The FCC-ee Project

Mogens Dam

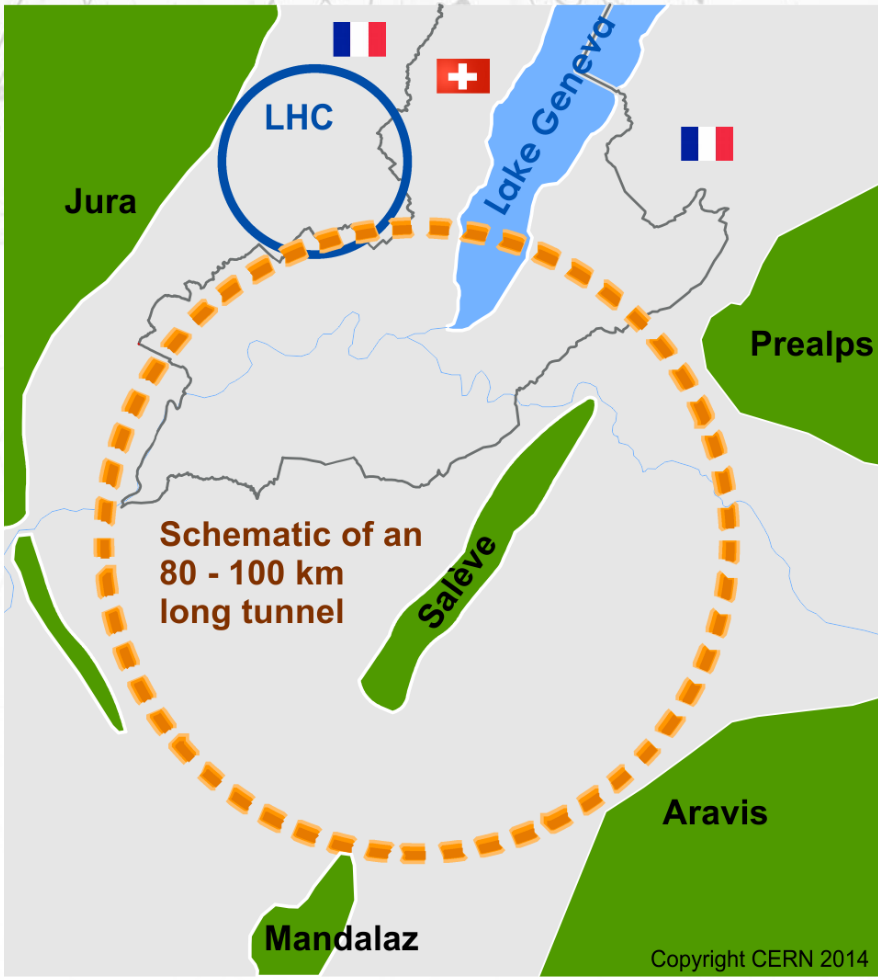
Niels Bohr Institute

31st FCAL Collaboration Workshop
Belgrade, 3-4 September 2017

Picture and slide layout, courtesy Jörg Wenninger

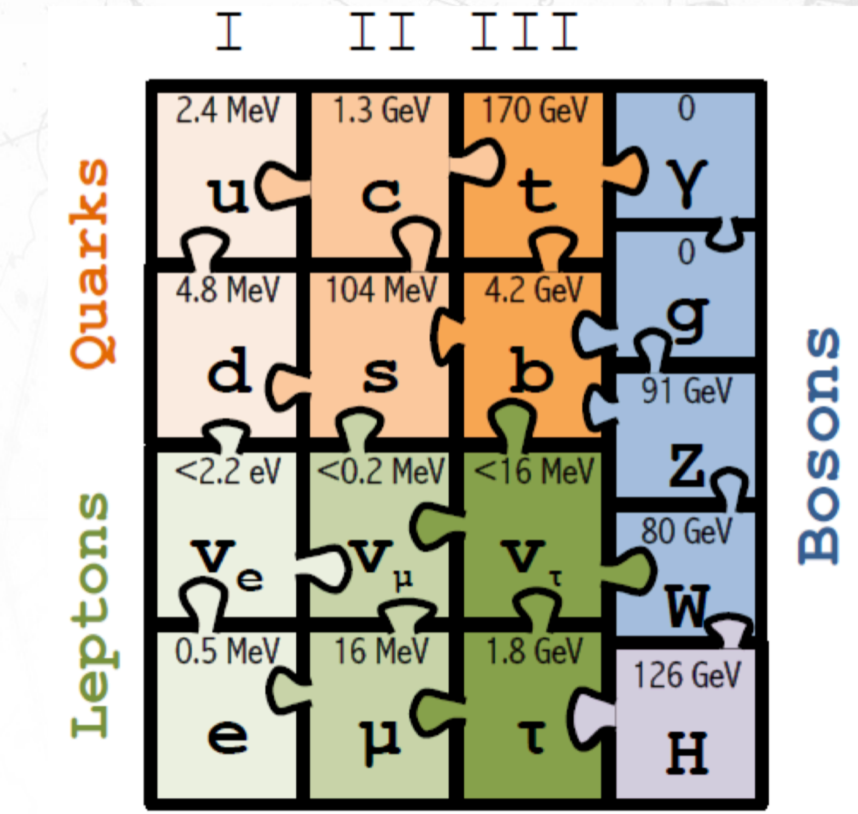
The FCC Study

- International FCC Collaboration (CERN as host lab) to study:
  - pp-collider (FCC-hh)
    - Main emphasis, defining infrastructure requirements
  - ~100 km tunnel infrastructure in Geneva area
  - e^+e^- collider (FCC-ee)
    - "potential first step"
  - Proton-electron option (FCC-he)
    - One IP, e^- from ERL
  - HE-LHC
    - With FCC-hh technology
  - CDR for end 2018

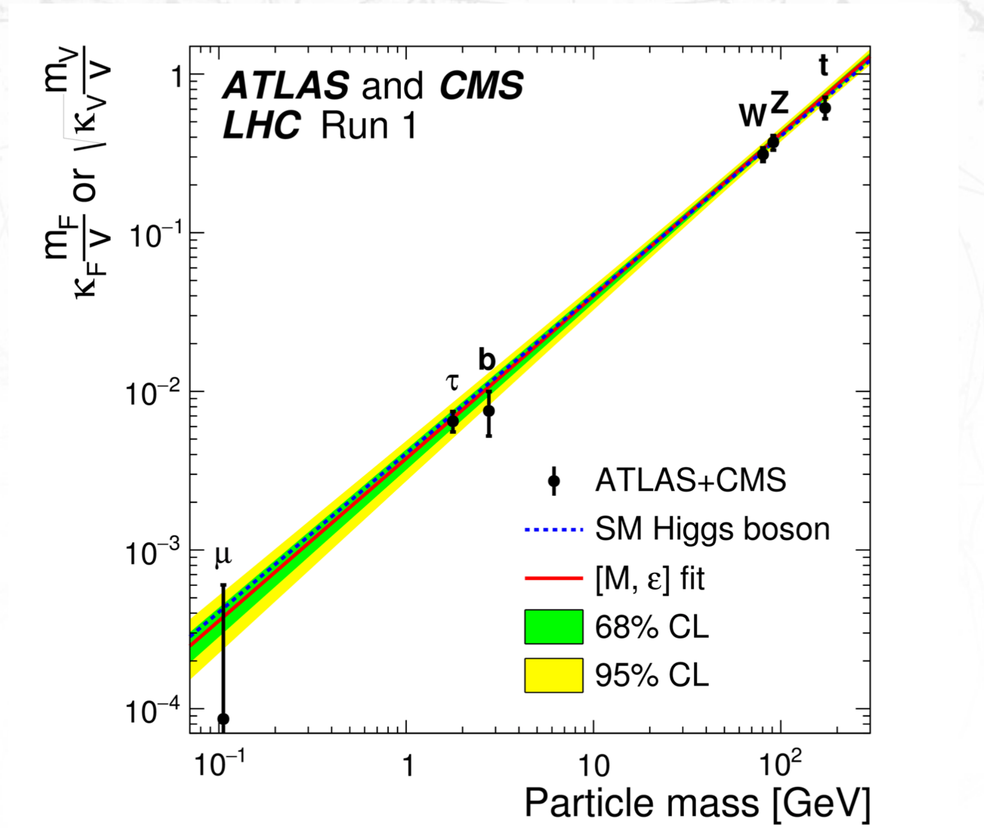


Well known Motivation (i)

Since 5 years we have a complete Standard Model

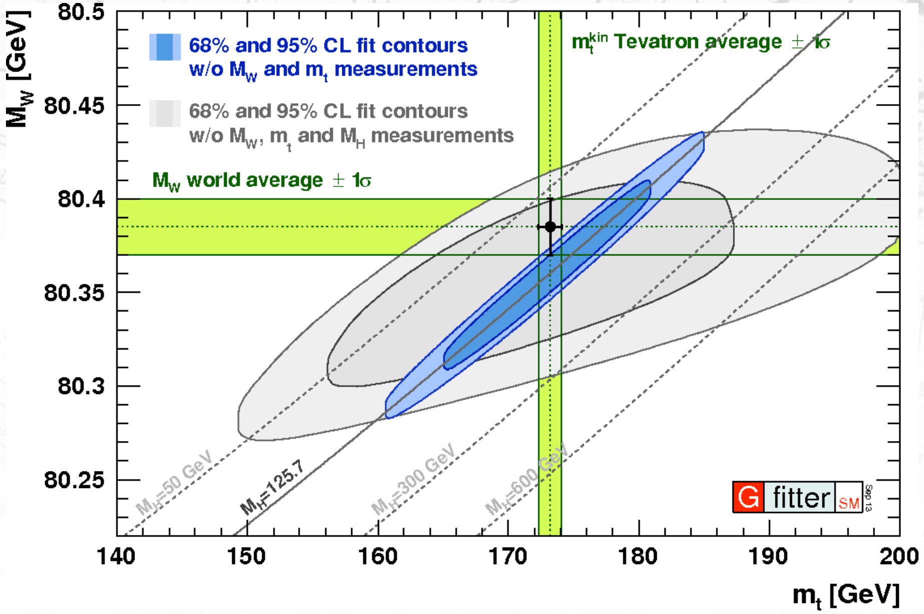


So far, the 125 GeV scalar is consistent with being a Standard Model Higgs



Well known Motivation (ii)

