Theoretical insights about the XYZ states ... and beyond

Christoph Hanhart

Forschungszentrum Jülich

Recent Review articles

A. Esposito, A. Pilloni, A.D. Polosa, Phys. Rep. 668 (2016) 1

H.X. Chen, W. Chen, X. Liu, S.L. Zhu, Phys. Rep. 639 (2016) 1

A. Ali, J.S. Lange, S. Stone, Prog. Part. Nucl. Phys. 97 (2017) 123

R.F. Lebed, R.E. Mitchell, E.S. Swanson, Prog. Part. Nucl. Phys. 93 (2017) 143

S.L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003

N. Brambilla, S. Eidelman, C.H., A. Nefediev, C.-P. Shen, C.E. Thomas, A. Vairo, C. Yuan, Phys. Rept. 873 (2020) 1

with focus on molecular states:

F.-K. Guo, C.H., U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Rev. Mod. Phys. 90(2018)015004

QCD vs. QED I

’t Hooft; Politzer; Gross, Wilczek

QCD as well as QED are local gauge theories (SU(3) vs. U(1))

The Lagrangian reads

$$\mathcal{L}_{\rm QCD/QED} = \bar{\psi}\left(\gamma_\mu D^\mu - M\right)\psi - \frac{1}{4T}\text{Tr}\left(F^{\mu\nu}F_{\mu\nu}\right)$$

where the covariant derivative and field strength tensor read

$$D_\mu = \partial_\mu - igG_\mu = \partial_\mu - ig\sum_a G_\mu^a T^a ,$$

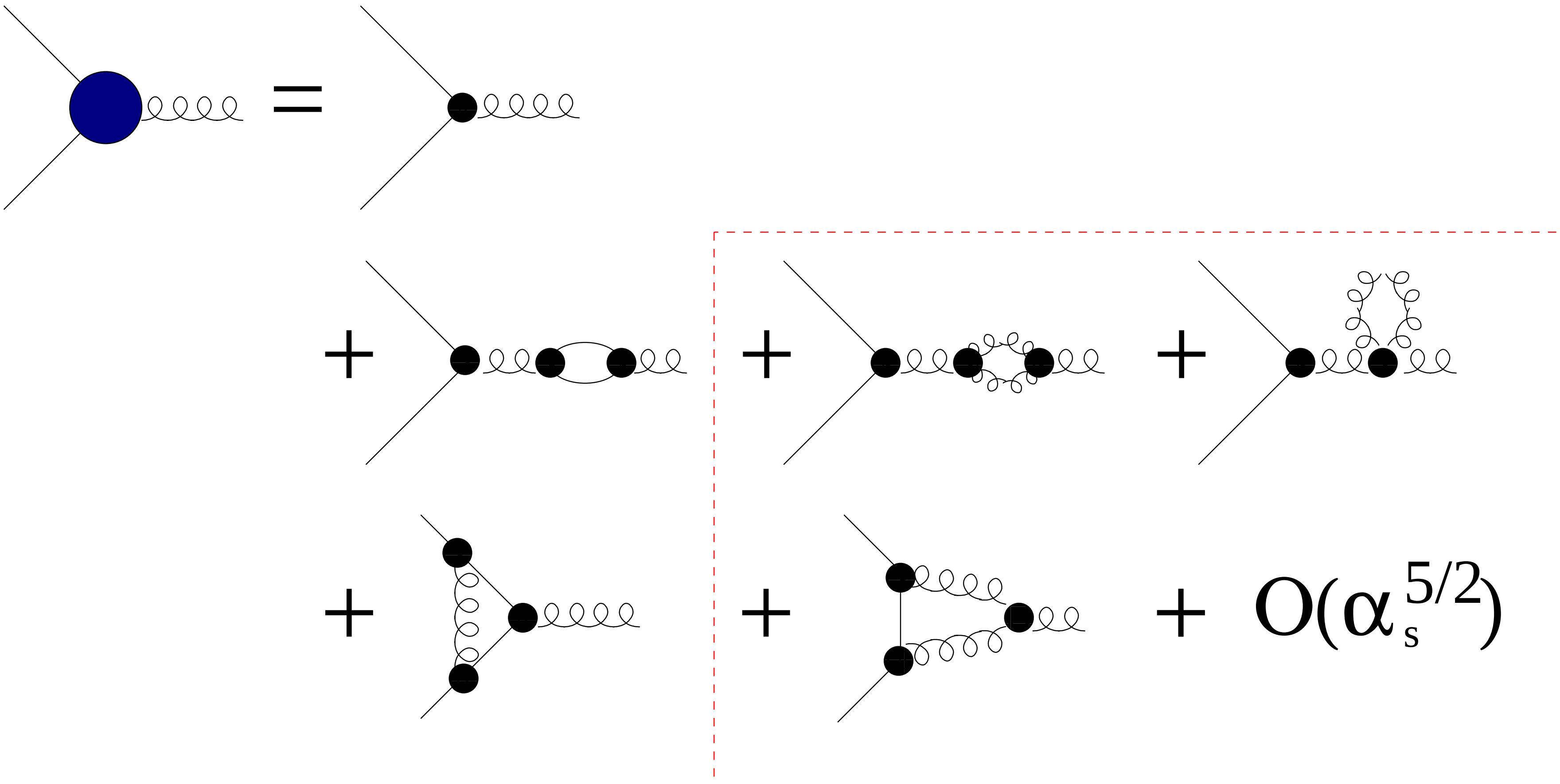
$$F_{\mu\nu} = \frac{i}{g}\left[D_\mu, D_\nu\right] = \partial_\mu G_\nu - \partial_\nu G_\mu - ig\left[G_\mu, G_\nu\right]$$

where $T^a =$ generators of the gauge group with Tr $\left(T^a T^b\right) = T\delta^{ab}$

QED: one charge; QCD: three charges (= colors)

QCD vs. QED II

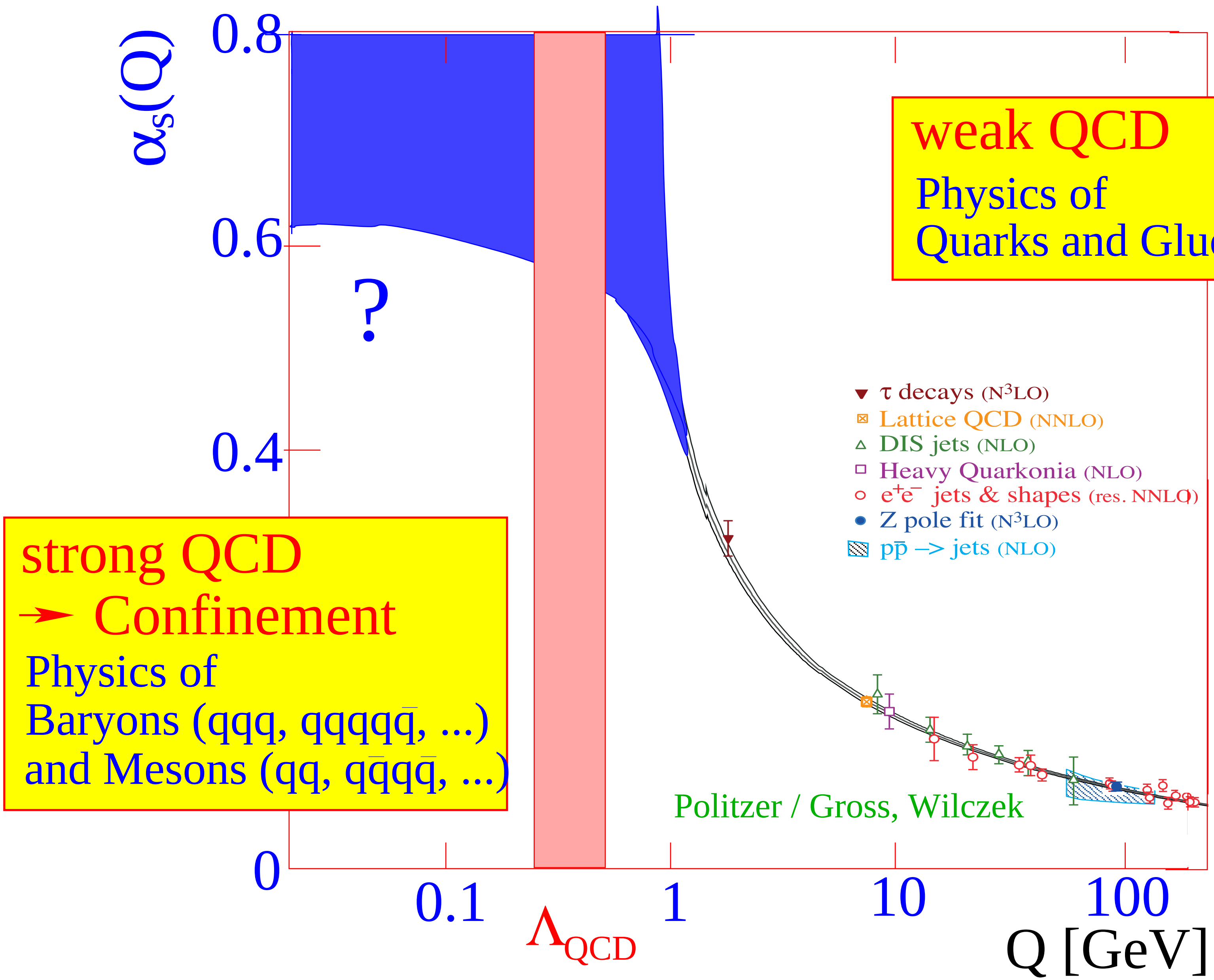
't Hooft; Politzer; Gross, Wilczek



with $b_0 = 11 - (2/3)n_F$ one gets (in QED: $b_0 = -4/3$ different sign)

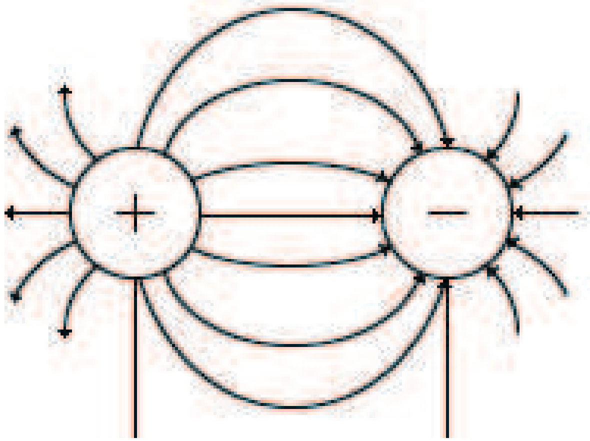
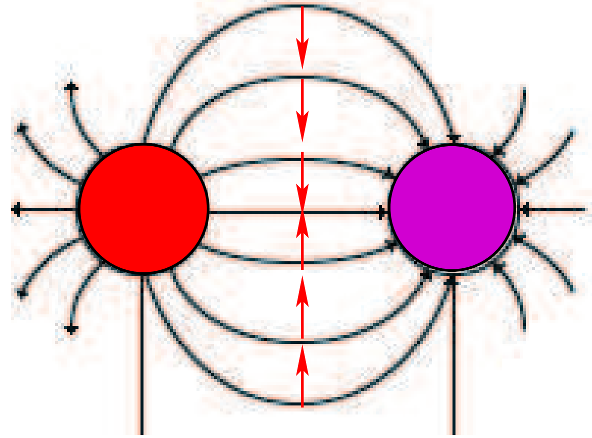
$$\alpha_s(q^2) = \frac{g_s(q^2)^2}{4\pi} = \frac{\alpha_s}{1 + (b_0\alpha_s/2\pi)\ln(q/M)} = \frac{2\pi}{b_0 \ln\left(q/\Lambda_{QCD}\right)}$$

