50 ans de l'école de Gif

École Polytechnique, Sept. 2019

Jean Iliopoulos

ENS, Paris

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HAPPY BIRTHDAY

FIFTY YEARS THAT CHANGED OUR PHYSICS

A most exciting and rewarding period in Physics.

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- Cargèse Summer School
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They followed different trajectories and evolved differently.

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From this time on the picture changes : the courses cover all subjects in the main stream of Particle Physics.

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- Notice the absence of Quantum Field Theory
  A totally marginal subject

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- They are all covered in the GIF School

I. THE WEAK INTERACTIONS. PHENOMENOLOGY

Fermi 1933

The Electroweak Standard Model

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

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

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

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

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)

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- At next-to-leading order

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

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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

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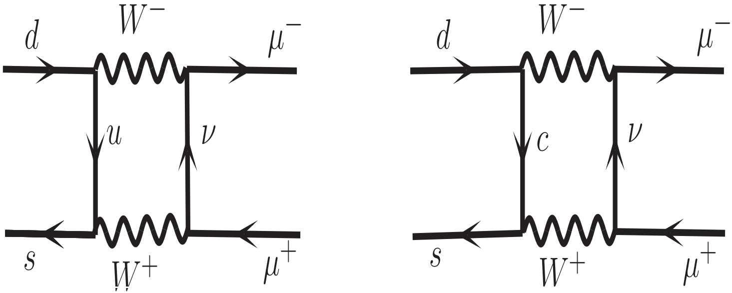
- At this point, however, the paradigm gradually changed from symmetries and currents to the quark model.



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- A model for leptons
  Weinberg 1967 ; 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*

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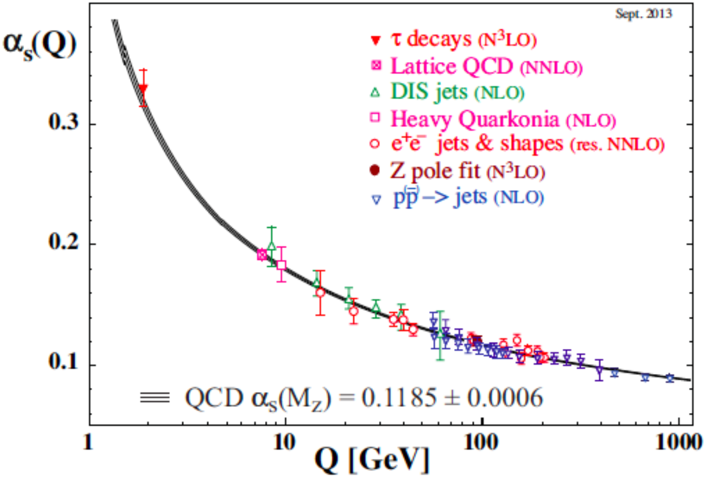
• Two physical applications :
(i) Phase transitions and critical phenomena *(Kadanoff, Fischer, Wilson)*
(ii) Scaling properties in DIS ⇒ Asymptotic freedom and QCD *(Gross, Politzer, Wilcek)*

QCD has been enormously successful

In perturbation



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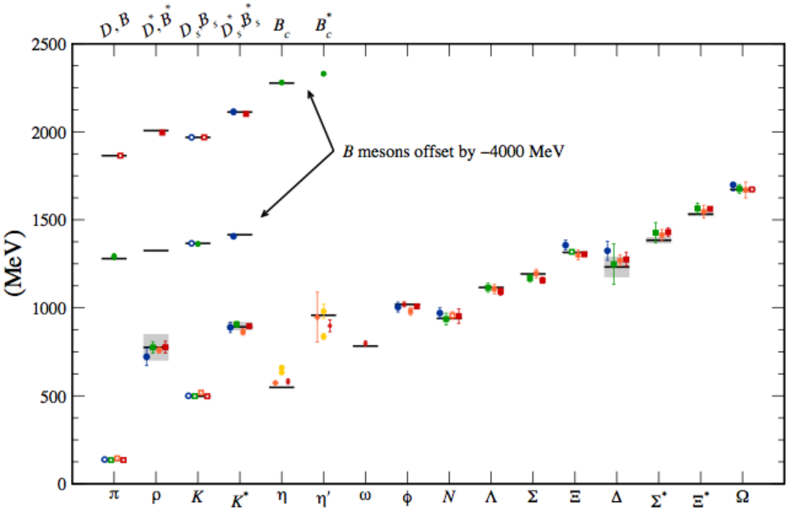

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- Dynamics=Geometry
  "Let no one ignorant of geometry enter my door", Platon

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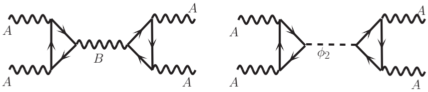
- The weak currents have a vector and an axial part. We know that, in general, we cannot enforce the conservation of both.

