Correctly Counting Light Neutrinos With Photons

Physics opportunities and initial design study of a precision sampling forward electromagnetic calorimeter (ECAL) for future e^+e^- Higgs factories

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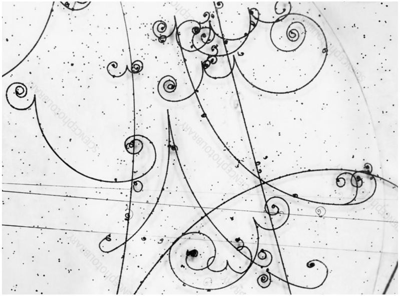


1. Counting neutrinos (one reason to care about luminosity and photon reconstruction)
2. Measuring absolute luminosity with $e^+e^- \to \gamma\gamma$
3. Forward ECAL design studies with emphasis on e/γ separation

How to count neutrinos

Two types of measurement at LEP (1989-2000) were used to count the number of light neutrino types, N_ν, that couple to the Z. Essentially these measure $N_\nu = \Gamma_{\rm inv}/\Gamma^{SM}_{\nu\overline{\nu}}$ where the denominator is for one neutrino generation.

1. Indirect measurement using the Z lineshape. Basically measure $\Gamma_{\rm inv} = \Gamma_{\rm tot} - \Gamma_{\rm had} - \Gamma_{\rm e} - \Gamma_{\mu} - \Gamma_{\tau}$.
2. Direct measurement using radiative events aka single photon events

- LEP had samples of 4×10^6 Z's per experiment.
- Future colliders can potentially create 10^{10} (ILC) to even 10^{12} Z's (FCC-ee/ReLiC) when running near the Z pole.

Challenge

Can future experiments exploit such statistics - reach the needed precision on center-of-mass energy and absolute integrated luminosity for such measurements?

Recent work (2209.03281 with Brendon) and 2308.10414 focused on tracker momentum-based center-of-mass energy using dileptons. Today focus on a "new" approach with $\gamma\gamma$ to luminosity measurement and the related calorimeter design.

Both N_ν methods are prime physics targets enabled by this work.

See P. Janot Wed. talk: Why Bhabha lumi. is tricky and N_ν from Z lineshape.

How to measure the absolute integrated luminosity?

1. Take a process whose cross-section within a well-defined experimental acceptance, $\sigma_{\rm acc}$, should be calculable precisely. For example a pure QED process like Bhabha scattering, $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}$, or $\mathrm{e^+e^-} \rightarrow \gamma\gamma$.
2. Count events consistent with this process, N, with modeled efficiency, ε.
3. Estimate any background processes, $N_{\rm bkg}$.
4. For a given data-set (a time interval where the instantaneous luminosity, $L(t)$, is varying), determine the integrated luminosity, as,

$$\int L(t)dt = \frac{N - N_{\rm bkg}}{\varepsilon\, \sigma_{\rm acc}}$$

- At LEP energies we wanted a high cross-section process with minimal contributions from electroweak effects. So "small-angle" Bhabha events were used and restricted to typically scattering angles in the 31 – 52 mrad range.
- This relies on precision theory (3.7×10^{-4}) and precision experiment.
- The state-of-the-art luminometer was the OPAL Si-W calorimeter (hep-ex/9910066) achieving 3.4×10^{-4} systematic experimental uncertainty.

N_ν from Z lineshape (PDG)

Number of Light ν Types

PDGID:S007NE INSPIRE

VALUE	DOCUMENT ID		TECN
2.9963 ± 0.0074	[1] JANOT	2020	
• • We do not use the following data for averages, fits, limits, etc. • •			
2.9918 ± 0.0081	[2] VOUTSINAS	2020	
2.9840 ± 0.0082	[3] LEP-SLC	2006	RVUE
3.00 ± 0.05	[4] LEP	1992	RVUE

[1] JANOT 2020 applies a correction to LEP-SLC 2006 using an updated Bhabha cross section calculation. This result also includes a correction to account for correlated luminosity bias as presented in VOUTSINAS 2020 .

[2] VOUTSINAS 2020 applies a correction to LEP-SLC 2006 to account for correlated luminosity bias.

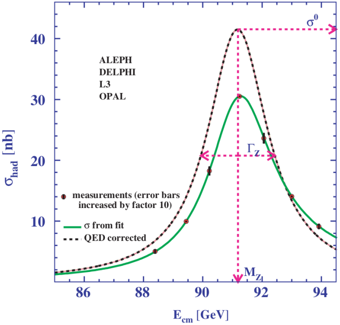
[3] Combined fit from ALEPH, DELPHI, L3 and OPAL Experiments.

[4] Simultaneous fits to all measured cross section data from all four LEP experiments.

References:

JANOT	2020	PL B803 135319	Improved Bhabha cross section at LEP and the number of light neutrino species
VOUTSINAS	2020	PL B800 135068	Beam-beam effects on the luminosity measurement at LEP and the number of light neutrino species
LEP-SLC	2006	PRPL 427 257	Precision Electroweak Measurements on the Z Resonance
LEP	1992	PL B276 247	Electroweak Parameters of the Z^0 Resonance and the Standard Model

Need to run near Z peak. Luminosity measurement is critical.



LEP1 Physics Reports article (2006)

$$\sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

$$R^0_{\rm inv} \equiv \frac{\Gamma_{\rm inv}}{\Gamma_{\ell\ell}} = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}}\right)_{\rm SM}$$

$$R^0_{\rm inv} = 5.943 \pm 0.016$$

$$N_\nu = 2.9840 \pm 0.0082$$

$$\delta N_\nu \simeq 10.5 \frac{\delta n_{\rm had}}{n_{\rm had}} \oplus 3.0 \frac{\delta n_{\rm lep}}{n_{\rm lep}} \oplus 7.5 \frac{\delta \mathscr{L}}{\mathscr{L}}$$

N_ν from single photon counting (PDG)

Number of Light ν Types from Direct Measurement of Invisible Z Width

PDGID:S007NI INSPIRE

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+ e^- \to \nu\bar{\nu}\gamma$. All are obtained from LEP runs in the $E^{ee}_{\rm cm}$ range $88 - 209$ GeV.

