Metrology challenges in integrated luminosity measurement at CEPC and ILC

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ILC Study is performed in the framework of the ILD Concept Group

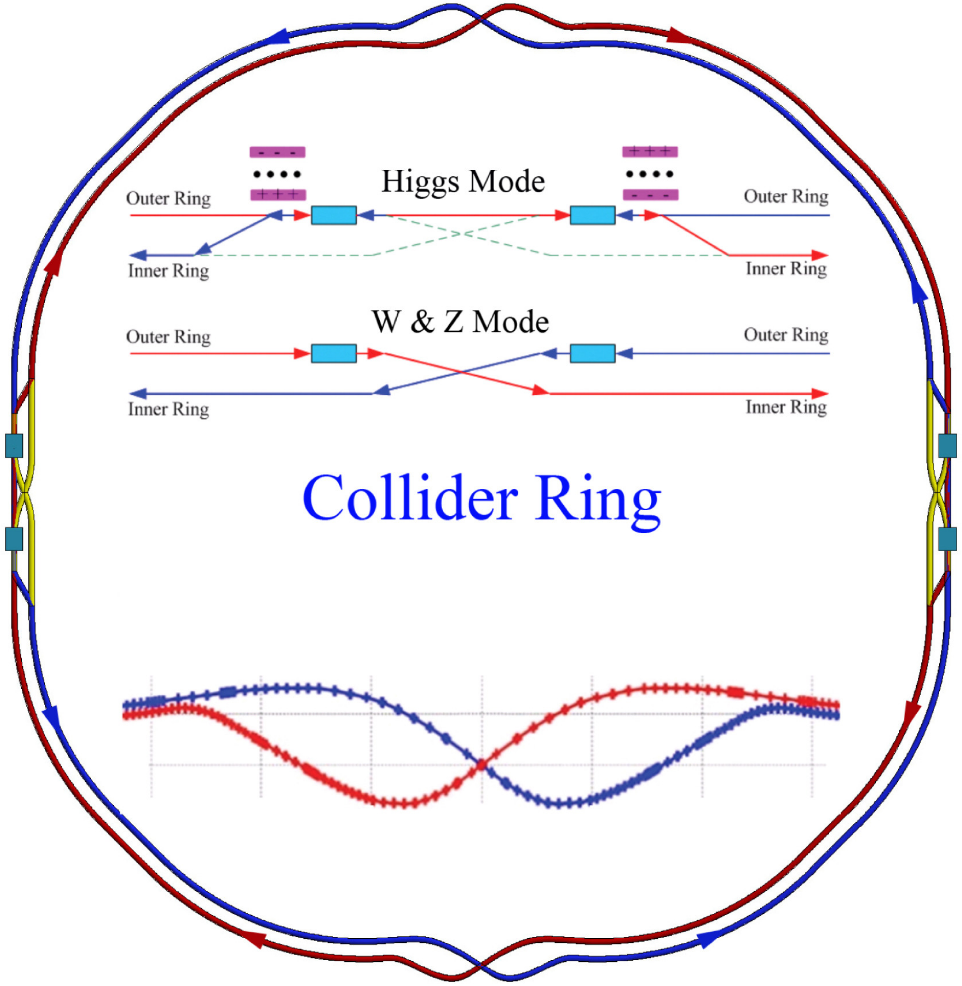
Overview

- Introduction
- Forward region at CEPC and ILC
- Metrology in the integrated luminosity measurement
  - Uncertainties from mechanics and positioning
  - MDI related uncertainties
- Conclusion

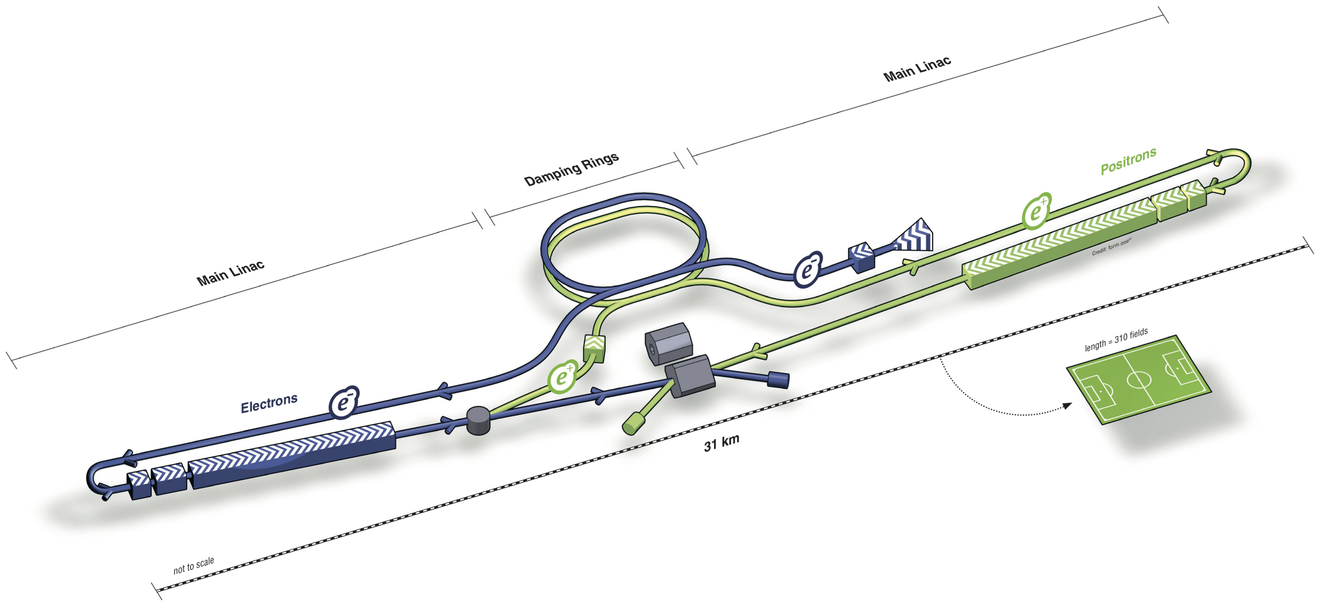
Introduction

- CEPC and ILC physics programs require relative uncertainty of the integrated luminosity measurement to be of order of 10^{-4} at the Z-pole and of order of 10^{-3} at 240/250 GeV CM energies and above
- Precision reconstruction of position and energy of electromagnetic showers generated by the Bhabha scattering at a high-energy e^+e^- collider can be achieved with a compact luminometer eventually preceded by a tracking plane
- The method is based on the Small Angle Bhabha Scattering (SABS) in a luminometer fiducial volume, independently of a technology choice
- Comprehensive list of systematic effects with SABS at future Higgs factories CEPC and ILC has to be studied in realistic conditions and known with the same accuracy as the integrated lluminosity, where we are currently focused on metrology from detector and beam-related properties

Introduction



CEPC overview**



ILC overview*

* By ILC Comms - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=22886133

** H. Zheng et. al, Higher order mode coupler for the circular electron positron collider, Nucl Instrum Meth A 951 (2020) 163094

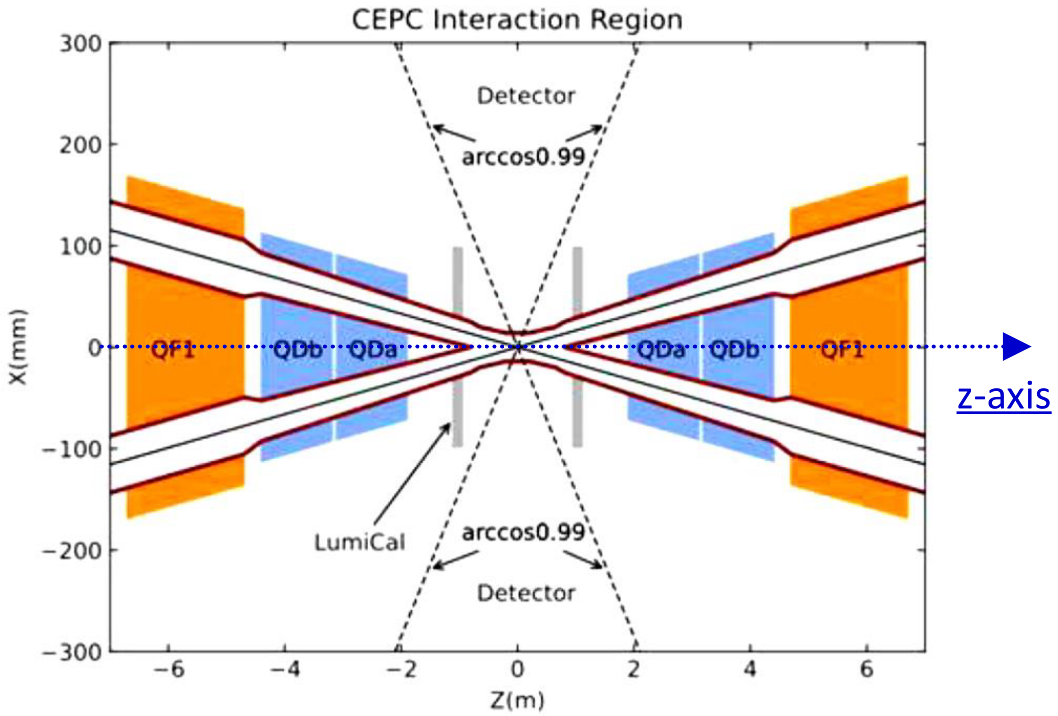
Introduction

Machine	CEPC	ILC
shape	circular	linear
length	100 km	31 km
operating cms energies	91.2GeV, 160 GeV, 240 GeV	91 GeV, 160 GeV, 250 GeV, 350-400 GeV, 500 GeV, ext. to 1 TeV
processes	• ultra-precision electroweak • ultra-precision W mass • precision Higgs properties + CPV • BSM studies	• similar physics program with enhanced sensitivity at higher energies (BSM, Higgs self-coupling)
number of IPs	2	1 (2)
physics background	• synchrotron radiation photons • beamstrahlung electrons • off-energy beam particles lost in the interaction region	• beamstrahlung electrons • gamma-gamma → hadrons • off-energy beam particles lost in the interaction region
luminometer's placement	z-axis or outgoing beam (s-axis), 0.95 m from the IP	s-axis, 2.5 m from the IP
luminometer's angular acceptance	30-105 mrad (full), 53-79 mrad (fiducial)	31-77 mrad (full), 41-67 (fiducial)

