Recent Physics Results from CDF and D0

Evelyn J. Thomson
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B physics
- $B_s$ and $\Lambda_b$ properties
- $B_s$ mixing

Electroweak physics
- $W$ width
- $Z$ FB asymmetry

Top physics
- Top production
- Top mass

QCD
- Inclusive jet production

Searches for new physics
- Extra dimensions
- SUSY
- Leptoquarks
- Rare decays

$tt \rightarrow \mu v q \bar{q} b \bar{b}$ candidate from CDF Run II
Performance of Fermilab Tevatron

Current Initial Luminosity
\( \sim 40 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1} \)

Integrated Luminosity
\( \sim 200 \text{ pb}^{-1} \) this year

Run II Goals
\( >2000 \text{ pb}^{-1} \) in 2007
\( >4000 \text{ pb}^{-1} \) in 2009

- Best Run I:
  \( 110 \text{ pb}^{-1} \)

Run I \( \rightarrow \) Run II
- \( E_{\text{CM}} = 1.8 \rightarrow 1.96 \text{ TeV} \)
- \( T_{\text{bunch}} = 3500 \rightarrow 396 \text{ ns} \)
CDF and D0 status: **Run II > Run I!**

CDF since June 2001
Delivered ~ 300 pb\(^{-1}\)
Recorded ~ 230 pb\(^{-1}\)
Summer 2003 prelim. results ~ 140 pb\(^{-1}\)

D0 since April 2002
Delivered ~ 240 pb\(^{-1}\)
Recorded ~ 180 pb\(^{-1}\)
Summer 2003 prelim. results ~ 130 pb\(^{-1}\)
“Physics at a hadron collider...”

...is like drinking from a fire-hose!”
...is like panning for gold!”
...is all about the trigger!’

Examine each pp collision (1.7 MHz)
Select few interesting events (<70 Hz)
Store for further offline analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross-section</th>
<th>Event Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic pp</td>
<td>60 mb</td>
<td>6 MHz</td>
</tr>
<tr>
<td>pp→b¯b (b p_T&gt;6 GeV,</td>
<td>10 µb</td>
<td>1 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp→WX→ℓνX</td>
<td>5 nb</td>
<td>0.4 Hz</td>
</tr>
<tr>
<td>pp→ZX→ℓℓX</td>
<td>0.5 nb</td>
<td>0.04 Hz</td>
</tr>
<tr>
<td>pp→tt→WWb¯b→ℓνb¯bX</td>
<td>2 pb</td>
<td>0.0002 Hz</td>
</tr>
<tr>
<td>pp→WH→νb¯b (if M_H=120GeV)</td>
<td>15 fb</td>
<td>0.0000015 Hz</td>
</tr>
</tbody>
</table>

Assume L =100x10^{30} cm^{-2}s^{-1}, ℓ=electron or muon

\[ \eta = 0.5 \ln \left( \frac{p + p_z}{p - p_z} \right) = -\ln \tan \frac{\theta}{2} \]
Three level trigger - CDF

1.7 MHz bunch crossing rate

46 L1 buffers

30 kHz L1 accept

4 L2 buffers

300 Hz L2 accept

300 CPU's

70 Hz L3 accept

>100Hz with data compression

Detector

L1 trigger

L2 trigger

L3 trigger

tape

Hardware tracking for \( p_T \geq 1.5 \text{ GeV} \)

Muon-track matching

Electron-track matching

Missing \( E_T \), sum-\( E_T \)

Silicon tracking

Jet finding

Refined electron/photon finding

Full event reconstruction
CDF Level 1 Track Trigger

Heart of CDF Run II trigger
L1 tracks $p_T > 1.5\text{GeV}$ every 132ns
Efficiency = 96% $\sigma(\Phi) = 5\text{mr}$
$\sigma(p_T) = (1.74 \ p_T)\%$

L1 electron = L1 track + EM cluster
L1 muon = L1 track + muon stub

L1 high $p_T$ lepton triggers for W/Z
L1 low $p_T$ lepton/track triggers for B

Low $p_T$ di-muon trigger:
2 L1 muons $p_T > 1.5 \text{ GeV}$
Collect $J/\psi$’s for calibration and B physics
CDF Level 2 Silicon Vertex Trigger

Exploit long b, c lifetimes in Trigger!
L1 track + Si hits = Impact parameter @L2
A first at a hadron collider!
CDF is a charm/ B Factory!

Lepton \((e, \mu)\) + displaced track trigger
Lepton: \(p_T > 4\) GeV
Track: \(p_T > 2\) GeV, \(d_0 > 120\) μm
Semi-leptonic B decays (\(B \rightarrow \ell \nu X\))

Displaced two track trigger
Tracks: \(p_T > 2\) GeV, \(d_0 > 120\) μm
\(\Sigma p_T > 5.5\) GeV
Fully hadronic B decays (\(B \rightarrow hh', B_s \rightarrow D_s \pi, D \rightarrow K\pi \ldots\))
CDF Momentum Scale Calibration

Essential for Mass differences Mass measurements

Use 500k J/Ψ → μ⁺μ⁻
Measure detector material to remove p_T dependence
➢ Energy loss corrections
Compare to PDG J/Ψ mass
➢ B field calibration

Using calibration from J/Ψ, test with
Low momentum (π): K_s → π⁺π⁻
High statistics (K, π): D⁰ → K⁺π⁻
High momentum (μ): γ → μ⁺μ⁻
D Meson Mass Difference

Test lattice QCD and Heavy Quark Expansion

\[ m(B_s^0) - m(B_d^0) = m(D_s^+) - m(D^+) \]

Displaced two track trigger

Common final decay state
Almost identical kinematics
Many systematics cancel

First Tevatron Run II publication
(PRD accepted June 2003)

\[ m(D_s^+) - m(D^+) = 99.41 \pm 0.38_{(\text{stat})} \pm 0.21_{(\text{sys})} \text{ MeV/c}^2 \]

