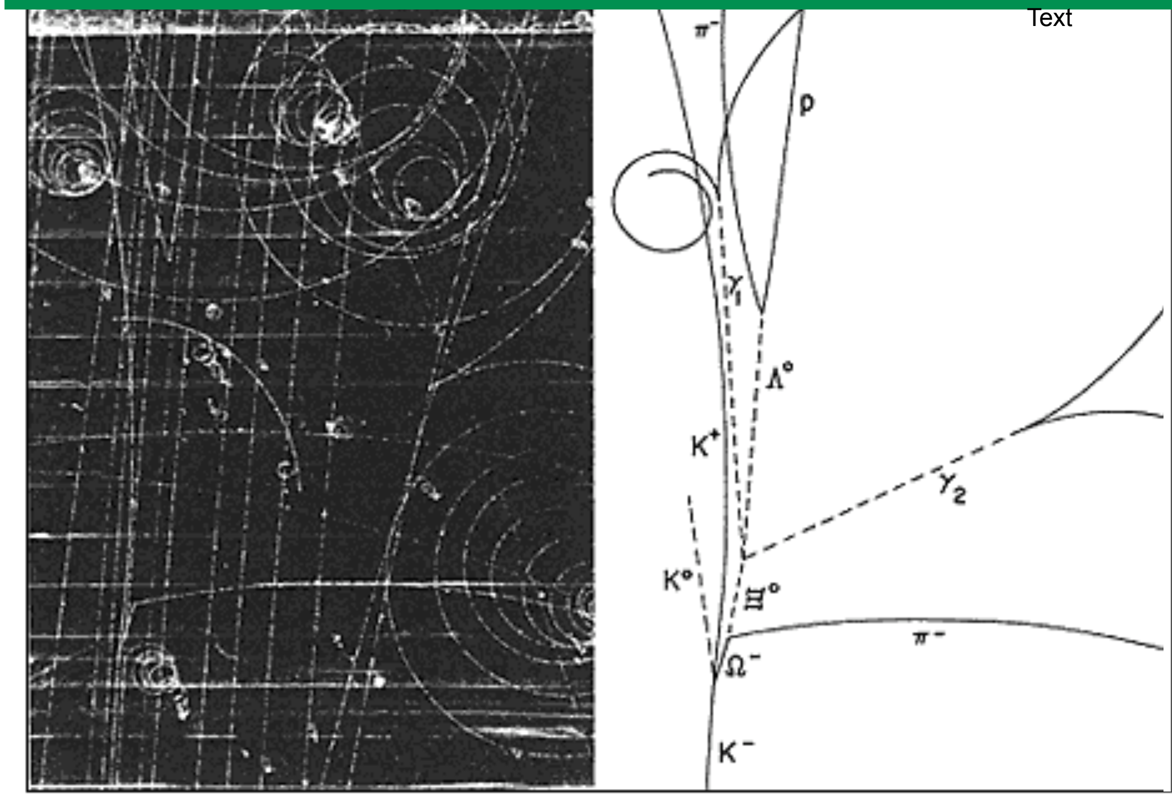
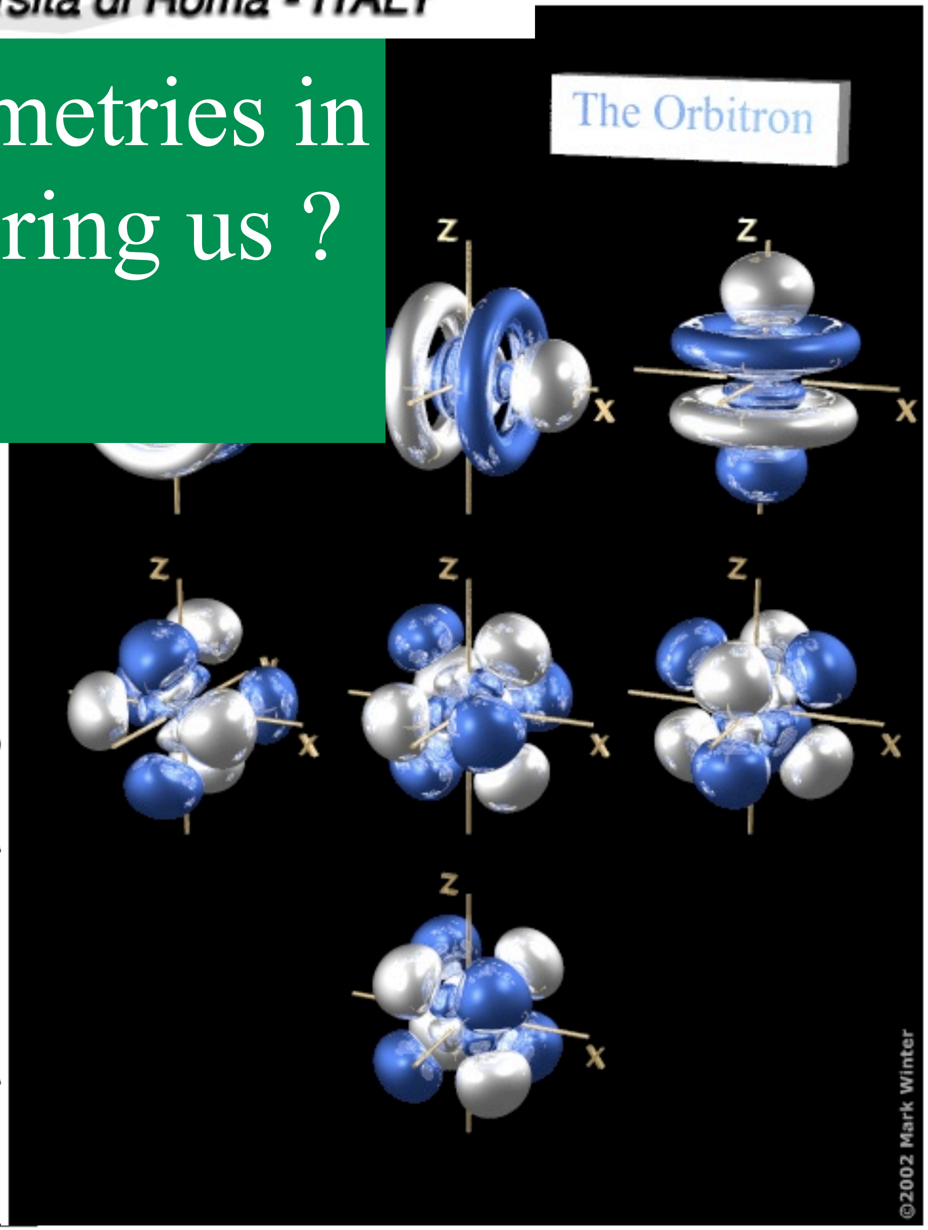
DISCRETE 2010
Symposium on Prospects in the Physics of Discrete Symmetries
6 - 11 December 2010, Sapienza Università di Roma - ITALY

Cabibbo, Radicati, the symmetries in the sixties: where did they bring us ?

Luciano MAIANI

Roma, December 11, 2010





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?

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(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 ?

Fermi&Yang's proposal:

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

related by a large symmetry? possibly including spin ?

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

Nuclear Democracy

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

$$\pi^+ = p\bar{n} \;\rightarrow\; ?? \;\rightarrow\; n = \bar{p}\pi^+$$

which is which?

