XIV International School 'Actual Problems of Microworld Physics'

Integral luminosity measurement at future e^+e^- colliders - feasibility and challenges

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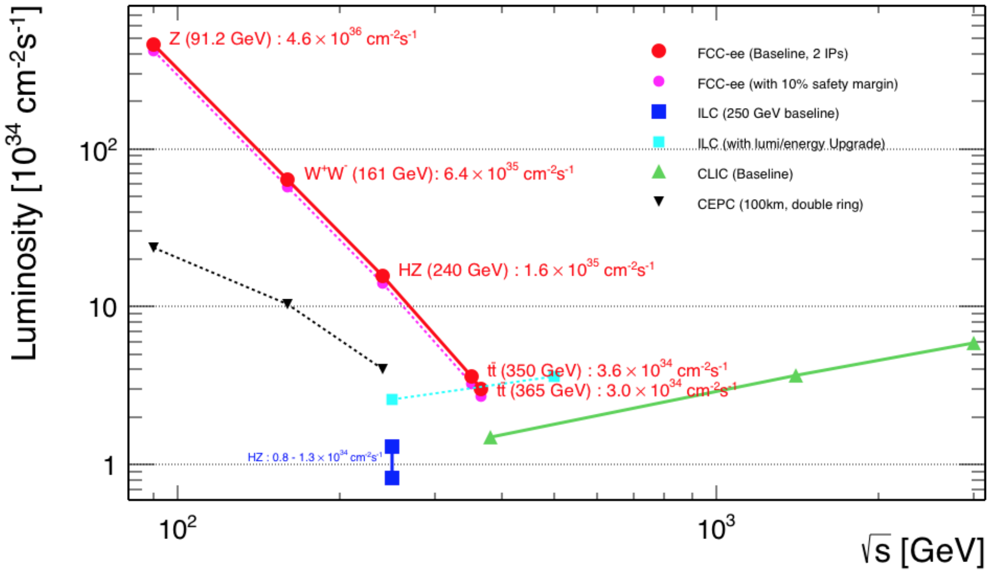

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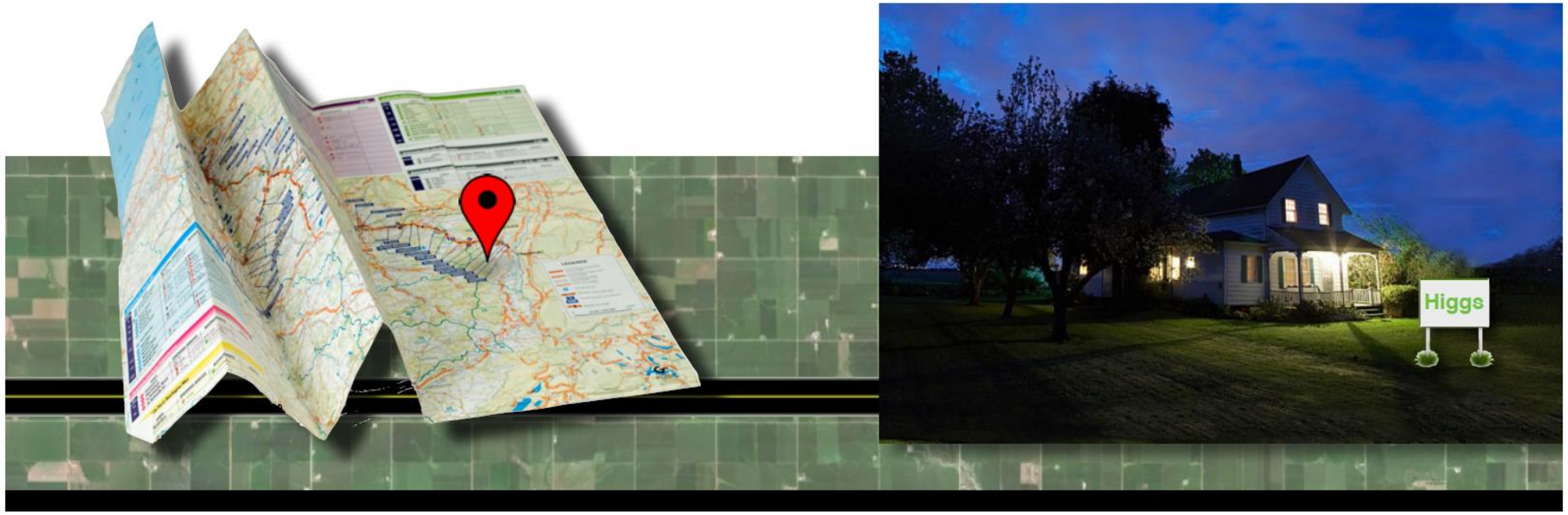
Overview

- Introduction
- Lesson 1: What is the luminosity and why do we need to know it?
- Lesson 2: How do we measure luminosity at e^+e^- colliders?
- Lesson 3: Impact of the beam-induced effects at linear colliders
- Lesson 4: Systematics from the mechanical precision and MDI
- Lesson 5: Feasibility of the luminosity precision goals at future e^+e^- colliders
- Summary and outlook

Introduction

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

IS THIS ALL?



'We have followed an unexpectedly accurate map all the way to the end.'

Credit: F. Simon, ALPS2017

The truth is out there…

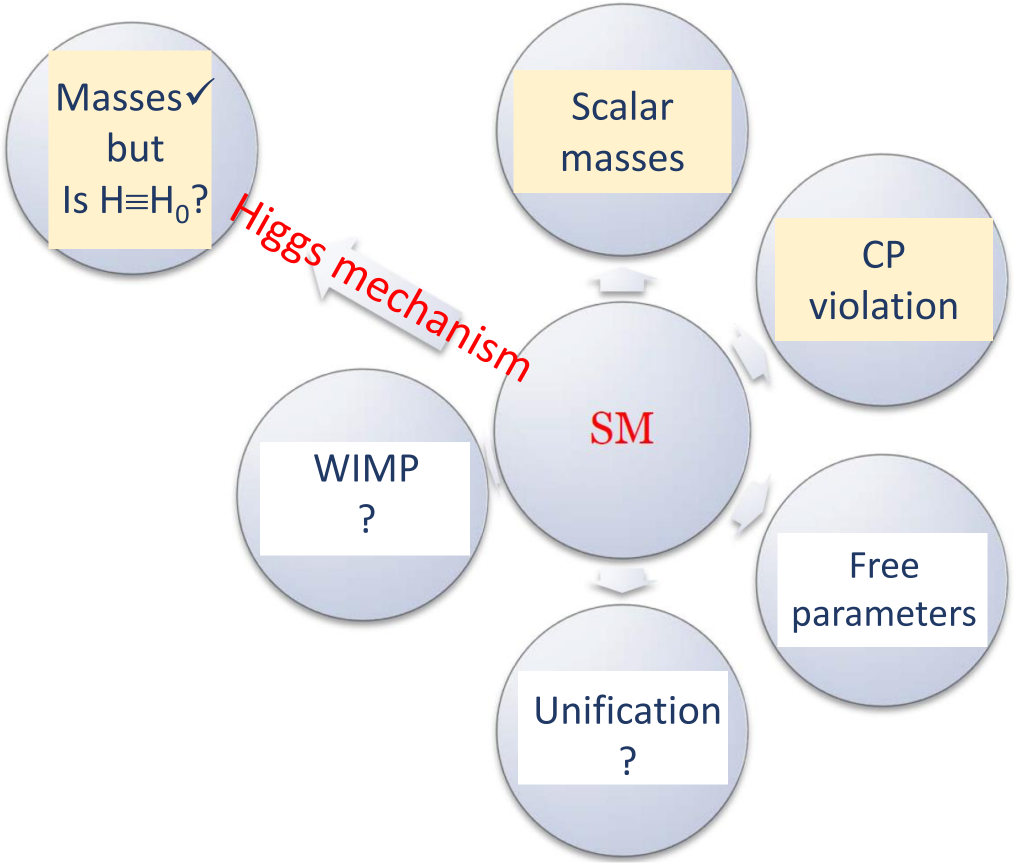
- Standard Model can not accommodate existing open questions
- There must be explanation beyond (BSM)
- BSM can be searched for through direct discoveries (so far none), or indirectly – identifying (small) deviations from the SM

Open questions

- Is the Higgs SM Higgs?
- Quadratic divergence of the Higgs (scalar) mass with the fundamental scale Λ (from one loop ffbar contributions) – hierarchy problem
- CP violation

- Free parameters (19 without neutrino masses) – SM is open
- Unification of fields – larger mathematical structures than SM
- WIMP candidate ….

…. and other cosmology related issues like dark energy, Higgs field contribution to the energy density of the Universe and so on…



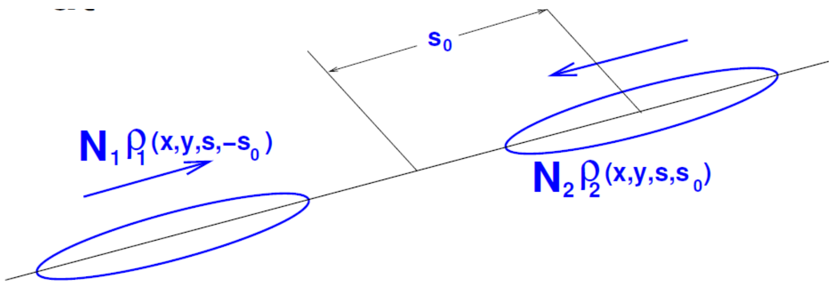
POSIBLE ANSWERS COULD BE MANIFESTED AS ANOMALIES IN THE SM ➡ **PRECISION MEASUREMENTS ARE NEEDED**

What is the luminosity and why do we need to know it?

- (Instantaneous) luminosity determines the statistical potential of a machine to provide us a sufficient event rate ($\frac{dR}{dt}$) of a process of interest (σ_p)

$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma_p$$

- It critically depends on the bunch population and sizes (bunches are very 'empty' – in an LHC bunch, if a proton size would be ~ 5 mm, the neighboring proton would be 65 km apart)



ρ_1 and ρ_2 are time-dependent beam density distribution functions

$$\mathcal{L} \propto K \cdot \iiint_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)dxdydsds_0$$

$K = \sqrt{(\vec{v_1} - \vec{v_2})^2 - (\vec{v_1} \times \vec{v_2})^2/c^2}$ $\quad$ $K \approx 2$ for exactly head-on collision bunches with $v \approx c$

- If density functions are uncorrelated in all planes, they are factorisible to give:

$$\mathcal{L} = 2N_1N_2fN_b \iiiint_{-\infty}^{+\infty} \rho_{1x}(x)\rho_{1y}(y)\rho_{1s}(s-s_0)\rho_{2x}(x)\rho_{2y}(y)\rho_{2s}(s+s_0)\;dxdydsds_0$$

- Analytical calculation of the integral above is not necessarily possible for an arbitrary beam profile
- In case of a Gaussian beam:

$$\mathcal{L} = \frac{N_1N_2fN_b}{4\pi\sigma_x\sigma_y}$$

N_1, N_2 – number of particles in colliding bunces

N_b – number of bunches in a beam

f – revolution frequency (circular machines)

