Reimagining Linear Collider Luminosity Measurements

Initial foray into **precision sampling** forward electromagnetic calorimeter (ECAL) design with upstream **tracking** for future e^+e^- Higgs factories

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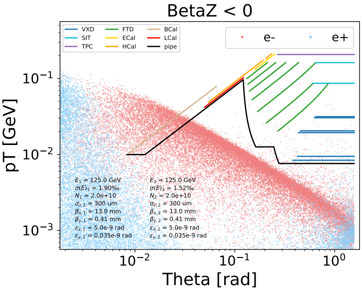
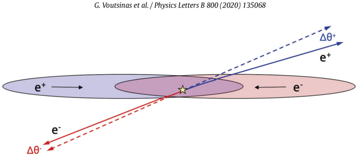
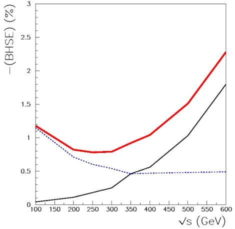
1. Abs. lumi. with $e^+e^- \to \gamma\gamma$
2. SA Bhabhas (SABH) challenging for $\Delta L/L = 10^{-4}$ at the Z
3. Forward ECAL design studies with emphasis on e/γ separation
4. Use upstream mini-tracker as lumi measurement? Use $(\vec{r}, \theta, z_{\rm vtx})$ for lumi & EM deflection (EMD) study.



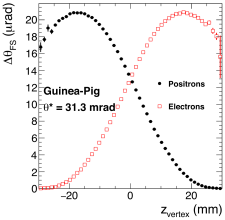
Small-angle Bhabhas (SABH) are very challenging.

As discussed in Rimbault et al for ILC, beamstrahlung (BS) (beam particle energy loss before collision) and beam-induced EM deflections (EMD) of the final-state e^- and e^+ in Bhabha events collectively affect the acceptance for Bhabhas in the luminometer. Bhabha suppression effect, BHSE (red) = BS (black) + EMD (dashed-blue).





- (left). ILC (Rimbault, Bambade, Moenig, Schulte)
- (right). LEP1 (Voutsinas, Perez, Dam, Janot)



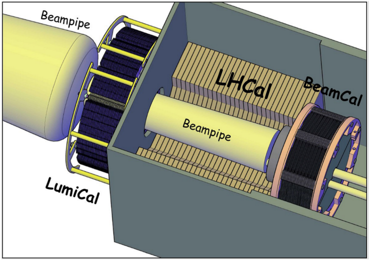
- Was a significant problem for LEP1 luminosity causing a 0.106% bias on supposed 0.034% systematic precision of OPAL. Bias correction relative error of 5% claimed.
- Useful z_{vtx} for SABH events at ILC impossible? (0.2mm z_{vtx} rms)
- More recent ILC studies (B-J, L, P, S): 5×10^{-4} uncertainty from EMD.

Apologies

- I normally plan to have significant increments of new work for presentations, and had hoped to have reasonable estimates for EM deflection issues for ILC using Guinea-PIG and effects of tracking resolution.
- Unfortunately I had an on-going chronic tropical medical issue that derailed me for 6 weeks from early May. I've now recovered, but I did not get very much new work done for this talk, as a result also of ongoing CMS responsibilities, and things turned out to be more difficult than expected.
- Nevertheless given the different audience to related past talks, this should still be useful for you, and pique your interest.

Current ILD Detector Design

ILD forward design (FCAL) is driven largely by the LumiCAL; very similar to the Gen2 LEP designs like OPAL designed mainly for SABH. FCC-ee squeezes into 62–88 mrad acceptance at $z = 1.07$ m copying ILD-LumiCAL (M. Dam).



ILD is now designed for L*=4.1m

- Conical beam-pipe with LumiCAL, LHCAL, BeamCal
- Currently 683mm for LumiCAL+LHCAL
- LHCAL helps with hermeticity
- May need more space in z if PLUG-Cal precision sampling calo. proves attractive (longer L*/smaller $z_{\min}$).

Physics drivers (not just R) include:

1. $\gamma/\mathrm{e}^-/\mathrm{e}^+$ tagging
2. hermeticity
3. azimuthal and energy resolution

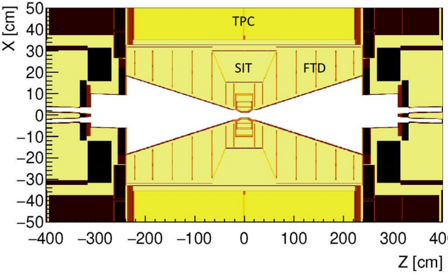
Current parameters.

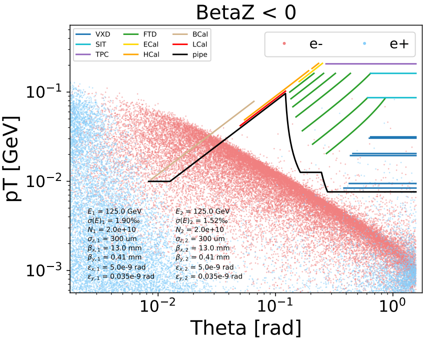
- $2412 < z < 2541$ mm.
- 30 layers of 1 X_0. W absorber + 0.32mm Si.
- $R - \phi$ pads, $\delta R = 1.8$mm, $\delta\phi = 7.5°$. [84, 194] mm in R.

Aside: OPAL had 0.25 X_0 upstream of luminometer.

ILD Tracking & Forward Region

Guinea-PIG pairs for ILC, B = 3.5T from Antoine Laudrain.

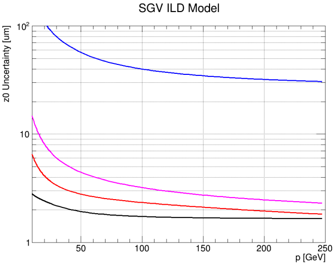


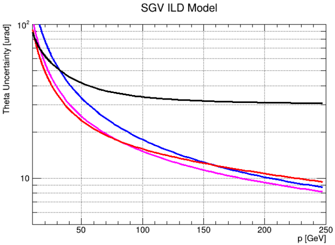


- For tracking upstream of LumiCAL will need to re-design beam-pipe
- WIP - see effect of extending FTD to r=0 using fast tracking simulation
- Pairs simulation - very encouraging. Clean upstream phase-space exists.
- Estimating well Bhabha z_{vtx} has a high priority - more so than minimal upstream material for Bhabha lumi measurement IMO.

SGV studies. Need excellent $\Delta(z_{\rm vtx})$ for EMD control

Target z_0 uncertainty of 41 μm at 45 GeV. Use geo4 detector model.



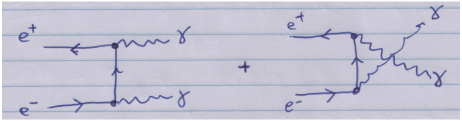


Plots for polar angles of 10° (blue), 20° (magenta), 30° (red), 90° (black). I tried to extend the geometry to smaller r, and run smaller angles, but issues ....
There are likely more correct analytic approaches, but naively, if one measures r_E, at z_E and θ, one can extrapolate to z_0 at $r = 0$ using,

$$z_0 = z_E - \frac{r_E}{\tan\theta}; \text{so } \Delta z_0 = \Delta z_E \oplus \Delta r_E / \sin\theta \oplus r_E \Delta\theta / \sin^2\theta$$

Uncertainty amplified by factors of 20 (Δr_E) and 400 ($\Delta\theta$) at $\theta = 50$ mrad. Need precise points at low z and less material.

Di-Photon Basics



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

Not so large. 40 pb at the Z (for 20°).

