# Gamma Gamma Collider Physics Report

Tim Barklow

SLAC

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# Context

- Hirotaka Sugawara has proposed that the construction of the ILC be staged, with a $W_{\gamma\gamma} = M_{\text{Higgs}} = 120$ GeV photon collider (PLC) as the initial stage.

- Following Sugwara's presentation to the ILCSC, Sakue Yamada asked the LOI Physics Panel to review the physics case for such an approach; Michael Peskin and I agreed to perform this review.

- At the same time, the GDE asked Andrei Seryi to develop machine designs for this kind of staged approach to ILC construction and operation. Jeff Gronberg agreed to furnish information on the laser technology, Peter Garbinicius agreed to provide a cost estimate, and a section on low emittance polarized gun issues was provided by Takashi Maruyama and Axel Brachman

- The results of these studies were presented in a paper by Andrei Seryi, Jeff Gronberg, Michael Peskin and myself to the GDE and Sakue Yamada on Feb 6, 2009. See http://www.slac.stanford.edu/~timb/PLC/PLCreportv8.pdf

- The paper advocates Sugawara's approach to staging the ILC.  Given this advocacy and the tight schedule,  it was not possible to obtain the endorsement of the ILC Physics panel.  The paper is therefore the  sole responsibility of the four authors listed above.
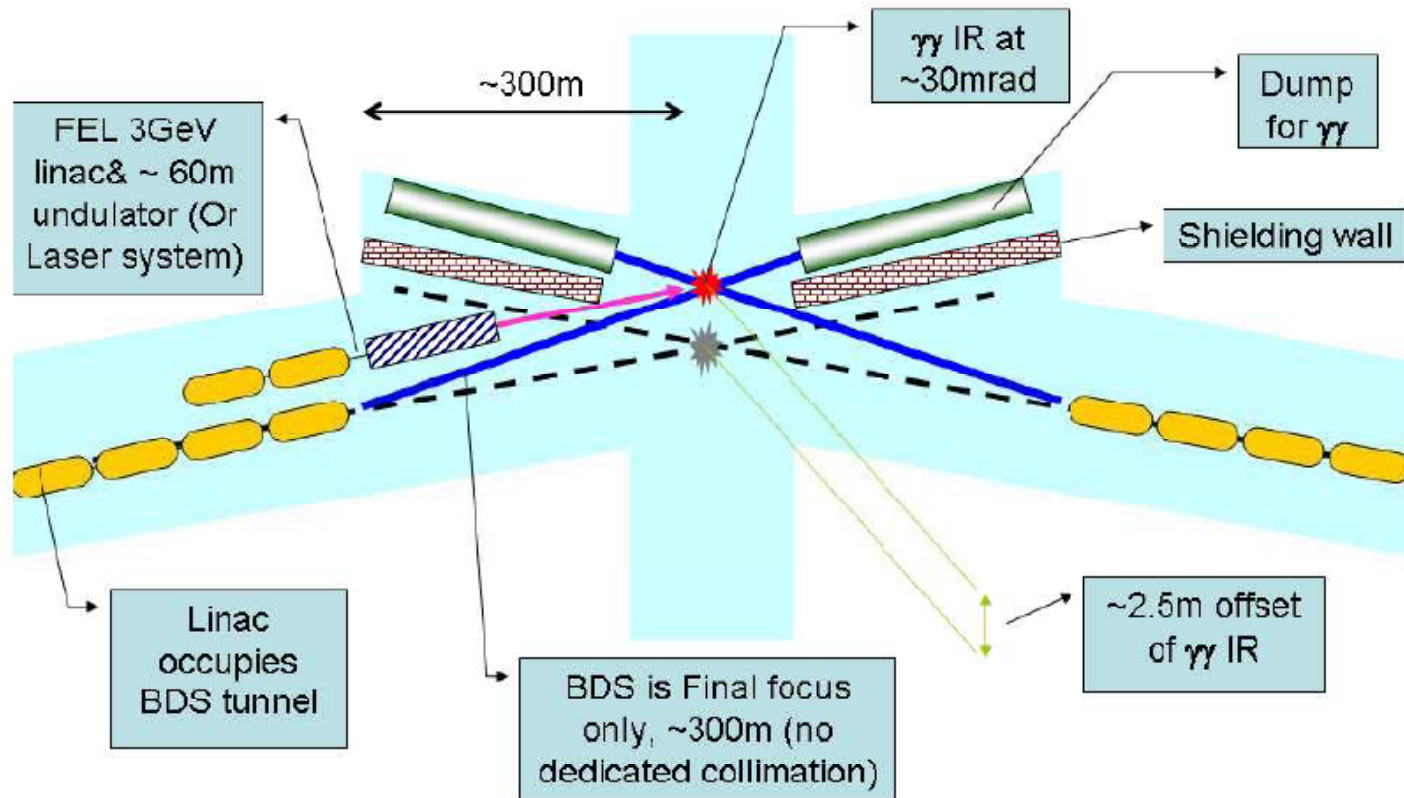
# Alternative First Stage

- An obvious alternative first stage that can also be used to study a 120 GeV Higgs boson is an $E_{cm}$=230 GeV $e^+e^-$ linear collider which we shall call the Higgs Linear Collider or HLC. Our report compared the Higgs boson physics of the LHC, PLC, HLC, and ILC, and contained a cost comparison of the HLC and PLC.
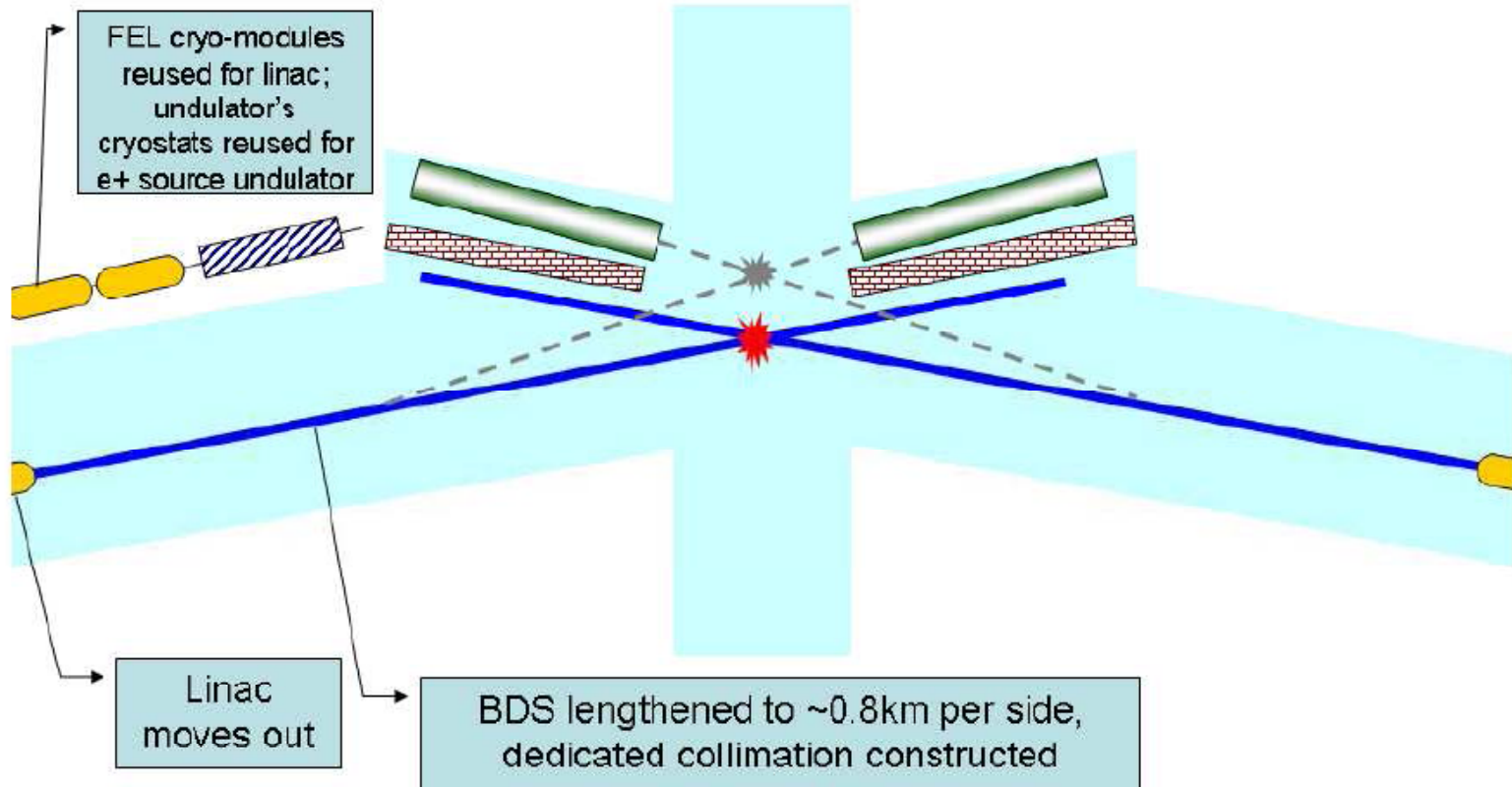
# Staged ILC with PLC as initial stage

| Stage | E CM (GeV) | Mode | E reach (GeV) | BDS (km per side) | Total site (km) | Lumi E34 | Physics program (yrs) | Features |
|---|---|---|---|---|---|---|---|---|
| 1st | 180 | $\gamma\gamma$ | 128 | 0.3 | 8.8 | 0.25 | 2 | Single DR |
| 2nd 3rd | 180 | $\gamma\gamma$ | 128 | 0.3 | 8.8 | 0.5 | 2 | Faster kicker or second DR |
| 4th | 230 | $e^+e^-$ | 230 | 0.8 | 12.1 | 0.9 | 3 | Add e+ source Lengthen BDS Add dedicated collimation |
| 5th | 500 | $e^+e^-$ | 500 | 2.2 | 27.2 | 2 | 5 | Lengthen BDS to 1 TeV layout |
| 6th | 500 | $\gamma\gamma$ | 400 | 2.2 | 27.1 | 4.5 | 2 | Lower DR $x$-emittance |

