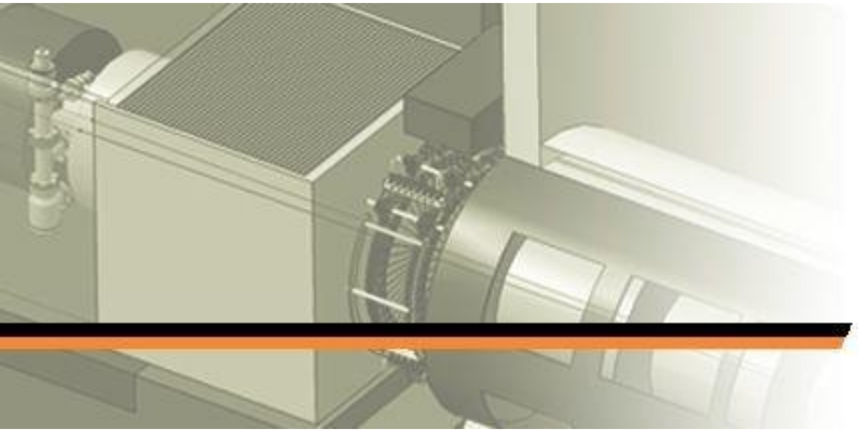

Instrumentation of the very forward region at a future linear collider

on behalf of the FCAL Collaboration

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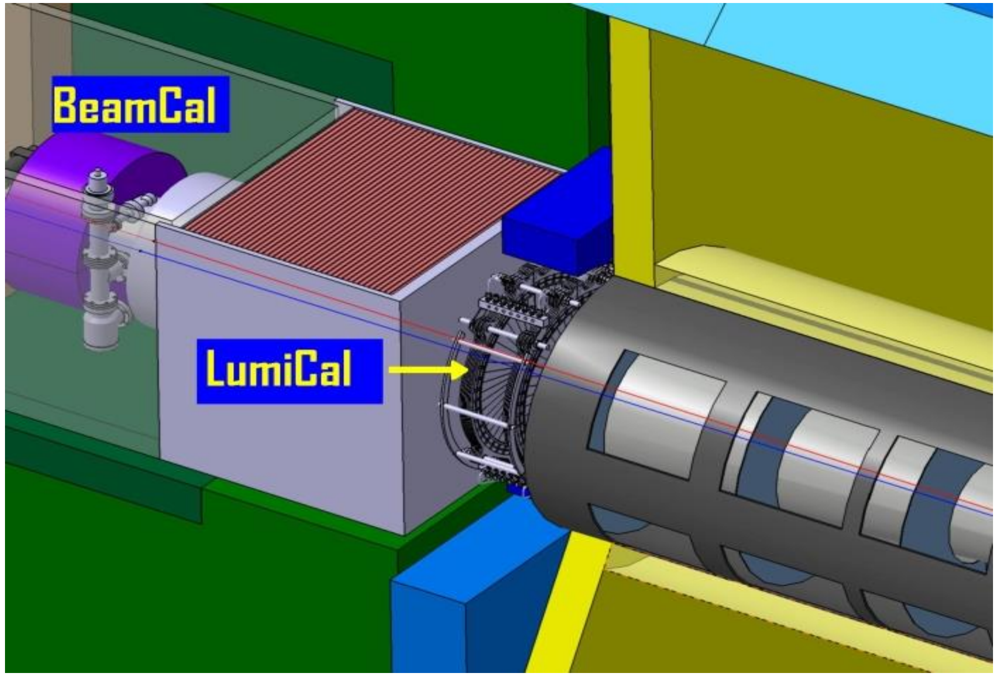
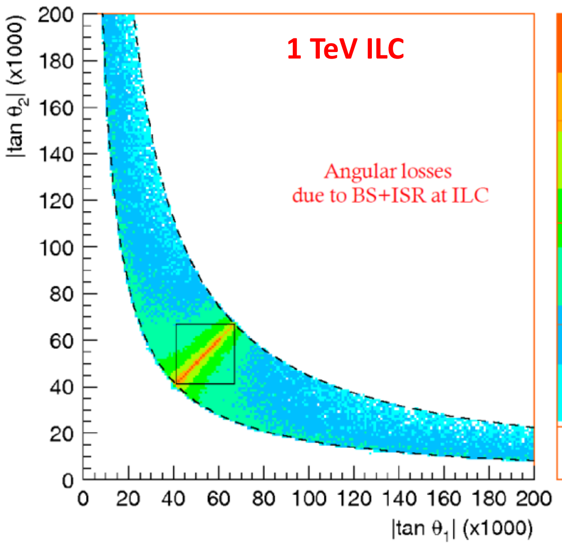
- This talk will be focused on ILC
- ILC vs. CLIC – many things are different (beam structure, cms energies, experimental environment), but even more are the same (main FCAL detectors are LumiCal and BeamCal, design and technology choice are similar, comparable performances)
- All developed within the FCAL Collaboration http://fcal.desy.de/

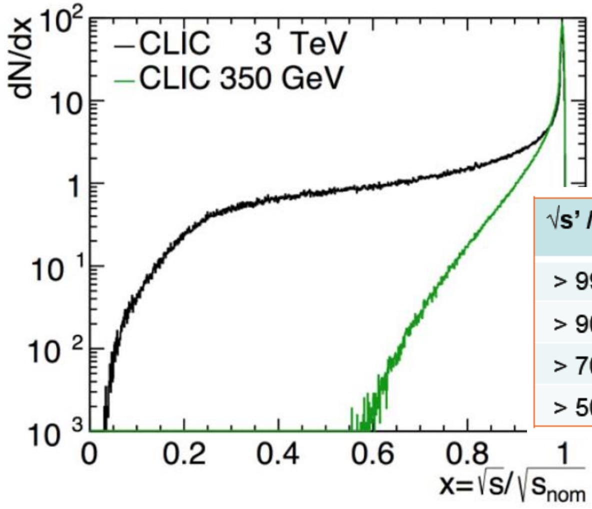


- *Single-pass acceleration ⇒ dense and short bunches ⇒ intense* ***Beamstrahlung (BS)*** *caused by EM interaction between the opposite bunches*
- ⇒ Energy loss of the initial state (often asymmetric) ⇒ loss of colinearity of Bhabha particles in the L-R arms of the LumiCal ⇔ counting losses (deterioration of the luminosity spectrum)

Data driven method is implemented to correct for the angular losses at a permille level [S. Lukic, IBJ, et al., JINST 8 P05008]

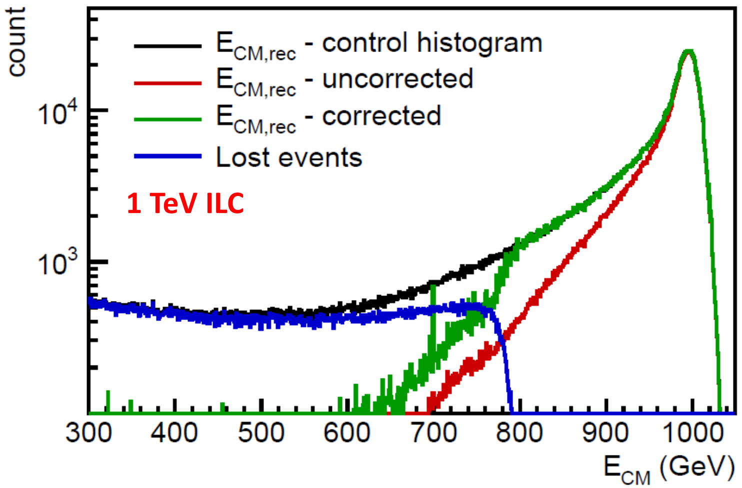


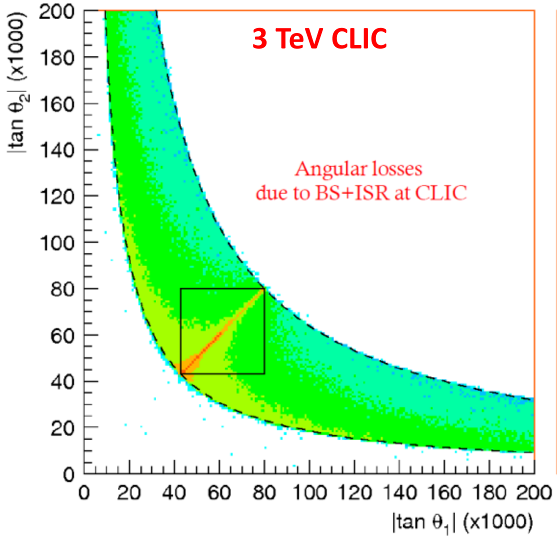
[S.Lukic et al. IHEP2012]



