Correction methods for counting losses induced by the beam-beam effects in luminosity measurement at ILC

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Outline

- Introduction
- Luminosity measurement and beam related effects
- Event simulation details
- Collision-frame method (corrects for the beamstrahlung and ISR)
- Correction for EMD
- Conclusion

Introduction

Luminosity measurement at ILC - measurement of event rate of the Bhabha scattering (Bhabha counts) in the very forward region of the detector - $\mathcal{L}_{int} = \frac{N_{th}}{\sigma_{Bh}}$.

Very strong beam-beam space charge effects in e^-e^+ collisions at ILC energies introduce counting losses.

beam-beam effects → CM system ≠ lab system → θ boost → counting loss

Solution: to find a reference frame accessible to both experiment (N) and theory (σ) → **collison frame**

Collision-frame method to correct for counting losses induced by beam related effects in the luminosity measurement at ILC will be discussed. In this method, the velocity of the collision frame of the Bhabha scattering can be experimentally determined, and the corresponding counting loss can be calculated and corrected event by event.

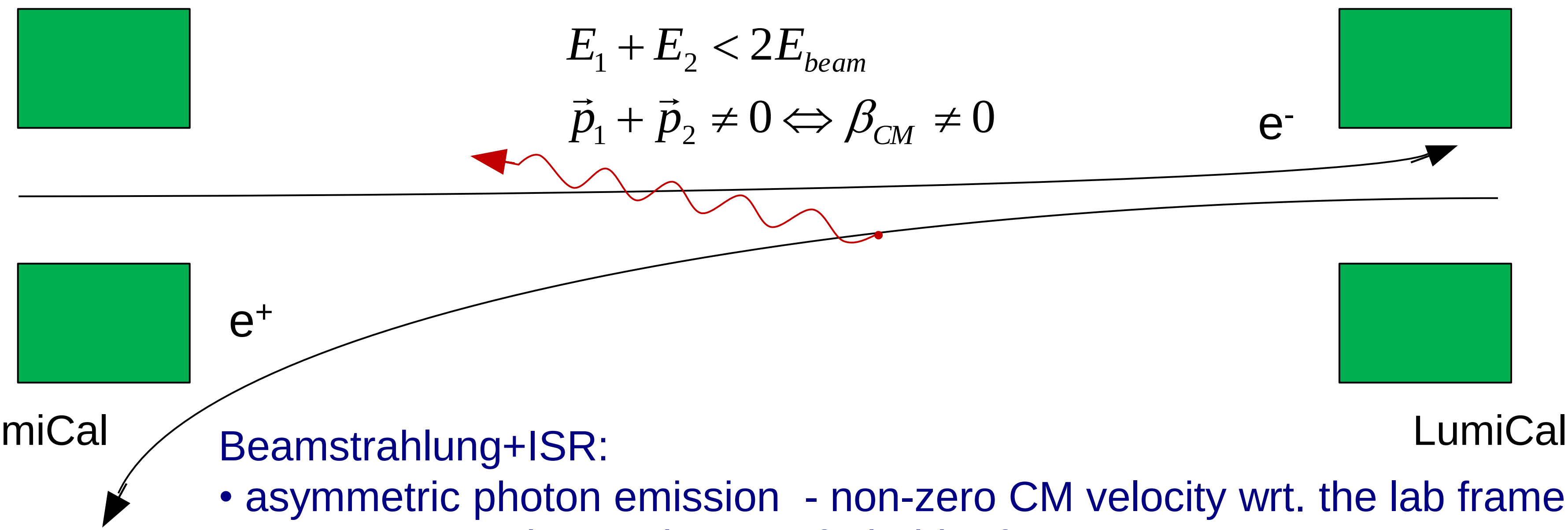
Collision-frame method doesn't correct for electromagnetic deflection. Therefore, an additional method for the correction of that effect will be also discussed.

Luminosity measurement and beam related effects

Integrated luminosity can be determined from the total number of Bhabha events produced in the acceptance region of the luminosity calorimeter and the corresponding theoretical cross-section:

$$\mathcal{L}_{int} = \frac{N_{th}}{\sigma_{Bh}}, \text{ but in reality, } \mathcal{L}_{int} = \frac{N_{\exp} - N_{bcg} - \ldots}{\varepsilon \sigma_{Bh}}.$$

Beamstrahlung, ISR and electromagnetic deflection (EMD) cause deviation from the ideally symmetric kinematics of the Bhabha process and, therefore, counting losses.



Beamstrahlung+ISR:

- asymmetric photon emission - non-zero CM velocity wrt. the lab frame

Consequences due to change of Bhabha four-vectors:

- counting loss (change of Bhabha polar angles)
- energy loss

Event simulation details

GuineaPig is used to simulate events with nominal ILC beam parameters and with beam imperfections.

• Events were generated with the scattering angle in the collision frame between 37 and 75 mrad.

• The standard beam parameter set from the ILC Technical Progress Report 2011 was used as the basis for both 500 GeV and 1 TeV.

Beam imperfections:

• bunch size and charge are varied by up to 20%;

• beam offset in x- and y-direction is varied by up to one respective bunch RMS width.

• 25 sets of beam parameters for each of the two energy options.

• Between 1.5 and 4 million Bhabha events in each simulation.

Event simulation details

The interaction with the detector was approximated as follows:

• The four-momenta of all photons (including the synchrotron radiation emitted due to EMD) found in the 5 mrad (Moliere radius of the high-energy showers in the LumiCal) cone around Bhabha adds up to the Bhabha four-momentum;

• The beamstrahlung photons were not included as they are emitted close to the beam axis (200-300 μrad);

• Assuming the Gaussian distribution of reconstructed energies, particle's energy is smeared to include for the LumiCal resolution effects;

• The finite angular resolution of the LumiCal was included by adding random fluctuations to the final particle polar angles. The nominal value of $\sigma_\theta = 2.2\times10^{-5}$ rad* estimated for the ILC version of LumiCal was used.

* I. Sadeh, Luminosity Measurement at the International Linear Collider, MSc thesis, Tel Aviv University, 2008.

Collision-frame method

• In the CM frame of the e^+e^- system after emission of ISR and before emission of the FSR – ***collision-frame***, the deflection angles in the collision are the same for both particles, according to the momentum-conservation principle, characterized by the unique scattering angle θ^{coll} .

• Velocity of the collision frame wrt. to the lab frame, β_{coll}, can be calculated for each event to a good approximation from measured polar angles and then used to calculate weighting factor to compensate for the loss event-by-event.

