From Quarks to Pentaquarks: a journey in Gatto’s and Cabibbo’s schools

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Roma Sapienza, INFN
and CERN

1. Introduction & Disclaimer

- Italian physics, in the second part of 1900, has lived an exceptional period of development, achievements and international recognition;
- this is true in particular for Theoretical Physics: several schools flourished in (from North to South): Torino, Milano, Padova, Genova, Bologna, Firenze, Roma+Frascati, Napoli, Bari, Lecce, Catania, led by interesting personalities
- too many to be recorded now, with the risk of important omissions.
- The Via Panisperna years and the years of reconstruction after the war have been amply described by Edoardo Amaldi, Emilio Segre' and many others.
- There (not yet?) a systematic historical reconstruction of the years from 1954 (INFN, Frascati and CERN establishment) to today: sixty crucial years, worth of an historical study of what happened in the Italian physics
- In my talk I shall follow my recollections, centered on the Schools that Gatto and Cabibbo created in Firenze and Roma, whom I participated personally,
- and following the evolution of quark theory, which eventually led to the Standard Theory we know today
- Much of the material will appear in a long interview by Luisa Bonolis for EJP-History
- DISCLAIMER: this is not a systematic hystorical recostruction
- comments, unhappinesses and suggestions are welcome!

THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893
SECOND SERIES, VOL. 76, No. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

I. INTRODUCTION

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

muon
strange particles
Δ^{++}
.....

composite by "constituents" which are more elementary ?

S-matrix, bootstrap, nuclear democracy?
particles are all on an equal footing: poles in S-matrix, solutions of self-consistency equations

Fermi&Yang's proposal:

$$\pi^+ = p\bar{n}$$

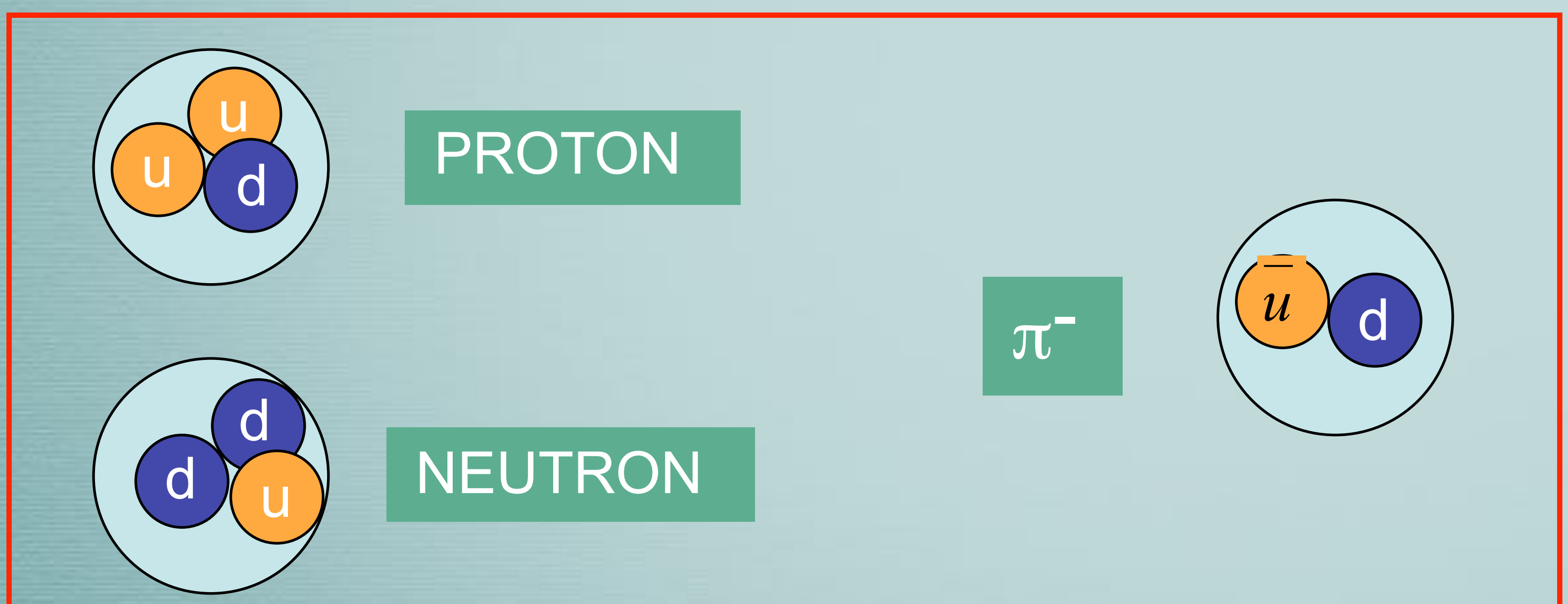
related by a large symmetry? possibly including spin ?

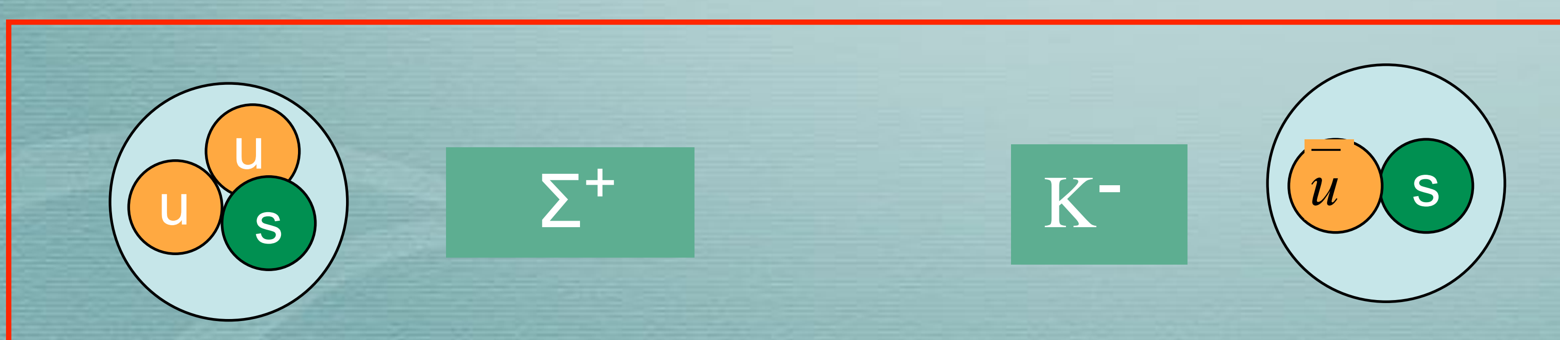
QUARKS !!

- Protons, neutrons, mesons, “strange particles” … are composite states of ***quarks*** and ***antiquarks (M. Gell-Mann, G. Zweig)***.
- Quarks and their masses ***explain*** the properties of the observed particles;
- A new « Table of Mendeleev » .

“Three quarks for Master Mark!” (M. Gell-Mann quoting J. Joyce)

Three kinds (flavors) of quarks and their antiparticles make up old and new (strange) particles





π meson structure vindicates the intuition of Fermi & Yang, and Sakata, with quarks up, down and strange replacing Proton, Neutron and Lambda

quarks display unexpected quantum numbers ! B=1/3, Q= +2/3 (up) -1/3 (down, strange)

2003- 2005: New hadrons are discovered which could indicate that more complex configurations do exists: Quantum Hadron Chemistry !!

Nuclear Democracy ??

- in the presence of very strong interactions (unitarity saturated) there is no clear distinction between composites and constituents:

$$\pi^+ = p\bar{n} \;\rightarrow\; ?? \;\rightarrow\; n = \bar{p}\pi^+ \quad \text{which is which?}$$

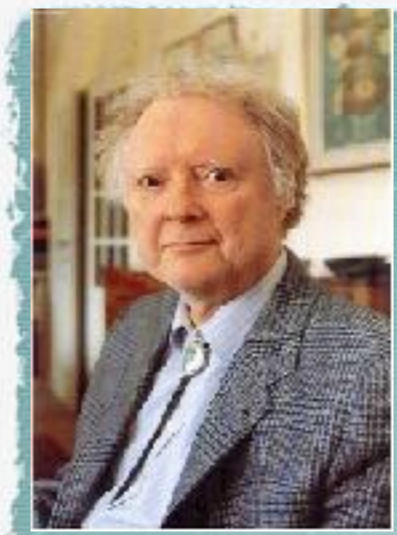
- for this reason, in the sixties a most natural approach was considered to be the ***nuclear democracy*** (G. Chew and S. Frautschi);

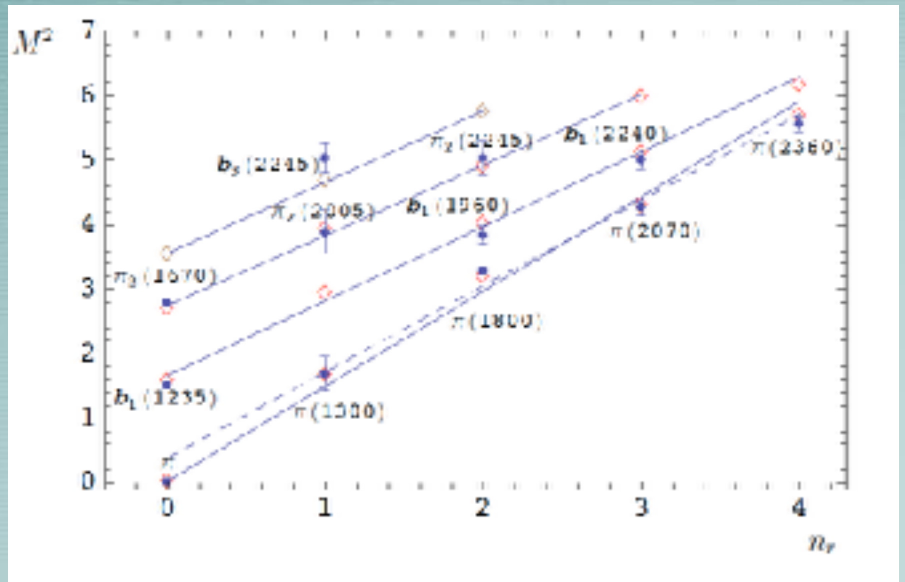
XVI. ARE ALL STRONGLY INTERACTING PARTICLES COMPOSITE?

