Precision Absolute Luminosity with Photon Pairs

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Measuring absolute luminosity with the pure QED process, $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$

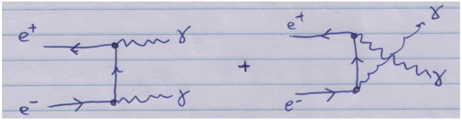
Largely a repeat of Paestum workshop talk – but with several updates

With acknowledgments to Brendon Madison who helped with the detector design studies

Outline

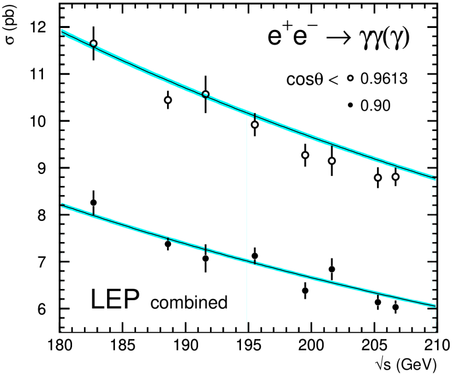
1. Di-Photon Basics
2. Luminosity Targets
3. Features of $e^+e^- \to \gamma\gamma$ for Absolute Luminosity
4. Design Ideas for PLUG-Cal / Revising Forward Calorimetry
5. GEANT4 Initial Design Studies
6. Longitudinal Design Studies
7. Transverse Design Investigations
8. Detector/Accelerator Constraints
9. Summary

Di-Photon Basics

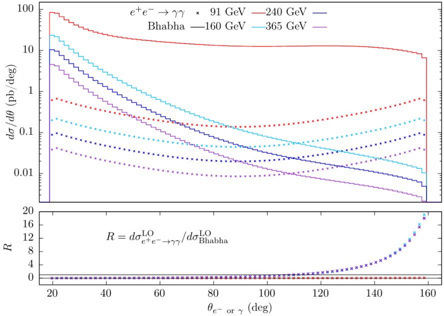


$$\frac{d\sigma^U_{\text{Born}}}{d|\cos\theta|} \approx \frac{2\pi\alpha^2}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right)$$

1302.3415



Here $\theta_\gamma > 16^\circ$ or $\theta_\gamma > 26^\circ$



$\sqrt{s}$ (GeV)	LO (pb)	NLO (pb)	w h.o. (pb)	Bhabha LO (pb)
91	39.821	41.043 [+3.07%]	40.870(4) [−0.43%]	2625.9
160	12.881	13.291 [+3.18%]	13.228(1) [−0.49%]	259.98
240	5.7250	5.9120 [+3.27%]	5.8812(6) [−0.54%]	115.77
365	2.4752	2.5581 [+3.35%]	2.5438(3) [−0.58%]	50.373

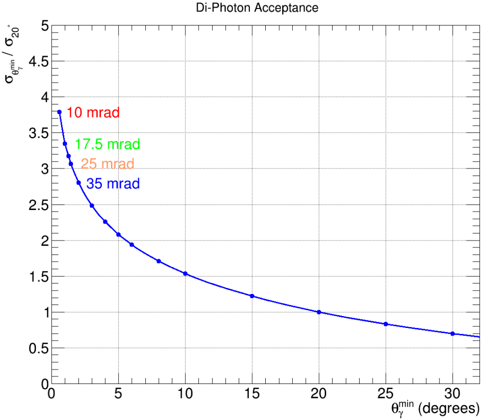
$20^\circ < \theta_\gamma < 160^\circ$, $x_2 > 0.5$ from 1906.08056

Maximizing the acceptance

The angular distribution favors more forward angles

$$\frac{d\sigma^{U}_{\text{Born}}}{d|\cos\theta|} \sim \frac{1}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right)$$

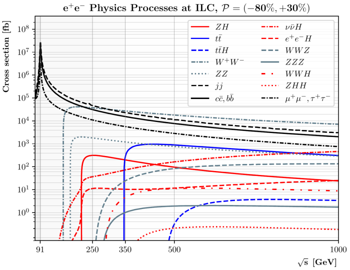
Note: $\sigma_{RL} = \sigma_{LR}$, $\sigma_{LL} = \sigma_{RR} \approx 0 \rightarrow$ assists beam polarization measurement.



- Significant increase in potential accepted cross-section for all $\sqrt{s}$ compared with a 20° acceptance cut[a].
- Factor of 2.5 – 3 increase feasible by extending to ILD LumiCal acceptance?
- Will need excellent Bhabha rejection.

