Luminosity measurement issues in the current MDI design at future circular colliders

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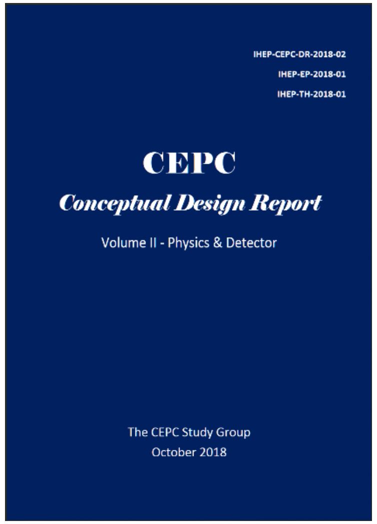
Overview

- News from the circular colliders
- CEPC and FCCee: current MDI design in the CDR
- Challenges for luminosity measurement
- Possible FCAL contribution

What is in common:

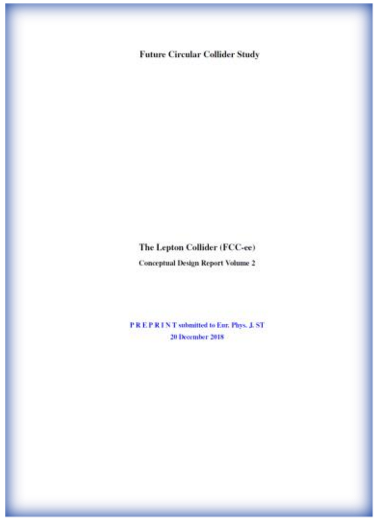
- CDRs released end-of 2018 for both CEPC and FCC
- MDI region among the most challenging at both experiments
- Flexibility to run at different CM energies (Z pole, WW production, Higgs factory) with a common detector layout
- Maximizing luminosity, minimizing synchrotron radiation (and other) background
- Precision issues in the integral luminosity measurement (10^{-4})
- Technologies for luminometer (currently derived from ILC and CLIC)



IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
October 2018



Future Circular Collider Study

The Lepton Collider (FCC-ee)
Conceptual Design Report Volume 2

P R E P R I N T submitted to Eur. Phys. J. ST
20 December 2018

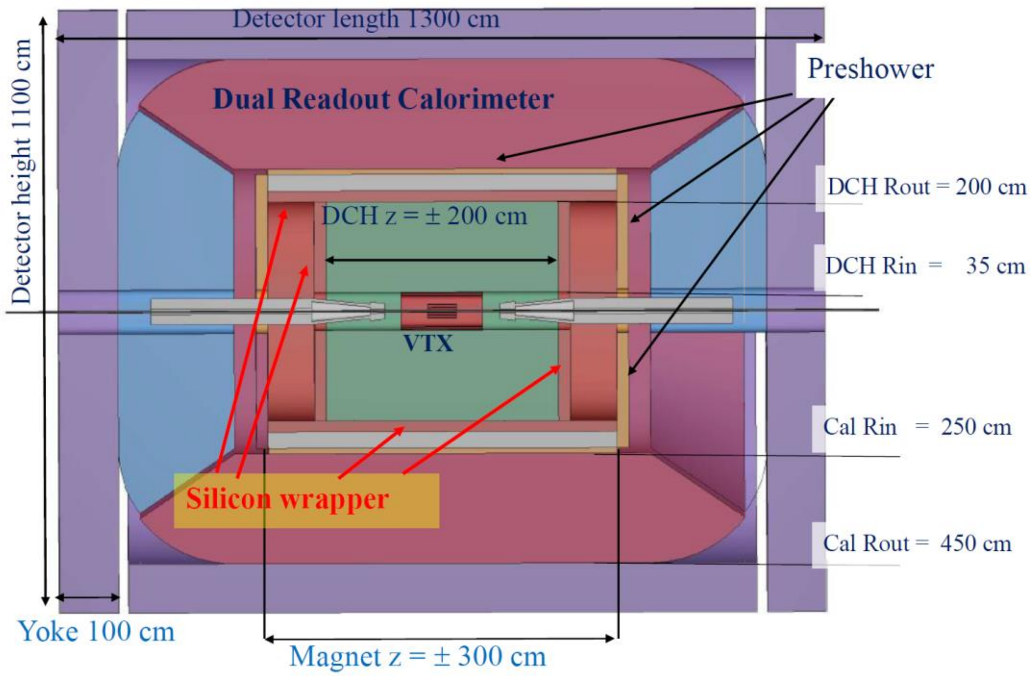
News from the circular colliders

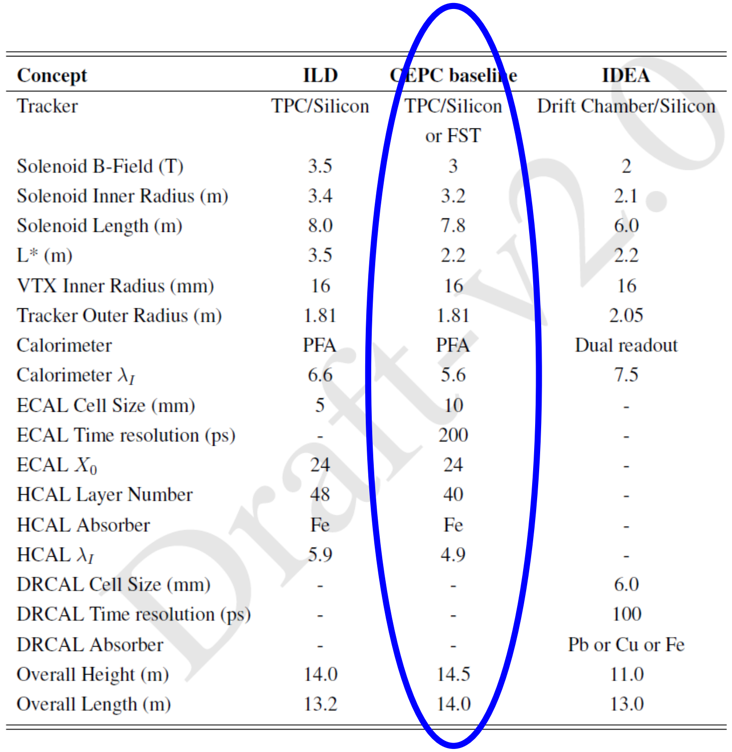
Detector concepts:

- CEPS: CEPC_ILD (baseline), IDEA
- FCC: CLD (baseline), IDEA

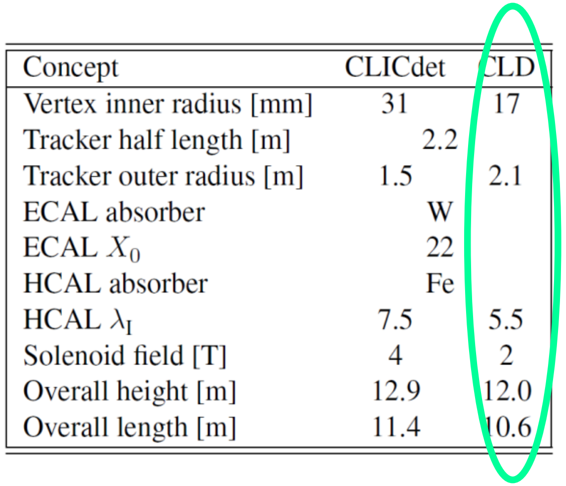
Si-pixel VTX, a large-volume extremely-light short-drift wire chamber surrounded by a layer of Si micro-strip detectors, a thin, low-mass superconducting solenoid coil (~0.8 X_0), a pre-shower detector, a dual-readout calorimeter, and muon chambers within the magnet return yoke.

