Exotic hadrons with heavy quarks

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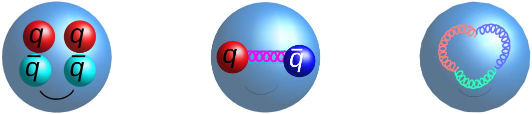
- Exotic hadrons and exotic quantum numbers
- Experimental observations of exotic candidates
- Distinguishing kinematic effects from genuine resonances
- Examples: $X(3872)$ and $Z_c(3900)$

A comprehensive review: H.-X. Chen, W. Chen, X. Liu, S.-L. Zhu, Phys.Rept.639(2016)1

Ordinary and exotic hadrons

- In quark model notation
  - ☞ Ordinary mesons and baryons

  - ☞ Exotic hadrons: multiquark states, hybrids and glueballs



- Hadronic molecules: extended, loosely bound states composed of asymptotic hadrons (distance $\gg$ hadron size), analogues of deutron and other light nuclei

- Once the same quantum numbers, always mix $\Rightarrow$ source of difficulties/confusions

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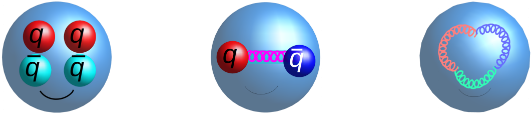

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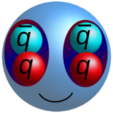

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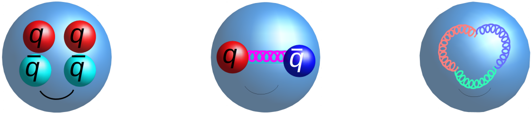

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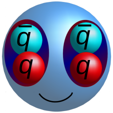

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Exotic quantum numbers: J^{PC}

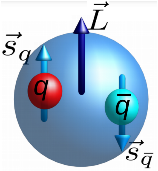
- J^{PC} of regular $q\bar{q}$ meson

  $P = (-1)^{L+1}$

  $C = (-1)^{L+S}$ for mesons without flavor

  L: orbital angular momentum

  $S = (0, 1)$: total spin of q and $\bar{q}$



☞ For $S = 0$, the meson spin $J = L$, one has $P = (-1)^{J+1}$ and $C = (-1)^J$

$$J^{PC} = \text{even}^{-+} \text{ and odd}^{+-}$$

☞ For $S = 1$, one has $P = C = (-1)^{L+1}$.

$$J^{PC} = 1^{--}, \{0, 1, 2\}^{++}, \{1, 2, 3\}^{--}, \ldots$$

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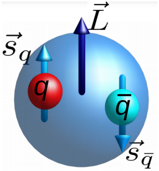

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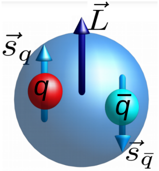

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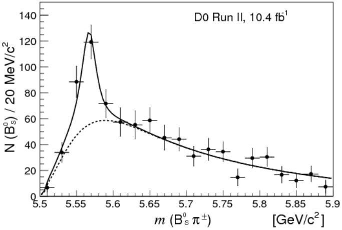
“Explicitly exotic” multiquarks

- Favorite multiquark candidates:
  explicitly flavor exotic: minimal number of quarks ≥ 4
- Example: $X(5568)$ by D0 Collaboration ($p\bar{p}$ collisions) PRL117(2016)022003



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$$\Gamma = \left(21.9 \pm 6.4^{+5.0}_{-2.5}\right) \text{ MeV}$$

$B_s^0\pi^+$: minimal quark contents is $\bar{b}s\bar{d}u$!

☞ immediately, negative result by LHCb LHCb-CONF-2016-004; arXiv:1608.00435
and by CMS CMS-PAS-BPH-16-002

☞ difficulties in all possible structure explanations

Burns, Swanson, arXiv:1603.04366; FKG, Meißner, Zou, Commun.Theor.Phys. 65 (2016) 593

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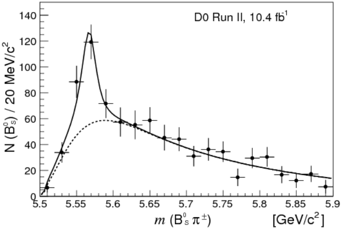

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Less "explicitly exotic" multiquarks: $Z_c^\pm$ and $Z_b^\pm$ with hidden $Q\bar{Q}$

- $Z_c^\pm$, $Z_b^\pm$: charged structures in heavy quarkonium mass region, $Q\bar{Q}\bar{d}u, Q\bar{Q}\bar{u}d$
  $Z_c(3900)$, $Z_c(4020)$, $Z_c(4200)$, $Z_c(4430)$, ... talks on Belle, BESIII, LHCb
- $Z_b(10610)$ and $Z_b(10650)$: Belle, arXiv:1105.4583; PRL108(2012)122001
  observed in $\Upsilon(10860) \to \pi^\mp[\pi^\pm\Upsilon(1S, 2S, 3S)/h_b(1P, 2P)]$

  also in $\Upsilon(10860) \to \pi^\mp[B^{(*)}\bar{B}^*]^\pm$ Belle, arXiv:1209.6450; PRL116(2016)212001

