Electroweak and Top Physics at High Energies
Results from Tevatron and Hera with predictions for LHC
on behalf of

Florencia Canelli
The University of Chicago and Fermilab
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Hadron Colliders

Hera, Desy
- 319 GeV proton – electron collider
- Run 1992-2007
- Accumulated luminosity ~200 pb\(^{-1}\) in e\(^{-}\)p and ~300 pb\(^{-1}\) in e\(^{+}\)p

Tevatron, Fermilab
- 1.96 TeV p-anti p collider
- Run II started in 2002
- Has delivered ~7 fb\(^{-1}\) of data since 2002, and running smoothly: expect ~12 fb\(^{-1}\) by end of 2011

LHC, Cern
- ≤ 14 TeV p-p collisions
- Expect to turn on late 2009 at 7 TeV
- Expect up to 200 pb\(^{-1}\) in the early run

Some results
Most of the results
Some prospects
Detecting High-Energy Hadron Collisions

- Similar detectors in hadron collider experiments:
  - Inner trackers
  - Calorimeters
  - Outer **muon detectors**
  - Most measurements in the transverse plane: $E_T$, $P_T$, missing $E_T$
Outline of this Talk

- **Establishing Electroweak and Top quark signatures**
  - W and Z bosons
  - Diboson
  - Top quark pairs
  - Single top quark

- **Standard model constrains using precision measurements**
  - W boson mass and top quark mass
  - Electroweak fit and predictions for Higgs boson

- **Top quark physics**
  - Measurements of properties
  - Searches beyond the standard model
Establishing Signatures

W and Z bosons
Diboson
Top quark pairs
Single top quark
Electroweak and Top Samples

- Span over a wide range of cross sections

- Until the past year only cleaner channels were observed: small background, lower statistics

  \[ \begin{align*}
  \text{CDF Run II} & \quad \text{D0 Run II} \\
  \text{Tevatron Run II Combined} & \\
  \end{align*} \]

- \( W_\gamma \rightarrow l\gamma \)
- \( Z_\gamma \rightarrow ll \gamma \)
- \( WW \rightarrow l\nu l\nu \)
- \( WZ \rightarrow l\nu ll \)
- \( ZZ \rightarrow llll \)
Electroweak and Top Samples

- Span over a wide range of cross sections

New this year: more data + the difficult channels, large backgrounds, no easy kinematic handles. 

Zγ → ννγ  WW → ℓνjj  WZ → ℓνjj  ZZ → ννjj  Single top → ℓνjj
Electroweak and Top Quark Physics

- Difficult signatures are interesting because they are backgrounds in Higgs boson searches
- Establishing processes in different channels
  - Allow us to Combine to improve precision
  - Gives us Confidence in different modeling and techniques
  - Establishes Consistency among channels
- In general, measuring cross sections:
  - Could point out to new physics through deviations from the standard model
  - Establishes samples for making other measurements possible
Measurement Techniques

More sophisticated methods are used as the experimental challenges increase (i.e., small S/B, signal and background kinematically similar)

Counting events
- Establish selection, estimate expected background
- Find number of data events
- Subtract expected background data from data events

Templates/Likelihood
- Reconstruct the best discriminating variable X (ex. an invariant mass)
- Form signal and background templates of X
- Perform a maximum likelihood fit between data and templates

Matrix Element
- Form per-event probability using matrix elements
- Evaluate the probability of each event for signal and background hypotheses
- Use probability into one likelihood (discriminant type or as a function of a parameter)

Neural Networks, Boosted Decision Trees
- Find good discriminating variables (well modeled in MC)
- Input variables from MC to train a multivariate package
- Use output as a discriminant, likelihood fit between data and MC
W at HERA

- Standard model prediction for W production at HERA $ep \rightarrow eW^\pm X$
- Striking signature: $l = e, \mu$ and $\nu$ in the same event, with high $p_T$
- Could be a signature for new physics
- Previously H1 reported an excess at high $p_T^X$
- Good agreement found, no excess observed

H1 + ZEUS (0.98 fb$^{-1}$):
$\sigma_w = 1.07 \pm 0.16 \text{(stat)} \pm 0.08 \text{(syst)}$ pb

SM prediction $\sigma = 1.26 \pm 0.19$ pb

At large $p_T^X > 25$ GeV:
e$^+p$: 23 / 14.0 ± 1.9
e$^-p$: 6 / 10.0 ± 1.3
W and Z

- **W production charge asymmetry expected to constrain PDFs**

- **Forward-backward asymmetry measured in $Z/\gamma^* \rightarrow e^+e^-$**
  - With 8 fb$^{-1}$ Tevatron can reach a precision comparable to the world average

