Integrated luminosity measurement at ILC: What can be learnt for CEPC?

I. Božović-Jelisavčić

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

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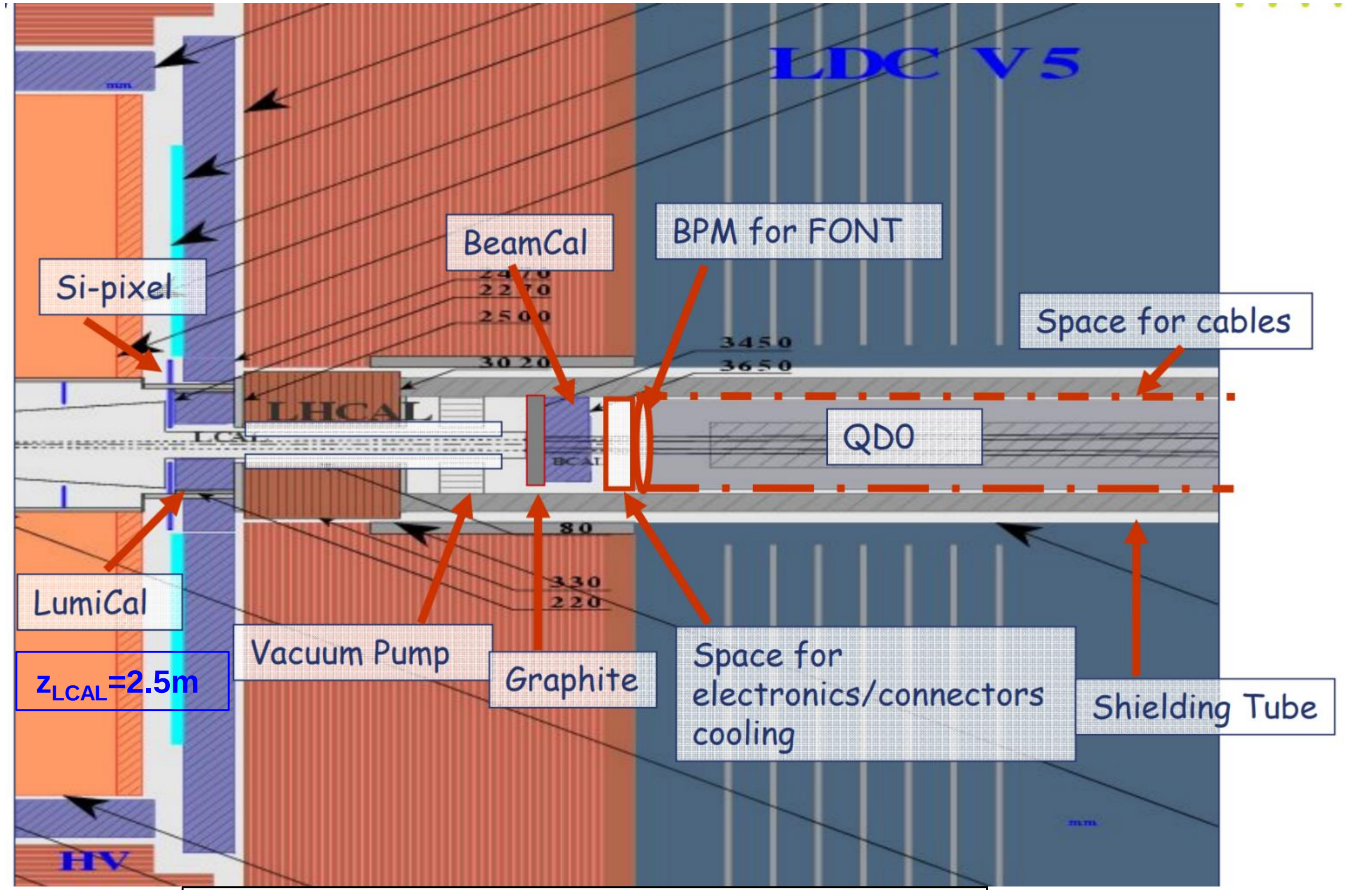
Overview

- Very forward region(s)
- Luminometer (impact on $\mathcal{L}$ measurement)
  - Design and performance
  - Metrology
- Beam-induced effects
- ECFA recommendations on $\mathcal{L}$ measurement
- Summary

Very forward region

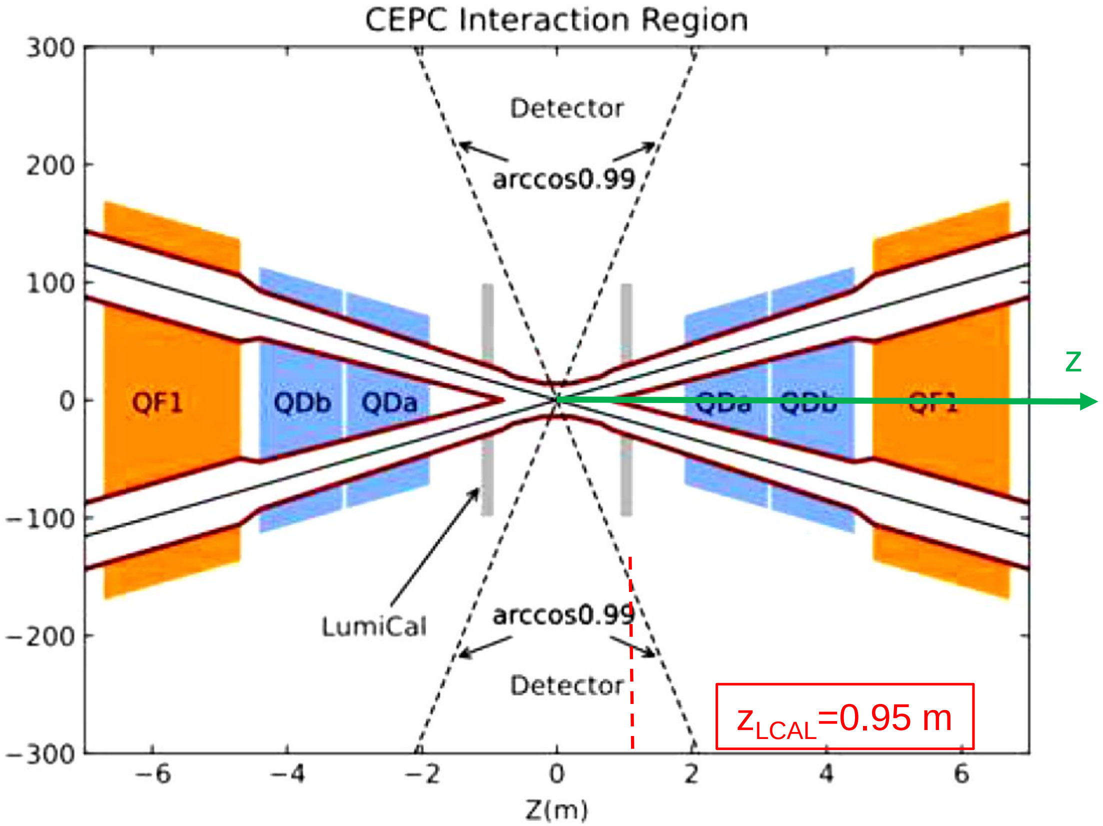


z_{LCAL}=2.5m

	Parameters	ILD
LumiCal	geometrical acceptance [mrad]	31-77
	fiducial acceptance [mrad]	41-67
	z (from IP) [mm]	2480
	number of layers (W+Si)	30

