Challenges of modern theoretical physics and the seven-year plan of BLTP JINR

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Outline

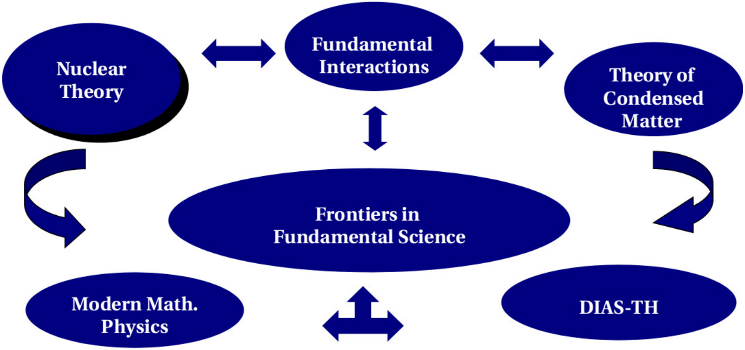
- Bogoliubov Laboratory of Theoretical Physics
- Status and crisis of fundamental physics
- Challenges to the modern theoretical physics
- Outlook

Bogoliubov Laboratory of Theoretical Physics

Bogoliubov Laboratory of Theoretical Physics

Scientific Policy:
Multidisciplinary research,
theoretical physics on the basis of advanced mathematics,
support of the JINR experimental programme,
strengthening of the efficiency of scientific staff through
the interplay of research and education.

Научная политика ЛТФ:
Междисциплинарные исследования,
Теоретическая физика на основе
современной математики,
поддержка экспериментальных программ ОИЯИ,
укрепление научного потенциала
через взаимодействие
науки и образования.



BLTP: themes and projects

Themes:

- Fundamental Interactions of Fields and Particles
- Theory of Nuclear Systems
- Theory of Complex Systems and Advanced Materials
- Modern Mathematical Physics: Gravity, Supersymmetry and Strings
- Dubna International Advanced School of Theoretical Physics (DIAS-TH)

Status and Crisis of Fundamental Physics

What is the Standard Model?

The SM is

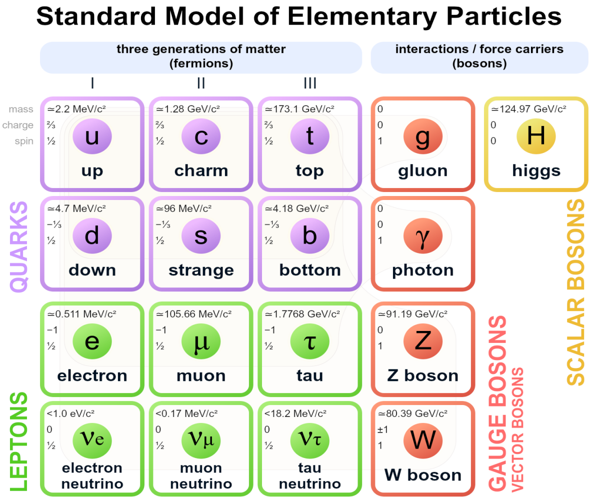
- — the most successful physical model ever
- — constructed within the Quantum Field Theory
- — based on symmetry principles
- — minimal
- — a model with an enormous predictive power

But we do not understand why it works so well…

Questions to the SM:

- Is the SM a fundamental theory?
- If not, where is the limit of its applicability?
- Are the fields and interactions of the SM fundamental?
- Is there anything beyond the SM and gravity?

Particle (field) content of the SM



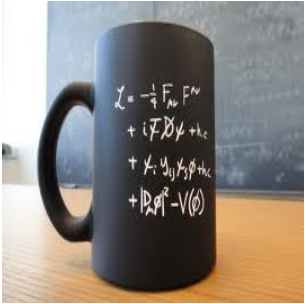
Courtesy to Wikipedia: "Standard Model of Elementary Particles" by MissMJ - Own work by uploader, PBS NOVA [1], Fermilab, Office of Science, United States Department of Energy, Particle Data Group.

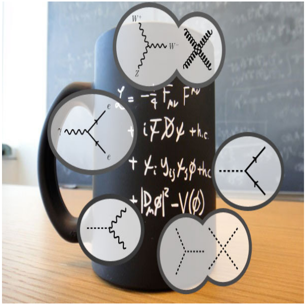
Interactions in the SM

How many fundamental interactions are there in Nature?

How many interactions are there in the Standard Model and General Relativity?

