Lecture 10

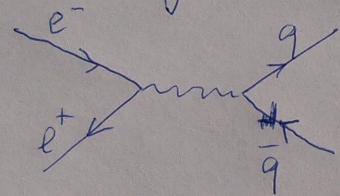
notes on QCD processes and factorization

the quark model and surprizes in hadron structure

Leading order QCD processes, factorization, and color

assume ultrarelativistic limit, $\beta \to 1$, massless fermions $f, \bar{f}$

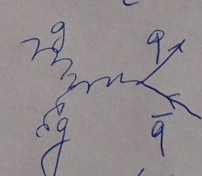
$e^+ e^- \to \gamma^* \to f \bar{f}$ (fermion pair) $\quad s = E_{cm}^2$



$$\frac{d\sigma}{d\Omega} = N_c \cdot \frac{\alpha^2}{4s} Q_f^2 \left[1 + \cos^2\theta \right]$$

the virtual photon couples to the quark charges
QCD enters via N_c = number of colors

analogously: $\quad q q \to q \bar{q}$

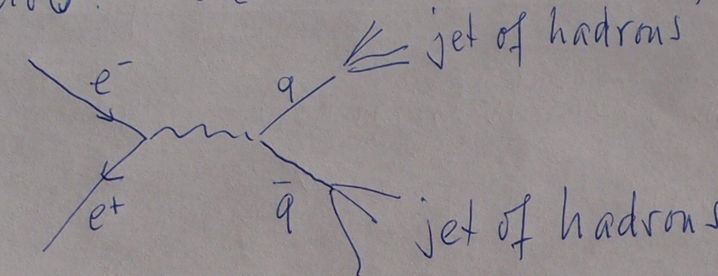


$t = -s \cdot \sin^2 \theta/2$
$u = -s \cos^2 \theta/2$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_s^2}{24 s} \left(t^2 + u^2 \right) \left(\frac{1}{t \cdot u} - \frac{9}{4 s^2} \right)$$

the gluon couples to the quark colors

now: $\sigma(e^+e^- \to \text{hadrons}) = \sigma(e^+e^- \to q\bar{q})$



2 jet production

every quark hadronizes into jet of hadrons

hadronization takes place well separated in time from the $q\bar{q}$ production, so $\sigma(e^+e^- \to \text{hadrons}) = \sigma(e^+e^- \to q\bar{q})$, the $q\bar{q}$ production 'factorizes' from the complicated process of hadron production, this is an example of factorization now R-factor: $R = \frac{\sigma_{e^+e^- \to hadrons}}{\sigma_{e^+e^- \to \mu^+\mu^-}}$

under factorization

$$R = R(Q^2 = s) = \frac{\sigma_{e^+e^- \to q\bar{q}}}{\sigma_{e^+e^- \to \mu^+\mu^-}} = N_c \cdot \sum Q_{quark}^2 \left(1 + \delta_{QCD}(Q^2)\right)$$

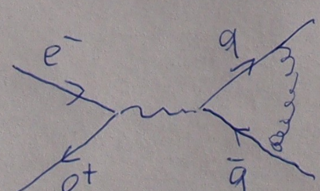
$$\delta_{QCD} = \sum_{n=1}^{\infty} c_n \cdot \left(\frac{\alpha_s(Q^2)}{\pi}\right)^n + \underbrace{\frac{1}{Q^4} \text{ correction}}_{\text{very small for large } Q^2}$$

the coefficients c_n have been computed up to $n = 4$

$c_1 = 1$, $c_2 = 1.9857 - 0{,}1152 \cdot n_f$

(number of quark flavors)

$n = 1$



$$\Rightarrow R_{n=1} = N_c \cdot \sum Q_{quark}^2 \left(1 + \frac{\alpha_s}{\pi}\right)$$

σ and R in e^+e^- Collisions

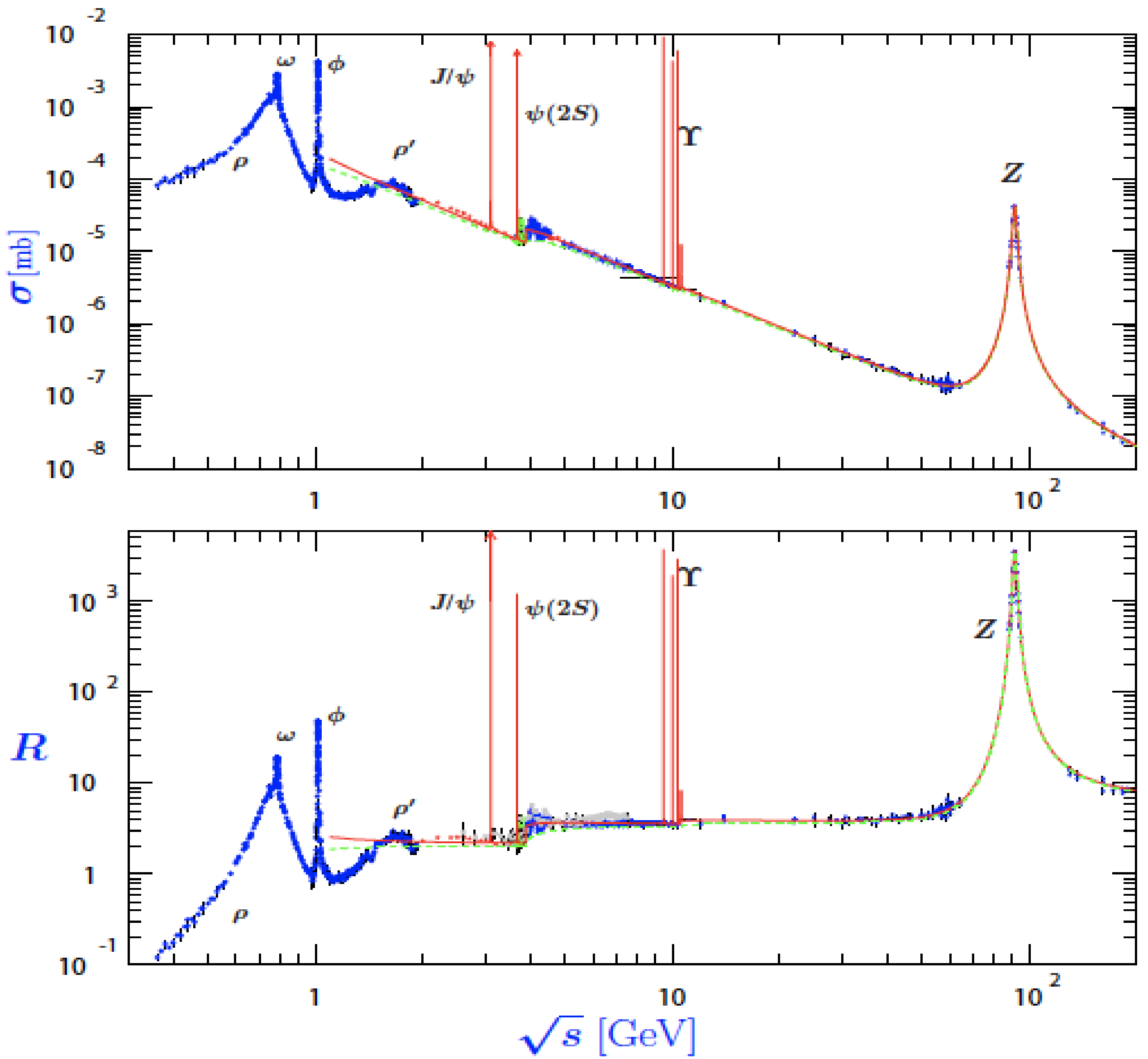


Figure 41.6: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see "Quantum Chromodynamics" section of this *Review*, Eq. (9.7) or, for more details, K. G. Chetyrkin *et al.*, Nucl. Phys. **B586**, 56 (2000) (Erratum *ibid.* **B634**, 413 (2002)). Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1, 2, 3, 4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in [arXiv:hep-ph/0312114]. Corresponding computer-readable data files are available at `http://pdg.lbl.gov/current/xsect/`. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, May 2010.) See full-color version on color pages at end of book.