IDEA

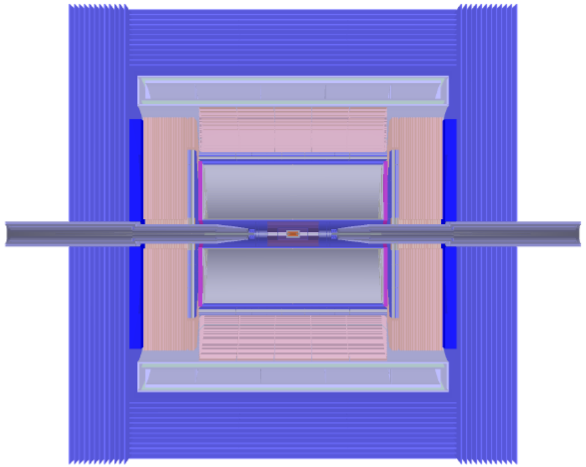


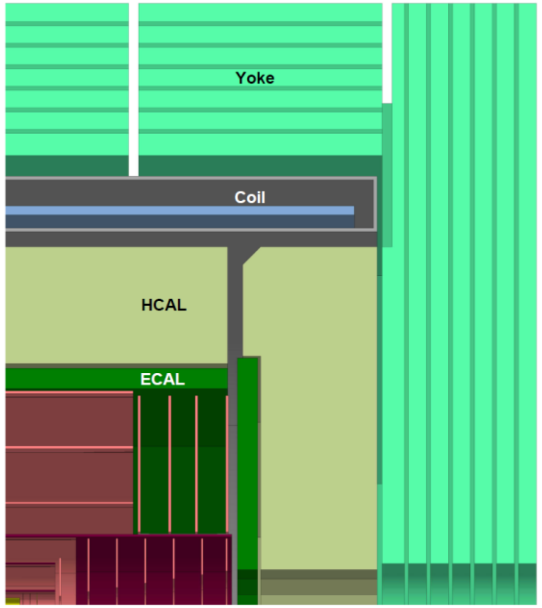


Concept	ILD	CEPC baseline	IDEA
Tracker	TPC/Silicon	TPC/Silicon or FST	Drift Chamber/Silicon
Solenoid B-Field (T)	3.5	3	2
Solenoid Inner Radius (m)	3.4	3.2	2.1
Solenoid Length (m)	8.0	7.8	6.0
L* (m)	3.5	2.2	2.2
VTX Inner Radius (mm)	16	16	16
Tracker Outer Radius (m)	1.81	1.81	2.05
Calorimeter	PFA	PFA	Dual readout
Calorimeter λ_I	6.6	5.6	7.5
ECAL Cell Size (mm)	5	10	-
ECAL Time resolution (ps)	-	200	-
ECAL X_0	24	24	-
HCAL Layer Number	48	40	-
HCAL Absorber	Fe	Fe	-
HCAL λ_I	5.9	4.9	-
DRCAL Cell Size (mm)	-	-	6.0
DRCAL Time resolution (ps)	-	-	100
DRCAL Absorber	-	-	Pb or Cu or Fe
Overall Height (m)	14.0	14.5	11.0
Overall Length (m)	13.2	14.0	13.0

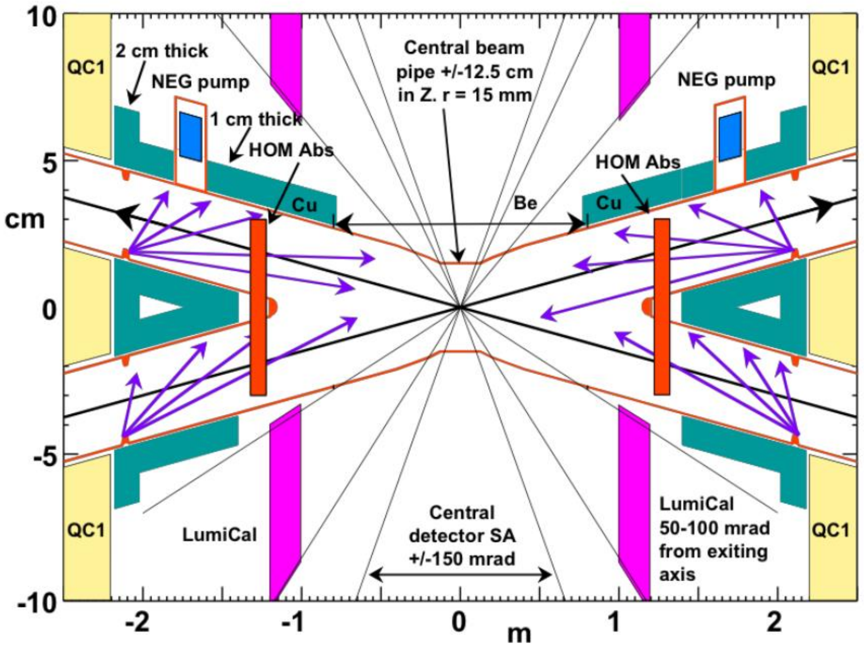


Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17
Tracker half length [m]	2.2	
Tracker outer radius [m]	1.5	2.1
ECAL absorber	W	
ECAL X_0	22	
HCAL absorber	Fe	
HCAL λ_I	7.5	5.5
Solenoid field [T]	4	2
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6





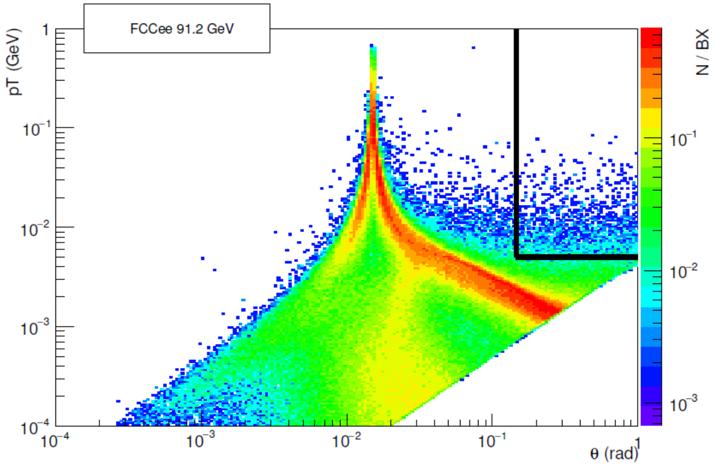
FCCee: current MDI design in the CDR and background issues



