Hadron Spectroscopy

Part I: Conventional Hadrons

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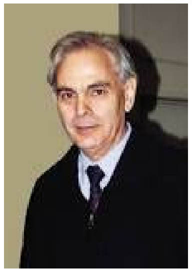
NSF
INSTITUTE for NUCLEAR THEORY

Introduction

- Plan:
  - Day 1: Conventional Hadron Spectroscopy
  - Day 2: Exotic Hadron Spectroscopy
- Hadron Spectroscopy is a very broad subject. A lot of interesting aspects of various systems. Hundreds of experimentalists and theorists involved in it.
- Instead of getting into very specialized topics, try to provide broad guide to various hadron families today.
- I apologize for this talk being perhaps too elementary. I start from reviewing atomic spectroscopy, historical intro, …
- I am an experimentalists, who has been active in heavy flavor experiments (Crystal Ball at DORIS, CLEO at CESR, LHCb). Selection of topics somewhat biased by my background.

Hadron?

- Hadron = strongly interacting particle
- The term "hadron" introduced by Lev Borisovich Okun at 1962 (11th) ICHEP conference in Geneva:



Лев Борисович
Окунь
1929 –2015

> "The point is that "strongly interacting particles" is a very clumsy term which does not yield itself to the formation of an adjective. For this reason, to take but one instance, decays into strongly interacting particles are called non-leptonic. This definition is not exact because "non-leptonic" may also signify "photonic". **In this report I shall call strongly interacting particles "hadrons", and the corresponding decays "hadronic" (the Greek *ἁδρός* signifies "large", "massive", in contrast to *λεπτός* which means "small", "light").** I hope that this terminology will prove to be convenient."

$0.5 < 140 < 938$ MeV

$M(e) < M(\pi) < M(p)$;

λεπτός ***ἁδρός***

lepton hadrons

μέσος ***βαρύς***

"intermediate" "heavy"

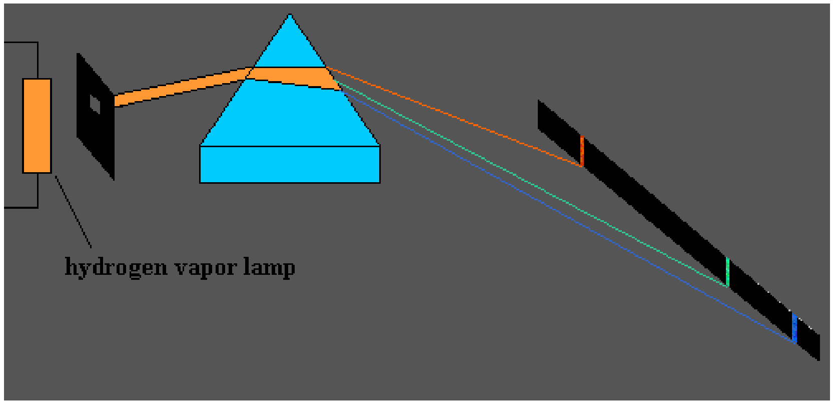
meson baryon

$1777 < 5279 < 5620$ MeV

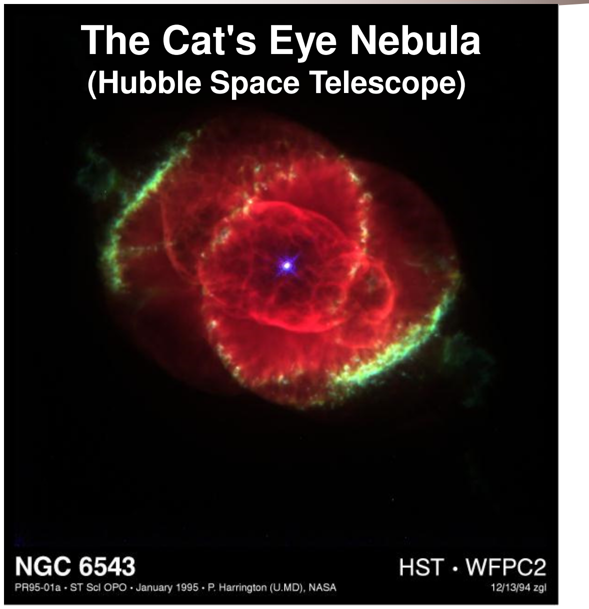
$M(\tau) < M(B) < M(\Lambda_b)$;

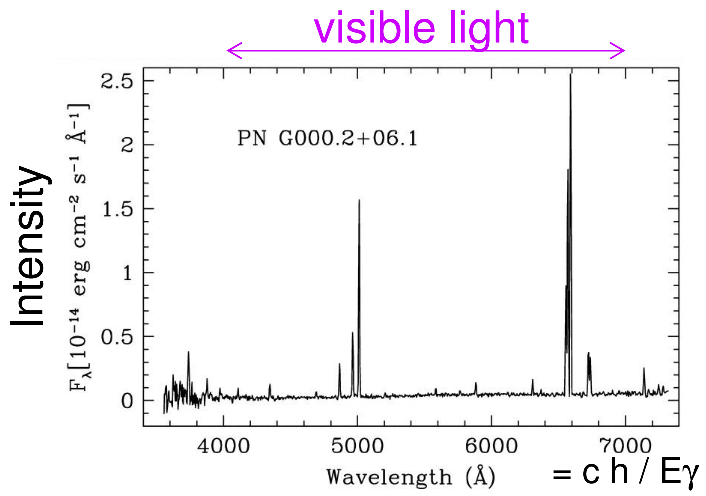
the mass hierarchy which led to this nomenclature still holds within each "generation"

Spectroscopy?

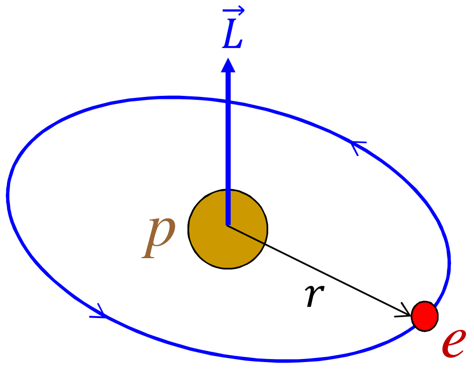


- Spectral lines were observed before their origin was understood.
- Led to development of quantum mechanics





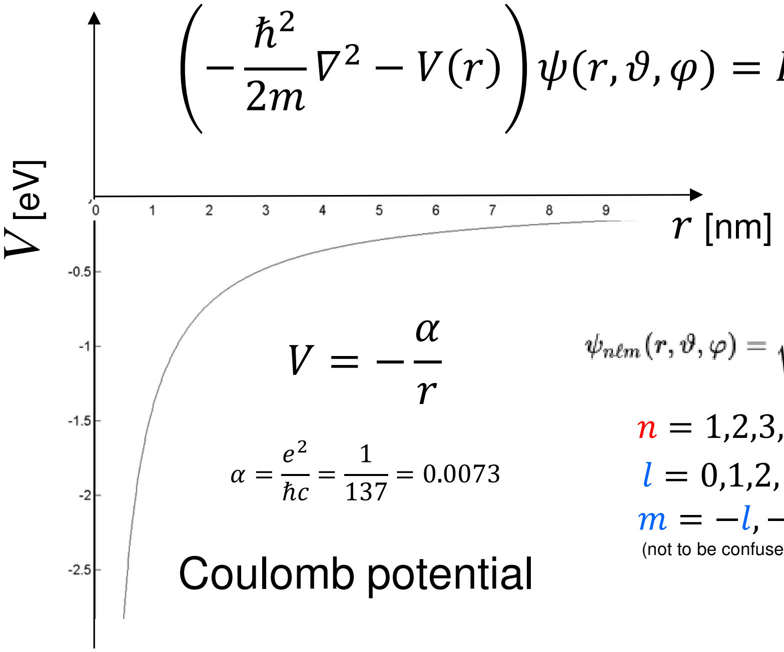
Hydrogen atom



Reduced mass:

$$m = \frac{1}{\frac{1}{m_e} + \frac{1}{m_p}} \approx m_e$$

$$\left(-\frac{\hbar^2}{2m}\nabla^2 - V(r)\right)\psi(r,\vartheta,\varphi) = E\psi(r,\vartheta,\varphi)$$



$$V = -\frac{\alpha}{r}$$

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137} = 0.0073$$

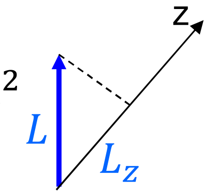
Coulomb potential

$$E_n = -\frac{mc^2\alpha^2}{2}\frac{1}{n^2}$$

$$\psi_{n\ell m}(r,\vartheta,\varphi) = \sqrt{\left(\frac{2}{na_0}\right)^3 \frac{(n-\ell-1)!}{2n(n+\ell)!}} e^{-\rho/2}\rho^\ell L^{2\ell+1}_{n-\ell-1}(\rho) Y^m_\ell(\vartheta,\varphi)$$

$n = 1,2,3,\ldots$
$l = 0,1,2,\ldots,n-1$
$m = -l,-l+1,\ldots,+l$
(not to be confused with reduced mass)

$$L^2 = l(l+1)\,\hbar^2$$
$$L_z = m\hbar$$



$$\rho = \frac{2r}{na_0} \qquad a_0 = \frac{\hbar^2}{me^2} = 0.053 \text{ nm}$$

$L^{2\ell+1}_{n-\ell-1}(\rho)$ generalized Laguerre polynomials have $n-l-1$ zero crossings (“nodes”)

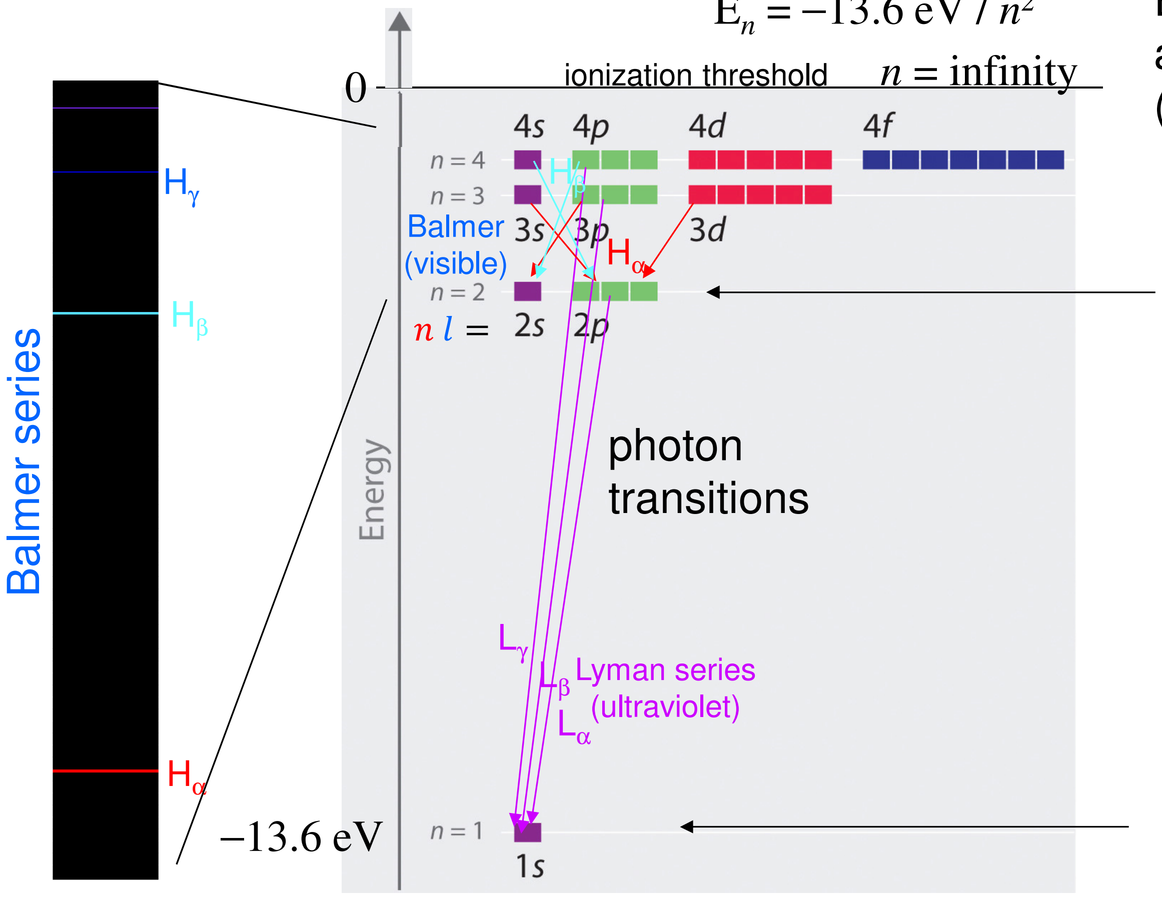
principal vs radial quantum number

If it was not due to the energy degeneracy in “principal quantum number” n, it would make more sense to define “radial quantum number” $n' = n - l$ and use $n'lm$ instead of nlm to label eigenstates of the system (l is not restricted by n' value).

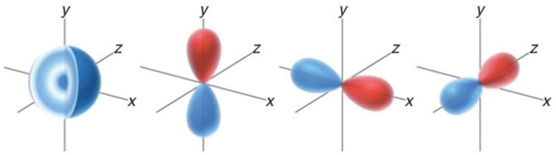
Energy depends on both radial (n') and orbital momentum (l) excitations. The degeneracy in $n' + l$ is accidental and happens only for $1/r$ potential.

Hydrogen Spectroscopy

$$E_n = -13.6\ \mathrm{eV} / n^2$$



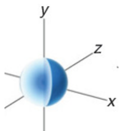
Each colored square represents a different quantum state (m_l labels not spelled out)



2s
$m = 0$

2p
$m = -1, 0, +1$

$$|\psi_{nlm}(r,\vartheta,\varphi)|^2$$



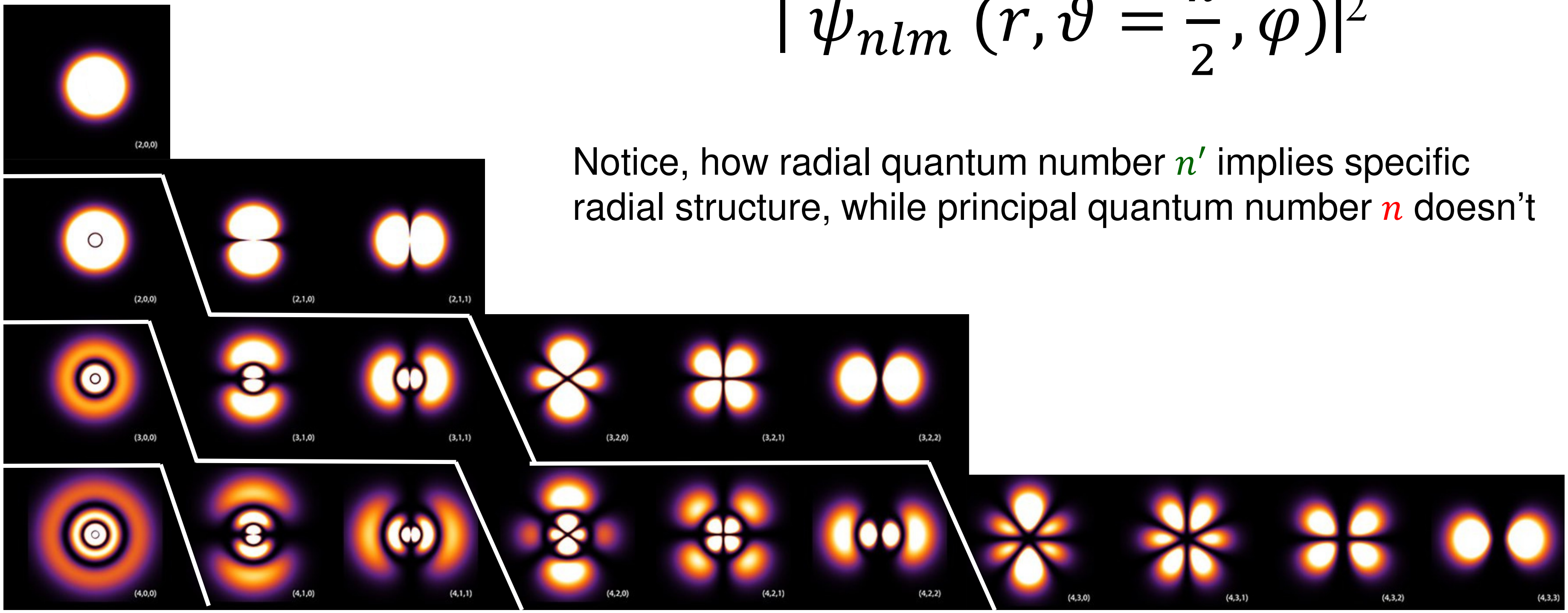
1s
$m = 0$

$n = 1, 2, 3, \ldots$
$l = 0, 1, 2, 3, \ldots, n-1$
$l = s, p, d, f, \ldots$

More Hydrogen Electron Orbitals

$$|\,\psi_{nlm}\,(r,\vartheta=\frac{\pi}{2},\varphi)|^2$$

Notice, how radial quantum number n' implies specific radial structure, while principal quantum number n doesn't



Fine-structure of hydrogen

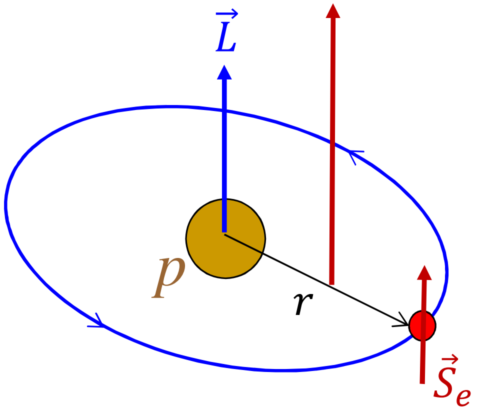
$$S^2 = s(s+1)\,\hbar^2$$
$$S_z = m_s \hbar$$

Particle with a spin has a magnetic dipole moment: $\vec{\mu} = -\frac{q}{mc}\vec{S}$

$$s_p = s_e = \frac{1}{2} \qquad \mu_p \sim \frac{m_e}{m_p}\mu_e = 0.0005\ \mu_e$$

Magnetic effects due to proton spin can be neglected relative to magnetic effects due to electron spin.

$$\vec{j}_e = \vec{L} + \vec{S}_e$$



SPIN-ORBIT INTERACTIONS

orbiting electron is like a current loop and sets up magnetic field

$$\vec{B} \propto \vec{L}$$

which interacts with magnetic dipole of electron

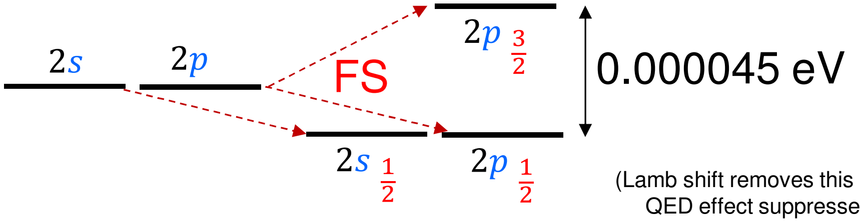
$$E_{LS} = -\overrightarrow{\mu_e} \cdot \vec{B} \quad \propto \quad \vec{S}_e \cdot \vec{L} \quad \propto \quad j_e^2$$

$$E_{jn} = -m_e c^2 \left[1 - \left(1 + \left[\frac{\alpha}{n - j - \frac{1}{2} + \sqrt{\left(j + \frac{1}{2}\right)^2 - \alpha^2}} \right]^2 \right)^{-1/2} \right]$$
$$\approx -\frac{m_e c^2 \alpha^2}{2n^2} \left[1 + \frac{\alpha^2}{n^2} \left(\frac{n}{j + \frac{1}{2}} - \frac{3}{4} \right) \right],$$

very small effect !

