2011 J. J. Sakurai Prize Address

The Boundless Horizons of Supercollider Physics

Chris Quigg
Fermilab
Jun John Sakurai (1933 – 1982)

1965 photo courtesy of Ken Sakurai
John David Jackson (2009)
The importance of the 1-TeV scale

_Gedanken_ experiment: high-energy scattering of

\[
W_L^+ W_L^- \quad Z_L^0 Z_L^0 / \sqrt{2} \quad H H / \sqrt{2} \quad H Z_L^0
\]

\[
M_H \leq \left( \frac{8 \pi \sqrt{2}}{3 G_F} \right)^{1/2} = 1 \text{ TeV}
\]

_condition for perturbative unitarity_

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

**Instrument of choice: multi-TeV hadron collider**
What is a proton?

(For hard scattering) a broad-band, unseparated beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

\[ f_i^{(a)}(x_a, Q^2), \]

...number density of species \( i \) with momentum fraction \( x_a \) of hadron \( a \) seen by probe with resolving power \( Q^2 \).

\( Q^2 \) evolution given by QCD perturbation theory

\[ f_i^{(a)}(x_a, Q_0^2): \text{nonperturbative} \]

EHLQ: LO, heavy flavors, \( Q^2 < 10^8 \text{ GeV}^2, x > 10^{-4} \)
Comprehensive PDF determinations at NLO . . .

MSTW 2008 NLO PDFs (68% C.L.)

$Q^2 = 10 \text{ GeV}^2$

$Q^2 = 10^4 \text{ GeV}^2$

Chris Quigg (FNAL)

Boundless Horizons of Supercollider Physics

APS Anaheim - May 1, 2011
Beyond traditional parton distributions

\[ f_i^{(a)}(x_a, Q_0^2) \]

No correlations, only longitudinal degrees of freedom

Generalized PDFs, \( q \rightarrow (qq) \) configurations, \ldots

Bjorken, 2010
QCD as background and signal

EHLQ focused on dijets, tabulated three-jet cross sections

Would > 6-point amplitudes ever be possible?

1986: Parke–Taylor formula ($N$ gluons at tree level)

Cascade of new techniques, inspired by supersymmetry, stringy methods, recursion, $S$-matrix style unitarity, seminumerical algorithms, ...
Advances in perturbative QCD: $N$ gluons @ 1-loop

![Graph showing time and number of gluons](image)

- New techniques (polynomial)
- Traditional methods (factorial)

Giele & Zanderighi '08

- 1985
- 1993
- 2006

Giulia Zanderighi
Advances in perturbative QCD:

The acceleration of (pQCD) history

<table>
<thead>
<tr>
<th>Process</th>
<th>Year</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \rightarrow W + 0 \text{ jet} )</td>
<td>1978</td>
<td>Altarelli, Ellis, Martinelli</td>
</tr>
<tr>
<td>( pp \rightarrow W + 1 \text{ jet} )</td>
<td>1989</td>
<td>Arnold, Ellis, Reno</td>
</tr>
<tr>
<td>( pp \rightarrow W + 2 \text{ jets} )</td>
<td>2002</td>
<td>Campbell, Ellis</td>
</tr>
<tr>
<td>( pp \rightarrow W + 3 \text{ jets} )</td>
<td>2009</td>
<td>BH+Sherpa</td>
</tr>
<tr>
<td>( pp \rightarrow W + 4 \text{ jets} )</td>
<td>2010</td>
<td>BH+Sherpa</td>
</tr>
</tbody>
</table>

*cf.* Z. Bern, c2 2
Our picture of matter

Pointlike \((r \simeq 10^{18} \text{ m})\) quarks and leptons

Interactions: \(\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y\) gauge symmetries
An unknown agent hides EW 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

*Unanswered Questions in the EW Theory, 0905.3958*
Why will it matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

- Electron and quarks would have no mass
- QCD would confine quarks into protons, etc.
  \textit{Nucleon mass little changed}
- Surprise: QCD would hide EW symmetry, give tiny masses to $W$, $Z$
- Massless electron: atoms lose integrity
- No atoms means no chemistry, no stable composite structures like liquids, solids, . . .

\textbf{Very different universe!}

If we find a Higgs boson . . .

Does it give mass to fermions?

If so, we will learn *why* the muon weighs

We will still not know (in theory) *what* the muon weighs

*Fermion mass implies physics beyond the standard model!*
The hierarchy problem

How to keep the distant scales from mixing in the face of quantum corrections? **OR**

How to stabilize the mass of the Higgs boson on the electroweak scale? **OR**

Why is the electroweak scale small?
Two Puzzles

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*

~ searches for forbidden or suppressed processes

2: Expect New Physics on TeV scale to stabilize Higgs mass, solve hierarchy problem, but no certified failures of EW theory
Unified theories: SU(5)

Unification of Forces?

\[ \log_{10} \left( \frac{E}{1 \text{ GeV}} \right) \]

- SU(3)\text{\_c}
- SU(2)\text{\_L}
- U(1)\text{\_Y}

\[ \frac{1}{\alpha} \]

5 10 15

Chris Quigg (FNAL)
Unified theories: SU(5) + light SUSY

Unification of Forces?

$\log_{10}\left(\frac{E}{1 \text{ GeV}}\right)$

$\frac{1}{\alpha}$

$SU(3)_c$

$SU(2)_L$

$U(1)_Y$
Unified theories: SU(5) + light SUSY

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

\[ \frac{1}{\alpha_s} \]

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

MSSM: \( \frac{3}{2\pi} \)
Issues for the Future (Now!)

1. What is the agent of EWSB? Is there 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?
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?
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?
Ultreia !