[a] typical LEP choice - driven by tracker

LUMI: Targets for Absolute Luminosity Precision



- The standard process used for **absolute** luminosity at LEP is small-angle **Bhabha** scattering, $e^+e^- \to e^+e^-$ (high statistics).
- This will be important for **relative** luminosity and could still lead in absolute precision.
- The pure QED process, $e^+e^- \to \gamma\gamma$, is now also considered very seriously for **absolute** luminosity, for both experimental and theoretical reasons.
- It emphasizes reconstruction (rejection) of high energy photons (electrons) over most of the detector's solid angle.

- Ideally match/exceed stat. precision of the accelerator. Denominator normalizing processes should have cross-sections exceeding the numerator.
- Example 1 (ILC): WW at 250 GeV. With 0.9 ab^{-1} (LR) $\to 1.7 \times 10^{-4}$.
- Example 2 (10^{12} Z with FCC) $\to 1.0 \times 10^{-6}$.

What is realistically achievable in terms of systematics is another matter. For now my assumption is to target 10^{-4}. Note ILC studies have typically stated 10^{-3}.

LUMI: $e^+e^- \to \gamma\gamma$ for absolute luminosity

Targeting 10^{-4} precision. Cross-sections (and ratios) at $\sqrt{s} = 161$ GeV.

θ_{min} (°)	$\sigma_{\gamma\gamma}$ (pb)	$\Delta\sigma/\sigma$ (10 μrad)	$\sigma(ee)/\sigma(\gamma\gamma)$
45	5.3	2.0×10^{-5}	6.1
20	12.7	2.2×10^{-5}	22
15	15.5	2.4×10^{-5}	35
10	19.5	2.9×10^{-5}	68
6	24.6	3.9×10^{-5}	155
2	35.7	8.1×10^{-5}	974

- Unpolarized Born cross-sections. $\pm$24% for (80%/30%) longitudinal beam polarization. Typical HO effects: + 5 to 10%.
  Counting statistics adequate for $\sqrt{s} \gg m_{\mathrm{Z}}$. Note: Use **whole** detector.
- For comparison, 10μrad knowledge for OPAL small-angle **Bhabha** lumi acceptance, corresponds to uncertainty of 100×10^{-5}.
  $\gamma\gamma$ has "relaxed" fiducial acceptance tolerances compared to Bhabhas.
- Bhabha rejection (e/γ discrimination) important. Can be aided by much better azimuthal measurements given electron bending in the B-field.
  FoM: $B\, z_{LCAL}$. ILD has 8.7 Tm. FCC about 2.2 Tm. OPAL was 1.04 Tm.
  Adequate rejection feasible within tracker acceptance? / challenging below.

Why is $e^+e^- \to \gamma\gamma$ attractive?

Focus here on experimental things. The hope and expectation is that theory will be able to keep up.

- Bhabha process looks problematic for precision absolute luminosity. It was even not under control experimentally at LEP1 due to the beam-induced effect biasing the luminosity acceptance at the 0.1% level (See 1908.01704).
- Di-photon process should be much less affected. Should check BW and BH.
- Di-photons much less sensitive to polar angle metrology than Bhabhas.
- Di-photons less sensitive to FSR than Bhabhas.
- Likely more feasible now with modern calorimeters to do a particle-by-particle reconstruction. Likely easier with di-photons.
- Current detector designs are arguably over-designed for Bhabhas with some compromises for overall performance especially for high energy photons in azimuthal and energy reconstruction, and perhaps for hermeticity.
- Di-photons at very low angle is challenging! - but gives significant added value to the assumed clean measurements in the tracker acceptance.

So let's design precision forward calorimetry for electrons AND photons inspired by various ideas (and avoiding some of the compromises) of related designs, CALICE, ILD, SiD, CMS-HGCAL, ALICE-FoCal, Fermi-LAT.

PLUG-Cal: Precision Luminosity Ultra-Granular Calo.

