Some issues in the integral luminosity measurement at future circular e+e- colliders

CEPC

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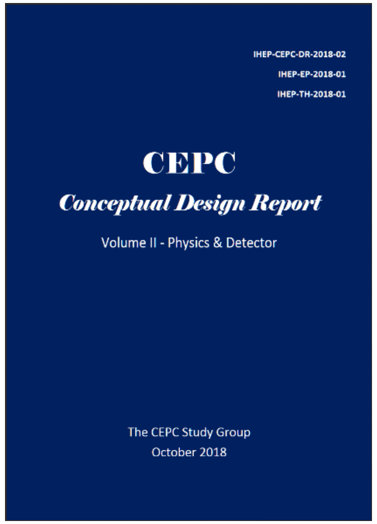
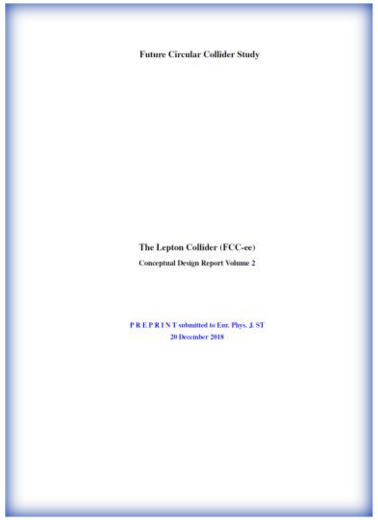
VINCA Institute 70 years in science

- Common issues (between CEPC and FCC):
  - Similar MDI design in the CDR
  - MDI related backgrounds
  - Challenges for luminosity measurement
- How feasible is 10^{-4}?
- Concluding remarks



- CDRs released end-of 2018 for both CEPC and FCC
- MDI region among the most challenging at both experiments
- Flexibility to run at different CM energies (Z pole, WW production, Higgs factory) with a common detector layout
- Maximizing luminosity ⇔ minimizing related backgrounds
- Precision issues in the integral luminosity measurement (10^{-4})
- Technologies for luminometer (currently derived from ILC and CLIC)



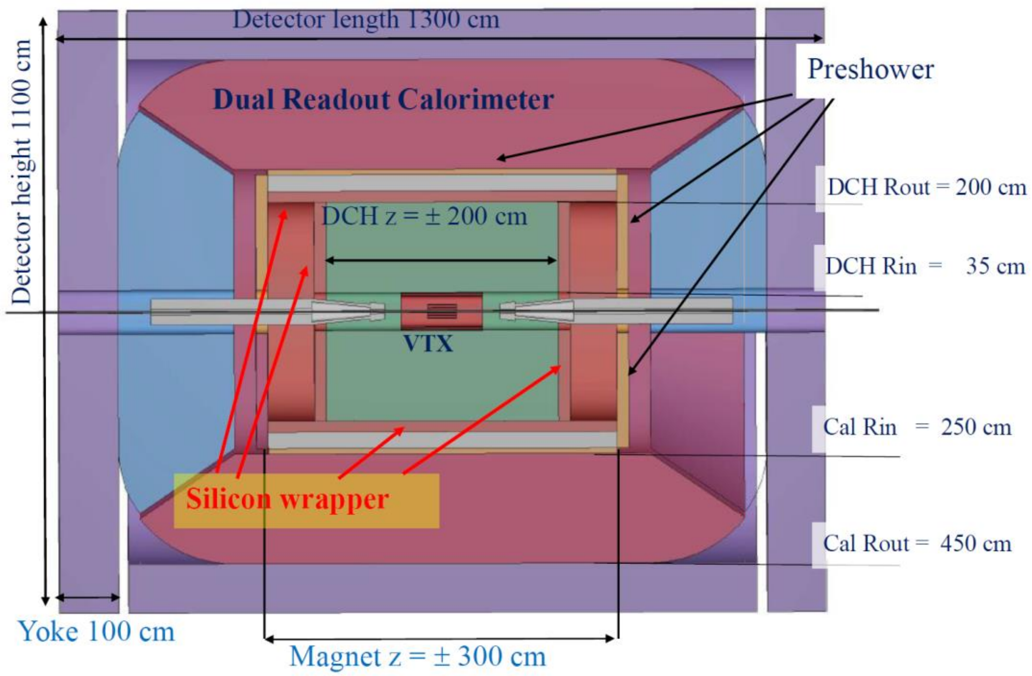
**Many things in common, similar challenges,
lots of space for new ideas**

Detector concepts:

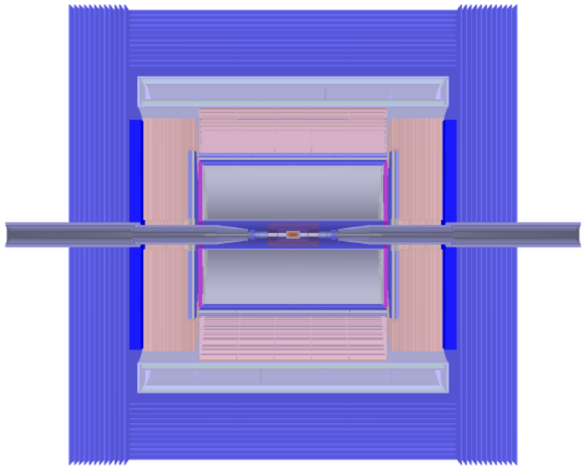
- CEPS: CEPC_ILD (baseline), IDEA
- FCC: CLD (baseline), IDEA

Si-pixel VTX, a large-volume extremely-light short-drift wire chamber surrounded by a layer of Si micro-strip detectors, a thin, low-mass superconducting solenoid coil (~0.8 X_0), a pre-shower detector, a dual-readout calorimeter, and muon chambers within the magnet return yoke.

