Metrology requirements for the integrated luminosity measurement at ILC

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Overview

- Small angle Bhabha scattering
- Luminometer at ILC
- Novel metrology study

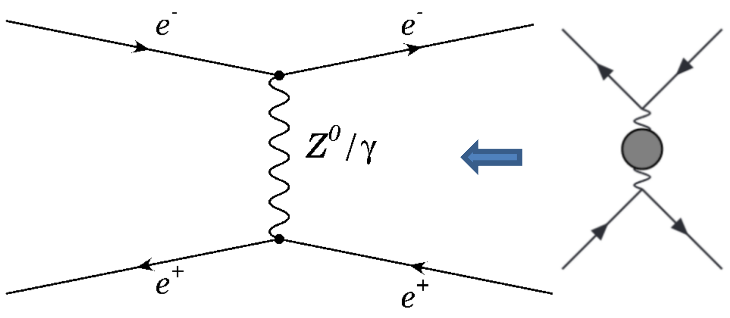
- Preparing the ECFA Focus Topics paper (arXiv:2401.07564v2 [hep-ph]) we have realized

⇒ NO METROLOGY STUDY EXISTS SINCE TESLA TIMES [LC-DET-2005-004 (2005)]

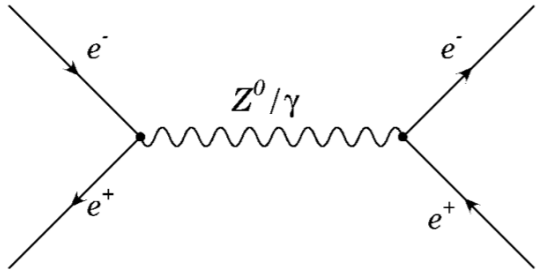
- We have performed a study at:
  Z-pole, 250 GeV, 500 GeV and 1 TeV

(*currently under internal ILD review to be submitted to PTEP*)

Low angle Bhabha scattering (LABS)



- Dominantly QED scattering at low polar angles
- BHLUMI 4.04: NLO QED corrections; higher-order QED corrections through the exclusive YFS exponentiation; No NLO EW corrections; partial implementation of s-channel γ/Z exchange
- Hadronic vacuum polarization in t-channel photon exchange can be a limiting factor for the x-section precision; Revised $\delta\sigma_B$ for LEP analyses $3.7 \cdot 10^{-4}$ [Physics Letters B 803 (2020) 135319]

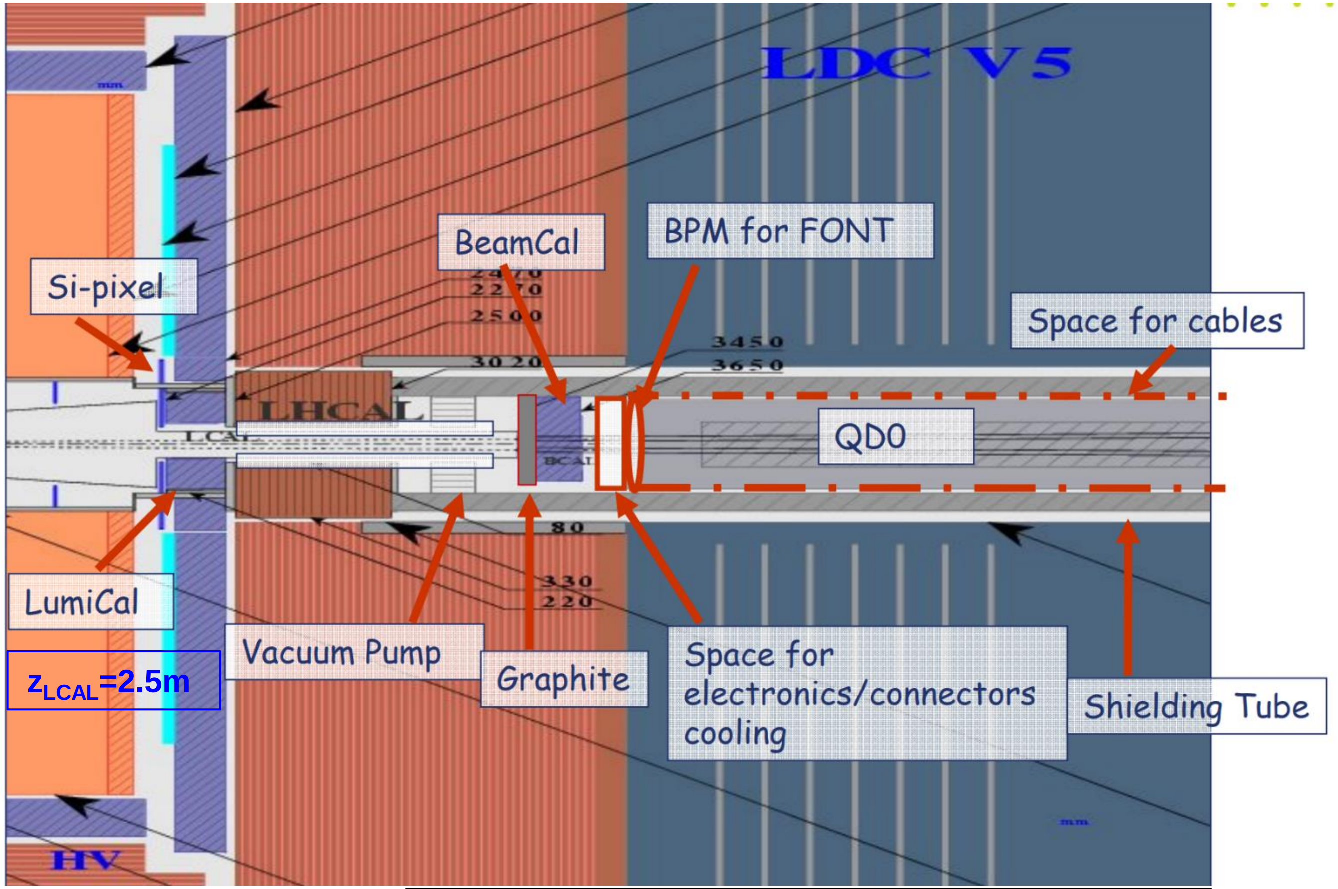


$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\frac{1}{\theta^3}$$

this is where μm precision of r_{in} is coming from

$\delta(\sigma_B) \approx \delta(s) = 10^{-4}$

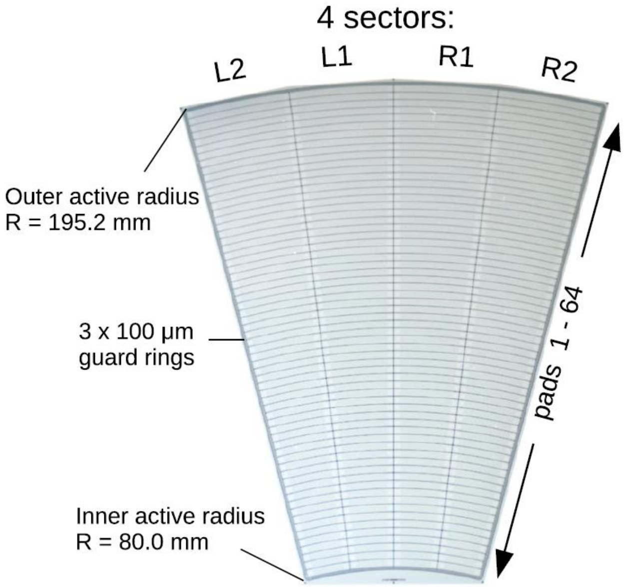
At the Z-pole, center-of-mass energy should be known at ~ 5 MeV
(up to a few hundreds of MeV at 1 TeV)



z_{LCAL}=2.5m

x-angle=14 mrad

	Parameters	ILD
LumiCal	geometrical acceptance [mrad]	31-77
	fiducial acceptance [mrad]	41-67
	z (from IP) [mm]	2480
	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

