**PARIS**, France
Venue: **Campus des Cordeliers**
**Sorbonne Université**
**https://cern.ch/fccweek2022**

30 May - 03 June

FCC
WEEK
2022

FUTURE
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# FCC-ee Luminosity Monitor

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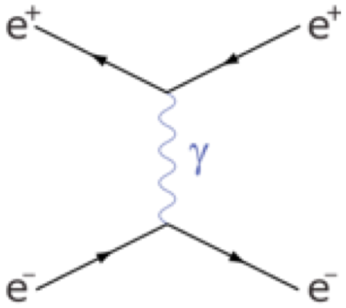
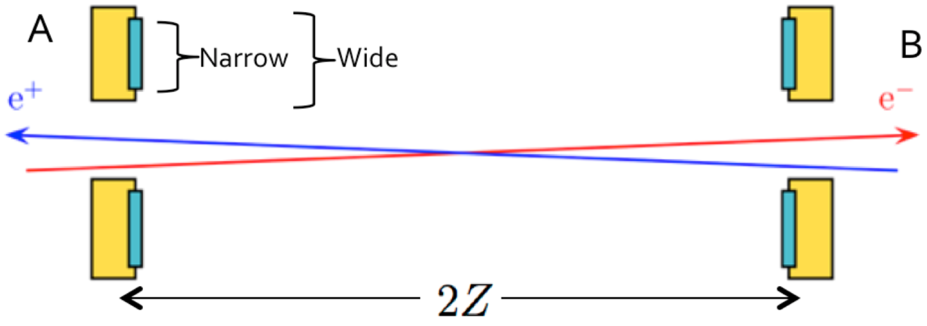
# Luminosity Measurement

- Standard lumi process is small angle elastic $e^+e^-$ (Bhabha) scattering
  - Dominated by *t*-channel photon exchange
  - Very strongly forward peaked

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



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



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

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

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

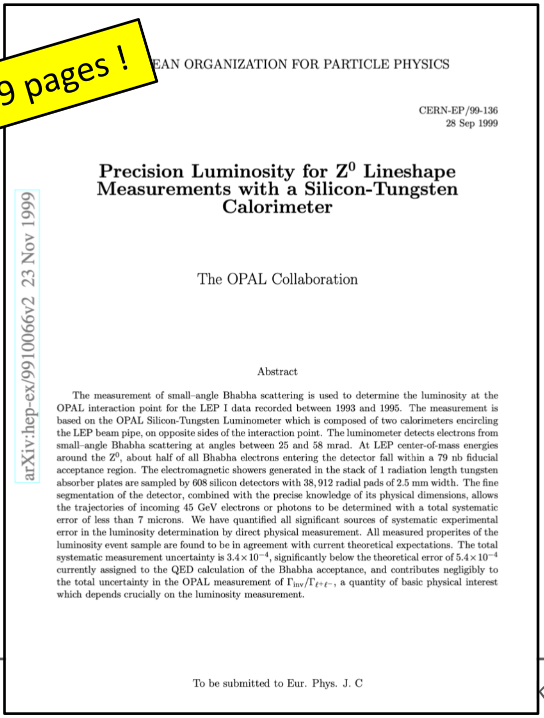
# Normalisation to $10^{-4}$

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

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

- Theory precision
  - Since LEP, theory precision has improved to **3.7 × $10^{-4}$** arXiv:1912.02067
  - And there is a path 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

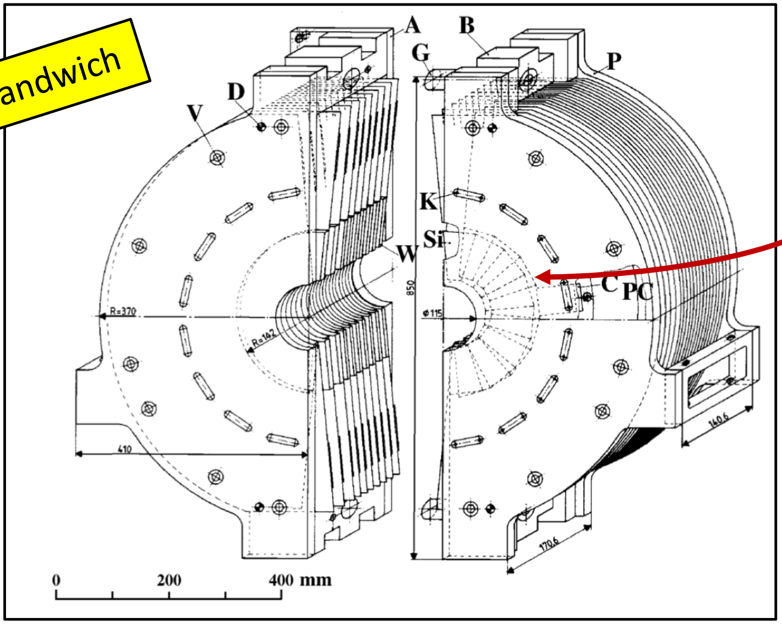
arXiv:hep-ex/9910066v2 23 Nov 1999

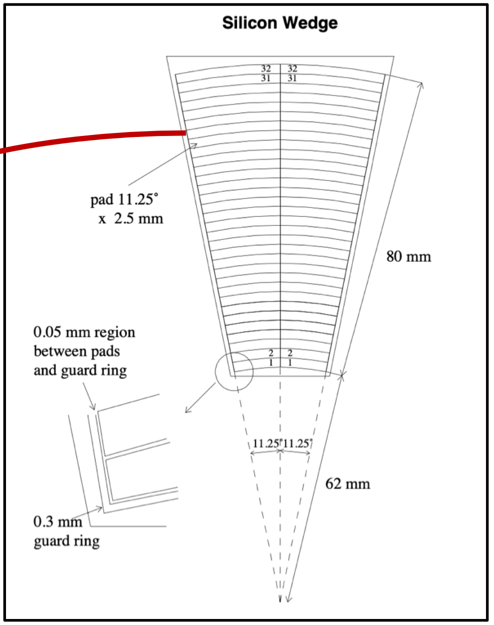
Abstract

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 properites of the luminosity event sample are found to be in agreement with current theoretical expectations. The total systematic measurement uncertainty is $3.4\times10^{-4}$, significantly below the theoretical error of $5.4\times10^{-4}$ currently assigned to the QED calculation of the Bhabha acceptance, and contributes negligibly to the total uncertainty in the OPAL measurement of $\Gamma_{\rm inv}/\Gamma_{\ell^+\ell^-}$, a quantity of basic physical interest which depends crucially on the luminosity measurement.

To be submitted to Eur. Phys. J. C

SiW sandwich

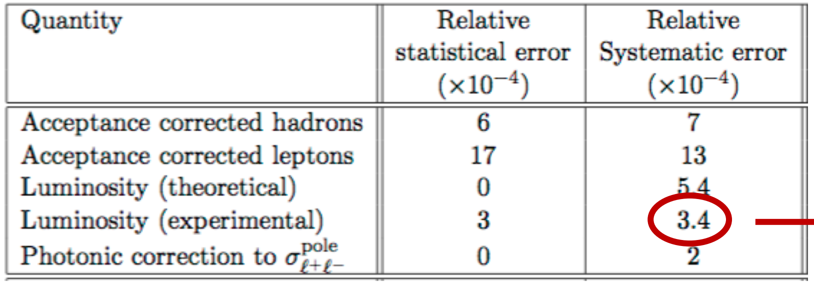




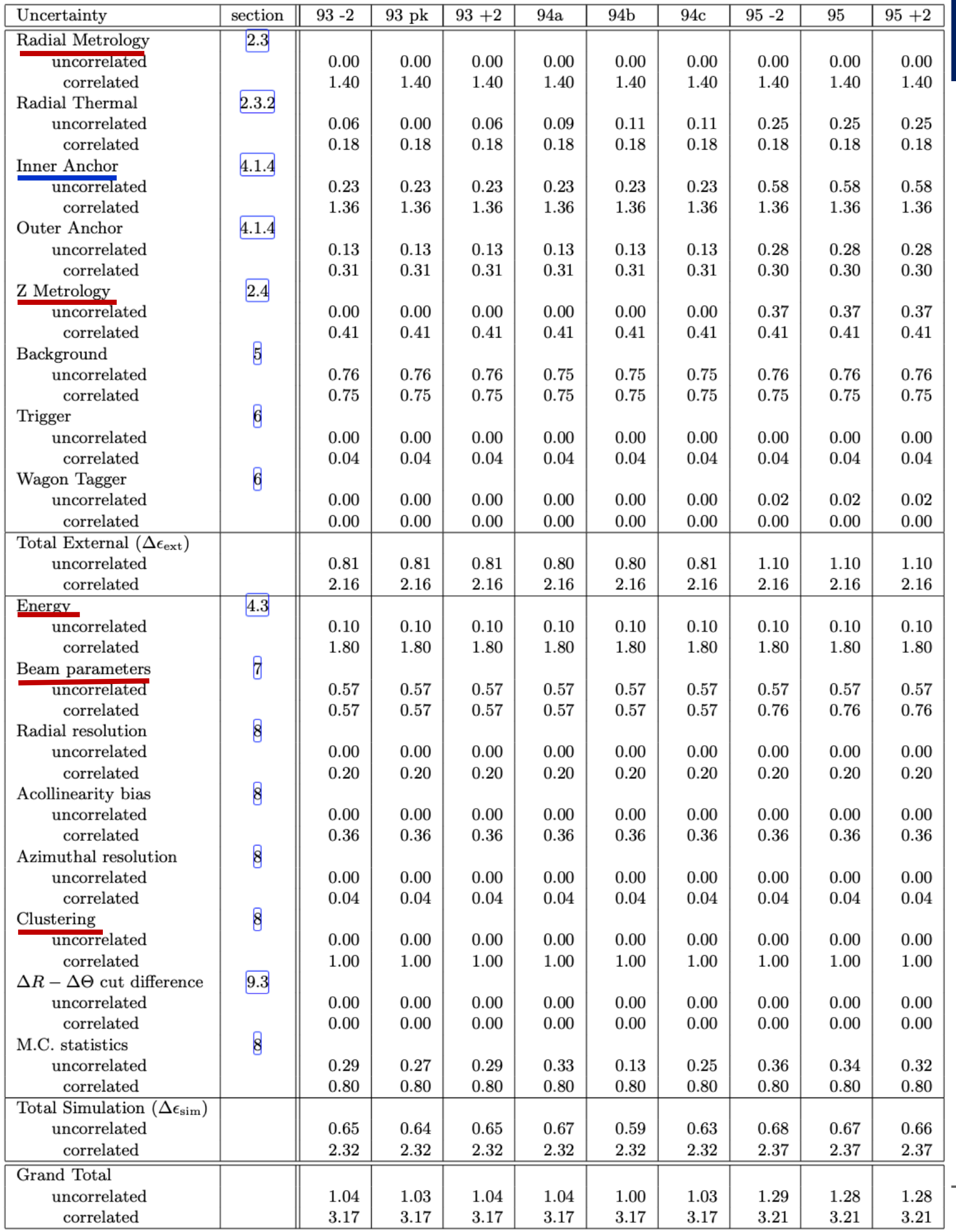
Via precise metrology, achieved 4.4 µm precision on inner acceptance border

# OPAL Summary of Systematics

× $10^{-4}$



| Quantity | Relative statistical error ($\times10^{-4}$) | Relative Systematic error ($\times10^{-4}$) |
|---|---|---|
| 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 |



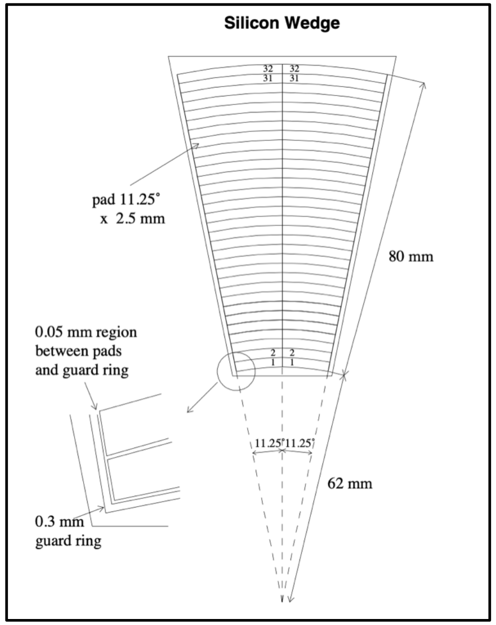
| Uncertainty | section | 93 -2 | 93 pk | 93 +2 | 94a | 94b | 94c | 95 -2 | 95 | 95 +2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Radial Metrology | 2.3 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 1.40 | 1.40 | 1.40 | 1.40 | 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 |