In the usual picture of atomic or nuclear physics, a very large number of composite atoms and nuclei are made up of electrons, neutrons, and protons. The electron, neutron, and proton are treated as elementary because most phenomena involve energies too low to excite their internal structure. In high-energy physics, on the other hand, the range of energies easily allows excitation and breakup of any particle. This circumstance motivated Chew and Frautschi[72)] to conjecture that they should all be treated on the same basis.

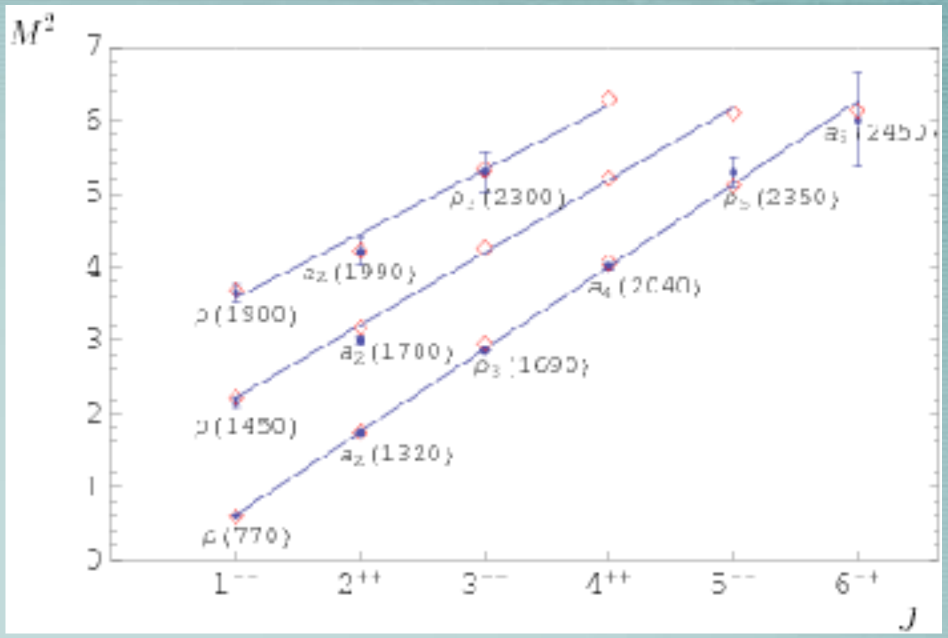
there is hope that their coupling constants and mass ratios can be determined from unitarity and maximal analyticity requirements. The way towards fulfilling this hope is believed to lie in the further development of the self-consistent or "bootstrap" method of calculation which was described in Chapter 7.

Regge Poles and the Chew - Mandelstam's Program





The (n_r, M^2) Regge trajectories for spin-singlet isovector mesons π, b_1, π_2 and b_3



Regge Trajectories: $J=\alpha(M^2)$

mesons and baryons fall on similar, linear Regge trajectories

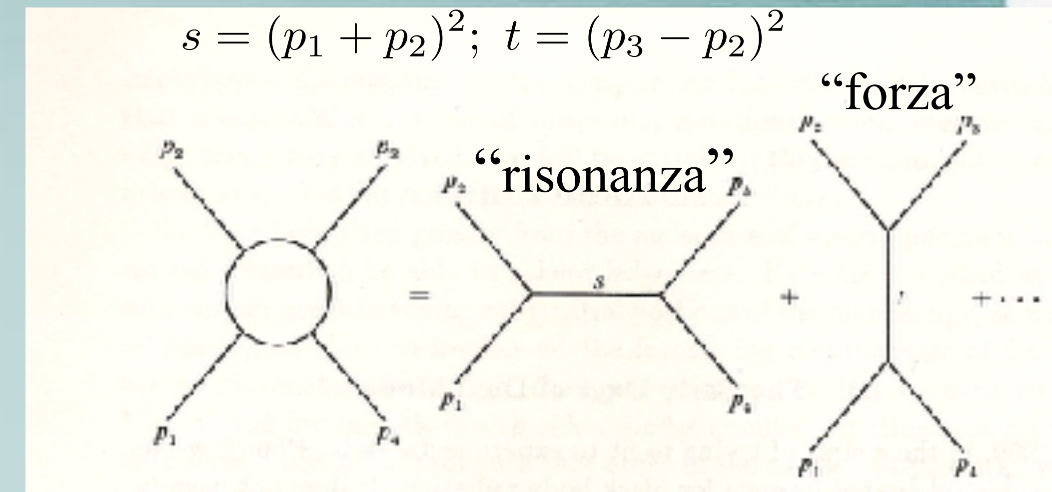
No reason to doubt that trajectories go up to infinity, constituents, if any, must be permanently confined (quarks are confined, no proton ***ionization***!)

This was the basis of the program proposed by Chew&Mandelstam in the 1950s-1960s.

- We see only the hadrons, that are on linearly rising Regge trajectories.
- hadron spectrum must result from self-consistency conditions requiring that ***the same Regge trajectory*** $\alpha(t)$ gives rise to
  - the hadron mass spectrum, M_J from the condition: $\alpha(M_J)= J$ integer (mesons) or half-integer (baryons):
  - the scattering amplitudes: $A=C\,E^{\alpha(t)}$
- We can forget about constituents, there is nothing else…
- But how do we find the self-consistency conditions ????

DHS Duality

- QED amplitudes are determined by the exchange of one particle
- we need to sum the amplitude with photon exchanged in both s and t channel



$$A(s,t)=A_s(s,t)+A_t(s,t)$$

$$A_s=g_J^2\frac{t^J}{s-M_J^2};\ \ A_t=g_J^2\frac{s^J}{t-M_J^2}$$

- Duality hypothesis (Dolen, Horn, Schmidt, 1968)
  - strong interactions require infinitely many particles exchanged
  - summing the amplitudes of one channel ***reproduces the amplitudes in the other***: ***forces=resonances***
- poles in s channel reconstruct the poles in the t channel

$$A(s,t)=\sum_J g_J^2\frac{(-t)^J}{s-M_J^2}\qquad\left[=\sum_J g_J^2\frac{(-s)^J}{t-M_J^2}\right]$$

  - Linear Regge trajectories and duality led to the Veneziano Model (1968)
  - and later to String Theories

Quarks and Regge Poles

- two visions (not necessarily?) in contrast:
  - -Subnuclear particles made by more elementary consitutents (Three quarks for muster Mark! Joyce-Gell-Mann) described by field theory, Fermi interaction, QED…
  - -Subnuclear particles determined by Regge trajectories in turn determined by self-consistency equations (forces=resonances)
- Italian physics divided: Cabibbo, Gatto, us….Regge, Veneziano, Fubini,..
- 1970 and following: Deep inelastic scattering (electrons, neutrinos) showed pointlike constituents, dual model could not describe the phenomenon.
- onwards….Standard Theory, new particles…Field Theory back again
- 1984 Green&Schwarz: dual model for Quantum Gravity!

Everybody found his place in History!

2. The Cabibbo Theory

- In a 1961 book, Richard Feynman vividly described his and Murray Gell-Mann’s satisfaction at explaining the close equality of the muon’s and neutron’s beta decay Fermi constants.
- They and, independently, other authors including the other 2010 Dirac medallist C. G. Sudarshan, had discovered the ***universality*** of the weak interactions, closely similar to the universality of the electric charge and a tantalising hint of a common origin of the two interactions.
- But Feynman recorded also his disconcert following the discovery that the Fermi constants of the strange particles, e.g. the Λ beta decay constant, turned out to be smaller by a factor of 4-5.

- It was up to Nicola Cabibbo (in 1963) to reconcile strange particle decays with the universality of weak interactions, paving the way to modern electroweak unification
- First formulated in the Eightfold Way scheme of Gell-Mann and Ne’eman, then in the quark model.

Erice School started in 1963… it gave great impetus to Italian Particle Physics

Weak and electromagnetic currents

Professor Cabibbo of CERN described some recent work on the computation of radiative corrections to beta decay, done in collaboration with L. Maiani and G. Preparata.

versions of the quark model with fractional charges. However, this requirement is easily met in models with only integrally charged particles. Professor Cabibbo discussed in detail one such model which reproduces most of the desirable results of the quark model.

scattering lengths, and the Callan-Treiman relations for K_{l3} and K_{l4} decays.

Relativistic quark model of baryons and mesons

The course given by Professor Gell-Mann, from California Institute of Technology.

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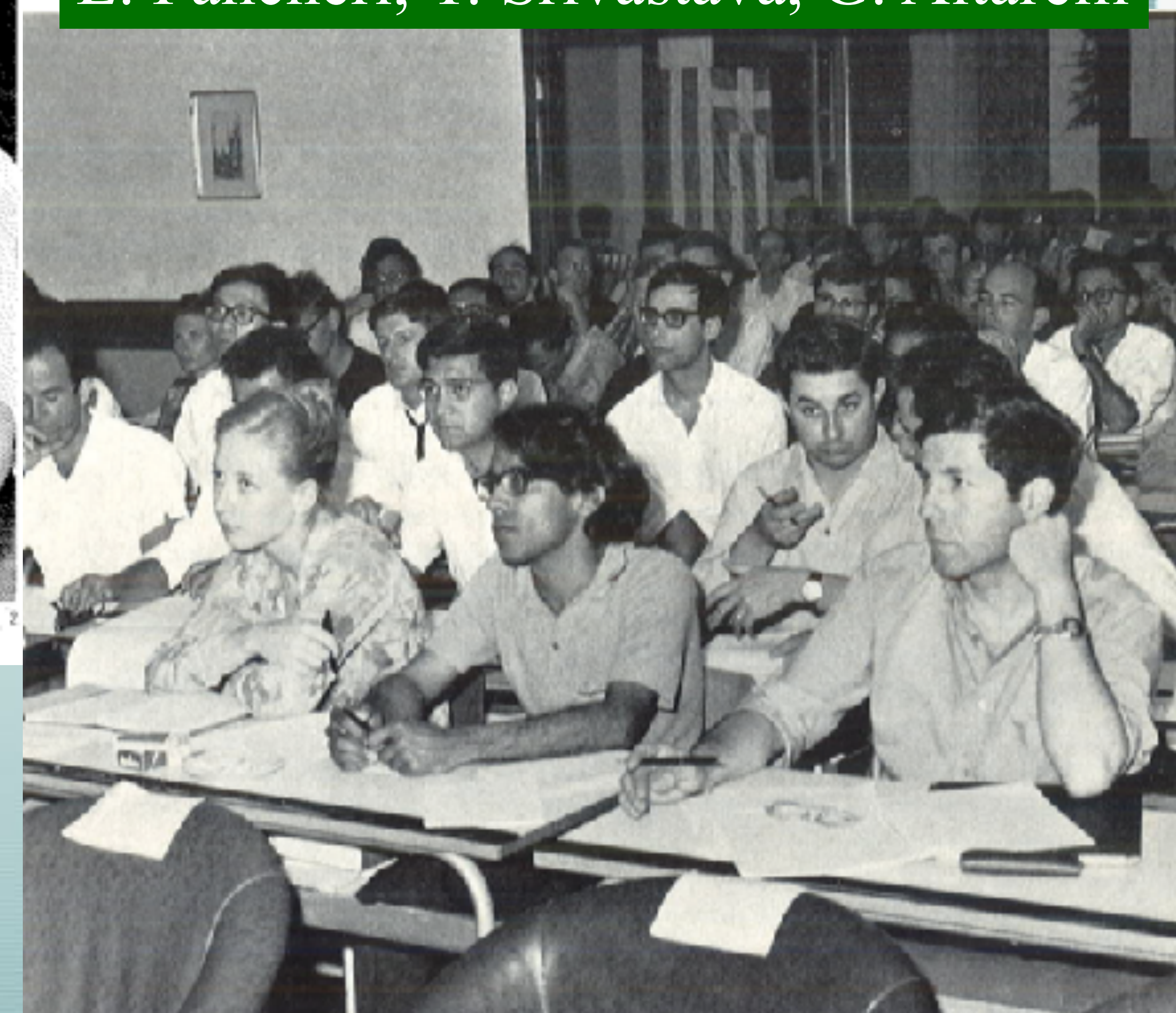
Erice 1967: making the Standard Model... B. Zumino, S. Coleman, A. Zichichi, N. Cabibbo, S. Glashow, M. Gell-Mann



