# FCC-ee Luminosity Measurement and LumiCal

FCC-ee MDI & IR Mockup Workshop
Nov 16 – 17, 2023
Laboratori Nazionali di Frascati

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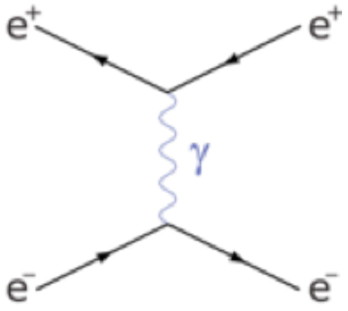
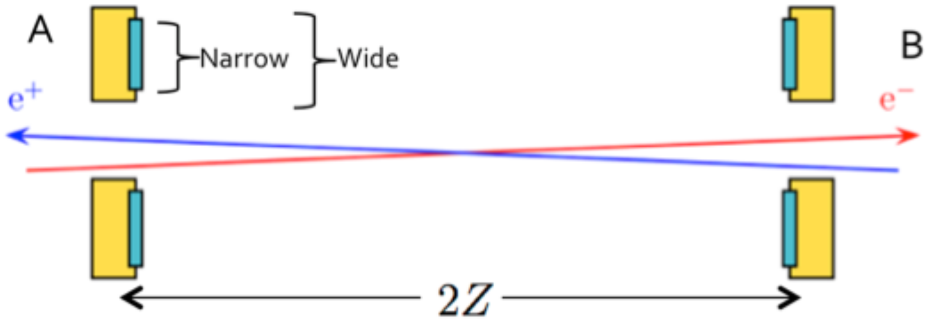
# Luminosity Measurement with Small-angle Bhabha Scattering

- Bhabha scattering = Elastic scattering $e^+e^- \rightarrow e^+e^-$
  - Dominated by *t*-channel photon exchange
  - Very strongly forward peaked

$$\boxed{\sigma^{\text{Bhabha}} = \frac{1040\ \text{nb GeV}^2}{s}\left(\frac{1}{\theta^2_{\text{min}}} - \frac{1}{\theta^2_{\text{max}}}\right)}$$



- Measured with set of two calorimeters; one at each side of the IP
  - Crossing beams: *Center monitors around outgoing beam lines*



**Two counting rates :**
**- SideA = NarrowA + WideB**
**- SideB = NarrowB + WideA**

  - Minimize dependence on beam parameters and misalignment:
    - ***Restricted acceptance***: Average over two counting rates: **Rate = ½ × (SideA + SideB)**
- Important systematics from acceptance definition: *In particular minimum scattering angle*

$$\boxed{\frac{\delta\sigma^{\text{acc}}}{\sigma^{\text{acc}}} \simeq \frac{2\delta\theta_{\text{min}}}{\theta_{\text{min}}} = 2\left(\frac{\delta R_{\text{min}}}{R_{\text{min}}} \oplus \frac{\delta z}{z}\right)}$$

# Normalisation to $10^{-4}$

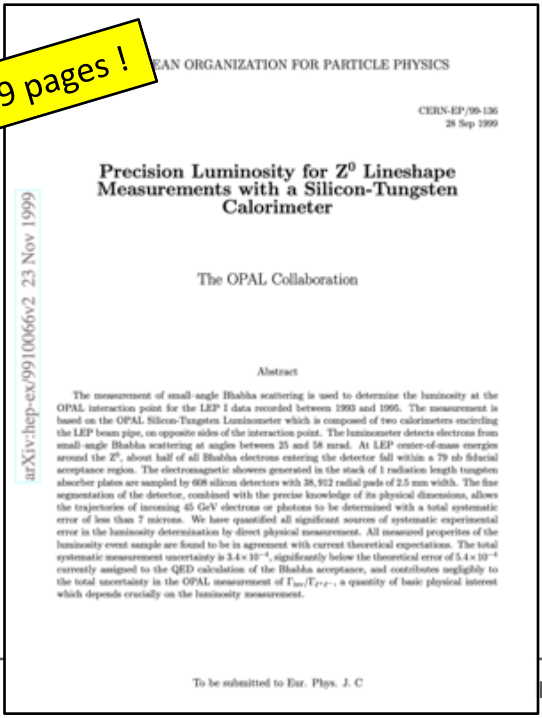
- The goal at FCC-ee is an **absolute normalization to $10^{-4}$**
- After much effort, the precision on the absolute luminosity at LEP was eventually dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

**Theory: $5.4 \times 10^{-4}$** **Experiment: $3.4 \times 10^{-4}$** arXiv:9910066

- Theory precision
  - Since LEP, theory precision has improved to **$3.7 \times 10^{-4}$** arXiv:1912.02067
  - And a path is outlined to reach **$10^{-4}$** arXiv:1902.05912
- Instrumental precision – major effort to go to sub-permille level

OPAL is **the** reference

89 pages !


EAN ORGANIZATION FOR PARTICLE PHYSICS

CERN-EP/99-136
28 Sep 1999

**Precision Luminosity for $Z^0$ Lineshape Measurements with a Silicon-Tungsten Calorimeter**

The OPAL Collaboration

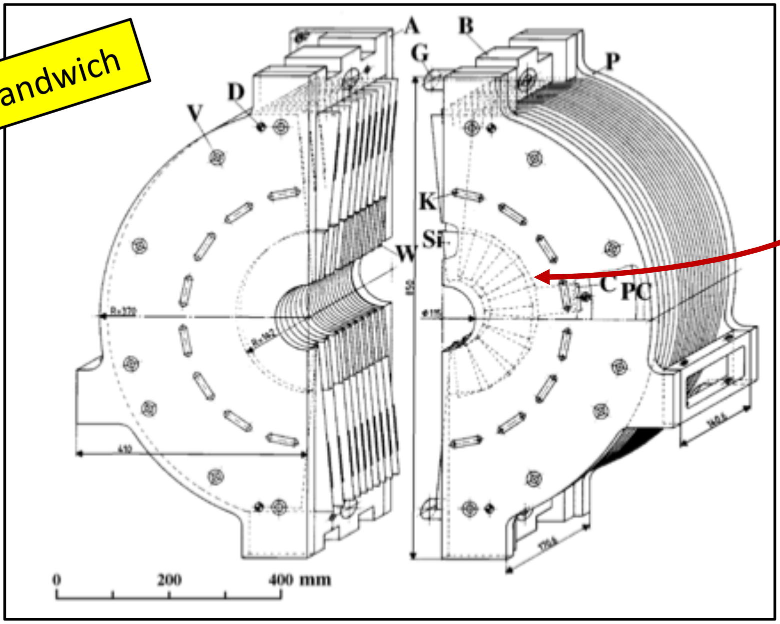
arXiv:hep-ex/9910066v2 23 Nov 1999

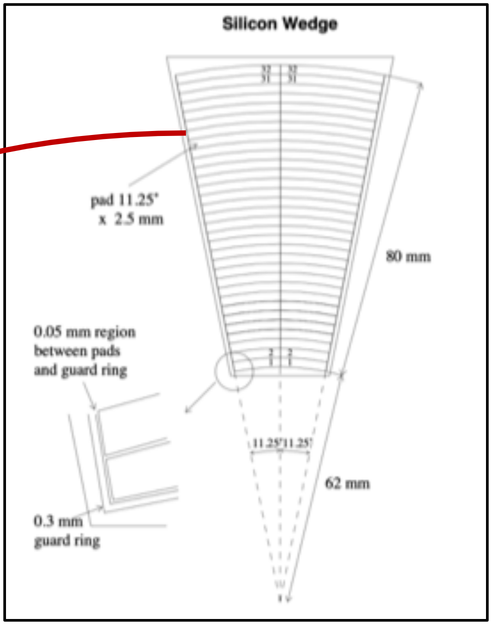
Abstract

The measurement of small-angle Bhabha scattering is used to determine the luminosity at the OPAL interaction point for the LEP I data recorded between 1993 and 1995. The measurement is based on the OPAL Silicon-Tungsten Luminometer which is composed of two calorimeters encircling the LEP beam pipe, on opposite sides of the interaction point. The luminometer detects electrons from small-angle Bhabha scattering at angles between 25 and 58 mrad. At LEP center-of-mass energies around the $Z^0$, about half of all Bhabha electrons entering the detector fall within a 79 nb fiducial acceptance region. The electromagnetic showers generated in the stack of 1 radiation length tungsten absorber plates are sampled by 608 silicon detectors with 38,912 radial pads of 2.5 mm width. The fine segmentation of the detector, combined with the precise knowledge of its physical dimensions, allows the trajectories of incoming 45 GeV electrons or photons to be determined with a total systematic error of less than 7 microns. We have quantified all significant sources of systematic experimental error in the luminosity determination by direct physical measurement. All measured properties of the luminosity event sample are found to be in agreement with current theoretical expectations. The total systematic measurement uncertainty is $3.4 \times 10^{-4}$, significantly below the theoretical error of $5.4 \times 10^{-4}$ currently assigned to the QED calculation of the Bhabha acceptance, and contributes negligibly to the total uncertainty in the OPAL measurement of $\Gamma_{inv}/\Gamma_{\ell^+\ell^-}$, a quantity of basic physical interest which depends crucially on the luminosity measurement.

To be submitted to Eur. Phys. J. C

SiW sandwich



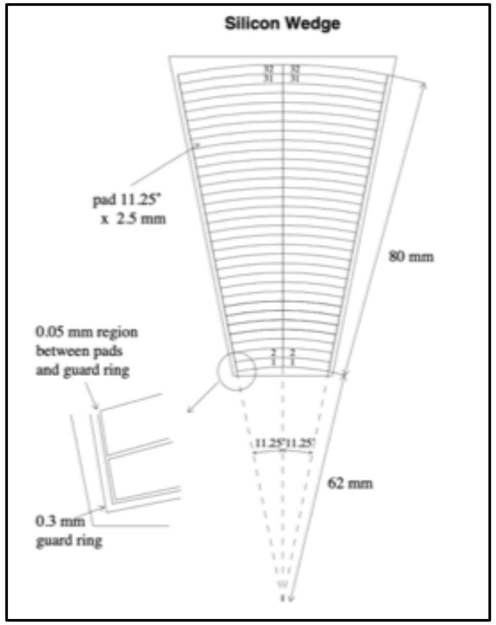


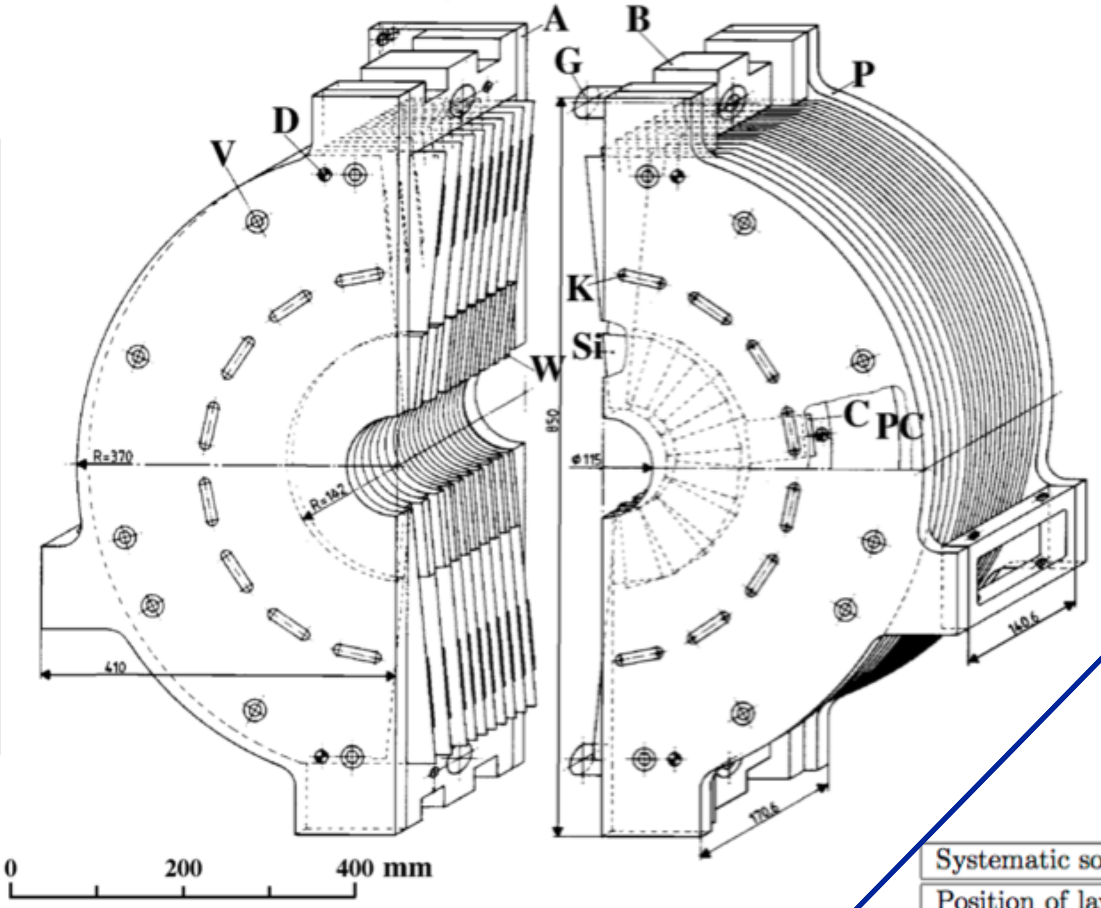
Via precise metrology, achieved 4.4 µm precision on inner acceptance border