Agrrees with old world average

99.5 \pm 0.50 \text{ MeV/c}^2

Recent BaBar PRD 65(2002)091104

98.4 \pm 0.1_{(\text{stat})} \pm 0.3_{(\text{sys})} \text{ MeV/c}^2
Prompt Charm Meson Cross-section

First measurement at a hadron collider
Above theory as for B mesons
Test NLO QCD (Rapidity<1)

\[ \sigma(D^0, p_T > 5.5 \text{ GeV}) = 13.3 \pm 0.2 \pm 1.5 \mu b \]
\[ \sigma(D^{*-}, p_T > 6.0 \text{ GeV}) = 5.2 \pm 0.1 \pm 0.8 \mu b \]
\[ \sigma(D^+, p_T > 6.0 \text{ GeV}) = 4.3 \pm 0.1 \pm 0.7 \mu b \]
\[ \sigma(D_s^+, p_T > 8.0 \text{ GeV}) = 0.75 \pm 0.05 \pm 0.22 \mu b \]

Submitted to PRL (hep-ex/0307080)
B Physics

Why should you care?

$B_s$ meson and $\Lambda_b$ baryon unique to Tevatron now
(Not produced at BaBar or Belle)

$B_s$ meson properties:
- Mass
- Lifetime
- $\Delta m_s$ frequency
- $\Delta \Gamma_s$
- CP violation
- CKM angle $\gamma$

$\Lambda_b$ baryon properties:
- Mass
- Lifetime
- CP violation
- Test of HQE

CKM matrix triangle

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SLAC Summer Institute August 7 2003
**B_s** Meson Mass and Lifetime

**B_s** → J/ψ Φ with J/ψ → μ⁺μ⁻ and Φ → K⁺K⁻
**B^+** → J/ψK^+, **B^0** → J/ψK^{*0}
check technique, systematics

**B_s** mass – PDG 5369.6 ± 2.4 MeV/c²
CDF 5365.5 ± 1.3_{(stat)} ± 0.9_{(sys)} MeV/c²
D0 5360 ± 5 MeV/c²

**B_s** lifetime - PDG 1.461 ± 0.057 ps
CDF 1.33 ± 0.14_{(stat)} ± 0.02_{(sys)} ps
D0 1.19 ± 0.19_{(stat)} ± 0.14_{(sys)} ps

Future:
Search for CP violation and measure β_s
Compare to lifetime from B_s → ℓνD_s and extract ΔΓ_s
**Check technique systematics**

**First lifetime from fully reconstructed $\Lambda_b$ decay!**

$\Lambda_b$ mass and lifetime

$\Lambda_b \rightarrow J/\Psi \Lambda$
with $J/\psi \rightarrow \mu^+ \mu^-$ and $\Lambda \rightarrow \pi \pi$

$\Lambda_b$ mass – PDG $5624 \pm 9$ MeV/c$^2$
CDF $5620.4 \pm 1.6_{\text{(stat)}} \pm 1.2_{\text{(sys)}}$ MeV/c$^2$
D0 in progress

$\Lambda_b$ lifetime – PDG $1.229 \pm 0.080$ ps
CDF $1.25 \pm 0.26_{\text{(stat)}} \pm 0.10_{\text{(sys)}}$ ps
D0 $1.05 \pm 0.21_{\text{(stat)}} \pm 0.12_{\text{(sys)}}$ ps

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CDF Run II Preliminary, $L = 65$ pb$^{-1}$

Unbinned Likelihood Fit To $\Lambda_b$ Lifetime
$ct = 374 \pm 78_{\text{(stat)}} \pm 29_{\text{(syst)}}$ μm

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In Future: Particle Identification!

CDF Run II Preliminary (Luminosity 65 pb⁻¹)

\[ \Lambda_b \rightarrow \Lambda_c \pi \ \text{candidates} \]

96 ± 13 \[ \Lambda_b \rightarrow \Lambda_c \pi \] candidates

- Four-prong B reflections
- Other B meson decays
- Other \( \Lambda_b \) decays
- \( \Lambda_b \rightarrow \Lambda_c K \)
- Combinatorial background

Add dE/dx particle id
Reduce reflection by ~3
Only lose ~15% signal

CDF Run II Preliminary (Luminosity 65 pb⁻¹)

83 ± 11 \[ \Lambda_b \rightarrow \Lambda_c \pi \] candidates
(with dEdx cut)

- Four-prong B reflections
- Other B meson decays
- Other \( \Lambda_b \) decays
- \( \Lambda_b \rightarrow \Lambda_c K \)
- Combinatorial background
Why do we care about B lifetimes, especially $\Lambda_b$?

Important Test of Heavy Quark Expansion

$\tau(B^-)/\tau(B^0)$

$\tau(B_s)/\tau(B^0)$

$\tau(\Lambda_b)/\tau(B^0)$

$\tau(b\text{ baryon})/\tau(B^0)$

B lifetime ratios

0.7 0.8 0.9 1 1.1 1.2

lifetime ratio

0.784±0.034
0.9 - 1.0

0.798±0.052
0.9 - 1.0

0.949±0.038
0.99 - 1.01

1.073±0.014
1.03 - 1.07

B Lifetime Working Group
July 2002
First observation!
- Fully reconstructed hadronic final state
- Two track trigger essential
- Production rate understood

Ratio of branching ratios cancels most systematics

\[
\frac{f_s \ BR(B_s \rightarrow D_s^- \pi^+)}{f_d \ BR(B^0 \rightarrow D^- \pi^+)} = 0.41 \pm 0.11^{(\text{stat})} \pm 0.11^{(\text{BR})} \pm 0.07^{(\text{sys})}
\]

Golden mode for $B_s$ mixing

In progress:
Flavour tagging ($\epsilon D^2$)
Exquisite ct resolution

---

First observation!
- Fully reconstructed hadronic final state
- Two track trigger essential
- Production rate understood

