Exotic spectroscopy

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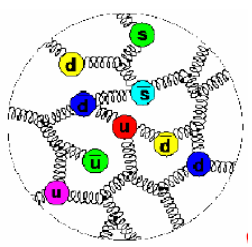
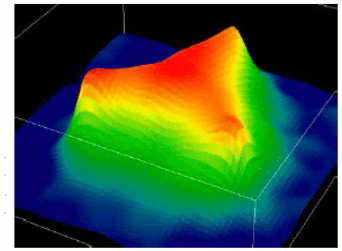
Why Hadron Spectroscopy:

laboratory for studying non pQCD & confinement.

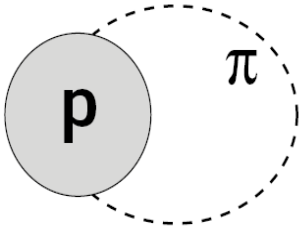
Perturbative		Transition	Non- Perturbative	
High energy Small distance	Asymptotic freedom	⟷	Low energy Large distance	Confinement

pQCD





Effective degrees of freedom (models)



Mesons & Baryons

<< 0.1 fm | 0.1 – 1 fm | > 1 fm

Hadron spectroscopy: lab. for QCD@ work

Bulk of mass of hadrons

Confinement

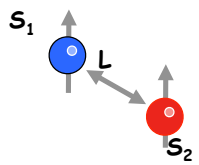
X,Y, Z, pentaquarks, etc. new hadron states

- Finally to claim new physics also in other sectors, a precise knowledge of non perturbative QCD observables is necessary if they are involved!

Meson spectrum

Constituent Quark Model

- Quark-antiquark pairs with total spin S=0,1 and orbital angular momentum L



$S=S_1+S_2$ $\quad J= L+S$

$P = (-1)^{L+1}$ $\quad C= (-1)^{L+S}$

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} 3^{+-} 3^{-+} 3^{--} …

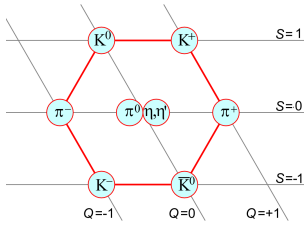
- SU(3) flavor symmetry
  → nonet (8⊕1) of degenerate states

$J^{PC}= 0^{-+}$ ⇒ (π,K,η,η')

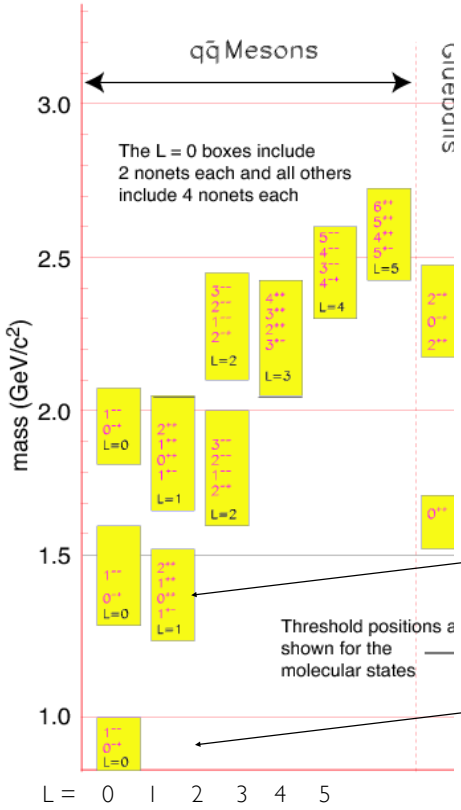
1^{--} ⇒ (ρ,K*,ω,Φ)

1^{+-} ⇒ (b_1,K_1,h_1,h_1')

…



- Great success in describing the lower mass states



Consider light quarks: u,d,s

a,K,f,f'
b,K,h,h'

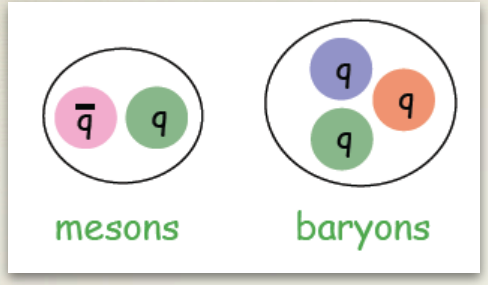
ρ,K*,ω,ϕ
π,K,η,η'

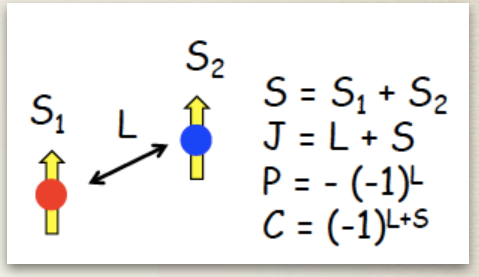
A number of predicted states is not experimentally observed and assignments are uncertain