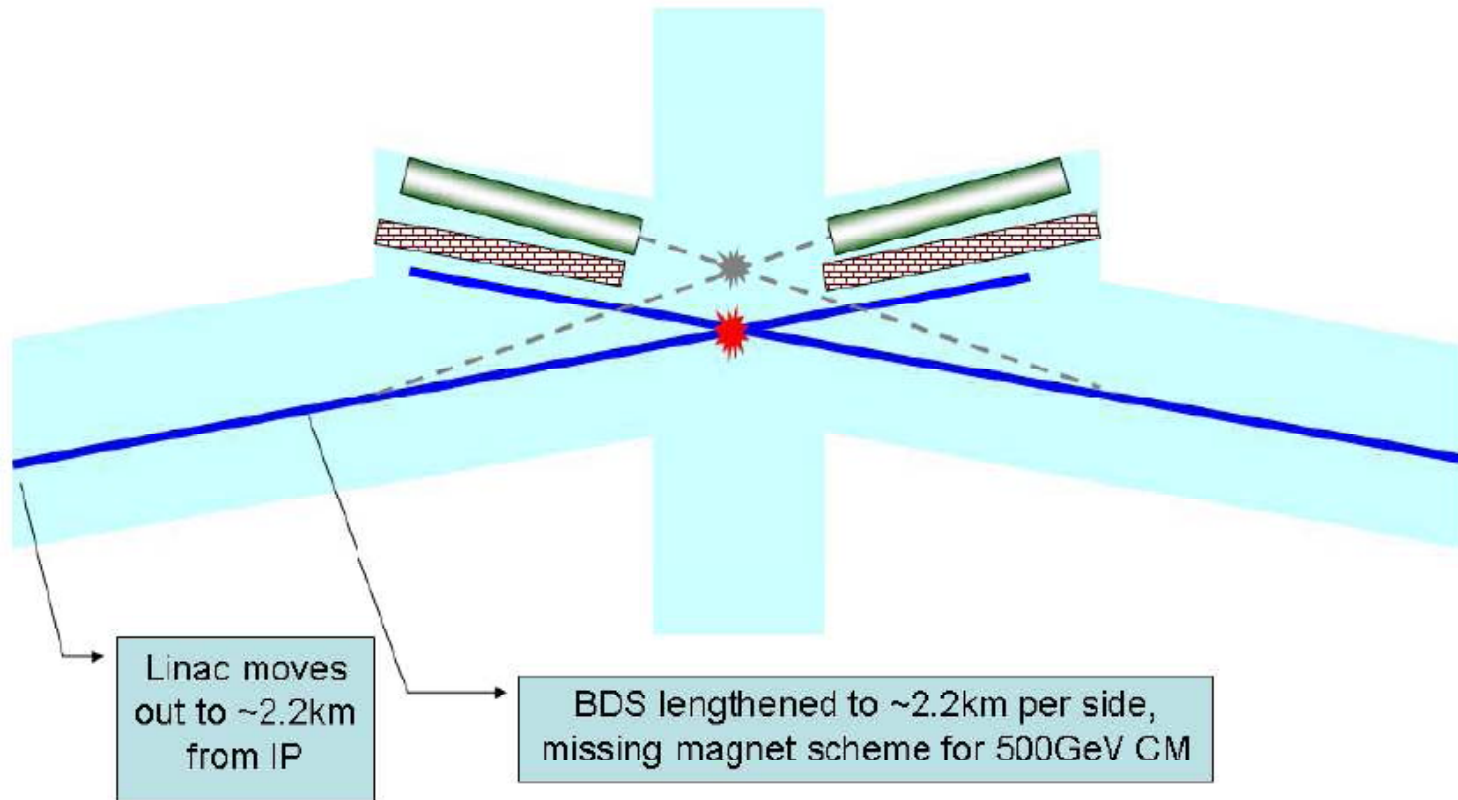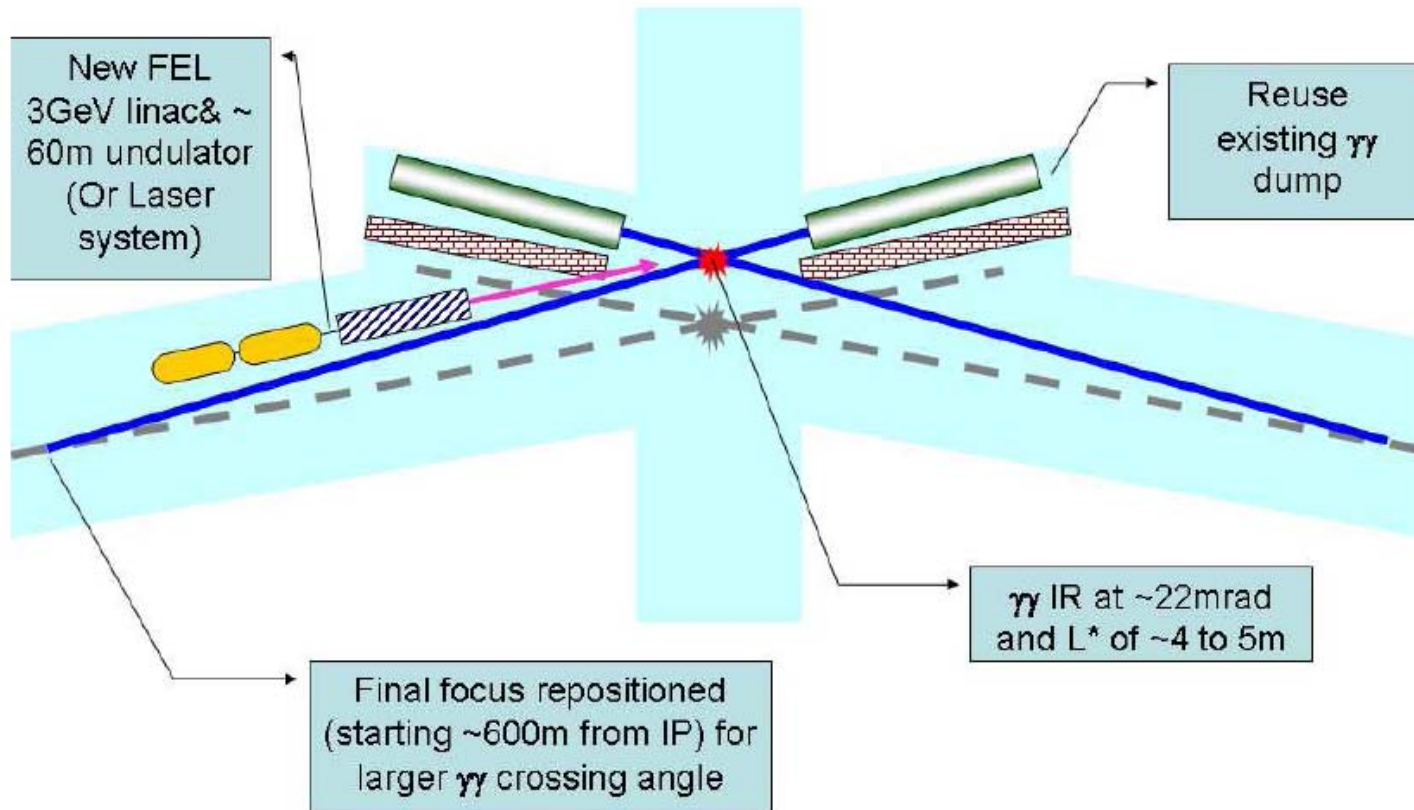# Stages 1-3 (PLC) with $E_{e^-e^-} = 180$ GeV and $E_{\gamma\gamma} = 128$ GeV

# Stage 4 (HLC) with $E_{e^+e^-} = 230$ GeV



FEL cryo-mocules reused for linac; undulator's cryostats reused for e+ source undulator

Linac moves out

BDS lengthened to ~0.8km per side, dedicated collimation constructed

# Stage 5 (ILC) with $E_{e^+e^-} = 500$ GeV



Linac moves out to ~2.2km from IP

BDS lengthened to ~2.2km per side, missing magnet scheme for 500GeV CM

# Stage 6 (PLC') with $E_{e^-e^-} = 500$ GeV and $E_{\gamma\gamma} = 393$ GeV

New FEL
3GeV linac& ~
60m undulator
(Or Laser
system)

Reuse
existing γγ
dump

γγ IR at ~22mrad
and L* of ~4 to 5m

Final focus repositioned
(starting ~600m from IP) for
larger γγ crossing angle

| Stages | single DR | faster kicker | 2nd DR | $e^+$ & linac | more linac | coda |
|---|---|---|---|---|---|---|
| Case ID | 1 | 2 | 3 | 4 | 5 | 6 |
| ECM [GeV] | 180 | 180 | 180 | 230 | 500 | 500 |
| Mode | $\gamma\gamma$ | $\gamma\gamma$ | $\gamma\gamma$ | $e^+e^-$ | $e^+e^-$ | $\gamma\gamma$ |

**IP Parameters:**

| | single DR | faster kicker | 2nd DR | $e^+$ & linac | more linac | coda |
|---|---|---|---|---|---|---|
| $\gamma\epsilon_x$ [m] | 1.0E-05 | 1.0E-05 | 1.0E-05 | 1.0E-05 | 1.0E-05 | 2.5E-06 |
| $\gamma\epsilon_x$ [m] | 3.6E-08 | 3.6E-08 | 3.6E-08 | 3.6E-08 | 3.6E-08 | 3.6E-08 |
| $\beta_x$ [m] | 4.0E-03 | 4.0E-03 | 4.0E-03 | 1.1E-02 | 1.1E-02 | 1.5E-03 |
| $\beta_y$ [m] | 4.0E-04 | 4.0E-04 | 4.0E-04 | 2.0E-04 | 2.0E-04 | 4.0E-04 |
| Travelling focus | no | no | no | yes | yes | no |
| $z$-distribution | Gauss | Gauss | Gauss | Gauss | Gauss | Gauss |
| $\sigma_x$(geom) [m] | 4.8E-07 | 4.8E-07 | 4.8E-07 | 7.0E-07 | 4.7E-07 | 8.8E-08 |
| $\sigma_y$(geom) [m] | 9.0E-09 | 9.0E-09 | 9.0E-09 | 5.7E-09 | 3.8E-09 | 5.4E-09 |
| $\sigma_z$ [m] | 4.0E-04 | 4.0E-04 | 4.0E-04 | 3.0E-04 | 3.0E-04 | 3.0E-04 |
| $U_{av}$ | 0.017 | 0.017 | 0.017 | 0.020 | 0.063 | 0.326 |
| $\delta_B$ | 0.013 | 0.013 | 0.013 | 0.010 | 0.039 | 0.576 |
| $P$(Beams.) [MW] | 0.01 | 0.02 | 0.02 | 0.02 | 0.21 | 3.04 |
| $n_\gamma$ | 1.76 | 1.76 | 1.76 | 1.21 | 1.71 | 7.82 |
| $H_D$ | 3.55 | 3.55 | 3.55 | 1.51 | 1.51 | 6.16 |
| L(geom) [/cm$^2$/s] | 2.4E33 | 4.9E33 | 4.9E33 | 5.31E33 | 1.15E34 | 4.4E34 |
| L (G-Pig) [/cm$^2$/s] | | | | 8.8E33 | 1.9E34 | |
| Physics [yr] | 2 | 2 | | 3 | 5 | 2 |

Two lasers are considered:

- MERCURY solid state optical laser

- 3 GeV FEL

Both would use an optical cavity first designed at

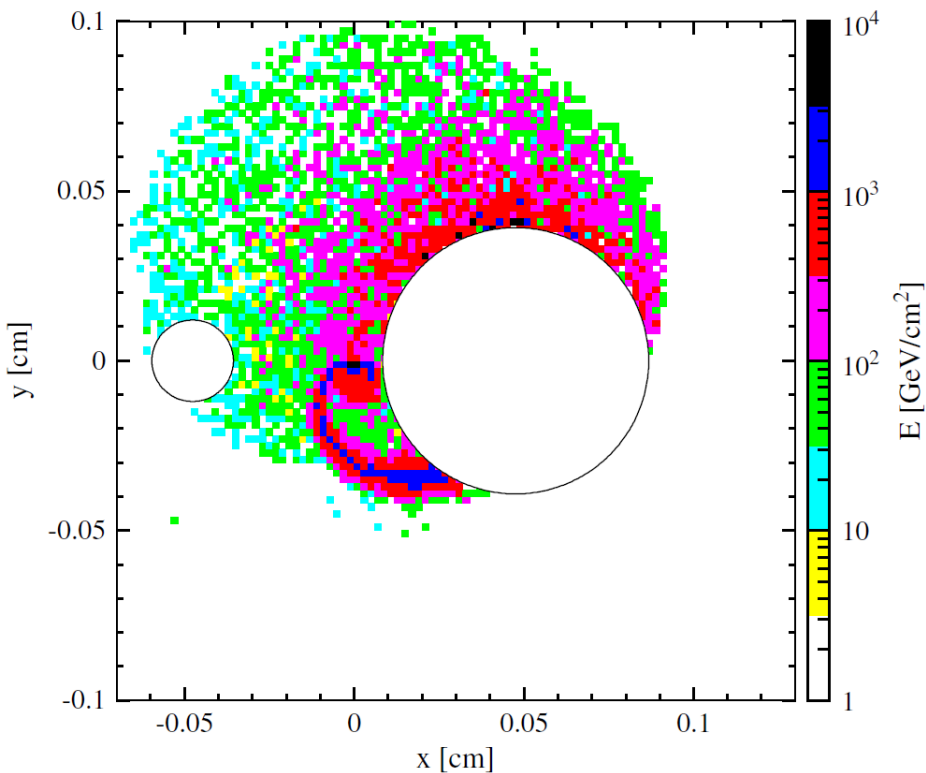DESY-Zeuthen and Max Born Institute
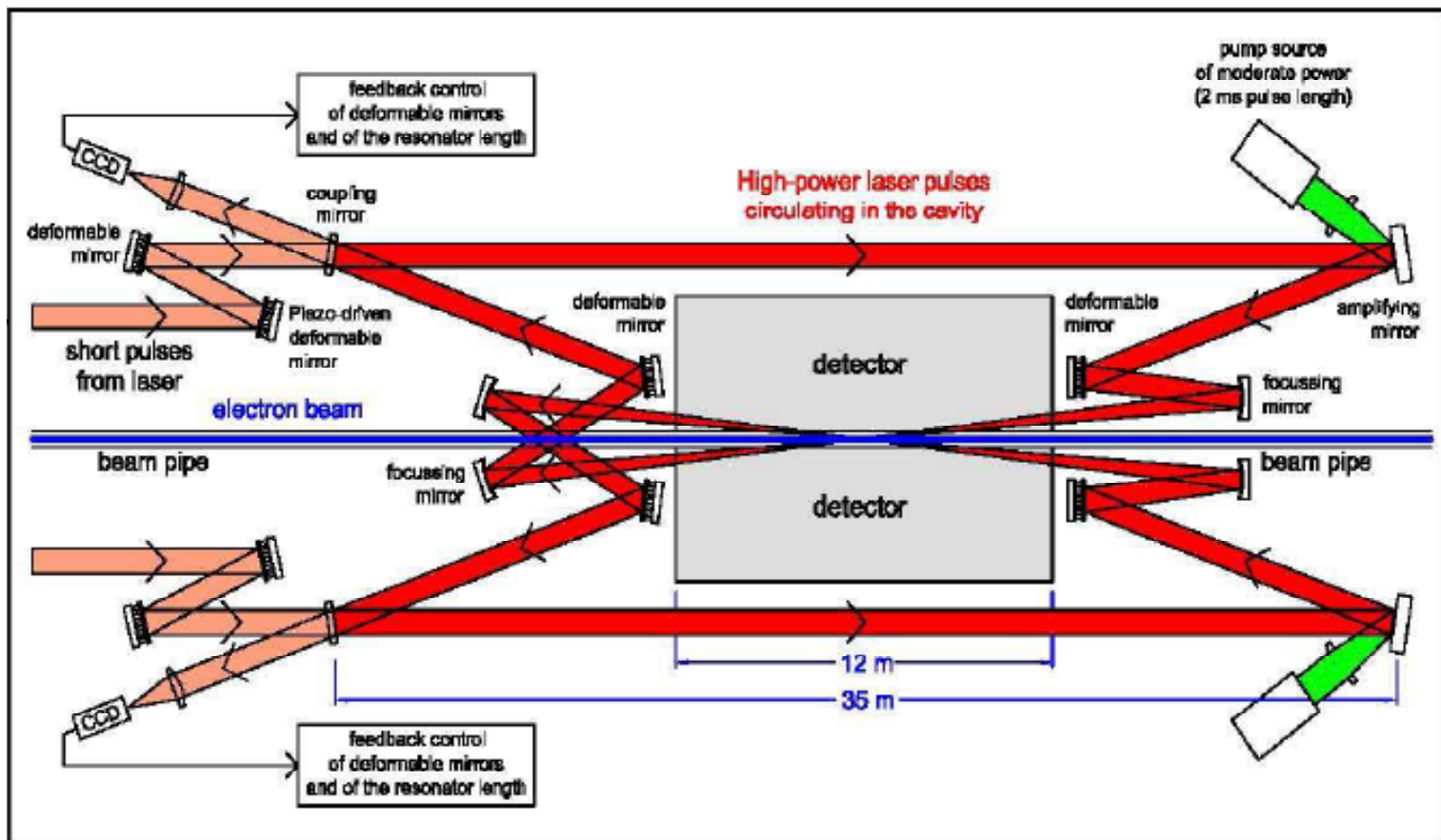
# PLC Detector

