Overview of the Tevatron Physics Program

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Introduction

• Very rich Tevatron program: probes physics at the highest $Q^2$
  - Direct searches
  - Top physics
  - High $E_T$ jets

• ...to intermediate $Q^2$
  - Precision electroweak physics

• ...to low $Q^2$
  - B and charm physics

• Selected topics discussed today span the range of
  - Statistical and systematic contributions to precision
  - Importance of tracking, calorimetry and particle identification
  - Connections to LHC physics
Outline

• **Top quark physics**
  – Cross sections in lepton+jets and dilepton channels
  – Top quark mass
• **Electroweak physics**
  – W boson mass
  – Pair production of gauge bosons
  – High mass Drell-Yan forward-backward asymmetry
• **QCD physics**
  – Jet and photon cross sections
• **SM Higgs search**
• **Other direct searches**
  – NonSM Higgs
  – SUSY and exotica
• **B physics**
  – B mixing
  – Rare decays
Top Signals

• Is it the standard model top quark? Or does its large mass give it access to new physics?

• Probes:
  – Spin structure: W helicity in top decays
  – Event topology
  – Comparing cross sections in different decay modes

\[ \mu e, b \text{ tag} \]

Dilepton channels
Top Cross Sections, lepton + jets channels

- Explore many different strategies: leave no stone unturned

Important to understand the shapes of the $W + n$ jet backgrounds: jet multiplicity and kinematics for large $n$, and $b$ quark content, especially @LHC energy.
Top Cross Sections Summary

Probing the $tWb$ electroweak vertex in top decays:

**Statistics-limited, consistent with standard model**

### Top Pair Production Cross Section

- **Dilepton:** Combined $7.0 \pm 2.4 \pm 1.7$ (L = 200 pb$^{-1}$)
- **Lepton+Lepton:** MET, # jets $8.6 \pm 2.2 \pm 1.1$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Kinematic $4.7 \pm 1.6 \pm 1.0$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Kinematic NN $6.7 \pm 1.1 \pm 1.0$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Vertex Tag + Kinematic $6.0 \pm 1.6 \pm 1.2$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Vertex Tag $5.6 \pm 1.6 \pm 0.9$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Double Vertex Tag $5.4 \pm 2.4 \pm 1.1$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Jet Prob Tag $5.8 \pm 1.3 \pm 1.6$ (L = 193 pb$^{-1}$)
- **Lepton+Jets:** Soft Muon Tag $4.2 \pm 2.0 \pm 1.4$ (L = 193 pb$^{-1}$)
- **All Hadronic:** Vertex Tag $7.8 \pm 2.5 \pm 1.7$ (L = 193 pb$^{-1}$)

### DØ Run II Preliminary

- $\ell \ell$ $143$ pb$^{-1}$ $13.1 \pm 5.9 \pm 2.2$ pb
- $e+jets$ $156$ pb$^{-1}$ $19.1 \pm 13.0 \pm 3.7$ pb
- $\mu+jets$ $140$ pb$^{-1}$ $11.7 \pm 9.7 \pm 2.8$ pb
- $l+jets$ $140$ pb$^{-1}$ $14.3 \pm 5.1 \pm 2.6$ pb
- $e+jets (soft \mu)$ $141$ pb$^{-1}$ $8.8 \pm 4.1 \pm 1.6$ pb
- $\mu+jets (soft \mu)$ $144$ pb$^{-1}$ $6.0 \pm 3.3 \pm 1.6$ pb
- $l+jets (soft \mu)$ $141$ pb$^{-1}$ $7.2 \pm 2.6 \pm 1.6$ pb
- $e+jets (soft \mu)$ $141$ pb$^{-1}$ $7.2 \pm 2.6 \pm 1.6$ pb
- $\mu+jets (SVT)$ $92$ pb$^{-1}$ $14.2 \pm 7.3 \pm 2.9$ pb
- $l+jets (CSIP)$ $94$ pb$^{-1}$ $9.5 \pm 5.2 \pm 2.1$ pb
- $l+jets (SVT)$ $92$ pb$^{-1}$ $11.4 \pm 4.1 \pm 2.0$ pb
- $l+jets (SVT)$ $158$ pb$^{-1}$ $11.1 \pm 4.3 \pm 1.4$ pb
- $l+jets (CSIP)$ $158$ pb$^{-1}$ $7.2 \pm 1.3 \pm 1.2$ pb
- $l+jets (CSIP)$ $158$ pb$^{-1}$ $8.2 \pm 1.3 \pm 1.2$ pb
- $all jets$ $162$ pb$^{-1}$ $7.7 \pm 3.4 \pm 4.7$ pb