Initial Design Ideas

1. Precise location of the high-energy photon interaction point (via conversion to $\mathrm{e^+e^-}$) in thin absorbers (see Fermi-LAT for extreme version of this).
2. 250 GeV photons need longitudinal containment to avoid large constant term. (10, 1)% of photons survive for (3, 6) X_0 prior to interaction.
3. Above items $\rightarrow$ Many thin layers assuming a sampling Si-W ECAL.
4. Calibration $\rightarrow$ More straightforward with uniform sampling.
5. Potential for adoption in part of pixel-based devices. FoCal prototype achieved 30 micron resolution for high energy electron showers with ALPIDE sensors (1708.05164). 2 planes adopted for ALICE-FoCal upgrade.
6. Include 0^{th}-layer and maybe more for enhanced e/γ discrimination.
7. Emphasize azimuthal measurements for $\mathrm{e^+e^-}$ / $\gamma\gamma$ discrimination. Expect about 57 mrad acoplanarity for $B\, z_{LCAL} = 8.7$ Tm at $\sqrt{s} = 91.2$ GeV.
8. Particle-by-particle reconstruction capabilities.
9. Limited solid-angle $\rightarrow$ cost is not an over-arching concern.
10. Retain or exceed performance for Bhabha-based measurement.

PLUG-Cal: Initial GEANT4 Design Studies

1. In collaboration with Brendon Madison. We have been exploring some aspects of the design using various GEANT4 (4-11-01-patch-02 [MT]) examples (TestEm3, HGCAL_testbeam, gammaray_telescope)
2. Basic **EM energy performance studies** using TestEm3. Range cut 1 micron. XY extent 50 cm. Adds up globally the energies deposited in each type of material. Apply to Si-W calorimeter with various absorber and sensor thicknesses. Main results are for 35 X_0 depth of W absorber with 140 samples with same Si sensor thickness as ILD.
3. Also recently started with HGCAL_testbeam example - looking at **position resolution** observables. This has hexagonal pads with similar transverse dimensions to standard ILD and SiD.

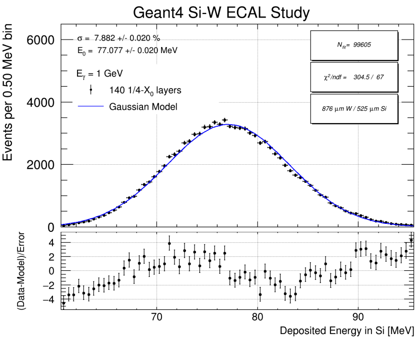
Longitudinal Studies for Energy Performance

Use GEANT4 TestEm3 example with sampling calorimeter with two materials.

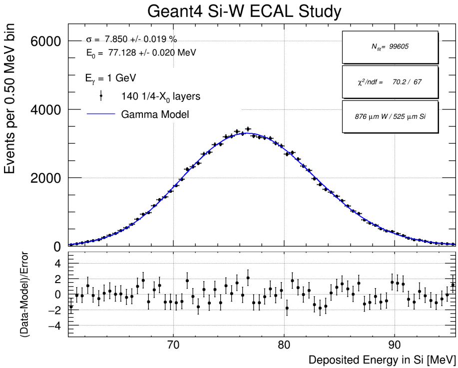
1. Tungsten: 0.876 mm
2. Silicon: 0.525 mm

Measuring Energy Linearity and Resolution

Typical calorimeter analyses fit Gaussian distributions to truncated regions of plots. Here instead a Gamma distribution is used to also model the skewness. The **two** parameters can be configured to be the mean, μ, and the fractional resolution, $(\sigma^{'}/\mu)$. The mean and fractional resolution are annotated as (E_0, σ) in the plots.

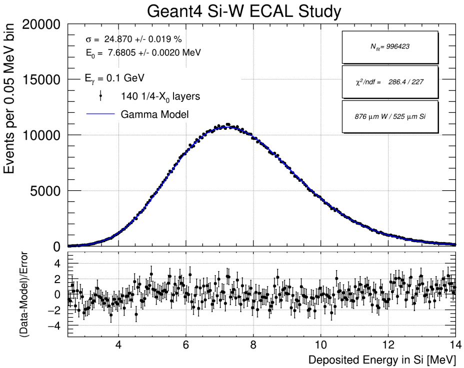


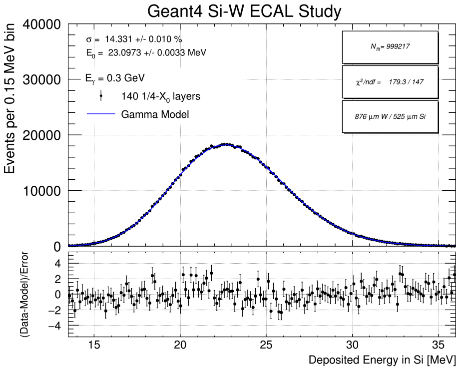
Unacceptable Gaussian fit. Low energies and worse designs give distinct positive skew. Not surprising given what we know about the Poisson and Landau distributions.



