Metrology requirements for the integrated luminosity measurement at ILC

I. Bozovic

I. Smiljanic & G. Kacarevic

Vinča Institute of Nuclear Sciences - National Institute of the Republic of Serbia

Supported through Grant No. 7699827 Project IDEAS HIGHTONE-P

Overview

- Luminometer at ILC
- Status of FCAL R&D
- Metrology (novel study)
- Discussion

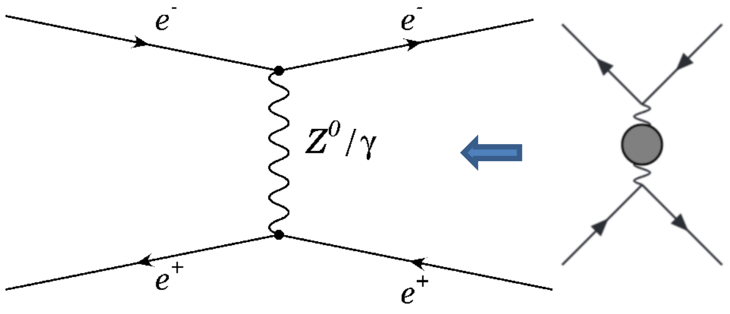
- Preparing the ECFA Focus Topics paper (arXiv:2401.07564v2 [hep-ph]) we have realized

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

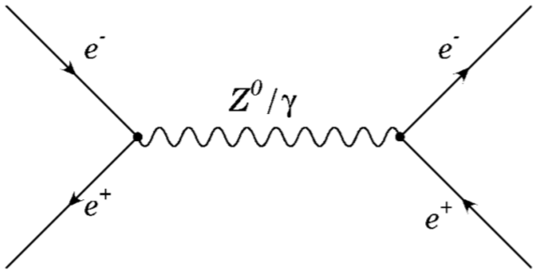
- We have performed a study at:
  Z-pole, 250 GeV, 500 GeV and 1 TeV

(*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
- *More in [arXiv:2401.07564v2 [hep-ph]]*



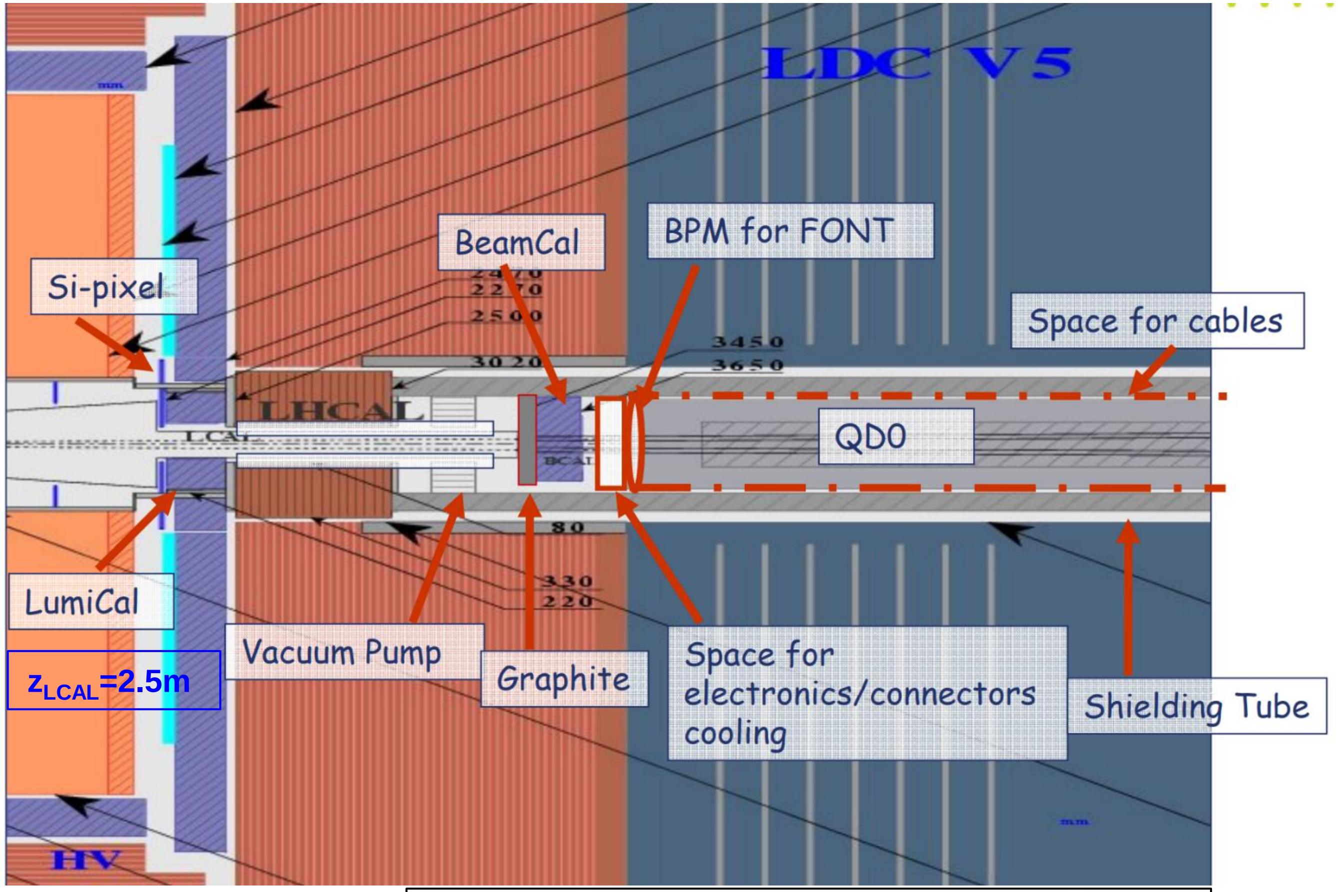
$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\,\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\,\frac{1}{\theta^3}$$

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)

