北京航空航天大學
BEIHANG UNIVERSITY

How to test the picture of

Hadronic Molecules

from 2 to 3

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1309.4743
1707.03802
1805.08330
1809.01059
1906.11995
1909.09021
2008.13014
2012.01134

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
- DDK molecule: R++(4140)
- $D\bar{D}^{*}K$ and $D\bar{D}K$ molecules: K*(4307) and Kc(4180)
- Where to search for these 3-body molecules
- Summary and outlook

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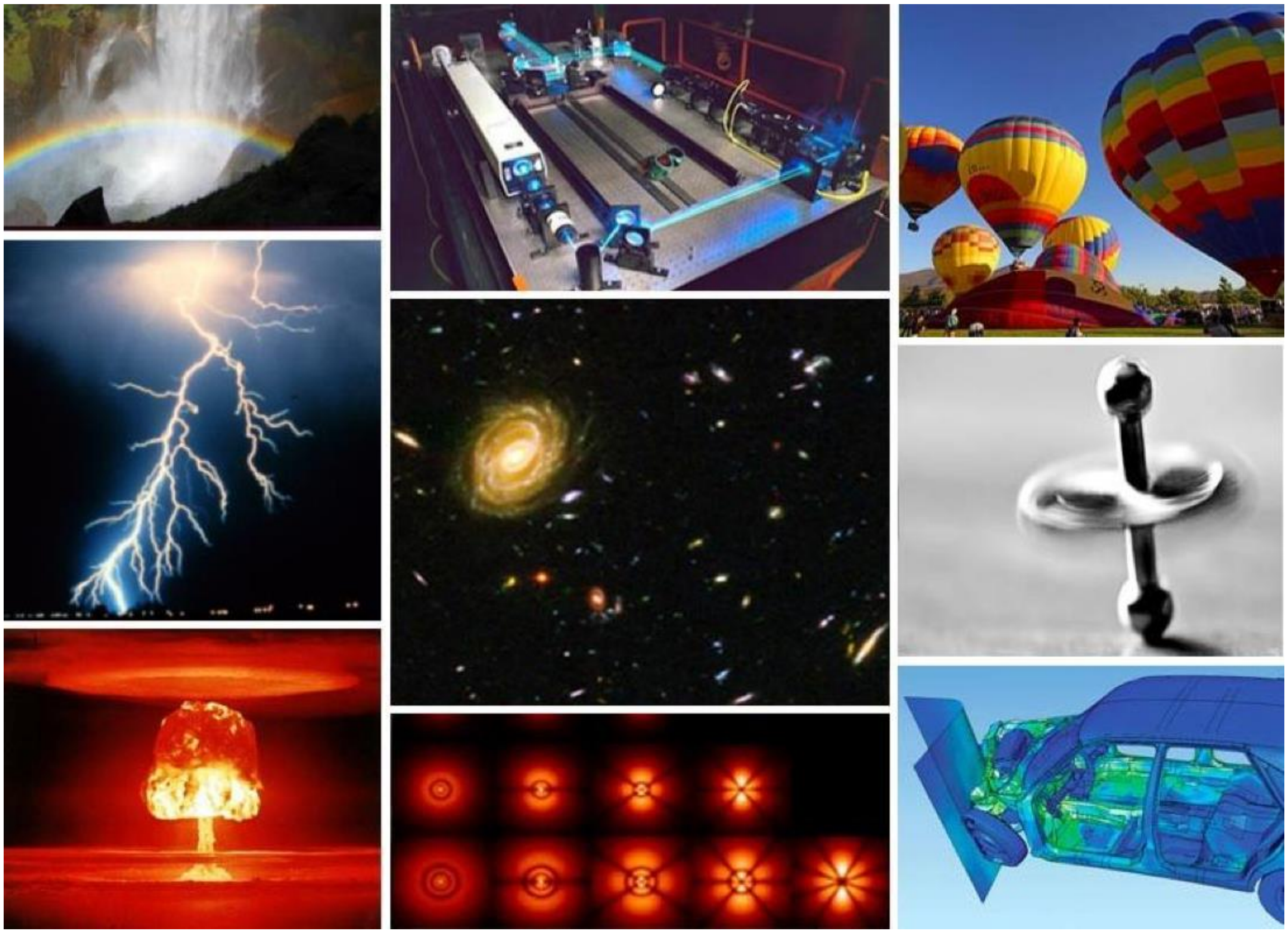
Reductionism vs. Emergence

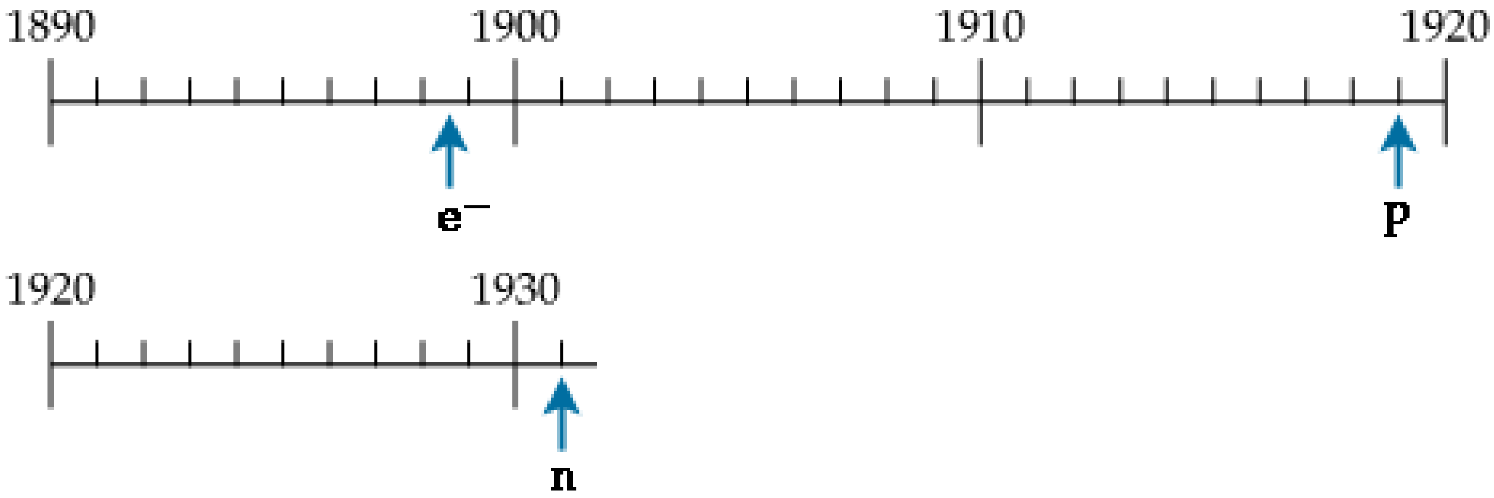
Top
Down

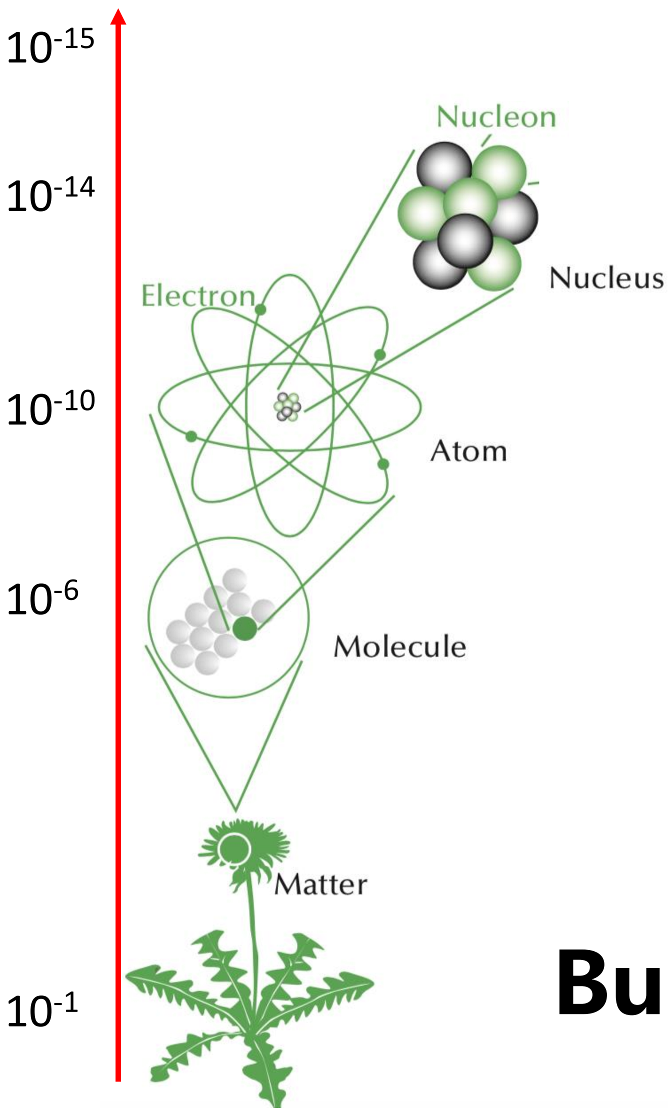


Bottom
Up

Search for the fundamental building blocks

Particles discovered before 1932





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.

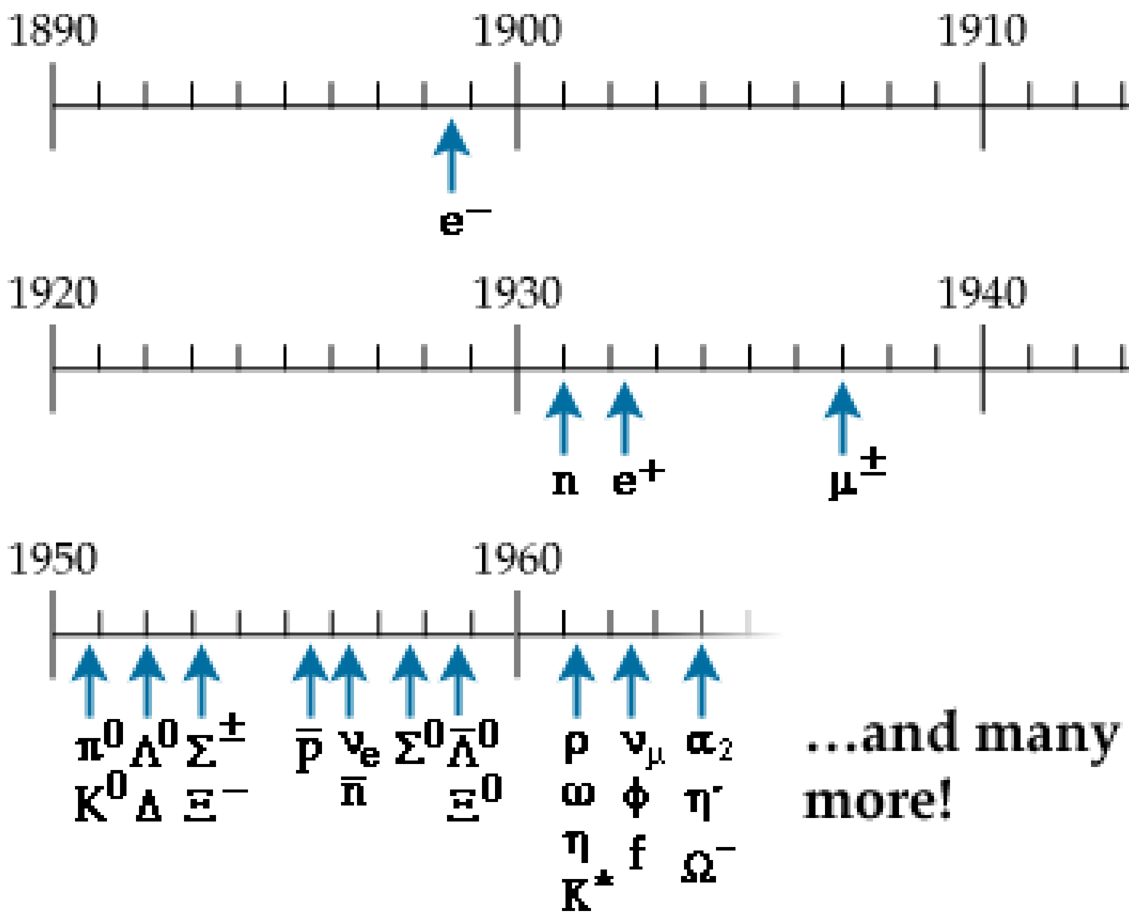
United Nations Educational, Scientific and Cultural Organization

2019 IYPT International Year of the Periodic Table of Chemical Elements

IUPAC

Building up the atomic world

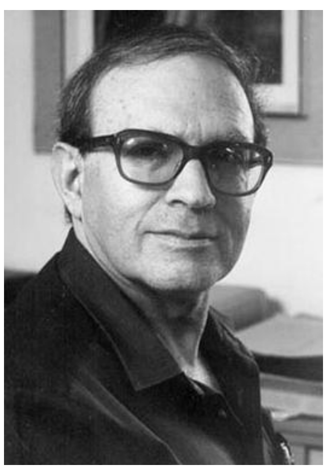
Nothing good lasts for ever



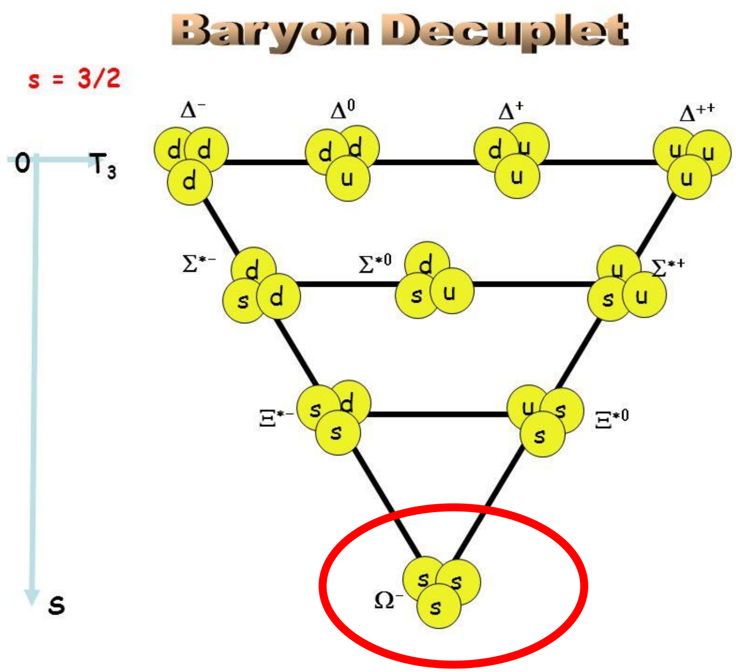
Hadron spectroscopy—QM—QCD

Put an end to the then chaotic situation

Murray Gell-Mann



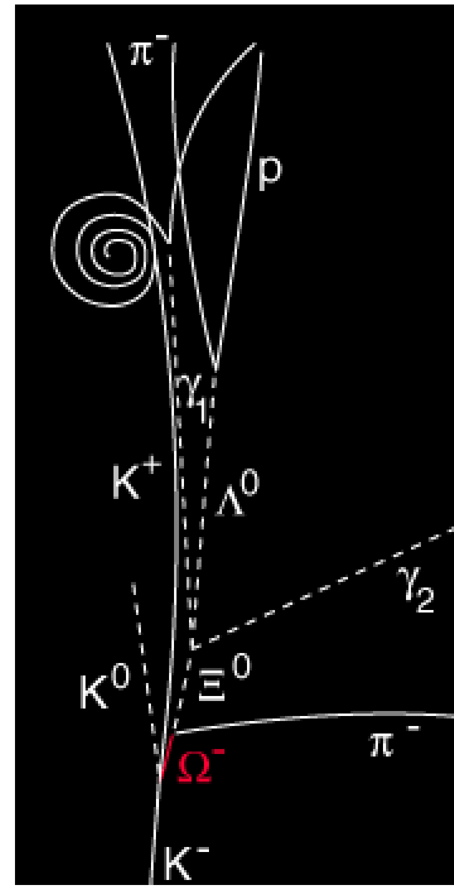
Yuval Ne'eman.