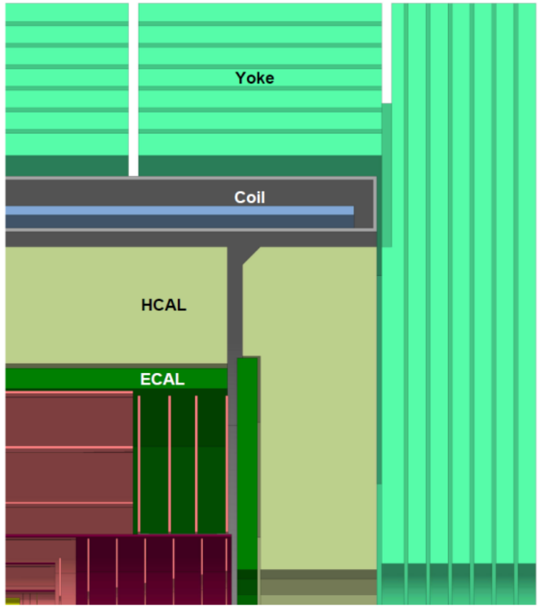
IDEA



Concept	ILD	CEPC baseline	IDEA
Tracker	TPC/Silicon	TPC/Silicon or FST	Drift Chamber/Silicon
Solenoid B-Field (T)	3.5	3	2
Solenoid Inner Radius (m)	3.4	3.2	2.1
Solenoid Length (m)	8.0	7.8	6.0
L* (m)	3.5	2.2	2.2
VTX Inner Radius (mm)	16	16	16
Tracker Outer Radius (m)	1.81	1.81	2.05
Calorimeter	PFA	PFA	Dual readout
Calorimeter λ_I	6.6	5.6	7.5
ECAL Cell Size (mm)	5	10	-
ECAL Time resolution (ps)	-	200	-
ECAL X_0	24	24	-
HCAL Layer Number	48	40	-
HCAL Absorber	Fe	Fe	-
HCAL λ_I	5.9	4.9	-
DRCAL Cell Size (mm)	-	-	6.0
DRCAL Time resolution (ps)	-	-	100
DRCAL Absorber	-	-	Pb or Cu or Fe
Overall Height (m)	14.0	14.5	11.0
Overall Length (m)	13.2	14.0	13.0



Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17
Tracker half length [m]	2.2	
Tracker outer radius [m]	1.5	2.1
ECAL absorber	W	
ECAL X_0	22	
HCAL absorber	Fe	
HCAL λ_I	7.5	5.5
Solenoid field [T]	4	2
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6

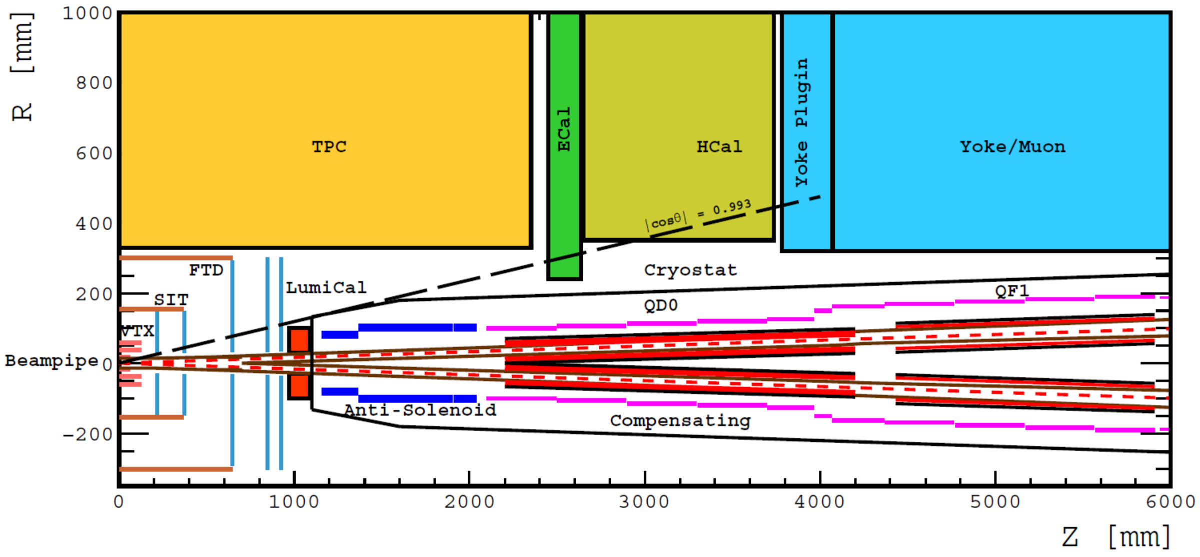


- MDI is a region not only to host very forward detectors
- It's the place where various beam (and detector) induced backgrounds are generated
- … and proliferate toward tracking systems

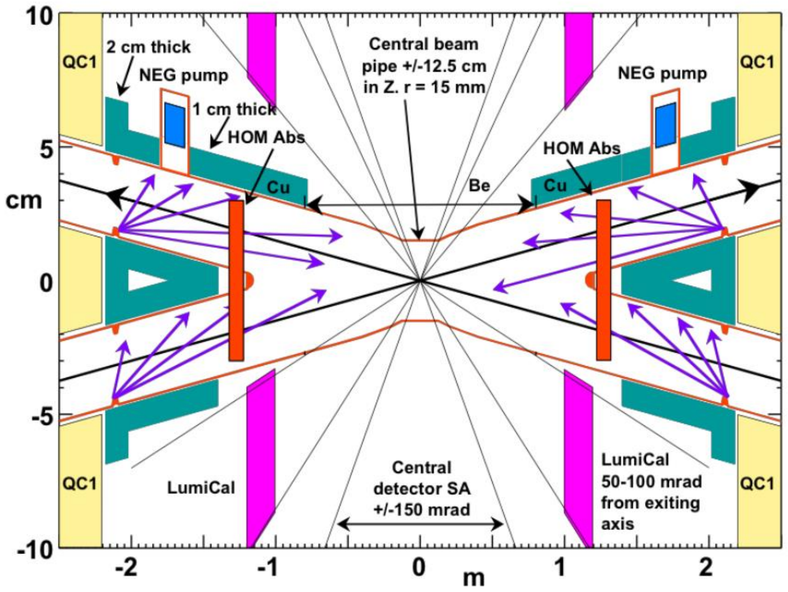
see H. Zhu talk

MDI layout

[CEPC CDR]



[FCCee CDR]



- 33 mrad double-ring x-angle, L*=2.2m
- LCAL: 950 cm
- LCAL coverage: 26-105 mrad geometrical acceptance (53-79 mrad fiducial volume)
- 680 ns, 25 ns and 210 ns bunch-spacing @ H, Z^0 and WW threshold $\rightarrow$ different level of background