√s' /√s	0.5 TeV	3 TeV
> 99 %	62 %	35 %
> 90 %	89 %	54 %
> 70 %	99 %	76 %
> 50 %	~100 %	88 %

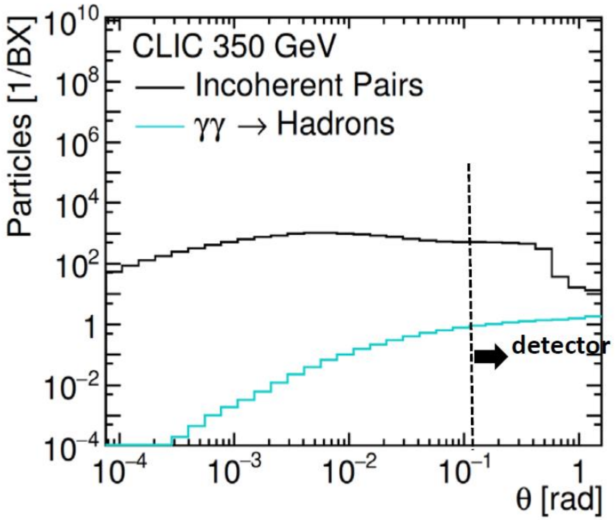
[IBJ, S. Lukic et al., JINST 8 P08012]





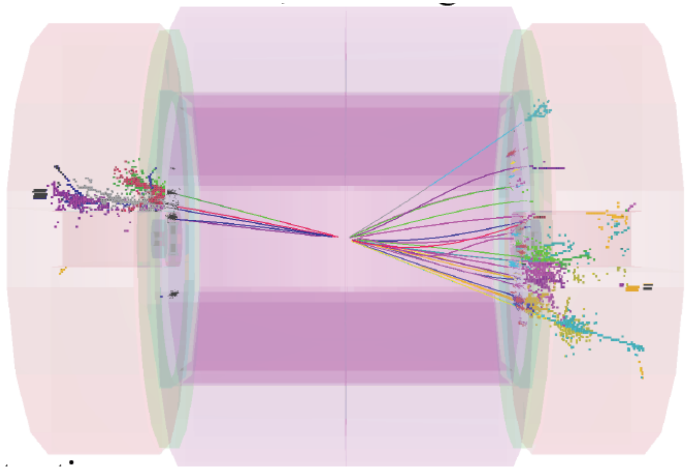
- *Single-pass acceleration $\Rightarrow$ dense and short bunches $\Rightarrow$ intense **Beamstrahlung (BS)** caused by EM interaction between the opposite bunches*
- $\Rightarrow$ In particular at high energies (i.e. above 1 TeV) interactions between BS photons become very frequent (3.2 per BX at 3 TeV CLIC) producing hadrons in the central region (main tracker, calorimeters)

[Physics and Detectors at CLIC, CDR, 2012]

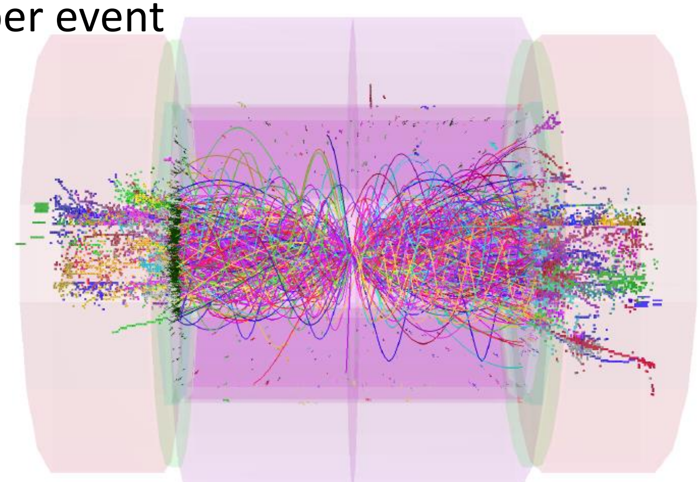


Resolved by 10 ns time-stamping + pT and timing cuts based on the reconstructed cluster-time in calorimeters

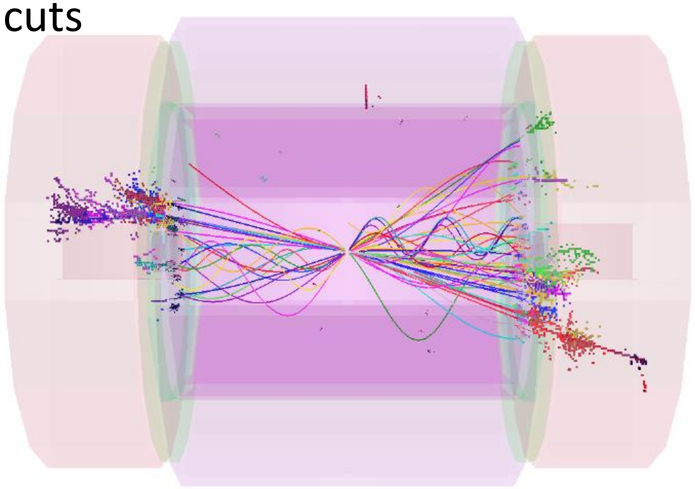
WW-pair production at 3 TeV CLIC



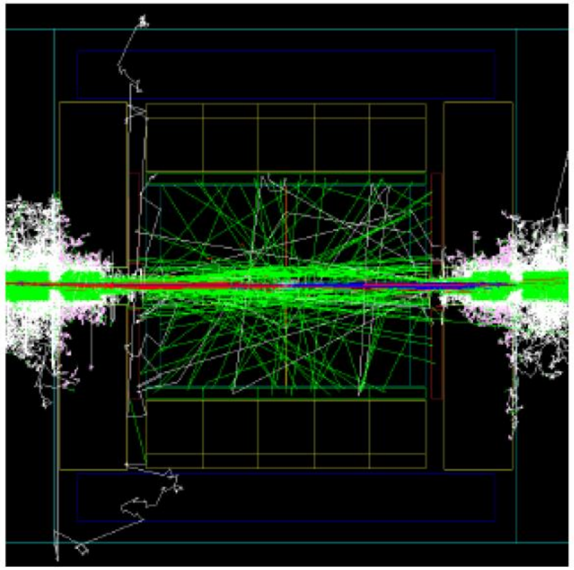
$\gamma\gamma \rightarrow$hadrons deposit in average 1.2 TeV per event



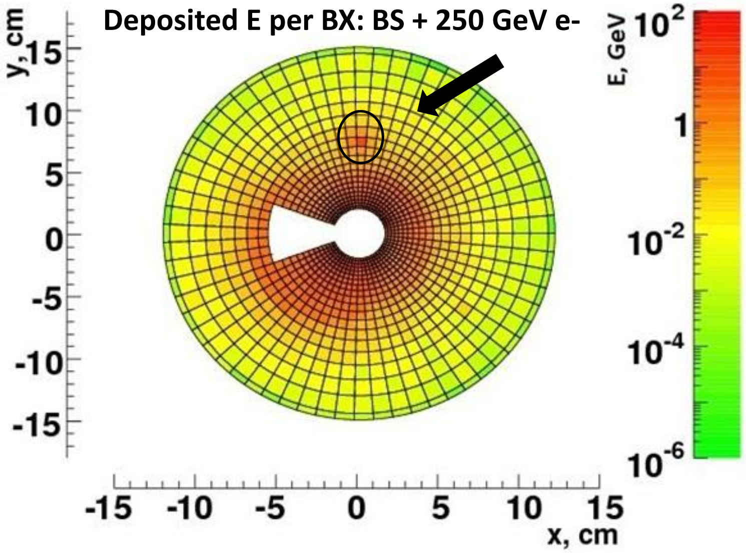
Reduced to ~100 GeV after p_T and timing cuts



- *Single-pass acceleration ⇒ dense and short bunches ⇒ intense **Beamstrahlung (BS)** caused by EM interaction between the opposite bunches*
- ⇒ BS photons get converted via incoherent production into e+e- pairs (i.e. 3.5 per BX in the detector acceptance region, at 3 TeV CLIC), depositing large doses (i.e. MGy per 500 fb^{-1} at 500 GeV ILC) in the very forward detectors (BeamCal) ⇒ issue of radiation hardness and occupancy
- ⇒ Pairs back-scattered of the forward detectors (mainly BeamCal) give rise to the occupancy of other detectors (charged particles in Si tracker, photon conversions in TPC, neutrons in end-cap calorimeters)



