Electron/Photon Separation for Diphoton Luminosity Measurement

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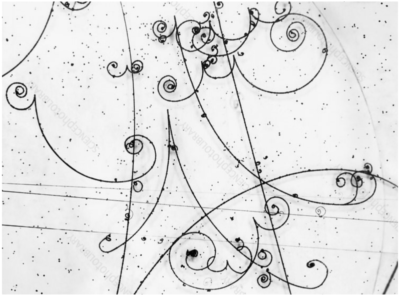
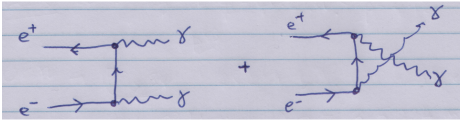


1. Measuring absolute luminosity with $\mathrm{e^+e^-} \to \gamma\gamma$
2. Considerations on tracker-based $\mathrm{e^+e^-} \to \gamma\gamma$ / $\mathrm{e^+e^-} \to \mathrm{e^+e^-}$ separation
3. Examples from LEP
4. (Recent forward ECAL design studies with emphasis on e/γ separation)

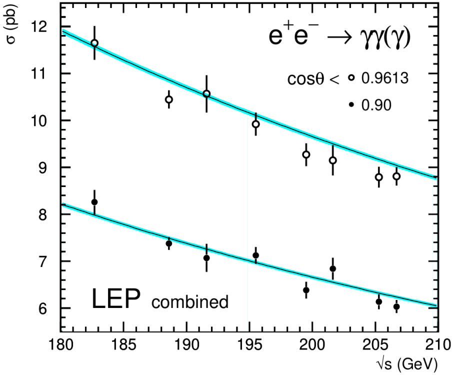
e/γ Separation & Di-Photons for Luminosity Outline



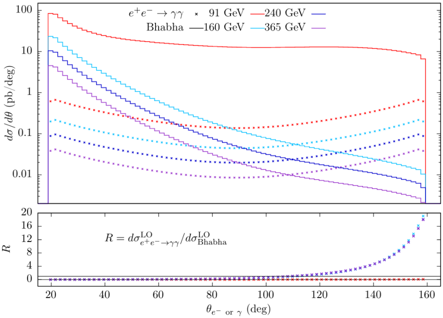
$$\frac{d\sigma^{U}_{\text{Born}}}{d|\cos\theta|} \approx \frac{2\pi\alpha^2}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right)$$

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

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

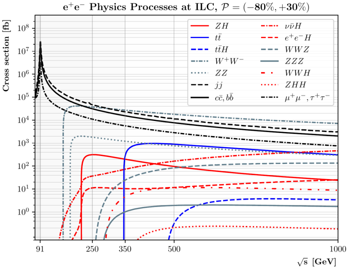
Why is $e^+e^- \to \gamma\gamma$ so attractive?

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.

Work on designing precision (long) forward calorimetry for electrons AND photons inspired by various ideas of related designs, CALICE, ILD, SiD, CMS-HGCAL, ALICE-FoCal, Fermi-LAT discussed in recent ILD workshop talk.
Today's focus. Explore requirements for $e^+e^- \to \gamma\gamma$ with $\theta_\gamma^{\min} \approx 10 - 20^\circ$ (tracker-based Bhabha vetoes).

LUMI: Targets for Absolute Luminosity Precision



- The standard process used for **absolute** luminosity at LEP is small-angle **Bhabha** scattering, $e^+e^- \to e^+e^-$ (high statistics). This will be important for **relative** luminosity.
- 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.

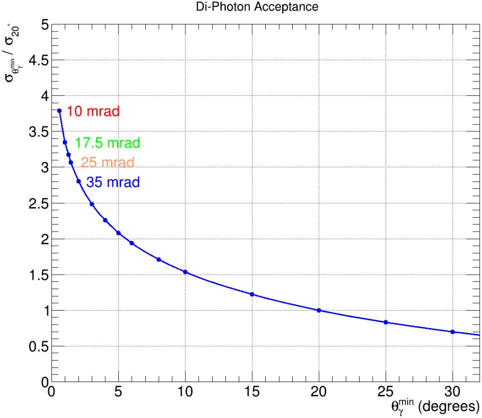
What is achievable in terms of systematics? For now assume the target of 10^{-4} for expt.+theory. For 10^{-4} at the Z, one has $\times 50$ (ILC) or $\times 10^4$ (FCC-ee) more hadronic Zs than needed. To match 10^{-4} lumi syst. precision with 10^{-4} lumi stat. precision at the Z, need $\sigma_{\mathrm{lumi}}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

