The Standard Model of Particle Physics
Steven Weinberg and his legacy

R. Barbieri
GGI, 19-01-2022

A one-hundred-years story, not over yet

- The making of the SM (circa 1910/20 → 1973(?))
- The amazing success of the SM, so far (1974 → now)
- The future of the SM (now → )
The making of the SM (circa 1910/20 → 1973(?))
A broad view and Weinberg legacy

The content

A. An effective theory of the weak (and the strong) interactions
B. A full fledged theory of the weak and the strong interactions

The methodology

1. A phenomenological approach: new concepts to agree with exp.s
2. The search for mathematical/logical consistency

Weinberg a leading actor in B, but in A as well and a master of equilibrium between 1 and 2
An effective theory of the weak and the strong int.s

1910/20 The continuous spectrum in $\beta$-decay (an energy crisis?)

1930 Pauli “neutron”: a new particle of spin 1/2

1934 Fermi: Tentativo di una teoria della emissione di raggi $\beta$

$$\mathcal{H}_I = g[\tau_-(\Psi_e^+(x)\Psi_\nu(x) + \tau_+(\Psi_\nu^+(x)\Psi_e(x))]$$
An effective theory of the weak and the strong int.s

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$$\mathcal{H}_I = g[\tau_- \Psi_e^+(x) \Psi_\nu(x) + \tau_+ \Psi_\nu^+(x) \Psi_e(x)]$$

1936  soon recognised to be problematic in its h.e. behaviour

$$\frac{d\sigma}{d\Omega}(\nu p \rightarrow en) \propto G_F^2 p_L^2$$

and gradually reduced (1950/60) to the current–current form

$$\mathcal{H}_I = \frac{G_F}{\sqrt{2}} J^\mu(x) J^\mu_+(x), \quad J^\mu(x) = l^\mu(x) + h^\mu(x)$$

$$l^\mu(x) = \bar{\nu}(x) \gamma_\mu (1 + \gamma_5) e(x) \quad \text{What about } h^\nu(x)?$$
What about $\hat{h}^\nu(x)$?

$\hat{h}^\mu = V_\mu + A_\mu$ = a current associated with a symmetry of the S.I.

1958 Conserved Vector Current $V_\mu = I_\mu^+$ making possible to establish $\beta$-decay ↔ $\mu$-decay universality

1960/62 PCAC: chiral invariance spontaneously broken $\pi$'s as Nambu-Goldstone bosons?

1962 Goldstone, Salam, Weinberg: a continuous symmetry and a non-invariant vacuum give massless scalars (a problem?)
What about $h^\nu(x)$?

$h^\mu = \mathcal{V}_\mu + A_\mu$ = a current associated with a symmetry of the S.I.

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making possible to establish $\beta$-decay $\leftrightarrow$ $\mu$-decay universality

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$\pi$'s as Nambu–Goldstone bosons?

1962  Goldstone, Salam, Weinberg: a continuous symmetry and a non-invariant vacuum give massless scalars (a problem?)

1963  $\beta \leftrightarrow \mu$-decay universality extended to strange particles

$h_\mu = \cos \theta h_\mu^{(\Delta S=0)} + \sin \theta h_\mu^{(\Delta S=1)}$  Cabibbo

1964  The algebra of currents (CA)

$U(3) \times U(3) = U(1) \times U(1) \times SU(3) \times SU(3) \rightarrow U(1)_V \times SU(3)_V$

1965/68  Weinberg: from CA to effective Chiral Lagrangians applied to $\pi, B, \rho$. "CA without CA"
Towards a full fledged gauge theory

1920/50  From $U(1)_{em}$ (late 40’s) to speculations on $SU(2)_I$

1954  Yang–Mills gauge theory for $SU(2)$

1957  Schwinger: from $\mathcal{H}_I = \frac{G_F}{\sqrt{2}} J^\mu(x) J^\mu_+(x)$ to $\mathcal{H}_I = g J^\mu(x) W^\mu_- + h.c.$

A triplet of vectors $Z^\pm_\mu, Z^0, Z^0_\mu = A_\mu$
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   A triplet of vectors $Z_{\mu}^{\pm,0}$, $Z_{\mu}^{0}$

1961 Glashow: $SU(2) \times U(1)$ $[\bar{O}, S] = 0$ $A_\mu = \cos \theta' Z_\mu^S + \sin \theta' Z_\mu^3$
   Explicit vector masses where from?

