The Tevatron Experiments  
– Status, Results, and Prospects –

Frank Fiedler, LMU München

Overview:

- introduction: the machine and the experiments
- bottom (and charm) physics
- top physics
- searches for the (SM) Higgs boson
- conclusions

(almost) all Tevatron Run II results are preliminary!
The Tevatron Collider
Both CDF and DØ: “standard” collider detector configuration

- silicon microvertex and tracking detectors within solenoid
- calorimeter and muon systems
- three trigger levels and DAQ, adapted to Tevatron Run II parameters

CDF:
- high rate silicon track trigger
- excellent tracking (i.p., mass resolution)
- particle ID (TOF and dE/dx)

DØ:
- large muon coverage: $|\eta| < 2.0$
- excellent calorimeter resolution
- central tracking coverage: $|\eta| < 1.6$
The DØ Detector

muon chambers

frontend electronics

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MPI Colloquium, 27. 1. 2004
DØ Muon Endcap Scintillators
The DØ Silicon Microvertex Detector

- track reconstruction up to pseudorapidity $|\eta| \leq 3$
- precise track reconstruction close to the primary vertex (d.c.a. resolution: $10 \mu m$ for high momentum tracks)
  ⇒ identification of tracks from secondary vertices ($\rightarrow b$ jets!) starting at the 2nd trigger level, and in the offline reconstruction
Data Taking Performance

Run II Integrated Luminosity

- Integrated luminosity (pb$^{-1}$)
- Efficiency: 77% average, 86% current
- Delivered vs. Recorded
- Tevatron shutdown
- 34 pb$^{-1}$ before 4/2004
- 234 pb$^{-1}$ today
- 305 pb$^{-1}$ today

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Why $b$ Physics at the Tevatron?

Production:

- large cross-section
- produce all $b$ hadrons
- incoherent production

but

- background cross-section even larger
- soft $p_t$ spectrum
- not always both $b$ jets in acceptance

Typical event numbers per year:

<table>
<thead>
<tr>
<th></th>
<th>SLC ('98)</th>
<th>LEP1 ('94)</th>
<th>PEPII / KEKB</th>
<th>Tevatron (today)</th>
<th>LHC (low lumi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(b\bar{b})$</td>
<td>7 nb</td>
<td>7 nb</td>
<td>1 nb</td>
<td>50 $\mu$b</td>
<td>500 $\mu$b</td>
</tr>
<tr>
<td>$\int \mathcal{L} dt$</td>
<td>$\leq 10$ pb$^{-1}$</td>
<td>50 pb$^{-1}$</td>
<td>40000 pb$^{-1}$</td>
<td>100 pb$^{-1}$</td>
<td>100000 pb$^{-1}$</td>
</tr>
<tr>
<td>number of $b$ quarks</td>
<td>$\mathcal{O}(1 \cdot 10^5)$</td>
<td>$\mathcal{O}(5 \cdot 10^5)$</td>
<td>$\mathcal{O}(4 \cdot 10^7)$</td>
<td>$\mathcal{O}(5 \cdot 10^9)$</td>
<td>$\mathcal{O}(5 \cdot 10^{12})$</td>
</tr>
<tr>
<td>$b$ quarks, $p_t \geq 20$ GeV</td>
<td>$\mathcal{O}(1 \cdot 10^5)$</td>
<td>$\mathcal{O}(5 \cdot 10^5)$</td>
<td>n.a.</td>
<td>$\mathcal{O}(3 \cdot 10^7)$</td>
<td>$\mathcal{O}(6 \cdot 10^{10})$</td>
</tr>
</tbody>
</table>
b Physics at the Tevatron

The Tevatron b physics program: complementary to B factories

- $b \bar{b}$ production cross-section
- spectroscopy
- lifetimes (especially $B_s^0$, $B_c^+$, $\Lambda_b$)
- searches, for example: $B_s \rightarrow \mu \mu$
- CKM physics:
  - CP violation
  - $B_s$ oscillations

Concentrate on CKM physics here, review other results on the way
CKM Physics

Status of the CKM triangle:

“Strategy” for CKM triangle measurements until LHCb:

B^0 \rightarrow \pi^+\pi^-  

b \rightarrow u\ell\nu

B^+ \rightarrow D^0K^+
B_S \rightarrow D_sK^+
B_S \rightarrow K^+K^-
B \rightarrow J/\Psi K_s,
B \rightarrow \phi K_s
B Reconstruction (I)

first step: central tracking calibration
→ use $J/\Psi \to \mu^+\mu^-$ decays

→ first Run II publication:
$m(D_s^+) - m(D^+) = 99.41 \pm 0.43$ MeV

second step: B mass peaks...

