Integrated luminosity systematic studies at CEPC

Ivanka Bozovic

VINCA Institute of Nuclear Sciences
University of Belgrade

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Overview

Uncertainties

- Process
- Detector
- Systematic effects

- Ongoing studies
- Outlook

$\mathcal{L}$ measurement – Small Angle Bhabha Scattering

$$N = \mathcal{L} \cdot \sigma \cdot \varepsilon$$

$$\Delta\mathcal{L}/\mathcal{L} = (\Delta N/N) \oplus (\Delta\varepsilon/\varepsilon) \oplus (\Delta\sigma/\sigma)$$

N – Bhabha experimental count

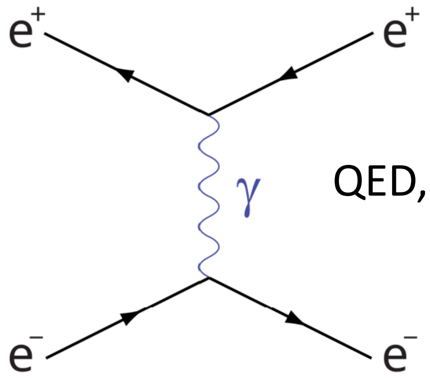
σ – theoretical cross-section

ε – total efficiency

ΔN – statistical ⊕ systematic uncertainty of the count (statistical typically 10^{-4})

Δσ – theoretical uncertainty (typically $\Delta\sigma/\sigma \sim 10^{-4}$)

Δε – selection efficiency (i.e. one rely on E, ϑ, φ measurement) ⊕ reconstruction efficiency



QED, t-channel photon exchange

Order		Type	Content
LO	α^0	tree	γ (s, t) $\frac{\sigma_{s\text{-channel}}}{\sigma_{\text{total}}} \sim 10^{-4}$ to 10^{-3}
NLO	α^1	1-loop + 1γ	vertex, self-energy, box, bremsstrahlung
NNLO	α^2	2-loop + multi-real	double loops, double emission, pairs

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ONE e^+ or e^- detected		e^+, e^- back-to-back detected	
θ>25 mRad	θ>25mR & |y|>25mm	θ>25 mRad	θ>25mR & |y|>25mm
133.5 nb	81.8 nb	85.4 nb	78.0 nb

Process

$\Delta\sigma$ – theoretical uncertainty (typically $\Delta\sigma/\sigma \sim 10^{-4}$)

Bhabha (BHLUMI) theoretical precision: 5×10^{-4}

What was included:

- Exact $O(\alpha)$ corrections
- Leading-log higher-order resummation (via exponentiation)
- Multi-photon radiation
- Vacuum polarization effects

- **Dominant uncertainties:**
- Missing subleading $O(\alpha^2)$ terms
- Hadronic vacuum polarization
- Precision of Monte Carlo integration

Other tools:
BabaYaga@NLO
current precision: $<3 \times 10^{-4}$

Dominant uncertainties:

- Hadronic vacuum polarization (requires input from $e^+e^- \to$ hadrons data)
- Missing higher orders – not all $O(\alpha^3)$ effects fully under control

BHLUMI vs. BHWIDE

BHLUMI: small-angle Bhabha scattering

- Dominated by t-channel photon exchange (<50 mrad)
- Huge enhancement in propagator $1/t^2$ for small θ:

$$t \simeq -\frac{s\,\theta^2}{2}$$

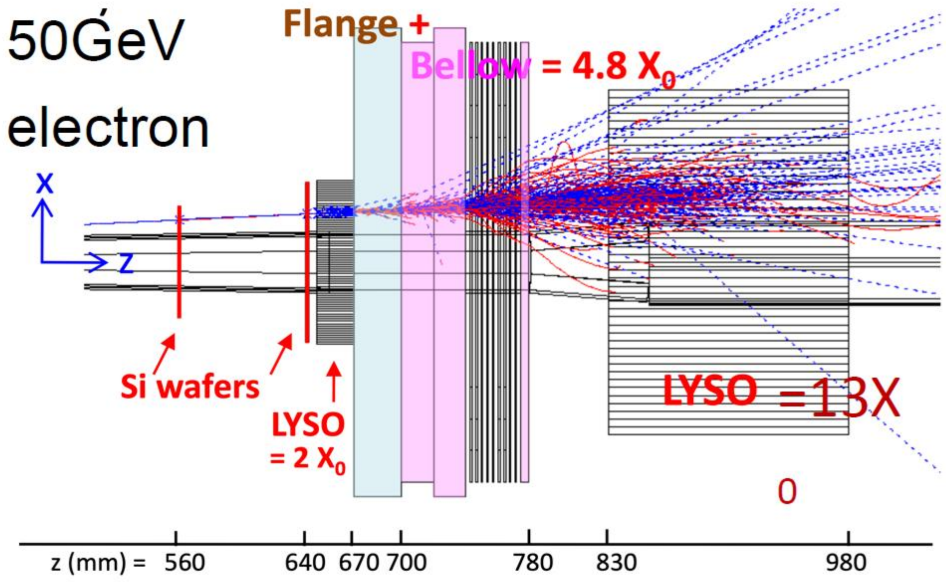
- Maximize control over multiple photon radiation

BHWIDE: Significant s-channel + Z exchange up to 1% (s-channel Z + Z-γ interference), typically at $\geq$ 100 mrad

Overlap range ~ 100 mrad

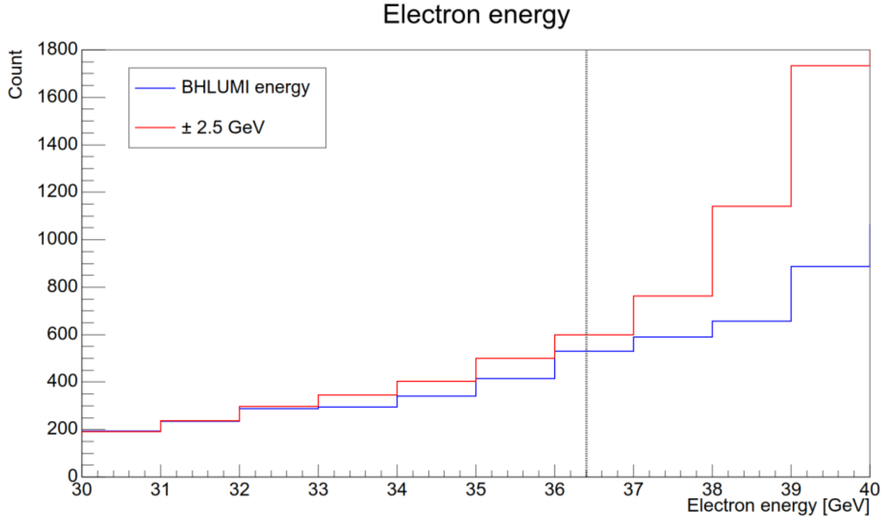
$\Delta\varepsilon$ – selection efficiency (i.e. one rely on E, ϑ, φ measurement) $\oplus$ reconstruction efficiency

- In most studies we haven't applied E cut, but**, it has to be considered what 4-5% resolution means for luminosity measurement**
- E cut (usually at 80% of E_{beam}) is needed for background suppression in realistic experimental environment
- The same applies for ϑ, φ if collinearity or coplanarity will required for Bhabha (however this can be supported by the Si tracking layers in front of the luminometer)

