Top and Electroweak Physics

TeV4LHC

experiment & phenomenology & theory

Evelyn J. Thomson

University of Pennsylvania

September 17 2004
Motivation

- Fundamental parameters of Standard Model
- Sensitive to Higgs mass and new physics through radiative corrections
  - Precision measurements
  - Theory challenges
- Standard Candles for detector calibration
  - Lepton identification
  - Energy/Momentum scale
  - Luminosity
- Backgrounds to many new physics signals
Outline

- Accelerators powerful enough to produce W, Z, top
  - Status
- W and Z physics
  - W and Z production cross-section
  - W charge asymmetry
  - W mass
- Top physics
  - Top production cross-section
  - Top decays
  - Top mass
- Standard Model (and beyond) global fit
Accelerators: The Decade of the Hadron Collider

- **e^+e^- SLC** 91 GeV, L = 2 miles
- **e^+e^- LEP** 91-209 GeV, C = 16 miles
- **e^+e^- ILC** 91-1000 GeV, L = 25 miles?

- **ppbar SPS** 600 GeV, C = 4.4 miles
- **ppbar Tevatron** 1.80-1.96 TeV, C = 3.9 miles
- **pp LHC** 14 TeV, C = 16 miles

- **1985**: W, Z boson discovery
- **1990**: Top quark discovery
- **1995**: ???????? discovery
- **2000**: ???????? discovery
- **2005**: ???????? discovery
- **2010**: ???????? discovery
- **2015**: ???????? discovery
- **2020**: ???????? discovery
Physics at a hadron collider is like:

- Drinking from a firehose
  - Collision rate huge
    - Tevatron – every 396 ns
    - LHC – every 25 ns
  - Total cross section huge ~0.1b
    - 2-3 interactions per collision
      - Tevatron L=10^{32}\,\text{cm}^{-2}\text{s}^{-1}
      - LHC initial/low lumi L=10^{33}\,\text{cm}^{-2}\text{s}^{-1}
    - 20 interactions per collision
      - LHC design/high lumi L=10^{34}\,\text{cm}^{-2}\text{s}^{-1}

- Panning for gold
  - W, Z, top are relatively rare
    - Need high luminosity
    - Trigger is crucial
      - Distinguish using high $p_T$ leptons
TeVatron Performance

- **Peak luminosity**
  - x2 increase since 2003
  - Reached $L=10^{32}\text{cm}^{-2}\text{s}^{-1}$

- **Future**
  - Run until 2009
  - Deliver 4-9 fb$^{-1}$
TeVatron Experiments

Top & Electroweak Physics need
Trigger
Electron/Muon/Tau identification
Tracking and b tagging
Calorimetry

Over 200 pb\(^{-1}\) more this year
Winter 2005 results
\(~400\)pb\(^{-1}\)

Summer 2004 results
\(~200\)pb\(^{-1}\)
W and Z Physics

Standard Candles at Tevatron and LHC
W/Z cross-sections → W width
W/Z asymmetries
W mass
WW, WZ, ZZ, Wγ, Zγ

Trigger on leptonic decays at Tevatron and LHC
Clean event signatures with low background
BR~11% per mode for W → ℓ ν
BR~3% per mode for Z → ℓ+ℓ−
CDF(D0) W and Z Event Selection

**W→ev**
1 electron $E_T>25$ GeV, $|\eta|<2.8(1.1)$
High MET $>25$ GeV

**W→μν**
1 muon $p_T>20$ GeV, $|\eta|<1.0(1.5)$
High MET $>20$ GeV

**Z^0→e^+e^-**
2 electrons $E_T>20$ GeV

**Z^0→μ^+μ^-**
2 muons $p_T>20(15)$ GeV
W and Z production cross section

\[ \sigma \cdot B = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{A} \cdot \mathcal{E} \cdot \int L} \]

Used with an additional luminosity uncertainty of 6% is 166 pb for W and 15 pb for Z.