The faces of QCD



Particle data group 2014

Consequences at low energies

lines of force for QED	lines of force for QCD
	
force $\sim 1/r^2$; energy $\sim 1/r$	force $\sim$ const.; energy $\sim r$

- The gluon fields produce a flux-tube similar to a rubber band
- there is a lot of energy stored in the field!
- When separating two quarks the flux tube breaks
  Energy released produces a new $q\bar{q}$–pair $\rightarrow$ CONFINEMENT

Consequences at low energies

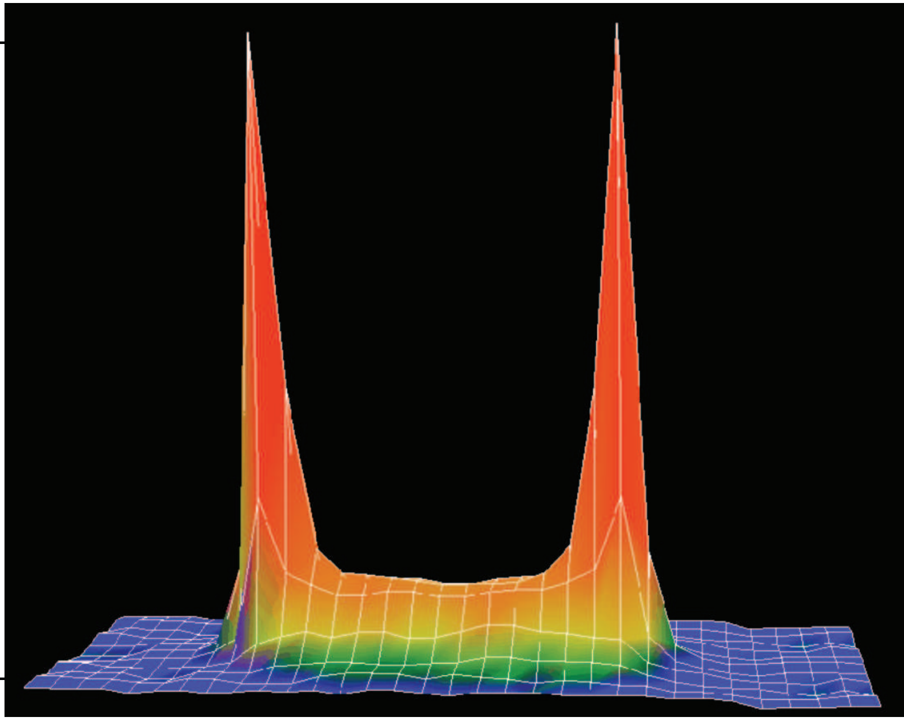
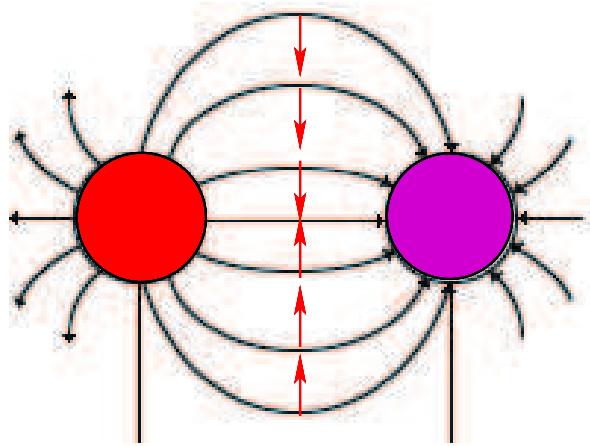


Fig. courtesy of G. Bali

lines of force for QCD



force $\sim$ const.; energy $\sim r$

- The gluon fields produce a flux-tube similar to a rubber band
- there is a lot of energy stored in the field!
- When separating two quarks the flux tube breaks

  Energy released produces a new $q\bar{q}$–pair $\rightarrow$ CONFINEMENT

Properties and Open questions

→ Confinement:

only color neutral objects travel long distances

→ Only certain quark/anti-quark combinations are allowed:

Mesons:

$\bar{q}q$ (regular), $\bar{q}\bar{q}qq$ (tetraquark), $\bar{q}\bar{q}\bar{q}qqq$ (baryonium), ...
GG, GGG, ... (glueball)

Baryons:

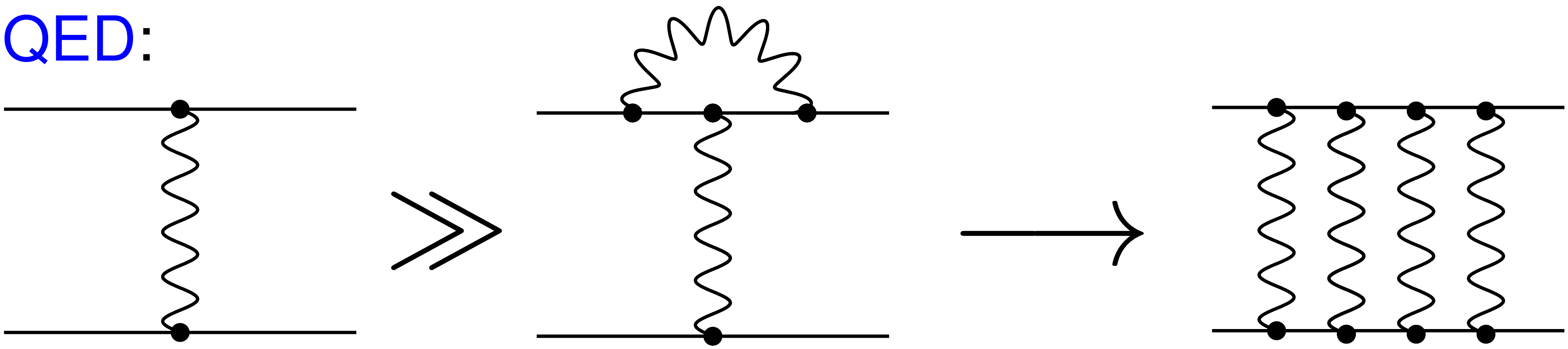
qqq (regular), $\bar{q}qqqq$ (penta-quark), $qqqqqq$ (di-baryon), ...

All those are expected; ~~only regular ones observed~~

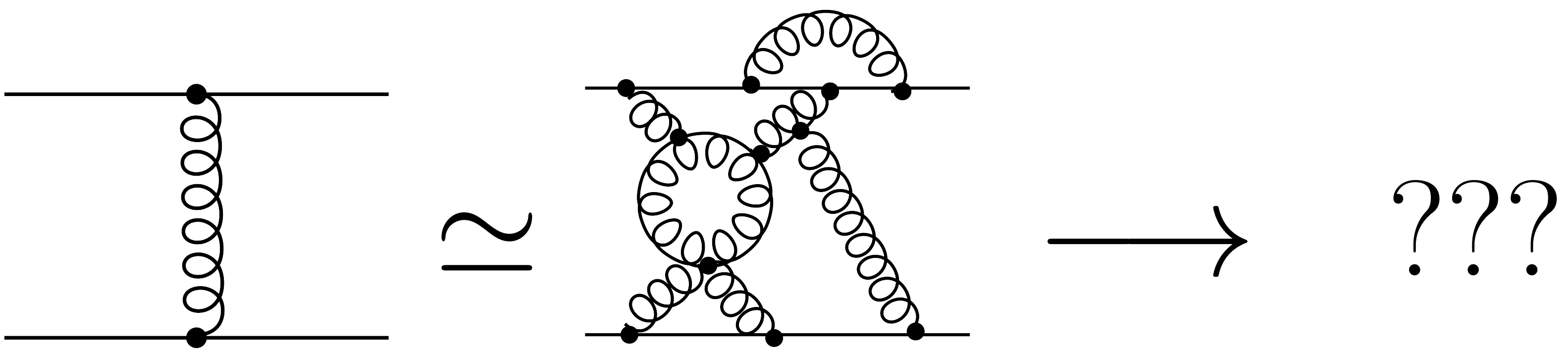
The problem:

Potential Bound states

QED:



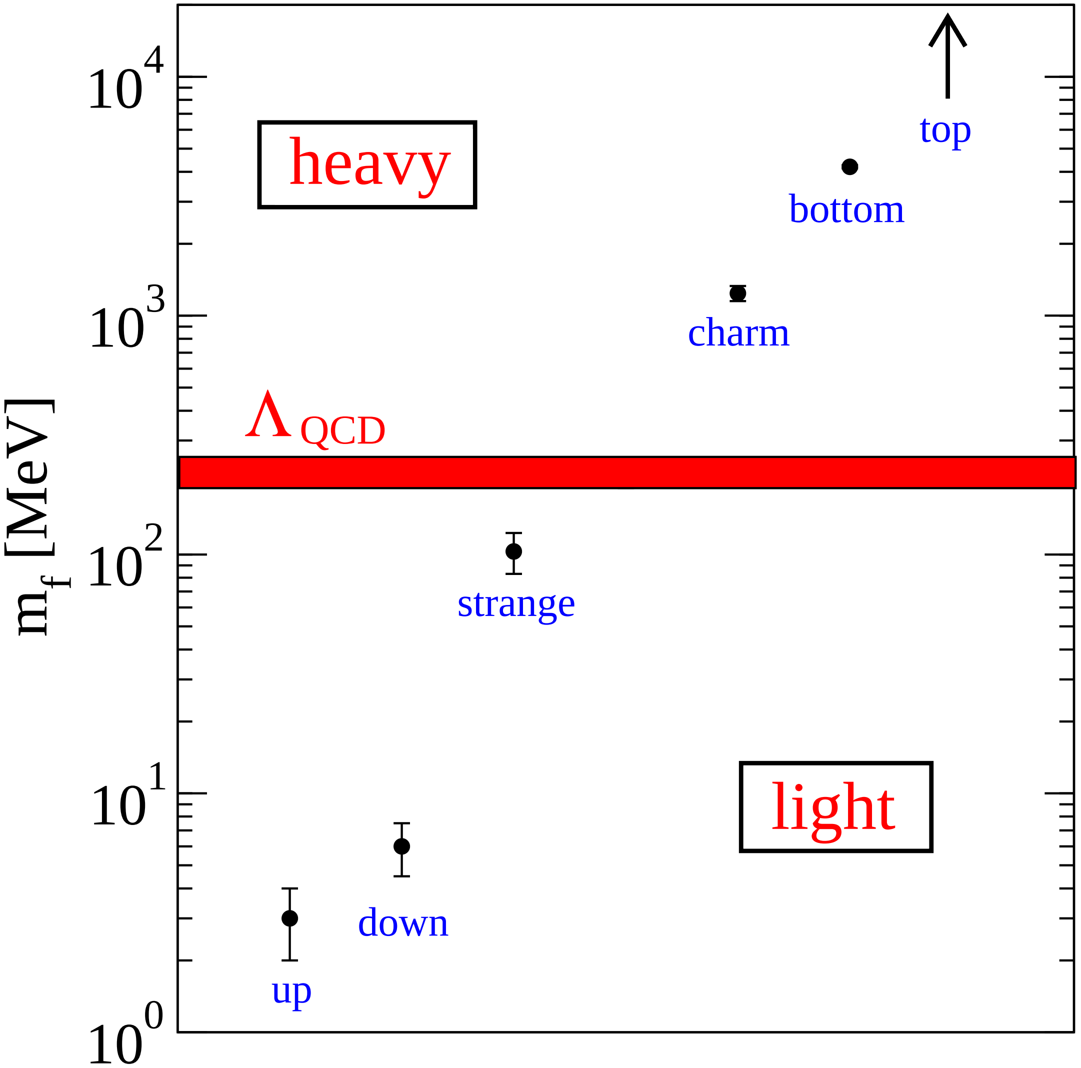
QCD at intermediate or large distances:



exception: low lying states between heavy quarks (see below)

Quark Masses

Quark Masses (in $\overline{\mathrm{MS}}$ at μ=2 GeV)



Particle Data Group (2008)

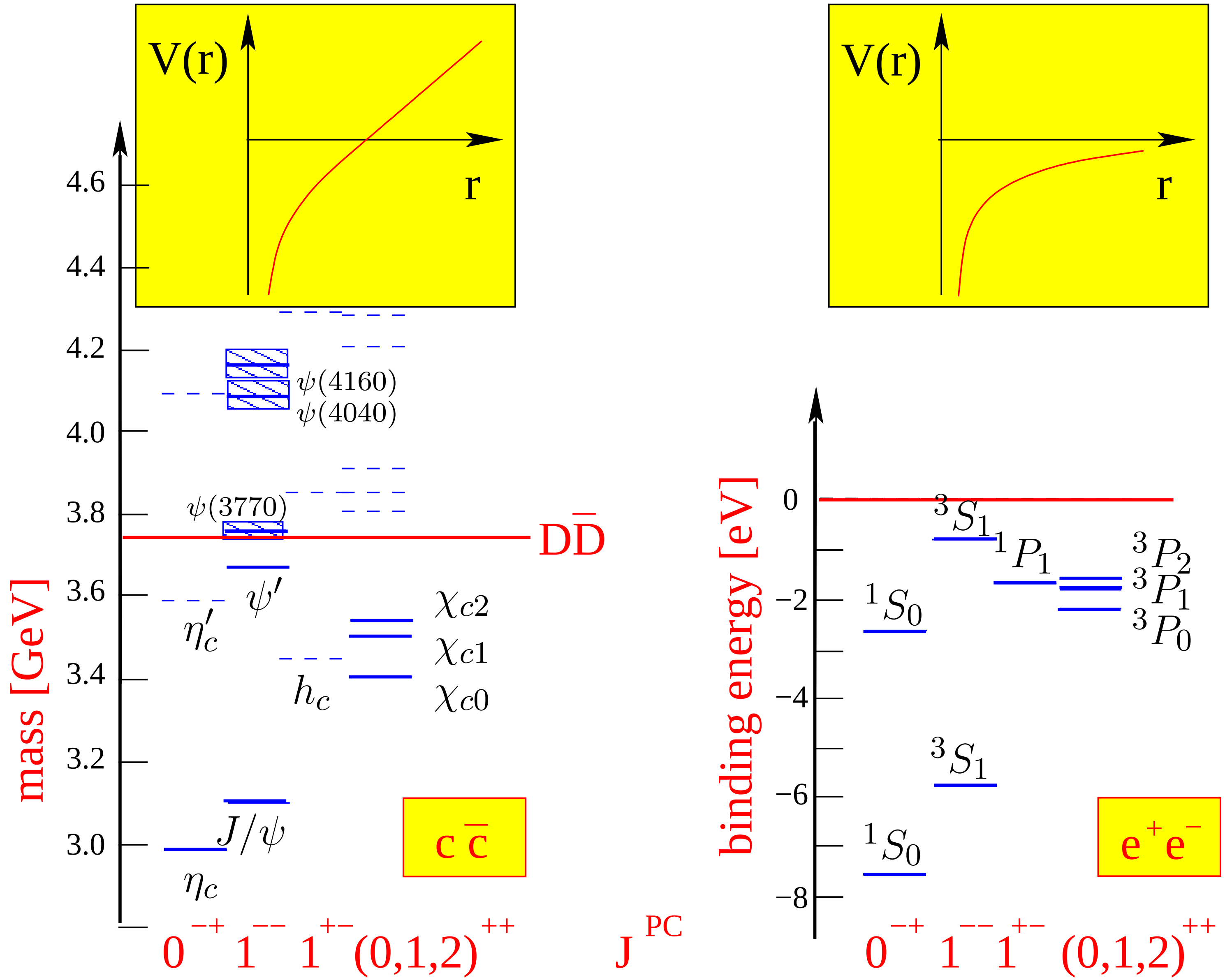
Expect very different phenomena for light (u,d,s) and heavy (c,b) quarks

- What are the spectra? Where are the poles?
- What structures are there?

Study systematically particle properties, decays, and interactions!

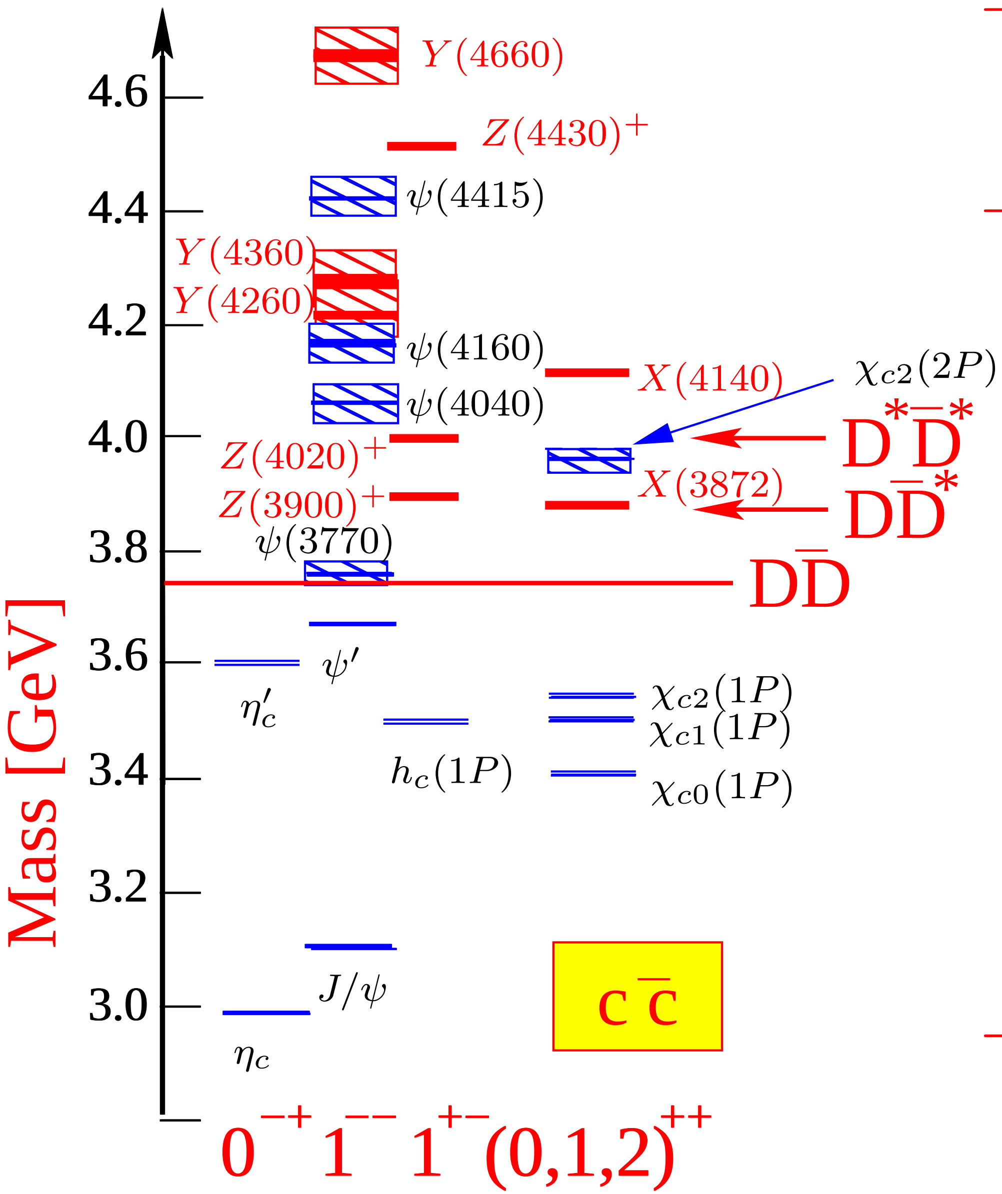
Charmonium before 2002

Quark-Model: Eichten et al. PRD 17 (1978)



Charmonium after 2002: XYZ-states

A new particle Zoo!



