# FCC-ee Luminosity Mesurement

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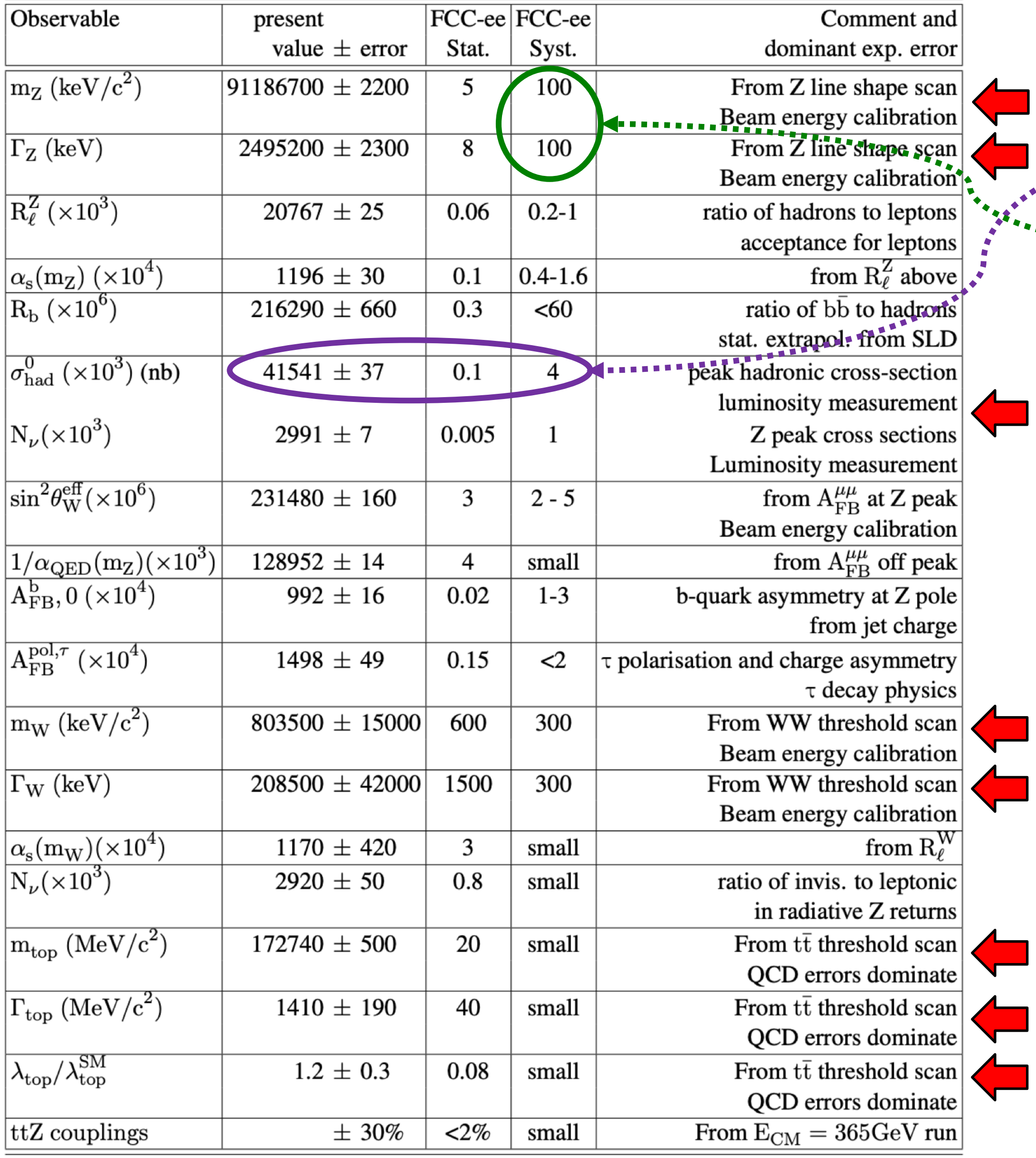
22.12.16

ECFA MiniWorkshop: Luminosity

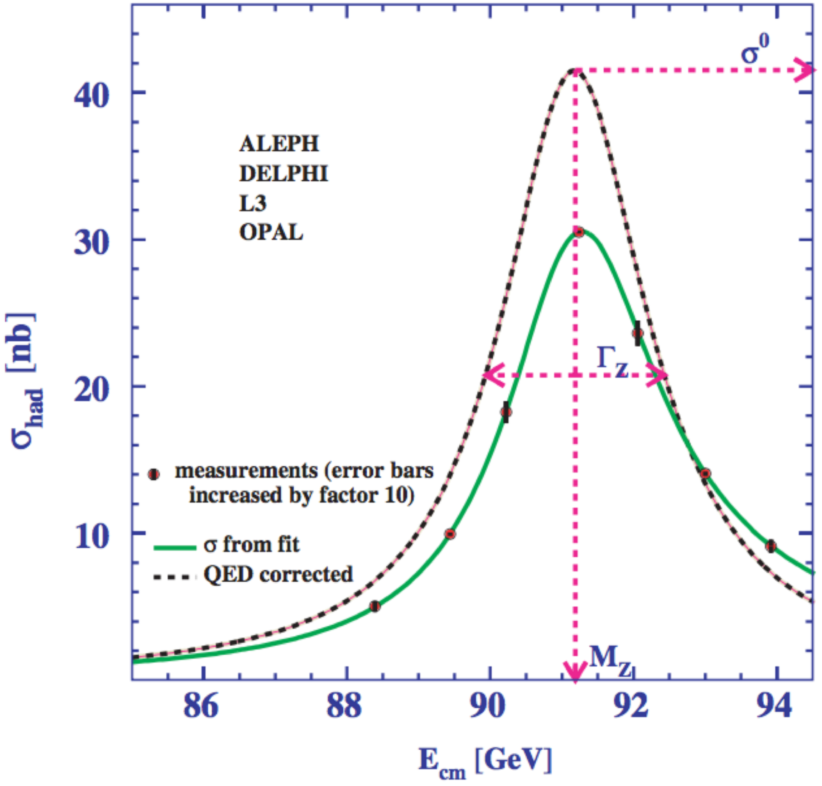
# Cross Section Measurements

FCC CDR Vol. 1



| Observable | present value ± error | FCC-ee Stat. | FCC-ee Syst. | Comment and dominant exp. error |
|---|---|---|---|---|
| $m_Z$ (keV/c$^2$) | 91186700 ± 2200 | 5 | 100 | From Z line shape scan<br>Beam energy calibration |
| $\Gamma_Z$ (keV) | 2495200 ± 2300 | 8 | 100 | From Z line shape scan<br>Beam energy calibration |
| $R_\ell^Z$ ($\times 10^3$) | 20767 ± 25 | 0.06 | 0.2-1 | ratio of hadrons to leptons<br>acceptance for leptons |
| $\alpha_s(m_Z)$ ($\times 10^4$) | 1196 ± 30 | 0.1 | 0.4-1.6 | from $R_\ell^Z$ above |
| $R_b$ ($\times 10^6$) | 216290 ± 660 | 0.3 | <60 | ratio of $b\bar{b}$ to hadrons<br>stat. extrapol. from SLD |
| $\sigma^0_{had}$ ($\times 10^3$) (nb) | 41541 ± 37 | 0.1 | 4 | peak hadronic cross-section<br>luminosity measurement |
| $N_\nu$($\times 10^3$) | 2991 ± 7 | 0.005 | 1 | Z peak cross sections<br>Luminosity measurement |
| $\sin^2\theta_W^{eff}$($\times 10^6$) | 231480 ± 160 | 3 | 2 - 5 | from $A_{FB}^{\mu\mu}$ at Z peak<br>Beam energy calibration |
| $1/\alpha_{QED}(m_Z)$($\times 10^3$) | 128952 ± 14 | 4 | small | from $A_{FB}^{\mu\mu}$ off peak |
| $A_{FB}^{b}, 0$ ($\times 10^4$) | 992 ± 16 | 0.02 | 1-3 | b-quark asymmetry at Z pole<br>from jet charge |
| $A_{FB}^{pol,\tau}$ ($\times 10^4$) | 1498 ± 49 | 0.15 | <2 | τ polarisation and charge asymmetry<br>τ decay physics |
| $m_W$ (keV/c$^2$) | 803500 ± 15000 | 600 | 300 | From WW threshold scan<br>Beam energy calibration |
| $\Gamma_W$ (keV) | 208500 ± 42000 | 1500 | 300 | From WW threshold scan<br>Beam energy calibration |
| $\alpha_s(m_W)$($\times 10^4$) | 1170 ± 420 | 3 | small | from $R_\ell^W$ |
| $N_\nu$($\times 10^3$) | 2920 ± 50 | 0.8 | small | ratio of invis. to leptonic<br>in radiative Z returns |
| $m_{top}$ (MeV/c$^2$) | 172740 ± 500 | 20 | small | From $t\bar{t}$ threshold scan<br>QCD errors dominate |
| $\Gamma_{top}$ (MeV/c$^2$) | 1410 ± 190 | 40 | small | From $t\bar{t}$ threshold scan<br>QCD errors dominate |
| $\lambda_{top}/\lambda_{top}^{SM}$ | 1.2 ± 0.3 | 0.08 | small | From $t\bar{t}$ threshold scan<br>QCD errors dominate |
| ttZ couplings | ± 30% | <2% | small | From $E_{CM}$ = 365GeV run |

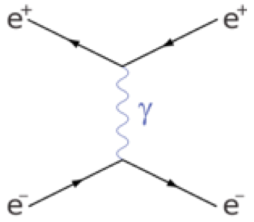
- Many EW observables depend on (absolute) cross section measurements
  - ❑ In the CDR, a precision of $10^{-4}$ on **absolute cross-section** measurements assumed
  - ❑ For the quoted accuracy of the Z lineshape parameters, a **relative, point-to-point precision of $10^{-5}$** is needed



# Method(s)

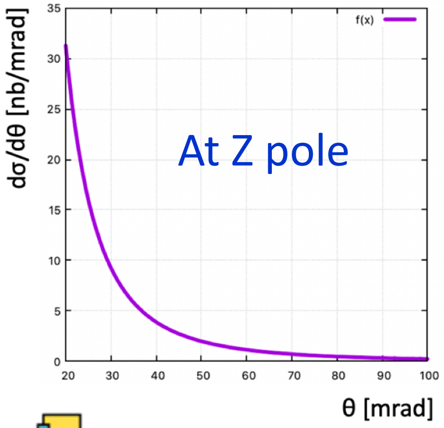
Exploit well known QED reference processes with no (or weak) dependence on EW parameters

## Small angle Bhabha scattering

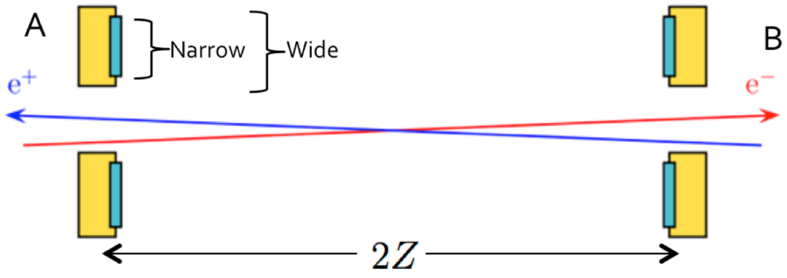


- ❑ Very strongly forward peaked
- ❑ Dominated by *t*-channel γ exchange

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



- ❑ Measured in very forward calorimetrers centered around outgoing beams

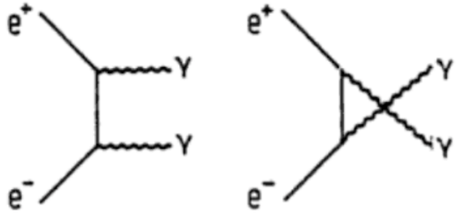


LumiCal

- ❑ Important systematics from acceptance definition ($\theta_{\text{min}}$)