Eightfold way-1961

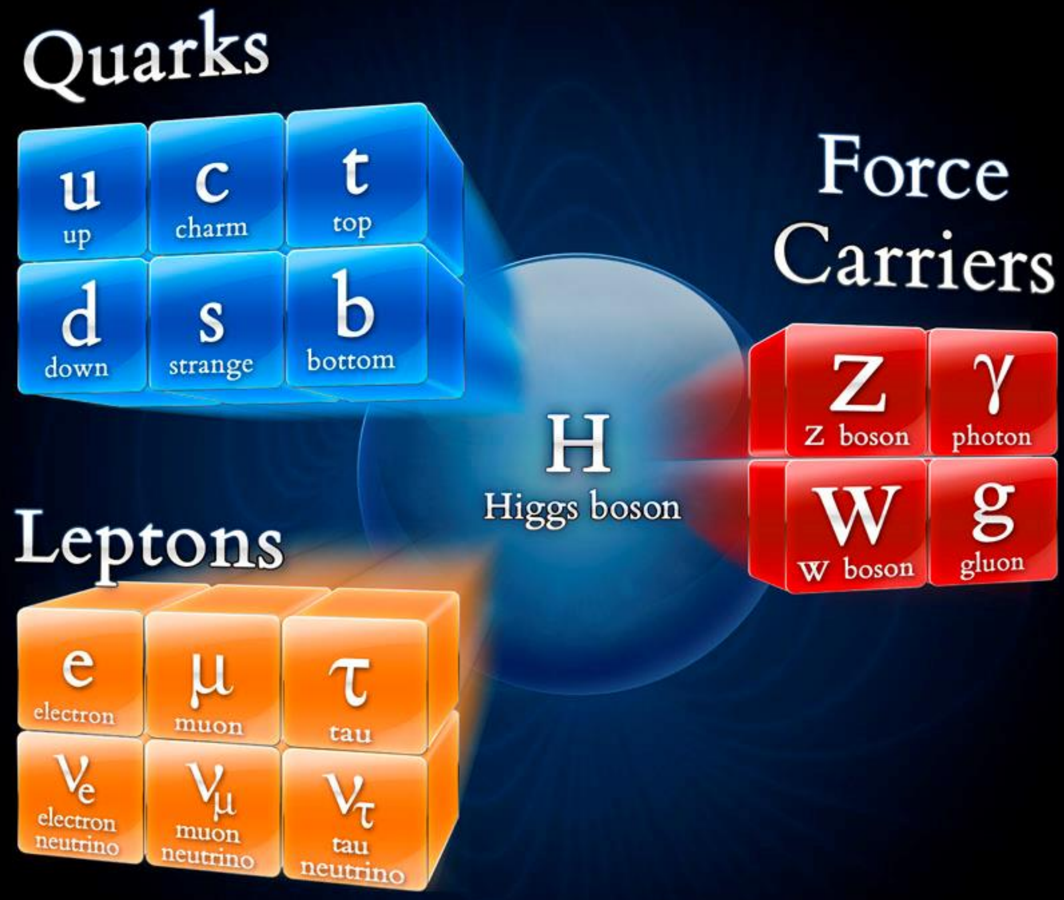
Quark model-1964

QCD/SM

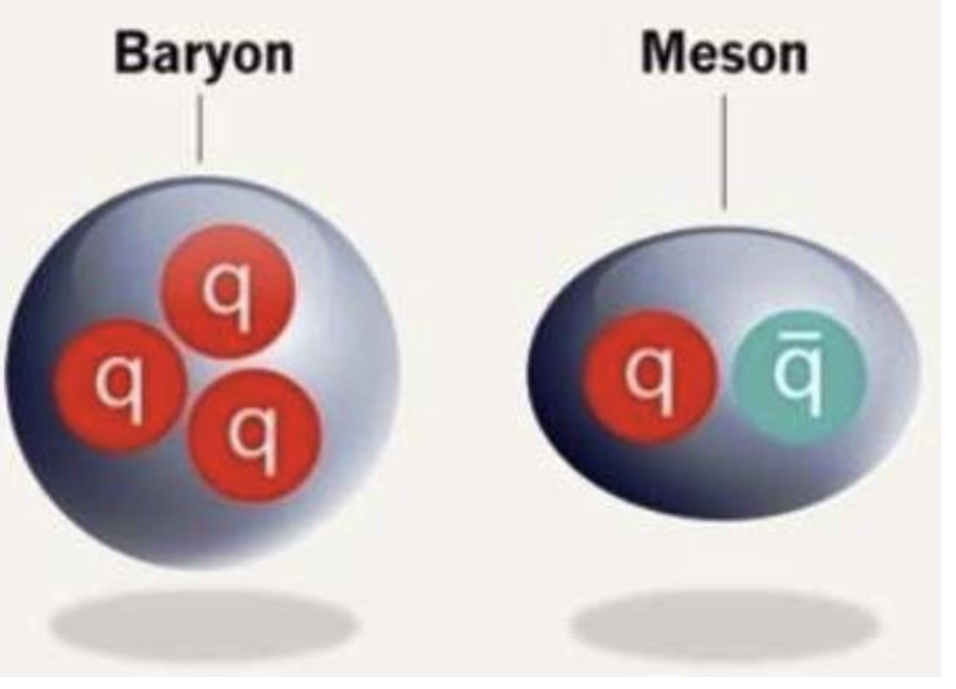


V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964)

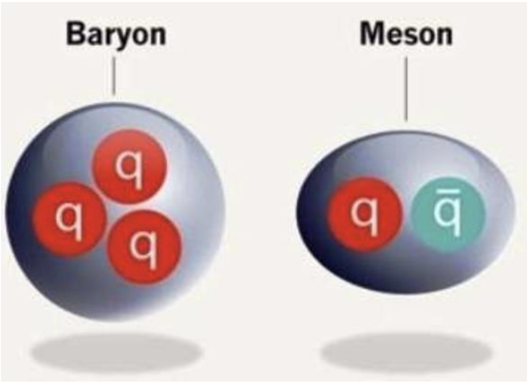
More quarks, more leptons, SM completed at 2012



Naive QM: hadron structure

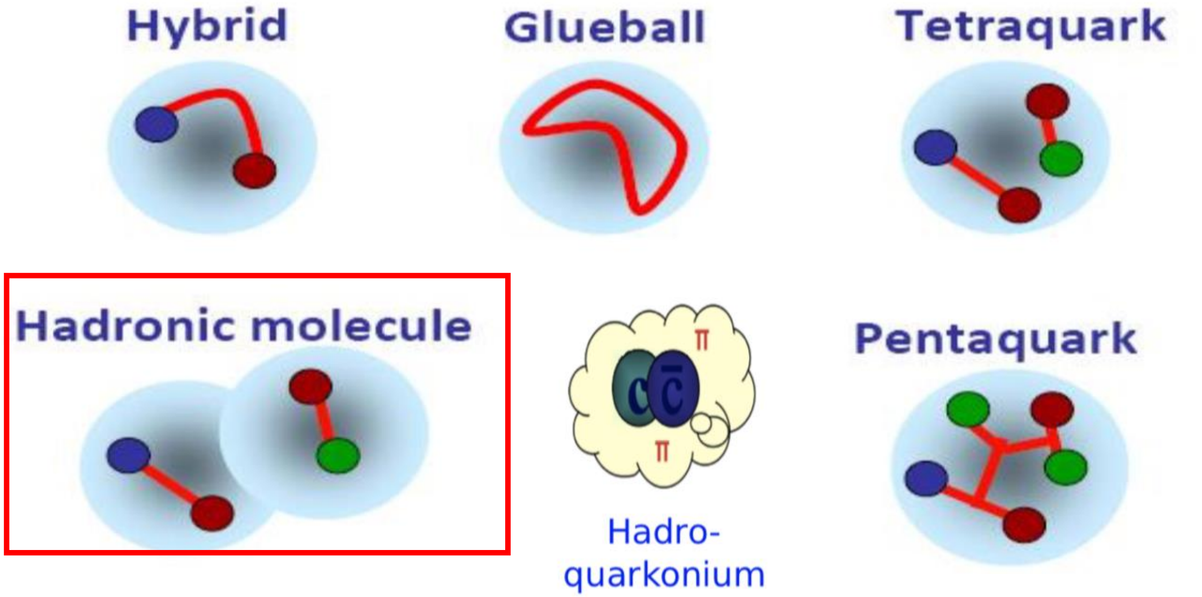


Beyond Naïve QM, more complicated structures allowed



In the naïve quark model

In principle, QCD allows



Not much happened until 2003

$\Lambda(1405)$, $N^*(1535)$,...
$f_0(500)$, $f_0(980)$, $a_0(980)$, ...

Beginning of a new era： 2003

LEPS, 0301020
> 1100

Θ^{+} (1540)

BaBar, 0304021
> 900

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

Belle, 0309032
> 1800

X(3872)

Beginning of a new era: 2003

LEPS, 0301020
> 1100

$\boldsymbol{\Theta^+}$ **(1540)**

BaBar, 0304021
> 900

$\boldsymbol{D^*_{s0}(2317)}$

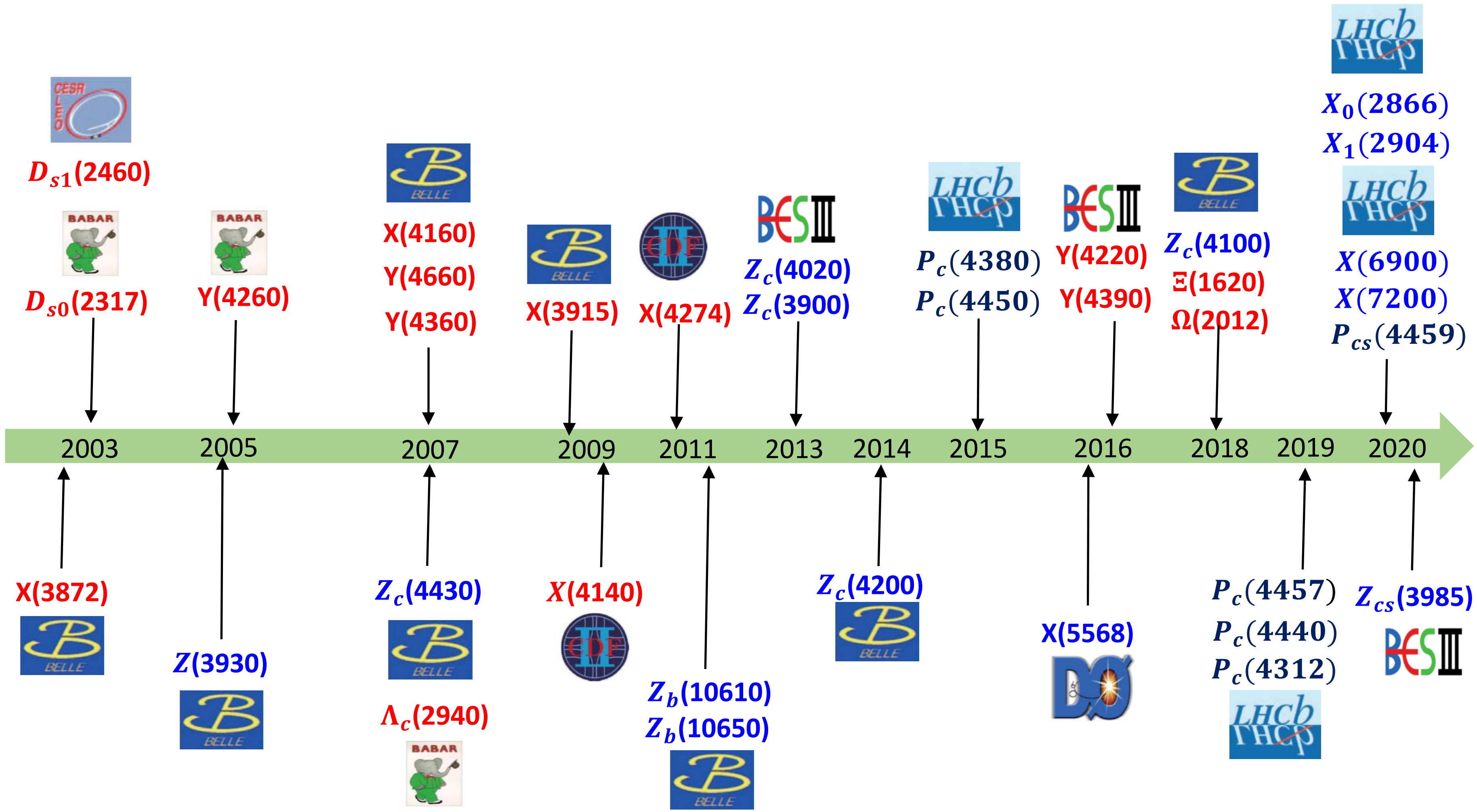
BABAR

Belle, 0309032
> 1800

X(3872)

