The Rise of GAUGE THEORIES

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- *From the Dark Ages to Enlightenment*

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- If the Scientific Institution appears to be more solid than the Economic one, it is because its foundations are made with ideas.

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- From dream to expectation.

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- Here I will talk only about the saga of gauge invariance:

  From CLASSICAL ELECTRODYNAMICS to
  THE STANDARD MODEL

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- 1867 : The first gauge condition $\partial_\mu A^\mu = 0$ by L.V. Lorenz
  and NOT Lorentz!!!

Classical Electrodynamics

- Around the years 1840 F.E. Neumann and, independently, W.E. Weber, studied the interaction between two closed electric circuits carrying currents I and I'.

  $\mathrm{d}W_N = \frac{II'}{c^2} \frac{\boldsymbol{n} \cdot \boldsymbol{n}'}{r} \mathrm{d}s \mathrm{d}s' \qquad \mathrm{d}W_W = \frac{II'}{c^2} \frac{(\boldsymbol{n} \cdot \hat{\boldsymbol{r}})(\boldsymbol{n}' \cdot \hat{\boldsymbol{r}})}{r} \mathrm{d}s \mathrm{d}s'$

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  $\mathrm{d}s\mathrm{d}s'\frac{\partial^2 r}{\partial s\partial s'} = \mathrm{d}s\mathrm{d}s'\frac{(\boldsymbol{n}\cdot\hat{\boldsymbol{r}})(\boldsymbol{n}'\cdot\hat{\boldsymbol{r}})-(\boldsymbol{n}\cdot\boldsymbol{n}')}{r}$

  and wrote the first family of gauges

  $\mathrm{d}W_\alpha = \frac{II'}{2c^2 r}[(1+\alpha)(\boldsymbol{n}\cdot\boldsymbol{n}') + (1-\alpha)(\boldsymbol{n}\cdot\hat{\boldsymbol{r}})(\boldsymbol{n}'\cdot\hat{\boldsymbol{r}})]\mathrm{d}s\mathrm{d}s'$

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- In terms of the vector potential

  $\boldsymbol{A}_\alpha = \boldsymbol{A}_N + \frac{1-\alpha}{2}\boldsymbol{\nabla}\Psi \qquad \Psi = -\frac{1}{c}\int \hat{\boldsymbol{r}}\cdot\boldsymbol{J}(\boldsymbol{x}', t)\mathrm{d}^3x'$

New gauge theories

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- 1914 : General Relativity as the gauge theory of Poincaré transformations.

  Although diffeomorphisms are logically unrelated to the gauge theories of the Standard Model, the fascination which general relativity had exerted to all this generation of physicists was such, that for many decades people were unable to separate them and they used gravitation even in places where it had no business to be there. I call it “the GR-syndrome”.

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- 1919 : Attempt to an EM-GR unification by H.K.H. Weyl.

  Enlarge diffeomorphisms by including local scale transformations

  $g \to \mathrm{e}^{2\lambda(x)} g$ "eichinvarianz" $\Rightarrow$ "gauge invariance"

  Weyl asked the right mathematical question but gave the wrong physical answer!

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- 1932 - 1938 W. Heisenberg - N. Kemmer : Isospin invariance of nuclear forces. The first non-Abelian internal symmetry.

  Naturally, one would expect the $SU(2)$ gauge theory to be constructed following the principles we sketched above: we had the global symmetry and we only needed to make it local.

New gauge theories

- The GR-syndrome. O. Klein (1938) and W. Pauli (1953)

  Fifteen years apart one from the other, they decided to construct the $SU(2)$ gauge theory for strong interactions and both choose to follow a totally counter-intuitive method.

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- 1956-1961 : Higher groups (R. Utiyama ; S.L. Glashow and M. Gell-Mann)

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- 1961 : S.L. Glashow : The $SU(2) \times U(1)$ model. The first unified description of weak and electromagnetic interactions. The photon is a linear combination of the fields associated to $U(1)$ and the third generator of $SU(2)$ with an angle called θ, (today it is called θ_W).