Machine	CEPC		ILC			
mode	**Z-pole**	**Higgs**	**Z-pole***	**Higgs**	**500 GeV**	**1 TeV**
Half crossing angle at IP (mrad)	16.5	16.5	7	7	7	7
Beam energy (GeV)	45.5	120	45	125	250	500
Bunch population (10^{11})	1.5	1.7	0.2	0.2	0.2	1.74
Bunch length (mm)	11.8	3.93	0.3	0.3	0.3	0.225
Beam size at IP σ_x/σ_y (µm/nm)	6.0/40	20.9/68	1.35/11.6	0.729/7.7	0.474/5.9	0.335/2.7
Energy spread (natural) (%)	.08	0.1	0.42	0.19	0.124	0.085
Luminosity per IP (10^{34} cm^{-2}s^{-1})	115	5.2	0.23	0.75	3.6	4.9
Total integrated luminosity (ab^{-1})	60-100	13-22	0.1	2	4	8

* Nick Walker, ILC possibilities at Z and W (2016)

Forward region at CEPC



A working assumption of forward region design (taken from the CEPC CDR):

- The Machine Detector Interface (MDI) of CEPC is about 6m from the IP
- The accelerator components inside the detector without shielding are within a conical space with an opening angle of arccos 0.993
- Lumical will be installed in longitudinal 0.95-1.11 m, with inner radius 28.5 mm and outer radius 100 mm, corresponding to the polar angle region between 26 mrad and 105 mrad (with fiducial volume between 53 mrad and 79 mrad)

Forward region at CEPC – luminometer around z-axis

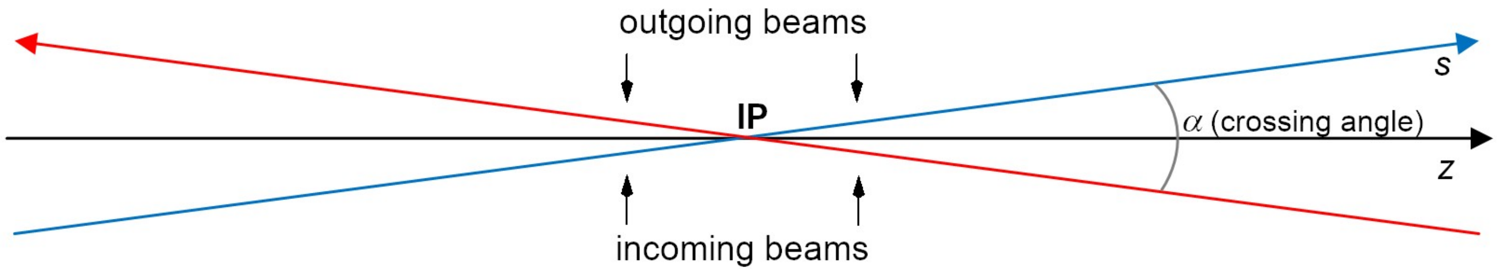
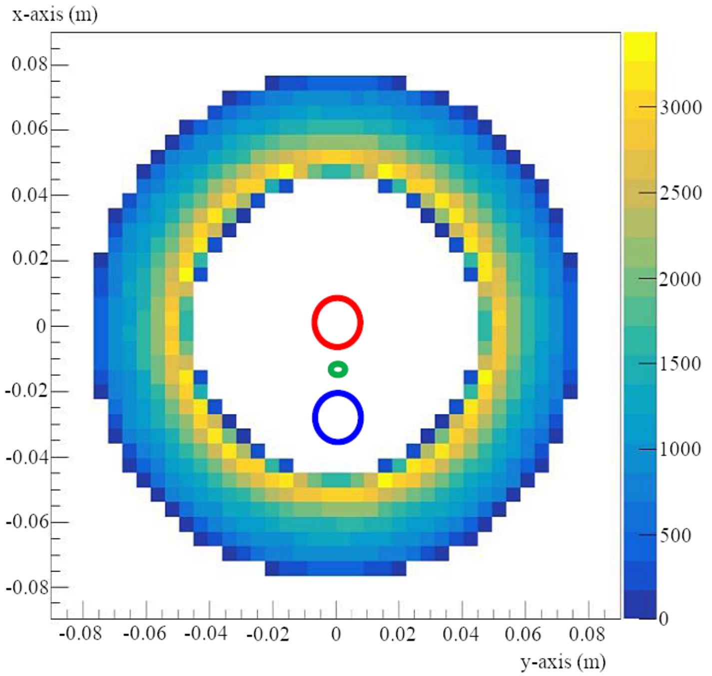
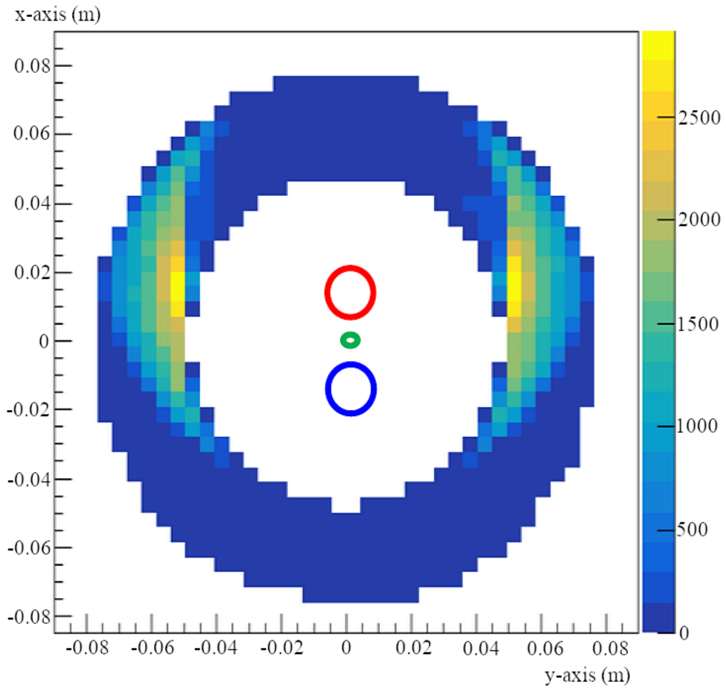