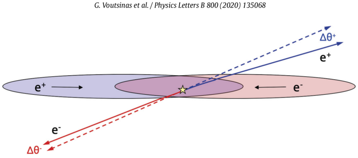


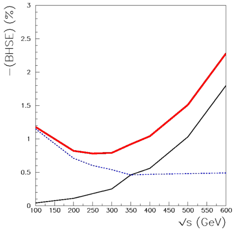
- Significant increase in potential accepted cross-section for all $\sqrt{s}$ compared with a 20° acceptance cut[a].
- Factor of 2.5 – 3 increase feasible by extending to ILD LumiCal acceptance?
- Will need excellent Bhabha rejection.
- Note: only use LumiCal to define $\theta_\gamma^{\min}$. No $\theta_\gamma^{\max}$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

[a] typical LEP choice - driven by tracker

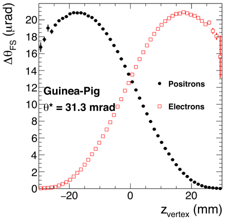
Small-angle Bhabhas (SABH) are very challenging.

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.

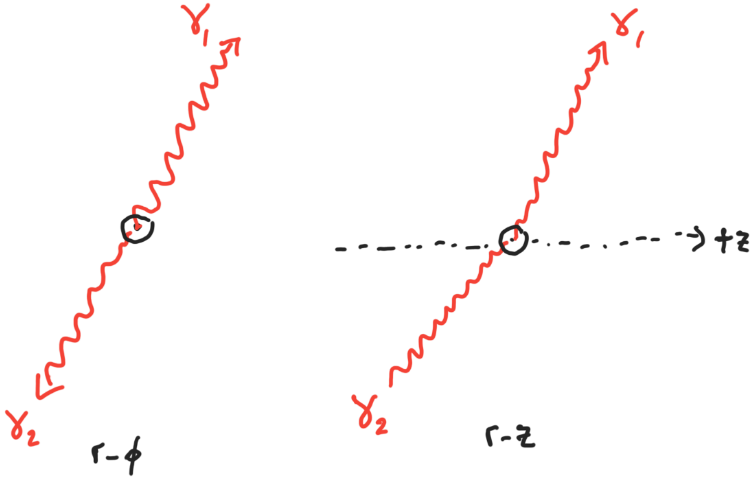
LUMI: $e^+e^- \to \gamma\gamma$ for absolute luminosity

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

$\theta_{\min}$ ($^\circ$)	$\sigma_{\gamma\gamma}$ (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

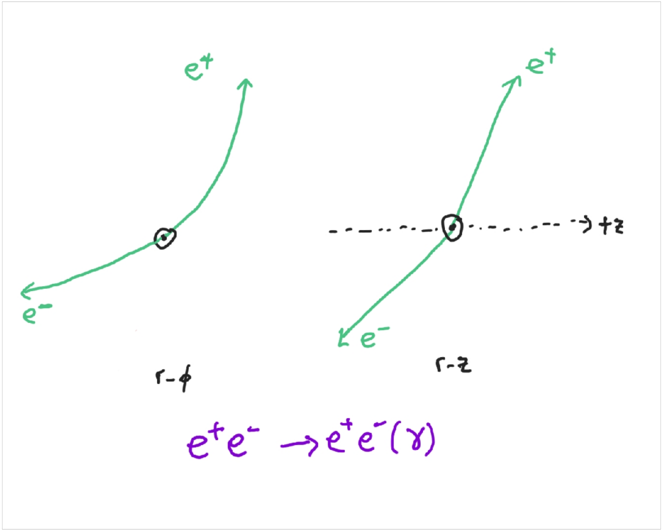
- Unpolarized Born cross-sections. $\pm 24\%$ for $\gamma\gamma$ with (80%/30%) longitudinal beam polarization. Typical HO effects: +5–10%.
  Counting statistics adequate for $\sqrt{s} \gg m_Z$. Note: Use **whole** detector.
- For comparison, 10μrad knowledge for OPAL small-angle **Bhabha** lumi acceptance, 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.

