Linear Collider: The Next Mega-Science Project?

Physics Colloquium
University of Victoria

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Outline

- What is a linear collider?
  - Why build a linear collider?
  - How can a linear collider be built?
  - Who, where, and when?
What is a linear collider?

- Next in the line of high energy \( e^+e^- \) colliders

SLAC/SLC

CERN/LEP
e^+e^- colliders at the frontier

Centre-of-mass energy (GeV)

Year


PETRA
PEP
TRISTAN
SLC
LEP - I
LEP - II
LC
why linear?

Circumference / Length (km)

Centre-of-mass Energy (GeV)

$R \propto E^2$

$L \propto E$

circular colliders

linear colliders
Outline

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Why build a linear collider?

- A linear collider will allow us to explore important fundamental issues regarding the nature of matter.

- To illustrate:
  - review our current understanding of matter at the smallest scales (The Standard Model)
  - focus on **one** of the many issues that a linear collider can provide further understanding:
    - the origin of mass
Review of Particle Physics

- Particle Physics (n): Study of matter at the smallest scales accessible:

- How small?
  - It is difficult to comprehend the scale of particle physics...

- typical smallest visible scale is $\sim 10 \, \mu m$
Explore a tiny dust speck, diameter 1 \( \mu \text{m} \)

Suppose you could shrink yourself down so small that the speck appeared to be the size of the earth... (magnification factor: \( 10^{13} \))

- atoms → cities
- nucleons → coins

Particle physics today studies matter at a scale of the size of a tiny dust speck in this new world

our scale: a speck in a speck’s world
Matter at small scales

- The speck’s world is an uncertain world governed by quantum mechanics
Matter fields

- complex fields that permeate all space
Matter field fluctuations

- Activity in a vacuum
Matter field fluctuations

- Activity in a vacuum
Different kinds of matter fields

- 12 kinds arranged into 3 families:
  - u: up quark
  - c: charm quark
  - t: top quark
  - d: down quark
  - s: strange quark
  - b: bottom quark
  - ν_e: e neutrino
  - ν_μ: μ neutrino
  - ν_τ: τ neutrino
  - e: electron
  - μ: muon
  - τ: tau
Mass spectrum

neutrinos
electron
muon
tau
up quark
down quark
strange quark
charm quark
bottom quark
top quark

Mass (GeV)

neutrinos ch. leptons quarks
Mass spectrum

- neutrinos
- electron
- muon
- tau
- up quark
- down quark
- strange quark
- charm quark
- bottom quark
- top quark

Mass spectrum graph showing the mass range from $10^{-10}$ to $10^3$ GeV with markers for different particles and quarks.
force fields

- another complex field
force fields

- another complex field
Matter and forces

- **Quarks:**
  - **u** (up quark)
  - **c** (charm quark)
  - **t** (top quark)
  - **d** (down quark)
  - **s** (strange quark)
  - **b** (bottom quark)

- **Neutrinos:**
  - **νₑ** (e neutrino)
  - **νᵩ** (μ neutrino)
  - **ντ** (τ neutrino)

- **Electrons:**
  - **e**
  - **μ** (muon)
  - **τ** (tau)

**Forces:**
- **EM**
- **Weak**
- **Strong**
The behaviour of the matter fields in the presence of the electromagnetic, weak, and strong forces is described by a Lagrangian, known as "The Standard Model".

- The Lagrangian formalism has its roots in classical mechanics:
  - systems with few degrees of freedom

- Remarkably, it also forms the basis for describing relativistic quantum field theory
Symmetries in classical systems

- From studies of classical systems, symmetries of the Lagrangian (invariance principles) were found to have important consequences
  - Noether’s theorem: For every symmetry transformation which leaves the Lagrangian invariant, there is a corresponding conservation law
  - Example: A classical system described by a Lagrangian invariant under space-time translation will conserve four-momentum
  - A deep question is answered (why $p$ conserved?)
Symmetries in particle physics

- Symmetries play a key role in “guessing” the Lagrangian of particle physics.
- In the Standard Model Lagrangian, interactions between matter fields are a consequence of imposing invariance under certain local (gauge) transformations.
  - Deep questions are answered (why are there interactions between the matter fields?)
Gauge bosons

free field Lagrangian + gauge symmetry \rightarrow new Lagrangian with interactions

