Detecting Massive Scalar Particles at Proton Colliders

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Outline

- Motivation for scalar particles in particle theories
  - The Higgs particle
  - Supersymmetry
- Hints of scalar particles
- The Tevatron collider and the CDF experiment
  - Review of Run 1 searches for Higgs and SUSY
  - Status of Run 2 and search prospects
- The Large Hadron Collider and the CMS experiment
  - Construction progress and search prospects
So far, all known matter is composed of spin-$\frac{1}{2}$ fermions

- electrons, protons, neutrons, ...

Thus, atomic and nuclear structure obeys the Pauli-Exclusion principle

Scalar objects do exist, but actually they are composites

- e.g. $^4\text{He}$, $\pi^+$

In fact, all nuclear particles are composed of spin-$\frac{1}{2}$ quarks

- $p = uuud$
- $n = uudd$
- $\pi^+ = uu\bar{d}$

Additionally, three of the fundamental forces are propagated by spin-1 bosons

- Electromagnetism: Photons ($\gamma$)
- Weak nuclear force: $W^+$, $W^-$, $Z$ bosons
- Strong nuclear force: gluons ($g$)

Quantum gravity would be propagated by a spin-2 boson

unified into one electro-weak theory
$m_{u,d} \sim 5 \text{ MeV}$

$m_t = 174 \text{ GeV}$

$m_\gamma = 0$

$m_g = 0$

$m_\nu \neq 0$ ?

$m_Z = 91.188 \text{ GeV}$

$m_W = 80.4 \text{ GeV}$

$m_e = 0.511 \text{ MeV}$

$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$
The electro-weak theory is described by the SU(2)×U(1) Weinberg-Salam Model.

The quantum field theory of the strong force is described by Quantum Chromodynamics.

Collectively, they are referred to as the “Standard Model”.

However, all masses are zero unless we introduce a scalar field, and this scalar field must obtain a non-zero vacuum expectation value through spontaneous symmetry breaking.

- Generates mass for the vector bosons
- Generates mass for the fermions
- Generates a massive neutral scalar
Self consistency of the Standard Model places upper and lower bounds on the Higgs mass:

- Wide mass range up to ~1 TeV allowed if new physics comes in at scale of 1 TeV
- Narrow mass range if new physics doesn't enter until Grand Unification scale
Detecting Massive Scalars

Indirect Experimental Constraints

Direct $m_W$, $m_t$ measurements

Indirect from electro-weak parameters

PDG, 2002

Direct (1$\sigma$)

Indirect (1$\sigma$)

All (90% CL)

SM predictions
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Direct Higgs Search at $e^+e^-$ Colliders

The Large Electron Positron (LEP) collider at CERN ran from 1989 until 2000

- In depth studies of the Z-boson resonance at 91 GeV
- Steadily increased energy to 209 GeV to study W production and to search for the Higgs
- Shut down to allow construction of the Large Hadron Collider

Possible hint of the Higgs?

$N_{\text{obs}} = 4$
$N_{\text{exp}} = 1.25$

$\Rightarrow P = 3\%$

Lower bound on Higgs mass assuming no signal is 114 GeV at the 95% CL
Why is all matter spin-$\frac{1}{2}$?
Antimatter is the charge conjugation of normal matter
\[ C |e^-\rangle = |e^+\rangle \]
\[ \text{Predicted by P.A.M. Dirac in 1928, observed in 1932} \]

Is there a spin conjugation as well?
\[ Q |\text{fermion}\rangle = |\text{boson}\rangle \]

Such “Supersymmetry” generalizes space-time symmetry

Predicts partners to all known particles with opposite spin statistics
\[ \text{Not so good for a theory, which ought to reduce the number of free parameters (28 for the Standard Model)!} \]

Points the way to a larger theory
\[ \text{When Supersymmetry is required to be a local symmetry, it can incorporate gravity (Supergravity)} \]
\[ \text{Supersymmetry is a prerequisite for string theories} \]
\[ \text{Allows for Grand Unification} \]
Grand Unification

- Coupling “constants” vary with the energy scale
- Minimal Supersymmetric models allow for the unification of 3 forces at one energy scale (would miss otherwise)

![Graph showing the unification of EM, Weak, and Strong forces]

- \(\alpha_s, \alpha, \alpha_w\) vary with energy scale
- \(M_{\text{Planck}} = 10^{19}\ \text{GeV}\)
- \(M_{\text{unification}} = 10^{16}\ \text{GeV}\)
- \(m_e, m_\mu, m_\tau, M_Z\) represent particle masses

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If Supersymmetry exists, there should be scalar partners to the fermions