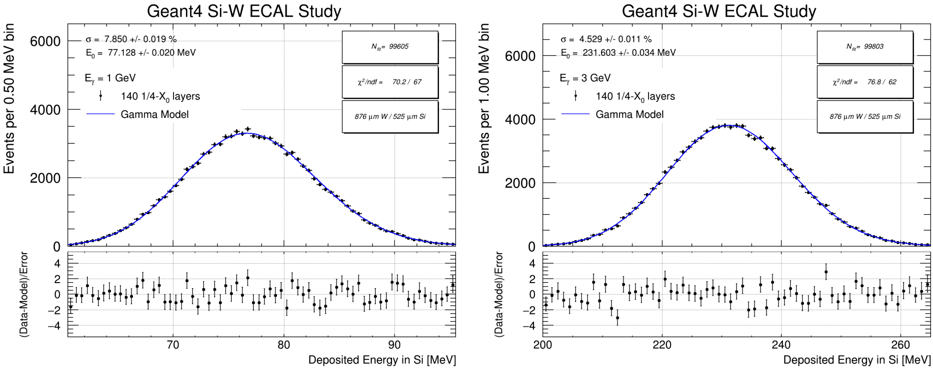
But fits great to Gamma. As σ improves it tends to a Gaussian (CLT).

Energy Linearity and Resolution: 0.1, 0.3 GeV Photons

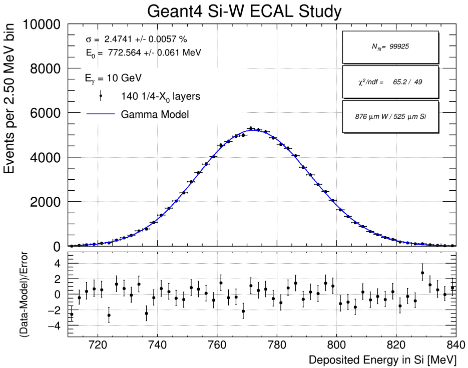


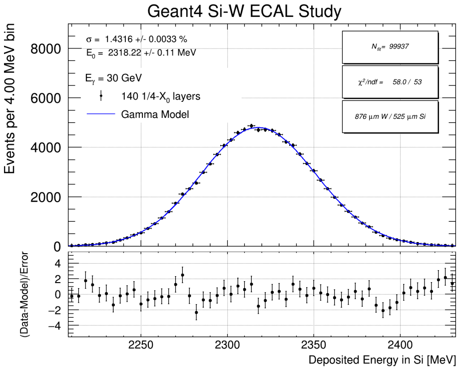


Energy Linearity and Resolution: 1 GeV, 3 GeV Photons

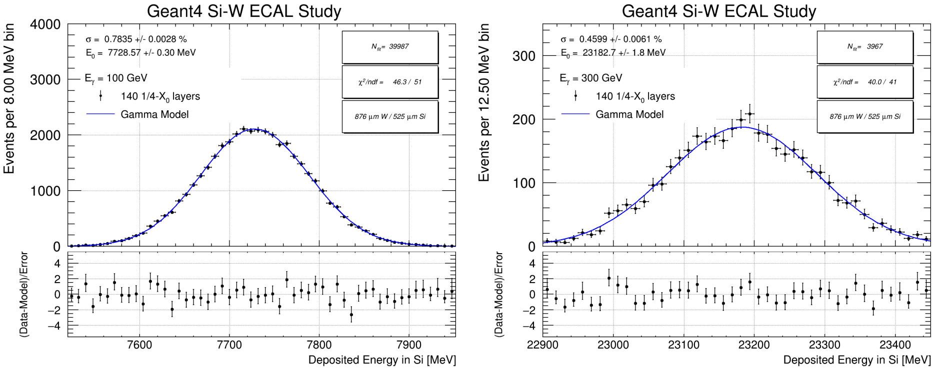


Energy Linearity and Resolution: 10 GeV, 30 GeV Photons

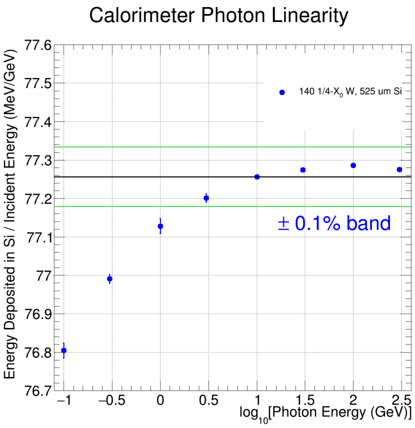




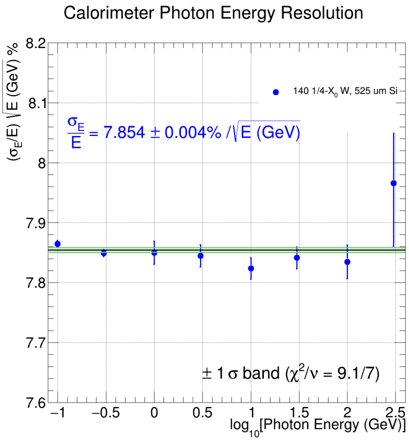
Energy Linearity and Resolution: 100, 300 GeV Photons



Energy Linearity and Resolution



Excellent linearity in [0.1, 300] GeV range. Within 0.1% above 2 GeV. Albedo affects $<$ 2 GeV. EM sampling fraction of 7.7%.



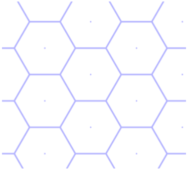
Fits OK with only a stochastic term and **no** constant term. Energy resolution of $0.460 \pm 0.006\%$ at 300 GeV.

Position Resolution Tests

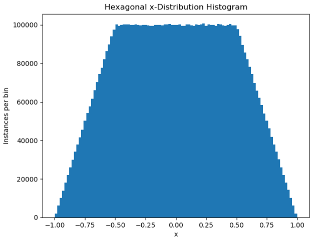
How much can the photon and electron position resolution be pushed with small cells? Can one localize the initial photon interaction point? thus measuring the γ scattering angle, $\theta = \tan^{-1}(r/z)$, and aiding in separating electrons and photons.

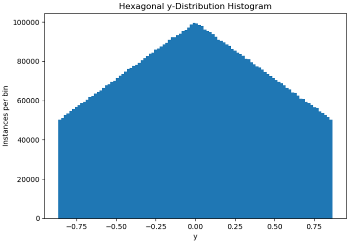
