ReneSANCe event generator for precise luminosity determination

Vitaly Yermolchyk
on behalf of the SANC team

JINR, Dubna

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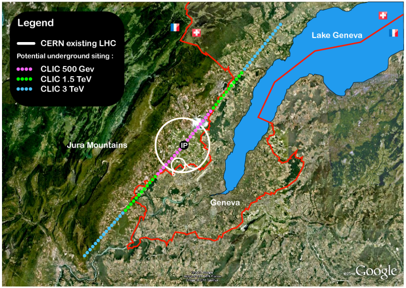
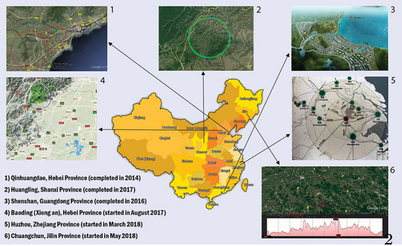
CLIC - Compact linear collider



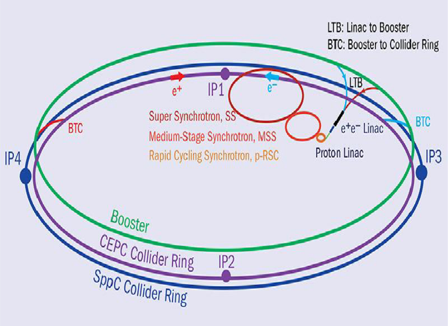
ILC - International linear collider

FCC - Future Circular Collider

CEPC - Circular e^+e^- Collider



The CEPC project



- The CEPC was proposed by the Chinese HEP community in 2012
- The CEPC aims to start operation in 2035, as a Higgs/Z/W/top factory
- The CEPC to produce Higgs/Z/W/top for high precision Higgs, EW measurements, studies of flavor physics & QCD, probes of BSM physics

Physics topics at CEPC

- Precision Higgs boson physics (**4M** $ee \to ZH$)
- Precision top quark physics (**500K** tt)
- Tera-Z: **4T** Z^0
  - Ultra-precise EW measurements
  - QCD measurements
  - Flavour physics (b/c/τ/CKM/...)
- Gamma-gamma collisions
- Searches for the new physics

Luminosity

- Luminosity measurement with precision 10^{-4} or better is necessary for all modern e^+e^- experiments
- Processes for luminosity measurements:
  - $e^+e^- \to e^+e^-$ – SABS (Small Angle Bhabha Scattering)
  - $e^+e^- \to e^+e^-$ – large angles Bhabha Scattering
  - $e^+e^- \to \mu^+\mu^-$ – lepton pair production
  - $e^+e^- \to \gamma\gamma$ – annihilation into photon pair
- Traditionally, `BHLUMI`, `BHWIDE`, `KKMC`, `BabaYaga`, `MCGPJ` have been used for theoretical estimation of luminosity
- `ReneSANCe`: Simulation of Bhabha and other processes used for luminosity monitoring, taking into account initial and final state polarization in the full phase space

Luminosity in ReneSANCe

- **DONE**: complete 1-loop corrections for all processes
- **DONE**: leading 2-loop contributions. They include **EW** corrections at $O(G_\mu^2)$ and the mixed **EWxQCD** at $O(G_\mu \alpha_s)$
- **UNDER DEVELOPMENT**: complete 2-loop for all lumi processes

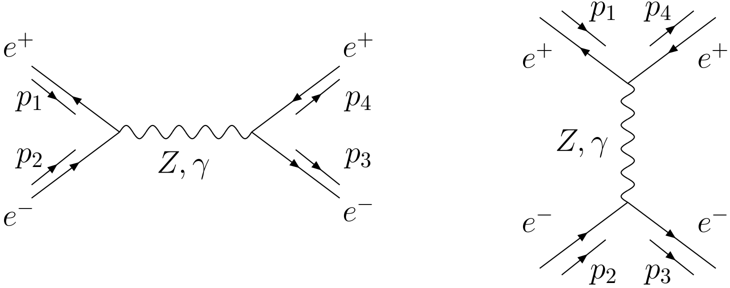
Small angle Bhabha scattering

We consider the process

$$e^+(p_1) + e^-(p_2) \to e^-(p_3) + e^+(p_4)(+\gamma(p_5))$$

at the complete one-loop electroweak level and evaluated the effects due to the working in the region of phase space when one of the electron is scattered by nearly zero angle.

The s and t channels of Bhabha processes at lowest order:



Features of SABS

- SABS is an almost purely electromagnetic process, which allows one to compute theoretical predictions for SABS within the perturbative theory approach with high accuracy.
- The differential distribution is strongly peaked at small angles where it behaves like $\sim 1/\theta^4$.
- Usually an MC generator has a cut-off for a minimum scattering angle to avoid divergence.

Experimental issues of SABS measurements

- The SABS cross section is usually measured with the help of calorimeters which are typically not equipped with tracking systems.
- Thus, it is impossible to distinguish a scattered electron from a radiated photon with the same energy.
- Potential background to Bhabha process are the events when one of the electrons is scattered by nearly zero angle, while an energetic photon is detected in the luminosity calorimeter.
- Another background is provided by the process of electron-positron annihilation into two (or more) photons which hit the luminosity calorimeters.