x-angle=14 mrad

The geometry of the interaction regions

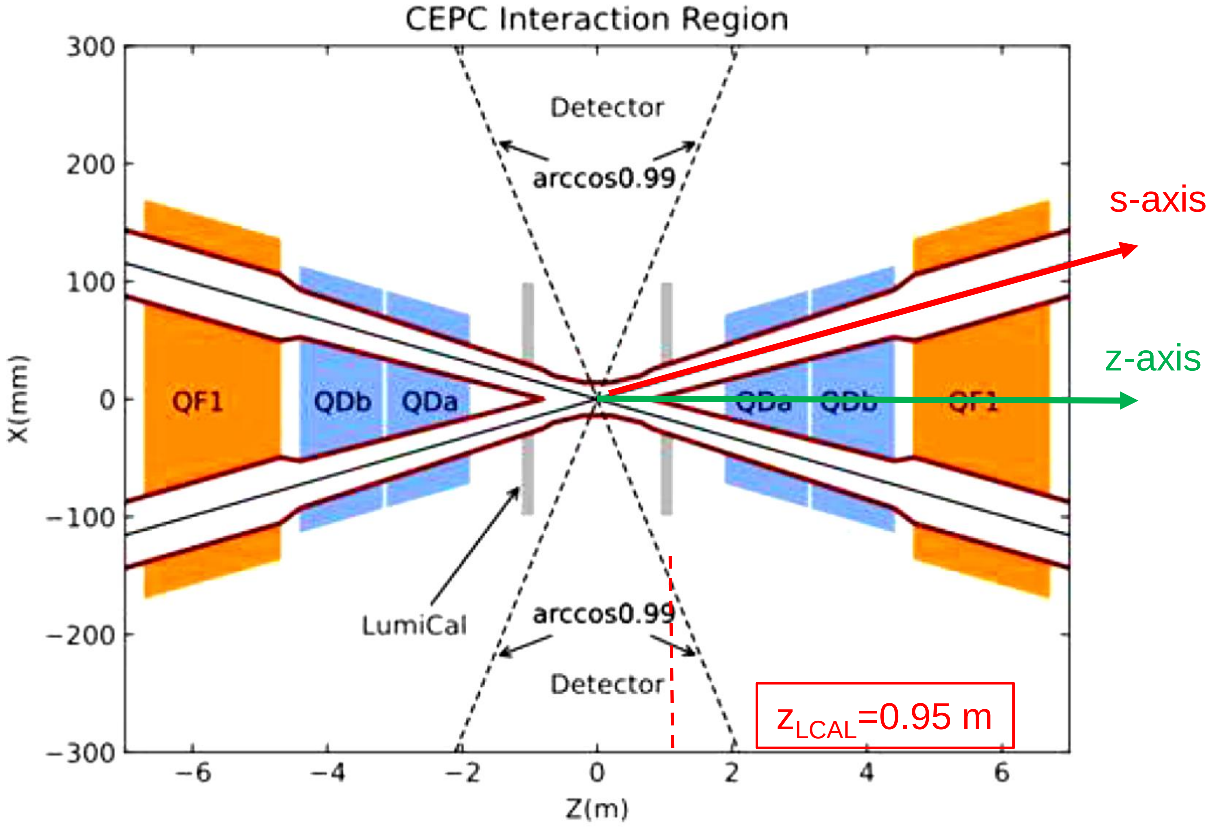


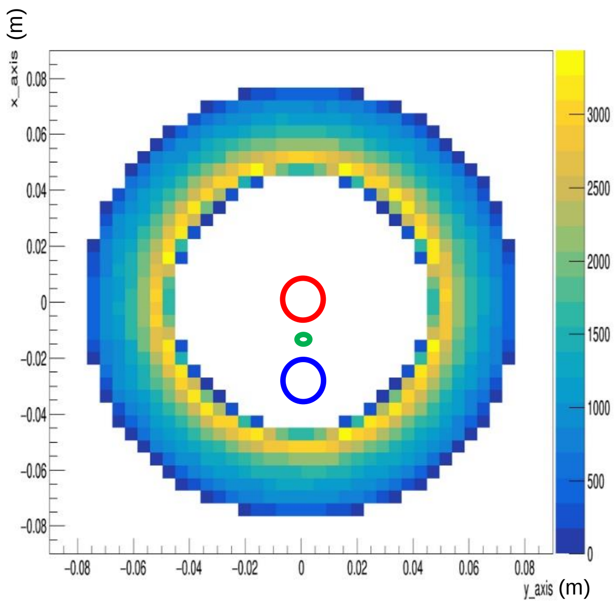
z_{LCAL}=0.95 m

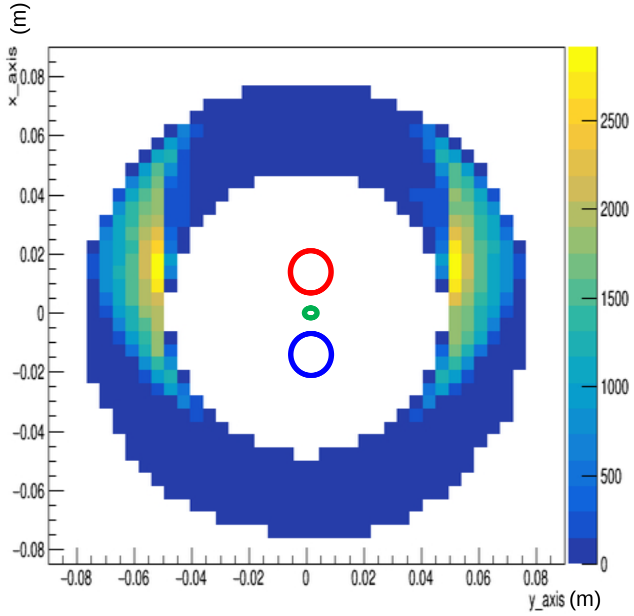
full coverage: 30-105 mrad
FV (CDR): 53-79 mrad
Z (from IP): 950 mm

x-angle= 33 mrad

Very forward region







Signal does not look the same at different axis

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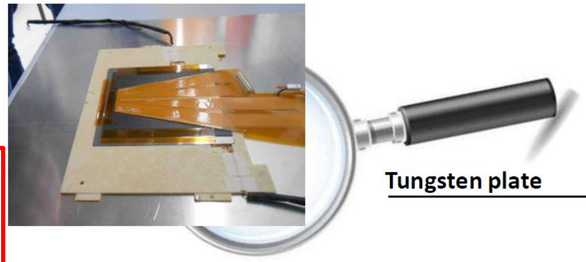
Implications on (the way) of counting

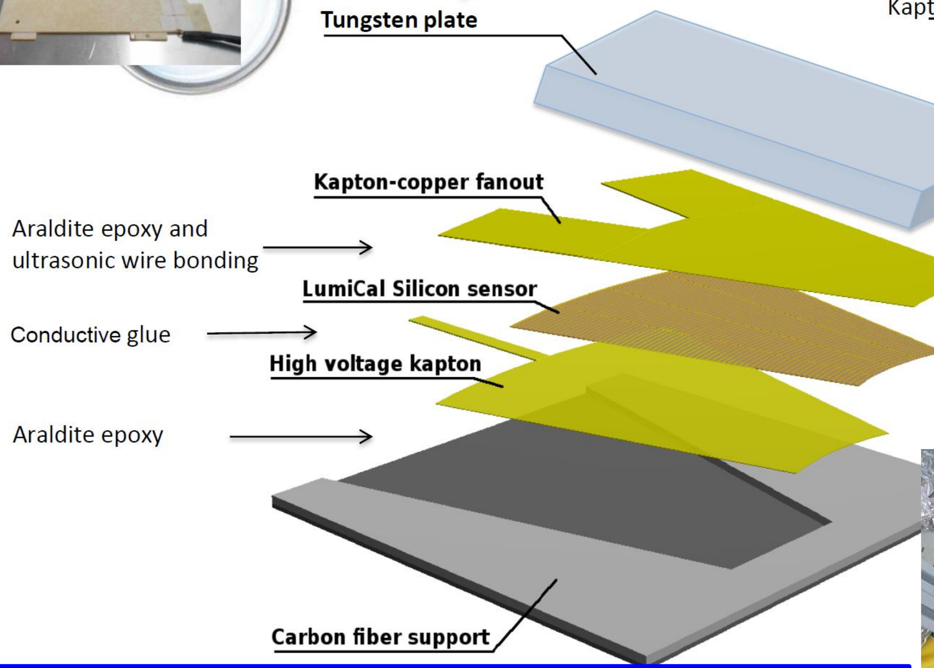
Device at ILC

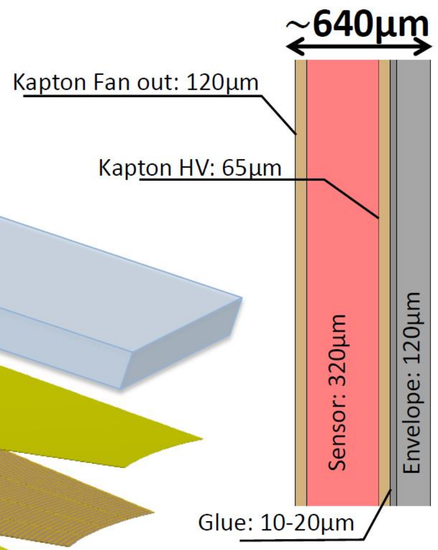
- High precision in polar angle measurement (~20 μrad)

