Estimation of systematic uncertainties in the integral luminosity measurement at CEPC

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[This talk is based on study by S. Lukic (VINCA Belgrade) presented in numerous occasions at CEPC LumiCal meetings
http://indico.ihep.ac.cn/category/323/]

Luminosity measurement based on Bhabha scattering is a counting experiment

$$\mathcal{L} = N_{Bh} / \sigma$$

Where,

- N_{Bh} is Bhabha count is the certain phase space and within the detector acceptance region
- σ is the theoretical cross-section in the same geometrical and phase space (keep it simple)
- Both have to be known at the $10^{-3(\text{or } -4)}$ level

But:

- In N_{Bh} miscounts from various sources are contained (physics background, off-momentum electrons + Bhabha) : $N_{Bh} \rightarrow N_X$
- To correct for it (recover N_{Bh}) implies that effects are known at the $10^{-3(\text{or } -4)}$ level

Also:

- Detector identification efficiency is not a 100%, $\sigma \rightarrow \varepsilon_{ff.}\ \sigma$
- How well do we know detector acceptance (IP, detector positioning issue)?
- How well do we know available center-of-mass energy?
- If any criteria on Bhaha energy or polar angle is applied, what is the impact of the uncertainty of these observables on $\mathcal{L}$ measurement?

All in all, event counting becomes nontrivial if you are allowed to be mistaken 1 in 1000 or 10000

A long list of sources of integral luminosity systematic uncertainties:

1. Beam related:

- Beam energy spread
- Bias of the beam energy
- IP position displacement and fluctuations
- Beam size at the IP
- Uncertainty of the (eventual) beam polarization

2. Detector related:

- Uncertainty of the LumiCal inner radius
- Positioning of the LumiCal (longitudinal L-R distance, radial detector displacements)
- Mechanical fluctuations of the LumiCal position w.r.t the IP (vibrations, thermal stress)
- Tilt and twist of the calorimeters
- Uncertainty of the sampling term
- Detector performance: energy and polar angle resolution

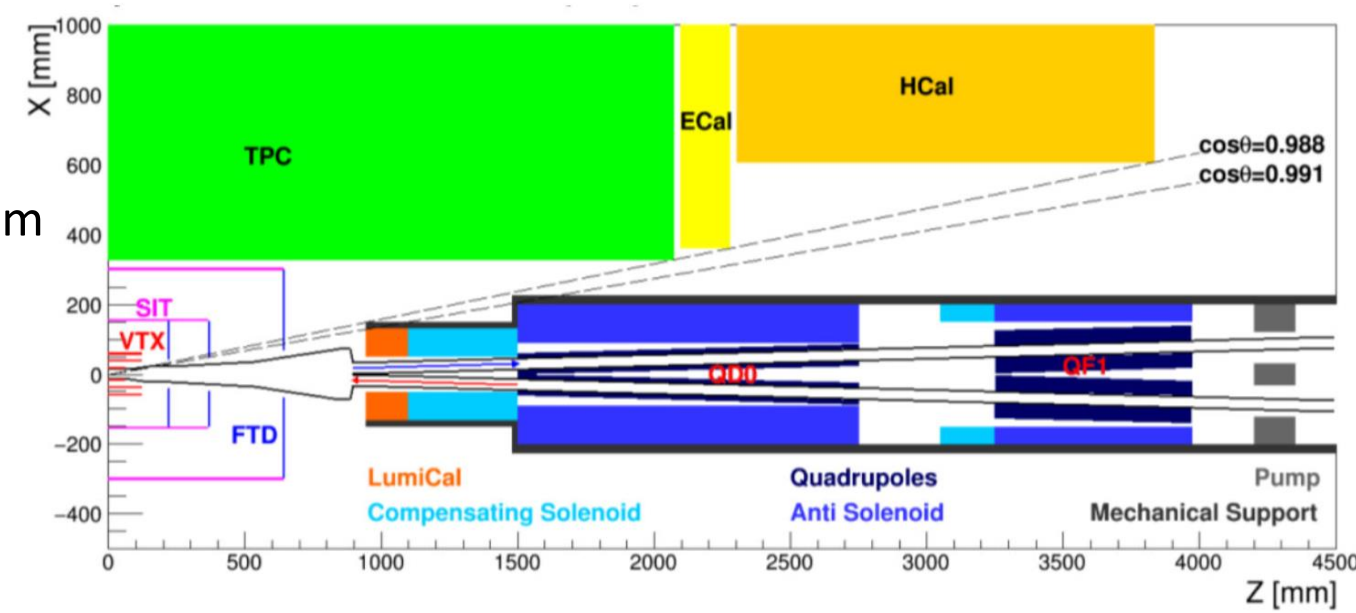
3. Physics interactions:

- Bhabha and physics background cross-section (uncertainty of the count)
- Bhabha acolinearity (due to ISR and FSR, beam energy spread, Beamstrahlung) – acceptance losses
- Machine-related backgrounds (conversions of BS photons into e+e- pairs, off-momentum electrons from the beam-gas scattering, etc.) – miscounts, occupancy

Modification of the acceptance region, effect on the Bhabha cross-section effects, selection based sensitivity

Geometry:

- Detector centered at the outgoing beam
- Geometrical coverage: r_{in} = 25 mm; r_{out} = 100 mm
- Fiducial volume: $r_{in,f}$ = 50 mm; $r_{out,f}$ = 75 mm
  that translates into θ_{FV}: (53-79) mrad
- d_{IP} = 950 mm



Event selection:

- Require asymmetric acceptance in θ (within the fiducial volume) on the L-R side of the detector – as i.e. applied at OPAL/LEP (move inner and outer fiducial radii towards each other for Δr)
- The above will cancel-out L-R symmetric systematics
- Only possible if the luminometer is centered at the outgoing beam
- Require high energy electrons(positrons) E>0.5 E_{beam}

[EPJC 14 (2000), 373]

Simulation:

- 10^7 events generated using BHLUMI Bhabha event generator at 240 GeV
- Final particle theta range from 45 to 85 mrad (including a 8 mrad margin outside of the FV to allow non-collinear FSR to contribute)
- The effective Bhabha cross-section in this angular range is ~ few nb
- Particle tracks are projected to the front LumiCal plane
- Close-by particles are summed up to imitate cluster merging
- Bias or smearing is applied to one systematic effect at a time, assuming it's contribution to the integral luminosity uncertainty of 10^{-3}

Symmetric bias on beam energy:

- Colliding beam energies can be symmetrically shifted for ΔE, resulting in 2 ΔE shift in CM energy

Effect:

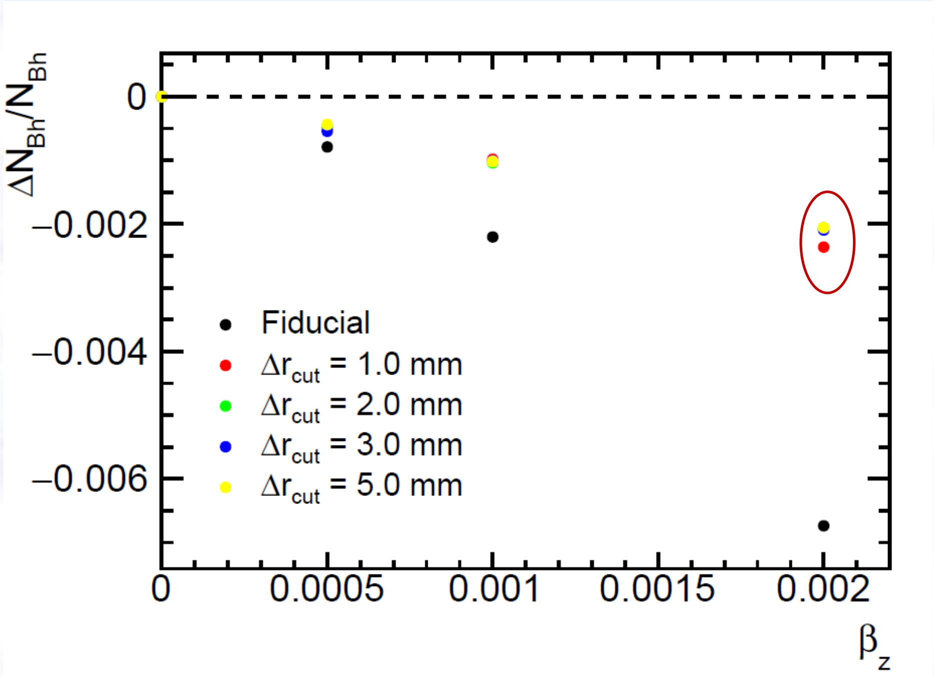
- Bhabha cross-section changes as ~1/s $\Rightarrow$ relative uncertainty on CM energy < $5 \cdot 10^{-4}$
- Counting bias due to the acceptance cut on energy - relative uncertainty on CM energy ~ 10^{-2}