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**CDF Preliminary Run II 1 fb$^{-1}$**

- CDF 1 fb$^{-1}$ data (stat. + syst.)
- NLO Prediction (CTEQ6.1M at $m_W = 80.4$)
- PDF uncertainty (CTEQ6.1M)

**DØ 1.1 fb$^{-1}$**

- $\chi^2$/d.o.f. = 10.6/14
- Statistical uncertainty
- Total uncertainty

**D0 (1.1 fb$^{-1}$):**

$$\sin^2\theta_w = 0.2326 \pm 0.0018 \text{(stat)} \pm 0.006 \text{(syst)}$$
Observed at the Tevatron with ~3% precision in the $Z \gamma \rightarrow \gamma \gamma$ channel - consistent with SM

First measurement using $Z \rightarrow \nu \nu$ decay

**D0 (3.6 fb$^{-1}$):**
$$\sigma (Z \gamma \rightarrow \nu \nu \gamma ) = 32 \pm 9 \text{(stat+syst)} \pm 2 \text{(lumi)} \text{ fb}$$

- First observation, 5.1 $\sigma$ significance
- A new channel to test non-abelian electroweak structure in detail

- Limits on anomalous triple gauge couplings (aTGC) combining with $Z \gamma \rightarrow \gamma \gamma \gamma$ to produce some of the most stringent limits on neutral aTGC

SM predicts $\sigma (Z \gamma \rightarrow \nu \nu \gamma ) = 39 \pm 4 \text{ fb}$
**WW**

- Measured in $WW \rightarrow l\nu l\nu$, offers a clean and relatively high statistics final state.

- A good understanding and modeling of $WW$ production is essential to any $H \rightarrow WW$ search.

**CDF (3.6 fb$^{-1}$):**

\[
\sigma (WW) = 12.1 \pm 0.9 \text{(stat)} \pm 1.6_{-1.4} \text{(syst)} \text{ pb}
\]

- D0 (1 fb$^{-1}$) measures \[\sigma (WW) = 11.5 \pm 2.1 \text{(stat)} \pm 0.7 \text{(syst)} \text{ pb}\]

- D0 and CDF use lepton $p_T$ to set limits on charged aTGC.

SM predicts $\sigma (pp \rightarrow WW) = 12.4 \pm 0.8$ pb

Use a matrix element likelihood method to assign probability to signal/background based on event kinematics.
**WW/WZ/ZZ**

- Search for VV (V=W,Z) where one boson decays hadronically
  - Signal / Background ~ 3%
  - EWK background: V+jets + top (~85%)
  - QCD background: instrumental (~15%)
- No charged lepton requirement
- Includes $\nu \nu \text{qq}'$ as well as $l \nu \text{qq}'$ final states

**CDF (3.5 fb$^{-1}$):**

$$\sigma (WW/WZZZ) = 18.0 \pm 2.8\text{ (stat)} \pm 2.6\text{ (syst)} \text{ pb}$$

- First observation of diboson with hadronic decays, 5.3 $\sigma$ significance

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**SM predicts**

$$\sigma (pp \rightarrow WW+WZ+WZ) = 16.8 \pm 0.5 \text{ pb}$$
**WW/WZ**

- WW/WZ → l ν jj where we require a lepton is the main background in WH and ZH searches
  - Different composition than previous analysis: overlap is ~20%

- WW and WZ are experimentally hard to distinguish in hadronic channels

**CDF (2.7 fb⁻¹):**

\[ \sigma (WW/WZ) = 17.7 \pm 3.9 \text{(stat)} \pm 1.6 \text{1.4(syst)} \text{ pb} \]

- First observation, 5.4 σ significance
- Evidence presented by D0 (1 fb⁻¹)
  \[ \sigma (WW+WZ) = 20.2 \pm 4.5 \text{ pb} \]

- First aTGC limits in this channel

**Discriminant based on probabilities built using matrix elements for signal and backgrounds**
TGC Summary

- **Charged TGC:** D0 combines limits using up to 1 fb\(^{-1}\) of data
  - WW/WZ \(\rightarrow l\nu jj\), WW \(\rightarrow l\nu l\nu\), WZ \(\rightarrow l\nu\gamma\)
  - \(\kappa = 1.07^{+0.16}_{-0.20}\), \(\lambda = 0.00^{+0.05}_{-0.04}\) and \(g_{1Z} = 1.05\)
  - Results close to LEP2 individual results in \(\lambda\); 2x \(g_{1Z}\); 2-3x \(\Delta\kappa\)
  - A combination with CDF results and 5 fb\(^{-1}\) of data will reduce the statistical uncertainty by a factor of 3, comparable or better results to LEP combined
  - W boson magnetic dipole moment \(\mu_W = 2.02^{+0.08}_{-0.09}(e/2M_W)\)
  - Electric quadrupole moment \(q_W = -1.00 \pm 0.09 (e/M_W^2)\)