σ_x, σ_y – transverse bunch dimensions

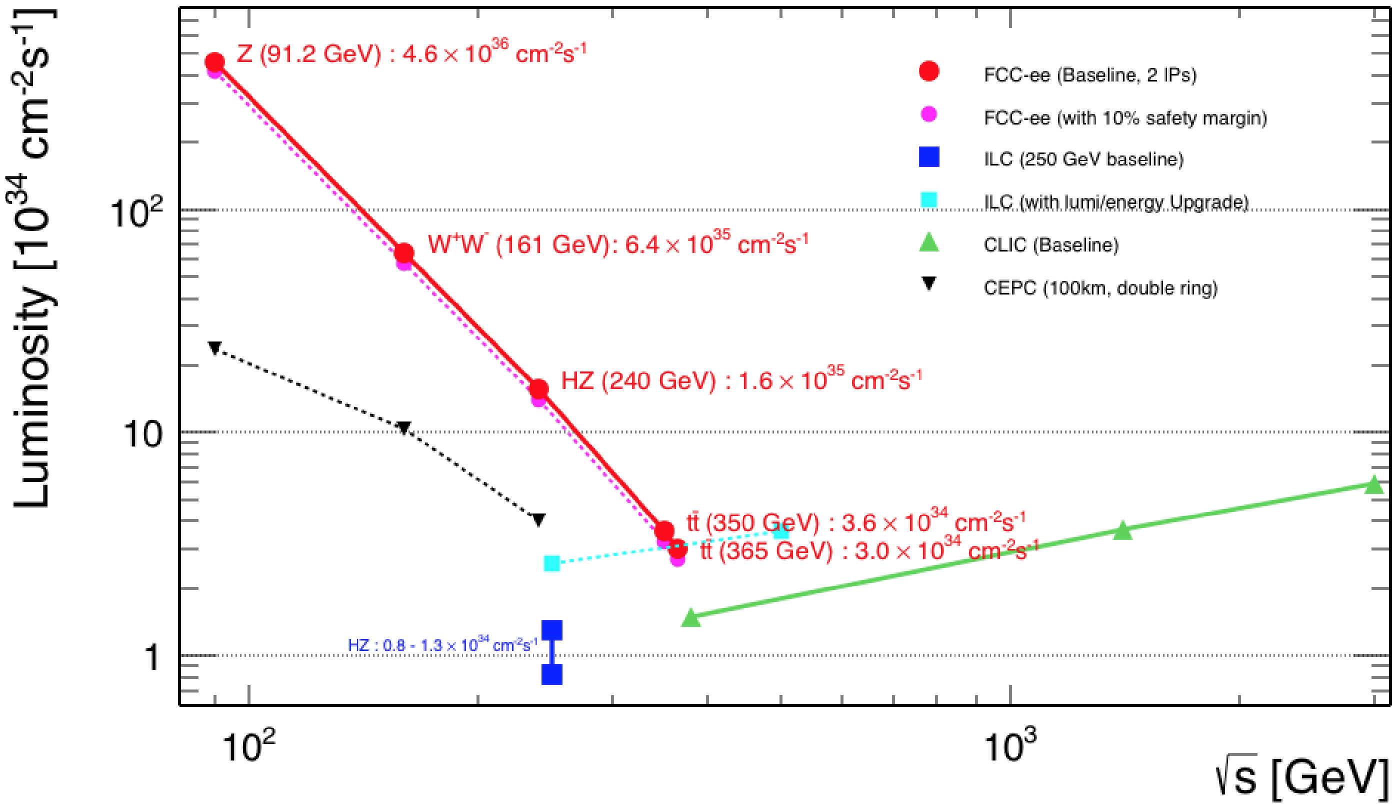
- Note that luminosity doesn’t depend on a bunch length due to the assumption on the uncorrelated beam densities

In reality…
- Crossing angle
- Collision offset
- Hour-glass effect
- Non-Gaussian beam profiles
- Non-zero dispersion at collision point

Apparently, (instantaneous) luminosity is nontrivial to calculate under realistic conditions

	Energy (GeV)	$\mathcal{L}$ $cm^{-2}s^{-1}$	rate s^{-1}	$\sigma x/\sigma_y$ $\mu m/\mu m$	Particles per bunch
SPS ($p\bar{p}$)	315x315	$6\ 10^{30}$	$4\ 10^{5}$	60/30	$\approx 10\ 10^{10}$
Tevatron ($p\bar{p}$)	1000x1000	$50\ 10^{30}$	$4\ 10^{6}$	30/30	$\approx 30/8\ 10^{10}$
HERA (e^+p)	30x920	$40\ 10^{30}$	40	250/50	$\approx 3/7\ 10^{10}$
LHC (pp)	7000x7000	$10000\ 10^{30}$	10^{9}	17/17	$11\ 10^{10}$
LEP (e^+e^-)	105x105	$100\ 10^{30}$	≤ 1	200/2	$\approx 5\ 10^{11}$
PEP (e^+e^-)	9x3	$3000\ 10^{30}$	NA	150/5	$\approx 2/6\ 10^{10}$
KEKB (e^+e^-)	8x3.5	$10000\ 10^{30}$	NA	77/2	$\approx 1.3/1.6\ 10^{10}$
linear (e^+e^-)					
ILC250	250	$7.1\ 10^{37}$		$22/0.5\ 10^{-3}$	$2\ 10^{10}$
CLIC3000	3000	$5.9\ 10^{34}$		$40/1\ 10^{-3}$	$3.7\ 10^{9}$

- Since there is no circulating beam, luminosity of linear colliders is busted by making the bunch more dense (i.e. via smaller transverse sizes)
- The above gives rise to stronger EM fields of the colliding bunches (beam-beam interaction) what is one of the major experimental difficulties in (integral) luminosity measurement at linear e^+e^- colliders (Lesson 3)
- At the other hand, increasing number of particles per bunch at hadron colliders (LHC, HL-LHC) gives rise to a pile-up (200 HL-LHC, up to 1000 interactions/BX at FCCpp)



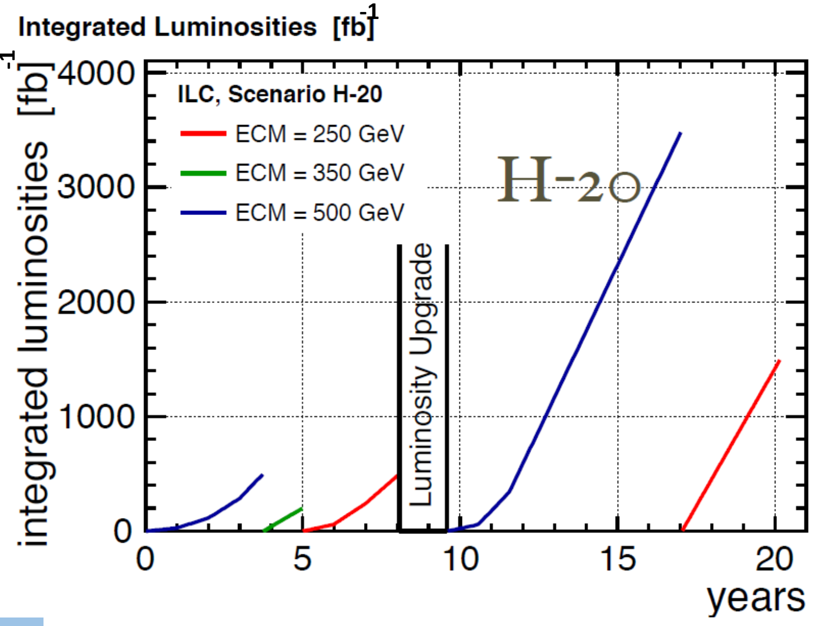
- Absolute luminosity is a clear advantage of a future circular e+e- machines
- While higher center-of-mass energies are achievable with linear colliders due to the absence of synchrotron radiation

Integral luminosity

- The figure of merit determining the number of events of a given process

$$\mathcal{L}_{\text{int}} = \int_0^T \mathcal{L}(t')dt' \qquad \boxed{\mathcal{L}_{\text{int}} \cdot \sigma_p = \text{number of events of interest}}$$

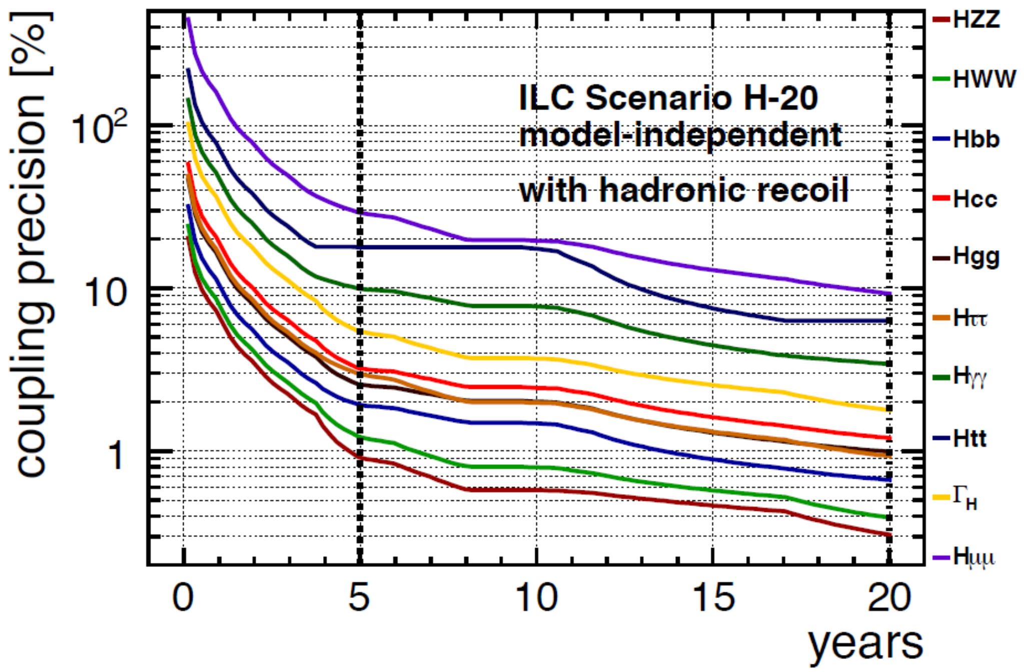
- Essential for any cross-section measurement
- Beam-parameter determination (i.e. bunch by bunch)
- Relative measurement by counting a well known (calculable) process σ_p



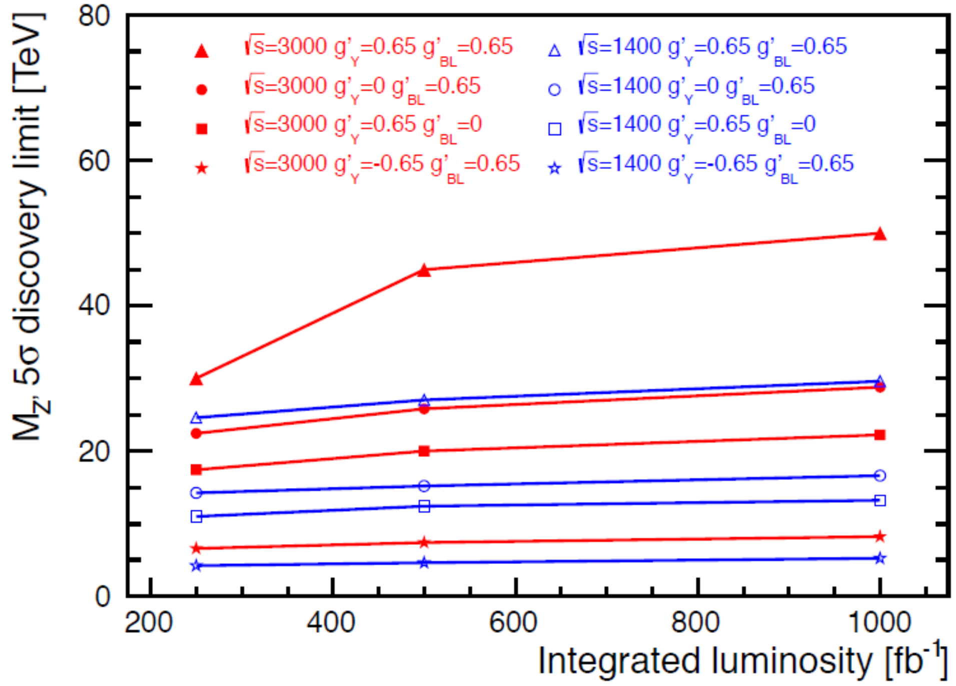
However, counting is nontrivial if you are allowed to be mistaken as 1 in 1000 or 10000

Why do we need luminosity?