1961 Yang-Mills extended to an arbitrary Lee algebra

1964 Brout-Englert-Higgs mechanism
   No massless particles anymore! A massive scalar
\[ \mathcal{L} = -\frac{1}{4}(\partial_{\mu} \vec{A}_\nu - \partial_{\nu} \vec{A}_\mu + g A_\mu \times \vec{A}_\nu)^2 - \frac{1}{4}(\partial_{\mu} B_\nu - \partial_{\nu} B_\mu)^2 - R \gamma^\mu (\partial_{\mu} - ig'B_\mu) R - L \gamma^\mu (\partial_{\mu} ig \cdot \vec{A}_\mu - i\frac{1}{2} g'B_\mu)L \\
-\frac{1}{2} \bar{\phi} - igA_\mu \cdot \vec{t} \phi + i\frac{1}{2} g'B_\mu \phi \bar{\phi}^2 - G_e (\bar{L} \phi R + \bar{R} \phi \bar{L}) - M_1 \phi \bar{\phi}^2 + h(\phi \bar{\phi})^2. \]
1967 Weinberg: A model of leptons

\[ \mathcal{L} = -\frac{1}{4}(\partial_{\mu} \vec{A}_{\nu} - \partial_{\nu} \vec{A}_{\mu} + g \vec{A}_{\mu} \times \vec{A}_{\nu})^2 - \frac{1}{4}(\partial_{\mu} B_{\nu} - \partial_{\nu} B_{\mu})^2 - R \gamma^{\mu}(\partial_{\mu} - ig'B_{\mu})R - L \gamma^{\mu}(\partial_{\mu} ig \cdot \vec{A}_{\mu} - i\frac{1}{2}g'B_{\mu})L \]

\[ -\frac{1}{2} \partial_{\mu} \phi - ig \vec{A}_{\mu} \cdot \vec{\tau} \phi + i\frac{1}{2}g'B_{\mu} \phi^2 - \frac{e^2}{4\sqrt{2}G_F}(L \phi R + R \phi^\dagger L) - M_1^2 \phi^\dagger \phi + h(\phi^\dagger \phi)^2. \]  

Spontaneous symmetry breaking: \((SU(2) \times U(1) \rightarrow U(1)_{em})\)

- used for the first time in weak interactions
- in generating vector boson masses

\[ m_W > \frac{e^2}{4\sqrt{2}G_F} \approx 40 \text{ GeV} \quad (g = e, g' \rightarrow \infty) \]

\[ m_Z > \frac{e^2}{2\sqrt{2}G_F} \approx 80 \text{ GeV} \quad (g = g' = \sqrt{2}e) \]

- in generating fermion masses

Is this model renormalisable? Yes, t’Hooft, Veltman 1971

How to include hadrons?
1970/73 The inclusion of hadrons (and the setting of QCD)

1970 $\Delta S = 1 (K_L \rightarrow \mu\mu)$ and $\Delta S = 2 (K_0 - K_0)$ need a low cutoff $\Lambda \approx 2 \div 3 \text{GeV}$

GIM: $h_\mu = \bar{u}\gamma_\mu(1 + \gamma_5)(c_\theta d + s_\theta s) + \bar{c}\gamma_\mu(1 + \gamma_5)(c_\theta s - s_\theta d)$

1972/73 G,W,P Asymptotic Freedom

1972/73 G,F,B,L “Coloured” quarks coupled to an octet of “gluons”
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\]