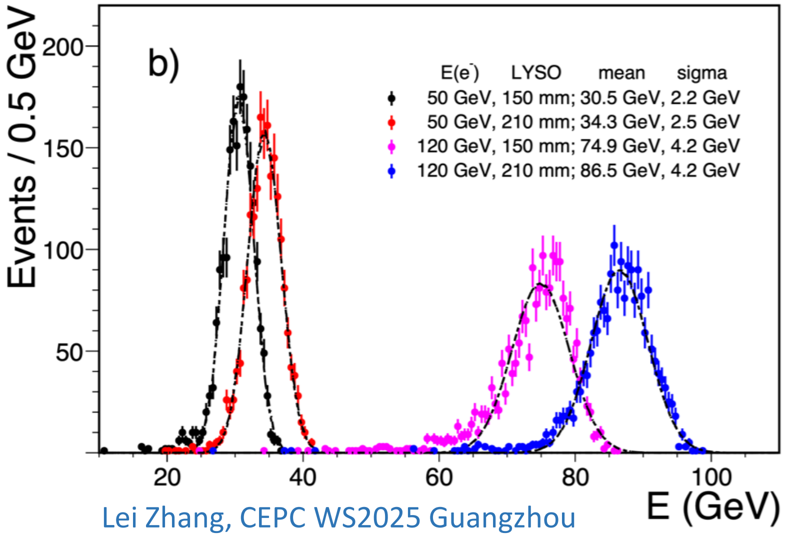


Detector – E resolution

- ❑ In most studies we haven’t applied E cut, but, it has to be considered what 4-5% resolution means for luminosity measurement
- ❑ E cut (usually at 80% of E_{beam}) is needed for background suppression in realistic experimental environment



- Length vs energy resolution
  - Roughly 4-5%



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Energy resolution of 2.5 GeV corresponds to count uncertainty of ~$7\cdot10^{-3}$

Ahead of us – more realistic simulations

Impact of realistic Bhabha reconstruction?

This refitment could also bring better control of the sensitive observable (count) by:

- ❑ Instead of θ from track momentum

  Use:
  - θ from **energy cluster in calorimeter**

  This automatically:
  - includes nearby photons (‘dress’ electrons)
  - stabilizes angle in terms of rigid cut in simulation;
- ❑ Mild energy cut (i.e. E_cluster>0.8·E_beam)

  Removes:
  - extreme ISR tail

  BUT:
  - assumes background that will impact measurement (to which extent?)
  - can 0.7·E_beam work?

Systematic effects

- **Systematics in integrated luminosity measurement at CEPC studied so far:**

  - **Effects from mechanical uncertainties and MDI** (240 GeV & Z-pole) *2022 JINST 17 P09014 (luminometer along s-axis), Progress of Theoretical and Experimental Physics ptae141 (2024) (luminometer along z-axis, Z-pole)*
  - **Physics processes as background to the Bhabha count** *2022 JINST 17 P09014*
  - **Impact of EMD** *arXiv: 2511.00687 [hep-ex], submitted to the Progress of Theoretical and Experimental Physics*

- **Data-driven correction of uncertainty of the crossing angle** *arXiv: 2511.00687 [hep-ex]*
- **Measurement of the beam energy spread (BES)** *2022 JINST 17 P09014*
- **Impact of BES uncertainty on precision EW observables** *2022 JINST 17 P09014*

Overview of issues requiring attention

- Effects from mechanical uncertainties and MDI (240 GeV & Z-pole)
  - maximal uncertainty of the luminometer inner radius ➡ ~ 1 μm
  - RMS of the Gaussian spread of the measured radial shower position with respect to the true impact position in the luminometer front plane ✔
  - maximal absolute uncertainty of the longitudinal distance between left and right halves of the luminometer ✔
  - RMS of the Gaussian distribution of mechanical fluctuations of the luminometer position with respect to the IP, caused by vibrations and thermal stress, radial and axial ✔
  - maximal absolute angular twist of the calorimeters corresponding to different rotations of the left and right detector axis with respect to the outgoing beam ✔
  - maximal deviation of the individual beam energy from its nominal value ➡ 7 MeV (is this critical?)
  - maximal uncertainty of the average net CM energy for the Bhabha cross-section ➡ relative uncertainty has to be the same as $\Delta L/L$
  - maximal radial and axial IP position displacements with respect to the luminometer, caused by the finite transverse beam sizes and beam synchronization ✔
  - maximal time shift in beam synchronization leading to the IP longitudinal displacement ✔
- Physics processes as background to the Bhabha count ✔
- Impact of EMD ➡ of order of ~ $4{\cdot}10^{-3}$ at Z-pole

- Data-driven correction of uncertainty of the crossing angle ✔
- Measurement of the beam energy spread (BES) 9 MeV uncertainty ✔
- Impact of BES uncertainty on precision EW observables ✔