- 30 mrad crab-crossing, L*=2.2m
- LCAL: 1.074m-1.190m from the IP
- LCAL coverage: 62-88 mrad

see S. Bai talk

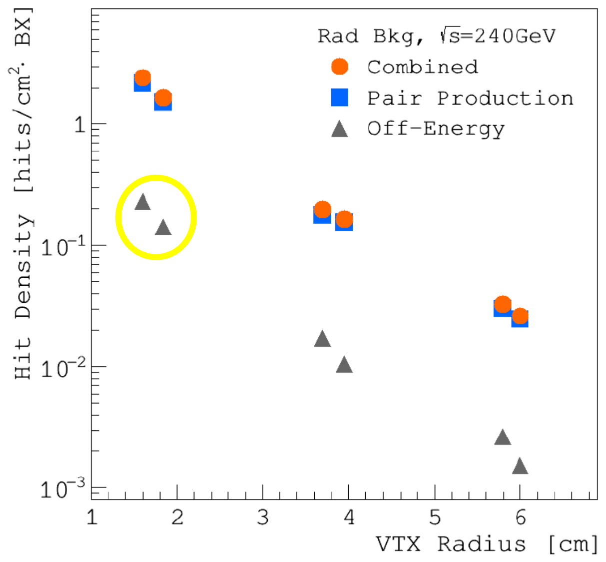
100 times LEP

[CEPC CDR]

Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} $cm^{-2}s^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158-172	10	1	2.6	2×10^7

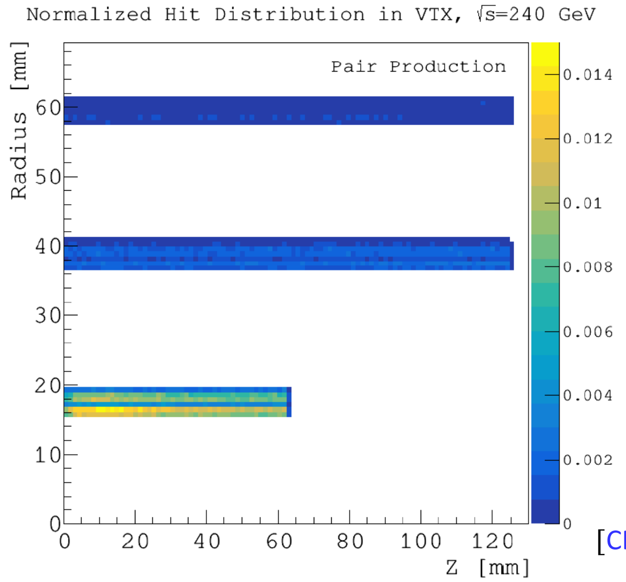
- Both machines are 'factories' (i.e. $\mathcal{L}=2\cdot10^{36}$ cm^{-2} s^{-1} (Z-pole) $\sim 10^5$ x LEP at FCCee)
- SR, BS, off-momentum particles, similar at both machines
- Less than 10^{-3} $\gamma\gamma \rightarrow$ *hadrons* interactions per BX @ Z^0 pole occurs with the $\gamma\gamma$ invariant mass above 2 GeV

240 GeV CEPC: first VTX layer2.4 particle/cm^2 per BX



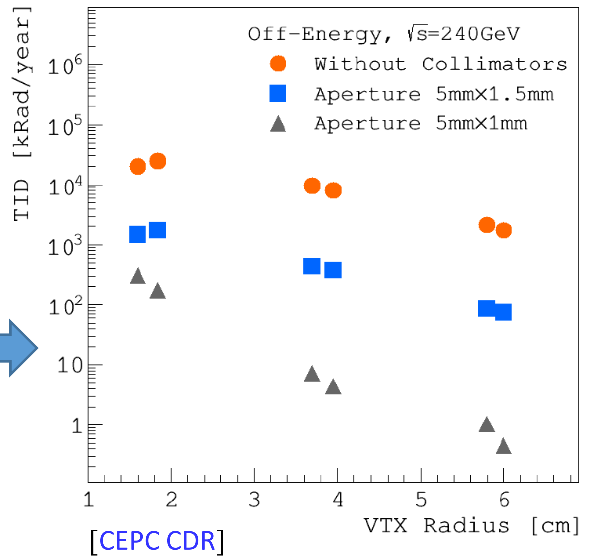
Circulating beam particles can lose significant amounts of energy in scattering processes. If exceeding 1.5% of the nominal energy scattered particles can be kicked off their orbit. Usual mechanisms are BS, radiative Bhabha and beam-gas interactions.

The challenge is to maximize performance in terms of luminosity whilst maintaining the related backgrounds at a tolerable level



[CEPC CDR]

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/cm^2 per BX

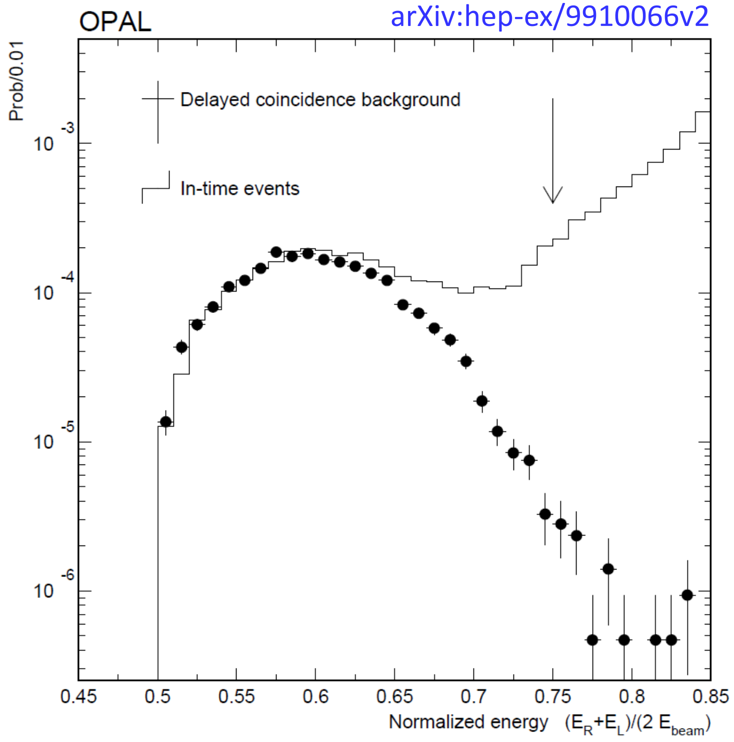


[CEPC CDR]

