THE STANDARD MODEL

is complete

J.Iliopoulos

Ecole Normale Supérieure, Paris

Windows on the Universe

Quy Nho'n, Viet Nam, August 2013

- **The recent discovery of a new particle at CERN made headlines in world media**

- **The recent discovery of a new particle at CERN made headlines in world media**

- **The discovery itself was a triumph of technology and ingeniouity**

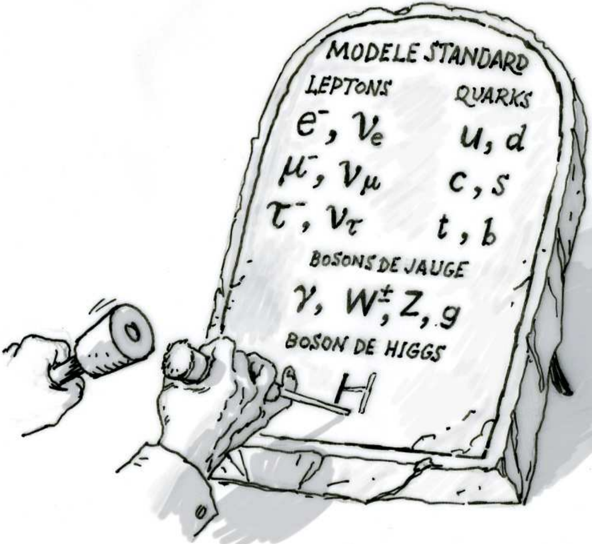
- **The recent discovery of a new particle at CERN made headlines in world media**

- The discovery itself was a triumph of technology and ingeniouity

- But the excitement was mainly due to its potential theoretical significance

- **The last stone in the Standard Model edifice**

- **The last stone in the Standard Model edifice**



The Standard Model has been enormously successful

- **The precision of the measurements often led to successful predictions of new Physics.**

The Standard Model has been enormously successful

- **The precision of the measurements often led to successful predictions of new Physics.**
- The discovery of weak neutral currents by Gargamelle in 1972

  $$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \quad ; \quad \nu_\mu + N \rightarrow \nu_\mu + X$$

  Both, their strength and their properties were predicted by the Model.

The Standard Model has been enormously successful

- **The precision of the measurements often led to successful predictions of new Physics.**
- The discovery of weak neutral currents by Gargamelle in 1972

  $\nu_\mu + e^- \to \nu_\mu + e^- \quad ; \quad \nu_\mu + N \to \nu_\mu + X$

  Both, their strength and their properties were predicted by the Model.
- The discovery of charmed particles at SLAC in 1974-1976

  Their presence was essential to ensure the absence of strangeness changing neutral currents, ex. $K^0 \to \mu^+ + \mu^-$

  Their characteristic property is to decay predominantly in strange particles.

The Standard Model has been enormously successful

- A necessary condition for the consistency of the Model is that $\sum_i Q_i = 0$ inside each family.

  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.

The Standard Model has been enormously successful

- A necessary condition for the consistency of the Model is that $\sum_i Q_i = 0$ inside each family.

  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.

- The discovery of the W and Z bosons at CERN in 1983

  The characteristic relation of the Standard Model with an isodoublet Higgs mechanism $m_Z = m_W / cos\theta_W$ is checked with very high accuracy (including radiative corrections).

The Standard Model has been enormously successful

- A necessary condition for the consistency of the Model is that $\sum_i Q_i = 0$ inside each family.

  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.

- The discovery of the W and Z bosons at CERN in 1983

  The characteristic relation of the Standard Model with an isodoublet Higgs mechanism $m_Z = m_W / cos\theta_W$ is checked with very high accuracy (including radiative corrections).

- The t-quark was *seen* at LEP through its effects in radiative corrections before its actual discovery at Fermilab.

The Standard Model has been enormously successful

- A necessary condition for the consistency of the Model is that $\sum_i Q_i = 0$ inside each family.

  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.

- The discovery of the W and Z bosons at CERN in 1983

  The characteristic relation of the Standard Model with an isodoublet Higgs mechanism $m_Z = m_W/cos\theta_W$ is checked with very high accuracy (including radiative corrections).

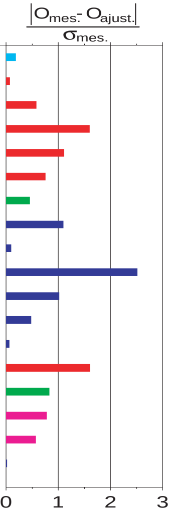
- The t-quark was *seen* at LEP through its effects in radiative corrections before its actual discovery at Fermilab.

