Luminosity Measurement

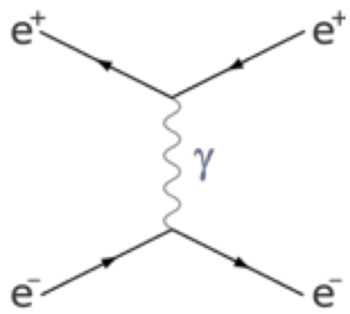
11th FCC-ee Workshop
CERN,
8-11 January 2019

Mogens Dam
Niels Bohr Institute
Copenhagen, Denmark

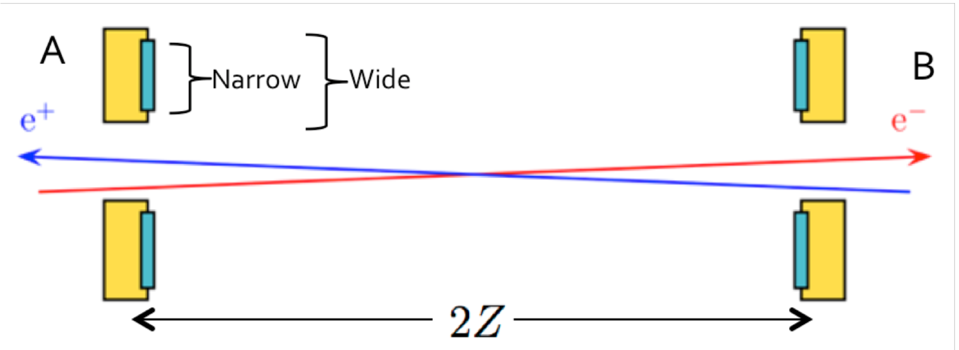
Luminosity Measurement

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

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



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



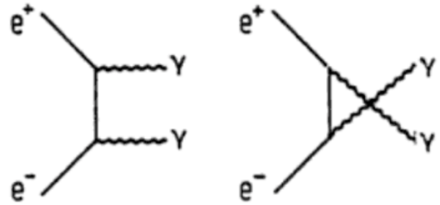
Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

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

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

Alternative Lumi Processes

- 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

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

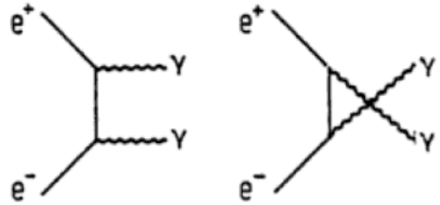
(θ_{min} defines the ECAL acceptance)

    - 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 ~10^{-6}
  - Example: $\theta > 20°$ 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

Alternative Lumi Processes

- 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 ~10^{-6}
  - Example: $\theta > 20°$ with respect to the beam axis ($\cos\theta < 0.94$) :

Work to do...

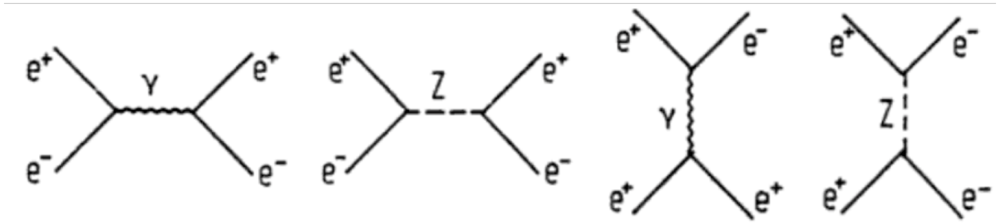
Energy	Process	Cross Section	Large angle $e^+e^- \to \gamma\gamma$	Large angle $e^+e^- \to e^+e^-$
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \to ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb	60 pb

Normalisation to 10^{-4}

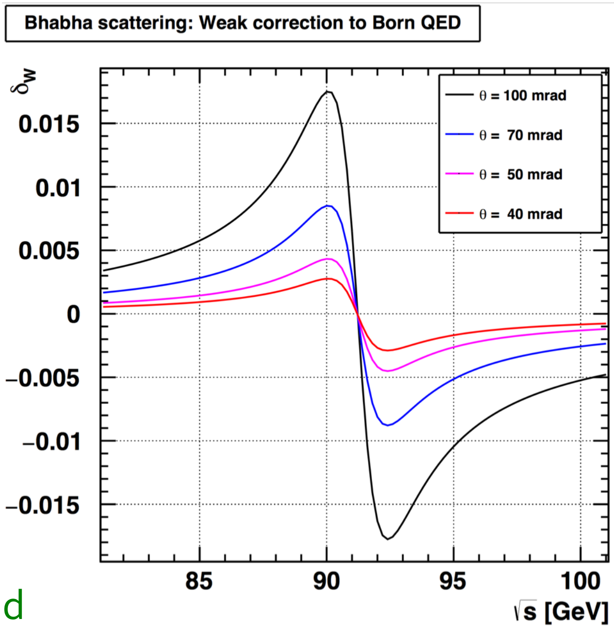
- The goal at FCC-ee is an absolute normalization to 10^{-4}
- After much effort, precision on absolute luminosity at LEP was dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

