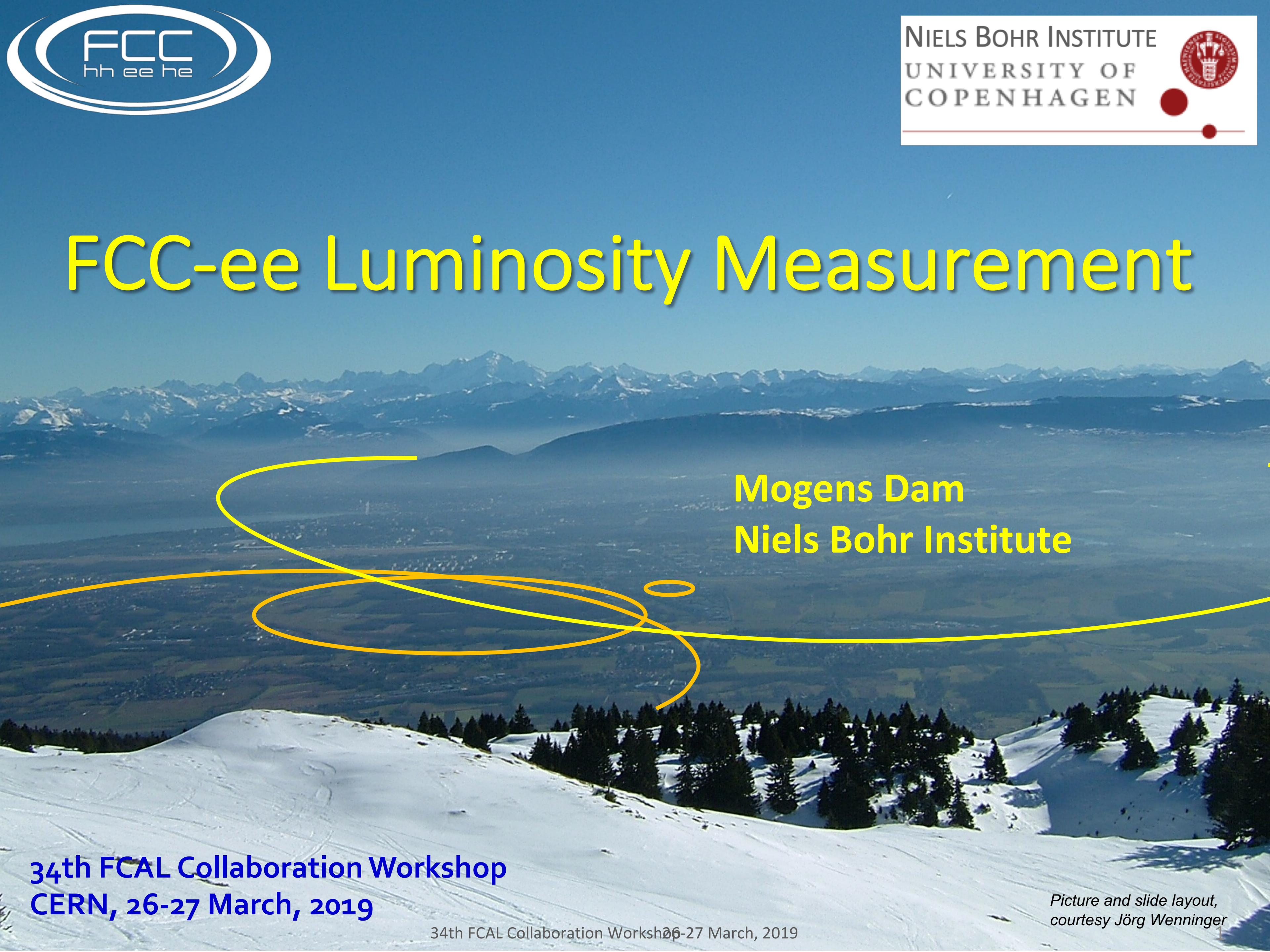


FCC-ee Luminosity Measurement

Mogens Dam
Niels Bohr Institute

34th FCAL Collaboration Workshop
CERN, 26-27 March, 2019

Picture and slide layout,
courtesy Jörg Wenninger

Future Circular Collider Study

International FCC collaboration to study (since 2014)

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- **Ultimate goal: ≥ 100 TeV pp-collider (FCC-hh)**

≥16 T magnets

→ defining infrastructure requirements

Two possible first steps:

