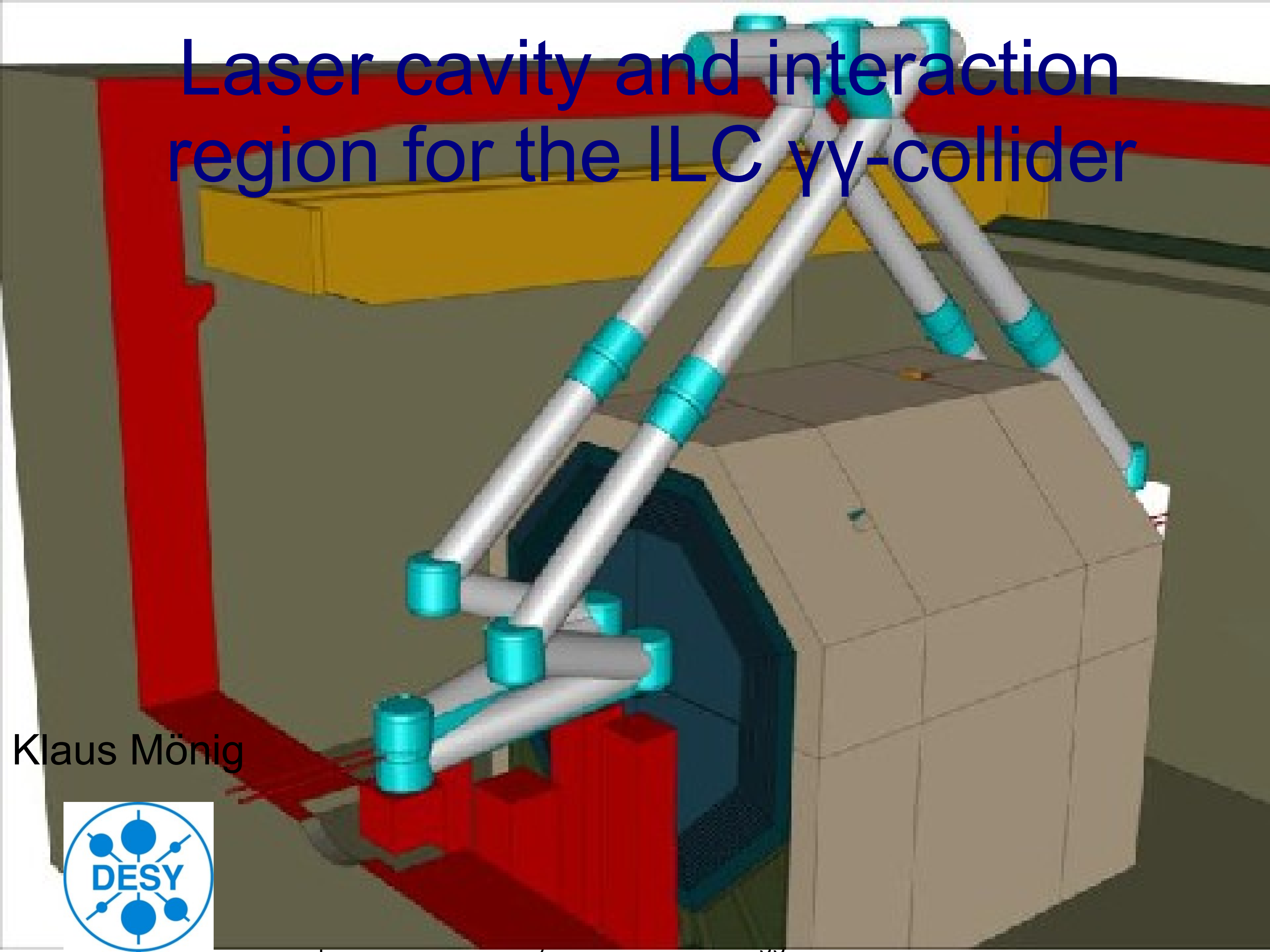
Laser cavity and interaction region for the ILC γγ-collider



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Outline

- Introduction
- Design issues for the ILC laser system
- Interaction region at a photon collider
- Scaling to the SAPPHiRE case
- Conclusions

Introduction

- For a photon-collider very high laser power is needed to “convert” electrons
- We studied the case for 500 GeV ILC and a 1 µm laser
- This requires roughly 10 J laser pulse energy with a spot size of 10 µm to reach high conversion rates
- Such pulse energies can only be reached if the laser pulses are stored in a cavity and are reused many times

Introduction (ii)

- ILC case:
  - Bunch spacing 300 ns → cavity length 100 m, fits naturally around the detector
  - 5 Hz train frequency and 0.5 ms train length → laser runs 0.5% of the time
- SAPPHiRE case:
  - Bunch spacing 5 μs → cavity length 1.7 km or several circulations between two bunch crossings
  - Laser needs to run continuously

Basic formulae

- Kinematics largely determined by e-γ cms energy:

$$x = \frac{4E_0\omega_0}{m^2c^4}\cos^2\frac{\alpha}{2} \simeq 19\left[\frac{E_0}{TeV}\right]\left[\frac{\mu m}{\lambda}\right]$$

- Maximum γ energy:

$$\omega_m = \frac{x}{x+1}E_0$$

- Need x<4.8 not to loose photons in $\gamma\gamma \rightarrow e^+e^-$
- ILC: x=4.8, SAPPHiRE: x=4.3
- Effective x somewhat lower due to non-linear effects

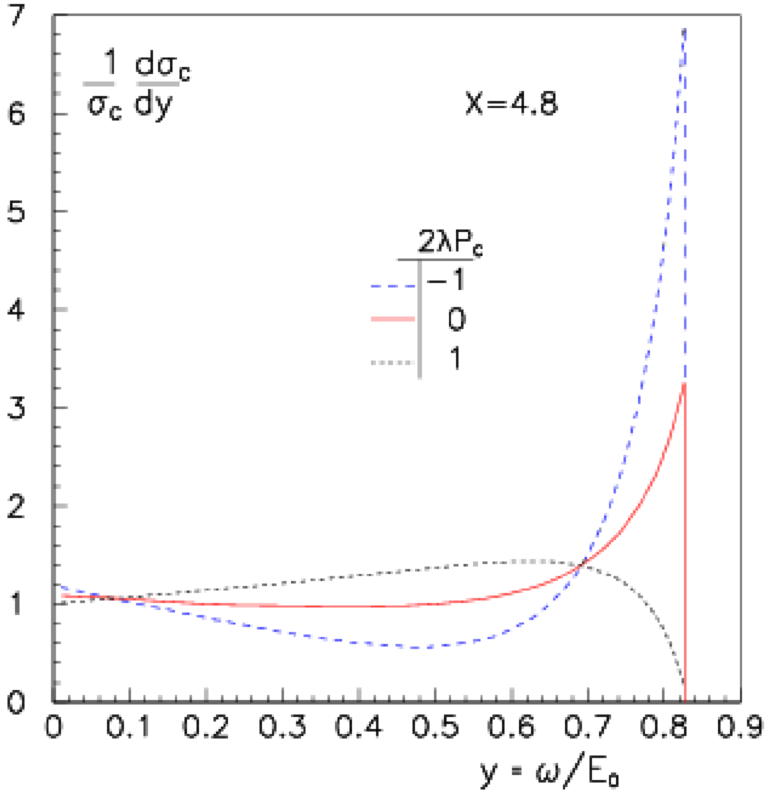
Basic formulae (ii)