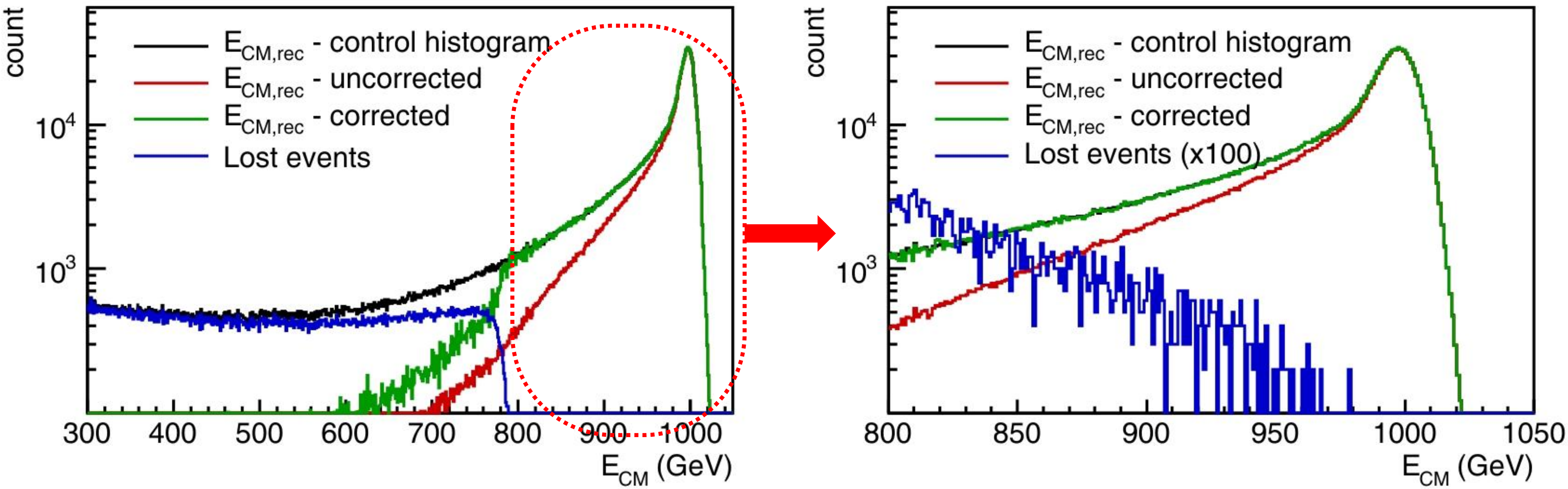
• β_{coll} is taken to be collinear with the z-axis (beam axis)

$$\beta_{coll} = \frac{\sin(\theta_1^{lab} + \theta_2^{lab})}{\sin\theta_1^{lab} + \sin\theta_2^{lab}}$$

$$w(\beta_{coll}) = \frac{\int_{\theta_{\min}}^{\theta_{\max}} \frac{d\sigma}{d\theta} d\theta}{\int_{\theta_{\min}^{coll}}^{\theta_{\max}^{coll}} \frac{d\sigma}{d\theta} d\theta}$$

Collision-frame method

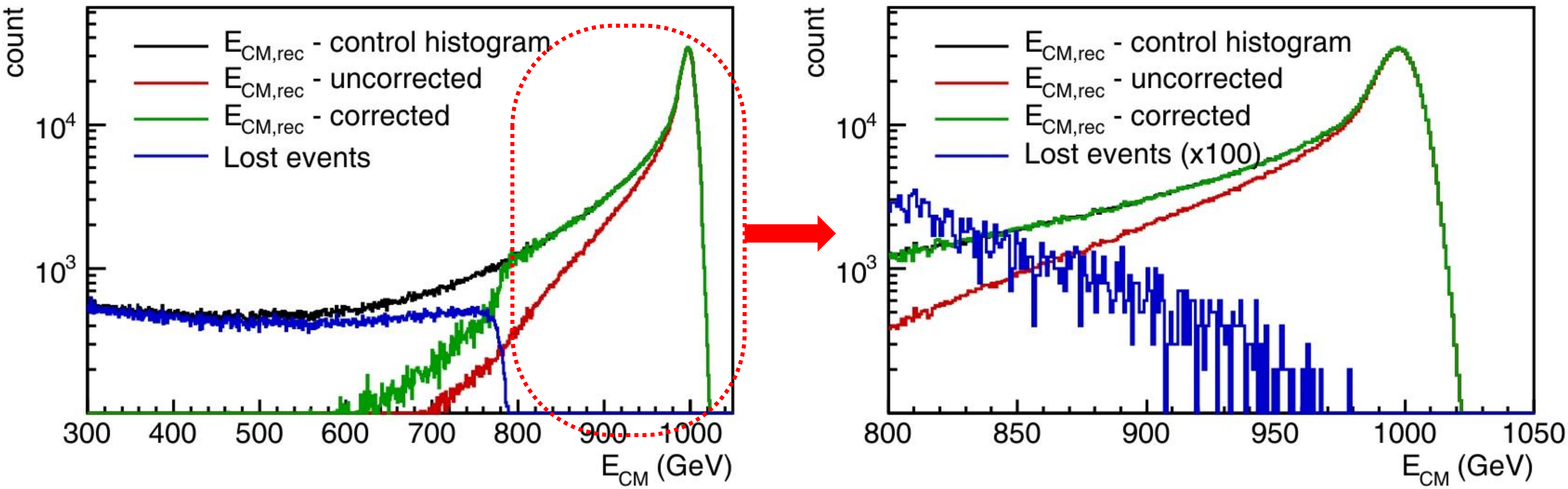
Following histos illustrate how efficiently this method corrects for counting losses:



Control histogram: All events that would hit the FV in the absence of the beamstrahlung and ISR - no counting losses – possible only in the simulation.

Collision-frame method

Following histos illustrate how efficiently this method corrects for counting losses:



Events affected by the beam related effects: Counting losses present up to highest energies (causing the counting loss of ~10% in the FV)

