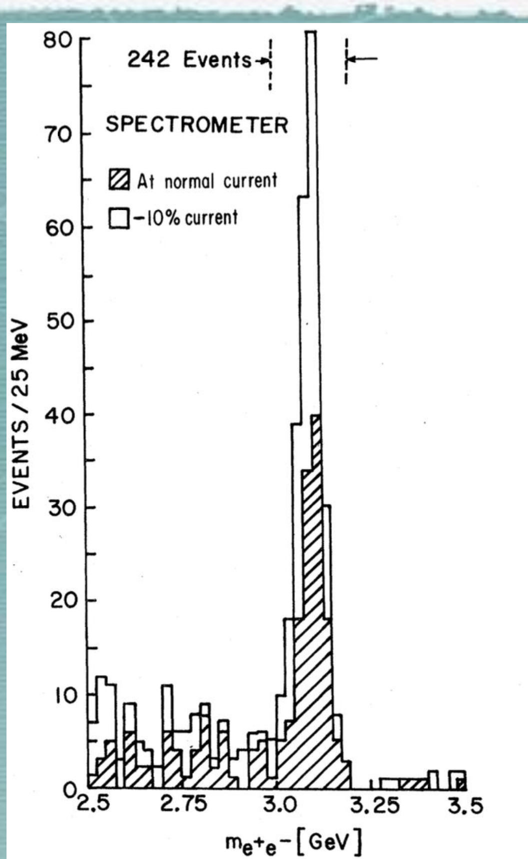
The Standard Theory of Fundamental Interactions 50 years after J/Psi Discovery. From Charmonium to Exotic Hadrons

Luciano Maiani
Università di Roma La Sapienza and INFN Sezione di Roma

Abstract

The November Revolution was initiated in 1974 by the discovery of J/Psi and led to the Standard Theory, the most successful description, until now, of the world of fundamental particles. I will summarize the progress made with the Standard Theory in the theoretical description of mesons as $q\bar{q}$ and baryons as qqq states, respectively. In 2003, the discovery of the X(3872) meson opened a new chapter, the so-called exotic hadrons, not fitting in the previous picture and presumably made by Tetraquarks ($Q\bar{Q}qq$, $QQ\bar{q}\bar{q}$) and Pentaquarks ($Q\bar{Q}qqq$). I will describe the recent progress in this field up to the latest studies in Roma and CERN of hidden charm and double charm tetraquarks.

1.The November Revolution (1974)



J.J. Aubert *et al.* PRL **33**, 12 Nov.1974

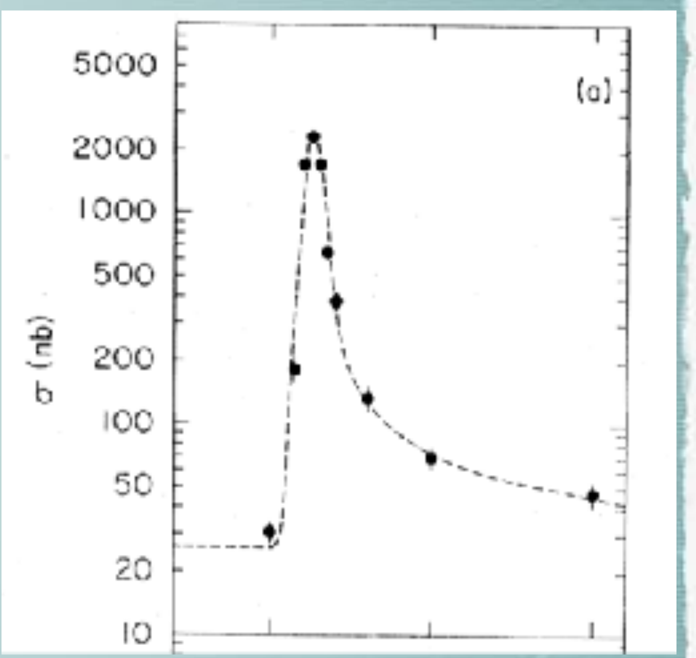
$p + p \to e^+ + e^- + \ldots.$

$M = 3.1\ \text{GeV},\ \Gamma \sim 100\ \text{KeV}!!$

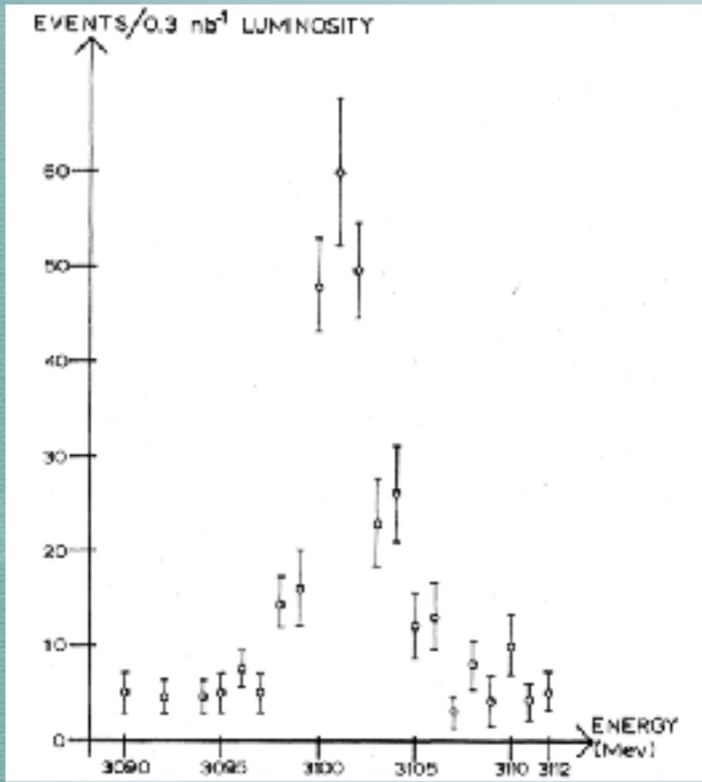
The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles[2] or a's[3] or Z_0's,[4] etc.

J.E. Augustin *et al.* PRL **33**, 13 Nov.1974

$e^+ + e^- + \to$ hadrons



It is difficult to understand how, without involving new quantum numbers or selection rules, a resonance in this state which decays to hadrons could be so narrow.



Confirmed by Adone (Frascati)

C.Bacci *et al.* PRL **33**, 18 Nov.1974

$e^+ + e^- + \to$ hadrons

Soon after the news that a particle of 3.1 GeV with a width consistent with zero had been observed at Brookhaven National Laboratory by the Massachusetts Institute of Technology group,[1] it was immediately decided to push ADONE beyond its nominal limit of energy (2×1.5 GeV) to look for this particle.

2. Late 1960's: hopes for a basic theory of strong, e.m. and weak interactions

- Well established results:
  - Gell-Mann-Zweig quarks in 3 flavours (baryons=qqq, etc.)
  - Cabibbo theory of semileptonic decays with ΔS=0,1:

$$q = \begin{bmatrix} u \\ d \\ s \end{bmatrix}$$

$$\mathcal{L}_F = \frac{G_F}{\sqrt{2}} J^\lambda J^+_\lambda$$
$$J^\lambda = \bar{\nu}_e \gamma^\lambda (1-\gamma_5) e + \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu + \bar{u}\gamma^\lambda(1-\gamma_5) d_C$$
$$d_C = \cos\theta d + \sin\theta s$$

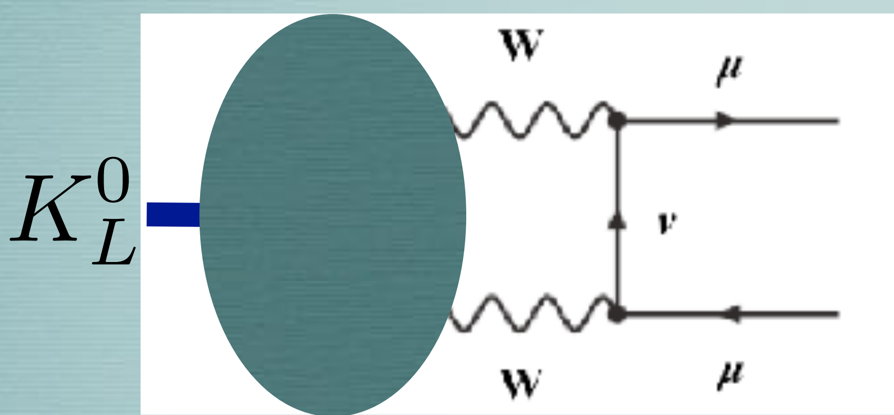
quarks: only one weak doublet

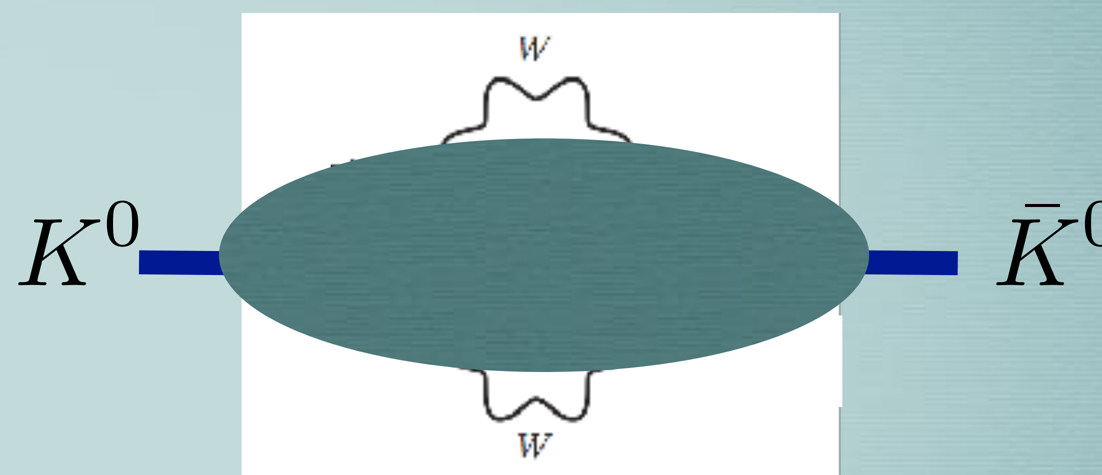
$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; (s_C)_L; d_R; u_R; s_R$$

- clouds:
  - do quark clash with Fermi-Dirac statistics? first ideas about color (Han-Nambu)
  - basic strong interactions: *gluon (abelian) mediated* ? *dual-like* (Veneziano model)
  - Fermi theory not renormalizable. W boson? strong interaction form factors?
- Schwinger ideas about EW unification with Yang-Mills:
  - Glashow's SU(2)⊗U(1) (1961)
  - Brout-Englert-Higgs Mechanism (1965) -> Weinberg-Salam (1967)
  - is Weinberg-Salam renormalizable?
- Embedding Cabibbo theory in SU(2) ⊗ U(1):
  - produces Flavour changing Neutral Currents
  - does Unification work for leptons only ?

The GΛ² puzzle, 1968

- The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin, indicating that $\Delta S = \pm 1$ neutral currents and $\Delta S=2$ amplitudes would result from higher order weak interactions, ***even in a theory with the charged W only***





- the amplitudes were found to be divergent, of order $G(G\Lambda^2)$, and in disagreement with experiments, ***unless limited by an ultraviolet cut-off $\Lambda \approx$ 3-4 GeV*** (from Δm_K);
- the result, based on current algebra commutators, shows that hadron form factors are irrelevant: ***current commutators imply hard constituents***;
- Similar results were found by R. Marshak and coll. and by F. Low.
- The exceedingly small value of the cut-off raised a wide disscussion.

first attempts

- Attempts were made during 1968-69 to explain the anomalously small ~ 3 GeVcut-off scale:

  - introducing more than one Intermediate Vector Boson (Gell-Mann, Low, Kroll, Ruderman) (too many were needed);

  - introducing negative metrics (ghost) states (T.D.Lee and G.C. Wick), of mass ~ 3 GeV!

- Other lines

  - it was realised that quadratic divergent amplitudes at order $G\Lambda^2$ would arise, in the IVB theory, with potential violations of strong interaction symmetries (parity, isospin, SU(3) and strangeness), implying even smaller values of the cu-off .

  - cancel the quadratic divergence, in correspondence to a specific value of the angle, i.e. “computing” the Cabibbo angle (Gatto, Sartori, Tonin);

- C. Bouchiat, J. Iliopoulos and J. Prentki observed that, with chiral $SU(3) \otimes SU(3)$ breaking described by a $(3,\bar{3})$ representation, the leading divergences give only diagonal contributions (no parity and strangeness violations).

