THE STANDARD MODEL AND EXPERIMENT

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The STANDARD MODEL in Particle Physics

A Quantum Field Theory describing in a unified framework

all

experimentally known interactions among elementary particles.

What is an ELEMENTARY PARTICLE?

or, **What is the World made of ?**

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- I. The constituents of matter

  Over the last century we have uncovered many layers of this cosmic onion:
  atoms $\rightarrow$
  nuclei + *electrons* $\rightarrow$
  protons + *neutrons* + *electrons* $\rightarrow$
  quarks + *electrons* $\rightarrow$ *??*

  There is no reason to believe that there exists such a thing as "an innermost layer" and, even less, that we have already reached it.

What is an ELEMENTARY PARTICLE?

or, **What is the World made of ?**

II. The Quanta of Radiation

Like the photon, they transmit the interactions.
We know that all interactions are mediated by the exchange of such quanta.
The range of every interaction depends on the mass of the corresponding quantum

$$V(r) \sim \frac{\mathrm{e}^{-mr}}{r}$$

TABLE OF ELEMENTARY PARTICLES		
QUANTA OF RADIATION		
Strong Interactions		Eight gluons
Electromagnetic Interactions		Photon (γ)
Weak Interactions		Bosons W^+ , W^- , Z^0
Gravitational Interactions		Graviton (?)
MATTER PARTICLES		
	Leptons	Quarks
1st Family	ν_e , e^-	u_a , d_a , $a = 1, 2, 3$
2nd Family	ν_μ , μ^-	c_a , s_a , $a = 1, 2, 3$
3rd Family	ν_τ , τ^-	t_a , b_a , $a = 1, 2, 3$
BROUT-ENGLERT-HIGGS BOSON		

This Table shows our present ideas on the structure of matter. Quarks and gluons do not exist as free particles and the graviton has not yet been observed

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- *The weak interactions.*
  Responsible for nuclear β-decay as well as the decays of other unstable particles.
- *The gravitational interactions.*
  Manifest in everyday life, they are responsible for the large scale structure of the Universe. At the microscopic level, their effects are too small to be observable.

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It is based on two fundamental principles:

- A Dynamical Theory $\equiv$ A Quantum Field Theory
- A property of Symmetry (a "gauge" symmetry) which brings Geometry into Physics.

I. The Dynamics

The two classical forces
-**Electromagnetism**
-**Gravitation**

are both described by the same classical potential:

$$V(r) \sim 1/r$$

which is singular for $r \to 0$.

A classical atom is unstable!

- Non-Relativistic Quantum Mechanics
  solves this problem

$$\Delta(x)\ \Delta(p) \geq \hbar$$

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- A remark: The uncertainty relations solve the problem of the $1/r$ potential.
  Not for every potential

- Modern theoretical Physics has a precise date of birth
  June 2-4 1947, the Shelter Island Conference

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- Quantum Electrodynamics seemed to be the only interesting case

Classical Mechanics $\Rightarrow [q(t), p(t)] = i\hbar \Rightarrow$ **Quantum Mechanics**

$q(t), p(t)$

$\Downarrow$ $\Downarrow$

$q_i(t), p_i(t)$ $\Rightarrow [q_i(t), p_i(t)] = i\hbar\delta_{ij}$

$i = 1, ..., N$

$N \to \infty$

$\Downarrow$ $\Downarrow$

Classical Field Theory $\Rightarrow [q(\vec{x}, t), p(\vec{y}, t)] = i\hbar\delta^3(\vec{x} - \vec{y}) \Rightarrow$ **Quantum Field Theory**

$q(\vec{x}, t), p(\vec{x}, t)$

- **Classical Field Theory**

  =

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  With an infinite number of degrees of freedom

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- It is always the case with a relativistic theory

Historical notes

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- 1933 : Fermi

  Fermions quantised. Quantum Field Theory becomes the language of microscopic physics

Renormalisable theories

In our four dimensional space there exist FIVE renormalisable quantum field theories:

- $\phi^3(x)$
- $\phi^4(x)$
- The Yukawa interaction: $\bar{\psi}(x)\psi(x)\phi(x)$
- QED: $\bar{\psi}(x)\gamma_\mu\psi(x)A^\mu(x)$
(and scalar QED)
- The Yang-Mills interaction: $Tr(F^{\mu\nu}(x)F_{\mu\nu}(x))$