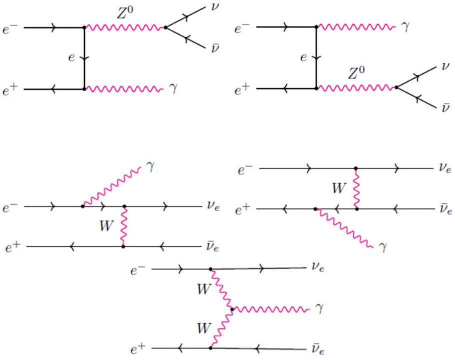
VALUE	DOCUMENT ID		TECN	COMMENT
2.92 ± 0.05 OUR AVERAGE Error includes scale factor of 1.2.				
2.84 ±0.10 ±0.14	ABDALLAH	2005B	DLPH	$\sqrt{s}$ = 180 – 209 GeV
2.98 ±0.05 ±0.04	ACHARD	2004E	L3	1990-2000 LEP runs
2.86 ±0.09	HEISTER	2003C	ALEP	$\sqrt{s}$ = 189 – 209 GeV
2.69 ±0.13 ±0.11	ABBIENDI,G	2000D	OPAL	1998 LEP run
2.89 ±0.32 ±0.19	ABREU	1997J	DLPH	1993--1994 LEP runs
3.23 ±0.16 ±0.10	AKERS	1995C	OPAL	1990 – 1992 LEP runs
2.68 ±0.20 ±0.20	BUSKULIC	1993L	ALEP	1990 – 1991 LEP runs

Data near Z peak - low energy photons - challenging but doable (OPAL 1995C was 4 years of my life). Data at higher energy - much easier - but lower sensitivity per unit luminosity.

$$\delta N_\nu = 3.0\,\frac{\delta n_\gamma}{n_\gamma} \oplus 3.0\,\frac{\delta L}{L}$$

(or potentially measure directly R_{inv} by normalizing $\nu\bar{\nu}\gamma(\gamma)$ to $\ell\ell\gamma(\gamma)$)

Radiative Neutrino Pair Production



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

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

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).

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

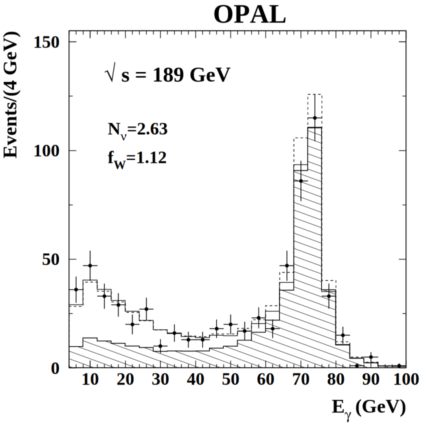


Figure 5: Photon energy distributions for single-photon events. The points with error bars are the data. The solid histogram is the prediction for the values $f_W = 1.12$, $N_\nu = 2.63$ most consistent with the data. The dashed histogram is the expectation for the Standard Model values $f_W = 1$, $N_\nu = 3$. 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.

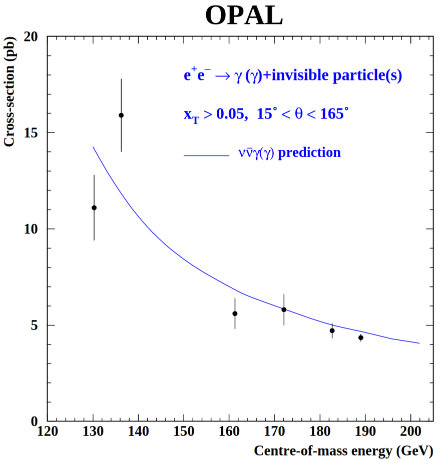
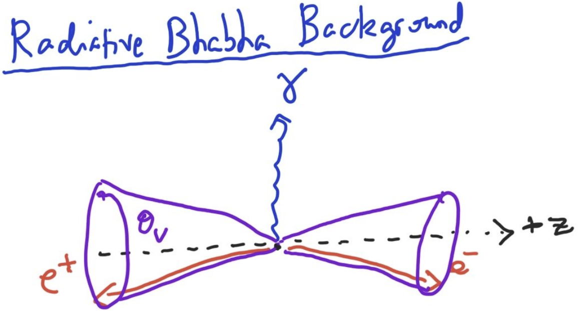


Figure 1: The measured value of $\sigma(e^+e^- \to \gamma(\gamma) + \text{invisible particle(s)})$, within the kinematic acceptance of the single-photon selection, as a function of $\sqrt{s}$. The data points with error bars are OPAL measurements at $\sqrt{s} = 130, 136, 161, 172, 183$ and 189 GeV. The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

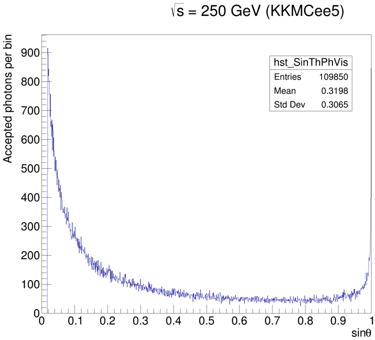
Can mimic $e^+e^- \to \nu\bar{\nu}\gamma$ if e^- and e^+ are undetected below polar angle, θ_V.

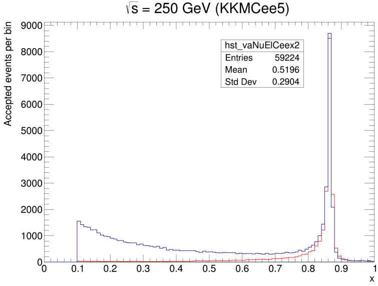


Require $$x_T^\gamma \equiv \frac{p_T^\gamma}{E_b} \geq \frac{2\sin\theta_V}{1+\sin\theta_V}$$

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 interference effect.

Longitudinal Polarization and Lumi. Spectrum Modeling

Two of the features that are essential for MC event generators that can be applied to all high energy $\mathrm{e^+e^-}$ colliders are proper treatment of

- beam polarization
- luminosity spectrum (beam energy spread and beamstrahlung)

These two features were not so relevant for LEP but are essential especially for linear colliders, and benefited in the past from Staszek's work.

N_ν

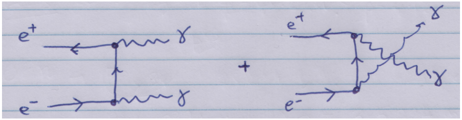
For $\nu\bar{\nu}\gamma(\gamma)$, longitudinal beam polarization should be very helpful for separating the ν_e and ν_μ/ν_τ components, and in particular for enhancing/suppressing the W contributions.

Thanks to Jacek Holeczek for helping me with the C++ version of KKMCee (V5). I was able to get started again with the neutrino channel but unfortunately with no polarization nor beamstrahlung. Support for previously developed features is important.