decreases with excitation level

$$\alpha^2 = 0.00005$$



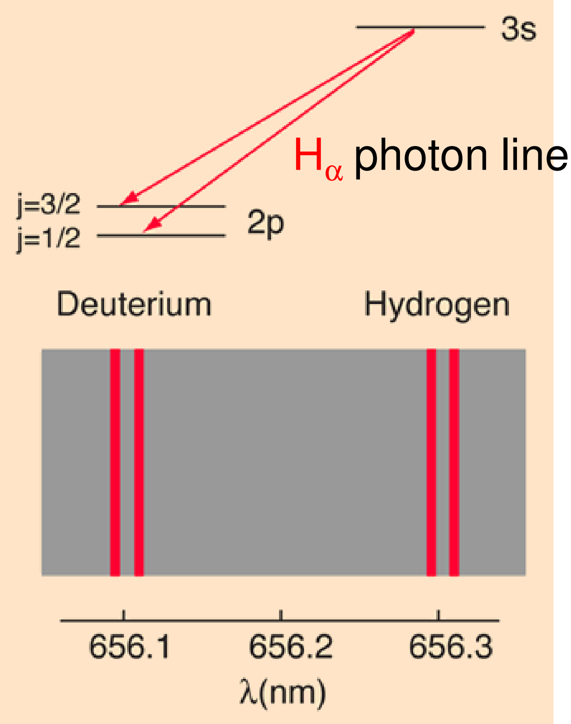
(Lamb shift removes this degeneracy: QED effect suppressed by α~0.01)

$$nl \qquad nl_{\,j_e}$$

Single-electron atoms

(*N*-nucleus)

- H (*N=p*), deuterium (*N=np*), He$^+$ (*N=2p2n*), Li^{2+} (*N=3p3n*),…
- Same energy spectrum up to fine structure, except for small shift due to the small change in the reduced mass of the system (H→deuterium), or larger rescaling due to increased charge of nucleus in ions



H_α photon lines

Reduced mass:

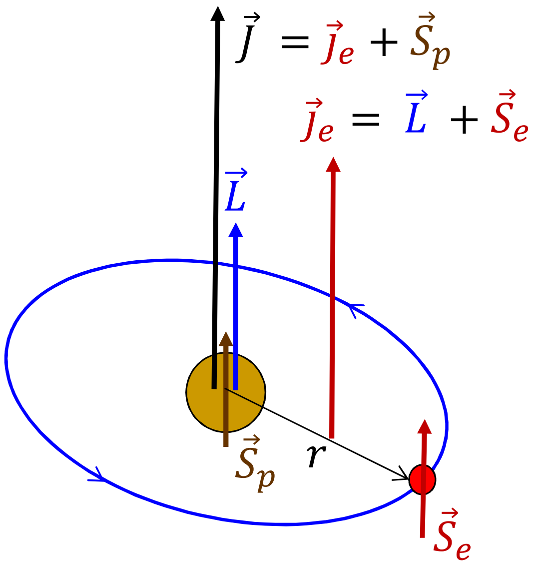
$$m = \frac{1}{\frac{1}{m_e} + \frac{1}{m_N}} \approx m_e\left(1 - \frac{m_e}{m_N}\right)$$

Hyperfine structure of hydrogen

Due to magnetic dipole moment of proton.
Suppressed relative to fine structure by:

$$\frac{m_e}{m_p}\gamma_p = 0.0005 \cdot 2.8 = 0.0015$$

γ_p - anomalous magnetic moment of proton since not a point-like particle



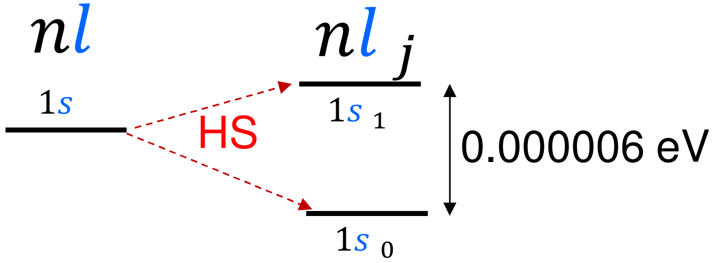
$$\vec{J} = \vec{j}_e + \vec{S}_p$$

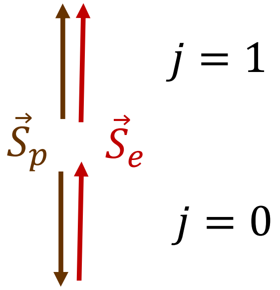
$$\vec{j}_e = \vec{L} + \vec{S}_e$$

$$\vec{J} = \vec{j}_e + \vec{S}_p$$

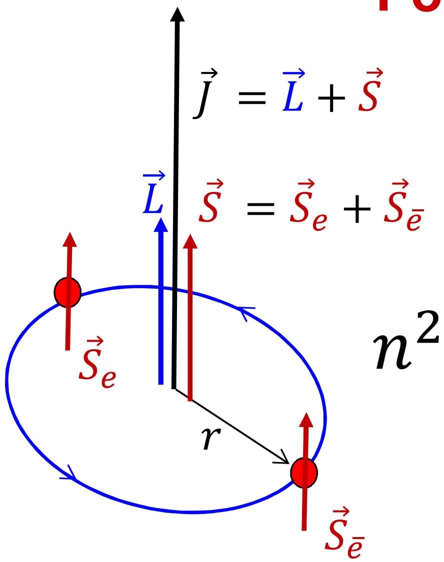
Hyperfine structure will be due to: $\vec{j}_e \cdot \vec{S}_p \propto j^2$

Hyperfine structure splits even $l = s$ states





Positronium – (e^+e^-)



$$\vec{J} = \vec{L} + \vec{S}$$

$$\vec{S} = \vec{S}_e + \vec{S}_{\bar{e}}$$

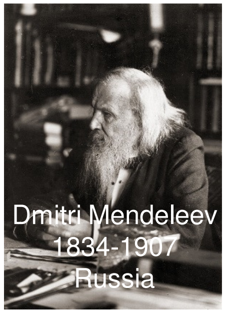
$$n^{2S+1}l_j$$

- In the leading order, the same energy spectrum as for hydrogen except for a factor of 2 smaller (larger) energies (sizes) of states:

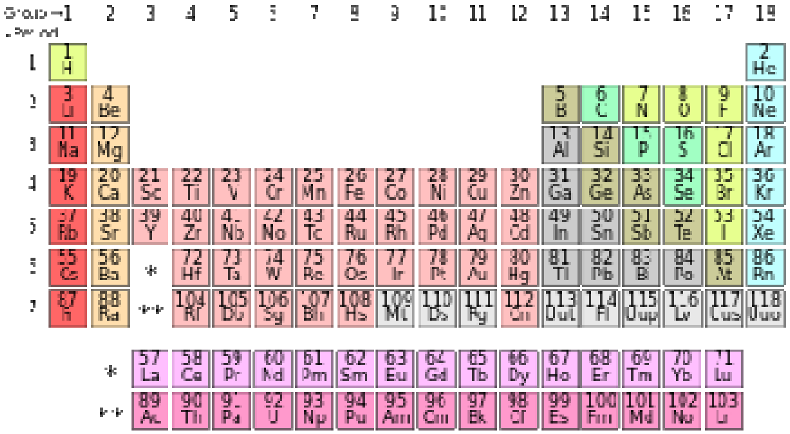
Reduced mass: $$m = \frac{1}{\frac{1}{m_e} + \frac{1}{m_e}} \approx m_e \frac{1}{2}$$

- Hyperfine and fine structures are of the same order of magnitude:
  - total spin $\vec{S} = \vec{S}_e + \vec{S}_{\bar{e}}$ is a “good quantum number”
  - spin-orbit interactions: $\vec{S} \cdot \vec{L}$
  - spin-spin interactions: $\vec{S}_{\bar{e}} \cdot \vec{S}_e$
  - tensor interactions: $3(\vec{S}_{\bar{e}} \cdot \hat{r}) \cdot (\vec{S}_e \cdot \hat{r}) - \vec{S}_{\bar{e}} \cdot \vec{S}_e$
- New element – even ground state is meta-stable and can annihilate to photons:
  - $\tau(1^1s_0 \to \gamma\gamma)$ =0.125 ns, $\tau(1^3s_1 \to \gamma\gamma\gamma)$ =142 ns

Pauli exclusion principle and periodic table

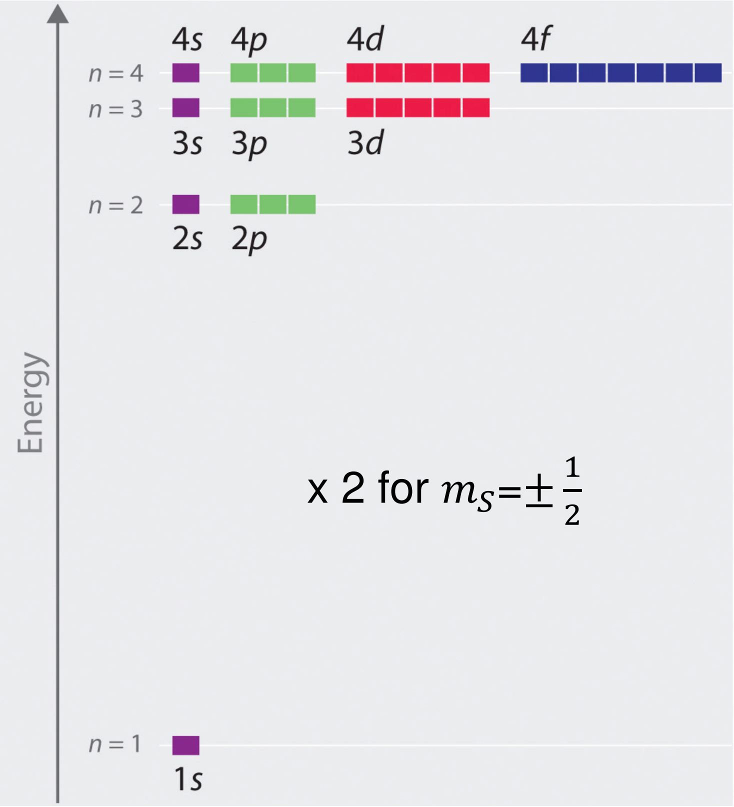


Periodic table of elements:



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

“magic numbers”
↓
2
8
…



x 2 for $m_S = \pm\frac{1}{2}$

Z

shell-3 …

shell-2 *8e*

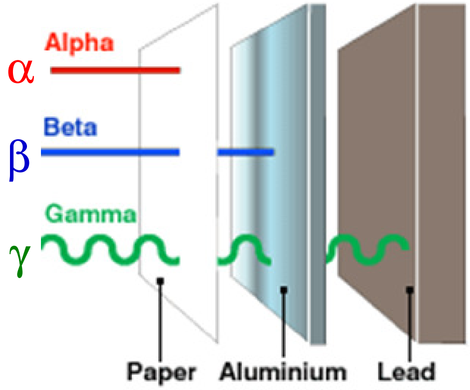
shell-1 *2e*

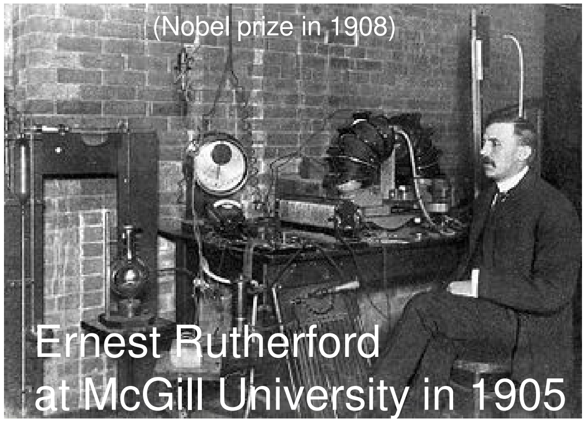
Wolfgang Pauli 1925
Identical fermions cannot occupy the same quantum state within a quantum system simultaneously.
(this also led to development of spin concept)

First hadrons discovered

- Alpha particles (~1900):

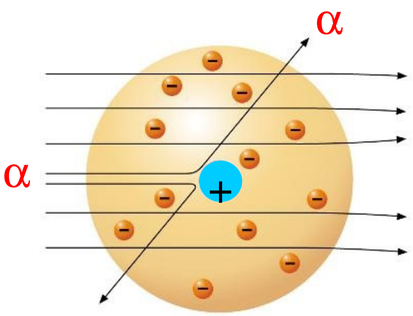
rays from radioactive decays classified according to their penetration ability



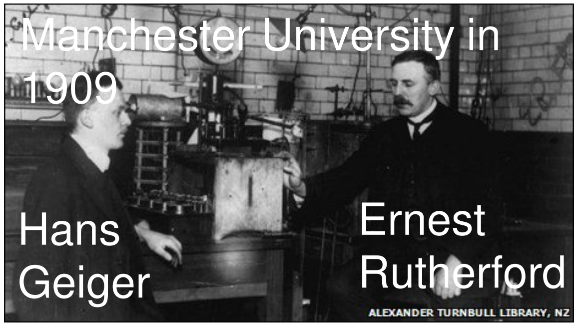

(Nobel prize in 1908)

Ernest Rutherford at McGill University in 1905

- Nuclei (1909-)



hard scattering centers in atoms
 - nucleus

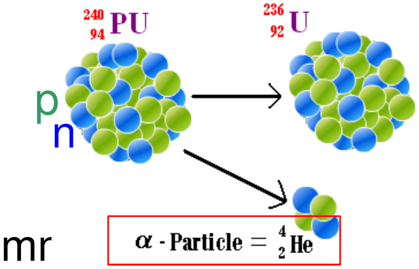

Manchester University in 1909

Hans Geiger

Ernest Rutherford

ALEXANDER TURNBULL LIBRARY, NZ

1919: proton as nucleus of hydrogen
alpha particles as nucleus of helium
1932: neutrons (highly penetrating radiations but not gamr



α - Particle = $^{4}_{2}$He

Isospin symmetry - 1932

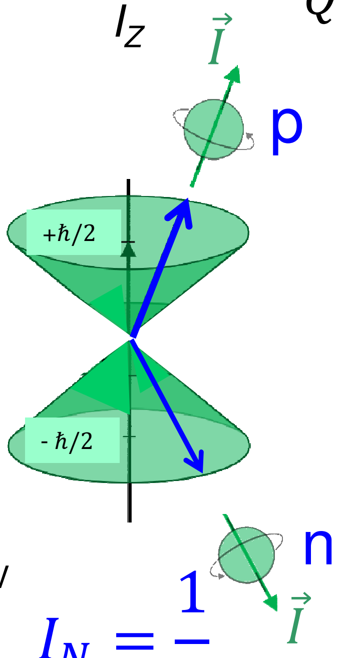
- Rotation in the isospin space is a symmetry of strong interactions.
- Total isospin is conserved in strong interactions.

$$|\vec{I}\,| = \sqrt{I(I+1)}\,\hbar \qquad I_z = m_I\,\hbar$$

$$Q = m_I + \frac{A}{2}$$

Q – electric charge
A – baryon number

M(p)=938.3 MeV



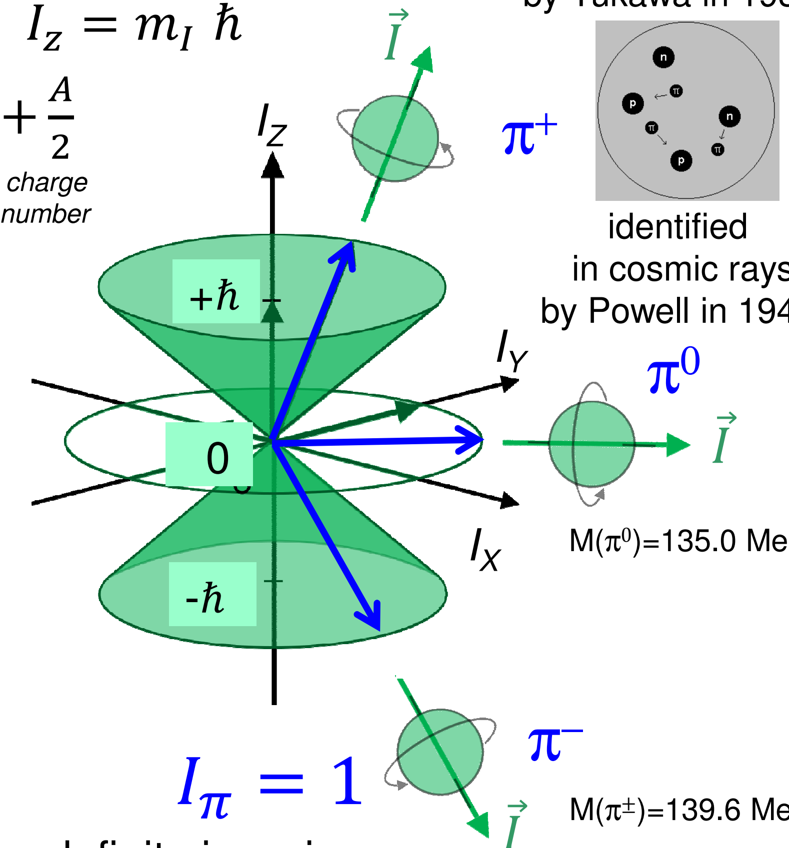
M(n)=939.5 MeV

$$I_N = \frac{1}{2}$$

(*N* – nucleon)

pion predicted by Yukawa in 1934

identified in cosmic rays by Powell in 1946



M(π^0)=135.0 MeV

M($\pi^\pm$)=139.6 MeV

$$I_\pi = 1$$

Any nucleus has a definite isospin.
Isospin ("Isotopic spin") very useful in nuclear physics.

ρ resonance: short-lived particle

- 1961: scattering charged pion beam (E=2 GeV) on stationary proton target and looking for two pions and a proton (or neutron) coming out:

$\pi^- p \to \pi^- \pi^0 p$ $\pi^- p \to \pi^- \pi^+ n$

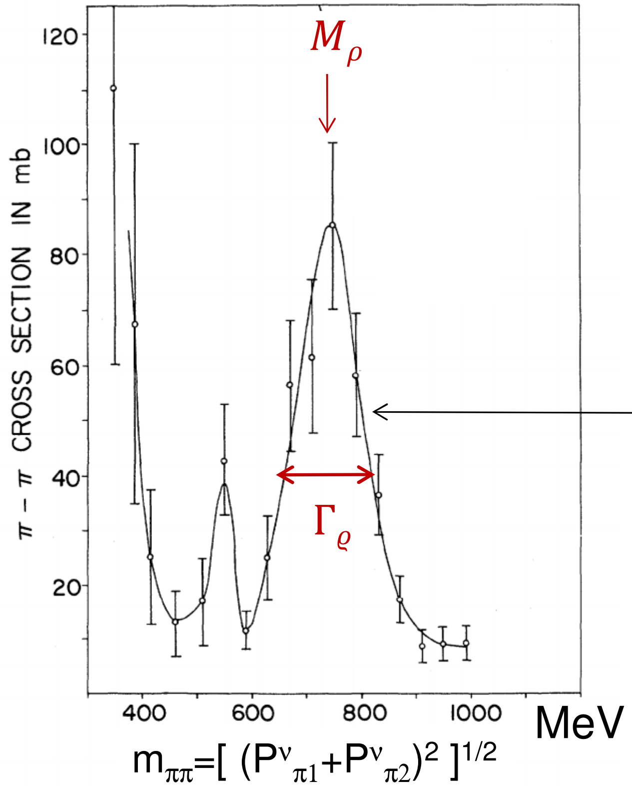
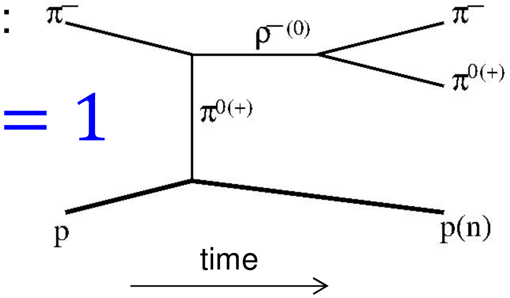


FIG. 3. The π-π cross section as deduced from cases with the four-momentum transfer less than 400 Mev/c.

