STANDARD MODEL AND PROSPECTS

J. Iliopoulos, ENS, Paris

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The STANDARD MODEL in Particle Physics

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- A Quantum Field Theory describing in a unified framework

  all

  experimentally known interactions among elementary particles.

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  experimentally known interactions among elementary particles.

- It is Renormalisable

  and invariant under gauge transformations

  $$U(1) \times SU(2) \times SU(3) \;\Rightarrow\; U(1)_{\mathrm{em}} \times SU(3)$$

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 Standard Model: The full Lagrangian

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

$$\begin{aligned}
D_\mu Q^i_L &= \left(\partial_\mu - ig_2\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu - i\frac{g_1}{6}B_\mu\right)Q^i_L \\
D_\mu U^i_R &= \left(\partial_\mu - i\frac{2g_1}{3}B_\mu\right)U^i_R \\
D_\mu D^i_R &= \left(\partial_\mu + i\frac{g_1}{3}B_\mu\right)D^i_R
\end{aligned}$$

The Standard Model: Arbitrary parameters

- The three gauge coupling constants g_1 and g_2 and g_3.
- 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.
- The QCD angle θ.
- + possible neutrino sector.
- All but three come from the scalar fields.

The Standard Model and experiment

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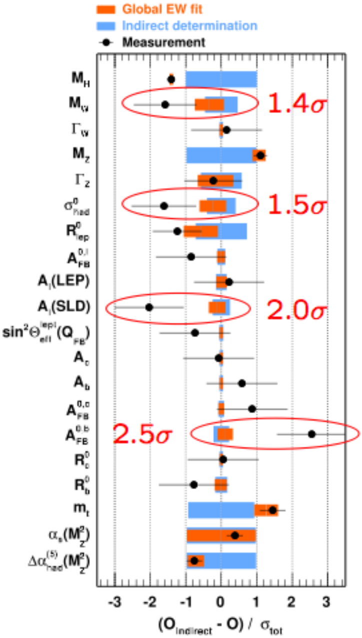
- **THE STANDARD MODEL HAS BEEN ENORMOUSLY SUCCESSFUL**
- It is no more THE STANDARD MODEL but THE STANDARD THEORY

