

# Integral luminosity measurement at CEPC

[on behalf of the CEPC LumiCal Group]



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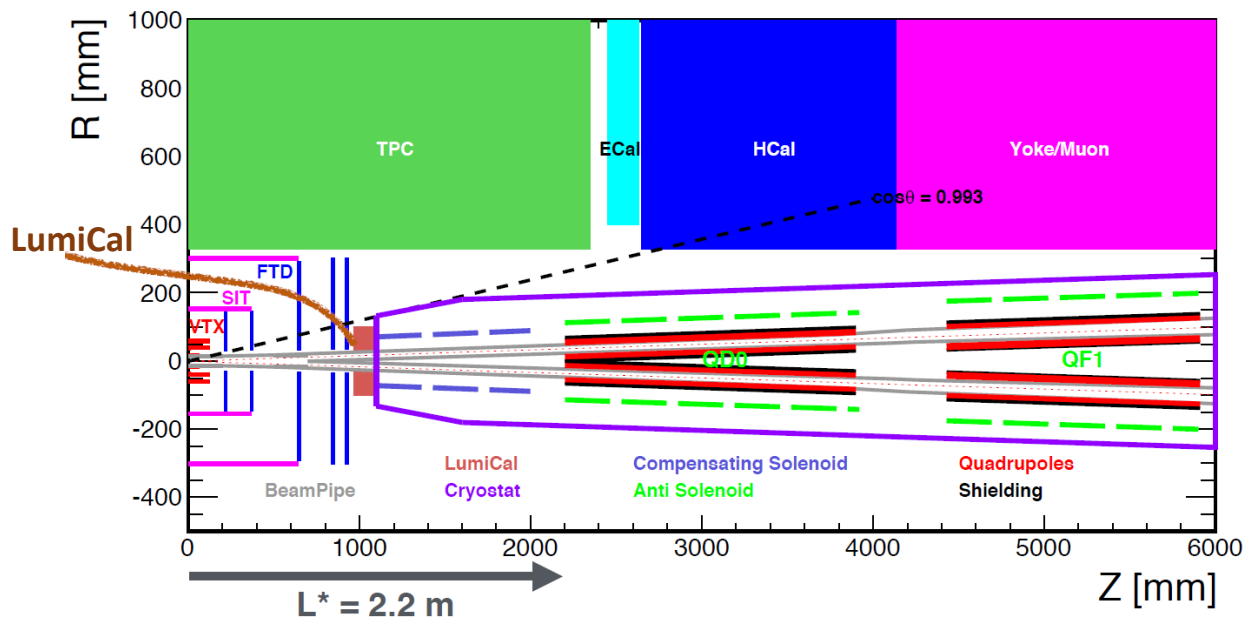
- CEPC luminometer technology options
- Luminosity measurement
  - Integral luminosity: uncertainties, motivation for precision
  - Systematic uncertainties from mechanics and MDI
    - 250 GeV run
    - Run at the  $Z^0$  pole
- Conclusion on feasibility of  $10^{-3}$  ( $10^{-4}$ ) precision



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## BGO scintillating crystals:

- 20  $X_0$  long, large number of moduls
- High density, high Z (Bi)
- Small radiation length, small Moliere radius (2.7 cm) -> compact showers -> excellent resolution in E and  $\theta$
- Simpler read-out than for the sandwich type, relatively slow

## Lumical geometry:

- Geometrical coverage:  
 $r_{in} = 25$  mm;  $r_{out} = 100$  mm, (26 - 105) mrad
- Fiducial volume:  $r_{in,f} = 50$  mm;  $r_{out,f} = 75$  mm that translates into  $\theta_{FV}$ : (53-79) mrad
- $d_{IP} = 950$  mm

Updated baseline parameters: 33 mrad crossing angle, 2.2 m focal length, 3 T solenoid field