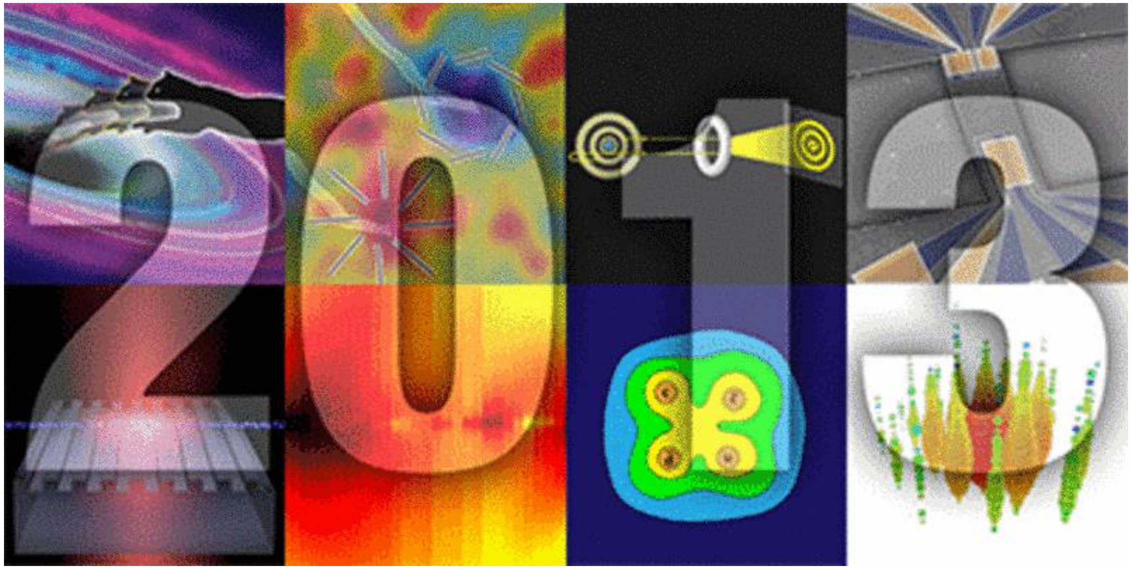
BELLE

Exotic mesons or baryons Tetraquark states Pentaquark states



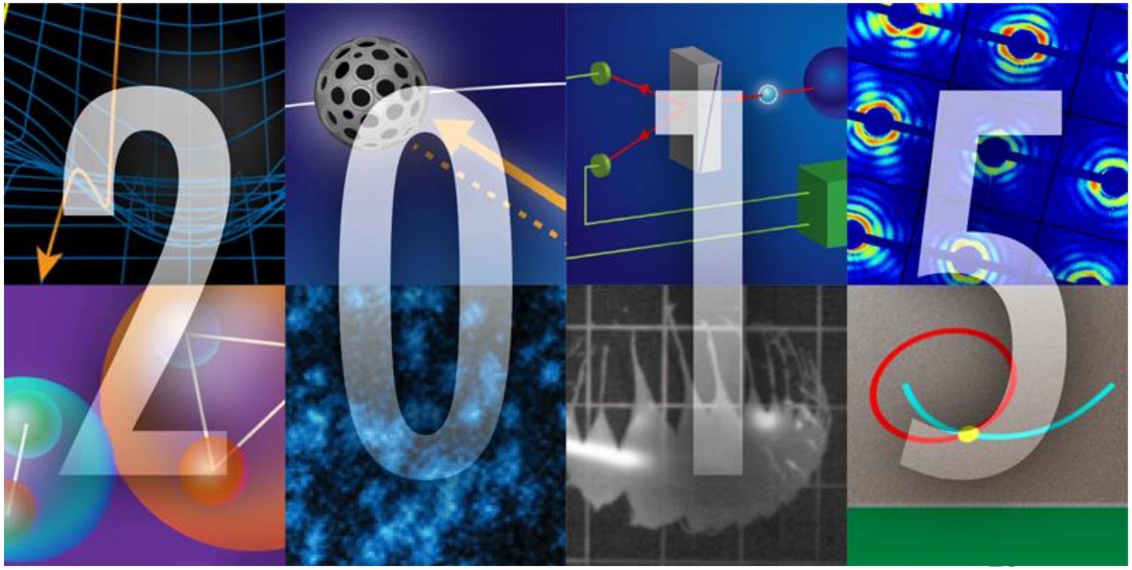
Highlights of the year

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

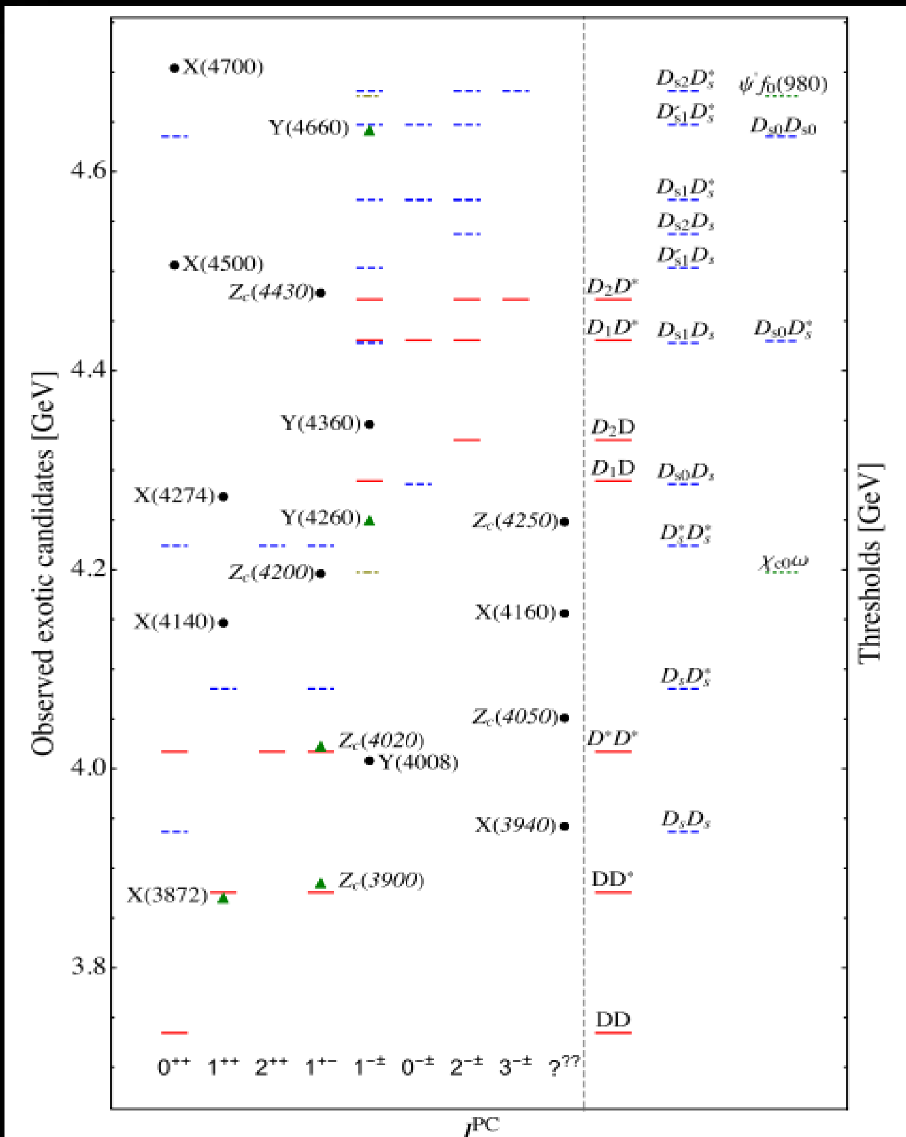


Four-Quark Matter/BESIII

Particle High Five/LHCb



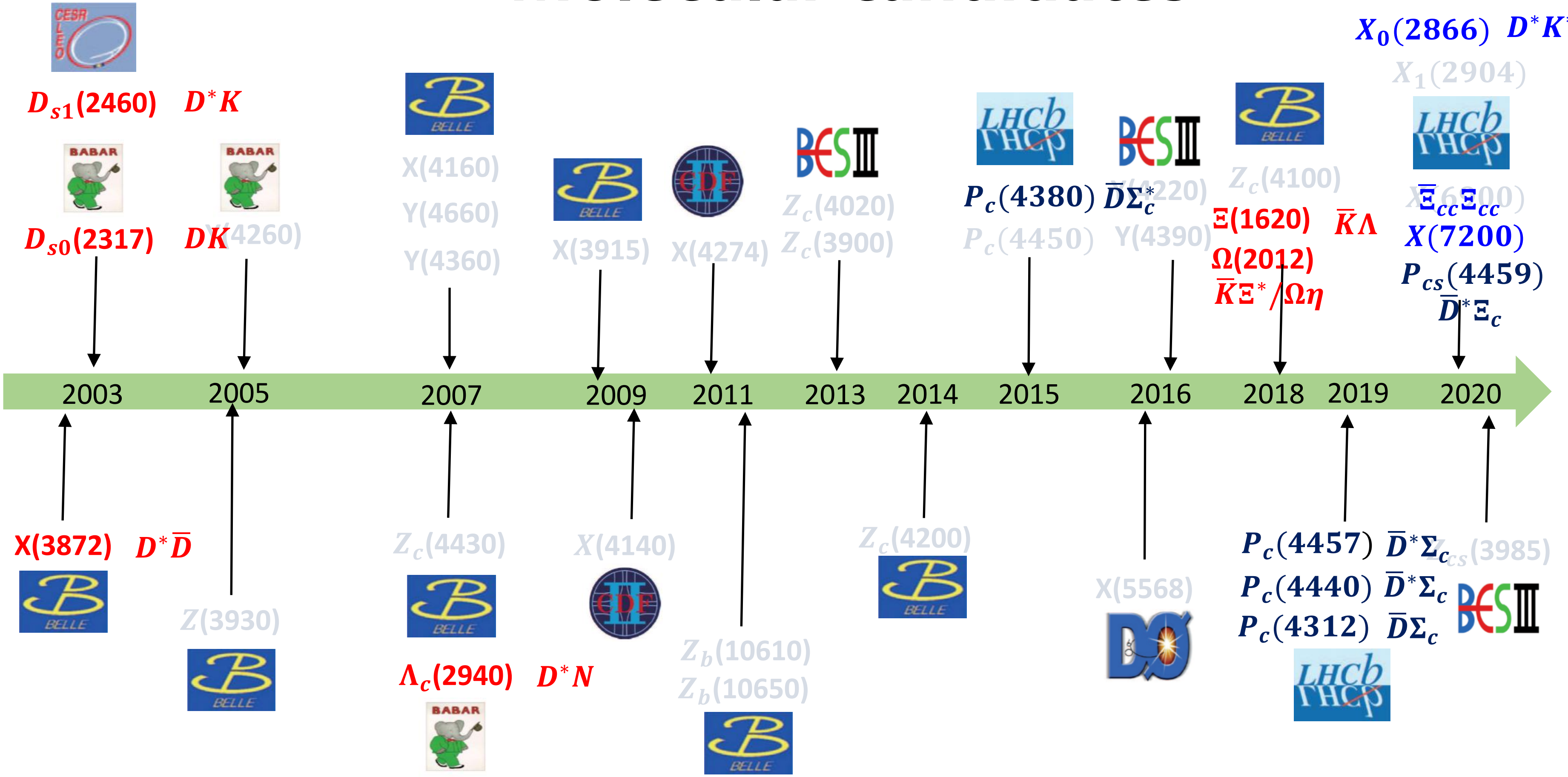
Many (if not all) of them close to thresholds



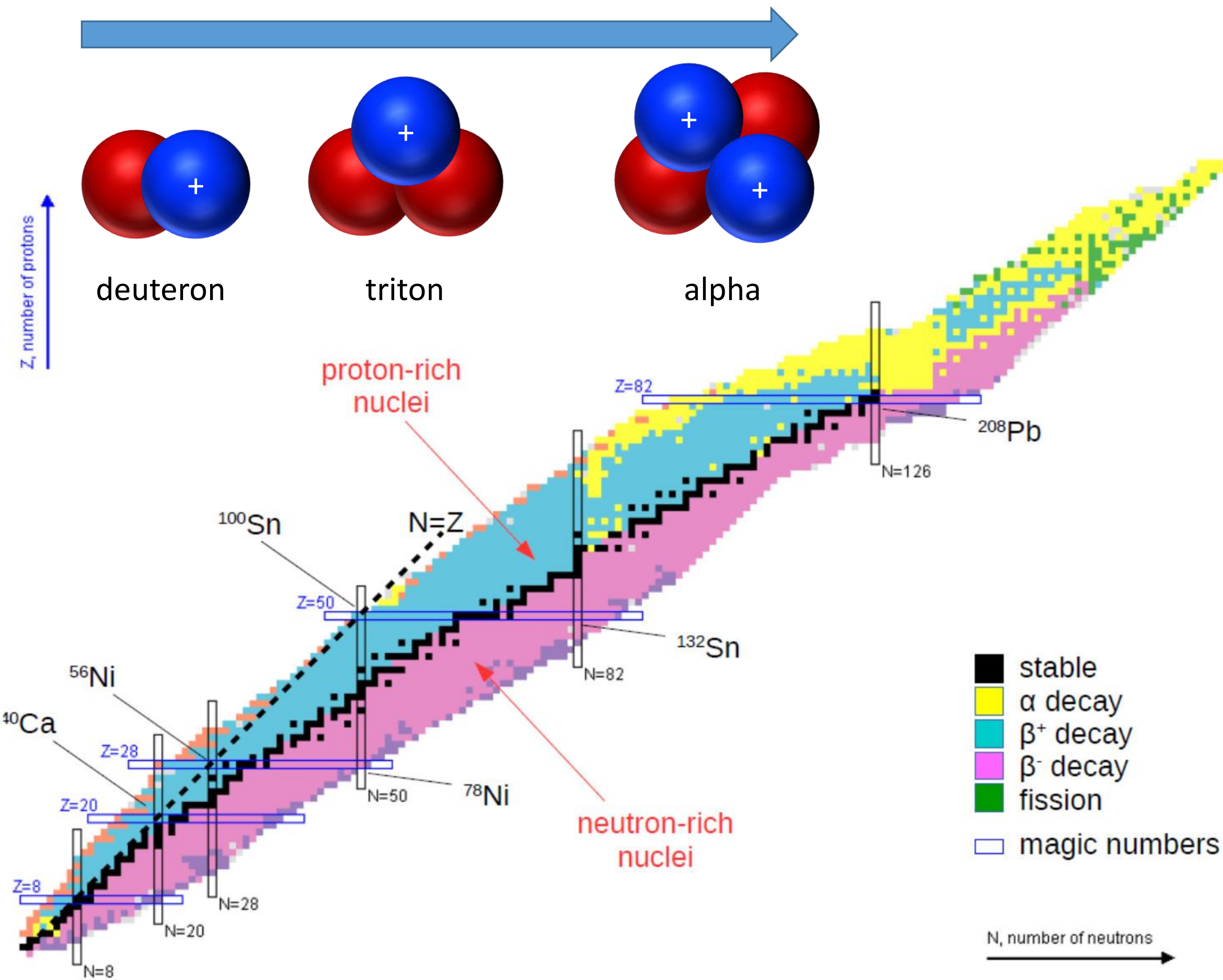
Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, Bing-Song Zou. Rev.Mod.Phys. 90 (2018) 015004.

Exotic mesons or baryons **Tetraquark states** **Pentaquark states**

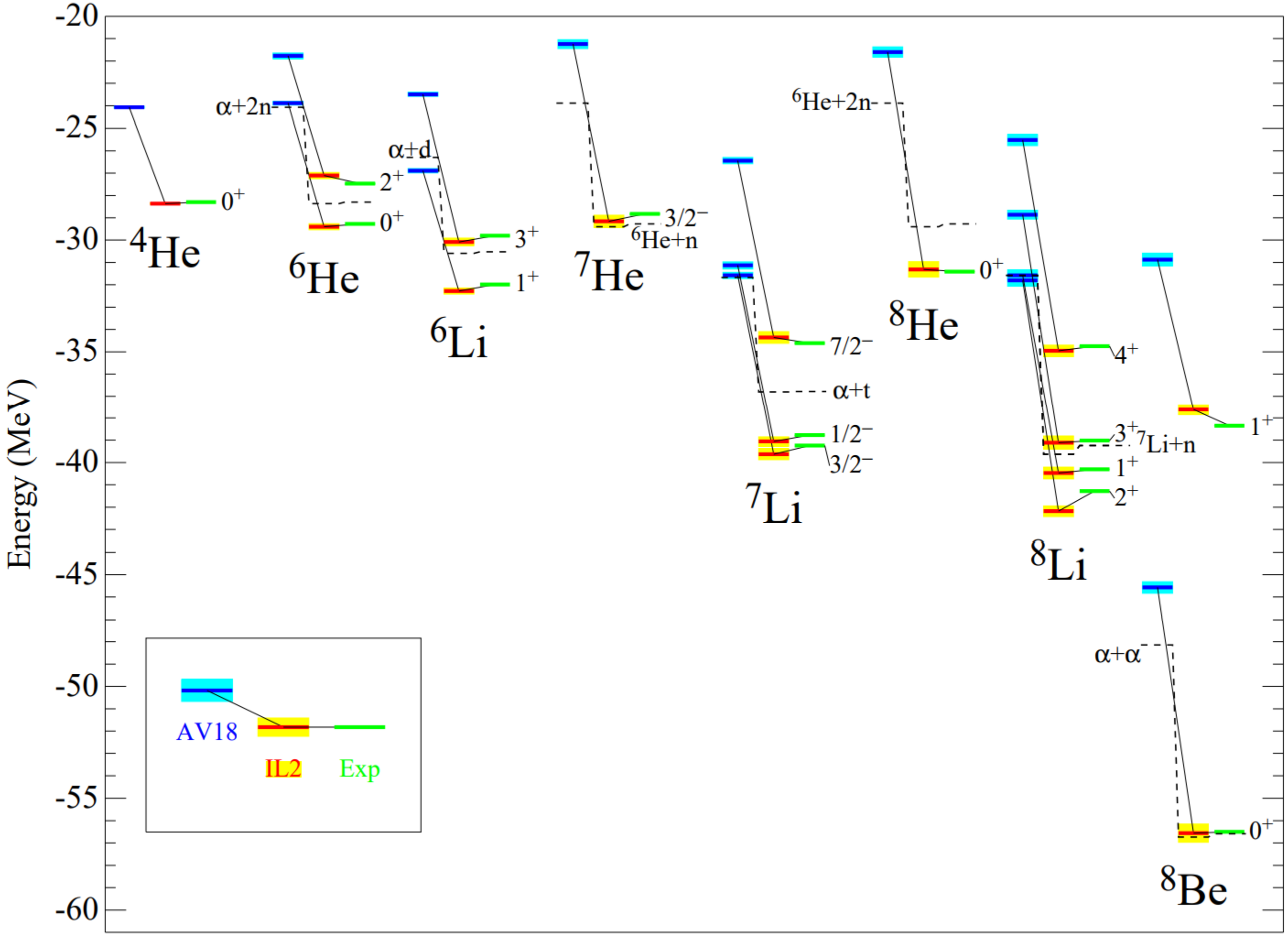
Molecular candidates



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
^{100}Sn
N=Z
^{56}Ni
^{40}Ca
^{78}Ni
^{132}Sn
^{208}Pb
Z=8
Z=20
Z=28
Z=50
Z=82
N=8
N=20
N=28
N=50
N=82
N=126
stable
α decay
β+ decay
β- decay
fission
magic numbers
N, number of neutrons

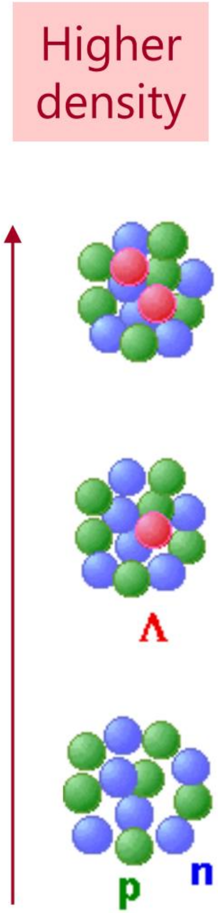
Quantum Monte Carlo Calculations of light Nuclei