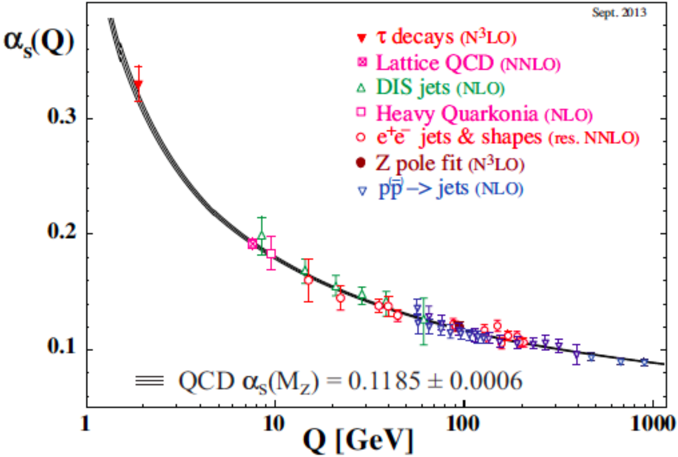


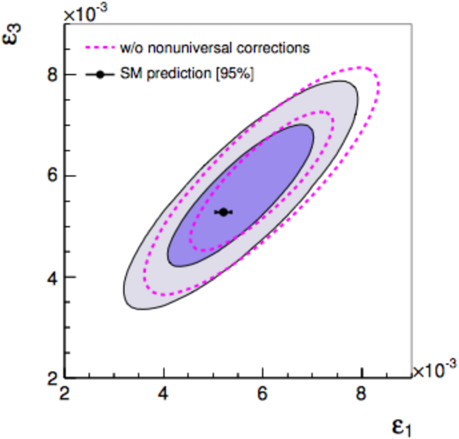
1.4σ

1.5σ

2.0σ

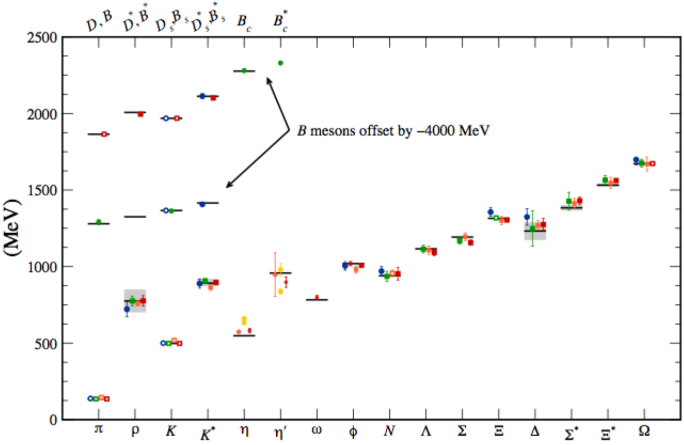
2.5σ


Sept. 2013
$\alpha_s(Q)$
▼ τ decays (N^3LO)
▩ Lattice QCD (NNLO)
△ DIS jets (NLO)
□ Heavy Quarkonia (NLO)
○ e^+e^- jets & shapes (res. NNLO)
● Z pole fit (N^3LO)
▽ $p\overset{(-)}{p}$ –> jets (NLO)
0.3
0.2
0.1
QCD $\alpha_s(M_Z) = 0.1185 \pm 0.0006$
1
10
100
1000
Q [GeV]


×10⁻³
ε3
w/o nonuniversal corrections
SM prediction [95%]
8
6
4
2
2
4
6
8
×10⁻³
ε1

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

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



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

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

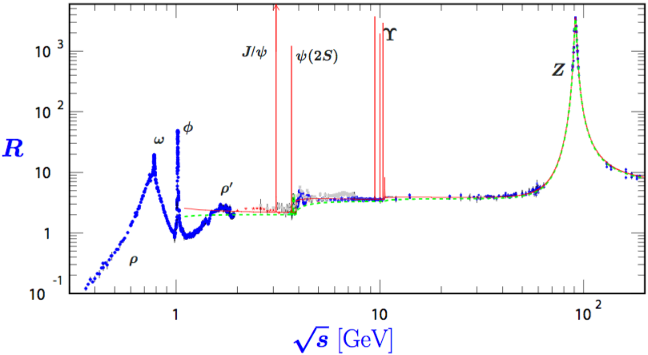
Both, their strength and their properties were predicted by the Model.

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.



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

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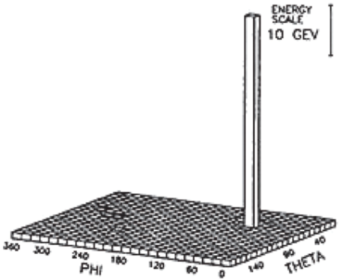
  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.
- The t-quark was *seen* at LEP through its effects in radiative corrections before its actual discovery at Fermilab.

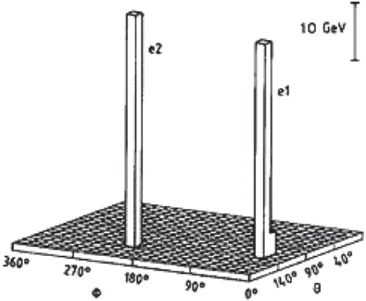
The Standard Model and experiment

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).



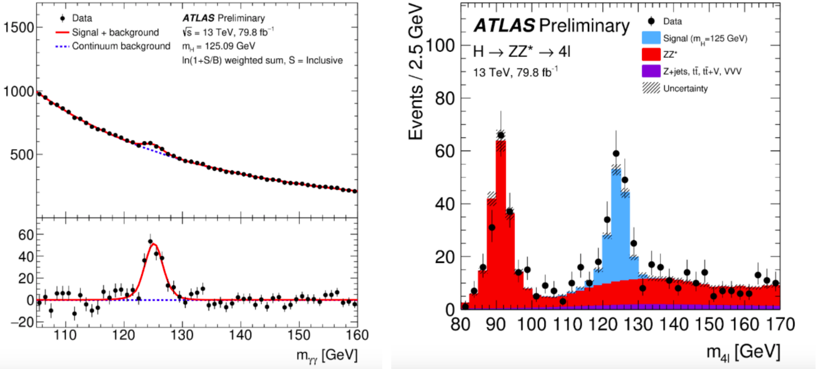
(a)