To answer the last question we have to look at the SM Lagrangian





N.B. How many bugs are there in the mugs?

Interactions in the SM

The complete SM Lagrangian look quite long and cumbersome:

Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
&W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
&\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
&1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
&\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
&\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
&igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{aligned}
$$

$+ \dots$

Nevertheless it is nothing else but the short one. Question: But why can it be so?

Parameters in the SM

Let us count:

- + 3 gauge charges (g_1, g_2, g_s)
- + 2 parameters in the Higgs potential
- + 9 Yukawa couplings for charged fermions
- + 4 parameters in the CKM matrix

So the canonical SM contains **18** free parameters

+ 1 strong CP parameter θ_{QCD} but it is not in canonical $\mathcal{L}_{QCD}$

+ 4 (or 6?) parameters of the PMNS matrix

+ 3 Yukawa couplings for neutrinos

N.B. There is only one primary dimensionful parameter in SM.
QUESTION: What is it?

Interactions in the SM

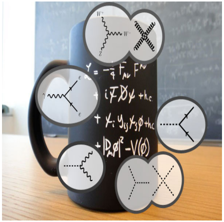
How to count them?

— number of different vertexes in Feynman rules?

— number of particles which mediate interactions?

— number of coupling constants?

The key point is to exploit symmetries...



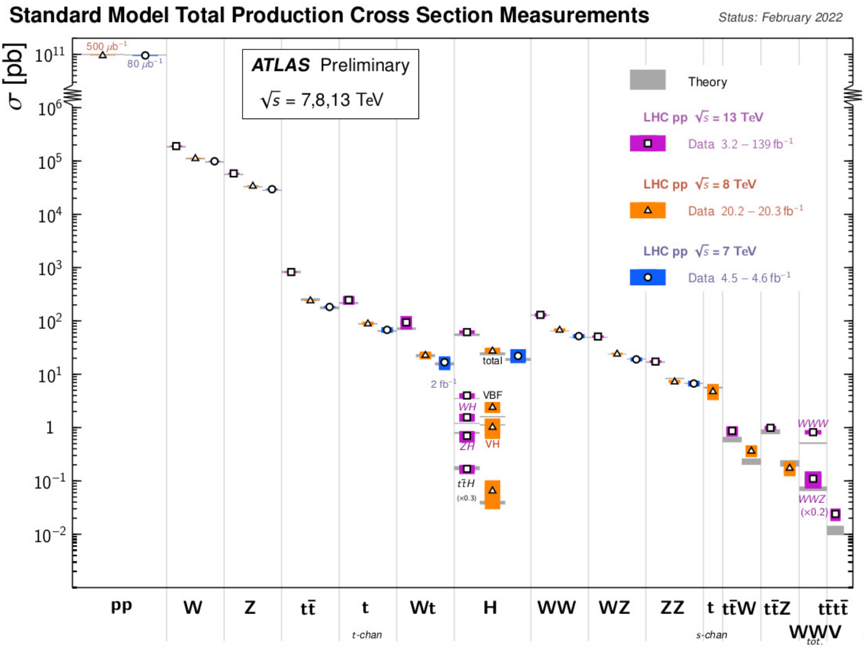
Let us count couplings:

- \+ 3 gauge charges ($g_1,\ g_2,\ g_s$)
- \+ 1 self-coupling λ in the Higgs potential
- \+ 9 Yukawa couplings for charged fermions

So the canonical SM contains **5 types** of interactions

N.B. We can not say that any of them is more fundamental than others

SM cross sections measured by ATLAS (public results) I



Standard Model at the ElectroWeak and Planck Scales

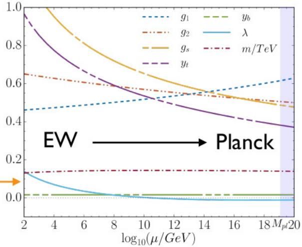
State-of-art analysis requires:

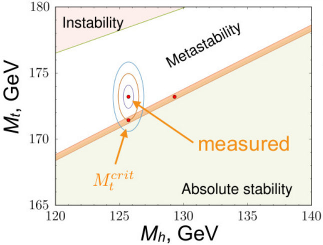
Measured value of the Higgs boson mass indicates that the SM can be extrapolated to a very high (e.g. Planck) scale.