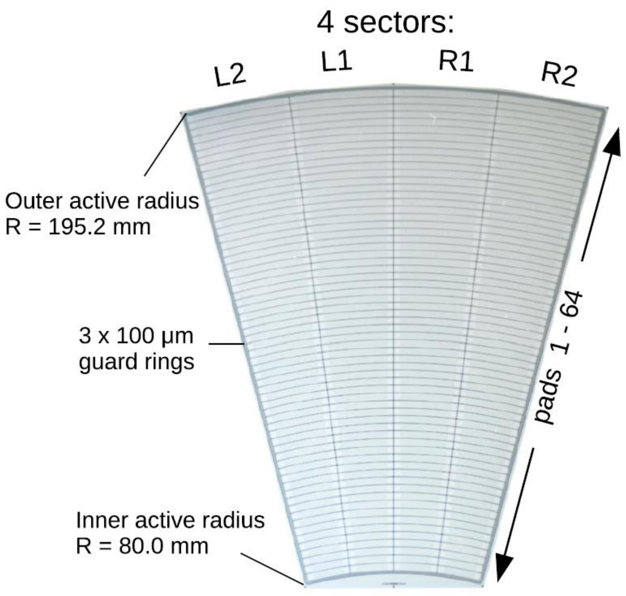
Very forward region Luminometer



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

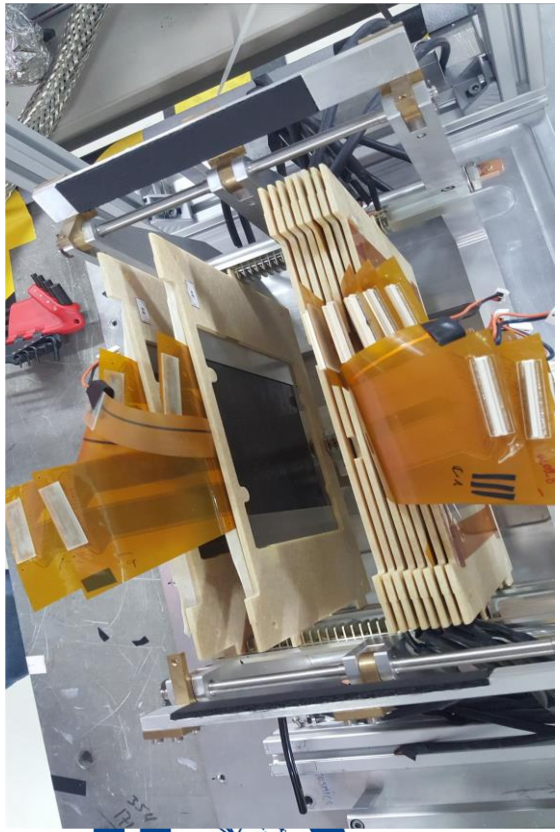
Luminometer prototype

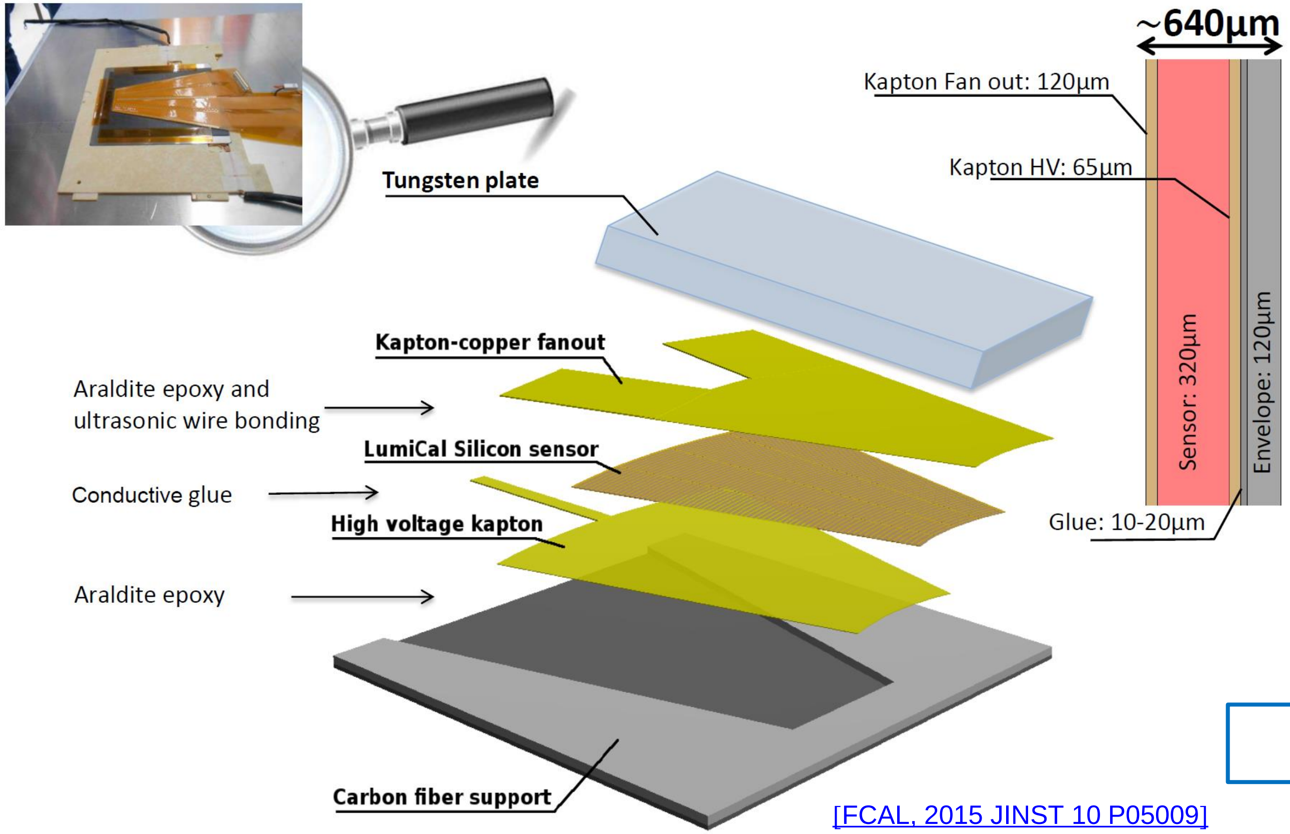
- High precision in polar angle measurement (~20 μrad)

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

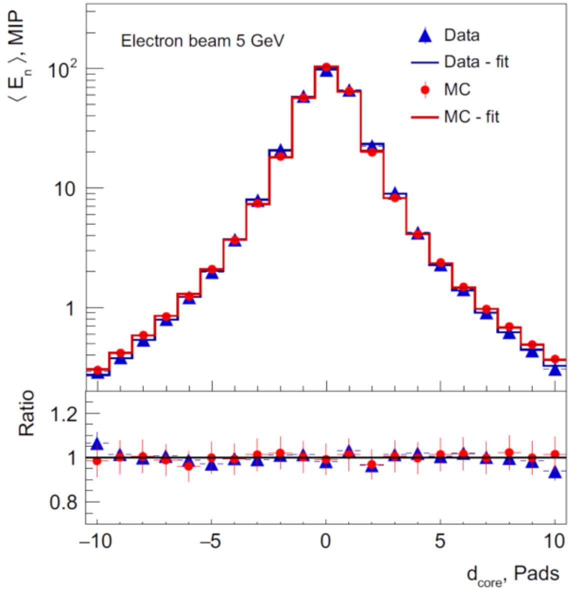
⇒ Compactness - small Moliere radius

- Feasibility demonstrated by the FCAL R&D Collaboration





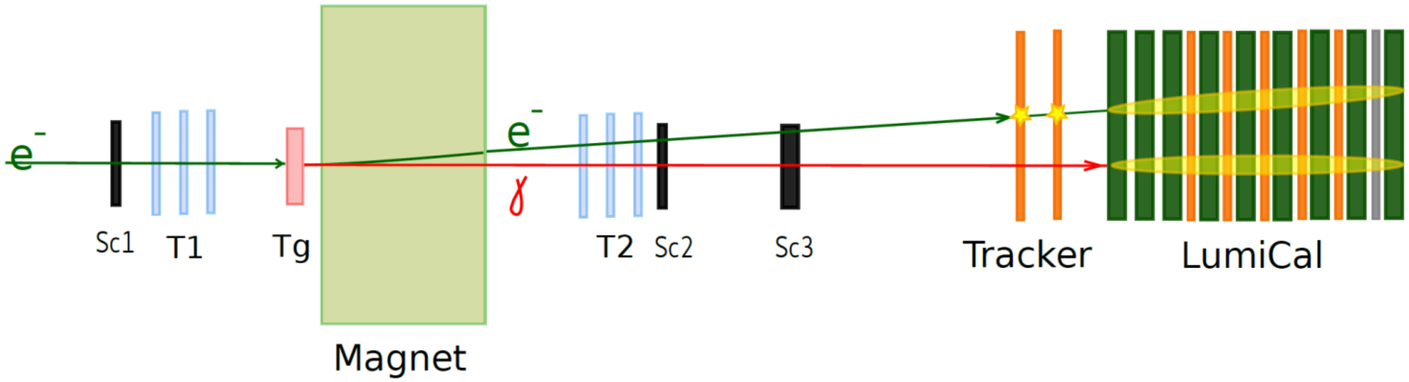
[FCAL, 2015 JINST 10 P05009]



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

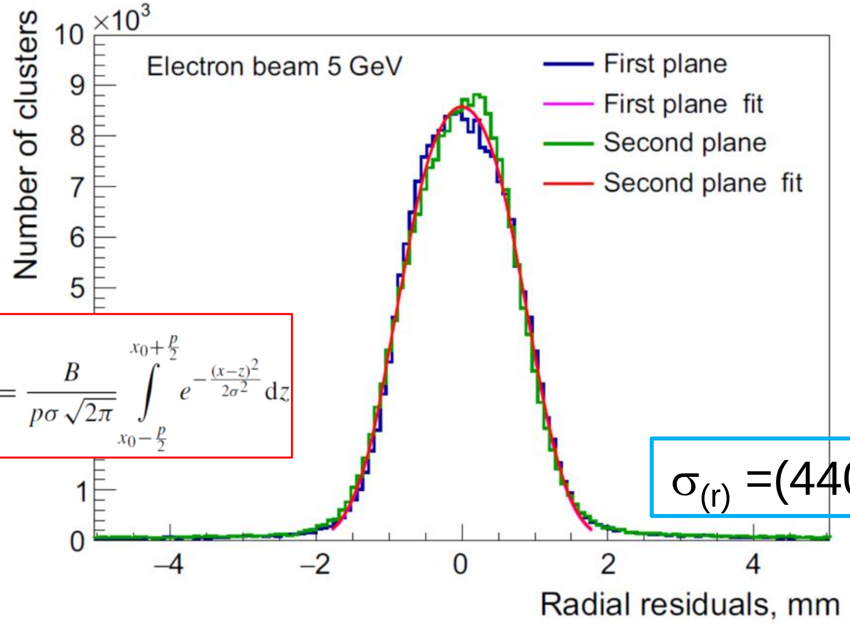
$R_M = (\mathbf{8.1} \pm 0.1_{stat.} \pm 0.3_{syst.})$ mm

Impact of design and performance



Dissipation of reconstructed hits in the luminometer front plane

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



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

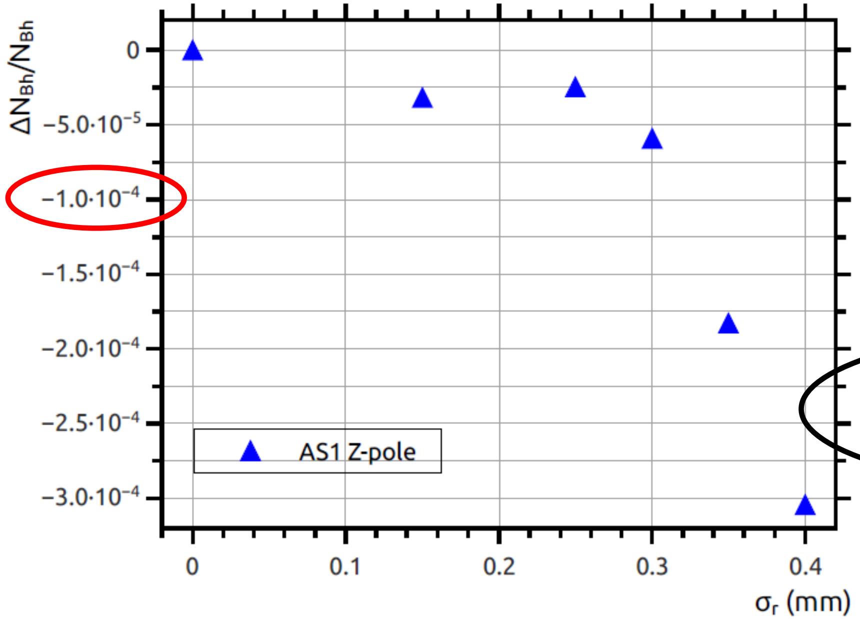
$\sigma_{(r)} = (440 \pm 20)\ \mu m$

- 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

[FCAL, 2015 JINST 10 P05009]

