Perspectives at the Energy Frontier

Chris Quigg
Fermi National Accelerator Laboratory

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A conceptual design study of options for a future high-energy frontier circular collider at CERN for the post-LHC era shall be carried out, implementing the request in the 2013 update of the European Strategy for Particle Physics.

Many results of the study will be site independent.

The design study shall be organised on a world-wide international collaboration basis under the auspices of the European Committee for Future Accelerators (ECFA) and shall be available in time for the next update of the European Strategy for Particle Physics, foreseen by 2018.
Ever since Galileo ... 

Phenomena .......... Laws
Explore

Search

Measure
Two New Laws of Nature +

Before LHC

Pointlike ($r \leq 10^{-18}$ m) quarks and leptons

Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries
A hitherto unknown agent hides electroweak symmetry

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions
The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *identify a tipping point*

\[ W^+ W^-, ZZ, HH, HZ \text{ satisfy s-wave unitarity,} \]

provided \[ M_H \leq (8\pi \sqrt{2/3} G_F)^{1/2} \approx 1 \text{ TeV} \]

- If bound is respected, perturbation theory is “everywhere” reliable
- If not, weak interactions among \( W^\pm, Z, H \) become strong on 1-TeV scale

*New phenomena are to be found around 1 TeV*
Issues for the Future (Starting now!)

1. What is the agent of EWSB? *There is a Higgs boson!* Might there be several?
2. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below 1 TeV?
Issues for the Future (Now!)

6. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature’s laws?

7. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?

8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does “minimal flavor violation” hold? If so, why?

9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?

10. What resolves the strong CP problem?
Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?
12. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy problem?
15. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? … for inflation? … for dark energy?
Issues for the Future (Now!)

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the neutrino masses set? Do they speak to the TeV scale, unification scale, Planck scale, ...?

20. How are we prisoners of conventional thinking?
Is it the standard-model Higgs boson?

*Do not get ahead of the evidence!*

How well must we know its properties?
Standard-model Higgs boson hides electroweak symmetry, gives masses to $W^\pm$ and $Z^0$, ensures good high-energy behavior.

$W^+W^- \rightarrow$ top pairs ...
Puzzle #1: Expect New Physics on TeV scale to stabilize Higgs mass, solve hierarchy problem, but no sign of flavor-changing neutral currents. Minimal flavor violation a name, not yet an answer.

Great interest in searches for forbidden or suppressed processes.

Puzzle #2: Expect New Physics on TeV scale to stabilize Higgs mass, solve hierarchy problem, but no quantitative failures of EW theory.

arXiv:0905.3187
**FCNC:** $(B^0, B_s) \rightarrow \mu^+ \mu^-$

LHCb + CMS: $\text{BR}(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$
Electric dipole moment $d_e$

$d_e < 8.7 \times 10^{-29} \text{ e} \cdot \text{cm}$

ACME Collaboration, ThO

(SM phases: $d_e < 10^{-38} \text{ e} \cdot \text{cm}$)
The unreasonable effectiveness of the standard model
QCD could be complete, up to $M_{\text{Planck}}$

... but that doesn’t prove it must be

Prepare for surprises!

How might QCD Crack?

(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing QCD
Correlations among the partons?

A proton knows it is a proton. Single-spin asymmetries imply correlations. What else?

Can we distinguish different configurations? *Interplay with multiple-parton interactions?*
Might LHC see the change in evolution?

\[ \log(Q \text{ [GeV]}) \]

SM: \( \frac{7}{2\pi} \)

MSSM: \( \frac{3}{2\pi} \)
E. Eichten
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

I. Hinchliffe
Lawrence Berkeley Laboratory, Berkeley, California 94720

K. Lane
The Ohio State University, Columbus, Ohio 43210

C. Quigg
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

Eichten et al. summarize the motivation for exploring the 1-TeV (=10^{12} \text{ eV}) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

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I. INTRODUCTION

The physics of elementary particles has undergone a remarkable development during the past decade. A host of new experimental results made accessible by a new generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject a new coherence. Our current outlook has been shaped by the identification of quarks and leptons as fundamental constituents of matter and by the gauge theory synthesis of the fundamental interactions. These developments represent an important simplification of...
1983-1984 was also a charmed time

Neutral currents
Parity violation in $e\bar{d}$
c, $\tau$, $b$ discoveries
W, Z discovery
Importance of TeV scale recognized
Tevatron (SC synchrotron) operated
Supersymmetry invented

SSC conceived, parameters not fixed
Very primitive tools:
No suitable pdfs

**Detectors limited to** $10^{32}$?
No SVX

SUSY $\sigma$ computed for $p^\pm p$ and $e^+ e^-$

Potential of VBF recognized
Explicit calculations + Parton luminosities

\[ \sqrt{s} = 2, 10, 20, 40, 70, 100 \text{ TeV} \]
Parton luminosities

FIG. 49. Quantity \( (r/s) d\mathcal{L} / d\tau \) for \( b\bar{b} \) interactions in proton-proton collisions.

\( \sqrt{s} = 2, 10, 20, 40, 70, 100 \text{ TeV} \)
Parton luminosity contours

FIG. 64. Contours of \( (\tau/s) d \mathcal{L} / d \tau \) for \( u\bar{u} \) interactions in \( pp \) collisions according to the parton distributions of Set 1. Lines correspond to \( 10^4, 10^3, 10^2, 10, 1, \) and 0.1 pb.
FIG. 57. Ratio of $\frac{(r/S')d\mathcal{L}}{d\tau}$ for $u\bar{u}$ interactions in $\bar{p}p$ and $pp$ collisions, according to the parton distributions of Set 2. Collider energies $\sqrt{s}$ are given in TeV.
Discovery reach: 2 jets

FIG. 104. Discovery reach of hadron colliders for the observation of two-jet events, according to the parton distributions of Set 2, for integrated luminosities of $10^{38}$, $10^{39}$, and $10^{40}$ cm$^{-2}$. The curves represent the cross section for two jets as a function of the center-of-mass energy $\sqrt{s}$ (TeV), with integrated luminosities denoted by $\int dt\mathcal{L} = 10^{38}$, $10^{39}$, and $10^{40}$.
It is premature to develop the scientific case for the “100-TeV” collider, but the right time to explore possibilities.

What we do for “100-TeV” can enhance what we achieve with LHC.

LHC might point to an energy landmark.
Develop examples that will stretch detector capabilities

The ability to tag and measure heavy quarks and tau leptons would significantly enhance the incisiveness of many searches.

Imagine special-purpose detectors

Explore a range of collider energies; investigate Luminosity / Energy tradeoffs

Develop tools that enable others to extend the work
Explore
Search
Measure