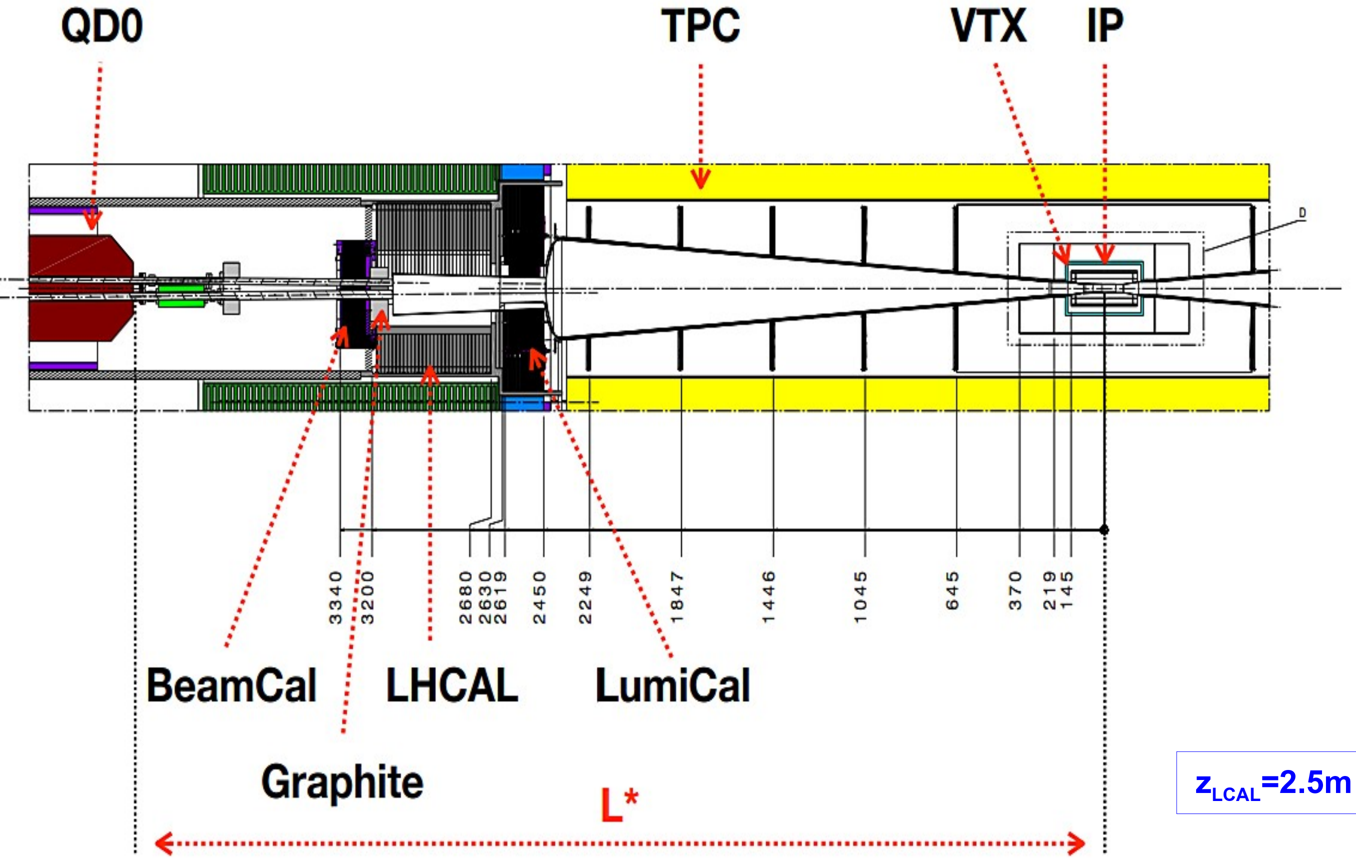
Illustration of s-axis and z-axis

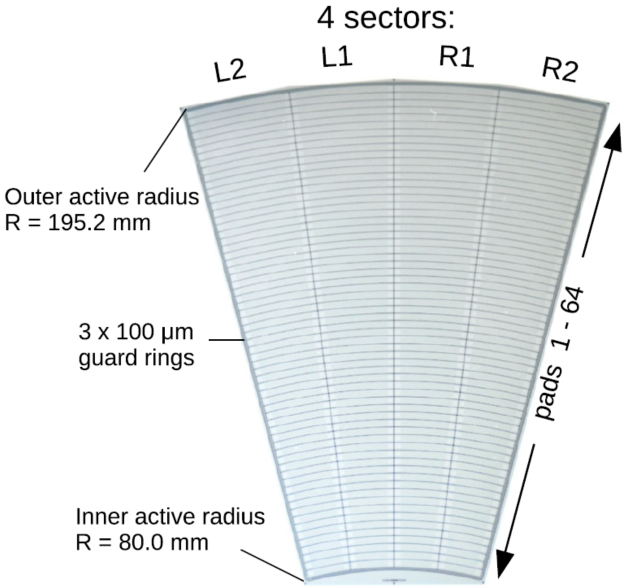




Hitmap of the first plane of the luminometer placed around the outgoing beam (left) and z-axis (right)

Forward region at ILC





z_{LCAL}=2.5m

x-angle=14 mrad

	Parameters	ILD
LumiCal	Geometrical acceptance (mrad)	31-77
	fiducial acceptance (mrad)	41-67
	number of layers (W+Si)	30

- Cylindrical Silicon-Tungsten sandwich
- 30 $1X_0$ (3.5 mm) absorber planes, 30 sensor planes
- 320 μm sensor thickness /1 mm gap between absorber planes
- Radial segmentation: 64 pads with 1.8 mm pitch
- Azimuthal segmentation: 48 sectors covering 7.5° each
- FE electronics outside the calorimeter

Considered metrology effects in the integrated luminosity measurement at CEPC and ILC

- Preparing the ECFA Focus Topics paper (arXiv:2401.07564v2 [hep-ph]), we have realized that no metrology study exists since TESLA times (LC-DET-2005-004 (2005)) -> updated with ILD-PHYS-2024-003
- At CEPC (Z-pole), the same is published in Progress of Theoretical and Experimental Physics, Volume 2024, Issue 10, October 2024, 103H02

Considered metrology effects:

1. Uncertainties from mechanics and positioning:

- uncertainty of the inner radius of the luminometer's counting volume (Δr_{in})
- spread of the measured radial shower position with respect to the true impact position in the luminometer front plane (σ_r)
- uncertainty of the longitudinal distance between left and right halves of the luminometer (Δl)
- mechanical fluctuations of the luminometer position with respect to the IP caused by vibrations and thermal stress, radial and axial (σ_{Xip}, σ_{Zip})
- twist of the calorimeters corresponding to different rotations of the left and right detector axis with respect to the outgoing beam ($\Delta\varphi$)

2. MDI related uncertainties:

- difference in energy between the colliding beams (ΔE)
- RMS of the Gaussian distribution of the beam energy spread (σ_{EBS})
- IP position displacements with respect to the luminometer, radial and axial (Δx_{IP}, Δz_{IP}), caused by the finite beam transverse sizes and beam synchronization, respectively
- time shift in beam synchronization (τ) leading to IP longitudinal displacement Δz_{IP}

Uncertainties from mechanics and positioning

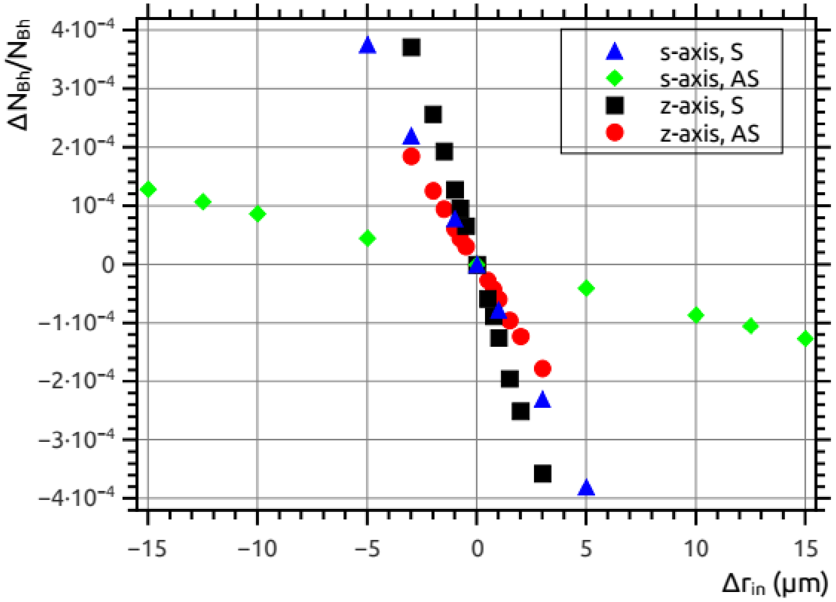
Simulation:

- At CEPC $2 \cdot 10^7$ Bhabha scattering events are generated with ISR and FSR included, using BHLUMI Bhabha event generator, at Z^0 production threshold and 10^7 events at 4 ILC center-of-mass energies: Z^0 production threshold, 250 GeV, 500 GeV and 1 TeV
- Final state particles are generated in the polar angle range from 30 mrad to 100 mrad at CEPC and from 20 mrad to 200 mrad at ILC, which is slightly wider than the fiducial volume, to allow events with non-collinear FSR to contribute
- We assumed that the shower leakage from the luminometer is negligible and that all boosts are longitudinal
- Each effect contributing as 10^{-4} (10^{-3}) to $\Delta L/L$, at the Z-pole (higher center-of-mass energies)

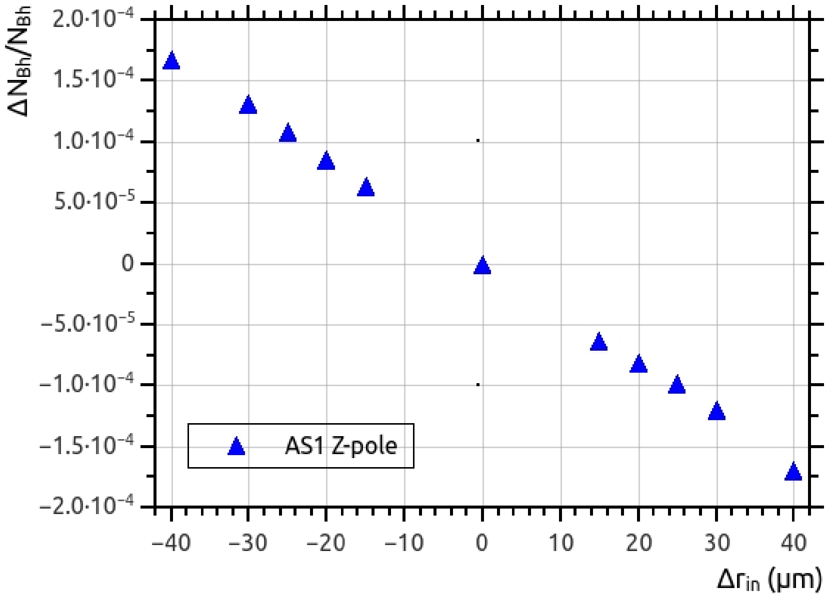
Selection:

- Symmetric selection - fiducial volume at both sides of the luminometer: for CEPC
- Asymmetric selection - asymmetric in polar angle acceptance on the left and right arm of the detector (like at OPAL) - at one side we consider the full fiducial volume, while at the other side we shrink the radial acceptance for Δr subsequently to the left (L) and right (R) side of the luminometer, event by event: for all other cases (ILC, CEPC)

