Integral luminosity measurement at CEPC

- luminometer requirements on mechanical precision and positioning -

CEPC

I. Bozovic Jelisavcic

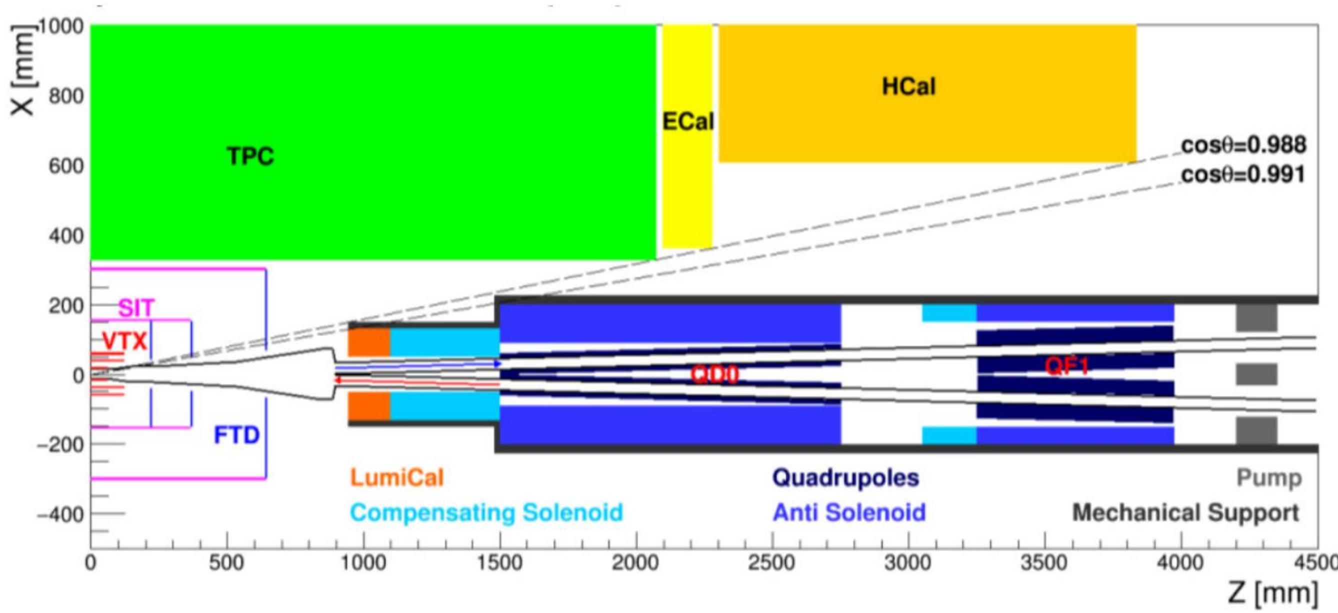
VINCA Institute of Nuclear Sciences, University of Belgrade, Serbia

[This talk is based on studies by the CEPC LumiCal group (Suen **Hou**, Strahinja **Lukic**, Manqi **Ruan**, Liu **Yang**, Kai **Zhu** and IBJ)]

VINCA Institute 70 years in science

- Detector technology options
  - BGO scintillator, SiW sandwich
- LumiCal requirements for precision luminosity measurement
  - Integral luminosity: measurement, uncertainties, motivation for precision
  - Systematic uncertainties from mechanics and MDI
    - 250 GeV run
    - Run at the Z^0 pole
- Impact of the upstream material on LumiCal
- LumiCal shower leakage
- Conclusion

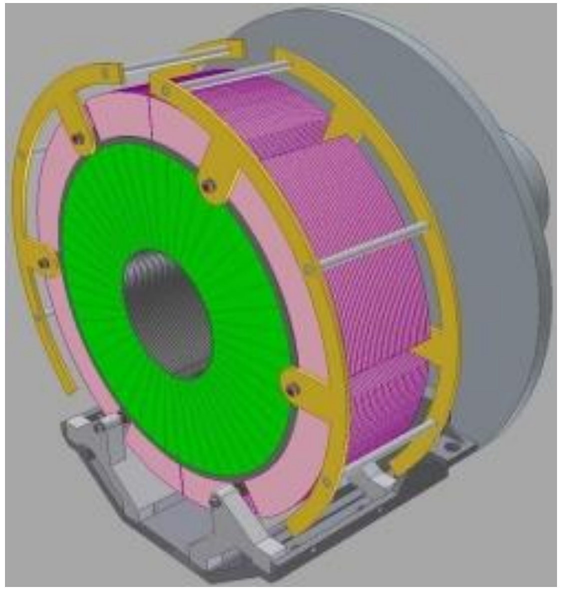
Geometry:
- Geometrical coverage: r_{in} = 25 mm; r_{out}= 100 mm, (26 - 105) mrad
- Fiducial volume: $r_{in,f}$ = 50 mm; $r_{out,f}$=75 mm, that translates into θ_{FV}: (53-79) mrad
- d_{IP} = 950 mm



