Linear Collider
Beam Instrumentation Overview

Linear Collider R&D Opportunities Workshop
May 31\textsuperscript{st}, 2002
SLAC

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*with M.Woods and D.Cinabro

- BI Overview
- Beam Energy
- Polarization
- Luminosity

http://physics.uoregon.edu/~torrence/talks/
Beam Instrumentation Topics

- Beam Energy Scale and Width
- Beam Polarization
- Integrated Luminosity and Spectrum

Instrumentation needed for physics...

State of Affairs

- Many conceptual ideas
- Few concrete designs or detailed studies
- First meeting of new study June 26th

http://www.slac.stanford.edu/~torrence/ipbi/

Significant Overlap

- Detector/Physics groups
- Beam delivery/Final focus activities
- Accelerator instrumentation
Beam Energy at LEP II

Production Threshold

Kinematic Fits

Common Scale Uncertainty \( \frac{\delta M_W}{M_W} \approx \frac{\delta E_{Beam}}{E_{Beam}} \)
Hadronic Final States

$$A_{LR} = \frac{1}{P} \frac{N_L - N_R}{N_L + N_R}$$

Leptonic Final States

$Z^0 \rightarrow \mu^+ \mu^- \ 97-98$

Combined

$$\sin^2 \theta_{\text{eff}}^W = 0.23098 \pm 0.00026$$

Still statistics limited...
Linear Collider Requirements

Beam Energy Scale

• $m_t$ from $t\bar{t}$ threshold
• $m_{H}$ from direct reconstruction
• $m_{\text{new}}$ from either

$$\frac{\delta E_b}{E_b} \sim 100-200 \text{ ppm}$$

Polarization

• SM asymmetries ($l^+l^-, q\bar{q}, WW, \ldots$)
• Background suppression of $WW$
• SUSY quantum numbers

$$\frac{\delta P}{P} \sim 0.25 - 0.5\%$$

Luminosity Spectrum

• $m_t$ from $t\bar{t}$ threshold
• most every physics result! (at some level)

Know $dL/dE \sim 1\%$

⇒ Very challenging in LC environment!
### Weak Mixing Angle

<table>
<thead>
<tr>
<th>( \Delta \sin^2 \theta_W )</th>
<th>( \Delta E_{\text{beam}} )</th>
<th>( \Delta P^- )</th>
<th>( \Delta P_{\text{eff}}^+/P_{\text{eff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLD 0.00026</td>
<td>25 MeV</td>
<td>0.50%</td>
<td></td>
</tr>
<tr>
<td>e(^-) only 0.00005</td>
<td>( \sim 5 ) MeV</td>
<td>0.25%</td>
<td></td>
</tr>
<tr>
<td>Blondel 0.00002</td>
<td>( \sim 2 ) MeV</td>
<td>0.25%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

\[
A_{LR} = \frac{1}{P_{\text{eff}}} \frac{N_L - N_R}{N_L + N_R}
\]

where \( P_{\text{eff}} = \frac{P^- + P^+}{1 + P^- P^+} \)

### WW Threshold

\[
\Delta m_W \sim 6 \text{ MeV} \Rightarrow \Delta E_b < 5 \text{ MeV}
\]

### Also Needed

- Low beamstrahlung (separate IP)
- Positron polarization
- Theory improvements

\( \Rightarrow \) Very challenging for BI!
Measurement time scales

- Luminosity averaged - months
- Operator tuning - minutes
- Train-to-train - 10 ms
- Bunch-to-bunch - 1 ns

Correlations between L, E, P need to be understood

Measurement Location

- At IP (luminosity weighted)
- Near IP in final focus (upstream/downstream)
- Elsewhere in machine

Measurement Frequency

- Every pulse - in collision
- Sampled (dropouts?)
- Dedicated runs

⇒ How much time needed for calibration?

Must compare physics needs to operational needs...
Linear Collider
Beam Energy Measurements
(E. Torrence)
Energy needs

- 100-200 ppm absolute energy scale
- pulse-by-pulse relative measurement?
- Detailed width measurement also

Can calibrate at Z-pole ~ yearly?

Potential beam methods

- WISRD-style spectrometer
- LEP-style BPM spectrometer
- Møller/Bhabha scattering target
- ‘Wire’ scanner at high dispersion
- Your good idea???

