Review of Heavy Meson Spectroscopy

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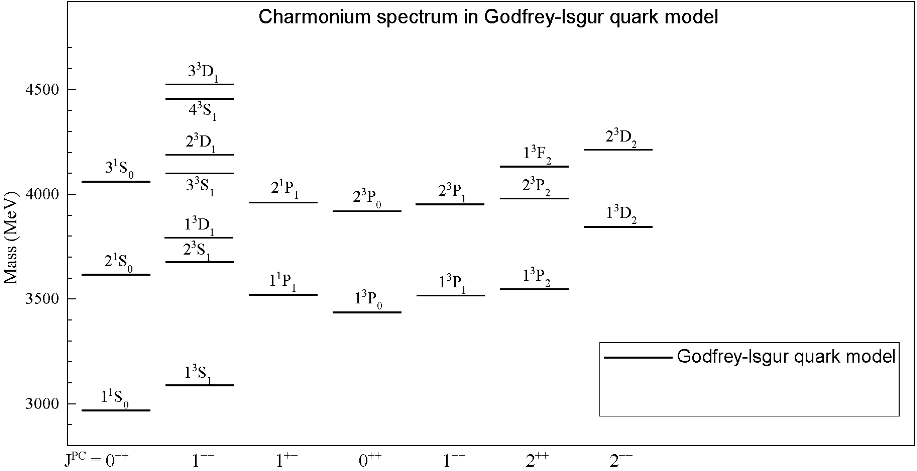
- Charmonium(-like) structures and heavy-strange mesons
- Kinematic effects versus genuine resonances
- Examples: $Z_c(3900)$, $X(3872)$, $D_{s0}^*(2317)$

Charmonium spectrum: too many structures



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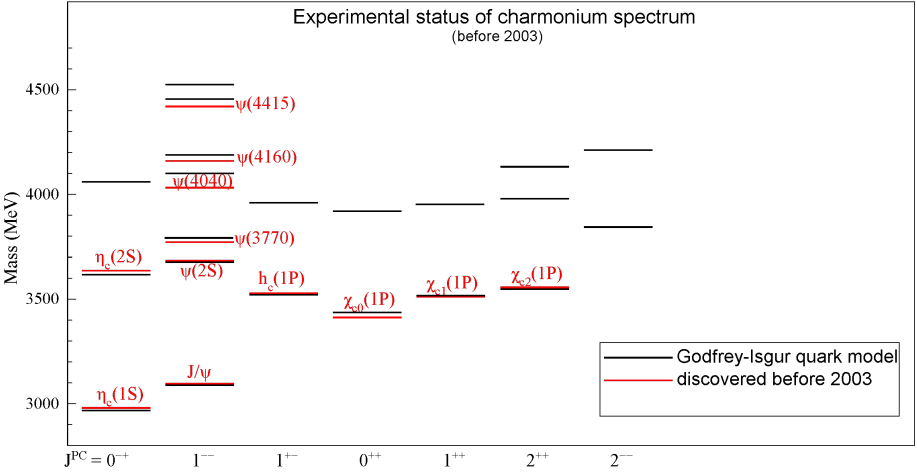

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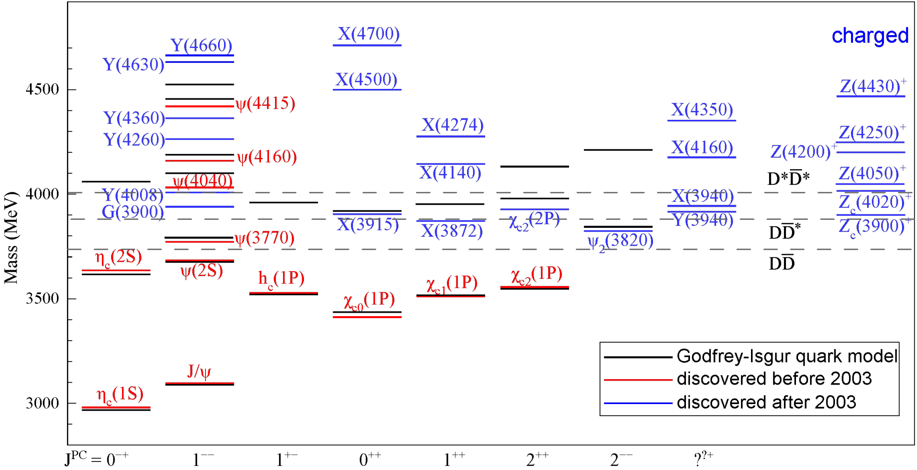


