Reimagining Si/W-based e^+e^- Collider Precision Luminometry*

Precision sampling forward ECAL design potentially with upstream **tracking**

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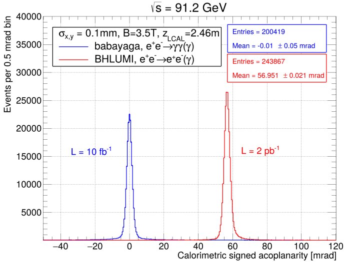
- Interested in $e^+e^- \to \gamma\gamma$ for abs. lumi.
- Small-angle Bhabhas (SABH) challenging for $\Delta L/L = 10^{-4}$ at the Z
- Forward ECAL design studies with emphasis on e/γ separation
- Initial EM deflection (EMD) studies for LEP/LC
- Use upstream mini-tracker in lumi measurement?



* See proceedings-1

Luminosity Measurement Introduction

Two predominantly QED processes considered for e^+e^- collider luminosity measurements at the 10^{-4} level (target especially for Z running for improving N_ν). Both can be under very good theoretical control.

1. **Bhabha Scattering**, $e^+e^- \to e^+e^-$. Used at LEP/SLC with small-angle Si/W-based calorimeters to restrict to the pure t-channel contribution. Current ILC and FCC-ee LumiCal designs follow this approach. $d\sigma/d\theta \sim 1/\theta^3$. Prone to systematics from knowledge of θ_{min} and EMD bias.
2. **Pair Annihilation into Photons**, $e^+e^- \to \gamma\gamma$. A pure QED process. $d\sigma/d\theta \sim 1/\theta$. Less sensitive to θ_{min} systematic. No θ_{max}. Lower event rate.

Integrated cross-sections are approximately:

$\sigma_{e^+e^-} = 1040 \text{ nb } (\theta_{\mathrm{min}}^{-2} - \theta_{\mathrm{max}}^{-2})/\, s[\mathrm{GeV}^2]$.

$\sigma_{\gamma\gamma}(\theta > \theta_{\mathrm{min}}) = 130 \text{ nb } (1 - P_{e^-} P_{e^+}) \left(\log_e\left(\frac{1+\cos\theta_{\mathrm{min}}}{1-\cos\theta_{\mathrm{min}}}\right) - \cos\theta_{\mathrm{min}}\right)/\, s[\mathrm{GeV}^2]$

For $\theta_{\mathrm{min}} = 31.3$ mrad and $\theta_{\mathrm{max}} = 51.6$ mrad (OPAL LEP1), the cross-sections are **81 nb** (Bhabhas) and **115 pb** ($\gamma\gamma$ unpolarized) at $\sqrt{s} = 91.2$ GeV.

My Take

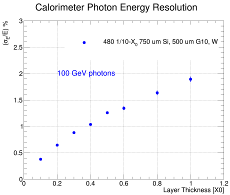
- Use Bhabhas for relative luminosity (especially for polarized beams).
- $e^+e^- \to \gamma\gamma$ can reach 10^{-4} statistical (at Z) with 1 ab^{-1} and $\theta_{\mathrm{min}} = 1.8^\circ$.
- Precision **absolute** lumi. is experimentally easier with $\gamma\gamma$ cf Bhabhas.

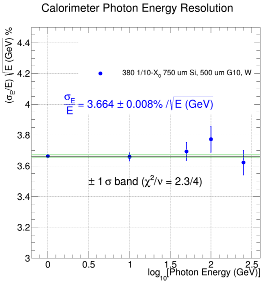
PLUG-Cal: Precision Luminosity Ultra-Granular Calo.

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. Many ultra-thin absorber 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 μm resolution for high energy electron showers with ALPIDE sensors (1708.05164). 2 planes adopted for ALICE-FoCal upgrade.
6. Include 0$^{\text{th}}$-layer and maybe more tracking for enhanced e/γ discrimination.
7. Emphasize **azimuthal** ECAL measurements for $\mathrm{e}^+\mathrm{e}^-$ / $\gamma\gamma$ discrimination. Expect 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 the over-arching concern.
11. Retain or exceed performance for Bhabha-based measurement.

Energy Resolution Landscape





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

Precision EM Calorimetry

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

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), and estimation of θ.