→ missing low lying states found

→ Above the $\bar{D}D$ threshold:

- ▷ Many new states (24 claimed, 10 estd.)
- ▷ most of them incompatible with quark model in mass & properties (22 of 24, 8 of 9)

→ Two states in bottomonium-sector

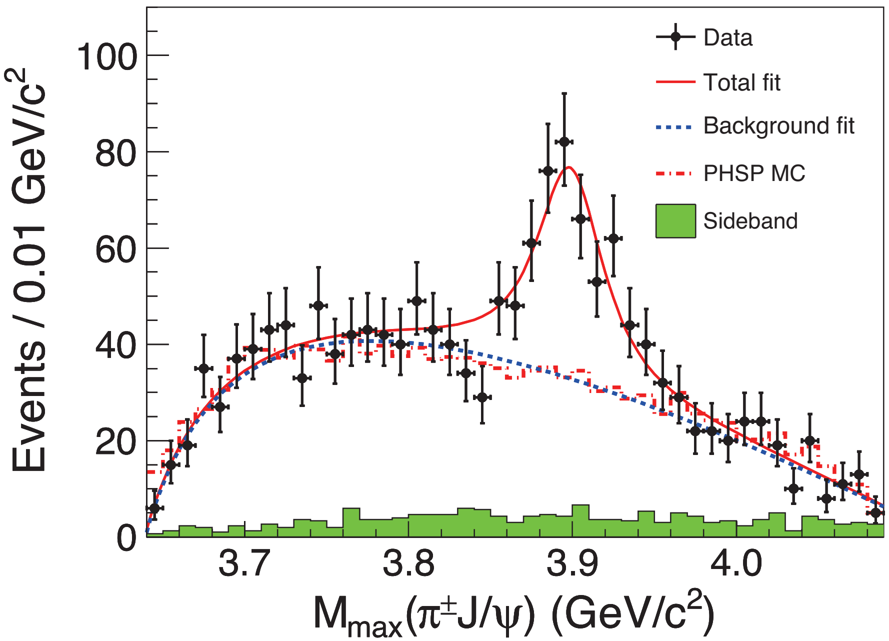
Explicit Exotics: Z-states

2012: Discovery of charged states at Belle in $\Upsilon(5S) \to [(\bar{Q}Q)\pi]\pi$

$\to$ must contain sizable $\bar{Q}$ and Q

$\to$ must contain light quarks;

$\to$ must contain at least 4 quarks



Example: $Z_c(3900)$

close to $\bar{D}D^*$ threshold

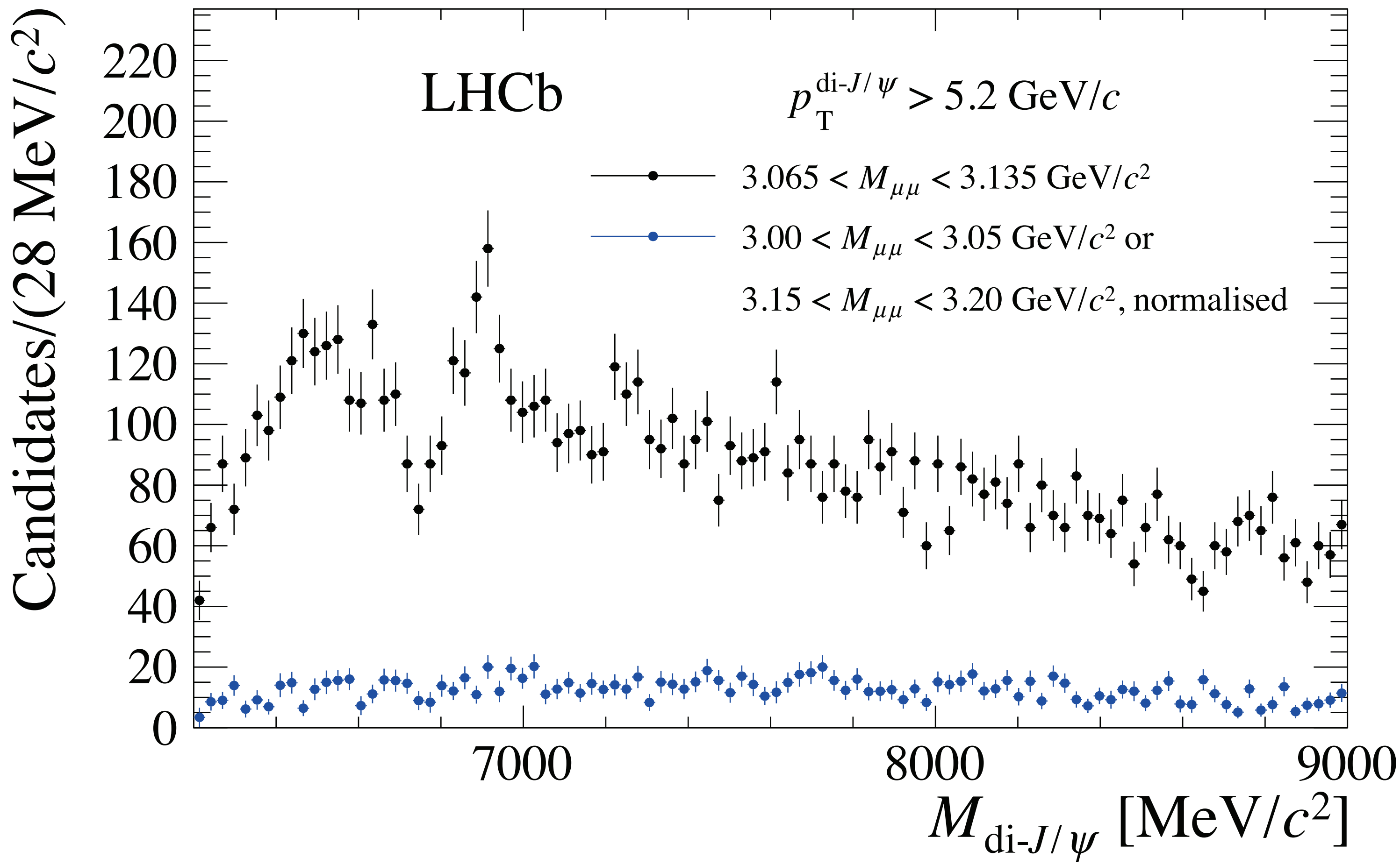
Data:

BES-III (China), 2013

Analogously: States seen in $J/\psi p$ channel must be Pentaquarks

Discovered by LHCb in 2015 and 2019 in $\Lambda_b^0 \to K^- J/\psi p$

... and beyond



LHCb 2020, arXiv:2006.16957

→ Clear structures found in $J/\psi J/\psi$ final state (above 5σ)

→ Must contain (at least) $\bar{c}\bar{c}cc$

Proposals

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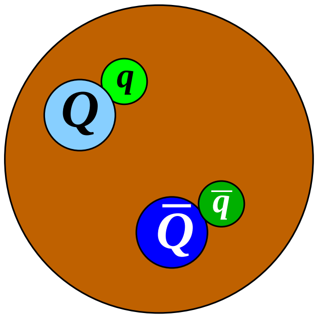
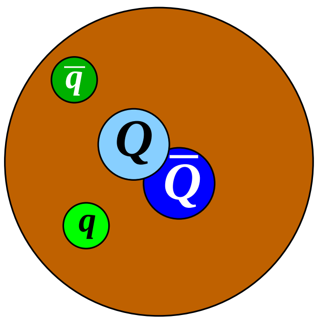
Focus: Multi-Quark States



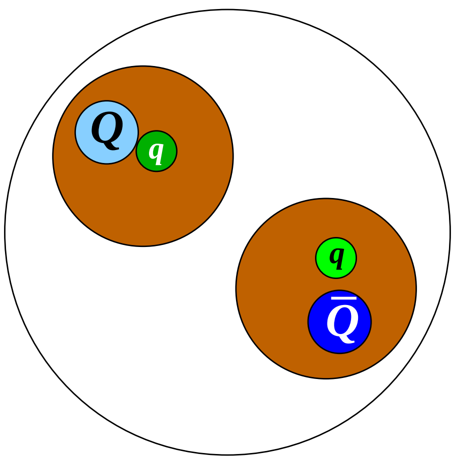
Tetraquark

→ Compact object formed from (Qq) and $(\bar{Q}\bar{q})$



Hadro-Quarkonium

→ Compact $(\bar{Q}Q)$ surrounded by light quarks



Hadronic-Molecule

→ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

Bohr radius = $1/\gamma = 1/\sqrt{2\mu E_b}$

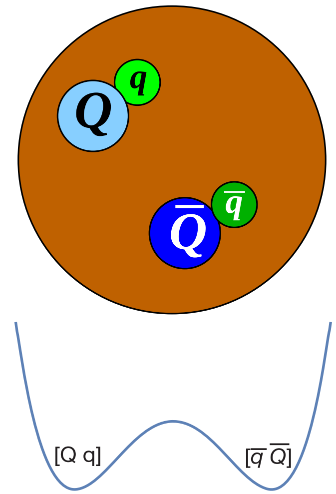
$\gg 1$ fm $\gtrsim$ confinement radius

for near threshold states

Heavy Tetraquarks

→ Straightforward extension of the quark model

M. Gell-Mann, PL8(1964)214



→ Mesons as diquark–anti-diquark systems

Jaffe, PRD15(1977)267, Maiani et al., PRD71(2005)014028

→ To account for spectrum spin-spin interaction needs to be dominant within diquarks

Maiani et al. PRD89(2014)114010

→ Separated by potential well

Selem and Wilczek, hep-ph/0602128; Maiani et al., PLB778(2018)247

alternative approaches, e.g., Cui et al., HEPNP31(2007)7; Stancu, JPG37(2010) 075017

→ and tensor force, S_{12}, needed

Ali et al. EPJC78(2018)29

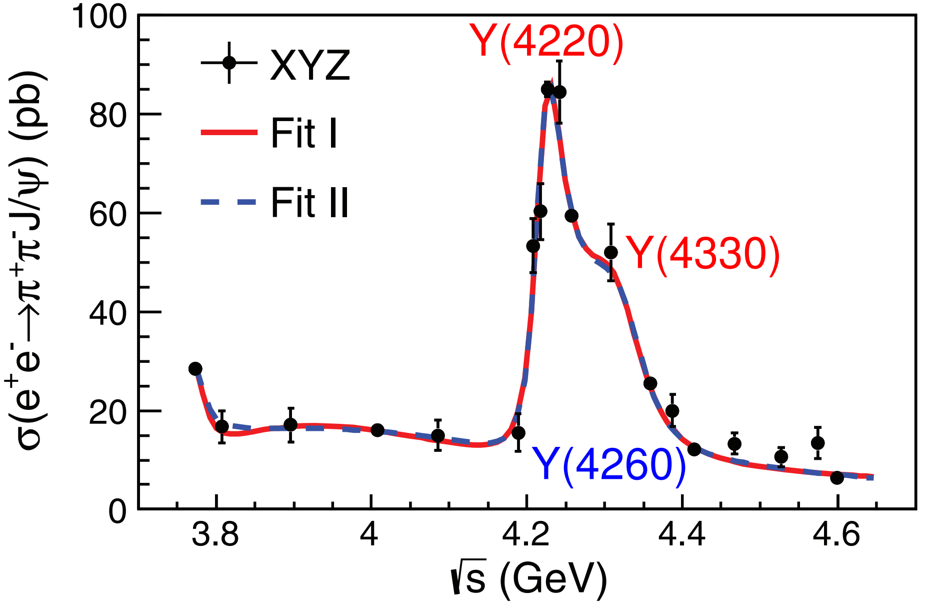
$$M = 2M_{\mathcal{Q}} + \frac{B_{\mathcal{Q}}}{2}\mathbf{L}^2 + 2a_Y \mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4}S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)$$