Di-Photons for Luminosity & Calorimetry Design Outline

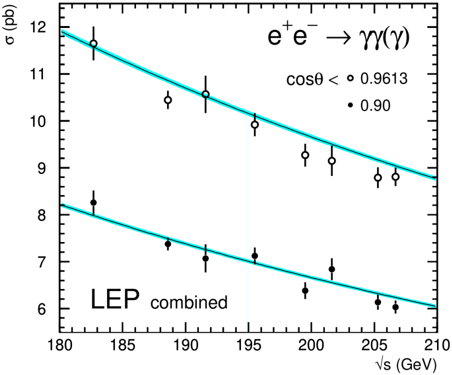
1. Di-Photon Basics
2. Luminosity Targets
3. Features of $\mathrm{e^+e^-} \to \gamma\gamma$ for Absolute Luminosity
4. Design Ideas for PLUG-Cal / Revising Forward Calorimetry
5. GEANT4 Initial Design Studies
6. Longitudinal Design Studies
7. Transverse Design Investigations
8. Acoplanarity
9. Detector/Accelerator Constraints
10. Recent studies. Backsplash/Annihilation Rejection/Shower Fitting/Long Profiles/ShowerShapes.
11. Summary

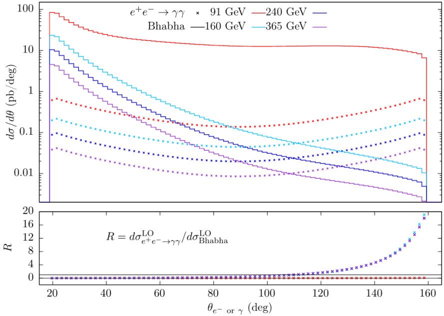
Di-Photon Basics



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

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

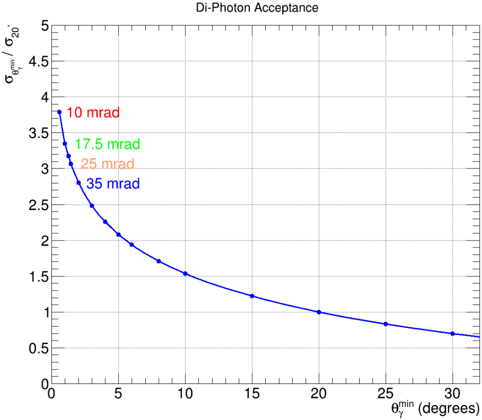
$20^\circ < \theta_\gamma < 160^\circ$, $x_2 > 0.5$ from 1906.08056

Maximizing the acceptance

The angular distribution favors more forward angles

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

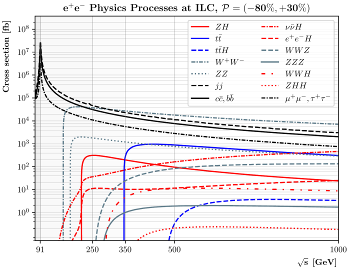
Note: $\sigma_{RL} = \sigma_{LR}$, $\sigma_{LL} = \sigma_{RR} \approx 0 \rightarrow$ assists beam polarization measurement.



- 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.
- Note: only use LumiCal to define $\theta_{\min}$.

[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, $e^+e^- \rightarrow e^+e^-$ (high statistics).
- This will be important for **relative** luminosity and could still lead in absolute precision.
- The pure QED process, $e^+e^- \rightarrow \gamma\gamma$, 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) $\rightarrow 1.7 \times 10^{-4}$.
- Example 2 (10^{12} Z with FCC) $\rightarrow 1.0 \times 10^{-6}$.

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.

$\theta_{\rm min}$ (°)	$\sigma_{\gamma\gamma}$ (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. ±24% for (80%/30%) longitudinal beam polarization. Typical HO effects: + 5 to 10%.
  Counting statistics adequate for $\sqrt{s} \gg m_Z$. 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 $e^+e^- \to \gamma\gamma$ so attractive?

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

- Bhabhas look problematic for precision absolute lumi. It was even not under control experimentally at LEP1 due to beam-induced EM deflections affecting 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.
- 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.

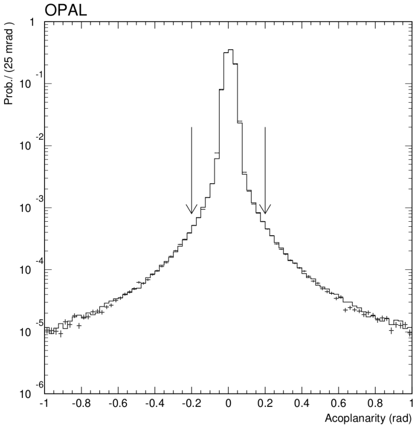
So let's design precision forward calorimetry for electrons AND photons inspired by various ideas (and avoiding some of the compromises) of related designs, CALICE, ILD, SiD, CMS-HGCAL, ALICE-FoCal, Fermi-LAT.

PLUG-Cal: Precision Luminosity Ultra-Granular Calo.

Initial Design Ideas

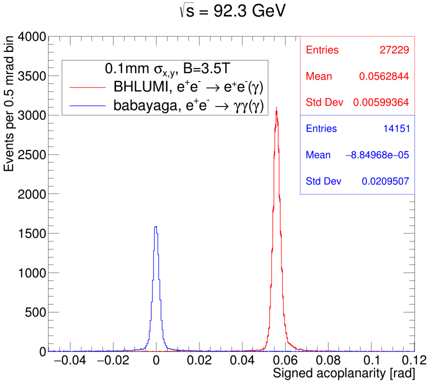
1. Precise **location** of the high-energy photon interaction point (via conversion to e^+e^-) in thin absorbers (see Fermi-LAT for extreme version of this).
2. 250 GeV photons need **longitudinal containment** to avoid large constant term. (10, 1)% of photons survive for (3, 6) X_0 prior to interaction.
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 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. 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.

OPAL luminometer (hep-ex/9910066)



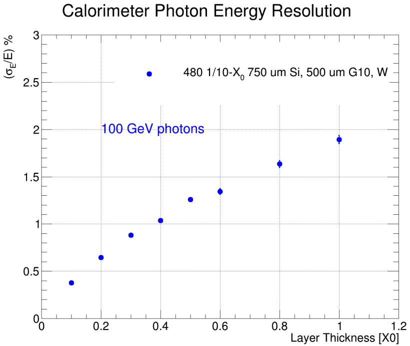
Lousy azimuthal resolution and **eight** times weaker B-field (0.435T)

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



Assumes B=3.5T. 0.1mm x, y resolution. 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 $3.66\%/\sqrt{E}[\mathrm{GeV}]$.

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.

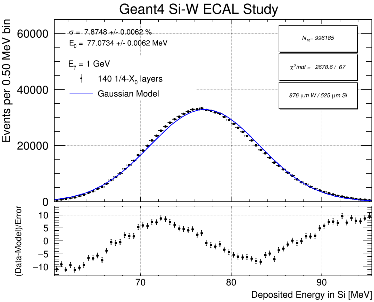
1. Tungsten: 0.876 mm
2. Silicon: 0.525 mm

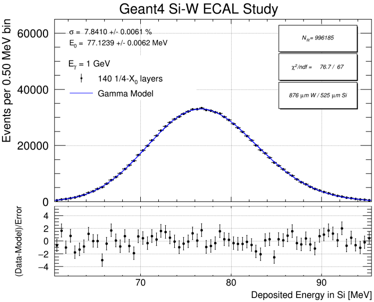
Later study (0.1 X_0 per layer) used

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

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.