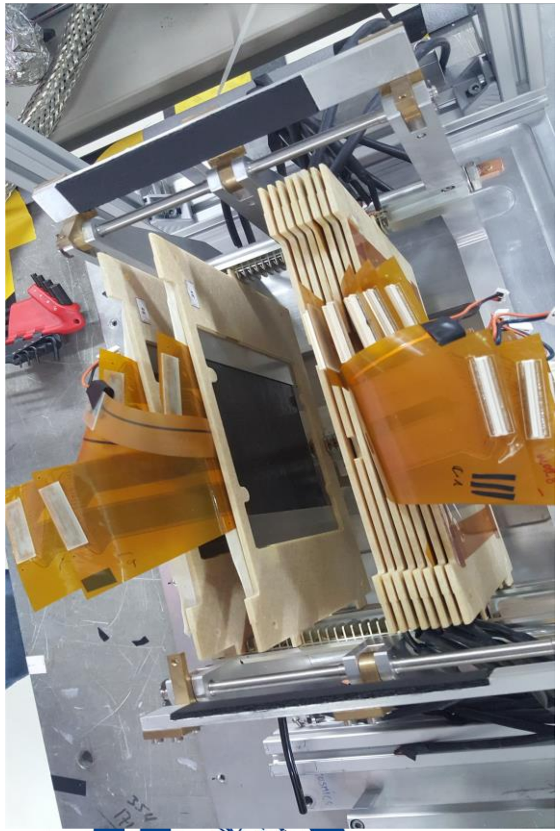
Luminometer prototype

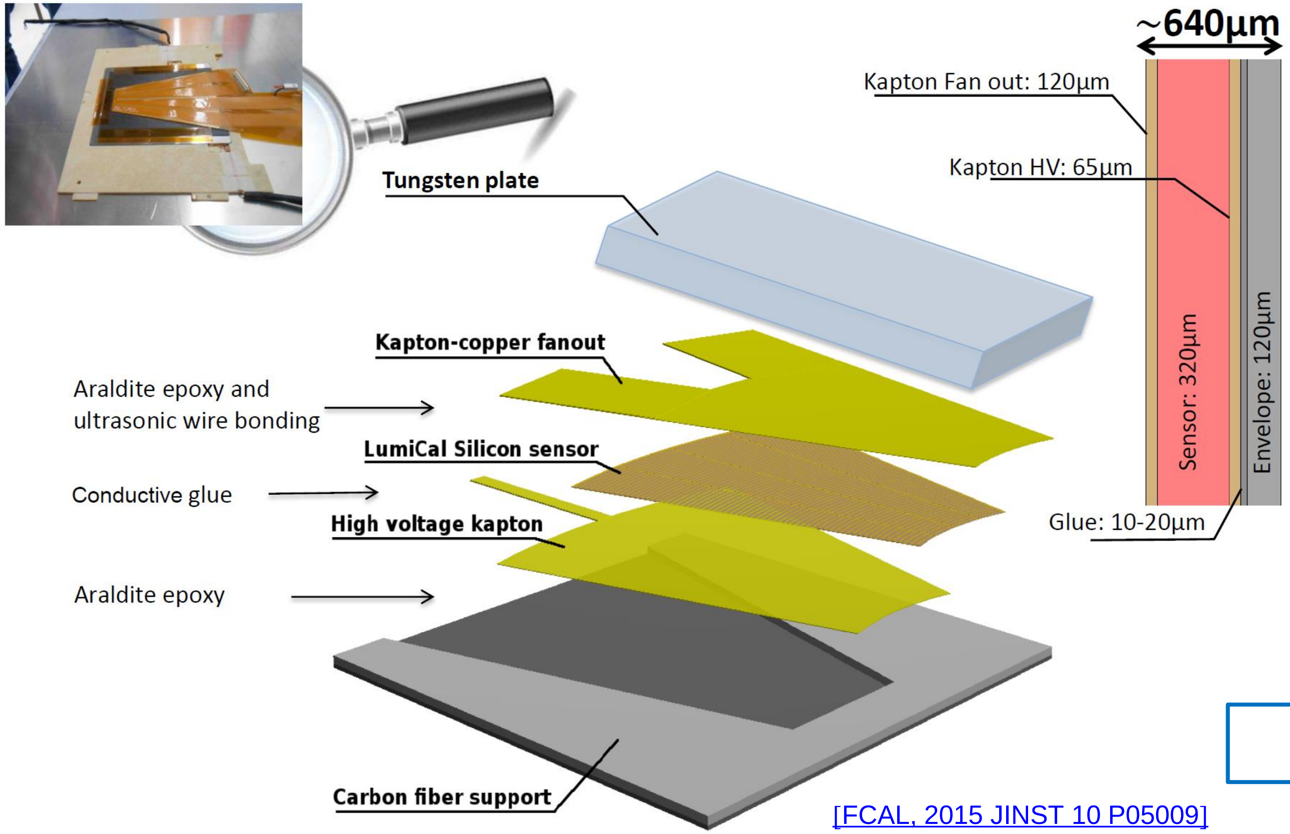
- High precision in polar angle measurement (~20 μrad)

⇒ Shower position and energy measurement on top of widely spread background

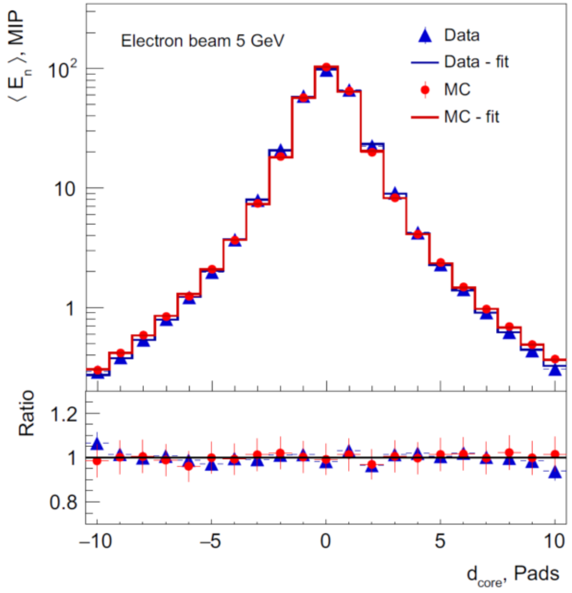
⇒ Compactness - small Moliere radius

- Feasibility demonstrated by the FCAL R&D Collaboration





[FCAL, 2015 JINST 10 P05009]



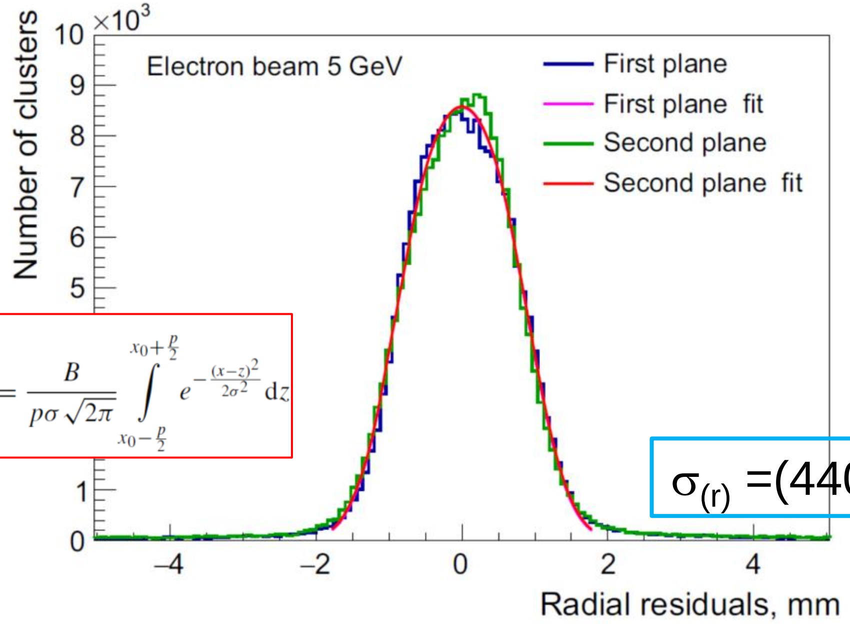
$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_M} F_E(r)\, r dr$$