    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***

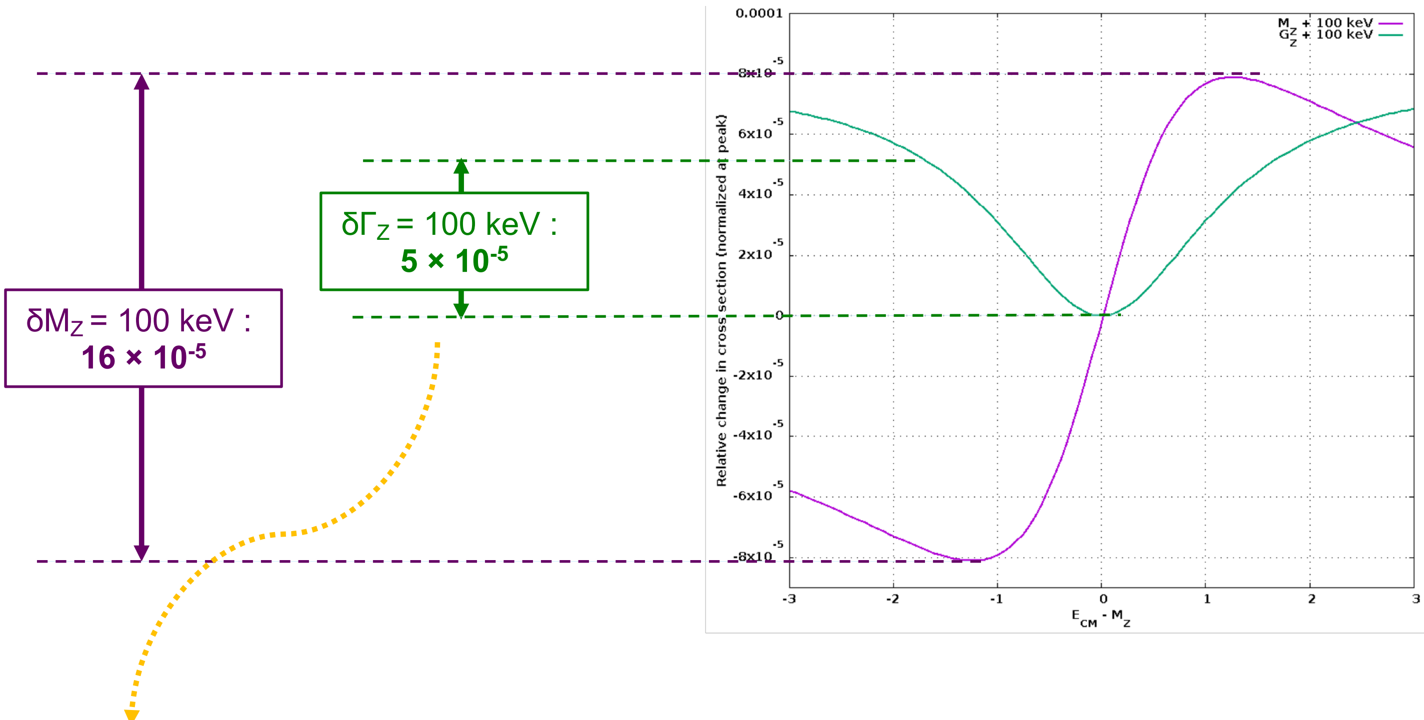


Relative Normalisation

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

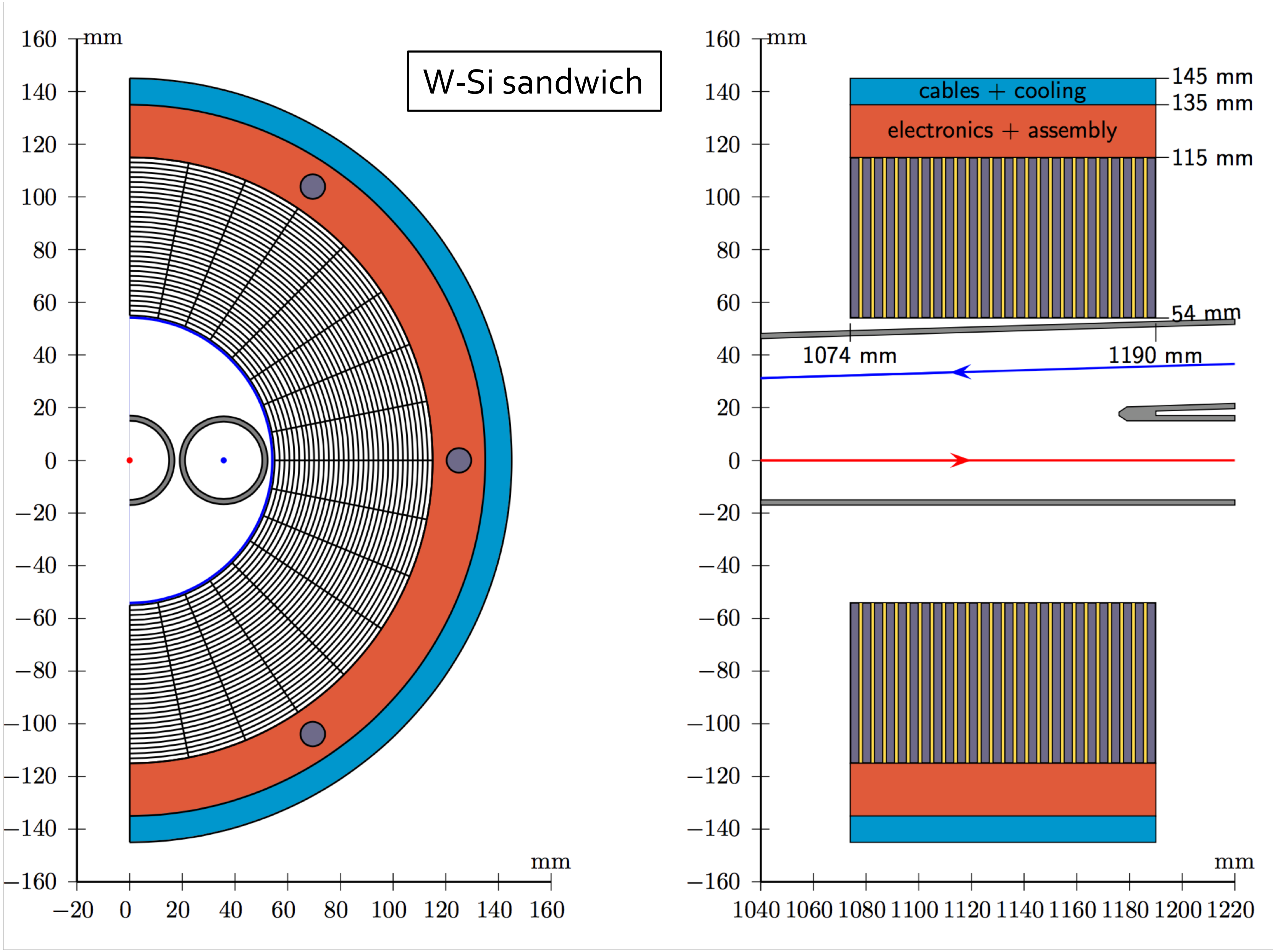
$\delta M_Z = 100$ keV ; $\delta \Gamma_Z = 100$ keV