- Differential cross section

$$\frac{d\sigma_c}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda_e P_c r x(1-2r)(2-y)\right]$$

$$y = \omega/E_0, \qquad r = \frac{y}{(1-y)x}, \qquad \sigma_0 = \pi r_e^2$$

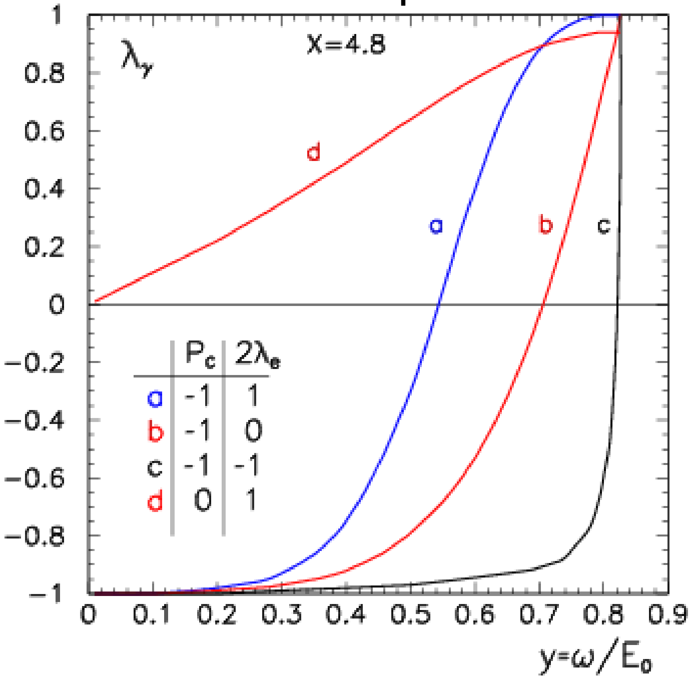
- Cross section depends on x and on polarisation product
- Laser and beam polarisation helps to get peaked spectrum and high photon-beam polarisation



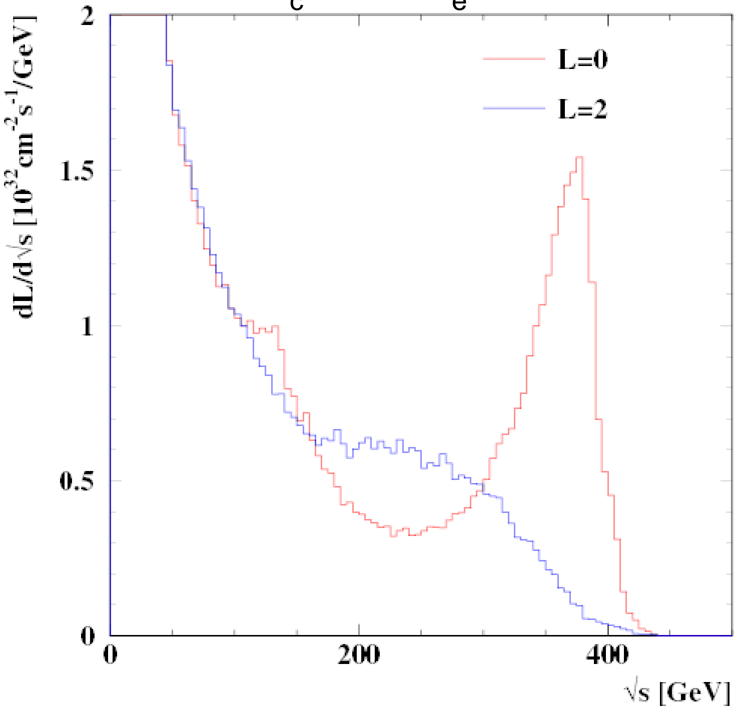
Final state polarisation

- Very high beam polarisation when electron beam and laser is polarised
- Gets preserved in real spectrum
- Electron polarisation is a must for Higgs physics

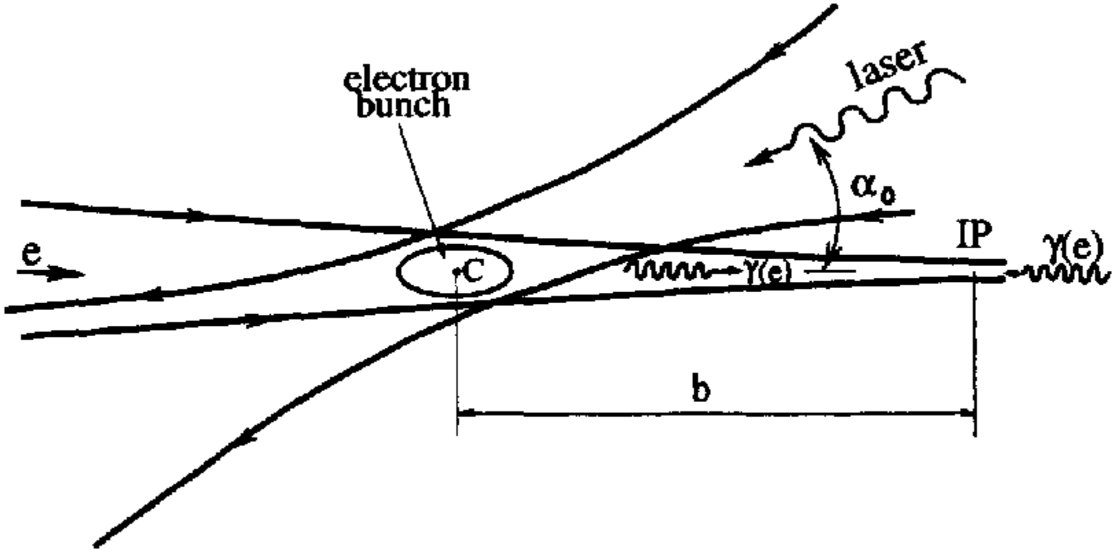
γ-polariation for different beam/laser polarisation