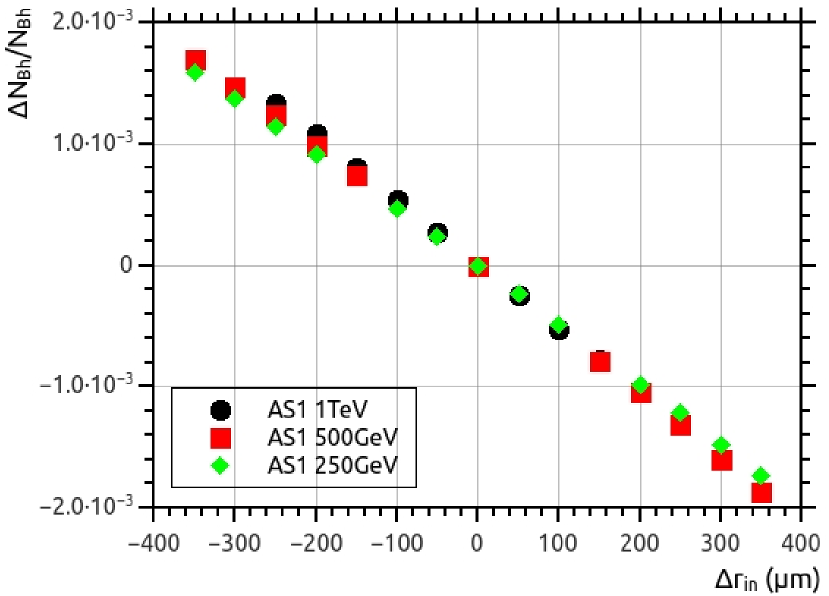
Relevant effects to be considered - Δr_{in}



CEPC – Δr_{in}, Z-pole



ILC – Δr_{in}, Z-pole

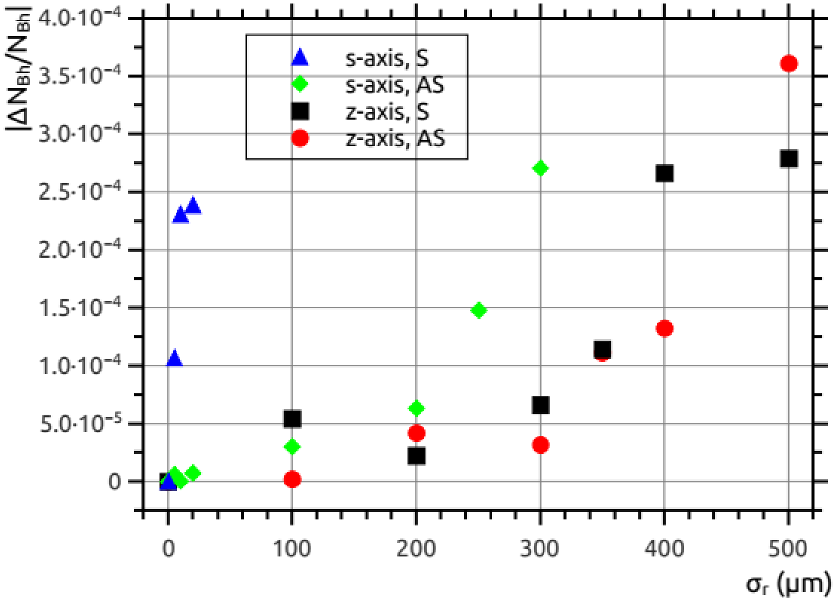


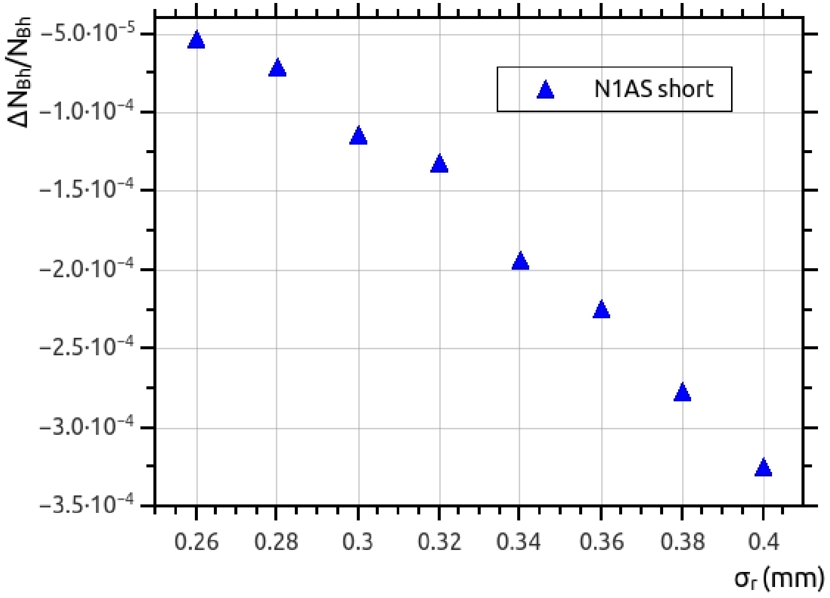
ILC – Δr_{in}, higher energies

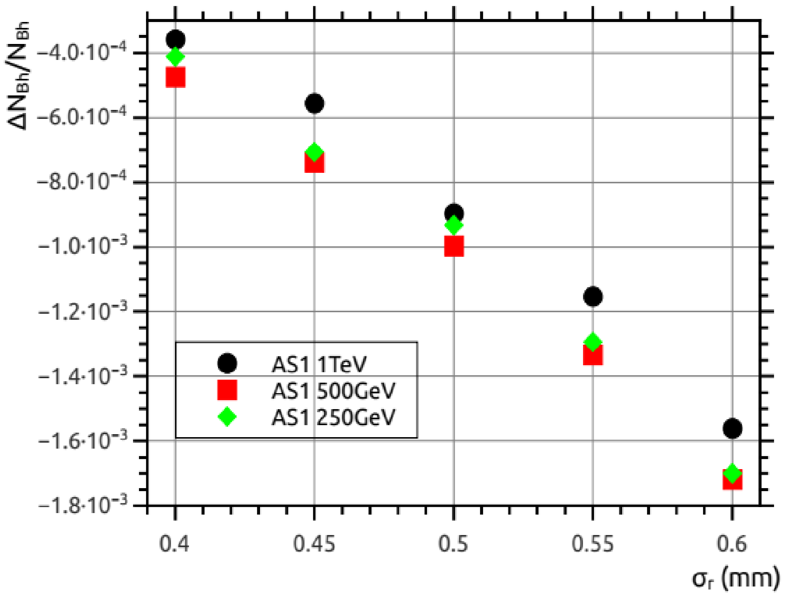
- µm precision for the luminometar @ z-axis
- can be relaxed with AS counting @ s-axis

- Z-pole: 20 µm @ s-axis with AS counting
- Higher energies: 200 µm @ s-axis with AS counting

Relevant effects to be considered - σ_r







CEPC – σ_r, Z-pole

ILC – σ_r, Z-pole

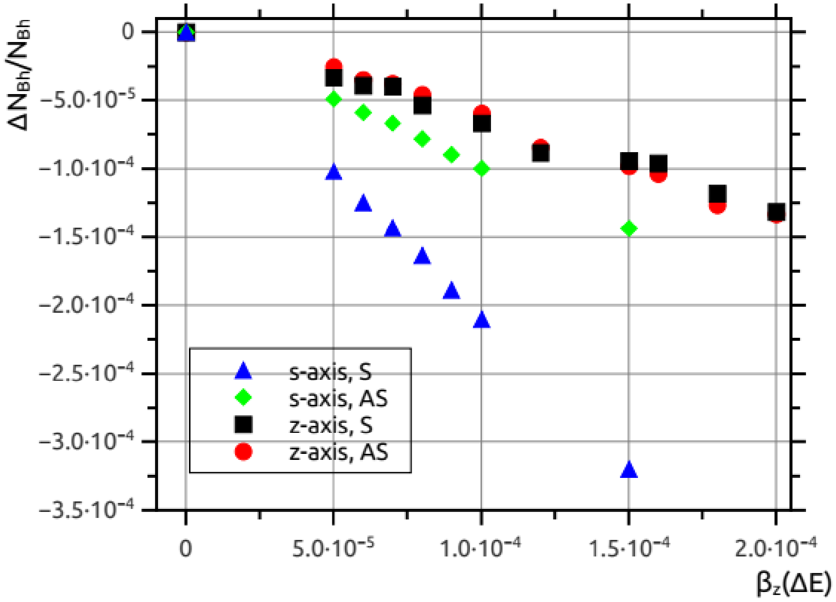
ILC – σ_r, higher energies

- 350 μm reconstruction precision in the luminometer front plane @ z-axis
- check feasibility once the technology is chosen
- can be improved to ~ μm with a tracker plane in front of the luminometer