A PLC detector identical to TESLA for polar angles above 7° was studied by F. Bechtel et al.  A GEANT3 simulation was performed for all backgrounds from the Compton collision process and the beam-beam interaction.
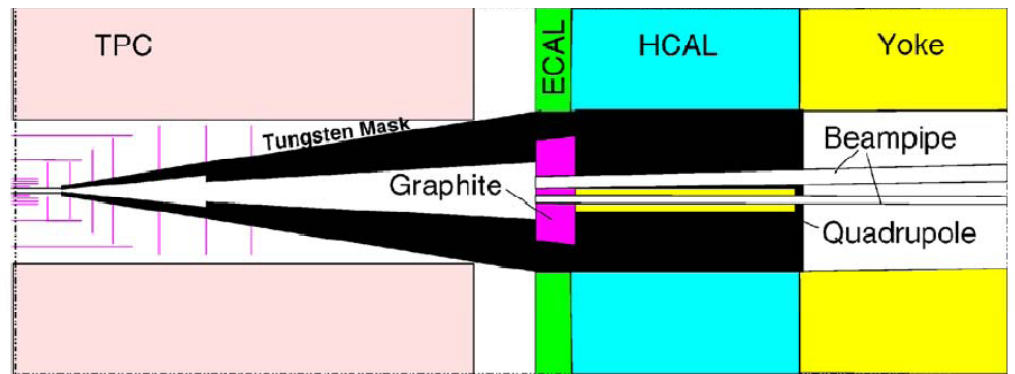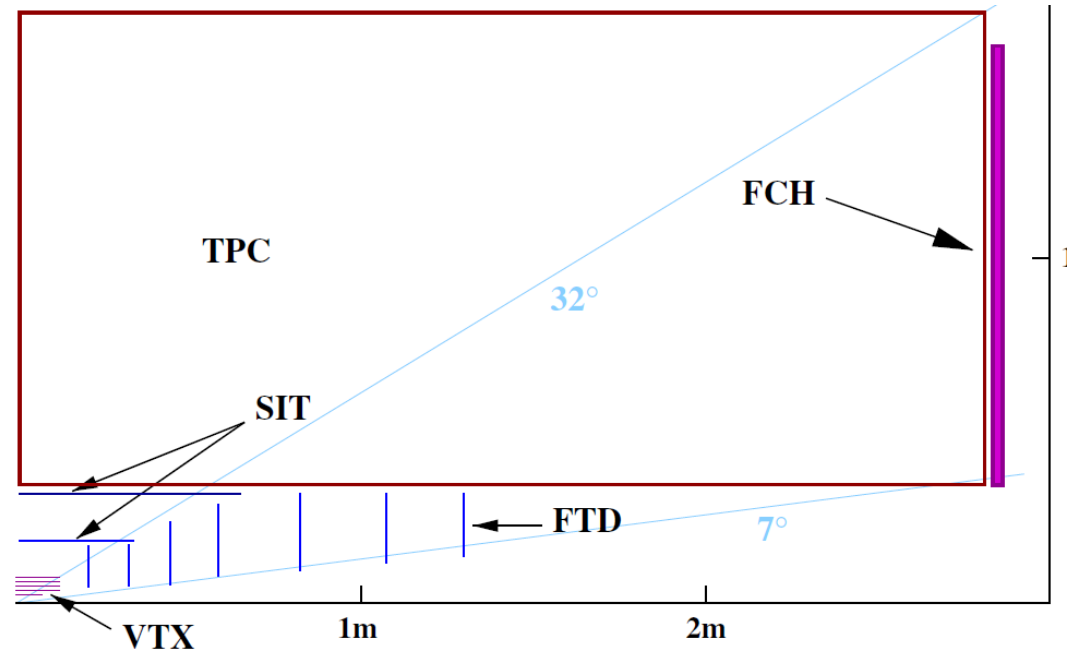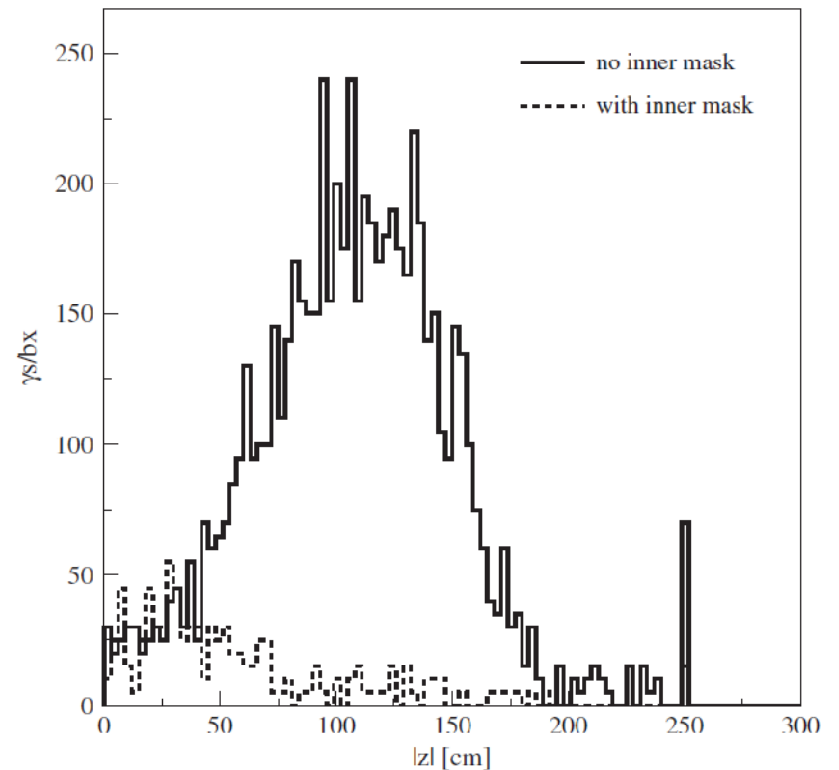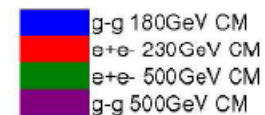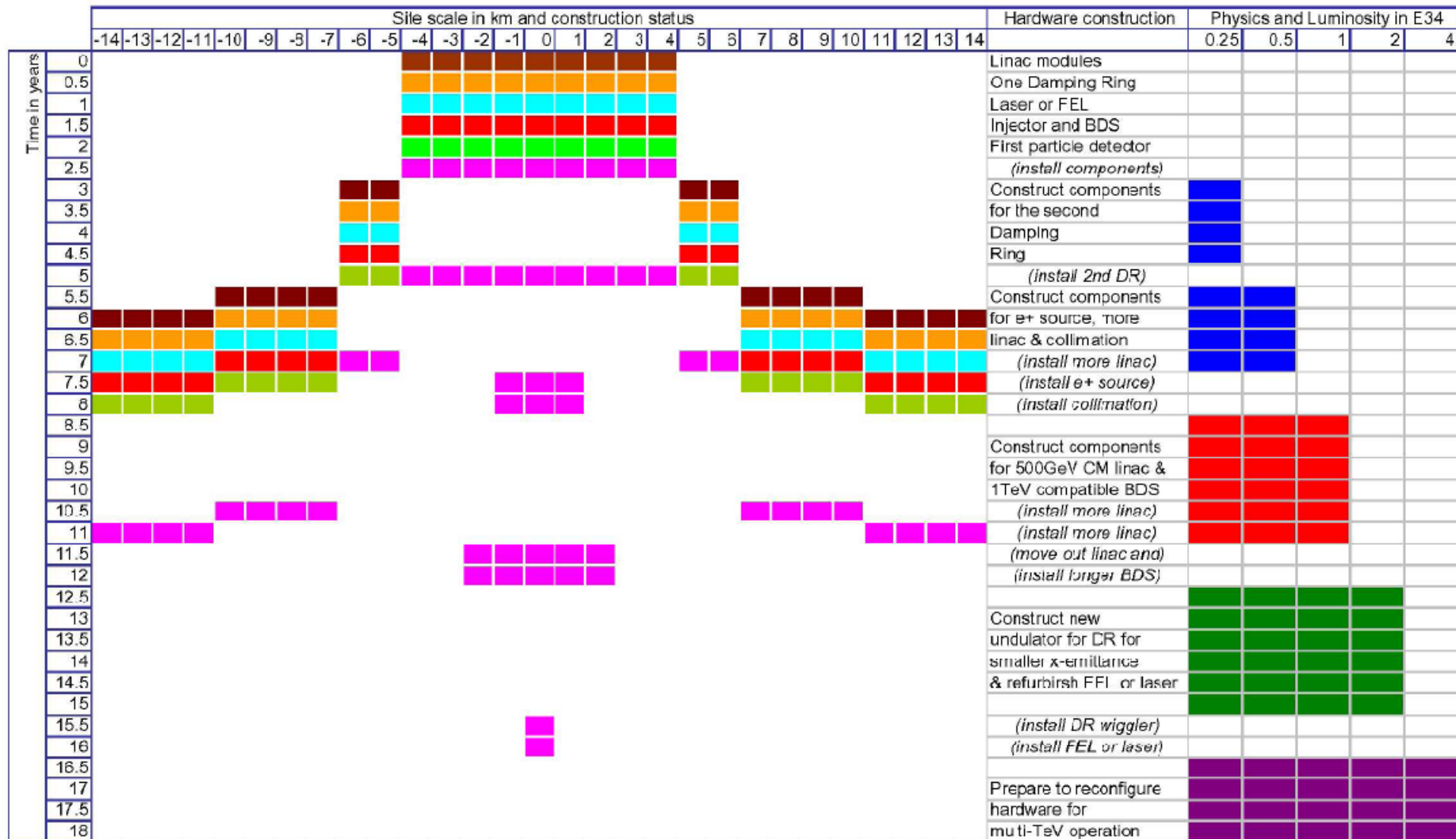
# GEANT3 Simulation of Backgrounds in PLC Detector

Energy at front face of
ECAL for 1 bunch crossing

z coordinate of photons
entering TPC

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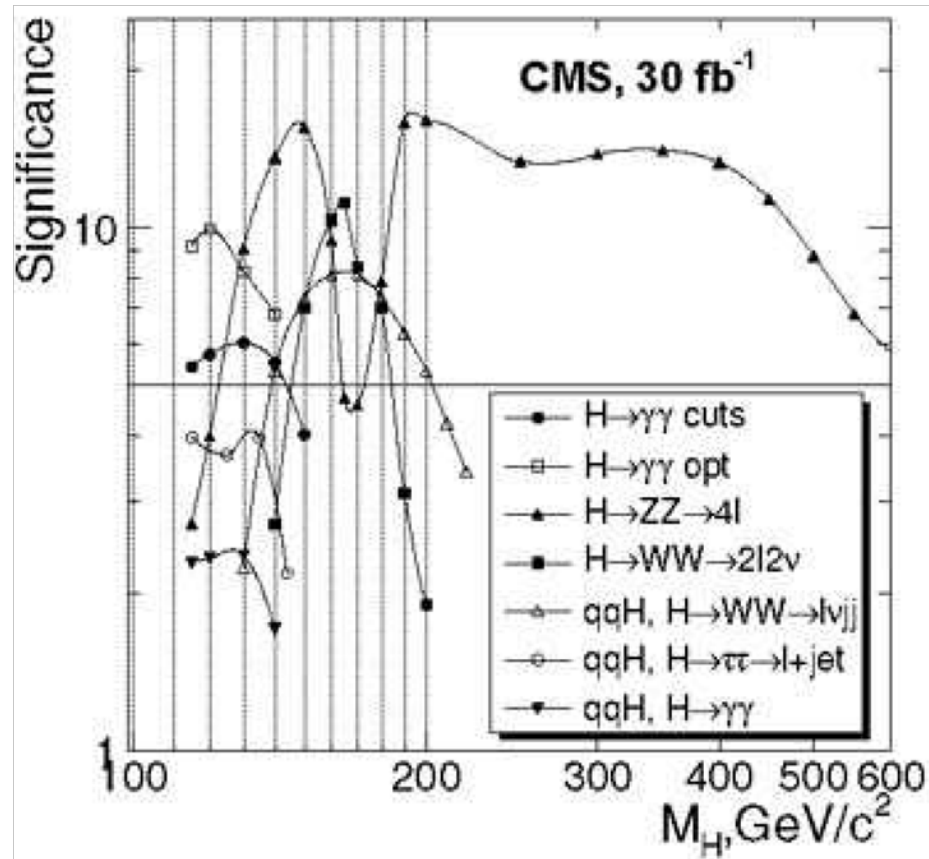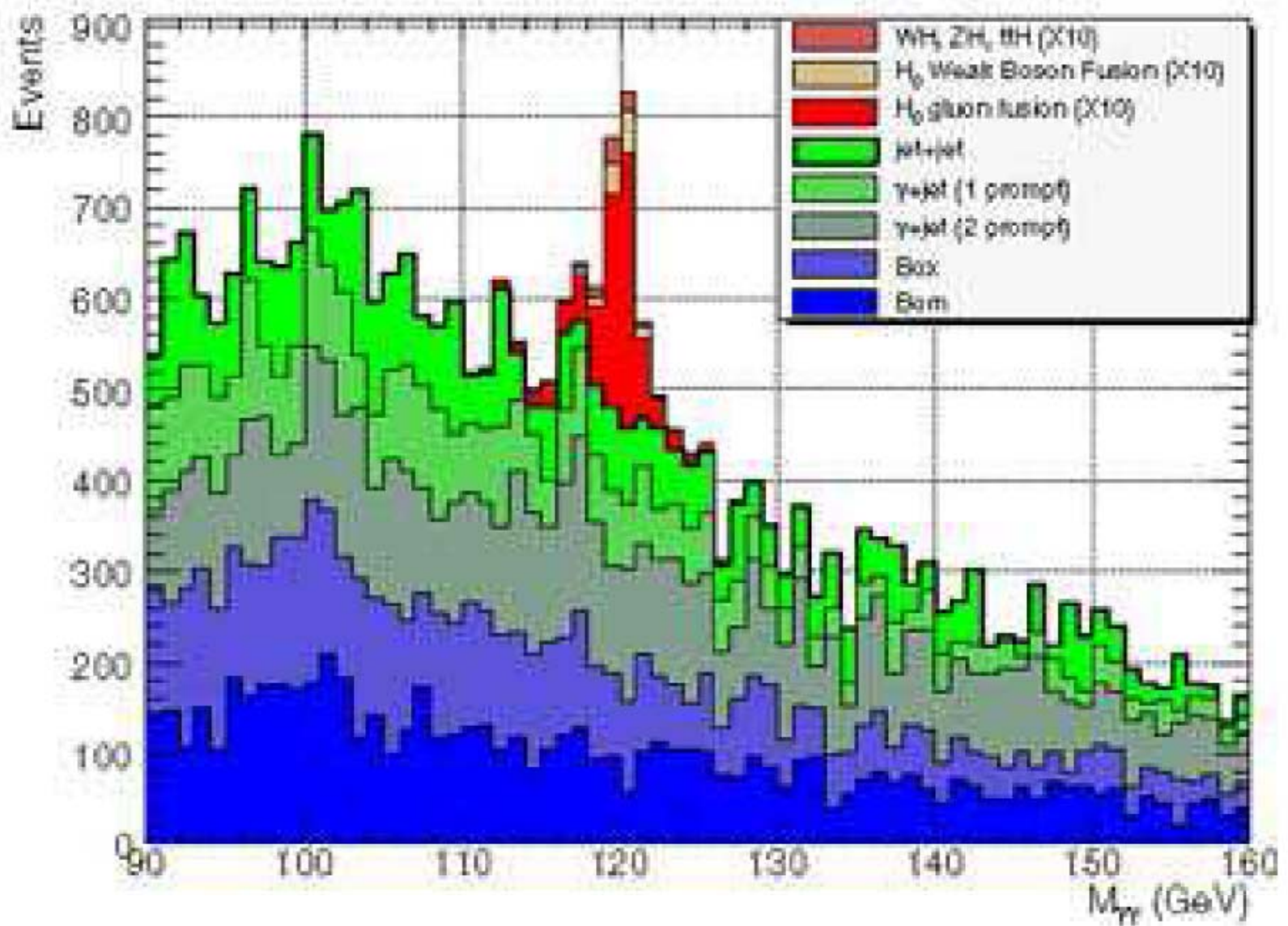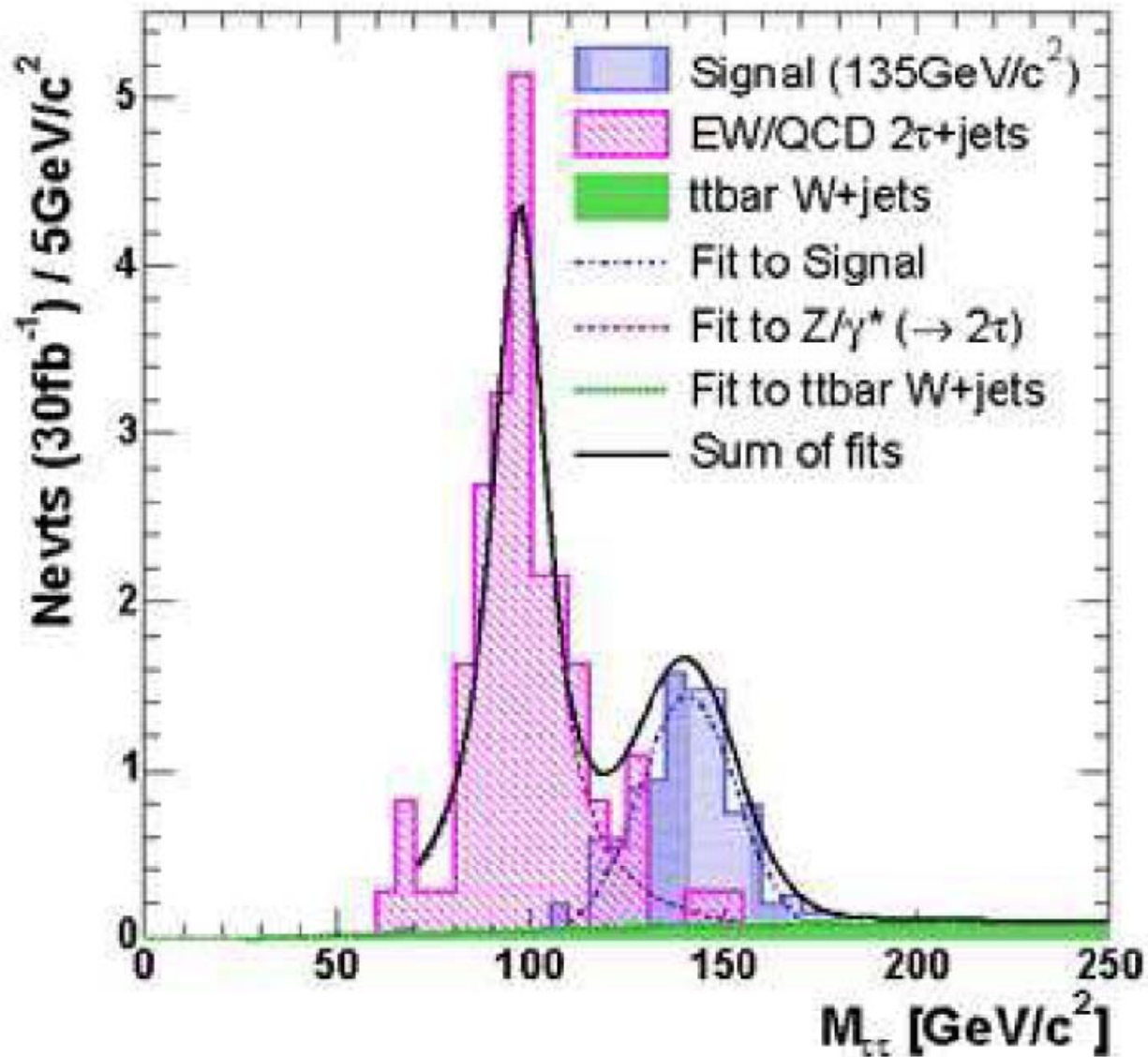# Higgs Boson at LHC

