强子物理中谱学阈值结构问题

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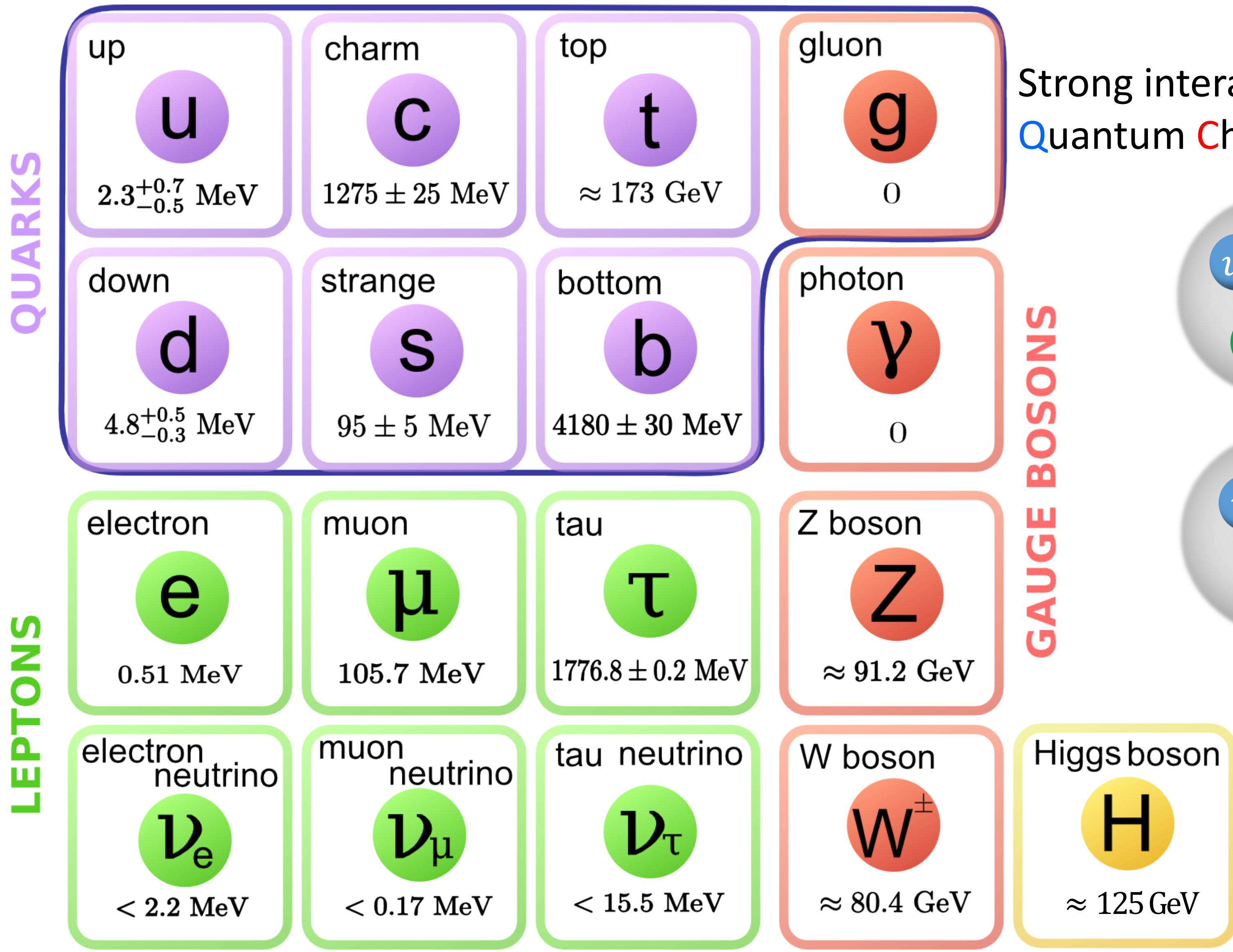
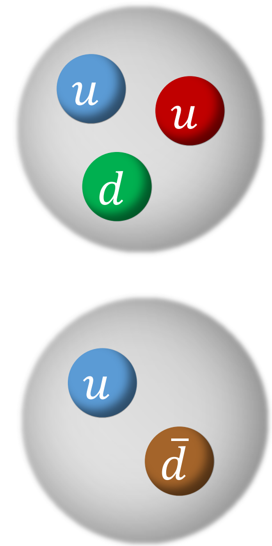
2021年国科大物理科学学院青年委员会研讨会

2021年11月15日

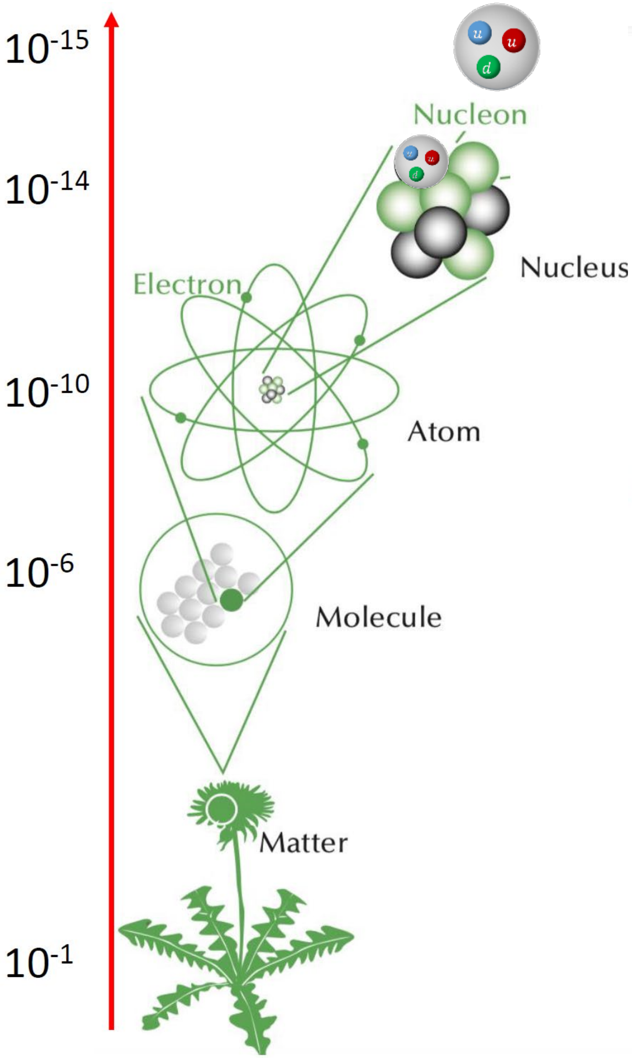
Elementary particles in the Standard Model



Strong interaction:
Quantum ChromoDynamics

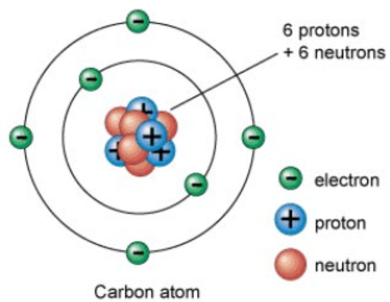


Origin of matter mass: Strong interaction

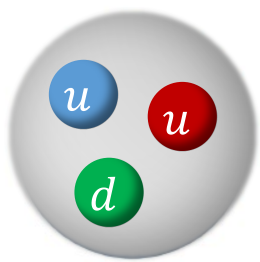


Length scale [m]

$$M_{\text{diamond}} \simeq \sum M_{C\,\text{atom}}$$

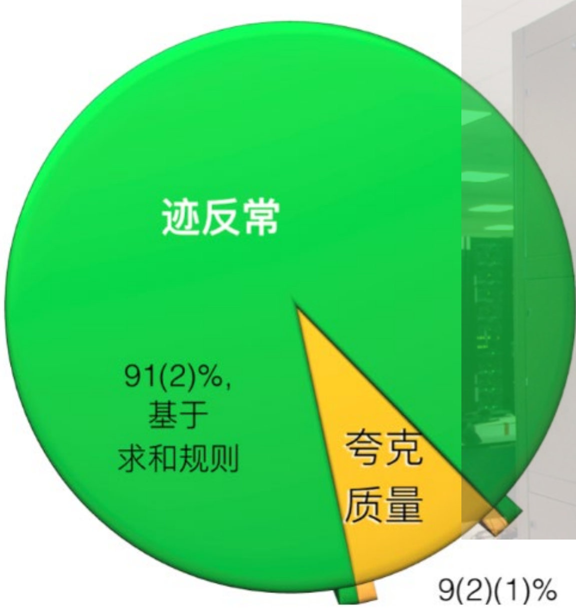


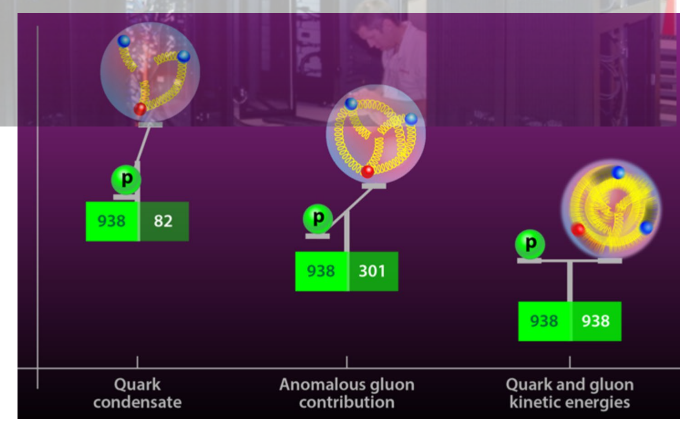
$$M_{C\,\text{atom}} \simeq 6(M_{\text{proton}} + M_{\text{neutron}} + M_{\text{electron}})$$



$$\underbrace{M_{\text{proton}}}_{938\ \text{MeV}} \overset{?}{\simeq} 2m_u + m_d$$