Preliminary CDR chapters, Novemer 2017, release fall 2018

## SiW sandwich calorimeter:

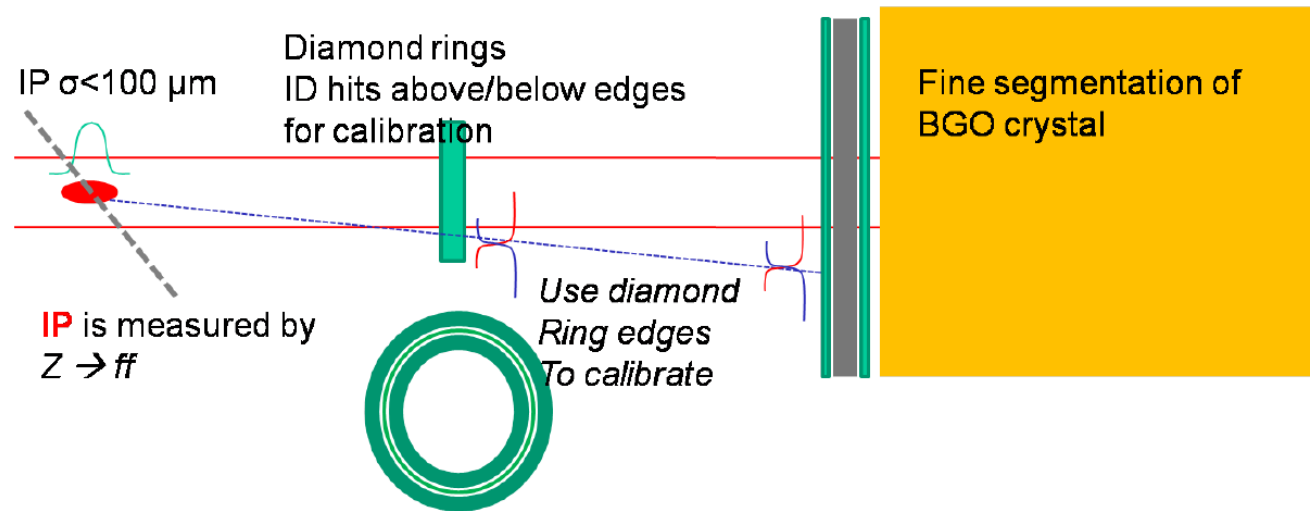
- 20 one- $X_0$  thick absorber (3.5 mm)
- Sensors placed in 2 mm air gaps
- Fine Si-pixel segmentation (i.e 48/64 azimuthal/radial)
- Small Moliere radius ( $\sim 2$  cm) -> excellent resolution in E and  $\theta$  [*Eur. Phys. J. C*, 78 2 (2018) 135]
- Requires fast and compact readout

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Both options can be supplemented with one layer of pixelated Si or diamond to enable :

- calibration
- $e/\gamma$  separation
- polar angle measurement with precision equivalent to  $1 \mu\text{m}$  radial uncertainty



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Integral luminosity measurement is counting experiment  $L=N_{bh}/\sigma$

BUT

Experimental  $N_{bh}$  contains miscounts due to various effects from detector, physics and beam-induced processes

To correct for it (recover  $N_{bh}$ ) implies that all effects have to be known at  $10^{-3}$ (or  $-4$ ) level

A long list of sources of integral luminosity systematic uncertainties

## 1. Beam related:

- Uncertainty of the average net CM energy ✓
- Uncertainty of the asymmetry in energy of the  $e^+$  and  $e^-$  beam ✓
  - Uncertainty of the beam energy spread ✓
- IP position displacement and fluctuations w.r.t. the LumiCal, finite beam sizes 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) ✓
- 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 – other sources of the acceptance losses (ISR and FSR, Beamstrahlung)
- Machine-related backgrounds (off-momentum electrons from the beam-gas scattering)



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### Assumptions:

- Generator (Bhlumi) level study @240 GeV and 91 GeV
- Shower leakage has a negligible effect on E and polar angle reconstruction
- Close-by particles are summed up to imitate cluster merging
- $10^7$  events per systematic effect
- Full-size impact on luminosity estimated, otherwise uncertainty of the effect translates into luminosity uncertainty

### Event selection:

- Require **asymmetric acceptance in  $\theta$**  (within the fiducial volume) on the L-R side of the detector (i.e. as applied at OPAL/LEP) -move inner and outer fiducial radii towards each other for  $\Delta r$
- The above will **cancel-out systematics originating from the requirement of L-R symmetry**
- Only possible if the luminometer is centered at the outgoing beam
- Require high energy electrons (positrons)  $E > 0.5 E_{\text{beam}}$