# OPAL SiW LumiCal

**Z = 250 cm**

**Sensitive depth: 140 mm / 22 $X_0$ ; 19 Si layers**

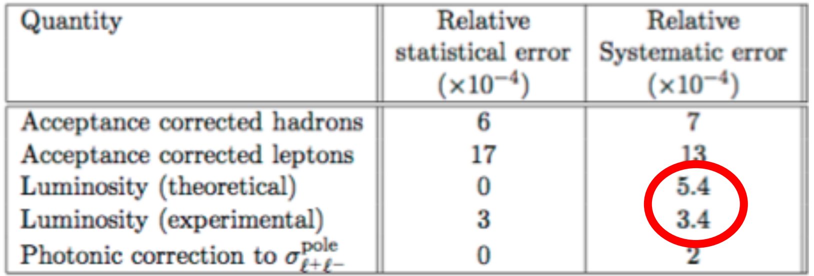




**Detector outer radius: 370 mm**
**Sensitive region up to: 142 mm**

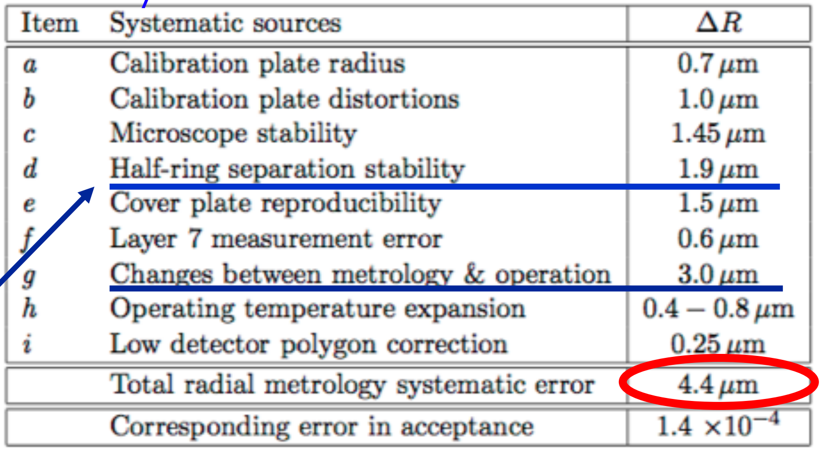
Clam shell opening around beam pipe

## Achieved lumi uncertainty



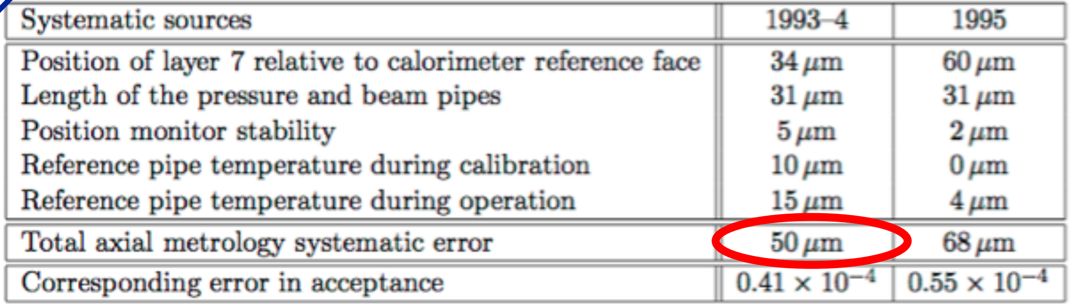
| Quantity | Relative statistical error ($\times 10^{-4}$) | Relative Systematic error ($\times 10^{-4}$) |
|---|---|---|
| Acceptance corrected hadrons | 6 | 7 |
| Acceptance corrected leptons | 17 | 13 |
| Luminosity (theoretical) | 0 | 5.4 |
| Luminosity (experimental) | 3 | 3.4 |
| Photonic correction to $\sigma^{\text{pole}}_{\ell^+\ell^-}$ | 0 | 2 |

## Systematics on radius measurement



| Item | Systematic sources | $\Delta R$ |
|---|---|---|
| *a* | Calibration plate radius | 0.7 $\mu$m |
| *b* | Calibration plate distortions | 1.0 $\mu$m |
| *c* | Microscope stability | 1.45 $\mu$m |
| *d* | Half-ring separation stability | 1.9 $\mu$m |
| *e* | Cover plate reproducibility | 1.5 $\mu$m |
| *f* | Layer 7 measurement error | 0.6 $\mu$m |
| *g* | Changes between metrology & operation | 3.0 $\mu$m |
| *h* | Operating temperature expansion | 0.4 – 0.8 $\mu$m |
| *i* | Low detector polygon correction | 0.25 $\mu$m |
| | Total radial metrology systematic error | 4.4 $\mu$m |
| | Corresponding error in acceptance | 1.4 $\times 10^{-4}$ |

## Systematics on z measurement



| Systematic sources | 1993–4 | 1995 |
|---|---|---|
| Position of layer 7 relative to calorimeter reference face | 34 $\mu$m | 60 $\mu$m |
| Length of the pressure and beam pipes | 31 $\mu$m | 31 $\mu$m |
| Position monitor stability | 5 $\mu$m | 2 $\mu$m |
| Reference pipe temperature during calibration | 10 $\mu$m | 0 $\mu$m |
| Reference pipe temperature during operation | 15 $\mu$m | 4 $\mu$m |
| Total axial metrology systematic error | 50 $\mu$m | 68 $\mu$m |
| Corresponding error in acceptance | $0.41 \times 10^{-4}$ | $0.55 \times 10^{-4}$ |

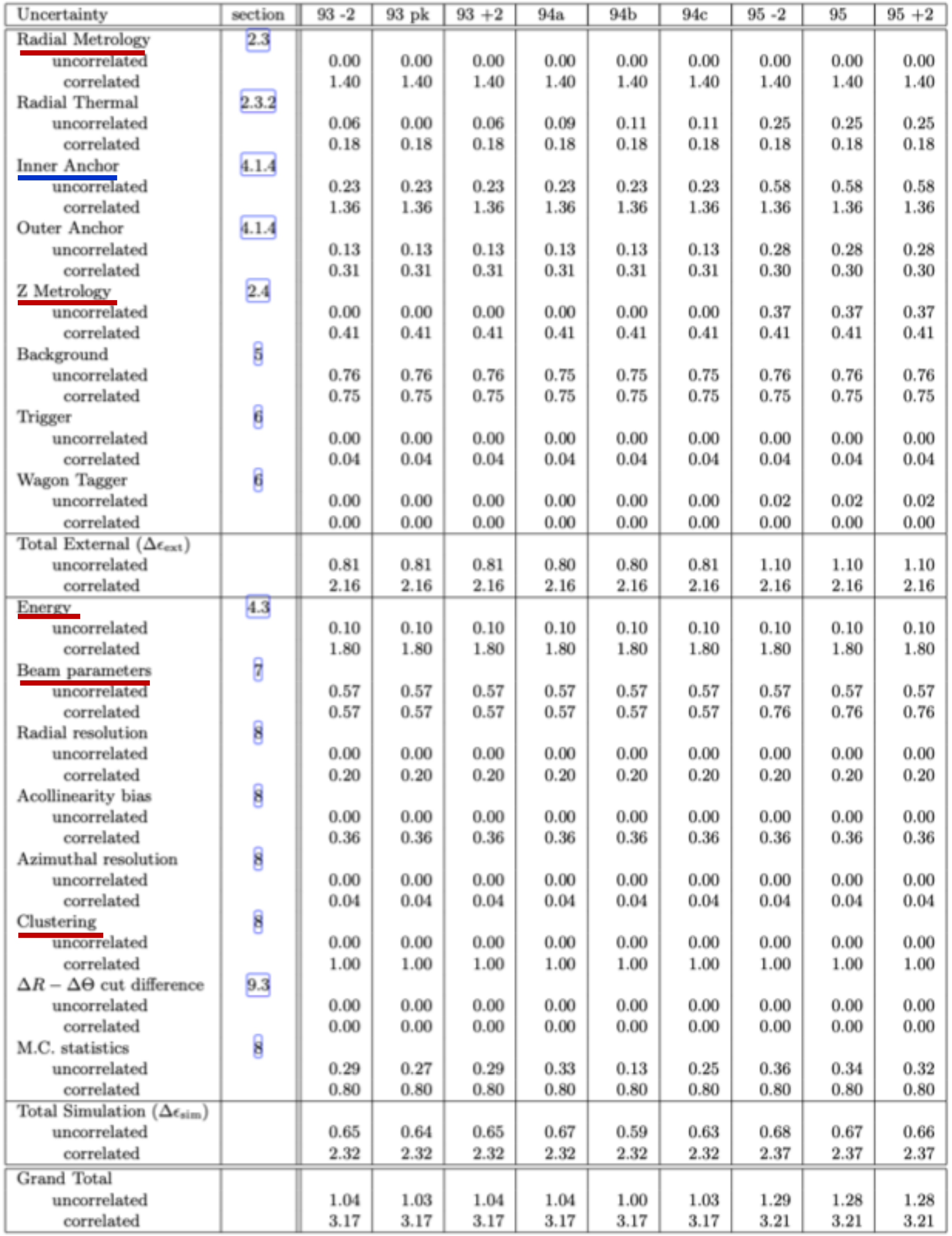
# OPAL Breakdown of Systematics

× $10^{-4}$

Table 24: This table summarizes the experimental systematic uncertainties on the absolute $L_{RL}$ luminosity measurement for the nine data samples. The lines labeled correlated and uncorrelated refer to errors correlated and uncorrelated among the samples. All errors are in units of $10^{-4}$.

*"external"*

*"simulation"*



| Uncertainty | section | 93 -2 | 93 pk | 93 +2 | 94a | 94b | 94c | 95 -2 | 95 | 95 +2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Radial Metrology | 2.3 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 |
| Radial Thermal | 2.3.2 | | | | | | | | | |
| uncorrelated | | 0.06 | 0.00 | 0.06 | 0.09 | 0.11 | 0.11 | 0.25 | 0.25 | 0.25 |
| correlated | | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| Inner Anchor | 4.1.4 | | | | | | | | | |
| uncorrelated | | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.58 | 0.58 | 0.58 |
| correlated | | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 |
| Outer Anchor | 4.1.4 | | | | | | | | | |
| uncorrelated | | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.28 | 0.28 | 0.28 |
| correlated | | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 | 0.30 | 0.30 | 0.30 |
| Z Metrology | 2.4 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.37 | 0.37 | 0.37 |
| correlated | | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| Background | 5 | | | | | | | | | |
| uncorrelated | | 0.76 | 0.76 | 0.76 | 0.75 | 0.75 | 0.75 | 0.76 | 0.76 | 0.76 |
| correlated | | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| Trigger | 6 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Wagon Tagger | 6 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 |
| correlated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total External ($\Delta\epsilon_{\text{ext}}$) | | | | | | | | | | |
| uncorrelated | | 0.81 | 0.81 | 0.81 | 0.80 | 0.80 | 0.81 | 1.10 | 1.10 | 1.10 |
| correlated | | 2.16 | 2.16 | 2.16 | 2.16 | 2.16 | 2.16 | 2.16 | 2.16 | 2.16 |
| Energy | 4.3 | | | | | | | | | |
| uncorrelated | | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| correlated | | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 |
| Beam parameters | 7 | | | | | | | | | |
| uncorrelated | | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 |
| correlated | | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.76 | 0.76 | 0.76 |
| Radial resolution | 8 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Acollinearity bias | 8 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Azimuthal resolution | 8 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Clustering | 8 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $\Delta R - \Delta\Theta$ cut difference | 9.3 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| M.C. statistics | 8 | | | | | | | | | |
| uncorrelated | | 0.29 | 0.27 | 0.29 | 0.33 | 0.13 | 0.25 | 0.36 | 0.34 | 0.32 |
| correlated | | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Total Simulation ($\Delta\epsilon_{\text{sim}}$) | | | | | | | | | | |
| uncorrelated | | 0.65 | 0.64 | 0.65 | 0.67 | 0.59 | 0.63 | 0.68 | 0.67 | 0.66 |
| correlated | | 2.32 | 2.32 | 2.32 | 2.32 | 2.32 | 2.32 | 2.37 | 2.37 | 2.37 |
| Grand Total | | | | | | | | | | |
| uncorrelated | | 1.04 | 1.03 | 1.04 | 1.04 | 1.00 | 1.03 | 1.29 | 1.28 | 1.28 |
| correlated | | 3.17 | 3.17 | 3.17 | 3.17 | 3.17 | 3.17 | 3.21 | 3.21 | 3.21 |