**Precision**

<table>
<thead>
<tr>
<th>Category</th>
<th>Channel 2.2%</th>
<th>Channel 2.4%</th>
<th>Channel 2.6%</th>
<th>Channel 3.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>W (\rightarrow) e(\nu)</td>
<td>37584</td>
<td>31722</td>
<td>4242</td>
<td>1785</td>
</tr>
<tr>
<td>W (\rightarrow) (\mu\nu)</td>
<td>0.2397 ± 0.0036</td>
<td>0.1970 ± 0.0025</td>
<td>0.3182 ± 0.0040</td>
<td>0.1392 ± 0.0027</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.749 ± 0.009</td>
<td>0.732 ± 0.013</td>
<td>0.713 ± 0.012</td>
<td>0.713 ± 0.015</td>
</tr>
<tr>
<td>Background</td>
<td>1656 ± 300</td>
<td>2990 ± 140</td>
<td>62 ± 18</td>
<td>13 ± 13</td>
</tr>
<tr>
<td>Cross section</td>
<td>2780 ± 14 ± 60</td>
<td>2768 ± 16 ± 64</td>
<td>255.8 ± 3.9 ± 5.5</td>
<td>248.0 ± 5.9 ± 7.6</td>
</tr>
</tbody>
</table>
**A: geometric and kinematic acceptance**

- Key quantity is boson rapidity, $y$
- Calculate $\mathcal{A}(y)$ from PYTHIA with GEANT detector simulation
  - Dominant systematics
    - $E_T, P_T$ scale <0.4%
    - Detector material < 1%
- Convolve with NNLO differential cross-section
  - First complete NNLO computation of a differential quantity for high energy hadron collider physics
    - Powerful new calculation
    - Applicable to many observables
    - Important for LHC
- Dominant $\mathcal{A}$ systematic
  - PDFs CTEQ6M (0.7-2.1%)
Experiment vs theory

- Precision measurements vs precision NNLO predictions
  - Theoretical uncertainty 2%
  - Experimental uncertainty 2%
  - Luminosity uncertainty 6%
- Future: instead use W and Z as a luminosity monitor at LHC

S. Frixione, M. Mangano
hep-ph/0405130

From W.J. Stirling

partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections
PDFs at LHC

Tevatron parton kinematics

$x_{1,2} = (M/1.96 \text{ TeV}) \exp(\pm y)$

$Q = M$

$q = M$

$LHC$ parton kinematics

$x_{1,2} = (M/14 \text{ TeV}) \exp(\pm y)$

$Q = M$

$LHC-HERA$ workshop on PDFs

J. Stirling, ICHEP'04
Constrain PDFs at large $x$ with Tevatron data

- $u$ quark carries more of proton momentum than $d$ quark
  - $W^+$ boosted along proton beam direction
  - $W^-$ boosted along anti-proton beam direction
- $W$ charge asymmetry sensitive to $u/d$ quark ratio at large $x$
  - Count $e^+$ and $e^-$ vs $\eta$
  - High $E_T$ sensitive to PDFs
  - Calorimeter-seeded Silicon tracking for electrons with $|\eta|>1$, charge mis-id < 2%
- At LHC? Total $W^+ / W^-$ ratio probes $(u\ d\bar{b}) / (u\bar{b}\ d)$ ratio
Radiative corrections make W mass sensitive to top and Higgs mass.

Recent theoretical calculation of full two-loop electroweak corrections:

\[ M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2} G_{\mu}} \left(1 + \Delta r\right) \]

Standard Model prediction for W mass dominated by error on top mass.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \delta M_{\text{top}} ) (GeV)</th>
<th>Prediction</th>
<th>( \delta M_W ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>4.3</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>TeV</td>
<td>2.5</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td>1.3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>LC</td>
<td>0.1</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

A. Freitas et al
hep-ph/0311148
Experimental measurements of W mass

Limited by uncertainty from Final State Interactions in 4q

Winter 2003 - LEP Preliminary

ALEPH [1996-2000] 80.379±0.058
DELPHI [1996-2000] 80.404±0.074
L3 [1996-2000] 80.376±0.077
OPAL [1996-1999] 80.490±0.065
LEP 80.412±0.042

