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NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

FCC-ee Luminosity Monitor

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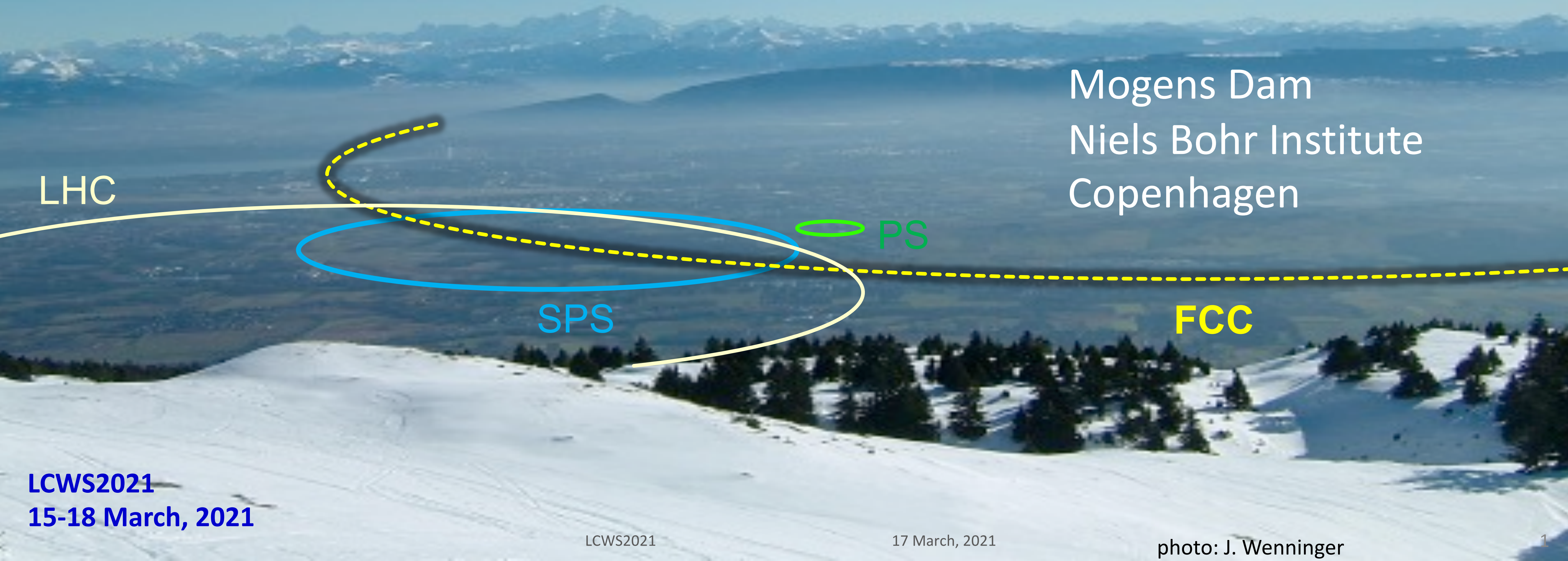


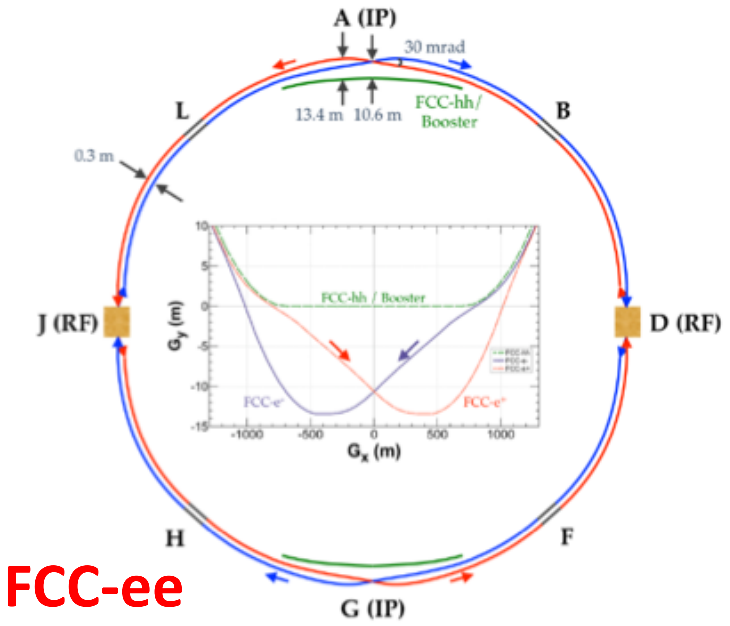
LCWS2021
15-18 March, 2021

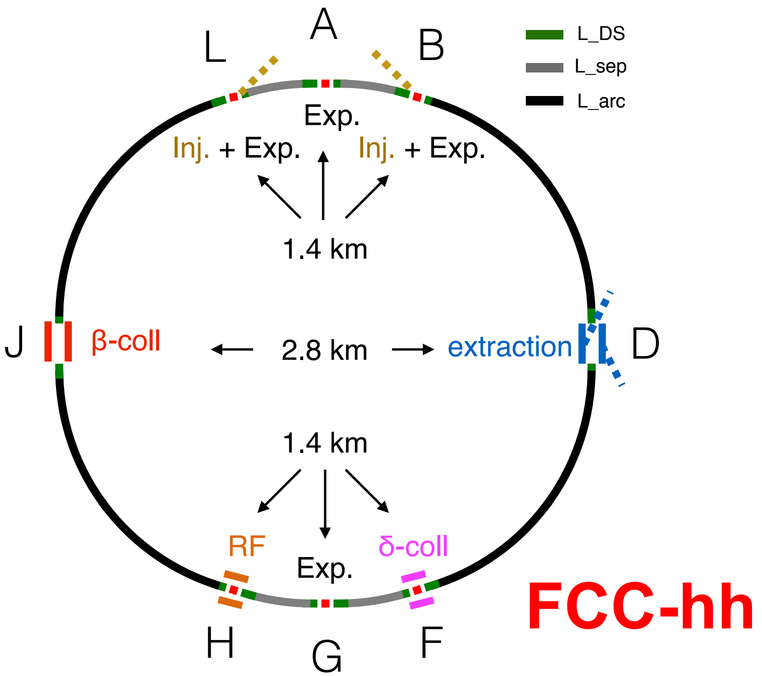
photo: J. Wenninger

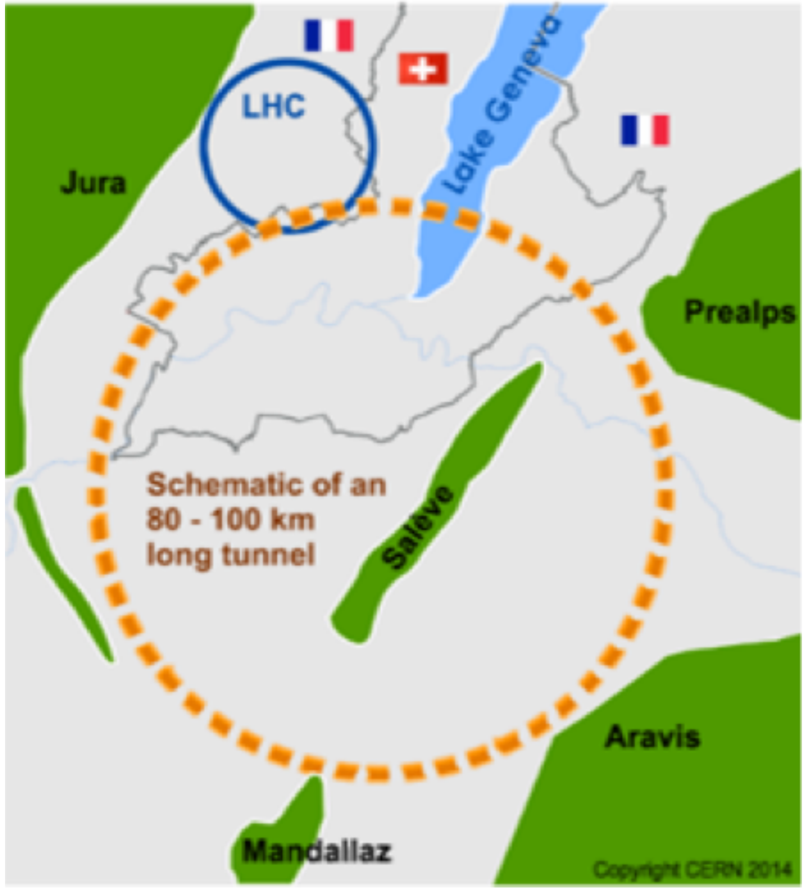
The FCC integrated program inspired by successful LEP – LHC programs

Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC

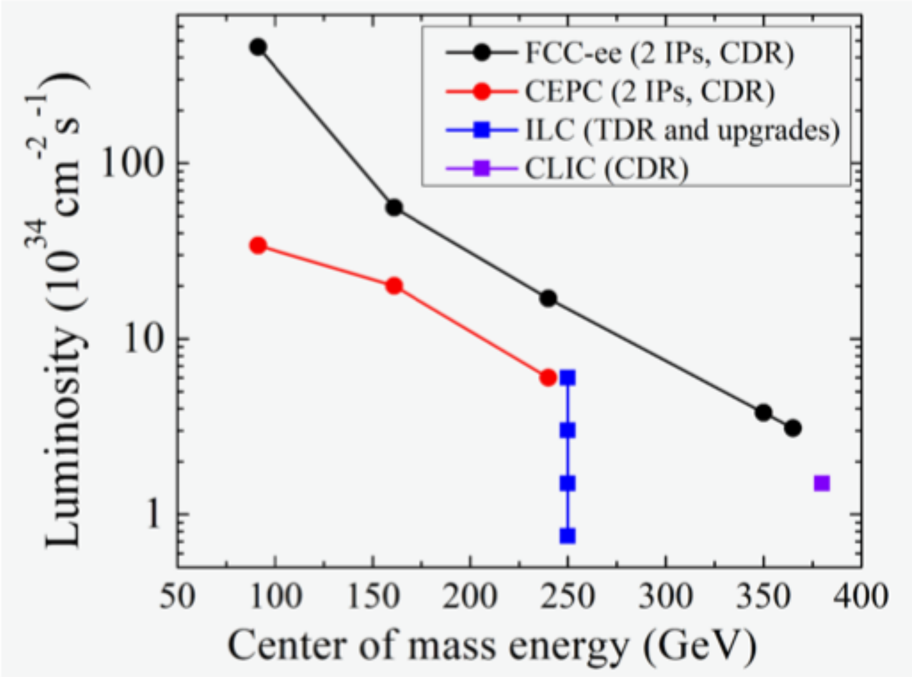


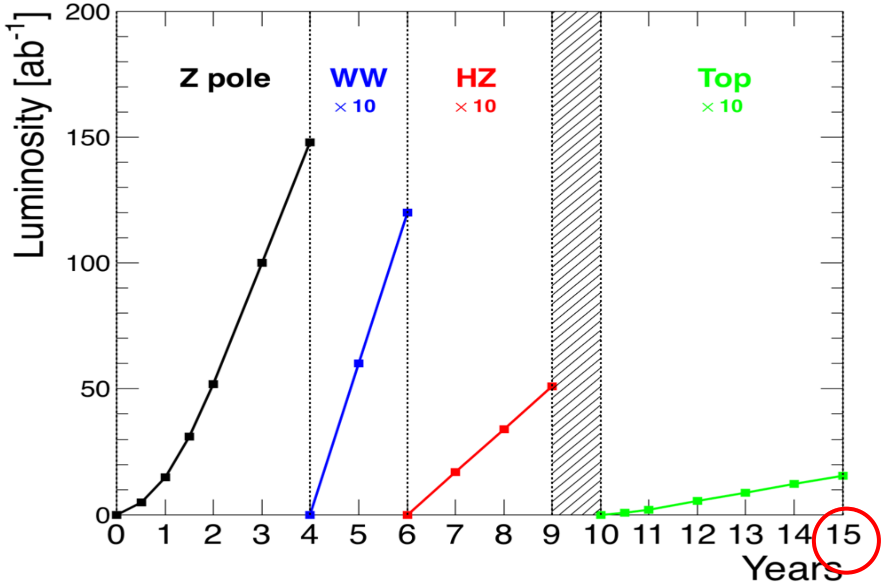




FCC-ee Luminosity, Operation Model and Statistics

Largest luminosities in the 88 – 365 GeV energy range





Event statistics

5×10^{12} $e^+e^- \to Z$	
10^8 $e^+e^- \to W^+W^-$	
10^6 $e^+e^- \to HZ$	
10^6 $e^+e^- \to tt$	

√s precision

100 keV
300 keV
1 MeV
2 MeV

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold…	… and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

FCC-ee Physics Landscape

"Higgs Factory" Programme

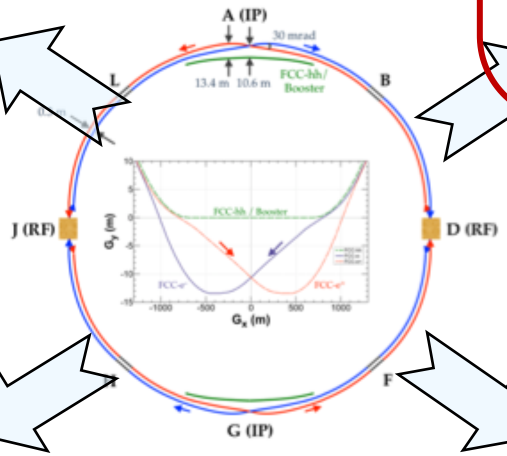
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW $\rightarrow$ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} $\tau\tau$
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. $b \rightarrow s\tau\tau$, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