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

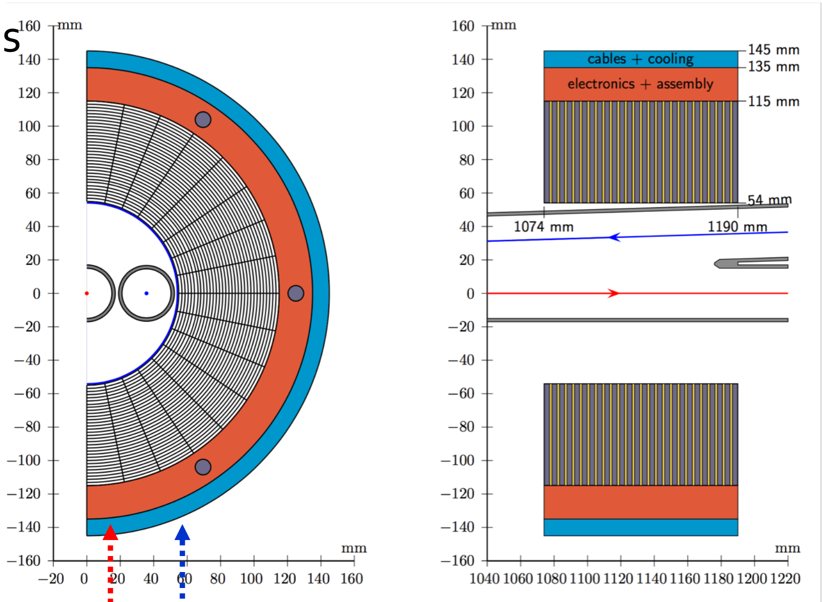


- Z width measurement most demanding: Need **relative** normalisation to about 5×10^{-5}
  - Need statistics of order 10^9
  - To optimize sensitivity of off-peak running, aim for cross section ~ σ_Z ; i.e $\gtrsim$ 10 nb

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?)

LumiCal Geometrical Tolerances

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

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

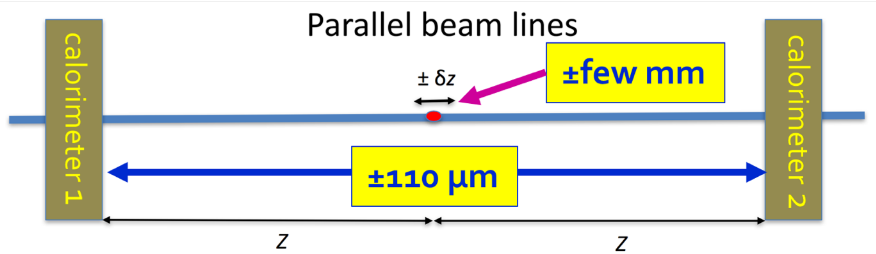
and

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

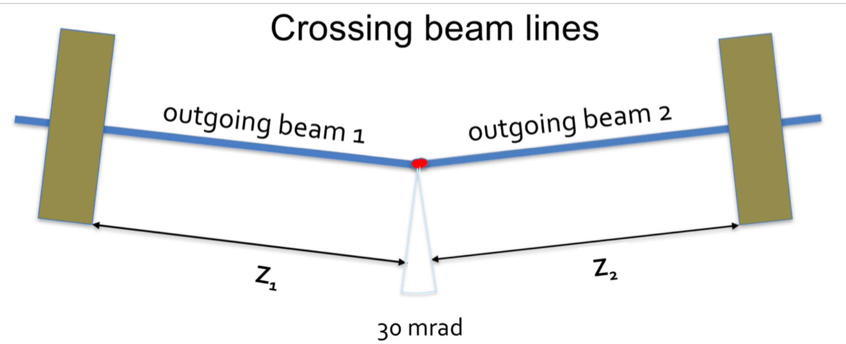
  - **Aim for construction and metrology precision of 1 µm**