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

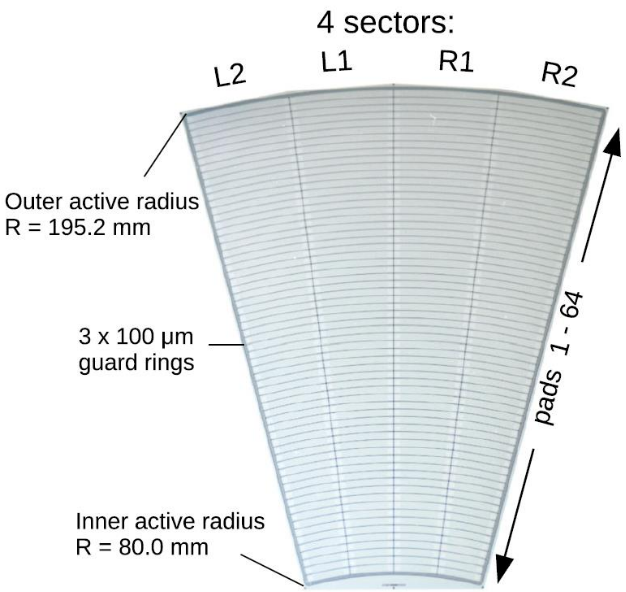
⇒ Compactness - small Moliere radius



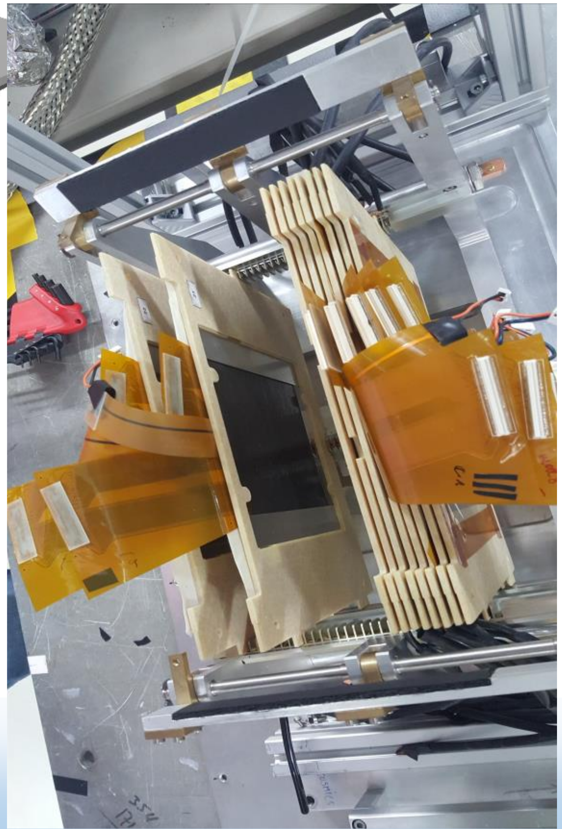




Credit: FCAL Collaboration



- 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



Impact of design and performance – shower position

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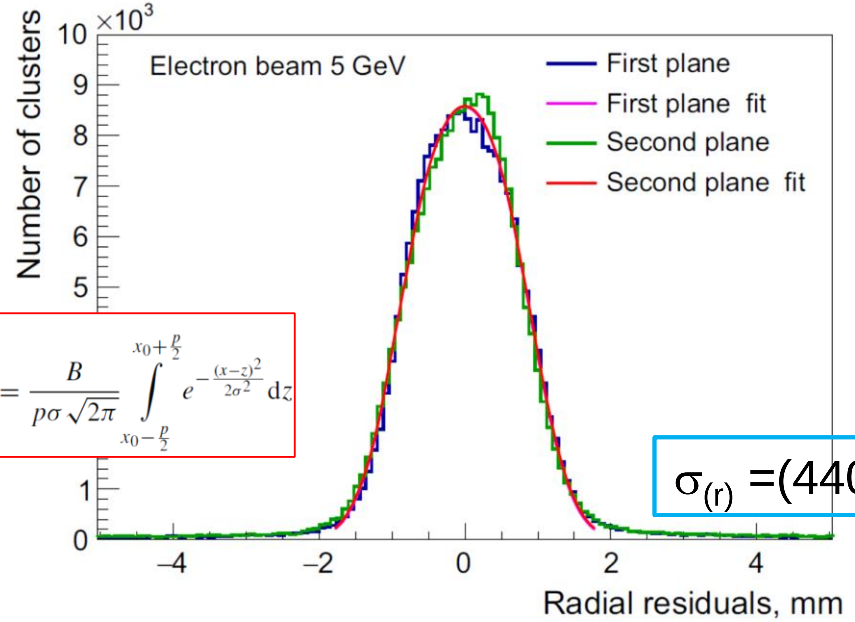
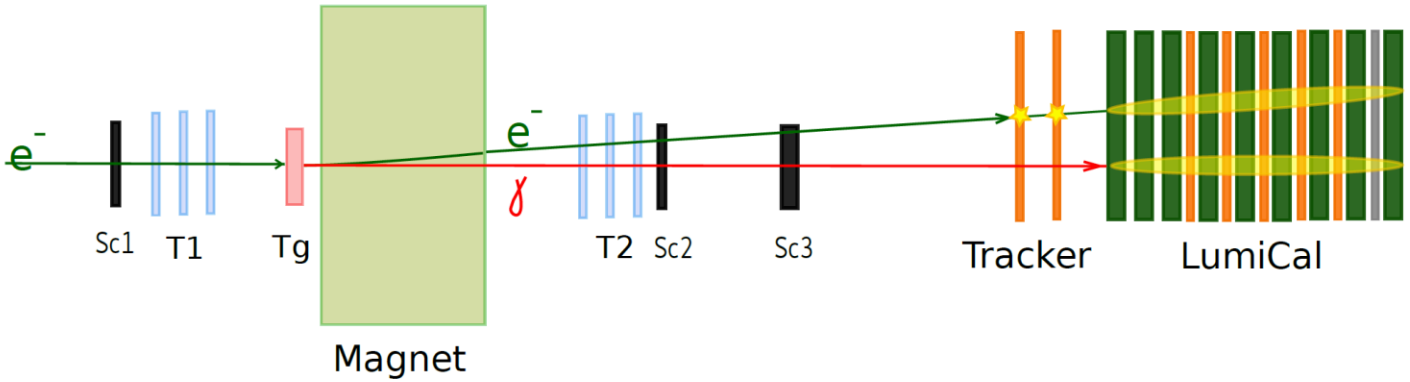


$$f(x) = \frac{B}{p\sigma\sqrt{2\pi}} \int_{x_0-\frac{p}{2}}^{x_0+\frac{p}{2}} e^{-\frac{(x-z)^2}{2\sigma^2}} \mathrm{d}z$$

