Flavour studies and searches at the Tevatron

at "Flavour in the era of the LHC"
Nov 8, 2005

Rolf Oldeman
University of Liverpool
for the CDF and D0 collaborations
The Tevatron

- 6.2km Ø
- 396 ns bunch spacing
- Run I: 1989-1995
- Run II: 2001-2009
Tevatron luminosity

Congratulations Fermilab!
Fermilab has set a world record for peak luminosity of a hadron collider!
Operations established store 4431 at 9:11 a.m. yesterday, October 4, with an initial luminosity of 141E30 cm^-2 sec^-1. This record exceeds the previous Tevatron record by almost 8 percent, and it exceeds the world record for peak luminosity of a hadron collider achieved 23 years ago by the ISR proton-proton collider at CERN. The ISR achieved a peak luminosity of 140E30 cm^-2 sec^-1 at a collision energy of 62 GeV. The Tevatron produces collisions between protons and antiprotons at a collision energy of 1900 GeV. The peak luminosity of the Tevatron has greatly increased since Fermilab began Run II in March 2001, and Fermilab expects to improve the Tevatron peak luminosity even further.

Again, Tevatron Sets World Record for Peak Luminosity
On Tuesday, October 25, at 3:28 a.m. the Tevatron improved its world-record peak luminosity to 144E30 cm^-2 sec^-1. Significant contributions came from the new electron cooling system, which will be featured in an upcoming luminosity series in Fermilab Today. Congratulations!

Fermilab Sets Another World Record for Luminosity!
The Tevatron recently made a vast improvement in peak luminosity. Operators set a new record on Thursday, October 27 at 2:54 a.m. The new record of 158E30 cm^-2 sec^-1 is almost 10 percent larger than the last record of 146E30 cm^-2 sec^-1.

Records Keep Coming
The flurry of Tevatron peak luminosity records of the last couple of months continues. On Monday, October 31, accelerator operators produced a special Halloween treat of 164E30 cm^-2 sec^-1. Since the beginning of the year, the peak luminosity record has increased by about 50 percent. Congratulations.

Already 5 overlapping collisions per bunch crossing

Expect 4-8fb^-1 by 2009
The Tevatron detectors

- Excellent momentum resolution
- High-bandwidth trigger
- Excellent calorimetry
- Wide muon coverage
- $4\pi$ general purpose detectors
- Superconducting solenoids
- Silicon vertex detectors
Triggering at hadron colliders

The trigger is the key to flavour physics at hadron colliders

CDF Detector

1.7 MHz crossing rate

Dedicated hardware

$42 L_1$ buffers

L1 trigger

25 kHz L1 accept

Hardware +

Linux PC's

$4 L_2$ buffers

L2 trigger

500 Hz L2 accept

Linux farm (200)

L3 farm

Disk/tape

Hardware tracking for $p_T \geq 1.5$ GeV

Muon-track matching

Electron-track matching

Missing $E_T$, sum-$E_T$

Silicon tracking

Jet finding

Refined electron/photon finding

Full event reconstruction

Hardware +

Linux PC's

Full event reconstruction
Overview

• Charm physics
  – $J/\psi$, open charm
• Beauty physics
  – $B_c$, Rare decays, $B_s$ mixing
• Top physics
  – Production, mass, decays
• Direct searches
  – SUSY, leptoquarks
Physics with J/ψ's

J/ψ → μ⁺μ⁻ easy trigger signature

CDF and D0 collected millions

extensively used for

- momentum calibration
- muon trigger efficiencies
- tracking calibrations

CDF 220pb⁻¹

J/ψ → μ⁺μ⁻

N = 1.21 ± 0.01 M
The X(3872)

- 2003: Belle finds new narrow state $X \rightarrow J/\psi \pi^+ \pi^-$
- Quickly confirmed & studied by CDF and D0

$m = 3871.3 \pm 0.7 \pm 0.4$ MeV

$m - m(J/\psi) = 774.9 \pm 3.1 \pm 4.0$ MeV

Does not fit any $c \bar{c}$ state.
Is it a $D^0 \bar{D}^{*0}$ 'molecule'?
Is it a $c \bar{c} g$ 'hybrid'

$m(\pi^+ \pi^-)$ spectrum consistent with $X \rightarrow J/\psi \rho$

$X$ behaves like $\psi'$
- $p_T$ spectrum
- $\eta$ spectrum
- prompt/b ratio
- helicity angles
- isolation