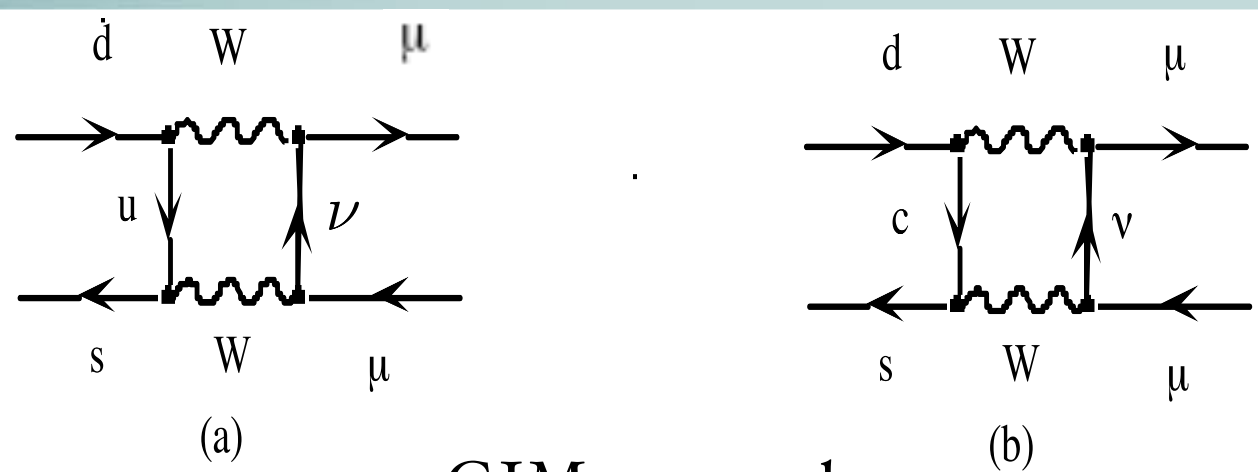
- ...but the small cutoff in the $G(G\Lambda^2)$ terms still called for an explanation.

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.



GIM proposal

$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; \begin{pmatrix} c \\ s_C \end{pmatrix}_L ; (d_C)_R ; (s_C)_R ; u_R ; c_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ; e_R ; \mu_R$$

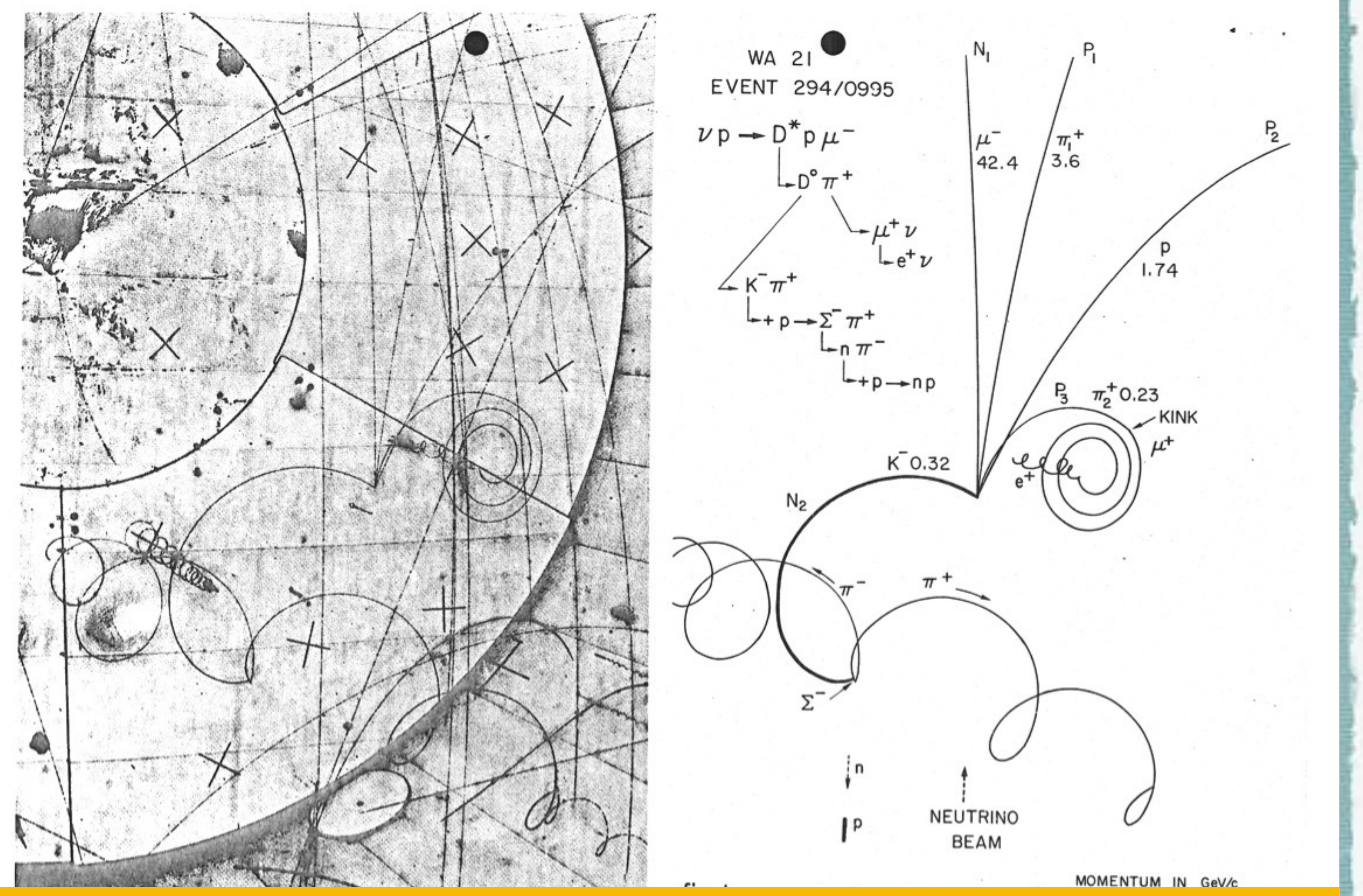
$$J_\mu^W(quark) = \bar{q} C \gamma_\mu q_L$$

divergent amplitude:
$\propto G(G\Lambda^2)[C,C^\dagger]$
= flavor diagonal!

finite amplitude: $\propto G[G(m_c^2 - m_u^2)][C, C^\dagger]$
Ioffe's cutoff becomes the prediction:
$m_c \sim 1.5$ GeV

(1976) The discovery of the first charmed particle

•In 1970 there was no experimental evidence of weakly decaying hadrons beyond the lowest lying strange baryons and mesons.



Blietschau, J., et al. Physics Letters B 86 (1979)108

•GIM's explanation: *...Suppose they are all relatively heavy, say 2 GeV.*

-*..will decay rapidly (10^{-13} sec) by weak interactions....into a very wide variety of uncharmed final states*

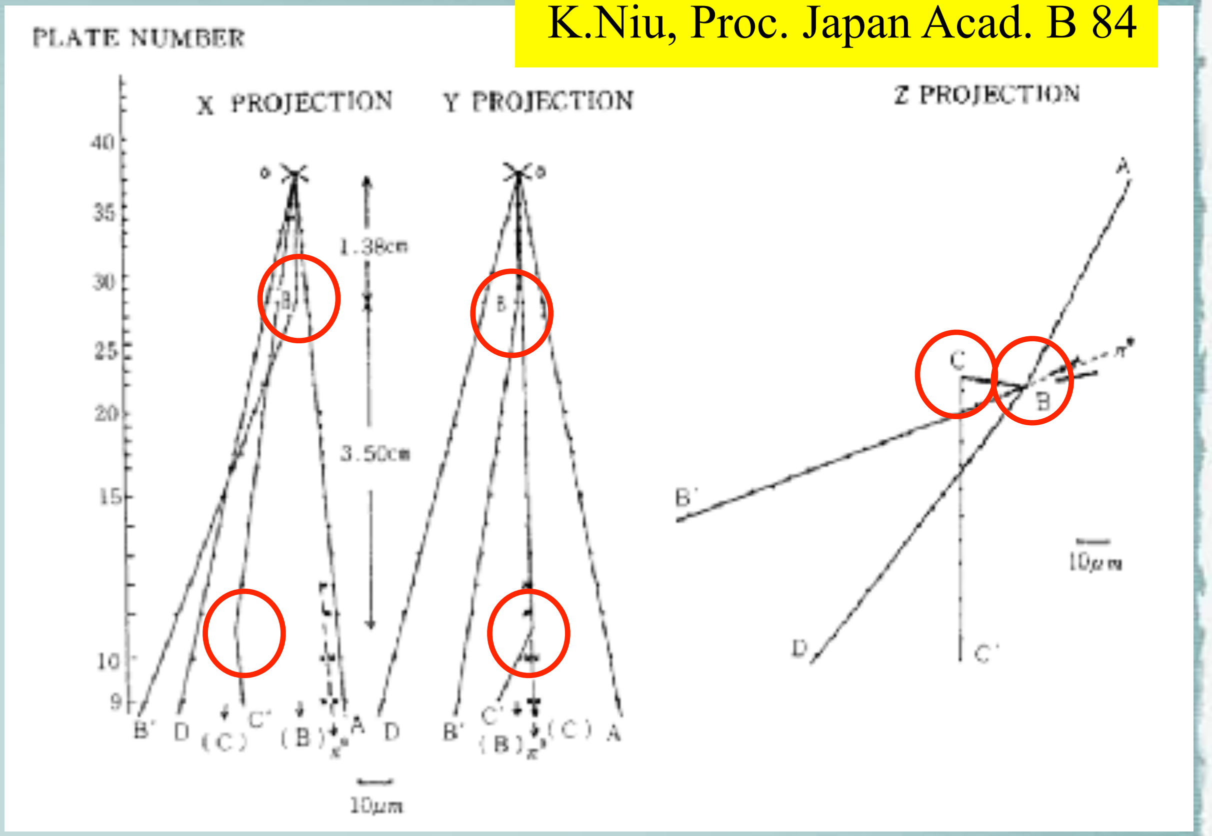
-*.....are copiously produced only in associated production, such events will necessarily be of very complex topology*

-*...Charmed particles could easily have escaped notice.*

Charmed particles produced by Cosmic Rays?

- In 1971, K. Niu and collaborators observed ***kinks*** in cosmic ray emulsion events, indicating unstable particles with lifetimes of order of 10^{-12} to 10^{-13} sec. These lifetimes are in the right ballpark for charmed particles and indeed they were identified as such in Japan.
- But cosmic rays events were paid not much attention in western countries.

K.Niu, Proc. Japan Acad. B 84



$$D^0 = c\bar{u} \; (1865 \text{ MeV})$$

the lightest weakly decaying charmed meson, D^0, is discovered by the Mark I detector (SLAC) in 1976.

The same year, Lederman and coll. discover the Υ=(b b-bar), the first evidence of the 3rd family

Guessing about the nature of J/Ψ

- First thoughts: charm ($M \sim 3$ GeV!)
- The association of J/Ψ with the $c\bar{c}$ threshold was done by C. Dominguez and M. Greco.
- The very narrow width (~ 100 keV) cast serious doubts on the $c\bar{c}$ interpretation
- in Roma, we noted that with Γ and M, we could compute a "Fermi constant" $G_{J/\Psi} = g^2/M^2$ and found $G_{J/\Psi} \sim G_F$, suggesting: $J/\Psi = W_0$, a light intermediate boson
- this suggestion evaporated a week later, when SLAC found the Ψ' .
- Harvard people had the key!! asymptotic freedom (see later) suggested a charmonium ~positronium (Applequist & Politzer)
- De Rujula & Glashow: asymptotic freedom makes $\Gamma_{J/\Psi} << \Gamma_\phi$
- De Rujula, Georgi and Glashow worked out charm particles and charmonia spectra, predicting P-wave charmonia with γ decay to ground state charmonia.
- P-wave charmonia seen in 1975.