### Mechanisms to influence the count:

- Modification of the acceptance region (either directly or through the loss of colinearity of Bhabha events via longitudinal boost)
- Effect on the Bhabha cross-section calculation (modification of the phase space and  $E_{\text{CM}}$ )
- Sensitivity of selection based observables (reconstructed energy, polar and azimuthal angles)



## Symmetric bias on beam energy

- Bhabha cross-section changes as  $\sim 1/s \Rightarrow$  **relative uncertainty on (average net) CM energy  $< 5 \cdot 10^{-4}$**
- Counting bias due to the acceptance cut on energy is negligible

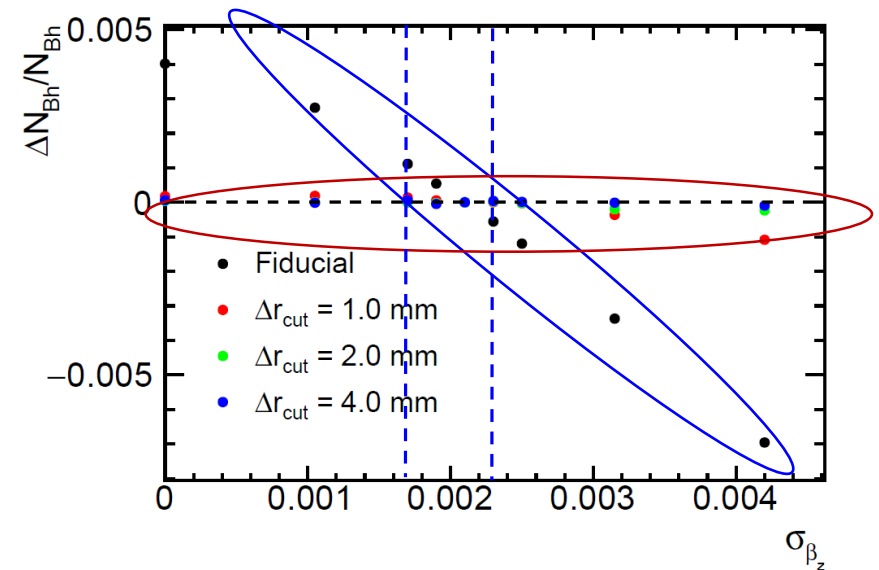
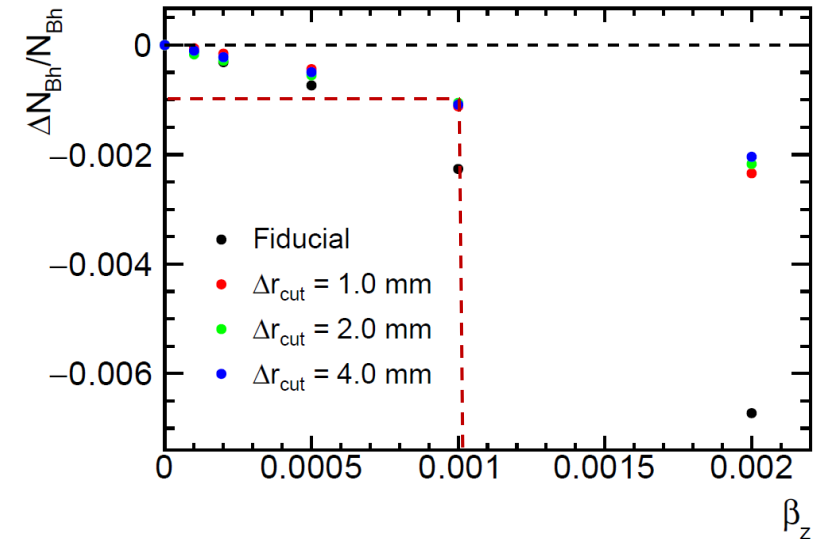
Asymmetric bias on beam energy  $|E_+ - E_-| = \Delta E \Rightarrow \beta_z = \Delta E / E_{\text{CM}}$ 

Longitudinal boost of the CM frame of the colliding particles to the lab frame  $\beta_z \Rightarrow$  counting loss due to the loss of colinearity