- Already many ground states
- Each level has isovector and isoscalar state ($cf.$ ρ and ω)

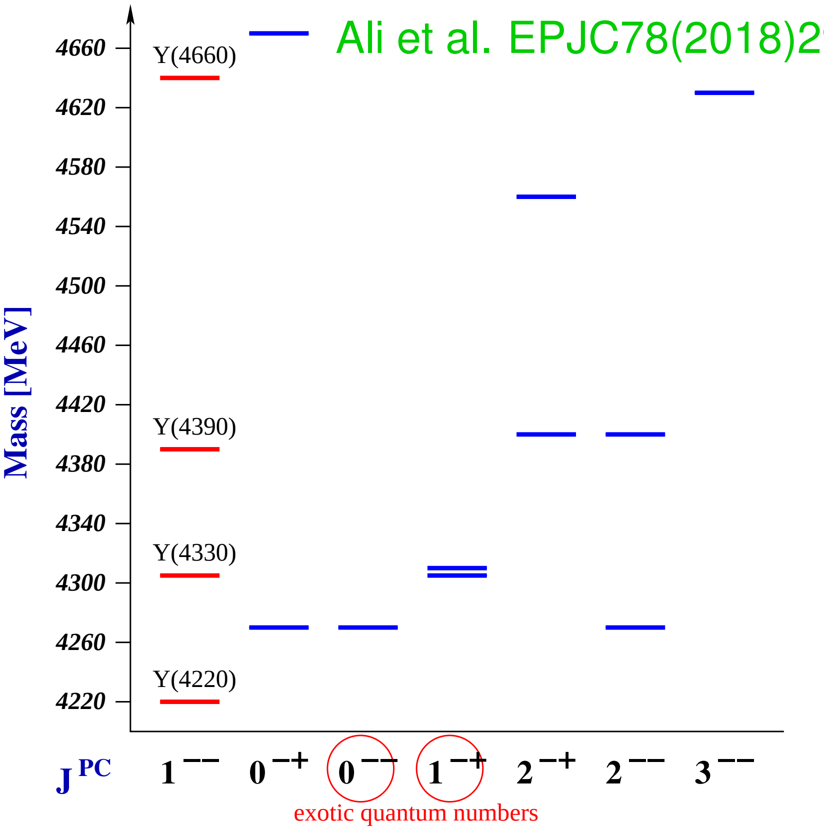
Results for negative parity states

→ four 1^{--} ground states

→ BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001



→ Threshold proximities accidental?

→ Many more states predicted than observed!

Maybe since di-quark picture too restrictive/constraining?

Extension of potential needed?

Richard et al., PRD95(2017)054019

J.F. Giron, R.F. Lebed, PRD102(2020)1

$QQ\bar{q}\bar{q}$ tetraquarks

Recently growing number of claims for those tetraquarks, e.g.

$\rightarrow$ from QCD sum rules — Du et al., PRD87(2013)014003

$\rightarrow$ from lattice QCD — Francis et al. PRL118(2017)142001

$\rightarrow$ from phenomenology — Ader et al., PRD 25(1982)2370

Karliner and Rosner, PRL119(2017)202001; Eichten and Quigg, PRL119(2017)202002

E.g. from the last work

$$m(QQ\bar{q}\bar{q}) - m(QQq) \simeq m(\bar{Q}\bar{q}\bar{q}) - m(\bar{Q}q)$$

exploiting heavy quark-diquark symmetry:

expansion in $r_{QQ}/r_q \sim \Lambda_{\rm QCD}/(M_Q v)$ — Savage and Wise, PLB248(1990)177

Once $m(QQq)$ is fixed from data or phenomenology,

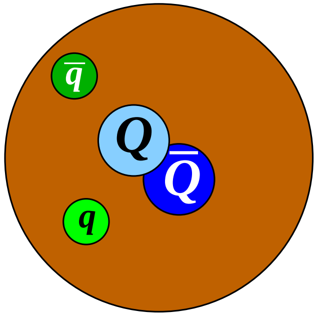
$\Longrightarrow m(QQ\bar{q}\bar{q})$ can be predicted.

$\rightarrow J^P = 1^+$ $(bb\bar{u}\bar{d})$ system $130 - 215$ MeV below BB^* threshold

Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455

→ Extra states are viewed as compact $\bar{Q}Q$ surrounded by light quarks

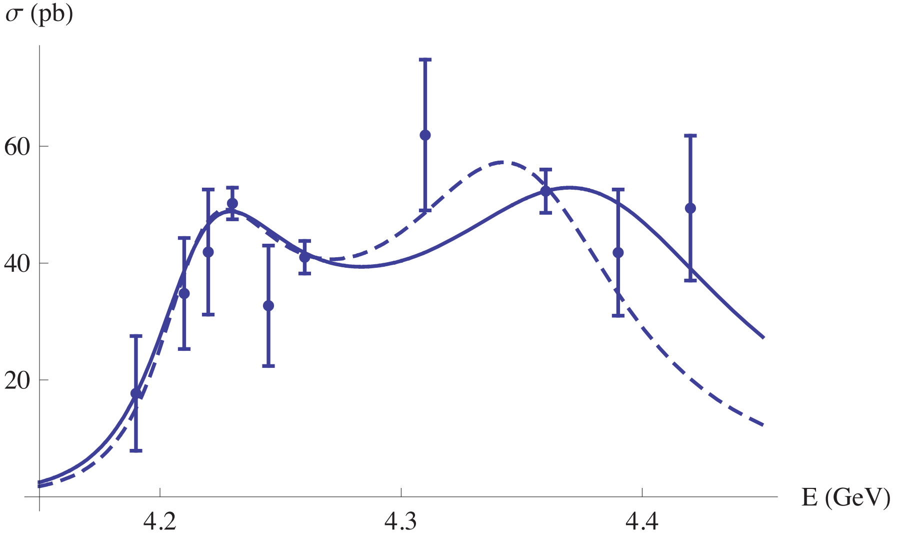


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ Heavy quark spin symmetry demands that spin of the core is conserved in decay to charmonia

→ Explaining $e^+e^- \to h_c\pi\pi$ needs mixing between states with $s_{\bar{c}c} = 0$ and $s_{\bar{c}c} = 1$ leading to $Y(4260)$ and $Y(4360)$

Li & Voloshin MPLA29(2014)1450060



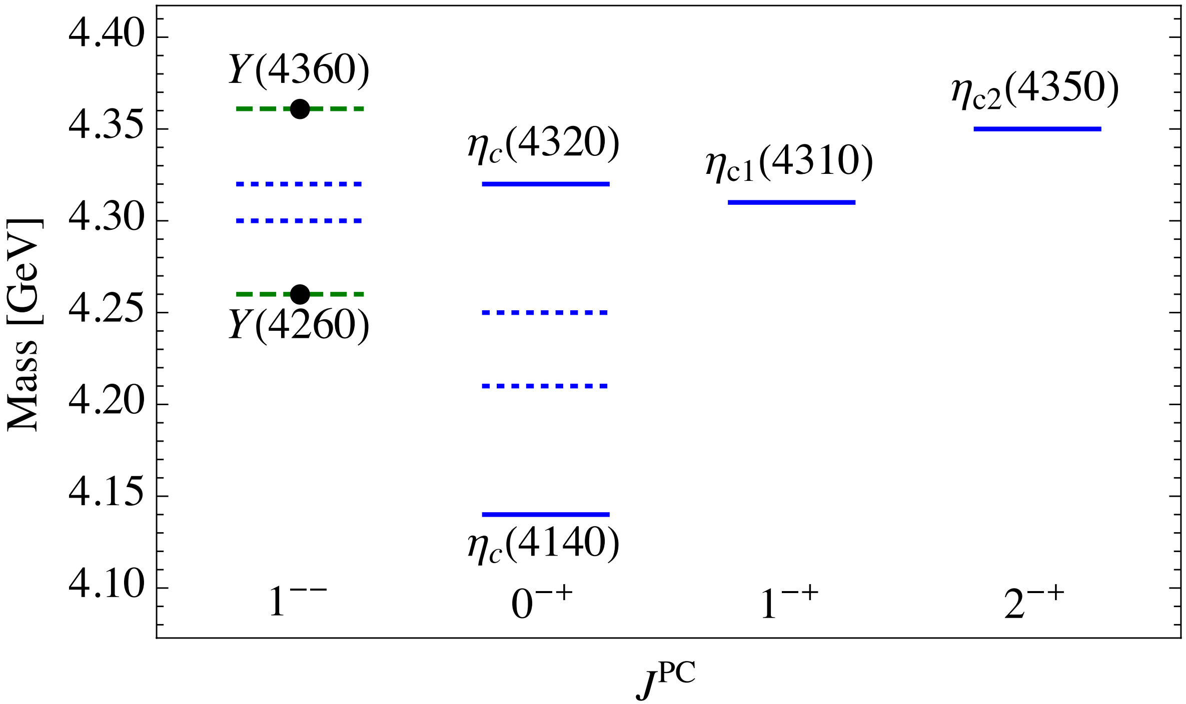
Hadrocharmonium: new states

The above mentioned mixing suggests for the unmixed states:

$$\Psi_3 \sim (1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}} \qquad \Psi_1 \sim (1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}} \ ,$$

where the heavy cores are ψ' and h_c.

$\longrightarrow$ get spin partners via $\psi' \to \eta_c'$ and $h_c \to \{\chi_{c0},\ \chi_{c1},\ \chi_{c2}\}$

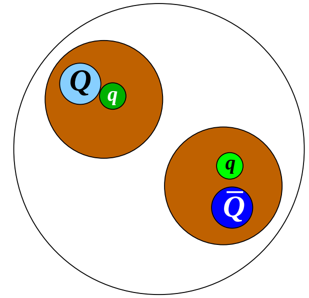


Cleven et al., PRD 92(2015)014005

Special feature: very light 0^{-+} state that should not decay to $D^*\bar{D}$

Hadronic Molecules

recent review article: Guo et al., Rev. Mod. Phys. 90(2018)015004



→ are few-hadron states, bound by the strong force

→ do exist: light nuclei.
e.g. deuteron as pn & hypertriton as Λd bound state

→ are located typically close to relevant continuum threshold;
e.g., for $E_B = m_1 + m_2 - M$ ($\gamma = \sqrt{2\mu E_B}$ $\mu = m_1 m_2/(m_1+m_2)$)

- ▷ $E_B^{\rm deuteron} \; = \; 2.22$ MeV ($\gamma = 40$ MeV)
- ▷ $E_B^{\rm hypertriton} = (0.13 \pm 0.05)$ MeV (to Λd) ($\gamma = 26$ MeV)

→ can be identified in observables (Weinberg compositeness):

$$\frac{g_{\rm eff}^2}{4\pi} = \frac{4M^2\gamma}{\mu} X_W \text{ with } a = -2\left(\frac{X_W}{1-X_W}\right)\frac{1}{\gamma}\;;\; r = -\left(\frac{1-X_W}{X_W}\right)\frac{1}{\gamma}$$

where compositness X_W=probability to find molecular component in bound state wave function