- The Standard Model provides an amazingly consistent description of "all" current experimental measurements

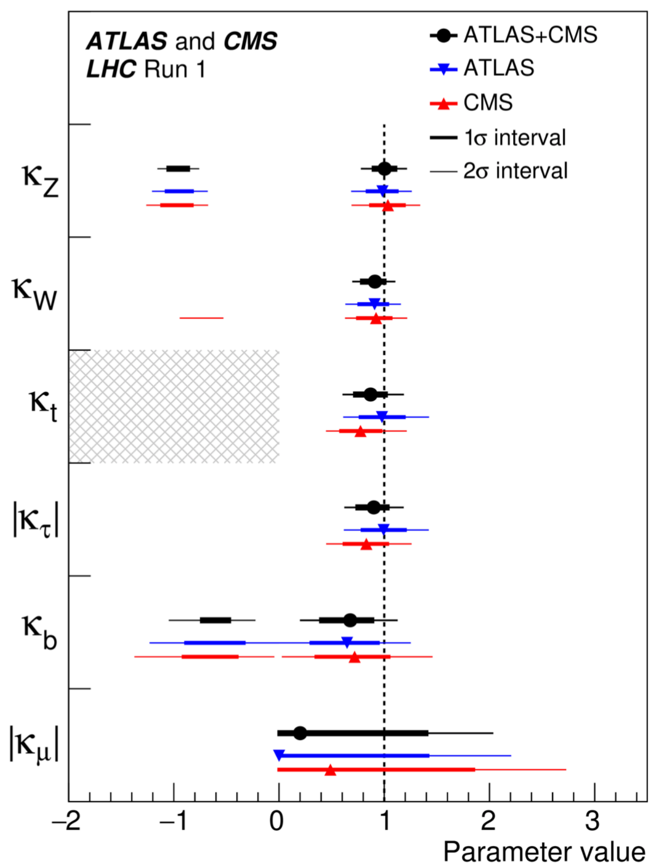


- And so far from LHC Run1 + 2, no indications of new BSM physics up to several hundred GeV
- In summary:

To current precision, "everything" looks to be rather Standard Model

Will SM survive higher precision: Higgs

Couplings currently measured to O(10%) level



Expected deviations of SM coupling strengths from New Physics are considerably smaller

- Dependence on NP scale

$$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\ \text{TeV}}{\Lambda_{NP}}\right)^2$$

with δ=

Snowmass '13

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

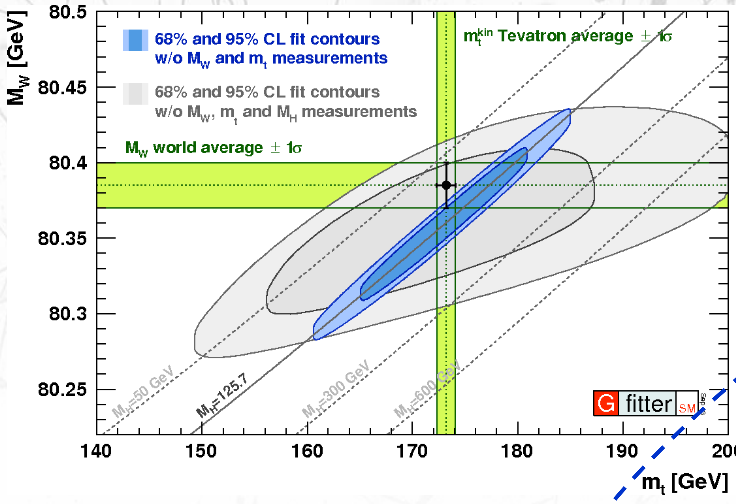
Need *at least* %-level accuracy for a 5σ observation for Λ_{NP} = 1 TeV

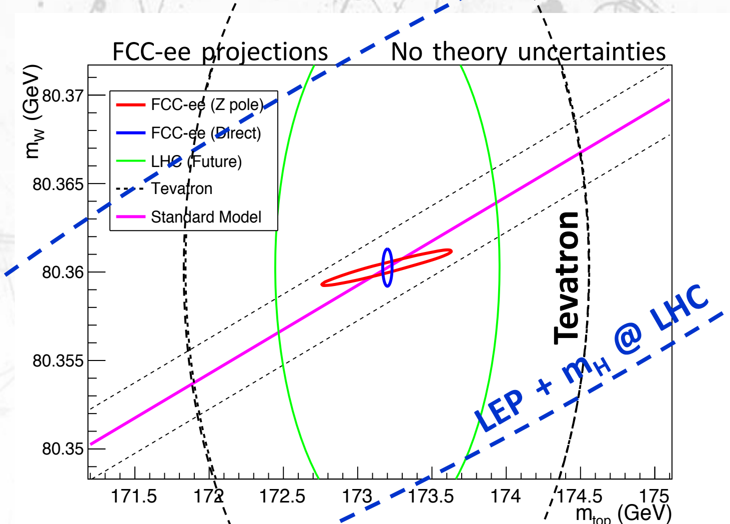
- And sub-% accuracy for multi-TeV NP scale

Need ≥ 1 million measured Higgs bosons

Will SM survive higher precision: EWPO

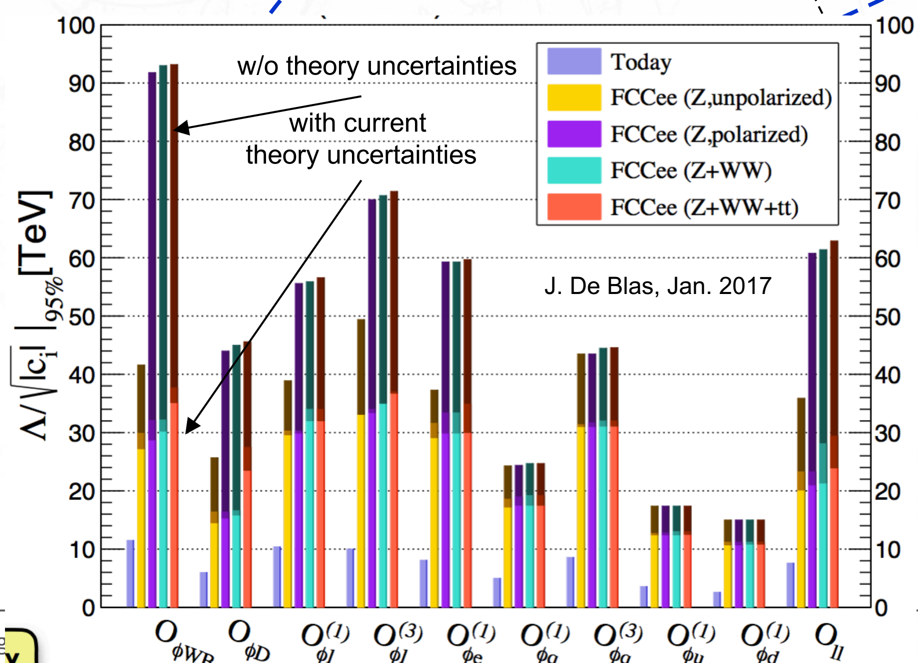
FCC-ee is proposing a dramatic increase in precision of all EW measurements





Standard Model Effective Field Theory analysis

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$



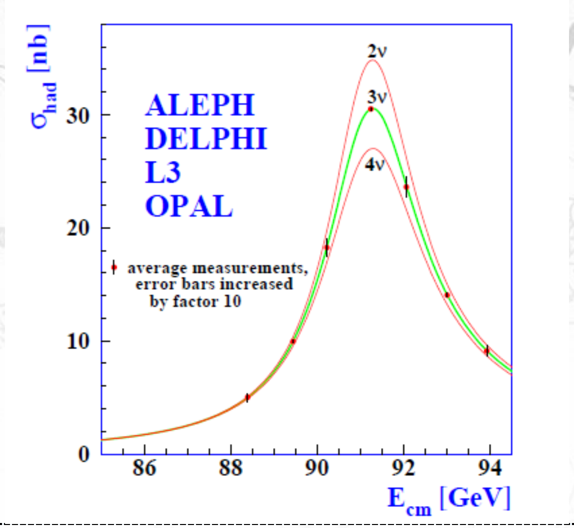
Today: Λ > 5-10 TeV

After FCC-ee: Λ > 50-100 TeV ?

