Physics at the Tevatron

Lecture II

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Outline

• Lecture I
  – The Tevatron, CDF and DØ
  – Production Cross Section Measurements
    • Lepton identification

• Lecture II
  – The W boson mass, the Top Quark and the Higgs Boson
    • Lepton calibration, jet energy scale and b-tagging

• Lecture III
  – $B_s$ mixing and $B_s \rightarrow \mu \mu$ rare decay
    • Vertex resolution and particle identification

• Lecture IV
  – Supersymmetry and High Mass Dilepton/Diphoton
    • Missing $E_T$

All lectures available at:
The W boson, the top quark and the Higgs boson

- Top quark is the heaviest known fundamental particle
  - Today: $m_{\text{top}} = 170.9 +\text{-}1.8 \text{ GeV}$
  - Run 1: $m_{\text{top}} = 178 +\text{-}4.3 \text{ GeV/c}^2$
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
      - $\langle H \rangle / (\sqrt{2} m_{\text{top}}) = 0.997 +\text{-}0.010$

- Masses related through radiative corrections:
  - $m_W \sim M_{\text{top}}^2$
  - $m_W \sim \ln(m_H)$

- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics
The $W^\pm$ boson
W Boson mass

• Real **precision** measurement:
  – LEP: $M_W = 80.367 \pm 0.033$ GeV/c$^2$
  – Precision: 0.04%
    • => Very challenging!

• Main measurement ingredients:
  – Lepton $p_T$
  – Hadronic recoil parallel to lepton: $u_||$

• $Z\rightarrow ll$ superb calibration sample:
  – but statistically limited:
    • About a factor 10 less Z’s than W’s
    • Most systematic uncertainties are related to size of Z sample
      – Will scale with $1/\sqrt{N_Z} (=1/\sqrt{L})$
Lepton Momentum Scale

• Momentum scale:
  – Cosmic ray data used for detailed cell-by-cell calibration of CDF drift chamber
  – E/p of e+ and e- used to make further small corrections to p measurement
  – Peak position of overall E/p used to set electron energy scale
    • Tail sensitive to passive material
Lepton Momentum Scale and Resolution

\[ \Delta p/p = (-1.504 \pm 0.088_{\text{stat}}) \times 10^{-3} \]

\[ \chi^2/\text{dof} = 32 / 22 \]

\[ M_Z = (91190 \pm 67_{\text{stat}}) \text{ MeV} \]

\[ \chi^2/\text{dof} = 34 / 38 \]

- Systematic uncertainty on momentum scale: 0.04%
Systematic Uncertainties

- Overall uncertainty 60 MeV for both analyses
  - Careful treatment of correlations between them
- Dominated by stat. error (50 MeV) vs syst. (33 MeV)
W Boson Mass

**CDF II preliminary**

- **Muons**
  - \( M_W = (80349 \pm 54_{\text{stat}}) \text{ MeV} \)
  - \( \chi^2/\text{dof} = 59/48 \)

- **Electrons**
  - \( M_W = (80493 \pm 48_{\text{stat}}) \text{ MeV} \)
  - \( \chi^2/\text{dof} = 86/48 \)

**Ultimate Run 2 precision:**
- \( \sim 15 \text{ MeV} \)

**World Average 2007**
- CDF Run I: 80433 ± 79 MeV
- DØ Run I: 80483 ± 84 MeV
- DELPHI: 80336 ± 67 MeV
- L3: 80270 ± 55 MeV
- OPAL: 80416 ± 53 MeV
- ALEPH: 80440 ± 51 MeV
- CDF Run II: 80413 ± 48 MeV

**New world average:**
- \( M_W = 80398 \pm 25 \text{ MeV} \)
The Top Quark
Top Quark Production and Decay

- At Tevatron, mainly produced in pairs via the strong interaction
  - 85%\[ \frac{q}{\bar{q}} \rightarrow g t \]
  - 15%\[ g \rightarrow t \bar{t} \]

- Decay via the electroweak interactions
  - $\text{Br}(t \rightarrow Wb) \sim 100\%$
  - Final state is characterized by the decay of the W boson

- **Dilepton**
- **Lepton+Jets**
- **All-Jets**

Different sensitivity and challenges in each channel
How to identify the top quark