Overview of issues requiring attention

- **Effects from mechanical uncertainties and MDI (240 GeV & Z-pole)** $\leq 3{\cdot}10^{-4}$
  - maximal uncertainty of the luminometer inner radius ~ 1 μm
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- Physics processes as background to the Bhabha
- Impact of EMD of order of ~ $4{\cdot}10^{-3}$ at Z-pole

Data driven correction required

- Data-driven correc... y of the crossing angle ✔
- **Measurement of t... spread (BES)** ✔
- Impact of BES unc... on EW observables ✔

$< 10^{-4}$

Ongoing systematic studies – work to do

- Impact of EMD requires correction from simulation: develop a correction method based on experimental data *(ongoing)*

- Do we fully understand simulation of beam-beam interactions (Guinea-Pig ++), in terms of control and reproducibility of the existing results?

- *A group has been formed for a dedicated study*

It is worth nothing that this issue affects all processes (not only Bhabha) including background to be tracked in the fields of incoming bunces with potential implications on detectors’ occupancies and shielding

- What is the impact of 20 mrad inner aperture acceptance on EMD2? (i.e. Bhabha will be more affected by the fields of the incoming bunches, but, also, some correction methods for EMD could work better with a larger statistics in the detector) *(planned)*

Ongoing systematic studies – few examples EMD1

- **Do we understand EM deflection of the initial state? – check through different approaches**
- GP gives pairs0 file when `do_bhabhas`
- a. Independent test with `do_lumi`, look into modified initial states in beam files
- b. Compare to FCCee results where:
  - $E_\perp = (Ne/2\pi\varepsilon_0)\cdot(\sigma_z\sqrt{\sigma_x\sigma_y})^{-1}$ $E_{||}\approx 0$ at relativistic energies

    what gives 40% larger fields at FCCee without x-angle

    and ~ 10% larger effects with x-angle

`do_lumi` test + comparison:

p_x-kick 5.8 CEPC vs. 6.9 FCC which is ~19% and is in the expected range

$\Delta L/L$ ~4 ‰ vs. FCC~ 2 ‰ (but luminometer FV starts at 62 mrad at FCC instead of 53 mrad at where the effect is stronger)

`do_bhahbas` – check pairs0:

$\Delta L/L$ ~3.6 ‰ (corrected energy with proper `ecmload`)

EMD1 seems to be OK in various approaches and consistent with FCCee

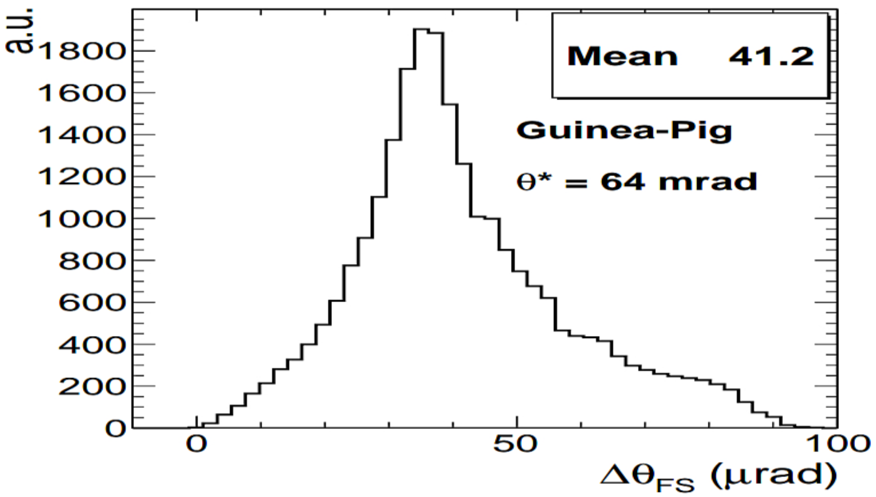
Yet, it doesn't mean that pair production will be ok too. Just that the initial state is consistently treated.