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

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



  - 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

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

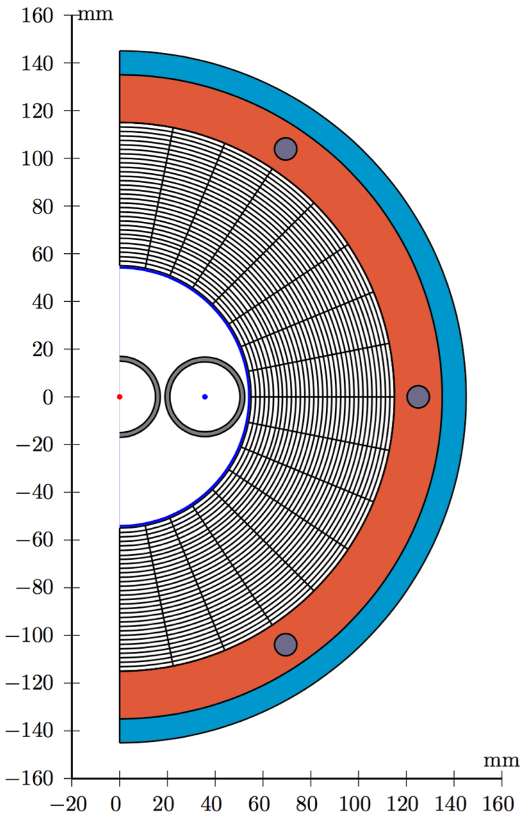
and

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

- **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

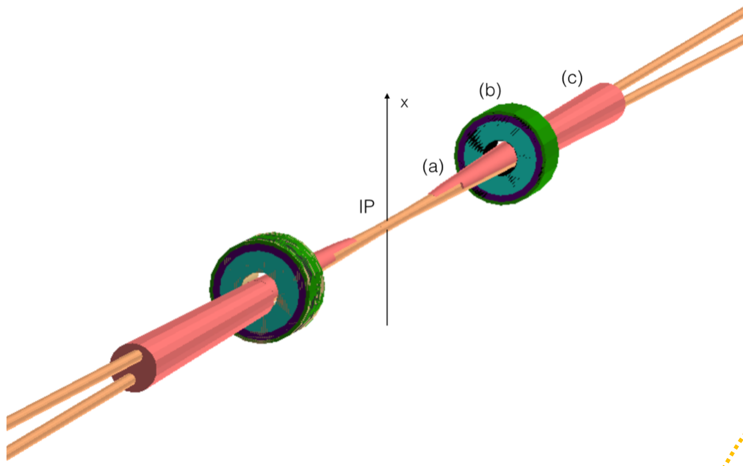
Geometry considerations

- 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 Anton Bogomyagkov)
  - Thread luminosity monitors onto beam pipe from end before complete beam pipe assembly is installed inside detectors?
  - Avoid vertical division...?

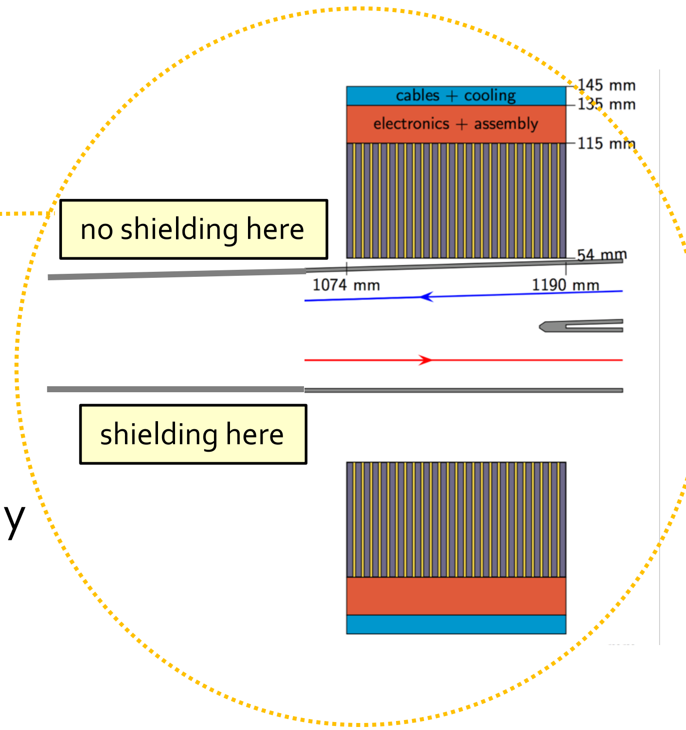


Beam-background: Synchrotron Radiation

- Tungsten shielding of beampipe effectively blocks synchrotron radiaiton



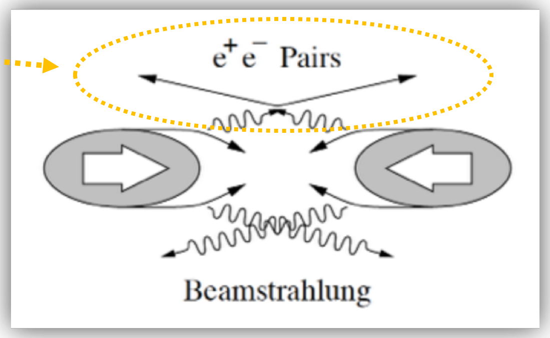
  - From z=370 mm to back of LumiCal:
    - 1 mm shielding with window for LumiCal
  - Behind LumiCal:
    - 15 mm shielding

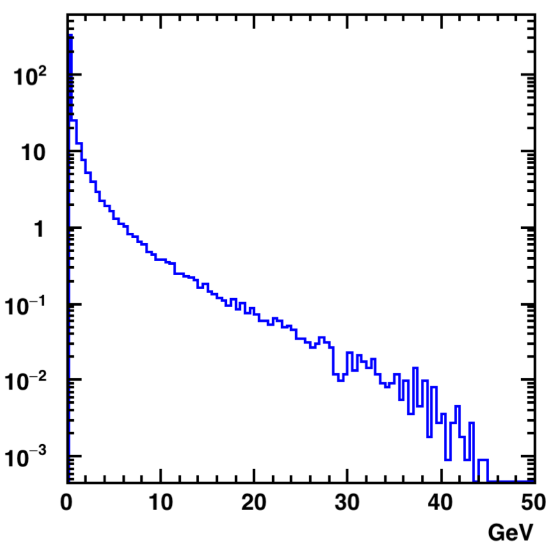


- Full GEANT4 simulation study: Shielding reduces energy from synchrotron radiation deposited in LumiCal from 340 MeV **to 7 MeV** at $\sqrt{s}$ = 365 GeV
  - Smaller deposits at lower beam energies
  - Negligible effect! ✓