SM: $t \bar{t}$ pair production, $\text{Br}(t \rightarrow bW) = 100\%$, $\text{Br}(W \rightarrow lv) = 1/9 = 11\%$

dilepton $(4/81)$ 2 leptons + 2 jets + missing $E_T$

$l+$jets $(24/81)$ 1 lepton + 4 jets + missing $E_T$

fully hadronic $(36/81)$ 6 jets

(here: $l=e,\mu$)
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Diagram:
- $q_1$, $\bar{q}_1$ leading to $W^+$, $W^-$
- $b$, $\bar{b}$
- More jets

Legend:
- $b$-jets
- $\nu$, $\bar{\nu}$, $q$, $\bar{q}$
- $l$, $\bar{l}$
- $E_T$
Top Event Categories

- \(\tau + \text{jets}\)
- \(\mu + \text{jets}\)
- \(e + \text{jets}\)
- Dileptons
- All jets

Legend:
- e-e: (1/81)
- mu-mu: (1/81)
- tau-tau: (1/81)
- e-mu: (2/81)
- e-tau: (2/81)
- mu-tau: (2/81)
- e+jets: (12/81)
- mu+jets: (12/81)
- tau+jets: (12/81)
- jets: (36/81)
• Top is overwhelmed by backgrounds:
  – Even for 4 jets the top fraction is only 30%
    • This is very different to the LHC (about 80%)
• Use b-jets to purify sample
  – Also analyses using Neural Network to separate top kinematically
Finding the b-jets

• Exploit large lifetime of the b-hadron
  – B-hadron flies before it decays: \( d = c \tau \)
    • Lifetime \( \tau = 1.5 \text{ ps}^{-1} \)
    • \( d = c \tau = 460 \mu \text{m} \)
    • Can be resolved with silicon detector resolution

• Procedure “Secondary Vertex”:
  – reconstruct primary vertex:
    • resolution \( \sim 30 \mu \text{m} \)
  – Search tracks inconsistent with primary vertex (large \( d_0 \)):
    • Candidates for secondary vertex
    • See whether three or two of those intersect at one point
  – Require displacement of secondary from primary vertex
    • Form \( L_{xy} \): transverse decay distance projected onto jet axis:
      – \( L_{xy} > 0 \): b-tag along the jet direction => real b-tag or mistag
      – \( L_{xy} < 0 \): b-tag opposite to jet direction => mistag!
    • Significance: \( \frac{\delta L_{xy}}{L_{xy}} > 7 \) i.e. 7\( \sigma \) significant displacement
Characterise the B-tagger: Efficiency

- Efficiency of tagging a true b-jet
  - Use Data sample enriched in b-jets
  - Select jets with electron or muons
    - From semi-leptonic b-decay
  - Measure efficiency in data and MC

Achieve about 40-50%
(fall-off at high eta due to limited tracking coverage)
Characterise the B-tagger: Mistag rate

• Mistag Rate measurement:
  – Probability of light quarks to be misidentified
  – Use “negative” tags: $L_{xy} < 0$
    • Can only arise due to misreconstruction
  – Mistag rate for $E_T = 50$ GeV:
    • Tight: 0.5% ($\varepsilon = 43\%$)
    • Loose: 2% ($\varepsilon = 50\%$)
  – Depending on physics analyses:
    • Choose “tight” or “loose” tagging algorithm
Jet Probability

- Complementary to full secondary vertex reconstruction:
  - Evaluate probability of tracks to be prompt
    - Multiply probabilities of individual tracks together
  - "Jet Probability"

- Continuous distribution
  - Can optimize cut valued for each analysis
  - Can also use this well for charm
Neural Net B-tagging

• Rather new for CDF and D0!
  – Nice to have continuous variable
  – Can be optimised depending on analysis requirements

• Several strategies
  – DØ uses 7 input variables from their three standard taggers
    • increase efficiency by 30% or purity by 30% over any single one
  – CDF uses 24 variables on top of SecVtx only
    • Improve purity of tags by 50-70%
    • Sacrifice 10% of efficiency
The Top Signal: Lepton + Jets

- Select:
  - 1 electron or muon
  - Large missing $E_T$
  - 1 or 2 b-tagged jets

\[ \sigma(t\bar{t}) = 8.3^{+0.6}_{-0.5}\text{(stat)} \pm 1.1 \text{(syst)} \text{ pb} \]

66 double-tagged events, nearly no background

Check backgrounds
Data and Monte Carlo Comparison

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
The Top Signal: Dilepton

- Select:
  - 2 leptons: ee, eμ, μμ
  - Large missing $E_T$
  - 2 jets (with or w/o b-tag)