$D^0$

$X(3872)$ yield per 20 MeV/c$^2$

CDF II Preliminary, 360 pb$^\dagger$

$X(3872) \rightarrow J/\psi \pi^+ \pi^-$

Multipole Expansions for $c \bar{c}$:
- $P_3$
- $J/\psi \pi \pi$ Phase-Space

$\psi(2S)$

Comparison

BSM searches at the Tevatron

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Open charm

Large, clean charm samples can be recorded at a hadron collider with a displaced track trigger:

CDF 5.8pb⁻¹

Cross-sections agree with theory (FONLL)

Cacciari, Nason \textbf{JHEP 0309:006, 2003}

CDF put stringent limits on direct CP violation in $D^0$ decays

<table>
<thead>
<tr>
<th>$D^0 \rightarrow K^- K^+$ [%]</th>
<th>$D^0 \rightarrow \pi^- \pi^+$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma/\Gamma(K^- \pi^+)$</td>
<td>$9.92 \pm 0.11 \pm 0.12$</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>$2.0 \pm 1.2 \pm 0.6$</td>
</tr>
<tr>
<td>$N_{D^0} = 68310 \pm 330$</td>
<td>$3.594 \pm 0.054 \pm 0.040$</td>
</tr>
<tr>
<td>$L = 123 \pm 7 \text{ pb}^{-1}$</td>
<td>$1.0 \pm 1.3 \pm 0.6$</td>
</tr>
</tbody>
</table>
New CDF 350pb$^{-1}$ D$^0 \rightarrow K^+\pi^-$ analysis

'Wrong sign' D$^0 \rightarrow K^+\pi^-$ decay
- Double Cabibbo suppressed decays
- D$^0$-D$^0$ mixing.

$$\frac{Br(D^0 \rightarrow K^+\pi^-)}{Br(D^0 \rightarrow K^-\pi^+)} = (0.405 \pm 0.021 \pm 0.012)\%$$

Next step: time dependent mixing analysis
B physics at hadron colliders has come a long way

From the first $B^+ \rightarrow J/\psi K^+$ in CDF Run I

- $2.6 \text{ pb}^{-1}$
- no silicon detector

To precision measurements by CDF and D0

- all know $B$-hadrons: $B^+, B^0, B_s, B_c, \Lambda_b$
- a myriad of decay modes:
  - $J/\psi$ modes e.g. $B_c \rightarrow J/\psi \pi$
  - leptonic e.g. $B_s \rightarrow \mu^+\mu^-$
  - semi-leptonic e.g. $B_s \rightarrow D_s \mu^+\nu_\mu$
  - hadronic e.g. $B_s \rightarrow D_s \pi$
  - charmless e.g. $B^0 \rightarrow \pi^+\pi^-$
**B_c** the last weakly decaying meson

D0:
Lifetime and mass in $B_c \rightarrow J/\psi \mu \nu$

- $m = (5.95^{+0.14}_{-0.12} \pm 0.34) \text{GeV}$
- $\tau = (0.45^{+0.12}_{-0.10} \pm 0.12) \text{ps}$

CDF:
Evidence for $B_c \rightarrow J/\psi \pi^+$

- $m = (6.2870 \pm 0.0048 \pm 0.0011) \text{GeV}$

$B_c$ has charm-like lifetime

<10^{-3} experiments give false positive result at this level

New! CDF 360pb$^{-1}$ $B_c \rightarrow J/\psi$ ev:
- $\tau = (0.47 \pm 0.07 \pm 0.03) \text{ps}$

Agrees with lattice QCD predictions
$B_S \rightarrow \mu^+\mu^-$

Standard model prediction: $\text{Br}(B_S \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$

MSUGRA prediction:
Dedes, Dreiner, Nierste PRL87:251804,2001
$tan\beta=50$, $A_0=0$, $\mu>0$, $m_t=175$ GeV

SUSY contribution
Find a $B_s \rightarrow \mu^+\mu^-$ in $10^{12}$ collisions?

Combine discriminating variables into a single likelihood ratio.

CDF 360 pb$^{-1}$

$B_s \rightarrow \mu^+\mu^- < 2.0 \times 10^{-7}$

Combined limit:

- $B_s \rightarrow \mu^+\mu^- < 1.5 \times 10^{-7}$

hep-ex/0508058
implications of $B_s \rightarrow \mu^+\mu^- < 1.5 \times 10^{-7}$
$B_d$ and $B_s$ oscillations

$B_d$ mixing $\propto V_{td}^2$

$\Rightarrow$ slow:
$\Delta m_d = 0.502 \pm 0.007 \text{ps}^{-1}$
$\Rightarrow$ large mixing phase:
$\sin 2\beta = 0.736 \pm 0.049$