•for this reason, for most of the sixties nuclear democracy (G. Chew and many others) was considered to be the most promising approach;

•it inspired Regge Poles, duality and ultimately the Veneziano string theory

• puzzle only solved in the 70's: ***fundamental strong interactions become weak at short distance*** (D. Gross & F. Wilczek, D. Politzer)

The constituent way, first attempts

• Fermi&Yang: only F=(p, n) are elementary,

$$mesons = F\bar{F}$$

• Sakata: one new constituent to account for strange particles: S= (p, n, Λ),

$$mesons = S\bar{S};\ baryons = SS\bar{S}$$

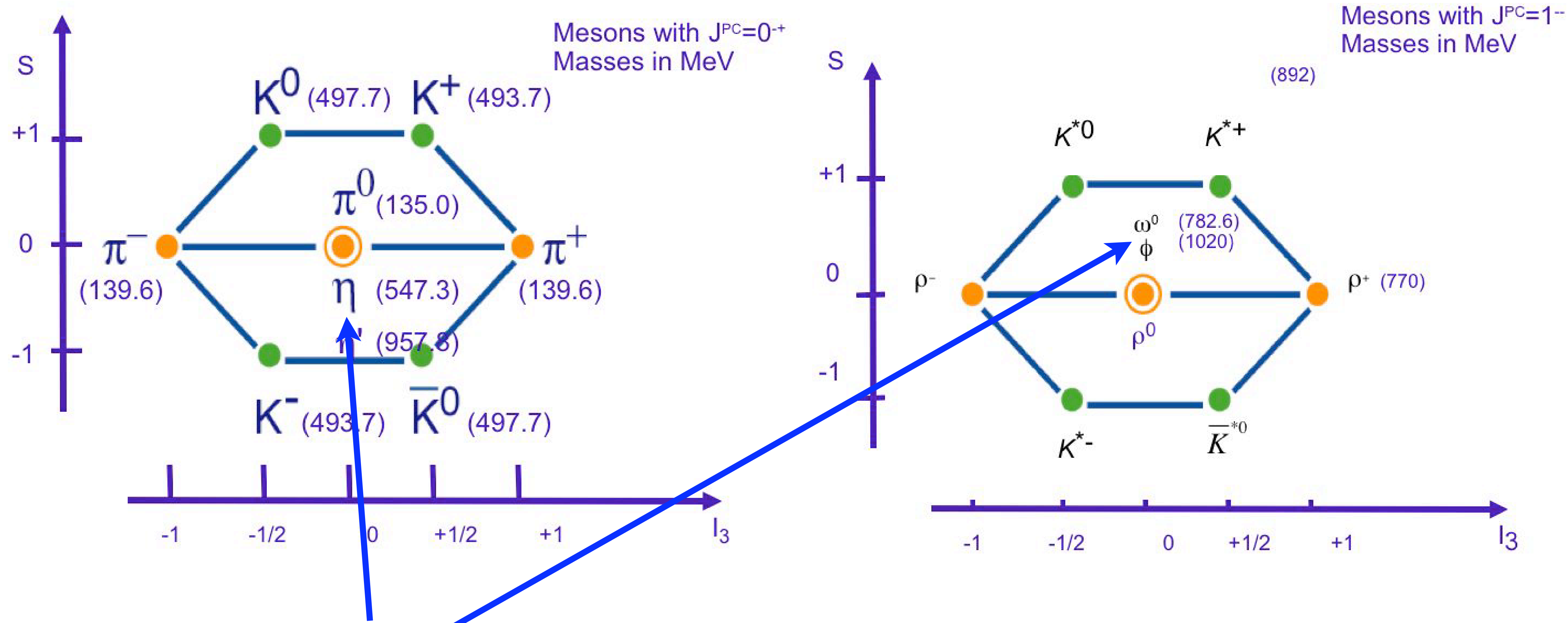
•one clear predictions: there must exist baryons with strangeness S=+1. ***Unfortunately it is a wrong prediction, no such particle seen until today*** !

• basic symmetry of Sakata model: SU(2)= isotopic spin symmetry ⇒ SU(3), unitary transformation of the Sakata triplet

The Eightfold Way

- assuming there ***is*** a Lagrangian, $\mathcal{L}$, and assuming that $\mathcal{L}$ ***is approximately symmetric*** under a group G, we can make predictions independent from dynamical details: particles in multiplets, intensity rules;
- no matter how you guess it, symmetry is testable a posteriori: like Mandeleev Table, ***symmetry*** leads to ***predictability***
- discovery of strangeness prompted attempts to find a symmetry group larger than isotopic spin SU(2)
- The approximate symmetry of subnuclear forces was identified with SU(3) by M. Gell-Mann and Y. Ne'eman, 1961 , the unitary transformations of complex 3-dimensional vectors;
- Sakata model was used to guess the symmetry of the strong interactions (3=3 constituents) then thrown away;
- Particles should fall into typical complex of:
    - octets and singlets (mesons)
    - octets and decuplets (baryons)

Meson patterns



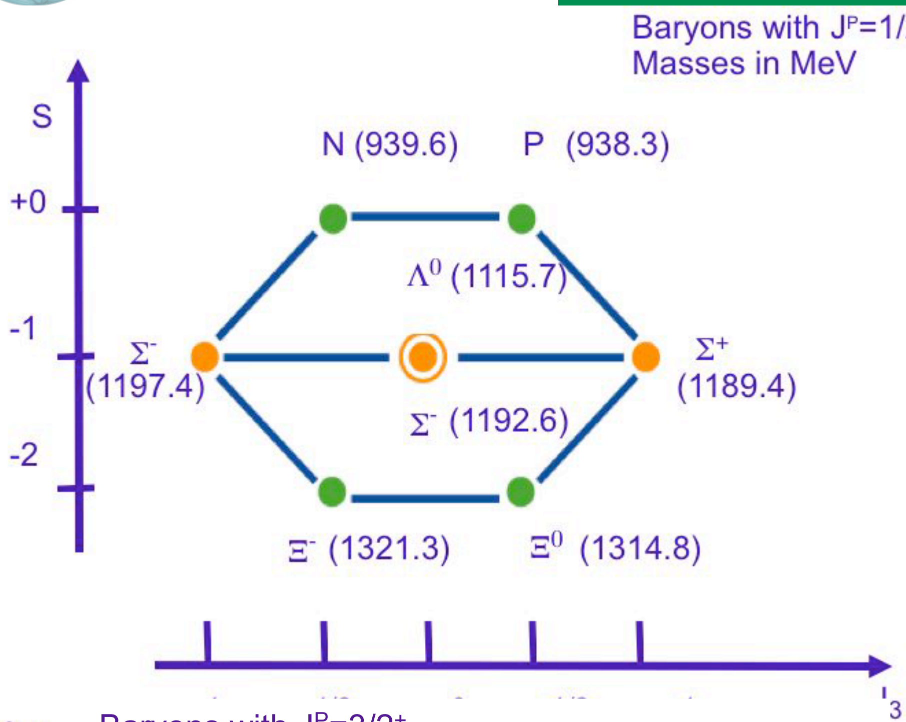
some particles (η, ω, φ) were not established when symmetry was proposed their confirmation reinforced the picture.
Earliest studies of η were done with the Italian Sincrotrone, just built in Frascati.

