CEPC Machine-Detector Interface

Hongbo Zhu (IHEP, Beijing)

For the CEPC MDI Working Group

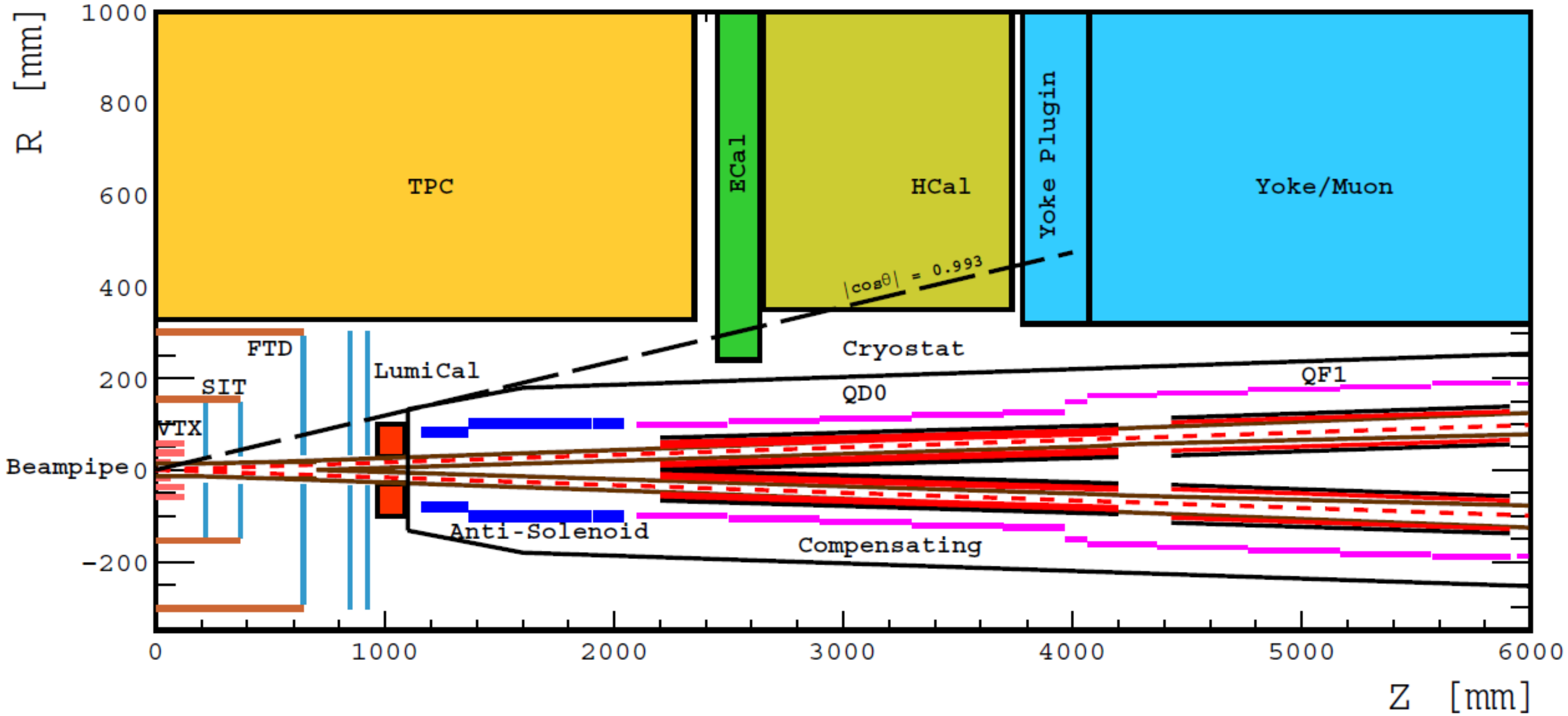
Outline

- Interaction region layout
- Final focusing and compensating magnets
- Beam pipe
- Radiation backgrounds
- LumiCal
- Summary

Interaction Region

- **Layout of the interaction region**: extremely limited space for several critical components → *trade-offs, optimizations toward a more realistic design*

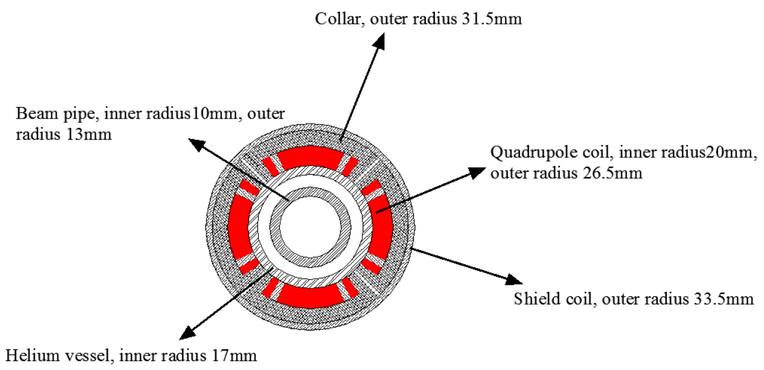
L = 2.2 m*
Crossing angle 33 mrad

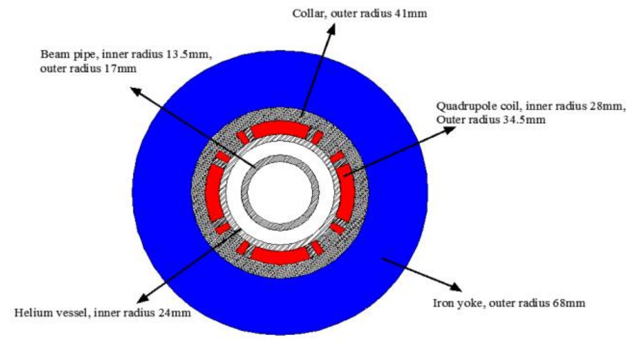


Final Focusing Magnets

- QD0 located at 2.2 m from the IP (defining the L^*)
- Double aperture design with Cos-Theta quadrupole coils using NbTi Rutherford cables; with (QD0) and without (QF1) iron yoke

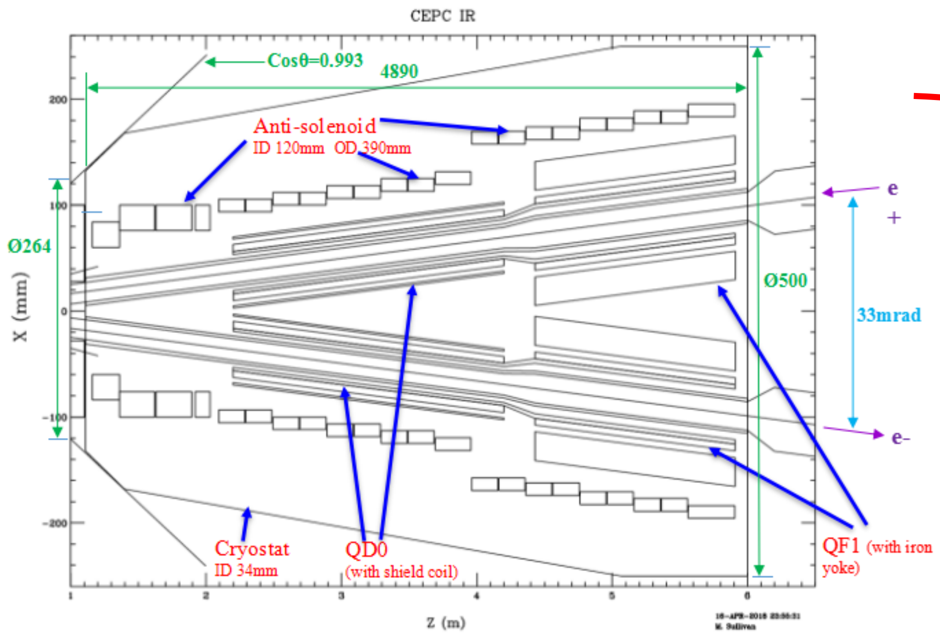
Magnet	QD0	QF1
Field gradient [T/m]	136	110
Magnetic length [m]	2.0	1.48
Coil turns per pole	23	29
Excitation current [A]	2510	2250
Coil layers	2	2
Stored energy [kJ]	25.0	30.5
Inductance [H]	0.008	0.012
Peak field in coil [T]	3.3	3.8
Coil inner diameter [mm]	40	56
Coil outer diameter [mm]	53	69
X direction Lorentz force/octant [kN]	68	110
Y direction Lorentz force/octant [kN]	-140	-120



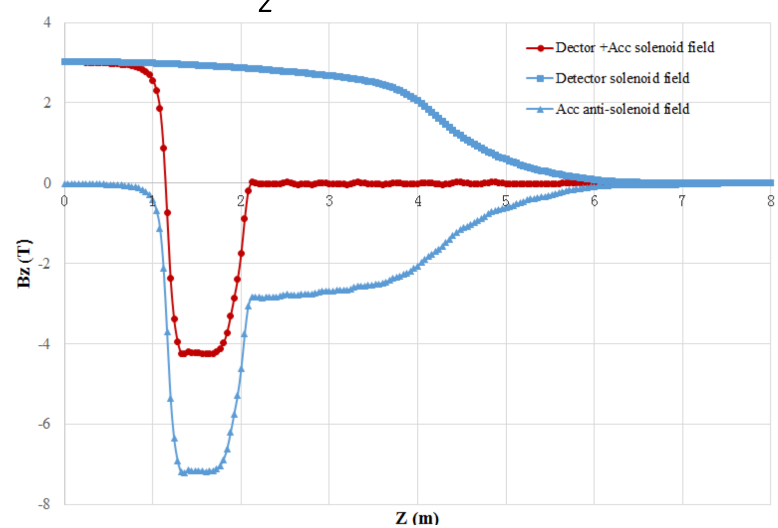


Compensating Magnets

- Compensating magnets segmented into 22 sections to minimize the disturbance of the detector solenoid on the beams;
- Peak field (before QD0) ~7.2 T, close to the limit of NbTi-Cu