Radial Metrology : 1.4

"Inner Anchor" : 1.4

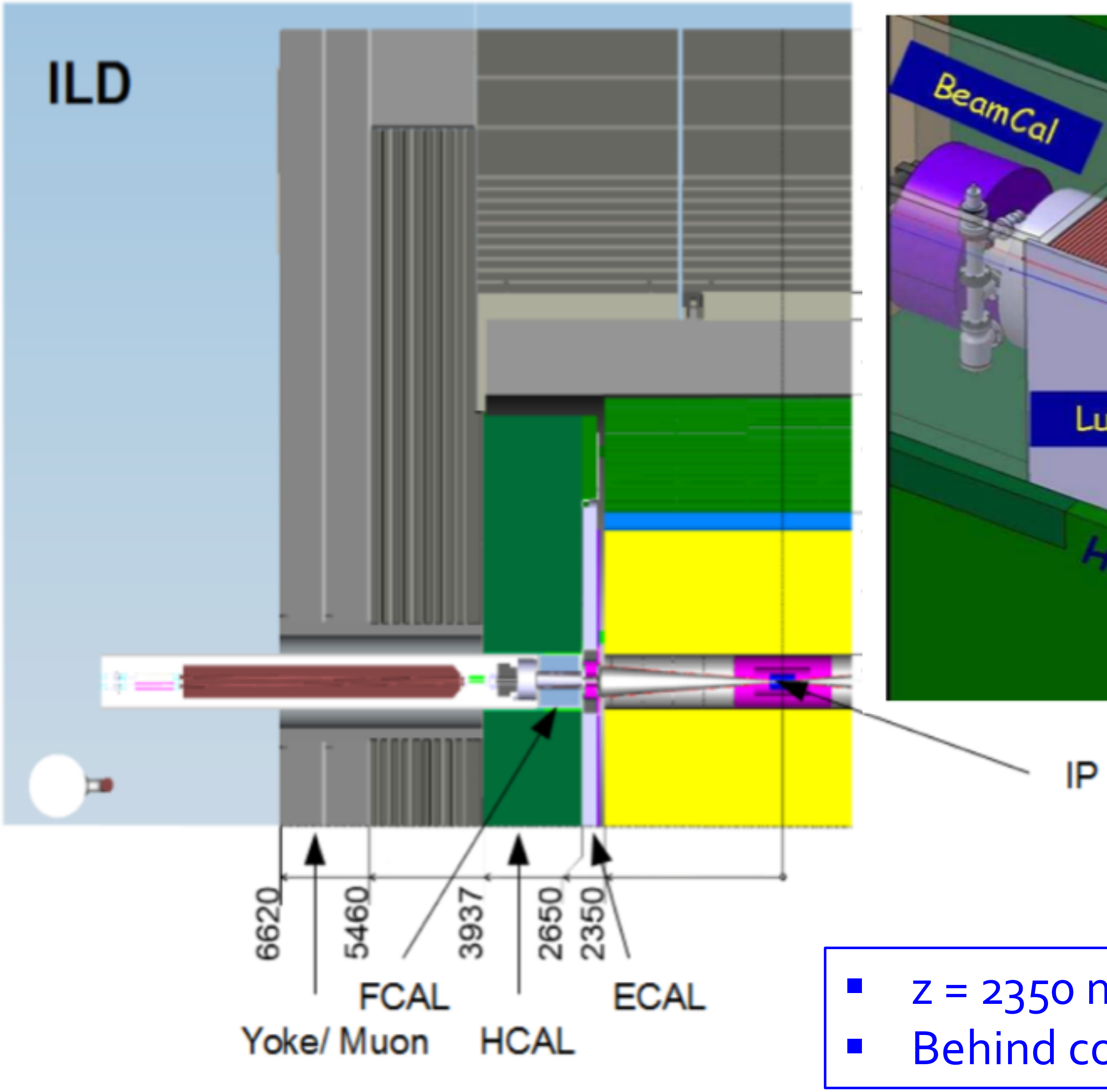
Z Metrology : 0.4

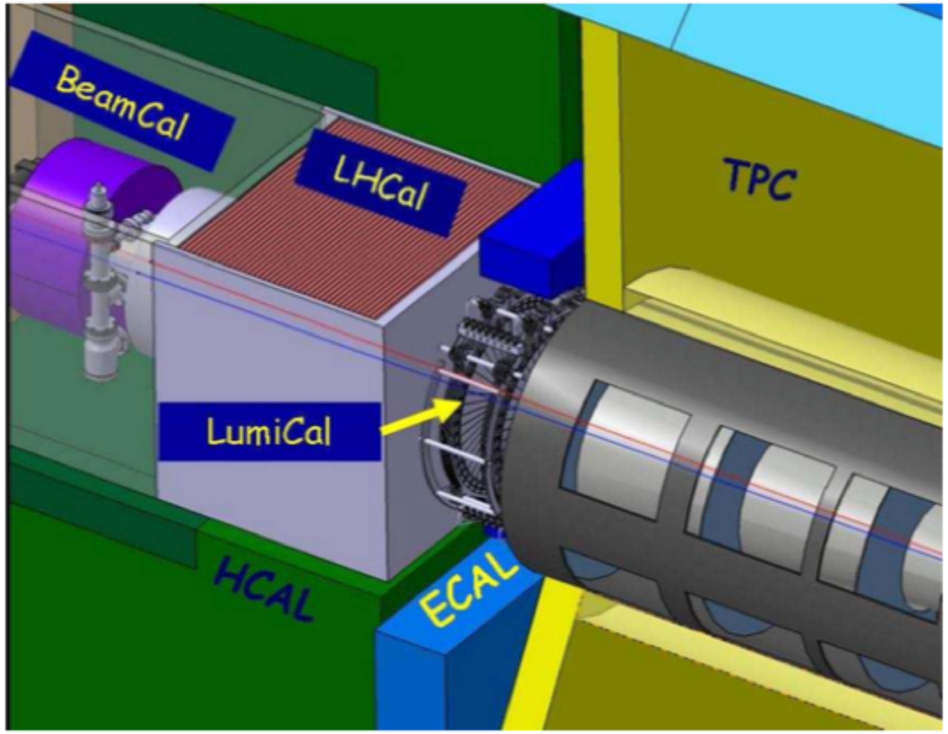
Energy Measurement : 1.8

Beam Parametrers : 0.6

Clustering : 1.0

# ILD LumiCal (i)



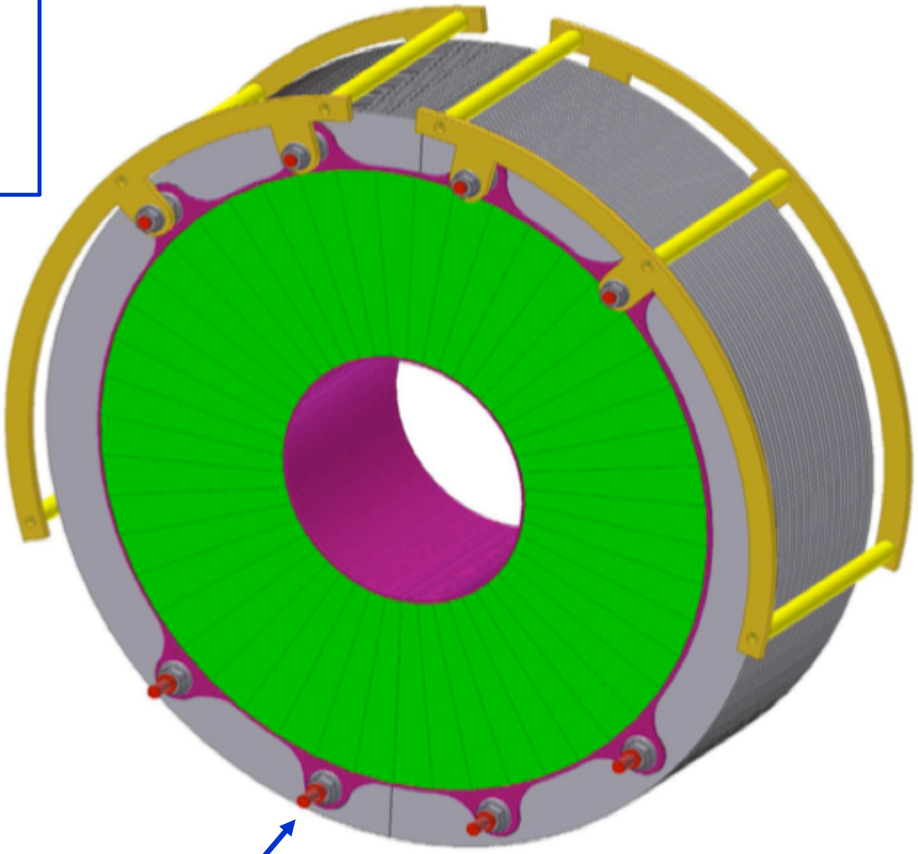


- z = 2350 mm - **like rest of ECAL**
- Behind conical beam pipe: thin window

# ILD LumiCal (ii)

Information on this and following slide: Work of Krakow group

- EUDET-Memo-2008-13
- EUDET-Memo-2009-10
- EUDET-Memo-2010-06



Bolts hold calorimeters together

30 layers of 1 $X_0$ deep tungsten

30 Si layers (320 microns)

- segmentation 1.8 mm x 7.5°

Depth:

- Calorimeter: 134 mm
- Total (incl. support): 175 mm

Inner radius:

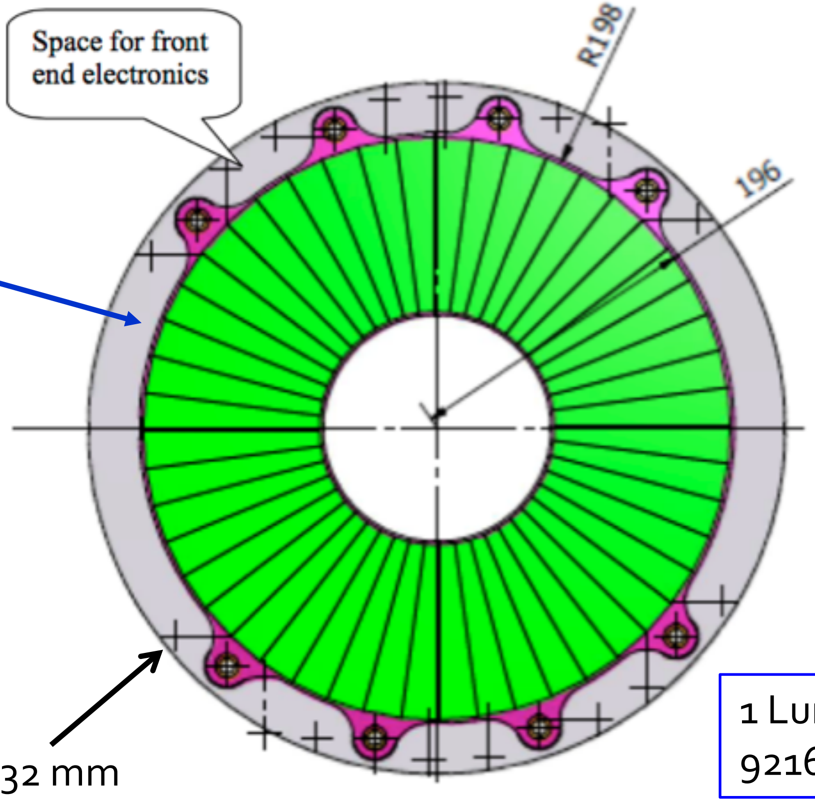
- Sensitive: 80 mm
- Mechanical: 76 mm

Outer radius:

- Sensitive: 195.2 mm
- Mechanical: 232 mm

# ILD LumiCal (iii)

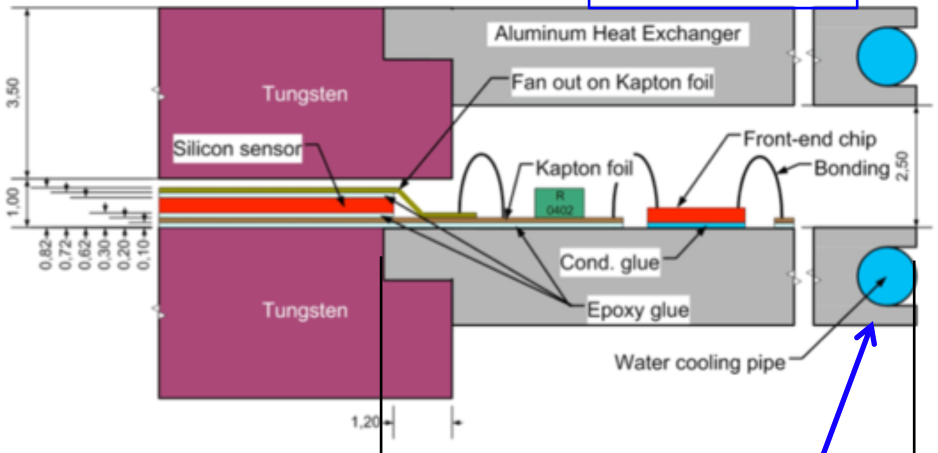
36 mm for assembly and electronics



232 mm

1 LumiCal:
92160 readout channels

128 channels



~11 mm

Cooling

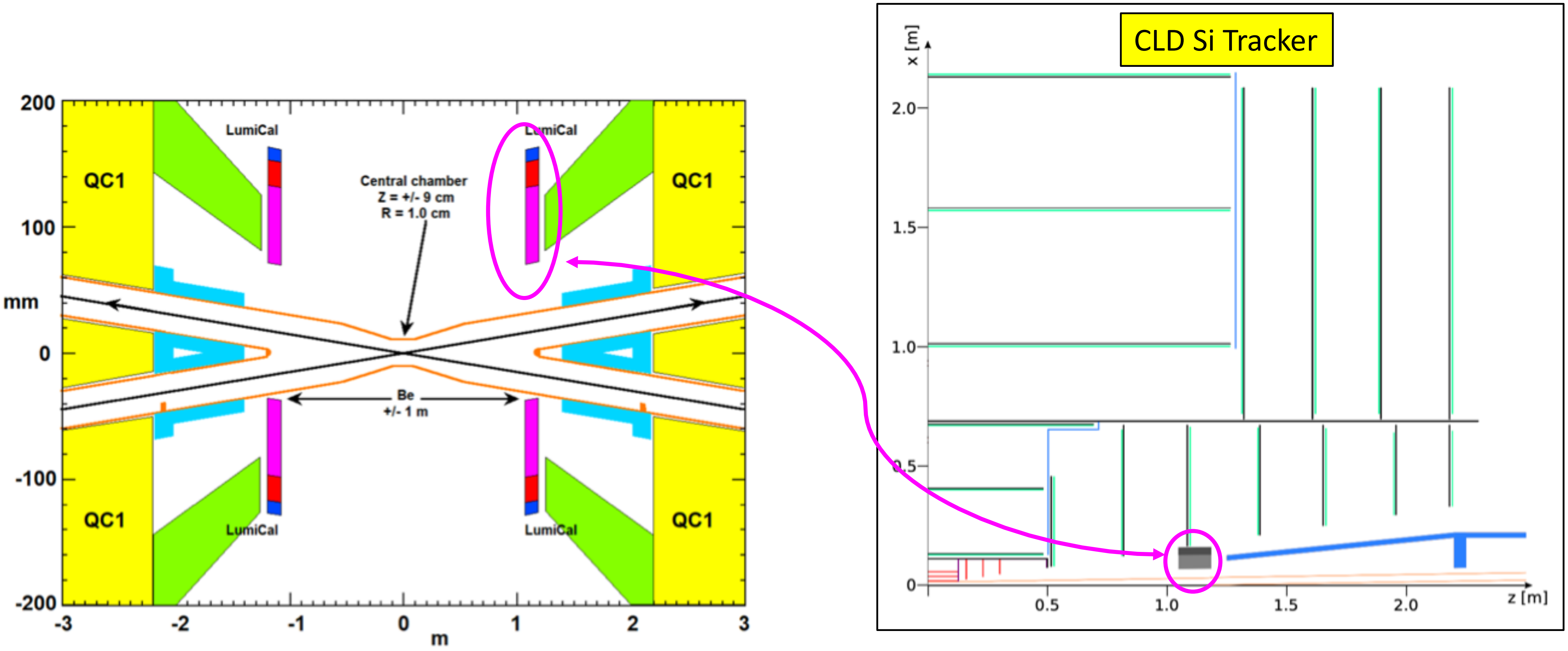
- Inner radius of acceptance varies by 0.33 µm/Cº
- Temperature stabilization within 1 cº safe. Probably within 0.2 Cº
- Total dissipated heat in one LumiCal: 30 W.
    - With power cycling: 1 ms active/199 ms breaks
- Water cooling: 15 l/min per LumiCal.