Erice 1967
L. Pancheri, Y. Srivastava, G. Altarelli

3. Gatto's many Schools

- Raoul Gatto (Catania 1930), graduated in Scuola Normale di Pisa. Assistant of Bruno Ferretti in Roma, in 1956 was taken as staff member at the Lawrence Radiation Laboratory in Berkely where the group of Luis Alvarez was discovering lot of new hadrons with the hydrogen bubble chamber
- In Berkeley, Gatto made several papers on the phenomenology of the weak interactions (Fermi's inprint !) in particular on the weak decays of hyperons, based on the data collected by the Alvarez group.
- Gatto brought back to Italy the new ideas concerning ***symmetry and group theory applied to particle physics***, that were flourishing at the time in the US.
- Director of the newly formed theory group at Frascati, he found, as a junior partner, Nicola Cabibbo, freshly graduated with Bruno Touschek.
- Gatto and Cabibbo wrote a long article that summarised the theoretical situation of high energy electron-positron collisions
- Called *The Bible,* by people in Frascati, the paper showed the potential for elementary particle physics of future experiments with Adone.
- Full professor in Cagliari while in Frascati, Gatto moved to Florence in 1963, followed by a group of young roman teorists, Altarelli, Buccella, Gallavotti and myself.
- In 2011, Gatto gave a nitid description of his program: *a research based on innovative theoretical ideas, in touch with the research programs of the big, international laboratories, with the participation of recently graduated investigators, several of which have later obtained scientifically prestigious positions*.
- Nobody like Nicola could fill this description any better.

The '59 ners in Roma

- A remarkable group of young students enrolled in Rome University *La Sapienza* in 1959.
- Besides Guido Altarelli, who graduated with the best votes, the class was really remarkable (in parenthesis their final destination):
  - Franco Buccella, Giovanni Gallavotti, Sergio Doplicher, myself (Th. Phys.)
  - Claudio Procesi (Math.),
  - Massimo Cerdonio (Grav. Waves), Piergiorgio Picozza (Pamela satellite)
- Promising young people kept their promises
- Guido went to Frascati with Buccella, to make a thesis in QED under Gatto and they graduated in september 1963;
- (I made an experimental thesis on solid state detectors, graduated in february 1964, then moved to Theory)
- Nicola Cabibbo meanwhile had gone to CERN (making few experiments (!!) and writing the paper on the Cabibbo angle (!!!)) and then to Berkeley.
- in 1963 Gatto moved to the University of Florence, followed by Guido, Buccella, Gallavotti and myself
- one year later, Giuliano Preparata joined,
- Gabriele Veneziano graduated with Gatto and left almost immediately to Weizmann.

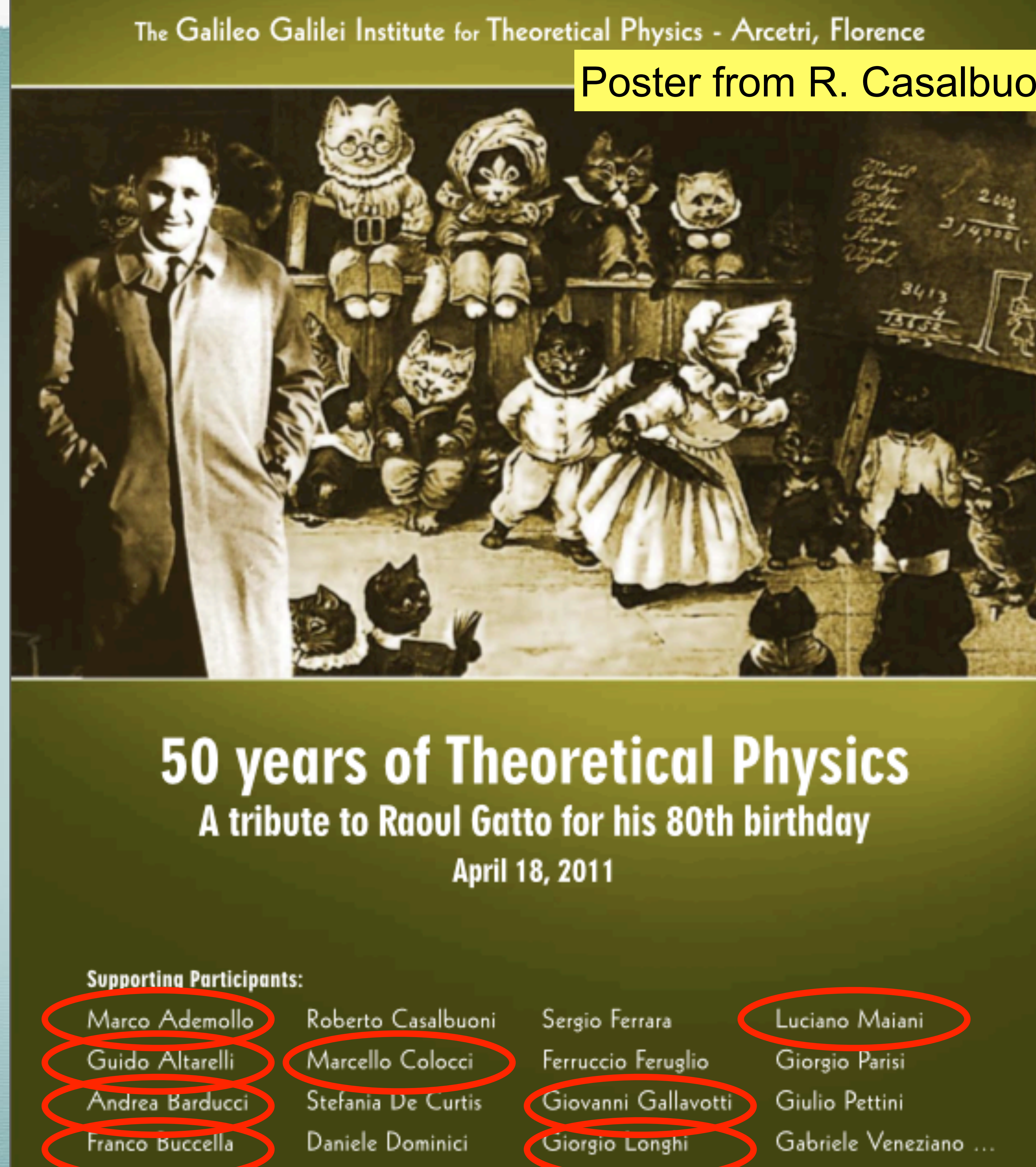
in 1964, the Roman branch of *gattini* was in place, at work

The “Florence School” under the guidance of Raoul Gatto attacked with enthusiasm the exploration of the newly discovered symmetries of the hadrons, the implications of quarks, the SU(6) symmetry proposed by Gursey and Radicati in 1964, and its “relativistic extensions” ....

in Florence at the time...

…and Giuliano Preparata

Poster from R. Casalbuoni



The Non Relativistic SU(6) of Feza Gursey and Luigi Radicati

VOLUME 13, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1964

SPIN AND UNITARY SPIN INDEPENDENCE OF STRONG INTERACTIONS*

F. Gürsey† and L. A. Radicati‡
Brookhaven National Laboratory, Upton, New York
(Received 15 July 1964)

- symmetry under $SU(3)_{flavor} \otimes SU(2)_{spin}$ can be promoted *à la* Wigner to SU(6)
- SU(6) reps decomposed in SU(3)⊗SU(2) denoted by: $(n, 2s+1)$
- dimension= $n \times (2s+1)$

$$quarks = (3,2),\ antiquarks = (\bar{3},2)$$

$$mesons = (3,2) \otimes (\bar{3},2) = [(8,1) \oplus (8,3) \oplus (1,3)] \oplus (1,1) = 35 \oplus 1$$

$$baryons = (3,2) \otimes (3,2) \otimes (3,2) = 20 \oplus 56 \oplus 70 \oplus 70'$$

symmetry character: A S M M

$$56 = (8,2) \oplus (10,4)$$

- Baryons and baryon resonances neatly fit in
- but total symmetry of the wave function (in flavor and spin) is inconsistent with Fermi statistics of quarks (spin 1/2), if baryons are in S-wave …***are quarks real*** ??