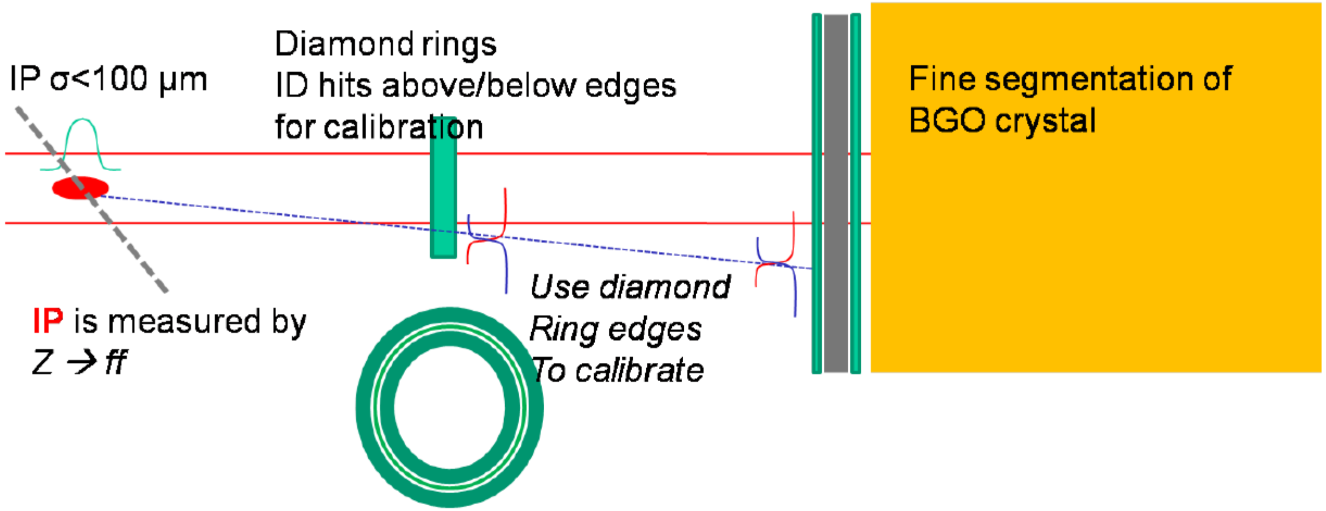
Technology options:

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 θ
- Simpler read-out than for the sandwich type

Disadvantages:
- High refractive index (2.19)
- Relatively low light output (i.e. 15% w.r.t. NaI)
- Cost



Credit: *FCAL Collaboration*



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 (~2 cm) -> excellent resolution in E and θ
- Requires fast and compact readout

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

- calibration
- e/γ separation
- polar angle measurement with precision equivalent to 1 μm radial uncertainty

<u>Integral luminosity measurement based on Bhabha scattering is a counting experiment</u>

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

Where,

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

But:

- In N_{Bh} miscounts due to various effects are contained: physics and beam–induced processes (physics background, off-momentum electrons + counted Bhabhas): $N_{Bh} \rightarrow N_X$
- To correct for it (recover N_{Bh}) implies that effects have to be known at $10^{-3 (\text{or } -4)}$ 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 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:
- 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)

Uncertainty of count is based on:
- 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_{CM})
- Sensitivity of selection based observables (reconstructed energy, polar and azimuthal angles)

- 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
  - W-pair production cross-section
  - Z^0 total hadronic cross-section at Z^0 pole
- This a ‘common knowledge’, 10^{-4} sensitivity should be proven through the dedicated physics analyses

Assumptions:

- Generator level study
- E_{CM} 240 GeV and 91 GeV
- Detector centered at the outgoing beam
- Fiducial volume: $r_{in,f}$ = 50 mm; $r_{out,f}$ = 75 mm
- Shower leakage has a negligible effect on E and polar angle reconstruction
- Full-size impact on luminosity estimated, otherwise uncertainty of the effect translates into luminosity uncertainty

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 systematics originating from the requirement of L-R symmetry
- Only possible if the luminometer is centered at the outgoing beam [*EPJC 14 (2000), 373*]
- Require high energy electrons (positrons) E>0.5 E_{beam}

NB: Selection can be refined with requirements on coplanarity ($|\varphi_+ - \varphi_-|$), helping to suppress physics background from 2-γ processes (Landau-Lifshitz)

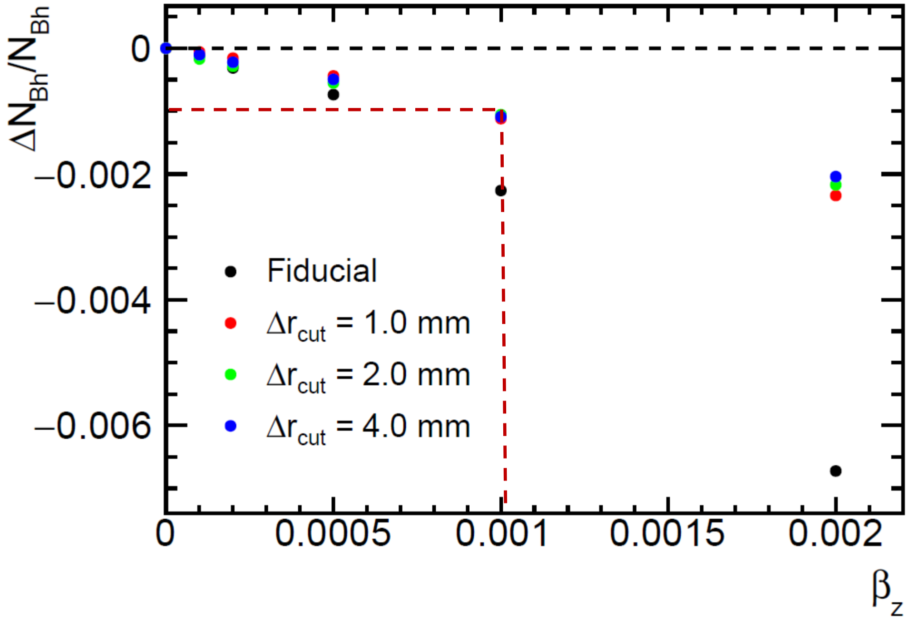
Simulation:

- 10^7 events generated using BHLUMI Bhabha event generator
- Final particle theta range from 45 to 85 mrad (including 8 mrad margin outside of the FV to allow events with 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 its contribution to the integral luminosity uncertainty of 10^{-3} at 240 GeV and 10^{-4} at the Z^0 pole

Symmetric bias on beam energy:

Colliding beam energies can be symmetrically shifted for ΔE, resulting in $2\cdot\Delta E$ shift in CM 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:

$|E_+ - E_-| = \Delta E \Rightarrow \beta_z = \Delta E/E_{CM}$

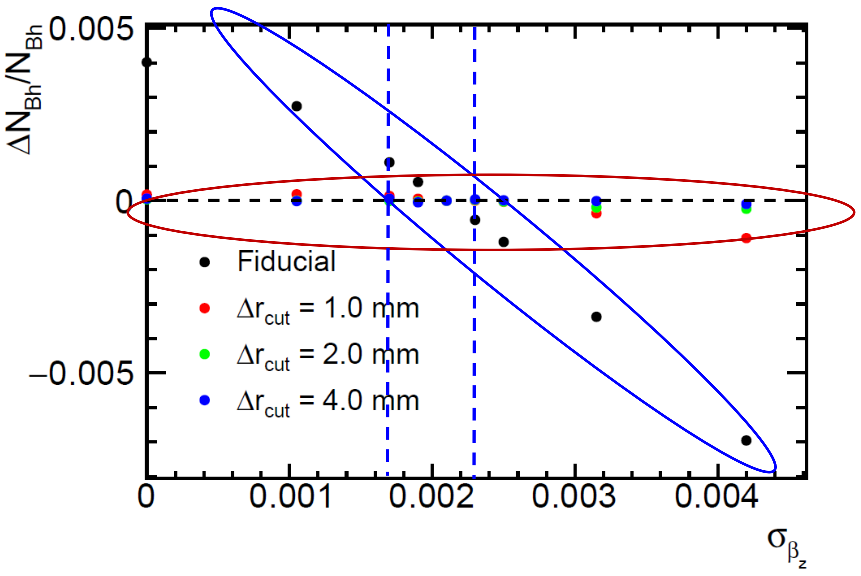
- Longitudinal boost of the CM frame of the colliding particles to the lab frame β_z

$\Rightarrow$ counting loss due to the loss of acolinearity

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

Beam energy spread

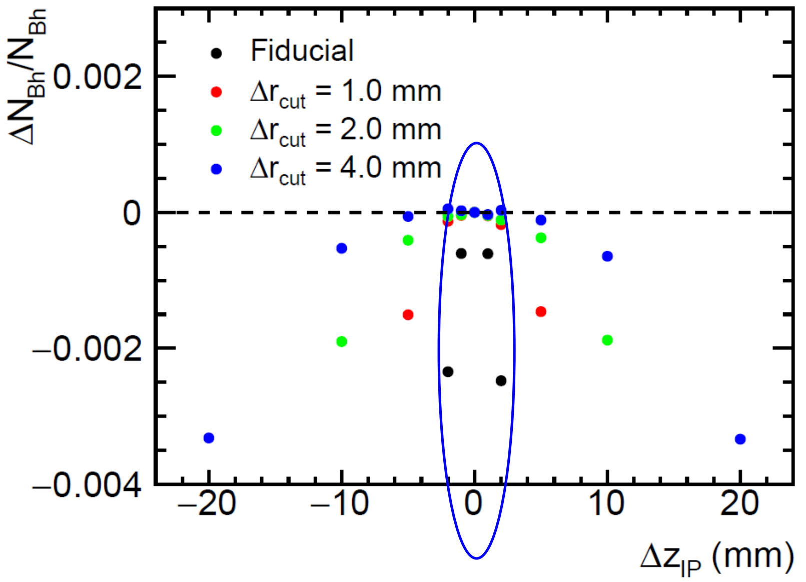
- Longitudinal boost of the CM frame of the colliding particles to the lab frame (β_z), on event by event basis
- Uncertainty of β_z Gaussian width ($\sigma_{\beta z}$) is a source of the uncertainty of Bhabha count
- Becomes negligible with the asymmetric acceptance cuts, otherwise beam spread must 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 Δz_{IP})

