Searches for Physics Beyond the Standard Model at CDF

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June 22, 1992

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Introduction

Several ways of probing "Beyond the Standard Model"

- Precision EWK tests
- Studies of phenomena sensitive to "new" physics
- Search for phenomena not predicted by the SM

High energy $p\bar{p}$ collider is a unique laboratory

- produce *anything* that couples to quarks and gluons
- large parton-parton $\sqrt{\hat{s}}$ and Q^2
- large integrated luminosities

The CDF Experiment

The Collider Detector at Fermilab

- 350 physicists from 26 institutions
- "general-purpose" detector studying 1.8 TeV $\overline{p}p$ collisions
  - excellent charged particle detection
  - hermitic calorimetry covering $|\eta| < 4.2$
  - electron, photon and muon identification

Took data in 1988-89

- Accumulated 4.2 pb^{-1}
- $\sim 2 \times 10^{11}$ $\overline{p}p$ interactions
- selected and recorded $\sim 6 \times 10^{6}$ events in real-time

CDF Data Sets

CDF data were classified into distinct data sets offline:

- Inclusive electron sample
- Inclusive muon sample
- High P_T ($>$ 120 GeV/c) jets
- Events with large missing E_T ($\not\!\!E_T >$ 25 GeV)
- Dimuon events (*e.g.* 2 μ with $P_T >$ 3 GeV/c)

Used standard "cuts" to define canonical event samples

- Physics analyses used these as basis for most studies
- Avoid discussing details...

Precision Standard Model Tests

W boson mass is an important SM test

- Stringent test of the EW radiative corrections
- Unique to $p\bar{p}$ colliders (S$p\bar{p}$S and Tevatron)
- Requires careful control of systematic uncertainties

M_W inferred from "transverse mass" distribution for $l\nu_l$ events

- ~ 1100 $e^{\pm}\nu_e$ candidates and ~ 600 $\mu\nu_\mu$ candidates
- Dominate systematic uncertainties arise from
  - structure functions
  - underlying event corrections

$$\Rightarrow M_W = 79.91 \pm 0.39 \text{ GeV/c}^2$$

Quark Compositeness

QCD assumes that quarks are point-like particles

- Quark sub-structure can be modelled by introducing a 4-fermion interaction with an energy scale Λ

- Would enhance rate of $q\bar{q} \to q\bar{q}$ scattering at large Q^2

Select inclusive jet events and compare P_T spectra with perturbative QCD

- Requires detailed understanding of jet energy calibration
- CDF relies on combination of
  - *in situ* measurement of calorimeter non-linearity
  - extensive test beam studies
  - detailed MC studies effects due to jet fragmentation and underlying event

Sets a quark compositeness scale

$$\Lambda > 1.4 \text{ GeV at } 95\% \text{ C.L.}$$

Lepton Substructure

Lepton substructure will modify Drell-Yan production at high Q^2.

$$p\bar{p} \rightarrow l^+l^-$$

- Model compositeness with the introduction of additional 4-fermion contact interaction in Lagrangian
- Predicts excess of l^+l^- events at large mass
- Backgrounds expected to be small

Select events with *isolated* electron pairs

- Z° provides excellent calibration signal
- Require lepton P_T> 20 GeV/c

Data in good agreement with Drell-Yan prediction

- Sets electron-quark compositeness scale

$$\Lambda_{-}^{LL} > 2.2 \text{ TeV at } 95\% \text{ C.L.}$$

$$\Lambda_{+}^{LL} > 1.7 \text{ TeV at } 95\% \text{ C.L.}$$

- Sets muon-quark compositeness scale

$$\Lambda_{-}^{LL} > 1.6 \text{ TeV at } 95\% \text{ C.L.}$$

$$\Lambda_{+}^{LL} > 1.4 \text{ TeV at } 95\% \text{ C.L.}$$

SUSY Searches

SUSY remains an attractive extension to the SM

- Provides a unified description of the 3 strongest forces
- Predicts a spectrum of new fermions and bosons
- Spurred by recent analysis of energy-dependence of gauge couplings

$\tilde{q}$'s and $\tilde{g}$'s couple strongly to $\overline{p}p$ initial state

- large production cross sections
- decay signature is large $\not{E}_T$ accompanied by additional jets

CDF's most recent search focuses on decay modes

$$\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$$
$$\tilde{q} \rightarrow q\tilde{g} \text{ for } M_{\tilde{q}} > M_{\tilde{g}}$$
$$\tilde{q} \rightarrow q\tilde{\gamma} \text{ for } M_{\tilde{g}} > M_{\tilde{q}}$$

- Require $\not{E}_T > 40$ GeV to identify LSP
- QCD Backgrounds reduced by requiring ≥ 2 jets
  - jet $E_T >$ 15 GeV
  - $|\eta| < 3.5$
- Results in 93 candidate events

Expect several SM backgrounds

$$\begin{aligned} Z \to \nu\bar{\nu}X &\quad\Rightarrow\quad 23 \pm 8 \\ W \to \tau\bar{\nu}X &\quad\Rightarrow\quad 41 \pm 15 \\ W \to \mu\bar{\nu}X &\quad\Rightarrow\quad 18 \pm 6 \\ W \to e\bar{\nu}X &\quad\Rightarrow\quad 9 \pm 3 \\ \text{Heavy Quarks} &\quad\Rightarrow\quad 4 \pm 4 \end{aligned}$$