Thought to happen:



$$I_\rho = 1$$

M_ρ~770 MeV

Γ_ρ ~150 MeV

$$\sim \frac{1}{(M_\rho{}^2 - m_{\pi\pi}{}^2)^2 + (M_\rho \Gamma_\varrho)^2}$$

Relativistic Breit-Wigner formula for a resonance

The ρ resonance is a very short-lived particle:

τ - average lifetime

$\tau_\rho = \hbar / \Gamma_\rho = 4.4\times10^{-24}$ s

$c\tau_\rho = 1.3$ fm *unmeasurably small*

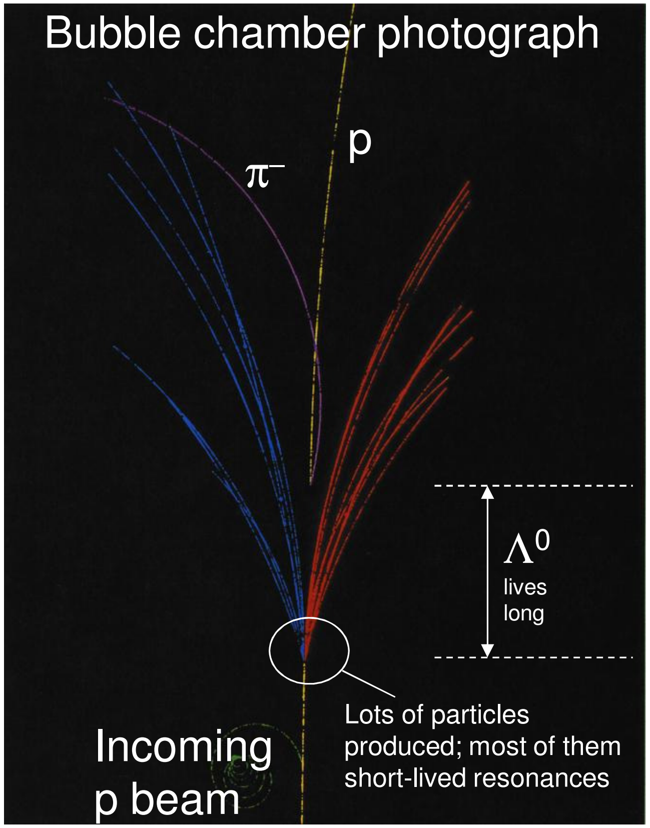
$\tau_{\pi\pm} = 2.6\times10^{-8}$ s

$c\tau_{\pi\pm} = 7.8$ m

$\Gamma_{\pi\pm} = 2.5\times10^{-8}$ eV *unmeasurably small*

vs. long-lived particle

Strange mesons and baryons



$\tau_\Lambda = 2.6\text{x}10^{-10}$ s
$c\tau_\Lambda = 7.8$ cm

Λ^0 baryon lives “strangely” long.

There are also strangely long-living mesons - kaons

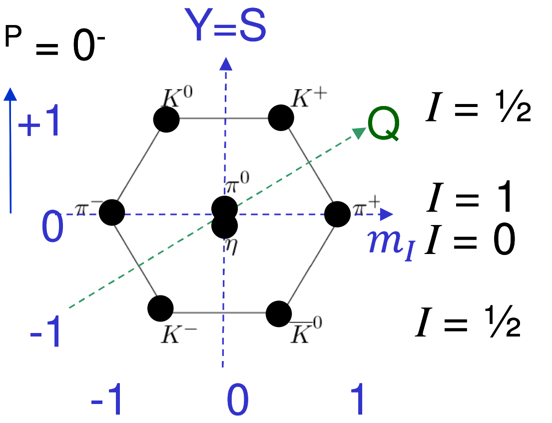
Quark hypothesis – SU(3) flavor symmetry

“Eightfold Way” symmetry – Gell-Mann 1961

“hypercharge” Y=S+A (not really a “charge”)

Strangeness

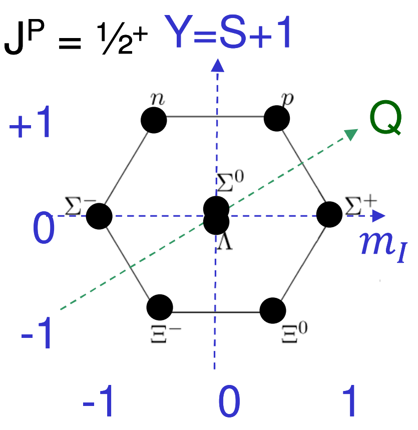
(how “strangely” long is the lifetime of the lightest version)

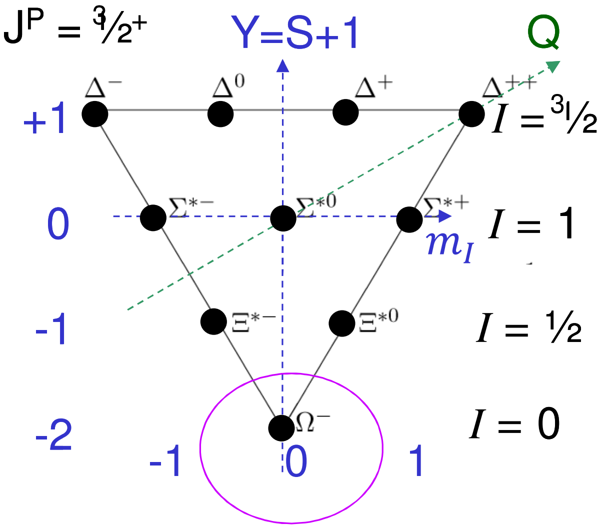


Q = m_I+ ½ Y

Isospin projection

(“charge index” in multi-charged particles)





Not known at that time:

(sss) *S = -3*

Meson

octet

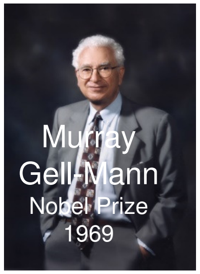
$(q\bar{q})$

Baryon

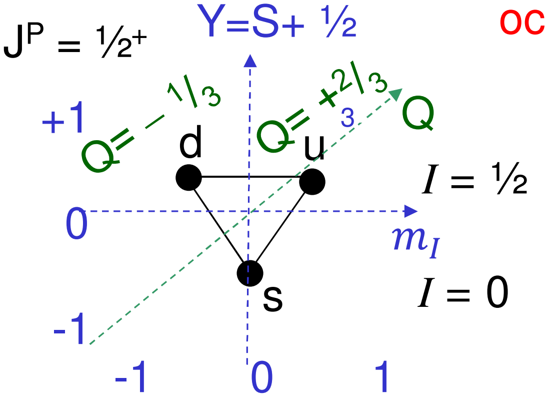
octet

decuplet

(qqq)



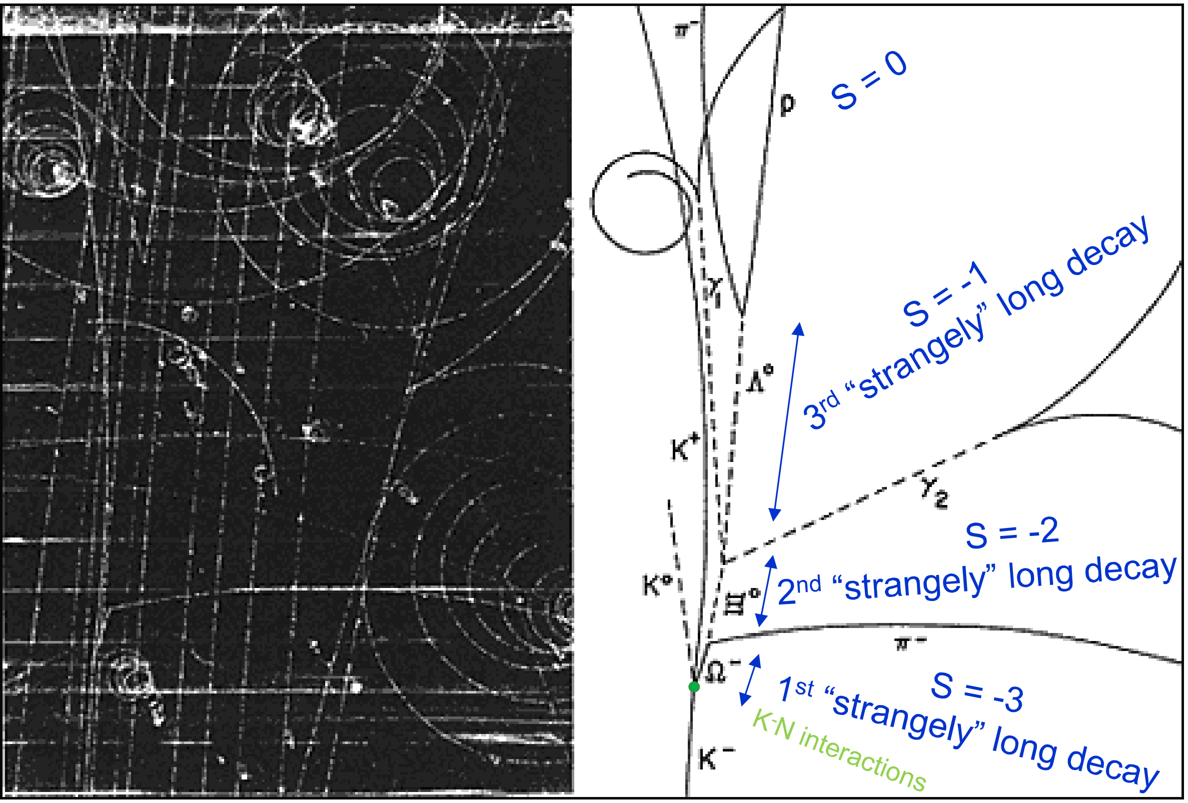
Quark triplet



These are “non-exotic” hadrons

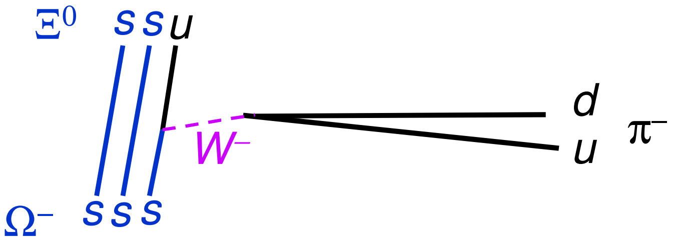
including baryonic molecules
i.e. nuclei $((qqq)(qqq)\ldots)$

Experimental discovery of Ω^- – 1964



- The discovery convinced some physicists that Gell-Mann was on the right track
- Quarks initially treated as mathematical abstraction. Many doubted that they existed since free quarks are not observed.

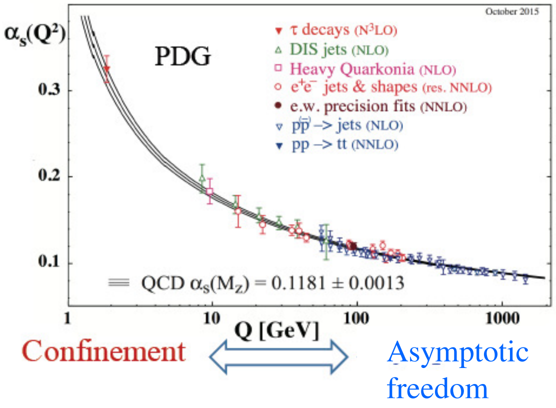
"strange" decays understood later as mediated via "weak" forces as opposed to "strong" (super short lifetimes) or electromagnetic forces (longer but still undetectably short decay paths)



- Ω^- is a ground state of three s quarks. Since their spins (1/2) have to add up to 3/2, they must be lined-up. Three identical fermions in identical quantum state?
- This was later understood as each s quark having a different charge of strong interactions.

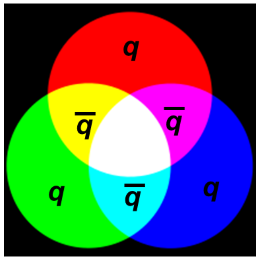
QCD: SU(3) color symmetry

- Fundamental parts of SU(3)$_{flavor}$ symmetry:
  - Quark flavor independence of strong interactions
  - Rules for making hadrons out of quarks
- Near degeneracy of u,d,s quark masses coincidental



- Exact theory of strong interactions: QCD based on SU(3)$_{color}$ symmetry

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}\,(\,i\gamma_\mu D^\mu - m_q\,)\,q \;-\; \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$

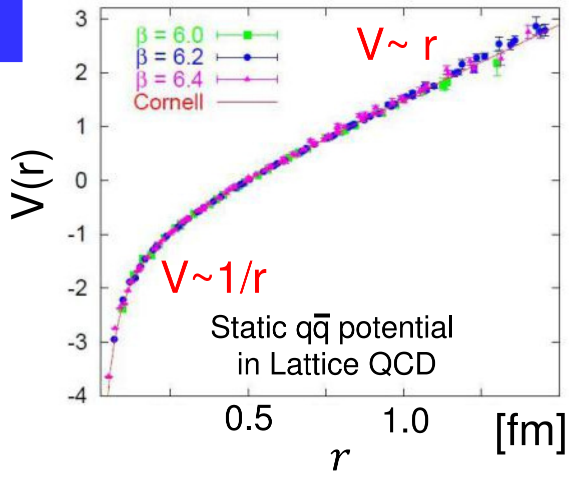


Unfortunately perturbative methods don't work at large quark separations (relevant to hadron creation) – need numerical methods i.e. Lattice QCD calculation. LQCD methods have their own limitations, especially when dealing with highly excited hadrons.

Observable hadrons are color neutral.

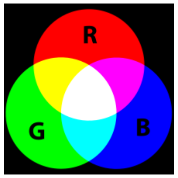
Hadrons spectra are often subject of QCD-motivated phenomenological modeling.

Quarks: 3 different color charges
Gluons: 8 different color+anticolor charges



Raising potential energy must lead to a quark pair creation, and **confinement** of color charge at large distances

Mesons from quarks & antiquarks in QCD

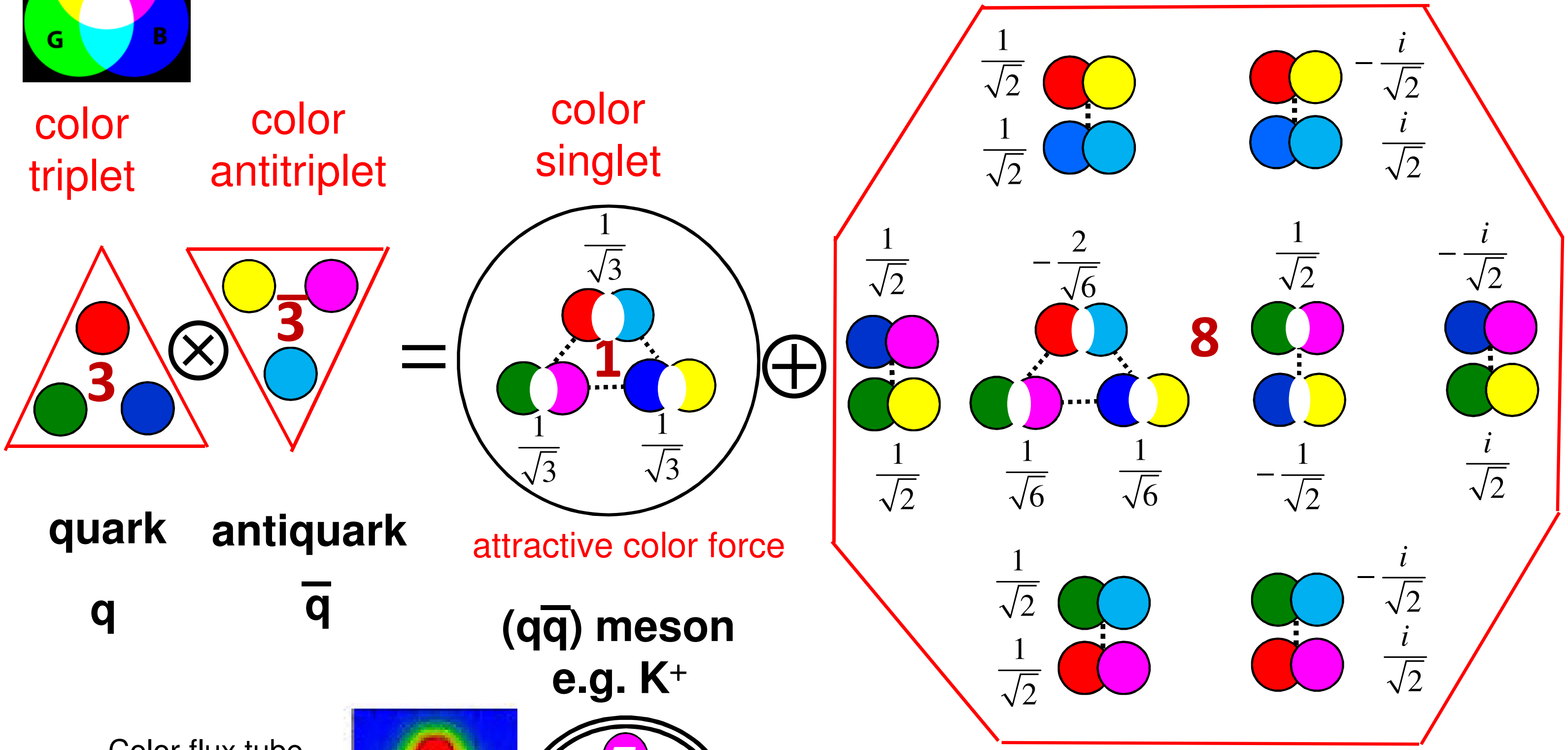


color triplet

color antitriplet

color singlet

color octet



quark

q

antiquark

$\bar{q}$

attractive color force

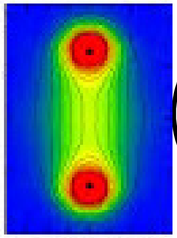
$(q\bar{q})$ meson
e.g. K^+

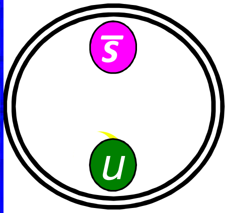
repulsive color force

quarks will pull apart in any octet configuration

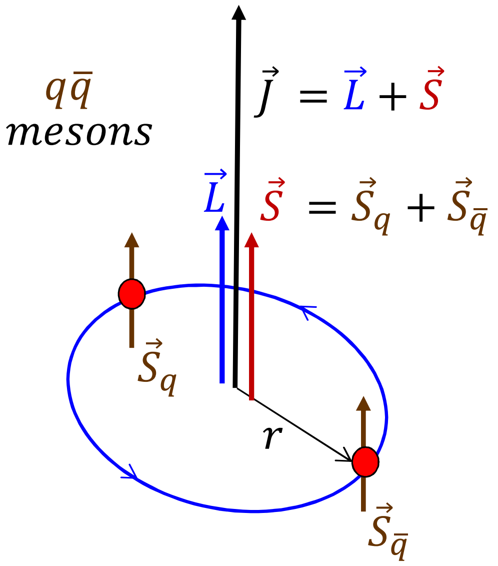
gluons happen to belong to the color octet

Color flux tube stretched between quark and antiquark with attractive potential



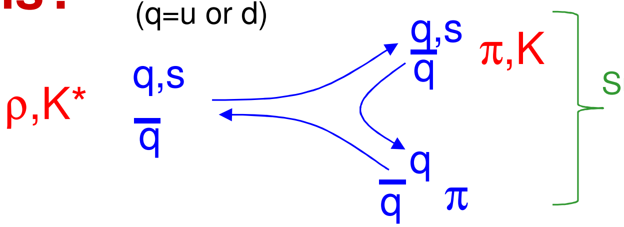


Light meson excitations?