- **Neutral TGC:** D0's best limits in
  - \(|h_{30}^r| < 0.033\), \(|h_{40}^r| < 0.0017\) and \(|h_{30}^Z| < 0.033\), \(|h_{40}^Z| < 0.0017\)
ZZ

- Smallest cross section of SM diboson states

- ZZ → ℓℓℓℓ striking signature!
  - First observation by D0, 5.3 σ significance

**CDF (4.8 fb⁻¹):**

\[ \sigma(ZZ) = 1.56^{+0.80}_{-0.63} \text{ (stat.)} \pm 0.25 \text{ (syst.) pb} \]

- 5.7 sigma significance

- ZZ → ℓℓjj or ZZ → ννjj mode not observed yet at the Tevatron
  - Important benchmark for Higgs searches (ZH)
W, Z, and Dibosons at the LHC

- **W, Z**
  - LHC experiments expected to have much higher cross section
    - ~2 million $Z \rightarrow \ell \ell$ in the first $fb^{-1}$
      - Tevatron now has reconstructed up to 1.6 million $Z \rightarrow \ell \ell$
    - With a 100 $fb^{-1}$ expect $\sin^2 \theta_W$ competitive result to current world average

- **Dibosons**
  - LHC experiments have 10 times the Tevatron cross section
  - In 10 $fb^{-1}$ of data -> factor of 100 in statistics and 10 in sensitivity relative to current TGC Tevatron
  - 200 fully reconstructed ZZ events in first 10 $fb^{-1}$ !!
Top Quark Pairs

- QCD pair production is the dominant source of top quarks for study
- Cross section measurement tests perturbative QCD at a higher energy scale
  - Surprisingly large mass, $m_t \approx 175$ GeV!
- Produced via QCD through $qq$ or $gg$ and decays via EWK, BR($t \rightarrow Wb) \approx 100$
- Striking signature defined by the decay of the W boson:

Dilepton

Lepton+Jets

All-Hadronic
Top Quark Pairs

- **Dilepton** (lepton = e or $\mu$) (7%):
  - Small rate, small backgrounds
  - Main background: Drell-Yan

- **Taus** (hadronic decay + lepton/jets) (15%):
  - Small rate, large backgrounds
  - Main backgrounds: multijet and W+jets

- **Lepton+Jets** (lepton = e or $\mu$) (34%):
  - Good rate and manageable backgrounds
  - Main background: W+jets

- **All-hadronic** (44%):
  - Large rate, large background
  - Main background: multijet

Can identify $b$-quarks through secondary vertex to reduce backgrounds (non-W without bottom/charm, W+light flavor jets)

SM predicts ($m_t=172.5$ GeV): $\sigma$ (NLO) = $7.4^{+0.5}_{-0.7}$ pb
Top Quark Pairs: Dilepton and All-Hadronic

- Measure cross section in a tagged and pre-tagged dilepton sample => good test of signal model
- Consistent results
- Measure cross section in a background dominated sample
- Background is hard to model
- Train NN on signal and background to purify the sample

CDF (4.5 fb$^{-1}$, $m_t=172.5$ GeV), b-tagged:
$\sigma_{tt}(\text{dil})=7.3\pm0.7\,(\text{stat})\pm0.4\,(\text{syst})\pm0.4\,(\text{lumi})\,\text{pb}$

CDF (4.5 fb$^{-1}$, $m_t=172.5$ GeV), pre-tagged:
$\sigma_{tt}(\text{dil})=6.6\pm0.6\,(\text{stat})\pm0.4\,(\text{syst})\pm0.4\,(\text{lumi})\,\text{pb}$

CDF (2.9 fb$^{-1}$, $m_t=172.5$ GeV):
$\sigma_{tt}(\text{all-had})=7.2\pm0.5\,(\text{stat})\pm1.5\,(\text{syst})\pm0.4\,(\text{lumi})\,\text{pb}$

D0 (1 fb$^{-1}$, $m_t=175$ GeV):
$\sigma_{tt}(\text{all-had})=6.9\pm1.3\,(\text{stat})\pm1.4\,(\text{sys})\pm0.4\,(\text{lumi})\,\text{pb}$
Top Quark Pairs: Lepton+Jets