$B_s$ mixing $\propto V_{ts}^2$

$\Rightarrow$ fast:
$\Delta m_s \approx 18 \text{ps}^{-1}$?
$\Rightarrow$ small mixing phase:
$\sin 2\beta_s \approx 0.02$?
New physics in $B_s$ oscillations

- Heavy $Z'$ with FCNC.

$$b \rightarrow Z' \rightarrow s$$

$$s \rightarrow b$$

**B_s oscillations**

**1. Final state reconstruction**

**2. High resolution on proper decay length**

**3. Tag B flavor at production time**

Pre-RunII world average includes LEP, SLC, CDF-RunII
\[ \Delta m_s > 14.5 \text{ps}^{-1}, \text{sensitivity} 18.3 \text{ps}^{-1} \]
Bs mixing – the D0 analysis

Very efficient low-p_T muon trigger
Bs→D_sμν, D_s→K^-K^+π^+, selecting φ and K*0 resonances

combine opposite side
muon, electron, jet charge:
εD^2=2.17±0.13±0.08%

Δm_s >7.3ps^{-1}, sensitivity 9.5ps^{-1}
**Bₜ mixing – the CDF analysis**

semileptonic $B_s \rightarrow D_s l$

larger yields

- Includes: $B_s \rightarrow D_s \pi \pi \pi$, $B_s \rightarrow D_s \pi$
- $D_s \rightarrow K K \pi, D_s \rightarrow \pi \pi \pi$

$\varepsilon D^2 = 1.55 \pm 0.09\%$

$\Delta m_s > 8.6 \text{ps}^{-1}$, sensitivity 13.0 ps\(^{-1}\)

CDF Run II Preliminary \( L = 355 \text{ pb}^{-1} \)

Lepton SVT Track

Combined Analyses CDF Fall 2005

Nov 8, 2005

Rolf Oldeman (University of Liverpool)
New world average

limit \( 14.5 \rightarrow 16.6 \text{ ps}^{-1} \)
sensitivity \( 18.3 \rightarrow 20.0 \text{ ps}^{-1} \)

Further improvements from
• more data
• more decay channels (e.g. \( B_s \rightarrow D_s^{*}\pi \))
• Same-side and opposite-side kaon tags
Top physics

Most massive fundamental particle.
Discovered only 10 years ago at the Tevatron!

5 orders of magnitude

Rolf Oldeman (University of Liverpool) Flavour studies and BSM searches at the Tevatron.
top physics at the Tevatron

SM: $t\bar{t}$ pair production, $\text{Br}(t \rightarrow bW)=100\%$

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

Tag one or both b-jets
$t\bar{t}$ production cross-section agrees
• between both experiments
• in all channels
• with the theoretical prediction!
The mass of the top quark

top, Higgs and new physics give radiative corrections to $m_W$

$\Delta M_W \propto m_T^2$ \quad $\Delta M_W \propto \ln M_H$

$m_t$ and $m_W$ constrain $m_H$

Tevatron Run I + LEP2 results favoured light Higgs

Experimental challenges:
• Missing neutrino
• Jet energy scale (JES)
• Understanding backgrounds
D0 Run II l+jets 320pb\(^{-1}\)

'Matrix-element method' :
All kinematic variables used in likelihood fit

Jet Energy scale determined from hadronic W decays in the \(t\bar{t}\) sample itself. 
cross-check with external calibration

\[ m_{\text{top}} = 169.5 \pm 3.0_{\text{stat}} \pm 3.2_{\text{(JES)}} \pm 1.7_{\text{(syst)}} \text{GeV} / c^2 \]

\[ \text{JES} = 1.034 \pm 0.034 \]
CDF Run II $l+\text{jets}$ $320\text{pb}^{-1}$

Template method:
Compare reconstructed $t,W$ mass to distributions from MC

Reconstructed Top Mass

$m_{top} = 173.5^{+2.7}_{-2.6} \text{ (stat)} \pm 2.5 \text{(JES)} \pm 1.3 \text{(syst)} \text{GeV} / \text{c}^2$

$\text{JES} = -0.10^{+0.78}_{-0.80} \sigma_{(\text{apriori)}}$

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>Uncertainty (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR/FSR</td>
<td>0.7</td>
</tr>
<tr>
<td>Model</td>
<td>0.7</td>
</tr>
<tr>
<td>b-jet</td>
<td>0.6</td>
</tr>
<tr>
<td>Method</td>
<td>0.6</td>
</tr>
<tr>
<td>PDF</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
</tr>
<tr>
<td>Jet Energy</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Tevatron combined top mass

Includes 8 measurements
• from Run I and Run II,
• from D0 and CDF
• di-lepton, l+jet, fully-had