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- Nature uses ALL five renormalisable theories, and ONLY them, as fundamental theories
- We only have approximate solutions
- The effective strength of the interaction depends in a calculable way on the energy, or distance, scale. (Renormalisation group)

The uses of Quantum Field Theory

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- Cosmology and astrophysics

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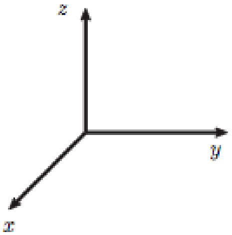
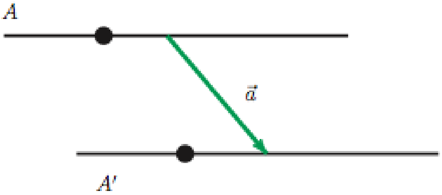
- The position of the origin of the coordinate system $\Rightarrow$
  We can move the coordinate system $\Rightarrow$
  Invariance under translations

- The direction of the axes in space $\Rightarrow$
  We can rotate the coordinate system $\Rightarrow$
  Invariance under rotations

Invariance under translations

$$\vec{x}' = \vec{x} + \vec{a}$$





If A is the trajectory of a free particle in the (x,y,z) system, its image, A', is also a possible trajectory of a free particle.

The first abstraction: Internal Symmetries

Heisenberg 1932

electron with spin up ⇑

electron with spin down ⇓

rotation

proton=nucleon with isospin up ⇑

neutron=nucleon with isospin down ⇓

rotation

in iso-space

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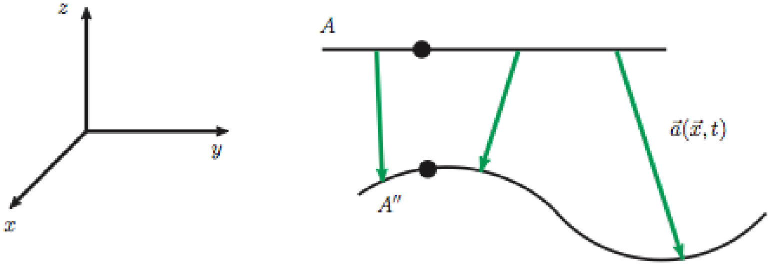
- With the discovery of new internal symmetries the idea was generalised to multi-dimensional internal spaces.
- The space of Physics became an abstract mathematical concept with non-trivial geometrical and topological properties.
- Only a part of it, the three-dimensional Euclidean space, is directly accessible to our senses.

A further abstraction: Local Symmetries

Einstein 1918

Local space translations

$$\vec{x}'' = \vec{x} + \vec{a}(\vec{x}, t)$$



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- **Surprise:** The Dynamics which is invariant under local translations is

GENERAL RELATIVITY

The resulting force is Gravity
One of the four fundamental forces.

Local Internal Symmetries

The gravitational forces are not the only ones which have a geometrical origin

- The example of the quantum mechanical phase:

  $\Psi(x) \rightarrow e^{i\theta}\Psi(x) \qquad \text{with} \qquad \theta \rightarrow \theta(x)$

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- Replacing ∂_μ by D_μ turns any equation which was invariant under the global phase transformation, invariant under the local (gauge) one.
  Fock 1926

Local Internal Symmetries

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- To obtain the fully interacting theory:

  Add the energy of the new vector field:

  $\sim F_{\mu\nu}^2 = (\partial_\mu A_\nu - \partial_\nu A_\mu)^2$

  The resulting interaction is:

  QUANTUM ELECTRODYNAMICS

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- **DYNAMICS = GEOMETRY**

  Platon : "Μηδείς αγεωμέτρητος εισίτω την στέγην."

  "Let no one ignorant of geometry enter under this roof"

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- It can be implemented in an internal space with as many as ten dimensions
- But then we faced a new problem:

  THE PROBLEM OF MASS

The problem of mass

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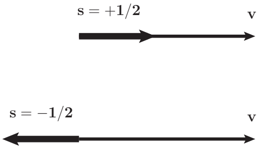
- 

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- Most of the particles in our Table are massive

  This was **THE PROBLEM OF MASS**

Spontaneous Symmetry Breaking (SSB)

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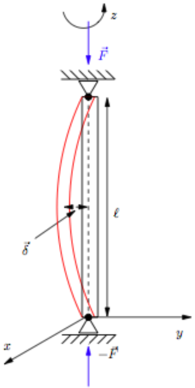
- An infinite system may exhibit the phenomenon of phase transitions. It often implies a reduction in the symmetry of the ground state.
- For a field theory, in many cases, we encounter at least two phases:

  (i) *The unbroken*, or, *the Wigner phase*: A symmetry is manifest in the spectrum of the theory whose excitations form irreducible representations of the symmetry group. For a gauge theory the vector gauge bosons are massless and belong to the adjoint representation.