Potential detector methods

- Radiative return ($\mu^+\mu^-\gamma$) kinematics
- Mu-pair momenta?
Meet the WISRD

Systematic Errors per Beam

\[ \Delta \int Bdl: \quad 100 \text{ ppm} \]
\[ \text{Alignment:} \quad 190 \text{ ppm} \]
\[ \text{Detector - IP:} \quad 135 \text{ ppm} \]
\[ \text{Total:} \quad 250 \text{ ppm} \Rightarrow 12.5 \text{ MeV at 50 GeV} \]

\[ \Rightarrow 1998 \text{ SLC } m_Z \text{ scan implies a } \sim 40 \pm 20 \text{ MeV offset in } E_{CM} \]

NLC Questions

- Stronger bend (and where)?
- Better detector technology
- Possible downstream (in collision)?
- Also measure energy shape?

\[ E_{beam} = \kappa \cdot \frac{l}{x} \cdot \int Bdl \]

\[ \int Bdl = 3.05 \text{ T m} \quad l = 15 \text{ m} \quad x = 27 \text{ cm at 50 GeV} \]
LEPII Spectrometer

- Relies heavily on frequent calibrations
- 1 micron stability for less than 8 hours
- Operated within tight dynamic range
- Beam position and bend held constant

⇒ Very low duty factor for LC operations

RF Spectrometer

- Compact 1m RF BPM triplet blocks
- Chicane layout for better alignment control
- Magnet system more complicated

⇒ 100 nm precision required...
  (assuming 1 mRad bending)
• Use angles only (need IP position)
• Use energy and angles (independent of IP position)

**LEP II Study** [LEP II Yellow Report]

\[ l = 30 \text{ meters} \]
\[ \theta = 2 - 6 \text{ mRad angular acceptance} \]
\[ \sigma_E/E = 3.37/E(\text{GeV})^{1/4} \% \text{ resolution} \]

\[ \Delta E_{stat} = 2\text{MeV in 30 minutes (~600 Hz)} \]
\[ \Delta E_{syst} \sim 2\text{MeV} \text{ (dominated by Fermi motion)} \]

⇒ Complete study for LC needed...
Radiative Returns at LEP

\[ s' = \frac{\sin \theta_1 + \sin \theta_2 - |\sin(\theta_1 + \theta_2)|}{\sin \theta_1 + \sin \theta_2 + |\sin(\theta_1 + \theta_2)|} \]

e^+e^- \rightarrow f \bar{f} \gamma \bar{f}

Statistics

Channel \hspace{1cm} \Delta E_{\text{beam}}

\begin{align*}
q\bar{q}\gamma & \sim 18 \text{ MeV} \\
\mu\mu\gamma & \sim 40 \text{ MeV} \\
e\bar{e}\gamma & \sim 70 \text{ MeV}
\end{align*}

LEP Potential
Statistics Only
2.7 \text{ fb}^{-1}

Systematics

- Theoretical Description
- Hadronization Uncertainties
- Detector Understanding

Opal Estimates
\begin{align*}
q\bar{q}\gamma & \ \Delta E_{\text{beam}} \sim 70 \text{ MeV} \\
\mu\mu\gamma & \ \Delta E_{\text{beam}} \sim 20 \text{ MeV} \\
e\bar{e}\gamma & \ \Delta E_{\text{beam}} \sim 80 \text{ MeV}
\end{align*}

Need absolute \( \theta \) measurement!
Symmetric production: $s' = m_Z^2$, $\Theta_1 = \Theta_2$

<table>
<thead>
<tr>
<th>Collision Energy</th>
<th>$\cos \Theta$</th>
<th>$\Theta$ (mRad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 $m_W$</td>
<td>0.522</td>
<td>1000</td>
</tr>
<tr>
<td>2 $m_t$</td>
<td>0.875</td>
<td>500</td>
</tr>
<tr>
<td>500 GeV</td>
<td>0.937</td>
<td>360</td>
</tr>
<tr>
<td>1 TeV</td>
<td>0.984</td>
<td>180</td>
</tr>
</tbody>
</table>

Need precision and accuracy at small $\Theta$

$\delta \Theta \approx 0.1\%$ per event ($\Gamma_Z$ limit)
Linear Collider Polarimetry
(M. Woods)
Polarization Needs

- $\delta P/P \sim 0.25 - 0.5\%$
- Each helicity state separately
- In vs. out of collision difference?

$\Rightarrow$ $e^+$ polarization a big help!

Location and Technology

- Source - Mott scattering
- Damping ring - Synchrotron?  
- DR - IP - Laser Wire?  
- Interaction point - WW pairs or Blondel ($e^+$)  
- Post IP - Compton scattering

Other issues

- Significant depolarization during collisions
- In-collision measurements desired
- Post-IP environment very difficult
Multiple Detectors

- Čerenkov counter - scattered $e^-$ asymmetry
- Photon counter - integral $\gamma E$ asymmetry
- Quartz fiber calorimeter - transverse $\gamma$ asym.