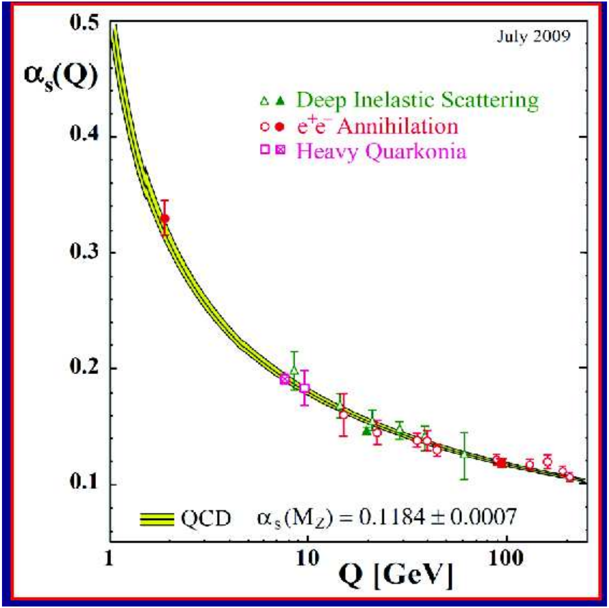
- The final touch: The recent discovery of the Brout-Englert-Higgs scalar

All this success is in fact the triumph of renormalised perturbation theory!

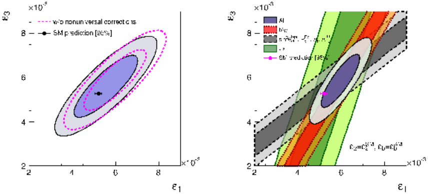
For the first time ALL fundamental interactions in High Energy Physics are tested at the level of radiative corrections

Observable	Mesure	Ajustement
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1





0.5
0.4
0.3
0.2
0.1
$\alpha_s(Q)$
July 2009
Deep Inelastic Scattering
e^+e^- Annihilation
Heavy Quarkonia
QCD $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
1
10
100
Q [GeV]



SM prediction [95%]
ε1
ε3

$$\epsilon_1 = \frac{3G_F m_t^2}{8\sqrt{2}\pi^2} - \frac{3G_F m_W^2}{4\sqrt{2}\pi^2} \tan^2\theta_W \ln\frac{m_H}{m_Z} + \ldots \tag{1}$$

$$\epsilon_3 = \frac{G_F m_W^2}{12\sqrt{2}\pi^2} \ln\frac{m_H}{m_Z} - \frac{G_F m_W^2}{6\sqrt{2}\pi^2} \ln\frac{m_t}{m_Z} + \ldots \tag{2}$$

Do we understand the Physics? I.

- Landau-Ginsburg vs BCS

Do we understand the Physics? I.

- Landau-Ginsburg vs BCS

- L.D. Landau and B.L. Ginzburg JETP **20** (1950) 1064

$$\Delta\vec{A} = \ldots\ldots.. + \frac{4\pi e^2}{mc^2}|\Psi|^2\vec{A} \quad \Rightarrow \quad \vec{A}(x) \sim \vec{A}(0)e^{-x/\lambda}$$

Do we understand the Physics? I.

- Landau-Ginsburg vs BCS

- L.D. Landau and B.L. Ginzburg JETP **20** (1950) 1064

$$\Delta\vec{A} = \dots\dots + \frac{4\pi e^2}{mc^2}|\Psi|^2\vec{A} \quad \Rightarrow \quad \vec{A}(x) \sim \vec{A}(0)e^{-x/\lambda}$$

- In BCS the physical meaning of Ψ is revealed

Do we understand the Physics? I.

- Landau-Ginsburg vs BCS
- L.D. Landau and B.L. Ginzburg JETP **20** (1950) 1064

$$\Delta\vec{A} = \ldots\ldots\ldots + \frac{4\pi e^2}{mc^2}|\Psi|^2\vec{A} \quad \Rightarrow \quad \vec{A}(x) \sim \vec{A}(0)e^{-x/\lambda}$$

- In BCS the physical meaning of Ψ is revealed
- **But here we see the particle!**

Do we understand the Physics? II.

- Gauge Theories contain two independent worlds:

Do we understand the Physics? II.

- Gauge Theories contain two independent worlds:
- The gauge bosons: Their number and their dynamics are determined by Geometry

Do we understand the Physics? II.

- Gauge Theories contain two independent worlds:
- The gauge bosons: Their number and their dynamics are determined by Geometry
- The fermions are arbitrary, but their dynamics is not.

Do we understand the Physics? II.