Collision-frame method

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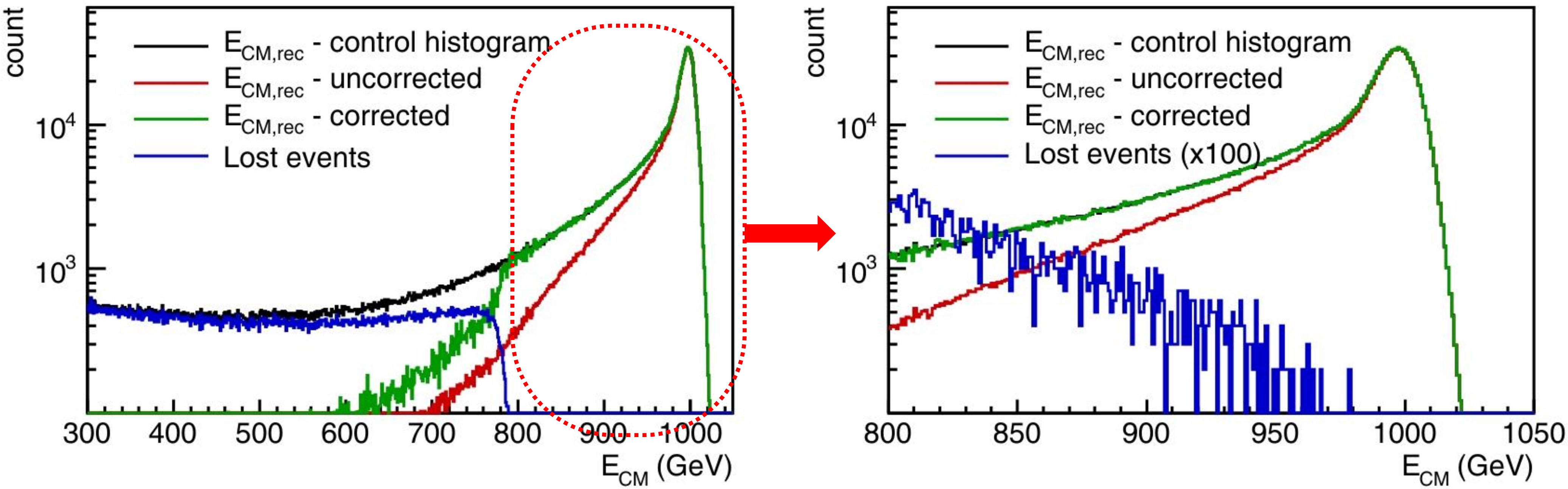
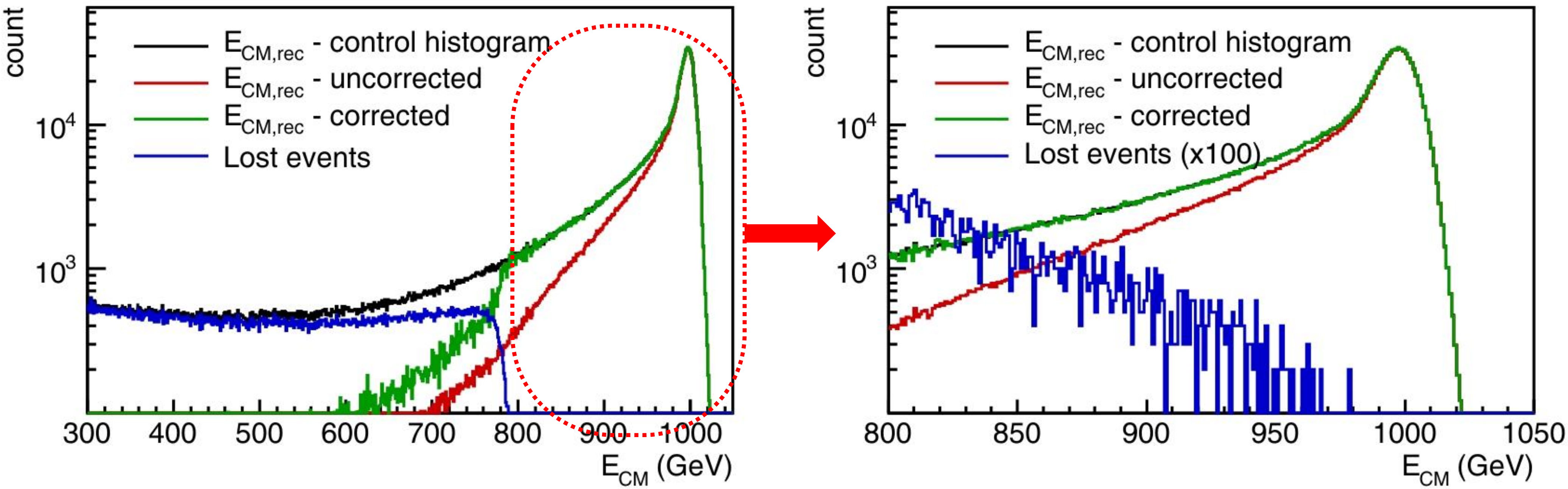


Weighted events: Events in the FV of the LumiCal in the lab frame, after weighting with *w.*

Collision-frame method

Following histos illustrate how efficiently this method corrects for counting losses:



Lost events: if β_{coll} is high enough, events can not be recovered in LumiCal, so significant part of low-energy (below ~780 GeV) spectrum is lost.

- A small fraction of lost events at energies above ~780 GeV (right figure) – relatively high radial component of β_{coll} - breaks the assumption that the β_{coll} is collinear with the beam axis.
- For events with energy above 80% of the nominal E_{CM} the relative bias due to such events is $(-1.29 \pm 0.03) \times 10^{-3}$ in the 1 TeV case, and $(-1.36 \pm 0.03) \times 10^{-3}$ in the 500 GeV case.

Collision-frame method

Sources of systematic uncertainty:

1. The assumption that β_{coll} is collinear with the beam axis induces a systematic bias of approximately -1.3‰ (the variation of this bias with the beam-parameter variation is smaller than 0.1‰),

2. The use of the approximate angular differential cross section for the Bhabha scattering in the calculation of *w*,

3. Assumption that all ISR is lost, and all FSR is detected, in the calculation of β_{coll} and *w*.

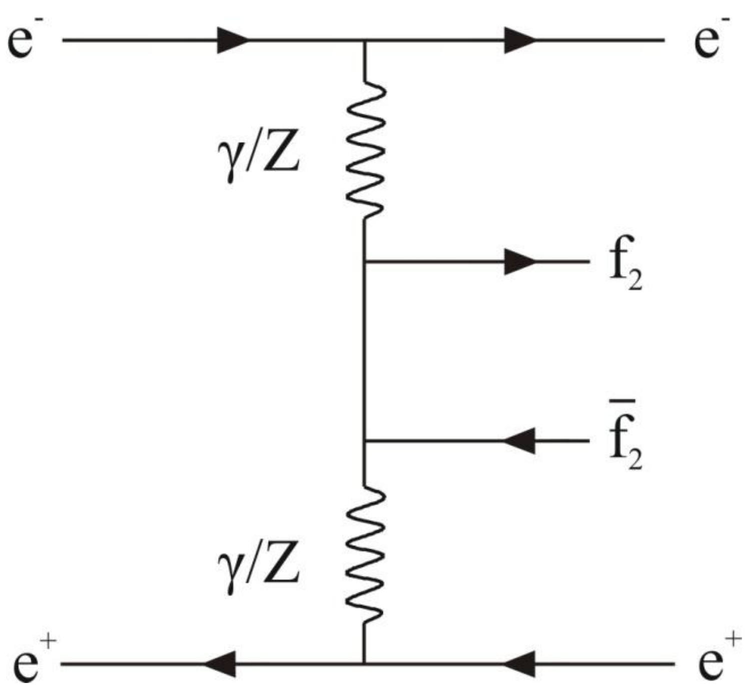
• The bias (1) can be **corrected by simulation**. After correction (including 2 and 3), the uncertainty of the method is 0.09‰ for 500 GeV, and 0.1‰ for 1TeV.

Collision-frame method – physics background

• Four-fermion NC processes $e^+e^- \to e^+e^- f\bar{f}$ - the main source of physics background for the luminosity measurement

• dominated by the multiperipheral processes (2-photon exchange)

• electron spectators can be miscounted as Bhabhas



• Some additional cuts needed to suppress the physics background

• Collision-frame method is Lorentz invariant $\to$ cuts should be Lorentz invariant as well

Collision-frame method – physics background

Cut on acoplanarity:

- Acoplanarity, $|\pi - |\Phi_1 - \Phi_2|| < \Delta\Phi_{max}$

- This criterion suppresses events that have radiated significant off-axis ISR before collision - reduces the fraction of lost events.