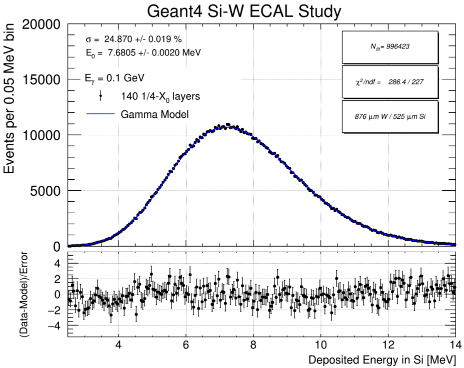


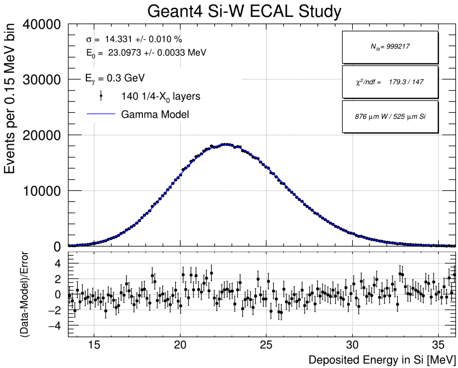


Unacceptable Gaussian fit. Low energies and worse designs give distinct positive skew. Not surprising given what we know about the Poisson and Landau distributions.

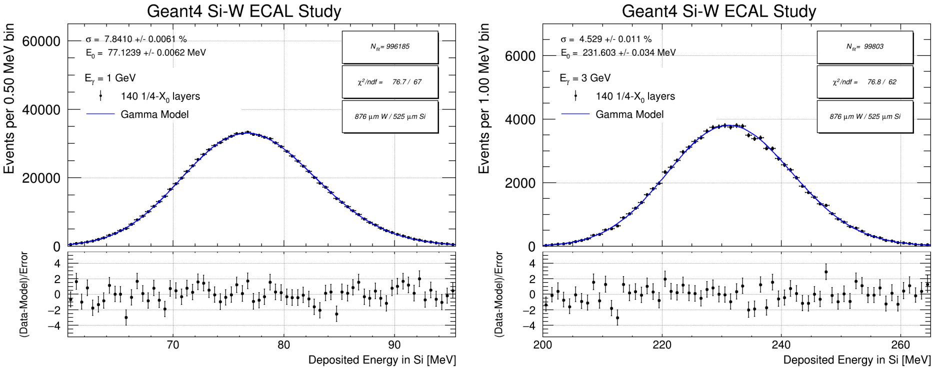
But same data fits great to Gamma. As σ_E/E improves, tends to a Gaussian. CLT in action!