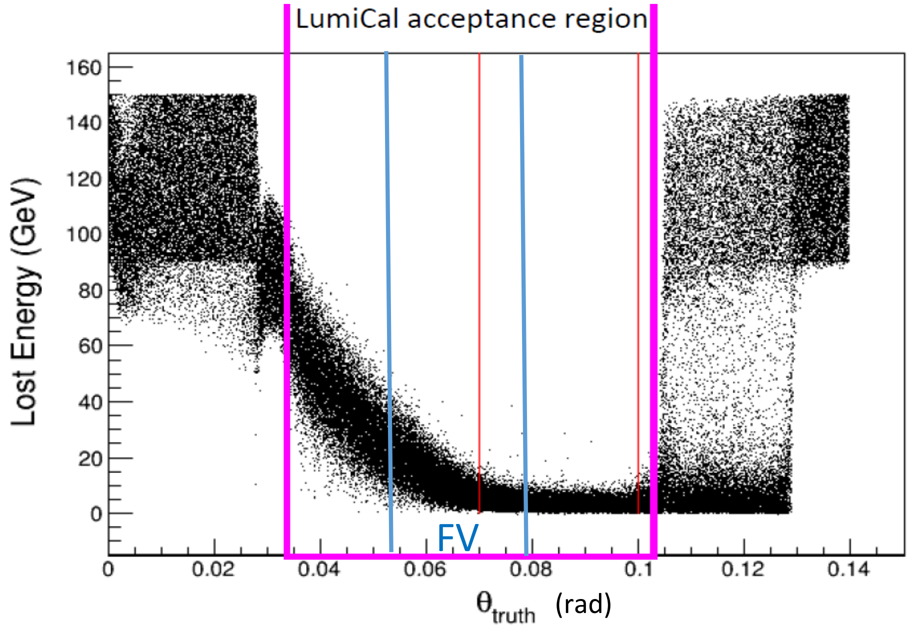
- Can influence luminosity measurement by accidental overlapping to the Bhabha signal and by coincidence in both detector halves that happens at the same rate as the signal.
- Off-momentum particles from beam-gas interaction were the main source of systematics in luminosity measurement at LEP ($0.1\text{-}0.6\cdot10^{-4}$). Nicely regulated by the (relative) energy cut.

Luminometer performance (energy determination) is important

arXiv:hep-ex/9910066v2



- Material budget in front of the LumiCal is important (left: optimization of the beam-pipe material for CEPC CDR studies)
- To keep the luminometer to perform, MDI materials (i.e. HOM absorbers) must be out of the way
- Design of this crowded region is under study



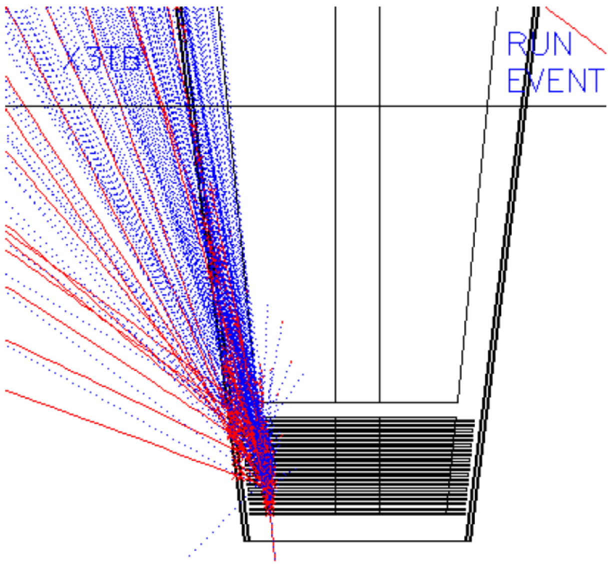
Large energy losses with Be pipe with a copper segments (CEPC V5) [credit: Y. Liu, Z. Kai]

LumiCal shower leakage

An iron cone of 5 mm thickness, positioned at cosθ = 0.992 (~120 mrad) is used to estimate filtering of shower secondaries

Two configurations were considered:

- TUBE: Cylindrical detector shape assembled of sensor-absorber disks with constant outer radii of 100 mm
- CONE: Shape with the outer radius r following a straight line projection from the IP at tan θ= 0.1 (~ 6 deg.), corresponding to r_{out} = 100 mm at z = 1 m.



[credit: S. Hou]

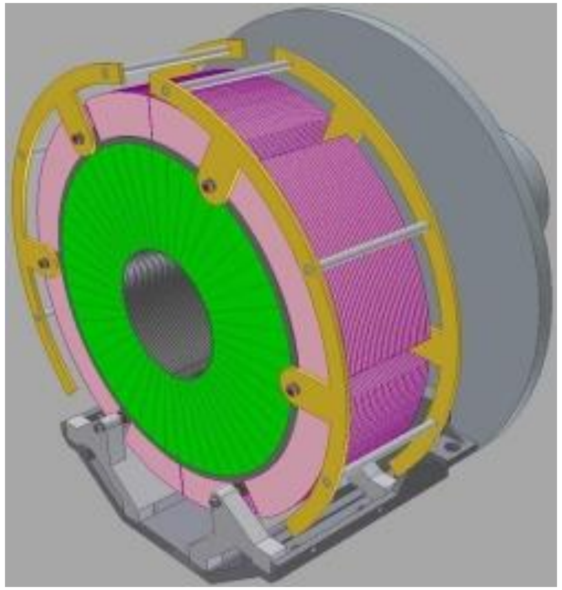
	50 GeV electrons		125 GeV electrons	
	TUBE	CONE	TUBE	CONE
θ (mrad)	N_{enter}/N_{pass}	N_{enter}/N_{pass}	N_{enter}/N_{pass}	N_{enter}/N_{pass}
40	15.4/5.6	13.6/5.8	38.0/16.0	35.8/14.7
90	392/155	173/76	1028/399	434/19.7
95	501/290	367/152	2389/720	937/382
98	762/216	860/284	1718/473	2176/725
99	553/140	1331/367	1102/273	3306/915

Table 1: Number of particles leaking out of the LumiCal outer radius (N_{enter}) and number of particles passing through the Fe-cone (N_{pass}). Two different detector designs (TUBE and CONE) and two shower energies (50 GeV and 125 GeV) are simulated.

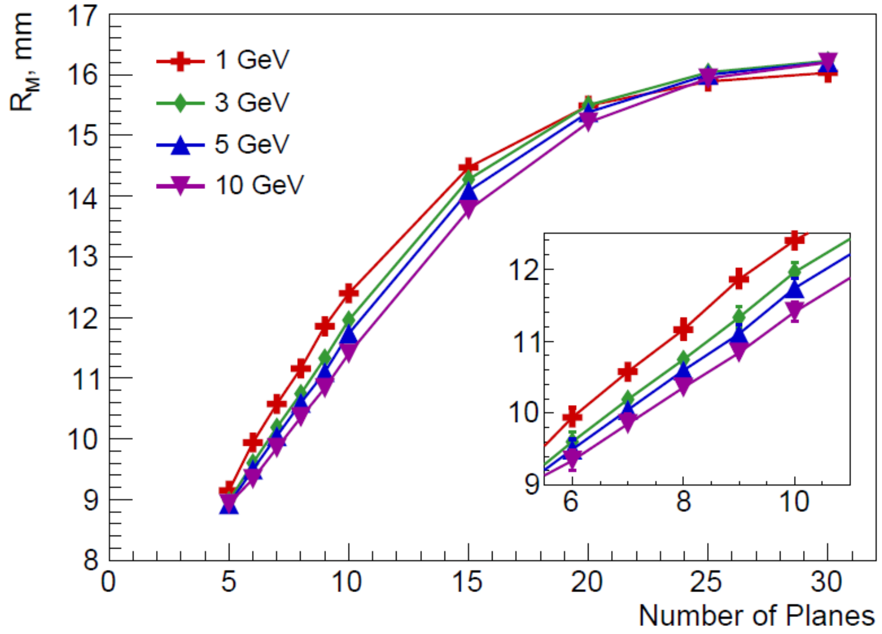
- There is a larger shower leakage (E< 100 MeV) for the CONE configuration - shower is developing at larger θ
- 5 mm Fe-cone reduces the number of secondaries up to 75%