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



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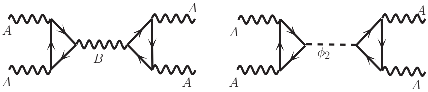

- Anomaly cancellation condition $\mathcal{A} = \sum_i Q_i = 0$

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- The 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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- This number is irreducible
  Any relation of the form $\lambda = f(g)$ *will not be respected by renormalisation*

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- The discovery of the BEH boson (CERN 2012)

THE STANDARD THEORY

In addition, it shows an impressive agreement with experiment in a very large number of detailed measurements.

For the first time we check weak interactions at the level of radiative corrections

The Standard Theory has become a
high precision theory

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The example of charm

Precision measurements at a given energy scale allow to guess new Physics at the next energy scale

Example : Yukawa's prediction of the π meson in 1934

The range of nuclear forces is of order 1 fermi ($\sim 10^{-13}$cm).

The Physics was correct, the details were not ! !

Example : The prediction for charmed particles in 1969

The absence, with very high accuracy, of certain weak decays

In the same way New Physics was predicted for LHC

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- Consider any 4-dim renormalisable theory.
- Integrate over all modes of the fields with energy above a given scale M.
- M does not have to correspond to a physical scale.
- You obtain an effective theory in terms of the « light » modes.
- The general form of this theory will be an infinite sum of terms :

$$\mathcal{L}_{\rm eff} = \sum_i C_i(g, M) O_i$$

Wilson's effective theory

Remarks :

• This expansion is valid irrespectively of whether the initial theory was "fundamental" or "effective".

• The operators O_i are all monomials in the fields and their derivatives compatible with the symmetries of the original quantum field theory.

• If the original theory was renormalisable, the c-number functions C_i can be computed order by order in perturbation.

• Their dependence on M can be deduced from dimensional analysis. If d_i is the dimension of the operator O_i, the corresponding coefficient is proportional to M to the power $(4 - d_i)$.

Wilson's effective theory

- "Irrelevant" operators : $d_i > 4$

- "Marginal" operators : $d_i = 4$

- Dominant" operators : $d_i < 4$

- In the Standard Model the only dominant operator is the scalar boson mass !
$O_{\phi^2} = \phi^2$ with $d = 2 \Rightarrow C_{\phi^2} \sim M^2$

- Can we make the corresponding coefficient equal to zero ? Yes, but we must introduce New Physics.

BUT . . .

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This time the argument failed.

- We were expecting new physics to be around the corner.....
  But we see no corner
- Or, maybe the corner is further away !

II. Specific points

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- The muon $g - 2$

  A persistant discrepancy between theory and experiment of order 3σ

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- Various other “small” effects

Neutrino masses and oscillations

Neutrino Physics

Fundamental Questions addressed by Diverse Neutrino Program

- What is the origin of neutrino mass?
- How are the neutrino masses ordered?
  - *Oscillation experiments*
- What is the absolute neutrino mass scale?
  - *Beta-decay spectrum*
  - *Cosmic surveys*
- Do neutrinos and anti-neutrinos oscillate differently?
  - *Oscillation experiments*
- Are there additional neutrino types and interactions?
  - *Oscillation experiments*
  - *Cosmic surveys*
- Are neutrinos their own anti-particles?
  - *Neutrinoless double-beta decay*

Neutrino masses and oscillations

My conclusion :

• A data-driven subject in which theorists have not played the major role.

• Substantial improvement in precision could be expected during the coming years.

• The significance of such improvements is not easy to judge.

• So far no real illumination came from leptons to be combined with the quark sector for a more complete theory of flavour

The trouble is that I do not see how this could change !

The easy answer : We need more data

Two problems : (i) We do not know what kind of data
(ii) They may not come for quite a long time

A rather frustrating problem !

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My Conclusions

- The Future of Particle Physics will undoubtedly be bright, but....
- I will not learn the answer
- We have a very successful Standard Theory and
  we will leave the problem of its completion to the younger generation.....