- **Asymmetry in beam energies should be smaller than  $10^{-3}$**

## Beam energy spread

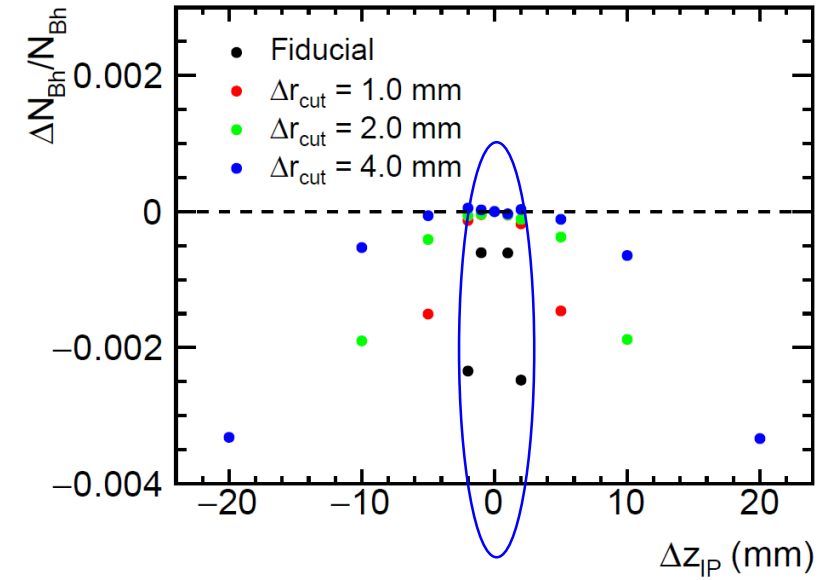
- Longitudinal boost of the CM frame of the colliding particles to the lab frame ( $\beta_z$ ), on event by event basis
- Uncertainty of  $\beta_z$  Gaussian width ( $\sigma_{\beta_z}$ ) is a source of the uncertainty of Bhabha count
- **Becomes negligible with the asymmetric acceptance cuts**, otherwise beam spread must be known within 20% uncertainty



### Longitudinal offset of the IP

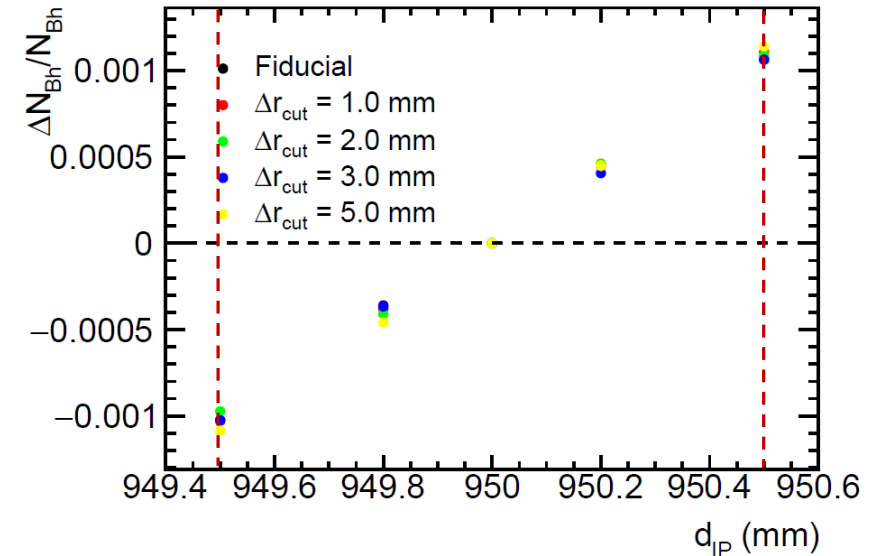
IP is not equidistant in  $z$  between left and right halves of the detector (or one LumiCal half is shifted w.r.t. IP for  $\Delta z_{IP}$ )

- Becomes negligible with asymmetric acceptance cuts: up to 10 mm axial offset easily tolerated,  $\sim 1$  mm in the full fiducial volume
- Implies a requirement on the synchronization of the colliding beams of better than 15 ps (1 ps without asymmetric cuts)