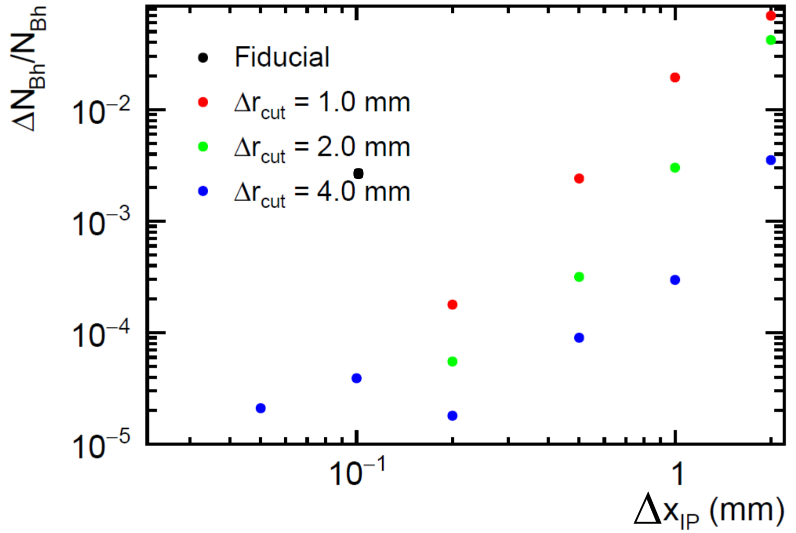
- Average longitudinal offset can be detected/corrected from the average acollinearity of the signal data
- Affects the acceptance
- Becomes negligible with asymmetric acceptance cuts: up to 10 mm axial offset easily tolerated, ~ 1 mm in the full fiducial volume
- Implies a requirement on the synchronization of the colliding beams of better than 15 ps (1 ps without asymmetric cuts)



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 Δx_{IP} (tilt of the calorimeters, beam alignment)

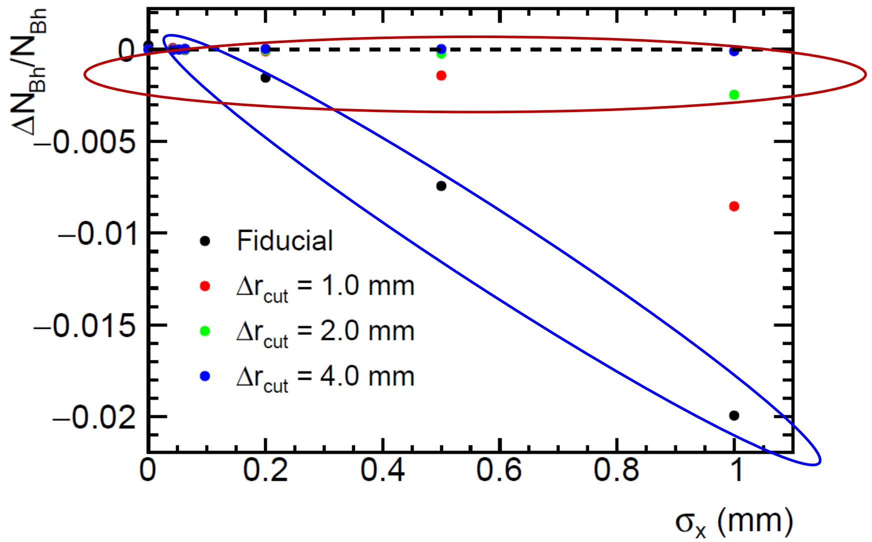
- Offset of the beam (detector) <u>creates shift in the acceptance region</u>.
- With a tilted calorimeter each particle will impact at a slightly larger radius and a larger polar angle is reconstructed
- 1 mm offset can be tolerated, ~100 μm for the full fiducial volume



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

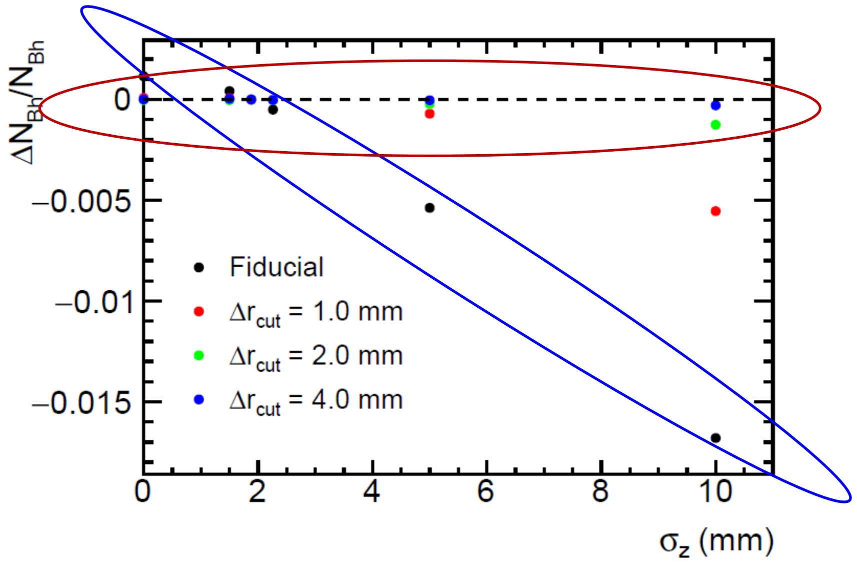
- <u>Modification of the acceptance region</u>
- Radial fluctuations up to 1 mm are acceptable with the asymmetric acceptance (0.1 mm without)