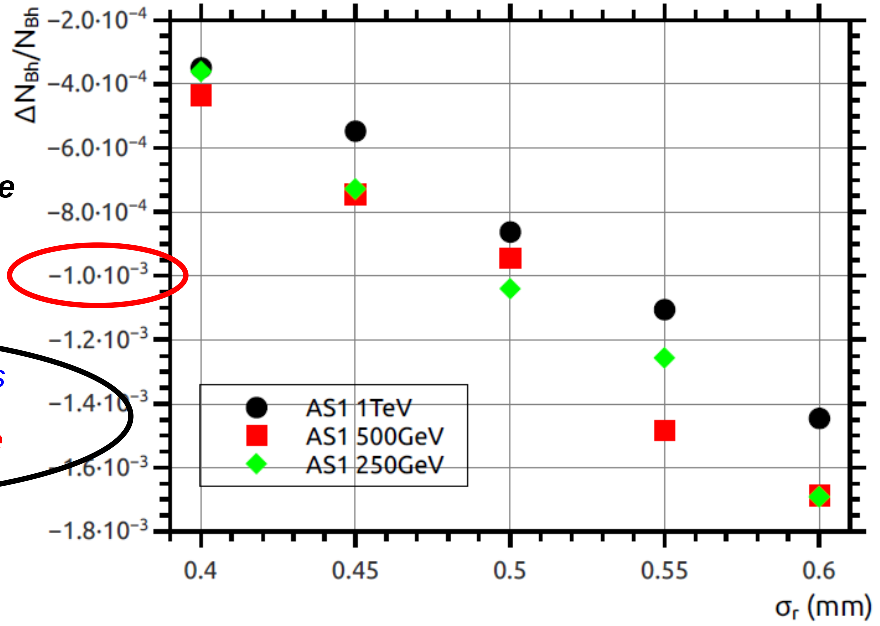
- 10 million low angle Bhabha scattering events using BHLUMI V4.04
- (20-200) mrad to allow events with non-collinear final state radiation to contribute
- No full detector simulation, no beam-beam effects, only FV (41-67) mrad
- s-axis, asymmetric counting (Δr=1mm)

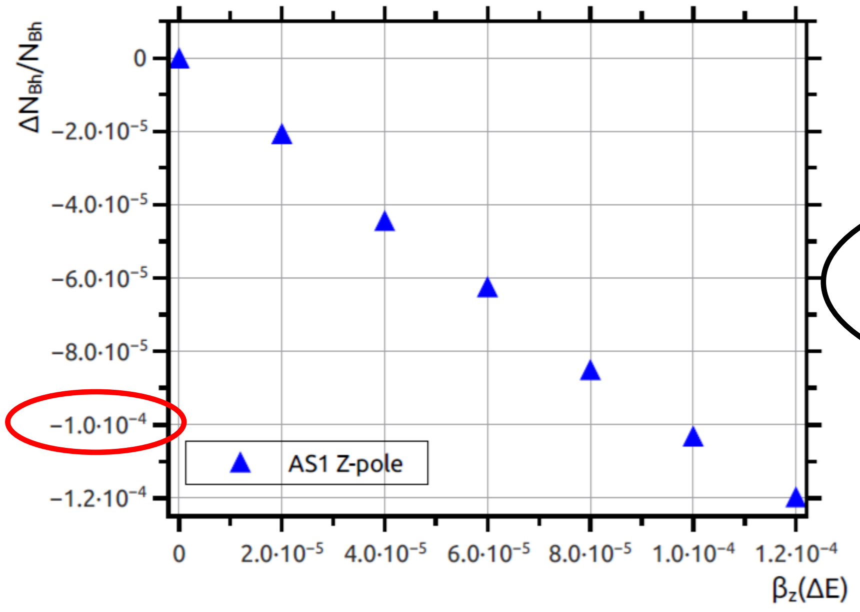


Dissipation of reconstructed hits in the luminometer front plane

< 500 μm ok at higher energies

~ 300 μm needed at the Z-pole



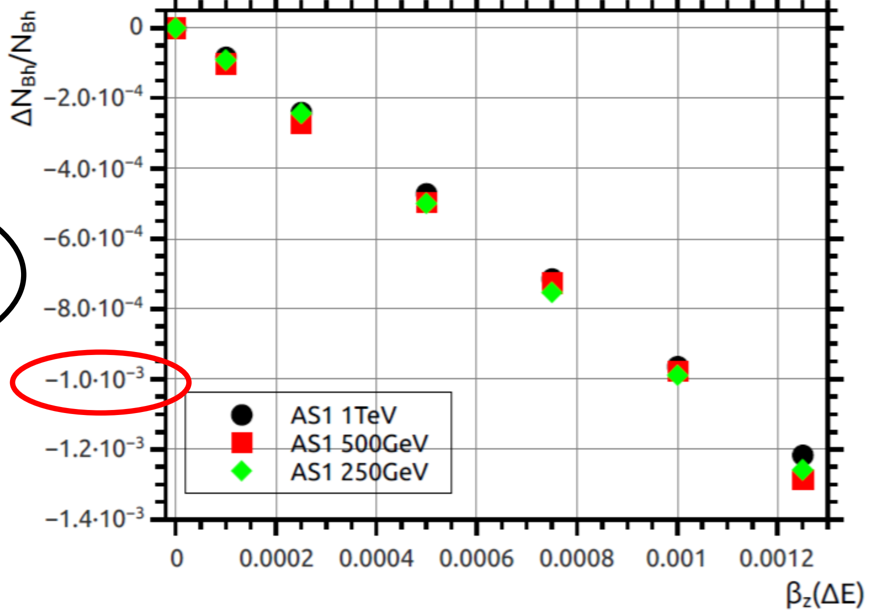


ΔE - asymmetry (bias) in beam energies

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

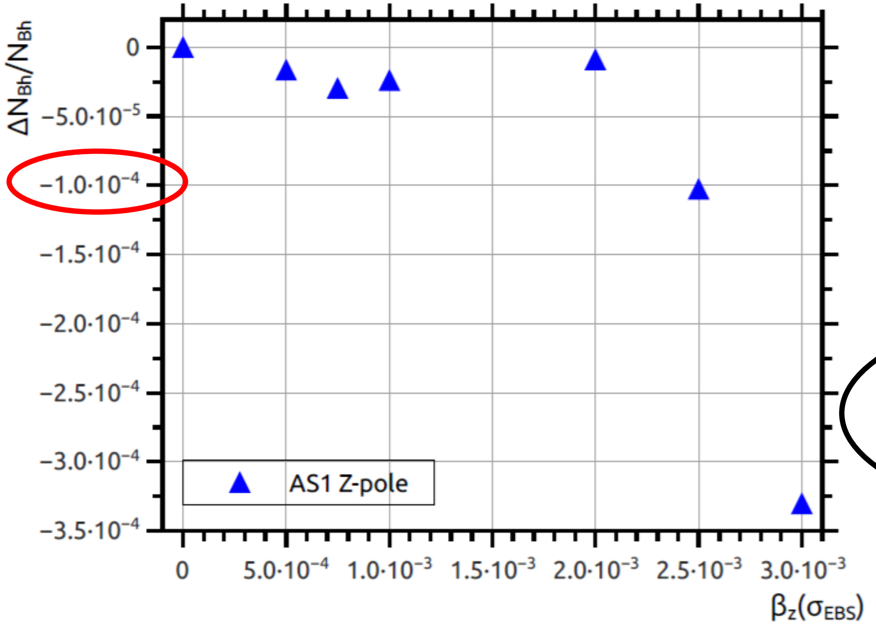
125 MeV, 250 MeV and 500 MeV at 250 GeV, 500 GeV and 1 TeV

~ 5 MeV needed at the Z-pole



- Metrology: What about the Beamspread?