Conclude that data is consistent with SM sources

- Acceptance for $\tilde{q}$ and $\tilde{g}$ pair production varies with SUSY particle mass
- Also depends on SUSY decay modes
  - Assumed naive decay model to set SUSY mass limit
- Fit the $\not{E}_T$ distribution to SUSY signal and background

Set SUSY mass limits of

$$M_{\tilde{g}} > 152 \text{ GeV/c}^2 \text{ at } 90\% \text{ C.L.}$$

$$M_{\tilde{q}} > 126 \text{ GeV/c}^2 \text{ at } 90\% \text{ C.L.}$$

W' and Z' Searches

Many extensions to SM that predict additional gauge groups

- Have two additional "degrees of freedom"
  - mass of gauge bosons
  - couplings of bosons to quark and lepton sectors

CDF has searched for such W' and Z' bosons

$$q\bar{q}' \to W' \to l\nu_l$$
$$q\bar{q}' \to Z' \to l^+l^-$$

Used event sample with very loose lepton ID cuts

- Data is quite clean
- Consistent with tail from W and Z decay

Resulting 95% C.L. limits are

$$\begin{aligned} M_{W'} &> 520 \text{ GeV/c}^2 \\ M_{Z'} &> 412 \text{ GeV/c}^2 \end{aligned}$$

Massive Stable Particles

Searched for evidence of massive, stable particles

- Assumed lifetime $\gamma\tau > 10^{-8}$ s
- Search for *slow* μ-like particle
- Required $P_T >$ 25 GeV/c

Observed 2 candidate events

- To be conservative, assumed both are signal
- Set 95% C.L. limits on cross section

Leptoquark Search

Leptoquarks are predicted in various SM extensions

- couple quarks and leptons of a given generation
- would be pair-produced in $\overline{p}p$ collisions
- decay to a lepton+quark final state

Searched for evidence of leptoquark production

- Searched for events with dileptons and accompanying jets
- Required
  - 2 electron candidates with $P_T >$ 20 GeV/c
  - 2 jets with $E_T >$ 20 GeV
- Removed $Z \rightarrow e^+e^-$ decays ($75 < M_{ee} < 105$ GeV/c^2)

Observe 0 events

- Can set lower limit on leptoquark mass M_{lq}

$$M_{lq} > 113\ \text{GeV/c}^2 \text{ at } 95\% \text{ C.L.}$$

Rare Decays

The radiative decay $W^{\pm} \rightarrow \pi^{\pm}\gamma$

- Suppressed in SM ($\Gamma(W \rightarrow \pi\gamma)/\Gamma(W \rightarrow e\nu_e) \sim 3 \times 10^{-8}$)
- Sensitive to $W - \gamma$ coupling and QCD effects

Have some sensitivity to such rare decay modes

- Produced $\sim 24,000$ $W + X$ events
- Inclusive photon used to trigger on $W^{\pm} \rightarrow \pi^{\pm}\gamma$
  - Select isolated γ candidate events with $P_T >$ 25 GeV/c
  - Require single charged particle jet with $E_T >$ 25 GeV

Selection results in 11 events

- 3 events in signal region $71 < M(\pi\gamma) < 89$ GeV/c^2
- Expect *at least* 1.4 events in signal region from QCD

Set upper limit

$$\frac{\Gamma(W^\pm \to \pi^\pm\gamma)}{\Gamma(W^\pm \to e^\pm\nu_e)} < 7.5 \times 10^{-3} \quad \text{at 95\% C.L.}$$

Using SM value for $BR(W^\pm \to e^\pm\nu_e) = 0.109$ ($M_{top} > M_W$)

$$BR(W^\pm \to \pi^\pm\gamma) < 8.2 \times 10^{-4}$$

High E_T Events?

Also systematically examined the highest E_T events

- Studied tail of $\sum E_T$ distribution
- Consistent with perturbative QCD jet production

Future Prospects at CDF

CDF is currently beginning a new data run

- Expect 25 pb^{-1} by summer 1993
- Expect 100 pb^{-1} by early 1994

$$\Rightarrow \times 25 \text{ increase in data sample}$$

Detector has also been significantly upgraded

- Inner Silicon Vertex Detector (SVX)
- Extended μ coverage to $|\eta| < 1.0$
- Incremental improvements to calorimetry and DAQ

Improve the probes into physics of the SM and beyond

- Uncertainty on $M_W \rightarrow 0.1$ GeV/c^2
- Observe top quark production if $M_{top} \lesssim 150$ GeV/c^2
- Improve sensitivity to very high-mass phenomena
  - Do not appear to be background-limited
  - Obtain factors of 5-10 in cross section limits
- Probe the bottom quark sector

Summary

CDF has not seen *any* hints of **NEW** physics

Searched for

- Supersymmetric particles ($\tilde{q}$ or $\tilde{g}$)
- W' and Z' gauge bosons
- quark or lepton compositeness
- $W \to \pi\gamma$
- Unusual (*e.g.* high $\sum E_T$) events

Expect to increase data set by $\times 25$ over next year

- Will increase sensitivity of these searches
- Study rarer processes (*e.g.* $W^{\pm}W^{\mp}$ production)
- Test consistency of SM with top quark search