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

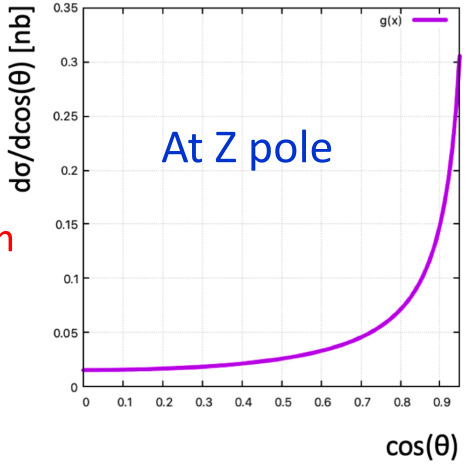
## Large angle γγ production



- ❑ Forward peaked

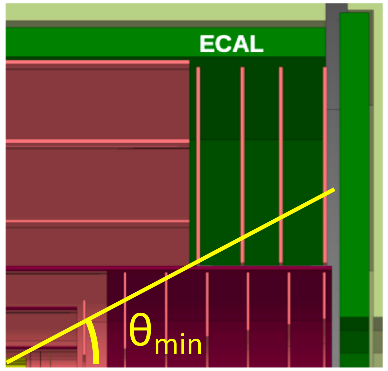
$$\sigma(e^+e^- \to \gamma\gamma) = \frac{2\pi\alpha^2}{s}\left\{\ln\frac{1+\cos\theta_{min}}{1-\cos\theta_{min}} - \cos\theta_{min}\right\}$$

($\theta_{\text{min}}$ defines the ECAL acceptance)



- ❑ Measured in main calorimeter system from minimum angle $\theta_{\text{min}}$ (to 90°)
- ❑ Rate larger than physics rates everywhere except at Z pole
  - ❖ Example $\theta_{\text{min}} = 20^{\circ}$ ($\cos\theta < 0.94$)

| Energy | Process | Cross Section | Large angle $e^+e^- \to \gamma\gamma$ |
|---|---|---|---|
| 90 GeV | $e^+e^- \to Z$ | 40 nb | 0.039 nb |
| 160 GeV | $e^+e^- \to W^+W^-$ | 4 pb | 15 pb |
| 240 GeV | $e^+e^- \to ZH$ | 0.2 pb | 5.6 pb |
| 350 GeV | $e^+e^- \to tt$ | 0.5 pb | 2.6 pb |

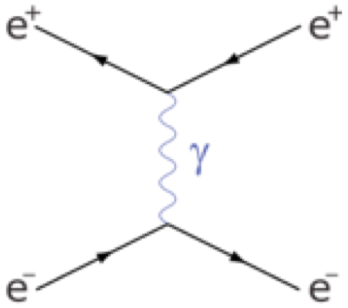


# Small Angle Bhabha Scattering

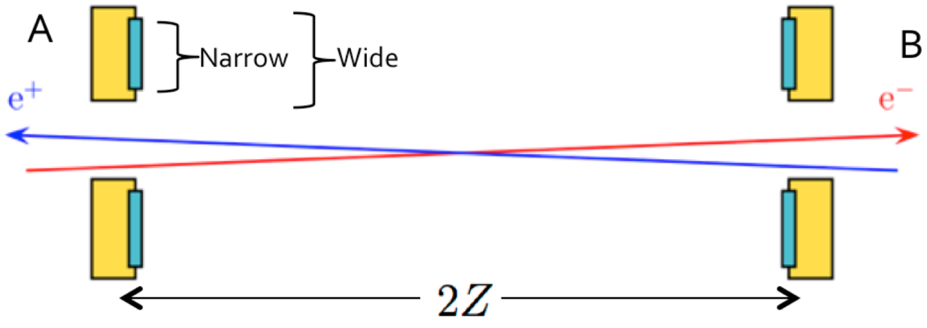
# Small Angle Bhabha Scattering

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

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



  - 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*

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

# Normalisation to $10^{-4}$

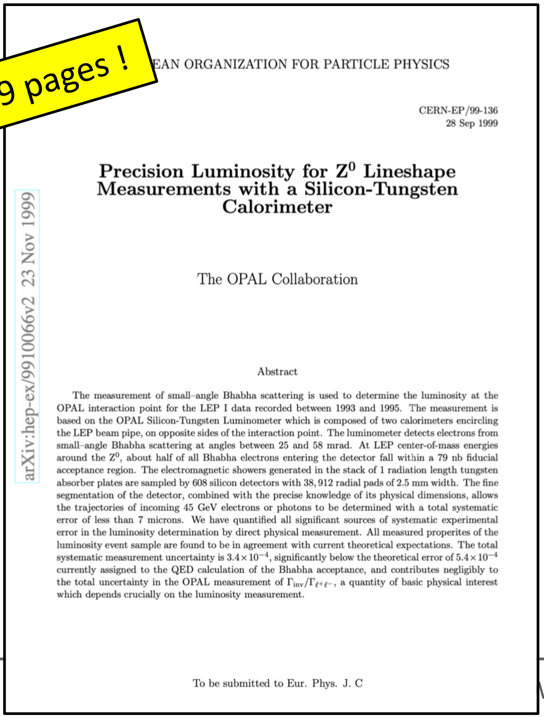
- The goal at FCC-ee is an **absolute normalization to $10^{-4}$**
- After much effort, precision on absolute luminosity at LEP was eventually dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

**Theory: $5.4 \times 10^{-4}$** **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 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

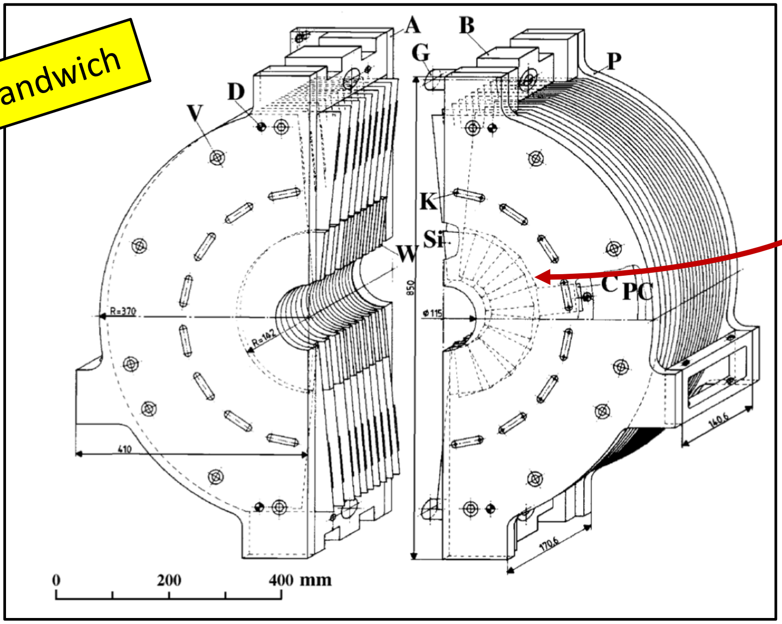
arXiv:hep-ex/9910066v2 23 Nov 1999

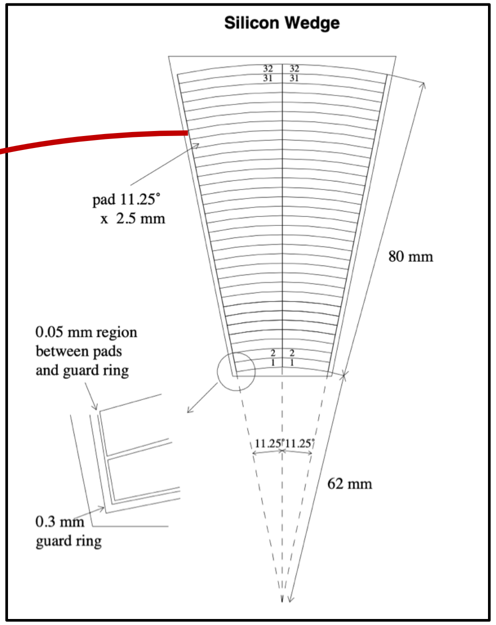
Abstract

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 $3.4 \times 10^{-4}$, 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 $\Gamma_{\mathrm{inv}}/\Gamma_{\ell^+\ell^-}$, a quantity of basic physical interest which depends crucially on the luminosity measurement.

To be submitted to Eur. Phys. J. C

SiW sandwich

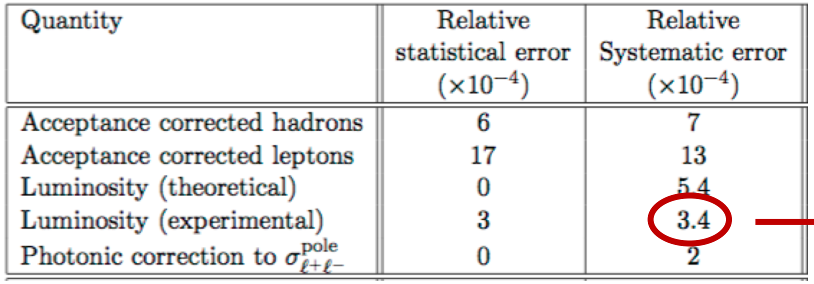




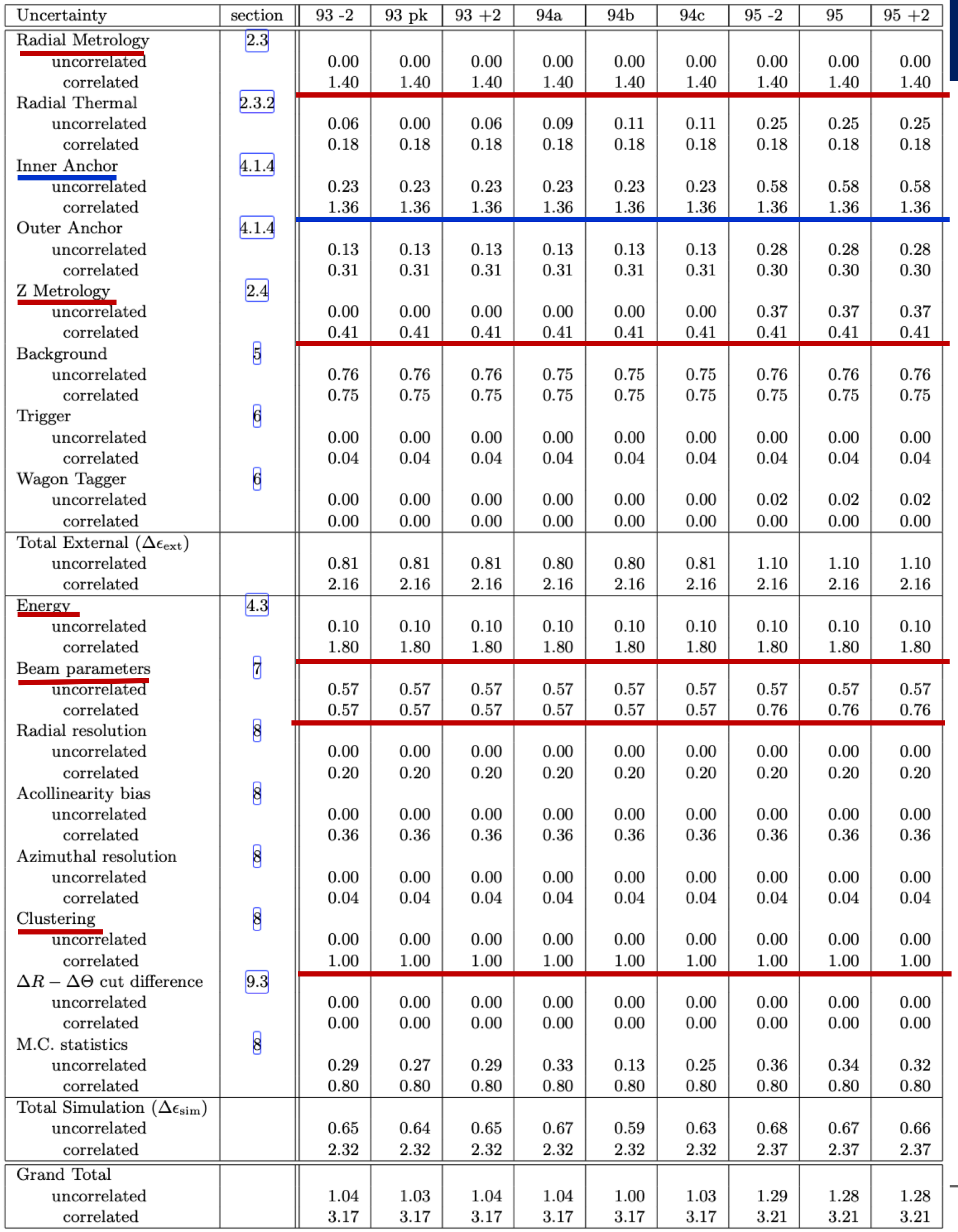
Via precise metrology, achieved 4.4 µm precision on inner acceptance border