120 GeV SM Higgs BRs:

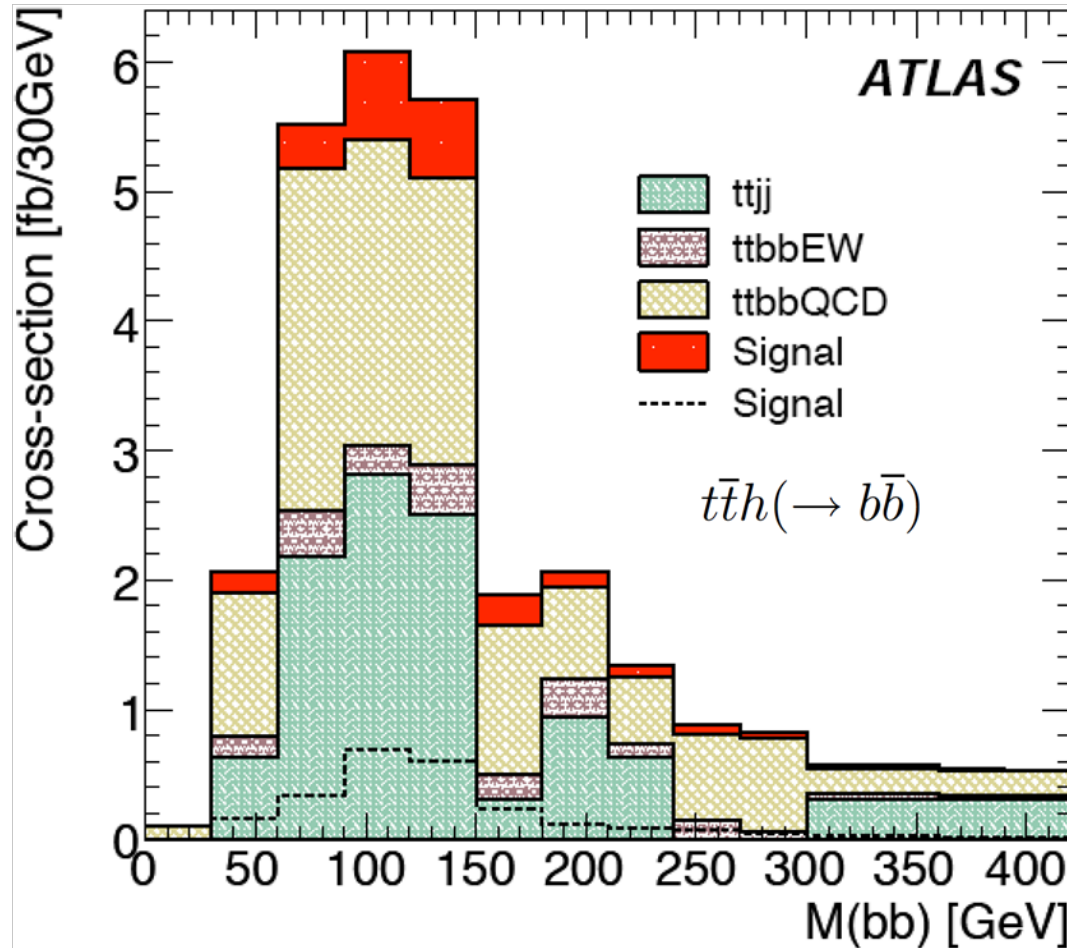| | | | |
|---|---|---|---|
| $BR(b\bar{b})$ : | 65.74% | $BR(c\bar{c})$ : | 3.60% |
| $BR(WW^*)$ : | 15.00% | $BR(ZZ^*)$ : | 1.72% |
| $BR(\tau^+\tau^-)$ : | 7.96% | $BR(\gamma\gamma)$ : | 0.29% |
| $BR(gg)$ : | 5.50% | $BR(\gamma Z)$ : | 0.13% |



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# Inclusive $H_0 \to \gamma\gamma$ signal $\times 10$ at LHC