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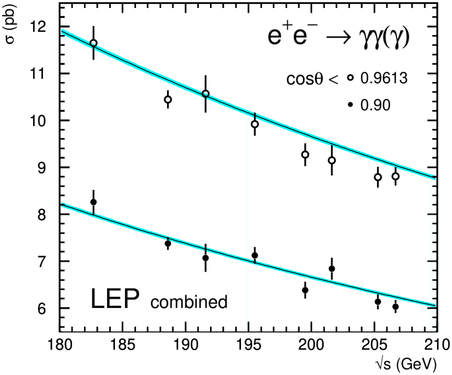
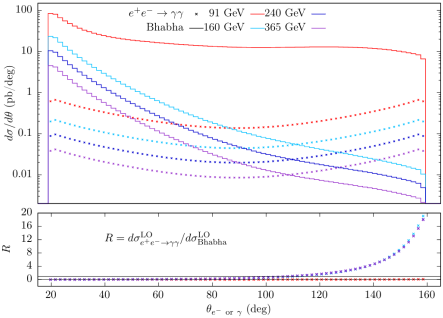


Here $\theta_\gamma > 16^\circ$ or $\theta_\gamma > 26^\circ$



$\sqrt{s}$ (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

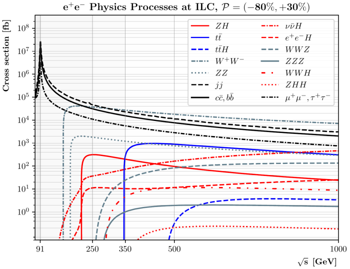
$20^\circ < \theta_\gamma < 160^\circ$, $x_2 > 0.5$ from 1906.08056

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

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

- Bhabhas look very **problematic** for high-precision absolute lumi. It was even not under control experimentally at LEP1. Beam-induced **EM deflections** affected the luminosity acceptance at the 0.1% level (see 1908.01704).
- Di-photon process should not be much affected.
- Di-photons much less sensitive to **polar angle metrology** than Bhabhas.
- Di-photons less sensitive to FSR than Bhabhas.
- More feasible now with modern calorimeters to do a **particle-by-particle reconstruction**. Likely easier with di-photons (no B-field effect).
- 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.



- 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.
- The pure QED process, $e^+e^- \to \gamma\gamma$, is now also considered very seriously for **absolute** luminosity, for both exptl. and th. reasons.
- It emphasizes reconstruction (rejection) of high energy photons (electrons) over most of the detector's solid angle.

- Ideally match/improve on the stat. precision of the accelerator. Denominator normalizing processes should have cross-sections exceeding the numerator.
- Ex. 1. ILC250, 0.9 ab^{-1} LR: $\sigma_{WW} \implies 1.7 \times 10^{-4}$. $\implies \sigma^*_{\mathrm{lumi}} \geq 30$ pb.
- Ex. 2. 10^{12} Z per expt. with FCC: $\implies 1.0 \times 10^{-6}$. $\implies \sigma_{\mathrm{lumi}} \geq 30$ nb.

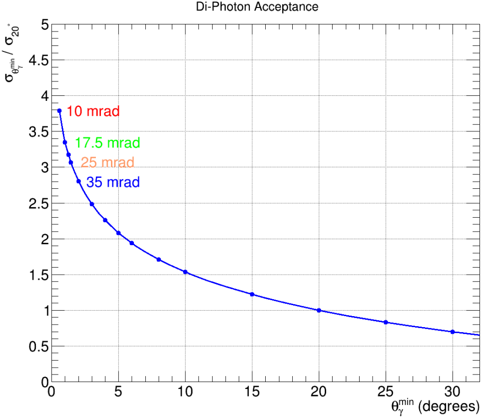
What is achievable in terms of systematics? For now assume the target of 10^{-4} for expt.+theory. For 10^{-4} at the Z, one has $\times 50$ (ILC) or $\times 10^4$ (FCC-ee) more hadronic Zs than needed. To match 10^{-4} lumi syst. precision with 10^{-4} lumi stat. precision at the Z, need $\sigma_{\mathrm{lumi}} \geq 2.5$ pb (FCC-ee) and ≥ 600 pb (ILC). Need to prioritize $\gamma\gamma$ acceptance at ILC; for 120 pb, lumi. stat. uncertainty is 2.2×10^{-4}.

Maximizing the $\gamma\gamma$ 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.
- Note: only use LumiCal to define $\theta_\gamma^{\min}$. No $\theta_\gamma^{\max}$ cut.

[a] typical LEP choice - driven by tracker

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

Targeting 10^{-4} precision. Cross-sections at $\sqrt{s} = 161$ GeV ($\sigma_{WW}^{U} \approx 3.5$ pb).

θ_{min} ($^\circ$)	$\sigma_{\gamma\gamma}$ (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 $\gamma\gamma$ with (80%/30%) longitudinal beam polarization. Typical HO effects: +5–10%.
  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 lumi. 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.

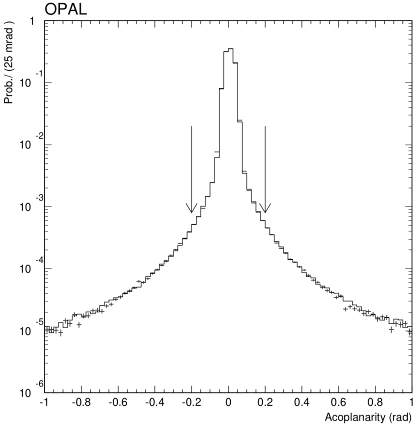
PLUG-Cal: Precision Luminosity Ultra-Granular Calo.

Initial Design Ideas

1. Precise **location** of the high-energy photon interaction point (via conversion to $\mathrm{e}^+\mathrm{e}^-$) 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 $\mathrm{e}^+\mathrm{e}^-$ / $\gamma\gamma$ 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. More emphasis on **energy resolution**.
10. Limited solid-angle $\rightarrow$ cost is not an over-arching concern.
11. Retain or exceed performance for Bhabha-based measurement.

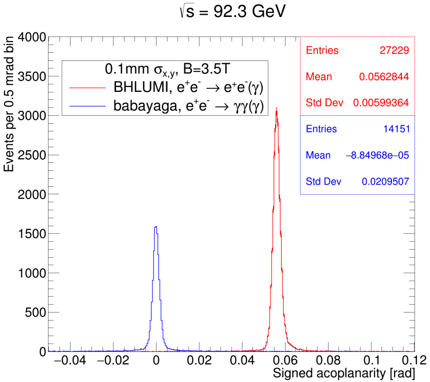
Use acoplanarity $= (\phi_R - \phi_L) - \pi$ for $\gamma\gamma/e^+e^-$ separation

OPAL luminometer (hep-ex/9910066)



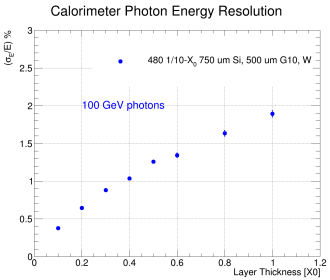
Lousy azimuthal resolution and **eight** times weaker B-field (0.435T)

Future e^+e^- collider. Use OPAL LumiCal acceptance ($z = 2.46$m)



Assumes B=3.5T, 0.1mm x, y resolution. (relative normalization arbitrary). Calo. rejection factors of 200 feasible.

Energy Resolution Landscape



- OPAL resolution was about $25\%/\sqrt{E}[\mathrm{GeV}]$ at 45 GeV.
- ILD LumiCal with 30 layers with 1 X_0 sampling. Thin sensors. About $20\%/\sqrt{E}[\mathrm{GeV}]$ at low energy.
- Should not under-specify 4-vector reconstruction. Issues like beamstrahlung etc.

Precision EM Calorimetry

- Many samples enables energy precision with a sampling calorimeter.
- Here 10 samples per radiation length - gives $3.66\%/\sqrt{E}[\mathrm{GeV}]$.