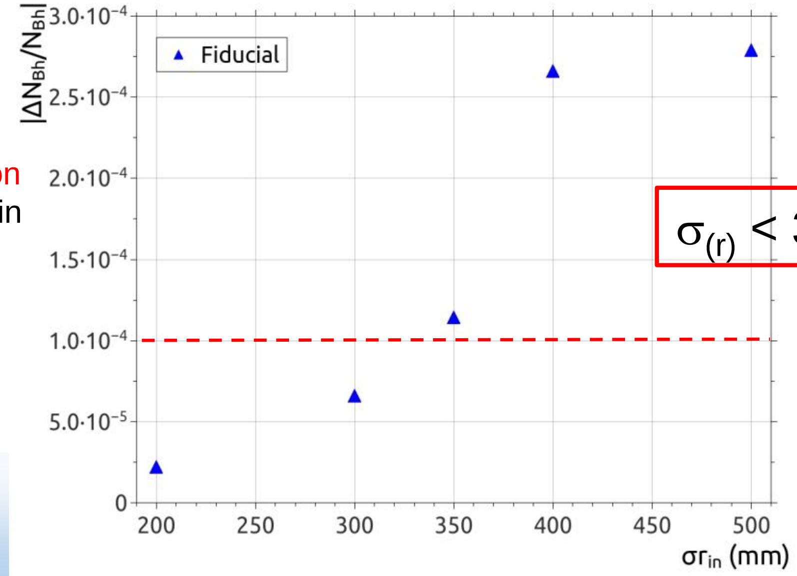
$\sigma_{(r)}$ =(440±20) μm



- 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

I. Smiljanic, I.B.J, G. Kacarevic, to be published

- CEPC simulation ~3·10^6 Bhabha in the FV
- z- axis
- symmetric counting

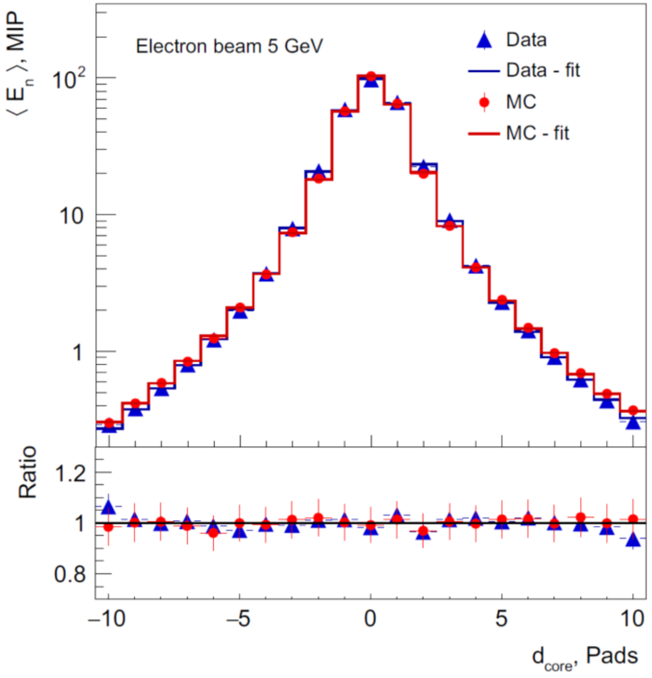


$\sigma_{(r)}$ < 350 μm

➢ **Si tracking layers :** detector σ_r < 5 μm

S. Hou, CEPC WS, Edinburgh

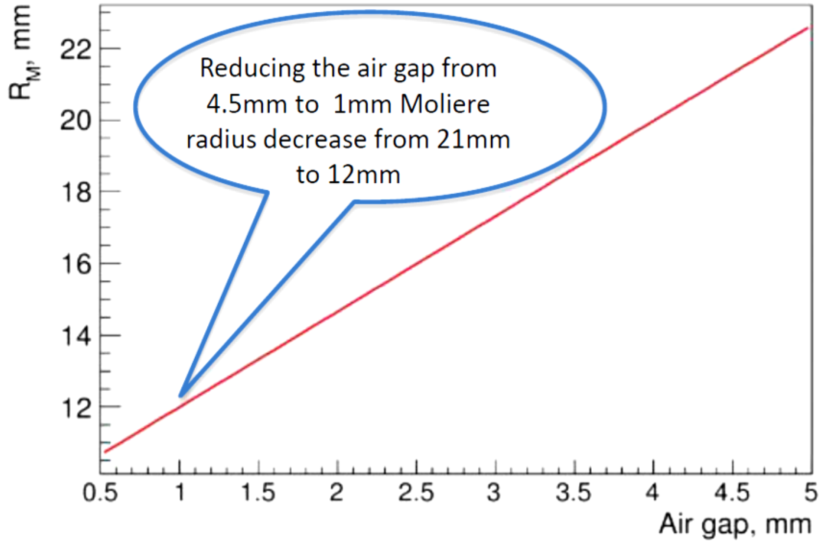
Impact of design and performance – Moliere radius



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

$$F_E(r) = A_C e^{-\left(\frac{r}{R_C}\right)^2} + A_T \frac{2r^\alpha R_T^2}{(r^2 + R_T^2)^2}$$

- Function F_E used to describe the transverse shower profile: Gaussian terms to describe shower core, Grindhammer-Peters term to describe the tail
- Very good agreement between data and Geant4 based MC



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

Demonstrated feasibility of constructing a compact calorimeter

Shower containment (R_M) also depends on the detector structure (i.e. air-gaps)

Metrology

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

ΔE - asymmetry (bias) in beam energies

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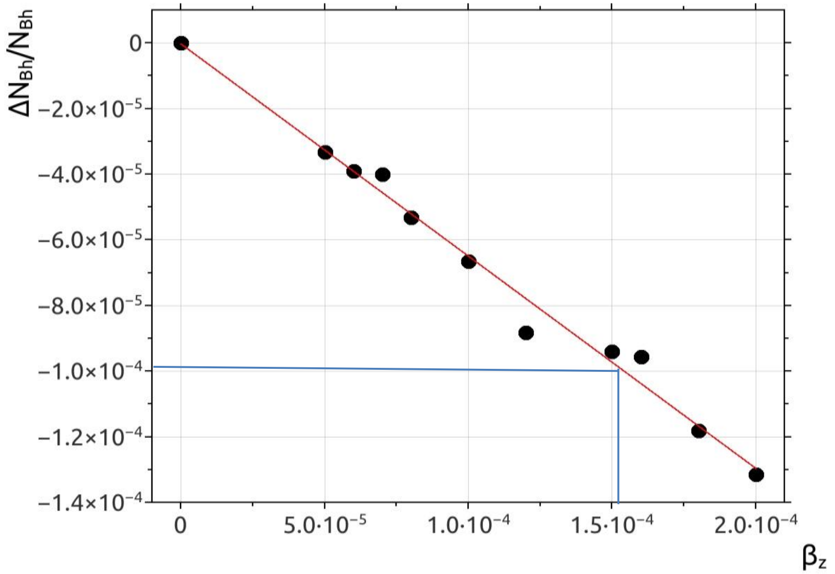
CEPC 91 GeV z-axis



$\Delta\mathcal{L}/\mathcal{L}=10^{-4} \rightarrow$ FV: $\Delta E \approx 7$ MeV

ILC 250 GeV s-axis

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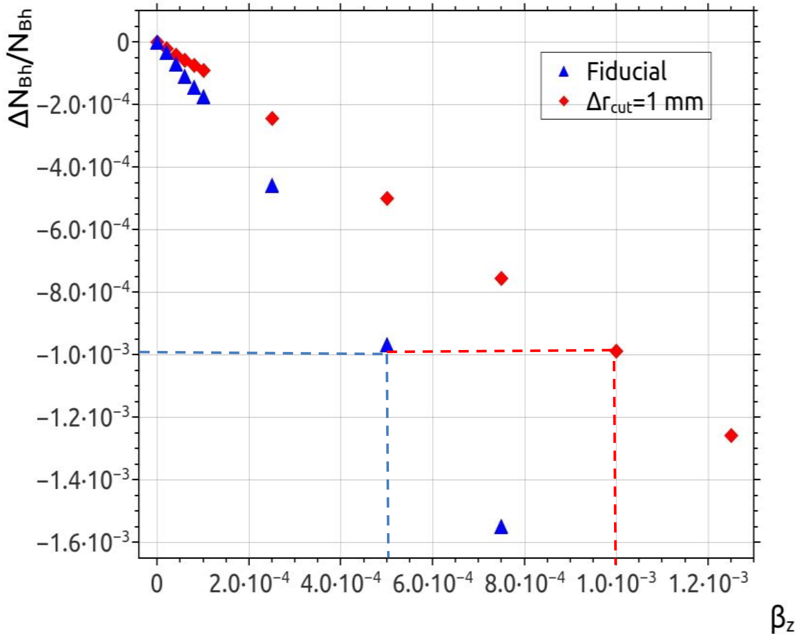

$\Delta\mathcal{L}/\mathcal{L}=10^{-3} \rightarrow$ FV: $\Delta E=75$ MeV
LEP-style: $\Delta E=125$ MeV

Metrology

- Metrology: What about the Beamspread?