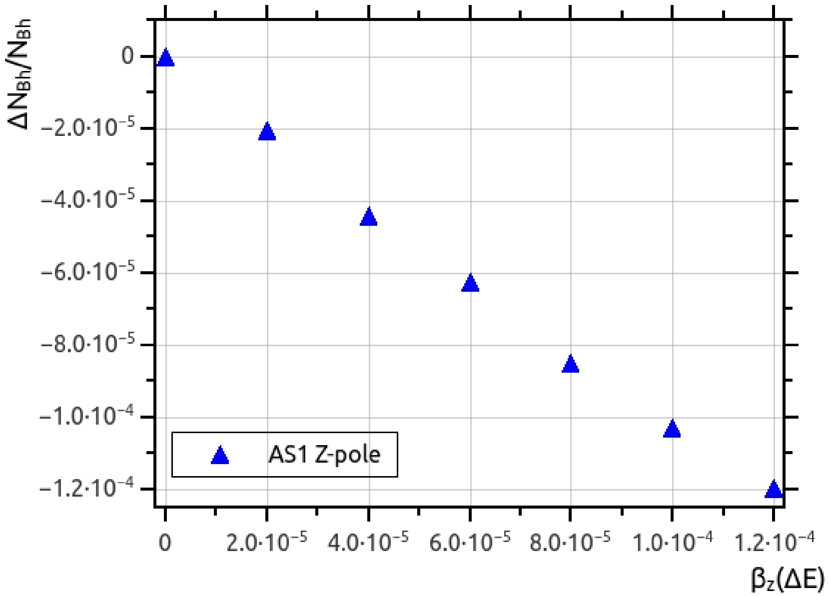
- Z-pole: 300 μm @ s-axis with AS counting
- 440 μm prototyped – can be improved with a tracker plane in front of the luminometer (or one can reconsider segmentation)
- Higher energies: 500 μm @ s-axis with AS counting

Relevant effects to be considered - ΔE (permanent bias)

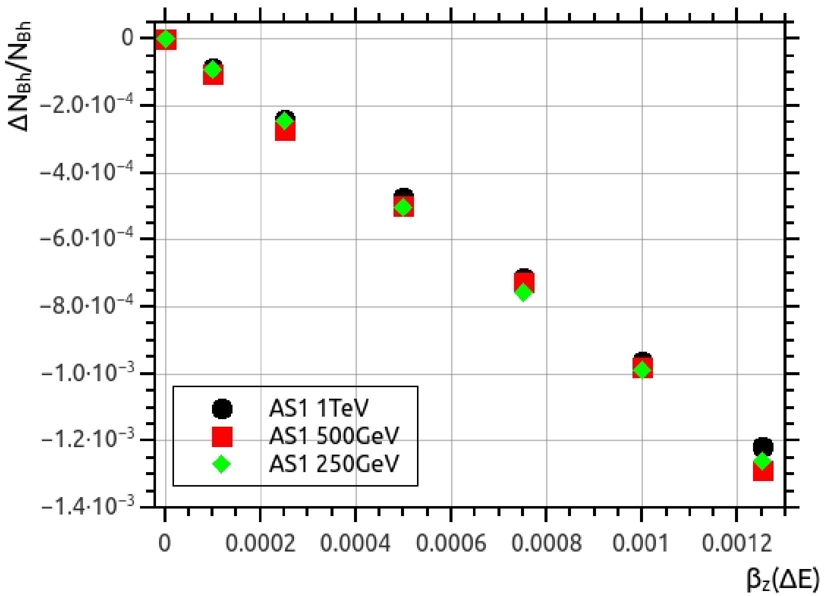
- Boost of the initial (final) state particles is biasing the count
- Boost can be caused by any asymmetry in energy of colliding particles



CEPC – ΔE, Z-pole



- **ILC – ΔE, Z-pole**

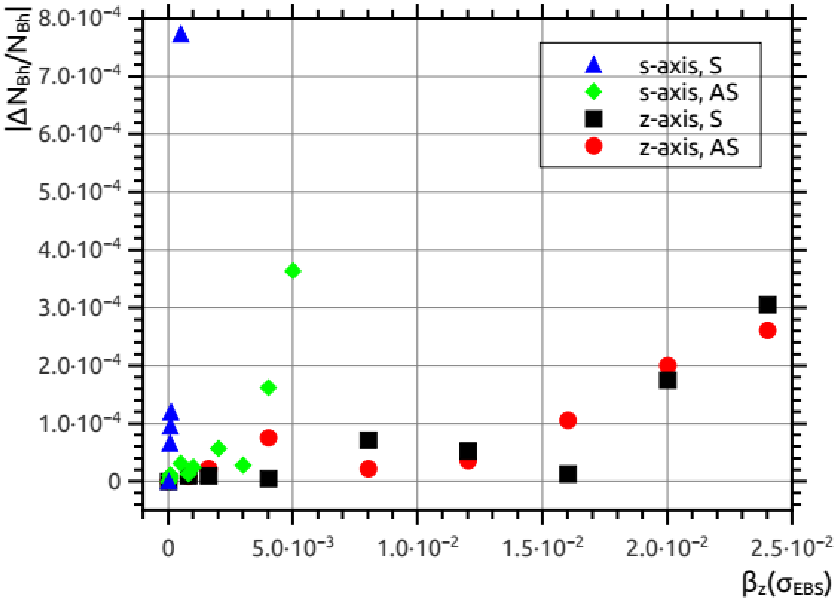


- **ILC – ΔE, higher energies**

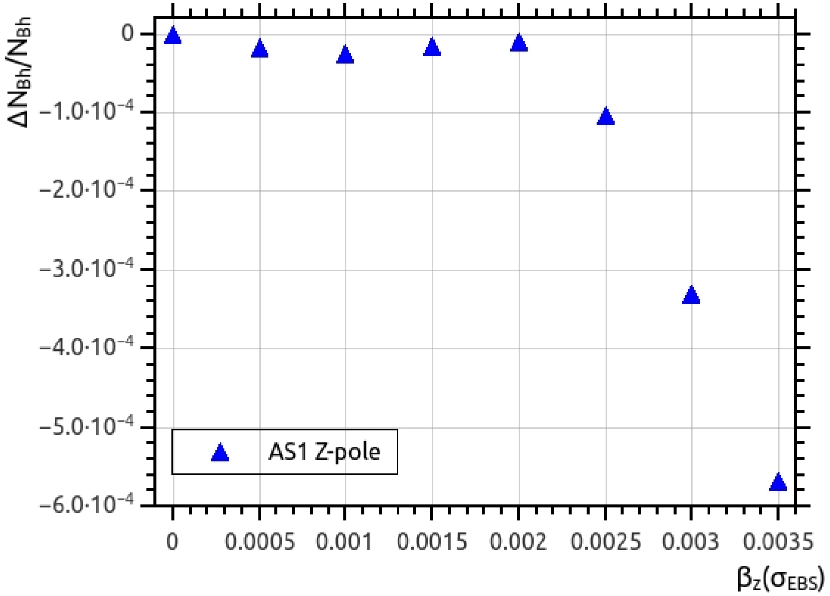
- up to 7 MeV tolerance of the difference in beam energies for the luminometar @ z-axis

- Z-pole: 5 MeV @ s-axis with AS counting
- Higher energies: hundreds of MeV @ s-axis with AS counting

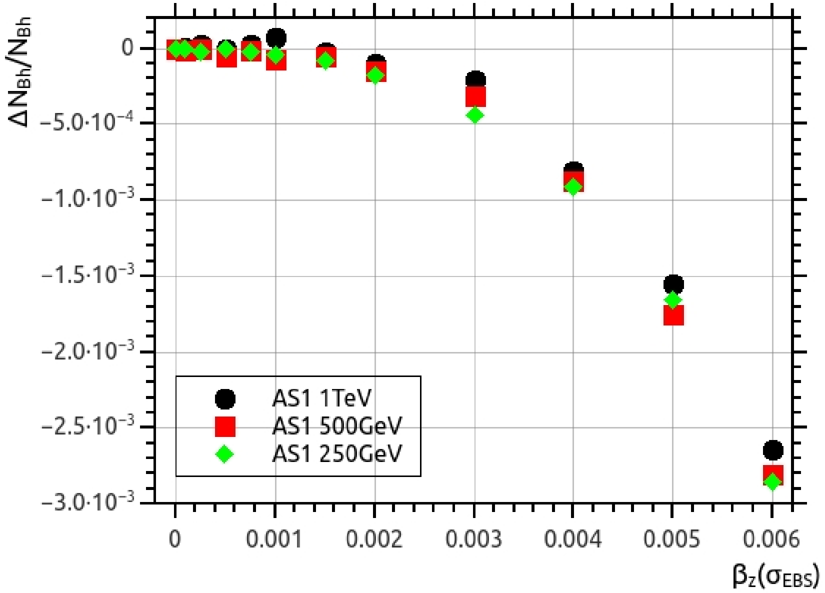
Relevant effects to be considered – σ_{EBS} (beam energy spread)



- **CEPC – σ_{EBS}, Z-pole**



- **ILC – σ_{EBS}, Z-pole**



- **ILC – σ_{EBS}, higher energies**

- 360 MeV for the luminometar @ z-axis
- RMS of the beam energy spread (**σ_{EBS}**) at CEPC is of order of magnitude smaller, ~36.5 MeV

- Z-pole: 110 MeV @ s-axis with AS counting; current design: 192 MeV
- Higher energies are OK: required < 0.2 %, as designed