  (ii) *The spontaneously broken phase*: Part of the symmetry is hidden from the spectrum. For a gauge theory, some of the gauge bosons become massive.

SSB: Global Symmetries

An example from Classical Mechanics



$$IE\frac{d^4X}{dz^4} + F\frac{d^2X}{dz^2} = 0 \quad ; \quad IE\frac{d^4Y}{dz^4} + F\frac{d^2Y}{dz^2} = 0$$

$X = X'' = Y = Y'' = 0$ for $z = 0$ and $z = l$

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  $X = C\sin kz \ \ ; \ \ kl = n\pi \ \ ; \ \ n = 1, \dots \ \ ; \ \ k^2 = F/EI$

  They correspond to lower energy.

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- What happened to the original symmetry?
- The ground state is degenerate.
- The state is characterised by the two-component vector $\vec{\delta} = |\vec{\delta}| e^{i\theta}$
  The modulus does have a physical meaning, the phase does not.

SSB: Global Symmetries

An example from Quantum Mechanics

The Heisenberg ferromagnet

$$H = -J_{ij}\vec{S}_i \cdot \vec{S}_j$$

Symmetry breaking $O(3) \to O(2)$

SSB: Global Symmetries

A field theory example

• $\mathcal{L}_1 \;=\; (\partial_\mu \phi)(\partial^\mu \phi^*) - M^2 \phi\phi^* - \lambda(\phi\phi^*)^2$

Invariant under $U(1)$ global transformations: $\phi(x) \;\;\rightarrow\;\; e^{i\theta}\phi(x)$

• The Hamiltonian is given by:

$\mathcal{H}_1 \;=\; (\partial_0\phi)(\partial_0\phi^*) + (\partial_i\phi)(\partial_i\phi^*) + V(\phi)$

$V(\phi) = M^2\phi\phi^* + \lambda(\phi\phi^*)^2$

• The symmetric solution is $\phi(x) = 0$.

• The minimum energy configuration corresponds to:

$\phi(x) =$ constant $= \phi$ such that $V(\phi)$ is minimum, solution of:

$V' = 0$

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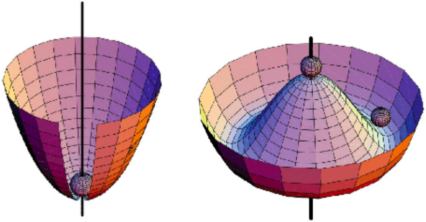

- The potential $V(\phi)$ with $\lambda > 0$ and $M^2 \geq 0$ (left).

The only solution is the symmetric one $\phi = 0$.

- The potential $V(\phi)$ with $\lambda > 0$ and $M^2 < 0$ (right).

$\phi = 0$ is a local maximum. An entire circle of minima at the complex ϕ-plane with radius $v = (-M^2/2\lambda)^{1/2}$. Any point on it corresponds to a spontaneous breaking of the $U(1)$ symmetry.

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- In order to reach the stable solution we translate the field ϕ.

  $\phi(x) = \frac{1}{\sqrt{2}}\left[v + \psi(x) + i\chi(x)\right]$

$$\mathcal{L}_1(\phi) \;\rightarrow\; \mathcal{L}_2(\psi,\chi) = \frac{1}{2}(\partial_\mu\psi)^2 + \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}(2\lambda v^2)\psi^2$$
$$- \lambda v\psi(\psi^2 + \chi^2) - \frac{\lambda}{4}(\psi^2 + \chi^2)^2$$

SSB: Global Symmetries

A field theory example

- Conclusion: $M^2 = 0$ is a critical point.

  For $M^2 > 0$ the symmetric solution is stable.

  For $M^2 < 0$ spontaneous symmetry breaking occurs.

- In order to reach the stable solution we translate the field ϕ.

  $\phi(x) = \frac{1}{\sqrt{2}}\left[v + \psi(x) + i\chi(x)\right]$

$$\mathcal{L}_1(\phi) \;\rightarrow\; \mathcal{L}_2(\psi,\chi) = \frac{1}{2}(\partial_\mu\psi)^2 + \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}(2\lambda v^2)\psi^2 - \lambda v\psi(\psi^2+\chi^2) - \frac{\lambda}{4}(\psi^2+\chi^2)^2$$

- χ is massless (*Goldstone mode*).