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1973 Weinberg synthesis:

A) \( G = G_S \times SU(2) \times U(1) \)

B) \( \psi \)'s form a non-chiral rep of \( G_S \)

C) \( \phi \)'s are \( G_S \)-neutral, so that \( < \phi > \) leaves \( G_S \) unbroken
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Why WI do not produce P and S violations of order \( \alpha \)?

\[
\mathcal{L}_{\text{strong}} = -\bar{\Psi}Z\gamma_\mu D_\mu \Psi - \bar{\Psi}m\Psi - 1/4Z_{ab}^A F_{a\mu\nu} F^{b\mu\nu}
\]

By \( \Psi \) redefinition, P and S are accidental symmetries of the strong (and the EM) interactions
1. Symmetry group \( L \times G \)

\( L = \text{Lorentz (space-time)} \)

\( G = SU(3) \times SU(2) \times U(1) \) (local)

2. Particle content (rep.s of \( L \times G \))

| Lorentz | \( h \) | \( Q \) | \( L \) | \( u \) | \( d \) | \( e \) |
|---------|------|------|------|------|------|------|
| Lorentz | 0    | \( 1/2_L \) | \( 1/2_L \) | \( 1/2_R \) | \( 1/2_R \) | \( 1/2_R \) |
| \( SU(3) \) | 1    | 3    | 1    | 3    | 3    | 1    |
| \( SU(2) \) | 2    | 2    | 2    | 1    | 1    | 1    |
| \( U(1) \) | \(-1/2\) | 1/6 | \(-1/2\) | 2/3 | \(-1/3\) | 1 |

3. All “operators” (local products of \( \Phi, \partial_\mu \Phi \) )

in \( \mathcal{L} \) of dimension \( \leq 4 \)

\( \hbar = c = 1 \implies [A_\mu] = [\phi] = [\partial_\mu] = M, \quad [\Psi] = M^{3/2}, \quad [\mathcal{L}] = M^4 \)
The amazing success of the SM, so far (1974 → now)
The discovery of neutral currents

1972 Weinberg

\[ 0.15 \leq \frac{d\sigma(\nu_\mu p \rightarrow \nu_\mu p)/dq^2}{d\sigma(\nu_\mu n \rightarrow \mu p)/dq^2} \leq 0.25 \]
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1974 CERN Gargamelle

\[ \frac{NC}{CC}(\nu_{\mu}) = 0.22 \pm 0.04 \]

D. Haidt

Gargamelle emerita
Today exhibited on CERN ground
The progressive discovery of all the expected particles

| $u(1968)$ | $d(1968)$ | $e(1897)$ | $\nu_e(1956)$ |
|-----------|-----------|-----------|---------------|
| $s(1968)$ | $\mu(1937)$ | $\nu_\mu(1962)$ |

$A_\mu(1905)$

In 1973, when all the ingredients of the SM were there, including CPV if 3 families,...
The progressive discovery of all the expected particles

In 1973, when all the ingredients of the SM were there, including CPV if 3 families,...
Precision in QCD

PDG, 2021

August 2021

1977 Sterman, Weinberg

\[ \alpha_s(M_Z^2) = 0.1179 \pm 0.0009 \]
Precision in QCD and in the electroweak $SU(2) \times U(1)$

Each predicted observable removed from the fit

deBlas et al, 2021

Sterman, Weinberg

1977
More on the precision of the “electroweak fit”

$m_t$ and $M_W$ NOT calculable in the SM

**However...**

- 1994: $m_t = 177 \pm 13^{+18}_{-19}$ GeV
- 2012: $m_H = 97^{+23}_{-17}$ GeV
More on the precision of the “electroweak fit”

$\mathcal{m}_t$ and $M_W$ NOT calculable in the SM

However...

\begin{align*}
\text{1994} & \quad m_t = 177 \pm 13_{-19}^{+18} \text{ GeV} \\
\text{2012} & \quad m_H = 97_{-17}^{+23} \text{ GeV}
\end{align*}