The basic parameters of targeting excellent energy and azimuthal resolution and photon/(electron - positron) separation are backed up by full simulation studies of various longitudinal configurations (primarily for energy resolution) and initial studies for transverse resolution (for x, y and so r, ϕ). See Brendon's talk tomorrow in Calorimetry for related θ, ϕ resolution studies.

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)
2. Basic **EM energy performance studies** using TestEm3. Range cut 1 micron. XY extent 100 cm. Adds up globally the energies deposited in each type of material. Apply to Si-W calorimeter with various absorber and sensor thicknesses.
   - Initial results were for 35 X_0 depth of W absorber with 140 samples with same Si sensor thickness as ILD.
   - New results based on simulations with 48 X_0 total depth with samples every 0.1 X_0. Allows to optimized longitudinal containment and obtain results for different sampling frequencies (every 0.2 X_0 etc).
3. Also using HGCAL_testbeam example to look at **position resolution** observables. This has hexagonal pads with similar transverse dimensions to standard ILD and SiD. Conclude 100 μm position resolution in x and y is well within reach.

Longitudinal Studies for Energy Performance

Initial study (0.25 X_0 per layer) used GEANT4 TestEm3 example with sampling calorimeter with two materials.

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

with a total of 140 layers.

Later study (0.1 X_0 per layer) used

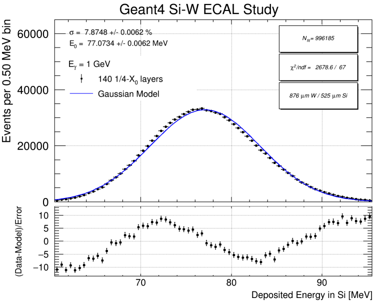
1. Silicon: 0.750 mm
2. G10 (PCB): 0.500 mm
3. Tungsten: 0.313 mm

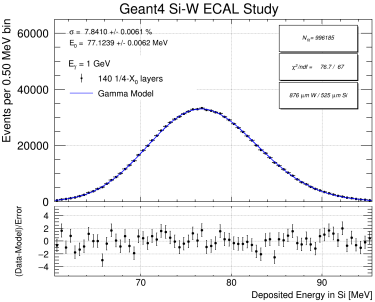
and 480 layers to facilitate a variety of actual "software thicknesses" and "ganging schemes".

The increased Si thickness was also partly chosen as a result of the re-observation that the first longitudinal layer hit in the ECAL **for photons** can easily be out-of-time and not associated directly with the initial interaction and resulting high-energy shower particles. Denote this as "backsplash" (see later Backsplash slide for more details) that can cause outliers in position measurements that overweight "shallow" energy deposits.

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.

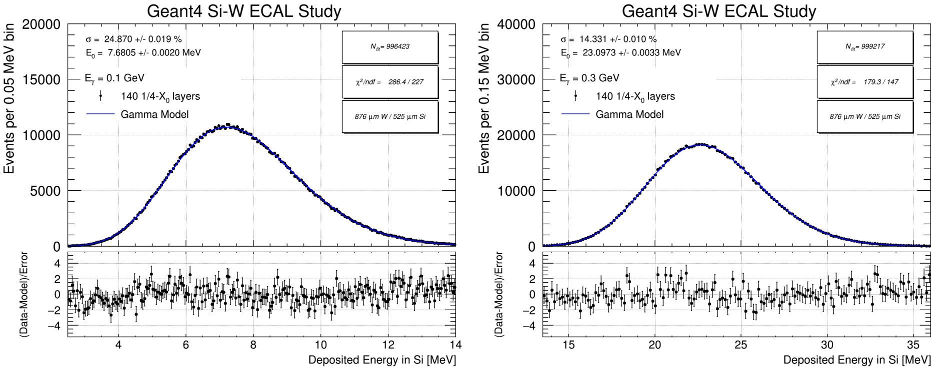




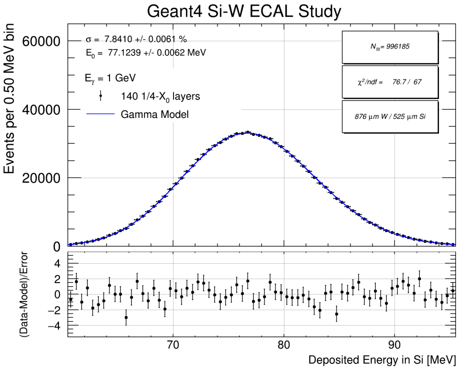
Unacceptable Gaussian fit. Low energies and worse designs give distinct positive skew. Not surprising given what we know about the Poisson and Landau distributions.

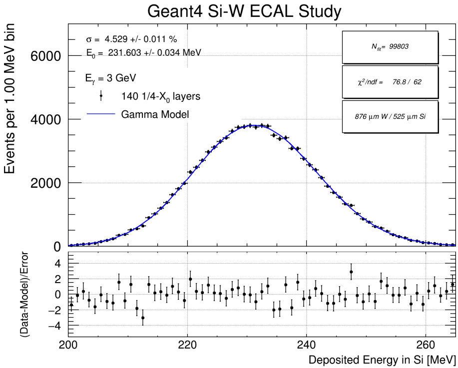
But same data fits great to Gamma. As σ_E/E improves, tends to a Gaussian. CLT in action!