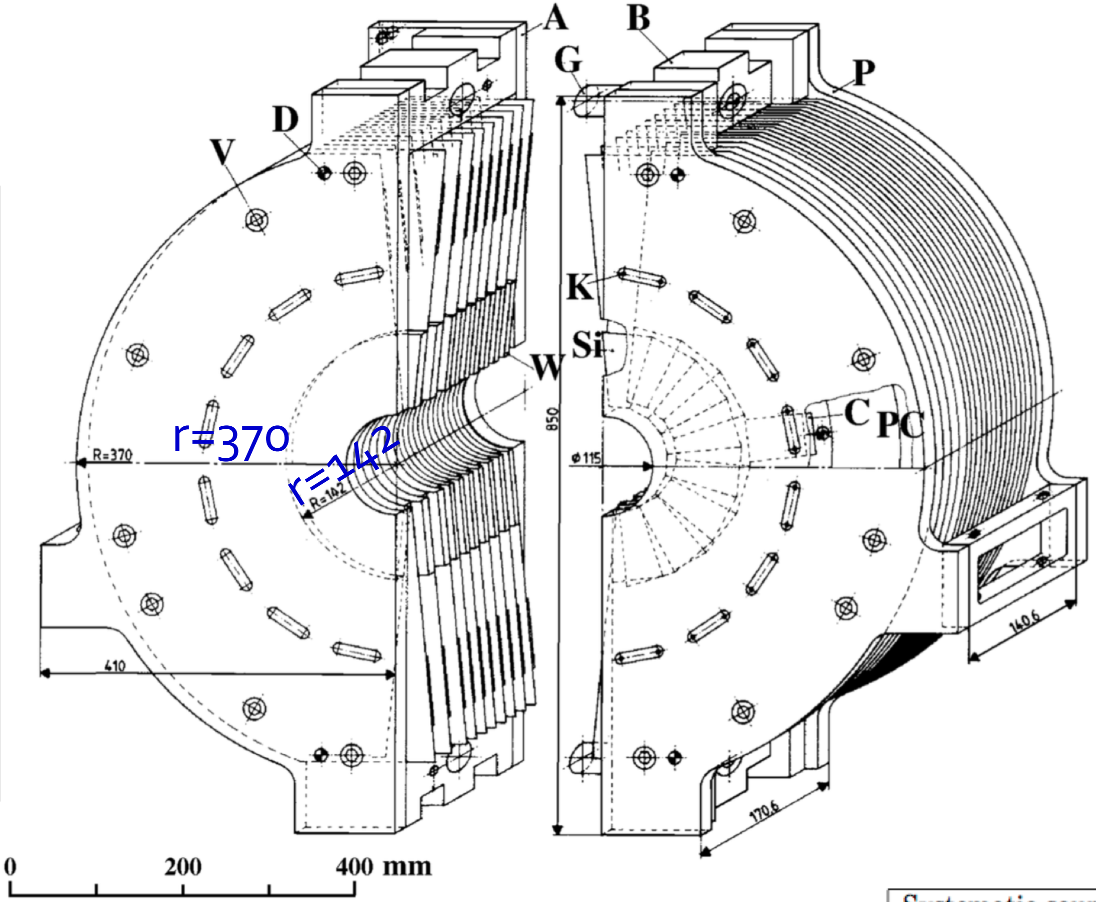
Table 24: This table summarizes the experimental systematic uncertainties on the absolute $L_{\text{RL}}$ luminosity measurement for the nine data samples. The lines labeled correlated and uncorrelated refer to errors correlated and uncorrelated among the samples. All errors are in units of $10^{-4}$.

# 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

Probably historical reason for large difference

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 | $1.4 \times 10^{-4}$ |

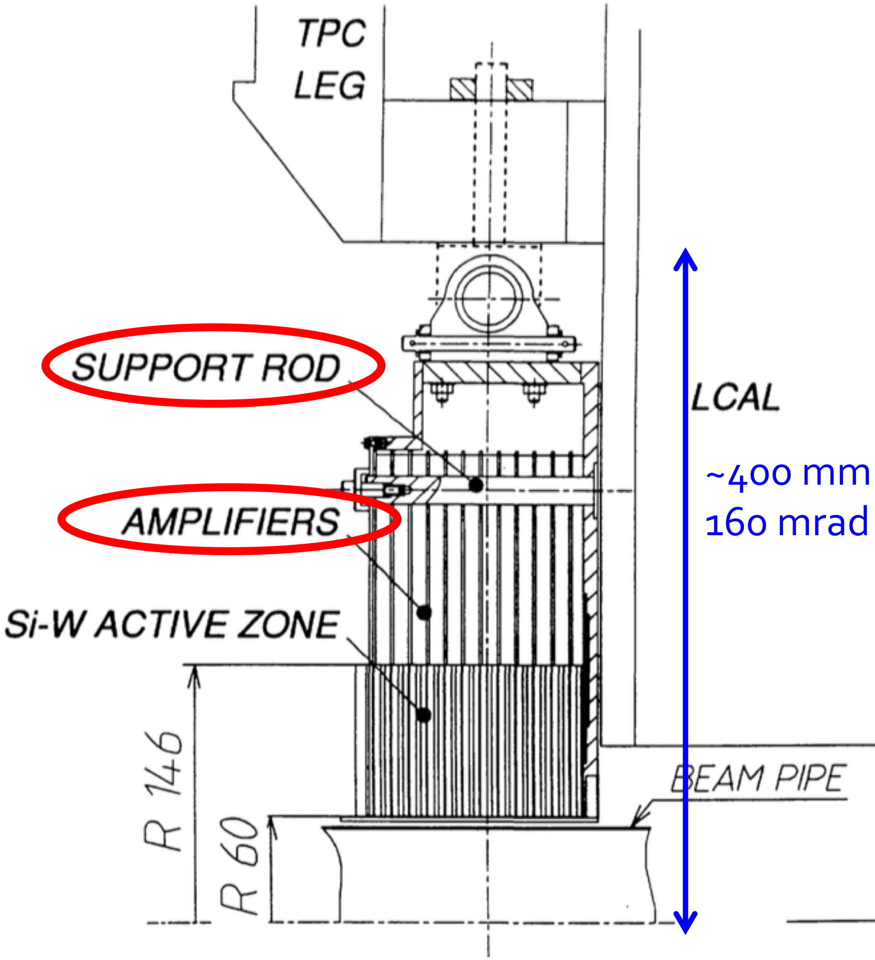
Systematics on z measurement

| 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 | $0.41 \times 10^{-4}$ | $0.55 \times 10^{-4}$ |

# Aleph SiCal Luminometer

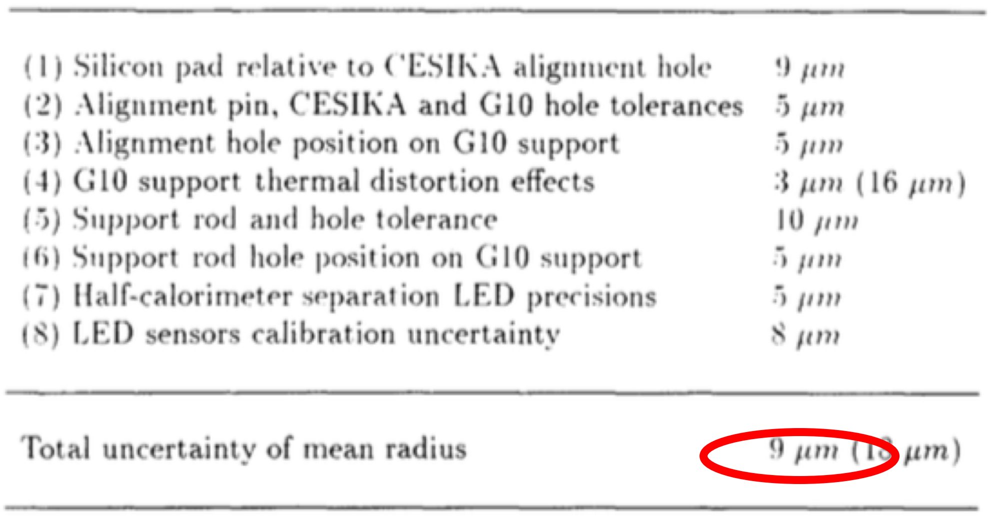
**Z = 250 cm**

Sensitive depth: 120 mm, 23 $X_0$
12 Si layers

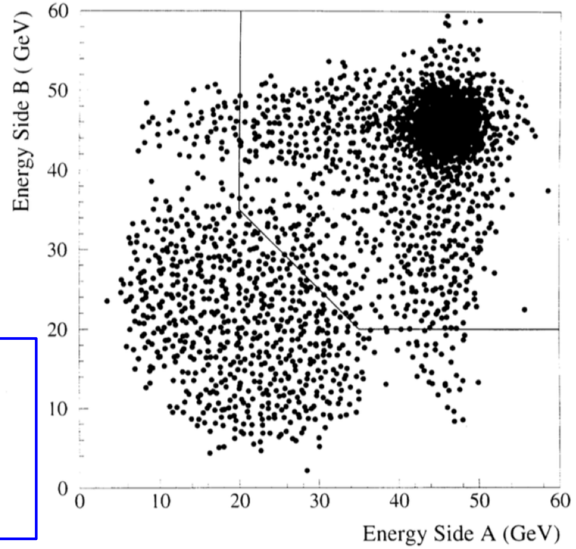


~400 mm @ z=2500 mm:
160 mrad

Radius uncertainty

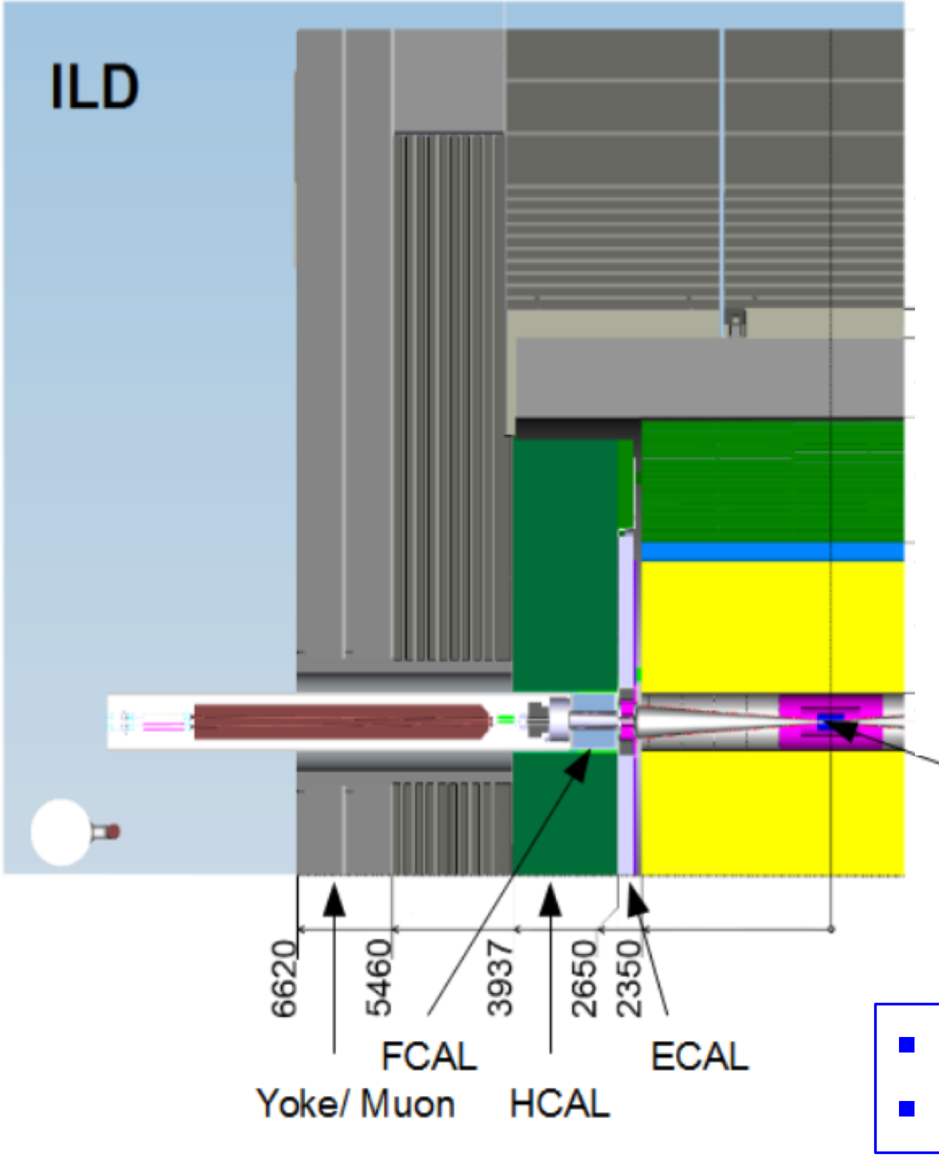


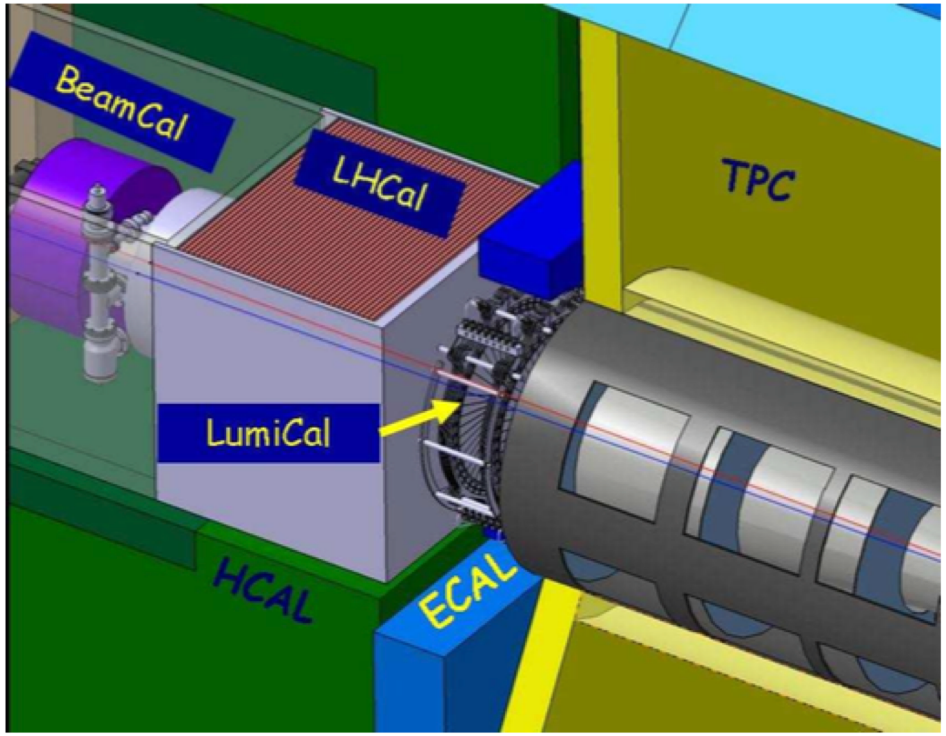
| | |
|---|---|
| (1) Silicon pad relative to CESIKA alignment hole | 9 $\mu m$ |
| (2) Alignment pin, CESIKA and G10 hole tolerances | 5 $\mu m$ |
| (3) Alignment hole position on G10 support | 5 $\mu m$ |
| (4) G10 support thermal distortion effects | 3 $\mu m$ (16 $\mu m$) |
| (5) Support rod and hole tolerance | 10 $\mu m$ |
| (6) Support rod hole position on G10 support | 5 $\mu m$ |
| (7) Half-calorimeter separation LED precisions | 5 $\mu m$ |
| (8) LED sensors calibration uncertainty | 8 $\mu m$ |
| Total uncertainty of mean radius | 9 $\mu m$ (18 $\mu m$) |