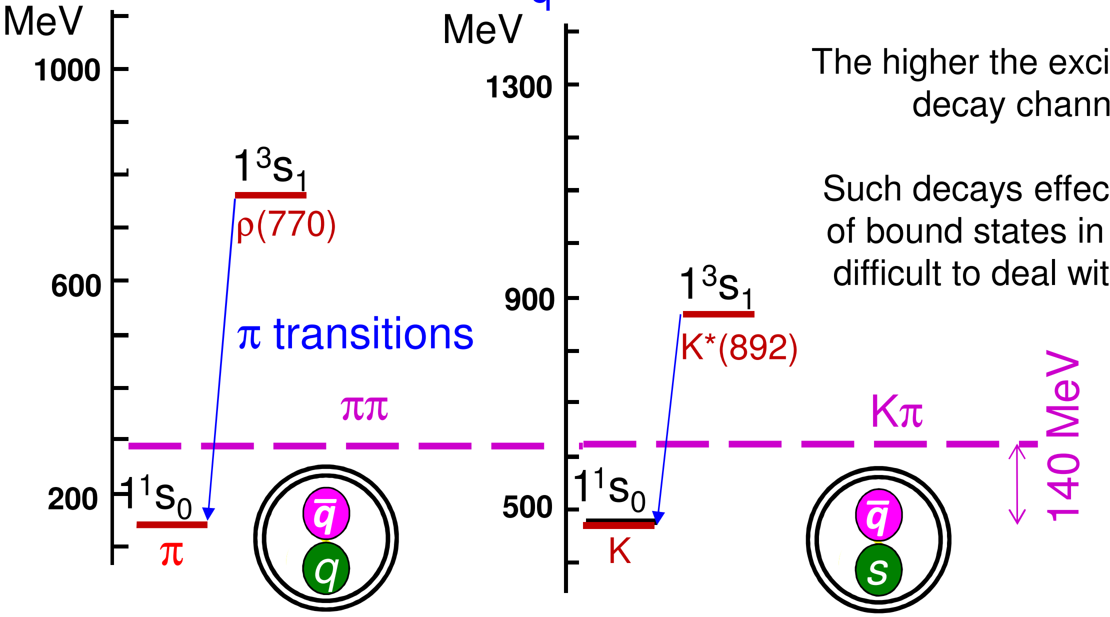


Expect positronium-like energy (i.e. mass) spectrum, though with different energy splittings

$$n^{2S+1}l_J$$



"OZI allowed decay"
Such fall-apart strong decays happen super fast, leading to a large mass indeterminacy i.e. large particle widths
$\Gamma \cdot \tau \sim \hbar$



The higher the excitation, the more decay channels open.

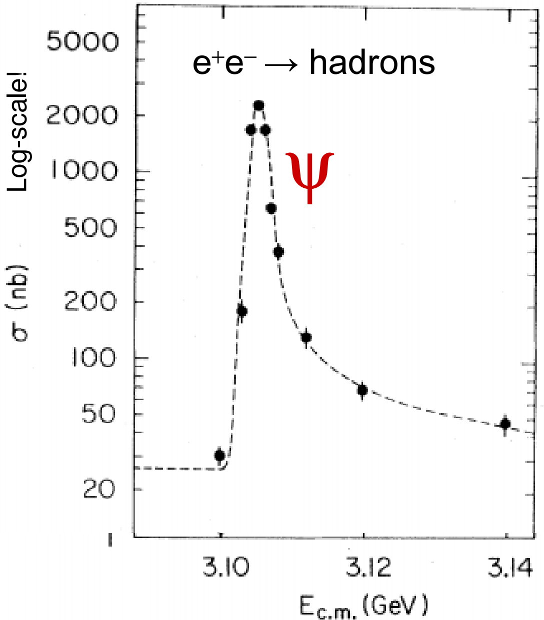
Such decays effect the properties of bound states in a way which is difficult to deal with theoretically.

Theoretical models of higher light hadron excitations tend to be qualitative only.

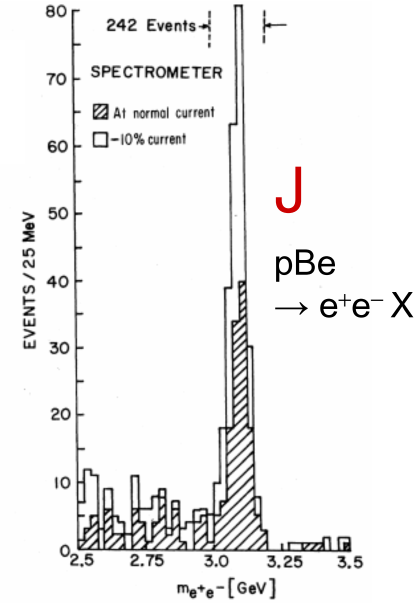
- Hyperfine mass splittings among light mesons are huge!
  - Reflects relativistic nature of light mesons, $\frac{\vartheta_q}{c} \sim 1$, while positronium is essentially non-relativistic, $\frac{\vartheta_e}{c} \sim 0$.

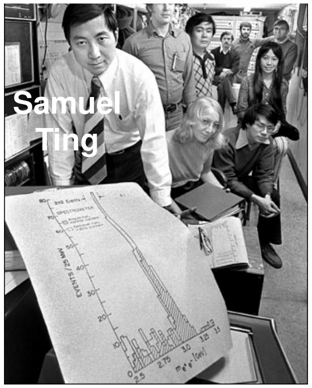
Initial impact of heavy flavors on hadron spectroscopy:

Dispute over quarks ended in 1974.



November revolution of 1974





Nobel Prize, 1976

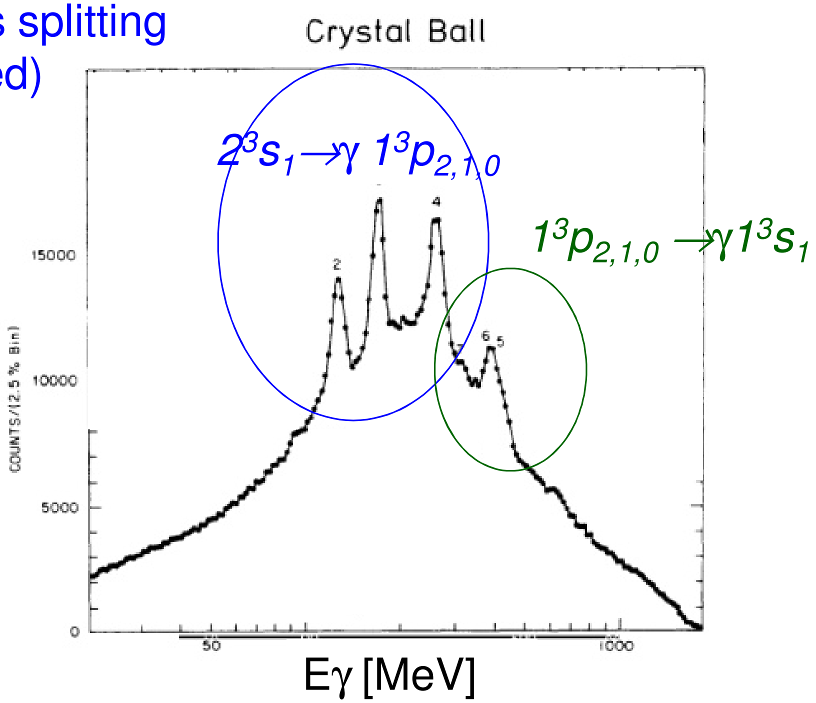
1^3S_1

$c\bar{c}$

state

Charmonium p-states

Fine-structure mass splitting
(LS dominated)

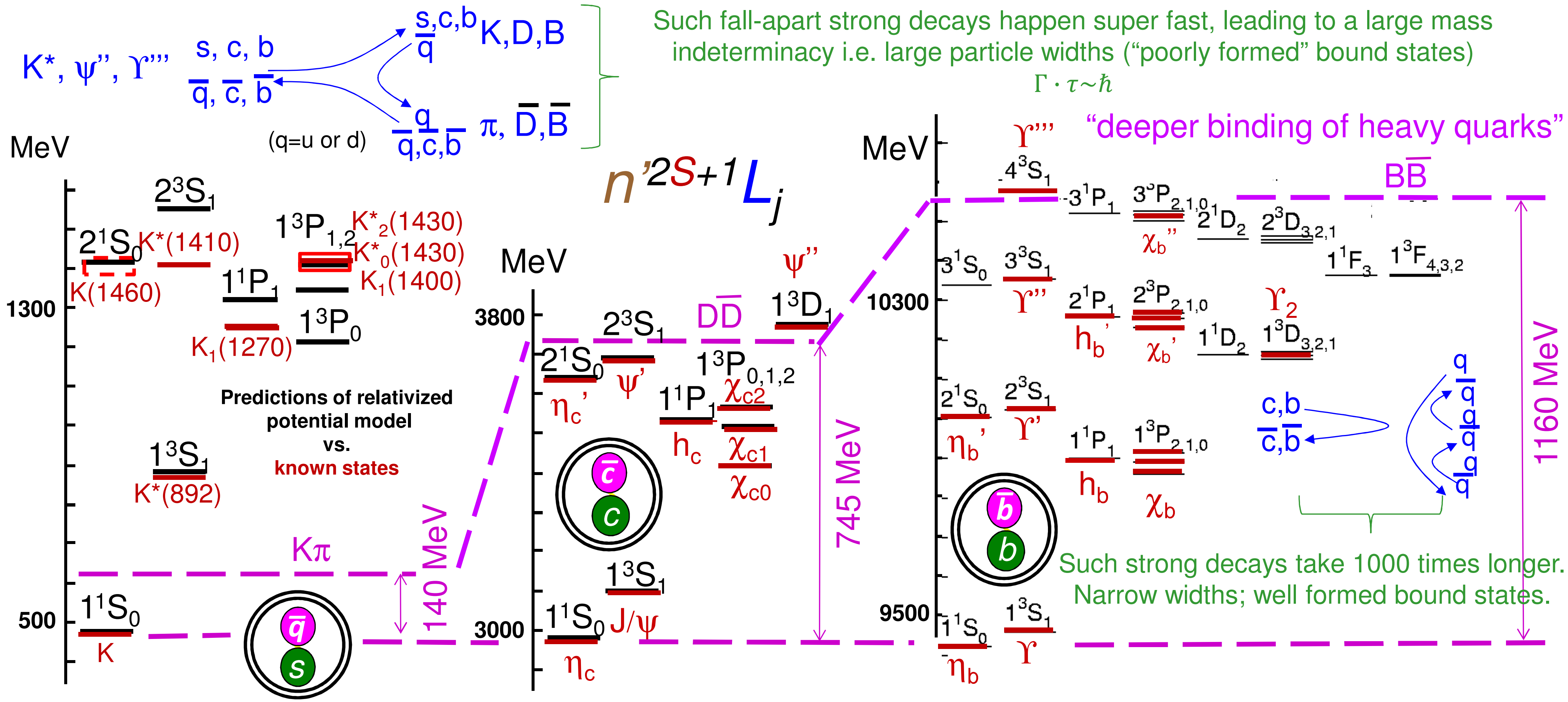


I am switching to use of radial quantum number to label the hadronic states:

$$n'^{2S+1}l_J$$

- In heavy-heavy mesons, photon spectroscopy of hadronic states is an important experimental tool

Initial impact of heavy flavors on hadron spectroscopy:



Such fall-apart strong decays happen super fast, leading to a large mass indeterminacy i.e. large particle widths (“poorly formed” bound states)

$\Gamma \cdot \tau \sim \hbar$

“deeper binding of heavy quarks”

Predictions of relativized potential model vs. known states

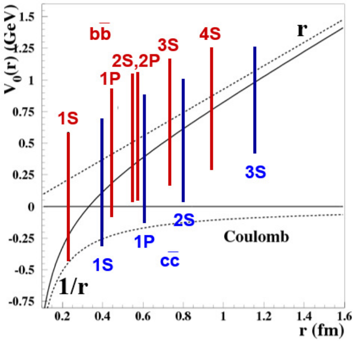
Such strong decays take 1000 times longer. Narrow widths; well formed bound states.

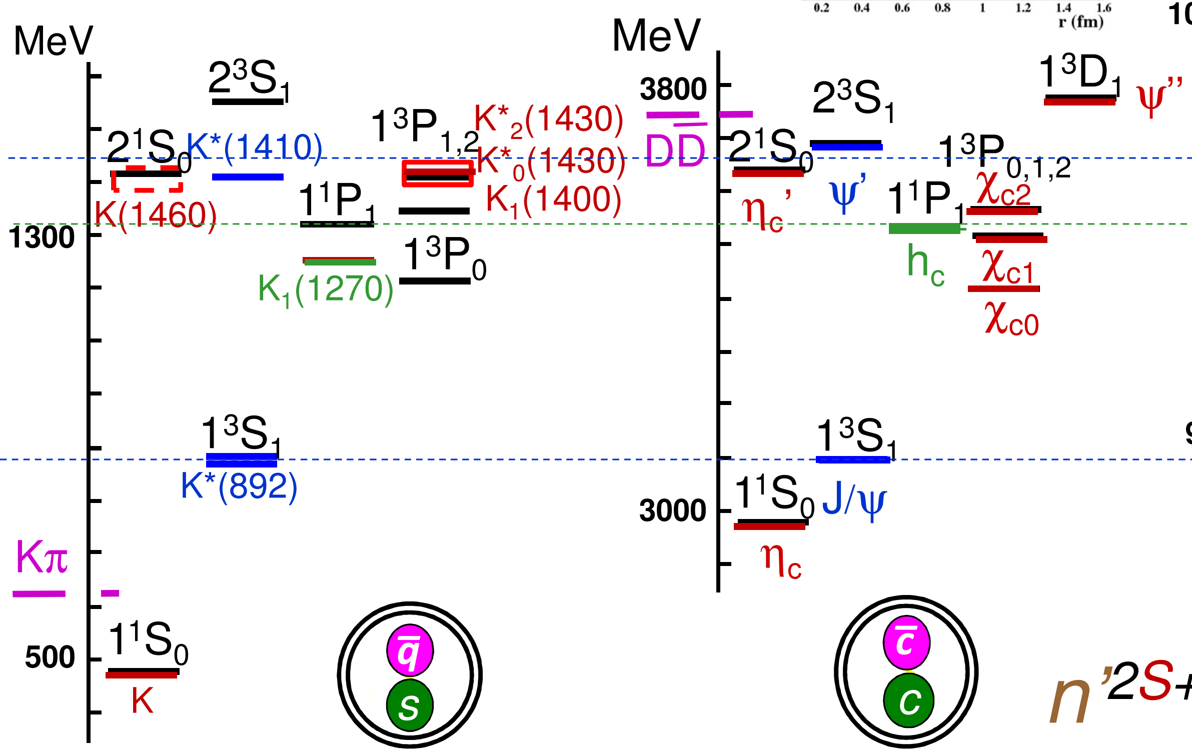
All excitations above the open flavor threshold.
Wide (short-lived) and highly relativistic (light quarks).
Only qualitative spectroscopy.

Plenty of excitations below the open flavor threshold.
Narrow (long-lived) and non-relativistic (heavy quarks).
Quantitative spectroscopy.

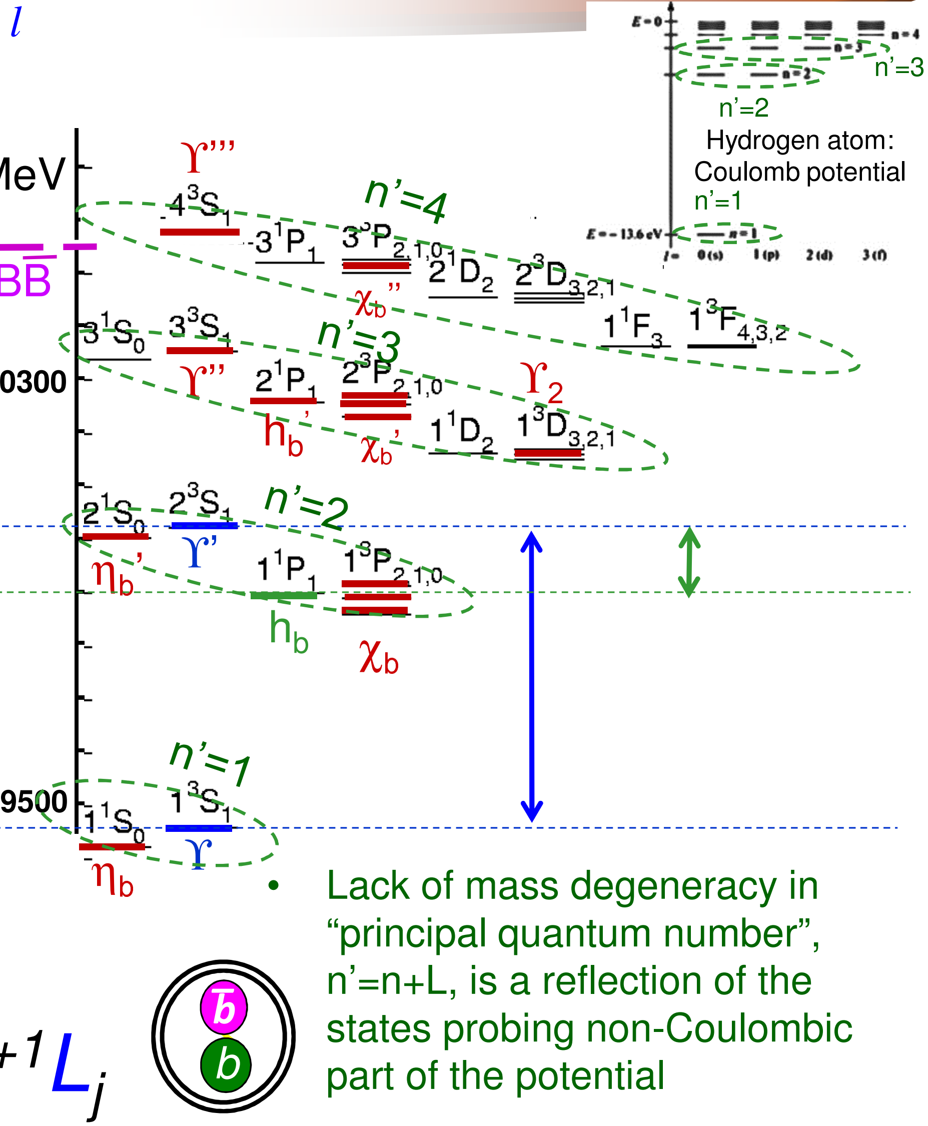
Dominant factor in meson mass spectra: *n'*, *l*

- Near universality of n,*l* driven mass splittings is a reflection of quark-flavor independence of strong interactions, and states probing the potential at similar distances for different meson species





$n'^{2S+1}L_j$



- Lack of mass degeneracy in "principal quantum number", n'=n+L, is a reflection of the states probing non-Coulombic part of the potential

Fine and hyperfine structure in meson spectra

$$V_{spin} = \frac{\vec{L}\cdot\vec{S}}{2\,m_Q{}^2}\,\frac{1}{R}\,\frac{\mathrm{d}}{\mathrm{d}R}\left(3\,V^{vect} - V^{scal}\right)$$

Spin-orbit

Significant since confining potential is effectively of scalar type
(requires non-zero L and S i.e. n^3P,n^3D,…)

$$- \frac{3(\vec{S}_1\cdot\hat{R})\,(\vec{S}_2\cdot\hat{R}) - \vec{S}_1\cdot\vec{S}_2}{12\,m_Q{}^2}\left(\frac{\mathrm{d}^2}{\mathrm{d}R^2} - \frac{1}{R}\,\frac{\mathrm{d}}{\mathrm{d}R}\right)V^{vect}$$

Tensor

Insignificant (requires non-zero L which does not probe small r)

$$+ \frac{2\,\vec{S}_1\cdot\vec{S}_2}{3\,m_Q{}^2}\,\nabla^2\,V^{vect}$$

Spin-spin

Significant only for states probing Coulomb part, i.e. short distances
(L=0 i.e. nS)

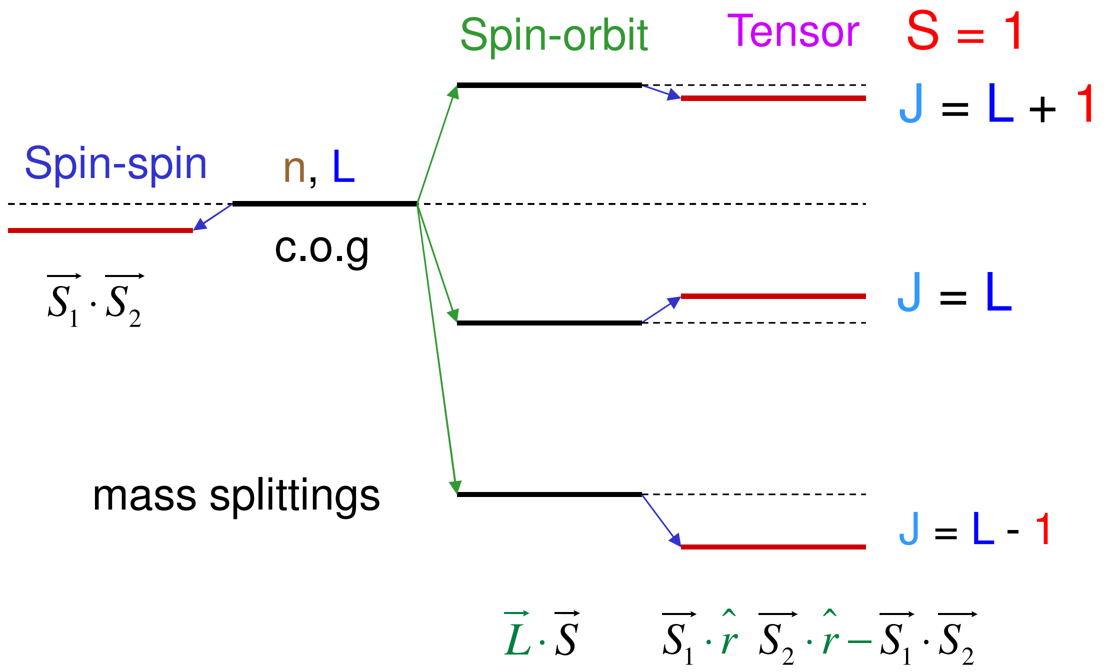
$$V_{NR} = V^{vect} + V^{scal}$$

1/r r

usual phenomenology
consistent with data
and with LQCD

Hyperfine structure

Fine structure



Spin-dependent mass splitting reflect magnetic interactions – they are relativistic effects.