(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

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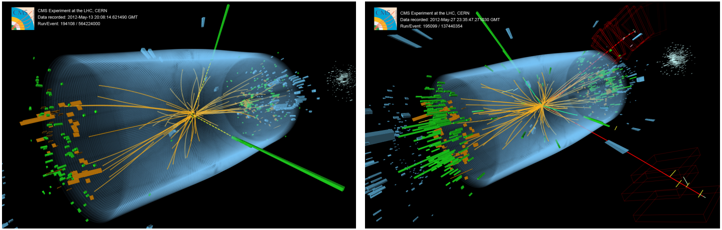

Two beautiful events among those which established the discovery. The left figure shows a 2γ decay with two photons shown as green tracks in the electromagnetic calorimeter. The right figure shows an $e^+e^-\mu^+\mu^-$ decay with the electrons as green tracks in the e.m. calorimeter and the muons as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

Beyond the Standard Model

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  What does Beyond mean?

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- III. Experimental questions

Examples of theoretical questions

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- Many others you can add

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- I claim that the "small" value of the scalar boson mass points to New Physics

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- You obtain an effective theory in terms of the « light » modes.
- The general form of this theory will be an infinite sum of terms:

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

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 there are only two dominant operators : the unit operator *(unobservable in the absence of gravity)* and 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.

Examples of phenomenological questions

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- Dark matter

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- Axions

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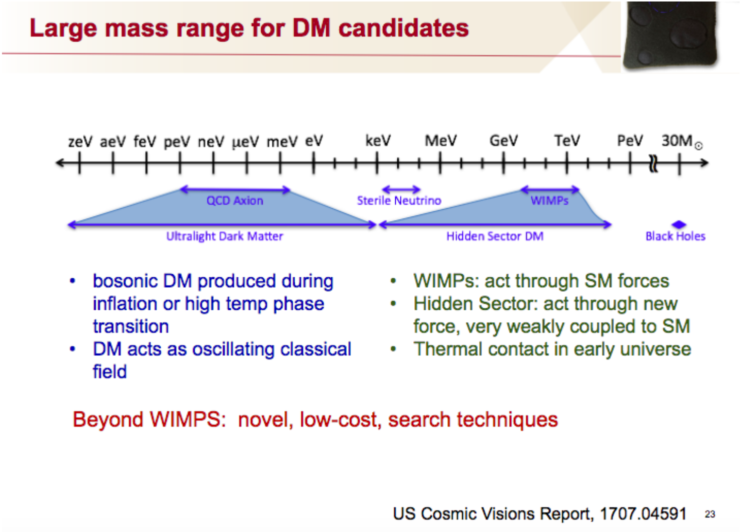
- Neutrino masses and oscillations

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

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- Modified theories of gravity
- To my taste, too much sacrifice of elegance to expediency

Axions

The QCD action contains an extra term:

$S_{eff} = S_{YM} + \frac{i\theta}{32\pi^2} \int d^4x \, \mathrm{Tr} \tilde{F}_{\mu\nu} F^{\mu\nu}$ with $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$

θ is a new, arbitrary, constant.

It is a strange term because we have:

$\partial^\mu G_\mu = \mathrm{Tr} \tilde{F}_{\mu\nu} F^{\mu\nu} \qquad G_\mu = 2\epsilon_{\mu\nu\rho\sigma} \mathrm{Tr} \left(A^\nu \partial^\rho A^\sigma + \frac{2}{3} A^\nu A^\rho A^\sigma \right)$

And, furthermore,

$n_+ - n_- = \nu = -\frac{1}{32\pi^2} \int d^4x \mathrm{Tr} \tilde{F}_{\mu\nu}(x) F^{\mu\nu}(x)$

This term conserves C but violates P and T

We could put $\theta = 0$ if the theory was exactly CP and/or chiral invariant (for ex. if at least one quark was massless)

Is $m_u = 0$???