Ratio of branching ratios cancels most systematics

\[
\frac{f_s \ BR(B_s \rightarrow D_s^- \pi^+)}{f_d \ BR(B^0 \rightarrow D^- \pi^+)} = 0.41 \pm 0.11^{(\text{stat})} \pm 0.11^{(\text{BR})} \pm 0.07^{(\text{sys})}
\]
Towards $B_s$ mixing

$B_s$ mixing World Average @95% C.L. $\Delta m_s \geq 14.4 \text{ ps}^{-1}$

- At least 30 times faster than $B_d$ mixing
  $\Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1}$

- Will need exquisite proper time resolution!

$$ct = L_{xy} \frac{m_B}{p_T^B}$$

- Minimise error on $p_T$ with fully reconstructed decays $B_s \rightarrow D_s \pi$

- $\text{CDF} \sim 60 \text{ fs} (45 \text{ fs with L00})$
  $D_0 \sim 75 \text{ fs}$

Flavour tagging
Need everything for $\epsilon D^2 \sim 10\%$
$\epsilon = \text{tag efficiency}$
$D = \text{tag correct (dilution)}$

Yield – need $\sim 1000$ events
CDF yield $\sim 50$ events in 65 pb$^{-1}$
Below expectations…
…but careful with your abacus!
Silicon coverage much improved
Trigger with majority logic
Add more decay modes
$$B_s \rightarrow D_s \pi, \ D_s \pi \pi \pi$$
$$D_s \rightarrow \phi \pi, \ K^* K, \ \pi \pi \pi$$

For 2 fb$^{-1}$, 5$\sigma$ sensitivity up to
$$x_s = 63 \ (S/B = 2/1) \quad x_s = \Delta m_s \tau(B_s)$$
$$x_s = 53 \ (S/B = 1/2)$$
Two-Body Charmless B decays

**Future: CKM angle γ**

- **B→h⁺h⁻ observed at CDF**
  - About 280 candidates (S:N=2:1)
  - Peak is a mix of \( B^0, B_s \rightarrow \pi\pi, \pi K, KK \)
  - Statistical separation with dE/dx and kinematics

**Raw fit results**

\[
\begin{align*}
N(B^0 \rightarrow K\pi) &= 148 \pm 17 \\
N(B^0 \rightarrow \pi\pi) &= 39 \pm 14 \\
N(B_s \rightarrow KK) &= 90 \pm 17 \text{ First observation!} \\
N(B_s \rightarrow K\pi) &= 3 \pm 11 \\
\end{align*}
\]

**BR results**

\[
\frac{BR(B^0_d \rightarrow \pi\pi)}{BR(B^0_d \rightarrow K\pi)} = 0.26 \pm 0.11 \pm 0.055
\]

agrees with PDG \( 0.29_{-0.12}^{+0.13} \pm 0.02 \pm 0.01 \)

\[
A_{CP} = \frac{\overline{B}_d^0 \rightarrow K^- \pi^+ - B_d^0 \rightarrow K^+ \pi^-}{\overline{B}_d^0 \rightarrow K^- \pi^+ + B_d^0 \rightarrow K^+ \pi^-} = 0.02 \pm 0.15_{\text{stat}} \pm 0.017_{\text{sys}}
\]
Disentangling Charmless B decays

Use $M\pi\pi$ vs $(1-p_1/p_2)q_1$

Use $K/\pi$ separation $dE/dx$ 1.16$\sigma$
Why should you care?

Standard Candles!

W/Z cross-sections

Ratio $\rightarrow$ W width

W mass

W charge Asymmetry

Z FB Asymmetry

WW, WZ, ZZ, W$\gamma$, Z$\gamma$

Trigger on leptonic decays

Clean low bkg event signatures

W: 1 high $p_T$ lepton + large MET

Z: 2 high $p_T$ leptons

BR $\sim$ 11% per mode for $W \rightarrow \ell \nu$

BR $\sim$ 3% per mode for $Z \rightarrow \ell^+\ell^-$
$\sigma(W) \times \text{BR}(W \rightarrow \ell \nu)$

$E_T > 25\,\text{GeV}, $ MET $> 25\,\text{GeV}$
CDF $|\eta| < 1.0, \quad$ D0 $|\eta| < 1.1$

$p_T > 20\,\text{GeV}, $ MET $> 20\,\text{GeV}$
CDF $|\eta| < 0.6, \quad$ D0 $|\eta| < 1.6$

$$M_T = \sqrt{2E_T E_\nu(1-\cos\phi_{\ell \nu})}$$

<table>
<thead>
<tr>
<th>CDF</th>
<th>CDF (all: 72pb$^{-1}$)</th>
<th>D0</th>
<th>D0 (e: 42pb$^{-1}$; $\mu$: 17pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell$ Events</td>
<td>$\sigma(W) \times \text{BR}(W \rightarrow \ell \nu)$ (nb)</td>
<td>Events</td>
<td>$\sigma(W) \times \text{BR}(W \rightarrow \ell \nu)$ (nb)</td>
</tr>
<tr>
<td>e</td>
<td>38625</td>
<td>27370</td>
<td>2.64 $\pm$ 0.01 $\pm$ 0.09 $\pm$ 0.16</td>
</tr>
<tr>
<td>$\mu$</td>
<td>21599</td>
<td>7352</td>
<td>2.64 $\pm$ 0.02 $\pm$ 0.12 $\pm$ 0.16</td>
</tr>
<tr>
<td>$\tau$</td>
<td>2346</td>
<td></td>
<td>2.62 $\pm$ 0.07 $\pm$ 0.21 $\pm$ 0.16</td>
</tr>
</tbody>
</table>

Theory prediction $2.731 \pm 0.002$ nb NNLO Stirling et al., Phys Lett B531 (2002)
$\sigma(Z) \times BR(Z \rightarrow \ell\ell)$

Opposite Sign (1830)

- $Z \rightarrow \ell\ell$ DATA
- $Z \rightarrow \ell\ell$ MC

CDF Run II Preliminary

\[ \int L \, dt = 72.0 \, \text{pb}^{-1} \]