- First, we need a device …

SiW sandwich calorimeter:
- 20 one-X_0 thick absorber (3.5 mm)
- 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 polar angle
- Requires fast and compact readout



[credit: FCAL Collaboration]



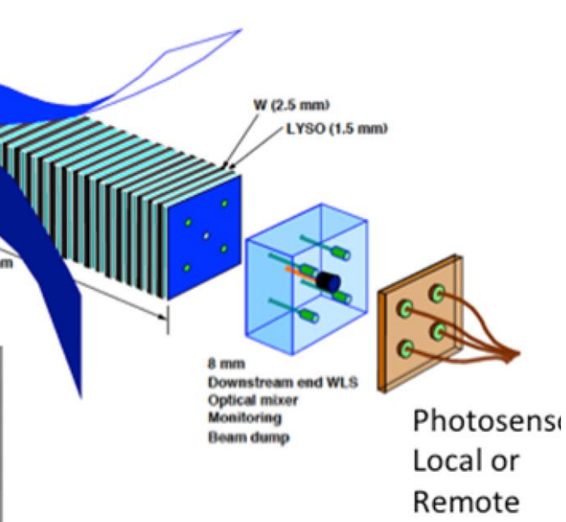
arXiv:1812.11426v1 [physics.ins-det]

Existing and proven technology in a test-beam (FCAL Collaboration)

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

- Luminometer technology options are open (CEPC and FCCee)
- Coarse segmentation, compact electronics, search feasible readout chips
- Is simpler read-out feasible?

Shashlik style module configuration



Transverse size of modules ~ ½ Swiss Franc

- Si-W 'ILC-like'
- BGO (has a 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)

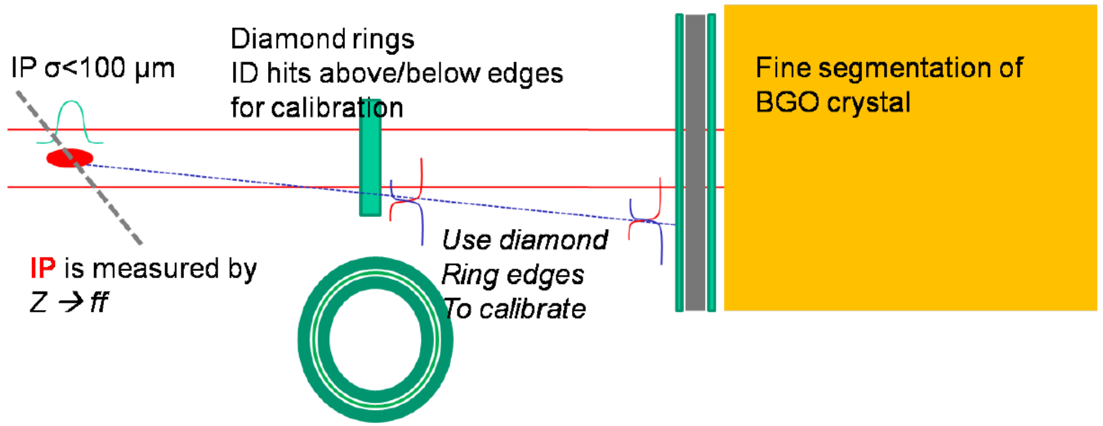
- Good light output - 70% of NaI(Tl), High density - 7.15 g/cm^3
- Fast decay times - c.45ns
- Energy resolution - <12%
- Not hygroscopic
- Are relatively inexpensive

Radiation hardness

1. Use of dense materials
2. Small Molière Radius
3. Rad-hard materials
4. Short optical paths
5. Rad-resistant, small pixel photosensor

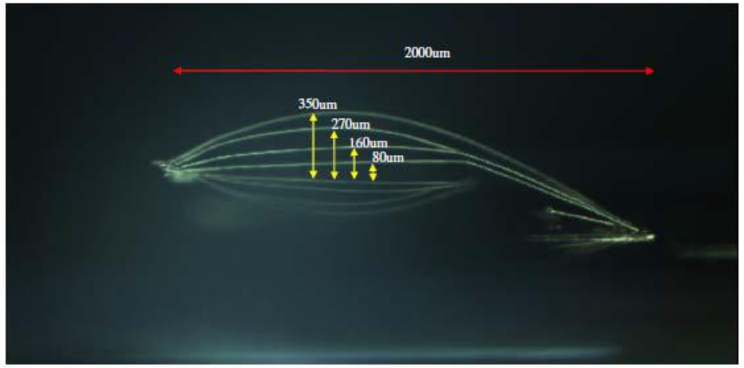
[Courtesy: S. Hou]

- Not the end of the story…
- Read-out, assembling, prototyping, testing….



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



此次打線實驗是以固定直線距離2000um 做弧高控制，弧高可以做到80um，考慮生產良率會控制在150um內。

Industry studies with Ag wire bonding 80 μm high.

[Courtesy: S. Hou]

Performance in terms **of energy and polar angle measurement** will play a key role in the control of systematics.