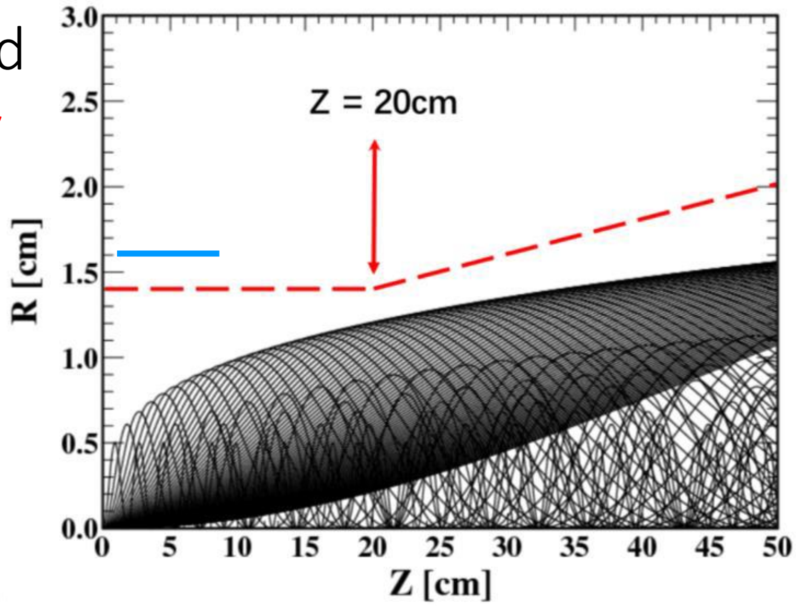


B_z distributions



Beam Pipe

- Central beam pipe ($\mathrm{z} = \pm 7\ \mathrm{cm}$) made with Beryllium (thin to minimize material but thick enough to sustain vacuum pressure), forward region with stainless steel or copper; gold coating to prevent SR photons?
- Shortest distance to the IP limited by backgrounds (*to be kept away from the kinematic edge formed by pair production*)
- Shape in the forward region optmized to avoid extreme high order mode (HOM) heating



Radiation backgrounds

- Important inputs in to detector (+machine) designs, e.g. detector occupancy, radiation tolerance …

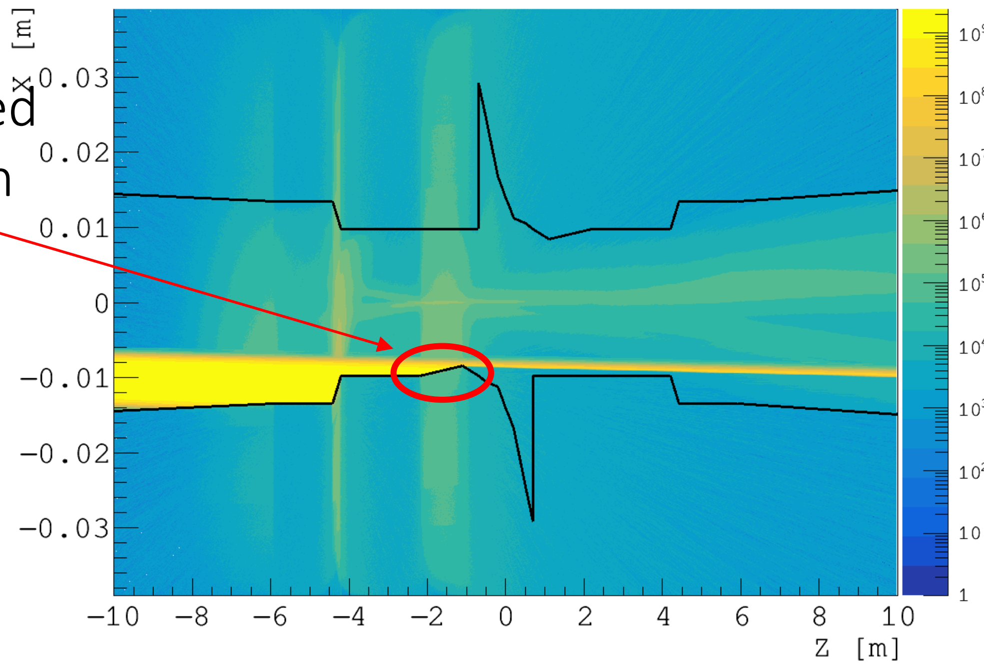
- Have investigated the most important sources of radiation backgrounds, including
  - *Synchrotron radiation*
  - *Beamstrahlung, Pair production*
  - *Beam lost/off-energy particles (Radiative Bhabha scattering, beamstrahlung, beam-gas interaction, etc.)*
  - *Extending into other but less critical sources*

Synchrotron Radiation

- Beam particles bent by magnets (last bending dipole, focusing quadrupoles) emit SR photons → important at circular machines
- BDSim to transport beam (core + halo) from the last dipole to the interaction region and record the particles hitting the central beryllium beam pipe

Large amount of photons scattered by the beam pipe surface between [1, 2 m] into the central region

Collimators made with high-*Z* material must be introduced to block those SR photons.