A Model of Leptons

1967 S. Weinberg (also A. Salam 1968)

In a single stroke solves three fundamental problems:
1) Uses the BEH mechanism to give masses to the intermediate gauge bosons.
2) Shows that the same mechanism generates a mass term for the charged lepton.
3) The same mechanism yet again gives rise to Glashow's mixing producing a mass for the Z^0 while leaving the photon massless.

Why did it go totally unnoticed?
(Practically no citations until 1972!)

Examples and Reasons
• Few understood it. • Few cared about the problems.
• Totally uninspired title
• We dismissed it at CERN. • In GIM none of us remebered it and we do not refer to it. • Even Weinberg had forgotten about it.

Fighting the infinite : Early attempts

- Vector and/or scalar intermediaries. $V - A$ is an illusion.

  1) W. Kummer and G. Segré, (1965).

  2) M. Gell-Mann, M.L. Goldberger, N.M. Kroll and F. Low, (1969)

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- Divergences and the Cabibbo angle

  1) R. Gatto, G. Sartori and M. Tonin, (1968, 1969)

  2) N. Cabibbo and L. Maiani, (1968, 1970)

  $\tan\theta = \sqrt{\frac{m_d}{m_s}} \quad ; \quad \frac{|m_d - m_u|}{m_d + m_u} \sim \mathcal{O}(1)$

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- It was fought in two fronts:

  1) The phenomenology, or the bottom-up front.
  Consider Fermi theory as an effective field theory valid up to a scale Λ and try to push Λ beyond reach.

  2) The field theory, or the top-down front.
  Prove that some version of massive Yang-Mills theory is renormalisable and hope it describes physics.

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- Victory in both fronts has been proven necessary for the final success.

  Weak Int. of the 60's DID NOT look like Yang-Mills!

Fighting the infinite : The bottom-up front

Fermi theory : The perturbation expansion

$$\mathcal{A} = \sum_{n=0}^{\infty} A_n^{(0)} g_{\rm eff}^n + G_F M^2 \sum_{n=0}^{\infty} A_n^{(1)} g_{\rm eff}^n + (G_F M^2)^2 \sum_{n=0}^{\infty} A_n^{(2)} g_{\rm eff}^n + \ldots$$

with $g_{\rm eff} = G_F \Lambda^2 \qquad G_F \sim 10^{-5} m_p^2$

- $\sum_{n=0}^{\infty} A_n^{(0)} g_{\rm eff}^n \quad \Rightarrow$ "Leading divergences" : $(G_F \Lambda^2)^n$
- $G_F M^2 \sum_{n=0}^{\infty} A_n^{(1)} g_{\rm eff}^n \quad \Rightarrow$ "Next-to-leading divergences"
- $(G_F M^2)^2 \sum_{n=0}^{\infty} A_n^{(2)} g_{\rm eff}^n \quad \Rightarrow$ "Next-to-next-to-leading divergences"

Naïve estimation : $g_{\rm eff} = G_F \Lambda^2 \sim 1 \quad \Rightarrow \quad \Lambda \sim 300$ GeV

Essentially infinite!

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- Why did most people not worry about it?
  (i) Ignorance. (ii) Mistrust in field theory in general and higher orders in particular. (iii) Religious belief that strong interactions would solve all problems, ...

  Ioffe and Shabalin had already pointed out that the divergences of weak interactions could not be affected by strong interactions, as long as the latter satisfy current algebra.

Fighting the infinite : The bottom-up front

- *The leading divergences. The breaking of* $SU(3) \times SU(3)$.

  At the limit of exact $SU(3) \times SU(3)$ there are no observable S and/or P violations. $\Rightarrow$ ALL such effects depend on the symmetry breaking mechanism.

  If chiral $SU(3) \times SU(3)$ is broken by a member of the $(3, \bar{3}) \oplus (\bar{3}, 3)$ representation, the matrix multiplying the leading divergent term is diagonal in flavor space.

  Cl. Bouchiat, J.I., J. Prentki (1968); J.I. (1969)

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- *The Next-to- leading divergences. Charm.*

  The solution of the leading divergence problem was found in the framework of the commonly accepted theory at that time. On the contrary, the next to leading divergences required a drastic modification, although, in retrospect, it is a quite natural one.