Decomposition of the proton mass

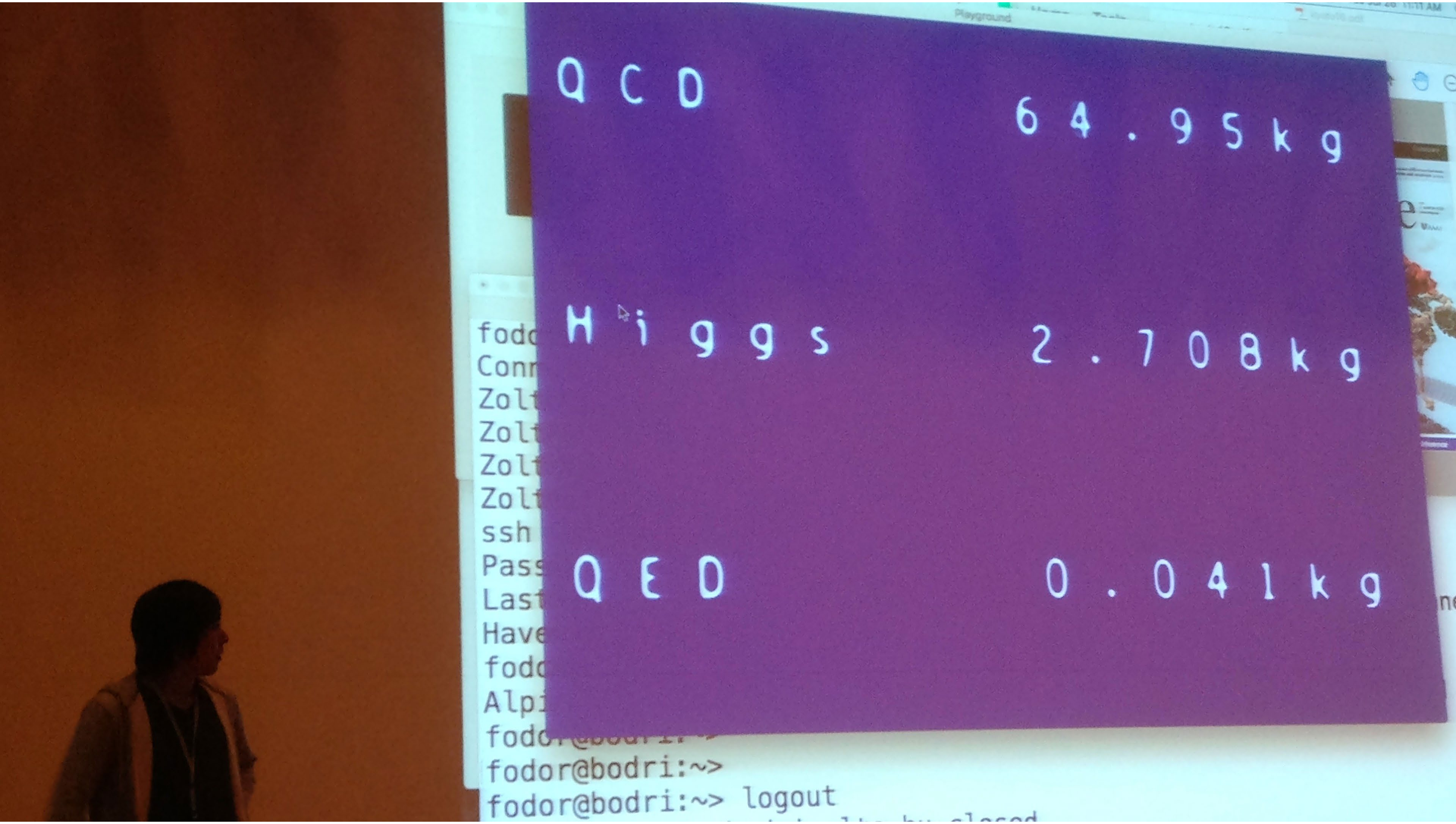




Y.-B. Yang et al., PRL121(2018)212001

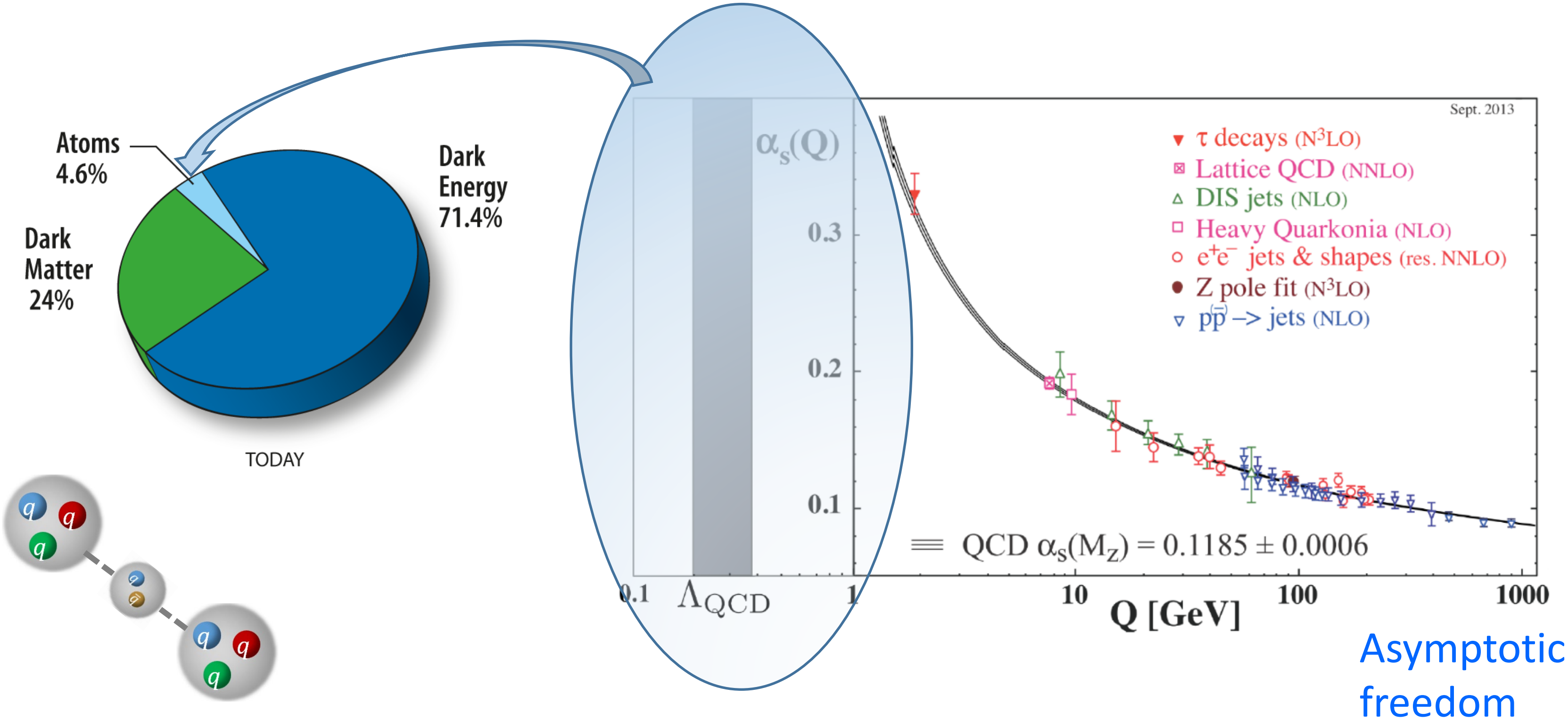
$$\underbrace{M_{\rm proton}}_{938\ \rm MeV} \simeq 100(2m_u + m_d) \simeq \sum_q \sigma_q m_q + 856\ \rm MeV$$

Decomposition of a physicist's weight



Taken at the talk by Fodor at MENU2016

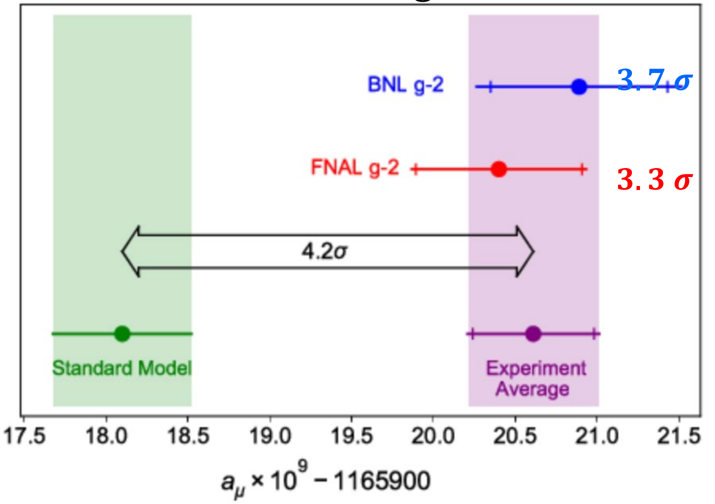
Nonperturbative dynamics



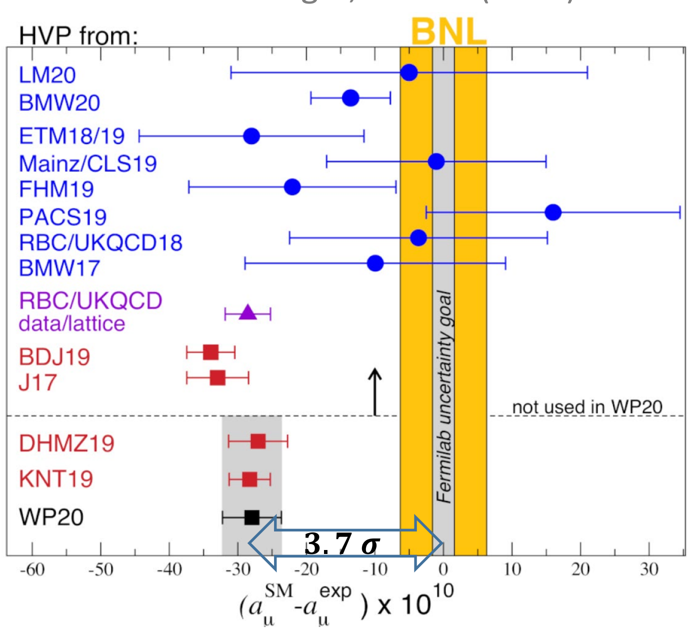
- Nonperturbative: extremely challenging!
- Color confinement: quarks and gluons are confined in hadrons; unsolved problem