Unique systematics help reduce errors
Cherenkov Detector

- 45° Al coated Stainless Mirrors
- Phototubes (Hamamatsu R1398)
- Preradiator 7 mm Pb
- Window 0.5 cm Al
- 250 µm Al walls in radiator region. All reflective surfaces coated with 1000 Å pure Al
- Electron (Beam Pipe)
- Proportional Tube Detector
- Pb Shielding
NLC Polarimetry Goals

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$\delta P / P$ SLD</th>
<th>$\delta P / P$ LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzing Power</td>
<td>0.40%</td>
<td>0.20%</td>
</tr>
<tr>
<td>Detector Linearity</td>
<td>0.20%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Laser Polarization</td>
<td>0.10%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Electronic Noise</td>
<td>0.20%</td>
<td>0.05%</td>
</tr>
<tr>
<td><strong>Total Uncertainty</strong></td>
<td><strong>0.50%</strong></td>
<td><strong>0.25%</strong></td>
</tr>
<tr>
<td><strong>IP Corrections</strong></td>
<td><strong>0.15%</strong></td>
<td><strong>&lt; 0.05%</strong></td>
</tr>
</tbody>
</table>

**Improvements**

- Better segmentation in Cherenkov counter
- Better design to define active volume
- Additional $e^-$ detectors?

Kinematics at high energy are favorable!

**Outstanding Issues**

- Extraction line design
- Background tolerance
- NLC bunch structure/timing

$\Rightarrow$ 1-2% depolarization in collision process!
Depolarization Effects

$\Delta P$ vs. $E_{\text{final}}$

K. Thompson
January 2001
SLAC PUB 8716

$\Delta P$ vs. $\Delta y/\sigma_y$

Total Outgoing Bunch $\Rightarrow$

Lumi weighted ~ 25% of bunch average $\Delta P$

Lumi Weighted $\Rightarrow$

How well can this be determined???
$\sigma = 12 - 7 \text{ pb at } \sqrt{s} = 350 - 500 \text{ GeV}$

$\delta P/P < 0.1\%$ for 500 fb$^{-1}$ at 350 GeV (9/1 L ratio)

$\Rightarrow$ Similar with $e^-$ only
Linear Collider
Luminosity Issues
(D. Cinabro)
Luminosity Needs

- Precise knowledge of $dL/dE$ (~ 1%)
- Need to know incoming energy distribution
- Want relative lumi monitor pulse-to-pulse?

Beam Instrumentation

- Beamstrahlung monitors
- Spot size/bunch length/deflection scans
- Pair monitor
- Radiative Bhabha
- Two photon monitor
- ?????

Detector Instrumentation

- Low angle $e^+e^-$ tagger
- Forward tracker ($e^+e^-$ acolinearity)
Beyond ISR

350 GeV Machine + ISR + Beamstrahlung + 0.3% Linac

Pandora
Assuming Gaussian energy spread

$\frac{dn}{dE}$

Luminosity spectrum highly dynamic!
Simple Model (D. Cinabro June 26th)

Flat tail + Gaussian core \( R = \frac{A_{\text{tail}}}{A_{\text{core}}} \)

\[ \frac{dm_t}{dR} = 40 \text{ MeV} / 1\% \]

\[ \frac{d\Gamma_t}{dR} = 100 \text{ MeV} / 1\% \]

Comparable to other systematics
Bhabha rates

- Forward (180-300 mRad) ~ 200 R
- Intermediate (300-800 mRad) ~ 100 R
- Barrel (> 800 mRad) ~ 8 R

Need rates from forward events, but not too far ...

Tracking Based (silicon)

- Excellent angular resolution $\sigma_{s} \sim 0.1\%$?
- Backgrounds and radiation?

Calorimeter Based (energy balance)

- $\sigma_{E}/E < 1\%$ at 100 GeV
- Need well understood acceptance/uniformity
- Need segmentation (backgrounds)

⇒ Detailed studies with backgrounds needed
General Thoughts

• Many conceptual ideas
• Need more concrete planning
• IPBI meeting June 26th to kick this off

Beam Energy

• Where to put spectrometer device?
• Detector requirements for radiative returns
• Other clever ideas???

Polarization

• Possible during collisions?
• Detailed polarimeter design
• Depolarization model

Luminosity

• Very challenging problem
• Large overlap with machine side
• Impacts detector design
• Detailed studies needed now!