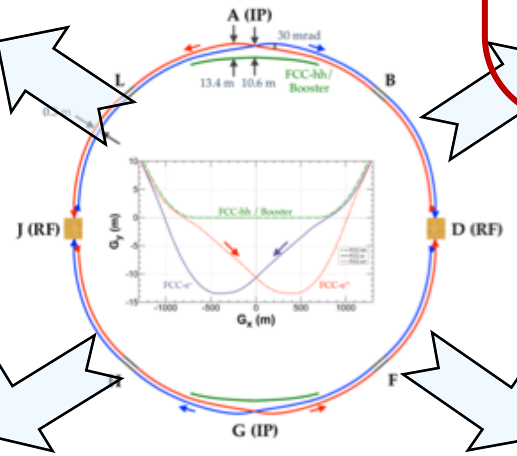
Detector Requirements in Brief

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

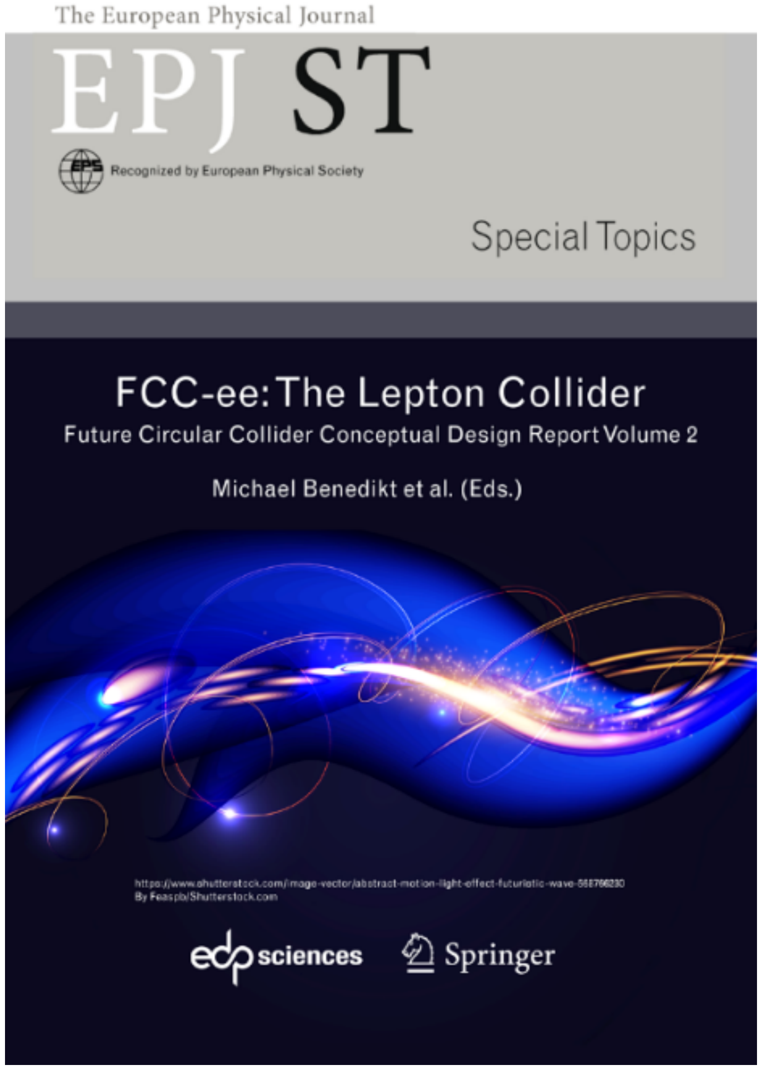
Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

Status of Work

- Work presented here is largely extracted from Conceptual Design Report published in 2019
  - Conceptual level – real design work ahead
- For Detector Design effort, a CDR+ is to be delivered for next European Strategy Update around ~2025
- Technical Design Report to follow

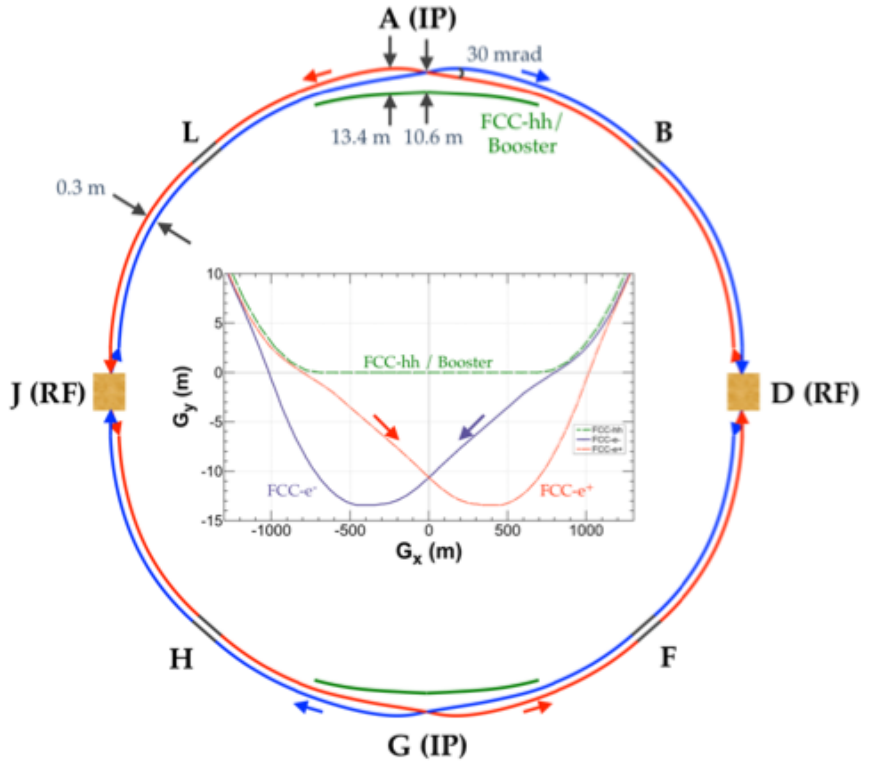


FCC-ee Conditions

FCC-ee parameters		Z	WW	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**230**	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	40,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	**92,000**	8,400	1	0.1
"Pile up" parameter [μ]	**10^{-6}**	1,800	1	1	1

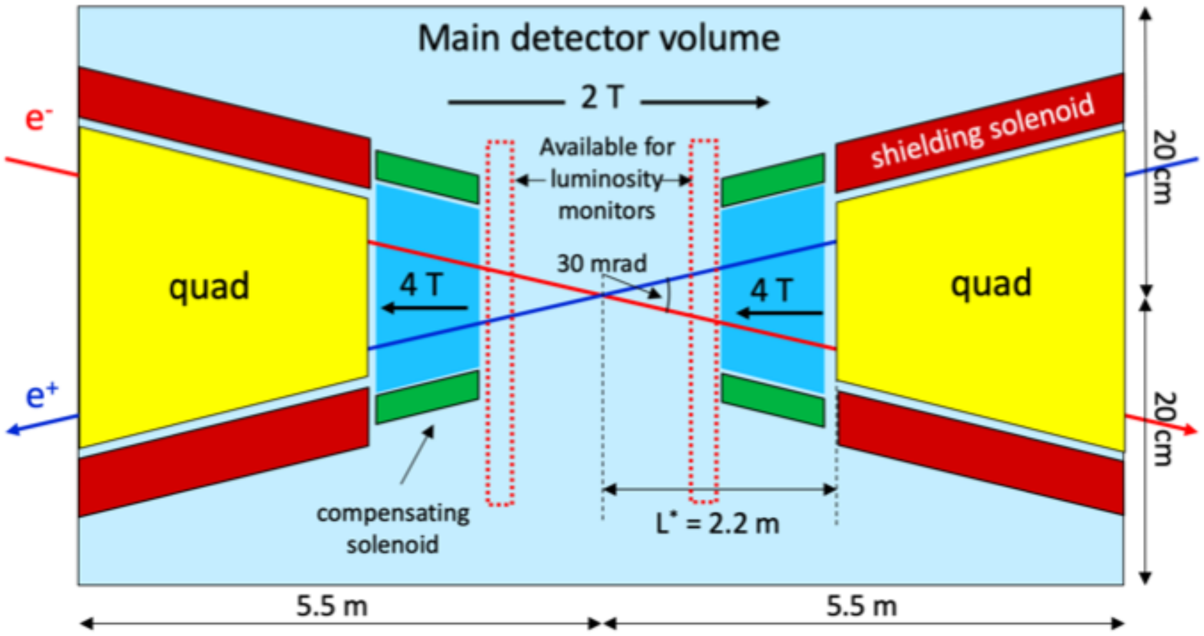
- Statistics
  - Very high statistics at the Z pole (70 kHz of visible Z decays)
  - Beam-induced background mild (compared to linear colliders), but not negligible
- Pile-up parameter very small (but not negligible for high precision measurements)
  - Aim at **10^{-4} absolute normalization** from small angle Bhabha scattering
  - Pile-up parameter ~20 times higher at Z-peak
- √s calibration and measurement of √s spread
  - 50 keV "continuous" E_{BEAM} measurement from resonant depolarization
  - Energy spread measurement from di-muon acollinearity (requires muon angular precision to better than 100 μrad)