Heavy-strange mesons

Charm-strange $I = 1$ $c\bar{s}$ mesons $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- $D_{s0}^*(2317)$: 0^+ BaBar (2003)

  $M = (2317.7 \pm 0.6)$ MeV,

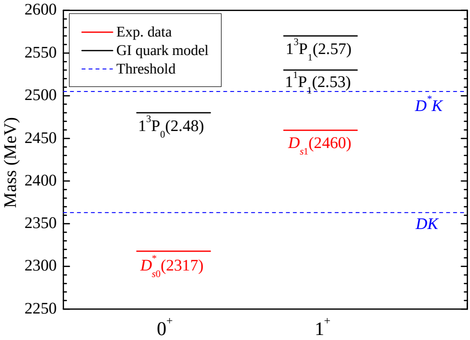
  $\Gamma < 3.8$ MeV

  The only hadronic decay: $D_s\pi$

- $D_{s1}(2460)$: 1^+ CLEO (2003)

  $M = (2459.5 \pm 0.6)$ MeV,

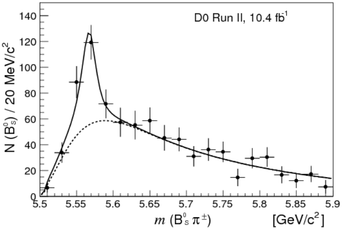
  $\Gamma < 3.5$ MeV



- Notable features:
  - ☞ masses are much lower than the quark model predictions for $c\bar{s}$ mesons
  - ☞ $M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} \simeq M_{D^*} - M_D$ +1 MeV

Observation in 2016: an "explicitly exotic" multiquark candidate

- $X(5568)$ by D0 Collaboration ($p\bar{p}$ collisions) PRL117(2016)022003



$$M = \left(5567.8 \pm 2.9^{+0.9}_{-1.9}\right) \text{ MeV}$$

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

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

☞ difficulties in all possible structure explanations

Burns, Swanson, PLB760(2016)627; FKG, Meißner, Zou, Commun.Theor.Phys. 65 (2016) 593

might be due to kinematic cuts in analysis Yang, Wang, Meißner, PLB767(2017)470

☞ immediately, negative result by LHCb PRL117(2016)152003

and by CMS CMS-PAS-BPH-16-002

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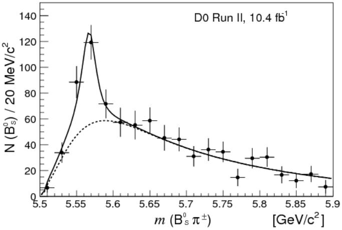

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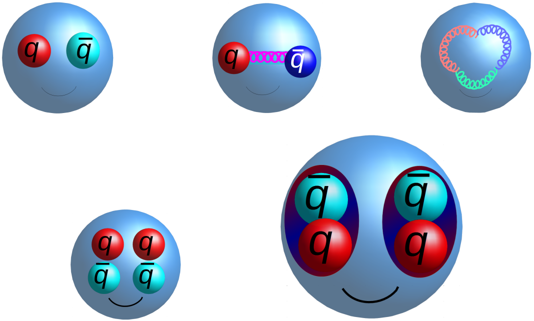
Interpretations

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:



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  - ☞ normal two-body threshold cusp
  - ☞ triangle singularity
  - ☞ . . .

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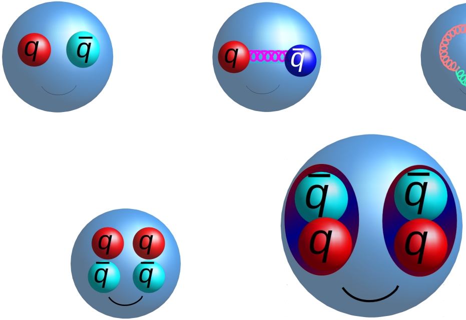

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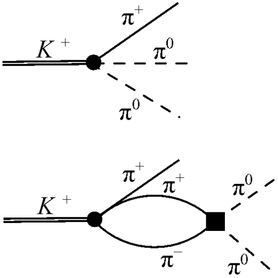
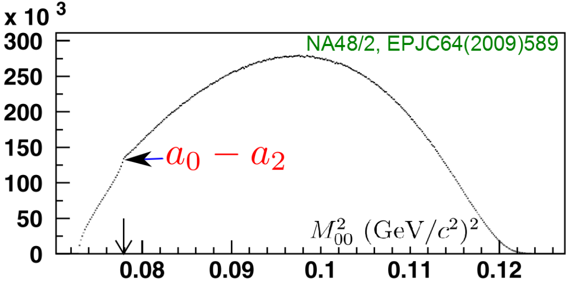
  - ☞ ...