Uncertainties from metrology

	CEPC, Z-pole				ILC, s-axis, AS			
Parameter	**s-axis, S**	**s-axis, AS**	**z-axis, S**	**z-axis, AS**	**Z-pole**	**250 GeV**	**500 GeV**	**1 TeV**
Δr_{in} (µm)	1	12	0.8	1.5	20	200		
σ_r (µm)	5	220	350	350	300	500		
σ_{Xip} (µm)	10	300	250	250	300	600		
σ_{Zip} (mm)	0.08	3	10	10	5	10		
Δl (mm)	0.1	0.1	0.1	0.1	0.2	2.5		
ΔE (MeV)	2	5	7	7	5	125	250	500
σ_{EBS} (MeV)	4	140	360	360	110	500	1000	2000
Δx_{IP} (µm)	5	200	150	150	300	600		
Δz_{IP} (mm)	0.05	2	2	2	4	8		
$\Delta \tau$ (ps)	0.2	7	7	7	13	27	27	30

Uncertainties from metrology

- The major challenges only at the Z-pole (CEPC, ILC)
- With the luminometer at the z-axis, inner aperture is to be controlled at the micron level (CEPC); inner aperture of the luminometer relaxed with the asymmetric counting with the detector at the s-axis (ILC)
- Position reconstruction in the first plane slightly below prototyped performance at ILC, can be resolved with a tracker plane in front of the luminometer; feasibility of 350 μm precision to be confirmed at CEPC
- Beam energy spread should be kept below 0.2% (ILC), 0.79%(CEPC) - significantly larger than in the current design
- Asymmetric bias in beam energies(~5 MeV) at both machines

Additional issues:

- Uncertainty of the center-of-mass energy for the cross-section calculation(~$5\cdot10^{-4}$)
- Theoretical uncertainty for the revised LEP analyses $3.7\cdot10^{-4}$ [Physics Letters B 803 (2020) 135319]

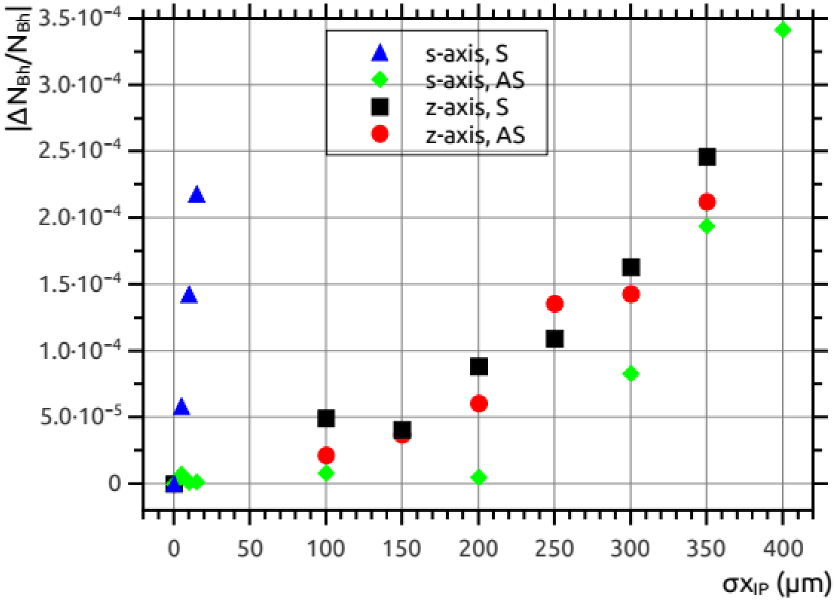
Conclusion

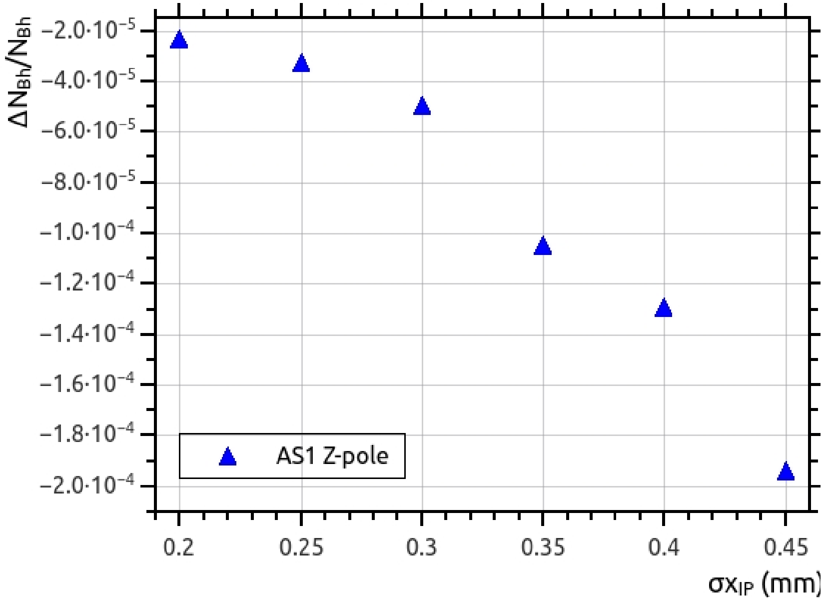
- A comprehensive list of the metrology requirements to achieve the targeted precision and to provide the guideline margins for the monitoring systems under development at CEPC and ILC
- The major issue at the Z-pole CEPC is the inner aperture if the detector is placed at the z-axis; at ILC it can be relaxed to 20 μm with the asymmetric counting
- The beam spread at ILC should not exceed 0.2% at the Z-pole, while it can be significantly relaxed at CEPC with the current design
- Systematic uncertainty of L is sensitive to bias in beam energy at both machines, at several MeV at the Z-pole
- One should be aware of additional uncertainties related to the SABS cross-section, like the uncertainty of the center-of-mass energy (~5 MeV @ Z-pole) and the theoretical uncertainty of the cross-section itself
- Detailed simulation of effects from metrology at ILC does not identify major challenges to measure integrated luminosity with the relative precision of 10^{-3} at 250 GeV and above and the same is to be expected at CEPC at 240 GeV (will be quantified in the ongoing study)

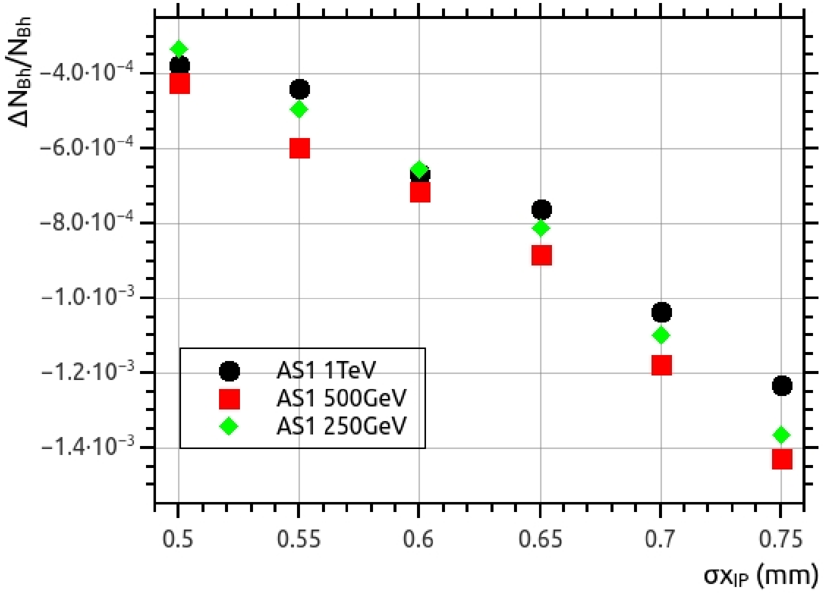
Thanks for your attention!