CDF $p_T > 20\text{GeV}$, D0 $p_T > 15\text{GeV}$

CDF $|\eta| < 0.6$, D0 $|\eta| < 1.8$

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>CDF (all: 72pb$^{-1}$)</th>
<th>D0</th>
<th>D0 (e: 42pb$^{-1}$; $\mu$: 32pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell$ Events</td>
<td>1830</td>
<td>0.267 ± 0.006 ± 0.015 ± 0.016</td>
<td>1139</td>
<td>0.275 ± 0.009 ± 0.009 ± 0.028</td>
</tr>
<tr>
<td>$e$ Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$ Events</td>
<td>1631</td>
<td>0.246 ± 0.006 ± 0.012 ± 0.015</td>
<td>1585</td>
<td>0.264 ± 0.007 ± 0.017 ± 0.026</td>
</tr>
</tbody>
</table>

Theory prediction $0.252 \pm 0.009$ nb NNLO


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W and Z cross-sections vs $E_{CM}$

Indirect Measurement of W Width

W, Z cross-sections systematics limited
Most of systematics cancel in ratio R

Indirect measurement of W width

\[ R = \frac{\sigma(pp \to W)}{\sigma(pp \to Z)} \times \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \times \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)} \]

**Theory**

**LEP**

**Table**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF e</td>
<td>9.88 ± 0.24 ± 0.44</td>
</tr>
<tr>
<td>CDF (\mu)</td>
<td>10.69 ± 0.28 ± 0.31</td>
</tr>
<tr>
<td>D0 e</td>
<td>10.34 ± 0.35 ± 0.49</td>
</tr>
<tr>
<td>Combined</td>
<td>10.36 ± 0.16 ± 0.27</td>
</tr>
</tbody>
</table>

\[ \Gamma(W) - PDG \ 2.118 \pm 0.042 \ \text{GeV} \]

Run II \( 2.181 \pm 0.074 \ \text{GeV} \)

\[ \Gamma(W) \to \Gamma(W) \]

\[ \Gamma(W) \to \Gamma(W) \]

TeVeWWG

**Diagram**

Standard Model

- World Average (RPP 2002)
  - (includes Run I results)

- Tevatron
  - Run I + II combined

- (from R)
  - Run II combined
  - D0 II(e)
  - CDF II(e)
  - CDF II(\(\mu\))

- (from R)
  - Run I combined
  - D0 Ia+b(e)
  - CDF Ia(e)

- UA2(e)
- UA1(e+\(\mu\))

\[ \Gamma(W) \to \Gamma(W) \]

\[ \Gamma(W) \to \Gamma(W) \]

\[ \Gamma(W) \to \Gamma(W) \]

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Forward-Backward Asymmetry

\[ A_{FB} = \frac{d\sigma(\cos \theta > 0) - d\sigma(\cos \theta < 0)}{d\sigma(\cos \theta > 0) + d\sigma(\cos \theta < 0)} \]

High mass reach unique to Tevatron
- Probe Z-\(\gamma^*\) interference
- Complements direct Z’ search
Result agrees with SM

Zoom into high stats Z pole region

Electron |\eta|<3 Forward calorimeter crucial!

CDF Run II Preliminary
\[ \int L=72pb^{-1} \]

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**Top Physics**

Top discovered by CDF and D0 in 1995

*Very heavy!* Top mass $= 174.3 \pm 5.1$ GeV

*Only ~30 events per experiment*

***Want more top events to study properties!!***

Run II $\sigma$ 30% higher at $\sqrt{s} = 1.96$ TeV

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- **W Helicity**
- **Top mass**
- **Production Cross Section**
- **Production Kinematics**
- **Top Spin Polarization**
- **Resonance Production**
- **Branching Ratios**
- **Rare Decays**
- **Non-SM decay ($t \rightarrow H^+ b$)**

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Top Quark Production & Decay

Top quarks produced in pairs via strong interaction: 85% qq, 15% gg

Top quark heavy => decays very fast!
\[ \Gamma(t\rightarrow bW) \sim 1.5 \text{ GeV}, \quad \tau_{\text{top}} \sim 4 \times 10^{-25} \text{s} \]
c.f. \[ \Lambda_{\text{QCD}} \sim 100 \text{ MeV}, \quad \Lambda^{-1} \sim 10^{-23} \text{s} \]
Too fast for hadronisation!
- No top mesons or baryons
- Decay products know top spin

3 characteristic event signatures from WW decay

Dilepton: BR small but pure
2 high \( p_T \) leptons, high MET, \( \geq 2 \) jets

Lepton+Jets: BR larger but less pure
1 high \( p_T \) lepton, high MET, \( \geq 4 \) jets (1 b-tag)

All-hadronic: BR largest but huge QCD bkg
\( \geq 6 \) jets (2 b-tags)
Top Pair Production cross-section

Why is it interesting?
- Re-discover top in Run II
- Does cross-section increase?
- Develop selections and background estimates for other top analyses

All measurements so far are counting experiments

$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{bkg}}{A \int L \, dt}$$

Run 1 cross section results ~100 pb\(^{-1}\)

- **DØ combined** (m\(_t\) = 172 GeV/c\(^2\))
  - 5.9 ± 1.7 pb
- **CDF combined** (m\(_t\) = 175 GeV/c\(^2\))
  - 6.5\(^{+1.7}_{-1.4}\) pb
- **DØ L+jets** (topological)
  - 4.1 ± 2.1 pb
- **CDF L+jets** (SVX b-tag)
  - 5.1 ± 1.5 pb
- **CDF L+jets** (Soft Lepton Tag)
  - 9.2 ± 4.3 pb
- **DØ L+jets** (Soft Lepton Tag)
  - 8.3 ± 3.6 pb
- **CDF Hadronic**
  - 7.6\(^{+3.5}_{-2.7}\) pb
- **DØ Hadronic**
  - 7.1 ± 3.2 pb
- **CDF Dilepton**
  - 8.4\(^{+4.5}_{-3.5}\) pb