The “gauge sector” of the SM established!
The “ultimate” precision

\[ a_{e}^{exp} = 1\,159\,652\,180.73(0.28) \times 10^{-12} \]
\[ a_{e}^{th} = 1\,159\,652\,181.78(6)(4)(3)(77) \times 10^{-12} \]

\[ a_{\mu}^{exp} = 1\,165\,920\,6.1(4.1) \times 10^{-10} \]
\[ a_{\mu}^{th} = 1\,165\,918\,1.0(4.0)(1.8) \times 10^{-10} \]

1972  Jackiw, Weinberg

\[ \Delta a_{\mu}(Weak) = \frac{G_{F}m_{\mu}^{2}}{\pi^{2}\sqrt{2}} \left[ \frac{5}{12} + \frac{4}{3}(\sin^{2}\theta_{W} - \frac{1}{4})^{2} \right] \]
The synthetic nature of Particle Physics, once again

\[ \mathcal{L}_{\sim SM} = -\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} + i\bar{\psi} \not{D}\psi \quad (\sim 1974-2000) \]

\[ + |D_\mu h|^2 - V(h) \quad (\sim 1990-2012\text{-}now) \]

\[ + \psi_i \lambda_{ij} \psi_j h + h.c. \quad (\sim 2000\text{-}now) \]

In (\() the approximate dates of the experimental confirmation
of the various lines (at different levels)
The synthetic nature of Particle Physics, once again

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In () the approximate dates of the experimental tests of the various lines (at different levels)

Weinberg: The world of physical phenomena reduced to a finite set of fundamental equations/principles
The future of the Standard Model (now →)
A difference in the two sectors of the SM?

\[ \mathcal{L}_{SM} = -\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} + i \bar{\Psi} D_\mu \Psi + |D_\mu \phi|^2 \]

\[ + M^2 |\phi|^2 - \lambda |\phi|^4 - \Lambda + \lambda_{ij} \phi \bar{\Psi}_i \Psi_j \]

The “gauge sector”

The “Higgs sector”
A difference in the two sectors of the SM?

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- **The “gauge sector”**
- **The “Higgs sector”**

The hierarchy problem

the CC problem

the flavour problem

In EFT they look much the same

No particle mass calculable

Can we tell for sure that we know the true nature of EWSB?

(a pretty conservative question, yes)
Comparing precision

H-couplings \((\frac{5}{20})\%\) against EWPT \((0.1 \div 0.3)\%\)
Comparing precision

This and the previous page make it clear that a “Higgs factory” is due...
(Best if on the way to a higher energy collider)

What for?

- precision in H-couplings below 1%
- test H-couplings to the 2nd generation
- test H-self coupling
- test rare (\(h \to Z\gamma, \tau\mu, \tau e, \mu e, CPV\)) and invisible H-decays
- ...

ATLAS Preliminary
\(\sqrt{s} = 13\) TeV, 36.1 - 139 fb\(^{-1}\)
\(m_H = 125.09\) GeV, \(|y_H| < 2.5, \rho_{3\mu} = 19\%\)

H-couplings against EWPT

(5 ÷ 20)\%  
(0.1 ÷ 0.3)\%
Problems of (questions for) the SM

0. Which rationale for matter quantum numbers?

\[ |Q_p + Q_e| < 10^{-21} e \]  
GG, GQW 1974

1. Phenomena unaccounted for

- neutrino masses
- Dark matter
- matter-antimatter asymmetry
- inflation?

2. Why \( \theta \lesssim 10^{-10} \) ?

\( \theta G_{\mu\nu} \tilde{G}^{\mu\nu} \)

Axions? PQ 1977 W 1977

3. \( O_i : d(O_i) \leq 4 \) only?

- neutrino masses
- Are the protons forever?