1. Three-loop evolution equations of all SM parameters
   Bednyakov, Pikelner, Velizhanin,
   - JHEP 1301 (2013), Phys.Lett. B722 (2013), Nucl.Phys. B875 (2013),
   - Nucl.Phys. B879 (2014), Phys.Lett. B737 (2014) (with flavor mixing)

and boundary values from

2. Relations between observables and the parameters:
   - Bednyakov, Phys.Lett. B741 (2015)
   - Kniehl, Pikelner, Veretin, Nucl.Phys. B896 (2015)





- Higgs self-coupling $\lambda(\mu) > 0$ tests the SM vacuum stability.
- Crucial dependence on physical masses of ***Top-quark*** and ***Higgs boson*** - M_t and M_H

For a fixed value of M_h=125.7 GeV
absolute SM stability leads to a bound on the measured

$$M_t < M_t^{crit} = 171.44^{-0.36}_{+0.17} \text{ GeV}$$

theoretical uncertainty - decreased by 10-20 % due to 3 loops

Nice features of the SM

- It is renormalizable and unitary $\Rightarrow$ finite predictions
- Its predictions do agree with the data
- Symmetry principles are extensively exploited
- Minimality
- All its particles are discovered
- The structure of interactions is fixed (but not yet tested everywhere)
- Not so many free parameters, all are fixed
- CP violation is allowed
- Flavor-changing neutral currents are not present
- There is a room to incorporate neutrino masses and mixing
- ...

Problems of the SM

A: not (well) understood features

- The origin of symmetries
- The origin of energy scales
- The origin of 3 fermion generations
- The origin of neutrino masses
- The absence of strong CP violation
- The naturalness problem
- …

B: phenomenological issues

- The baryon asymmetry
- The dark matter
- The dark energy
- $R_{K(D)}$ puzzles, $(g-2)_\mu$, not much else…
- …

Challenges

1. Theory of everything challenge

The Holy Grail of theoretical physics

The (Super) String Theory and later M-theory pretended to be such a ToF

But reduction to the unique version of our physics is unclear

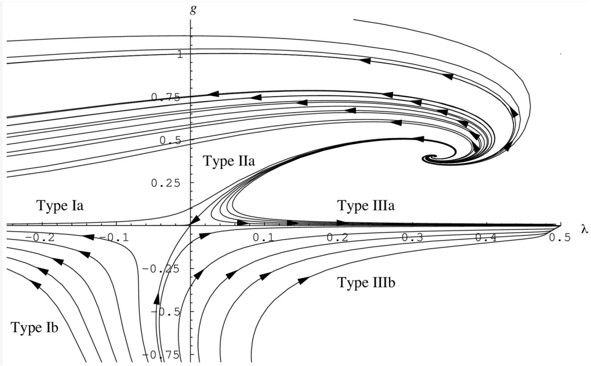
Come back to the anthropic principle?

2. Geometrization of physics challenge

Should the physics laws come from the geometry of the space-time?

Some laws do come: types of elementary particles, gauge interactions

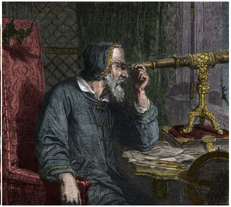
But not much else so far

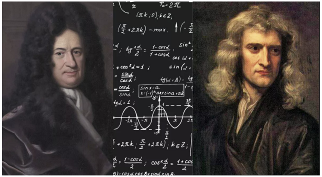


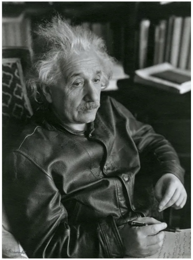
3. Gaps between theory, experiment, and applications

- Development of pure (academic) science is of great importance
- The history proves that (remind electricity)
- But here and now we still need justification and *useful* outcome of our theoretical work
- Theoretical predictions and support for current and future experiments
- a bit of outcome for applied science: solid state physics, nuclear physics, etc.