# *WW* fusion production of Higgs with $H \to \tau^+\tau^-$

It is very difficult to observe $h \to b\bar{b}$ at the LHC:
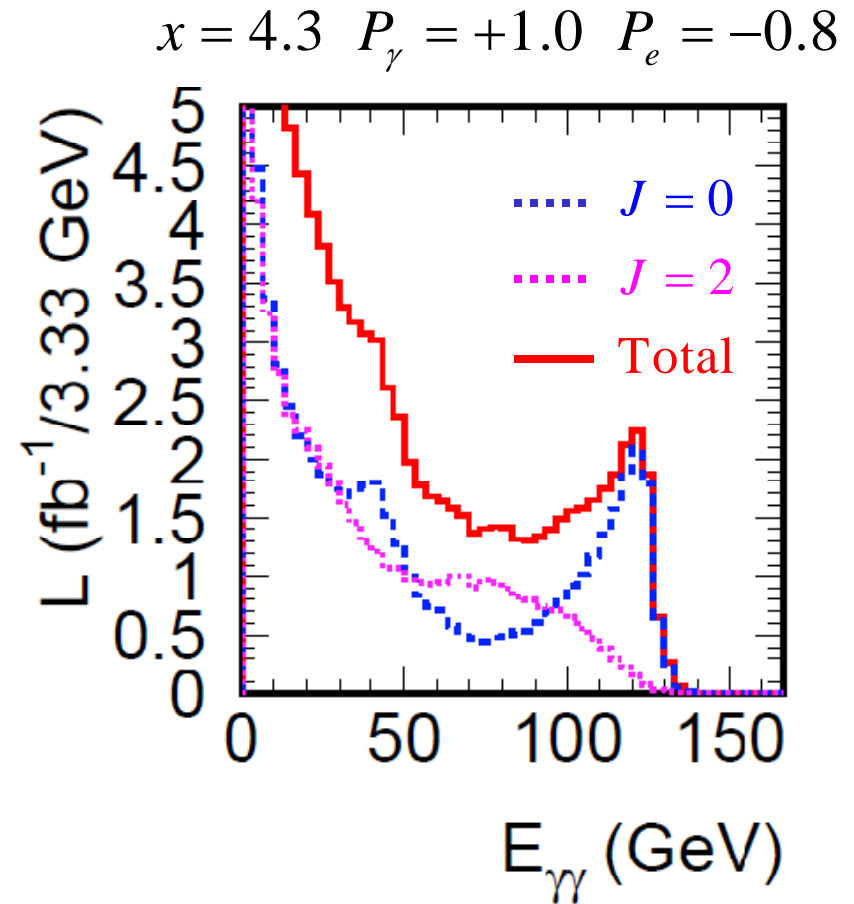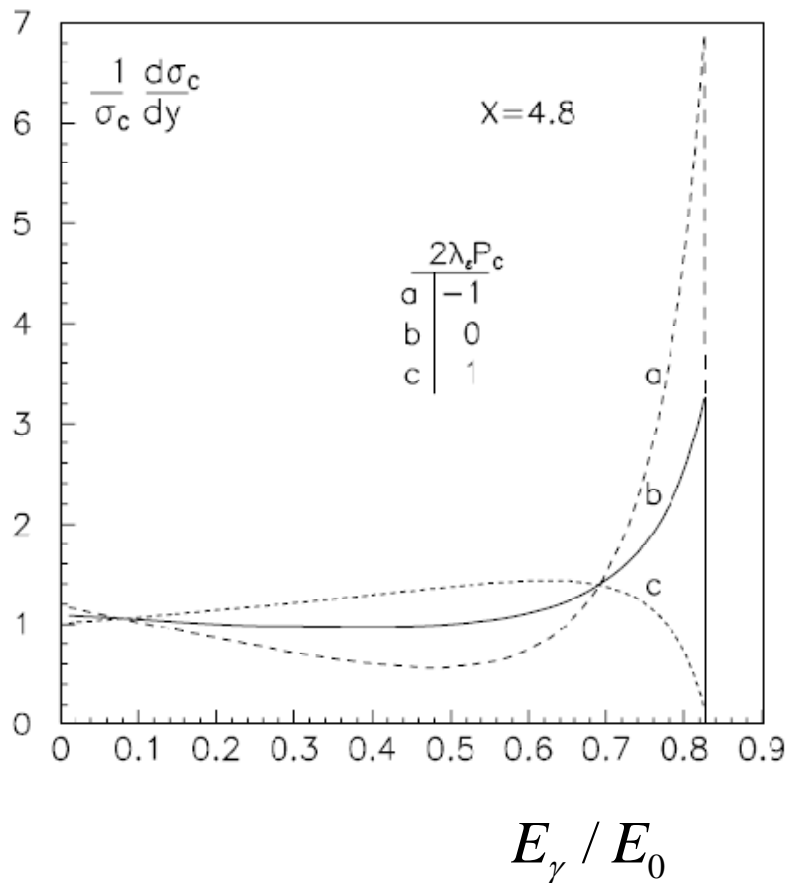


We shall assume that this Higgs decay is not measured at the LHC

# Higgs boson observables from LHC assuming $M_H$=120 GeV and 100 fb$^{-1}$ per experiment

| observable | relative error |
| --- | --- |
| $\sigma(gg) \cdot BR(\gamma\gamma)$ | 20% |
| $\sigma(WW) \cdot BR(\gamma\gamma)$ | 60% |
| $\sigma(WW) \cdot BR(\tau^+\tau^-)$ | 25% |
| $BR(h^0 \to ZZ^*)/BR(h^0 \to \gamma\gamma)$ | 28% |
| $BR(h^0 \to \tau^+\tau^-)/BR(h^0 \to W^+W^-)$ | 44% |

# Higgs Boson at PLC



$x = 4.3 \quad P_\gamma = +1.0 \quad P_e = -0.8$

High electron polarization enhances the luminosity at high $E_{\gamma\gamma}$

High electron polarization provides another benefit.

At the high end of the photon energy spectrum ($E_\gamma / E_0 > 0.6$) the helicity $\lambda_\gamma$ of the backscattered photons follows the helicity $\lambda_e$ of the incoming electrons.
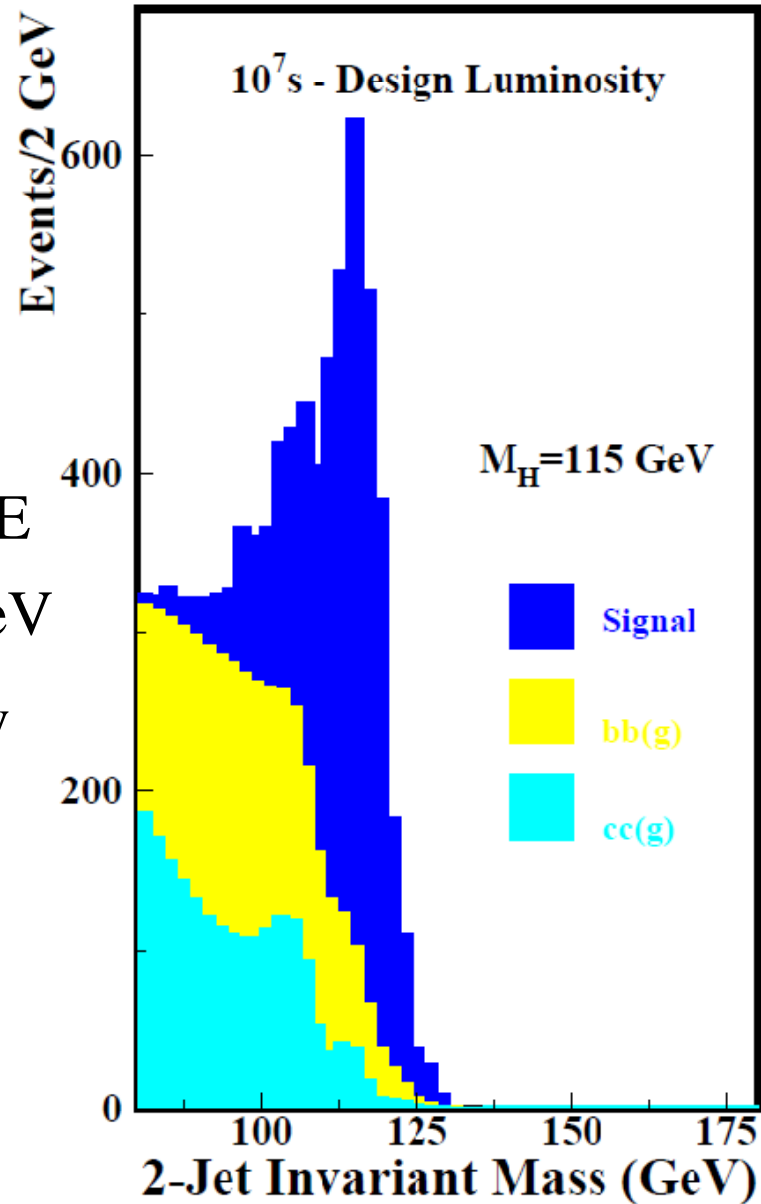
Without high electron polarization the enhancement of the J=0 Higgs signal and suppression of the J=2 $b\bar{b}$ background would collapse.
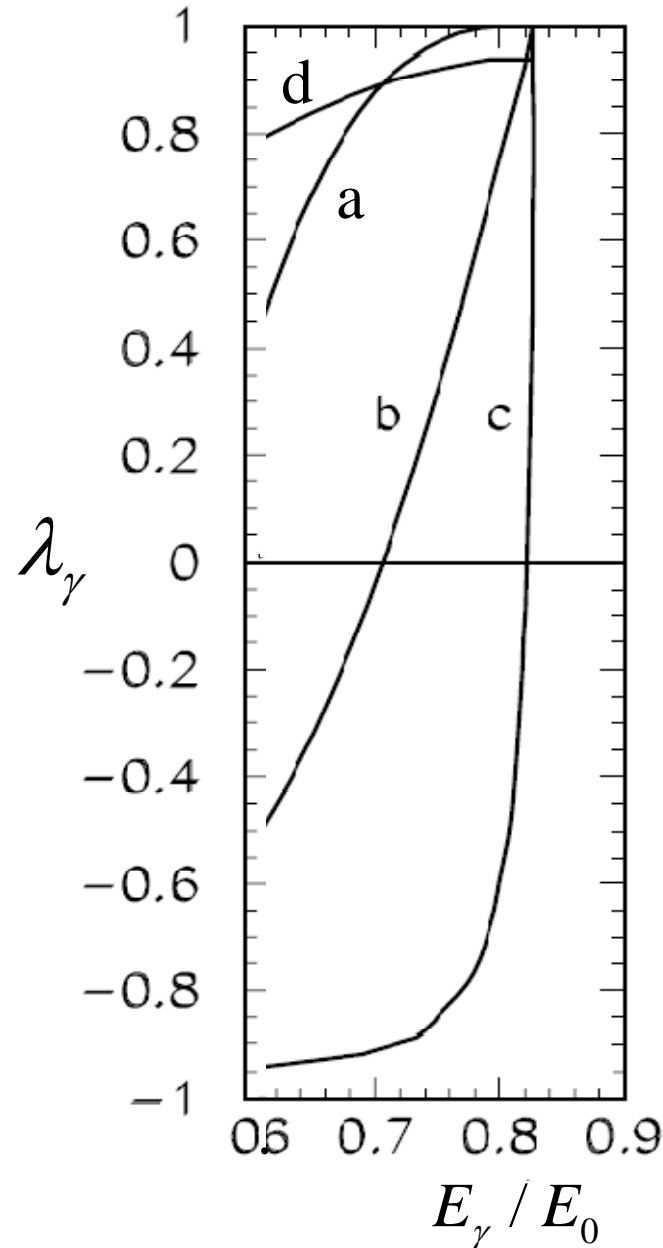