The value of R

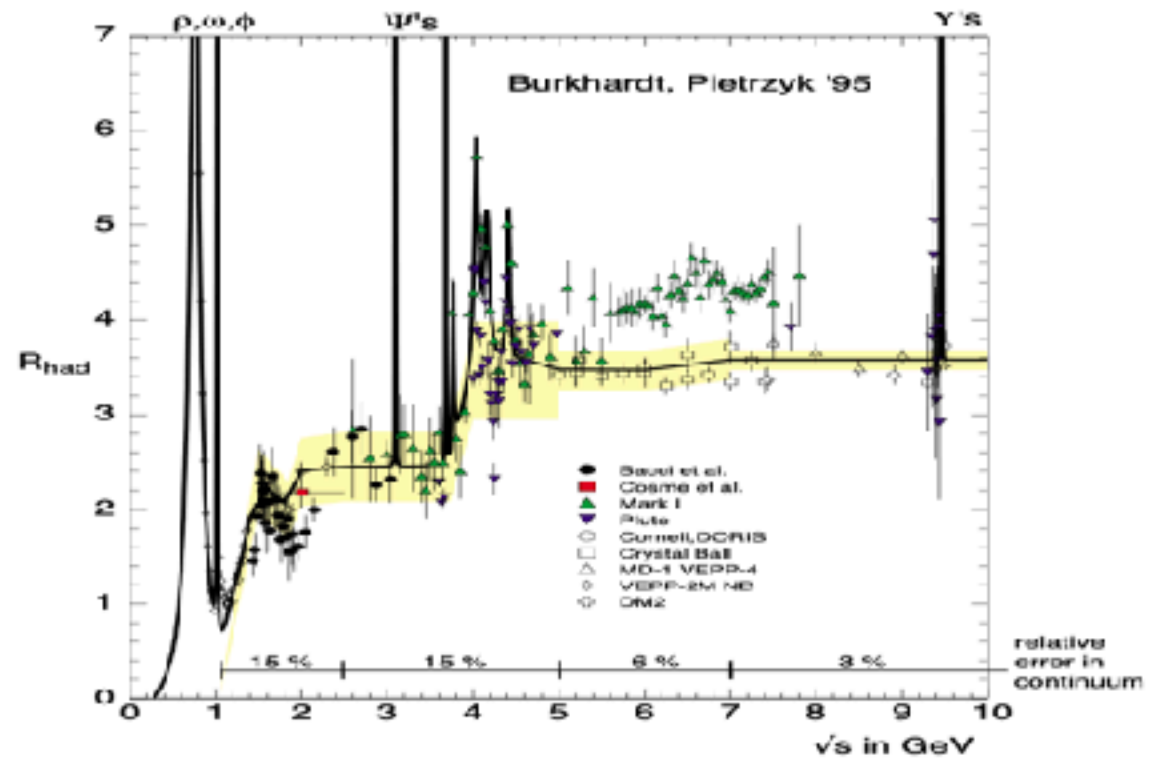


Figure 1: Experimental R values in the energy region below 10 GeV, from [10]. The relative errors on R in the continuum is given in numbers at the bottom of the figure.

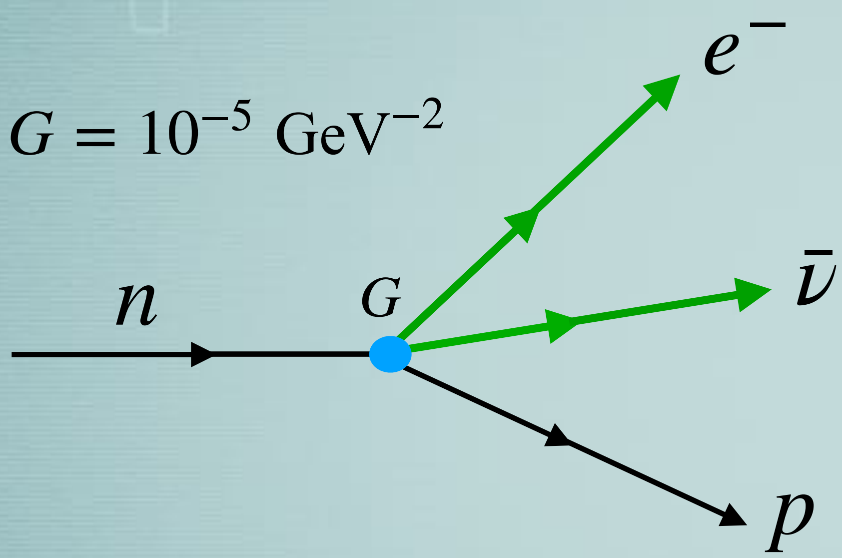
Expected values $R = \dfrac{\sigma(e^+e^- \to \text{hadrons}}{\sigma(e^+e^- \to \mu^+\mu^-)}$ of in the Standard Theory:

$$u,\ d,\ s\ \text{(colored, light quarks)} = 2$$
$$c\ \text{(colored, charmed quark)} = 1.3$$
$$\tau\ \text{(lepton)} = (0.6)^2 = 0.36$$
$$c\ \text{(colored, beauty quark)} = 0.33$$

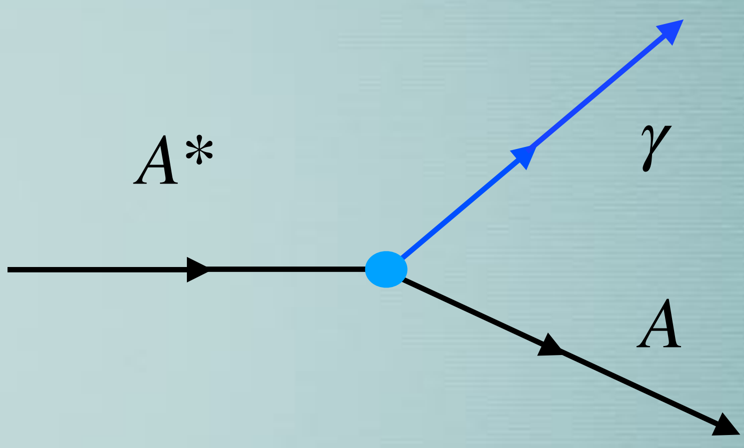
3. Towards a Unified Theory of Electromagnetic and Weak Interaction

- In 1933, after the discovery of the neutron as a component of the atomic nuclei and following the neutrino hypothesis by W. Pauli, E. Fermi proposed a theory of β-radioactivity as due to the decay:

$G = 10^{-5}\ \mathrm{GeV}^{-2}$



The neutron emits the $e^-\bar{\nu}$ pair, in analogy with the electromagnetic de-excitation of an atom:



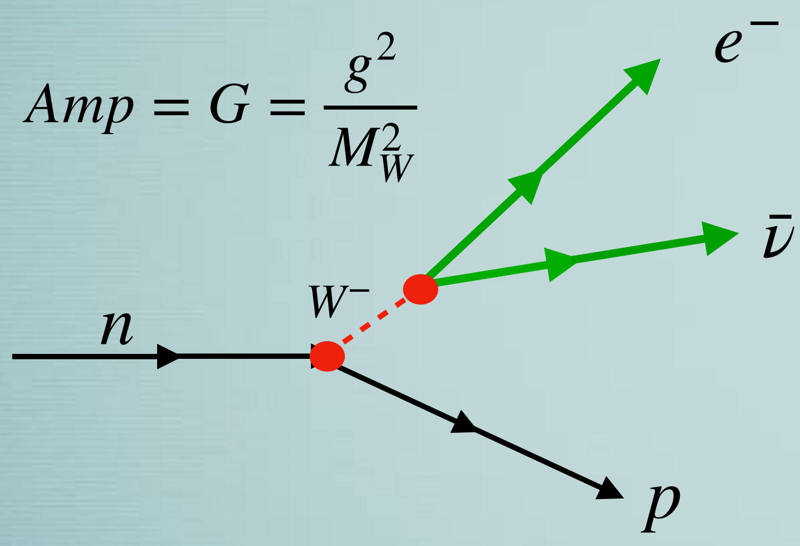
- The process is regulated by a very small coupling, the Fermi constant G
- and, accordingly, neutrino has a very ***weak interaction*** with matter

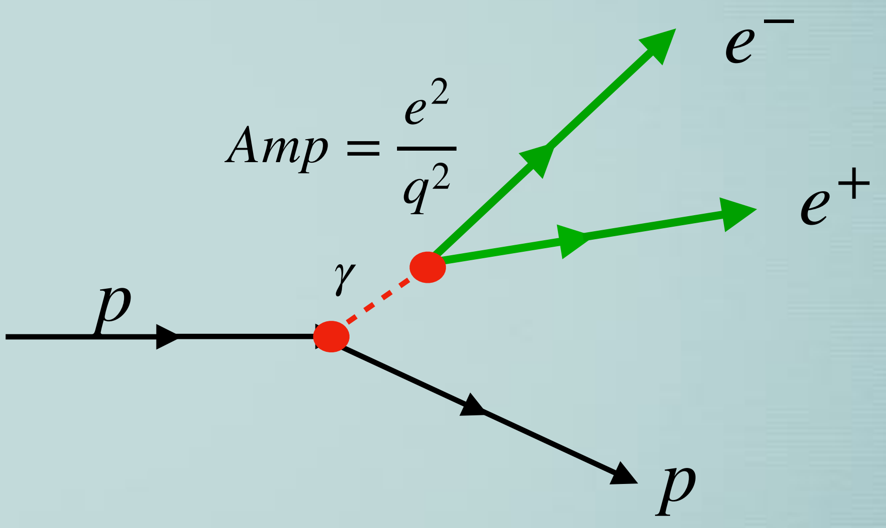
However, if you have a very intense flux of neutrinos, as in a nuclear reactor, you may observe events of the inverse beta decay process: $\bar{\nu} + p \to e^+ + n$ (Reines and Cowan,1953).

The neutrino is not a ghost, but a real particle,!!

Towards a Unified Theory of Electromagnetic and Weak Interaction (cont'd)

- The first step toward *a real* unification was the hypothesis that Weak Interactions are transmitted by a new particle called *the Intermediate Vector Boson.*
- To reproduce Fermi theory IVB has to have a very large mass





- In 1961, Sheldon Glashow proposed a Unified Theory ***with 4 intermediaries***: W^+, W^-, Z^0, γ. The theory was able to describe W&E.m. interactions of electrons and muons;

- the theory predicted new fenomena, like the existence of neutrino reactions in which a neutrino appears in the final state (***neutral current processes***), instead of transforming into a charged lepton as in the inverse beta decay (***charged current processes***).

Unified Theory of Electromagnetic and Weak Interaction (cont'd)

The 1961 Glashow theory left 3 questions open. ***The answers led to the present Unified Standard Theory:***

1. Can we give a mass to the IVB leaving the photon massless? (Weinberg&Salam, 1967: the Higgs -Brout-Englert boson);
2. Can we extend the interaction to the hadrons, i.e with a coupling of the neutral IVB (Z^0) in agreement with the observed strong suppression of $K \to \mu^+\mu^-$? (Glashow, Iliopoulos,Maiani: GIM mechanism, 1970, charmed particles predicted);
3. Can we obtain a consistent renormalizable quantum theory like QED? (proved by 't-Hooft &Veltman, 1972).

•**1973.** The Gargamelle Collaboration led by the French physicist André Lagarrigue, operating the heavy liquid, large bubble chamber exposed to the high energy CERN ν_μ beam, observes *muonless neutrino events:* events in which a hadronic jet is produced without an energetic muon track, interpreted as the neutral current process

$$\nu_\mu + N \to \nu_\mu + \text{hadrons}$$

- The Collaboration observed also events with an isolated electron track, interpreted as