R_M=(**8.1**±0.1$_{stat.}$±0.3$_{syst.}$) mm

Design and performance

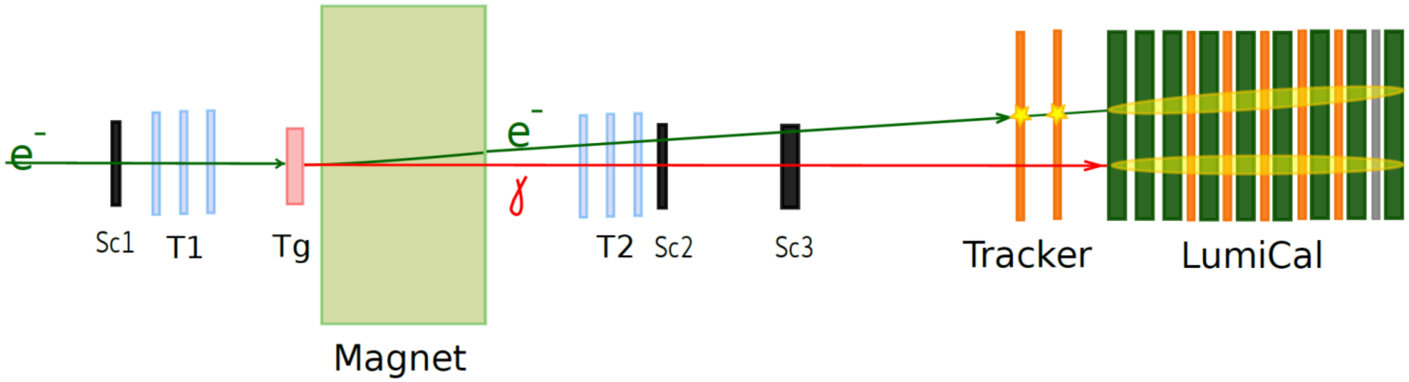
Dissipation of reconstructed hits in the luminometer front plane

Eur. Phys. J. C (2019) 79:579



$$f(x) = \frac{B}{p\sigma\sqrt{2\pi}} \int_{x_0-\frac{p}{2}}^{x_0+\frac{p}{2}} e^{-\frac{(x-z)^2}{2\sigma^2}} \mathrm{d}z$$

$\sigma_{(r)}$ =(440±20) μm

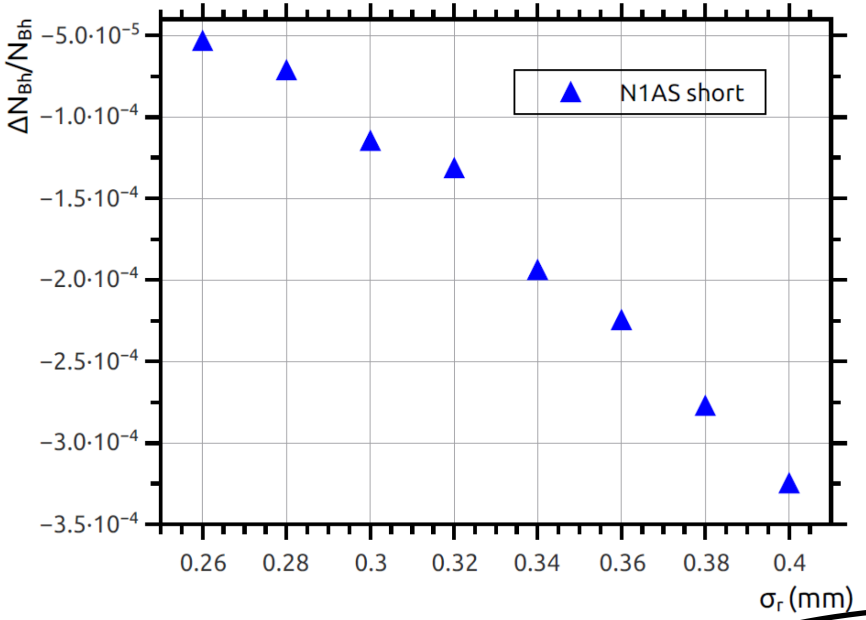


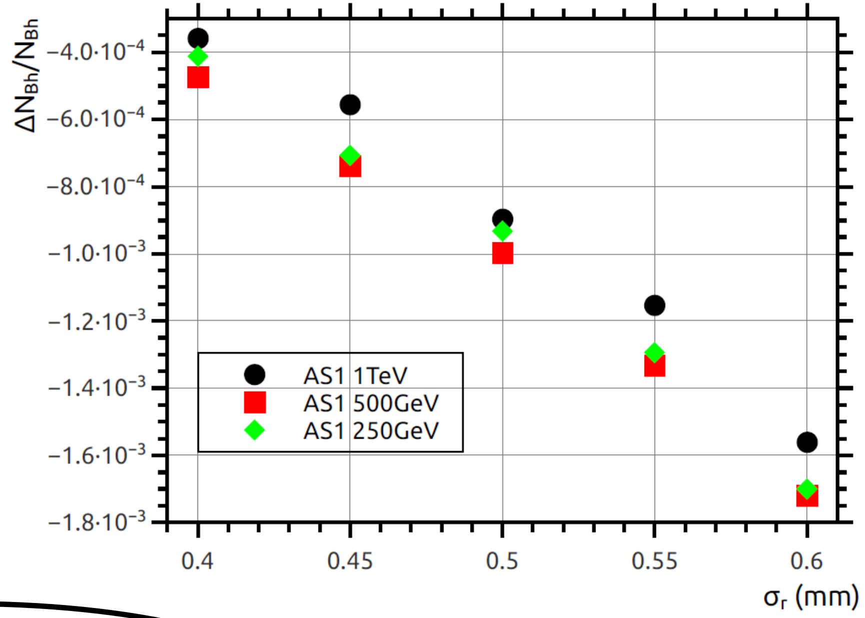
- DESY-II Synchrotron electron beam 1-5 GeV (beam size 5x5 mm^2)
- T1, T2 Eudet telescopes each with 3 MIMOSA Si-pixel planes
- Sc1,2,3 scintillator trigger
- Tg copper target

- Dipole magnet –13 kGs for e/γ separation
- 8 detector planes (6 -LumiCal, 2-tracker)
- 128 read-out channels per plane
- 8 W absorber plates
- External electronics

- 10 million low angle Bhabha scattering events using BHLUMI V4.04
- (20-200) mrad to allow events with non-collinear final state radiation to contribute
- No full detector simulation, no beam-beam effects, only FV (41-67) mrad
- s-axis, asymmetric counting (Δr=1mm)