### Distance between left and right LumiCal halves (symmetric to the IP)

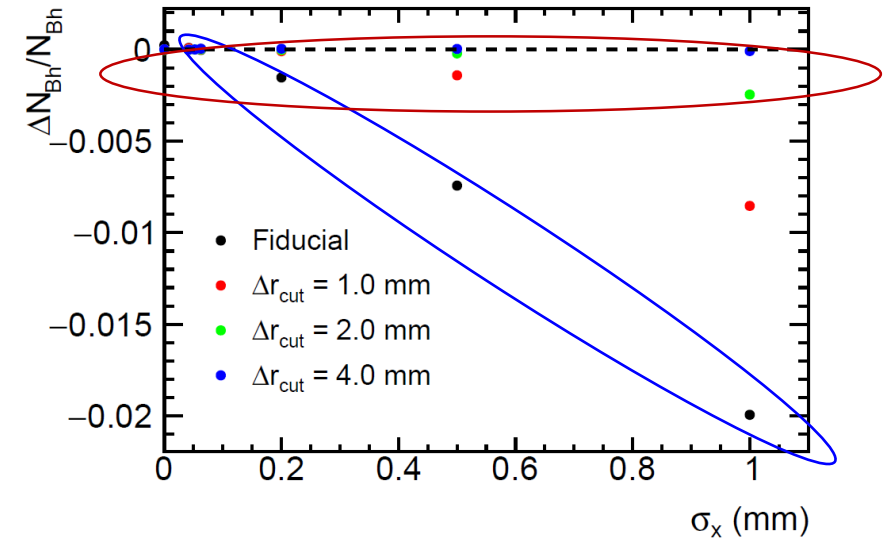
- Position of individual LumiCal half w.r.t to the IP has to be controlled at  $\sim 1/2$  mm level over 950 mm



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

Can be caused by vibrations, thermal stress or by the finite transverse dimension of the bunches or fluctuation of the bunch center

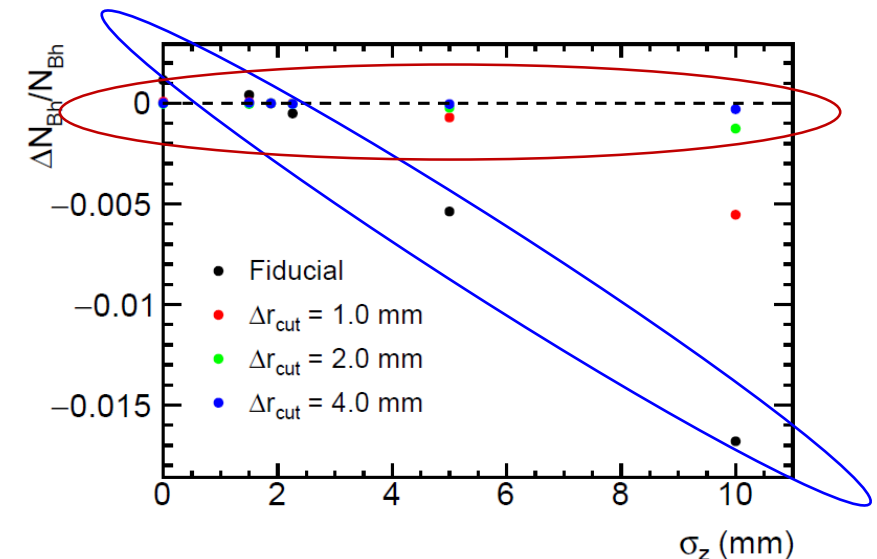
- Radial fluctuations up to 1 mm are acceptable with the asymmetric acceptance (0.1 mm without)



### Axial fluctuations of the relative position of the LumiCal w.r.t. the IP

The longitudinal position of a colliding particle within the bunch ( $\sigma_z$  not negligible), actual axial fluctuations of the relative position of the IP w.r.t. LumiCal due to beam synchronization

- Axial fluctuations up to 10 (1) mm are acceptable with (without) the asymmetric acceptance