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Top cross-section: Dilepton

2 high $p_T$ leptons, high MET, ≥2 jets

### CDF: 72 pb⁻¹

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
<th>Total $\ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.10 ± 0.06</td>
<td>0.09 ± 0.05</td>
<td>0.10 ± 0.04</td>
<td>0.30 ± 0.12</td>
</tr>
<tr>
<td>tt→$\ellννvbb$</td>
<td>0.47 ± 0.05</td>
<td>0.59 ± 0.07</td>
<td>1.44 ± 0.16</td>
<td>2.50 ± 0.30</td>
</tr>
<tr>
<td>SM expectation</td>
<td>0.57 ± 0.08</td>
<td>0.68 ± 0.09</td>
<td>1.54 ± 0.17</td>
<td>2.80 ± 0.32</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

CDF $\sigma(t\bar{t}) = 13.2 ± 5.9_{(stat)} ± 1.5_{(sys)} ± 0.8_{(lum)}$ pb

New! Lepton + isolated track (126 pb⁻¹)

CDF $\sigma(t\bar{t}) = 7.3 ± 3.4_{(stat)} ± 1.7_{(sys)}$ pb

### D0: 107 pb⁻¹

<table>
<thead>
<tr>
<th></th>
<th>ee: 107 pb⁻¹</th>
<th>μμ: 90 pb⁻¹</th>
<th>eμ: 97 pb⁻¹</th>
<th>Total $\ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.58 ± 0.51</td>
<td>0.70 ± 0.44</td>
<td>0.60 ± 0.42</td>
<td>1.88 ± 0.79</td>
</tr>
<tr>
<td>tt→$\ellννvbb$</td>
<td>0.63 ± 0.10</td>
<td>0.46 ± 0.10</td>
<td>1.73 ± 0.26</td>
<td>2.81 ± 0.30</td>
</tr>
<tr>
<td>SM expectation</td>
<td>1.21 ± 0.52</td>
<td>1.16 ± 0.45</td>
<td>2.33 ± 0.49</td>
<td>4.69 ± 0.64</td>
</tr>
<tr>
<td>Data</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

D0 $\sigma(t\bar{t}) = 8.7 ± 6.4_{(stat)} ± 2.7_{(sys)} ± 0.9_{(lum)}$ pb

CDF $\ell\ell$

S:B = 8:1

Very pure!

D0 $\ell\ell$

S:B = 3:2

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SLAC Summer Institute August 7 2003
Top cross-section: Lepton + Jets

1 high \( p_T \) lepton, high \( \text{MET} \), \( \geq 3 \) jets, 1 b-tag

- **SVX**: secondary vertex
  - CDF \( L_{xy} > 3\sigma(L_{xy}) \)
  - D0 \( L_{xy} > 5\sigma(L_{xy}) \)

- **CSIP**: count tracks with significant \( d_0 \)
  - \( \geq 2 \) tracks with \( d_0 > 3\sigma(d_0) \)
  - \( \geq 3 \) tracks with \( d_0 > 2\sigma(d_0) \)

45-55% efficiency for 1 b-tag in tt MC

Use 1, 2 jet events to check bkg model

Look for excess in \( \geq 3 \) jet region
D0 Run II Electron + Jets Candidate

Event is b-tagged by both SVX and CSIP (run 169923 event 16396718)

4 jets
Electron $p_T = 27$ GeV
Jet $p_T = 51, 36, 30, 53$ GeV
Missing $E_T = 58$ GeV
$H_T = 207$ GeV
Aplanarity = 0.11

Primary vertex
$N_{\text{track}} = 17$
$z = -4.6$ cm
Top cross-section: Lepton + Jets

**CDF** \( \sigma(t\bar{t}) = 3.9 \pm 1.3^{(\text{stat})} \pm 0.7^{(\text{sys})} \pm 0.2^{(\text{lum})} \text{ pb} \)

**D0 CSIP** \( \sigma(t\bar{t}) = 7.4 \pm 4.4^{(\text{stat})} \pm 2.1^{(\text{sys})} \pm 0.7^{(\text{lum})} \text{ pb} \)

**D0 SVX** \( \sigma(t\bar{t}) = 10.8 \pm 4.9^{(\text{stat})} \pm 2.1^{(\text{sys})} \pm 1.1^{(\text{lum})} \text{ pb} \)

**D0 SLT + KIN** \( \sigma(t\bar{t}) = 8.0 \pm 2.4^{(\text{stat})} \pm 1.7^{(\text{sys})} \pm 0.8^{(\text{lum})} \text{ pb} \)

---

**CDF II preliminary 108 pb\(^{-1}\)**

- **Data**
  - Number of jets in W+jets
    - Jet multiplicity
      - 0
      - 1
      - 2
      - 3
      - 4
  - Number of tagged events
    - 0
    - 10
    - 20
    - 30
    - 40

**D0 II preliminary 45 pb\(^{-1}\)**

- **D0 SVX**
  - Data
  - Error on Bgr
  - Error on Bgr+Signal

---

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Top Quark Mass and the Standard Model

Why is it interesting?
Over-constrains SM
Confronts indirect predictions with direct measurements

- See good agreement
- Both prefer lighter Higgs

\[ m_H = 91^{+58}_{-37} \text{ GeV} \]
\[ m_H < 211 \text{ GeV} @ 95\% \text{CL.} \]

Top strongly correlated with Higgs
5 GeV shift in \( m_{\text{top}} \) => 37% shift in \( m_H \)
(M. Gruenewald DESY-Zeuthen ’03)

Top mass measurement crucial to indirect prediction from SM fit!
Run II goal: \( m_{\text{top}} \) error < 3 GeV
CDF Run II Top Mass: Lepton + Jets

- 1 high $p_T$ lepton, high MET, ≥3 jets, 1 b-tag
- 4th jet $E_T > 8$ GeV (usually 15 GeV)
- 22 events, expect $6.5 \pm 2.0$ from bkg