Nonperturbative dynamics

Example: the muon $g-2$



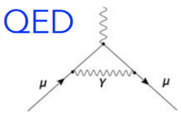
Muon g-2, PRL126(2021)141801

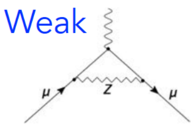


From talk by Luchang Jin

Contributions from known particles: The Standard Model

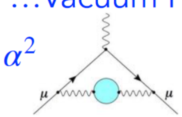
$$a_\mu(\text{SM}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

QED  $+\ldots$ $116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

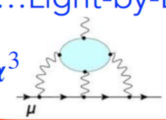
Weak  $+\ldots$ $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

α^2  $+\ldots$ $6845\,(40) \times 10^{-11}$ [0.6%] 0.37 ppm

…Light-by-Light (HLbL)

α^3  $+\ldots$ $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

Numbers from Theory Initiative Whitepaper

Uncertainty dominated by hadronic contributions

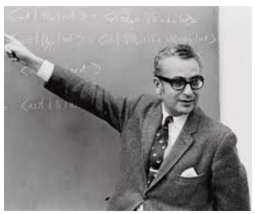
From talk by C. Lehner

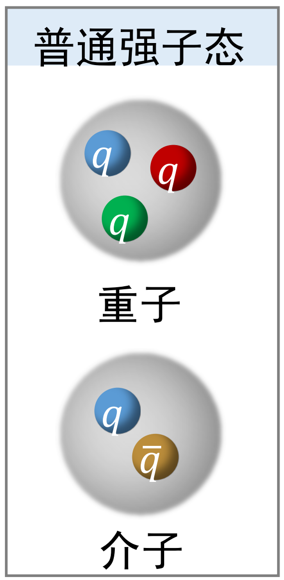
Quarks are confined in hadrons

u ~2 MeV | d ~5 MeV | s ~100 MeV $\ll \Lambda_{QCD} \ll$ c 粲 ~1.3 GeV | b ~4.2 GeV | t ~173 GeV

Light quarks (u, d, s) — Heavy quarks (c, b, t)

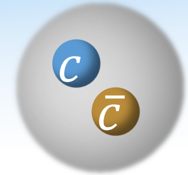
- What forms of matter (hadrons) are allowed by QCD (confinement)?



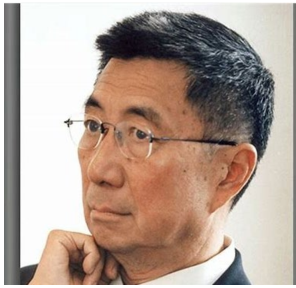


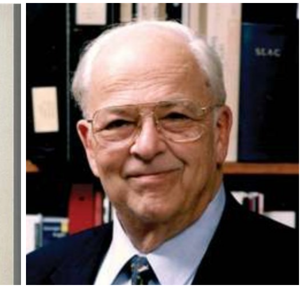
- How do excited hadrons get their masses?
    - Radial excitations?
    - Excitation of light quark-antiquark pairs?
    - Hadron-hadron pairs?

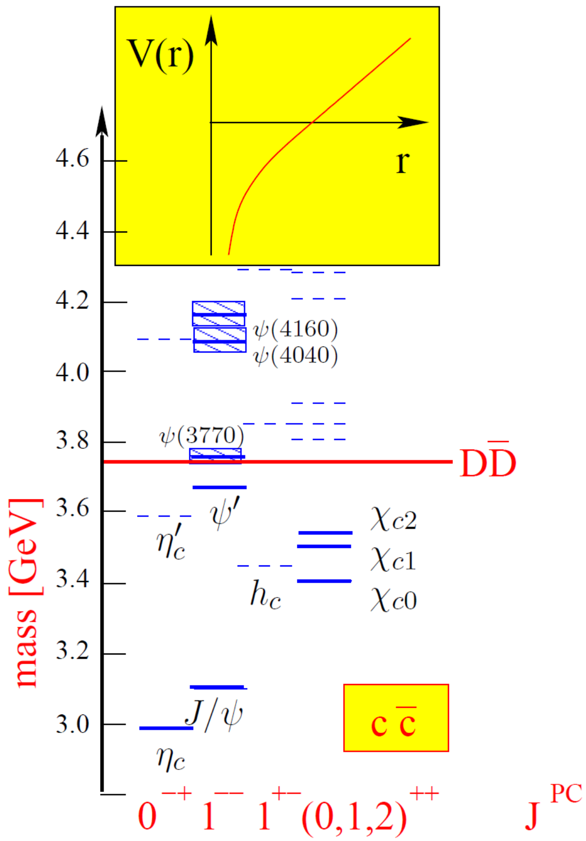
Charmonium

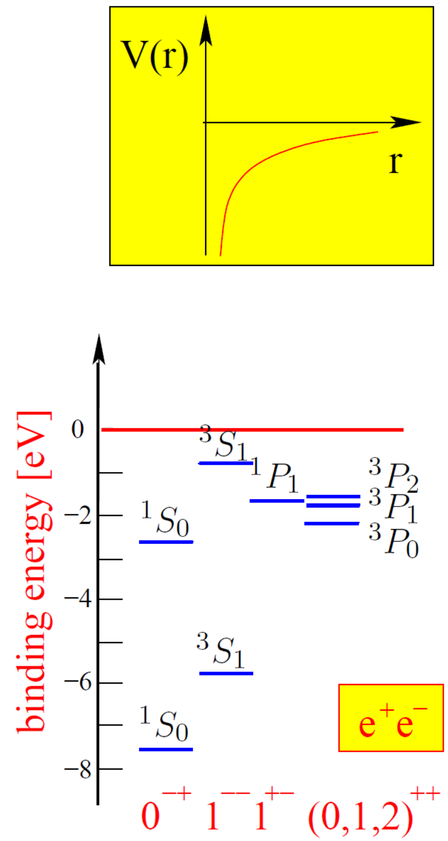


- Meson consisting of a charm quark and an anticharm quark
  - The first charmonium: J/ψ
  - Probing both perturbative and nonperturbative QCD