As for OPAL, energy resolution not the best.
Realtively few Si layers.
Small sampling fraction

# ILD LumiCal (i)

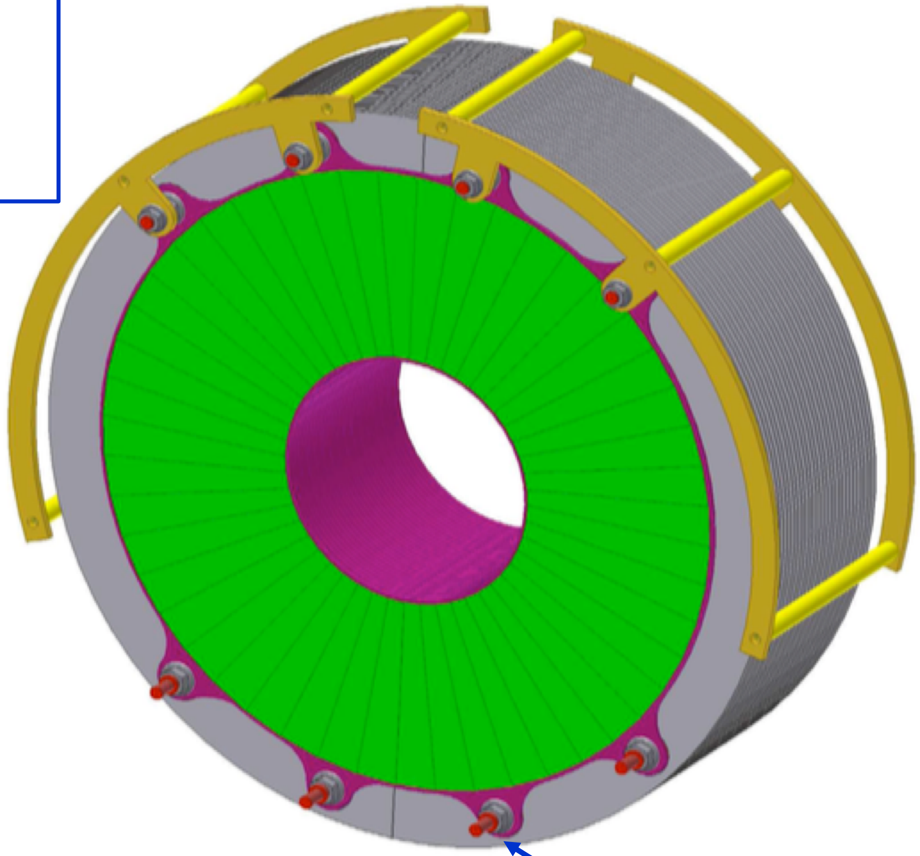




- z = 2350 mm **like rest of ECAL**
- Behind conical beam pipe: thin window

# ILD LumiCal (ii)

Information on this and following slide work of Crakow 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 |

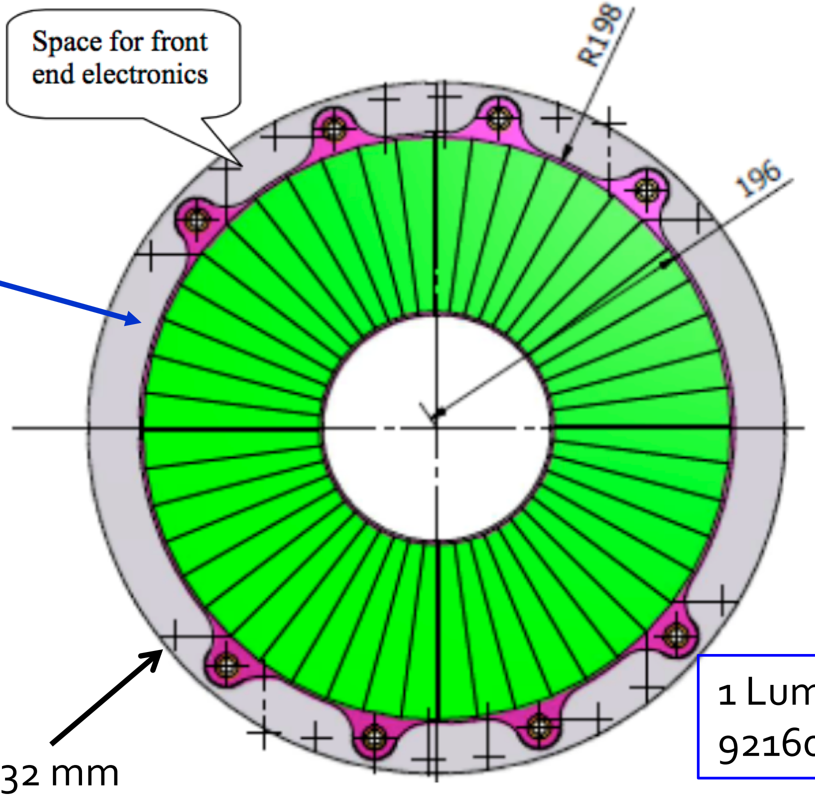
Inner radius:

| | |
|---|---|
| Sensitive: | 80 mm |
| Mechanical: | 76 mm |

Outer radius:

| | |
|---|---|
| Sensitive: | 195.2 mm |
| Mechanical: | ~260 mm |

# ILD LumiCal (ii)

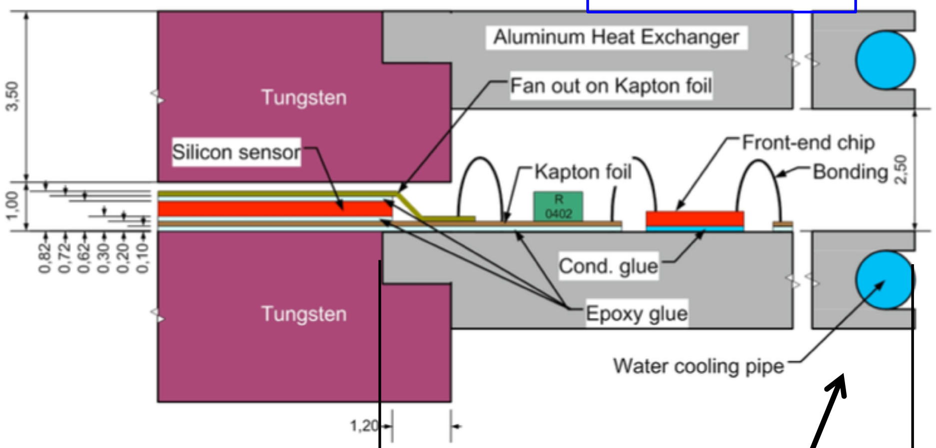


36 mm for assembly and electronics

232 mm

1 LumiCal:
92160 readout channels

128 channels



~11 mm

Note on cooling:

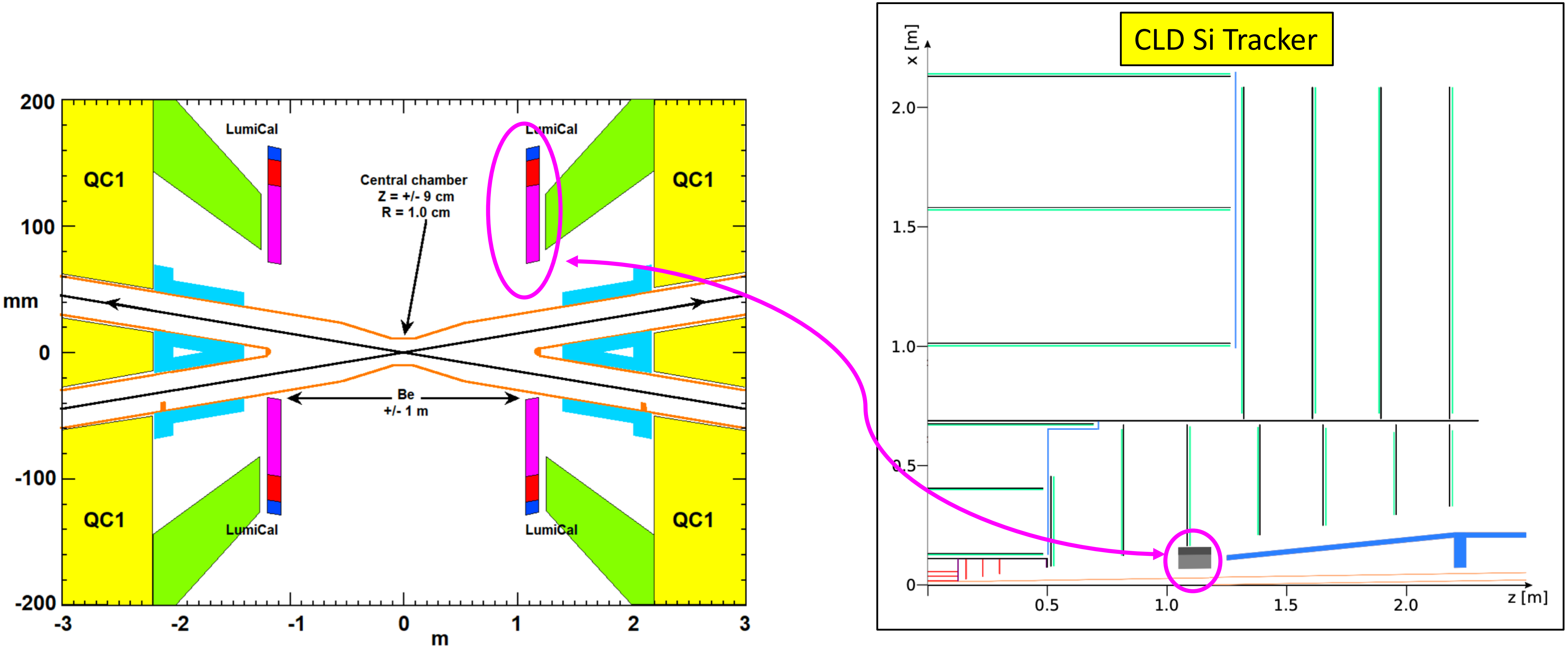
- Inner radius of acceptance varies by 0.33 µm/C°
- Temperature stabilization within 1 c° safe. Probably within 0.2 C°
- Total dissipated heat in one LumiCal: 30 W.
  - With power cycling: 1 ms active/199 ms breaks
- Water cooling: 15 l/min per LumiCal.

At FCC-ee, no power cycling.
Need more efficient cooling?
Space requirement?

# LumiCals @ FCC-ee

Challenge:

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



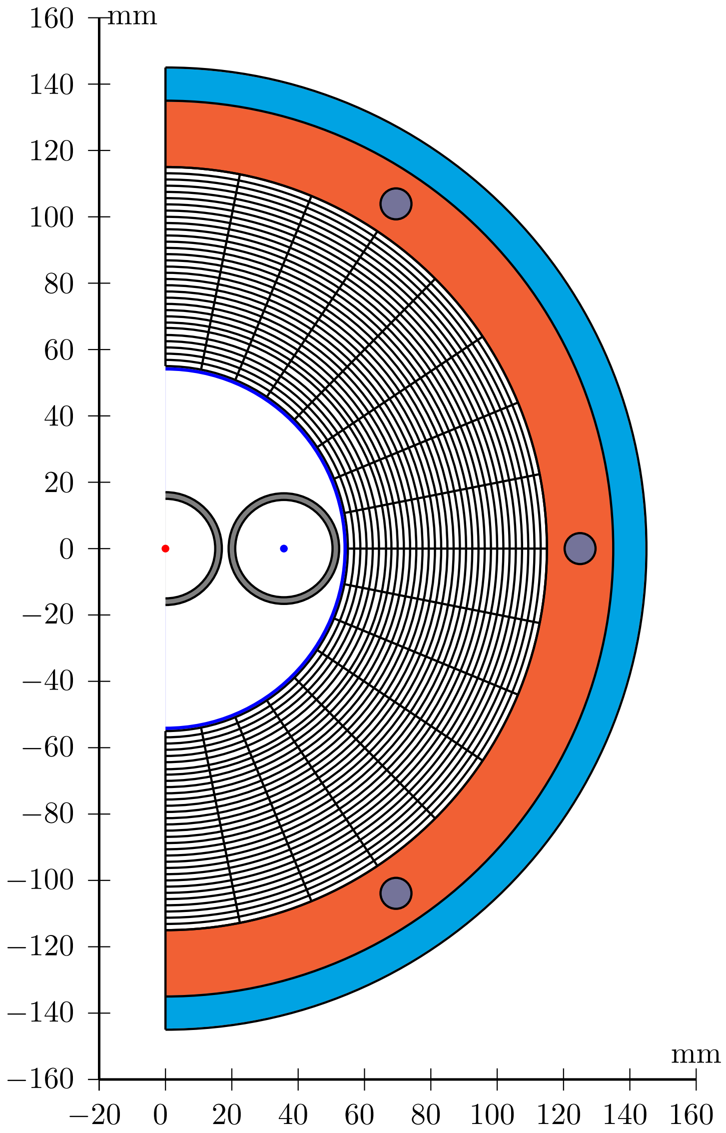
# CDR LumiCal Design

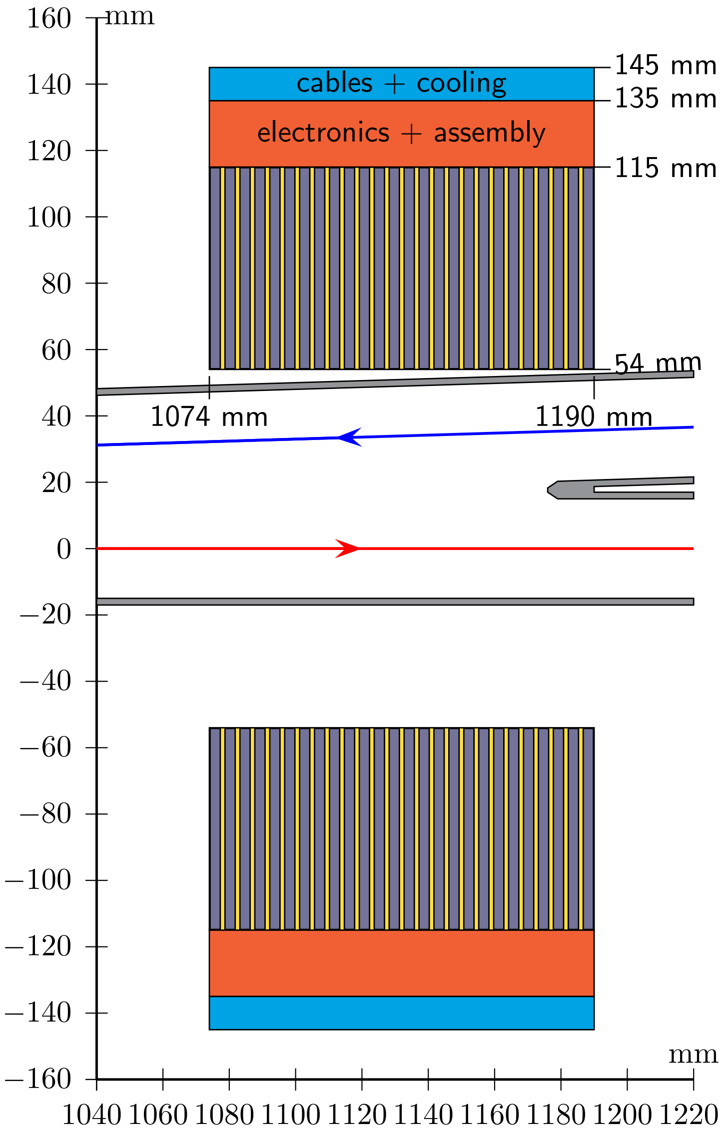
Design considerations:

- Need to control geometry to a precision of $\mathcal{O}(1\ \mu m)$
  - ❑ Keep geometry as simple as at all possible

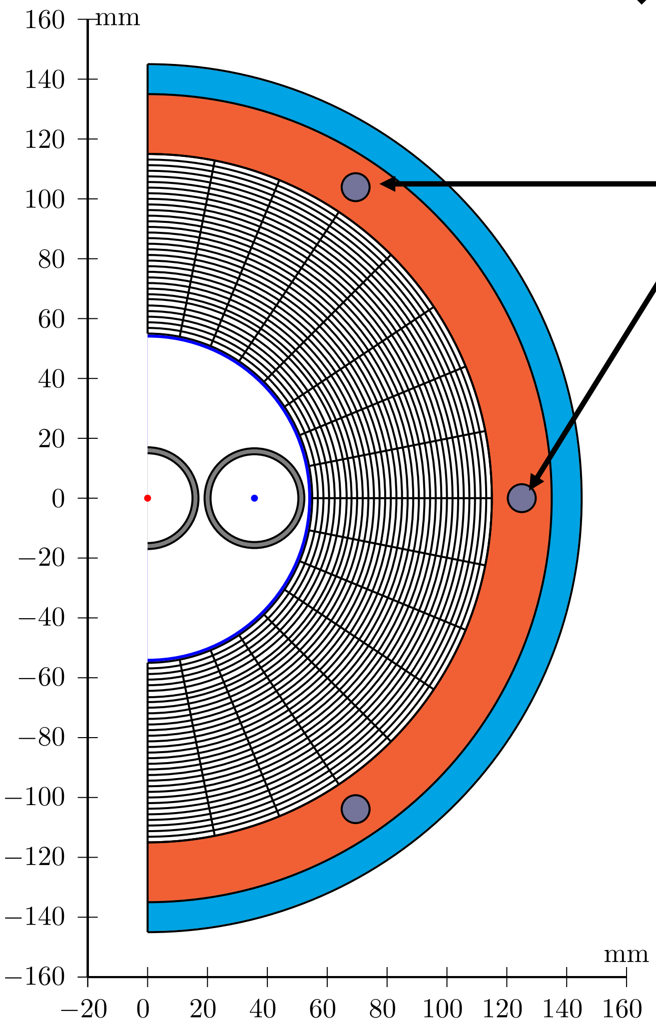
**Multilayer barrels where all layes have identical circular geometry**

- 25 layer SiW sandwich
  - ❑ 3.5 mm W (1 $X_0$) + 1.0 mm gap for Si pads
- Physical dimensions
  - ❑ Sensitive region: r = 54-115 mm
  - ❑ Region for ”services”: 115-145 mm
  - ❑ Calorimeter face at x = 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





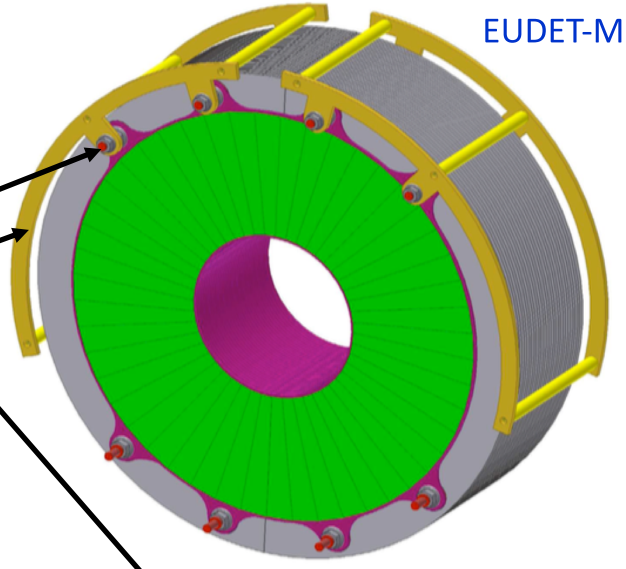
# LumiCal Assembly & Support

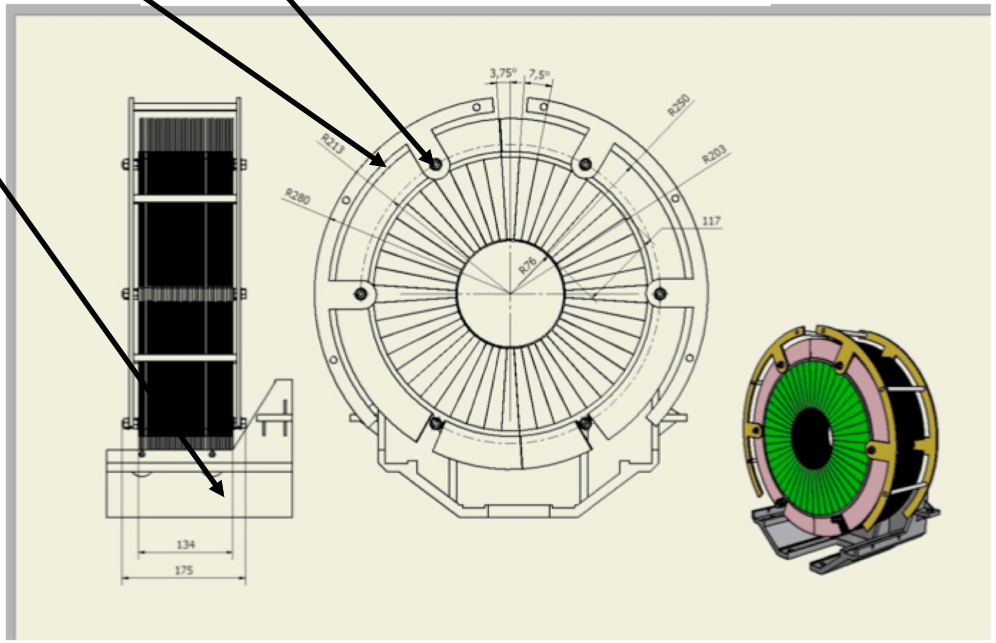


- Much engineering work to be done on this
  - ❑ Only thoughts so far
    - ❖ ”Bolts” needed to keep assembly together
  - ❑ However, ILC LCAL also has rails …
  - ❑ … and it is supported by a tray
  - ❑ At FCC-ee we do not like these items protruding further outwards
  - ❑ How can we support the assembly and still maintain the geometric tolerances?
    - ❖ Each end of bolts probably need external support to avoid sag under own weight

