Integrated luminosity measurement at CEPC

I. Smiljanić[a]

I. Božović-Jelisavčić[a], G. Kačarević[a], N. Vukašinović[a], T. Agatonović-Jovin[a], G. Milutinović-Dumbelović[a], J. Stevanović[b], M. Radulović[b]

On behalf of the CEPC Collaboration

[a]*Vinča Institute of Nuclear Sciences - National Institute of the Republic of Serbia, University of Belgrade, Belgrade, Serbia*

[b]*Department of Physics, Faculty of Science, Kragujevac University, Kragujevac, Serbia*

Overview

- Reminder on luminosity measurement as a counting experiment
- MDI layout (see Haoyu Shi's talk in MDI session)
- Luminometer at CEPC
- Systematics in luminosity measurement at CEPC
  - Effects from mechanical uncertainties and MDI
  - Data-driven correction of the uncertainty of the effective center-of-mass energy
  - Discussion on EMD
  - Physics processes as background to the Bhabha count
- Summary

Reminder on luminosity measurement as a counting experiment

- Integrated luminosity measurement based on Bhabha scattering is a counting experiment

$$\mathcal{L} = \frac{N_{Bh}}{\sigma}$$

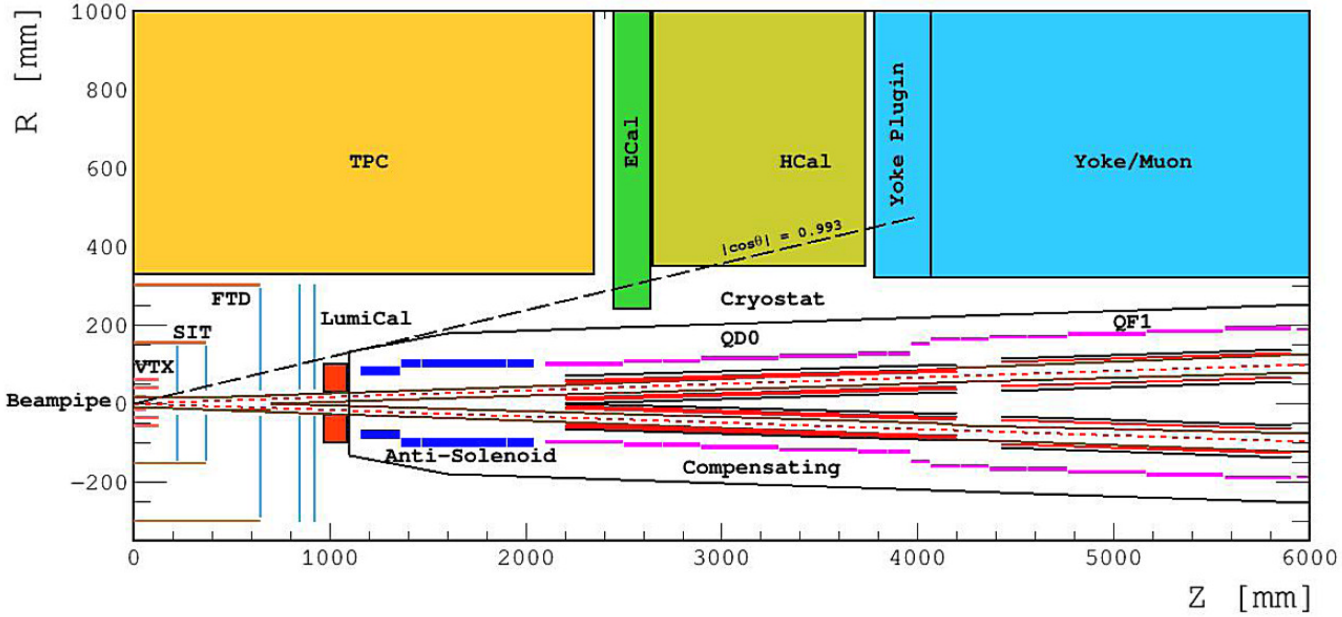
- N_{Bh} is Bhabha count in the certain phase space of physics parameters including the detector acceptance (fiducial) region
- σ is the theoretical cross-section in the same geometrical and phase space
- Both N_{Bh} and σ have to be known at the luminosity uncertainty level ($10^{-3(\text{or } -4)}$)

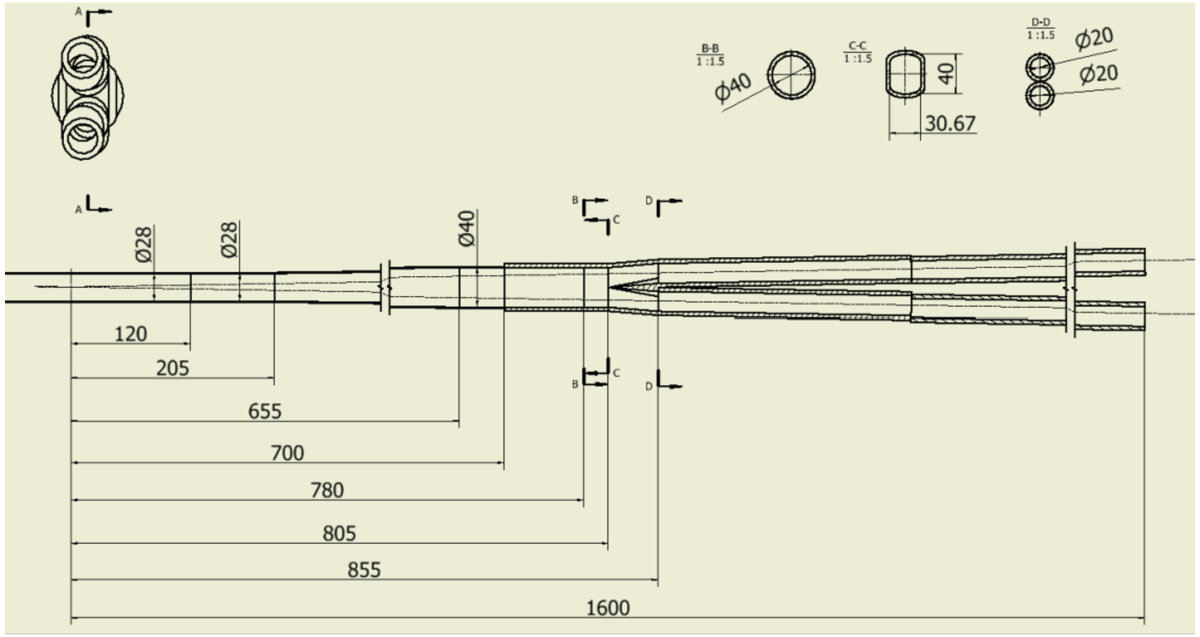
In experiment, $N_{Bh} \rightarrow N_X$

- N_x, effected by miscounts due to various effects:
  - detector resolution
  - mechanics (positioning and alignment) ✓
  - center-of-mass energy, beam synchronization, IP displacements ✓
  - physics background ✓
  - beam–induced processes (EMD) ✓
  - off-momentum electrons (addressed in the [CEPC CDR])

To correct for it (recover N_{Bh}) implies that effects have to be known at $10^{-3(\text{or } -4)}$ level