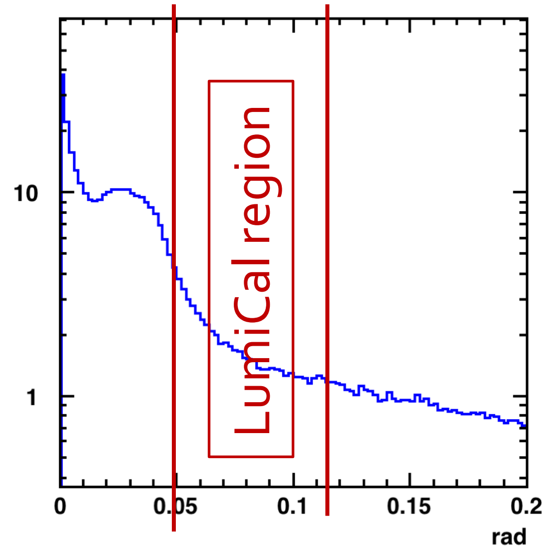
Beam-background: e^+e^- pairs (i)

- 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

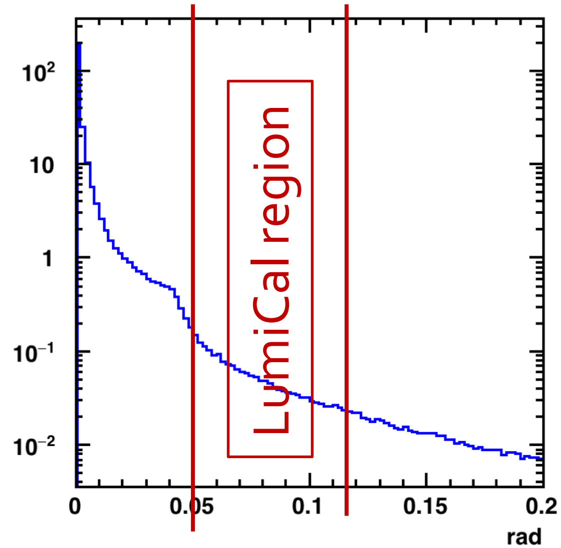




Energy of pair $e^\pm$ particles
- Average energy: 636 MeV
- # $e^\pm$ per BX per endcap: 404



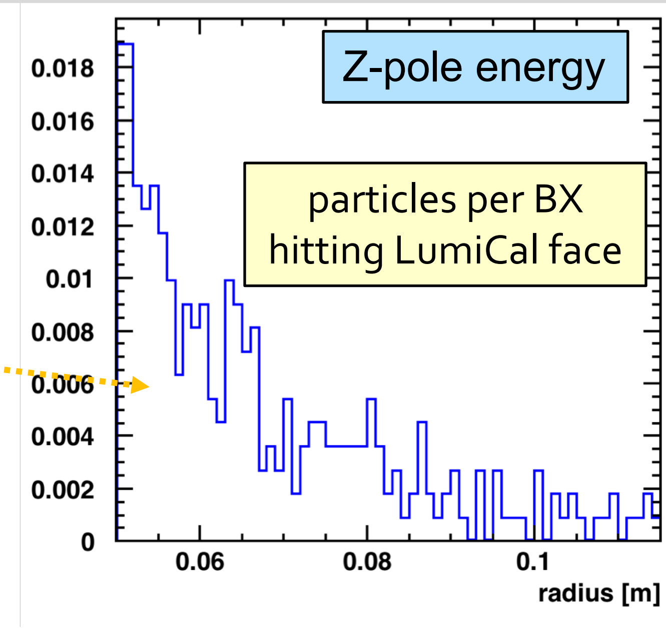
Polar angle of pair $e^\pm$ particles
- Peak at zero along beam line
- Bump around 30 mrad: focussing by other beam

