The DØ Detector and Physics Program

Roger Moore
Michigan State University
• **DØ** is a large (5,000 tons) experiment on the Tevatron proton/anti-proton collider at Fermilab
• Run by a Collaboration of ~550 physicists

• ~75 institutions, 18 countries
The Tevatron Collider

- Currently world's highest energy collider
- Recently upgraded for Run II (pre-upgrade Run I)
- Collides bunches protons and anti-protons
  - Centre-of mass energy $1.96 \text{TeV} = 10^{12} \text{eV}$ eV=electron volt
  - 6.2km circumference
  - Design luminosity $5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ (Run I: $10^{31} \text{cm}^{-2}\text{s}^{-1}$)
  - Bunch spacing 396ns -> 132ns? (Run I: 3.5µs)
- Superconducting magnets
  - Energy limited by magnetic field strength
  - Larger ring means less powerful magnets needed
- Protons are composite particles (quarks/gluons)
  - Collisions occur over a range of energies $\sim 1 \text{GeV} - 1 \text{TeV}$
The Tevatron Collider

FERMILAB’S ACCELERATOR CHAIN

MAIN INJECTOR

TEVATRON

DZERO

CDF

PROTON

MESON

NEUTRINO

RECICLER

TARGET HALL

ANTIPROTON SOURCE

BOOSTER LINAC

COCKCROFT/WALTON

Booster

CDF

p source

Main Injector (new)

Tevatron

DØ

Chicago

21/03/03

R. Moore, Michigan State
Scales

• Colliders force high energy interactions between particles
• The higher the energy the smaller the scale probed
• Recreate very high temperatures last observed in the early Universe
  • Understand processes occurring just after the Big Bang

21/03/03
R. Moore, Michigan State
Big Bang

Now (13.7 billion years) [WMAP]

Stars form (1 billion years)

Atoms form (380k yrs) [WMAP]

Nuclei form (180s)

Protons/Neutrons form (10^{-10}s)

Fermilab: 4x10^{-12}s
LHC: 10^{-13}s

Strong CP Violation?

??? Quantum gravity?

Michigan State
Early Universe
The Standard Model

- Describes the fundamental (as far as we know) building blocks of matter and how they interact
- All matter consists of quarks and leptons (fermions)
  - 6 quarks, 6 leptons each divided into 3 generations
- Interact by exchanging force carriers (bosons)
  - gluon: strong force, binds nuclei
  - W/Z: weak force, β decay
  - photon: electromagnetic force
- EM and weak forces unified above ~100GeV
  - Single Electroweak force
The Standard Model

• Annoyingly persistent: survived for > 20 years
  • but cracks (finally!) starting to appear....
    • neutrino oscillations

• We know it isn't complete
  • Four forces: Gravity?
  • Higgs boson (or something else) needed to give particles mass
  • Dark matter

• Many theories (SM included) expect new physics between EW and TeV (100GeV-1TeV)
  • DØ pushing at boundaries, LHC will cover them

21/03/03
R. Moore, Michigan State
Particle Detectors

- **Tracking detectors**, inside magnetic field
  - Measure momentum and charge of charged particles
- **Calorimeters**: EM + Hadronic
  - Measure particle energies from showers
- **Muons**: penetrate entire detector, charged
- **Neutrinos**: penetrate light years of material
  - neutral, missing transverse momentum

21/03/03
R. Moore, Michigan State
The DØ Detector

- DØ detector recently heavily upgraded for the newly upgraded Tevatron
  - Bunch crossing down to 132/396ns from 3.5μs
  - Practically a new detector!
    - Only Calorimeter remains mainly unchanged
- Central tracking system completely replaced
  - Magnetic field added (no field in Run I!)
- Trigger and DAQ system completely replaced
  - Higher trigger rate due to increased luminosity
  - Need to make decision once every bunch crossing
The DØ Timeline

1983   First meeting at Stonybrook
1984   Approval from U.S. DoE
1985-1987  Detector R&D
1988-1991  Construction
1992-1996  Data taking for Run I
1993   First Paper published
1995   Discovery of Top Quark
1996-2000  Upgrade for Run II
2000   100th Paper Published
2001   Run II starts...
The DØ Detector

- \( \eta = 0 \) 
- \( +\eta \) 

- protons 
- antiprotons 

- Beamline Shielding 
- Calorimeters 
- Tracker 
- Muon System 
- Electronics 

21/03/03  
R. Moore, Michigan State
The DØ Tracking Detectors

- Two types of tracking detector
  - Silicon: 800,000 channels
  - Scintillating fibre
- Inside super-conducting solenoid which provides 2T magnetic field
The DØ Calorimeter