Related R&D Agenda/EOI

Project scope addresses the fundamental issue of the normalization strategy for future e^+e^- experiments, and opens up the potential for choosing high performance forward calorimetry for physics exploitation.

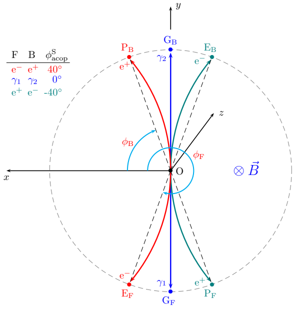
Preliminary multi-year goals: mostly simulation.

1. Understand EMD effects and design detector/accelerator mitigation strategy.
2. Develop robust 3-d position reconstruction algorithms.
3. Develop robust electron/photon discrimination design.
4. Investigate use of multi-variate approaches to improve energy reconstruction.
5. Evaluate sparser (more cost optimized) longitudinal sampling arrangements.
6. Investigate limitations on photon reconstruction from back-splash.
7. Collaborate on understanding technological issues for thicker silicon.
8. Inform quantitative conclusions on feasibility of Bhabha and $\gamma\gamma$ based precision luminosity measurements and detector/accelerator requirements.

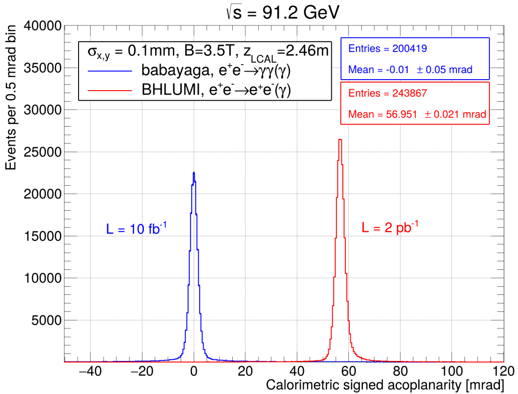
More details in later slides.

Calorimetric Signed Acoplanarity

z is e^- beam direction.
F $= +z$, B $= -z$.



$\phi^S_{acop} \equiv [(\phi_F - \phi_B) \bmod 2\pi] - \pi$



$G_F - G_B$ = back-to-back $\gamma\gamma$
$E_F - P_B$ = forward-scattered Bhabha

OPAL-like acceptance [25, 58] mrad. With much higher B z_{LCAL} and azimuthal resolution.

Various ECAL designs studied by Brendon

- Focus has been trying to understand the limits for position/angle resolution
- Configurable transverse granularity (keeps GEANT hits)
- Need to also keep desired excellent energy resolution.
- (My favored design is still 750μm Si, 0.1 X_0 sampling, $3.7\%/\sqrt{E}$)

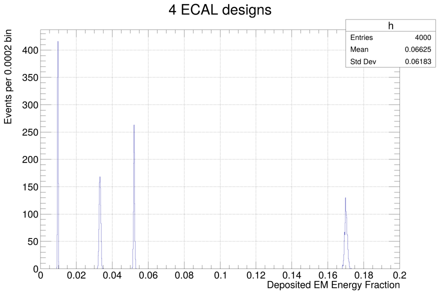
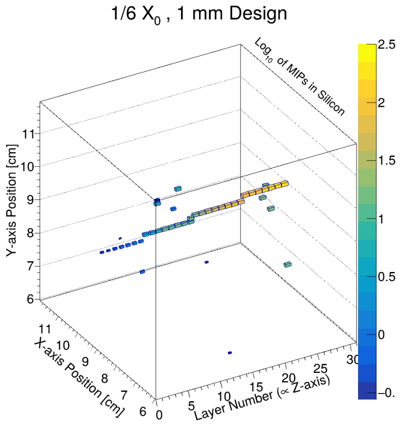


Table 2. Five different Si/W electromagnetic calorimeter designs with simulated deposited electromagnetic energy fractions, fractional energy resolution for 128 GeV photons (with E in GeV), and computed Molière radius. All calorimeters are sufficiently deep to guarantee excellent longitudinal containment (here at least $40X_0$.) and negligible simulated constant term. The length is given for 35 radiation lengths. The last design is simulated with 500 μm G10 and no air gap, the other designs assume more conservatively 1mm G10 and 1mm air gap.