The extra interaction terms included in the Lagrangian describe mediation via new fields (gauge bosons)
Gauge bosons

free field Lagrangian + gauge symmetry → new Lagrangian with interactions

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Gauge bosons

- free field Lagrangian
- gauge symmetry
- new Lagrangian with interactions

The extra interaction terms included in the Lagrangian describe mediation via new fields (gauge bosons)
Gauge boson mass spectrum

Mass (GeV)

- Photon: EM
- W⁺ / W⁻: weak
- Z: weak
- Gluons (8): strong
Symmetry breaking

- The electromagnetic and weak interactions are a consequence of invariance under the transformations under U(1) and SU(2) groups.
- The procedure yields massless gauge bosons.
  - Adding explicit mass terms for the weak gauge bosons is not allowed – Lagrangian would no longer be invariant.
- A clever modification of the Lagrangian leaves it invariant, but allows for massive gauge bosons.
Symmetry breaking

- Clever modification (by Peter Higgs):
  - add a new self-interacting doublet field $\phi$ to the Lagrangian

- the Lagrangian expressed about the minimum, has massive gauge bosons and an extra scalar (Higgs)
- Higgs scalar responsible for matter field masses
The gauge bosons resulting from the U(1) and the SU(2) symmetries mix together to form the electroweak gauge bosons:

\[ Z^0 \]

\[ SU(2) \]

\[ U(1) \]

\[ \gamma \]

\[ \theta_W \]

A free parameter of the standard model: \( \sin^2 \theta_W \)
Tests of the Standard Model

- Basic tests (1st order):

- fix two parameters from precision measurements:
  - $\alpha_{\text{QED}} = 1/137.035989(6)$
  - $G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$

- free parameter:
  - $\sin^2 \theta_W$
Tests of the Standard Model

Precise measurement of $M_Z$ from LEP: 91.187(2) GeV

$determines \sin^2\theta_W$

$M_W$ correctly predicted
Tests of the Standard Model

\[ \sin^2 \theta_W \text{ from } M_Z \]

Partial decay widths correctly predicted

\[ Z \rightarrow e^+ e^- \]

\[ Z \rightarrow \nu \overline{\nu} \]

\[ W \rightarrow e \nu \]
Tests of the Standard Model

- Detailed tests (higher order)
  - account for quantum effects: field fluctuations
  - Standard Model calculations depends on masses of objects not yet well measured: top quark and Higgs scalar
  - compare large number of precise measurements, with the Standard Model calculations
    - detailed check of Standard Model
    - indirect estimates of $M_t$ and $M_H$
  - mass of top was correctly predicted in this way
## Tests of Standard Model

### Overall goodness of fit:

\[
\chi^2 / \text{dof} = 22.9 / 15
\]

prob. = 8.6 %
Higgs mass

Indirect estimate:

\[ m_H = 88 \pm 53 \text{ GeV} \]
\[ m_H < 196 \text{ GeV} @ 95\% \text{ CL} \]

Direct searches:

\[ m_H > 114 \text{ GeV} @ 95\% \text{ CL} \]
Higgs mass

Just above the reach of LEP?

hope to see it directly at high energy proton colliders: Tevatron or LHC
Triumphs of the Standard Model

- The Standard Model...
  - relativistic quantum field theory
  - matter field interactions arise from gauge symmetries
  - gauge bosons given mass by Higgs mechanism
  - matter fields given mass by Higgs scalar

... works extremely well! All experiments are in complete agreement with the SM!

- Is this the final theory? No!
Shortcomings of the SM

- Too many open questions
  - why 3 generations?
  - why does electron charge = proton charge?
  - why 3+1 space-time coordinates?
  - why such wide variety of mass scales?
  - why the particular gauge symmetries?
  - how does gravity fit in?

- predictions from the Higgs sector problematic:
  - expected masses, modified by fluctuations, way too high
    - new theories (supersymmetry) might solve this
  - Higgs contribution to cosmological constant way too high
What can the Linear Collider do?