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

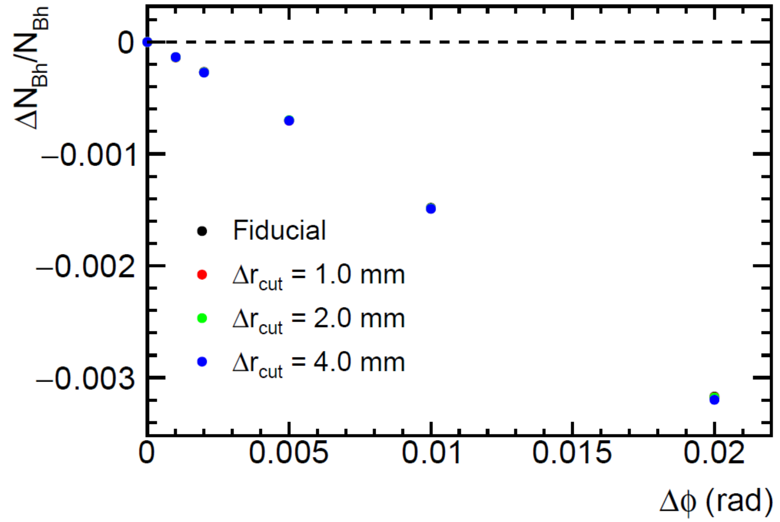
The longitudinal position of a colliding particle within the bunch (σ_Z not negligible), actual axial fluctuations of the relative position of the IP w.r.t. LumiCal due to beam synchronization

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



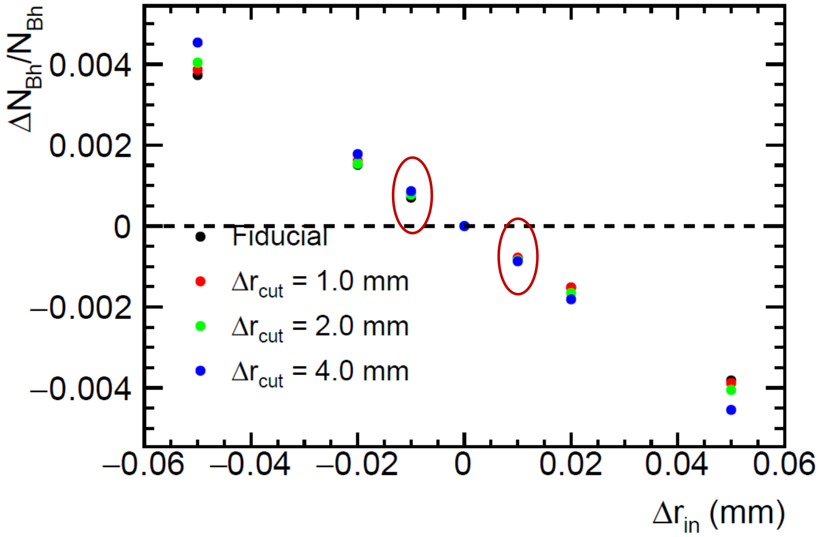
Azimuthal twist between left and right LumiCal halves (rotation around the outgoing beam)

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



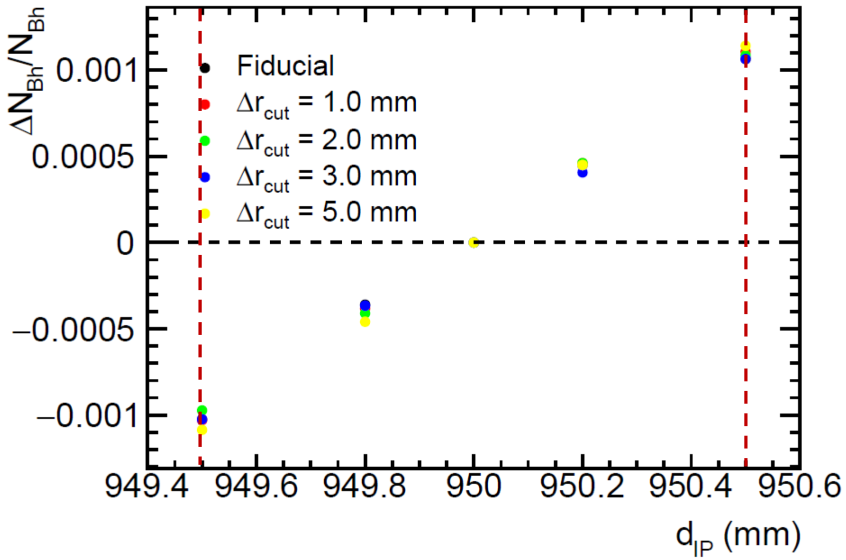
Inner radius of the luminometer

- Uncertainty of the inner radius translates into counting uncertainty since the Bhabha cross-section scales like $1/\theta^3$
- Acceptance definition
- ~10 μm uncertainty of the inner radius translates into 10^{-3} luminosity uncertainty
- Possibly the most critical requirement on mechanical issues