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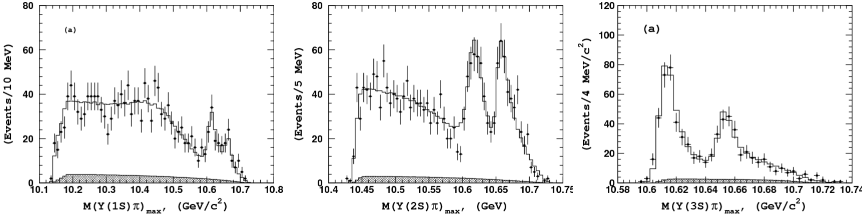

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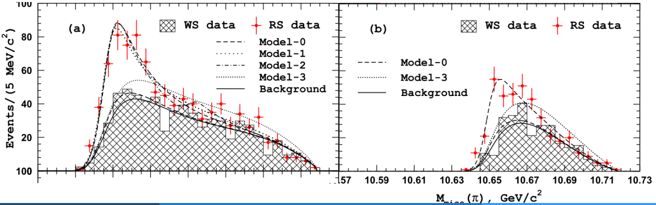
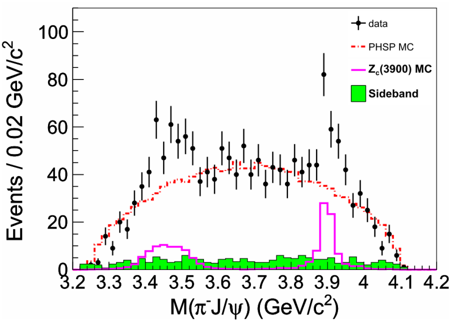
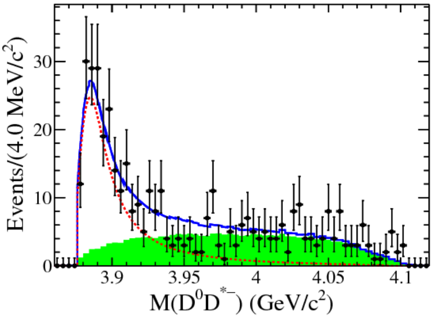


$Z_c^\pm$ and $Z_b^\pm$ with **hidden** $Q\bar{Q}$ (II)

- $Z_c(3900/3885)^\pm$: structure around 3.9 GeV seen in $J/\psi\pi$ by BESIII and Belle in $Y(4260) \to J/\psi\pi^+\pi^-$, BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002
  and in $D\bar{D}^*$ by BESIII in $Y(4260) \to \pi^\pm(D\bar{D}^*)^\mp$ BESIII, PRD92(2015)092006

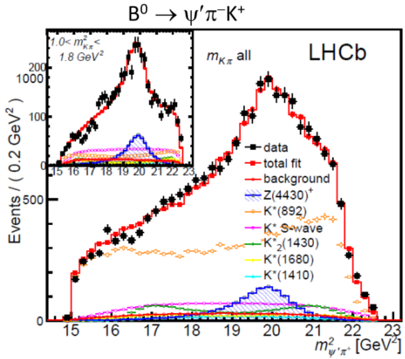




- can be described by the same state Aldaladejo et al., PLB755(2016)337

$P_c(4380, 4450)$: pentaquark-like with hidden $c\bar{c}$ LHCb, PRL115(2015)072001

PRL 112, 222002 (2014)



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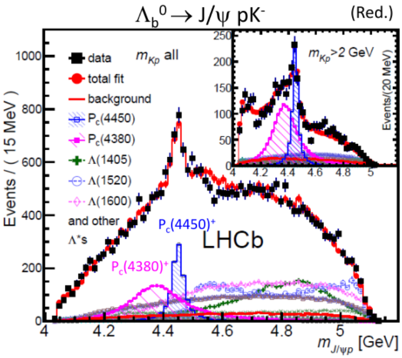

State	Mass (MeV)	Width (MeV)	Fit frac. (%)	Sig.
$Z_c(4430)^+$	$4475 \pm 7^{+15}_{-25}$	$172 \pm 13^{+37}_{-34}$	$5.9 \pm 0.9^{+1.5}_{-3.3}$	14σ
Belle	$4485 \pm 22^{+28}_{-11}$	$200 \pm 46^{+26}_{-35}$	$10.3 \pm 3.5^{+4.3}_{-2.3}$	5σ

State	Mass (MeV)	Width (MeV)	Fit frac. (%)	Sig.
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2	9σ

- $J^P=1^+$ at 9.7σ incl. syst. (in Belle at 3.4σ)
- Best fit has J^P=($3/2^-$, $5/2^+$), also ($3/2^+$, $5/2^-$) & ($5/2^+$, $3/2^-$) cannot be ruled out

