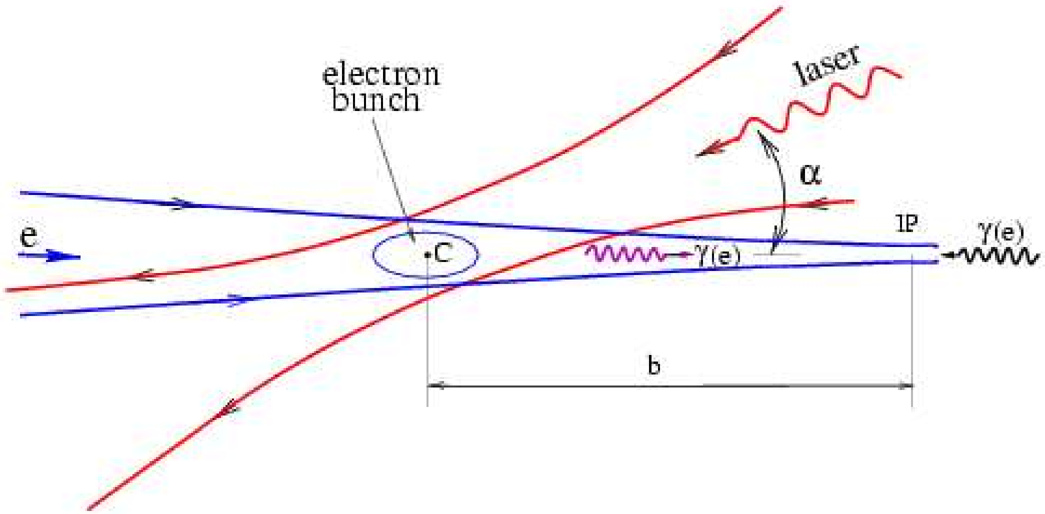
Photon Collider at ILC

Higgs Physics at Future Colliders workshop
2004/2005

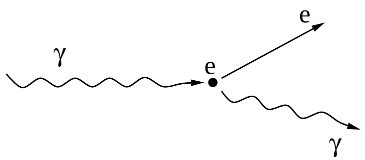
A.F.Żarnecki
12.01.2005

Photon Collider

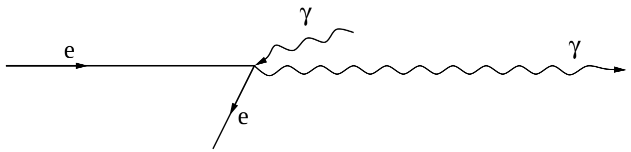
High energy, high intensity photon beam can be obtained using Compton backscattering of laser light off the high energy electrons



Compton scattering:

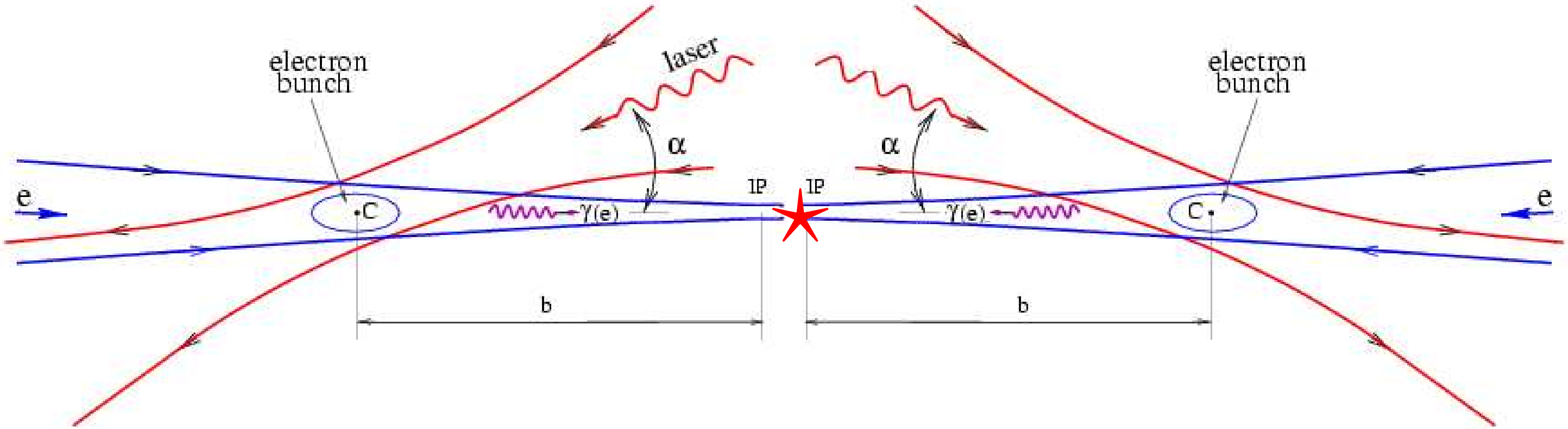


backscattering:



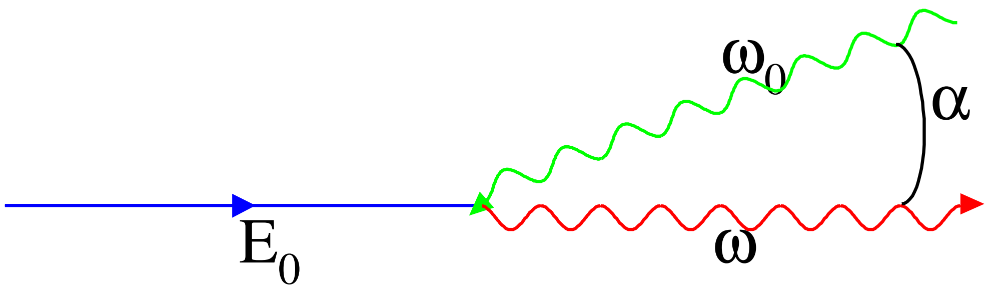
Photon Collider

High energy, high intensity photon beam can be obtained using Compton backscattering of laser light off the high energy electrons



PC: natural extension of all e^+e^- linear collider projects

Compton scattering



Maximum γ energy

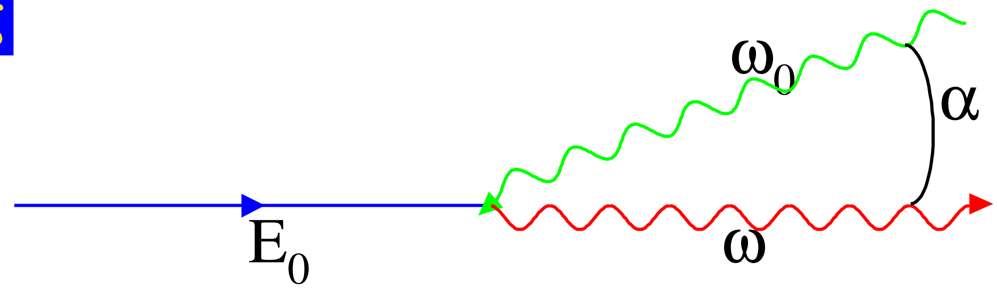
$$\omega_m = \frac{x}{x+1} E_0$$

with

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

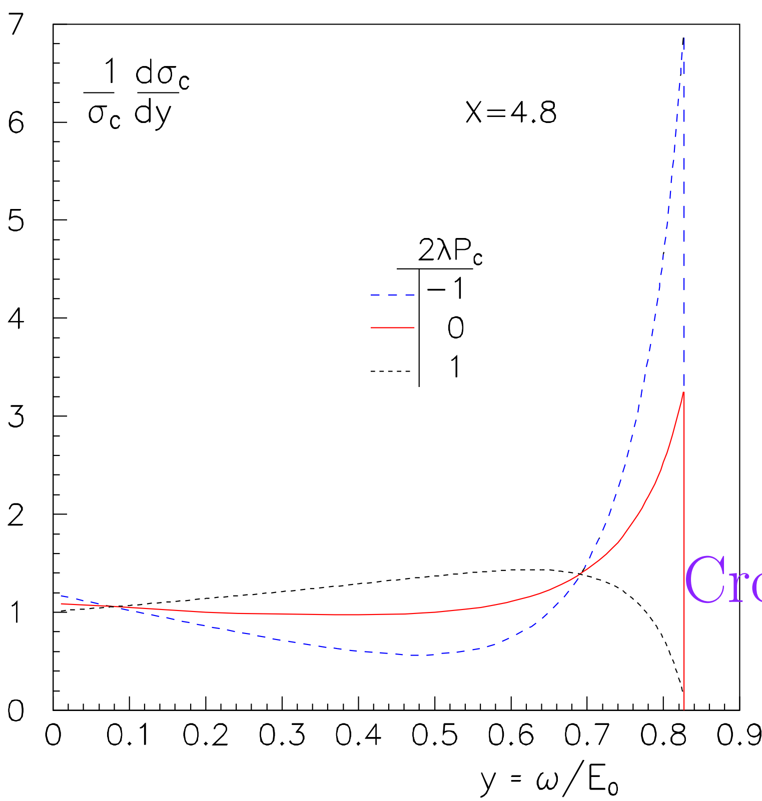
(To avoid $\gamma\gamma \to e^+e^-$ need $x < 4.8$)

Compton scattering



Differential Compton cross section:

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



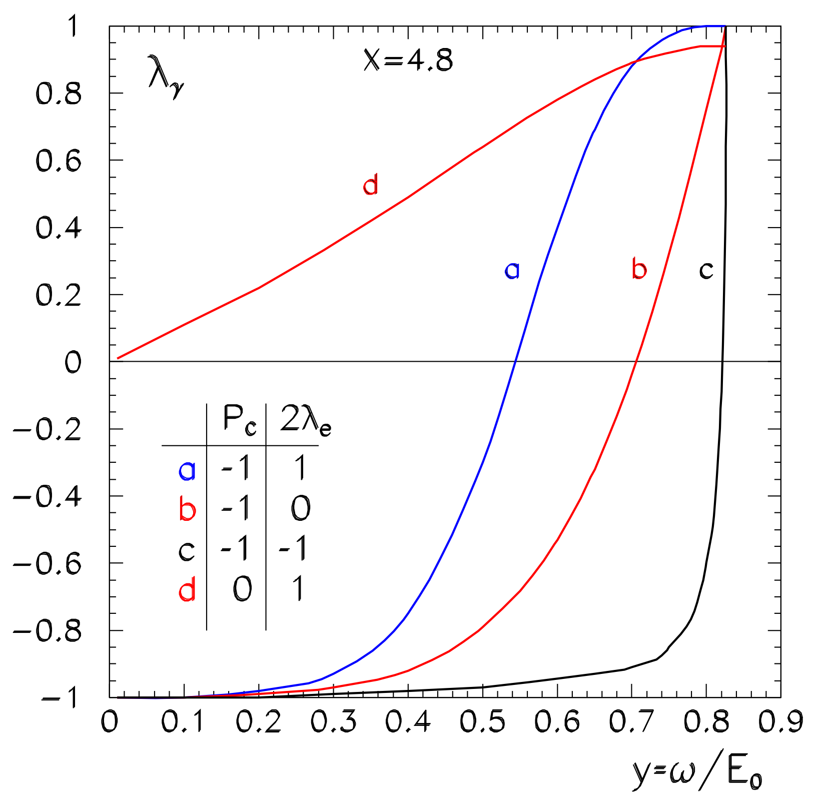
$$y = \omega/E_0, \quad r = \frac{y}{(1-y)x}, \quad \sigma_0 = \pi r_e^2$$

