The Future of TeV-Scale Particle Physics

Wolfgang Kilian

University of Siegen, Germany

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Warning: I'm a theorist, and the talk will be theory-biased.

Plan

1. Implications of the Standard Model
2. Beyond the Standard Model
3. Theories
4. Projects

PART I: The Present

Implications of the Standard Model

In 2012, the LHC experiments ATLAS and CMS have announced the discovery of a new particle that is consistent with the signature of the Higgs boson.

Since then, more refined measurements have established this consistency to a decent degree.

This is often described as: the Standard Model is complete, the Higgs boson is the missing keystone.

This is an important discovery.

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How does this discovery change our expectations towards future discoveries?

Scales and Symmetries

Modern Theories of elementary particles are expressed in terms of scales and symmetries.

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All phenomena?

Somewhat more precise:

The SM Lagrangian is determined by

- Lorentz invariance
- the gauge symmetry with associated gauge fields
- a number of fermion representations of this symmetry as matter fields (which together must be anomaly free)
- a single scalar representation (Higgs fields)
- all interactions have mass dimension ≤ 4

This observation does not refer just to structure:

- There are no dimensionless coupling parameters with natural size 4π. All couplings have a numerical value (at the TeV scale) below 1. (Various couplings are much smaller.)

  $\Rightarrow$ all fields are just weakly interacting

- The model contains a single dimensionful parameter, the unshifted Higgs mass $-\mu^2$. This parameter defines the inherent scale of the Standard Model.

Implications for phenomenology:

Colliding particles with TeV energies, and detecting collision products which are separated by TeV distance in momentum space,

all relevant data can be calculated directly from the SM Lagrangian.

The calculation methods are completely defined: Perturbation theory, expressed in terms of Feynman rules.

(For genuine TeV-scale phenomena, we do not need to consider non-perturbative effects or a non-perturbative definition.)

We believe that essentially all particle-physics observables at lower energies can also be derived from this Lagrangian.

- QED: charged particles interact via QED
- Weak Interactions
- Strong interactions: existence of mesons and baryons, and some static parameters, can almost be derived from QCD as part of the SM (Lattice QCD)

  Some properties follow from chiral symmetry breaking, which is believed to be a nonperturbative effect of QCD.

  Some interactions (diffractive scattering) cannot currently be derived from QCD, but are believed to be consistent with QCD.

Peculiarities of the SM

Some facts are part of the Standard Model, but call for an explanation.

- Quark flavor physics. The Yukawa couplings of quarks (determine masses and mixing) have a strong hierarchical structure. Except for the top quark, all Yukawa couplings are strongly suppressed, without any obvious reason.

  This is not expressible in terms of symmetry arguments, in any simple way.

- Similarly, for the charged leptons.

- Neutrino physics. Neutrino masses and mixings can be easily explained, but this requires extra states (probably right-handed neutrinos) with an extremely large mass parameter.

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Such a symmetry does not unify the three generations of matter.

Outside the SM

The following facts are outside of the SM of particle physics:

??? **Dark matter.**

Something in the universe is a source of gravitation, but not associated to known particles.

It may be unknown particles.

It may be something else.

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- The gravitational coupling of matter points to a large energy scale (10^{19} GeV).
- There is an extra effect (dark energy) which could also be geometry, or something else.
- We don't have a reasonable ansatz for a quantum formulation.

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Beyond the SM

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Two sources of particle mass terms:

1. Mass term of the Higgs field which determines other masses via Yukawa couplings and symmetry breaking
2. Masses of hadrons are due to the low-energy singularity of the scale-dependent QCD coupling (dimensional transmutation).

Scaling Up:

An effective Lagrangian will keep its form, with only slight variation of the scale-dependent couplings, over many orders of magnitude, if certain requirements are met.

- The Lagrangian contains only spin-0, spin-$1/2$, and spin-1 particles.
- Spin-1 particles can occur only as the gauge bosons of some gauge symmetry.
- If this happens, the other fields are organized in multiplets of that symmetry.
- The couplings (dimensionless parameters) are weak, i.e., $g \lesssim 1$.