MDI layout and IR design





Revised beampipe design

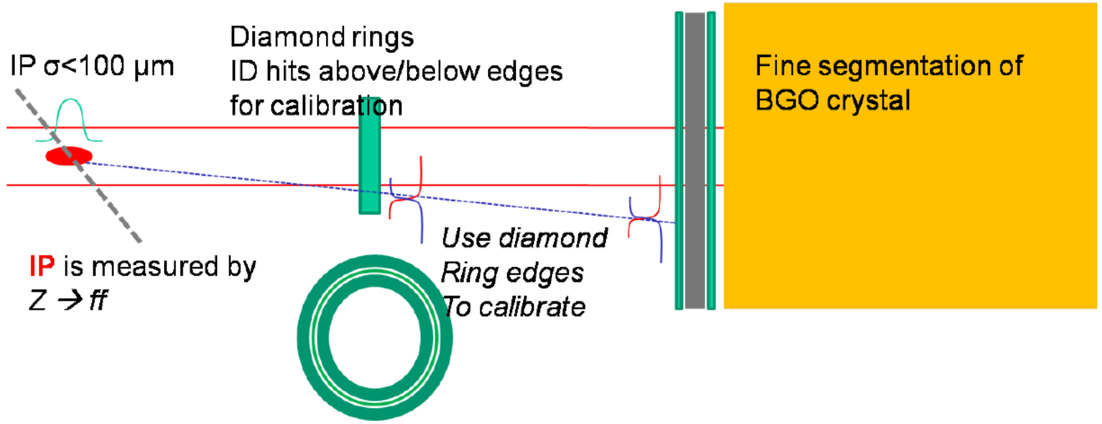
- The Machine Detector Interface(MDI) of CEPC is about 6m long from the IP.
- The accelerator components inside the detector without shielding are within a conical space with an opening angle of arccos 0.993.
- The two beams collide at the IP with a crossing angle of 33 mrad in horizontal plane, and the final focus length is 2.2m
- Lumical will be installed in longitudinal 0.95-1.11 m, with inner radius 28.5 mm and outer radius 100 mm.

[Haoyu Shi, Status on CEPC MDI IR design]

Luminometer at CEPC

- Luminometer technology options are open
- Coarse segmentation, compact electronics, search feasible readout chips
- Performance in terms **of energy and polar angle measurement** will play a key role in the control of systematics.

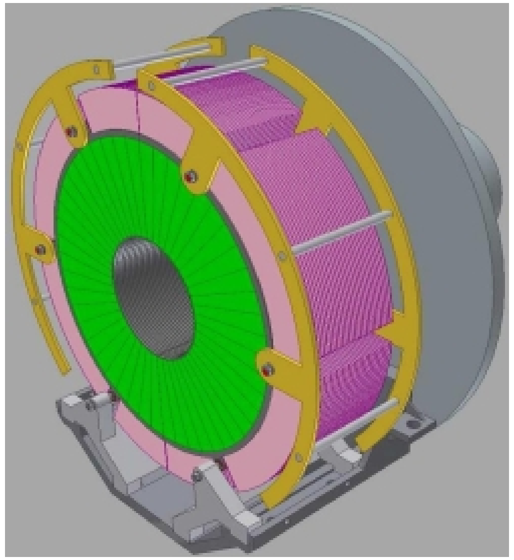
- **Si-W 'ILC-like' – used in our studies**
- BGO (bunch spacing of 25 ns is an issue at Z^0 pole CEPC);
- Lutetium Yttrium Orthosilicate (Lu_2SiO_5:Ce) may works in a CMS-like shashlik type of calorimeter
- SciFi spaghetti calorimeter with individually read-out fibers (prototyped for J-PARC K_L experiment)

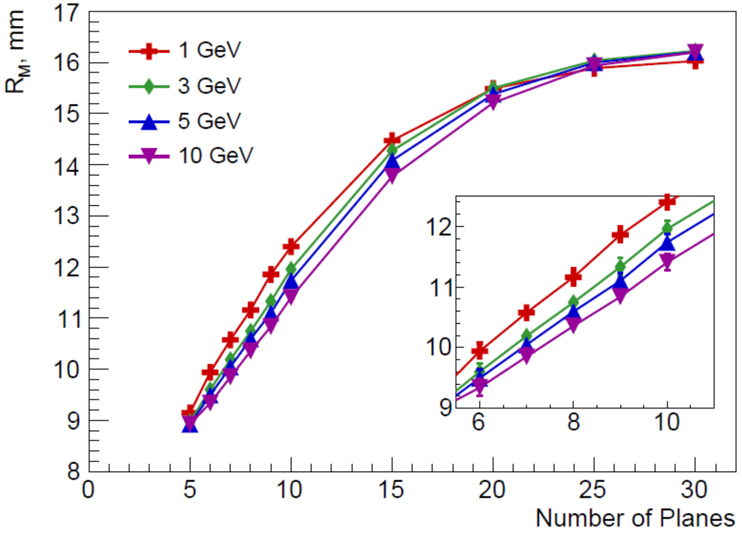


Si or diamond layer in front of the luminometer seems to be a viable option to enable:

- calibration
- e/γ separation
- polar angle measurement with precision equivalent to 1 μm radial uncertainty

[Courtesy: S. Hou]





arXiv:1812.11426v1 [physics.ins-det]

- Si-W sandwich type of calorimeter, over 20 X_0 (longitudinal, not larger than 10 cm)
- distance from IP: ~100 cm
- polar angle coverage: 26 mrad – 105 mrad
- fiducial volume: 53 mrad – 79 mrad
- Sensors placed in 2 mm air gaps
- Fine Si-pixel segmentation (i.e 48/64 azimuthal/radial)
- Small (effective) Moliere radius (~2 cm)
- -> **Excellent resolution in E and θ**: 20% sampling term, 10^{-3} mrad in θ

Existing and proven technology in a test-beam (FCAL Collaboration) - see FCAL talk by Alina

arXiv:1812.11426v1 [physics.ins-det], Eur.Phys.J. C78 (2018) no.2, 135, arXiv:1411.4431 [physics.ins-det]

Sources of systematic uncertainty in luminosity measurement at CEPC

Goal: relative uncertainty of the integrated luminosity measurement:
~10^{-4} at Z^0 pole and ~10^{-3} at 240 GeV

$$\mathcal{L} = \frac{N_{Bh}}{\sigma}$$

Uncertainty of $\mathcal{L}$:

- Modification of the acceptance region (either directly or through the loss of colinearity of Bhabha events via longitudinal boost)
- Effect on the Bhabha cross-section calculation (modification of the phase space and E_{CM})
- Sensitivity of selection based observables (reconstructed energy, polar and azimuthal angles)

A long list of sources of integrated luminosity systematic uncertainties:

1. Beam related:
- Uncertainty of the average net CM energy
- Uncertainty of the asymmetry in energy of the e^+ and e^- beam
- Uncertainty of the beam energy spread
- IP position displacement and fluctuations w.r.t. the LumiCal, finite beam sizes at the IP

2. Detector related:
- Uncertainty of the LumiCal inner radius
- Positioning of the LumiCal (longitudinal L-R distance)
- Mechanical fluctuations of the LumiCal position w.r.t the IP (vibrations, thermal stress)
- Tilt and twist of the calorimeters
- Uncertainty of the sampling term
- Detector performance: energy and polar angle resolution

3. Physics interactions:
- Bhabha and physics background cross-section (uncertainty of the count)
- Bhabha acolinearity – other sources of the acceptance losses (ISR and FSR, Beamstrahlung)
- Machine-related backgrounds – EMD
- Off-momentum electrons from the beam-gas scattering