Gattini at work in Florence

• Gatto was masterly leading the large group of ambitious, young *gattini* as well as the somewhat older people he had found in Firenze (Marco Ademollo, Claudio Chiuderi, Giorgio Longhi)

•he was putting everybody in front of advanced but accessible problems (radiative corrections, SU(3), SU(6), U(12), quark statistics, CP violation, weak interactions…you name it) he would discuss your results, send you back if not convinced, or write a draft paper

•we learned that we could compete with other groups, in US and Israel

•Sid Meshkov defined us the *italian mafia*, opposed to the *israeli mafia* of Harari & co, who were working on the same subjects

• Guido emerged for his authority, clarity and sense of humour, and also for his capacity to work with the Firenze people: he worked with Giorgio Marco Longhi, became good friend of Marco Ademollo and of Claudio Chiuderi

•however exciting, we *gattini* were mostly taking the measure to physics and to life….
• the best work out of Firenze came from the old hands: Gatto Ademollo's theorem of non renormalisation (of Cabibbo's vector amplitudes by 1st order SU(3) breaking)
•the Firenze school dissolved in 1967-1968:
Gatto went to Geneva and then to Padova (working with Costa, Tonin, Sartori, Masiero, Feruglio….) and later to Roma, then Uni Geneve, making new schools and new gattini
Guido went to New York University (with Rita and new born Claudia) and then to Rockefeller Institute
Giuliano and I went back to Roma to work with Cabibbo (in 1967),
later Giuliano went to Princeton, then to SLAC, CERN.

- Nicola presented in Erice 1967 our first joint work, Cabibbo, Maiani, Preparata

Weak and electromagnetic currents

Professor Cabibbo of CERN described some recent work on the computation of radiative corrections to beta decay, done in collaboration with L. Maiani and G. Preparata.

The discussion was centered on the ultra-violet divergences which can appear in radiative corrections, making their computation impossible. The requirement that such divergences do not appear, considerably limits the range of possible models of hadrons, excluding the simple versions of the quark model with fractional charges. However, this requirement is easily met in models with only integrally charged particles. Professor Cabibbo discussed in detail one such model, which reproduces most of the desirable results of the quark model.

In modern terms:
with Fermi interaction (no W) quarks must be integrally charged;
if W exists, quarks can be fractionally charged (A. Sirlin)

Guido Altarelli taking a video at Hyde Park, London. Helping him, Massimo Altarelli, on the left Giorgio Capon, early ’60 ?

Claudia with Guido, 1968

- winter 1970 with Pucci at Brandeis University, at the time of the GIM Mechanism.

4. The Rise of the Standard Theory

• At the end of the 60's, dual models dominated the scene as the theory of strong interactions. The years 1971-1973 brought decisive discoveries.

- 1970: GIM mechanism, a new heavy quark and a new quantum number: charm
- 1971, 't Hooft and Veltman showed that the Weinberg-Salam theory is renormalisable.
- 1972, Bouchiat, Iliopoulos and Meyer proved the cancellation of Adler anomalies in the Electroweak theory with four quarks. In a letter from John: ***there must be charm, quarks have color and are fractionally charged***.
- 1973 the discovery of neutral currents by Gargamelle at CERN
- …and in the same year came the discovery of asymptotic freedom of the Yang-Mills theory by Gross and Wilczeck and Poltzer .
- Shortly after, the idea of color interaction of quarks was put forward by Fritzsch, Gell-Mann and Leutwyler.

• In three years, the paradigm of particle interactions ad hshifted completely towards field theory, a shining example of what Thomas Kuhn in 1962 had called a ***scientific revolution***.

• In 1974, the discovery of the J/Psi opened another chapter: heavy fermions, initiated with charm and later continued with the heavy lepton, beauty and top.

• The ***Standard Theory*** was taking form, everybody became Electroweak & Free, at least Asymptotically.

Life in Roma in the 1970s

• In Roma, my wife Pucci and I used to see Guido and Nicola out of work, with wives and small kids. Sometime we would go to Fregene, in the nice seaside house of the Altarelli's, or to Grottaferrata, in the country house of the Cabibbo's, and to the lake of Bracciano with Pucci's family. We saw also other Roma professors, Giorgio Salvini, Marcello Conversi, Giorgio Careri and families.

• New younger people had joined, following Massimo Testa and Giorgio Parisi.

• Keith Ellis, a young italian-scottish speaking student, attracted to Roma by Preparata and recruited in our group by Guido,

• Roberto Petronzio, then a *laureando* of Nicola,

• Guido Martinelli, also recruited by Guido.

• You will find their names appearing first in the literature in association with Nicola, with Guido and sometimes with me.

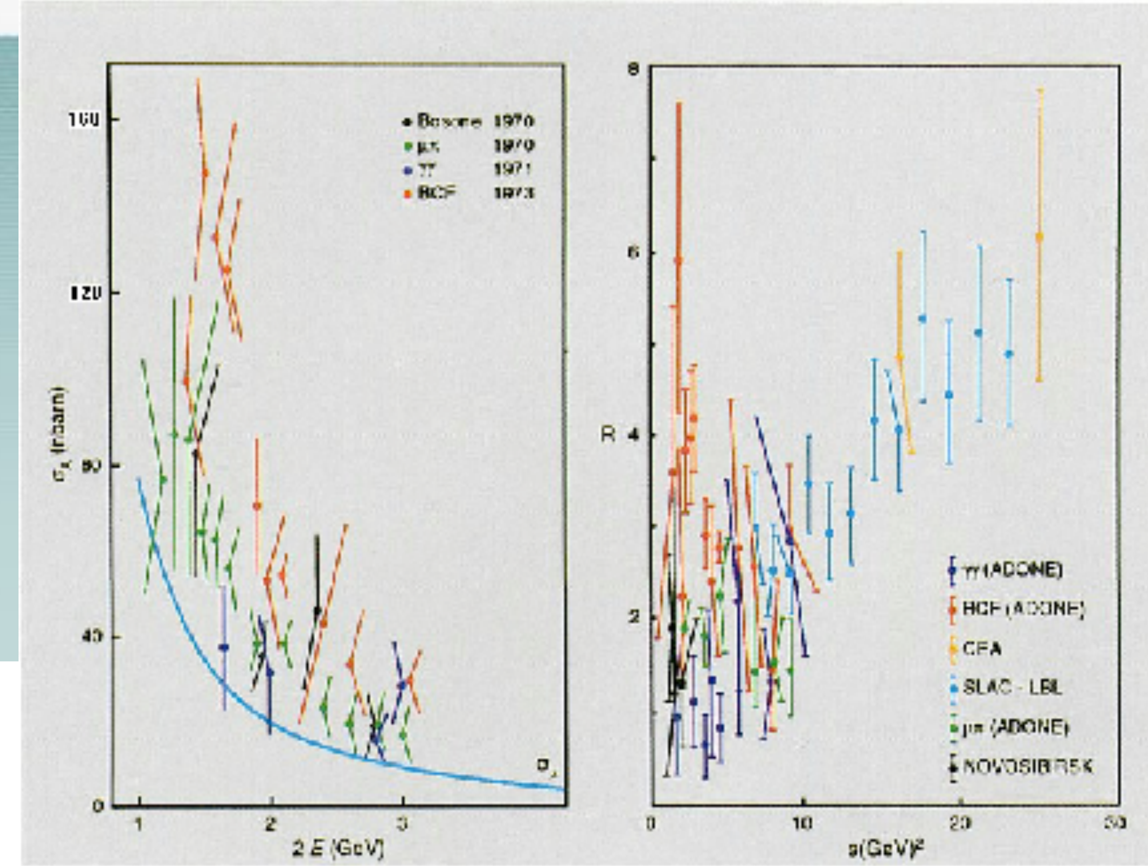
•From time to time the Physics Department was occupied by the students, but we could find always a quiet office in Istituto Superiore di Sanitá, across the road, where I worked.

•To be sure, Roma and Italy were struck by social turmoil and terrorism, but our was a quiet, intellectually stimulating, academic life that I remember with pleasure and that never did come back.

•I moved to the University La Sapienza as full professor in 1976 and Guido took the chair shortly after, in 1980.

Adone’s Legacy

- *Multihadron production results obtained in Frascati from 1969 to 1974 (left plot): the blue line shows the muon pair production cross section. The right plot shows world data on R (multihadron to muon production rate) up to 1974.*



login

Wolfgang Panofsky to Marcello Conversi: *We are all very excited about the progress of Frascati ring and its relationship to the SLAC deep inelastic scattering. We think that these results probably will open up some of the most fundamental ideas in physics today and time will tell whether the parton idea will be the only surviving explanation* (8 December 1970)

Press cutting

Title	**Frascati results suggest the pion may be pointlike**
In:	*New Sci.* (21 Jan 1971) pp.106
Subject category	Particle Physics - Research
Free keywords	Adone ; Frascati ; Pions
Abstract	Electron-positron collisions at the Adone storage ring have yielded suprisingly high cross-sections for the production of strongly interacting particles such as positive and negative pion pairs. Some physicists are interpreting these results as meaning that the pion may have pointlike constituents or behaves like a structureless particle like the electron or muon (4 paragraphs).

Cabibbo, Parisi, Testa, 1970

Record created 2004-02-26, last modified 2007-01-10

Similar records

The first parton model analysis of Adone data

LETTERE AL NUOVO CIMENTO VOL. IV, N. 1 4 Luglio 1970

Hadron Production in e^+e^- Collisions (*).

N. Cabibbo

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

G. Parisi and M. Testa

Istituto di Fisica dell'Università - Roma

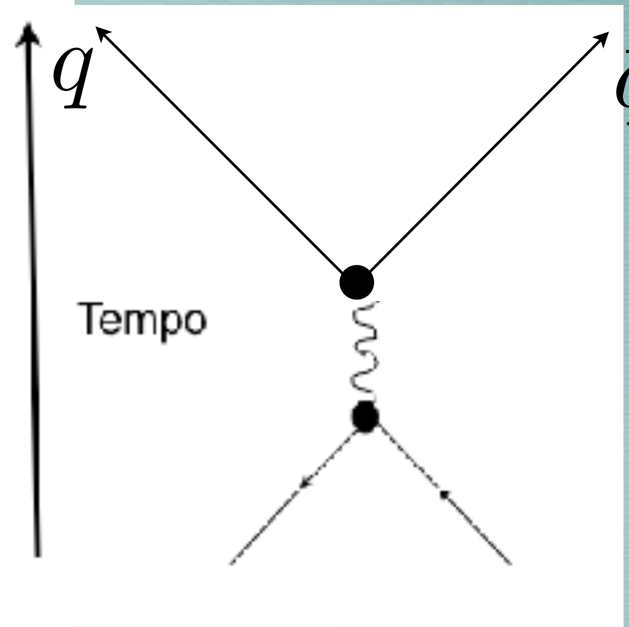
(ricevuto il 30 Maggio 1970)

1. – The simple properties of deep inelastic electron-proton scattering has suggested models where these processes arise as interactions of virtual photons with an « elementary » component of the proton. These as yet unspecified elementary components of the proton have been given the name of « partons » by Feynman [1]. The model has been studied by Bjorken and Paschos [2] and successively by Drell, Levy and Tung Mow Yan [3] who gave a field-theoretical treatment of the parton model, and were able to recover some of the experimentally observed properties of this process. In this letter we wish to extend the method of ref. [3] to the study of the total cross-section of electron-positron annihilation into hadrons.

