Luminosity determination at the TEVATRON

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for CDF and D0 collaborations

CDF

DØ

- Tevatron Luminosity
- Reference processes
- L measurement at B0 (CDF)
- L measurement at D0 (DØ)
- Summary

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Tevatron Luminosity in Run II

Run I: $\bar{p}p$ at $E_{cm} = 1.8\text{TeV}$
Run II: $\bar{p}p$ at $E_{cm} = 1.96\text{TeV}$

Current peak Luminosity $\sim 3 \times 10^{31}\text{cm}^{-2}\text{sec}^{-1}$

Expected
$L \sim 2 \times 10^{32}\text{cm}^{-2}\text{sec}^{-1}$
$\mu \sim 6 \text{PPbar}/\text{BC}$
Inelastic cross-section

- $55.50 \pm 2.20$ mb (E710: Phys.Rev.Let, 68, p2433, 1992)
- $60.33 \pm 1.40$ mb (CDF: Phys.Rev.D, 50, p5550, 1994)

measured @1.8TeV using the optical theorem, along with the total & elastic x-sections

What $\sigma_{\text{inel}}$ to use? Run I: CDF(BBC), DØØ (world); Run II (CDF&E811?)

What is the error for $\sigma_{\text{inel}}$? CDF&E811 combined: ~4% (PDG)

For Run II CDF & DØ do not quote the error associated with $\sigma_{\text{inel}}$ yet

Detected with dedicated L monitor at small angles

- real-time, instantaneous&integrated, delivered&live, bunch by bunch luminosity
- $z$ profile of collisions
- minimum bias trigger
inelastic p-pbar (continue)

- Luminosity measurement
  \[ R_{pp} = \mu_{pp} \cdot f_{BC} = \sigma_{\text{inel}} \cdot \varepsilon_{pp} \cdot \delta(L) \cdot L \]
  \(L\) - luminosity
  \(f_{bc}\) - Bunch Crossing rate
  \(\mu_{a}\) - # of pp /BC

- \(\sigma_{\text{inel}} \sim 60\text{ mb}\) hard core
- \(\sigma_{\text{dd}} = 9.54 \pm 0.43\text{ mb}\) double diffractive (CDF, E710)
- \(\sigma_{d} = 9.54 \pm 0.43\text{ mb}\) single diffractive (CDF, E710)
- recent CDF measurement of \(dd\) x-section: PRL 87 141802 (2001) \(\Rightarrow \sigma_{dd} = 7.5 \pm 2.0\text{ mb}\)

\[ \varepsilon_{pp} = \frac{\varepsilon^h \cdot \sigma_h + \varepsilon^d \cdot \sigma_d + \varepsilon^{dd} \cdot \sigma_{dd}}{\sigma_{\text{inel}}} \]

\(\Rightarrow\) requires large acceptance LM or
its normalization against large acceptance detector with \(\varepsilon^h \sim \varepsilon^{dd} \sim 100\%\)

\(\Rightarrow\) \(\varepsilon_{pp}\) can be obtained from simulation with a few percent uncertainty
total expected \(\delta L\) due to uncertainty of \(\sigma_{\text{inel}} \varepsilon_{pp} < 5\%\)
Methods of L measurement with inelastic PPbar

- Counting of BC with no interactions (zeroes):
  - requires large acceptance detector
  - non-linear corrections due to pile-up of PPbar interactions at large $\mu$
  - Used both by DØ and CDF

\[ P_0 = e^{-\mu} \]
\[ \mu = -\ln\left( \frac{N_{zeroBC}}{N_{totalBC}} \right) \]
\[ P_0 = 0.2\% @ \mu = 6 \]

- Counting of hits
  - requires high granularity to achieve low occupancy
  - very non-linear for large $\mu$

\[ \mu = \left\langle \frac{N_{hits/BC}}{N_{hits/pp}} \right\rangle \]