- Use GEANT4 example HGCal_testbeam (CMS). The software was well adapted to the task - but is NOT the proposed design concept.
- Uses **hexagonal** Si pads with 28 layers totalling 27 X_0. Absorbers included Pb, Cu, CuW (quite a mix...).
- In a first step changed hexagonal pixel areas from 1.09 cm^2 to 0.301 cm^2.
- So far, longitudinal structure unchanged - except beam starts inside Al box.

Beam particles are incident on the array with a Gaussian profile with spread in x and y of 1.5 cm. Residuals for calorimeter position observables are calculated with respect to the randomized true beam position event-by-event.

hexagon x horizontal  hexagon y vertical

- For random points within a hexagon of side-length, a, with $a = 1$, centered on $(x, y) = (0, 0)$, the x-coordinate extends from (-1.0, 1.0) while the y-coordinate extends from $(-\frac{\sqrt{3}}{2}, \frac{\sqrt{3}}{2})$.
- The hexagon area is $\frac{3\sqrt{3}}{2}a^2$.
- The square with **identical** area has side-length, $d = 1.61185\ a$.
- The distributions are a superposition of uniform and triangular components.

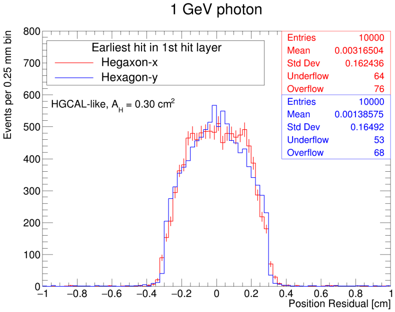


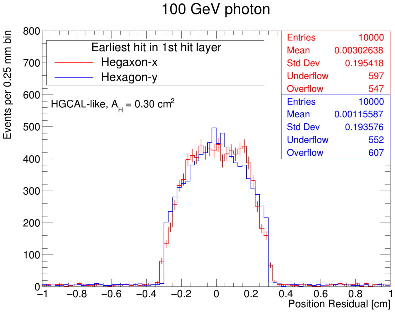


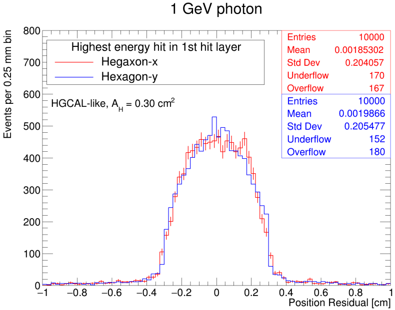
For the same area, surprisingly hexagons have 2% better localisation resolution??