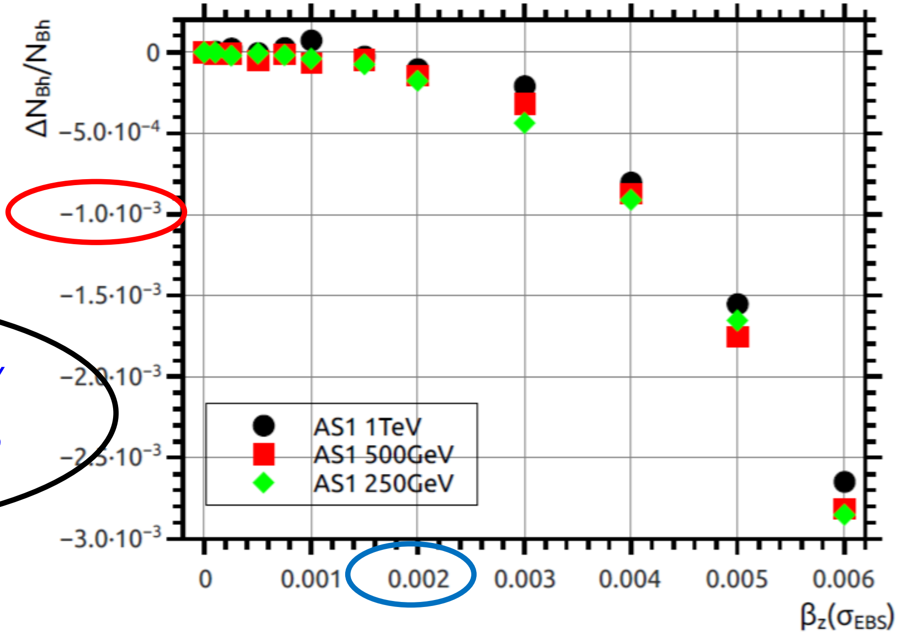
current BES (250 GeV): $\Delta\mathcal{L}/\mathcal{L} < 2{\cdot}10^{-4}$



BES - beam energy spread

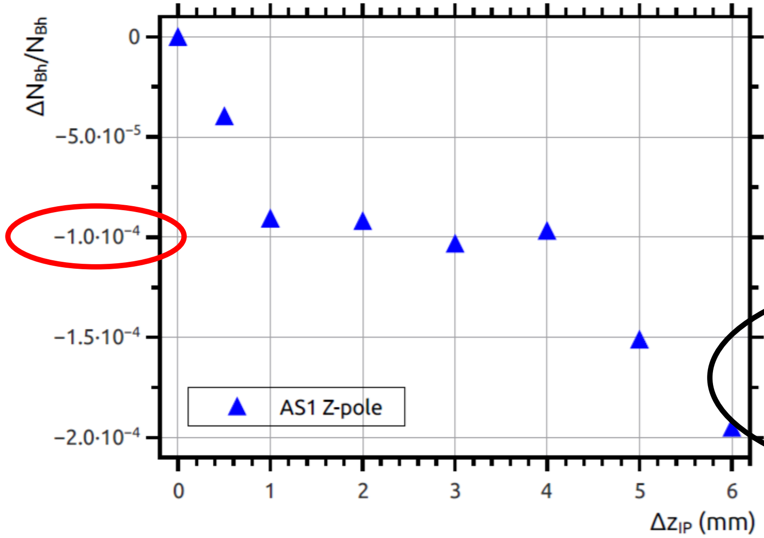
500 MeV, 1 GeV and 2 GeV
at 250 GeV, 500 GeV and 1 TeV

~ 114 MeV needed at the Z-pole
(<0.2% BES should be ok)