Dissipation of reconstructed hits in the luminometer front plane

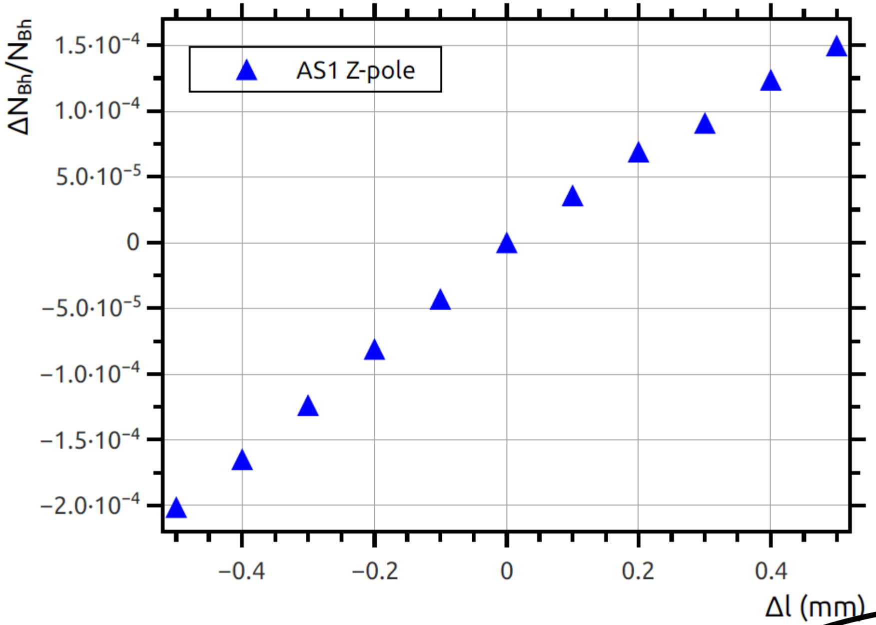


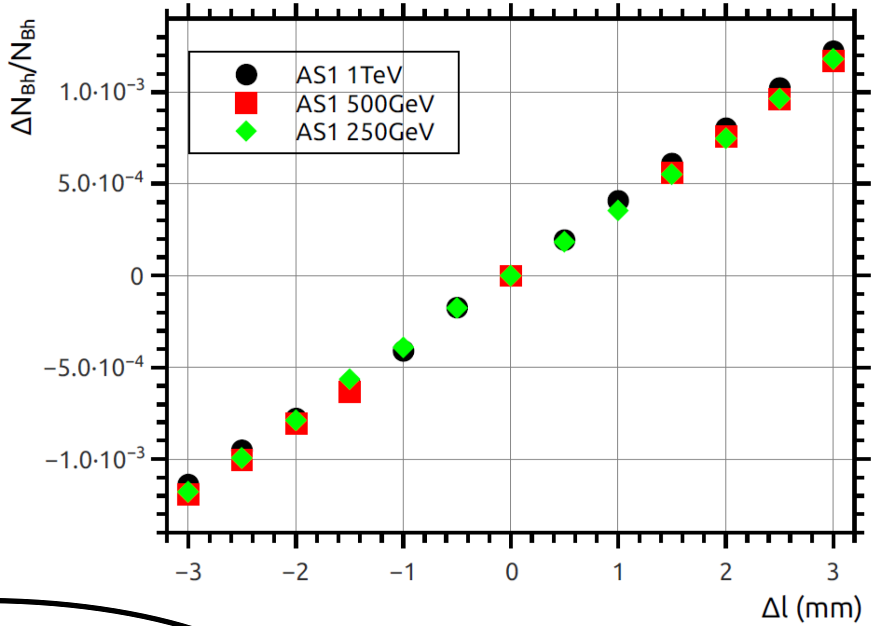


< 500 μm ok at higher energies

$\leq$ 300 μm needed at the Z-pole

Distance between luminometer halves (symmetric)

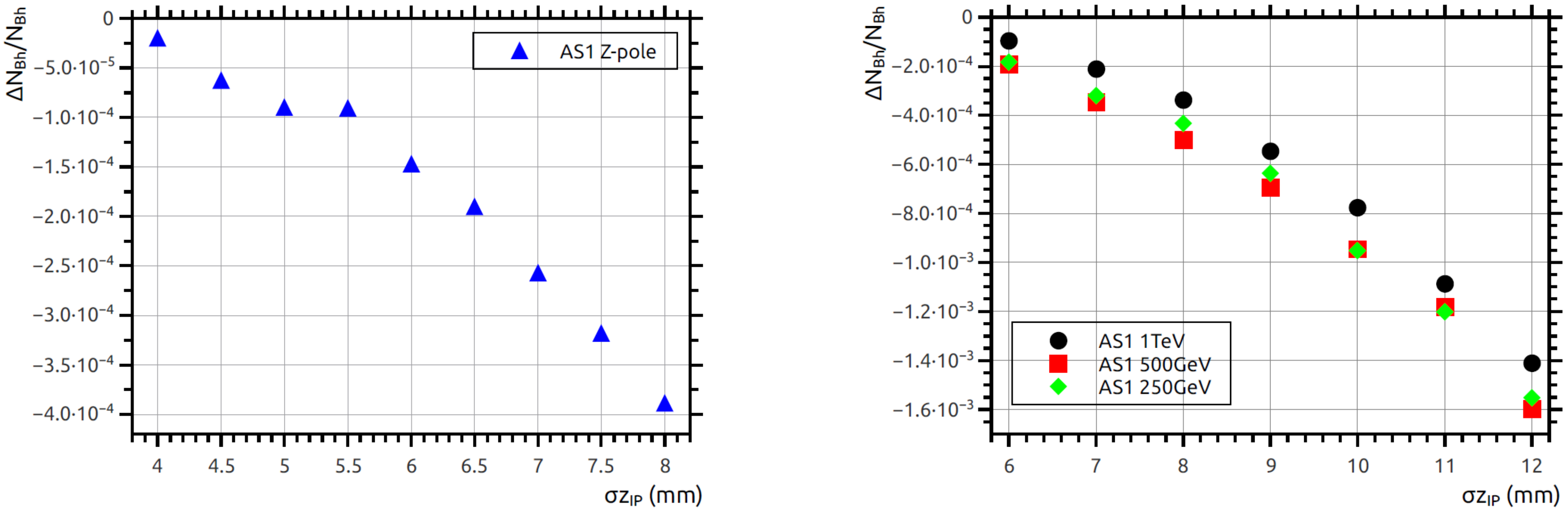




~ 2.5 mm at higher energies

~ 200 μm at the Z-pole (feasible with FSI)