- e.g. scalar electrons, which would not obey the Pauli-Exclusion Principle in atoms

So far, no such particles are observed at low energy

Supersymmetry cannot be an exact symmetry, and must spontaneously break at some energy scale

Particle masses should be less than about 1 TeV

Lightest Higgs boson (there are at least 5 of them) must have mass < 135 GeV
Leptoquarks: also a source of scalars

There is no explanation in the Standard Model for why atoms are electrically neutral

- Specifically, the relationships between quark and lepton electroweak charges exactly cancel triangle anomalies in the Standard Model

  - Makes the Standard Model a renormalizable theory

Leptoquarks arise in Grand Unification models, “technicolor”, Supersymmetry, and compositeness

- Connects the lepton sector to the quark sector, which otherwise are just ad hoc ingredients to the SM

LQs are color triplet bosons (scalar or vector) with lepton number and fractional electric charge

Hint of leptoquarks in data taken by the HERA electron-proton collider in 1997, but no longer seems likely
Cosmological Implications of Scalars

In the Minimal Supersymmetric Standard Model, the lightest supersymmetric particle is stable:
- Generally a neutral, weakly interacting particle (neutralino)
- Good candidate for Cold Dark Matter

Scalar particles can obtain a non-zero vacuum expectation value (vacuum energy):
- May give rise to a cosmological constant

Current consensus among cosmologists from measurements of the cosmic microwave background, supernovae, Big Bang nucleosynthesis, clusters of galaxies, ...:
- $\Omega \approx 1$ (flat universe)
- $\Omega_\Lambda \approx 0.7$, $\Omega_m \approx 0.3$
- $\Omega_m = \Omega_b + \Omega_{CDM}$; $\Omega_b \approx 0.04$
The Fermi National Accelerator Laboratory

Batavia, Illinois
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The Tevatron

Proton-Antiproton collider

$E_{\text{beam}} = 1 \text{ TeV}$

$R = 1 \text{ km}$

In operation since 1985
Major upgrade completed in 1999
A very large, general purpose "microscope" to study the structure of matter
Hundreds of researchers participate

Run 1: 1992 – 1996
L=120 pb⁻¹
Discovery of the Top Quark in 1995

Discovery of the Top Quark in 1995

\[ t \bar{t} \rightarrow b \bar{b} W^+ W^- \rightarrow b \bar{b} q q' e \nu \]

Relatively long-lived

\[ M_{\text{top}} = 174 \pm 5 \text{ GeV} \]
Bottom quarks and charm quarks have a lifetime of about 1 ps.

Tag bottom and charm quarks by reconstructing the secondary vertex of their decay products.

Measure the flight distance ($L$):
- Typically several hundred microns, extending up to a few mm.
- This is still within the beam pipe, not in the detectors, so we must extrapolate a precisely measured track.

An important signature of the decay of heavier particles...
Tagging $b$ quarks is important to discover a light Higgs
**Higgs Production**

*Note:*

\[ \sigma = \text{scattering cross section} \]

1 pb = \(10^{-36}\) cm\(^2\)

\[ L \cdot \sigma = N \ (\text{number of events}) \]

\(L = 120 \ \text{pb}^{-1}\) for Run 1
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Relative Yields at the Tevatron

1 fb = $10^{-3}$ pb

SUSY and Background Cross-Sections

- Jets
- Bottom
- W/Z
- SUSY
- Top
- Higgs
- Squarks
- sleptons

Background

Signal

(one in a billion collisions!)
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Observed events agree well with background expectations

Require 10–100X more data to be sensitive to SM Higgs production

No anomalous production
Signatures of Supersymmetry

Larger cross sections for the production of scalar quarks and gluons rather than leptons at a proton collider because of the strong force couplings

Examples:

\[
\begin{align*}
\bar{p}p & \rightarrow \bar{q}q, \bar{q}g, \bar{g}g \\
\bar{p}p & \rightarrow \bar{G}Gg, \bar{G}\bar{G}q \\
\bar{p}p & \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1
\end{align*}
\]

\[
\begin{align*}
\tilde{q}, \tilde{g}, \tilde{G} & \Rightarrow E_T + \text{jets} \\
\tilde{t}, \tilde{b} & \Rightarrow E_T + \text{HF jets}
\end{align*}
\]

Signatures:

- Jets (from the hadronization of quarks and gluons)
- Missing energy (from undetected lightest SUSY particle)

Backgrounds:

- QCD jets
- W/Z production
- Top quarks

Orders of magnitude larger

Review just one search of many here
Scalar Top Quark Search

The heavy top quark mass gives rise to a large mixing between the left- and right-handed scalar top eigenstates