- ***e*⁺*e*⁻ collider (FCC-ee)**

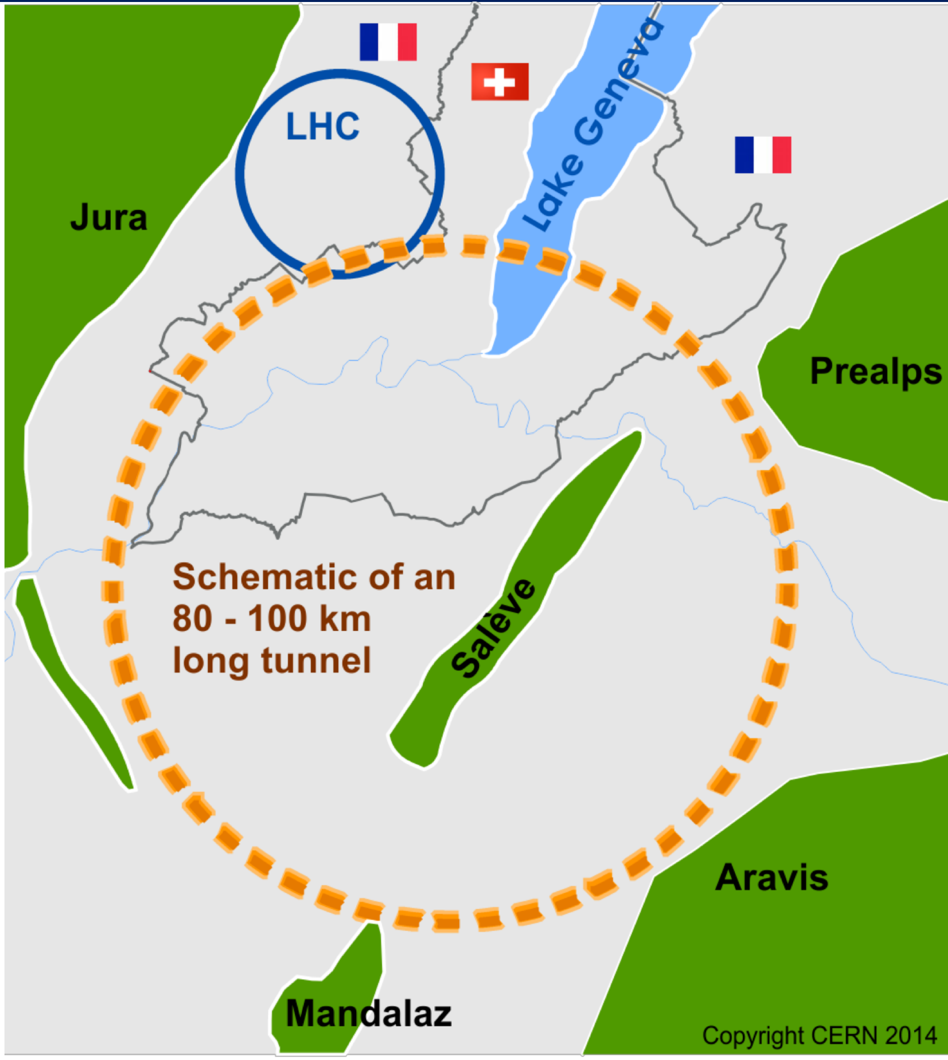
  High Lumi, E_{CM} = 90-400 GeV

- ***HE-LHC:* 16 T ⇒ 27 TeV**

  in LEP/LHC tunnel

Possible addition

- **p-e (FCC-he)**



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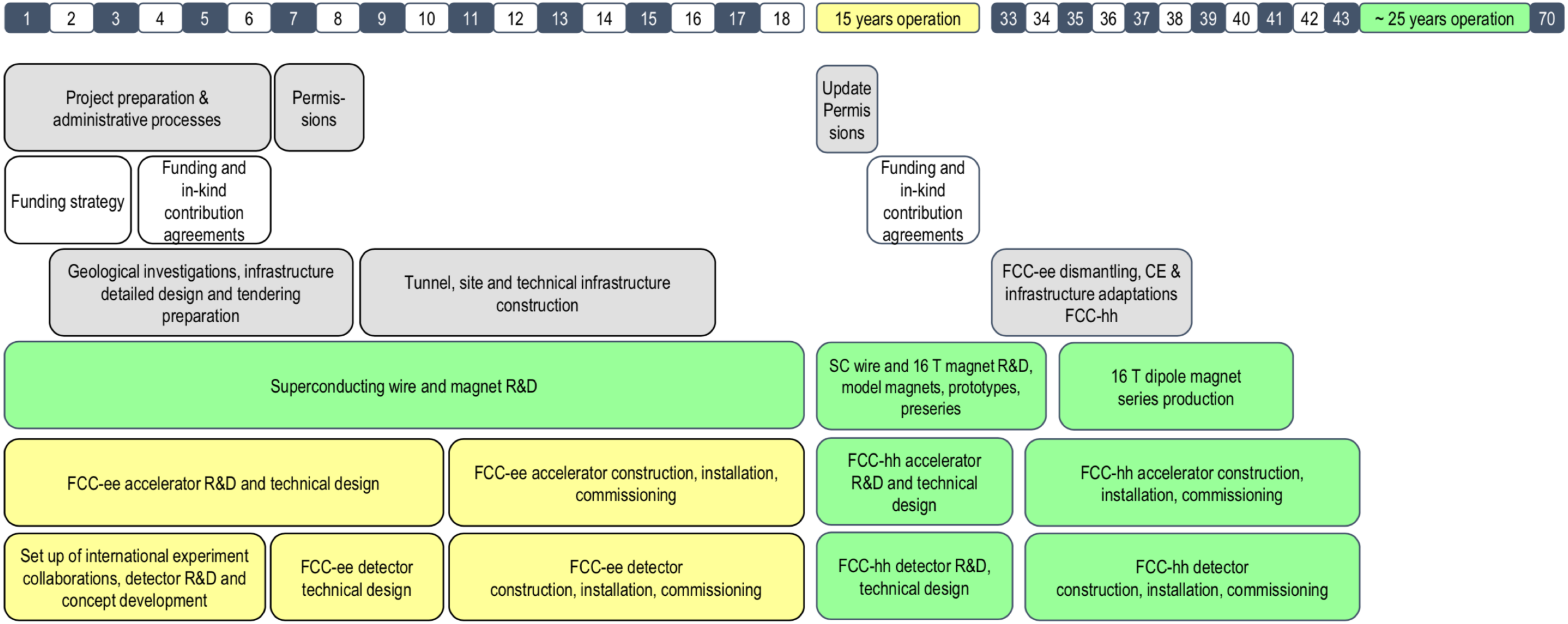
FCC CDRs available at

http://fcc-cdr.web.cern.ch/

FCC integrated project technical timeline



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 33 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Funding strategy

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

Superconducting wire and magnet R&D

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

Update Permis sions

Funding and in-kind contribution agreements

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC-hh accelerator R&D and technical design

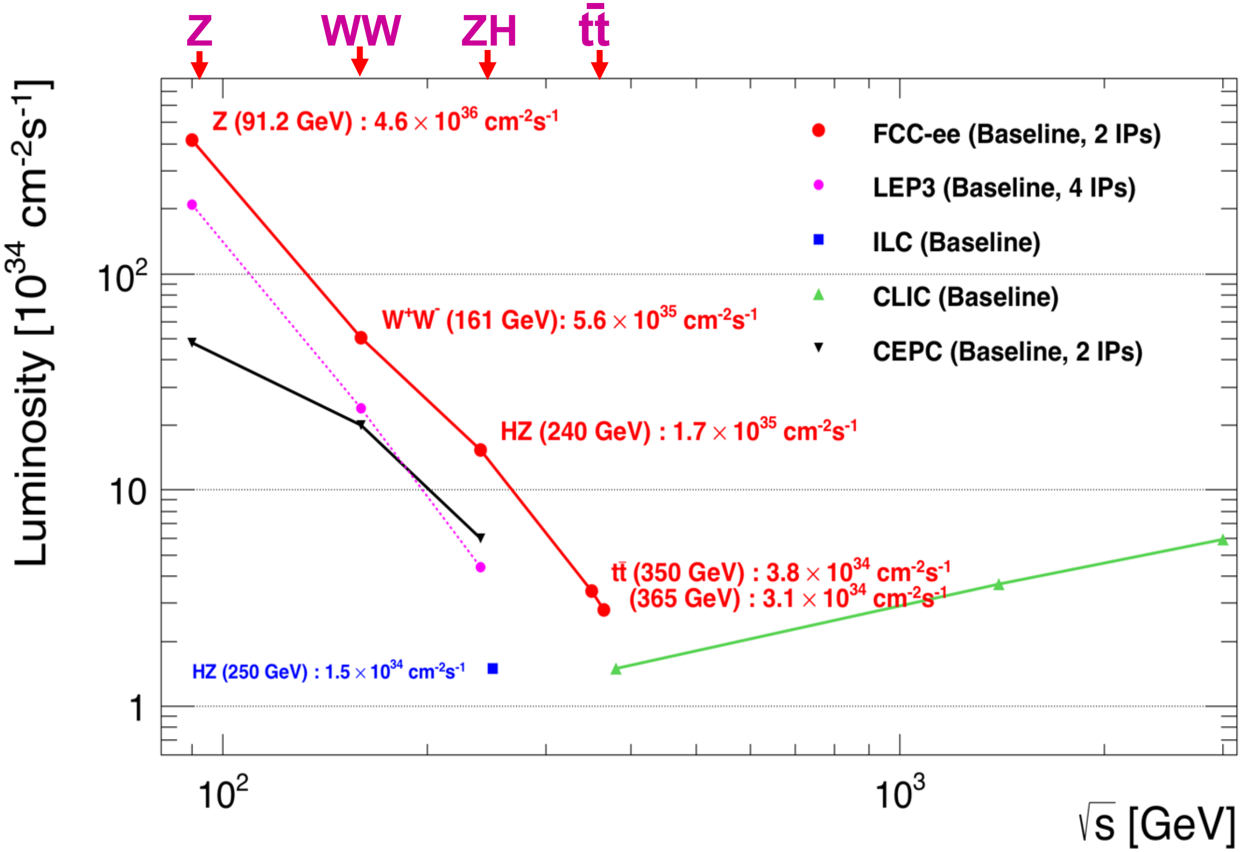
FCC-hh accelerator construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

EW factories: Energies and luminosities

The FCC-ee offers the largest luminosities in the 88 → 365 GeV √s range



Ultimate statistics/precision:

- 100 000 Z / second
  - 1 Z / second at LEP
- 10 000 W / hour
  - 20 000 W at LEP
- 1 500 Higgs bosons / day
  - 10 times ILC
- 1 500 top quarks / day

  in each detector

PRECISION and SENSITIVITY
to rare or elusive phenomena

The FCC-ee discovery potential (excerpt)

- EXPLORE the 10-100 TeV energy scale
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
      - m_Z, m_W, m_{top}, Γ_Z, $\sin^2 \theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$, $\alpha_s(m_z, m_W, m_\tau)$, top EW couplings …
    - Up to 10-fold more precise and model-independent Higgs couplings measurements

arXiv:1512.05544

arXiv:1603.06501

arXiv:1503.01325

- DISCOVER that the Standard Model does not fit
  - NEW PHYSICS ! Pattern of deviations may point to the source.
- DISCOVER a violation of flavour conservation / universality
  - Examples: $Z \rightarrow \tau\mu$ in 5×10^{12} Z decays; or $\tau \rightarrow \mu\gamma$ / $\tau \rightarrow e\gamma$ in 2×10^{11} τ decays; …
  - Also $B^0 \rightarrow K^{*0}\tau^+\tau^-$ or $B_S \rightarrow \tau^+\tau^-$ in 10^{12} bb events
- DISCOVER dark matter as invisible decays of Higgs or Z
- DIRECT DISCOVERY of very-weakly-coupled particles
  - in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, …
    - Motivated by all measurements / searches at colliders (SM and "nothing else")

