1997-1998 ACADEMIC TRAINING PROGRAMME
LECTURE SERIES ON LHC DETECTORS

PLACE: AUDITORIUM

<table>
<thead>
<tr>
<th>TITLE OF LECTURE</th>
<th>LECTURER</th>
<th>DATE</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey of previous results from hadron colliders and physics motivation for LHC</td>
<td>K. EINSWEILER</td>
<td>09.02.1998</td>
<td>10:15 to 11:00</td>
</tr>
<tr>
<td>Requirements and design criteria for ATLAS</td>
<td>M. FERNANDEZ-BOSMAN</td>
<td>09.02.1998</td>
<td>11:15 to 12:00</td>
</tr>
<tr>
<td>Requirements and design criteria for CMS</td>
<td>F. PAUSS</td>
<td>10.02.1998</td>
<td>10:15 to 11:00</td>
</tr>
<tr>
<td>Tracking at LHC</td>
<td>L. ROSSI</td>
<td>10.02.1998</td>
<td>11:15 to 12:00</td>
</tr>
<tr>
<td>Calorimetry at LHC</td>
<td>B. MANSOULIE</td>
<td>11.02.1998</td>
<td>10:15 to 11:00</td>
</tr>
<tr>
<td>Muon identification and measurements at LHC</td>
<td>A. BENVENUTI</td>
<td>11.02.1998</td>
<td>11:15 to 12:00</td>
</tr>
<tr>
<td>Electronics at LHC</td>
<td>G. HALL</td>
<td>12.02.1998</td>
<td>10:15 to 11:00</td>
</tr>
<tr>
<td>Trigger/DAQ at LHC</td>
<td>P. SPHICAS</td>
<td>12.02.1998</td>
<td>11:15 to 12:00</td>
</tr>
<tr>
<td>Physics performance : SM, alternative EWSB</td>
<td>K. JACOBS</td>
<td>13.02.1998</td>
<td>10:15 to 11:00</td>
</tr>
<tr>
<td>Physics performance: MSSM Higgs, Sparticles</td>
<td>J. WOMERSLEY</td>
<td>13.02.1998</td>
<td>11:15 to 12:00</td>
</tr>
</tbody>
</table>
1997–1998 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES ON LHC DETECTORS

PLACE: AUDITORIUM
DATE: 9 February 1998

SPEAKER: K. EINSWEILER / LBL, Berkeley, USA
TITLE: Survey of previous results from hadron colliders and physics motivation for LHC
TIME: from 10.15 to 11.00 hrs

The present state of knowledge of the Standard Model and several examples beyond the Standard Model physics is summarized. Special emphasis is placed on results from hadron colliders, particularly the FNAL Tevatron. Expectations for the remainder of the pre-LHC period are discussed, leading to an estimate of our expected level of understanding prior to LHC startup.

SPEAKER: M. FERNANDEZ-BOSMAN / IFAE, Barcelona, Spain
TITLE: Requirements and design criteria for ATLAS
TIME: from 11.15 to 12.00 hrs

The Atlas detector is a general-purpose pp detector designed to exploit the full discovery potential of the LHC. The overall concept of the detector is reviewed in the context of the main physics performance goals. The choice of the magnet configuration and the design of the main components of the detector, calorimetry, inner detector, muon detector and trigger system are discussed in terms of the required performances for electron, gamma, muon, jet and missing transverse energy measurement and jet-tagging capability. The variety of signatures that will be available at the high LHC luminosity and at the initial phase of lower luminosity are reviewed.
Hadron Collider Physics in the Pre-LHC Era

K. Einsweiler, LBNL

What are the major issues?

- Standard Model Physics
- Beyond the Standard Model Physics

What do we know now, and what will we know in 2005?

- Emphasize CDF/D0 results from Tevatron Run 1 (92-96) and expectations for Run 2

Look briefly at physics topics most relevant to the LHC program and survey what we know today and what we expect to know when the LHC turns on.

Attempt to speculate on what will be the most exciting issues as LHC experiments begin producing physics results...
Major Issues in Hadron Collider Physics

Standard Model is remarkably successful at describing all data:

- Strong interactions well-described by “confining” SU(3) gauge theory based on gluons and quarks carrying color charges known as Quantum Chromodynamics (QCD).