Axions

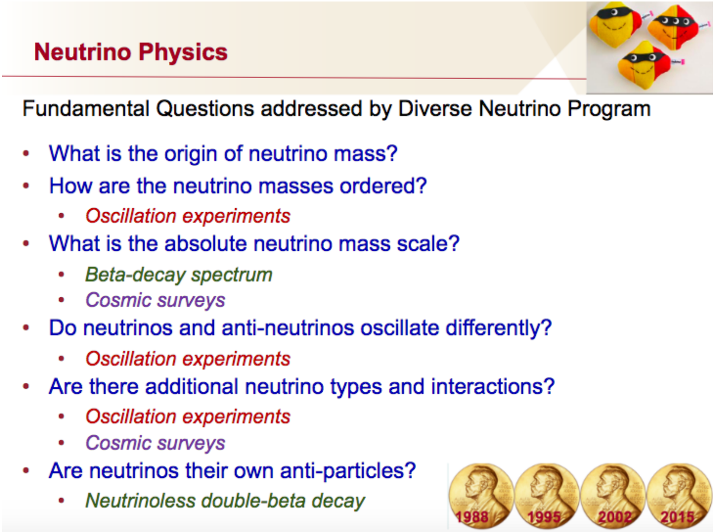
The Peccei-Quinn solution was to enlarge the symmetry of the Standard Model to include a new $U(1)$ chiral symmetry, but it implies the existence of a 0^- pseudo-Goldstone particle

the axion

Phenomenological problem :

Granted that an axion is predicted, why has no axion been found?

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*

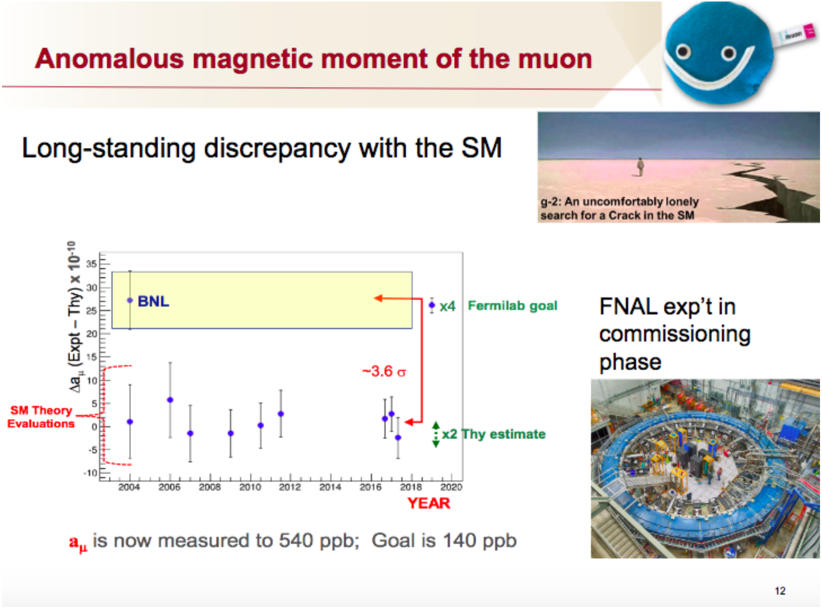
Neutrino masses and oscillations

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.
- The non-vanishing of all mixing angles offers exciting possibilities for *CP* violation in the lepton sector.
- The neutrino mass matrix does not look at all like the CKM one.
- 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!