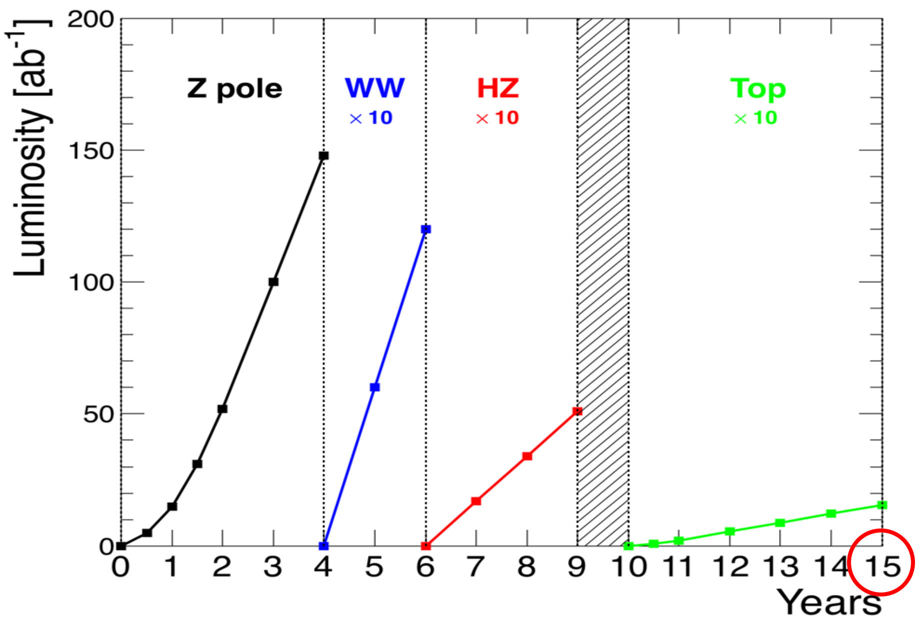
FCC-ee is not only a Higgs factory: **Z, WW, and $t\bar{t}$ factories are important for discovery potential**

First look at the physics case of TLEP https://arxiv.org/abs/1308.6176 (Aug. 2013)

The FCC-ee operation model and statistics

- 185 physics days / year, 75% efficiency, 10% margin on luminosity

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**



Total : 15 years

Event statistics

5×10^{12} $e^+e^- \rightarrow Z$

10^8 $e^+e^- \rightarrow W^+W^-$

10^6 $e^+e^- \rightarrow HZ$

10^6 $e^+e^- \rightarrow t\bar{t}$

√s precision

100 keV

300 keV

1 MeV

2 MeV

FCC-ee Conditions

FCC-ee parameters		**Z**	**W^+W^-**	**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

Need detectors to match conditions

- Extremely large statistics / statistical precision
  - …need small systematics to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
  - Continous beams, no power pulsing
- No pileup, no underlying event, …

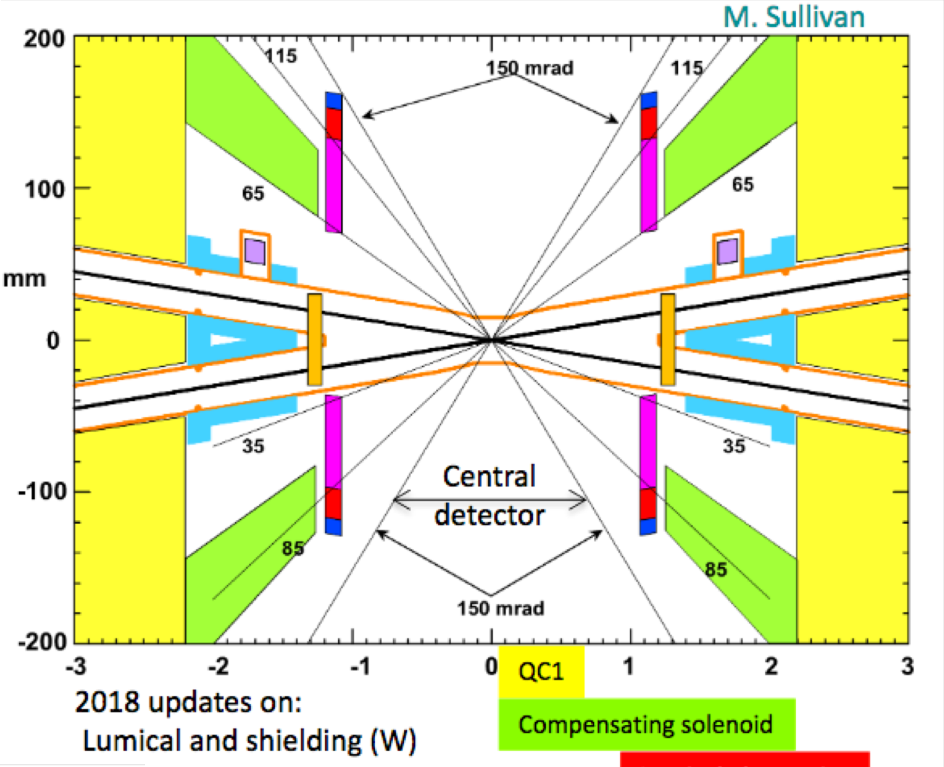
Important features for precision measurements

- Statistics
  - Very high statistics at the Z pole (70 kHz of visible Z decays)
  - Beam-induced background are mild compared to linear colliders, but not negligible
    - Readout must be able to cope with both
    - CW running imposes constraints on detector cooling
- Luminosity measurement
  - Aim at 0.01% from small angle Bhabhas
    - Requires μm precision for LumiCal
  - Need to study $e^+e^- \rightarrow \gamma\gamma$ to possibly approach 0.001%
- √s calibration and measurement of √s spread
  - 50 keV "continuous" E_{BEAM} measurement with resonant depolarization
  - Powerful cross checks from di-muon acollinearity and polarimeter/spectrometer
    - Requires muon angle measurement to better than 100 μrad
- Flavour tagging
  - Small beam pipe radius: Vertex detector 1st layer at 17 mm.
    - Impact parameter resolution: 3-5 μm (cτ = 89 μm for τ and more for Bs)
    - New CEPC studies claim Purity × Efficiency ~ 97% for H → bb. And at FCC-ee ?

Interaction Region Layout

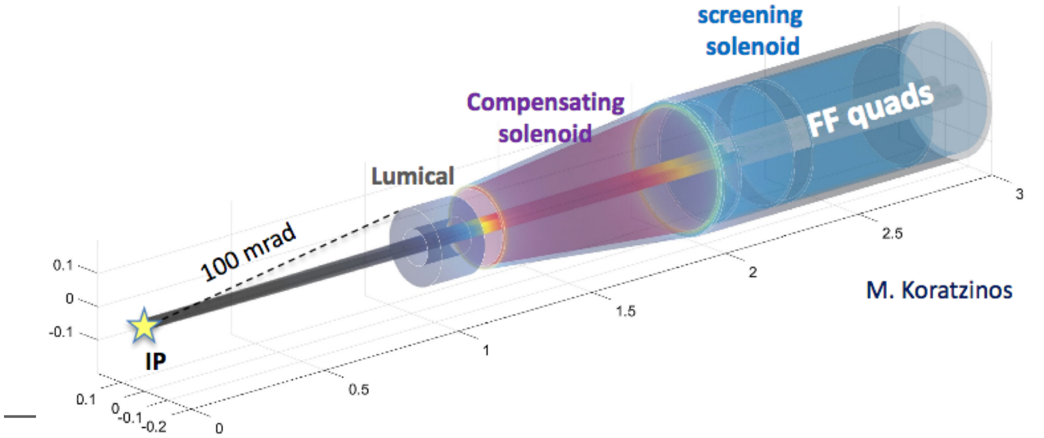
- Unique and flexible design at all energies
  - $L^* = 2.2$ m
    - Acceptance: 100 mrad
  - Solenoid compensation scheme
    - Reduce ε_y blow-up ⇒ $B_{Detector} \leq 2T$
  - Beam pipe
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - R = 15 mm in central region
      - 1st vertex detector layer 17 mm from IP
    - SR masks, W shielding
  - Mechanical design and assembly concept
    - Under engineering study

