The Second Life of Quantum Field Theory: A Review
Москва, June 10, 2019

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Our today’s understanding of Nature at the fundamental level is based on Quantum Field Theory (QFT) which is \( \sim 90 \) years old.

So far there is no direct empiric evidence calling for going beyond QFT!
QFT = quantum mechanics (QM) + relativity

In 1926 relativity meant photons

Physicists knew about electromagnetic field. First application of QM to fields came in the founding paper of QM itself (1926). Born, Heisenberg, and Jordan considered electromagnetic field in empty space, in the absence of any electric charges or currents.
If quantum mechanics and Einstein’s relativity were revolutions, QFT was a humble child. Born, Heisenberg, and Jordan canonically quantized $\gamma$ field using creation & annihilation operators.

“Practical” QED with electrons: 1927, P. Dirac.
Final touches (1929-30): Heisenberg and Pauli

“Material particles could be understood as the quanta of various fields, in just the same way that the photon is the quantum of the electromagnetic field…”

Subsequent 18 years: struggle with $\infty \infty \infty \infty$. Mysterious holy grail searches.

QED remained the only respectable QFT till 1970s!
Renormalizability: 1948-51; Feynman et al.

QFT = PT generated by Feynman graphs

Awe before renormalizable QFT (QED,...)

(1953–54: Landau’s zero charge)

\[ M_{\text{uv}} = \infty \]

Landau: QFT is DEAD!

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The Dawn of New Era
Logic: Asymptotically free QFT is given by a local \( L \) at \( M_{uv} \) where couplings are small. Use Wilson flow.

If Higgs does not stop RG flow, arrive at strong coupling in IR.

Strong coupling in YM \( \Rightarrow \) Confinement, conformality or other phases unknown previously.
\[ \{\bar{Q}_{\dot{\alpha}}, Q_{\beta}\} = 2 \sigma^\mu_{\dot{\alpha}\beta} P_\mu \]

Superalgebra and 4D SUSY Theories
1970; Golfand and Likhtman

\( N=1 \) SUSY without central extensions

(Defying Coleman–Mandula theorem)
Верный вид гамильтона в представлении взаимодействия, можно восстановить по нему лагранжиан в гейзенберговском представлении:

\[ L(x) = (\partial_\alpha \phi^* - igA_\alpha \phi^*)(\partial_\alpha \phi + igA_\alpha \phi) - m^2\phi^*\phi + (\partial_\alpha \omega^* - igA_\alpha \omega^*) \times \]
\[ (\partial_\alpha \omega + igA_\alpha \omega) - m^2\omega^*\omega + \frac{i}{2} \psi_1 \gamma_\alpha \partial_\alpha \psi_1 - m\bar{\psi}_1 \psi_1 - g \psi_1 \gamma_\alpha \psi_1 A_\alpha + \]
\[ + \frac{i}{2} \psi_2 \gamma_\alpha \partial_\alpha \psi_2 - \mu \bar{\psi}_2 \psi_2 - \frac{1}{2} (\partial_\beta A_\alpha)^2 + \frac{\mu^2}{2} A_\alpha A_\alpha + \frac{1}{2} (\partial_\alpha \chi)^2 - \frac{\mu^2}{2} \chi^2, \]
\[ + g \mu (\phi^* \phi - \omega^* \omega) \chi - \frac{g^2}{2} (\phi^* \phi - \omega^* \omega)^2 + \sqrt{2} g (\bar{\phi}_1 s \psi_2 \phi + \bar{\psi}_2 s \psi_1 \phi^*) - \sqrt{2} g (\psi_1^c \bar{s} \psi_2 \omega^* + \bar{\psi}_2 \bar{s} \psi_1^c \omega), \]

(7)

Таким образом, получена модель взаимодействия квантованных полей с несохранением четности, инвариантная относительно алгебры (1).

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Поступила в редакцию 10 марта 1971 г.

Литература

[1] С. Швеber. Введение в релятивистскую квантовую теорию поля.
ИИЛ, 1963.
In 1+3 dimensions

\{t, x, y, z\} \rightarrow \{t, x, y, z; \theta^i_\alpha\}

Superspace

Salam and Strathdee, 1975

Wess & Zumino, 73

1973 and later

\theta^2 = 0

"fermion" direction of the superspace
New QFT born after the revolution

Dramatic Conceptual Changes

- Infinities are not an issue, $M_{\text{UV}} \neq \infty$
  - Renormalizable QFT are singled out technically; no need in UV completion

- Asymptotic freedom makes QFT self-consistent
  - Landau pole evaded
  - Wilson’s renormalization group (RG) flow logic

- Uniqueness of vacuum gone
  - Multiple vacua, highly complicated vacua, not reducible to harmonic oscillations
Two faces of SUSY and Strings

Phenomenology of superparticles

Tool in QFT at strong coupling

Deferred Indefinitely

Strings

Qualitative tool in QFT at strong coupling

Theory of everything – Penomenology

* Swampland?
What is confinement? (Example)

Superconductor of the 2nd kind

Cooper pair condensate

Abrikosov (ANO) vortex (flux tube)

The Meissner effect: 1930s, 1960s

DUAL MEISSNER EFFECT (Nambu–'t Hooft-Mandelstam, ~1975)
First demonstration of the dual Meissner effect: Seiberg & Witten, 1994

Monopoles become light if $|\varphi^3| \lesssim \Lambda \Rightarrow \text{At two points, massless!}$

$N=1$ deform. forces $M$ condensation $\Rightarrow$

$U(1)$ broken, electric flux tube formed

Abelian

- gluons+complex scalar superpartner
- two gluinos
- Georgi-Glashow model built in

SU(2) $\rightarrow$ U(1), monopoles $\Rightarrow$
Exact results in QFT are possible!
Gauge symmetry is a redundancy!!
Hence, Seiberg dualities !!!

$$SU(N)_{\text{gauge}}, \, N_f \, \text{flavors} =$$
$$SU(N_f-N)_{\text{gauge}}, \, N_f \, \text{flavors}$$

NSVZ $\beta$ function: Conformal Window
Gluino condensate: order parameter (N vacua)
“Non-Abelian” string is formed if all non-Abelian degrees of freedom participate in dynamics at the scale of string formation.

SU(2)/U(1) = CP(1)~O(3) sigma model

Classically gapless excitation

2003: Hanany, Tong
Auzzi et al.
Yung + M.S.
Kinks appear on soliton vortex strings

Kink = Confined Monopole

2D kink mass = 4D monopole mass!!!
QFT approaches 90 with very recent discoveries:
1) 1-form anomalies and their consequences;
2) Unexpected suppression of the vacuum energy density in non-SUSY;
3) Proliferation of methods at strong coupling,
4) ......
Instead of conclusions

With new understanding and reformulation QFTs thrive. New theories and new phases are being discovered!!!

A treasure trove of novel ideas, methods, solutions. Rejuvenation!

Thank you!