The gluons and the meson spectrum

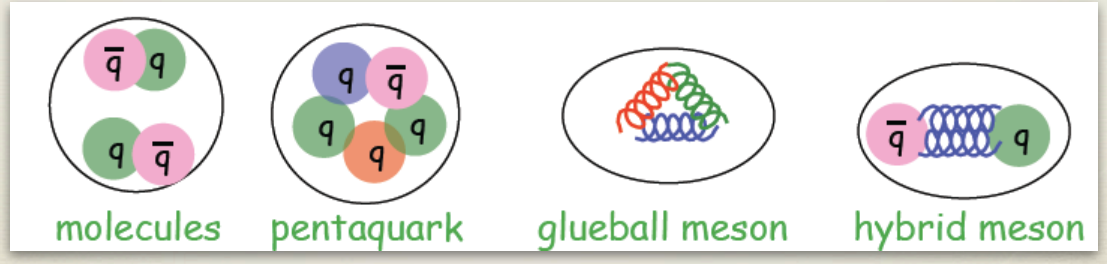
Neutralize color

... the simple way





... or the "exotic" way



(flavor) exotic

exotic of the II kind

$J^{PC}=0^{--},0^{+-},1^{-+},2^{+-}$...

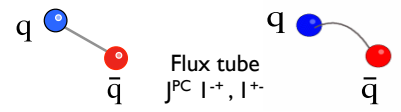
Gluonic excitation models

Flux tube model

- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay

Normal meson: flux tube in ground state m=0 CP=$(-1)^{S+1}$

Hybrid meson: flux tube in excited state m=1 CP=$(-1)^{S}$



Lightest multiplet
$(0,1,2)^{-+},(0,1,2)^{+-}, 1^{--}, 1^{++}$

Bag model

- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

Lightest multiplet
$(0,1,2)^{-+},1^{--}$

CQM + constituent gluon

- qq + massive transverse quasi-gluon (J_g^{PgCg})
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

qq in S-wave + $J_g^{PgCg}=1^{--}$ in S-wave

Lightest multiplet
$(0,1,2)^{++},1^{+-}$

qq in P-wave + $J_g^{PgCg}=1^{--}$ in S-wave

Lightest multiplet
$0^{--},(1^{--})^3,(2^{--})^2,3^{--},0^{-+},0^{++},1^{-+}, 2^{-+}$

or QCD in physical gauge: Guo, Szczepaniak, Santopinto **PRD78** 056003 (2008)

- Repulsive 3-body force selects $J_g^{PgCg}=1^{+-}$ in relative P-wave added to a qq pair is S-wave or P-wave

qq in S-wave + $J_g^{PgCg}=1^{+-}$ in P-wave

Lightest multiplet
$(0,1,2)^{-+},1^{--}$

qq in P-wave + $J_g^{PgCg}=1^{+-}$ in P-wave

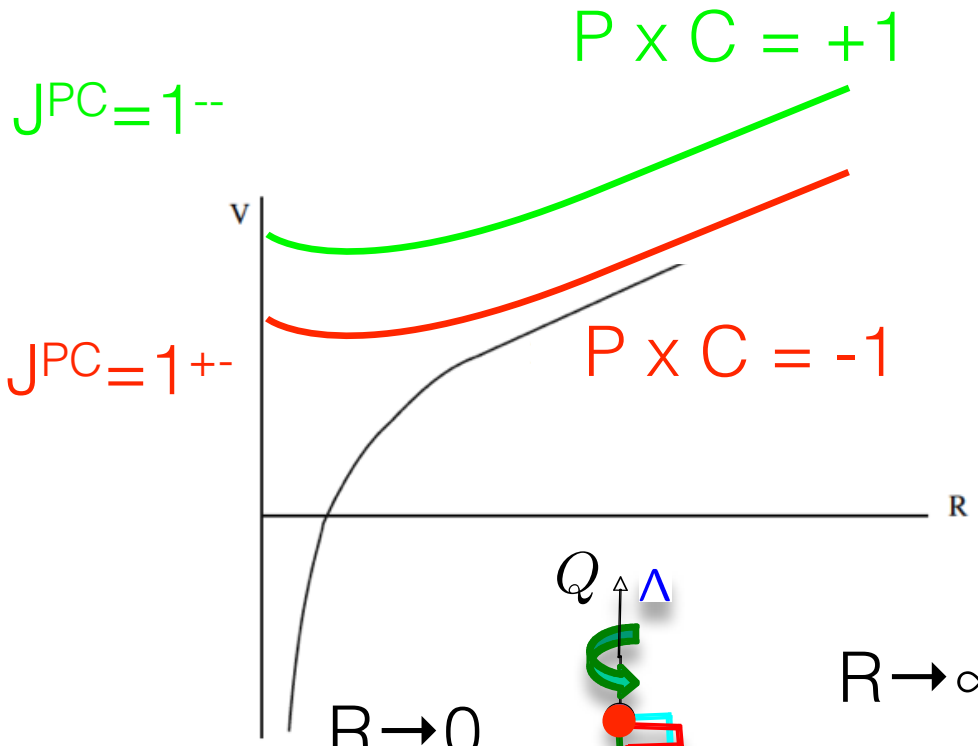
Lightest multiplet
$0^{+-},(1^{+-})^3,(2^{+-})^2,3^{+-}, (0,1,2)^{++}$