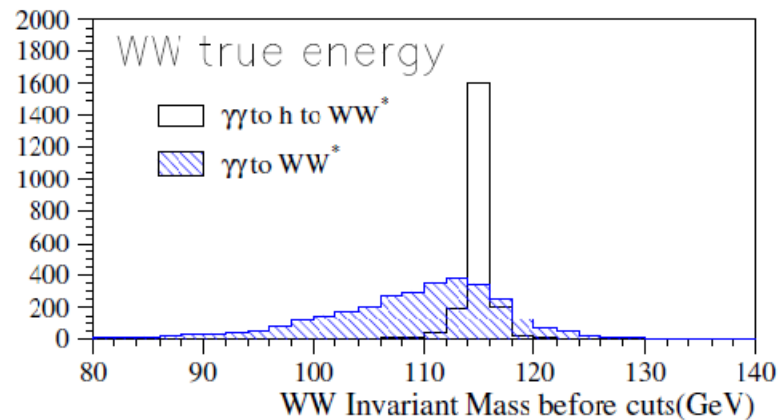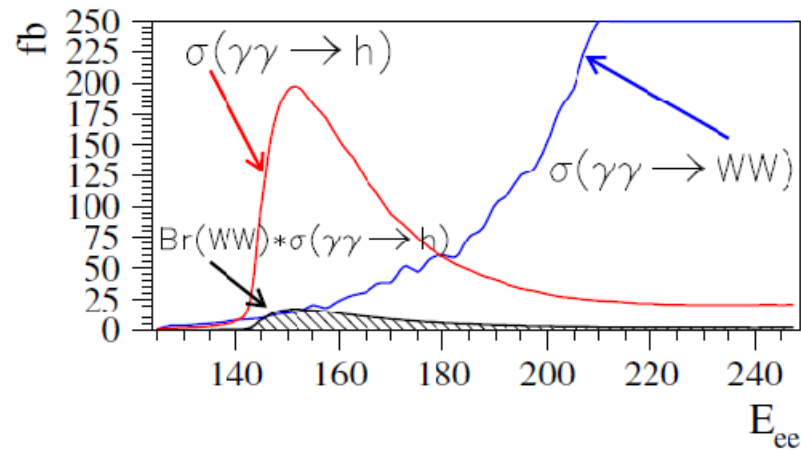| | $P_c$ | $2\lambda_e$ |
|---|---|---|
| a | -1 | 1 |
| b | -1 | 0 |
| c | -1 | -1 |
| d | 0 | 1 |

# PLC Measurement of $H \rightarrow b\bar{b}$

This plot is from the CLICHE study assuming $M_H$=115 GeV and 200 fb$^{-1}$. There are many other examples like this.

At $\sqrt{s}_{\gamma\gamma} = 120$ GeV the continuum rate for $\gamma\gamma \rightarrow WW^*$ is smaller than $\gamma\gamma \rightarrow H$ and comparable to $\gamma\gamma \rightarrow H \rightarrow WW^*$



True
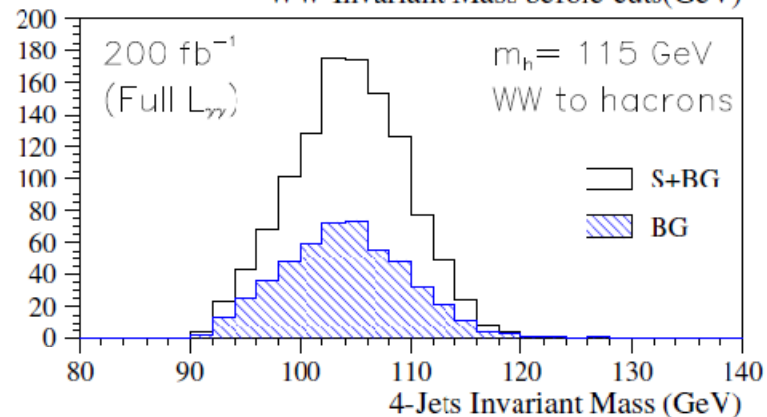
Reco

Higgs boson observables from PLC assuming
$M_H$ =120 GeV and 60 fb$^{-1}$ of total $\gamma\gamma$ luminosity
(Two years at stage 1 & two years at stage 2 or 3)

| observable | relative error |
|---|---|
| $\sigma(\gamma\gamma) \cdot BR(b\bar{b})$ | 4% |
| $\sigma(\gamma\gamma) \cdot BR(WW)$ | 9% |
| $\sigma(\gamma\gamma) \cdot BR(ZZ)$ | 20% |
| $\sigma(\gamma\gamma) \cdot BR(\gamma\gamma)$ | 40% |

# Higgs Boson at HLC (Ecm=230 GeV e⁺e⁻)
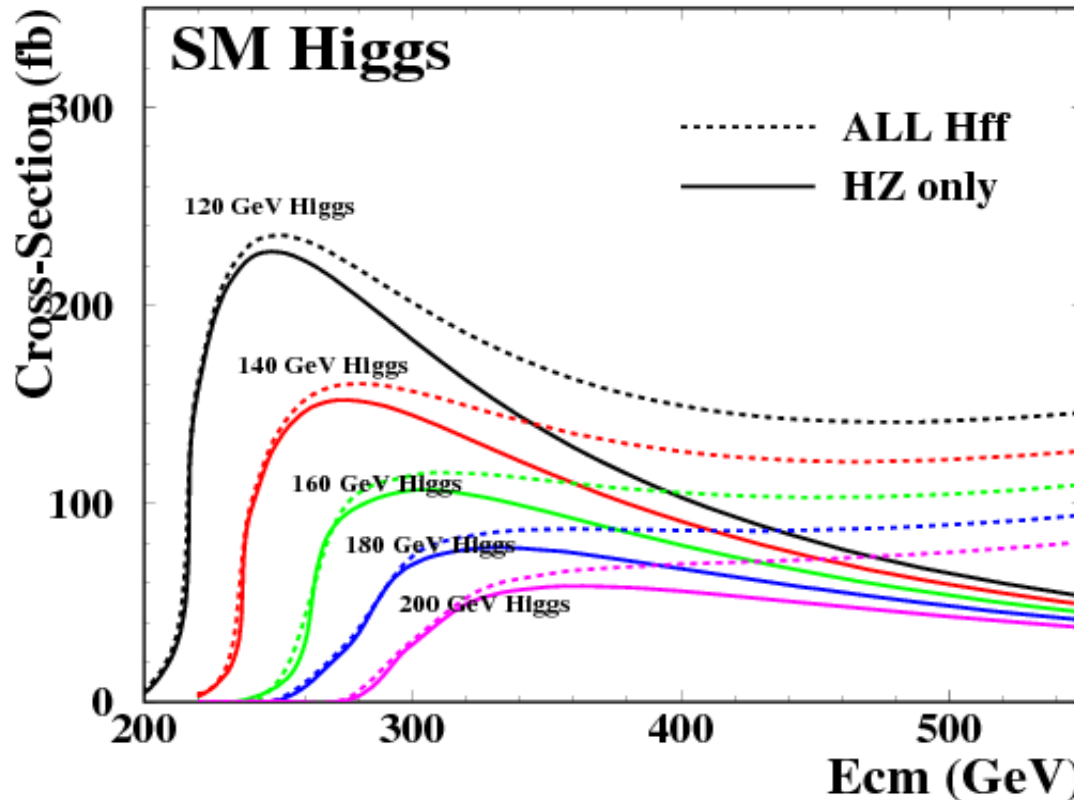


At HLC the WW fusion production of Higgs is difficult to observe.

To obtain partial widths at HLC we will make the assumption

$g(hWW)/g(hZZ) = \cos^2\theta_W$   Only when the WW fusion production

of Higgs bosons is measured at the ILC with $E_{cm} = $ 350 or 500 GeV

will the Higgs partial width measurement be fully model indepdent.

$$\frac{\sigma(e^+e^- \to ZH)|_{\sqrt{s}=230 \text{ GeV}}}{\sigma(e^+e^- \to ZH)|_{\sqrt{s}=350 \text{ GeV}}} = 1.91 \qquad \text{no ISR, no beamstrahlung}$$

$$\frac{\sigma(e^+e^- \to ZH)|_{\sqrt{s}=230 \text{ GeV}}}{\sigma(e^+e^- \to ZH)|_{\sqrt{s}=350 \text{ GeV}}} = 1.46 \qquad \text{with ISR and beamstrahlung}$$

Following table assumes 250 fb$^{-1}$ at $\sqrt{s} = 230$ GeV with

$$\frac{\sigma(e^+e^- \to ZH)|_{\sqrt{s}=230 \text{ GeV}}}{\sigma(e^+e^- \to ZH)|_{\sqrt{s}=350 \text{ GeV}}} = 2.00$$

HLC precision:

| observable | relative error |
| --- | --- |
| BR($b\bar{b}$) | 2% |
| BR($WW$) | 5% |
| BR($gg$) | 6% |
| BR($\gamma\gamma$) | 23% |
| BR($c\bar{c}$) | 8% |
| BR($\tau^+\tau^-$) | 5% |
| $\sigma(e^+e^- \to ZH)$ | 3% |

Define $\Gamma(X) \equiv \Gamma(h \to X)$ & $BR(X) \equiv BR(h \to X)$

LHC and PLC measure quantities such as $\dfrac{\Gamma(X_i)\Gamma(X_j)}{\Gamma_{tot}}$ & $\dfrac{\Gamma(X_i)}{\Gamma(X_j)}$,

the HLC measures $\dfrac{\Gamma(X_i)}{\Gamma_{tot}}$, and the ILC measures $\Gamma(X_i)$.

To compare LHC , PLC , HLC & ILC we

make the mild assumption that the Higgs is a mixture

of $SU(2)$ singlets and doublets only $\Rightarrow$

$g(hWW) / g(hZZ) = \cos^2\theta_W$

$\Gamma(WW) \leq \Gamma(WW)|_{SM}$

(Mild since $SU(2)$ triplets strongly constrained by $M_W = M_Z \cos\theta_W$)