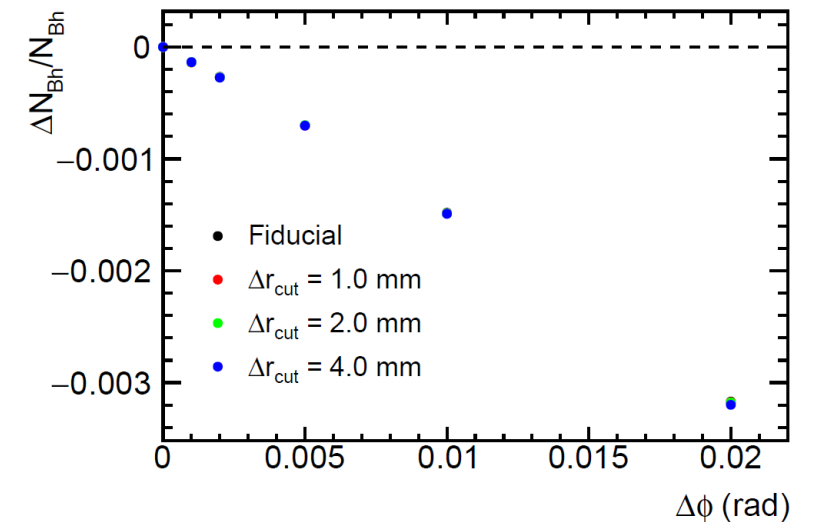
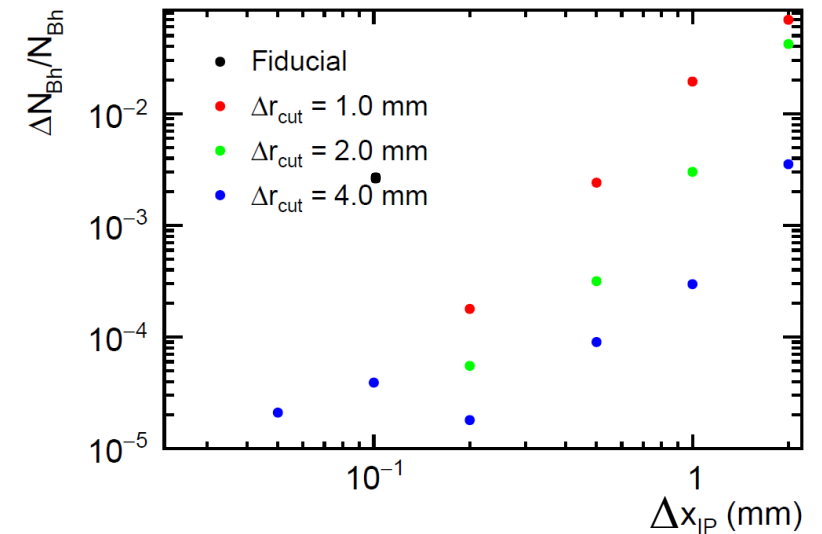
### Radial offset of the detector axis w.r.t. the outgoing beam (or IP w.r.t. the LumiCal)

Detector axis is radially offset from the beam axis by the amount  $\Delta x_{IP}$  (tilt of the calorimeters, beam alignment)

- With a tilted calorimeter each particle will impact at a slightly larger radius and a larger polar angle is reconstructed
- 1 mm offset can be tolerated,  $\sim 100 \mu\text{m}$  for the full fiducial volume

### Azimuthal twist between left and right LumiCal halves (rotation around the outgoing beam)

- Translates into uncertainty of the azimuthal angle
- We assume that Bhabha particles should be coplanar within 7.5 deg (i.e. in order to reduce background from 2- $\gamma$  processes)
- Azimuthal twist of 6 mrad between left and right detector axis can be tolerated