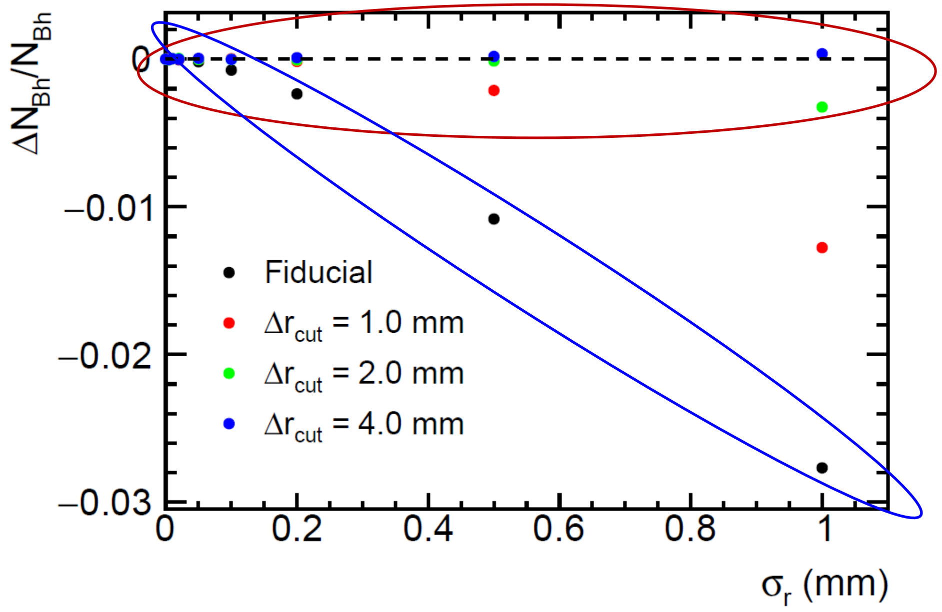
Distance between left and right LumiCal halves (symmetric to the IP)

- Uncertainty of the distance between the LumiCal halves is causing change of the acceptance
- Position of individual LumiCal half w.r.t to the IP has to be controlled at ~ ½ mm level over 950 mm



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 ~0.1 mm)
- Easily achievable with the existing technology choices for LumiCal design (fine sensor segmentation)



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}	mm	1	1
$\Delta\varphi_{tilt}$	mrad	6	6

It is important message that many systematic effects are less severe – manageable if asymmetric acceptance in polar angle is required for Bhabha scattering (LEP style)

NB The above is applicable if detector is centered at the outgoing beam (or there is no crossing angle)

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

- Inner radius of the luminometer: ~10 µm for 10^{-3} luminosity uncertainty ✓
- CM energy has to be known at the level ~100 MeV ⇔ $5\cdot10^{-4}$ (due to the fact that Bhabha x-section scales as 1/s); $2.7\cdot10^{-4}$ (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, requirement for 10^{-4} relative uncertainty of the integral luminosity mainly comes from the precision of the Z^0 total hadronic cross-section
- Posing a more stringent requirements on MDI and mechanical positioning of the LumiCal

Parameter	unit	limit
ΔE_{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
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	7
r_{in}	µm	1
$\sigma_{r_{\mathrm{shower}}}$	mm	0.2
Δd_{LC}	µm	80
$\Delta\phi$	mrad	0.8

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 ~80 µm over app. 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 with √s as Bhabha in which case the effect cancels out.

- 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-γ) 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 uncertaintiies of the 2-γ 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 [*see R. Tenchini talk*]

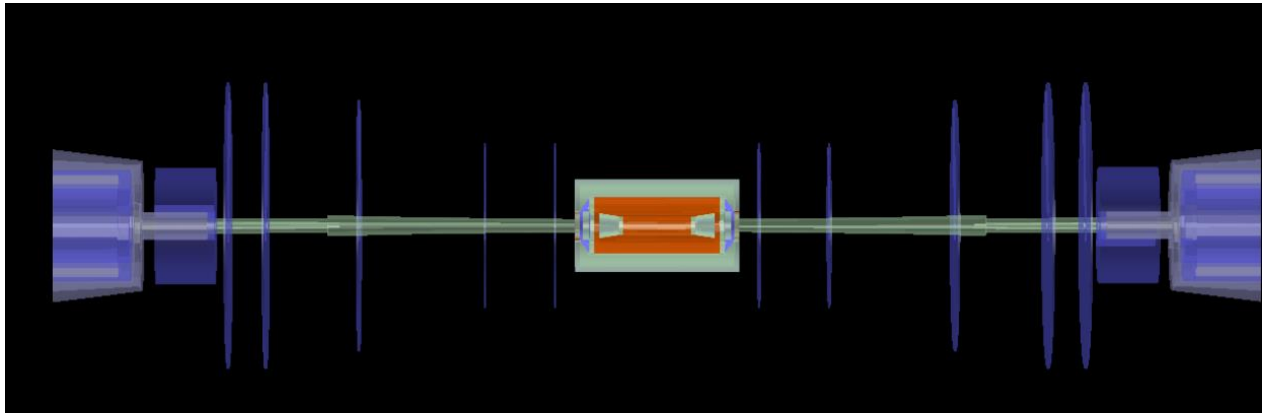
Software: Mokka (Geant4 based)