[S. Schuwalow, FCAL WS, Tel Aviv 2016]

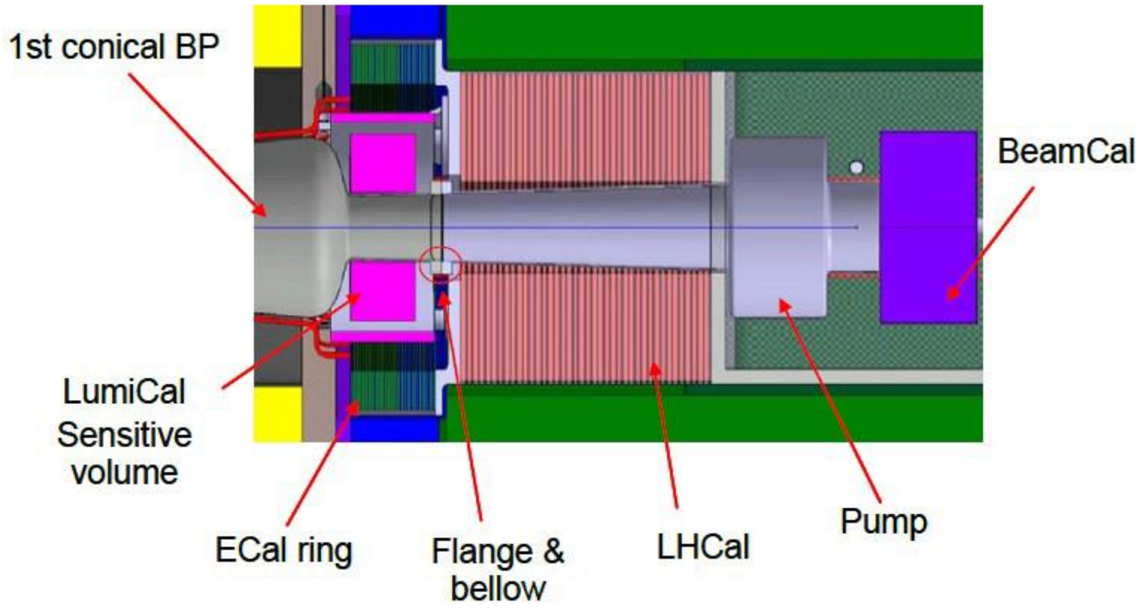


- Particle acceleration in a single pass (linear collier) posses several challenges:
  - Accelerator vise - compact and dense bunches, high EM filed gradient
  - Intense Beamstrahlung (rising with energy) deteriorates luminosity spectrum and produces systematic effects on luminosity measurement
  - Beamstrahlung is a source of background in central and forward detectors

- Beamstrahlung is not an issue at circular machines
- Nevertheless it has to be quantified and proven through simulation that it can be accounted for with uncertainty $\leq$ luminosity precision
- BS ‘side-effects’ in terms of detector occupancies have to be determined

- Angular coverage down to the lowest polar angles 5 (15) mrad at ILC (CLIC)
- Beam-induced backgrounds at low angles determines calorimeters apertures, drive sensors radiation-hardness and trade-of between cell-sizes and occupancies
- Very forward region is instrumented to provide:
  - **Precision measurement of integral luminosity (permille level in the top 20% at ILC and CLIC)**
  - **Instantaneous luminosity determination using BS (bunch by bunch at ILC)**
  - **Tuning of the beam parameters**
  - **Identification of high-energy electrons at very low polar angles**
  - **Detector hermeticity (forward jet reconstruction, missing energy signatures)**
  - **Shielding of the central detectors from the particles backscattered of the QD0 magnet**

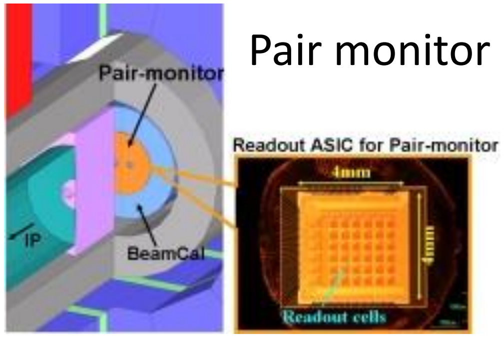
L*=4.4m [ILD TR]



Fiducial volume [mrad]	CEPC	ILC	CLIC
BeamCal		5-45	15-38
LumiCal	53-79	42-67	38-110

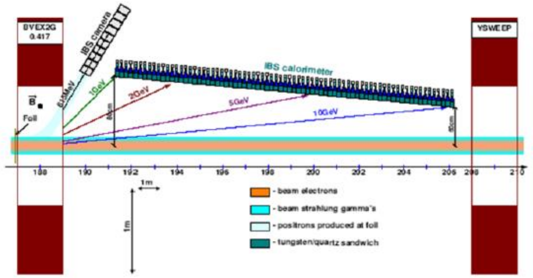
Forward detectors

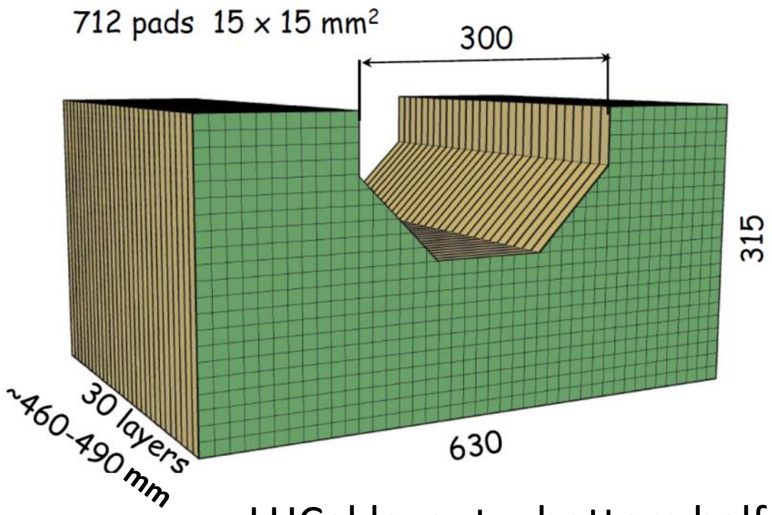
- LumiCal – precision integrated luminosity measurement (small-angle Bhabha scattering), hermeticity
- $\Delta L/L < 10^{-3}$ for $\sqrt{s}$ = 0.5-1TeV
- $\Delta L/L < 2{\cdot}10^{-4}$ for GigaZ – very challenging!
- LHCal – PID behind LumiCal, hermeticity (WSi-pads)
- BeamCal – instantaneous luminosity optimization, beam parameter determination, hermeticity
- Pair monitor – Si-pixel layer in front of the BeamCal to assist beam-tuning ($2 \cdot 10^5$ (0.4 x 0.4) mm pixels), beam parameter determination (averaged over several BXs)
- GamCal - instantaneous luminosity optimization (BS photons detector at z =190 m), improves beam diagnostics, reduced correlations between observables for beam parameter determination; Can be particularly useful for low instantaneous luminosity – small BeamCal depositions.