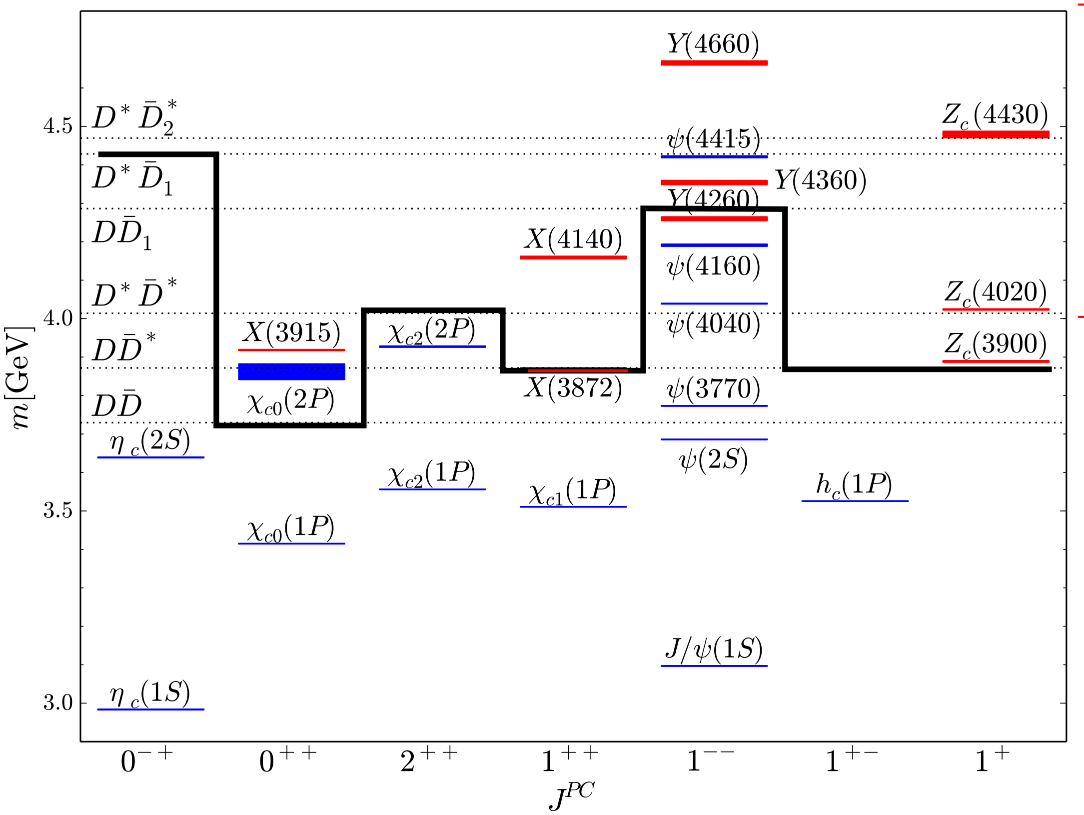
Are there mesonic molecules?

General considerations

Constituents must be narrow. Heavy candidates (M, Γ in MeV)

$D\ (0^-, M = 1865, \Gamma \simeq\ 0)$; $D^*(1^-, M = 2007, \Gamma \simeq 0.1)$
$D_1(1^+, M = 2420, \Gamma \simeq 30)$; $D_2^*(2^+, M = 2460, \Gamma \simeq 50)$

$D_0(2400)$ and $D_1(2430)$ with $\Gamma = 300$ MeV too broad ...



→ Explains mass gap between $J^P = 1^+$ and 1^- states:

$M_{Y(4260)} - M_{X(3872)}$=388 MeV
$\simeq M_{D_1(2420)} - M_{D^*}$=410 MeV

→ Predicts, e.g.,
$M(0^-) - M(1^-) \simeq$
$M_{D^*} - M_D \simeq +100$ MeV,
if it exists

Note: for hadrocharmonium:
$M(0^-) - M(1^-) \simeq -100$ MeV

Cleven et al., PRD 92 (2015) 014005

Example:

Lets investigate the implications of the molecular assignments:

→ the isoscalar 1^{++} state $\chi_{c1}(3872)$ aka $X(3872)$ as

$$X \sim \frac{1}{\sqrt{2}}(D^{*\,+}D^- + D^{*\,0}\bar{D}^0)$$

→ the isoscalar $J^{PC} = 1^{--}$ state $\psi(4260)$ aka $Y(4260)$ as

$$Y(4260) \sim \frac{1}{\sqrt{2}}(D_1(2420)\bar{D} - D\bar{D}_1(2420))$$

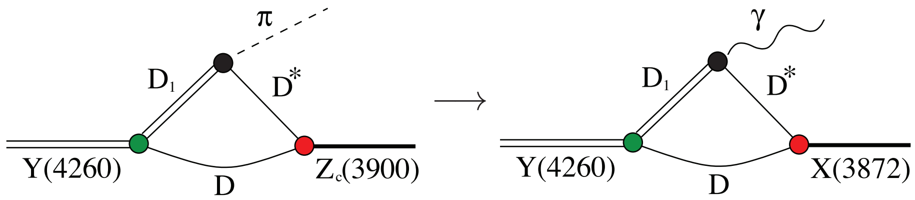
→ the isovector $J^{PC} = 1^{+-}$ states $Z_c(3900)$ as

$$Z_c^+ \sim D^{*\,+}\bar{D}^0\,, \quad Z_c^0 \sim \frac{1}{\sqrt{2}}(D^{*\,+}D^- - D^{*\,0}\bar{D}^0)\,, \quad Z_c^- \sim D^{*\,-}D^0$$

Decays

→ Natural explanation for $Y(4260) \to \pi Z_c(3900)$ and

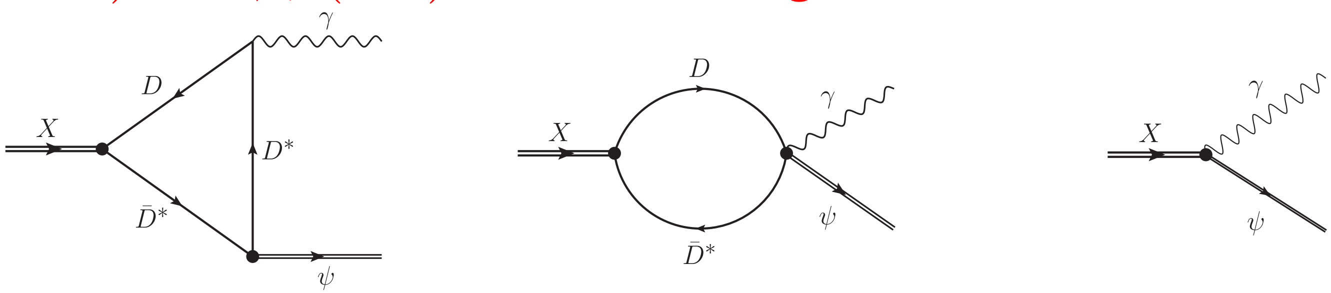
Wang, C. H., Zhao, PRL111 (2013) no.13, 132003



prediction of $Y(4260) \to \gamma X(3872)$ Guo et al., PLB 725 (2013) 127-133

confirmed at BESIII Ablikim et al. PRL 112 (2014), 092001

→ Not all observables sensitive to molecular component!
e.g. $X(3872) \to \gamma\psi(nS)$ has leading order counter term



In particular: $$R = \frac{\mathcal{B}(X(3872) \to \gamma\psi')}{\mathcal{B}(X(3872) \to \gamma J/\psi)} \simeq 2.5$$ Aaij et al. [LHCb], NPB 886 (2014) 665

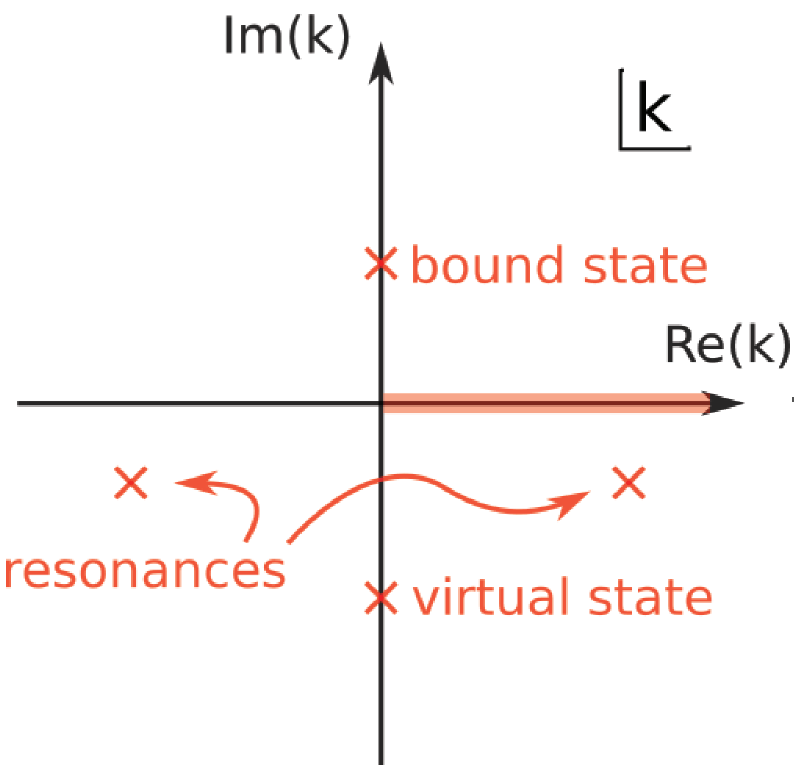
can be easily described within molecular approach