- Weak interactions well-described by the unified Electroweak theory based on SU(2)xU(1) gauge theory based on $W^\pm/Z/\gamma$ as force carriers. The coupling to six “flavors” of quarks appears to be described by the CKM matrix.

- The Electroweak symmetry manifests itself as a “hidden” or “spontaneously broken” symmetry in which the W and Z are massive gauge bosons (in a fully symmetric world, all Electroweak force carriers would be massless, not just the photon). This means that the Lagrangian exhibits the SU(2)xU(1) symmetry, but the world in which we live has chosen a vacuum state which only displays a remnant U(1) symmetry.

- Many theoretical arguments indicate that the mechanism which breaks the Electroweak symmetry (Higgs mechanism) must be visible below the TeV mass scale. It may involve fundamental scalar particles (Higgs bosons) or some strongly interacting composite equivalent.

**Major Issues:**

- Study Strong and Electroweak interactions in detail and **look for deviations from SM**.

- **Search for Higgs bosons** or alternative manifestations of EWK symmetry breaking.
Many indications of “incompleteness” of Standard Model:

- “Naturalness” or “fine-tuning” problem: in SM, there is one parameter with a dimension of mass which determines the Electroweak scale. However, this parameter has a quadratic divergence when the bare Lagrangian is renormalized. Hence, if there is no new physics to cut-off this divergence, would expect the weak scale to be roughly the Planck scale. Present $\approx 10^{16}$ separation in scales requires exquisite cancellations.

- “Gauge Coupling Unification”: Would hope that a complete theory would be based on a single gauge group, not a product of several independent groups. Also, evolution of strong, weak, and electromagnetic couplings to higher energy indicates they converge.

Strong arguments in favor of Supersymmetric extensions of Standard Model:

- Naturalness problem is resolved by elimination of the quadratic divergence due to cancellation of fermion and boson contributions. Only logarithmic divergences remain.

- Observed pattern of quark masses (top mass is roughly at EWK scale, others are “light”) can be related to EWK symmetry breaking by radiative effects. Specifically, in a SUSY world where there is a quark with Yukawa coupling of order one, the negative mass-squared term needed for symmetry breaking appears as a radiative correction.

- “Prediction” of String Theory, which is presently the only framework which provides a consistent quantum description of gravity.
Supersymmetry Issues:

- Clearly, no SUSY particles are observed in everyday life, so SUSY must be another "hidden" symmetry. It must be "softly" broken to retain the virtue of no quadratic divergences. This requires that the breaking takes place in a "hidden sector" and is transmitted to our world via a "messenger sector" which connects us to the "hidden sector" only via loop diagrams. There are MANY free parameters in this breaking, which diminishes the predictive power of SUSY theories...

- Contemporary models typically use a "gravity mediated" or "gauge mediated" SUSY breaking, leading to rather different phenomenologies. The gravity-mediated cases have the LSP (lightest SUSY particle) as a neutralino (fermionic partner of the gauge bosons and Higgs bosons of the SM) whereas gauge-mediated cases have the LSP as the gravitino (fermionic partner of graviton). This is a rapidly evolving area - it is hard for experimenters to follow, and hence to quantify the results of their searches.

- Nevertheless, if we are to harvest the benefits of SUSY described previously, it must manifest itself at the weak scale! Hence, existing experiments, or those under construction, will either find weak-scale SUSY or rule it out.

Other Issues:

- In general, in "Grand Unified" theories, expect additional types of states, such as new gauge bosons, leptoquarks (colored objects containing both quark and lepton quantum numbers), and possibly other oddities.
Hadron Collider Physics at the FNAL Tevatron

The FNAL proton-antiproton collider operates at 1.8 TeV CMS energy, and defines the present energy frontier in HEP:

This machine has operated at luminosities up to $2.5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, and has delivered an integrated luminosity to the two general purpose experiments of roughly 100 pb$^{-1}$.
Tevatron Experiments

There are two general purpose experiments at the Tevatron Collider, CDF and D0:

- CDF began construction in early 80's, has excellent magnetic tracking, silicon vertex reconstruction over central region, complete calorimeter coverage with adequate performance after corrections, and reasonable muon coverage in central region:
D0 was built in the late 80's, and has non-magnetic tracking. It has a uniform, hermetic LAr calorimeter with fine segmentation. The muon system relies on iron toroids, and provides complete coverage with modest momentum resolution and low backgrounds.
Run 1 at the Tevatron extended from May 1992 - Feb 1996:

CDF Integrated Luminosity -- Run 1 (pb-1)

• Run 1a: initial 1 year run, Run 1b: long 1.5 year run, Run 1c: short 3 month final run
Some Highlights of Physics Results from Run 1

QCD Studies:
- Analysis of dijet production: $E_T$ distributions and angular distributions

Electroweak Studies:
- Measurement of $W$ mass and width
- Gauge boson self-couplings ($WW\gamma$, $WWZ$)

Heavy quark studies:
- Measurement of $t$ quark properties (mass, BR)
- Measurement of $b$ quark properties (lifetimes, mixing, rare decays)

Searches for New Physics:
- SUSY searches (squarks, gluinos, etc.)
- New gauge bosons ($W'$, $Z'$)

Many more substantial results, too numerous for this talk!
QCD Studies in Run 1

Many detailed tests of perturbative QCD carried out.

Highlight: inclusive jet cross-section and angular distributions:

- Must combine data samples satisfying many different trigger requirements to piece together spectrum (cross section varies by 10 orders of magnitude!)
- Must carefully correct for detector effects, and must apply "unsmearing" procedure to correct for measurement effects on $E_T$ distribution.

- In high $E_T$ region, cross section is dominated by QQ scattering, but QG still plays a role.
- This implies a certain "theoretical" uncertainty in the cross section predictions, arising from uncertainties in the parton distribution functions.
CDF Run 1a result for jet $E_T$ distribution (Data-Theory)/Theory:

- Good agreement with QCD prediction at lower mass.
- Indication of a deviation at high mass, beyond estimated systematic uncertainty.
- Dominant contributors to uncertainty at high jet $E_T$ are response to high $P_T$ pions and fragmentation effects.

- Deviations at high jet $E_T$ or small $\cos\theta^*$ could be indication of compositeness (analog of classic Rutherford scattering experiments in which nucleus was discovered).
Both CDF and D0 produced results using Run 1b sample:

CDF Preliminary
Run 1B (87 pb⁻¹)
with run 1A results overlayed
NLO QCD CTEQ3M scale Et/2

Statistical errors only

CDF confirmed its previous results, and D0 claimed consistency with QCD.
Careful analysis and comparison by both collaborations indicated that the two sets of experimental data were also consistent with each other within errors...
Both Collaborations have studied angular distributions:

- Sensitive to "compositeness" signal, but less sensitive to jet response details.

- Define angular variable: 
  \[ \chi = \frac{1 + \cos \theta^*}{1 - \cos \theta^*} \]

- Classical Rutherford scattering is flat in \( \chi \).

- QCD is slightly peaked near small values of \( \chi \).

- Compositeness is very significantly peaked near small values of \( \chi \).

- Both experiments performed careful measurements, concluding there is no evidence for compositeness for scales \( \Lambda < 1.8 \text{ TeV} \). This is a hard way to find new physics!
Electroweak Studies in Run 1

Major topic is detailed measurements of $W$ boson properties:

- Concentrate on $M(W)$ and $\Gamma(W)$, but significant work done on non-Abelian gauge couplings. Measurements prove that delicate cancellations in SM which ensure renormalizability are present, otherwise excess $WW$ and $WZ$ events would be seen.

- Hadron colliders must measure $M(W)$ directly with no assistance from machine energy. This places enormous emphasis on the energy and momentum scales in the detector, which must be known to 0.1% or better.

$W$ properties measured with leptonic decays: $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$

- Both CDF and D0 have samples of roughly 50K leptonic $W$ decays to work with.

- Mass is best determined through use of "transverse mass" variable ($P_T(\nu)$ unknown):

$$M_T^2 = 2P_T(l)P_T(\nu)[1 - \cos\Delta\phi(l\nu)]$$

- $M_T$ distribution fit using numerical likelihood functions from fast, accurate, and flexible physics and detector model.

- Careful study of systematic uncertainties is required to achieve overall error $\approx 0.1$%

- CDF scale is derived from magnetic tracking, combined with high statistics measurement of $M(\psi \rightarrow \mu\mu)$ which is normalized to low-energy $e^+e^-$ measurements.

