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Requirements to beams sizes at photon colliders and problems of realization

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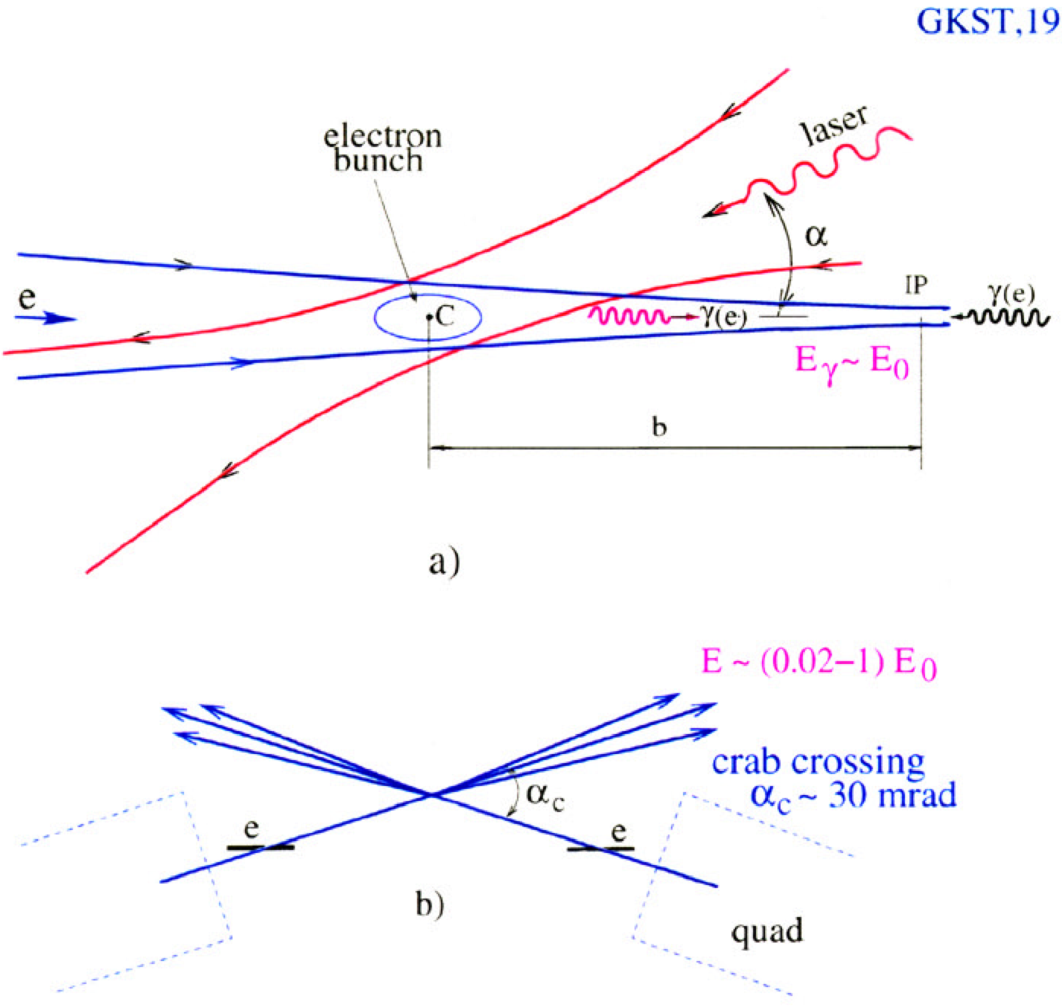
Scheme of $\gamma\gamma$, γe collider



$$\omega_m = \frac{x}{x+1} E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right]$$

$E_0 = 250$ GeV, $\omega_0 = 1.17$ eV ($\lambda = 1.06\ \mu$m) $\to x = 4.5$ and $\omega_m = 0.82 E_0 = 205$ GeV

$x = 4.8$ is the threshold for $\gamma\gamma_L \to e^+e^-$ in the conversion region. Due to the nonlinear effects in Compton scattering $x_{th} \sim 4.8(1+\xi^2)$, where $\xi \sim 0.3$ is acceptable.

