FIFTY YEARS THAT CHANGED OUR PHYSICS

As seen through the Moriond meetings

Moriond, March 2016

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ENS, Paris

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- Each one involved new physical concepts, new mathematical tools and new champions

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- Yet, they influenced profoundly our way of looking at the fundamental laws of Nature
- They were mostly rejected by the champions of the previous revolutions

Moriond 1966

- 20 Participants
- Almost all talks were in French
- The subjects were mostly of local interest :

Photoproduction, Electroproduction, The deuteron,
Some projects for $e^+ - e^-$ physics

Moriond 1967

- 32 Participants

- Still most talks were in French

- The subjects expand to cover topics from the main stream of international research :

Analyticity, Regge poles, Bootstrap, *CP*-violation, Quark model

Moriond 1968

- 39 Participants
- Still most talks in French
- The subjects cover practically all the international research :

Analyticity, Regge poles, CP-violation, Weak interactions, Current algebras

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- Symmetries and Current Algebras, Weak Interactions and CP-violation
  Secondary subjects
- Notice the absence of Quantum Field Theory
  A totally marginal subject

The analytic S-matrix theory

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- A series of (more or less) reasonable axioms formulated directly on the scattering amplitudes.
  - Invariance under Poincaré and internal symmetries
  - Crossing symmetry
  - Unitarity $2\text{Im}\,T = TT^\dagger$
  - Maximum analyticity
  - Polynomial boundedness

  Not very well defined, fuzzy rules

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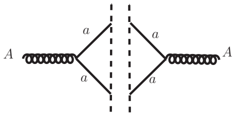
- An important addition : Analyticity in the complex angular momentum plane (Regge)

Some important by-products

- Cutcosky unitarity relations



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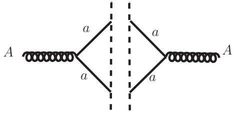
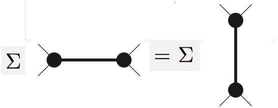


- Duality (*Dual Resonance Model*)



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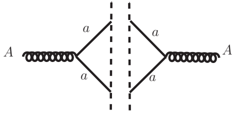

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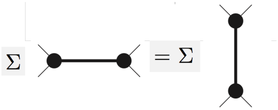

- The Veneziano amplitude

$$A(s,t) \sim \frac{\Gamma(-1+s/2)\Gamma(-1+t/2)}{\Gamma(-2+(s+t)/2)}$$

(Moriond 1969)

This amplitude, appropriately generalised, was the starting point of a concept which turned out to be seminal and important :

The string model

Initially, it was meant to be a theory for hadronic physics and gave rise to phenomenological models such as *the Lund model*

But it was soon realised that it contains a version of quantum gravity
(more about that later)

Symmetries and Current Algebras, Weak Int. and *CPV*

SYMMETRIES

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- The pre-history
  - Space-time symmetries
  - Internal symmetries (Heisenberg 1932, Kemmer 1937, Fermi 1951)
  - Gauge symmetries (Gauss ? ?, Einstein 1914, Fock 1926, Klein 1937, Pauli 1953, Yang and Mills 1954)

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  • Gauge symmetries (Gauss ? ?, Einstein 1914, Fock 1926, Klein 1937, Pauli 1953, Yang and Mills 1954)

- Early history
  • Higher symmetry (Gell-Mann 1961 (+ Ne'eman)) $SU(3)$
  • Current Algebras (Gell-Mann 1962)

$$[V, V] = V \quad ; \quad [V, A] = A \quad ; \quad [A, A] = V$$

  Treated in many Moriond sessions, starting already in 1966
  • Quarks (Gell-Mann 1964 (+Zweig))
  Also present in many Moriond sessions starting in 1967

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- The construction of the Standard Electroweak Model
- The renormalisation group and QCD
- The importance of anomalies
- They are all covered in the Moriond series

I. THE WEAK INTERACTIONS. PHENOMENOLOGY

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The Electroweak Standard Model

I. THE WEAK INTERACTIONS. PHENOMENOLOGY
Fermi 1933

- The Fermi theory of the weak interactions was phenomenologically very successful

$$\mathcal{L}_W = \frac{G}{\sqrt{2}} J^{\mu}_{(w)}(x) J^{\dagger}_{(w)\mu}(x)$$

- But it was a non-renormalisable theory, Fierz 1936

$$d\sigma(\bar{\nu} + p \to n + e^{+}) = \frac{G_F^2}{2\pi^2} p_{\nu}^2 d\Omega$$

$$
\begin{array}{lllll}
A & \sim & C_0^1(G_F\Lambda^2) & +C_1^1 G_F M^2 & \\
 & + & C_0^2(G_F\Lambda^2)^2 & +C_1^2 G_F M^2(G_F\Lambda^2) & +C_2^2(G_F M^2)^2 \\
 & + & ..... & & \\
 & + & C_0^n(G_F\Lambda^2)^n & +C_1^n G_F M^2(G_F\Lambda^2)^{n-1} & +.... \\
 & + & ..... & &
\end{array}
$$