λ_e: e-helicity, P_c: circular laser polarisation

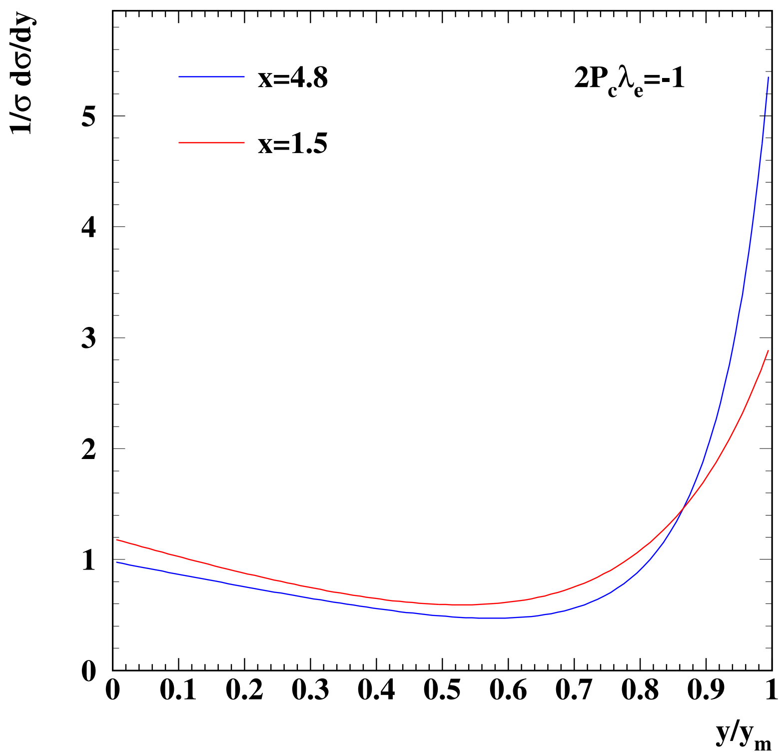
Cross section depends on helicity product $2\lambda_e P_c$

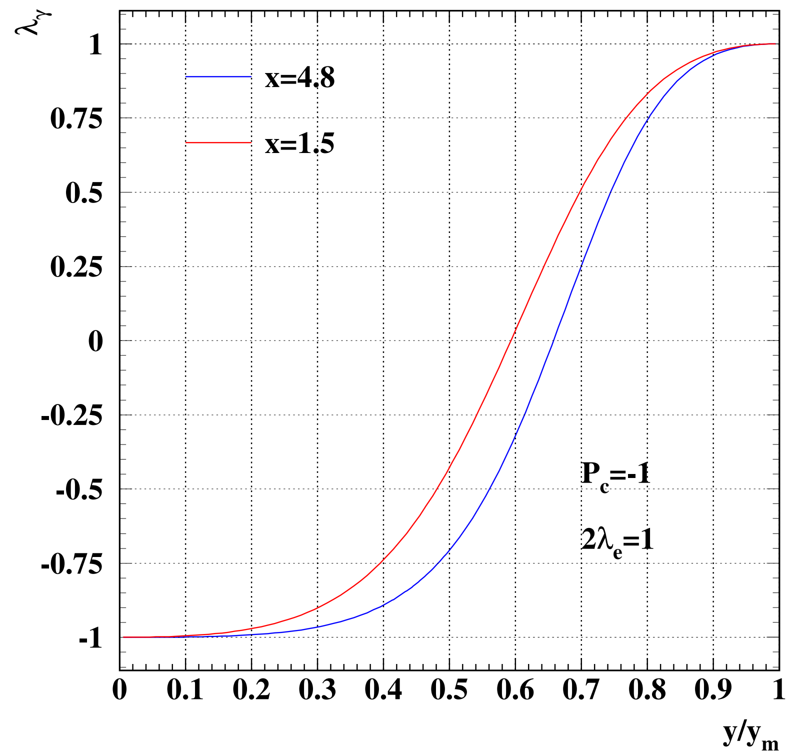
Mean helicity of scattered photons:

$$\langle \lambda_\gamma \rangle = \frac{-P_c(2r-1)[(1-y)^{-1}+1-y]+2\lambda_e xr[1+(1-y)(2r-1)^2]}{(1-y)^{-1}+1-y-4r(1-r)-2\lambda_e P_c xr(2-y)(2r-1)}$$



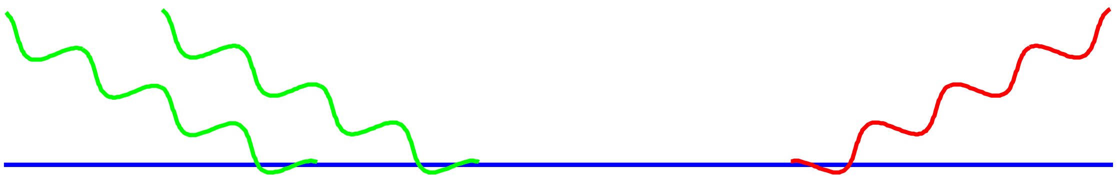
$x < 4.8$ makes spectrum less peaked with little effect on polarisation





Non-linear effects

In a high field an electron can interact with several photons simultaneously



Non linearity parameter:

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

$\bar{F}$ = field strength of laser field, n_γ = photon density

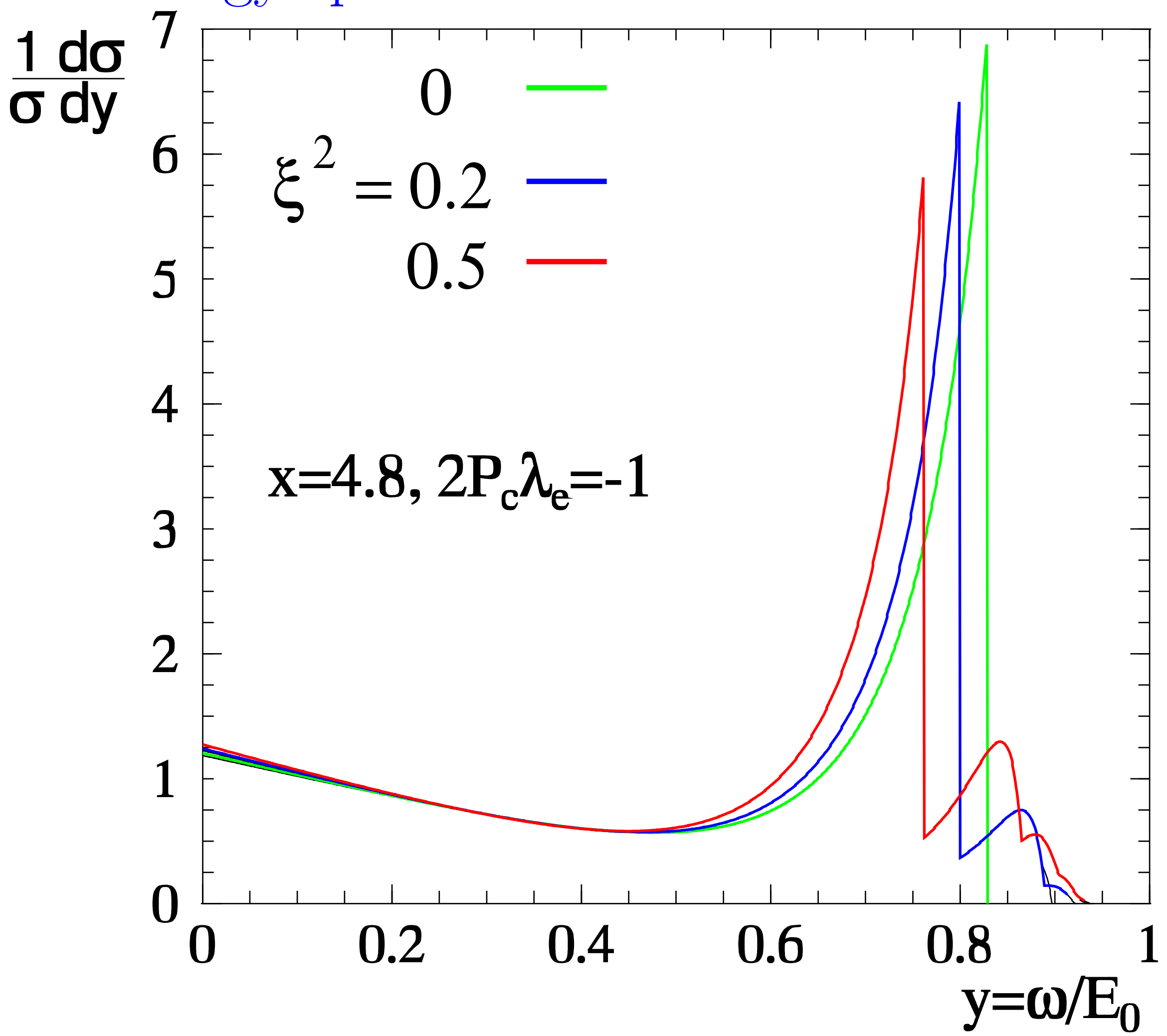
Non linear effects:

- increase effective electron mass to $m^2(1 + \xi^2)$

$\Rightarrow$ decreases ω_m to $\omega_m / E_0 = x/(1 + x + \xi^2)$

- create tail at high ω from n-photon interactions

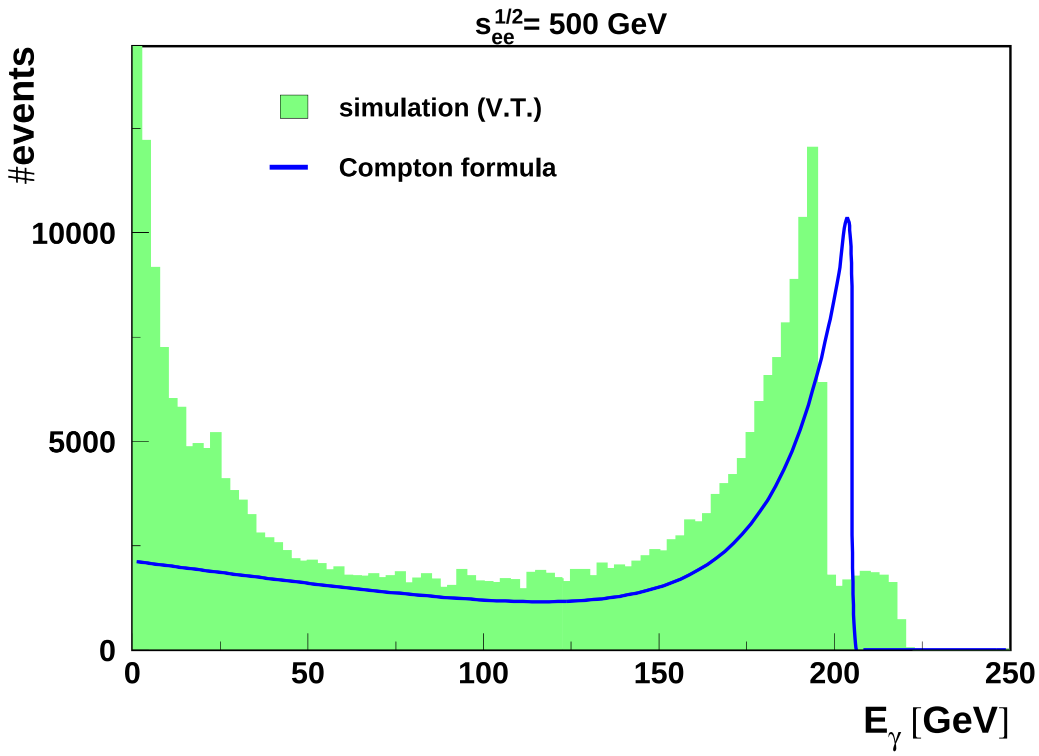
Photon energy spectrum for different non-linearities



CompAZ

Parametrization of the photon energy spectrum

Compton formula



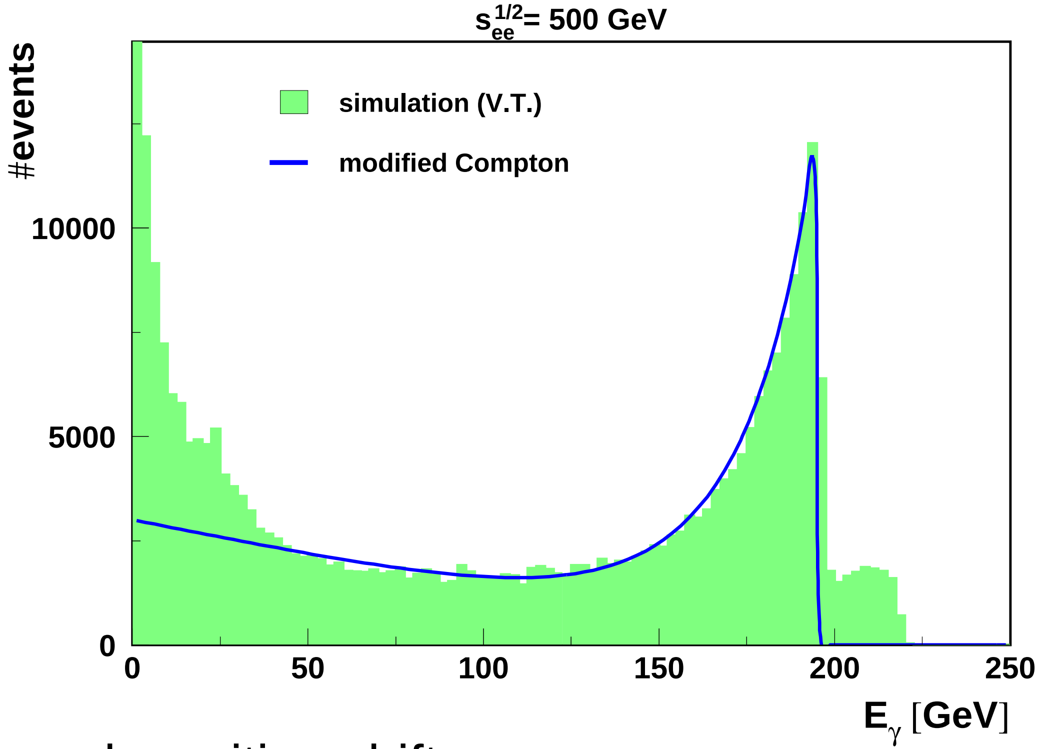
CompAZ

Parametrization of the photon energy spectrum

Compton formula

corrected for:

- nonlinear effects



non-linear effects $\Rightarrow$ peak position shift

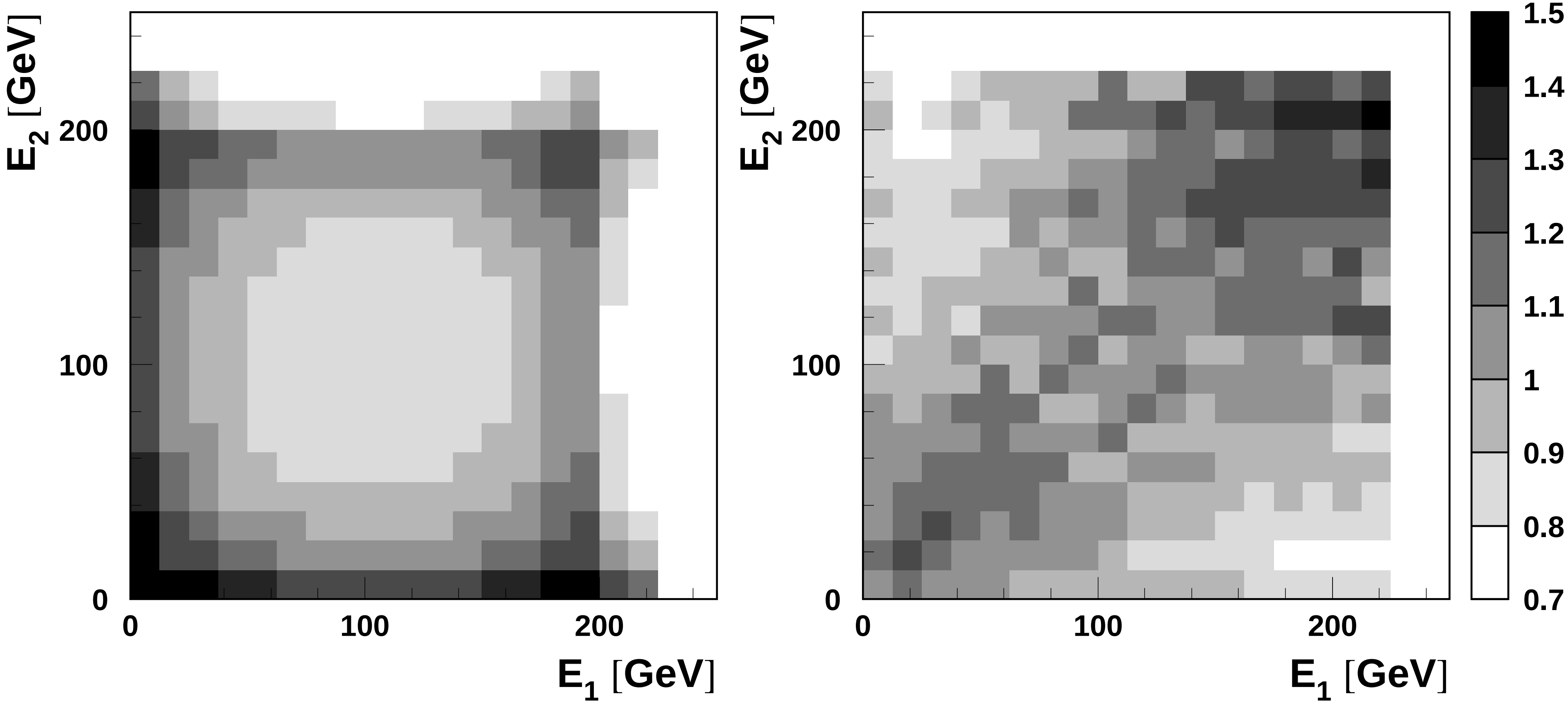
$$x = \frac{4 E_e \omega_L}{m_e^2} \longrightarrow \frac{x}{1+\zeta^2}$$

Beam energy correlations

There are large correlations between energies of two beams

energies

normalized to uncorrelated supperposition



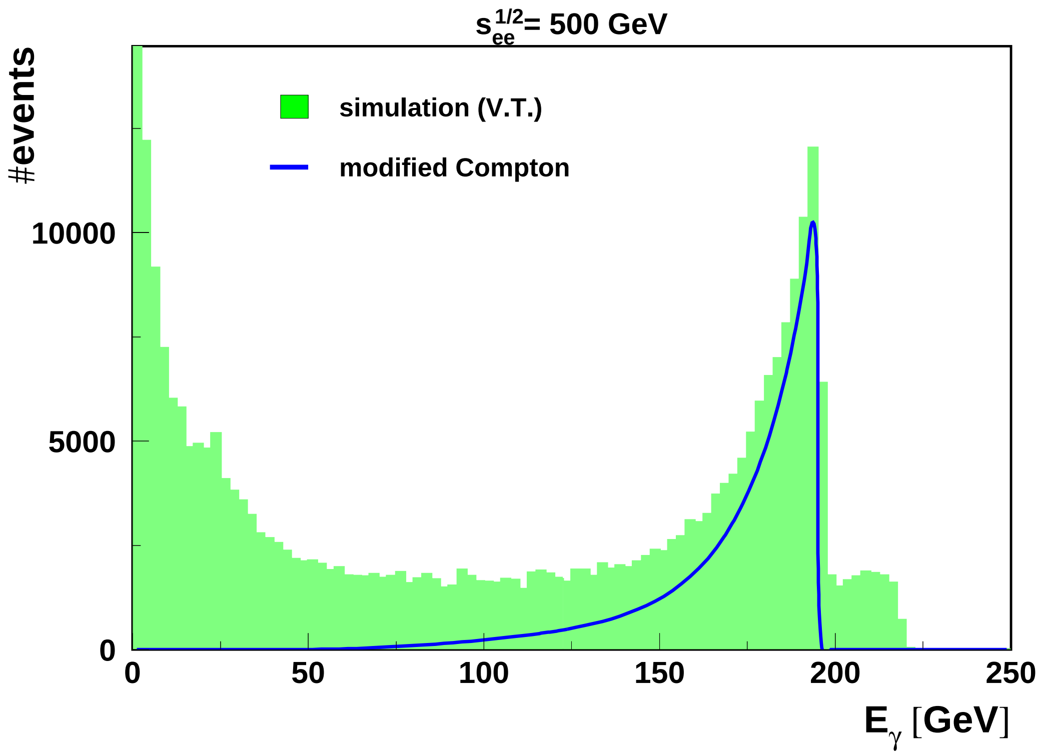
CompAZ

Parametrization of the photon energy spectrum

Compton formula

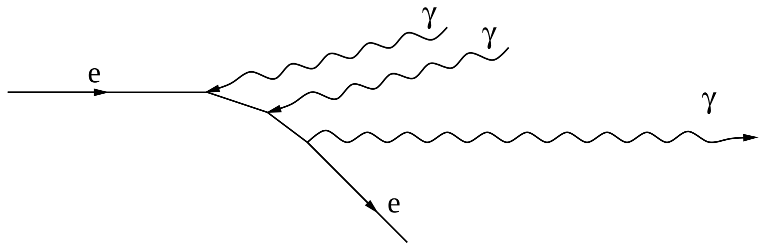
corrected for:

- nonlinear effects
- angular correlations

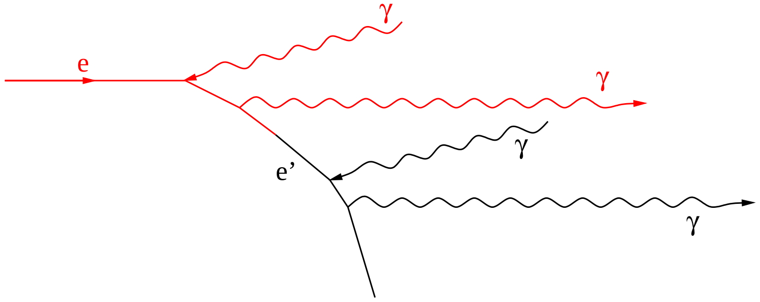


Additional contributions from 'higher-order' processes:

Scattering of two laser photons



Scattering on secondary electrons



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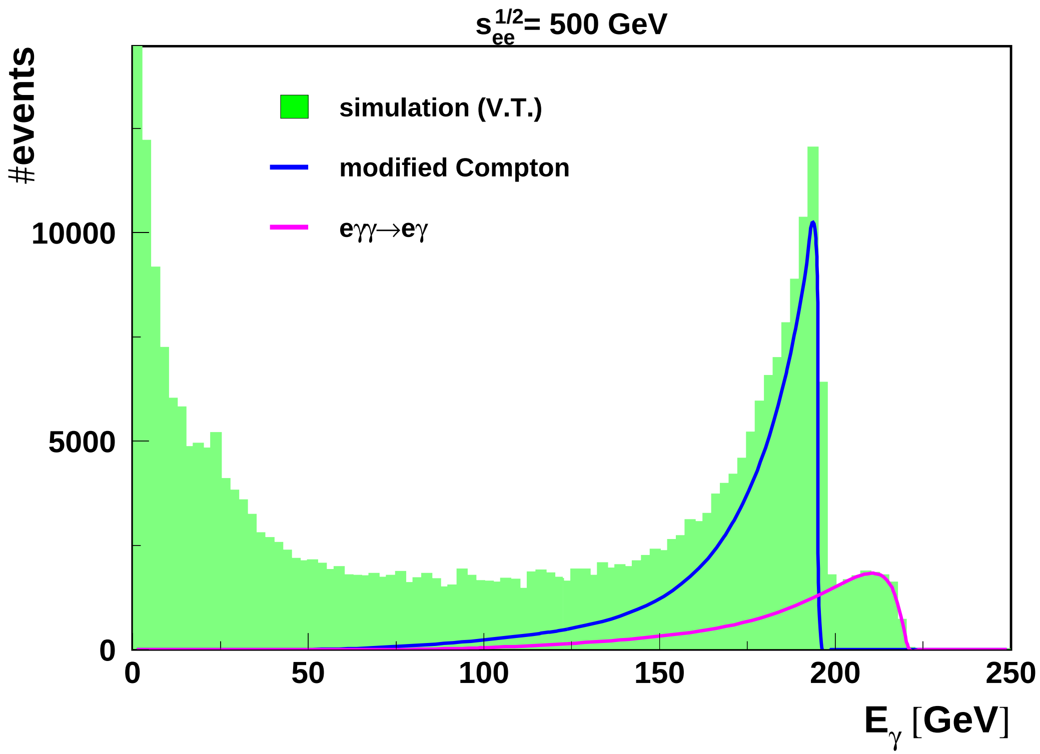
Parametrization of the photon energy spectrum

Compton formula

corrected for:

- nonlinear effects
- angular correlations
- two photon scattering



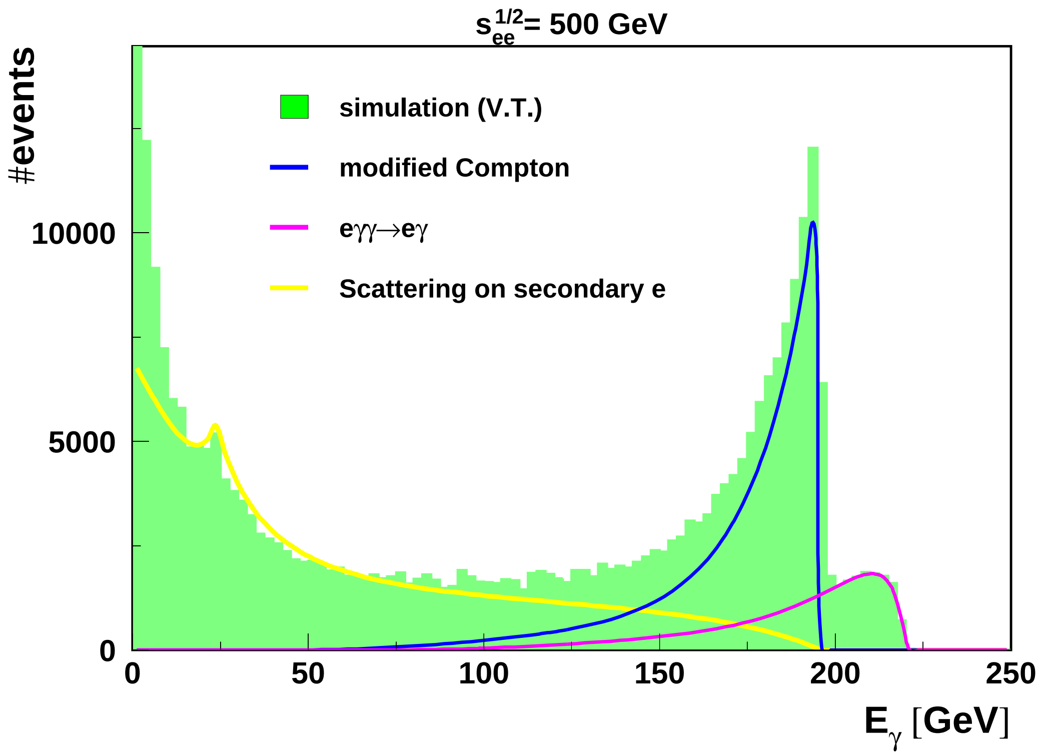
CompAZ

Parametrization of the photon energy spectrum

Compton formula

corrected for:

- nonlinear effects
- angular correlations
- two photon scattering
- electron rescattering



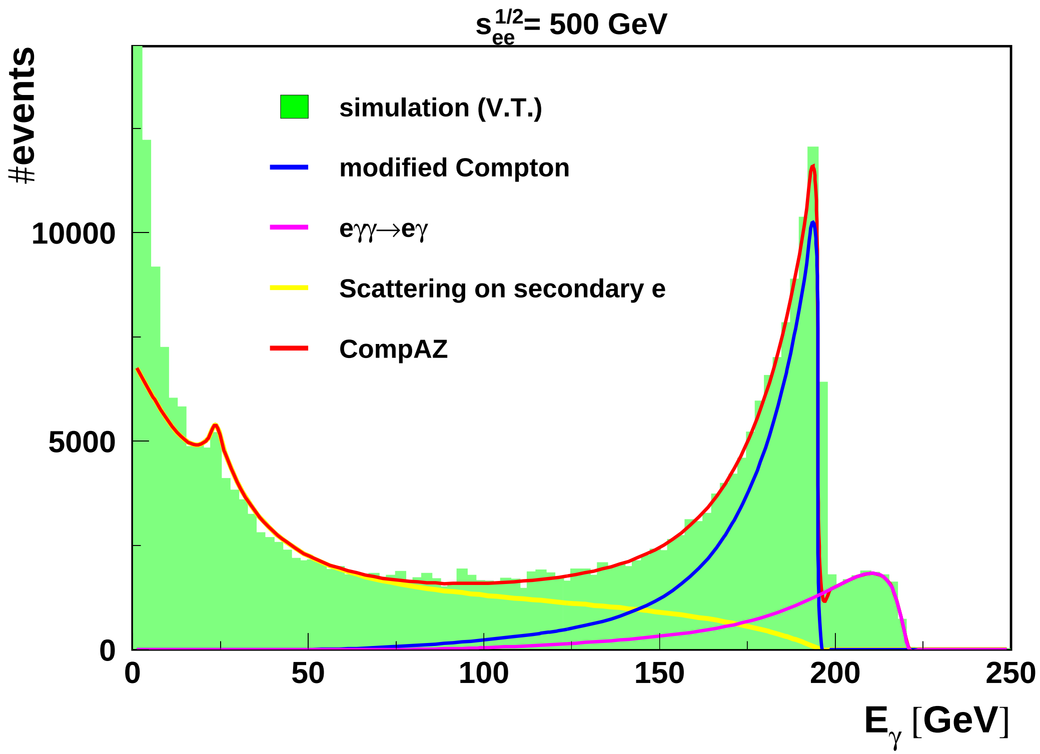
CompAZ

Parametrization of the photon energy spectrum

Compton formula

corrected for:

- nonlinear effects
- angular correlations
- two photon scattering
- electron rescattering

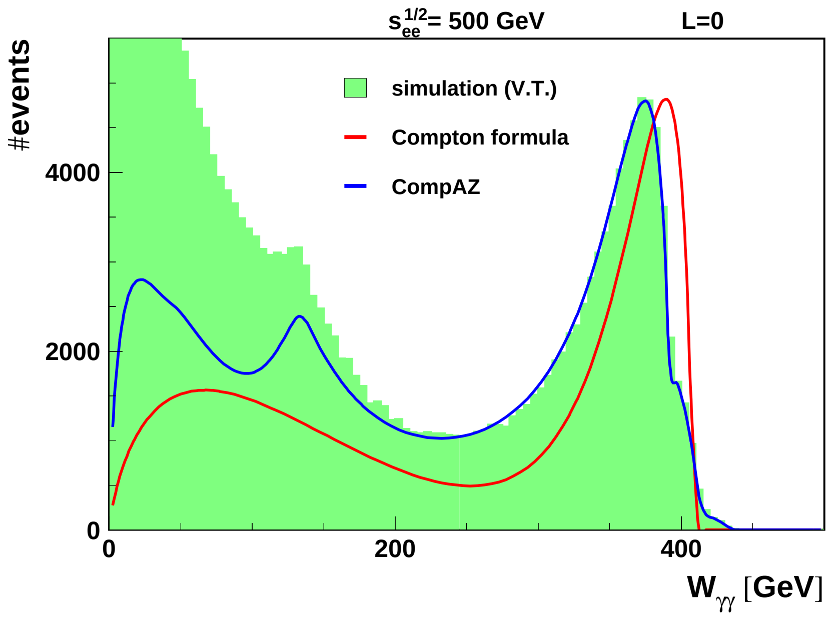


⇒ CompAZ

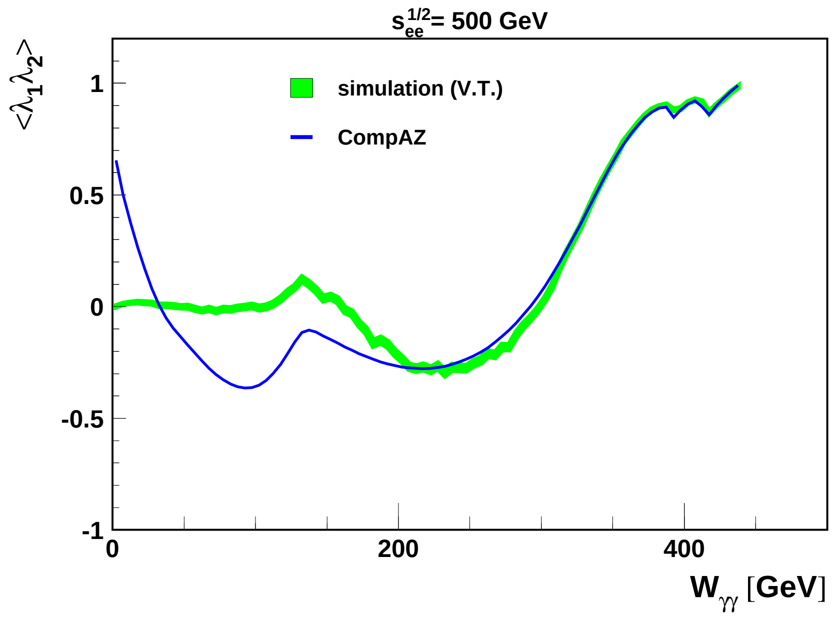
CompAZ

TESLA Photon Collider luminosity spectra parametrization
Very good description of the high energy part

$\gamma\gamma$ invariant mass



polarization



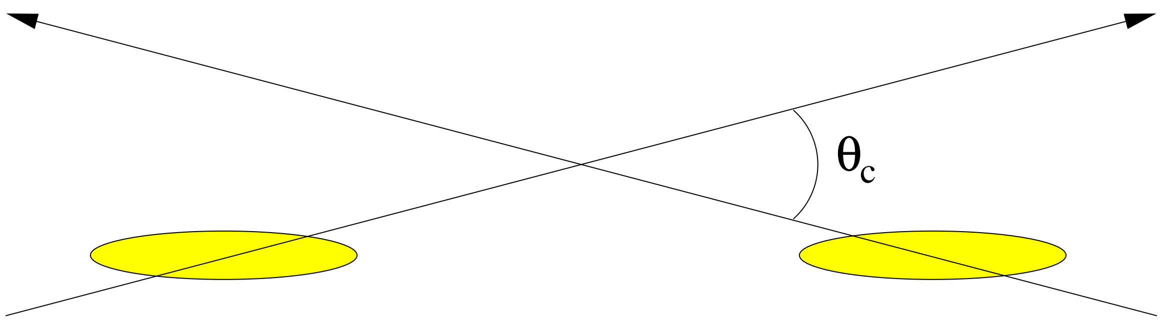
Crab crossing:

in $\gamma\gamma$ the disruption angle is larger than in e^+e^- because of the beam-laser interaction

$\Rightarrow$ outgoing beam no longer fits through final quadrupole

$\longrightarrow$ need crossing angle to have separate beam pipe for in- and outgoing beam

Crab crossing scheme allows crossing angle without luminosity loss



- need $\theta_c \sim 35$mrad
- apparent transverse beam dimension for beam-laser interaction larger

The Laser

Wavelength of powerful solid state lasers is in the 1μm range, e.g. Nd:YAG $\lambda = 1.06\mu$m

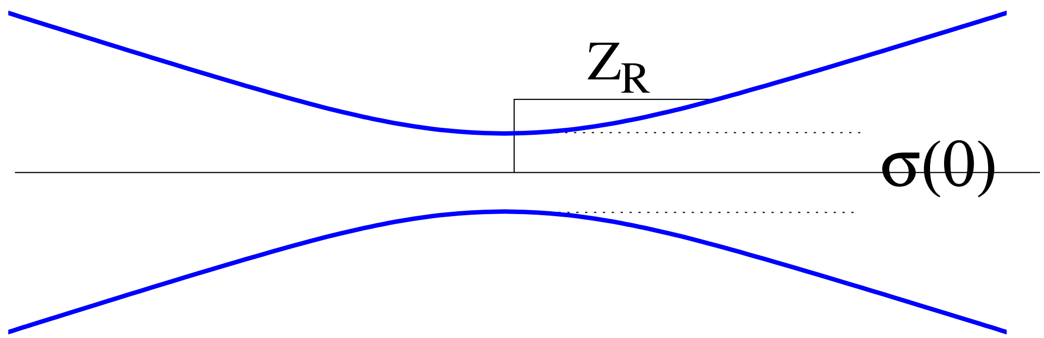
($x = 4.5$ for $\sqrt{s} = 500\,\text{GeV}$)

(If really needed can double or triple frequency)

Laser focusing in diffraction limited region:

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

Z_R: Rayleigh length



→ cannot vary length and diameter of laser spot simultaneously

Optimum around $Z_R \approx \sigma_z$ ➟ half opening angle of $\mathcal{O}(1^\circ)$

Fraction of converted electrons:

$$k = N_\gamma / N_e \approx 1 - \exp(-A/A_0)$$

A: pulse energy of laser

For $Z_R \approx \sigma_z$ and head on laser-beam collisions:

$$A_0 \approx \frac{\pi \hbar c \sigma_z}{\sigma_c} \approx 1.5\mathrm{J}$$

$\Rightarrow$ need $A \approx 2J$ (corresponds to $\xi^2 \approx 0.2$)
(for head on e^--laser collisions)

