A Photon Collider at TESLA, how does it work?

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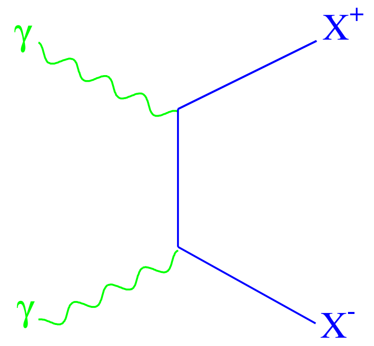
- Physics motivation
- Basic idea
- Compton scattering
- Non linear effects
- Beam issues
- Laser issues
- Background and luminosity
- Conclusions

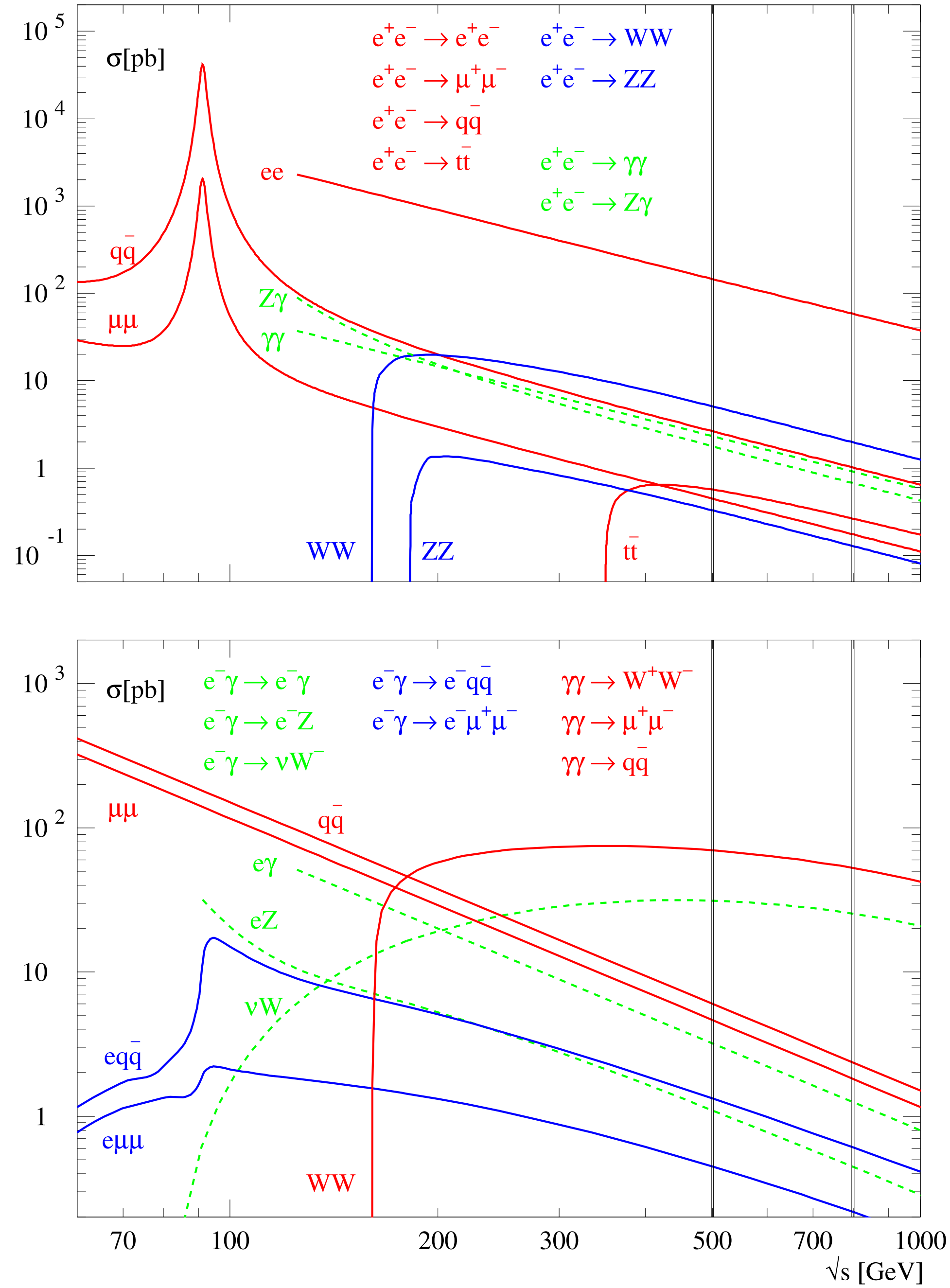
Physics motivation

Charged particle production

- Basic production process



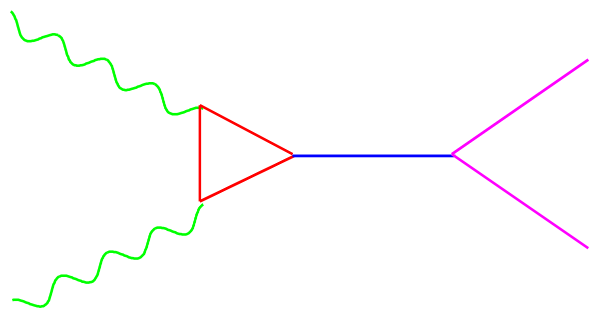
- Cross sections typically larger than in e^+e^- $\rightarrow$ plot
- Production mechanism very simple (no γZ or ST interference)
- Example $\gamma\gamma \rightarrow W^+W^-$
  - cross section factor 10 larger than in e^+e^-
  - only diagram with triple gauge coupling
  - ➡ should be very sensitive to triple gauge coupling
  - However e^+e^- equally sensitive due to gauge cancellations



σ[pb]
e+e− → e+e−
e+e− → μ+μ−
e+e− → qq̄
e+e− → tt̄
e+e− → WW
e+e− → ZZ
e+e− → γγ
e+e− → Zγ
ee
qq̄
μμ
Zγ
γγ
WW
ZZ
tt̄
σ[pb]
e−γ → e−γ
e−γ → e−Z
e−γ → νW−
e−γ → e−qq̄
e−γ → e−μ+μ−
γγ → W+W−
γγ → μ+μ−
γγ → qq̄
μμ
qq̄
eγ
eZ
νW
eqq̄
eμμ
WW
√s [GeV]

Higgs Physics

- Higgs produced via loop diagram



➠ all heavy charged particles contribute (W, t, new physics)
➠ cross section very interesting in itself

- expect $\mathcal{O}(10000)$ events for $m_{\mathrm{h}} \sim 120\,\mathrm{GeV}$
- heavy SUSY Higgses in $\mathrm{e^+e^-}$ pair produced
  $\rightarrow$ mass reach $\sim 0.5\sqrt{s}$
  in $\gamma\gamma$ single production possible
  $\rightarrow$ mass reach $\sim 0.8\sqrt{s}$
- Access to CP structure with linear photon polarisation

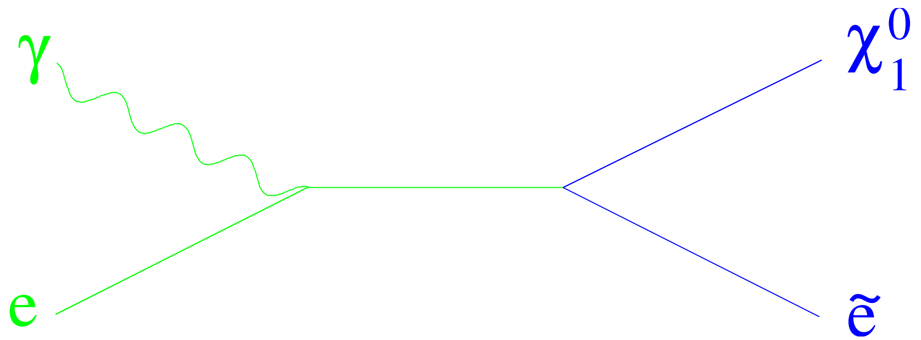
SUSY:

In general profit from large cross section for charged particles

➠ Branching ratio measurements?

Possible discovery channel:

e$\gamma \rightarrow \tilde{e}\chi_1^0$ if $\tilde{e} - \chi_1^0$ mass difference is large



(e$\gamma \rightarrow \nu W$ background?)

Physics and Polarisation

Circular polarisation in $\gamma\gamma$

- Helicity suppression: $\sigma(\gamma\gamma \rightarrow \mathrm{f\bar{f}}) \propto \frac{m^2}{s}$ for J=0
- Higgs production requires J=0
- TGC sensitivity in $\gamma\gamma \rightarrow \mathrm{W^+W^-}$ better for J=2

Linear polarisation in $\gamma\gamma$:

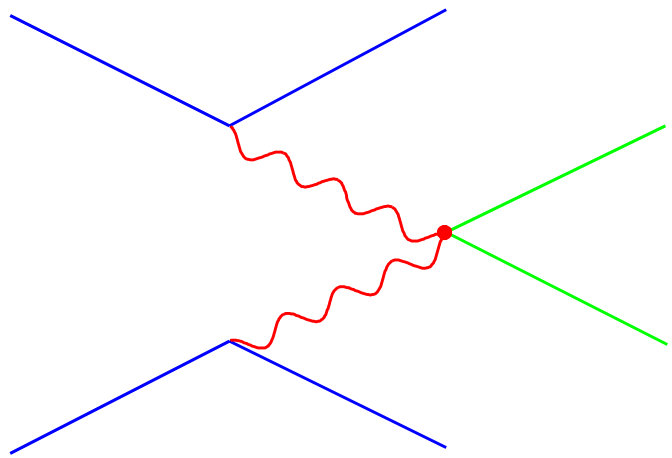
- Production of CP even particle: $\sigma \propto \vec{\varepsilon_1} \cdot \vec{\varepsilon_2}$
- Production of CP odd particle: $\sigma \propto [\vec{\varepsilon_1} \times \vec{\varepsilon_2}] \cdot \vec{k_\gamma}$

Circular polarisation in eγ:

- electron s-channel exchange only for J=1/2
- eW coupling only for left handed electrons

The basic idea

$\gamma\gamma$ physics in the past:

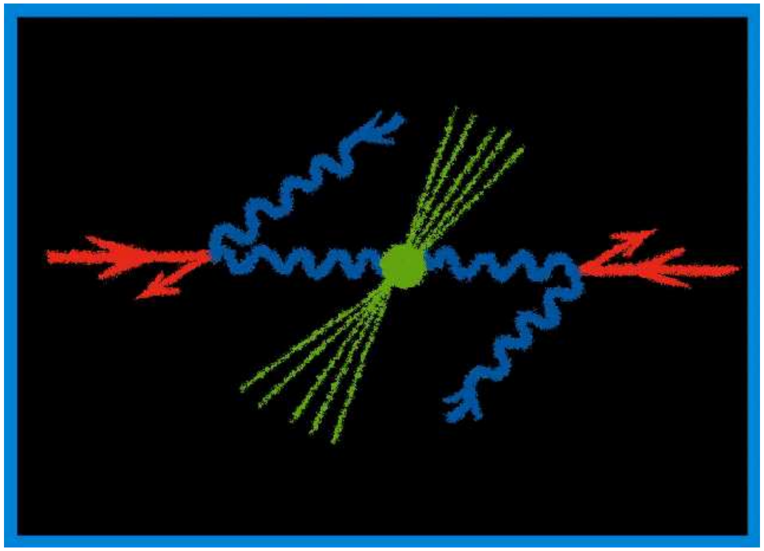


- only "used" electrons are lost
- however photon flux peaks at low energy
- mainly useful for QCD studies

Linear collider

- electrons are used only once

➠ can "convert" electrons to high energy γs
$\Rightarrow$ Compton scattering



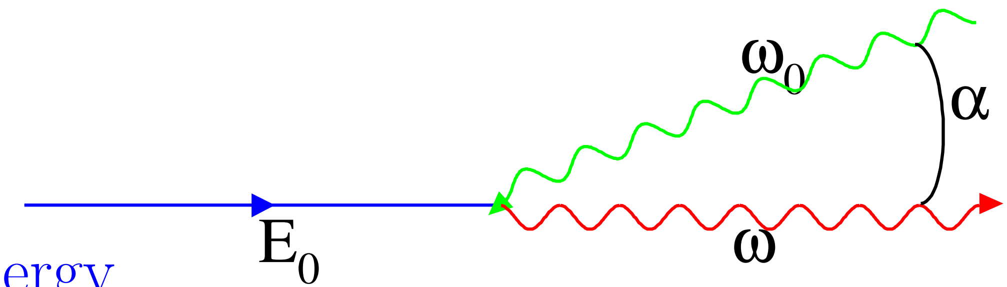
- high energy photons follow e-direction