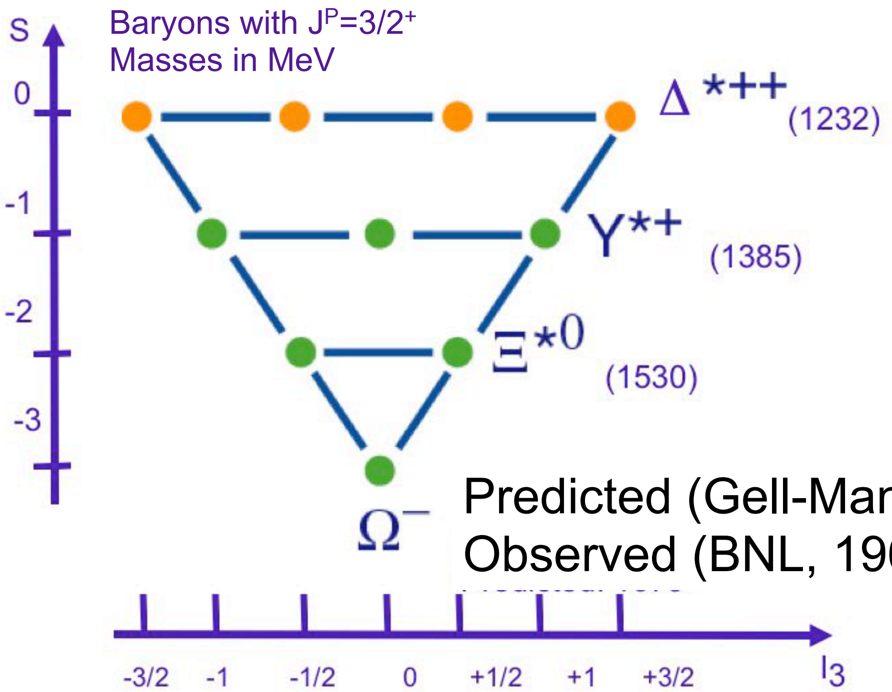
Note:

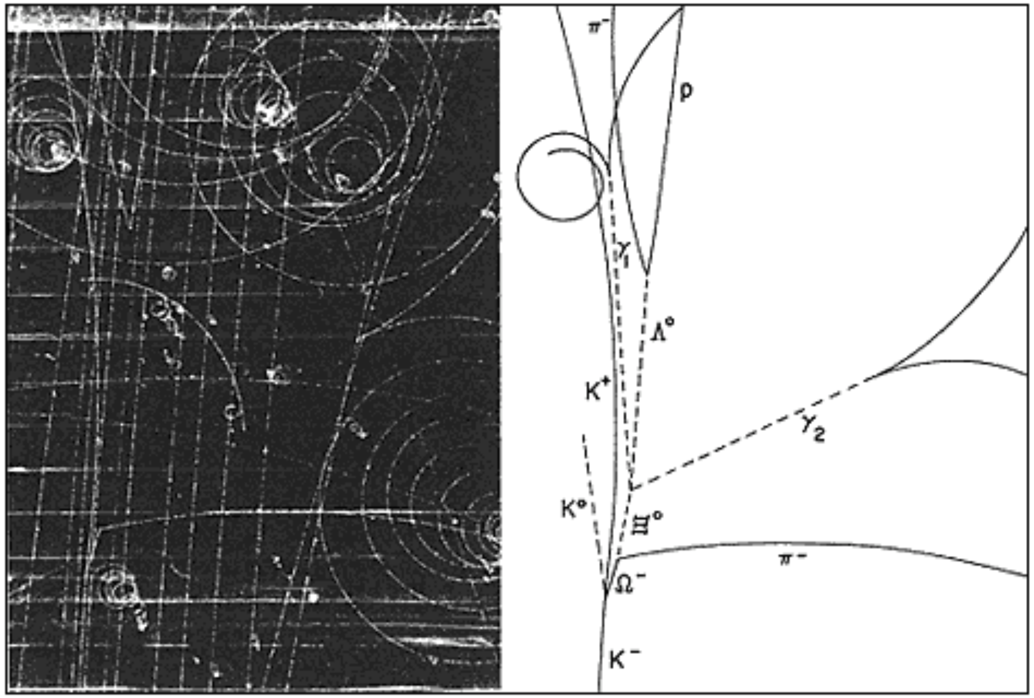
$$(8+1)+(8+1)\times 3 =$$

$$= 36\ states$$

The Ω^- missing link







The bubble chamber picture of the first Omega-minus (N. Samios and coworkers)

Predicted (Gell-Mann, 1962) M=1679
Observed (BNL, 1964) M= 1672

Note:

$$8 \times 2 + 10 \times 4 =$$
$$= 56 \; states$$

Universal Weak Interactions

- 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, Marshak & Sudarshan, Gershtein & Zeldovich) 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 to reconcile strange particle decays with the universality of weak interactions, paving the way to modern electroweak unification.

Currentx Current theory and the Strange Particle decay puzzle

natural from one assumption. That is that the Fermi couplings are of the nature of the interaction of a kind of current with itself:

$$J \longleftrightarrow J \qquad (12\text{-}4)$$

and the problem is to find the composition of the current J, the sum of several parts. The couplings (6-4), (6-5), and (6-6) described previously result if J is written

$$J = (\bar{\nu} e) + (\bar{\nu} \mu) + (\bar{p} n) + X \qquad (12\text{-}5)$$

Experimentally the coefficient of all first three terms are equal. All our three new couplings will result if we add to J just one term, say X, which changes strangeness. Above we have suggested solely as an example what X might be but we shall now have to consider more seriously what properties the term X might have.

An immediate consequence of this idea is that the coefficients of X to each of the three currents $(\bar{\nu}e)$, $(\bar{\nu}\mu)$, and $(\bar{p}n)$ are equal. That is, the couplings (12-1), (12-2), and (12-3) must all have the same coefficient [although it need not equal the coefficient of (6-4), (6-5), and (6-6)].

electron-muon universality well obeyed in Strange Particle decays

What is the strenght of X ?

4. *Leptic decays with change of strangeness are relatively much slower than those without change of strangeness* (although the $K^+ \to \mu^+ + \nu$ is a possible violation).

But if the coefficients in X are of the order of 0.1 for lepton coupling, we should expect them to be exactly the same for the $(\bar{p}n)$ coupling. This is uncomfortable because the nonleptic decays seem too fast for this. They seem to require coefficients of order unity, but we cannot be sure, for we cannot really calculate these processes because of the virtual states of strongly interacting particles that are involved.

In the JxJ theory, the ***suppression of leptonic strange particle decays*** got mixed with the so called ***I=1/2 enhancement*** of non-leptonic decays.

A real mess !!

Gell-Mann and Levy

An observation made in a 1960 by M. Gell-Mann and M. Levy is often quoted as a precursor or source of inspiration for Cabibbo. This is justified to some extent, but the role of Gell-Mann and Levy's observation needs not to be overestimated. The Gell-Mann and Levy's paper is quoted by Cabibbo and was well known to all those working in the field.

In G-M & L paper, the weak current is written in the Sakata model, with elementary P, N and Λ. All hadrons are supposed to be made by these three fundamental fields.
G-M & L observe that one could relate the reduction of the Λ w.r.t. the muon coupling by assuming the following form of the weak vector current:

$$V_\lambda = \frac{1}{\sqrt{1-\epsilon^2}} \left[\bar{P}\gamma_\lambda \left(N + \epsilon\Lambda\right)\right]$$

But:

nobody knew how to proceed from the G-M&L formula to a real calculation of meson and baryon decays, for two reasons:

• The Sakata model was already known to be substantially wrong, due to the absence of the positive-strangeness hadrons. Thus the inclusion of the decays of the S=-1 and S=-2 hyperons was completely out of reach.

•The important point of the non-renormalisation was missed. In Gell-Mann and Levy's words: *There is, of course, a renormalization factor for that decay*, (i.e. Λ decay) *so we cannot be sure that the low rate really fits in with such a picture*.

SU(3) Symmetry and weak interactions

Gatto & Cabibbo (1961) and others observed that the Noether currents associated to the newly discovered SU(3) symmetry include a *strangeness changing current* that could be associated with strangeness changing decays, in addition to the *isospin current* responsible for strangeness-non-changing beta decays (CVC).