Pair monitor

GamCal





LHCal layout – bottom half

- Si-W sampling calorimeters (30/40 layers at ILC/CLIC)
- One X_0 (3.5 mm) thickness of the absorber
- Compact calorimeters – Moliere radius ~ 2 cm
- LumiCal sampling 48/64 (azimuthal/radial) segmentation of silicon sensor
- BeamCal W absorber +poly(mono)crystaline CVD diamond/GaAs/rad-hard Si

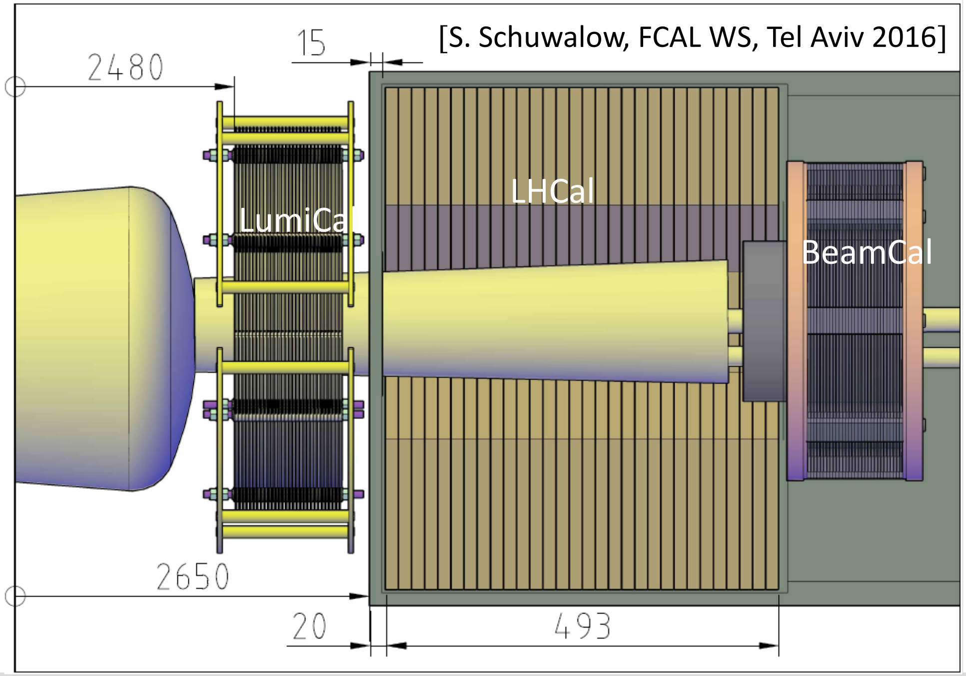
- 14 mrad x-angle
- Detectors are centered at the outgoing beam
- Anti DID fields parallel with the outgoing beam
- Optimized to minimize background
- This set-up enables OPAL-style acceptance cuts cancelling L-R symmetric systematic effects in luminosity measurement

- LumiCal
- Polar angle and energy reconstruction of Bhabha particles is relevant for any energy and colinearity based selection in luminosity measurement

$\sigma_\theta = 2.2 \times 10^{-2} mrad$

Polar angle: $\Delta\theta = 3.2 \times 10^{-3} mrad$

Energy: $\frac{\sigma_E}{E} = \frac{0.21}{\sqrt{E/GeV}}$



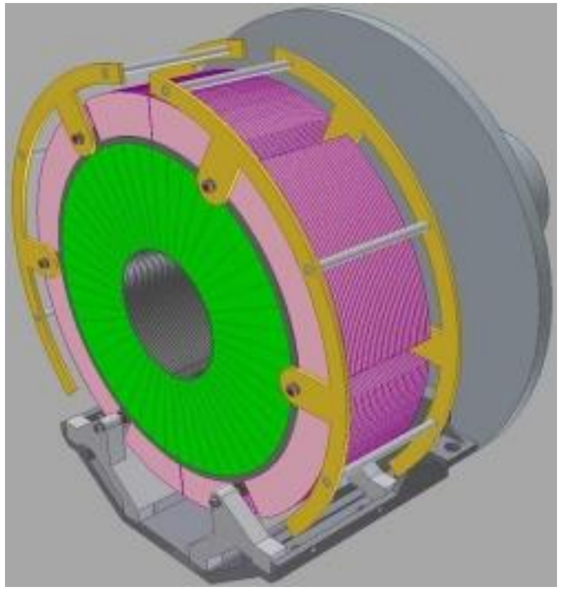
		Unit	
Absorber layer	1 X_0	mm	3.5
Air gap		mm	0.1
Sensor thickness + pad metalization		mm	0.320 + 0.020
Fanout thickness		mm	0.4
Total plane thickness		mm	4.355
Total X_0		int	30
x/y/z position		mm	+15.9/0/2500
R_{inner}* (sensitive area)		mm	76
R_{outer} (sensitive area)		mm	280
θ_{inner}		mrad	30.4
θ_{outer}		mrad	111.5
Tilt		mrad	7
Space for electronics (outside the plane)		mm	4.5
Mass of the LCAL (1 arm)		kg	211.319

Table 3: LumiCal geometry.

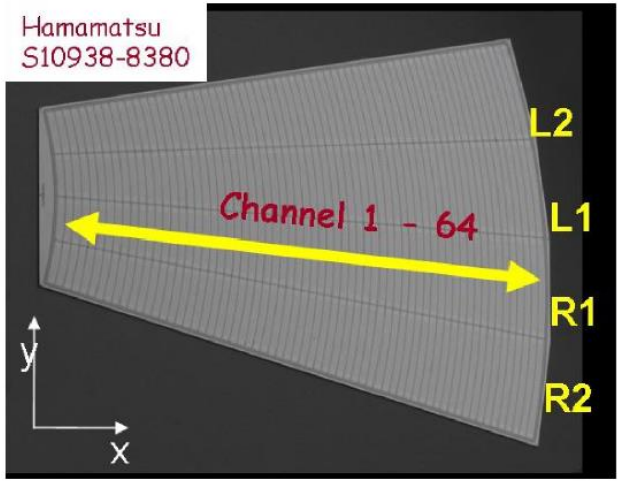
*We assume an Anti-Detector Integrated Dipole field: the magnetic field is parallel to the outgoing beams. Optimized for low backgrounds.

		Unit	
Pad design - std	Azimuthal sectors	int	48
	$\Delta\varphi_{sec}$	mrad	131
	Radial sectors	int	64
	ΔR	mm	1.76
	pads/layer	int	3072

Table 4: LumiCal segmentation (for 14 mrad crossing angle).



7.5 deg LumiCal tiles.



		Unit	14 mrad
Graphite shield thickness		mm	100
Absorber layer	$1\ X_0$	mm	3.5
Sensor layer		mm	0.3
Readout plane /air gap		mm	0.2
total X_0		int	30
x/y/z position		mm	+24.2/0/±3595
R_{inner} (sensitive area)		mm	20
$R_{outer}{}^{*}$ (sensitive area)		mm	150
$R_{beam\_in}{}^{**}$		mm	15
θ_{inner}		mrad	5.6
θ_{outer}		mrad	41.7
Tilt		mrad	7
~ Weight of absorber and sensor (sensitive area)		kg	144.4

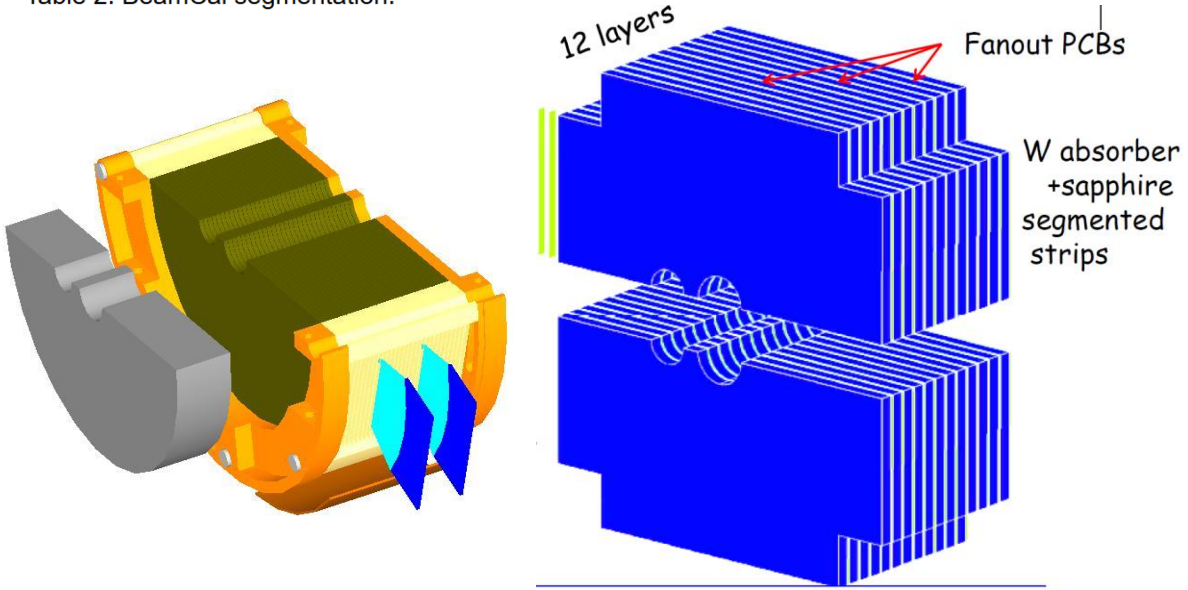
Table 1: BeamCal geometries for different beam settings.

* We assume an Anti-Detector Integrated Dipole field: the magnetic field is parallel to the outgoing beams. Optimized for low backgrounds.