➧ focusing as in e^+e^-

Run in e^-e^- mode:

- easier to achieve low emittance
- easier to reach high polarisation
- less disturbing background in e^-e^- interactions than in e^+e^-
- less beamstrahlung in e^-e^- than in e^+e^-

Compton scattering



Maximum γ energy

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

with

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

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

Differential Compton cross section:

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

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

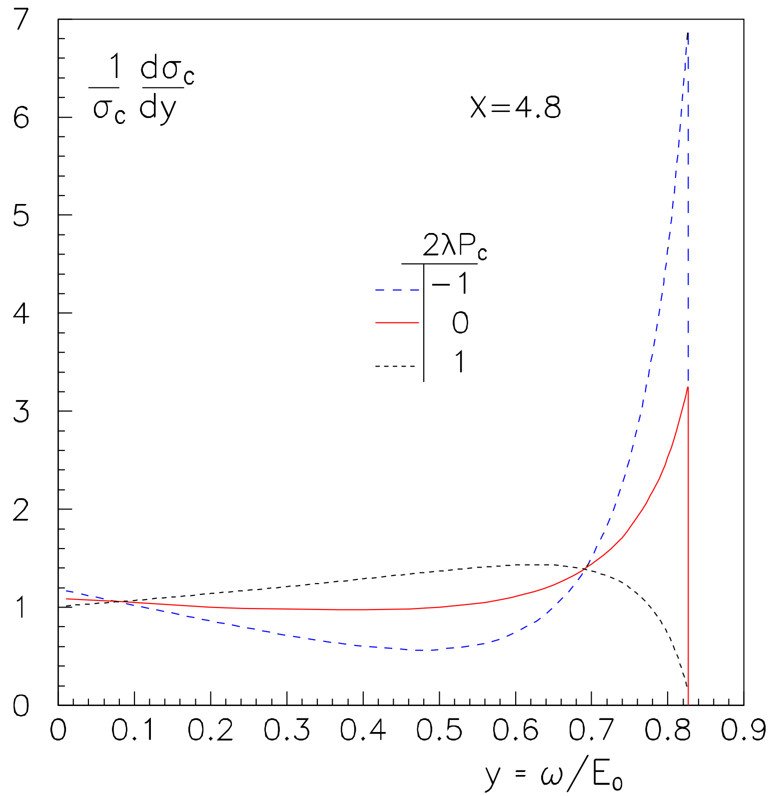
λ_e: e-helicity, P_c: circular laser polarisation

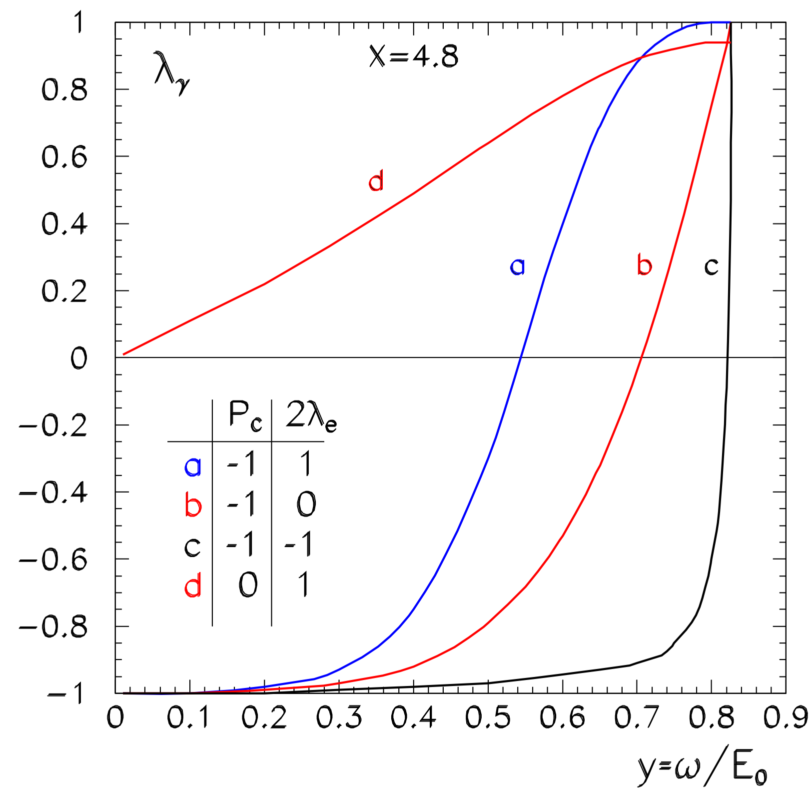
Cross section depends on helicity product $2\lambda_e P_c$

Mean helicity of scattered photons:

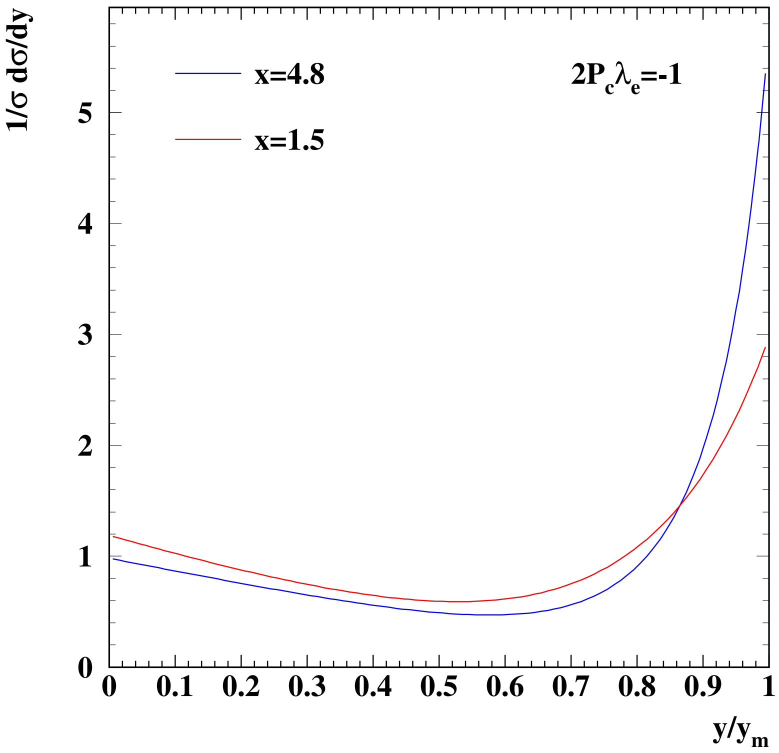
$$\langle\lambda_\gamma\rangle = \frac{-P_c(2r-1)[(1-y)^{-1}+1-y]+2\lambda_e xr[1+(1-y)(2r-1)^2]}{(1-y)^{-1}+1-y-4r(1-r)-2\lambda_e P_c xr(2-y)(2r-1)}$$

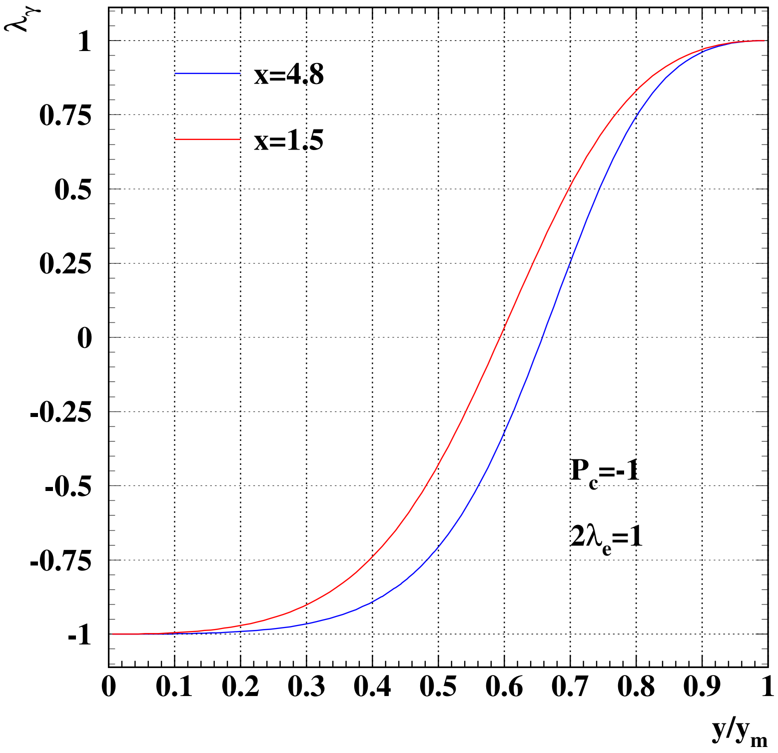
Differential Compton cross section and mean circular polarisation:



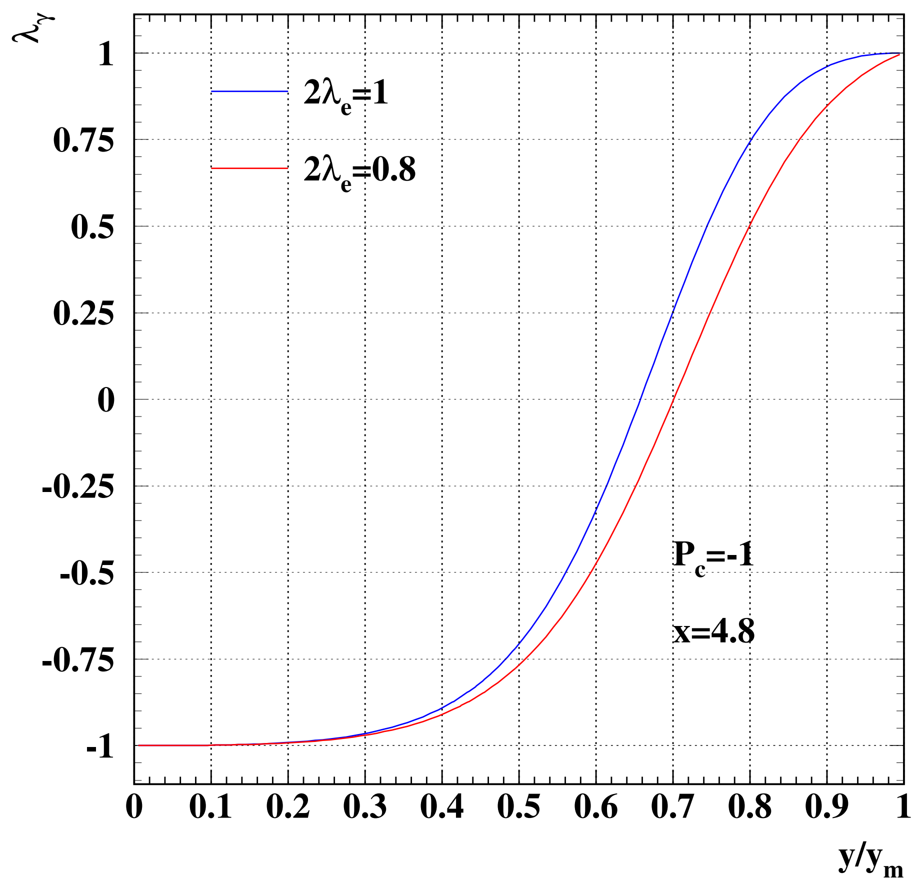


$x < 4.8$ makes spectrum less peaked with little effect on polarisation





For realistic electron polarisation photon polarisation varies rapidly at $y < y_{\max}$