$e^+e^- \to \gamma\gamma(\gamma)$ SIGNAL



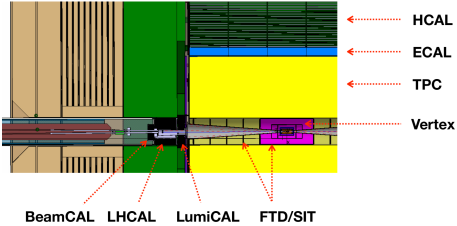
$e^+e^- \to \gamma\gamma(\gamma)$

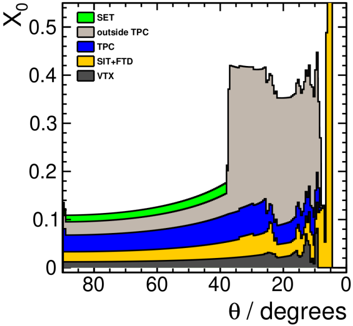
$e^+e^- \to e^+e^-(\gamma)$ (Bhabha scattering) BACKGROUND



B-field is into the page (the dot is meant to be the IP not the B-field arrow tip ...)

Detector Material - use ILD as example



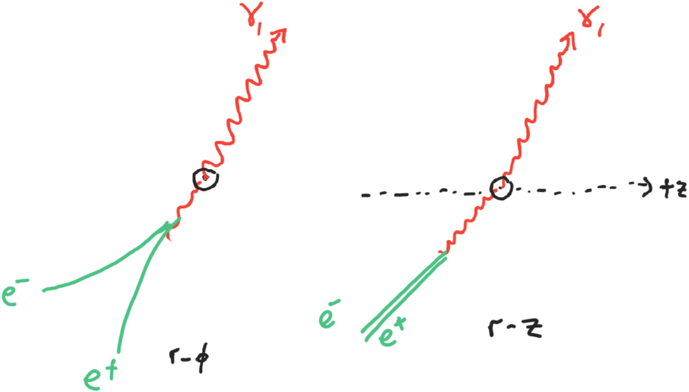


Writing, $t = x/X_0$,

$$p_{\rm conv} = 1 - \exp\left(-\frac{7}{9}t\right) \approx \frac{7}{9}t \ \text{ for small } t$$

Depending on charged-particle rejection algorithm and polar angle, the inefficiency per photon from conversions should be limited to $p_{\rm conv}$ values below 4% ($t = 0.0525$) and more likely 1–2%.

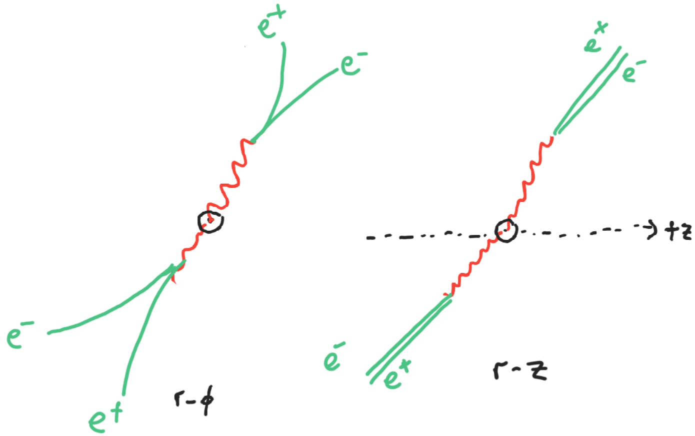
$e^+e^- \to \gamma\gamma(\gamma)$ SIGNAL