4. Computer revolution in theoretical physics

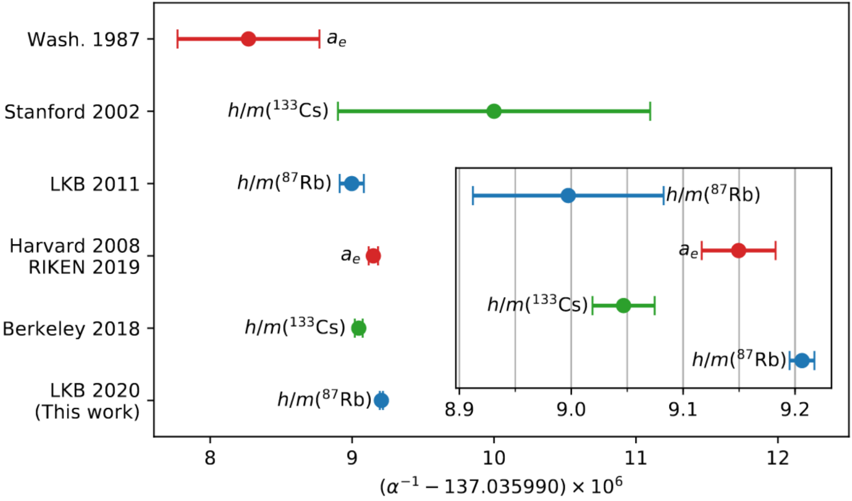






5. High precision challenge

$\alpha_{QED}(0)$: recent developments



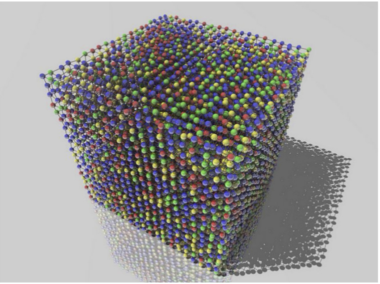
6. Ab initio challenge

In physics, there are many effective models which are widely used

We just believe that they can be derived from the SM

E.g., proton mass is not yet calculated starting from the pure QCD Lagrangian

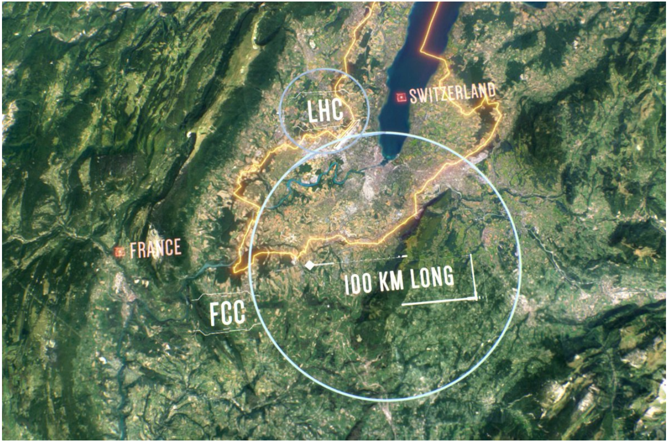
Lattice QCD



7. Future collider challenge

BLTP should provide theoretical support for current and future experiments

Future high-energy colliders like ILC, FCCee, CEPC, FCChh, Super c-τ Factory are a big challenge for the community



8. NICA challenge

Currently, the NICA physics is a real challenge for theory and a crucial task for BLTP

Complex multi-disciplinary theoretical problems:

- particle physics
- nuclear physics
- thermodynamics
- hydrodynamics
- statistical physics
- lattice QCD
- etc.

NICA

9. Boom in ν physics, astrophysics, and cosmology

Neutrino physics: many experiments and theories

Interesting problems

- neutrino mass origin
- Dirac or Majorana
- sterile neutrino
- CP violation
- sources of high-energy ν

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Astrophysics and Cosmology

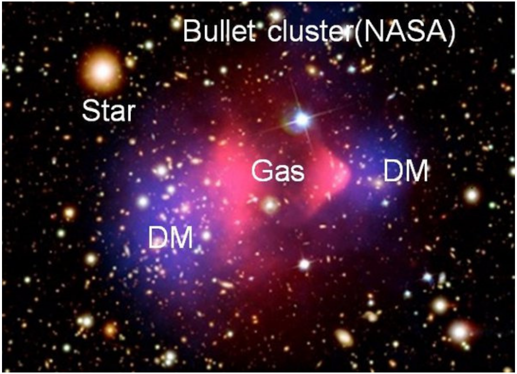
- a lot of accurate data
- boom in theory
- old crude models fail
- dark matter and dark energy

10. Puzzles in observations

There are rare cases where SM predictions disagree with experimental or observational data:

$(g-2)_\mu$; R_K, R_D; M_W;