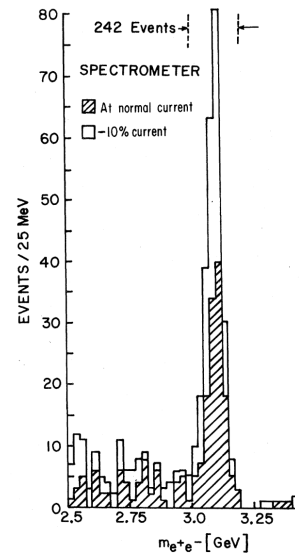




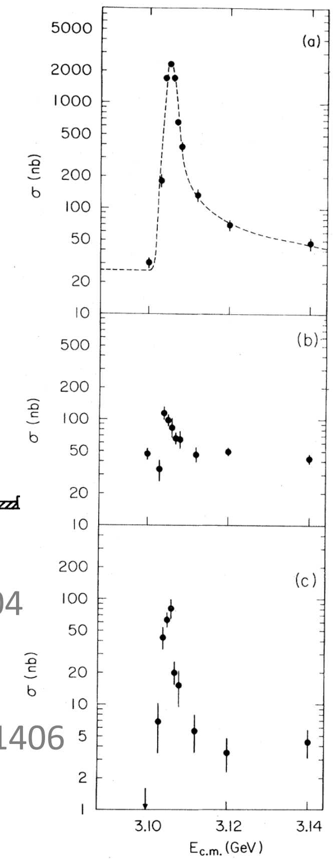


Cornell potential model:
Eichten et al., PRD17(1978)3090

From talk by Hanhart at APS2018

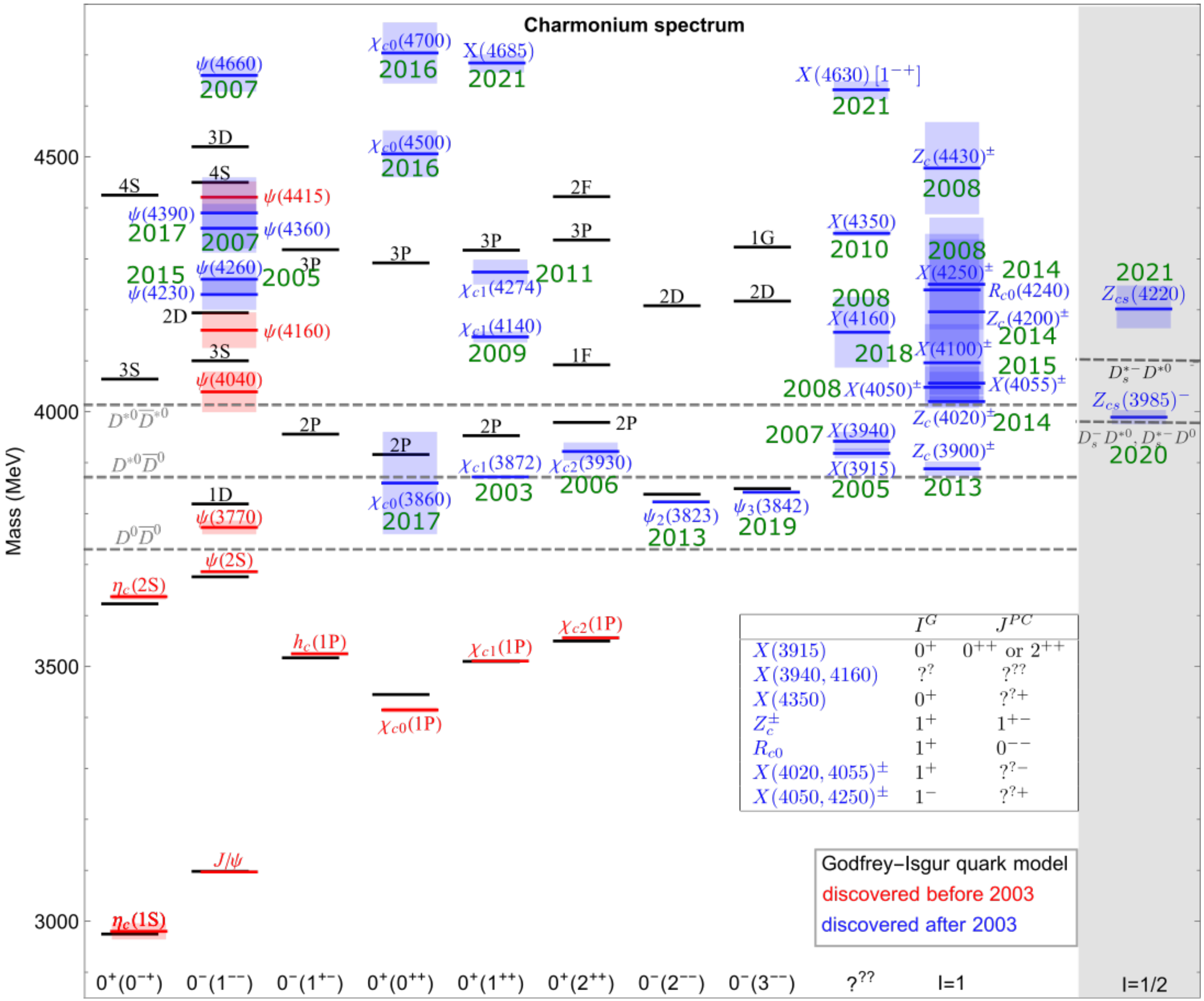


PRL33(1974)1404



PRL33(1974)1406

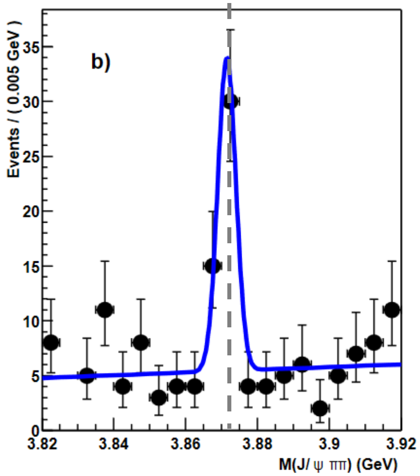
Charmonium(-like) structures: XYZ states



Charmonium-like structures

- X(3872) $D^0\overline{D}^{*0}$ thr.

Belle, PRL91(2003)262001



Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays #2

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

pdf links DOI cite 2,029 citations

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^-$ J/ψ at $\sqrt{s}$ =4.26 GeV #1

BESIII Collaboration • M. Ablikim (Beijing, Inst. High Energy Phys.) et al. (Mar 24, 2013)

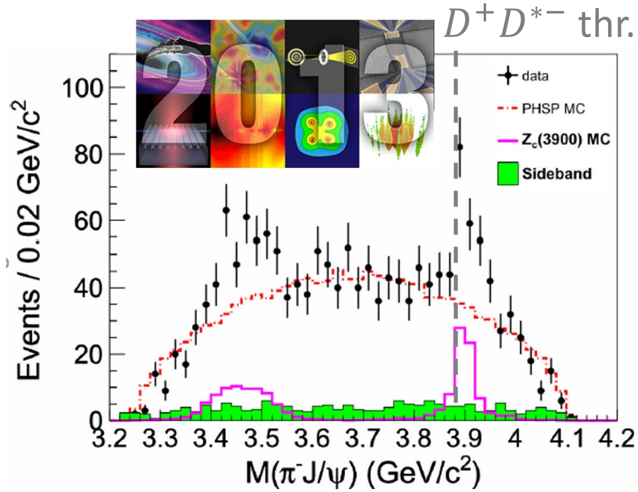
Published in: *Phys.Rev.Lett.* 110 (2013) 252001 • e-Print: 1303.5949 [hep-ex]

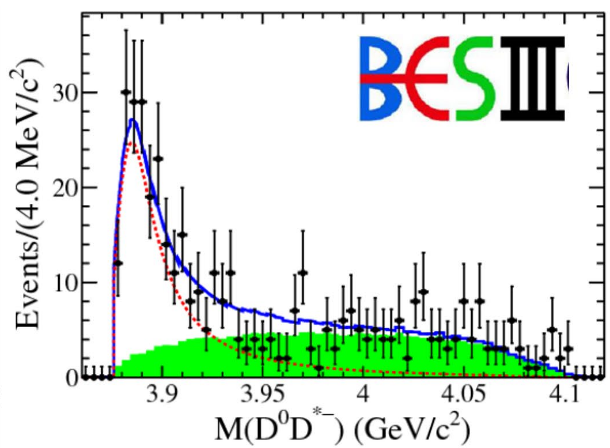
pdf links DOI cite 898 citations

- $Z_c(3900)^{\pm}$

BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002

D^+D^{*-} thr.

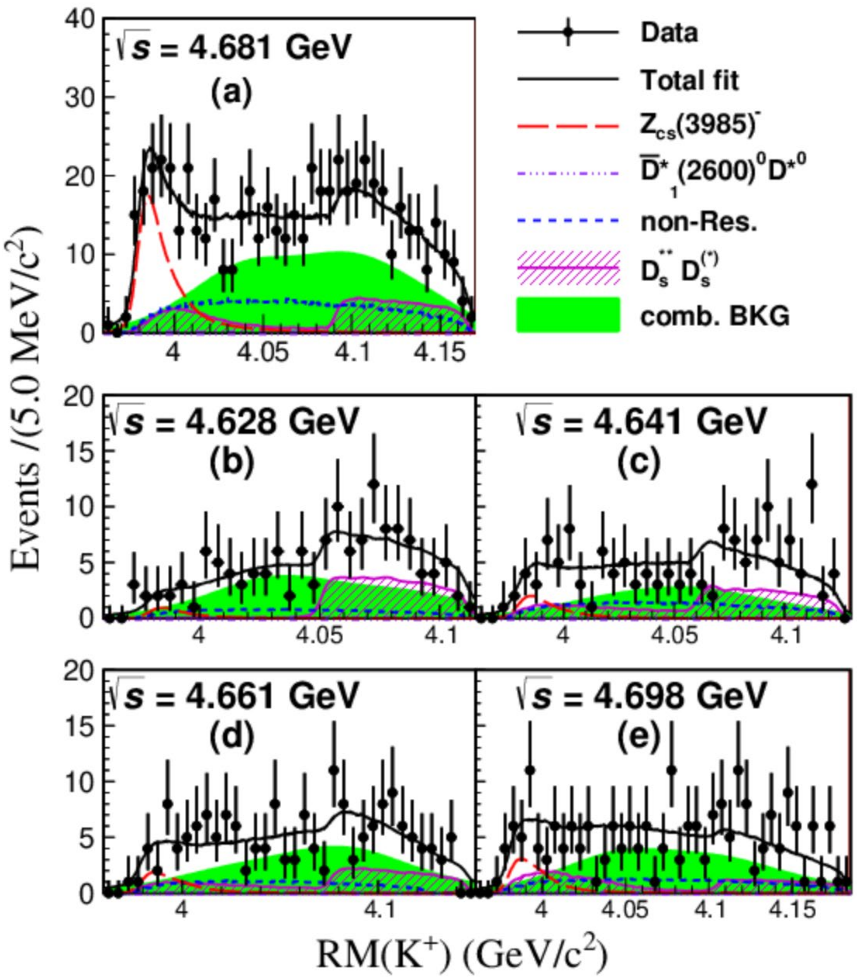




Charmonium-like structures

- $Z_{cs}(3985)^-$

BESIII, PRL126(2021)102001



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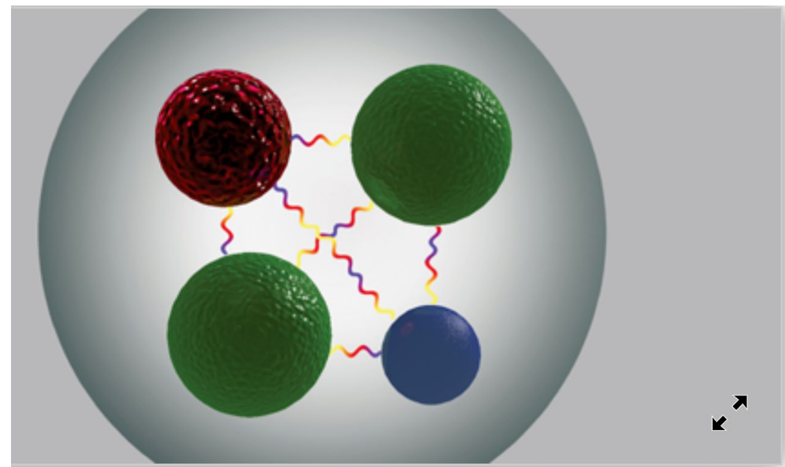
SYNOPSIS

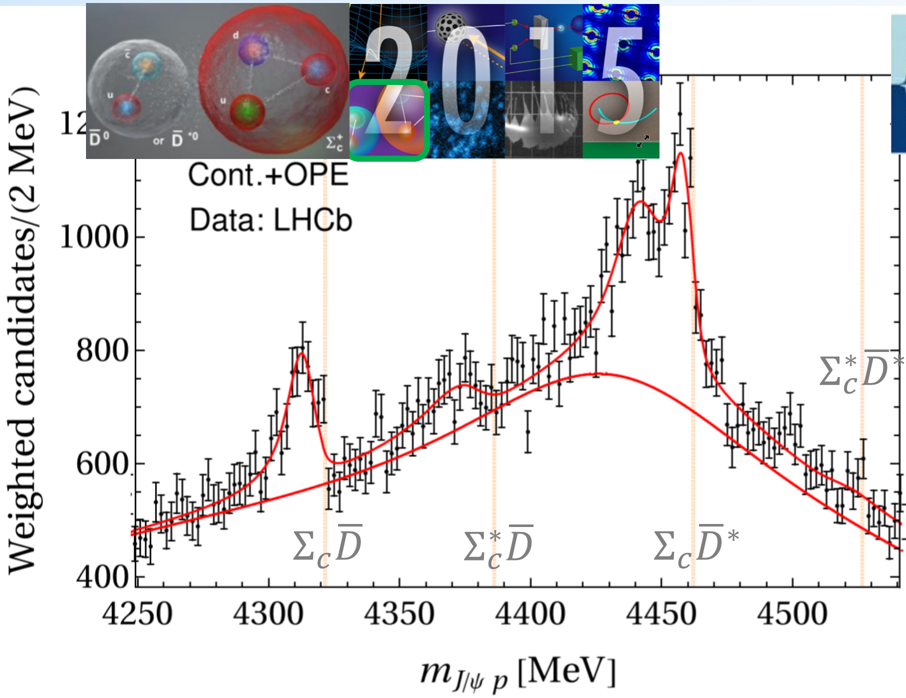
New Tetraquark Spotted in Electron-Positron Collisions