Statistics-limited, consistent with standard model
Top Quark Mass

- Important standard model parameter, ingredient of indirect Higgs constraint
- Complicated event topology => many fitting techniques, with different sensitivities to modelling
  - Histogram & template-fitting method
  - “per-event” mass extraction method

**Maximum Likelihood Mass**

CDF Run II Preliminary (162 pb\(^{-1}\))

Signal MC : \(M_{\text{top}} = 175\text{GeV/c}^2\)

- **MC Prediction**
- **Signal \(t\bar{t}\)MC**
- **Background(MC)**
- ▼ **Data 22 events**

![Histogram & template-fitting method](image1)

![Template method](image2)

![Top signal](image3)

![W+jets background](image4)
Top Quark Mass Summary

- Run 2 measurements catching up in precision to latest Run 1 result \( M_t = 178.0 \pm 4.3 \text{ GeV} \)

Systematics: jet energy scale (experimental) and gluon radiation (theoretical) need continuous improvements to match statistics
Electroweak Physics

- Direct measurement of W boson mass and width
- W and Z boson cross section measurements
  - Extract BR(W->lν) from W/Z ratio, lepton universality
  - Establish baseline of detector performance
  - Luminosity measurement technique
- W and Z asymmetries
- Pair production of gauge bosons
  - Fundamental prediction of electroweak gauge theory
  - Establish baseline for multiple lepton-photon-jet-missing $E_T$ final states, relevant for
    - Top physics (WW->dileptons, lν+jets)
    - Higgs search (WZ->lν + bb)
    - Searches (e*, μ*, leptoquarks, SUSY...
W boson mass

- Radiative corrections to W mass probe a wide range of new physics: SM Higgs, non-SM Higgs, SUSY...anything that couples to the W boson

- Energy / momentum calibration is THE KEY aspect of this measurement
  - Other systematics: QED corrections, parton distribution functions, \( p_T(W) \) model continue to reduce with improved calculations, tools and judicious use of collider data

![Graphs showing Upsilon decay to \( \mu\mu \) and Electron E/\( p \) fit]
W and Z boson mass fits

CDF Run 2 preliminary

Z\rightarrow ee

\chi^2/\text{dof} = 53 / 38

CDF Run 2 preliminary

Z\rightarrow \mu\mu

\chi^2/\text{dof} = 45 / 30

CDF Run 2 preliminary

W\rightarrow ev

\chi^2/\text{dof} = 69 / 58

CDF Run 2 preliminary

W\rightarrow \mu\nu

p_T(\mu) fit

\chi^2/\text{dof} = 68 / 58
CDF Run 2 preliminary

**W boson mass**

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Electrons (Run 1)</th>
<th>Muons (Run 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Energy Scale and Resolution</td>
<td>70 (80)</td>
<td>30 (87)</td>
</tr>
<tr>
<td>Recoil Scale and Resolution</td>
<td>50 (37)</td>
<td>50 (35)</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>20 (5)</td>
<td>20 (25)</td>
</tr>
<tr>
<td>Statistics</td>
<td>45 (65)</td>
<td>50 (100)</td>
</tr>
<tr>
<td>Production and Decay Model</td>
<td>30 (30)</td>
<td>30 (30)</td>
</tr>
<tr>
<td>Total</td>
<td>105 (110)</td>
<td>85 (140)</td>
</tr>
</tbody>
</table>