$e^+e^- \to \gamma\gamma(\gamma)$

WITH ONE CONVERSION

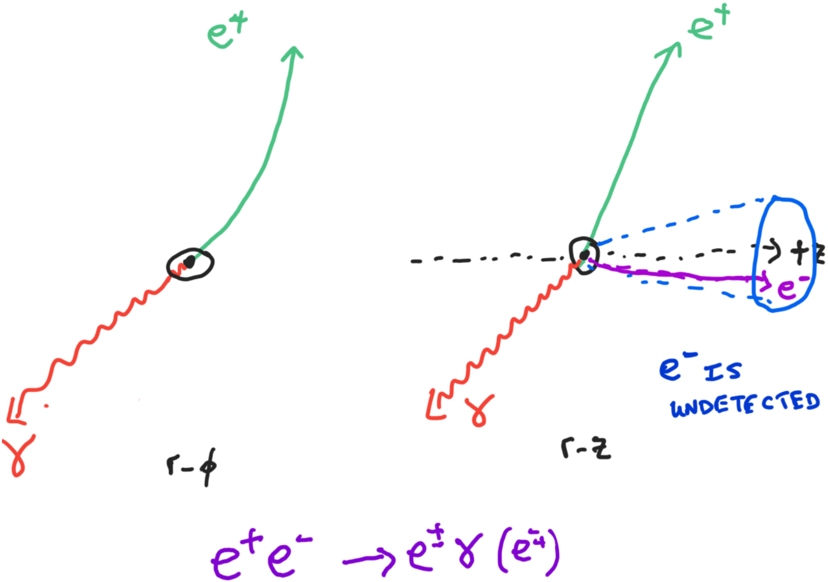
$e^+e^- \to \gamma\gamma(\gamma)$ SIGNAL



$e^+e^- \to \gamma\gamma(\gamma)$

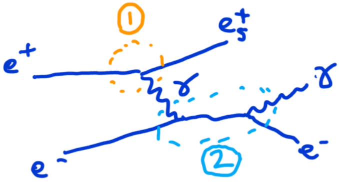
WITH TWO CONVERSIONS

$e^+e^- \to e^\pm\gamma(e^\mp)$ (also Bhabha scattering)



$e^+e^- \to e^\pm\gamma(e^\mp)$ (also Bhabha scattering)

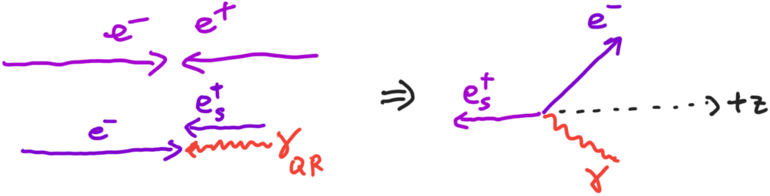
Low Q^2 radiative Bhabha scattering



Can use EPA / WW to decompose as

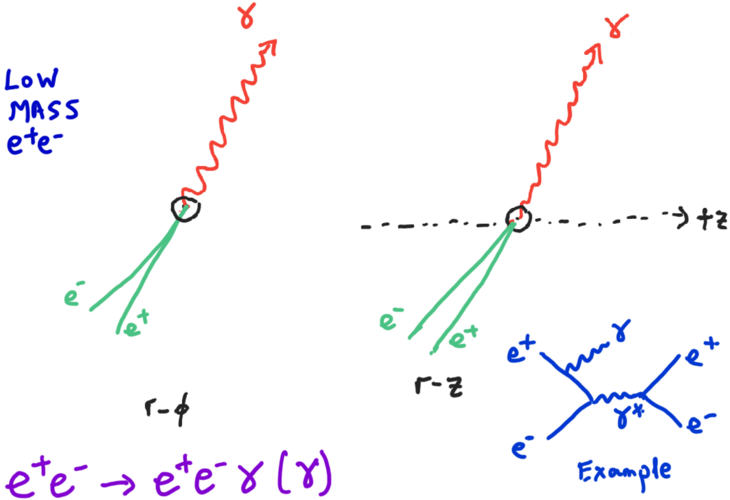
1. photon flux from e^-/e^+
2. $\gamma_{QR} e^- \to \gamma e^-$.