$\Rightarrow$ total laser power of $\sim 2 \times 30\,\mathrm{kW}$ needed

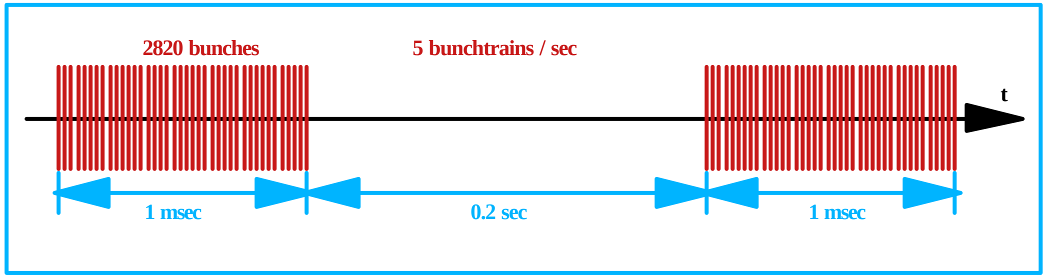
➡ $\sim$ 60 Mercury lasers from the Livermore fusion program

Laser requirements

- **Laser pulses of**

$\approx 5\,\mathrm{J}$	pulse energie
≈ 1 - $3\,\mathrm{ps}$	pulse duration (FWHM)
$\approx 14\,\mu\mathrm{m}$	spotsize $(1/e^2)$
$\approx 1\,\mu\mathrm{m}$	wavelength
$2.5^\circ - 4^\circ$	e^- - IR crossing angle

- **have to match the TESLA bunch-structure:**
  - 2820 bunches/train
  - 337 ns spacing
  - 5 Hz repetition rate



Requires:

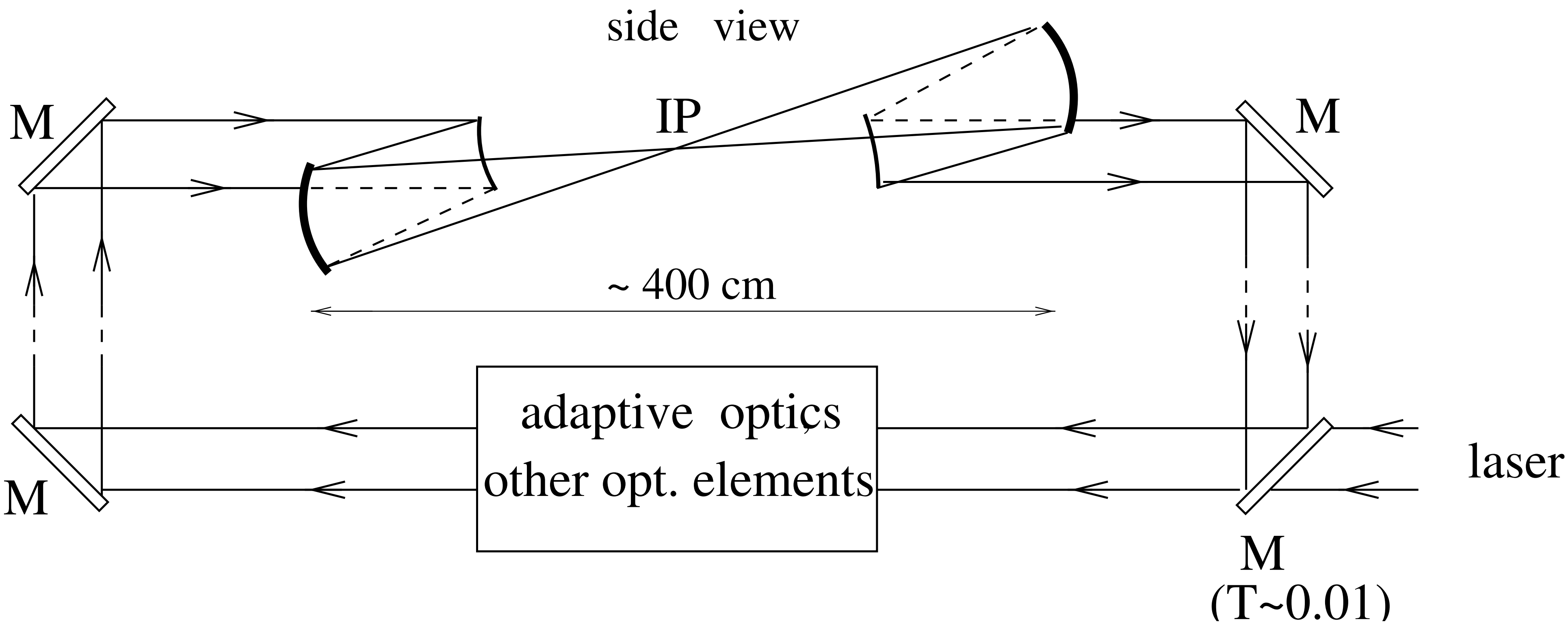
- high peak power ($\approx$ 2 TW)
- high average power ($\approx$ 70 kW)
- precise timing, low jitter (1 ps)

One solution:

Pulsed laser with the correct timestructure and relaxed power requirements feeds a resonant cavity for enhancement of power

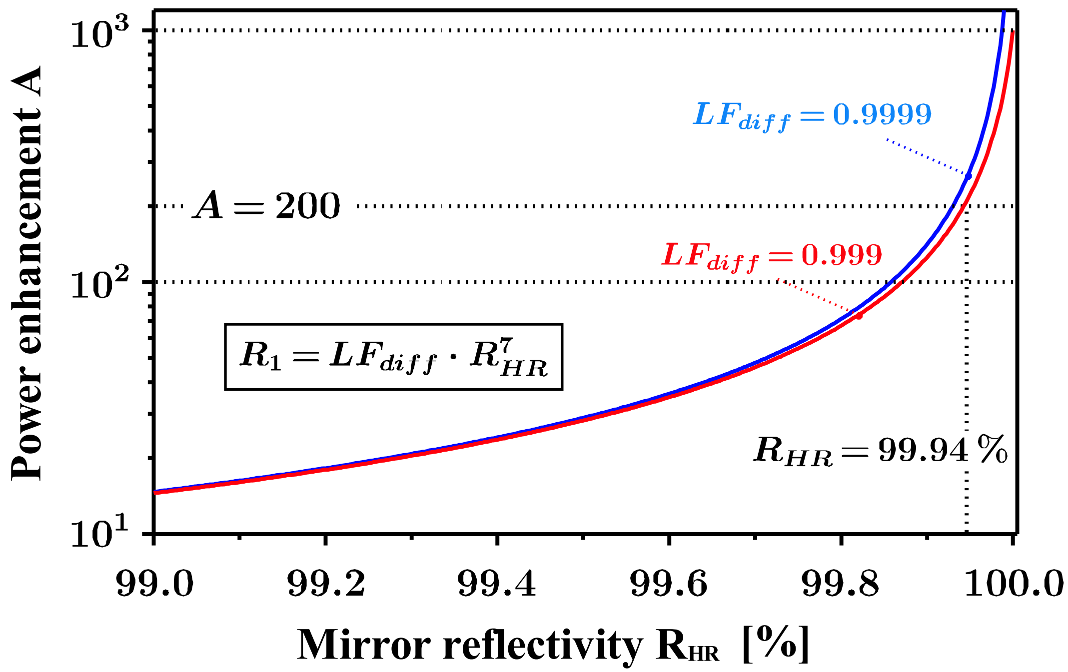
However the number of used laser photons is negligible

Better idea: recycle laser pulses



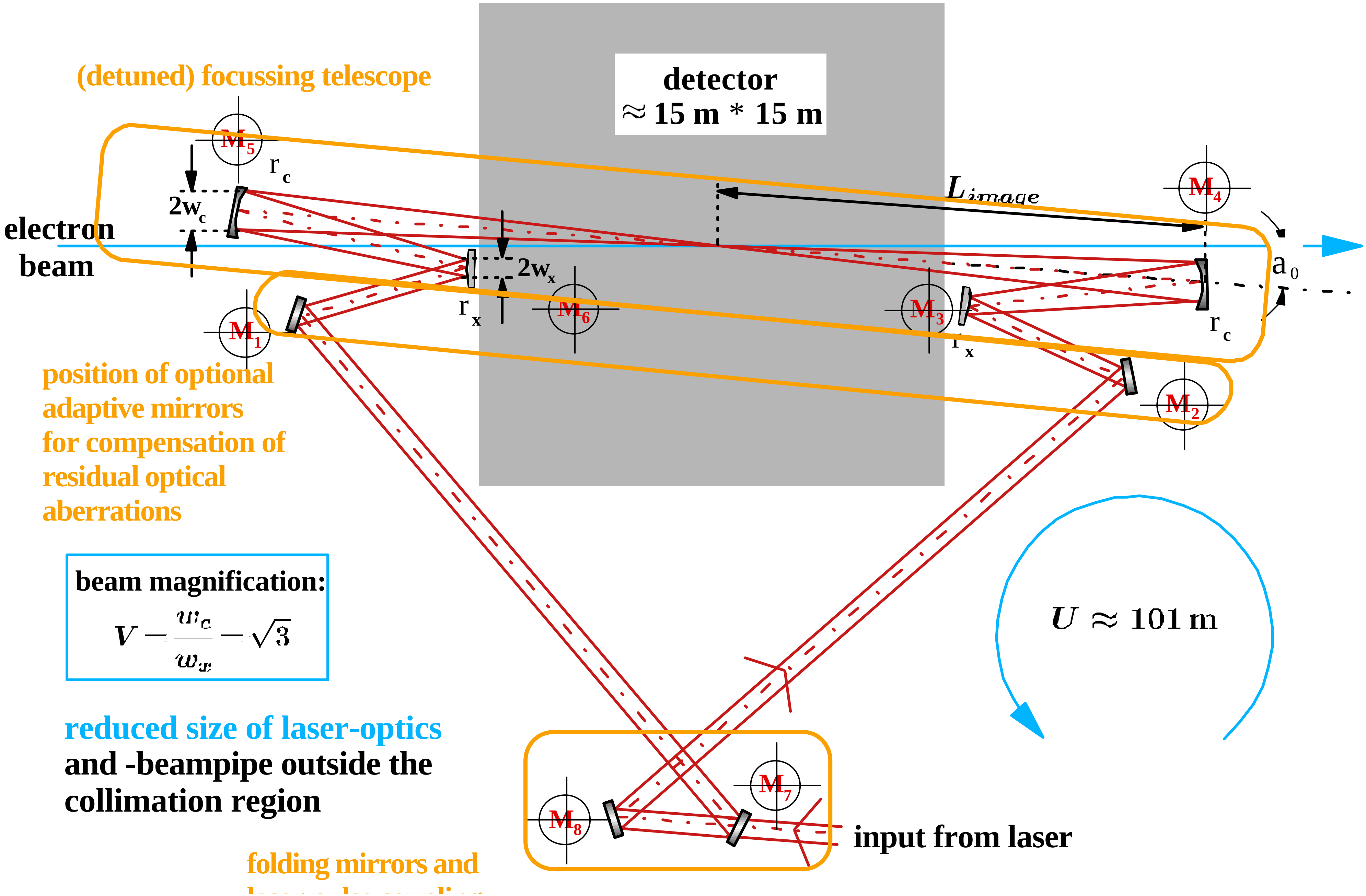
Principles of a cavity

- cavity with N mirrors with reflectivity R_i
- loss per round trip $V = R_2 \cdot R_3 \ldots \cdot R_N \cdot L$ (L = other losses)
- power enhancement of cavity $A = \frac{1-R_1}{(1-\sqrt{R_1 V})^2}$ (R_1 =coupling mirror)
- maximal for $R_1 = V$