- D0 scale is derived from $M(Z \rightarrow ee)$ which is normalized to LEP1 measurements.
M(W) Measurement of CDF

Preliminary Run 1b result uses muons - electrons in progress:

- Measurement of $M(\psi)$ based on a sample of $\approx 250K \, \psi \rightarrow \mu\mu$ events.

- Measurement of $M(Z)$ and $\Gamma(Z)$ using $Z \rightarrow \mu\mu$ events.
CDF W Mass result:

CDF(1B) Preliminary

\[ \chi^2/df = 158/139 \ (50 < M_T < 120) \]
\[ \chi^2/df = 62/69 \ (65 < M_T < 100) \]

M_w = 80.430 \pm 0.100 \ (\text{stat}) \ 
\pm 0.040 \ (\text{scale}) \ 
\pm 0.115 \ (\text{syst}) \ \text{GeV}
CDF Direct Measurement of $\Gamma(W)$

Fit $\Gamma(W)$ directly by using the transverse mass distribution:

- Rely on fact that Breit-Wigner does not fall as rapidly as Gaussian resolution smearing, hence for large $M_T$, the shape of the $M_T$ distribution becomes sensitive to $\Gamma(W)$ without being very sensitive to the resolution $\sigma(M_T)$.

- Fit to region $110 < M_T < 200$ GeV
- This region contains 210 events
- Result is:
  $\Gamma(W) = 2.19 \pm 0.17$ (stat) $\pm 0.09$ (syst)
- SM predicts 2.08 GeV
M(W) Measurement of D0

Final Run 1b result uses central electrons only:

- $Z \rightarrow ee$ events, in combination with some lower mass states ($\psi$ and $\pi^0$), establish the energy scale and offset once linearity is assumed.
D0 W Mass result:

M(W) = 80.44 ± 0.10 (stat) ± 0.07 (syst) GeV
Top Quark Studies in Run 1

Within the SM, top quarks decay $\approx 100\%$ to $W+b$:

- These decay in turn to dilepton final states (5%), and lepton+jets finals states (30%):

Signatures include leptons, missing $E_T$, and $b$ quarks...
First Indications of Top in Run 1:

- CDF saw a very interesting $e+4\text{jet}$ event with 2 detached vertices in 92, and D0 saw a very energetic $e-\mu$ event in 93. Both were essentially background-free.

Run 40758 Event 44414
top candidate

\[ t \rightarrow W^+ + b \]
\[ \bar{t} \rightarrow W^- + \bar{b} \]
\[ \rightarrow 2 \text{jets} \]
Run 1b led to significantly larger data samples which confirmed the initial evidence from Run 1a.

- CDF used its silicon vertexing capability to develop a sophisticated b-tagging algorithm, based on secondary vertex identification in jets, which was used to select very clean samples of top decays.
- D0 used carefully crafted kinematic criteria to select reasonably pure samples of top decays without the need for B-tagging.

**Top now observed in all final states:**

- Dileptons, including $ee$, $\mu\mu$, $e\mu$, and a hint in $\tau$+lepton.
- Single lepton+jets, both $e$+jets and $\mu$+jets.
- All hadronic mode (6 jets) by using kinematic criteria as well as B-tagging.

**Detailed measurements concentrate on “high statistics” lepton + jets channel:**

- All kinematic distributions consistent with Standard Model top production and decay.
- Interesting CDF result from careful analysis of B-tagging multiplicities and efficiencies giving $BR(t\rightarrow Wb)/BR(t\rightarrow Wq) = 0.99 \pm 0.29$, or $|V_{tb}| = 0.99 \pm 0.15$. 
CDF measurement of the top mass (total sample = 76 events):

- Measure by kinematic fitting to WWbb → lνj jbb final state. Use 2 M(W) constraints, plus M(t) = M(t̄bar). Unknown P_z(ν) then leads to an over-constrained 2C fit.
- Different tag multiplicities combined to give M(top) = 175.9 ± 4.8 (stat) ± 4.9 (syst) GeV.
D0 measurement of top mass (total sample = 31 events):

- Measure top quark mass using kinematic selection (no vertex tagging) in the lepton+jets final state. Result is: \( M(\text{top}) = 173.3 \pm 5.6 \) (stat) \( \pm 6.2 \) (syst) GeV.
- World average is \( M(\text{top}) = 174.9 \pm 5.7 \) GeV, including common systematics.
Comparison of Tevatron $M(W)$ and $M(\text{top})$ with SM and LEP/SLC:

- Within SM, some preference for lighter $M(\text{Higgs})$.
- Within SUSY extensions, always have one light Higgs. If all other new states are heavy, looks just like the SM. Even if they are light, results are still consistent with this data.