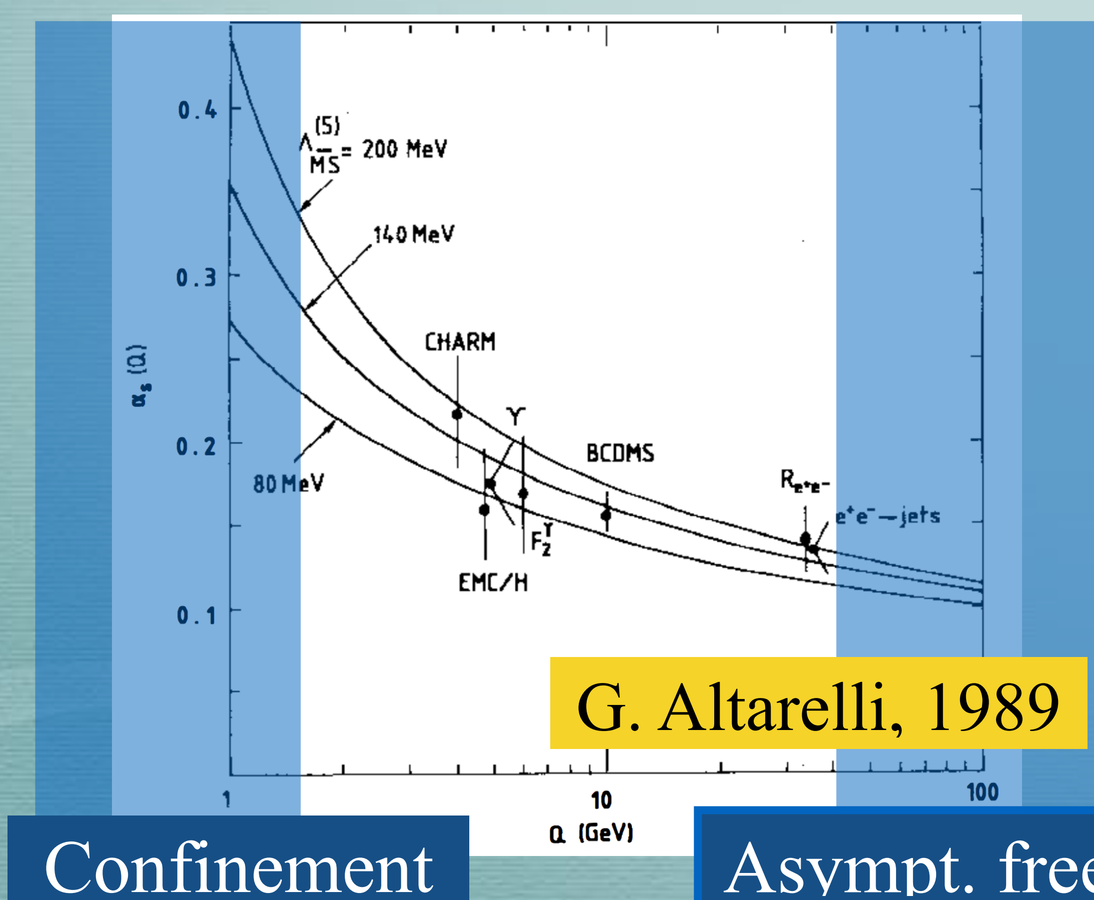
$$\nu_\mu + e \to \nu_\mu + e$$

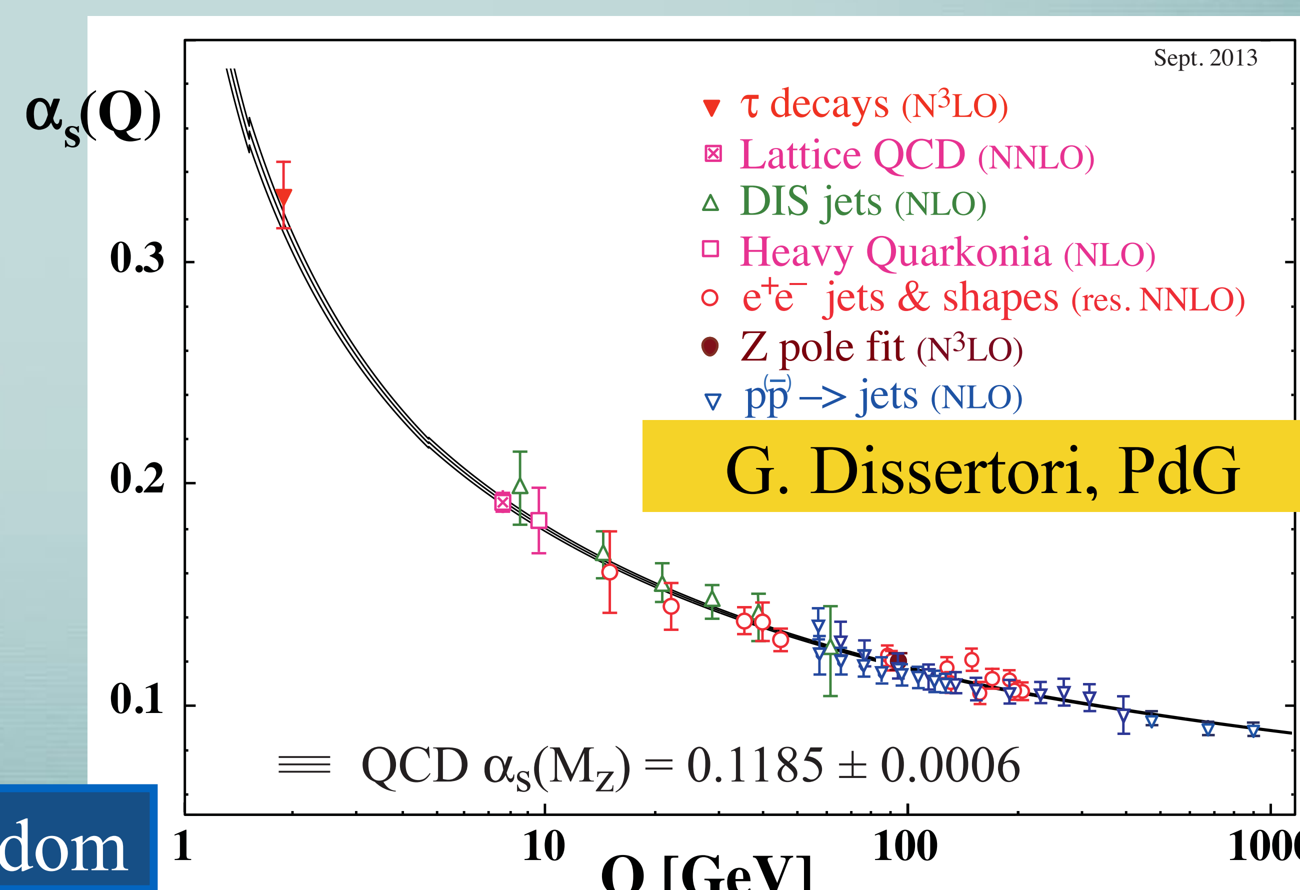
4. Flavor meets Color in the early seventies

•Towards the end of the 60’, it became clear that quarks, beside flavor, had to have another quantum number, to reconcile the structure of baryons (symmetric under orbital, spin⊗flavor exchange, in contrast with being spin 1/2 particles).

•The idea of *Color* prevailed: a non abelian gauge symmetry called QCD (Quantum Chromo Dynamics) by Bardeen, Fritzsch and Gell-Mann (1972).

• QCD was shown to be asymptotically free by D. Gross and F. Wilczeck and by Politzer in 1972.





QCD gave the answer to (almost) any question

- Quarks carry **color symmetry**, $\mathbf{SU(3)_{col}}$, and are confined inside **color singlet hadrons**,
- $\Delta^{(++)} = \epsilon^{\alpha\beta\gamma} u_\alpha^\uparrow u_\beta^\uparrow u_\gamma^\uparrow$: Fermi statistics is obeyed
- increasing q², quarks radiate gluons (the Altarelli-Parisi picture of scaling violations)
- at large q², we see quarks and neutral gluons as almost free partons.

Constituent Quarks

QCD Partons

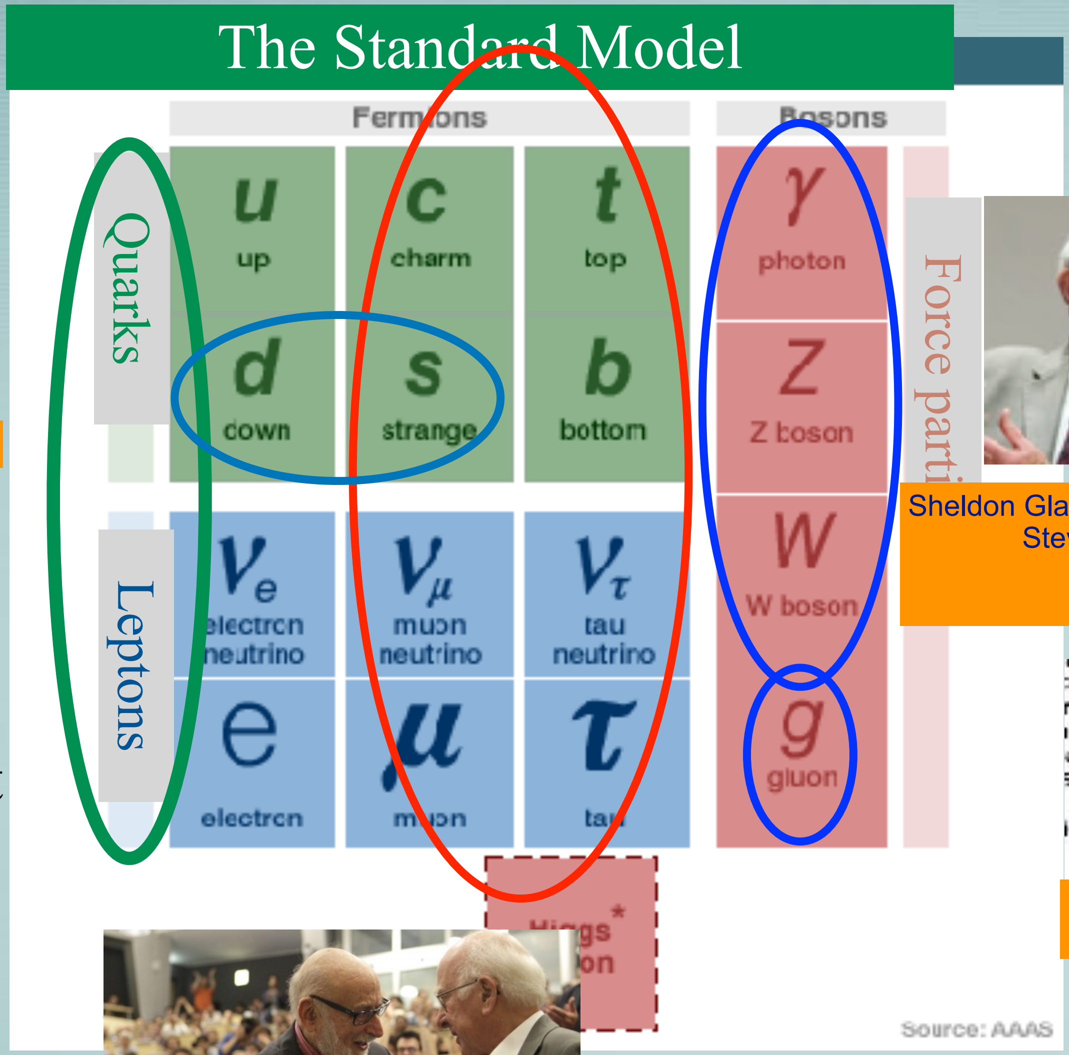
- ***Charm and asymptotic freedom explain the mass and the very small width of J/Psi:***
  1. $J/\Psi = (c\bar{c});\ M(J/\Psi) \sim 2m_c$
  2. $J/\Psi \to 3$ ***gluons (D. Politzer and T. Appelquist, 1972)***
  3. $\Gamma \propto \alpha_s^3$ ***(A. de Rujula, S. Glashow, 1974)***

Heavy quarks ($m_Q >> \Lambda_{QCD}$ ***)***:

- $c\bar{c}$ or $b\bar{b}$ bound states involve short distance forces: a calculable spectrum of charmonia/bottomonia;
- inside hadrons, $c\bar{c}$ or $b\bar{b}$ pairs are not easily created or destroyed:
- a hadron decaying into J/Ψ or $\Upsilon + \ldots$ indicates a valence $c\bar{c}$ or $b\bar{b}$ pair
- ***heavy-quark counting is possible***.

5. Constituentsof matter and fundamental forces (circa 2016)


Murray Gell-Mann




Nicola Cabibbo




Sheldon Glashow
Steven Weinberg
Abdus Salam
@ ICTP Trieste


Carlo Rubbia


Sheldon Glashow, John Iliopoulos, Luciano Maiani


Makoto Kobayashi , Toshihide Maskawa

Ordinary matter is made of the lightest quarks and leptons


Robert Englert e Peter Higgs

Heavier quarks are unstable: what is their role in the Universe?

Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free
Gross&Wilczeck, Politzer (1973)

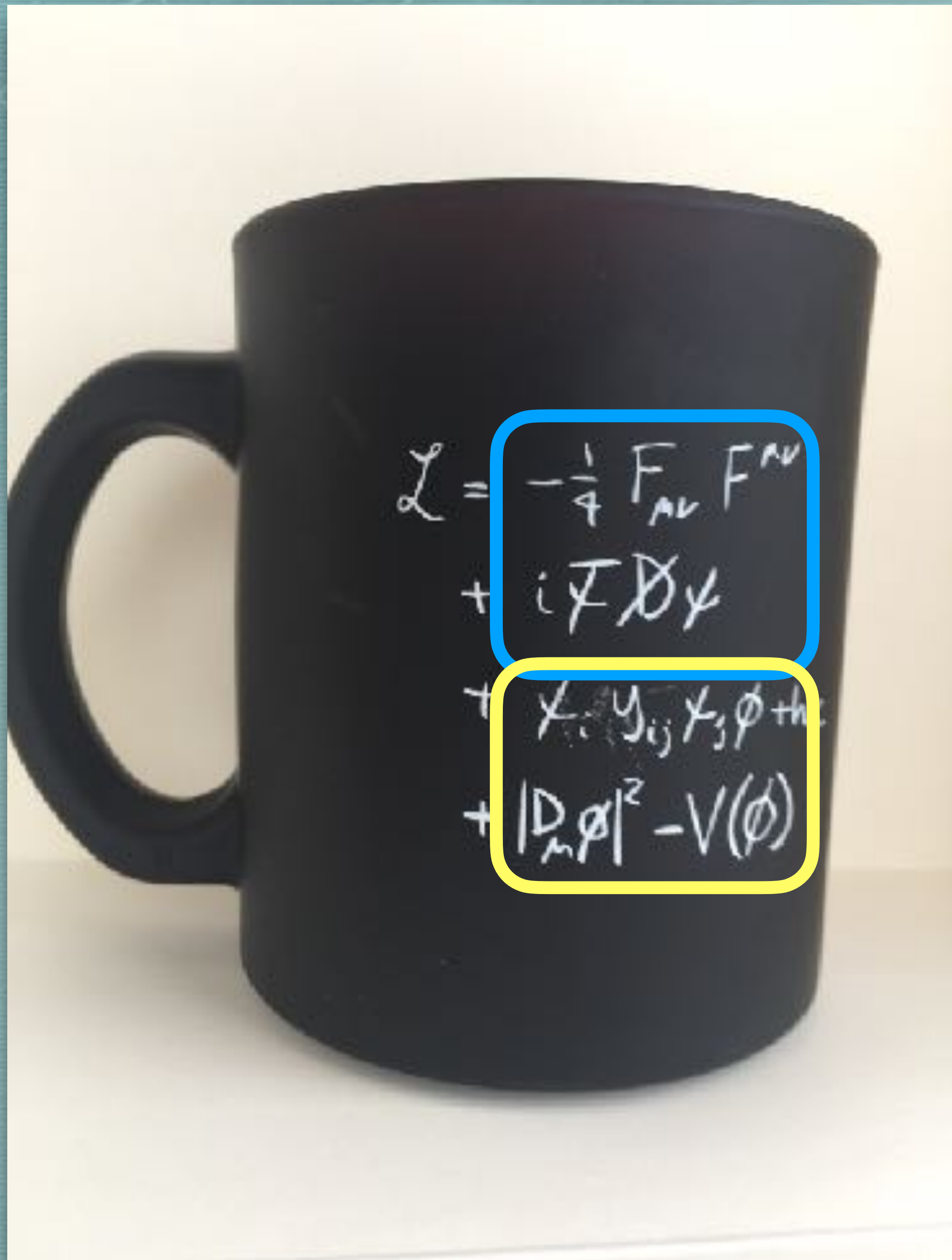
THE STANDARD THEORY OF PARTICLE PHYSICS

Essays to Celebrate CERN's 60th Anniversary

Editors

Luciano Maiani and Luigi Rolandi

World Scientific



Theory is so simple that it can be written on a coffee mug

Paraphrasing Einstein, ST is like *the two wings of a house, one wing ...made of fine marble, but the other wing ...built of low grade wood.*

- the marble wing is determined by the symmetry: *currents, gauge interactions, quarks and leptons*.
- the wooden wing is symmetry breaking: an *elementary scalar doublet* whose vacuum expectation value provides the masses of vector bosons, quarks and leptons: only partly determined by symmetry, many arbitrary couplings…

Adding Quantum Chromodynamics, another pure marble wing, makes the Standard Theory as we know it.