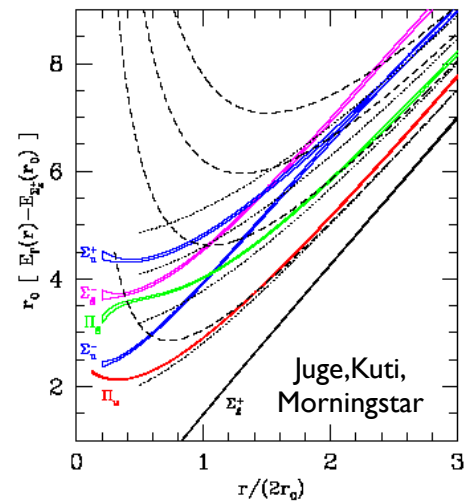
Start from the study of the glue-lamp
(lamp of gluons or “ quasi gluon”) as obtained from QCD in physical gauge

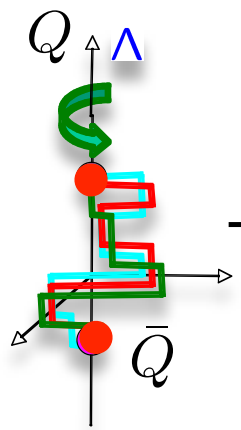
Gluelamp in QCD in physical gauge,
Guo, Szczepaniak, Santopinto,PRD78 056003 (2008)

it is easy to study the ccbar –gluon system, i.e. the hybrids (next two slides)

Flux tube and strings







R→0

glue-lump ←

R→∞

→ flux tube

"constituent gluons"

"gluon chain"

Gluelamp

Guo, Szczepaniak Santopinto PRD2008

Greensite e Thorn's chain model

Ostrander Szczepaniak Santopinto PRD2014

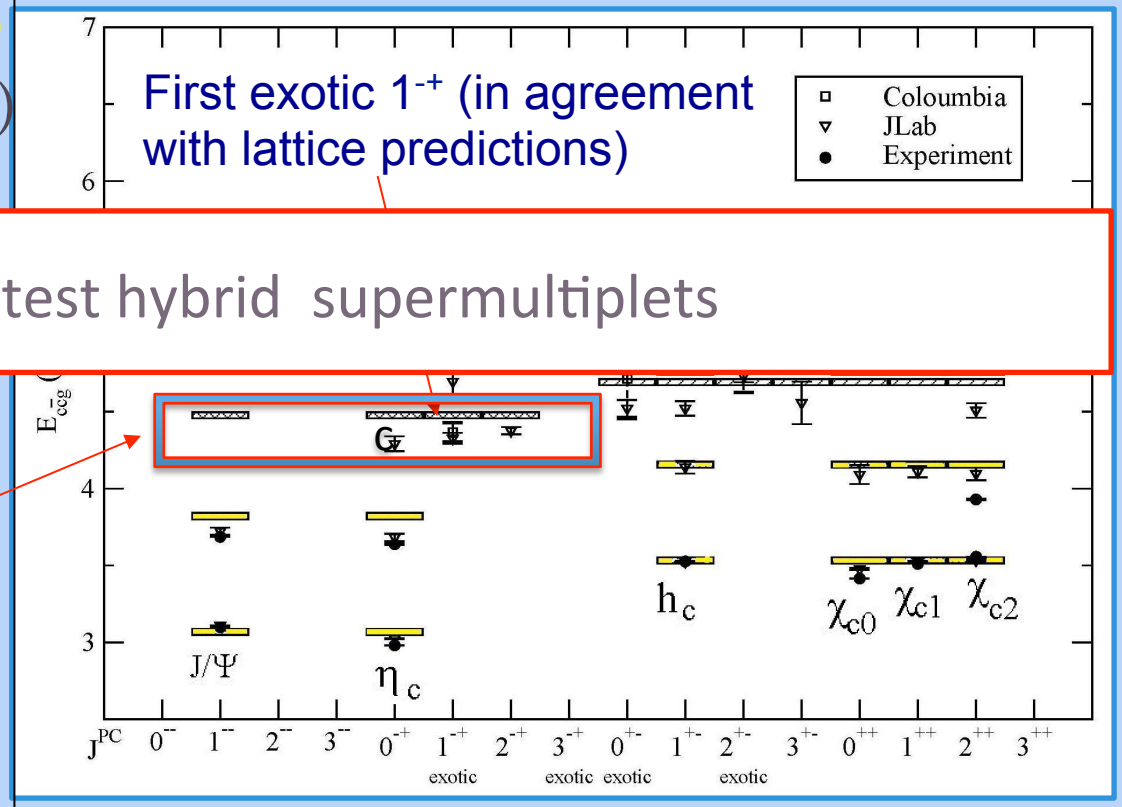
Charmonia (qq bar) & hybrids (qqg)