Machine Detector Interface



- Large horizontal crossing angle 30 mrad
- Beams only mildly bent before IP to minimize synchrotron radiation into detector volumes
  - Beams bent mainly after IP

Central part of detector volume – top view

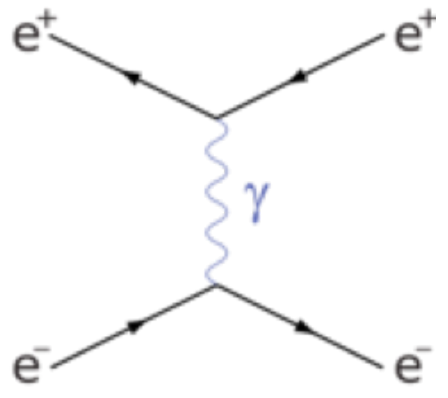


- Focussing quadrupoles protrude into detector volume
  - QC1 down to distance L^* = 2.2 m
  - Necessary to shield quads from detector field
- Beams cross detector field at 15 mrad crossing angle
  - Compensate for detector field to avoid ε_y blow-up
  - Limits detector field to B = 2 Tesla
  - **Luminosity calorimeters inside main detector volume at 1-1.2 m from IP**

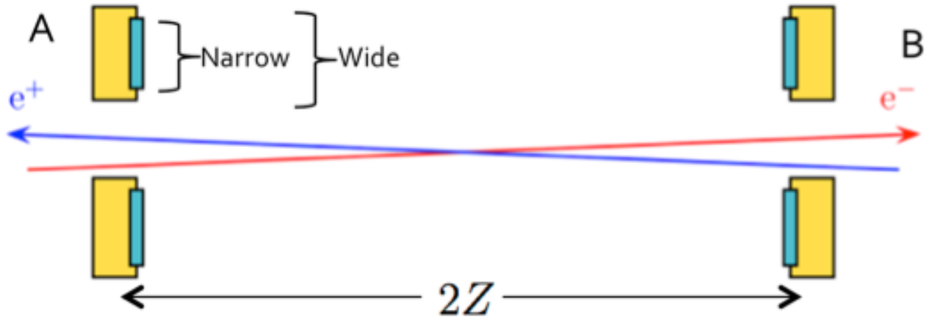
Luminosity Measurement

- Luminosity process: small angle elastic e^+e^- (Bhabha) scattering
  - Dominated by *t*-channel photon exchange
  - Very strongly forward peaked

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



  - 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: *minimum scattering angle*

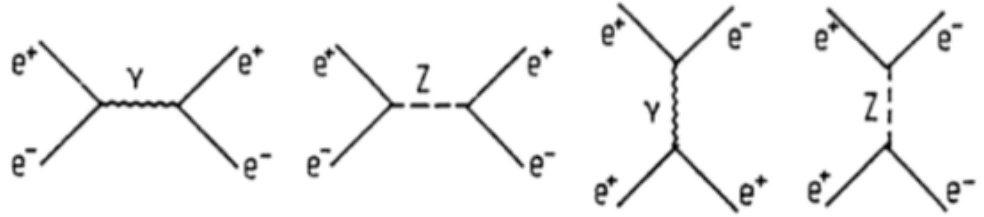
$$\frac{\delta\sigma^{\text{acc}}}{\sigma^{\text{acc}}} \simeq \frac{2\delta\theta_{\text{min}}}{\theta_{\text{min}}} = 2\left(\frac{\delta R_{\text{min}}}{R_{\text{min}}} \oplus \frac{\delta z}{z}\right)$$

Normalisation to 10^{-4}

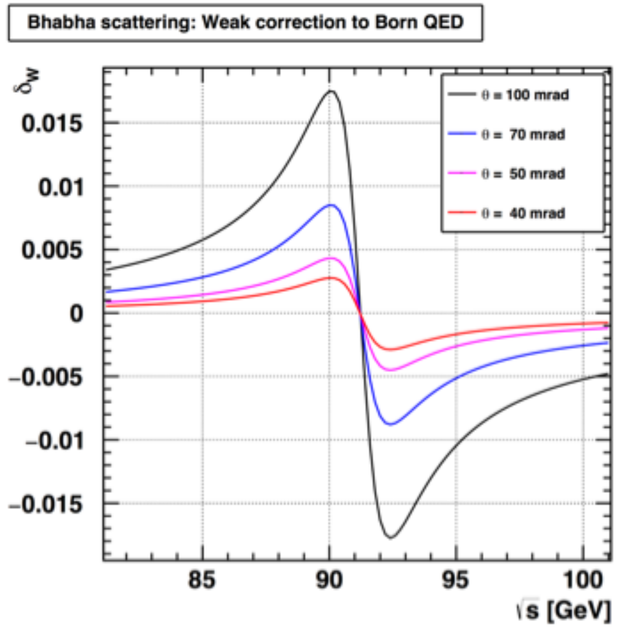
- At LEP, after much effort, precision on absolute luminosity was dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

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

  - Since then, theory precision has improved to **3.8×10^{-4}** [Jadach et al, 1812.01004]
- Ambitious FCC-ee goal: Total precision to **10^{-4}**
  - Will require major effort within **theory**
    - Four graphs already at lowest order



    - Dependence on Z parameters (increasing with angle)
    - Lots of radiative corrections between initial and final legs
  - Will require major effort **experimentally**
    - Second generation LEP luminosity monitors constructed and monitored to ***tolerances better than 5 μm***