# OPAL Summary of Systematics

$\times 10^{-4}$



| 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 |



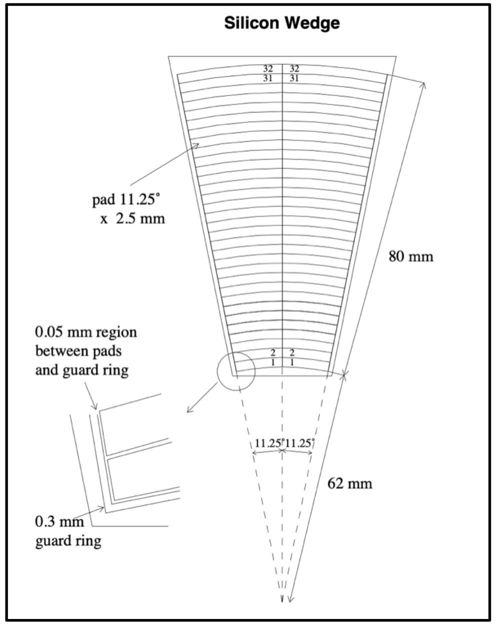
| Uncertainty | section | 93 -2 | 93 pk | 93 +2 | 94a | 94b | 94c | 95 -2 | 95 | 95 +2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Radial Metrology | 2.3 | | | | | | | | | |
| uncorrelated | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| correlated | | 1.40 | 1.40 | 1.40 | 1.40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

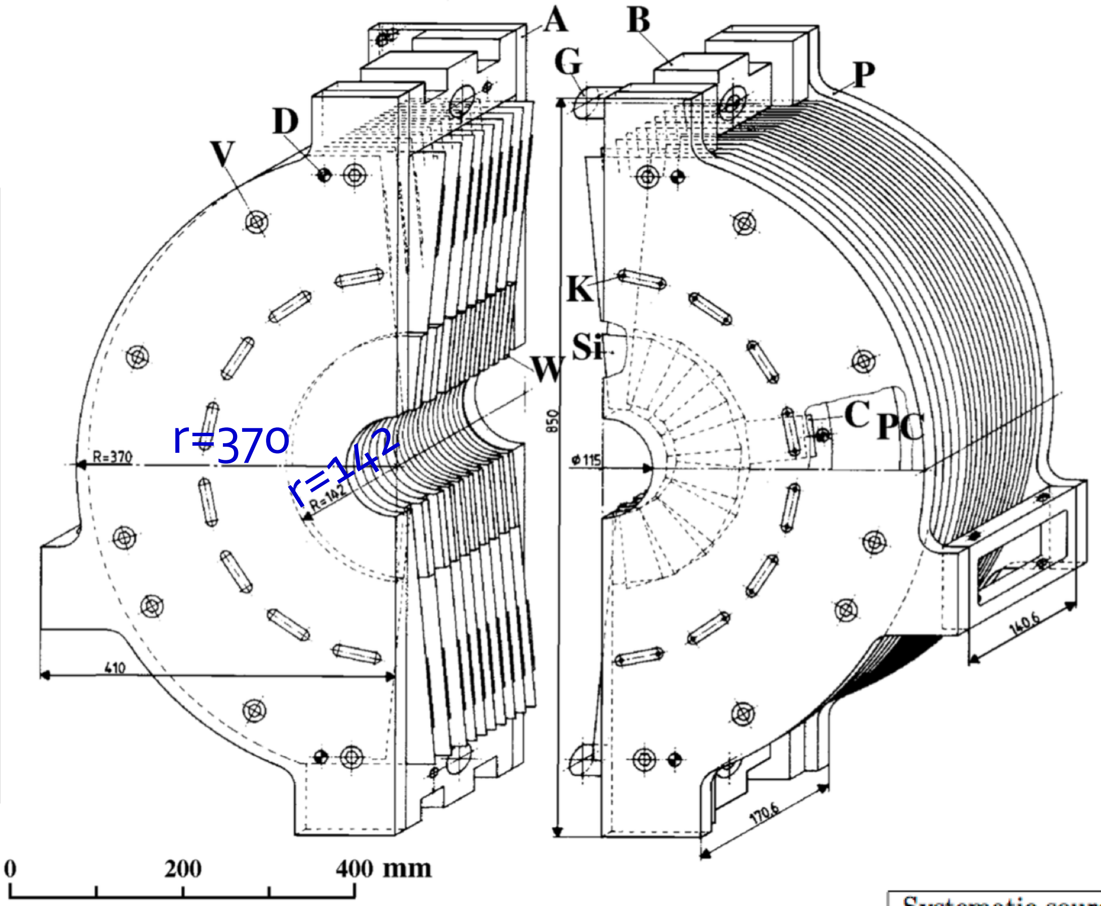
Table 24: This table summarizes the experimental systematic uncertainties on the absolute $L_{\text{RL}}$ luminosity measurement for the nine data samples. The lines labeled correlated and uncorrelated refer to errors correlated and uncorrelated among the samples. All errors are in units of $10^{-4}$.

# OPAL SiW LumiCal

**Z = 250 cm**

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

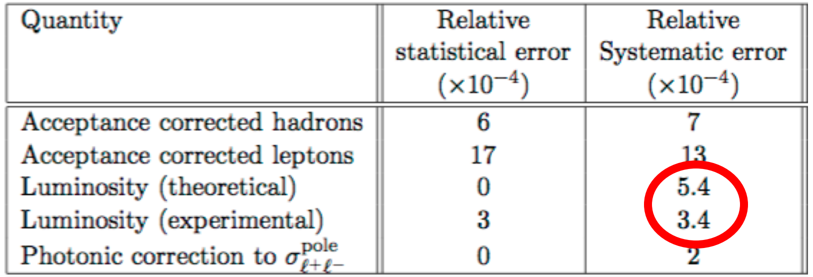




Detector outer radius: 370 mm
Sensitive region up to: 142 mm

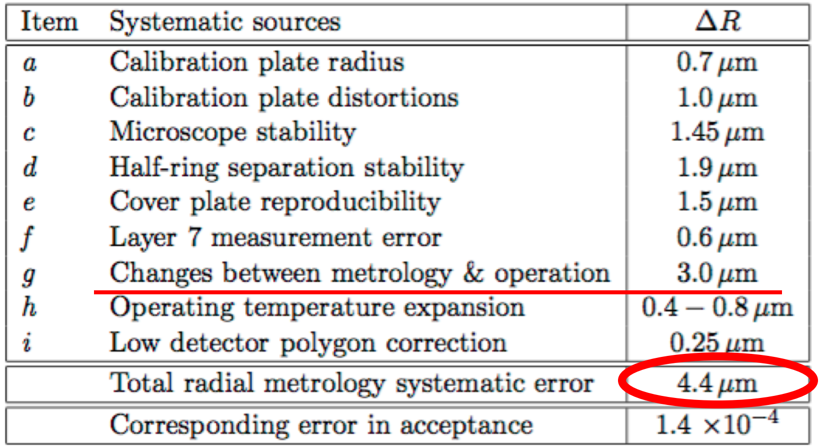
Probably historical reason
for large difference

Achieved lumi uncertainty



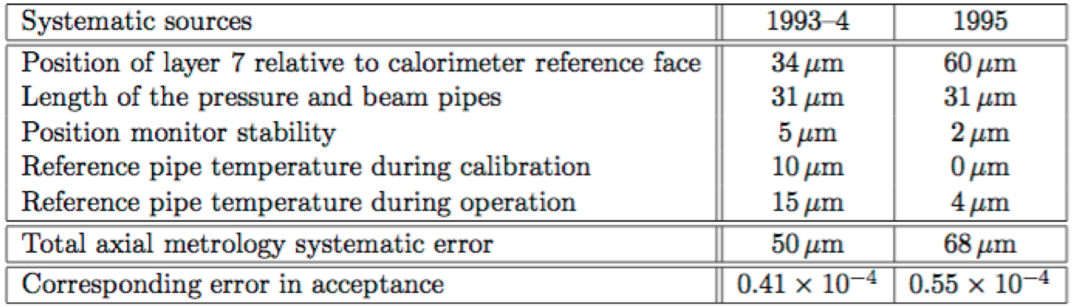
| Quantity | Relative statistical error ($\times10^{-4}$) | Relative Systematic error ($\times10^{-4}$) |
|---|---|---|
| Acceptance corrected hadrons | 6 | 7 |
| Acceptance corrected leptons | 17 | 13 |
| Luminosity (theoretical) | 0 | 5.4 |
| Luminosity (experimental) | 3 | 3.4 |
| Photonic correction to $\sigma^{\text{pole}}_{\ell^+\ell^-}$ | 0 | 2 |