- Further on beams: axial displacement of the IP

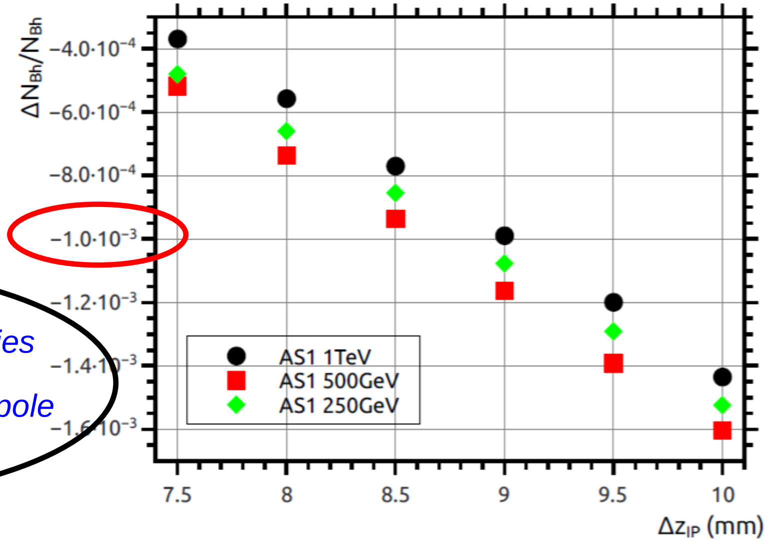
$\Rightarrow$ beam synchronization

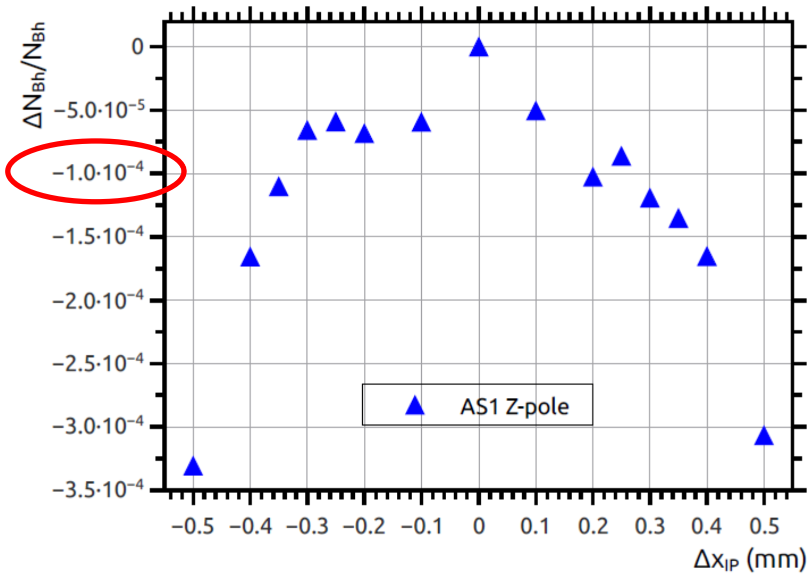


Axial displacement of the IP

~ 9 mm (30 ps) at higher energies

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

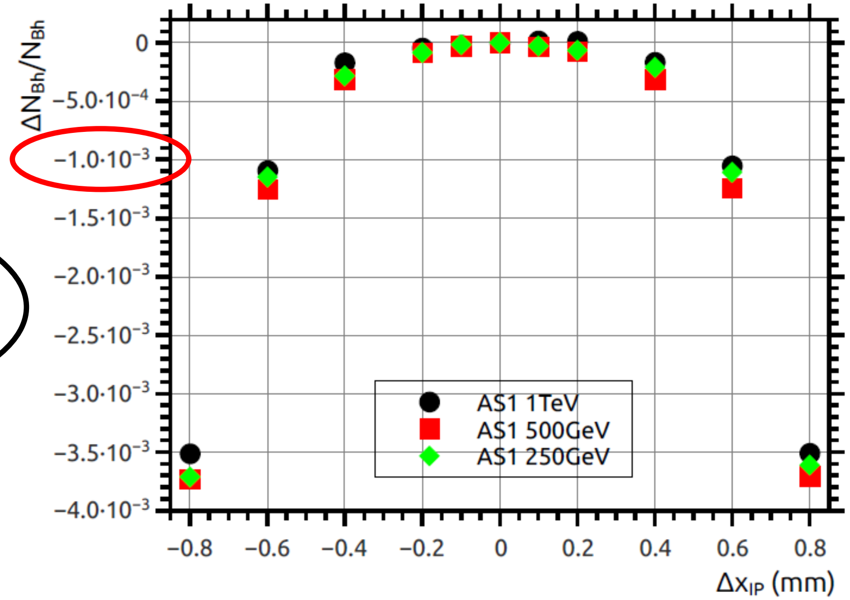


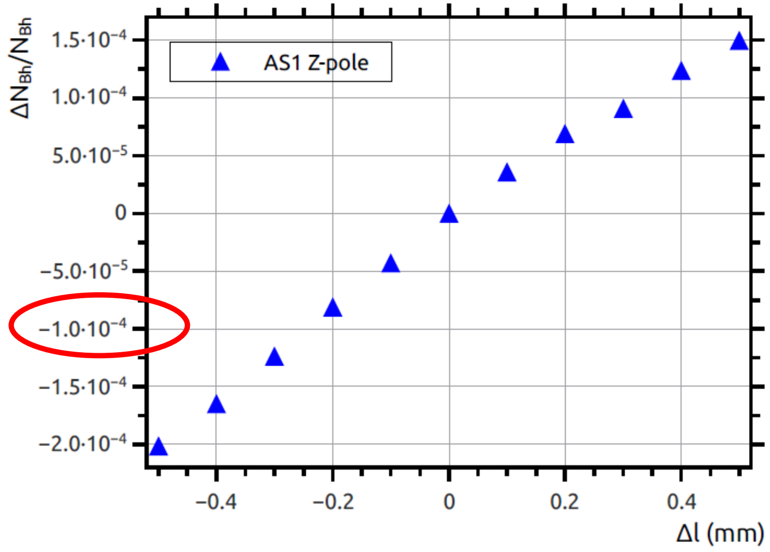


Radial displacement of the IP

~600 μm at higher energies

~300 μm at the Z-pole

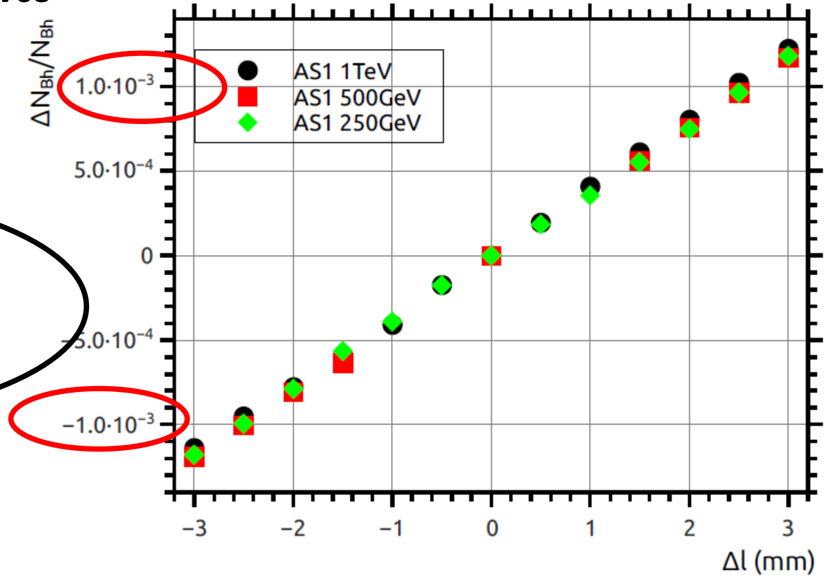


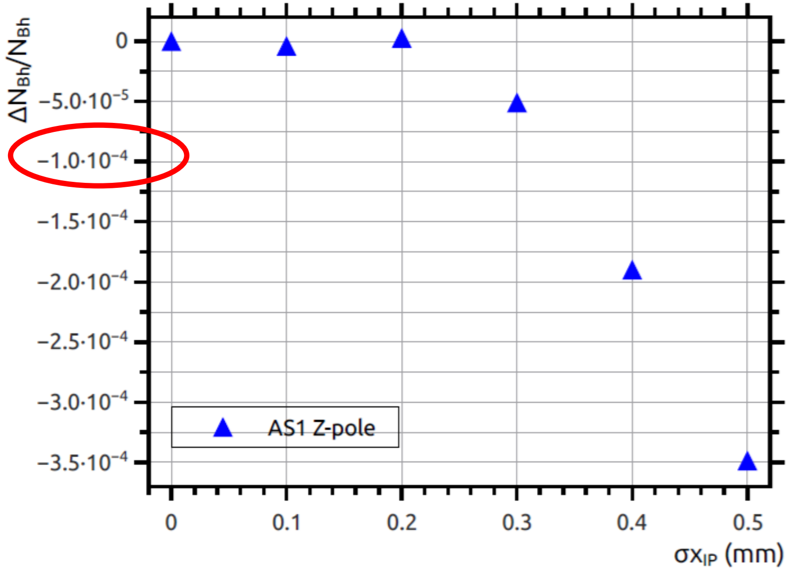


Distance between luminometer halves (symmetric)