Collimator Design

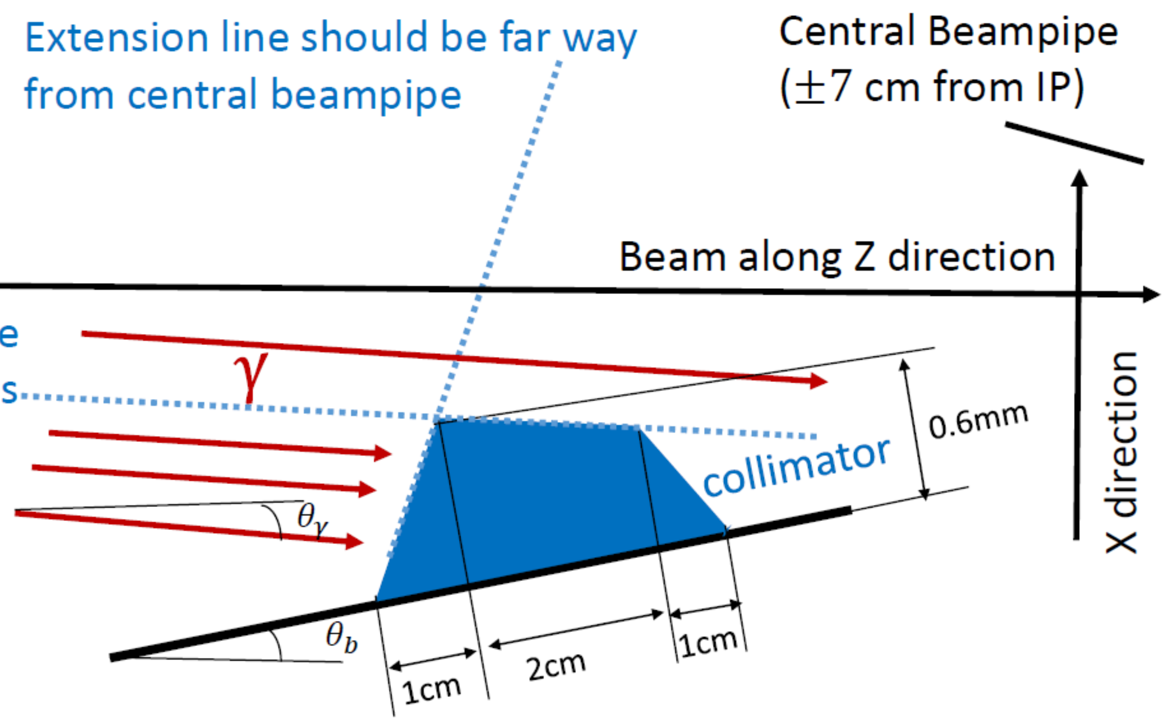
Collimator shape

θ_b= 1.17 mrad

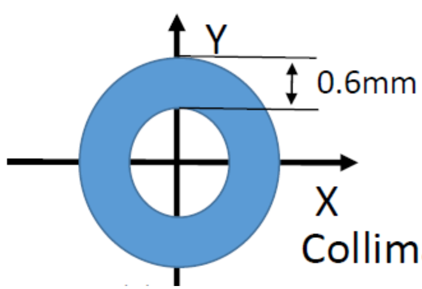
θ_γ= -127 ± 7 μrad at Z=-1.51m

θ_γ= -130 ± 8 μrad at Z=-1.93m

Extension line should be parallel with SR photons



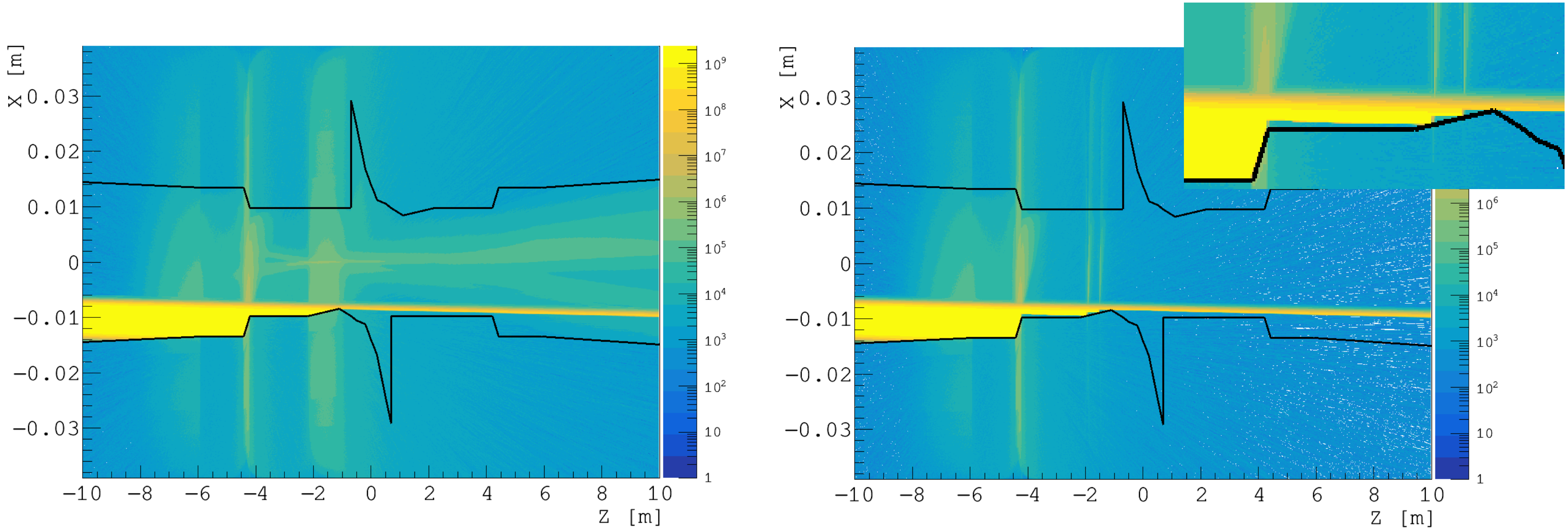
Collimator at Z=-4.2m: just a box



Collimator at X-Y plane: a ring

With Collimation

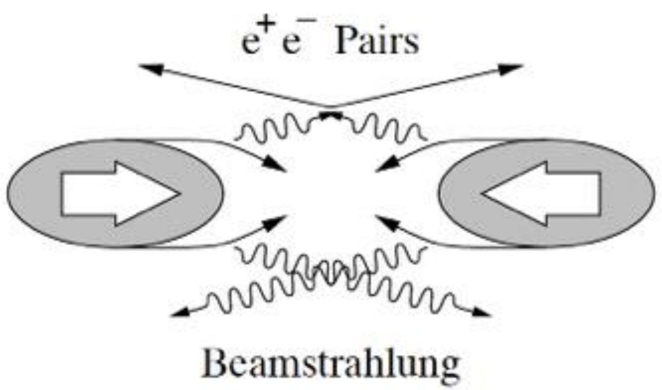
- Three masks at 1.51, 1.93 and 4.2 m along the beam pipe to the IP to block SR photons → shielding to the central beam pipe



- Number of photons per bunch hitting the central beam pipe from one side dropping from 40, 000 to 80 → consistent with analytical calculation (Acc. CDR)

Pair Production

- Estimated as the most important background at Linear Colliders, *not an issue for lower energy/luminosity machines*
- Charged particles attracted by the opposite beam emit photons (**beamstrahlung**), followed by electron-positron pair production (*dominate contributions from the incoherent pair production*)



Simulated with GUINEAPIG with external field implemented

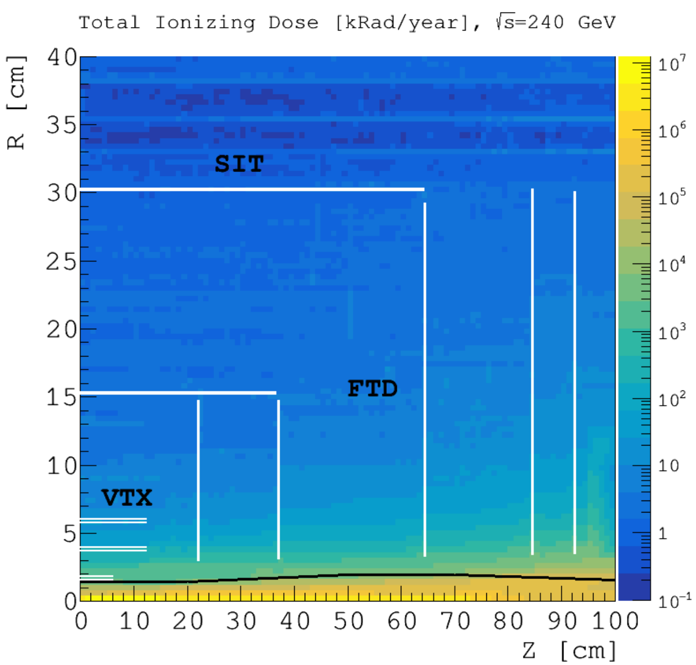
Most electrons/positrons are produced with low energies and in the very forward region, and can be confined within the beam pipe with a strong detector solenoid;

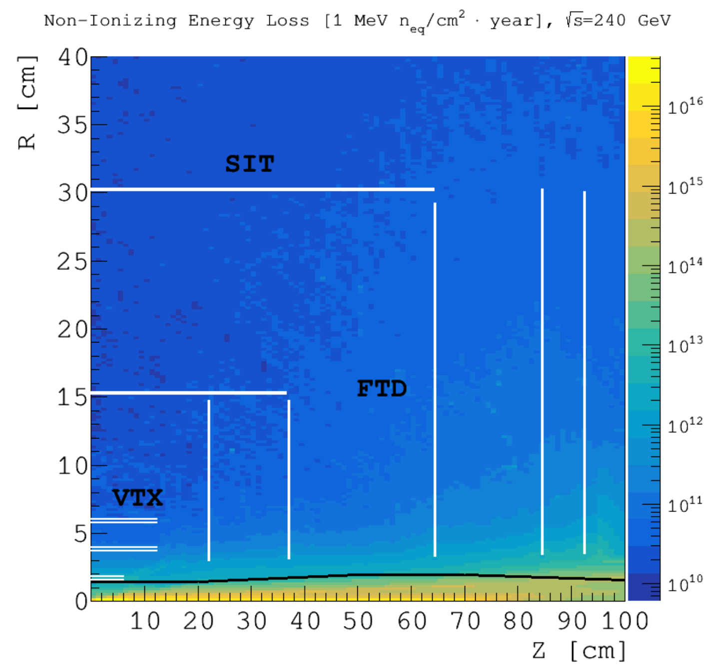
However, a non-negligible amount of electrons/positrons can hit the detector → **radiation backgrounds**

Hadronic backgrounds much less critical

Radiation Background Levels

- Using hit density, total ionizing dose (TID) and non-ionizing energy loss (NIEL) to quantify the radiation background levels
- Adopted the calculation method used for the ATLAS background estimation (ATL-GEN-2005-001), safety factor of ×10 applied