M. Sullivan



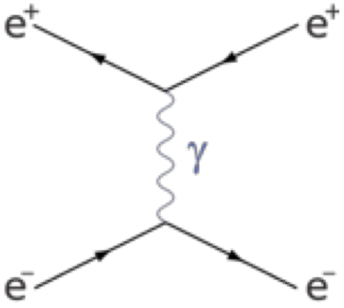
2018 updates on:
Lumical and shielding (W)

- 🟨 QC1
- 🟩 Compensating solenoid
- 🟪 Lumical
- 🟥 Lumical electronics
- 🟦 Lumical cables
- 🟧 HOM absorbers
- W shielding



M. Koratzinos

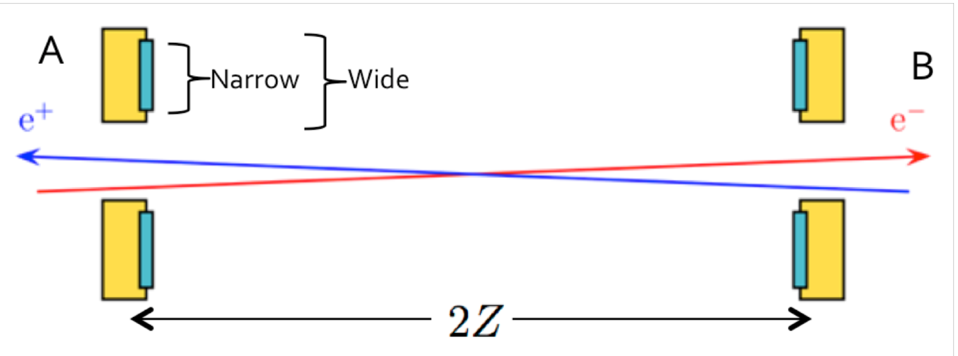
Luminosity Measurement



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

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

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



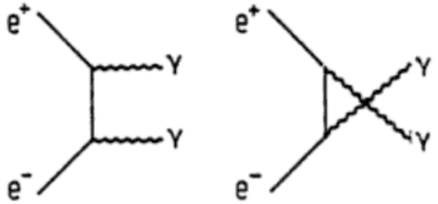
Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

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

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

Alternative Lumi Processes (to be studied)

- Possible alternative lumi process: **Large angle photon-pair production**
  - Only “one” graph at lowest order



H.-U. Martyn, Adv.Ser.Direct.High Energy Phys. 7 (1990) 92-161

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

(θ_{min} defines the ECAL acceptance)

    - Current precision at NLO at the 10^{-3} level [C.M.C Calame, FCC-ee workshop, Pisa, Feb. 2015]
  - Pure QED process with few radiative corrections between initial legs and propagator
  - Cross section is *much smaller* than small angle Bhabha scattering, but adequate everywhere but at Z-pole running. Provides interesting x-check at Z-pole.
  - Main experimental background: Large angle Bhabha scattering ($e^+e^- \to e^+e^-$)
    - > O(10) larger than signal. Have to control Bhabha contamination to $\sim 10^{-6}$
  - Example: $\theta > 20^\circ$ with respect to the beam axis ($\cos\theta < 0.94$) :

Energy	**Process**	**Cross Section**	**Large angle $e^+e^- \to \gamma\gamma$**	**Large angle $e^+e^- \to e^+e^-$**
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \to ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb	60 pb

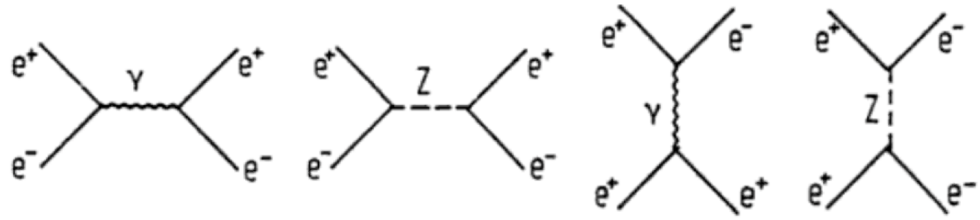
Normalisation to 10^{-4}

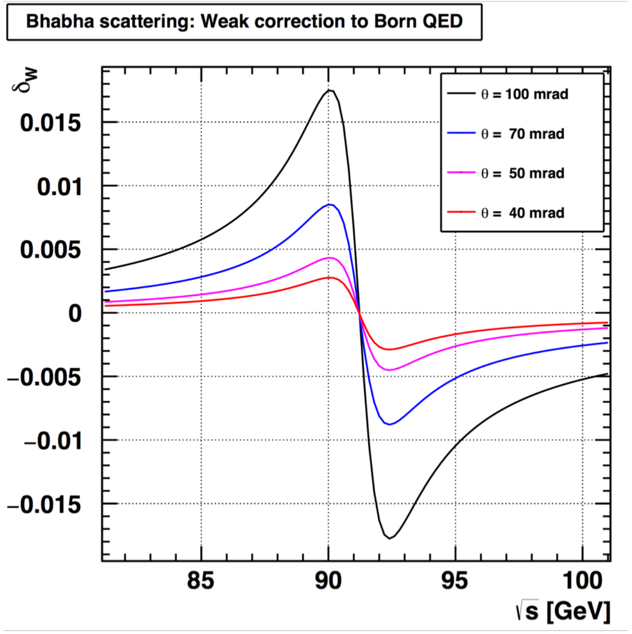
- The goal at FCC-ee is an absolute normalization to 10^{-4}
- After much effort, precision on absolute luminosity at LEP was dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

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 uncertainty to precision of **10^{-4}**
  - Will require major effort within **theory**
    - Four graphs already at lowest order