$\sigma = 6.2 \pm 0.9$ (stat) \(\pm 0.9\) (sys) pb
### The Top Cross Section

**Measurement Techniques and Results**

- **Dilepton**
  - $(L = 750 \text{ pb}^{-1})$
  - $8.3 \pm 1.5 \pm 1.0 \pm 0.5$

- **Lepton+Jets: Kinematic ANN**
  - $(L = 700 \text{ pb}^{-1})$
  - $6.0 \pm 0.6 \pm 0.9 \pm 0.3$

- **Lepton+Jets: Vertex Tag**
  - $(L = 695 \text{ pb}^{-1})$
  - $8.2 \pm 0.6 \pm 0.9 \pm 0.5$

- **Lepton+Jets: Soft Muon Tag**
  - $(L = 193 \text{ pb}^{-1})$
  - $5.3 \pm 3.3 \pm 1.3 \pm 0.3$

- **MET+Jets: Vertex Tag**
  - $(L = 311 \text{ pb}^{-1})$
  - $6.1 \pm 1.2 \pm 1.4 \pm 0.4$

- **All-hadronic: Vertex Tag**
  - $(L = 311 \text{ pb}^{-1})$
  - $8.0 \pm 1.7 \pm 3.3 \pm 0.5$

- **Combined**
  - $(L = 760 \text{ pb}^{-1})$
  - $7.3 \pm 0.5 \pm 0.6 \pm 0.4$

**Assumptions**

- Assume $m_t = 175 \text{ GeV/c}^2$

**Summary**

- Measured using many different techniques
- Good agreement
  - between all measurements
  - between data and theory
- Can be used to extract top mass:
  - $m_{\text{top}} = 166.9 \pm 7.0 - 6.4 \text{ GeV/c}^2$
Top Mass Measurement: \( tt \to (bl\nu)(bqq) \)

- 4 jets, 1 lepton and missing \( E_T \)
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags \( \Rightarrow \) 2 combinations
  - 1 b-tag \( \Rightarrow \) 6 combinations
  - 0 b-tags \( \Rightarrow \) 12 combinations
- Two Strategies:
  - Template method:
    - Uses “best” combination
    - Chi2 fit requires \( m(t) = m(\bar{t}) \)
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top
Top Mass Determination

- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,v} = -(p_{T,l} + p_{T,UE} + \sum p_{T,jet})$
- Constraints:
  - $M(lv) = M_W$
  - $M(q\bar{q}) = M_W$
  - $M(t) = M(\tau)$
- Unknown:
  - Neutrino $p_z$
- 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure $M(t)$ for each event: $m_t^{reco}$

Selecting correct combination 20-50% of the time
Jet Energy Scale

- **Jet energy scale**
  - Determine the energy of the partons produced in the hard scattering process
  - **Instrumental effects:**
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - **Physics effects:**
    - Initial and final state radiation
    - Underlying event
    - Hadronization
    - Flavor of parton
- **Test each in data and MC**
Jet Energy Scale Studies

- Measure energy response to charged particles
  - Test beam and in situ
  - CDF: Response rather non-linear
  - DØ: compensating => has better response
    - Some compensation “lost” due to shorter gate in run 2

- CDF uses fast parameterized showers:
  - GFLASH
  - Tuned to data

- DØ uses full GEANT
Testing Jets in Photon-Jet and Z-Jet Data

- Agreement within 3% but differences in distributions!
  - Data, Pythia and Herwig all a little different in photon-jet data

- These are physics effects!
  - Detailed understanding with higher statistics and newer MC in progress
Jet Energy Scale Uncertainties

About 3% of $m_{top}$ when convoluted with ttbar $p_T$ spectrum
**In-situ** Measurement of JES

- Additionally, use $W \rightarrow jj$ mass resonance ($M_{jj}$) to measure the jet energy scale (JES) uncertainty

Measurement of JES scales directly with data statistics

2D fit of the invariant mass of the non-b-jets and the top mass:

$$\text{JES} \propto M(jj) - 80.4 \text{ GeV/c}^2$$
Template Analysis Results on $m_{\text{top}}$

- Using 307 candidate events in 1.7 fb$^{-1}$
- Using in-situ JES calibration results in factor two improvement on JES

$m_{\text{top}} = 171.6 \pm 2.1 \pm 1.1 = 171.6 \pm 2.4$ GeV/c$^2$
Matrix Element Results on $m_{\text{top}}$