Systematic uncertainties from mechanics and MDI

- **Simulation:**
- 10^{-7} Bhabha scattering events generated using BHLUMI Bhabha event generator, at two CEPC center-of-mass energies: 240 GeV and Z^0 production threshold
- The effective Bhabha cross-section in fiducial volume is of order of a few nb
- Final state particles are accepted in the polar angle range from 45 mrad to 85 mrad that is slightly wider than the fiducial volume, to allow events with non-collinear FSR to contribute
- Close-by particles are summed up to imitate cluster merging
- We assumed that the shower leakage from the luminometer is negligible

- **Event selection:**
- asymmetric in polar angle acceptance on the left and right arm of the detector (like at OPAL) - at one side we consider the full fiducial volume, while at the other side we shrink the radial acceptance for Δr; this has been done subsequently to the left (L) and right (R) side of the luminometer, event by event
- high-energy electrons carry more than 50% of the available beam energy

Systematic uncertainties from mechanics and MDI

Considered detector-related uncertainties arising from manufacturing, positioning and alignment:

- uncertainty of the luminometer inner radius (Δr_{in}),
- spread of the measured radial shower position w.r.t. to the true impact position on the luminometer front plane (σ_r),
- uncertainty of the longitudinal distance between left and right halves of the luminometer (Δd),
- mechanical fluctuations of the luminometer position with respect to the IP caused by vibrations and thermal stress, radial and axial (σ_{Xip}, σ_{Zip}),
- twist of the calorimeters corresponding to different rotations of the left and right detector axis with respect to the outgoing beam ($\Delta\varphi$)

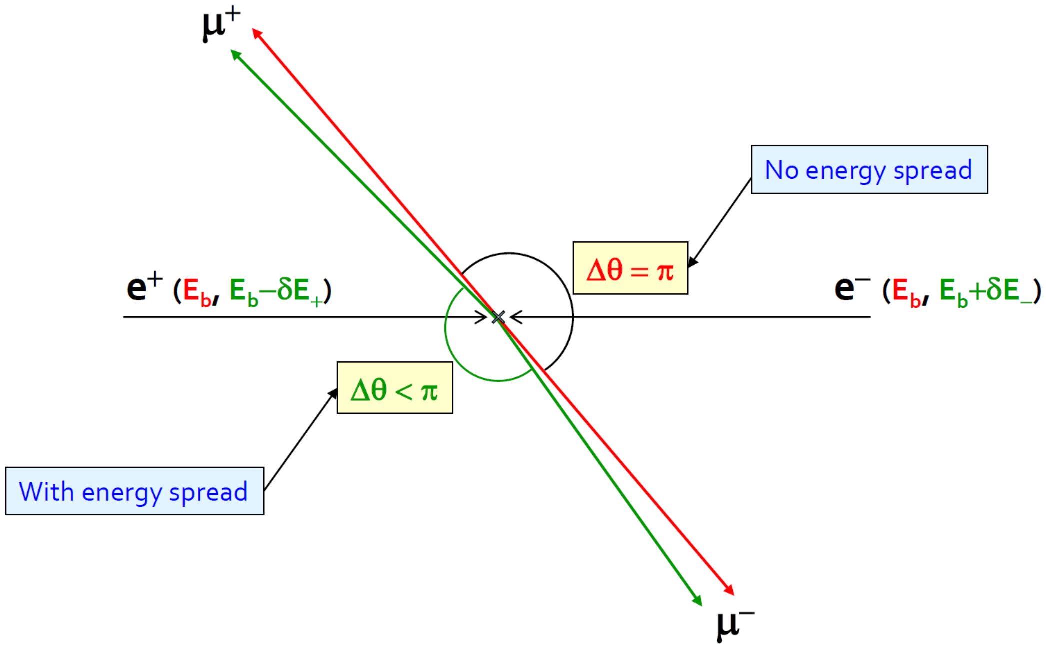
Considered MDI related effects:

- uncertainty of the average net center-of-mass energy (ΔE_{CM}),
- uncertainty of the asymmetry in energy of the e^+ and e^- beams, ($|E_{e+}-E_{e-}|$),
- IP position displacements with respect to the luminometer, radial and axial (Δx_{IP}, Δz_{IP}), caused by the finite beam transverse sizes and beam synchronization, respectively.

parameter	limit@240 GeV $\Delta L/L=10^{-3}$	limit@91 GeV $\Delta L/L=10^{-4}$
ΔE_{CM} (MeV)	120	5
$\lvert E_{e+}-E_{e-}\rvert$ (MeV)	240	11
Δx_{IP} (mm)	1.0	0.5
Δz_{IP} (mm)	10.0	2.0
beam synch. (ps)	15	3
Δr_{in} (μm)	10	1
σ_r (mm)	1.00	0.20
Δd (mm)	1.00	0.08
σ_{Xip} (mm)	1.0	0.5
σ_{Zip} (mm)	10	7
$\Delta\varphi$ (mrad)	6.0	0.8

Main systematic effects are coming from the uncertainty of the luminometer inner radius and the effective center-of-mass energy

Systematic uncertainty from the uncertainty of effective center-of-mass energy



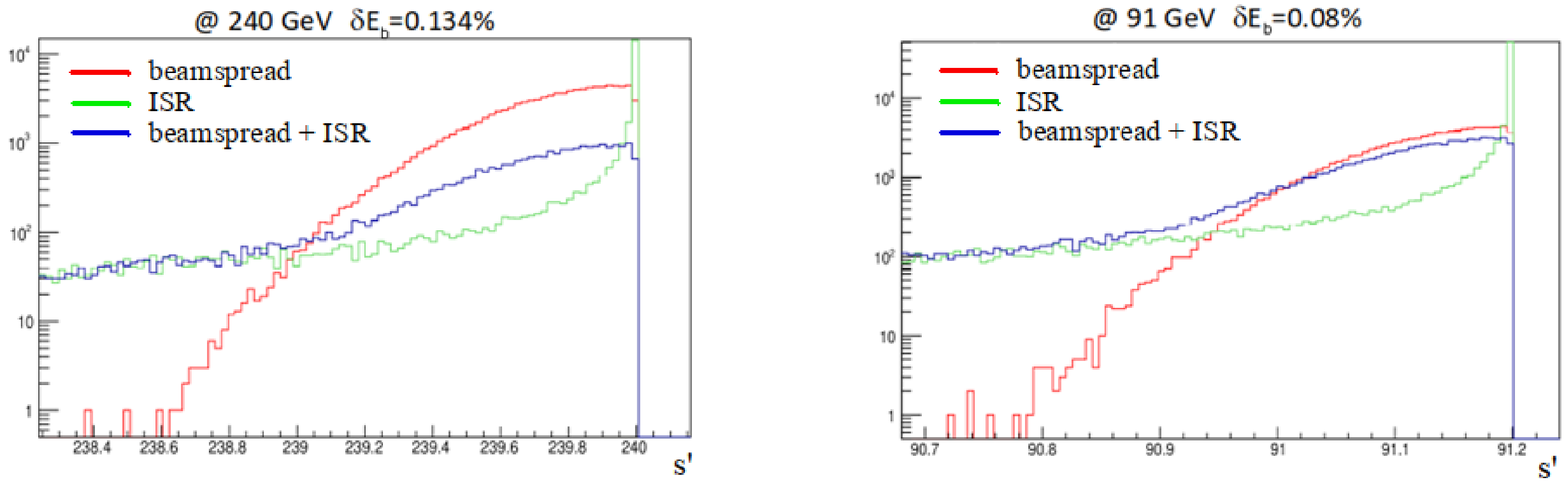
[P. Janot, Beam Energy Spread Measurement @ FCC-ee]