The identification, however, implied the rule ΔS= ΔQ in the decays, in conflict with some alleged evidence from $K^0 - \bar{K}^0$ oscillations of a ΔS= -Δ Q component of strangeness changing weak interactions (Padua-Winsconsin).

In addition, the problem remained how to formulate correctly the concept of CVC and muon-hadron universality in the presence of the three Noether currents:

$$V_\lambda^{lept} = \bar{\nu}_\mu \gamma_\lambda \mu + \bar{\nu}_e \gamma_\lambda e \; (\Delta \mathrm{Q} = 1);$$

$$V_\lambda^{(1)} + i V_\lambda^{(2)} \; (\Delta \mathrm{S} = 0, \; \Delta \mathrm{Q} = 1)$$

$$V_\lambda^{(5)} + i V_\lambda^{(6)} \; (\Delta \mathrm{S} = \Delta \mathrm{Q} = 1)$$

Enters Cabibbo

In his 1963 paper, Nicola made a few decisive steps.

- he decided to ignore the evidence for a ΔS= -ΔQ component, which indeed was later disconfirmed (P. Franzini had a role on this).
- he ignored also the problem of the normalization of non-leptonic processes and of the I=1/2 enhancement (see later)
- he formulated a notion of universality between the *leptonic current* and *one, full hadronic current*, a combination of the SU(3) currents with ΔS=0 and ΔS=1, such as to be *equally normalized* to the lepton current.

Axial currents are inserted via the V-A hypothesis. In formulae:

$$V_\lambda^{(hadron)} = a\left[V_\lambda^{(1)} + iV_\lambda^{(2)}\right] + b\left[V_\lambda^{(5)} + iV_\lambda^{(6)}\right]$$

$$a^2 + b^2 = 1$$

$$J_\lambda^{lept} = \bar{\nu}_\mu \gamma_\lambda (1-\gamma_5)\mu + \bar{\nu}_e \gamma_\lambda (1-\gamma_5) e;$$

$$J_\lambda^{(hadron)} = \cos\theta\left[J_\lambda^{(1)} + iJ_\lambda^{(2)}\right] + \sin\theta\left[J_\lambda^{(5)} + iJ_\lambda^{(6)}\right];$$

$$J_\lambda^{(i)} = V_\lambda^{(i)} - A_\lambda^{(i)}$$

The angle θ is a new constant of Nature, since known as *the Cabibbo angle*.

The weak current of baryons

The form of $J_\lambda^{(had)}$, well readable in terms of the SU(3) symmetry, laeds to a form of the current in terms of the individual baryon fields remarkably complicated (F and D are phenomenological coefficients related to axial current renormalization):

$$J_\mu^{(had)} = \cos\theta\;\bar{p}\left[\gamma_\mu - (F+D)\gamma_5\right]n + \sin\theta\left\{-\sqrt{\frac{3}{2}}\bar{p}\left[\gamma_\mu - (F+\frac{1}{3}D)\gamma_5\right]\Lambda\right\} +$$

$$+\sin\theta\left\{-\bar{n}\left[\gamma_\mu - (F-D)\gamma_5\right]\Sigma^- - \bar{\Sigma}^+\left[\gamma_\mu - (F+D)\gamma_5\right]\Xi^0 + \sqrt{\frac{3}{2}}\bar{\Lambda}\left[\gamma_\mu - (F-\frac{1}{3}D)\gamma_5\right]\Xi^-\right\} + \cdots$$

Ademollo-Gatto (and Fubini et al.) theorem: matrix elements of the vector current are not renormalized to first order in SU(3) symmetry breaking

$$F \sim 0.46$$

$$D \sim 0.80$$

$$\sin\theta \sim 0.22$$

- Currents belong to SU(3)xSU(3)
- Partial conservation of the vector and axial vector currents protects the normalization of strenght
- Gatto-Ademollo theorem: vector current is non renormalized to first order in SU(3) breaking

The phenomenological success of the Cabibbo theory for semileptonic decays has made it clear that the ***I=1/2 enhancement of non-leptonic decays*** must have a different origin than the normalization of the strange particle current, X. This was understood later as a renormalization group effect (K. Wilson) due to QCD (B.W. Lee and M.K. Gaillard, G. Altarelli and L. Maiani, 1974).

The agreement has been but reinforced by the most recent data from Frascati, FermiLab and CERN.

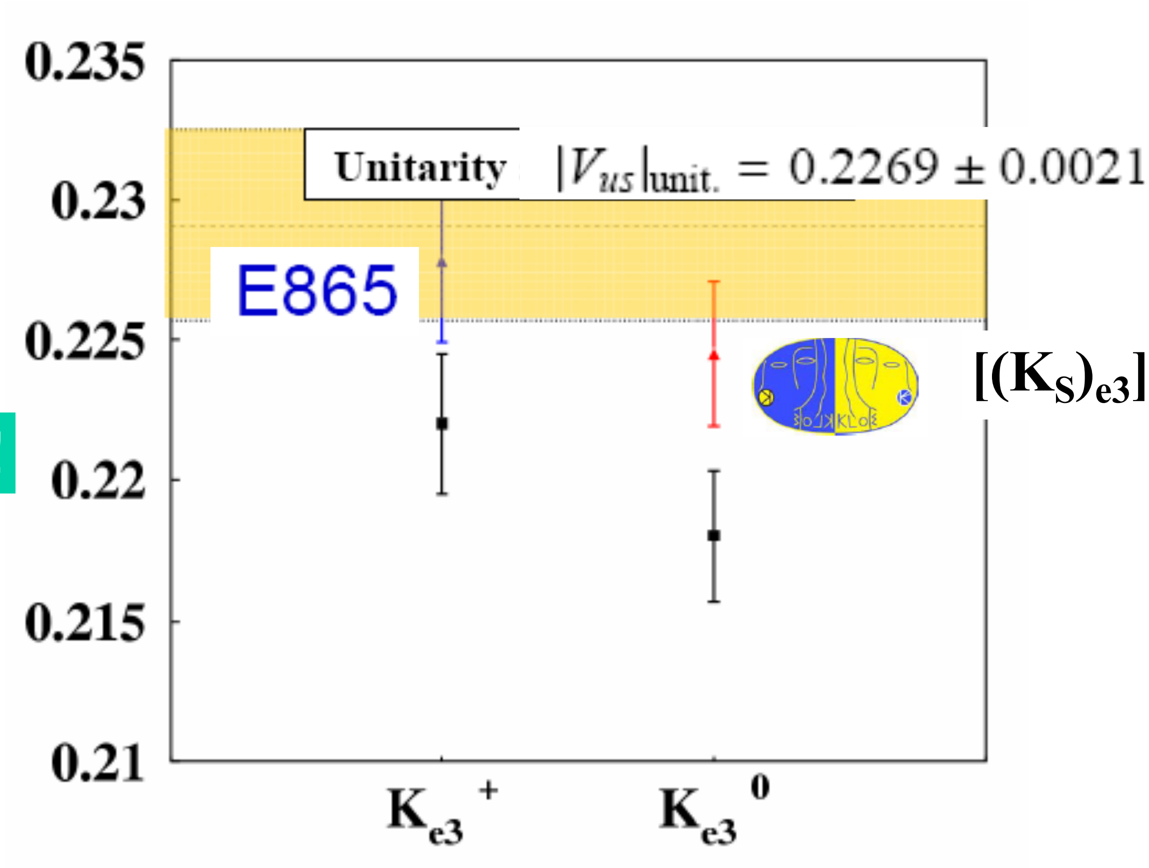
$K_s \to \pi e \nu$ decay: V_{us} determination

PDG02, CKMwg use

$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

From **Leutwyler, Roos**
Z.Phys. C 25 1984

- p^4 contr. in χPT



Hyperon decays: NA48 data!