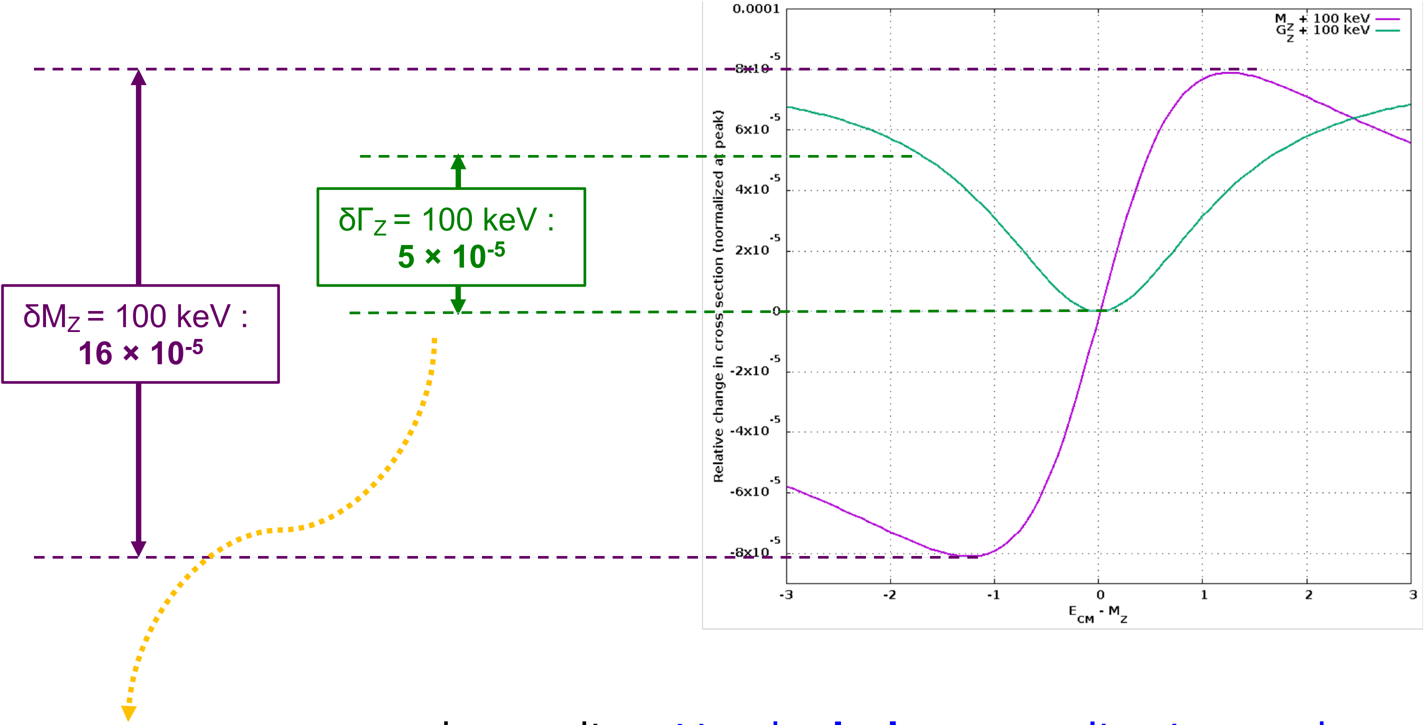
    - Dependence on Z parameters (increasing with angle)
    - Lots of radiative corrections between initial and final legs
  - Will require major effort **experimentally**
    - Second generation LEP luminosity monitors constructed and monitored to ***tolerances better than 5 μm***

Relative Normalisation

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

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

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

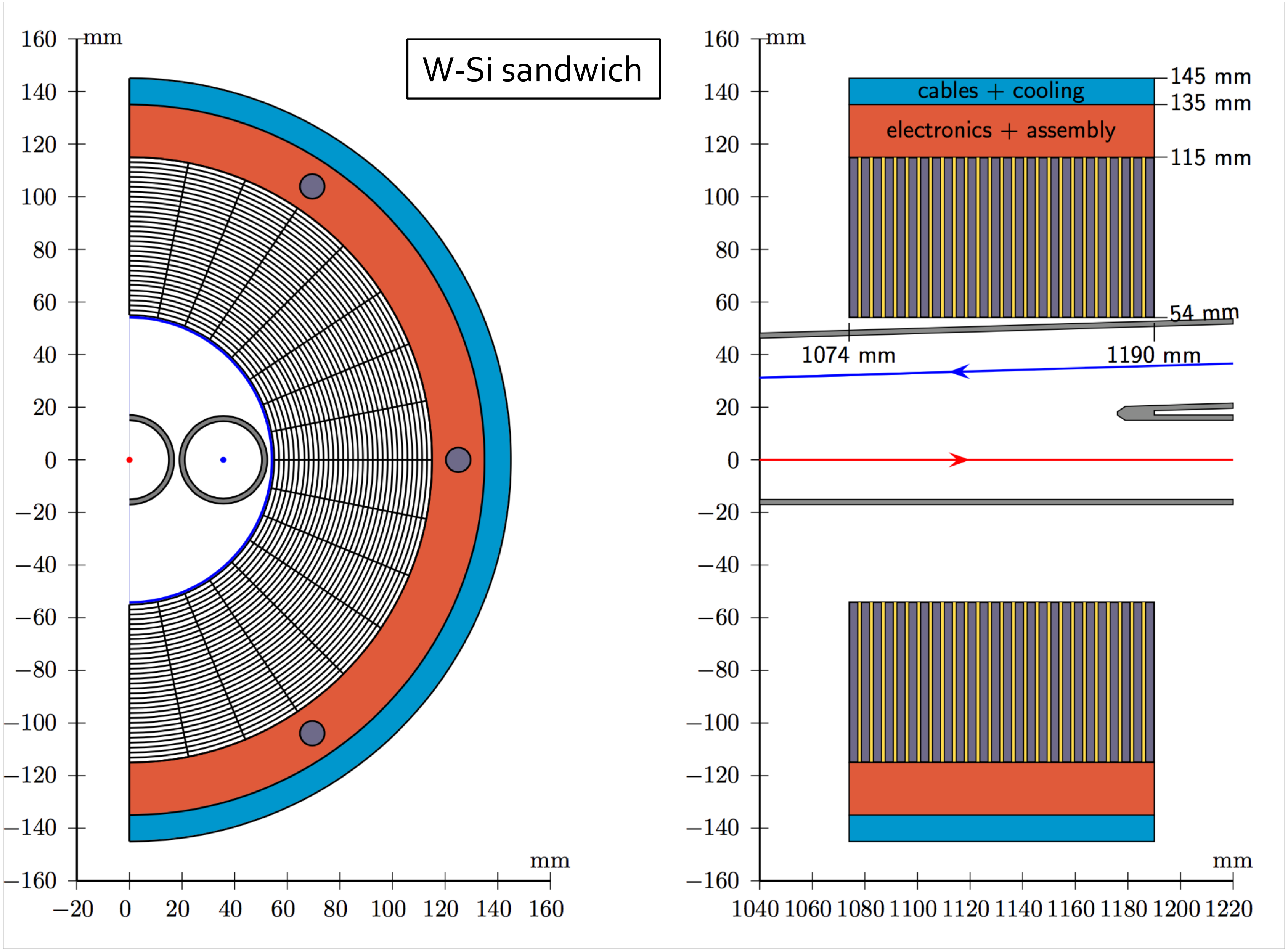


$\delta\Gamma_Z = 100$ keV :
5×10^{-5}

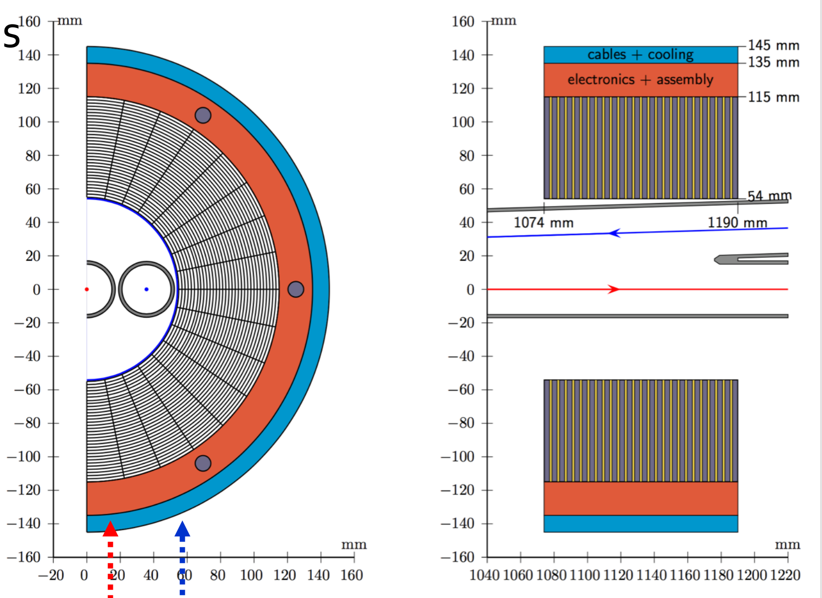
$\delta M_Z = 100$ keV :
16×10^{-5}

- Z width measurement most demanding: Need **relative** normalisation to about **5×10^{-5}**
  - Need statistics of order 10^9
  - To optimize sensitivity of off-peak running, aim for cross section ~ σ_Z ; i.e $\gtrsim 10$ nb

LumiCal Design



LumiCal Design



- 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 FCAL work (in particular Crakow group)