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**B_s → D_s h Decays**

- fully reconstructed decay → interesting for B_s mixing
- B_s → D_sK decays → CKM angle \( \gamma \)

CDF Run II Preliminary, \( L = 119 \text{ pb}^{-1} \)

first measurement:

\[
Br(B_s \rightarrow D_s \pi) = (4.8 \pm 1.2 \text{ (stat)} \pm 0.8 \text{ (syst)} \pm 1.8 \text{ (br)} \pm 0.6(f_s/f_d)) \cdot 10^{-3}
\]
• $B_s$ mixing results so far (HFAG, Summer 2003):

- World average (prel.)

  - data ± 1σ
  - 1σ CL limit: 14.4 ps$^{-1}$
  - sensitivity: 18.7 ps$^{-1}$

- LEP, SLD, and CDF I results

- significance of a mixing measurement:

  \[ \sim \sqrt{\frac{S}{S+B}} \cdot e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2} \cdot \sqrt{\epsilon D^2} \]

  - signal purity
  - proper time resolution
  - limitation for large $\Delta m_s$
  - flavour tag performance

• Measurement conditions:

  \[ \sigma_L = 200 \mu m \]
  \[ \sigma_L = 60 \mu m \]

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Proper time reconstruction: 
\[ t = \frac{L}{\beta \gamma} = \frac{m}{p_t} \cdot L_{xy} \]

- **hadronic decays**: fully reconstructed
  - \( \sigma(L_{xy}) \) dominates
  - CDF: \( \sigma(t) = 0.067 \) ps
  - DØ: \( \sigma(t) = 0.110 \) ps

- **semileptonic decays**: neutrino contribution unknown
  - \( \sigma(p_t)/p_t \sim 15\% \)
  - \( \sigma(t) = 0.150 \) ps

**Lifetime**: Key for understanding proper time reconstruction
CDF: simultaneous fit to mass and decay time distributions

<table>
<thead>
<tr>
<th>b hadron</th>
<th>CDF result</th>
<th>PDG value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+$</td>
<td>$(1.63 \pm 0.05 \pm 0.04)$ ps</td>
<td>$(1.671 \pm 0.018)$ ps</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$(1.51 \pm 0.06 \pm 0.02)$ ps</td>
<td>$(1.537 \pm 0.015)$ ps</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$(1.33 \pm 0.14 \pm 0.02)$ ps</td>
<td>$(1.461 \pm 0.057)$ ps</td>
</tr>
<tr>
<td>$\Lambda_b$</td>
<td>$(1.25 \pm 0.26 \pm 0.10)$ ps</td>
<td>$(1.229 \pm 0.080)$ ps</td>
</tr>
</tbody>
</table>
1. identify the B flavour at decay:
   - e.g. pion from $B_s \rightarrow D_s^- \pi^+$ decay
   - e.g. lepton from semileptonic $B_s$ decay

2. identify the B flavour at production:
measure tagging power $\epsilon D^2$ in data with $B^+ \rightarrow J/\Psi K^+$ decays:

- look for muons opposite to the identified decay ($\Delta \phi > 1.1$)
- take the muon with the largest $p_t$ ($p_t > 1.9$ GeV)
- $Q(\text{muon}) \neq Q(\text{kaon}) \rightarrow$ correct tag
- $Q(\text{muon}) = Q(\text{kaon}) \rightarrow$ wrong tag
- no muon $\rightarrow$ no tag

### $\epsilon D^2$ results

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>fragmentation track</td>
<td>2.1±0.7%</td>
<td>5.5±2.0%</td>
</tr>
<tr>
<td>jet charge</td>
<td>(3.0%)</td>
<td>3.3±1.7%</td>
</tr>
<tr>
<td>soft muon</td>
<td>0.6±0.1%</td>
<td>1.6±1.1%</td>
</tr>
<tr>
<td>soft electron</td>
<td>(0.7%)</td>
<td>?</td>
</tr>
<tr>
<td>opp. side kaon</td>
<td>(2.4%)</td>
<td>—</td>
</tr>
</tbody>
</table>

$\epsilon$: efficiency of finding a tag

$D$: correct–wrong tags sum
analyses of $B_s$ oscillations well underway:
- triggering and reconstruction of $b$ hadrons is impressive
- lifetime measurements $\rightarrow$ calibration of decay length reconstruction
- determination of flavour tagging performance

expected sensitivity:
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- introduction: the machine and the experiments
- bottom (and charm) physics
- **top physics**
- searches for the (SM) Higgs boson
- conclusions

(all Tevatron Run II results are preliminary!)
What do we want to know about the top quark?