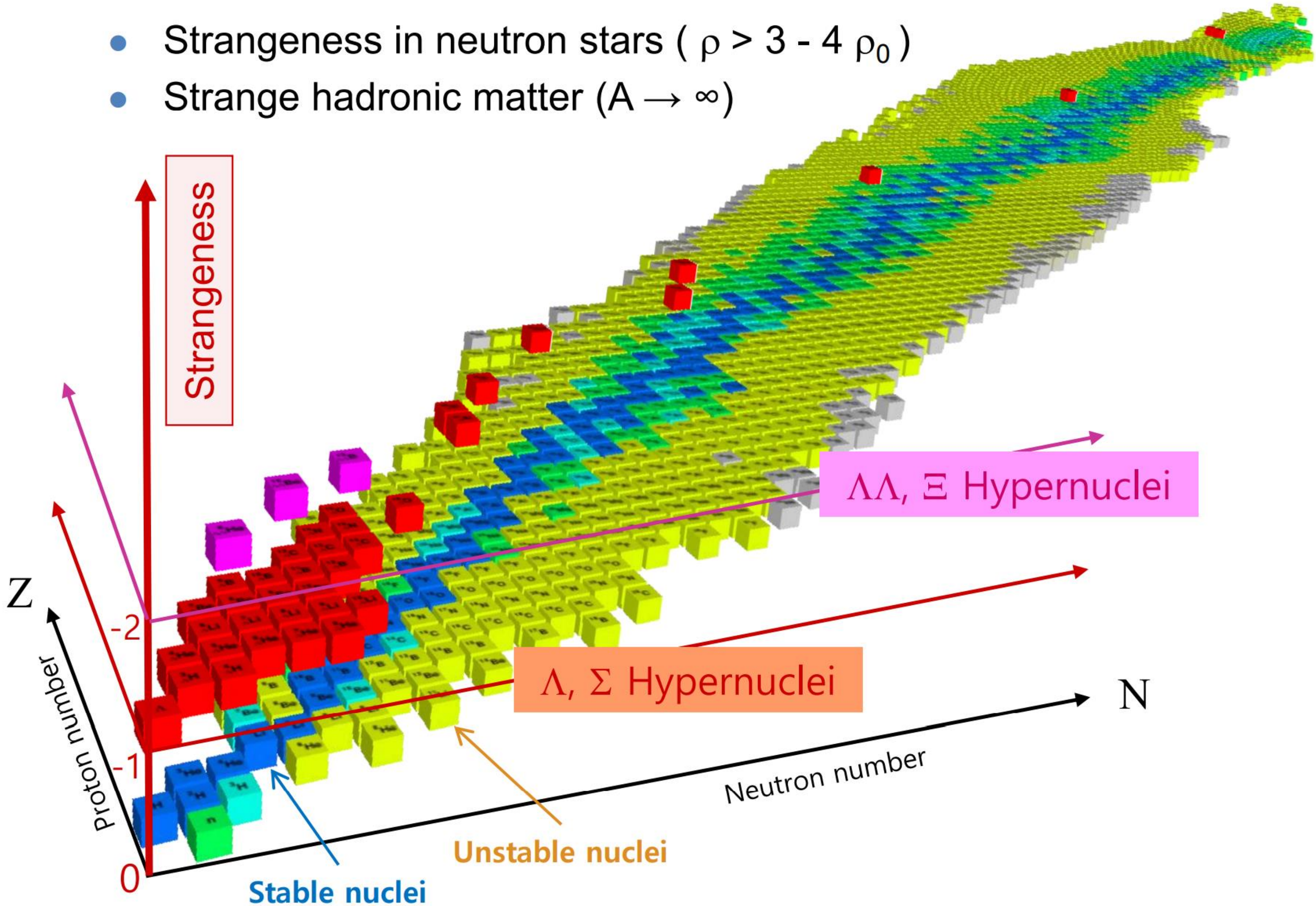


Annu. Rev. Nucl. Part. Sci. 2001. 51:53–90

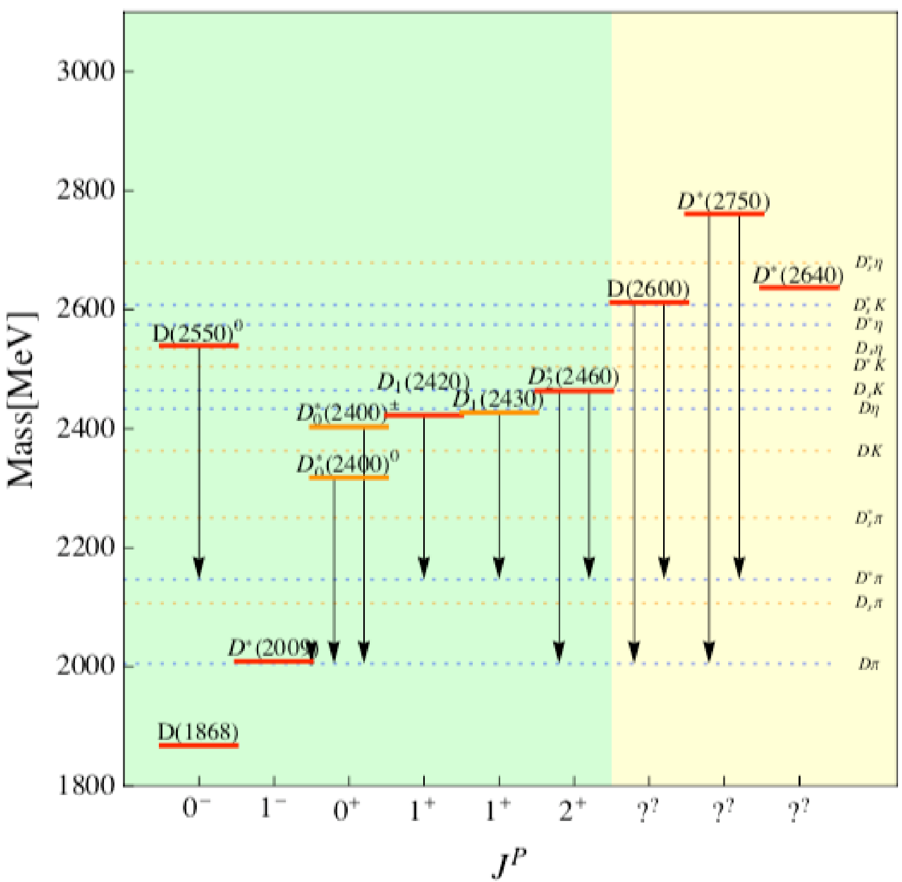
Adding hyperons→ three D nuclear chart

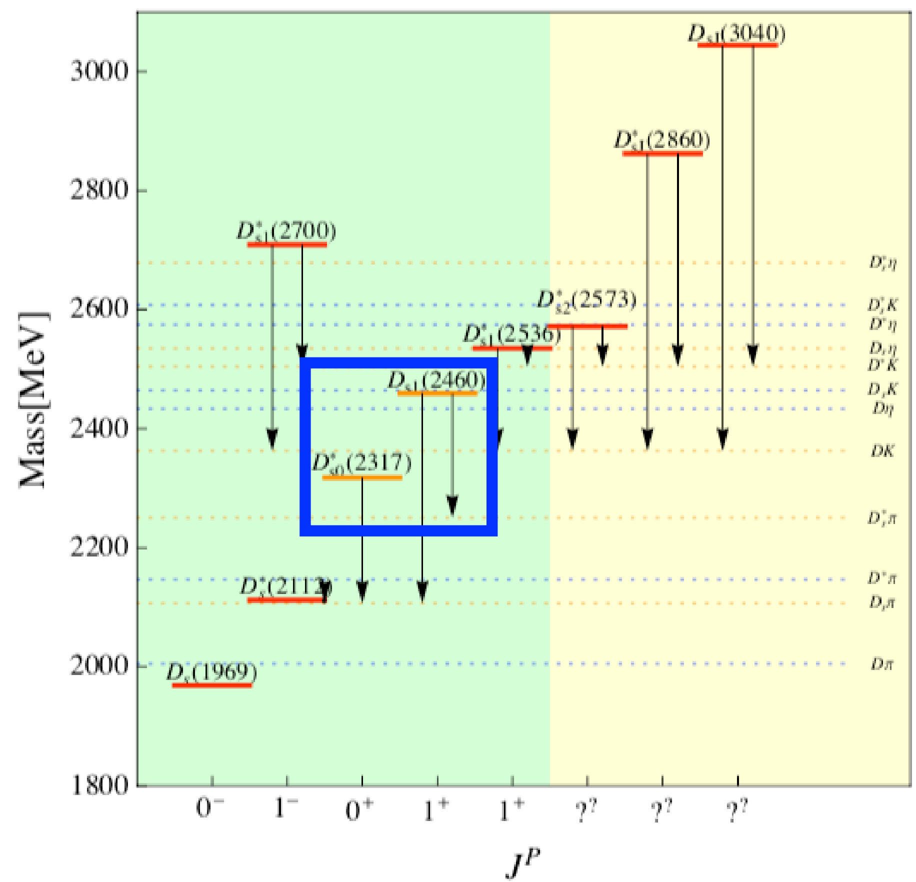
- Strangeness in neutron stars ($\rho > 3 - 4\ \rho_0$)
- Strange hadronic matter ($A \to \infty$)





Next best two-body molecule candidates

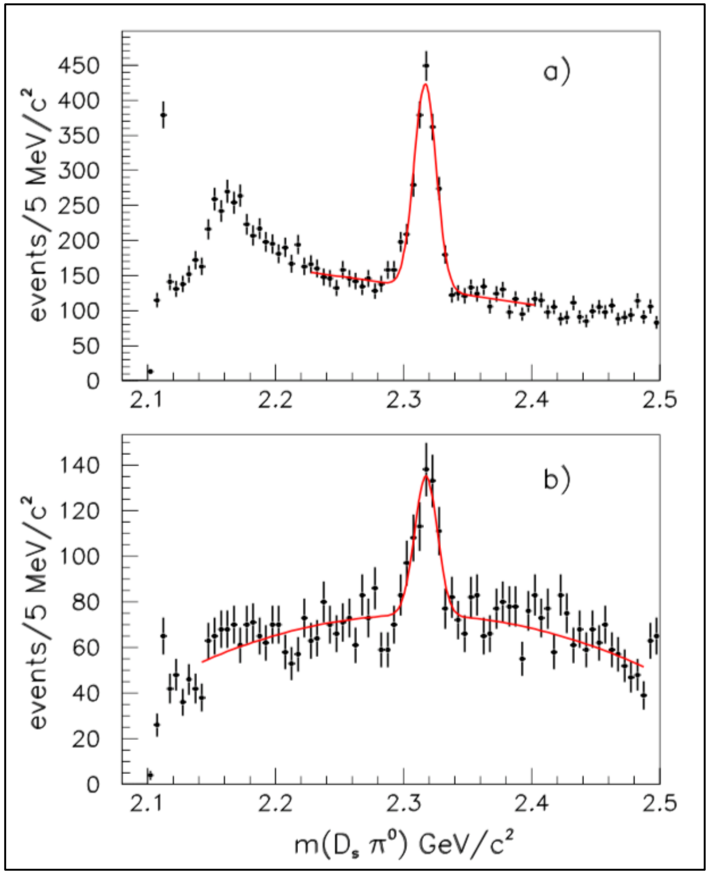




Ds0*(2317) **Ds1(2460)**

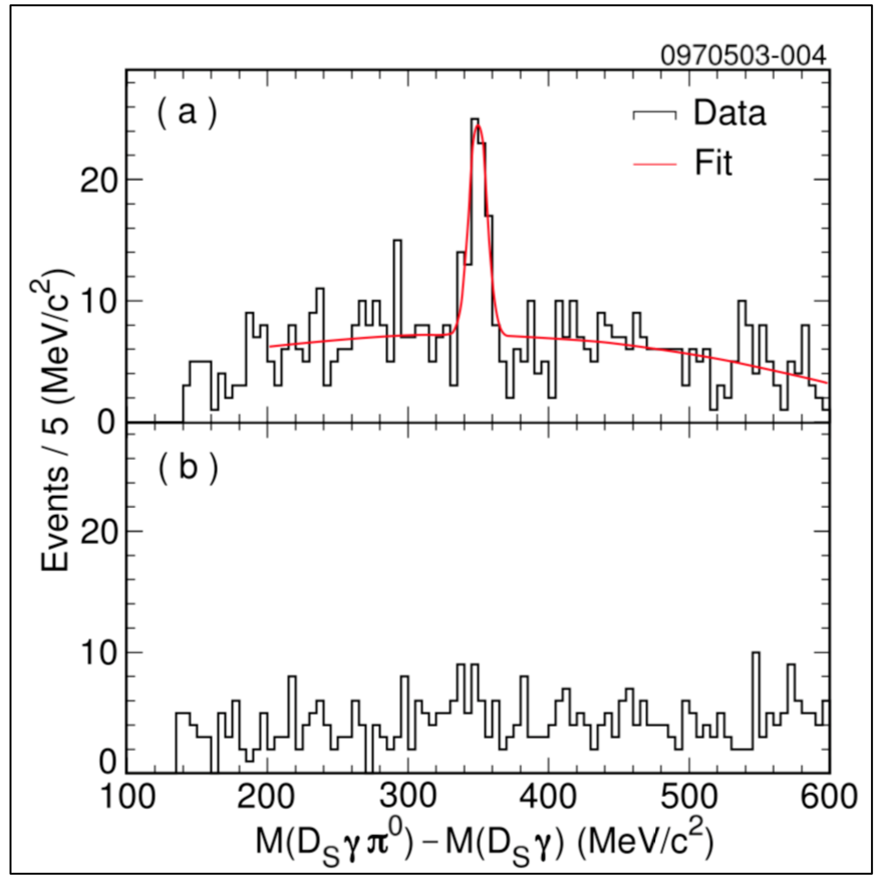
Discovery channels

Ds0*(2317)



BaBar PRL90,242001(2003)

Ds1(2460)



CLEO PRD68,032002(2003)

What are special about these two states

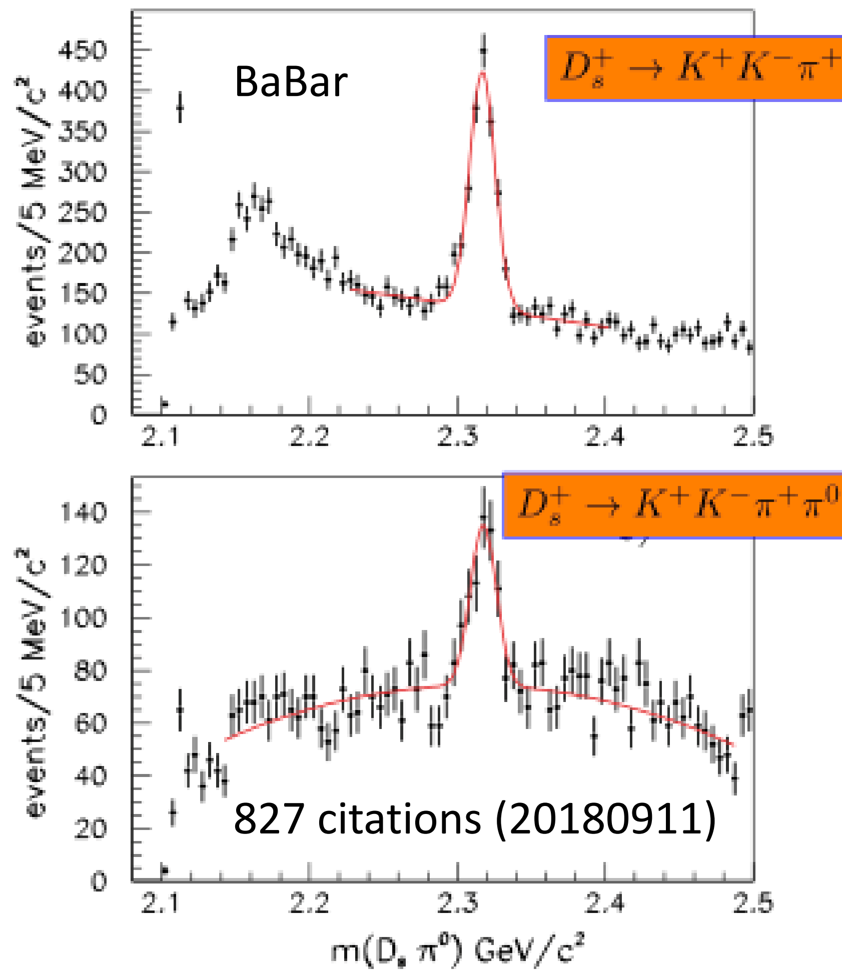
- $\mathbf{D^*_{s0}(2317),\ D_{s1}(2460)}$

- 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, [SEP]
  - ✓ 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)

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- (Future) experimental searches
- Summary and outlook

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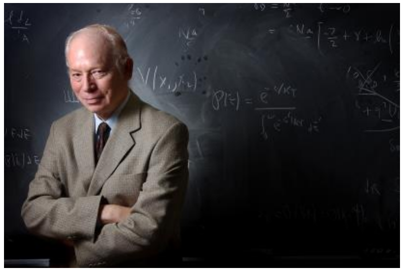
UChPT in Bethe-Salpeter equation



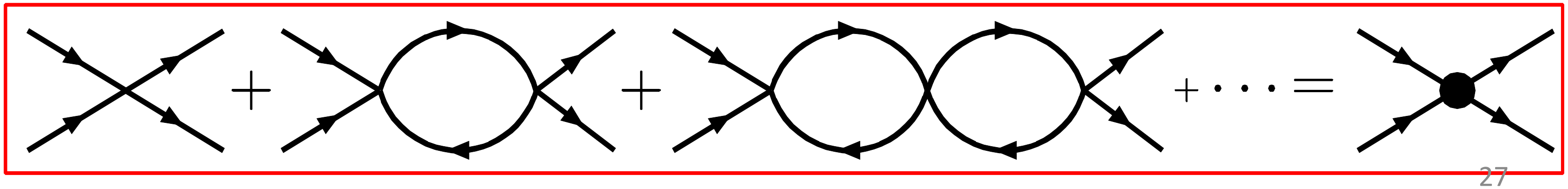
- ☐ **Model independent DK interaction from ChPT**