LumiCal Geometrical Tolerances

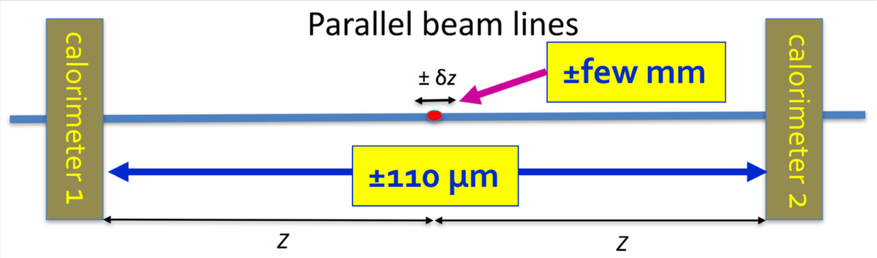
- Acceptance depends on **inner and outer radius** of acceptance definition

$$\boxed{\frac{\Delta A}{A} \approx -\frac{\Delta R_{\text{in}}}{1.6\,\mu\text{m}} \times 10^{-4}} \quad \text{and} \quad \boxed{\frac{\Delta A}{A} \approx +\frac{\Delta R_{\text{out}}}{3.8\,\mu\text{m}} \times 10^{-4}}$$

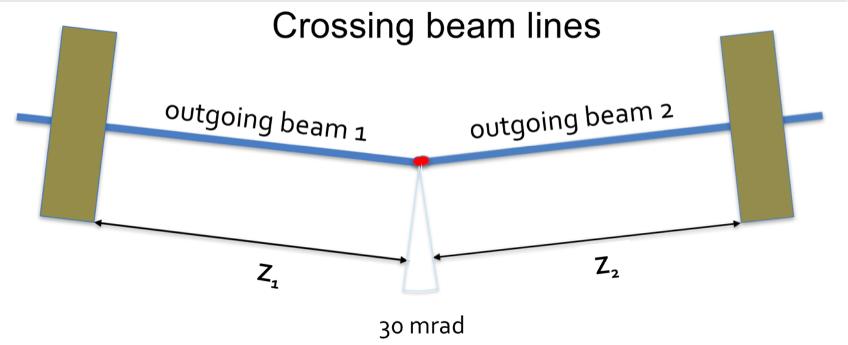
  - **Aim for construction and metrology precision of 1 µm**

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

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



  - 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



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**

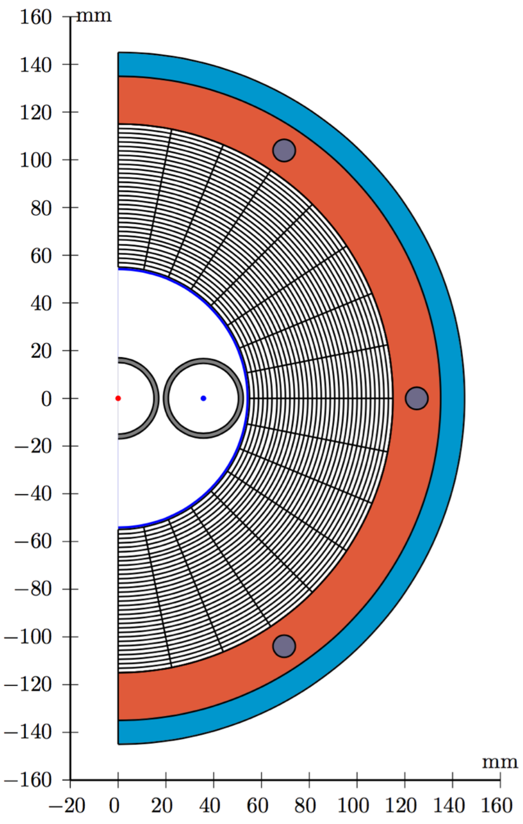
- Within these tolerances, the acceptance depends rather weakly on IP displacements

$$\boxed{\frac{\Delta A}{A} \approx + \left(\frac{\delta r}{0.6\,\mathrm{mm}}\right)^2 \times 10^{-4}} \quad \text{and} \quad \boxed{\frac{\Delta A}{A} \approx - \left(\frac{\delta z}{6\,\mathrm{mm}}\right)^2 \times 10^{-4}}$$

- **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

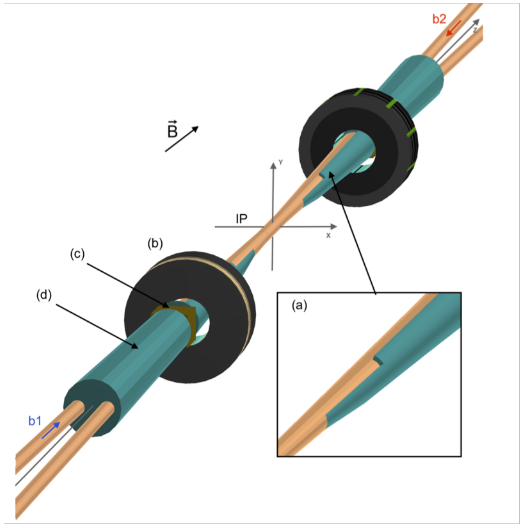
Geometry considerations

- Most critical parameter is inner radius of acceptance which has to be controlled to a precisio of **~1 μm**
- LumiCal is compact: Outer radius of Si sensors is only 155 mm
- This opens the possibility to construct each Si sensor from one crystal only
  - ❑ Geometrical precison given by wafer production: Far below 1 μm
- However, we have to be able to mount monitors around beam pipe
  - ❑ Critical issue: Vertical assembly
- Possible alternative?? (inspired by idea by A. Bogomyagkov, BNPI)
  - ❑ Thread luminosity monitors onto beam pipe from end before complete beam pipe assembly is installed inside detectors?
  - ❑ Avoid vertical division…?

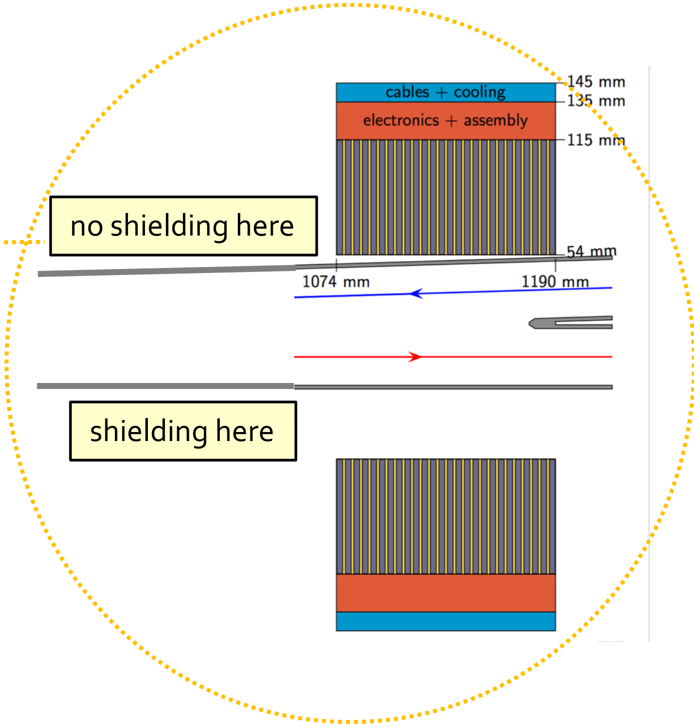


Beam-background: Synchrotron Radiation

- Tungsten shielding of beampipe effectively blocks synchrotron radiation



  - From z=370 mm to back of LumiCal:
    - 1 mm shielding with window for LumiCal
  - Behind LumiCal:
    - 15 mm shielding