- two independent symmetries, which call for further unification
- no quantum gravity

6. Unanticipated charmonia X, Y, Z… and more

- ***Hidden charm/beauty resonances not fitting in predicted charmonium/bottomonium spectra.***
  - **X**, e.g. $X(3872)$: neutral, typically seen in Ψ + pions, positive parity, $J^{PC} = 0^{++}, 1^{+}, 2^{++}$
  - **Y**, e.g. Y(4260): neutral, seen in e^+e^- annihilation with *Initial State Radiation* (ISR)

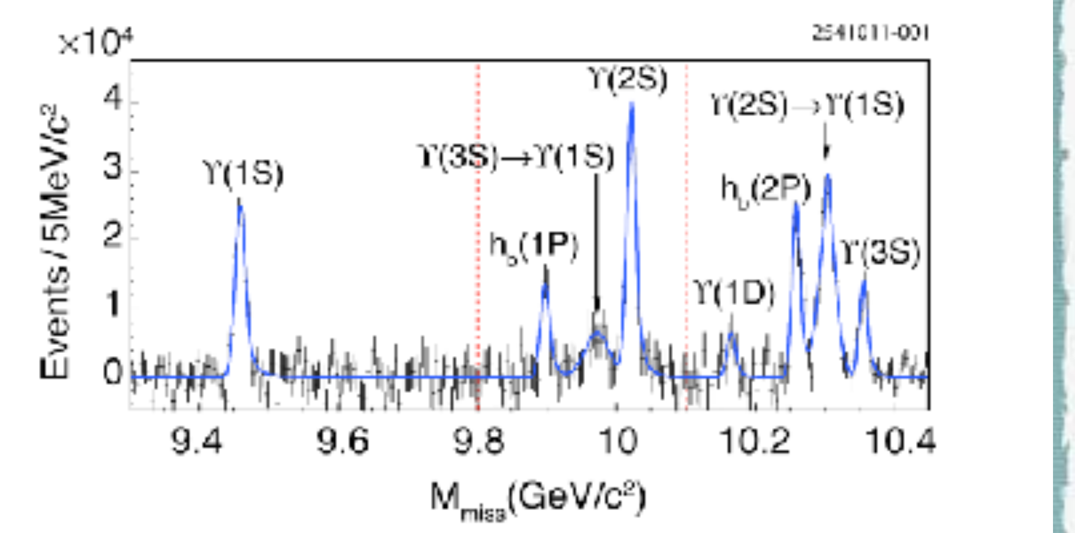


Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, M_{miss}, in e^+e^- collision

- $(e^+e^- \to e^+e^- + \gamma_{ISR} \to Y + \gamma_{ISR})$, therefore $J^{PC} = 1^{--}$,
- **Z**, e.g. Z(4430): charged/neutral, typically positive parity, 4 valence quarks manifest, mostly seen to decay in Ψ+ π and some in $h_c(1P)$ +π (valence quarks: $c\bar{c}u\bar{d}$); Z_b observed ($b\bar{b}u\bar{d}$).

A new wave of Exotic Hadrons from 2015:

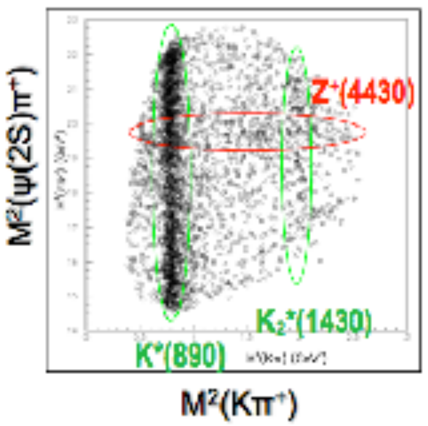
- Hidden charm pentaquarks, $\mathscr{P} \to J/\Psi + p$;
- Hidden charm and Hidden strangeness (LHCb), e.g. $X(4140) \to \Psi + \phi$, $J^{PC} = 1^{++}$
- 4 charm tetraquarks seen as di-Ψ resonances(LHCb), $X(6900) \to \Psi + \Psi \to 2(\mu^+\mu^-)$
- Hidden charm- Open strangeness ($c\bar{c}u\bar{s}$),: $Z^+_{cs}(3985) \to \Psi + K^+$ (BES III) and $Z^+_{cs}(4003) \to \Psi + K^+$ (LHCb).
- Double charm tetraquark: $\mathscr{T}^+_{cc}(3875) \to D^0 D^0 \pi^+$ (valence quarks: $cc\bar{u}\bar{d}$) by LHCb.

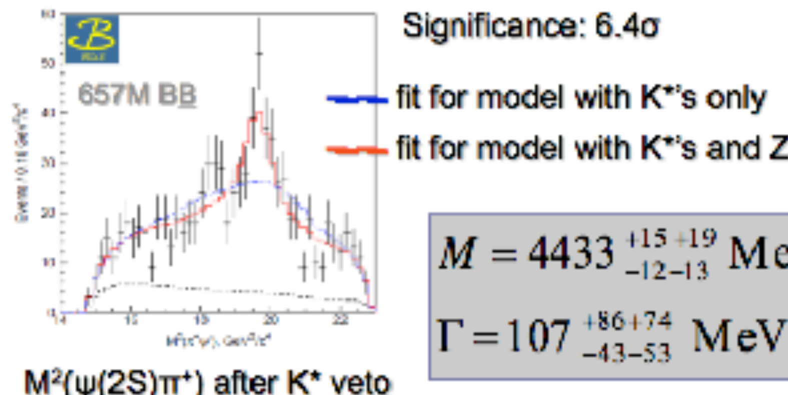
The saga of $Z^{\pm}(4430)$

Belle observed $Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$

PRL100, 142001 (2008)

- Found in $\psi(2S)\pi^+$ from $B \to \psi(2S)\pi^+ K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B \to \psi(2S)\pi^+ K$
- $B \to \psi(2S)\pi^+ K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^* \to K\pi^+$ resonances only
  all known $K^* \to K\pi^+$ and $Z^+ \to \psi(2S)\pi^+$ ⇨ favored by data





$$M = 4433 ^{+15}_{-12} {}^{+19}_{-13} \text{ MeV}$$
$$\Gamma = 107 ^{+86}_{-43} {}^{+74}_{-53} \text{ MeV}$$

PRD80, 031104 (2009)

- [cu][cd] tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*\underline{D}_1(2420)$ molecule? should decay to $D^*\underline{D}^*\pi$

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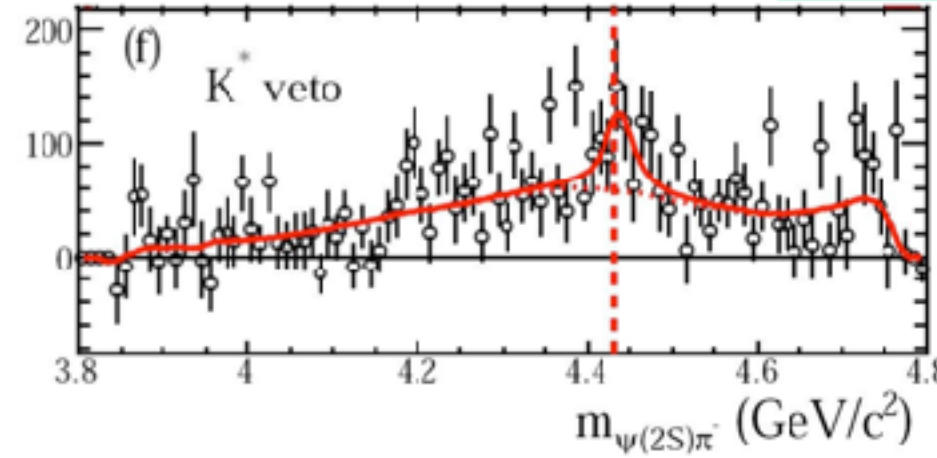
BaBar doesn't see a significant $Z(4430)^+$

PRD79, 112001 (2009)



"For the fit ... equivalent to the Belle analysis...we obtain mass & width values that are consistent with theirs,... but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

$BF(B^0 \to Z^+K) \times BF(Z^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

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- Babar inserts in the fit all K* resonances
- is Belle effect due to K* reflections ???

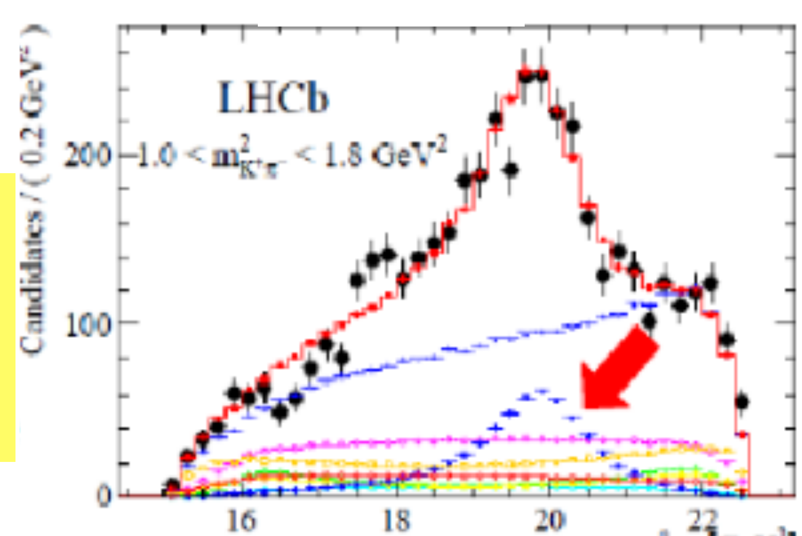
LHCB:

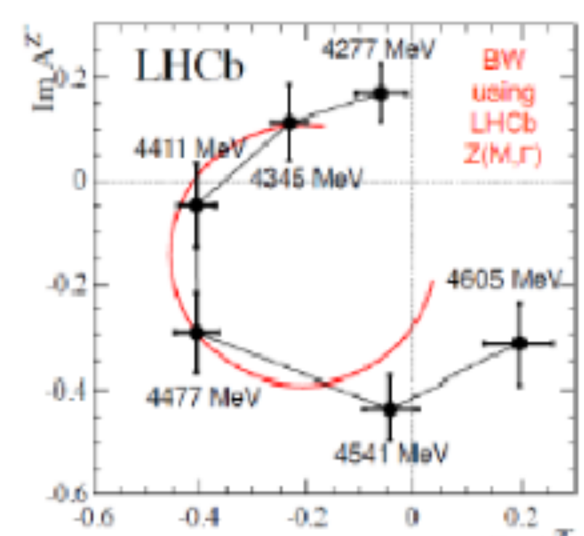
- confirms BELLE's observation of a bump, $J^{CP} = 1^{+-}$

- CANNOT be built as a molecule of standard states: $D^*\bar{D}_1$ in S-wave may have J=1 but has negative parity.

