XXXVIII\textsuperscript{th} Rencontres de Moriond
Electroweak Interactions and Unified Theories
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Tevatron $p\bar{p}$ collider

- **Main Injector**: injector optimizes $\bar{p}$ production
- **Recycler**: store and cool $\bar{p}$ (ready 2004)
- **Collision rate**: 396 ns crossing time
  $(36 \times 36$ bunches) $\rightarrow \sim 2M$ collisions per second
- **Center of Mass energy**: 1.96 TeV

Today: **record luminosity**: $3.7 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$

4 to 7 pb$^{-1}$/week delivered

**Goal**: inst. luminosity: $O(1) \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

16 pb$^{-1}$/week delivered

**Results** of this talk based on $\int L dt \leq 70 \text{pb}^{-1}$

Dec 2002 – Feb 2002

D. Tonelli - B Physics at CDF - Moriond EW - March 03
• Total inelastic x-section: \( \sim 10^3 \times \sigma(b\bar{b}) \)

• BRs for interesting processes: \( \sim O(10^{-6}) \)
  - S/B at production @ Tevatron is: \( \sim 1/10^9 \)
  - S/B at production at B-factory \( \sim 1/10^6 \)

• Mean multiplicity of tracks/event \( \sim \times 4\Upsilon(4S) \)
  - Combinatoric background

• Events pile-up within the same beam x-ing
  - Combinatoric background
  - Typical S/B at analysis level: \( \sim O(0.5\div5) \)
**Tracking:** Si strips + drift chamber (in 1.4T)

- 3D-track, 7/8 layers, \(|\eta| < 2, 1.6 \text{ cm} < R < 28 \text{ cm}\)
- 100 ns drift, \(0.3 \text{ m} < R < 1.4 \text{ m}\), \(\sigma(1/\text{Pt}) \sim 0.1\% \text{ GeV}^{-1}\), dE/dx info

**Muons:**

- **Central:** \(|\eta| < 1\)
- **Fwd:** \(1 < |\eta| < 1.6\)

**Time of flight**

Scintill. PID \((p,K,\pi)\)

- 100 ps @ 140 cm

**Trigger**

2D-silicon tracks at Level 2

DISCRIMINATE

B events from background reconstructing a decay vertex displaced wrt the point of primary interaction

**EM + HAD calor.**

- **Central:** scintillat.
- **“Plug”:** tile-fiber
B Triggers and data samples

Larger yield: lower Pt threshold wrt RunI: e (μ): 8 (2.2) → 4 (1.5) GeV
Better S/N → trigger on long-lived decays (displaced tracks)

Di-Muon (J/ψ)
Pt(μ) > 1.5 GeV
J/ψ modes down to low Pt(J/ψ) (~ 0 GeV)

- CP violation
- Masses, lifetimes
- Quarkonia, rare decays

Displaced trk + lepton (e, μ)
IP(trk) > 120μm
Pt(lepton) > 4 GeV

Semileptonic modes

- High statistics lifet.
- Sample for tagging studies

2-Track Trig.
Pt(trk) > 2 GeV
IP(trk) > 100 μm

fully hadronic modes

- B_s mixing
- CP asymmetry in 2-body charmless decays

D. Tonelli - B Physics at CDF - Moriond EW - March 03
Detector calibration: p scale & B-field correction

**MASS SCALE:** \( M_{\text{CDF}} = M_{\text{PDG}} - \Delta M(P_t) \)

Use \( J/\psi \) to correct for B field and energy loss:

\[ \sigma(\text{scale})/\text{scale} \sim 0.02\% \]

Sanity check with known signals: \( D^0 \) and \( \Upsilon \)
Mass measurements

<table>
<thead>
<tr>
<th></th>
<th>CDF mass (only ~20 pb⁻¹)</th>
<th>$\Delta_{PDG}/\sigma_{CDF}$</th>
</tr>
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<tbody>
<tr>
<td>$B^+$</td>
<td>5280.6 ± 1.7 ± 1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>$B_d$</td>
<td>5279.81 ± 1.9 ± 1.4</td>
<td>0.2</td>
</tr>
<tr>
<td>$B_s$</td>
<td>5360.3 ± 3.8 ± 2.1</td>
<td>-2.1</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>3686.43 ± 0.54</td>
<td>0.9</td>
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</tbody>
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$M(B_s)$ is already the second best in the world (after CDF RunI)

$D_s^\pm - D^\pm$ mass difference
Both $D \to \phi \pi (\phi \to KK)$

$\Delta m = 99.28 \pm 0.43 \pm 0.27$ MeV

PDG: 99.2 ± 0.5 MeV

(CLEO2, E691)