- Using most recent analysis of 343 candidates in 1.7 fb$^{-1}$ $m_{\text{top}}$ is:

$$m_t = 172.7 \pm 1.3 \text{ (stat.)} \pm 1.2 \text{ (JES)} \pm 1.2 \text{ (syst)} \text{ GeV/c}^2 = 172.7 \pm 2.1 \text{ (total)} \text{ GeV/c}^2$$

Consistent result. Slightly better precision than Template Method.
Combining $M_{\text{top}}$ Results

- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- New uncertainty: 1.8 GeV
  - Dominated by systematic uncertainties

### Best Tevatron Run II (preliminary, March 2007)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass (GeV/c²)</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Jets: CDF</td>
<td>171.1±4.3</td>
<td></td>
</tr>
<tr>
<td>(943 pb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilepton: CDF</td>
<td>164.5±5.6</td>
<td></td>
</tr>
<tr>
<td>(1030 pb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilepton: D0</td>
<td>172.5±8.0</td>
<td></td>
</tr>
<tr>
<td>(1000 pb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: CDF</td>
<td>170.9±2.5</td>
<td></td>
</tr>
<tr>
<td>(940 pb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: D0</td>
<td>170.5±2.7</td>
<td></td>
</tr>
<tr>
<td>(900 pb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tevatron</td>
<td>170.9±1.8</td>
<td></td>
</tr>
<tr>
<td>(Run I/Run II, March 2007)</td>
<td>$\chi^2$/dof = 9.2/10</td>
<td></td>
</tr>
</tbody>
</table>

Top Quark Mass (GeV/c²)
Implications for Higgs Boson

$m_H$ constrained in the Standard Model

Direct searches at LEP2:
$m_H > 114.4 \text{ GeV} \ @ 95\% \text{CL}$

Indirect constraints:
$m_H < 144 \text{ GeV} \ @ 95\% \text{CL}$
Higgs Production at the Tevatron

\[ \sigma (pb) \]

- dominant: \( gg \rightarrow H \)
- subdominant: \( HW, HZ \)

\[ \sigma (p_{p\rightarrow H+X}) [pb] \]

- \( \sqrt{s} = 2 \text{ TeV} \)
- \( M_H = 175 \text{ GeV} \)

CTEQ4M

**Diagram:**
- \( gg \rightarrow H \)
- \( q\bar{q} \rightarrow HW \)
- \( q\bar{q} \rightarrow HZ \)
- \( gg, q\bar{q} \rightarrow Hb \)
- \( gg, q\bar{q} \rightarrow H\bar{b} \)

**Legend:**
- \( b \text{ jet} \)
- \( e/\mu \)
**WH→lνbb**

- **WH selection:**
  - 1 or 2 tagged b-jets
  - electron or muon with $p_T > 20$ GeV
  - $E_T^{\text{miss}} > 20$ GeV

Now looking for 2 jets

Expected Numbers of Events:
- WH signal: $0.85 + 0.65$
- Background: $62\pm13 + 69\pm12$
ZH → ννbb

• Big challenge:
  – Background from mismeasurement of missing $E_T$
  – QCD dijet background is HUGE
    • Generate MC and compare to data in control regions
    • Estimate from data

• Event selection:
  – $\geq 1$ tagged b-jets
  – Two jets
  – $E_T^{\text{miss}} > 70$ GeV
  – Lepton veto
  – Veto missing $E_T$ along jet directions

• Control:
  – Missing $E_T$ direction
  – Missing $E_T$ in hard jets vs overall missing $E_T$
QCD Jet Background to $ZH \rightarrow \nu\nu\bar{b}b$

- DØ uses data
  - Define variable that can be used to normalize background
  - Asymmetry between
    - missing $E_T$ inside jets and
    - overall missing $E_T$
  - Sensitive to missing $E_T$ outside jets
    - Background has large asymmetry
    - Signal peaks at 0
Background understanding using MC

- CDF use MC and check it in detail against data

“QCD” control region:
Jet aligned with missing $E_T$
$\Rightarrow$ Completely dominated by QCD jets and mistags

“EWK” control region:
Identified lepton in event
$\Rightarrow$ Dominated by top

Look at data only when control regions look satisfactory
Dijet Mass distributions

- Backgrounds still much larger than the signal:
  - Further experimental improvements and luminosity required
  - E.g. b-tagging efficiency (40->60%), *NN selection*, higher lepton acceptance