Design	t_{Si} [μm]	EM Fraction	Energy Resolution	ρ (Molière) [mm]	Length [cm]
1 X_0	300	0.964%	$18.4\%/\sqrt{E}$	14.6	20.2
1 X_0	1000	3.31%	$15.7\%/\sqrt{E}$	15.9	22.6
1/6 X_0	300	5.21%	$6.6\%/\sqrt{E}$	34.8	59.9
1/6 X_0	1000	17.0%	$4.8\%/\sqrt{E}$	37.8	74.1
1/10 X_0	750	21.2%	$3.7\%/\sqrt{E}$	27.5	54.7

Event display (View 1) first 5 rad. lengths

128 GeV photons. Original from Brendon

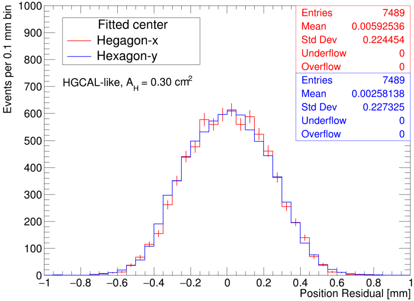


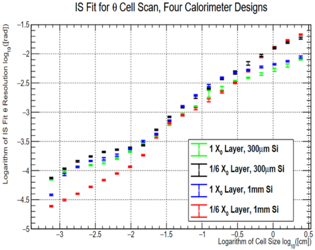
UHGC (left) : LumiCal-like (right). See backup slides for more views.

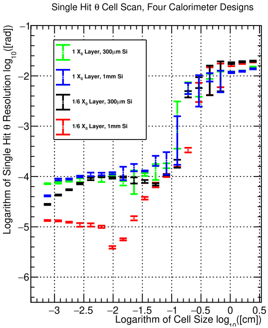
Position Resolution Studies

Longitudinally-integrated fit for transverse center using test-beam setup, using (CMS) HGCal_testbeam G4 example. Find position resolution of 225μm for 100 GeV photons (Improves to 112μm for 1.25 mm^2 cells).

100 GeV photon







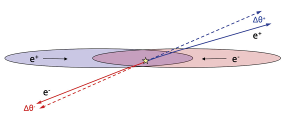
Right plots (cheated): For 128 GeV photons at $\theta = 50$ mrad. Top - using initial shower hits. Bottom using closest hit. More details in proceedings-2. Track-like resolution.

Small-angle Bhabhas (SABH) are very challenging.

As discussed by 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 both affect the acceptance for Bhabhas in the luminometer.

Bhabha suppression effect, BHSE=BS+EMD (dashed).

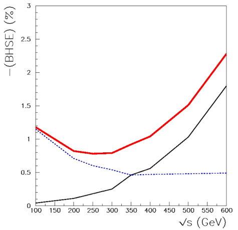
G. Voutsinas et al. / Physics Letters B 800 (2020) 135068



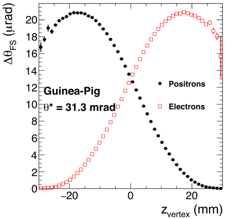
$$N \propto \int_{\theta_{\min}}^{\theta_{\max}} \frac{d\theta}{\theta^3},$$

the bias induced by this angular deflection reads

$$\frac{\Delta N}{N} = \frac{-2}{\theta_{\min}^{-2} - \theta_{\max}^{-2}} \left(\frac{\Delta\theta_{\rm FS}(\theta = \theta_{\min})}{\theta_{\min}^3} - \frac{\Delta\theta_{\rm FS}(\theta = \theta_{\max})}{\theta_{\max}^3} \right), \quad (3)$$



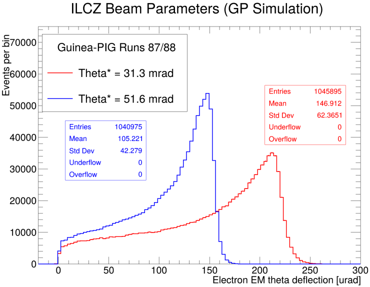
- (left) ILC RDR: Rimbault, Bambade, Moenig, Schulte
- LEP1 (right): Voutsinas, Perez, Dam, Janot



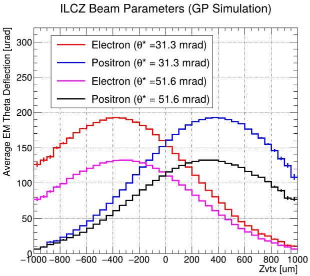
- EMD was a significant problem for LEP1 lumi. causing a 0.106% bias on supposed 0.034% systematic precision (OPAL). Bias correction relative error of 5% claimed.
- Useful $z_{\rm vtx}$ for SABH events at ILC very challenging $\sigma(z_{\rm vtx})$ 264/200 μm (Z/250).