Systematics dominated by background modeling
Exclusive lifetime $B_s \rightarrow J/\psi \phi$

Probe of CDFII vertexing performance

Important for simultaneous measurement

<table>
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<tr>
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<th>Lifetime (ps)</th>
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<tbody>
<tr>
<td>$B^+$</td>
<td>$1.57 \pm 0.07 \pm 0.02$</td>
</tr>
<tr>
<td>$B_d$</td>
<td>$1.42 \pm 0.09 \pm 0.02$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$1.26 \pm 0.2 \pm 0.02$</td>
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$\frac{\tau(B_s)}{\tau(B_d)} = 0.89 \pm 0.15$

$\frac{\tau(B^+)}{\tau(B_d)} = 1.11 \pm 0.09$

Use control channels: $B_u \rightarrow J/\psi K^+$ and $B_d \rightarrow J/\psi K^0\ast$

Main systematics from alignment and resolution function

Systemat. & statist. errors already @ Run I level

$B_s \rightarrow J/\psi \phi$

$\tau$, [cm]

$L = 70 \text{ pb}^{-1}$

Fit prob: 97%

CDF - Moriond EW -
**B_s (1): from di-muon**

**B_s \rightarrow J/\psi \ \phi \rightarrow [\mu\mu] \ [KK]**

- **Weak phase of V_{ts}**:  
  - Time-dependent asymmetry in decay rates. (quick oscillat.)  
  - Needs tagging  
  - Mix of CP-odd/CP-even states  
  - \( \Delta \Gamma_s \):  
    - Exclusive lifetime + angular analysis

**ONLY @ Tevatron**

![Graph showing B_s decay to J/\psi \ \phi with 74 \pm 11 events]

World's largest B_s fully reconstructed sample

Yield/Lumi = 2 x RunI

D. Tonelli - B Physics at CDF - Moriond EW - March 03
**$B_S (2)$: from:**

lepton + displaced track

$B_S \rightarrow D_s \nu \rightarrow [\phi \pi] \nu \rightarrow [[KK] \pi] \nu$ **ONLY @ Tevatron**

**HIGH STATISTICS SAMPLE:**

- Inclusive lifetime: $\frac{\tau(B_S)}{\tau(B_d)}$
- Mixing (moderate $X_s$):
  
good S/N, limited time resolution: back-up sample

**Systematics of trigger bias**

**Efficiency vs $c\tau$**

**Yield/Lumi ~ Run I x 3**

**S/N ~ Run I x 2**

CDF Run ll Preliminary  60 pb$^{-1}$

$N_{Ds} : 385 \pm 22$

$N_{D^+} : 112 \pm 19$

$385 \pm 22 \, D_s$

$112 \pm 19 \, D^+$
**B_s (3): from 2-Track Trigger**

Many fully reconstructed channels

ONLY @ Tevatron

\[ B_s \rightarrow D_s^{(*)-}\pi^+, B_s \rightarrow D_s^{(*)}3\pi, \]

\[ B_s \rightarrow D_s^{(*)-}D_s^{(*)+}. \]

Combine them to reach high statistics

\[ B_d \rightarrow D\pi \text{ control sample} \]

- \( B_s \) mixing: “golden sample” for \( x_s \rightarrow \Delta M_s \)

**Needs:**

- Excellent proper time resolution
- Good flavour tagging

Monte Carlo Data February 26th 2003 CDF Run 2

\[ D_s \text{ Uncorr. Mean: } 5138 \pm 8 \text{ MeV} \]
\[ \text{Sigma: } 66 \pm 10 \text{ MeV} \]

\[ D_s \text{ Uncorr. Mean: } 5367 \pm 2 \text{ MeV} \]
\[ \text{Sigma: } 16 \pm 1 \text{ MeV} \]
B_s (3): from 2-Track Trigger

\[ B_s \rightarrow D_s(\pi) \pi \rightarrow [\phi \pi] \pi \rightarrow [[K\bar{K}] \pi] \pi \]

FULLY RECONSTRUCTED

Promising:
other hadronic channels to be seen soon

DATA

40 ± 10 D_s
65 ± 20 D_s^*
$\Lambda_b (1)$: from di-muon

$\Lambda_b \rightarrow J/\psi \Lambda \rightarrow [\mu \mu][p \pi]$ ONLY @ Tevatron

Fully reconstructed

- Lifetime $\rightarrow \frac{\tau(\Lambda_b)}{\tau(B^0)}$
  discrepancy with theory: is it valid for baryons?
- Mass