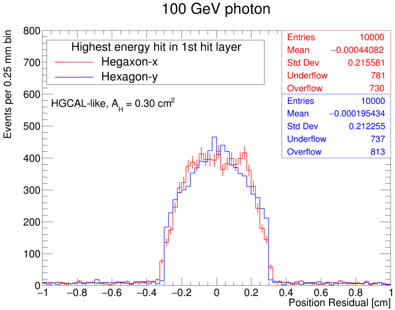
$$\sigma_x^{\text{hex}} = \sigma_y^{\text{hex}} = \sqrt{\frac{5}{24}}\ a = 0.4564\ a \quad \text{while} \quad \sigma_x^{\text{square}} = \sigma_y^{\text{square}} = \frac{d}{\sqrt{12}} = 0.4653\ a$$

Choosing the best hit in the first hit layer

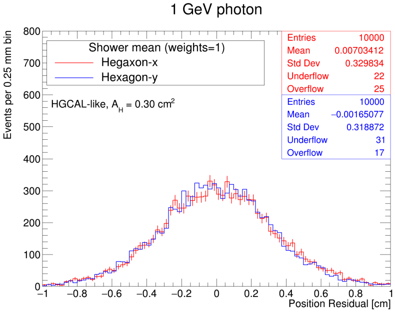


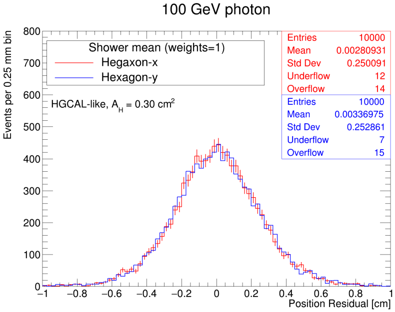


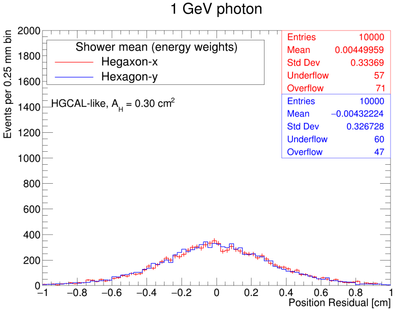


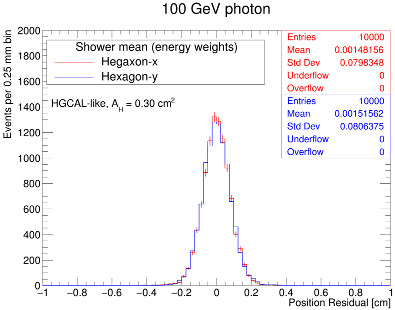


Shower center-of-gravity (all layers)