- 30 mrad crab-crossing, L*=2.2m
- LCAL: 1.074m-1.190m from the IP
- LCAL coverage: 62-88 mrad
- Target $\mathcal{L}$=2·10^{36} cm^{-2} s^{-1} (Z-pole) ~5xLEP
- Keep the detector SR hits 'free' (i.e. 2.5 hits/BX in the tracker volume @ 240 GeV)
- Less than 10^{-3} $\gamma\gamma \rightarrow$ *hadrons* interactions per BX @ Z^0 pole occurs with the $\gamma\gamma$ invariant mass above 2 GeV

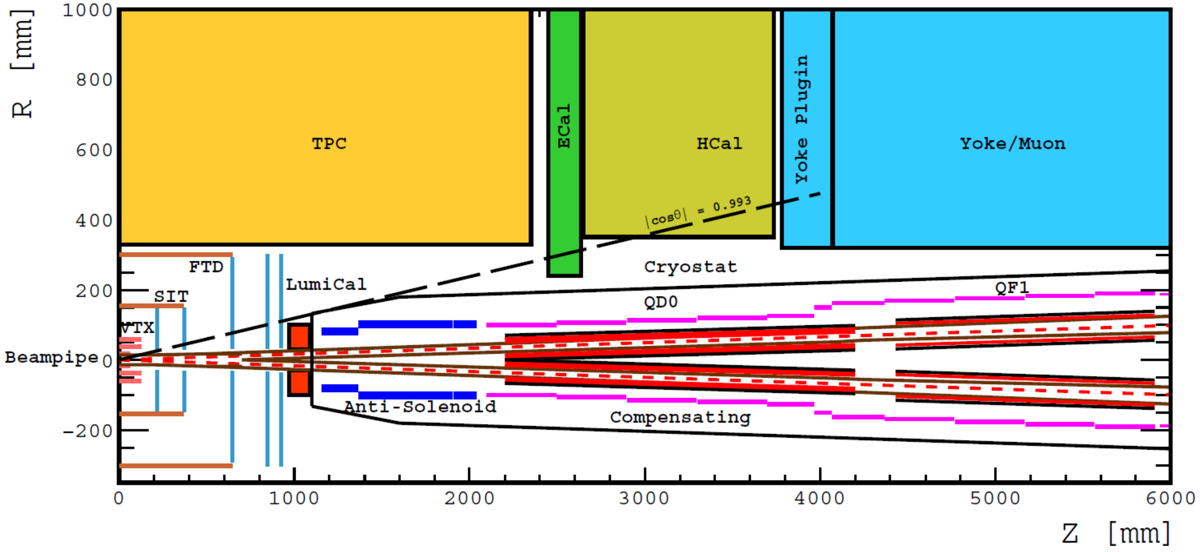
The number of incoherent electrons from BS that would reach CLD vertex detector per BX in the solenoid 2 T field is given in the last row

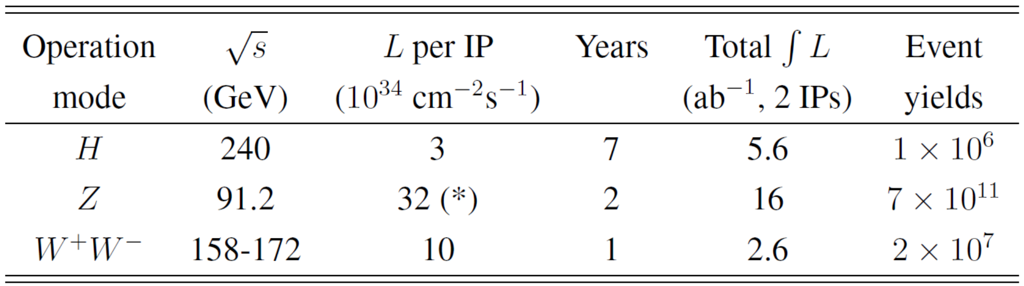
$\sqrt{s}$ [GeV]	91.2	365
Total particles	800	6200
Total E (GeV)	500	9250
Particles with $p_T \geq 5\,\text{MeV}$ and $\theta \geq 8^\circ$	6	290



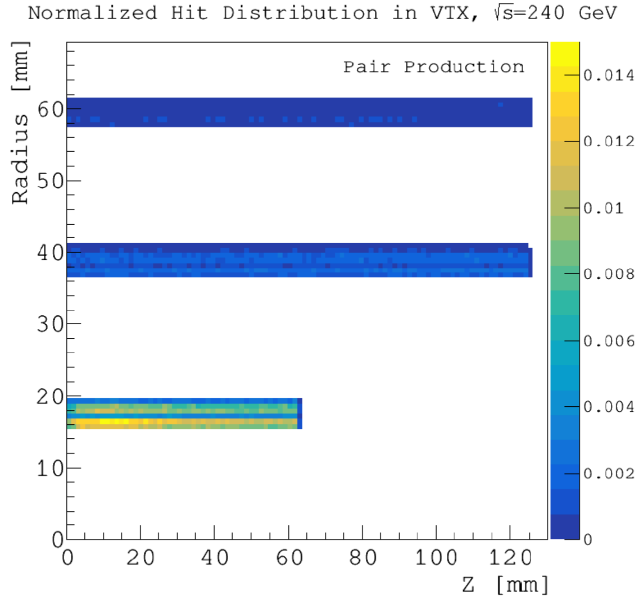
Incoherent pairs at FCCee with maximum depositions around 15 mrad.

CEPC: current MDI design in the CDR and background issues





Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158-172	10	1	2.6	2×10^7



Incoherent pair background from BS in the CEPC VTX

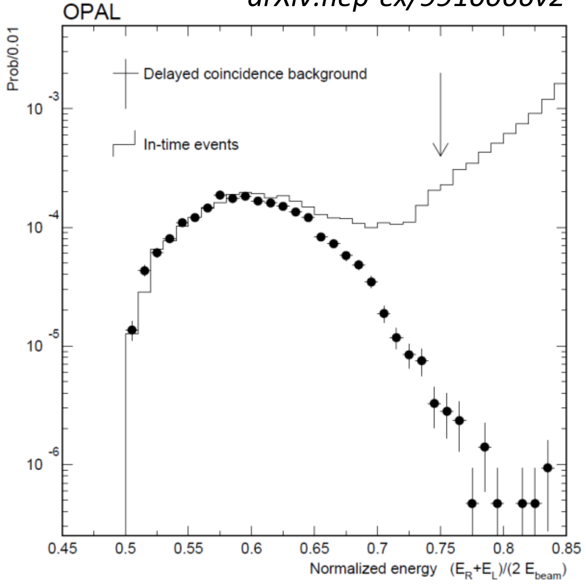
- 33 mrad double-ring x-angle, L*=2.2m
- LCAL: ~1m, 26-105 mrad geometrical acceptance (53-79 mrad fiducial volume)
- 680 ns, 25 ns and 210 ns bunch-spacing @ H, Z^0 and WW threshold → different level of background
- SR, BS, off-momentum particles, similar as at FCEee (first VTX layer: 2.4 particle/cm^2 per BX @240GeV)