Threshold cusp

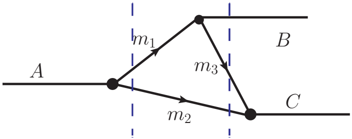
- There is always a cusp at an S-wave threshold
- Cusp effect has been well-known for a long time:
  - ☞ example of the cusp in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$
  - ☞ strength of the cusp measures the interaction strength!

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





Triangle singularity



- Conditions (Coleman–Norton theorem (1965)):
  - ☞ all three intermediate particles can go on shell simultaneously
  - ☞ $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)
- requires very special kinematics

  $\Rightarrow$ process dependent!
- S-wave TS can produce a narrow peak mimicking a resonance

  Bayar et al., PRD94(2016)074039
- many recent applications

  reviews: Q.Zhao, JPS Conf.Proc.13(2017)010008;

  FKG et al., arXiv:1705.00141

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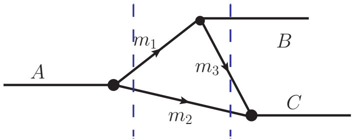

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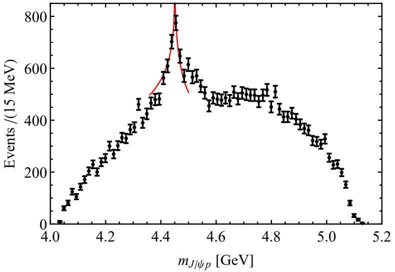
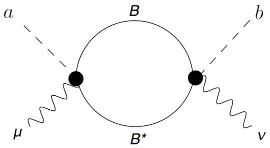
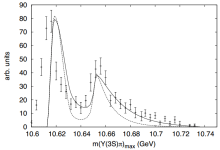


Threshold cusp — example: Z_b/Z_c

- 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; . . .

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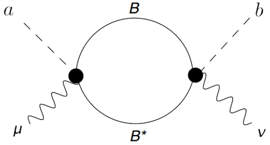

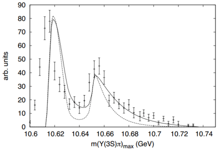

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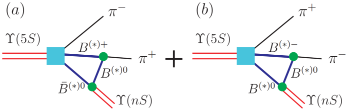
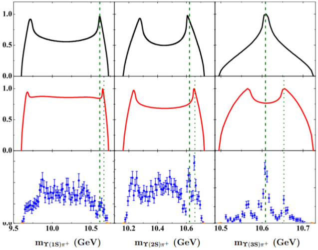
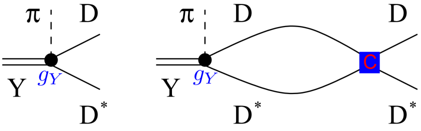
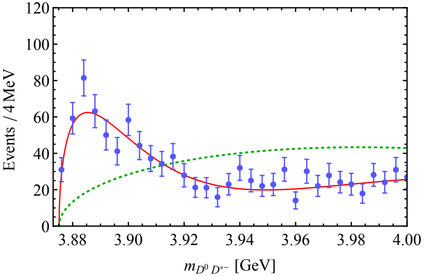




- But $Z_c(3900)[Z_b]$ as a narrow peak in $D\bar{D}^*[B\bar{B}^*]$ distribution cannot be only due to cusp: prominent cusp ⇒ strong int. ⇒ pole!

FKG, Hanhart, Wang, Zhao, PRD91(2015)051504





Black curve: up to 1 loop with $C_\Lambda\, G_\Lambda(E_{\rm th}) = -1/2$,
no narrow peak any more!