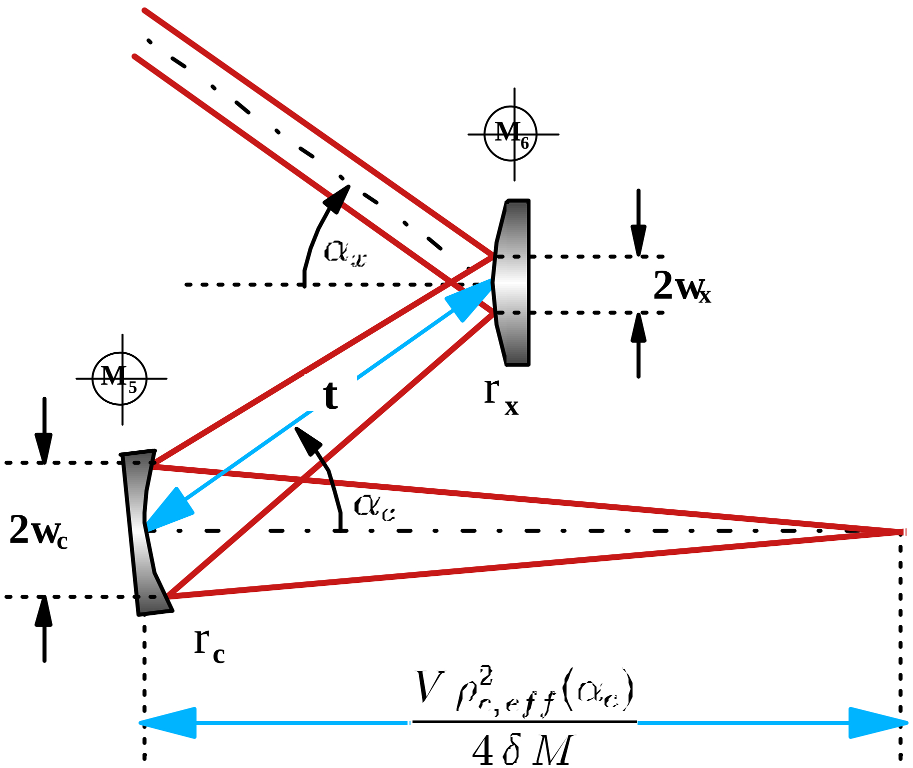


Power enhancement > 100 possible for realistic reflectivities

Present geometry of telescopic, passive, resonant cavity



Aberration-compensated focussing telescope



spherical surfaces:

$$V = \frac{w_c}{w_x} = 2 + \sqrt{5}$$

$$\rho_c = \frac{t}{4} \cdot (1 + \sqrt{5})$$

$$\rho_x = \frac{t}{4} \cdot (1 - \sqrt{5})$$

$$\alpha_x = f(\alpha_c)$$

⇒ **reduced spherical aberration, coma, astigmatism, field curvature**

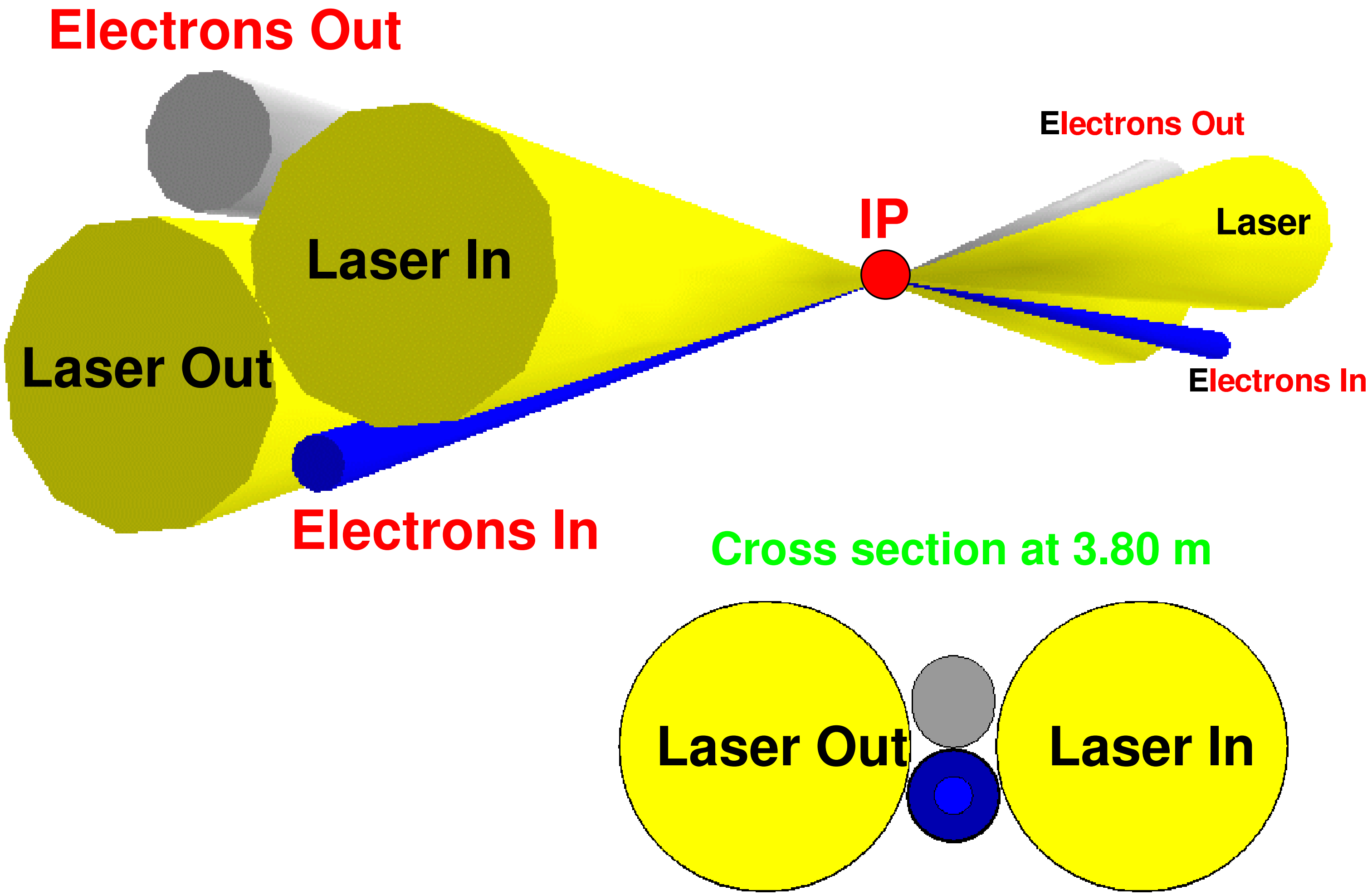
general:

$$t = \frac{\rho_x + \rho_c}{2} + \delta$$

$$M = -\frac{\rho_c}{\rho_x}$$

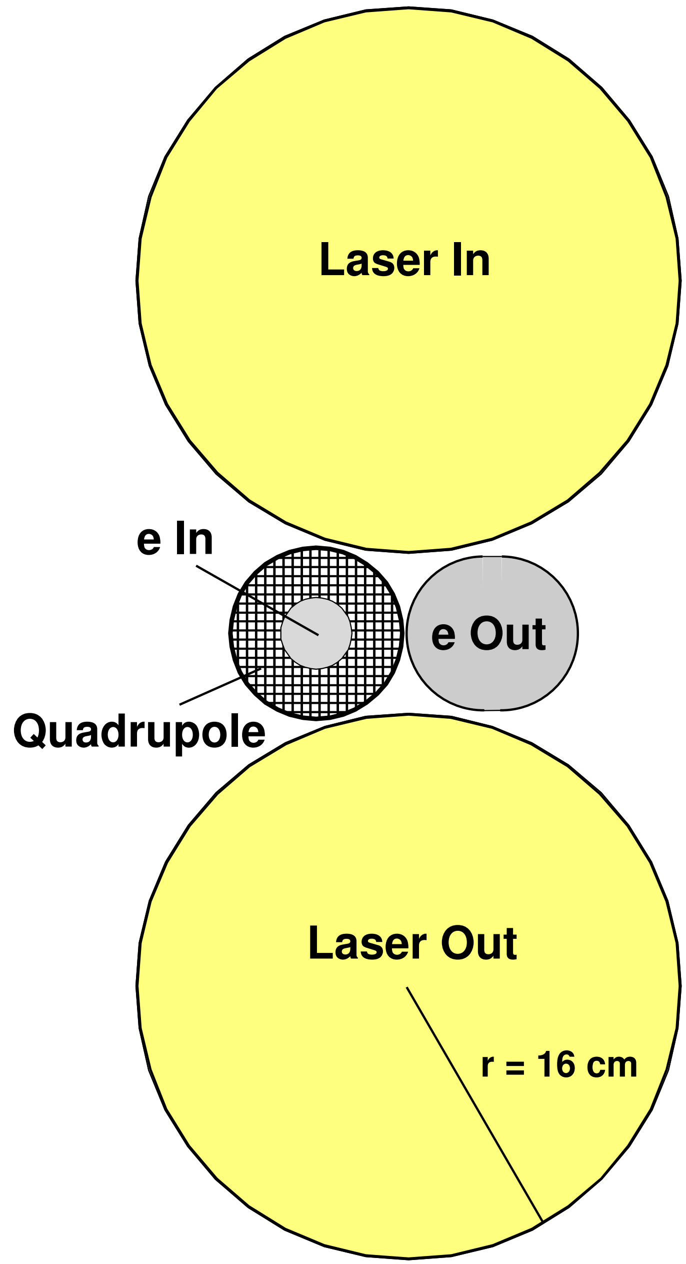
$$V = M - \frac{2\,\delta}{\rho_x}$$

Layout of the Beams

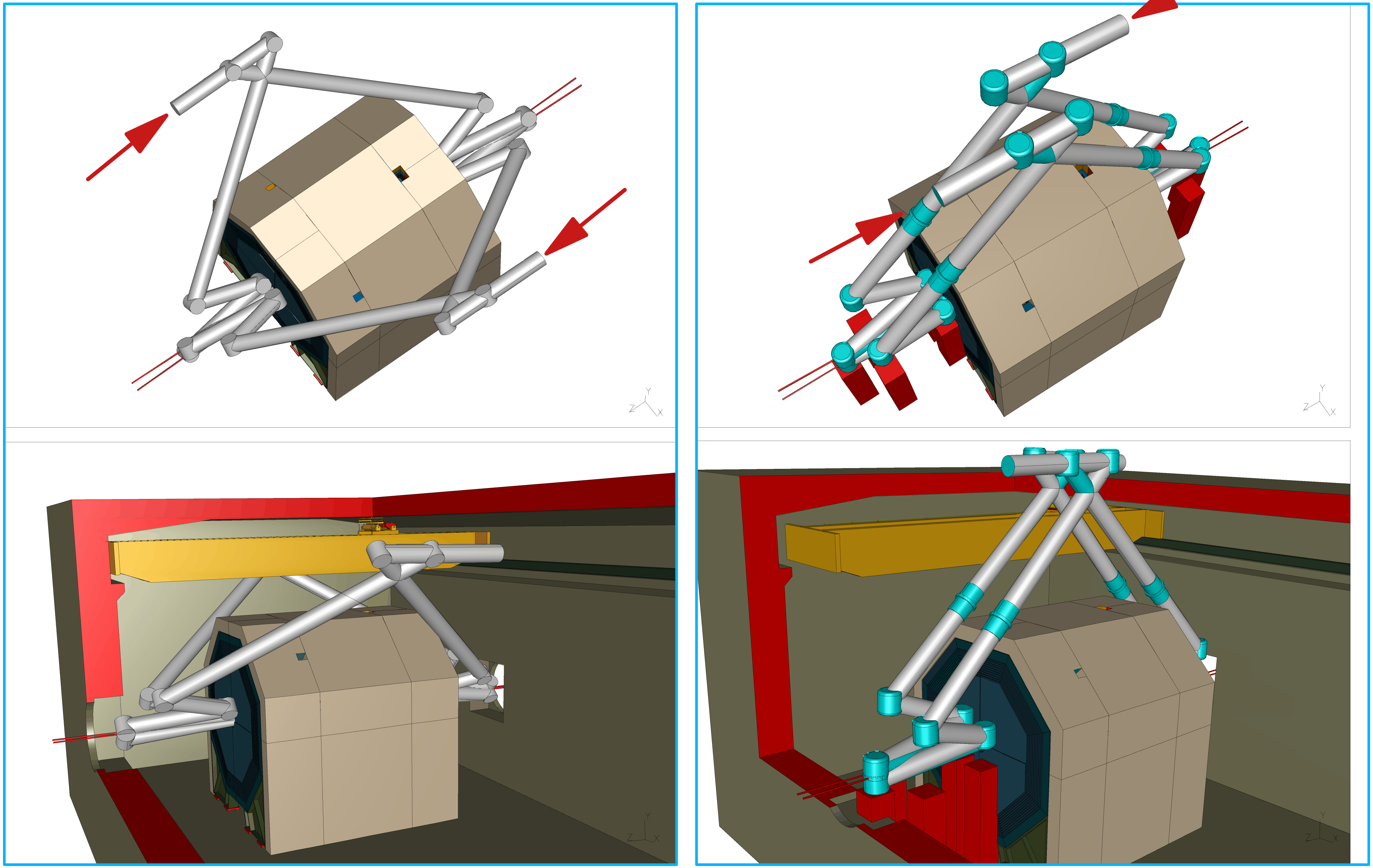


- To have highly efficient mirrors need crossing angle beam-laser
- crossing angle results in smaller conversion probability
- laser divergence and therefore mirror size depends on Rayleigh length
- finite mirrors result in diffraction losses and broadening of the focus
- have to find optimum crossing angle/Rayleigh length