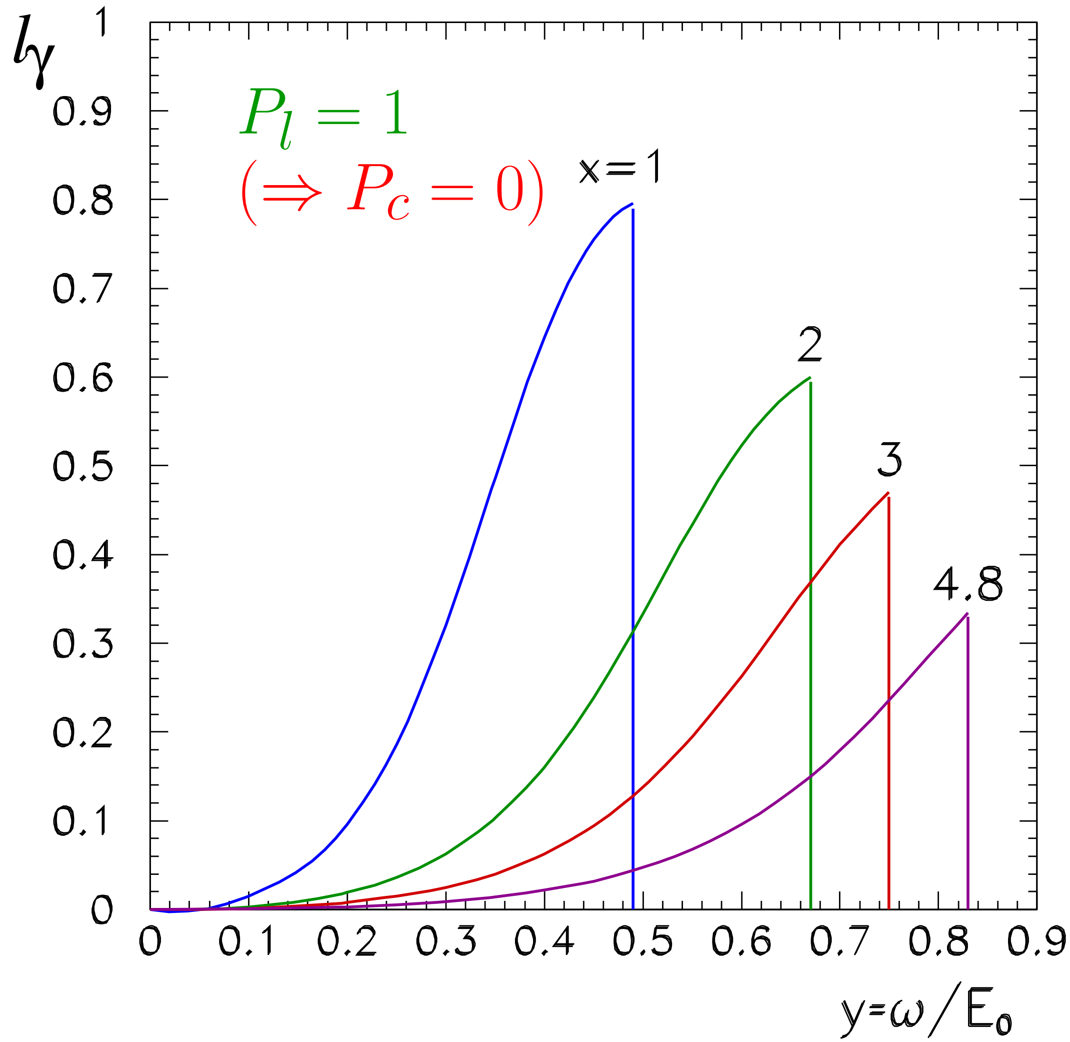


Linear polarisation

Why?

e.g. CP-studies of Higgses

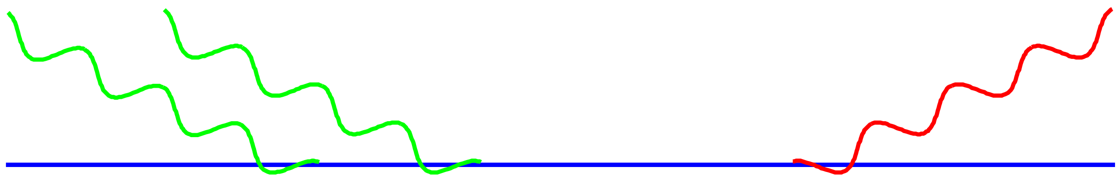
- CP even: $\sigma \propto \vec{\varepsilon_1} \cdot \vec{\varepsilon_2}$
- CP odd: $\sigma \propto [\vec{\varepsilon_1} \times \vec{\varepsilon_2}] \cdot \vec{k_\gamma}$
- Linear beam polarisation possible with linear laser polarisation
- High linear polarisation can only be reached with small x!



$$\langle l_\gamma \rangle = \frac{2r^2 \, P_l}{(1-y)^{-1} + 1 - y - 4r(1-r) - 2\lambda_e P_c x r (2-y)(2r-1)}$$

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

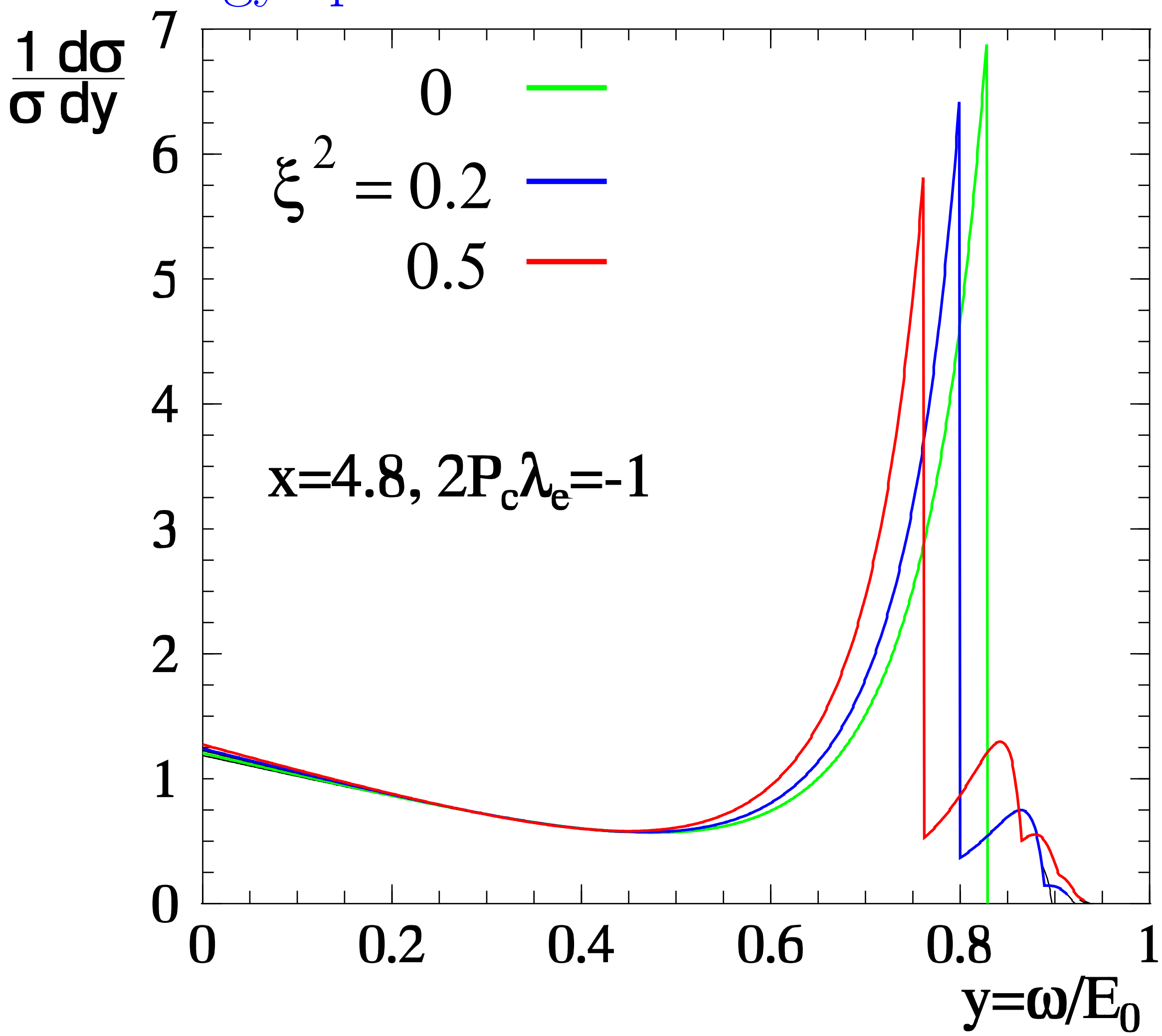
Non linear effects:

- 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



The Beam

Luminosity:

$$\mathcal{L} = f_{rep} \frac{N^2}{4\pi\sigma_x\sigma_y}$$

Beamstrahlung:

$$\delta_b \propto \frac{1}{\sigma_x + \sigma_y}$$

$\Rightarrow$ need flat beams!

$\gamma\gamma$:

- BS only relevant for pair background
- BS only created from unconverted electrons
- BS in e^-e^- is less than in e^+e^-

$\Rightarrow$ Can work with "rounder" beam in $\gamma\gamma$ than in e^+e^-

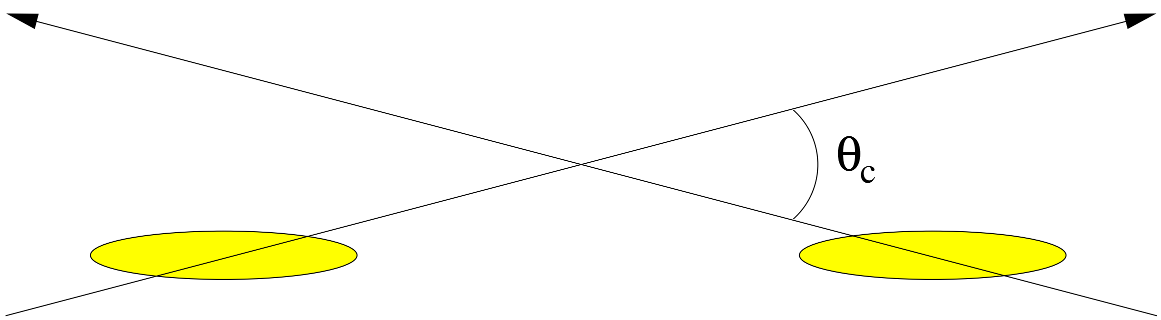
Crab crossing:

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

Beam parameters for $\sqrt{s_{ee}} = 500\,\text{GeV}$

	e^+e^-	$\gamma\gamma$	$\gamma\gamma$ (optimistic)
$N/10^{10}$	2	2	2
σ_z [mm]	0.3	0.3	0.3
pulses/train	2820	2820	2820
Repetition rate [Hz]	5	5	5
$\gamma\epsilon_{x/y}/10^{-6}$ [m·rad]	10./0.03	3./0.03	2.5/0.03
$\beta_{x/y}$ [mm] at IP	15/0.4	4/0.4	1.5/0.3
$\sigma_{x/y}$ [nm]	553/5	157/5	88/4.3
$\mathcal{L}(z > 0.8z_m)$ [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	3.4	0.6	1.1

The Laser

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

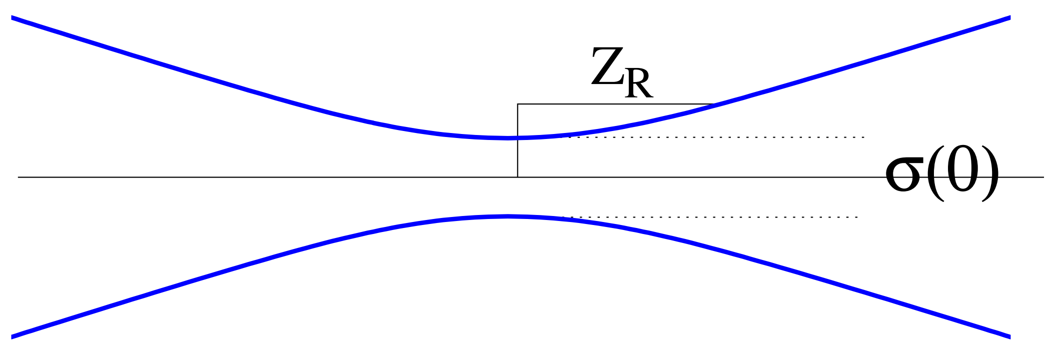
($x = 4.5$ for $\sqrt{s} = 500\,\mathrm{GeV}$)