Correlations taken into account

Dominated by CDF and D0 Run II l+jet

Lower than but consistent with Run I average 178.0±4.3GeV

Details in hep-ex/050791
Implication of new top mass

Standard model interpretation: Light Higgs favoured

But LEP2 excludes $m(H) < 114 \mathrm{GeV}$

BSM interpretation: SUSY favoured over SM

New Tevatron top mass pushes EW fit further towards light Higgs/SUSY!
Beyond masses and cross-sections

- Production cross-section
- Resonance production
- Production kinematics
- Top Spin Polarization
- Rare/non SM Decays
- Branching Ratios
- $|V_{tb}|$
- Top Width
- W helicity
- Anomalous Couplings
- CP violation
- W helicity

- $p p \rightarrow t b W^+ l^+ \bar{\nu}$
- $W^{-}$
- $l^+$
- $\bar{\nu}$
- $X$
- $q$
top decays to non-b jet

Measuring $R = \frac{\text{BR}(t \rightarrow Wb)}{\text{BR}(t \rightarrow Wq)}$

$$R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2$$

Unitarity of the CKM matrix predicts $R = 0.999999$

a 4th generation can change this prediction

method:
• Select $t\bar{t}$ events without requiring b-tags
• Compare 0/1/2 b tags

CDF 161 pb$^{-1}$:
$$R = 1.12^{+0.21+0.17}_{-0.19-0.13} \, \text{(stat + syst)}$$

D0 230 pb$^{-1}$:
$$R = 1.03^{+0.19}_{-0.17} \, \text{(stat + syst)}$$

Both experiments confirm within 20%:
All jets from $t \rightarrow Wq$ decays are b-jets
$t \rightarrow bH^+$ in MSSM

- $t \rightarrow H^+b$ can compete with $t \rightarrow W^+b$ in MSSM
- $H^+ \rightarrow t^*b, \tilde{c}s, \tau \nu, Wh^0$
- Analyse $\sigma(t\bar{t})$
  - "dilepton",
  - "lepton + jets" 1 b-tag
  - "lepton + jets" 2 b-tag
  - "lepton + hadronic $\tau$"

Excluding MSSM phase space

$t \rightarrow H^+b$ search

CDF Run II Preliminary

Excluded 95% CL

$M_t = 175 \text{ GeV/c}^2$

$\int L dt = 192 \text{ pb}^2$

Excluded MSSM phase space assuming $H^+ \rightarrow \tau \nu$

Tautonic Higgs Model

CDF Run II Preliminary

Excluded 95% CL

$M_t = 175 \text{ GeV/c}^2$

$\int L dt = 192 \text{ pb}^2$

$BR(H \rightarrow \tau \nu) = 1$; $BR(H \rightarrow c\bar{s}) = BR(H \rightarrow t^* \bar{b}) = BR(H \rightarrow W^+ W^-) = 0$
Direct searches for BSM flavour

• Leptoquarks
• Exited leptons
• Scalar quarks and leptons

Typical signature: e, μ, τ, b-jet + jet, γ, or missing $E_T$

Most models require pair-production
⇒ even more distinct signatures!
Leptoquarks

Carry both quark and lepton number

Most GUT's predict Lepto-quarks

key parameter:

\[ \beta = \frac{B(LQ \rightarrow \ell^\pm q)}{B(LQ \rightarrow \ell^\pm q) + B(LQ \rightarrow \nu q')} \]

\( \beta = 1.0 \) : \( LQLQ \rightarrow qq\ell^+\ell^- \)

\( \beta = 0.5 \) : \( LQLQ \rightarrow qq\ell^+\ell^- \) (25%) \( qq\nu\ell \) (50%) \( qq\nu\nu \) (25%)

\( \beta = 0.0 \) : \( LQLQ \rightarrow qq\nu\nu \)

1\textsuperscript{st} generation: \( LQ_1 \rightarrow qe / q\nu_e \)

2\textsuperscript{nd} generation: \( LQ_2 \rightarrow q\mu / q\nu_\mu \)

3\textsuperscript{rd} generation: \( LQ_3 \rightarrow q\tau / q\nu_\tau \)
1st and 2nd gen. leptoquark results

1st and 2nd generation leptoquarks excluded up to \( m \approx 120 \text{GeV}(\beta = 0) \) to \( m \approx 250 \text{GeV}(\beta = 1) \)
3rd generation leptoquarks

Signature: 2 b-jet + 2τ
same signature as RP-violating stop!