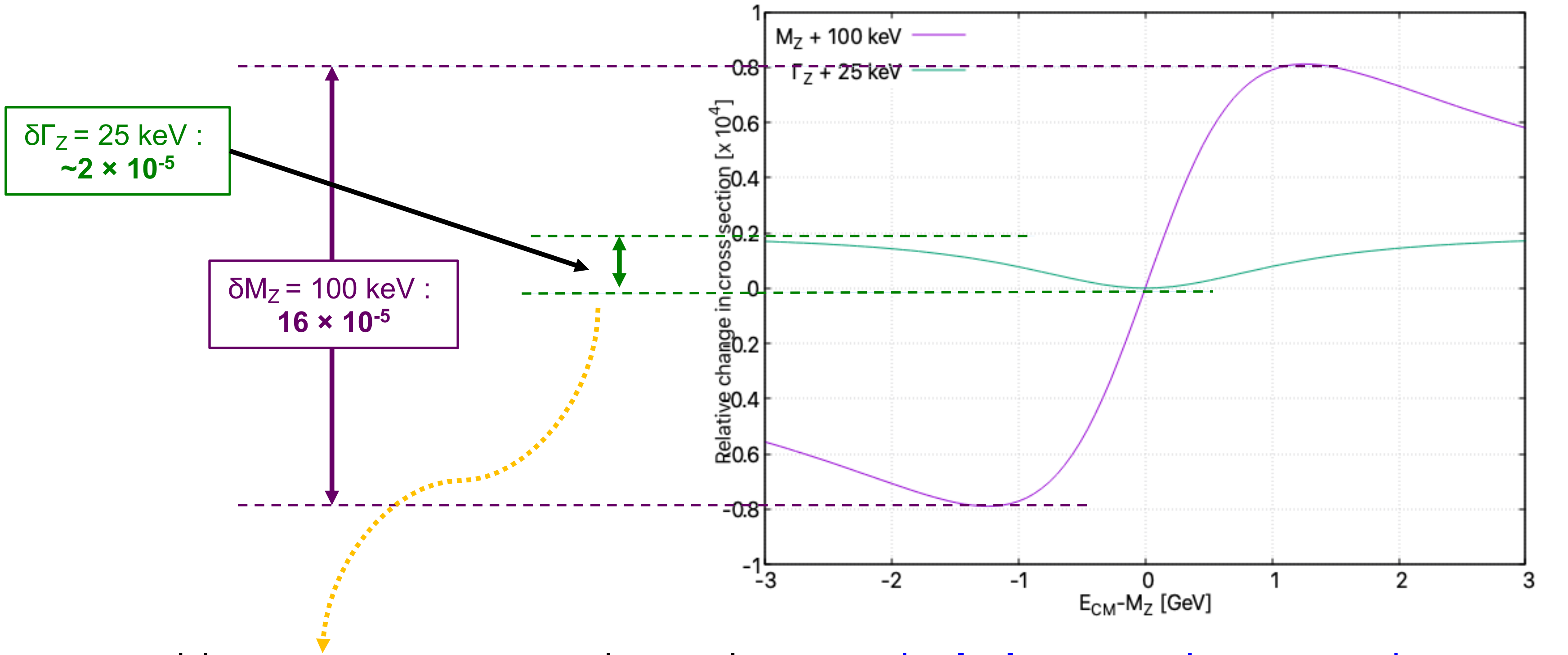


Relative Normalisation

- FCC-ee goal: Via Z line-shape scan, determine Z parameters to precisions:

$\delta M_Z = 100$ keV ; $\delta\Gamma_Z = 25$ keV

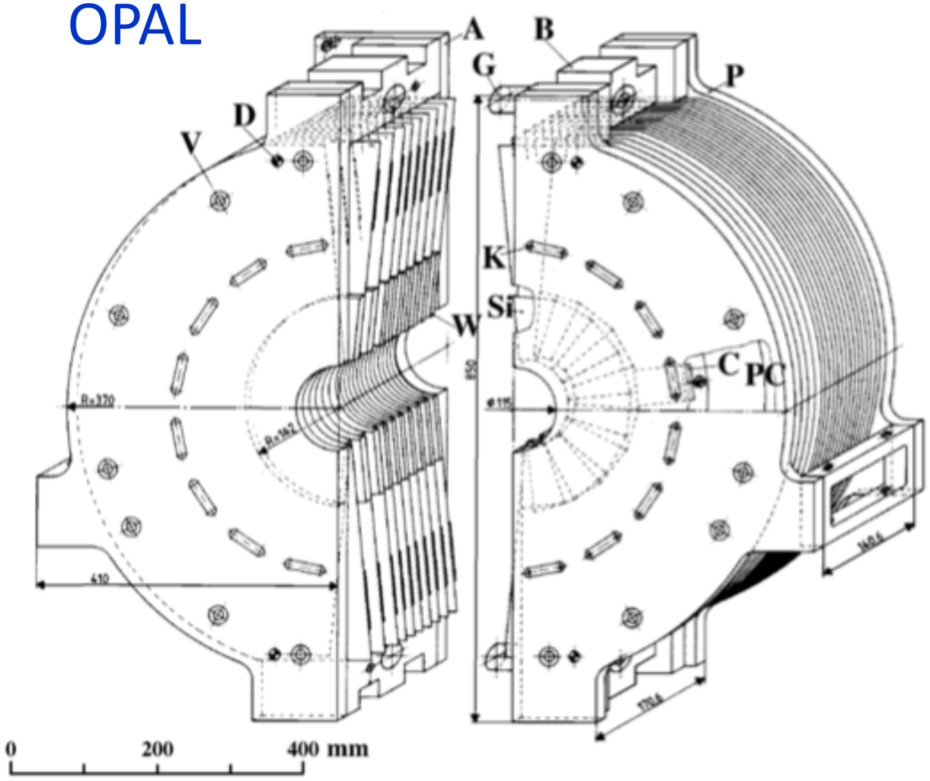
  - Plot shows relative change in cross section across Z resonance for parameter variation of this size



- Z width measurement most demanding: Need **relative** normalisation to about **10^{-5}**
  - Need statistics of order 10^{10}
  - Need careful control of energy dependent effects

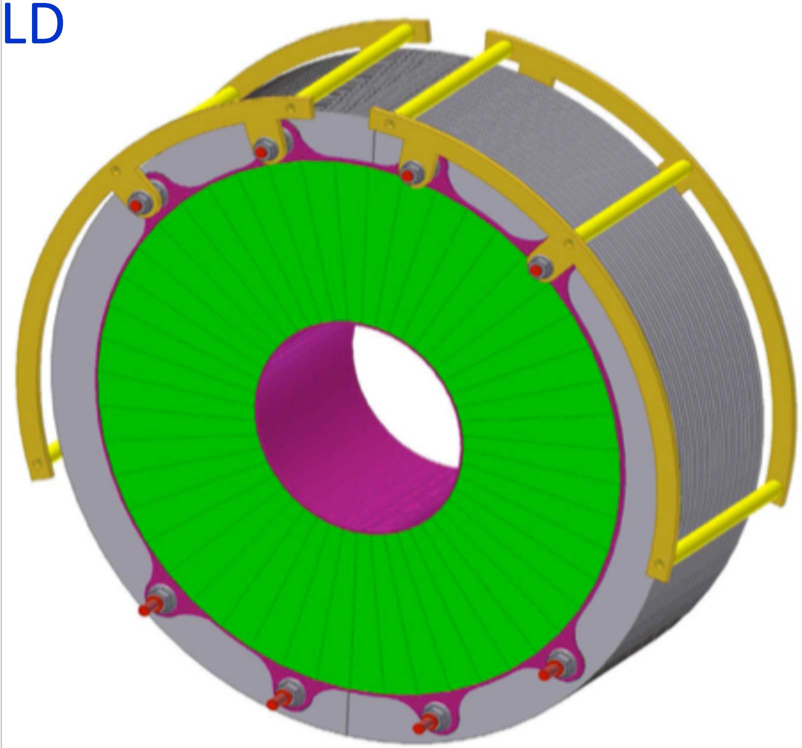
LumiCal Design Inspiration

OPAL



Eur. Phys. J. C14 (2000) 373–425

FCAL/ILD



EUDET-Memo-2010-06

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:

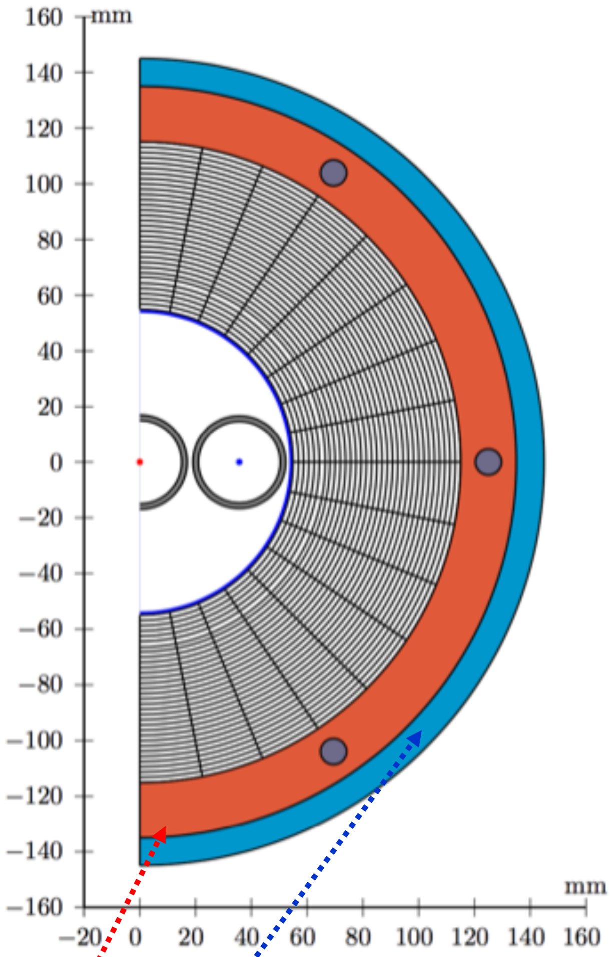
- Sensitive: 80 mm
- Mechanical: 76 mm

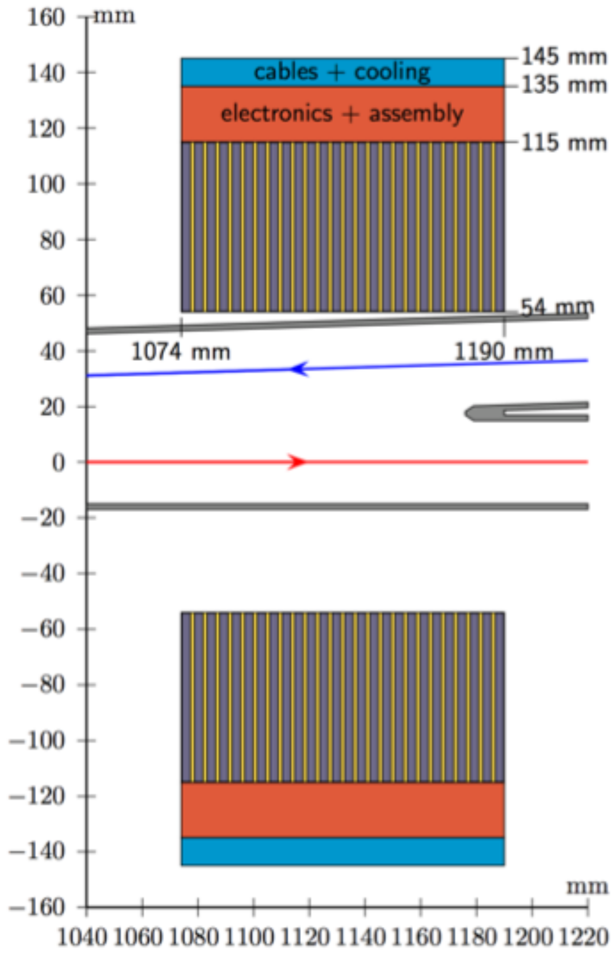
Outer radius:

- Sensitive: 195.2 mm
- Mechanical: ~260 mm

FCC-ee CDR LumiCal Concept

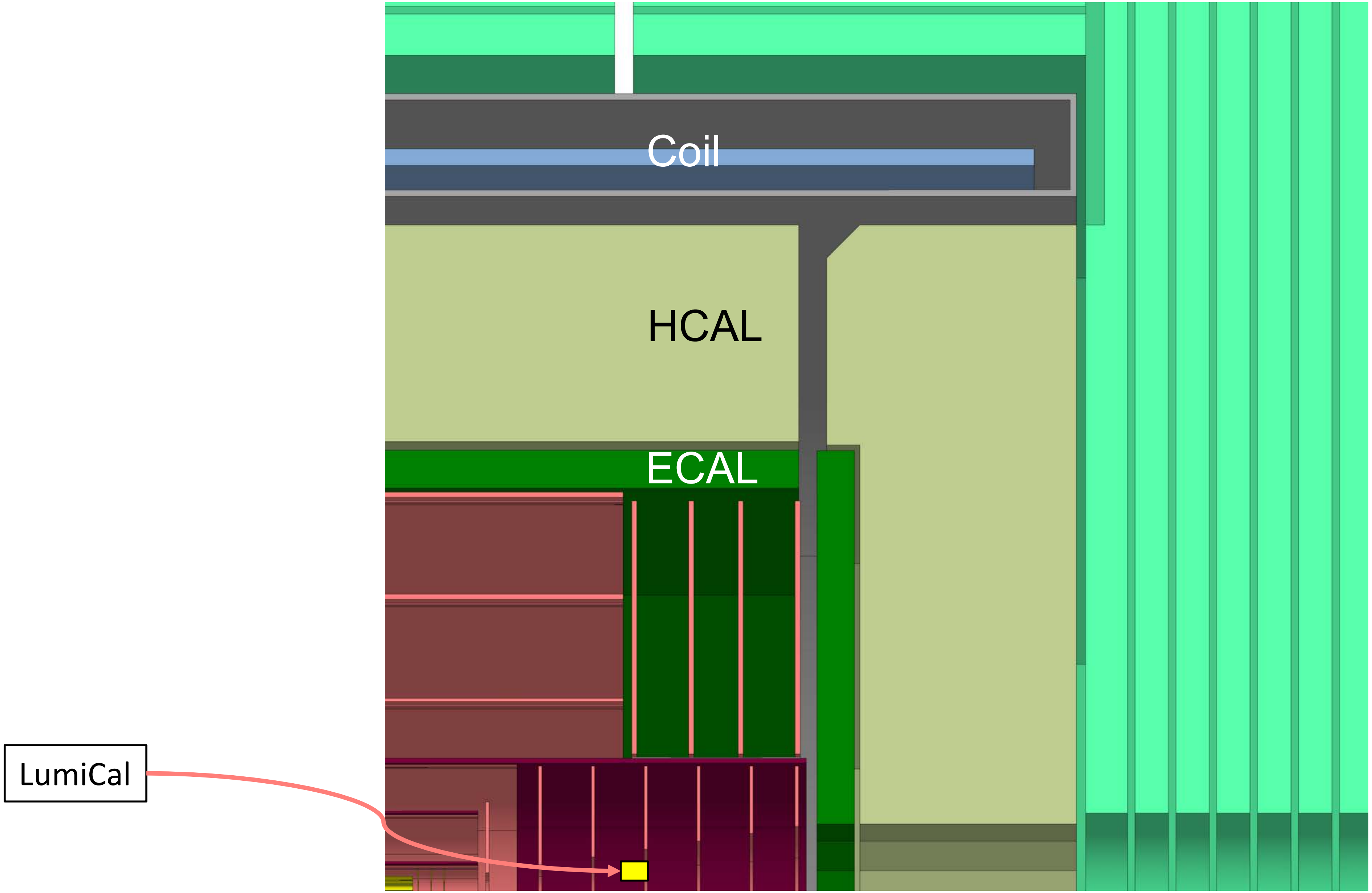
- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Moliere radius: ~15 mm
- 25 layers total: 25 X_0
- Cylindrical detector dimensions:
  - Radius: 54 < r < 145 mm
  - Along outgoing beam line: 1074 < z < 1190 mm
- Sensitive region:
  - 55 < r < 115 mm;
- Detectors centered on and perpendicular to outgoing beam line
- Angular coverage (>1 Moliere 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?)