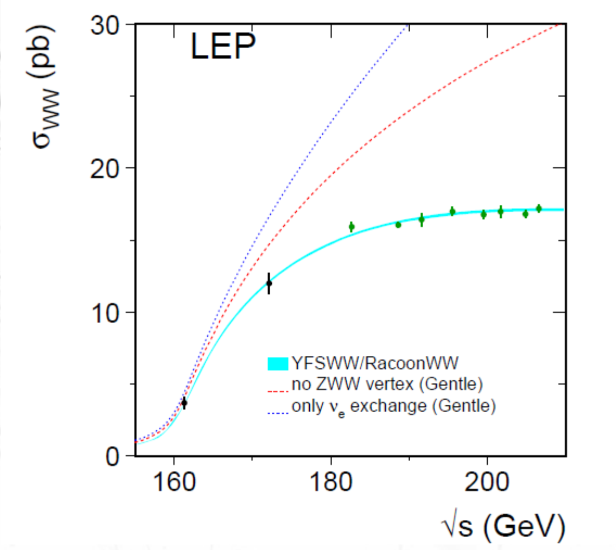
FCC-ee Physics Programme

arXiv:1308.6176

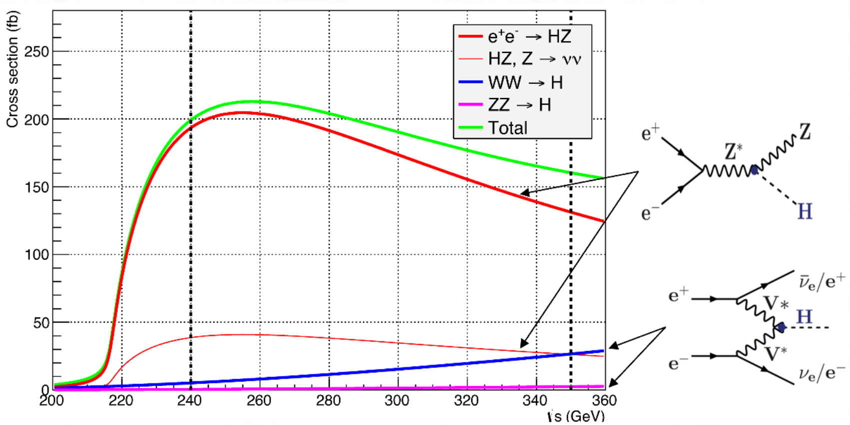
a) **Z resonance: TeraZ**



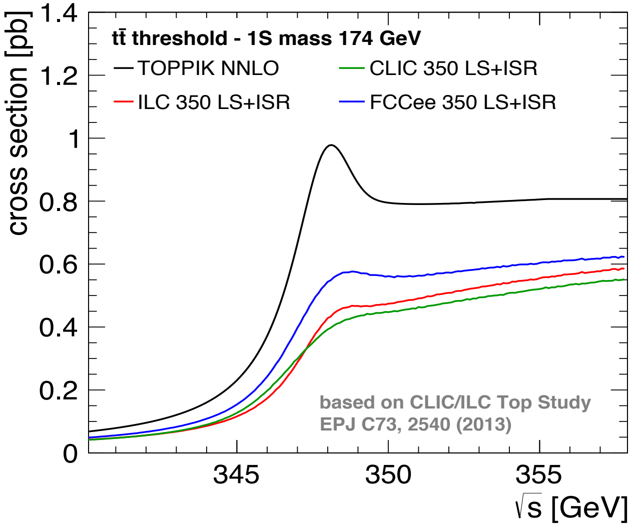
b) **WW threshold scan: OkuW**



c) **Higgs factory: MegaHiggs**



d) **tt threshold scan: MegaTop**



FCC-ee Physics Programme

arXiv:1308.6176

a)

Z resonance: TeraZ

Lineshape

- Exquisite E_{beam} (unique!)
- m_Z, Γ_Z to < 100 keV (2.2 MeV)

Asymmetries

- $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
- $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

b)

WW threshold scan: OkuW

Threshold scan

- m_W to 0.5 MeV (15 MeV)

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002

Radiative return $e^+e^- \to Z\gamma$

- N_ν to 0.0004 (0.008)

c)

Higgs factory: MegaHiggs

Coupling/Quantity	HL-LHC	FCC-ee
κ_W	2-5%	0.19%
κ_Z	2-4%	0.15%
κ_b	4-7%	0.42%
κ_c	–	0.71%
κ_τ	2-5%	0.54%
κ_μ	~10%	6.2%
κ_γ	2-5%	1.5%
κ_g	3-5%	0.8%
$\kappa_{Z\gamma}$	~12%	?
BR_{invis}	~10-15%?	< 0.1%
Γ_H	~50%?	0.9%
κ_t	7-10%	13% (*)
κ_H	30-50% ?	80%(*)

(*) indirect

d)

tt threshold scan: MegaTop

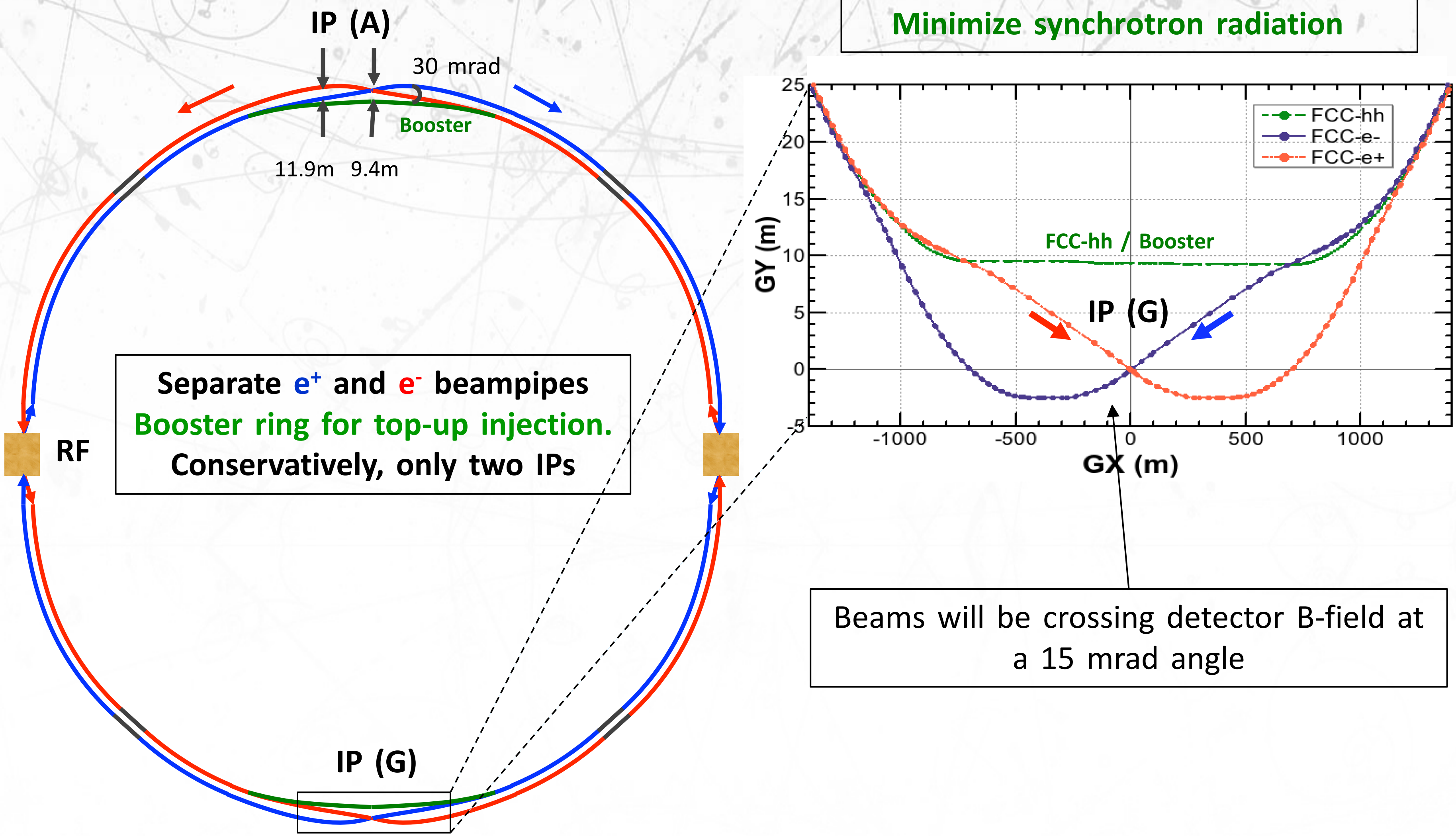
Threshold scan

- m_{top} to 10 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 1%

FCC-ee baseline layout

- Designed to fit the FCC-hh tunnel and footprint

Asymmetric beam crossing at the IPs
Minimize synchrotron radiation



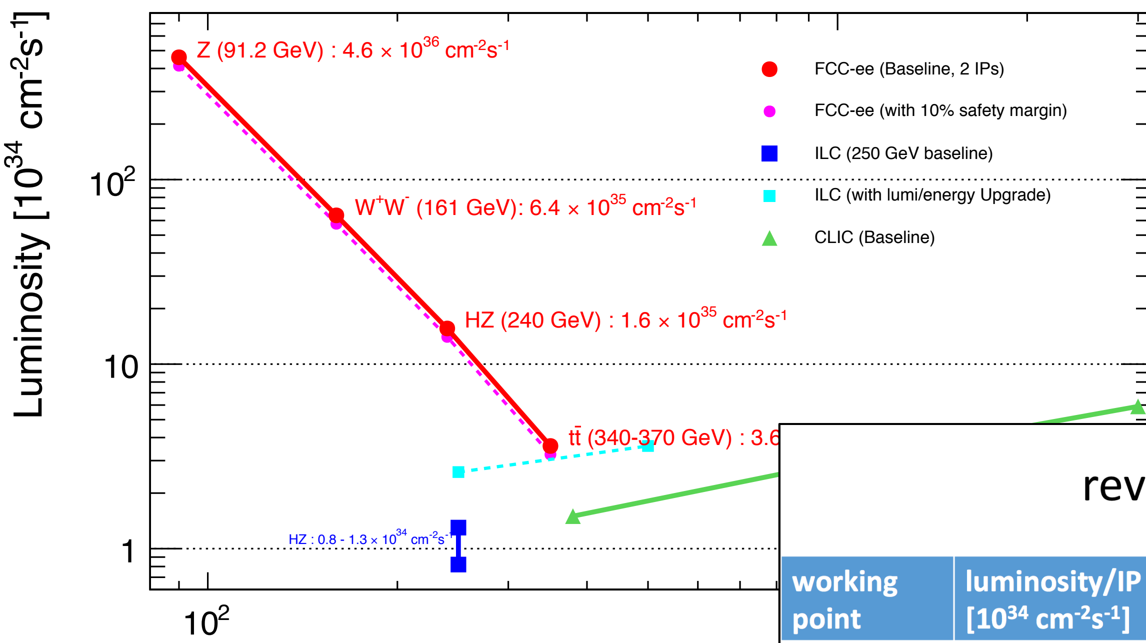
Beams will be crossing detector B-field at a 15 mrad angle