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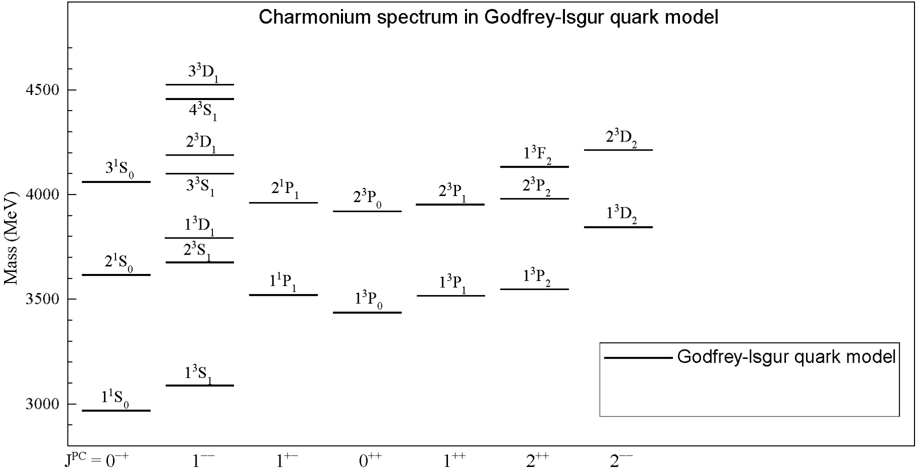
from Liming Zhang's talk

Charmonium spectrum: too many structures



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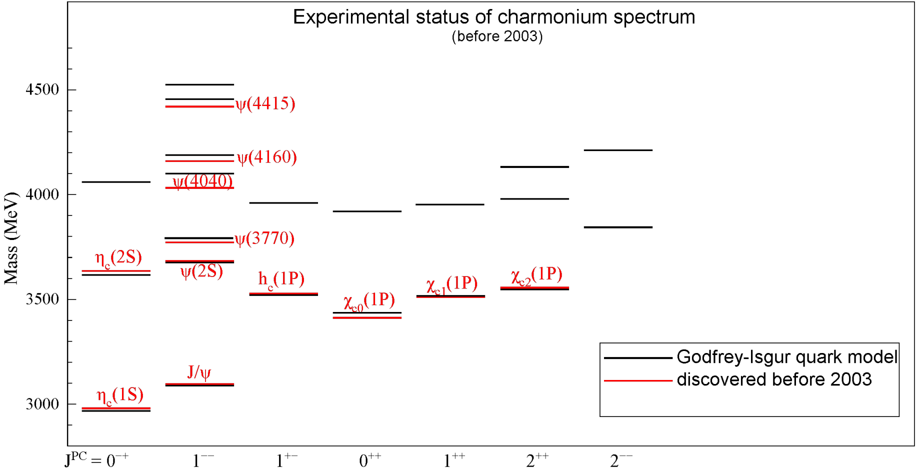

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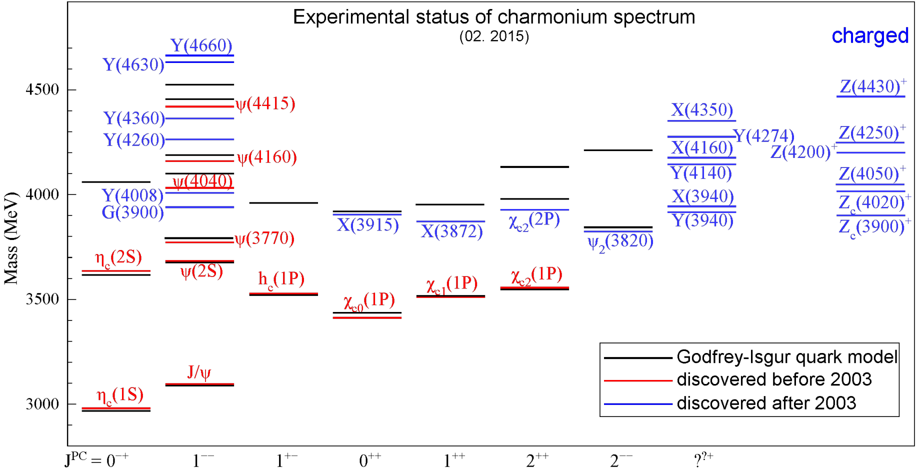

Note: $X(3915)$ is listed by PDG as $\chi_{c0}(2P)$, also suggested in X. Liu, Z.-G. Luo, Z.-F. Sun, PRL104(2010)122001; problems: FKG, Meißner, PRD86(2012)091501; Olsen, PRD91(2015)057501

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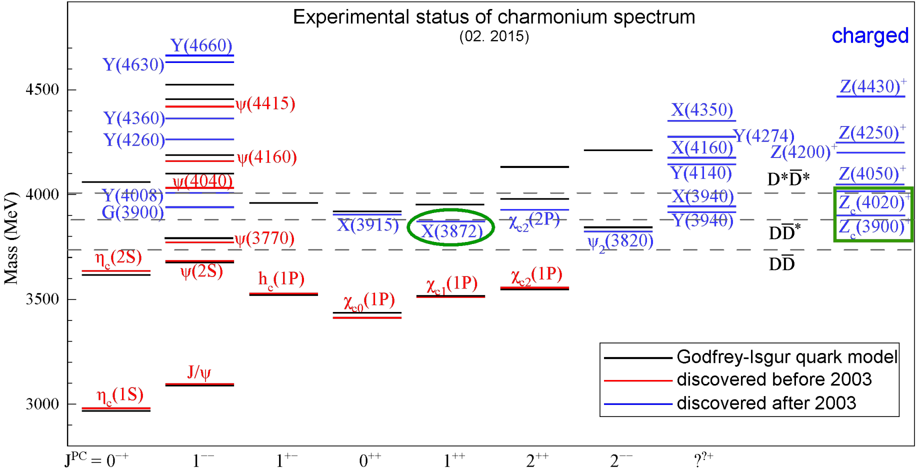