Asymmetric bias on beam energy:

- $E_+ - E_- = \Delta E$

Effect:

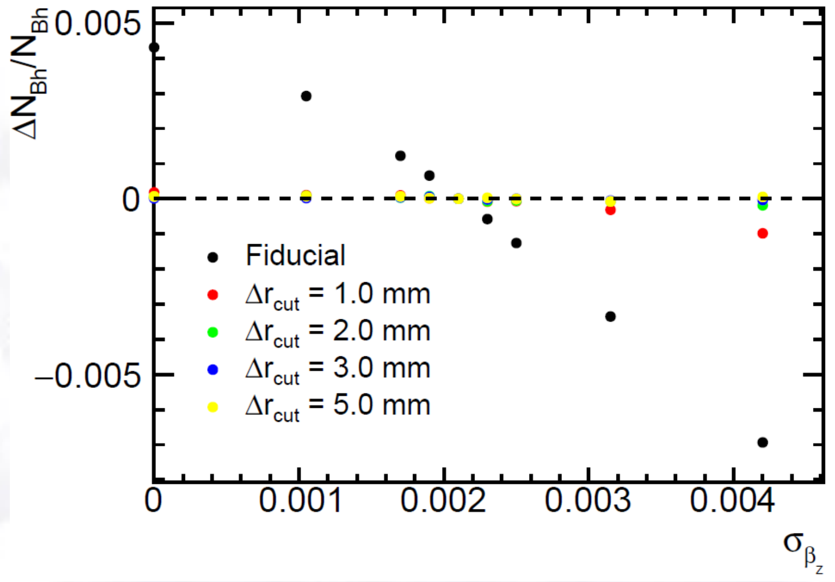
- Longitudinal boost of the CM frame of the colliding particles to the lab frame β_z
- $\Rightarrow$ counting loss due to the loss of acolinearity
- Asymmetry in beam energies should be smaller than 10^{-3}



Beam energy spread

Effect:

- <u>Longitudinal boost</u> of the CM frame of the colliding particles to the lab frame β_z <u>on event by event basis</u>
- Uncertainty of β_z is a source of the <u>Bhabha count uncertainty</u>
- Becomes negligible with asymmetric acceptance cuts

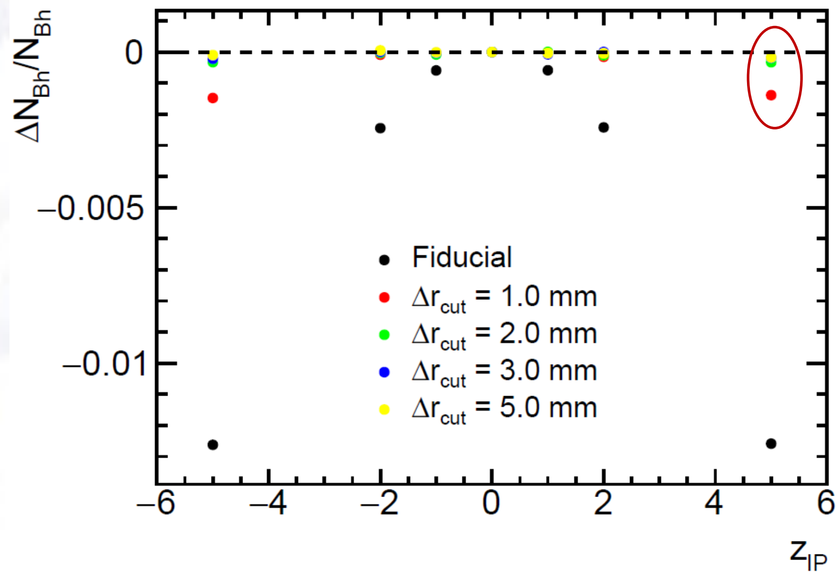


Longitudinal offset of the IP

- IP is not equidistant in z between left and right halves of the detector (z_{IP} in mm)