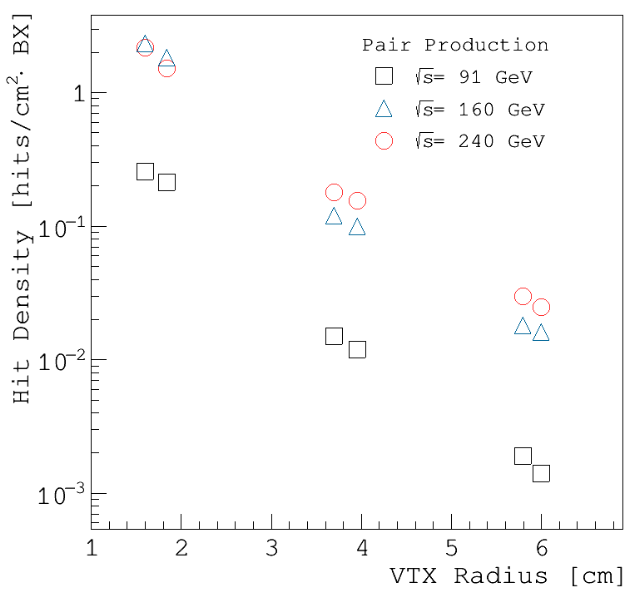


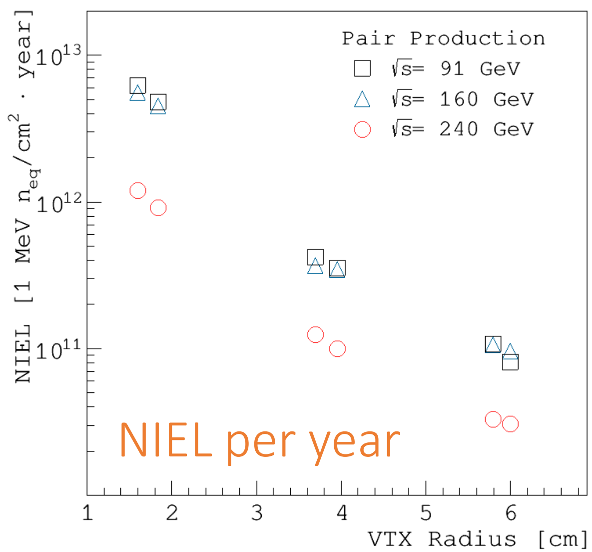


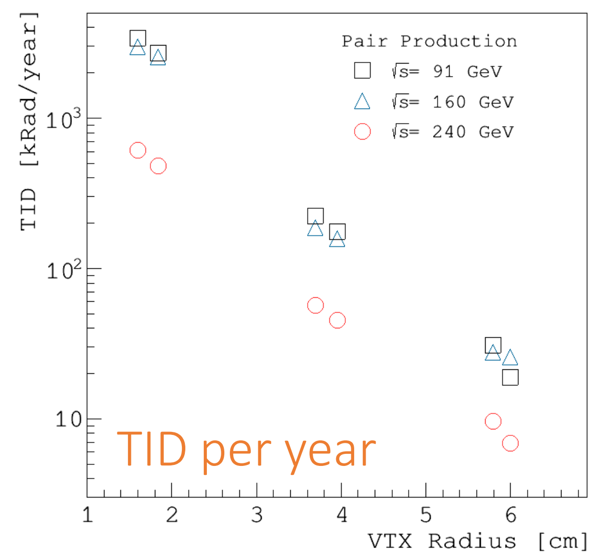
Pair Production Bkg.

- Hit density, TID and NIEL levels at different vertex detector layers
- Reminder of bunch spacings: 680 (H)/210 (W)/25 (Z) ns

Hit density (per bunch crossing)



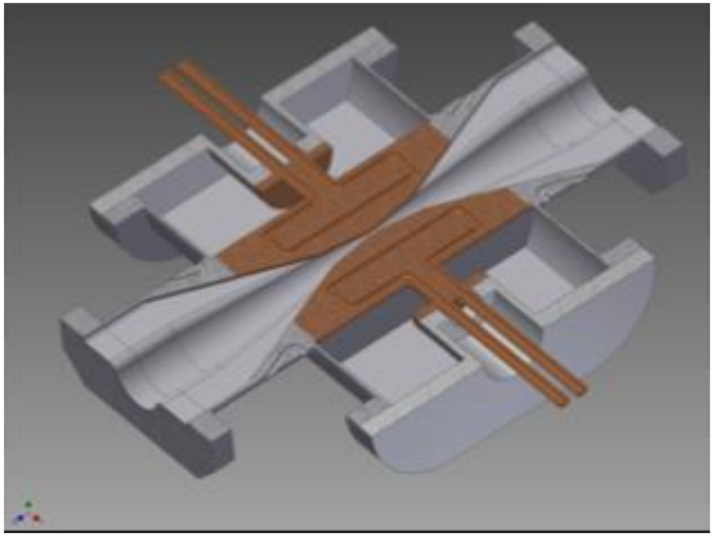




Off-Energy Particles

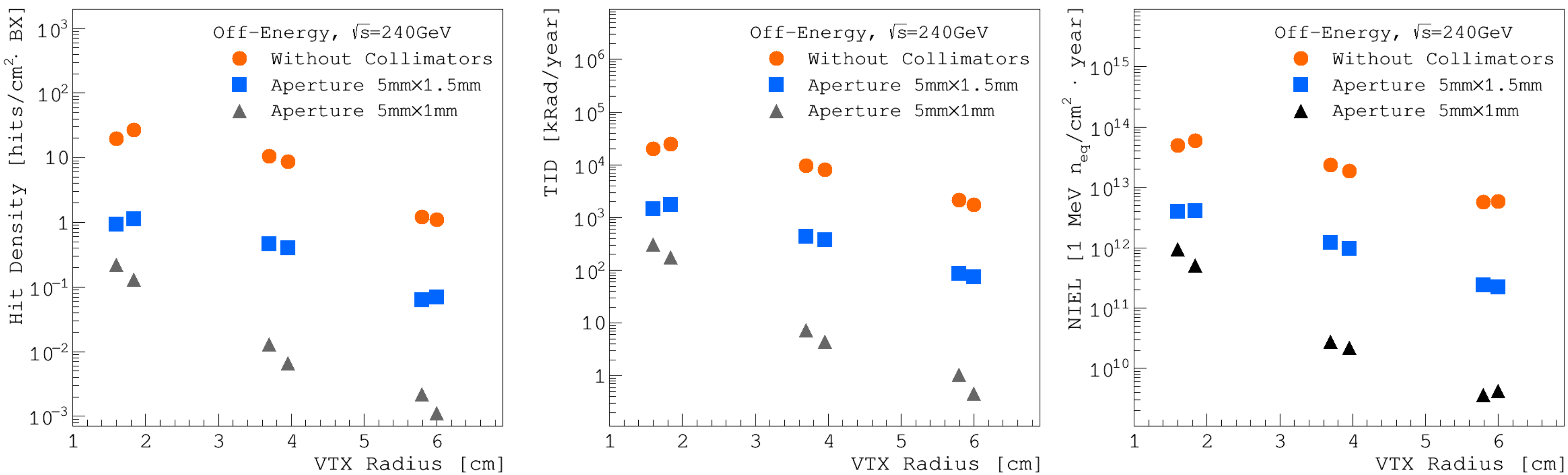
- Beam particles losing energies (radiative Bhabha scattering, beam-gas interaction, beam-gas interaction, etc.) larger than acceptance kicked off their orbit → lost in the interaction region
- Two sets of collimators placed upstream to stop off-energy beam particles, sufficiently away from the beam clearance area (aperture size subject to optimization)

What shape?
SuperKEKB Type (PEP-II as reference)



Effectiveness of Collimators

- Suppression of detector backgrounds, close to a factor of 100 in reduction → remaining backgrounds controlled to be smaller than that from pair production

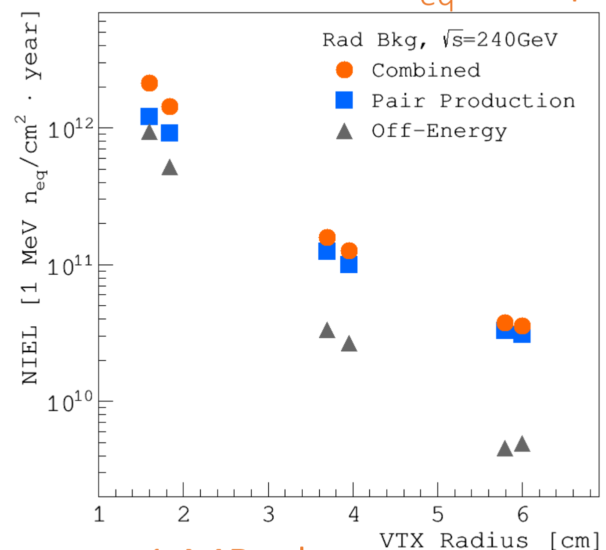


- Collimators subject to further optimization in line with machine design evolution → demonstration of effective design

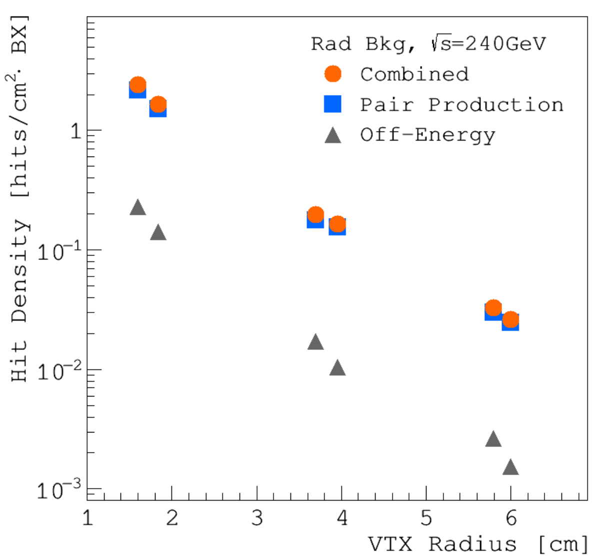
Combined Backgrounds

- Radiation backgrounds from pair production, radiative Bhabha scattering + beamstrahlung
- Most significant contributions from pair production

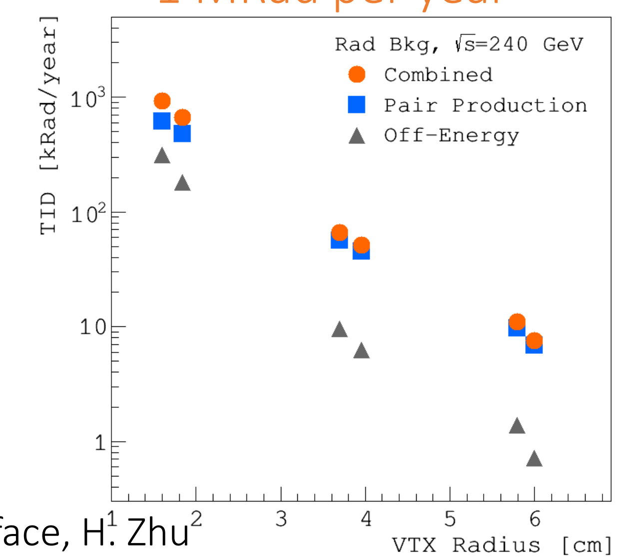
$\sim 2\times10^{12}$ 1MeV n_{eq}/cm^2 per year