- top mass, correlation with W and Higgs mass:
  ⇒ precision test of the Standard Model

- top spin and charge:
  ⇒ is it really the top quark?

- $p\bar{p} \rightarrow t\bar{t}$ production cross-section:
  ⇒ test of the $t\bar{t}$ production process (strong interaction)

- single top quark production in $p\bar{p}$ collisions:
  ⇒ CKM matrix element $|V_{tb}|$ → unitarity, 4th quark generation?

- anomalous production and decays:
  ⇒ top quarks as tool in the search for “new physics”
Top Production at Hadron Colliders (I)

Top pair production (strong interaction)

Feynman diagrams (LO):

Events:

Production cross-section:

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp 1.8 TeV</td>
<td>90%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>5 pb</td>
<td>800 pb</td>
</tr>
<tr>
<td>Run II</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>pp 1.96 TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>7 pb</td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp 14 TeV</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>800 pb</td>
<td></td>
</tr>
</tbody>
</table>
single top quark production: (electroweak interaction)

Feynman diagrams (LO):

1.) “s-channel”

2.) “t-channel”

3.) t+W associated production

production cross-sections:

<table>
<thead>
<tr>
<th></th>
<th>Tevatron Run I</th>
<th>Tevatron Run II</th>
<th>LHC pp 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp 1.8 TeV</td>
<td>0.7 pb</td>
<td>0.9 pb</td>
<td>10 pb</td>
</tr>
<tr>
<td>pp 1.96 TeV</td>
<td>1.7 pb</td>
<td>2.4 pb</td>
<td>250 pb</td>
</tr>
<tr>
<td>pp 14 TeV</td>
<td>0.07 pb</td>
<td>0.12 pb</td>
<td>60 pb</td>
</tr>
</tbody>
</table>

- roughly half the $t\bar{t}$ cross-section
- larger backgrounds
- not yet seen
**t\bar{t} Event Topologies (I)**

- **Graphical Representation**
  - Diagram showing the decay processes of **t** and **\bar{t}** quarks.
  - Arrows indicating the direction of decay.

- **Statistical Breakdown**
  - **5%** dilepton events
  - **30%** lepton+jets events
  - **44%** hadronic events
  - **21%** events with τ leptons

- **Mathematical Conclusion**
  - $|V_{tb}| \gg |V_{ts}|, |V_{td}|$
  - $\Rightarrow \text{Br}(t \rightarrow Wb) \sim 100\%$
### Event Topologies (II)

#### dilepton events:
- 2 energetic, isolated leptons of opposite charge
- 2 energetic b jets
- missing transverse energy
  - event kinematics underconstrained
  - 2 possible jet combinations
  - lepton+jets trigger

#### lepton+jets events:
- 1 energetic, isolated lepton
- 4 energetic jets (of which 2 b jets)
- missing transverse energy
  - 2 solutions for neutrino momentum component along beam axis
  - event kinematics otherwise fully determined
  - 2 \cdot 12 possible jet combinations
    - (fewer with b identification)
  - lepton+jets trigger

#### hadronic events:
- 6 energetic jets (of which 2 b jets)
- event balanced in transverse plane
  - many combinations (⇒ b identification!)
  - large background (⇒ b identification!)
  - only jet based trigger

#### events with τ leptons:
- additional neutrino from τ decay
  - difficult to reconstruct

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An “electron+jets” event at DØ:

jet 1 with identified b decay:

- primary vertex $t \rightarrow Wb$
- secondary vertex $B \rightarrow DX$
- tertiary vertex $D \rightarrow Y_{s}Z$

tracks extrapolated to the interaction region:

view of the transverse plane
A “muon+jets” event at DØ:
A “di-electron” event at CDF:

- $E_T$ (jet 1) = 48 GeV
- $E_T$ (jet 2) = 78 GeV
- $E_T$ (e1) = 78 GeV
- $E_T$ (e2) = 57 GeV
- Missing $E_T$ = 47 GeV

- $\Delta \phi$ (missing $E_T$, closest jet / electron) = 79°
  $\Rightarrow$ “real” missing transverse energy
- $m_{ee} = 59$ GeV $\Rightarrow$ $Z^0$ hypothesis unlikely
- Scalar sum of transverse energies: $H_T = 302$ GeV
  $\Rightarrow$ $t\bar{t}$ hypothesis favoured
Study high momentum muons with $Z \rightarrow \mu^+ \mu^-$ events:

1. **muon efficiency** measurement (trigger and offline)

2. **momentum resolution** of the central tracker

result: $Z$ production cross-section

$$
\sigma(Z) \cdot \text{Br}(Z \rightarrow \mu^+ \mu^-) = (261.8 \pm 5.0 \pm 8.9 \pm 26.2) \text{pb}
$$

(stat.) (syst.) (lumi.)

(corresponding studies for electrons)
W decays: essential ingredient in top reconstruction:

- $t\bar{t}$ events correspond to
  - “2 $W + 2$ jets” \text{(dilepton channel)}
  - “1 $W + 4$ jets” \text{(lepton+jets channel)}
- Berends scaling: production rate of “$W + n$ jets” events $\sim C^n$
- + detector acceptance $\Rightarrow$

\begin{itemize}
  \item \text{dilepton channel}
  \item \text{lepton+jets channel (with $\geq 1$ identified b jet)}
\end{itemize}
Lepton+Jets Channel: Kinematics

Consistency check for a measurement of the total $t\bar{t}$ cross-section

Working towards differential cross-section measurements
The $t\bar{t}$ Production Cross-Section

production cross-section $\sigma(p\bar{p}) \rightarrow t\bar{t} + X$

dependence on the $p\bar{p}$ centre-of-mass energy:

$E_{cm}$ [GeV]  

$\Rightarrow$ agreement with the SM prediction
The top quark decays before hadronisation: $\Gamma_t = 1.4 \text{GeV} > \Lambda_{\text{QCD}}$

$\Rightarrow$ allows a measurement of the quark mass!

Most precise measurement in lepton+jets events:
enough statistics, good S/B ratio, full kinematic reconstruction

“Traditional” method:

- **analyse** all 12 possible jet combinations per event,
  choose one combination (smallest $\chi^2$) per event
- **fill a top mass histogram** from all chosen combinations
- **compare** with template histograms from the simulation:
  a) $t\bar{t}$ signal (for arbitrary top masses, using interpolation techniques)
  b) background: mainly $W$+jets events
- **vary** the normalisation and the top mass in a fit.
Top Mass Measurements, Traditionally (II)

CDF Run II Preliminary (~108 pb⁻¹)

\[ M_{\text{top}} = 177.5 \pm 12.7 \, \text{(stat.)} \pm 7.1 \, \text{(syst)} \]

- Data (22 evts)
- Signal + Bkgd
- Bkgd only

Reconstructed Top Mass, Tagged Events (GeV/c²)
The “traditional” method is not optimal:

- take the jet combination with the smallest $\chi^2$
  $\Rightarrow$ choose the correct combination in only 40% of the events!

- all events are weighted equally
  $\leftrightarrow$ different events can contain different amounts of information!

**example: reconstruction of $X \rightarrow \mu^+ + \text{jet}$ decays**

- high-momentum muon $\rightarrow$ well-measured

- low-momentum muon $\rightarrow$ well-measured
  $\Rightarrow$ mass $m_X$ well-measured
New measurement technique, pioneered by DØ for Run I:

- utilize information from every possible jet combination
- determine a mass-dependent probability \( P_i = P_i(m_t) \)
  for every combination \( i \) in every event

\[ P_{\text{signal}} \times P_{\text{background}} \rightarrow P(m_t) \]

- probability given by:
  1. matrix element (depends on \( m_t \) for signal events)
  2. detector resolution

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Top Mass: Results

DØ Run I
- 168.4 ± 12.8 GeV DØ dilepton
- 173.3 ± 7.8 GeV DØ lepton+jets “traditional”
- 172.1 ± 7.1 GeV DØ combined