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 $\times10^{-4}$ |

Systematics on z measurement

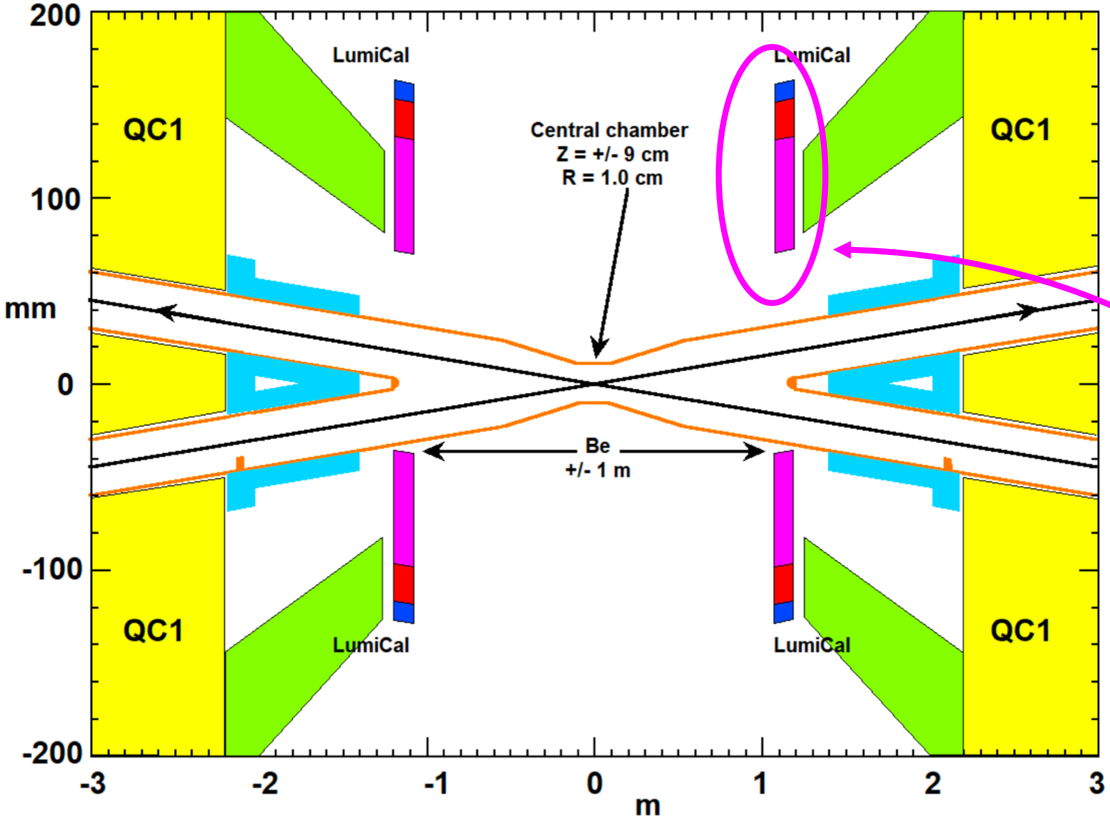


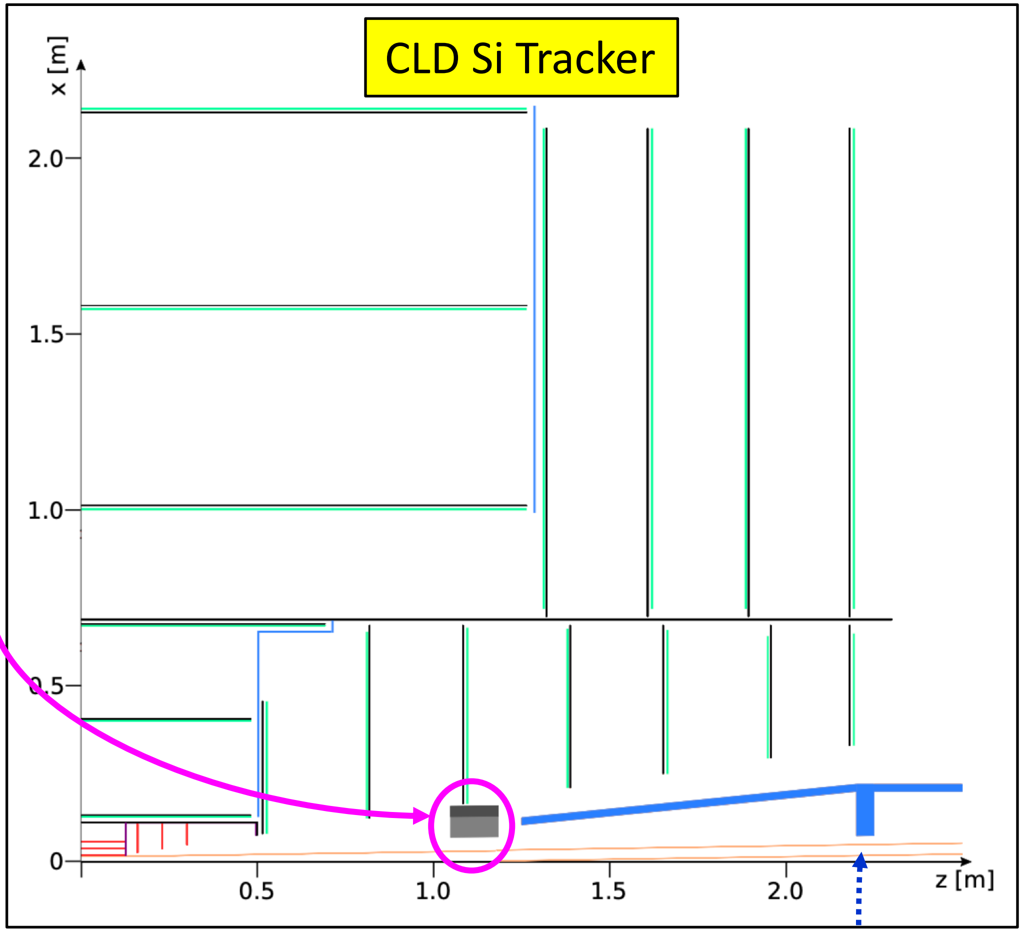
| Systematic sources | 1993–4 | 1995 |
|---|---|---|
| Position of layer 7 relative to calorimeter reference face | 34 $\mu$m | 60 $\mu$m |
| Length of the pressure and beam pipes | 31 $\mu$m | 31 $\mu$m |
| Position monitor stability | 5 $\mu$m | 2 $\mu$m |
| Reference pipe temperature during calibration | 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 | $0.41\times10^{-4}$ | $0.55\times10^{-4}$ |

# LumiCals @ FCC-ee

Challenge:

- MDI region is very busy, LumiCals pushed far inside main detector volume
- Not much space + increased requirements to precision

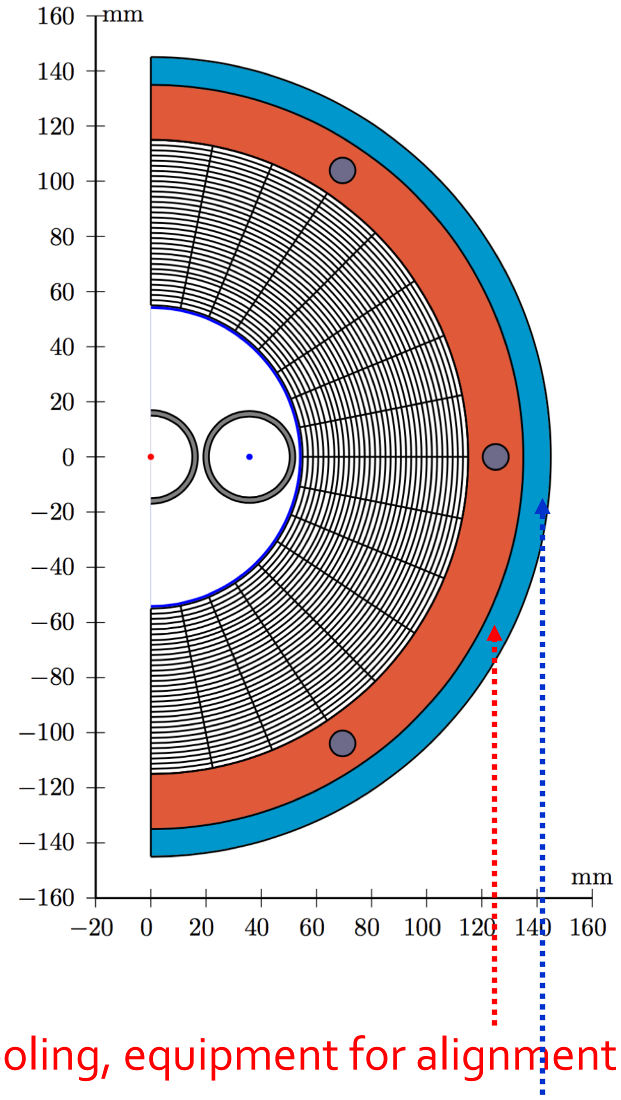


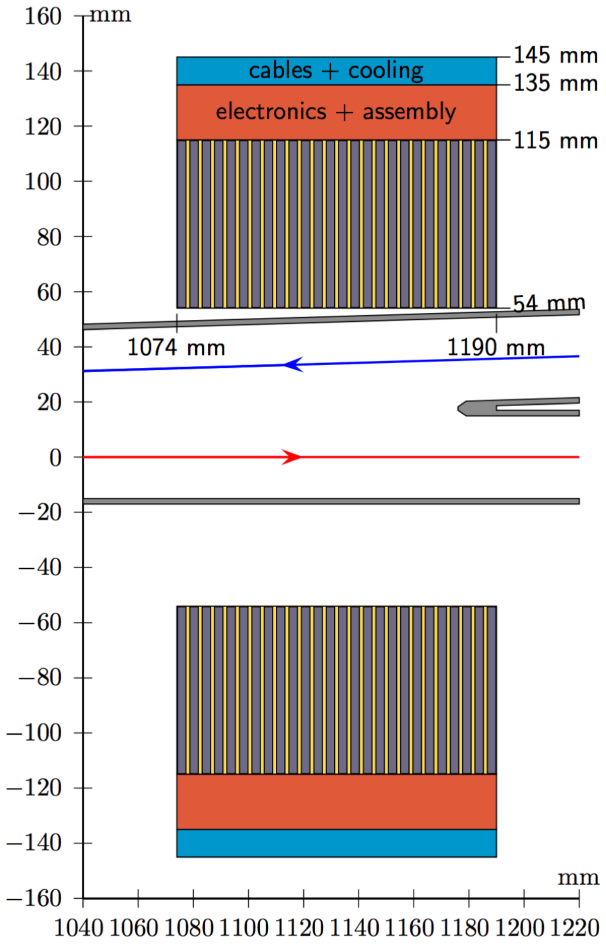


LEP (& ILC) LumiCals positioned about here

# 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?)



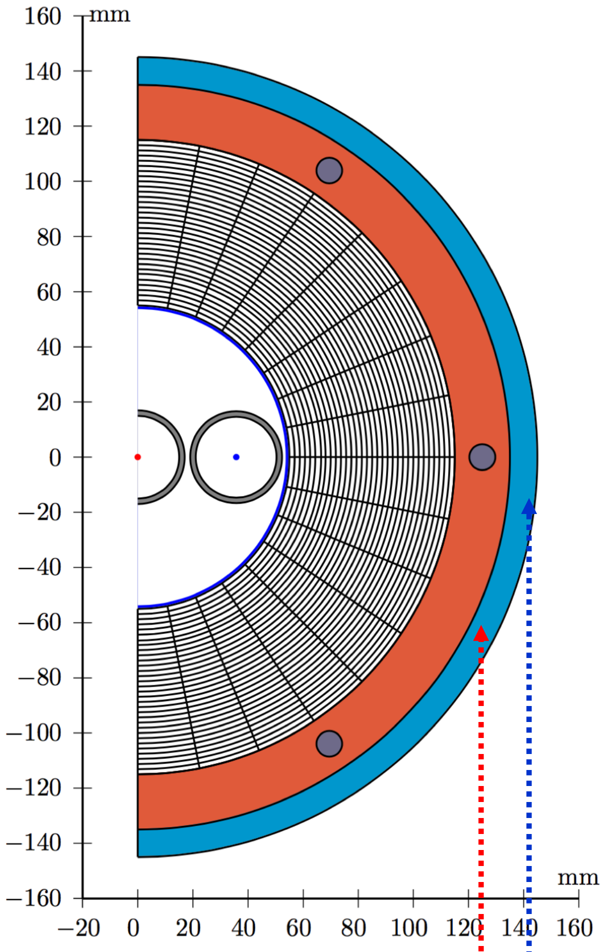


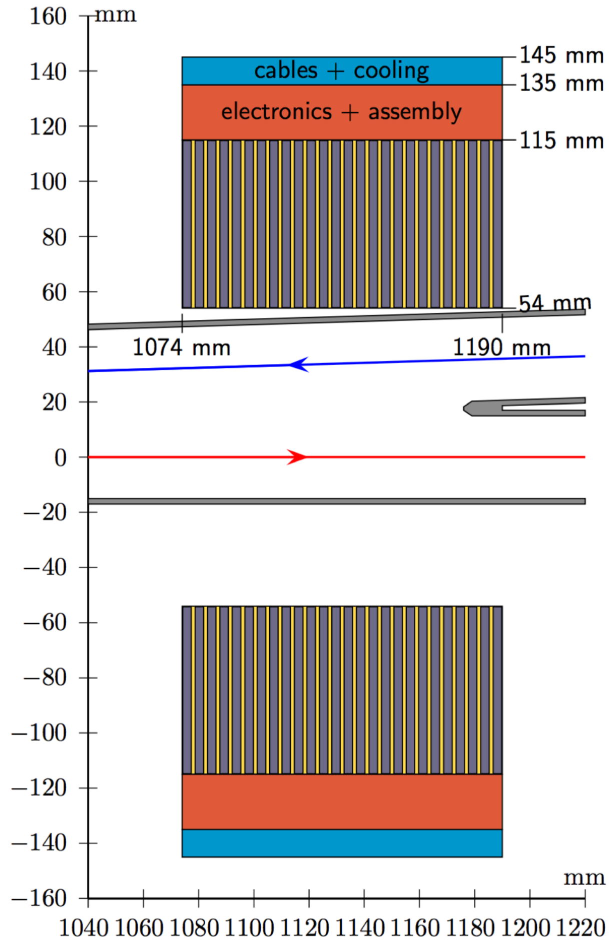
Precision goal: $1 \times 10^{-4}$

# LumiCal CDR Design

Numbers for OPAL Experiment @ LEP

- 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 Geometrical Tolerances

Precision goal: 1 x $10^{-4}$

- Acceptance depends on **inner and outer radius** of acceptance definition

$$\frac{\Delta A}{A} \approx -\frac{\Delta R_{\mathrm{in}}}{1.6\,\mu\mathrm{m}} \times 10^{-4}$$