March 11, 2021 • *Physics* 14, s33

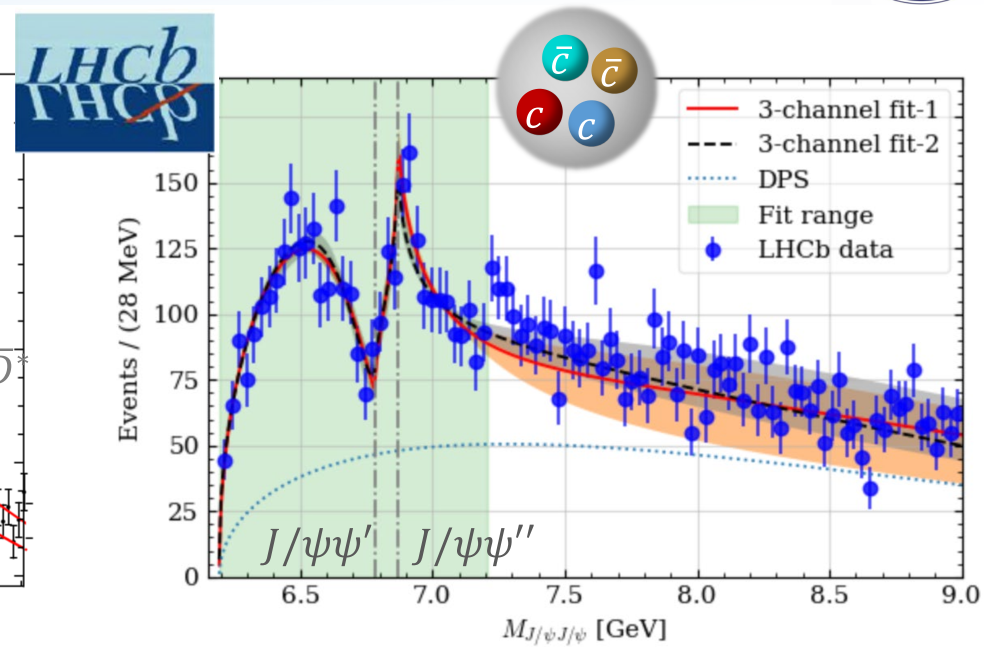


Xiao-Rui Lyu/University of Chinese Academy of Sciences

P_c and double-J/ψ structures



data from LHCb, PRL122 (2019) 222001;
fit from
M.-L. Du, V. Baru, FKG et al., PRL124 (2020) 072001



data from LHCb, Sci.Bull.65 (2020) 1983;
fit from
X.-K. Dong, V. Baru, FKG et al., PRL126 (2021) 132001

Most new hidden-charm structures are near thresholds of a pair of charm hadrons

Why are there so many (near-)threshold structures in heavy-hadron spectrum?

Is there any rule?

What are XYZ?

Einstein:

If A is success in life, I should say the formula is $A = X + Y + Z$. X is work, Y is play, and Z is keeping your mouth shut.

Some recent reviews

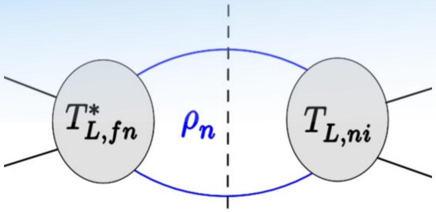
Lots of new hadron structures were found since 2003, a new era:

- H.-X. Chen et al., *The hidden-charm pentaquark and tetraquark states*, Phys. Rept. 639 (2016) 1
- R. F. Lebed, R. E. Mitchell, E. Swanson, *Heavy-quark QCD exotic*a, Prog. Part. Nucl. Phys. 93 (2017)143
- A. Esposito, A. Pilloni, A. D. Polosa, *Multiquark resonances*, Phys. Rept. 668 (2017) 1.
- FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, *Hadronic molecules*, Rev. Mod. Phys. 90 (2018) 015004
- S. L. Olsen, T. Skwarnicki, *Nonstandard heavy mesons and baryons: Experimental evidence*, Rev. Mod. Phys. 90 (2018) 015003
- Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu, S.-L. Zhu, Pentaquark and tetraquark states, Prog. Part. Nucl. Phys. 107 (2019) 237
- N. Brambilla et al., *The XYZ states: experimental and theoretical status and perspectives*, Phys. Rept. 873 (2020) 154
- FKG, X.-H. Liu, S. Sakai, *Threshold cusps and triangle singularities in hadronic reactions*, Prog. Part. Nucl. Phys. 112 (2020) 103757

Threshold structures

X.-K. Dong, FKG, B.-S. Zou, Phys.Rev.Lett.126 (2021) 152001

(Near-)threshold behavior



- Unitarity: there is always a cusp at an S-wave threshold
- Consider effective-range expansion: $$f_0^{-1}(k) = \frac{1}{a_0} + \frac{1}{2} r_0 k^2 - ik + \mathcal{O}\left(\frac{k^4}{\beta^4}\right)$$

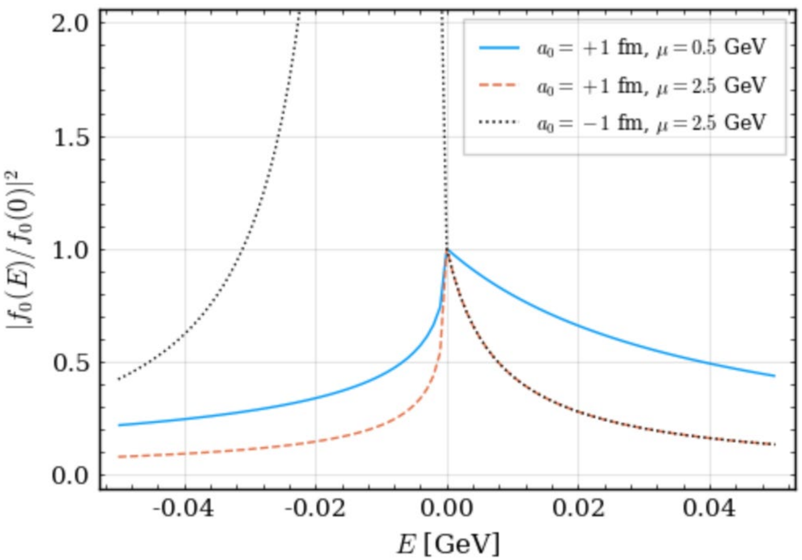
a_0: S-wave scattering length; negative for repulsion or attraction w/ a bound state
positive for attraction w/o bound state

Very close to threshold, then scattering length approximation: $f_0^{-1}(E) = \frac{1}{a_0} - i\sqrt{2\mu E}$

$$|f_0(E)|^2 = \begin{cases} \dfrac{1}{1/a_0^2 + 2\mu E} & \text{for } E \geq 0 \\ \dfrac{1}{\left(1/a_0 + \sqrt{-2\mu E}\right)^2} & \text{for } E < 0 \end{cases}$$

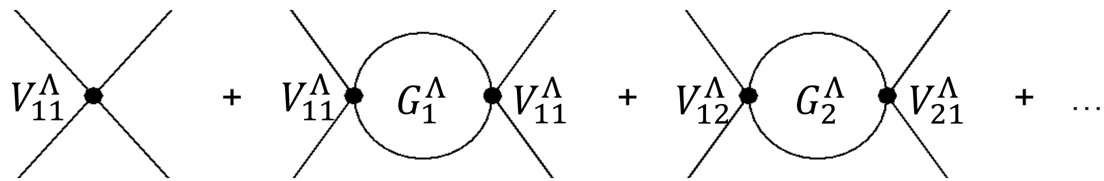
- Cusp at threshold (E=0)
- Maximal at threshold for positive a_0 (attraction)
- Half-maximum width: $\frac{2}{\mu a_0^2}$;

  virtual state pole at $E_{\text{virtual}} = -1/(2\mu a_0^2)$
- Strong interaction, a_0 becomes negative, pole below threshold, peak below threshold



Coupled channels

- Full threshold structure needs to be measured in a lower channel ⇨ coupled channels
- Consider a two-channel system, construct a nonrelativistic effective field theory (NREFT)
  - ➢ Energy region around the higher threshold, Σ_2
  - ➢ Expansion in powers of $E = \sqrt{s} - \Sigma_2$
  - ➢ Momentum in the lower channel can also be expanded



- NREFT at leading order

$$T(E) = 8\pi\Sigma_2 \begin{pmatrix} -\frac{1}{a_{11}} + ik_1 & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & -\frac{1}{a_{22}} - \sqrt{-2\mu_2 E - i\epsilon} \end{pmatrix}^{-1}$$

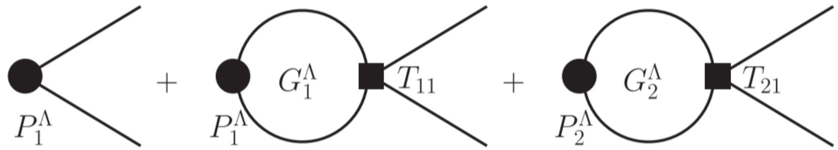
Nonanalyticity only from here

Effective scattering length with open-channel effects becomes complex, $\mathrm{Im}\,\frac{1}{a_{22,\text{eff}}} \leq 0$

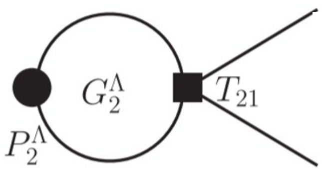
$$T_{22}(E) = -\frac{8\pi}{\Sigma_2}\left[\frac{1}{a_{22,\text{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}$$

NREFT at LO

- Consider a production process, must go through final-state interaction (unitarity)