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Is the Standard Model (part of) the fundamental theory?

Scaling Down:

Let us start with

- any fundamental theory defined at a high-energy scale
- some of its degrees of freedom stay relevant at much lower energies

$\Rightarrow$ The relevant fields must be spin-0, spin-1/2, and spin-1 particles.

$\Rightarrow$ Spin-1 particles can occur only as the gauge bosons of some gauge symmetry.

$\Rightarrow$ If this happens, the other fields are organized in multiplets of that symmetry.

$\Rightarrow$ The couplings (dimensionless parameters) are weak, i.e., $g \lesssim 1$.

$\Rightarrow$ Any additional higher-dimension terms become irrelevant.

Summarizing, the existence and structure of the SM as a weakly interacting gauge theory is just a hint that

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But

- Gauge symmetry can, but need not be, a property of the fundamental theory
- The known fields may or may not be elementary.
- Almost any additional fields and interactions are possible, if sufficiently heavy

Hierarchy Problem?

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However, there is no evidence for strong interactions connected to the Higgs mass term.

If this relation was different, our world would not exist. The hierarchy of the Standard Model vs. gravitationis therefore a precondition. The hierarchy problem may not be a useful tool in searching for physics beyond the Standard Model.

The SM is a complete quantum field theory. It can be scaled up (unchanged) or scaled down (with symmetry breaking).

This does not tell us whether it is the fundamental theory, or just a part of it.

The SM may be incomplete if we are confining the question to a small range in scale, say up to some 10 TeV.

Recall, the clear evidence for physics beyond the SM is not associated with a scale within that range. It does not help in predicting TeV physics.

Summary: Lessons from the Standard Model

1. None of the known evidence for physics beyond the Standard Model indicates new physics in the TeV range.

   This is a new situation for the field of elementary particle physics.

2. The SM contains the coincidence of Higgs-induced masses with QCD-induced masses.

   There is no good reason that this should be the complete set of phenomena in the TeV range.

PART II: The Future

What We Should Not Expect

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Some Examples:

- A fourth generation of matter (mass from Higgs mechanism)
- Violation of electroweak gauge symmetry
- Compositeness of gauge bosons
- A gauge symmetry that couples leptons to quarks
- Flavor structure without CKM hierarchy

What Is Allowed?

Some Examples:

- Spin-0 and spin-1/2 particles with masses not from Higgs mechanism (non-chiral = vector-like)
- Some extensions of gauge symmetry, with gauge bosons
- Extended Higgs sector
- New Physics coupled to the Higgs sector
- Particles which carry a new conserved quantum number
- New physics with CKM-like flavor structure
- [New Physics not coupled to anything]

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Effective Theory

Anomalous effects associated with mass scale M are generically suppressed by a factor of at least

$$\frac{E^2}{M^2} \quad \text{or} \quad \frac{m_W^2, m_Z^2, m_H^2, m_t^2}{M^2}$$

This is observable only if

- The mass M is less than a TeV
- The energy is more than $M/10$
- The precision of the measurement is better than $1\,\%$
- The effect is suppressed in the Standard Model

For many scenarios, neither condition is satisfied.

Theories

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Some examples that have been popular:

Supersymmetry

Supersymmetry arises in string theories, which reconcile quantum field theory with (some aspects of) gravitation.

The supersymmetric version of the SM is called MSSM.

Properties:

- Spin-0 and spin-1/2, with mass not originating from the Higgs mechanism
- Extended Higgs sector
- New conserved parity

Unexplained by supersymmetry:

- Mass scale (soft breaking) is arbitrary, like in the SM.
- Flavor structure is not necessarily CKM-like
- No source for the CKM structure
- No reason for the coincidence of Higgs-induced masses with QCD singularity.

Topcolor

Extension of the QCD gauge structure. The extension also affects the third generation of quarks.

Properties:

- new heavy, colored gauge bosons
- heavy fermions with mass not from the SM Higgs mechanism

Little Higgs

Extension of gauge and Higgs sectors, also extra fermions.

Higgs mass is an order of magnitude smaller than the actual symmetry-breaking scale.