Energy Linearity and Resolution: 0.1, 0.3 GeV Photons

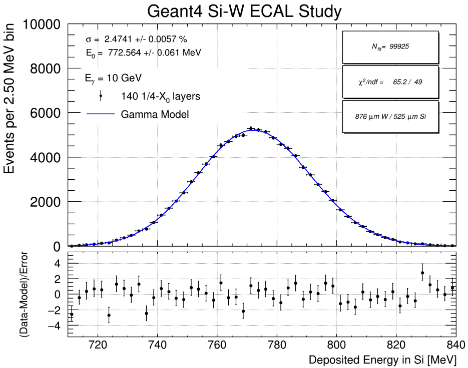


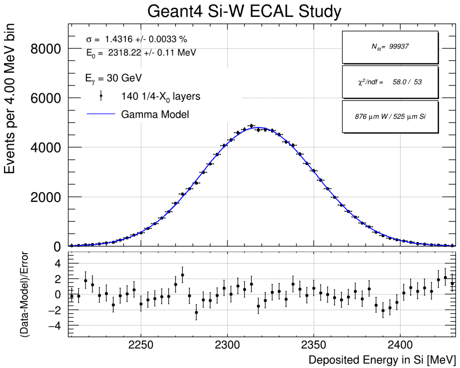


Energy Linearity and Resolution: 1 GeV, 3 GeV Photons

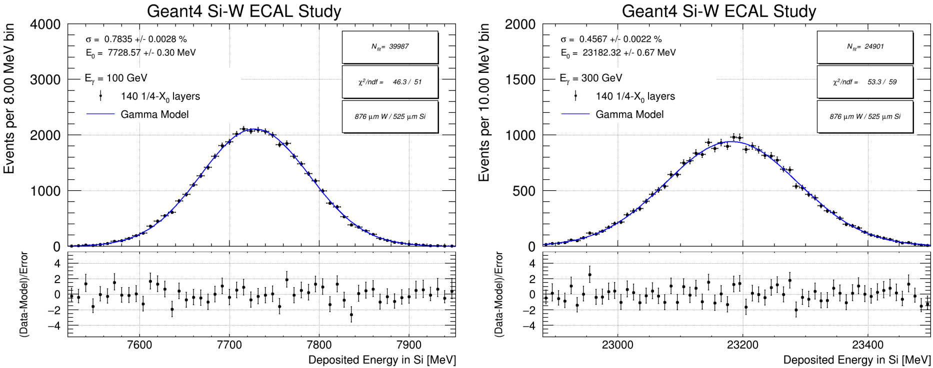


Energy Linearity and Resolution: 10 GeV, 30 GeV Photons

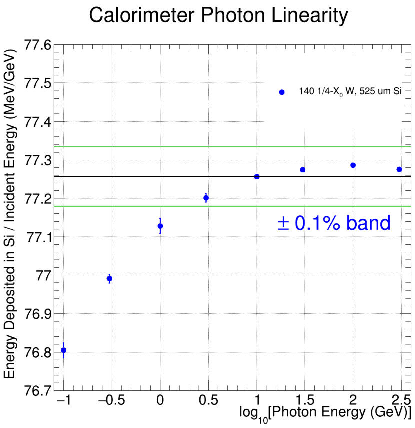


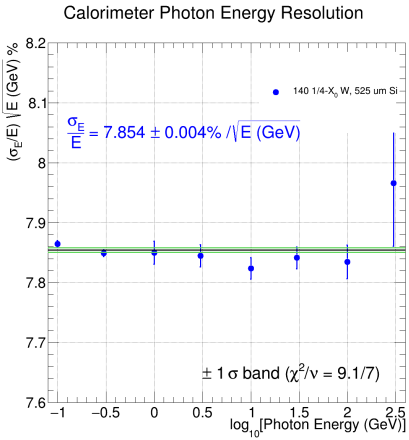


Energy Linearity and Resolution: 100, 300 GeV Photons



Energy Linearity and Resolution



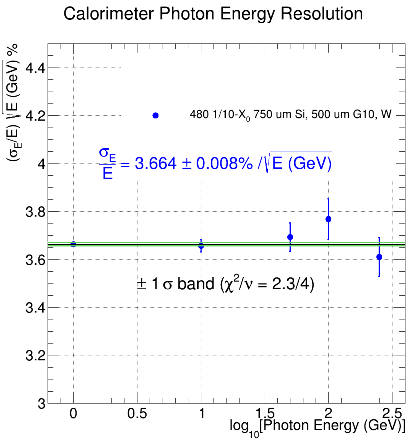


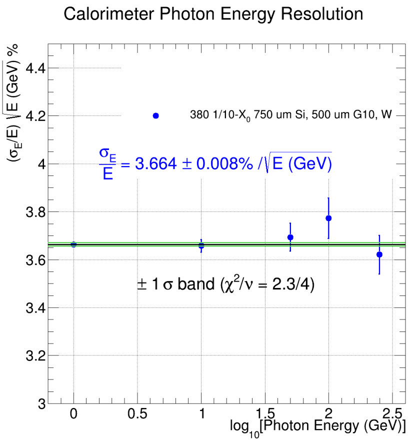
Excellent linearity in [0.1, 300] GeV range. Within 0.1% above 2 GeV. Albedo affects < 2 GeV. EM sampling fraction of 7.7%.

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

Current Calorimeter Model Energy Resolution

More layers. Thicker Si. Include gap material.





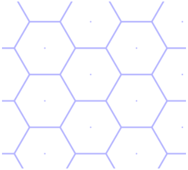
- Need 38 X_0 to avoid energy resolution degradation up to 250 GeV.
- Length around 60 cm.
- Very competitive with homogeneous calorimetry.

Position Resolution Tests

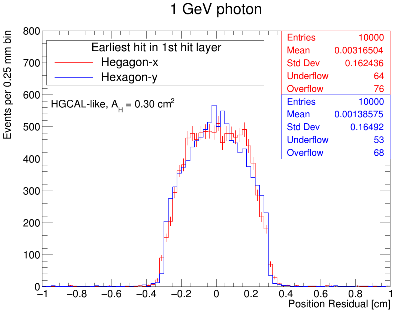
How much can the photon and electron position resolution be pushed with small cells? Can one localize the initial photon interaction point? thus measuring the γ scattering angle, $\theta = \tan^{-1}(r/z)$, and aiding in separating electrons and photons.

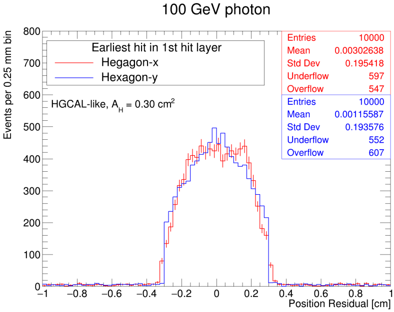
- Use GEANT4 example HGCal_testbeam (CMS). The software was well adapted to the task - but is NOT the proposed design concept.
- Uses **hexagonal** Si pads with 28 layers totalling 27 X_0. Absorbers included Pb, Cu, CuW (quite a mix...).
- In a first step changed hexagonal pixel areas from 1.09 cm^2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

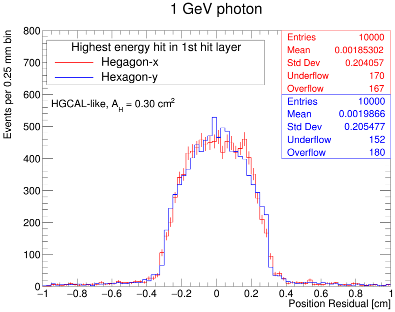
Beam particles are incident on the array with a Gaussian profile with spread in x and y of 1.5 cm. Residuals for calorimeter position observables are calculated with respect to the randomized true beam position event-by-event.

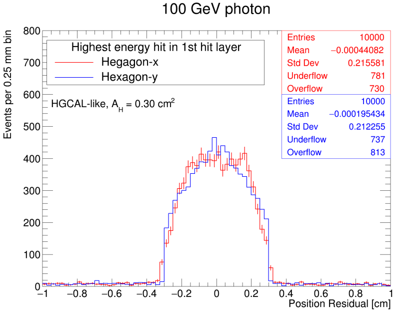
hexagon x horizontal  hexagon y vertical