$J_g^{PC} = 1^{+-}, 1^{--}$

$J_g^{P_g}$	This work [GeV]	J^{PC}	Lattice [14] [GeV]
1^+	4.476	$0^{-+}, 1^{-+}, 2^{-+}, [1^{--}]$	4.291(48),4.327(36),4.376(24), [?]
1^-	4.762	$1^{+-}, 2^{++}, [0^{++}, 1^{++}]$	4.521(48),4.508(48), [?,?]
2^+	5.144	$1^{-+}, [2^{--}, 2^{-+}, 3^{-+}]$	4.696(103), [?,?,?]
2^-	5.065	$2^{+-}, [1^{++}, 2^{++}, 3^{++}]$	4.733(42), [?,?,?]

[14]:J. J. Dudek, R. G. Edwards, N. Mathur, and D. G.Richards, Phys. Rev. D 77, 034501 (2008)

c-cbar states (yellow)
hybrids (gray-dashed)

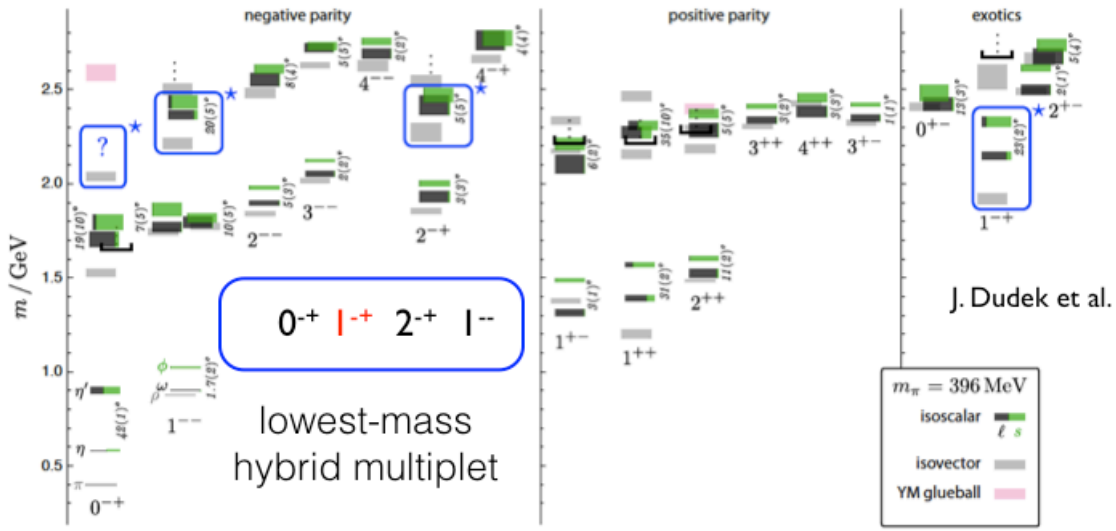


The lightest hybrid supermultiplets

Y(4260)

Guo, Szczepaniak, Santopinto , Phys.Rev. D78 056003(2008)

The ligthest hybrid supermultiplet predicted (and explained) for charmonia and bottomonia by QCD in physical gauge , $1^{--}(0,1,2)^{-+}$, is predicted also by LQCD



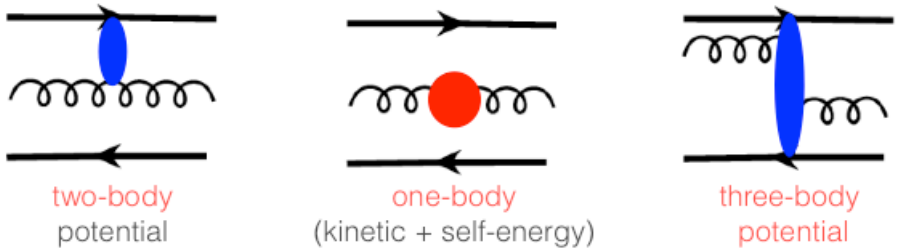
Physical gauge QCD (Hamiltonian)