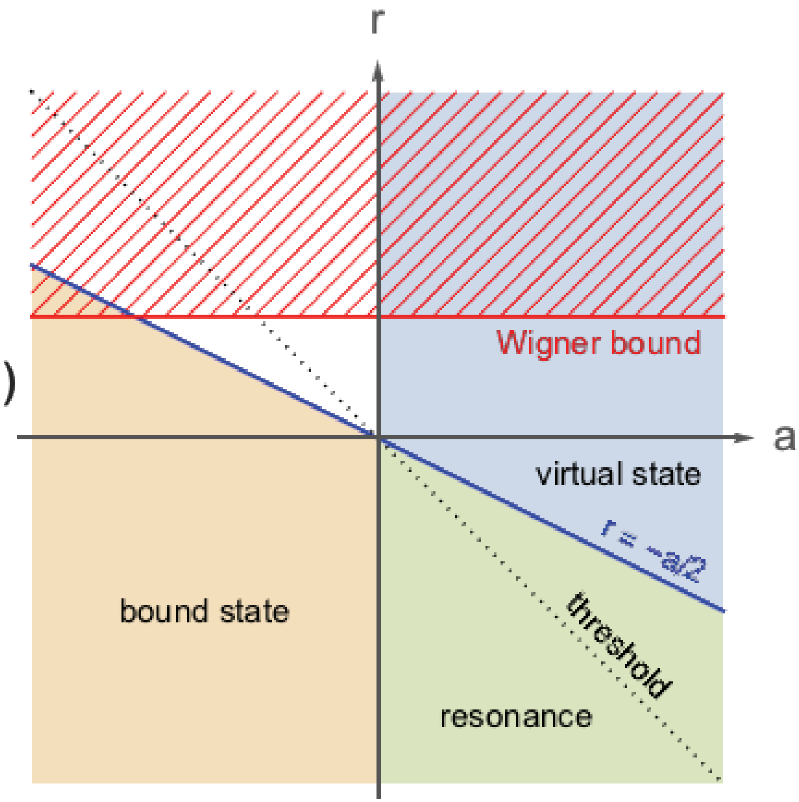
Guo et al., PLB 742 (2015) 394

Generalisation of Weinbergs analysis

I. Matuschek et al., arXiv:2007.05329

Model independent criterion for virtual states and resonances





$T(E) = -(2\pi/\mu)1/(1/a + (r/2)k^2 - ik)$, with $k = \sqrt{-2\mu E}$

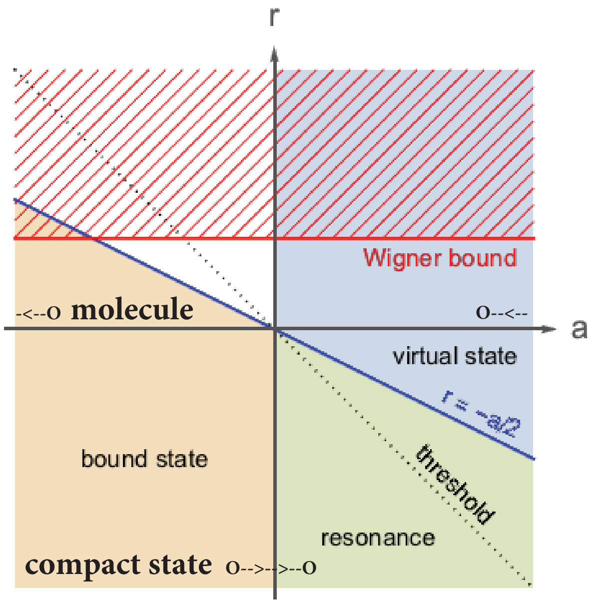
Poles at

$$k = \frac{i}{r}\left(1 \pm \sqrt{1 + \frac{2r}{a}}\right)$$

Generalisation of Weinbergs analysis

I. Matuschek et al., arXiv:2007.05329

Assume attractive interaction (bound state $a<0$, all others $a>0$)



Weinberg (for bound states):

Molecules:

$|a| \gg |r|$ and $|r| \simeq$ range

Compact states:

$|a| \ll |r|$ and $r < 0$ with $|r| \gg$ range

What happens when a changes sign? (r fixed)

Molecule: turns into a virtual state (and eventually a resonance)

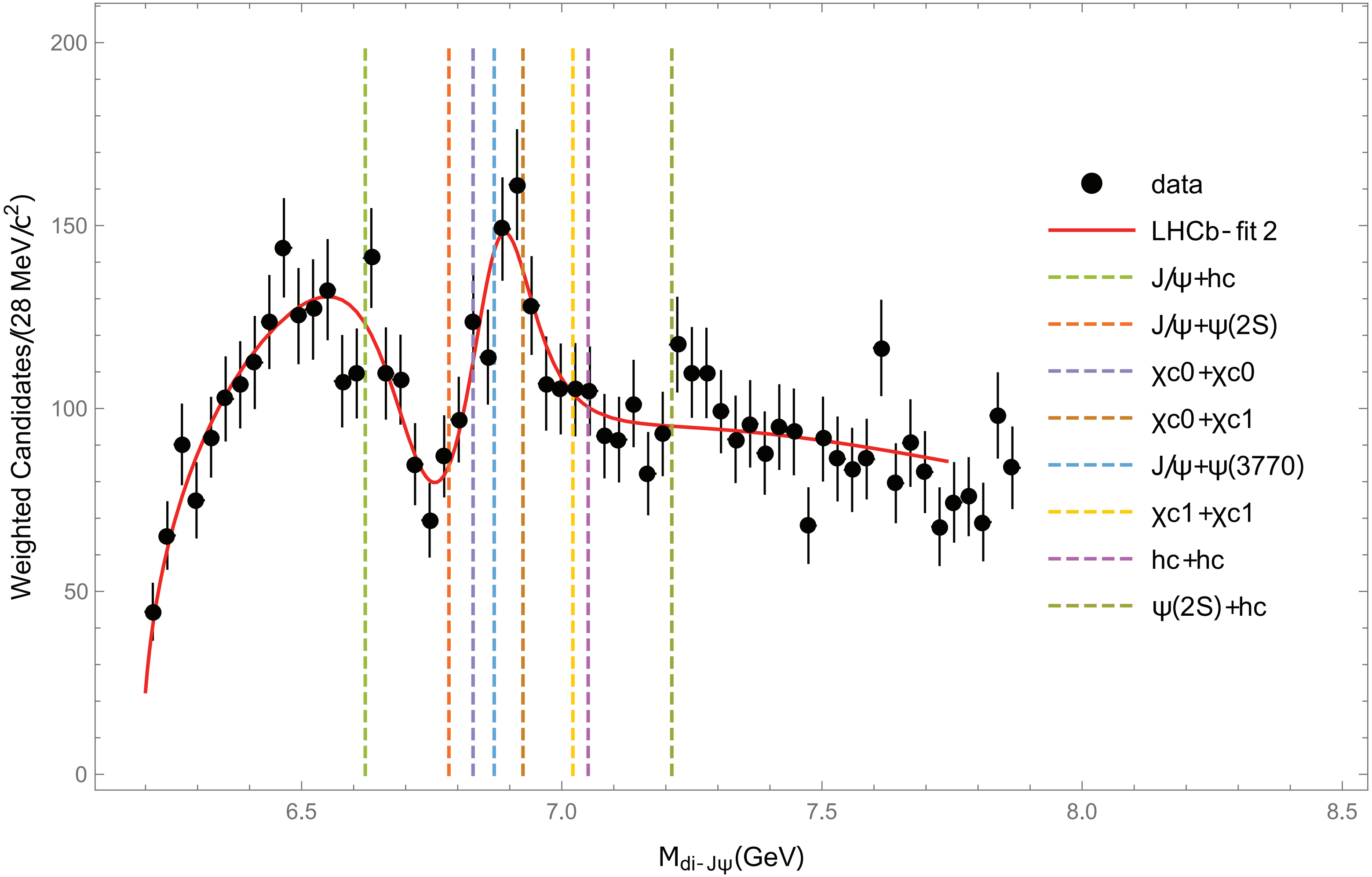
Compact state: turns into a resonance directly

Subsummed in compositness: $\bar{X}_A = 1/\sqrt{1+|2r/a|}$

other approaches: Sekihara, Hyodo, Oset, Oller, Nieves, Jido ...
mostly relying on on-shell factorisation of the potential; little about virtual states

Back to the double J/ψ spectrum

Are these states tetraquarks or molecules?
There are many thresholds in the mass range:



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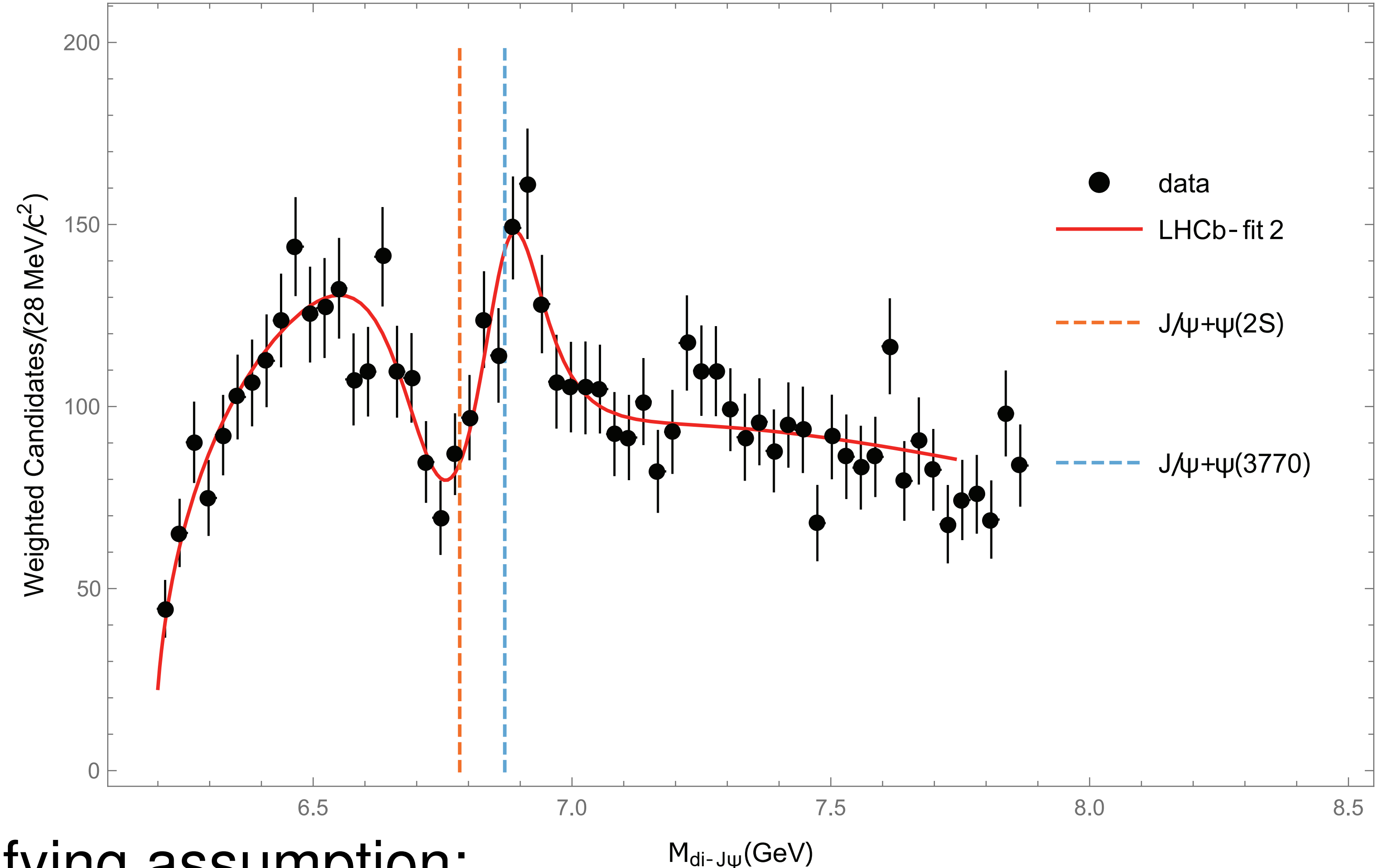