(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

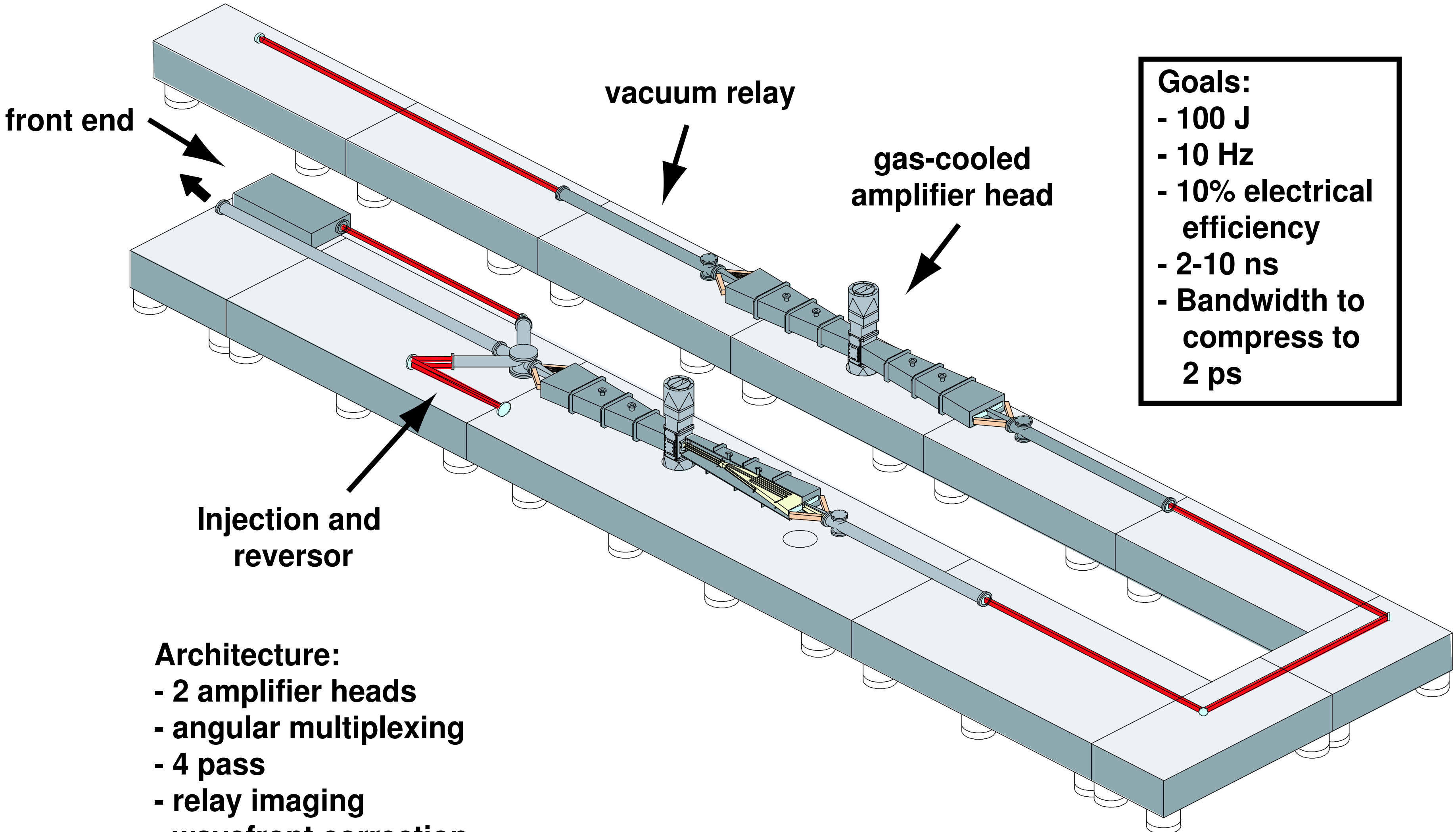
For $Z_R \approx \sigma_z$ and head on laser-beam collisions:

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

$\Rightarrow$ 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

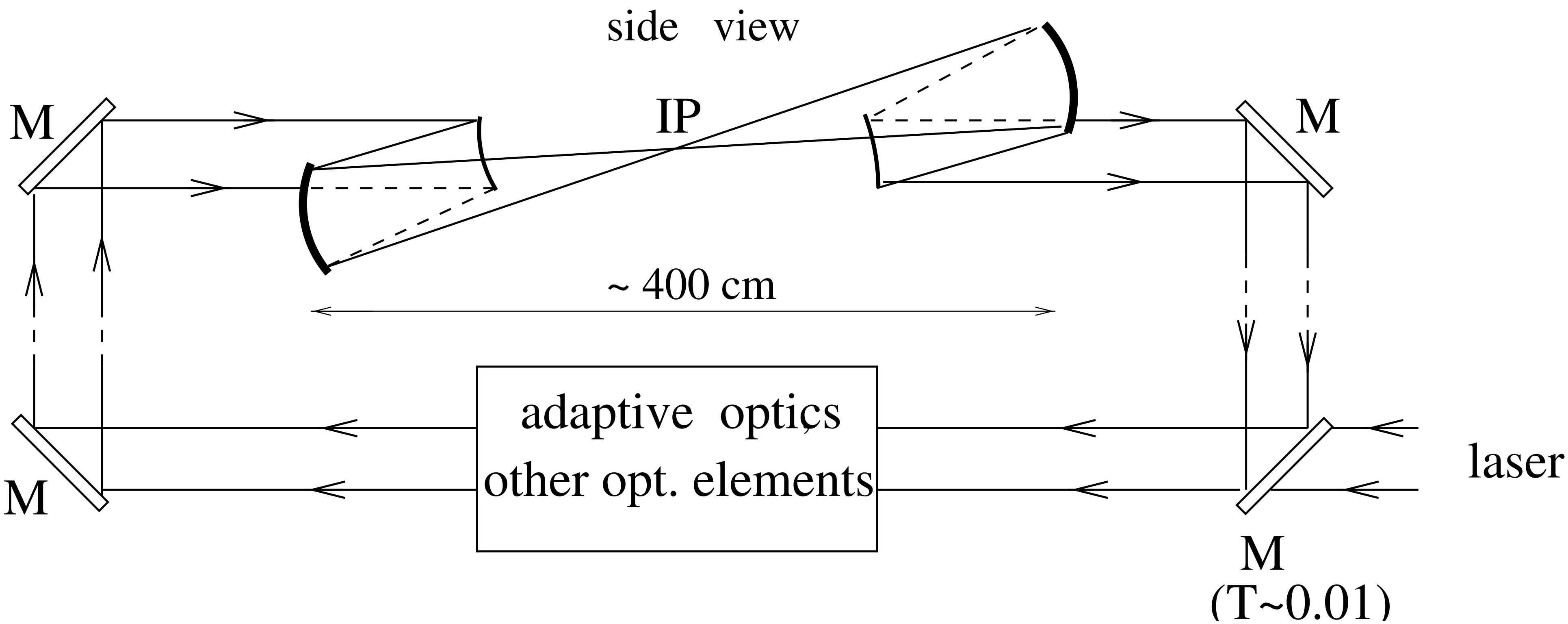


Goals:
- 100 J
- 10 Hz
- 10% electrical efficiency
- 2-10 ns
- Bandwidth to compress to 2 ps

Architecture:
- 2 amplifier heads
- angular multiplexing
- 4 pass
- relay imaging
- wavefront correction

However the number of used laser photons is negligible

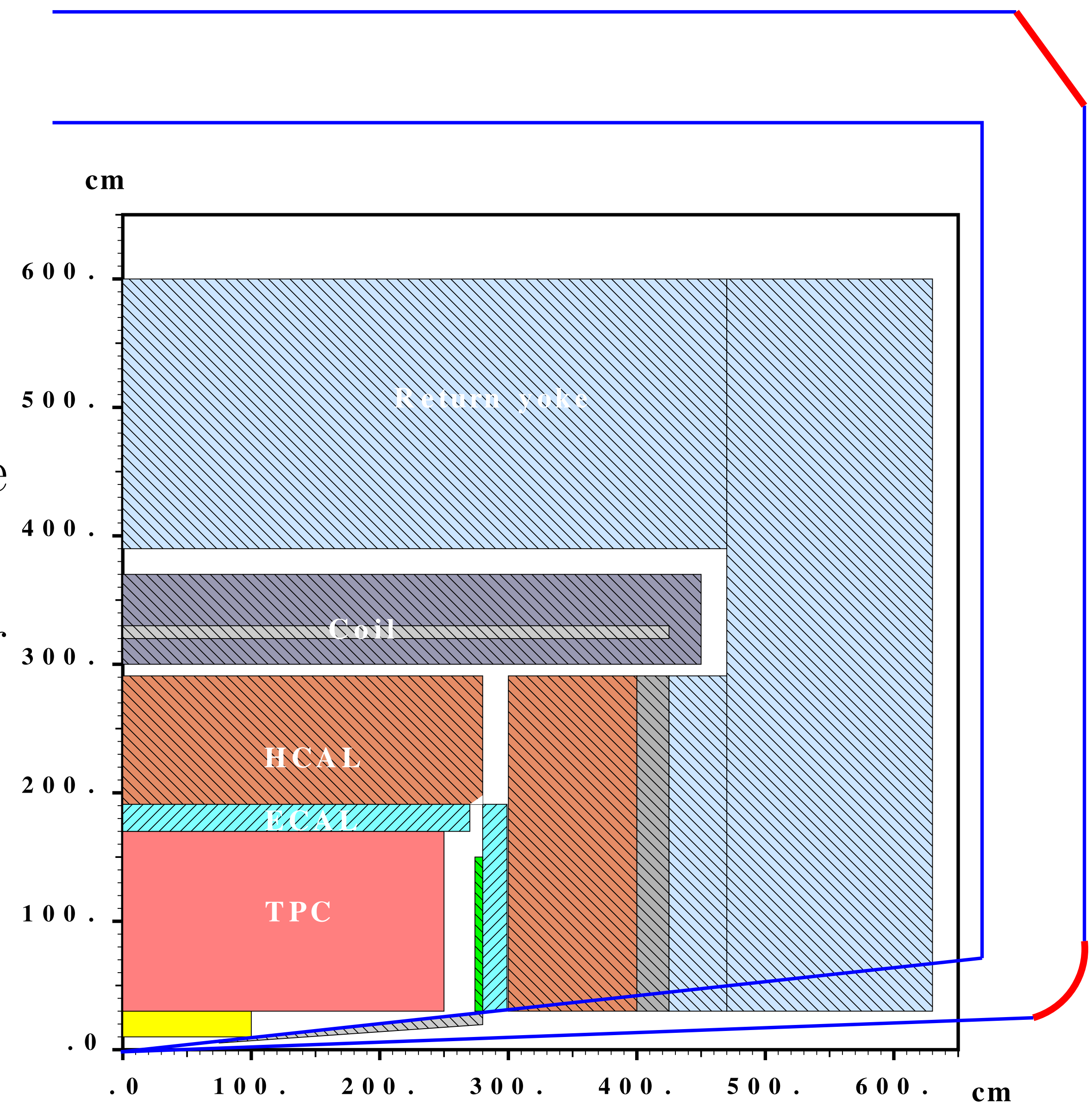
Better idea: recycle laser pulses



Bunch spacing at TESLA $\approx$ 300ns $\Rightarrow$ cavity length $\approx$ 100 m

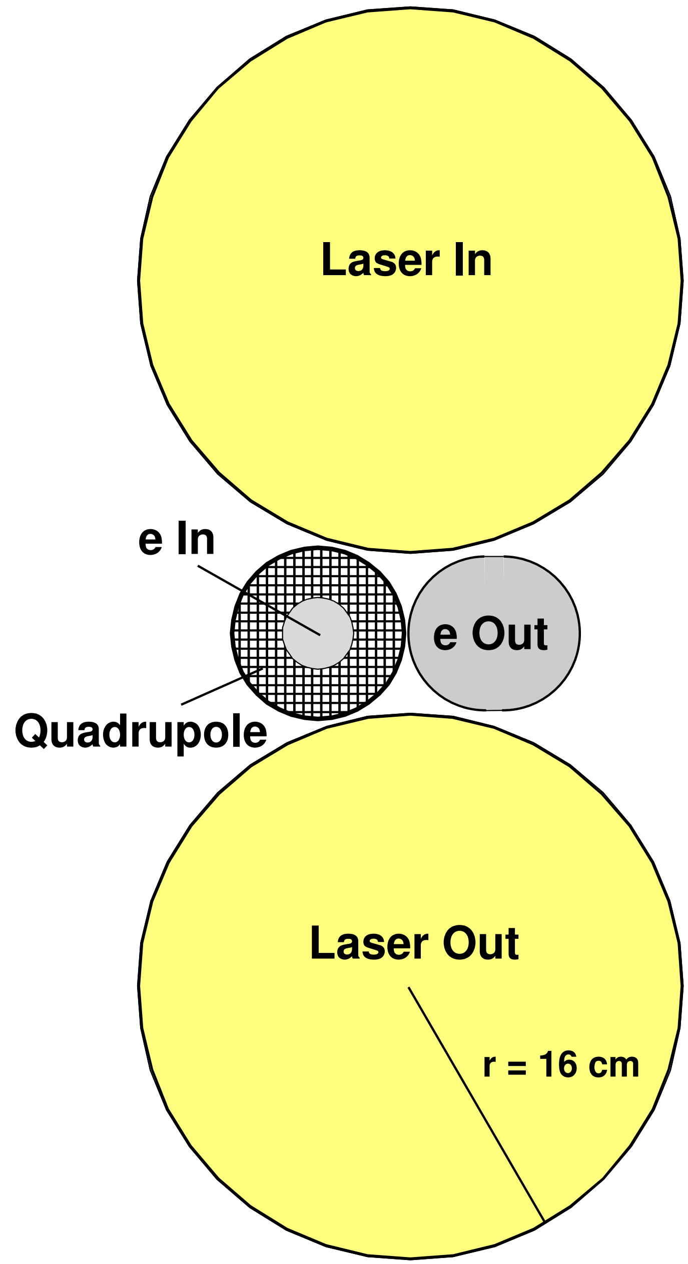
Basic idea:

- cavity mounted around the detector
- all mirrors outside detector

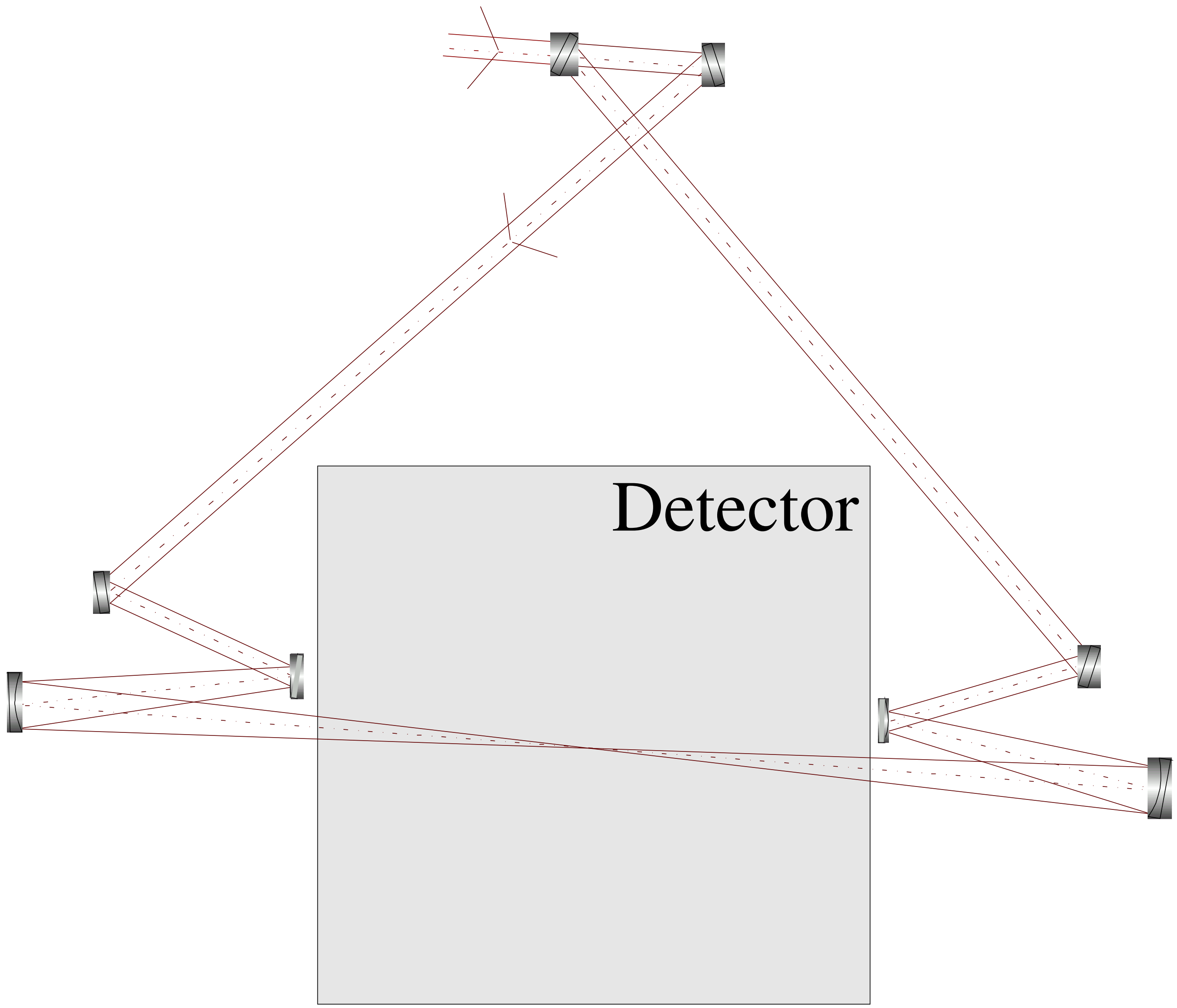


- To have highly efficient mirrors need crossing angle beam-laser
- crossing angle results in smaller conversion probability
- laser divergence and therefore mirror size depends on Rayleigh length
- finite mirrors result in diffraction losses and broadening of the focus
- have to find optimum crossing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

