B-Physics & Trigger at the DØ experiment
- operational experience

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Motivation

Can the experience gained at Fermilab help prepare for \((b\text{-physics at})\) the LHC?

- Yes.
- No. Nothing can prepare you for the LHC.
- Maybe, but we'd like to make our own mistakes, thank you.

Making the transition from an \(e^+e^-\) to a hadron collider can be an interesting experience.
$b$-physics at an $e^+e^-$ collider
(simplified view)
$b$-physics at a hadron collider (simplified view)
Background

• Talks given at Beauty2006 (Oxford) and IOP “Tevatron for LHC” meetings.

\(b\)-physics at hadron colliders ↔ \(b\)-physics at \(e^+e^-\) machines:
• No fixed centre of mass energy.
• Triggers! Triggers! Triggers!
• The mess we refer to as underlying event/additional interactions.

Additionally at DØ:
• No particle ID.
• Competition with high \(p_T\) programme.
Overview

- The DØ Detector at Fermilab
- B-physics Highlights
- Trigger/High Luminosity Challenges
  - Trigger system
  - Doing $b$-physics at a multi purpose detector
  - $b$-physics triggers
- Conclusions
Run I 1992-1995
\(E_{CM} = 1.8 \text{ TeV}\)
125 pb\(^{-1}\)

Run II
\(E_{CM} = 1.96 \text{ TeV}\)
2.5 fb\(^{-1}\)
Run II Integrated Luminosity

19 April 2002 - 20 May 2007

April 02

July 07

2.48

2.93

Run IIa

Run IIb

Delivered

Recorded
The upgraded DØ Detector

- Forward mini drift chambers
- Central Scintillator
- Forward Scintillators
- Shielding
- Solenoid, CFT, SMT, Preshowers

+ New Electronics, Trig, DAQ
Silicon Microstrip Tracker (SMT)

Hybrid design: 6 barrels with 8 layers (+ Layer 0), 12 F-Disks, 4(2) H-Disks

Essential for \textit{b}-physics trigger \textit{and} analysis:
Tracking, primary and secondary vertex reconstruction, impact parameter.
Design provides tracking up to $|\eta| < 3.0$, but
\begin{itemize}
  \item Most analyses also require tracks to have hits in the CFT.
  \item H-disks had high rate of failure, most forward disks have now been decommissioned to make room for Layer 0 readout cables.
\end{itemize}
Silicon Microstrip Tracker Layer 0

30% improvement in impact parameter resolution vs RunIIa → great news for $b$-physics

Impact parameter resolution from cosmics: 21 μm

Commissioned and up and running.
Central Fibre Tracker (CFT)

16 doublet layers of scintillating fibres, arranged in 8 superlayers

Radius 20 – 52 cm

Track reconstruction up to $|\eta| < 2.0$

CFT standalone used for triggering at lowest trigger level.
Tracker Event Displays at $70 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

Run 232768 Evt:24762658 Thu May 10 02:43:58 2007
ET scale: 31 GeV

Run 232768 Evt:28249675 Thu May 10 03:55:26 2007
ET scale: 19 GeV
Tracker Event displays at $140 e^{30} \text{cm}^{-2} \text{s}^{-1}$

If this was the LHC you probably wouldn't see the detector underneath all the tracks.
Muon system

Main features:
- 3 layers of drift tubes.
- 3 layers of scintillators: triggering, improved resolution in wire direction, rejection of cosmics.
- Toroid magnet (1.8 T) after the first layer: local $p_T$ measurement (trigger).
- Toroid and solenoid polarities reversed on regular basis.
- Track matched muons up to $|\eta| < 2.2$
Muon System

Mini Drift Tube plane

Scintillator plane
Calorimeter

Designed for high $p_T$ physics, but low $p_T$ electrons can be used for $b$-tagging: E.g. Measurement of $B_d$ mixing using opposite-side flavour tagging, PRD 74, 112002(2006)

Tagging efficiency $\varepsilon = \frac{N_{\text{tag}}}{N_{\text{tot}}}$

Dilution $D = \frac{N_R - N_W}{N_R + N_W}$

Tagging power = $\varepsilon D^2$

$\varepsilon D^2(\mu) = 1.48\%$

$\varepsilon D^2(e^-) = 0.21\%$
Results

With this detector we have seen all sorts of $b$,...