N. Cabibbo, E. C. Swallow and R. Winston, hep-ph/0307214, hep-ph/0307298.

$$|V_{us}|_{\rm Hyp} = 0.2250 \pm 0.0027_{\rm exp}$$

New!!! KTeV ($K_L l3$):

$$|V_{us}| = 0.2252 \pm 0.0008_{\rm KTeV} \pm 0.0021_{\rm ext}$$

S.Miscetti 21

Cabibbo Theory with quarks

•The Gell-Mann-Levy formula *was given a new life* after the consolidation of the Cabibbo theory, *in the context of the quark model*. If quarks and flavor-singlet gluons are the fundamental particles, as we know today, beta decays of baryons simply reflect the two transitions

$$d \rightarrow u, \;\; s \rightarrow u$$

•(this is similar to Fermi's idea that beta decays of nuclei are simply the manifestation of the $n \rightarrow p$ transition)

•in the quark picture, the Cabibbo weak current takes the simple form:

$$J_\lambda = \cos\theta \left[\bar{u}\gamma_\lambda(1-\gamma_5)\,(d+\tan\theta s)\right] =$$
$$= \bar{u}\gamma_\lambda(1-\gamma_5)d_C$$

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 in a SU(6) symmetry
- 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

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

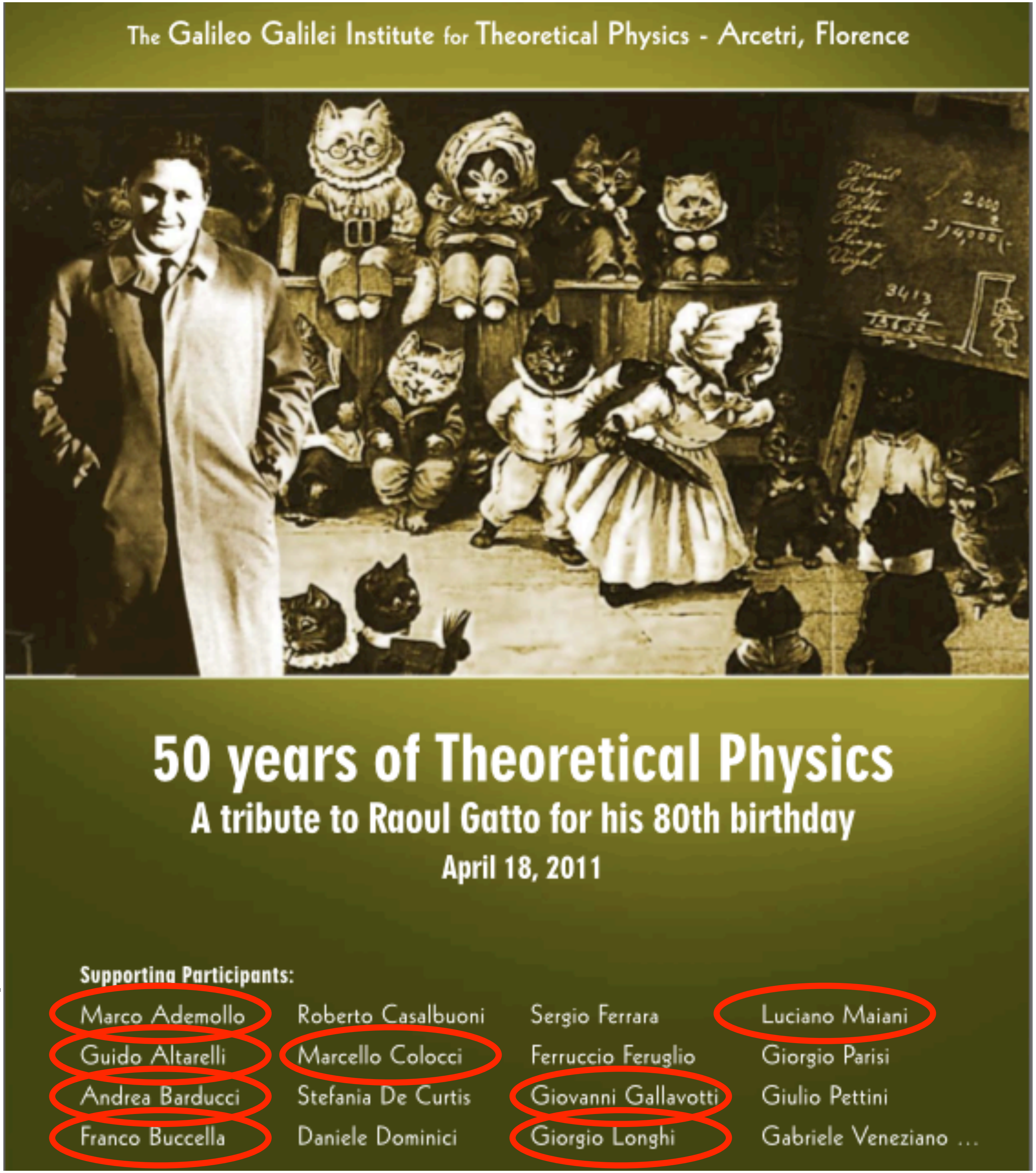
- Baryons and baryon resonances neatly fit in
- but total symmetry of the wave function (in flavor and spin) is inconsistent with Fermi statistics of quarks (spin 1/2), if baryons are in S-wave ????...***are quarks real*** ??

COLOR and QCD

•$\Delta^{++} = (u^{\uparrow} u^{\uparrow} u^{\uparrow})$?
•***is impossible*** by Pauli exclusion principle
•quarks have an additional "quality" called color, with three values (conventionally: red, green, blue);
•$\Delta^{++} = u_r^{\uparrow} u_g^{\uparrow} u_b^{\uparrow}$ ***is possible***, and is unique (color singlet: Han&Nambu)

•if being color singlet is the rule...
•the lowest state of six quarks will collapse into two color singlet baryons: THIS IS HOW NUCLEI ARE MADE, hence atoms
• Quantum Chromo Dynamics: gives a dynamical meaning to color (like electric charge in electrodynamics

The “Florence School” under the guidance of Raoul Gatto attacked with enthusiasm the exploration of the newly discovered symmetries of the hadrons, in particular the SU(6) symmetry and its “relativistic extensions” ....



in Florence at the time...

and Giuliano Preparata

summing up the SU(6) predictions...

	SU(6) prediction	expt
μ_p	-	2.79
μ_n	-	-1.91
Ratio= μ_p/μ_n	- 3/2 = - 1.5	-1.46
Mass spacing of decuplet	130 MeV	145 MeV
D/F (axial current)	3/2	1.7
g_A/g_V (=D+F)	- 5/3 = -1.67	-1.2694 ± 0.0028

The Cabibbo angle as a dynamical problem

The weak angle specifies the direction in SU(3) octet space of a *weak isospin group* with respect to the direction identified by the medium-strong interactions responsible for the breaking of the SU(3) symmetry itself. In the absence of symmetry breaking, one could identify the weak isospin group with the isospin symmetry and the strange particles would be stable under weak decays.

The interplay of the weak and medium-strong interactions to determine the value of θ proved to be far-reaching, it has remained in the present unified theory in the form of a *misalignment between the weak isospin subgroup of the flavor symmetry and the quark mass matrix*, which arises from the spontaneous symmetry breaking of the weak isospin.