parameter D. Shatilov	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	175
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.34
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.95
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0343)
longitudinal damping time [ms]	414	77	23	7.5
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8
total RF voltage [GV]	0.10	0.44	2.0	9.5
RF acceptance [%]	1.9	1.9	2.3	5.0
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.33
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7
no. of bunches / beam	16640	2000	393	48
beam current [mA]	1390	147	29	6.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**230**	**32**	**7.8**	**1.8**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.095 / 0.157
luminosity lifetime [min]	70	50	42	39
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	12
actual lifetime by BS ("weak") [min]	> 200	20	20	24

D. Shatilov

parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	175
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.34
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.95
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0343)
longitudinal damping time [ms]	414	77	23	7.5
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8
total RF voltage [GV]	0.10	0.44	2.0	9.5
RF acceptance [%]	1.9	1.9	2.3	5.0
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.33
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7
no. of bunches / beam	16640	2000	393	48
Beam X'ing time [ns]	20	167	850	6900
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.095 / 0.157
Beam polarisation	Transverse polarisation for beam energy measurement via resonant spin depolarisation: $\delta E_{beam} \simeq 100$ keV		Unpolarised	
actual lifetime by BS ("weak") [min]	> 200	20	20	24

FCC-ee Luminosity and Operation Model



revised operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ year	physics goal	run time [years]
Z first 2 years	115	30 ab^{-1}/year	150 ab^{-1}	3.5
Z later	230	60 ab^{-1}/year		
W	32	8.3 ab^{-1}/year	10 ab^{-1}	~1
H	7.8	2.0 ab^{-1}/year	5 ab^{-1}	2.5
top	1.8	0.5 ab^{-1}/year	1.5 ab^{-1}	3

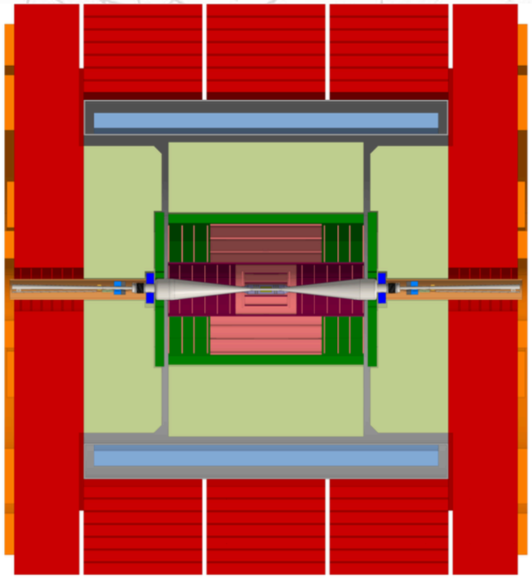
total run time: 10-11 years

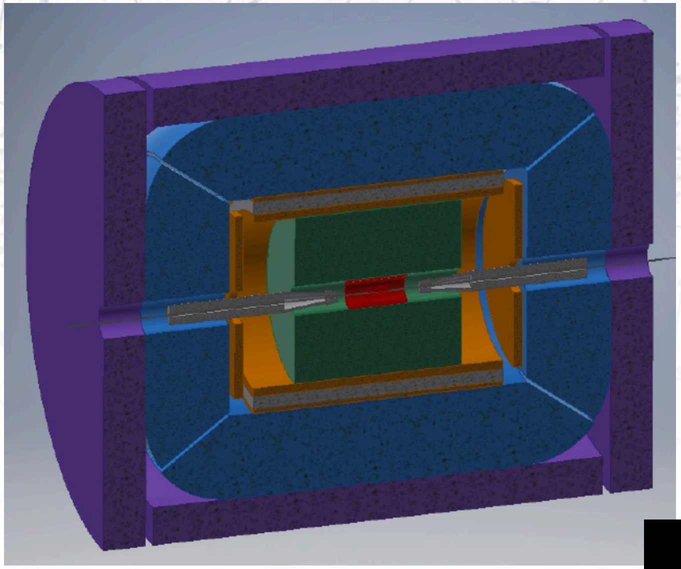
- **Assumptions:**
  - 200 scheduled physics days per year, i.e. 7 months minus 13 days of MD/stops.
  - "Hübner factor" H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  - Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)

1.3 × 10^7 s/year

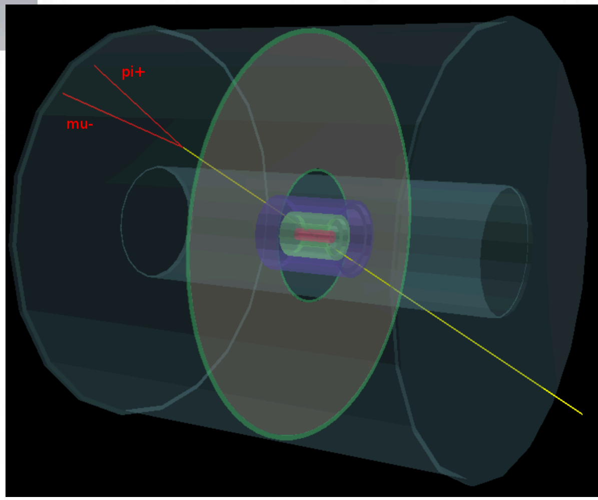
Detector designs

- Designs driven by the unprecedented precision of the measurements
  - "CLIC-detector revisited" "IDEA"





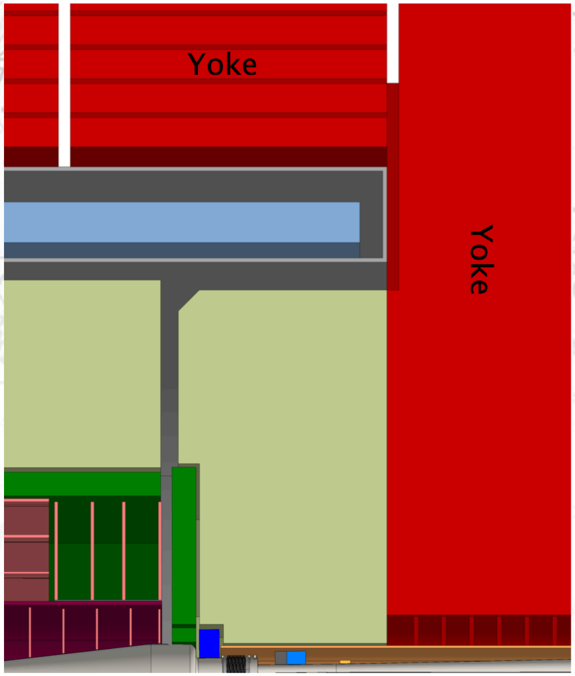
- Vertex detector: ALICE
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke



- Possibly surrounded by large tracking volume (R = 8m)
  - Very weakly coupled (long-lived) particles
    - E.g., RH neutrinos as DM candidates