SSB: Global Symmetries

A field theory example

- $\mathcal{L}_2$ is still invariant.

  $\delta\psi = -\theta\chi \quad ; \quad \delta\chi = \theta\psi + \theta v$

  We still have a conserved current:

  $j_\mu \sim \psi\partial_\mu\chi - \chi\partial_\mu\psi + v\partial_\mu\chi$

  $\partial^\mu j_\mu(x) = 0$

  It is the minimum energy configuration which is not invariant.

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- *Goldstone Theorem:* Spontaneous breaking of a continuous symmetry $\Rightarrow$ A massless particle
  (*Needs Lorentz invariance and positivity*)

SSB: Gauge Symmetries

- Consider the gauge theory extension of the previous model:

  $\mathcal{L}_1 = -\frac{1}{4}F_{\mu\nu}^2 + |(\partial_\mu + ieA_\mu)\phi|^2 - M^2\phi\phi^* - \lambda(\phi\phi^*)^2$

  $\mathcal{L}_1$ is invariant under the gauge transformation:

  $\phi(x) \quad \rightarrow \quad e^{i\theta(x)}\phi(x) \quad ; \quad A_\mu \quad \rightarrow \quad A_\mu - \frac{1}{e}\partial_\mu\theta(x)$

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- Same analysis for $\lambda > 0$ and $M^2 < 0$ yields:

$$\mathcal{L}_1 \rightarrow \mathcal{L}_2 = -\frac{1}{4}F_{\mu\nu}^2 + \frac{e^2v^2}{2}A_\mu^2 + evA_\mu\partial^\mu\chi$$
$$+ \frac{1}{2}(\partial_\mu\psi)^2 + \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}(2\lambda v^2)\psi^2 \quad + \ldots$$

SSB: Gauge Symmetries

- $\mathcal{L}_2$ is invariant under the gauge transformation:

$$\begin{aligned}
\psi(x) &\rightarrow cos\theta(x)[\psi(x)+v] - sin\theta(x)\chi(x) - v \\
\chi(x) &\rightarrow cos\theta(x)\chi(x) + sin\theta(x)[\psi(x)+v] \\
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- $\mathcal{L}_2$ contains a term proportional to A^2. A massive photon??
- Degrees of freedom:

  $\mathcal{L}_1$: 2+2=4

  $\mathcal{L}_2$: 2+3=5 ??

  Notice the term $evA_\mu\partial^\mu\chi$

SSB: Gauge Symmetries. Conclusions:

The Brout-Englert-Higgs Mechanism

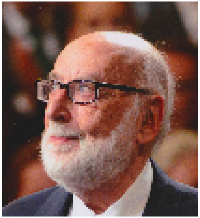
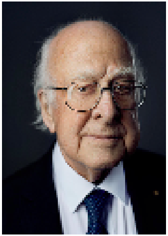
• The vector bosons corresponding to spontaneously broken generators of a gauge group become massive.

• The corresponding Goldstone bosons decouple and disappear from the physical spectrum.

• Their degrees of freedom become the longitudinal components of the vector bosons.

• Gauge bosons corresponding to unbroken generators remain massless.

• There is always at least one physical, massive, scalar particle.

Robert Brout, François Englert, Peter Higgs

Brout died in 2011 and did not assist to the triumph of the theory he contributed to formulate.

The Standard Model: The full Lagrangian

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\vec{W}_{\mu\nu}\cdot\vec{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + |D_\mu\Phi|^2 - V(\Phi) \\
&+ \sum_{i=1}^{3}\left[\bar{\Psi}^i_L i\not{D}\Psi^i_L + \bar{R}_i i\not{D}R_i - G_i(\bar{\Psi}^i_L R_i\Phi + h.c.)\right. \\
&+ \left.\bar{Q}^i_L i\not{D}Q^i_L + \bar{U}^i_R i\not{D}U^i_R + \bar{D}^i_R i\not{D}D^i_R + G^i_u(\bar{Q}^i_L U^i_R\tilde{\Phi} + h.c.)\right] \\
&+ \sum_{i,j=1}^{3}\left[(\bar{Q}^i_L G^{ij}_d D^j_R\Phi + h.c.)\right]
\end{aligned}
$$

$$
\begin{aligned}
D_\mu Q^i_L &= \left(\partial_\mu - ig\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu - i\frac{g'}{6}B_\mu\right)Q^i_L \\
D_\mu U^i_R &= \left(\partial_\mu - i\frac{2g'}{3}B_\mu\right)U^i_R \\
D_\mu D^i_R &= \left(\partial_\mu + i\frac{g'}{3}B_\mu\right)D^i_R
\end{aligned}
$$