First experience with complete Run 2 analysis of 200/pb

Combined Run 2 uncertainty of 76 MeV already better than Run 1 from CDF (79 MeV) or D0 (84 MeV)

Mass value internally blinded with random offset until cross-checks completed

400/pb on tape: precision of best single measurement (ALEPH, 58 MeV) and combined LEP (42 MeV) within reach
Good agreement with SM in rate and kinematics, giving confidence in photon techniques

\[ \sigma (Z\gamma \rightarrow l\ell\gamma) = 3.86 \pm 0.46 \text{(stat & sys)} \pm 0.25 \text{(lum)} \text{ pb} \quad \text{(SM: 4.3 pb)} \]

\[ \sigma (Z\gamma \rightarrow l\ell\gamma) = 5.3 \pm 0.6 \text{(stat)} \pm 0.3 \text{(sys)} \pm 0.3 \text{(lum)} \text{ pb} \quad \text{(SM: 5.4 \pm 0.3 pb)} \]

\[ \sigma (W\gamma \rightarrow l\nu\gamma) = 19.3 \pm 6.7 \text{(stat & sys)} \pm 1.2 \text{(lum)} \text{ pb} \quad \text{(SM: 16.4 \pm 0.4 pb)} \]

\[ \sigma (W\gamma \rightarrow l\nu\gamma) = 19.7 \pm 1.7 \text{(stat)} \pm 2.0 \text{(sys)} \pm 1.1 \text{(lum)} \text{ pb} \quad \text{(SM: 19.3 \pm 1.4 pb)} \]
WW→dileptons

**D0:** \[ \sigma (WW) = 13.8^{+4.3}_{-3.8} \text{(stat)}^{+1.0}_{-0.8} \text{(sys)} \pm 0.9 \text{(lum)} \text{ pb} \]

**CDF Tight cuts:** \[ \sigma (WW) = 14.3^{+5.6}_{-4.9} \text{(stat)} \pm 1.6 \text{(sys)} \pm 0.9 \text{(lum)} \text{ pb} \]

**CDF Loose cuts:** \[ \sigma (WW) = 19.4 \pm 5.1 \text{(stat)} \pm 3.5 \text{(sys)} \pm 1.2 \text{(lum)} \text{ pb} \]

**SM prediction 12.5 ± 0.8 pb**

Agreement with SM in rate and kinematics, tight and loose selection cuts

Checks top and H→WW background
Drell-Yan Forward-Backward Asymmetry

- Probes new physics at high-mass through interference with SM (linear in coupling strength of new physics $\alpha_{\text{new}}$)
  - Complementary to cross section based search (quadratic in $\alpha_{\text{new}}$)
- Consistent with SM
- Statistics-limited
- Important to maintain charge-discrimination at high momentum
Higgs and Other Searches
SM Higgs Search

- Associated production: \( W, Z + H (\rightarrow bb) \) for \( M_H < 130 \text{ GeV} \)
- \( H \rightarrow WW \) for \( M_H > 130 \text{ GeV} \)

Leptonic \( W \) decays used

Improvements from: better \( b \) tagging, using topological (spin 0) information, more channels (Z), mass resolution (Z-\( \rightarrow bb \) sample very important)
SM Higgs Search

Exploit angular (spin 0) information for $H \to WW$ mode

Limits already exceeding Run 1 results

Sensitivity beyond LEP exclusion starts at $\sim 2/fb$

...but interesting sensitivity to other new physics sooner
MSSM Higgs Search

Enhanced cross sections, heavy flavors ($b$, $\tau$) preferred @ high $\tan\beta$

$\sim 131$ pb$^{-1}$

$\tau_1 \tau_h$ mode
Doubly-Charged Higgs Search

Predicted by Left-Right Symmetric Model (motivated by neutrino mass) & light in SUSY-LR