here, N_c = 3 is assumed

Building mesons from quarks I

I : only light quarks u, d

mesons are bound states of $q\bar{q}$

quantum numbers of these mesons

l orbital ang. momentum

s spin $\vec{s} = \vec{1/2} + \vec{1/2}$

$\vec{J}$ total angular momentum $\vec{J} = \vec{s} + \vec{l}$

Parity P (see below)

Charge Parity C (see below)

meson wave function

$$\psi_{\ell J M_J P} = u_{n\ell}(r) \sum_{\substack{m_1 m_2 \\ m_s m_\ell}} (\tfrac{1}{2} m_1 \, \tfrac{1}{2} m_2 | s \, m_s) \cdot Y_{\ell m_\ell}(\Omega)$$

$$\times (\ell m_\ell \, s \, m_s | J M) \, | q(1) \rangle | \bar{q}(2) \rangle$$

this implies $|\ell - s| \le J \le \ell + s$

what is parity of this wave function?

$$P \, \psi(\vec{r}) = \psi(-\vec{r})$$

$$P^2 \psi = \psi \Rightarrow P = \pm 1$$

now

$$P \cdot \Psi_{\ell J M_J} = (-)^{\ell} \cdot (-1)$$

from $Y_{\ell m}$ from rel. parity of particles and antiparticles

$$P = (-)^{\ell+1}$$

the charge parity operator changes particle into antiparticle

so, from symmetry of Clebsch Gordan coefficients

$$C = (-)^{\ell+1} \cdot (-)^{S+1} = (-)^{\ell+S}$$

(note: change $q \leftrightarrow \bar{q}$ and relabel $1 \leftrightarrow 2$ in the wave function) now

$$P \cdot \psi_{\ell J M_J} = (-)^{\ell} \cdot (-1)$$

from $Y_{\ell m}$ — from rel. parity of particles and antiparticles

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(note: change $q \leftrightarrow \bar{q}$ and relabel $1 \leftrightarrow 2$ in the wave function)

Only neutral particles are eigenstates of C
also, for strong interactions electric charge is not visible so π^+, π^0, π^- are indistinguishable

therefore, define G parity

$$G = C \cdot e^{i\pi I_2}$$

$$\Rightarrow G \begin{Bmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{Bmatrix} = \eta_G \cdot \begin{Bmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{Bmatrix}$$

$$\eta_G = C \cdot (-)^I \qquad I : \text{isospin}$$

for $q\bar{q}$ systems $\eta_G = (-)^{S+L+I}$

so $\eta_G = -1$ for π

Application to pseudoscalar and pseudovector mesons

further rules

since $P = (-)^{\ell+1}$ $\Rightarrow$ states with $P = (-)^J$

must have $S = 1$ (for $S = 0$ $J = \ell$ and $P = (-)^{J+1}$)

$\Rightarrow$ such states have $C \cdot P = (-)^{\ell+1} \cdot (-)^{\ell+1} = +1$

consequently all states with $P = (-)^J$ and $C \cdot P = -1$ are forbidden in the $(q\bar{q}')$ model

These states are:

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

Also, for $J = 0$, $\ell = S$ implying $\ell = 0$ or 1

for $\ell = 0 \Rightarrow S = 0 \Rightarrow P = -1, C = +1$ so $J^{PC} = 0^{--}$ is also forbidden all mesons can be classified in J^{PC} multiplets

for $\ell = 0$ $= \begin{cases} 0^{-+} & \text{pseudoscalars} \\ 1^{--} & \text{vectors} \end{cases}$

for $\ell = 1$ $= \begin{cases} 0^{++} & \text{scalars} \\ 1^{++}, 1^{+-} & \text{axial vectors} \\ 2^{++} & \text{tensors} \end{cases}$

states with $P = (-)^J$ are called natural spin parity states

radial excitations (nodes in the bound state radial wave function) are classified by radial quantum number n

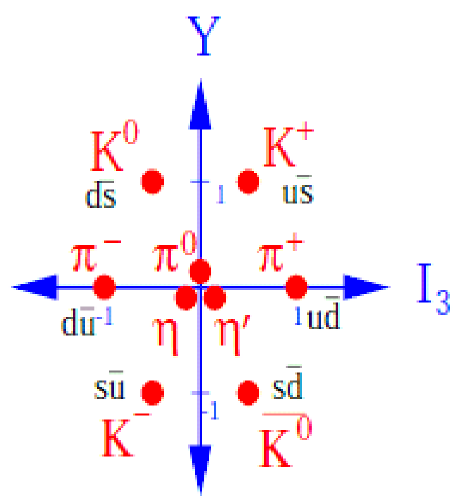
b) application to decays of
pseudo-scalar and vector
mesons

remember: hypercharge Y
$Y = B + S$
and charge q
$q = I_3 + Y/2$

Under the quark hypothesis the mesons are $q\bar{q}$ states. With 3 flavours, u, d, s we have 9 combinations $q\bar{q}$.

- The pseudoscalar nonet $J^P = 0^-$ are 9 states with spins ↑↓ (L=0)
- The vector nonet $J^P = 1^-$ are 9 states with spins ↑↑ (L=0)

<u>Pseudoscalar Mesons</u>



$m(K^0)$, $m(\overline{K^0})$	497.7 MeV
$m(K^+)$, $m(K^-)$	493.7 MeV
$m(\pi^+)$, $m(\pi^-)$	139.6 MeV
$m(\pi^0)$	135.0 MeV
$m(\eta)$	547.5 MeV
$m(\eta')$	957.8 MeV

The $I_3 = 0$, $Y = 0$ states π^0, η, η' will be linear combinations of the states $u\bar{u}$, $d\bar{d}$, $s\bar{s}$.

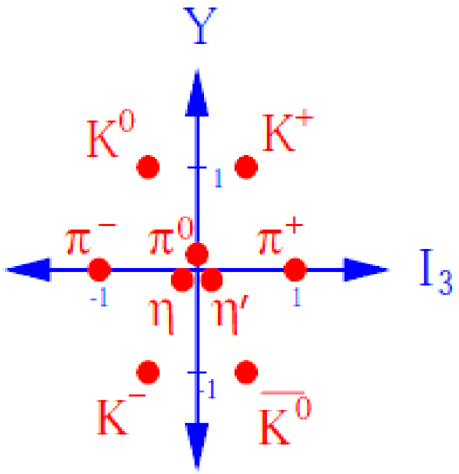
Since the π^0 forms an isospin triplet with π^+ ($u\bar{d}$) and π^- ($d\bar{u}$) it is reasonable to expect the wavefunction will involve u, d only. In fact it is

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$$

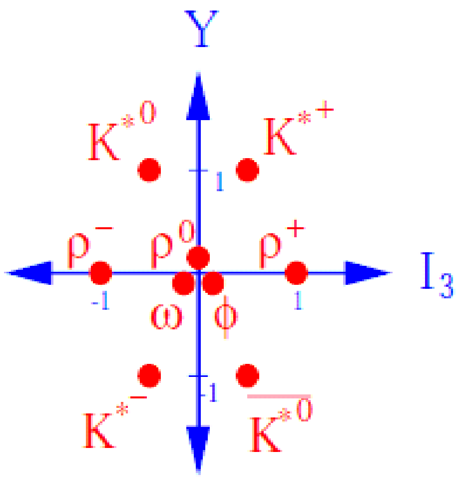
MESON MULTIPLETS

The observed lowest mass meson states form the following multiplets, which are nonets.