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

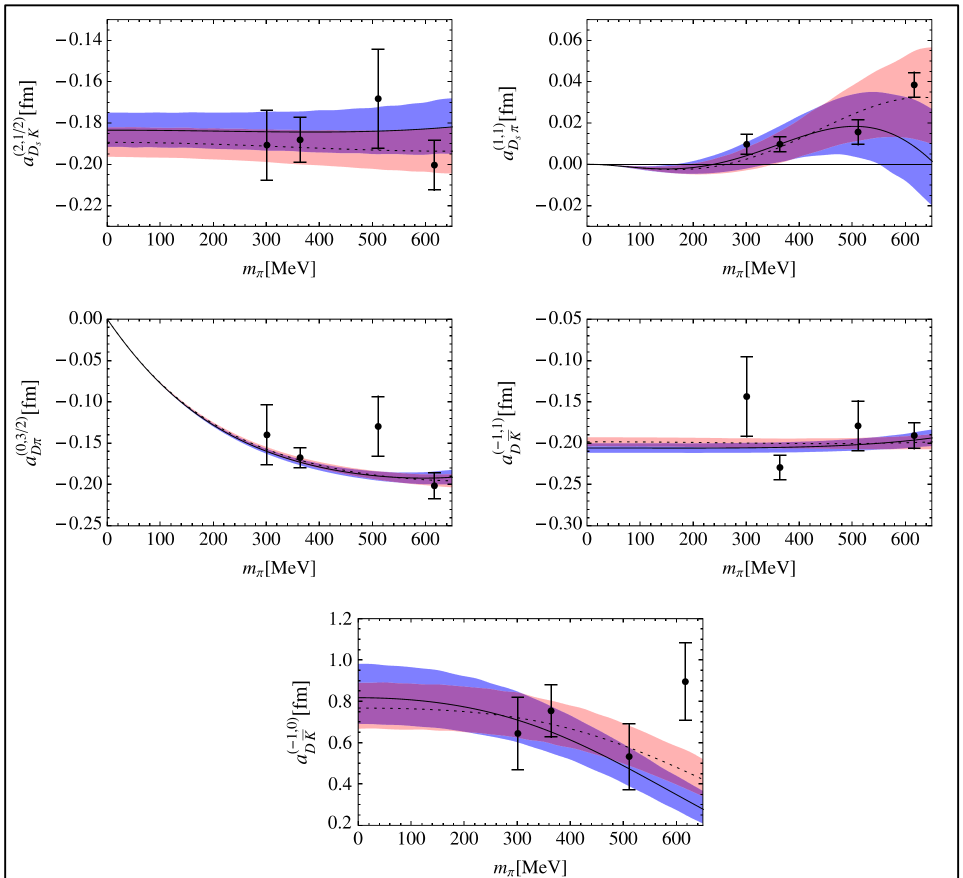
Weinberg-Tomazawa

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

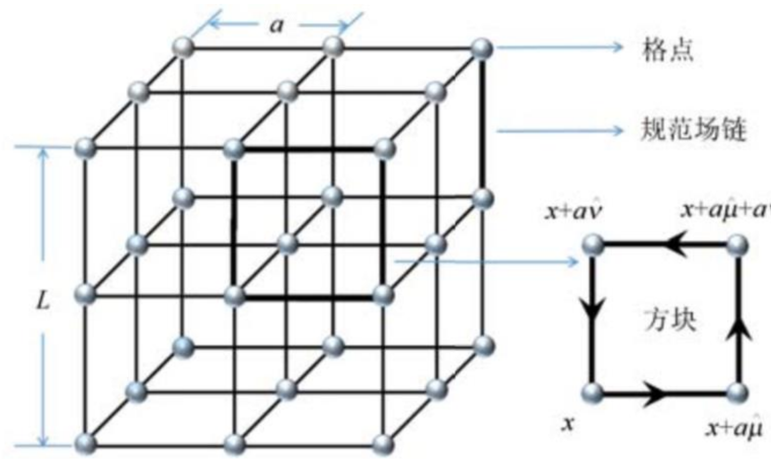
- ☐ **Resumed in the Bethe-Salpeter equation (two-body elastic unitarity)**



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.



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Ds0 and Ds1 dynamically generated

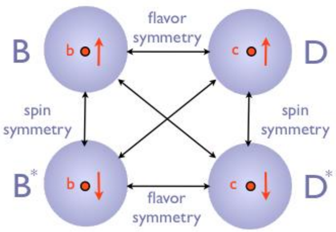
- **Charm sector**

"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 ± 10	2457 ± 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 ± 28	5778 ± 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

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

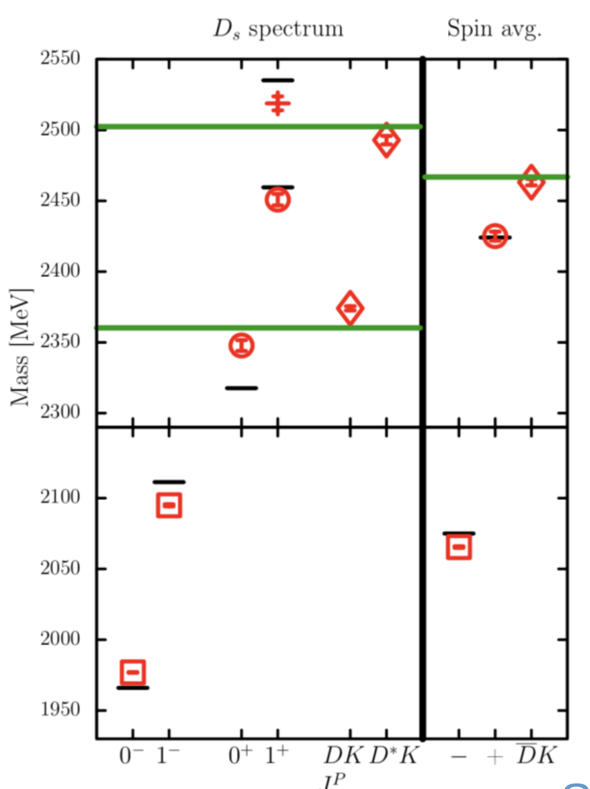
Table 5
Comparison of masses from this work to results from various model based calculations; all masses in MeV.

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 χ-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

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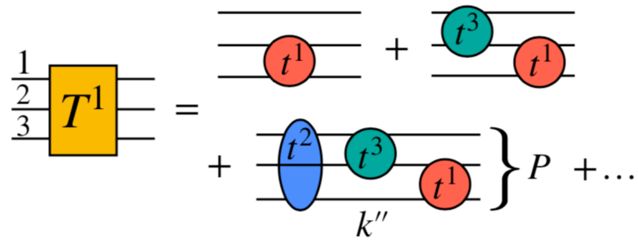
- $D\bar{D}^*K$ and $D\bar{D}K$ molecules: K*(4307) and Kc(4180)
- (Future) experimental searches
- Summary and outlook

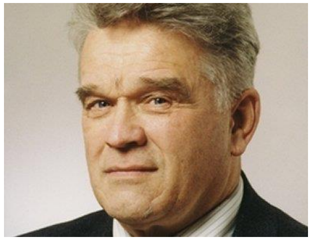
1809.01059

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*

1809.01059

Two-body inputs

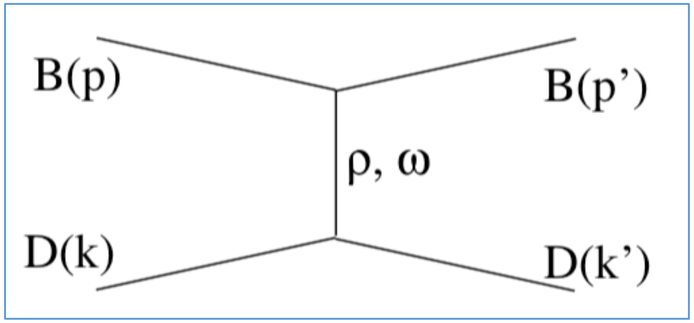
- **DK: leading order UChPT** DK, $D_s\eta$ and $D_s\pi$

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

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

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

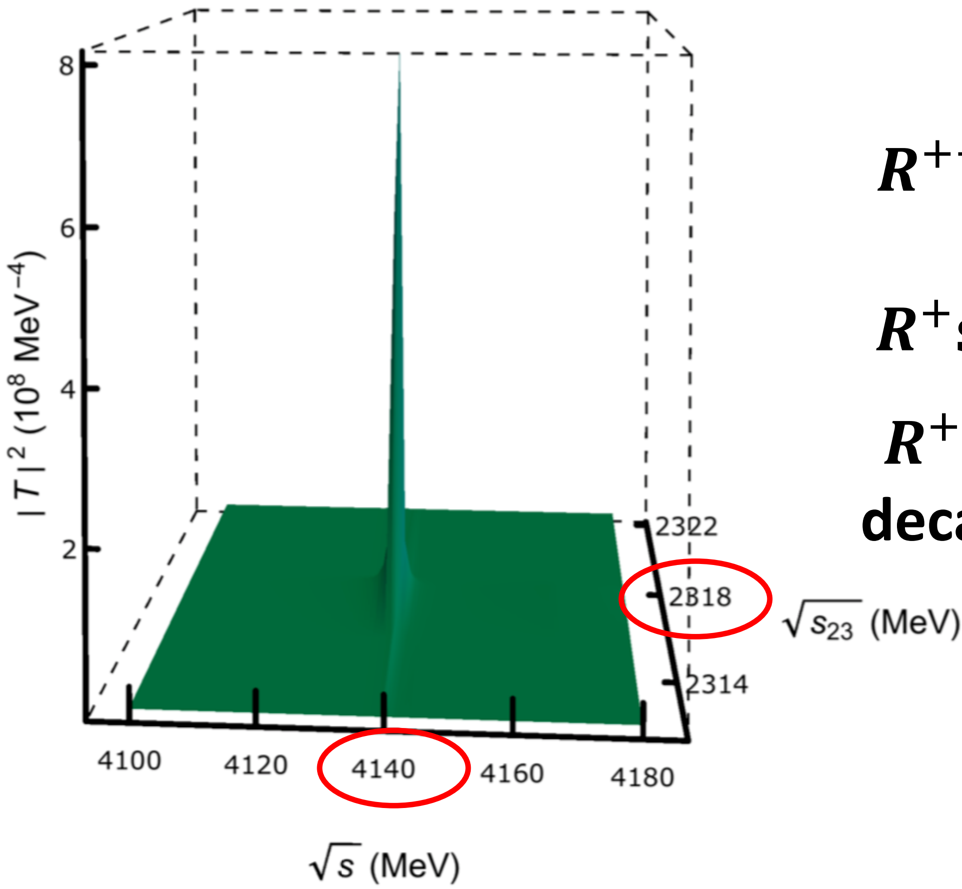
- **DD(Ds): local hidden gauge theory**



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

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

Three-body amplitudes



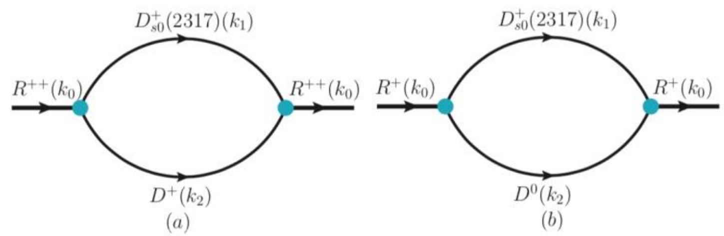
$$R^{++} = (I, I_{23}) = (\frac{1}{2}, 0)$$

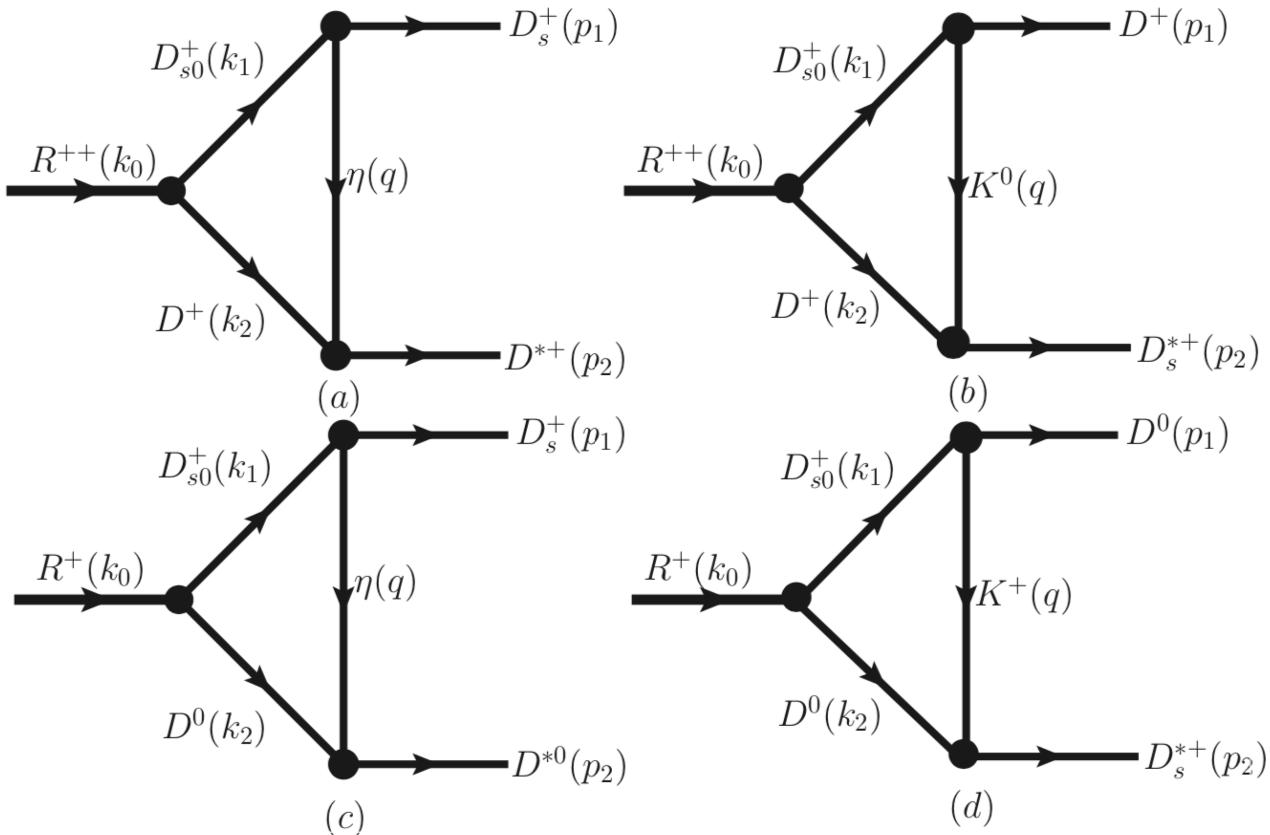
R^{+} should also exist

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

1909.09021

Two-body decay width

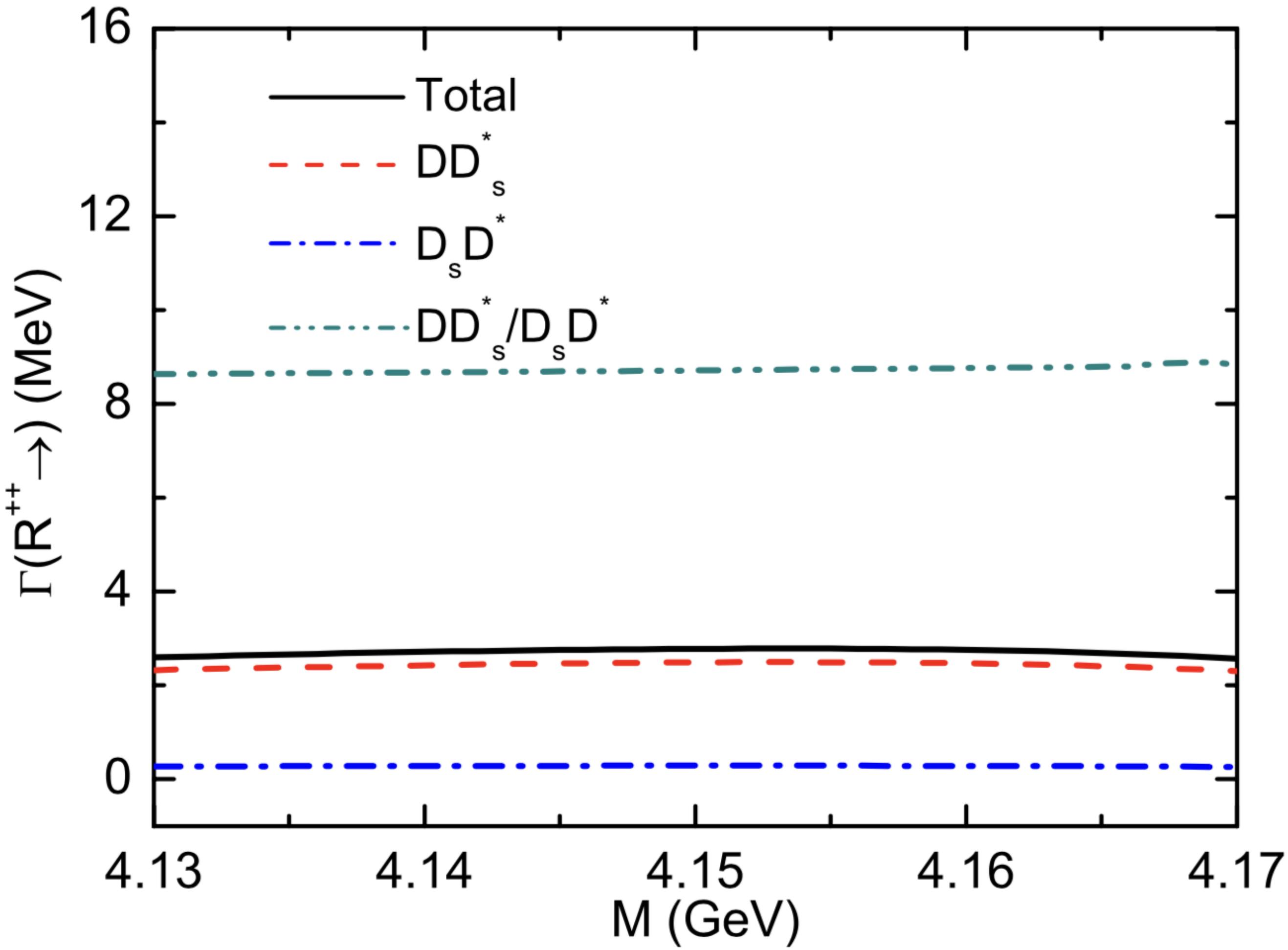




[1909.09021](1909.09021)