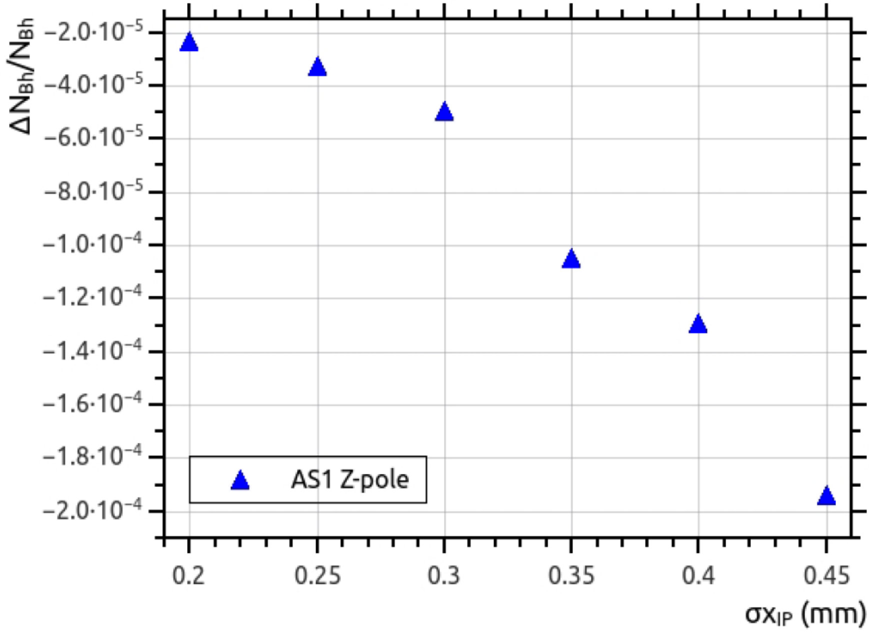
Axial vibrations of the luminometer

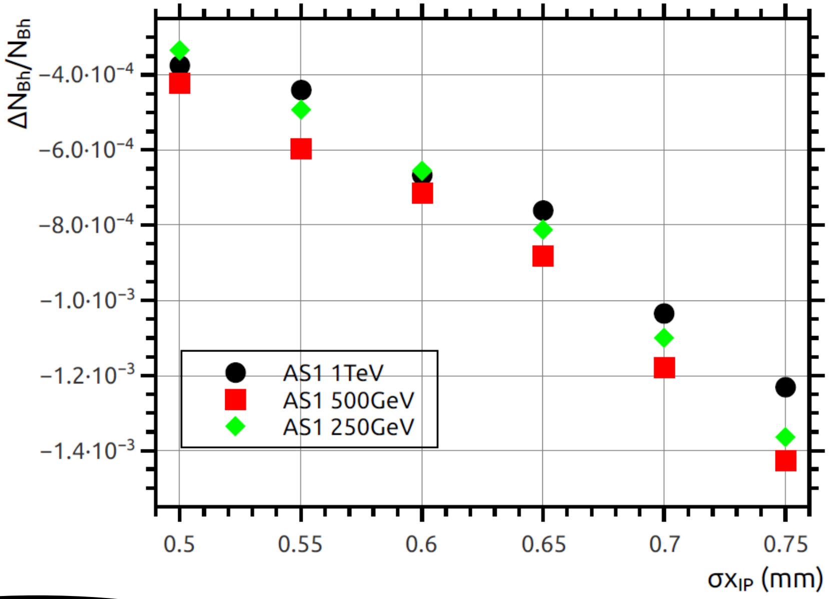


~ 10 mm at higher energies

~ 5 mm at the Z-pole

Radial vibrations of the luminometer

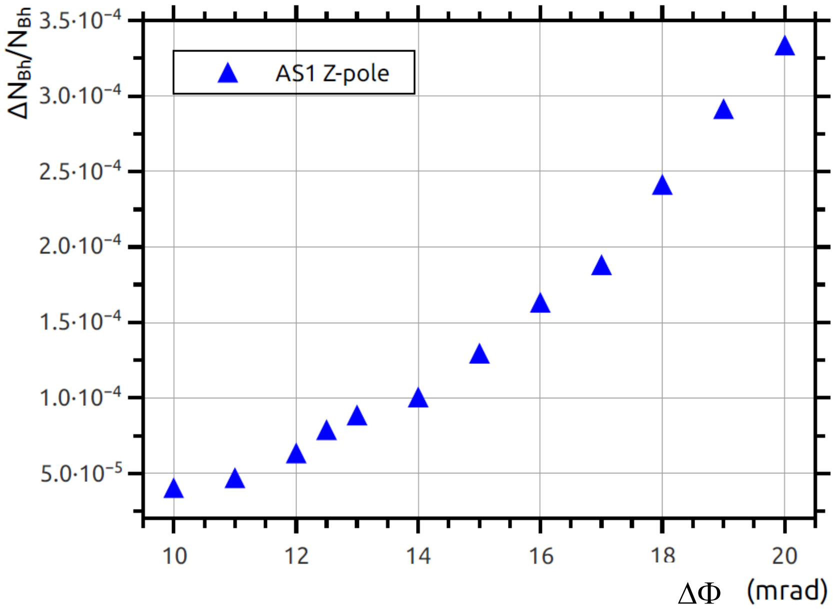


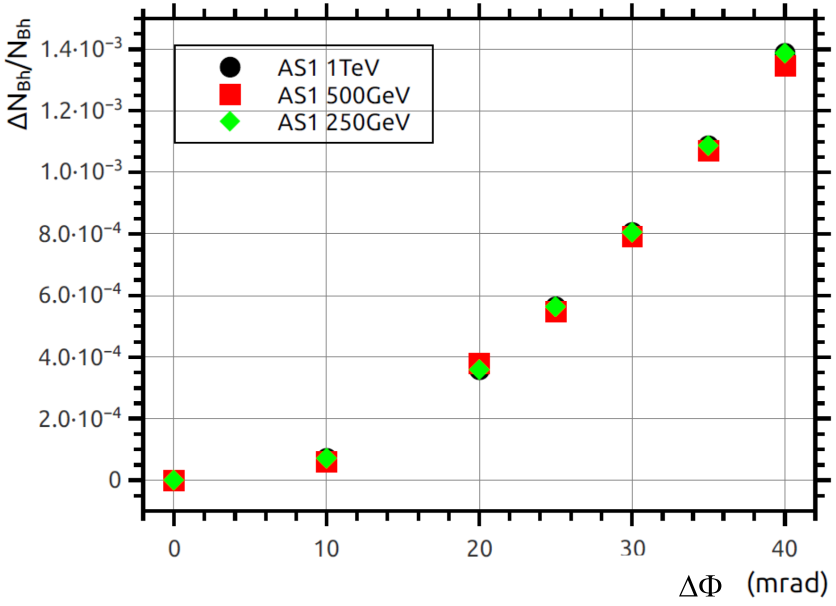


< 700 μm at higher energies

~ 350 μm at the Z-pole

Tilt (rotation around y-axis) of the luminometer





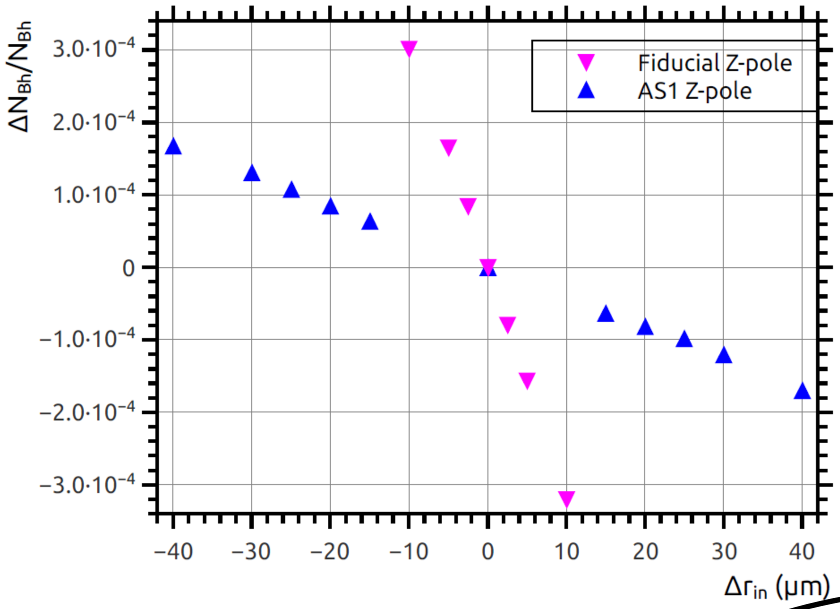
~ 35 mrad at higher energies

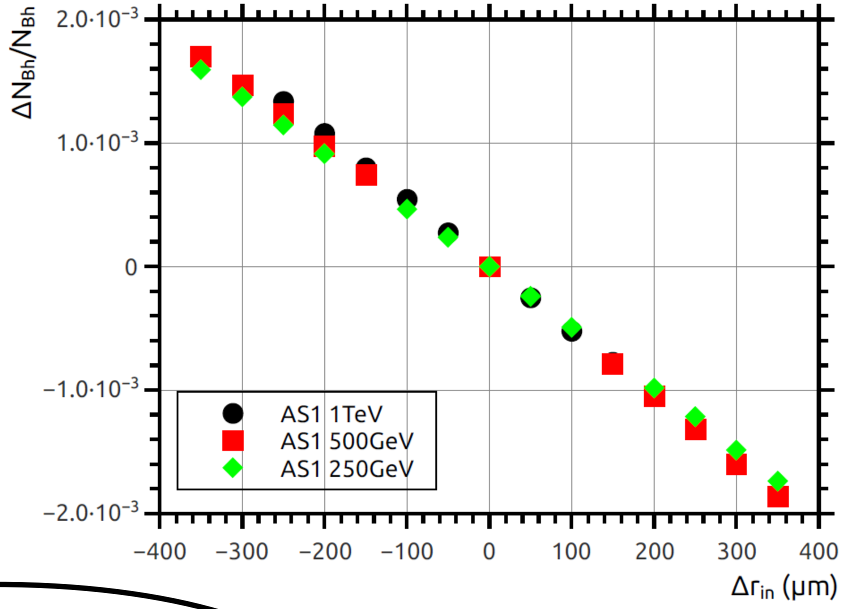
~ 14 mrad at the Z-pole

- Metrology for **the inner aperture** depends on:
  - What is a counting volume: full acceptance, FV?
  - Way of counting (LEP-style, full FV)?