Effect:

- <u>Affects the acceptance</u>
- Becomes negligible with asymmetric acceptance cuts: 10 mm axial offset easily tolerated
- <u>Implies a requirement on the synchronization</u> of the colliding beams of better than 15 ps

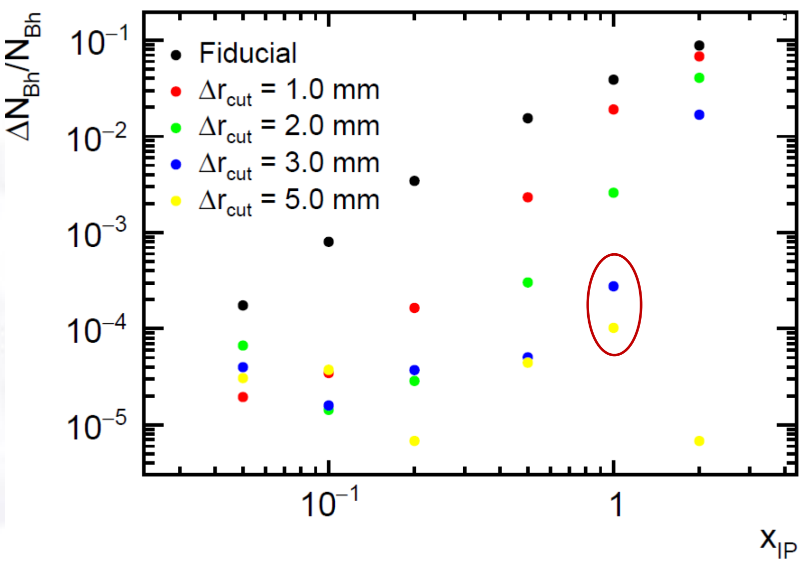


Radial offset of the detector axis

- Detector axis is radially offset from the beam axis by the amount x_{IP} (in mm)

Effect:

- Offset of the beam(detector) creates an azimuthal asymmetry in the Bhabha rate from which the offset can be extracted.
- 1 mm offset can be tolerated

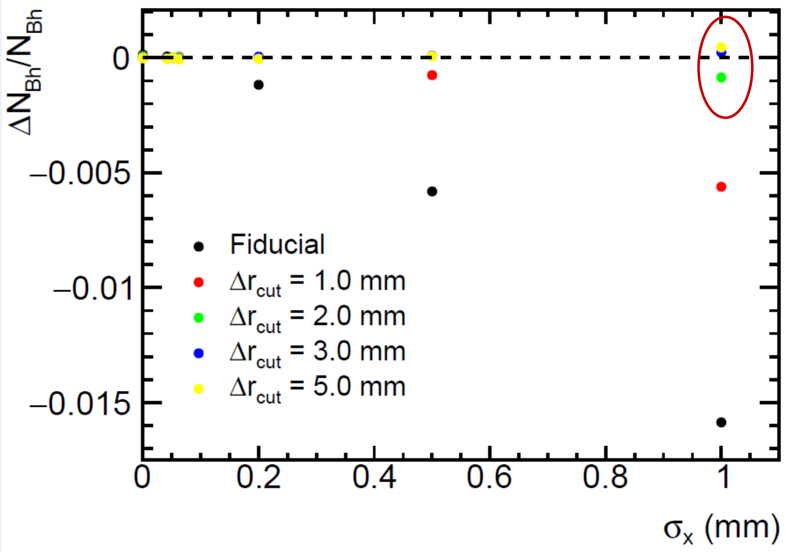


Radial fluctuations of the relative position of the LumiCal w.r.t. the IP

- Can be caused by vibrations, thermal stress

Effect:

- Modification of the acceptance region
- Radial fluctuations up to 1 mm are acceptable