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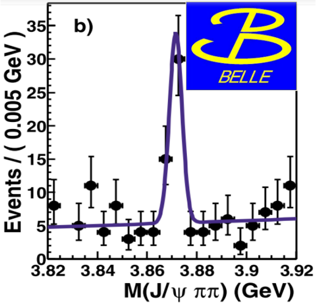
$X(3872)$: best established Belle, BaBar, BESIII, CDF, CMS, D0, LHCb

- $X(3872)$ Belle, PRL91(2003)262001



- Discovered in $B^{\pm} \to K^{\pm} J/\psi\pi\pi$, mass extremely close to the $D^0\bar{D}^{*0}$ threshold
  $M_X = (3871.69 \pm 0.17)$ MeV

  $M_{D^0} + M_{D^{*0}} - M_X = (0.12 \pm 0.19)$ MeV

- $\Gamma < 1.2$ MeV Belle, PRD84(2011)052004
- $J^{PC} = 1^{++}$ LHCb PRL110(2013)222001

  $\Rightarrow$ S-wave coupling to $D\bar{D}^*$

- Observed in the $D^0\bar{D}^{*0}$ mode as well
  BaBar, PRD77(2008)011102
- Large coupling to $D^0\bar{D}^{*0}$:
  $\mathcal{B}(X \to D^0\bar{D}^{*0}) > 24\%$ PDG2014
- Large isospin breaking:
  $$\frac{\mathcal{B}(X \to \omega J/\psi)}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$$

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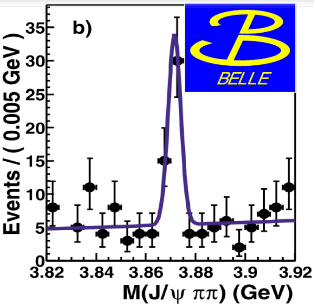

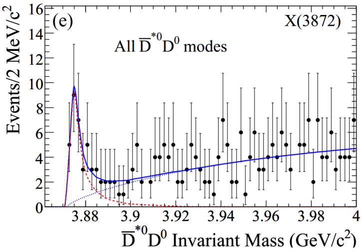

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Interpretations

Always many models for each observed structure:

- Dynamics $\Rightarrow$ poles in the S-matrix: genuine physical states. The origins of the poles can be different:
  - ☞ normal $Q\bar{Q}$
  - ☞ hybrid states
  - ☞ tetraquarks
  - ☞ hadronic molecules
  - ☞ hadro-charmonia / hadro-bottomonia: heavy quarkonium bound inside light hadronic matter S. Dubynskiy, M.B. Voloshin, PLB666(2008)344
- Kinematic effects $\Rightarrow$ branching points of S-matrix
  - ☞ normal two-body threshold cusp
  - ☞ triangle singularity

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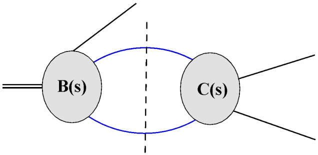
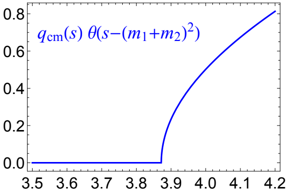
First, need to distinguish kinematic effects from a genuine state

Threshold cusp (I)

- Cusps due to kinematical effect:

$\mathcal{A}(s) \quad =$ 



Unitarity $\Rightarrow$ $\text{Im}\,\mathcal{A}(s) \propto C^*(s)\frac{q_{\rm cm}(s)}{\sqrt{s}}B(s)\theta(s-(m_1+m_2)^2)$

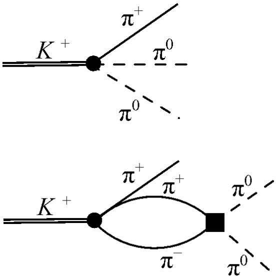
Analyticity $\Rightarrow$ dispersion relation: $\mathcal{A}(s) = \frac{1}{\pi}\int_{s_0}^{\infty} ds' \frac{\text{Im}\,\mathcal{A}(s')}{s'-s-i\epsilon}$

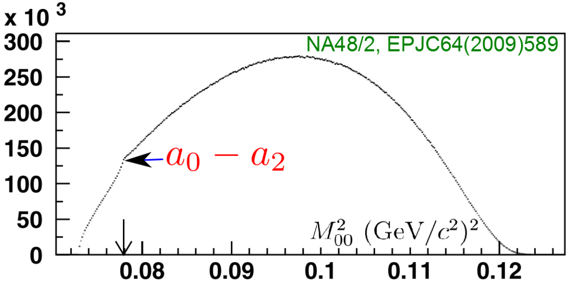
- There is always a cusp at an S-wave threshold if they couple
- Strength of the cusp measures the interaction strength

Threshold cusp (II)

- Cusp effect has been well-known for a long time:
  - ☞ example of the cusp in $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$
  - ☞ the most precise measurement of $\pi\pi$ scattering length by NA48/2

Meißner, Müller, Steininger (1997); Cabibbo (2004); Colangelo, Gasser, Kubis, Rusetsky (2006); . . .