Background: off-momentum beam particles

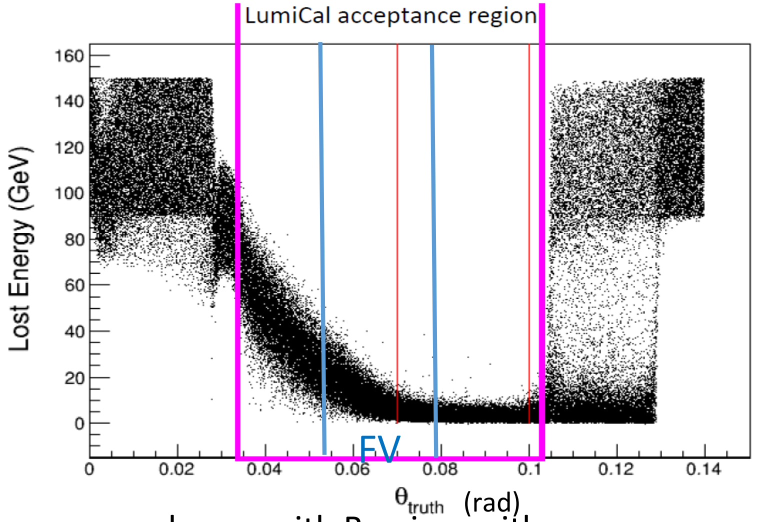
Circulating beam particles can lose significant amounts of energy in scattering processes. If exceeding 1.5% of the nominal energy scattered particles can be kicked off their orbit. Usual mechanisms are BS, radiative Bhabha and beam-gas interactions.

- Can influence luminosity measurement by accidental overlapping to the Bhabha signal and by coincidence in both detector halves that happens at the same rate as the signal.
- Off-momentum particles from beam-gas interaction were the main source of systematics in luminosity measurement at LEP ($0.1\text{-}0.6 \cdot 10^{-4}$). Nicely regulated by the (relative) energy cut.

arXiv:hep-ex/9910066v2



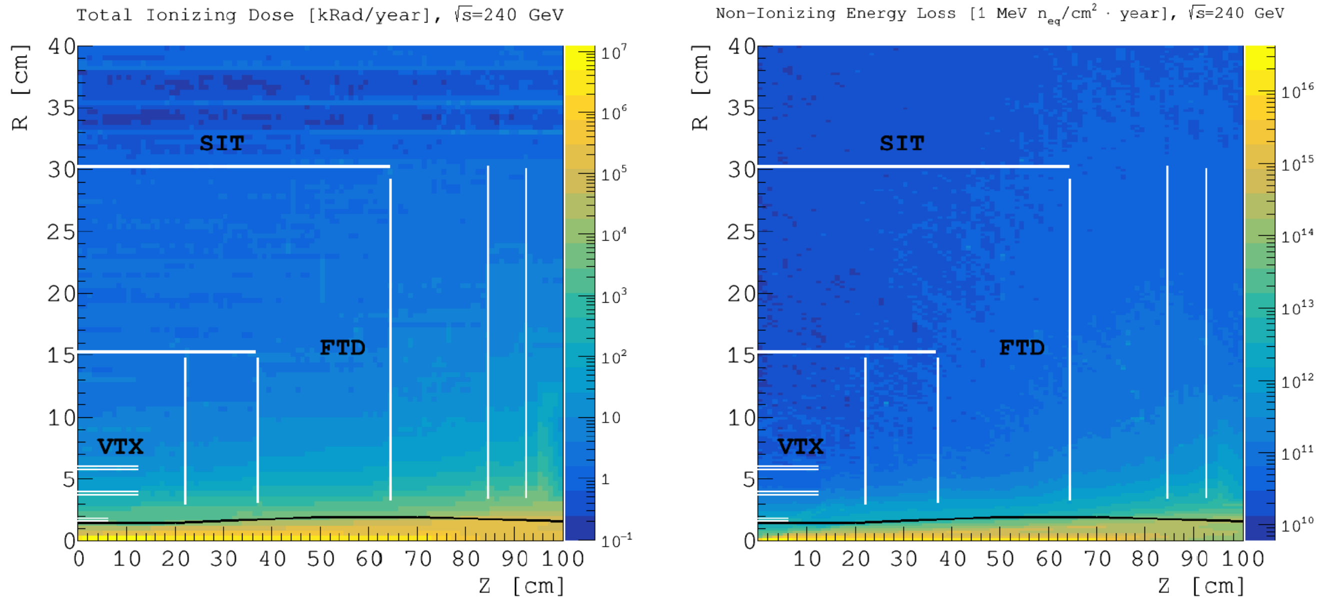
- Material budget in front of the LumiCal is important (left: optimization of the beam-pipe material for CEPC CDR studies)
- To keep the luminometer to perform, MDI materials (i.e. HOM absorbers) must be out of the way
- Design of this crowded region is under study



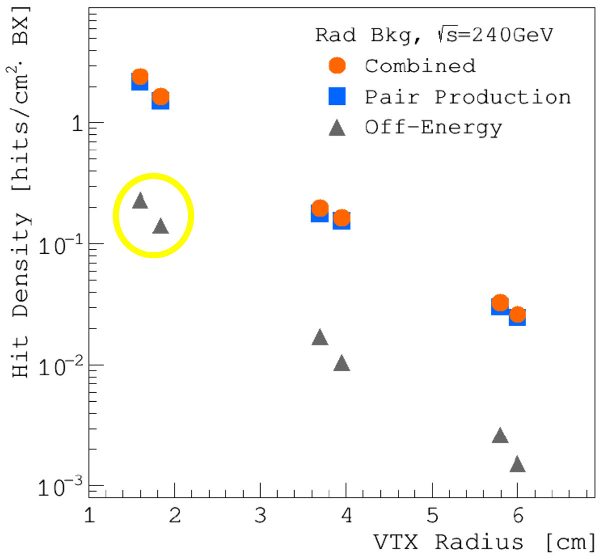
Large energy losses with Be pipe with a copper segments (CEPC V5)

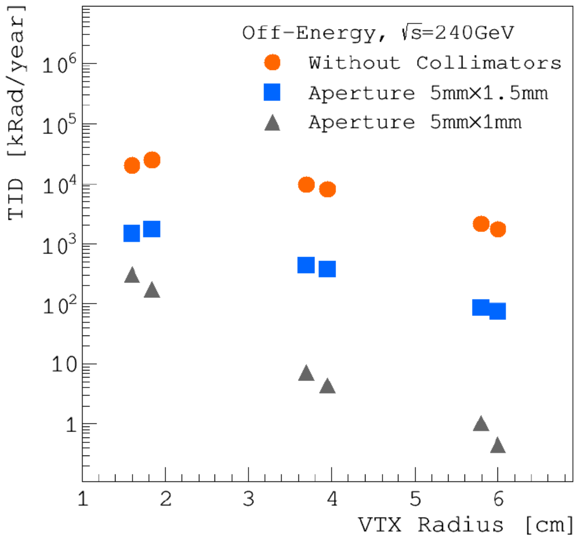
Background: combined

CEPC simulations shows that proper size collimators can be employed to suppress off-momentum particles in the first VTX detector layer to 0.22 hits/cm^2 per BX