• Liquid Argon/Uranium - first time used
  • Both EM and hadronic regions: EM, FH, CH
  • Nearly compensating: e/h = 1.04-1.11
• Granularity 0.05x0.05 - 0.10x0.10 in η, φ

Electrons: \[ \frac{\sigma}{E} = \frac{16\%}{\sqrt{E}} \oplus \frac{0.14}{E} \oplus 0.003 \]

Pions: \[ \frac{\sigma}{E} = \frac{41\%}{\sqrt{E}} \oplus \frac{1.28}{E} \oplus 0.03 \]

Jets: \[ \frac{\sigma}{E} \approx \frac{80\%}{\sqrt{E}} \]
The DØ Muon Detector

- DØ muon system has three planes: A, B and C
- Surrounds detector, fewer planes underneath
- Combination of technologies
  - Wire chambers for position
  - 2-3 scintillator planes for timing
  - Toroid magnet between A and B
The DØ Trigger

• Tevatron beams cross every 396ns
• Why not just readout on every crossing?
  • Need to digitize all channels at 7.5MHz (expensive)
  • Enormous output data rate
    • 7.5MHz x 0.25MB = 1.9TB/s!
  • Most of what we readout will be very uninteresting
• Need to decide if it is worth reading out for a given beam crossing...need a Trigger!
• Must be a lot faster than the full readout
  • Use fraction of full readout data
  • Run simple algorithms - not a full reconstruction
• Must cope with a large variety of physics signatures
The DØ Trigger

- DØ Trigger split into 3 levels
- "LO" trigger fires every beam crossing

Diagram:
- Detector -> L1 Trigger
  - 6kHz
  - 7.5MHz (132ns/decision)
- L1 Trigger -> L2 Trigger
  - 1kHz
- L2 Trigger -> L3 Trigger
  - 50Hz 250kB/ev
- L3 Trigger -> Reconstruction Farm
- SVXII chip Digitization Rate
DØ Detector Status

• Commissioning complete
  • Tracking trigger mostly in place but not yet certified
• Accelerator luminosity currently ~15% design
  • Run II peak luminosity 4.1x10^{31} cm^{-2}s^{-1} (4.1 x Run I)
  • Just returned from a shutdown when material was removed from the beam pipe
• 80pb\textsuperscript{-1} Integrated luminosity delivered to date
  • Current data taking efficiency ~85%
• Predicted luminosity by the summer conferences will be ~200pb\textsuperscript{-1} or 2 x Run I
  • 200pb\textsuperscript{-1} means a process with \(\sigma=1\) pb will happen 200 times
DØ Luminosity

• Moriond 2002: 1 pb⁻¹ data, Summer: > 5 pb⁻¹ data
• Moriond 2003: > 50 pb⁻¹ data
• Summer 2003: > 200 pb⁻¹ data
Large variety of physics being studied in Run II at DØ

- Search for New Phenomena
- Search for the Higgs Boson
- Top physics
- B Physics
- Electro-weak physics
- QCD
Search for New Phenomena

• Currently Tevatron is the highest energy accelerator in the world
  • Good place to look for new things
• Many candidate theories being looked for:
  • Supersymmetry (see tomorrow's seminar)
  • Lepto-quarks
    • Symmetry between quark and lepton sectors
  • Large extra dimensions
    • Possibility of > 3 spatial dimensions
• Generic searches
  • Sleuth and Quaero (web based access to DØ data)
Leptoquarks

- Lepton and quark sectors of the Standard Model appear very similar
  - 6 of each divided into 3 generations
- Theories suggesting a symmetry between the two give rise to new particles called Leptoquarks
  - Couple to the strong and weak forces
- Produced in pairs
  - Scalar and vector
    - Consider scalar
- Three generations of Leptoquark: \( LQ_1, LQ_2, LQ_3 \)
  - Decays to same generation of quarks/leptons
  - Prevents processes like: \( e \rightarrow \mu, \mu \rightarrow \text{c} \) (Flavour Changing NC)

21/03/03
R. Moore, Michigan State
Leptoquarks

- Decay products are quark + lepton
  \[ LQ \xrightarrow{q} e, \mu, \tau \]

  Branching Ratio = \[\beta\]  
  Branching Ratio = \[1 - \beta\]

- Final states looked for are 2 jets + 2 leptons
  - 2 jets + 2 e, 2 jets + 2 \(\mu\), 2 jets + missing ET