Energy Linearity and Resolution: 0.1, 0.3 GeV Photons

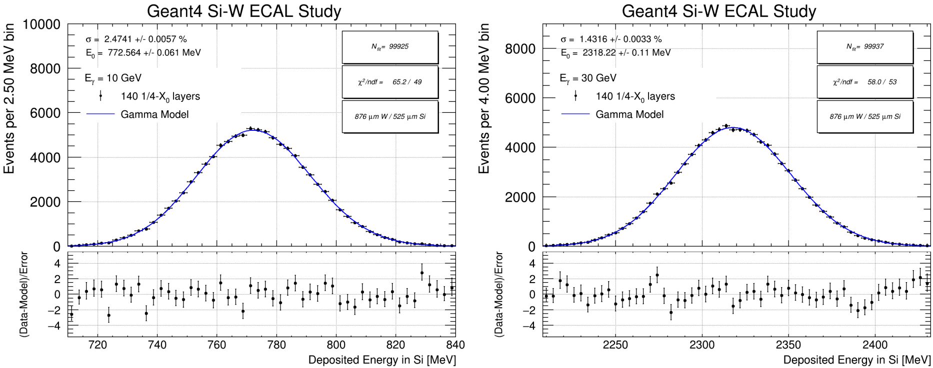


Energy Linearity and Resolution: 1 GeV, 3 GeV Photons

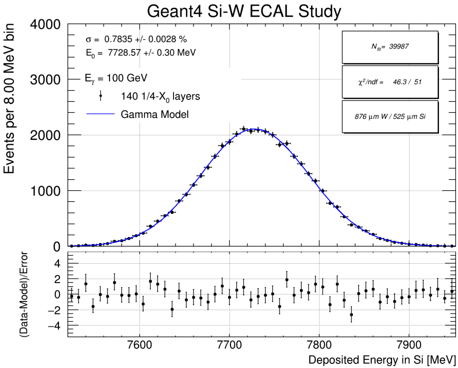


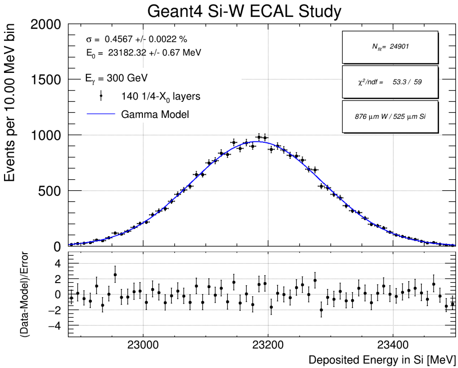


Energy Linearity and Resolution: 10 GeV, 30 GeV Photons

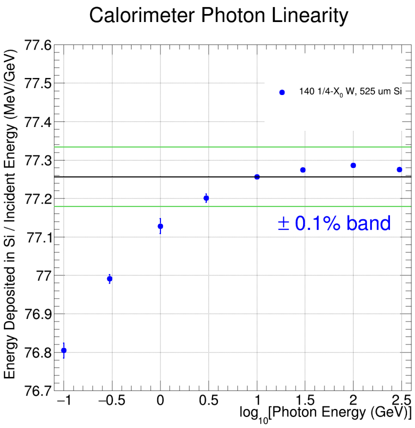


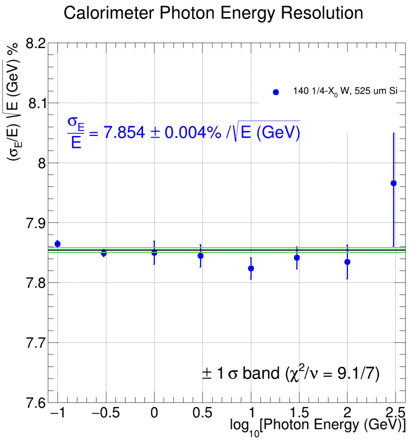
Energy Linearity and Resolution: 100, 300 GeV Photons





Energy Linearity and Resolution



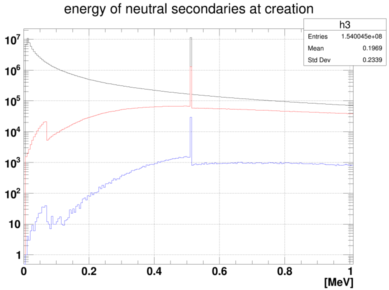


Excellent linearity in [0.1, 300] GeV range. Within 0.1% above 2 GeV. Albedo affects < 2 GeV. EM sampling fraction of 7.7%.

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

What causes the out-of-time back splash?

Some part of the shower energy travels towards the front of the calorimeter in more isotropic processes like Compton scattering (back scatter peak around 250 keV) and positron annihilation (leads to back-to-back 511 keV photons). Simulate 10,000 photons of 100 GeV impinging on 24 mm of Tungsten (6.8 X_0). Measure flux of photons created (black), exiting the rear, exiting the front.



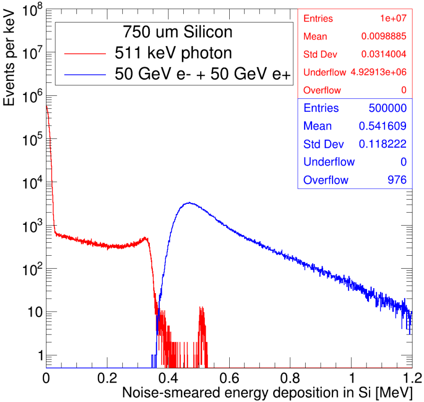
Note the discontinuities (W X-ray K-edge) and forward CS continuum below the 511 keV peak

- A significant portion of the backward going photon flux is from positron annihilation in matter resulting in 511 keV annihilation photons.
- Suggests considering designing the active layer for veto potential against energy depositions from soft photons (energy $\leq$ 511 keV).
- Also may want to understand how to properly model the time delays in annihilation photon emission (positron thermalization in matter - and sometimes positronium formation)

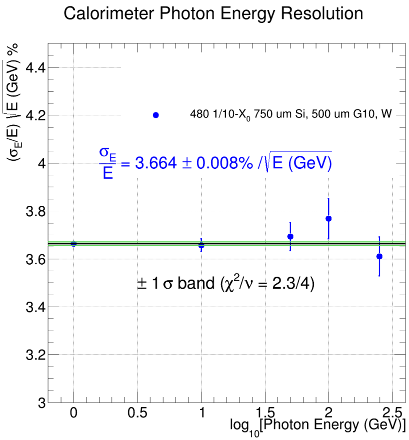
Si thickness choice for clean 511 keV photon rejection

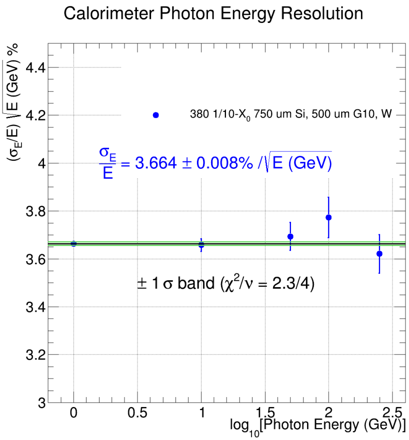
ILD Si-W ECAL design currently has 525 μm thick Si layers. Thicker, 725 μm layers were already envisaged for future productions. I chose 750 μm to allow for noise. Current noise model is 1250 $\sqrt{t/t_{\rm ref}}$ e- with $t_{\rm ref} = 325$ μm.

- Choose Silicon volume pixel of 2.0mm*2.0mm*0.75mm.
- Shoot both 511 keV photons (red) and 50 GeV electrons at center of front face.
- Add energies from odd and even electron events (blue) to simulate"double-MIP" pair expected from a 100 GeV converted photon.
- Smear by noise amount.
- Find $99.941 \pm 0.003\%$ pair efficiency for 380 keV cut (the 511 keV Compton edge is at 340 keV) with probability of $(2.3 \pm 0.2) \times 10^{-5}$ to mis-id a 511 keV photon.



More layers. Thicker Si. Include gap material.





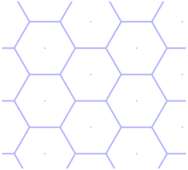
- Need 38 X_0 to avoid energy resolution degradation up to 250 GeV.
- Length around 60 cm. Can be further reduced. Coarser deep layers and/or fitted leakage corrections.
- Very competitive with homogeneous calorimetry.

Position Resolution Tests

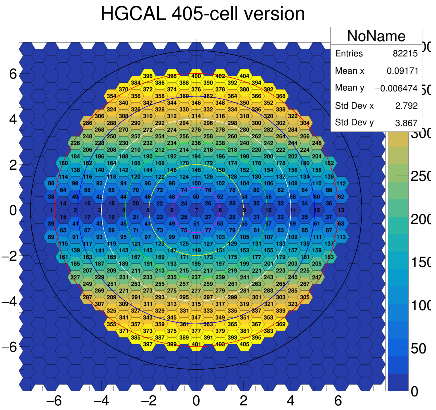
How much can the photon and electron position resolution be pushed with small cells? Can one localize the initial photon interaction point? thus measuring the γ scattering angle, $\theta = \tan^{-1}(r/z)$, and aiding in separating electrons and photons.

- 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.