Extra parity can be included.

Confined New Strong Interactions

Used to be known as technicolor

. . . its original form incomplete and experimental excluded.

Similar theories possible if connected to the Higgs sector.

(New strong interactions don't necessary imply new particles.)

Extra Dimensions

Above the TeV scale, four-dimensional quantum field theory resolves into a higher-dimensional quantum theory.

Properties: resonances of some or all particles of the Standard Model.

Similar phenomenology: deconstructed models

Summary: Models for BSM physics

A large number of widely different of models satisfy the constraints imposed by current data and analysis, and nevertheless provide BSM physics within reach.

Experiments so far could exclude only a restricted subset of models, namely those with large effect on low-energy gauge or flavor structure.

But those models typically address only a few of the interesting problems raised by the SM gauge and coupling structure.

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the experimental program must cover the accessible energy range completely..

The physics case for new TeV-scale collider experiments is about searching for new matter particles, scalar particles, particles coupled to the Higgs, strong interactions etc.

Previous projects did (successfully) search for the top quark, the Higgs boson, etc. They were looking for missing pieces.

There is no missing piece in the SM. But there are lots of possibilities for new physics.

Can we cover the TeV range completely, and how far can we go beyond?

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The Future of the LHC

The current LHC setup allows for many further and refined studies. An upgrade in luminosity is planned and likely.

Expectations:

- Higher reach in energy for searches, in particular colored particles
- Some measurements in the electroweak sector become possible
- Searches for some rare processes become possible (top, Higgs decays)
- Improved precision for quantitative measurements, Higgs in particular (but nowhere near $1\,\%$.

More Physics at the high-lumi LHC:

New QCD data. (Involving also the top quark.)

- Parton distribution functions
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Option: electron-proton collisions

- Parton distribution functions
- But also some hard processes

What the LHC can't do:

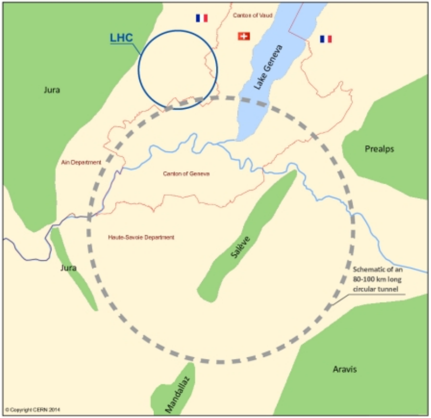
- Analyze flavor structure
- Precision measurements
- Cover the spectrum below a TeV

Future hadron collider:

A hadron collider after LHC must have a significantly higher energy. Increasing luminosity is not as useful (systematics!)

- Higher discovery reach, in particular colored particles
- Electroweak interactions far above the EWSB scale
- Another level-up for the variety of QCD interactions

CERN: FCC



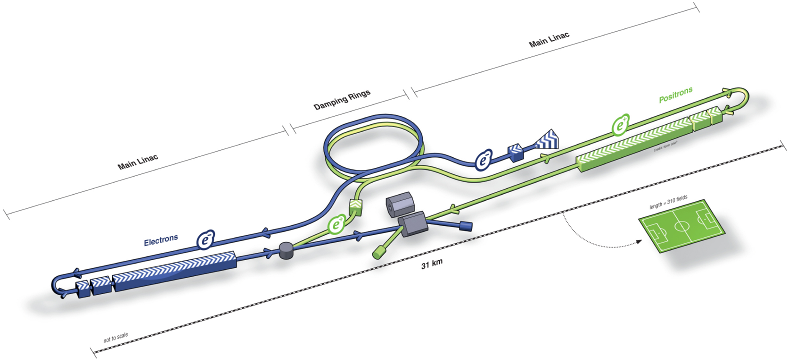
Study currently under way. Envisioned energy: up to 100 TeV

Future Lepton Colliders

Lepton colliders must complement the capabilities of hadron colliders:

- Cover accessible spectrum completely.
- High precision possible. Clean initial state.
- Jet physics in clean environment, no initial-state connection

ILC

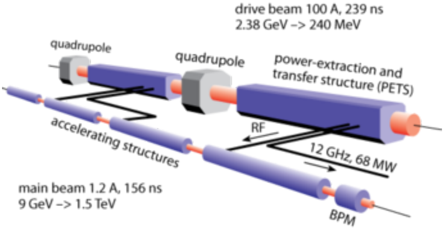


Global project. Japan proposes to host the collider and laboratory, at a site in the north of Japan.