- Preliminary RunII analysis looks for second generation scalar Leptoquarks
  - i.e. 2 jets + 2 muons [assume \(\beta = 1\)]
  - Scalar LQs have model independent cross-section

- Backgrounds from standard model processes
  - \(Z+\text{jets} (Z \rightarrow \mu\mu), \text{ttbar} \rightarrow \mu\mu+2\text{jets+MET}, WW+\text{jets} (W \rightarrow \mu\nu)\)

21/03/03 R. Moore, Michigan State
Leptoquark Event Selection

• 2 muons each with
  • Transverse momentum, $p_T > 15 \text{ GeV/c}$
  • $|\eta| < 2.0$ after excluding the region where $|\eta| < 1.0$ and $-1.96 < \phi < -1.17$ (detector supports)

• Cosmic ray muons removed (timing cut)

• Invariant muon mass, $M_{\mu\mu} > 60 \text{GeV/c}^2$

• Muon isolation requirements
  • Calorimeter halo $< 2.5 \text{ GeV}$ (0.4 cone-0.15 cone)
  • Track Halo $< 2.5 \text{ GeV/c}$ (track momenta in 0.5 cone)

• At least 2 jets (0.5 cone algorithm) with transverse energy, $E_T > 20 \text{ GeV}$ and $|\eta| < 2.4$
Preliminary LQ₂ Results

• Final cut: $M_{\mu\mu} > 110\text{GeV}/c^2$ (removes $Z\rightarrow\mu\mu$)

• Zero events observed ($SM \sim 4\pm0.6 \text{ [stat.]}$)
  • $M_{LQ^2} > 157\text{GeV}/c^2$ for $\beta=1$ [Run I $M_{LQ^2} > 200\text{GeV}/c^2$]
Leptoquark Events

• Event with highest $M_{\mu\mu} = 108\text{GeV}/c^2$ and 2 jets

Run 170361 Event 9909397 Wed Mar 5 17:13:01 2003

Run 170361 Event 9909397 Wed Mar 5 17:13:04 2003

E scale: 38 GeV

Bins: 252
Mean: 0.465
Rms: 2.11
Min: 0.00949
Max: 32.9

mE_t: 33.6
phi_t: 179 deg

21/03/03
R. Moore, Michigan State
Extra Dimensions

• Possibly > 3 spatial dimensions
  • "Extra" dimensions compactified to a small scale (otherwise we would already see them!)

• Extra dimensions only accessed by gravity
  • Relative weakness of gravity at large distances is because it is "diluted" by volume of extra space

• Theories have 3 free parameters:
  • Fundamental mass scale, $M_S$ ($M_D$)
  • Compact dimension's radius, $R$
  • Number of compact, extra dimensions, $n$
Other Experimental Limits

• Limits on $R$ come from measurements of the gravitational potential, assuming $M_S \sim 1 \text{TeV}/c^2$
  • $n=1$ excluded by solar system
  • $R < 0.19 \text{ mm}$ for $n=2$ (Eötvös-wash)

• Cooling of SN1987A by graviton emission (preventing the neutrino flux) limits $M_S$:
  • $M_S > \sim 30 \text{ TeV}/c^2$, $n=2$; $M_S > \sim 2 \text{ TeV}/c^2$, $n=3$

• Smoothness of the cosmic diffuse gamma radiation (CDG) due to graviton decay, $G_{KK} \rightarrow \nu\nu$
  • $M_S > \sim 100 \text{ TeV}/c^2$, $n=2$; $M_S > \sim 5 \text{ TeV}/c^2$, $n=3$
Extra Dimensions Signature

- Look fermion or boson pair production by virtual graviton exchange
  - Two additions to SM cross-section
    - Interference term
    - Gluon term

Cross section given by:

\[
\frac{d^2 \sigma}{dM d \cos \theta^*} = f_{SM} + f_{int} \eta_G + f_{KK} \eta_G^2
\]

- \( f_{SM}, f_{int} \) and \( f_{KK} \) are functions of \( (M, \cos \theta^*) \)
- \( \eta_G = F/M_S^4 \) \( F \) is model dependent \( \approx 1 \)