- CEPC CDR: beam-energy spread will not exceed 0.134% of the E_{beam} @240 GeV and 0.08% of the E_{beam} @ 91.2 GeV
- Non-zero beam-spread will result in accolinearity of final state muons produced in $e^{+}e^{-} \rightarrow \mu^{+}\mu^{-}$
- CEPC: muon polar angle resolution over the whole tracking volume foreseen be 0.1 mrad, which corresponds to 100 μm position resolution in TPC
- The effective center-of-mass energy s' can be calculated from the reconstructed muons' polar angles from the TPC:

$$\frac{s'}{s} = \frac{sin\theta^{+} + sin\theta^{-} - |sin(\theta^{+} + \theta^{-})|}{sin\theta^{+} + sin\theta^{-} + |sin(\theta^{+} + \theta^{-})|}$$

Systematic uncertainty from the uncertainty of effective center-of-mass energy

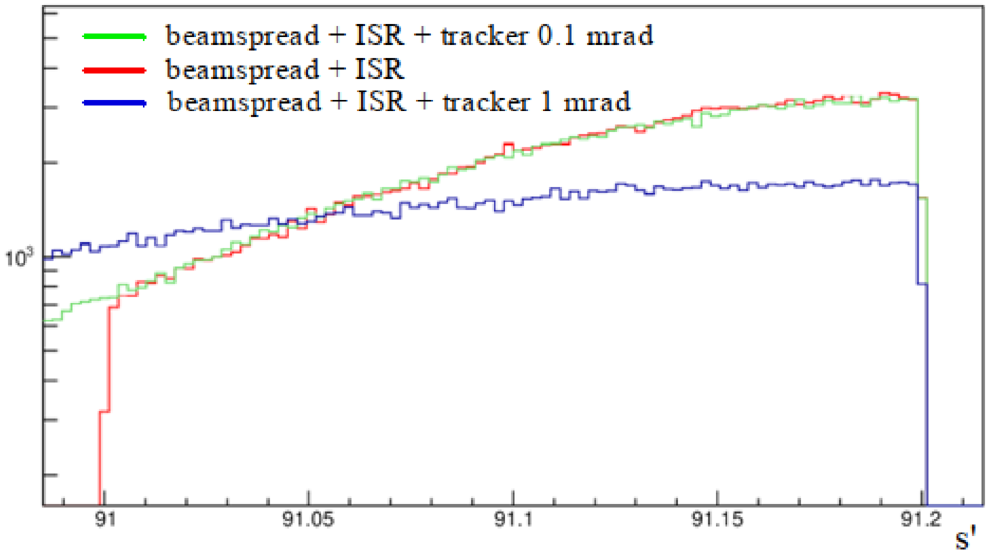
- In WHIZARD 2.6.2 we generated between 100K and 250K $e^+e^- \rightarrow \mu^+\mu^-$ events at 91.2 GeV and 240 GeV, in polar angle range 8°- 172°, which is the angular acceptance of the TPC at CEPC
- Events are generated without any additional effects, in order to study individual effects of ISR, beamstrahlung and muon angular resolution competing with the beam-spread
- Detector energy resolution is simulated by performing Gaussian smearing of the muons' polar angles in case of a few different central tracker reconstruction capabilities



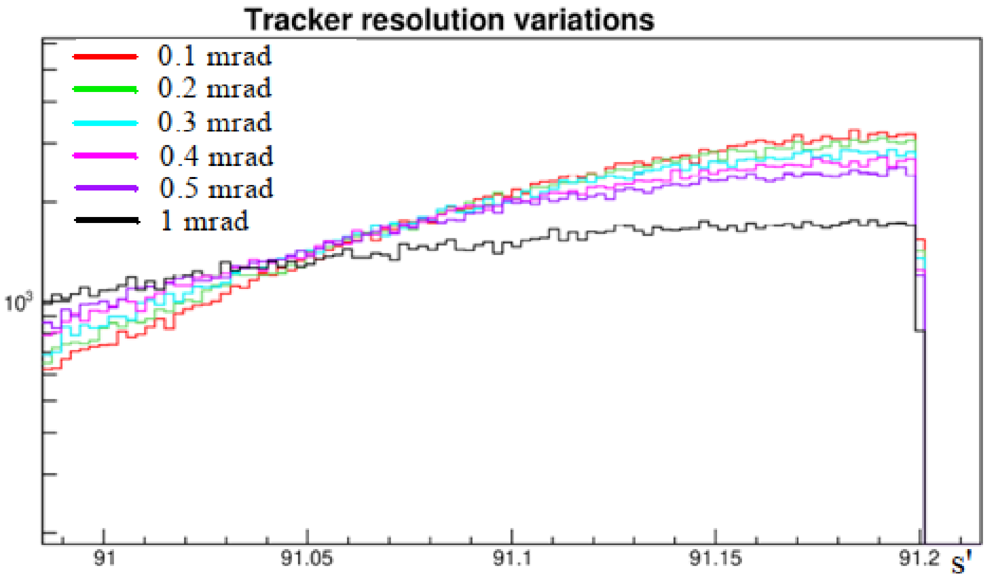
s' distribution in the presence of ISR and the beam-spread

- Tracker (muon polar angle) resolution is not considered
- At both energies the beam-spread dominates the s' shape at energies close to the nominal center-of-mass energy
- In order to rely on this method, excellent theoretical description of ISR effect is required

Systematic uncertainty from the uncertainty of effective center-of-mass energy



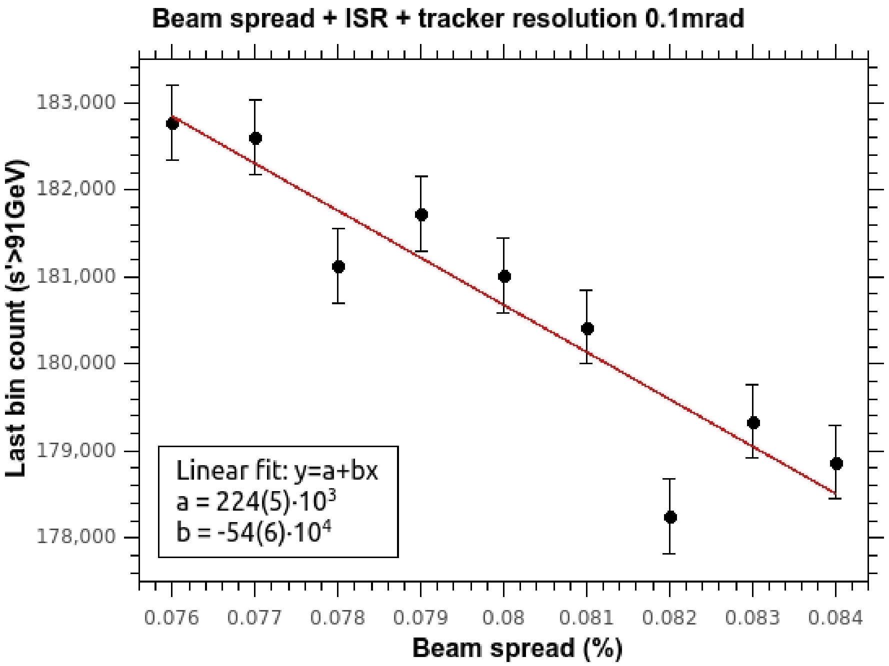
s' sensitivity to 0.1 mrad and 1 mrad tracker resolutions at 91.2 GeV