- A genuine resonance

[PRL 112 (2014) 222002]

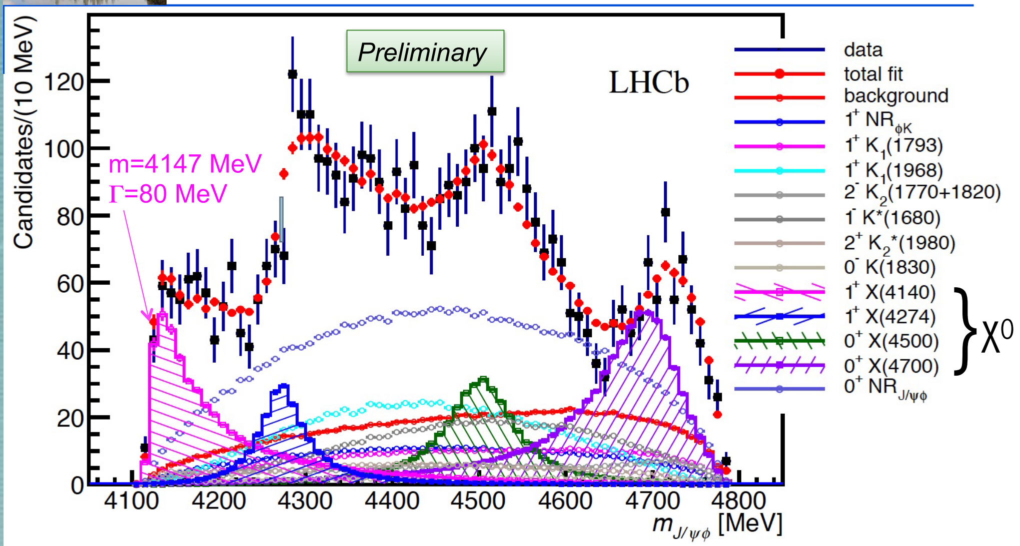




Exotics: the New Wave

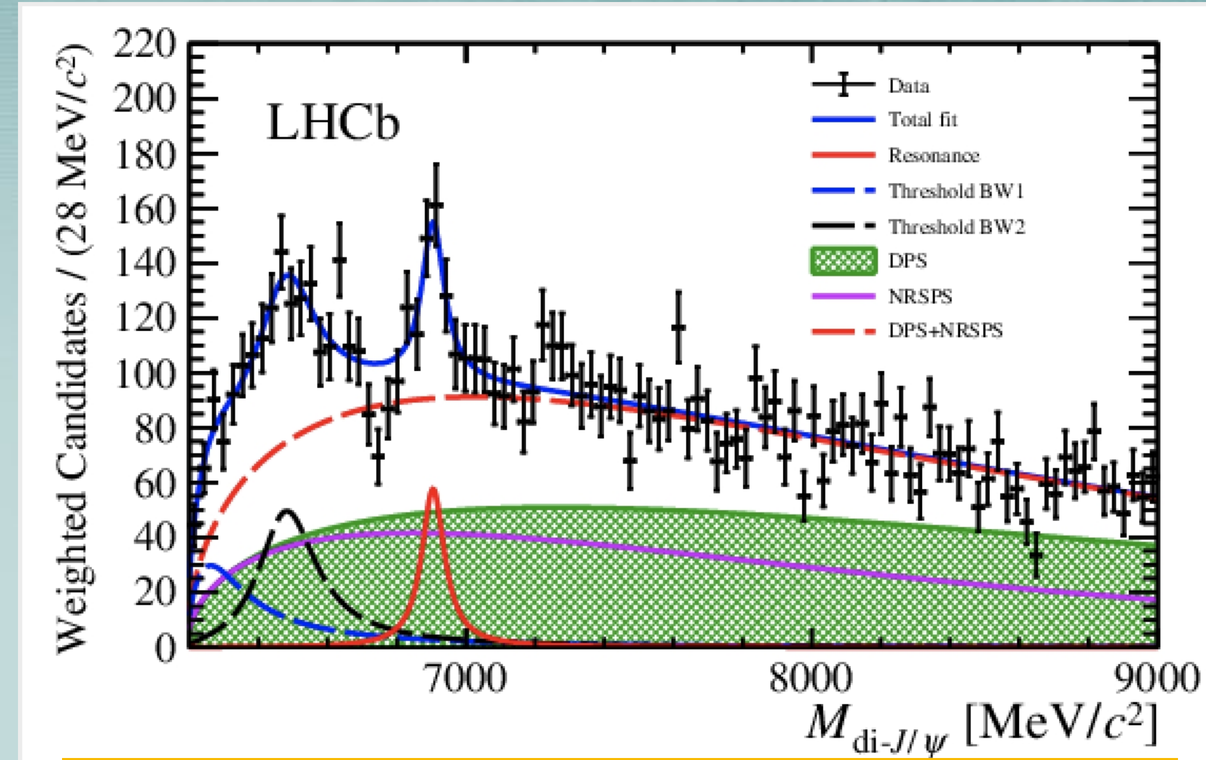
$B^+ \to K^+ + X(4140) \to K^+ + \phi\ \Psi$, etc .

Results of fit: m(J/ψφ)



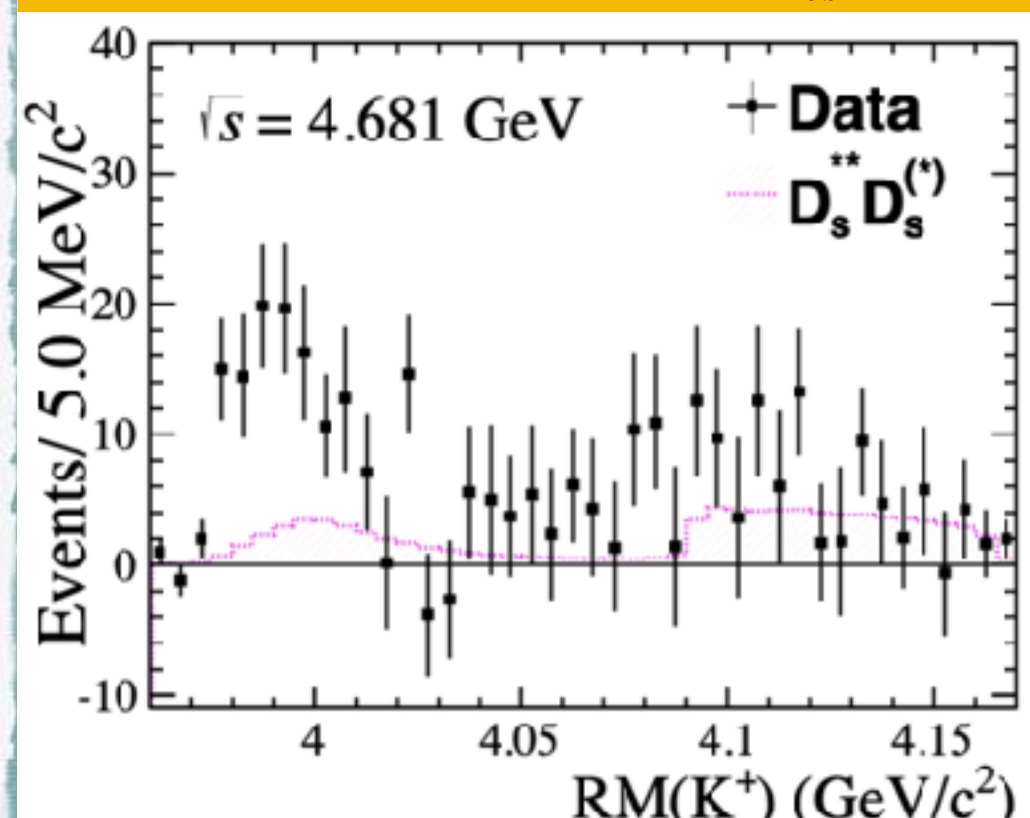
- 4 visible structures fit with BW amplitudes

LHCb (2016): $\Psi\ \phi$ resonances (2016)