Luminosity spectrum for P_c=-1, $2\lambda_e$=0.85



Principle setup

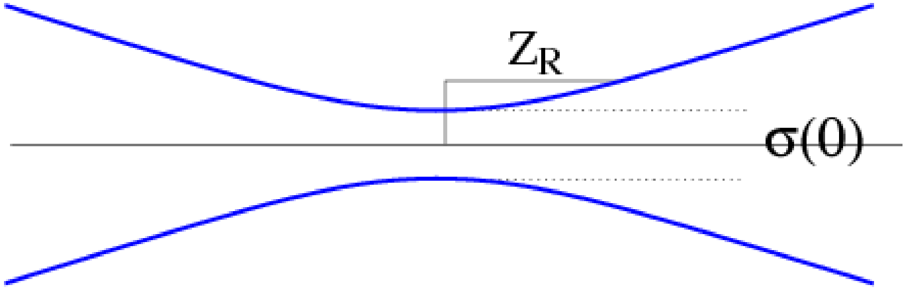


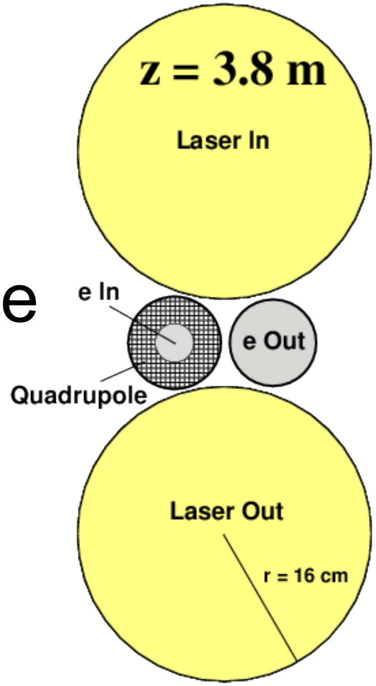
- Collide laser with e-beam few mm in front of IP
- Photons follow e-direction and keep focussing
- Need electron-laser crossing angle to place mirrors outside the beam
- γγ, eγ and ee interactions simultaneously

Laser shape at IP

- The laser beam at the IP has a similar shape as a particle beam with $\gamma=\lambda$ and $\beta=z_R$

$$\sigma_{L,r}(z) = \sigma_{L,r}(0)\sqrt{1 + z^2/Z_R^2} \qquad \sigma_{L,r}(0) = \sqrt{\frac{\lambda Z_R}{2\pi}}$$

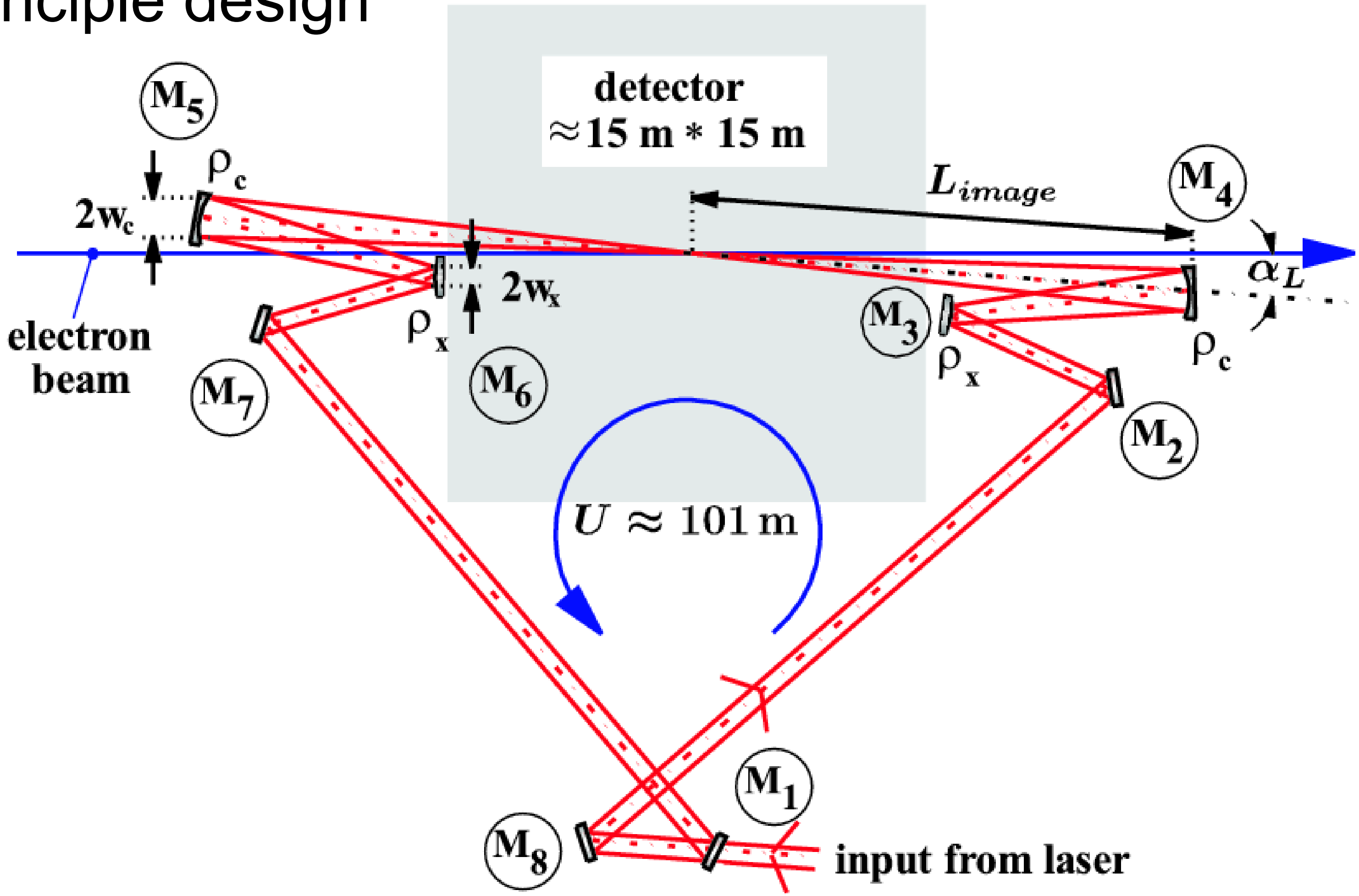




- Small spot sizes result in large divergence
- Large divergence results in large laser-beam crossing angle
- $\alpha \approx 1^\circ$ for $\sigma \approx 8\mu m$