**Need for dedicated engineering effort!**

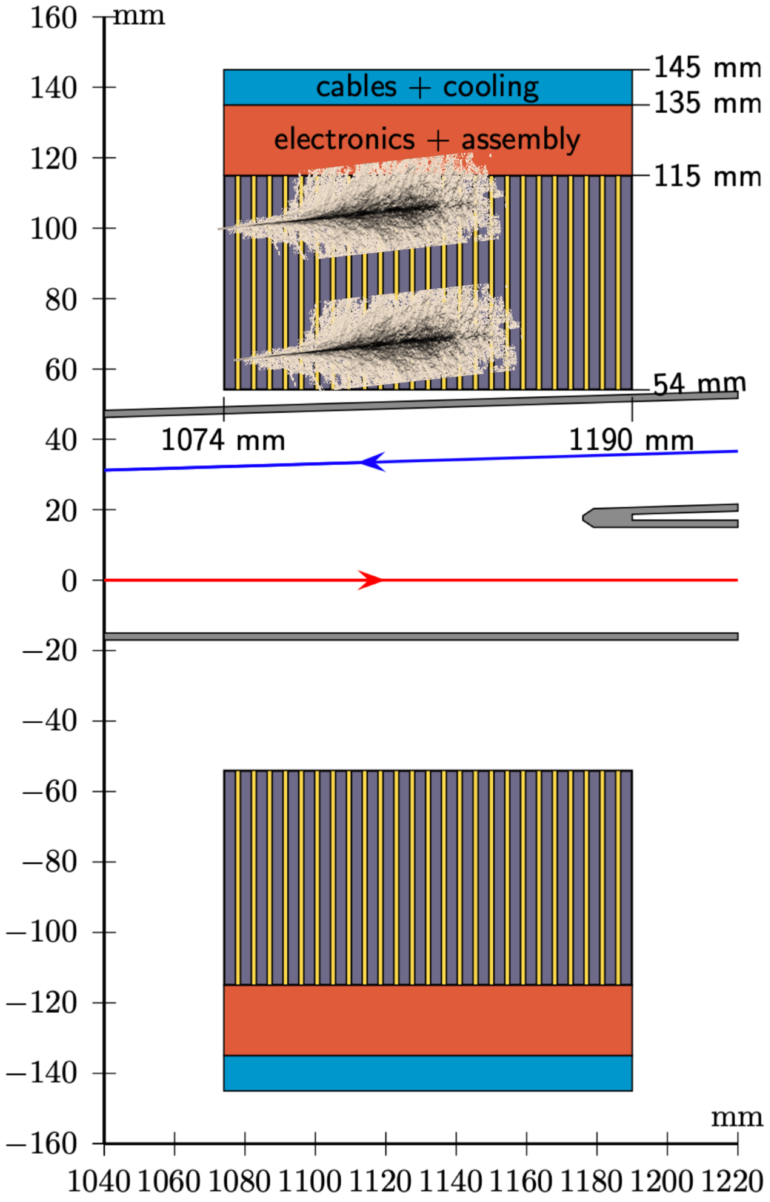
EUDET-Memo-2010-06



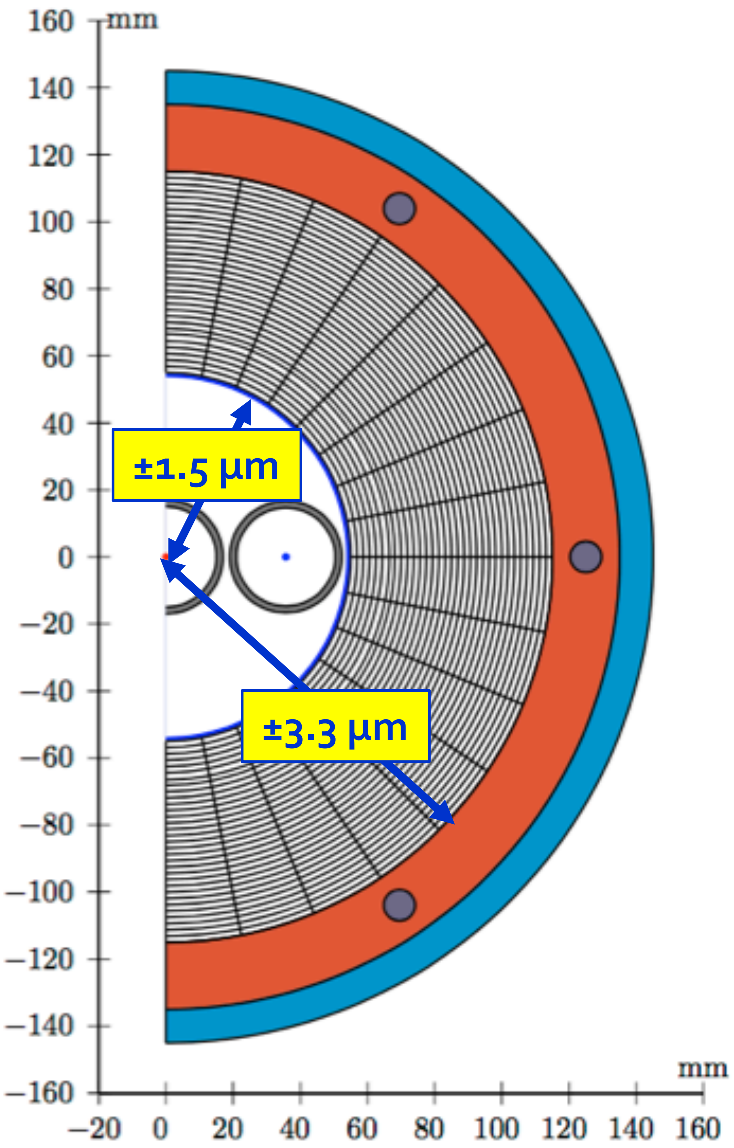


# Acceptance and tolerances

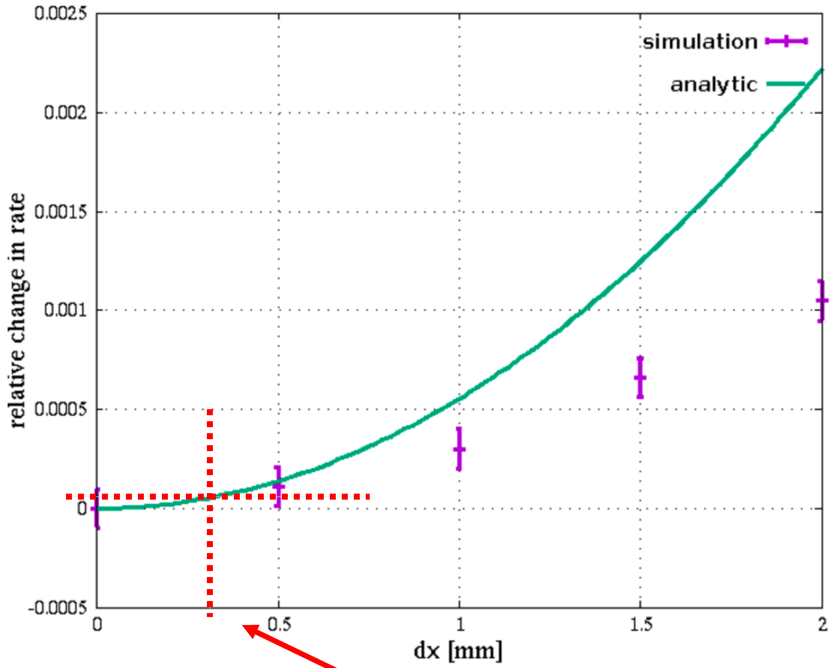
- Effective Moliere radius of W-Si sandwich: **~15 mm**
- Stay 1 Moliere radius away from both inner radius and somewhat more at outer radius
    - To be optimised
- => **Wide acceptance:** **62 – 88 mrad**
- Slightly smaller **narrow acceptance**: **64 – 86 mrad**
    - ☐ **Bhabha cross section: 14 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: $\delta Z$ = ± 55 µm**



# Geometric tolerances - radial



**Centering of calorimeters around beam line**

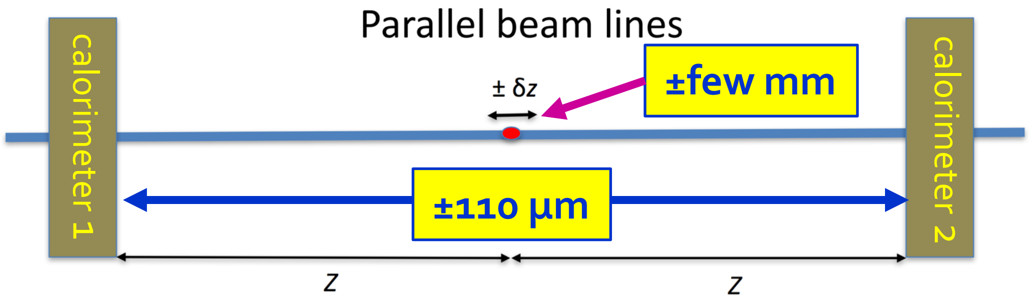


Simulation study:
Bhlumi + simple
shower emulation

Transverse shifts should be δr < 300 µm

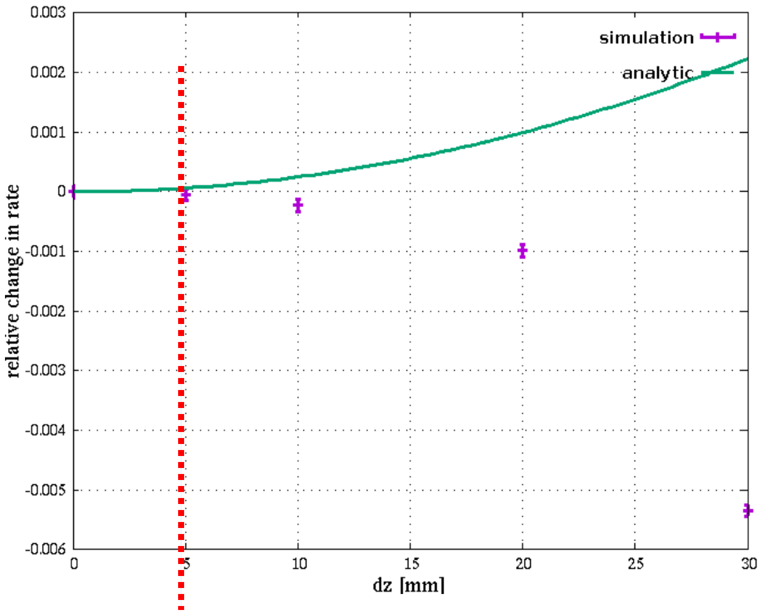
# Geometric tolerances – longitudinal

First, consider example of parallel beams



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

Simulation study:
Bhlumi + simple
shower emulation

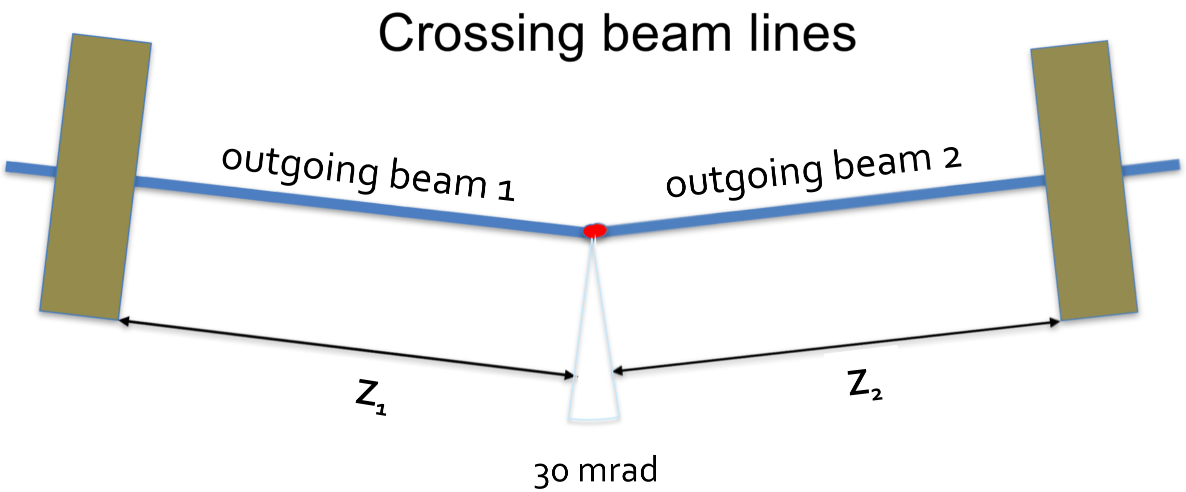


Longitudinal shifts of IP position up to few mm are tolerable

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

Analytic (lowest order) calculation not precise.
Even sign is wrong.
This because of radiation 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**
- Drift of the IP of the order of few mm in the ”longitudinal” direction still tolerable
  - Of course, now, longitudinal and transverse coordinates are (weakly) coupled

**Notice:**

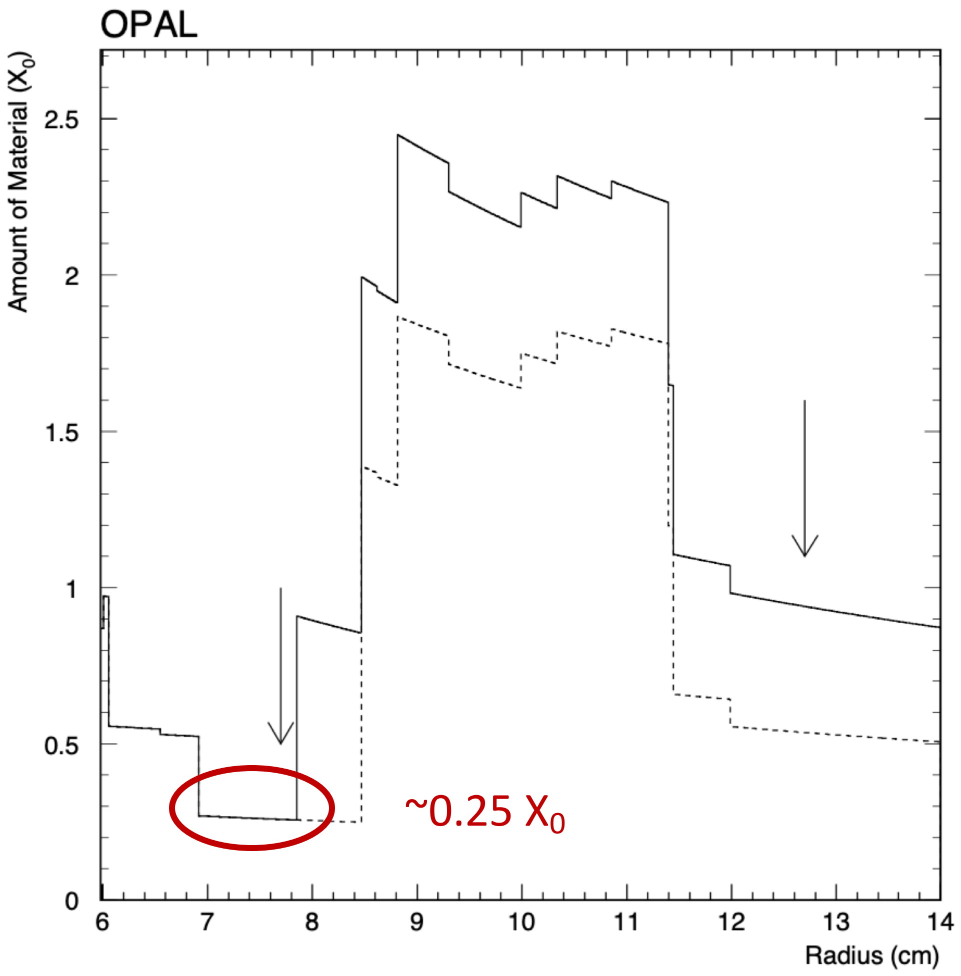
- As indicated, the face of each LumiCals shall be perpendicular to the corresponding outgoing beam line.
- The two faces will not be parallel, they are each tilted by 15 mrad w.r.t. the global coordinate system.

# Summary of geometric tolerances

- **Geometric tolerance on (system of two) LumiCals:**
  - **Inner radius: $\delta R_{min} = \pm 1.5\ \mu m$**
  - **Outer radius: $\delta R_{min} = \pm 3.3\ \mu m$**
  - **Longitudinal distance between each LumiCal and nominal IP: $\delta Z = \pm 55\ \mu m$**
    - This is a challenge: the z of the LumiCal shall be the z defining the shower position measurement.

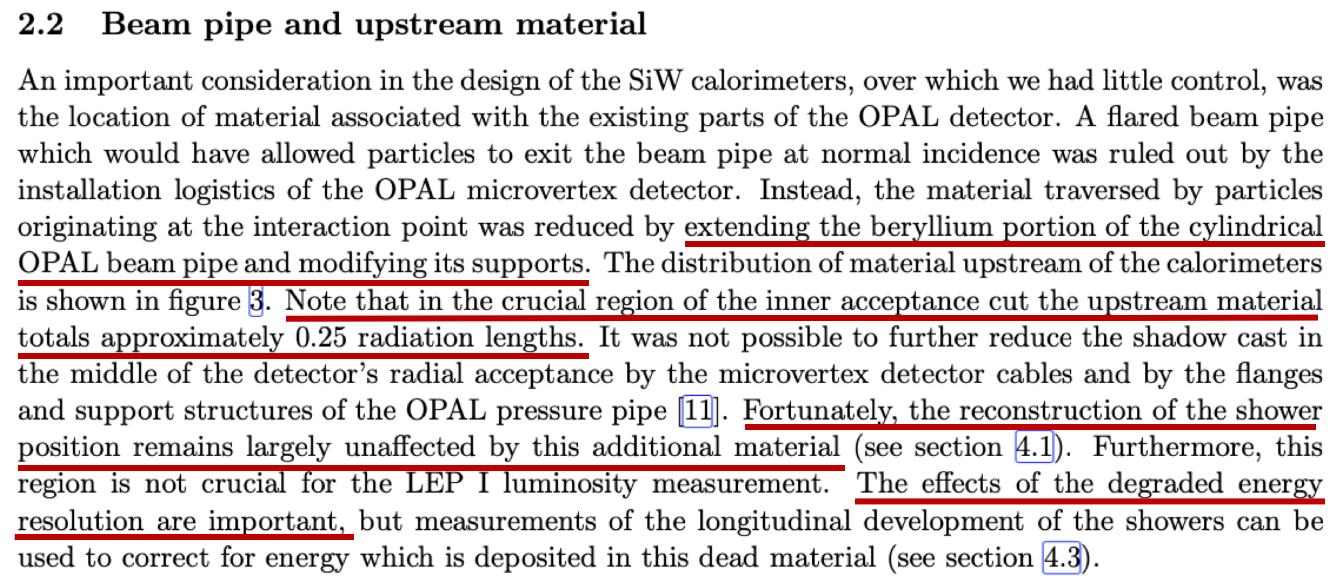
- **Geometric tolerance of IP position w.r.t. LumiCal system:**
  - **Transverse: few tenths of a mm**
  - **Longitudinal: few mm**

# OPAL: Material in front of LumiCals



~0.25 $X_0$

Figure 3: The calculated material traversed by particles originating at the interaction point as a function of calorimeter radius, measured at the reference plane (246 cm) for the 1993–1994 detector configuration. The solid curve corresponds to the left, the dotted curve to the right side. The larger amount of material on the left is due to the passage of cables from the OPAL microvertex detector. The arrows show the location of the acceptance definition cuts on shower radius.