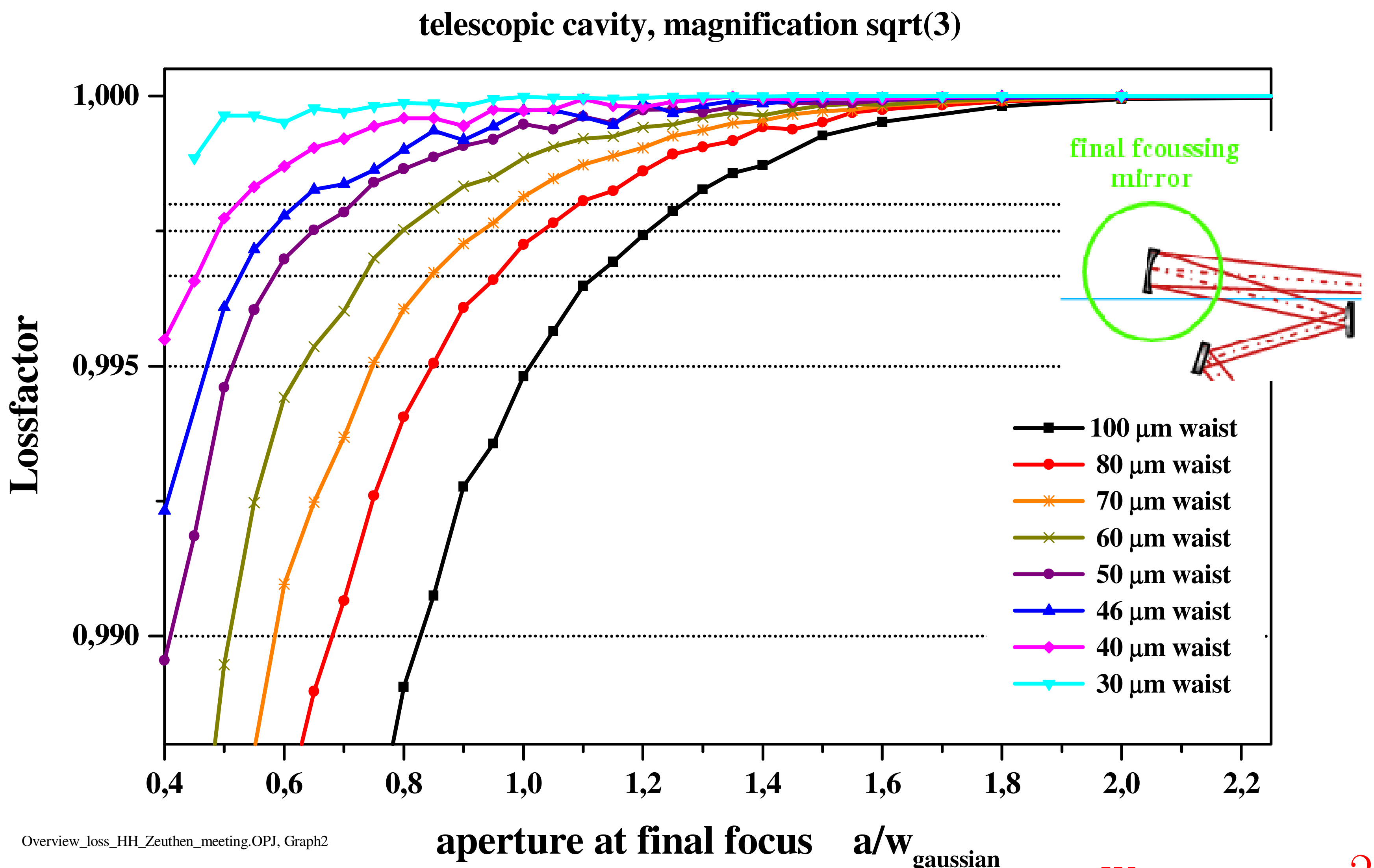
⇒ even higher laser power needed



Layout of the cavity

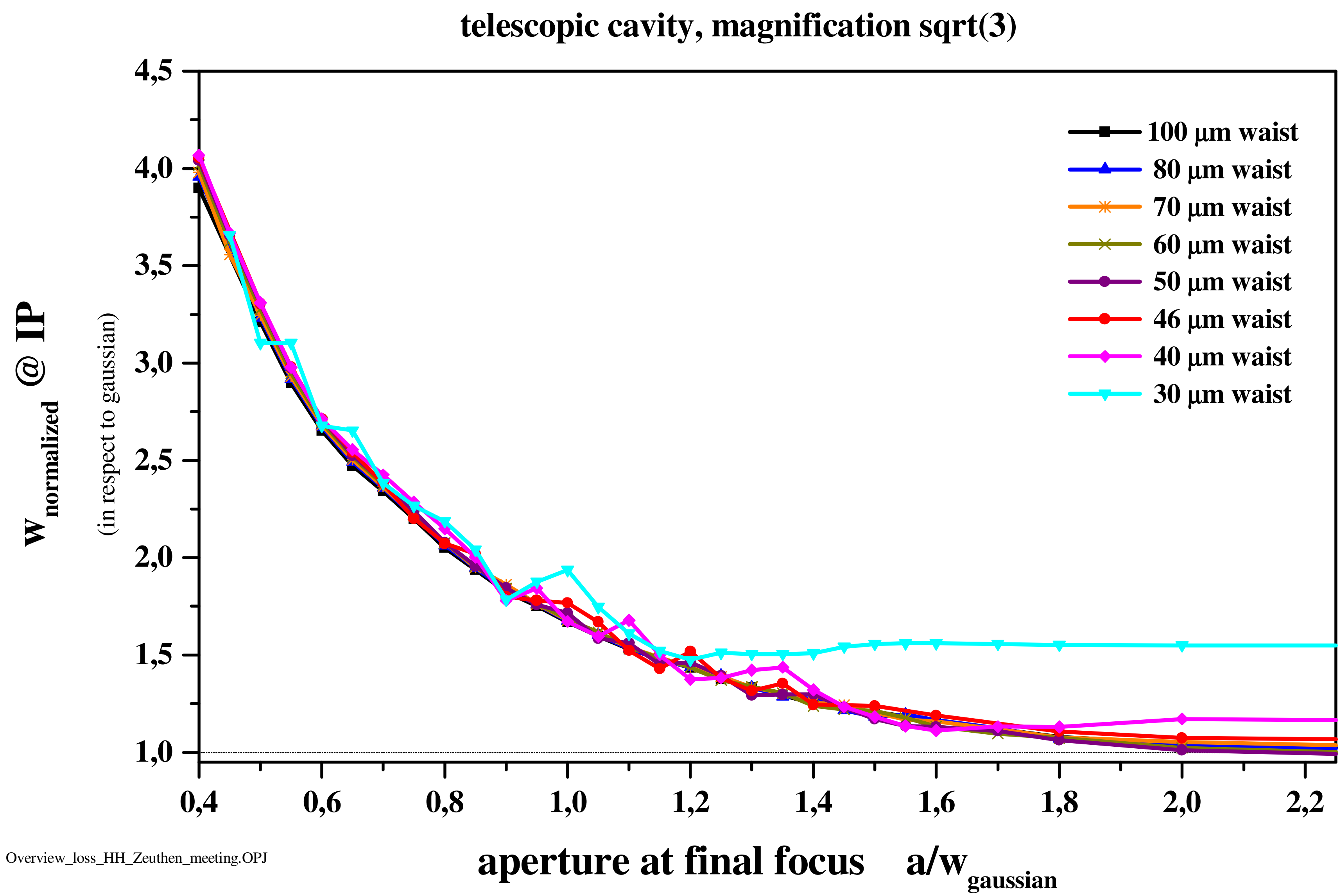


Diffraction losses are small even for small mirrors

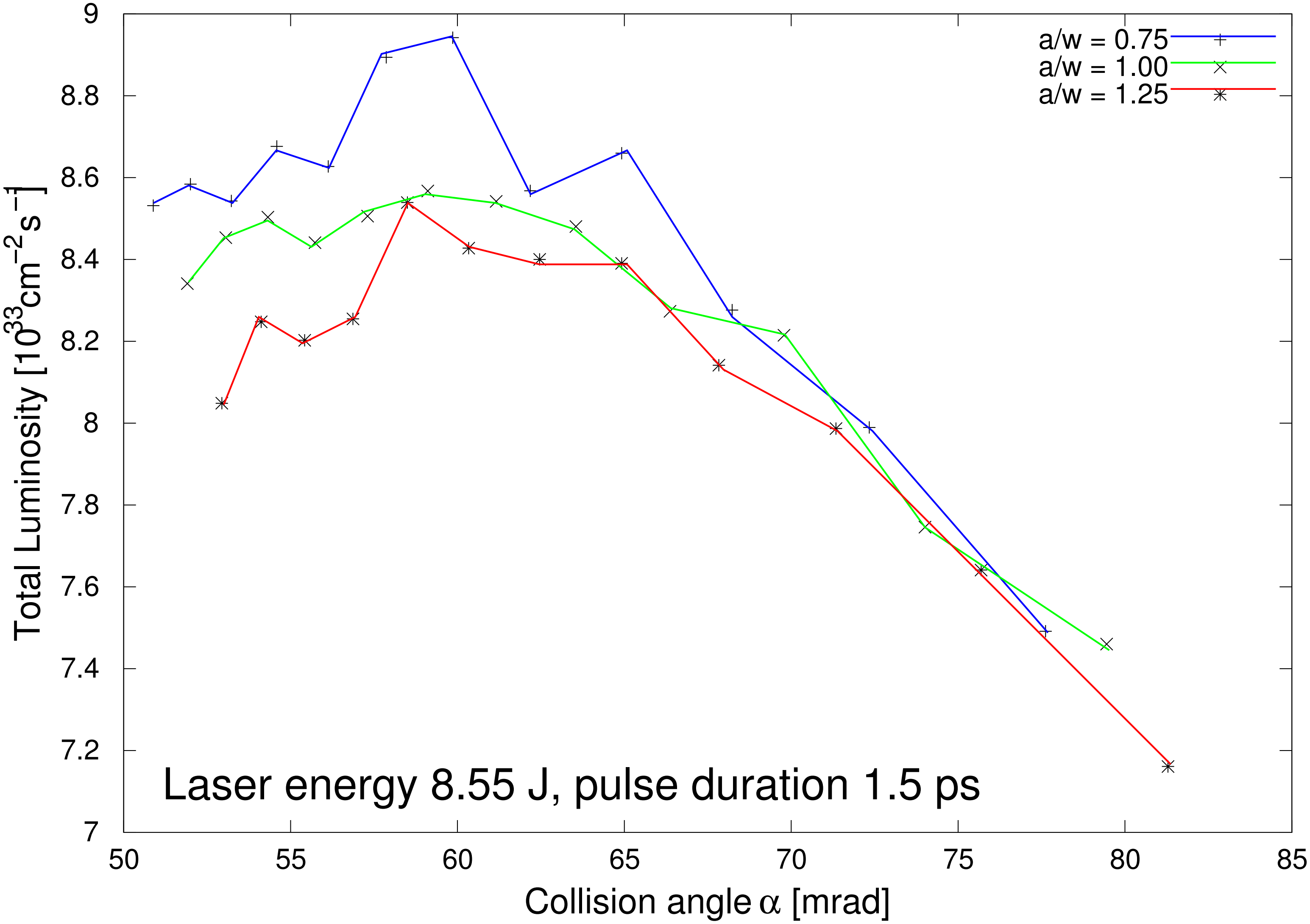


$w_{gaussian} = 2\sigma$

However diffraction broadening is serious



Optimum for relatively small mirrors



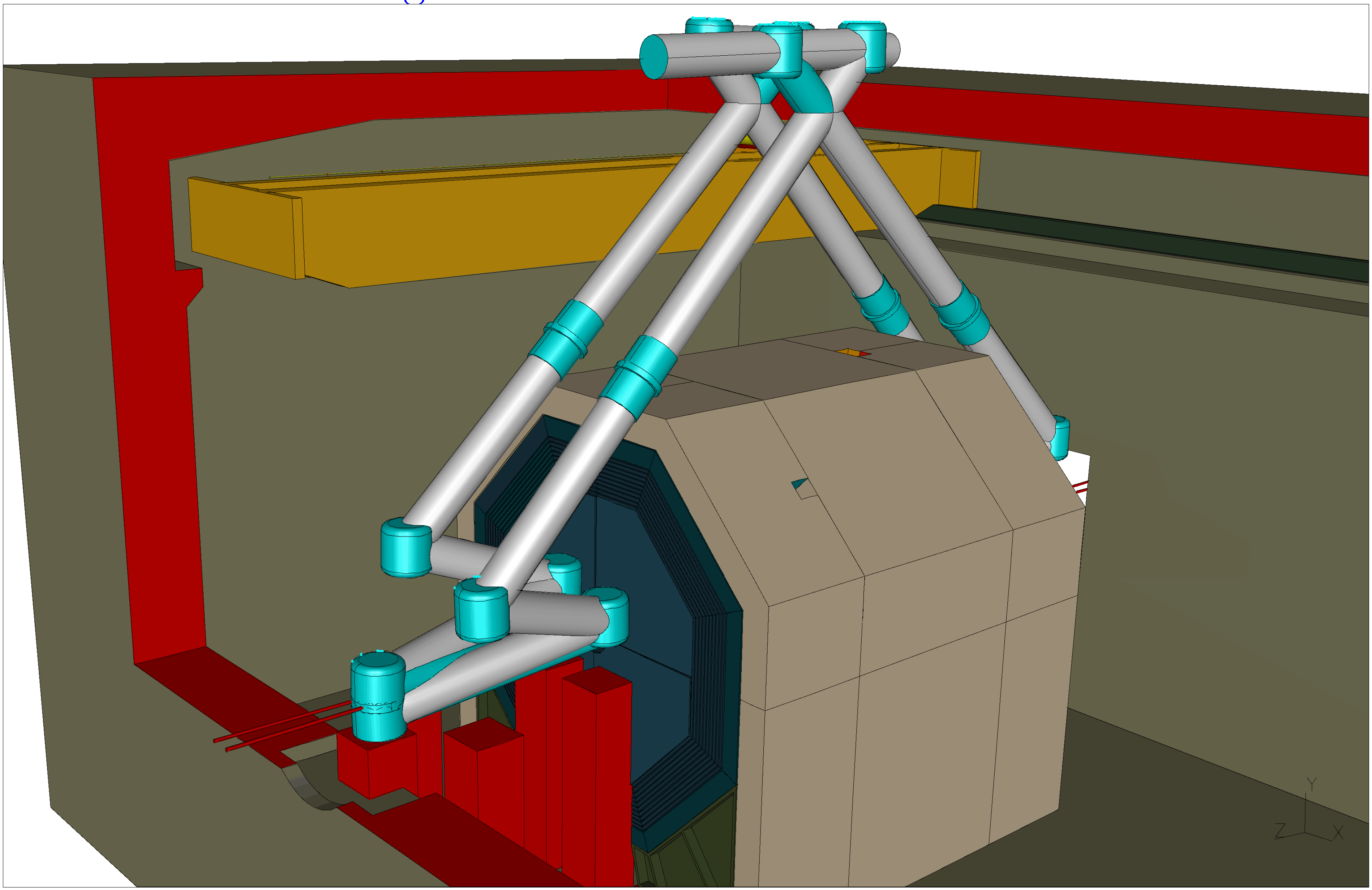
Optimum parameters

Laser parameters	TDR pt. VI	This study
Rayleigh length Z_R	0.35 mm	0.63 mm
Collision angle α_0		55.1 mrad
Laser energy A	5 J	9.0 J
pulse duration $\sigma_{L,z}$	1.5 ps	1.5 ps
nonlinearity parameter ξ^2	0.30	0.30
Total Luminosity $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.10	1.05

TDR parameters can be reproduced

However mirror tolerances $\mathcal{O}(10\mathrm{nm})$

Design of the laser resonator in the hall



Luminosity and Background

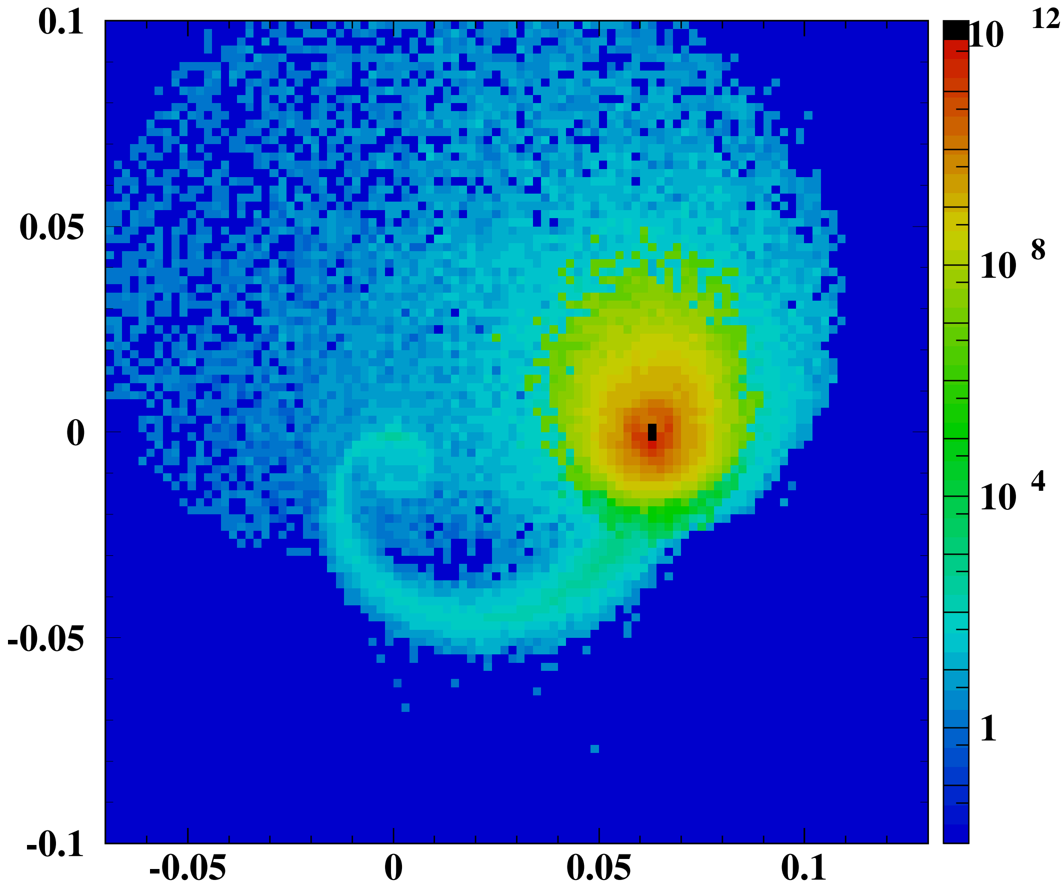
Special programs exist to calculate luminosity and background including

- multiple Compton scattering
- finite scattering angle
- non-linear effects
- coherent processes at IP (Beamstrahlung)
- non-coherent processes (large angle pairs)
- depolarisation effects

Backgrounds in the detector are calculated from

- direct hits
- backscattering from the mask
- neutrons from the beam dump

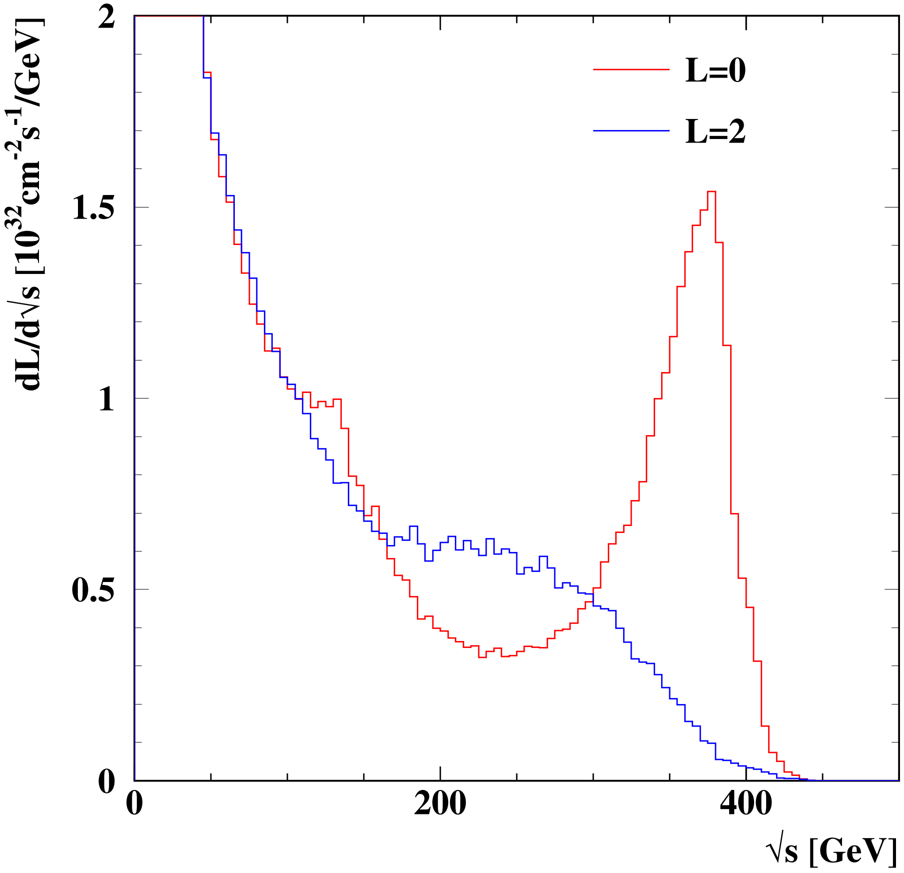
Energy disruption on the calorimeter face from one bunch crossing