CDF Run II Preliminary, $L=25pb^{-1}$

$27 \pm 7$ evts

$\mu \mu p \pi$ Mass [GeV]
$\Lambda_b (2)$: from lepton + displaced track

$\Lambda_b \rightarrow \Lambda_c l \nu \rightarrow [p K_\pi] l \nu$

- Branching Ratio
- Measure $\frac{1}{\Gamma} \frac{d\Gamma}{dQ^2}$

$Q^2 = m(l\nu)$

Important for theory

Experimental challenge:

disentangle from decays through excited baryons

Yield/Lumi = 4 x Run I
S/N ~ 2 x Run I

Time of flight

dE/dx +

D. Tonelli - B Physics at CDF - Moriond EW - March 03
$\Lambda_b (3)$: from 2-Track trigger

$\Lambda_b \rightarrow \Lambda_c \pi \rightarrow [pK\pi] \pi$

Fully reconstructed channel
$\rightarrow$ high resolution on secondary vertex

• Precise Lifetime $\rightarrow \frac{\tau(\Lambda_b)}{\tau(B^0)}$

Discrepancy with theory:
Is it valid for baryons?

• BR still unknown

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\( B \rightarrow h^+h^- \) from 2-Track Trigger

\( B_d(B_s) \rightarrow K\pi, \, \pi\pi \) (KK,K\pi) FIRST charmless B @ hadronic coll.

CP asymmetry \( \rightarrow \sin2(\beta + \gamma) \)
- Time dependent analysis
- Tagging
- Exploit \( x_s \gg x_d \)

Direct CP violation in \( B_d \rightarrow K\pi \)
- self-tagging

Extract yield of each individual channel:
- Branching Ratio \( B_s \rightarrow KK/K\pi \)

\( S/N \) better than expectations
\( \pi\pi \) Mass [GeV]

301 \( \pm \) 27 evts

CDF Run 2 Preliminary

301 \( \pm \) 27 signal events
Mean 5.241 \( \pm \) 0.004 GeV/c^2
Width 0.041 \( \pm \) 0.004 GeV/c^2

L = 85 \( \pm \) 4 pb^-1
B → h⁺h⁻ from 2-Track Trigger

Experimental challenge:
Disentangle 4 channels:

\[ B_d \rightarrow \pi\pi \]
\[ B_d \rightarrow K\pi \]
\[ B_s \rightarrow K\pi \]
\[ B_s \rightarrow KK \]

Final resolution expected is
\[ \sigma_{Acp} \sim O(15\%) \]
Summary and Conclusion

CDFII today: the detector is well calibrated, scale of masses and vertexing resolution are accurately understood providing lifetimes and mass measurements already competitive with RunI results.

Promising perspectives for the flagship analyses: tuning of the machinery to study $B_S$ mixing, $\Delta\Gamma_S$, $\Lambda_b$, charmless $B$-decays and many other topics unique to Tevatron is in progress.

CDFII is underway to produce exciting new results.
Backup Slides
Goals for the RunII:

- $2 \times 10^{32}$ cm$^{-2}$sec$^{-1}$ with Recycler
- 2 fb$^{-1}$ RunII

Today:

- $3.7 \times 10^{31}$ cm$^{-2}$sec$^{-1}$
- 7 pb$^{-1}$/week
- ~70 pb$^{-1}$ available for winter conferences

Still a factor 1.3÷2 below expectations, but constantly in progress

~×5 during 2002
**Quadrant of CDF II Tracker**

**TOF:** 100ps resolution, 2 sigma K/π separation for tracks below 1.6 GeV/c (significant improvement of B_s flavor tag effectiveness)

**COT:** large radius (1.4 m) Drift C.
- 96 layers, 100ns drift time
- Precise P_T above 400 MeV/c
- Precise 3D tracking in |η|<1
  \( \sigma(1/P_T) \sim 0.1\% GeV^{-1}; \sigma(\text{hit}) \sim 150 \mu m \)
- dE/dx info provides 1 sigma K/π separation above 2 GeV

**SVX-II + ISL:** 6 (7) layers of double-side silicon (3cm < R < 30cm)
- Standalone 3D tracking up to |η|= 2
- Very good I.P. resolution: ~30µm (~20 µm with Layer00)

**Layer 00:** 1 layer of radiation-hard silicon at very small radius (1.5 cm)
(achievable: 45 fs proper time resolution in B_s → D_s π )
CDFII Trigger system

**XFT**: “**Ex**tremely **F**ast **T**racker”
- 2D COT track reconstruction at Level 1
  - $p_T$ res. $\Delta p_T/p_T^2 = 2% \text{ (GeV}^{-1})$
  - azimuthal angle res. $\Delta \phi = 8 \text{ mrad}$

**SVT**: “**Si**licon **V**ertex **T**racker”
- precise 2D Silicon+XFT tracking at Level 2
  - impact parameter res. $\sigma_d = 35 \mu m$
  - Offline accuracy !!