Two-body decay width

Kaon-Exchange Dominant



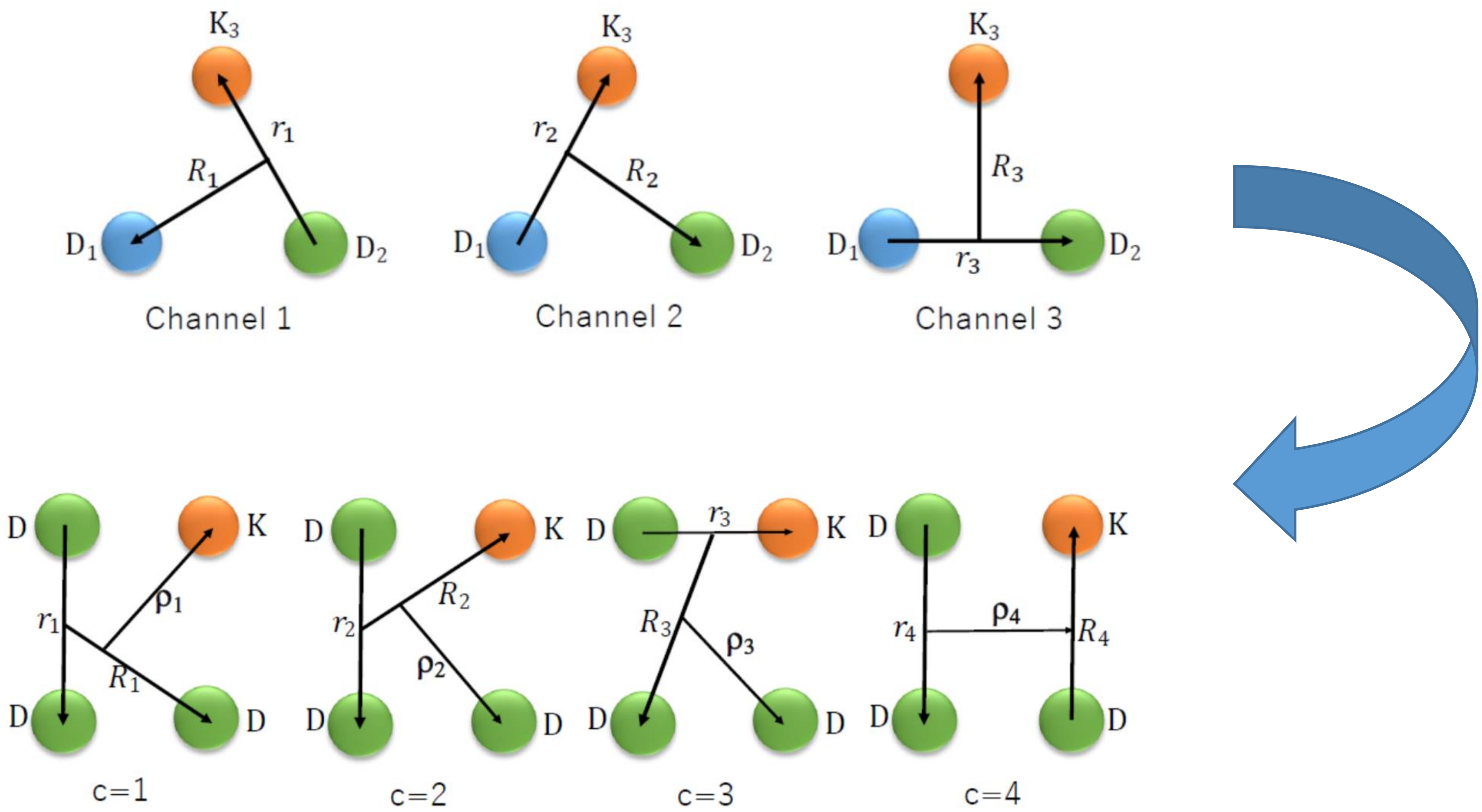
A DDDK state

1906.11995

1(0+)

Gaussian Expansion Method

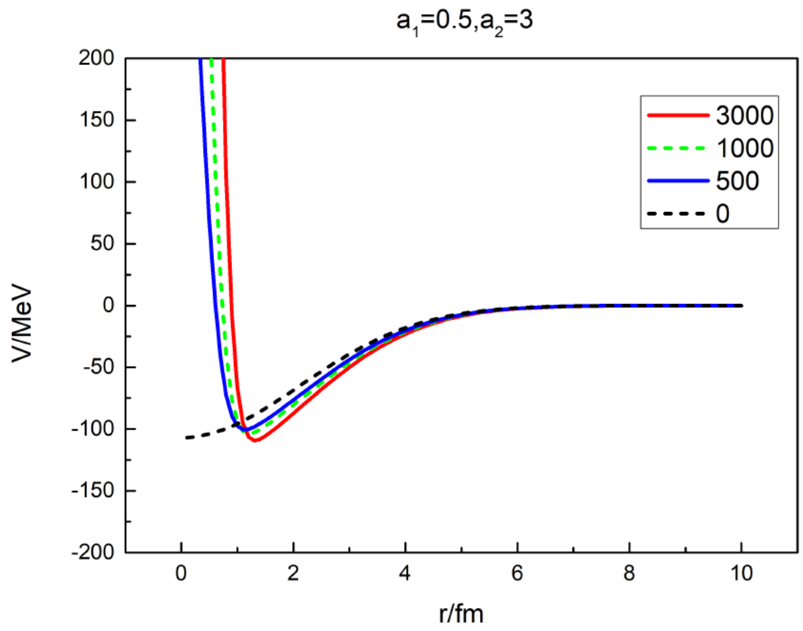
What if we add one more D?

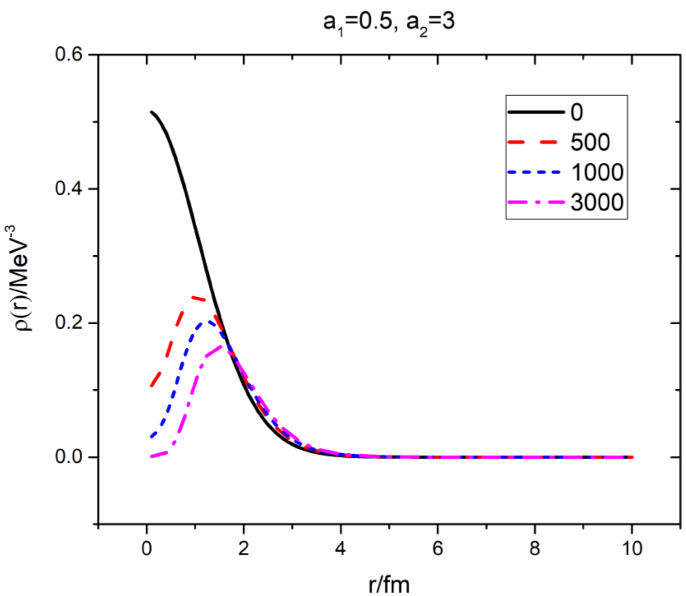


A DDDK state 1(0+)

1906.11995

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

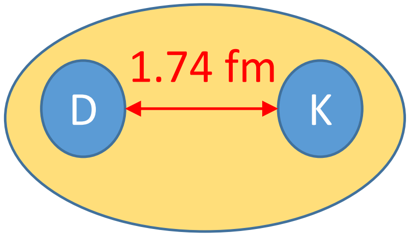
$\frac{C_S}{\pi R_S^3}$	$\frac{C(R_c)}{\pi R_c^3}$	E_2	E_3(only V_{DK})	$E_3(V_{DK}+V_{DD})$	E_4(onlyV_{DK})	$E_4(V_{DK}+V_{DD})$
		$R_S=0.5$fm		$R_c=1$fm		
0	−320.1	−45.0	−65.8	−71.2	−89.4	−106.8
500	−455.4	−45.0	−65.8	−70.4	−89.2	−103.5
1000	−562.6	−45.0	−65.7	−69.7	−88.8	−101.4
3000	−838.7	−45.0	−65.0	−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

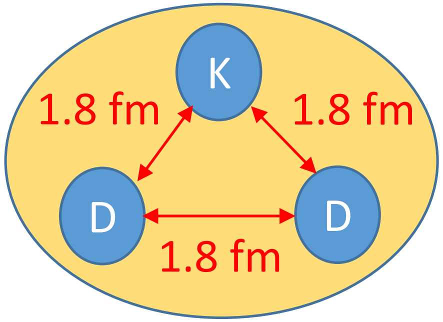
1906.11995

$\frac{C_S}{\pi R_S^3}$	$\frac{C(R_c)}{\pi R_c^3}$	$r_2(DK)$	$r_3(DK)$	$r_3(DD)$	$<T>$	$<V_{DK}>$	$<V_{DD}>$
$R_S = 0.5$fm $R_c = 1$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
$R_S = 0.5$fm $R_c = 2$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
$R_S = 0.5$fm $R_c = 3$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)



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Instead of a D, adding a $\overline{D^*}$ to the DK pair

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

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

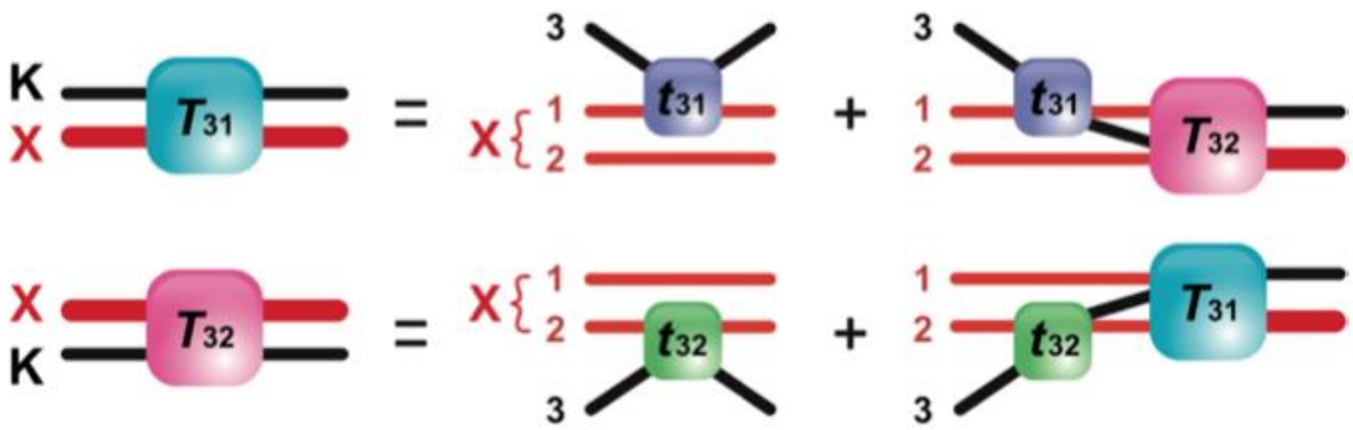
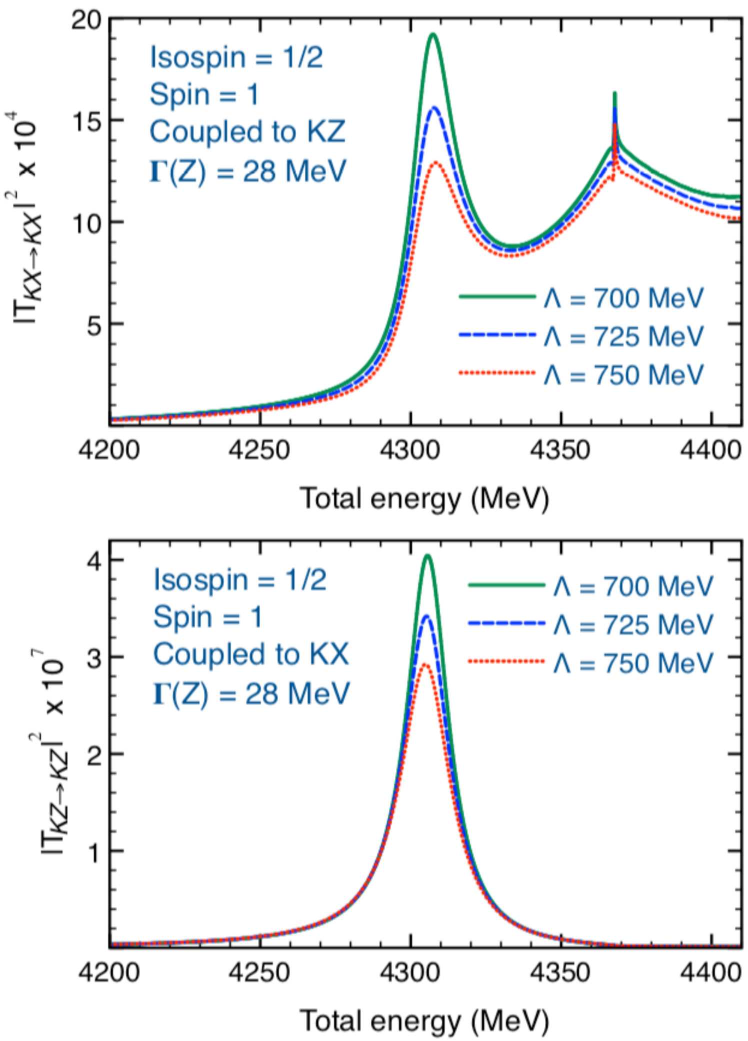
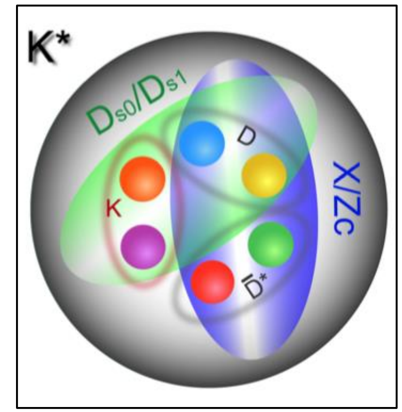


Figure 2: Diagrams showing the scattering of the particle labeled "3" (K) on a cluster (X) made of particles 1 (D) and 2 ($\bar{D}^*$).

1805.08330

K*(4307)





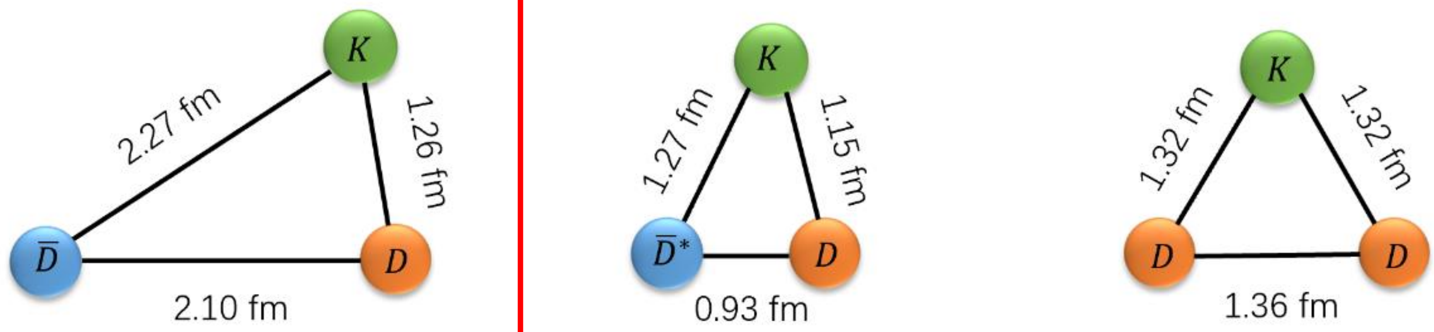
- **Treating KX and KZ as coupled channel systems**
- **A resonance with M=(4307 ± 2) – i(9 ± 2) MeV with I(J^P) = 1/2(1^-)**

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

Instead of a D, adding a $\bar{D}$ to the DK pair

2012.01134

The Three Musketeers

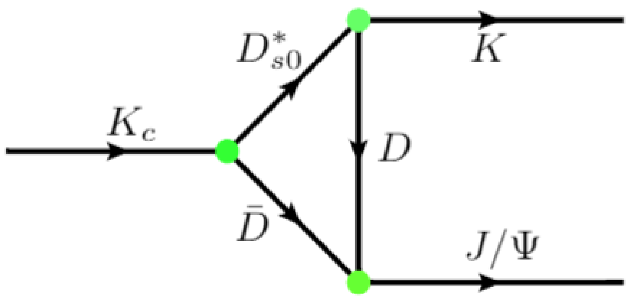


Kc(4180) K*(4307) R(4140)