χ²/dof = 29.6 / 37

Average 80.425 ± 0.034
χ²/DoF: 0.3 / 1

NuTeV 80.136 ± 0.084

pp-colliders 80.452 ± 0.059

LEP2 80.412 ± 0.042

LEP1/SLD 80.373 ± 0.033

LEP1/SLD/m_t 80.386 ± 0.023

m_W [GeV]
CDF RUN II PRELIMINARY 200pb$^{-1}$

Measure $W$ mass from fit to

- $W$ Transverse mass
  - Hadronic recoil model
- Muon $P_T$ or electron $E_T$
  - $W$ $p_T$ model

Run II fit results are still blinded!

- Statistical error 50 MeV per channel

Dominant systematic uncertainty from lepton energy/momentum scale and resolution

- Most time and effort spent on detector calibration
- This is a very difficult and demanding measurement

C. Hays Top/EWK Thursday
Run 1 W mass Systematic Uncertainties

Combined Run I uncertainty 59 MeV
How do we reach 40 MeV per channel per experiment in Run II?
And 15 MeV per experiment at LHC?
Most of the systematics are statistics-limited…get smarter with more data!
Theory uncertainties important above 1 fb⁻¹

<table>
<thead>
<tr>
<th>TeVatron Run 1</th>
<th>CDF W→μν</th>
<th>CDF W→eν</th>
<th>D0 W→eν</th>
</tr>
</thead>
<tbody>
<tr>
<td>W statistics</td>
<td>100</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>Lepton Energy scale</td>
<td>85</td>
<td>75</td>
<td>56</td>
</tr>
<tr>
<td>Lepton resolution</td>
<td>20</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>Selection bias</td>
<td>18</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>25</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Recoil model</td>
<td>35</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>PT(W)</td>
<td>20</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>PDFs</td>
<td>15</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>QED corrections</td>
<td>11</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>$\Gamma_w$</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Correlated!
Lepton Energy scale

Some advantages to a hadron collider – many calibration samples!
And uncertainties decrease with higher statistics

Muon momentum scale/resolution
use $J/\psi$, $Y$
cross-check with $Z \rightarrow \mu^+\mu^-$
Preliminary syst. 30 MeV !!! (87)

Electron energy scale/resolution
use $E/p$ in $W \rightarrow e\nu$
cross-check with $Z \rightarrow e^+e^-$
Preliminary syst. 70 MeV (70)

Accurate model of detector material
important due to electron bremsstrahlung
Source of 55 MeV uncertainty

ATLAS/CMS take note!
QCD & QED corrections

- QED radiative corrections
  - Multiple QED radiation
  - QCD+QED(FSR) in RESBOS-A
- Transverse momentum resummation at small-x?
  - TeVatron – may be visible at high rapidity
  - LHC important everywhere

C. Calame et al hep-ph/0402235
Q. Cao, C.P.Yuan hep-ph/0401026
S. Berge et al., hep-ph/0401128
DPF parallel session

U. Baur
P. Nadolsky
Top/EWK Thursday
WW, WZ, ZZ production

- First observation of WW production at a hadron collider
- Still searching for WZ
  - TGC - Hard to beat LEP with 40k WW pairs
  - Important backgrounds to Higgs search!

CDF: \[ \sigma(WW) = 14.3 \pm 5.6 \pm 1.8 \text{ pb} \]

D0: \[ \sigma(WW) = 13.8 \pm 4.3 \pm 1.3 \text{ pb} \]

\[ \sigma(WZ) < 13.9 \text{ pb}@95\% \text{ C.L.} \]

\[ \sigma(WZ) < 15.1 \text{ pb}@95\% \text{ C.L.} \]
Top Physics

Top discovered by CDF and D0 in 1995
Very heavy! Top mass = 178.0 ± 4.3 GeV
But only ~30 events per experiment
!!!Want more top events to study properties!!!
Run II σ 30% higher at √s=1.96 TeV