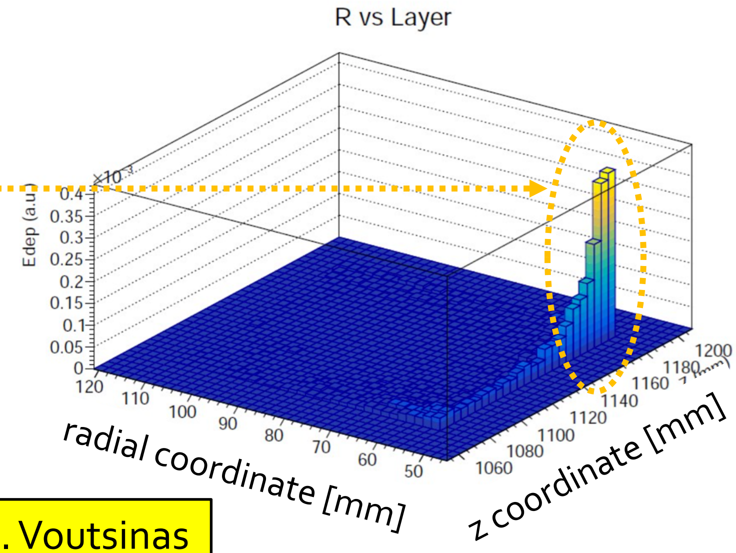


Energy weighted polar angle of pair $e^\pm$ particles
- Strongly forward peaked

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





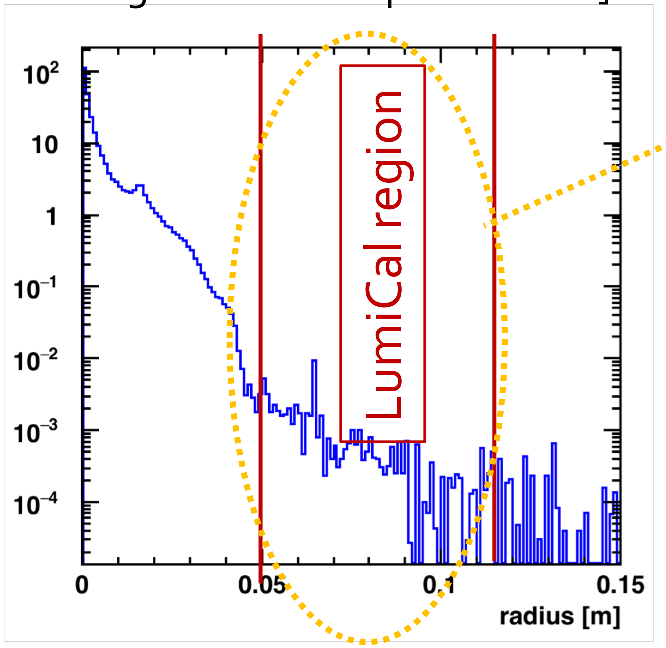
G. Voutsinas

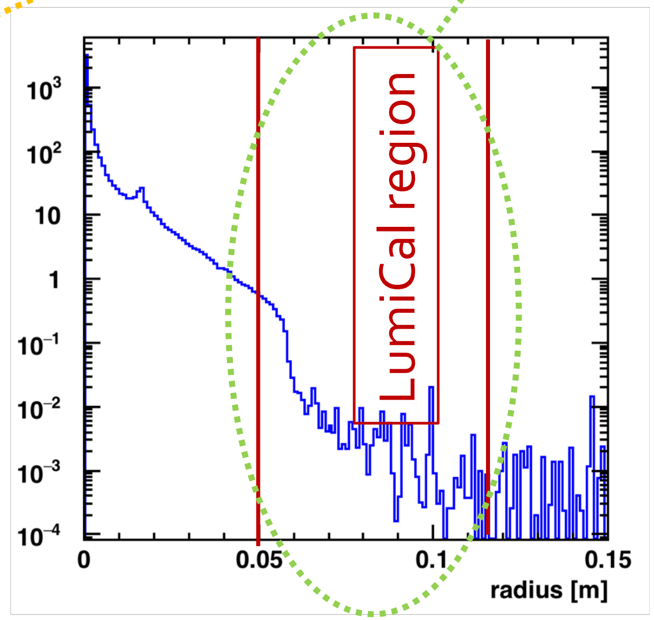
Beam-background: e^+e^- pairs (iii)

- 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 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]



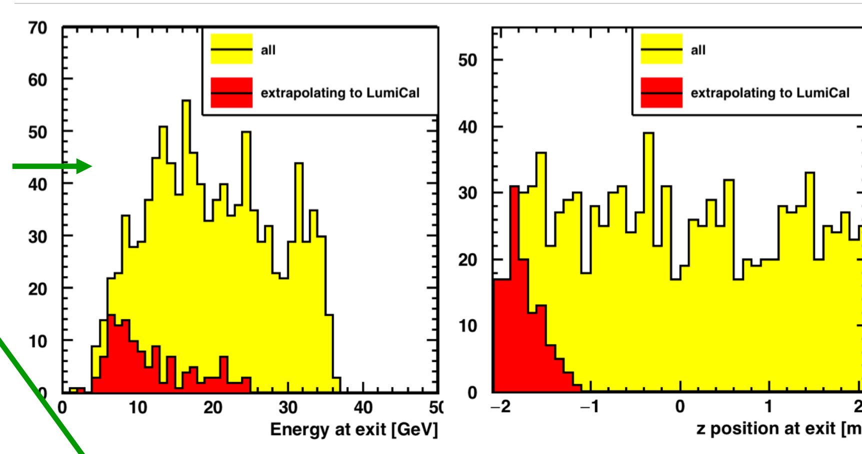


Beam-gas background

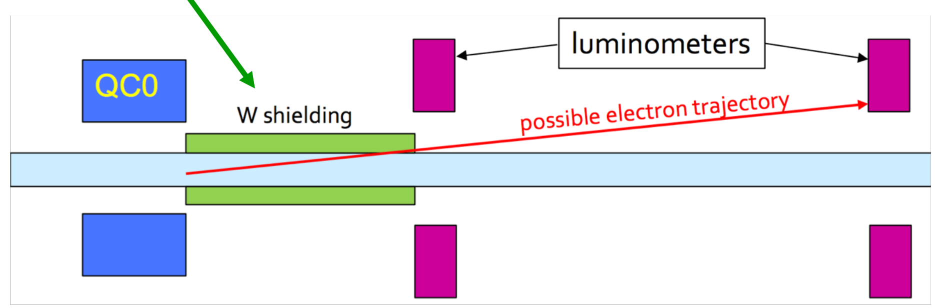
- At LEP, off-momentum particles from inelastic beam-gas scattering was the main background process to the luminosity measurement
- FCC-ee simulation of beam-gas scattering **at Z-pole energy** has been performed
  - Loss rate inside region of **± 2.1 m around IP** of **2 MHz/beam** @ 10^{-9} mbar of N_2 at 300 K

O. Blanco, F. Collamati

- 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



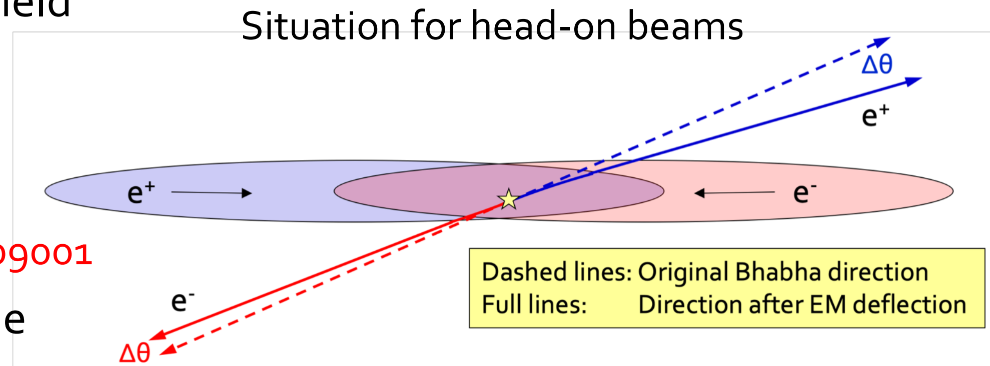
- From this: Estimate of coincidence rate before any energy or angular cuts: **< 10^{-7} per BX**
- Negligible compared to Bhabha rate: **6.4×10^{-4} per BX**