Main detector differences CLIC → FCC-ee

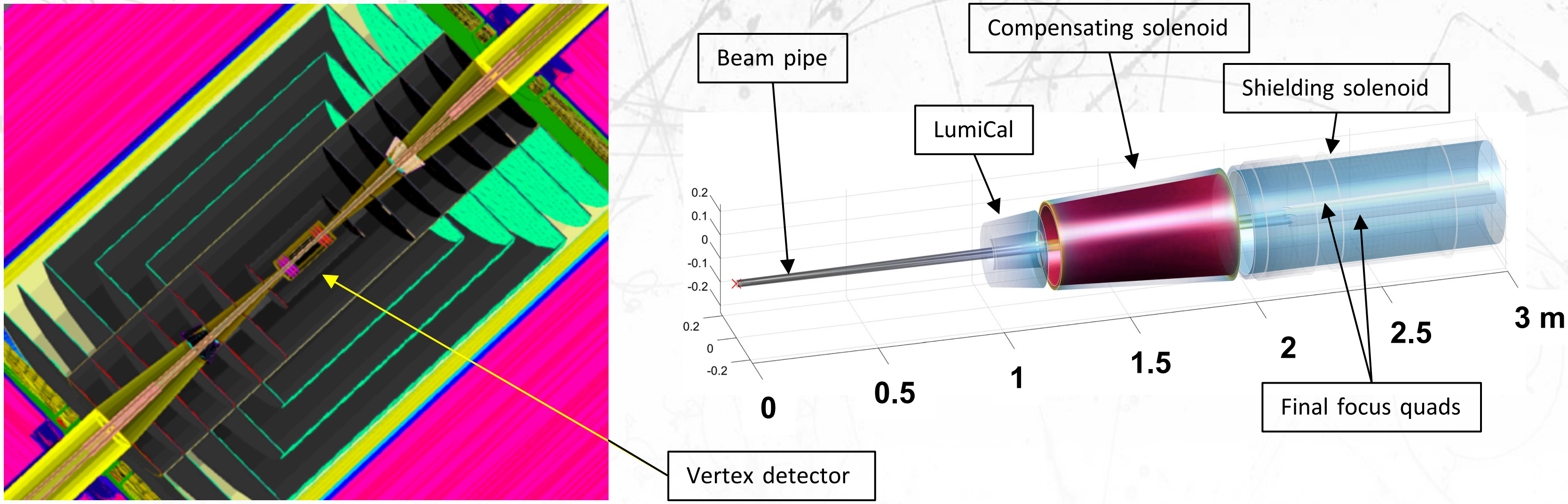
- Smaller beam pipe radius — 30 mm → 15 mm
  - First vertex detector layer — 31 mm → 17 mm
- Lower B-field strength — 3.5 T → 2.0 T
  - Due to 15 mrad crossing angle
- Larger radius tracker / ECAL — 1.5 m → 2.1 m
- Thinner HCAL — $7.5\ \lambda_0$ → $5.5\ \lambda_0$
  - Lower max energy
- Coil dimension largely unchanged
- Thinner yoke: Outer radius — 6.45 m → 6.00 m



- At FCC-ee, collisions are continuous; no bunch trains; no power pulsing
  - Detector cooling issues to be investigated

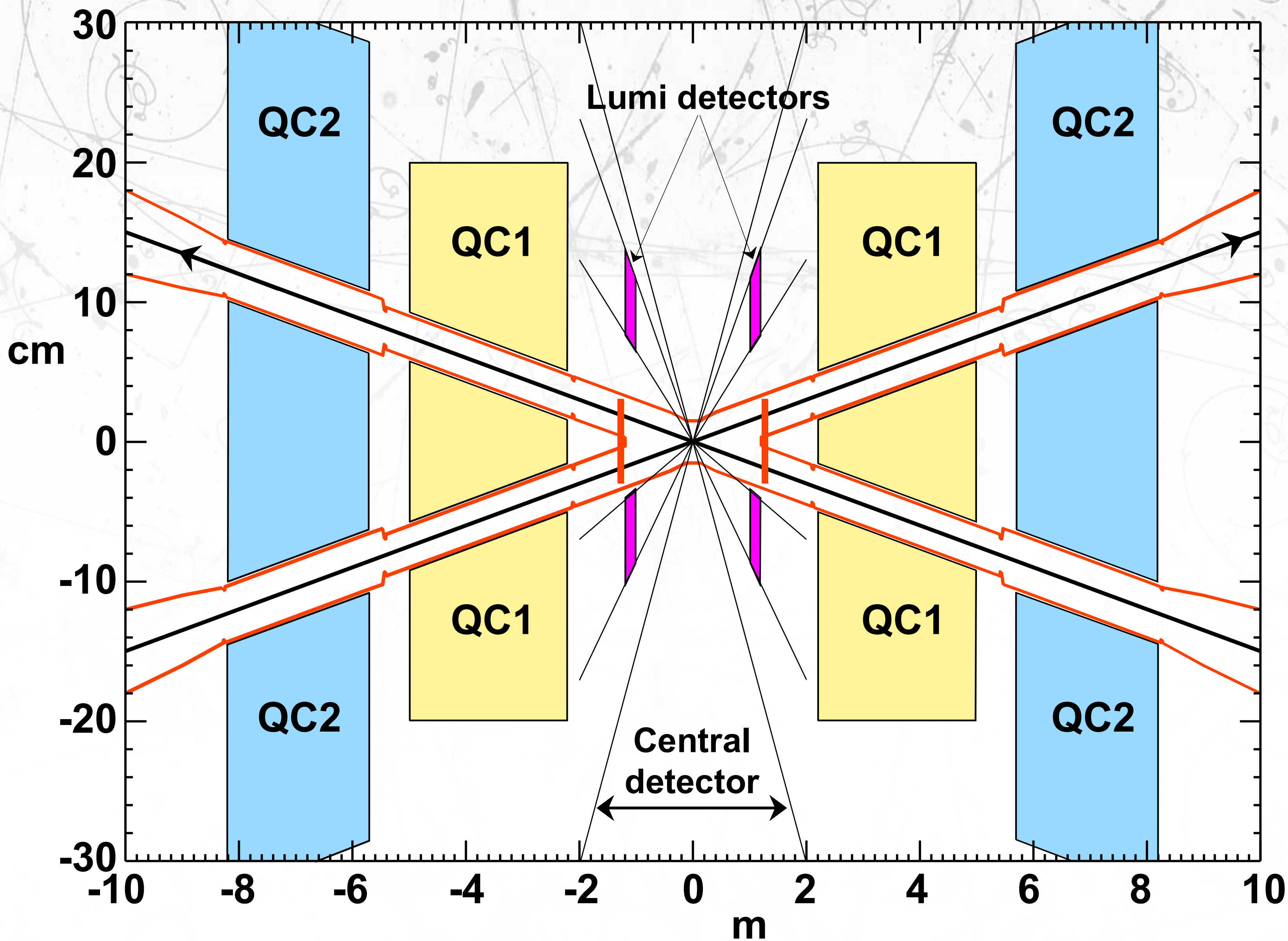
MDI and experimental environment

- Busy interaction region with 30 mrad crossing angle
  - Quadrupole, shielding and compensating solenoids, lumiCal, are inside the detector

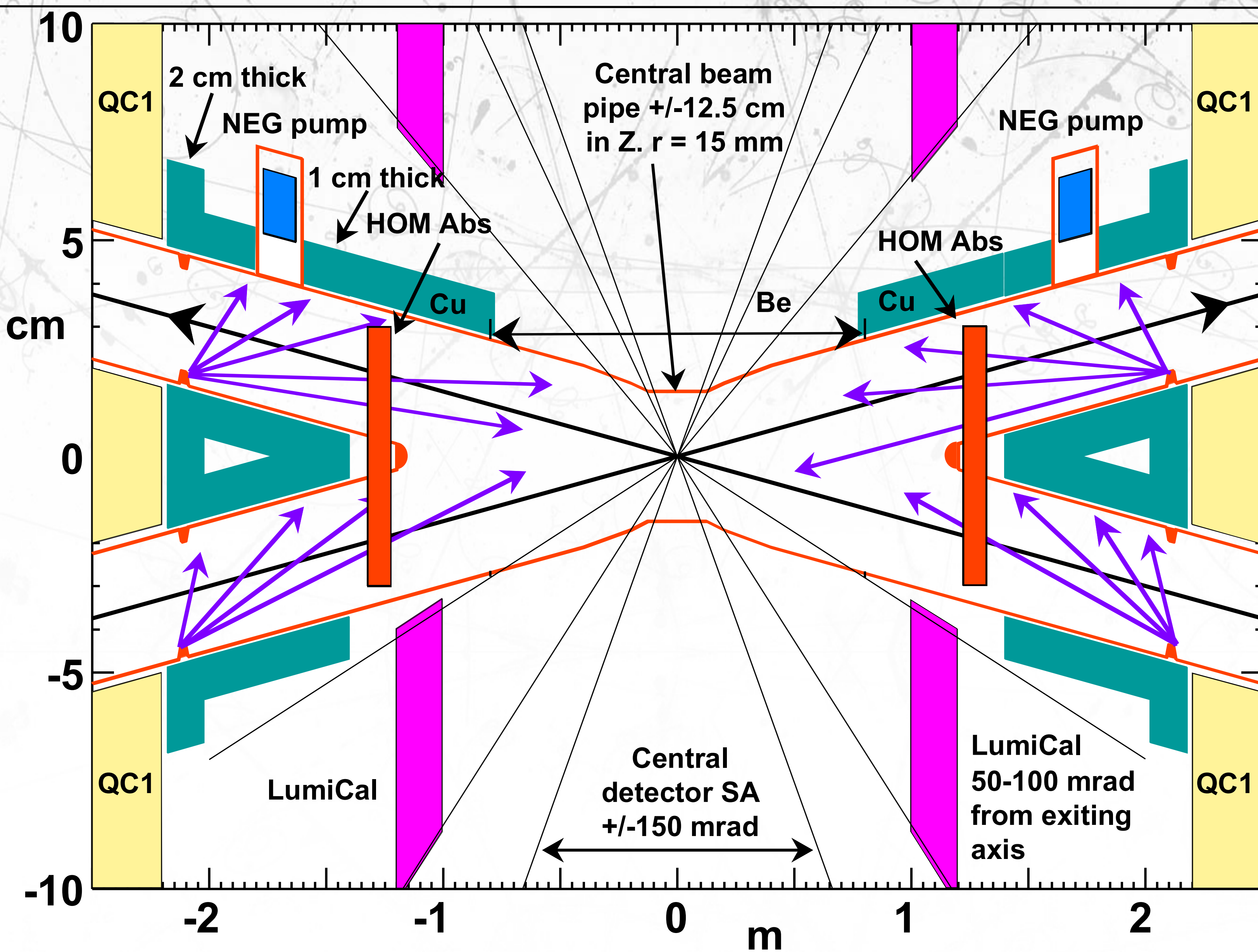


- Important beam backgrounds in the detector
  - Synchrotron radiation requires Tantalum beam-pipe shielding
  - Beamstrahlung at IP gives rise to γγ collisions (γγ → e^+e^- and γγ → qq)
  - First investigations show detector occupancies at the 10^{-5} level or smaller
    - Up to the highest centre-of-mass energies (top threshold)
- Next: understand online selection and readout requirements
  - In particular: readout speed with one bunch crossing every 10-20 ns at the Z