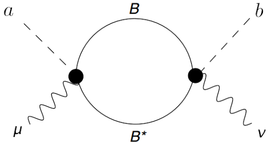


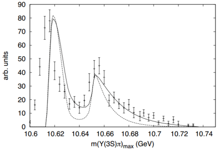


$2M_{\pi^0} = 270$ MeV $<$ $2M_{\pi^\pm} = 279$ MeV

Threshold cusp (III)

- Models of $Z_b(10610, 10650), Z_c(3900, 4020)$ as threshold cusps
  - ☞ Bugg, Swanson: D. Bugg, EPL96(2011)11002; E. Swanson, PRD91(2015)034009





  - ☞ Initial pion radiation: D.-Y.Chen, X.Liu, PRD84(2011)094003; PRD84(2011)034032; Chen, Liu, Matsuki, PRD84(2011)074032; PRL110(2013)232001; . . .

- But $Z_c(3900)[Z_b]$ as a narrow peak in $D\bar{D}^*[B\bar{B}^*]$ cannot be only due to cusp: prominent cusp $\Rightarrow$ strong int. $\Rightarrow$ pole! FKG, Hanhart, Wang, Zhao, PRD91(2015)051504

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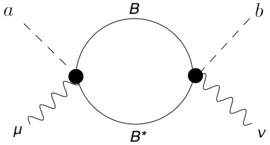

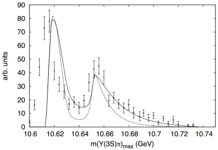

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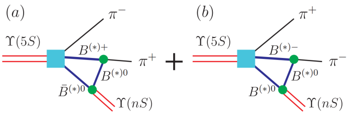
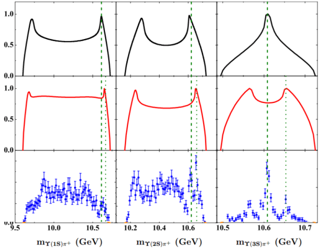




$\Leftarrow B\bar{B}^* + c.c.$ loops

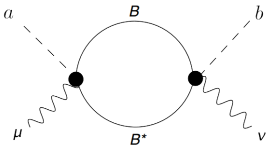
$\Leftarrow B^*\bar{B}^*$ loops

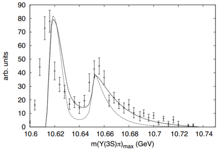
$\Leftarrow$ Belle data

- But $Z_c(3900)[Z_b]$ as a narrow peak in $D\bar{D}^*[B\bar{B}^*]$ cannot be only due to cusp: prominent cusp $\Rightarrow$ strong int. $\Rightarrow$ pole! FKG, Hanhart, Wang, Zhao, PRD91(2015)051504

Threshold cusp (III)

- Models of $Z_b(10610, 10650), Z_c(3900, 4020)$ as threshold cusps
  - ☞ Bugg, Swanson: D. Bugg, EPL96(2011)11002; E. Swanson, PRD91(2015)034009





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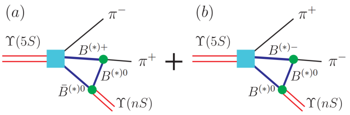

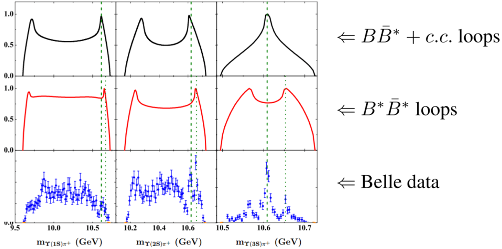

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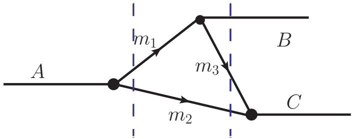

- Triangle singularity: leading Landau singularity of a triangle diagram, anomalous threshold; solution of Landau equation Landau (1959)
- Coleman–Norton theorem: S. Coleman and R. E. Norton, Nuovo Cim. 38 (1965) 438
  The singularity is on the physical boundary if and only if the diagram can be interpreted as a classical process in space-time.
- Translation:
  ☞ all three intermediate particles can go on shell simultaneously
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- requires very special kinematics $\Rightarrow$ process dependent!