ILC Laser cavity

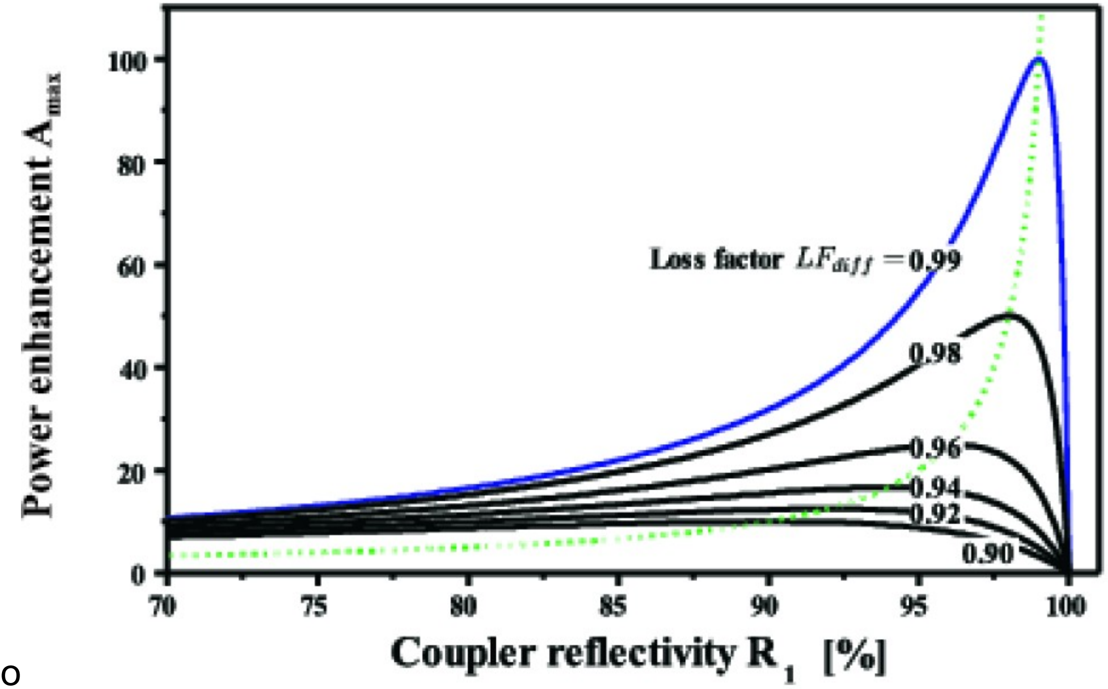
- Principle design



Quality factor and filling

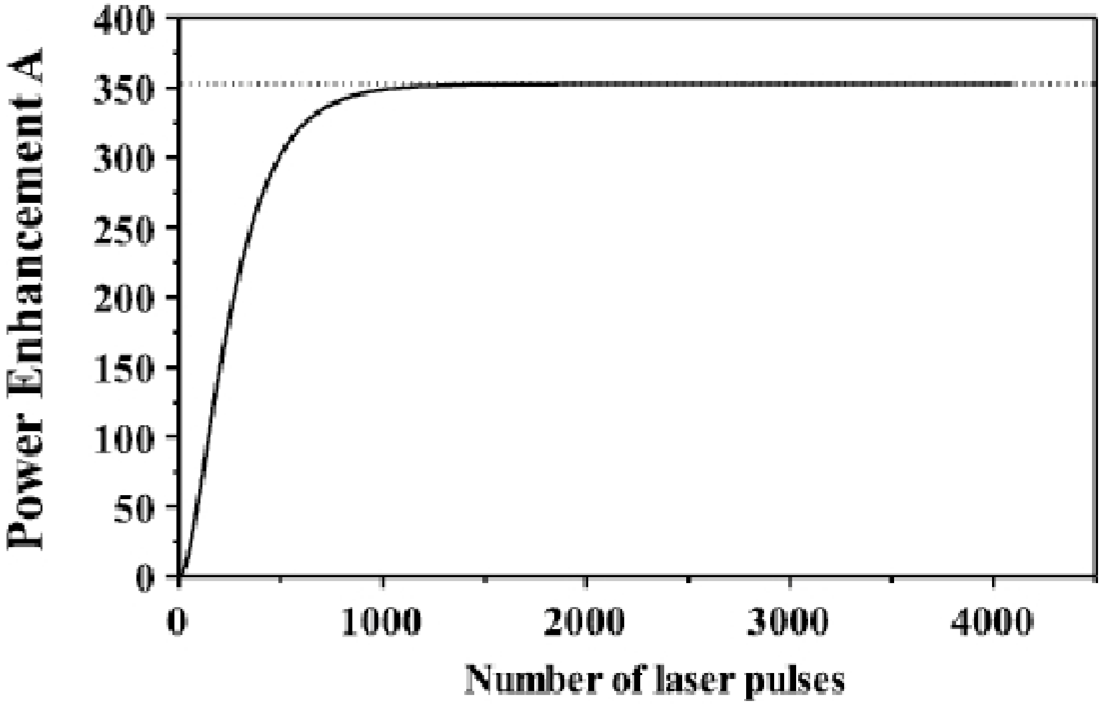
- The quality factor depends on the losses in M2-M8 (V)
- The power enhancement is given by V and the reflectivity of the input mirror R_1
- Optimum for R_1=V

$$A_{max} = \frac{1 - R_1}{\left(1 - \sqrt{R_1\, V}\right)^2}$$



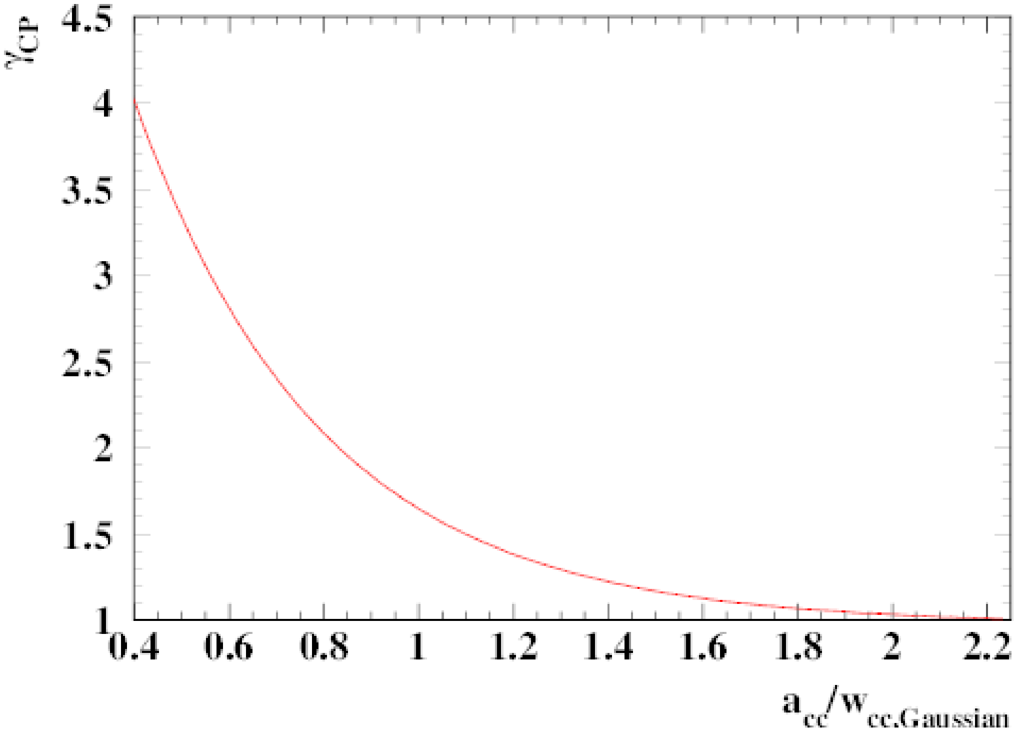
Quality factor and filling (ii)

- Need at least 3 x enhancement factor pulses to reach steady state
- For the SAPPHiRE scheme this would require continuous operation of the laser