At FCC-ee, no power cycling.
More efficient cooling needed?

# LumiCals @ FCC-ee

Challenge:

- MDI region is very busy, LumiCals pushed deep inside detector volume



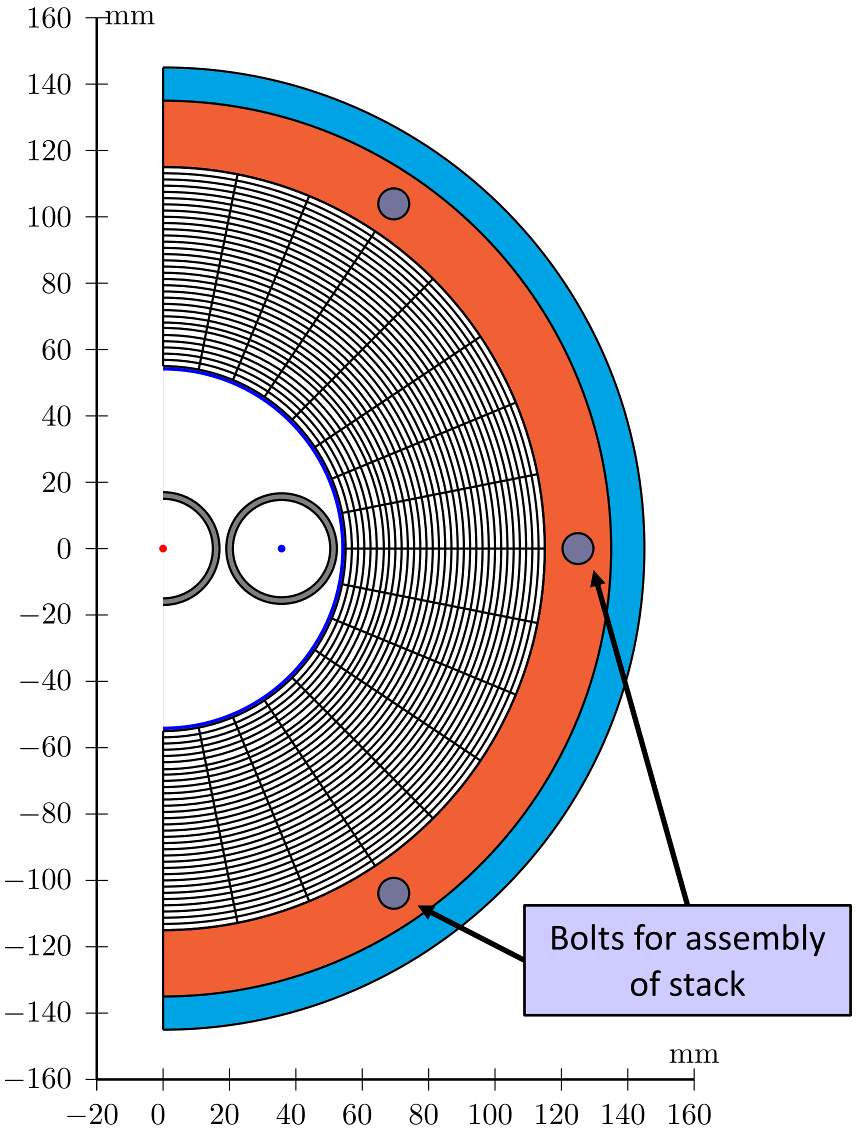
# CDR LumiCal Design

Design considerations:

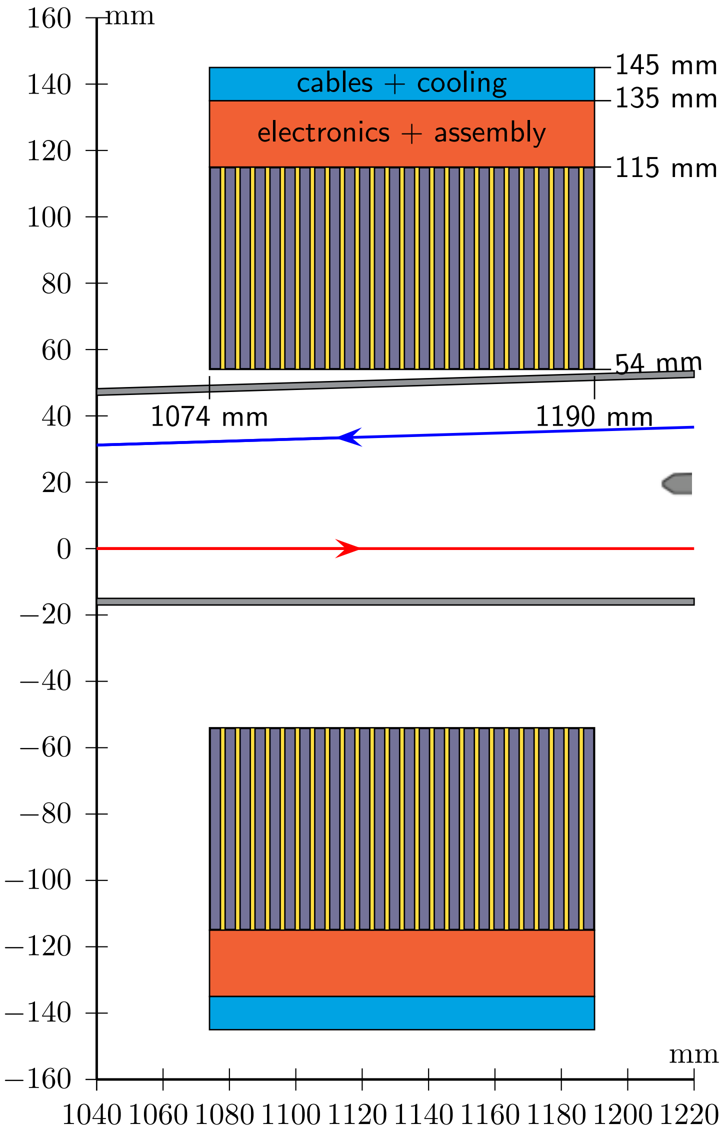
- Need to control geometry to precision of $\mathcal{O}$(1 µm)
  - Keep **geometry as simple as at all possible**

**Multilayer barrels where all layers have identical circular geometry**

- 25 layer SiW sandwich
  - 3.5 mm W (1 $X_0$) + 1.0 mm gap for Si sensors
- Physical dimensions
  - Sensitive region: *r* = 54-115 mm
  - Region for "services": 115-145 mm
  - Calorimeter front face at *z* = 1074 mm
- Proposed segmentation
  - 32x32 pads/layer (1.9 x 10-22 $mm^2$ pads)
  - 25,600 channels per LumiCal
- Weight
  - About 65 kg per LumiCal

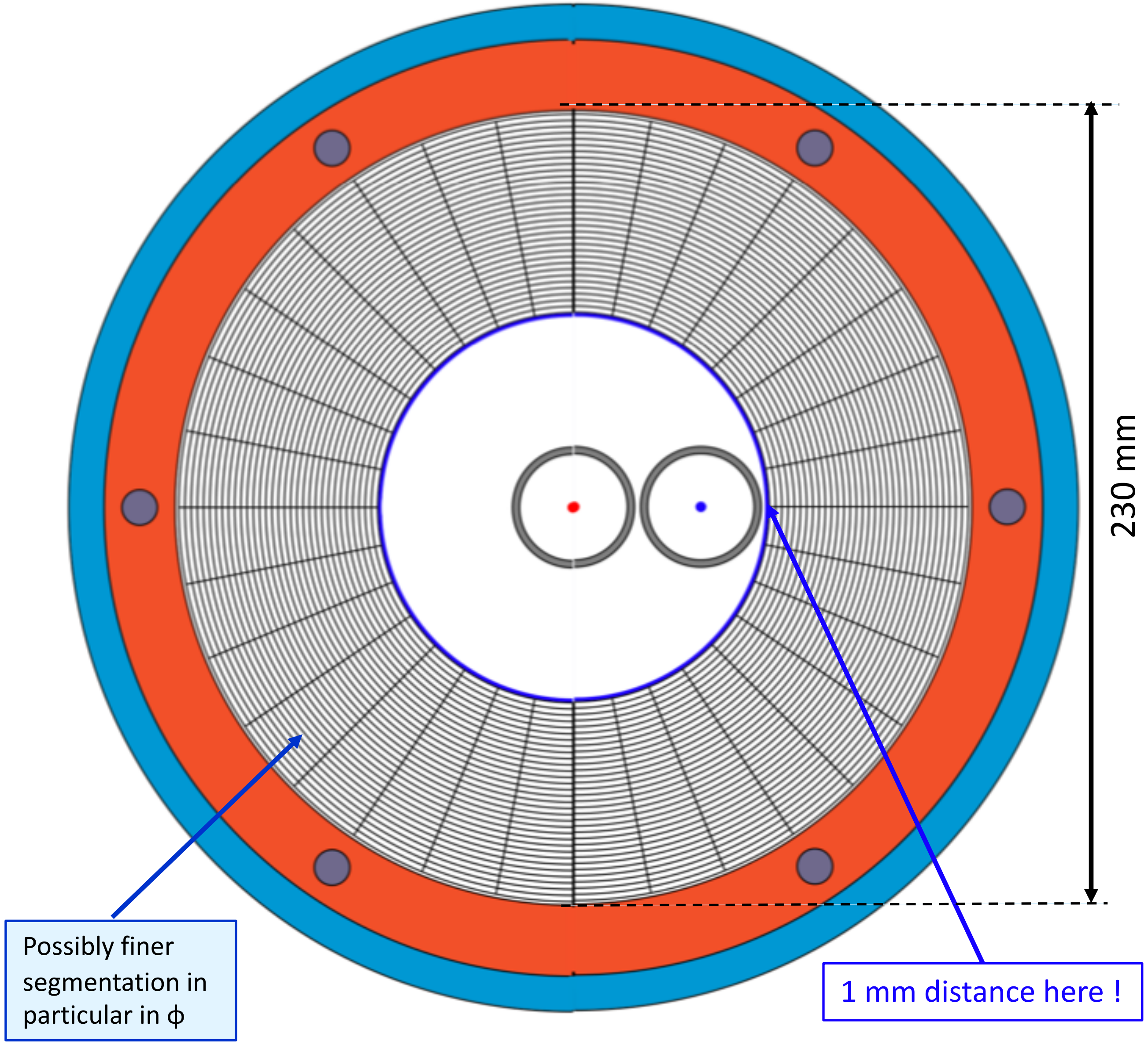


Bolts for assembly of stack



# Condiderations and Concerns

- Considerations for improved precision on radial coordinates:
  - Construct LumiCals as full barrels and not (as previously) as two half barrels
    - Avoid uncertianty from half barrel separation
  - Fabricate each Si layer from one single Si crystal
    - Uncertainty on inner (and outer) radius basically controlled by ”Hamamatsu”
- Concerns:
  - By (ignorant) design, LumiCal sits very close to incomming beam pipe
    - Only 1 mm clearance – is this sufficient ?
  - For control of LumiCal geometry, temperature shall be controlled to $\mathcal{O}$(1 degree) and gradients should be minimized
    - Again the close proximity to the beam pipe is a concern – What is its temperature?
    - High temperature would also accelerate aging
    - Aim to operate at ”room temperature”