Atoms are highly non-relativistic; tiny effects in QED.

Can be very large for light-quark mesons.

Decrease in importance with quark mass $\sim 1/m_Q^2$

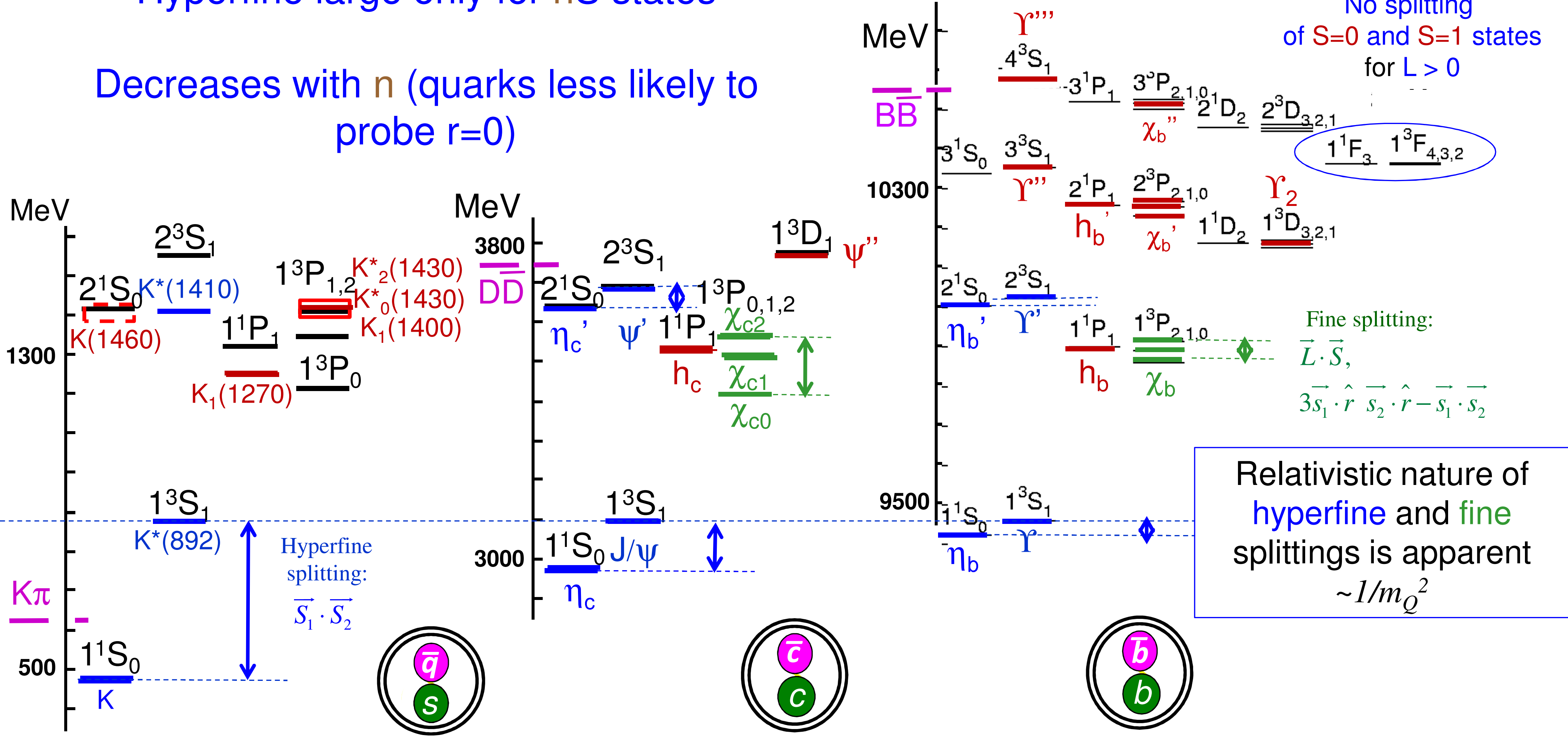
Hyperfine and fine structure in meson spectra

$n'^{2S+1}l_j$

Hyperfine large only for nS states

Decreases with n (quarks less likely to probe r=0)

No splitting of S=0 and S=1 states for L > 0



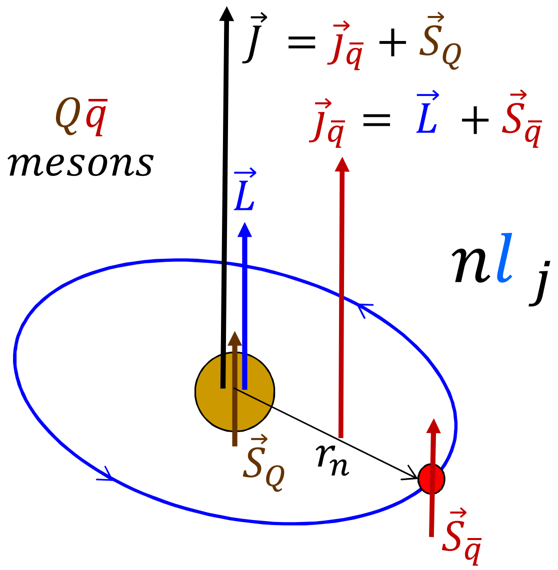
Relativistic nature of hyperfine and fine splittings is apparent

$\sim 1/m_Q^2$

Heavy-Light Mesons $(Q\bar{q})$: D, D$_s$, B, B$_s$

- Naively expect light-quark spin effects to dominate over heavy-quark spin effects

In the limit of $\frac{m_q}{m_Q} \rightarrow 0$

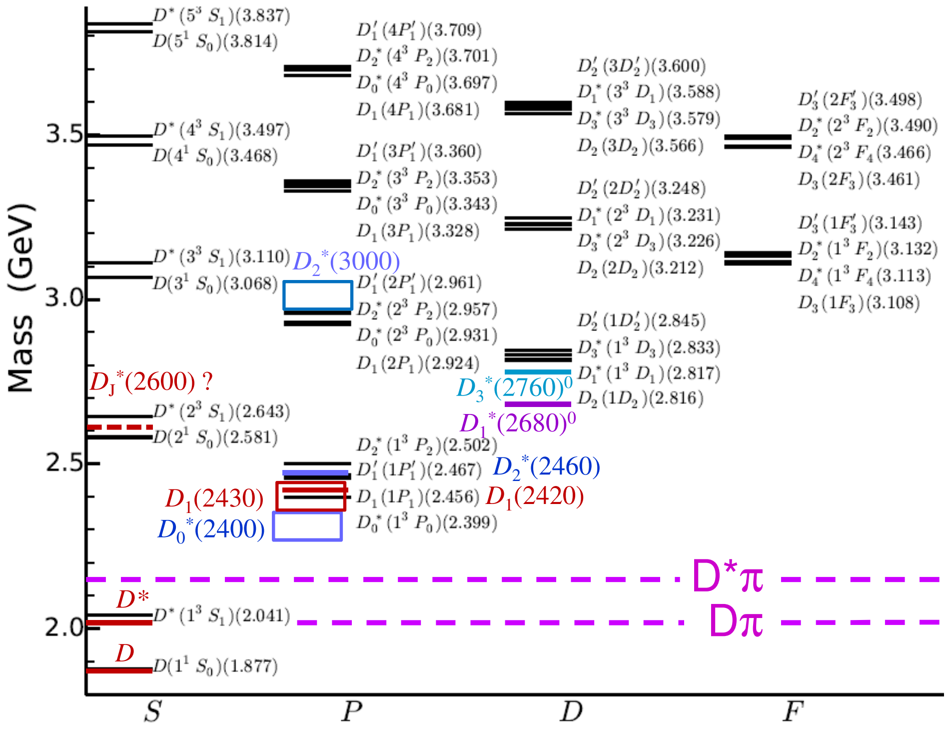


- Hydrogen-like fine, and hyper-fine structures
- Heavy Quark Symmetry: no difference between D and B systems (like symmetry between single-electron atoms!)
- Transitions do not change heavy quark spin

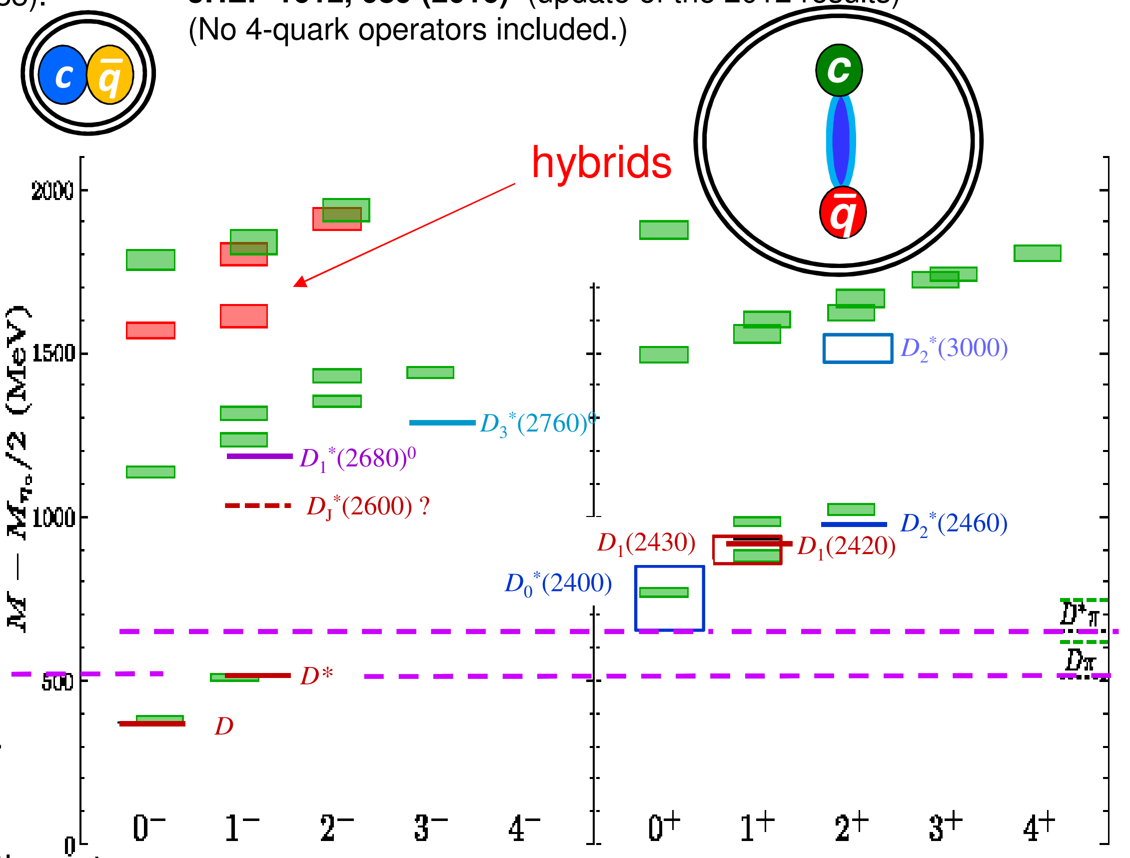
- In practice, $\frac{m_q}{m_c} \sim 0.2 \quad (\frac{m_q}{m_b} \sim 0.07)$, not as small as in hydrogen, $\frac{m_e}{m_p}\gamma_p = 0.0015$:
  - Hyperfine splitting of *s*-states is still sizable
  - Heavy-Quark Effective Theory (HQET): use $\frac{m_q}{m_Q} = 0$ as the lowest order, then implement corrections

Status of D meson spectroscopy

S. Godfrey, K. Moats PR D93, 034035 (2016)
Relativized potential Quark Model (revamp of Godfrey-Isgur 1985).
(Includes predictions for decay widths).



Hadron Spectrum Collaboration (LQCD m_π=240 MeV)
JHEP 1612, 089 (2016) (update of the 2012 results)
(No 4-quark operators included.)

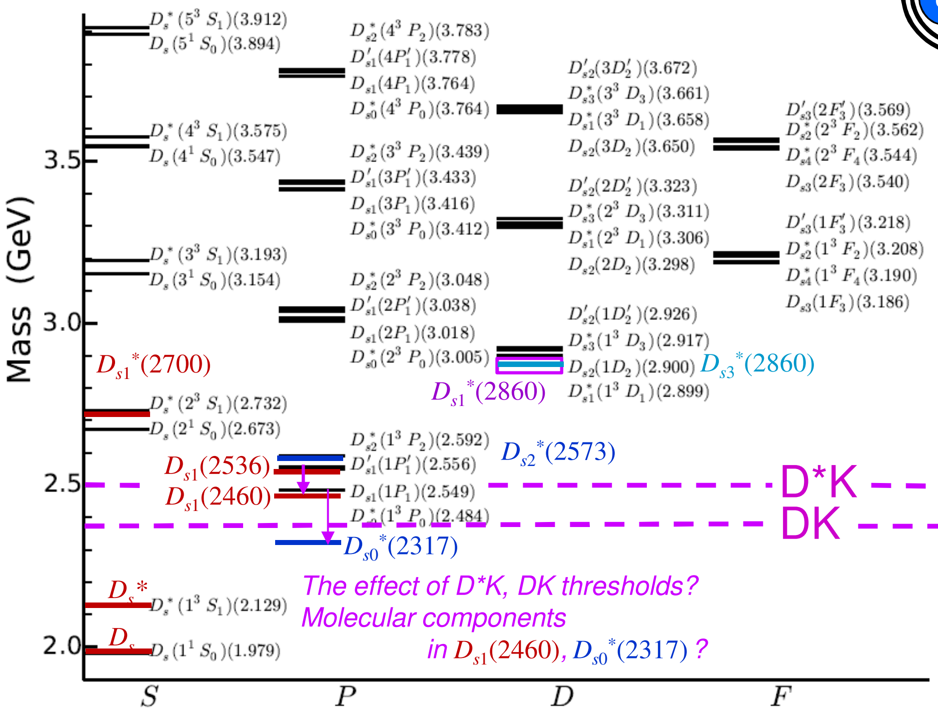


- 1S,1P and half of 1D states have been detected
- Detecting higher excitations is hard (broad, small production rates, many decay channels open)
- Not clear how many of heavier predicted states will ever by detected
- Like for other spectroscopies of short-lived states, theoretical predictions, either phenomenological models or lattice QCD (no couplings to decay channels are simulated above), are qualitative in nature

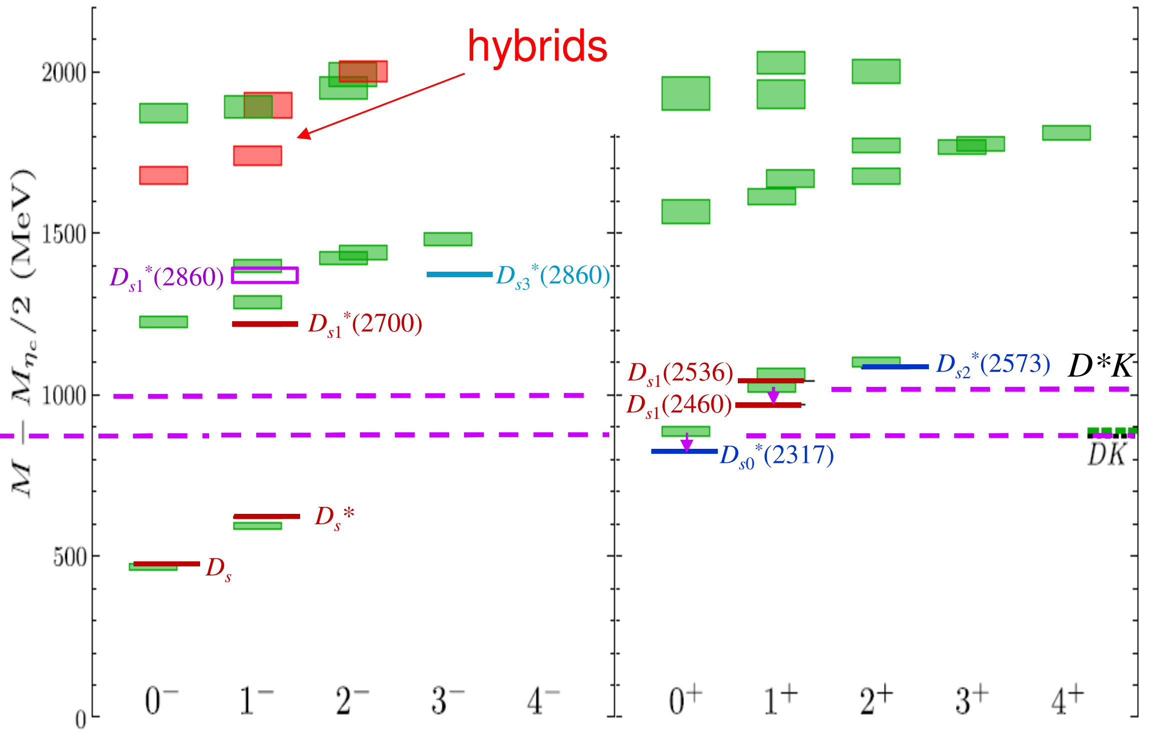
Status of D_s meson spectroscopy

S. Godfrey, K. Moats PR D93, 034035 (2016)

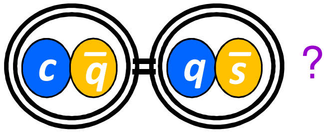
Hadron Spectrum Collaboration (LQCD m_π=240 MeV)
JHEP 1612, 089 (2016)



*The effect of D*K, DK thresholds?*
Molecular components
in $D_{s1}(2460)$, $D_{s0}^*(2317)$?