CDF Run I
- 167.4 ± 11.4 GeV CDF dilepton
- 175.9 ± 7.1 GeV CDF lepton+jets “traditional”
- 186.0 ± 11.5 GeV CDF fully hadronic
- 176.0 ± 6.5 GeV CDF combined

CDF Run II
- 174.3 ± 5.1 GeV Tevatron combined
- 180.1 ± 5.4 GeV DØ lepton+jets “ME method”

CDF Run II
- 177.5 $^{+14.5}_{-11.8}$ GeV CDF dilepton, preliminary
- 175.0 $^{+19.1}_{-18.7}$ GeV CDF lepton+jets, preliminary
- in the Standard Model:
  predicted cross-section depends on top mass

- measurements:
  trigger and reconstruction efficiencies depend on top mass

agreement!

$\Rightarrow$ assumption of Standard Model $p\bar{p} \rightarrow t\bar{t}$ production process confirmed
Dependence of the $W$ mass because of loop corrections...

- quadratically on $m_t$
- logarithmically on $m_H$

$\Rightarrow$ before 1995: indirect determination of the top mass

$\Rightarrow$ indirect constraints on the Higgs mass
- from direct measurements of the W and top masses
- from other electroweak measurements
Further $t\bar{t}$ Measurements

total $p\bar{p} \rightarrow t\bar{t}$ cross-section and top mass: “foundation”
refinement of Standard Model tests:
- more precise measurements at Run II (higher statistics, better detectors)
- additional measurements:
  - differential cross-sections
  - spin correlations
  - $W$ helicity in top decay
  - rare top decays: search for anomalous couplings, new particles
**Top Physics: Outlook**

$\bar{t}t$ measurements at Run I: mostly statistically limited
- $\bar{t}t$ cross-section
- top mass ($\rightarrow$ new method)
- partial cross-sections, top decays, ...

Top physics at Run II:
- currently: working to reproduce the Run I results
- soon: more accurate measurements of top production and decay
- soon: better top mass measurement
- in several years: measurement of SM single top production possible

**LHC:**
- after commissioning (!) of machine and detectors:
- top mass measurement systematically limited
- top as “tool”: for example search for $\bar{t}tH$ production
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Current Standard Model Higgs limits from LEP and CDF I:

- Standard Model Higgs physics looks very far away for the Tevatron...
New Higgs sensitivity study:

Were previous assumptions on detector resolution realistic?

- use current simulation
- use experience from top/WZ analyses
- concentrate on $115 \text{ GeV} < m_H < 140 \text{ GeV}$
- channels: $p\bar{p} \rightarrow WH \rightarrow (\ell\nu)(b\bar{b})$
  
  
  $p\bar{p} \rightarrow ZH \rightarrow (\nu\bar{\nu})(bb)$
- combine both experiments
- study: b jet identification
  - dijet mass resolution
  - cut optimisation
b jet ID studies at DØ

Run 2A, ZH + 7.5 MB

Dijet mass resolution studies at CDF

MTL Higgs mass (GeV)

Raw Higgs mass (GeV)
possible SM Higgs signals and corresponding sensitivity:

need for:
- integrated luminosity!
- excellent detector understanding!
- clever analyses & new ideas!
New Tevatron Run II Higgs Results

- look for $H \rightarrow WW \rightarrow (\ell\nu)(\ell\nu)$
- important for high mass Higgs: $\approx 140 \text{ GeV} < m_H < 2m_{Z^0}$
- clean final state: two isolated energetic leptons, missing $E_t$
Highlighted some important Tevatron Run II measurements:

- $B_s$ oscillations
- top mass measurement
- search for the Standard Model Higgs boson

Tevatron physics includes areas that were not mentioned:

- QCD studies
- electroweak measurements
- searches for physics beyond the Standard Model

CDF and DØ are very active in all of these areas.
Some world averages / limits have already been improved.
Many more exciting results to come!
Backup Slides