$g_Y\, [1 + C_\Lambda\, G_\Lambda(E) + C_\Lambda\, G_\Lambda(E) C_\Lambda\, G_\Lambda(E) + \ldots]$ produces a pole

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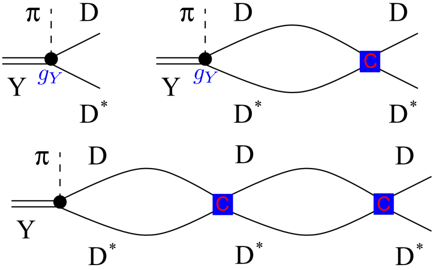

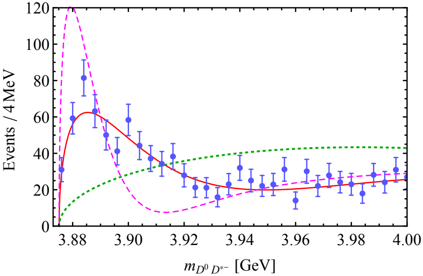

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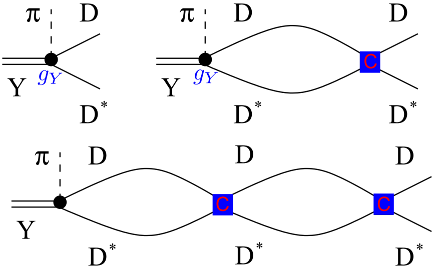

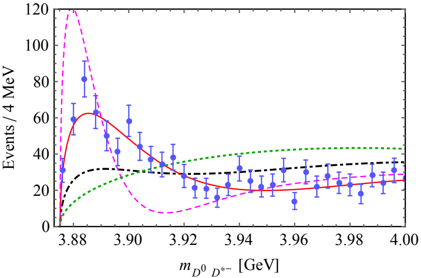

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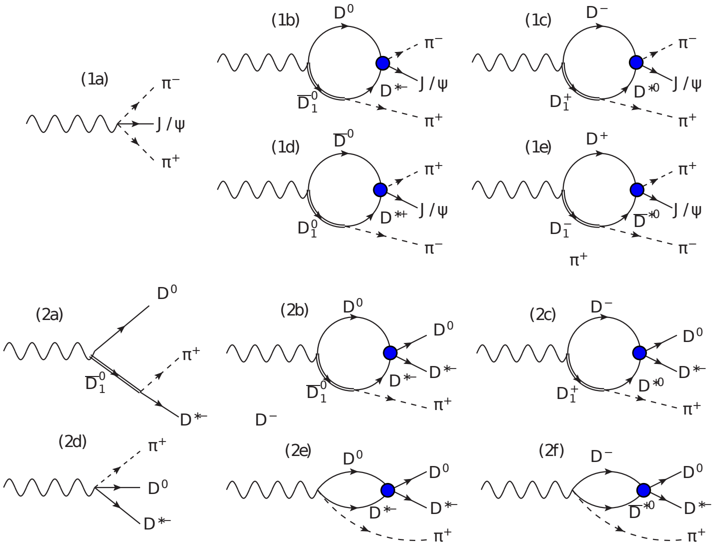
More about $Z_c(3900)$

Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337



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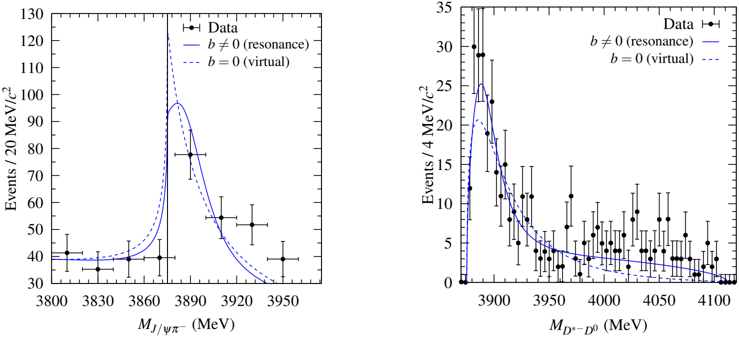


M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	[1] (BESIII)	$J/\psi\ \pi$
3895 ± 8	32 ± 18	[2] (Belle)	$J/\psi\ \pi$
3886 ± 5	19 ± 5	[3] (CLEO-c)	$J/\psi\ \pi$
3884 ± 5	12 ± 6	[4] (BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	[5] (BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$
$3831 \pm 26^{+7}_{-28}$	virtual state	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$
$3844 \pm 19^{+12}_{-21}$	virtual state	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$

resonance pole

or virtual state

new BESIII data on $J/\psi\pi^+\pi^-$ channel published (next slide), needs to be updated