Design inspired by LEP gen2 LumiCals and ILC/FCAL work (in particular Crakow group)

LumiCal inside CLD detector concept



LumiCal Geomtrical Tolerances

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

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

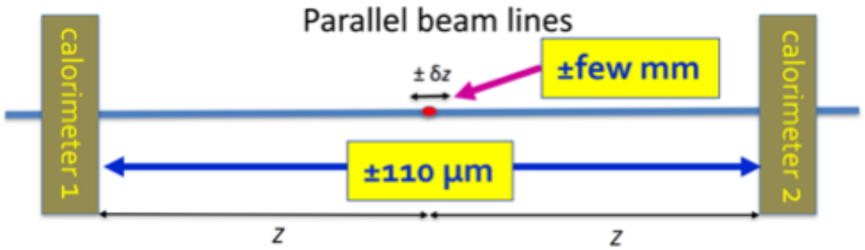
and

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

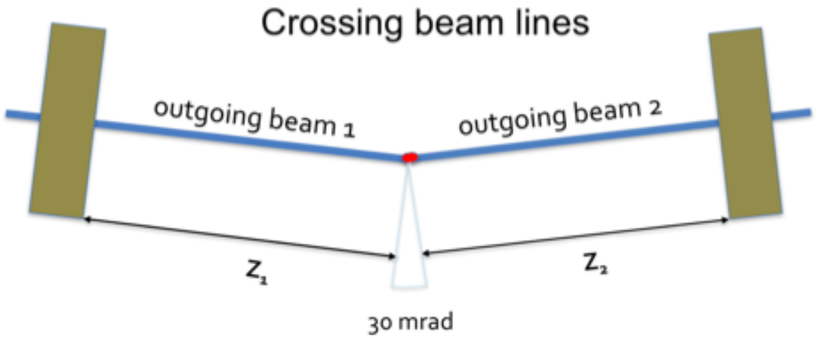
  - **Aim for construction and metrology precision of 1 µm**

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

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



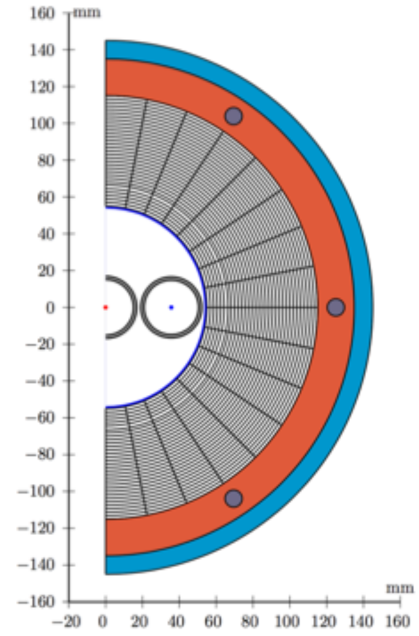
  - Situation is somewhat more complicated due to the crossing beam situation
  - Now, it is the sum of distances, **$Z_1 + Z_2$**, which has **to be known to 110 µm**
  - Idea to be pursued: Alignment using tracking detector as intermediate:
    - IP/tracker: dimuon events
    - LumiCal/tracker: laser tracks



Most critical parameter: Inner acceptance radius to ~1 µm

Very compact device:

- Possible to construct Si sensors from a single Si crystal
- However, vertical assembly of half barrels
- Or possibly build as one piece and thread onto beam pipe ?



Alignment relative to IP position

- With 2 mrad difference between **narrow** and **wide,** the acceptance depends to only second order on displacements of IP relative to LumiCal system for displacements up to

  δr = 0.5 mm transverse and δz = 20 mm longitudinal

  - Should dispacements be larger, need to redefine **narrow** and **wide**

- Within these tolerances, the acceptance depends rather weakly on IP displacements

$$\frac{\Delta A}{A} \approx + \left(\frac{\delta r}{0.6\,\mathrm{mm}}\right)^2 \times 10^{-4}$$

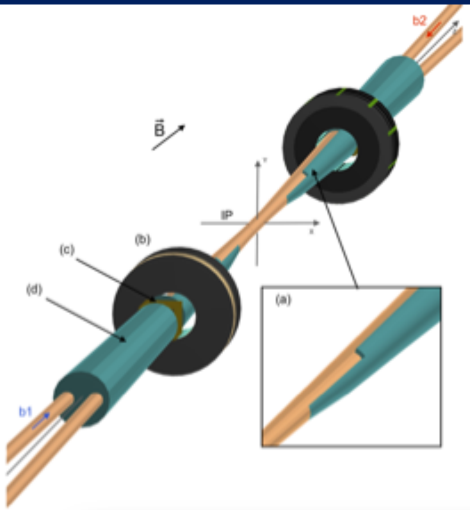
and

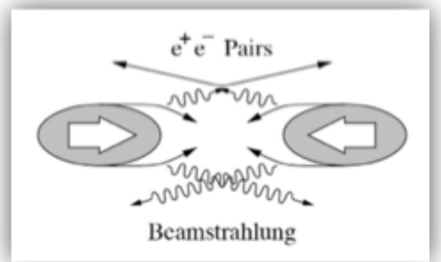
$$\frac{\Delta A}{A} \approx - \left(\frac{\delta z}{6\,\mathrm{mm}}\right)^2 \times 10^{-4}$$

- **Conclusion**: Optimal situation is if interaction point is centered wrt LumiCal coordinate system within the following tolerances:
  - Few hundred microns in radial direction
  - Few mm in longitudinal direction

Backgrounds

- Synchrotron radiation
  - Reduced to **negligible** level of 7 MeV per BX into LumiCal at √s = 365 GeV by beam-pipe shielding
    - Before shielding, 340 MeV per BX
    - Lower at lower √s
- Beam-gas
  - **Dominant background at LEP**: Two arm coincidence of off-momentum electrons from beam-gas interaction scattered into LumiCal acceptance by the quadrupoles
  - At FCC-ee, due to stronger focussing, the luminosity to beam current ratio is far higher
  - Correspondingly, this background found to be **very small after beam-pibe shielding**
- e^+e^- pairs from beam-beam interactions (dominant process: Incoherent pair production)
  - Particles generally very soft ⇒ strongly focussed by detector field and by strong electromagnetic field of opposing beam





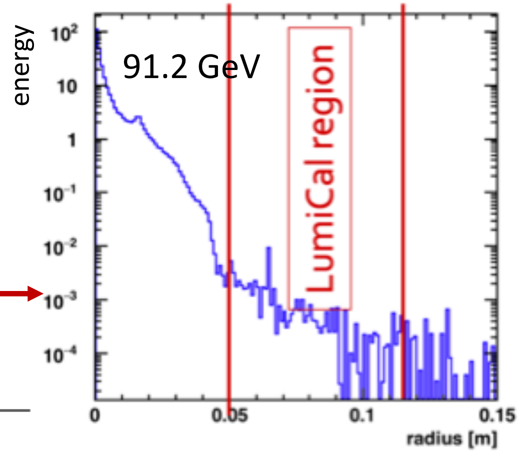
Guinea-Pig study

√s	# e± total	Energy total	# e± LumiCal	Energy LumiCal
91.2 GeV	400	250 GeV	0.3	0.06 GeV
365 GeV	3100	4500 GeV	15	3.2 GeV

[N.B. Numbers given are per end/LumiCal]

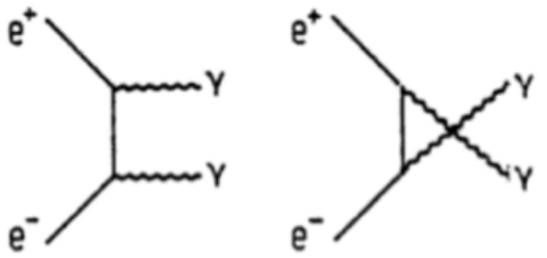
Rather many particles, large energy

Most particles / energy generated and/or focussed away from LumiCals.
At √s = 91 GeV, negligible. Increasing with √s