- Two different methods with very different S:B
  - **pre-tagged**: topological separation of signal and background via neural net
  - **b-tagged**: counting experiment

- Luminosity is the largest uncertainty in both measurements
  - Reduce by normalizing to the measured Z cross section $\sigma_{tt} = R \cdot \sigma_{Z}^{\text{theory}}$
  - Measure R and multiply by Z cross section from theory

CDF (4.6 fb⁻¹, $m_t = 172.5$ GeV), pre-tagged: $\sigma_{tt}(l+j)=7.6\pm0.4(\text{stat})\pm0.3(\text{syst})\pm0.1(\text{lumi})$ pb

CDF (4.3 fb⁻¹, $m_t = 172.5$ GeV), b-tagged: $\sigma_{tt}(l+j)=7.1\pm0.3(\text{stat})\pm0.6(\text{syst})\pm0.1(\text{lumi})$ pb
Top Quark Pairs: Combination

- Most CDF measurements with more than 4 fb\(^{-1}\)!
- Measurements in all channels
- All channels are consistent with each other and with theory
- Different methods to measure \(\sigma_{\text{tt}}\) produce consistent results
- Tevatron combination underway

6% precision!
Single Top Quark

- Electroweak production of single top quark

- Predicted in ~1985
  - $t$-channel: Willenbrock and Dicus, PRD 34, 155 (1986)
  - $s$-channel: Cortese and Petronzio, PLB 253, 494 (1991)

- Observed in 2009: 14 years after the top quark discovery!

- Not an easy measurement!
  - Small cross section
  - Large backgrounds with large uncertainties

- Allows measurement of CKM matrix element $|V_{tb}|$
In March 2009 the Tevatron experiments reported observation of with about $5\sigma$ significance (to be published in PRL this week)

CDF and D0 combined their results using a Bayesian approach:

**CDF**
- **Lepton+jets** $3.2\,\text{fb}^{-1}$
- $2.17 \pm 0.56 \pm 0.55\,\text{pb}$

**D0**
- **Lepton+jets** $2.3\,\text{fb}^{-1}$
- $3.94 \pm 0.88 \pm 0.88\,\text{pb}$

**Tevatron Combination**
- Preliminary
- $2.76 \pm 0.58 \pm 0.47\,\text{pb}$

LP09

**Tevatron (3.2 fb$^{-1}$), PRD66 054024, 2002**

$|V_{tb}| = 0.91 \pm 0.08$ (stat+syst)

13% improvement

**Single Top Quark Cross Section**

- **CDF** Lepton+jets $3.2\,\text{fb}^{-1}$
- $2.17 \pm 0.56 \pm 0.55\,\text{pb}$
- **CDF** MET+jets $2.1\,\text{fb}^{-1}$
- $5.0 \pm 2.6 \pm 2.3\,\text{pb}$
- **D0** Lepton+jets $2.3\,\text{fb}^{-1}$
- $3.94 \pm 0.88 \pm 0.88\,\text{pb}$
- **Tevatron Combination** Preliminary
- $2.76 \pm 0.58 \pm 0.47\,\text{pb}$

$m_{\text{top}} = 170\,\text{GeV}$
Single Top Quark at Hera

- Search for single top in the e, u and hadronic W decay
- Standard model single top is strongly suppressed
- Upper limit on single top production via FCNC process \( \sigma (ep \rightarrow etX) \) and limits on the anomalous couplings \( \kappa \)

![Graph showing events vs. \( M^{evb} \) in the Electron Channel]

![Graph showing limits on single top quark production via FCNC]

\( \Lambda = m_{\text{top}} = 170 \text{ GeV} \)
\( \kappa_{\text{cty}} = 0 \)
Top Pairs and Single Top at the LHC

- Top quark pairs will be produced mainly by gg fusion in contrast with the Tevatron
  - With 20pb⁻¹ and 10 TeV in muon+jets channel 6% (stat)±30%(syst)+10% (lumi) (CMS)
  - Long run expect to reach comparable precision or better than the Tevatron

- Important calibration tools for b-tagging algorithms and jet energy scale corrections and systematic uncertainties

- Given the richness of the top signatures “when top measured, experiment is ready for discovery phase” from K. Jon-And’s talk

- Single top quarks production channels will include associated production (Wt) and not very sensitive to s-channel
  - Precision measurements of properties of top in electroweak produced top quarks will be possible
Precision Measurements

W boson mass
Top quark mass
Predictions for Higgs boson mass
W Boson, Top Quark, and Higgs Boson