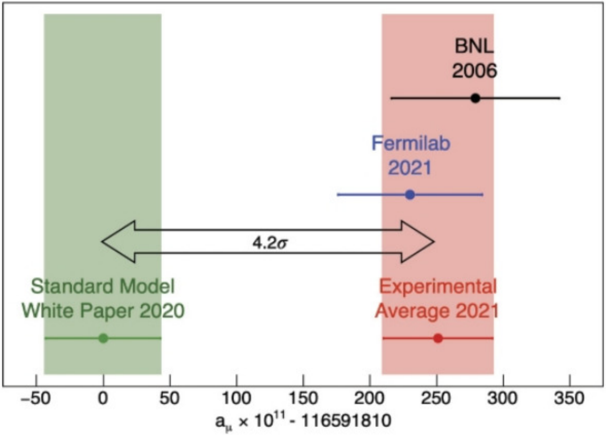
dark matter; dark energy; baryogenesis



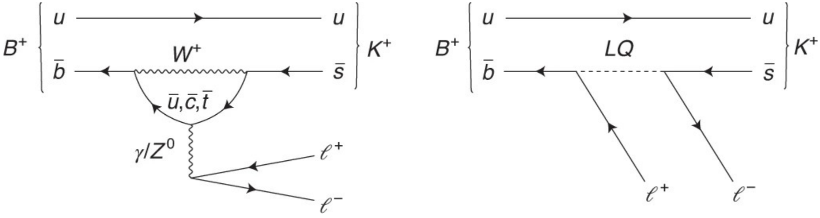
The anomalous magnetic moment of muon

New experiment vs. SM

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 251\,(59) \times 10^{-11}$$



R_K (and R_D) anomalies

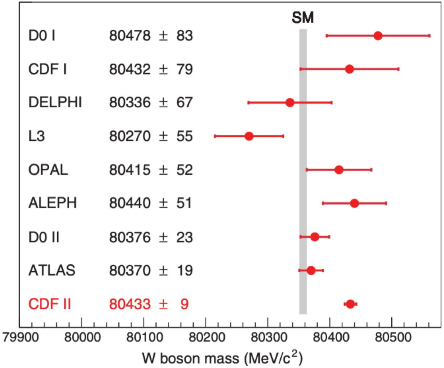


$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}l\nu)}, \qquad R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

$$|R^{\mathrm{exp}}_{D^{(*)}} - R^{\mathrm{SM}}_{D^{(*)}}| \sim 3 \cdot \sigma, \qquad |R^{\mathrm{exp}}_{K} - R^{\mathrm{SM}}_{K}| \sim 3.1 \cdot \sigma$$

N.B. Remind the 5-sigma rule

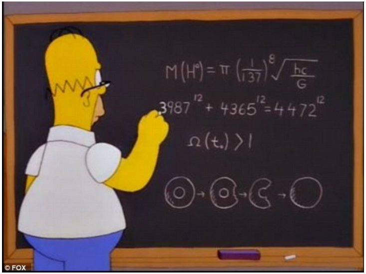
W boson mass puzzle?



11. New physics challenge

New physics:

- at which energy scale?
- new particle?
- new interactions?
- grand unification?
- unparticles?
- something unexpected?



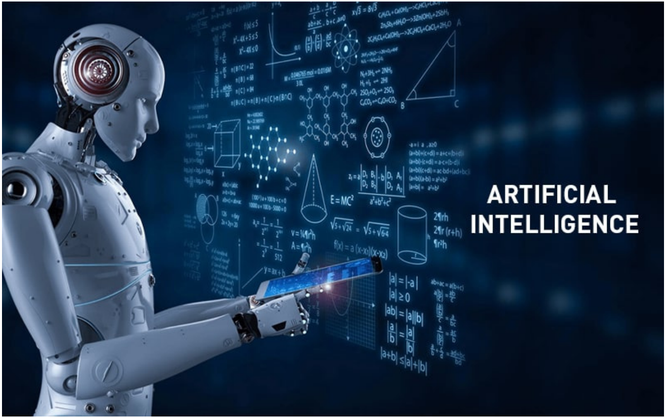
New physics $\approx$ Measurement $-$ SM prediction

N.B. New physics can be found also in the old one:
remind superconductivity, neutrino oscillations, confinement, charged vacuum, etc.

12. AI, ML, Big data challenge

Not much in theory so far, but we should expect a breakthrough soon

Quantum computers are very interesting and promising but there are obstacles and the progress is too slow



13. (International) cooperation challenge

Participation in experimental collaborations (rare)

Workshops, e.g., in the EW working group

Individual contacts and common work

Conferences, visits etc.

14. Education of new generations challenge

We keep learning new things all our lives

BLTP is on duty: we do teaching, public lectures, schools for young scientists etc.

Conclusions

- Crisis is not only a trouble but also time of opportunity
- BLTP is one of the best places in the world to do theory
- Theoretical physics is hard but interesting
- BLTP is open for contacts, discussions, and collaboration
- The 7-year plan of BLTP is a reply to the challenges