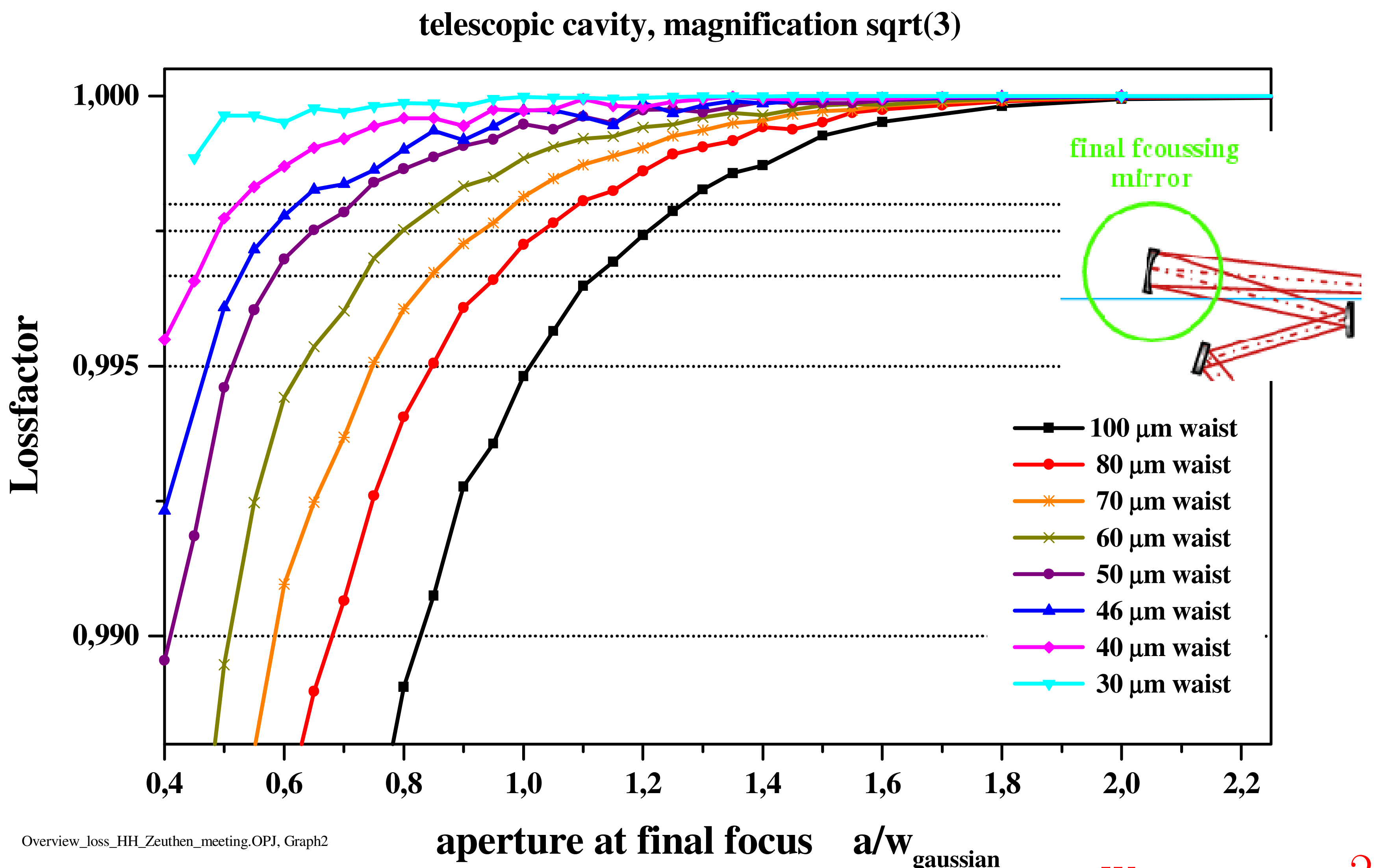
⇒ even higher laser power needed



Folding the cavity around the TESLA detector

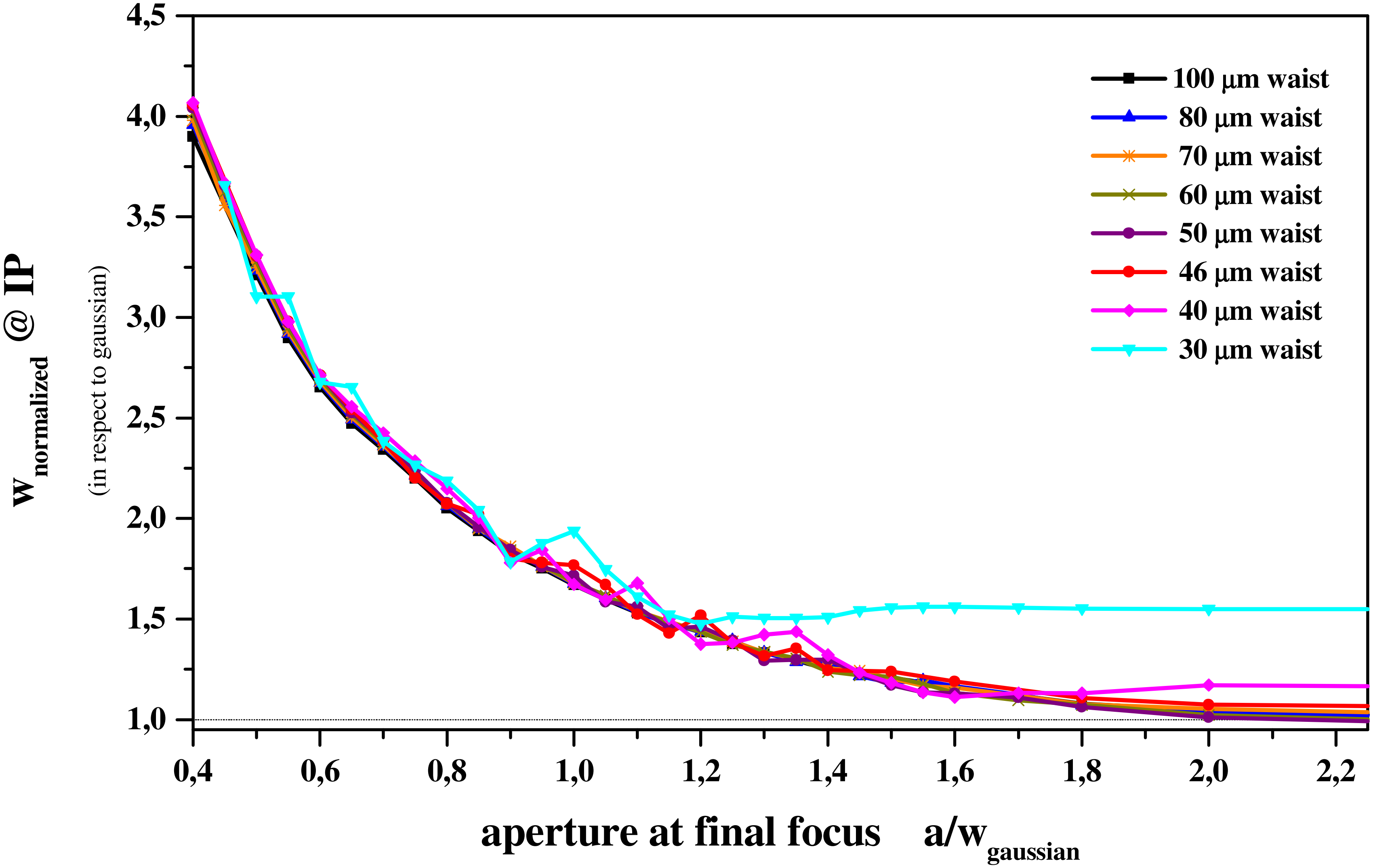


Diffraction losses are small even for small mirrors



$w_{gaussian} = 2\sigma$

However diffraction broadening is serious

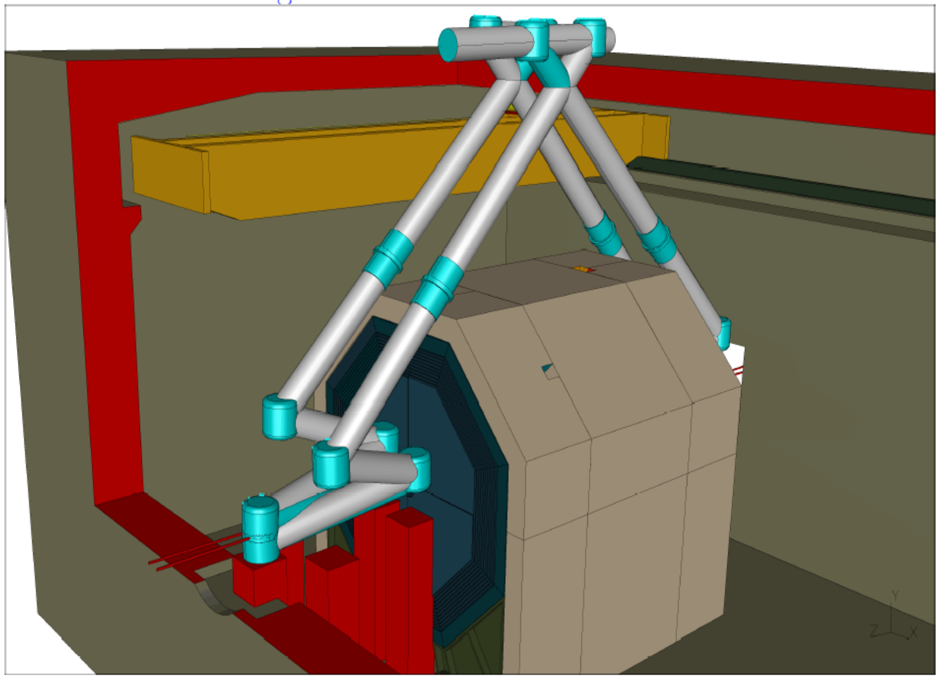


γγ technical work at Zeuthen

Design study for a laser cavity

- a laser cavity with a power enhancement around 100 can decrease the needed laser power by the same amount
- with the TESLA bunch structure the length of the cavity is 100 m and can be mounted around the detector
- to increase the conversion rate and to minimise the dead region the laser-beam crossing angle should be as small as possible
- if the mirrors cut into the laser beam the diffraction losses stay small, however the broadening of the focus is serious