2.4 hits/cm^2 per bunch crossing



~ 1 MRad per year



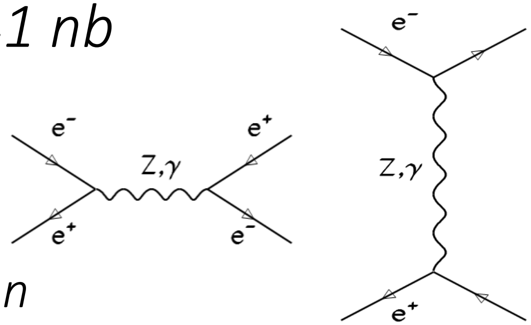
Different Operation Energies

	H (240)	W (160)	Z (91)
Hit Density [hits/cm^2·BX]	2.4	2.3	0.25
TID [MRad/year]	0.93	2.9	3.4
NIEL [10^{12} 1MeV n_{eq}/cm2·year]	2.1	5.5	6.2

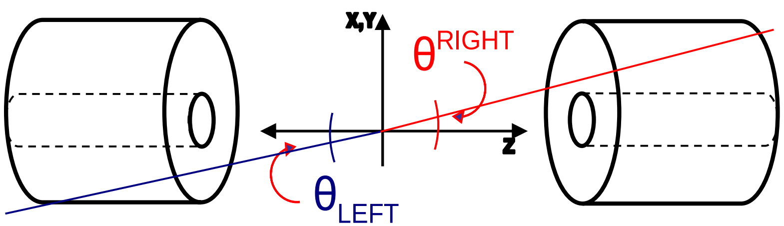
Dominant contributions from pair production

Luminosity Measurement

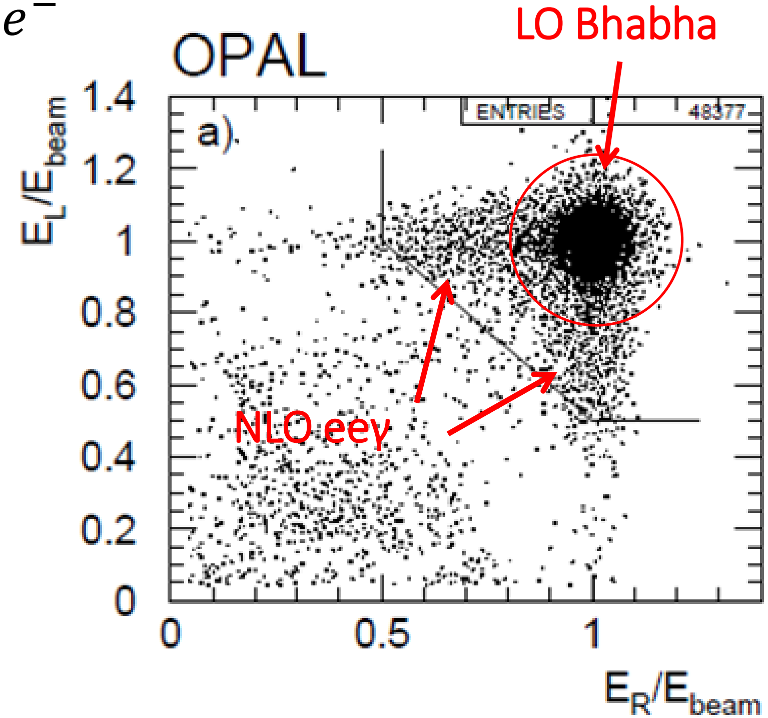
- *Z line-shape, $e^+e^- \to Z \to q\bar{q}$ dominant, σ = 41 nb*
- *Luminosity best provided by detecting Bhabha elastics scattering, $e^+e^- \to e^+e^-$*
  - *pure QED process, theoretical MC to <0.1% precision*
  - *triggering on a pair of scattered e^+e^-*



$$\sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta^2_{min}} - \frac{1}{\theta^2_{max}}\right)$$



$\Delta\theta \equiv \theta_{RIGHT} - \theta_{LEFT}$



Precision

- Luminosity by counting Bhabha events in a fiducial θ region

$$\mathcal{L} = \frac{1}{\varepsilon}\frac{N_{\text{acc}}}{\sigma^{\text{vis}}} \qquad \sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta^2_{min}} - \frac{1}{\theta^2_{max}}\right)$$

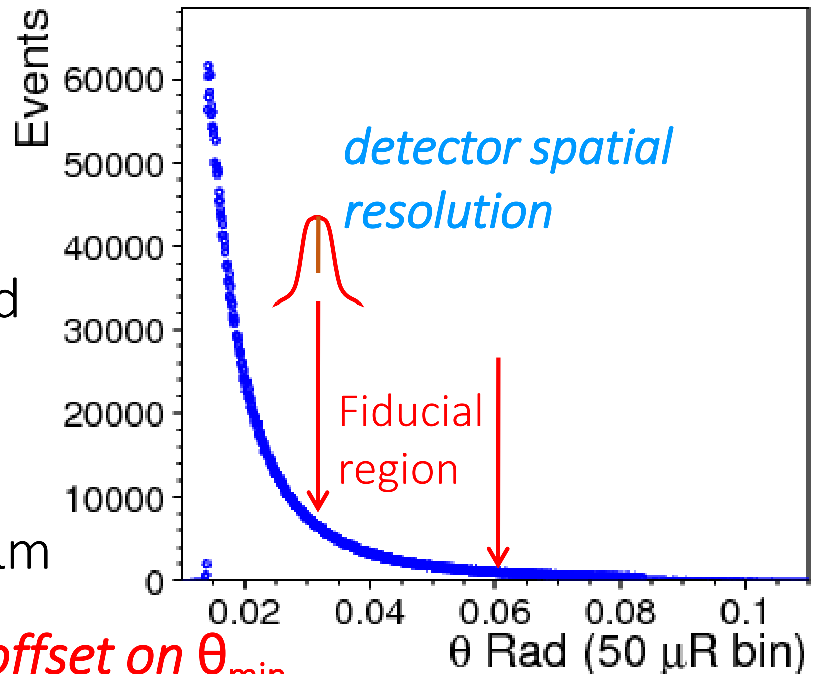
- Dominant systematic error

$$\Delta L/L \sim 2\Delta\theta/\theta$$

- For a precision of $\Delta L/L < 10^{-3}$
  - LumiCal at z= ±1 m, θ_{min}= 30 mrad

  → Δθ = 15 µRad or Δ r = 15 µm
  - Error due to offset on Z

  → 0.1 mm on z or Δ r = Δ Rxθ = 3 µm



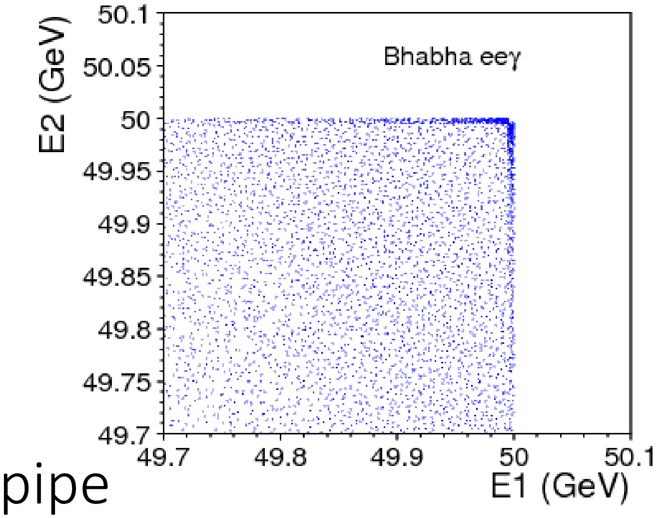
*offset on the **mean of spatial resolution** = **offset on** θ_{min}*

*→dominant **LUMINOSITY error***

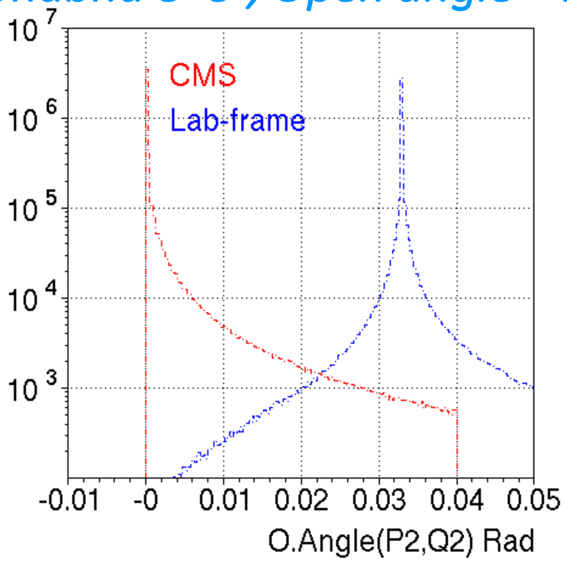
Boost by the Beam Crossing Angle

- BHlumi theoretical precision <0.05%
  - LO elastic e+ e− scattering dominant
  - $E(e^+) = E(e^-) = E_{beam}$, Open Angle = π
- $CMS(e^+e^-)$ boosted by beam crossing
- $e^\pm$ boosted ~16.5 mrad off ring-center