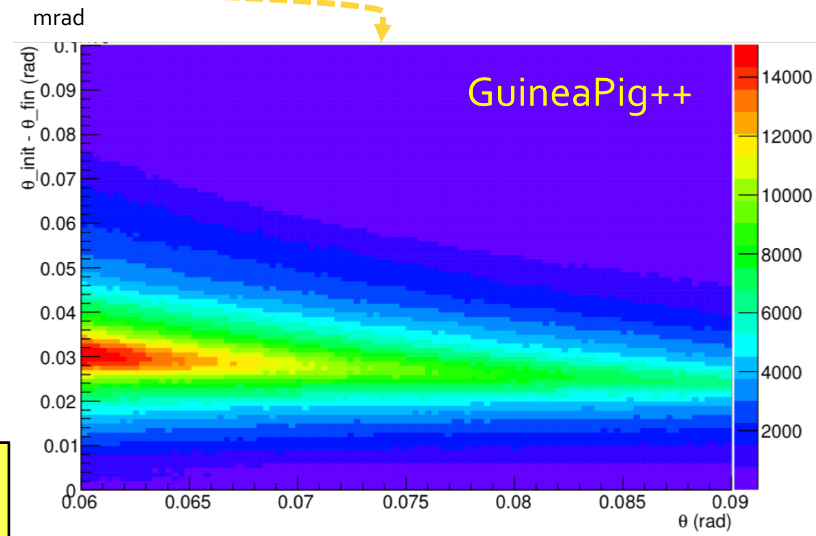


- Background seems to be negligible
  - To be checked through full simulation study

Electromagnetic Focussing of Bhabha electrons (i)

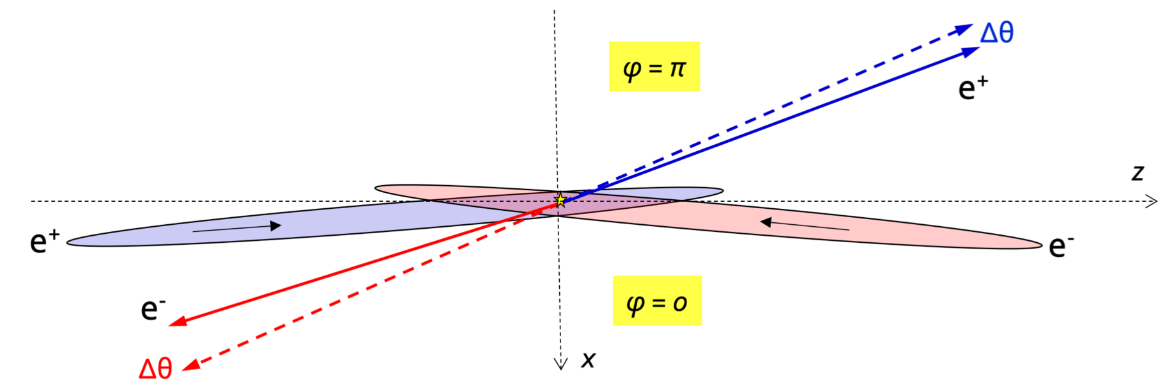
- Well-known ***pinch effect***: beam particles are focussed by the strong electromagnetic field of the opposing beam
- By the same, mechanism also (forward) scattered particles are focussed
  - First described in 2007 for ILC in JINST 2 P09001
- Important effect at FCC-ee where average focussing angle over the LumiCal acceptance is **about 30 μrad**.
- This is equivalant to a change of the effective acceptace of LumiCals of **-15×10^{-4}**
  - i.e. 15 times the goal on the luminosity measurement precision
- With which precision can we correct for this effect?

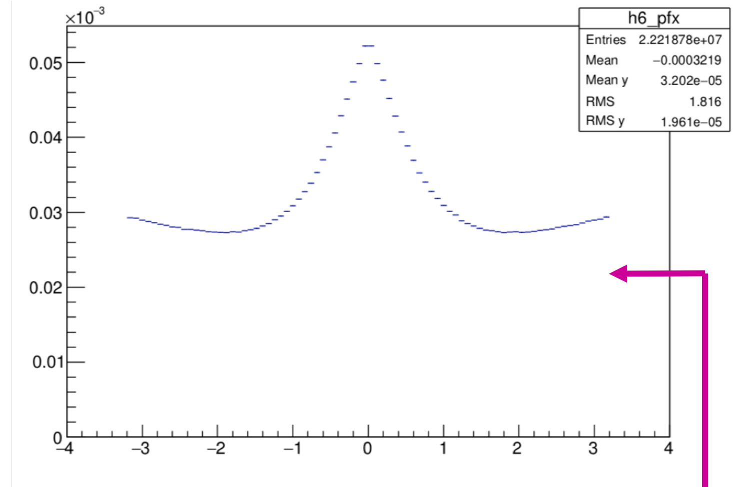




Studies by G. Voutsinas by use of GuineaPig++

Electromagnetic Focussing of Bhabha electrons (ii)