FCC-ee Interaction Region (i)



FCC-ee Interaction Region (ii)

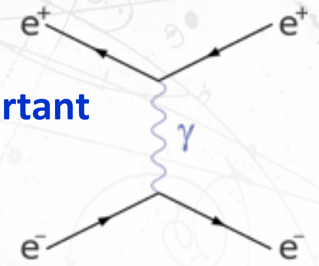


Luminosity Monitoring with Bhabha scattering

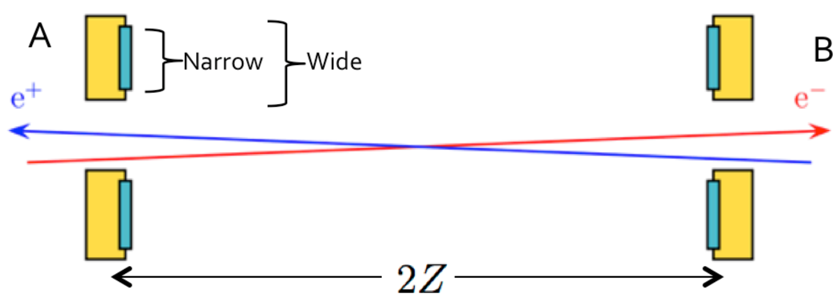
Luminosity monitoring:

- **Absolute – target precision 10^{-4}**
  - May be best achieved through the process $e^+e^- \rightarrow \gamma\gamma$ (?)
- **Relative for Z lineshape measurement – need a relative precision of 2-5 x 10^{-5}**
  - Need cross section comparable to Z production:, i.e. ≥ 10 nb
  - Can be achieved via small angle Bhabha scattering $e^+e^- \rightarrow e^+e^-$
    - Very strongly forward peaked – control of angular acceptance very important

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



- Measured with set of two calorimeters; one at each side of the IP

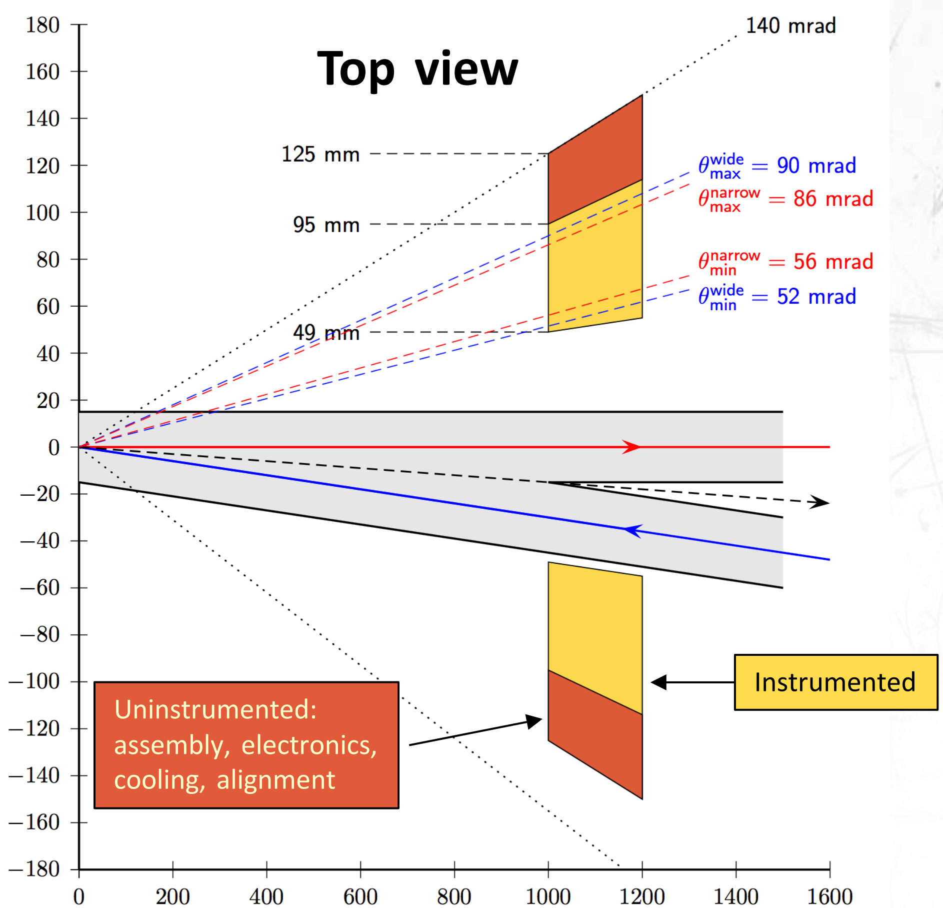


Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

- Average over SideA and SideB rates: Only dependent to second order on beam paramaters:

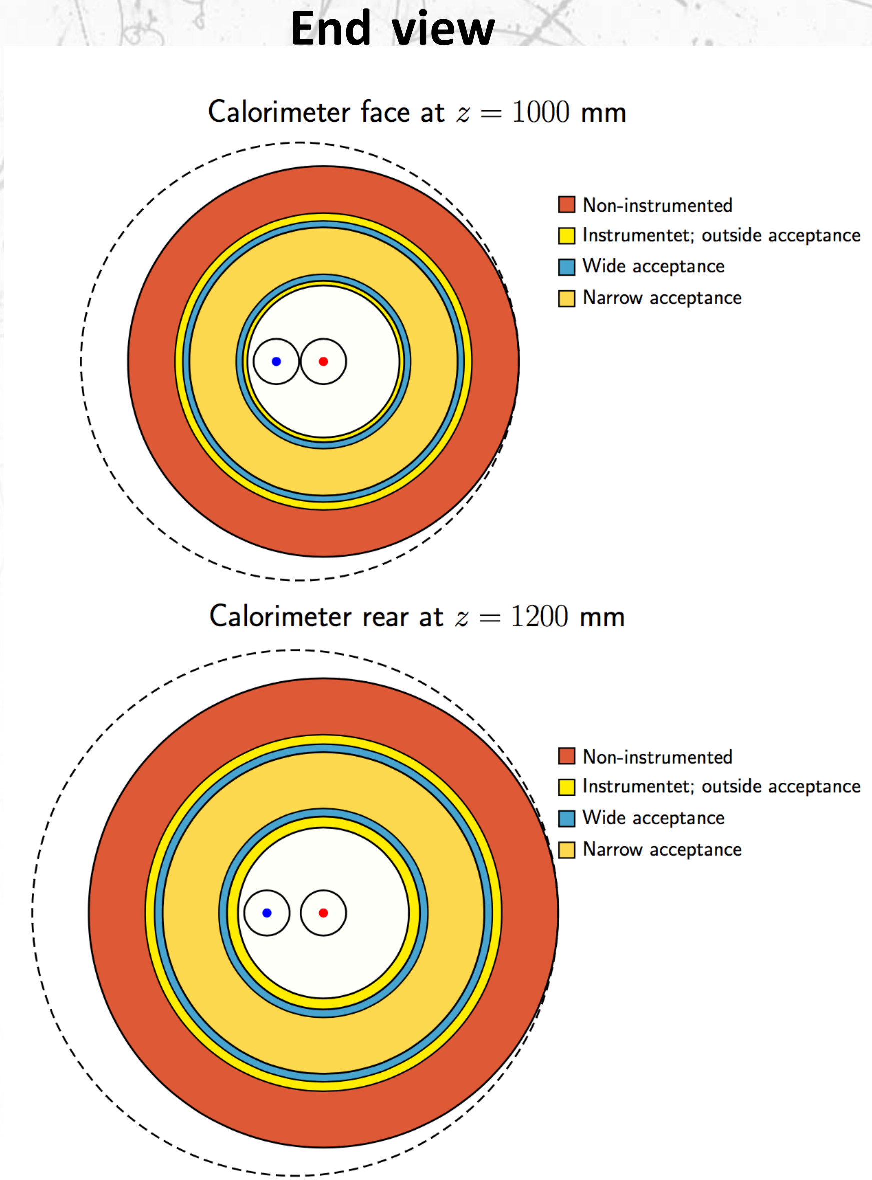
$$\frac{\delta \bar{R}}{\bar{R}} = 3 \left(\frac{\delta z}{Z} \right)^2 \qquad \frac{\delta \bar{R}}{\bar{R}} = 2 \left(\frac{\delta x}{r_{\text{min}}} \right)^2$$