... on the following pages ...
Tevatron Luminosity Forecast (I)

integrated luminosity/week (pb⁻¹)

electron cooling of antiprotons in the Recycler

design

base

fiscal year 2003
fiscal year 2004
fiscal year 2005
fiscal year 2006
fiscal year 2007
fiscal year 2008
fiscal year 2009
Tevatron Run II:
- main injector (150 GeV)
- antiproton accumulator (under commissioning)
- centre-of-mass energy: 1.8 → 1.96 TeV
- number of bunches: 6 → 36,
  396 ns crossing time
- luminosity today: ≤ 6 \cdot 10^{31} \text{cm}^{-2}\text{s}^{-1}
- luminosity goal: 8 \cdot 10^{31} \text{cm}^{-2}\text{s}^{-1} (Run IIa)
- luminosity goal: 2 – 4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1} (Run IIb)
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Data Taking Performance

Tevatron performance

DØ data taking efficiency

⇒ similar numbers for CDF
⇒ already surpass Run I integrated luminosity by a factor 2
⇒ physics analyses typically use $>100 \text{ pb}^{-1}$ so far
Triggering on b Events (I)

The DØ trigger system:

- **Detector**
- **Level 1 Trigger**
- **Level 2 Trigger**
- **Level 3 Trigger**

Current rates:
- 2.5 MHz (beam crossing rate)
- 1–2 kHz (L1 output)
- 400–1000 Hz (L2 output)
- 50 Hz (rate to tape)

Decisions on 3 levels:
- **L1:** hardware, subdetector-oriented
- **L2:** preprocessors for every detector element, then event wide correlations
- **L3:** software, fast event reconstruction

- **Important for b physics:**
  - muons
  - tracks with large impact parameter
  - (jets, electrons)
CDF’s advantage:

- can trigger on *tracks with large impact parameter*
  at **higher rate**:
  
  50kHz Level 1 output rate
  
  $\Rightarrow$ large samples of
  hadronic B (and D) decays
B → h⁺h⁻ Decays

Superposition of 4 contributions – statistical separation:

- decay kinematics
- dE/dx information

(CDF: ~ 1.3σ K/π separation)

![CDF Run 2 Preliminary](image)

Based on 65 pb⁻¹:

- \( \frac{f_s}{f_d} \frac{Br(B^0_s \rightarrow KK)}{Br(B^0 \rightarrow K\pi)} = 0.74 \pm 0.20 \pm 0.22 \)
- \( \frac{Br(B^0 \rightarrow K\pi)}{Br(B^0 \rightarrow \pi\pi)} = 0.26 \pm 0.11 \pm 0.055 \)
- \( A_{CP}(B^0 \rightarrow K\pi) = 0.02 \pm 0.15 \pm 0.017 \)

→ statistical errors: ≈ twice BaBar’s
Steps towards a mixing measurement:

0. identify the B decay
   - fully reconstructed → need track trigger
   - semileptonic → decay time estimation difficult

1. determine the proper decay time
   \[ t = \frac{L}{\beta \gamma} = \frac{m}{p_t} \cdot L_{xy} \]

2. identify the B flavour at decay
   - e.g. pion from \( B_s \rightarrow D_s^- \pi^+ \) decay
   - e.g. lepton from semileptonic \( B_s \) decay

3. identify the B flavour at production

\[ \gamma \sqrt{\frac{S}{S+B}} \cdot e^{-\frac{1}{2}(\Delta m \sigma)^2} \cdot \sqrt{D^2} \]
Steps towards a mixing measurement:

0. identify the B decay
   • fully reconstructed → need track trigger
   • semileptonic → decay time estimation difficult

1. determine the proper decay time
   \[ t = \frac{L}{\beta \gamma} = \frac{m}{p_t} \cdot L_{xy} \]

CDF Run I result on $B^0$ mixing:

CDF Run II Preliminary, $L = 119 \text{ pb}^{-1}$

about 100 $B^0 \rightarrow D_s^+ \pi^-$

compare: best LEP measurement uses 3000 semileptonic $B_s$ decays, S/B=10%
• measure tagging power $\epsilon D^2$ in data with
$B^+ \rightarrow J/\Psi K^+$ decays:

### Examples:

- same side fragmentation track

### Results:

<table>
<thead>
<tr>
<th>$\epsilon D^2$ results</th>
<th>$\epsilon$</th>
<th>$D$: correct–wrong tags [\sum]</th>
</tr>
</thead>
<tbody>
<tr>
<td>fragmentation track</td>
<td>2.1±0.7%</td>
<td>5.5±2.0%</td>
</tr>
<tr>
<td>jet charge</td>
<td>(3.0%)</td>
<td>3.3±1.7%</td>
</tr>
<tr>
<td>soft muon</td>
<td>0.6±0.1%</td>
<td>1.6±1.1%</td>
</tr>
<tr>
<td>soft electron</td>
<td>(0.7%)</td>
<td>?</td>
</tr>
<tr>
<td>opp. side kaon</td>
<td>(2.4%)</td>
<td>—</td>
</tr>
</tbody>
</table>