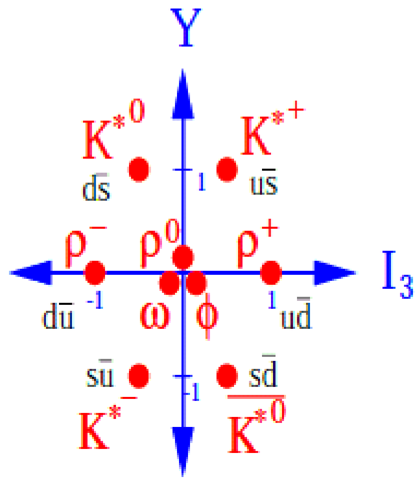
Pseudoscalar Mesons $\quad J^P = 0^-$



Vector Mesons $\quad J^P = 1^-$



Vector Mesons



$m(K^{*0})$, $m(\overline{K^{*0}})$ } 896.1 MeV

$m(K^{*+})$, $m(K^{*-})$ } 891.6 MeV

$m(\rho^+)$, $m(\rho^-)$, $m(\rho^0)$ } 768.5 MeV

$m(\omega)$ 781.9 MeV

$m(\phi)$ 1019.4 MeV

Again, the 3 central states ρ^0, ω, ϕ are linear combinations of the states $u\overline{u}$, $d\overline{d}$, $s\overline{s}$

$$|\rho^0\rangle = \frac{1}{\sqrt{2}}(d\overline{d} - u\overline{u})$$

$$|\phi_1\rangle = \frac{1}{\sqrt{3}}(u\overline{u} + d\overline{d} + s\overline{s})$$

$$|\phi_8\rangle = \frac{1}{\sqrt{6}}(2s\overline{s} - u\overline{u} - d\overline{d})$$

The physical states ω and ϕ turn out to be linear combinations (mixtures) of the ϕ_1 and ϕ_8 states

$$\begin{pmatrix} |\phi\rangle \\ |\omega\rangle \end{pmatrix} = \begin{pmatrix} cos\theta_V & sin\theta_V \\ -sin\theta_V & cos\theta_V \end{pmatrix} \begin{pmatrix} |\phi_8\rangle \\ |\phi_1\rangle \end{pmatrix}$$

where $\theta_V \approx +35^o$.

Selection rules for meson decays

Particle mass (GeV)	$\pi\,(0.14)$	$\eta\,(0.549)$	$\rho\,(0.77)$	$\omega\,(0.78)$	$\eta'\,(0.96)$	$\phi\,(1.02)$
quantum number						
J^P	0^-	0^-	1^-	1^-	0^-	1^-
I	1	0	1	0	0	0
G	-1	$+1$	$+1$	-1	$+1$	-1
decays into	$(\pi^0 \to 2\gamma)$	3π 2γ	2π	3π	$\eta\pi\pi$ (5π) $\rho^0\gamma$ $\gamma\gamma$	3π $K\bar{K}$

Table from PDG

Table 14.2: Suggested $q\overline{q}$ quark-model assignments for some of the observed light mesons. Mesons in bold face are included in the Meson Summary Table. The wave functions f and f' are given in the text. The singlet-octet mixing angles from the quadratic and linear mass formulae are also given for some of the nonets. The classification of the 0^{++} mesons is tentative and the mixing angle uncertain due to large uncertainties in some of the masses. The $f_0(1500)$ in the Meson Summary Table is not in this table as it is hard to accommodate in the scalar nonet. The light scalars $a_0(980)$, $f_0(980)$ and $f_0(600)$ are often considered as meson-meson resonances or four-quark states and are therefore not included in the table. See the "Note on Non-$q\overline{q}$ Mesons" at the end of the Meson Listings.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\overline{d}$, $\overline{u}d$, $\frac{1}{\sqrt{2}}(d\overline{d}-u\overline{u})$	I = $\frac{1}{2}$ $u\overline{s}$, $d\overline{s}$; $\overline{d}s$, $-\overline{u}s$	I = 0 f'	I = 0 f	θ_{quad} [°]	θ_{lin} [°]
$1\,^1S_0$	0^{-+}	$\boldsymbol{\pi}$	$\boldsymbol{K}$	$\boldsymbol{\eta}$	$\boldsymbol{\eta'(958)}$	−11.5	−24.6
$1\,^3S_1$	1^{--}	$\boldsymbol{\rho(770)}$	$\boldsymbol{K^*(892)}$	$\boldsymbol{\phi(1020)}$	$\boldsymbol{\omega(782)}$	38.7	36.0
$1\,^1P_1$	1^{+-}	$\boldsymbol{b_1(1235)}$	$\boldsymbol{K_{1B}}$†	$h_1(1380)$	$\boldsymbol{h_1(1170)}$		
$1\,^3P_0$	0^{++}	$\boldsymbol{a_0(1450)}$	$\boldsymbol{K_0^*(1430)}$	$\boldsymbol{f_0(1710)}$	$\boldsymbol{f_0(1370)}$		
$1\,^3P_1$	1^{++}	$\boldsymbol{a_1(1260)}$	$\boldsymbol{K_{1A}}$†	$\boldsymbol{f_1(1420)}$	$\boldsymbol{f_1(1285)}$		
$1\,^3P_2$	2^{++}	$\boldsymbol{a_2(1320)}$	$\boldsymbol{K_2^*(1430)}$	$\boldsymbol{f_2'(1525)}$	$\boldsymbol{f_2(1270)}$	29.6	28.0
$1\,^1D_2$	2^{-+}	$\boldsymbol{\pi_2(1670)}$	$\boldsymbol{K_2(1770)}$†	$\eta_2(1870)$	$\boldsymbol{\eta_2(1645)}$		
$1\,^3D_1$	1^{--}	$\boldsymbol{\rho(1700)}$	$\boldsymbol{K^*(1680)}$‡		$\boldsymbol{\omega(1650)}$		
$1\,^3D_2$	2^{--}		$\boldsymbol{K_2(1820)}$‡				
$1\,^3D_3$	3^{--}	$\boldsymbol{\rho_3(1690)}$	$\boldsymbol{K_3^*(1780)}$	$\boldsymbol{\phi_3(1850)}$	$\boldsymbol{\omega_3(1670)}$	32.0	31.0
$1\,^3F_4$	4^{++}	$\boldsymbol{a_4(2040)}$	$\boldsymbol{K_4^*(2045)}$		$\boldsymbol{f_4(2050)}$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$					
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\boldsymbol{\pi(1300)}$	$K(1460)$	$\boldsymbol{\eta(1475)}$	$\boldsymbol{\eta(1295)}$	−22.4	−22.6
$2\,^3S_1$	1^{--}	$\boldsymbol{\rho(1450)}$	$\boldsymbol{K^*(1410)}$‡	$\boldsymbol{\phi(1680)}$	$\boldsymbol{\omega(1420)}$		

† The $1^{+\pm}$ and $2^{-\pm}$ isospin $\frac{1}{2}$ states mix. In particular, the K_{1A} and K_{1B} are nearly equal (45°) mixtures of the $K_1(1270)$ and $K_1(1400)$.

‡ The $K^*(1410)$ could be replaced by the $K^*(1680)$ as the $2\,^3S_1$ state.

which states are exotic?

Exotic hadron: a state beyond the quark model, the nature of which is not understood, yet.

But:

- Quark model is foremost a **model of flavour**
- Quark models with **potentials can provide guidance but have serious flaws**
- ... in particular when coupled channels are not taken into account
- What are the correct degrees of freedom to describe the spectrum?
- **Unique exotic signatures:**
  - Only mesons: Spin exotics
  - States outside the flavour multiplets (e.g. a charged charmonium state)
- Shifted masses and peculiar widths need more detailed investigation.