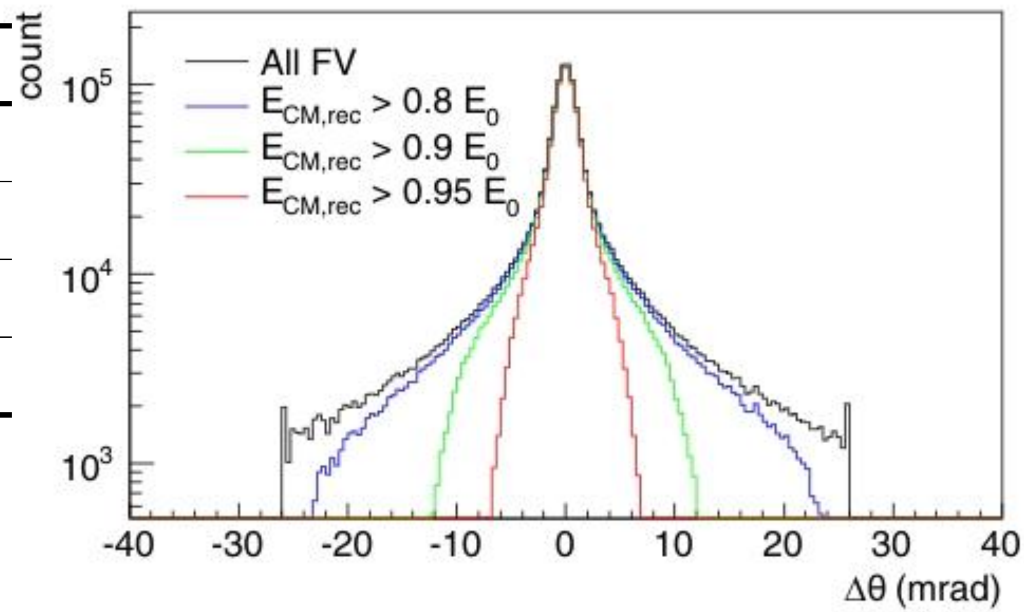
$\Delta\phi_{max}$ (°)	$(\Delta N/N)_{lost} \cdot 10^{-3}$	$N \cdot 10^6$
π (any acoplanarity)	1.34±0.03	1.358
57.3	1.18±0.03	1.358
10	0.59±0.02	1.354
5	0.36±0.02	1.346

Cut on CM energy:

- LEP-type cuts (relative energy, accolinearity) doesn't work – not Lorentz invariant

- Figure shows the simulated distribution of the parameter $\Delta\theta = \theta_2 - \theta_1 - \pi$ for several different cuts on E_{CM}.

- Event weighting from the collision-frame method was applied.



Correction of the EMD component

Electromagnetic deflection (EMD)

• deflection of outgoing Bhabhas due to the interaction with the EM field of the opposite beam

• Consequence - systematic error in counting: deformation of polar angles

$$(\Delta\theta)_{EMD} \sim 0.1\, mrad$$

Correction of the EMD component

• EMD shifts the polar angles of the outgoing particles towards smaller angles

• due to the Bhabha cross section θ dependence ($\sim 1/\theta^3$),the net result of EMD is an effective decrease in the Bhabha count

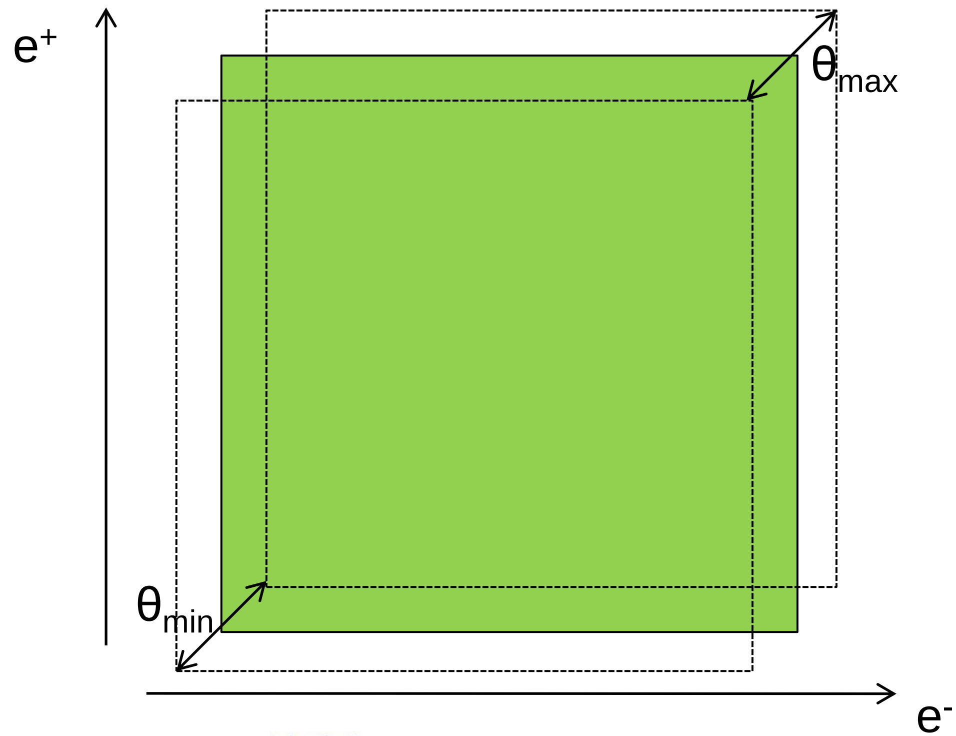
• equivalent to a parallel shift of θ_{min} and θ_{max} (fiducial volume of LumiCal) by an effective mean deflection Δθ in the opposite directions

• a quantity to measure: $x_{EMD} = \frac{1}{N}\frac{\Delta N}{\Delta\theta}$, where N is the Bhabha count in the fiducial volume, Δθ is a parallel small shift of both θ_{min} and θ_{max} and ΔN is the difference in counts in the “real” and shifted FV.

Correction of the EMD component

Obtaining x_{EMD}:

• shifting the FV for small increments θ_{shift} and counting the number of events N_{shift} for each θ_{shift}
• calculate $\Delta N = N_{shift} - N_{FV}$, where N_{FV} is the count in FV
• fitting the slope $\Delta N/\Delta\theta_{shift}$
• This can be done both with simulated and experimental data.



Correction of the EMD component

- Calculate the EMD component of the BHSE in the simulation as $(\Delta L/L)_{sim} = (\Delta N/N)_{sim}$
- From the quantities obtained in the simulation, calculate the effective mean deflection as:

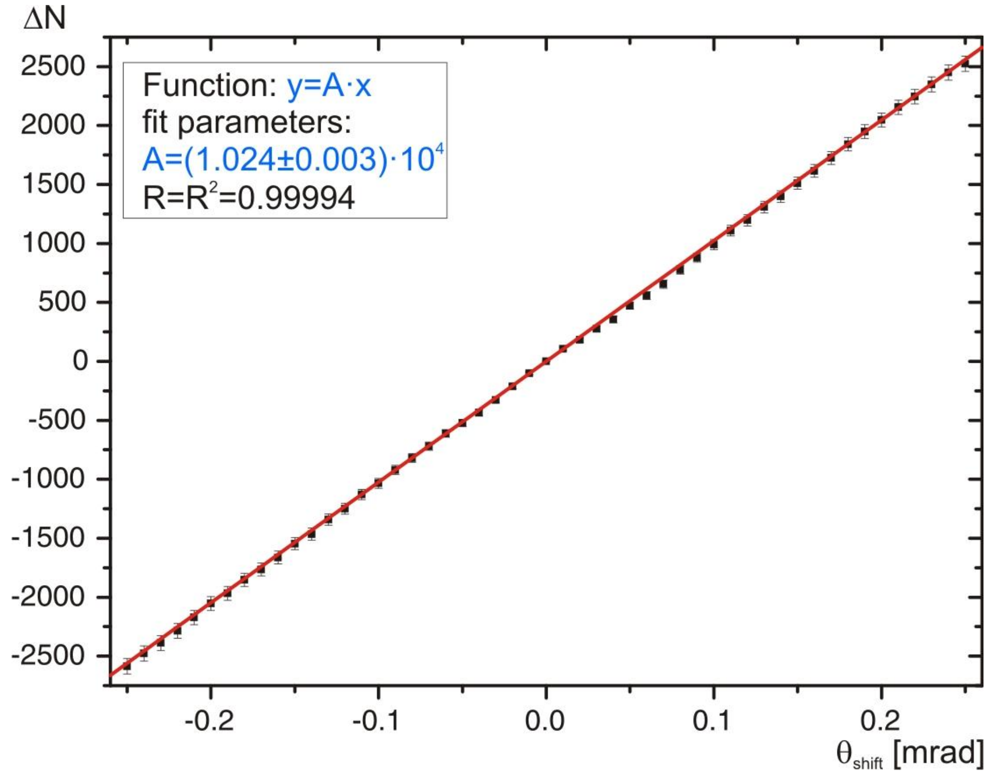
$$(\Delta\theta)_{sim} = \frac{(\Delta L / L)_{sim}}{\left(\frac{1}{N}\frac{dN}{d\theta}\right)_{sim}}$$

- In the experiment, obtain $(dN/d\theta)_{exp}$ in the analysis

- Calculate the EMD component in the experiment as:

$$\left(\frac{\Delta L}{L}\right)_{\exp} = \left(\frac{1}{N}\frac{dN}{d\theta}\right)_{\exp} (\Delta\theta)_{sim}$$

Correction of the EMD component

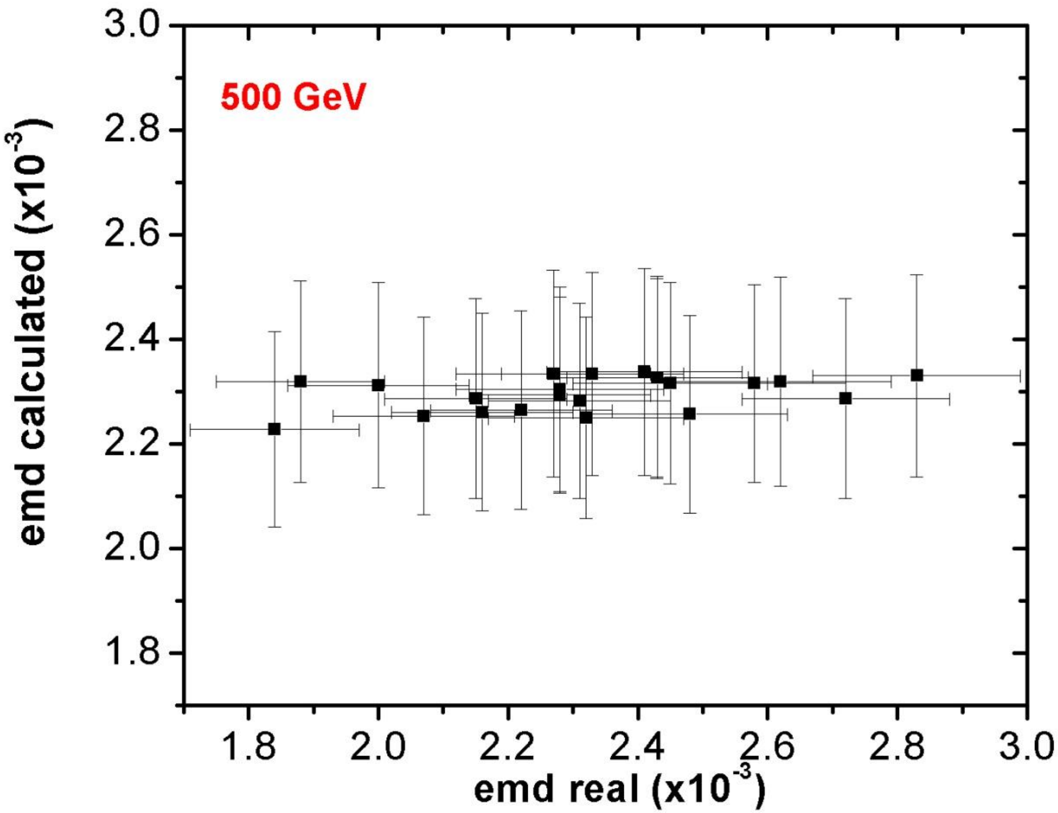


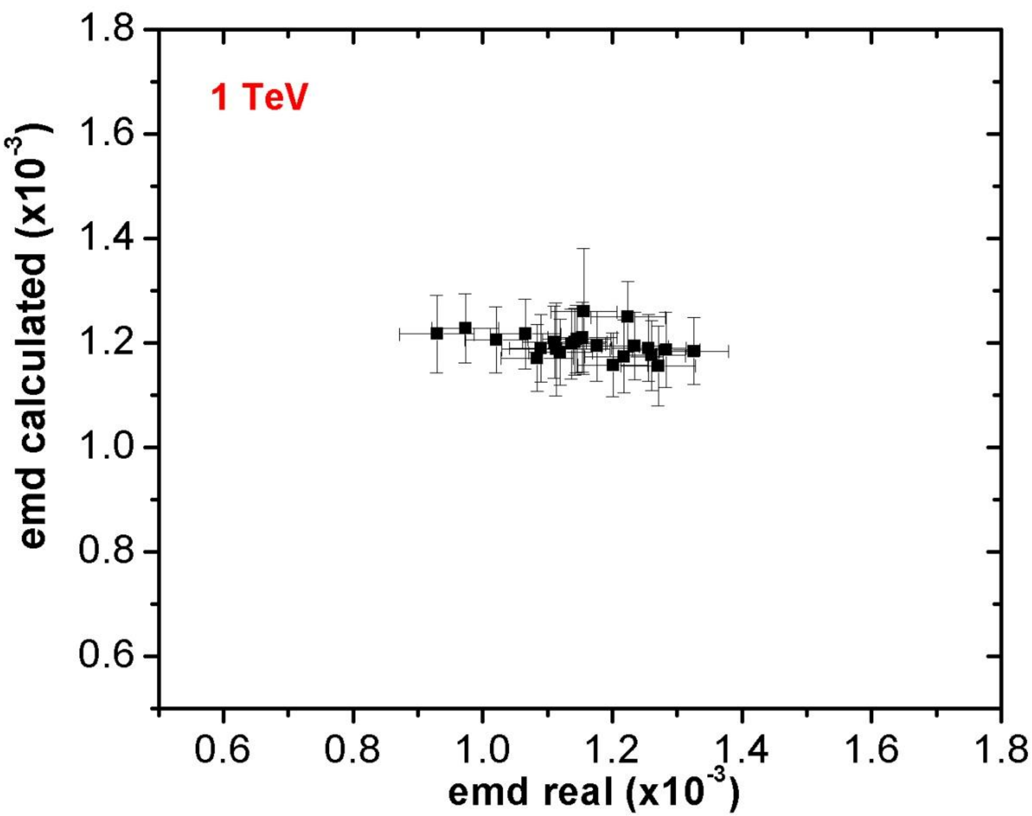
500 GeV case:

- $dN/d\theta=(1.024\pm0.003)\cdot10^{4}$ mrad^{-1}
- number of counts in the FV in the simuilation $N_{FV}\approx165000$
- uncorected EMD contribution to the luminosity uncertainty: $(2.29\pm0.14)\cdot10^{-3}$
- resulting effective mean deflection $\Delta\theta=(0.0367\pm0.0023)$ mrad

- uncertainty of $\Delta\theta$ comes from the limited statistics in the simulation, and contributes to a relative uncertainty in luminosity of $(\Delta L/L)\sim2\cdot10^{-4}$ (500 GeV case) and $(\Delta L/L)\sim1\cdot10^{-4}$ (1 TeV case).

Correction of the EMD component





- $\Delta\theta$ value obtained with the nominal beam parameters
- various beam imperfections assumed
- figure shows that beam imperfections contribute to the uncertainty
- error on EMD estimate due to the beam imperfections (including the error of $\Delta\theta$) results in uncertainty of $\pm 5 \cdot 10^{-4}$ of the total luminosity (500 GeV case) and $\pm 2 \cdot 10^{-4}$ (1 TeV case)

Summary

METHOD	ΔL/L, 500 GeV (‰)	ΔL/L, 1 TeV (‰)
No corrections	~128 (12.8%)	~140 (14%)
Collision-frame method, weighted events	1.4	1.3
Collison-frame method + corrected bias	0.5	0.2
EMD correction	0.5	0.2
Collision frame + corrected bias + EMD correction	0.7	0.3
Total (including background corrections)	2.4	0.9

Conclusion

- **Collision frame method** corrects for angular counting losses due to beamstrahlung and ISR in simulation-independent manner.

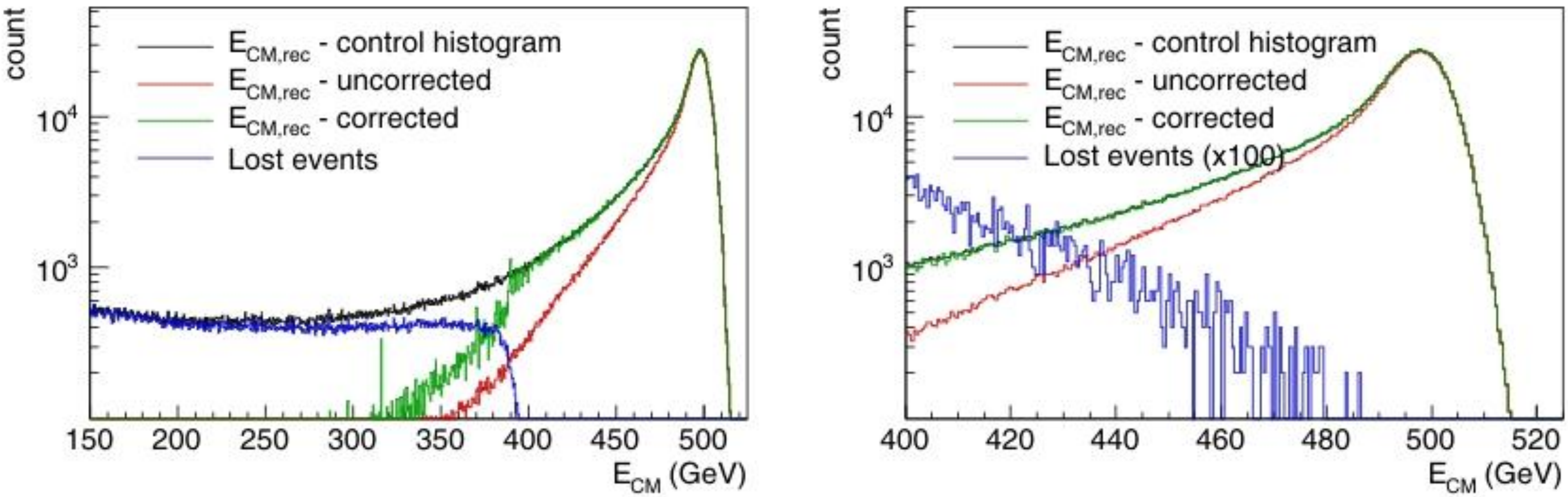
- The two simulation-dependent corrections (for the bias of the method and EMD correction) additionally reduce the uncertainty.

- **Combining collision frame method with selection cuts that suppress physics background, we can propose the selection for luminosity measurement at ILC that minimizes uncertainties related to the beam induced effects.**

Thanks!

Backup

Collision-frame method



Correction of counting losses at 500 GeV

The compensation method

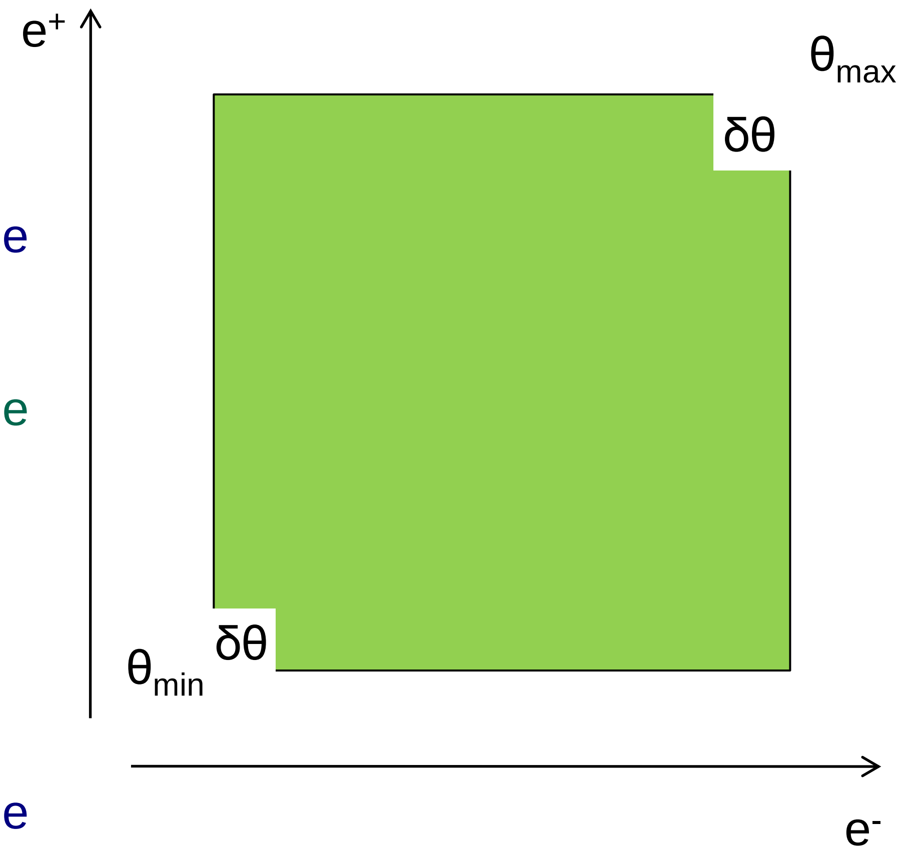
- Inspired by LEP-type (OPAL, DELPHI and L3) asymmetric selection algorithms

- Based on appropriately tailored counting volume

- Compensates between beamstrahlung and EMD.