EMD deflection studies with Guinea-PIG

Guinea-PIG = beam-beam simulator. Simple 2-particle Bhabha events with fixed CoM scattering angles are superimposed proportional to the luminosity distribution and tracked through the electromagnetic field of each beam.



Observed polar deflection angle for these two scattering angles for nominal ILC-Z conditions. The bias in the Bhabha count rate and the resulting lumi. estimate is -1.25% (Eqn. 3, p5).



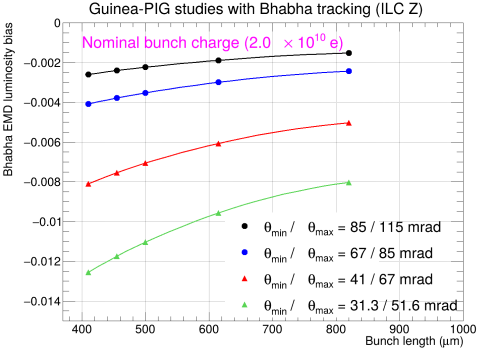
If the longitudinal vertex position can be determined at least statistically, can form some asymmetries related to how much the observed electron/positron has traveled through the opposing bunch after the Bhabha scattering event. See 1908.01704 for details. For ILCZ, $\sigma(z_{\mathrm{vtx}}) = 264\mu\mathrm{m}$. Challenging!

Reducing the Bhabha EMD Luminosity Bias

Two methods - besides reducing the bunch charge (and luminosity) come to mind

1. Changing the fiducial acceptance (wider angles - less deflection). Reduces the Bhabha counts. Bias reduction of factor of 3 for factor 7.5 loss in statistics (blue).
2. Longer bunches (reducing the bunch compression). Lower charge density so less deflection. Higher disruption, modest lumi. increase, smaller energy spread (σ_E/E).

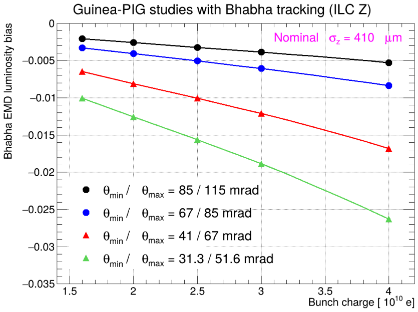
ILC-Z nominal bunch length: 410 μm.

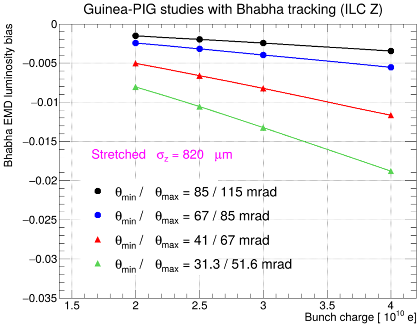


- Bhabha cross-sections at the Z: 80.7 / 46.5 / 10.6 / 7.8 nb
- Compared with $\sigma_{\text{had}} = 31$ nb.

What about **Increasing** the Bunch Charge (N)?

ILC nominal bunch charge is 2×10^{10}e with sources designed with 50% margin.

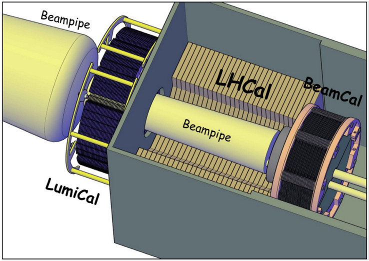




- As expected the bias increases substantially with N. The lumi. per bunch crossing increases by a factor of 7.7 from nominal to doubled bunch charge and doubled bunch-length (another talk ...) - much more than the factor of 4 in geometric lumi.
- Longer bunches helpful for EMD mitigation presuming this can be integrated into the accelerator design. Two reasons: less deflection, easier $z_{\rm vtx}$ diagnostics.
- When targeting 10^{-4} lumi. precision with Bhabhas, should plan on understanding a 1% bias to 1 part in 300. If feasible: need excellent diagnostics.