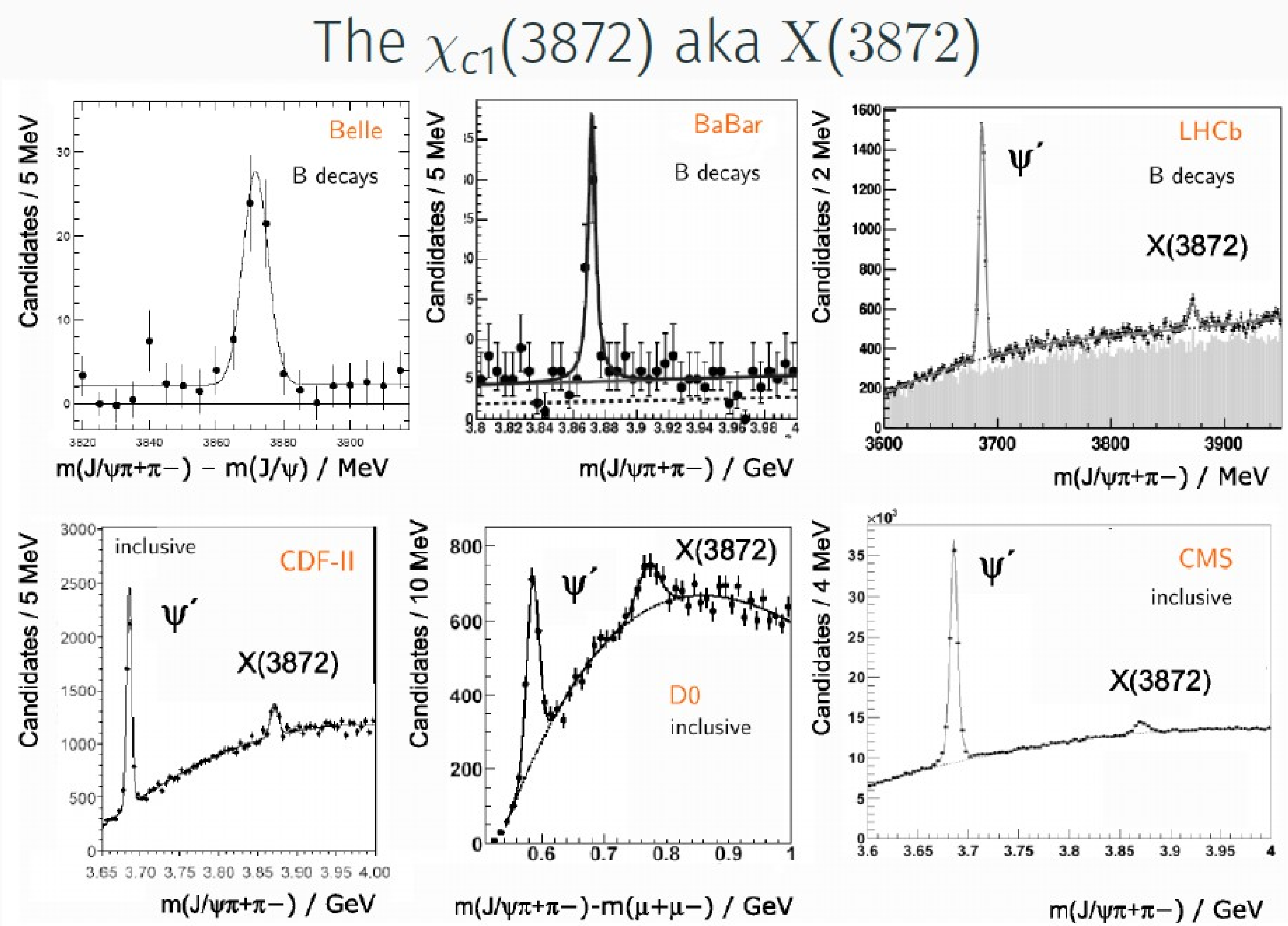
definition taking from Sebastian Neubert
Schleching 2020 lectures

here: focus on mesons only, but there are also candidates for exotic baryons, such as penta-quarks, and for quark-less particles consisting of gluons only, glueballs

all mesons which exhibit quantum numbers different from those of the above discussed sequence are exotic.In addition, a new family in the charm sector are the X,Y,Z states.

let's consider a particular case: the X(3872) particle

this and the following slides adapted from Sebastian Neubert, Schleching 2020



for a recent review of X,Y,Z states, see:
A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai and S. Yasui,
Exotic hadrons with heavy flavors: X, Y, Z, and related states,
PTEP (2016) no.6, 062C01
[arXiv:1603.09229 [hep-ph]].

X(3872) continued

- $J^{PC} = 1^{++}$ established $\Rightarrow$ PDG nomenclature $\chi_{c1}(3872)$
  LHCb [PRL110(2013)222001][PRD92(2015)011102]

- Mass $m = 3871.69 \pm 0.17\, MeV$ (in $\mathrm{X}(3872) \rightarrow \mathrm{J}/\psi\ X$ decays)
- $D\bar{D}^*$ threshold: $3871.81 \pm 0.09\, MeV$
- Mass difference $m_X - m_{\mathrm{J}/\psi} = 775 \pm 4\, MeV$
- Width $\Gamma < 1.2$ MeV Belle [PRD84(2011)052004]

- Observed in Charmonium-like decay modes:
  $\mathrm{D}^{*0}\overline{\mathrm{D}}^0$, $\mathrm{J}/\psi\pi\pi$, $\mathrm{J}/\psi\omega$, $\mathrm{J}/\psi\gamma$, $\psi(2\mathrm{S})\gamma$, $\chi_{c1}\pi^0$
- Mass and decay modes disfavour pure $\mathrm{c}\bar{\mathrm{c}}$ state.
  $\chi_{c1}(2P)$ predicted to be few 10 MeV higher in mass

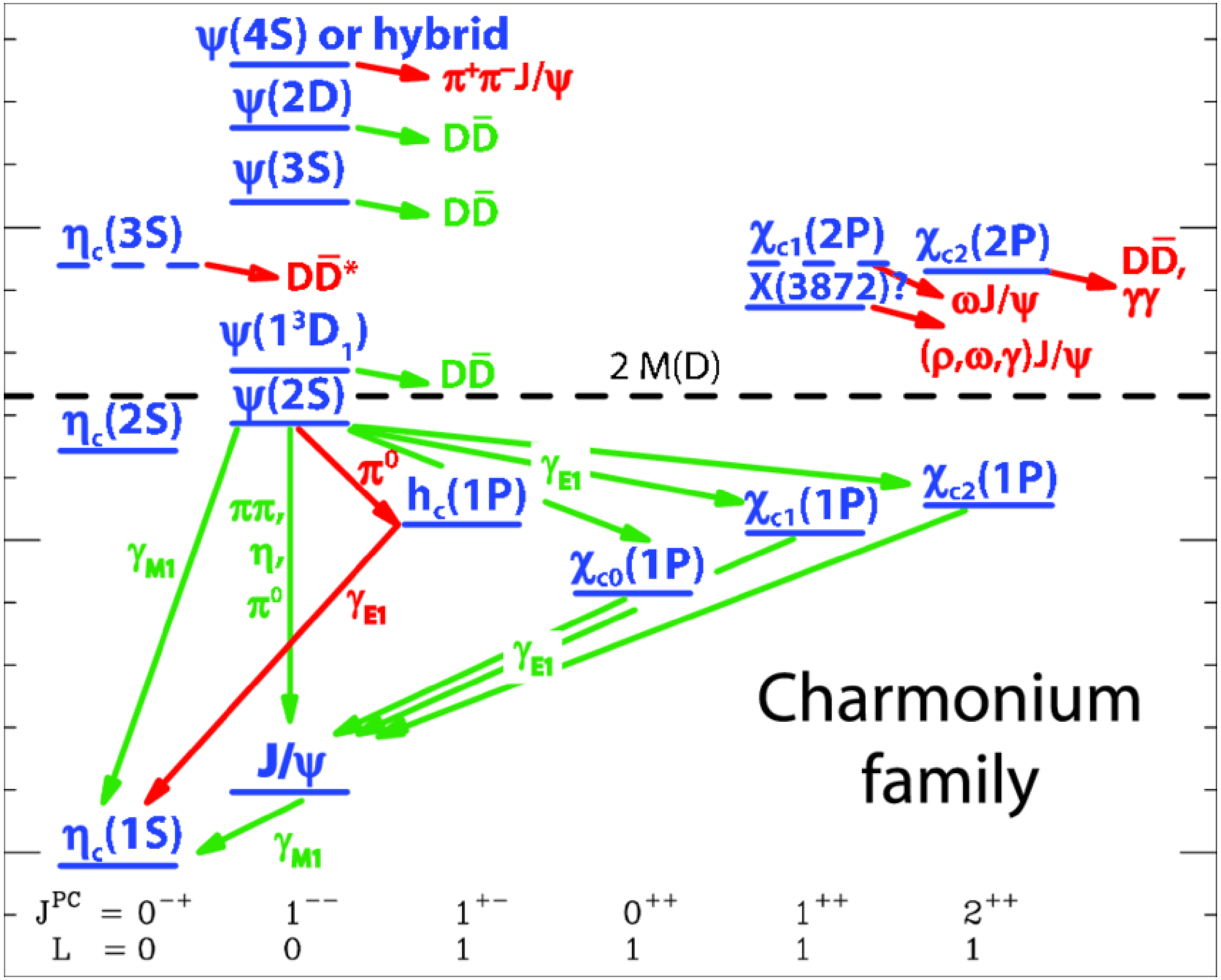
- No charged partner, no $C = -1$ partner found
  - $X \rightarrow \mathrm{J}/\psi\pi^+\pi^0$ Belle[PRL111(2013)032001],BaBar[PRD71(2005)031501]
  - $X \rightarrow \mathrm{J}/\psi\eta$ Belle[PTEP(2014)043C01],Belle[PRL111(2013)032001]