- Counting volume can be tuned to reduce the counting sensitivity to beam parameters.

- The method has a possibility to reduce the counting loss to zero.



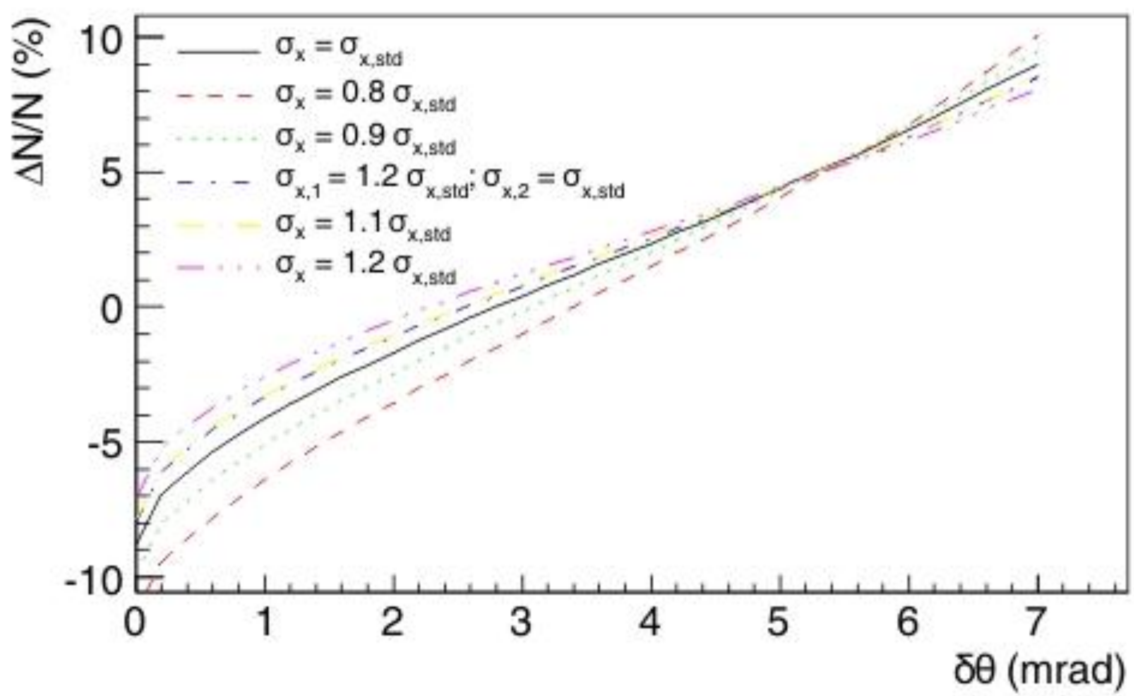
Disadvantages:

- $\delta\theta$ is optimized using simulation.

- More complex theoretical estimation of the Bhabha x-section for a 'dented volume'.

The compensation method

Total (Beamstrahlung and EMD) counting bias as a function of δθ for five different simulated bunch widths σ_x:



When the entire set of beam imperfections is taken into account, taking δθ = 5.6 mrad in the 1 TeV case count variation with respect to the standard beam parameters is 2.4 ‰. Similarly, in the 500 GeV case, δθ = 4.6 mrad results in the maximum counting variation of 2.8 ‰.

The luminosity spectrum method

Motivation:
Counting loss due to beam related effects is correlated with the radiative energy loss*.

• Beamstrahlung component estimated by measuring the ratio between integrals of the reconstructed luminosity spectrum in the tail and in the peak.

• The correlation with the counting loss is determined using simulation.

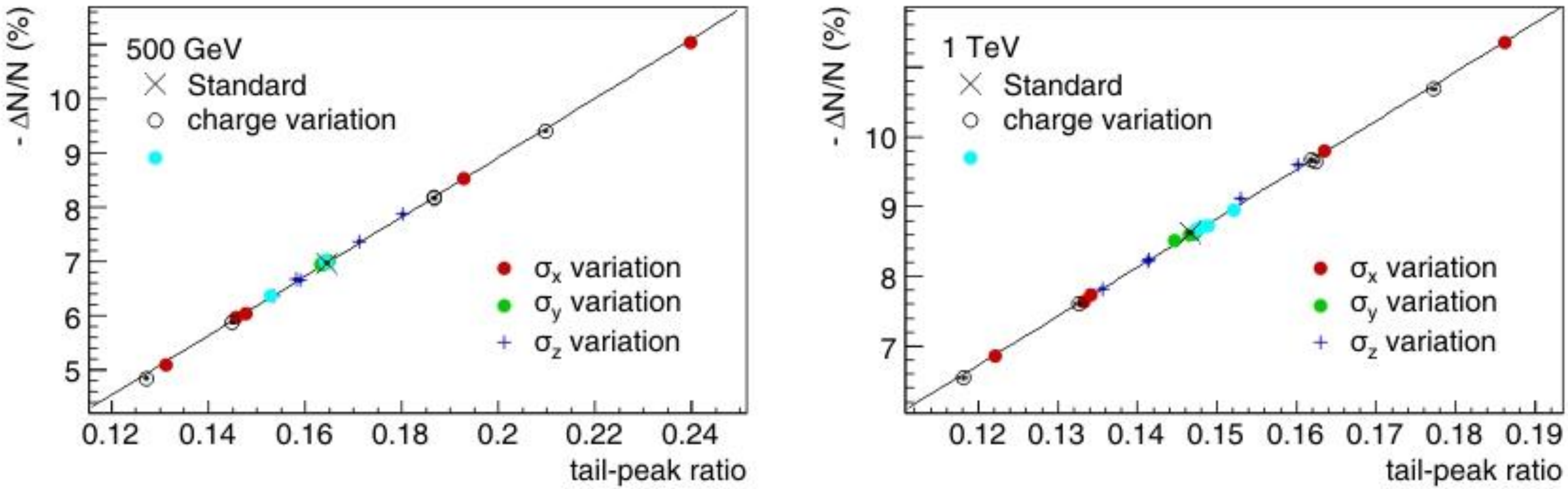
• Tail integral range: 400 to 475 GeV (500 GeV case); 800 to 945 GeV (1 TeV case)

• Peak integral: from 475 GeV upwards (500 GeV case); 945 GeV upwards (1 TeV case).

• These energy ranges of the tail and the peak are optimized to ensure a correlation stays as linear as possible in the presence of beam imperfections.