Triangle singularity — example: $Y(4260) \to Z_c\pi$

- Importance of TS in $Y(4260) \to Z_c\pi$ already noticed, but Z_c pole still needed

  Q.Wang, Hanhart, Q.Zhao, PRL111(2013)132002; PLB725(2013)106

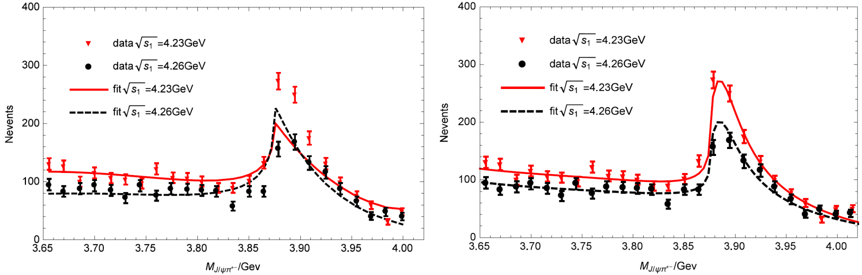
- however, debate continues:
  - ☞ opposite claim: whether Z_c pole is needed is inconclusive

    Pilloni et al. (JPAC), PLB772(2017)200
  - ☞ updated combined analysis of $e^+e^- \to J/\psi\pi\pi$ and $e^+e^- \to (D\bar{D}^*)^{\mp}\pi^{\pm}$

    $\Rightarrow$ necessity of Z_c pole (virtual or resonance) Albaladejo et al., PLB755(2016)337

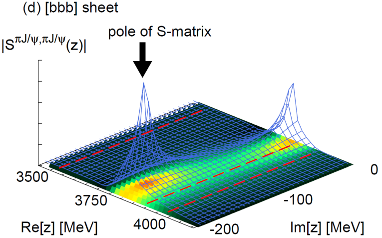
    TS only not favored by using the latest data of BESIII, PRL119(2017)072001

    Q.-R. Gong et al., arXiv:1612.08159



$Z_c(3900)$: negative lattice results

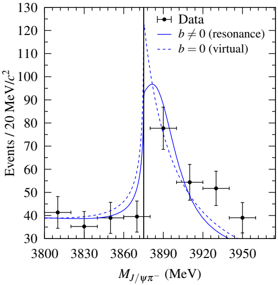
- So far, no evidence for $Z_c(3900)$ in lattice QCD: talk by Y. Chen
  - ☞ CLQCD: PRD89(2014)094506
    $I = 1\ D\bar{D}^*$ weakly repulsive ⇒ no bound state ($M_\pi \geq 300$ MeV)
  - ☞ Prelovsek et al.: PRD91(2015)014504
    "no additional eigenstate" corresponding to $Z_c(3900)$ ($M_\pi = 266$ MeV),
  - ☞ HALQCD: PRL117(2017)242001
    virtual state pole with a very low mass and deep in the complex plane ($M_\pi \geq 410$ MeV)

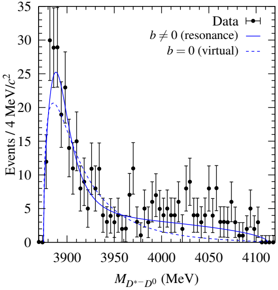


Ikeda for HALQCD, arXiv:1706.07300

- Are they in conflict with experiments?
  For HALQCD: recall the virtual state pole in Albaladejo et al., PLB755(2016)337 is much closer to the threshold

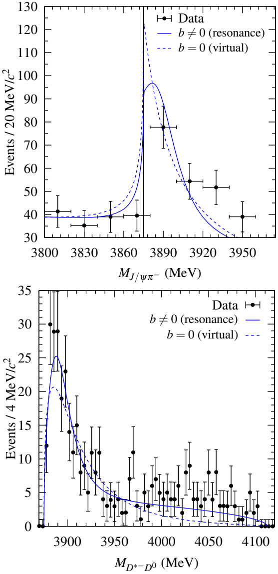
Albaladejo, Fernandez-Soler, Nieves, EPJC76(2016)573



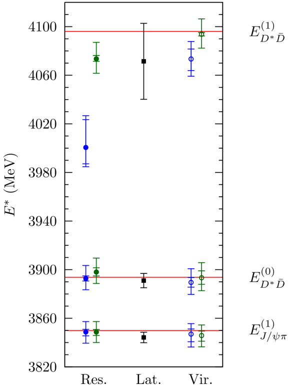


- Model fitted to BESIII data with: (1) resonance, or (2) virtual state Albaladejo et al., PLB755(2016)337
- In finite volume ($L = 2$ fm): consistent with lattice energy levels, but with a pole in continuum!

