Measurement of the integrated luminosity and the luminosity spectrum at the linear collider

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1. Requirements for the luminosity measurement
2. Measurement principle and instrumentation
3. Systematic effects in luminosity measurement
4. Conclusions

Requirements for the luminosity measurement

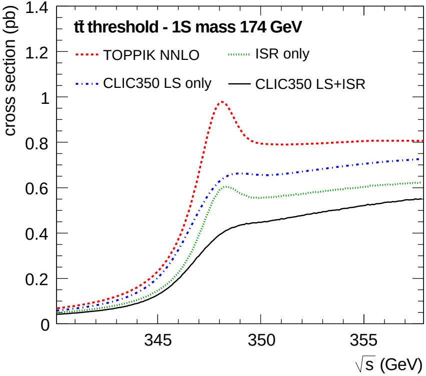
Matching the precision potential of linear colliders

Integrated luminosity

Permille precision required to match the precision of the most planned cross section measurements

Luminosity spectrum

- Requirements quantified per case
- Top-pair threshold scan: peak width uncertainty below 20% required



Influence of the luminosity spectrum on the top-pair threshold scan (source: K. Seidel et al., Eur. Phys. J. C (2013) 73:2530)

Measurement principle and instrumentation

Low-angle Bhabha scattering

- High cross-section → good statistics
- Theoretically well known → precise calculation of xs possible
- Relative uncertainty achieved at LEP $\approx 0.6 \times 10^{-3}$
- Experimental signature: High-energy electrons at low angles in coincidence on both sides of the IP

Angular and energy selection

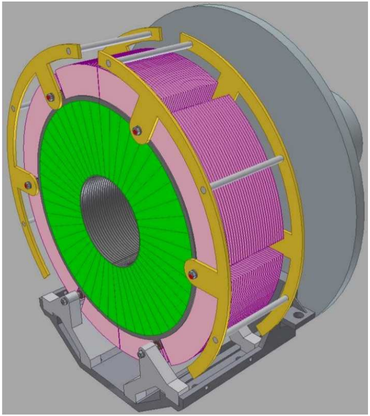
$$L = \frac{N_{Bh}(\Xi(E_{1,2}^{lab}, \Omega_{1,2}^{lab}))}{\sigma_{Bh}(Z(E_{1,2}^{CM}, \Omega_{1,2}^{CM}))}$$

Ξ – Selection function in the experiment
Z – Selection function for the cross-section integration
$E_{1,2}$ – Energies of the final particles
$\Omega_{1,2}$ – Energies of the final particles

Precision depends critically on precise application of Ξ and Z

The luminosity calorimeter

- Twin Si-W sampling calorimeters
- 30/40 layers (ILC/CLIC)
- At ca. 2.5 m from the IP, centered around the outgoing beam
- Segmented in r, ϕ
- Molière radius 11 mm
- Precise reconstruction of the 4-momenta of the showers
- Fiducial volume in the angular range 41–67 mrad (ILC) or 43–80 mrad (CLIC)

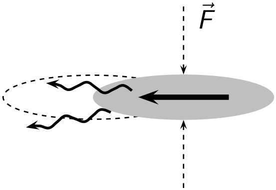


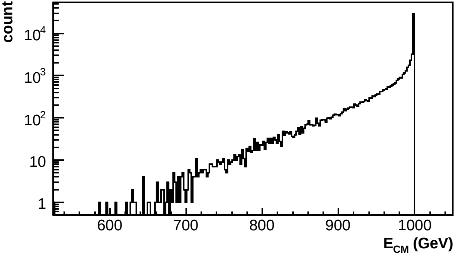
LumiCal sketch

Systematic effects in luminosity measurement

Beam-beam effects at linear colliders

- Transverse component of Lorentz force seen by a bunch scales with the Lorentz factor of the opposing bunch. At future LC, $\gamma \sim 10^{12}$
- "Pinch" effect – strong focusing of the bunches
  - Luminosity enhanced
  - *Beamstrahlung* emission – energy loss by individual electrons in the bunch



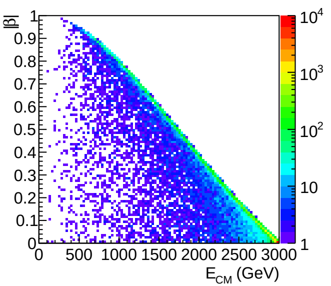


Luminosity spectrum at 1 TeV ILC simulated by Guinea-Pig

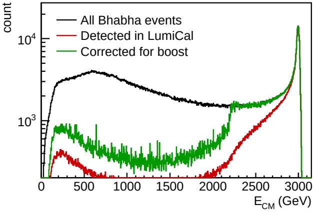
Boost of the event CM frame

- Beamstrahlung is a random process
- Initial electrons often have asymmetric energy loss
- Boost of the CM frame correlated with the energy loss
- Acollinearity of the final particles increases with the boost, → Bhabha counting loss $\mathcal{O}(10\%)$ in the upper 20% of the spectrum
- Boost can be calculated from the final particle angles:
  - **Event-by-event correction** for the effective angular acceptance
  - Uncertainty after correction below 10^{-3}