W 1979

4. Lack of calculability

- the hierarchy problem
- the flavour problem
Current anomalies (a partial list)

- $R_K$ [1, 1.6]
- $R_{K^*}$ [0.045, 1.1]
- $R_{K^{-}}$ [1.1, 6]
- $R_{pK}$ [0.1, 6]
- $P_s^0$ [2.5, 4]
- $P_s^0$ [4, 6]
- $B(B_s^0 \rightarrow \phi \mu^+ \mu^-)$ [1, 6]
- $B(B_s^0 \rightarrow \mu^+ \mu^-)$
- $B(B_s^0 \rightarrow \mu^+ \mu^-)$
- Muon $g-2$

Semi-leptonic B-decays

Neutral

Charged

figure credit: Patrick Koppenburg
Current anomalies (a partial list)

Neutral

Charged

Semi-leptonic B-decays

General lessons:
- in many cases $\sigma_{th} << \sigma_{exp}$
- a precision programme to be followed in the coming years in flavour as in flavourless physics

If confirmed, in my view:
- the coherence of B-decay anomalies suggestive of an approximate $U(2)^n$ flavour symmetry
- $\Delta a_\mu$ “easily” interpreted as a sign of supersymmetry

If they are roses... they will flourish
Where is the scale of flavour?

1. Flavour physics confined to high energy

\[ \mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^\alpha}{(\Lambda_i^\alpha)^2} (\bar{f} f \bar{f} f)^\alpha \quad \frac{\Lambda^\alpha}{\sqrt{C^\alpha} \text{TeV}} \]

\( i = 1, \ldots, 5 \) = different Lorentz structures
\( \alpha = K, D, B_d, B_s \)

2. New physics in the multiTeV hidden by a suitable (approximate) flavour symmetry
Let us make Weinberg speak
From NYRB, November 7, 2012 “Physics: What We Do and Don’t Know”

“Even so, the Standard Model is clearly not the final theory. Its equations involve a score of numbers, like the masses of quarks, that have to be taken from experiment without our understanding why they are what they are. [...] Further, the SM does not include the longest-known and most familiar force, the force of gravitation”
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A few paragraphs later

“Inflation is naturally chaotic. Bubble form in the expanding universe [...] perhaps each with different values for what we usually call the constants of nature.

If this is true, then the hope of finding a rational explanation for the precise values of quark masses and other constants of the SM that we observe in our big bang is doomed. [...] We would have to content ourselves with a crude anthropic explanation of some aspects of the universe we see.

So far, this anthropic speculation seems to provide the only explanation of the observed value of the dark energy.”
A violation of Lepton Flavour Universality?

\[ R_{D(*)} = \frac{BR(B \to D(*)\tau\nu)}{BR(B \to D(*)l\nu, l = \mu, e)} \]

Bernlochner et al 2021

\[ R_{K(*)} = \frac{BR(B \to K(*)\mu\mu)}{BR(B \to K(*)ee)} \]

Yet too early to say together with other observables
Still in the limbo, but

| Observable                  | Current LHCb | LHCb 2025 | Upgrade II |
|-----------------------------|--------------|-----------|------------|
| **EW Penguins**             |              |           |            |
| $R_K$ ($1 < q^2 < 6 \text{ GeV}^2 c^4$) | 0.1 [4]      | 0.025     | 0.007      |
| $R_{K^*}$ ($1 < q^2 < 6 \text{ GeV}^2 c^4$) | 0.1 [5]      | 0.031     | 0.008      |
| **$b \to c\ell^- \bar{\nu}_\ell$ LUV studies** |              |           |            |
| $R(D^*)$                    | 0.026 [15, 16]| 0.0072    | 0.002      |
| $R(J/\psi)$                 | 0.24 [17]    | 0.071     | 0.02       |

the expected future precision will settle the issue
Higgs couplings

\[ \mathcal{L} = g_f k_F H \bar{f} f \rightleftharpoons g_V k_V V_\mu H^+ \partial_\mu H \]

\[ \xi = \frac{v^2}{f^2} \]

\[ k_F = k_V = \sqrt{1 - \xi} \]