This treatment leads to an asymptotic (very high cross-section c.m. energy, $2E$) of the form

(1) $$\sigma \to \frac{\pi\alpha^2}{12E^2}\left[\sum_{\text{spin }0}(Q_i)^2 + 4\sum_{\text{spin }\frac{1}{2}}(Q_i)^2\right], \qquad = \frac{\pi\alpha^2}{12E^2}[4R]$$

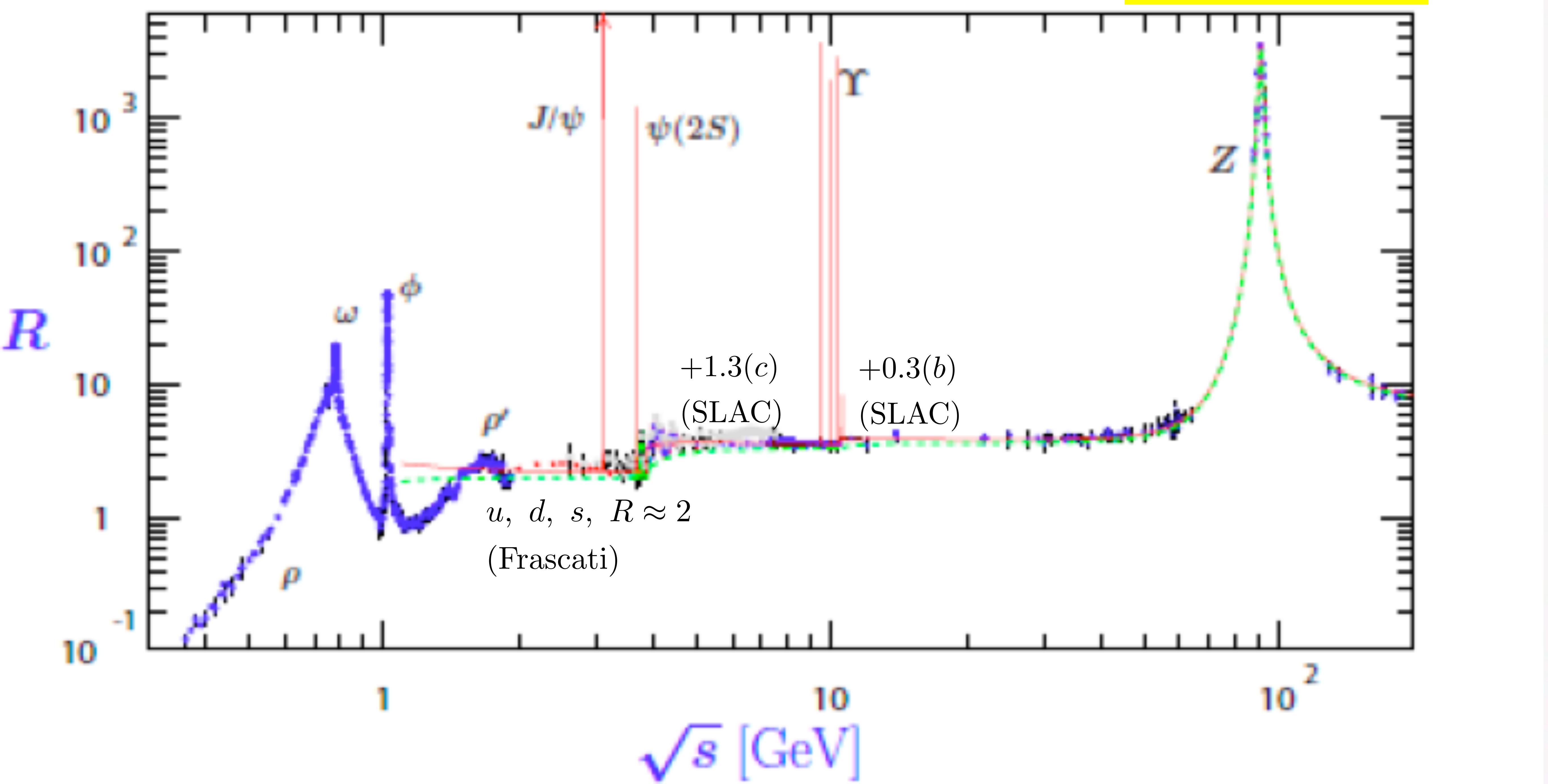
where Q_i is the charge of the i-th parton in units of e. This is simply the sum of the



$$R = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3},$$
for u, d, s, no color

R as function of energy, today

Particle Data Group



5. New Hadron States

> Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q q̄), etc., while mesons are made out of (q q̄), (q q q̄ q̄), etc. It is assuming that the lowest

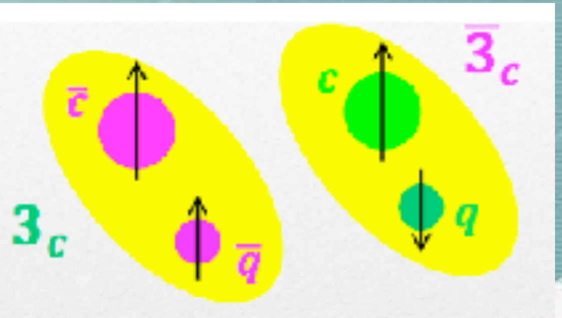
M. Gell-Mann, A Schematic Model of Baryons and Mesons, PL **8**, 214, 1964

- For long, we lived with the simplest paradigm:

$$\text{mesons} = q\bar{q}, \quad \text{baryons} = qqq$$

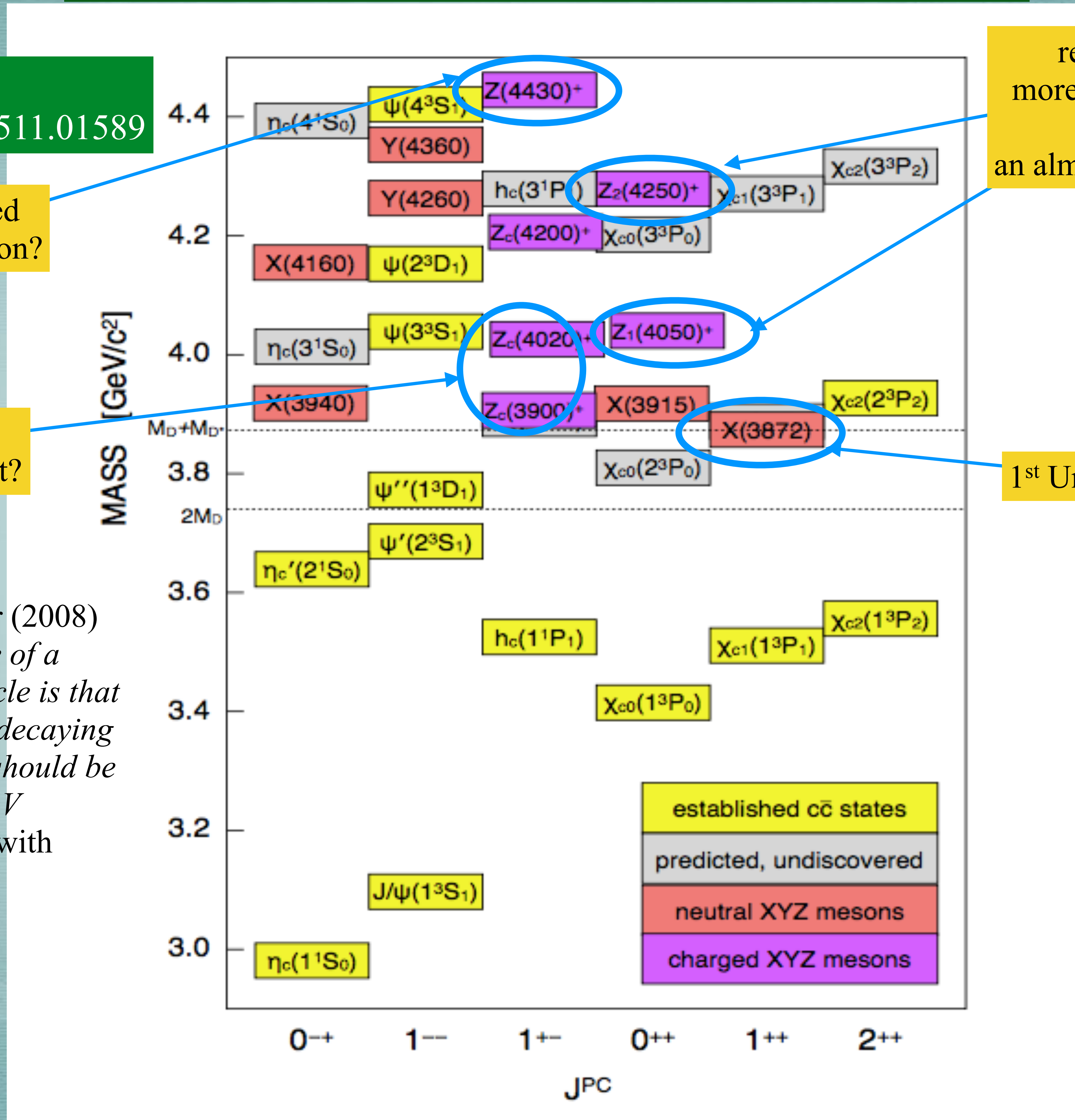
- Paradigm rested on the absence of I=2, ππ resonances and of S>0 baryons.
- The case had to be revisited, because the lowest lying, octet of scalar mesons- $f_0(980)$, $a_0(980)$, kappa(800) and sigma(600)- does not fit in the picture.
- The X(3872), narrow width, with decays into J/Psi+ 2π/3π, discovered by Belle in 2003, does not fit into the "charmonium" states,
- since then, Belle, BaBar, BES and LHcB have reported many other states that do not fit the charmonium picture, called X (1^{++}) and Y(1^{--}) states: molecules? hybrids? tetraquarks?
- In 2007, Belle observed a charged "charmonium", $Z^+(4430) \rightarrow \psi(2S) + \pi$, that could not be interpreted as molecule, but later Babar suggested it was simply a reflection of K* states
- LHCb has confirmed the $Z^+(4430)$ while other similar states, $Z^+(3900)$ and $Z^+(4020)$, have been discovered by BES III and confirmed by BELLE and by CLEOc.
- Pentaquark discovered (P-> Ψ p) by LHCb in 2015
- New structures in Ψ φ spectrum in 2016…. more to follow?