LumiCal

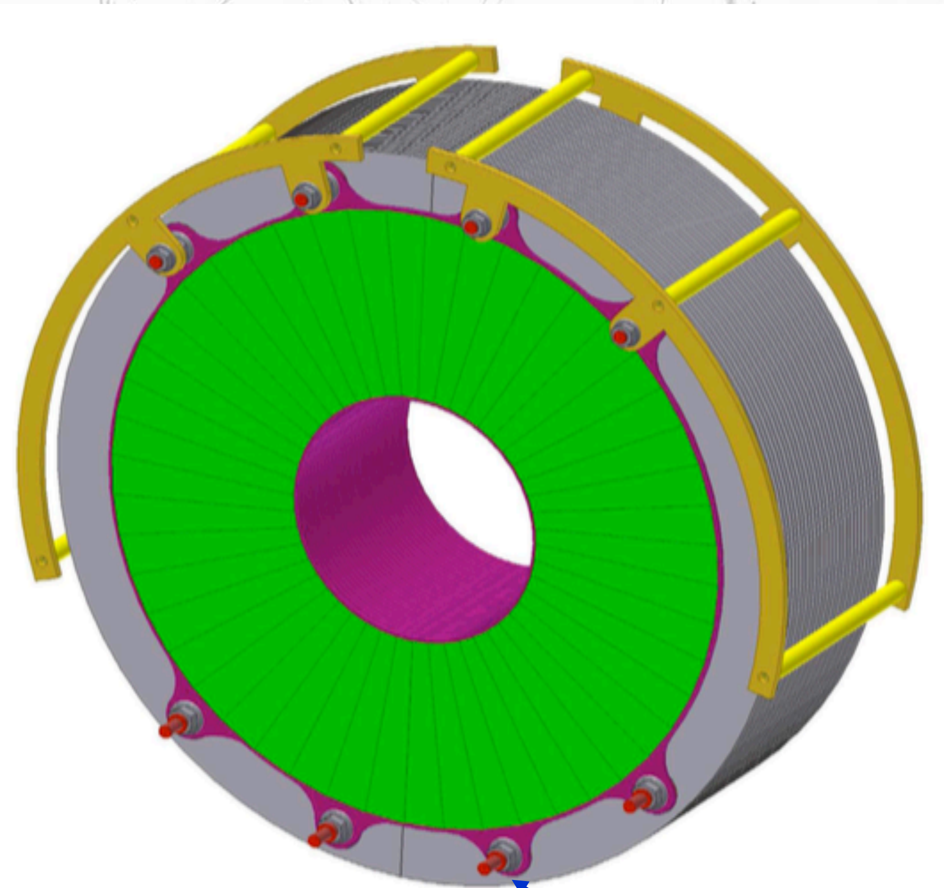


Bhabha cross section: σ = 23 nb
Geometric precision needed for absolute normalisation to 10^{-4}

- δz = 50 μm
- δr_{min} = 1.6 μm
- δr_{max} = 5.8 μm



FCC-ee LumiCal sketch based freely on ILD Design



Bolts hold calorimeters together

30 layers of 1 X_0 deep tungsten
30 Si layers (320 microns)

- segmentation 1.8 mm x 7.5^0

Depth:

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

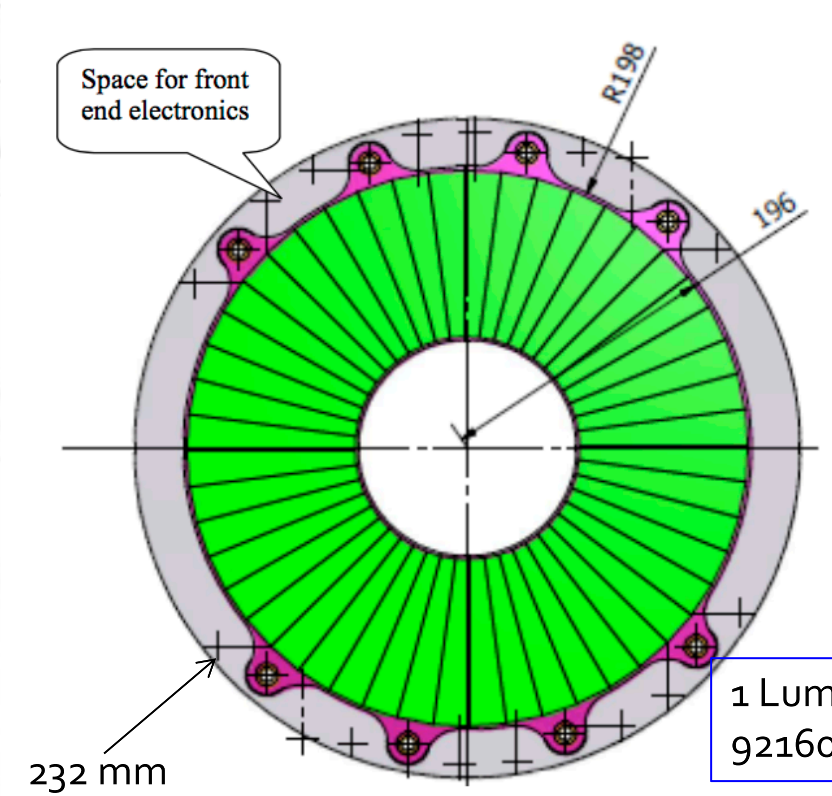
Inner radius:

- Sensitive: 80 mm
- Mechanical: 76 mm

Outer radius:

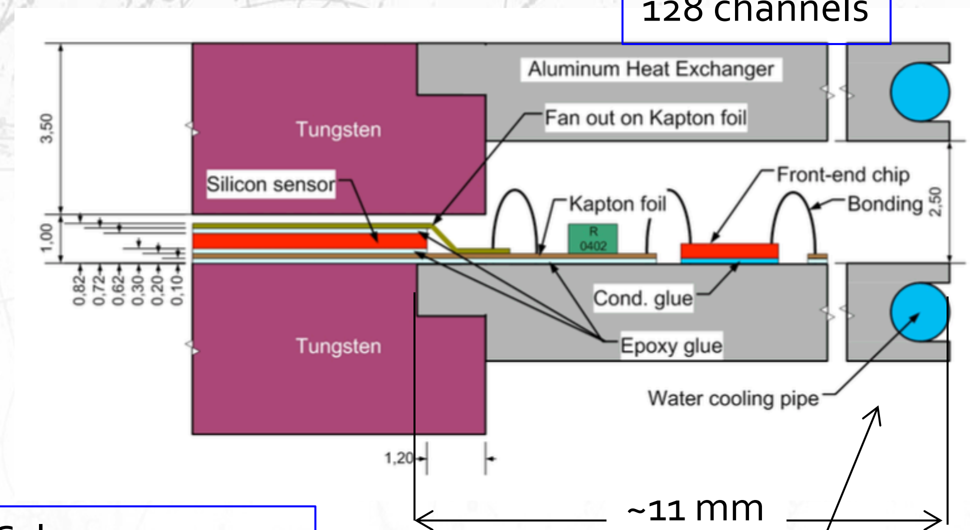
- Sensitive: 195.2 mm
- Mechanical: ~260 mm

More on ILD LumiCal



1 LumiCal:
92160 readout channels

128 channels



Note on cooling:

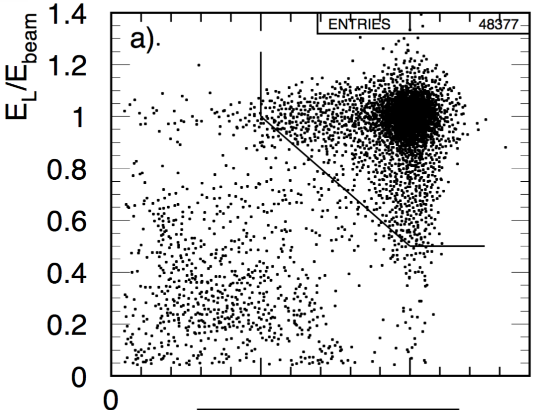
- Inner radius of acceptance varies by 0.33 µm/C⁰
- Temperature stabilization within 1 c⁰ safe. Probably within 0.2 C⁰
- Total dissipated heat in one LumiCal: 30 W.
  - With power cycling: 1 ms active/199 ms breaks
- Water cooling: 15 l/min per LumiCal.

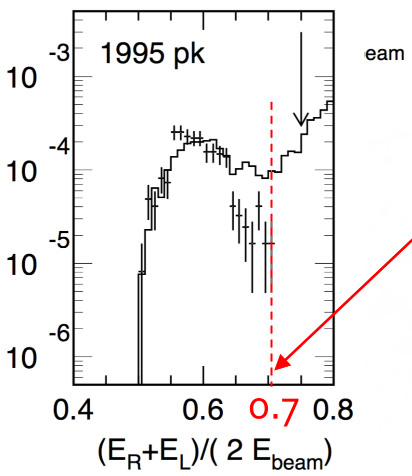
At FCC-ee, no power cycling.
Need more efficient cooling…
Space requirement?

Off-momentum particles

Experience from OPAL @ LEP

The primary source of background to the luminosity measurement is from off-momentum electrons and positrons generated by beam-gas scattering in the straight RF sections on either side of the experiment which are deflected by the mini-beta quadrupoles into the luminosity monitor. The size of this background varies with time, and depends on the quality of the vacuum in the straight sections on either side of the OPAL interaction region and on the settings of the LEP collimators.