- Measuring the $W$ boson mass and top quark mass precisely allows for prediction of the mass of the Higgs boson

- Constraint on Higgs can point to physics beyond the standard model

- Constrains the Higgs mass now, precision check of the EW theory after/if Higgs is found
W Boson Mass: Most Precise Result

- At hadron colliders, rely on transverse variables: $m_T$, $p_T$, missing $E_T = \text{inferred neutrino } p_T\nu$
  - $m_T$ most accurate
  - Requires precise measure of charged lepton $p_T$ and hadronic recoil

- Use well-measured resonances to calibrate $Z$ boson, $J/\psi$, $\Upsilon$
  - Requires detailed knowledge of detectors

- Perform **fits to templates** generated from calibrated simulation by varying $m_W$

- Measurement in the electron channel combining 3 fits: $m_T$, $p_T$ and missing $E_T$

**D0 (1 fb$^{-1}$):**

$m_W = 80401 \pm 21\text{(stat)} \pm 38\text{(syst)}\text{MeV}$
W Boson Mass: Most Precise Result

- At hadron colliders, rely on transverse variables: $m_T$, $p_T^e$, missing $E_T = \text{inferred neutrino } p_T^\nu$
  - $m_T$ most accurate
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- Use well-measured resonances to calibrate Z boson, J/$\psi$, $\Upsilon$
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Using similar techniques and dataset, D0 measures W top width by fitting $m_T$ tail

**D0 (1 fb$^{-1}$):**

\[ \Gamma_W = 2.028 \pm 0.072 \text{(stat)} \pm 38 \text{ GeV} \]

**D0 (1 fb$^{-1}$):**

\[ m_W = 80401 \pm 21 \text{(stat)} \pm 38 \text{(syst)} \text{ MeV} \]
**W Boson Mass: Future Precision**

- Limited by the size of the Z sample. Will improve with more data.
- Tevatron measurements improving the precision of parton distributions functions (ex. W charge asymmetry previously shown)

**D0 $m_W$ Systematic Uncertainties (1 fb$^{-1}$)**

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>$\delta m_W$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy scale</td>
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<tr>
<td>Electron energy resolution model</td>
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<td>Electron energy nonlinearity</td>
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<td>W and Z electron energy loss differences</td>
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<td>Recoil model</td>
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<td>Electron efficiencies</td>
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<td>Backgrounds</td>
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<td>PDF</td>
<td>9</td>
</tr>
<tr>
<td>QED</td>
<td>7</td>
</tr>
<tr>
<td>Boson $p_T$</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37</strong></td>
</tr>
</tbody>
</table>
W Boson Mass: Tevatron Combination

- Combine previous results, including CDF Run II measurement using 200 pb\(^{-1}\): \(m_W = 80413 \pm 34\) (stat) \(\pm 34\) (syst) MeV

- Tevatron Average: \(m_W = 80420 \pm 31\) MeV

- World Average: \(m_W = 80399 \pm 23\) MeV
Top Quark Mass

- Measurements in the 3 channels: dilepton, lepton +jets, all-hadronic
- Different difficulties than in W mass measurement
  - Can only measure jets resulting from quarks
  - Jet-parton assignment
  - QCD radiation
- Jet energy scale (JES) uncertainty dominates [~3%]
  - Can be reduced via in situ measurement from hadronic W mass
Top Quark Mass: Most Precise Result

- **Lepton + Jets and All-hadronic channels**
  - Fully reconstructable final state
  - Reduce jet combinatorics and background by requiring $\geq 1$ b-tag
  - Matrix element or reconstructed $m_t$ technique for probabilities
  - *In situ* JES calibration
  - Form 2D likelihood as function of top mass and shift in JES error
  - Complementary techniques independent of JES
    - $L_{xy}$, lepton $p_T$

- **Dilepton channel**
  - Two neutrinos result in kinematically underconstrained system
  - Requires integration over at least one variable
  - Can’t constrain JES
  - Matrix element or templates integrating over one variable

CDF Run II Preliminary 4.3 fb$^{-1}$

CDF (4.3 fb$^{-1}$):

$m_t(l+j) = 172.6 \pm 0.9\text{(stat)} \pm 0.7\text{(JES)} \pm 1.1\text{(syst)} \text{GeV}$
Top Quark Mass: Tevatron Combination

Tevatron (Winter 09):
\[ m_t = 173.1 \pm 0.6 \text{ (stat)} \pm 1.1 \text{ (syst)} \text{ GeV} \]
\[ m_t = 173.1 \pm 1.3 \text{ (stat+syst)} \text{ GeV} \]