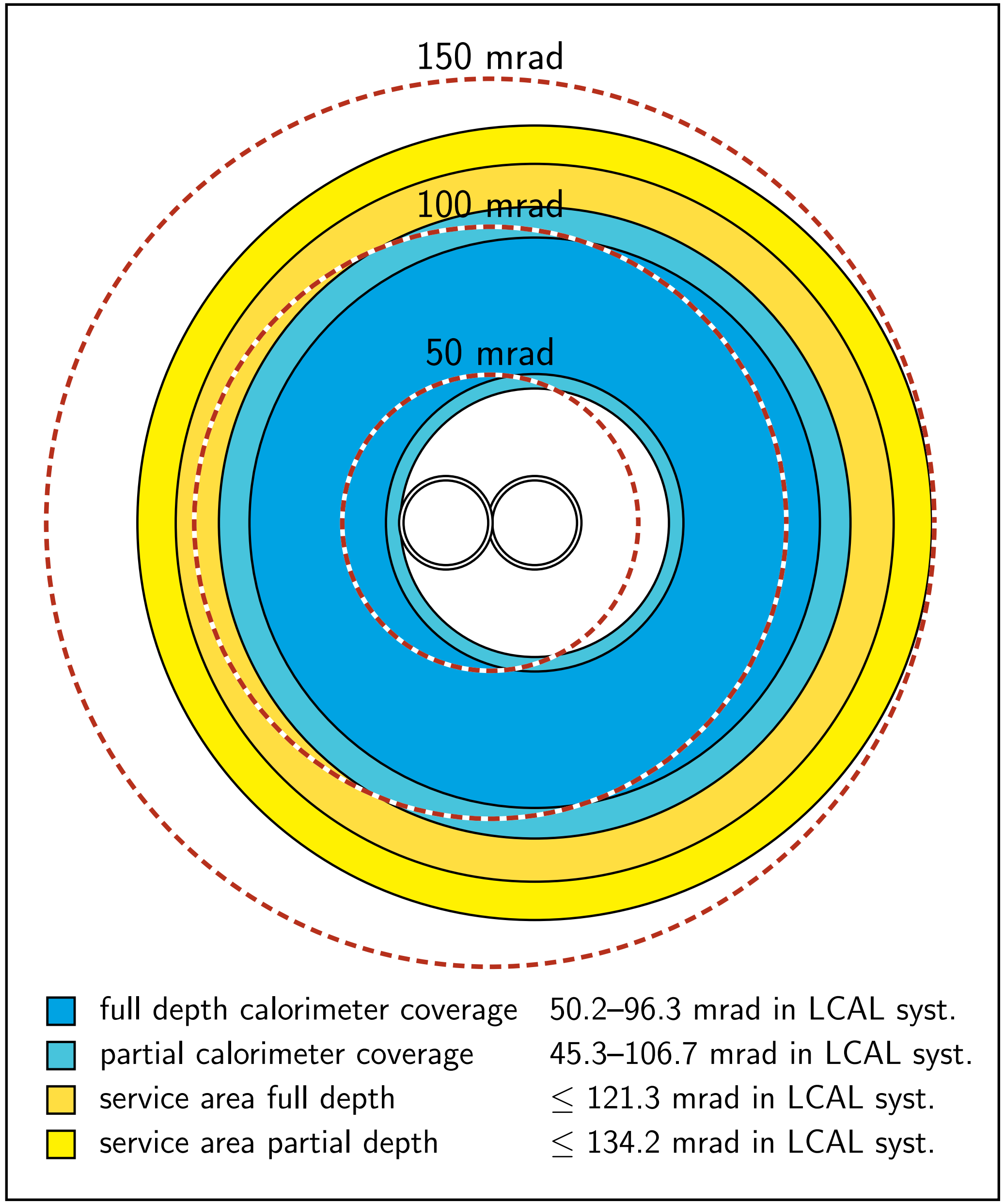


### 2.2 Beam pipe and upstream material

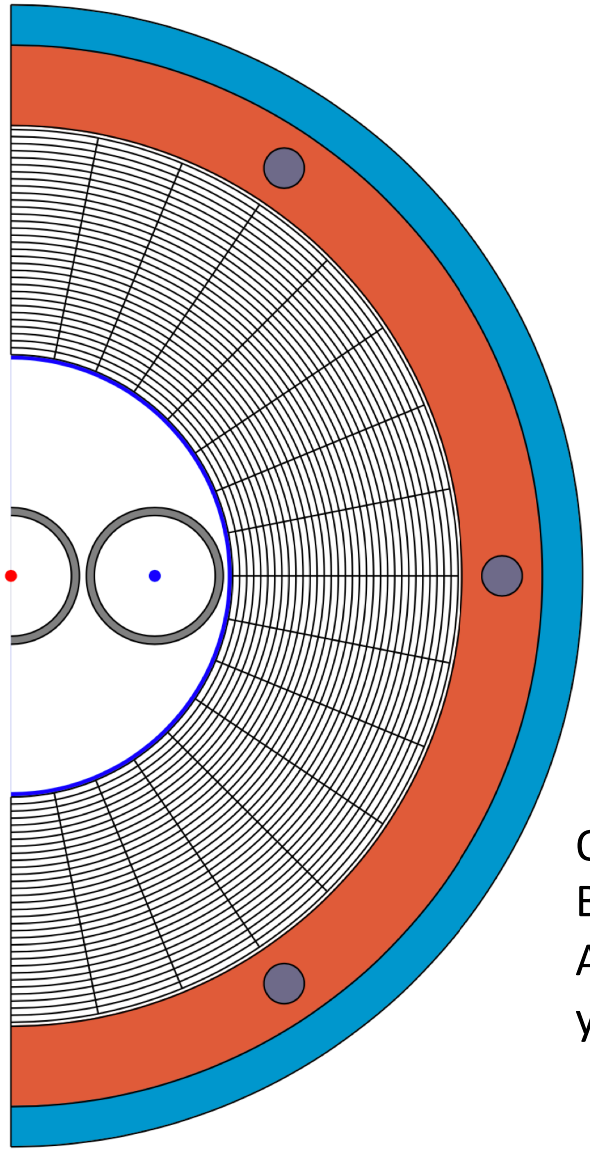
An important consideration in the design of the SiW calorimeters, over which we had little control, was the location of material associated with the existing parts of the OPAL detector. A flared beam pipe which would have allowed particles to exit the beam pipe at normal incidence was ruled out by the installation logistics of the OPAL microvertex detector. Instead, the material traversed by particles originating at the interaction point was reduced by extending the beryllium portion of the cylindrical OPAL beam pipe and modifying its supports. The distribution of material upstream of the calorimeters is shown in figure 3. Note that in the crucial region of the inner acceptance cut the upstream material totals approximately 0.25 radiation lengths. It was not possible to further reduce the shadow cast in the middle of the detector's radial acceptance by the microvertex detector cables and by the flanges and support structures of the OPAL pressure pipe [11]. Fortunately, the reconstruction of the shower position remains largely unaffected by this additional material (see section 4.1). Furthermore, this region is not crucial for the LEP I luminosity measurement. The effects of the degraded energy resolution are important, but measurements of the longitudinal development of the showers can be used to correct for energy which is deposited in this dead material (see section 4.3).

# Problems with CDR LumiCal design

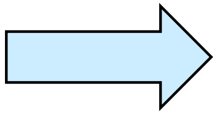
- Stays inside 100 mrad cone around z-axis (bisector of beam lines)?
  - Certainly not!
- Stay inside 150 mrad cone around z-axis ?
  - Yes, per design!
  - Interfers with tracker acceptance below this angle
- Sits assymetric w.r.t. the main detector symmetry axis
  - Actually it is the LumiCal which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



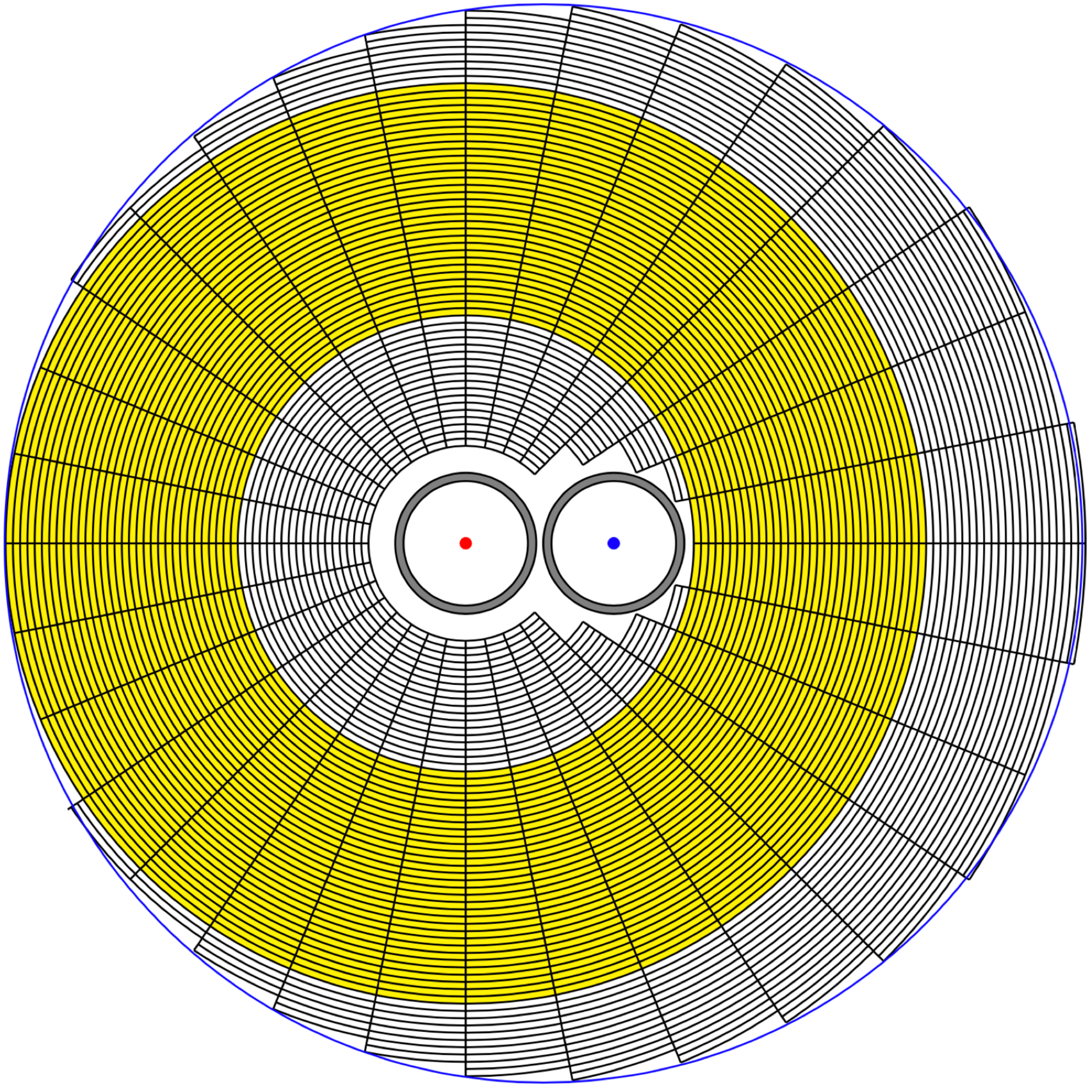
# Centered on outgoing beam but still "symmetric" in global system



Pads shown in yellow identical between two drawings



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



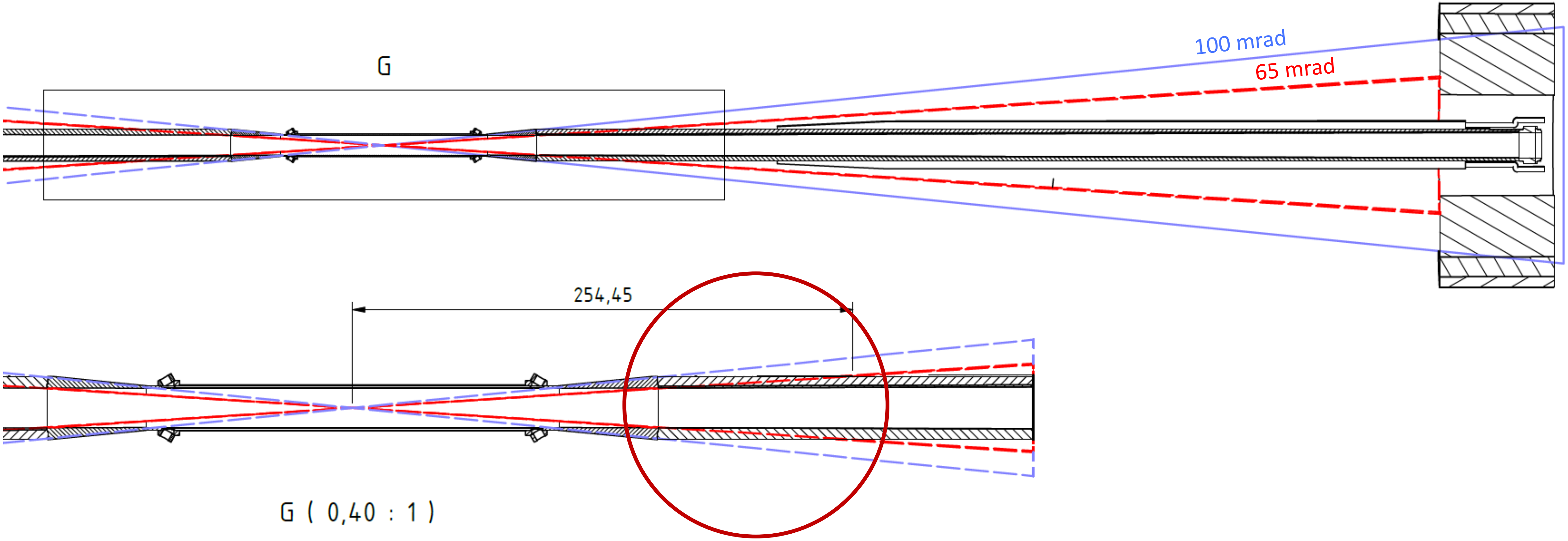
Coverage from global θ = ~35 to 110 mrad for all ϕ