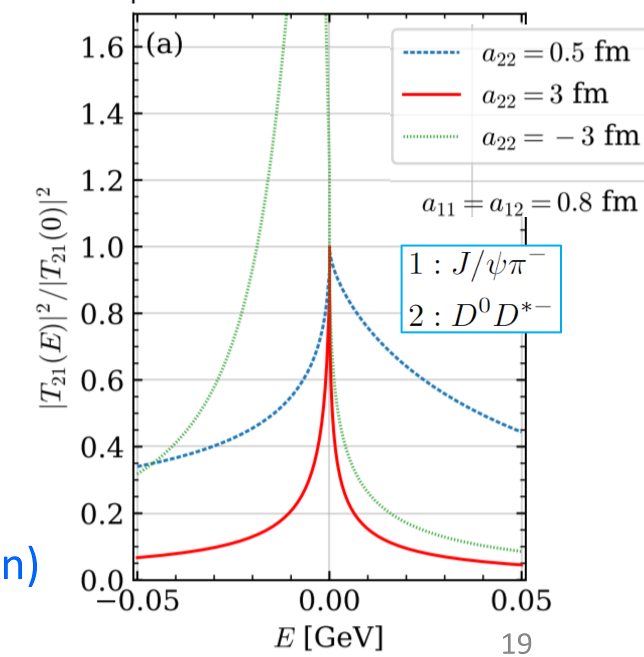
- All nontrivial energy dependence are contained in $T_{11}(E)$ and $T_{21}(E)$
- Case-1: dominated by $T_{21}(E)$,



$$T_{21}(E) = \frac{-8\pi\Sigma_2}{a_{12}(1/a_{11} - ik_1)}\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}.$$

$$|T_{21}(E)|^2 \propto |T_{22}(E)|^2 \propto$$

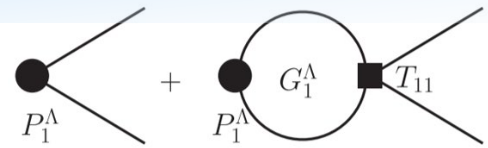
$$\begin{cases} \left[\left(\mathrm{Re}\,\frac{1}{a_{22,\mathrm{eff}}}\right)^2 + \left(\mathrm{Im}\,\frac{1}{a_{22,\mathrm{eff}}} - \sqrt{2\mu E}\right)^2\right]^{-1} & \text{for } E \geq 0 \\ \left[\left(\mathrm{Im}\,\frac{1}{a_{22,\mathrm{eff}}}\right)^2 + \left(\mathrm{Re}\,\frac{1}{a_{22,\mathrm{eff}}} + \sqrt{-2\mu E}\right)^2\right]^{-1} & \text{for } E < 0 \end{cases}$$



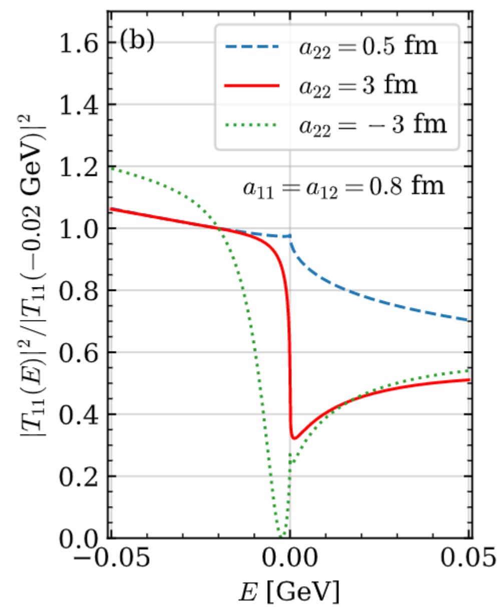
- ➢ Cusp at threshold (E=0)
- ➢ Maximal at threshold for positive $\mathrm{Re}(a_{22,\mathrm{eff}})$ (attraction)
- ➢ Peaking at pole for negative $\mathrm{Re}(a_{22,\mathrm{eff}})$

NREFT at LO

- Case-2: dominated by $T_{11}(E)$



$$T_{11}(E) = \frac{-8\pi\Sigma_2\left(\frac{1}{a_{22}} - i\sqrt{2\mu_2 E}\right)}{\left(\frac{1}{a_{11}} - i\,k_1\right)\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]}$$



Poles in complex momentum plane:

$(0.37 - i0.08)$GeV

$(0.04 - i0.08)$GeV

$(-0.09 - i0.08)$GeV

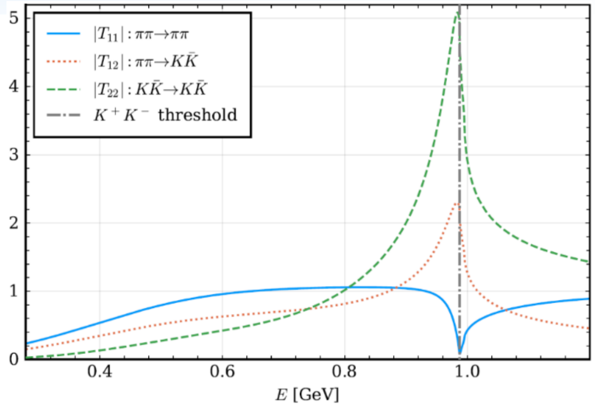
- Cusp at threshold (E=0)
- One pole and one zero
- For strongly interacting channel-2 (large a_{22}), there must be a dip around threshold
- Abrupt drop if there is a nearby pole

- More complicated line shape if both channels are important for the production

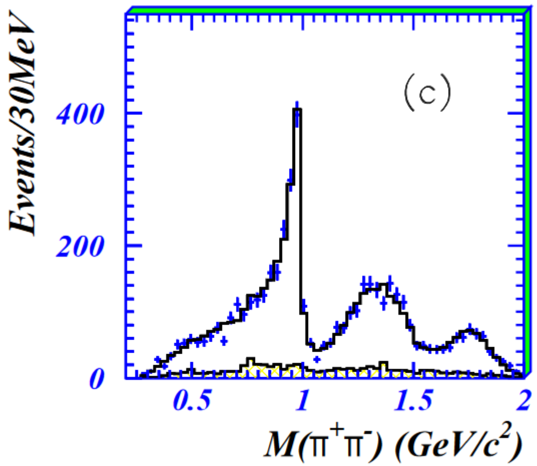
Phenomenology

- T-matrix for $\pi\pi$ and $K\bar{K}$ coupled channels

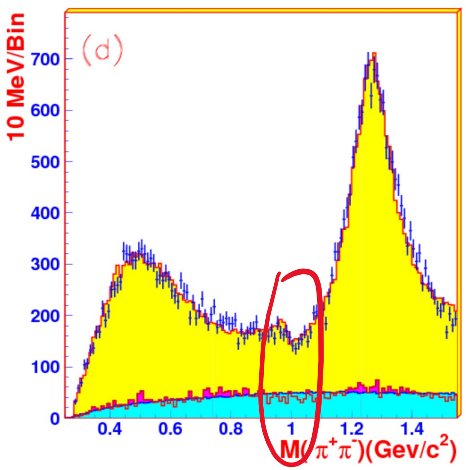
  with the T-matrix from
  L.-Y. Dai, M. R. Pennington, PRD90(2014)036004



- $f_0(980)$ in $J/\psi \to \phi\pi^+\pi^-$ and $J/\psi \to \omega\pi^+\pi^-$ Channels: $\pi\pi$ and $K\bar{K}$



BES, PLB607(2005)243



BES, PLB598(2004)149

Driving channel: $K\bar{K}$

$J/\psi \to \phi K\bar{K} \to \phi\pi^+\pi^-$

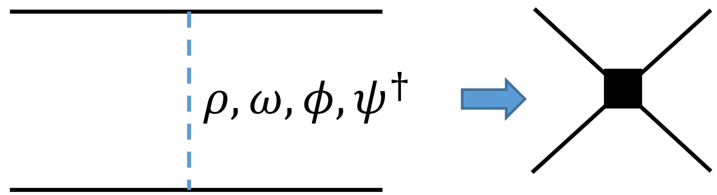
Driving channel: $\pi\pi$

$J/\psi \to \omega\pi\pi \to \omega\pi^+\pi^-$

Model estimate of near-th. interactions

- Constant contact terms saturated by light-vector-meson exchange, similar to VMD in the resonance saturation of the low-energy constants in CHPT