The Standard Model: Arbitrary parameters

- The two gauge coupling constants g and g'.
- The two parameters of the scalar potential λ and μ^2.
- Three Yukawa coupling constants for the three lepton families, $G_{e,\mu,\tau}$. ($m_\nu = 0$).
- Six Yukawa coupling constants for the three quark families, $G_u^{u,c,t}$, and $G_d^{d,s,b}$.
- Four parameters of the KM matrix, the three angles and the phase δ.
- All but two come from the scalar fields.

The Standard Model and experiment

The Standard Model and experiment

- The Standard Model has 17 arbitrary parameters.

  They are related to masses and coupling constants and should be determined experimentally.

  All have been measured.

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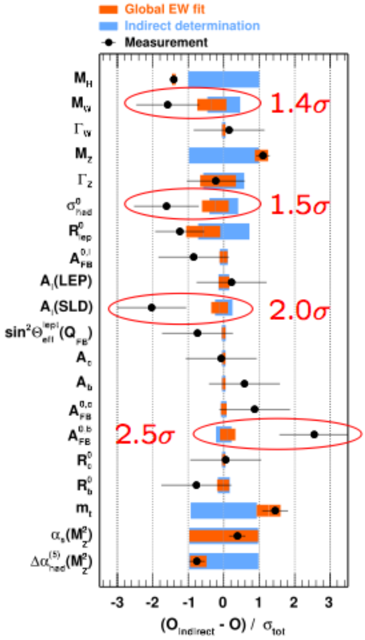
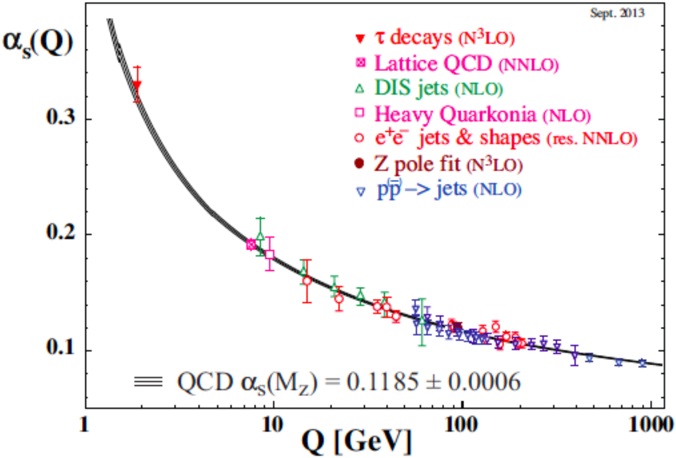
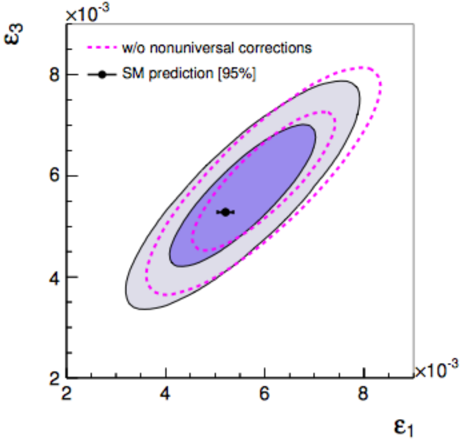
  All have been measured.
- The Model gives a large number of predictions.
- THE STANDARD MODEL HAS BEEN ENORMOUSLY SUCCESSFUL


Global EW fit
Indirect determination
Measurement
M_H
M_W
Γ_W
M_Z
Γ_Z
σ⁰_had
R⁰_lep
A_FB^{0,l}
A_l(LEP)
A_l(SLD)
sin²Θ_eff^lept(Q_FB)
A_c
A_b
A_FB^{0,c}
A_FB^{0,b}
R⁰_c
R⁰_b
m_t
α_s(M_Z²)
Δα_had^(5)(M_Z²)
1.4σ
1.5σ
2.0σ
2.5σ
-3
-2
-1
0
1
2
3
(O_indirect - O) / σ_tot