Uses one quantity per event
- All events carry same weight
- Fit to shapes from MC

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>6.2</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>2.6</td>
</tr>
<tr>
<td>PDF</td>
<td>2.0</td>
</tr>
<tr>
<td>Other MC modeling</td>
<td>1.0</td>
</tr>
<tr>
<td>Generators</td>
<td>0.6</td>
</tr>
<tr>
<td>Bkgd shape</td>
<td>0.5</td>
</tr>
<tr>
<td>b-tag</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.1 GeV</strong></td>
</tr>
</tbody>
</table>

CDF Run II preliminary 108 pb$^{-1}$

$$m_{top} = 177.5 \pm 12.7^{+9.4}_{-1.7} \text{ (stat)}\pm 7.1 \text{ (sys)} \text{ GeV} / c^2$$

Reconstructed Top Mass, Tagged Events (GeV/c$^2$)
Reconstructed event-by-event top mass

Use constrained fit technique with 2 dof

\( M_{t\nu} = M_W, M_{jj} = M_W, M_{t_1} = M_{t_2}, p_T \) balance

4 jets = 12 possible jet-parton combinations
x 2 solutions for neutrino \( p_z \)
!!!Use b-tagging to reduce permutations!!!

Choose combination with lowest \( \chi^2 \)
Improved D0 Run I Top Mass

Uses event probabilities
- Full set of event observables
- Better measured events carry more weight
Reduces background
91 original candidates
77 after exactly 4 jets
22 after Pbkg<11

$M_{\text{top}} = 180.1 \pm 3.6 \pm 4.0 \text{ GeV}$

Old stat error was 5.6 GeV!
Like 2.4 increase in statistics!
Top Mass – Expected Statistical Errors

CDF Run II (108 pb\(^{-1}\))
Preliminary
Expected 8.8 GeV
Observed +12.7, -9.4 GeV

D0 Run I (125 pb\(^{-1}\))
Preliminary
Expected 5.4 GeV
Observed 3.6 GeV

Data -ve

Data +ve

Expected stat. error (GeV)

Observed errors consistent with expectations
QCD - Inclusive Jet Production

Why should you care? Mother of all backgrounds!
Jet cross-section – sensitive to gluon distribution in proton
Better predictions of many new physics processes at high energies

Highest $E_T$ jets ever!
8 orders of magnitude!
Systematics dominated by Jet Energy Scale...to be reduced

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QCD – Dijet cross-section

Cross-section well reproduced by NLO theory over 6 orders of magnitude

Systematics dominated by Jet Energy Scale

\[
\left< \sigma(d\sigma/dM_{jj}) \right> \text{[nb/GeV]}
\]

\[
\begin{align*}
200 & \quad 400 & \quad 600 & \quad 800 & \quad 1000 & \quad 1200 & \quad 1400 \\
\end{align*}
\]

\[
\begin{align*}
\left< \sigma(d\sigma/dM_{jj}) \right> \text{[nb/GeV]} & = 10^{-8} \\
& = 10^{-7} \\
& = 10^{-6} \\
& = 10^{-5} \\
& = 10^{-4} \\
& = 10^{-3} \\
& = 10^{-2} \\
& = 10^{-1} \\
\end{align*}
\]

cone \( R=0.7, |\eta_{\text{jet}}| < 0.5 \)

- \( \text{RunII, } L=34 \text{ pb}^{-1} \)
- \( \text{NLO CTEQ6, } R_{\text{sep}}=1.3 \)
- \( \mu_F = \mu_R = 0.5 \ E_T^{\text{max}} \)

\( R_{\text{sep}} = 1.3, \mu_F = \mu_R = 0.5 \ E_T^{\text{max}} \)

DØ Run II preliminary

NLO QCD (JETRAD)

CTEQ6

maxT = 0.5 \ E_R

\( \mu = F \)

QCD ± Dijet cross-section

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Searches for New Physics

Why? Standard Model is incomplete!

Why $M_{EW} \ll M_{Pl}$?
How to achieve grand unification?
How to include gravity?
What explains proliferation of quarks and leptons?
What determines their mixings?

More general theories make predictions that can be tested at the Tevatron
Searches for New Physics

Tevatron is the world’s highest energy accelerator and is the most likely place to directly discover a new particle or force

Search for Extra Dimensions, Z’
- Study of high $E_T$ tails

Search for SUSY
- Jets + MET
- Photons + MET
- Trileptons

Search for Leptoquarks
- First generation $e e jj$
- Second generation $\mu \mu jj$
- All generations $v v jj$

Search for Rare Decays
- $D^0 \rightarrow \mu + \mu -$
- $B_s \rightarrow \mu + \mu -$

What is dark matter?
- SUSY LSP?
- Extra dimensions?

Tevatron can put limits on models

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$
$\Omega_B h^2 = 0.0224 \pm 0.0009$

WMAP, astro-ph/0302207
**Extra Dimensions Overview**

**SM particles confined to 4 dimensions**
**Gravity propagates in extra dimensions**
**Solves the hierarchy problem!**
**Can explain dark matter!**

**ADD Model** (Arkani-Hamed, Dimopoulos, Dvali)

n “large” extra dimensions of size
\[ R \sim \frac{1}{M_s} \left( \frac{M_{Pl}}{M_s} \right)^{2/n} \]

n=1 R~10^8 km – excluded!

n=2 R~1 mm ~ tabletop realm

n≥3 R≤3 nm - collider realm

**Randall-Sundrum Model**

One “small” extra dimension warped by factor \( e^{-2kr_c\pi} \)

Spin-2 resonance

- Graviton mass
- Coupling k/M_{Pl}

**Experimental signatures**

Virtual graviton exchange modifies fermion/boson pair production

- Direct graviton emission
  - Jets + MET
  - Photon + MET

**Diagram**:

- (a) Virtual graviton exchange modifies fermion/boson pair production
- (b) Direct graviton emission
- (c) Direct graviton emission
Extra Dimensions – ADD Model