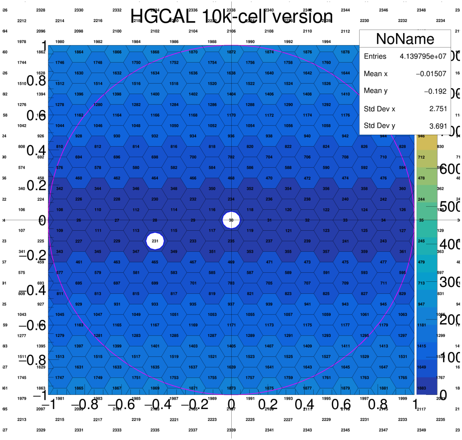
Beam particles are incident on the array with a Gaussian profile with spread in x and y of 1.5 cm. Residuals for calorimeter position observables are calculated with respect to the randomized true beam position event-by-event.

hexagon x horizontal  hexagon y vertical

HGCAL models

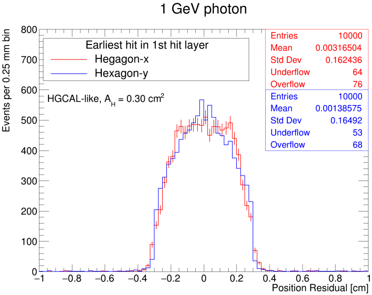


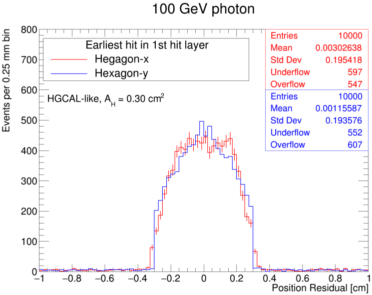
405 cells per wafer, area = 30.1 mm^2

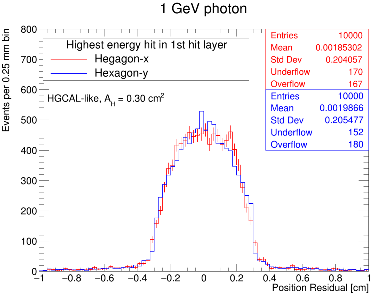


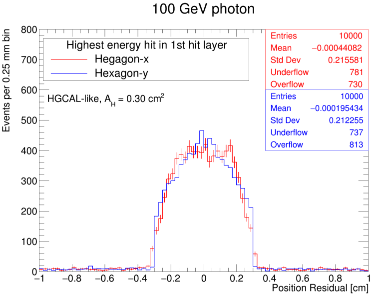
9275 cells per wafer, area = 1.25 mm^2.
Zoomed into R=1cm.

Choosing the best hit in the first hit layer



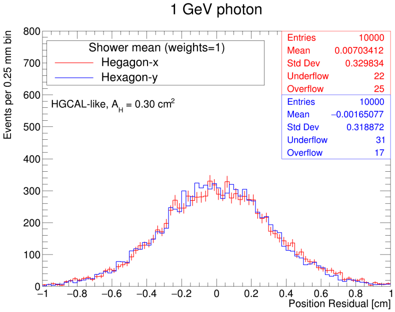


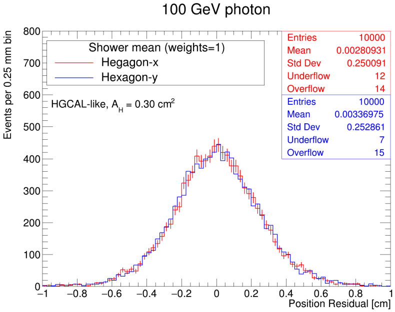


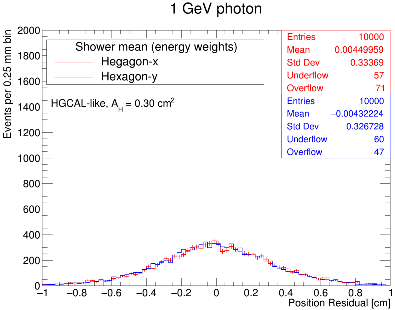


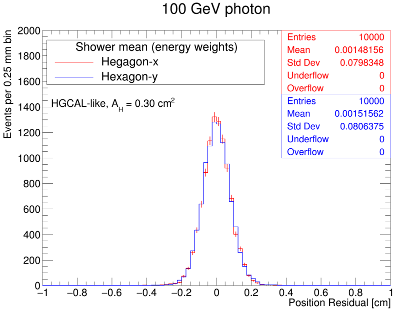
Note: often outliers from "back-splash" (more prevalent at the higher energy)

Shower center-of-gravity (all layers)



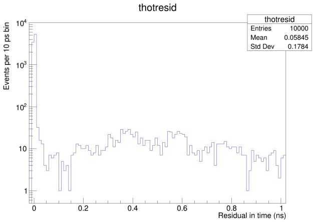




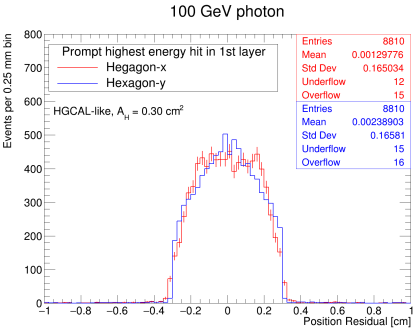


Timing/Promptness Potential (Work In Progress)

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 with 180 keV cut.



Only look at the 88% of events where the chosen hit is prompt.



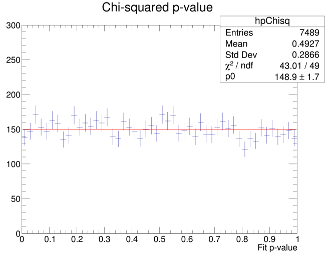
Define prompt hit as within 0.1ns of expected time. In 12% of events the hit previously chosen based on its energy to define the position is non-prompt.

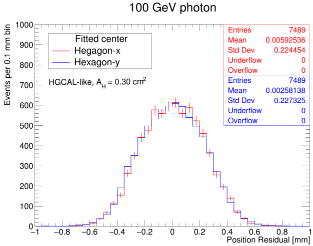
Can recuperate close to perfect hexagonal pitch resolution even for high energy showers. Here perfect would be $\sigma_{x,y} = 0.155$ cm.
To do: use alternate position estimator for the missing 12% - like next layer.

HGCTB Shower Fitting for Position

- Use default 300 μm thick Si sensors.
- Add cells into longitudinally integrated "towers" if cell energy exceeds 180 keV (a double-MIP like cut).
- Then fit for the shower transverse center (x, y) using the energy depositions in each hexagonal tower with more than 0.5% of the observed energy with a mixture model with a shower core and a shower tail.
- Used MC integration in 2-d (about 1s per event for fit).

Very promising results (imposed a $R < 25$ mm cut).





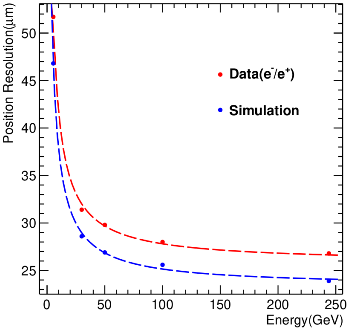
Very acceptable fits

Position resolution improves to 225μm.

Still to use 3-d information (narrow shower start)

Is 100 microns feasible? YES.

- Found 225 microns for 100 GeV photons with HGCAL test beam set up. Limited especially by cell-size of 0.30 cm^2. Latest results with 1.25 mm^2 cells: 112 microns (100 GeV) and 75 microns (250 GeV) with shower fitting.
- Likely can still be improved. Should be even better with the 100+ thick-layer designs (much more sampling information but also R_M degradation).
- The FoCal prototype 1708.05164 as shown below gives EM-shower position resolution on the 25 micron scale for 30 GeV showers!



FoCal prototype

- Note offset zero
- Simulation neglects beam divergence.