Choosing the best hit in the first hit layer

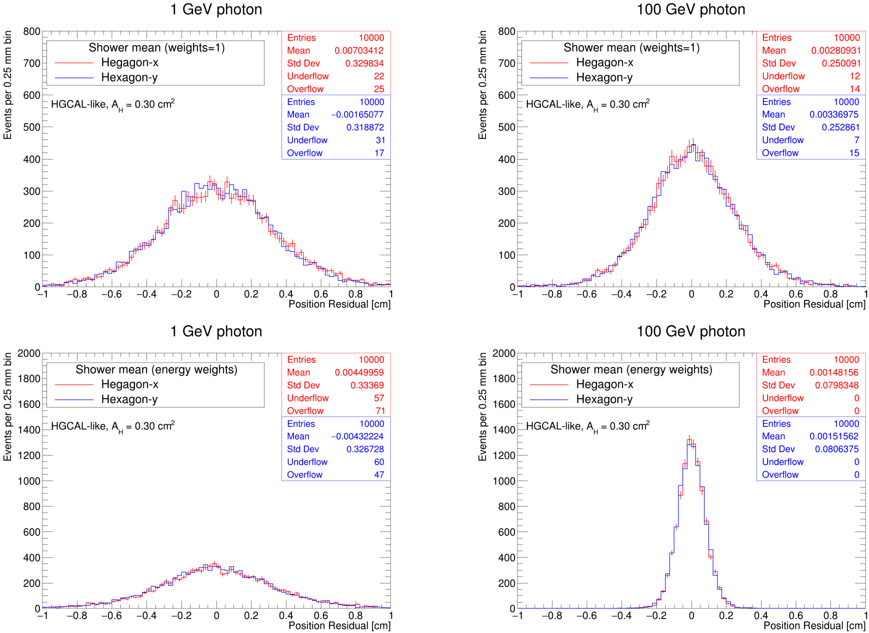




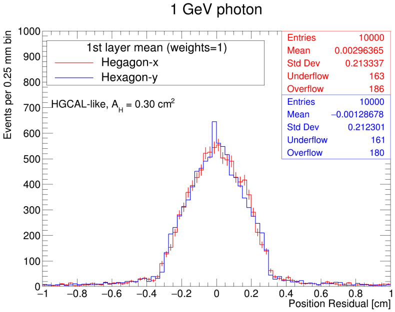


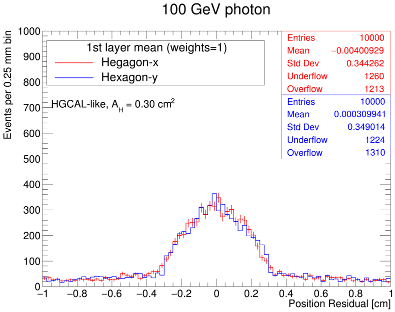


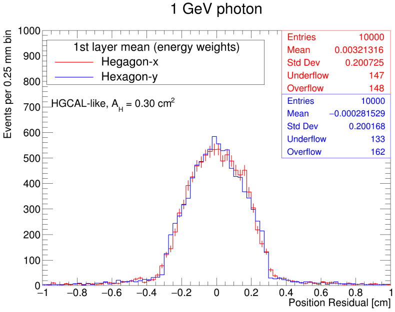
Shower center-of-gravity (all layers)

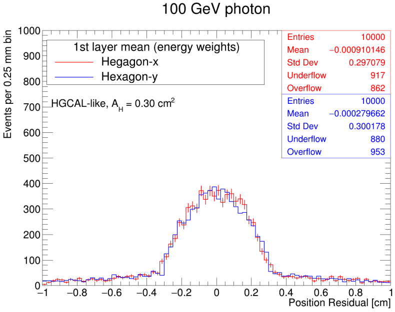


First Hit Layer CoG

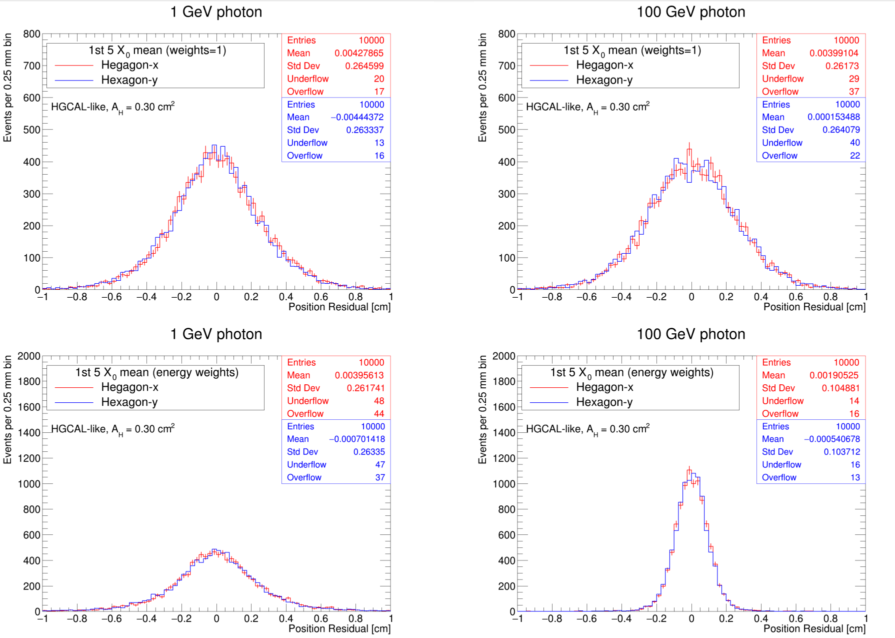






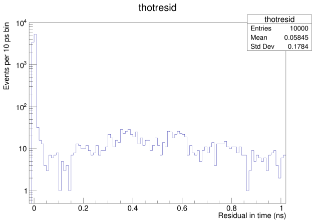


CoG from layers within 5 X_0 of 1st hit layer

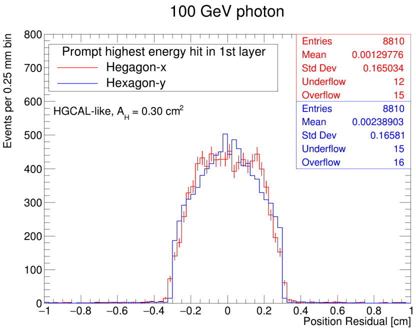


Timing/Promptness Potential (Work In Progress)

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.



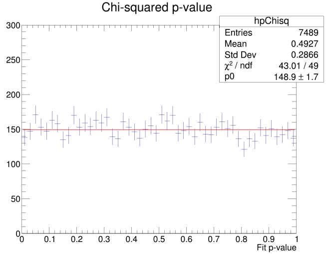
Define prompt hit as within 0.1ns of expected time. In 12% of events the hit previously chosen based on its energy to define the position is non-prompt.

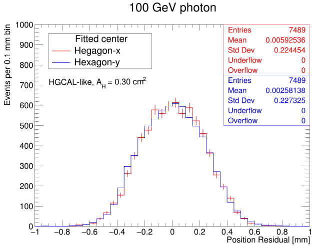
Can recuperate close to perfect hexagonal pitch resolution even for high energy showers. Here perfect would be $\sigma_{x,y} = 0.155$ cm.
To do: use alternate position estimator for the missing 12% - like next layer.

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).





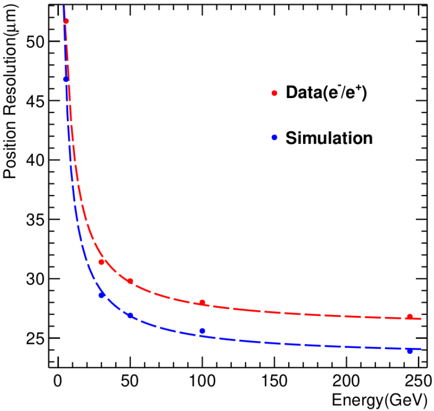
Very acceptable fits

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.
- The FoCal prototype 1708.05164 as shown below gives EM-shower position resolution on the 25 micron scale for 30 GeV showers!



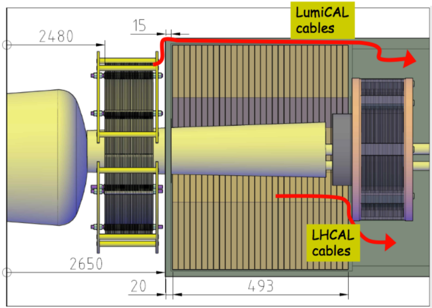
FoCal prototype

- 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.

Some Thoughts on Detector/Accelerator Constraints

See 1701.01923 with some considerations on ILD forward calorimetry layout.