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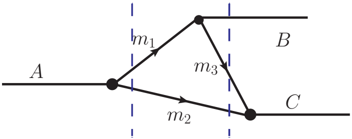

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- Models of triangle singularity for exotic candidates with hidden $Q\bar{Q}$
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  - ☞ triangle singularities relevant for P_c FKG, Meißner, W.Wang,Z.Yang, PRD92(2015)071502; X.-H.Liu,Q.Wang,Q.Zhao, PLB757(2016)231
- Schmid theorem: C. Schmid, Phys. Rev. 154 (1967) 1363

  see also, A. V. Anisovich, V. V. Anisovich, Phys. Lett. B 345 (1995) 321

  Triangle singularity cannot produce an additional peak in the invariant mass distribution of the elastic channel when neglecting inelasticity

  Nearby the triangle singularity: $\mathcal{A}_{(a)+(b)}(s) \sim e^{2i\,\delta_{\chi_{c1}p}(s)}\mathcal{A}_{(a)}(s)$

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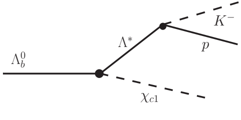
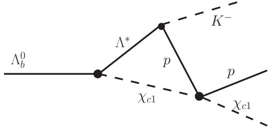


(a)



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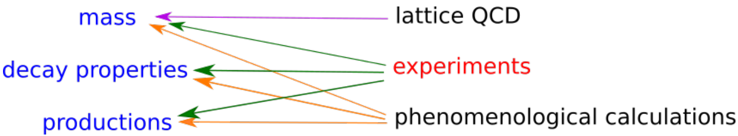
If the observed structure are due to a genuine resonance ⇒ what is its nature?

Difficult to answer generally!



- Phenomenological calculations: sometimes model dependence is hard to quantify

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  ☞ at quark-gluon level: quark model, QCD sum rules

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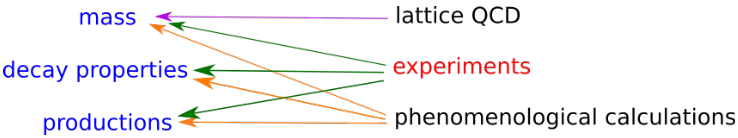

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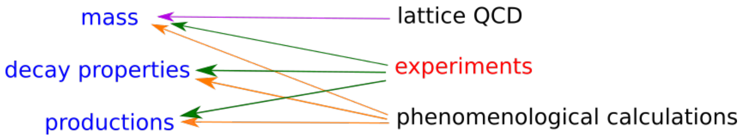

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$X(3872)$ (I)

- Many models:
  - ☞ hadronic molecule— $D\bar{D}^*$ bound state Törnquist (2003); Voloshin (2004); Braaten (2004); Swanson (2004); ... virtual state Hanhart et al. (2007)
    various models calculating the mass;
    low-energy EFT based ⇒ long-distance decay processes, focus on $D\bar{D}^*$
  - ☞ $c\bar{c} + D\bar{D}^*$ coupled-channel effects Kalashnikova (2005); Meng, Gao, Chao (2005); Zhang, Meng, Zheng (2009); Li, Chao (2009); Danilkin, Simonov (2010); Zhou, Xiao (2014); ...
    large coupling to $D\bar{D}^*$ ⇒ a large $D\bar{D}^*$ component
  - ☞ tetraquark Maiani et al. (2005); ...
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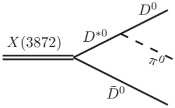
$X(3872)$ (II)

- Processes sensitive to long-distance $D\bar{D}^*$ structure, (calculable using low-energy EFT):

  $X(3872) \to D^0\bar{D}^0\pi^0$, $X(3872) \to D^0\bar{D}^0\gamma$

  Voloshin (2004); Fleming et al. (2007); Braaten, Lu (2007); Hanhart et al. (2007); FKG et al. (2014) . . .



  $\Rightarrow$ directly measuring the $D\bar{D}^*$ component in $X(3872)$

- $J^{PC} = 1^{++} \Rightarrow$ S-wave coupling , probability of finding $D\bar{D}^*$ in X, $1 - Z$, is related to coupling constant

  Weinberg, PR137(1965); Baru *et al.*, PLB586(2004); Hyodo, IJMPA28(2013)1330045; . . .

  see also, e.g., Weinberg's books: QFT Vol.I, Lectures on QM

$$g_{\rm NR}^2 \approx (1 - Z)\frac{2\pi}{\mu^2}\sqrt{2\mu E_B}$$

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  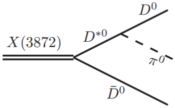

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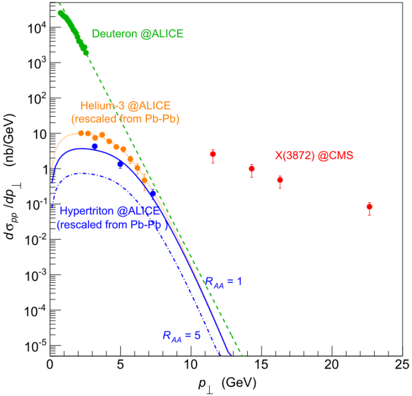
$X(3872)$ (III)

- Processes driven by short-distance $c\bar{c}$ physics:
  Examples:
  - ☞ production of $X(3872)$ in B decays, at hadron colliders with large p_T

    Braaten et al. (2004,2005,2006,2009); Meng, Gao, Chao (2005); Bignamini et al. (2009); . . .
- Often used to blame the $D\bar{D}^*$ molecular interpretation, e.g.