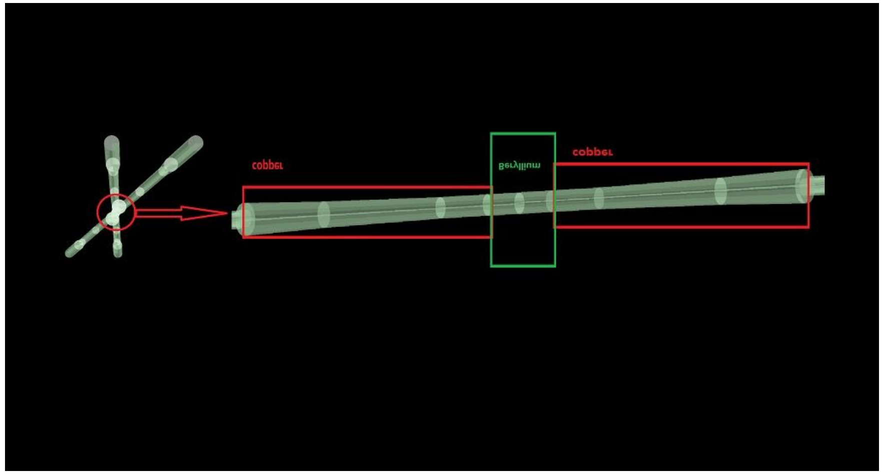
Geometry **CEPC V4 and V5**

- vxd07 (vertex detector)
- ftd (ftd for cepc double pipe)
- tube (tube for cepc double pipe)
- LumiCal (luminosity calorimeter for cepc without angle)
- mask (Forward mask for cepc double pipe)

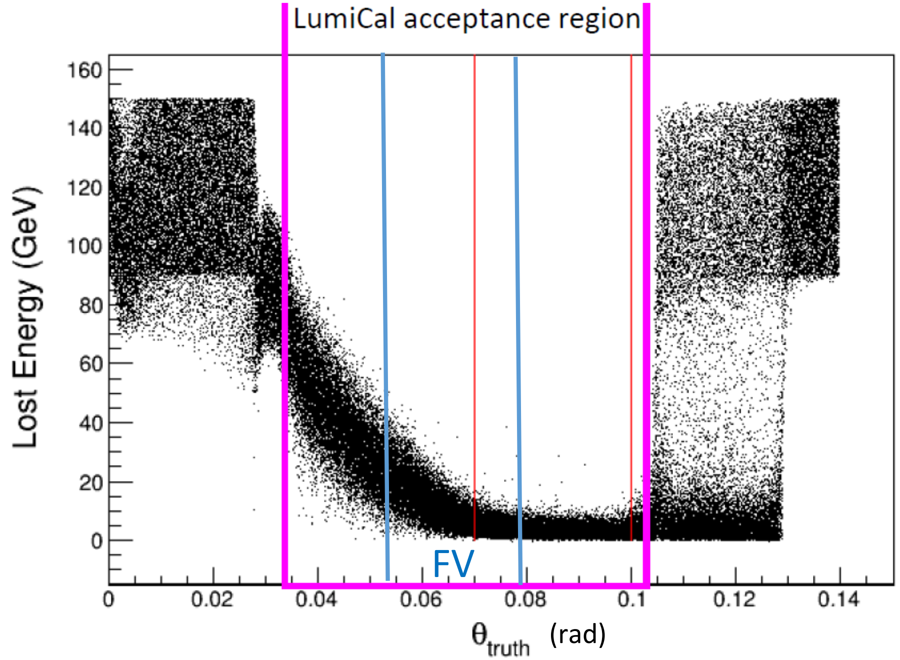
Assumption of the study:

- LumiCal geometrical coverage: r_{in} = 32.26 mm r_{out}= 98.80 mm, (34.0 – 103.4) mrad
- 10^5 positrons of 120 GeV generated around the detector axis (z-axis – no crossing angle) in 8 deg. cone
- Direction and energy uniformly smeared