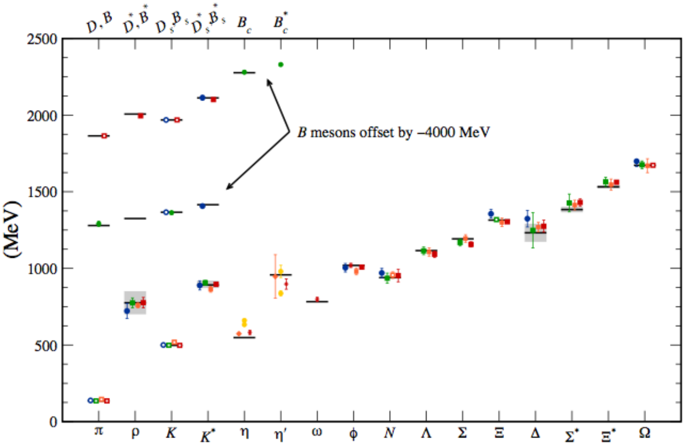
Sept. 2013
τ decays (N3LO)
Lattice QCD (NNLO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e+e− jets & shapes (res. NNLO)
Z pole fit (N3LO)
pp̄ –> jets (NLO)
$\alpha_s(Q)$
0.3
0.2
0.1
QCD $\alpha_s(M_Z) = 0.1185 \pm 0.0006$
1
10
100
1000
Q [GeV]



$\times 10^{-3}$
ε_3
w/o nonuniversal corrections
SM prediction [95%]
8
6
4
2
2
4
6
8
$\times 10^{-3}$
ε_1

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

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



The spectrum of hadrons, computed by lattice QCD simulations and compared with the experimental results.

The Standard Model and experiment

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

The discovery of weak neutral currents by Gargamelle in 1972

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

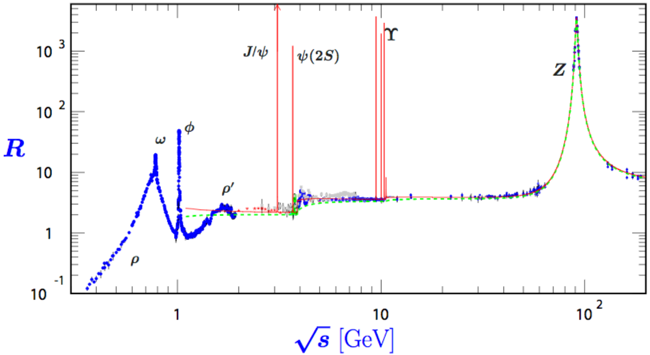
Both, their strength and their properties were predicted by the Model.

The Standard Model and experiment

The discovery of charmed particles at SLAC in 1974

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 and experiment

- 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 and experiment

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

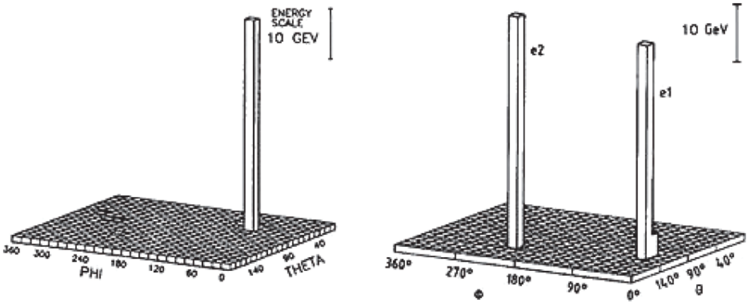
  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.

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

The Standard Model and experiment

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

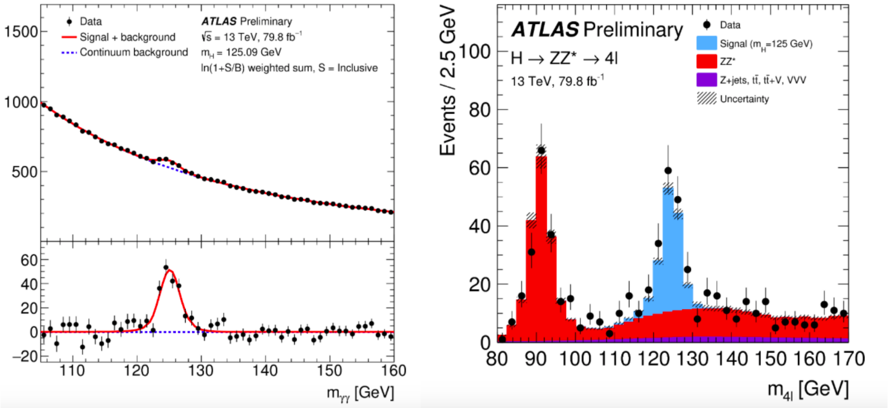
The characteristic relation of the Standard Model with an isodoublet BEH mechanism $m_Z = m_W / cos\theta_W$ is checked with very high accuracy (including radiative corrections).