**3 levels**: 5 MHz (pp rate)
- $\rightarrow$ 50 Hz (disk/tape storage rate)
- almost no dead time (< 10%)

**Matched to L1 ele. and muons**
- enhanced $J/\psi$ samples
Typical $\beta\gamma c\tau$ for B hadrons:
$\sim 2 \times 370 \div 500 \ \mu m \sim 0.5 \div 1 \ \text{mm}$

- Typical resolution on "impact parameter" with silicon vertex detector is:
  $\sigma_{IP} = 30 \ \mu m \otimes \text{Beam Spot} \cong 50 \ \mu m$

- IP discriminates B from background:
  - IP(B tracks) $>>$ IP(BG tracks)
  - Available at second Level of Trigger

2D Si tracks within 20$\mu$s

Online, deadtimeless
Hadronic Triggers

**“Two body decays”**

**Level 1:**
- 2 XFT tracks
- $P_T > 2$ GeV
- $\Delta \phi < 135^\circ$
- $P_{T1} + P_{T2} > 5.5$

**“Multi-body decays”**

**Level 2**
- $d > 100$ $\mu$m
- $20^\circ < \Delta \phi < 135^\circ$
- $L_{xy} \geq 200$ $\mu$m
- $d_B < 140$ $\mu$m

**Level 3**
- SAME with refined tracks & Mass cuts
- $d > 120$ $\mu$m
- $2^\circ < \Delta \phi < 90^\circ$
- $L_{xy} \geq 200$ $\mu$m

Decays:
- $B^0 \rightarrow \pi \pi$
- $B^0 \rightarrow K \pi$
- $B_s \rightarrow K K$
- $B_s \rightarrow \pi K$
- $\Lambda_b \rightarrow p \pi(K)$
Trigger (XFT+SVT): Performance today ...

- SVT Efficiency
- Online!
- XFT eff.
- $\sim 95\%$ per $P_t>1.6$ GeV/c
- $\sim 5$ hrs @ $4 \times 10^{31}$
- $\sim 1$ hr @ $2 \times 10^{32}$
- $D^0 \rightarrow K\pi$ Online!
- $D^0 \rightarrow K\pi$
- Today $\sim 90\%$
- $\sigma = 48 \ \mu$m
TOF: performance today ...

Resolution ~120 ps (first calibration round)
Already useful for PID

Reconstructed mass VS p
BG reduction ×20 @ 80% eff.

φ → K⁺K⁻
Masses

CDF Run II Preliminary

$N(B_d) = 82.4 \pm 11.5$

CDF Run II Preliminary

$N(B^+) = 152.7 \pm 14.0$
Lifetimes

CDF Run II Preliminary

$B^+ \rightarrow J/\psi K^+$

$37 \pm 33$ signal candidates
Fit prob: 71%

CDF Run II Preliminary

$B^0 \rightarrow J/\psi K^0$

$747 \pm 33$ signal candidates
Fit prob: 13%

CDF Run II Preliminary

$B^0 \rightarrow J/\psi K^0$

$37 \pm 27$ signal candidates
Fit prob: 34%

CDF Run II Preliminary

$B^0 \rightarrow J/\psi K^0$

$37 \pm 27$ signal candidates
Fit prob: 19%
Di-muon: $\sin(2\beta)$

$B_d \rightarrow J/\psi K_s \rightarrow [\mu\mu] K_s$

Benchmark of B physics performance of detector:

$\sin(2\beta)$ analysis uses all experimental ingredients and RunI cross-check:
- Reconstruction (Vertexing)
- Time dependent Asymmetry
- Flavor Tagging (dominates in error)

Yield = RunI x 5

$B^0$ Candidates with SVX muons

103 $\pm$ 14 signal events

$\sim$20 fb$^{-1}$
Displaced track + lepton (1): semileptonic B

High statistics, excellent S/N ratio wrt to RunI:
Signal yield ~ RunI x 5 , S/N ~ RunI x2
Mass, lifetimes x-check and use this sample to measure effective dilution of tagging algorithms
\[ \gamma \text{ via } B^0 \rightarrow \pi^+\pi^- / B_s \rightarrow K^+K^- \]