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 replicating 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 $z_{\min}$).

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.

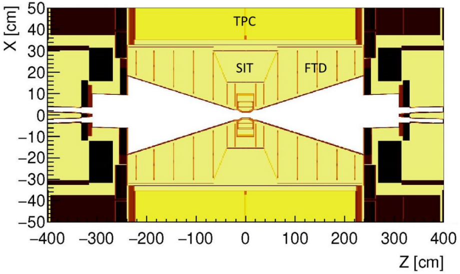
Physics drivers (not just R) include:

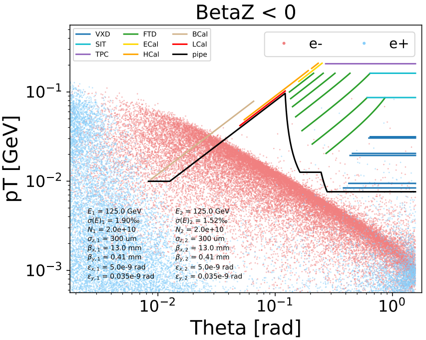
1. $\gamma/e^-/e^+$ tagging
2. hermeticity
3. azimuthal and energy resolution

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.

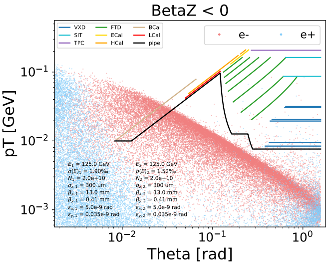


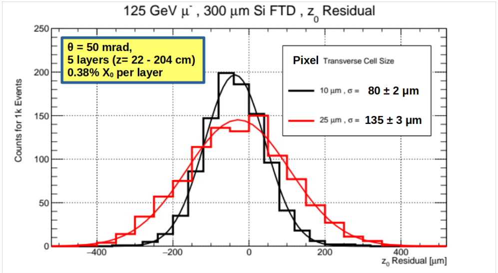


- For tracking upstream of LumiCAL will need to re-design beam-pipe.
- Pairs simulation - very encouraging. Clean upstream phase-space exists.
- Estimating well Bhabha z_{vtx} has a high priority - more so than minimal upstream material for Bhabha lumi measurement IMO.

Initial look at small-angle forward tracking

Left plot: view of the pair background in ILD for ILC at $\sqrt{s} = 250$ GeV. Note the beam-pipe (black), the LumiCal (LCal) acceptance in red, and the green forward tracking disks (FTD), above $\theta = 100$ mrad. The region upstream of LCal is relatively quiet. Can envisage tracking in front of LCal.





Right plot: GEANT4 simulation of 5 square pixellated Si layers in z with 0.38% X_0 per layer for 125 GeV tracks at 50 mrad (with Brendon Madison). Single pixel response assumed. The results for z_0 from r-z straight line fits are shown.

Outlook

Can use both Bhabha tracks, but it will be challenging to achieve 250 μm at the Z on the longitudinal event vertex with a less invasive and practical design (including beam-pipe).

Outlook/Concluding Remarks

- 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 designs (like ILD/CLD) 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** for beam energy particles is also key in defining the acceptance and background rejection. Will have electron tracking layers (also may help with EM deflection diagnostics).
- Radiative neutrino counting (with ISR photons) is a great physics motivation for **electron/γ separation** beyond the tracker. See recent Cracow Epiphany Conference talk. Radiative-return to the Z photons are 108 GeV ($\sqrt{s} = 250$ GeV).
- LC Vision meeting is Jan. 8-10, 2025 at CERN. More on higher lumi at the Z then.

Backup Slides

More details are in recent talks from Cracow, CERN, LCWS (Tokyo), ECFA (Paestum, Paris).

Related R&D Agenda/EOI

Preliminary multi-year goals: mostly simulation.