(a) (b)

The Standard Model and experiment

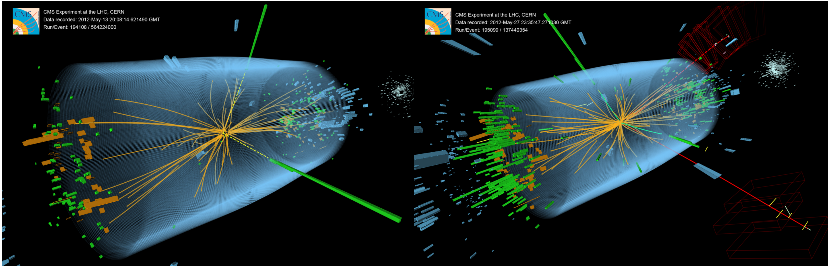
The final touch: the discovery of the BEH scalar at CERN



The discovery of the BEH scalar in the decay modes 2γ (left) and $4l$ (right). The figures include the data of $\sqrt{s} = 13$ TeV.

The Standard Model and experiment

The final touch: the discovery of the BEH scalar at CERN



Two beautiful events among those which established the discovery. The left figure shows a 2γ decay with two photons shown as green tracks in the electromagnetic calorimeter. The right figure shows an $e^+e^-\mu^+\mu^-$ decay with the electrons as green tracks in the e.m. calorimeter and the muons as red tracks in the muon chambers.

Beyond the Standard Model

- Given this impressive success...
  What does Beyond mean?

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Beyond the Standard Model

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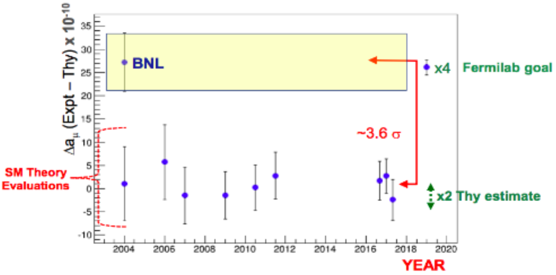
- Or, What is wrong with the Standard Theory??
- I. General questions
- II. Specific points

High precision measurements

Anomalous magnetic moment of the muon

Long-standing discrepancy with the SM

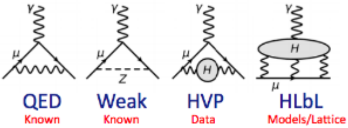


FNAL exp't in commissioning phase

a_μ is now measured to 540 ppb; Goal is 140 ppb

High precision measurements

Arduous computation of ever more precise SM prediction



New lattice computation for HLBL term

- physical pion mass and large lattice
- Statistical precision x2 improvement
- Systematics in progress

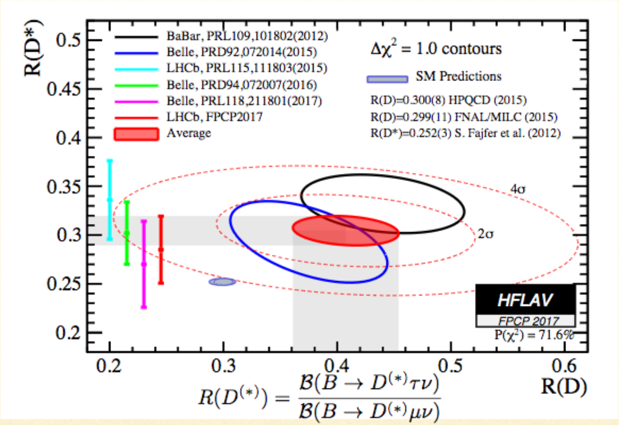
Blum etal, 1705.01067, 1610.04603

Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED	11 658 471.895	0.008
Electroweak Corrections	15.4	0.1
HVP (LO) [7]	692.3	4.2
HVP (LO) [8]	694.9	4.3
HVP (NLO)	-9.84	0.06
HVP (NNLO)	1.24	0.01
HLbL	10.5	2.6
Total SM prediction [7]	11 659 181.5	4.9
Total SM prediction [8]	11 659 184.1	5.0
BNL E821 result	11 659 209.1	6.3
Fermilab E989 target		≈ 1.6

$$a_\mu^{\mathrm{HLbL}} = 5.35(1.35) \times 10^{-10}$$

Heavy flavour decays

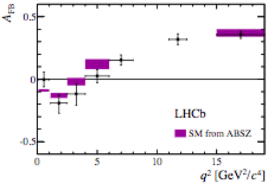
LEPTON FLAVOUR UNIVERSALITY VIOLATION?