- Integral luminosity measurement is challenged
- … by the detector design and performance,
- positioning and mechanics,
- beam-induced uncertainties,
- physics processes and their theoretical description

How feasible is 10^{-4} – mechanical and beam-related uncertainties

- Detector positioning and beam related uncertainties have to be strictly controlled
- Luminometer has to be centered at the outgoing beam to 'naturally' apply asymmetric acceptance selection (LEP style) and thus relax systematics

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

Parameter	Unit	Limit
ΔE_{CM}	MeV	120 $5\cdot10^{-4}$
$E_{e^+} - E_{e^-}$	MeV	240 10^{-3}
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		effect canceled
Δx_{IP}	mm	<1
Δz_{IP}	mm	10
Beam synchronization	ps	7
$\sigma_{x_{\mathrm{IP}}}$	mm	1
$\sigma_{z_{\mathrm{IP}}}$	mm	10
r_{in}	mm	10
$\sigma_{r_{\mathrm{shower}}}$	mm	1
Δd_{IP}	µm	500

[VINCA HEP Group for the CEPC CDR]

Some requirements are on the technological limit:

- Inner radius of the luminometer: ~1 µm (4.4 µm at OPAL contributing $1.4\cdot10^{-4}$ uncertainty in L)
- Distance between calorimeters ~80 µm over app. 1m. Should be easily achieved with FSI.
- ΔE_{CM} and beam asymmetry at the level of a few MeV: $5\cdot10^{-5}$ for the cross-section calculation ($2.7\cdot10^{-4}$ at LEP) and ~ 10^{-4} for the acceptance loss due to the beam energy asymmetry.

$\Delta\mathcal{L}/\mathcal{L}=10^{-4}$, Z^0 pole

Parameter	unit	limit
ΔE_{CM}	MeV	4.5 $5\cdot10^{-5}$
$E_{e^+} - E_{e^-}$	MeV	11 10^{-4}
$\frac{\delta\sigma_{E_{beam}}}{\sigma_{E_{beam}}}$		Negligible up to at least factor 2
Δx_{IP}	mm	0.5
Δz_{IP}	mm	2
Beam synchronisation	ps	3
$\sigma_{x_{\mathrm{IP}}}$	mm	0.5
$\sigma_{z_{\mathrm{IP}}}$	mm	7
r_{in}	µm	1
$\sigma_{r_{\mathrm{shower}}}$	mm	0.2
Δd_{LC}	µm	80
$\Delta\phi$	mrad	0.8

[IBJ, CEPC WS Rome, 2018]

@240 GeV CEPC

Inner radius of the luminometer

- Uncertainty of the inner radius translates into counting uncertainty since the Bhabha cross-section scales like $1/\theta^3$

Symmetric bias on beam energy:

Colliding beam energies can be symmetrically shifted for ΔE, resulting in $2\cdot\Delta E$ shift in CM 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

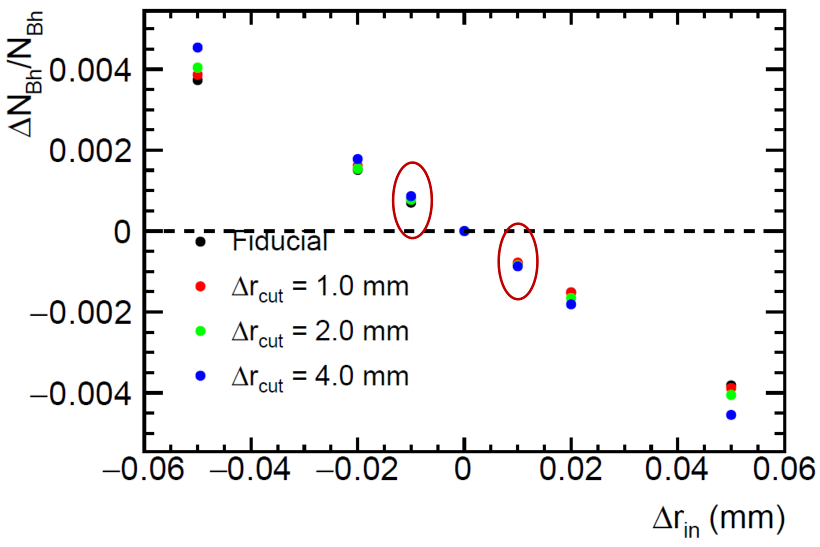
Asymmetric bias on beam energy:

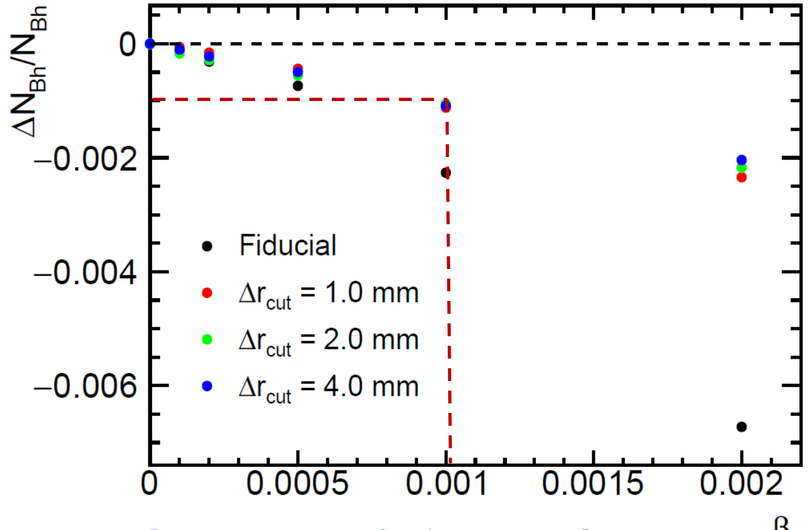
$|E_+ - E_-| = \Delta E \Rightarrow \beta_z = \Delta E/E_{CM}$

- Longitudinal boost of the CM frame of the colliding particles to the lab frame β_z