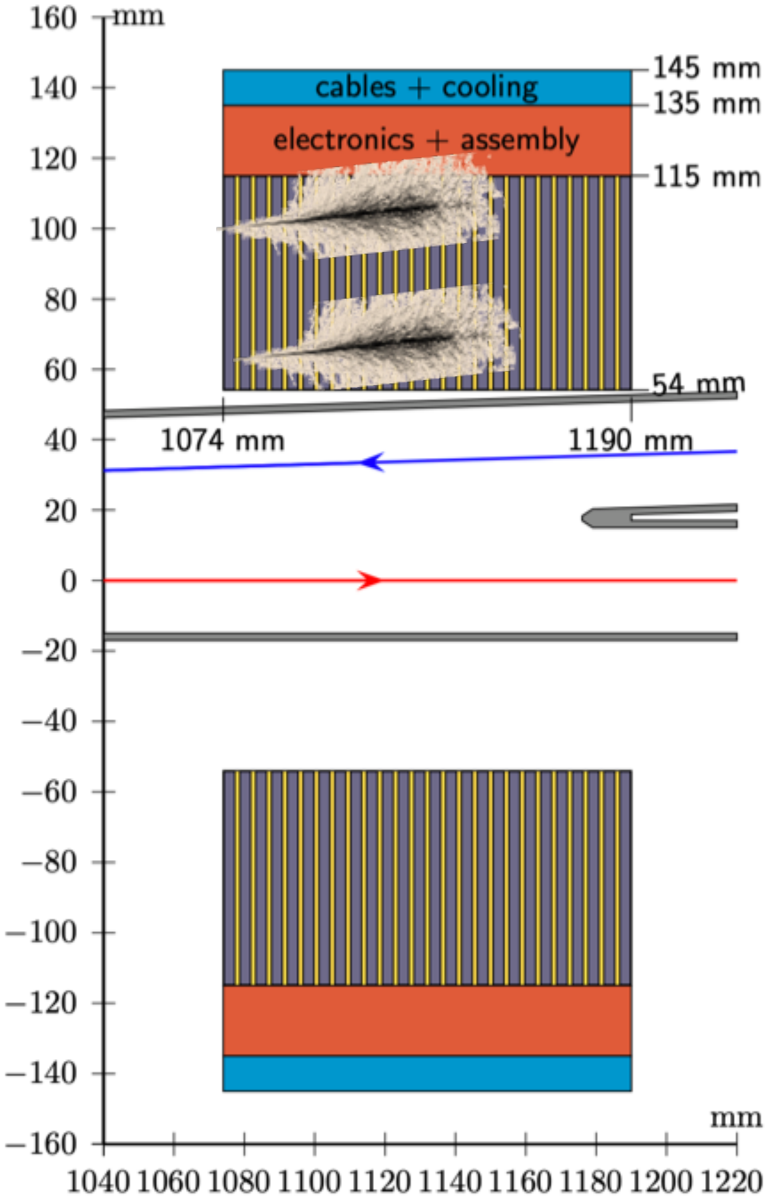
Possibly finer segmentation in particular in $\phi$

1 mm distance here !

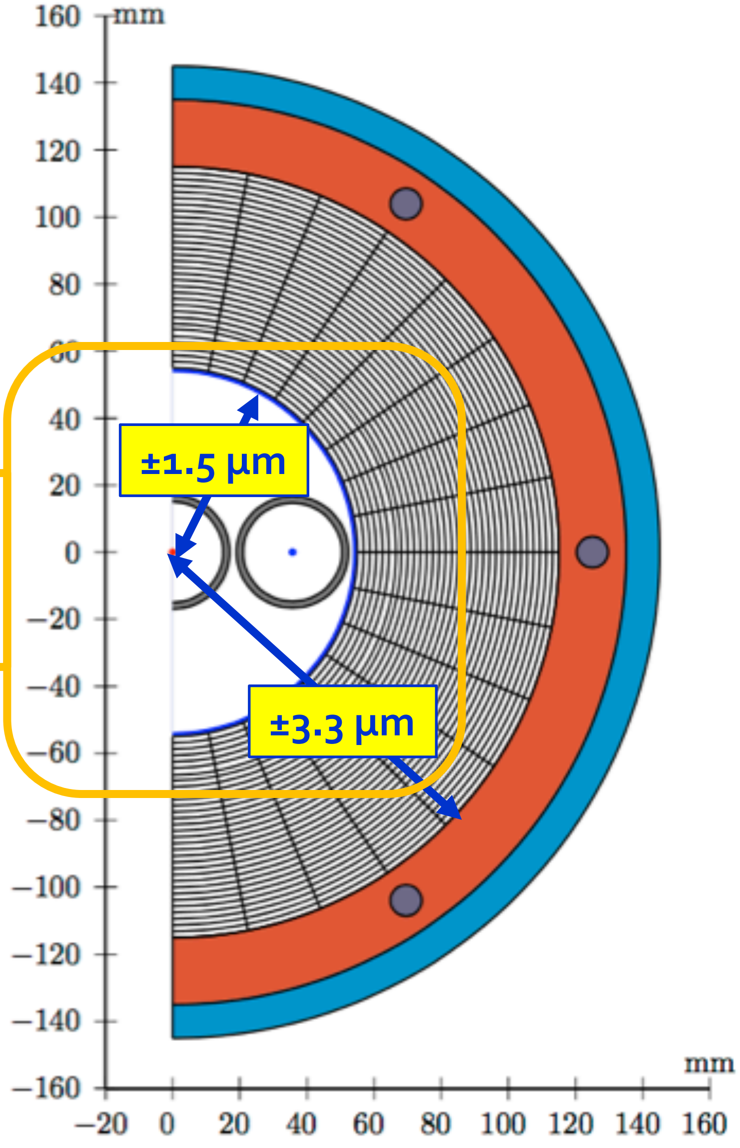
# Acceptance and tolerances

- Effective Moliere radius of W-Si sandwich: **~15 mm**
- Stay 1 Moliere radius away from inner radius and somewhat more from outer radius
  - To be optimised – simulation studies ongoing
- => **Wide acceptance: 62 – 88 mrad**
- Slightly smaller **narrow acceptance**: **64 – 86 mrad**
  - **Bhabha cross section: 14 nb**
    - Compared to 30 nb multihadronic Z decays at  peak

- Geometrical tolerances for shift in acceptance of $10^{-4}$ :
  - **Inner border:   $\delta\Theta_{min}$ = ± 1.3 µrad ;            $\delta R_{min}$ = ± 1.5 µm**
  - **Outer border: $\delta\Theta_{max}$ = ± 3.0 µrad ;            $\delta R_{max}$ = ± 3.3 µm**
  - **Half distance between two calorimeters:  δZ = ± 55 µm**

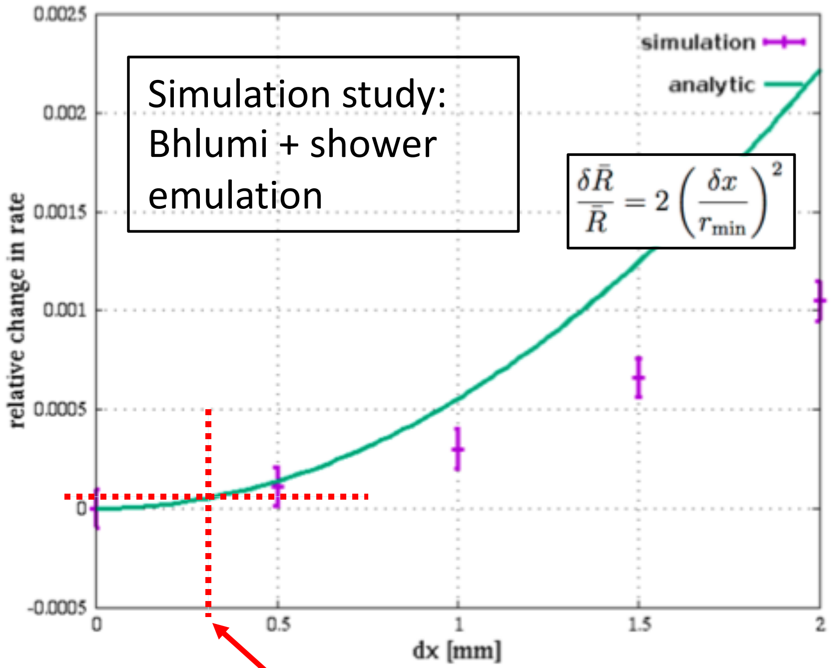


# Geometric tolerances - radial



Required construction precisions

## Centering of calorimeters around beam line



Simulation study: Bhlumi + shower emulation

$$\frac{\delta \bar{R}}{\bar{R}} = 2\left(\frac{\delta x}{r_{\min}}\right)^2$$

dx = x-coordinate shift of LumiCal system wrt true IP position

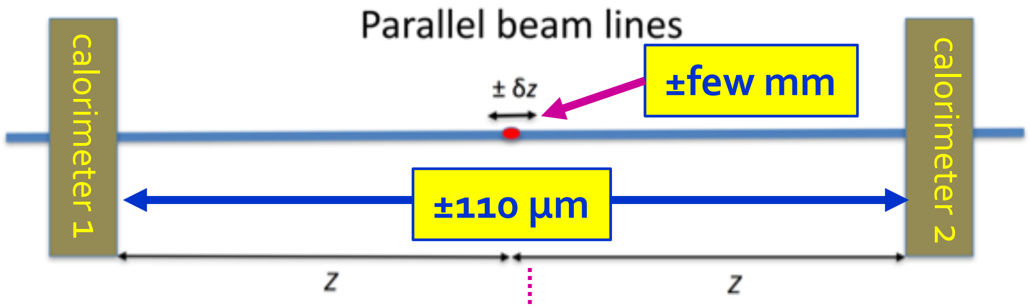
y-coordinate shifts give similar behaviour

Transverse shifts should be δr ≲ 0.3 mm

- Simulation study confirms that dependence is second order (due to use of rescricted acceptance)
- Amplitude smaller in simulation than in analytic estimate: simulation includes radiative correction – events are not perfectly back-to-back

# Geometric tolerances on positioning w.r.t. IP – longitudinal

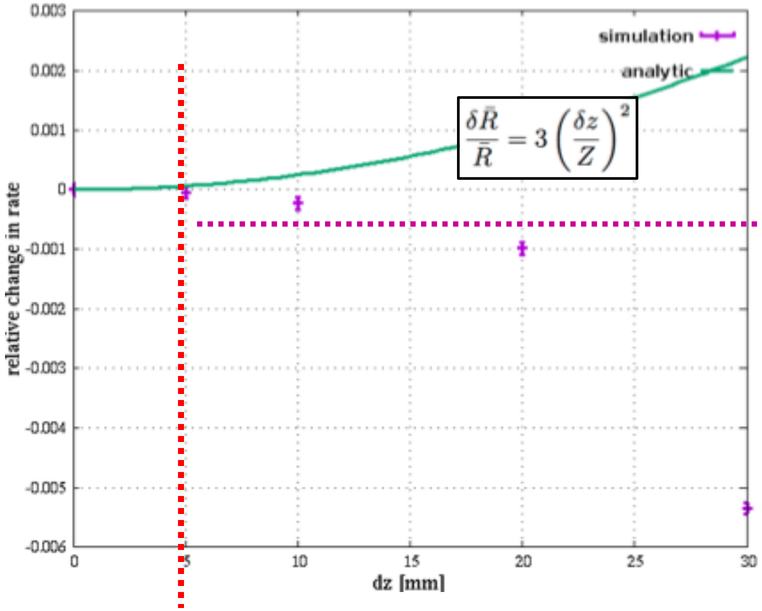
First, consider example of parallel beams



- **Distance between two calorimeters should be known to**
  **2 x δZ = 2 x 55 µm = 110 µm**
- **IP position w.r.t. two-calorimeter system can be off by few mm**

## Centering of IP w.r.t. two-calorimeter system

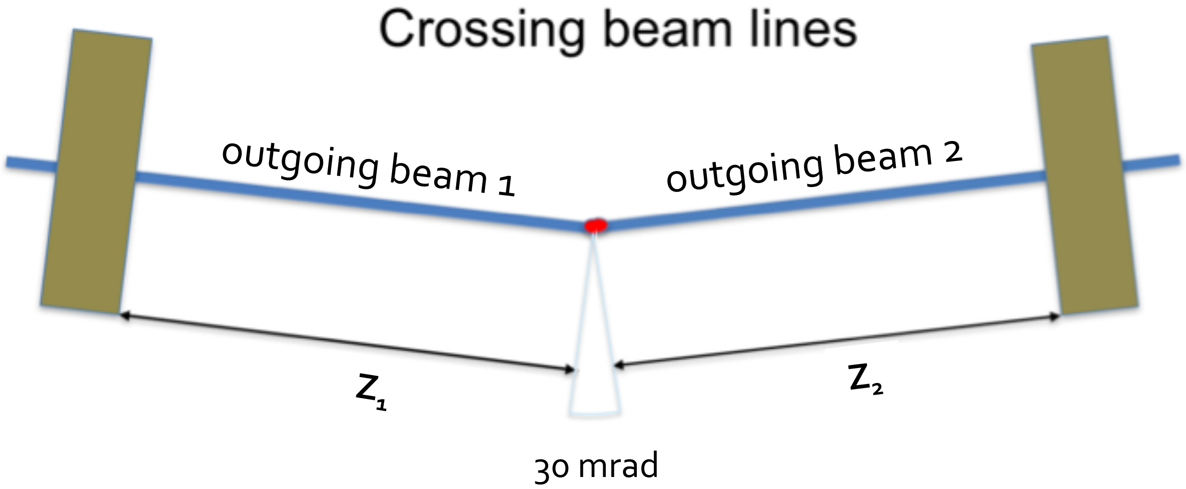
Simulation study:
Bhlumi + shower emulation



dz = z-coordinate shift of LumiCal system wrt true IP position

Analytic (lowest order) calculation is not precise.
Even sign is wrong!
This because of radiative effect:
With longitudinal shifts, one cuts into acollinearity distribution