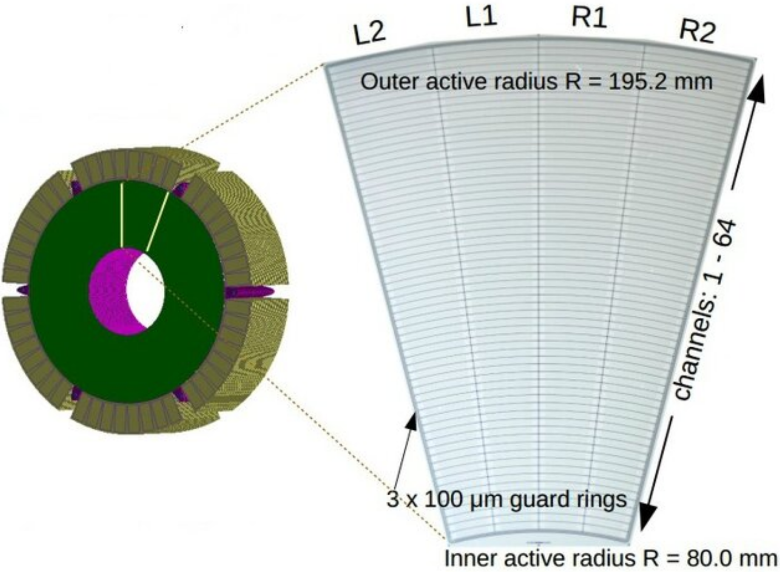
In fact 100 microns looks to be a good target for 45 GeV photons given the wish to cleanly separate Bhabhas from $\gamma\gamma$ using acoplanarity at all energies. Improved resolution at higher energy should offset some of the separation degradation from less magnetic deflection.

Conclusions

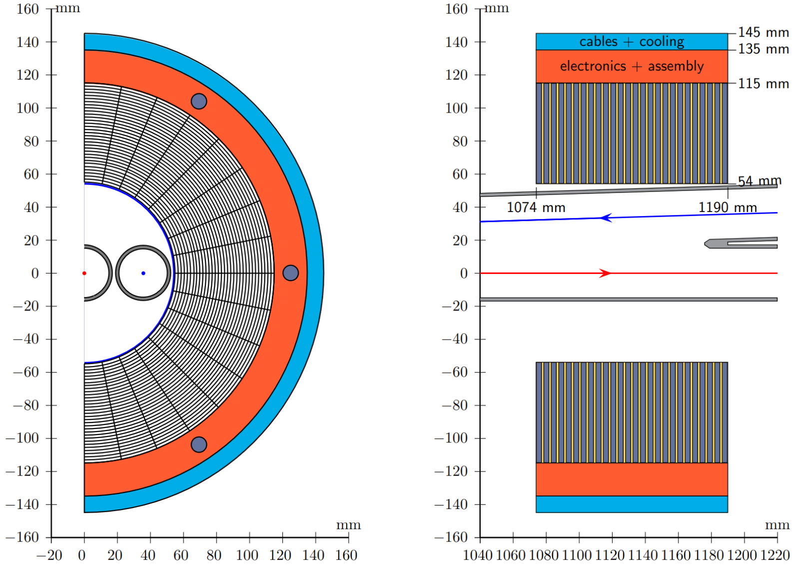
- I believe the PLUG-Cal concept has potential for superior performance for **luminosity measurements** even with $\mathrm{e^+e^-} \to \gamma\gamma$ below the tracker acceptance. Potential doubling of acceptance. Very detailed shower reconstruction. Many Bhabhas for calibration/cross-checks.
- It can likely make radial measurements better than ILD LumiCal but with longer Molière radius and better **energy** and **azimuthal** resolutions and hermeticity. So competitive for Bhabha-based measurements too.
- Key issue for luminosity: systematic uncertainty on the **acceptance definition**. Easier with a **tracking-like** focus on the position response of the **shower start** and **neutral particles** (EMD concerns).
- Plan to benchmark against current ILD design for electrons and photons once baseline PLUG-Cal design has emerged.
- How to optimize for **position resolution** not yet clear. I'm wary of compromising the analog performance as energy resolution is also a key part of defining the acceptance and background rejection. Will have electron tracking layers (also may help with EM deflection diagnostics).
- Radiative neutrino counting is a great physics motivation for **electron/photon separation** beyond the tracker. See recent Cracow Epiphany Conference talk. At $\sqrt{s} = 250$ GeV, the radiative-return to the Z photons have 108 GeV.

Backup Slides

ILD LumiCal

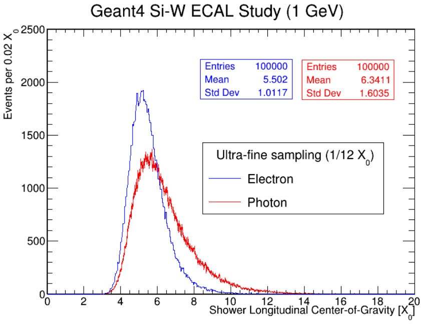

L2
L1
R1
R2
Outer active radius R = 195.2 mm
channels: 1 - 64
3 x 100 µm guard rings
Inner active radius R = 80.0 mm

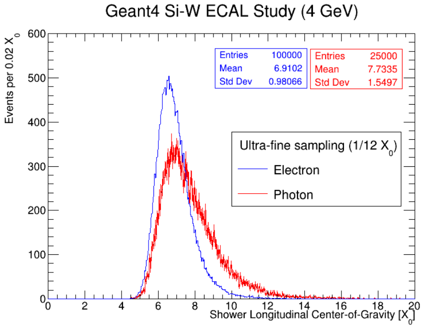
FCC-ee LumiCal



Shower Shapes Examples

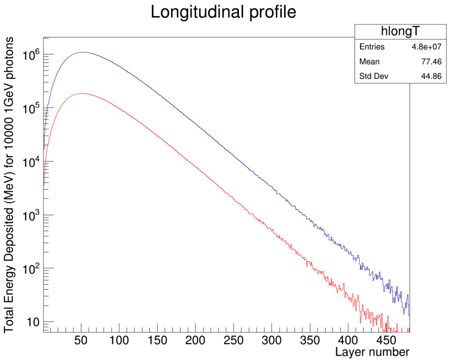
With 12 samples per X_0 these are measured really well. At 4 GeV the C-o-G resolution is 0.07 X_0 - see approximate $1/\sqrt{E}$ scaling of resolution.
Here use W / 1mm G10 / 525 um Si (totaling 1/12 X_0).

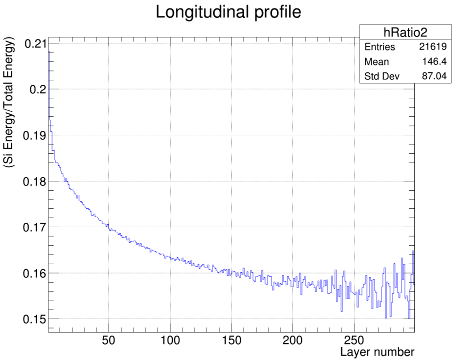




Averaged Shower Longitudinal Profiles

Same calorimeter model as previous slide (1/12 X_0 samples). 1 GeV photons.





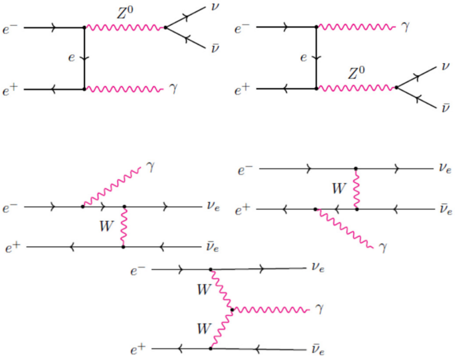
Energy deposited (Si+G10+W) per layer

Energy deposited in Si per layer

Si/(Si+G10+W) energy ratio per layer

This well-known pernicious "shower-age" effect means that the e/MIP ratio tends to get smaller with shower depth, but in an energy dependent way. Makes it non-trivial to calibrate calorimeters with nonuniform sampling.