Surpass LEP limits for $h_{ll} < 0.02$

Possibly long-lived due to limited decay modes => highly ionizing

Background $< 10^{-5}$ due to drift chamber $dE/dx$

CDF: $m(H^{±±}) > 134$ GeV @95%CL (LEP limit ~ 98 GeV)
SUSY Searches

**Stop quark**

use new Run 2 capability: Time-of-Flight detector

\[ M(\text{stop}) > 97-107 \text{ GeV} \at95\% \text{CL} \]

(LEP limit 95 GeV)

improvements in event time and ToF reconstruction in progress, will suppress backgrounds

**Indirect Search: \( B_s \to \mu\mu \)**

BR proportional to \( \tan^6 \beta \)
SUSY Searches

Stop quark
use new Run 2 capability:
Time-of-Flight detector

M(stop) > 97–107 GeV @95%CL
(LEP limit 95 GeV)

improvements in event time and
ToF reconstruction in progress, will
suppress backgrounds

Indirect Search: $B_s \rightarrow \mu\mu$  BR proportional to $\tan^6\beta$

Sensitive to $\tan\beta \sim 40$ for BR $\sim 10^{-7}$

World's best limit from D0,
CDF & D0 combined limit: BR ($B_s \rightarrow \mu\mu$) < $2.7 \times 10^{-7}$ @90%CL

Start to limit $\tan\beta$ as more data analysed
SUSY Searches

Squark-gluino search

signature: 2 jets + missing $E_T$

For mSugra @ $m_0 = 25$ GeV, $\tan\beta = 3$, $A_0 = 0$, $m < 0$, exclude $m$(squark/gluino)$ < 292/333$ GeV improves Run 1 limits

Chargino-neutralino search using trileptons

One of the golden discovery modes at Tevatron and LHC

Analysis of data already on tape will extend sensitivity beyond LEP
Very-High $P_T$ Physics

Jet spectra
probing high-x gluons and compositeness

Good dilepton, diphoton mass resolution for $Z'$, large extra dimensions searches

New best limits on RS gravitons and LED (D0) and $Z'$ (D0:ee, CDF:$\mu\mu, \tau\tau$)

**DØ Run II Preliminary**

**Best limit: $M_S > 1.28$ TeV**

**345/pb, $\gamma\gamma$**
B Physics
**B_s Mixing Sensitivity**

B_d mixing => prepare machinery for B_s mixing analysis

Flavor tagging at production: **maximize effective efficiency** \( \epsilon D^2 \)

eg. CDF combined tagger: \( \epsilon D^2 = 1.82 \pm 0.114 \% \)

Maximize \( c\tau \) resolution \( \sigma_{\tau} \)

\[ \Delta m = 0.536 \pm 0.037 \text{(stat)} \pm 0.009 \text{(s.c.)} \pm 0.015 \text{(sys) ps}^{-1} \]

\[ \Delta m = 0.506 \pm 0.055 \text{(stat)} \pm 0.049 \text{(sys) ps}^{-1} \]
B_s Mixing Sensitivity

Predictions based on observed B_s signals

eg. $5\sigma$ discovery $\Delta m_s = 19/\text{ps}$ with $1.5/\text{fb}$
Motivation: lifetime difference between $B_s$ eigenstates could be sizable, interesting to measure

CDF:
$\Delta \Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \text{(stat)} \pm 0.01 \text{(sys)}$

SM expectation:
$\frac{\Delta \Gamma}{\Delta m_s} = (3.7^{+0.8}_{-1.5}) \times 10^{-3}$

Implies $\Delta m_s = 125^{+69}_{-55}$
Summary

- Run 2 is firmly established, with >3 x Run 1 data recorded
- Many new results, often already world's best
- Anticipate ~2 fb$^{-1}$ by 2007
  - 2M leptonic W's and 200k leptonic Z's
- ...and 4-8 fb$^{-1}$ by 2009
- Continue to build on success, expect much more physics!
- Invaluable experience for LHC