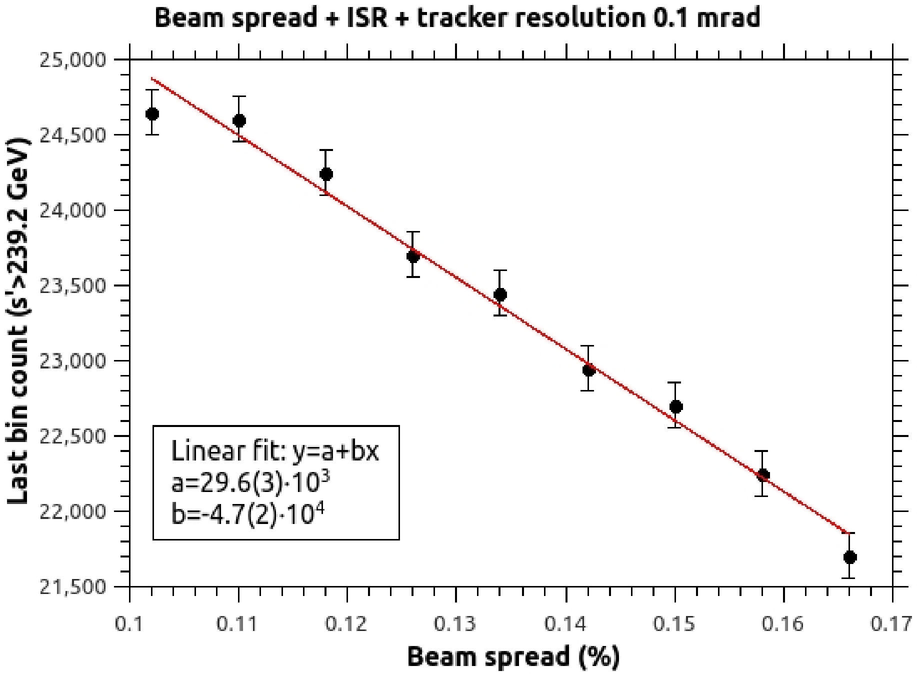
s' sensitivity to the different tracker resolutions at 91.2 GeV

- Foreseen 0.1 mrad central tracker resolution of muons' θ reconstruction does not affect the s' distribution at the Z-pole
- The same stands for 240 GeV

Systematic uncertainty from the uncertainty of effective center-of-mass energy



Most energetic muons count dependence on the beam-spread @ Z^0 pole



Most energetic muons count dependence on the beam-spread @240 GeV

- The effective beam-spread can be determined from the count of the top-part of the s' distribution
- Increase of the beam-spread leads to increase of acolinearity of outgoing muons, and the corresponding reduction of the center-of-mass energy available for a collision
- The muon count dependence on the beam-spread can be fitted using a simple linear fit where statistical uncertainty of the muon count corresponds to the uncertainty of the beam-spread (effective center of mass determination)

Systematic uncertainty from the uncertainty of effective center-of-mass energy

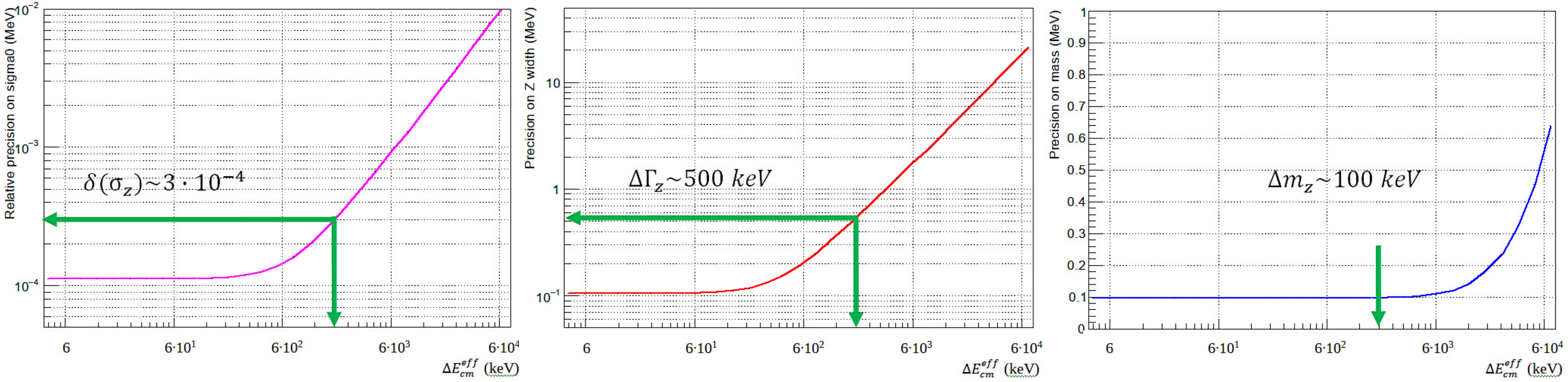
CEPC	Luminosity @ IP (cm^{-2} s^{-1}) CDR/post-CDR	Nominal beam-spread δE_b (%)	Number of events	σ $e^+e^- \rightarrow \mu^+\mu^-$	Collecting time (approximate)	Beam-spread variation (δE_b)	s' uncertainty (MeV)
Z^0 pole	$3.2\cdot10^{35}/1.02\cdot10^{36}$	0.080	250 kEvt.	1.5 nb	9 min/3 min	$1.4\cdot10^{-2}\cdot\delta E_b$	1.8
					3 min/<1 min for 10^{-4} of ΔL/L	$7.0\cdot10^{-2}\cdot\delta E_b$	5
240 GeV	$3.0\cdot10^{34}/5.2\cdot10^{34}$	0.134	100 kEvt.	4.1 pb	9.4 days/5.2 days	$4.7\cdot10^{-2}\cdot\delta E_b$	15
					1.2 days/16h for 10^{-3} of ΔL/L	$37.6\cdot10^{-2}\cdot\delta E_b$	120

- With a statistics of 250K events at Z^0 pole and 100K events at 240 GeV, relative variations of the nominal beam-spread of 2.5% (1.5%) can be measured, respectively
- For such relative precision in determination of the effective beam-spread, only ~3 minutes of collecting the most energetic muons are needed at the Z^0 pole which corresponds to the uncertainty of the effective center-of-mass energy of 1.8 MeV

To control the relative uncertainty of the integrated luminosity at the level of 10^{-4} , less than 1 minute of collecting muons are needed at the Z^0 pole