S. Lukic et al., JINST 8 (2013), P05008

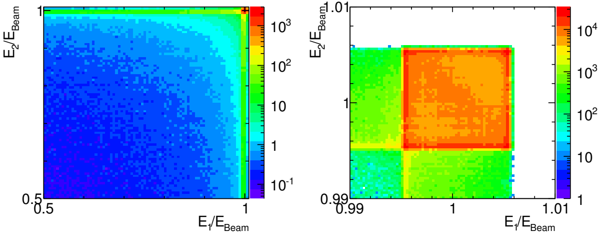


Correlation of the CM energy with the boost of the CM frame after Beamstrahlung



CM energy spectrum of Bhabha events compared to events detected in LumiCal

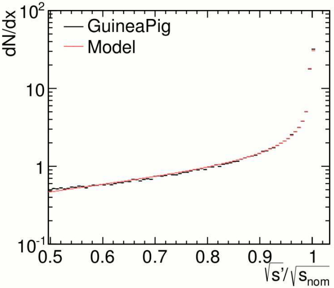
Precise luminosity spectrum shape



2D luminosity spectrum

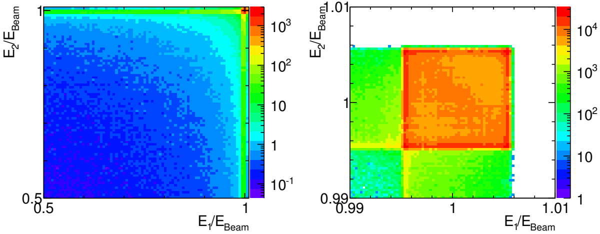
- Use wide-angle Bhabha events
- Fit of a luminosity spectrum model as a function of three observables: Acollinearity and the energies of both final electrons
- Data from the entire detector is used
- Excellent reconstruction of the spectrum shape
- Percent-level precision down to $0.5\sqrt{s_{nom}}$

A. Sailer and S. Poss, LCD-Note-2013-008



Reconstructed spectrum

Precise luminosity spectrum shape



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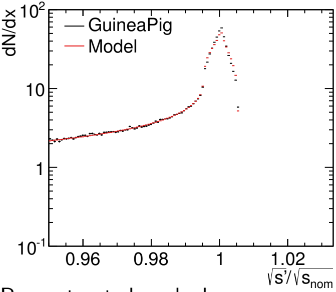
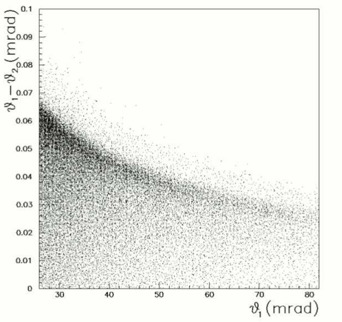


Reconstructed peak shape

Electromagnetic deflection (EMD)

- Deflection of the **final** particles by the EM field of the opposite bunch
- Deflection angles typically below 0.1 mrad
- Counting bias due to the θ^{-3} dependence of the Bhabha cross section
- Can be estimated using simulation of bunch-collision (e.g Guinea-Pig) with uncertainty of a fraction of permille due to beam-parameter uncertainties



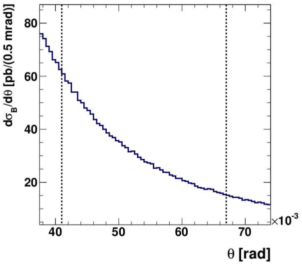
EMD deflection angles vs. Bhabha scattering angle
(C. Rimbault et al, JINST 2 (2007), P09001)

Counting loss due to EMD

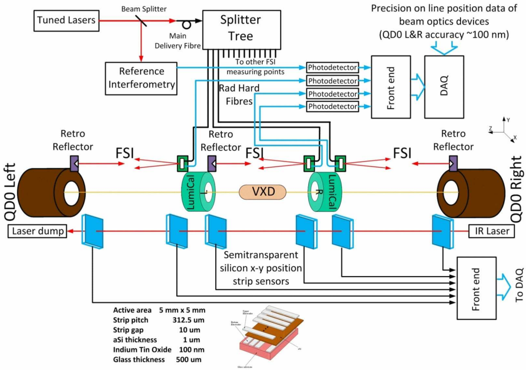
Collider	ILC 500 GeV	ILC 1 TeV	CLIC 3 TeV
$\Delta L_{EMD}/L(10^{-3})$	2.3	1.2	0.5
$\Delta L_{EMD,corr}/L(10^{-3})$	0.5	0.2	–