CDF 320 pb⁻¹ analysis:
• 1 τ→lepton, 1 τ→hadrons.
• No b-tag applied to jets

Z→τ⁺τ⁻ control sample

CDF Run II Preliminary (322 pb⁻¹)

σ(\bar{p}p→LQ₃LQ₃)×Br(LQ₃→bt) pb

95% C.L. upper limit:
- Observed
- Expected (±σ)

m(LQ₃)>155 GeV for β=1
less strict than for 1st and 2nd generation leptoquark

m searches at the Tevatron
Excited leptons

Signature: 2 leptons + photon

contact interaction
gauge mediated

similar limits on e*
Scalar quarks (SUSY)

'Classic' inclusive signature: jets + missing transverse energy

Inspired by MSUGRA models: $\tilde{q} \rightarrow q\chi^0$, or $\tilde{g} \rightarrow qg\chi^0$

$\chi^0$ is stable, neutral, weakly interacting $\Rightarrow$ missing $E_T$

$\sigma (\tilde{q}\tilde{q}) \propto N_{\text{flav}} \times N_{\text{col}}$ $\Rightarrow$ large cross-section, relatively clean signature $\Rightarrow$ very large mass range

Important background: $Z$+jets, $Z \rightarrow \nu\nu$
D0 squark/gluino search

2 jets
Main BG: Z→νν+2 j
expect: $12.8 \pm 5.4$
observe: 12

3 jets
Main BG: W→τν+2 j
expect: $6.3 \pm 31$
observe: 5

4 jets
Main BG: t¯t
expect: $7.1 \pm 0.9$
observe: 10

Indirect limit from LEP2
(in SUGRA, $m(\tilde{g}) \approx 3m_{\chi^{\pm}}$)

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Conclusions

- Tevatron has achieved an extremely rich flavour program:
  - charm
  - top
  - beauty
  - exotic

- Possible thanks to versatile general-purpose detectors:
  - tracking with high $p_T$ resolution
  - electron, muon and photon identification
  - large trigger bandwidth

- Expect first 1fb$^{-1}$ analyses this winter
BACKUP
Lifetime difference in $B_s \rightarrow J/\psi \phi$

- Both the $J/\psi$ and the $\phi$ are vector-mesons
  - spin 1 ⇒ polarization degree of freedom
- Three components in VV final state:
  - $A_0$ : longitudinal component  \(\text{CP even}\)
  - $A_{||}$ : transverse parallel component  \(\text{CP even}\)
  - $A_{\perp}$ : transverse perpendicular comp.  \(\text{CP odd}\)
- Standard model prediction:
  - CP-even = short lived
  - CP-odd   = long lived
  - $\Delta \Gamma/\Gamma = 0.12 \pm 0.06$
- New physics can only(?) decrease $\Delta \Gamma$
Bs mixing I – Lifetime difference

- $B_s \rightarrow J/\psi \phi \rightarrow \mu^+\mu^- K^+K^-$
- $B \rightarrow VV$ decays: Heavy and Light state decay with distinct angular distributions and different lifetimes.

- CDF (260 pb$^{-1}$) $\frac{\Delta \Gamma_s}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01$
  - 1/4 heavy - 3/4 light state
  - Lifetime - $\tau_{\text{heavy}} \sim 2 \times \tau_{\text{light}}$

- D0 (450 pb$^{-1}$) $\frac{\Delta \Gamma_s}{\Gamma_s} = 0.21^{+0.33}_{-0.45}$
Top Production at the Tevatron

• Pair production
  \[ \sigma_{\text{pair-theory}} = 6.7 \text{ pb.} \]

  All of these theoretical values assume a top quark mass of 175 GeV/c² at a center of mass energy of 1.96 TeV.

• Single top
  - Not yet observed
  - \( \sigma_{\text{s-channel-theory}} = 0.88 \text{ pb.} \)
  - \( \sigma_{\text{t-channel-theory}} = 1.98 \text{ pb.} \)
Test of Standard Model

Impact of CDF+D0 Top Quark Mass = 172.7 ± 2.9 GeV

Good agreement between
direct measurements
and
indirect SM prediction

m_H [GeV] = 91 ±^{45}_{32} GeV

< 186 GeV @ 95% C.L.

< 219 GeV with LEP Excluded
Heavy states decaying to $t\bar{t}b\bar{t}$

**D0 370 pb$^{-1}$ l+jets**

*CDF 320 pb$^{-1}$ l+jets*

Both experiments exclude $X \rightarrow t\bar{t}b\bar{t}$ $\text{Br} \times \sigma$ larger than a few pb$^{-1}$.

Leptophobic $Z$ in topcolor models with $\Gamma(Z)=0.012 m(Z)$ are excluded for up to $Z'$ masses of about 700 GeV.
sbottom and stop searches

• to be completed