< 3 mm at higher energies

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

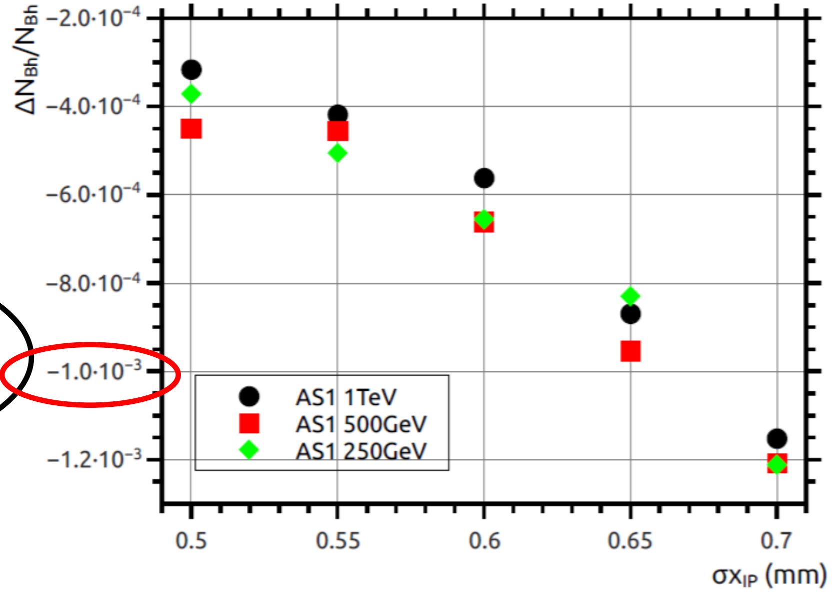


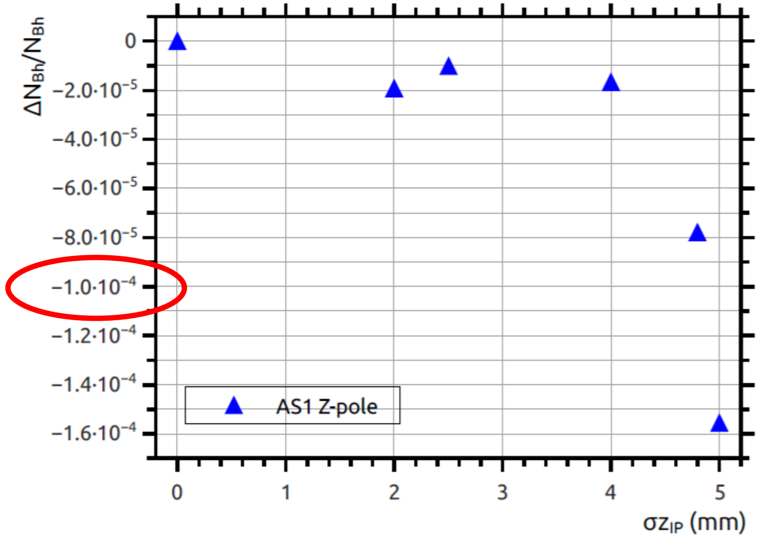


Radial vibrations of the luminometer

~ 650 μm at higher energies

~ 350 μm at the Z-pole

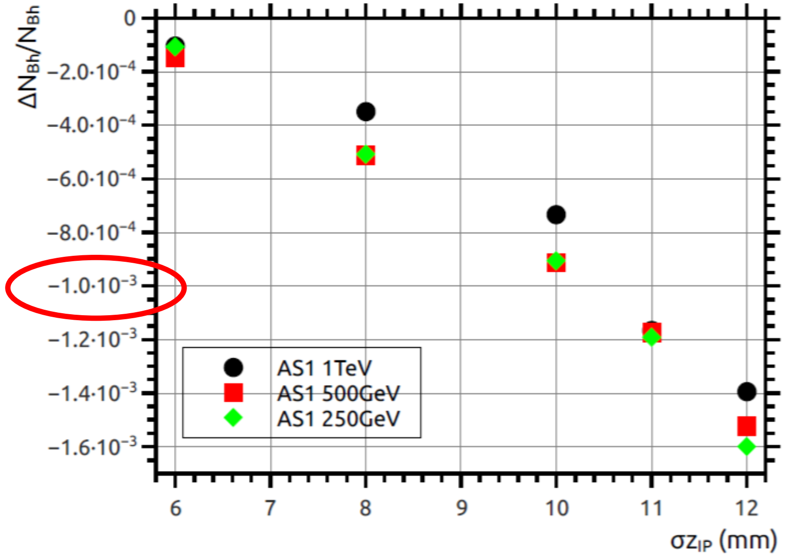


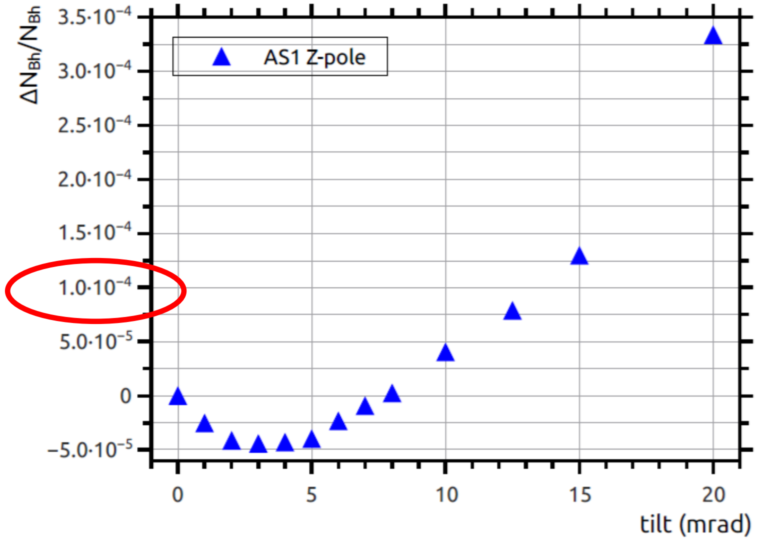


Axial vibrations of the luminometer

~ 10 mm at higher energies

~ 5 mm at the Z-pole

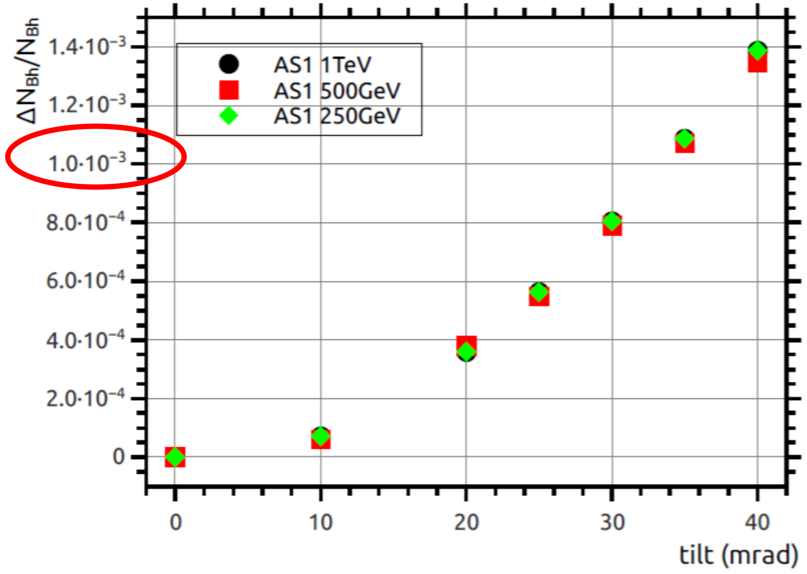




Tilt (rotation around y-axis) of the luminometer

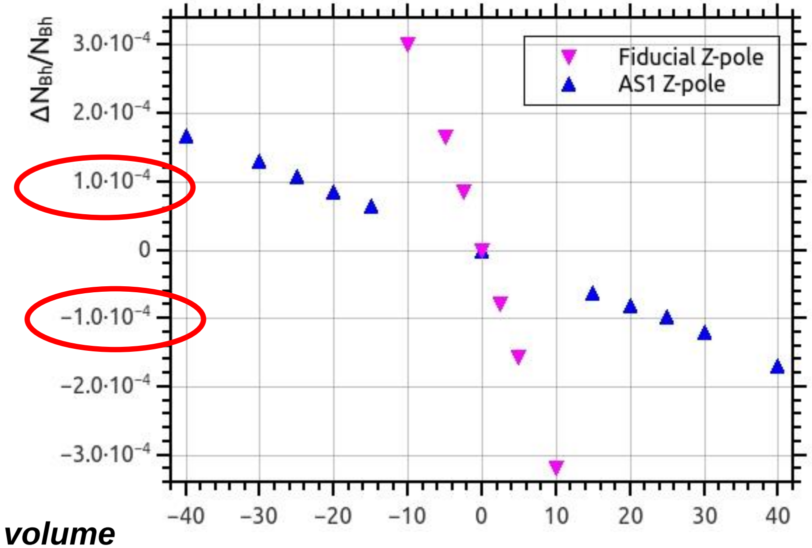
~35 mrad at higher energies

~14 mrad at the Z-pole



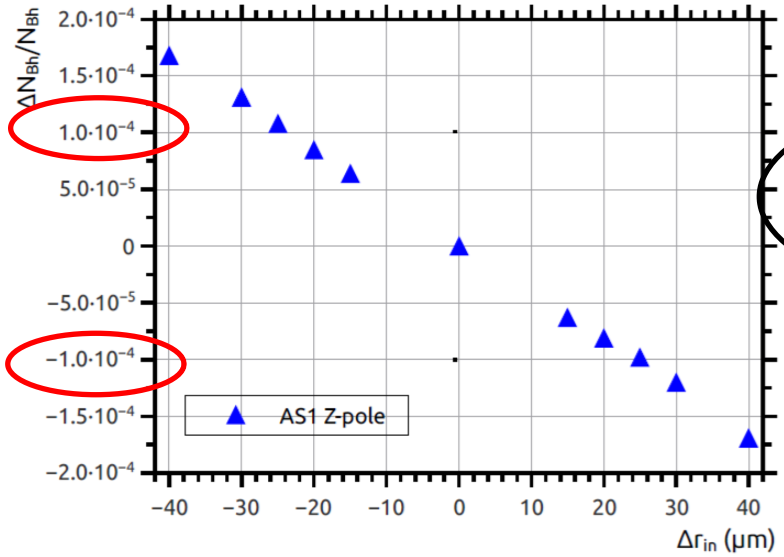
Detector mechanics and positioning

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



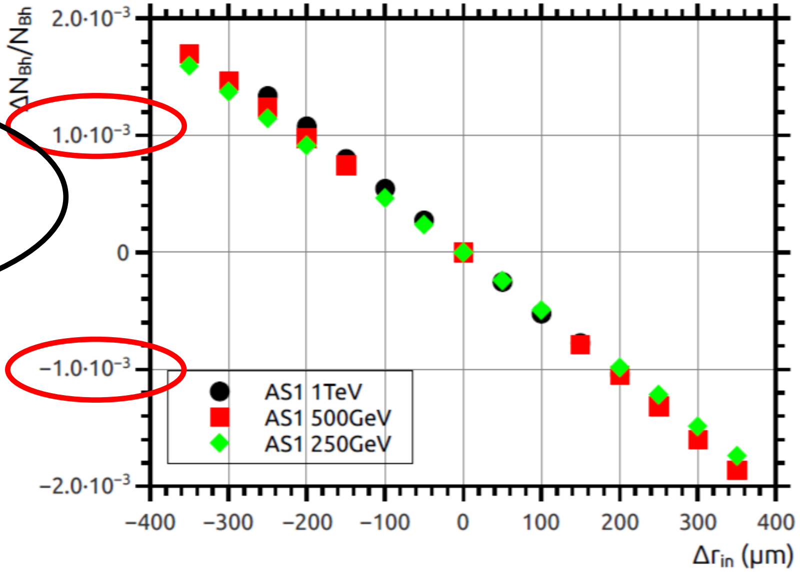
- Asymmetric counting (Δr=1 mm at one side) compensates for smaller variations ~ 20 μm (of the counting volume) at the other
- Symmetrical counting requires ~ 1 μm precision at the Z-pole
- Asymmetric counting only applicable o the s-axis

Inner aperture of the counting (FV) volume

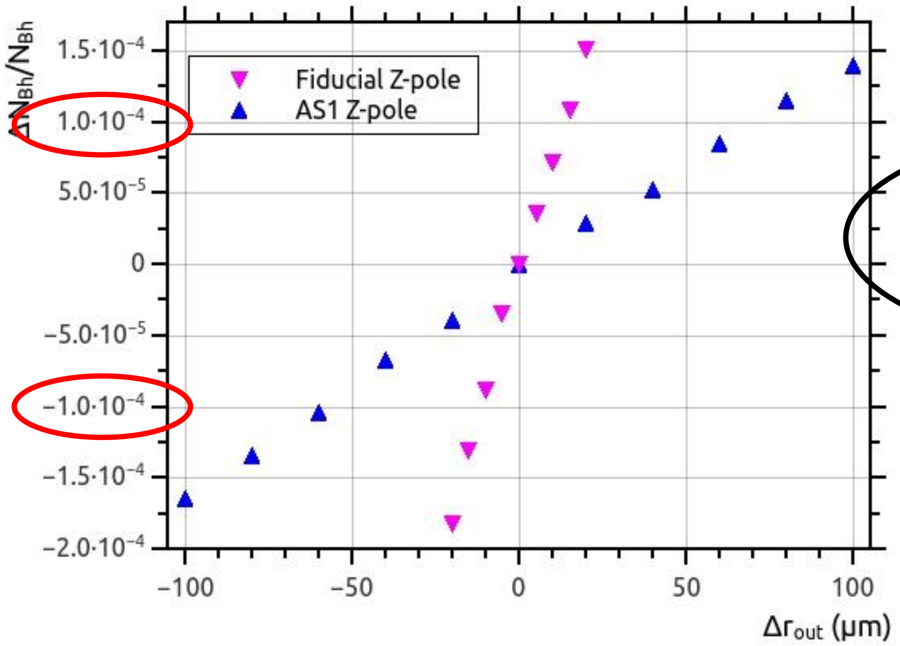


~200 μm at higher energies

~20 μm at the Z-pole

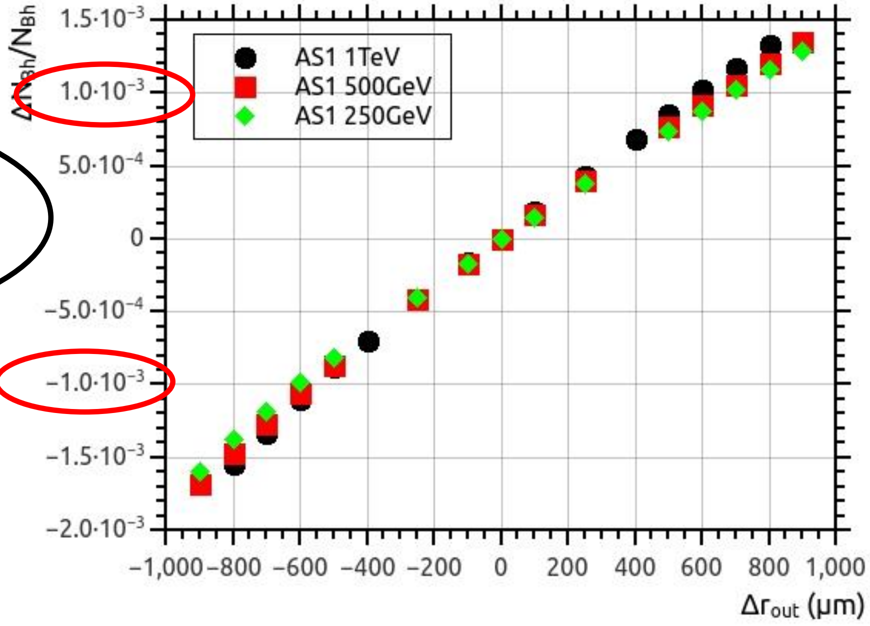


Outer aperture of the counting (FV) volume



~ 600 μm at higher energies

~ 60 μm at the Z-pole



Conclusion on metrology

parameter	Z-pole	250 GeV	500 GeV	1 TeV
Δr_{in} (μm)	20	200	200	200
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)	0.35	0.65	0.65	0.65
$\sigma_{z_{IP}}$ (mm)	5	10	10	10.5
tilt (mrad)	14	35	35	35
Δx_{IP} (mm)	0.3	0.6	0.55	0.6
Δz_{IP} (mm)	4	8.5	8.5	9
$\Delta\tau$ (ps)	13	27	27	30
$\sigma_{E_{BS}}$ (MeV)	114	500	1000	2000
ΔE (MeV)	4.5	125	250	500
Δr_{out} (μm)	60	600	600	600
$\Delta\mathcal{L}/\mathcal{L}$	$3.3 \cdot 10^{-4}$	$3.3 \cdot 10^{-3}$		