Total ionizing and non-ionizing doses at CEPC Si subdetectors





The challenge is to maximize performance in terms of luminosity whilst maintaining the related background at a tolerable level

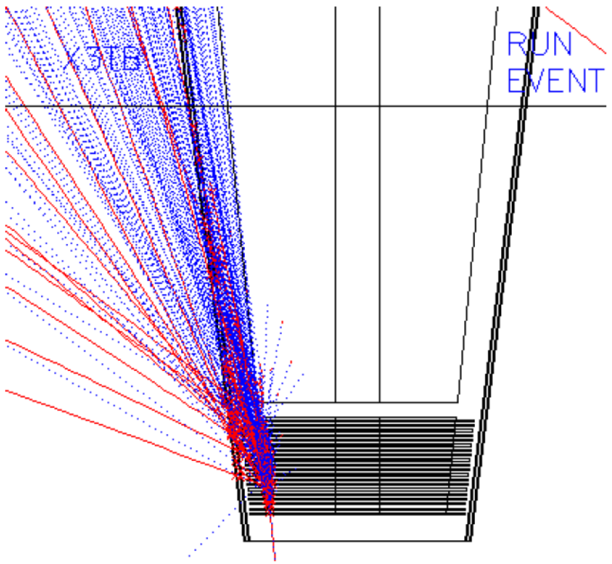
Other sources of contamination of the tracking volume

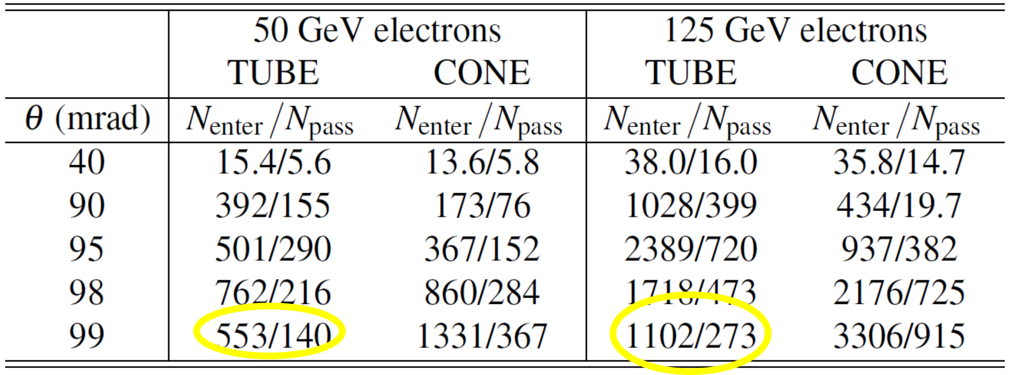
LumiCal shower leakage

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%

LumiCal technologies

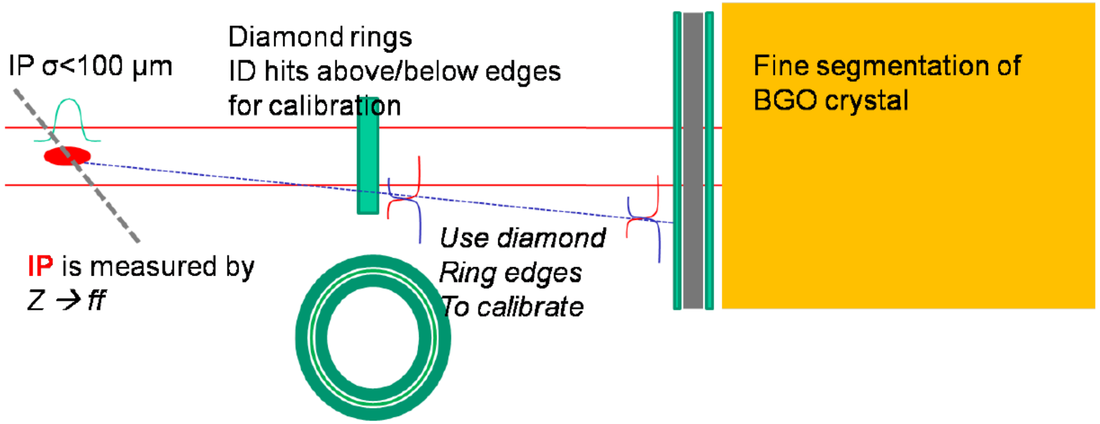
Si or diamond layer in front of the luminometer seems to be a viable option to enable:

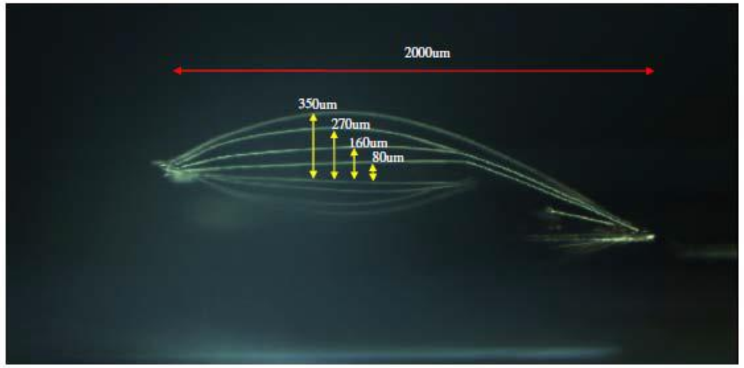
- calibration
- e/γ separation
- polar angle measurement with precision equivalent to 1 μm radial uncertainty

- LumiCal technology options are open (CEPC and FCCee)
- Si-W ‘ILC-like’ sandwich is an option
- But, is a detector with a simpler readout possible?

- Readout and assembly of SiW detector
- Coarse segmentation, compact electronics, search feasible readout chips

Detector technology is still open, but, it is clear that performance in terms **of energy and polar angle measurement** will play a key role in the control of systematics.