Systematic uncertainty from the uncertainty of effective center-of-mass energy

Impact of *s'* precision on other EW observables at CEPC

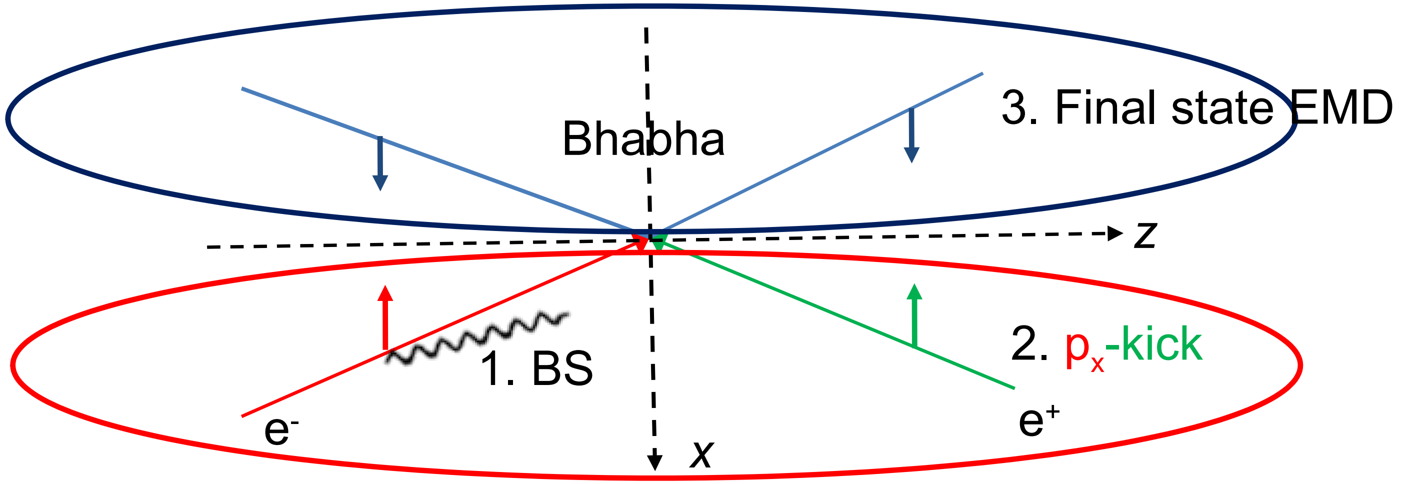


General facts

- Interaction of beams happens prior to the physics interaction at the IP (1 and 2) and final state particles may interact with incoming beam (3)
- 1. EM field of the incoming bunch of the opposite charge induces radiation (*Beamstrahlung*) of the **initial state**
- 2. EM field of the outgoing (opposite-charged) beam impacts the **initial state** leading to effective reduction of the crossing angle (p_x kick)
- 3. Similar deflection affects the Bhabha **final state** by the EM field of the incoming bunches

We are going to discuss 2 and touch 3.

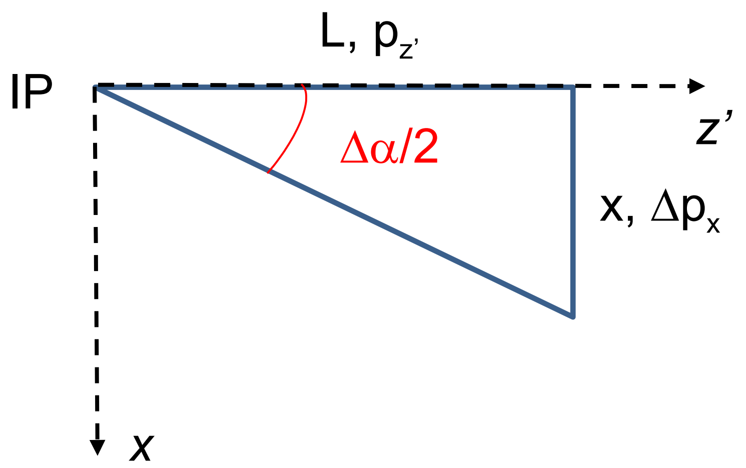
- Both 2 and 3 contribute to *Electromagnetic deflection (EMD)* effect in luminosity measurement

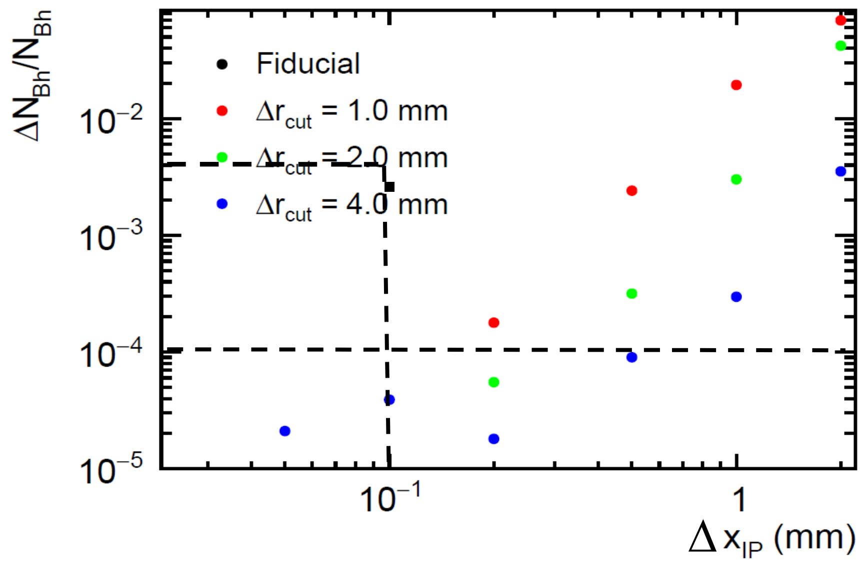


What is the impact of the initial state p_x kick ($2\cdot\Delta p_x$) on integrated luminosity measurement?

- Knowing that Δp_x is equivalent to $\Delta\alpha/2$, we can describe the p_x kick of the initial state as the effective shift (x) of the luminometer along the (-x)-axis, positioned at the distance L from the IP, **along the outgoing beam-pipe z'**
- From the relations between the sides of the triangle if follows: $x=L\cdot(\Delta p_x/p_{z'}) = L\cdot tg(\Delta\alpha/2)$
- Assuming that $p_{z'}\approx E_{beam}$ and L=0.95m, for $(2\cdot\Delta p_x)$:5-10 MeV at Z-pole CEPC

With detector is at the outgoing beam, asymmetric selection can be tuned to keep luminosity insensitive ($\Delta L/L \approx 10^{-4}$) to the x-shift almost up to 1 mm