H signal x10

ZH→ννbb

WH→lνbb
Single Top Quark Production

- Interesting benchmark for Higgs production
  - Same final state as WH
    - cross section 10 times higher though!
  - S/B too low for counting experiment
    - Advanced techniques are employed:
      - Boosted decision trees (DØ)
      - Neural Networks (CDF/DØ)
      - Matrix Element (CDF/DØ)
      - Likelihood (CDF)

- 12/06: DØ see $3.4\sigma$ with 0.9 fb$^{-1}$: $\sigma=4.9\pm1.4$ pb
- 07/07: CDF see $3.1\sigma$ with 1.5 fb$^{-1}$: $\sigma=3.0^{+1.2}_{-1.1}$ pb
- Both Agree with SM: $\sigma=2.9\pm0.4$ pb

\[ S = 61^{+/-11}_{-11} \]
\[ B=1042^{+/-218} \]
• Construct neural network can be powerful to improve discrimination:
  – Here 10 variables are used in 2D Neural Network

• Critical:
  – understanding of distribution in control samples

\[ \sigma_{SM(ZH) \times 19} \]
H → WW(*) → l⁺l⁻νν

- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in H → WW(*) → l⁺l⁻νν are collinear
- Main background: WW production

10x 160 GeV Higgs
H→WW(*)→l⁺l⁻νν (l=e,μ)

• **Event selection:**
  – 2 isolated e/μ:
    • $p_T > 15, 10$ GeV
  – Missing $E_T > 20$ GeV
  – Veto on
    • Z resonance
    • Energetic jets

• **Separate signal from background**
  – Use matrix-element or Neural Network discriminant to

• **Main backgrounds**
  – SM WW production
  – Top
  – Drell-Yan
  – Fake leptons
• Further experimental improvements and luminosity expected
  – Will help to close the gap
  – Expect to exclude 160 GeV Higgs boson soon
  – At low mass still rather far away from probing SM cross section
Conclusions

- The W boson, top quark and Higgs boson require
  - Lepton momentum scale
  - b-tagging
  - Jet energy calibration
- Probe electroweak sector of the Standard Model
  - $\delta M_W/M_W=0.07\%$, $\delta M_{\text{top}}/M_{\text{top}}=1\%$
  - $m_H<144\text{ GeV at 95\% CL}$
- Higgs searches ongoing
  - Steady progress towards probing SM cross section
    - Expectations were set high and collaborations are working on meeting these specs
    - Expect sensitivity to 160 GeV Higgs with $\int L=2-4\text{ fb}^{-1}$
Backup
### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta m_{\text{top}}$ (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remaining JES</td>
<td>1.0</td>
</tr>
<tr>
<td>Initial State QCD radiation</td>
<td>0.3</td>
</tr>
<tr>
<td>Final State QCD radiation</td>
<td>0.2</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>0.3</td>
</tr>
<tr>
<td>MC modelling</td>
<td>0.2</td>
</tr>
<tr>
<td>background</td>
<td>0.6</td>
</tr>
<tr>
<td>B-tag</td>
<td>0.2</td>
</tr>
<tr>
<td>MC model</td>
<td>0.2</td>
</tr>
<tr>
<td>total</td>
<td>1.16</td>
</tr>
</tbody>
</table>

#### CDF Top Mass Uncertainty

- (l+l and l+j channels combined)

<table>
<thead>
<tr>
<th>Integrated Luminosity (pb⁻¹)</th>
<th>$\Delta M_{\text{total}}$ (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \text{ fb}^{-1}$</td>
<td>10.0</td>
</tr>
<tr>
<td>$2 \text{ fb}^{-1}$</td>
<td>5.0</td>
</tr>
<tr>
<td>$4 \text{ fb}^{-1}$</td>
<td>2.5</td>
</tr>
<tr>
<td>$8 \text{ fb}^{-1}$</td>
<td>1.25</td>
</tr>
</tbody>
</table>

- CDF Results
- Run IIa goal (TDR 1996)
- $\Delta M / M < 1\%$

#### Scale
- $\Delta \text{(stat)} / \sqrt{L}$, Fix $\Delta \text{(syst)}$
- (assumes no improvements)
- Scale $\Delta \text{(total)} / \sqrt{L}$
- (improvements required)
ZH → ννbb candidate

$E_T = 145$ GeV

$E_T = 55$ GeV

$E_T = 100$ GeV