Cross-check with the 1996 LEP Workshop

Firstly, we compare the technical precision of our codes with results presented in the proceedings of the CERN Workshop for `SABS` at LEP era. For the tuned comparison we used non-calorimetric event selection (ES) called BARE1 and calorimetric ES called CALO1.
All numbers produced in setup of the Workshop[1] for the $\mathcal{O}(\alpha)$ matrix element without contribution of the Z exchange, up-down interference and vacuum polarization. The results are shown with various values of the energy-cut $z_{min} = s'/s$, where s' is the collision energy after ISR.

[1] Jadach, S. and others, *Event generators for Bhabha scattering*, CERN Workshop on LEP2 Physics (followed by 2nd meeting, 15-16 Jun 1995 and 3rd meeting 2-3 Nov 1995), hep-ph/9602393

Technical agreement: ReneSANCe vs BHLUMI

Comparison of BARE1 and CALO1 for the $\mathcal{O}(\alpha)$ matrix element. Z exchange, up-down interference and vacuum polarization are switched off. The center of mass energy is $\sqrt{s} = 92.3$ GeV. The results are shown with various values of the energy-cut $z_{min} = s^{'}/s$.

z_{min}	ReneSANCe	BHLUMI	ReneSANCe	BHLUMI
	BARE1: σ [nb]		CALO1: σ [nb]	
.100	166.01(1)	166.05(2)	166.33(1)	166.33(2)
.300	164.71(1)	164.74(2)	166.05(1)	166.05(2)
.500	162.19(1)	162.24(2)	165.26(1)	165.29(2)
.700	155.41(1)	155.43(2)	161.77(1)	161.79(2)
.900	134.36(2)	134.39(2)	149.91(1)	149.93(2)

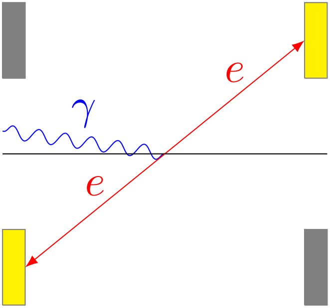
Generator cuts

We generated Bhabha events, where each arm of the luminometer registered an energy shower from an electron or photon. **No restriction on minimum scattering angle was set.**

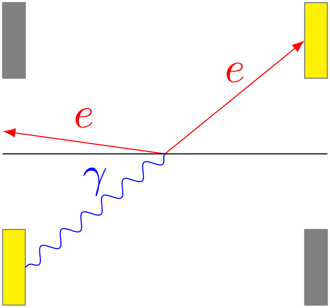
- Electrons were allowed to scatter by any angle, down to zero.
- Luminosity acceptance was assumed 30 mrad $< \vartheta <$ 174.5 mrad.

Geometry and acceptance event selection

- **ES-BARE** – each arm of the luminometer is hit by an electron (positron) with the energy $E_{e^\pm} > 0.5 E_{\text{beam}}$ without taking into account photons.
- **ES-CALO** – each arm of the luminometer is hit by electron and/or photon(s) with total energy $E_{e^\pm,\gamma} > 0.5 E_{\text{beam}}$.



BARE



CALO

Results for the ES-BARE

To represent numerical result of each contributions we evaluate corresponding relative corrections defined as

$$\delta = \frac{\sigma^{\text{contr.}}}{\sigma^{\text{Born}}} - 1, \%$$

$\sqrt{s}$, GeV	91.18	240
σ^{Born}, pb	135008.970(1)	19473.550(1)
$\delta^{\text{one-loop}}$, %	−1.562(1)	−0.821(1)
δ^{total}, %	−1.420(1)	−0.574(1)
δ^{QED}, %	−6.296(1)	−7.002(1)
δ^{VP}, %	4.6527(1)	6.1866(1)
δ^{weak}, %	0.0088(1)	−0.0064(1)
δ^{ho}, %	0.1418(1)	0.2475(1)

Results: ES-BARE vs ES-CALO

- The ES-CALO cross-section at $\sqrt{s} = 240$ GeV is 3% larger than ES-BARE Bhabha cross-section, when both beam particles must hit the luminometer.
- Majority of the effect is due to the events with collinear photon or due to the events when electron is scattered by an angle LARGER than the luminosity acceptance, while hard ISR photon hits the luminometer.
- Such events can be (and have been!) taken into account by any NLO Bhabha generator.

New effect

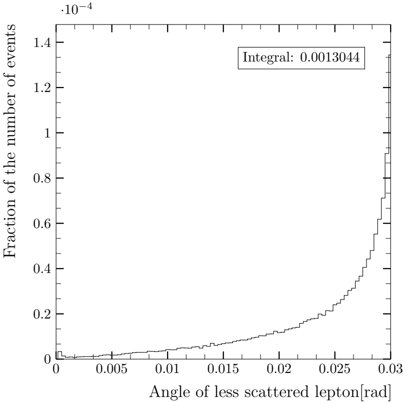
- About $\sim$ **1.3** permille of the total cross-section (both at $\sqrt{s} = 91.18$ and 240 GeV) is represented by of events with electron scattering angle **below** the luminometer acceptance. [Chin.Phys.C, v48, 4, p.043002, (2024)]
- Those events have been missed by earlier generators.