Virtual graviton exchange
Look for excess at high dilepton or diphoton mass

ee and γγ: 2 EM objects $p_T>25$ GeV

<table>
<thead>
<tr>
<th>SM Prediction</th>
<th>D0 Run II Preliminary</th>
<th>Data</th>
</tr>
</thead>
</table>

Consistent with no signal
D0 now has world’s best limit!
Probe up to 2 TeV with 2 fb$^{-1}$

<table>
<thead>
<tr>
<th>95% C.L.</th>
<th>GRW</th>
<th>HLZ</th>
<th>Hewett</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_S$ (TeV)</td>
<td>$n=2, 3, 7$</td>
<td>$\lambda=+1$</td>
<td></td>
</tr>
<tr>
<td>D0 diEM</td>
<td>1.28</td>
<td>1.42, 1.52, 1.01</td>
<td>1.14</td>
</tr>
<tr>
<td>D0 μμ</td>
<td>0.88</td>
<td>1.05, 0.88, 0.70</td>
<td>0.79</td>
</tr>
<tr>
<td>CDF diEM</td>
<td>-</td>
<td>-</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Extra Dimensions - Randall-Sundrum Model

Spin-2 graviton
Look for resonances in dilepton mass
Consistent with no signal

CDF Run II Preliminary

\[ \int L \, dt = 72 \text{ pb}^{-1} \]

**Dielectron Mass (GeV/c^2)**

- Data
- Drell - Yan
- QCD Background
- \( \tau \tau, WW, WZ, tt \)

**Dimuon Mass (GeV/c^2)**

- Data
- DY \( Z \rightarrow \mu \mu \), DY \( Z \rightarrow \tau \tau \), WW, WZ, \( t \bar{t} \)

**Graviton mass (GeV/c^2)**

\[ \int L \, dt = 72 \text{ pb}^{-1} \]

- \( \sigma \cdot \text{Br}(G \rightarrow ll) \) limit (95% C.L.)
- \( \sigma \cdot \text{Br}(G \rightarrow ll) \) PYTHIA \times 1.3

Randall-Sundrum Model

- \( k / M_p = 0.1 \)
- \( k / M_p = 0.055 \)
- \( k / M_p = 0.025 \)
- \( k / M_p = 0.01 \)

Extra Gauge Bosons

Predicted by many models
Look for resonance in dilepton mass
Consistent with no signal

D0 m(Z') > 719 GeV @ 95% C.L. ~100pb⁻¹
World’s best limit

CDF m(Z') > 665 GeV @ 95% C.L
Close to Run I 690 GeV

Probe up to 1 TeV with 2 fb⁻¹
Dijet Resonances

Sensitive to a variety of new physics
Probes highest energies
Axigluon mass > 1.1 TeV@95%C.L.
Scalar Leptoquarks

Directly couple quarks to leptons
Predicted by Grand Unified Theories

First generation LQ₁ LQ₁ → eₑjj

D₀ Run 2 Preliminary

Cross Section * BR [pb]

D₀ Run2, Mₐ > 231 GeV
D₀ Run2 and D₀ Run1, Mₐ > 253 GeV
D₀ Run2 and D₀+CDF Run1, Mₐ > 262 GeV
NLO Theory

D₀ M(LQ₁) > 253 GeV @ 95% C.L.

CDF M(LQ₁) > 230 GeV @ 95% C.L.

All three generations LQ LQ → vᵥjj

Jets + MET

CDF M(LQ) > 107 GeV @ 95% C.L.

Second generation LQ₂ LQ₂ → μμjj

D₀ Run II Preliminary

~100 pb⁻¹

Sₜ = \sum \muμjj(Eₜ) [GeV]

CDF in progress

D₀ M(LQ₂) > 186 GeV @ 95% C.L.

CDF M(LQ₁) > 230 GeV @ 95% C.L.

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SUSY – Search for Long-lived Stop

Long-lived massive charged particles?

- Move slowly
- Measure time-of-flight!
- $\Delta\text{TOF}=\text{TOF}$ candidate – TOF at $c$

**Selection**

- Tracks with $p_T>40$ GeV
- $\Delta\text{TOF}>2.5$ ns
- Observe 7 events in 53pb$^{-1}$
- Expect $2.9 \pm 0.7_{\text{(stat)}} \pm 3.1_{\text{(syst)}}$

Consistent with no signal

$m(\text{stop})>107$ GeV @95% C.L.

LEP limit is 95 GeV
SUSY – Sbottoms from Gluino Decays

Gluino pair production cross-section large
Very distinctive signature of 4 b jets + MET

$$\tilde{g}\tilde{g} \rightarrow (b\tilde{b}_1)(b\tilde{b}_1) \rightarrow (bb\tilde{\chi}_1^0)(bb\tilde{\chi}_1^0)$$

Selection
3 or more jets
MET> 50 GeV
Lepton veto

Assume
$$m_{\tilde{\chi}_1^0} = 60 GeV$$
$$m_{\tilde{g}} = 220 GeV$$
$$m_{\tilde{b}_1} = 160 GeV$$

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Expected Background</th>
<th>Expected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>4</td>
<td>5.6 ± 1.4</td>
<td>10.6 ± 1.7</td>
</tr>
<tr>
<td>Double</td>
<td>1</td>
<td>0.5 ± 0.1</td>
<td>4.4 ± 0.9</td>
</tr>
</tbody>
</table>

Gluino mass (GeV/c^2)

CDF Run I 95% C.L. excluded

CDF Run II Preliminary

$$\int L dt = 38.4 pb^{-1}$$

BR(\tilde{g} → b \tilde{b})=100%
m(\tilde{g}) = 500 GeV/c^2
m(\tilde{\chi}_1^0)=80 GeV/c^2

\tilde{g} → bb_1 kinematically forbidden

95% C.L. excluded region
SUSY Trileptons

“Golden” channel with low backgrounds but
- Leptons are soft ($p_T < 20$ GeV)
- $\tan\beta > 8$ most leptons are taus!