• Top mass
• W Helicity
• Production Cross Section
• Production Kinematics
• Top Spin Polarization
• Resonance Production
• Branching Ratios
• Rare Decays
• Non-SM decay (t→H⁺b)
Top Production

Top pairs via strong interaction

LHC $\sqrt{s}=14$ TeV
833 ± 100 pb

$0.8$ events per second at initial/low lumi LHC

Cacciari et al
Kidonakis et al
PRD 68 114014 (2003)

TeVatron $\sqrt{s}=1.96$ TeV

<table>
<thead>
<tr>
<th>$m_t$ (GeV)</th>
<th>- PDF NLO $\sigma$(pb)</th>
<th>+PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>6.8</td>
<td>7.8</td>
</tr>
<tr>
<td>175</td>
<td>5.8</td>
<td>6.7</td>
</tr>
<tr>
<td>180</td>
<td>5.0</td>
<td>5.7</td>
</tr>
</tbody>
</table>

0.8 events per hour at recent lumi

Single top via weak interaction

0.88 ± 0.11 pb
10.6 ± 1.1 pb

1.98 ± 0.25 pb
246.6 ± 11.8 pb

<0.1 pb
62.0+16.6-3.6 pb

Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024

Tait, PRD 61 (00) 034001
Belyaev, Boos, PRD 63 (01) 034012

85% qq 15% gg
10% qq 90% gg

833 ± 100 pb

0.8 events per hour at recent lumi

85% qq 15% gg
10% qq 90% gg
Why is qq annihilation dominant at the TeVatron but gg fusion at LHC?

Why does cross section increase by x100 for only x7 increase in $\sqrt{s}$?

$$x \approx \frac{m_t}{\sqrt{s}/2}$$

$\sqrt{s} = 1.96\, \text{TeV} \ x \approx 0.18$

$\sqrt{s} = 14\, \text{TeV} \ x \approx 0.025$
Top Decay

- $\text{BR}(t \rightarrow Wb) \approx 100\%$ in Standard Model
- Top lifetime $10^{-25}$ s ($\Gamma(t \rightarrow Wb)=1.5$ GeV)
  - No top mesons or baryons ($\Lambda_{\text{QCD}}=0.1$ GeV)
  - Top spin observable via decay products

Final States in Top Pair Production

5% Dilepton
Both $W \rightarrow l\nu$ ($l=e$ or $\mu$)
2 leptons
Missing ET
2 b-jets

30% Lepton+Jets
One $W \rightarrow l\nu$ ($l=e$ or $\mu$)
1 lepton
Missing ET
4 jets (2 b-jets)

46% All hadronic
Both $W \rightarrow q\bar{q}$

Top lifetime $10^{-25}$ s ($\Gamma(t \rightarrow Wb)=1.5$ GeV)
No top mesons or baryons ($\Lambda_{\text{QCD}}=0.1$ GeV)
Top spin observable via decay products
2 Lepton/isolated track $p_T > 20$ GeV  
MET > 25 GeV  
MET > 40 GeV if $m_{ll} [76,106]$ GeV  
≥2 jets $E_T > 20$ GeV

**Dilepton**

**Observe 19 lepton/isolated track events in 200 pb⁻¹**
**Estimated background 6.9 ± 1.7 events**

**Observe 13 lepton/lepton events in 200pb⁻¹**
**Estimated background 2.7 ±0.7 events**

$$\sigma(\bar{t}t) = 7.0 \pm^{2.4}_{2.1}(\text{stat}) \pm^{1.6}_{1.2}(\text{syst}) \text{ pb}$$

**Background estimates**

- Data
- Shape PYTHIA MC Normalisation from data
- Statistics-limited

**Shape PYTHIA MC Normalisation from NLO Campbell, Ellis PRD60 113006 (1999)**

**Estimated background**

- WW + WZ + ZZ
- + Drell-Yan
- + fakes
- + $\bar{t}t$ ($\sigma_{SM} = 6.7$ pb)
Dilepton kinematics

Leptons Transverse Momentum

Kinematics consistent with Standard Model so far

$N_{\text{jet}} \geq 2$

Total Transverse Energy (scalar sum)