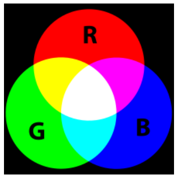


- No experimental progress in the last 2 years
- Status similar to that of D mesons
- Masses of $D_{s0}^*(2317)$ and one of $D_{s1}(2460)$ states are shifted relative the expectations to below the DK,D*K thresholds. Molecular components?

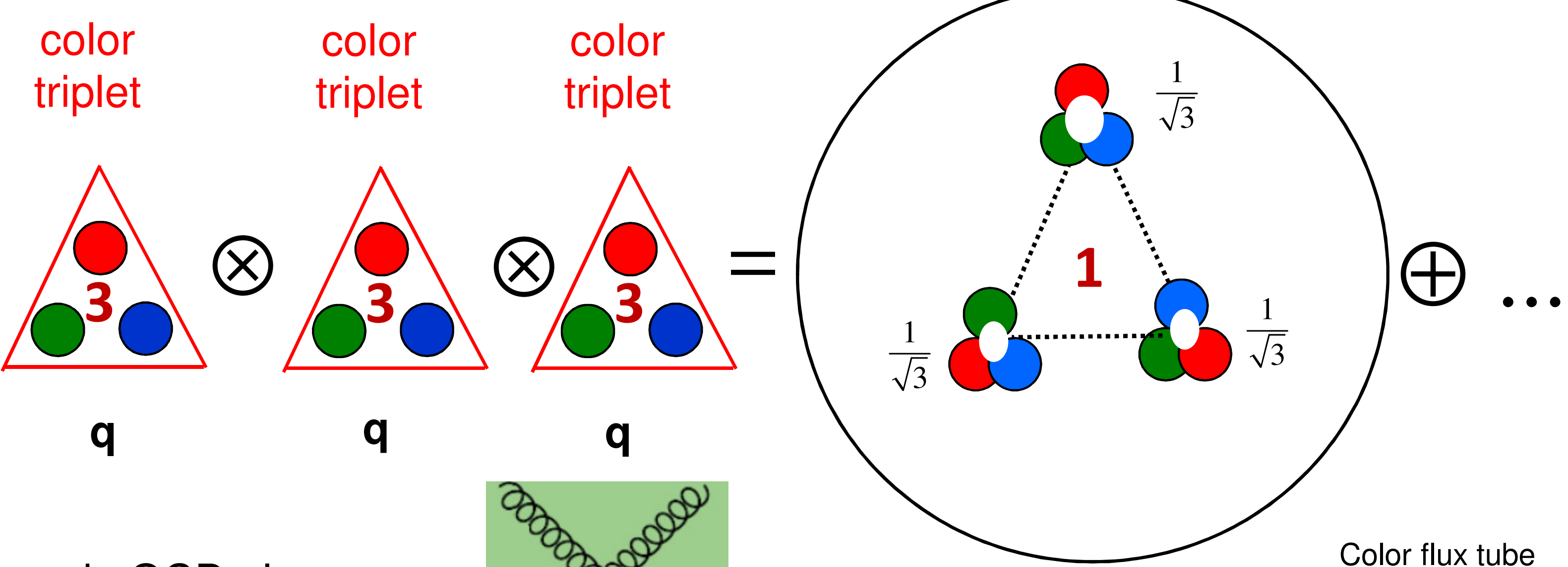


- Spectroscopy of $B_{(s)}$ mesons even less experimentally developed

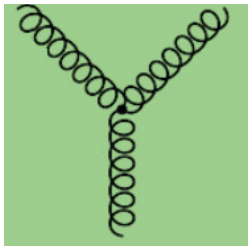
Baryons directly from 3 quarks



color singlet

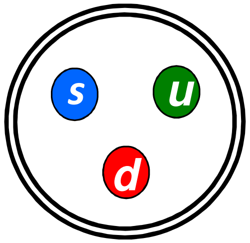


in QCD gluons can couple to each other

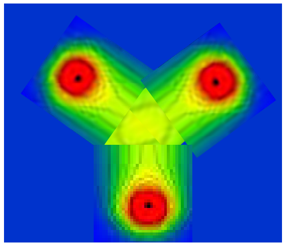


attractive color force

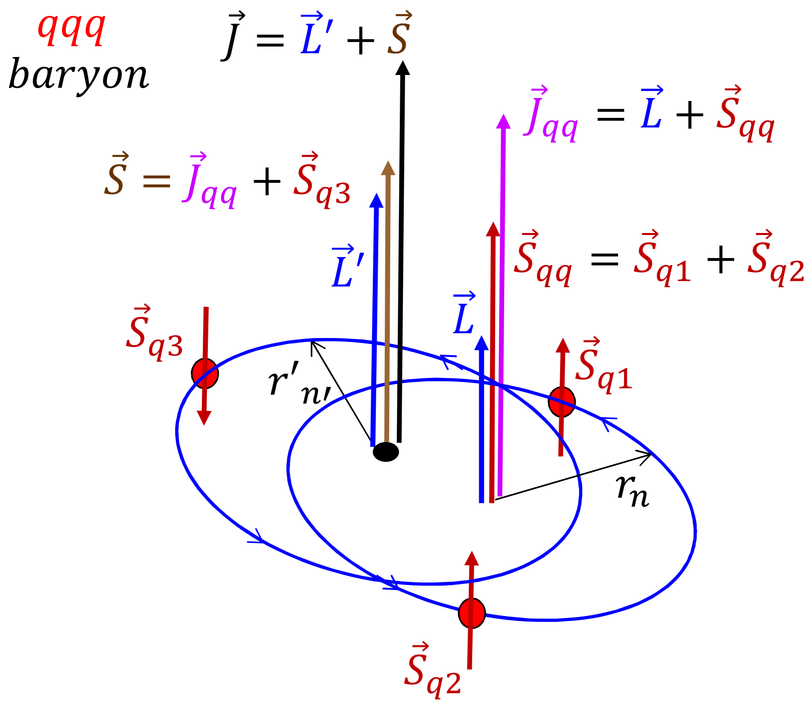
(qqq) baryon



Color flux tube stretched between three quarks

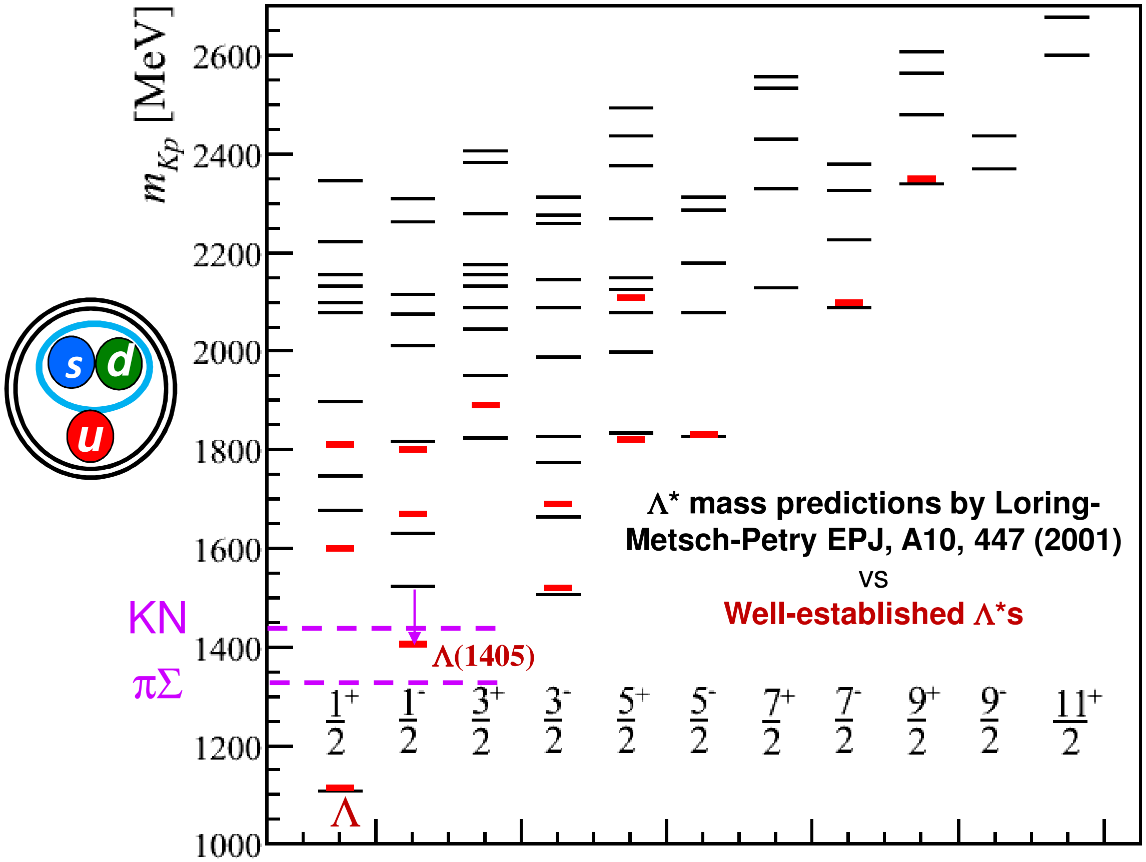


Generic model of baryon excitations



- In principle two radial quantum numbers *n,n'* and two orbital angular *l,l'* momenta – **huge number of excitations**
- Additional symmetrization requirements from SU(3)$_{\text{flavor}}$ if quarks are light
- Three quark spins to couple to two angular momenta – **very complicated (hyper)fine structure**

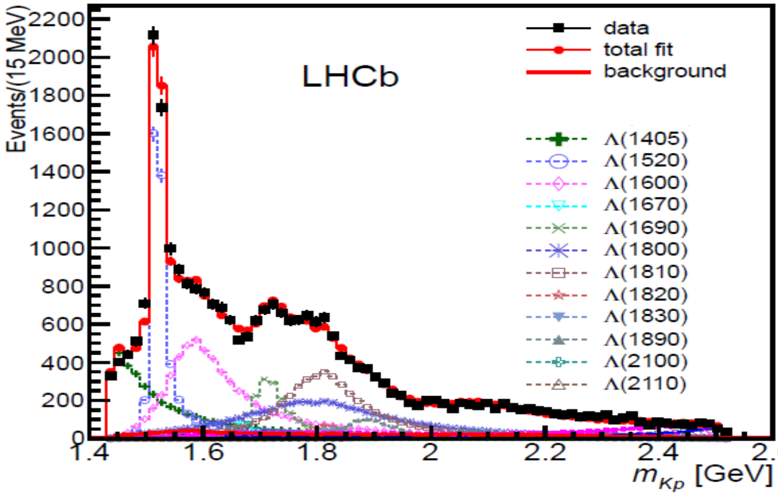
Example: Λ excitations



Λ* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

vs

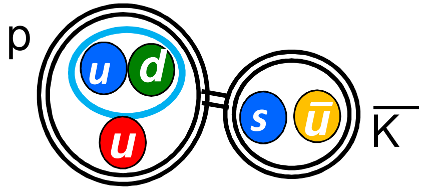
Well-established Λ*s



Short-lived states (broad).

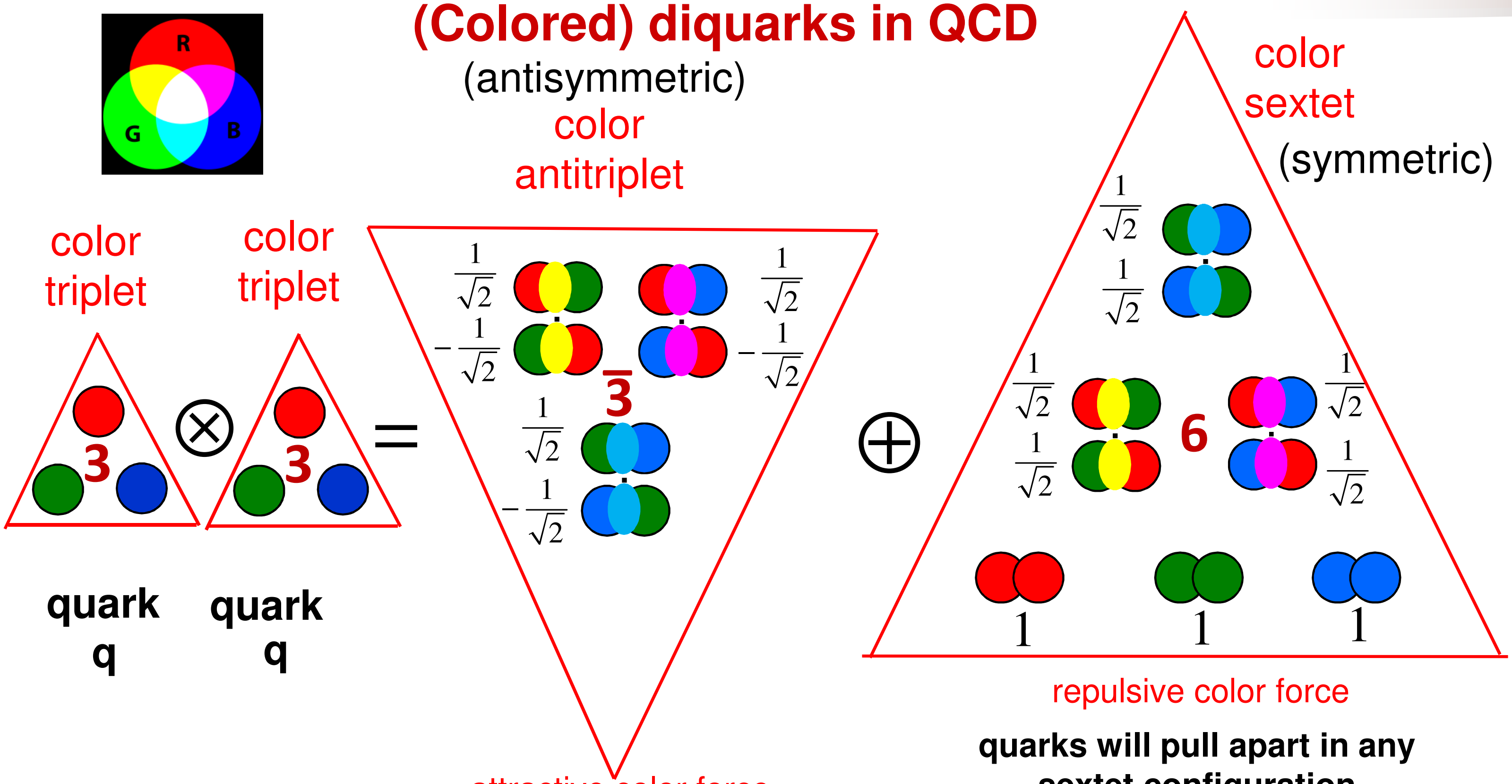
Mostly qualitative spectroscopy.

- Mass of **Λ(1405)** significantly shifted relative the expectations to below the KN threshold. Molecular components?



Phenomenological models often restrict some degrees of freedom which has some motivation in QCD.

(Colored) diquarks in QCD



color triplet

color triplet

quark q

quark q

(antisymmetric) color antitriplet

attractive color force

(half as strong as in the meson)

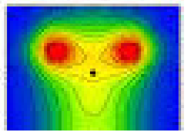
color sextet (symmetric)

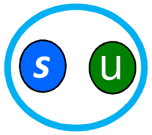
repulsive color force

quarks will pull apart in any sextet configuration

(qq) diquark

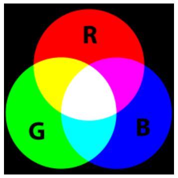
Color flux tube stretched between the quarks and extending to other color partners



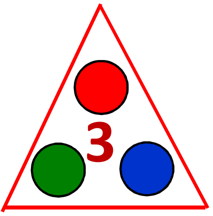


Not a particle, just a building block in QCD

Baryons from quarks and diquarks



color triplet

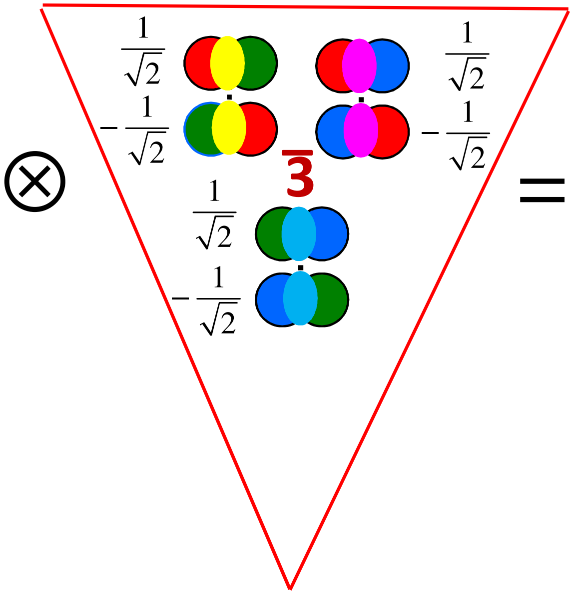


quark

q

$\otimes$

color antitriplet

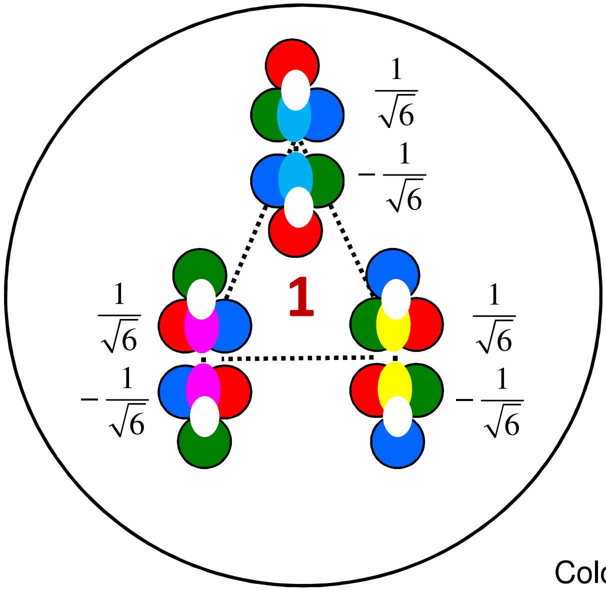


attractive color force

(qq) diquark

$=$

color singlet



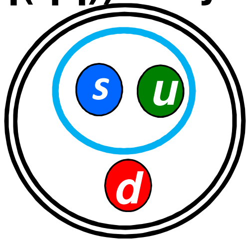
attractive color force

(q(qq)) baryon

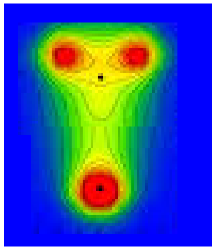
$\oplus$ …

Relative importance of this internal baryon structure vs more democratic quark configuration is a question mark