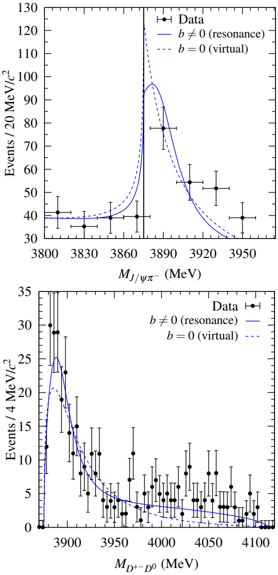
  Esposito et al., PRD92(2015)034028 :



- but deutron and X are very different at short distances:
  - ☞ deutron: 6 quarks
  - ☞ X: dominantly produced by $c\bar{c}$ at short distances

$Z_c(3900)$: negative lattice results

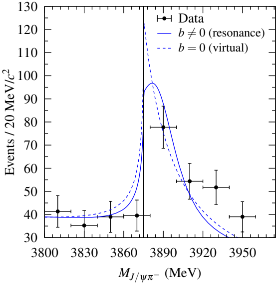
- So far, no evidence for $Z_c(3900)$ in lattice QCD:
  - ☞ CLQCD: PRD89(2014)094506
    $I = 1$ $D\bar{D}^*$ weakly repulsive $\Rightarrow$ no bound state ($M_\pi \geq 300$ MeV)
  - ☞ Prelovsek et al.: PRD91(2015)014504
    "no additional eigenstate" corresponding to $Z_c(3900)$ ($M_\pi = 266$ MeV),
  - ☞ HALQCD: arXiv:1602.03465
    virtual state pole with very low masses and deep in the complex plane ($M_\pi \geq 410$ MeV)
- Are they in conflict with experiments?

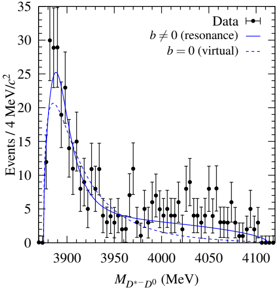


M. Albaladejo, J. Nieves, P. Fernandez-Soler, arXiv:1606.03008

- Model fitted to BESIII data with: (1) resonance, or (2) virtual state   Albaladejo et al., PLB755(2016)337
- In finite volume ($L = 2$ fm): consistent with lattice energy levels, but with a pole in continuum!

$Z_c(3900)$: Interpreting lattice results by Prelovsek et al.





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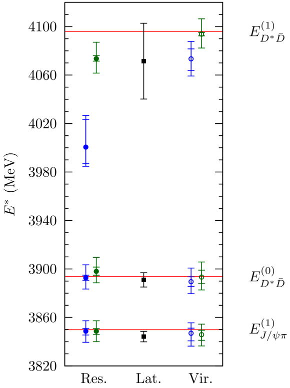

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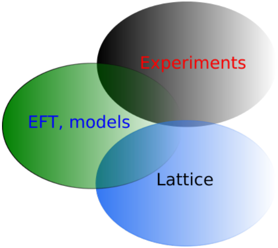
Not a summary



- The study of exotic hadrons is difficult: nonperturbative QCD, confinement.
  - ☞ Why are exotic hadrons so scarce?
  - ☞ Searching for and confirming states with exotic quantum numbers
  - ☞ Calculating QCD spectrum using lattice simulations
  - ☞ For the confirmed states: understanding their structures,

    why is the spectrum organized as such?

  $\Rightarrow$ learning about confinement
- lots of progress in recent years, but still a long way to go

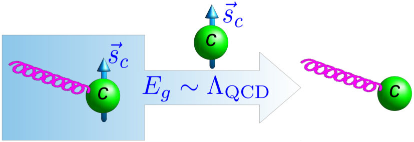
  $\Rightarrow$ more joint efforts needed !

谢 谢 大 家！

Backup slides

HQSS — hadro-charmonia

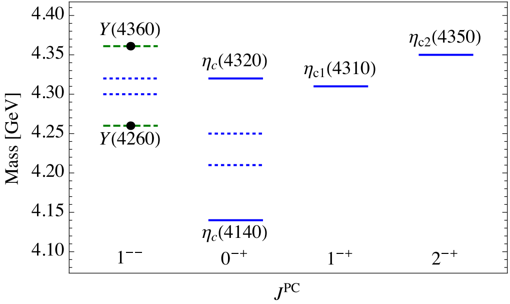
- Heavy quark spin symmetry (HQSS):



- Example: implications for hadro-charmonia Cleven et al., PRD92(2015)014005

  If the $Y(4260)$ and $Y(4360)$ are mixed hadro-charmonia with h_c and ψ' core

  Li, Voloshin, MPLA29(2014)1450060



- Very old knowledge from 1960s:

  Classical books:

  R. J. Eden, P. V. Landshoff, D. I. Olive and J. C. Polkinghorne, *The Analytic S-Matrix* Cambridge University Press, 1966.

  张宗燧, "色散关系引论"两册 (科学出版社，1980, 1983年出版, 著于1965年).

  Recent lecture notes by one of the key players:

  I. J. R. Aitchison, arXiv:1507.02697 [hep-ph]. *Unitarity, Analyticity and Crossing Symmetry in Two- and Three-hadron Final State Interactions*.

张宗燧

(1915–1969)

Multiquark states: $X(5568)$?