$H_T$ is scalar sum of transverse energies of jets, leptons and MET

$N_{\text{jet}} \geq 2$
Lepton+Jets

Dominant background from W+jets

Go beyond single variable like $H_T$

Combine seven kinematic variables in a 7-7-1 neural network to improve discrimination

Top shape from PYTHIA

W+jets background shape from ALPGEN+HERWIG MC

Observe 519 events

Fit result $91.3 \pm 15.6_{(\text{stat})}$ top events

$\sigma(\bar{t}t) = 6.7 \pm 1.1_{(\text{stat})} \pm 1.6_{(\text{syst})}$ pb

Dominant systematics are
(1) Jet energy scale uncertainty
(2) $Q^2$ scale for W+jets MC since no well-defined scale for W+jets

1 Lepton $p_T>20$ GeV
MET>20 GeV
$\geq 3$ jets $E_T>15$ GeV, $|\eta|<2.0$
b-Tagging: Vertices and Soft Muons

Recall Standard Model $t \rightarrow Wb$ branching ratio is $\sim 100$

- Every top signal event contains 2 B hadrons
- Only 1-2% of dominant W+jets background contains heavy flavor

**Improve S:B by exploiting knowledge that B hadrons are long-lived and massive**

**Vertex displaced tracks**
- Jet probability

**May decay semileptonically**

- Identify low-$p_T$ muon

- $b \rightarrow \ell \nu c$ (BR $\sim 20$
- $b \rightarrow c \rightarrow \ell \nu s$ (BR $\sim 20$

55% Top Event Tag Efficiency  15%
0.5% False Tag Rate (QCD jets)  3.6%
**Lepton+Jets: Single vs Double b-tags**

Double-tagged events – cleanest sample of top quarks!

Separate into 8 subsamples – single or double tag, 3 or ≥4 jets, e or μ

\[ \sigma(\bar{t}t) = 7.2 \pm^{1.3}_{1.2} \text{(stat)} \pm^{1.9}_{1.4} \text{(syst)} \text{ pb} \]

Background estimate b-tag efficiency

F. Rizatdinova
Top/EWK/QCD Friday

---

**Double b-tag**

**Single b-tag**

D0 II Preliminary 158-169 pb\(^{-1}\)
MC issue #1: How to use LO ME?

Leading Order Matrix Element
ALPGEN W,Z+≤6 jets
MADGRAPH W+≤9 jets

Parton Shower MC
PYTHIA
HERWIG

STOP!
Hard gluon described better by W+3p ME

Good: Hard/wide-angle
Bad: Soft/collinear (ME diverges)

Interpolation needed!
“matching”
Veto hard emissions in Parton Shower
that are already accounted for by Matrix Element
“avoid double-counting”

CKKW for e+e- hep-ph/0109231
Adapted to hadron collider
PYTHIA/HERWIG S. Mrenna, P. Richardson hep-ph/0312274
SHERPA F. Krauss hep-ph/0407365
Alternative approach from M. Mangano
**MC issue #1: how to use LO ME?**

- **W+≥1 jet at LHC**
- **Leading jet pT in W+≥1 jet**
- **Shape of Matched LO Matrix Element MC agrees with NLO prediction**
- **Total rate still needs scale-factor**

Important for modeling of kinematics at TeVatron and LHC

W+jets for top is like ttbar+jets for VBF

SHERPA F. Krauss hep-ph/0407365

Add matched LO Matrix Element MC from 0 to n partons to obtain inclusive W+jet model!
## MC issue #2: how to use NLO?