Design of the laser resonator in the hall

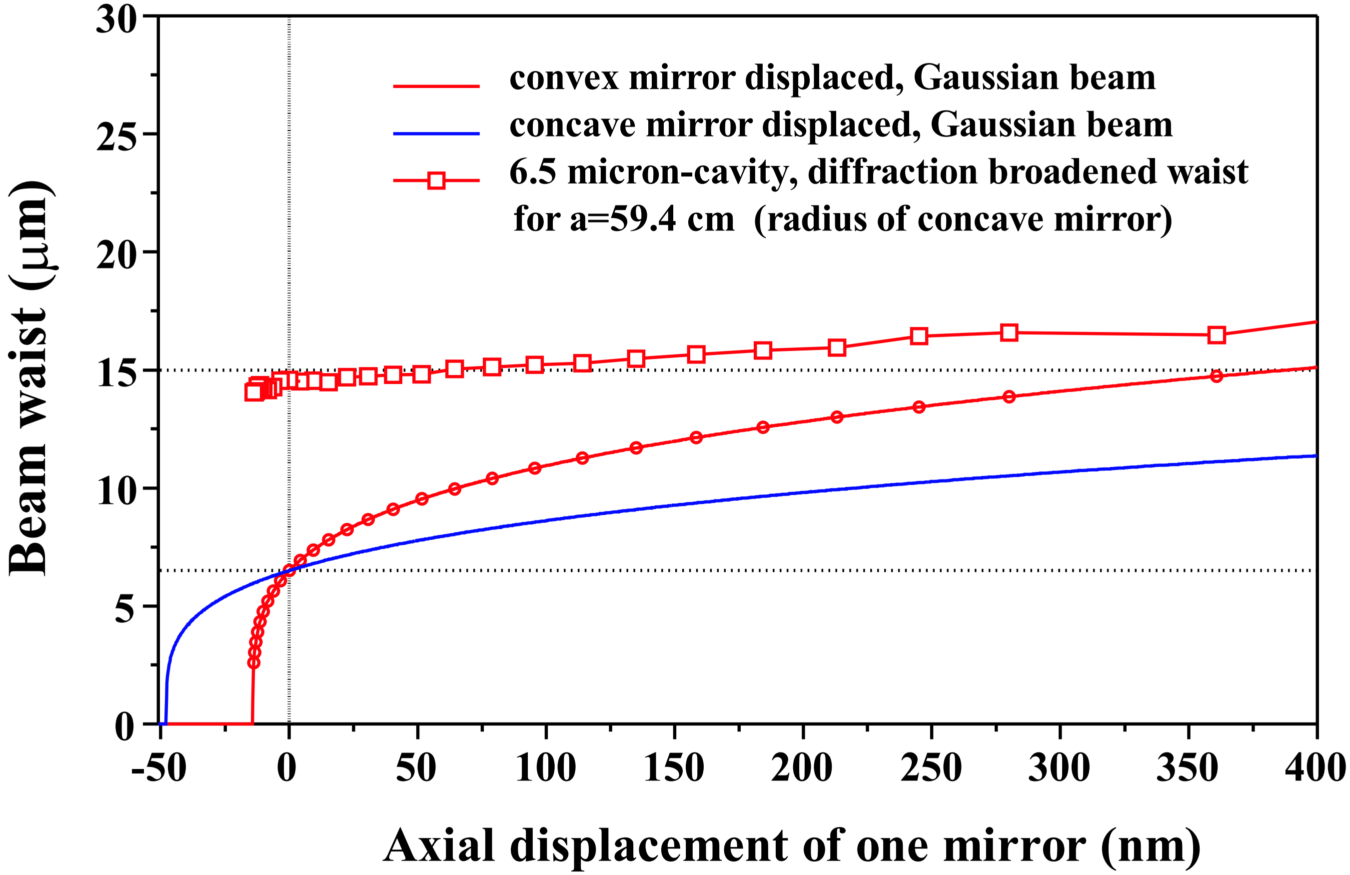


Alignment tolerances

Total length of cavity: $\Delta L \sim 0.3\text{nm}$

Correction procedure understood e.g. from gravitational wave antennas

Misalignment of focusing telescope:



Need precision of $\sim 100\text{nm}$

Conclusions

- No showstoppers found so far
- The laser-cavity seems difficult but possible
- Backgrounds are under control
- However the price to pay is a dead detector below 7.5°
- Neutrons may be a problem for the vertex detector
- If you want the photon collider to become a reality you have to work on the technical issues

The Photon Collider in the LC project

Valery Telnov

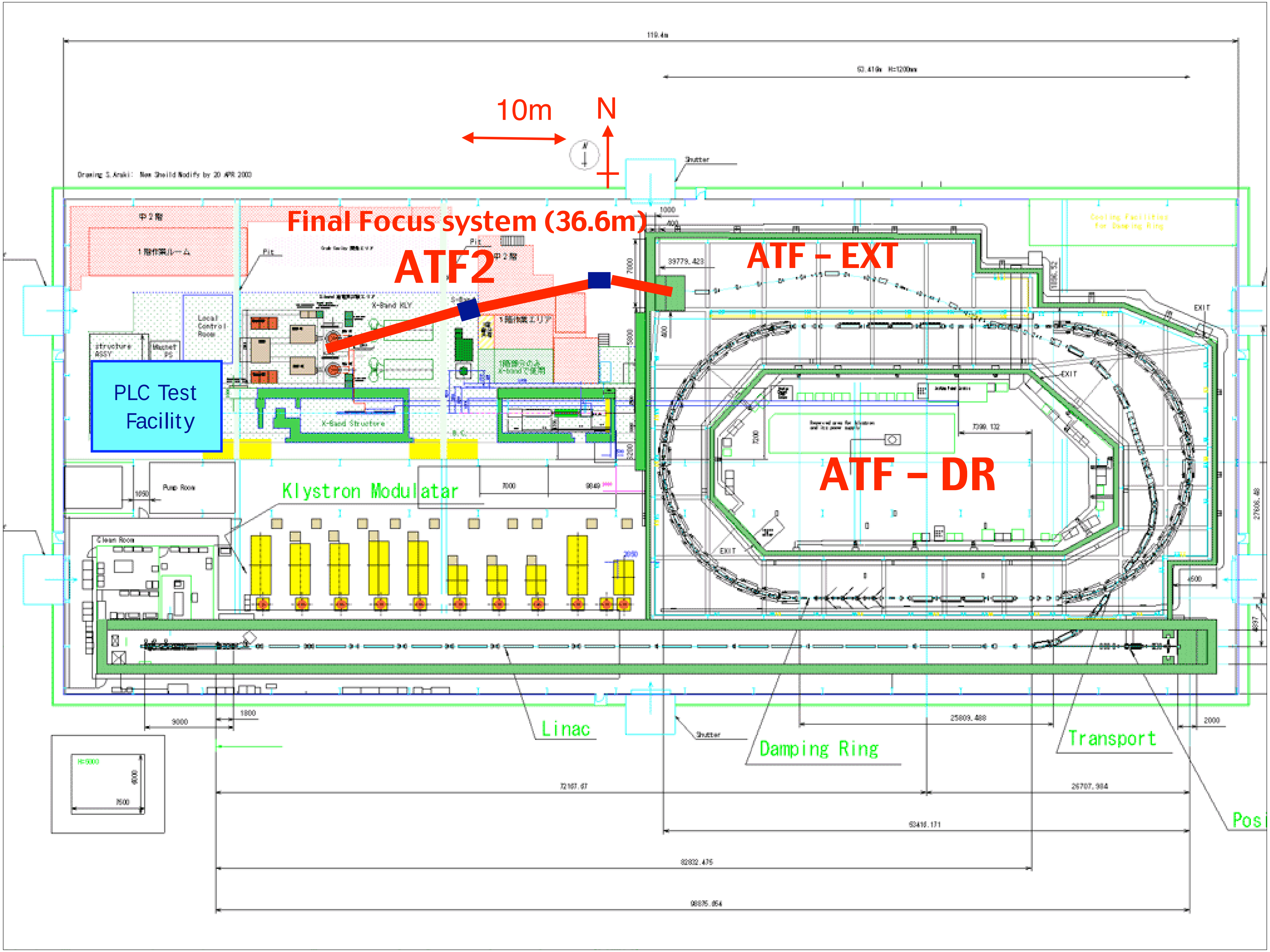
Letter submitted to:

- **International Steering Committee on Linear Colliders**
- **Worldwide Study Organizing Committee**

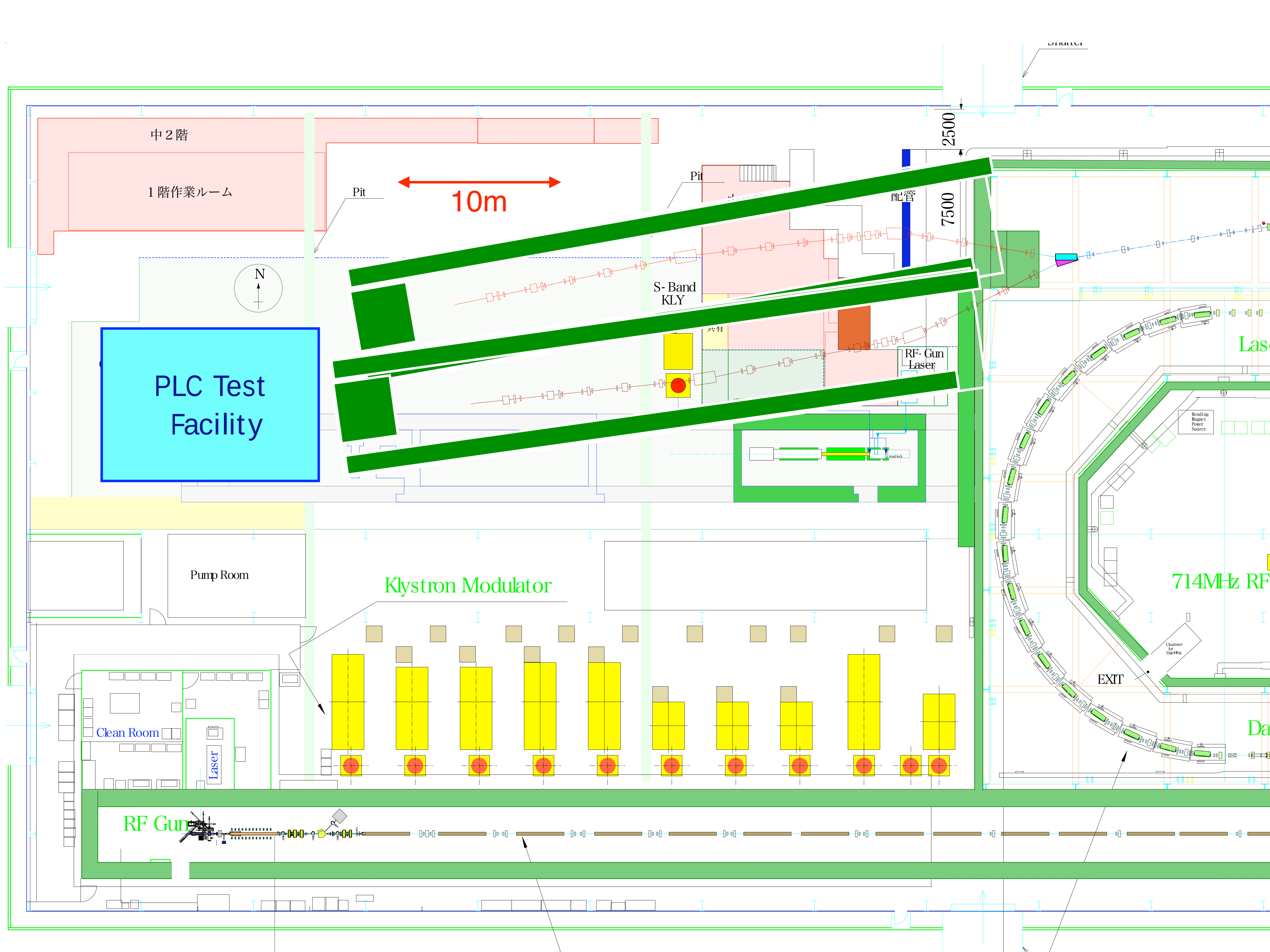
Special requirements for photon collider:

- **Crossing angle > 30 mrad**
- **Horizontal and vertical emittances as small as possible**
- **Spot size at IP as small as possible**
- **Beam dump**
- **Detector design allowing replacement of elements in the forward region**
- **Space for laser lines and housing**

Signed by: J.Gronberg, V.Telnov, T.Takahashi, K.Cheung, A.De Roeck, M.Krawczyk, K.Mönig, M.Velasco



10m
N
Final Focus system (36.6m)
ATF2
ATF – EXT
ATF – DR
PLC Test Facility
Klystron Modulatar
Linac
Damping Ring
Transport
Shutter
Local Control Room
Pump Room
Clean Room
X-Band Structure
X-Band KLY
Cooling Facilities for Damping Ring
EXIT
119.4m
53.416m H=1200mm
Drawing S.Araki: New Sheild Modify by 20 APR 2003



中２階
1 階作業ルーム
Pit
10m
Pit
配管
2500
7500
N
S- Band
KLY
RF- Gun
Laser
PLC Test
Facility
Pump Room
Klystron Modulator
Clean Room
Laser
RF Gun
714MHz RF
EXIT

Schedule

2005.2 optics design (Local correction, S.Kuroda)

2005.3 “international” proposal with ILC-WG4

2005.4 construction starts

2007.3 completion

2007.4-6 achievement of $\sigma_y^* = 37$nm

- 2008 nanometer stabilization of final quadrupole

2009-α PLC test facility

strong QED experiments