World Average Measurements:

$$M_W = 80.43 \pm 0.08 \text{ GeV/c}^2$$

$$M_{\text{top}} = 174.9 \pm 5.7 \text{ GeV/c}^2$$
B Quark Studies in Run 1

Hadron colliders have enormous production rates:

- Tevatron produced \( \approx 5 \times 10^9 \) \( b \bar{b} \) pairs in the central region of CDF and D0 in Run 1b
- This is accompanied by poor S/N \( \approx 10^{-3} \) \( \Rightarrow \) leptonic decays of one \( b \) are required.

Concentrate on CDF results since silicon vertexing is essential.

\( B \) lifetimes:

- Can be measured inclusively \( (B \to \psi + X) \), but this includes unknown mixture of \( B \) states
- Can be measured semi-exclusively \( (B \to Dl+X \text{ or } B \to D^*l+X, \ B_s \to D_s l+X, \ \Lambda_b \to \Lambda_c l+X) \) with good statistics, but non-negligible systematics.
- Can be measured exclusively \( (B \to \psi K \text{ or } B \to \psi K^*, \ B_s \to \psi \phi) \) with small systematics.

\( B^0 \) and \( B_s \) Mixing:

- Develop algorithms for "flavor" tagging (distinguishing \( B \) and \( B \bar{b} \))
- For time-dependent mixing measurement, need \( B \) flavor at production and decay, as well as decay time information

Rare \( B \) decays: look for \( B \to \mu \mu \) or \( B \to \mu \mu + X \).
B Lifetime Measurements in CDF

CDF B Lifetimes

\[ \tau(B^0) \quad 1.52 \pm 0.06 \text{ ps} \]
\[ \tau(B^+) \quad 1.66 \pm 0.05 \text{ ps} \]
\[ \tau(B_s^0) \quad 1.39 \pm 0.10 \text{ ps} \]
\[ \tau(\Lambda_b) \quad 1.32 \pm 0.17 \text{ ps} \]
\[ \text{inc. } \tau(b) \quad 1.53 \pm 0.04 \text{ ps} \]
\[ \tau(B^+)/\tau(B^0) \quad 1.09 \pm 0.05 \]

CDF combined lifetime results: errors are as good as combined LEP results.

Lifetime fit for \( B^+ \rightarrow \psi K^+ \) and \( B^+ \rightarrow \psi K^{*+} \).
**B Mixing Measurements in CDF**

- For mixing, and CP violation studies, it is necessary to measure the B flavor at production ($\text{SST} =$ same side tag, $Q_{\text{jet}} =$ jet charge tag, or $\text{SLT} =$ soft lepton tag) and decay (lepton charge), in addition to the B decay distance (reconstruct decay vertex).

- **SST:** Exploit charge correlation between B flavor and nearby "fragmentation" tracks. Both resonant ($B^{**}$) and non-resonant correlations contribute.

- **$Q_{\text{jet}}$:** Sum $P_T$-weighted total charge of tracks recoiling against B, and use correlation with underlying quark charge.

- **SLT:** Use charge of leptons recoiling against B, and exploit correlation of leading lepton charge with B flavor.
Summary of results from several CDF analyses:

CDF $\Delta m_d$ Results

<table>
<thead>
<tr>
<th>Method</th>
<th>$\Delta m_d$ [ps$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*_{lep} / SST$</td>
<td>$0.446 \pm 0.057 \pm 0.034 \pm 0.031$ ps$^{-1}$</td>
</tr>
<tr>
<td>$lep / Q^{jet,SLT}$</td>
<td>$0.467 \pm 0.057 \pm 0.035 \pm 0.040$ ps$^{-1}$</td>
</tr>
<tr>
<td>$e / \mu$</td>
<td>$0.450 \pm 0.045 \pm 0.051$ ps$^{-1}$</td>
</tr>
<tr>
<td>$D^*_{lep} / lep$</td>
<td>$0.512 \pm 0.095 \pm 0.031 \pm 0.038$ ps$^{-1}$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.464 \pm 0.030 \pm 0.026$ ps$^{-1}$</td>
</tr>
</tbody>
</table>