- Just as LEP/SLC studied *electroweak symmetry* to high precision, the LC will study *electroweak symmetry breaking* to high precision:
  - LEP/SLC firmly established the electroweak theory
    - likewise, LEP/SLC could have shown the Standard Model to be incorrect
    - the large variety of measurements would have pointed to the new theory
  - The LC will either firmly establish the mechanism of mass generation,
    - or it will provide critical data to point to the new theory
At LEP the golden processes for studying the electroweak sector were:

\[ e^+ e^- \rightarrow Z^0 \quad e^+ e^- \rightarrow W^+ W^- \]

At the LC the golden processes for studying the Higgs sector are:

\[ e^+ e^- \rightarrow Z^0 H \quad e^+ e^- \rightarrow H \nu \bar{\nu} \]

LEP beam energies were not sufficiently high enough for these process to occur
Higgs production at a LC

Example of the golden topology:

\[ e^+ e^- \rightarrow Z^0 H \]
\[ Z^0 \rightarrow \mu^+ \mu^- \]
\[ H \rightarrow b\bar{b} \]

provides a model independent tag
Higgs production at a LC
Higgs measurements at a LC

The following measurements can be made:

- Higgs mass
- Higgs production rate
- Higgs decay rates into specific particle combinations
- Higgs self coupling
- Higgs quantum numbers

... critical measurements to understand electroweak symmetry breaking and mass generation
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How can a linear collider be built?

- Two designs for a linear collider exist:
  - **TESLA**: led by the German laboratory, DESY
    - lower frequency (1.3 GHz) superconducting cavities
    - Initially: \( E_{\text{cm}} = 500 \text{ GeV} \quad L = 3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
    - Later: \( E_{\text{cm}} = 800 \text{ GeV} \quad L = 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
    - Lower wakefields, looser tolerances, higher luminosity
  - **NLC/JLC**: led by the US & Japan laboratories, SLAC & KEK
    - higher frequency (11.4 and 5.7 GHz) warm cavities
    - Initially: \( E_{\text{cm}} = 500 \text{ GeV} \quad L = 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
    - Later: \( E_{\text{cm}} = 1 – 1.5 \text{ TeV} \quad L = 4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
    - highest gradients
Accelerator structures

- The heart of the linear collider:
Accelerator structures

- The heart of the linear collider:
Accelerator structures

- The heart of the linear collider
- Standing EM waves in resonant cavities:
Accelerator structures

- The heart of the linear collider
- Standing EM waves in resonant cavities
- Electron (positron) bunches accelerated:
Damping rings

TESLA

damping ring

linear accelerator

e\textsuperscript{−}
Damping rings

damping ring

linear accelerator

e^{-}

TESLA
Positron source

TESLA

positron preaccelerator

positron source

aux. positron and 2nd electron source

e"
Accelerator physics challenges

- technical challenges for a linear collider:
  - high gradients
    - TESLA: TTF has performed according to design gradient
    - higher gradient cavities now routinely constructed
    - NLC: gradients achieved in NLCTA, but damage observed
    - redesign underway
  - low emittance
    - damping ring test facility (ATF at KEK) successful
  - small spot size (high luminosity)
    - final focus test facility shows required demagnification
The costs...

- TESLA completed an accurate costing:
  - 3.1 Billion Euro, European costing
    - does not include lab personnel
    - does not include contingency
  - Particle physics detector: 0.2-0.3 Billion
  - Free electron laser laboratory: 0.3 Billion

- NLC cost estimate, without contingency:
  - $3.5 Billion
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✓ What is a linear collider?
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Who?

- Worldwide consensus is growing...
  - ICFA
    - “... recommends continuous vigorous pursuit of the accelerator R&D on a linear collider in TeV energy range... should be built in a timely way with international participation”
  - ECFA & ACFA
    - linear collider is highest priority for new facility
  - APS-DPF, Snowmass consensus statement includes:
    - “There are fundamental questions concerning electroweak symmetry breaking and physics beyond the Standard Model that cannot be answered without a physics program at a Linear Collider overlapping that of the Large Hadron Collider. We therefore strongly recommend the expeditious construction of a Linear Collider as the next major international High Energy Physics project.”
Where?

US: California and Illinois sites under consideration

DE: site selected in Hamburg
When?

- TESLA TDR submitted to German Science Council
  - will be reviewed together with other large science projects including
    - European Spallation Source
    - a heavy ion accelerator facility
  - report expected 2002
- German Federal Government decision 2003 (?)
- Construction timescale: 8 years
  - 4 years of civil construction + 4 years machine installation
- US: complete TDR in 2003
- Japan: to request funds for TDR in 2002
The Standard Model of Particle Physics is tremendously successful. It deserves a promotion: “model” → “theory”. However, it fails to answer many “deep” questions. Mass generation is on shaky ground. It is important to bring a linear collider online soon. The linear collider is entering the political phase... once approval comes, then the real excitement starts!