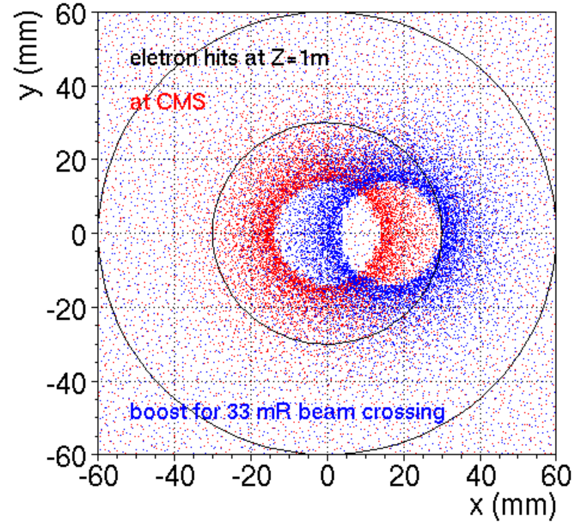
→back-to-back offset → $e^\pm$ lost into beam-pipe



Bhabha $e^+ e^-$, Open angle −π



Bhabha e− @detector r-φ, z=1m



Boosted Bhabha

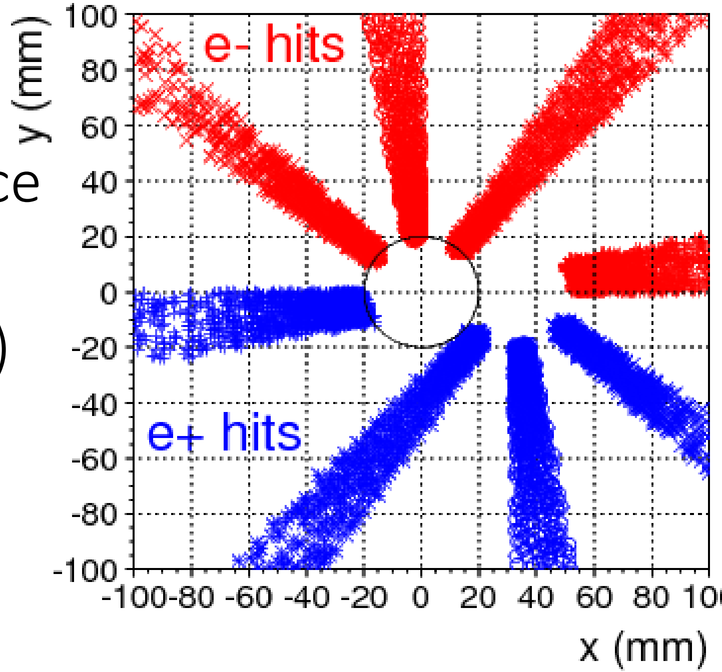
BHLUMI colliding e^+e^- back-to-back

Boost CEPC crossing angle of 33 mrad

Boost BHLUMI e^+, e^- to CEPC → ***E is larger by ~.01%***

Ebeam = 50 GeV → boosted E = 50.0068 GeV

- Boosted LO Bhabha (e^+e^-, no γ)
- e^+ and e^- detected in fiducial acceptance of r > 20 mm
- r-ϕ plotted in bands (every 45 deg in ϕ)
- Event loss 163 nb → 98 nb
    - Loss is SIGNIFICANT
    - LumiCal with a small inner r, in OVAL shape if feasible

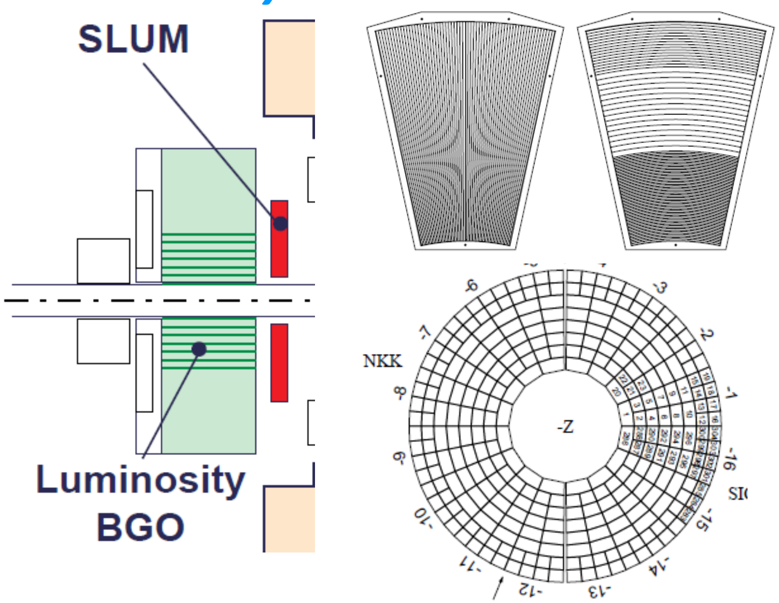


Hits on detector x-y planes @z=1m

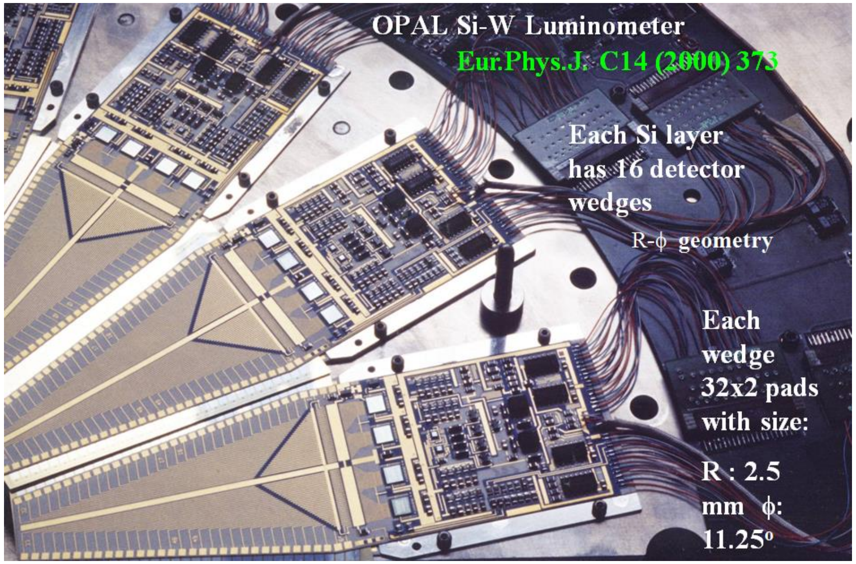
Detector Options

- Luminosity precision = $e^{\pm}$ detection in r, at inner radius of fiducial
  - → Silicon strip is the choice!
  - → Alignment CAN NOT reach 1 μm
  - → Wide strip (~2mm) CAN NOT reach 10 μm resolution
  - → A stand-alone LumiCal CAN NOT calibrate its offsets to IP