A new spectroscopy of mesons and baryons revealed



1. Expected and Unexpected Charmonia

figure by:
S. L. Olsen, arXiv:1511.01589



recent additions:
more than coincidence?
or
an almost filled multiplet?

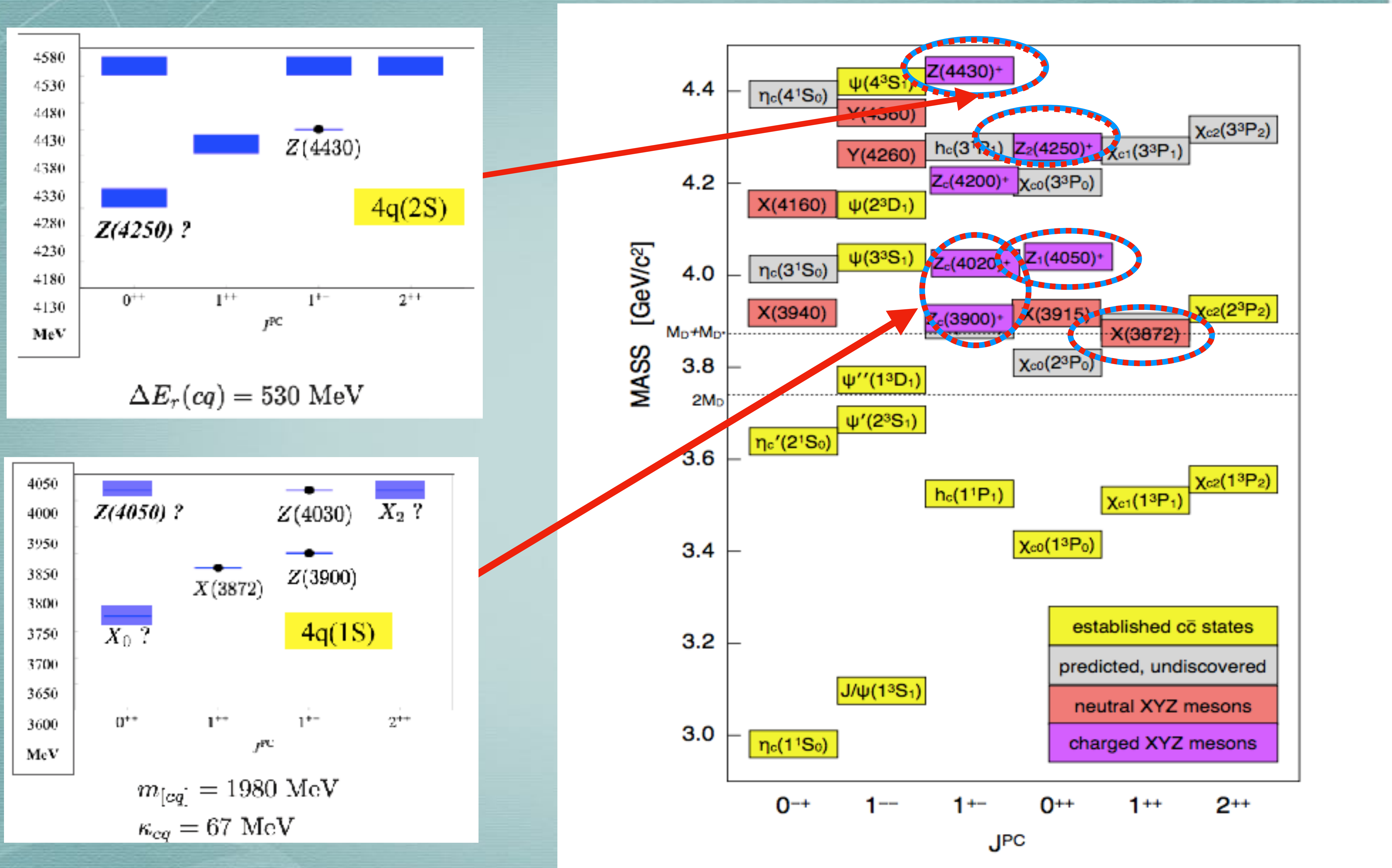
2nd Unexpected
a radial excitation?

3rd case:
start a multiplet?

1st Unexpected

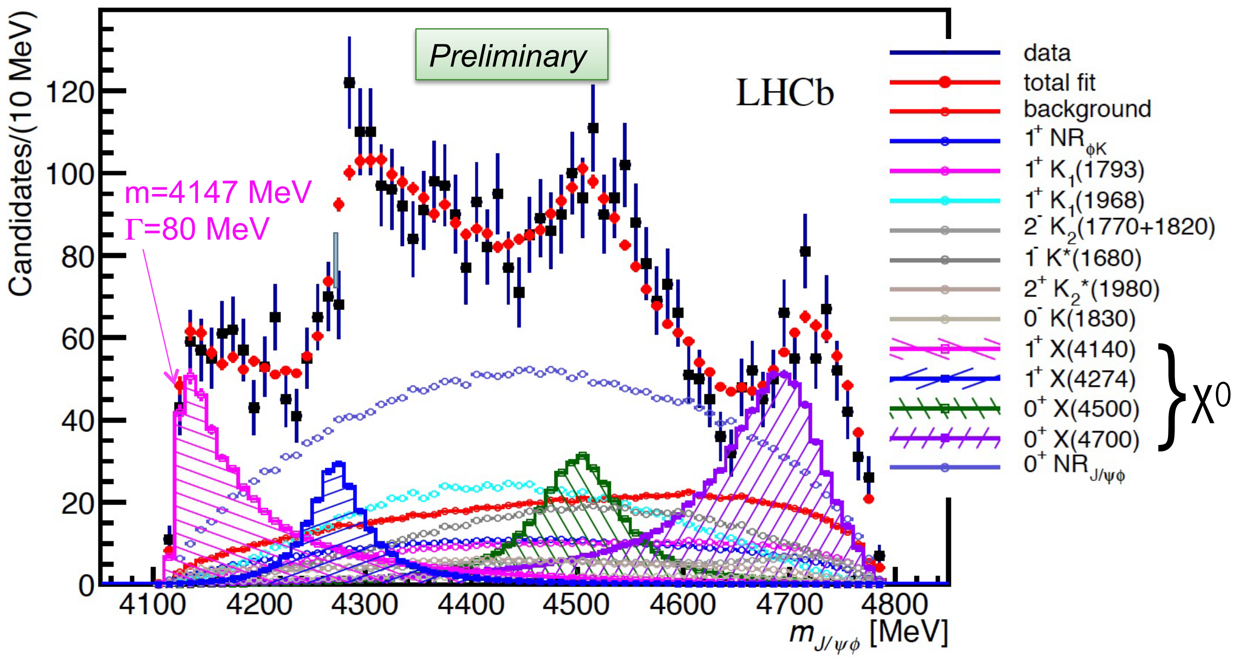
Maiani, Polosa, Riquer (2008)
a crucial consequence of a Z(4430) charged particle is that another charged state decaying into $\Psi(1S)\ \pi^\pm$ or $\eta_c\ \rho^\pm$ should be found around 3880 MeV
i.e. almost degenerate with X(3872)

1. Expected and Unexpected Charmonia



Old and new structures observed by LHCb
arXiv:1606.07895

Results of fit: m(J/ψϕ)



- 4 visible structures fit with BW amplitudes

28 Recontres de Blois, June 2, 2016 36

Results of fit

- J^P also measured all with >4σ significances

Particle	J^P	Signif-icance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	8.4 σ	$4146.5\pm4.5^{+4.6}_{-2.8}$	$83\pm21^{+21}_{-14}$	$13.0\pm3.2^{+4.8}_{-2.0}$
X(4274)	1^+	6.0 σ	$4273.3\pm8.3^{+17.2}_{-3.6}$	$56\pm11^{+8}_{-11}$	$7.1\pm2.5^{+3.5}_{-2.4}$
X(4500)	0^+	6.1 σ	$4506\pm11^{+12}_{-15}$	$92\pm21^{+21}_{-20}$	$6.6\pm2.4^{+3.5}_{-2.3}$
X(4700)	0^+	5.6 σ	$4704\pm10^{+14}_{-24}$	$120\pm31^{+42}_{-33}$	$12\pm5^{+9}_{-5}$
NR	0^+	6.4 σ			$46\pm11^{+11}_{-21}$

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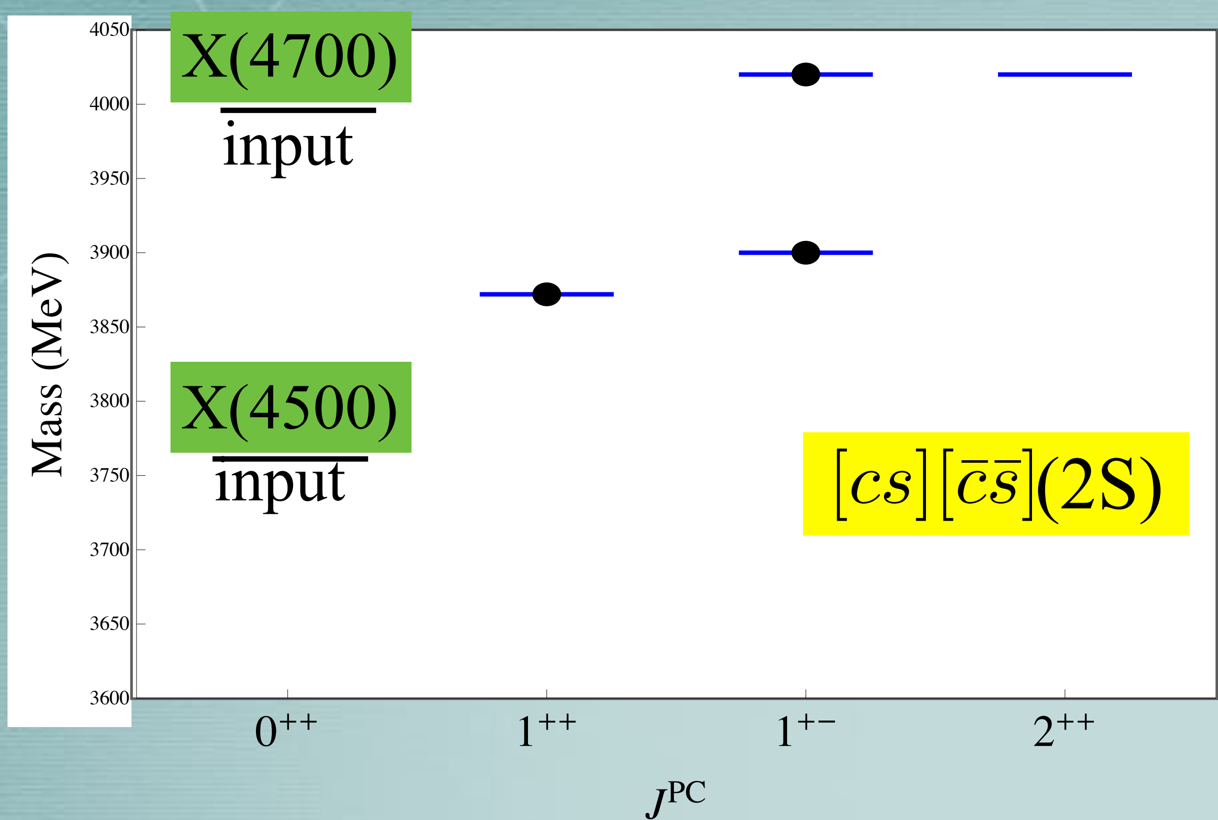
- Four structures
- positive parity, J=0 and 1, positive charge conjugation
- X(4140) seen previously by CDF, D0, CMS and by BELLE