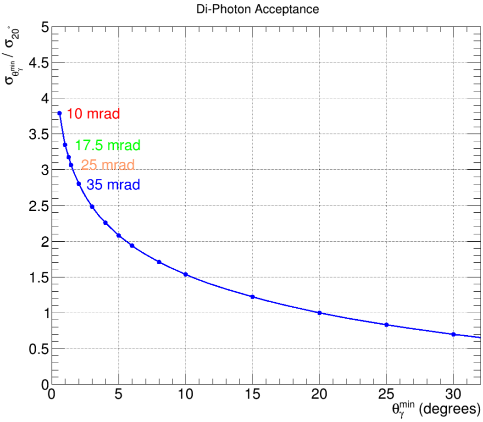
1. Evaluate using beam-beam simulations the size of the electromagnetic deflection (EMD) issue and develop luminosity calorimeter design based mitigation strategies/performance requirements (in progress).
2. Develop robust 3-d position reconstruction algorithms taking advantage of Si pixel geometry to address performance vs pixel size, layer-to-layer staggering, and prospects for understanding of the fiducial acceptance.
3. Develop robust electron/photon discrimination design, likely emphasizing several thin non-absorber front tracking layers, and look into feasibility of electron/positron charge discrimination.
4. Investigate use of multi-variate approaches to improve energy reconstruction.
5. Evaluate less conservative (and cheaper) longitudinal sampling arrangements that will need proper weighting and in some cases leakage corrections.
6. Investigate limitations on photon reconstruction measurements from back-splash, and investigate further the use of timing to mitigate back-splash (Comptons and positron annihilation). May need to model better the effective positron lifetime ($\tau \approx 100$ ps) in calorimetric materials - lab measurements with β^+ sources?
7. Collaborate on understanding some of the technological issues for thicker silicon. Should be cheaper but full depletion voltage goes as t_{Si}^2.

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.

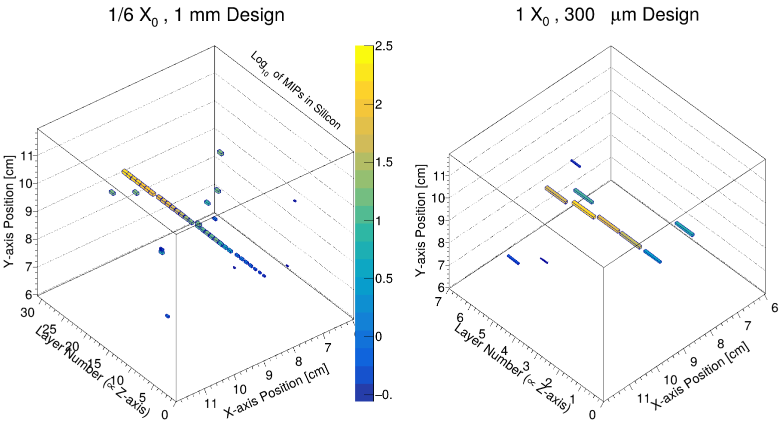


- Significant increase in potential accepted cross-section for all $\sqrt{s}$ compared with a 20° acceptance cut[a].
- Factor of 2.5 – 3 increase feasible by extending to ILD LumiCal acceptance?
- Will need excellent Bhabha rejection.
- Note: only use LumiCal to define $\theta_\gamma^{\min}$. No $\theta_\gamma^{\max}$ cut.

[a] typical LEP choice - driven by tracker

Event display (View 2) first 5 rad. lengths

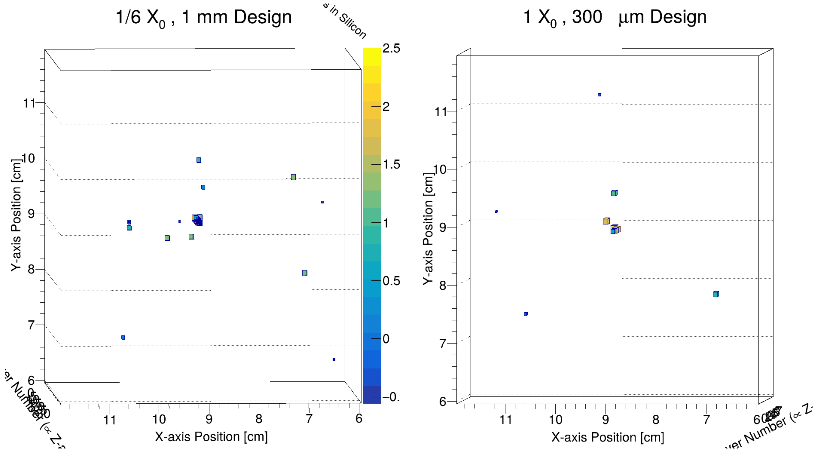
Rotated a bit. 31 connected energy deposits vs 4 connected energy deposits.