X(3872) is not spin-exotic

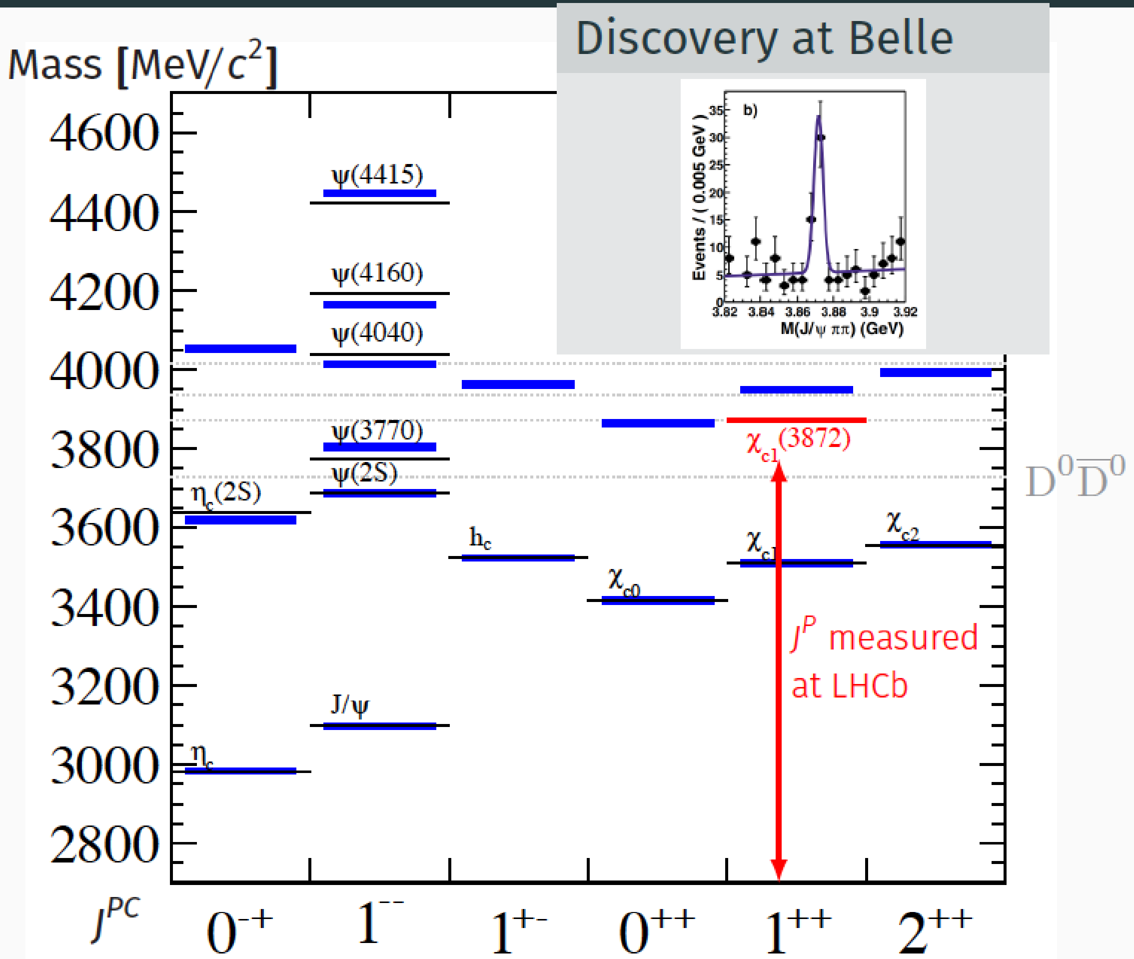
width is too small

is it a charmonium-like state?

charmonium and charmonium-like states



The $\chi_c(3872)$ aka X(3872)



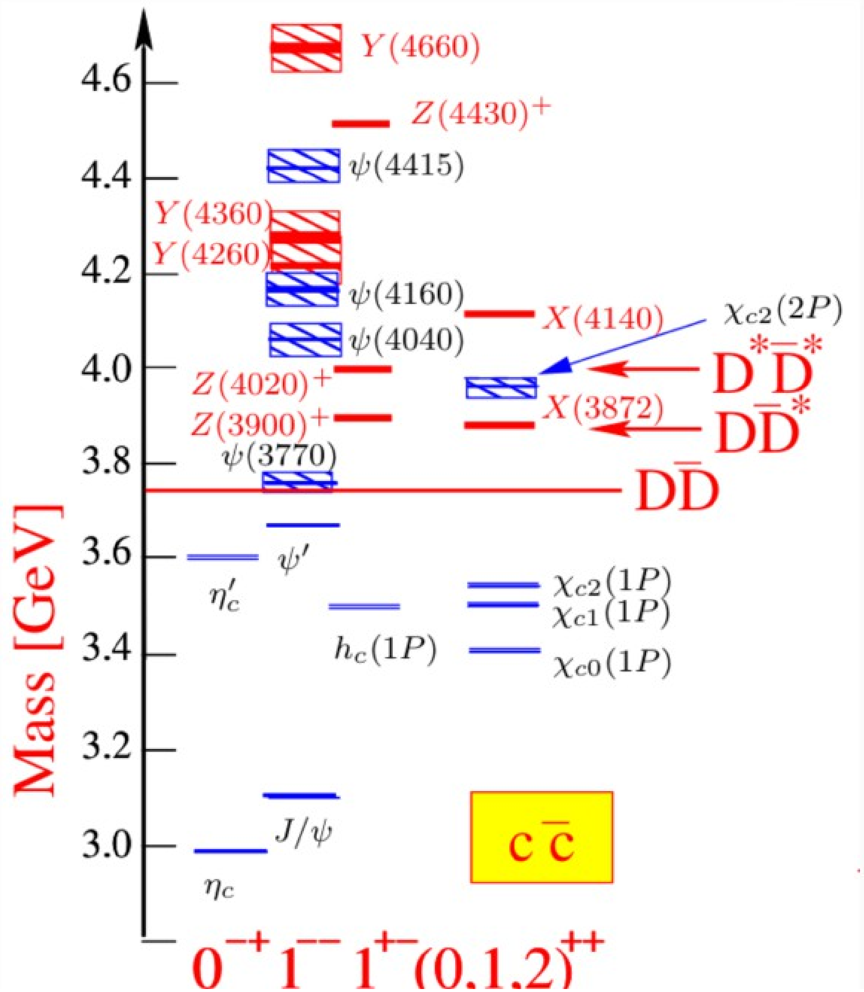
- Discovered in $J/\psi\pi\pi$
- $m = 3871 \pm 0.17$ MeV
- above the open charm threshold
- right at $D^0\overline{D}^{*0}$ threshold
- very narrow $\Gamma < 1.2$ MeV
- $BR(D^0\overline{D}^{*0}) > 30\%$
- Started spectroscopy renaissance
- Best studied exotic

psi(2s) and psi(3770)