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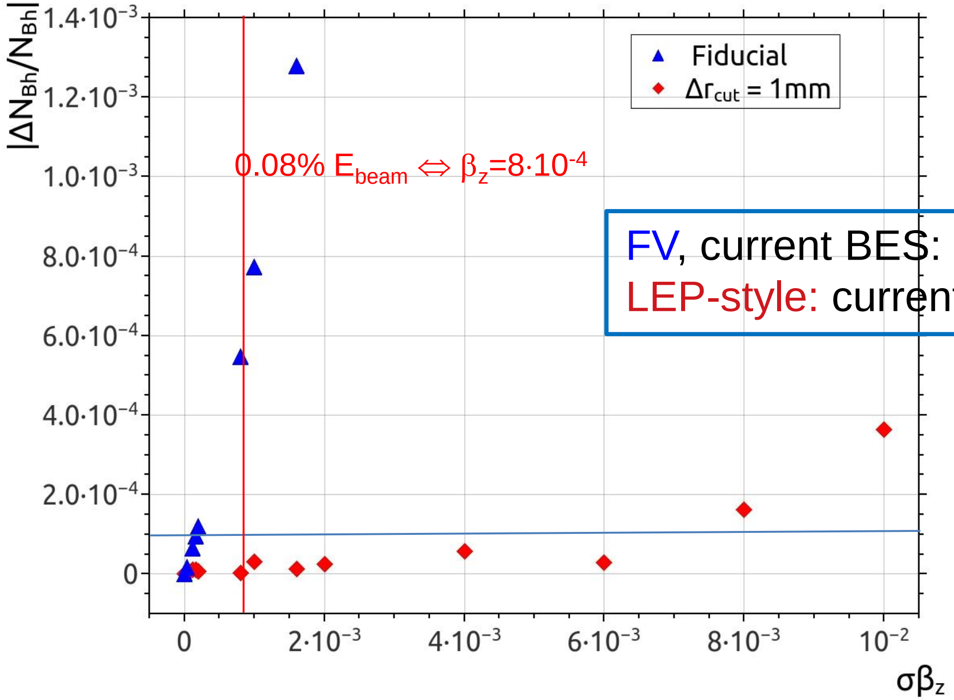
CEPC 91 GeV s-axis



FV, current BES: $\Delta\mathcal{L}/\mathcal{L} \approx 5.5 \cdot 10^{-4}$

LEP-style: current BES: $\Delta\mathcal{L}/\mathcal{L} < 5 \cdot 10^{-5}$

$\Delta\mathcal{L}/\mathcal{L} = 10^{-4} \rightarrow$ FV: $RMS_{(BES)} < 8$ MeV

LEP-style: $RMS_{(BES)} < 300$ MeV

CEPC 91 GeV z-axis

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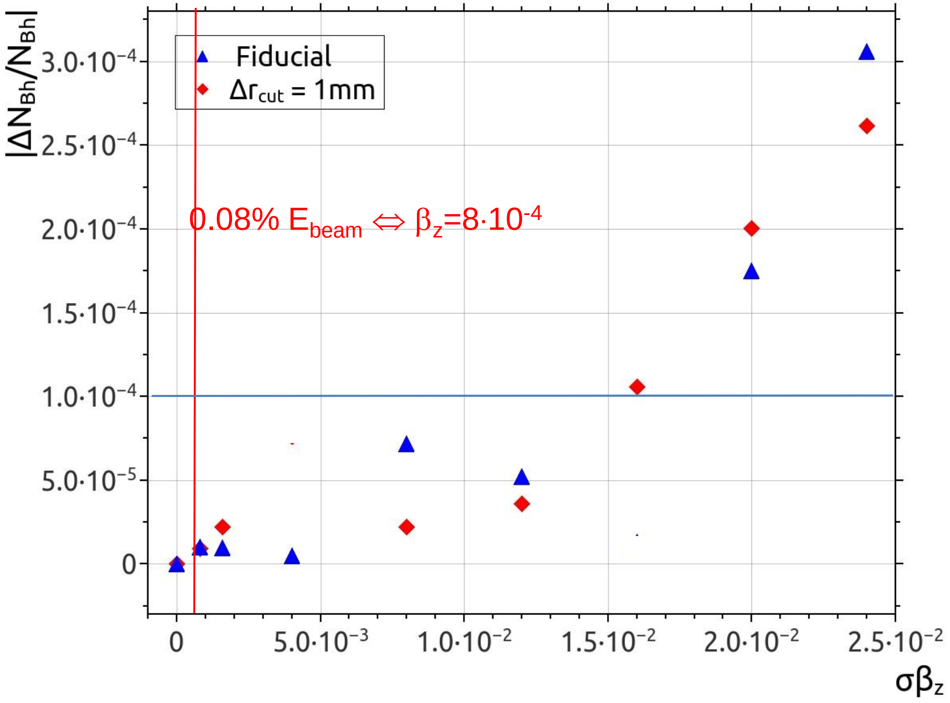

Current BES: $\Delta L/L < 3 \cdot 10^{-5}$

BES can be relaxed to ~ 600 MeV (currently 37 MeV ⇔ 0.08% E_{beam})

Metrology

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

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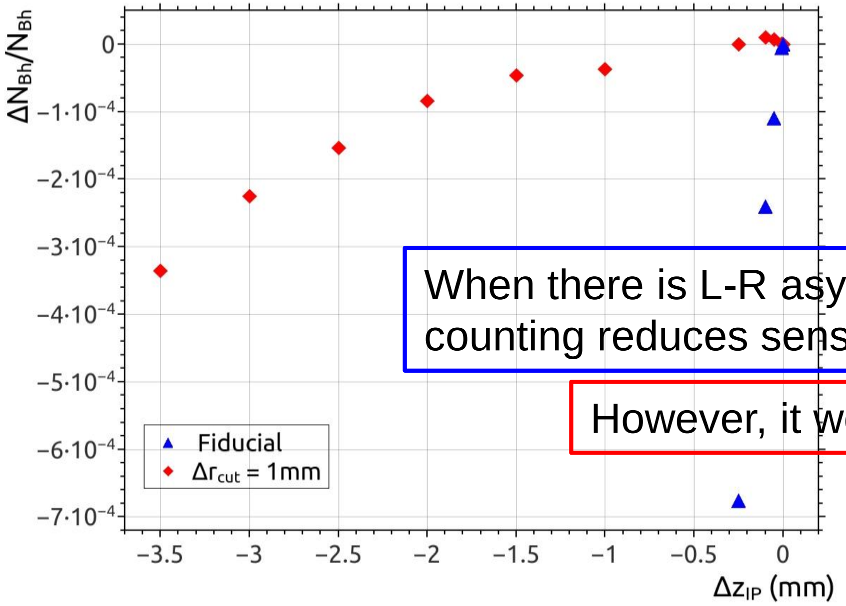
CEPC s-axis, 91 GeV