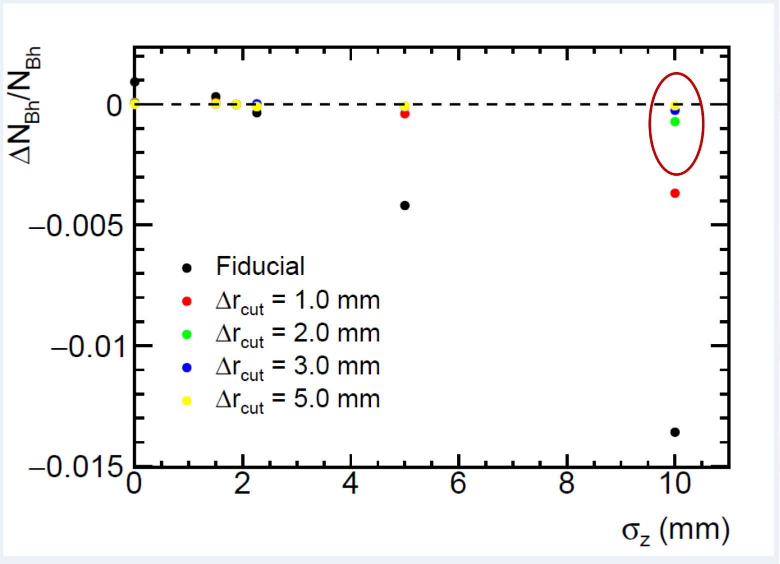
Axial fluctuations of the IP

Effective longitudinal IP location varies event by event can be caused by:

- Longitudinal position within the bunch (σ_Z not negligible)
- Actual axial fluctuations of the relative position of the IP w.r.t. LumiCal.

Effect:

- <u>Modification of the acceptance region</u>
- Axial fluctuations up to 10 mm are acceptable.

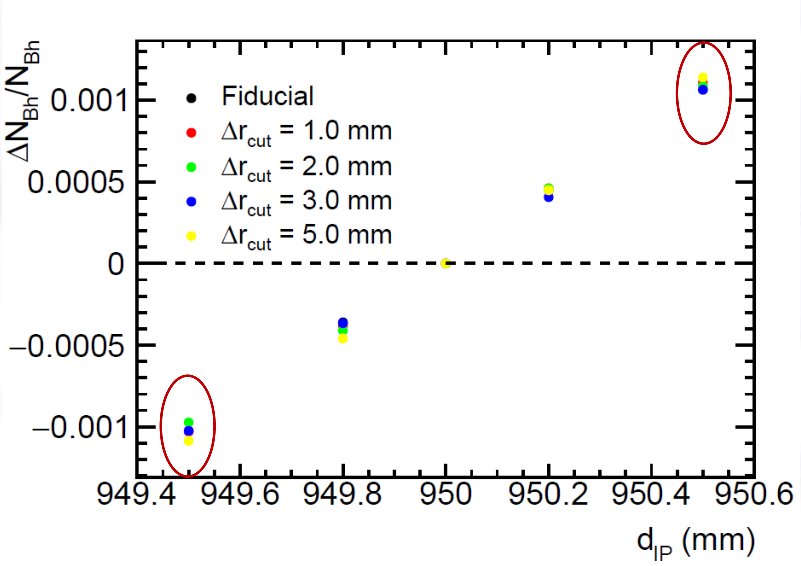


Distance between left and right LumiCal halves

- Can be caused by vibrations, thermal stress

Effect:

- <u>Modification of the acceptance region</u>
- Up to 500 µm distance bias over a distance of 950 mm.