More energy in the detector than in e^+e^- because of

- disruption from beam-laser interaction
- large crossing angle

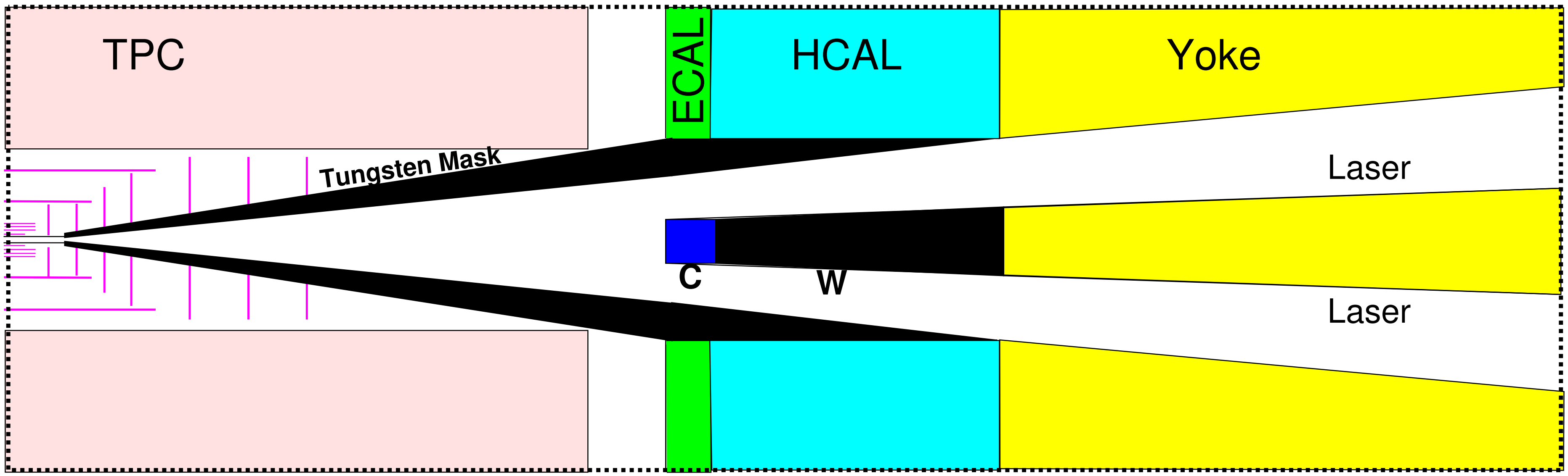
Luminosity spectra for $L = 0, 2$ with $\sqrt{s} = 500\,\mathrm{GeV}$ and $2\lambda_e = 0.85$



- Total $\gamma\gamma$ luminosity for $z > 0.8 z_m$: $\mathcal{L} = 1.1 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Total $e\gamma$ luminosity for $z > 0.8 z_m$: $\mathcal{L} = 0.9 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Total e^-e^- luminosity for $z > 0.65$: $\mathcal{L} = 0.07 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

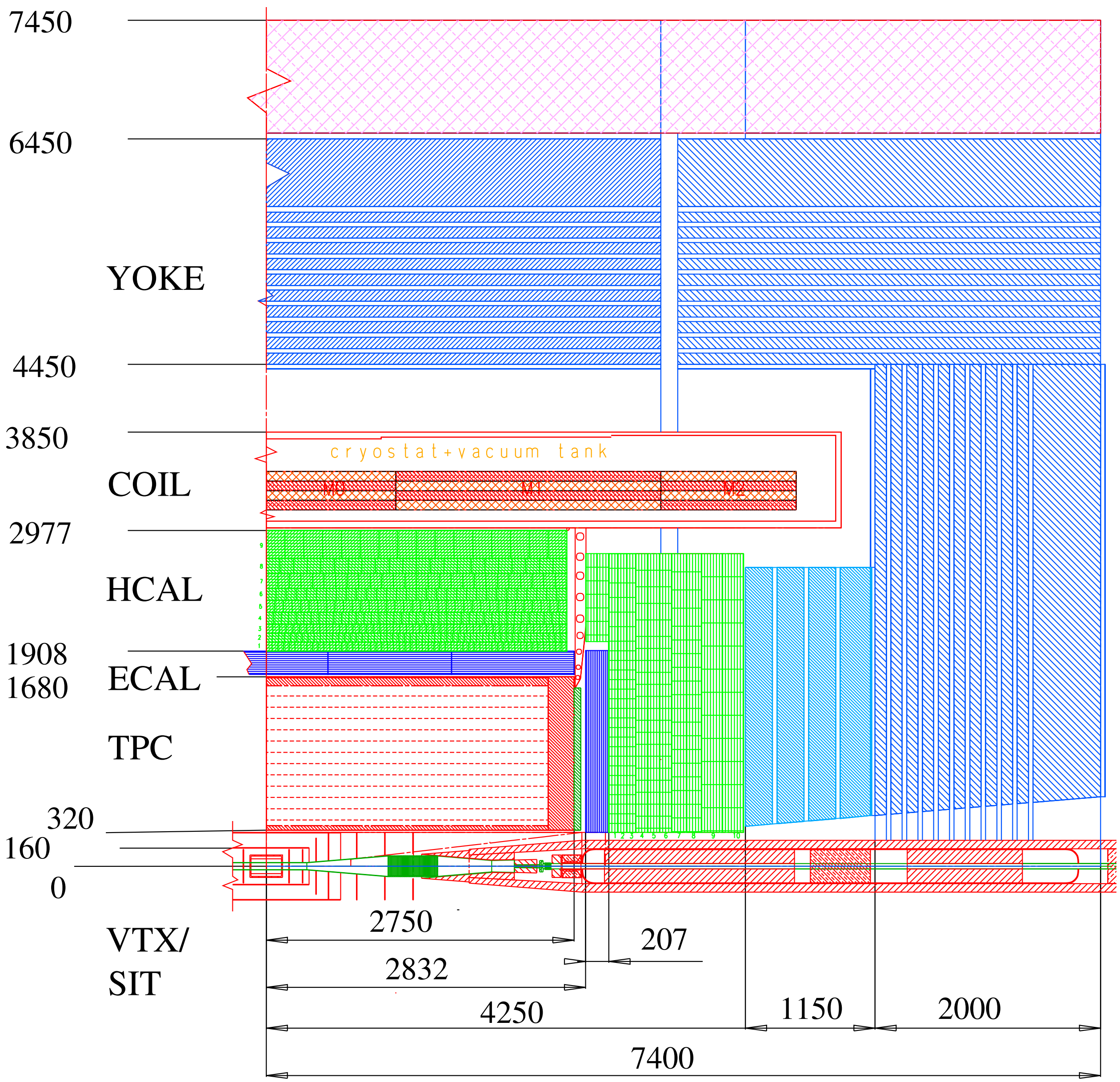
The Detector

- as much as possible the TDR e^+e^- detector should be used $\longrightarrow$ plot
- at low angles $\theta < 7^\circ$ a redesign is needed

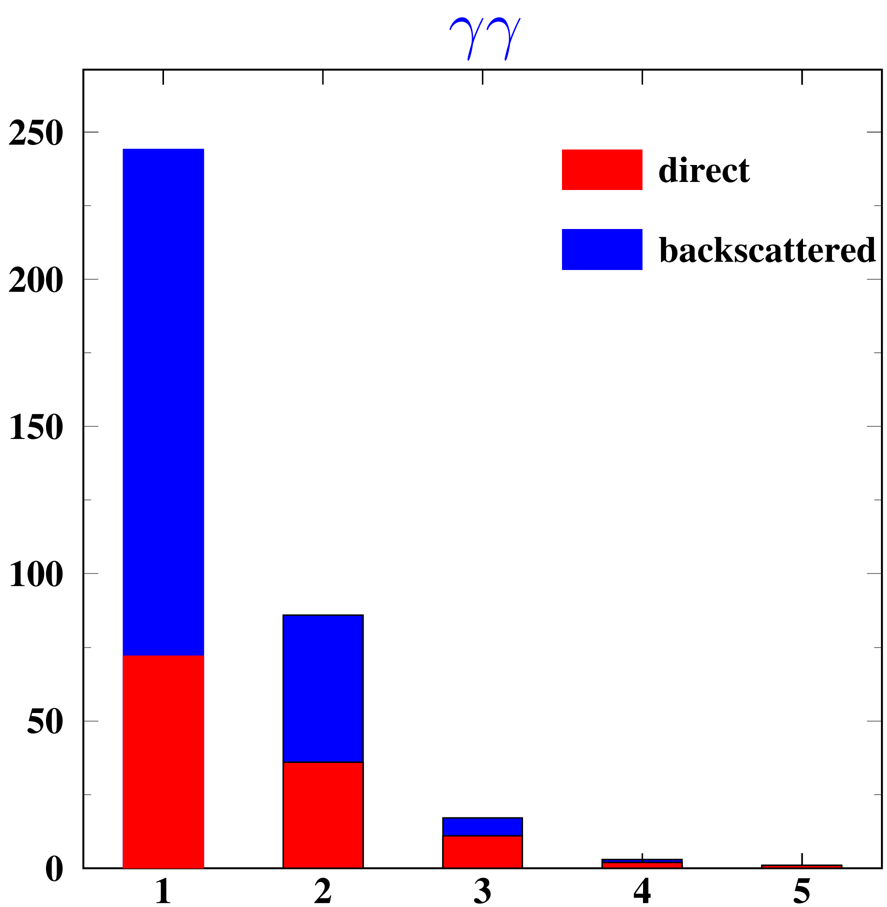


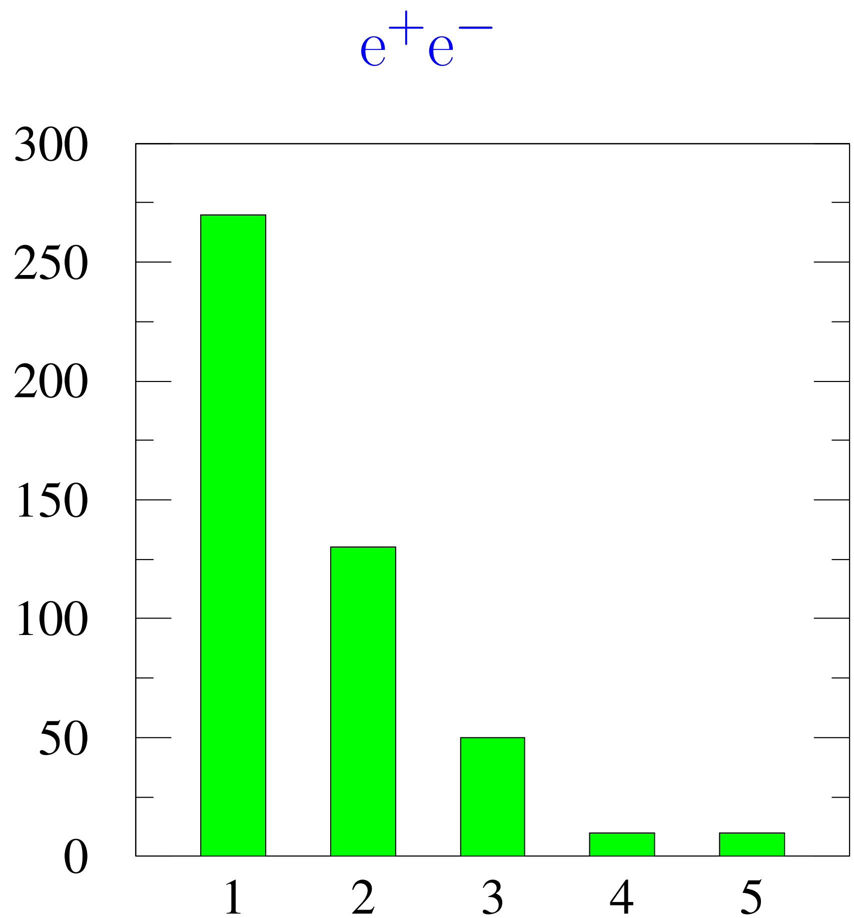
- Need space for the pipes
- Tungsten mask to shield additional background
- Detector dead below $\theta = 7^\circ$