i.e. quasi-real Compton scattering

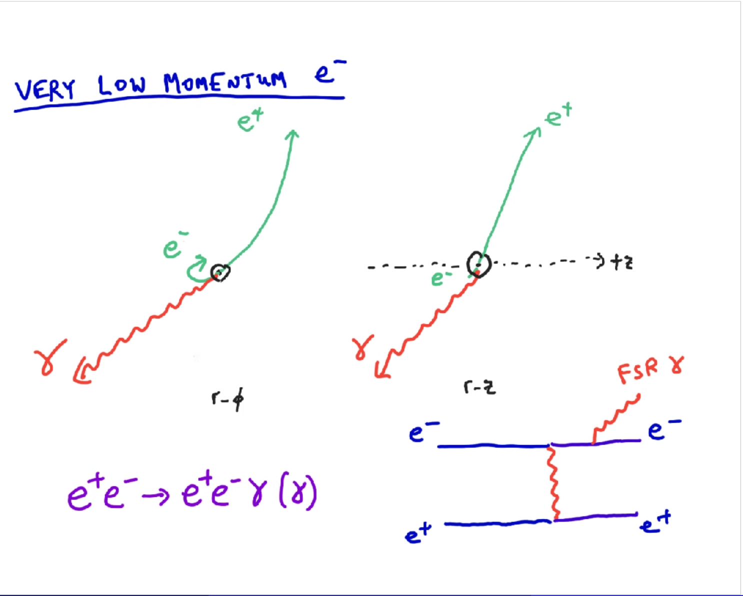


This is the "E-GAMMA" process in TEEGG.

$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$ (also Bhabha scattering)



$e^+e^- \to e^+e^-\gamma(\gamma)$ (also Bhabha scattering)



Eur. Phys. J. C 26, 331–344 (2003)
Digital Object Identifier (DOI) 10.1140/epjc/s2002-01074-5

Multi-photon production in e^+e^- collisions at $\sqrt{s}$ =181–209 GeV

The OPAL Collaboration

- Took OPAL LEP2 paper. 672.3 pb^{-1}. Mean 1/s gives ECM=196 GeV.
- Uses $|\cos\theta| < 0.93$ (21.5°). (In an earlier iteration I used 15°.)
- MC samples prepared with exponentiated BabaYaga ($\gamma\gamma(\gamma)$), BHWIDE (wide-angle Bhabhas), KKMCee ($\nu\bar{\nu}(\gamma)$), TEEGG-LO (e-γ Bhabha topology).
- Simulate 10 times the OPAL luminosity.
- 4-vector level kinematic analysis.
- Experimentally charged-particle vetoes applied using hits in Silicon and at most 50% of inner wires of CV and CJ drift chambers while allowing reconstructed conversions.

"Reproduce" LEP2 $e^+e^- \to \gamma\gamma$ analysis II

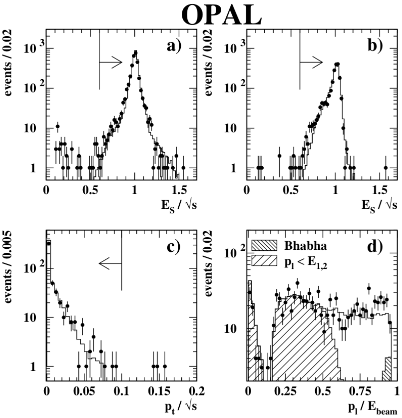
Table 2. Definition of classes *I*, *II*, *III* and *IV*. All collinear events are contained in class *I*. Other events are distributed according to the number of photon candidates N_γ and the aplanarity $\xi_{\rm aplan}$

$\xi_{\rm acol} < 10°$	$\xi_{\rm acol} > 10°$		
I	*II*	$N_\gamma = 2$	
	III	$\xi_{\rm aplan} < 0.1°$	N_γ
	IV	$\xi_{\rm aplan} > 0.1°$	$= 3$
		$N_\gamma \geq 4$	

Table 3. Cuts for the kinematic event selection. The cut variables depend on the class, see text. For class *I* events no cuts on the missing longitudinal and transverse momenta are applied

event class	*I*	*II*	*III*, *IV*	cut
energy sum	E_S^I	E_S^{II}	E_S^{III}	$> 0.6\sqrt{s}$
transverse momentum	–	$\mathcal{B}$	$p_{\rm t}$	$< 0.1\sqrt{s}$
longitudinal momentum	–	$E_{\rm lost}$	$p_{\rm l}$	$< E_1, E_2$

Background of this type is suppressed using information



Emphasis was on a rather loose kinematic selection including highly radiative ones as long as the radiated photon is less energetic than the measured wide-angle photons. Likely not the best approach for luminosity.