NLO theory up to $W+2\text{jets}$ and $Wbb$


### Calculations still needed

- $W+3\text{jets}$ (a distant goal)
- Inclusion of $b$ mass effects in $Wbb$

<table>
<thead>
<tr>
<th>NLO</th>
<th>Good</th>
<th>Bad</th>
<th>Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+\text{jets}$</td>
<td>Hard emissions</td>
<td>Soft&amp;collinear emissions</td>
<td>Theorists</td>
</tr>
<tr>
<td></td>
<td>Total rates</td>
<td>Hadronisation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Wbb$ Heavy flavour fraction at NLO</td>
<td>No events</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NNLO</th>
<th>Good</th>
<th>Bad</th>
<th>Users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soft&amp;collinear emissions</td>
<td>Hard emissions</td>
<td>Experimentalists</td>
</tr>
<tr>
<td></td>
<td>Hadronisation</td>
<td>Total rates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outputs events</td>
<td>For example, $W+4\text{jets}$ is $O(\alpha_s^4)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scale uncertainty of 10% leads to 40% uncertainty on total rate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**MC $\cap$ NLO = $\emptyset$ ?**

*(From S. Frixione, HCP’04)*
Studies with realistic experimental cuts for these processes:
Single vector boson W, Z – no W/Z+jets yet!
Diboson WW, WZ, ZZ
Top pairs
Higgs
Lepton pairs

Top acceptance and kinematics at NLO
e.g. $p_T$ of ttbar system at the Tevatron
MC@NLO rate = NLO rate
MC@NLO and MC predicted shapes are identical
where MC does a good job

Top anti-top asymmetry
only at NLO
only at Tevatron
Search for Single Top

Single top is kinematically between W+jets and top pair production.
NLO calculations for rate and shape very important, especially at LHC.


Q. Cao
R. Schwienhorst
Top/EWK
Thursday

95% C.L. limits Observed (Expected)

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF (pb)</th>
<th>D0 (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s+t</td>
<td>&lt;17.8 (13.6)</td>
<td>&lt;23 (20)</td>
</tr>
<tr>
<td>t</td>
<td>&lt;10.1 (11.2)</td>
<td>&lt;25 (23)</td>
</tr>
<tr>
<td>s</td>
<td>&lt;13.6 (12.1)</td>
<td>&lt;19 (16)</td>
</tr>
</tbody>
</table>
Why search for single top? New physics!

- **t-channel** Sensitive to FCNCs
- **s-channel** Sensitive to resonances

---

**Tait, Yuan PRD63, 014018 (2001)**

- Standard Model
- Top-Flavor
  - \( m_X = 1 \text{ TeV} \)
- Z-t-c FCNC
  - \( g_{Ztc} = g_Z \)
- 4th Family
  - \( V_{ts} = 0.5 \)
- \( H^+ \)
  - \( M_{H^+} = 250 \text{ GeV} \)

---

**Theoretical precision**
Many different measurements
- Test different assumptions
- Compare to look for new physics
- Combination ~20% precision
- Currently statistics-limited
Does top decay to a charged Higgs instead of a W? Compare observed number of events in 3 final states

- **Dilepton**
  - $m_H = 120\text{ GeV}$
- **Lepton + Jets**
  - $m_H = 120\text{ GeV}$
- **Lepton + H. Tau**
  - $m_H = 120\text{ GeV}$

All lower, Lepton+$\tau$ higher
Helicity of W from top decays

Standard Model is V-A theory: predicts W from top are

\[ F_0 = 70\% \] longitudinal, \[ F_- = 30\% \] Left-handed

- Assume \( F_+ = 0.0 \) (ie no V+A)
  - Measure \( F_0 \)
    \[ F_0 = 0.89 \pm 0.30 \pm 0.17 \]
  - \( F_0 > 0.25 \) @ 95% C.L.

“Who says it’s a fermion?”
Top squark could mimic final state but W polarisation would be different

- Assume \( F_0 = 70\% \)
  - Set limit on V+A fraction
    - \( F_+ < 0.269 \) @ 90% C.L.

Assume \( F_+ = 0.0 \) (ie no V+A)

- Measure \( F_0 \)
  \[ F_0 = 0.89 \pm 0.30 \pm 0.17 \]
- \( F_0 > 0.25 \) @ 95% C.L.