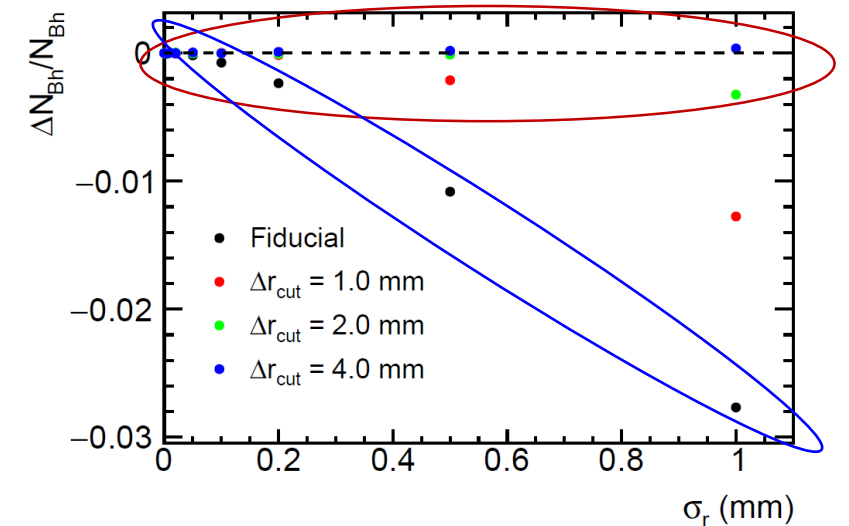
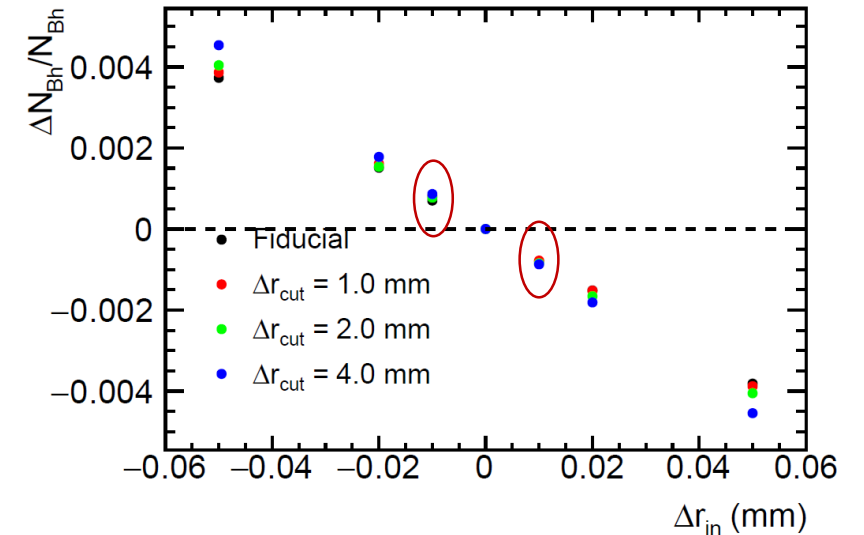


### Inner radius of the luminometer

- Uncertainty of the inner radius translates into counting uncertainty since the Bhabha cross-section scales like  $1/\theta^3$
- $\sim 10 \mu\text{m}$  uncertainty of the inner radius translates into  $10^{-3}$  luminosity uncertainty
- Possibly the most critical requirement on the detector mechanical issues

### Spread of the measured radial shower position (w.r.t. to the true impact position on the LumiCal front plane)

- Translates into uncertainty of the polar angle
- Sensitive to the pad size
- 1 mm spread can be allowed (mrad in radial position) for asymmetric acceptance cuts (otherwise  $\sim 0.1$  mm)
- Easily achievable with the existing technology choices for LumiCal design (fine sensor segmentation)



Parameter	unit	limit (Fiducial)	limit (LEP style)
$\Delta E_{\text{CM}}$	MeV	120	120
$E_{e^+} - E_{e^-}$	MeV	120	240
$\delta\sigma_{E_{\text{beam}}}$		20%	Effect cancelled
$\sigma_{E_{\text{beam}}}$			
$\Delta x_{\text{IP}}$	mm	0.1	1
$\Delta z_{\text{IP}}$	mm	1.4	10
Beam synchronisation	ps	1	15
$\sigma_{x \text{ IP}}$	mm	0.1	1
$\sigma_{z \text{ IP}}$	mm	1	10
$r_{\text{in}}$	$\mu\text{m}$	13	10
$\sigma_{r_{\text{shower}}}$	mm	0.15	1
$\Delta d_{\text{IP}}$	mm	1	1
$\Delta\phi_{\text{tilt}}$	mrad	6	6