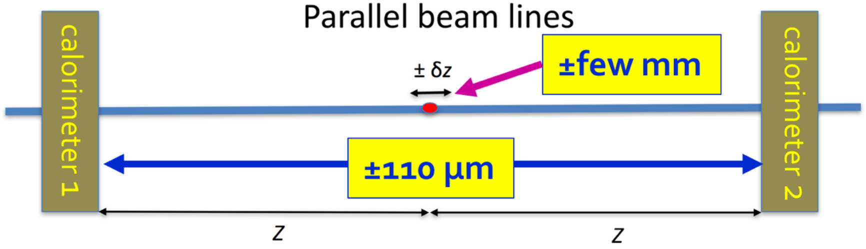
and

$$\frac{\Delta A}{A} \approx +\frac{\Delta R_{\mathrm{out}}}{3.8\,\mu\mathrm{m}} \times 10^{-4}$$

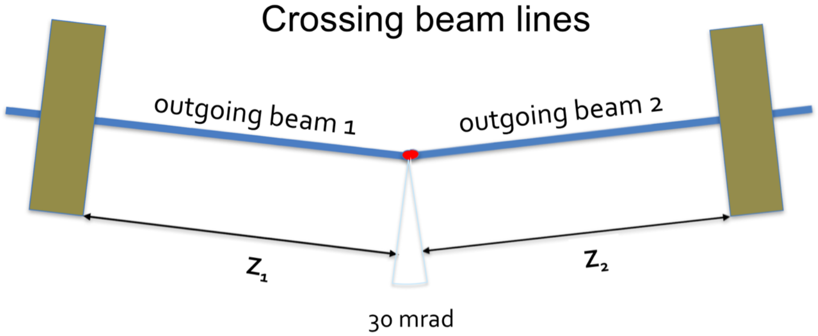
  - ❑ **Aim for construction and metrology precision of 1 µm**

- Acceptance depends on (half) **distance between the two luminometers**

$$\frac{\Delta A}{A} \approx +\frac{\Delta Z}{55\,\mu\mathrm{m}} \times 10^{-4}$$



  - ❑ Situation is somewhat more complicated due to the crossing beam situation
  - ❑ Now, it is the sum of distances, $Z_1 + Z_2$, which has **to be known to 110 µm**



# LumiCal Geometrical Tolerances

Numbers for OPAL Experiment @ LEP

Precision achieved: 3.4 x $10^{-4}$

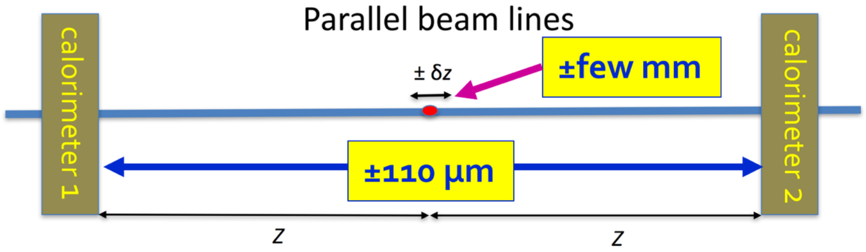
- Acceptance depends on **inner and outer radius** of acceptance definition

$$\boxed{\frac{\Delta A}{A} \approx -\frac{\Delta R_{\text{in}}}{2.5\ \mu\text{m}} \times 10^{-4}} \quad \text{and} \quad \boxed{\frac{\Delta A}{A} \approx +\frac{\Delta R_{\text{out}}}{11\ \mu\text{m}} \times 10^{-4}}$$

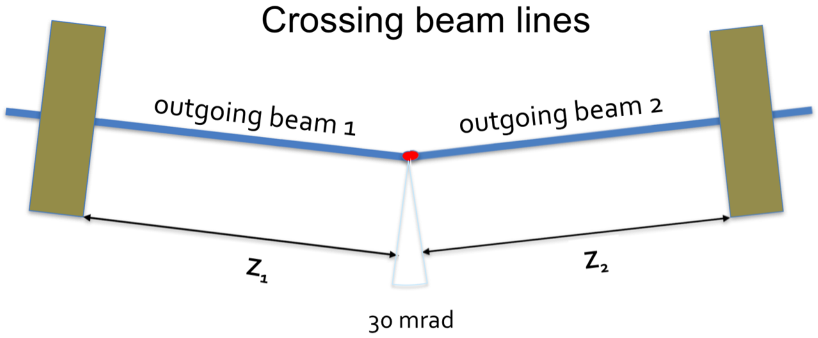
  - ❑ **Aim for construction and metrology precision of 1 µm**

- Acceptance depends on (half) **distance between the two luminometers**

$$\boxed{\frac{\Delta A}{A} \approx +\frac{\Delta Z}{123\ \mu\text{m}} \times 10^{-4}}$$



  - ❑ Situation is somewhat more complicated due to the crossing beam situation
  - ❑ Now, it is the sum of distances, $\mathbf{Z_1 + Z_2}$, which has **to be known to 110 µm**

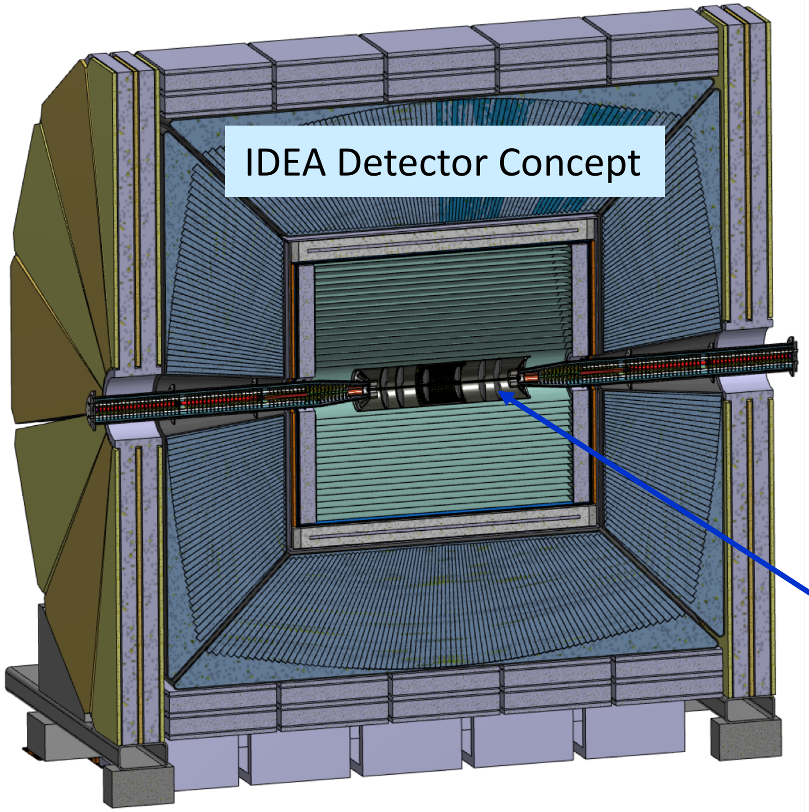


Compared to OPAL:

- Need factor ~2 better geometrical accuracy for same luminosity precision
- Factor 4 more ambitious goal

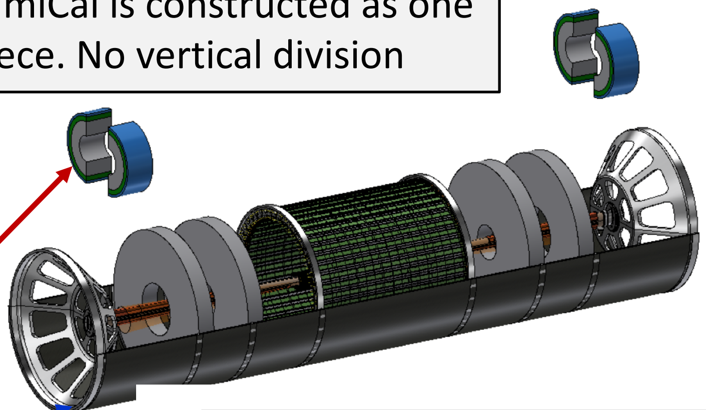
An experimental challenge…

# FCC-ee LumiCal finding its place inside MDI Engineering Design



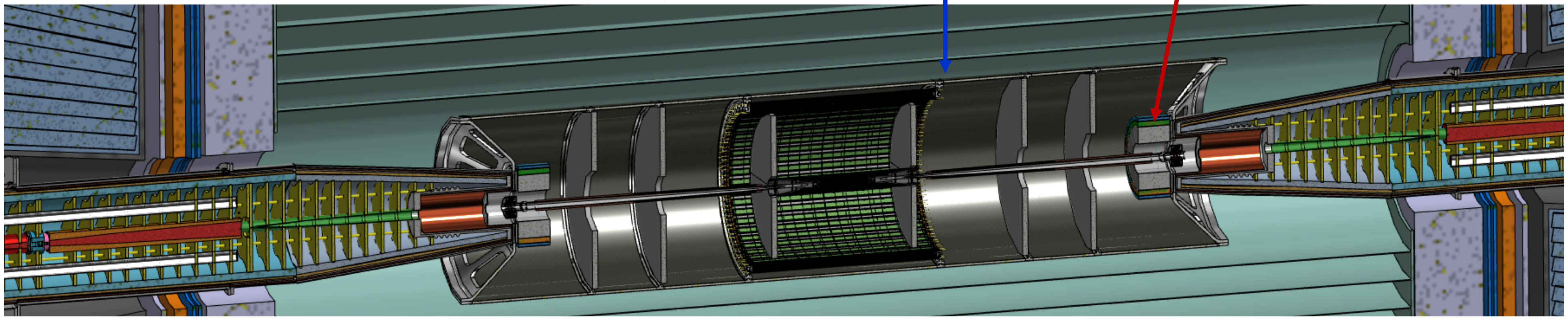
INFN Pisa, Frascati:
F.Palla, F.Bosi, S.Lauciani et al.

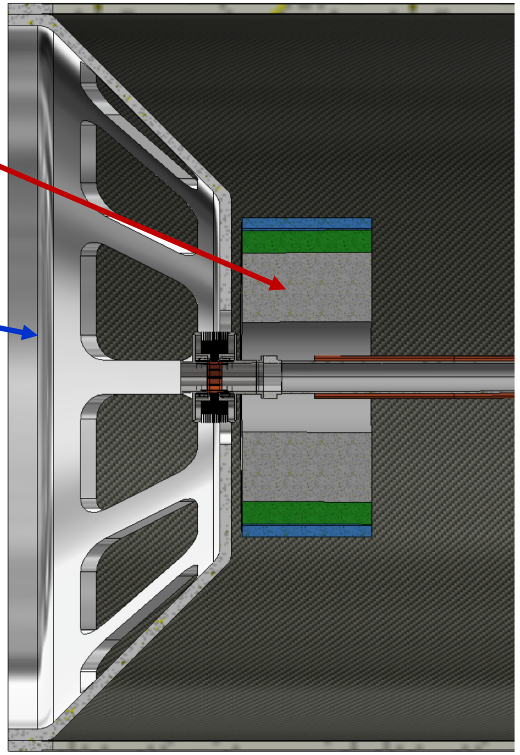
Considering design where LumiCal is constructed as one piece. No vertical division



LumiCal

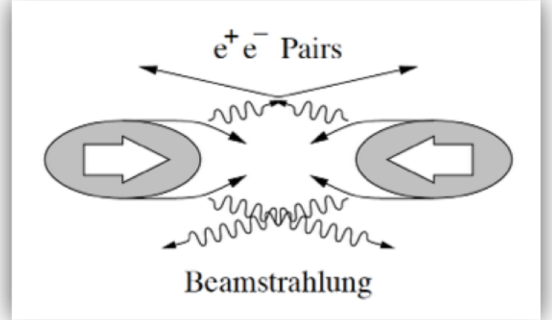
Carbon fiber support tube for inner tracking detectors and LumiCals