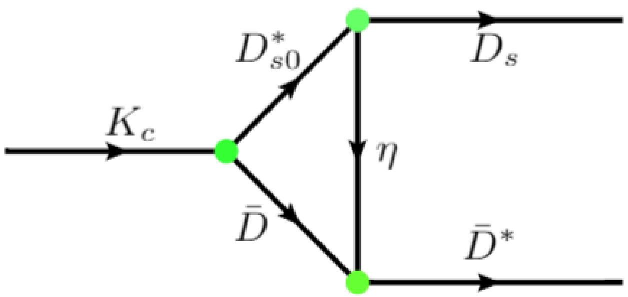
	This work	Ref [28]	Ref [29]
Method	GEM(SE)	BOA(SE)	FCA(FE)
Interaction Models	χEFT+OBE	delocalized π bond	χEFT+OBE
$\frac{1}{2}(0^-)\ D\bar{D}K$	$4181.2^{+2.4}_{-1.4}(B_3 \simeq 48.9^{+1.4}_{-2.4})$	-	-
$\frac{1}{2}(1^-)\ D\bar{D}^*K$	$4294.1^{+6.6}_{-3.1}(B_3 \simeq 77.3^{+3.1}_{-6.6})$	$4317.92^{+6.13}_{-6.55}(B_3 \simeq 53.52^{+6.55}_{-6.13})$	$4307 \pm 2(B_3 \simeq 64 \pm 2)$

$K_c(4180)$ decay

2012.01134

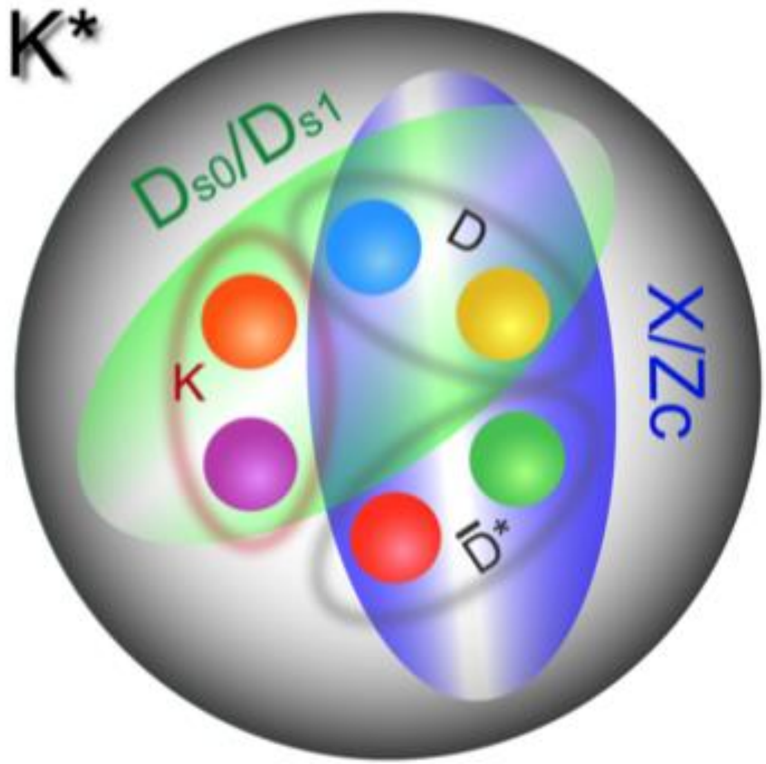


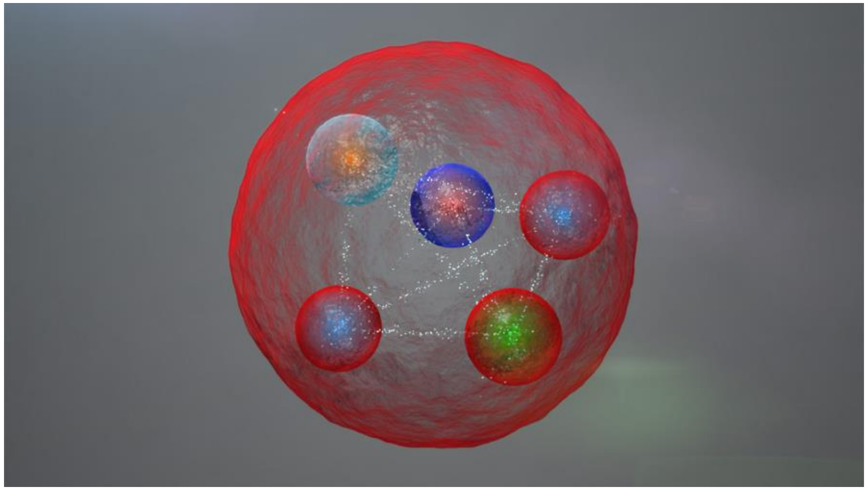
~1 MeV



~1 MeV

Kc(4180)—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

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- Where to search for these 3-body molecules
- Summary and outlook

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

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

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

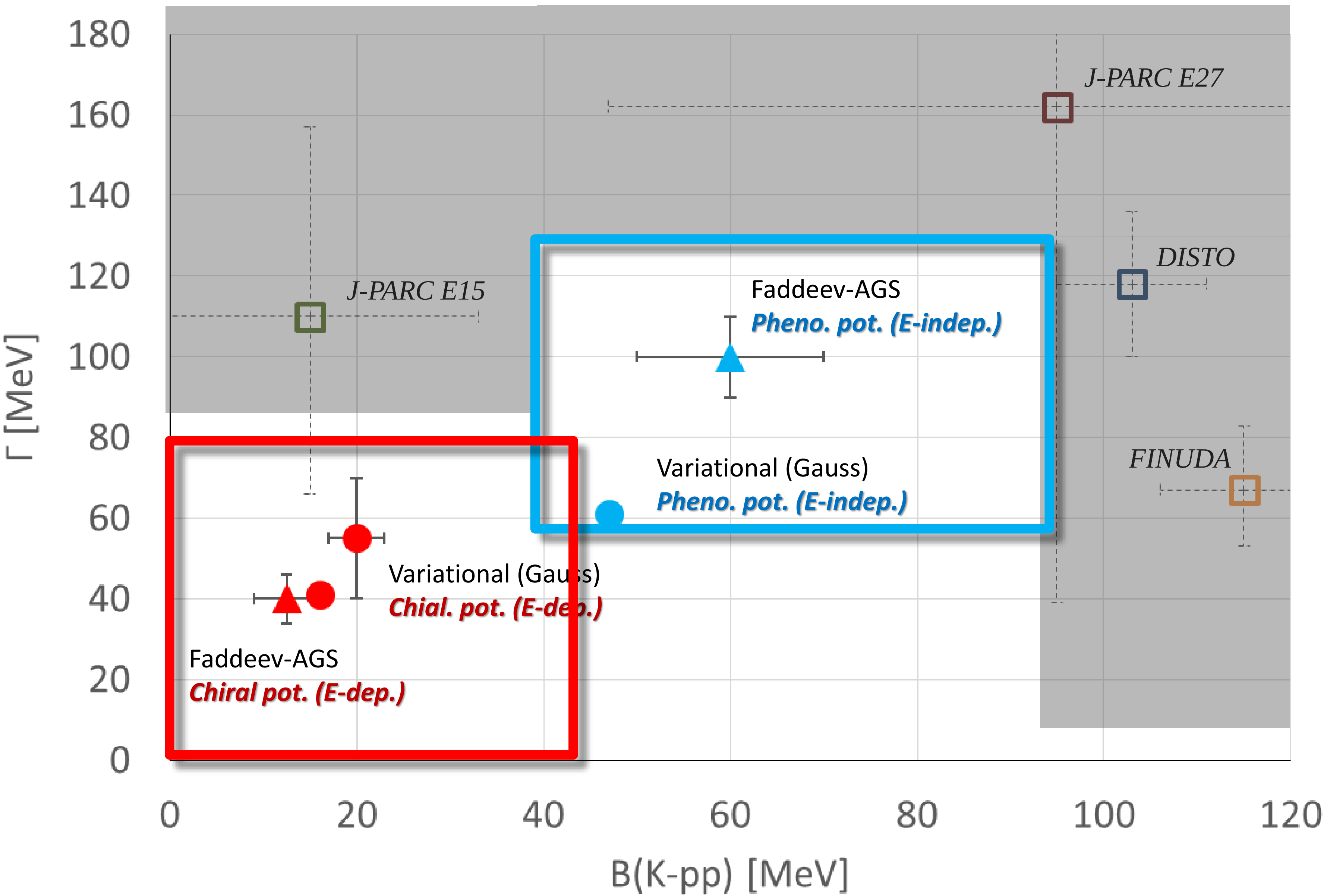
$\boldsymbol{\Lambda(1405)}$

- 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



Search for the DDK bound state by Belle

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

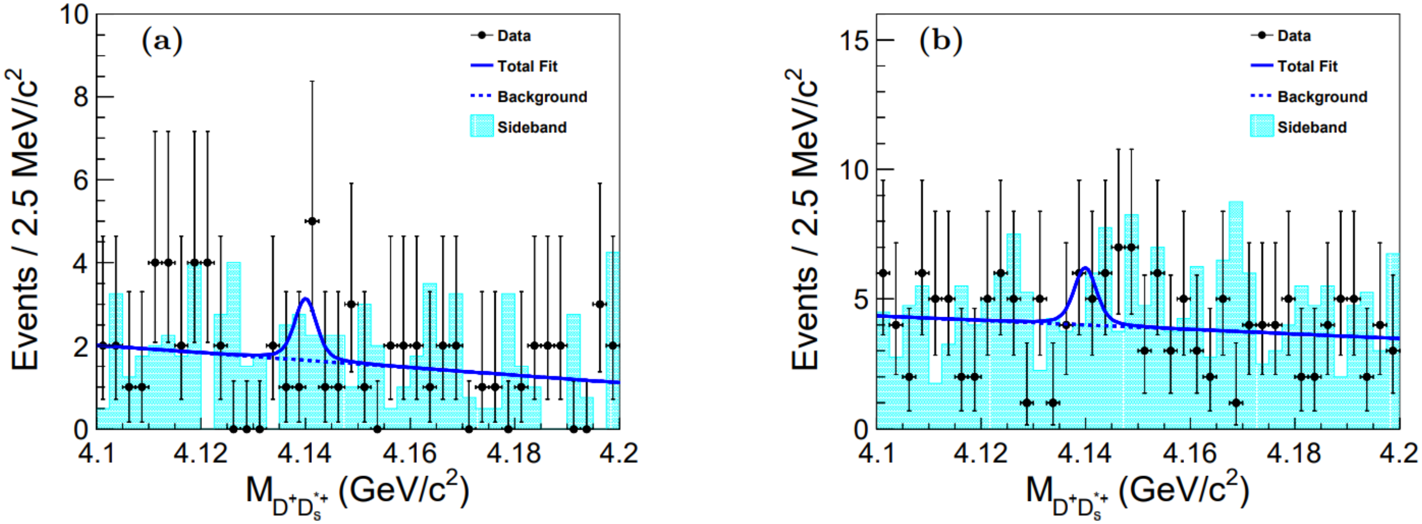


FIG. 4: The invariant-mass spectra of $D^+D_s^{*+}$ in the (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$ data samples. The cyan shaded histograms are from the normalized M_{D^+} and $M_{D_s^{*+}}$ sideband events. The blue solid curves show the fitted results with the R^{++} mass fixed at 4.14 GeV/c^2 and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

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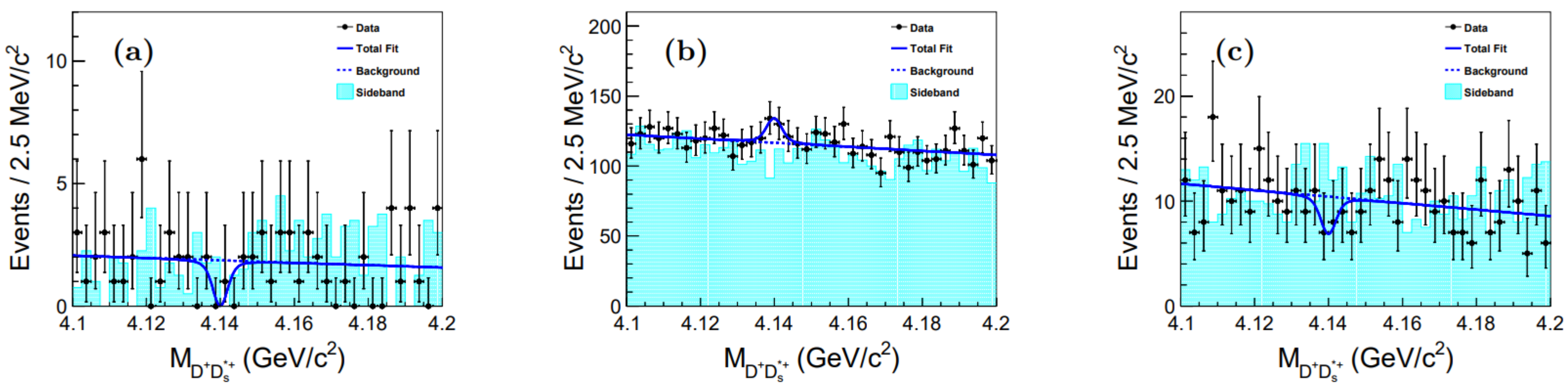


FIG. 10: The invariant-mass spectra of the $D^+D_s^{*+}$ from e^+e^- annihilations at (a) $\sqrt{s}=10.520$ GeV, (b) $\sqrt{s}=10.580$ GeV, and (c) $\sqrt{s}=10.867$ GeV data samples. The cyan shaded histograms are from the normalized M_{D^+} and $M_{D_s^{*+}}$ sideband events. The blue solid curves 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.

Where to search for Kc(4180)

$$\Lambda_b \to J/\psi K P$$

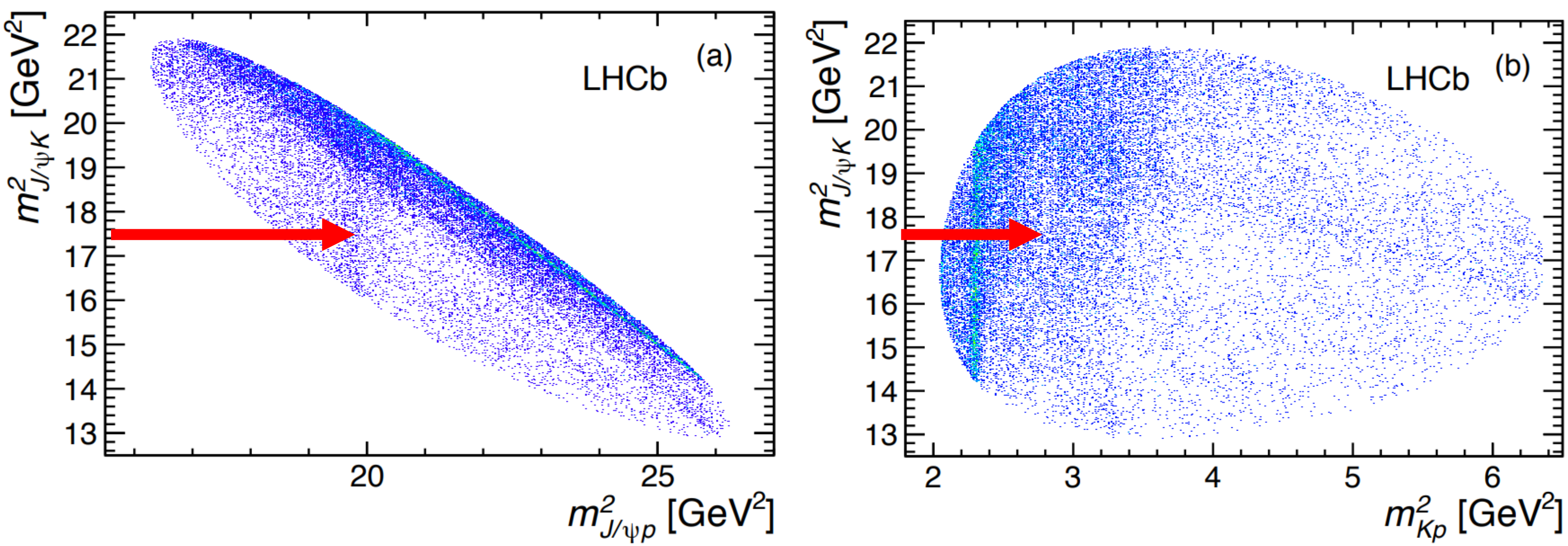


Figure 10: (a) Invariant mass squared of $J/\psi K^-$ versus $J/\psi p$ and (b) of $J/\psi K^-$ versus $K^- p$ for candidates within ±15 MeV of the Λ_b^0 mass.