- Channels are consistent with each other
- Different methods to measure \( m_t \) produce consistent results
- Working on improving systematic uncertainties: are all effects covered, are they covered more than once?
Top Quark Mass: Future Precision

- Using CDF as example

CDF $m_t$ (l+j) Systematic Uncertainties 4.3 fb$^{-1}$

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>$m_{top}$ (GeV)</th>
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<tbody>
<tr>
<td>Calibration</td>
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<td>b-jet energy scale</td>
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<td>PDFs</td>
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<tr>
<td>Background</td>
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<tr>
<td>Color reconnection</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.1</strong></td>
</tr>
</tbody>
</table>

Magnitude of systematic uncertainties are comparable. Single experiment top quark mass precision reaching 1 GeV
World top quark mass and W boson mass included, from LEP/TEVEWK working group:

- $m_H = 87^{+35}_{-26}$ GeV
- $m_H < 157$ GeV (95% CL)
- $m_H < 186$ GeV (when LEP limit included)

**In)direct Constraints on Higgs Mass**

![Graph showing constraints on Higgs mass](image)

- **LEP2 and Tevatron (prel.)**
- **LEP1 and SLD**

In August 2009, the LEP collaboration reported a limit on the Higgs boson mass, with $m_H < 157$ GeV at 95% confidence level. This limit is consistent with the Tevatron results, which also exclude certain regions of the parameter space. The LEP collaboration also presented preliminary results on the top quark mass, with $m_t > 175$ GeV at 95% CL. The combined results provide strong constraints on the Higgs boson mass and further support the search for the Higgs boson.
W Boson and Top Quark Mass at the LHC

- **W boson mass:**
  - Expectations using 15 pb\(^{-1}\) and 14 TeV (ATLAS)
    - \(m_{T}^{W} \approx 60\) (stat) \(\pm 114\) (syst) MeV
    - \(p_{T}^{l} \approx 110\) (stat) \(\pm 230\) (syst) MeV
  - Reaching Tevatron precision will require time

- **Top quark mass:**
  - Expect 2 GeV with 1fb\(^{-1}\) and 14 TeV
    - Constraining the light JES, main uncertainty will come from b-JES
    - With enough statistics the LHC experiments should be able to reach 1 GeV
  - Large datasets should provide good handles on systematic uncertainties
Top Quark Properties

Properties of the top quark

Searches in the top quark sample
The best evidence so far it is the SM top quark comes from the agreement of $\sigma_{tt}$ with theoretical expectations but a priori there is no guarantee that this is the SM top
## Top Quark Properties Summary