- Asymmetric counting (Δr=1 mm at one side) compensates for smaller variations ~ 20 μm (of the counting volume) at the other
- Symmetrical counting requires ~ 1 μm precision at the Z-pole
- Asymmetric counting only applicable with luminometer on the s-axis

Inner aperture of the counting (FV) volume

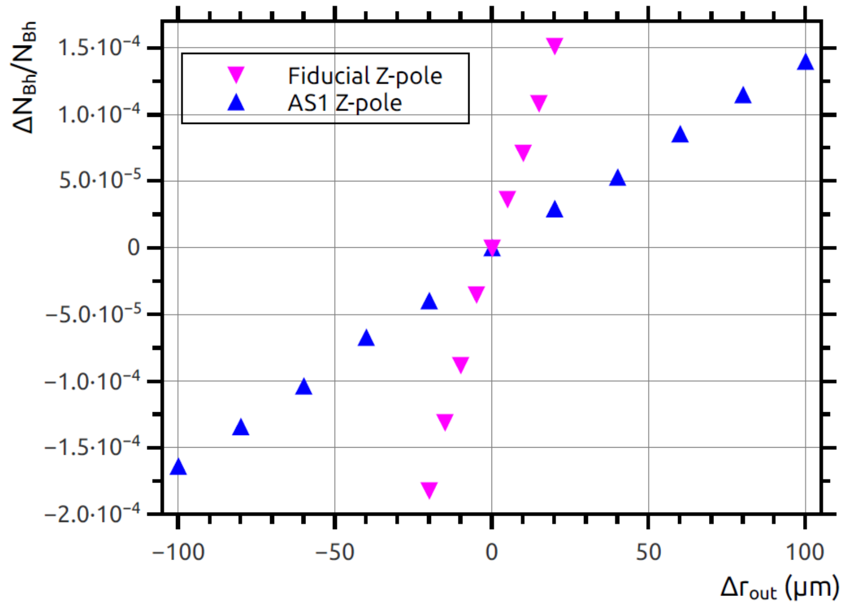


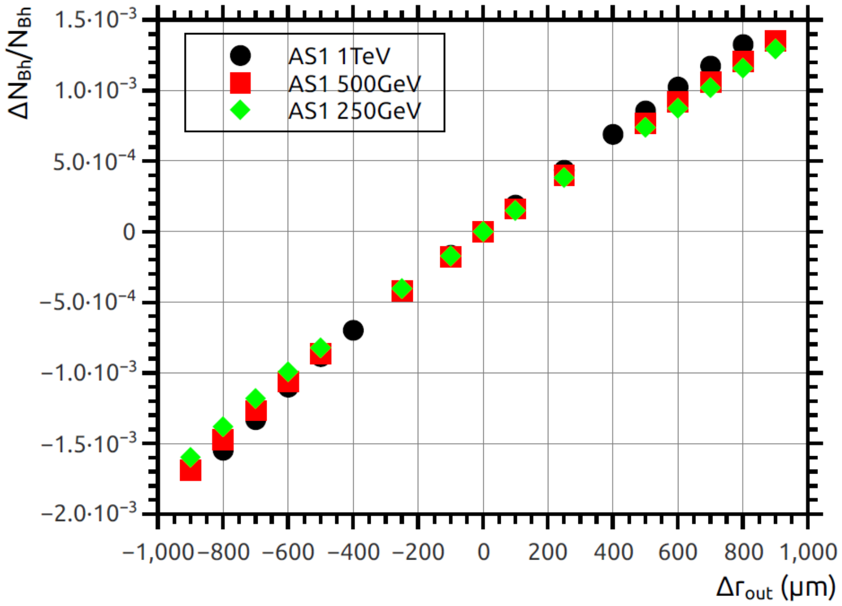


~200 μm at higher energies

~20 μm at the Z-pole

Outer aperture of the counting (FV) volume



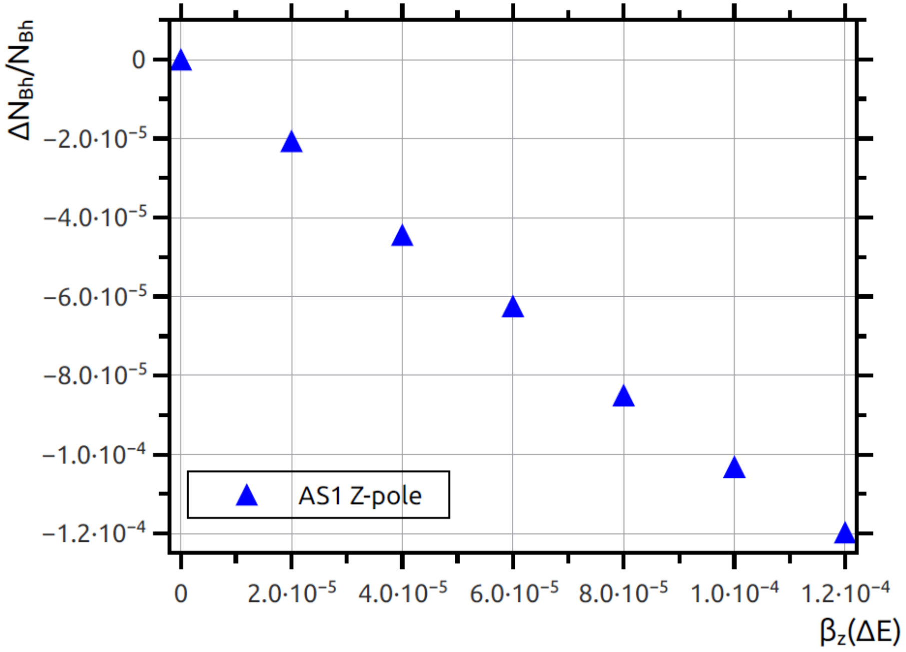


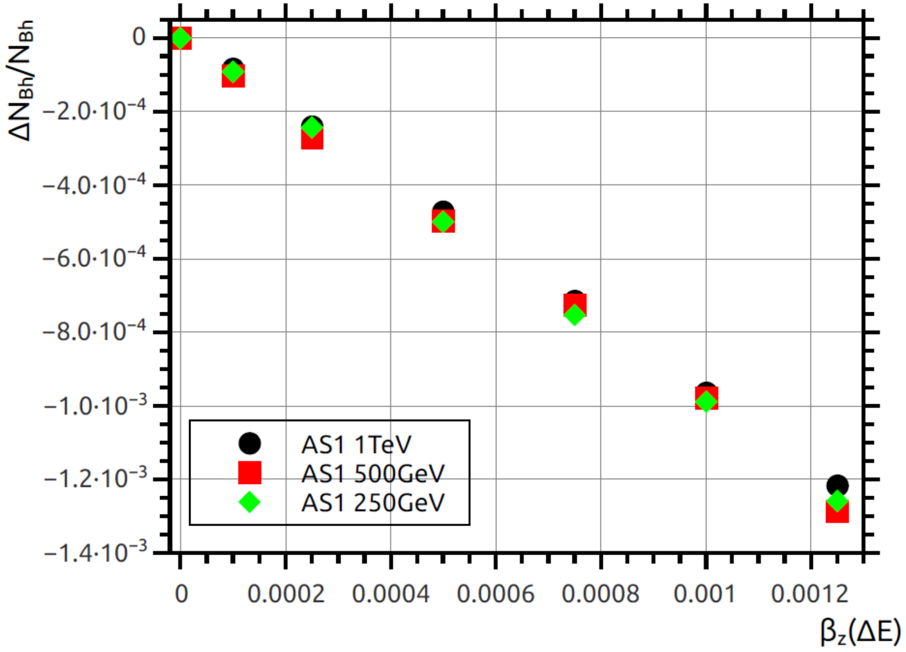
~ 600 μm at higher energies