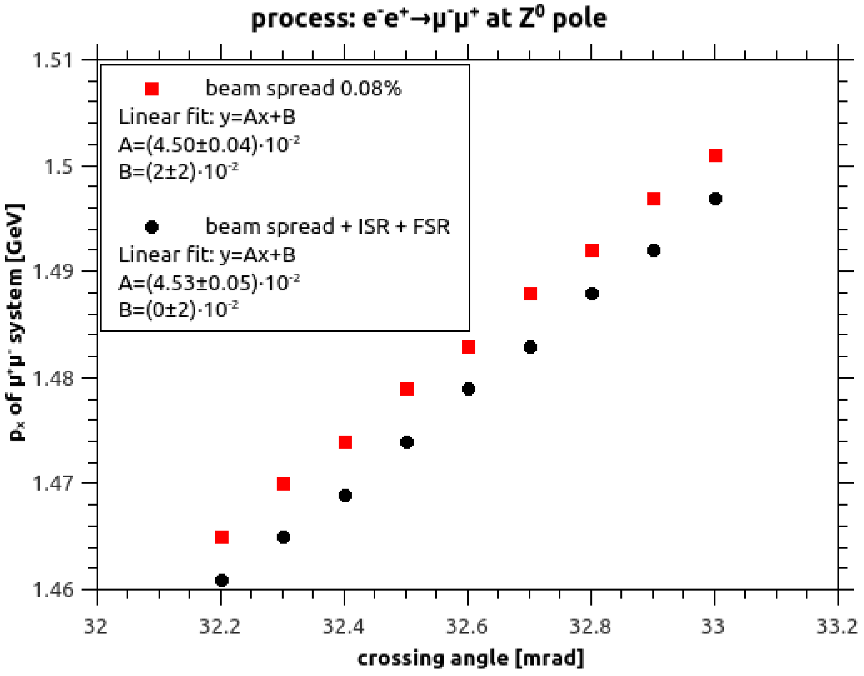


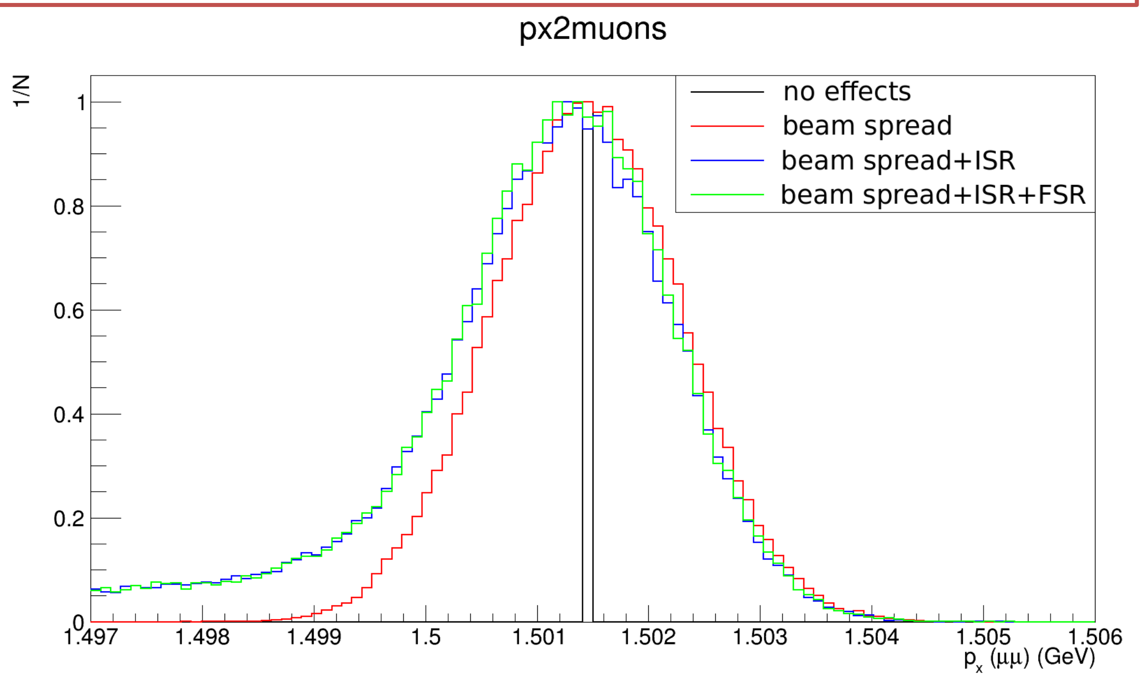


Discussion on electromagnetic deflection (EMD)

Can we measure the effective x-angle from the p_x kick?

- 10^5 simulated di-muon events (1 min of integrated L at Z^0 pole – post CDR design),
- TPC acceptance $|\cos\theta|<0.78$, $\Delta p_t/p_t^2 \sim 10^{-5}$
- Detector resolution contributes insignificantly (10s of keV) to the p_x width.
- Beam-spread and ISR widen the p_x distribution
- p_x mean remains linearly proportional to the effective crossing angle (calibration plot)
- Effective crossing angle can be measured with 1% uncertainty





Discussion on electromagnetic deflection (EMD)

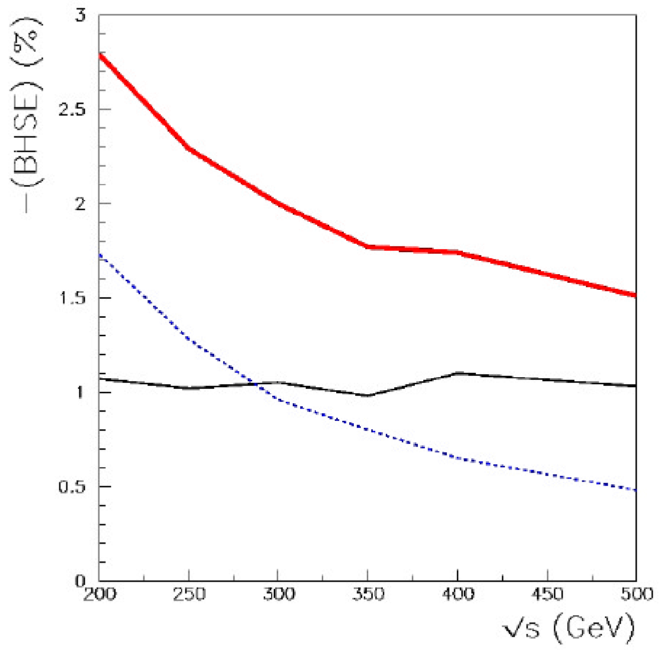
What about EMD of the final state?

1. We can talk about the overall focusing effect on the final state that will include p_x kick + final state EMD
2. The net effect will be effective shift of the luminometer along –x axis for $\Delta\theta_{EMD}$
3. The count will become asymmetric for different φ
4. 2. and 3. can be exploited to define observable(s) describing the effect

[S. Lukic, et al. , 2013 JINST 8 P08012]
[Y. Voutsinas, 34 FCAL WS, CERN, 2019]

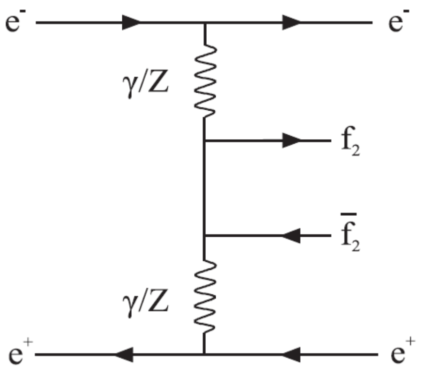
With detector is at the outgoing beam, asymmetric selection can be tuned to keep luminosity insensitive ($\Delta L/L \approx 10^{-4}$) to the x-shift almost up to 1 mm

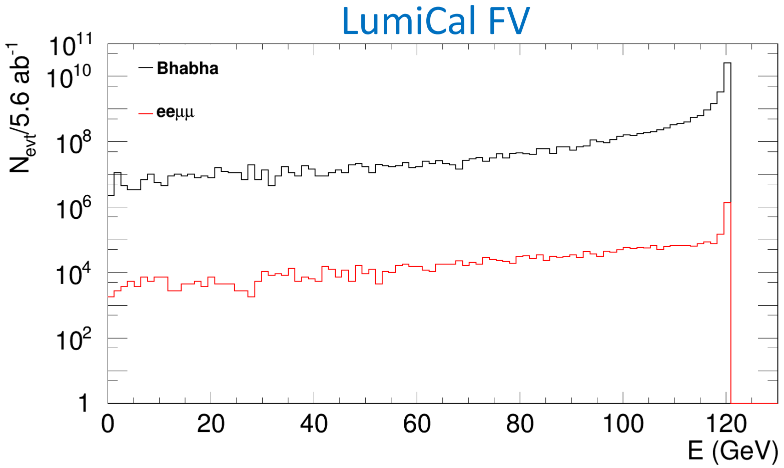
The effect is smaller at larger center-of-mass energies (i.e. for the CLIC beam we have estimated $\Delta\theta_{EMD}$ to be 43 μrad @ 500 GeV and 20 μrad @ 1 TeV [JINST 8 P08012, 2013], at FCCee Z^0 it amounts up to 150 μrad [arXiv:1908.01698v3 [hep-ex]]