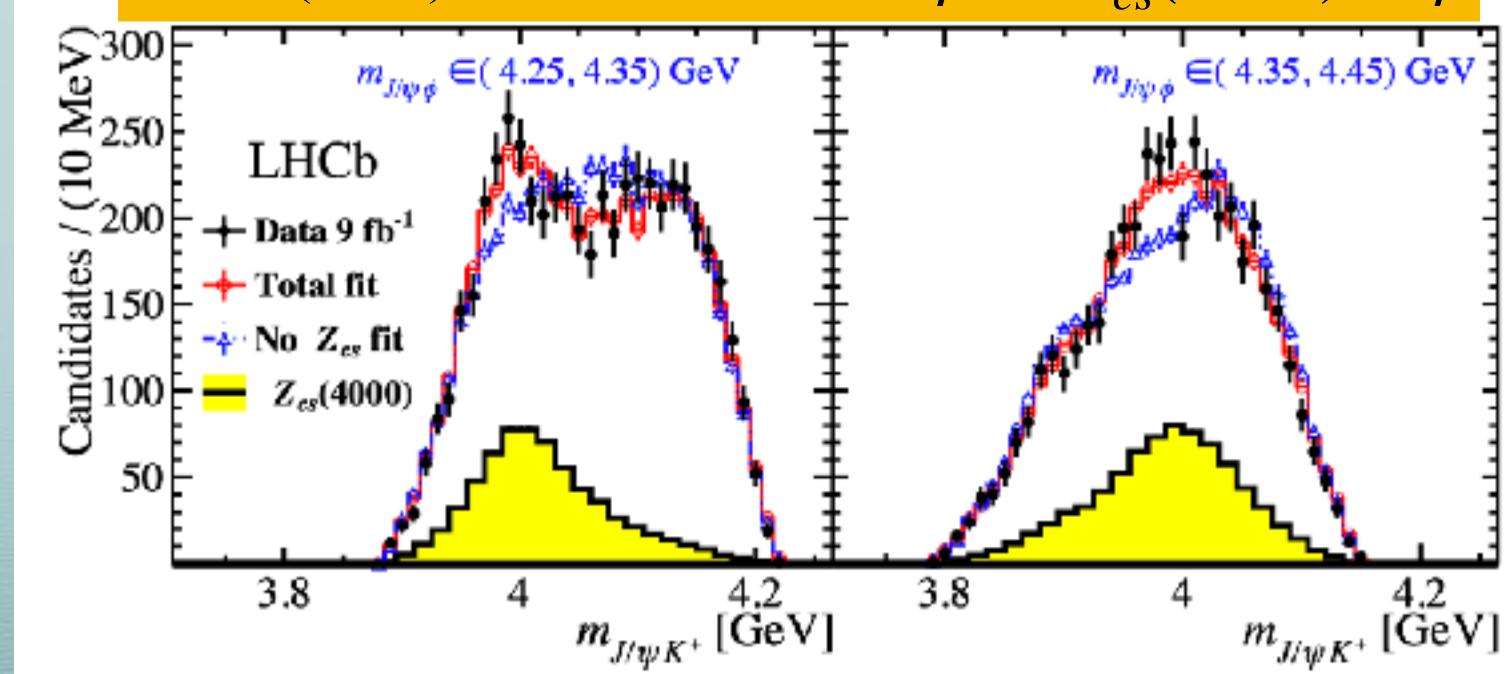


LHCb (2020): di-Ψ resonance(s) spectrum

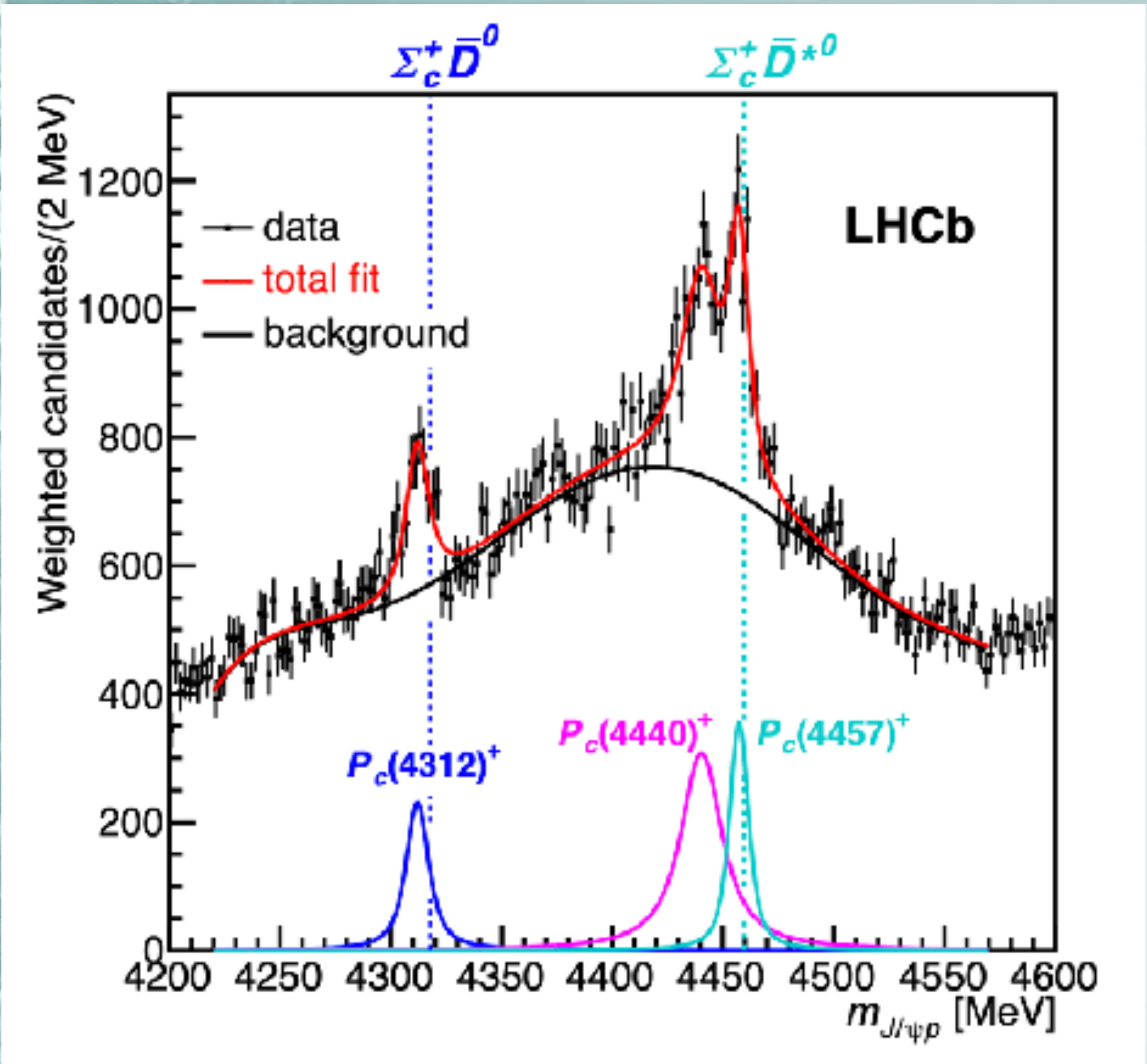
BES III(2021): $e^+e^- \to K^+ + Z_{cs}^-(3985) \to K^+(D_s^* D^0 + D_s^- D^{*0})$



LHCb (2021): $B \to \Psi + K^+ + \phi \to Z_{cs}(4003) + \phi$



Pentaquarks:
three lines observed in $p + J/\Psi$ and $\Lambda + J/\Psi$



Three non strange pentaquarks

P^N (4312): M = 4311.9 ± 0.7+6.8, Γ = 9.8 ± 2.7+3.7

P^N(4440): M = 4440.3 ± 1.3+4.1, Γ = 20.6 ± 4.9+8.7

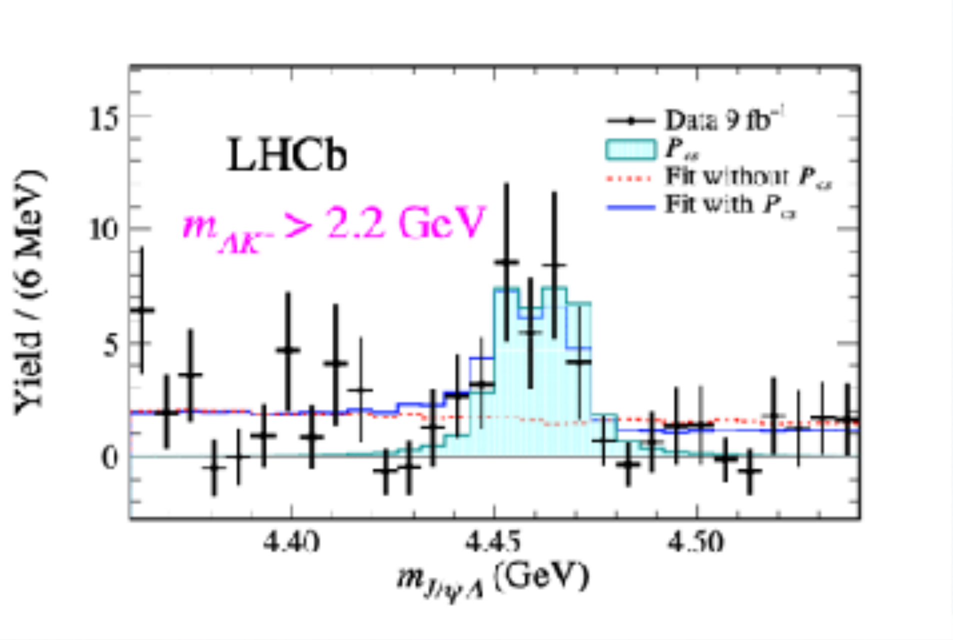
P^N(4457): M = 4457.3 ± 0.6+4.1, Γ = 6.4 ± 2.0+5.7

in addition, one + two (?) strange pentaquarks

P^Λ (4338) : M = 4338.2 ± 0.7 MeV, Γ=7.0±1.2MeV

P^Λ (4455) : M = 4454.9 ± 2.7 MeV, Γ = 7.5 ± 9.7 MeV

P^Λ (4468) : M = 4467.8 ± 3.7 MeV, Γ = 5.2 ± 5.3 MeV

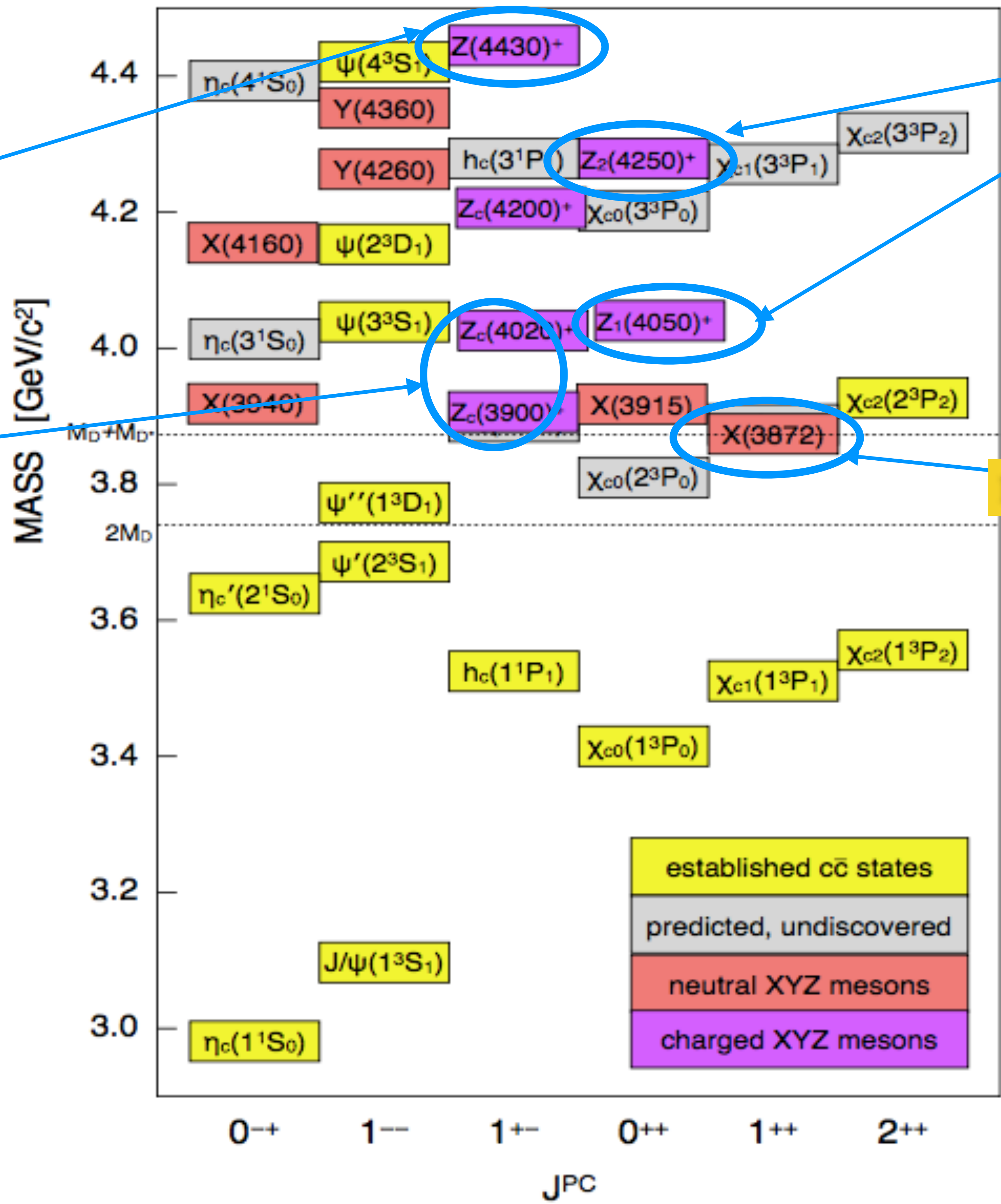


Expected and Unexpected Charmonia in 2015

figure by:
S. L. Olsen (2015)
arXiv:1511.01589

2nd Unexpected (2007)
a radial excitation?

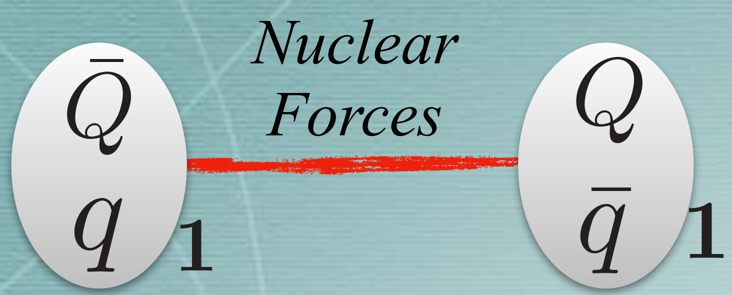
3rd Unexpected (2013):
a multiplet ground
state Tetraquarks?



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

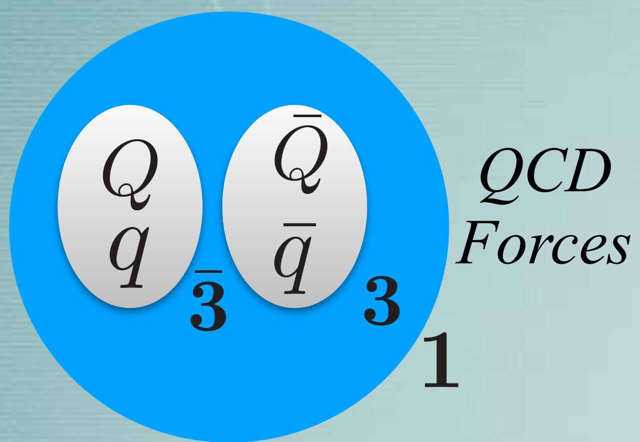
1st Unexpected (2003)

No consensus, yet



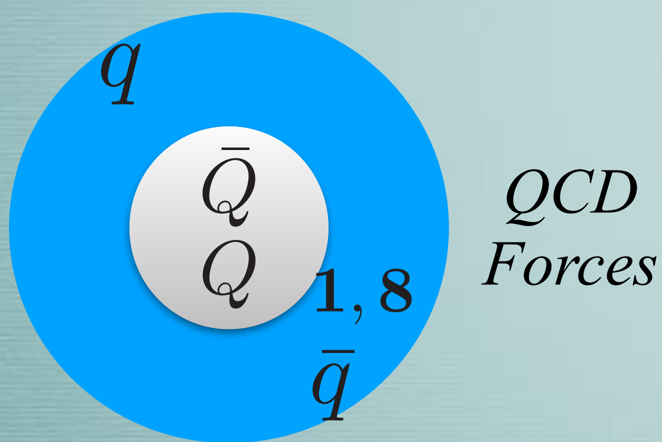
Hadron Molecule

F-K. Guo, C. Hanhart, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



Compact Diquark-Antidiquark

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71 (2005) 014028; **D 89** (2014) 114010.

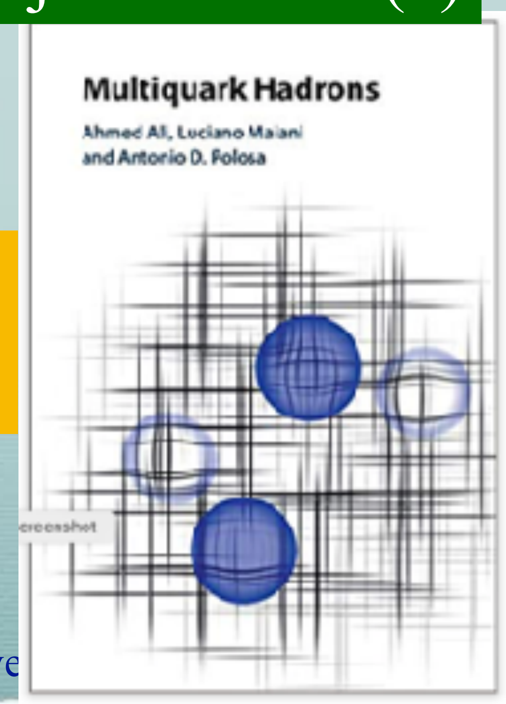


HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

S. Dubynskiy, S. and M. B.Voloshin, Phys. Lett. **B 666**,(2008) 344.

E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. **D 90** (2014) 01404

For a review, see:
A. Ali, L. Maiani and A.D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)



The New wave of Exotic Hadrons

- Starting from 2016, new kinds of exotic hadrons have been discovered:

  -$J/\Psi\ \phi$ resonances, $di - J/\Psi$ resonances,

  -open strangeness Exotics: $Z_{cs}(3082)$ and $Z_{cs}(4003)$

- No pion exchange forces could bind them as hadron molecules made by color singlet mesons

- molecular models applied to the new hadrons have to stand on the existence of "phenomenological forces" with undetermined parameters

- The New Exotics arise very naturally as $([cq]^{\bar{\mathbf{3}}}[\bar{c}\bar{q}']^{\mathbf{3}})_{\mathbf{1}}$ bound in color singlet.