ILC 250 GeV



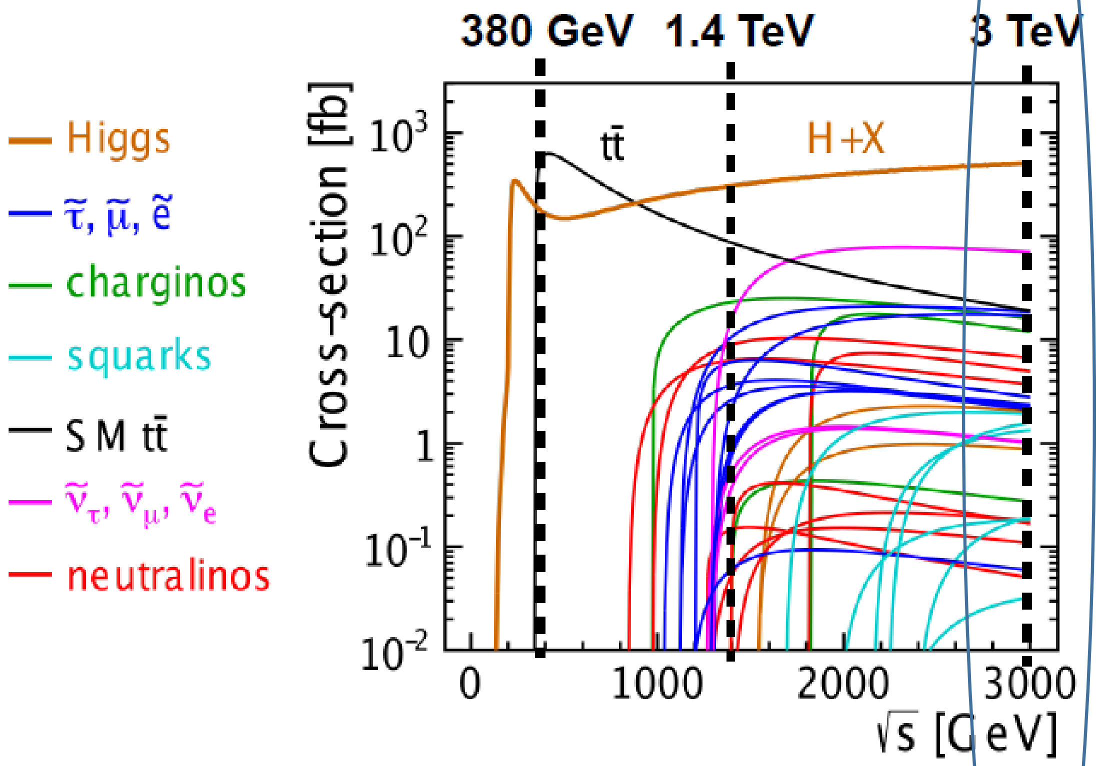
CLIC 3 TeV



Obviously, statistics is needed both for SM and BSM searches

ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• **g**HWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak couplings of the top quark	✔		
• precision **W** couplings	✔	✔	
• precision search for **Z′**	✔		
• search for supersymmetry	✔		
• search for Dark Matter	✔		
• top quark mass from threshold scan		✔	
• precision Higgs mass			✔

CLIC



But, energy also matters…

Where the precision requirements are coming from?

- Usually from the available statistics (systematic uncertainty induced by the luminosity uncertainty should be smaller than the statistical one)

Expected number of events at FCCee

Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	$e^+e^- \rightarrow Z$
WW threshold	E_{cm} : 161 GeV	10^{8}	$e^+e^- \rightarrow WW$
ZH threshold	E_{cm} : 240 GeV	10^{6}	$e^+e^- \rightarrow ZH$
$t\bar{t}$ threshold	E_{cm} : 350 GeV	10^{6}	$e^+e^- \rightarrow t\bar{t}$

Obviously, more (statistically) powerful future collider will push the limit for the integral luminosity precision

Current (integral) luminosity precision goals

Physics cases where 10^{-3} precision should be sufficient:

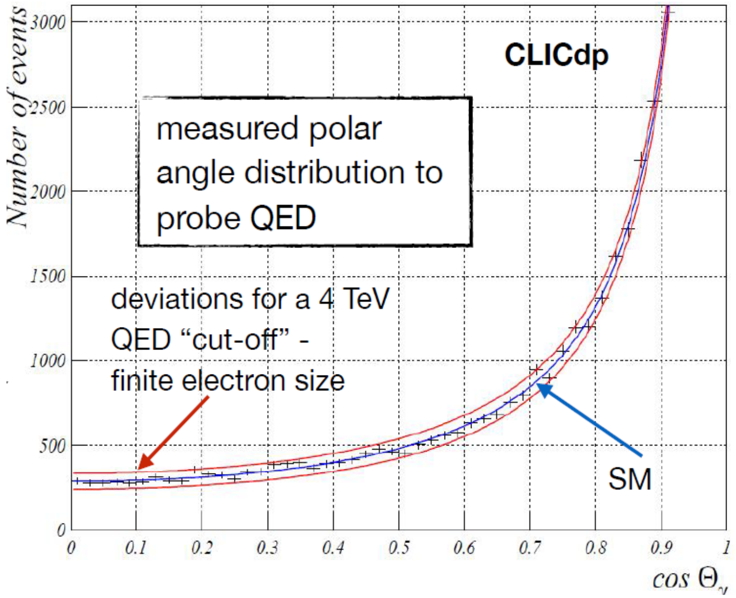
- Precision of the cross-section measurements
- Anomalous TGCs measurement
- Single-photon production with E_{mis} (BSM, dark matter)
- *Di-photon production (various BSM models)*
- Extended theories (Z') at high energies
- Precision EW observables at Z^0 pole

10^{-4} integral luminosity precision requirement:

- Fermion-pair production cross-section (higher order corrections)
- W-pair production cross-section
- Z^0 total hadronic cross-section at Z^0 pole

$e^+e^- \rightarrow \gamma\gamma$

Cross-section and photon angular distribution can be used to restrict various BSM models

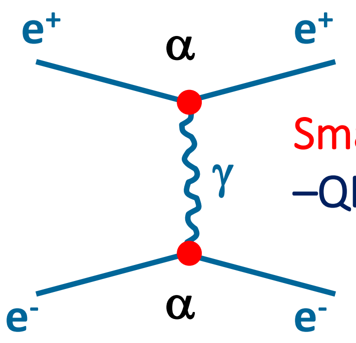


Scenario 2 ab^{-1} 3 TeV CLIC	ΔL = 0.2 %	ΔL = 0.5 %	ΔL = 1 %
QED cut-off (finite electron size) **Λ_{QED} (95% CL)**	6.52 TeV	6.33 TeV	6.01 TeV
Contact interactions **Λ' (95% CL)**	20.7 TeV	20.1 TeV	18.9 TeV
Extra dimensions **$M_S/\lambda^{1/4}$ (95% CL)**	16.3 TeV	15.9 TeV	15.3 TeV
Excited electron **M_{e^*} (95% CL)**	5.03 TeV	4.87 TeV	4.7 TeV

Lesson 1 in brief

- Integral luminosity is a figure of merit of a statistical potential of a collider
- It is nontrivial to calculate and measure it (Lessons 3 and 4) under realistic experimental conditions
- At future e^+e^- colliders integral luminosity will amount to several ab^{-1} to provide the needed statistics for precision physics measurements (both SM and BSM)
- Luminosity precision requirements are driven by physics , but also by a statistical power of future colliders
- Circular colliders are superior in luminosity w.r.t. linear, while linear colliders can provide higher energy reach needed for i.e. Higgs self-coupling determination and BSM searches

How do we measure luminosity at e^+e^- colliders?

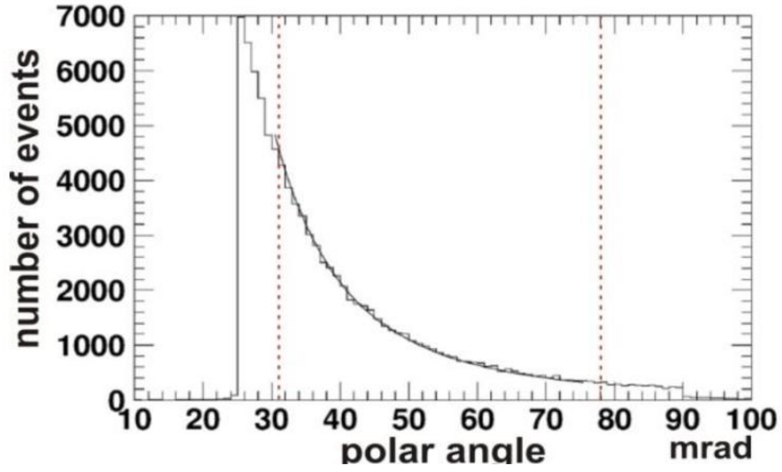


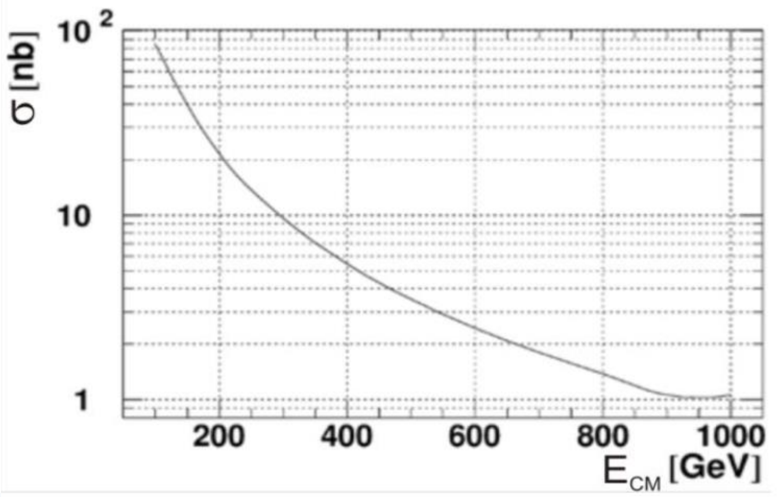
Small angle Bhabha scattering
–QED t-channel γ exchange

- Cross-section known at NNLO
- Z contribution < 1% (i.e. at ILC energies)
- At larger θ (≥10 deg.) s and t-channel interference can not be neglected
- Ideally, two collinear EM showers carrying most of the beam energy (signal to count)
- Differential x-section (to the first order):

$$\frac{d\sigma_{Bhabha}}{d\Omega} = \frac{2\pi\alpha^2}{s} \frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha^2}{s} \frac{1}{\theta^3}$$

- **Uncertainty in the detector aperture leads to the counting uncertainty** (Lesson 4)
- Statistics gets smaller with the rising center-of-mass energy





Cross-section issue

$$\frac{d\sigma}{dt} = \frac{d\sigma^{(0)}}{dt}\left[\frac{\alpha(t)}{\alpha_0}\right]^2 (1+\varepsilon)(1+\delta_\gamma)+\delta_Z$$

- Theoretically well described gauge process
- $\delta(\sigma_{BH})$ =5.4 10^{-4} where 4 10^{-4} comes from the vacuum polarization, at LEP1 and LEP2 energies and polar angles (below 60 mrad)
- A similar precision is needed at energies and in the acceptance region of any future e^+e^- collider

Born term for t-channel single γ exchange

$$\frac{d\sigma^{(0)}}{dt} = \frac{4\pi\alpha_0^2}{t^2}$$

$\alpha_0 \cong 1/137.036$

$$\left(\frac{1}{1-\Delta\alpha(t)}\right)^2$$

Δα-contribution from the vacuum polarization, modifying photon propagator due to a fermion loop

Z interference correction

s-channel γ exchange correction

Photonic radiative corrections

$$\delta_Z\ ,\ \delta_\gamma << \varepsilon$$

- In general, Bhabha cross-section has to be known in the same phase space where the counting is performed
- In addition, collision frame (CM) of particles interacting after emitting ISR (and even more significantly Beamstrahlung) is not the same as the lab frame where events are counted
- $\mathcal{L}_{\text{int}} \cdot \sigma_p = \text{number of events of interest}$ → $L = \dfrac{N(\Xi(\Omega_{1,2}^{lab}, E_{1,2}^{lab}))}{\sigma(Z(\Omega_{1,2}^{CM}, E_{1,2}^{CM}))}$