I have focused on the collinear events with a cut at 10 degrees (Class I) and have tightened the energy sum cut to 0.75 $\sqrt{s}$.

LEP2 $e^+e^- \to \gamma\gamma$ analysis III

Table 4. The number of events observed in data after the cuts, the signal expectation and the most important background sources indicated by their final state are given. The row labelled kinematic cuts contains only the cuts on the energy sum and the missing transverse momentum; the cut on the missing longitudinal momentum is listed separately. The neutral event selection is split up into the double veto and the single veto. For the numbers of events in the final selection after the single veto, the statistical error is also given. All Monte Carlo predictions are normalised to the integrated luminosity of the data

cut	data	ΣMC	$\gamma\gamma(\gamma)$	$e^+e^-(\gamma)$	$e\gamma(e)$	$\nu\bar{\nu}\gamma(\gamma)$	$q\bar{q}(\gamma)$	$\tau^+\tau^-(\gamma)$
preselection	192558	123751	5826	107791	7280	105	398	2352
cosmic bkg.	133099	122898	5823	107697	7194	104	244	1835
kinematic cuts	120515	119674	5809	107048	6310	6.6	130	370
longitudinal mom.	108832	110082	5520	103833	539	0.55	68	122
double veto	6367	6152	5505	68	515	0.55	52	12
single veto	5235	5261	5258	0.38	1.55	0.55	1.10	0.05
		±12	±12	±0.19	±0.43	±0.09	±0.24	±0.03

- Require at least two photon candidates (includes electron and positron) with $|\cos\theta| < 0.93$ and $E/E_{\mathrm{beam}} > 0.1$.
- Find 5599 (BabaYaga), 107787 (BHWIDE), 5556 (TEEGG), 42 (KKMCee) events (scaled to OPAL lumi).
- Reasonable agreement around "kinematic cuts" stage. Generators not identical - nor generator settings - nor cuts, and 4-vectors vs full sim (OPAL).

LEP2 $e^+e^- \to \gamma\gamma$ analysis IV

cut	data	ΣMC	$\gamma\gamma(\gamma)$	$e^+e^-(\gamma)$	$e\gamma(e)$	$\nu\bar{\nu}\gamma(\gamma)$	$q\bar{q}(\gamma)$	$\tau^+\tau^-(\gamma)$
preselection	192558	123751	5826	107791	7280	105	398	2352
cosmic bkg.	133099	122898	5823	107697	7194	104	244	1835
kinematic cuts	120515	119674	5809	107048	6310	6.6	130	370
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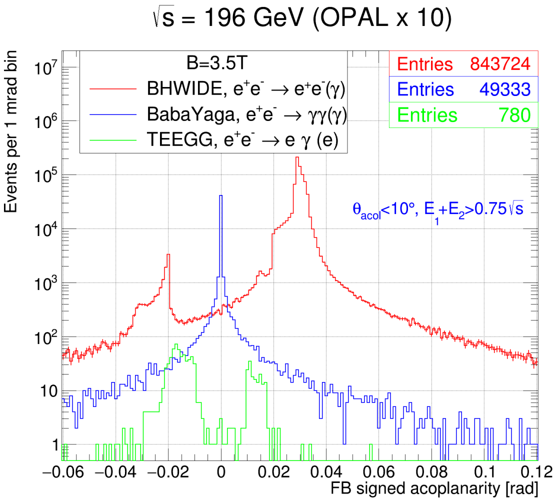
double veto	6367	6152	5505	68	515	0.55	52	12
single veto	5235	5261	5258	0.38	1.55	0.55	1.10	0.05
		$\pm$12	$\pm$12	$\pm$0.19	$\pm$0.43	$\pm$0.09	$\pm$0.24	$\pm$0.03

- Next require only two accepted photon candidates. Their acollinearity should be less than 10° and energy sum $> 0.75\sqrt{s}$.
- Find 4933 (BabaYaga), 84372 (BHWIDE), 78.0 (TEEGG), 0.0 (KKMCee) events (scaled to OPAL lumi).
- Note factor of 71 rejection of TEEGG events compared to factor of 12 rejection for the OPAL cuts.
- The OPAL charged-particle rejection criteria (double-veto followed by single-veto) led to R factors of 273,000 for the 2 charged-prong Bhabhas and 348 for the 1 charged-prong e-γ events with $\varepsilon = 0.955$.
- Reliable estimate of charged-particle rejection capability of a future e^+e^- collider detector is (way) beyond the scope of today's talk.