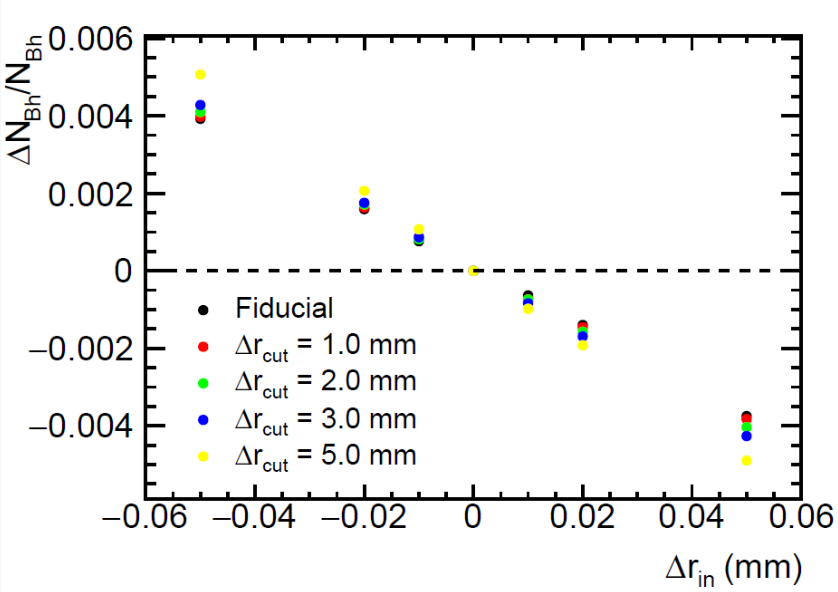


Inner radius of the luminometer

- Uncertainty of the inner radius translates into counting uncertainty since Bhabha cross-section scales like $1/\theta^3$
- To the first order independent of the center-of-mass energy.

Effect:

- 13 μm uncertainty of the inner radius translates into 10^{-3} luminosity uncertainty
- Possibly the most critical requirement on mechanical issues

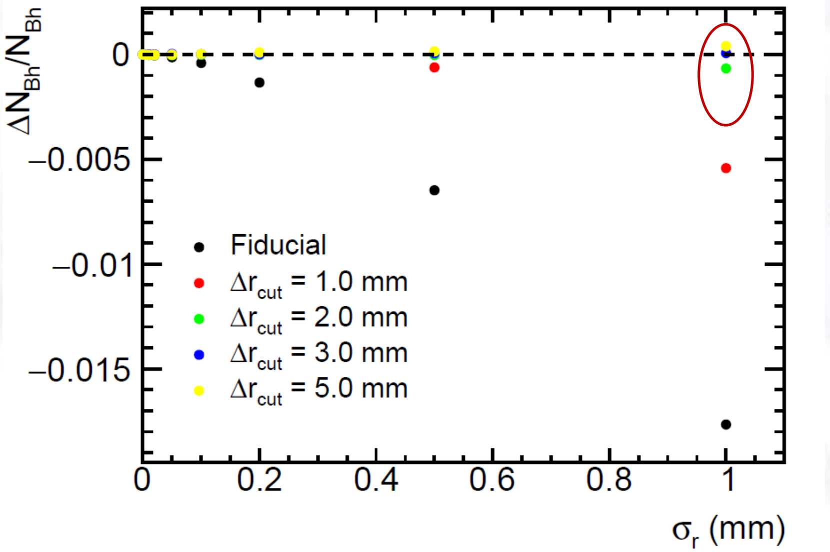


Spread of the measured radial shower position

- Translates into uncertainty of the polar angle
- Sensitive to pad size

Effect:

- 1 mm spread can be allowed ⇔ mrad in radial position
- Easily achievable with the existing technology choices for LumiCal design (fine sensor segmentation)



Summary on MDI and mechanical requirements

Parameter	unit	limit (Fiducial)	limit (LEP style)
ΔE_{CM}	MeV	120	120
$E_{e^+} - E_{e^-}$	MeV	120	240
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		20%	Effect cancelled
Δx_{IP}	mm	0.1	>1
Δz_{IP}	mm	1.4	10
Beam synchronisation	ps	1	15
$\sigma_{x\ IP}$	mm	0.1	1
$\sigma_{z\ IP}$	mm	1	10
r_{in}	µm	13	10
$\sigma_{r_{shower}}$	mm	0.15	1
Δd_{IP}	µm	500	500

As at ILC [A. Stahl, LC-DET-2005-004] several effects are of concern:

- Inner radius of the luminometer: ~10 µm for 10^{-3} luminosity uncertainty ✓
- Distance between calorimeters should be controlled ~500 µm over one meter distance ✓
- CM energy has to be known at the level ~100 MeV (due to the fact that Bhabha x-section scales as 1/s); $2.7 \cdot 10^{-4}$ (25 MeV) beam energy uncertainty at LEP2 – seems to be feasible [M. D. Hildereth, IHEP98] ✓