- Counting of “particles”
  - Detector response proportional to energy flux or number of particles
  - best for high $L$ ($\mu \gg 1$)
  - Used by CDF Run II luminosity monitor CLC

\[ \mu = \sum A_i / \left\langle A_{pp} \right\rangle \]
Reference processes: $W \rightarrow \text{lep,nu}$

- **x-section @ 1.96 TeV ~2.73 nb**
  - with ~4% theoretical uncertainty
    - PDF, EWK param, scale variation, higher order corrections

- **Expected rate @L=2 \(10^{32}\) ~ 0.5Hz**
  - good for off-line L

- **Not trivial:**

\[
N_W = L \cdot \sigma(p\bar{p} \rightarrow WX) \cdot B(W \rightarrow e\nu) \cdot \varepsilon_{Et} \cdot \varepsilon_{ET,z} \cdot \varepsilon_{Trk} \cdot \varepsilon_{P_{T}} \cdot \varepsilon_{Isol} \cdot \varepsilon_{ID} \cdot \varepsilon_{Event} \cdot \varepsilon_{Trig}
\]

- **Trigger + selection efficiency ~25%**
- **Background: QCD, Z \rightarrow ll, W \rightarrow \tau\nu,..**

\[\delta L of 5\% is feasible, which is comparable with the inelastic p-pbar\]
Luminosity measurements in Run I

CDF

CDF/PUB/Electroweak/4956 April 1999

- process: inelastic PPbar scattering
- detector: BBC
  - 16X2 scintillating counters
  - Rapidity coverage: 3.24<\(\eta<5.90\)
  - BBC x-section: 51.15 \(\pm 1.60\) mb
    measured along with total, elastic and single diffractive x-section
- method: counting of zeroes
- \(\delta L: 3.6\% (1a), 4.1\% (1b)\)

DØ


- process: inelastic PPbar scattering
- detector: LØØ
  - 36X2 scintillating counters
  - Rapidity coverage: 2.2<\(\eta<3.9\)
  - LØØ x-section: 43.2 \(\pm 2.5\) mb
    determined from MC and world average of the inelastic x-section.
- method: counting of zeroes
- \(\delta L: 5.6\%\)

peak L: \(\sim 3\times10^{31}\)cm\(^{-2}\)sec\(^{-1}\)
integrated L: \(\sim 90\)pb\(^{-1}\)

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Run II integrated luminosity

Delivered $L = 90 \, pb^{-1}$
Run II instantaneous luminosity

CDF Delivered Inst. Lum →
DØ Delivered Inst. Lum →
Delivered Tot. Lum →
CDF MB trigger rate →

GxPB 1: CDF/DØ Luminosity Sep 19 2002

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Run II peak luminosity

Collider Run IIA Peak Luminosity

Graph showing the peak luminosity over time with dates from 04/01/01 to 09/23/02.
LM detector:

- 2 units at small angles
- 24 scintillating counters BC-408 per unit
- Rapidity coverage: 2.7<|\eta|<4.4
- Mesh PMTs Hamamatsu R5505
- Time resolution – 200ps

L measurement:

- counting of empty bunch crossings

Large acceptance

- \( \varepsilon_{hc} = 97\% \), \( \varepsilon_{sd} = 15\% \), \( \varepsilon_{dd} = 70\% \)

Current DØ L uncertainty ~10%

* http://www.hep.brown.edu/lm/detector.htm*
DØ Luminosity Counters

371 mm
CDF Cherenkov Luminosity Counters

- low mass, radiation hard, fast
- insensitive to soft particles (Ch. threshold)
- less sensitive (then SC) to secondary particles
- Amplitude calibration using Ch peak
- rapidity coverage 3.7<h <4.7
- large acceptance for inelastic events
- Several methods of L measurement
  - hits (rates)
  - “particles” (total amplitude/Ao)
  - empty crossings


Isobutane @ 1atm
Light yield ~110 p.e.
The CLC modules

2 modules X 3 layers X 16 counters = 96 counters

Light collector (Al)