Diffraction losses (i)

- All formulae are valid, when the full Gaussian beam is contained in the cavity → infinite size mirrors
- Losses due to finite mirror sizes turn out to be negligible
- However significant broadening of laser spot at IP

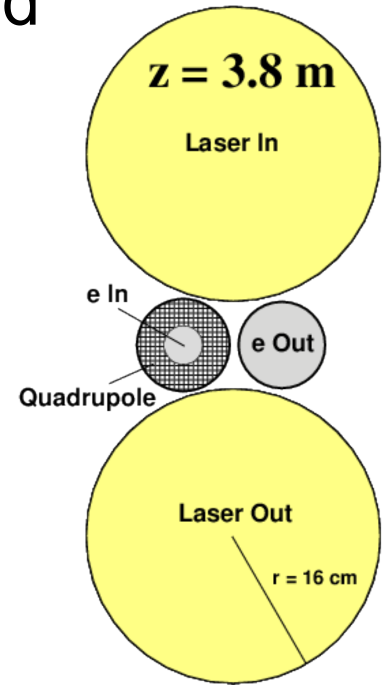


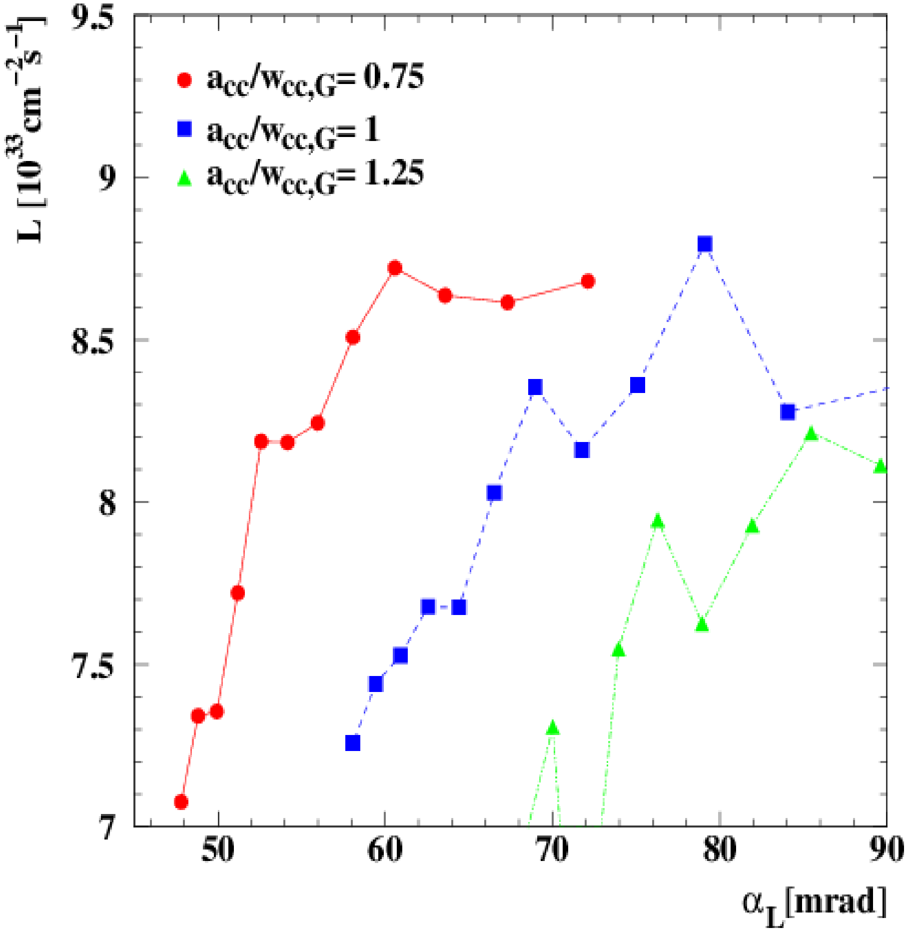
a_{cc}: mirror radius

$w_{cc,Gaus}$: Beam width in $1/e^2$ convention

Diffraction losses

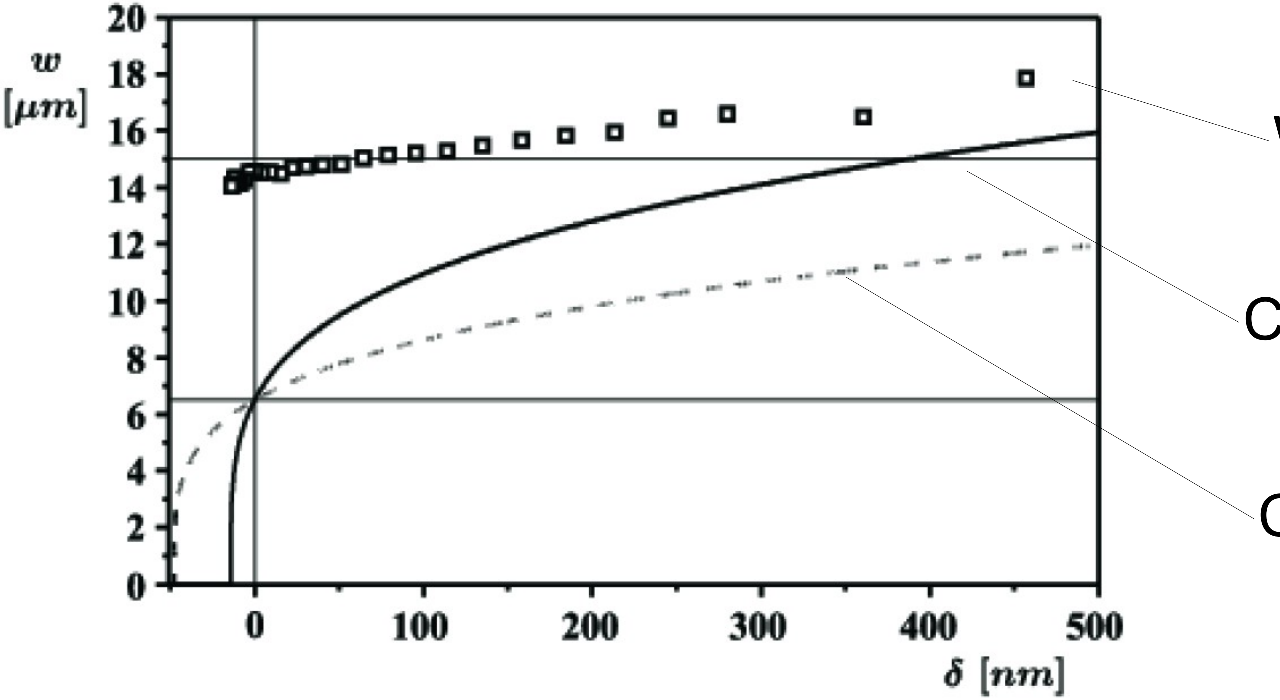
- Careful optimisation needed between mirror size and crossing angle
- Relatively small mirrors preferred





Tolerances

- Local tolerance must be much better than laser wavelength → can be achieved by adaptive mirror
- Tolerance of final focus 10nm without diffraction broadening, gets somewhat relaxed by the broadening



With diff. broad.