- Results in a large mass splitting between the two mass eigenstates

Thus, the “stop” could be the lightest scalar quark

Search for the pair production of stop quarks

Look for the decays:

- $\tilde{t} \rightarrow b\chi_1^\pm$

- $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ (if first closed)
Use Missing transverse energy data sample

- 2 or 3 jets, $E_T \geq 15$ GeV and $|\eta| \leq 2$
- No jets with $7 \leq E_T \leq 15$ GeV and $|\eta| \geq 3.6$

- Cuts on jet-MET, jet-jet angles
- No $l$ with $P_T > 10$ GeV
- $MET > 40$ GeV

Require $\geq 1$ charm quark tag

Expect $14.5 \pm 4.2$ events
Observe 11

Main Backgrounds:

$W \rightarrow \tau\nu + 1(2,3,...) \text{ jet}$
$Z \rightarrow \nu\bar{\nu} + 2(3,4,...) \text{ jet}$
QCD

Published: PRL, 84,5704(2000)
Scalar Top Quark Limits

$M(\tilde{t}_1) = M(b) + M(\nu)$

$\text{BR}(\tilde{t}_1 \to b l^\pm \bar{\nu}) = 100\%$

CDF Excluded Region $\equiv \sigma_{95\% CL}(\tilde{t}_1 \tilde{t}_1) < \sigma_{NLO}(\tilde{t}_1 \tilde{t}_1)$

$\sigma_{NLO}: \mu = m(\tilde{t}_1), \text{CTEQ3M}$

(hep-ph/9611232)

$\eta_{\text{stop}} = 0$

ALEPH $\sqrt{s} = 189 \text{ GeV}$

$\eta_{\text{stop}} = 0$

OPAL $\sqrt{s} = 189 \text{ GeV}$

$\eta_{\text{stop}} = 0$

CDF - 88 pb$^{-1}$

95% CL

D0 7.4 pb$^{-1}$

$\eta_{\text{stop}} = 0$

$\eta_{\text{stop}} = 0$
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CDF II Detector

Goal:

Run 2a: 2001 – 2004
(2000 – 4000 pb\(^{-1}\))
Run 2b: 2004 – 2007+
(15000 pb\(^{-1}\))

Completely new electronics
New plug calorimeter
New muon chambers
New central tracker
New silicon vertex detector
Silicon Vertex Detector

- Radius: inner = 1.35 cm, outer = 29 cm
- Length: 90 cm
- Strip pitch: 60 µm
- Double-sided layers for r–φ, stereo r–φ, r–z

New

$20M
Run 2 Integrated Luminosity (CDF)

≈70 pb⁻¹ delivered
≈50 pb⁻¹ recorded

Best instantaneous luminosity: \(2.8 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}\)
Design goal: \(8.6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}\)

Expect 100–200 pb⁻¹ delivered by end of year
\[ \sigma(W) \times BR(W \to e\nu) \text{ (nb)} = 2.60 \pm 0.07_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.26_{\text{lum}} \]

- Consistent with Run 1 results rescaled for higher collision energy:
  \[ 2.72 \pm 0.02_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.09_{\text{lum}} \]
Clear evidence of $Z \rightarrow \mu^+\mu^-$

- Signal shown for opposite sign muons detected in both inner and outer muon chambers

-57 candidate events in $66 < M_{\text{inv}} < 116$ range

CDF run II preliminary
16 pb$^{-1}$
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Tagged Muon in CDF

Note: B mesons decay into soft leptons about 10% of the time

Muon

Contains in a jet with $E_T = 9 \text{ GeV}$

Et = 5.33 GeV
Zoom-in of previous event:

Jets containing soft muons exhibit low probability of coming from the primary vertex

Event was tagged by the “Jet Probability” algorithm we are developing at UF for tagging bottom and charm jets
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SM Higgs Search in Run II

Run II Higgs WG
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\[ \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 \]

E_{CM} = 2.0 \text{ TeV}

L = 20 \text{ fb}^{-1}

L = 4 \text{ fb}^{-1}

L = 2 \text{ fb}^{-1}

Run 1

LEP \chi_1^0 \text{ limit}

Run II

D.Tsybychev's thesis topic
Scalar Leptoquark Prospects

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A. Moorhead, 2002 REU project

Existing Run 1 limits

Projected limit for 2 fb⁻¹

Same topology as for scalar top quark search

Leptoquark Mass (GeV/c²)

Charged lepton branching ratio

β

Leptoquark Mass (GeV/c²)

D0 Scalar
CDF Scalar eejj
CDF Scalar vv

First Generation Limits

A.Moorhead,
2002 REU project

Existing Run 1 limits

Projected limit for 2 fb⁻¹

Same topology as for scalar top quark search

Leptoquark Mass (GeV/c²)
The CERN Laboratory

Geneva, Switzerland
Detecting Massive Scalars

The Large Hadron Collider

R = 4.5 km
E = 7 TeV
L = 100 fb^{-1}/year

CERN

2 proton rings housed in same tunnel as LEP
Completion: mid 2007
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The Compact Muon Solenoid Expt.