# Geometric tolerances – longitudinal (ii)

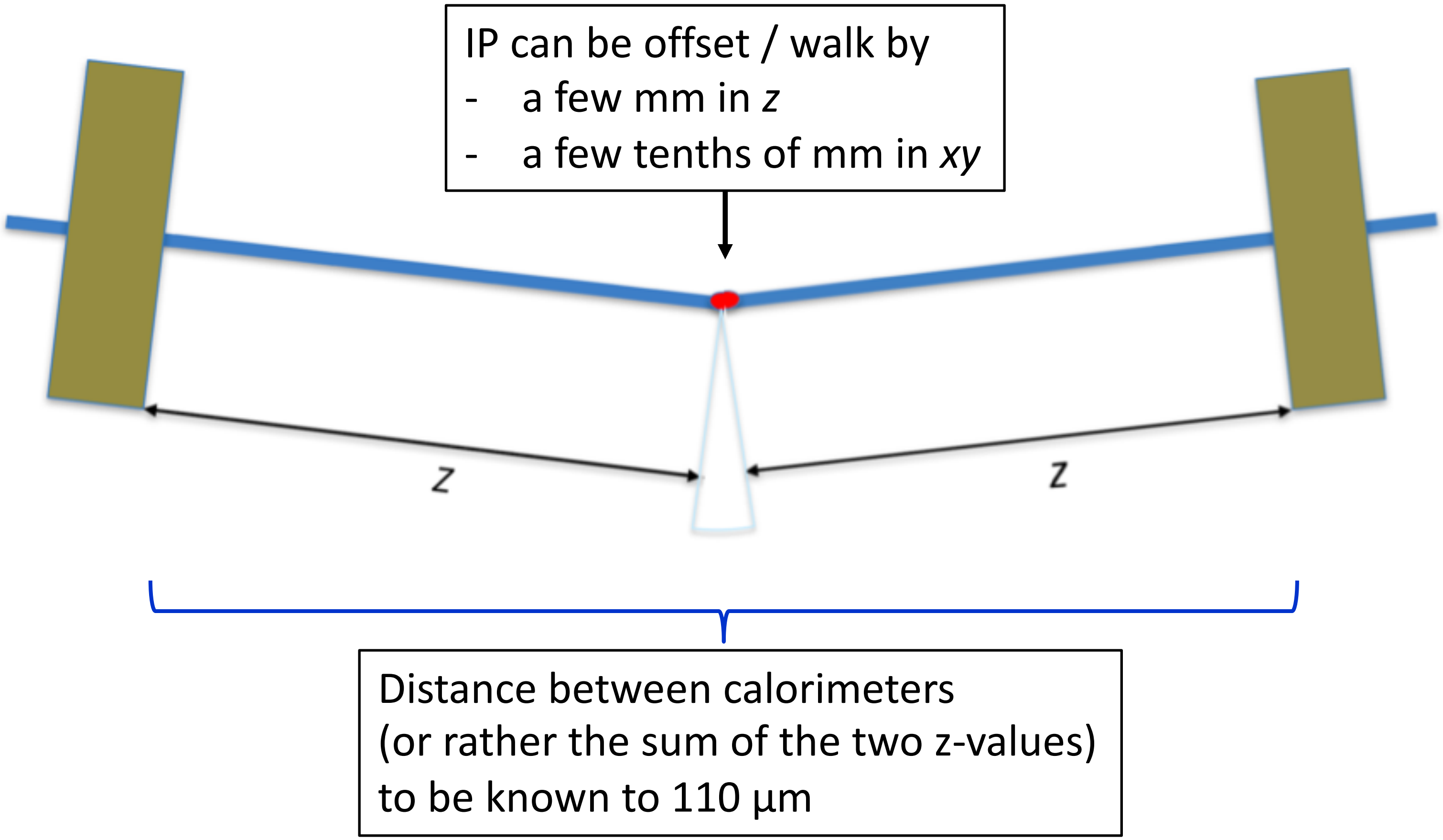


- Now, have two distances, **$Z_1$** and **$Z_2$**, to measure, each to **±55 µm**
  - To be measured **w.r.t.** fiducual marker indicating **nominal IP position**
- Offset / walk of the IP of the order of few mm in the longitudinal direction still tolerable

**Notice:**

- As indicated, the face of each LumiCals shall be perpendicular to the corresponding outgoing beam line.
- The two faces will not be parallel, they are each tilted by 15 mrad w.r.t. the global coordinate system.

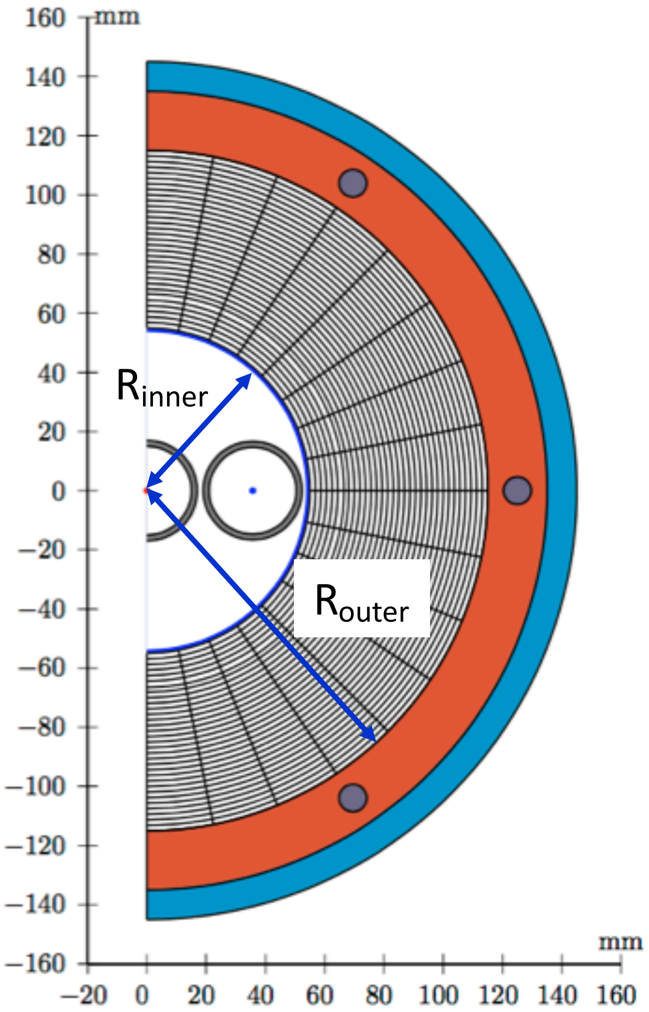
# Summary of geometric tolerances



IP can be offset / walk by
- a few mm in *z*
- a few tenths of mm in *xy*

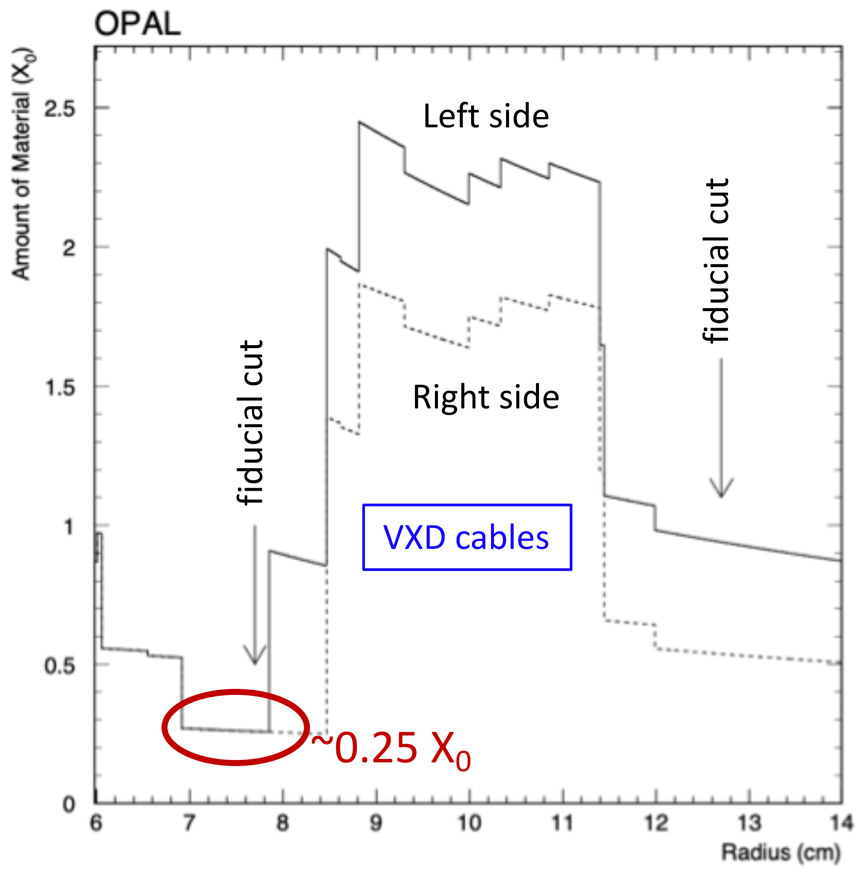
Distance between calorimeters
(or rather the sum of the two z-values)
to be known to 110 µm

Radii to be known to
$R_{inner}$ : 1.5 µm
$R_{outer}$ : 3.3 µm

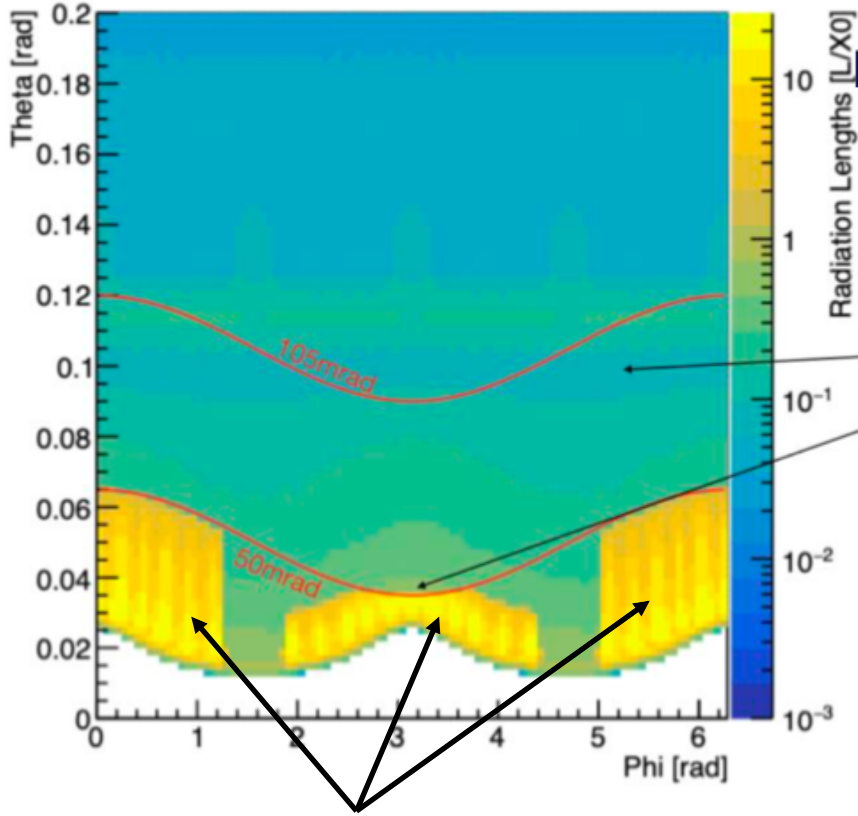


# Material in front of LumiCals

**OPAL**



**FCC-ee**



FCC-ee MDI Meeting #48 and FCCIS WP2.3 Meeting #19

11/09/2023

Francesco Fransesini

**Minimum X0 in LumiCal cone: 0.07**

**Maximum X0 in LumiCal cone: 0.52**

**Average X0 in LumiCal cone: 0.16**

**Looks promising**

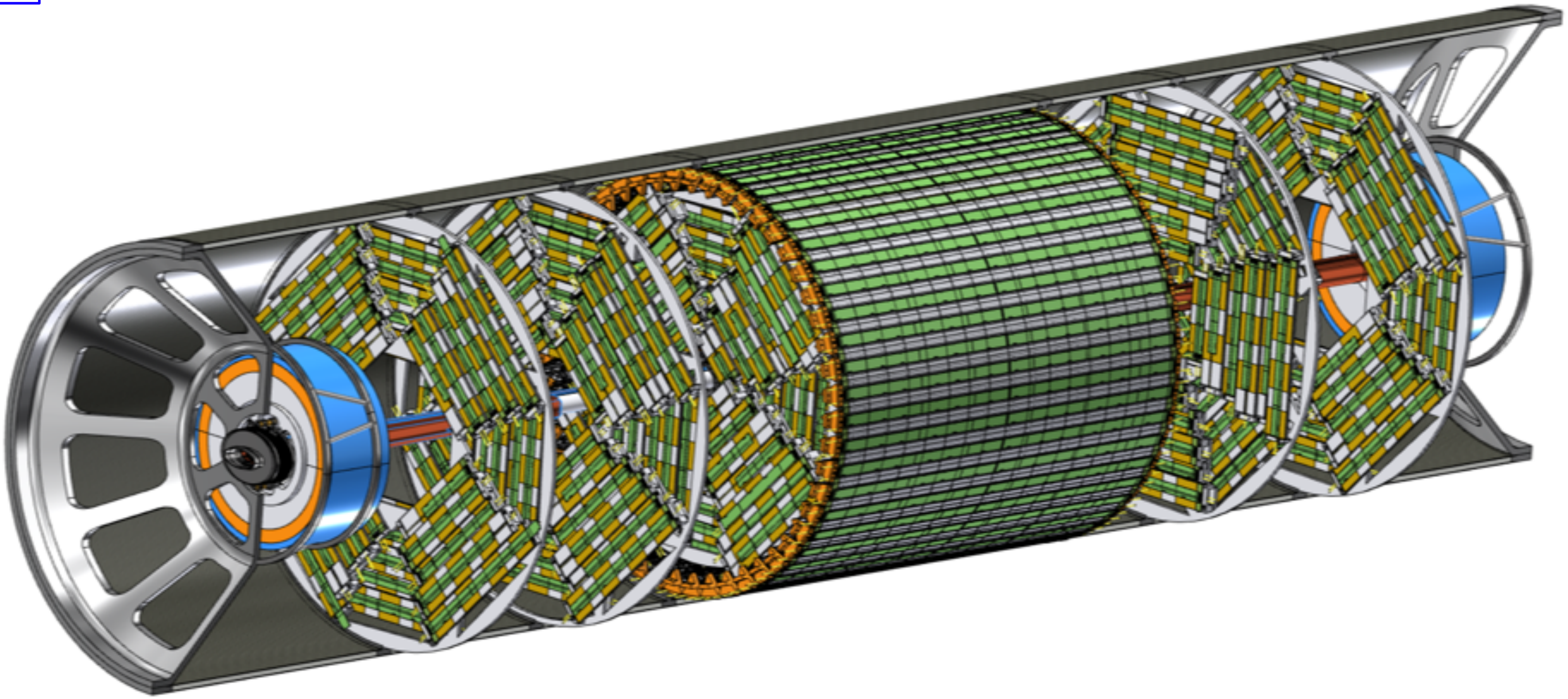
however

The very heavy Cu cooling manifolds are very close

- High rate showering into LumiCal acceptance?
- To be studied – studies starting…

# LumiCal Integration !!

Beautiful !