When there is L-R asymmetry, LEP-style counting reduces sensitivity

However, it works only at s-axis

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

FV: Δz_{IP}=50 µm

LEP-style: Δz_{IP}=2 mm

CEPC z-axis, 91 GeV

Δz_{IP} - axial IP position displacements with respect to the luminometer

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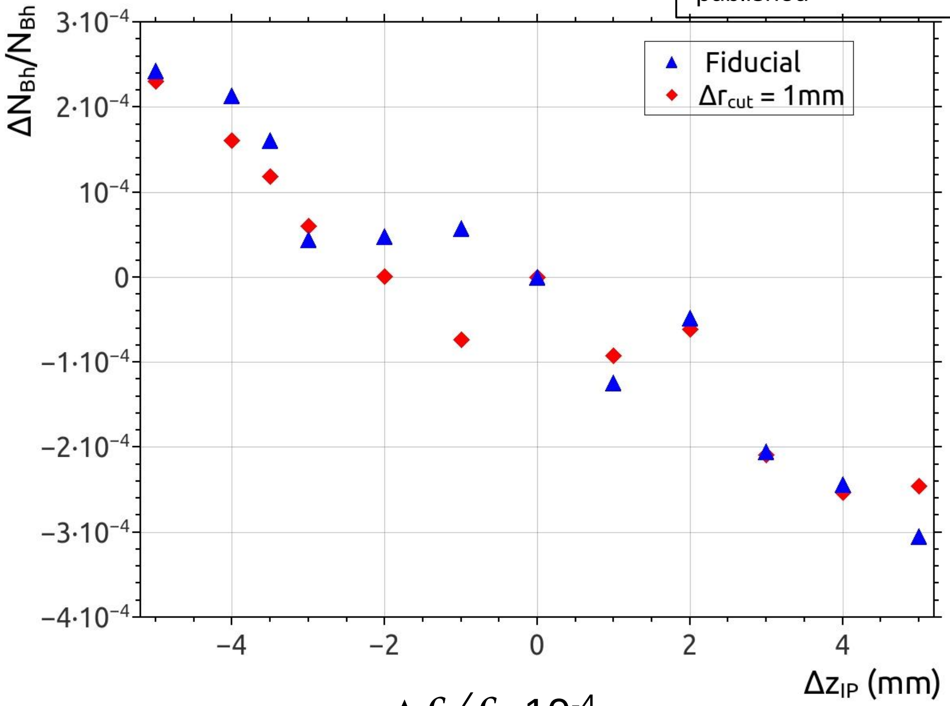


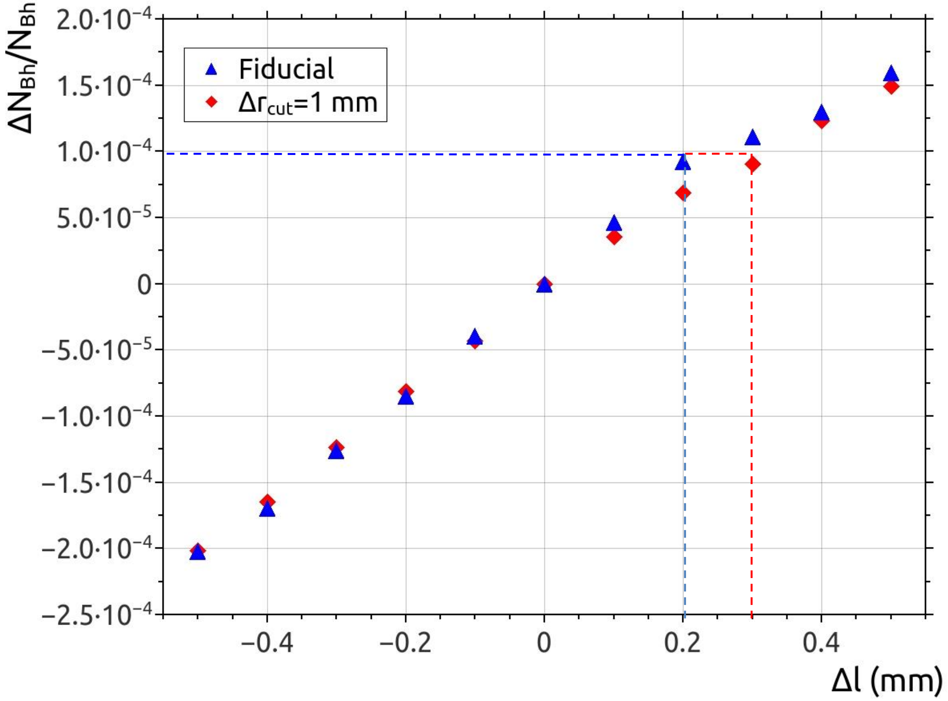
$\Delta\mathcal{L}/\mathcal{L}=10^{-4} \rightarrow$

FV≈LEP-style: Δz_{IP}<3 mm

Metrology

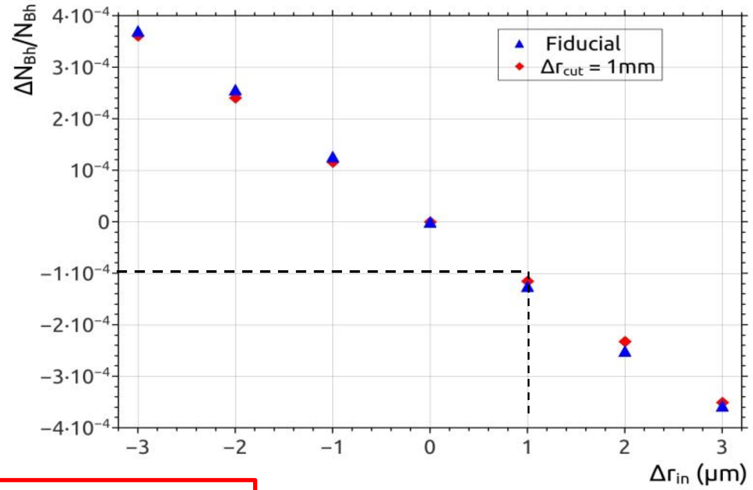
- Metrology depends on:
  - Way of counting (LEP-style, full FV)
  - LEP-style doesn't work for L-R symmetrical effects (also on the s-axis)

ILC 250 GeV



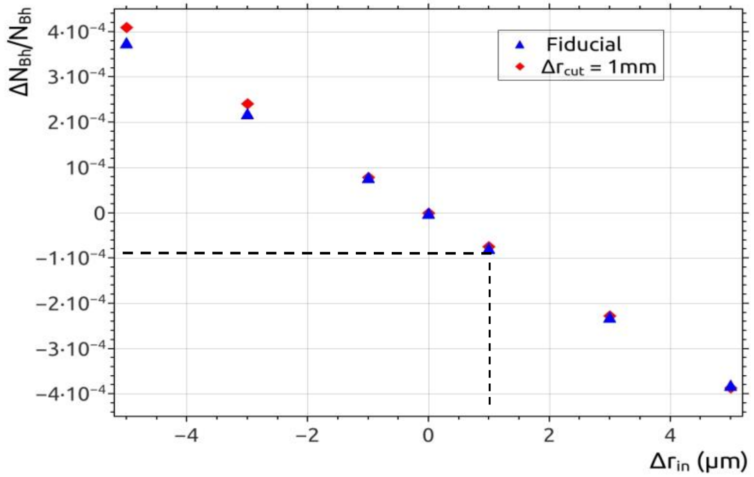
distance between luminometer halves: Δl=200-300 μm

CEPC 91 GeV, z-axis



$\Delta\mathcal{L}/\mathcal{L}=10^{-4} \rightarrow \Delta r_{in}=1\ \mu m$

CEPC 91 GeV, s-axis



I. Smiljanic, I.B.J, G. Kacarevic, to be published

Conclusion on metrology

- CEPC:
  - There has been detailed study on CEPC metrology with the detector placed at s-axis *[Ivan Smiljanic, Ivanka Bozovic Jelisavcic, Goran Kacarevic, et al., Systematic uncertainties in integrated luminosity measurement at CEPC, JINST 17 P09014, 2022]*
  - And ongoing study with luminometer at the z-axis
- ILC: Ongoing full metrology review for luminosity measurement at all ILC energies