ANNALS OF PHYSICS: **66**, 758–783 (1971)

Properties of the Breaking of Hadronic Internal Symmetry

LOUIS MICHEL

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AND

LUIGI A. RADICATI

Scuola Normale Superiore, Pisa, Italy

Received October 1, 1970

The directions of breaking of the hadronic internal symmetry by the electromagnetic, semileptonic—and nonleptonic—weak and *CP* violating interactions are characterized by remarkable mathematical properties. These directions correspond to idempotents or nilpotents of an algebra and they are critical, i.e., every invariant function for the symmetry group, e.g., $(SU(3) \times SU(3)) \times (1, P, C, PC)$ has an extremum on these directions.

Michel & Radicati (cont'd)

- identify "natural minima " of a potential made by invariants of a given group G
- hope to find the value of θ_C this way?
- M&R investigated SU(3) with octet symmetry breaking
- Cabibbo and myself extended to SU(3)⊗SU(3) with:

$$(3,\bar{3}) \oplus (\bar{3},3) \text{ and } (8,1) \oplus (1,8) \text{ breaking}$$

- Interesting but unsuccessfull approach to the value of θ_C
- later used to justify symmetry breaking patterns of Unified and Grand Unified theories

The quest for Relativistic SU(6)

• many attempts to find the relativistics SU(6) (notably by Salam and collaborators): U(12), SU(6)$_W$, etc..
• it was soon realized by Sid Coleman (1965) that "unifying " internal symmetries with the Lorentz group was troublesome
• the story ended with the no-go theorem by S. Coleman and J. Mandula: non-trivial S-matrix requires factorization of the internal symmetry and Poicare group

PHYSICAL REVIEW VOLUME 138, NUMBER 5B 7 JUNE 1965

Trouble with Relativistic *SU*(6)*

SIDNEY COLEMAN†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 18 January 1965; revised manuscript received 5 February 1965)

PHYSICAL REVIEW VOLUME 159, NUMBER 5 25 JULY 1967

All Possible Symmetries of the *S* Matrix*

SIDNEY COLEMAN† AND JEFFREY MANDULA‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 16 March 1967)

• non relativistic SU(6) justified by the constituent quark model: effective quarks move non-relativistically

•approximate description of the properties of lowest baryons and perhaps first orbital excitations (70, L=1) to organize negative parity resonances

•in naive quark model, there are only spin 1/2 constituents: no need to unify different spins

• but how can we unify "fundamental" particles with different spin ?

Volume 49B, number 1 PHYSICS LETTERS 18 March 1974

A LAGRANGIAN MODEL INVARIANT UNDER SUPERGAUGE TRANSFORMATIONS

J. WESS
Karlsruhe University, Germany
and
B. ZUMINO
CERN, Geneva, Switzerland

Received 4 January 1974

answer is supersymmetry: operators that change spin are FERMIONIC, graded Lie algebras evade C&M theorem !

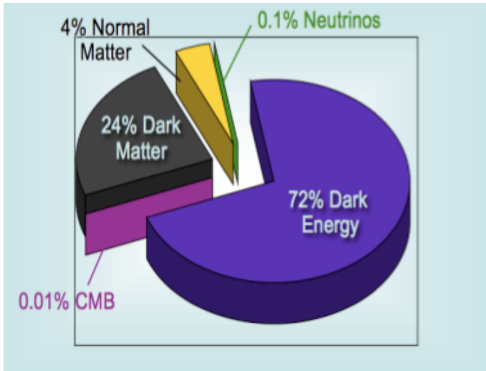
New Challenges

- Find the Higgs Boson **The Origin of mass**

The Higgs boson is needed for theory to agree with Nature...
but gives a vision of Vacuum which may explain new phenomena :
(inflation, chaotic universe, …)

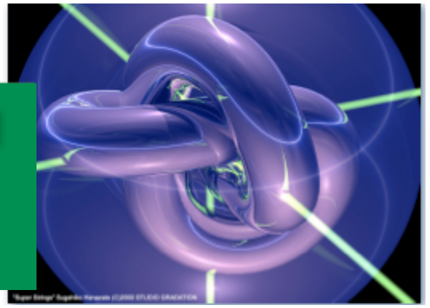
- Find the Supersymmetric Particles **The Origin of Spin**

The Unification of Forces **requires** a Symmetry to relate different spins: this is the SUPERSYMMETRY discovered at CERN in the 70s by J. Wess and B. Zumino



- Identify the Dark Matter present in the Universe **Cosmic Supersymmetry**

- Test for new space-dimensions



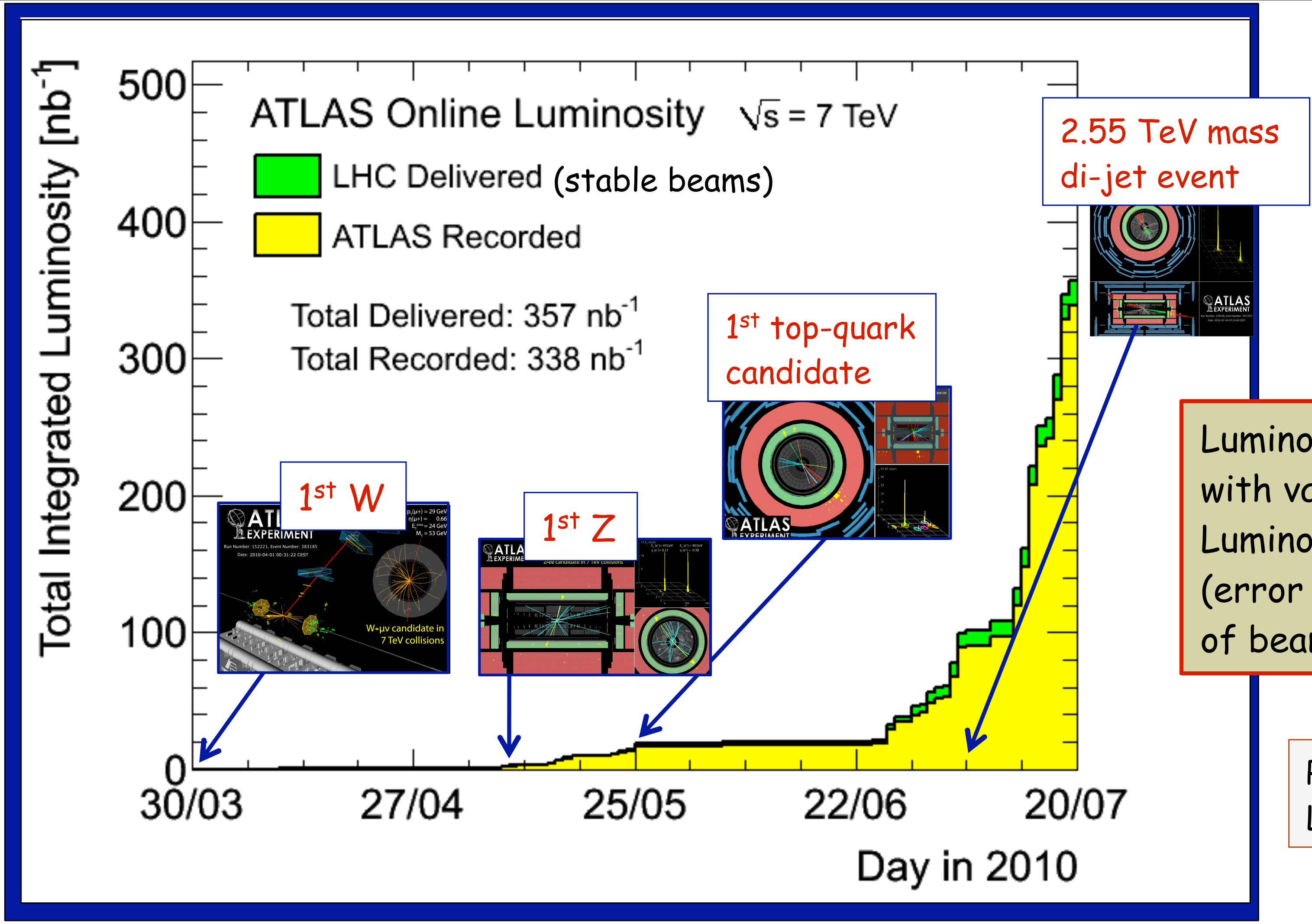
String formulation of Quantum Gravity is not consistent in 3+1 dimensions. Curved extra-dimensions are needed.
How small is R ?