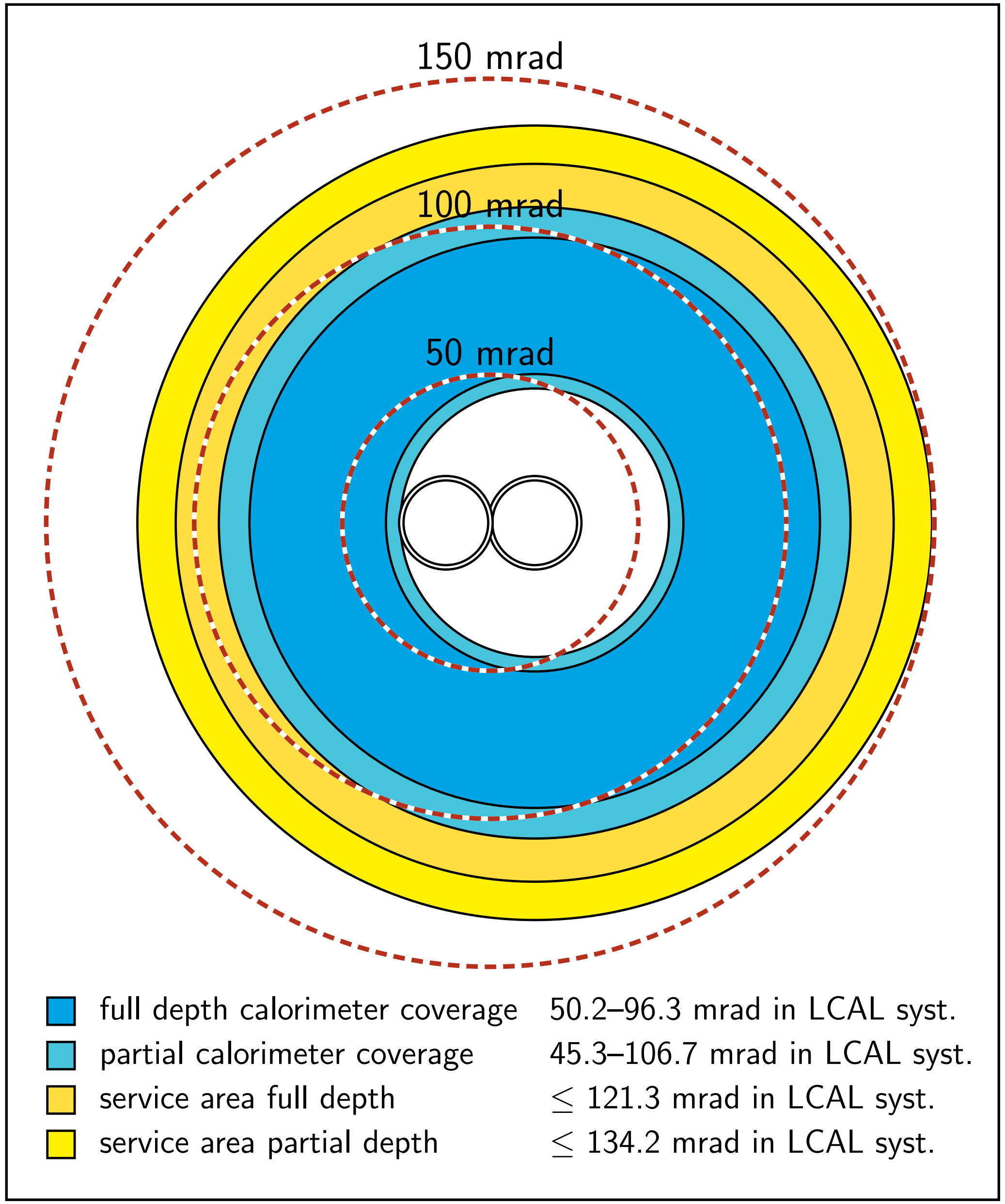


Copied from F. Palla's talk yesterday

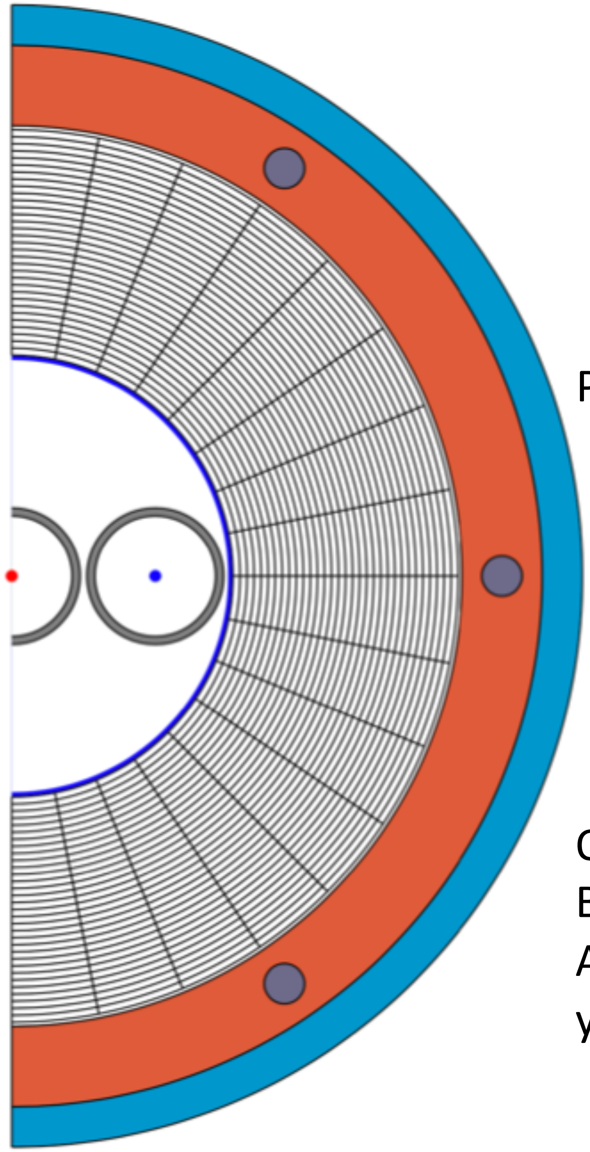
# Problems with CDR LumiCal design

- Stays inside 100 mrad cone around *z*-axis (bisector of beam lines)?
  - Certainly not!
- Stays inside 150 mrad cone around z-axis ?
  - Yes, per design!
- Sits asymetric w.r.t. the main detector symmetry axis
  - It is, of course, LumiCal which sits ”correct” w.r.t. the (forward) physics
- In global coordinate system
  - ϕ dependent full depth coverage of scattering angle (θ)
    - Minimum scattering angle: 35.2 – 65.2 mrad
    - Maximum scattering angle: 81.3 -- 111.3 mrad
  - To ensure hermeticity: forward ECAL must cover down to 81 mrad
  - Inner hole: No instrumentation below a ϕ-dependent θ angle
    - Maximum: 61 mrad
    - Minimum: 31 mrad

Yes, it is really rather confusing with the two systems



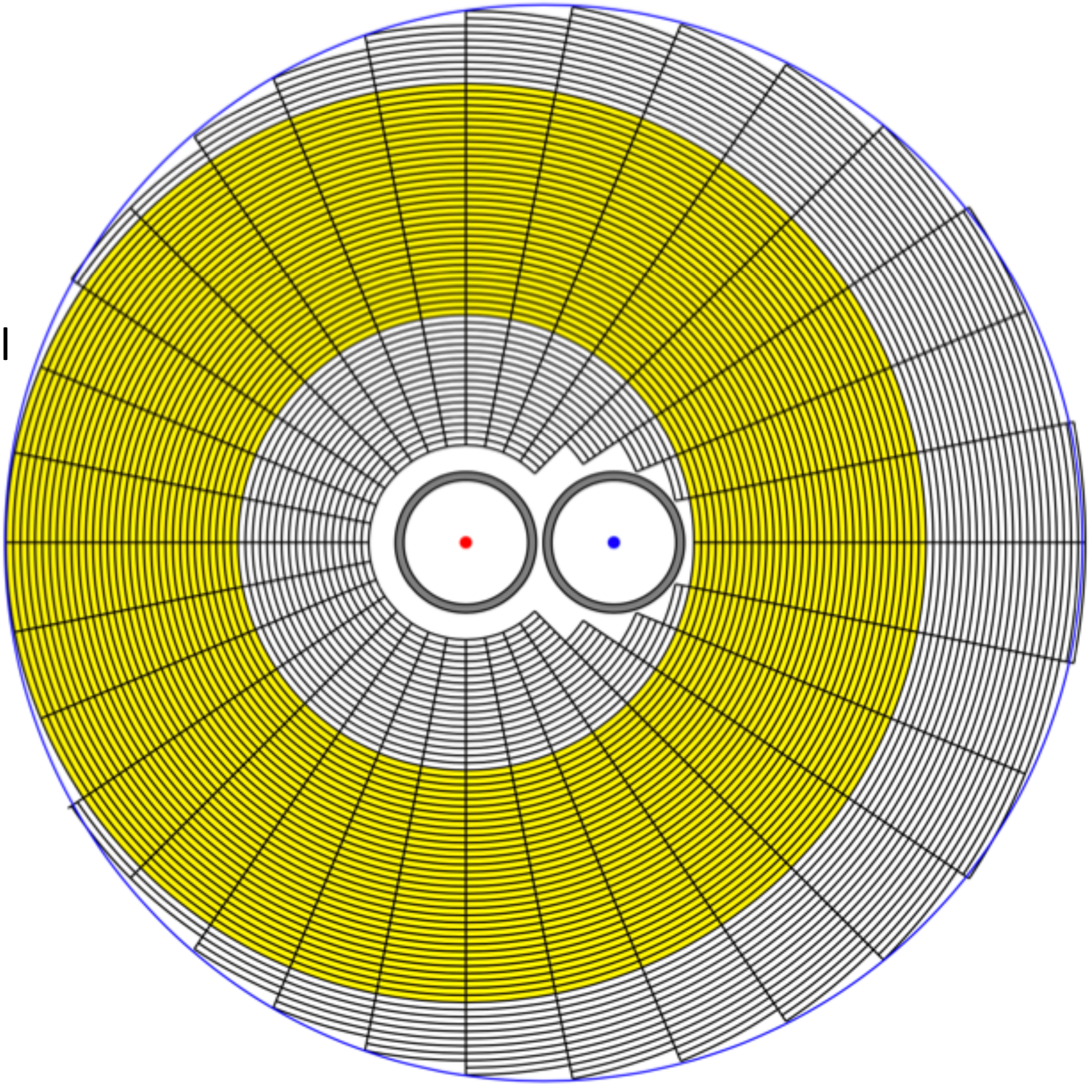
# Centered on outgoing beam but still ”symmetric” in global system



Pads shown in yellow are identical between two drawings

Why not?

On paper, one can draw anything!
But can it be built?
And how to control geometry of yellow region to $\mathcal{O}$(1 µm) ??