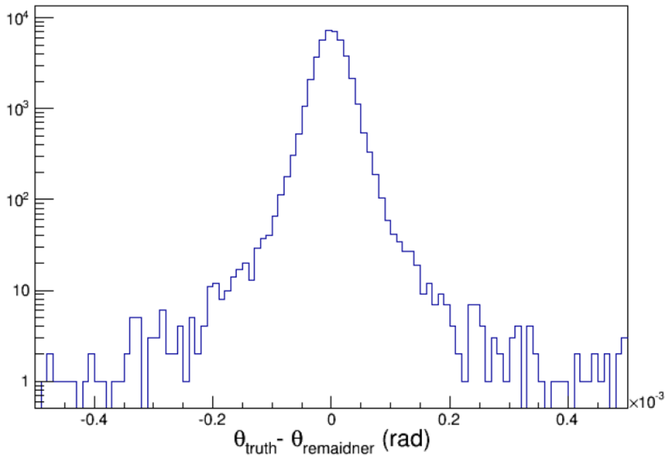


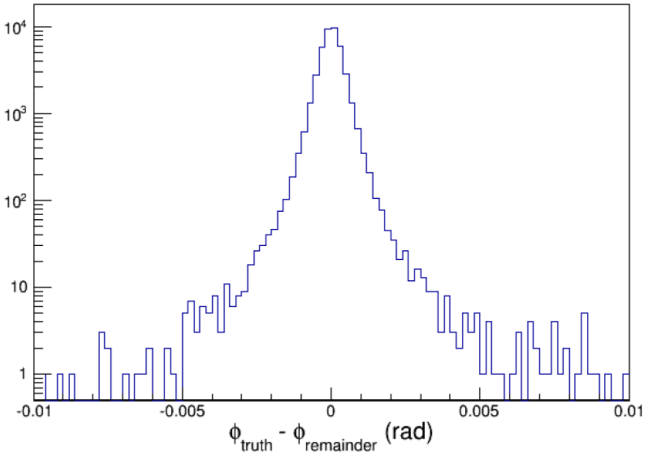


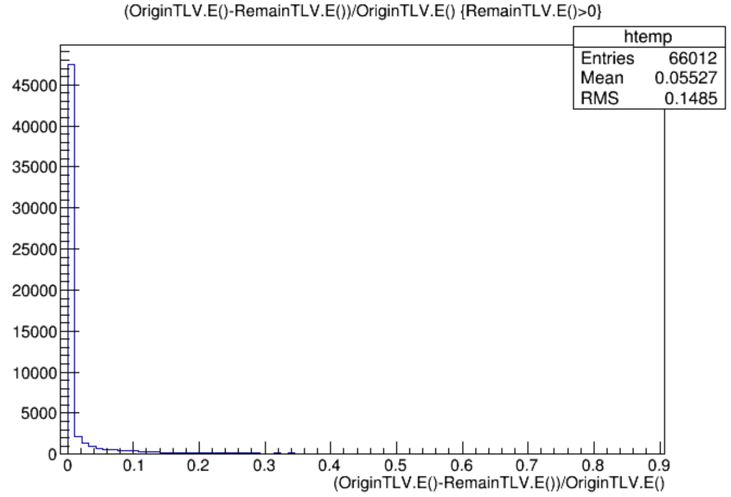
- Primary particles will keep most of their energies before entering the LumiCal
- Momentum gets negligibly smeared (~mrad in θ and φ)
- Energy losses are larger with the CEPC V5 beam pipe introducing copper segments



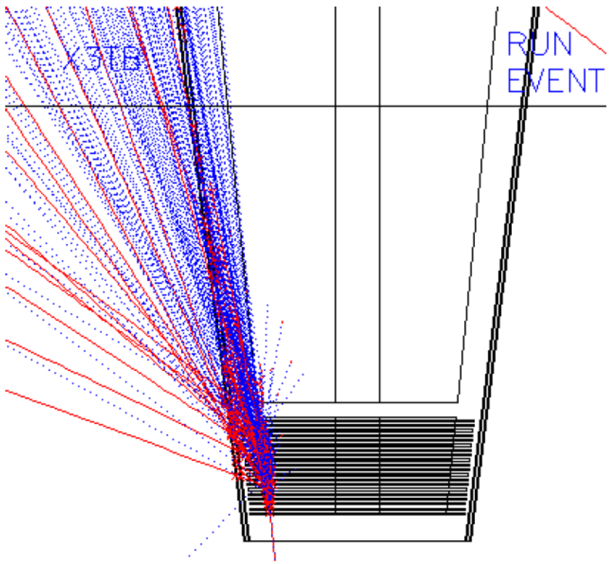
$$70mrad < \theta_{truth} < 100mrad$$







Geant4 simulation is done for the SiW sandwich LumiCal in order to estimate shower leakage



An iron cone of 5 mm thickness, positioned at cosθ = 0.992 (~120 mrad) is used to estimate filtering of shower secondaries

Two configurations were considered:

- TUBE: Cylindrical detector shape assembled of sensor-absorber disks with constant outer radii of 100 mm
- CONE: Shape with the outer radius r following a straight line projection from the IP at tan θ= 0.1 (~ 6 deg.), corresponding to r_{out} = 100 mm at z = 1 m.

	50 GeV electrons		125 GeV electrons	
	TUBE	CONE	TUBE	CONE
θ (mrad)	N_{enter}/N_{pass}	N_{enter}/N_{pass}	N_{enter}/N_{pass}	N_{enter}/N_{pass}
40	15.4/5.6	13.6/5.8	38.0/16.0	35.8/14.7
90	392/155	173/76	1028/399	434/19.7
95	501/290	367/152	2389/720	937/382
98	762/216	860/284	1718/473	2176/725
99	553/140	1331/367	1102/273	3306/915

Table 1: Number of particles leaking out of the LumiCal outer radius (N_{enter}) and number of particles passing through the Fe-cone (N_{pass}). Two different detector designs (TUBE and CONE) and two shower energies (50 GeV and 125 GeV) are simulated.

- There is a larger shower leakage (mostly partcles < 100 MeV) for all electron energies for the CONE configuration, due to the fact that shower is developing at larger θ
- 5 mm Fe-cone reduces the number of secondaries up to 75%

- Instrumentation of the very forward region is very important for the realization of the CepC physics program
- There are available proven technology options (i.e. BGO, SiW) that can satisfy performance requirements of a luminometer at CEPC
- From the point of view of the 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 $1 \cdot 10^{-3}(10^{-4})$. Also, beam energy has to be known at the level of ~10^{-4}, what might be an issue at the Z^0 pole

- 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 challenging
- In order to cope with the complex systematics, it is recommended to keep Bhabha events symmetrical w.r.t. the detector axis (center luminometar at the outgoing beam)

BACKUP

CEPC Parameters

	Higgs	*W*	*Z*
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/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	
β_{IP} x/y (m)		0.36/0.002	
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/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 σ_z (mm)	2.72	2.98	3.67
Bunch length σ_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}/IP (10^{34}cm^{-2}s^{-1})	2.0	3.9	1.0