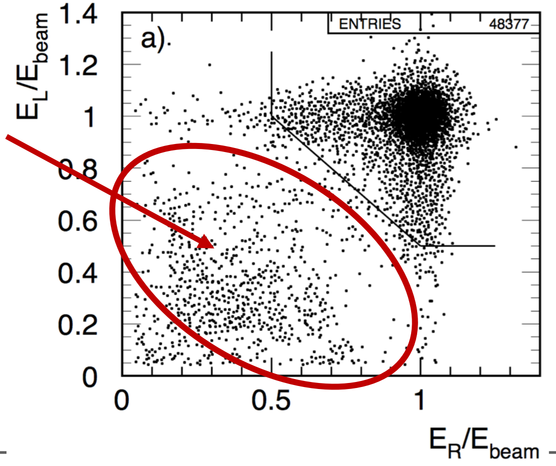
# LumiCal effects: Backgrounds

- Synchrotron radiation:
  - Negligible
    - Largest effect at $\sqrt{s}$ = 365 GeV, where beam-pipe shielding reduced deposit to $\mathcal{O}$(10 MeV) per LumiCal
- Beamstrahlung background – $e^+e^-$ pairs
  - In general, (very) low energy particles – effectively focussed by detector magnet
  - GuineaPig simulation with parametrized magnetic field (helix extrapolation)



| $\sqrt{s}$ | # $e^\pm$ total | # $e^\pm$ LumiCal | Energy total | Energy LumiCal |
|---|---|---|---|---|
| 91.2 GeV | 400 | 0.3 | 250 GeV | 0.06 GeV |
| 365 GeV | 3100 | 15 | 4500 GeV | 3.2 GeV |

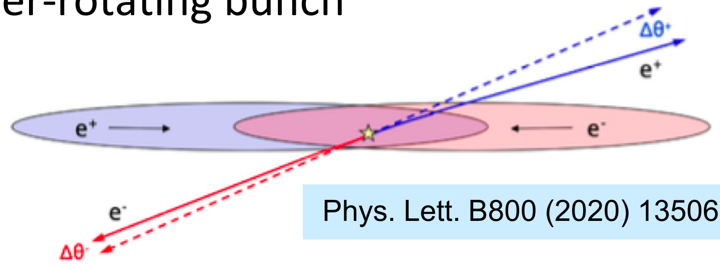
    - Negligible at low $\sqrt{s}$
    - Strong energy dependence, at tt energy, starts to become important
- Beam-gas scattering
  - Coincidence of off-momentum particles from beam-gas scattering was main background process at LEP
    - $10^{-4}$ level after energy and angular cuts
  - At FCC-ee, ratio between æuminosity and beam current is far higher
    - Expected to be completely negligible
      - Supported by first study of sample of simulated off-momentum particle



# LumiCal effects: Focussing of final state particles

- Small angle final state particles feel focussing effect while traversing through counter-rotating bunch
  - Effect was present already at LEP but only corrected for in 2019
  - LEP Bhabha cross sectins were overestimated by about 0.1%
    - Integrated luminosities were underestimated
  - cross sections were overestimated by about 0.1%
    - Number of neutrino generations was underestimated by 0.26%

$$\boxed{N_\nu = 2.9840 \pm 0.0082} \quad \rightarrow \quad \boxed{N_\nu = 2.9918 \pm 0.0081}$$



Phys. Lett. B800 (2020) 135068

- At FCC-ee, situation more complicated due to finite beam-crossing angle
  - Detailed Guinea-Pig simulation studies
    - Average angular focussing of 41 µrad @ 45.6 GeV and @ 64 mrad
    - Aceptance effect of the same magnitude as at LEP
      - **0.19%**
      - ~20 times luminosity accuracy goal !!
  - Focussing effect is reflected in also acollinerity angle distribution of Bhabha events
    - Allows a correction to be done to an estimated $10^{-4}$ accuracy

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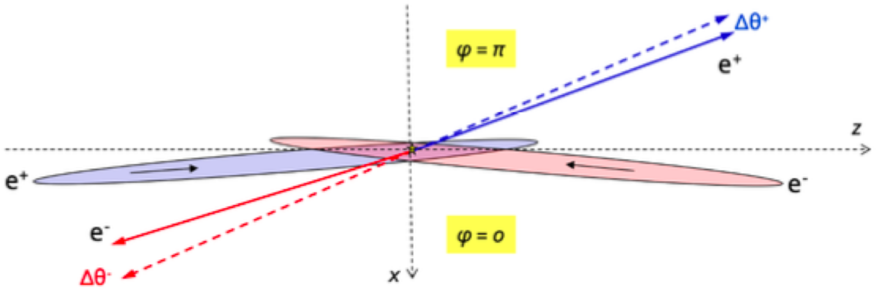
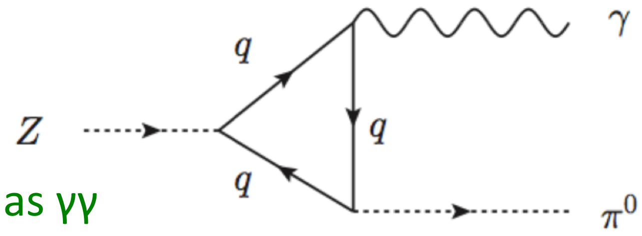


# Large Angle γγ Production

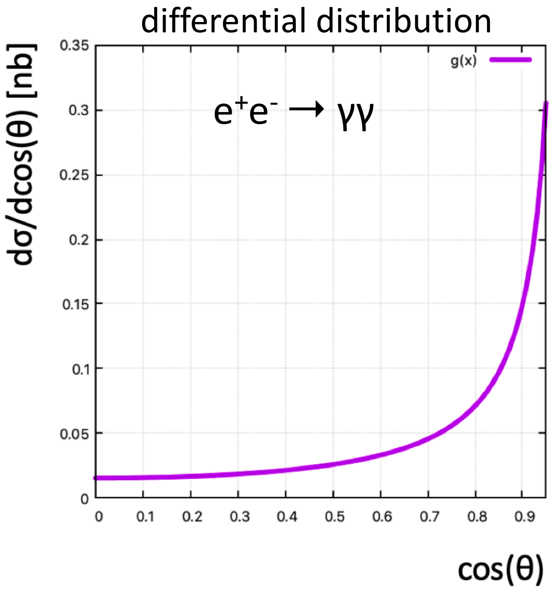
# Normalisation via $e^+e^- \rightarrow \gamma\gamma$

Some experimental challenges

- Backgrounds
  - A potential background is large angle **Bhabha scattering**, $e^+e^- \rightarrow e^+e^-$ faking $e^+e^- \rightarrow \gamma\gamma$ in case both tracks are lost
    - At Z pole energies, large angle Bhabha rate is about 100 times γγ signal rate
    - For normalisation to $10^{-4}$, have to control $e^+e^-$ faking γγ to $10^{-6}$ level, i.e. $10^{-3}$ per track
    - Need to control tracking efficiency (for beam energy electrons) to $10^{-3}$ level inside acceptance
      - Ideally, tracking efficiency > 99.9%
  - **$Z \rightarrow \pi^0\gamma$** ($Z \rightarrow \gamma\gamma$, $Z \rightarrow \pi^0\pi^0$ disallowed)
    - Z production rate at pole ~$10^3$ times $e^+e^- \rightarrow \gamma\gamma$ rate
    - Need to know $\mathcal{B}(Z \rightarrow \pi^0\gamma) \times F$ to $10^{-7}$, where $F$ is fraction of $\pi^0\gamma$ being identified as γγ
    - Current limit: $\mathcal{B}(Z \rightarrow \pi^0\gamma) < 2 \times 10^{-5}$
    - Have to be able to make per mille experimental separation of γ and $\pi^0$ at 45.6 GeV
      - γγ separated by ~2 cm at ECAL
    - Can $\mathcal{B}(Z \rightarrow \pi^0\gamma)$ be theoretically estimated ?
- Acceptance, see next slide



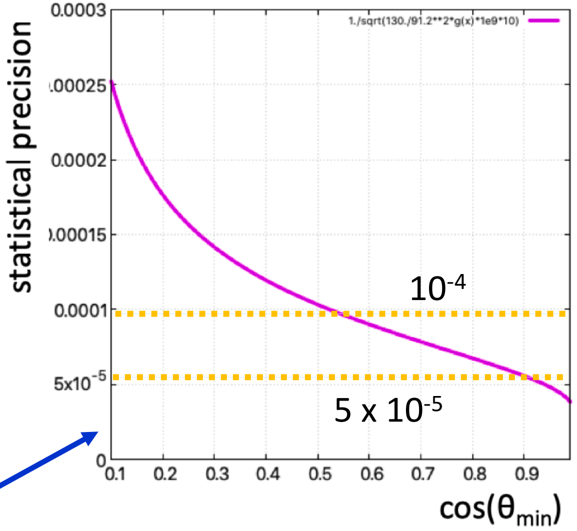
# Normalisation via $e^+e^- \rightarrow \gamma\gamma$ - Acceptance



Example:

For 10 $ab^{-1}$ sample

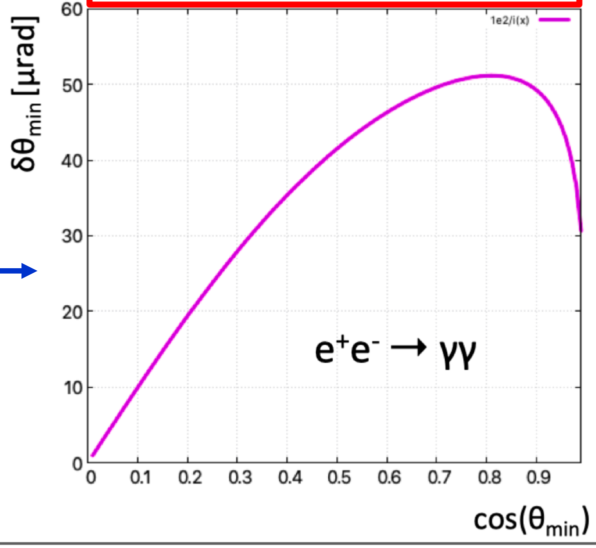
1/15'th of full Z sample



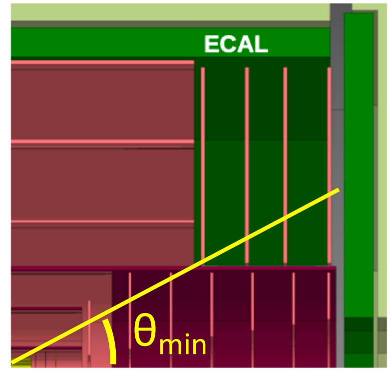
To exploit statistical power, include forward region up to cosθ-values of 0.8-0.9 or higher (37°-25° or lower)

Reaching $10^{-4}$ level precision on the acceptance requires knowledge of $\theta_{min}$ to **50 μrad** or better

required accurary on $\theta_{min}$ for $10^{-4}$ accuracy on acceptance

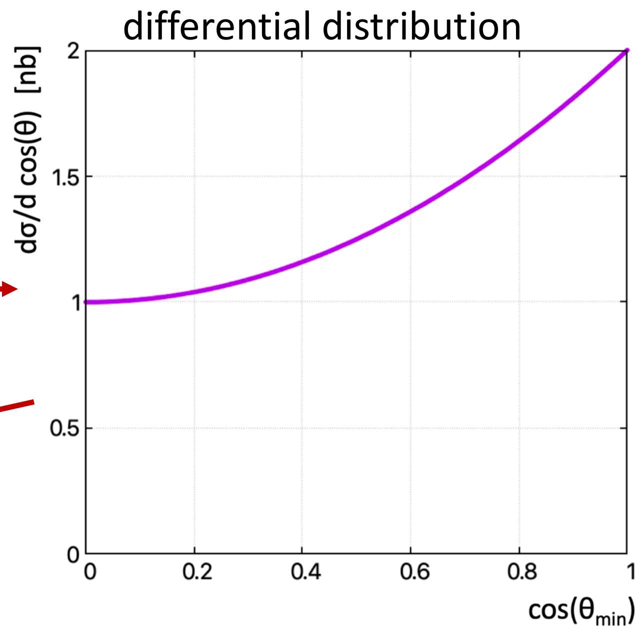


- In practice, probably advantageous to go forward to something like cos($\theta_{min}$) = 0.94 (20°)
  - Higher rate
  - May be easier to control $\delta\theta_{min}$ at lower $\theta_{min}$ values?
- For cos($\theta_{min}$) = 0.94, $\delta\theta_{min}$ = 46 μrad is required
  - At $z_{ref}$ = 2.25 m, this corresponds to
    - Acceptance inner radius: $r_{min}$ = 0.82 m
    - Inner acceptance radius to be known to better than $\delta r_{min}$ = 100 μm, *if* $z_{ref}$ *perfectly known*
    - $z_{ref}$ to better than 300 μm, *if* $r_{min}$ *perfectly known*
- All other contributions have to be kept very low
  - No holes, no cracks …