$+ B^+, B_c, X(3872), ...$
DØ \( b \)-physics publications

- Measurement of the charge asymmetry in semileptonic \( B_s \) decays, PRL 98, 151801 (2007)
- Lifetime difference and CP violating phase in the \( B_s \) system, PRL 98, 121801 (2007)
- Measurement of \( B^0 \) mixing using opposite-side flavor tagging, PRD 74, 112002 (2006)
- Measurement of the \( B_s \) lifetime in Semileptonic Decays PRL 97, 241801 (2006)
- Measurement of the CP-violation parameter of \( B^0 \) mixing and decay with \( pp\bar{p} \rightarrow \mu\mu X \) data PRD 74, 092001 (2006)
- Search for the Rare Decay \( B_s \rightarrow \Phi\mu^+\mu^- \) with the DØ Detector, PRD 74, 031107 (2006)
- Direct Limits on the \( B_s \) Oscillation Frequency, PRL 97, 021802 (2006)
- Measurement of the ratio of \( B^+ \) and \( B^0 \) meson lifetimes, PRL 94, 182001 (2005)
- Measurement of the \( \Lambda_b \) lifetime in the decay \( J/\psi \Lambda \) decays..., PRL 94, 102001 (2005)
- A search for the flavour-changing neutral current decay \( B_s \rightarrow \mu^+\mu^- \), PRL 94, 071802 (2005)
- Measurement of the \( B_s \) lifetime in the exclusive decay channel \( B_s \rightarrow J/\psi \Phi \), PRL, 94, 042001 (2005)
- Measurement of the lifetime difference in the \( B_s \) system, PRL 95, 171801 (2005)
- Measurement of semileptonic branching fractions of \( B \) mesons to narrow \( D^{**} \) states, PRL 95, 171803 (2005)
- Observation and Properties of the \( X(3872) \) Decaying to \( J/\psi \pi^+\pi^- \)..., PRL 93, 162002 (2004)
1) First direct two-sided bound on the $B_0(s)$ oscillation frequency.
   Press Release.
e-Print: hep-ex/0603029

2) Precision electroweak measurements on the $Z$ resonance.
e-Print: hep-ex/0509008
**B_s Mixing**

- $B_s$ ($\sim b\bar{s}$), $\bar{B}_s$($\sim b\bar{s}$) are produced in one of the two possible flavour states.
- This initial state evolves into a time-dependent superposition of the two states according to:

$$i\frac{\partial}{\partial t} \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix} = (M - i\frac{\Gamma}{2}) \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}$$

$M =$ mass matrix  
$\Gamma =$ decay matrix

$B_s$ mixing via the dominant top-quark process
CP violating phase: The level of CP violation in the Standard Model is too small to produce the observed baryon number density → looking at all sources of CP violation → CP violation in SM is expected to be small
The Big Picture

[Graph with various parameters and regions labeled, such as $\sin 2\beta$, $\varepsilon_K$, $|V_{ub}/V_{cb}|$, $\gamma$, $\Delta m_d$, $\Delta m_s & \Delta m_d$, etc.]

[Excluded area has CL > 0.95]

[Label indicating solution with $\cos 2\beta < 0$ (excl. at CL > 0.95)]

[Logo: CKMfitter BEAUTY 2006]
Measuring $\Delta m_s$ at DØ

$B_s \rightarrow \mu^+ D_s^- X$
$D_s^- \rightarrow \Phi \pi^-$
$\Phi \rightarrow K^+ K^-$

Problem.
$\rightarrow$ limited reach in $\Delta m_s$
Measuring $B_s$ mixing at DØ

Limited reach in $\Delta m_s$, but ....
Results (DØ and CDF)

First !!

17 < Δm_s < 21 ps⁻¹
at 90% confidence level
semileptonic decays only

Best !!

Δm_s = 17.77 ± 0.10 (stat) ± 0.07 (syst) ps⁻¹
semileptonic + hadronic decays

⇒ |V_{td}/V_{ts}| = 0.26060 ± 0.0007 (exp) ±^{0.0081}_{0.0060} (theory)
ΔΓ_s and φ_s from B_s → J/ψ φ

**scalar → VV decay**

➤ 3 amplitudes

L = 0 (even), 1 (odd), 2 (even)

described in *transversity* basis

In J/Ψ restframe:

K^+K^- plane defines (x,y) plane

K^+ defines +y direction

Θ, Ψ polar and azimuthal angles of μ^+

φ in Φ restframe: angle(K^+, -J/Ψ)

\[
B_s^H = \frac{1}{\sqrt{2}} (|B_s\rangle + |\overline{B_s}\rangle) = CP - odd
\]

\[
B_s^L = \frac{1}{\sqrt{2}} (|B_s\rangle - |\overline{B_s}\rangle) = CP - even
\]

5.26 < M(B_s) < 5.46 GeV

c/t/σ(ct) > 5

Data

Total Fit

CP-even

CP-odd

Total Signal

Background
**$B_s \rightarrow \mu X$ asymmetry**

Dimuon Asymmetry

World Average: $\tau_{fs}$

$\Delta \Gamma_s = 0.13 \pm 0.09$ ps$^{-1}$

SM prediction*: $0.088 \pm 0.017$ ps$^{-1}$

$\Phi_s = -0.70 \pm 0.47^{+0.39}_{-0.39}$

SM prediction*: $(4.2 \pm 1.4) \times 10^{-3}$

*Lenz, Nierste hep-ph/0612167
Triggers

Go ahead, make my data !!!!!
Data taking rates
The DØ trigger system

- **Detector**
  - 1.7 MHz

- **L1 Trigger**
  - 2kHz

- **L2 Trigger**
  - 1kHz

- **L3 Trigger**
  - <50Hz>
    - 250kB/ev

- **Reconstruction Farm**

- **SVXII chip Digitization Rate**

The DØ trigger system acts as a series of filters, reducing the rate of data from the detector to the reconstruction farm.
Trigger System: Level 1 & Level 2

Level 1 triggers
Calorimeter: 0.2x0.2 η-φ triggers towers (+E_T)
Central Track Trigger (CTT): uses axial layers of the CFT to find tracks
  4 p_T bins
  Tracks can be confirmed by muon hits.
Muon: Looks for hits (wire & scintillator) consistent with muons.

Level 2 triggers
• Refine L1 trigger terms using added event information (e.g. wire and
  scintillator times for muons).
• Results are combined in a global L2 term.
• Silicon Track Trigger for displaced vertices, improved momentum
  measurement.
Silicon Track Trigger

- L1 CTT tracks are used to define roads into the SMT.
- SMT hits are clustered in these roads.
- Track is refit within the road.

→ Improved $p_T$ measurement wrt L1.
→ Impact parameter measurement.

Under-used by $b$-physics in RunIIa:
- Impact parameter bias difficult to model/analyze.
- (Planned) late commissioning: Triggers already well established with sufficient rate reduction.
- No displaced track only trigger due to L1 bandwidth limitations.

RunIIb: $b$-physics and Higgs group are the main users of the STT.
Trigger System: Level 3

- Software based.
- Goal: To perform a (partial) reconstruction of the event.

Tools of the trade:
- muons
- electrons
- tracking
- taus
- jets
- missing $E_T$
- primary & secondary vertexing
- isolation (muons, electrons)
- impact parameter (tracks, muons)
- invariant mass

... and almost any combination thereof
Doing *b*-physics at a multi-purpose experiment

Trigger strategy:
- The trigger menu needs to accommodate all physics groups.
- Most physics aiming for maximum *luminosity* on a given trigger.
- Most *b*-physics needs the maximum of *b*-events.

![Graph showing rate of *b*-triggers and non-*b*-triggers over time.](image)
At the end of RunIIa there were 56 b-triggers (out of ~ 300 triggers total).
The number of triggers was limited by the number of L1/L2 bits (128).
Only L1/L2 bits could be prescaled individually.

300 triggers should be enough for everybody, right?

Apparently not:
RunIIb has seen L2 oring/splitting and a doubling of the number of triggers:
• Needs increasingly sophisticated tools (and databases) to administer this list.
• Difficulties in identifying problematic triggers during run time.
• Automated performance monitoring helps, but you still need a brain to analyse it.
• Only 10% (or so) of all triggers are actually used for analysis.
• Manpower ~ triggers
• Yes, I am bitter.
In RunIIa there were 3 major groups of $b$-physics triggers:

- single muons, impact parameter unbiased ('low' lumi)
- single muons with impact parameter requirement (all luminosities)
- di-muons (all luminosities)

Additionally:
- tri-lepton
- electron-muon
- muon+jets

Apart from requiring one or more muons, the $b$-physics triggers also use the following trigger requirements:

- track match for muons: tracks required to have SMT hits
- tracks (number of tracks, $p_T$)
- impact parameters (for muons and/or tracks)
- invariant mass filters: $\Phi$, $J/\psi$, $\Upsilon$
- charge (opposite sign)
- primary vertex: $\pm 35$ cm
Anatomy of three 'best-of' (late) RunIIa triggers

**unbiased single muon trigger (up to 55e$^{30}$, 100e$^{30}$ RunIIb)**
- semileptonic decays, mixing
- L1: tight scintillator, loose wire, pT > 3 GeV (from CTT), primary vertex
- L2: one medium muon (RunIIb: track match requirement)
- L3: track matched, 3-layer muon with pT > 3,4,5 GeV, 
  $|z \text{ (primary vertex)}| < 35 \text{ cm}$

**single muon trigger with impact parameter (all luminosities)**
- use muon for tagging to avoid IP bias in the signal (hadronic decays)
- L1: tight scintillator, loose wire, pT > 5 GeV (from CTT), primary vertex
- L2: one medium muon (RunIIb: track match requirement)
- L3: track matched 3-layer muons with IP significance > 3 and pT > 5 GeV
  $|z \text{ (primary vertex)}| < 35 \text{ cm}$

Beloved by trigger people, hated by analysers → data goes unused.
di-muon trigger (all luminosities)

- $J/\psi$ (e.g. $\Delta \Gamma/\Gamma$, $\Upsilon$, $B_s \rightarrow \mu \mu$
- L1: 2 muons, no pT cut, (RunIIb: one match to a CTT track required)
- L2: one or two muons, depending on luminosity
- L3: 2 muon system only muons, pT > 2 GeV, one or two muons must have hits in all 3 layers.
Challenges ahead: Increasing instantaneous luminosity

Peak Luminosities RunII
Challenges ahead: Increasing instantaneous luminosity

- Reconstruction of the events dominated by track finding.
- The same tracking algorithm has to run at all luminosities!

![Graph showing reconstruction time vs initial luminosity](image)

**so far, so good**

- **RunIIa**
- **RunIIb**
- **b-physics (RunIIa)**
- **b-physics (RunIIb)**
- **unbiased single muon triggers prescaled**
Triggers – timing is (almost) everything

\textit{b}-physics triggers often require low \( p_T \) tracks → triggers are intrinsically slow:
• optimize trigger ordering
• move rate reduction from L3 to L1/L2 (e.g. STT)

RunIIb tracker 3 x faster than RunIIa tracking, but still not fast enough:
→ More CPUs.
Remember the event display from the beginning of the talk?

Offline reconstruction

We can't do everything.

seconds  milliseCONDS
High occupancy will kill your trigger.
Coincidence makes great tracks.

* same number of clusters per CFT layer as before, randomly distributed

Special thanks to R. Beuselinck for making these plots.
What do we do now?

- More layers: Singlet equations at L1, SMT requirement at L3
- Less noise (new AFE boards)
- Luminosity levelling?
- So far everything is under control.....
The RunIIa $b$-physics programme has been a great success!

By playing to our strengths, i.e. making optimal use of our wide muon coverage and upgraded tracking system, DØ

- published 15 $b$-physics papers (4 more are submitted, plus 13 preliminary results)
- Results are also available on the web: [http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm](http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm)

- Increasing luminosity is a challenge and an opportunity.
- Layer 0 working as expected.
- High expectations for RunIIb.
CKM Matrix

Quarks: Weak Eigenstates ≠ Mass Eigenstates
⇒ CKM Mixing Matrix
* 3 angles
* 1 complex phase ⇒ CP-violation

Wolfenstein parametrization:
\[ \lambda = |V_{us}| \]
CKM triangle(s)

\[ \bar{\rho} = (1-\lambda^2/2)\rho \]
\[ \bar{\eta} = (1-\lambda^2/2)\eta \]

Wolfenstein parametrization:
\[ \lambda = |V_{us}| \]
\[ \eta: \text{CP violation} \]

Triangles identical up to \( \lambda^3 \)
\[ \Delta m_s \rightarrow |V_{ts}/V_{td}| \]

\[
\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f^2_{Bs} B_{Bs}}{f^2_{Bd} B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}
\]

Inputs:
- \( m(B^0)/m(B_s) = 0.9830 \) (PDG 2006)
- \( \xi = 1.21^{+0.047}_{-0.035} \) (M. Okamoto, hep-lat/0510113)
- \( \Delta m_d = 0.507 \pm 0.005 \) (PDG 2006)