* Proposed in C. Rimbault, P. Bambade, K. Mönig, D. Schulte, Impact of beam-beam effects on precision luminosity measurements at the ILC, Journal of Instrumentation 2 (09) (2007) P09001.

The luminosity spectrum method



• Linear correlation - beamstrahlung in the integral measurement can be estimated from the mean value of the tail-to-peak ratio, regardless of the fluctuations of the bunch parameters.

• In the 500 GeV case, the maximum residual difference of the simulated beamstrahlung from the fitted values is 0.86 ‰ of the total luminosity, and in the 1 TeV case, 0.79 ‰ of the total luminosity.

•The deviations for all points correspond well to expected deviations from the statistical uncertainties of the simulated counting bias, and the errors of the fit parameters.

Luminosity spectrum method

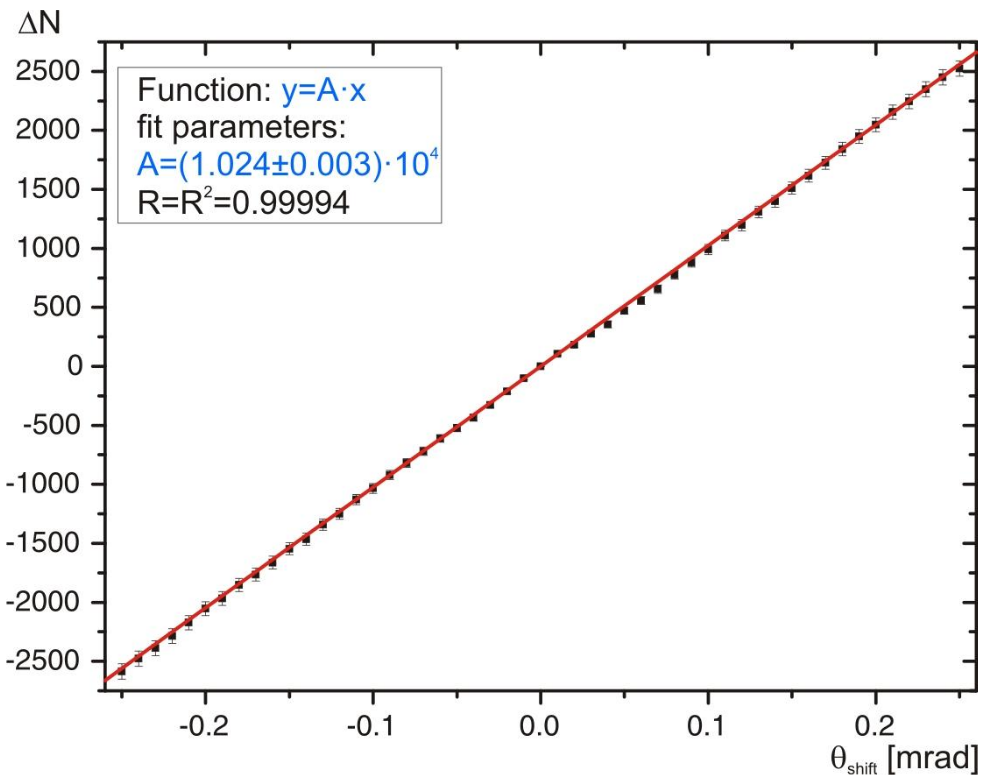
The CM energies are reconstructed as in *:

$$\frac{\sqrt{s'}}{\sqrt{s}} = \sqrt{1 - 2\frac{\sin(\theta_1 + \theta_2)}{\sin(\theta_1 + \theta_2) - \sin\theta_1 - \sin\theta_2}}$$

where θ_1 and θ_2 are are polar angles of the final state charged particles.

* K. Mönig, Measurement of the differential luminosity using bhabha events in the forward-tracking region at TESLA (LC-PHSM-2000-60-TESLA).

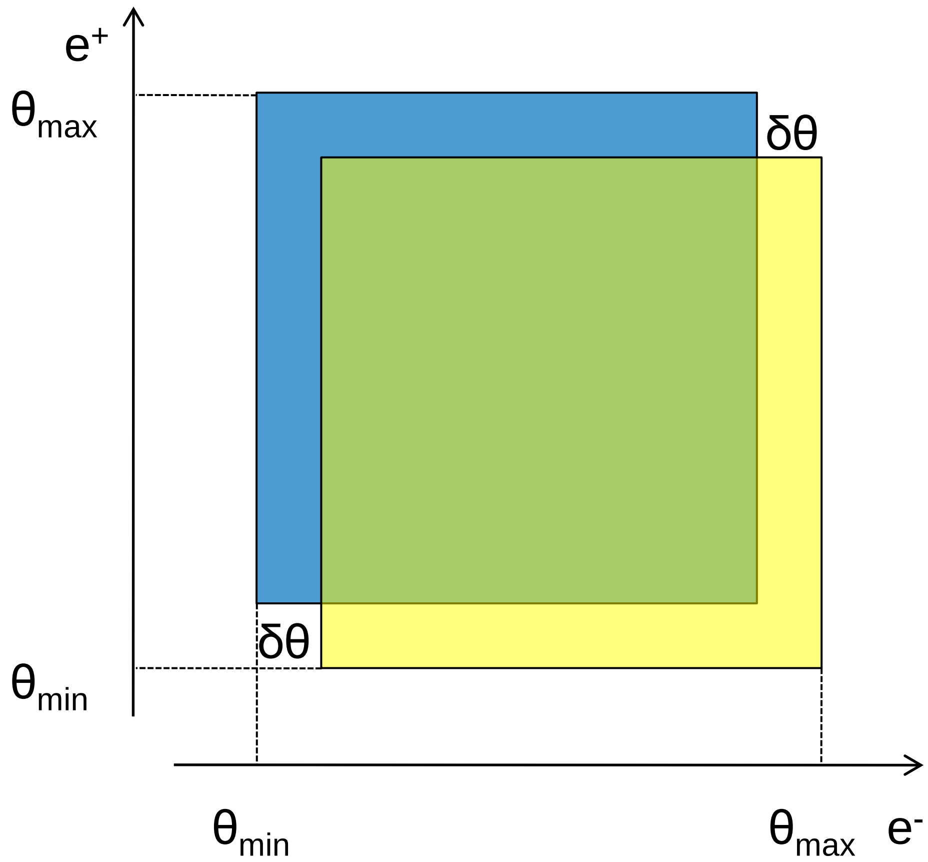
Getting the EMD component of the BHSE



$\Delta N = N_{shift} - N_{FV}$, the difference between counts in the shifted FV ($\theta_{min}+\theta_{shift}$, $\theta_{max}+\theta_{shift}$) and real FV ($\theta_{min}$, θ_{max})

statistical errors of ΔN were estimated as $\delta(\Delta N)=\sqrt{(n_{shift}+n_{FV})}$, because $N_{shift}=N'+n_{shift}$ and $N_{FV}=N'+n_{FV}$, and N' is the number of events inside the intersection of the FV with the shifted FV.

The compensation method



• More complicated theoretical estimation of the Bhabha x-section for a 'dented volume':

$$\sigma_{Bhabha} = \sigma_{blue} + \sigma_{yellow} - \sigma_{green}$$