- PbWO₄ Crystals
- $\gamma/e$ detection
- Silicon Tracker
- Hadronic calorimeter
- Jets, missing $E_\nu$
- 4T magnet
- Muon chambers
“There’s no scale”

The inner vacuum tank of the magnet cryostat
Endcap Muon System

Iron disk of endcap muon system
One of 540 chambers to be mounted

System will have 0.5 million electronic channels
CMS DAQ Architecture

CMS has a multi-tiered trigger system:

- **L1** reduces rate from 40 MHz to 75 kHz
  - Custom hardware processes calorimeter and muon data to select electrons, photons, jets, muons, $E_T$ above threshold

- **L2, L3, ... (HLT)** reduces rate from 75 kHz to 100 Hz
  - Commercial CPU farm runs online programs to select physics channels

Large telecomm switch (500 Gbit/s)

~1000 node PC cluster

40 MHz BX rate ⇒ 1 GHz of collisions

40 TB/s

100 MB/s
Detecting Massive Scalars

Programmable logic performs massively parallel computation to reconstruct muons in real-time.

100 billion operations per second

UF Muon Trigger Prototype

**Final Selection Unit**
XCV150BG352

**Extrapolation Units**
XCV400BG560

**Assignment Units**
XCV50BG256 & 2M x 8 SRAM

**Track Assemblers**
256k x 16 SRAM

**Bunch Crossing Analyzer**
XCV50BG256

Successfully tested in 2000

3 GB/s input
Detecting Massive Scalars

3 other boards merged

1 chip contains all logic of previous board!

To be tested this winter –

Design/test involves
3 engineers, 1 grad student,
1 undergrad

The Next Generation
Detecting Massive Scalars

**SM Higgs – Intermediate Mass**

\[ H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^- \ (\ell = e, \mu) \]

- Very clean
- **Resolution:** ~ 1 GeV
- Works for the mass range \( 130 < M_H < 500 \text{ GeV}/c^2 \)

\[ H \rightarrow ZZ^* \rightarrow 4 \ell^\pm \]

![Graph showing events vs. mass](image)

**Diagram:**
- Production of Higgs boson (H) decays into ZZ
- ZZ further decays into four leptons (\( \ell^+ \ell^- \ell^+ \ell^- \))
- Resolution: ~ 1 GeV
- Mass range: \( 130 < M_H < 500 \text{ GeV}/c^2 \)
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**SM Higgs – Low Mass**

\[ H \rightarrow bb \text{ via} \]

\[ ttH \rightarrow ttbb \rightarrow l\nu b + bjj + bb \]

- Use likelihood for top quark decays & event kinematics
  - \( S/B \approx 0.8 \)

\[ H \rightarrow \gamma\gamma: \text{ decay is rare (B~10^{-3})} \]
- good resolution essential
- reason for PbWO\(_4\) crystals
- at 100 GeV, \( \sigma \approx 1\text{GeV} \)
  - \( S/B \approx 1:20 \)
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**SM Higgs Prospects at CMS**

- $H \rightarrow ZZ \rightarrow 4l$ covers widest mass range
  - Good muon coverage

- $H \rightarrow \gamma \gamma$ important at low mass
  - Good calorimetry

Greater than 5σ discovery potential over full mass range from LEP limit to 1 TeV in 1 year at design luminosity

LEP limit
Conclusion

Scalar particles are the key to understanding the nature of the fundamental forces and space-time

→ Higgs
  □ Strong indirect evidence of its existence, though no direct measurement yet. Last particle to be discovered in SM

→ Supersymmetry
  □ Compelling theoretical framework, but no experimental evidence

→ Leptoquarks
  □ Stranger things could happen...

CDF II is operating well, but data coming slowly

→ Expect 100–200 pb\(^{-1}\) delivered by end of year (≈ Run 1)
→ Goal is to collect ~15000 pb\(^{-1}\) of data by 2007
→ Good heavy-flavor tagging (\(b, c\) quarks) is essential

If not discovered at the Tevatron, the LHC will be capable of discovering the Higgs and ruling in/out Supersymmetry, starting in 2007