<table>
<thead>
<tr>
<th>Property</th>
<th>Run II Measurement</th>
<th>SM prediction</th>
<th>Luminosity (fb⁻¹)</th>
</tr>
</thead>
</table>
| $m_t$    | CDF: 172.6 ± 0.9(stat) ± 1.2(syst) GeV  
D0: 174.2 ± 0.9(stat) ± 1.5(syst) GeV |               | 4.3  
3.6 |
| $\sigma_{t\bar{t}\text{bar}}(@m_t=172.5 \text{ GeV})$ | CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb  
D0: 7.84 $^{+0.46-0.45}$ (stat)$^{+0.66-0.54}$ (syst)$^{+0.54-0.46}$ (lumi) pb | 7.4 ± 0.6 pb  
8.06 +0.6 pb | 4.5  
1 |
| $\sigma_{t\bar{t}\text{bar}}(@m_t=170 \text{ GeV})$ | Tevatron: 2.76 $^{+0.58-0.42}$ (stat+syst) | 2.86±0.8 pb | 3.2-2.3 |
| $|V_{tb}|$ | Tevatron: 0.91 ± 0.08 (stat+syst) | 1 | 3.2-2.3 |
| $\sigma(gg\rightarrow t\bar{t}\text{bar})/\sigma(qq\rightarrow t\bar{t}\text{bar})$ | D0: 0.07+0.15-0.07(stat+syst) | 0.18 | 1 |
| $m_t - m_{t\bar{t}\text{bar}}$ | D0: 3.8 ± 3.7 GeV | 0 | 1 |
| $\sigma(tt\rightarrow ll)/\sigma(tt\rightarrow l+l+jets)$ | D0: 0.86 $^{+0.19-0.17}$ (stat+syst) | 1 | 1 |
| $\sigma(tt\rightarrow \tau l)/\sigma(tt\rightarrow ll + l+jets)$ | D0: 0.97 $^{+0.32-0.29}$ (stat+syst) | 1 | 1 |
| $\sigma_{t\bar{t}\text{bar}+jets}(@m_t=172.5 \text{ GeV})$ | CDF: 1.6 ± 0.2 (stat) ± 0.5 (syst) | 1.79+0.16 -0.31 pb | 4.1 |
| $CT_{top}$ | CDF: 52.5 $\mu$m @ 95%C.L. | $10^{-10}$ $\mu$m | 0.3 |
| $T_{top}$ | CDF: $<13.1$ GeV @ 95%C.L. | 1.5 GeV | 1 |
| $BR(t\rightarrow Wb)/BR(t\rightarrow Wq)$ | CDF: $>0.61$ @ 95% C.L.  
D0: 0.97 $^{+0.09-0.08}$ (stat+syst) | 1 | 0.2  
0.9 |
| $F_0$ | CDF: 0.62 ± 0.11  
D0: 0.490 ±0.106 (stat) ± 0.085 (syst) | 0.7 | 2  
2.7 |
| $F_+$ | CDF: -0.04 ± 0.05  
D0: 0.110 ±0.059 (stat) ± 0.052 (syst) | 0.0 | 2  
2.7 |
| Charge | CDF: - 4/3 excluded with 87% C.L.  
D0: 4e/3 excluded at 92% C.L. | 2/3 | 1.5  
0.37 |
| Spin correlations | CDF: $\kappa = 0.32 +0.55 -0.78, -0.46 < K < 0.87$ @ 68%C.L.  
D0: $\kappa = -0.17 +0.65 -0.52$ (stat + syst) | 0.78 -0.022 $^{+0.027}$ | 2.8  
4.2 |
| Charge asymmetry | CDF: 0.19 ± 0.07(stat) ± 0.02(syst) %  
D0: 12 $\pm$ 8 (stat) ± 1 (syst) % | 0.05 ± 0.015 | 3.2  
0.9 |
Searches in the Top Quark Sample

- Top produced via resonances?
- Something hiding under top?

- DØ Run II Preliminary
- CDF Run II Preliminary
- CDF II Preliminary

- Expected limit 95% CL
- Expected limit 68% CL
- Observed X cross-section
- Topcolor Z’ (CTEQ6L1)

- DØ Run II Preliminary, L=3.6 fb⁻¹ Preliminary
- CDF Run II Preliminary, L=885 pb⁻¹

- CDF II Preliminary, 2.2 fb⁻¹
- Theory, NLO
- Upper limit @ 95% CL

- Observed 95% CL
- 95% C.L. Observed Limit - CDF Run II Preliminary, 1.9 fb⁻¹
Top anti-Top Spin Correlations

- Only top quark decays before its spin flips
- Information on the spin carried by the decay products

- Measurement can give an upper limit on lifetime, lower limit on V_{tb} and also limits beyond SM physics

- First results from Run II (dilepton channel)

\[ \kappa = \frac{N(\uparrow \uparrow) + N(\downarrow \downarrow) - N(\uparrow \downarrow) - N(\downarrow \uparrow)}{N(\uparrow \uparrow) + N(\downarrow \downarrow) + N(\uparrow \downarrow) + N(\downarrow \uparrow)} \]

SM predicts \( \kappa = 0.78 \)

**CDF (2.8 fb\(^{-1}\))**:
\[ \kappa = 0.32 \pm 0.55 -0.78 \]

**D0 (4 fb\(^{-1}\))**:
\[ \kappa = -0.17 \pm 0.64 -0.53 \]
Search for CPT Violation

- Measure mass difference between $t$ and $t\bar{t}$

- No violations ever observed, but this is the first CPT measurement in the quark sector

- Releasing constraint on $m_t = m_{t\bar{t}}$, measured in lepton + jets events using matrix element technique

Consistent with SM expectations

**D0 (1 fb$^{-1}$):**

$\Delta m_t = 3.8 \pm 3.7$ GeV

*Summer 09*
Searches in \( tt \) Production

- No resonance production in \( tt\bar{t} \) system is expected in the standard model
- Some models predict \( tt\bar{t} \) bound states
  - Top color assisted technicolor predicts leptophobic \( Z' \) with strong 3\textsuperscript{rd} generation coupling
- Experimental check: search for bumps in \( tt\bar{t} \) reconstructed mass spectrum
- Sufficiently narrow so that width is dominated by detector effects

\[ Z' \text{ with 1.2\% width:} \]