J^{PC} glue

$J^{PC}\,Q\bar{Q}$

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

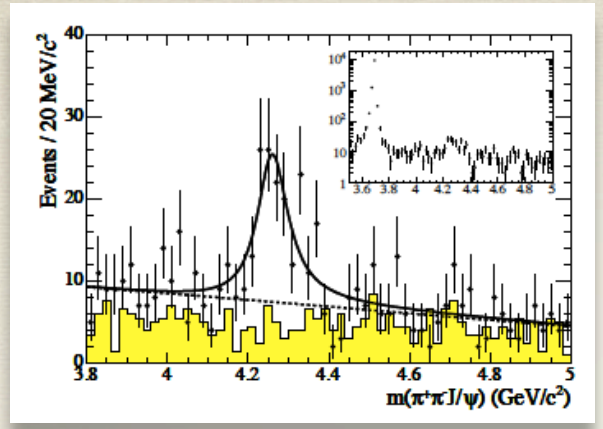
$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

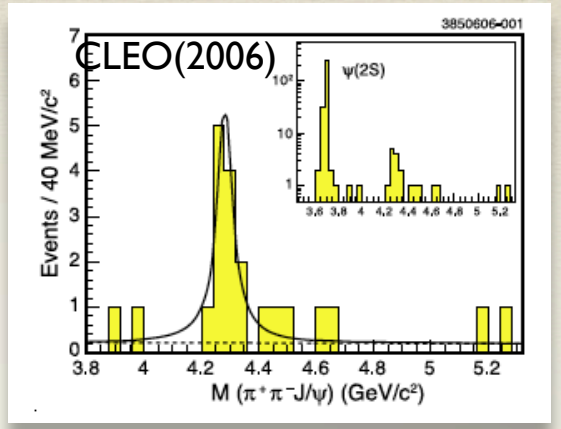


Guo,Szczepaniak,Santopinto,PRD2008

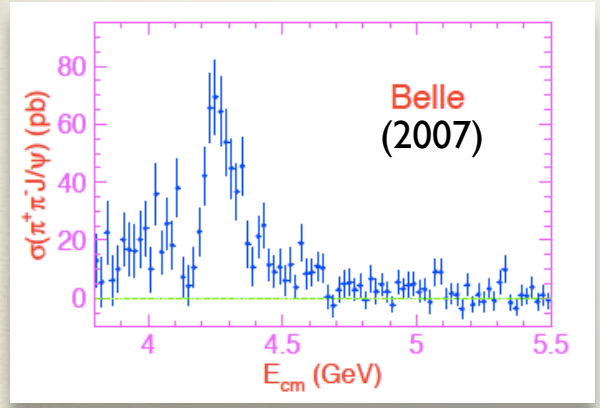
20XX experimental confirmation - discovery ?

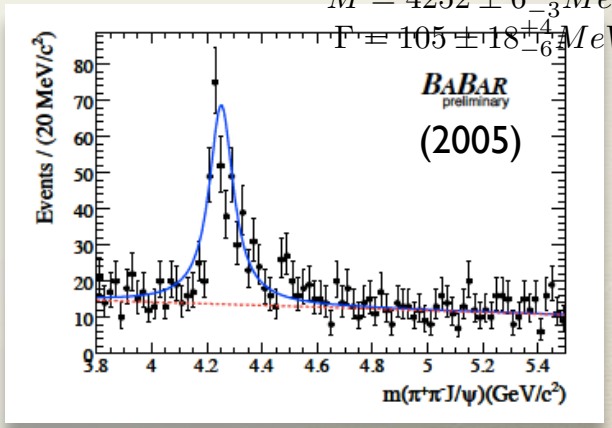
- **Y(4260)** **discovered by BaBar in J/ψ π⁺π⁻ (2005) confirmed by CLEO,Belle other modes from BaBar**
  $J^{PC}=1^{--}$ (from e^+e^-) width O(100MeV)





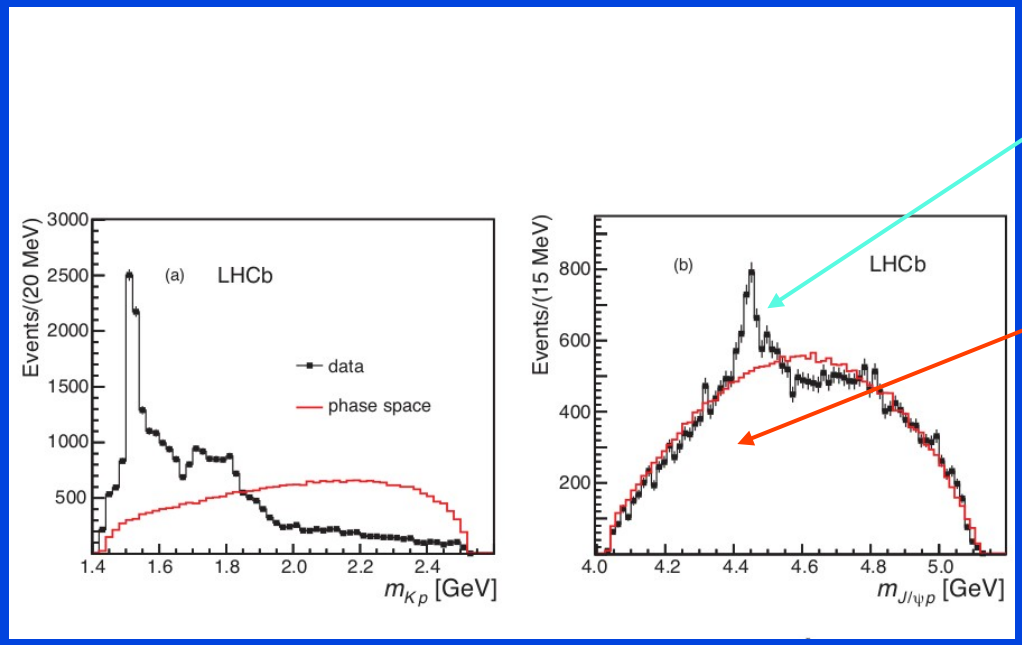
$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$