Alternative luminosity process – Large angle $e^+e^- \to \gamma\gamma$

QED process

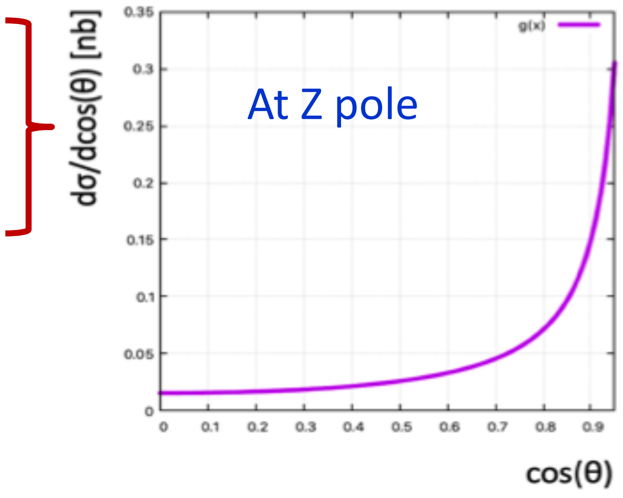


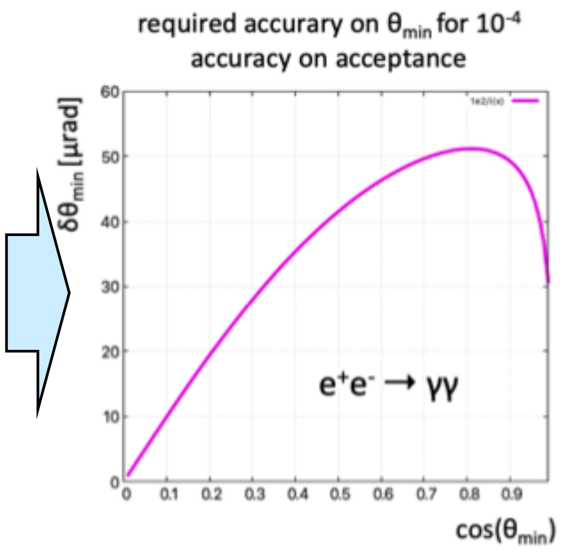
Goal: Absolute luminosity to 10^{-4}

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

(θ_{min} defines the ECAL acceptance)

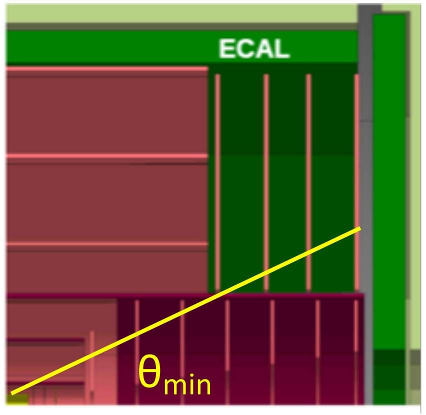
Forward peaked





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

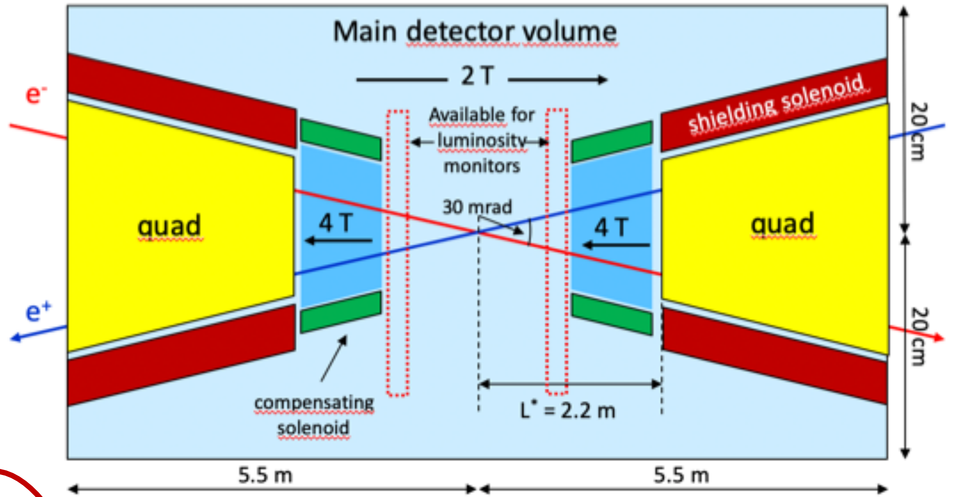
Energy	Process	Cross Section	Large angle $e^+e^- \to \gamma\gamma$
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb
240 GeV	$e^+e^- \to ZH$	0.2 pb	5.6 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb

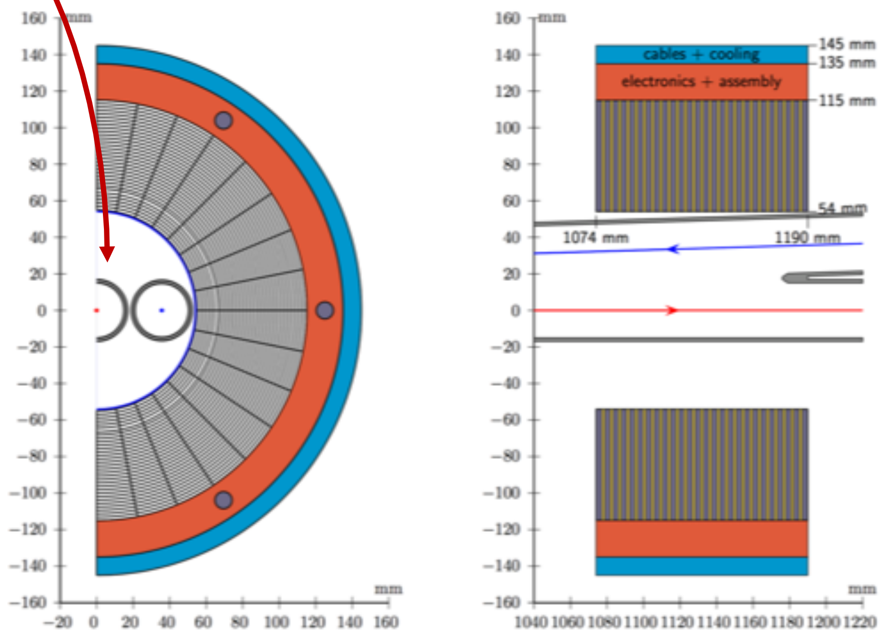


- For $\cos(\theta_{min})$ = 0.94, $\delta\theta_{min} \simeq$ 46 μrad is required
  - At z_{ref} = 2.25 m, corresponds to
    - Acceptance inner radius: r_{min} = 0.82 m
    - Inner acceptance radius to be known to better than δr_{min} = 100 μm, *if z_{ref} perfectly known*
  - Experimental challenge
    - Precisely machined pre-shower device?
    - All other contributions to be kept very low
      - No holes, no cracks …

Other forward instrumentation ?

- So far, focus has been primarily on very ambitious goal of normalisation to 10^{-4}
  - Cylindrical device chosen in order to maintain control over geometry
- Need also to consider hermeticity of detector down towards beam line
  - There seems to be no room for instrumentation behind LumiCals
    - Area very densely packed with magnet system
  - Room at some azimuthal angles for instrumentation at lower radii than current LumiCal concept
  - Not obvious how to instrument this region and at the same time retain 1µm precison on acceptance definition of LumiCal





Outlook

- Much work ahead for design of lumionosity monitors and forward region
  - Detailed layout of very crowded MDI region including (compensating) magnet system(s), flanges, pumps, etc.
  - Design and integration of very forward region of main detector system towards MDI and luminosity monitors
  - Engineering level design of luminosity monitors:
    - Mechanical design satisfying ~1 μm precision of acceptance borders
      - Closing as hermetically as posisble towards beam line without sacrificing mechanical precision
    - Fast readout electronics preferentially operating at 20 ns BX spacing to minimize event pile-up
    - Cooling system to maintain temperature to within tolerance of about ±1 K
    - Support structure with minimal coupling to magnet system
    - Design of system for maintaining and monitoring geometrical precision of monitors via metrology and alignment
  - Control of lower angle of main detector accetance to 100 μm for alternative lumi process $e^+e^- \rightarrow \gamma\gamma$

Extras