$\Rightarrow$ counting loss due to the loss of acolinearity

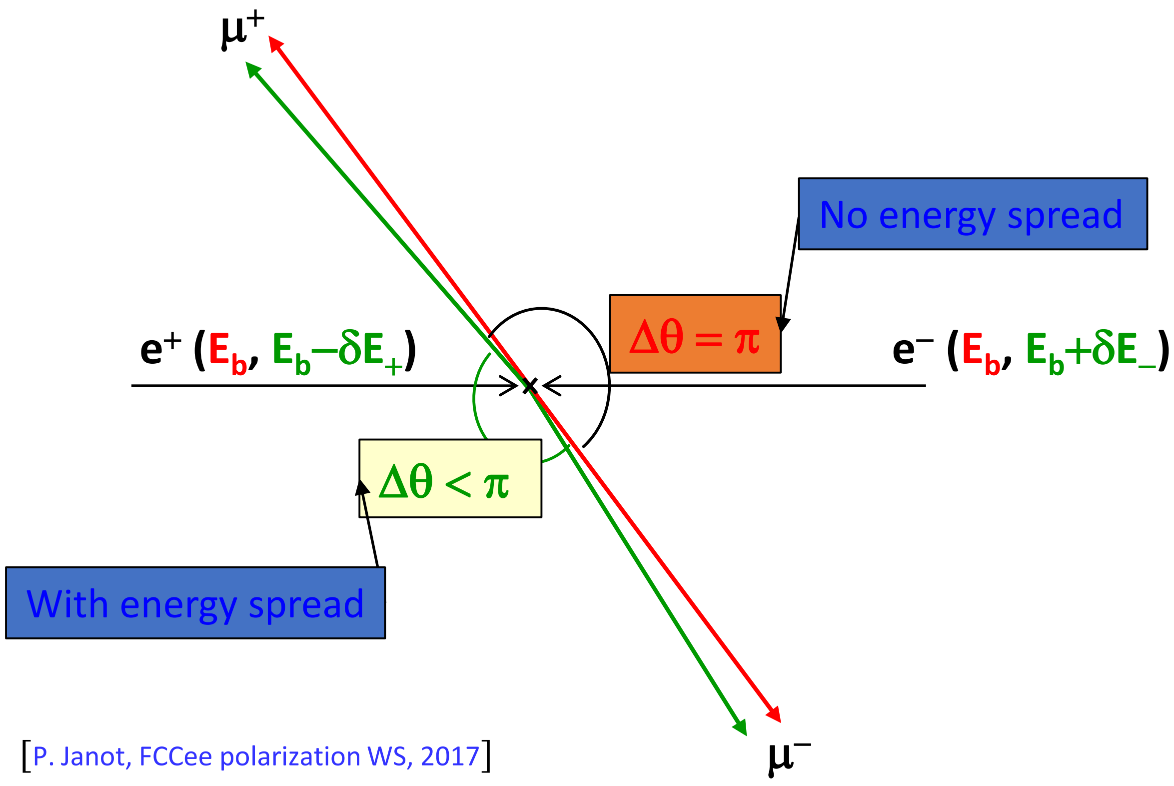
- Asymmetry in beam energies should be smaller than 10^{-3}





[VINCA HEP Group for the CEPC CDR]

Interesting treatment of this type of uncertainty (asymmetry in beam energies) is proposed for FCCee



[P. Janot, FCCee polarization WS, 2017]

With:

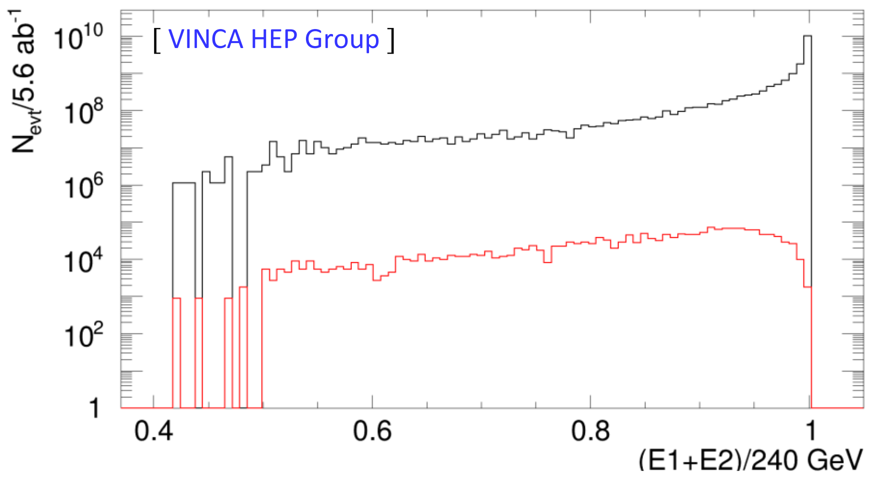
- 1.5 nb x-section for $\mu^+\mu^-$ production at the Z^0 pole

+ muon angular reconstruction 10^{-2} mrad in θ

- Provides 50 keV sensitivity (< 10^{-6}) to the beam-energy asymmetry every 5 min of data collection (~10^6 muons) @ Z^0 pole

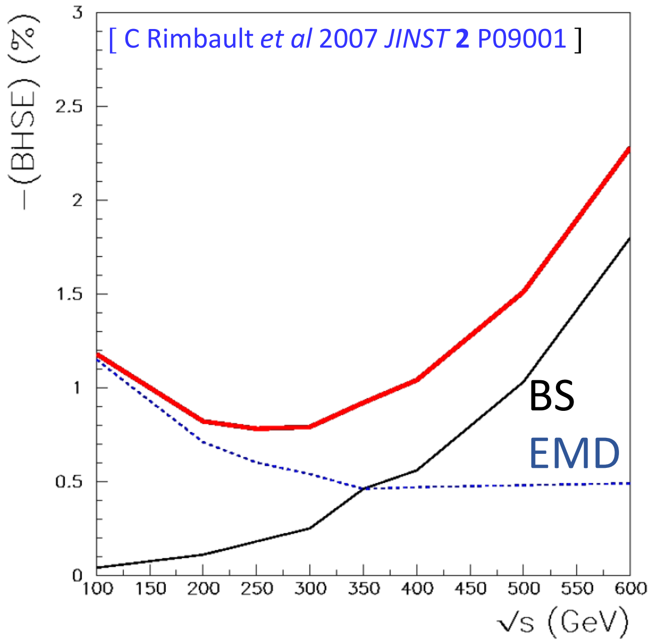
2-γ physics background

- Initial contamination (without any selection) of the detector volume is $\sim 10^{-4}$ w.r.t. the signal at 240 GeV CEPC
- B/S $\sim$ 10 times smaller than at 500 GeV ILC. This is mostly due to the Bhabha x-section dependence as 1/s, while 2-γ x-section is scaling like $\ln^2(s)$
- Similar situation should be at FCCee Higgs factory
- With the relative energy E_{rel}>0.8, B/S ratio is $\sim 8\cdot 10^{-5}$



EM deflection of Bhabha particles

- Outgoing Bhabha electrons/positrons can be deflected towards lower polar angles due to interaction with incoming bunches
- Like with BS, the EM field depends on a bunch transverse sizes: $\sim 1/(\sigma_x+\sigma_y)$
- The effect is at a % level at ILC at Z_0 pole (left), meaning that it will be of the order of 10^{-3} at 240 GeV CEPC and $\sim 3\cdot 10^{-3}$ at Z^0 pole, just on the basis of the beam parameters.
- This requires consideration for a precision goal of $\Delta\mathcal{L}/\mathcal{L}=10^{-4}$



EM deflection of Bhabha particles

- The effect has been discussed for ILC in [C Rimbault *et al* 2007 *JINST* **2** P09001]
- First, data-driven method has been proposed in

  [S. Lukic, IBJ et al. , 2013 JINST 8 P05008] and [IBJ, S. Lukic, et al. , 2013 JINST 8 P08012]