Run at 91 GeV CM energy, $\Delta L/L = 10^{-4}$

- At low energies, 10^{-4} relative uncertainty of the integral luminosity comes mainly from the precision of the Z^0 total hadronic cross-section measurement

Parameter	unit	limit
ΔE_{CM}	MeV	4.5
$E_{e^+} - E_{e^-}$	MeV	9
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		Effect cancelled
Δx_{IP}	mm	0.5
Δz_{IP}	mm	2
Beam synchronisation	ps	3
$\sigma_{x_{\mathrm{IP}}}$	mm	0.5
$\sigma_{z_{\mathrm{IP}}}$	mm	5
r_{in}	μm	1
$\sigma_{r_{shower}}$	mm	0.5
Δd_{IP}	μm	50

Some requirements are on the technological limit:

- Inner radius of the luminometer: ~1 μm (4.4 μm at OPAL contributing $1.4 \cdot 10^{-4}$ uncertainty in L)
- Distance between calorimeters should be controlled ~50 μm over one meter distance. FSI for the position control of the luminometer (μm over 1 meter distance should be easily achieved).
- CM energy has to be known at the level of a few MeV what seems to be impossible (?), but some relevant processes might have the same x-section dependence as Bhabha in which case the effect cancels out.

Several other effects from MDI and/or mechanical side have to be quantified in addition, though they are expected [A. Stahl, LC-DET-2005-004] to contribute no more than 10^{-4} each to the relative uncertainty of $\mathcal{L}$:

- Tilt of the calorimeters: detectors are rotated (both L and R) w.r.t. the y-axis
  - With a tilted calorimeter each particle will impact at a slightly larger radius and a larger polar angle is reconstructed
  - At ILC tolerance is ~ 2mm for the movement of the back plane of the luminometer;
- Twist of calorimeters (rotation around outgoing beam)
  - Affects azimuthal angle reconstruction that can be useful in event selection to suppress the physics background
  - Tolerance at ILC ~ 0.1 mrad what is an order of magnitude looser than the achievable θ reconstruction
- Beam size (x,y,z) deviations from the nominal values (at the IP)
  - Broaden the acolinearity distribution of Bhabhas
  - Irrelevant at ILC, at LEP i.e ~100 µm uncertainty in horizontal (x) size results in ~10^{-4} uncertainty in $\mathcal{L}$
- Calibration – uncertainty of the sampling term
  - At ILC [IBJ et al., JINST 8 P08012] sampling term should be known with the 20% relative uncertainty to contribute as $1 \cdot 10^{-4}$ to the uncertainty of $\mathcal{L}$

- Instrumentation of the very forward region is very important for the realization of the CepC physics program. Luminosity measurement uncertainty can affect:
  - Precision of the cross-section measurements
  - Anomalous TGCs measurement
  - Single-photon production with E_{mis} (BSM, dark matter)
  - Di-photon production (various BSM models)
  - Extended theories (Z') at high energies
  - Precision EW observables at Z^0 pole
- In most cases 10^{-3} precision of luminosity should be sufficient
- In particular, 10^{-4} uncertainty of integral luminosity comes from:
  - Fermion-pair production cross-section - access to the higher order corrections (at high energies)
  - W-pair production cross-section (10^{-3} still can be sufficient?)
  - Z^0 total hadronic cross-section at Z^0 pole
- 10^{-4} case should be proven by the dedicated physics analyses

- Instrumentation of the very forward region is very important for the realization of the CepC physics program.
- Integral luminosity uncertainty of 10^{-3} seems to satisfy the most of precision requirements from physics analyses (claim based on other future projects studies)
- From the point of view of MDI, beam and mechanical requirements the most critical parameter is the inner radius of the luminometer to be known at ~10(1) μm to contribute to the luminosity uncertainty as $1 \cdot 10^{-3}(10^{-4})$
- 10^{-3} uncertainty of the integral luminosity (from MDI and mechanical issues side) seems to be feasible with the current technology options
- For 10^{-4} uncertainty goal, precision limits on the available center-of-mass energy and the inner radius of the luminometer have to be investigated

NB: Simulation studies have been performed at the generator level. In order to be more strict on the precision requirements, full (or fast) detector simulation of luminosity measurement should be performed with consideration of the full list of individual systematic effects.