Need $>300 \text{pb}^{-1}$ to improve on LEP

Understanding soft electrons!
- Two electrons $p_T > 10$ GeV
- At least one electron $p_T < 20$ GeV

Understanding taus!
- CDF has tau ($p_T > 5$ GeV) and di-tau triggers

Data

- $Z \rightarrow ee$
- $Z \rightarrow \tau \tau$
- $W$ incl.
- QCD

CDF Run II Preliminary
Search for Gauge Mediated SUSY

Gaugino pair production and LSP = gravitino NLSP = neutralino

Experimental signature $\gamma\gamma + \text{MET}$

Close to Run I limits

$p\bar{p} \rightarrow \text{gauginos} \rightarrow W, Z, \gamma + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma + \tilde{G}\tilde{G} + \chi$

**Graphs and Plots:**

- D0 Run 2 preliminary $\sim 50 \text{ pb}^{-1}$
- D\O\ Run II Preliminary

**Equations:**

- $\Lambda$ vs. $m_{\chi^0}$
- $\sigma [\text{pb}]$ vs. Mass (GeV/c$^2$)

**Diagrams:**

- Diboson production
- Gaugino pair production

**Additional Information:**

- Evelyn J. Thomson, The Ohio State University
- SLAC Summer Institute August 7 2003
Rare Decays

Search for FCNC $B_s \rightarrow \mu^+\mu^-$
CDF 1 candidate in $B_s$ and $B_d$ window
$\text{BR}(B_s \rightarrow \mu\mu) < 9.5 \times 10^{-7}$ @ 90% CL
$< 1.2 \times 10^{-6}$ @ 95% CL
$\text{BR}(B_d \rightarrow \mu\mu) < 2.5 \times 10^{-7}$ @ 90% CL
$< 3.1 \times 10^{-7}$ @ 95% CL

D0 3 candidates in $B_s$ window
$\text{BR}(B_s \rightarrow \mu\mu) < 1.6 \times 10^{-6}$ @ 90% CL

World’s best limits for $B_s$
May catch up to BaBar/Belle for $B_d$

SM $\text{BR}(B_s \rightarrow \mu^+\mu^-) \sim 3.8 \times 10^{-9}$

Various SUSY models predict enhancement by 10 to 1000

Recently interesting since same SUSY models predict deviations of $(g-2)_\mu$

Exp: *PRL 89 (2002) 101804, 129903*
Theory: *PRL 87 (2001) 251804*
Rare Decays

CDF
1 event in $B_s$ and $B_d$ search window

Expected bkg
0.54 ±0.20 (for $B_s$)
0.59 ±0.22 (for $B_d$)

D0
3 events in $B_s$ search window

Expected bkg
3.42 ±0.79 (for $B_s$)
Search for the SM Higgs Boson

20th century CDF/D0 sensitivity study still valid
21st century CDF/D0 search will need:
- Sophisticated techniques to improve sensitivity
- Excellent understanding of backgrounds and systematics
- Enough data!

In 50% of experiments

LEP $m_H > 114.4$ GeV @ 95% CL

Higgs Sensitivity Study ('03)
statistical power only
(no systematics)

SUSY/Higgs Workshop
('98-'99)

PRELIMINARY

5σ discovery
3σ evidence
95% CL exclusion

80 100 120 140 160 180 200
$m_H$ (GeV)

100
10
1

integrated luminosity (fb$^{-1}$/exp.)
Conclusions

CDF and D0 are back!

First physics measurements well underway
Displaced track trigger for B physics
$B_s$ meson and $\Lambda_b$ baryon
$W$ and $Z$ bosons
Top quark
Searches for new physics

In next few years
$B_s$ mixing
Top quark mass error < 3 GeV
World’s best limits for searches...
...or discovery of new physics!
CDF Detector Upgrades

7-8 silicon layers
1.6 < r < 28 cm, |z| < 45 cm
|\eta| ≤ 2.0, \cos{\theta} = 0.964
\sigma(\text{hit}) \sim 14 \mu m

Some resolutions:
\( p_T \sim (0.7 \oplus 0.1 p_T)\% \)
J/\Psi mass \sim 15 \text{ MeV}
EM E \sim 16\%/\sqrt{E}
Had E \sim 100\%/\sqrt{E}
d_0 \sim 6+22/p_T \mu m
Primary vtx \sim 10 \mu m
Secondary vtx
r-\Phi \sim 14 \mu m
r-z \sim 50 \mu m

96 layer drift chamber |\eta| ≤ 1.0
44 < r < 132 cm, 30k channels
\sigma(\text{hit}) \sim 150 \text{ mm}
dE/dx for p, K, \pi id

Tile/fiber endcap calorimeter
1.1 < |\eta| < 3.5

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
COT tracks @L1
SVX tracks @L2
30000/300/70 Hz
~no dead time

Time-of-flight
100 ps@150cm
p, K, \pi id

\mu coverage to
|\eta| ≤ 1.5
80% in phi

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D0 Detector Upgrades

4 silicon layers + disks
Suited to limited space
2.8 < r < 10 cm
|η| ≤ 3.0, cosθ = 0.993

2.0 T magnetic field
Lever arm 52 cm

Now! Sci-Fi tracks @ L1
Next! Silicon tracks @ L2
5000/1000/50 Hz

Some resolutions:

p_T ~ (2.0 + 0.2 p_T)%
J/Ψ mass ~ 27 MeV
EM E ~ 15% / √E
Had E ~ 80% / √E
d_0 ~ 13 + 50 / p_T μm
Primary vtx ~ 15 μm
Secondary vtx
r-Φ ~ 40 μm
r-z ~ 80 μm

8 layer Sci-Fi tracker |η| ≤ 1.7
10 < r < 52 cm, 80k channels
VLPC’s at 9K, 85% QE
σ(hit) ~ 100 μm

μ coverage to
|η| ≤ 2.0
90% in phi

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