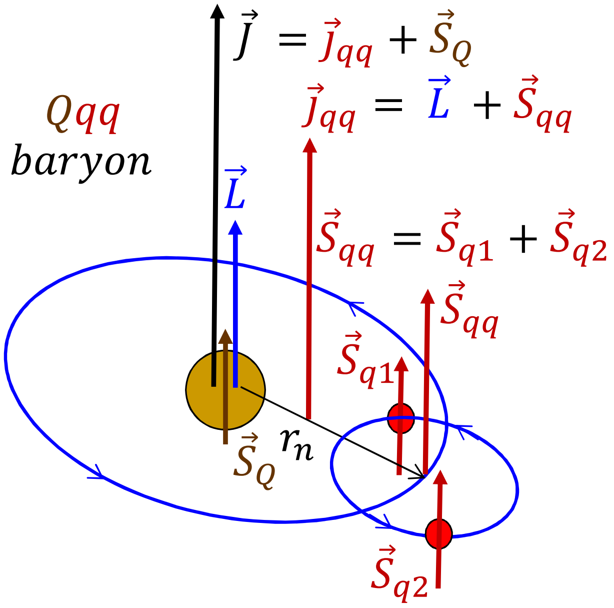
e.g. Λ



Color flux tube stretched between the diquark and the third quark



Heavy-light-light baryons



In usual diaquark model: S_{qq}=0,1

n_{qq} =1 $\vec{L}_{qq}$=0

Scalar and axial-vector diquarks

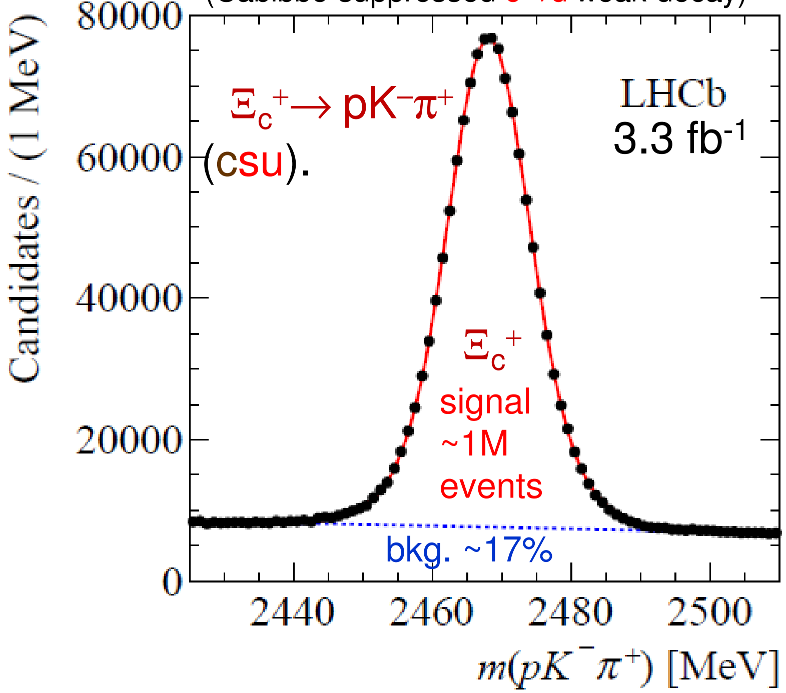
- Qqq baryons are a perfect place to study light diquark structures as the heavy quark spin decouples from light quark spins
- QCD motivated diquarks need to be in the ground state, n_{qq}=1, L_{qq}=0 ,which eliminates a large number of possible excitations:
  - States can be labeled with ***n*,*L*** of the diquark orbiting around the heavy quark, which will be a dominant effect in mass
  - The main mass level hierarchy like among mesons!
- Diaquark spin S_{qq} can be 0 or 1 (scalar and axial vector diquarks):
  - Since quarks are light (relativistic), and the diquark is in L_{qq}=0 state, their hyperfine mass splitting $\vec{S}_{q1} \cdot \vec{S}_{q2}$ can be large.
- Also important is fine structure from $\vec{L} \cdot \vec{S}_{qq}$ couplings
- Small hyperfine structure from $\vec{J}_{qq} \cdot \vec{S}_Q$

Heavy-light baryons: excitations of Ω_c^0

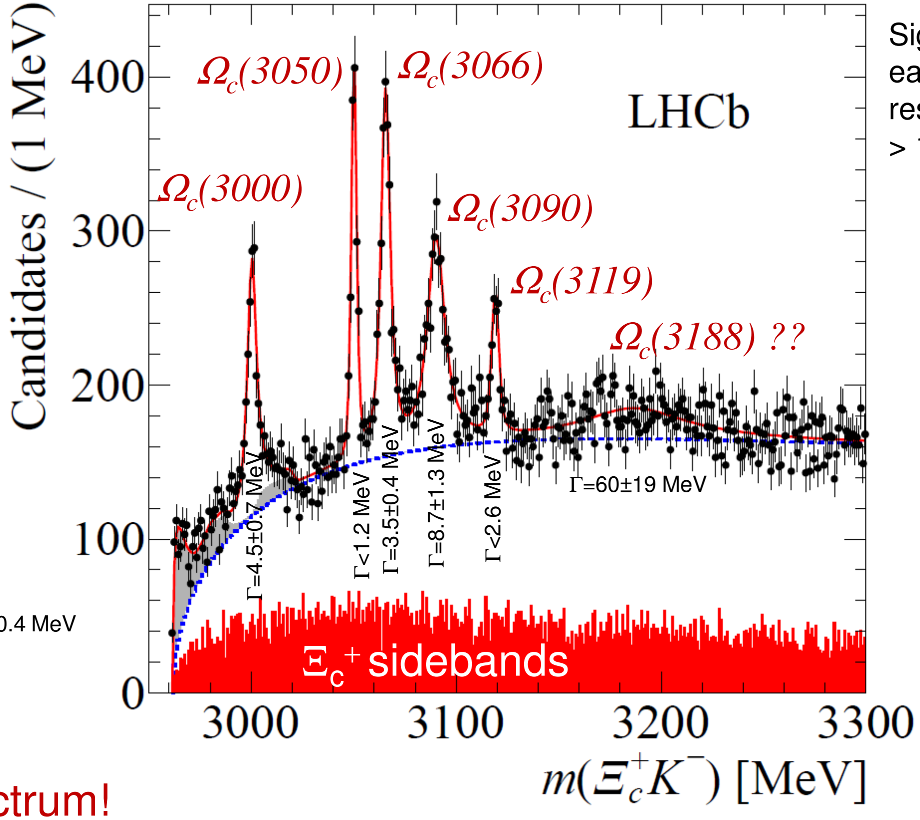
LHCb-PAPER-2017-002, CERN-EP-2017-037, arXiv:1703.04639.

- Only two ground states (1S) have been known before: $^1/_2{}^+$ Ω_c^0, $^3/_2{}^+$ $\Omega_c(2770)^0$

(Cabibbo suppressed c→d weak decay)

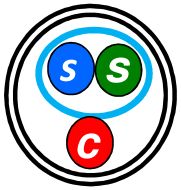


$\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$ (Strong decay)



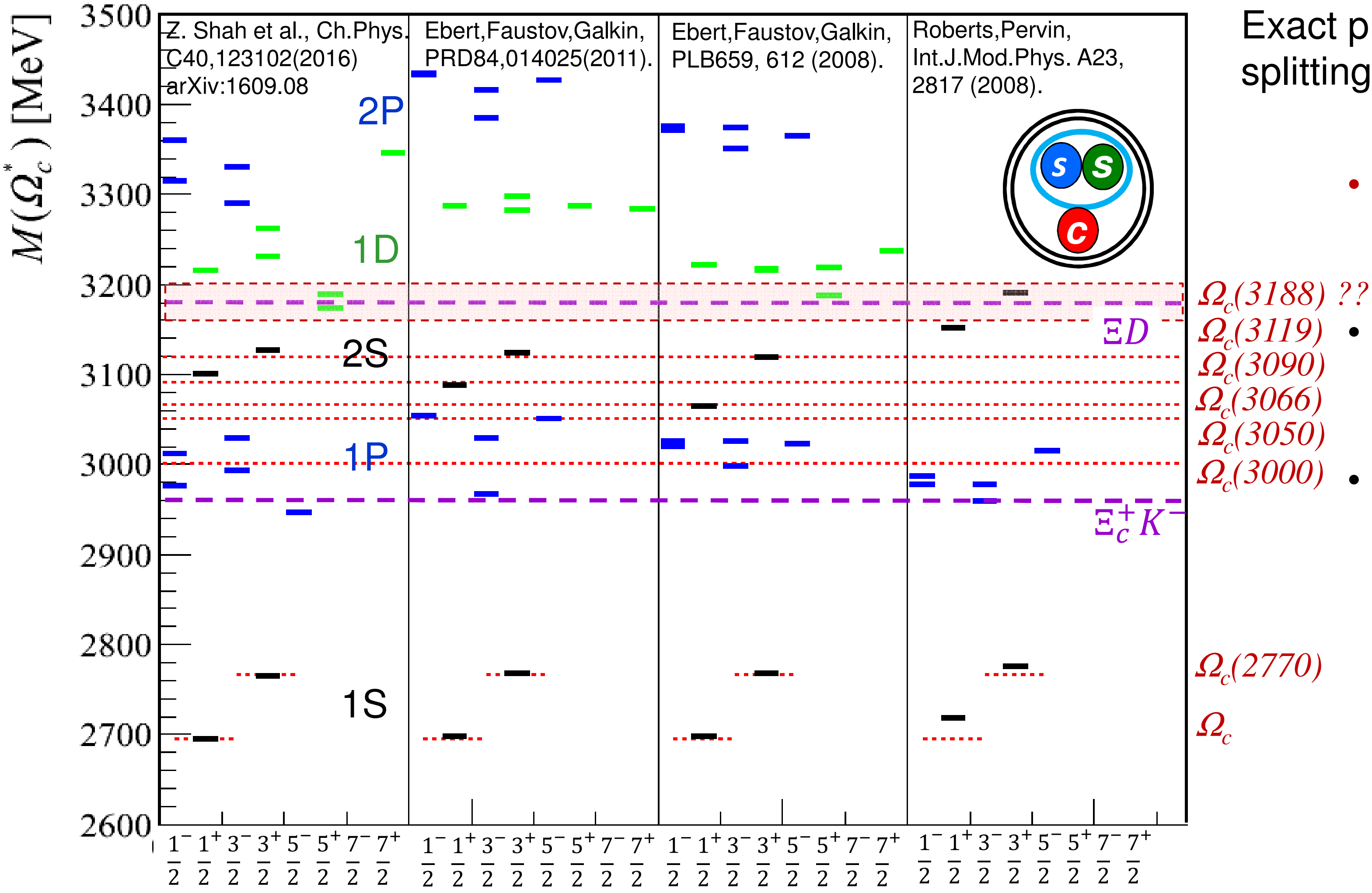
Γ=3.5±0.4 MeV

Significance of each of the narrow resonances > 10σ



5 narrow, new states in single mass spectrum!
Excellent place to test baryon models (long-lived states).

Interpretation of Ω_c excitations observed by LHCb



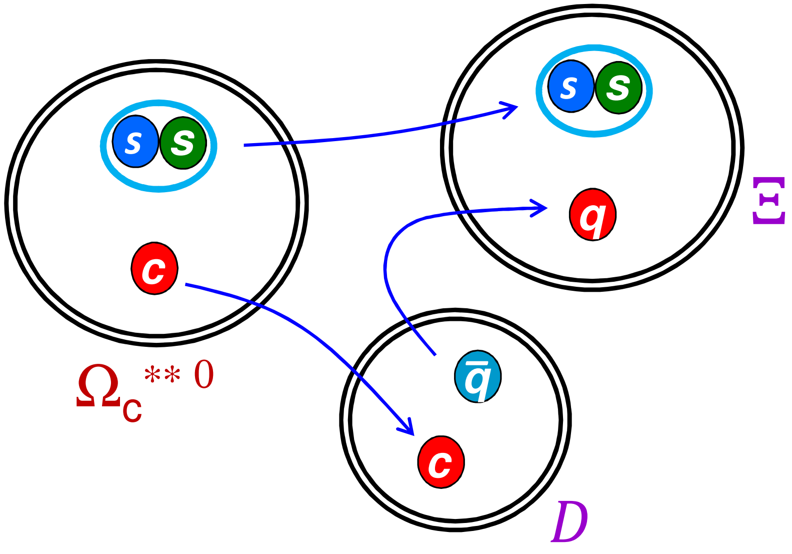
Exact predictions for (hyper)fine splittings are model dependent.

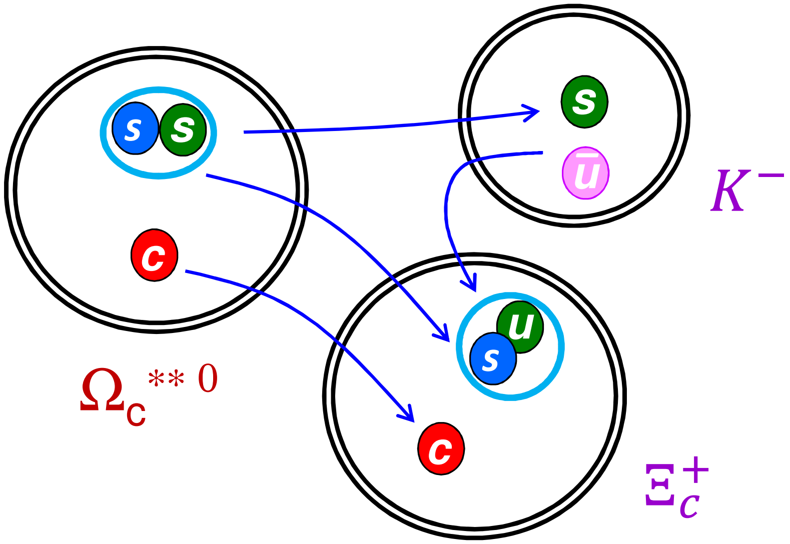
- The states newly observed by LHCb are likely 1P and 2S
- None of the models predicted the mass splitting exactly
- Determining their J^Ps is important for constraining the models (will be done).

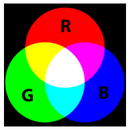
Why the observed $\Omega_c^{**\,0}$ states are narrow?

- They are below the threshold for the preferred fall-apart mode ΞD

- They decay to $\Xi_c^+ K^-$,which requires ripping apart the diquark – less likely process, longer lifetime, smaller width.



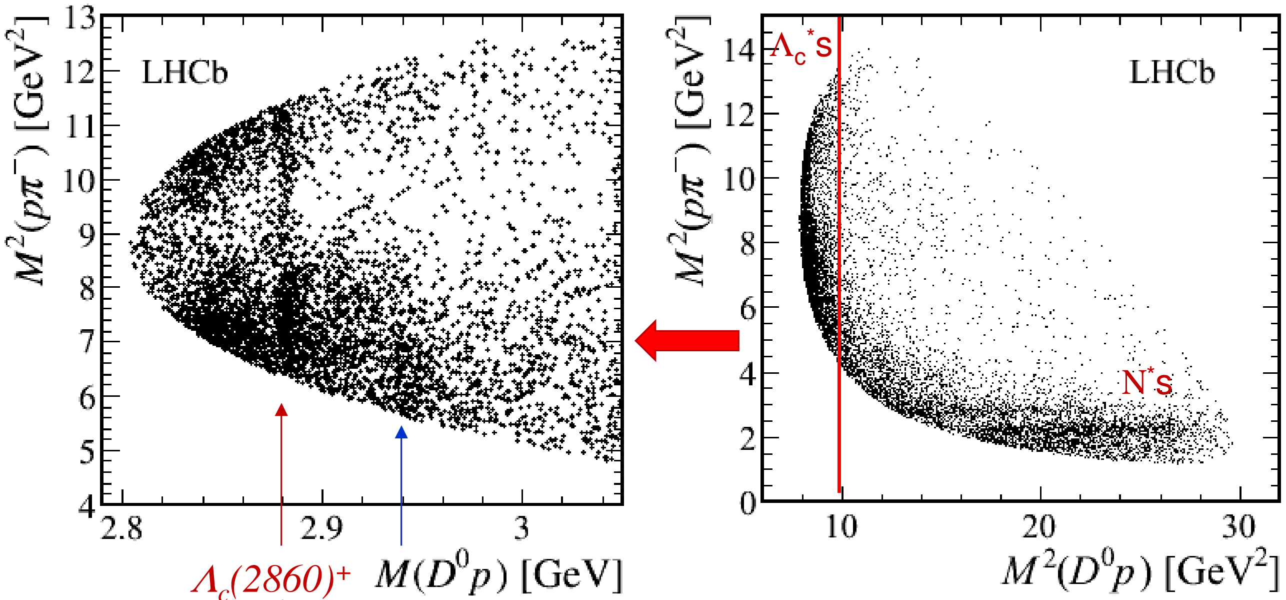


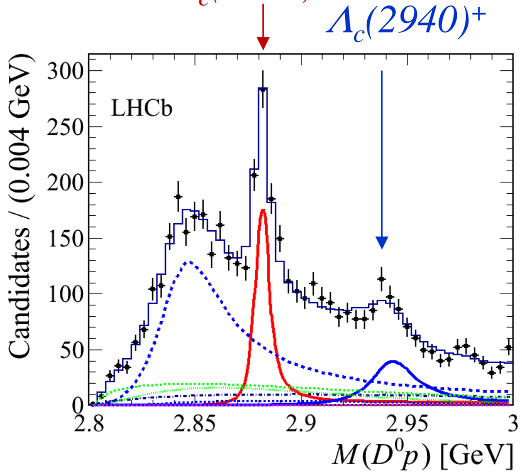


Except for the possible 6th one, $\Omega_c(3188)$, which is broad!

Their narrowness is the nice evidence for QCD-motivated diquarks!

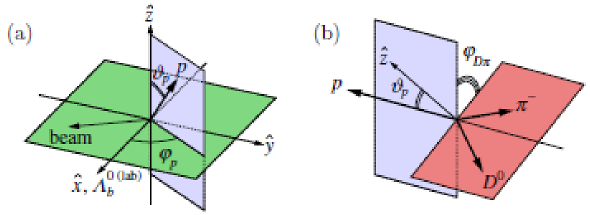
Λ_c^+ excitations

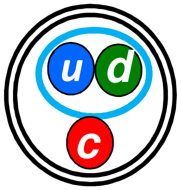




- Recent LHCb amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$

LHCb-PAPER-2016-61
arXiv:1701.07873





- New resonance: $\Lambda_c(2860)^+$, $J^P = 3/2^+$

First observations

$$M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV}$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

- $\Lambda_c(2940)^+$: preferred $J^P = 3/2^-$

Known before,
J^P determined for the first time

$$M(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5} \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\ \text{MeV}$$

$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0} \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\ \text{MeV}$$

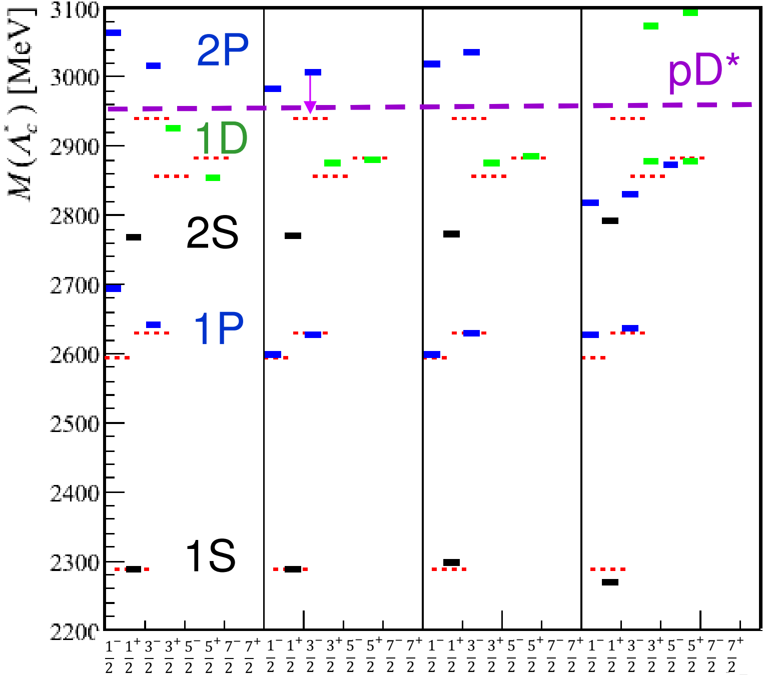
Interpretation of Λ_c and of Ξ_c excitations

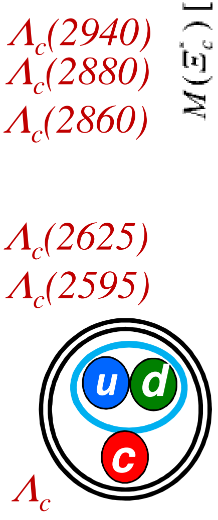
Z. Shah et al., Ch.Phys. C40,123102(2016) arXiv:1609.08

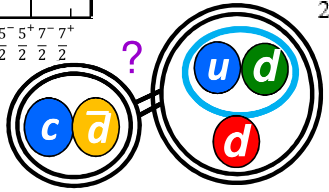
Ebert,Faustov,Galkin, PRD84,014025(2011).