LHCb:1507.03414: an integrated luminosity of 3 $\mathbf{fb^{-1}}$

Where to search for Kc(4180)

$B_s \to J/\psi K K$

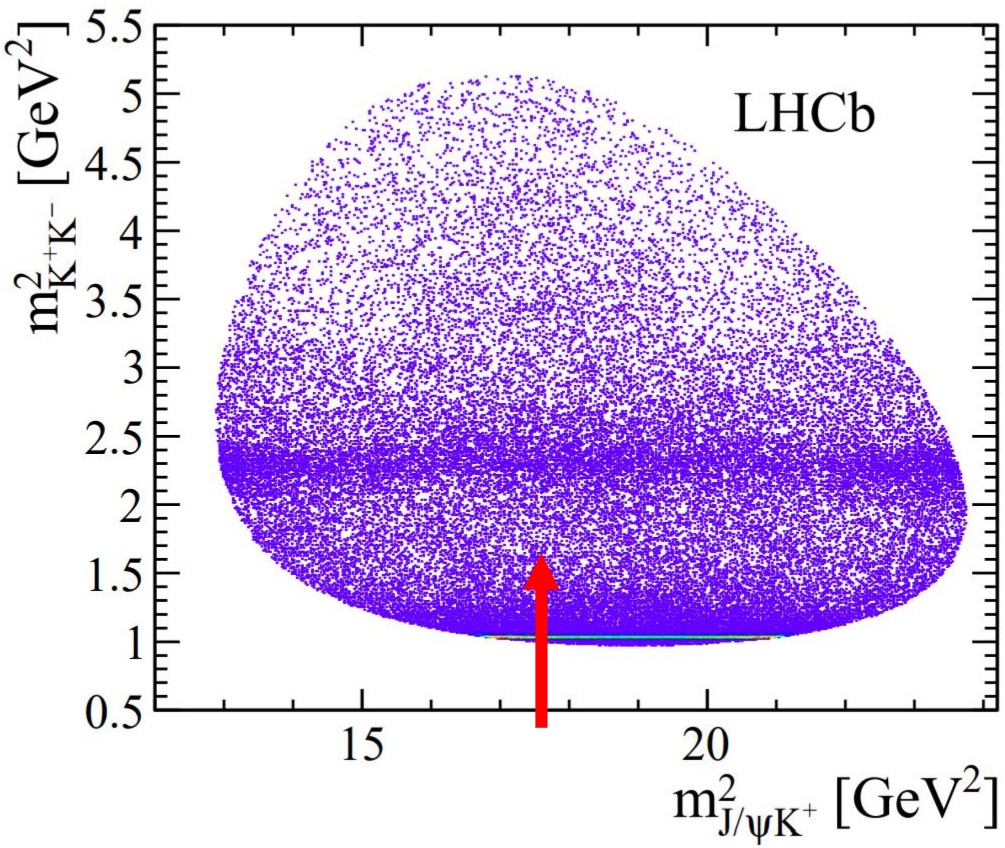
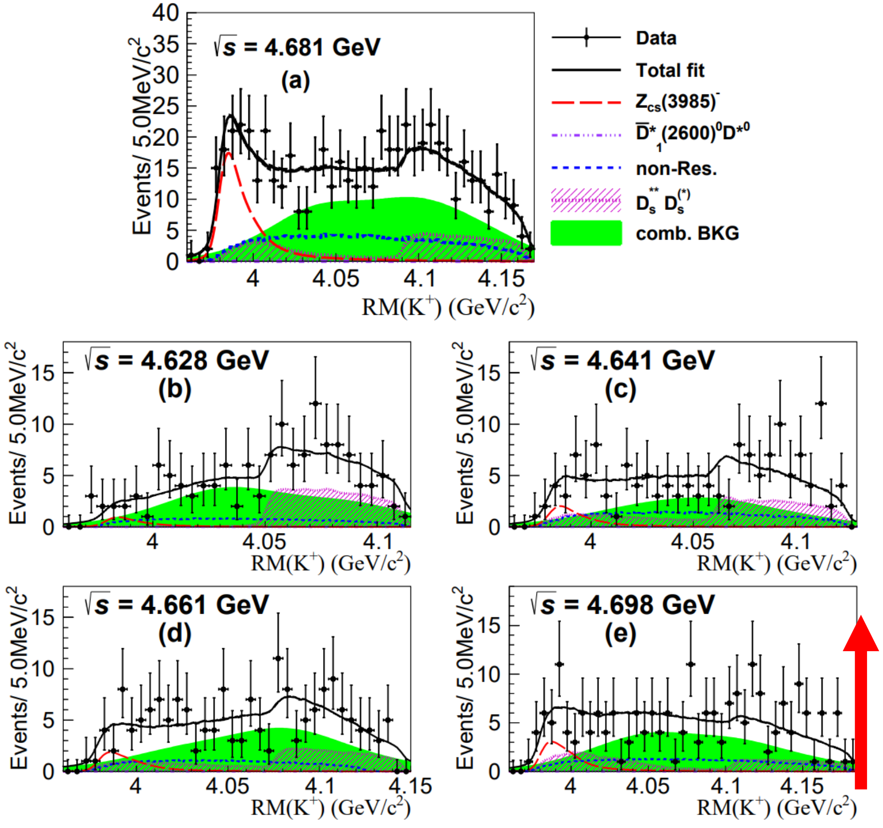


Figure 3: Invariant mass squared of K^+K^- versus $J/\psi K^+$ for $B_s^0 \to J/\psi K^+K^-$ candidates within ± 15 MeV of the B_s^0 mass peak. The high intensity $\phi(1020)$ resonance band is shown with a line (light green).

LHCb: 1704.08217: an integrated luminosity of 3 $\mathbf{fb^{-1}}$

Where to search for Kc(4180)



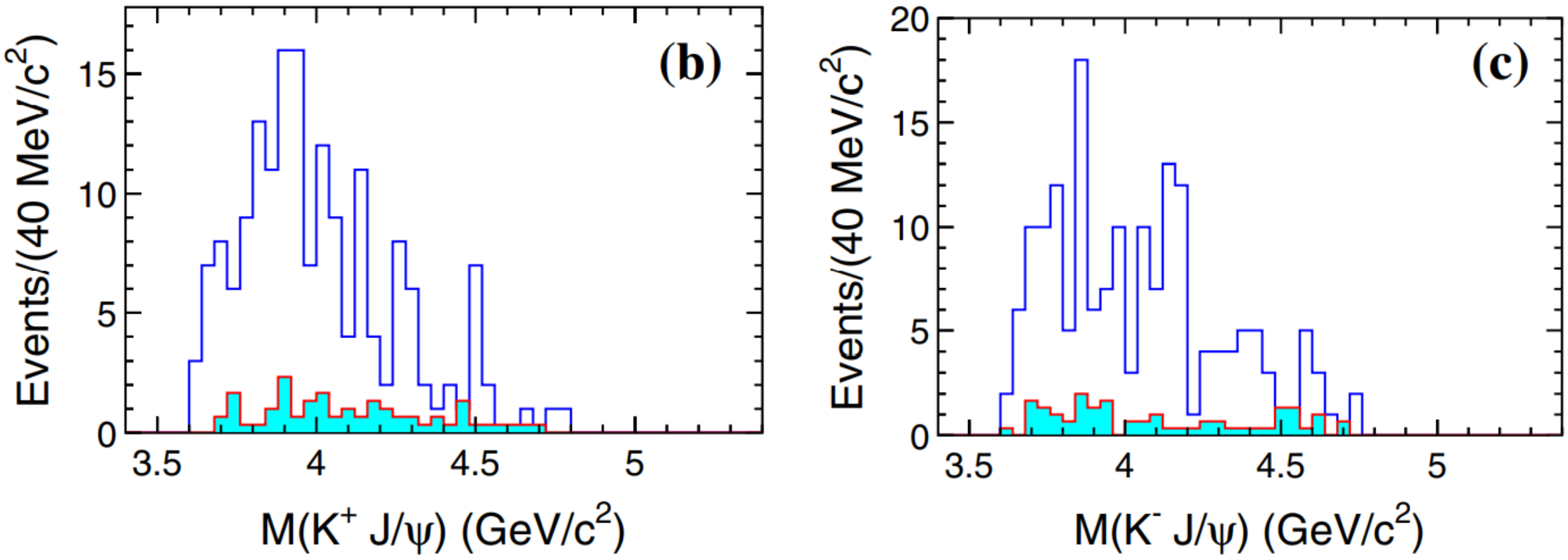
$$e^+e^- \to K D^* \bar{D}_s$$

FIG. 3. Simultaneous unbinned maximum likelihood fit to the K^+ recoil-mass spectra in data at $\sqrt{s}$=4.628, 4.641, 4.661, 4.681 and 4.698 GeV. Note that the size of the $D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ component is consistent with zero.

BESIII: 2011.07855: an integrated luminosity of 3.7 $\mathbf{fb^{-1}}$

Where to search for Kc(4180)

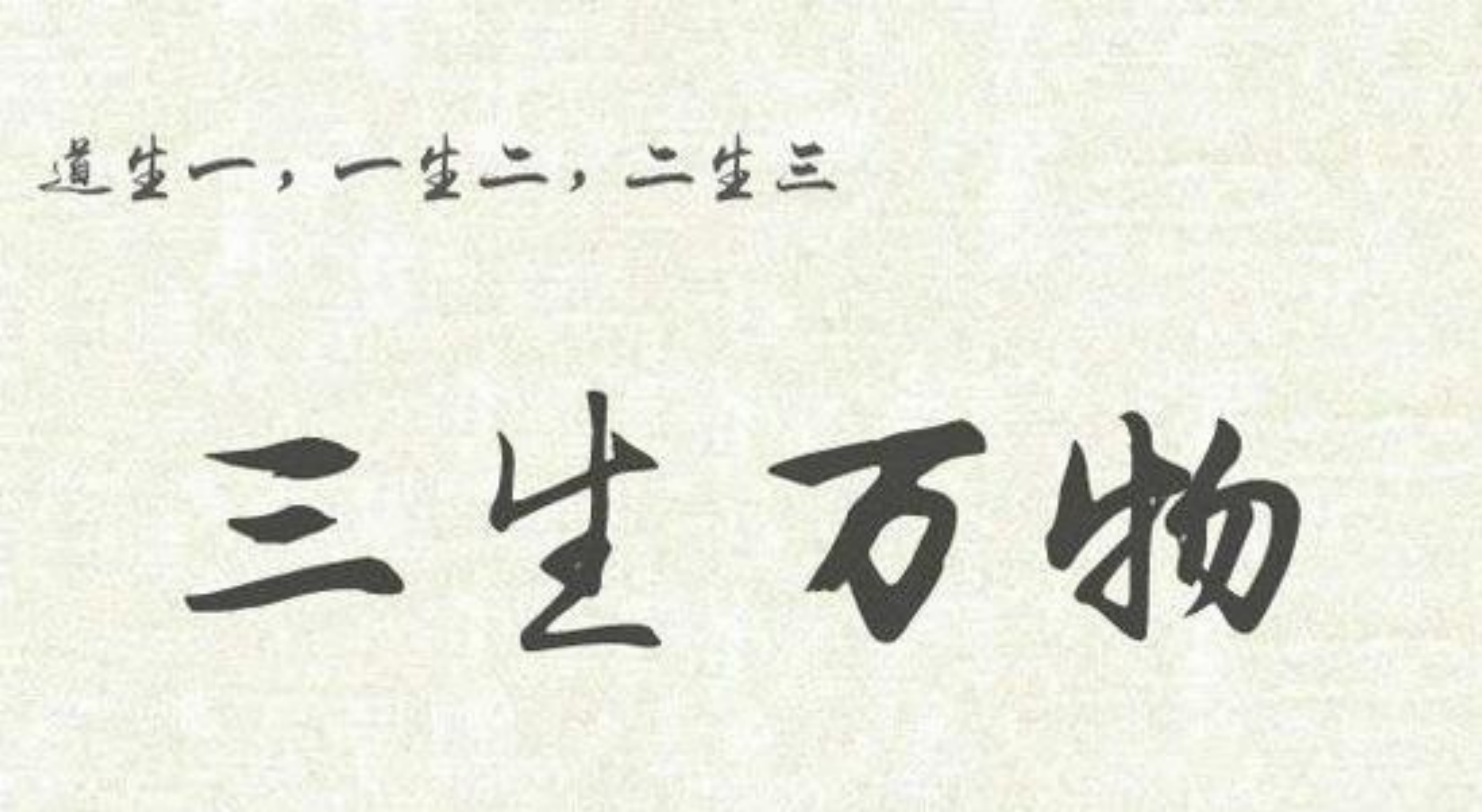
a few pb $\quad (ISR)\ e^+e^- \rightarrow K^+K^-J/\psi \quad 4.4 < M(K^+K^-J/\psi) < 5.5\ \mathrm{GeV}/c^2$



Belle: 1402.6578 : 980 $\mathbf{fb}^{-1}$

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 $DDK, D\overline{D^*}K, D\bar{D}K$ and DDDK states **bind**
- Now we need experimental or lattice QCD confirmations and further theoretical studies on their production and decay mechanisms



Thanks for your attention！

DDK system in finite volume

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

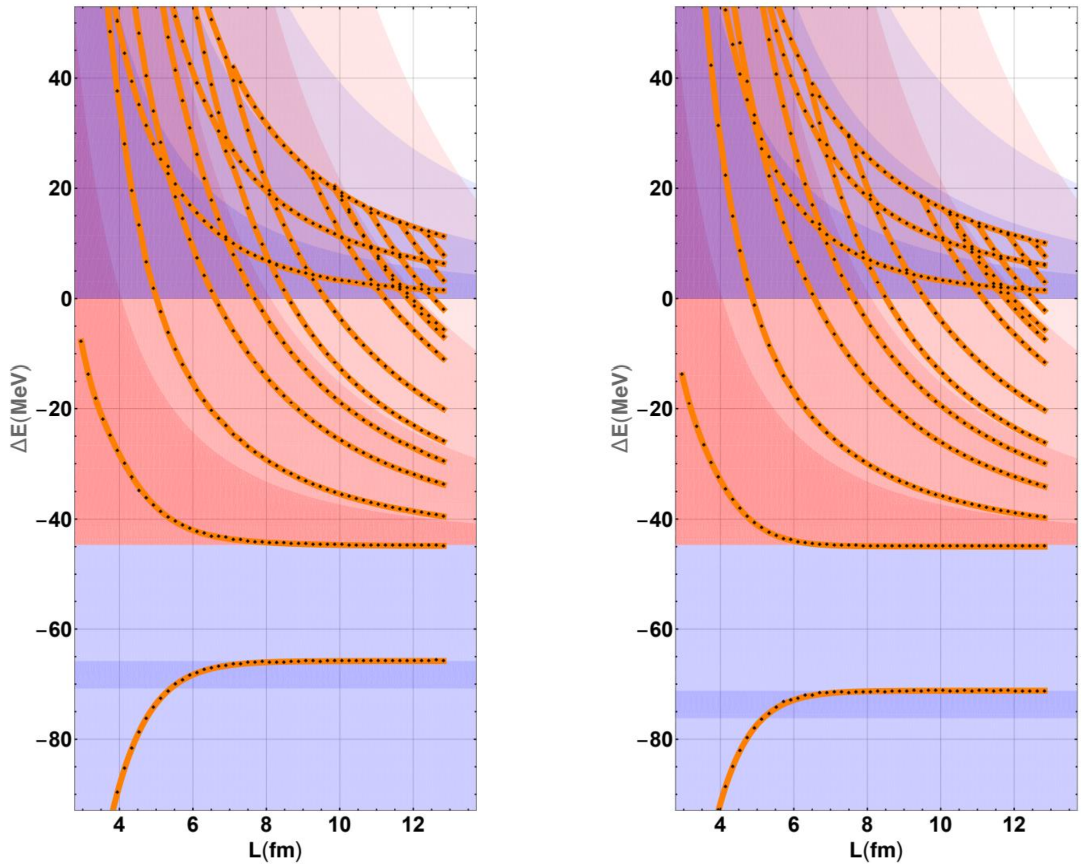


Figure 5: DDK states in finite volume. Left: only the DK interaction is considered. Right: both DK and DD interactions are taken into account. The upper blue regions indicate the case of 3 free particles in finite volume. The red regions indicate the case of free $D^*_{s0}(2317)$ and D. The lower blue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

Magnetic formfactor of Triton—textbook example

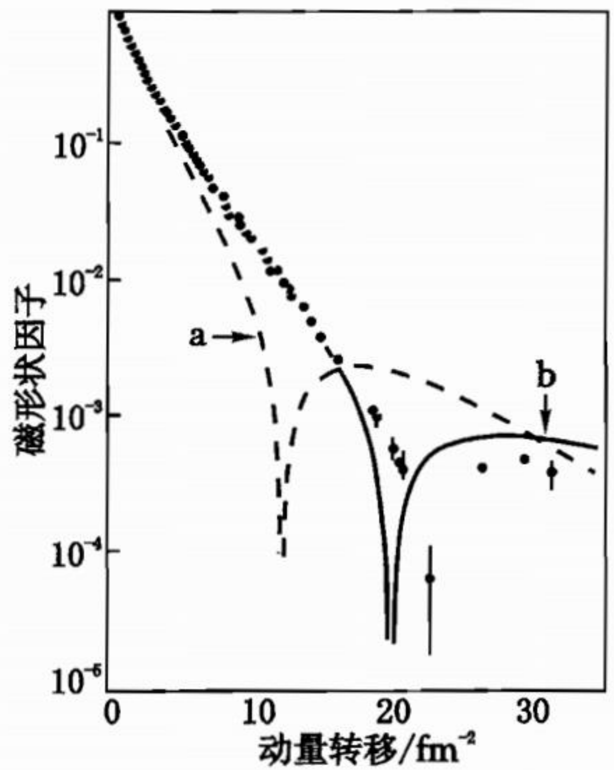


图 8-30 ^{3}H 的磁矩及其理论解释①

a: only nucleon degrees of freedom
b: pion cloud