The e^+e^- TDR-Detector



Background in the vertex detector





Similar as in e^+e^-

Background in the TPC:

Roughly factor two larger than in e^+e^-

$\Rightarrow$ still acceptable

Neutrons from dump:

Photons cannot be deflected electrically or magnetically

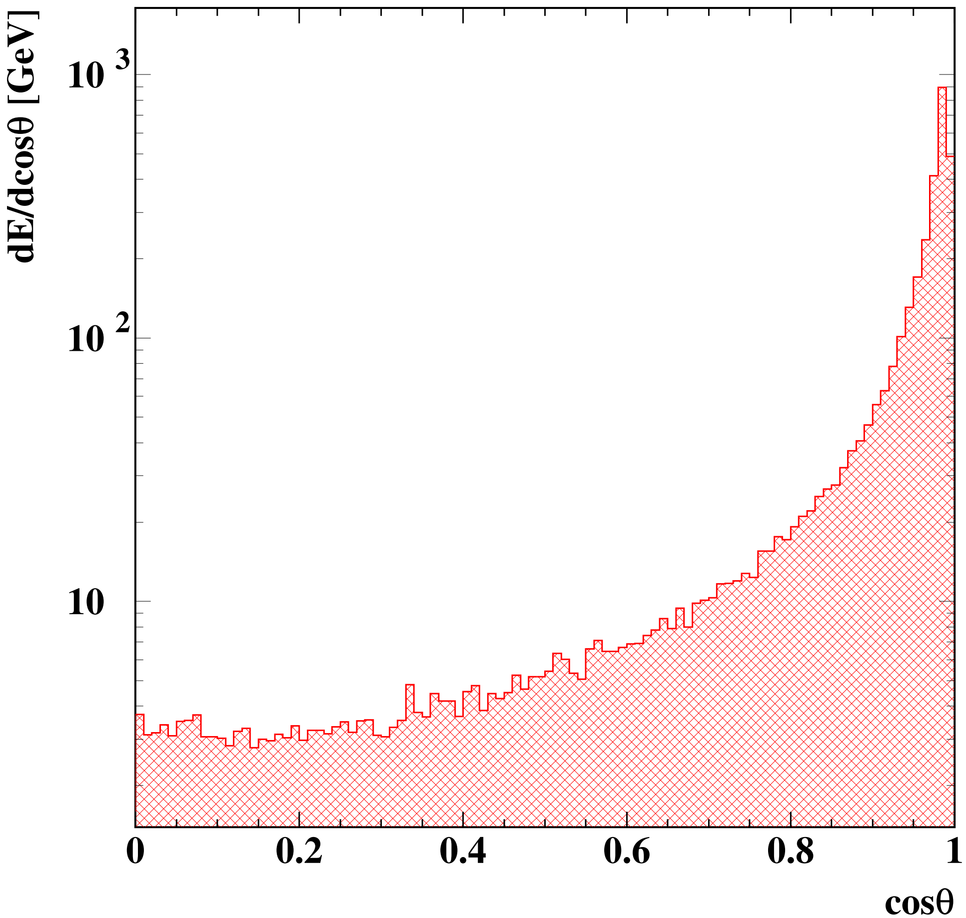
- there is a straight line from the IP to the dump
- 1 neutron/cm^{-2}/bx $\Rightarrow$ 10^{11} neutrons/cm^{-2}/year
- Marginally acceptable for CCD vertex detector

Low energy q$\bar{\mathrm{q}}$ background

- Large luminosity and large cross section $\gamma\gamma \to \mathrm{q}\bar{\mathrm{q}}$ at low $\sqrt{s}$

➡ $\mathcal{O}(1)$event/bx overlaid to physics events (pileup)

- Due to large boost pileup tracks are forward peaked
- Can be largely rejected if physics in not forward peaked (like $\gamma\gamma \to \mathrm{W}^+\mathrm{W}^-$)

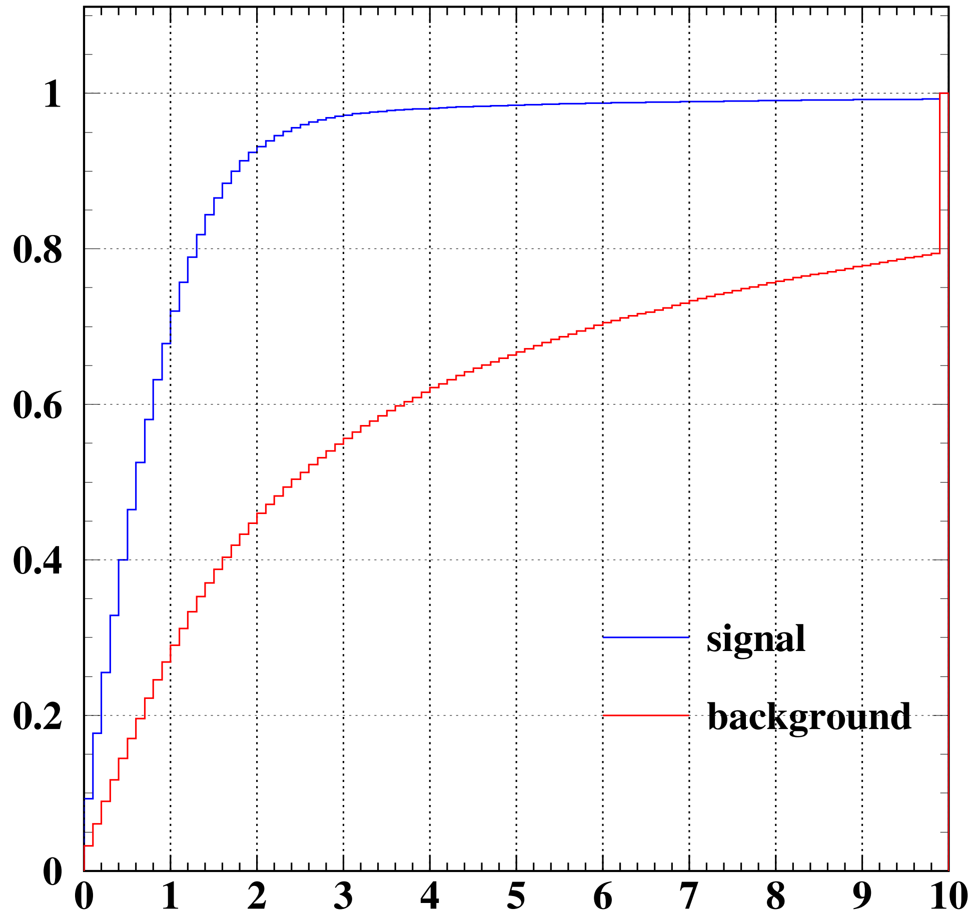


- Additional help/complication: beamspot length $\sim 300\mu m$

$\Rightarrow$ signal and pileup separated in z

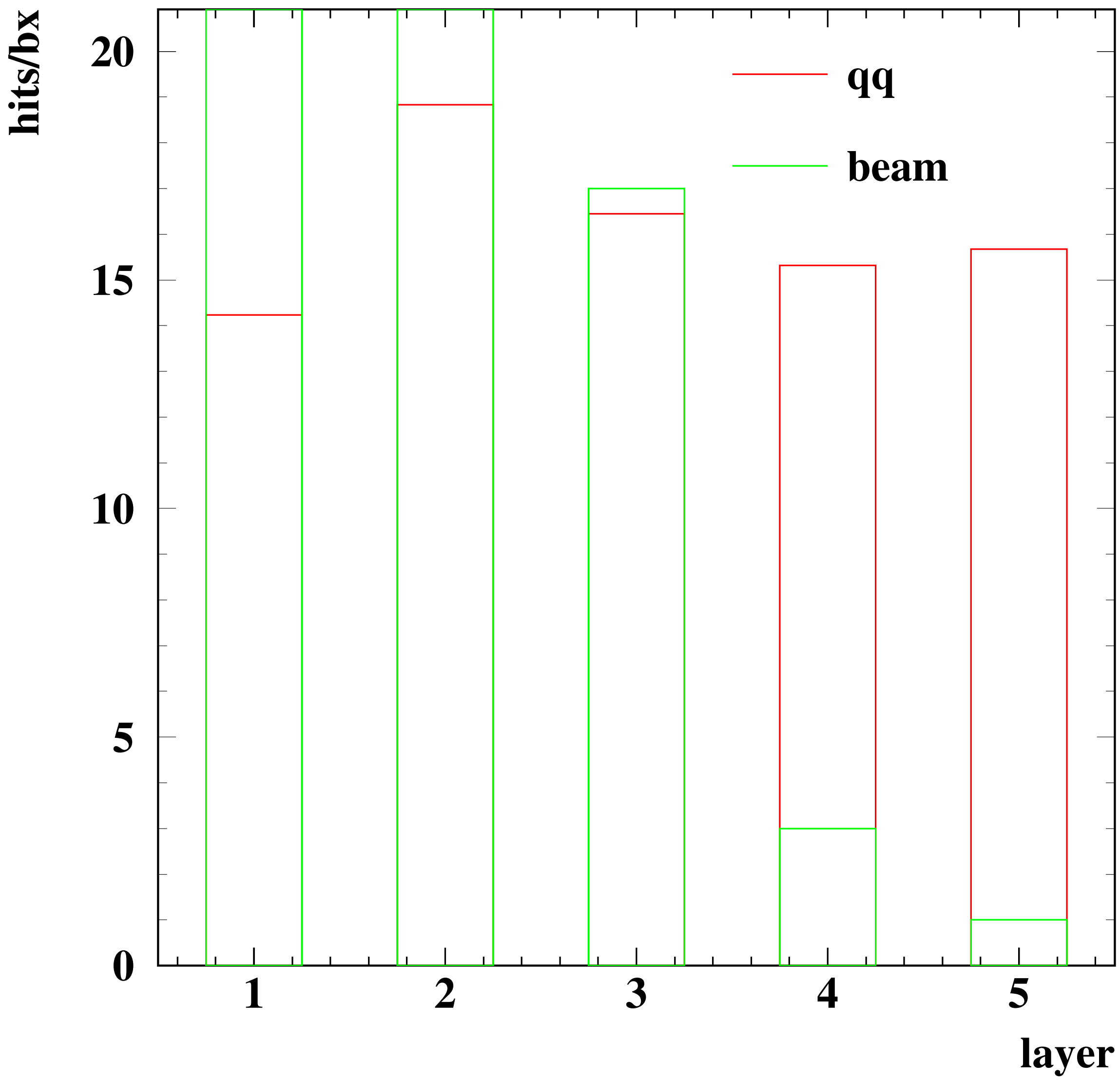
- microvertex detector can help to separate
- can screw up b-tagging, e.g. in Higgs analysis

Integrated Impact Parameter distribution for signal and pileup



Pileup gives also non negligible background in detector

Hits in vertex detector from beam and pileup



$\sqrt{s} \neq 500$ GeV :

$\sqrt{s(\gamma\gamma)} \sim m_{\mathrm{H}} \sim 120$ GeV:

- can run with $\lambda = 1.06\mu$m, $\sqrt{s} = 200$ GeV $\Rightarrow x = 1.8$

➡ high linear polarisation

- if really needed can run with frequency trippler
  $\Rightarrow x = 4.3 \qquad (\sqrt{s} = 160$ GeV$)$

➡ worse linear polarisation, but better peaked spectrum

$\sqrt{s} \sim 800$ GeV:

- have to live with $\lambda = 1.06\mu$m $\Rightarrow x = 7.1$
- However need $\xi^2 \approx 0.4$ to get high k^2

➡ $x_{\mathrm{eff}} = 1/(1+\xi^2) \sim 5$ still acceptable

Can run all energies at TESLA with the same laser system

Conclusions

- TESLA offers the possibility to work as a $\gamma\gamma$ (or $e\gamma$) collider with $\sqrt{s(\gamma\gamma)} \leq 0.8\sqrt{s(\mathrm{e^+e^-})}$

- The luminosity might be 20-30% of the $\mathrm{e^+e^-}$ luminosity

- Detector and beams of lower quality then in $\mathrm{e^+e^-}$

- However one should be aware that the photon collider is far from being guaranteed and some difficult problems need to be solved.