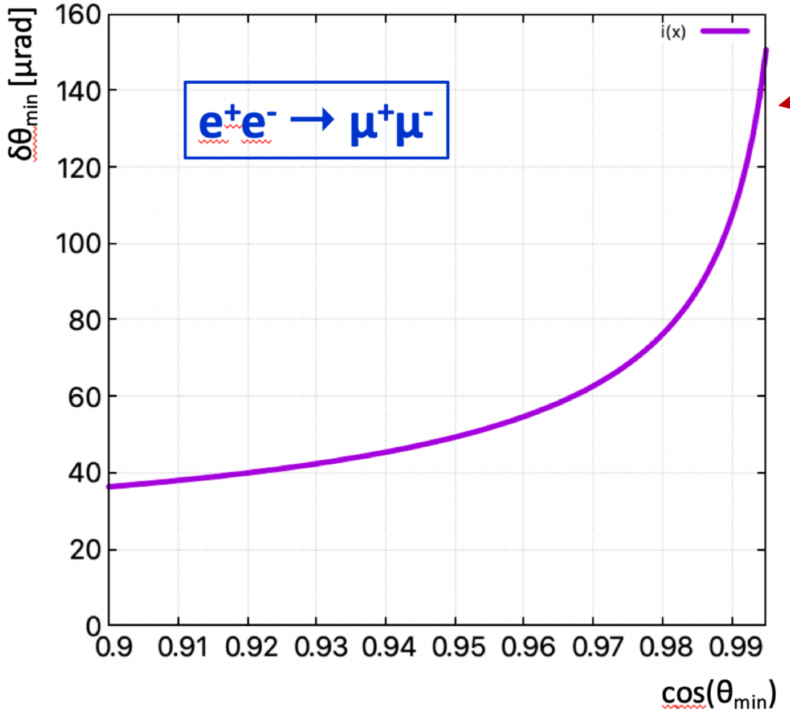


# A similar challenge: $R_\ell = \Gamma(Z \rightarrow \text{hadrons}) / \Gamma(Z \rightarrow \ell^+\ell^-)$

- Goal is to measure $R_\ell$ to $10^{-5}$
- Say, there would be no uncertainty on the number of multihadronic events
- Then, have to measure $\Gamma(Z \rightarrow \ell^+\ell^-)$ to $10^{-5}$
    - ❑ In practice, probably primarily considering the muon channel, $Z \rightarrow \mu^+\mu^-$
- $Z \rightarrow \ell^+\ell^-$ at Z pole has (approximately) the angular dependence $1+\cos^2\theta$



**Required accurary on $\theta_{min}$ for $10^{-5}$ accuracy on acceptance**



**To reach $10^{-5}$, have to control $\theta_{min}$ to $\mathcal{O}$(50 μrad)**

# 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 small angle Bhabha monitors plus a huge analysis effort

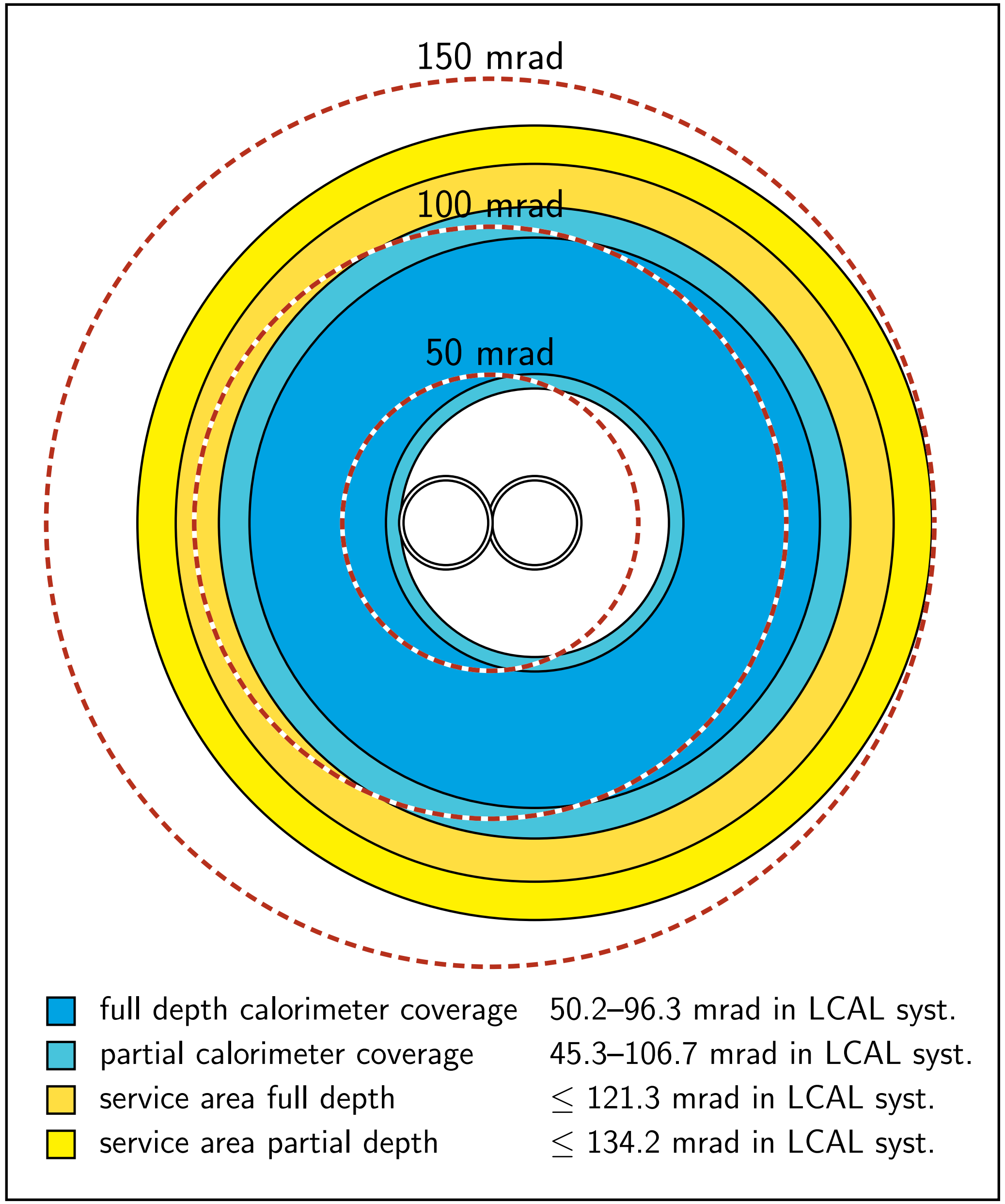
- Small angle Bhabha scattering and LumiCal challenges
  - Compared to LEP, FCC-ee LumiCals sit in a more complicated location at z=1 m inside main detector volume
  - Detector geometry to be controlled to $\mathcal{O}(1\ \mu\mathrm{m})$ in radius [4.4 μm achieved in OPAL]
    - Can in principle produce each complete sensor layer from a single 10 inch Si wafer
  - Distance between two monitors to be controlled to $\mathcal{O}(100\ \mu\mathrm{m})$ [100-140 μm achieved in OPAL]
  - Engineering level design needed
    - Electronics, cooling, mechanics (promising recent work on support structure by INFN groups)
  - Several other effects to consider for $10^{-4}$ level precision: energy response, backgrounds, Bhabha patricle focussing,

- Compementary lumi process: **large angle γγ production**
  - Competitive statistics at all energy points except at Z pole where statistics is down by a factor 1000 relative to Z
    - Still $\mathcal{O}(10^9)$ events at pole – Sufficient for $\delta\mathcal{L}/\mathcal{L} \simeq 10^{-4}$
  - Full study still to be done:
    - Theory?, Backgrounds?, Acceptance (few × 10 μm $r \simeq 80$ cm ($20^o$) in forward direction)