Commun. Theor. Phys. **65** (2016) 593–595 Vol. 65, No. 5, May 1, 2016

How the $X(5568)$ Challenges Our Understanding of QCD*

Feng-Kun Guo (郭奉坤),[1,†] Ulf-G. Meißner,[1,2,3,‡] and Bing-Song Zou (邹冰松)[1,4,§]

- mass too low for $X(5568)$ to be a $\bar{b}s\bar{u}d$: $M \simeq M_{B_s} + 200$ MeV
  - ☞ $M_\pi \simeq 140$ MeV because pions are pseudo-Goldstone bosons of spontaneous chiral symmetry breaking SU$(2)_L \times$SU$(2)_R \to$SU$(2)_V$
  - ☞ Gell-Mann–Oakes–Renner: $M_\pi^2 \propto m_q$; chiral counting: $M_\pi = \mathcal{O}(p)$
  - ☞ For any matter field: $M_R = \mathcal{O}(p^0) \gg M_\pi$; we expect $M_{\bar{q}q} \sim M_R \gtrsim M_\sigma$

$$M_{\bar{b}s\bar{u}d} \gtrsim M_{B_s} + 500 \text{ MeV} \sim 5.9 \text{ GeV}$$

- heavy quark flavor symmetry predicts an isovector X_c:

$$M_{X_c} = M_{X(5568)} - \bar{M}_{B_s} + \bar{M}_{D_s} + \mathcal{O}\left(\Lambda_{\text{QCD}}^2\left(\frac{1}{m_c} - \frac{1}{m_b}\right)\right) \simeq (2.24 \pm 0.15) \text{ GeV}$$

but in $D_s\pi$, only isoscalar $D_{s0}^*(2317)$ was observed! BaBar (2003)

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Compositeness (I)

Weinberg, PR137(1965); Baru *et al.*, PLB586(2004); ...

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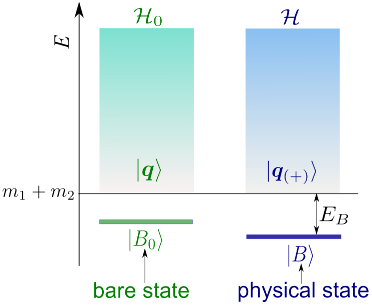
Model-independent result for S-wave loosely bound composite states:



Consider a system with Hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + V$$

$\mathcal{H}_0$: free Hamiltonian, V: interaction potential

- Compositeness:

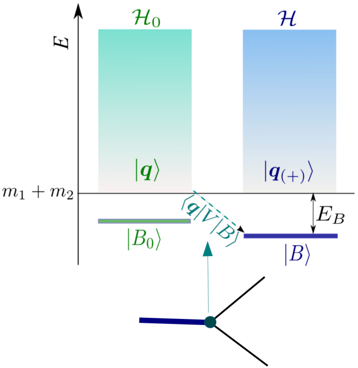
  the probability of finding the physical state $|B\rangle$ in the 2-body continuum $|\boldsymbol{q}\rangle$

$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$$

- $Z = \left|\langle B_0|B\rangle\right|^2, \qquad 0 \leq (1-Z) \leq 1$
  - ☞ $Z = 0$: pure bound (composite) state
  - ☞ $Z = 1$: pure elementary state

Compositeness (II)

Compositeness : $1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$



- Schrödinger equation

$$(\mathcal{H}_0 + V)|B\rangle = -E_B|B\rangle$$

multiplying by $\langle \boldsymbol{q}|$ and using $\mathcal{H}_0|\boldsymbol{q}\rangle = \frac{\boldsymbol{q}^2}{2\mu}|\boldsymbol{q}\rangle$

$$\langle \boldsymbol{q}|B\rangle = -\frac{\langle \boldsymbol{q}|V|B\rangle}{E_B + \boldsymbol{q}^2/(2\mu)}$$

- S-wave, small binding energy so that $R = 1/\sqrt{2\mu E_B} \gg r$, r: range of forces

$$\langle \boldsymbol{q}|V|B\rangle = g_{\rm NR}\left[1 + \mathcal{O}(r/R)\right]$$

- Compositeness:

$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \frac{g_{\rm NR}^2}{\left[E_B + \boldsymbol{q}^2/(2\mu)\right]^2} \left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right] = \frac{\mu^2 g_{\rm NR}^2}{2\pi\sqrt{2\mu E_B}} \left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right]$$

Compositeness (III)

- Coupling constant measures the compositeness for an S-wave bound state with a small binding energy (model-independent)

$$g_{\mathrm{NR}}^2 \approx (1-Z)\frac{2\pi}{\mu^2}\sqrt{2\mu E_B} \le \frac{2\pi}{\mu^2}\sqrt{2\mu E_B}$$

- Z can be measured directly from observables, such as scattering length a and effective range r_e — Weinberg (1965)

$$a = -\frac{2R(1-Z)}{2-Z}\left[1+\mathcal{O}\left(\frac{r}{R}\right)\right], \quad r_e = \frac{RZ}{1-Z}\left[1+\mathcal{O}\left(\frac{r}{R}\right)\right]$$

- Example: deuteron as pn bound state. Exp.: $E_B = 2.2$ MeV, $a_{^3S_1} = -5.4$ fm

$$a_{Z=1} = 0 \text{ fm}, \qquad a_{Z=0} = (-4.3 \pm 1.4) \text{ fm}$$