50 nm Al + 50 nm MgF₂

Inner CLC assembly

2 cm

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CLC amplitude distribution

- Single Particle Peak (spp)
  - SPP clearly seen after isolation cut
  - Used for amplitude calibration of the counters
Inelastic charge multiplicity ~5 per unit of $\eta$
Total hit multiplicity ~20/side (mainly electrons)

Tuned Pythia (full inelastic)
Summary: CDF Luminosity Uncertainty

<table>
<thead>
<tr>
<th>Systematic error</th>
<th>2 layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLC acceptance (2 layers):</td>
<td>4.0 %</td>
</tr>
<tr>
<td>Geometry &amp; material</td>
<td>3.0 %</td>
</tr>
<tr>
<td>Event generator</td>
<td>2.0 %</td>
</tr>
<tr>
<td>Beam</td>
<td>1.0 %</td>
</tr>
<tr>
<td>CLC simulation</td>
<td>1.0 %</td>
</tr>
<tr>
<td>amplitude calibration</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Detector stability</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Online $\rightarrow$ offline transfer (accounting)</td>
<td>$\sim$ 0 %</td>
</tr>
<tr>
<td>Luminosity method</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Losses</td>
<td>$&lt;1.0$ %</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>4.5 %</strong></td>
</tr>
</tbody>
</table>

The error due to uncertainties in the inelastic x-section is not quoted.

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Measure CLC acceptance using a reference detector with large acceptance ($\epsilon_\text{h} \rightarrow 100\%$) $\rightarrow$ less dependent on simulation

$$\epsilon_{\text{clc}} = \left( \frac{N_{\text{clc}}}{N_R} \right) \cdot \epsilon_R$$

Measure experimentally
Find from simulation

- CLC alone (simulation)
- CLC.AND. plug

Plug threshold: 3 5 10 20 5 5 (GeV)
CLC threshold: 250 250 250 250 200 225 (ADC)

2% acceptance uncertainty is feasible!
Data:
Construct bunch crossings with large $\mu$ superimposing zero bias events at low $\mu$.

Counting of hits:
$\text{<number> of hits /BC}$

Counting of "particles":
Total amplitude / $A_0$
$A_0 = \text{amplitude of single particle peak}$

Precise high luminosity measurement is feasible!
Data Sample:
- Luminosity $\sim 7.5\,\text{pb}^{-1}$
- No. of $W \rightarrow e$: $3493 \pm 75 \pm 296$
- No. of $Z \rightarrow ee$: $186 \pm 14 \pm 10$

$\sigma_Z \times B(Z \rightarrow ee) = 266 \pm 20_{\text{stat}} \pm 20_{\text{syst}} \pm 21_{\text{lumi}}\,\text{pb}$

$\sigma_W \times B(W \rightarrow e\nu) = 2.67 \pm 0.06_{\text{stat}} \pm 0.33_{\text{syst}} \pm 0.27_{\text{lumi}}\,\text{nb}$
W cross section:

\[ \sigma W^* BR(W \to e\nu) \, (nb) = 2.60 \pm 0.07_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.26_{\text{lum}} \]

Background (8\%):
- QCD: 260 \pm 34 \pm 78
- Z \to ee: 54 \pm 2 \pm 3
- W \to \tau\nu: 95 \pm 6 \pm 1

5547 candidates in 10 pb^{-1}
Run I luminosity uncertainty at ~5% level using inelastic PPbar scattering

In Run II two methods of luminosity measurement are available

- *Inelastic Ppbar scattering (on-line, instantaneous, delivered, off-line, …)*
- *W production (off-line)*
- *Yield comparable uncertainty on luminosity of ~5%*

Expected luminosity uncertainty in Run II below 5% level

CDF&DØ are working on nailing down the systematic errors

- *Generators, Simulation, material, thresholds, etc. etc.*

Tevatron luminosity is $3 \times 10^{31}$ and increasing

- *preparation for L measurement in the regime with multiple Ppbar interactions per bunch crossing.*