- Luminometer positioned at s-axis offers LEP style counting reducing L-R sensitive systematics (ILC)
- However, preliminary studies indicate that precision $\mathcal{L}$ measurement at z-axis is also feasible (CEPC)

- The major challenges remain (both ILC and CEPC):
  - Inner aperture of the luminometer (1 μm)
  - Asymmetric bias in beam energies (~ 7 MeV)
  - $\Delta(\sqrt{s})$ for the cross-section calculation ($\sigma_{Bh} \sim 1/s$), ~5 MeV

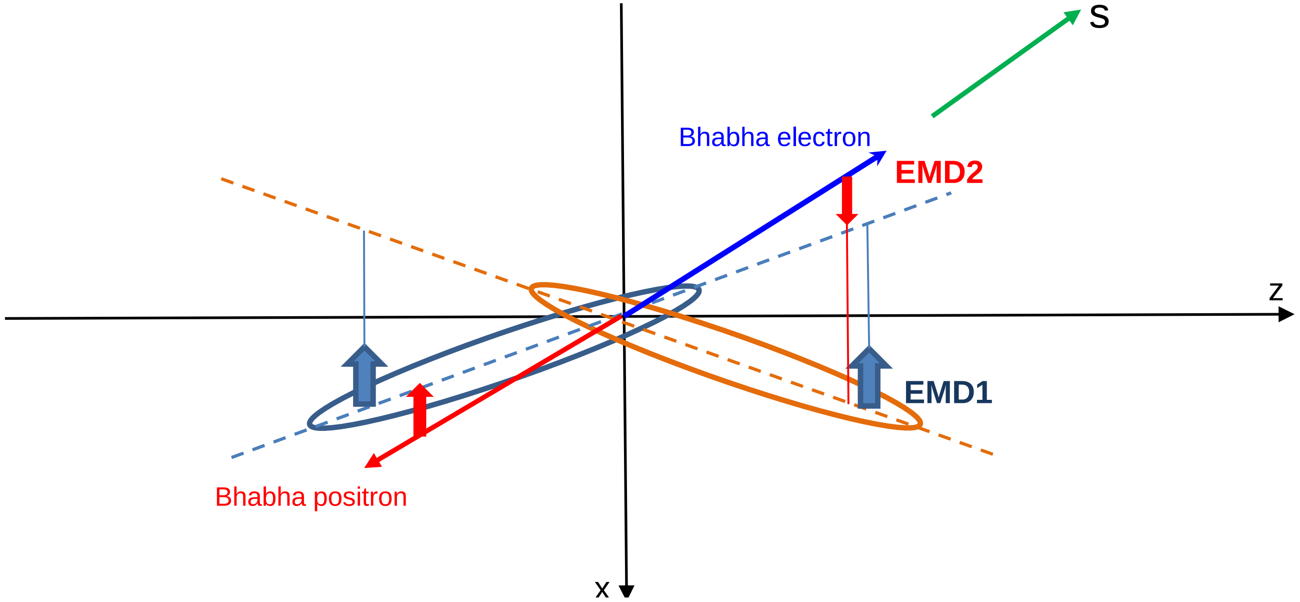
EMD1 – p_x-kick of the initial state
EMD2 – focusing of the final state

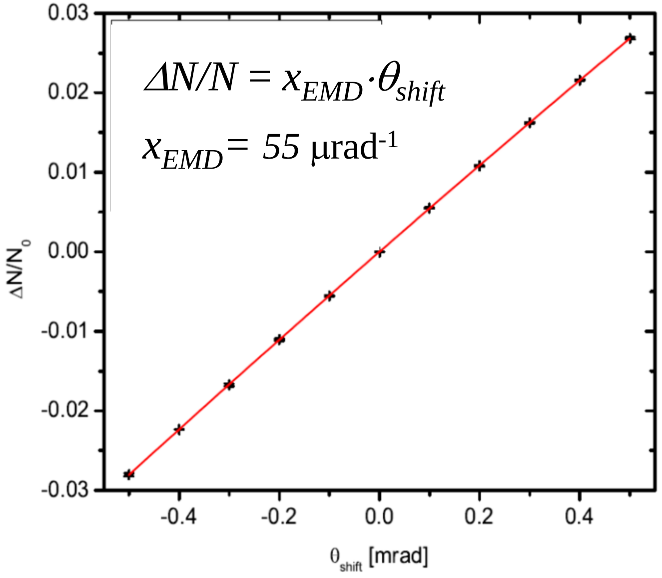
- EMD1 not quantified at ILC
- EMD2 – simulation dependent correction proposed *[IBJ et al, 2013 JINST 8 P08012, arXiv:1304.4082v3]*

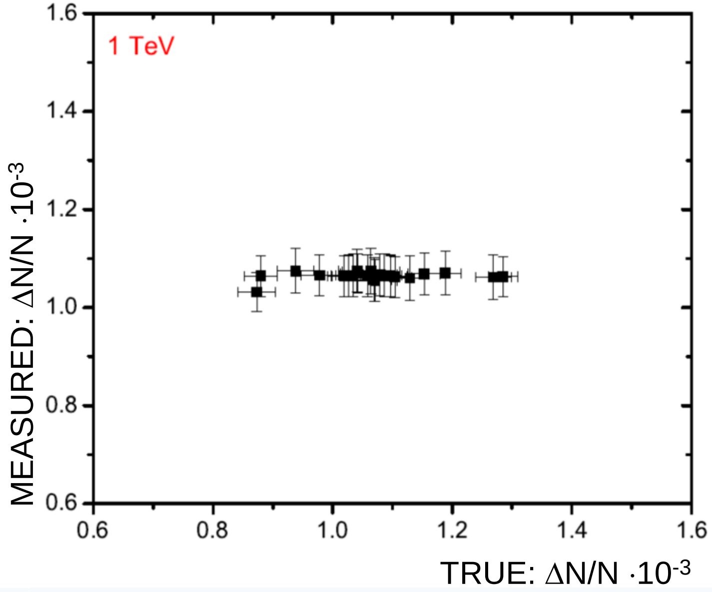
$\Delta\mathcal{L}/\mathcal{L} = x_{\mathcal{EMD}} \cdot \Delta\theta_{eff}$