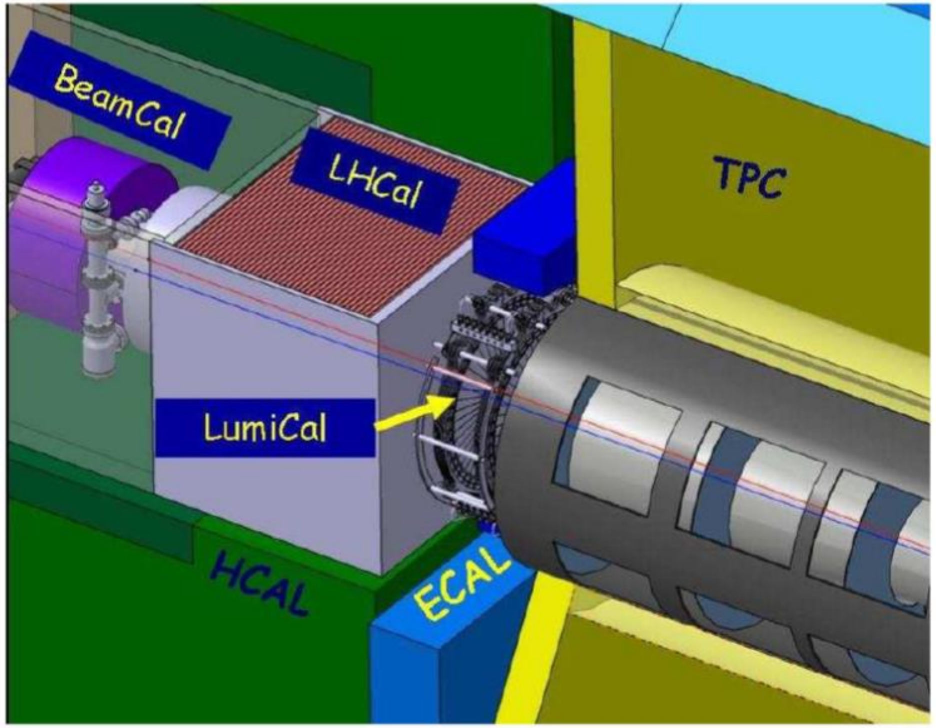
where Ξ and Z are functions of angles (Ω) and energies (E) of the final state particles in the corresponding reference frames

- Whenever radiative (momentum) loss of initial state is present, **Ξ and Z do not have the same form**
- **Neglecting the above leads to the systematic uncertainty in the integral luminosity measurement**

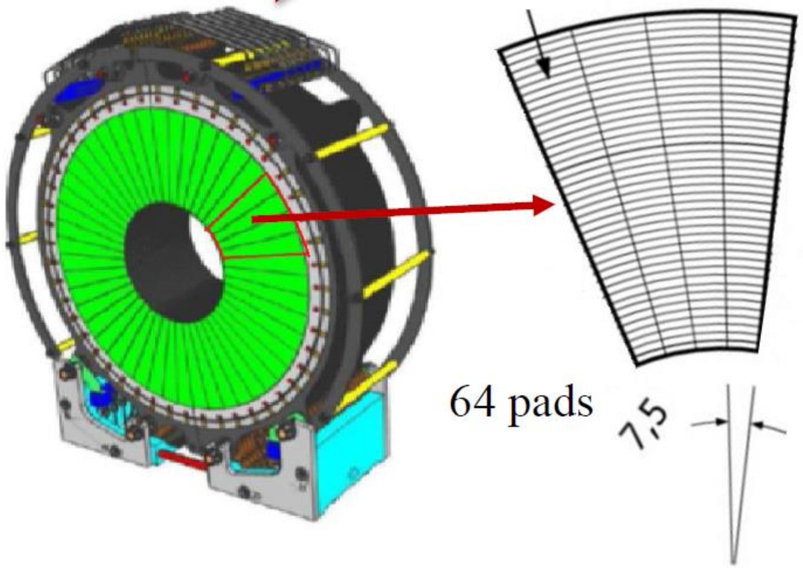
Data driven method to take into account initial state radiative losses is needed for precision luminosity measurement (Lesson 3)

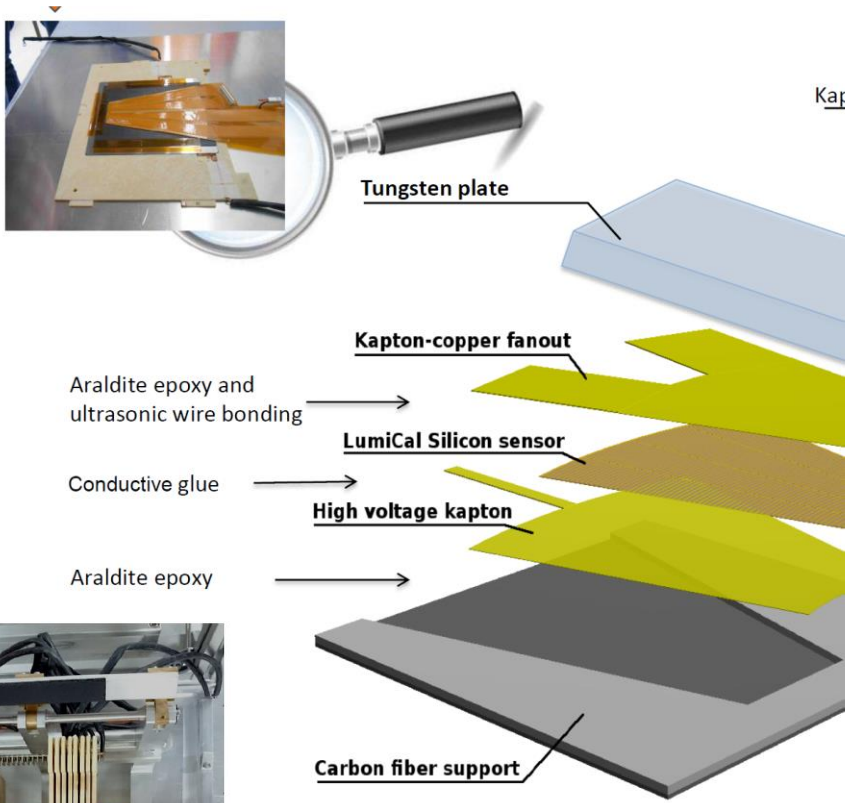
Luminometer at (future) e^+e^- colliders

- Compact calorimeter to identify EM showers from Bhabha scattering
- Compactness stand for a small Moliere radius (~ cm) -> excellent resolution in E and ?
- May be supplemented by a Si-pixel layer to enable:
  - calibration
  - e/γ separation
  - Improvement of the polar angle measurement
- Aperture and mechanical precision of such a device critically affect the luminosity precision (see Lesson 4)



Design of the very forward region at ILC





- Cover small polar angles 31-77 mrad
- Inner/outer radius 76/280 mm
- 30 sensor/absorber layers (ILC)
- 12 tiles divided into 4 azimuthal sectors (7.5 deg) and 64 rings with 1.8 mm pitch
- 1 X_o W absorber (3.5 mm), 320 μm sensor
- Anti-Detector Integrated Dipole field (Anti-DID): the magnetic field is parallel to the outgoing beams, optimized for low backgrounds

- Such a structure is compact ($R_M \leq 1$cm) for 5 GeV electrons
- Position of an electromagnetic shower is reconstructed by performing a weighted average over the energy deposits in individual pads

$$\mathscr{W}_i = \max\{\,0,\ \mathscr{C} + \ln(E_i/E_{tot}\,)\}$$

Where $\mathscr{C}$ =const. chosen in a way that σ_θ is minimal

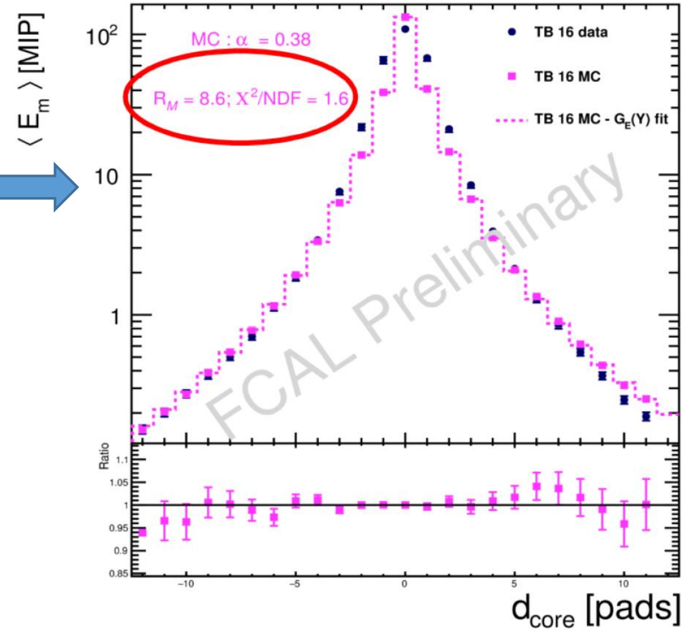
- **Polar angle resolution** $\sigma_\theta = (2.2 \pm 0.01) \times 10^{-2}$ mrad

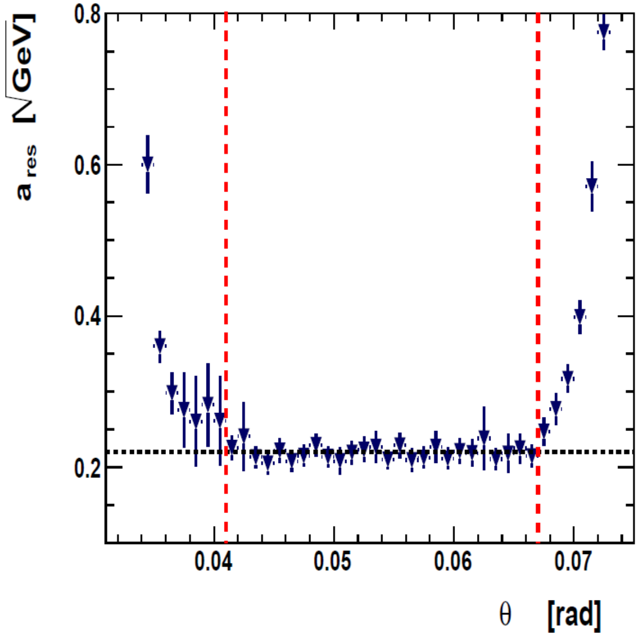
is resulting in 1.6 10^{-4} luminosity uncertainty

- Energy resolution is parameterized as $\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}\ (GeV)}}$

giving $a_{res} = (0.21 \pm 0.02)\ \sqrt{GeV}$

- **Energy resolution contributes as ~ 10^{-4} to the relative uncertainty of luminosity**



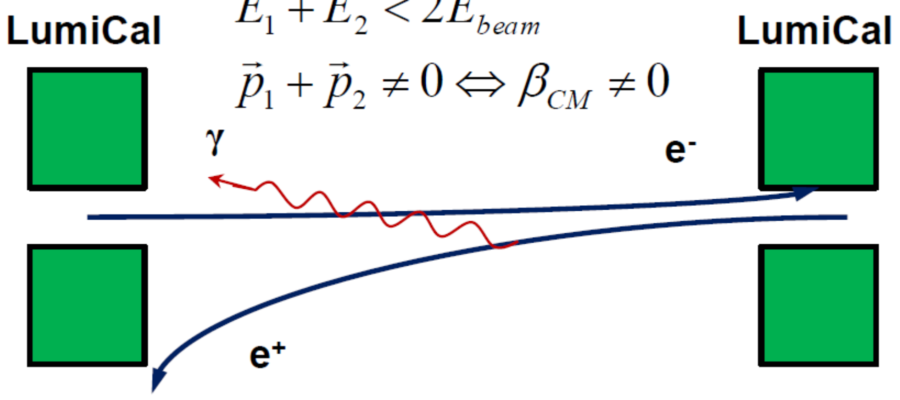


Lesson 2 in brief

- Precision knowledge of the theoretical Bhabha cross-section is needed at energies and phase spaces dedicated for luminosity measurement at future e^+e^- colliders. So far, that job has been done for LEP
- Whenever momentum losses of the initial state are present, laboratory frame (counting) and collision frame are not the same. This has to be taken into account (see how in Lesson 3) to correct for the counting losses
- Limited performance of the luminometer itself (energy and polar angle resolution) contributes to the integral luminosity uncertainty
- However, compact and precision calorimeters can be realized to match the physics precision goals (i.e. see work of the FCAL Collaboration for ILC) https://fcal.desy.de/