Convex mirror

Concave mirror

A note on non-linearity

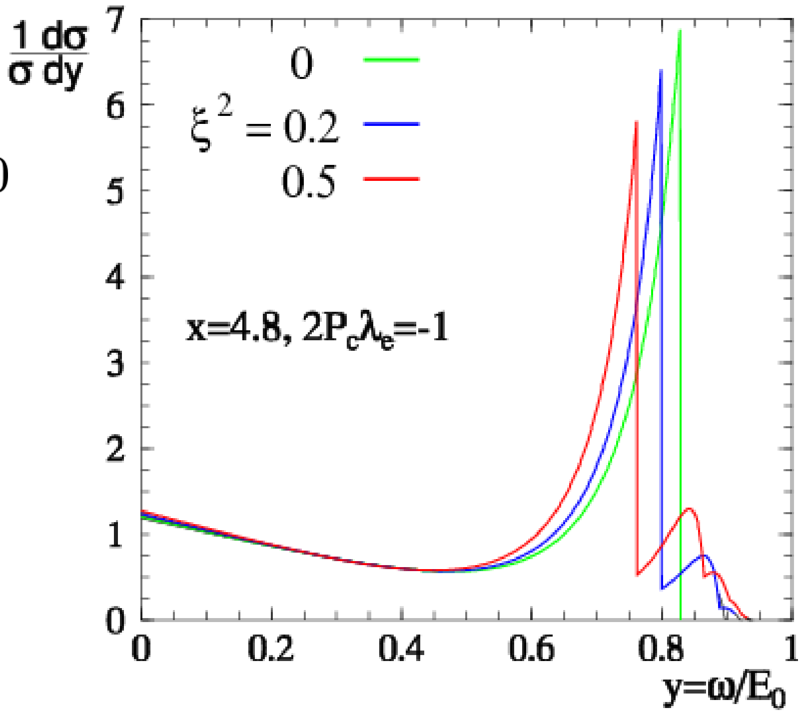
- At high photon density non-linear effects play a role parametrised by

$$\xi^2 = \frac{e^2 \bar{F}^2 \hbar^2}{m^2 c^2 \omega_0^2} = \frac{2 n_\gamma r_e^2 \lambda}{\alpha}$$

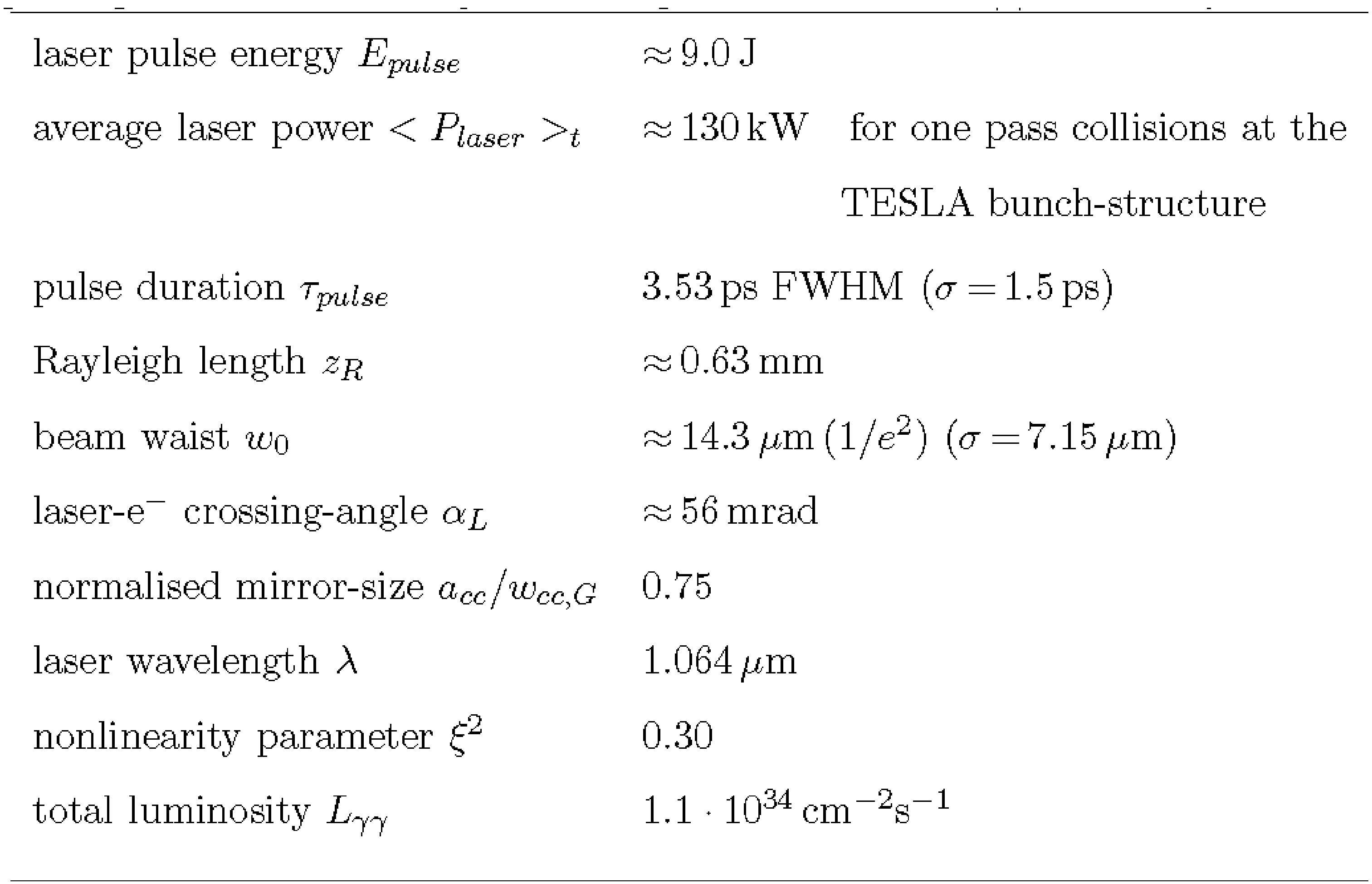
- Main effect: shift of maximum energy to