R. Moore, Michigan State
21/03/03
Extra Dimensions Signature

• Gravity enhanced by phase space
  • Kaluza-Klein excitations
    • Winding of graviton about the compactified dimensions
    • Interaction as $1/M_S^2$, not $1/M_{\text{planck}}^2$
  • Two analyses using Run II data at DØ:
    • $G_{\text{KK}} \rightarrow e^+e^-/\gamma\gamma$ and $G_{\text{KK}} \rightarrow \mu\mu$
    • $G_{\text{KK}} \rightarrow e^+e^-/\gamma\gamma$ uses 50 pb$^{-1}$ data
      • 2 EM objects with $E_T > 20$ GeV, EM fraction > 0.9
      • Within good fiducial region of the calorimeter
        • $|\eta| < 1.1$ or $1.5 < |\eta| < 2.4$ (gap between cryostats)
      • Cut events with $> 2$ EM objects with $E_T > 5$ GeV and with $> 25$ GeV of missing $E_T$
Extra Dimensions Di-EM

- Compare SM+instrumental backgrounds to data
  - Drell-Yan + direct photon events
  - Jets faking electrons
- Measure: $\eta_G < 2.1 \text{ TeV}^4$ 95% CL
- $M_s > 1.12 \text{ TeV}/c^2$ [F=1]
- Run I limit: > 1.2 TeV/c$^2$

DiEM Mass Spectrum

DØ Run II Preliminary

SM Prediction  DØ Run II Preliminary  Data

ED Signal

QCD Background
LED Di-EM Candidate

Run 169521 Event 3579842 Thu Feb 6 13:08:46 2003

E scale: 86 GeV

Bins: 102
Mean: 2.08
Rms: 9.01
Min: 0.0179
Max: 84.5

mE_t: 37.7
phi_t: 23.4 deg

21/03/03
R. Moore, Michigan State
LED Di-Muon Analysis

- Look for the same physics but with $G_{kk} \to \mu\mu$
  - 30pb$^{-1}$ data used
- Events similar to LQ analysis:
  - Transverse momentum, $p_T > 15$ GeV/c, $(\eta, \phi)$ acceptance...
  - Isolation cuts: E-Halo < 2.5 GeV and Track-Halo < 2.5 GeV/c
  - $\mu\mu$ mass > 40 GeV/c$^2$
- Data consistent with SM background
  - $\eta_\gamma < 2.5$ TeV$^{-4}$ 95% CL
  - $M_S < 0.79$ TeV/c$^2$ [F=1]
Sleuth

• Search for new physics in a model independent way
  • Divide data up into regions about sets of data points
  • Choose the region which is most "interesting"
    • Defined as: "disagrees with SM background the most"
  • Determine # hypothetically similar experiments which would produce even more interesting data

• Result for Run I in several channels
  • 89% of similar experiments would be more interesting!

• Tested with Top
  • 1.9σ excess in ℓµ+MET+2jets vs. 4.6σ for top analysis
  • Not as good as targeted search...but model independent
Search for the Higgs

• The Standard Model needs the Higgs boson to give particles their mass
• Upper limit for Higgs mass from $W^+W^-$ unitarity limit: $M_{\text{Higgs}} < 1 \text{ TeV/c}^2$
  • Above this $>100\%$ chance of interaction!
• Current best limits on the Higgs mass come from LEP II at CERN (electron-positron collider)
  • LEP II limit: $M_{\text{Higgs}} > 116 \text{ GeV/c}^2$
• Only missing SM parameter is Higgs mass
  • Plug in other parameters and calculate the Higgs mass
  • Current best fit of SM favours $M_{\text{Higgs}} < \text{LEP II limit}$

21/03/03  R. Moore, Michigan State
Higgs Mass Mechanism

• Higgs field "slows" particles down = mass
• Particle mass depends on coupling strength

Low mass case: small coupling, easy to move

High mass case: strong coupling, crowd to move

Higgs boson case: no real person, self-coupling

21/03/03
R. Moore, Michigan State
Tevatron Higgs Signal

- Higgs hunting is hard at the Tevatron
  - Low cross-section, lots of background
- Search for Higgs uses associated production
  \[ p\bar{p} \rightarrow WH + X, \quad p\bar{p} \rightarrow ZH + X \]
  - Decay $H \rightarrow b\bar{b}b\bar{b}$: dominant for $M_{Higgs} < 130\text{GeV/c}^2$
  - Decay $H \rightarrow WW(*)$ dominant for $M_{Higgs} > 130\text{GeV/c}^2$
- Run IIa $\sim 2$ fb\(^{-1}\) integrated luminosity
  - Limit $\sim$ LEP II, then the silicon detector dies!
- Run IIb total of 6-11 fb\(^{-1}\) integrated luminosity
  - ...but Run IIb very close to LHC turn on (1-2 years?)