Experimental questions



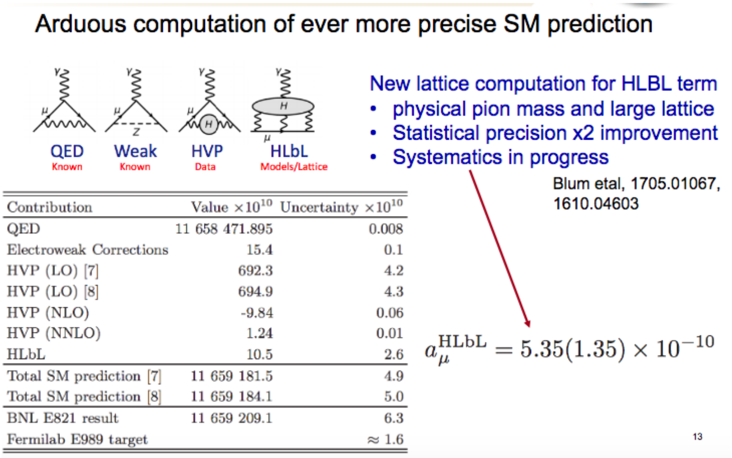
Anomalous magnetic moment of the muon

Long-standing discrepancy with the SM

g-2: An uncomfortably lonely search for a Crack in the SM

FNAL exp't in commissioning phase

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



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

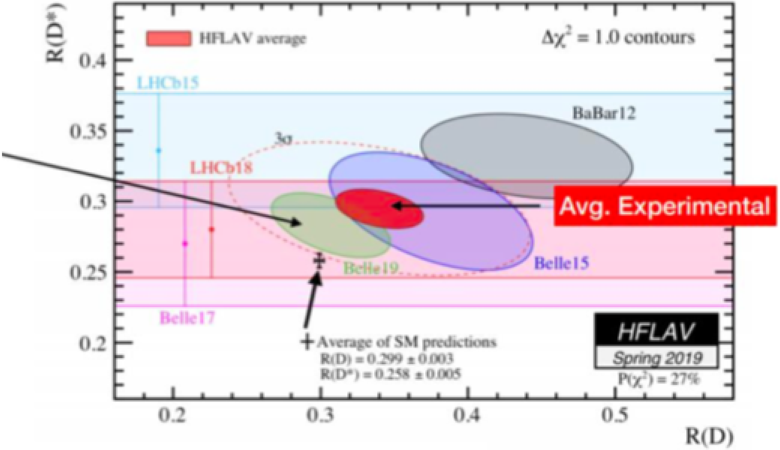
Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED	11 658 471.895	0.008
Electroweak Corrections	15.4	0.1
HVP (LO) [7]	692.3	4.2
HVP (LO) [8]	694.9	4.3
HVP (NLO)	-9.84	0.06
HVP (NNLO)	1.24	0.01
HLbL	10.5	2.6
Total SM prediction [7]	11 659 181.5	4.9
Total SM prediction [8]	11 659 184.1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

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

However, a new ab initio lattice calculation gave in the same units for HVP the result

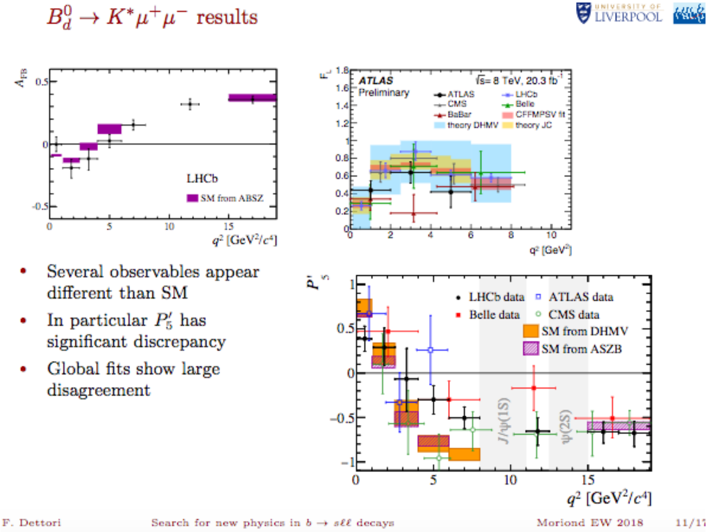
$$707.5 \pm 5.5$$

Heavy flavour decays



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

F. Dettori Search for new physics in $b \to s\ell\ell$ decays Moriond EW 2018 11/17

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- When LHC was commissioned we were all convinced that New Physics was around the corner!
- The problem is that no corner has been found
- The only sure thing is that I will not learn the answer