events. The blue solid curves show the fitted results with the $R^{++}$ mass fixed at 4.14 GeV/$c^2$ and width fixed at 2 MeV, and the blue dashed curves are the fitted backgrounds.

# Experimental search by the Belle Collaboration

**2008.13341**

**Search for a doubly-charged $DDK$ bound state in $\Upsilon(1S,2S)$ inclusive decays and via direct production in $e^+e^-$ collisions at $\sqrt{s}=10.520$, $10.580$, and $10.867$ GeV**

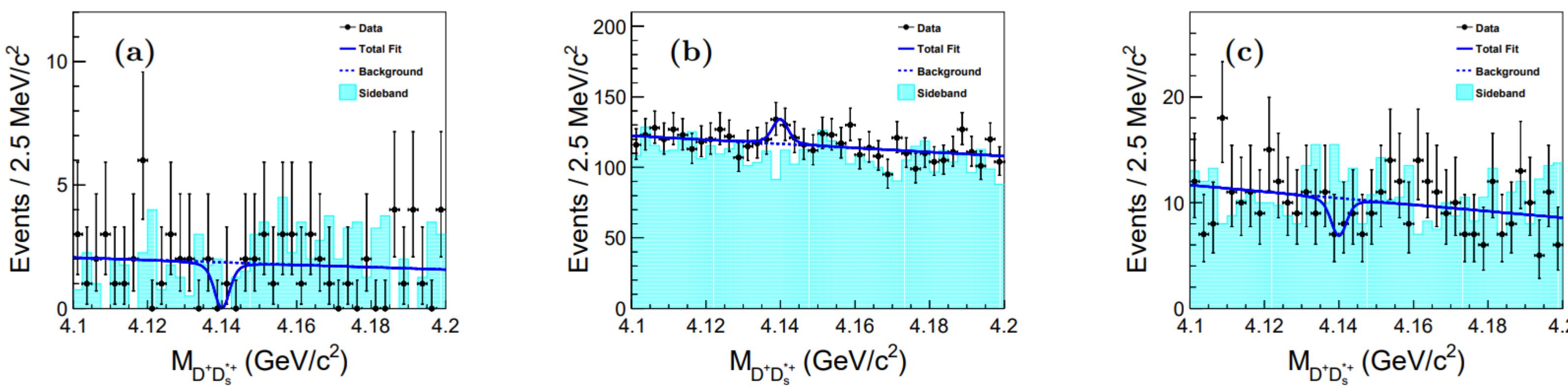



FIG. 10: The invariant-mass spectra of the $D^+D_s^{*+}$ from $e^+e^-$ annihilations at (a) $\sqrt{s}=10.520$ GeV, (b) $\sqrt{s}=10.580$ GeV, and (c) $\sqrt{s}=10.867$ GeV data samples. The cyan shaded histograms are from the normalized $M_{D^+}$ and $M_{D_s^{*+}}$ sideband events. The blue solid curves show the fitted results with the $R^{++}$ mass fixed at 4.14 GeV$/c^2$ and width fixed at 2 MeV, and the blue dashed curves are the fitted backgrounds.

# Looking into future

- We may have a better chance with Belle II, whose statistics will be larger by 50 times

- How about LHCb?

Invited theory talk (vidyo pin: 2018)

星期三 2018年10月10日 下午2:00 → 下午4:00 Europe/Zurich

32/1-A24 (CERN)

视频会议室 DK_DDK_DDDK_molecules Join

下午2:00 → 下午4:00 **DK/DDK/DDDK molecules** 2h

The Ds0*(2317) is widely accepted as a DK molecule. Its existence indicates that the DK interaction is attractive and strong enough to form a bound state. A natural question is then whether the system will still bind with one or more D mesons added. In a series of recent works, we explored such possibilities and showed that the DDK three-body molecular state exists, with a mass around 4140 MeV and a width of about 10 MeV. Due to the doubly charmed and doubly charged nature, such a state is apparently exotic. We have also performed a preliminary study of the DDDK system. In this talk, I will report on these studies and a few new binding mechanisms which have led to rather model independent predictions on the existence of hadronic molecules.
References:
1309.4743, 1704.06123, 1705.00516, 1707.03802, 1805.08330, 1809.01059

报告人: Lisheng Geng (Beihang University)