21/03/03  R. Moore, Michigan State  38
Search for the Higgs
Top Physics at DØ

• Top quark physics
  • Top quark discovered in Run I
  • Tevatron is the only place in the world where you can study the Top quark until the LHC starts up
• Far more top in Run II than in Run I (10's→100's)
  • Increase in energy from 1.8 to 1.96 TeV increases t\bar{t} cross section by ~30%
  • Luminosity will give factor ~20 more t\bar{t} in Run IIa
• Lots of interesting, new physics to study
  • Improve top mass and cross-section measurements
  • Search for single top production
  • Unconfined quark physics since top decays very quickly
t-tbar Cross-section

• Preliminary measurement of cross-section from RunII data at 1.96 TeV
  • Run I measured cross-section at 1.8 TeV
• Top decays too fast to observe directly
  • look for decay products
• Predominant decay: \( t \to Wb \)
  • \( W \) decays to quarks (jets) or \([e,\mu,\tau]+\)neutrino
  • \( b \) quark produces a jet
• Several different sets of decay products to look for
Decay Channels

- 6 decay channels considered (all jets in progress)
  - Only use states with one or more e,μ
  - τ heavy enough to decay to hadrons: looks like a jet
- Tagged b jets: b → Wc and W → μν
  - look for jets with an associated muon

2 leptons+jets

lepton+jets

lepton+tagged jet

Pure and efficient, low branching ratio

Efficient but not pure

Pure, but not efficient
Analysis

- **Data sample:** 30-50 pb\(^{-1}\) depending on channel
  - 12 pb\(^{-1}\) without \(\mu\) data
  - 8 pb\(^{-1}\) with low tracking efficiency (recoverable)
- **Trigger:** calorimeter and muon detectors
  - Conditions applied at all three levels: L1,L2,L3
- **Selection criteria similar to those for NP analyses**

21/03/03

R. Moore, Michigan State
Results

• Theory expects cross-section to be ~30% higher at 1.96 TeV vs. 1.8 TeV (Run I)
  • 6.7–7.5 pb Next to Leading Order (NLO) calculations
  • 8.8 pb NNLO estimate
• Run II preliminary result with all channels combined
  \[ \sigma_{\bar{t}t} = 8.4^{+4.5}_{-3.7} (\text{stat})^{+5.3}_{-3.5} (\text{sys}) \pm 0.8(\text{lum}) \text{ pb} \]
• Observe 3σ excess of combined signal over background
  • Top quark is still there!
• New top results in the pipeline...
Two leptons + jets

- Candidates from $e\mu+$jets and $e+$jets channels
Conclusions

• DØ starting to probe a very interesting range of energies...will be continued by LHC
  • Something new between 100-1,000 GeV
  • Could be the Higgs: more exciting if it isn't!
• Even if we find the Higgs why it is so light compared to the Planck scale (10^{19} \text{GeV})?
  • Heirarchy problem...see tomorrow's seminar
  • Large extra dimensions and Supersymmetry
• Lots of hints for other new physics (but not necessarily in reach of DØ or even LHC)
  • WMAP non-baryonic matter fraction of the Universe
  • Neutrino oscillations: lepton flavour violation

21/03/03

R. Moore, Michigan State
Conclusions

• Currently a very busy, and very exciting, time on DØ!
  • Detector and trigger now complete and working well
  • Working hard on understanding the data
    • Tracking algorithms and alignment
    • Calorimeter noise
• A lot more data is coming very soon
  • ~200pb⁻¹ by summer conferences
  • Will exceed Run I luminosity in next few months
• Physics results starting to come...

21/03/03
R. Moore, Michigan State
Particle Detectors

- Particle physics detectors split into components
  - Each optimized for a specific purpose

- Tracking detectors, inside magnetic field
  - Measure position accurately at points, join to get track
  - Curvature of track gives momentum and charge
  - Don't detect neutral particles (no ionization energy)
Particle Detectors

- **Electro-Magnetic Calorimeter**
  - $e^+/e^-$ and photons create EM showers in matter
  - Showers narrow and not penetrating
  - Finely divided calorimeter

- **Hadron Calorimeter**
  - Jets or hadrons create hadronic showers (strong int.)
  - Broader and more penetrating than EM
  - Bigger cells than EM and more material
**Particle Detectors**

- **Muons**
  - Too heavy to bremstrahlung like electrons, do not interact via strong force and have a long lifetime
  - Penetrate entire detector, detected by counters which ring the outside of the experiment

- **Neutrinos**
  - weakly interacting, neutral and stable
    - penetrate light years of material!
  - *Carry away momentum: signature missing transverse p*

---

21/03/03  
R. Moore, Michigan State