- **Do we understand EM deflection of the final state (EMD2)?**

The transverse kick comes from the collective field of the opposite bunch:

$$\Delta\theta \sim \frac{N_b}{\sigma_x \sigma_y} \times f\left(\frac{z}{\sigma_z}\right)$$

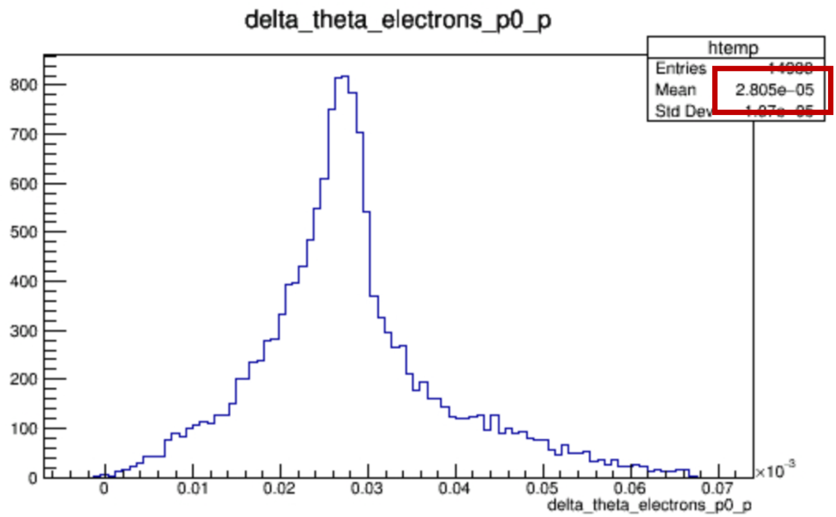
FCCee



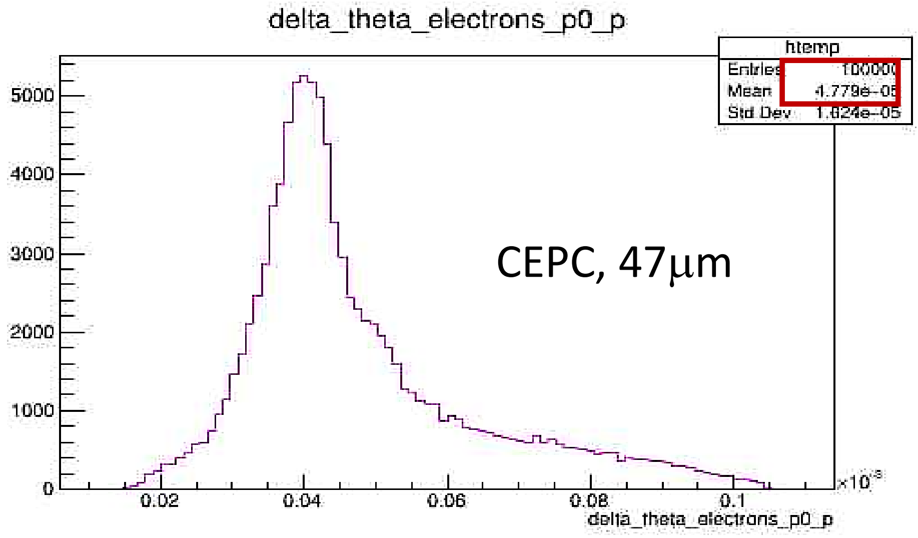
Z-pole, FCCee

Quantity	2019 CDR	~2026 (latest)	Change
Bunch population (N_b)	1.7 × 10^{11}	1.6–1.7 × 10^{11}	≈ no change
σ_x (horizontal size)	6.4 µm	8.4 µm	↑ ~30%
σ_y (vertical size)	28 nm	33.7 nm	↑ ~20%
σ_z (bunch length)	12.1 mm	15.4 mm	↑ ~25–30%

FCC reduces Beamstrahlung and EMD2



Ongoing systematic studies – few examples EMD



Z-pole, CEPC

Quantity	CDR (~2018)	~2025	Change
Bunch population	0.8×10^{11}	$1.4–1.5 \times 10^{11}$	**↑ ~×1.8**
σ_x	6 µm	6 µm	≈ same
σ_y	40 nm	35 nm	**↓ ~10–15%**
σ_z	8.5 mm	10–11 mm	**↑ ~25%**