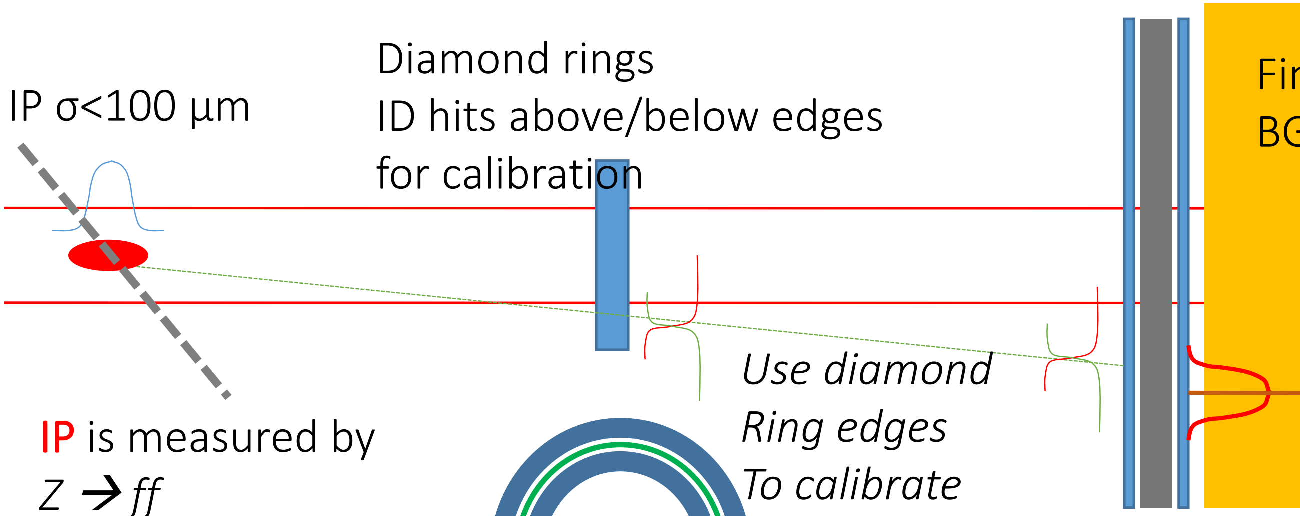
L3 Silicon layer + BGO

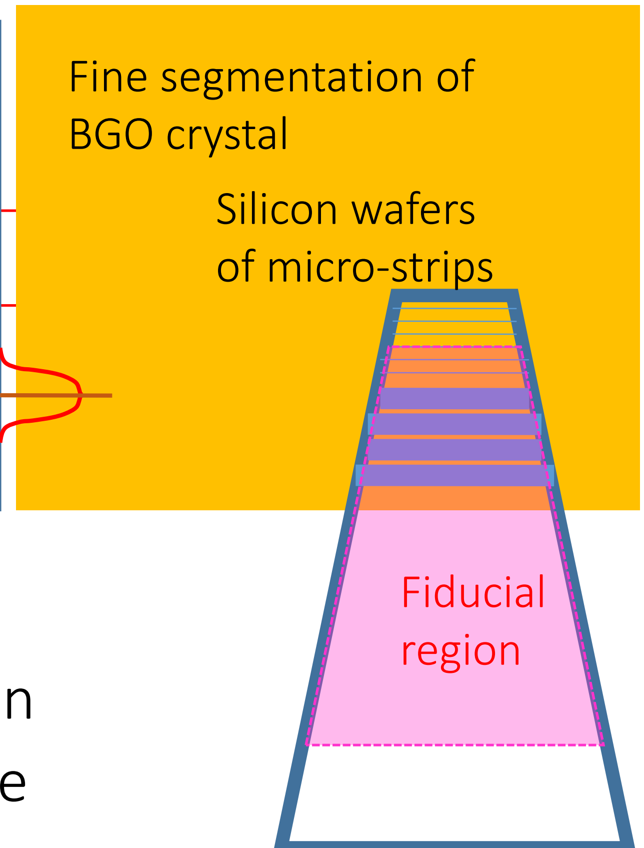


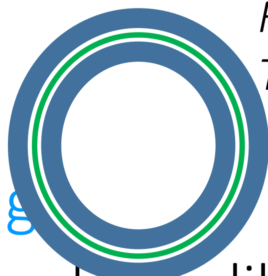
OPAL Si-W sandwich



Tracking Ring







3-point tracking

- IP + Diamond → calibrate strip position
- Diamond + LumiCal → measure IP size

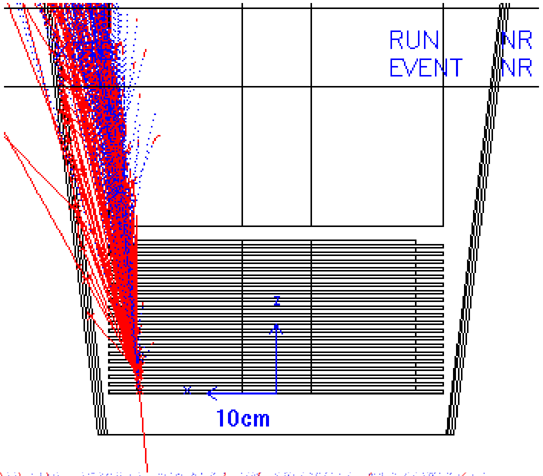
- Calibrate offset of the mean of error at inner radius

Silicon strip resolution ~ 5 um,

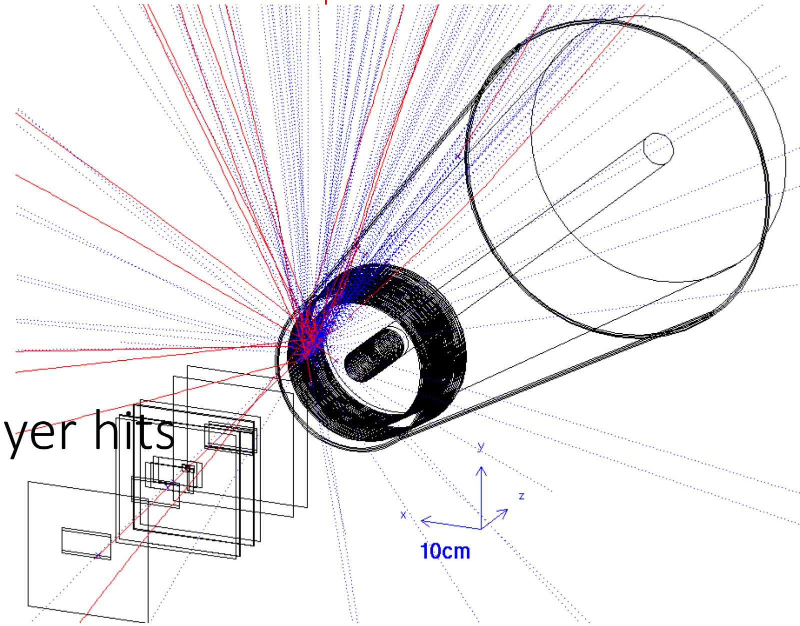
error on mean much smaller, CAN reach 1 µm, ΔL/L ~ 0.01 %

Silicon-Tungsten

- Detector assembly:
  - **first layer**: high resolution tracking for electron hit r, ϕ position
  - **energy resolution**: Si-wafer detector charged particles only; a MIP of Landau ionization charge; EM shower = # of charged particles.



- e±/γ Identification:
  - photon no signal on Si-wafer
  - photon fragmentation after ~1 X0
  - photon ID: EM shower with no 1^{st} layer hits
  - photon spatial resolution: Calo segmentation