Impact of the beam-induced effects at linear colliders

- Bunches have to be denser at linear (than circular) colliders in order to maintain (instantaneous) luminosity
- The above results in the intense EM fields of the opposite bunches, initiating photon emission (Beamstrahlung)
- Emission of the Beamstrahlung photons changes the four-momenta of the initial and final state particles
- In addition, final state particles may be deflected by the EM field (of the opposite beam) – EM deflection (smaller effect than BS)



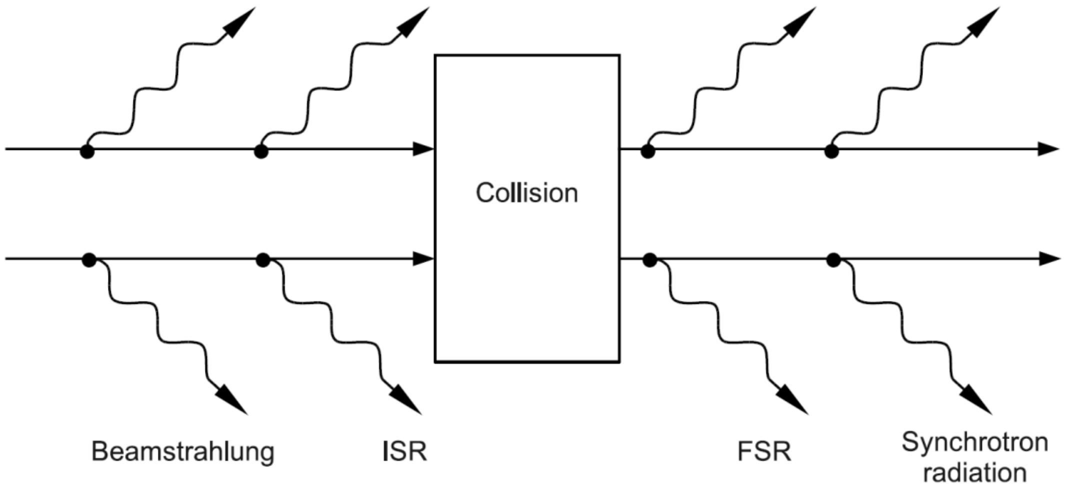
$$E_1 + E_2 < 2E_{beam}$$

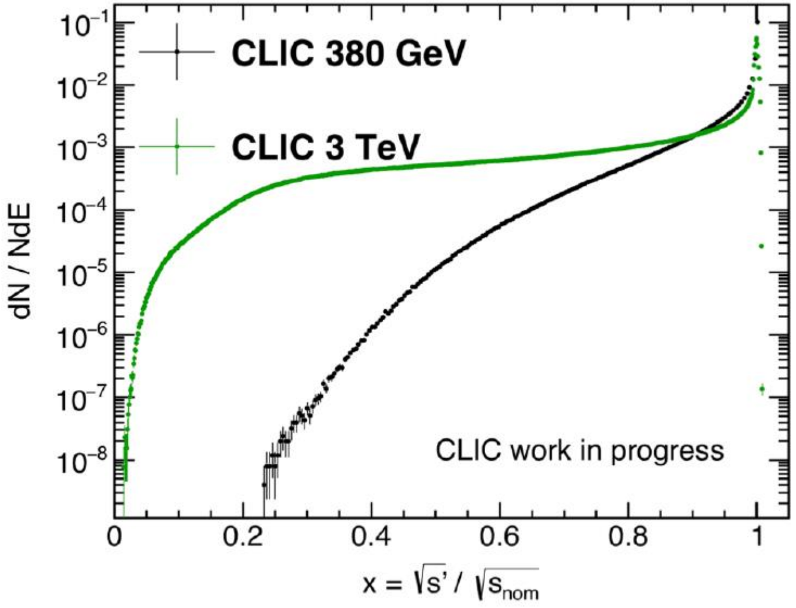
$$\vec{p}_1 + \vec{p}_2 \neq 0 \Leftrightarrow \beta_{CM} \neq 0$$

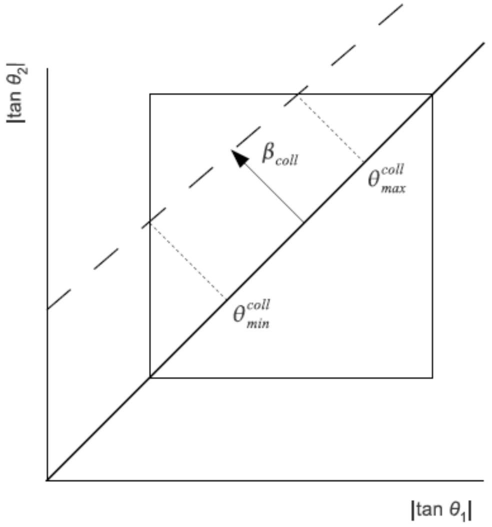
- Nominal center-of-mass energy is not available anymore for the collisions
- Collision frame is boosted w.r.t. the lab frame (β_{CM})
- Bhabha electron and positron are no more collinear ⇒ counting losses
- Effect is asymmetric and gives rise to the Bhabha counting loss of ~10% at ILC(500 GeV)

Impact of the beam-induced effects at linear colliders

- Other effects may be (are) present as well: pinch effect, ISR, final state radiation, synchrotron radiation
- The dominant momentum losses are caused by the Baemastrahlung at linear and synchrotron radiation at circular colliders





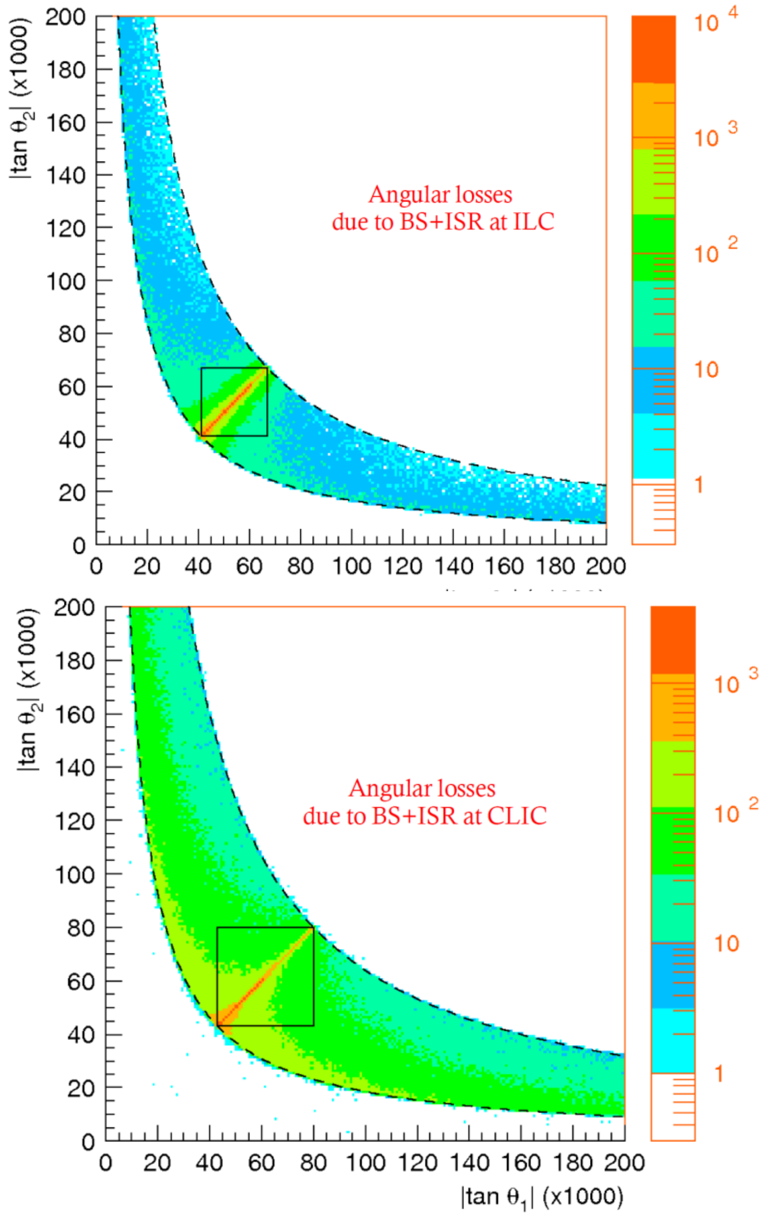


- $\beta_{coll}\neq 0$ results in the effective shrinking of the detector fiducial volume 'seen' by the Bhabha particle (counting loss)
- From the scattered angles (θ_1 and θ_2) of final state e^+ and e^- it is possible to calculate an event weight in order to recover for the counting loss on event-by-event basis:

$$w(\beta_{coll}) = \frac{\int_{\theta_{\min}}^{\theta_{\max}} \frac{d\sigma}{d\theta}\, d\theta}{\int_{\theta_{\min}^{coll}}^{\theta_{\max}^{coll}} \frac{d\sigma}{d\theta}\, d\theta}$$

where $\beta_{coll} = \frac{\sin(\theta_1^{lab}+\theta_2^{lab})}{\sin\theta_1^{lab}+\sin\theta_2^{lab}}$

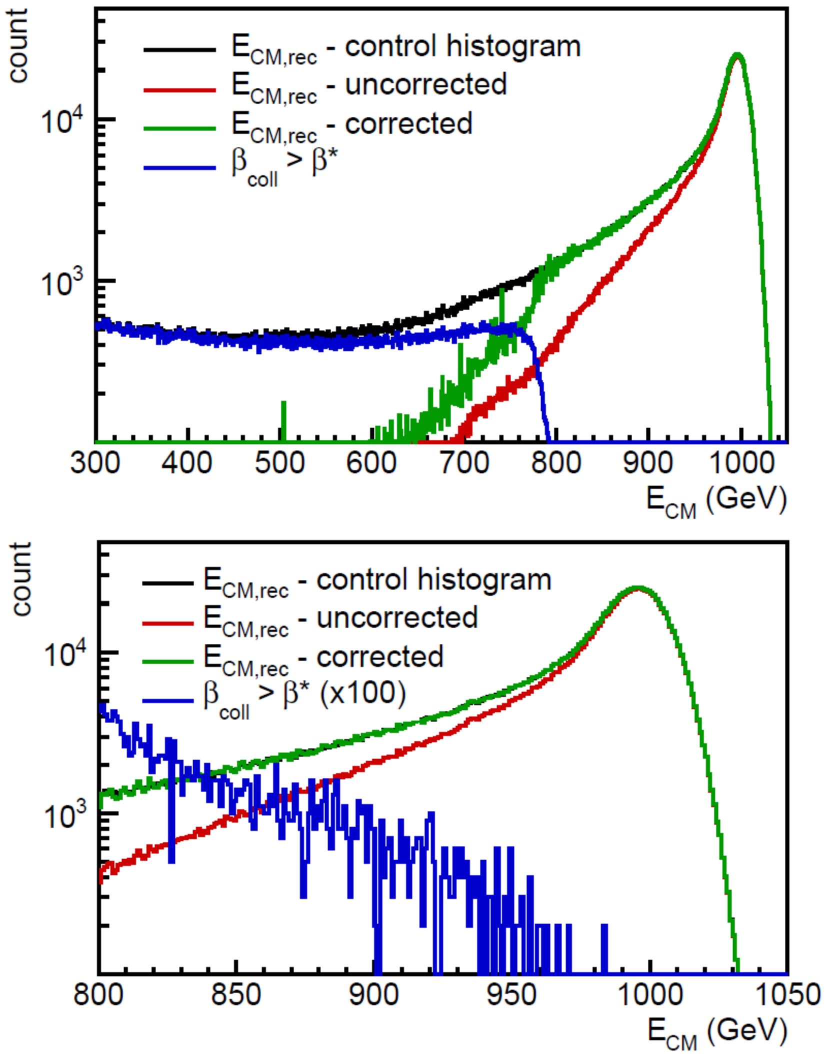
- If $\beta_{coll} > \beta^*$, event is irreducibly lost (effective fiducial volume is 0)