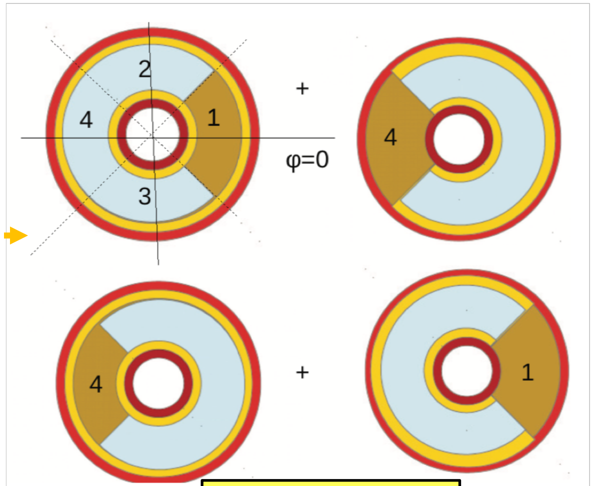




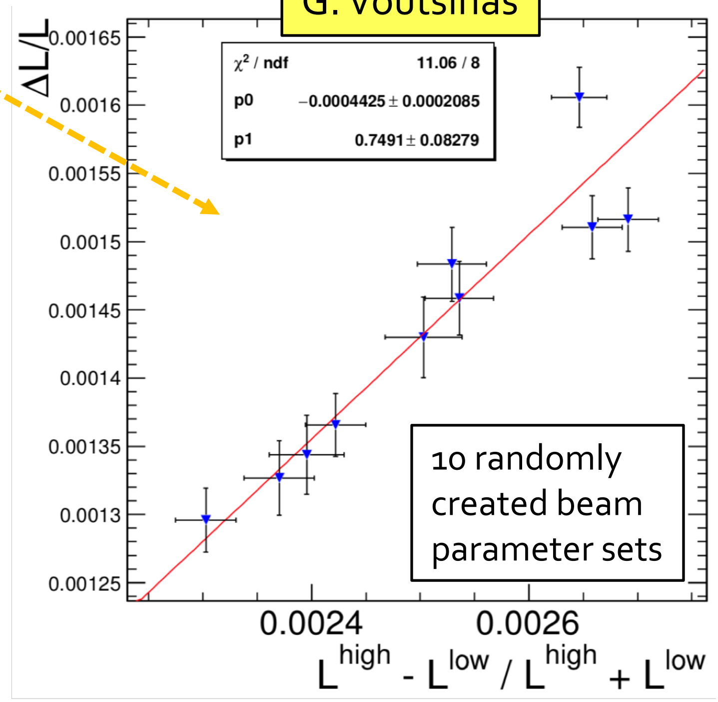
- Introduction of beam crossing angle (30 mrad) introduces an asymmetry
  - Particles scattered towards inside of FCC-ee ring ($\varphi = 0$) spend more time close to opposing beam: Focussed more
  - Particles scattered towards outside of FCC-ee ring ($\varphi = \pi$) are further away from opposing beam: Focussed less
- How could this be exloited:
  - A **φ-symmetric focussing** leads to a broadening of the acollinearity distribution of Bhabhas by ~10 μrad. Far below experimental resolution (~200 μrad); not likely to be observable
  - A **φ-dependent focussing** leads to a **φ-modulated non-zero average acollinearity distribution** which may be measurable (~25 μad effect / ~200 μrad resolution event-by-event)
  - In case φ-dependent part is proportional to the full effect, this may be a way to measure effect

Electromagnetic Focussing of Bhabha electrons (iii)

- On-going study
  - Construct observable which is sensitive to φ modulation of acollinearity angle
    - here a counting rate asymmetry)
  - Vary beam parameters randomly
    - Population; offset x, y; bunch dimensions σ_x, σ_y, σ_z
    - Find that, luminosity primarily depends on bunch population and σ_z
  - Study shows an approximate linear dependence of luminosity correction on the measured asymmetry parameter
  - However, a similar 25 μrad acollinearity bias will be also produced by a ~10 μm mis-alignment in x of the the IP position wrt the LumiCal system.
    - Such misalignment will however create a cosine-shaped modulation of counting rates in azimuth
    - But will the focussing effect not do the same?
    - Studies ongoing to attempt disentangling of focussing effect from alignment



G. Voutsinas



Conclusion / Summary / Outlook (i)

- Very precise normalization needed to match the fabulous statistics of FCC-ee. Goal:
  - Absolute to **10^{-4}**
  - Relative (point-to-point Z line shape scan) to **5×10^{-5}**
- Large angle $e^+e^- \to \gamma\gamma$ scattering is an interesting process - *to be studied*
- Small angle $e^+e^- \to e^+e^-$ scattering is the main "*workhorse*"
- Zeroth order LumiCal design exists. *Many challenges remain:*
  - Geometrical precision of construction and metrology to **1 μm level**
    - 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.
  - Cooling – keep temperature constant within 1 degree for geometrical precision
  - Equipment for alignment
  - …

Conclusion / Summary / Outlook (ii)

- Beam-backgrounds have been studied through full GEANT4 simulation and/or parametrisations – mostly find that backgrounds are small / negligible
  - **Synchrotron radiation** effectively stopped by beam-pipe shielding to **negligible** level
  - Beam-beam interactions produce large background of **e^+e^- pairs**
    - At $\sqrt{s}$ = 91.2 GeV: 800 particles / 500 GeV per BX
    - At $\sqrt{s}$ = 365 GeV: 6200 particles / 9000 GeV per BX
    - Most particles are very soft and strongly focused below LumiCal acceptance
    - Into each LumiCal points:
      - At $\sqrt{s}$ = 91.2 GeV: 0.3 particles / 0.06 GeV per BX
      - At $\sqrt{s}$ = 365 GeV: 15 particles / 3.2 GeV per BX
    - Validation via full Geant4 simulation:
      - At $\sqrt{s}$ = 91.2 GeV, this background is small and most likely negligible
  - First study of off-momentum particle background from beam-gas scattering
    - Negligible
- Focussing of Bhabha electrons by magnetic field of opposing beam
  - Significant bias (15×10^{-4}) to the luminosity acceptance. Correction needed!
  - Ongoing study: Analyze effect and possibly identify handle for correction