- DØ (3.6 fb\(^{-1}\)): \( >820 \text{ GeV} \)
- CDF (2.8 fb\(^{-1}\)): \( >805 \text{ GeV} \)

\[ \text{CDF Run II preliminary, } L=2.8\text{fb}^{-1} \]

- Green: QCD
- Red: SM \( tt \)
- CDF data, \( N_{ev}=2086 \)
Searches in $tt$ Production

- Forward-backward asymmetry
  \[ A_{fb} = \frac{F - B}{F + B} \]

- Parity violating new physics can appear as a large asymmetry

- Because the LHC is dominated by $gg$ production this measurement will be far more difficult

CDF (3.2 $fb^{-1}$): $A_{fb} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)}$ %

- SM predicts at NLO $A_{fb} = 0.05 \pm 0.015$ %

- Agrees with SM within 2 $\sigma$

- D0 result using 1 $fb^{-1}$:
  $A_{fb}^{\text{det}} = 0.12 \pm 0.08 \pm 0.01$ %

Summer 09
Summary and Conclusions
Summary and Conclusions

- Tevatron making **precision measurements** to help constrain SM
  - Examples shown: W charge asymmetry, $\sin^2 \theta_W$

- In the last year we have **expanded our experimental reach** on signatures
  - Confidence in our experimental tools while establishing challenging processes on our way to the Higgs boson (diboson, single top)

- Top quark cross section known to 6.5% (better than theory!)

- Top quark mass known to 0.7%
  - Tevatron should be able to reach 1 GeV

- W boson mass Tevatron combination better than LEP2 average!
  - Tevatron should be able to reach 20 GeV

- Top quark physics beginning to have sensitivity to unexpected in particle properties and in the data samples

- In the near future, LHC will rediscover top and use it as most likely the most important stepping stone to find new physics
Backup Slides
Single Top Quark: Results

- Combine different multivariate analyses into one:
  - D0 using 2.3 fb\(^{-1}\)
    - neural networks, matrix element, boosted decision trees
  - CDF using 3.2 fb\(^{-1}\)
    - neural networks, matrix element, boosted decision trees, likelihood

Missing ET+jets selection:
Recover badly reconstructed e, $\mu$: include $\tau$

CDF Run II Preliminary, L = 3.2 fb\(^{-1}\)
- Single Top
- W+HF
- $t\bar{t}$
- QCD+Mistag
- Other
- Data
Single Top Quark: t-channel

- Measure t-channel cross section by removing s/t channel constraint
- Ratio could be changed due to additional quark generation, new heavy bosons, FCNC, anomalous quark couplings

- Measure t-channel and s-channel simultaneously

D0 (2.3 fb⁻¹):

\[\sigma_t(\text{t-channel}) = 3.14^{+0.94}_{-0.81} \text{(stat + syst)} \text{pb}\]

First evidence with 4.8 \(\sigma\)

Summer 09
Searches in \( tt \) Decay

- Search for charged Higgs using e+jets, \( \mu \)+jets, ee, \( e\mu, \mu\mu, \tau e \) and \( \tau \mu \) final states from top quark pair production event

- Different scenarios of possible \( H^+ \) where
  - decays purely hadronically into c and s quarks
  - decays into a \( \tau \) lepton and a \( \tau \) neutrino
  - both decays appear

### DØ Run II Preliminary

![Graph showing event counts and \( \tan \beta \) vs. \( M_{H^+} \)]
WZ

- WZ→l ν ll observed in 2007
  - TGC limits by D0 and CDF
- WZ→l ν jj not yet observed at Tevatron
  - Could distinguish from WW via b-tagging
  - Higher cross section than low mass Higgs but softer (WH)
- WZ→jjll not yet observed at Tevatron
  - CDF calculates TGC limits using the leptonic ($M_{ll}$) and hadronic ($M_{jj}$) invariant masses
  - First charged aTGC limits in this channel

SM predicts $\sigma (pp \rightarrow WZ) = xx \pm xx$ pb
tt +jets Cross Section

- Important test of perturbative QCD
  - NLO effects play an important role in the calculation of the theoretical cross section

- Most top events at the LHC will be produced with additional jets
  - Background for many new physics signals

- Measurement using b-tagged events in the lepton plus jets channel
  - Data-driven background expectation
  - 2D likelihood simultaneously measure tt+jet and tt without jet cross sections.

CDF (4.1 fb⁻¹):
\[\sigma_{tt+jets} = 1.6 \pm 0.2\text{(stat)} \pm 0.5\text{(syst)} \text{ pb}\]

SM predicts \[\sigma_{tt+jets} = 1.79^{+0.16}_{-0.31} \text{ pb}\]