Forward-backward signed acoplanarity in ECAL

A new tool for separating e^+e^- from $\gamma\gamma$. Need high B-field, precise ECAL cluster azimuth measurements, large z, large R. Used ILD at ILC for numerical values.



With $|\Delta\phi_{\mathrm{FB}}| < 7.5$ mrad,

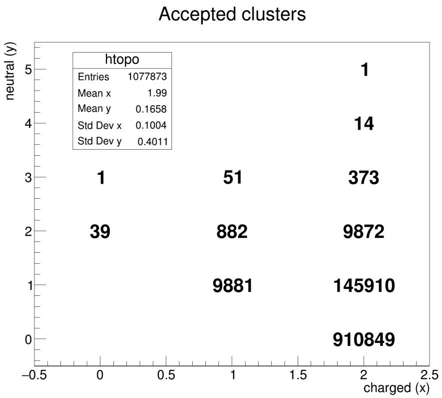
- $R = 171$ (BHWIDE)
- $R = 34$ (TEEGG)
- for $\varepsilon = 0.945$.

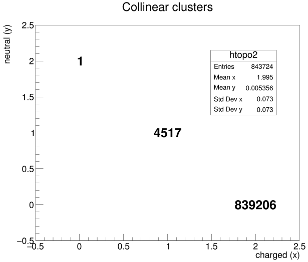
$\gamma\gamma(\gamma)$ is charge symmetric. BHWIDE is F-peaked. TEEGG is B-peaked (Compton scattering). Expect room for improvement (eg. the pimple), but also need to simulate conversions and bremsstrahlung.

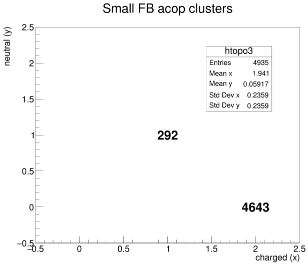
Note this only uses the bending in the solenoid field - NO TRACKING.

Is this gain topology independent?

Check BHWIDE charged and neutral cluster counts.







No, but FB acoplanarity gets a factor of 15 rejection for the (C=1, N=1) topology. (Many of these are events with an electron beyond the $|\cos\theta| < 0.93$ cut). (generator cut of 20°)

Summary

- Made progress resuscitating various MC event generators relevant to $\gamma\gamma$ for luminosity: RADCOR, BabaYaga, BHWIDE, BHLUMI, KKMCee, TEEGG. Agrees reasonably with OPAL. (Need consistent SW framework.)...
- I am convinced that Bhabha rejection for $\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma\gamma$ will not be a limiting factor for "wide-angle" $\gamma\gamma$. One does not need to reduce the background to 1 part in 10^4 to assure a 10^{-4} measurement but neither does that look that challenging for a modern $\mathrm{e}^+\mathrm{e}^-$ detector.
- Would be good to make sure that all the Bhabha phase-space is covered.
- Inefficiencies associated with charged-particle vetoes should be manageable (conversion reconstruction, material modelling, tracker occupancy ...)
- Exploiting more of the solid angle is challenging. I am exploring going to the 1–2° region in the context of ILD@ILC. Would have the advantage of a coherent fiducial acceptance definition with Bhabhas.
- Acoplanarity is really wonderful. Note that it also benefits from reconstructing low-angle particles with balancing p_T.
- The forward acceptance can be critical for many physics processes.
- There are other higher σ processes (such as $\gamma\gamma \rightarrow \mathrm{e}^+\mathrm{e}^-$ and $\gamma\gamma \rightarrow \mu^+\mu^-$) which could play a role in luminosity measurements.