- 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
- Asymmetric bias in beam energies (~ 5 MeV)
- $\Delta(\sqrt{s})$ for the cross-section calculation (~ $5 \cdot 10^{-4}$)

Complement the existing results

[Focus topics for the ECFA study on Higgs / Top / EW factories, [arXiv:2401.07564v2 [hep-ph]]

	LEP [144]	FCC-ee (Z pole)	ILC [146], [147] ($\sqrt{s} > 250$ GeV)
LumiCal distance from IP [m]	2.5	1.1	2.48
Precision target	3.4×10^{-4}	10^{-4}	10^{-3}
Tolerance for			
inner radius [μm]	4.4	$\mathcal{O}(1)$	4
outer radius [μm]	?	$\lesssim 3$	?
distance between two LumiCals [μm]	$\mathcal{O}(100)$	< 100	200

Z-pole	≥ 250 GeV
4 (full FV)/ 20 (Δr=1mm)	200
55	600
200	2500

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

$5.4 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$
$4.2 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$

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

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

- Detailed simulation of effects from metrology does not identify major challenges to measure integrated luminosity with the relative precision of 10^{-3} at 250 GeV and above

- At the Z-pole: inner aperture of the luminometer relaxed to 20 μm with asymmetric counting, beam energy asymmetry $\sim$ 5 MeV), position reconstruction can be improved (if needed) with a tracker plane in front of the luminometer

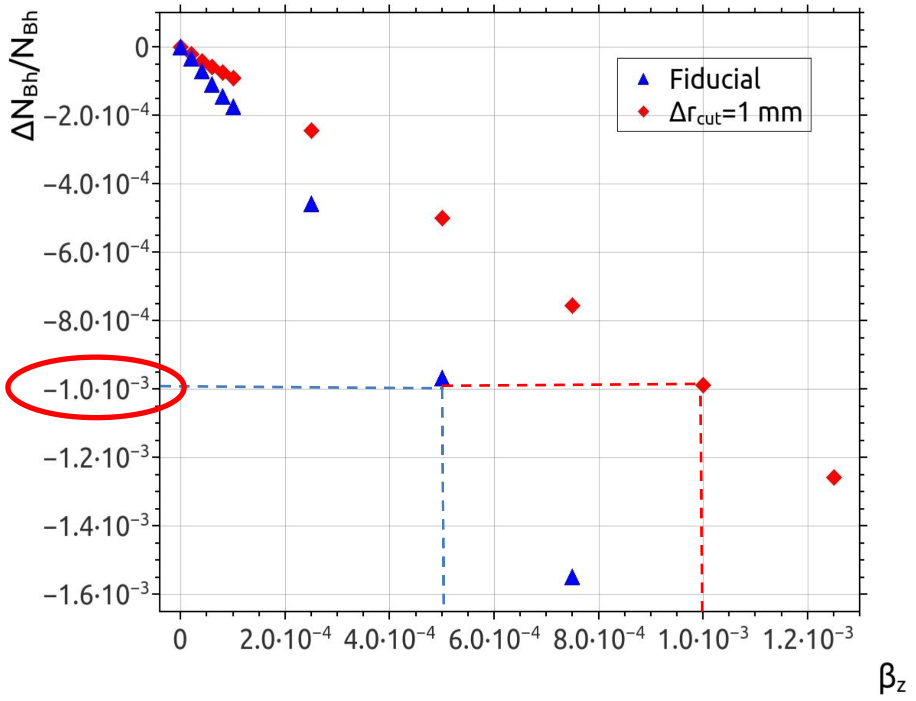
- Input will be provided for the ECFA study on Higgs / Top / EW factories, LCWS2024 contribution, topical paper under ILD review

BACKUP

- Metrology depends on:
  - Where is the detector (s-axis or z-axis)
  - Way of counting (LEP-style, full FV)

ILC 250 GeV s-axis

ΔE - asymmetry (bias) in beam energies



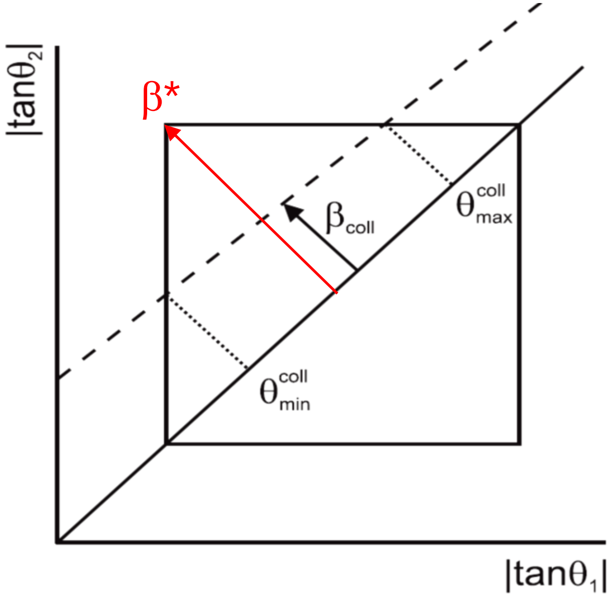
$\Delta\mathcal{L}/\mathcal{L}=10^{-3}$ → FV: ΔE=75 MeV
LEP-style: ΔE=125 MeV

Beam-induced effects: Beamstrahlung

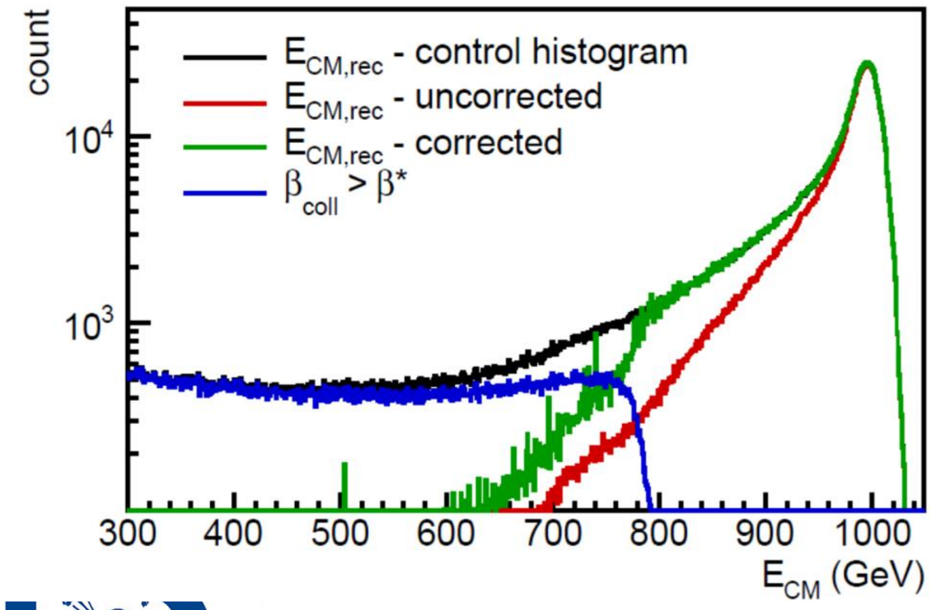
- An issue at linear machines (correction of the luminosity spectrum)
- Pronounced at high √s

1. Longitudinal boost can be determined from experimental data ($\theta_{1,2}$)
2. Effective reduction of the cross-section can be found
3. Correction weight $w(\beta_{coll})$ can be applied on event-by-event basis
4. θ measurement in the luminometer better than 20 mrad

$$\beta_{coll} = \frac{sin(\theta_1^{lab} + \theta_2^{lab})}{sin(\theta_1^{lab}) + sin(\theta_2^{lab})}$$



$$w(\beta_{coll}) = \frac{\int_{\theta_{min}}^{\theta_{max}} \frac{d\sigma}{d\theta} d\theta}{\int_{\theta_{min}^{coll}}^{\theta_{max}^{coll}} \frac{d\sigma}{d\theta} d\theta}.$$



Source of uncertainty	$\Delta L/L$ (500 GeV)	$\Delta L/L$ (1 TeV)
Beamstrahlung + ISR[1]	$-1.1 \cdot 10^{-3}$	$-0.7 \cdot 10^{-3}$
Beamstrahlung + ISR[2]	$0.4 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$