** Crossing angles of 14 or 20mrad require an additional hole in each BeamCal for the incoming beams.

		Unit	14 mrad
$0.8\ R_M$ cell size	Rings	int	16
	ΔR	mm	8.125
	Sectors	int	8 of 45 degree
	Cells per sector	int	160
	Cells/layer	int	1280
	Blind area	degree	±22.5 around incoming beam, rings with R>63.4 are complete (n > 6)

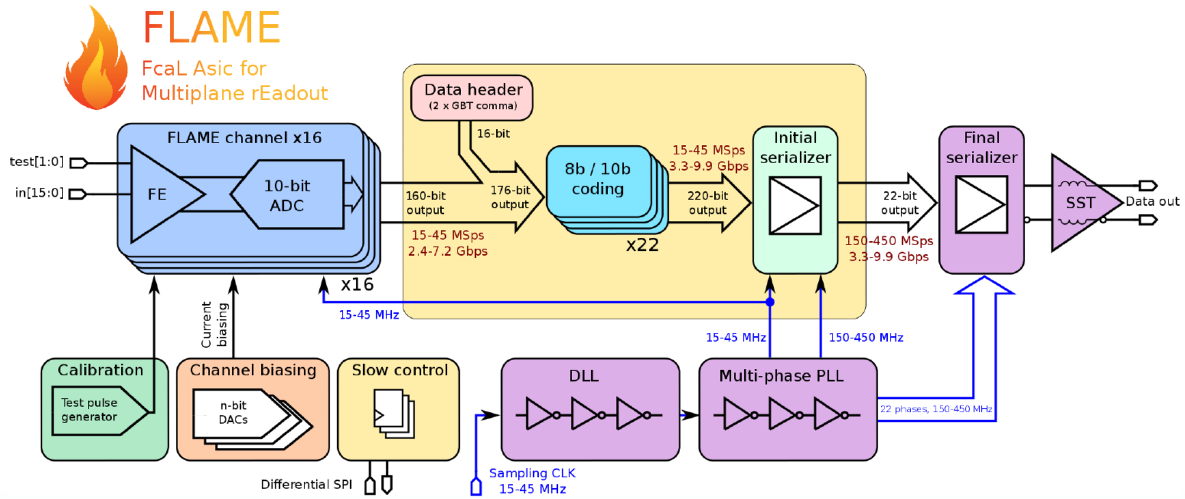
Table 2: BeamCal segmentation.

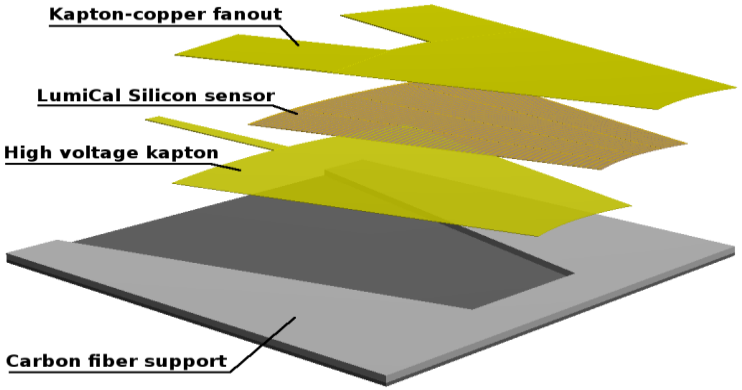


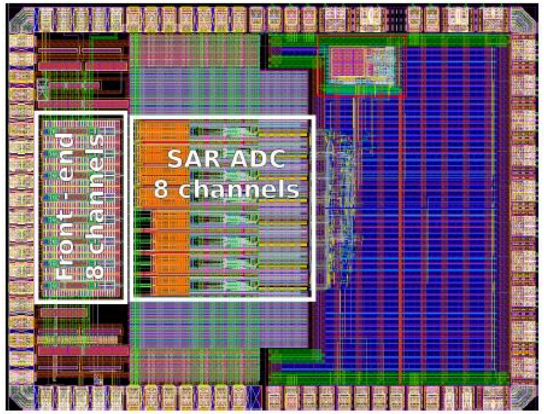
But, other technologies under study i.e sapphire sensors, GaAs, CVD,…

- FE ASICS designed for physics (up to 10 pC per channel) and calibration modes (MIP 4 fC)
- Fast enough to process subsequent bunches (~300 ns at ILC)
- Shower reconstruction in LumiCal and BeamCal need 8 to 10-bit ADC (to maintain energy resolution)
- Power dissipation can be reduced in the power-pulsing mode (power switched-off after every train - 200 ms)

- FLAME: 16-channel ultra-low power readout ASIC in CMOS 130 nm technology
  - FE&ADC in each channel,
  - fast serialization and data transmission,
  - all functionalities in single ASIC
- 8-channel FLAME chip V0 designed and prototyped



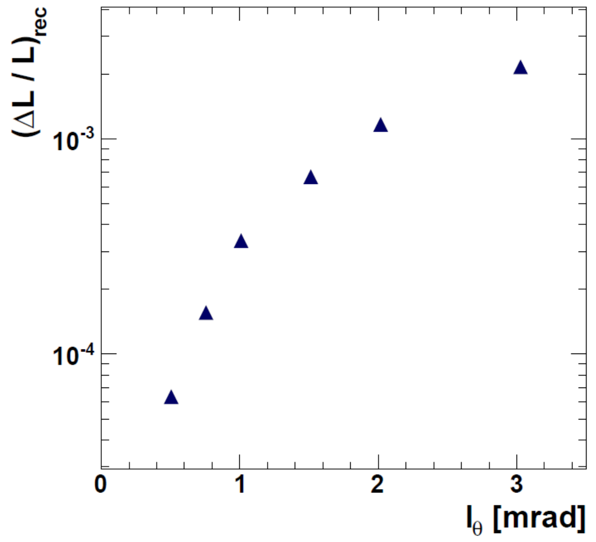


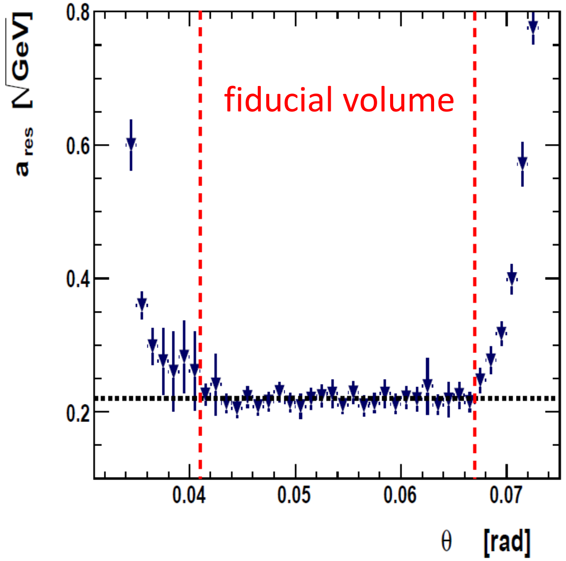


[M. Idzik, FCAL WS Belgrade 2017]

- θ reconstruction
- Depositions are read-out from each pad
- Each deposition is logarithmically weighted $W_i = \{0, \max(C + \ln(E_i/E_{tot}))\}$
- Larger the deposited energy – more relevant pad
- C=const, optimized to minimize σ_θ
- σ_θ and $\Delta\theta$ are Gaussian width and mean of the $|\theta_{rec}-\theta_{gen}|$, $\Delta\theta = (3.2 \pm 0.1) \times 10^{-3}$ mrad, $(\Delta L/L)_{rec} = 1.6 \times 10^{-4}$.
- $\Delta\theta$ is due to the non-linear signal sharing between pads, depends on pad size l_θ
- E reconstruction
- Almost all e and γ deposit energy in the detector
- Usual parameterization of the relative E resolution $\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}\ (\mathrm{GeV})}}$ $a_{res} = (0.21 \pm 0.02)\ \sqrt{\mathrm{GeV}}$.