Coverage from global θ = 35 to 110 mrad for ”all” ϕ

# Summary & Conclusions

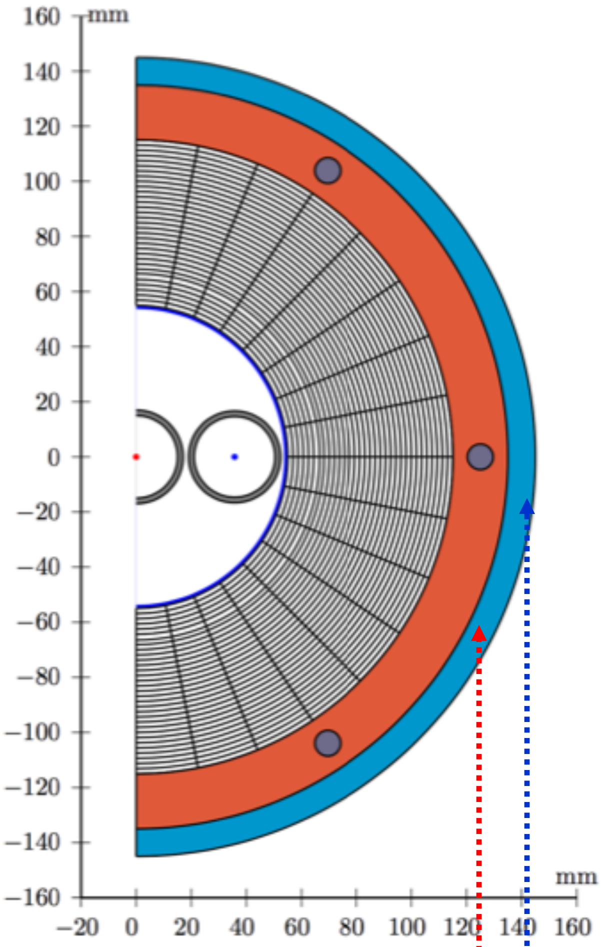
- Very ambitious FCC-ee absolute normalisation goal of $10^{-4}$
    - More than a factor 3 better than at LEP
- Compared to LEP, the FCC-ee LumiCals are placed in a more complicated location
    - At about z=1 m from the IP, inside the general detector volume
- Many challenges
    - Detector geometry to be controlled to $\mathcal{O}(1\ \mu\text{m})$ in radius [4.4 μm achieved in OPAL]
    - Distance between the two monitors to be controlled to 100 μm [100-140 μm achieved in OPAL]
    - LumiCal design squeezed from two sides
        - i) Stay away from beam pipe; and ii) Stay inside 150 mrad cone
        - Visible cross section rather small: 14 nb compared to 30 nb for Z → qq
    - Furthermore, the CDR design has a hermeticity challenge
        - Coverage towards very small angles
        - Overlap with lower edge of forward ECAL

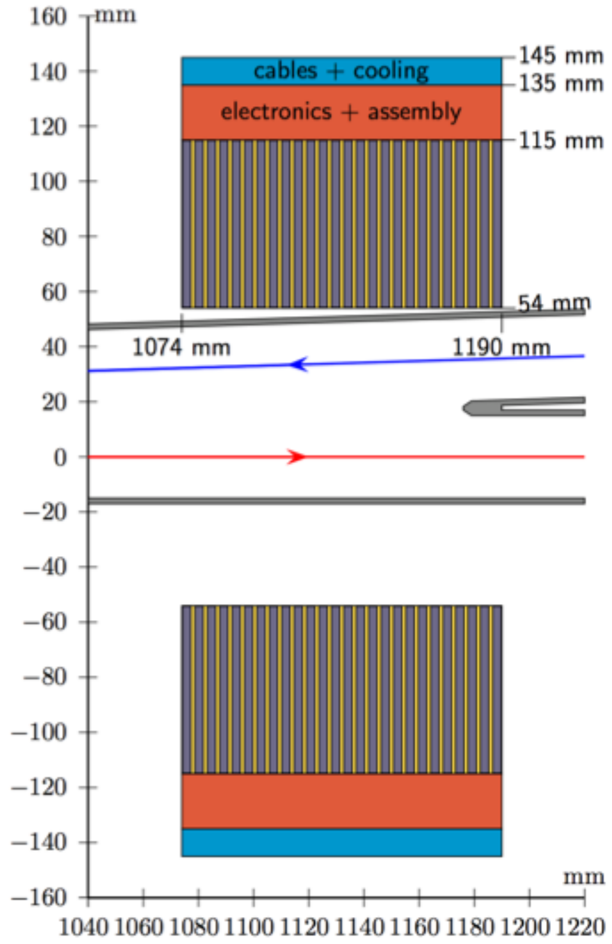
- Detailed simulation studies needed
    - Currently in start-up phase
- Proper engineering design needed

# Extra slides

# LumiCal CDR Design

- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Molière radius: ~15 mm
- 25 layers total: 25 $X_0$
- Cylindrical detector dimensions:
  - Radius: 54 < r < 145 mm
  - Along outgoing beam line: 1074 < z < 1190 mm
- Sensitive region:
  - 55 < r < 115 mm;
- Detectors centered on (and perpendicular to) outgoing beam line
- Angular coverage (>1 Molière radius from edge):
  - Wide acceptance: 62-88 mrad
  - Narrow acceptance: 64-86 mrad
  - Bhabha cross section @ 91.2 GeV: 14 nb
- Region 115 < r < 145 mm reserved for services:
  - Red: Mechanical assembly, **read-out electronics**, cooling, equipment for alignment
  - Blue: Cabling of signals from front-end electronics to digitizers (behind LumiCals?)



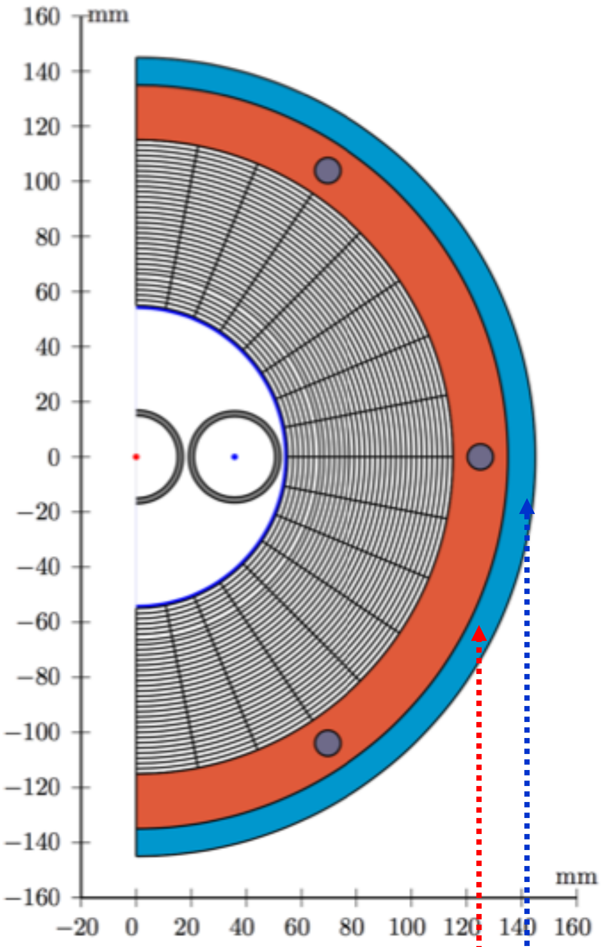


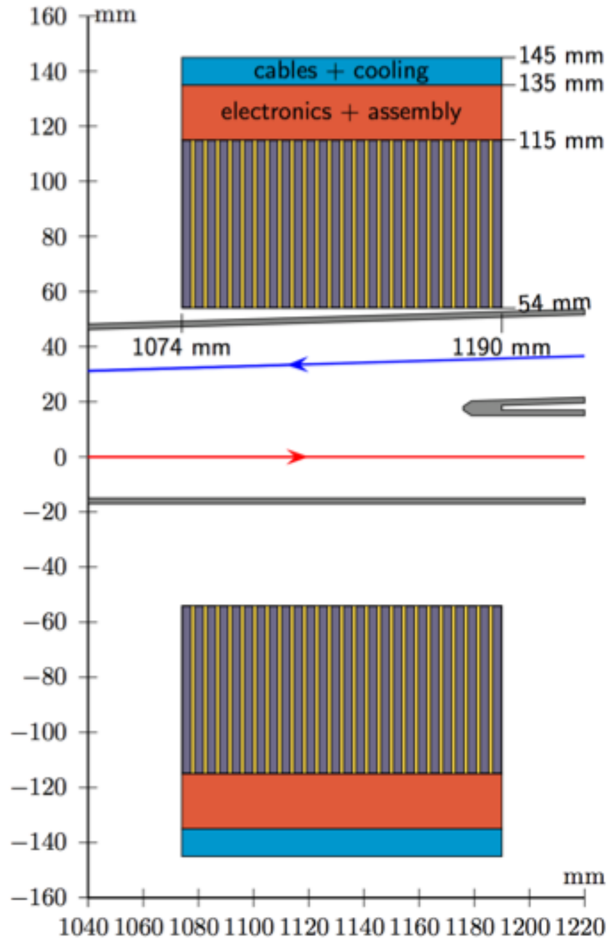
Precision goal: $1 \times 10^{-4}$

# LumiCal CDR Design

Numbers for OPAL

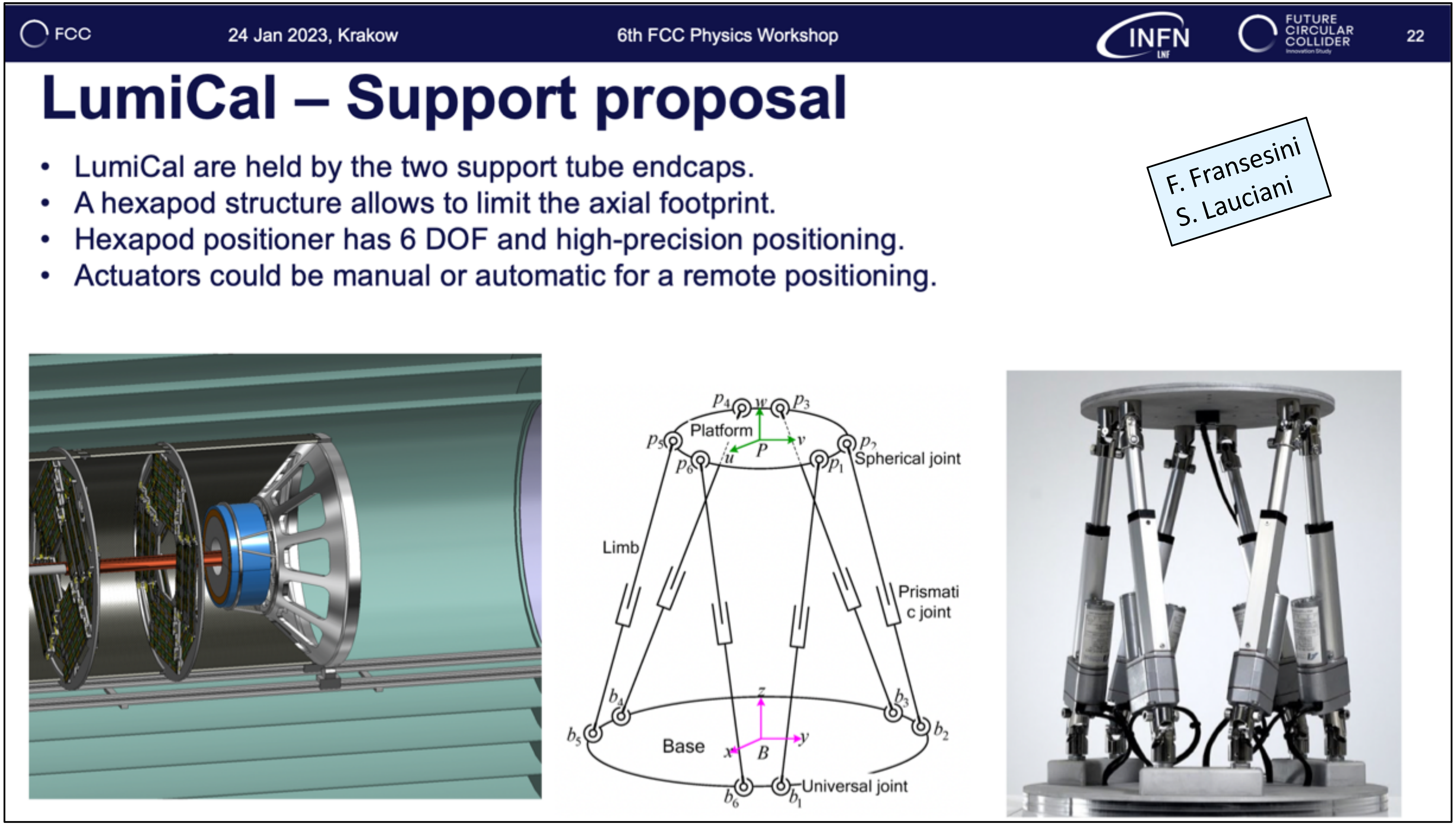
- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
  - ❑ Effective Molière radius: ~15 mm
- 18 layers total 22 $X_0$
- Cylindrical detector dimensions:
  - ❑ Radius: 54 < r < 145 mm
  - ❑ Along outgoing beam line 2460 < z < 2600 mm
- Sensitive region:
  - 62 < r < 142 mm;
- Detectors centered on (and perpendicular to) outgoing beam line
- Angular coverage (>1 Molière radius from edge):
  - ❑ Wide acceptance: 27-55 mrad
  - ❑ Narrow acceptance: 31-51 mrad
  - ❑ Bhabha cross section @ 91.2 GeV: 83 nb
- Region 115 < r < 145 mm reserved for services:
  - ❑ Red: Mechanical assembly, **read-out electronics**, cooling, equipment for alignment
  - ❑ Blue: Cabling of signals from front-end electronics to digitizers (behind LumiCals?)





Precision achieved: $3.4 \times 10^{-4}$

# LumiCal Support – Interesting proprosal in Krakow



FCC 24 Jan 2023, Krakow 6th FCC Physics Workshop INFN LNF FUTURE CIRCULAR COLLIDER Innovation Study 22

## LumiCal – Support proposal

- LumiCal are held by the two support tube endcaps.
- A hexapod structure allows to limit the axial footprint.
- Hexapod positioner has 6 DOF and high-precision positioning.
- Actuators could be manual or automatic for a remote positioning.

F. Fransesini
S. Lauciani

FUTURE
CIRCULAR
COLLIDER

NIELS BOHR INSTITUTE
UNIVERSITY OF
COPENHAGEN

# Detector Constraints for the FCC-ee Interaction Region and Luminosity Measurement

FCC-ee MDI & IR Mockup Workshop
Nov 16 – 17, 2023
Laboratori Nazionali di Frascati

Mogens Dam
Niels Bohr Institute, Copenhagen