Simplifying assumption:

only vector-vector channels matter

Two models

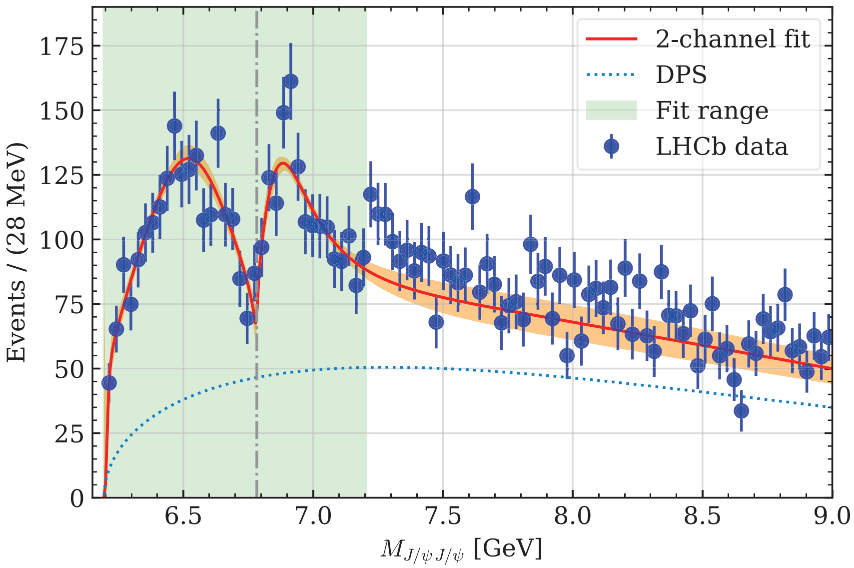
JÜLICH Forschungszentrum

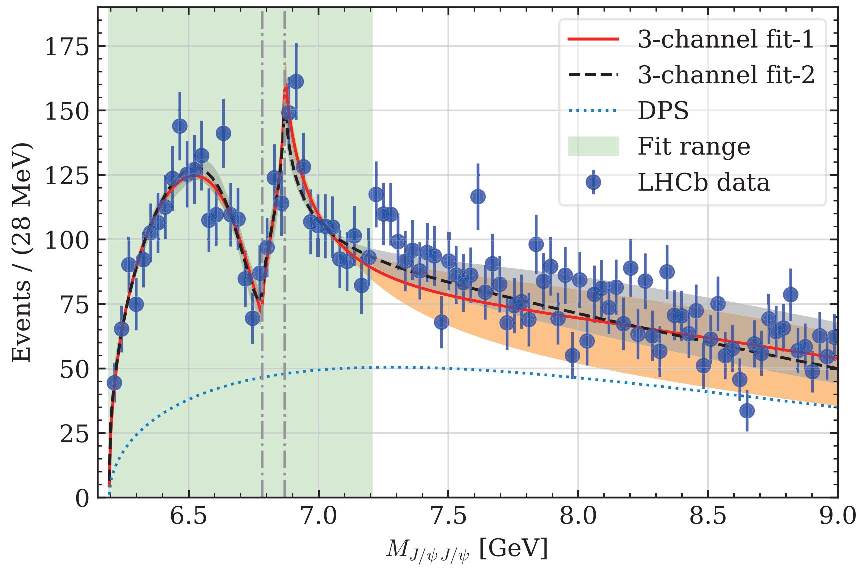
Xiang-Kun Dong et al., arXiv:2009.07795

We calculate $T(E) = V(E) \cdot [1 - G(E)V(E)]^{-1}$, with either

$$V_{2\text{ch}}(E) = \begin{pmatrix} a_1 + b_1 k_1^2 & c \\ c & a_2 + b_2 k_2^2 \end{pmatrix} \text{ or } V_{3\text{ch}}(E) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix},$$

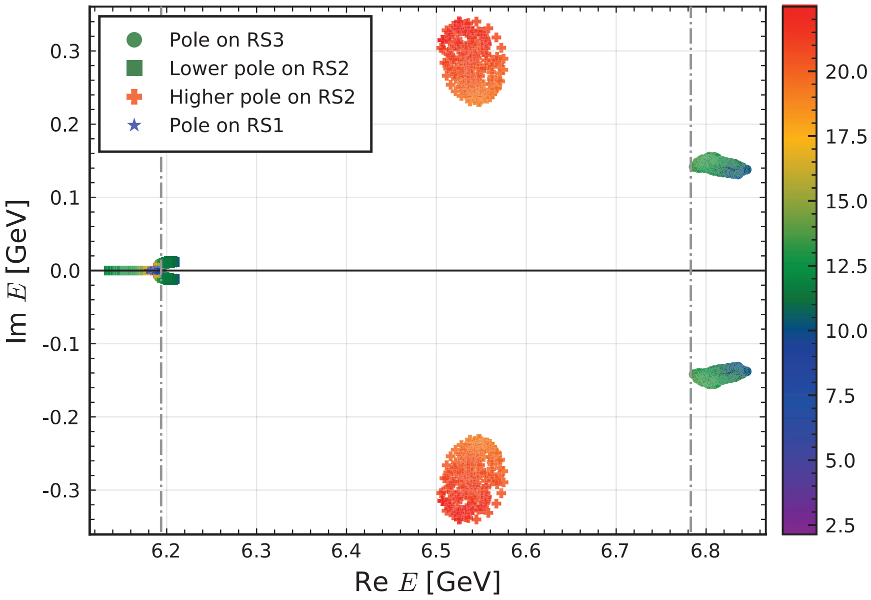
where the $J/\psi J/\psi$, $\psi(3686)J/\psi$ (and $\psi(3770)J/\psi$) were included





Both models provide excellent description of data

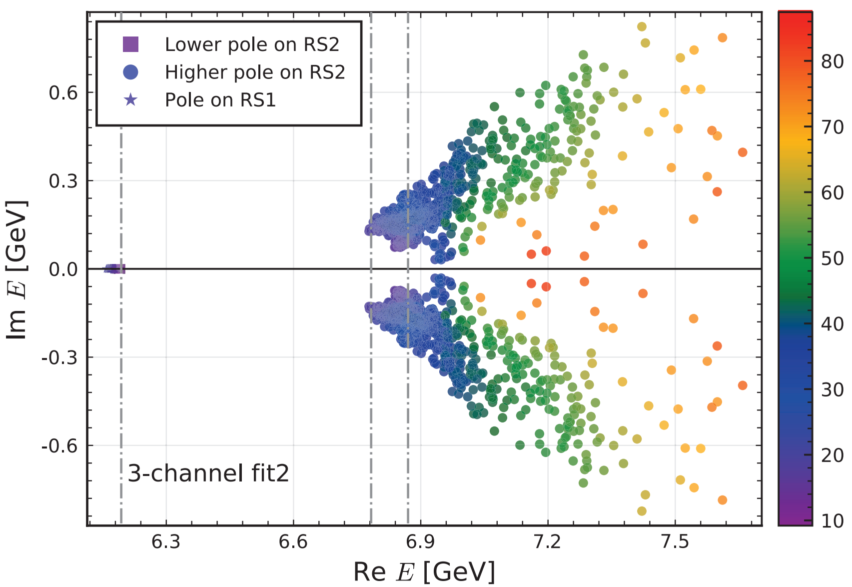
The pole structure is very different:



In total 3 states:

1 close to $J/\psi J/\psi$-thresh.,

2 to produce structures
(via interplay with threshold)



In total 2 states

1 close to $J/\psi J/\psi$-thresh.,

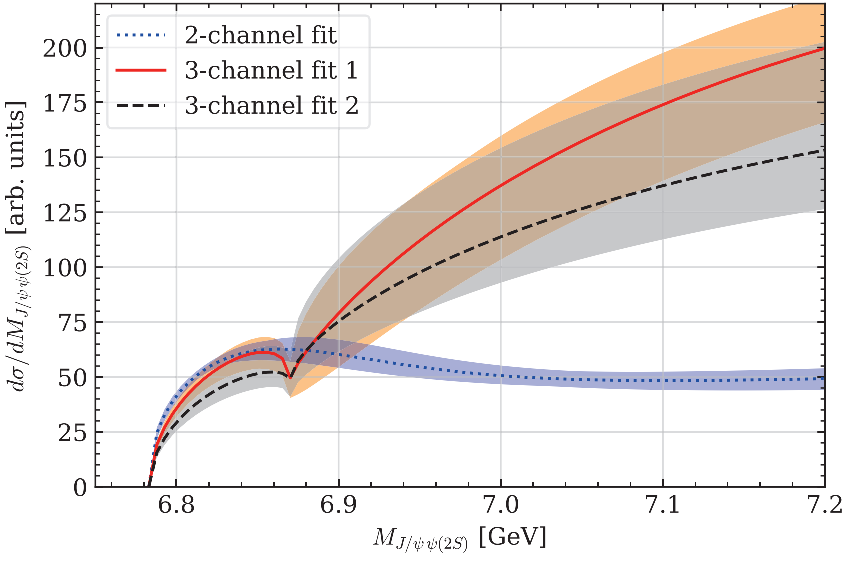
1 to produce structures
(via interplay with thresholds)

Discussion

Very close to threshold state always present!

	2-ch. fit	3-ch. fit 1	3-ch. fit 2
$a(\mathrm{fm})$	≤ -0.49 or ≥ 0.48	$-0.61^{+0.29}_{-0.32}$	≤ -0.60 or ≥ 0.99
$r(\mathrm{fm})$	$-2.18^{+0.66}_{-0.81}$	$-0.06^{+0.03}_{-0.04}$	$-0.09^{+0.08}_{-0.05}$
$\bar{X}_A$	$0.39^{+0.58}_{-0.12}$	$0.91^{+0.04}_{-0.07}$	$0.95^{+0.04}_{-0.06}$

Different models give different nature of $J/\psi J/\psi$ state! E.g. two channel model consistent with compact and composite



The two scenarios can be easily distinguished!

e.g. via $\psi(2S)J/\psi$ final state

What is needed for further progress

→ Excellent data especially for different spin states (spin symmetry violation sensitive to the nature of a state)

→ More refined theory predictions with controlled uncertainties

- ▷ Role of the regular $\bar{q}q$ states?
  - do they mix in — E. Cincioglu et al., EPJC76(2016)576
  - or not? — I.K. Hammer, CH and A. V. Nefediev, EPJA 52(2016)330
- ▷ For molecules: How to construct the potential?
  - With pion exchange perturbative — J. Nieves, M.P. Valderrama, PRD84 (2011) 056015
  - or non-perturbative? — V. Baru et al., PRD84(2011)074029

Thanks a lot for your attention