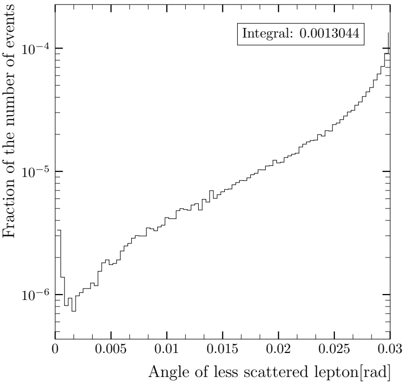
Integrated cross section and relative corrections

- $\delta_1^{\rm QED} = \delta(\text{ES-BARE})$: each arm of the luminometer is hit by an electron, (positron) with the energy $E_{e^\pm} > 0.5 E_{\rm beam}$ without taking into account photons.
- $\delta_2^{\rm QED} = \delta(\text{ES-CALO}, \vartheta > 0.030)$: **ES-CALO** setup with electron scattering angles larger than the minimum luminosity acceptance
- $\delta_3^{\rm QED} = \delta(\text{ES-CALO})$: **ES-CALO** setup with arbitrary electron scattering angles.

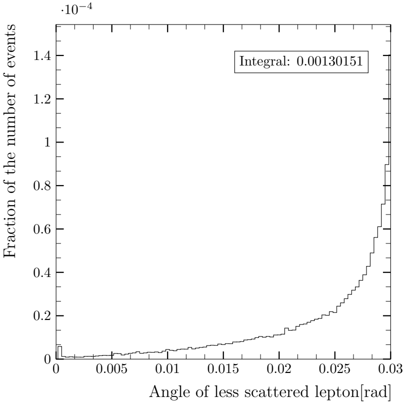
$\sqrt{s}$, GeV	91.18	240
$\sigma^{\rm Born}$, pb	135008.970(1)	19473.550(1)
$\delta_1^{\rm QED}$, %	−6.296(1)	−7.002(1)
$\delta_2^{\rm QED}$, %	−3.618(1)	−3.986(1)
$\delta_3^{\rm QED}$, %	−3.488(1)	−3.854(1)
$\Delta^{\rm QED}(\vartheta < 0.030)$	$1.30(1) \times 10^{-3}$	$1.32(1) \times 10^{-3}$

Distribution of lepton scattering angle at $\sqrt{s} = 91.18$ GeV





Distribution of lepton scattering angle at $\sqrt{s} = 240$ GeV



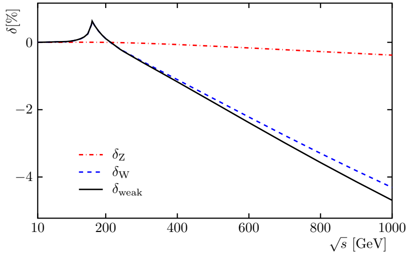
Advantages of $e^+e^- \to \gamma\gamma$

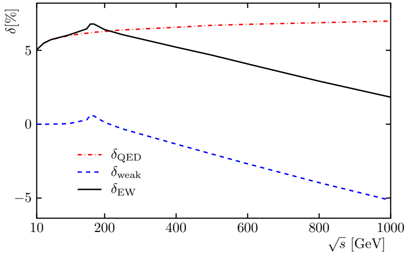
- The cross section value estimated for large angles is **large enough**.
- **A clean signature** for selection among other detected particles.
- **No vacuum polarization** effects at 1-loop level.

Technical agreement: `ReneSANCe` vs `BabaYaga`

$\sqrt{s}$, GeV	91	160	240	365
		Born, pb		
ReneSANCe	39.822(1)	12.884(1)	5.7252(1)	2.4758(2)
BabaYaga	39.821	12.881	5.7250	2.4752
		NLO QED, pb		
ReneSANCe	41.04(1)	13.289(3)	5.907(1)	2.556(1)
BabaYaga	41.043	13.291	5.9120	2.5581

Impact of Weak corrections





Conclusions

- MC generator ReneSANCe is available for LUMI processes: small and large angle Bhabha scattering, lepton-pair production in e^+e^- collisions, large angle e^+e^- annihilation into photon pair.

  For SABS:
  - Technical agreement with LEP-era generators is achieved.
  - A unique feature of the ReneSANCe generator is the possibility to simulate electron scattering by infinitely small angles. This allows to take into account events in which one arm of the luminosity calorimeter is fired by an energetic ISR photon, while an electron is scattered by very small angle and escapes detection. If not taken into account, this effect leads to a luminosity bias of 1.3-1.4 ‰, both at Z pole and at 240 GeV.
  - The bias can be avoided by generating events down to 10 mrad scattering angles. In this case the bias value becomes less than 10^{-4}.

  For $e^+e^- \to \gamma\gamma$:
  - Technical agreement with BabaYaga is achieved.
  - Importance of weak corrections for luminosity measurements at high energy colliders is shown.

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Thank you for your attention!