- **CDF not “optimized” to measure final states with } \pi^0, \gamma \]
  - Measurement of } \alpha \text{ in } B \rightarrow h^+h^- \text{ not competitive with } B\text{-factories}
- **Promising alternative approach (R.Fleischer):**
  - } B^0 \rightarrow \pi^+\pi^- \text{ measures } \sin2(\beta+\gamma) \text{ with } O(30\%) \text{ penguin pollution}
  - Contamination is canceled using } B_s \rightarrow K^+K^- \text{ up to } U\text{-spin symmetry breaking } O(20\%)

**Decays related by exchange } d\leftrightarrow s \text{ (SU(3) } U\text{-spin)**

- **Measurement of the 4 time-dependent asymmetries**
- **Combined fit to the 4 experimental observables} (\sin(2\beta)) \text{ from } J/\psi K_s\text{):**
  - } d = P/T \sim 0.3, \ \theta = \text{strong phase of the ratio } P/T, \gamma, \beta \text{ weak phases**
B flavour tagging

“Identify the flavor of B at production”

Crucial item for mixing measurements

**OST** (opposite side tagging):
B’s are produced in pairs \(\rightarrow\) measure flavor of opposite B

- **JETQ**: sign of the weighted average charge of opposite B-Jet
- **SLT**: identify the soft lepton from semileptonic decay of opposite B

**SST** (same side tagging):
\(\bar{B}^0\) (\(B^0\)) is likely to be accompanied close by a \(\pi^+\) (\(\pi^-\))

- Search for the track with minimum \(P_T^{REL}\)
NEW: “Kaon b-taggers”

- Exploit $K/\pi$ separation of new TOF
- Well suited for strange $B$ mesons

**Same Side $K$:** a $B_{0s}$ $(B_{0s}^0)$ is likely to be accompanied close by a $K^+$ ($K^-$) from fragmentation

**Opposite Side $K$:** due to $b \to c \to s$ it is more likely that a $B$ meson will contain in final state a $K^-$ than a $K^+$

⇒ to identify a $B_{0s}$ look for a $K^-$ from the decay of the opposite $B$
B Flavor tagging in CDF

Total Tagging Effectiveness

<table>
<thead>
<tr>
<th>$\varepsilon D^2$ (%)</th>
<th>RunI</th>
<th>RunII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B°</td>
<td>B_s</td>
</tr>
<tr>
<td>OS Soft Lept</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>OS Jet Charge</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>OS Kaon</td>
<td>2.4 (0)</td>
<td>2.4 (0)</td>
</tr>
<tr>
<td>SST</td>
<td>1.0</td>
<td>1.9 (1.4)</td>
</tr>
<tr>
<td>SST Kaon</td>
<td></td>
<td>4.2 (1.0)</td>
</tr>
<tr>
<td>Total</td>
<td>5.7</td>
<td>9.0 (6.3)</td>
</tr>
</tbody>
</table>

$\varepsilon$: efficiency
- How many times it is possible to apply the tag
$D = (1-2P_w)$: dilution
- How many times the tag is wrong
$\varepsilon D^2$: determines the effective statistics of the sample:
$S \rightarrow \varepsilon D^2 S$

$A_{mis} = DA$

$\delta A \propto \frac{1}{\sqrt{\varepsilon D^2 S}}$

*Without TOF

- Through identification of $\pi$, K (e p) the TOF allows $\sim$ doubling $\varepsilon D^2$ for $B^0$ and $B_s$
Lots of Charm from hadr. triggers:

With ~10 pb$^{-1}$ of "hadronic trigger" data:

Relative BR of Cabibbo-suppressed $D^0$ decays:

\[
\frac{\Gamma(D \to KK)}{\Gamma(D \to K\pi)} = 11.17 \pm 0.48 \pm 0.98 \text{ (syst)} \%
\]
\[
\frac{\Gamma(D \to \pi\pi)}{\Gamma(D \to K\pi)} = 3.37 \pm 0.20 \pm 0.16 \text{ (syst)} \%
\]

$O(10^7)$ fully reconstructed decays in 2fb$^{-1}$

⇒ Foresee a quite interesting charm physics program:

- D cross sections,
- CP asymmetries and Mixing in D sector, Rare decays, ...
Production

- Wide production of all $B$ hadron species \( \rightarrow \)
  Tevatron ideal environment to study production mechanisms
- X-section $pp \rightarrow B + X$ measured in RunI is a factor 1.7 above QCD expectations
- Rich event sample will allow precise test of the observed effect.

- High statistics + improved acceptance
  \( \rightarrow \) precision measurements of the correlations in $bb$ production (separation of various production mechanisms)

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... possible explanation (Cacciari/Nason)