✱ **Theory: Hybrid candidate**

LHCb



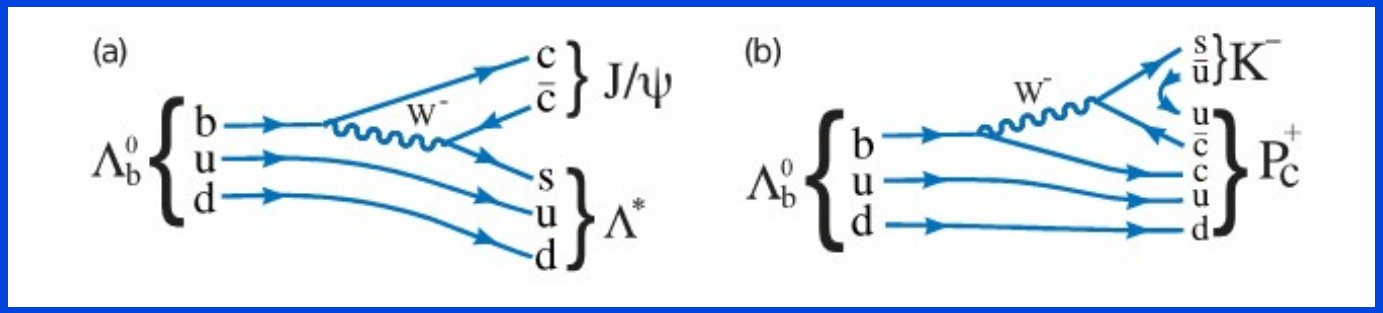
$P_c^+(4450) = (4449.8 \pm 39)$ MeV

$P_c^+(4380) = (4380 \pm 205)$ MeV

Statistical signifiance greater then 9 sigma !

$$\Lambda_b^0 \longrightarrow J/\psi + \Lambda^*, \Lambda^* \longrightarrow K^- + p$$

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



The lightest resonance, the $P_c^+(4380)$, according to LHC_b has a mass $M = 4380 \pm 8 \pm 29$ MeV and a width $W = 205 \pm 18 \pm 86$ MeV

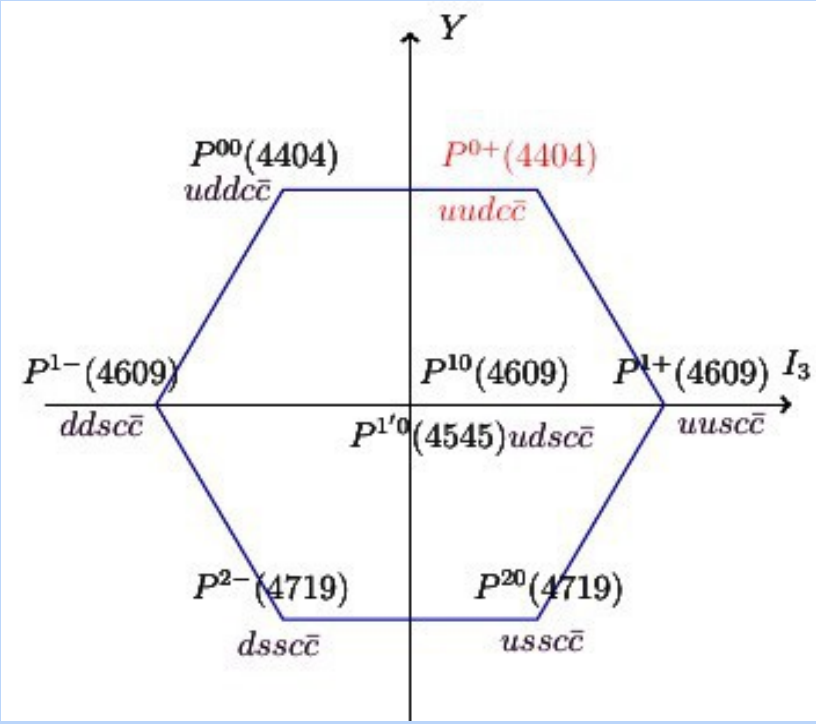
The predicted theor. value of the mass is 4404 MeV in agreement with the exp. $M = 4380 \pm 8 \pm 29$ MeV