Fighting the infinite : The bottom-up front

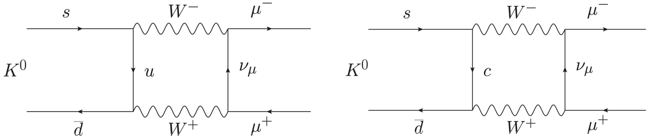
The Next-to- leading divergences. Charm.

It took us some time to find the answer because we were not thinking in terms of symmetry. In fact the answer was implicit in the Cabibbo theory:

Left-handed fermions must form doublets!

Weak Interactions with Lepton - Hadron Symmetry

The bonus with the bottom-up approach was an upper limit of m_c:



$m_c \leq 3$ GeV $\Rightarrow$ Weak Interactions as a Y-M theory.
No mention of BEH or Weinberg-Salam??

S.L. Glashow, J.I., L. Maiani (1970).

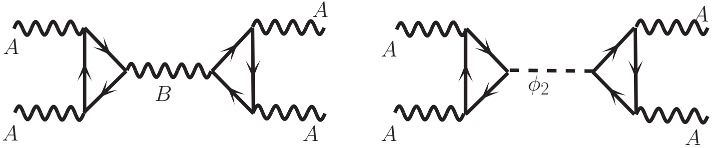
Fighting the infinite

Anticipate and go to 1972:

• For consistency of the underlying field theory, the currents coupled to the Y-M vector bosons must be conserved.

• In the Weinberg-Salam lepton model they are not because of the anomalous conservation of the axial current.

• As a result, the Ward identities are violated and the renormalisability and unitarity proofs fail.



Solution: Again Lepton - Hadron Symmetry. $\tau \Rightarrow t, b$

Families must be complete! *Cl. Bouchiat, J.I., Ph. Meyer (1972), D. Gross, R. Jackiw (1972)*

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- Formally derived by L.D. Faddeev and V.N. Popov using the Feynman path integral in 1967. $\Rightarrow$ Faddeev-Popov ghosts.

Fighting the infinite : The top-down front

- No serious study of Y-M field theories for many years.
- Early attempts only as a laboratory for gravitation
- The Feynman rules not easy to guess. Experience from QED misleading.
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- Formally derived by L.D. Faddeev and V.N. Popov using the Feynman path integral in 1967. $\Rightarrow$ Faddeev-Popov ghosts.
- None of these results was widely known.

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- For several years, the only systematic study was that of Martinus (Tini) Veltman (1966 –).
- He started with the divergence equations of the weak currents and derived a set of generalised covariant derivatives. This prompted him to look at the theory of charged vector fields.
- The corresponding field theory is highly non renormalisable, but Veltman discovered by direct calculation that many divergences cancel if the values of the electric charge, magnetic moment and quadrupole moment of the vector fields satisfy a certain relation: $\mu = e(1+\kappa)/2m_W$ and $Q = -e\kappa/m_W^2$ with $\kappa = 1$. It is the value predicted by a theory in which $W^{\pm}$ and the photon form a Yang-Mills triplet. For Veltman this was a clear signal that the theory of weak and electromagnetic interactions must obey a Yang-Mills gauge invariance.

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- Their work was a real "tour de force". They had to re-invent essentially everything: Feynman rules, ghosts, regularisation scheme, BEH mechanism, ect.
- Their success in 1972 is a landmark in the theory of elementary particles.
  S. Weinberg : *"...and then, all hell broke loose!"*

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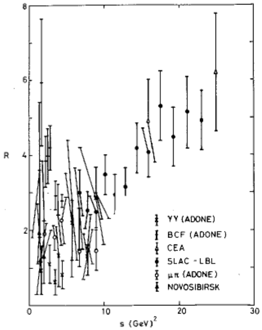
- Admittedly, it takes a solid faith in quantum field theory to accept all these claims.

The Price of the Standard Model

Scaling violations in DIS

The ratio $R(Q^2) = \frac{\sigma(e^+ + e^- \rightarrow \text{hadrons})}{\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)}$

should be a constant. But it seemed to be rising !!