此次打線實驗是以固定直線距離2000um 做弧高控制，弧高可以做到
80um，考慮生產良率會控制在150um內。

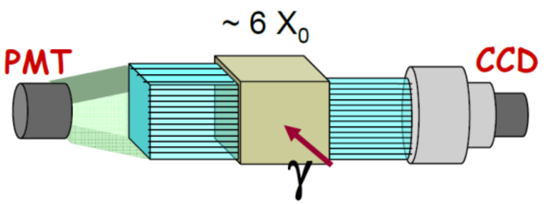
Industry studies with Ag wire bonding 80 μm high. Courtesy: S. Hou

Alternative technological options

Courtesy: S. Hou

- Si-W ‘ILC-like’
- BGO (has a bunch spacing of 25 ns is an issue at Z^0 pole CEPC);
- Lutetium Yttrium Orthosilicate (Lu_2SiO_5:Ce) may works in a CMS-like shashlik type of calorimeter
- SciFi spaghetti calorimeter with individually read-out fibers (prototyped for J-PARC K_L experiment)

- Good light output - 70% of NaI(Tl), High density - 7.15 g/cm^3
- Fast decay times - c.45ns
- Energy resolution - <12%
- Not hygroscopic
- Are relatively inexpensive



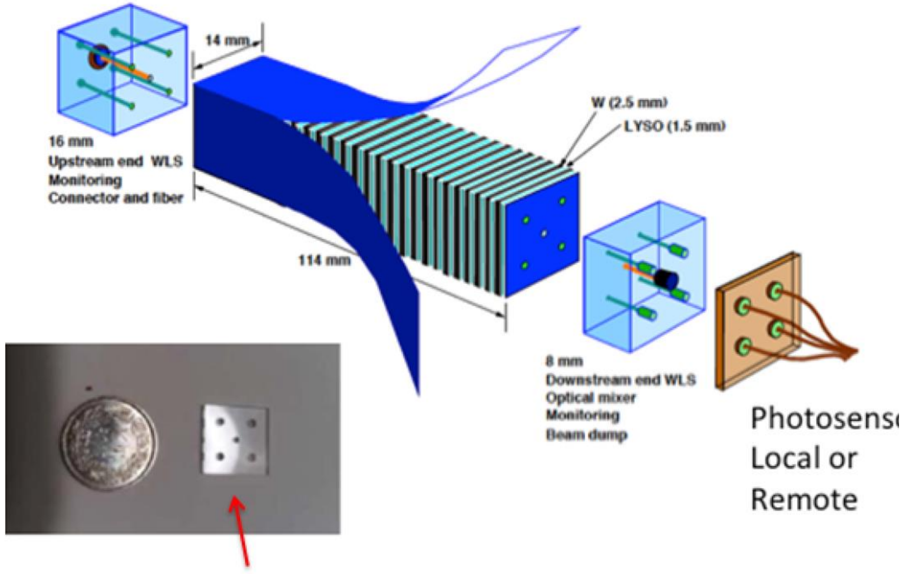
Number of fiber-hits and the energy deposit measured by PMT

Linear correlation

Energy deposit can be measured by just counting the number of fiber

http://www.nda.ac.jp/cc/radiation/presen/DPF2006_toru.pdf

Shashlik style module configuration



Transverse size of modules ~ ½ Swiss Franc

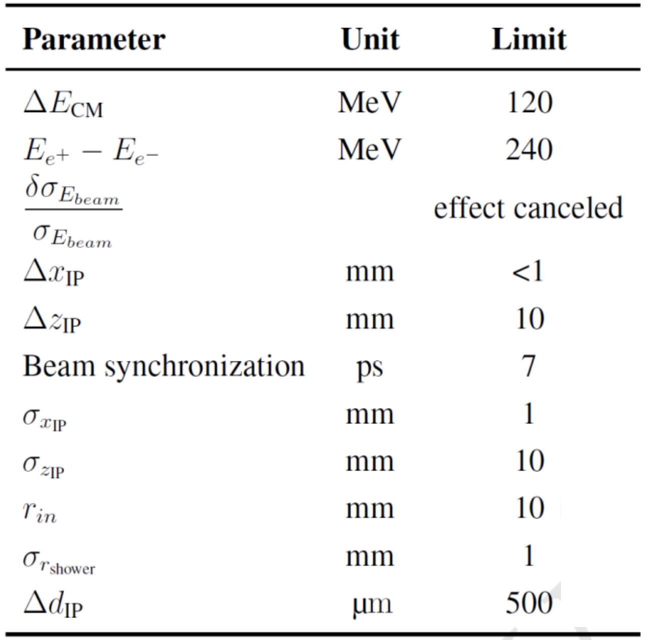
Radiation hardness

1. **Use of dense materials**
2. **Small Molière Radius**
3. **Rad-hard materials**
4. **Short optical paths**
5. **Rad-resistant, small pixel photosensor**

Challenges for luminosity measurement: systematics

- Detector positioning and beam related uncertainties have to be strictly controlled (down: is $\Delta\mathcal{L}/\mathcal{L}=10^{-3}$ per uncertainty at 240 GeV CEPC)
- Luminometer has to be centered at the outgoing beam to 'naturally' apply asymmetric acceptance selection (LEP style) and thus relax systematics

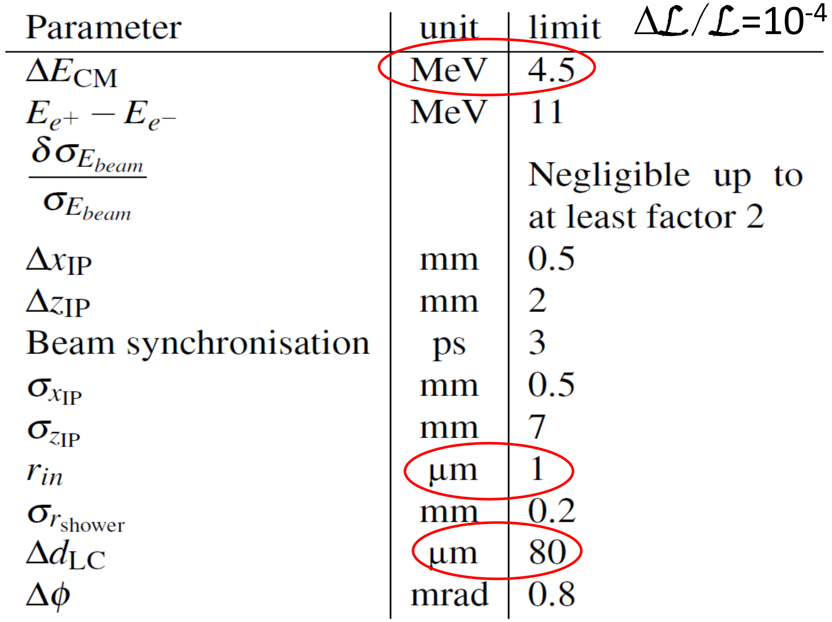
$\Delta\mathcal{L}/\mathcal{L}=10^{-3}$



Parameter	Unit	Limit
ΔE_{CM}	MeV	120
$E_{e^+} - E_{e^-}$	MeV	240
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		effect canceled
Δx_{IP}	mm	<1
Δz_{IP}	mm	10
Beam synchronization	ps	7
$\sigma_{x_{\mathrm{IP}}}$	mm	1
$\sigma_{z_{\mathrm{IP}}}$	mm	10
r_{in}	mm	10
$\sigma_{r_{\mathrm{shower}}}$	mm	1
Δd_{IP}	µm	500

Some requirements are on the technological limit:

- Inner radius of the luminometer: ~1 µm (4.4 µm at OPAL contributing $1.4\cdot10^{-4}$ uncertainty in L)
- Distance between calorimeters ~80 µm over app. 1m. Should be easily achieved with FSI.
- ΔE_{CM} and beam asymmetry at the level of a few MeV for the cross-section calculation ($2.7\cdot10^{-4}$ at LEP in ΔE) but some relevant processes might have the same x-section dependence with √s as Bhabha in which case the effect cancels out.