~ 60 μm at the Z-pole

ΔE - asymmetry (bias) in beam energies

$$\beta_z = 2\Delta E/\sqrt{s}$$



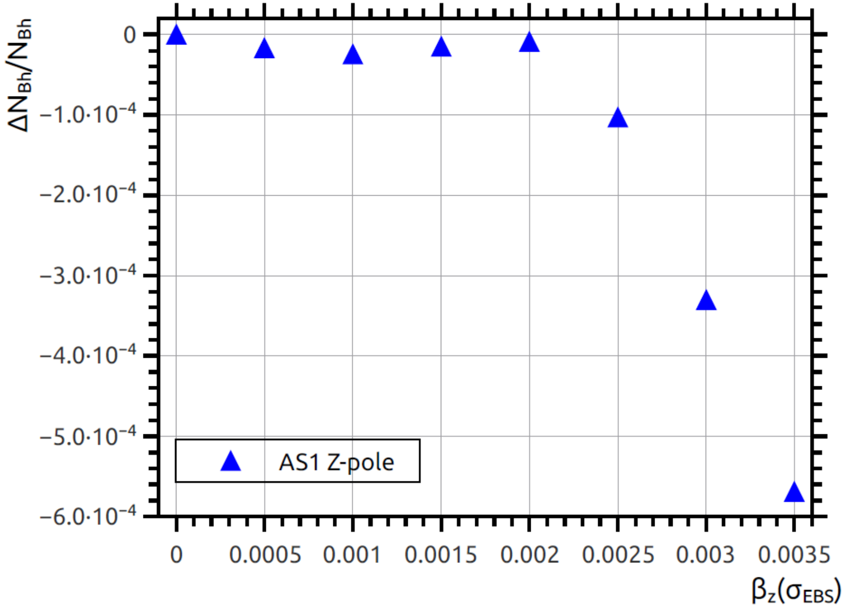


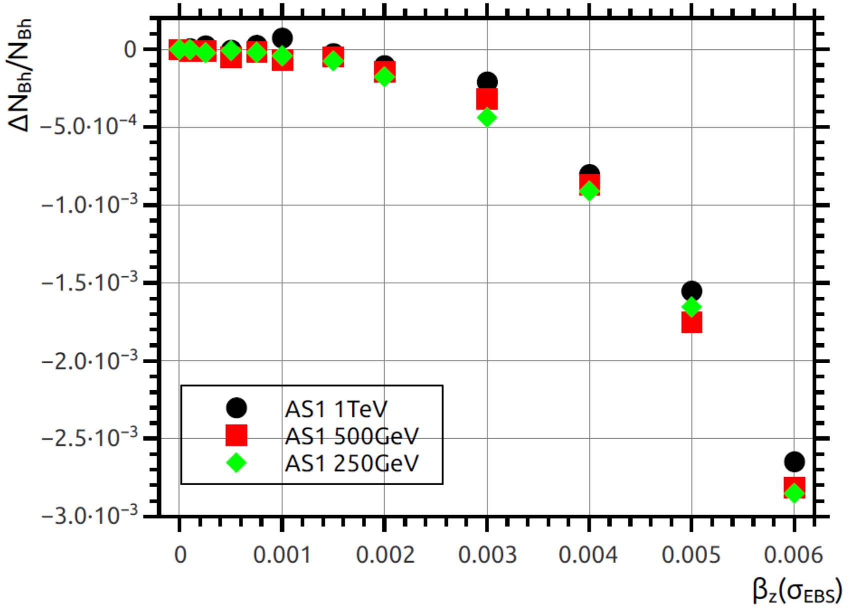
125 MeV, 250 MeV and 500 MeV at 250 GeV, 500 GeV and 1 TeV

~ 5 MeV needed at the Z-pole

BES - beam energy spread

current BES (250 GeV) 0.019: $\Delta\mathcal{L}/\mathcal{L} \sim 3 \cdot 10^{-5}$

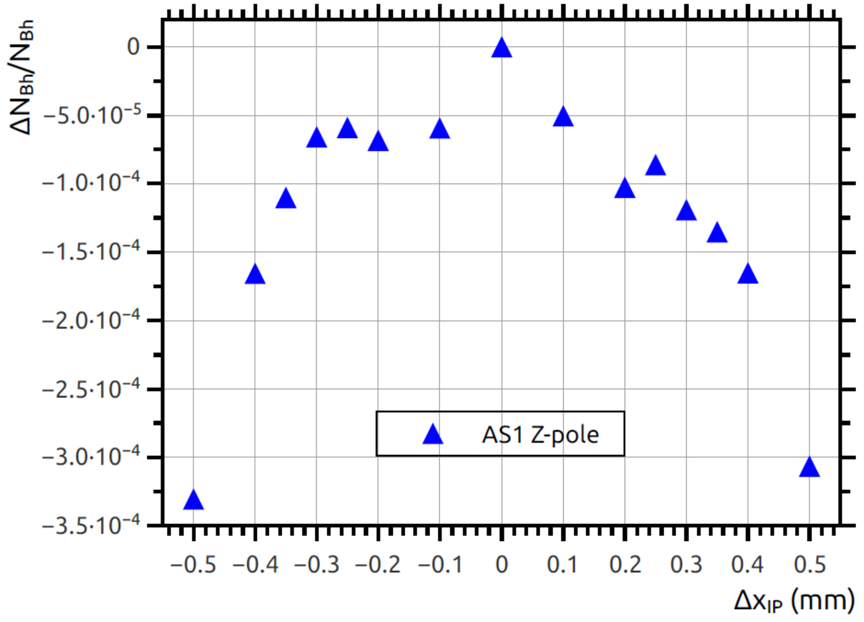


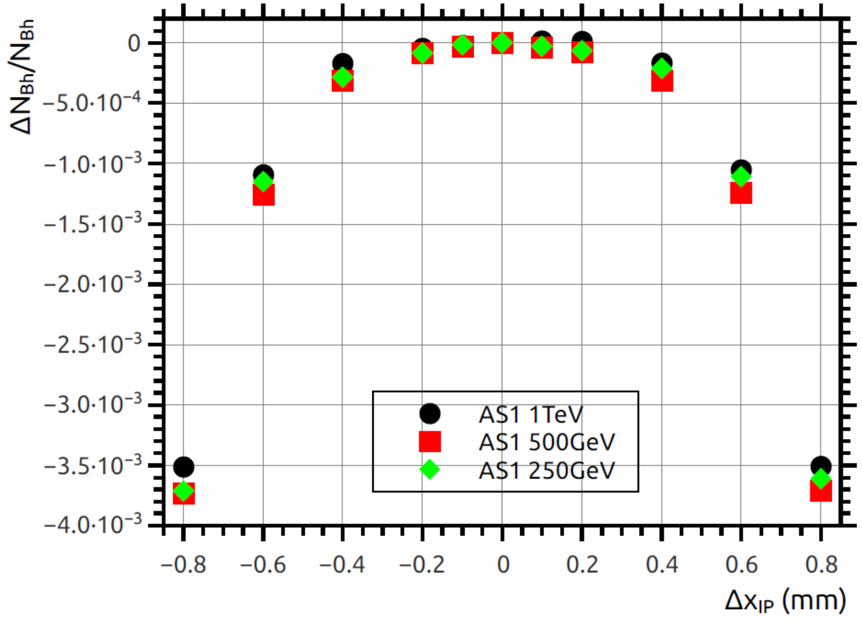


500 MeV, 1 GeV and 2 GeV
at 250 GeV, 500 GeV and 1 TeV

~ 110 MeV needed at the Z-pole
(<0.2% BES should be ok)