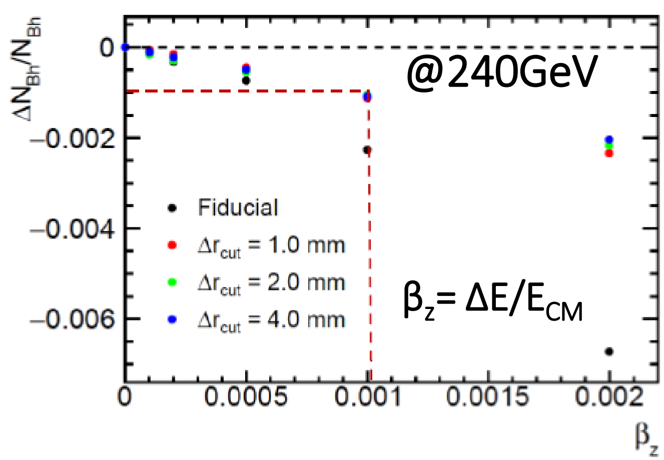
Systematic Uncertainties

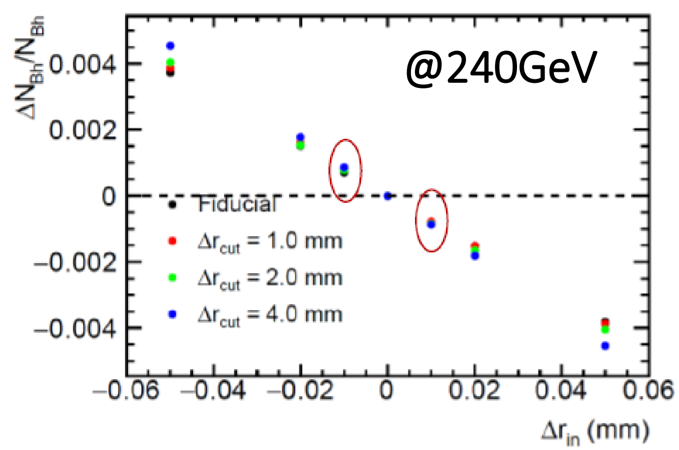
$\Delta L/L \sim 10^{-3}$ @ 240 GeV

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

$\Delta L/L \sim 10^{-4}$ @ Z-pole

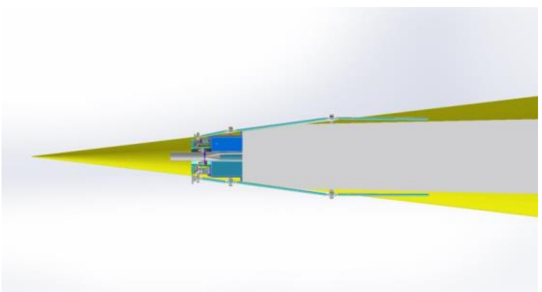
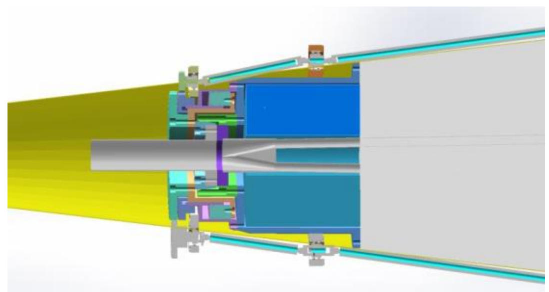
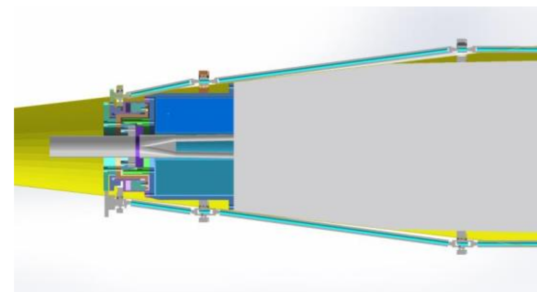
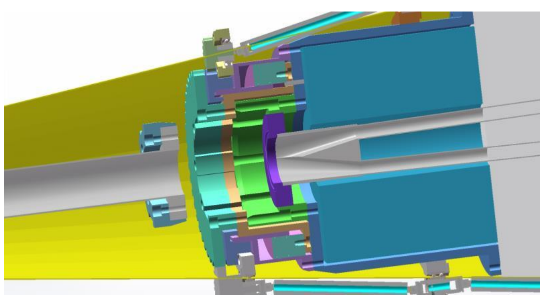
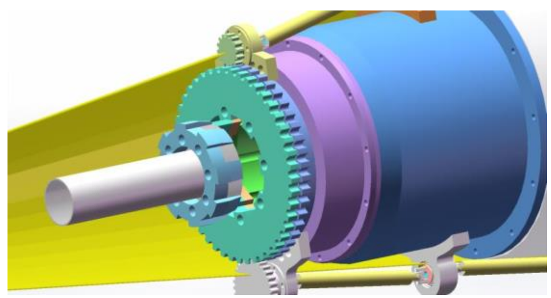
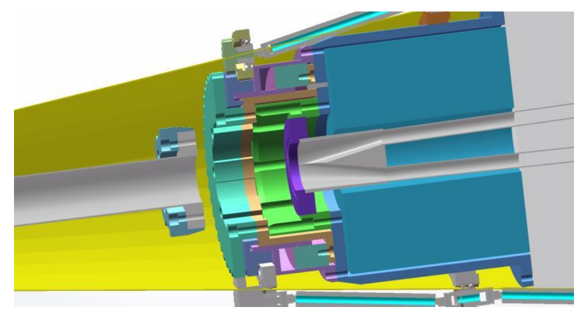
Parameter	unit	limit
ΔE_{CM}	MeV	4.5
$E_{e^+} - E_{e^-}$	MeV	11
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		Negligible up to at least factor 2
Δx_{IP}	mm	0.5
Δz_{IP}	mm	2
Beam synchronisation	ps	3
$\sigma_{x_{IP}}$	mm	0.5
$\sigma_{z_{IP}}$	mm	7
r_{in}	µm	1
$\sigma_{r_{shower}}$	mm	0.2
Δd_{LC}	µm	80
$\Delta\phi$	mrad	0.8





Installation Scheme

- No easy solution to install all the critical components in the interaction region with high precision; inspired by the Remote Vacuum Connection (RVC) developed by SuperKEKB

Summary

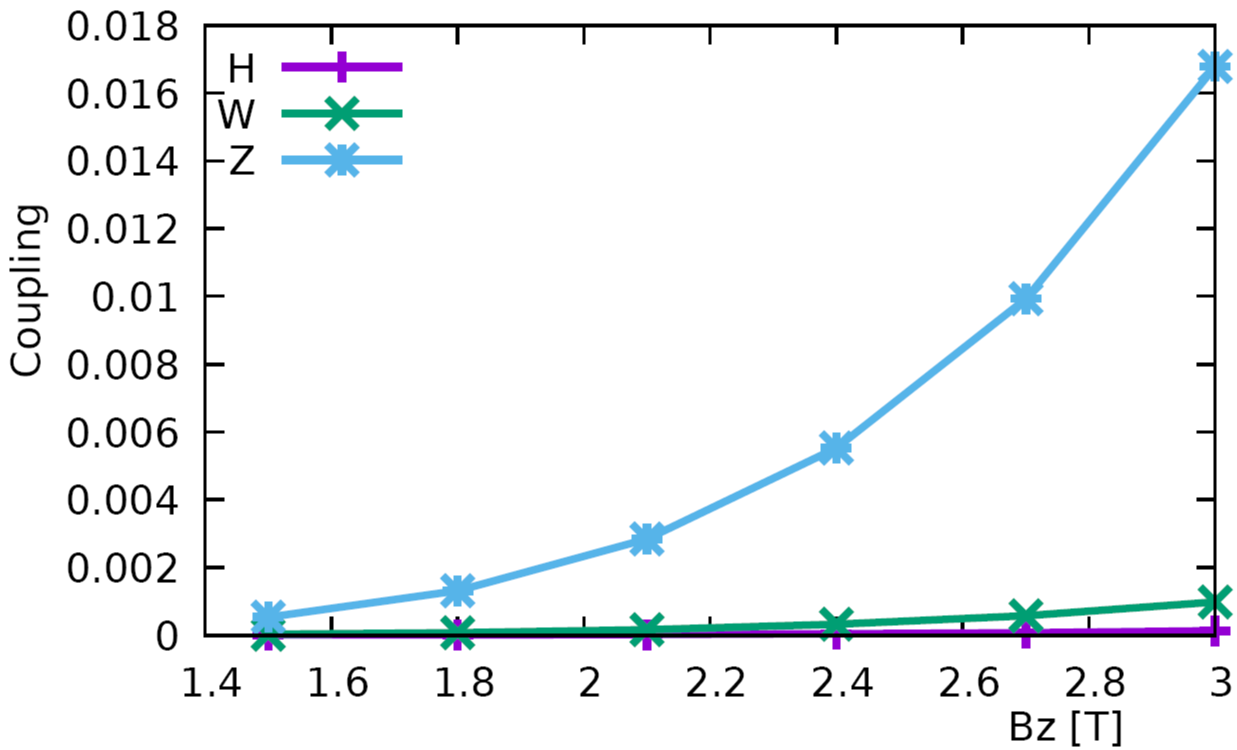
- Layout of the interaction region design → further optimization
- Design of final focusing magnets and compensating magnets
- Investigated the main radiation backgrounds from pair production and off-energy particles, for Higgs operation
  - Hit density: 2.4 hits/cm^2 per bunch crossing
  - TID: ~1 MRad per year
  - NIEL: $\sim 2 \times 10^{12}$ 1MeV n_{eq}/cm^2 per year
- LumiCal design concept, technical options and systematics
- Promising installation scheme based on RVC

Machine Parameters

	Higgs	W	Z（3T）	Z（2T）
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP s_x /s_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x /ξ_y	0.031/0.109	0.013/0.106	0.004/0.056	0.004/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length s_z (mm)	2.72	2.98	2.42	
Bunch length s_z (mm)	3.26	5.9	8.5	
Damping time $t_x/t_y/t_E$ (ms)	46.5/46.5/23.5	156.4/156.4/74.5	849.5/849.5/425.0	
Natural Chromaticity	-493/-1544	-493/-1544	-520/-1544	-520/-3067
Betatron tune $\nu_x/\nu_y/\nu_s$	363.10 / 365.22 / 0.065			
HOM power/cavity(2cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.40	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L ($10^{34}cm^{-2}s^{-1}$)	2.93	10.1	16.6	32.1

Detector Solenoid

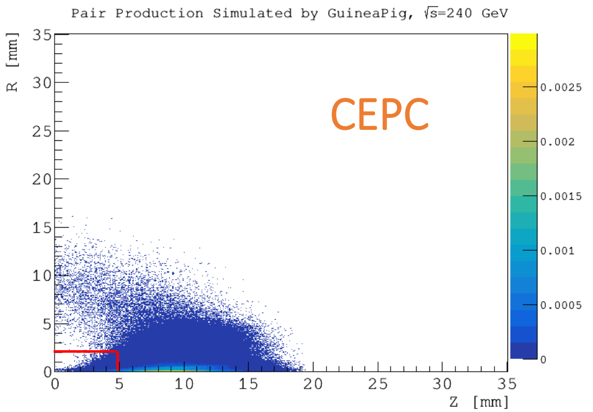
- Emittance growth caused by the fringe field of solenoids → limit the achievable luminosity

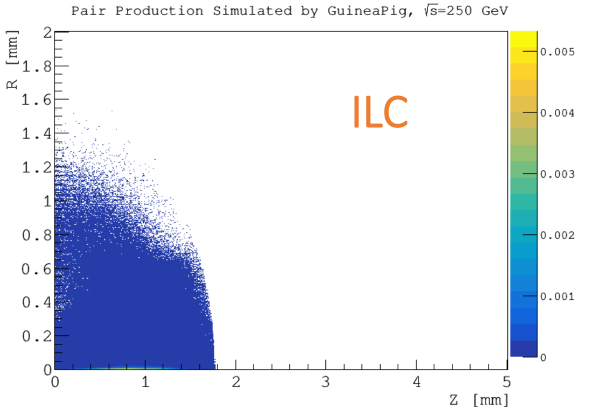


Event Generation

- Pair production process simulated with the GuineaPig program and the output fed into Geant4 detector simulation
- *Long* time for colliding bunches to cross each other (e.g. Higgs operation with bunch length ~3.6 mm)
- Caveat: charged particles travelling over certain distance without seeing the solenoidal field, which unfortunately introduces bias to the hit positions

→ To implement external field in the GuineaPig, feature request sent to the author (to be followed up)





Pair Production @ W/Z

- More prominent at W/Z because of event longer bunch sizes and charged particles traveling over even longer distances