- Gauge Theories contain two independent worlds:
- The gauge bosons: Their number and their dynamics are determined by Geometry
- The fermions are arbitrary, but their dynamics is not.
- Do we need a third world, The world of scalars?

  Many arbitrary parameters. Their masses are unstable Why??

Do we understand the Physics? II.

- Possible theoretical answers:

Do we understand the Physics? II.

- Possible theoretical answers:
- No elementary scalars.

  Does not seem to work

Do we understand the Physics? II.

- Possible theoretical answers:
- No elementary scalars.

  Does not seem to work
- Supersymmetry. The scalars complete the massive vector supermultiplet.

  We do not know where and how it is broken.

Do we understand the Physics? II.

- Possible theoretical answers:
- No elementary scalars.

  Does not seem to work
- Supersymmetry. The scalars complete the massive vector supermultiplet.

  We do not know where and how it is broken.
- Could the scalars become also geometrical?

Do we understand the Physics? III.

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

Do we understand the Physics? III.

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

- But the internal symmetry transformations are only local in space-time.

  Is Kaluza-Klein the answer?

Do we understand the Physics? III.

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

- But the internal symmetry transformations are only local in space-time.

  Is Kaluza-Klein the answer?

- Question: Is there a space on which Internal symmetry transformations act as Diffeomorphisms?

Do we understand the Physics? III.

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

- But the internal symmetry transformations are only local in space-time.

  Is Kaluza-Klein the answer?

- Question: Is there a space on which Internal symmetry transformations act as Diffeomorphisms?

- Answer: Yes, but it is a space with non-commutative geometry.

  A space defined by an algebra of matrix-valued functions

History

- Short distance singularities. ???

Heisenberg $\to$ Peierls $\to$ Pauli $\to$ Oppenheimer $\to$ Snyder

History

- Short distance singularities. ???

  Heisenberg $\rightarrow$ Peierls $\rightarrow$ Pauli $\rightarrow$ Oppenheimer $\rightarrow$ Snyder

- External fluxes.

  Landau (1930) ; Peierls (1933)

History

- Short distance singularities. ???

  Heisenberg $\rightarrow$ Peierls $\rightarrow$ Pauli $\rightarrow$ Oppenheimer $\rightarrow$ Snyder

- External fluxes.

  Landau (1930) ; Peierls (1933)

- Seiberg-Witten map.

History

- Short distance singularities. ???

  Heisenberg $\rightarrow$ Peierls $\rightarrow$ Pauli $\rightarrow$ Oppenheimer $\rightarrow$ Snyder

- External fluxes.

  Landau (1930) ; Peierls (1933)

- Seiberg-Witten map.

- The construction of gauge theories using the techniques of non-commutative geometry.

History

- Short distance singularities. ???

  Heisenberg $\rightarrow$ Peierls $\rightarrow$ Pauli $\rightarrow$ Oppenheimer $\rightarrow$ Snyder

- External fluxes.

  Landau (1930) ; Peierls (1933)

- Seiberg-Witten map.

- The construction of gauge theories using the techniques of non-commutative geometry.

- Large N gauge theories and matrix models.

Large N field theories

- $\phi^i(x)\ i = 1, ..., N\ ;\ N \to \infty$

  $\phi^i(x) \to \phi(\sigma, x)\ 0 \leq \sigma \leq 2\pi$

  $\sum_{i=1}^{\infty} \phi^i(x)\phi^i(x) \to \int_0^{2\pi} d\sigma(\phi(\sigma, x))^2$

Large N field theories

- $\phi^i(x)\ i = 1, ..., N\ ;\ N \to \infty$

  $\phi^i(x) \to \phi(\sigma, x)\ 0 \leq \sigma \leq 2\pi$

  $\sum_{i=1}^{\infty} \phi^i(x)\phi^i(x) \to \int_0^{2\pi} d\sigma(\phi(\sigma, x))^2$

- but

  $\phi^4 \to (\int)^2$

Large N field theories

- $\phi^i(x)\ i = 1, ..., N\ ;\ N \to \infty$

  $\phi^i(x) \to \phi(\sigma, x)\ 0 \leq \sigma \leq 2\pi$

  $\sum_{i=1}^{\infty} \phi^i(x)\phi^i(x) \to \int_0^{2\pi} d\sigma(\phi(\sigma, x))^2$