We suggest to fit the structures in two tetraquark multiplets, S-wave ground state and the first radial excitation, with composition $[cs][\bar{c}\bar{s}]$.

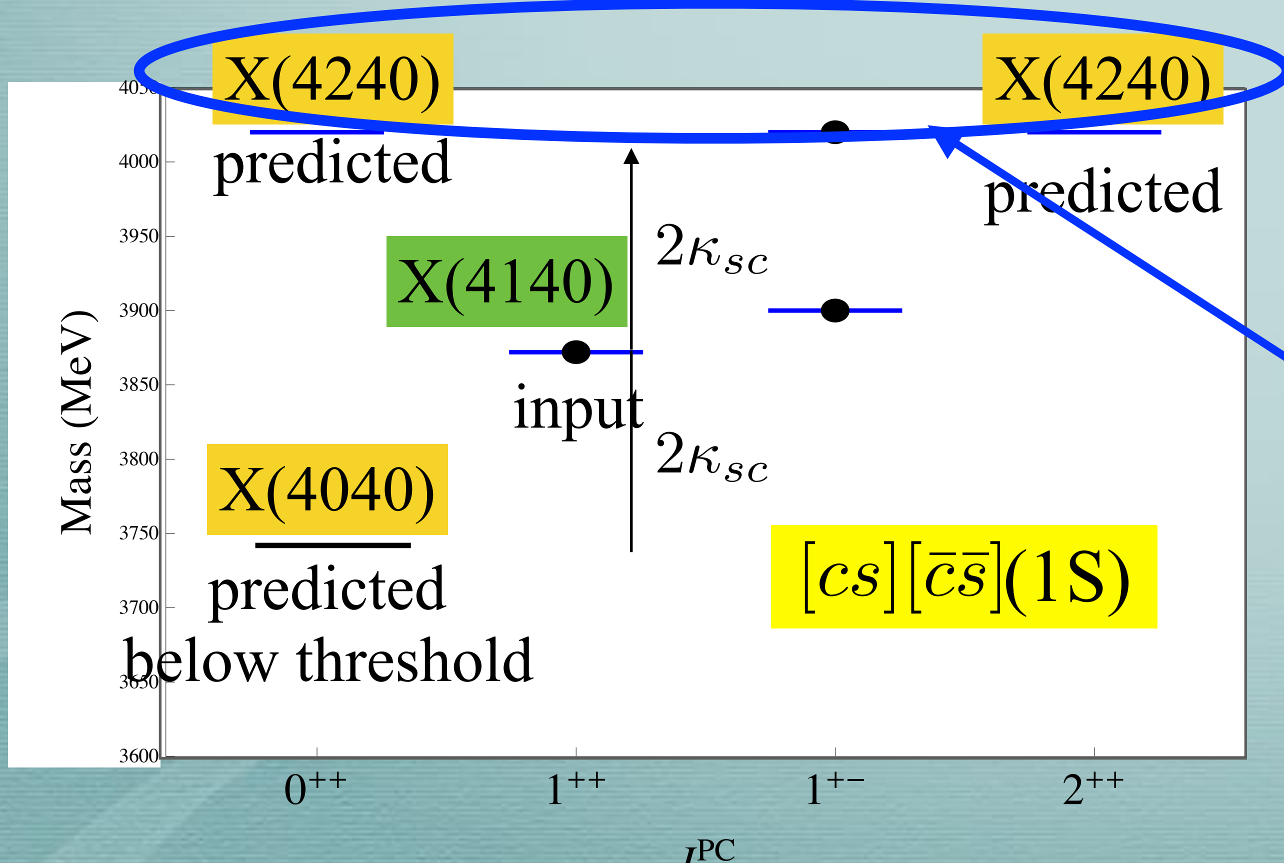
L. Maiani, A. Polosa, V. Riquer, PRD **94** (2016) 054026

With the previously identified $[cq][\bar{c}\bar{q}]$ $(q = u,\ d)$ multiplet, the new resonances would make a step towards a ***full nonet*** of S-wave tetraquarks made by c c-bar with a pair of light (u, d, s) quarks.

J/Ψ-φ structures and S-wave tetraquarks



rad. exc. en.



$\Delta m = m_{cs} - m_{cq} = 129$ MeV;

$\kappa_{sc} = 50$ MeV ($\kappa_{qc} = 67$ MeV)

radial excit. = 460 MeV

$[Z(4430) - Z(3900) = 530$ MeV$]$

NOTE :

$X(4140) - X(3872) \sim 270$ MeV;

$\phi(1020) - \rho(770) \sim 244$ MeV

X(4274) cannot be 1^{++}

- **0^{++} ?**
- **2^{++} ?**
- **2 unresolved, almost degenerate lines with $0^{++} + 2^{++}$??**

Decay modes of $J^P=1^+$, C=-1:

$s_{c\bar{c}} = 1 : J/\Psi + \eta, \chi_c + \eta \ (P - wave)$

$s_{c\bar{c}} = 0 : \eta_c + \phi, h_c + \phi \ (P - wave)$

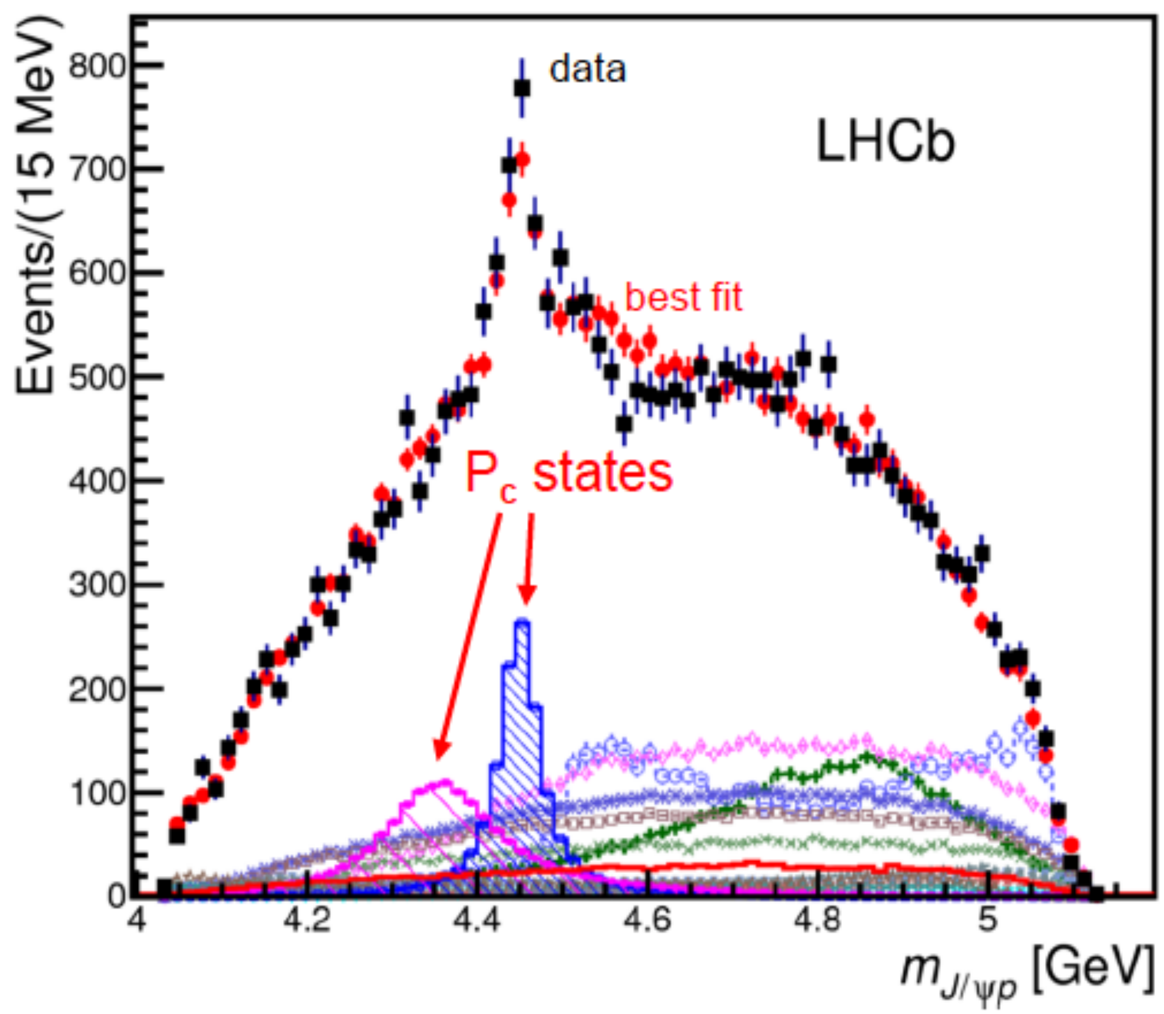
$J/\Psi p$ resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