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

- Inner radius of the luminometer:  $\sim 10 \mu\text{m}$  for  $10^{-3}$  luminosity uncertainty ✓
- CM energy has to be known at the level  $\sim 100 \text{ MeV} \Leftrightarrow 5 \cdot 10^{-4}$  (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] ✓



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Parameter	unit	limit
$\Delta E_{CM}$	MeV	4.5
$E_{e^+} - E_{e^-}$	MeV	11
$\frac{\delta \sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		Negligible up to at least factor 2
$\Delta x_{IP}$	mm	0.5
$\Delta z_{IP}$	mm	2
Beam synchronisation	ps	3
$\sigma_{xIP}$	mm	0.5
$\sigma_{zIP}$	mm	7
$r_{in}$	$\mu m$	1
$\sigma_{r_{shower}}$	mm	0.2
$\Delta d_{LC}$	$\mu m$	80
$\Delta \phi$	mrاد	0.8

- At low energies, requirement for  $10^{-4}$  uncertainty of the integral luminosity mainly comes from the precision of the  $Z^0$  total hadronic cross-section
- Inner radius of the luminometer  $\sim 1 \mu m$  ( $4.4 \mu m$  at OPAL contributing  $1.4 \cdot 10^{-4}$  uncertainty in L)
- Distance between calorimeters should be controlled  $\sim 80 \mu m$  over app. one meter distance. FSI for the position control of the luminometer ( $\sim \mu m$  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 with  $\sqrt{s}$  as Bhabha in which case the effect cancels out.

Some requirements are on the technological limit

- Instrumentation of the very forward region is very important for the realization of the CEPC physics program
- There are available technology options that can satisfy performance requirements of a luminometer at CEPC
- $10^{-3}$  uncertainty of the integral luminosity (from MDI and mechanical issues side) seems to be feasible with the current technology options
- $10^{-4}$  uncertainty goal, with the precision limits on the available center-of-mass energy and the inner radius of the luminometer is more challenging



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# BACKUP

- 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  $E_{\text{mis}}$  (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
  - W-pair production cross-section
  - $Z^0$  total hadronic cross-section at  $Z^0$  pole



- 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 L

- Physics background ( $2\text{-}\gamma$ ) is expected to be present at a permille level [*IBJ et al., JINST 8 P08012*]. This is the full-size effect that can be taken as correction once the uncertainties of the  $2\text{-}\gamma$  cross-sections are known at i.e. 240 GeV.
- Off-momentum electrons from the beam-gas scattering were a primary source of background in luminosity measurement at LEP [*OPAL Collaboration, arXiv:hep-ex/9910066v2*] and contributed to the level  $< 10^{-4}$  level, seems to be negligible at FCCee [*R. Tenchini, CEPC WS, Rome 2018*]



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# CEPC Parameters

	<i>Higgs</i>	<i>W</i>	<i>Z</i>
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)	16.5		
Piwinski angle	2.96	4.74	11.7
$N_e/\text{bunch}$ ( $10^{10}$ )	12.9	3.6	1.6
Bunch number	304	5230	11720
Beam current (mA)	18.8	90.5	90.1
SR power /beam (MW)	31.7	30	3.1
Bending radius (km)	10.9		
Momentum compaction ( $10^{-5}$ )	1.14		
$\beta_{TP}$ x/y (m)	0.36/0.002		
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse $\sigma_{TP}$ (um)	20.9/0.086	13.9/0.060	7.91/0.076
$\xi_x/\xi_y/\text{IP}$	0.021/0.088	0.008/0.051	0.0034/0.023
RF Phase (degree)	128	134.4	138.6
$V_{RF}$ (GV)	2.14	0.465	0.053
$f_{RF}$ (MHz) (harmonic)	650		
Nature bunch length $\sigma_z$ (mm)	2.72	2.98	3.67
Bunch length $\sigma_z$ (mm)	3.75	4.0	5.6
HOM power/cavity (kw)	0.47 (2cell)	0.31 (2cell)	0.08 (2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance requirement (%)	1.12		
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
Lifetime due to beamstrahlung (hour)	1.0		
$F$ (hour glass)	0.93	0.96	0.986
$L_{max}/\text{IP}$ ( $10^{34}\text{cm}^{-2}\text{s}^{-1}$ )	2.0	3.9	1.0