Ecker, Gasser, Pich, de Rafael, NPB321(1989)311

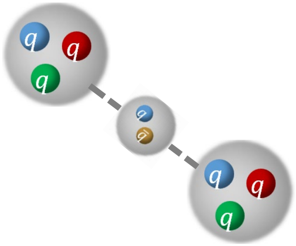


- List of attractive pairs

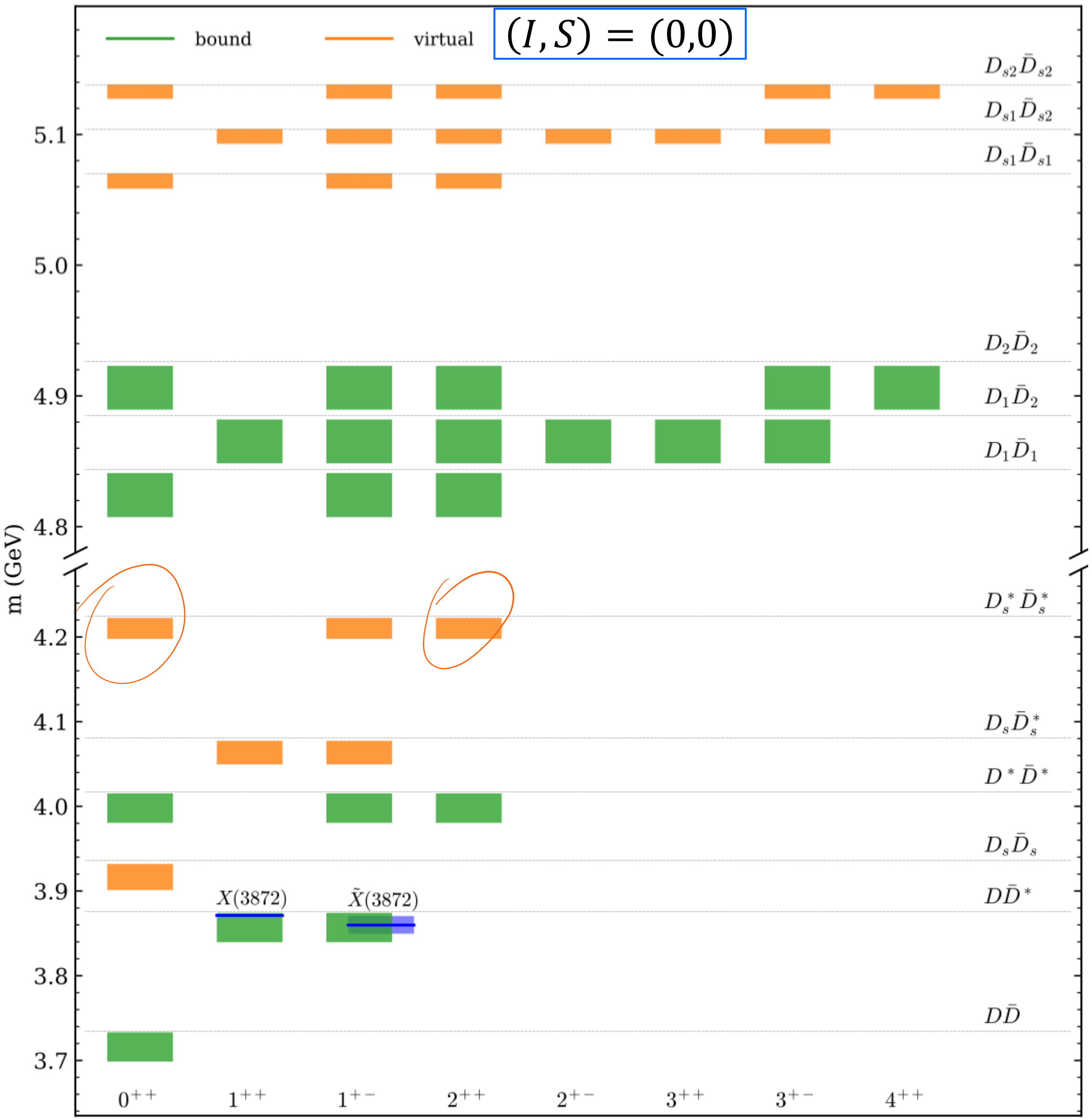
$H\bar{H}$	$D^{(*)}\bar{D}^{(*)}[0,1^\dagger]$;	$D_s^{(*)}\bar{D}^{(*)}$ $[\frac{1}{2}^\dagger]$;	$D_s^{(*)}\bar{D}_s^{(*)}$ $[0]$
	$X(3872), Z_c(3900,4020)$	$Z_{cs}(3985)$	$X(4140)$
	$Z_b(10610,10650)$		
$\bar{H}T$	$\bar{D}^{(*)}\Xi_c$ $[0]$;	$\bar{D}_s^{(*)}\Lambda_c$ $[0^\dagger]$	
	$P_{cs}(4459)$		
$\bar{H}S$	$\bar{D}^{(*)}\Sigma_c^{(*)}$ $[\frac{1}{2}]$;	$\bar{D}_s^{(*)}\Sigma_c^{(*)}$ $[1^\dagger]$;	$\bar{D}^{(*)}\Xi_c'^{(*)}$ $[0]$;
	$P_c(4312,4440,4457)$		
	$\bar{D}^{(*)}\Omega_c^{(*)}$ $[\frac{1}{2}^\dagger]$		
$T\bar{T}$	$\Lambda_c\bar{\Lambda}_c$ $[0]$;	$\Lambda_c\bar{\Xi}_c$ $[\frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c$ $[0,1]$
$T\bar{S}$	$\Lambda_c\bar{\Sigma}_c^{(*)}$ $[1]$;	$\Lambda_c\bar{\Xi}_c'^{(*)}$ $[\frac{1}{2}]$;	$\Lambda_c\bar{\Omega}_c^{(*)}$ $[0^\dagger]$;
	$\Xi_c\bar{\Sigma}_c^{(*)}$ $[\frac{3}{2}^\dagger, \frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c'^{(*)}$ $[1,0]$;	$\Xi_c\bar{\Omega}_c^{(*)}$ $[\frac{1}{2}]$
$S\bar{S}$	$\Sigma_c^{(*)}\bar{\Sigma}_c^{(*)}$ $[2^\dagger,1,0]$;	$\Sigma_c^{(*)}\bar{\Xi}_c'^{(*)}$ $[\frac{3}{2}^\dagger, \frac{1}{2}]$;	$\Sigma_c^{(*)}\bar{\Omega}_c^{(*)}$ $[0^\dagger]$;
	$\Xi_c'^{(*)}\bar{\Xi}_c'^{(*)}$ $[1,0]$;	$\Xi_c'^{(*)}\bar{\Omega}_c^{(*)}$ $[\frac{1}{2}]$;	$\Omega_c^{(*)}\bar{\Omega}_c^{(*)}$ $[0]$

Hadronic molecules

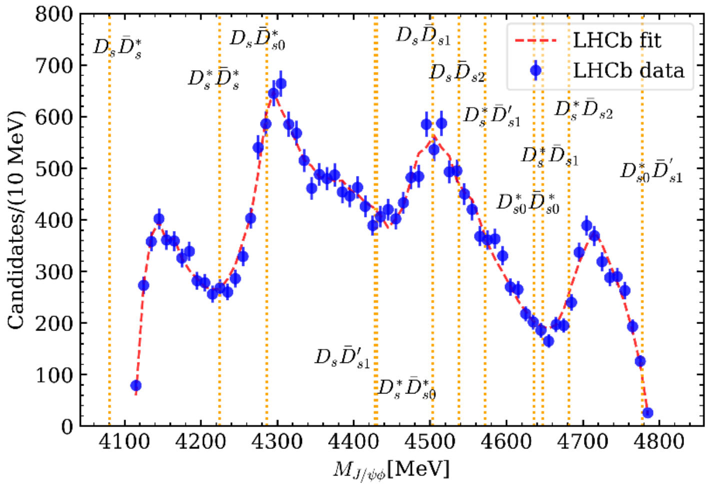
X.-K. Dong, FKG, B.-S. Zou, 《物理学进展》41 (2021) 65 [arXiv:2101.01021]



X(3872) and related states

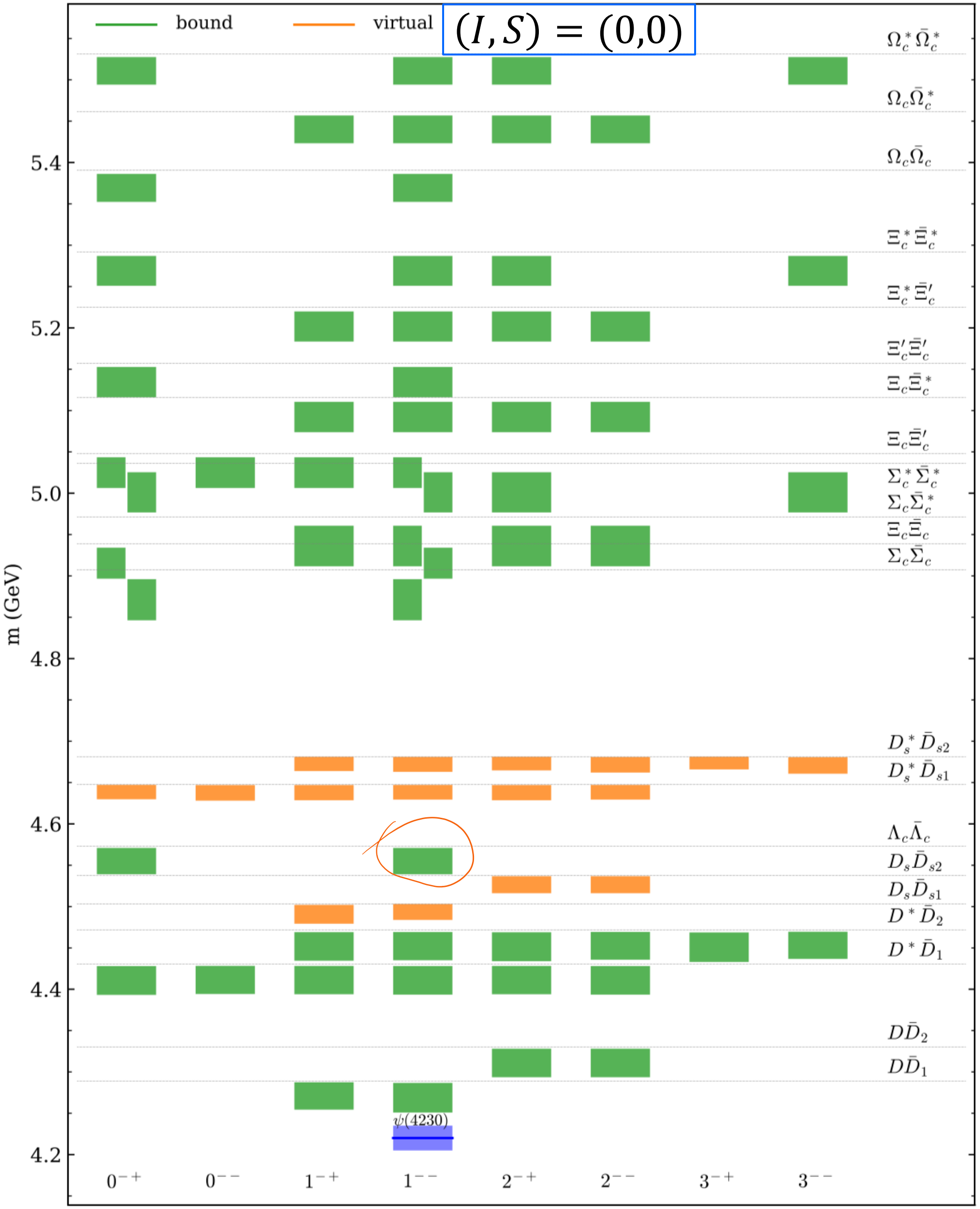


- ✓ $X(3872)$ as a $\bar{D}D^*$ bound state
- ✓ Negative-C parity partner observed by COMPASS PLB783(2018)334
- ✓ $\bar{D}D$ bound state predicted with lattice Prelovsek et al., 2011.02542
- ✓ Evidence for a $D_s^*\bar{D}_s^*$ virtual state in LHCb data?