psi(2s): below D D_{bar} threshold, width = 294 keV, mass = 3686 MeV

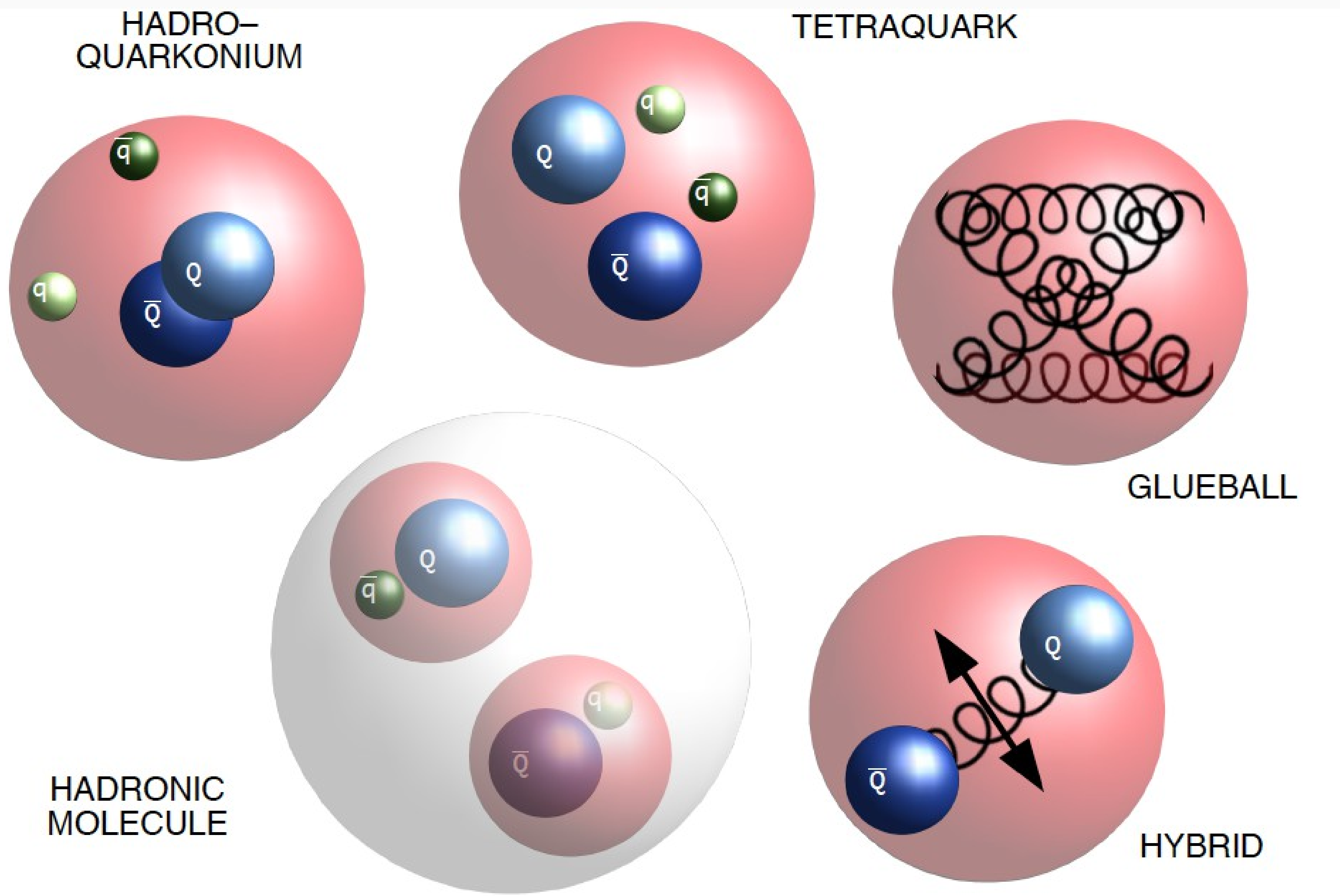
psi(3770): above D D_{bar} threshold, width is 27 MeV, mass = 3773 MeV

Many new states in the charmonium sector

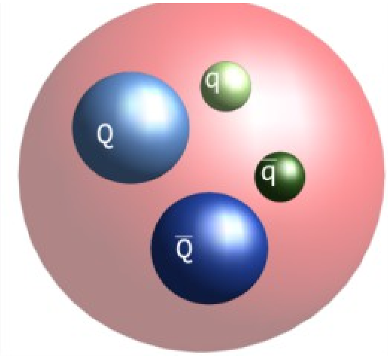


- Above $\mathrm{D\bar{D}}$ threshold: 24 claimed, 10 established new states 22/24 (8/10) incompatible with quark model
- Two charged states in bottomonium sector

Recent reviews:
Prog. Part. Nucl. Phys. 97 (2017) 123
Prog. Part. Nucl. Phys. 93 (2017) 143
Rev. Mod. Phys. 90 (2018) 015003
arXiv:1907.07583

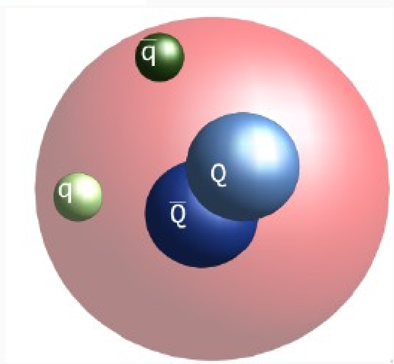


Graphics: C. Hanhart



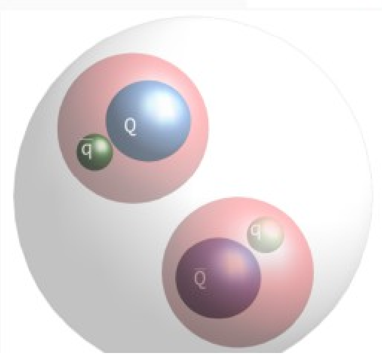
Tetraquarks

- **Compact** object made from $|\, Qq\rangle$ and $|\, \bar{Q}\bar{q}\rangle$ diquarks



Hadro-Quarkonium

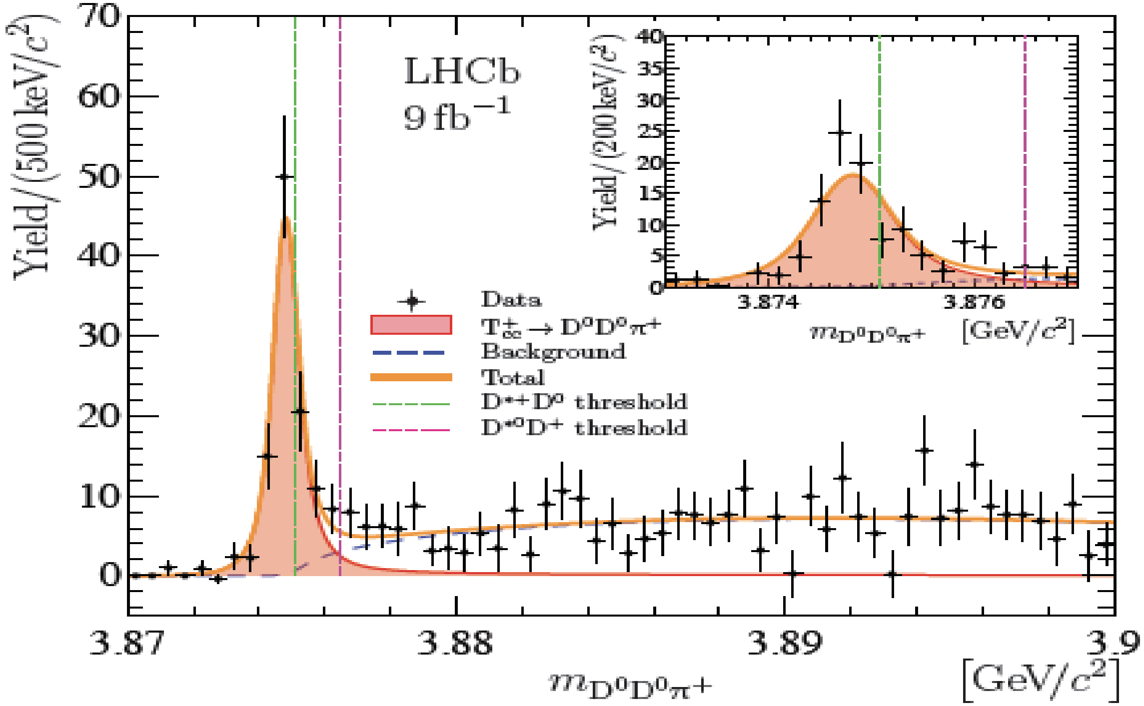
- **Compact** $|\, Q\bar{Q}\rangle$ color singlet surrounded by a light-quark / pion cloud.