Feasibility of the Beamstrauhlung (+ISR) correction

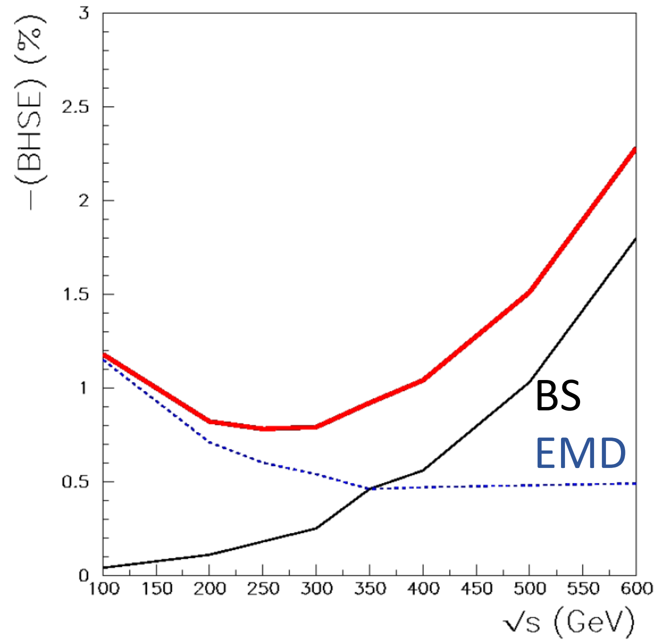
ILC 500 GeV

- Above 80% of the nominal CM energy, **the counting loss before correction is ~10 %** (500 GeV ILC)
- **After the correction the counting loss is ~ permille**
- Relative uncertainty of the correction* translates into the (relative) uncertainty of luminosity
- **ΔL/L=7 10^{-4} at 500 GeV ILC**

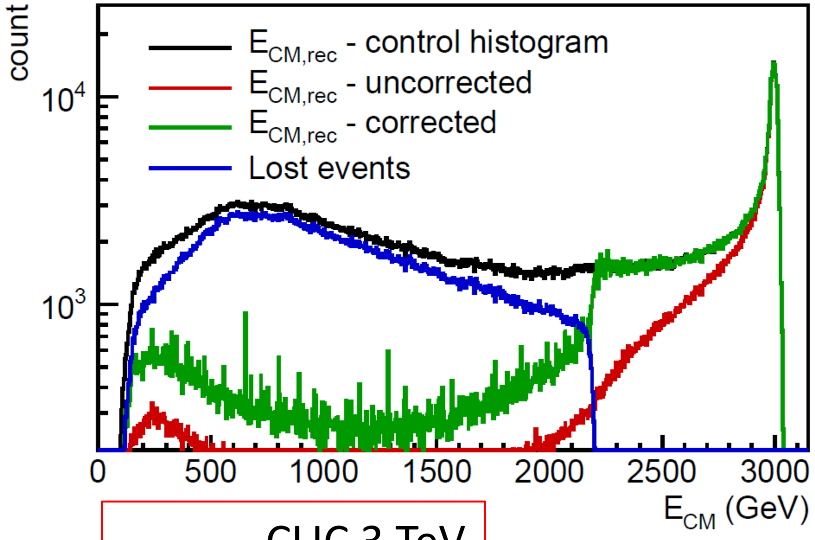


**Fraction of high β_{coll} events due to the off-axis emission of ISR, approximations in the Bhabha differential cross-section, assumption that all ISR is lost and FSR detected*

- The effect is more pronounced at higher energies
- **Between 80% and 90% of the nominal CM energy, the counting loss at 3 TeV CLIC ~43 %, and in the peak region above 95% the loss is ~4%**
- **Uncertainty of the corrected spectrum is ~ 4 permille between 80% and 90% of the nominal CM energy**
- **And it the top 5% of the spectrum ~ 10^{-4}**



- Described method is data driven – based on polar angle measurement of the final state particles
- The method is robust w.r.t. bunch sizes and transverse beam offset
- Further corrections are possible in a simulation dependent way
- NB: EM deflection is (still) not correctable in a fully simulation independent way



CLIC 3 TeV

Lesson 3 in brief

- Beamstrahlung at high-energy e^+e^- linear colliders leads to severe counting losses in the integral luminosity measurement (tens of %)
- The effect is more pronounced at higher center-of-mass energies
- Momentum losses of the initial state lead to the loss of colinearity of Bhabha events and the effective reduction of the detection volume ⇔ counting loss
- By appropriate event-by-event weighting, number of events can be recovered with a permille uncertainty or better
- Correction can be made in a data driven way (independently from simulation)

Systematics from the mechanical precision and MDI

- What we consider as a detector fiducial volume can be effectively changed by various beam-detector displacements
- Every single change in the fiducial volume and/or available center-of-mass energy leads to the uncertainty in integral luminosity
- To correct for it implies that all the effects have to be known with the same precision required for the integral luminosity

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
- *Uncertainty of the (eventual) beam polarization*

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*

Mechanisms to influence the count:

- **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)

Selection matters

- Require asymmetric acceptance in θ (within the fiducial volume) on the L-R side of the detector (i.e. as applied at OPAL/LEP) - move inner and outer fiducial radii towards each other for Δr
- The above will cancel-out systematics originating from the requirement of L-R symmetry
- Only possible if the luminometer is centered at the outgoing beam

+ Look into the top (50%) part of the spectrum

240 GeV CEPC , $\Delta L/L=10^{-3}$

Beam energy uncertainties

Symmetric bias on beam energy

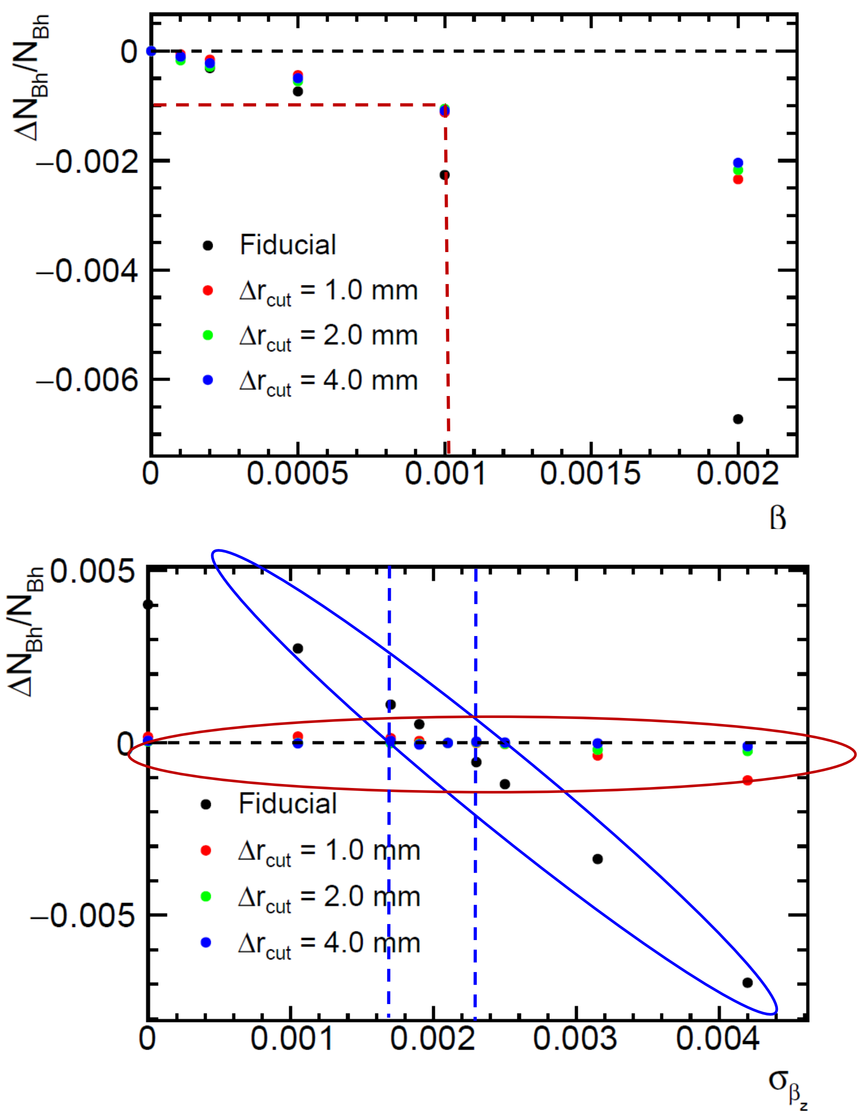
- Bhabha cross-section changes as $\sim 1/s \Rightarrow$ relative uncertainty on (average net) CM energy $< 5 \cdot 10^{-4}$
- Counting bias due to the acceptance cut on energy is negligible

Asymmetric bias on beam energy $|E_+ - E_-| = \Delta E \Rightarrow \beta_z = \Delta E/E_{CM}$

- $\beta_{coll} \neq 0 \Rightarrow$ counting loss due to the loss of colinearity
- Asymmetry in beam energies should be smaller than 10^{-3}

Beam energy spread

- Different $\beta_{z(CM,\, coll)}$ for each event
- Uncertainty of β_z Gaussian width ($\sigma_{\beta z}$) is a source of the uncertainty of Bhabha count
- Becomes negligible with the asymmetric acceptance cuts, otherwise beam spread must be known within 20% uncertainty

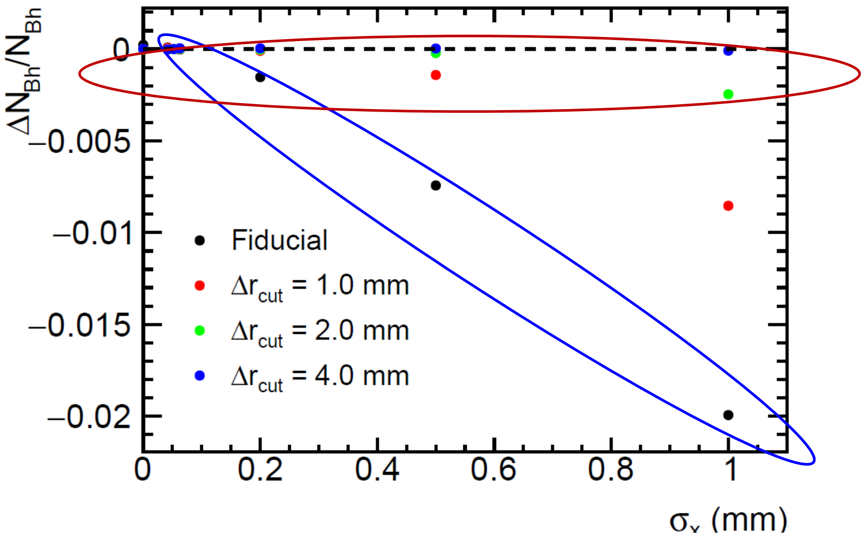


240 GeV CEPC , $\Delta L/L=10^{-3}$ — Various beam and detector displacements

Radial fluctuations* of the LumiCal w.r.t. the IP

**Can be caused by vibrations, thermal stress or by the finite transverse dimension of the bunches or radial fluctuations of the bunch center*