[H. Abramowitz et al., JINST 5 P12002]

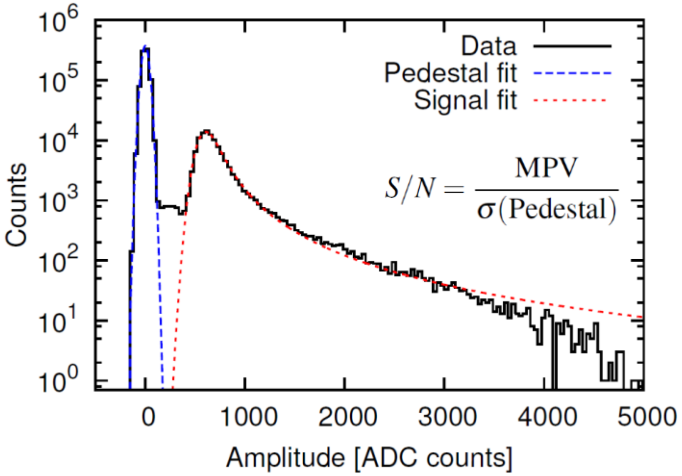


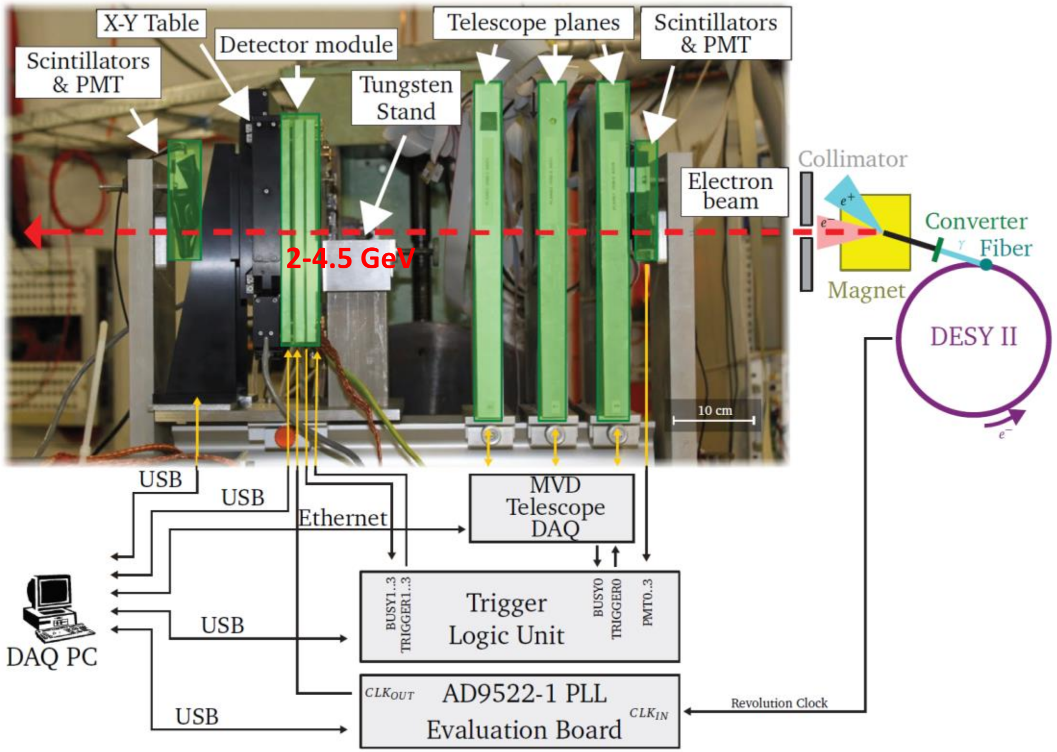


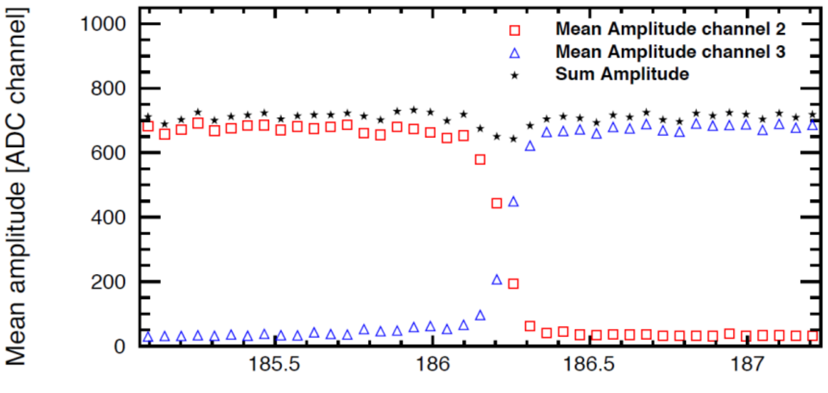
Several test-beam campaigns

- In previous campaigns dedicated tests to FE and ADC ASICs have been performed
- In particular to measure S/N ratio needed for MIP measurement (high-energy muons are foreseen for calibration, alignment and radiation damage determination)
- Full functionality of single sensor planes was demonstrated with S/N ratio of about 20 for relativistic single electrons

[H. Abramowitz et al., JINST 10 P05009]





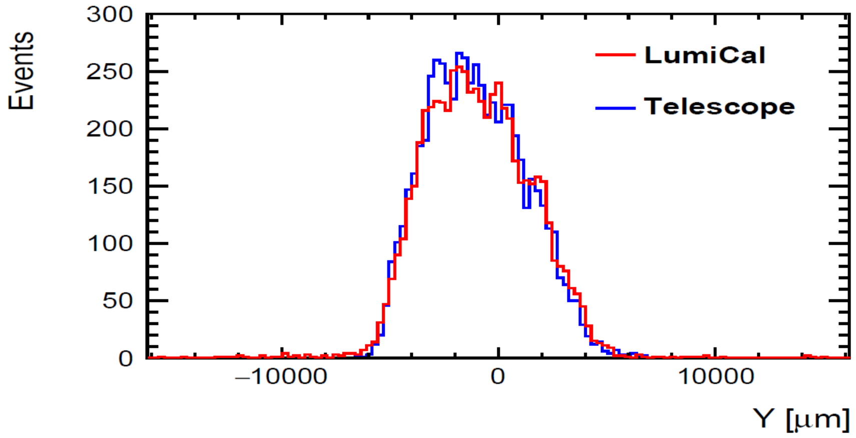


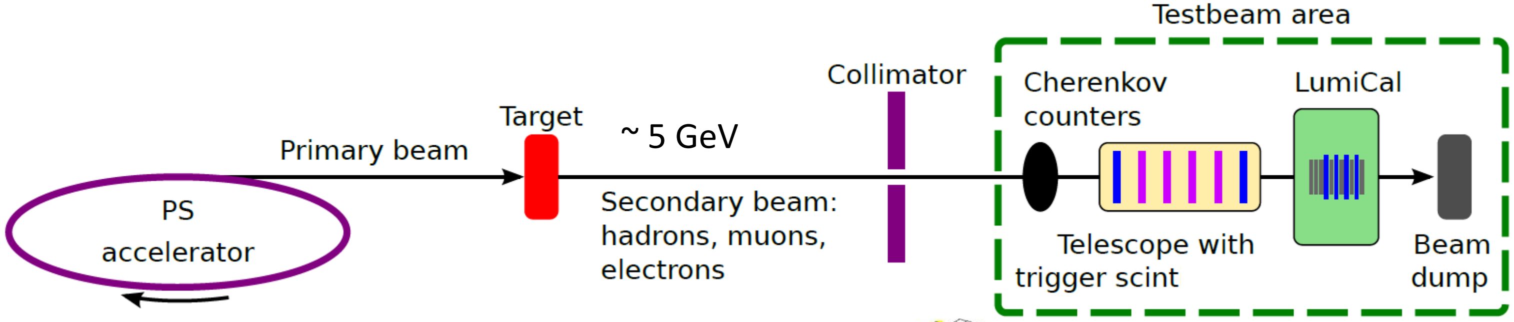
Signal loss ≤ 10% between the pads (100 μm gap)