Energy: 500 GeV, upgradeable.

Acceleration by superconducting cavities (proven technology).

CERN: CLIC



Energy: up to 3 TeV projected.

CERN would host the machine

Acceleration by drive-beam (new technology, test facility exists)

CERN: TLEP

renamed as: FCC-ee. This could be an e^+e^- collider built in the FCC tunnel.

	LEP1	LEP2	Z	W	H	tt
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Beam energy [GeV]	45.4	104	45.5	80	120	175
Beam current [mA]	2.6	3.04	1450	152	30	6.6
Bunches / beam	12	4	16700	4490	1360	98
Bunch population [10^{11}]	1.8	4.2	1.8	0.7	0.46	1.4
Transverse emittance ε - Horizontal [nm] - Vertical [pm]	 20 400	 22 250	 29.2 60	 3.3 7	 0.94 1.9	 2 2
Momentum comp. [10^{-5}]	18.6	14	18	2	0.5	0.5
Betatron function at IP β* - Horizontal [m] - Vertical [mm]	 2 50	 1.2 50	 0.5 1	 0.5 1	 0.5 1	 1 1
Beam size at IP σ* [μm] - Horizontal - Vertical	 224 4.5	 182 3.2	 121 0.25	 26 0.13	 22 0.044	 45 0.045
Energy spread [%] - Synchrotron radiation - Total (including BS)	 0.07 0.07	 0.16 0.16	 0.04 0.06	 0.07 0.09	 0.10 0.14	 0.14 0.19
Bunch length [mm] - Synchrotron radiation - Total	 8.6 8.6	 11.5 11.5	 1.64 2.56	 1.01 1.49	 0.81 1.17	 1.16 1.49
Energy loss / turn [GeV]	0.12(1)	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	0.3(1)	11	50			
Total RF voltage [GV]	0.24	3.5	2.5	4	5.5	11
RF frequency [MHz]	352		800			
Longitudinal damping time τ_E [turns]	371	31	1320	243	72	23

China: Future Large Collider

China would also be a possible host for a future large high-energy collider (analogous to FCC). Plan: e^+e^-, later pp.

In any case, China should take a major part in the future development of TeV scale particle physics.

Center set up for preparing dedicated study and conceptual design report:

FHEP

Center for Future High Energy Physics

高能物理前沿研究中心

Low-Energy Experiments

While this talk is about TeV-scale physics, low-energy experiments must

- further push the knowledge about flavor structure. (Really just CKM?)
- Particularly improve the precision or limits for all processes that are suppressed or forbidden in the Standard Model.

These experimental facilities complement our gain in knowledge from the large high-energy machines. They provide experimental opportunities outside the very big collaborations and during construction phases.

Global Effort

Acting together, combining results, hadron and e^+e^- colliders will cover the accessible range in energy (new particles) and interactions.

Full coverage of the TeV energy range is possible only by a combination of projects.

The projects are technically possible. They obviously require

- Formal scientific cooperation on a global scale. This has successfully been practized on the European scale at CERN. Informal cooperation is no problem, anyway.
- Political cooperation and financial agreements on a global scale. This is apparently much more difficult.

New Technology

Further increasing energy or precision will require new, unproven technology.
There are various ideas, but

no certainty whether the limits can be pushed even further.

The Desirable Future of TeV Particle Physics

- New projects will improve our understanding of the fundamentals of particle physics. They are necessary.
- It is unfortunate if theorists' models are quoted as prime motivation.
- Future colliders can and will cover the spectrum and all new phenomena within the energy reach that we can access.
- The countries with a major scientific community take part in these efforts, renewing their interest in fundamental science.
- It is essential to build and run both hadron and lepton colliders.