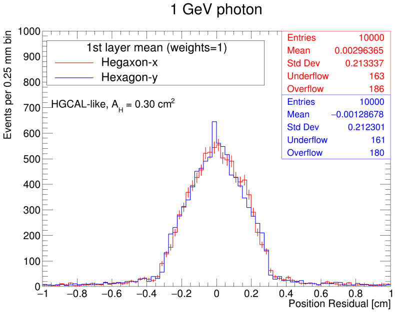


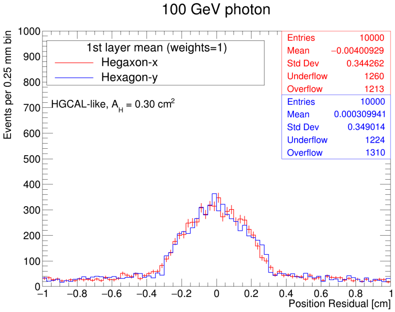


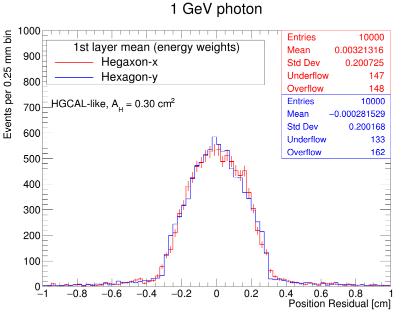


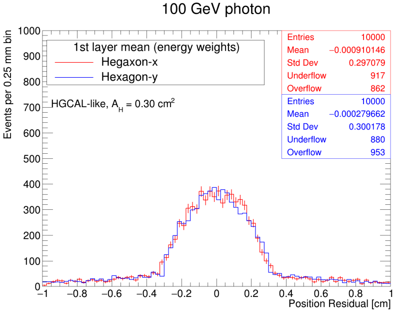


First Hit Layer CoG

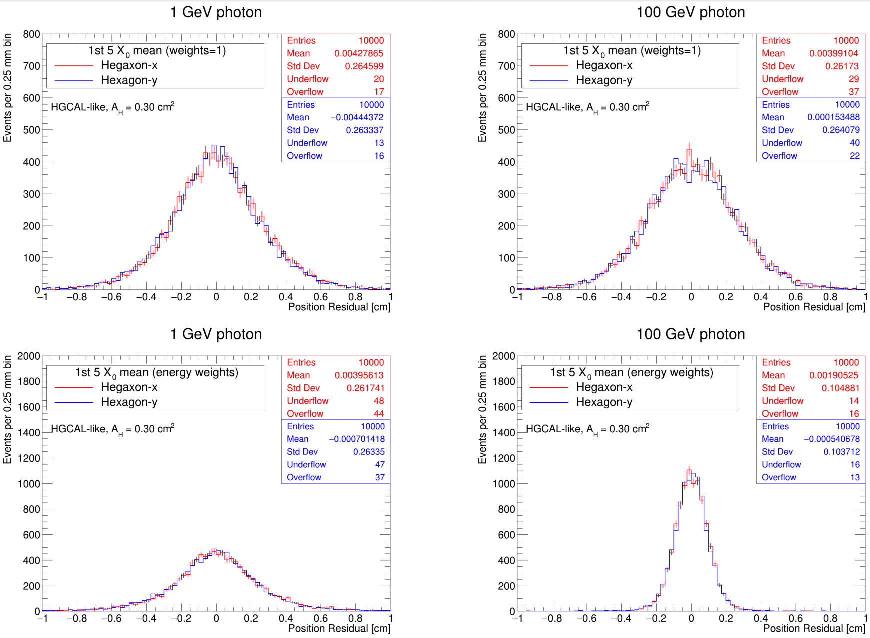






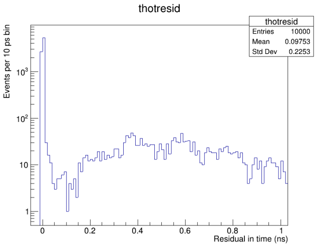


CoG from layers within 5 X_0 of 1st hit layer

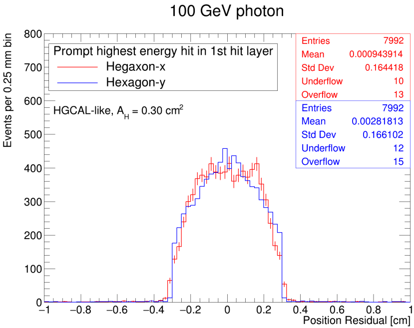


Timing/Promptness Potential (Work In Progress)

Check consistency of true time-of-flight with speed-of-light. Here for the highest energy hit in the 1st hit layer for 100 GeV photon (slide 19d).



Only look at the 80% of events where the chosen hit is prompt.



Define prompt hit as within 0.1ns of expected time. In 20% of events the hit previously chosen based on its energy to define the position is non-prompt.

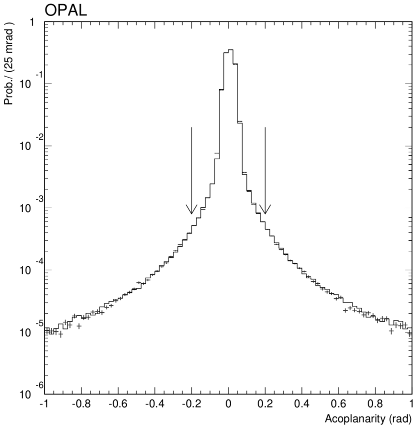
Can recuperate close to perfect hexagonal pitch resolution even for high energy showers (compare with slide 19d). Here perfect would be $\sigma_{x,y} = 0.155$ cm.
To do: use alternate position estimator for the missing 20% - like next layer.