Geng-LHCb-1010.pdf

# Summary and outlook

- Many interpretations exist for newly discovered exotic hadrons and are difficult to be distinguished from each other
- We proposed a **novel way** to **validate the molecule picture**. Taking the Ds0*(2317) as an example, if it **is indeed a molecule of DK**, then new forms of matter may be built upon them, similar to the build up of the periodic table.
- **We have performed explicit few-body studies**–demonstrating that indeed both DDK/DDbar*K and DDDK states **bind**
- Now we need experimental or lattice QCD confirmations and further theoretical studies on their production and decay mechanisms

道生一，一生二，二生三

# 三生万物

# Thanks for your attention!

# DDK system in finite volume

*Jin-Yi Pang, Jia-Jun Wu , and Li-Sheng Geng, 2008.13014*

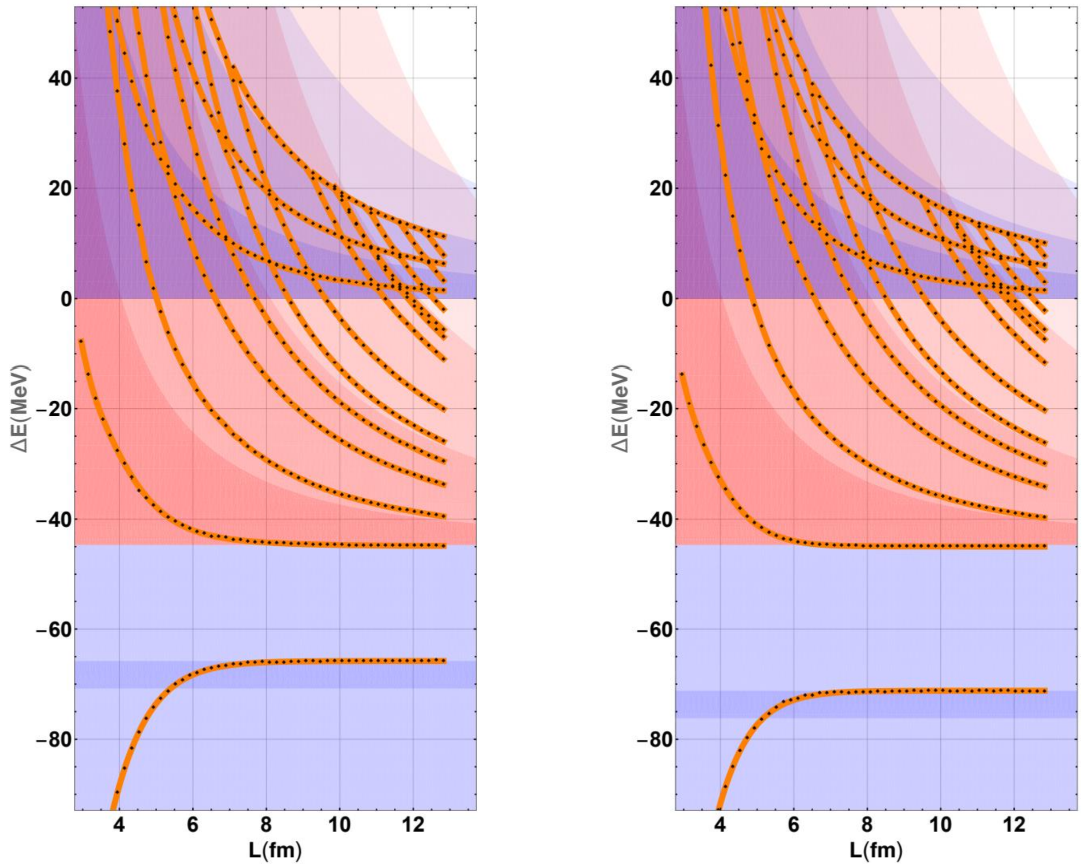



Figure 5: $DDK$ states in finite volume. Left: only the $DK$ interaction is considered. Right: both $DK$ and $DD$ interactions are taken into account. The upper blue regions indicate the case of 3 free particles in finite volume. The red regions indicate the case of free $D_{s0}^*(2317)$ and $D$. The lower blue regions indicate the $DDK$ bound state below the $DD_{s0}^*(2317)$ threshold.