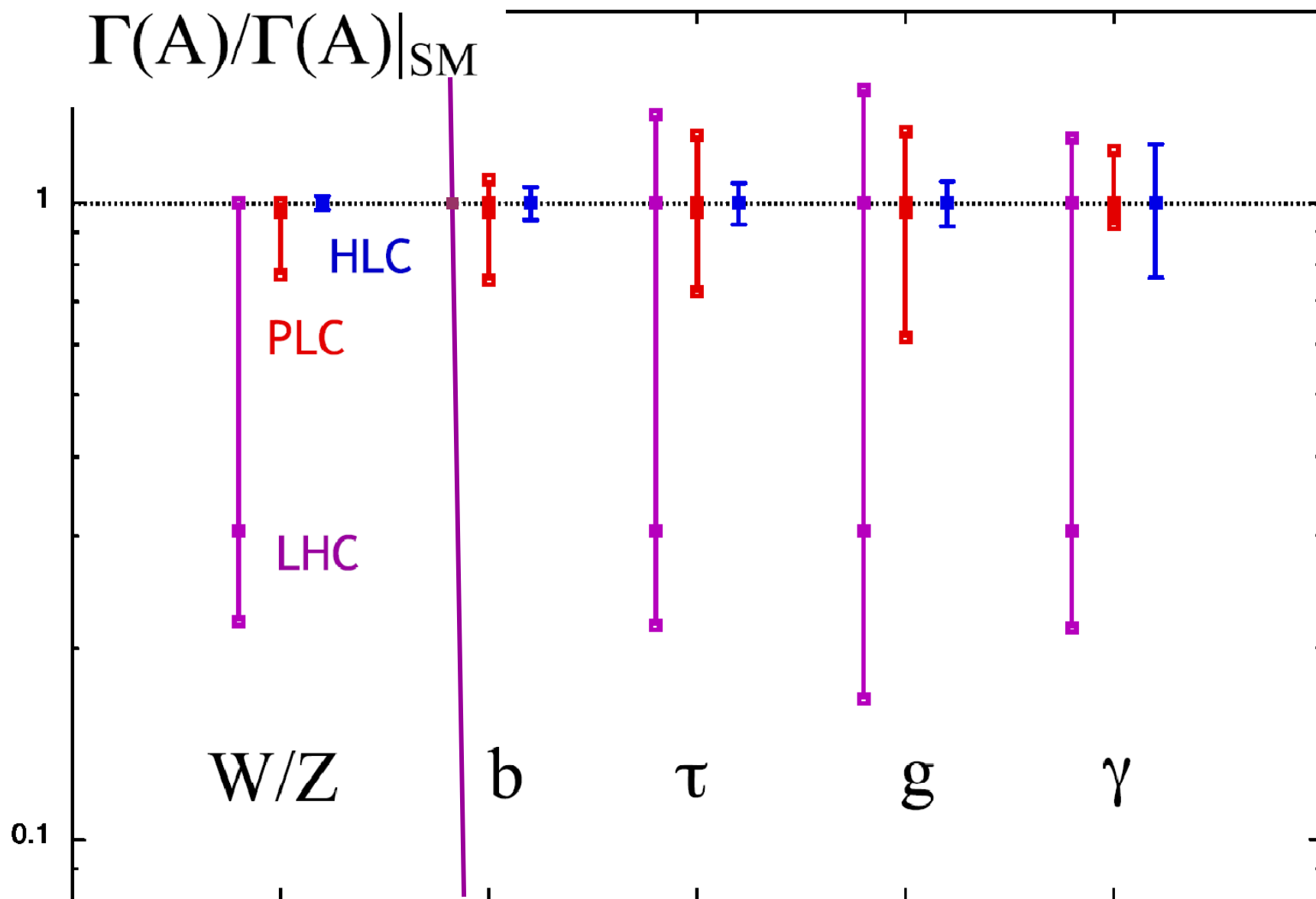The relation $\Gamma(WW) \leq \Gamma(WW)|_{SM}$ provides an upper bound for $\Gamma(WW)$

To obtain a lower bound on $\Gamma(WW)$ note

$$\Gamma(WW) \geq \Gamma(WW) \sum_{\text{observed decays } i} \mathrm{BR}(X_i) = \sum_{\text{observed decays } i} \frac{\Gamma(WW)\Gamma(X_i)}{\Gamma_{tot}}$$

In some cases $\dfrac{\Gamma(WW)\Gamma(X_i)}{\Gamma_{tot}}$ is measured directly in LHC $WW$ fusion

analyses or in measurements of the $WW^*$ decay at the PLC; otherwise use products such as

$$\frac{\Gamma(WW)\Gamma(\gamma\gamma)}{\Gamma_{tot}} = \frac{\Gamma(WW)\Gamma(\tau^+\tau^-)}{\Gamma_{tot}} \frac{\Gamma(\gamma\gamma)}{\Gamma(ZZ)} \frac{\Gamma(WW)}{\Gamma(\tau^+\tau^-)} \frac{1}{\cos^4\theta_W}$$

$\Gamma(A)/\Gamma(A)|_{SM}$

HLC

PLC

LHC

1

0.1

W/Z    b    τ    g    γ

# Cost Estimate

- In order to compare PLC cost with ILC cost of 6.74 billion ILC units, the following changes were made to Andrei's PLC design:
    - full power instead of low power configuration
    - 6.7 km damping ring instead of 3 km.
- To obtain the PLC cost 72 mods were made to the RDR ILC design. For example,
    - Reduce acceleration of each linac from 235 GeV to 75 GeV
    - Each BDS length reduced from 2.62 km to 0.3 km
    - Positron source deleted
    - BDS beam tunnels widened to accommodate 14 mrad ($e^+e^-$) and 30 mrad ($\gamma\gamma$) crossing angle
- Bottom line is PLC cost is 3.52 billion ILC units or 52% of ILC
- Similar analysis puts HLC cost at 4.52 billion ILC units or 67% of ILC.

# Paths to a reduced PLC cost

- Start with the low power configuration and reduce damping ring circumference from 6.7 km to 3 km.

- Lower $E_{cm}(ee)$ from 180 GeV to 150 GeV
  - The electron energy was increased from 150 to 170 GeV because the x value had to be lowered from 5.2 to 2.85 to reduce the disruption angle from 24 mrad to 14.3 mrad.  If a method could be found to deal with the backgrounds at x=5.2 then 20 GeV of electron energy could be saved.
  - Safety margin of 8 GeV was added to $\gamma\gamma$ energy reach so that background could be studied up to $W_{\gamma\gamma}$=128 GeV.  Data obtained colliding photons of opposite helicity below 120 GeV can be used to tune QCD models for J=2.  If perturbative QCD can reliably extend J=2 background to J=0 then there is no need to run above the Higgs, and another 10 GeV of electron energy could be saved.

- Remove the damping ring by using a low emittance polarized RF gun.

# Very low minimum electron energy following multiple Compton collisions at x=5.2
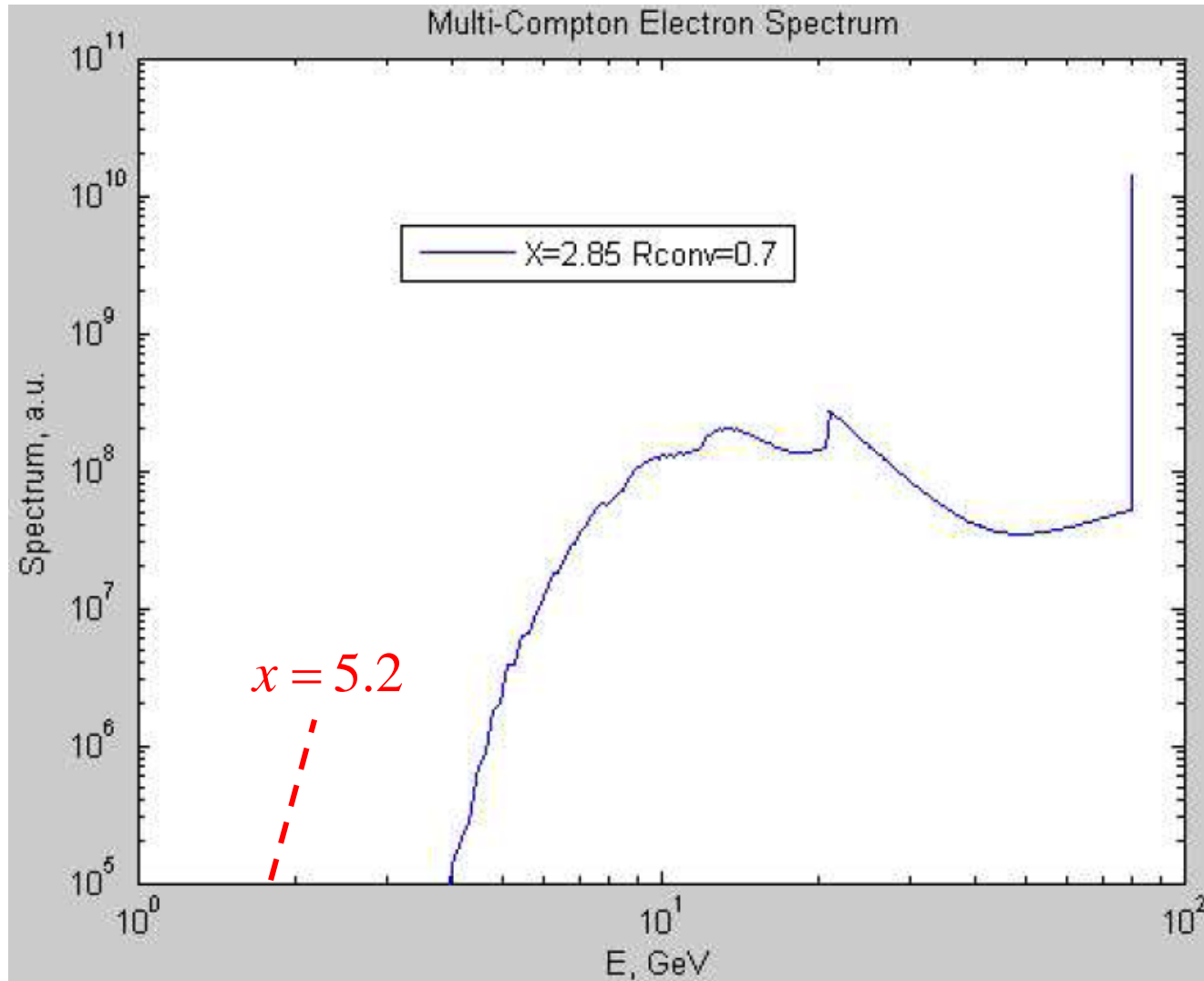
# Low emittance polarized gun

- High electron polarization is essential for Higgs physics at the PLC. Unfortunately, the emittance of electron bunches from existing high polarization electron sources is too large to use directly in the PLC linac - an ~ $ 1 billion damping ring is required between the polarized gun and the linac.

- Unpolarized RF guns exist which meet the linac emittance spec. What are the prospects for a high polarization low emittance RF gun?

# Low emittance polarized gun

- Cathodes must be made of negative electron affinity (NEA) materials such as GaAs to produce highly polarized electrons. Such cathodes require a vacuum of $10^{-11}$ torr to survive.

- During RF pulses the vacuum in an RF gun shoots up to $10^{-9}$ torr and a GaAs cathode is destroyed after a certain number of pulses. The main problem is damage to the cathode surface by the bombardment of light ions and field emitted electrons.

- Two solutions:
  - Develop NEA cathode materials that can survive $10^{-9}$ torr vacuum
  - Develop RF guns with an improved pulse vacuum

# Low emittance polarized gun

- Ongoing SBIR project by Mulhollan and Bierman at Saxtet Surface Science to develop more robust GaAs photocathode – they site polarized RF gun for the ILC as one of the major motivations

- Brookhaven is working on a superconducting RF gun with the hope that $10^{-12}$ torr can be obtained with cryogenic pumping.

- Another approach to low vacuum is the normal conducting L-band plane wave transformer (PWT) electron photoinjector under development by DULY Research. It has a quasi-open standing wave structure that can be more easily pumped down to a vacuum of $10^{-11}$ torr .

# Summary

- The PLC is one option for the first phase of a staged ILC. It is the least costly option among those that can directly study the Higgs boson.

- The Higgs physics case for the PLC is strong. If it were the first facility after the LHC to study the Higgs boson it would add significantly to our knowledge of Higgs physics.

- The cost difference between the PLC and HLC in ILC units may not seem compelling at the moment. However, there are avenues of research which, if successful, would bring the PLC cost down to about 2 billion ILC units.