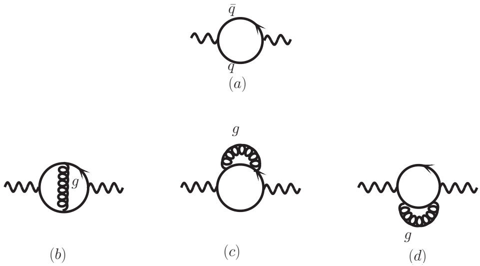


A compilation of all early measurements of the ratio R, as presented in the 1974 London International Conference on High Energy Physics by Burton Richter.

The long road to verification

II. The rising R and the hidden charm

The QCD corrections at order α_s are given by the diagrams:



$$R(Q^2) = \sum_i e_i^2 \left(1 + \frac{\alpha_s(Q^2)}{\pi} + \mathcal{O}(\alpha_s^2)\right)$$

with

$$\alpha_s(Q^2) = \frac{1}{4\pi b_0 \ln(Q^2/\Lambda^2)} \text{ and } \Lambda \sim \mathcal{O}(200 \text{ MeV})$$

R should approach the value of 2 from above

The long road to verification

II. The rising *R* and the hidden charm

Excerpts from my report on Gauge Theories at the London Conference:

"...the hadron production cross section, which absolutely refuses to fall, creates a serious problem. The best explanation may be that we are observing the opening of the charmed thresholds, in which case everything fits together very nicely."

Charm would add 4/3 to R. Accident: τ was at the same energy.

"I have won already several bottles of wine by betting for the neutral currents and I am ready to bet now a whole case that if the weak interaction sessions of this Conference were dominated by the discovery of the neutral currents, the entire next Conference will be dominated by the discovery of the charmed particles."

The long road to verification

II. The rising *R* and the hidden charm : In November 1974 both Brookhaven and Stanford published their results. SPEAR decided to sweep the region above 3 GeV in fine steps of 1 MeV. To their great surprise they obtained a totally different picture.

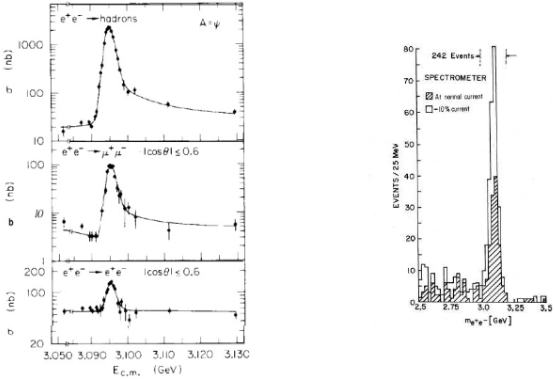


Figure 2.1: The discovery of the J/ψ meson in November 1974 independently by two experiments, SPEAR (left) and AGS (right). Both exhibit peaks in the oppositely charged dielectron mass spectrum consistent with the J/ψ mass at 3.1 GeV.

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  ϕ : m_ϕ=1020 MeV, Γ_ϕ=4.2 MeV, but $\phi \to K\bar{K} = 83\%$
  despite the tiny phase space
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- Okubo-Zweig-Iizuka (OZI) rule
  Another empirical rule with no theoretical foundation in the dark ages
- Good explanation in QCD and a prediction (post-diction ?) of $\Gamma_{J/\psi} \approx$ 80 keV !!!

The long road to verification

III. The real charm and heavier flavours

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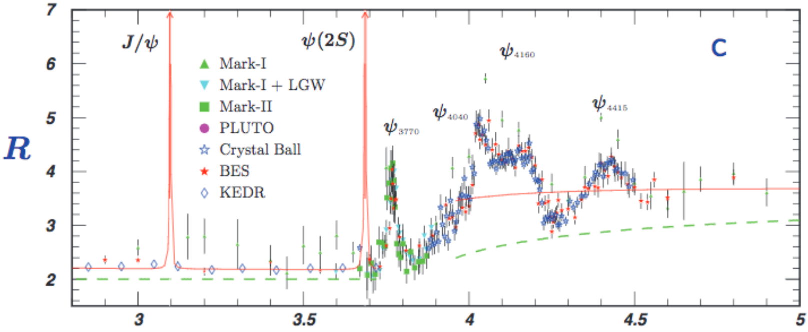
- 

  The value of R for energies between 3 and 5 GeV.