The compact tetraquark model makes a firm prediction:
hidden charm tetraquarks must form ***complete multiplets of flavor SU(3)*** with mass differences determined by the quark mass difference

$$m_s - m_{u,d}$$

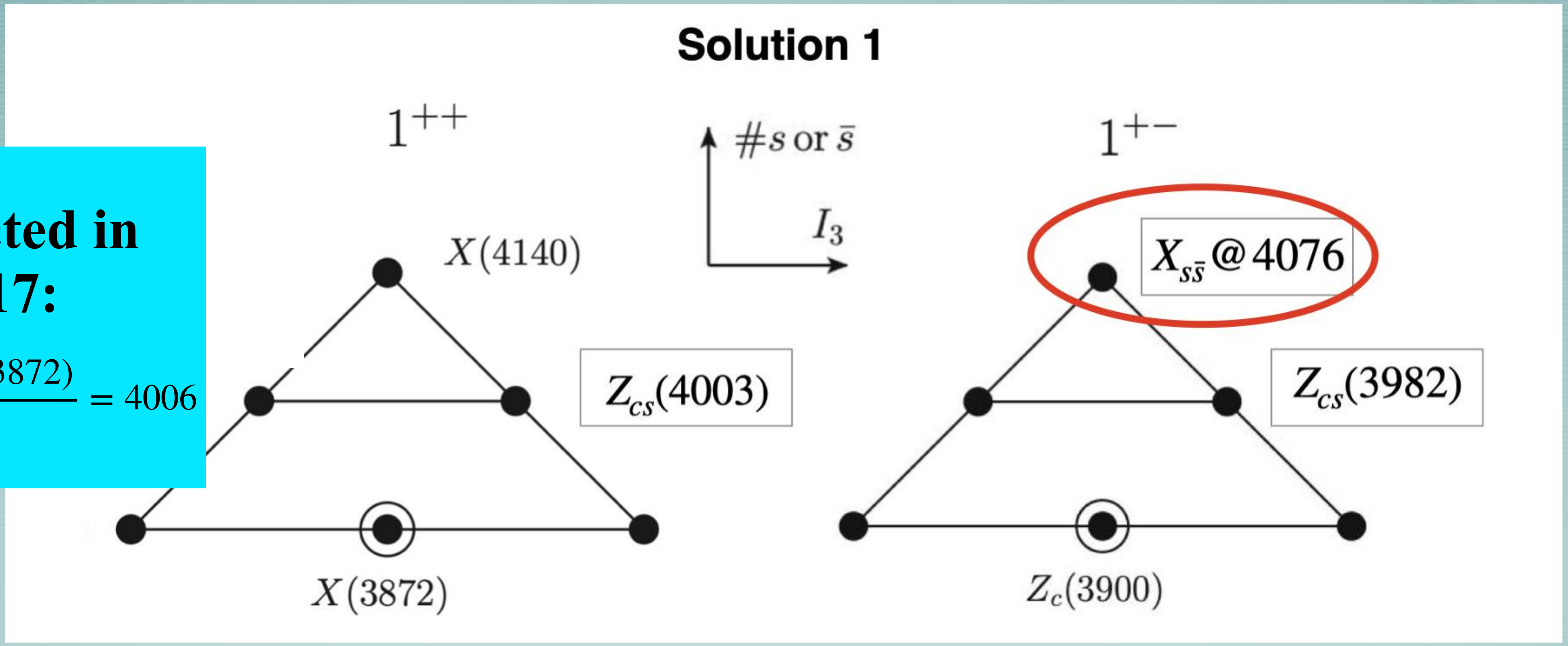
with $Z_{cs}(3082)$ and $Z_{cs}(4003)$ we can almost fill two tetraquark nonets with the expected scale of mass differences

Z_{cs}: three nonets

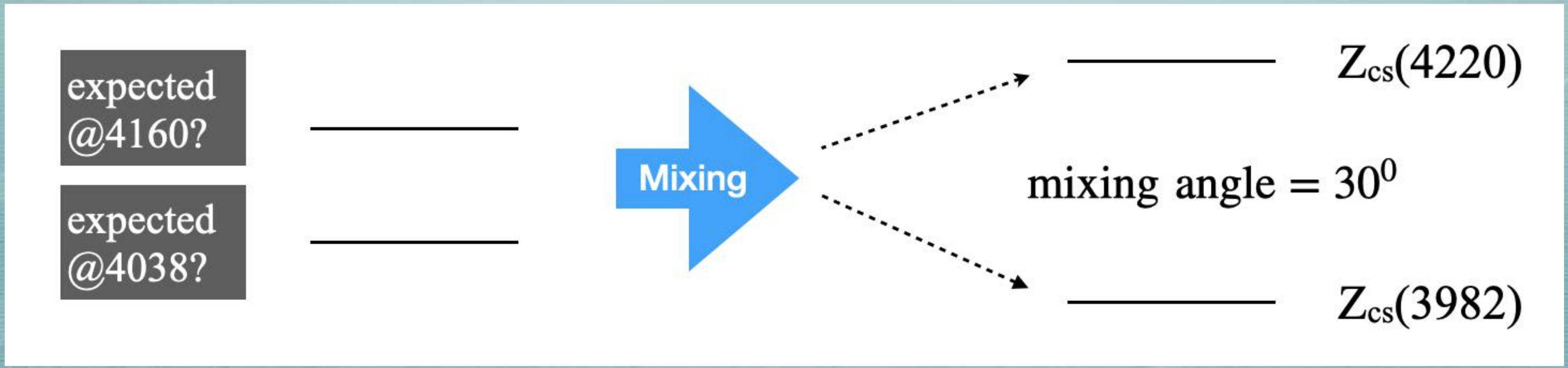
L. Maiani, A. D. Polosa and V. Riquer, Sci. Bull. **66** (2021), 1616, arXiv:2103.08331

Predicted in 2017:

$$\frac{X(4140) + X(3872)}{2} = 4006$$



- There is a ***third nonet*** associated to $Z_c(4020)$, $J^{PC} = 1^{+-}$: a third Z_{cs} is required, Mass=4150 - 4170
- ***LHCb sees a $Z_{cs}(4220)$, $J^P = 1^+$or 1^-: is it too heavy ?*** A bold proposal:



Missing Exotics

- The new wave of exotics supports the idea of ***compact multiquark hadrons bound by QCD***

determination of the lineshapes of X(3872) and $T_{cc}(3785)$ seem to go in the same direction.

No consensus yet, but it seems we are on a promising road.

- QCD requires Multiquark hadrons to fill $SU(3)_f$ multiplets

what is missing at present ? ***a shopping list:***

- $X_{s\bar{s}}$, $M = 4076$, decays: $\eta\psi$, $\eta_c\ \phi$, $D_s^* \bar{D}_s$ (if phase space allows)
- the I=1 partner of X(3872), decays: $X^+ \to J/\psi\ \rho^\pm \to J/\psi\ \pi^+\pi^0$
- are there two states inside the $X(3872)$ line?
- the I=0 partners of $Z_c(3900)$ and $Z_c(4020)$, possibly decaying into: $J/\psi + \sigma_0(500)$, L=1

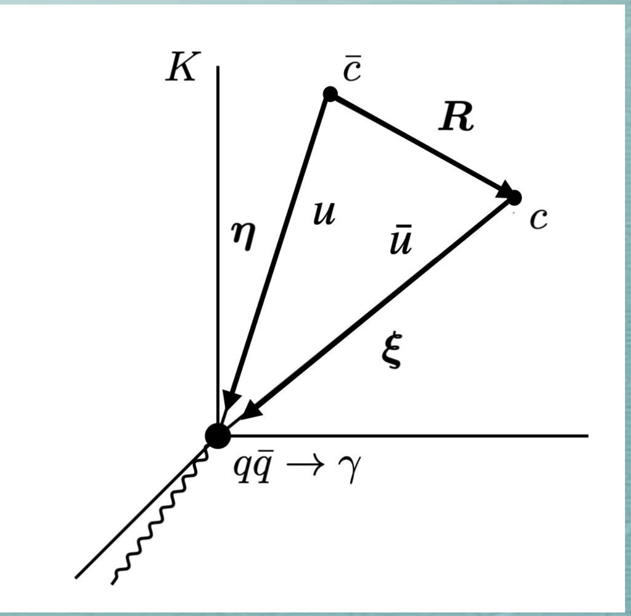
8. $X(3872)$ radiative decays into Charmonium states

B.Grinstein, L. M. and A. Polosa, arXiv:2401.11623

•The decays: $X(3872) \to \psi(3092) + \gamma$ and $X(3872) \to \psi(3690) + \gamma$ have both observed, with a ratio of rates (see PdG)

$$\mathcal{R} = \frac{\Gamma(X \to \psi'\gamma)}{\Gamma(X \to \psi\gamma)} = 2.6 \pm 0.6; \text{ (phase space ratio=0.26 !!!)}$$

- the result is somewhat surprising, since the Q-values of the two decays favour by far ψ over ψ' decay ($Q \sim 780,\ 180$ GeV).
- Errors are going to be reduced in the near future by LHCb at CERN, the ratio could provide a clearcut discrimination between molecule and compact tetraquark.
- Decays are due to the annihilation in a single point of the light quark pair, coming either from the $D^0\bar{D}^{*0}$ molecule or from the diquark-antidiqark in the compact tetraquark. The annihilation transforms the X into a pure charmonium state, $\psi_{1S}(|\mathbf{r}_c - \mathbf{r}_{\bar{c}}|)$ or $\psi_{2S}(|\mathbf{r}_c - \mathbf{r}_{\bar{c}}|)$



X decay: molecule (cont'd)

- Numerical results:

Molecule:

- we find: $\mathscr{R} = \dfrac{\mathscr{B}(X \to \psi'\gamma)}{\mathscr{B}(X \to \psi\gamma)} = 0.036$; the ratio grows for larger values of the

meson radius, it gets above 1 only for D/D^* radius >1 fm (fit to mass spectra give rather radius=0.83 fm).

Compact tetraquark:

- we find: $\mathscr{R}_{\rm min} = \dfrac{\mathscr{B}(X \to \psi'\gamma)}{\mathscr{B}(X \to \psi\gamma)} = 0.95^{+0.01}_{-0.07}$

the error corresponds to the uncertainty on the starting point of the string confining the diquark orbitals.

The PdG value $\mathscr{R} = \dfrac{\Gamma(X \to \psi'\gamma)}{\Gamma(X \to \psi\gamma)} = 2.6 \pm 0.6$ is easily reproduced by the tetraquark, more difficult for the molecule.

9. Closing Remarks

- ***First class results on Exotic Hadrons have been obtained in the last decade by BELLE, BES III and LHCb.***
- ***The nex decade will see substantial progress***

- Exotic SU(3) flavour multiplets, with a characteristic scale of symmetry breaking is a distinctive prediction of compact tetraquarks.
- The newly found strange exotics are close in mass, like X(3872) and Z_c(3900), and fit into their nonets: a clear score in favour.
- Much remains to be done, to produce more precise data and to search for still missing particles, to complete the flavour multiples required by QCD bound, multiquark Exotics.
- Among the missing particles:
  - $X(3872)^+$,
  - is X(3872) split into two lines: $X(3872) \to X_u + X_d$?
  - $\mathcal{T}_{cc}^{++}(?)$, $\mathcal{T}_{bb}^{-}(?)$
- many other states are still missing, with well defined mass and decay modes
- Quantum numbers of Pentaquarks and of $di - J/\Psi$
- Exotic hadrons produced in hadron collisions at large p_T: are there other, besides X(3872)?

- ***Tough orders***: more luminosity, better energy definition, detectors with exceptional qualities… a lot of work…

- ***Close exchange between theory and experiments*** is essential and it has to continue.

so much accomplished, and so much more left to do (Winston Churchill)

Dreams about the future??

- 100 TeV proton Collider is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problem which we have been confronted in the last 100 years

1950's: National Laboratories in IT, FR, UK, DE... united forces to make CERN-Europa
2030's: Regional Laboratories in Europe, America, Asia … will they unite in a
Global Accelerator Network - The World ??