$\Delta m_d$ Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Delta m_d$ [ps$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>$0.441 \pm 0.020 \pm 0.022$ ps$^{-1}$</td>
</tr>
<tr>
<td>DELPHI</td>
<td>$0.503 \pm 0.027 \pm 0.025$ ps$^{-1}$</td>
</tr>
<tr>
<td>L3</td>
<td>$0.452 \pm 0.041 \pm 0.028$ ps$^{-1}$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$0.468 \pm 0.022 \pm 0.020$ ps$^{-1}$</td>
</tr>
<tr>
<td>SLD</td>
<td>$0.531 \pm 0.035 \pm 0.042$ ps$^{-1}$</td>
</tr>
<tr>
<td>CDF</td>
<td>$0.464 \pm 0.030 \pm 0.026$ ps$^{-1}$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.473 \pm 0.011 \pm 0.014$ ps$^{-1}$</td>
</tr>
</tbody>
</table>

Results are competitive, will improve since systematics driven by size of control samples.
CDF Searches for Rare B Decays

Simplest search is for $B^0 \rightarrow \mu\mu$ and $B_s \rightarrow \mu\mu$:

- Take advantage of clean final state and large hadron collider production cross section.
- Standard Model predicts BR of $1.5 \times 10^{-9}$, so any enhancements above this could signal some new physics.
- Use vertex detector to require that two muons come from common vertex, and have a lifetime ($c\tau > 100\mu$) in order to suppress backgrounds. Also rely on good mass resolution of $\sigma \approx 35$ MeV to further suppress backgrounds:

Limits are:

- $\text{BR}(B^0 \rightarrow \mu\mu) < 6.8 \times 10^{-7}$
- $\text{BR}(B_s \rightarrow \mu\mu) < 2.0 \times 10^{-6}$
- Still far from SM expectation, but a strong sign of improvements to come
Beyond the Standard Model Searches in Run 1

Vast array of possibilities - here choose a few simple cases:

**SUSY searches:**

- First searches were for SUSY partners of quarks and gluons (squark and gluino), since they are copiously produced in hadron collider. Characteristic signature of jets and large missing $E_T$, arising from cascade decays resulting in quarks, gluons and LSP’s. In SUGRA models, stop is expected to be lightest squark, with decays involving b’s.

- Additional searches are for charginos and neutralinos, analogs of the gauge bosons and Higgs bosons of the SM, which are produced via EWK couplings. Final states include tri-leptons, and di-leptons and missing $E_T$.

- SUSY Higgs searches for charged Higgs ($H^+$) in top decays has also been performed. Their discovery would constitute only indirect evidence for SUSY.

**Extra Gauge Bosons:**

- Search for new $W'$ or $Z'$ bosons in leptonic decay channels
Searches for Squarks and Gluinos:

- CDF result uses di-leptons and missing $E_T$, D0 uses high $E_T$ jets and with missing $E_T$
- Exclude squarks/gluinos below $\approx 250$ GeV. In SUGRA models, $M_0$ and $M_{1/2} > 100$ GeV.

CDF Preliminary $\sqrt{s} = 81$ pb$^{-1}$

**MSSM Supergravity Inspired Constraints**
- $\tan \beta = 4$
- $\mu = -400$ GeV/c$^2$
- $\Lambda = -100$ GeV/c$^2$
- $m_A = 500$ GeV/c$^2$

excluded by Run 1B SUSY
dilepton analysis at 95% CL

- Run 1A SUSY Dilepton
  PRL 76, 2006 (1996)
- D0 Multijets+$F_T$
  PRL 75, 618 (1995)
- CDF Multijets+$F_T$

**No corresponding mSUGRA model**
Searches for new $Z'$ gauge bosons:

- Require two high $P_T$ leptons (ee or $\mu\mu$). Final state is very clean. Highest mass CDF event has $M(\text{ee}) = 496$ GeV! Limits are model dependent, but are $\approx 600$ GeV.

Limits on $Z'$ production (95% C.L.)