Radiative Neutrino Pair Production



Approximate Born cross-section ($M_W \to \infty$ limit, neglect TGC graph) where $x \equiv E_\gamma / E_{\text{beam}}$, $y = \cos\theta_\gamma$.

$$\frac{d^2\sigma_0}{dx\,dy} = \frac{G_F^2 \alpha s (1-x)\left[(1-\frac{x}{2})^2 + \frac{x^2 y^2}{4}\right]}{6\pi^2 x (1-y^2)} \cdot \left(2 + \frac{N_\nu\,(g_v^2 + g_a^2) + 2\,(g_v + g_a)\left[1 - \frac{s(1-x)}{M_Z^2}\right]}{\left[1 - \frac{s(1-x)}{M_Z^2}\right]^2 + \Gamma_Z^2/M_Z^2}\right),$$

Note. $s(1-x) = M^2_{\nu\overline{\nu}}$

Cross-section Features

- 3 components: Pure Z exchange (for $\nu_e\overline{\nu}_e, \nu_\mu\overline{\nu}_\mu, \nu_\tau\overline{\nu}_\tau$ proportional to N_ν), pure W exchange (for $\nu_e\overline{\nu}_e$ only), W-Z interference (for $\nu_e\overline{\nu}_e$ only).
- Angular distribution mostly $1/\sin^2\theta_\gamma$.

Recent paper discusses measuring Γ_{ν_e} using W-Z interference (Aleksan, Jadach 1908.06338).

Example Data from OPAL (ABBIENDI 2000D)

Kinematic acceptance: $x_\mathrm{T} \equiv p_\mathrm{T}^{\gamma}/E_{\mathrm{beam}} > 0.05$, $15^\circ < \theta < 165^\circ$.

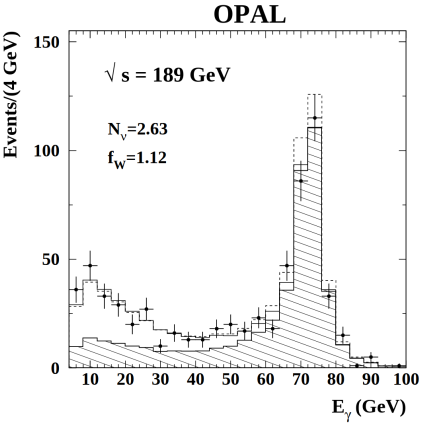


Figure 5: Photon energy distributions for single-photon events. The points with error bars are the data. The solid histogram is the prediction for the values $f_W = 1.12$, $N_\nu = 2.63$ most consistent with the data. The dashed histogram is the expectation for the Standard Model values $f_W = 1$, $N_\nu = 3$. The hatched region indicates the pure s-channel Z^0 contribution for $N_\nu = 2.63$. All predicted distributions were calculated using the NUNUGPV98 generator.

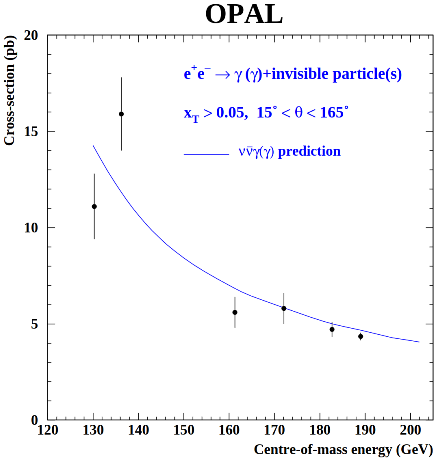
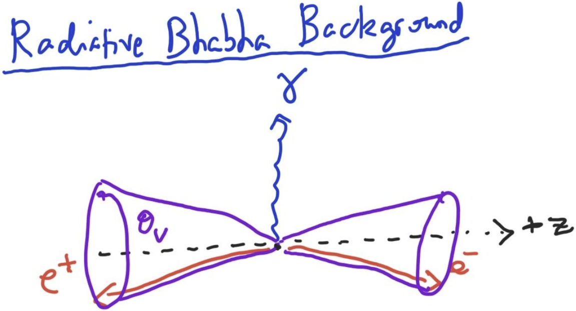


Figure 1: The measured value of $\sigma(e^+e^- \to \gamma(\gamma)$ + invisible particle(s)), within the kinematic acceptance of the single-photon selection, as a function of $\sqrt{s}$. The data points with error bars are OPAL measurements at $\sqrt{s} = 130, 136, 161, 172, 183$ and 189 GeV. The curve is the prediction for the Standard Model process $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$ from the KORALZ generator.

Note x_T cut driven by need to veto radiative Bhabhas. Inner edge of forward calorimeter at 25 mrad in OPAL.

Radiative Bhabha Scattering

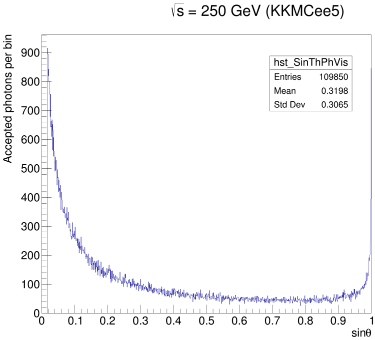
Can mimic $e^+e^- \to \nu\bar{\nu}\gamma$ if e^- and e^+ are undetected below polar angle, θ_V.

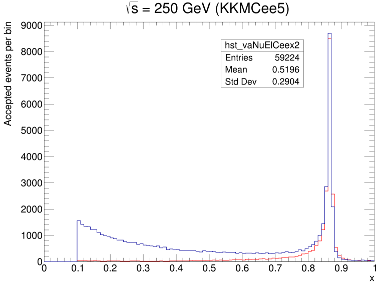


Require $x_T^\gamma \equiv \frac{p_T^\gamma}{E_b} \geq \frac{2\sin\theta_V}{1+\sin\theta_V}$

Examine potential for $\sqrt{s} = 250$ GeV

Kinematic acceptance: $x_T > 0.01$, $1^\circ < \theta < 179^\circ$. $(x > 0.1)$.



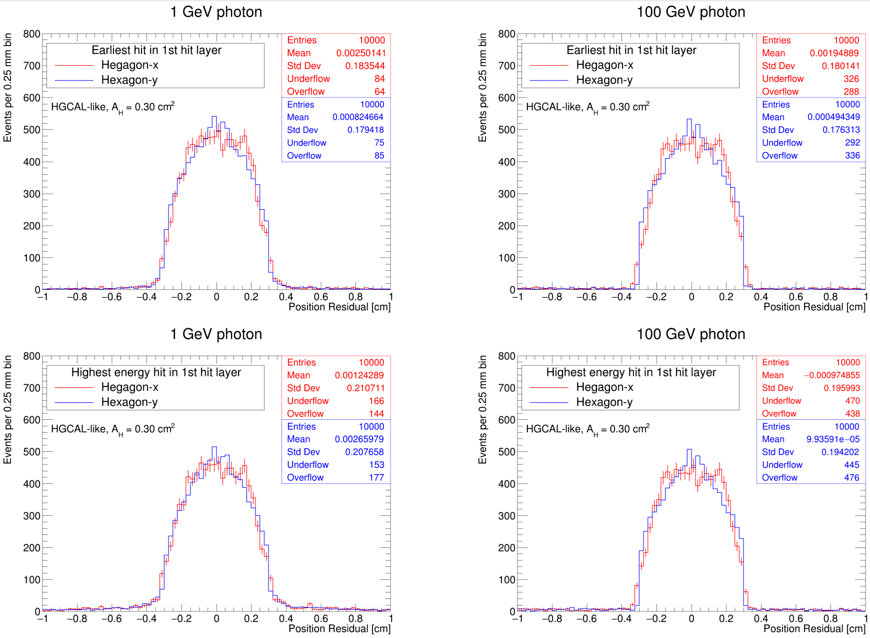


- RH plot shows $\nu_e \overline{\nu}_e \gamma(\gamma)$ in blue and $\nu_\mu \overline{\nu}_\mu \gamma(\gamma)$ in red.
- Loosening of acceptance increases cross-section to 13.7 pb at $\sqrt{s} = 161$ GeV and to 5.5 pb at 250 GeV.
- Needs very good electron/photon discrimination down to 1° and beam calorimeter (BCAL) veto to 5–10 mrad (feasible for ILC not FCC-ee).
- Excellent energy resolution in forward calorimeter can help resolve the W-Z