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$\epsilon$: efficiency of finding a tag

$D$: correct–wrong tags \[\sum\]
analyses of $B_s$ oscillations well underway:
- triggering and reconstruction of $b$ hadrons is impressive
- lifetime measurements → calibration of decay length reconstruction
- determination of flavour tagging performance

expected sensitivity:

CDF (combined)

reach until LHC startup

surpass current limits with 2004/5 statistics

PDG2002 updated

All regions cross at one point!

expectation for 500 $\text{pb}^{-1}$

expectation for 2 $\text{fb}^{-1}$

D$\phi$ ($B_s \rightarrow D_s \pi$ only)

current HFAG limit

current HFAG sensitivity

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MPI Colloquium, 27. 1. 2004
New narrow state observed by Belle in $B \rightarrow J/\Psi \pi^+\pi^-K$ decays

Tevatron: CDF and DØ see the state at the same mass.

Belle reports that the $\pi^+\pi^-$ mass distribution suggests a $\rho$ resonance.

Consistent with Tevatron findings.
Reconstruct the transverse mass in $W \rightarrow \ell \bar{\nu}_\ell$ decays:

$$m_T = \sqrt{2p_T(\ell)p_T(\nu) \left(1 - \cos \theta(\ell, \nu)\right)}$$

for a $W$ mass measurement: will need accurate knowledge of momentum / energy resolution and background!
Largest systematic error on the top mass at the Tevatron:
jet energy scale determination!

idea: use reconstructed hadronic W decays
find them in top events)
potential for reduced jet energy scale error (3.3 GeV so far)
needed for Run II)

Run II goal:
\( m_t = 2 \text{ GeV} \)

22 candidate events

\( \frac{P}{P_{\text{max}}} \)

\( m_W \text{ (GeV)} \)
● (V–A) structure of the weak interaction

⇒ spins of top decay products are fixed:

\[ b \quad t \quad W \]

b quark: top quark: W boson:

\[ \Leftrightarrow \quad \Leftrightarrow \quad \Leftrightarrow \]

(spin component along b/W momentum axis)

⇒ SM predictions: fraction of top decays with a...

left-handed W boson \[ F_- = 1 - F_0 \]

longitudinal W boson \[ F_0 = \frac{1}{1 + 2m_W^2/m_t^2} \approx 0.70 \]

right-handed W boson \[ F_+ = 0 \]
DØ additional parameter in the matrix element (cf. $m_t$ measurement)
⇒ fraction of longitudinally polarised W bosons $56 \pm 31\%$ (Run I)

CDF: lepton $p_t$ in lepton+jets events depends on the W helicity:

**simulation:**

**Run II data:**

CDF II preliminary
- left-handed W
- longitudinal W
- right-handed W

left: $\chi^2/\text{ndf} = 38.4/49$, S.L. = 54.4%
longitudinal: $\chi^2/\text{ndf} = 43.7/45$, S.L. = 52.5%
right: $\chi^2/\text{ndf} = 16.8/51$, S.L. = 4.9%

CDF II preliminary
- Long+L.h.+bg
- Long
- Left-handed
- Background
- Data $108/126\text{ pb}^{-1}$
Rare Top Decays

In the Standard Model: 
\[ \text{Br}(t \rightarrow bW) = 100\% \]
\[ \text{Br}(t \rightarrow sW) = 0.16\% \]
\[ \text{Br}(t \rightarrow dW) = 0.01\% \]

⇒ No sensitivity at the Tevatron for decays other than \( t \rightarrow bW \)

⇒ Search for new physics! For example:

– FCNC: SM expectation \( \text{Br}(t \rightarrow c \, g/\gamma/Z) = O(10^{-11} - 10^{-13}) \)

– SUSY: charged Higgs with \( m_{H^\pm} < m_t \)?