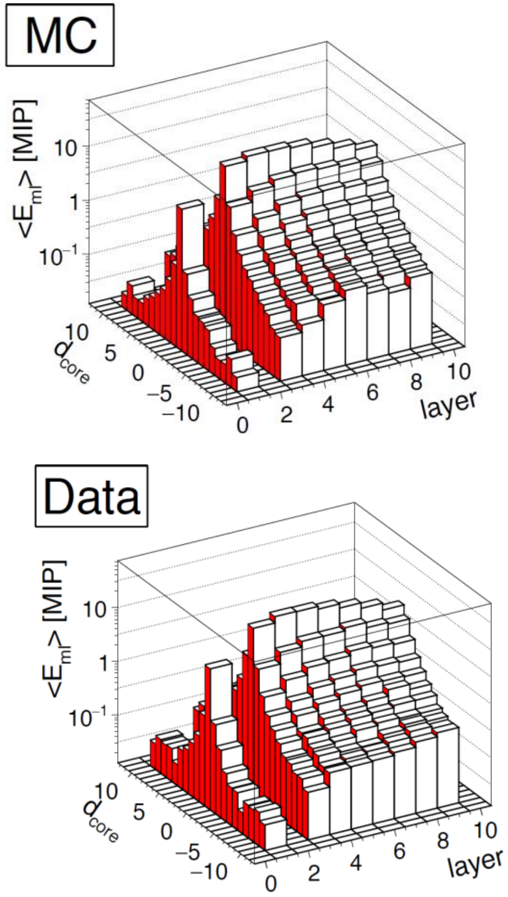
- Several test-beam campaigns
- 2014 campaign published in http://arxiv.org/abs/1705.03885 , submitted to Eur.Phys.Journal C
- Study EM shower development – compare it with (Geant 4 based) simulation
- Determine the Moliere radius

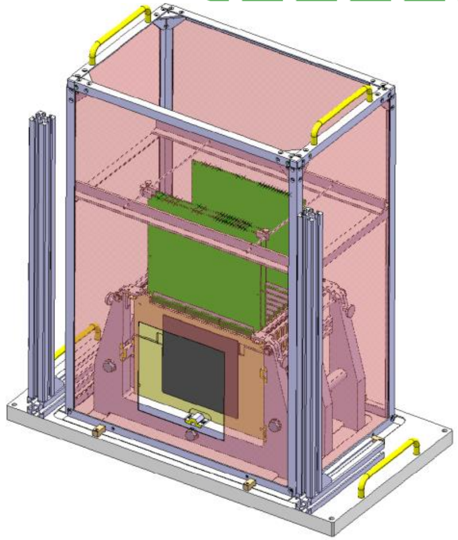
$$R_{\mathcal{M}} = 24.0 \pm 0.6(\text{stat.}) \pm 1.5(\text{syst.})\text{mm}$$

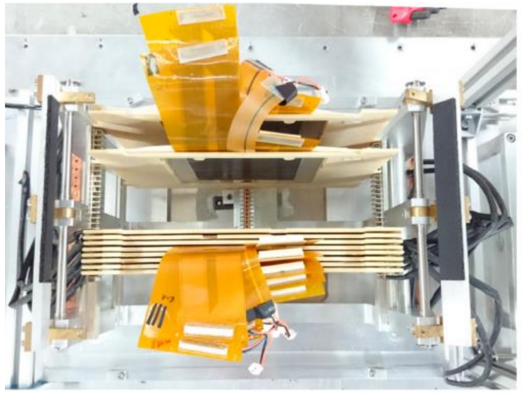
- Good data-MC agreement







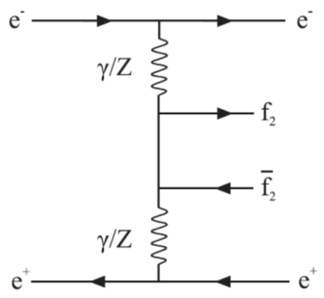


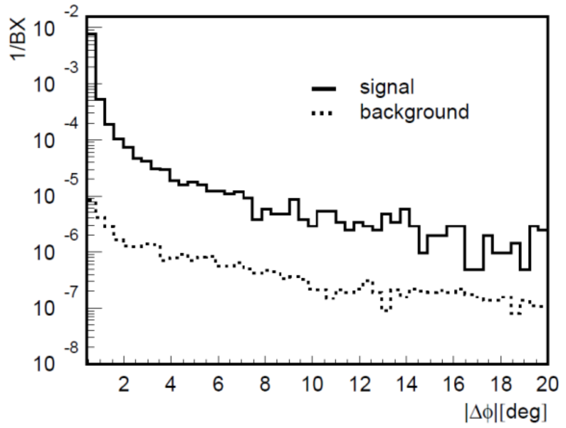


- Luminosity measurement based on small-angle Bhabha scattering
- In 99% percent at ILC energies (within LumiCal acceptance) pure QED process (t-channel γ exchange)
  - NB: Won't be the case at the Z^0 pole
- L-R asymmetric cuts in polar angle acceptance (OPAL-style), applied to the LumiCal halves
  - This is to accommodate for the loss of acceptance due to BS
  - And, importantly, to reduce systematics arising from L-R symmetric geometrical effects (positioning and alignment)
- Corrective method for BS introduced [S. Lukic et al. JINST 8 P05008]
  - Calculate the velocity of the e+e- CM frame after ISR emission (collision frame) w.r.t. the lab frame
  - Weight each event on the basis of the collision frame velocity to ensure compensation of the counting losses
- Acoplanarity cut applied on reconstructed showers to reduce physics background from 2-photon processes (high cross-section ~ several nb)
- Look into the top 80% of the luminosity spectrum

- Message: position (θ) and energy reconstruction in the LumiCal is important for luminosity measurement

[IBJ et al., JINST 8 P08012]





		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	$0.6 \cdot 10^{-3}$	$0.1 \cdot 10^{-3}$
$\Delta L/L$		$2.2 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$

Full-size effect of physics background on luminosity uncertainty - can be taken as correction once the higher-order contributions to the x-section are known.

- Due to the presence of BS precision luminosity measurement at LC is challenging
- Data driven method (based on polar angles of the Bhabha particles) is developed to correct for the counting loss
- There is (still) no simulation independent way to correct for the electromagnet deflection of the final state particles (due to the attractive EM fields of the opposite bunches)
- Beam energy has to be known at the level of 10^{-3} (several hundreds of MeV at ILC energies)
- 2-γ background is estimated conservatively as ≤2 events per 1000 Bhabha scattering
- Bhabha cross-section has to be known at the level of 10^{-4} at all relevant energies
- It is assumed as realistic that all mechanical uncertainties contribute no more than 10^{-4} per effect

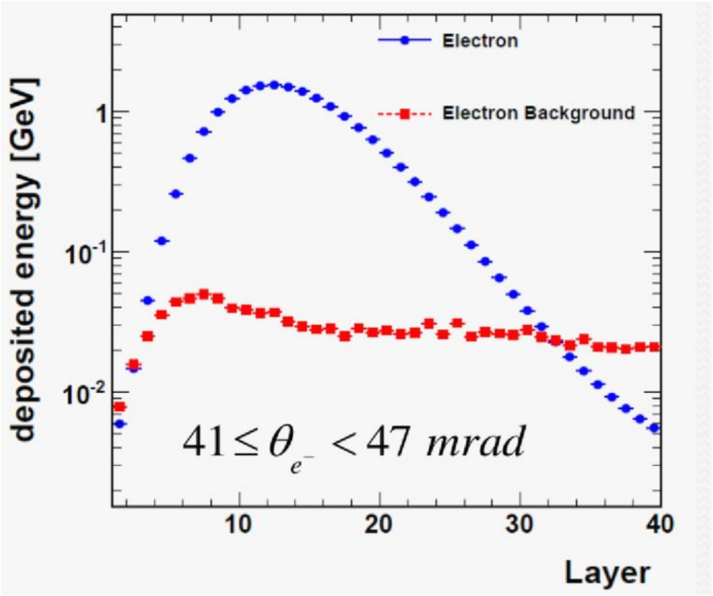
[A. Stahl, LC-DET-2005-004]

[IBJ et al., JINST 8 P08012]

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	$0.5 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$
$(\Delta L/L)^1$	$4.3 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
$(\Delta L/L)^2$	$2.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$

- In an analysis high-energy electron can be emitted in the FCAL region both by the signal and background – forward electron tagging is important (Higgs sector, E_{miss} signature, BSM)
- Candidate EM shower for tagging is constructed from particles (electrons, photons) in a 5 mrad cone
- Look if deposited energy is 4σ above the average background in the layer with maximum deposition
- Take into account variations from E resolution and bkg. fluctuations

- Alternatively, one can look into fully simulated energy background deposits in the calorimeter cells.
- Make tagging probability maps as function of E, θ and φ
- The same shape of tagging efficiency for the two approaches



Longitudinal profile of energy deposition by EM showers and by incoherent pairs in luminometer at CLIC

Process	Rejection rate by EM shower tagging
$e^+e^- \to e^+e^- \mu^+\mu^-$	44%
$e^\pm\gamma \to e^\pm \mu^+\mu^-$	38%
Signal	0.2%

Background and signal rejection rates in σ_{prod}xBR($H \to \mu\mu$) measurement at 1.4 TeV CLIC