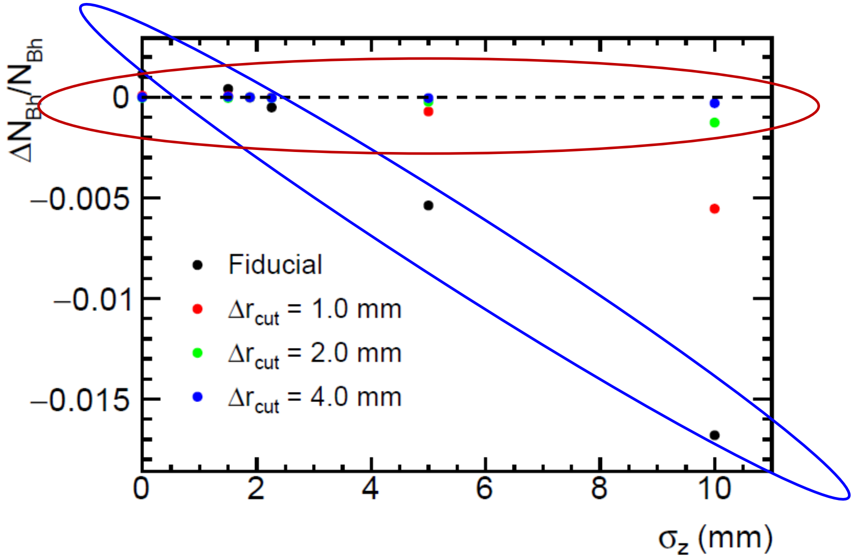
- Radial fluctuations up to 1 mm are acceptable with the asymmetric acceptance (0.1 mm without)



Axial fluctuations* of the LumiCal w.r.t. the IP

**The longitudinal position of a colliding particle within the bunch (σ_Z not negligible), actual axial fluctuations of the relative position of the IP w.r.t. LumiCal due to beam synchronization*

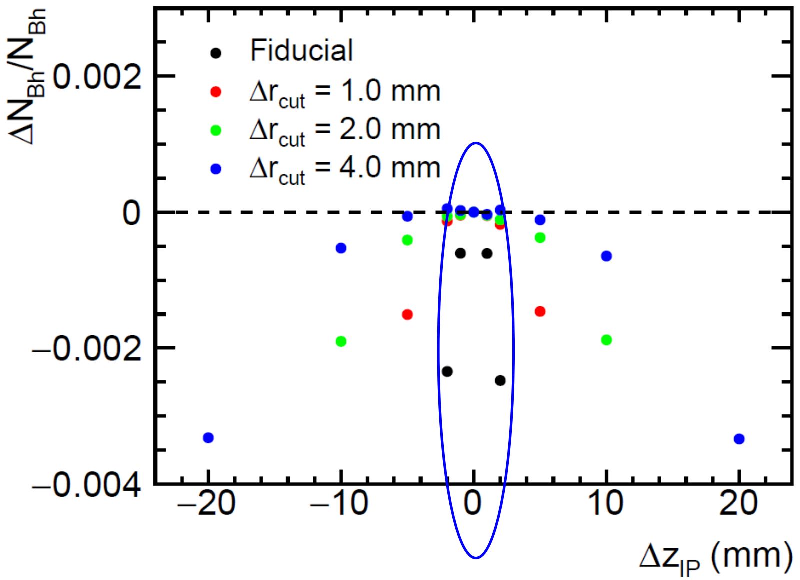
- Axial fluctuations up to 10 (1) mm are acceptable with (without) the asymmetric acceptance



Longitudinal offset of the IP

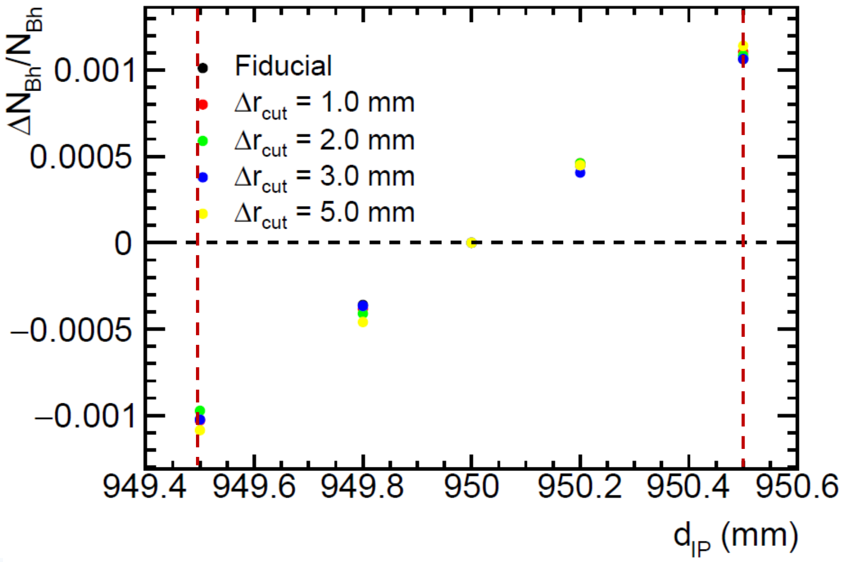
IP is not equidistant in z between left and right halves of the detector (or one LumiCal half is shifted w.r.t. IP for Δz_{IP})

- Becomes negligible with asymmetric acceptance cuts: up to 10 mm axial offset easily tolerated, ~ 1 mm in the full fiducial volume
- Implies a requirement on the synchronization of the colliding beams of better than 15 ps (1 ps without asymmetric cuts)



Distance between left and right LumiCal halves (symmetric to the IP)

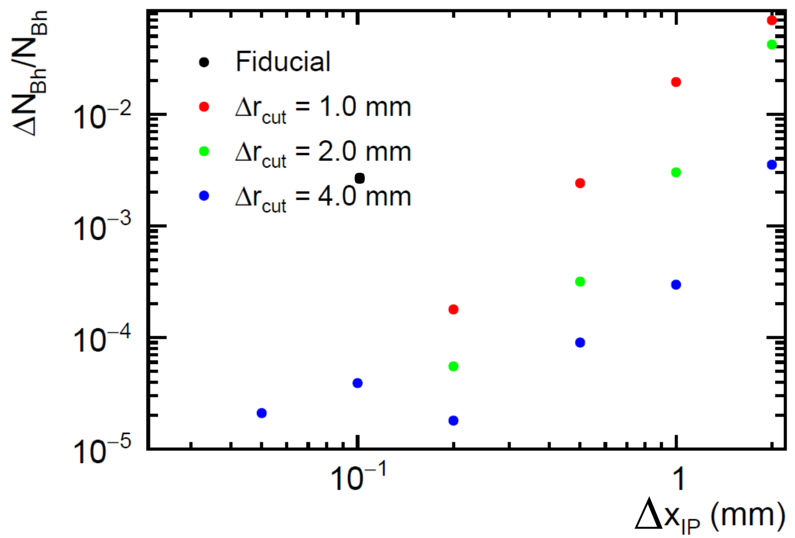
- Position of individual LumiCal half w.r.t to the IP has to be controlled at ~ ½ mm level over 950 mm



Radial offset* of the detector axis w.r.t. the outgoing beam (or IP w.r.t. the LumiCal)

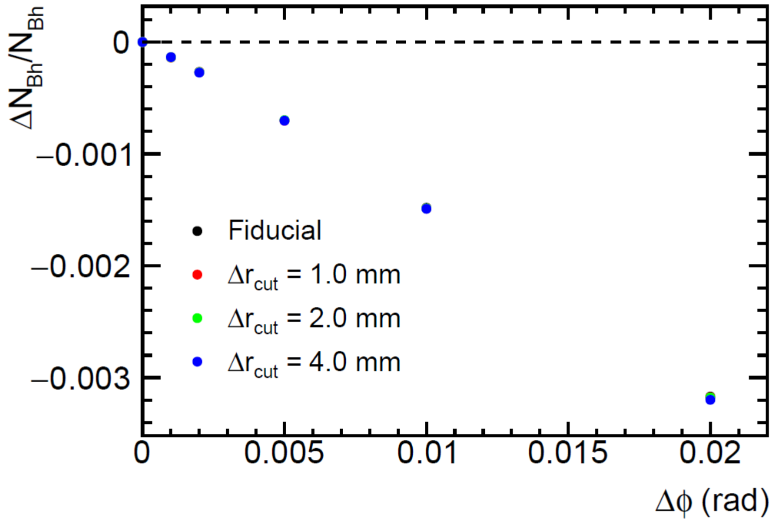
**Tilt of the calorimeters, beam alignment*

- Particle will impact at a slightly larger radius and a larger polar angle is reconstructed
- 1 mm offset can be tolerated, ~100 μm for the full fiducial volume



Azimuthal twist between left and right LumiCal halves (rotation around the outgoing beam)

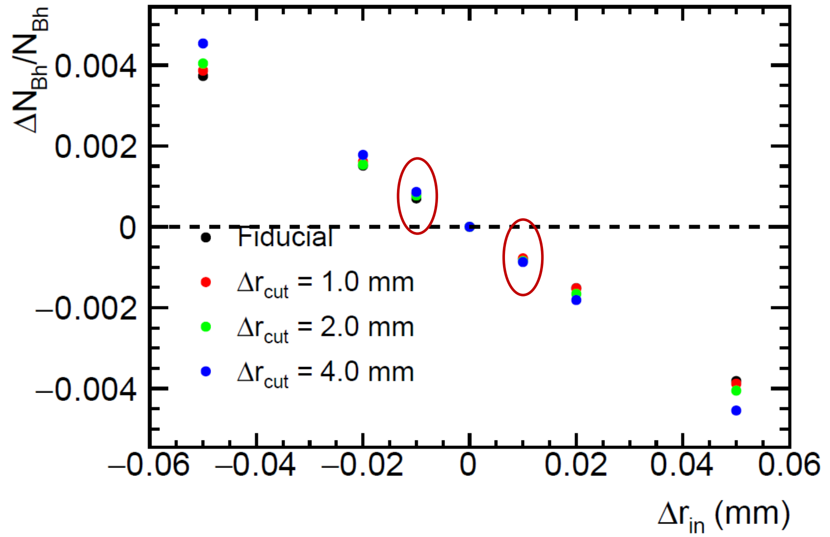
- Translates into uncertainty of the azimuthal angle
- We assume that Bhabha particles should be coplanar within 7.5 deg (i.e. in order to reduce background from 2-γ processes)
- Azimuthal twist of 6 mrad between left and right detector axis can be tolerated



240 GeV CEPC , $\Delta L/L=10^{-3}$ Inner radius and radial shower reconstruction

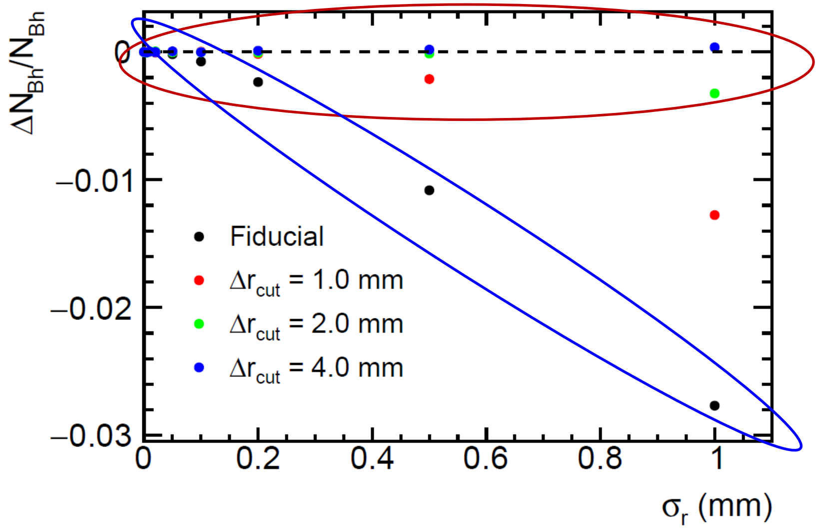
Inner radius of the luminometer

- Uncertainty of the inner radius translates into counting uncertainty with the Bhabha cross-section scaling ~ $1/\theta^3$
- ~10 µm uncertainty translates into 10^{-3} luminosity uncertainty
- Possibly the most critical requirement on the detector mechanical issues