- but

  $\phi^4 \to (\int)^2$

- however

  For a Yang-Mills theory, the resulting expression is local

Gauge theories on surfaces

Given an $SU(N)$ Yang-Mills theory in a $d-$dimensional space

$$A_\mu(x) \ = \ A_\mu^a(x)\ t_a$$

there exists a large N limit such that:

$$(A_\mu(x))^a_b \to \mathcal{A}_\mu(x,\sigma_1,\sigma_2) \qquad (F_{\mu\nu}(x))^a_b \to \mathcal{F}_{\mu\nu}(x,\sigma_1,\sigma_2)$$

Gauge theories on surfaces

- The gauge transformations of the $SU(N)$ Yang-Mills theory become area preserving diffeomorphisms of the surface:

$$
\begin{aligned}
\delta A_\mu &= \partial_\mu \omega(x) + [A_\mu, \omega] \ \rightarrow \ \delta \mathcal{A}_\mu \ = \ \partial_\mu \omega(x, \sigma_1, \sigma_2) + \{\mathcal{A}_\mu, \omega\} \\
\delta F_{\mu\nu} &= [F_{\mu\nu}, \omega] \ \rightarrow \ \delta \mathcal{F}_{\mu\nu} \ = \ \{\mathcal{F}_{\mu\nu}, \omega\} \\
\mathcal{F}_{\mu\nu} &= \partial_\mu \mathcal{A}_\nu \ - \ \partial_\nu \mathcal{A}_\mu \ + \ \{\mathcal{A}_\mu, \mathcal{A}_\nu\}
\end{aligned}
$$

Gauge theories on surfaces

- The gauge transformations of the $SU(N)$ Yang-Mills theory become area preserving diffeomorphisms of the surface:

$$
\begin{aligned}
\delta A_\mu &= \partial_\mu \omega(x) + [A_\mu, \omega] \ \rightarrow \ \delta \mathcal{A}_\mu \ = \ \partial_\mu \omega(x, \sigma_1, \sigma_2) + \{\mathcal{A}_\mu, \omega\} \\
\delta F_{\mu\nu} &= [F_{\mu\nu}, \omega] \ \rightarrow \ \delta \mathcal{F}_{\mu\nu} \ = \ \{\mathcal{F}_{\mu\nu}, \omega\} \\
\mathcal{F}_{\mu\nu} &= \partial_\mu \mathcal{A}_\nu \ - \ \partial_\nu \mathcal{A}_\mu \ + \ \{\mathcal{A}_\mu, \mathcal{A}_\nu\}
\end{aligned}
$$

- The $SU(N)$ matrix commutators are replaced by Poisson brackets with respect to the variables σ_1 and σ_2

Gauge theories on surfaces

- The gauge transformations of the $SU(N)$ Yang-Mills theory become area preserving diffeomorphisms of the surface:

$$
\begin{aligned}
\delta A_\mu &= \partial_\mu \omega(x) + [A_\mu, \omega] \;\rightarrow\; \delta \mathcal{A}_\mu \;=\; \partial_\mu \omega(x, \sigma_1, \sigma_2) + \{\mathcal{A}_\mu, \omega\} \\
\delta F_{\mu\nu} &= [F_{\mu\nu}, \omega] \;\rightarrow\; \delta \mathcal{F}_{\mu\nu} \;=\; \{\mathcal{F}_{\mu\nu}, \omega\} \\
\mathcal{F}_{\mu\nu} &= \partial_\mu \mathcal{A}_\nu \;-\; \partial_\nu \mathcal{A}_\mu \;+\; \{\mathcal{A}_\mu, \mathcal{A}_\nu\}
\end{aligned}
$$

- The $SU(N)$ matrix commutators are replaced by Poisson brackets with respect to the variables σ_1 and σ_2
- The classical action becomes

$$
S \;\sim\; -\frac{1}{4} \int Tr F_{\mu\nu} F^{\mu\nu} d^4 x \;\rightarrow\; \mathcal{S} \;\sim\; \frac{1}{4} \int \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu} d^4 x d\sigma_1 d\sigma_2
$$

Gauge theories on surfaces

- The $SU(N)$ algebra $\rightarrow$ The algebra of the area preserving diffeomorphisms of a closed surface.

Gauge theories on surfaces

- The $SU(N)$ algebra $\rightarrow$ The algebra of the area preserving diffeomorphisms of a closed surface.
- The structure constants of $[SDiff(S^2)]$ are the limits for large N of those of $SU(N)$.

