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

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

- 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: SideA + 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

\[
\begin{align*}
\sigma(e^+e^- \to \gamma\gamma) &= \frac{2\pi \alpha^2}{s} \left\{ \ln \frac{1 + \cos \theta_{\text{min}}}{1 - \cos \theta_{\text{min}}} - \cos \theta_{\text{min}} \right\} \\
(\theta_{\text{min}} & \text{ defines the ECAL acceptance})
\end{align*}
\]

- 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: $\theta_{\text{min}} = 20^\circ$ ($\cos \theta < 0.94$):

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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:
  
  \[
  \text{Theory: } 5.4 \times 10^{-4} \quad \text{Experiment: } 3.4 \times 10^{-4}
  \]

- 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 \( \mu \)m**
Relative Normalisation

- **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 \(1 \times 10^{-5}\)

- Need statistics of order \(10^{10}\)

- 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: 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Moliere radius: \(\sim 15\) 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
  
  \[
  \frac{\Delta A}{A} \approx -\frac{\Delta R_{in}}{1.6 \, \mu m} \times 10^{-4}
  \]
  
  and
  
  \[
  \frac{\Delta A}{A} \approx +\frac{\Delta R_{out}}{3.8 \, \mu m} \times 10^{-4}
  \]

- 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 \( \sim 1 \, \mu m \)
- 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!
**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^± particles per BX (with E > 5 MeV)
  - 500 GeV radiated in total per BX

---

**Energy of pair e^± particles**
- Average energy: 636 MeV
- # e^± per BX per endcap: 404

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

**Energy weighted polar angle of pair e^± particles**
- Strongly forward peaked
Beam-background: $e^+e^-$ pairs (ii)

- Radiated $e^\pm$ 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
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 $\Leftrightarrow$ Focussing becomes realistically weaker
  - At Z-pole energy, very low energy into LumiCal region
  - At top-energy, energy into LumiCal region at the GeV level

<table>
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<tr>
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<th>$# e^\pm$ total</th>
<th>$# e^\pm$ LumiCal</th>
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<td>91.2 GeV</td>
<td>400</td>
<td>0.3</td>
<td>250 GeV</td>
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<td>3100</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 N\textsubscript{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 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
- Need to understand this effect to better than 5% level
Electromagnetic Focussing of Bhabha electrons (ii)

Introduction of beam crossing angle (30 mrad) introduces an asymmetry

- Particles scattered towards inside of FCC ring ($\varphi = 0$) spend more time close to opposing beam: Focussed more
- Particles scattered towards outside of FCC 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 $\sim 10$ $\mu$rad. Far below experimental resolution ($\sim 200$ $\mu$rad); not likely to be observable
- A $\varphi$-dependent focussing leads to a $\varphi$-modulated non-zero average acollinearity distribution which may be measurable ($\sim 30$ $\mu$rad effect / $\sim 200$ $\mu$rad resolution event-by-event)
Specific study

- Construct observable which is sensitive to $\varphi$ modulation of acollinearity angle
  - Here a counting rate asymmetry
- Vary beam parameters by realistic amounts:
  - 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 ~10 $\mu$m mis-alignment in $x$ of the the IP position wrt the LumiCal system.

- Need precise alignment information of LumiCal system wrt IP.
Electromagnetic Focussing of Bhabha electrons (iv)

- **p_x-kick**
  - Due to beam-beam interactions, the colliding beams will receive a p_x-kick prior to collisions

  ![Diagram of electron beams and focussing](image)

  - This will increase the effective crossing angle by ~0.18 mrad (0.6%)
  - Hence two (linked) sources of change in acollinearity angle in the x-plane
    - p_x-kick: ~0.18 mrad  [Also for large angle tracks; measureable in μ⁺μ⁻ events]
    - Bhabha focussing: ~0.025 mrad  [Only for LumiCal events]

  - Precise monitoring of the two linked effects promises to provide a detailed understanding of the (modeling) of beam-beam interaction and to control its effect on the lumi measurement

See detailed presentation by E. Perez Thursday morning
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 $1 \times 10^{-5}$

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** negligible after beam-pipe shielding
- **e⁺e⁻ pairs** from beam-beam interactions negligible (except at top-energies)
- **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!
- Beam-beam interaction has many measurable consequences, e.g. \(p_x\)-kick
  - Promising: Several handles for detailed study
LumiCal Design

W-Si sandwich
Electromagnetic deflection of Bhabhas

Dashed lines: Original Bhabha direction
Full lines: Direction after EM deflection
\[
\varphi = \pi \\
\varphi = 0
\]