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



Albaladejo, Fernandez-Soler, Nieves, EPJC76(2016)573



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$X(3872)$ (I)

- Very important features:

  $M_{D^0} + M_{\bar{D}^{*0}} - M_X = (0.00 \pm 0.18)$ MeV; $\mathrm{Br}(X \to D\bar{D}^{*0} + c.c.) > 24\%$

- Many models:
  - ☞ hadronic molecule

    $D\bar{D}^*$ bound state Törnquist (2003); Voloshin (2004); Braaten (2004); Swanson (2004); ...

    virtual state Hanhart et al. (2007)
  - ☞ $c\bar{c} + D\bar{D}^*$ coupled-channel effects

    Kalashnikova (2005); Meng, Gao, Chao (2005); Zhang, Meng, Zheng (2009); Li, Chao (2009); Danilkin, Simonov (2010); Zhou, Xiao (2014); ...

    if large coupling to $D\bar{D}^* \Rightarrow$ a large $D\bar{D}^*$ component
  - ☞ tetraquark Maiani et al. (2005); ...

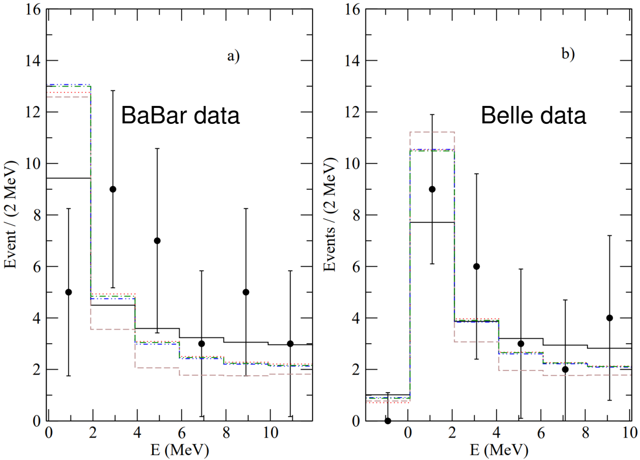
    generally predicting too many states
  - ☞ cusp, $c\bar{c}g$, ...: not under active discussion any more

$X(3872)$ (II)

- Very precise measurements in the $X \to D^0\bar{D}^0\pi^0$ channel needed:

  current data allow for several possible senarios with the compositeness ranging from nearly 0 (blue, green, weak coupling to $D\bar{D}^*$) to 1 (black solid, strong coupling to $D\bar{D}^*$)

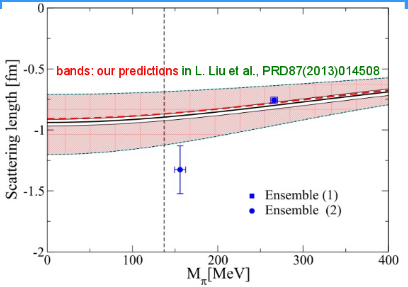
  X.-W. Kang, J. A. Oller, EPJC77(2017)399



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

- Early studies using only $c\bar{s}$-type interpolators typically give mass larger than that for $D^*_{s0}(2317)$

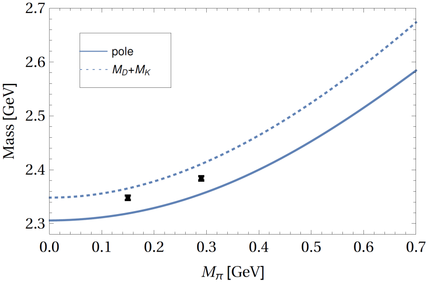
  Bali (2003); UKQCD (2003); ...