$$\omega_m = \frac{x}{x+1+\xi^2} E_0$$

- Plus small tail at high energy from simultaneous interaction with two photons

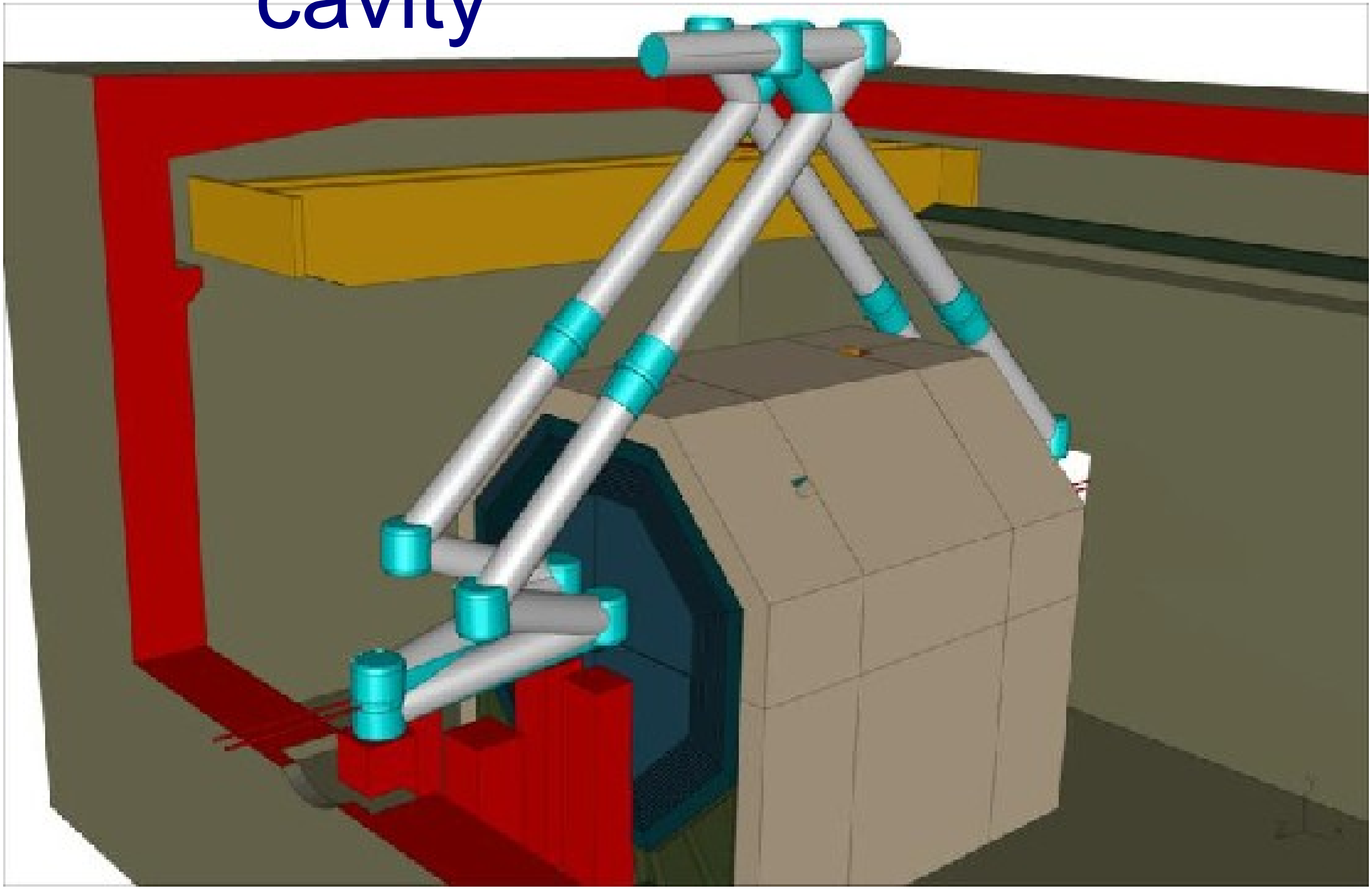


Laser parameters for the ILC case



laser pulse energy E_{pulse}	$\approx 9.0\,\mathrm{J}$	
average laser power $< P_{laser} >_t$	$\approx 130\,\mathrm{kW}$	for one pass collisions at the TESLA bunch-structure
pulse duration τ_{pulse}	$3.53\,\mathrm{ps}$ FWHM $(\sigma = 1.5\,\mathrm{ps})$	
Rayleigh length z_R	$\approx 0.63\,\mathrm{mm}$	
beam waist w_0	$\approx 14.3\,\mu\mathrm{m}\,(1/e^2)$ $(\sigma = 7.15\,\mu\mathrm{m})$	
laser-e$^-$ crossing-angle α_L	$\approx 56\,\mathrm{mrad}$	
normalised mirror-size $a_{cc}/w_{cc,G}$	0.75	
laser wavelength λ	$1.064\,\mu\mathrm{m}$	
nonlinearity parameter ξ^2	0.30	
total luminosity $L_{\gamma\gamma}$	$1.1 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	

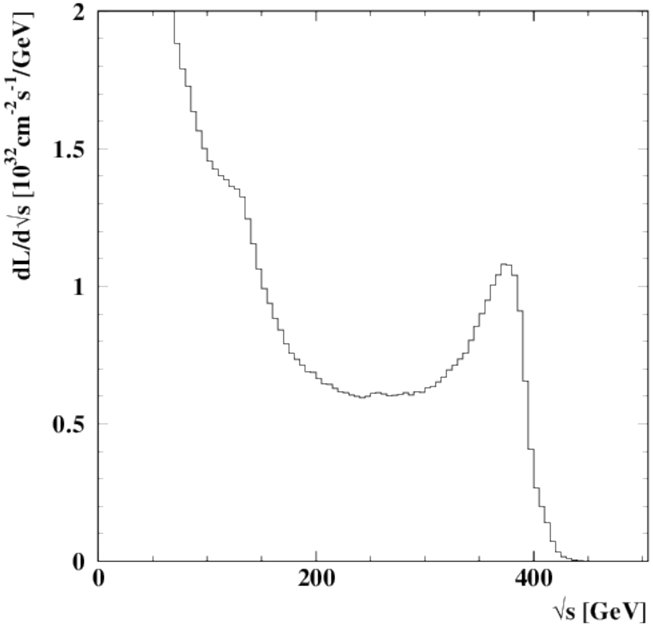
Possible arrangement of a 100m cavity



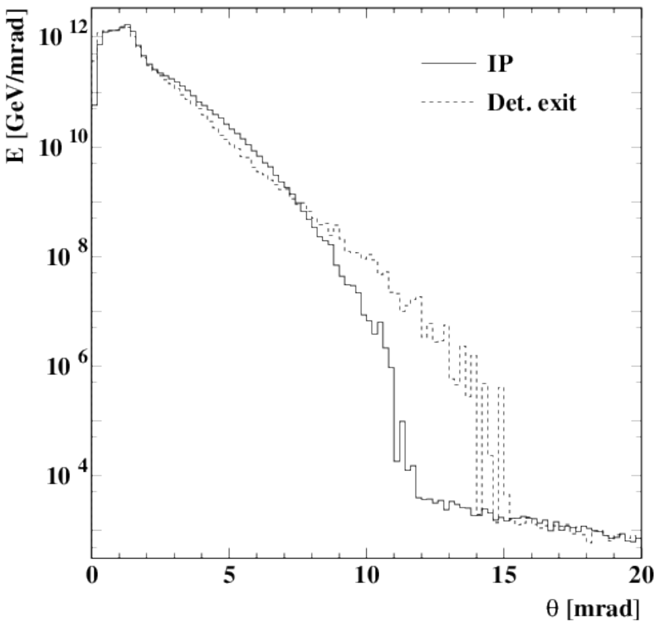
The interaction region

- eγ cross section rises for lower cms energy → high probability that scattered electrons interact again → very large luminosity at low γ energies and relatively large e disruption angles
- Assumed 34mrad crossing angle to pass by final quad