# Conclusions

- Very ambitious FCC-ee absolute normalisation goal of $10^{-4}$
  - Best at LEP was OPAL at $3.4 \times 10^{-4}$ with their second generator monitors and a huge analysis effort
- Compared to LEP, the FCC-ee LumiCals are placed in a much more complicated position
  - Just above z=1 m from the IP, right inside the general detector volume
- Challenges
  - Detector geometry to be controlled to $\mathcal{O}$(1 μm) in radius [4.4 μm achieved in OPAL]
    - Can in principle produce each (half) sensor layer from a single 10 inch Si wafer
  - Distance between two monitors to be controlled to $\mathcal{O}$(100 μm) [100-140 μm achieved in OPAL]
    - Tolerances refer to the sensitive layer(s) that determine the scattering angle
  - CDR LumiCal design squeezed from two sides
    - Stay away from beam pipe + stay inside 150 mrad cone
    - Visible cross section rather small: 14 nb compared to 30 nb for Z → qq
  - No engineering design perfromed for CDR LumiCals
    - Electronics, cooling, …
    - Mechanics: assembly, tolerances, support, …
      - How to construct adequate support without protruding further into detector region
      - …
  - And even if we had a such design, there are problems with detector hermeticity
    - Coverage towards very small angles
    - Overlap with lower edge of forward ECAL

# Extra slides

# Beam pipe side view

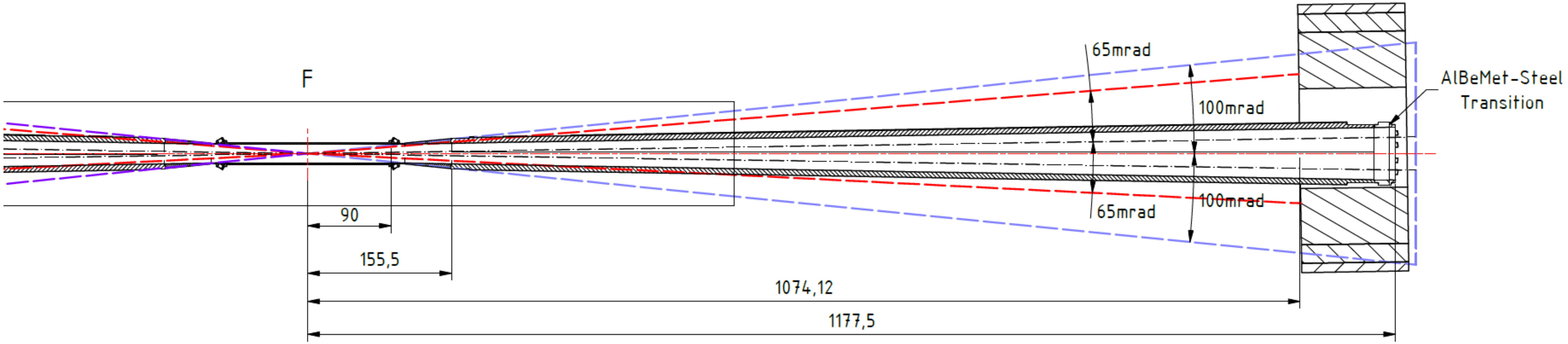


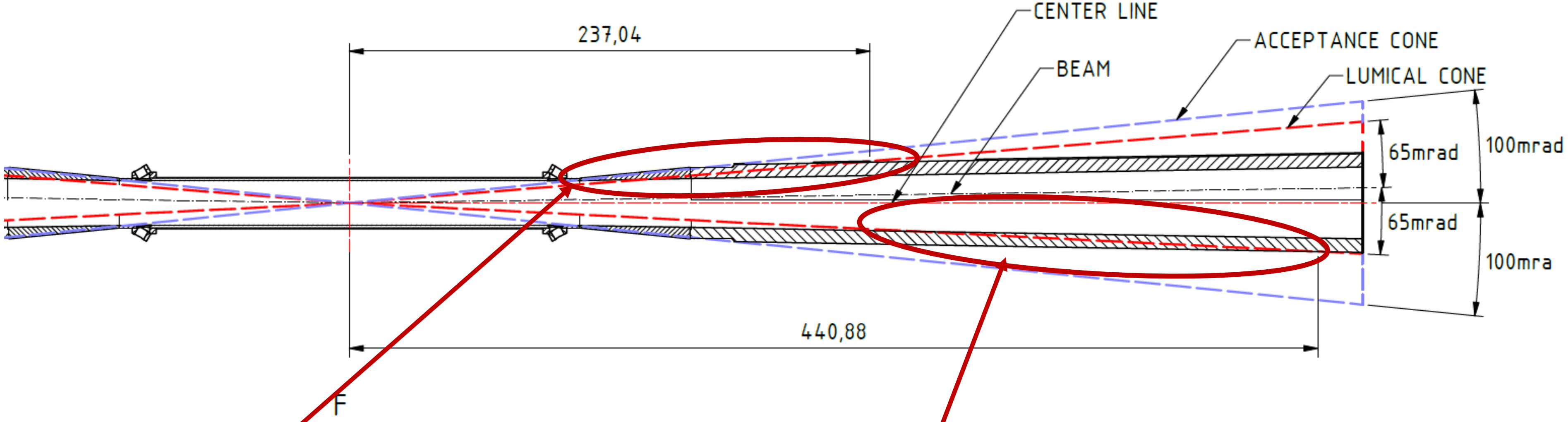
At minimum acceptance angle, $\theta_{min} \simeq 60$ mrad, electrons will see a material length $L = d/\theta_{min} \simeq 17 * d$

d: material thickness. Looks from drawing to be 6 mm => L = 100 mm

Radiation length of AlBeMet: ~ 200 mm [compared to Al: 90 mm]. **Electrons will see 0.5 X0.**

# Beam pipe top view





Sees ~ 100 mm AlBeMet => **0.5 X0**

Crosses at (60 – 2*15 mrad) = 30 mrad. Sees 200 mm AlBeMet => **1 X0**

# What does this material do

- Secondary interactions
  - Calorimeter is sensitive to direction of energy, which will be much less affected that direction of electric charge
  - However, we are also sensitive to deposited energy (energy cut for signal vs. background)
  - Have to be studied with full geant4 simulation.
- Multiple scattering
  - Gaussian approximation

$$\boxed{\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]}$$

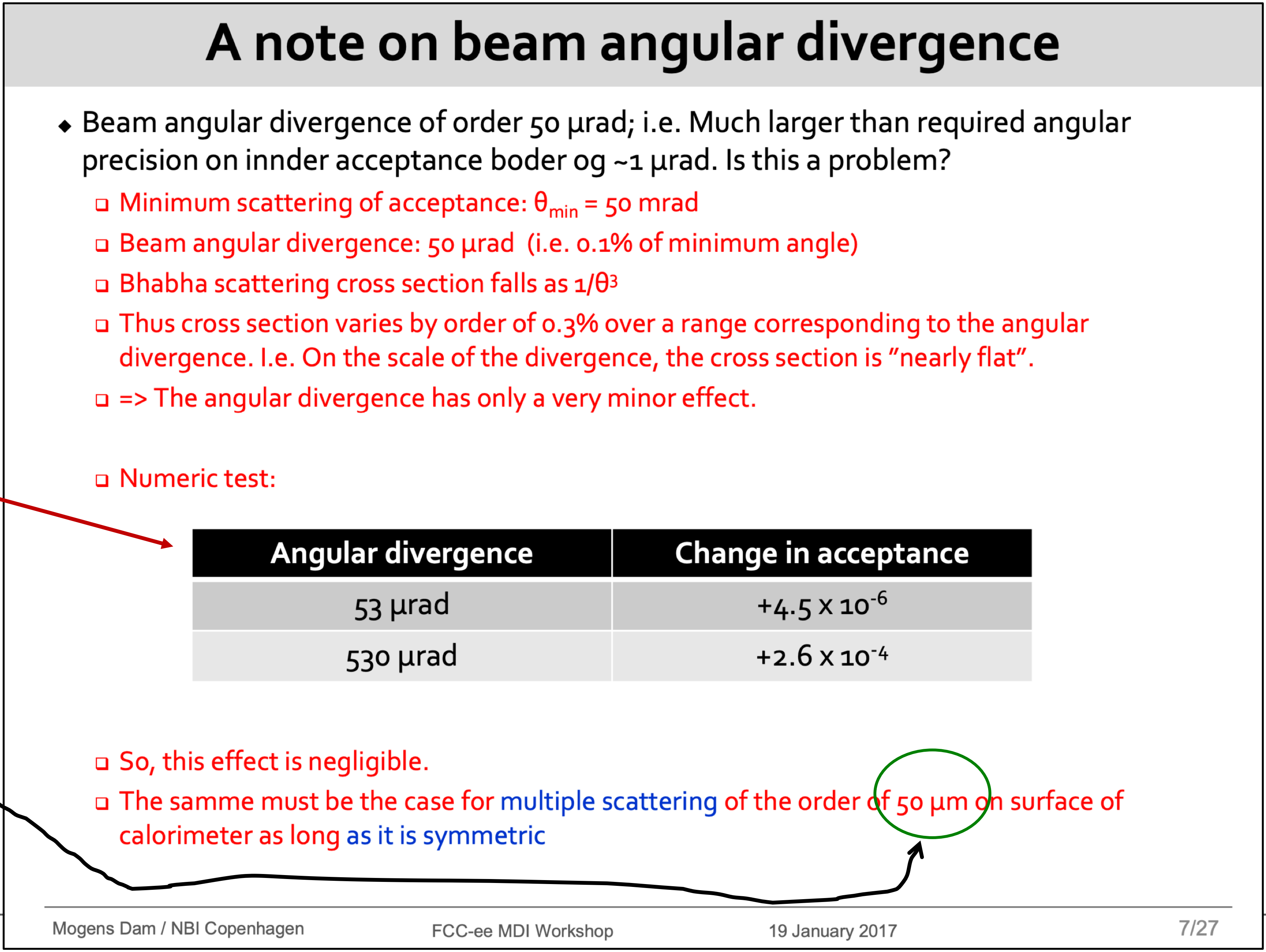
  - Hence, for p=45.6 GeV, $\theta_0$ = 300 µrad
  - Electrons will fly ~80 mm after leaving pipe material. RMS scattering : **δr = 240 µm**

  - Remember, that we need to measure average scattering angle around 60 mrad to 1 µm.
    - Is a 240 µm smearing from MS then not a problem?

# Multiple scattering and the precision luminosity measurement

A 5 year old slide

- As I commented then, the effect of MS is equivalent to that of beam divergence.
- Effect on visible acceptance seems to scale ~ quadratic in strength of scattering
- So, for 240 µrad (240 µm over 1 m), expects a $10^{-4}$ effect.
  - Starting to become an important effecgt we have to watch.
- Five years ago, I had much more optimistic (naive!) expectations



## A note on beam angular divergence

- Beam angular divergence of order 50 µrad; i.e. Much larger than required angular precision on innder acceptance boder og ~1 µrad. Is this a problem?
  - Minimum scattering of acceptance: $\theta_{min}$ = 50 mrad
  - Beam angular divergence: 50 µrad (i.e. 0.1% of minimum angle)
  - Bhabha scattering cross section falls as $1/\theta^3$
  - Thus cross section varies by order of 0.3% over a range corresponding to the angular divergence. I.e. On the scale of the divergence, the cross section is "nearly flat".
  - => The angular divergence has only a very minor effect.