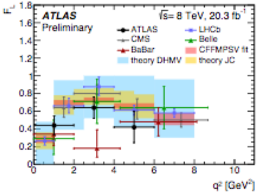


Heavy flavour decays

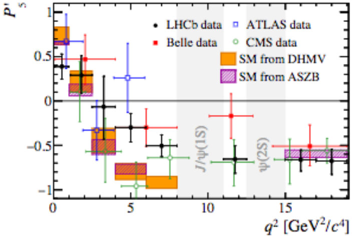
Flavour changing neutral currents

$B_d^0 \to K^* \mu^+ \mu^-$ results





- Several observables appear different than SM
- In particular P_5' has significant discrepancy
- Global fits show large disagreement



Heavy flavour decays

Summary of B anomalies

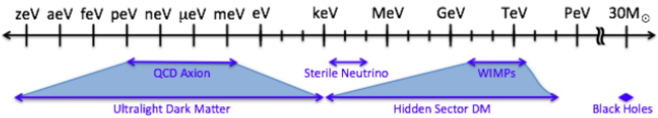
Are we there yet?

1. Low $b \to s\mu\mu$ branching fractions
2. Discrepancies in angular observables of $B_d^0 \to K^*\mu^+\mu^-$
3. Signs of lepton non-universality in: $B^+ \to K^+\mu^+\mu^-$ and $B_d^0 \to K^*\mu^+\mu^-$

- All seems to be related to a change in the C_9 coefficient (or maybe C_9 and C_{10}, but V-A)
- Global fits start to exhibit several standard deviations of discrepancy
- $c\bar{c}$ interference explanation seems not justified
- Additional discrepancies in tree-level $B \to D^{(*)}\ell\nu$ decays
- Many NP explanations: Z', leptoquarks, low mass resonances etc

Dark matter

Large mass range for DM candidates



- bosonic DM produced during inflation or high temp phase transition
- DM acts as oscillating classical field

- WIMPs: act through SM forces
- Hidden Sector: act through new force, very weakly coupled to SM
- Thermal contact in early universe

Beyond WIMPS: novel, low-cost, search techniques

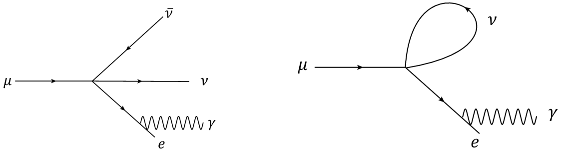
US Cosmic Visions Report, 1707.04591

Neutrino masses and oscillations

For years we thought that:

- There are three distinct neutrinos.

(i) The absence of $\mu \to e + \gamma$ shows that e.m. interactions conserve lepton numbers.
(ii) Schwinger postulated $\nu_\mu \neq \nu_e$.
(iii) Feinberg made it more precise:



- LEP confirmed that there are three distinct light neutrinos.

Neutrino masses and oscillations

We also thought that all neutrinos were massless

- A totally unexplained degeneracy

(i) In Nature only CPT related states, i.e. particle–anti-particle, are known to be degenerate. Neutrinos were the exception.
(ii) Each neutrino carried a separate lepton number, but this was only measurable dynamically.

- Attempts to make at least one of the neutrinos a Goldstone fermion failed. (No Adler's decoupling.)

- The discovery that neutrinos have different masses solved this conceptual degeneracy problem.

- But created another one: Why the masses are so small?

- Neutrino physics as a portal to Physics Beyond the Standard Model.

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!

More general questions

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- Unification
- Quantum gravity
- Many others you can add

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Conclusions

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- We were expecting new physics to be around the corner.....
  But we see no corner
- The easy answer: We need more data
- Two problems: (i) We do not know what kind of data
  (ii) They will not come for quite a long time
- A rather frustrating problem!

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- 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.....