Positioning uncertainties LumiCal vs. IP

$$\frac{d\sigma_B}{d\theta} \approx \frac{32\pi\alpha^2}{s}\frac{1}{\theta^3}$$



- Inner diameter of the LumiCal FV must be known to better than 4μm
- Relative radial offset IP w.r.t LumiCal precision several 10 μm
- Longitudinal distance between the halves must be known to 100 μm

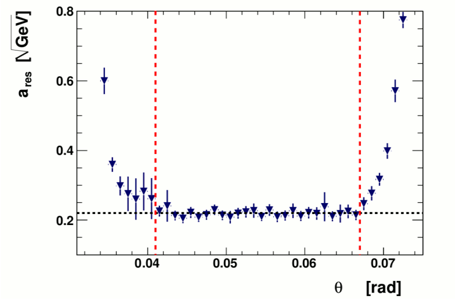


Active area	5 mm x 5 mm
Strip pitch	312.5 um
Strip gap	10 um
aSi thickness	1 um
Indium Tin Oxide	100 nm
Glass thickness	500 um

Laser alignment system for the very forward calorimeters (IFJ PAN, Cracow)

Intrinsic reconstruction uncertainties

- Clustering with logarithmic weighting
  - Polar angle bias: $\Delta\theta = 3.2 \times 10^{-3} mrad$
  - Polar angle resolution: $\sigma_\theta = 2.2 \times 10^{-2} mrad$
- Energy resolution: $\frac{\sigma_E}{E} = \frac{0.21}{\sqrt{E/GeV}}$
  - The shower must be fully contained in the calorimeter – definition of the FV



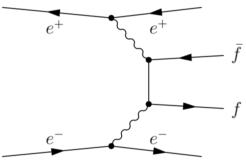
Energy resolution as a function of the polar angle for the ILC LumiCal

Uncertainties of the theoretical calculation

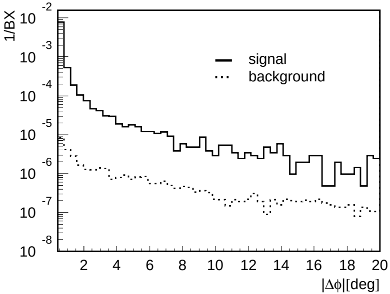
- LEP precision 0.54×10^{-3}
- At future linear colliders, new effects play a significant role:
    - Z-boson exchange
    - Shape of the luminosity spectrum
- New Bhabha generator under development at BSU Minsk
    - Inclusion of small, as well as large angles
    - Luminosity spectrum
    - backgrounds
    - polarization
    - N...NLO

Backgrounds

- Processes mimicking Bhabha event signature
- Dominant type $e^+e^- \rightarrow e^+e^- f\bar{f}$
- Background to signal cross-section ratio of the order 10^{-3}
- Theoretical calculations for the correction as yet unavailable. Precision at LEP: 20% of the full-size background contribution



Multiperipheral (two-boson exchange) process giving the dominant contribution to the background cross section



Acoplanarity distribution of the Bhabha signal and the 4-fermion background detected under the same conditions

- Rejection based on acoplanarity and the CM energy removes up to 60% of the background
- Final **uncorrected** background contribution 2.2×10^{-2} at 500 GeV ILC, or 0.8×10^{-2} at 1 TeV ILC

An early calculation of the total uncertainty at ILC

Source of uncertainty	500 GeV (10^{-3})	1 TeV (10^{-3})
Bhabha cross section	0.54	0.54
Polar-angle resolution	0.16	0.16
Polar-angle bias	0.16	0.16
IP lateral position	0.1	0.1
IP longitudinal position	0.1	0.1
Energy resolution	0.1	0.1
Energy scale	1	1
Beam polarization	0.19	0.19
Correction of angular losses due to the boost of the CM frame	0.4	0.7
ISR deconvolution	0.4	0.8
EMD correction	0.5	0.2
Physics background (uncorrected)	2.2	0.8
Total	2.6	1.8

H. Abramowicz et al., JINST 5 (2010), P12002
I. Božović-Jelisavčić et al., JINST 8 (2013), P08012
S. Jadach, hep-ph/0306083

Conclusions

- Integrated luminosity precision requirement: 10^{-3}
- Significant results towards this goal for the peak of the spectrum
- Method for precise luminosity spectrum reconstruction demonstrated
- The two measurements can be combined for a precise absolute luminosity spectrum down to $1/2\ \sqrt{s_{nom}}$
- Open issues:
    - Precise calculation of the background contribution
    - Measurement of the tail of the luminosity spectrum (large acollinearities – must measure at large angles – vulnerable to backgrounds)