- $c\bar{s} + DK$ interpolators:

  Mohler et al., PRL111(2013)222001; Lang et al., PRD90(2014)034510

- Latest lattice results   Bali et al. (RQCD), arXiv:1706.01247



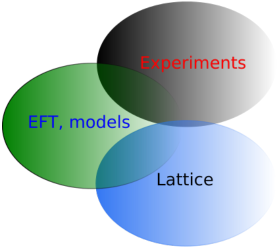
compositeness: $= 1.04(0.08)(+0.30)$

M_π [MeV]	150	290
$M_{D^*_{s0}(2317)}$ [MeV]	2348 ± 4	2384 ± 3
M_{D_s} [MeV]	1977 ± 1	1980 ± 1

curves: prediction in Du et al., arXiv:1703.10836

Exp: to measure the width of $D^*_{s0}(2317) \to D_s\pi$ precisely

Not a summary

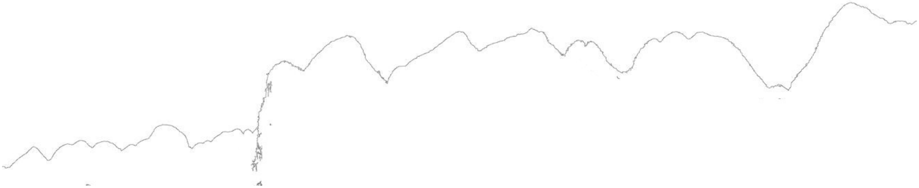


- The study of exotic hadrons is difficult: nonperturbative QCD, confinement
  - ☞ Why are exotic hadrons so scarce?
  - ☞ Searching for and confirming states with exotic quantum numbers
  - ☞ Calculating QCD spectrum using lattice simulations
  - ☞ For the confirmed states: understanding their structures,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

Another example of peaking structures



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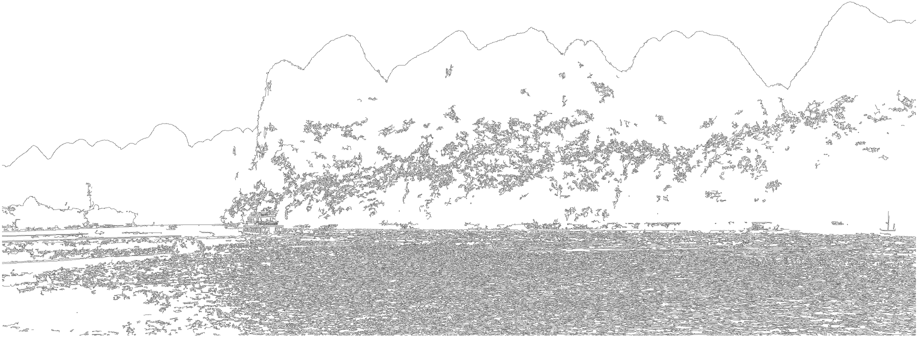


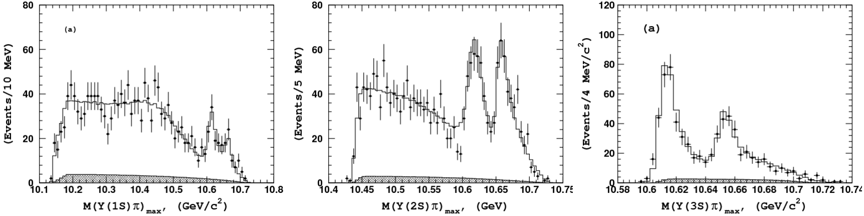
Another example of peaking structures

谢 谢！

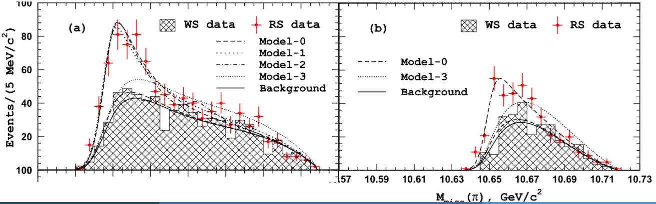
Backup slides

“Explicitly exotic” multiquarks: $Z_c^\pm$ and $Z_b^\pm$ with **hidden** $Q\bar{Q}$