The long road to verification

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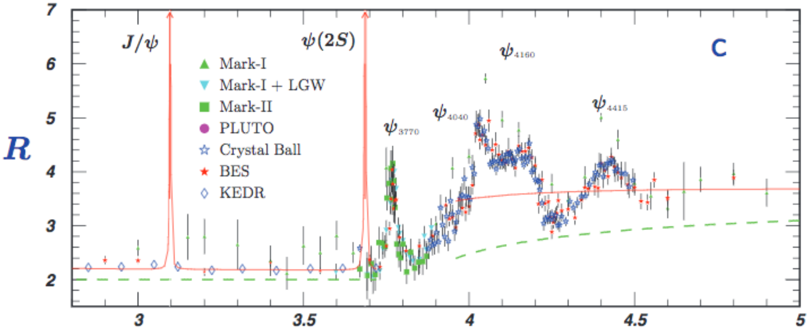
- 

  The value of R for energies between 3 and 5 GeV.

- Families are complete : Existence of τ implies that of b and t

The long road to verification

III. The real charm and heavier flavours

Mesons with naked charm were naturally discovered among the decay products of the broad resonances we see above 4 GeV. It was in 1976. In the meantime a rich charmonium spectroscopy was discovered in full agreement with the theoretical predictions. Although nobody paid the bet I offered in the 1974 Conference, the entire 1976 one was indeed dominated by charmed particles and gauge theories.

The phase transition was complete.

The order parameter has been the fraction of physicists who changed their views: from many models to one theory; a small minority before 1974 to the large majority after 1976.

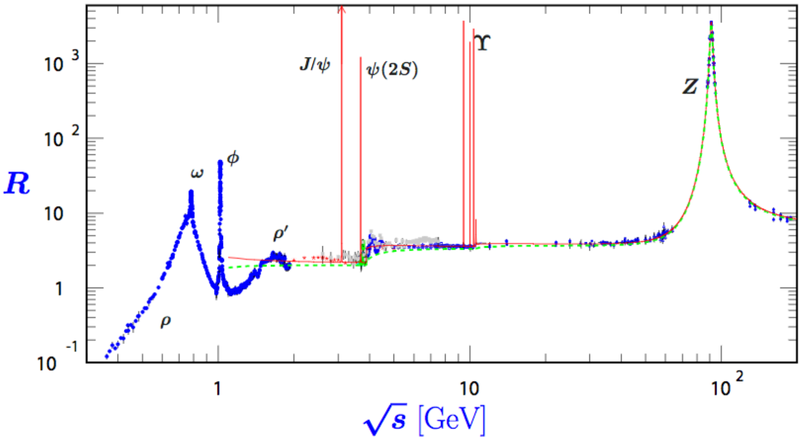
The long road to verification

• The complete verification took many more years and many great discoveries, but the mood of the community had changed.

• The following discoveries of the vector bosons, the top, the gluon jets and the BEH scalar as well as the very good general fit using all available data, were no more great surprises, they were expected.

THE STANDARD MODEL has become THE STANDARD THEORY

What next?



The ratio R from low energies, up to and above the Z mass. The green curve is the parton model prediction and the red one includes QCD corrections. Remarkable agreement.

What next?

A striking feature of the data is that perturbation theory is reliable – outside the region of strong interactions – beyond any expectation! Why?

$A_n \sim \alpha^n (2n-1)!!$

Perturbation theory breaks down when $A_n \sim A_{n+1}$

$2n+1 \sim \alpha^{-1}$

For QED $n >> 1$; For QCD ???

$\Rightarrow$ It seems that we have an experimental fact saying that perturbation theory can be trusted, even if we do not fully understand why.

What next?

In a talk I gave at a meeting of the European Physical Society in 2011, I said:

I want to exploit this experimental fact and argue that the available precision tests of the Standard Model allow us to claim with confidence that new physics is present at the TeV scale and the LHC can, probably, discover it.
The argument assumes the validity of perturbation theory and it will fail if the latter fails. But, as we just saw, perturbation theory breaks down only when strong interactions become important. But new strong interactions imply new physics.

My conclusion was that, for LHC, which was about to start operating, new physics was around the corner!

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- Today we know that LHC found no corner!

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THANK YOU