EMD2 1.5 – 2 times larger than in CDR2

CEPC boosting instantaneous luminosity at the expense of EMD

Good news is that for $\mathcal{L}$ measurement changes in electron deflection angle of this magnitude are not significant – relative uncertainty of $\mathcal{L}$ stays at $\sim(2\pm1) \cdot 10^{-3}$

Outlook

- Open issues (in luminosity measurement) are identified
- Studies should converge toward more realistic simulation including Bhabha reconstruction in the luminometer
- Impact of beam-related background should be studied to see the effect (if any)
- Observables used in selection (energy, angles) should be tuned to realistic measurement (instead of using 'naked' kinematics from simulation)
- Effects induced by beam-beam interactions have to be fully controlled at the simulation level (reaching that) and advanced towards realistic fields present in the MDI region
- Correction effects (EMD2) have to developed (EMD1 can be corrected from x-angle measurement)
- Acceptance effects should be addressed for different luminometer positioning (i.e. from 20 mrad) as the most studies have been done for ~50-80 mrad fiducial volume (this may come with benefits like increased sensitivity of experimental observables to measure EMD2, but also with a price due to $\sigma \sim 1/\theta^3$ Bhabha cross-section sensitivity)

$\Delta\mathcal{L}/\mathcal{L} \sim 10^{-4}$ at the Z-pole is feasible but not guaranteed

If you are interested, you are welcome to join this effort!
shihy@ihep.ac.cn, ibozovic@vinca.rs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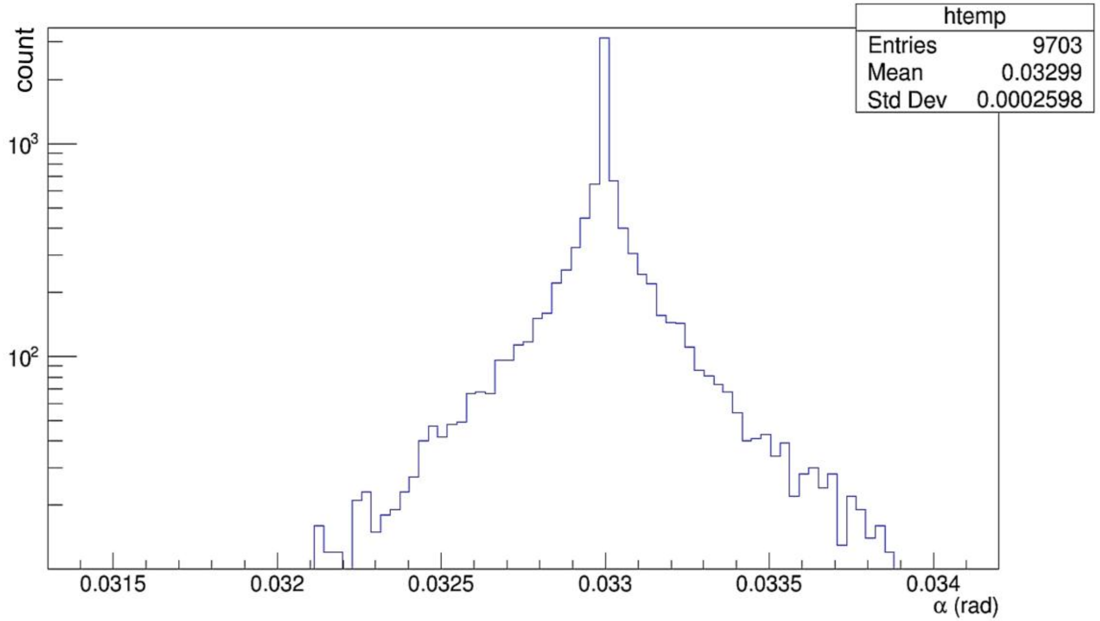
Crossing angle determination from di-muon production at the Z^0 pole, in ~70 pb^{-1} of integrated luminosity.



Standard error gives 260 μrad/$\sqrt{N_{\mu\mu}}$
10^6 events takes ~10min