Backup

Results - σx_{IP}

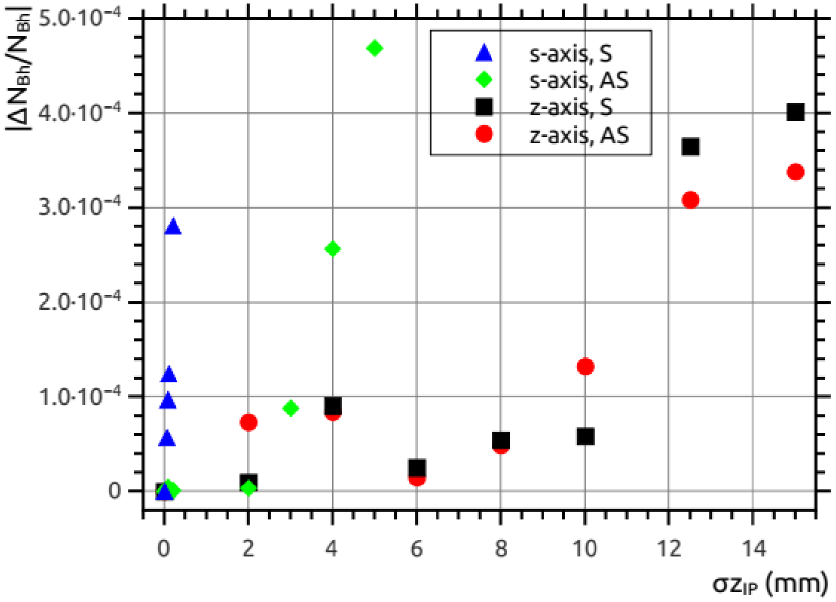




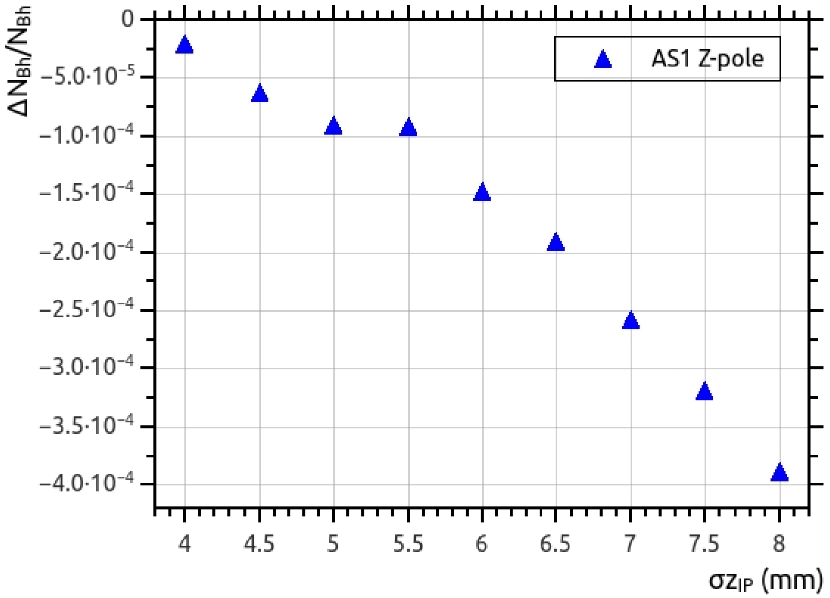


- **CEPC – σx_{IP}, Z-pole**
- **ILC – σx_{IP}, Z-pole**
- **ILC – σx_{IP}, higher energies**