Position Resolution Conclusions

- Good sensitivity at the single cell level for low energy photons.
- More ambiguities for higher energy photons, but much more information from whole shower.
- Much higher granularity can benefit a lot. See eg. FoCal prototype. Dimensions (in microns) of 50*50, 30*30, 25*100, 12.5*50 are all possibilities for pure digital approach.
- Need to also make sure that layer-to-layer alignment is randomized enough.
- Need to do some clustering too.
- Hexagons are different!
- Timing adds potential.

Acoplanarity: $(\phi_R - \phi_L) - \pi$

OPAL luminometer (hep-ex/9910066)



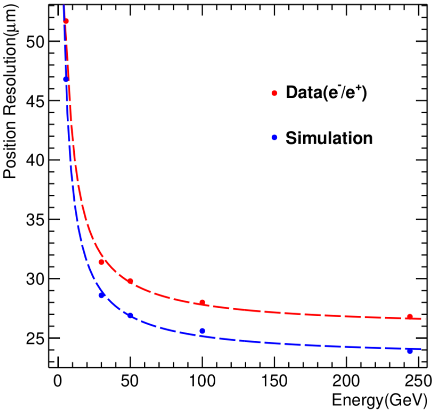
Lousy azimuthal resolution and **eight** times weaker B-field.

Assuming 100 microns position resolution in x and y for the two photons with PLUG-Cal:

- Can measure the acoplanarity to 0.8 mrad at $\theta = 70$ mrad and 1.6 mrad at $\theta = 35$ mrad for $z = 2.48$m.
- Assuming $B = 3.5$ T, $\mathrm{e}^+\mathrm{e}^-$ should have acoplanarity of $+57$ mrad for forward scattered Bhabhas at $\sqrt{s} = 91$ GeV, and $+10.4$ mrad at $\sqrt{s} = 500$ GeV.
- Implies radial resolution of 100 microns.

Is 100 microns feasible? YES.

- Found 782 $\pm$ 6 microns for 100 GeV photons with HGCAL test beam set up and 735 $\pm$ 13 microns for 250 GeV photons. Limited by cell-size of 0.30 cm^2.
- The FoCal prototype 1708.05164 as shown below gives EM-shower position resolution on the 30 micron scale for 30 GeV showers!



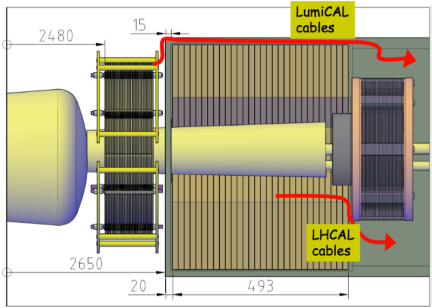
FoCal prototype

- Note offset zero
- Simulation neglects beam divergence.

In fact 100 microns looks to be a good target for 45 GeV photons given the wish to cleanly separate Bhabhas from $\gamma\gamma$ using acoplanarity at all energies. Improved resolution at higher energy should offset some of the separation degradation from less magnetic deflection.

Some Thoughts on Detector/Accelerator Constraints

See 1701.01923 with some considerations on ILD forward calorimetry layout.



ILD is now designed for L*=4.1m

- Conical beam-pipe with LumiCAL, LHCAL, BeamCal
- Currently 683mm for LumiCAL+LHCAL
- LHCAL helps with hermeticity especially for jets
- May well need more space in *z* if PLUG-Cal concept is proved attractive (longer L*?).

Envisaged as much as possible having the readout and services in plane. Pro - more hermetic. Cons - more *z*-space needed and larger Molière radius. Coarsening the longitudinal sampling can help with the constraints but will worsen photon vertexing and energy performance.

Conclusions

- I believe the PLUG-Cal concept has potential for superior performance for luminosity measurements even with $e^+e^- \to \gamma\gamma$ below the tracker acceptance. Potential doubling of acceptance.
- It can likely make radial measurements better than ILD LumiCal but with longer Molière radius and better energy and azimuthal resolutions and hermeticity.
- Note the key issue for luminosity is the systematic uncertainty on the acceptance definition. Likely easier with a tracking-like focus on the position response of the shower start.
- Plan to benchmark against current ILD design for electrons and photons once baseline PLUG-Cal design has emerged.
- What fraction if any of digital-only planes - not clear. Could also consider combined analog + digital planes if digital thin enough. I'm wary of compromising the analog performance as energy resolution is also a key part of defining the acceptance and background rejection.