Ebert,Faustov,Galkin, PLB659, 612 (2008).

Roberts,Pervin, Int.J.Mod.Phys. A23, 2817 (2008).







Molecular pD* component in $\Lambda_c(2940)$?

Ortega,Entem,Fernandez, PL B718, 1381 (2013) 1381.

J. Zhang, PRD89, 096006 (2014).

Z. Shah et al., Ch.Phys. C40,123102(2016) arXiv:1609.08

Ebert,Faustov,Galkin, PRD84,014025(2011).

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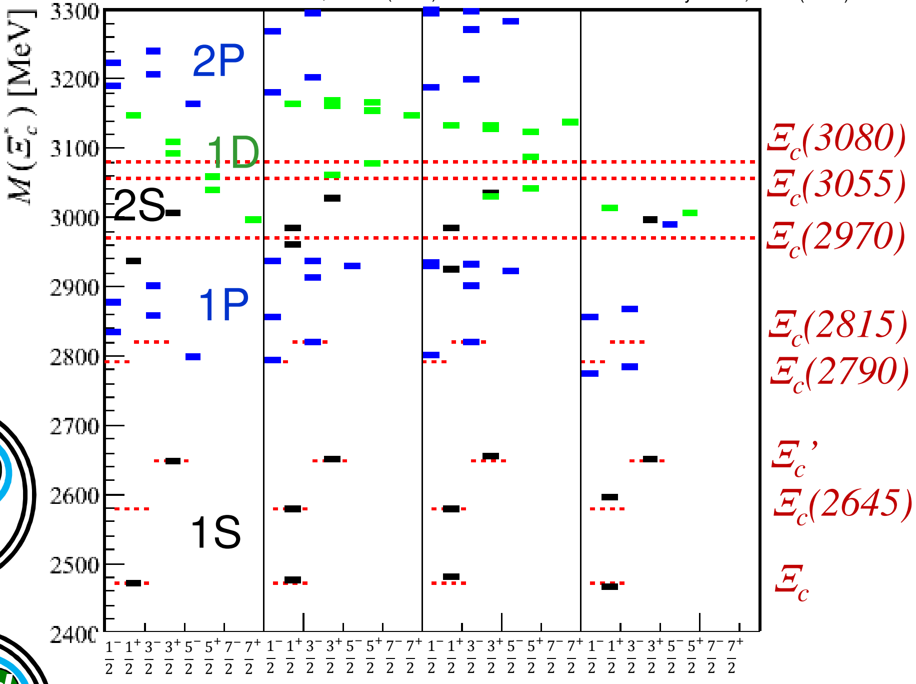
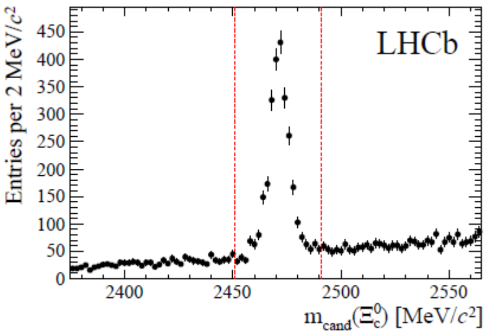
Roberts,Pervin, Int.J.Mod.Phys. A23, 2817 (2008).



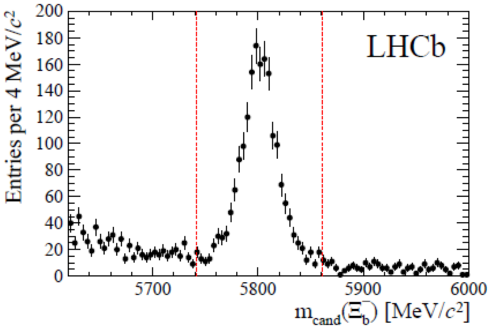
Beauty baryons

LHCb JHEP 1605, 161 (2016)



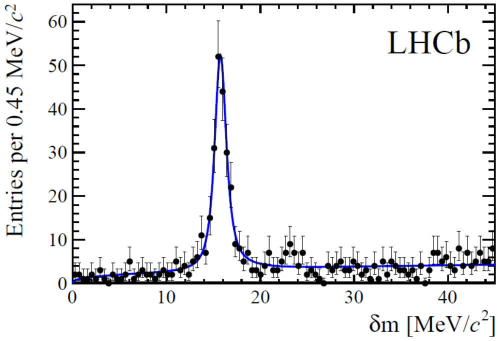
$\Xi_c^0 \to pK^-K^-\pi^+$

(Cabibbo favored
c→s weak decay)



$\Xi_b^- \to \Xi_c^0\pi^-$

(CKM favored
b→c weak decay)



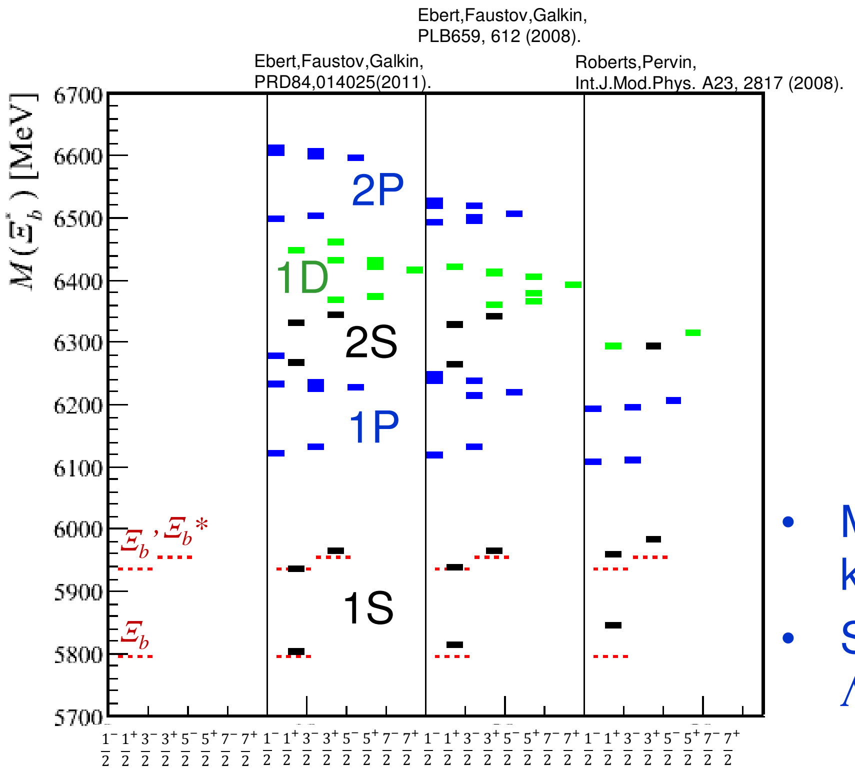
$m_{\rm cand}(\Xi_b^-\pi^+) - m_{\rm cand}(\Xi_b^-) - m(\pi^+)$

$\Xi_b^{*0} \to \Xi_b^-\pi^+$

(Strong decay)

- Recent measurement: precision determination of Ξ_b^{*0} - Ξ_b^- mass difference by LHCb (Ξ_b^{*0} first observed by CMS in 2012):

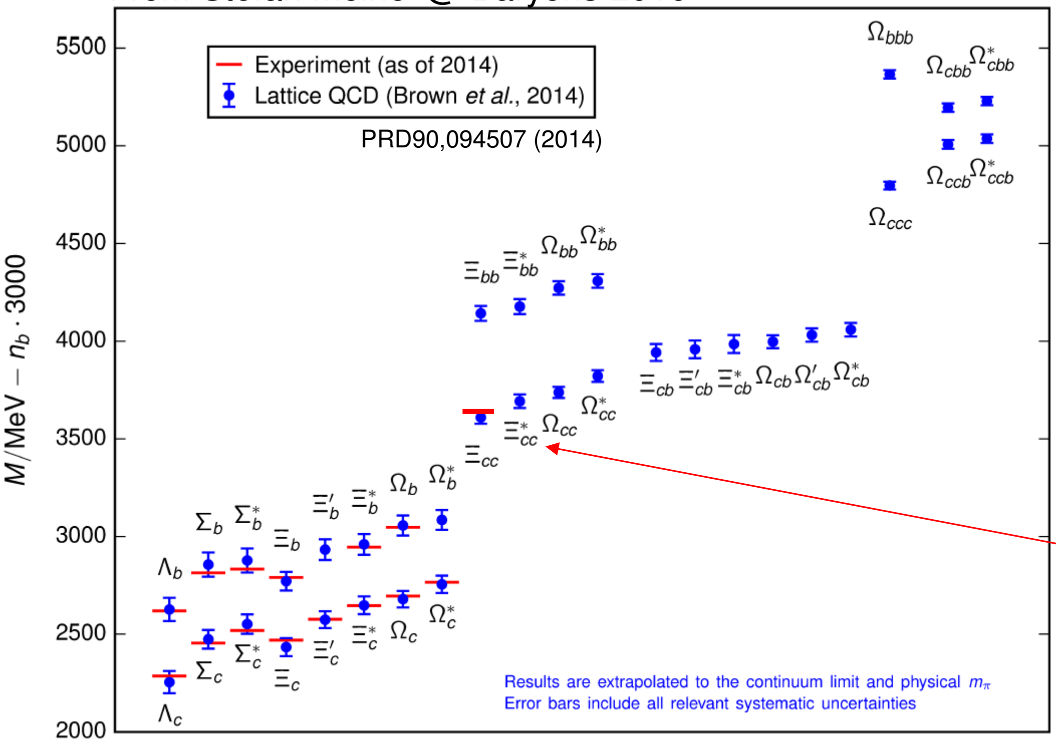
$$
\begin{aligned}
m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) &= 15.727 \pm 0.068\,(\text{stat}) \pm 0.023\,(\text{syst})\ \text{MeV}/c^2,\\
\Gamma(\Xi_b^{*0}) &= 0.90 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst})\ \text{MeV}.
\end{aligned}
$$



- Much fewer excitations known than for charm
- Similar situation for Λ_b,Σ_b

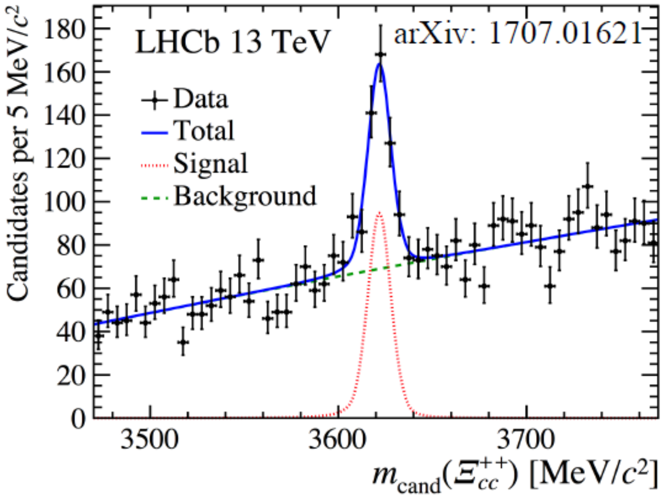
Heavy-baryons and lattice QCD

From Stefan Meinel @ Baryons 2016



- Masses of ground states simulated on lattice agree well with the experimental results
- Preliminary simulations of excited states have been shown at conferences, but not published

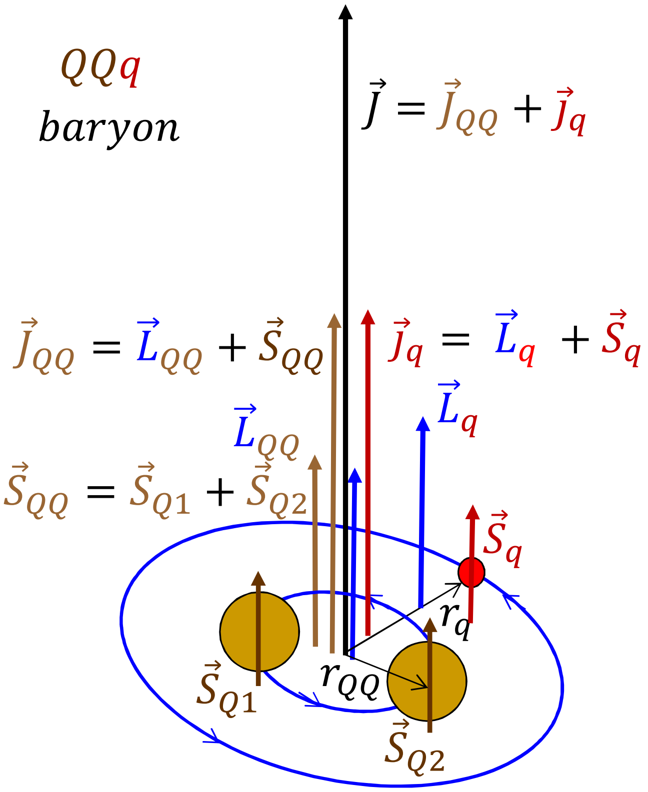
Result which is only 1 week old!



$\Xi_{cc}^{++} \to . \Lambda_c^+ K^- \pi^+ \pi^+$

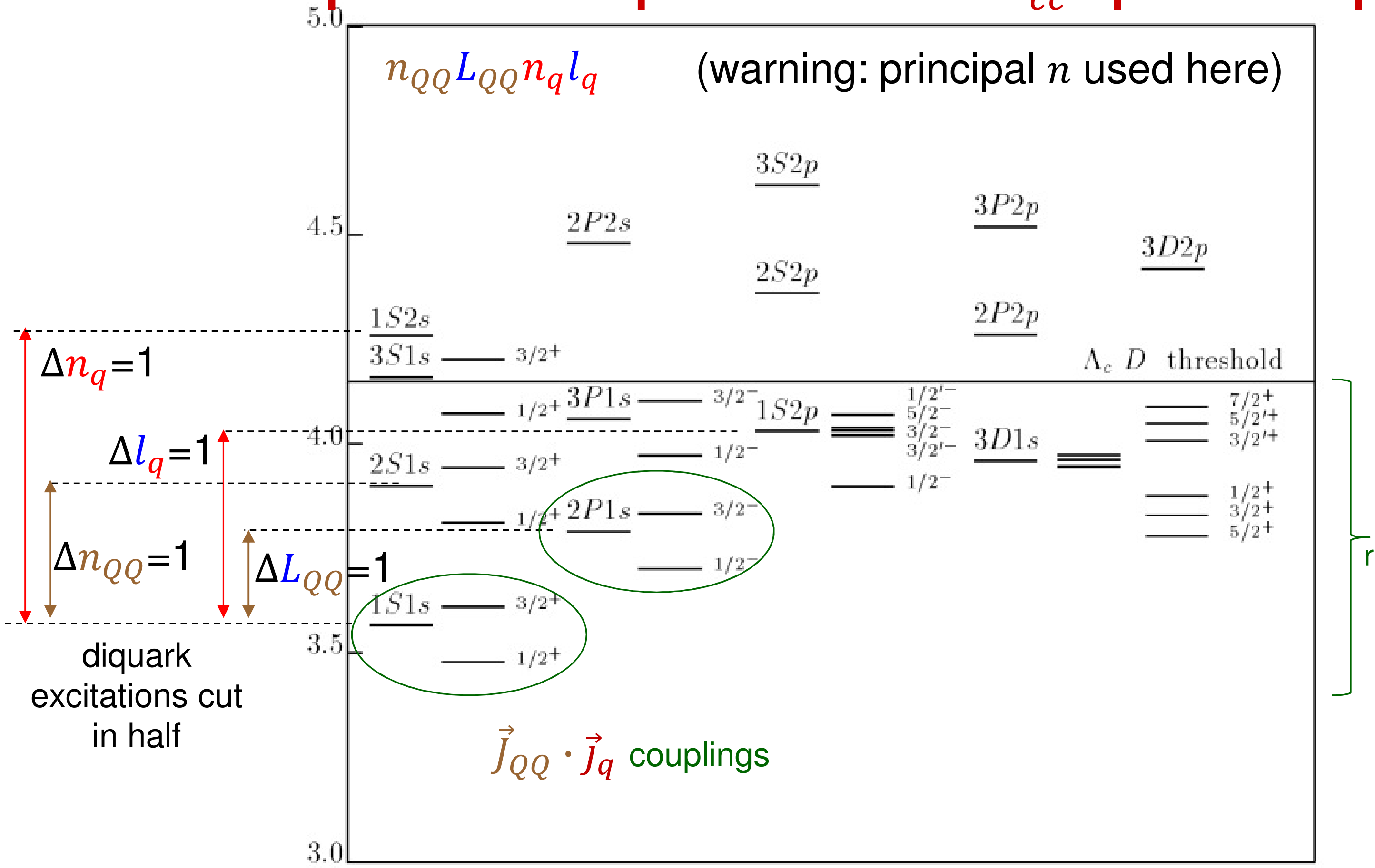
First convincing observation of doubly-heavy baryon!

Heavy-heavy-light baryons

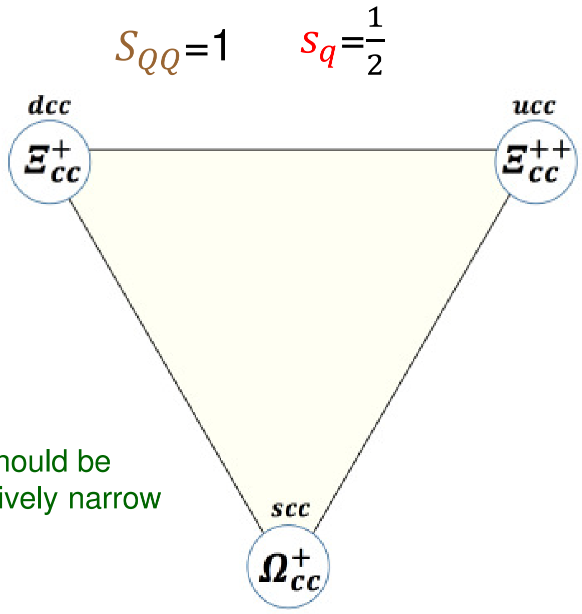


- Light and heavy quark spins decoupled
- Place to study heavy diquarks.
  - QQ will have its own quarkonium-like excitation spectrum (n_{QQ}, L_{QQ}, S_{QQ}), with radial excitation energies diminished by half.
- Light quark will behave like in heavy-light meson, with $\bar{Q}$ replaced by QQ
  - It will have its own n_q, L_q, S_q structure
- Finally, heavy $\vec{J}_{QQ}$ and light $\vec{j}_q$ total spins will couple

Example of model predictions for Ξ_{cc} spectroscopy



should be relatively narrow



- No excitations have been detected yet to verify this picture. Many should be detectable in LHCb.

Conclusions

- Conventional hadron spectroscopy can be understood via analogies to atomic spectroscopy.
- Hierarchy and magnitude of spin dependent splittings can be very different.
- Studies of hadrons with heavy quarks offer hadron families where quantitative spectroscopy is easier:
  - Heavy quark masses are so well separated from other quark masses, that no mixing of states with different quark content
  - Many long-lived excitations thanks to “deeper binding”
  - Less-relativistic systems, intuitive potential model approaches work well
- Baryons with different number of heavy quarks offer an insight into diquark substructures suggested by QCD:
  - So far the data are consistent with diquark picture. More stringent tests with more excitations, hopefully to be detected soon.

END