Notation: $P^{IJ}(M)$ where I is the number of s quarks; J the electric charge; M predicted mass

Santopinto, Giachino PRD 2017

$SU_{fl}(3)$ multiplet	$SU_I(2)$ submultiplet	I	Y	mass (MeV)	isospin states
$[21]_8 \equiv$  8	 2	$\frac{1}{2}$	1	4404	$P^{00}(4404)$, $P^{0+}(4404)$
	S	0	0	4545	$P^{1'0}(4545)$
	 3	1	0	4609	$P^{1+}(4609)$, $P^{10}(4609)$ $P^{1-}(4609)$
	 2	$\frac{1}{2}$	-1	4719	$P^{20}(4719)$, $P^{2-}(4719)$

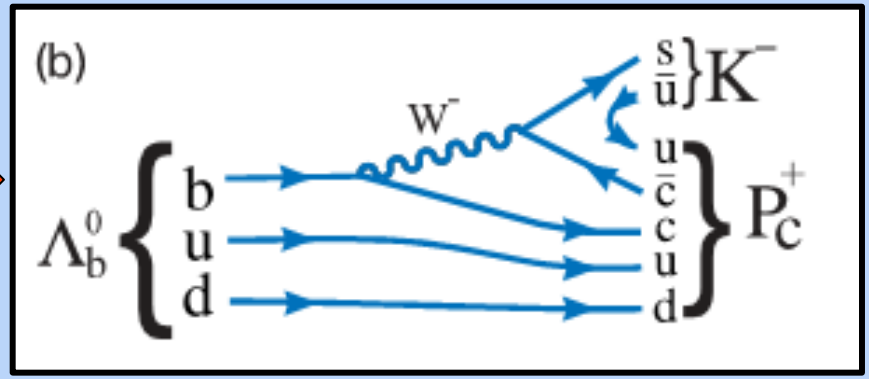
Santopinto, Giachino, PRD 2017



we have predicted the masses, but also suggested possible decay channels where the experimentalists can try to look for them

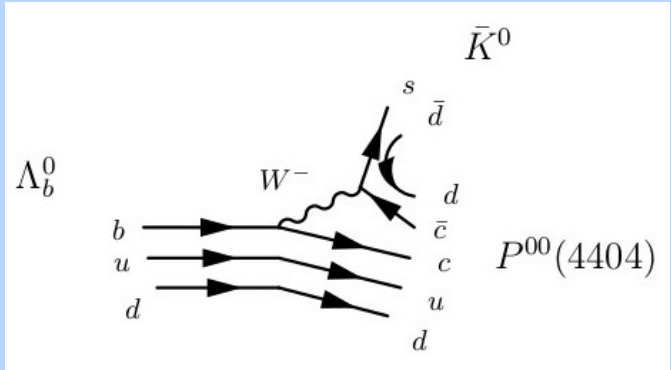
HOW TO OBSERVE OTHER PENTAQUARK STATES?

Santopinto, Giachino, PRD 2017



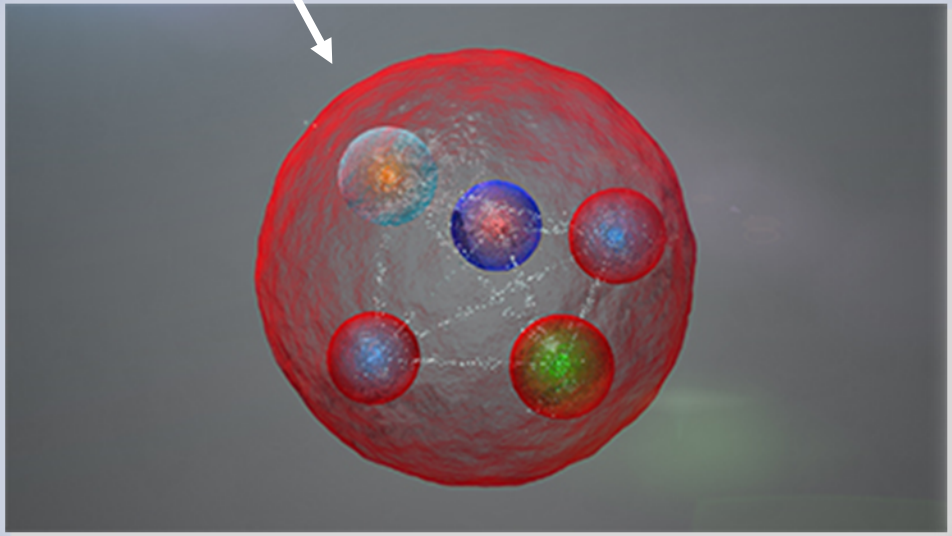
In order to observe the isospin partner $P^{00}(4404)$ of the charged P^{0+} we consider a pair creation of the type d anti d (instead of u anti u)