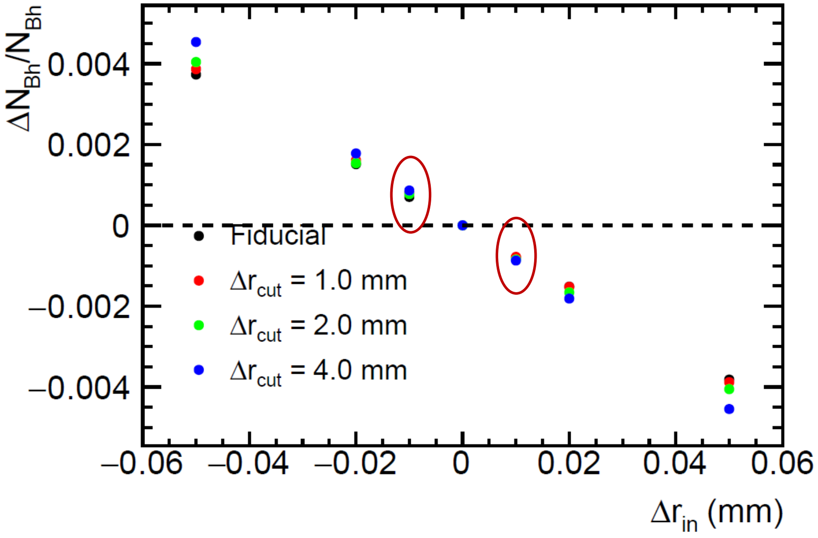
$\Delta\mathcal{L}/\mathcal{L}=10^{-4}$

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

Challenges for luminosity measurement: systematics

Inner radius of the luminometer

- Uncertainty of the inner radius translates into counting uncertainty since the Bhabha cross-section scales like $1/\theta^3$



Symmetric bias on beam energy:

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

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

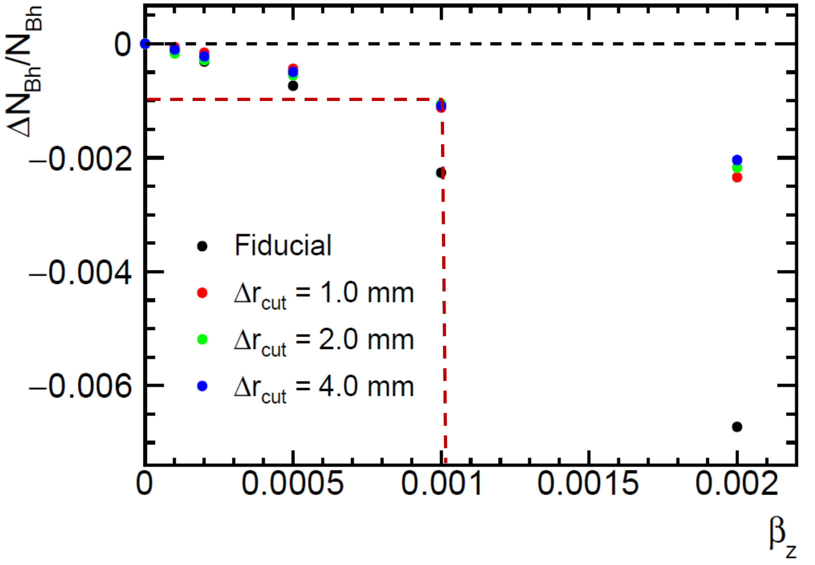
Asymmetric bias on beam energy:

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

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

⇒ counting loss due to the loss of acolinearity

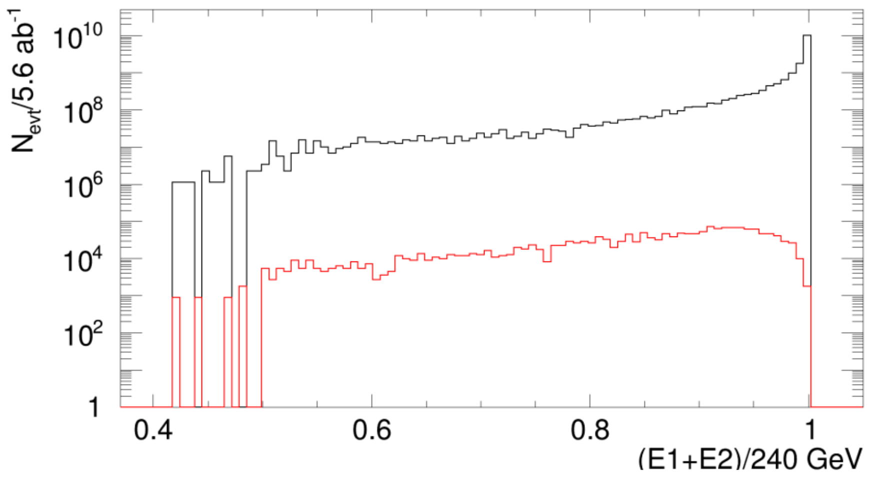
- Asymmetry in beam energies should be smaller than 10^{-3}



Challenges for luminosity measurement: systematics

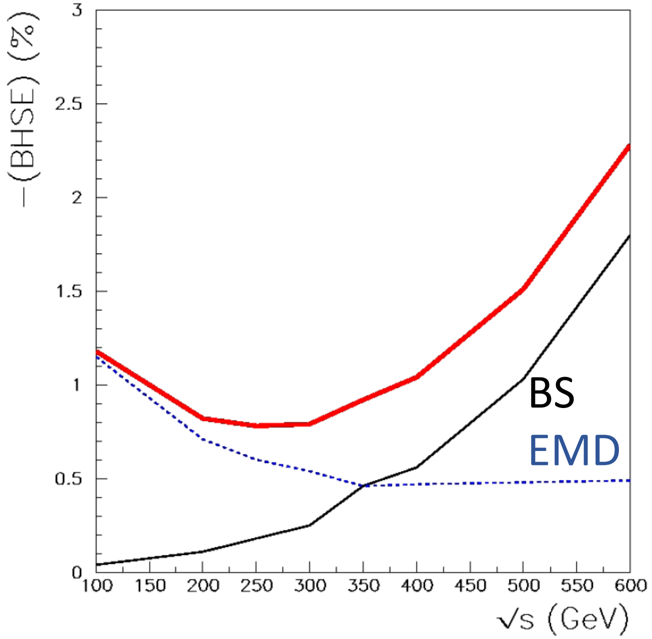
2-γ physics background

- Initial contamination (without any selection) of the detector volume is ~10^{-4} w.r.t. the signal at 240 GeV CEPC
- B/S ~ 10 times smaller than at 500 GeV ILC. This is mostly due to the Bhabha x-section dependence as 1/s, while 2-γ x-section is scaling like $\ln^2(s)$
- Similar situation should be at FCCee Higgs factory
- With the relative energy $E_{rel}>0.8$, B/S ratio is ~ $8 \cdot 10^{-5}$