UHGC (left) : LumiCal-like (right).

Note: With idealized staggering can strive for $\Delta/(N\sqrt{12})$ at high E_γ.

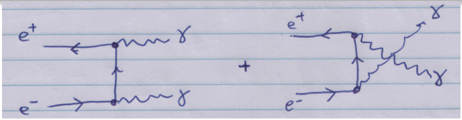
Aligned to observed photon direction



UHGC (left) : LumiCal-like (right)

Getting the correct initial photon conversion is critical (and not picking up hits from soft back-scattered photons).

Di-Photon Basics



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

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

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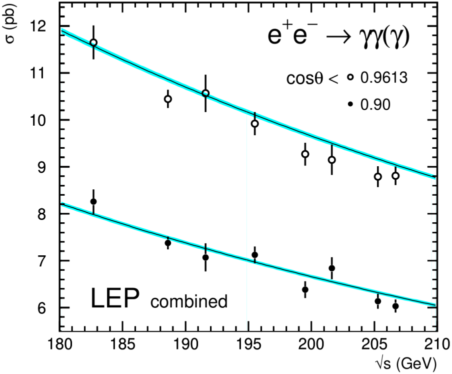
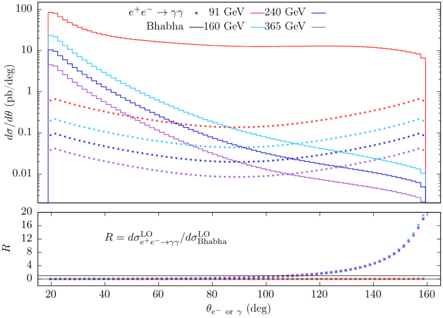


Here $\theta_\gamma > 16^\circ$ or $\theta_\gamma > 26^\circ$



$\sqrt{s}$ (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.

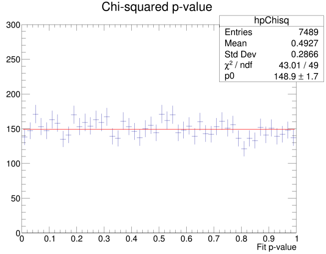
- Bhabhas look very **problematic** for high-precision absolute lumi. It was even not under control experimentally at LEP1. Beam-induced **EM deflections** affected the luminosity acceptance at the 0.1% level (see 1908.01704).
- Di-photon process should not be much affected.
- Di-photons much less sensitive 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.

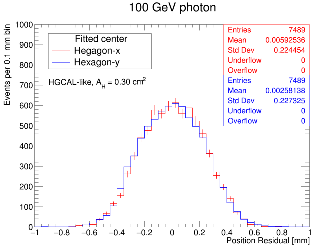
So let's design precision forward calorimetry for electrons AND photons inspired by various ideas (and avoiding some of the compromises) of related designs, CALICE, ILD, SiD, CMS-HGCAL, ALICE-FoCal, Fermi-LAT.

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).





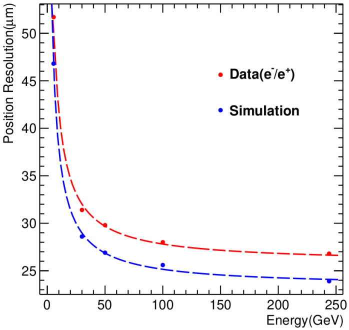
Very acceptable fits

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!



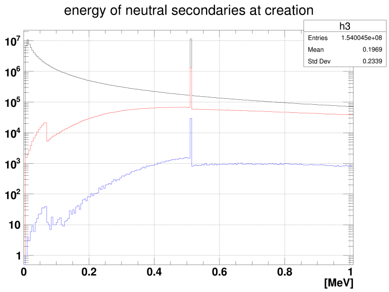
FoCal prototype

- 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.

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 $\sqrt{t/t_{\mathrm{ref}}}$ e- with $t_{\mathrm{ref}} = 325$ 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.