Radial displacements of the IP



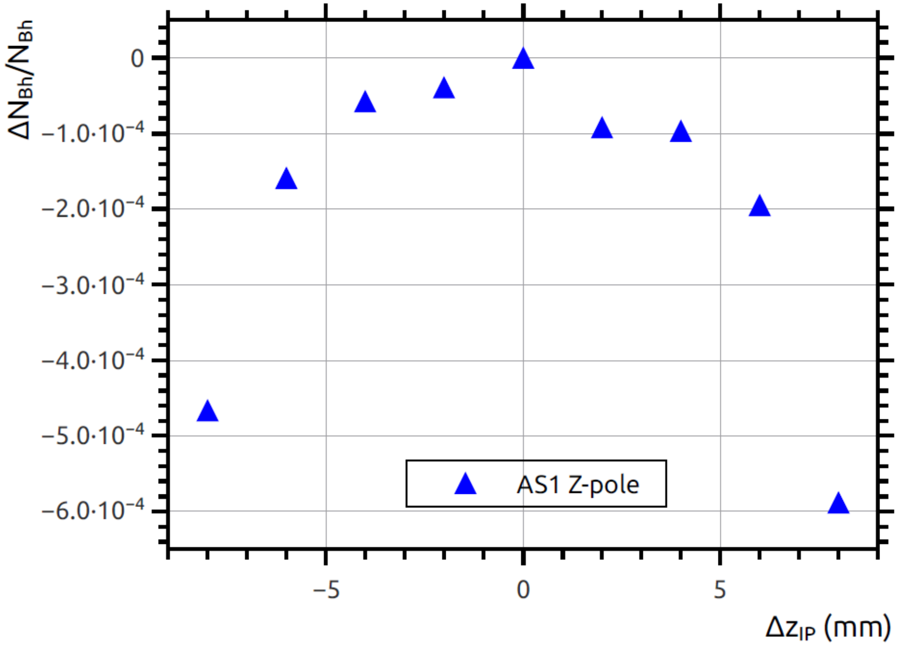


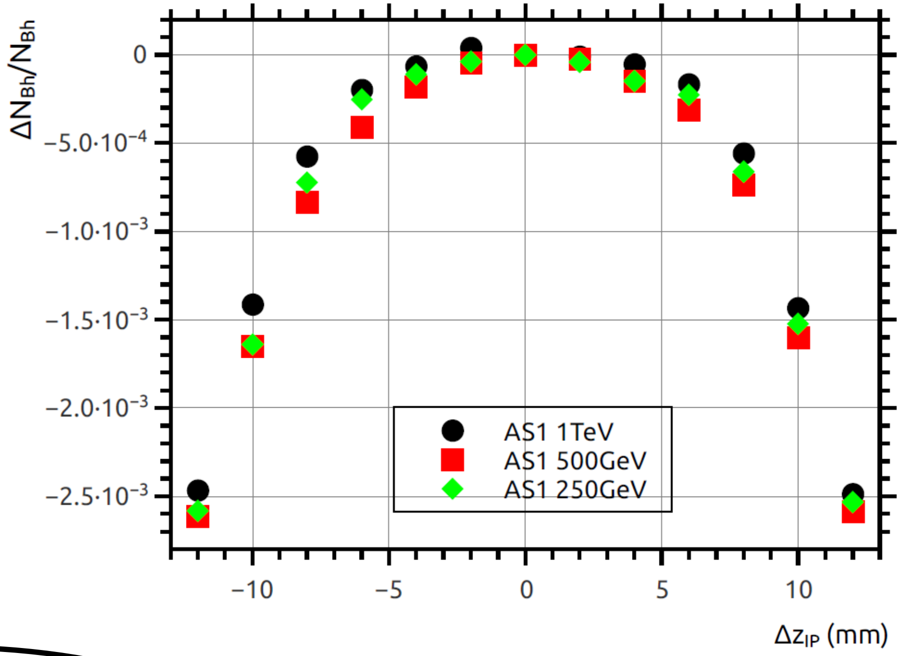
~ 600 μm at higher energies

~ 300 μm at the Z-pole

- Axial displacement of the IP ⇒ beam synchronization

Axial displacements of the IP





~ 9 mm (30 ps) at higher energies

~ 4 mm (13 ps) needed at the Z-pole

Conclusion on metrology

parameter	Z-pole	250 GeV	500 GeV	1 TeV
Δr_{in} (μm)	20	200	200	200
Δr_{out} (μm)	60	600	600	550
σ_r (mm)	0.3	0.5	0.5	0.5
Δl (mm)	0.2	2.5	2.5	2.5
$\sigma_{x_{IP}}$ (mm)	0.3	0.6	0.6	0.6
$\sigma_{z_{IP}}$ (mm)	5	10	10	10
tilt (mrad)	14	35	35	35
Δx_{IP} (mm)	0.3	0.6	0.6	0.6
Δz_{IP} (mm)	4	8	8	8
$\Delta\tau$ (ps)	13	27	27	30
$\sigma_{E_{BS}}$ (MeV)	110	500	1000	2000
ΔE (MeV)	5	125	250	500

$\Delta\mathcal{L}/\mathcal{L}$	$< 3.3 \cdot 10^{-4}$	$< 3.3 \cdot 10^{-3}$

- The major challenges only at the Z-pole
- Inner aperture of the luminometer relaxed with the asymmetric counting
- Position reconstruction in the first plane (300 μm) slightly below prototyped performance (440 μm); Can be resolved with a tracker plane in front of the luminometer
- Beam energy spread should be kept ≤ 0.2%
- Asymmetric bias in beam energies (~ 5 MeV)

- $\Delta(\sqrt{s})$ for the cross-section calculation (~ $5 \cdot 10^{-4}$)
- Theoretical uncertainty for the revised LEP analyses $3.7 \cdot 10^{-4}$ [Physics Letters B 803 (2020) 135319]

Summary

- ILC/ILD has a past of extensive simulation studies on integrated luminosity measurement by the FCAL Collaboration

- FCAL Collaboration has demonstrated in prototype a feasibility of the compact calorimetry for the very forward region of an e^+e^- collider

- Completed with the metrology study at ILC energies – aiming to derive precision limits on individual parameters, not on the integrated luminosity itself

- Input to the ECFA study on Higgs / Top / EW factories prepared, topical paper under ILD review

BACKUP

Complementing the existing results

<table>
<tr><th>Source of uncertainty</th><th>$\Delta L/L$ (500 GeV)</th><th>$\Delta L/L$ (1 TeV)</th><th colspan="2">Comment</th></tr>
<tr><td>Bhabha cross-section σ_B</td><td>$5.4 \cdot 10^{-4}$</td><td>$5.4 \cdot 10^{-4}$</td><td colspan="2" rowspan="3">If needed, can be resolved with Si-tracker plane</td></tr>
<tr><td>Polar angle resolution σ_θ</td><td>$1.6 \cdot 10^{-4}$</td><td>$1.6 \cdot 10^{-4}$</td></tr>
<tr><td>Bias of polar angle $\Delta\theta$</td><td>$1.6 \cdot 10^{-4}$</td><td>$1.6 \cdot 10^{-4}$</td></tr>
<tr><td>IP lateral position uncertainty</td><td>$1 \cdot 10^{-4}$</td><td>$1 \cdot 10^{-4}$</td><td colspan="2">Quantified to 200 μm</td></tr>
<tr><td>Energy resolution a_{res}</td><td>$1.0 \cdot 10^{-4}$</td><td>$1.0 \cdot 10^{-4}$</td><td colspan="2" rowspan="7">Unchanged</td></tr>
<tr><td>Energy scale</td><td>$1.0 \cdot 10^{-3}$</td><td>$1.0 \cdot 10^{-3}$</td></tr>
<tr><td>Beam polarization</td><td>$1.9 \cdot 10^{-4}$</td><td>$1.9 \cdot 10^{-4}$</td></tr>
<tr><td>Physics background B/S</td><td>$2.2 \cdot 10^{-3}$</td><td>$0.8 \cdot 10^{-3}$</td></tr>
<tr><td>Beamstrahlung + ISR[1]</td><td>$-1.1 \cdot 10^{-3}$</td><td>$-0.7 \cdot 10^{-3}$</td></tr>
<tr><td>Beamstrahlung + ISR[2]</td><td>$0.4 \cdot 10^{-3}$</td><td>$0.7 \cdot 10^{-3}$</td></tr>
<tr><td>EMD[1]</td><td>$-2.4 \cdot 10^{-3}$</td><td>$-1.1 \cdot 10^{-3}$</td></tr>
<tr><td>EMD[2]</td><td>$0.5 \cdot 10^{-3}$</td><td>$0.2 \cdot 10^{-3}$</td><td colspan="2">(< $3.3 \cdot 10^{-3}$ from metrology)</td></tr>
<tr><td>$(\Delta L/L)^1$</td><td>$4.3 \cdot 10^{-3}$</td><td>$2.3 \cdot 10^{-3}$</td><td>$5.4 \cdot 10^{-3}$</td><td>$4.0 \cdot 10^{-3}$</td></tr>
<tr><td>$(\Delta L/L)^2$</td><td>$2.6 \cdot 10^{-3}$</td><td>$1.6 \cdot 10^{-3}$</td><td>$4.2 \cdot 10^{-3}$</td><td>$3.7 \cdot 10^{-3}$</td></tr>
</table>

[FCAL, 2010 JINST 5 P12002] and
[IBJ et al., 2013 JINST 8 P08012]

ILC beam parameters

Machine	ILC			
mode	**Z-pole***	**Higgs**	**500 GeV**	**1 TeV**
Half crossing angle at IP (mrad)	7	7	7	7
Beam energy (GeV)	45	125	250	500
Bunch population (10^{11})	0.2	0.2	0.2	1.74
Bunch length (mm)	0.3	0.3	0.3	0.225
Beam size at IP σ_x/σ_y (μm/nm)	1.35/11.6	0.729/0.7	0.474/5.9	0.335/2.7
Energy spread (natural) (%)	0.42	0.19	0.124	0.085
Luminosity per IP (10^{34} cm^{-2}s^{-1})	0.23	0.75	3.6	4.9