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

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







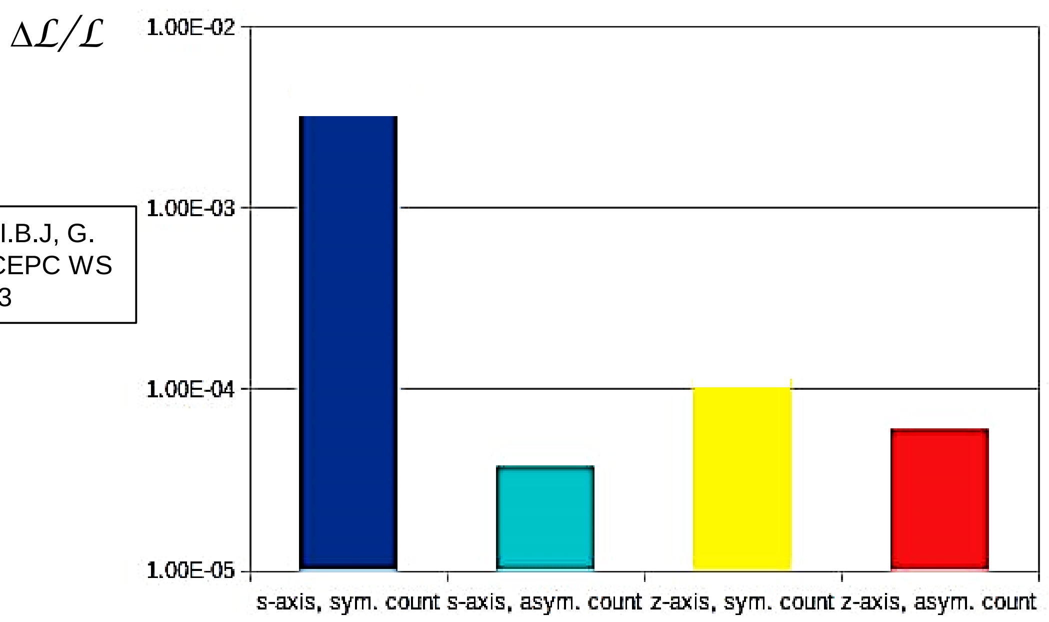
Beam-induced effects: EMD1 and EMD2

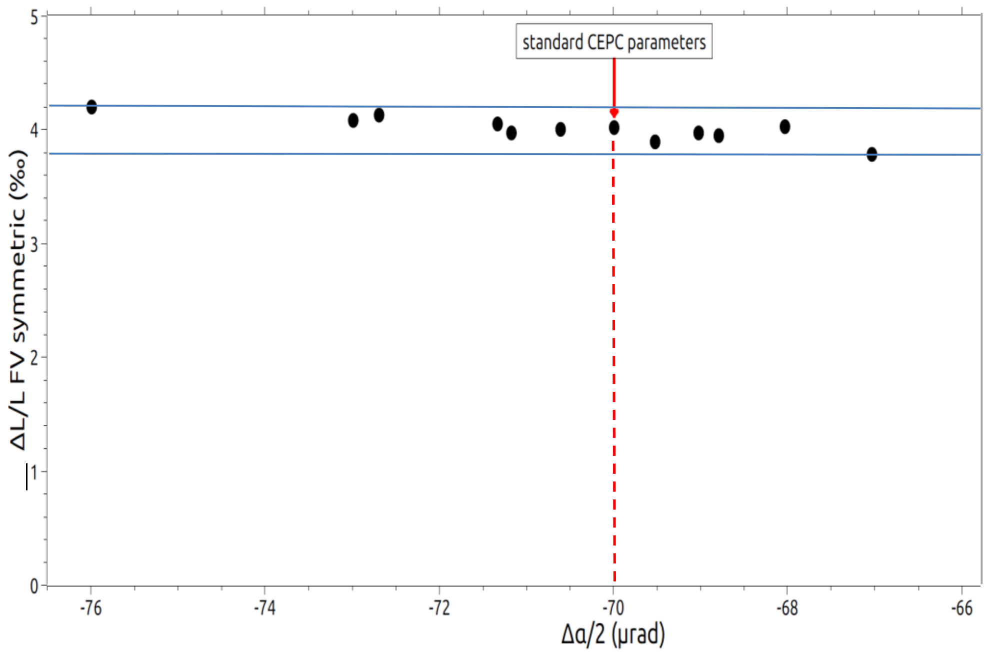
EMD1 – p_x-kick of the initial state
EMD2 – focusing of the final state

- **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





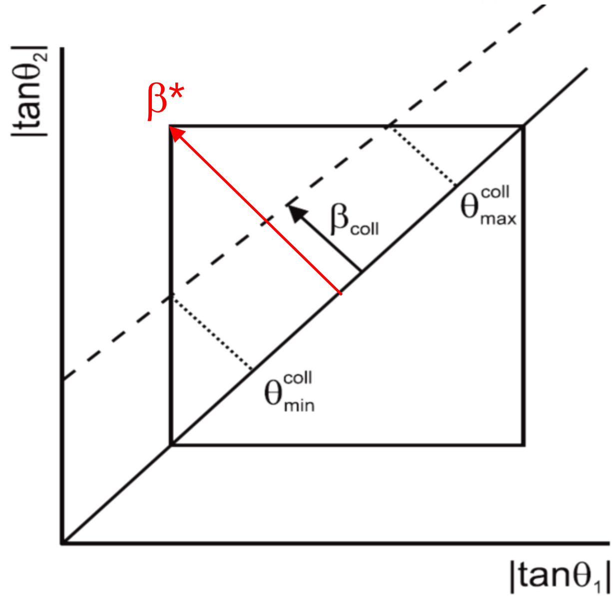
Beam-induced effects: Beamstrahlung

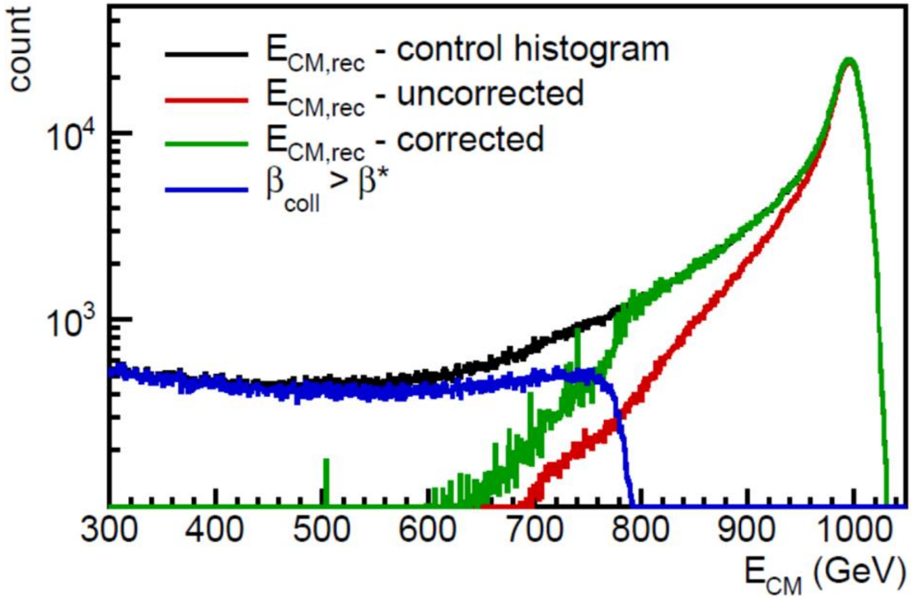
- An issue at linear machines (correction of the luminosity spectrum)
- Pronounced at high √s

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

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

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





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, arXiv:1304.4082v3

ECFA Focus Group(s) recommendations for $\mathcal{L}$ measurement

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

- Systematics for Bhabha measurement at very small angles is numerous and complex
- Main challenges comes from metrology and beam-induced effects
- Often one relies on polar angle measurement in the luminometer

⇩

Calls for alternative central process like di-photon or di-muon production

$e^+e^- \rightarrow \gamma\gamma$

- Limited statistical precision (in the central region): 10^{-5} (10 ab^{-1}, Z-pole), $4 \cdot 10^{-4}$ (5 ab^{-1}, 250 GeV)
- Bhabha as background (100 times larger cross-section, to be reduced by a factor 10^6)
- 50 μrad for the detector acceptance
- Calibration

G. Wilson, PLUG-Cal: Precision Luminosity Ultra-Granular Calo, ECFA meeting, Paestum, Italy, 2023

Summary

- ILC has a past of extensive simulation studies on integrated luminosity measurement that may provide guidelines for future Higgs factories
- FCAL R&D Collaboration has demonstrated in prototype a feasibility of the compact calorimetry for the very forward region of an e^+e^- collider
- The main difference in metrology w.r.t. CEPC comes in detector positioning (z-axis) and (consequently) the way of Bhabha counting
- Preliminary studies at CEPC indicate that no effect seems to be more critical at z-axis (than at the s-axis)
- Identified challenges from metrology: inner aperture of the luminometer (1 μm), and asymmetric bias in beam energies (~ 10 MeV), and Bhabha production cross-section calculation ($\Delta(\sqrt{s}) \sim 5$ MeV, hadronic vacuum polarization)
- Presence of numerous and complex systematics (for low-angle Bhabha measurements) at future Higgs factories calls for novel ideas both for instrumentation of the very forward region and alternatives to Bhabbha scattering
- Ongoing work both at ILC, CEPC (and FCCee) with open questions identified by the ECFA LUMI Focus Topic

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