Bhabha suppression due to beamstrahlung (black line) and electromagnetic deflections (blue line), as well as the combined effect (red line) [2007 JINST 2 P09001]

2-photon processes



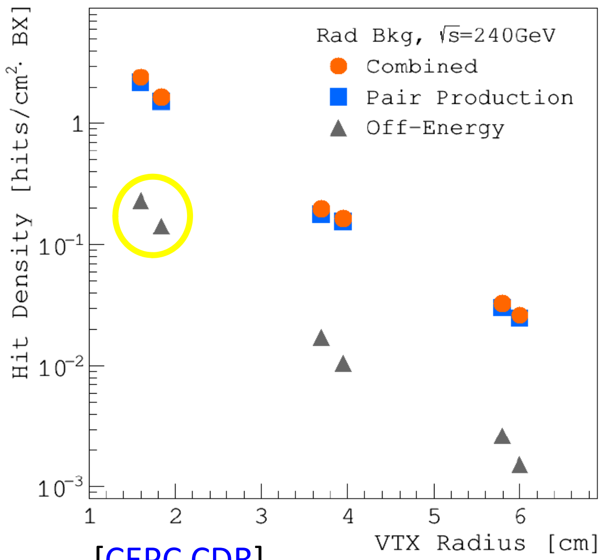


- Multiiperipheral process ~nb x-section
- High energy e- spectators can fake the signal
- Most of spectators go below luminometer acceptance
- Initial contamination (without any selection) of the detector volume is ~10^{-4} w.r.t. the signal at 240 GeV CEPC
- With the relative energy $(E_1+E_2)/2E_{beam}=E_{rel}>0.8$, B/S ratio is ~$8\cdot10^5$
- Even smaller at the Z^0-pole since 2-photon x-section is scaling like $\ln^2(s)$

Off-momentum particles

- Can influence luminosity measurement by accidental overlapping to the Bhabha signal in both detector halves that happens at the same rate as the signal.
- Off-momentum particles from beam-gas interaction were the main source of systematics in luminosity measurement at LEP (0.1-0.6)·10^{-4} [arXiv:hep-ex/9910066v2]. Nicely regulated by the (relative) energy cut.

CEPC simulations shows that proper size collimators can be employed to suppress off-momentum particles in the first VTX detector layer to 0.22 hits/cm2 per BX



[CEPC CDR]

240 GeV CEPC: first VTX layer- 2.4 particle/cm² per BX

Discussion and summary

- Several sources of the systematic uncertainty in integrated luminosity determination have been studied at CEPC (Z^0-pole and 240 GeV)
- The uncertainty of the luminometer inner radius at the micron level together with the uncertainty of the available center-of-mass energy are posing the most challenging requirements
- The method of experimental determination of the effective center-of-mass energy based on di-muon production at Z^0-pole CEPC, enables luminosity precision of 10^{-4} after less than 1 min of data taking
- At 240 GeV, 10^{-3} precision goal on integrated luminosity requires 16 hours of data taking, due to significantly smaller x-section for di-muon production
- Changes of the nominal crossing angle due to the EMD (p_x-kick and EMD of the Bhabha final state) can be relaxed with the asymmetric selection in polar angle (LEP-style) in integrated luminosity measurement
- Effective crossing angle can be determined with 1% relative uncertainty for < 1 min of collecting di-muon events at the Z^0-pole, in a semi-dependent way from the simulation
- Physics processes (2-photon and off-momentum background) can be suppressed with the cut on relative energy

Thanks for your attention!

Backup

MDI parameters

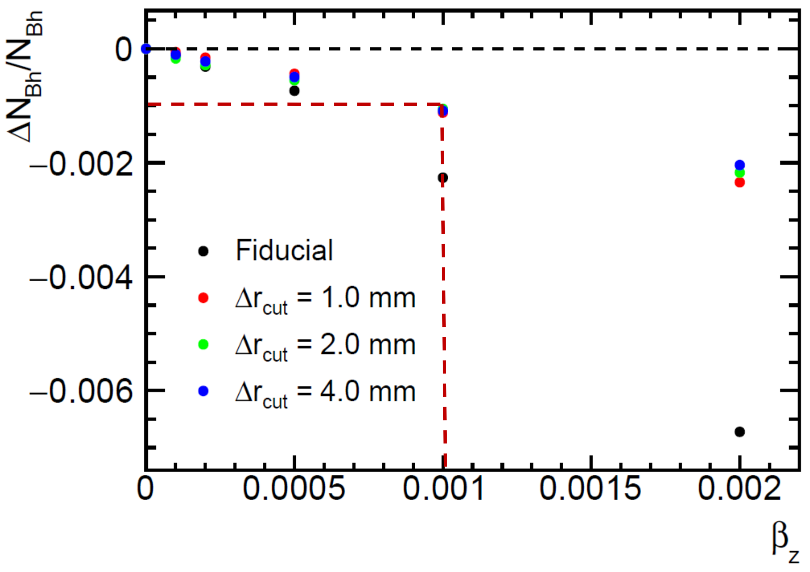
	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	**0.36/0.0015**	**0.36/0.0015**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L (10^{34}cm^{-2}s^{-1})	**2.93**	**10.1**	**16.6**	**32.1**

CEPC parameters from CDR

[Haoyu Shi, Status on CEPC MDI IR design]

Uncertainty of the beam-asymmetry

- CEPC CDR: beam-energy spread will not exceed 0.134% of the E_{beam} @240 GeV and 0.08% of the E_{beam} @ 91.2 GeV
- Difference in energy of colliding particles can be as large as 322 MeV @240 GeV and up to 73 MeV @ Z^0-pole
- Uncertainty of count of 10^{-4} implies knowledge of the asymmetry in beam energies at the level of 12.5% of the beam-spread at the Z^0 pole, which is below the natural energy-spread of the beam



- Longitudinal boost of the center-of-mass (CM) frame of colliding particles with respect to the lab frame, β_{coll}
- Leading to the counting loss in luminometer, due to acolinearity of Bhabha final states
- β_{coll} can be determined from the measured polar angles of Bhabha e+, e- in the luminometer or from a di-muon system:

$$\beta_{coll} = \frac{\sin(\theta_1^{lab} + \theta_2^{lab})}{\sin\theta_1^{lab} + \sin\theta_2^{lab}} = \Delta E/\sqrt{s}$$

Determination of electromagnetic deflection of the Bhabha final state

Our method proposed for ILC/CLIC [JINST 8 P08012, 2013]

- $\Delta L/L = x_{EMD} \cdot \Delta\theta_{EMD}$
- Calibrate from experiment (measure slope x_{EMD})
- Determine from $\Delta\theta_{EMD}$ simulation - down-side, but
- $\Delta\theta_{EMD}$ is stable w.r.t. the variation of beam parameters (bunch size variations by ±10 and ±20% of both bunches and one-sided variations by +20%, of bunch charge and dimensions) ⇒ dissipation gives uncertainty of the method