Luminosity Measurement

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Luminosity Measurement

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

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

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

- Minimize dependence on beam parameters and misalignment:
  - Average over two counting rates: $\text{SideA} + \text{SideB}$

- Important systematics from acceptance definition: *minimum scattering angle*

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

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

![Diagram of photon-pair production](image)

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

\((\theta_{\text{min}})\) 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 \((e^+e^- \rightarrow e^+e^-)\)
  - > O(10) larger than signal. Have to control Bhabha contamination to \(\sim 10^{-6}\)
- Example: \(\theta > 20^\circ\) with respect to the beam axis \((\cos\theta < 0.94)\):

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  - $\sim 10^6$ larger than signal. Have to control Bhabha contamination to $\sim 10^{-6}$
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Work to do...
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: $5.4 \times 10^{-4}$  
    Experiment: $3.4 \times 10^{-4}$
  - Since then, theory precision has improved to $3.8 \times 10^{-4}$  
    [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*
FCC-ee goal: Via Z line-shape scan, determine Z parameters to precisions:

\[ \delta M_Z = 100 \text{ keV} ; \quad \delta \Gamma_Z = 100 \text{ keV} \]

- 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 \( 5 \times 10^{-5} \)
  - Need statistics of order \( 10^9 \)
  - To optimize sensitivity of off-peak running, aim for cross section \( \sim \sigma_Z \); i.e. \( \geq 10 \text{ nb} \)
LumiCal Design

W-Si sandwich
LumiCal Design

- **W+Si sandwich:** 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Moliere radius: \( \sim 15 \text{ mm} \)
- 25 layers total: 25 \( X_0 \)
- Cylindrical detector dimensions:
  - Radius: \( 54 < r < 145 \text{ mm} \)
  - Along outgoing beam line: \( 1074 < z < 1190 \text{ mm} \)
- Sensitive region:
  - \( 55 < r < 115 \text{ mm} \);
- 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 \( @ 91.2 \text{ GeV} \): 14 nb
- Region \( 115 < r < 145 \text{ mm} \) 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

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

- Aim for construction and metrology precision of 1 \(\mu m\)

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

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

- 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 \(\mu m\)**

- 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

$$\delta r = 0.5\, \text{mm\, transverse} \quad \text{and} \quad \delta z = 20\, \text{mm\, longitudinal}$$

- Should displacements be larger, need to redefine narrow and wide

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

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

- **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 precision of \( \approx 1 \, \mu m \)
- 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 precision given by wafer production: Far below 1 \( \mu m \)
- 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 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 $\sqrt{s} = 365$ GeV
  - Smaller deposits at lower beam energies
  - Negligible effect!

8 January 2019

FCC-ee Workshop
**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

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**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 $\sqrt{s}$
  - Also energy per radiated particle increases $\Rightarrow$ Focussing becomes relatively weaker
  - At Z-pole energy, very low energy into LumiCal region
  - At top-energy, energy into LumiCal region at the GeV level

<table>
<thead>
<tr>
<th>Energy</th>
<th>$# e^+ \text{ total}$</th>
<th>$# e^+ \text{ LumiCal}$</th>
<th>Energy total</th>
<th>Energy LumiCal</th>
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<tr>
<td>91.2 GeV</td>
<td>400</td>
<td>0.3</td>
<td>250 GeV</td>
<td>0.06 GeV</td>
</tr>
<tr>
<td>365 GeV</td>
<td>3100</td>
<td>15</td>
<td>4500 GeV</td>
<td>3.2 GeV</td>
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[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 N₂ 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 x 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 equivalent to a change of the effective acceptace of LumiCals of **-15 x 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 exploited:
  - A $\varphi$-symmetric focussing leads to a broadening of the acollinearity distribution of Bhabhas by ~10 $\mu$rad. Far below experimental resolution (~200 $\mu$rad); not likely to be observable
  - A $\varphi$-dependent focussing leads to a $\varphi$-modulated non-zero average acollinearity distribution which may be measurable (~25 $\mu$ad effect / ~200 $\mu$rad resolution event-by-event)
  - In case $\varphi$-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 $\varphi$ modulation of acollinearity angle
    - here a counting rate asymmetry
  - Vary beam parameters randomly
    - Population; offset $x$, $y$; bunch dimensions $\sigma_x$, $\sigma_y$, $\sigma_z$
    - Find that, luminosity primarily depends on bunch population and $\sigma_z$
  - Study shows an approximate linear dependence of luminosity correction on the measured asymmetry parameter
  - However, a similar $25 \mu$rad acollinearity bias will be also produced by a $\sim 10 \mu$m 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
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 \(5 \times 10^{-5}\)

Large angle \(e^+e^- \rightarrow \gamma\gamma\) scattering is an interesting process - to be studied.

Small angle \(e^+e^- \rightarrow e^+e^-\) scattering is the main "workhorse”

Zeroth order LumiCal design exists. Many challenges remain:
- Geometrical precision of construction and metrology to 1 \(\mu m\) 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
- …
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 ($15 \times 10^{-4}$) to the luminosity acceptance. Correction needed!
  - Ongoing study: Analyze effect and possibly identify handle for correction