- $\sigma B(\mathcal{Z} \rightarrow \text{dileptons})$
  - $\sigma B$ predicted using SM couplings
  - Phys. Rev. D 51, R949 (1995) (CDF ee, $19.7\text{pb}^{-1}$)
  - 505 GeV/$c^2$
  - 690 GeV/$c^2$

- 95% C.L. $\sigma B$ limit (CDF ee+$\mu\mu$, $110\text{pb}^{-1}$)

- $\sigma Br$ (pb) $Z' \rightarrow$ dileptons
  - $Z_X$
  - $Z_{ALRM}$
  - 595 GeV/$c^2$
  - 600 GeV/$c^2$
  - $Z_\Psi$
  - $Z_I$
  - 590 GeV/$c^2$
  - 565 GeV/$c^2$
  - $Z_\eta$
  - $Z_{LR}$
  - 620 GeV/$c^2$
  - 630 GeV/$c^2$
The Main Injector Upgrade at FNAL

The luminosity will be improved by removing old Main Ring, replacing it with Main Injector ring, and adding Recycler ring:

- This will significantly increase the antiproton production rate, and allow operation with a much larger number of bunches in the machine. The increase will be from the present 6x6 bunches with 3.5 μs crossings to 36x36 bunches with 396 ns crossing separation.

- The peak luminosity will increase up to $\approx 1-2 \times 10^{32}$, with roughly the same number of interactions per crossing, allowing a 10-20 fold increase in integrated luminosity:
Upgrades to the CDF and D0 Detectors for Run 2

The accelerator upgrade is accompanied by detector upgrades:

- The decreased time between bunch crossings and the increased luminosity require major upgrades to Trigger and DAQ systems, as well as some detector systems.

**CDF**: replacing forward calorimetry and tracking system, extending muon coverage, and replacing Trigger and DAQ:
D0: Installing a solenoidal magnet and new tracking, plus replacing electronics, DAQ, and Trigger:

The machine commissioning, along with some detector commissioning, will begin in 1999.
First real physics should begin in early 2000.
Physics Expectations for Run 2 (2 fb$^{-1}$)

**QCD Studies:**

- Continued study, with improved jet response calibrations from Z+jets. Probe NLO QCD in more detail to look for signs of deviations from QCD predictions.

**Electroweak Studies:**

- Twentyfold increase in statistics is expected to provide a measurement of $M(W)$ to 40 MeV or better, with much of the systematic error being in common between e and $\mu$ channels, and between experiments. A similar precision should be achievable in $\Gamma(W)$.
- Gauge boson couplings will be studied in more detail, leading to limits on anomalous couplings of perhaps $\Delta\kappa < 0.2$, $\lambda < 0.1$ for each experiment.

**B Quark Studies:**

- B physics will move beyond “engineering” phase.
- Precision on all lifetimes should reach 1-2% level.
- Precise values for $B^0$ mixing will be obtained, and direct measurements of $B_s$ mixing should extend to $x_s \approx 15$. Indirect limits from $\Delta\Gamma_s/\Gamma_s$ should cover remaining $x_s$ range.
- Observation of rare B decays such as $B \rightarrow K^*\gamma$, $B \rightarrow \rho\gamma$, and $B_s \rightarrow \phi\gamma$ should be possible.
Extrapolation of present CDF flavor tagging results suggests that CP violation in the B system can be observed in $B \rightarrow \psi K_s$ and possibly in $B \rightarrow \pi \pi$. The expected precision on $\sin 2\beta$ is $\approx 0.1$, based on existing measured values of $\varepsilon D^2$ for present flavor tagging algorithms and extrapolating slightly for detector improvements. Limits could be placed on CP violation in $B_S \rightarrow \psi \phi$ (not expected in SM).

**Top Quark Studies:**
- Increased samples of $\approx 1000$ tagged ttbar events will be acquired, allowing a determination of the mass to a precision of $\approx 2$ GeV.
- Detailed studies of kinematics and decays will be made to search for any anomalies.

**EWK Symmetry Breaking:**
- There is a small window of opportunity (perhaps) for a light Higgs boson, decaying to $bb$, below $\approx 100$ GeV to be observed via associated production with a W/Z boson if one acquires 10 fb$^{-1}$ of integrated luminosity.

**Searches for New Physics:**
- SUSY searches will become more systematic, with squark/gluon limits extending into the 300-400 GeV range, and chargino/neutralino limits extending to 150-200 GeV range. A more diverse range of signatures can be examined with the high statistics.
- Searches for new $W'$ could reach 1 TeV and new $Z'$ could reach 800-900 GeV.