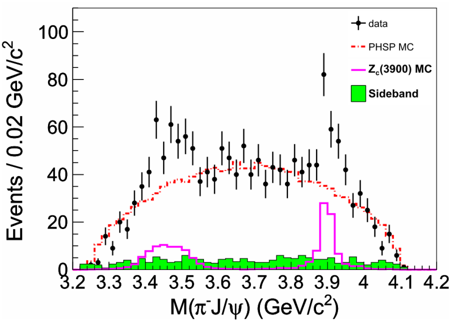
- $Z_c^\pm$, $Z_b^\pm$: charged structures in heavy quarkonium mass region, $Q\bar{Q}\bar{d}u, Q\bar{Q}\bar{u}d$
  $Z_c(3900)$, $Z_c(4020)$, $Z_c(4200)$, $Z_c(4430)$, ... talks by R.Mitchell, C.-Z.Yuan, L.-M.Zhang
- $Z_b(10610)$ and $Z_b(10650)$: Belle, arXiv:1105.4583; PRL108(2012)122001
  observed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

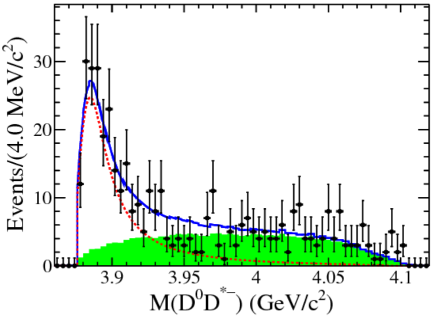


also in $\Upsilon(10860) \to \pi^\mp[B^{(*)}\bar{B}^*]^\pm$ Belle, arXiv:1209.6450; PRL116(2016)212001



- $Z_c(3900/3885)^\pm$: 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

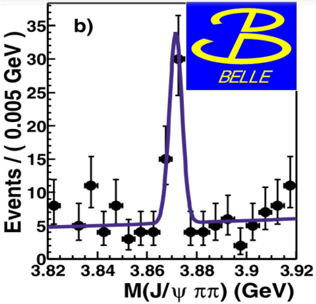




- can be described by the same state Aldaladejo et al., PLB755(2016)337

$X(3872)$: 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

  $M_{D^0} + M_{D^{*0}} - M_X = (0.00 \pm 0.18)$ 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 $D^0\bar{D}^{*0}$:

  $\mathcal{B}(X \to D^0\bar{D}^{*0}) > 24\%$ PDG2016

- 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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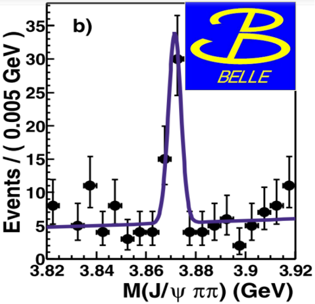

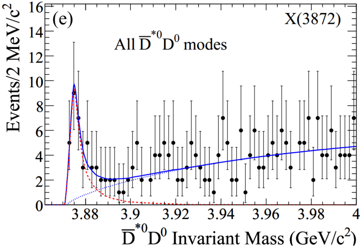

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Multiquark states: $X(5568)$?

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:

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

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

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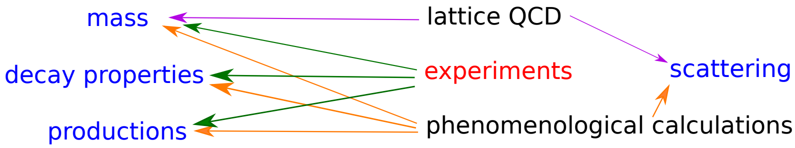
but in $D_s\pi$, only isoscalar $D^*_{s0}(2317)$ was observed! BaBar (2003)

Difficulties in interpreting experimental observations

If the observed structure are due to a genuine resonance $\Rightarrow$ what is its nature?

Difficult to answer generally!



- Phenomenological calculations:

  model dependence often hard to quantify

- Lattice calculations:

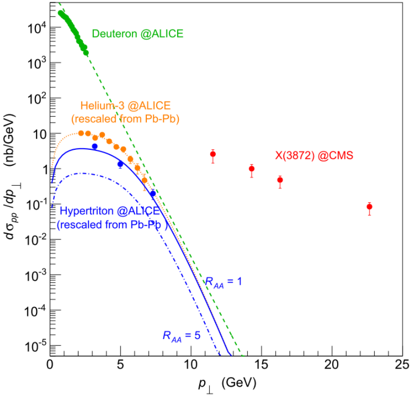
  energy levels in finite volume, interpretation not straightforward

$X(3872)$ (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