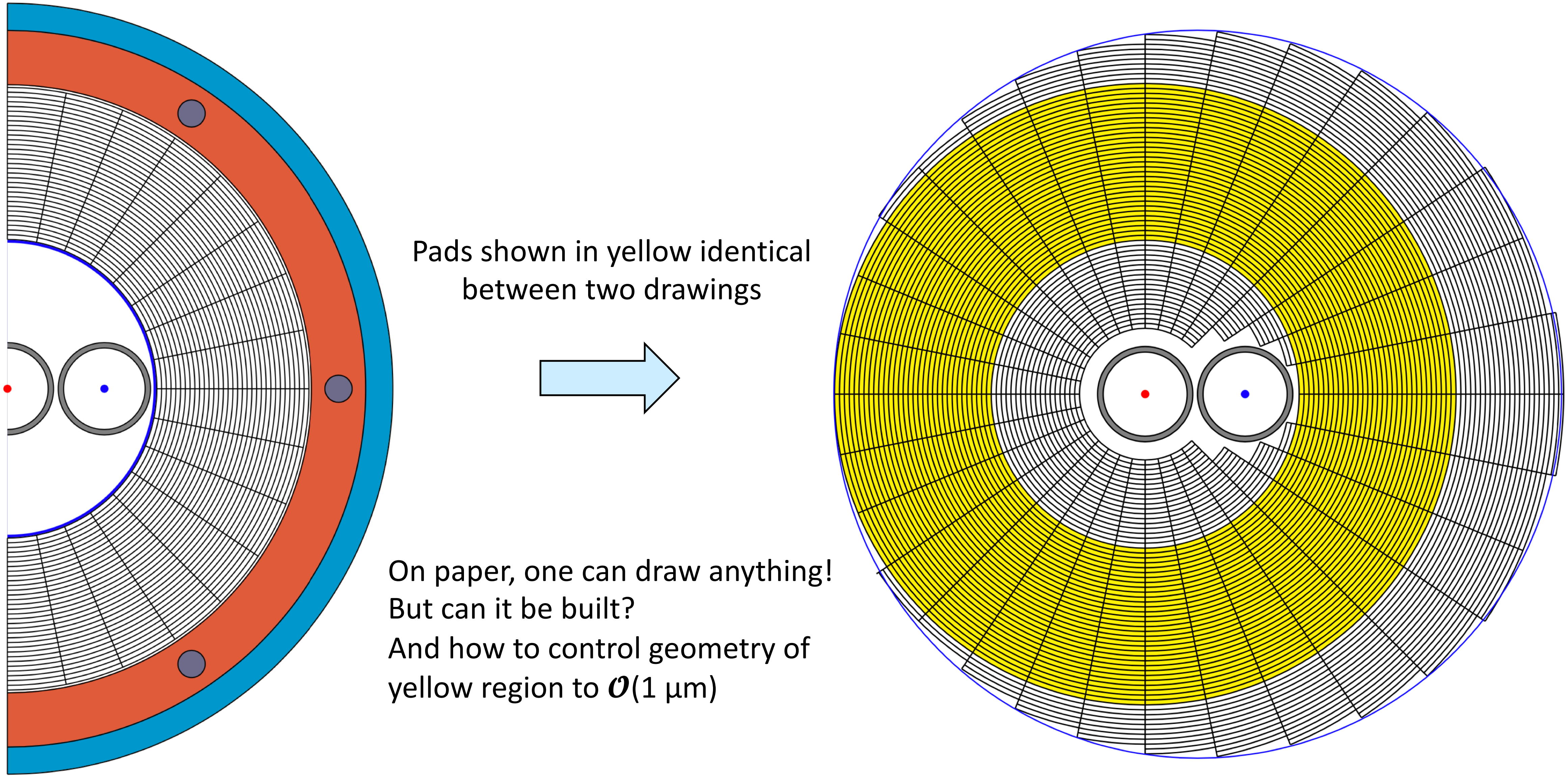
# Extra slides

# 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

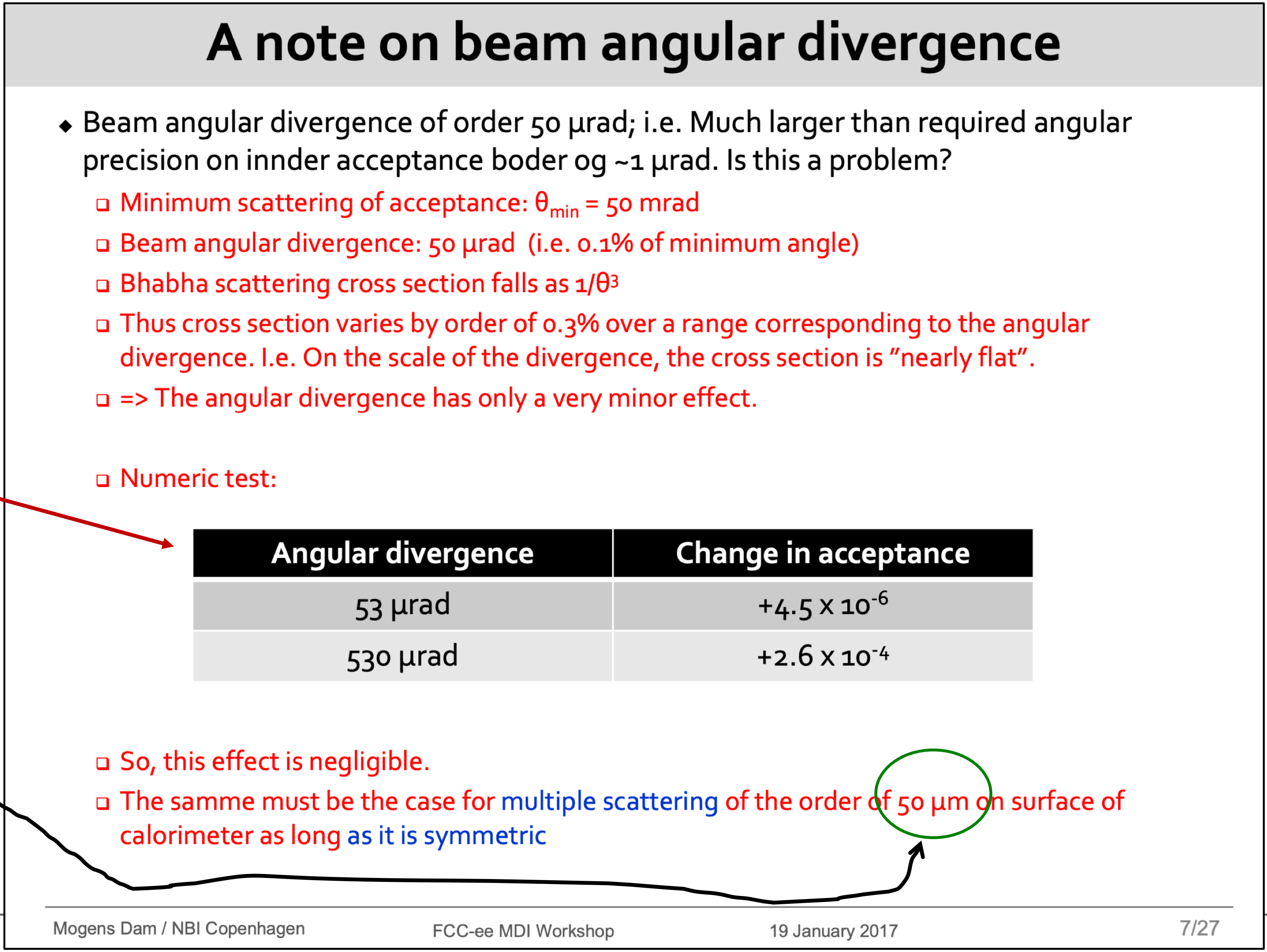
On paper, one can draw anything!
But can it be built?
And how to control geometry of yellow region to $\mathcal{O}$(1 µm)

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

# 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

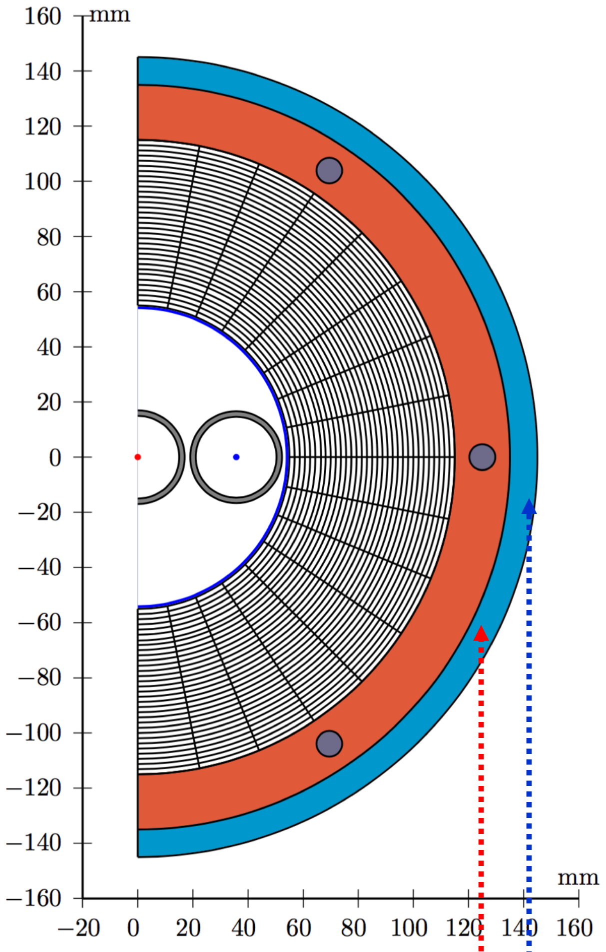
- Beam angular divergence of order 50 µrad; i.e. Much larger than required angular precision on innder acceptance boder og ~1 µrad. Is this a problem?
  - ❑ Minimum scattering of acceptance: $\theta_{min}$ = 50 mrad
  - ❑ Beam angular divergence: 50 µrad (i.e. 0.1% of minimum angle)
  - ❑ Bhabha scattering 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:

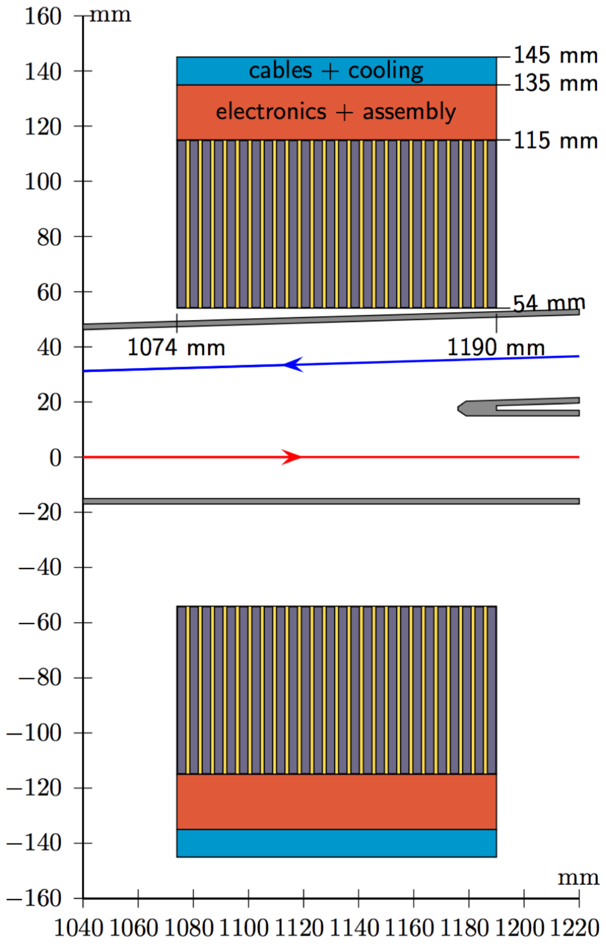
| Angular divergence | Change in acceptance |
|---|---|
| 53 µrad | $+4.5 \times 10^{-6}$ |
| 530 µrad | $+2.6 \times 10^{-4}$ |

- ❑ 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

# 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?)



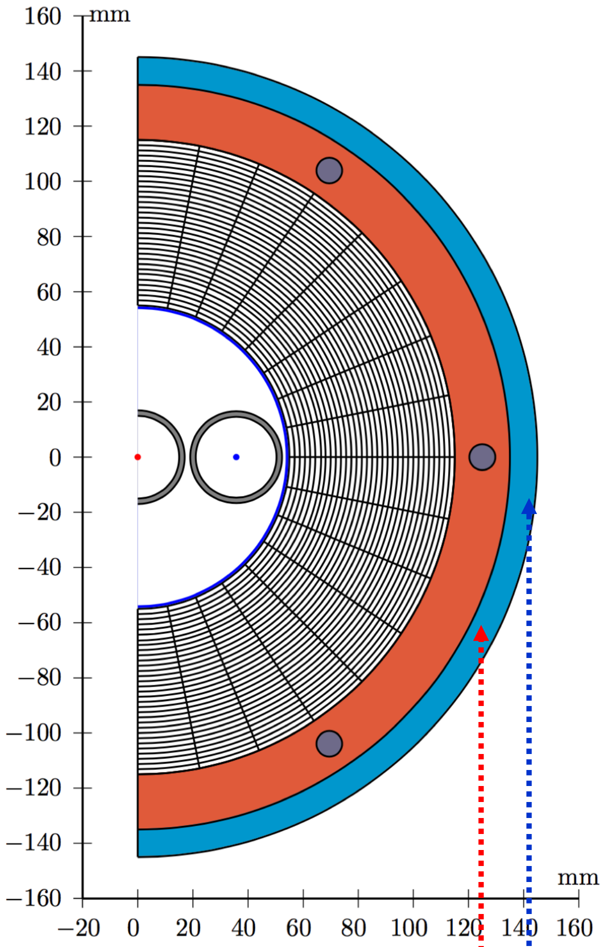


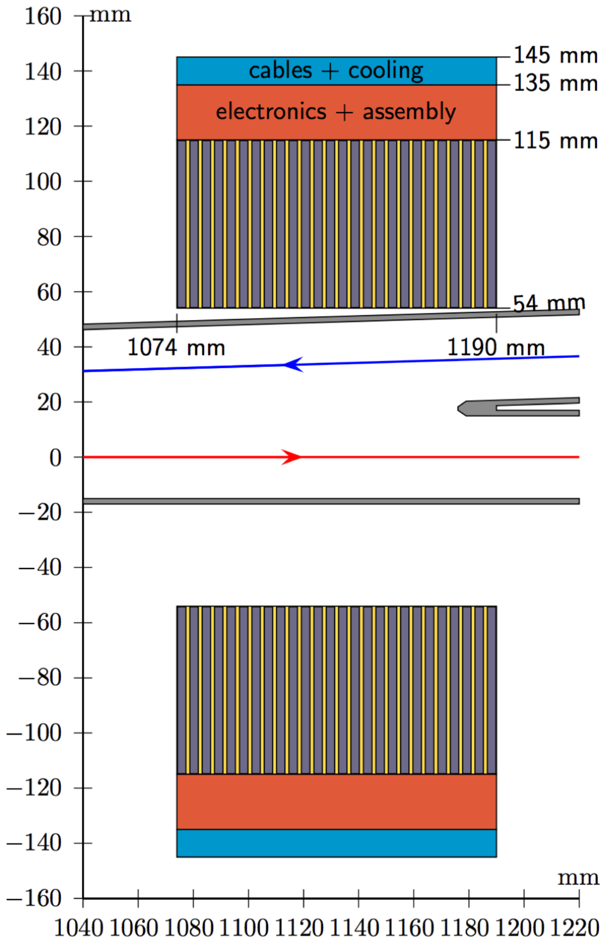
Precision goal: 1 x $10^{-4}$

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