Effective coupling constant : $\lambda = G_F\Lambda^2$

$A \sim \lambda^n + G_F M^2 \lambda^{n-1} + ...$

A $\sim$ "leading" + "next-to-leading" + ...

The Theory is valid up to a scale $\sim \Lambda$

$G_F\Lambda^2 \sim 1 \Rightarrow \Lambda \sim 300$ GeV

BUT PRECISION MEASUREMENTS CAN DO BETTER

B.L. Joffe and E.P. Shabalin (1967)

- At leading order

  Limits on Parity and Strangeness violation in strong interactions

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- At next-to-leading order

  Limits on $K^0 \rightarrow \mu^+\mu^-$ and $K^0 - \bar{K}^0$ mass difference

  $G_F \Lambda^2 << 1 \Rightarrow \Lambda \sim 3$ GeV

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- The leading divergences respect all the strong interaction symmetries
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- Following this line attempts were made to "determine" the properties of the weak interactions, for example to calculate the value of the Cabibbo angle.
  Gatto, Sartori, Tonin ; Cabibbo, Maiani ; Gell-Mann, Goldberger, Kroll, Low

The argument on the leading divergences can, and has been, phrased entirely in terms of currents and symmetries of the strong interactions, although the assumption of an intermediate charged vector boson was always made. The Wilson short distance expansion was not used.

$$A \sim \frac{G}{\sqrt{2}} \int d^4k \; e^{ikx} < a|T(J_\mu(x), J_\nu(0))|b > \frac{k^\mu k^\nu / m_W^2}{k^2 - m_W^2}$$

$\Rightarrow$

Only the symmetry properties of the currents are used, not their explicit expression in terms of elementary fields.
The argument can be generalised to all orders in perturbation theory *(J.I.)*

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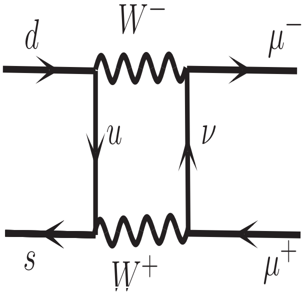
- At this point, however, the paradigm gradually changed from symmetries and currents to the quark model.



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- A model for leptons
  Weinberg 1976 ; Salam 1968
- Both went totally unnoticed

II. THE WEAK INTERACTIONS. FIELD THEORY

Developed in parallel, kind of a sub-culture

Both, the phenomenological approach and the field theory approach, aimed at controlling the divergences of perturbation theory. In the first, you do not know the fields, you do not know the interactions. In the second you start from a given field theory.

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- The electrodynamics of charged vector bosons
  ξ-limiting formalism *Lee and Yang ; Lee 1962*

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- Understand why it works. *Becchi, Rouet, Stora ; Tyutin*

First conclusion

The 1960's was an extraordinary decade....

although no one at the time had realised that a revolution was taking place !

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- But they soon became the subjects of dedicated sections after 1973

The renormalisation group and QCD

Contrary to what you may think, the study (rather the re-birth) of the renormalisation group was not initially motivated by the SLAC results on DIS.

A short history

• The RG equation was first written down by Stückelberg and Petermann in 1953

$$[M\frac{\partial}{M} + \beta\frac{\partial}{\partial\lambda} + \gamma_m m\frac{\partial}{\partial m} - n\gamma]\Gamma^{(2n)}(p_1, ..., p_{2n}; m, \lambda; M) = 0$$

It was meant to clarify the meaning of the subtraction in the renormalisation procedure

• Gell-Mann and Low in 1954 observed that it can be used to study the asymptotic behaviour of the theory, but, in the late sixties, the emphasis was to use the equation $\beta = 0$ for QED as an eigenvalue equation to determine α

The renormalisation group and QCD

• In the very late sixties Callan and Symanzik wrote an independent equation, which was *the broken scale invariance Ward identity*

$$\left[m_R \frac{\partial}{\partial m_R} + \beta \frac{\partial}{\partial \lambda_R} + n\gamma \right] \Gamma_R^{(2n)} = m_R^2 \; \delta \; \Gamma_{\phi^2 R}^{(2n)}$$