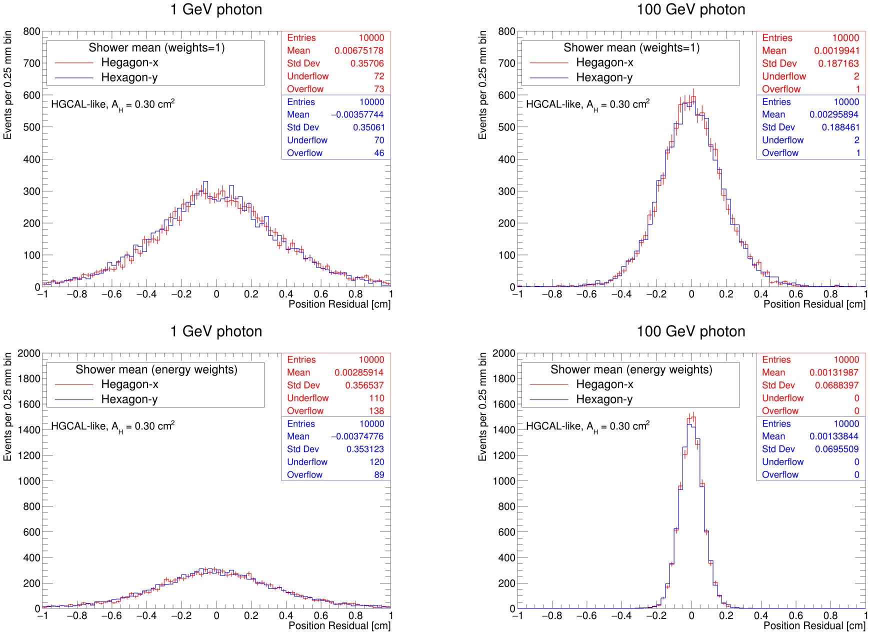
New plots with energy threshold

Only count hits with $>$ 180 keV in 300 micron Si layer.

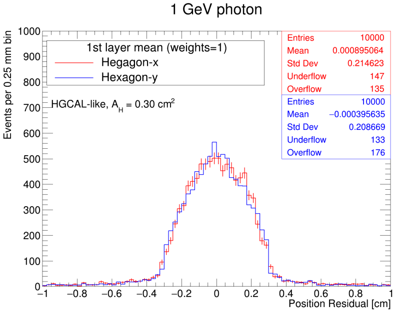
Choosing the best hit in the first hit layer

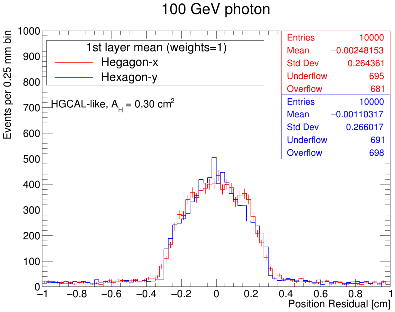


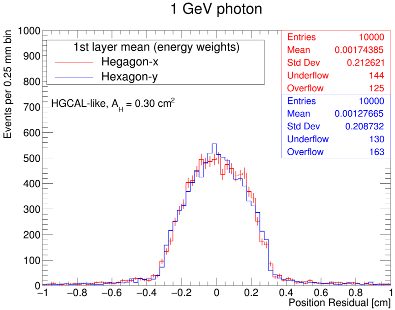
Shower center-of-gravity (all layers)

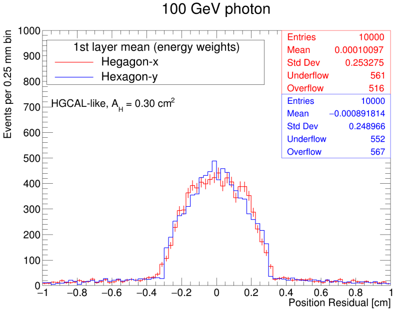


First Hit Layer CoG

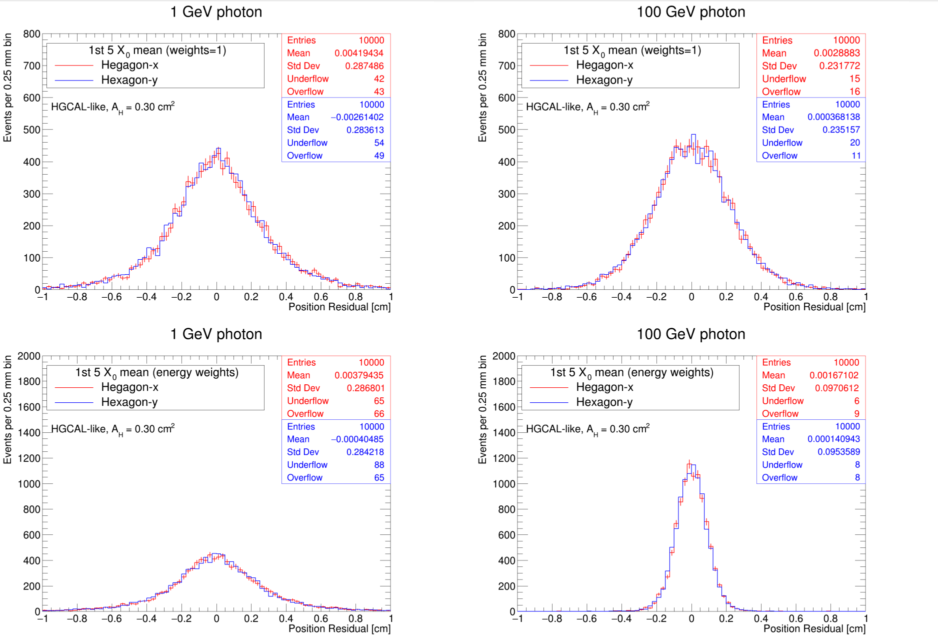






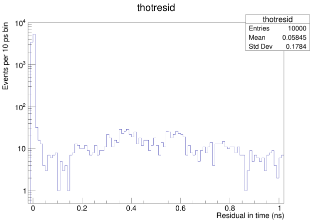


CoG from layers within 5 X_0 of 1st hit layer

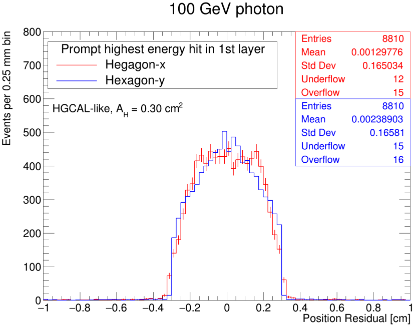


Timing/Promptness Potential (Work In Progress)

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 with 180 keV cut.



Only look at the 88% of events where the chosen hit is prompt.



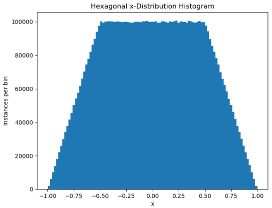
Define prompt hit as within 0.1ns of expected time. In 12% of events the hit previously chosen based on its energy to define the position is non-prompt.

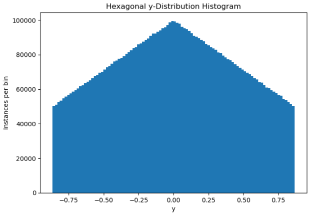
Can recuperate close to perfect hexagonal pitch resolution even for high energy showers. Here perfect would be $\sigma_{x,y} = 0.155$ cm.

To do: use alternate position estimator for the missing 12% - like next layer.

Fun facts on hexagons

- For random points within a hexagon of side-length, a, with $a = 1$, centered on (0,0), x extends from (-1.0, 1.0) while y 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 localization resolution??

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