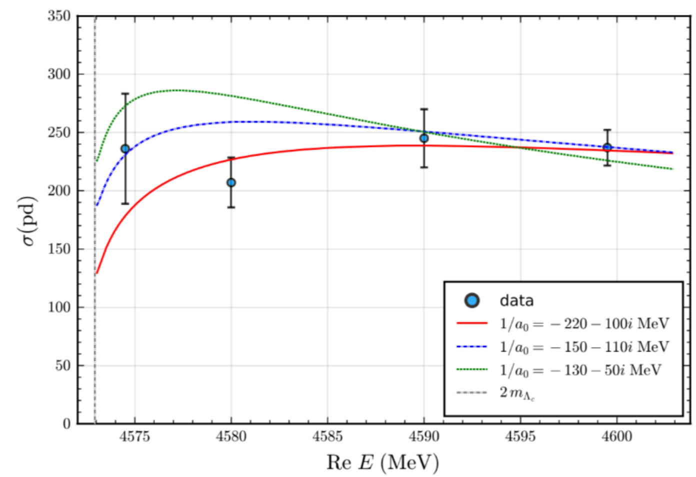


LHCb data, arXiv:2103.01803

Isoscalar vectors and related states



- ✓ Evidence for 1^{--} $\Lambda_c\bar{\Lambda}_c$ bound state in BESIII data
  - Sommerfeld factor
  - Near-threshold pole
  - Different from $Y(4630/4660)$

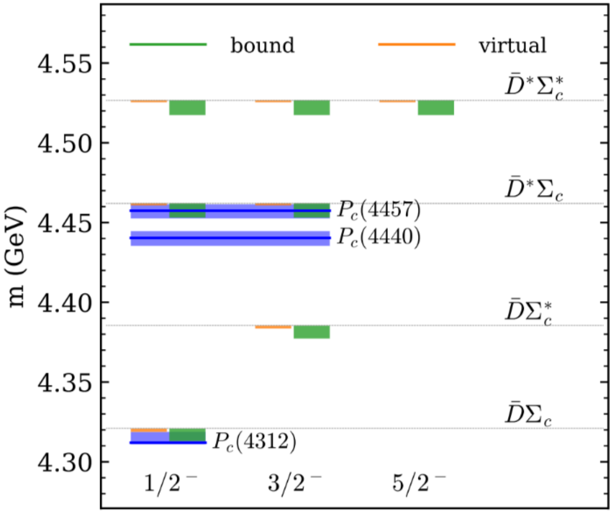


Data taken from BESIII, PRL120(2018)132001

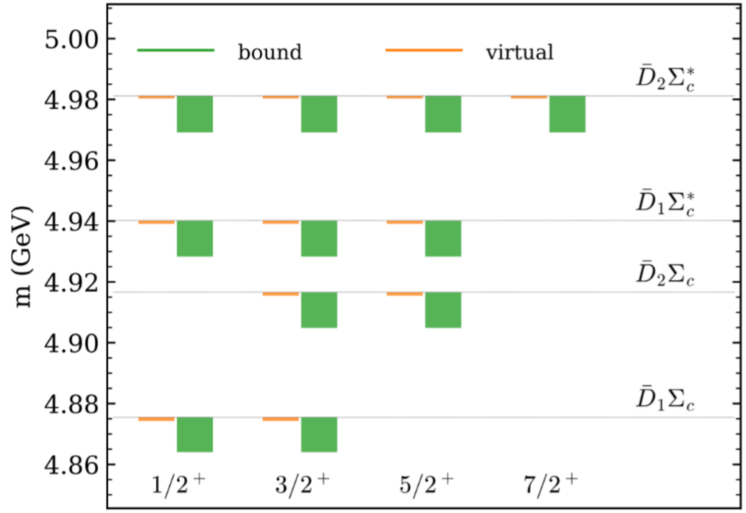
- ✓ Many 1^{--} states in [4.8, 5.6] GeV
- ✓ Opportunities for Super Tau-Charm Factory (STCF)

Hidden-charm pentaquarks

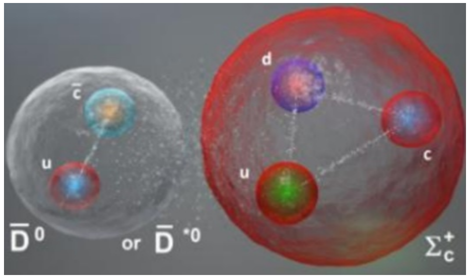
$(I,S) = (1/2,0)$



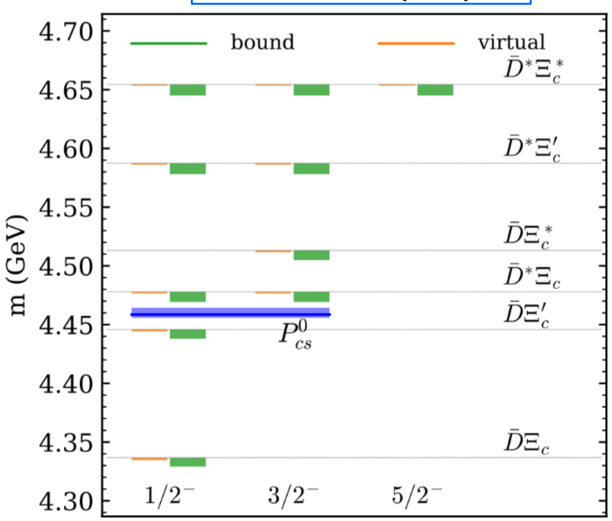
$(I,S) = (1/2,0)$



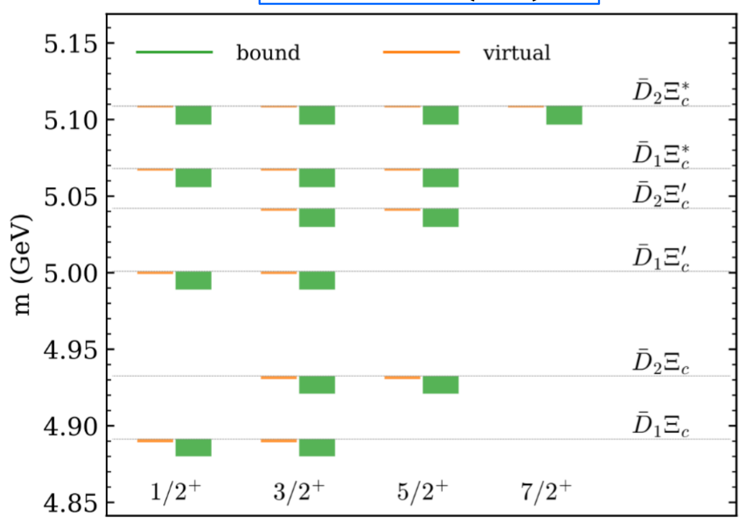
- ✓ The LHCb P_c states as $\bar{D}^{(*)}\Sigma_c$ molecules



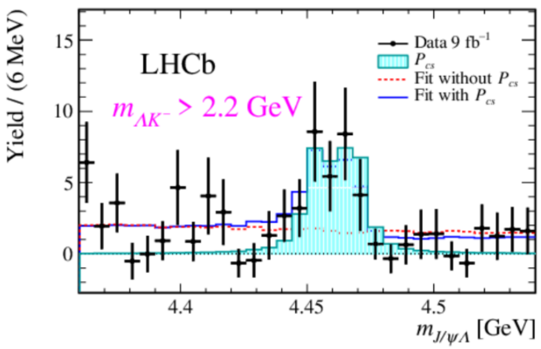
$(I,S) = (0,1)$



$(I,S) = (0,1)$



- ✓ The $P_{cs}(4459)$ could be two $\bar{D}^*\Xi_c$ molecules



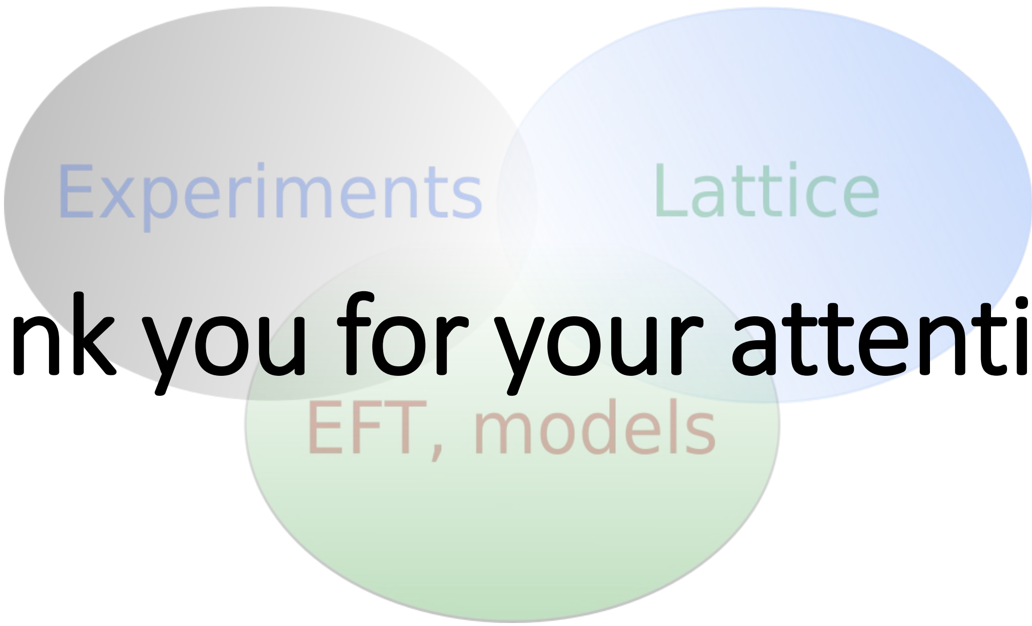
LHCb, 2012.10380

- ✓ Many more molecular states above 4.7 GeV, beyond the current exp. reach

Summary

- Threshold structures (threshold cusp or near-threshold peak) are generally expected for a pair of heavy hadrons with attractive interaction; strong attraction, then hadronic molecules below threshold, otherwise threshold cusps (poles are virtual states)

- Threshold structure: general phenomenon beyond hadron physics for any short-range attractive interaction



Thank you for your attention!