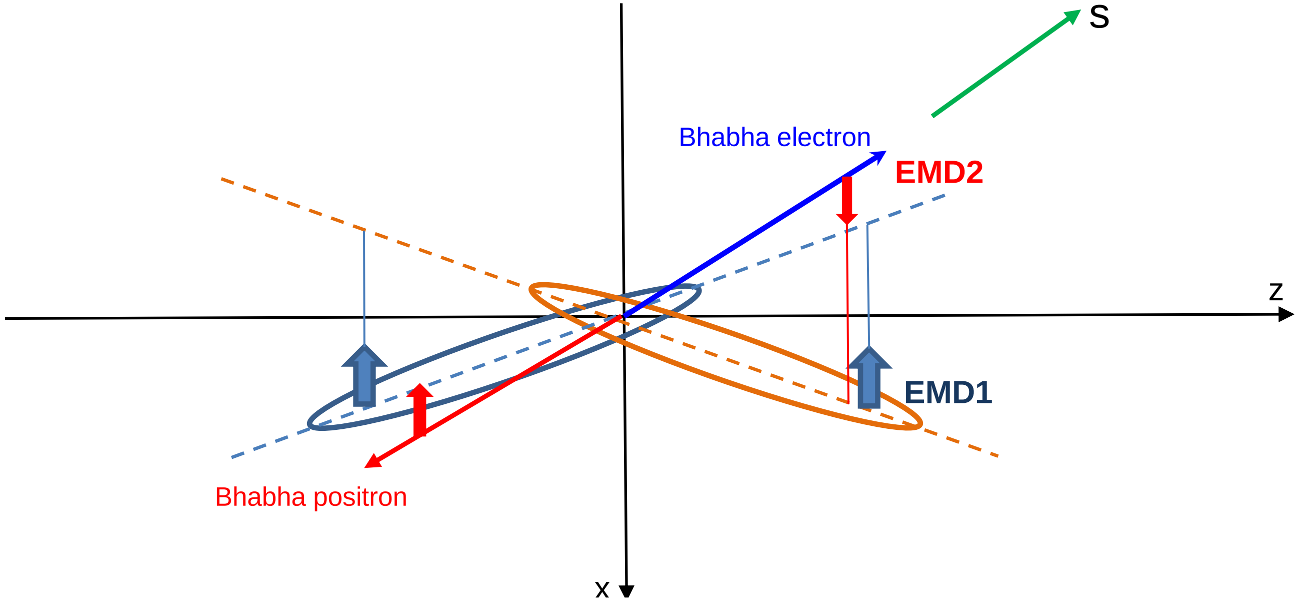
1 = uncorrected, 2 = corrected

[IBJ et al., 2013 JINST 8 P08012]

Beam-induced effects: EMD1 and EMD2

EMD1 – p_x-kick of the initial state
EMD2 – focusing of the final state

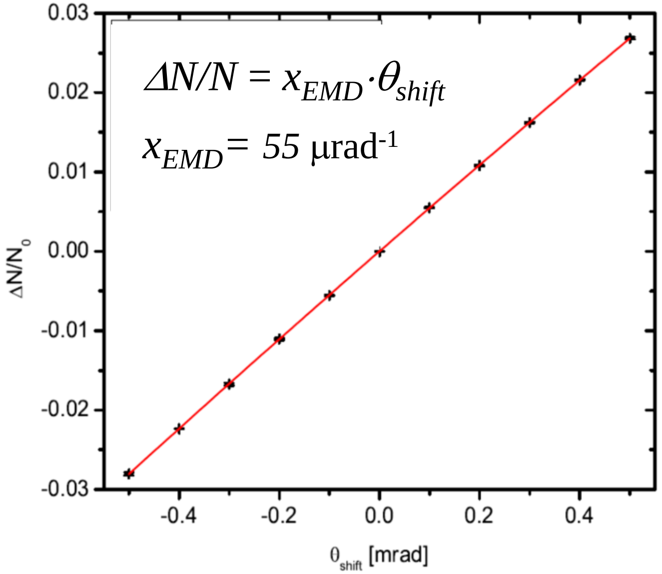
- EMD1 not quantified at ILC
- EMD2 – simulation dependent correction proposed [*IBJ et al, 2013 JINST 8 P08012*, *and arXiv:1304.4082v3*]

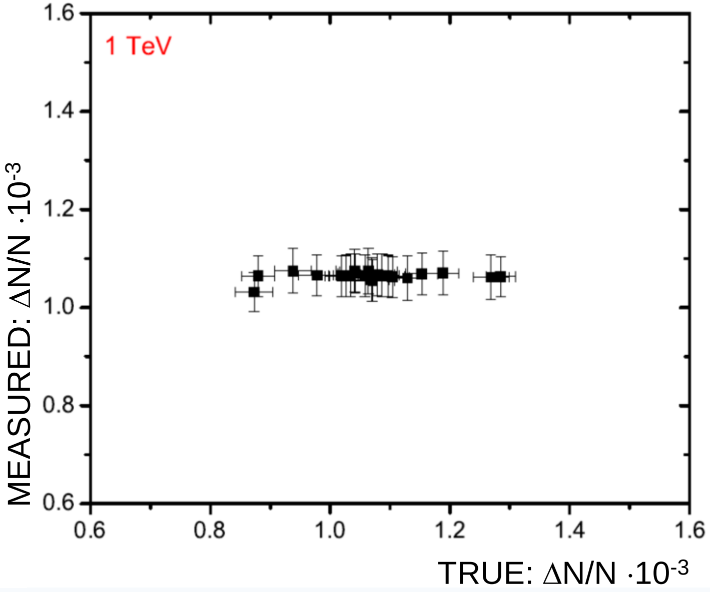


$\Delta\mathcal{L}/\mathcal{L} = x_{\mathcal{EMD}} \cdot \Delta\theta_{eff}$

- $x_{\mathcal{EMD}}$ – can be determined experimentally
- $\Delta\theta_{eff}$ - from simulation as the effective shift of luminometer due to EMD(2)
- $\Delta\theta_{eff}(1\ \mathrm{TeV}) = 20\ \mu\mathrm{rad}$

At 1 TeV ILC:
- Uncorrected $\Delta\mathcal{L}/\mathcal{L} = 1.1\cdot10^{-3}$
- Uncertainty of the correction ~ $2\cdot10^{-4}$





Backup

Systematic uncertainties on Moliere radius

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

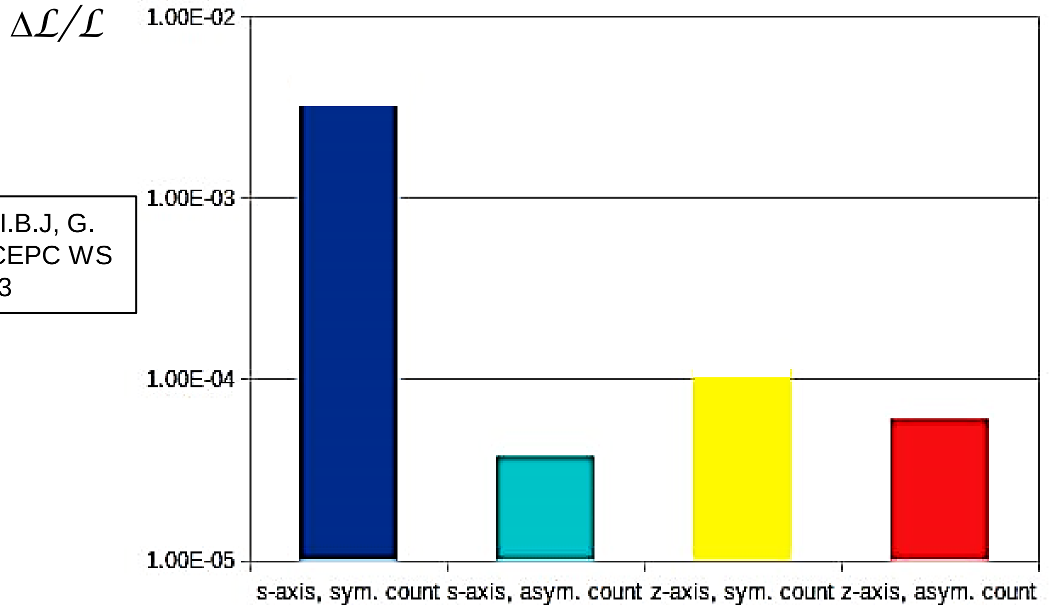
- Uncertainty of the measured efficiency of the signal identification ± 0.16 mm
- Uncertainty of the particle impact position ± 0.13 mm
- Misalignment of detector planes ± 0.08 mm
- Uncertainty due to bad channels ± 0.14 mm
- Noise uncertainty - negligible
- Calibration uncertainty of 5% for the APV read-out ± 0.14 mm

Beam-induced effects: EMD1 and EMD2

EMD1 – p_x-kick of the initial state
EMD2 – focusing of the final state

- **EMD1 quantified at CEPC**
- EMD2 – ongoing study

- As shown for other colliders (i.e. ILC and FCCee), the EMD1 effect on $\Delta\mathcal{L}/\mathcal{L}$ is reduced with asymmetric counting at s-axis
- x-angle effectively reduced for 140 μrad (δα), 70 μrad per beam
- e^+e^- system receives kick of ~5.8 MeV in x-direction, or ~2.9 MeV per particle in average
- p_x-kick is equivalent to a luminometer shift of ~60 μm along the x-axis
- **s-axis:** $\Delta\mathcal{L}/\mathcal{L} \approx 6\cdot10^{-5}$ LEP-style counting, with symmetric in FV: $\Delta\mathcal{L}/\mathcal{L} \approx 4\cdot10^{-3}$
- **z-axis: $\Delta\mathcal{L}/\mathcal{L} \leq 10^{-4}$**



I. Smiljanic, I.B.J, G. Kacarevic, CEPC WS Nanjing 2023