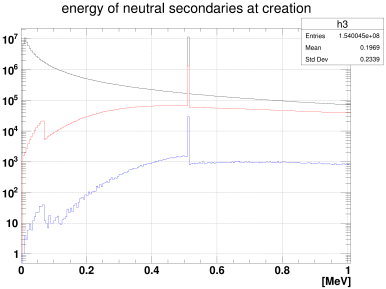
ILD is now designed for L*=4.1m

- 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.

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.



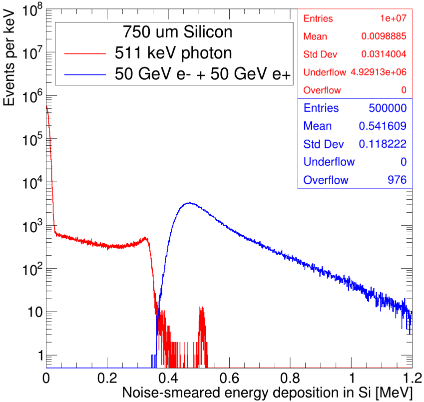
Note the discontinuities (W X-ray K-edge) and forward CS continuum below the 511 keV peak

- A significant portion of the backward going photon flux is from positron annihilation in matter resulting in 511 keV annihilation photons.
- Suggests designing the active layer to be able to veto energy depositions from soft photons (energy $\leq$ 511 keV).
- Also may need to understand how to model the time delays associated with 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.



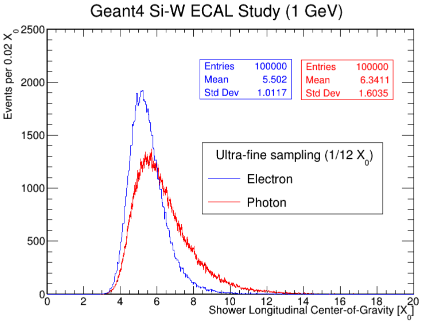
Conclusions

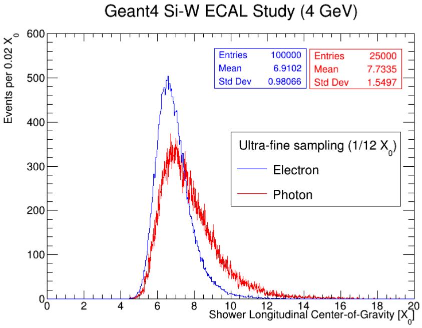
- I believe the PLUG-Cal concept has potential for superior performance for luminosity measurements even with $e^+e^- \to \gamma\gamma$ below the tracker acceptance. Potential doubling of acceptance. Very detailed shower reconstruction.
- It can likely make radial measurements better than ILD LumiCal but with longer Molière radius and better energy and azimuthal resolutions and hermeticity.
- Key issue for luminosity: systematic uncertainty on the acceptance definition. 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.
- 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.

Backup Slides

Shower Shapes Examples

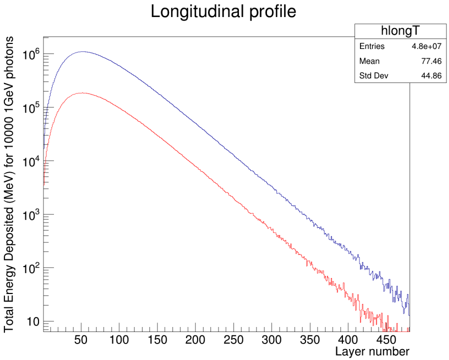
With 12 samples per X_0 these are measured really well. At 4 GeV the C-o-G resolution is 0.07 X_0 - see approximate $1/\sqrt{E}$ scaling of resolution.
Here use W / 1mm G10 / 525 um Si (totaling 1/12 X_0).

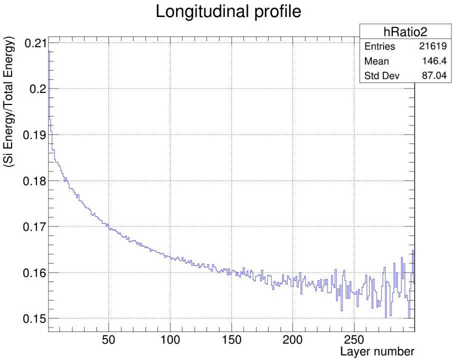




Averaged Shower Longitudinal Profiles

Same calorimeter model as previous slide. 1 GeV photons.





Energy deposited (Si+G10+W) per layer
Energy deposited in Si per layer

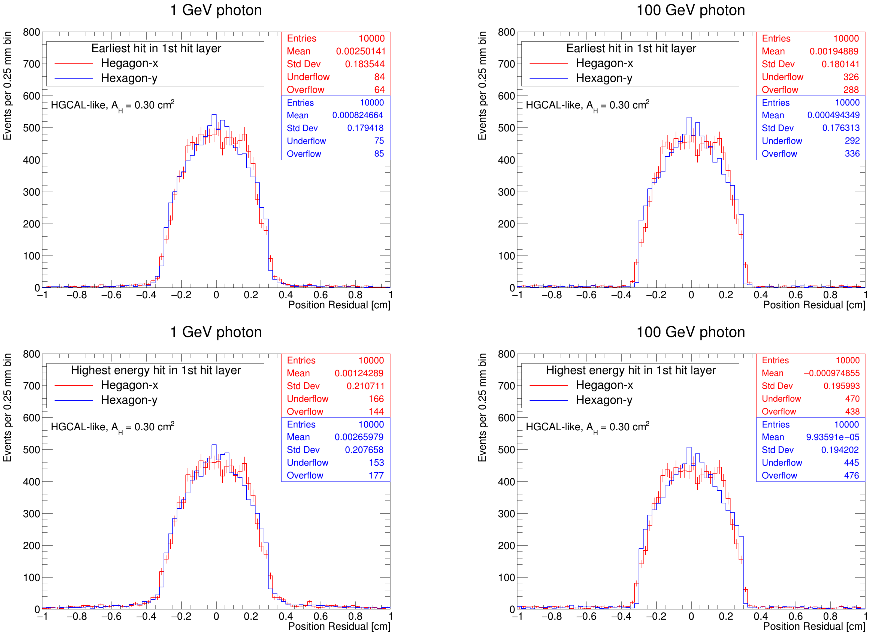
Si/(Si+G10+W) energy ratio per layer

This well-known pernicious "shower-age" effect, means 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.