CDF Run II Preliminary (162 pb⁻¹)

Who says it’s a fermion?”
Top squark could mimic final state but W polarisation would be different

- Assume \( F_0 = 70\% \)
  - Set limit on V+A fraction
    - \( F_+ < 0.269 \) @ 90% C.L.
Examine photon $p_T$ and angular distributions

Measure $t\bar{t}\gamma$ coupling at LHC to 3-10%
  - More difficult at Tevatron due to QED ISR from $qq$
  - Difficult at $e^+e^-$ linear collider to disentangle $t\bar{t}\gamma$ and $t\bar{t}Z$
Top Mass: Reconstruction

- Lepton+Jets
  - Neutrino undetected
    - \( P_x, P_y \) from energy conservation
    - 2 solutions for \( P_z \) from \( M_{lv}=M_W \)
  - Combinatorics of 4 highest \( E_T \) jets
    - 12 ways to assign jets to partons
    - 6 if 1 b-tag
    - 2 if 2 b-tags (beware of charm!)
- ISR
  - Extra jets
  - 4 highest \( E_T \) jets not always from top decay
- FSR
  - Poorer resolution if extra jet not included or jet clustering leaves no well-defined jet-parton match
- Dilepton
  - Lower statistics
  - Two undetected neutrinos
  - Fewer combinations – only 2 jets
  - ISR/FSR as above

Final state from LO matrix element

What you actually detect

+ underlying event from proton remnants
+ multiple interactions!

U.K. Yang
Top/EWK/QCD Friday
Top Mass: MC Template

\[ \mathcal{P}(\text{measurement}|\text{mtop}) = \mathcal{P}(\text{measurement}|\text{partons}) \propto \mathcal{P}(\text{partons}|\text{mtop}) \]

- MC + GEANT detector simulation + reconstruction

- Choose best combination and neutrino solution with a kinematic fit
- Parameterise reconstructed mass shape with MC
- Maximise Likelihood
- Dominant systematic from jet energy scale

\[ m_{\text{top}} = 176.7 \pm 6.0 \pm 7.1 \text{ GeV/c}^2 \]
Run II goal is 2.5 GeV per experiment

Trying out many different techniques at this early stage

Dominant systematic from jet energy scale

None of the Run II preliminary measurements are in the world average
Jet Energy Scale

- Dominant systematic on current Tevatron top mass measurements. Will decrease soon as
  - Simulation improves
  - Get smarter with more statistics
- Absolute energy scale is the key!
  - No $J/\psi$ for jets 😞
  - Mission impossible to trigger on $Z \rightarrow qq$, though trying $Z \rightarrow bb$
  - Must tune Calorimeter simulation at single particle level!!!
- Accurate inner detector material description important
- Data control samples
  - $\gamma$+jet
  - $Z$+jet
  - di-jet
  - Hadronic W in top events!
1 Lepton $p_T>20$ GeV
MET$>20$ GeV
$\geq 4$ jets $E_T>40$ GeV, $|\eta|<2.5$
2 b-tags

- **Much higher statistics...can reduce systematics**
  - Double b-tags: reduce background and combinatorics
    - 87,000 top with S/B~78 with 10 fb$^{-1}$
  - Calibrate jet energy scale *in situ* using hadronic W decay!
  - b-jets – achieve 1% calibration with Z+b?
- **Precision 1 GeV per experiment**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Hadronic $\delta M_{\text{top}}$ (GeV)</th>
<th>Fitted $\delta M_{\text{top}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet scale</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>b-jet scale</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>b-quark fragmentation</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>ISR</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>FSR</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Combinatorial bkg</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Stat</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$\sigma=10.6$ GeV

Not background but wrong combinations!

SN-ATLAS-2004-040

**Top mass @ LHC**
Global Standard Model Fit

Changes since Summer 2003
Only use high $Q^2$ measurements from LEP, SLC and Tevatron

Theory input
Complete two-loop for $M_W$
hep-ph/0311148
Fermionic two-loop for $\sin^2 \theta^\text{eff}_{\text{ lept}}$
hep-ph/0407317

Experimental input
HF combination (LEP/SLC)
W mass combination (CDF/D0 Run I)
top mass (D0 Run I)
SM constraint on Higgs boson mass

\[ M_H = 114 \pm 69 - 45 \text{ GeV} \]

\[ M_H < 260 \text{ GeV} \ @ 95\% \text{ C.L.} \]

Top mass and Higgs mass 70\% correlated in SM

D0 run I updated result increased world average top mass by +3.7 GeV and increased 95\% C.L. Higgs mass by +32 GeV

Vital to measure W and top mass well at TeVatron in next few years
Conclusions

Tevatron delivering high luminosities – expect 4-9 fb⁻¹
- More W bosons and top quarks than ever before
- Precision measurements of top properties – is it really top?