LHC Startup, 10 September 08

The 2010 run

Fabiola Gianotti @ ICHEP 2010

Integrated luminosity vs time
(from first √s =7 TeV collisions on 30 March to beginning of ICHEP on 22 July)



Luminosity detectors calibrated with van der Meer scans. Luminosity known today to 11% (error dominated by knowledge of beam currents)

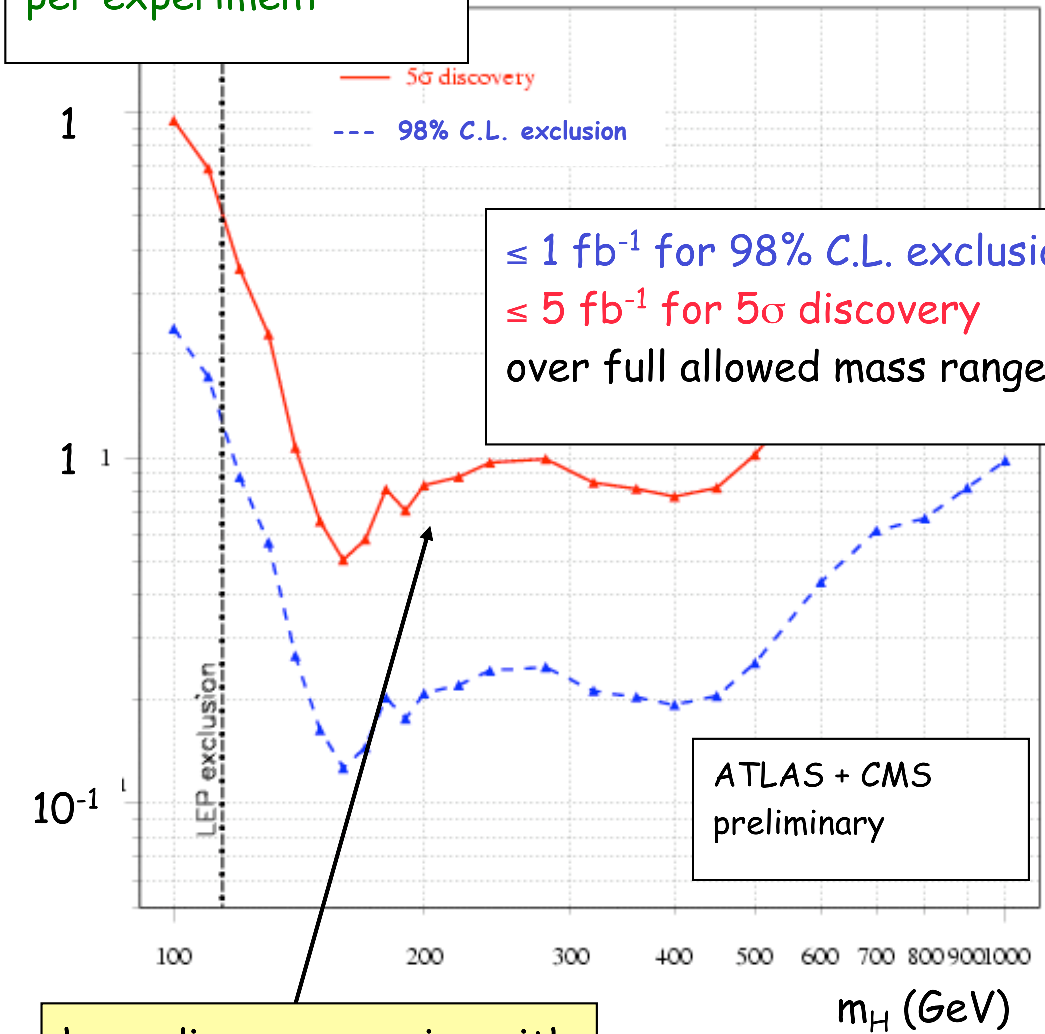
Peak luminosity in ATLAS $L \sim 1.6 \times 10^{30}\ cm^{-2}\ s^{-1}$

Overall data taking efficiency (with full detector on): 95%

What about the SM Higgs boson ?