Gauge theories on surfaces

- **To all orders in** $1/N$

Gauge theories on surfaces

- **To all orders in** $1/N$
- Given an $SU(N)$ Yang-Mills theory in a $d-$dimensional space

$$A_\mu(x) \;=\; A_\mu^a(x)\; t_a$$

Gauge theories on surfaces

- **To all orders in** $1/N$

- Given an $SU(N)$ Yang-Mills theory in a $d-$dimensional space

$$A_\mu(x) \; = \; A^a_\mu(x) \; t_a$$

- There exists a reformulation in $d+2$ dimensions

$$A_\mu(x) \to \mathcal{A}_\mu(x, z_1, z_2) \qquad F_{\mu\nu}(x) \to \mathcal{F}_{\mu\nu}(x, z_1, z_2)$$

with $$[z_1, z_2] = \frac{2i}{N}$$

- $[A_\mu(x), A_\nu(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \mathcal{A}_\nu(x, z_1, z_2)\}_{Moyal}$

  $[A_\mu(x), \Omega(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \Omega(x, z_1, z_2)\}_{Moyal}$

  $\int d^4x \;\; Tr\left(F_{\mu\nu}(x) F^{\mu\nu}(x)\right) \quad \to$
  $\int d^4x dz_1 dz_2 \;\; \mathcal{F}_{\mu\nu}(x, z_1, z_2) * \mathcal{F}^{\mu\nu}(x, z_1, z_2)$

- $[A_\mu(x), A_\nu(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \mathcal{A}_\nu(x, z_1, z_2)\}_{Moyal}$

  $[A_\mu(x), \Omega(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \Omega(x, z_1, z_2)\}_{Moyal}$

  $$\int d^4x \;\; Tr\left(F_{\mu\nu}(x) F^{\mu\nu}(x)\right) \quad \to$$
  $$\int d^4x dz_1 dz_2 \;\; \mathcal{F}_{\mu\nu}(x, z_1, z_2) * \mathcal{F}^{\mu\nu}(x, z_1, z_2)$$

- **Gauge theories are equivalent to field theories on fuzzy surfaces**

- $[A_\mu(x), A_\nu(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \mathcal{A}_\nu(x, z_1, z_2)\}_{Moyal}$

  $[A_\mu(x), \Omega(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \Omega(x, z_1, z_2)\}_{Moyal}$

  $$\int d^4x \;\; Tr\,(F_{\mu\nu}(x)F^{\mu\nu}(x)) \quad \to$$
  $$\int d^4x dz_1 dz_2 \;\; \mathcal{F}_{\mu\nu}(x, z_1, z_2) * \mathcal{F}^{\mu\nu}(x, z_1, z_2)$$

- **Gauge theories are equivalent to field theories on fuzzy surfaces**

- Non-Commutative Geometry is a property of gauge theories

- $[A_\mu(x), A_\nu(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \mathcal{A}_\nu(x, z_1, z_2)\}_{Moyal}$

  $[A_\mu(x), \Omega(x)] \to \{\mathcal{A}_\mu(x, z_1, z_2), \Omega(x, z_1, z_2)\}_{Moyal}$

  $\int d^4x \;\; Tr\left(F_{\mu\nu}(x) F^{\mu\nu}(x)\right) \quad \to$
  $\int d^4x dz_1 dz_2 \;\; \mathcal{F}_{\mu\nu}(x, z_1, z_2) * \mathcal{F}^{\mu\nu}(x, z_1, z_2)$

- **Gauge theories are equivalent to field theories on fuzzy surfaces**

- Non-Commutative Geometry is a property of gauge theories

- Whether it will turn out to be a useful property is still questionable.

Conclusions

- **The completion of the Standard Model strongly indicates that new and exciting Physics is around the corner**

Conclusions

- **The completion of the Standard Model strongly indicates that new and exciting Physics is around the corner**
- **But, for the moment, we see no corner!**

To end, a story:

- A Chinese, an Italian and a Greek were arguing which one among these three ancient civilisations was the most advanced.

To end, a story:

- A Chinese, an Italian and a Greek were arguing which one among these three ancient civilisations was the most advanced.
- The Chinese: We invented printing, cast iron, explosives.....

To end, a story:

- A Chinese, an Italian and a Greek were arguing which one among these three ancient civilisations was the most advanced.
- The Chinese: We invented printing, cast iron, explosives.....
- The Italian: All these are not High Tech. When we excavated under Rome, we found traces of cables. The ancient Romans had a fully operating telephone system!

To end, a story:

- A Chinese, an Italian and a Greek were arguing which one among these three ancient civilisations was the most advanced.
- The Chinese: We invented printing, cast iron, explosives.....
- The Italian: All these are not High Tech. When we excavated under Rome, we found traces of cables. The ancient Romans had a fully operating telephone system!
- The Greek: Old fashion technology. When we excavated under Athens, we found nothing. The ancient Greeks were using wireless communications!