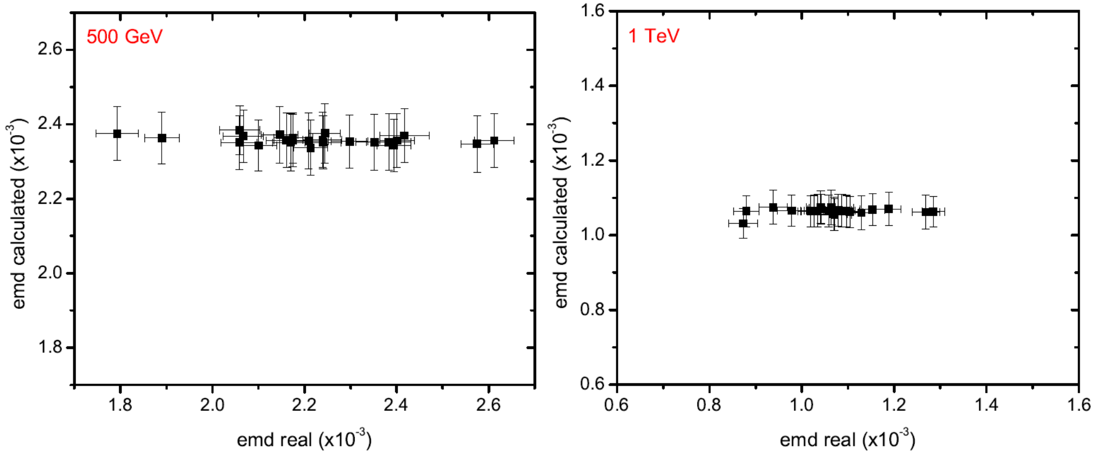
- The effect can be measured from the measured polar angles of Bhabha: $x_{EMD}=(1/N)\cdot(dN/d\theta)$
- The effective shift $\Delta\theta$ of the luminometer fiducial volume is determined from simulation
- The luminosity uncertainty is obtained as:

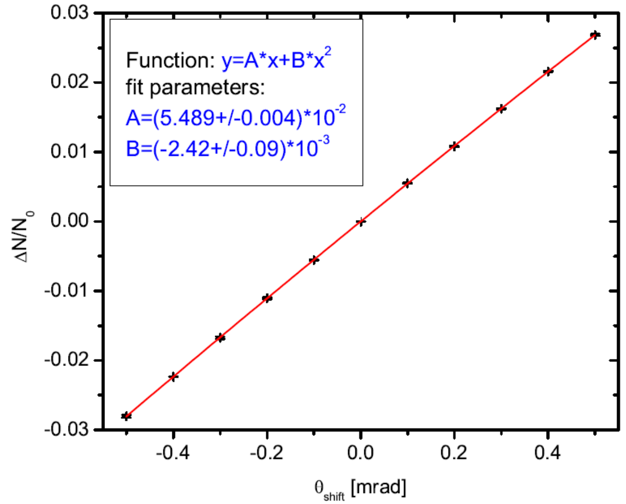
$$\Delta\mathcal{L}/\mathcal{L}=x_{EMD}\cdot\Delta\theta$$

Resulting relative uncertainty of $\mathcal{L}$: ~ $5(2)\cdot10^{-4}$ at 500 GeV (1 TeV) – EM deflection grows with decreasing CM energy

- Similar approach is proposed for FCCee [Y. Voutsinas, 34 FCAL WS, CERN, 2019]

The method is robust w.r.t. the variation of the beam parameters (bunch charge and sizes)





[IBJ, S. Lukic, et al. , 2013 JINST 8 P08012]

- A challenging interplay between maximizing luminosity and constraining related backgrounds at a tolerable level
- MDI region is facing numerous requirements, not only to host a luminosity monitor
- It is clear that, in order to control complex systematics in luminosity measurement:
  - Luminometer has to be placed at the outgoing beam (cancelation of the positioning systematics)
  - No MDI material in front of a luminometer to compromise energy measurement (i.e. off-momentum suppression)
  - Electron (positron) polar angle measurement is important to correct for EM deflection
  - Inner radius control of order of micron is required
  - Interesting idea (FCCee) to determine actual beam-energy asymmetry (center-of-mass energy) from the acolinearity of muons produced in $e^+e^- \rightarrow \mu^+\mu^-$

- Instrumentation of the very forward region is very important for realization of physics program at any future machine
- Circular colliders (CEPC and FCCee) are facing particular challenges to reach luminosity precision goal of 10^{-4} (of particular importance at the Z^0 pole), where the most critical challenges are coming from mechanics and beam-induced uncertainties
- At last, but not at least, practical challenges related to detector design, read-out, prototyping, assembly, etc. have to be addressed in parallel


THANK YOU!
Oxford Universiy

A long list of sources of integral 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
- 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

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 (off-momentum electrons from the beam-gas scattering)

Uncertainty of count is based on:
- 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)

- Instrumentation of the very forward region is very important for the realization of the CepC physics program. Luminosity measurement uncertainty can affect:
  - 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
- In most cases 10^{-3} precision of luminosity should be sufficient
- In particular, 10^{-4} uncertainty of integral luminosity comes from:
  - Fermion-pair production cross-section - access to the higher order corrections
  - W-pair production cross-section
  - Z^0 total hadronic cross-section at Z^0 pole
- This a 'common knowledge', 10^{-4} sensitivity should be proven through the dedicated physics analyses

CEPC CDR Parameters

	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.73	0.34	0.036
Half crossing angle (mrad)	16.5		
Piwinski angle	2.58	7.74	23.8
N_e/bunch (10^{10})	15	15	8.0
Bunch number (bunch spacing)	242 (0.68us)	1220 (0.27us)	12000 (25ns+10%gap)
Beam current (mA)	17.4	87.9	461
SR power /beam (MW)	30	30	16.5
Bending radius (km)	10.6		
Momentum compaction (10^{-5})	1.11		
β_{IP} x/y (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.17/0.004
Transverse σ_{IP} (um)	20.9/0.068	13.9/0.049	5.9/0.078
ξ_x/ξ_y/IP	0.031/0.109	0.013/0.12	0.0041/0.056
V_{RF} (GV)	2.17	0.47	0.1
f_{RF} (MHz) (harmonic)	650 (216816)		
Nature bunch length σ_z (mm)	2.72	2.98	2.42
Bunch length σ_z (mm)	3.26	6.53	8.5
HOM power/cavity (kw)	0.54 (2cell)	0.87(2cell)	1.94(2cell)
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	0.29	0.44	0.55
Lifetime _simulation (min)	100		
Lifetime (hour)	0.33 (20 min)	3.5	7.5
F (hour glass)	0.89	0.94	0.99
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.93	11.5	16.6