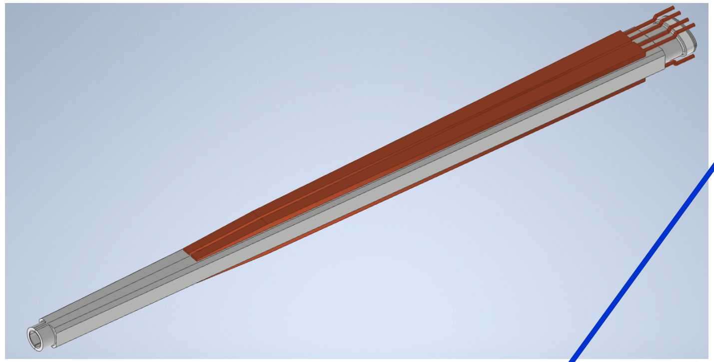
  - Numeric test:

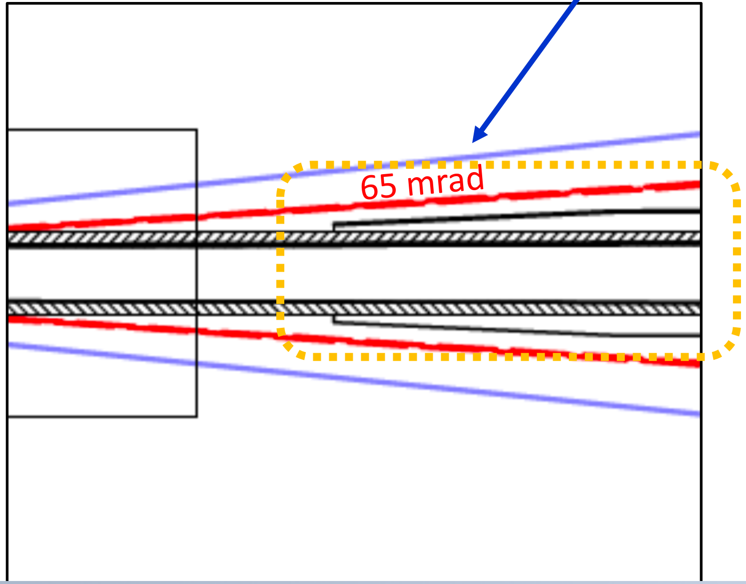
| Angular divergence | Change in acceptance |
|---|---|
| 53 µrad | $+4.5 \times 10^{-6}$ |
| 530 µrad | $+2.6 \times 10^{-4}$ |

  - So, this effect is negligible.
  - The samme must be the case for multiple scattering of the order of 50 µm on surface of calorimeter as long as it is symmetric

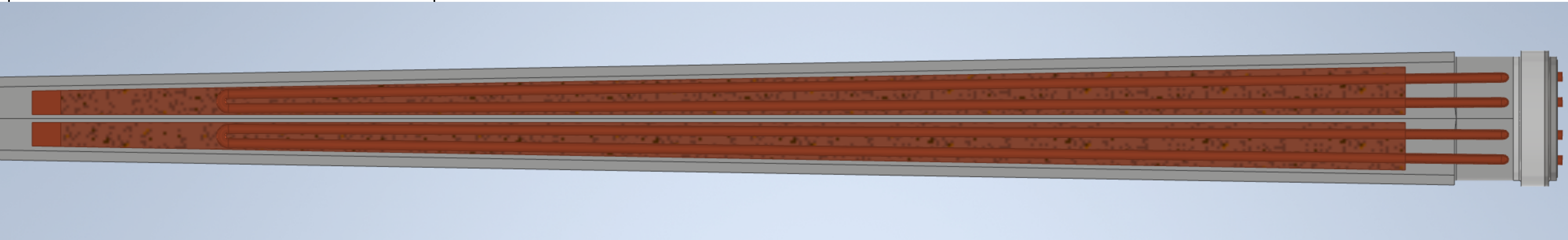
Mogens Dam / NBI Copenhagen FCC-ee MDI Workshop 19 January 2017 7/27

# Cooling manifold

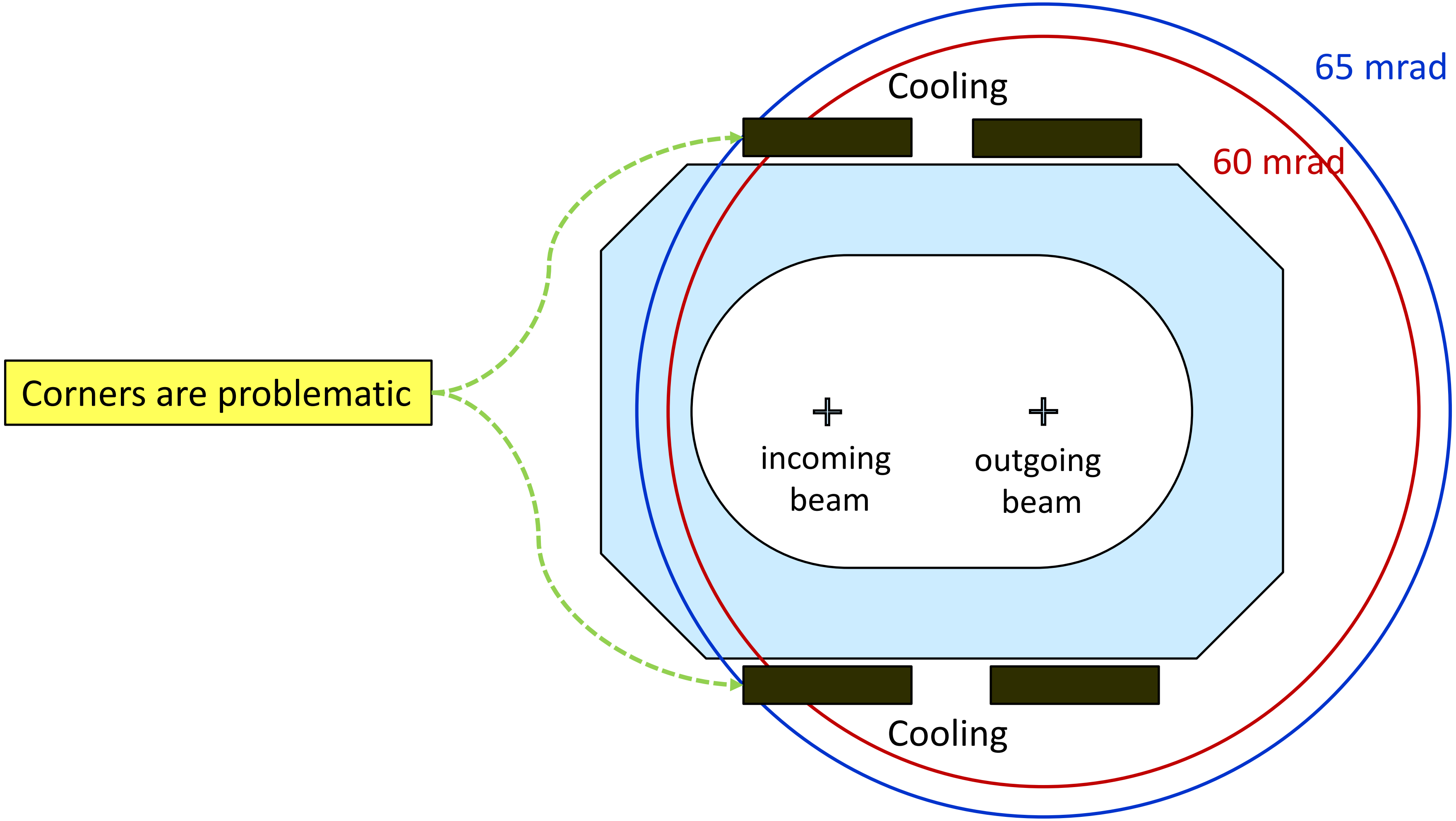




- Cooling manifold not touching 60 mrad (or even 60 mrad) opening in vertical plane
- However, ”corners” extend beyond
  - Trying to understand, see next page



# My understanding of situation at z ≃ 400 mm where cooling starts

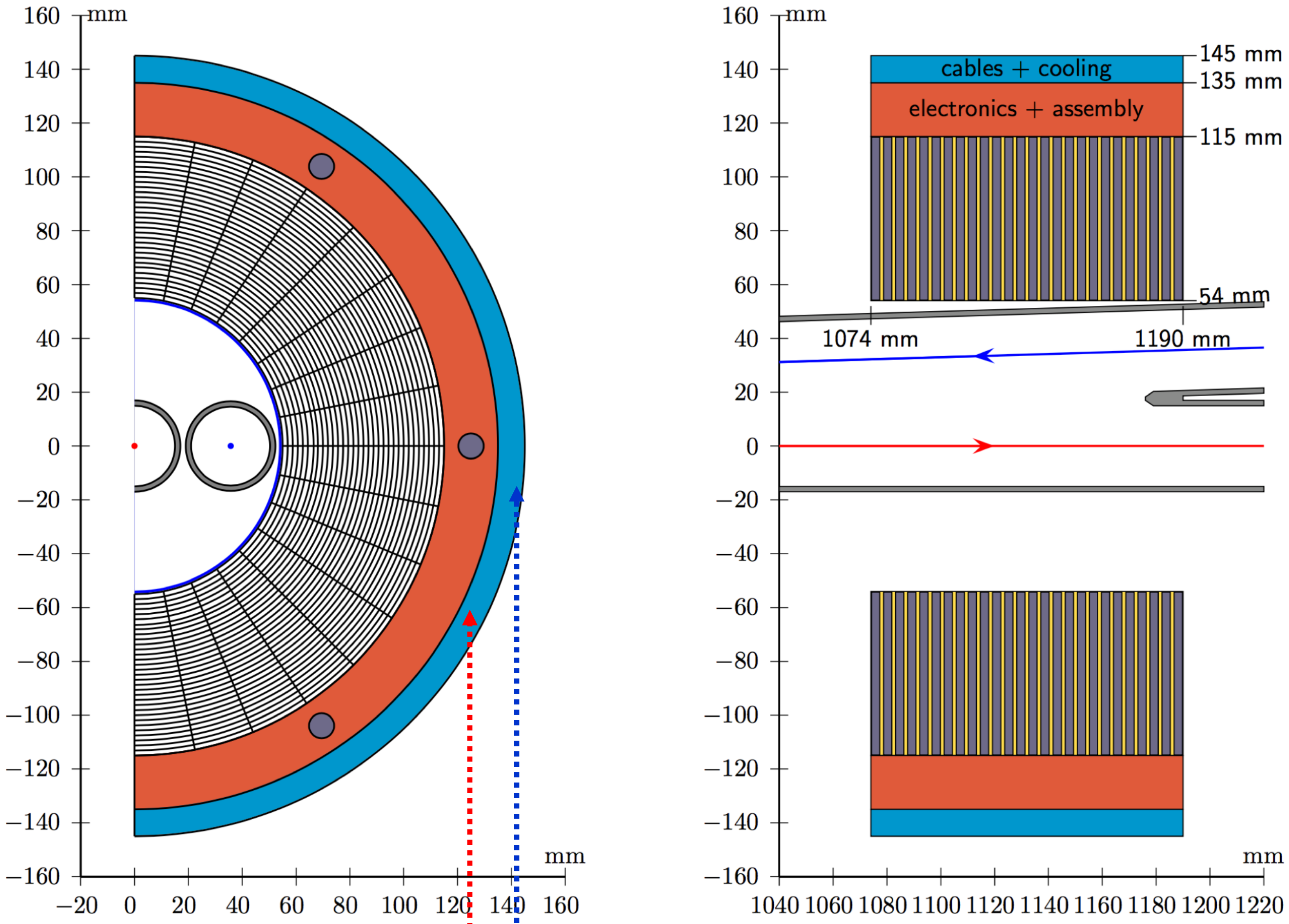


Mitigation (?)

- Simply cool along outgoing beam direction, and rely on transverse heat transport in AlBeMet
- Avoid serparate cooling manifold. Micro (or in this case, mini) channel cooling in beam pipe material.
- Cooling manifold from lighter material: AlBeMet, carbin fibre, …
- …

# 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?)

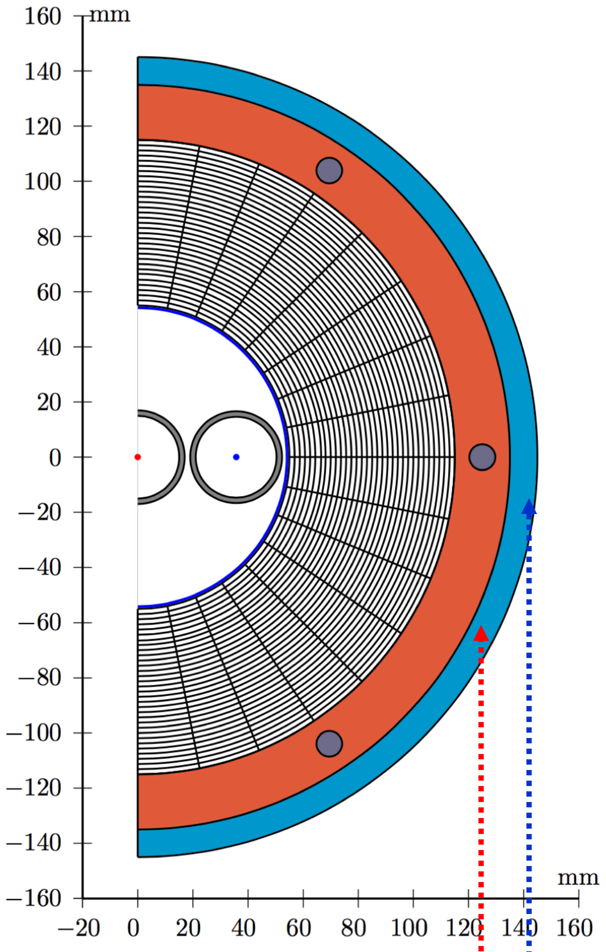


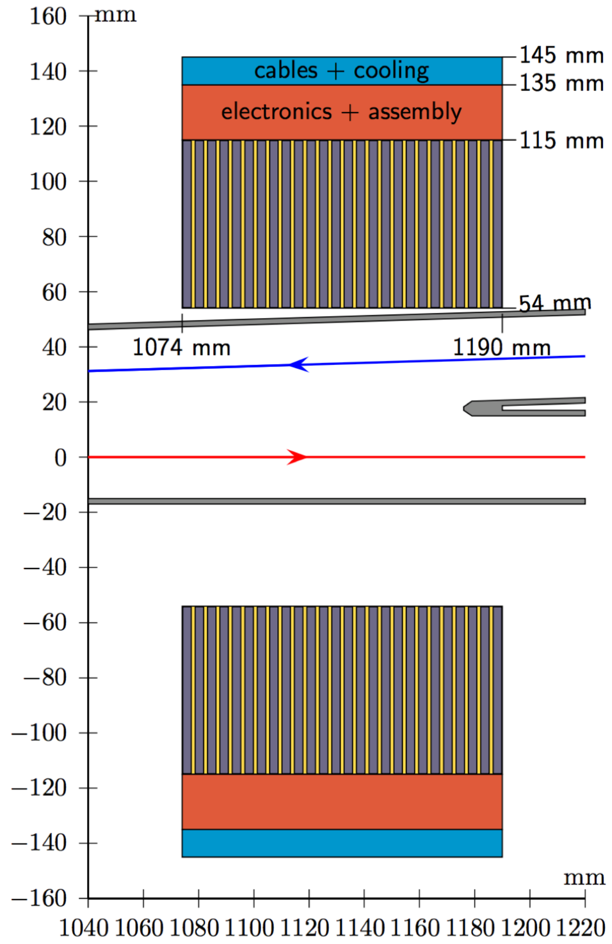
Precision goal: $1 \times 10^{-4}$

# 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: $3.4 \times 10^{-4}$