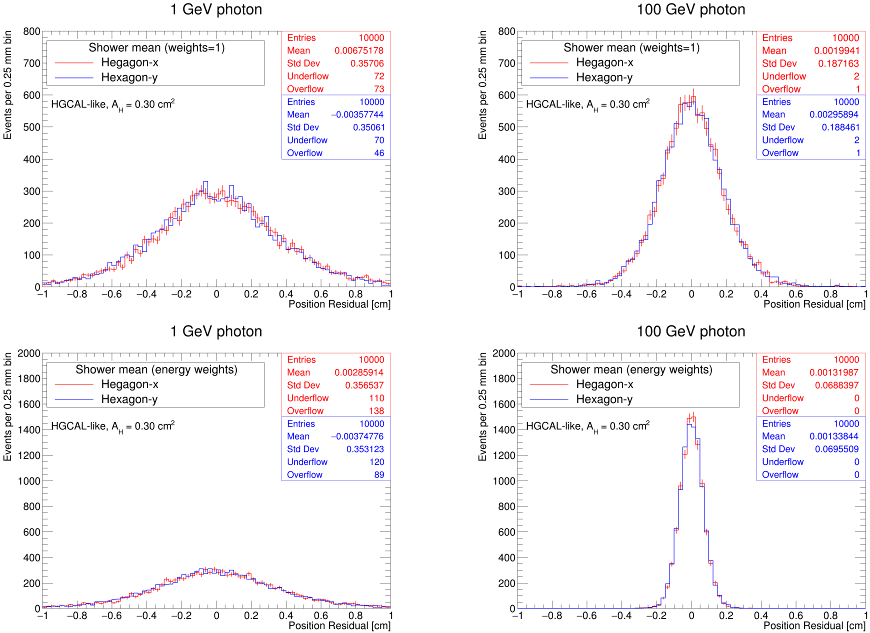
New plots with energy threshold

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

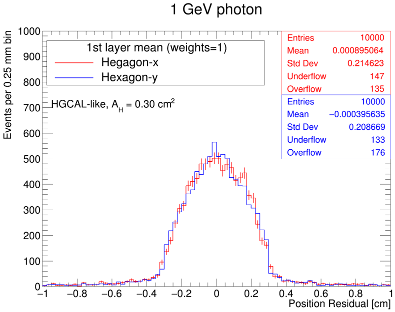
Choosing the best hit in the first hit layer

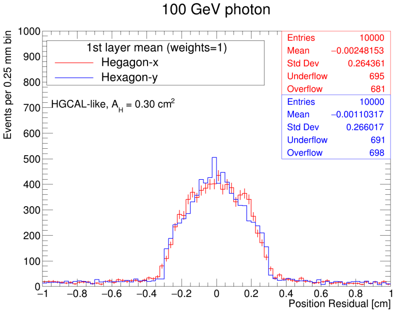


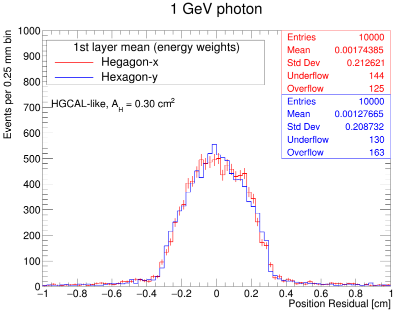
Shower center-of-gravity (all layers)

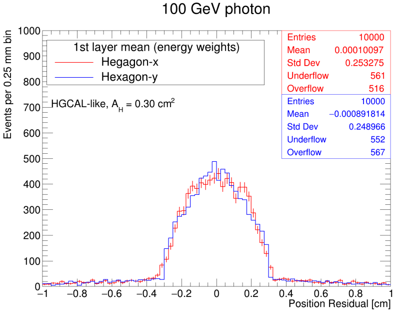


First Hit Layer CoG

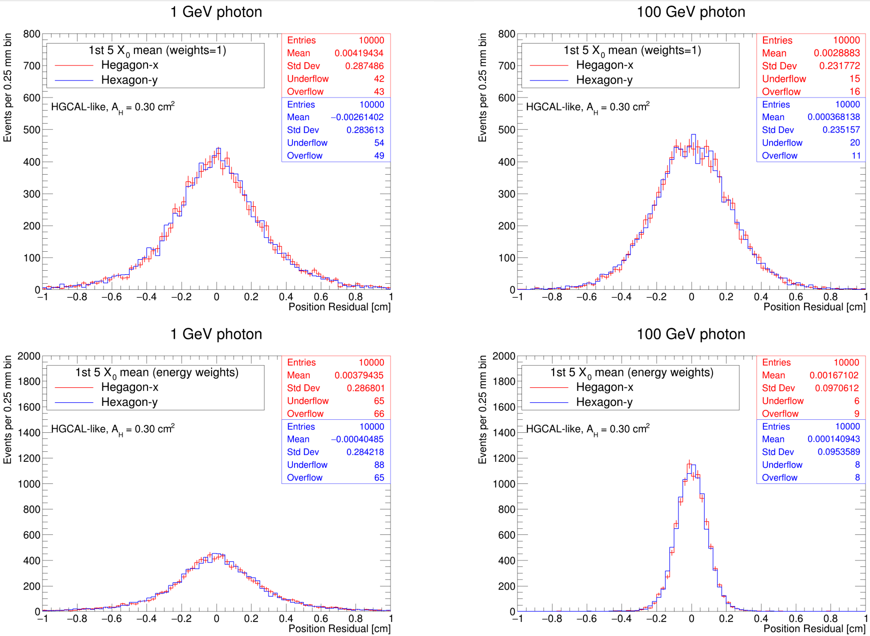








CoG from layers within 5 X_0 of 1st hit layer



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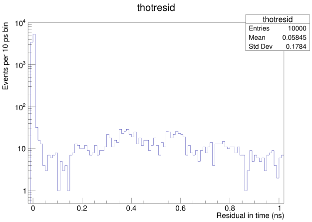

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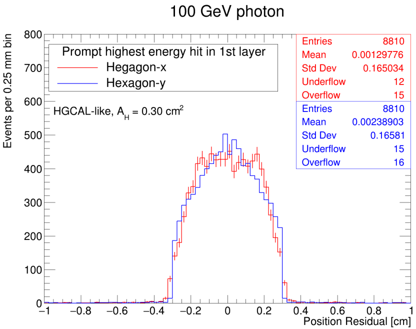

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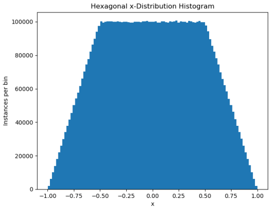
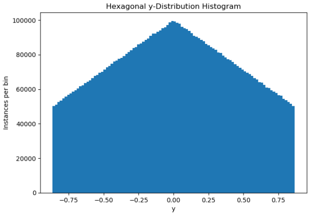
Can recuperate close to perfect hexagonal pitch resolution even for high energy showers. Here perfect would be $\sigma_{x,y} = 0.155$ cm.
To do: use alternate position estimator for the missing 12% - like next layer.

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??

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