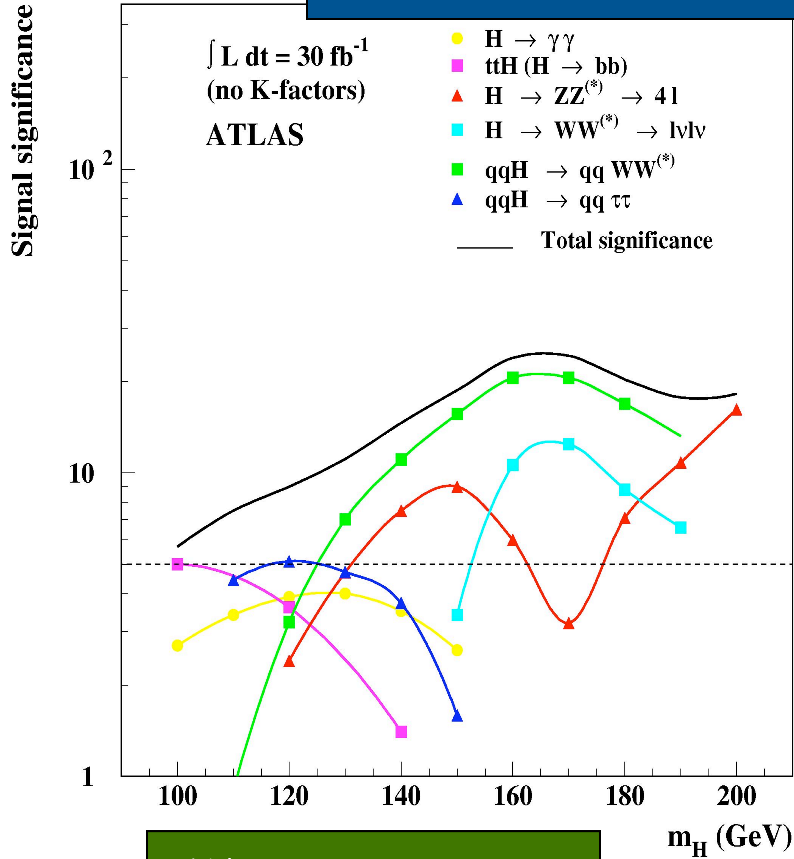
F. GIANOTTI. ICHEP 06

Needed ∫Ldt (fb^{-1}) per experiment

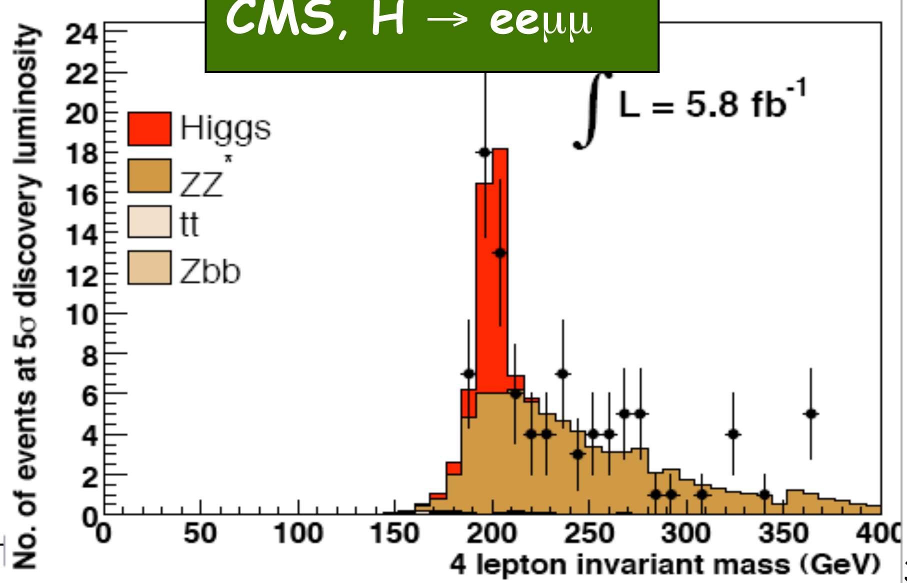


≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range

here discovery easier with gold-plated H → ZZ → 4l
→ **by end 2008 ?**



CMS, H → eeμμ



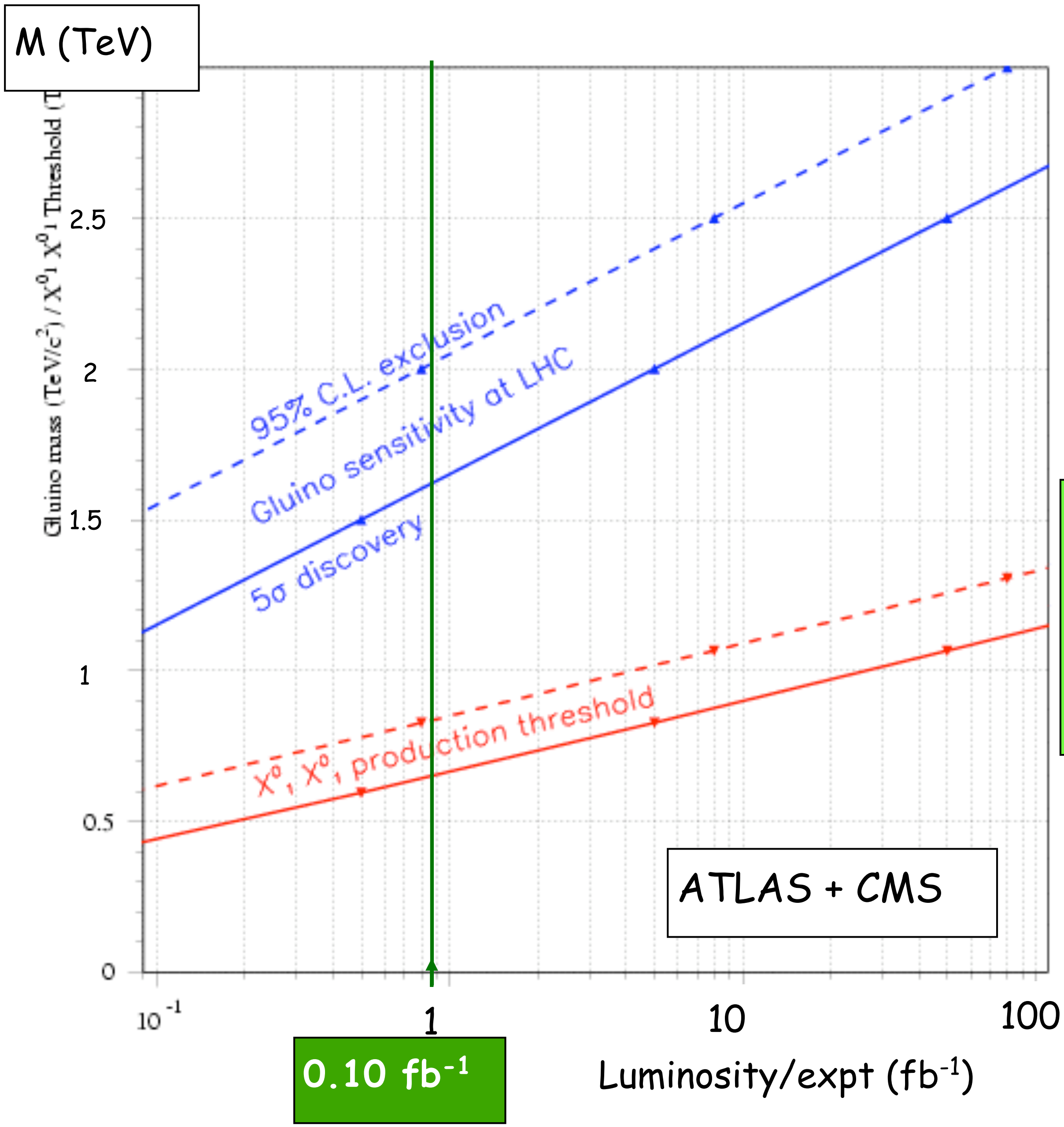
H → 4l : narrow mass peak, small background
H → WW → lνlν (dominant at the Tevatron): counting channel (no mass peak)

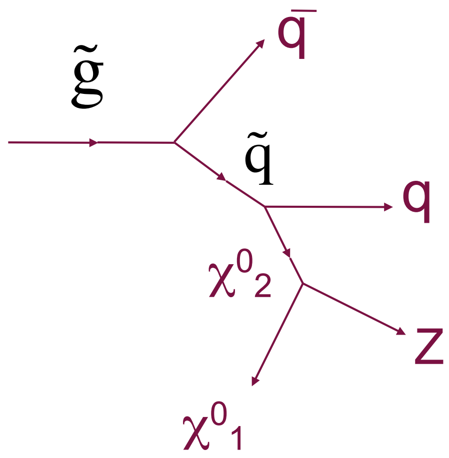
Example of "early" discovery: Supersymmetry ?

F. GIANOTTI. ICHEP 06

If SUSY at TeV scale → could be found "quickly" .... thanks to:

- large $\tilde{q},\tilde{g}$ cross-section → ≈ 10 events/day at 10^{32} for $m(\tilde{q},\tilde{g}) \sim 1$ TeV
- spectacular signatures (many jets, leptons, missing E_T)





Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 (good) pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

BUT: understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.

Short term Objectives

Steve Myers @ ICHEP 2010

Integrated luminosity of $\geq 1 fb^{-1}$ by the end of 2011

- requires a peak luminosity of $\geq 1x10^{32}$ $cm^{-2}s^{-1}$ during 2011
- → must reach ~1 $x10^{32}$ $cm^{-2}s^{-1}$ during 2010

DONE !

NOTE: this is ≥3000 time what was obtained in May to July run of 2010 !!!

Conclusion

• Decoding the structure of subnuclear particles took about 25 years
• interplay of experimental and theoretical results, globalization of science
• Continuous internal symmetries discovered ad exploited in the 60‘s, SU(3), SU(6), SU(3)⊗SU(3), played the role of the Mendeleev Table: patterns that had to be filled by particles with definite properties
• Quarks and QCD are the explanation of (flavour) symmetries, much like electrons, nuclei and Quantum Mechanics explain Mendeleev’s Table
• Gauge symmetry (Yang&Mills, 1954): symmetry determines the dynamics, much alike geometry in Einstein’s gravity theory
•....these are the ingredients of today’s STANDARD THEORY

Conclusions (cont'd)

• ..however: the Standard Theory is not complete

•we expect to find new phenomena beyond the Higgs boson that will help understand what the next step is

•and hope that the LHC will lead us to a new cycle of unexpected experimental results to be confronted with unexpected theories, that made physics in 50's to 70's so exciting.