γγ luminosity



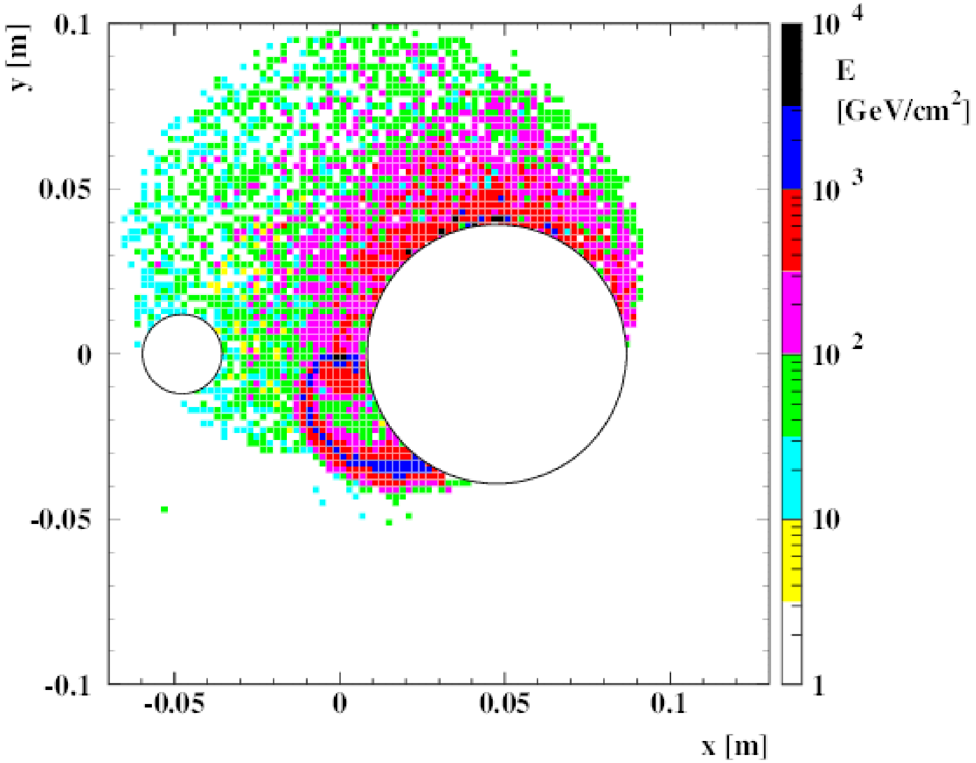
E-weighted e angle



Forward particle flow

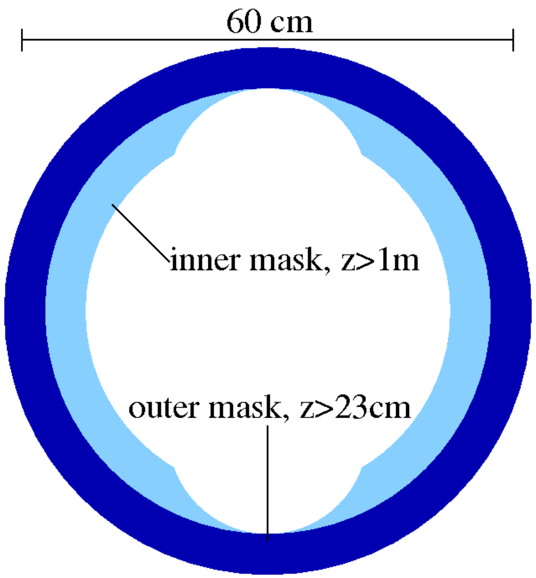
- Forward e-flow similar to e^+e^- (40TeV/bunch crossing)
- However more is swept out due to the large crossing angle

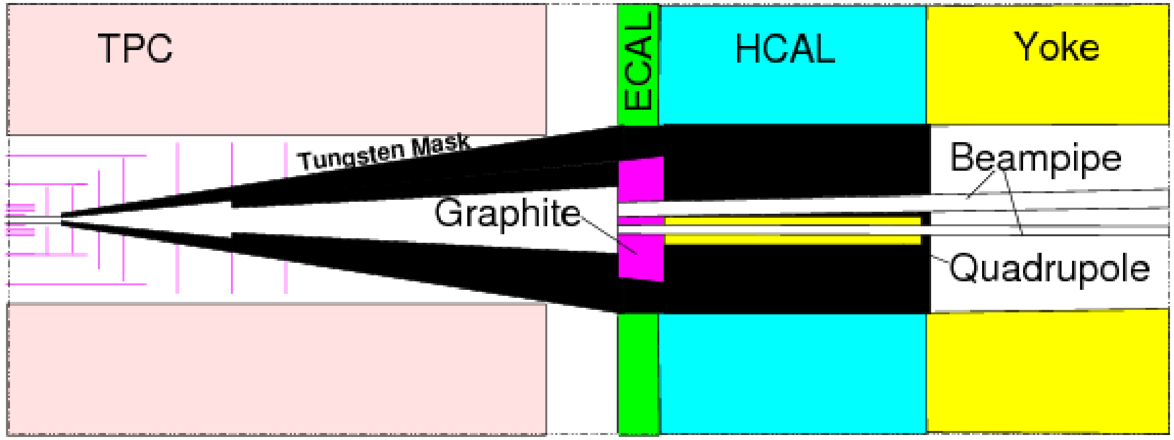
Energy deposition at z=2.8m



Forward masks

- Need strong masking in forward region to protect central detector from backscattering
- Detector dead below 7˚
- However for Higgs physics this should no be a problem





Scaling to SAPPHiRE

- Laser wavelength 1/3rd of ILC
- Same x → same Compton cross section
- However need factor 3 higher energy density for same photon density

$$\sigma(0) = \sqrt{\frac{\lambda Z_R}{2\pi}} \quad \frac{d\sigma}{dz} = \frac{\sigma(0)}{Z_R} = \sqrt{\frac{\lambda}{2\pi Z_R}}$$

- In principle need √3 smaller σ(0) → with factor 3 smaller λ still √3 smaller dσ/dz
- However loose one factor σ(0) due to large crossing angle → need same dσ/dz for same photon density

Conclusions

- A laser for a γγ collider needs a cavity to reduce the power to a reasonable level
- Due to the large crossing angle needed the laser power is in the 10J range
- Assuming for SAPPHiRE a 1.5km cavity with an enhancement factor 100 a laser power of 2kW would be needed
- Due to the large background heavy masking in the forward region of the detector is needed, for Higgs physics this should be no problem.