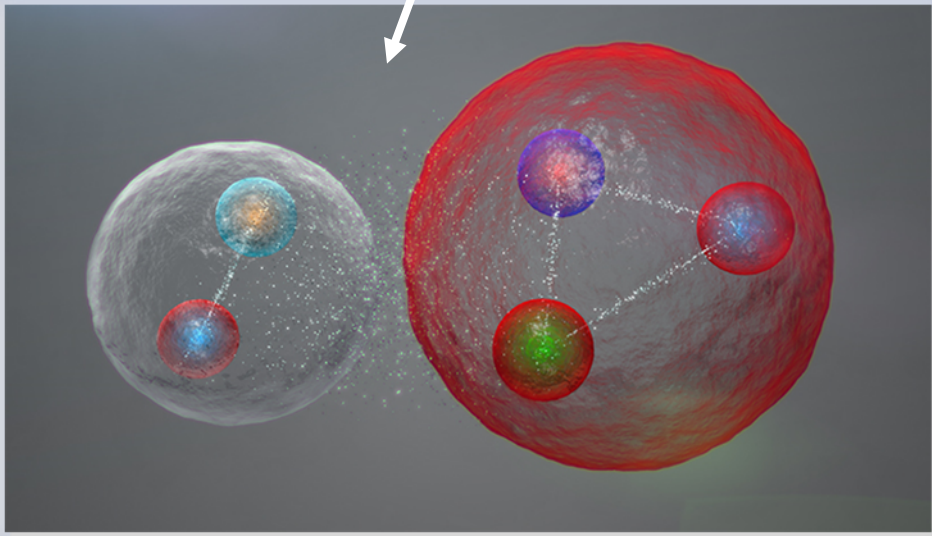
$$\Lambda_b^0 \longrightarrow P^{00} + \bar{K}^0, \; P^{00} \longrightarrow J/\Psi + n$$



Compact Pentaquark

Molecular state $D^* \Sigma_C$





HOW TO OBSERVE OTHER PENTAQUARK STATES?

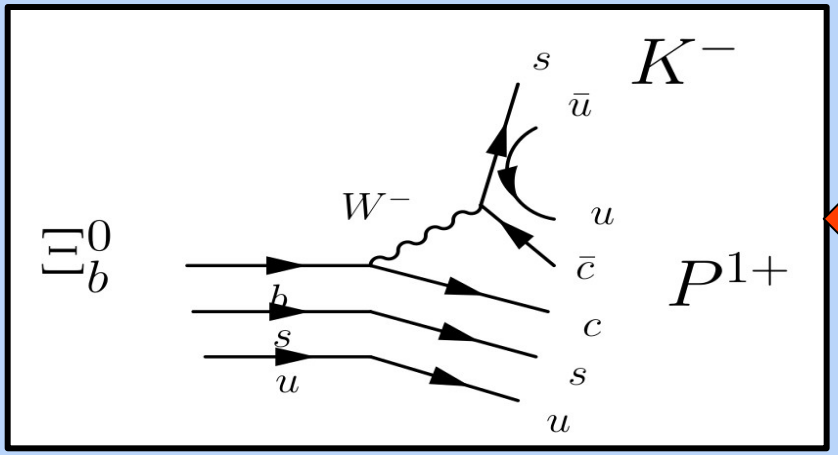
Santopinto, Giachino, PRD 2017, hep-ph 1604.03769

Regarding other pentaquark states, we can consider other hyperons decays

$$\Xi_b^- \longrightarrow J/\psi + \Xi^-$$

$$\Omega_b^- \longrightarrow J/\psi + \Omega^-$$

The charged $P^{1+}(4414)$ state is the most intresting from the experimental point of view, since all the final state particles **are charged particles, so easier to be detected :**



$$\Xi_b^0 \longrightarrow P^{1+} + K^-,\ P^{1+} \longrightarrow J/\Psi + \Sigma^+$$

Hidden-charm meson-baryon molecules with full-channel coupling

Y. Yamaguchi, E. Santopinto, **PRD 2017, hep-ph** 1606.08330

- Meson-baryon thresholds closed to the observed pentaquarks are considered for the first time.
  Full-coupled channel analysis is performed for the first time.
- The meson exchange potential respecting the heavy quark spin symmetry is employed.
- The J^P assignment of $P(4380)$ and $P(4450)$ is $3/2^+$ and $5/2^-$, respectively.
- New states are predicted in $J^P = 3/2^{\pm}$.

Thanks for the attenction!