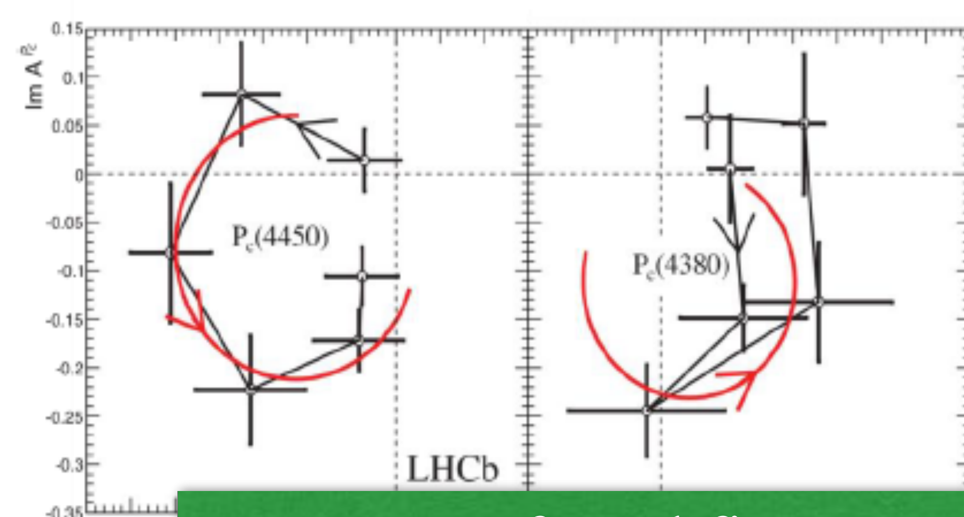
$P_c(4380)$:
$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,
$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$

$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$
$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

Need to add two states with content uudccbar.
Best fit has J=3/2 and 5/2 with opposite parities.

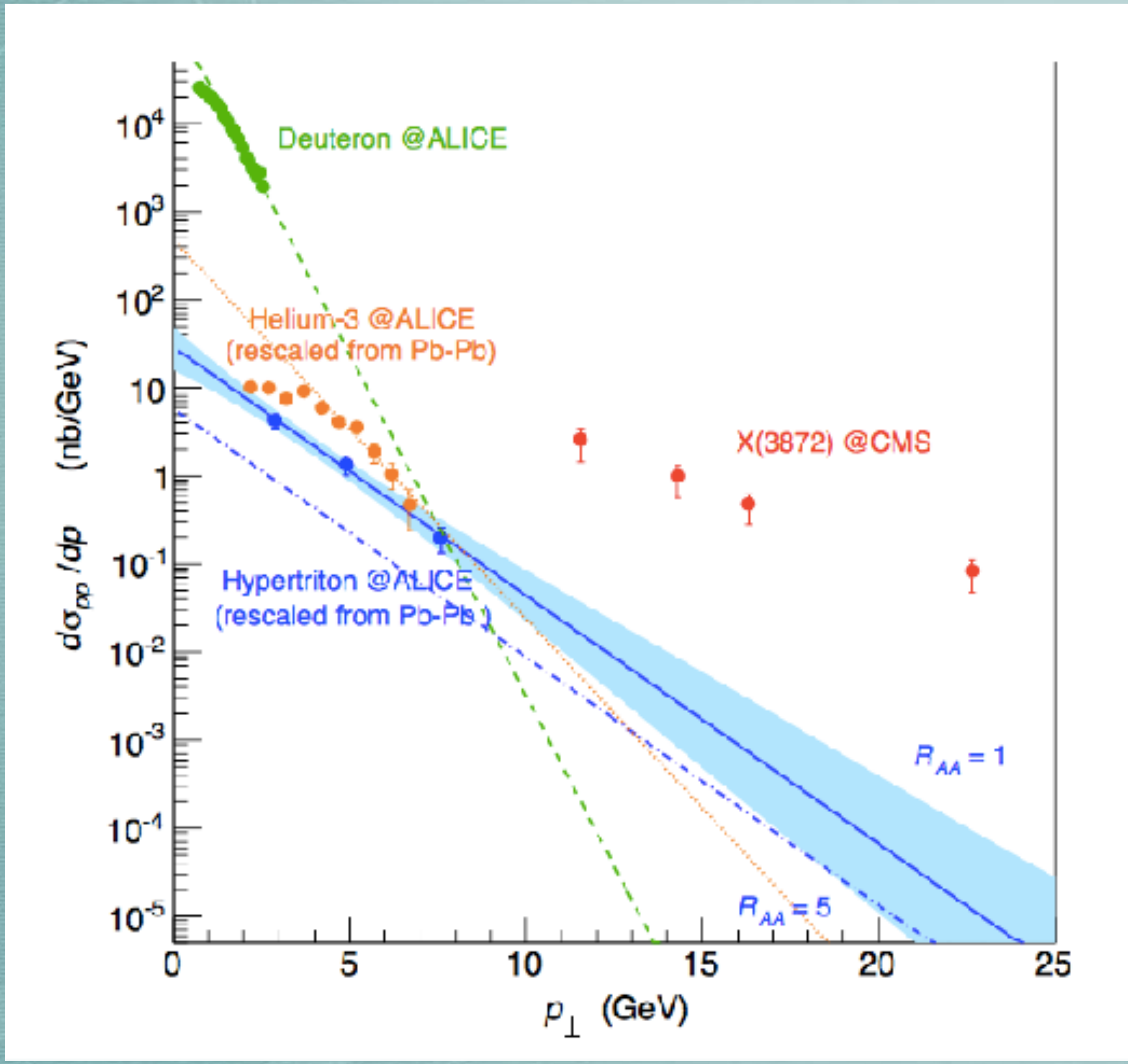


Clear resonant behaviour for narrow state,
Need more statistics to elucidate other state.



preferred fit
P(4380)=3/2$^-$, P(4450)=5/2$^+$

To compare with the CMS cross section of X(3872), light nuclei cross-sections from ALICE Pb-Pb data have been rescaled to p-p cross sections with Glauber model

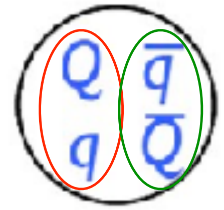


- There is a vast difference in the probability of producing X(3872) and that of producing light nuclei, true "hadronic molecules", in high energy collisions
- high energy production of suspected exotic hadrons from quark-gluon plasma at Heavy Ion colliders can be a very effective tool to discriminate different models
- a long list of suspects: $f_0(980)$, X(3872), $Z^{\pm}(3900)$, $Z^{\pm}(4020)$, $Z^{\pm}(4430)$, X(4140)....

Models for XYZ Mesons

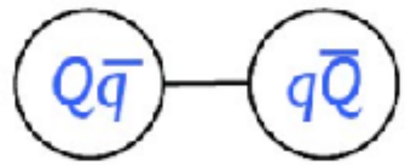
Quarkonium Tetraquarks

- compact tetraquark



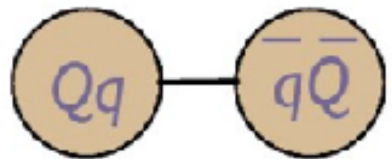
L. Maiani, A. Polosa, V. Riquer, F, Piccinini, Phys. Rev. D **89**, 114010 (2014) and reffs therein

- meson molecule



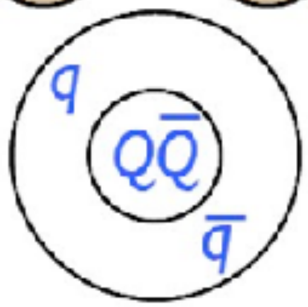
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

- diquark-onium



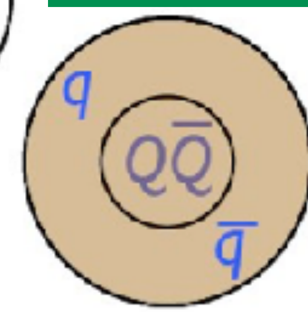
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

- hadro-quarkonium



X.Li, M.B.Voloshin, Mod. Phys. Lett. **29**(2014) 12, 1450060 and refs. therein

- quarkonium adjoint meson



Few think that X, Y, Z are kinematic effects due to the opening of new channels: see E. S. Swanson, *Cusps and Exotic Charmonia*, arXiv:1504.07952 [hep-ph]
However, it takes a lot of unconventional dynamics to produce the X(3872) as a “cusp”
Also, the phase of Z(4430) goes at 90^0 at the peak, like a text-book Breit-Wigner resonance...

6. Conclusions: Quarks and QCD

- Quarks and QCD are here to stay.
- Italian physics made a lot to get to this point.
- Quarks and QCD give a perfect descripton of "deep inelastic" phenomena (Asymptotic Freedom)
- We still do not master QCD where strong interactions are strong
- The constituent quark model, CQM, is an approximate description of hadron spectroscopy, and it works quite well, given its intrinsic simplicity
- qualitative success
  - -quantum numbers of meson& baryon resonances,
- and quantitative success
  - -mass formulae with few parameters, which remain consistent across a wide spectrum, from s to c to b quark
- QCD with large N reproduces several features of the CQM,
- … and new features like duality
- Data have shown that there are "structures" beyond (q q bar) or (qqq)
- in line with the CQM prediction that color 3bar is an attractive channel
- tetraquarks, pentaquarks and dibaryons are predicted.

Conclusions: Exotic Hadrons

- Tetraquarks:
  - S-wave multiplets are slowly filling up;
  - orbital excitations seen : Y states and the heavier pentaquark
  - J/Ψ-φ resonances go well with simple, S-wave, tetraquarks....except for the puzzling 1^{++} duplication of X(4140) and X(4270).
- An important prediction: dibaryons.
- Dibaryons can be searched for in Λ_b decays for a wide range of masses (from 4680 down to 2135 MeV);
- if found, dibaryons would complete a second layer of hadron spectroscopy, following the Gell-Mann Zweig layer and completing the saturation possibilities of one and three QCD strings.
- Open heavy flavour exotics is the new frontier
- exotics seen until now contain heavy quark flavours: an experimental reexamination of the lack of existence of light exotic mesons ("bad" diquarks) and positive strangeness baryons is in order.
- Much remains to be done, in theory and experiments, LHCb and electro-positron colliders to play a crucial role;

Hadron Spectroscopy is not simple "botanics". It may teach us something fundamental about the, essentially unknown, non-perturbative QCD