Hadronic Molecules

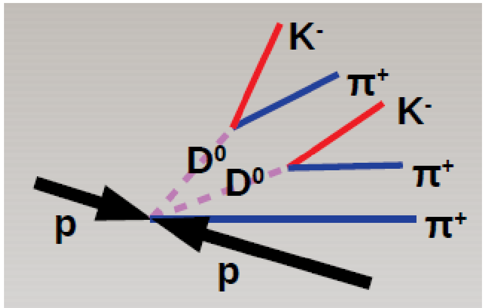
- **Extended** object made from two hadrons $|\, Q\bar{q}\rangle$ and $|\, q\bar{Q}\rangle$
- Typical size $\sim \dfrac{1}{\sqrt{2\mu E_b}} \gg 1\,\text{fm}$
- near two-body threshold

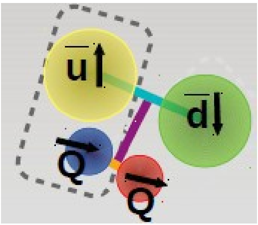
what about T_{cc}^{+} very recently discovered by LHC_b
2109.01038 [hep-ex]



this loosely mesonic bound state has net charge +, charm number 2, cannot be a quark-antiquark state, very different from charmonia

produced in pp collisions at LHC energy





mass = 3874.75 ± 0.11 MeV
mass is very close to that of $D^0{}^*D^+{}_{bar}$
width = 48 ± 2 + 0 - 14 keV

binding energy: 360 ± 40 keV
T_{cc}+ → D0 D0 π+
angular momentum: J=1, isospin I = 0

see LHCb papers
2109.01038 [hep-ex]
2109.01056 [hep-ex]

summary: X(3872) and Tcc+ are truly exotic

in the last 5 years, many candidates for exotic states

for 30 years the quark model with a quark-antiquark pair for mesons and three quarks for baryons seemed to describe everything

the race is on to determine the structure of the new exotics

no trace yet for glue balls

extra pages

general quantum mechanics result

a bound state close to a 2-body threshold that couples to the two bodies via an s-wave interaction has universal properties:

its rms radius depends only on its binding energy B.E. and not on interaction potentials, i.e.

$$R_{rms} = (4\ \mathrm{B.E.}\ M_{red})^{-1/2} \text{ as B.E. } \longrightarrow 0$$

examples: the deuteron (B.E. 2.2 MeV, M_{red} = 470 MeV, R_{rms} = 3.1 fm
measured: 2.1 fm)

the hypertriton (B.E. 0.13 MeV, M_{red} = 700 MeV, R_{rms} = 10.3 fm)

the X(3872) (B.E. 0.12 MeV, M_{red} = 967 MeV, R_{rms} = 9.2 fm)

see, e.g., Steven Weinberg, Lectures on Quantum Mechanics, Cambridge University Press, 2015, especially chapter 8.8

if this is the correct interpretation,
the hyper-triton and the X(3872) are bigger
than a Pb nucleus!
n.b.: typical hadron sizes are < 1 fm

Lectures on Quantum Mechanics

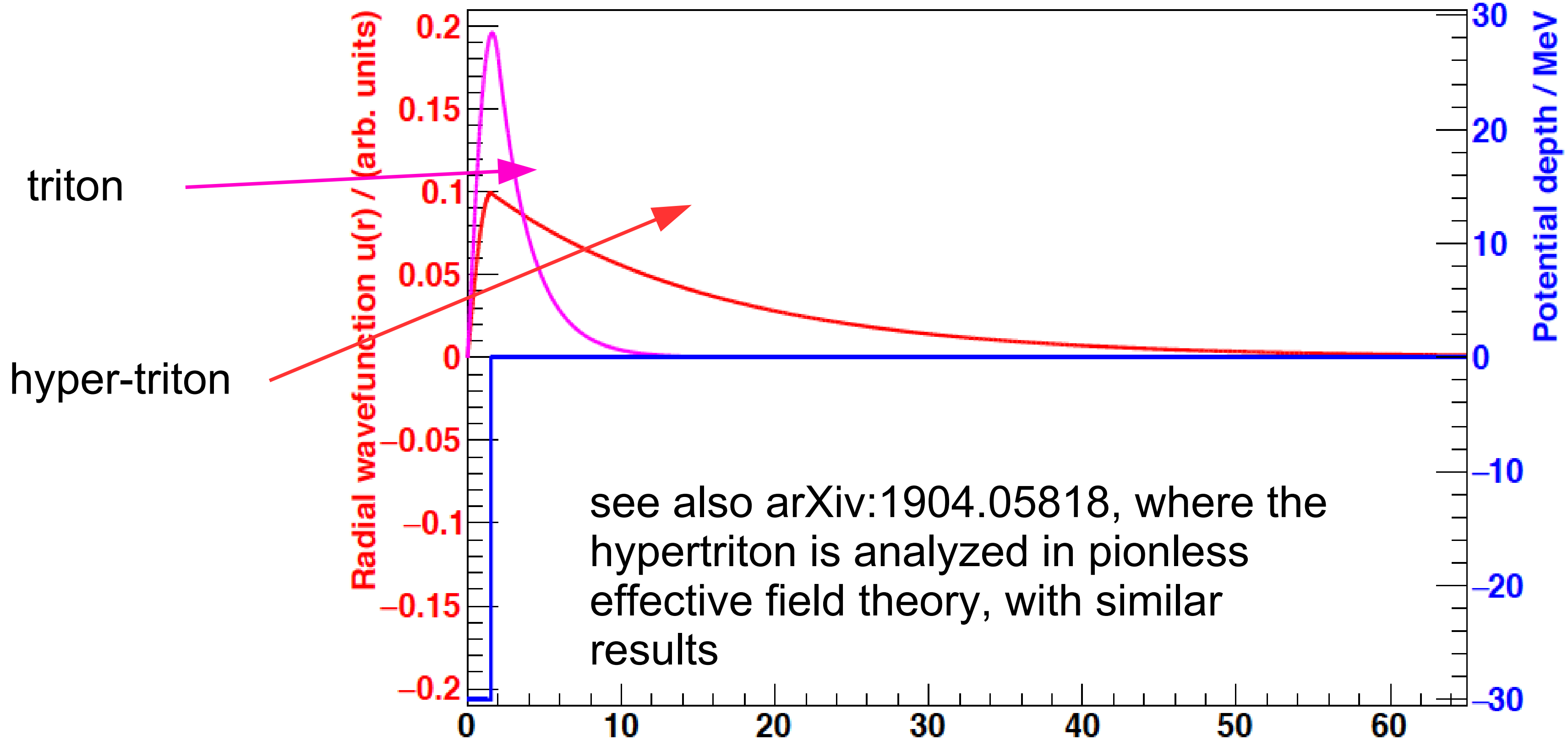
Steven Weinberg,

Cambridge University Press, 2015

especially chapter 8.8

wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017



Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve shows a "triton" like object using a similar calculation as the hypertriton, namely a deuteron and an added nucleon, resulting in a much narrower object as the hypertriton.