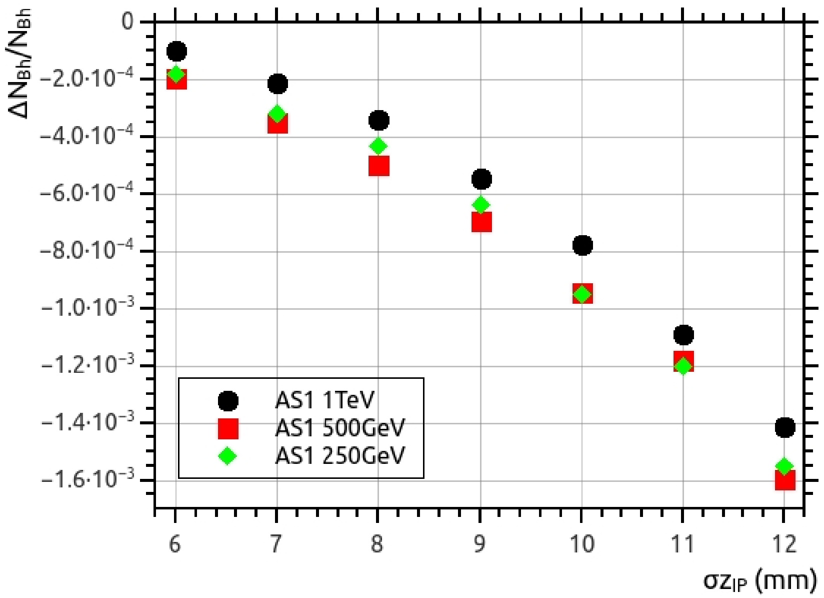
Results - σz_{IP}



CEPC – σz_{IP}, Z-pole

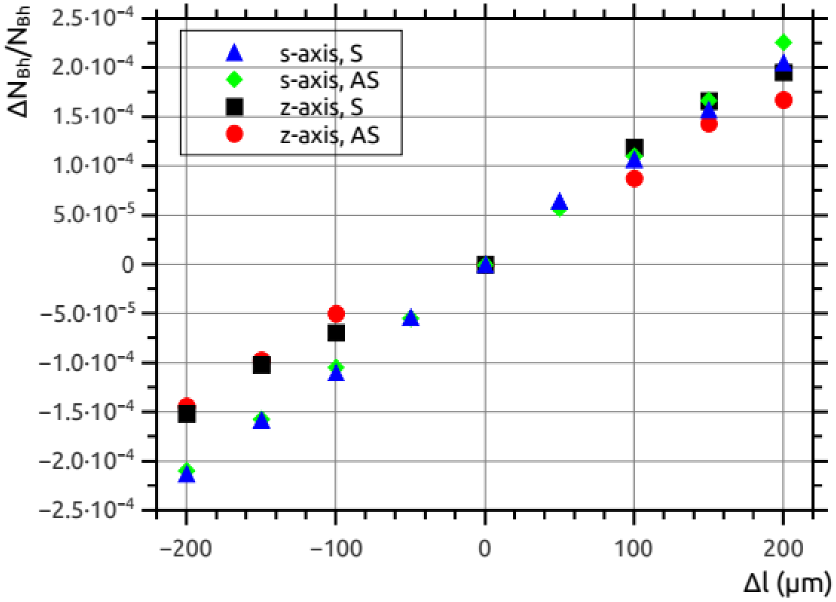


ILC – σz_{IP}, Z-pole

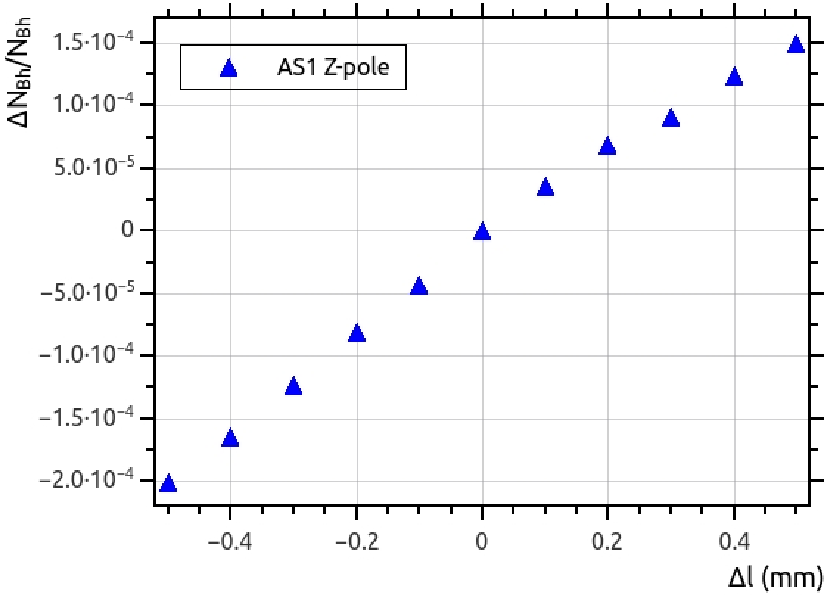


ILC – σz_{IP}, higher energies

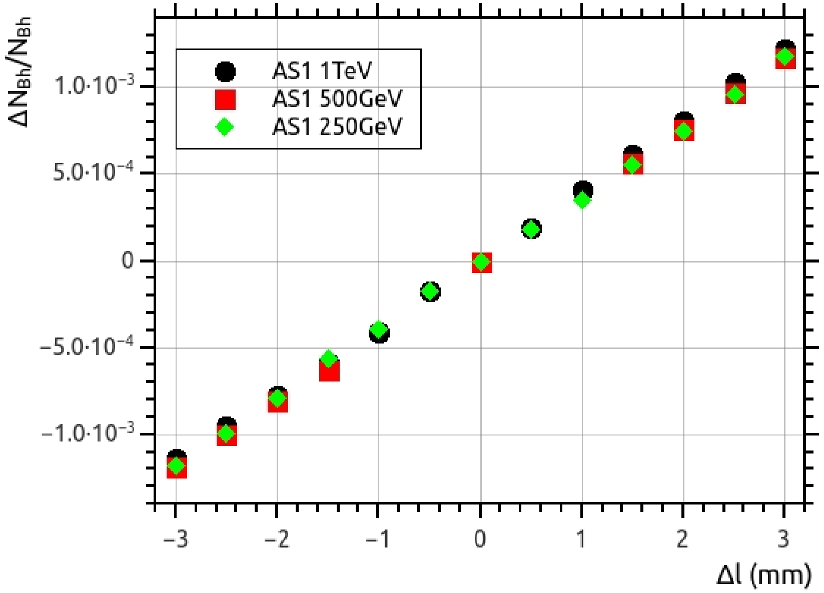
Results - Δl



CEPC – Δl, Z-pole

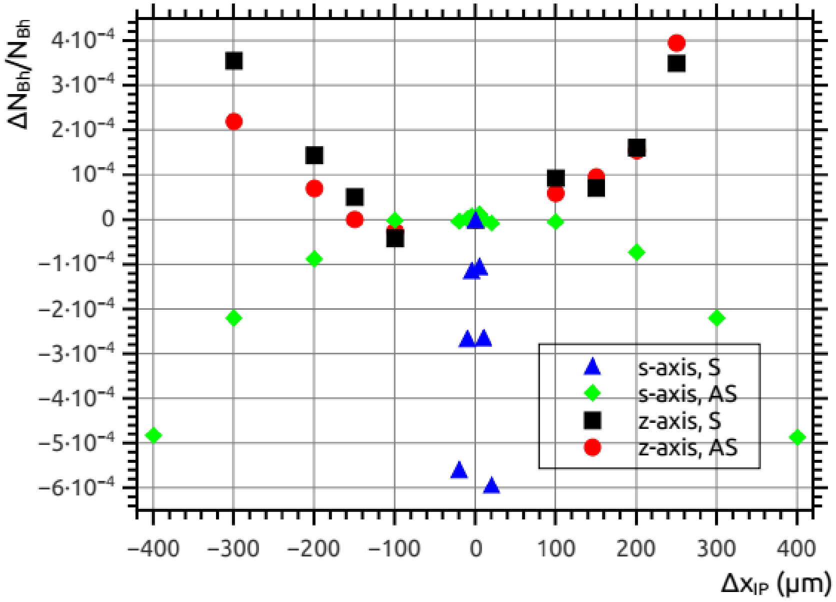


ILC – Δl, Z-pole

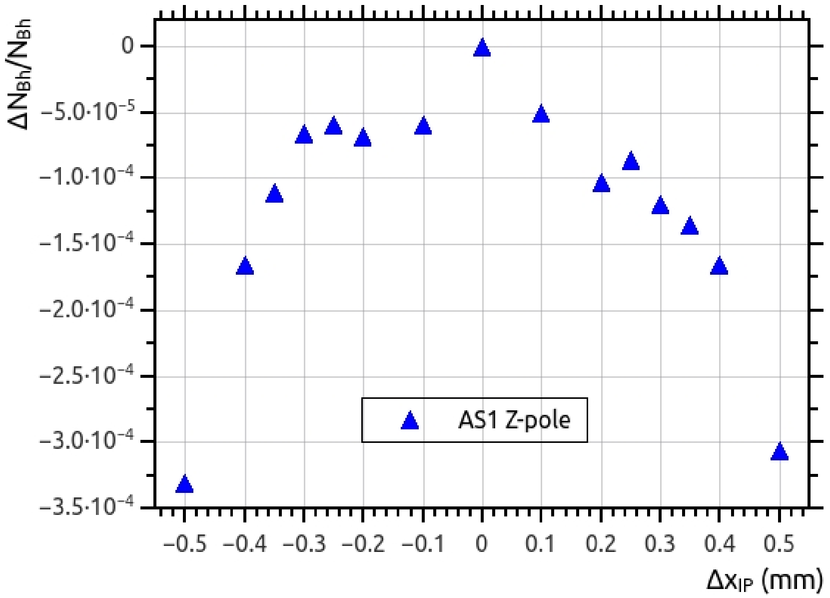


ILC – Δl, higher energies

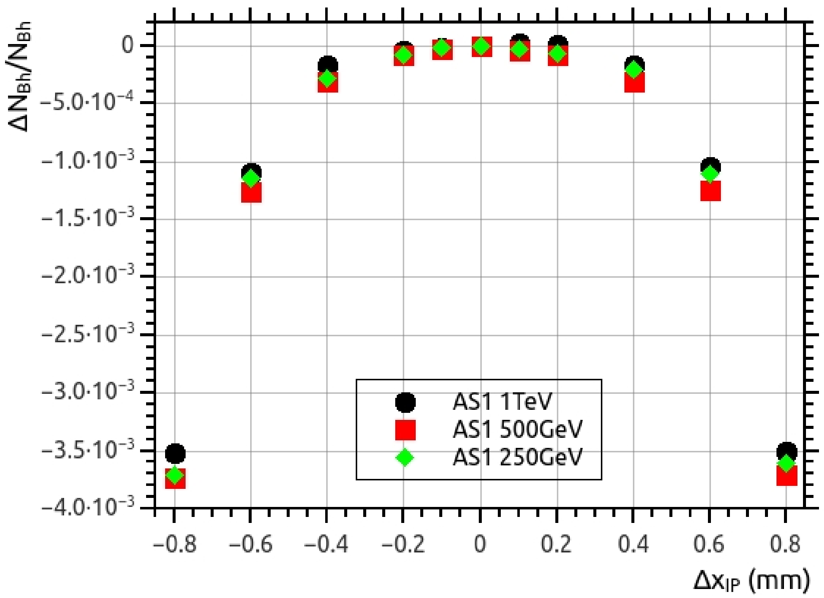
Results - Δx_{IP}



CEPC – Δx_{IP}, Z-pole

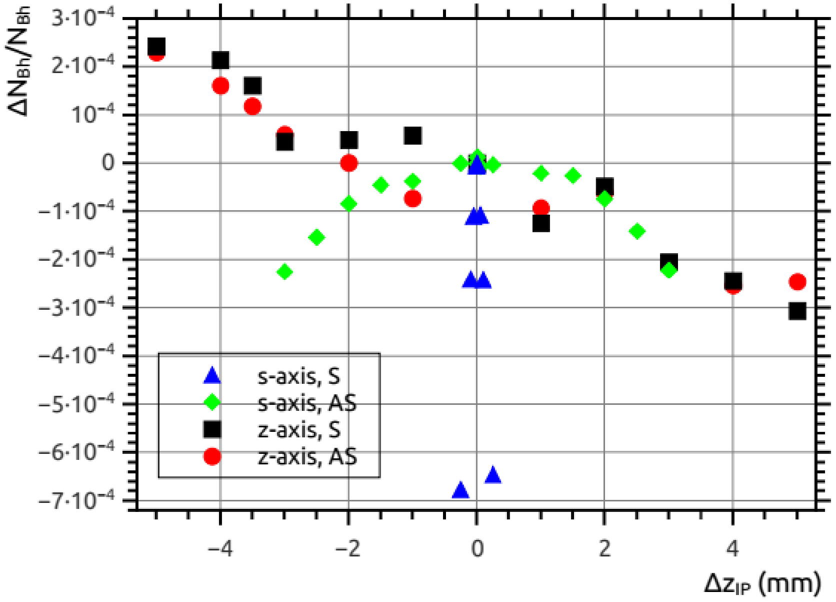


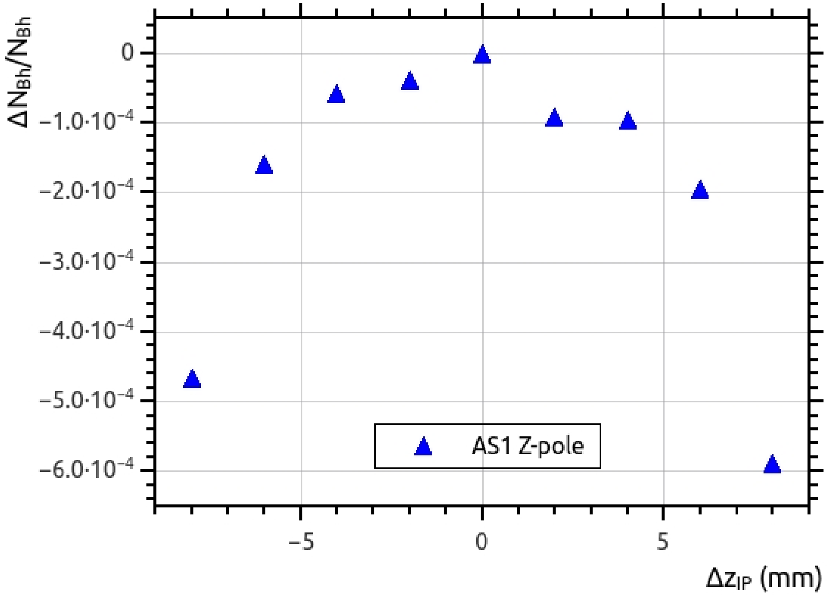
ILC – Δx_{IP}, Z-pole

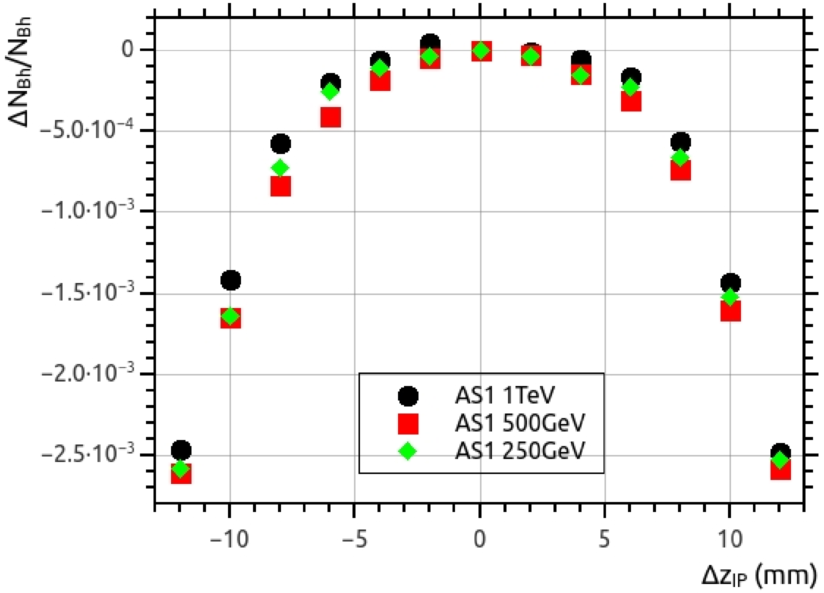


ILC – Δx_{IP}, higher energies

Results - Δz_{IP}







- **CEPC – Δz_{IP}, Z-pole**
- **ILC – Δz_{IP}, Z-pole**
- **ILC – Δz_{IP}, higher energies**

MDI 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 (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (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 $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_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	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural 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	0.1	0.05	0.023	
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

CEPC parameters from CDR