Spread of the measured radial shower position (w.r.t. to the true impact position on the LumiCal front plane)

- Translates into uncertainty of the polar angle
- Sensitive to the pad size
- 1 mm spread can be allowed (mrad in radial position) for asymmetric acceptance cuts (otherwise ~0.1 mm)
- Easily achievable with the existing technology choices for LumiCal design (fine sensor segmentation)



Parameter	unit	limit (Fiducial)	limit (LEP style)
ΔE_{CM}	MeV	120	120
$E_{e^+} - E_{e^-}$	MeV	120	240
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		20%	Effect cancelled
Δx_{IP}	mm	0.1	>1
Δz_{IP}	mm	1.4	10
Beam synchronisation	ps	1	7
$\sigma_{x\ IP}$	mm	0.1	1
$\sigma_{z\ IP}$	mm	1	10
r_{in}	µm	13	10
$\sigma_{r_{shower}}$	mm	0.15	1
Δd_{IP}	µm	500	500

- Similar situation at ILC and CEPC w.r.t. systematics uncertainties from mechanics and MDI
- Inner radius uncertainty ~10 µm for 10^{-3} luminosity uncertainty
- CM energy has to be known at the level ~100 MeV ⇔ $5\cdot10^{-4}$ (Bhabha x-section scales as 1/s)
- $2.7\cdot10^{-4}$ (25 MeV) beam energy uncertainty at LEP2 [M. D. Hildereth, IHEP98] – seems to be feasible

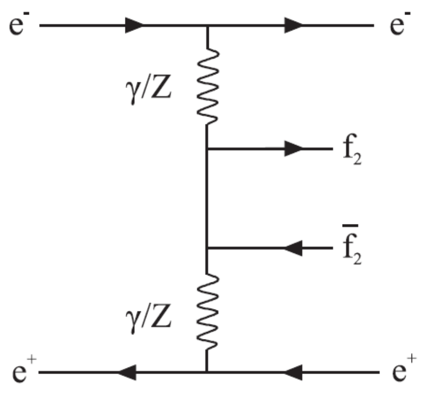
Counting based on a left-right asymmetric polar angle selection (as at LEP) leads to the significant relaxation of mechanics and MDI requirements

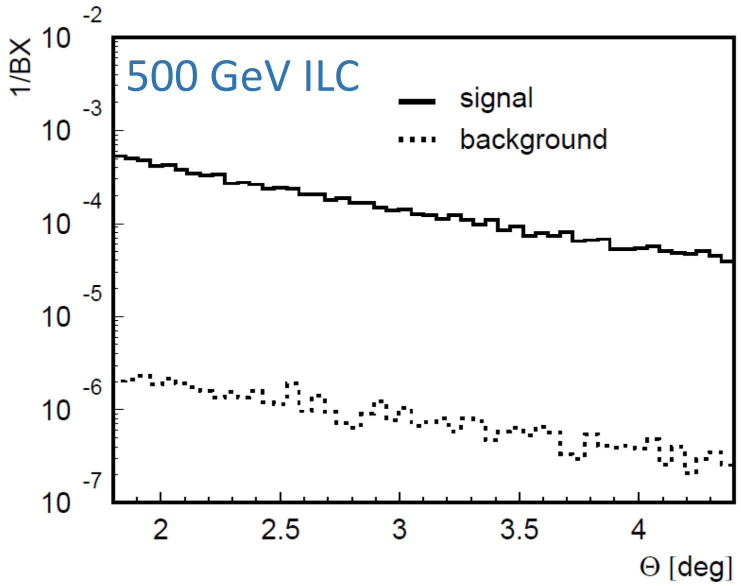
Lesson 4 in brief

- A long list of systematic effects rising from MDI and mechanics related uncertainties
- Each effect has to be known with the same precision as the integral luminosity
- With the appropriate event selection (asymmetric polar-angle regions required on the left and right side of the detector subsequently), majority of MDI and mechanics requirements can be relaxed
- To apply such approach, luminometer has to be placed at the outgoing beam
- However, due to the Bhabha x-section dependence on polar angle and the available center-of-mass energy, the most demanding requirements remain:
  - Inner radius uncertainty ~10 µm
  - $5 \cdot 10^{-4}$ uncertainty of the available center-of-mass energy
- For the reasons above, situation is more or less similar at all future e^+e^- colliders

Feasibility of the luminosity precision goals at future e+e- colliders

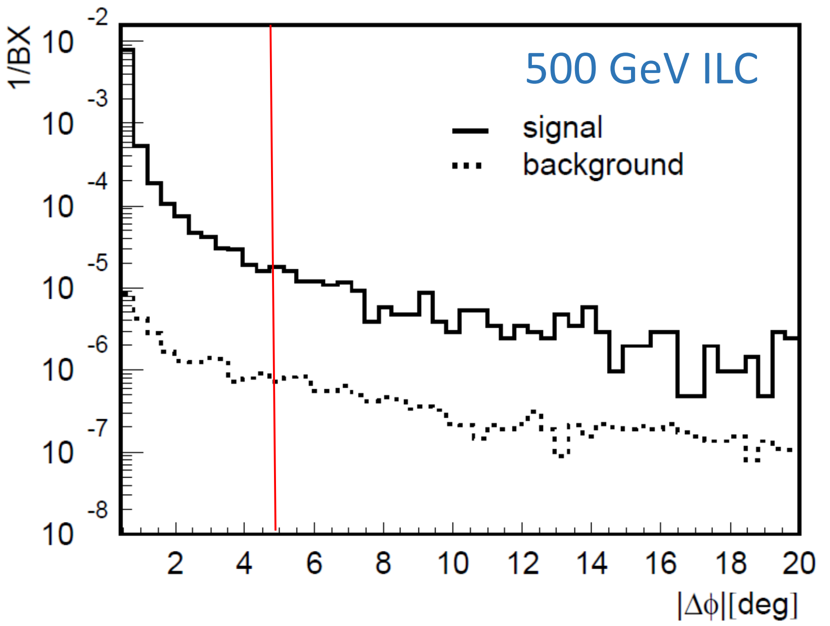
- A (long) list of systematic uncertainties is not exhausted yet…
- **Systematic effects from physics interactions**:
  - Background from physics processes
  - Bhabha acolinearity – other sources of the acceptance losses (ISR and FSR, Beamstrahlung) – Lesson 3
  - Machine-related backgrounds (off-momentum electrons from the beam-gas scattering)





- High energy $e^{\pm}$ spectators can fake the signal
- Most of 2-γ events go below luminometer
- Contamination of the fiducial volume is ~ $6 \cdot 10^{-3}$ at 250 GeV ILC
- ~ 2 permille at 1 TeV since the process is peaked more forward

- Requirement on coplanarity can be used to suppress 2-γ processes (in addition to the energy cut)
- The above reduces the fraction of $\beta_{coll} > \beta^*$ events in the high-energy part of the spectrum
- The full size effect can be corrected for once the cross-section uncertainty in a given phase space is available (for 2-γ processes)



abs(Δφ)<5 deg., E>0.8 E_{beam}

ILC		500 GeV	1 TeV
Signal	E_s	94 %	94 %
Leptonic background	R_{bck}	60%	56%
$e^+e^- \to e^+e^-e^+e^-$	B/S	$1.6 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$
Hadronic background	R_{bck}	70 %	91 %
$e^+e^- \to e^+e^-q\bar{q}$	B/S	$0.6 \cdot 10^{-3}$	$0.1 \cdot 10^{-3}$
$\Delta L/L$		$2.2 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$

Feasibility of the luminosity precision

CEPC 10^{-4} precision requirements at Z^0 pole

Parameter	unit	limit
ΔE_{CM}	MeV	4.5
$E_{e^+} - E_{e^-}$	MeV	11
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		Negligible up to at least factor 2
Δx_{IP}	mm	0.5
Δz_{IP}	mm	2
Beam synchronisation	ps	3
$\sigma_{x_{IP}}$	mm	0.5
$\sigma_{z_{IP}}$	mm	7
r_{in}	µm	1
$\sigma_{r_{shower}}$	mm	0.2
Δd_{LC}	µm	80
$\Delta\phi$	mrad	0.8

ILC systematics at 500 GeV and 1 TeV

Source of uncertainty	$\Delta L/L$ (500 GeV)	$\Delta L/L$ (1 TeV)
Bhabha cross-section σ_B	$5.4\cdot 10^{-4}$	$5.4\cdot 10^{-4}$
Polar angle resolution σ_θ	$1.6\cdot 10^{-4}$	$1.6\cdot 10^{-4}$
Bias of polar angle $\Delta\theta$	$1.6\cdot 10^{-4}$	$1.6\cdot 10^{-4}$
IP lateral position uncertainty	$1\cdot 10^{-4}$	$1\cdot 10^{-4}$
Energy resolution a_{res}	$1.0\cdot 10^{-4}$	$1.0\cdot 10^{-4}$
Energy scale	$1.0\cdot 10^{-3}$	$1.0\cdot 10^{-3}$
Beam polarization	$1.9\cdot 10^{-4}$	$1.9\cdot 10^{-4}$
Physics background B/S	$2.2\cdot 10^{-3}$	$0.8\cdot 10^{-3}$
Beamstrahlung + ISR^1	$-1.1\cdot 10^{-3}$	$-0.7\cdot 10^{-3}$
Beamstrahlung + ISR^2	$0.4\cdot 10^{-3}$	$0.7\cdot 10^{-3}$
EMD^1	$-2.4\cdot 10^{-3}$	$-1.1\cdot 10^{-3}$
EMD^2	$0.5\cdot 10^{-3}$	$0.2\cdot 10^{-3}$
$(\Delta L/L)^1$	$4.3\cdot 10^{-3}$	$2.3\cdot 10^{-3}$
$(\Delta L/L)^2$	$2.6\cdot 10^{-3}$	$1.6\cdot 10^{-3}$

Lesson 5 in brief

- Current studies (i.e. at ILC and CEPC) show that it's feasible to control systematic effects in integral luminosity measurement at the level of several permille
- The most critical parameter from physics side seems to be background from 2-γ processes that, however, can be taken as a correction to the count once the cross-section uncertainty in a counting phase space is available
- Mechanical precision of the inner radius of the luminometer as well as the knowledge on the available center-of-mass energy seem to be the most critical on detector and MDI side
- For the luminosity precision aiming at 10^{-4} (at the Z^0 pole), to know CM energy at the level of a few MeV seems to be impossible, however some relevant processes might have the same x-section dependence with $\sqrt{s}$ as Bhabha in which case the effect cancels out

Summary and outlook

- Precision measurements are apparently the 'light motive' of future e^+e^- colliders
- To achieve that goal, statistical potential of future machines is increased and luminosity precision is to follow
- Dedicated (long-time) studies (i.e. at ILC) have demonstrated the feasibility to design and construct a compact precision device (luminometer)
- Mechanical precision of the inner radius of a luminometer as well as the knowledge on the available center-of-mass energy seem to be the most critical parameters on detector and MDI side
- Physics background from 2-γ processes can be taken as a correction, once its cross-section in a counting phase space is available with the same precision required for the integral luminosity
- For the luminosity precision aiming at 10^{-4} (at the Z^0 pole), to know CM energy at the level of a few MeV seems to be impossible, however some relevant processes might have the same x-section dependence with $\sqrt{s}$ as Bhabha in which case the effect cancels out

Despite differences in design, technology and (not so much) physics program
all future e^+e^- colliders (ILC, CLIC, CEPC, FCCee)
share the same luminosity precision goals
and consequently facing similar challenges (up to a difference between linear and circular...)

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