Interaction with theorists & experimentalists very important
- Modeling hadron collisions to required accuracy is hard!
- Tools/calculations from QCD needed
- Theorists need funding and jobs too!

LHC beam in 900 days
- Sharpen tools for ATLAS/CMS physics with experience/data at CDF/D0
- Funding agencies want to see transfer from Tevatron to LHC
- Graduate students & postdocs need data now to learn analysis skills

Let’s get to work in the next year with Tev4LHC!
Top Mass: Matrix Element

\[ P_{tt} = \frac{1}{\sigma_{tot}} \int dp_{jet1} dm_{top1}^2 dM_{W1}^2 dm_{top2}^2 dM_{W2}^2 \sum_{comb,v} W_{jet}(x,y) f(q_1) f(q_2) \phi_6 |M|^2 \]

**Updated D0 Run I measurement**

- Use LO matrix element...
  - Exactly 4-jets for final state
  - Background from W+jets VECBOS
- ...but LO matrix element needs partons
  - 20 parameters to describe initial (2) and final state (18)
  - Measure lepton momentum (3) and jet angles (8)
  - Energy and momentum conservation (4)
  - Integrate over 5 unknowns
    - Choose W and top masses (4) and a jet momentum (1)
    - Relate poorly-measured jet energies to partons with transfer functions from MC

**Advantages**

- Use all 24 combinations – correct one always included
- Well-measured events carry more weight
- 2x statistical power!
- Systematic from jet energy scale reduced by 40%

<table>
<thead>
<tr>
<th></th>
<th>Events</th>
<th>(top, bkg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Template (\chi^2) cut</strong></td>
<td>77</td>
<td>(29,48)</td>
</tr>
<tr>
<td>ME ==4 jets</td>
<td>71</td>
<td>(16,55)</td>
</tr>
<tr>
<td>ME ==4 jets and (\mathcal{g}_{bkg})</td>
<td>22</td>
<td>(12,10)</td>
</tr>
</tbody>
</table>
**Top Mass: Matrix Element**

\[ m_{\text{top}} = 180.1 \pm 3.6 \pm 3.9 \text{ GeV}/c^2 \]

New world average
April 2004
hep-ex/0404010

世界平均
Run I only

\[ \chi^2 / \text{dof} = 2.6 / 4 \]

178.0 ± 4.3
(old 174.3 ± 5.1)

Nature 429 638-642
06/10/2004
Top mass @ ILC

- Scan cross-section at threshold for top pair production
  - Theory calculation in good shape
  - Choose safe definition
- Ultimate limit of 100 MeV
  - Top carries colour charge, mass not well-defined below 100 MeV
- What is $\sqrt{s}$? Need to understand
  - Beam energy spread
  - Beamstrahlung
  - ISR

A. Hoang, hep-ph/0310301

D. Miller, S. Boogert
http://www.linearcollider.ca/victoria04/
Important to test coupling between Higgs and top quark
Combine LHC and LC for model independent measurement
- LHC: pp \(\rightarrow\) ttH+X – measure \(\sigma(ttH) \times BR(H\rightarrow WW)\) to 20-50%
- ILC: \(e^+e^-\rightarrow ZH\) - measure \(BR(H\rightarrow WW)\) to 2% \(\sigma(ttH) \propto g_{ttH}^2\)
- Can do with 500 GeV Linear Collider

**SM prediction is**

\[
g_{ttH} = \frac{\sqrt{2m_{\text{top}}}}{246 \text{ GeV}} = 1.02 \pm 0.02
\]