EM deflection of Bhabha particles

- Outgoing Bhabha electrons/positrons can be deflected towards lower polar angles due to interaction with incoming bunches
- Like with BS, the EM field depends on a bunch transverse sizes: $\sim 1/(\sigma_x+\sigma_y)$
- The effect is at a % level at ILC at Z_0 pole (left), meaning that it will be of the order of 10^{-3} at 240 GeV CEPC and ~$3 \cdot 10^{-3}$ at Z^0 pole, just on the basis of the beam parameters.
- This requires consideration for a precision goal of $\Delta\mathcal{L}/\mathcal{L}=10^{-4}$



Summary & Possible FCAL contribution

- Instrumentation of the very forward region is very important for realization of physics program at any future machine

- Circular colliders (CEPC and FCCee) are facing particular challenges to reach luminosity precision goal of 10^{-4} (of particular importance at the Z^0 pole), where the most critical challenges are coming from mechanics and MDI

- Many issues are in common between CEPC and FCCee (also with linear colliders)

- ► LumiCal technology options are open
- ► Readout is a challenge, as well as assembling and prototyping
- ► If the FCAL Collaboration is interested, it's a great space to contribute

BACKUP

Sources of systematic uncertainty

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

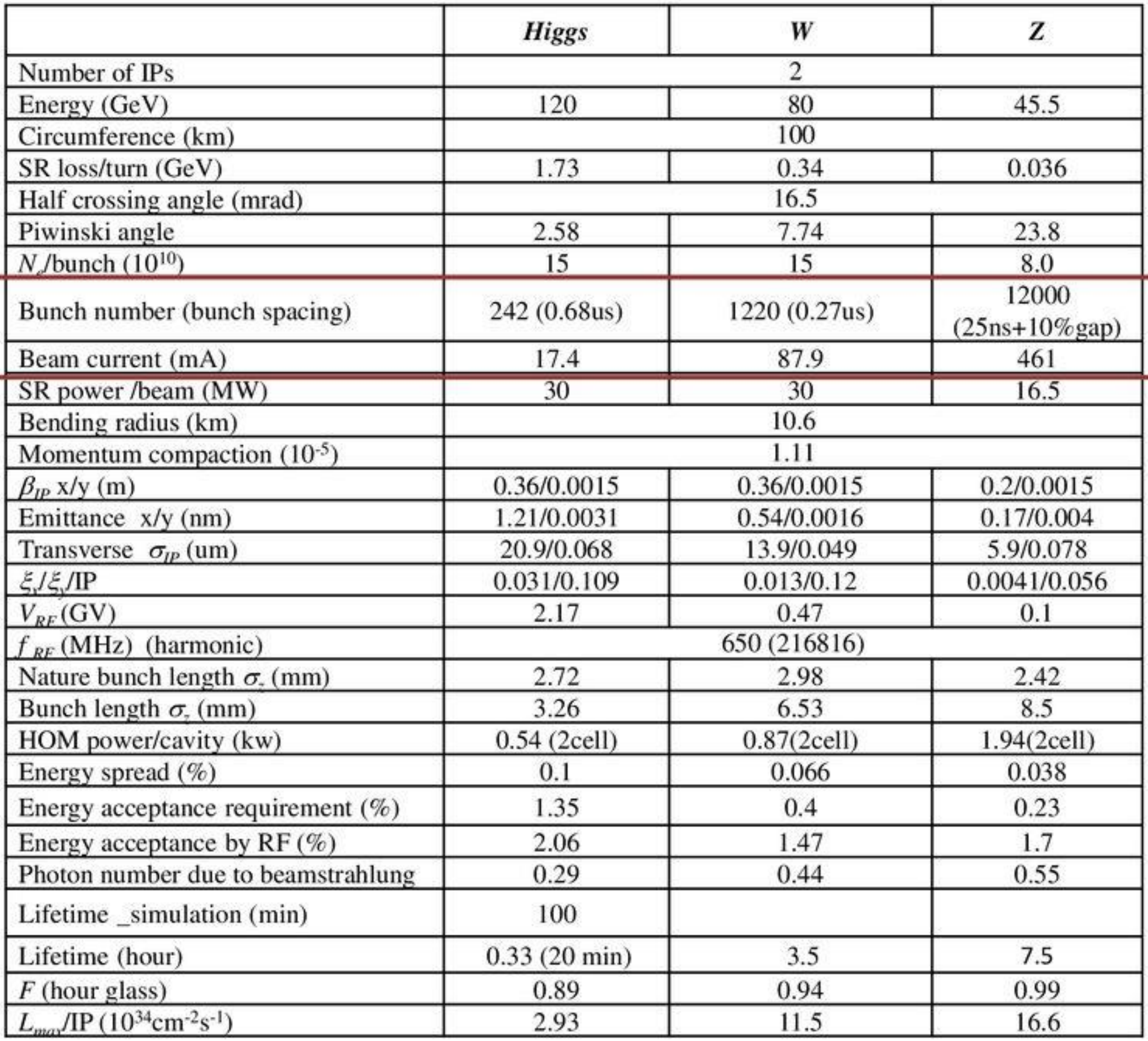
3. Physics interactions:
- Bhabha and physics background cross-section (uncertainty of the count)
- Bhabha acolinearity – other sources of the acceptance losses (ISR and FSR, Beamstrahlung)
- Machine-related backgrounds (off-momentum electrons from the beam-gas scattering)

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)

Where and why do we need luminosity precision?

- 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

CEPC CDR Parameters



	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.73	0.34	0.036
Half crossing angle (mrad)	16.5		
Piwinski angle	2.58	7.74	23.8
N_e/bunch (10^{10})	15	15	8.0
Bunch number (bunch spacing)	242 (0.68us)	1220 (0.27us)	12000 (25ns+10%gap)
Beam current (mA)	17.4	87.9	461
SR power /beam (MW)	30	30	16.5
Bending radius (km)	10.6		
Momentum compaction (10^{-5})	1.11		
β_{IP} x/y (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.17/0.004
Transverse σ_{IP} (um)	20.9/0.068	13.9/0.049	5.9/0.078
ξ_x/ξ_y/IP	0.031/0.109	0.013/0.12	0.0041/0.056
V_{RF} (GV)	2.17	0.47	0.1
f_{RF} (MHz) (harmonic)	650 (216816)		
Nature bunch length σ_z (mm)	2.72	2.98	2.42
Bunch length σ_z (mm)	3.26	6.53	8.5
HOM power/cavity (kw)	0.54 (2cell)	0.87(2cell)	1.94(2cell)
Energy spread (%)	0.1	0.066	0.038
Energy acceptance requirement (%)	1.35	0.4	0.23
Energy acceptance by RF (%)	2.06	1.47	1.7
Photon number due to beamstrahlung	0.29	0.44	0.55
Lifetime _simulation (min)	100		
Lifetime (hour)	0.33 (20 min)	3.5	7.5
F (hour glass)	0.89	0.94	0.99
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.93	11.5	16.6