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• Two physical applications :
(i) Phase transitions and critical phenomena *(Kadanoff, Fischer, Wilson)*
(ii) Scaling properties in DIS $\Rightarrow$ Asymptotic freedom and QCD *(Gross, Politzer, Wilcek)*

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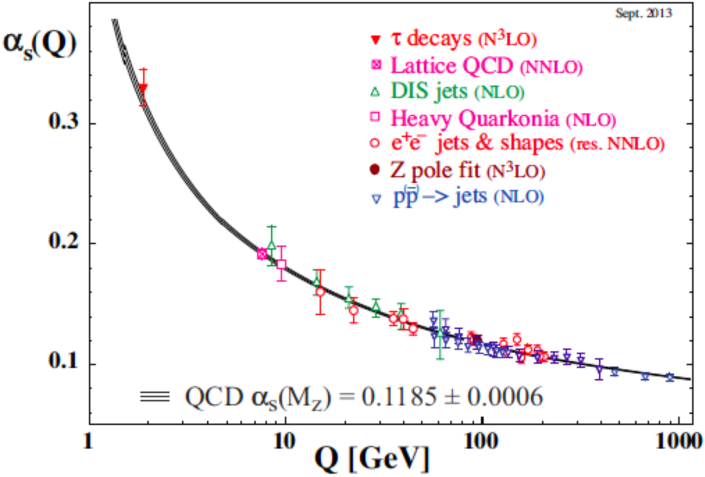
- The synthesis : The Altarelli-Parisi equations
  The best of two worlds ; Often presented in Moriond

QCD has been enormously successful

In perturbation



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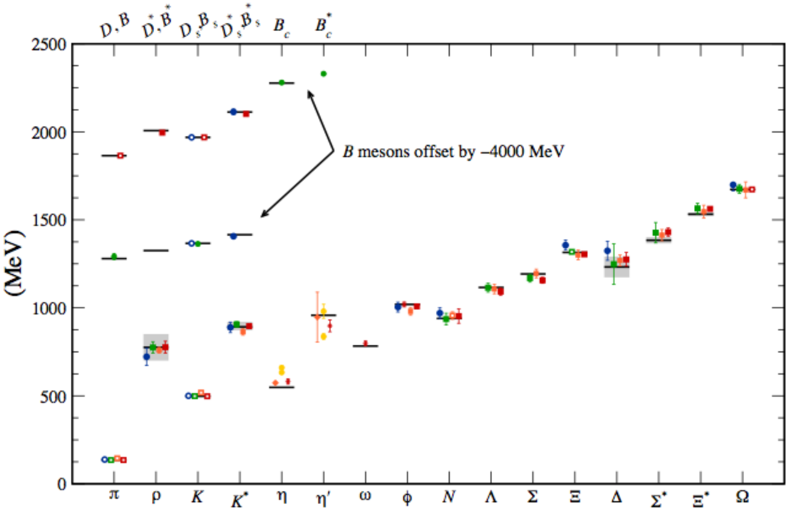
In the non-perturbative region



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Omnipresent in Moriond

- Gauge theories describe *ALL* interactions among elementary particles (?)
- Dynamics=Geometry
  "Let no one ignorant of geometry enter under this roof", Platon

THE STANDARD MODEL and anomalies

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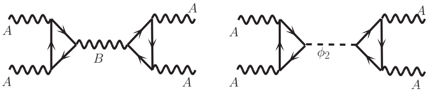
- The weak currents have a vector and an axial part. We know that, in general, we cannot enforce the conservation of both.

$$\partial^\mu j_\mu^{(5)}(x) = \frac{e^2}{8\pi^2}\epsilon_{\nu\rho\sigma\tau}F^{\nu\rho}(x)F^{\sigma\tau}(x)$$



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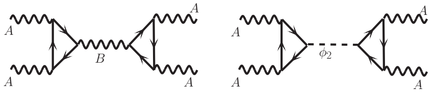

- Anomaly cancellation condition $\mathcal{A} = \sum_i Q_i = 0$

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- The presence of anomalies is a general feature of gauge theories, including gravitation
- Anomalies should be cancelled at all levels
- For the Standard Model, once the τ lepton was found, we could predict the existence of the b and t quarks
- The discovery of a very special anomaly cancellation in string theories, established the super-string theory as the only viable candidate for a quantum gauge theory of all interactions *(Green and Schwarz, 1983)*

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