→ subtle changes in event topology according to \( H^\pm \) decay:

large \( \tan \beta \):
\[ H^+ \rightarrow \tau \nu \]
excess of \( \tau \) decays in \( t\bar{t} \) events

small \( \tan \beta \):
\[ \begin{align*}
H^+ &\rightarrow c\bar{s} \\
H^+ &\rightarrow Wb\bar{b}
\end{align*} \]
excess of fully hadronic \( t\bar{t} \) events
2 extra \( b \) jets in \( t\bar{t} \) events

→ “\( t\bar{t} \) disappearance experiment”
single top quark production:
(electroweak interaction)

Feynman diagrams (LO):

1.)

\[ q 
\quad \rightarrow \quad W 
\quad \rightarrow \quad t 
\quad \rightarrow \quad b \]

“s-channel”

2.)

\[ q' 
\quad \rightarrow \quad q 
\quad \rightarrow \quad W 
\quad \rightarrow \quad t 
\quad \rightarrow \quad b \]

“t-channel”

3.)

\[ g 
\quad \rightarrow \quad t 
\quad \rightarrow \quad b 
\quad \rightarrow \quad W 
\quad \rightarrow \quad t \]

t+W associated production

production cross-sections:

<table>
<thead>
<tr>
<th></th>
<th>Tevatron Run I</th>
<th>Tevatron Run II</th>
<th>LHC pp 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p\bar{p} 1.8 TeV</td>
<td>p\bar{p} 1.96 TeV</td>
<td>pp 14 TeV</td>
</tr>
<tr>
<td>1.)</td>
<td>0.7 pb</td>
<td>0.9 pb</td>
<td>10 pb</td>
</tr>
<tr>
<td>2.)</td>
<td>1.7 pb</td>
<td>2.4 pb</td>
<td>250 pb</td>
</tr>
<tr>
<td>3.)</td>
<td>0.07 pb</td>
<td>0.12 pb</td>
<td>60 pb</td>
</tr>
</tbody>
</table>
Does a 4th quark generation exist?

⇒ unitarity of the $3 \times 3$ CKM matrix? ⇒ $|V_{tb}|$?

- cannot measure $|V_{tb}|$ in top decays:

$$\text{Br}(t \rightarrow bW) = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = \frac{|V_{tb}|^2}{1} \text{ in the SM}$$

$$= \frac{|V_{tb}|^2}{?} \text{ for } > 3 \text{ generations}$$

⇒ single top production: cross-section $\sim |V_{tb}|^2!$
Reconstruction of Single Top Events

- hadronic $W$ decay $\rightarrow$ cannot be separated from background
- event topologies with leptonic $W$ decay:
  like $\ell + \text{jets} t\bar{t}$ events, but 2 jets less
  $\Rightarrow$ background larger by 2 orders in $\alpha_s$

limits from Run I:
- $\sigma(\text{single top}) < ...$
  - s channel $\quad$ t channel
    - CDF $\quad 17.6 \text{ pb} \quad 13.3 \text{ pb}$
    - DØ $\quad 17 \quad \text{ pb} \quad 22 \quad \text{ pb}$
  - corresponds to $|V_{tb}| < 2.8$
  $\Rightarrow$ need (much) more int. luminosity

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Compare Higgs and Top

How much farther is the Higgs compared with $\bar{t}t$ and single top?

$t\bar{t}$ reconstruction is much easier:

- cross-section: factor $\sim 35$ larger than $p\bar{p} \rightarrow HW$ at $m_H = 120$ GeV

- more jets per event:
  lepton+jets, dilepton events “easy” to distinguish from background

single top physics:

- cross-section: still factor $\sim 15$ larger than $p\bar{p} \rightarrow HW$ at $m_H = 120$ GeV
Example: CDF Run I measurements of the $m(t\bar{t})$ and $p_t(t)$ distributions

- CDF Data (63 events)
- $t\bar{t}$ and W+jets Simulations (63 events)
- W+jets Simulation (31.1 events)

CDF Run I
SM

$X \rightarrow t\bar{t}$ Simulation
$M_X = 500 \text{ GeV}/c^2$
$\Gamma = 0.012 M_X$

Events / (25 GeV/$c^2$)

Reconstructed $M_{tt}$ (GeV/$c^2$)

Reconstructed $M_{tt}$ (GeV/$c^2$) vs. Events / (25 GeV/$c^2$)

fraction of events

CDF Run I
SM

$pt$ (top) (GeV)

$pt$ (top) (GeV) vs. fraction of events

Events / (25 GeV/$c^2$)