The Hypertriton

mass = 2990 MeV, binding energy = 2.3 MeV

Lambda sep. energy = 0.13 MeV

molecular structure: (p+n) + Lambda

2-body threshold: (p+p+n) + pi- = ^{3}He + pi-

rms radius = $(4\ \mathrm{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

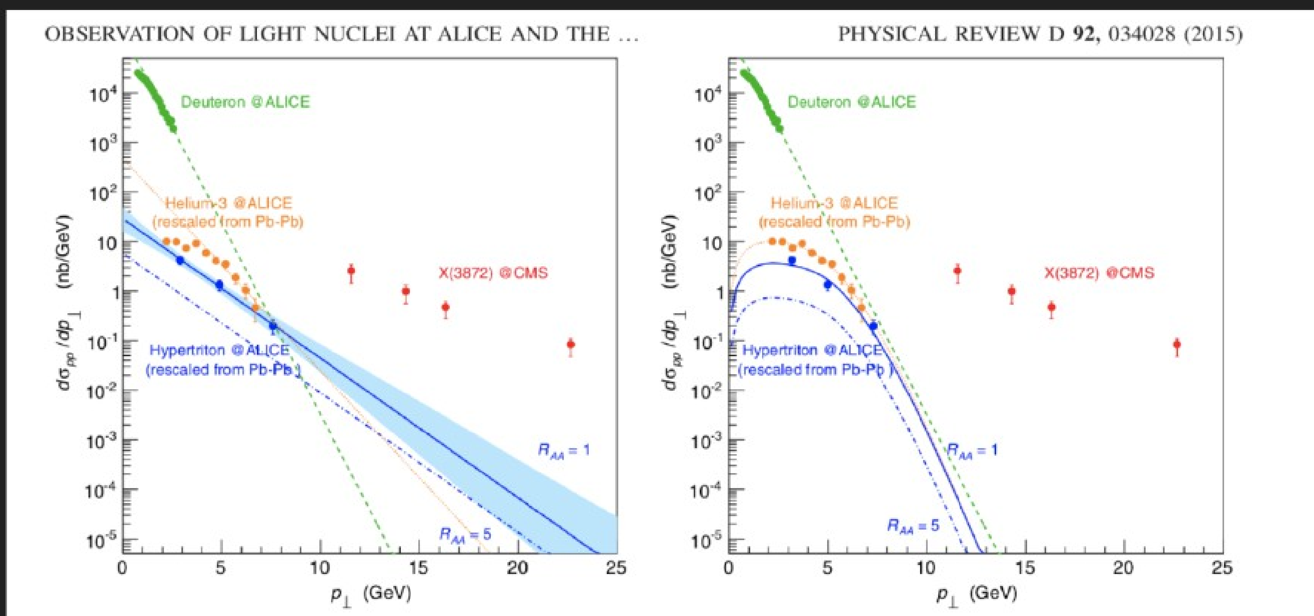
in that sense: hypertriton = (p n Lambda) =
(d Lambda) is the ultimate halo state

so hyper-triton sits 130 keV below the Lambda-deuteron threshold – similar case as for X(3872)

The X(3872)

The X(3872) sort of anomalous charmonium with **1⁺⁺** quantum numbers

right at DD^* threshold and rather close to $J/\psi+\rho$.



Esposito et al. PRD92 (2015) 034028

Bignamini, Grinstein, Piccinini, ADP, Sabelli, PRL103 (2009) 162001
Esposito, Grinstein, Maiani, Piccinini, Pilloni, ADP, Riquer, 1709.09631

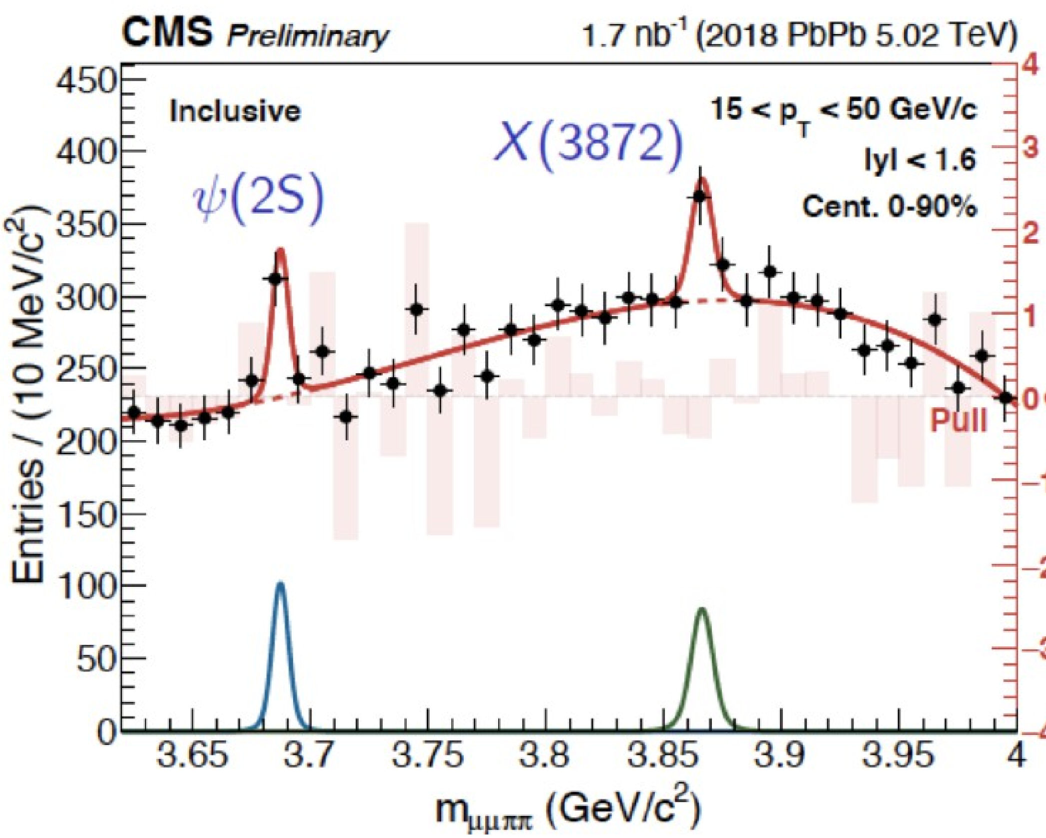
[Talk of A. Polosa at the charm hadronization workshop]

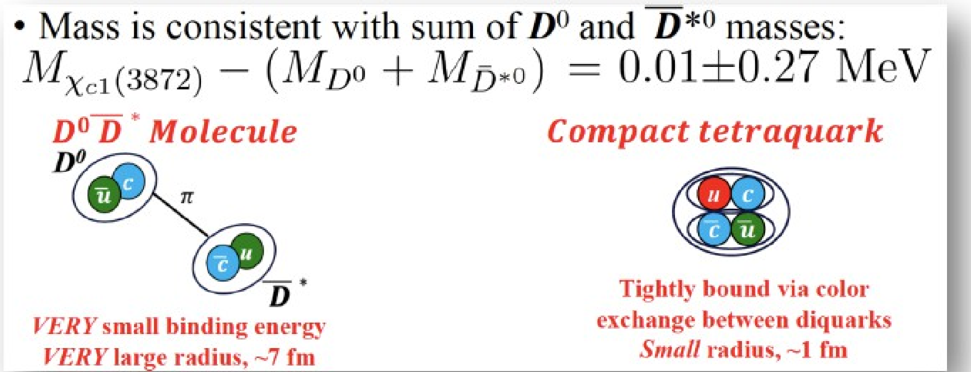
if the size of the X(3872) is very large, cross section should be strongly suppressed, seems not to be the case

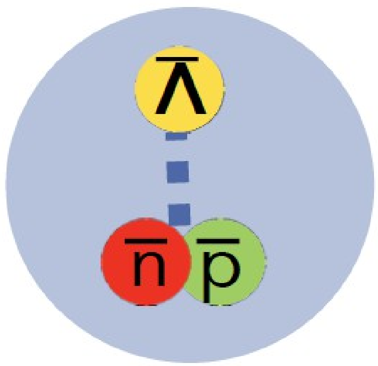
Loosely bound objects in heavy-ion collisions

[Y. Jie Lee]
[J. Durham]

→ The X(3872) will not be suppressed if its behavior is like a hyper-triton!







m = 2.991 GeV/c^2, B_Λ = 130 keV
→rms-radius = 10.3 fm

see Alexander Kalweit, CERN workshop on 'origin of nuclear clusters in hadronic collisions', May 19-20, 2020