Probability of a cluster of E > 1 GeV to be found per BX

calorimeter	1993	1994	1995
right	8.0×10^{-3}	5.1×10^{-3}	8.4×10^{-3}
left	5.1×10^{-3}	3.7×10^{-3}	6.2×10^{-3}

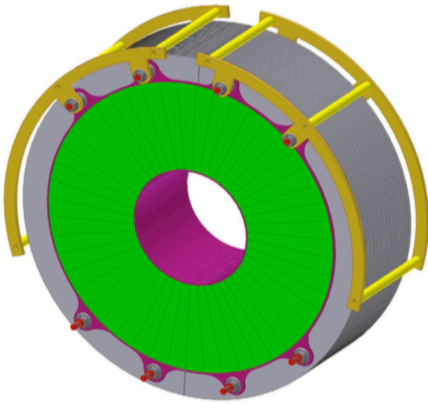
Probability of coincidence: **~5 x 10^{-5}**

- Comparable to rate of Bhabha events
- Reduced to 0.1-0-15 x 10^{-4} by cuts (energy, angle, …)

- 100 times higher off-momentum than Bhabha rate into calorimeters
  - ~50 x more deposited energy from off-momentum

FCC-ee LumiCal Challenges

- Interaction region very crowded, LumiCal close to IP, face at z = 100 cm
- Very ambitious goals for luminosity measurement
  - 10^{-4} absolute
  - 2×10^{-5} relative (energy-point to energy-point)
- Very low bunch crossing times
  - Varying from ***20 ns*** at √s = 91.2 GeV to ***6 μs*** at √s =350 GeV
    - In earlier versions of FCC-ee optimisation, down to as low as ***3 ns*** at √s = 91.2 GeV
  - Continuous collisions, no bunch trains, no power pulsing
- Physics rates
  - Z production: 90 kHz
    - No pileup, μ = 0.002
  - Double arm Bhabhas of the same order, single arm Bhabhas somewhat higher
    - Off-momentum rate × 10 higher(?) … 10 GHz (?)



- Suggest a set of two SiW calorimeters, like OPAL, ALPEH, ILD, CLIC
  - With given geometry, need mechanical precision at the 1 μm level
- To save space, suggest to use a conical geometry
  - Challenge: Stability of mechanical precision
  - Need detailed plan for mechanical design and assembly

FCC-ee LumiCal Challenges (cont'd)

- Very dense environment, high (repetition) rate, and no power pulsing
  - Challenge: Heat dissipation/cooling
    - ILD quotes 30 W;
      - ×100 from no power pulsing?; ×10 from higher BX rate?
  - Need to keep temperature very stable to maintain geometrical precision
- Readout electronics
  - At LEP, we read out each BX separately; can hardly be done at 20 ns (or even 3 ns) ?
  - Probably need to integrate over multiple bunch crossings?
    - Scheme for multi-bunch readout – triggered or not
    - Off-momentum background will increase as square of number of BX integrated over
  - Power consumption
- Mechanical design of forward region
  - How is LumiCal (and everything else in forward region) supported
- Geometrical alignment
  - How?
- High integrated rate especially at (important) inner radius
  - Possibly need for radiation tolerant sensors and electronics

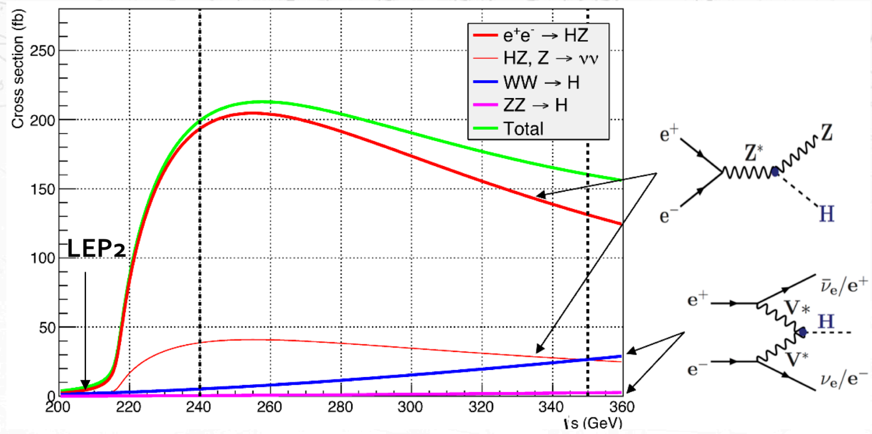
Summary and Outlook

- FCC-ee is a very ambitious project aiming for ultimate precision tests of the Standard Model
  - Z lineshape measurement and rare Z decay search with 5×10^{12} Z decays
  - WW threshold scan with 10^8 W bosons
  - Per mille level Higgs couplings with 10^6 HZ events
  - Top quark mass and couplings from tt threshold scan with 10^6 events
- On accelerator design, lots of progress has been already made
  - Technology ready… on paper
- State-of-the-art detectors developed for ILC/CLIC adaptable for FCC-ee, however …
  - Detector solenoid field limited to 2 T due to ±15 mrad beam crossing angle
  - Cooling issues related to lack of power pulsing
  - Low angle forward region is very densely packed
    - LumiCal @ 1m; compensating solenoid between 1.2 and 2.2 m
- Forward calorimetry is probably the most difficult part of instrumentation
  - Currently only worrying about LumiCal – have not been able to locate space for BeamCal
  - Very high demands on luminosity measurement: 10^{-4} absolute
  - Almost all question about LumiCal design are still open:
    - technology (probably SiW), mechanical construction, readout electronics, cooling, alignment, support
    - Any help, advice, input is very welcome

Extra Slides

LEP3

- If we do not have funding to construct a new tunnel, neither circular nor linear
  - After HL-LHC refurbish LEP/LHC tunnel with a state of the art modern e^+e^- collider
    - Will be comfortably able to work as a Higgs factory (remember LEP was close)



    - Will of course be able to cover Z and WW programmes
    - However, will not be able to operate at $t\bar{t}$ threshold
      - Synchrotron energy loss of 35 GeV per turn, i.e. 20%
      - Missing out on top mass and couplings and some of the Higgs programme (g_{HHH}, g_t)
    - Fast estimate says that luminosity could be ¼ of that of FCC-ee
      - However, we can operate with four detectors and regain a factor of ~2
  - Cost effective way to carry through Z, WW, and Higgs parts of FCC-ee programmme

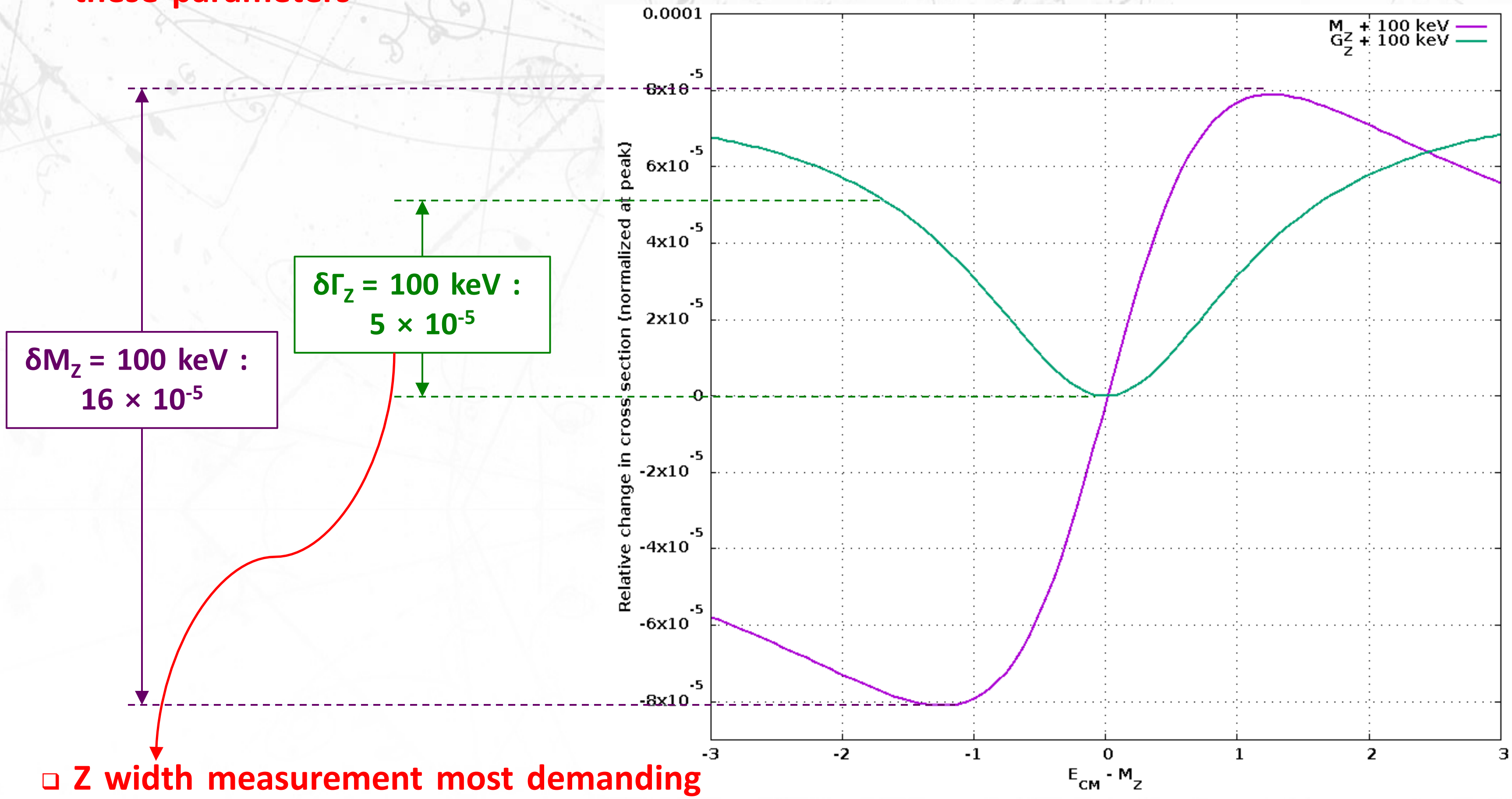
Further studies needed

Tera-Z Relative Normalisation

- FCC-ee goal: 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 variation of this size in these parameters



  - Z width measurement most demanding
    - Need relative normalisation to about 2×10^{-5}