Now \( f \gtrsim 600 \div 800 \text{ GeV} \)

\[ \xi \approx \frac{g_\ast v^2}{m_\ast^2} \]

| Collider | Energy | Luminosity | \( \xi \) [1\(\sigma\)] |
|----------|--------|------------|----------------------|
| LHC      | 14 TeV | 300 fb\(^{-1}\) | 6.6 \(- 11.4 \times 10^{-2}\) |
| LHC      | 14 TeV | 3 ab\(^{-1}\)   | 4 \(- 10 \times 10^{-2}\) |

\[ f \rightarrow 1 \div 1.5 \text{ TeV} \]
How can we reach these goals?
IF $\Delta a_\mu$ confirmed

SUSY as an "EASY" and "MOTIVATED"

1. Relevant (low energy)

$M_1 \tilde{b} \tilde{b}, \ M_2 \tilde{w} \tilde{w}, \ m_{\tilde{\mu}_L} \tilde{\mu}_L \tilde{\mu}_L, \ m_{\tilde{\mu}_R} \tilde{\mu}_R \tilde{\mu}_R, \ \mu H_1 H_2, \ \tan \beta = \frac{<H_2>}{<H_1>}$

2. Size of the effect:

$\Delta a_\mu|_{SUSY} \approx \frac{g_1^2}{16\pi^2} m_{\mu}^3 M_1 \mu \tan \beta \approx (2.5 \cdot 10^{-9}) \frac{\tan \beta}{10} \frac{\mu}{1 \text{ TeV}} \frac{M_1}{100 \text{ GeV}} \frac{200 \text{ GeV}}{m_{\tilde{\mu}_L}} \frac{200 \text{ GeV}}{m_{\tilde{\mu}_R}}^2$
3. Main constraints on parameter space (high energy)

- No coloured partners below $1 \div 2 \text{ TeV}$

$$M_3 \tilde{g}, \quad M_3 \gtrsim \text{a few TeV}$$

- No flavour violations $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \text{etc}$

$$m_{\tilde{e}_L} = m_{\tilde{\mu}_L} = m_{\tilde{\tau}_L} \quad \text{(and similarly for } m_{\tilde{t}_R})$$

Due to $m_{LR}^2(\tau) = m_{\tau\mu}\tan\beta \approx (150 \text{ GeV})^2 \frac{\tan\beta}{10} \frac{\mu}{\text{TeV}} \Rightarrow \tilde{\tau} = \text{lightest s-lepton}$

- Cancellations needed

$$m_Z^2 = -2(m_{H_2}^2 + |\mu|^2)$$

- If non-zero phases, from $d_e < 1.2 \cdot 10^{-29} e \cdot cm$

$$m_{\tilde{\nu}_{eL}} \gtrsim 40 \text{ TeV}(\sin \phi_{\mu} \tan \beta)^{1/2}$$
4. Direct signals

$\tilde{l}_R$  $\tilde{\tau}_R$  $\tilde{l}_L$  $\tilde{\tau}_L$

- **LHC**
  \[ \sigma(pp \rightarrow \tilde{l} \tilde{l}) \approx 1 \div 10 \text{ fb} \]
  backgrounds: \( VV, V + jets, V^* \rightarrow \tilde{l} \tilde{l}, t \bar{t}, t + V \)

- **DM**
  \( \tilde{\chi}_1^0 \rightarrow \tilde{\tau} \)  \( \text{co-annihilation} \)
  \[ \Delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0} \lesssim 15 \text{ GeV} \]

\[ M_1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < M_2 < \mu < M_3 \]

Cox et al, 2021

- green: \( a_{\mu} \) at \( 1\sigma \)
- blue: \( a_{\mu} \) at \( 2\sigma \)
Baer et al, 1993