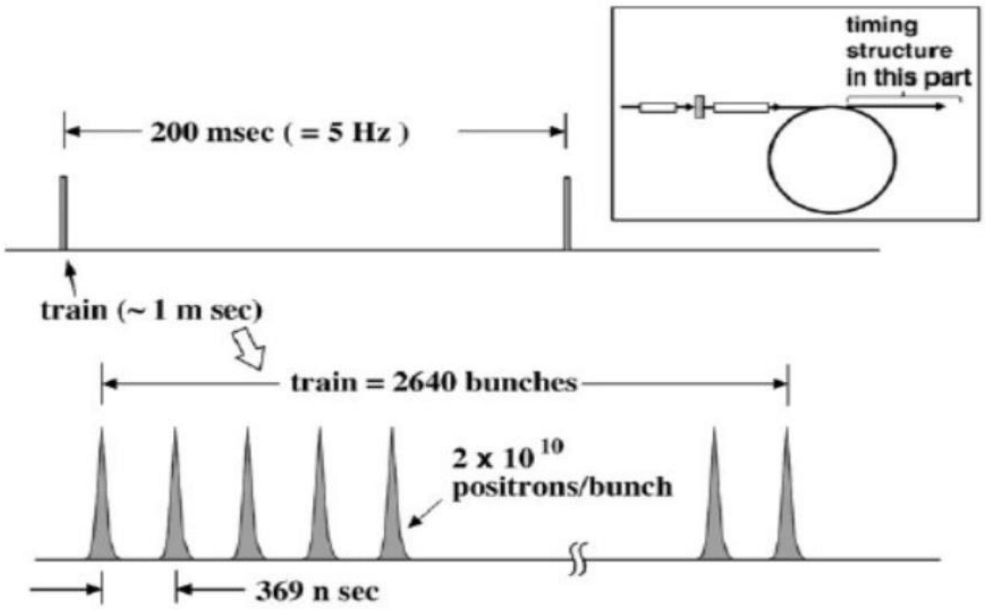
[G. Milutinovic et al., Eur. Phys. J. C 75 (2015) 515]

- Adequate instrumentation of the very forward region is important for multiple reasons (integral luminosity measurement, forward electron tagging, detector hermeticity, etc.)
- Its performance is relevant for physics measurements not only in the very forward region (BSM, dark matter, Higgs sector) .
- Particular challenge for instrumentation and measurements in the very forward region at linear colliders comes from the Beamstrahlung.

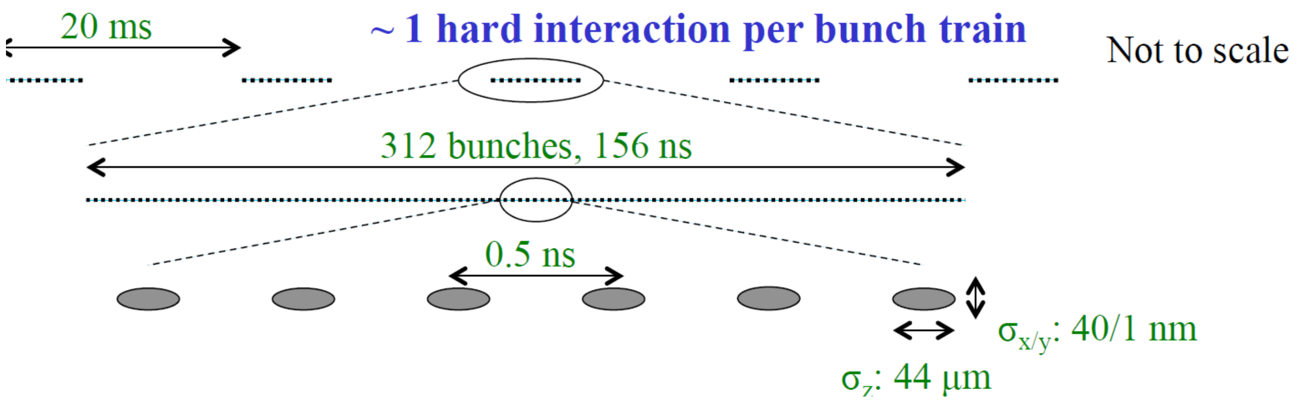
- Compact and finely granulated calorimeters have been proposed to provide precision E and θ measurements of EM showers.
- Simulation studies have shown that the integral luminosity can be measured with 10^{-3} uncertainty at ILC energies.
- For the first time a multi-plane operation of a prototype of a luminometer designed for a future e^+e^- collider detector was carried out by the FCAL Collaboration.
- Ongoing studies on optimal solutions for forward detectors (i.e. LumiCal: ultrathin sensors, bonding technique sensor-fanout, tracker in front the LumiCal for e/γ separation, etc.)

BACKUP

ILC


timing
structure
in this part
200 msec (= 5 Hz)
train (~ 1 m sec)
train = 2640 bunches
2 x 10 10
positrons/bunch
369 n sec

CLIC


20 ms
~ 1 hard interaction per bunch train
Not to scale
312 bunches, 156 ns
0.5 ns
σx/y: 40/1 nm
σz: 44 µm

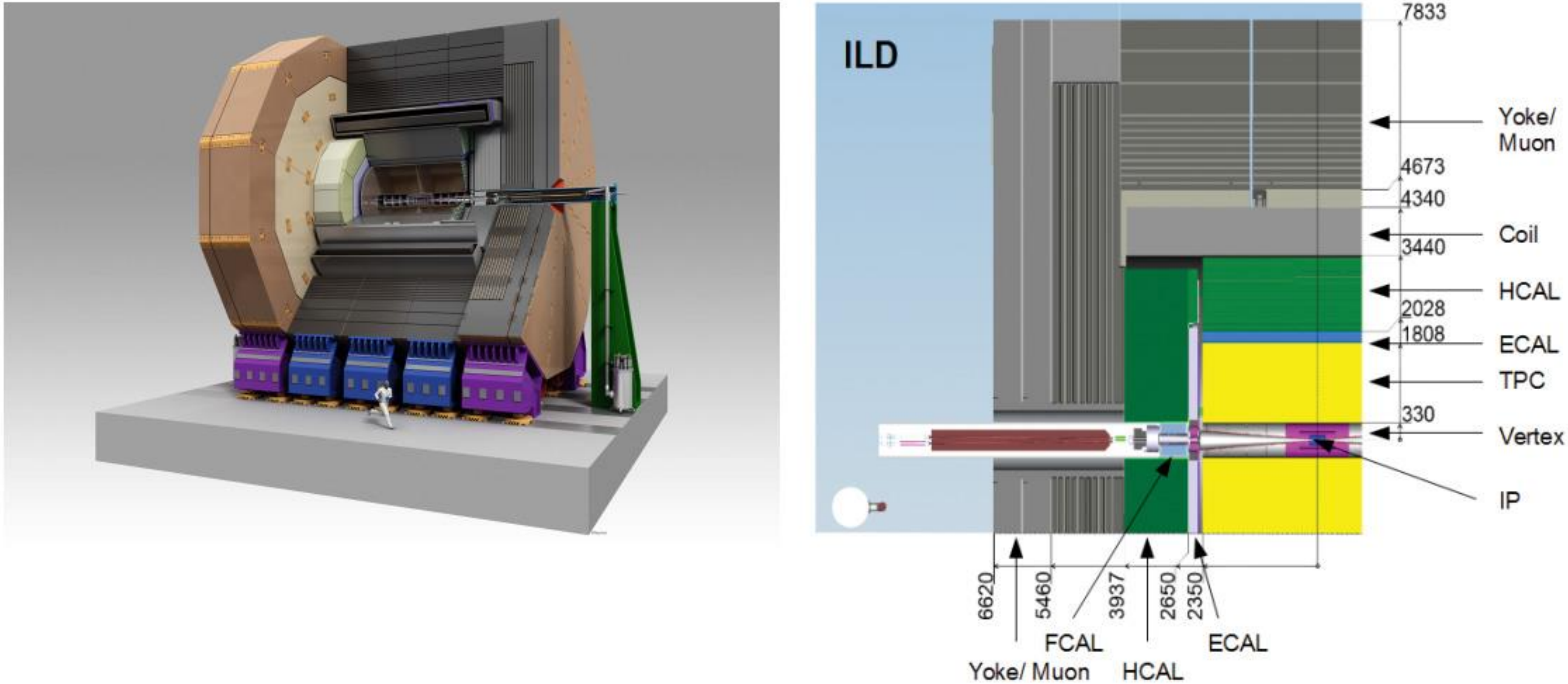


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.