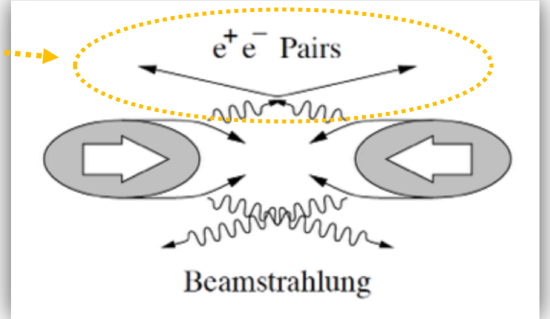


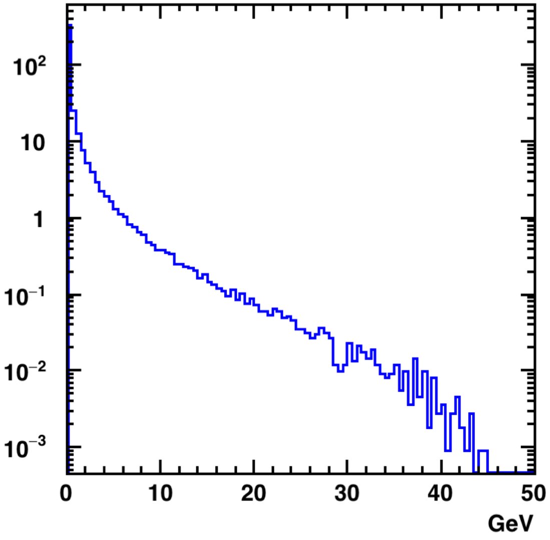
- Full GEANT4 simulation study: Shielding reduces energy from synchrotron radiation deposited in LumiCal from 340 MeV **to 7 MeV** at √s = 365 GeV
  - Smaller deposits at lower beam energies
  - Negligible effect!

✓

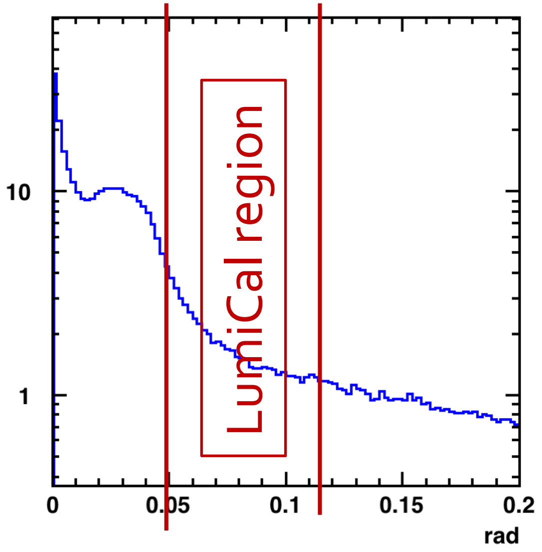
Beam-background: e^+e^- pairs (i)

- e^+e^- pairs created in beam-beam interactions
  - Dominant process at FCC-ee: Incoherent pair production
  - Events studied/generated by GuineaPig program
- Example: **Z-pole energy**
  - 800 $e^\pm$ particles per BX (with E > 5 MeV)
  - 500 GeV radiated in total per BX

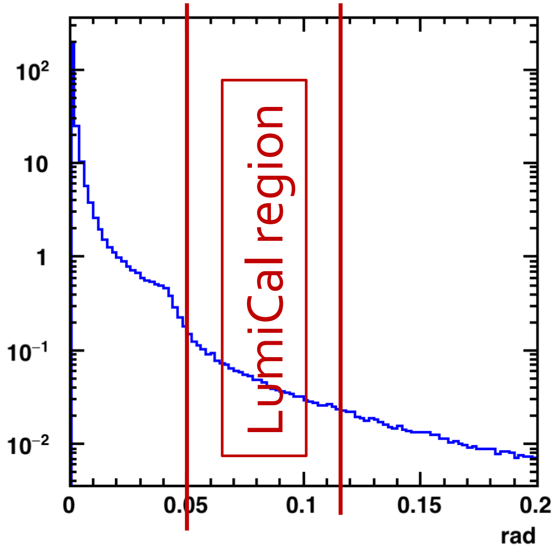




Energy of pair $e^\pm$ particles
- Average energy: 636 MeV
- # $e^\pm$ per BX per endcap: 404



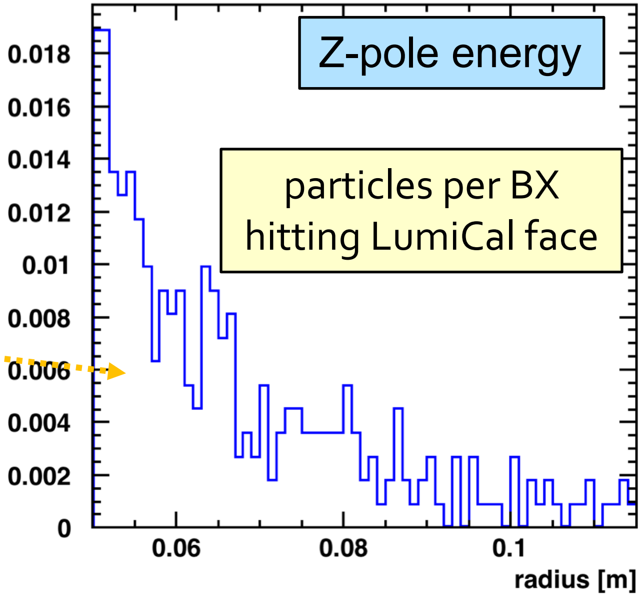
Polar angle of pair $e^\pm$ particles
- Peak at zero along beam line
- Bump around 30 mrad: focussing by other beam

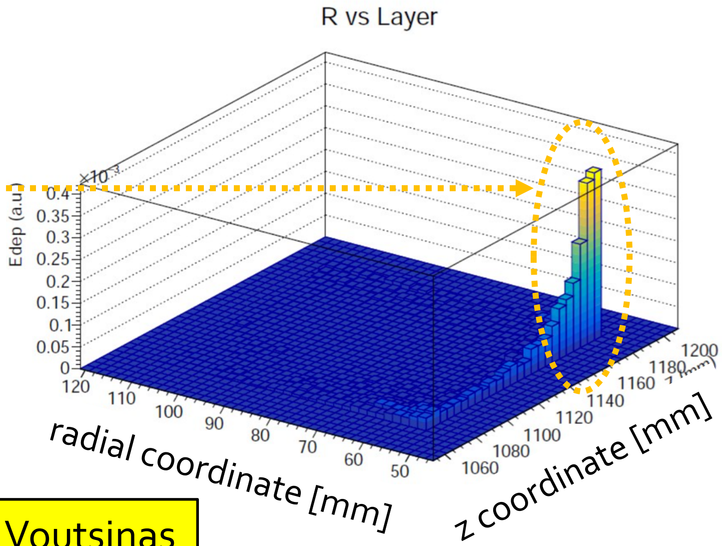


Energy weighted polar angle of pair $e^\pm$ particles
- Strongly forward peaked

Beam-background: e^+e^- pairs (ii)

- Radited $e^\pm$ particles tend to be (very) soft
  - Strong focussing by detector solenoidal field
- Helix extrapolation study (no material effects):
  - # particles hitting LumiCal face: **0.3 per BX**
  - Energy hitting LumiCal face: **60 MeV per BX**
- Compare to full GEANT4 simulation
  - Energy hitting LumiCal: **300 MeV per BX**
    - Factor 5 above helix study
  - Energy mainly concentrated at inner radius at rear of calorimeter
    - Secondaries scattered from beam pipe split(?)
    - Would be easy to shield by thin layer of W
    - Study ongoing





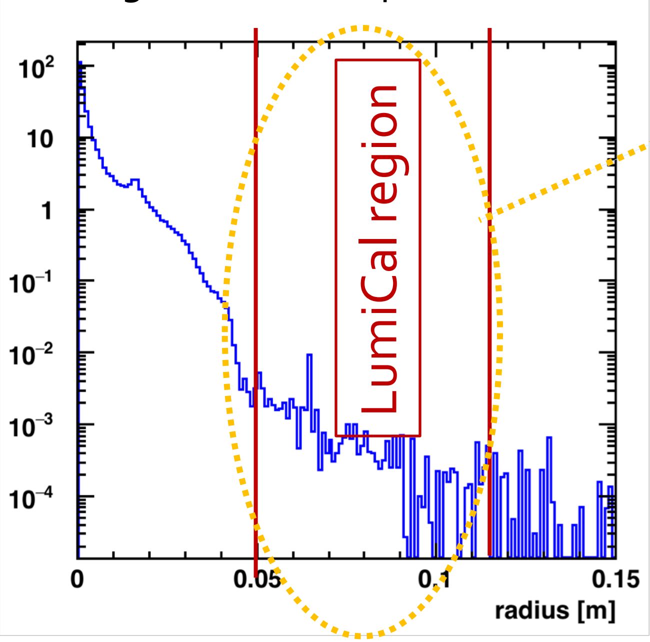
G. Voutsinas

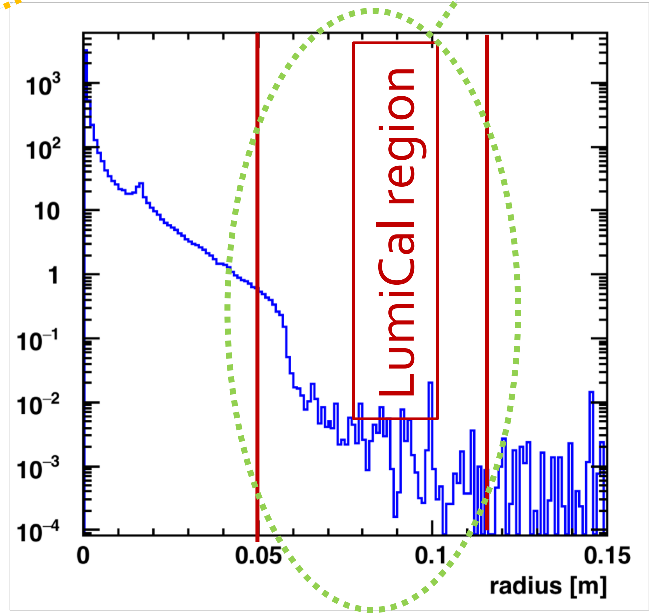
Beam-background: e^+e^- pairs (iii)

- Number of radiated particles and their total energy evolve strongly as function of √s
  - Also energy per radiated particle increases ➪ Focussing becomes realtively weaker
  - At Z-pole energy, very low energy into LumiCal region
  - At top-energy, energy into LumiCal region is at the GeV level

Energy	**# e± total**	**# e± 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

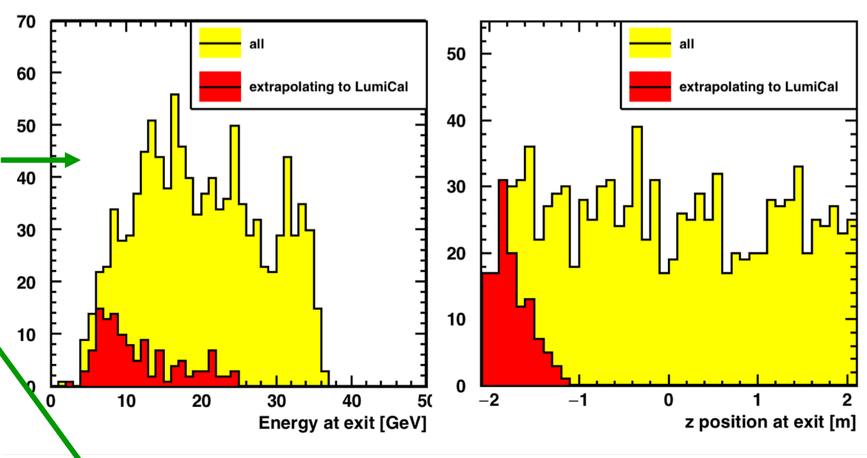
[N.B. Numbers given here are per LumiCal]

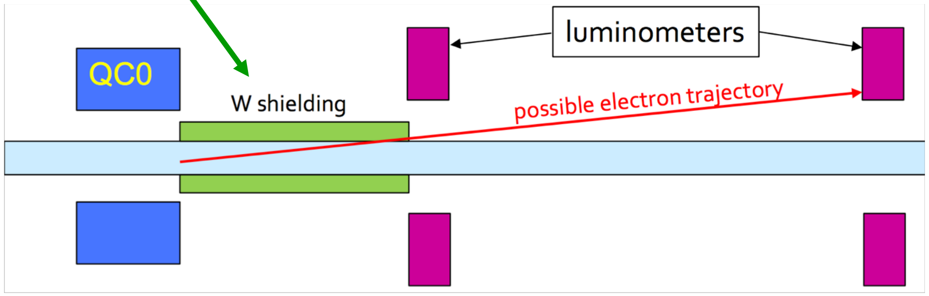




Beam-gas background

- At LEP, off-momentum particles from inelastic beam-gas scattering was the main background process to the luminosity measurement
- FCC-ee simulation of beam-gas scattering **at Z-pole energy** has been performed
  - Loss rate inside region of **± 2.1 m around IP** of **2 MHz/beam** @ 10^{-9} mbar of N_2 at 300 K
- First study of effect on LumiCals: From beam pipe exit point, simple straight line extrapolation to face of opposite LumiCal
  - 12% extrapolate to opposite LumiCal face
  - Energy tends to be low and they leave early
  - Will be effectively stopped by shielding
- From this: Estimate of coincidence rate before any energy or angular cuts: **< 10^{-7} per BX**
- Negligible compared to Bhabha rate: **6.4×10^{-4} per BX**





- Background appears be negligible
  - To be checked via full simulation study

Summary / Outlook

- Very precise normalization needed to match fabulous statistics of FCC-ee. Goal:
  - Absolute to **10^{-4}**; Relative (energy-point-to-energy-point for scans) to **10^{-5}**
- Zeroth order LumiCal design exists. *Many challenges remain:*
  - Geometrical precision of construction and metrology to **~1 μm**
    - Positive: Compact devices – Si sensors for each (half-)barrel from one crystal
  - Support and alignment to order of 100 micron precision
    - Pursuing idea to support "from the back" independently of machine magnets
  - Front-end-electronics
    - Fast (20 ns) shaping within tolerable power budget
    - Large dynamic range: sensitivity to *mips* (muons for alignment) and EM showers.
    - Read-out scheme
      - Have to think about "*pile-up events*": chance of a double Bhabha is ~10^{-3}
  - Cooling – keep temperature constant within ~1 degree for geometrical precision
  - Alignment
  - Current design has absolutely no engineering input so far
    - Can it be build as designed? Electronics, assembly, cooling, alignment, … ?

☞ Many interesting challenges. Plenty of room for collaboration with new groups

Luminosity Measurement at FCC-ee

The FCC-ee, which is now clearly the first step in the FCC integrated program,
is an Electroweak Factory, deliberately designed to comprise an extreme luminosity stage
at the Z and W boson. (2.5×10^{12} Z decays and 5×10^{7} WW at each of 2 or 4 (w.i.p.) IPs).
The aims comprise
-- measurements of the Z mass and width with a few keV statistical precision,
-- peak cross-section with a relative precision of 10^{-4} ,
-- forward-backward asymmetries at few 10^{-6} level ,
-- W mass m_W at ±0.5 MeV, etc..
Together with the Higgs program and the top quark mass and couplings this offers superb
opportunity of discovery of elusive new physics by means of i) precision measurements
ii) observation of rare processes or iii) violations of the SM symmetries and conservation laws.

This is also a source of considerable challenges in metrology:
the luminosity determination is a central foundation of the FCC-ee program!

We would be extremely happy to invite the members of FCAL collaboration
to contribute in finding solutions for some of these many challenges.
The experimental conditions are gentler than at the linear colliders…
. but the aims scale with the offered luminosity!

Prof. Mogens Dam is leading this effort and can be your point of contact.

Alain Blondel, FCC-ee P&E coordinator