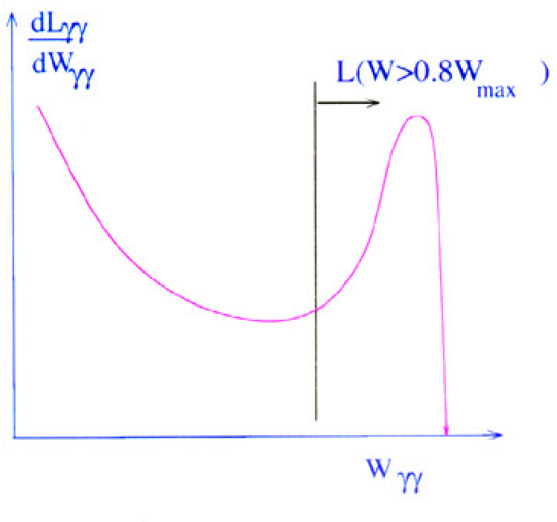
Energy and luminosity of $\gamma\gamma$,γe collider based on TESLA

$\lambda_{laser} = 1.06\ \mu$m.

$2E_0$ (GeV)	200	500	800
$L_{geom}, 10^{34}$	4.8	12.0	19.1
$W_{\gamma\gamma,max}$ (GeV)	122	390	670
$L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma}), 10^{34}$	0.43	1.1	1.7
$W_{\gamma e,max}$ (GeV)	156	440	732
$L_{e\gamma}(z > 0.8 z_{m,\gamma e}), 10^{34}$	0.36	0.94	1.3
$L_{e^+e^-}, 10^{34}$	1.3	3.4	5.8

$$L_{\gamma\gamma}(z > 0.8 z_m) \sim \frac{1}{3} L_{e^+e^-}$$

where $z = W_{\gamma\gamma}/2E_0$.

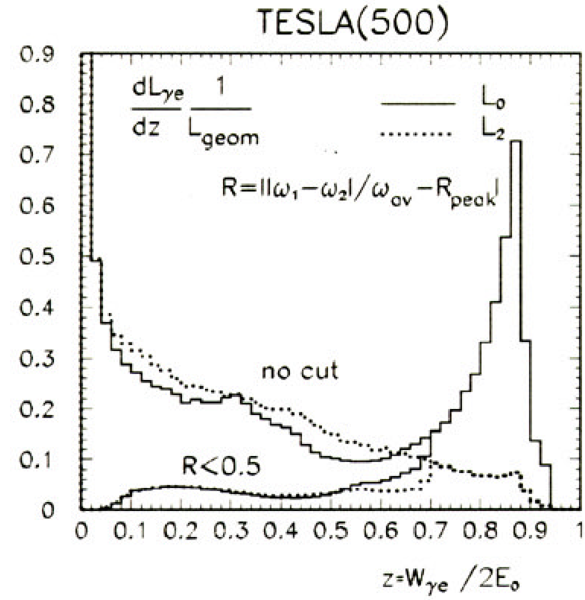


$W_{max} \sim 0.8 \times 2E_0$ in $\gamma\gamma$

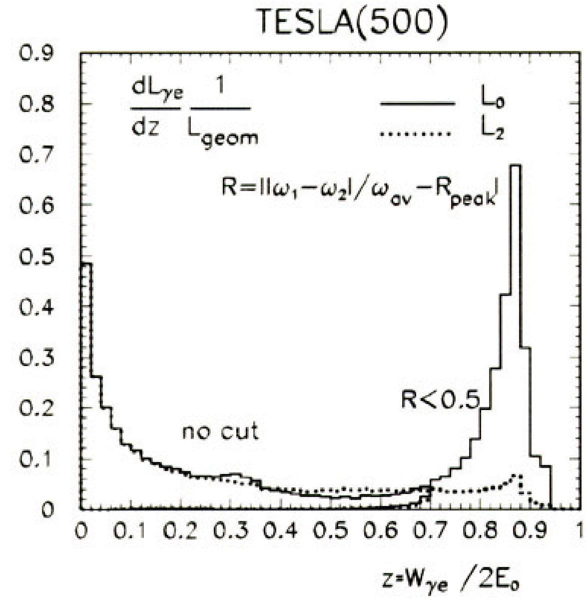
($W_{max} \sim 0.9 \times 2E_0$ in $e\gamma$)

γe luminosity spectra

($\gamma\gamma$ collisions are optimized, γe conversions for both beams, $b = 2.1$ mm)

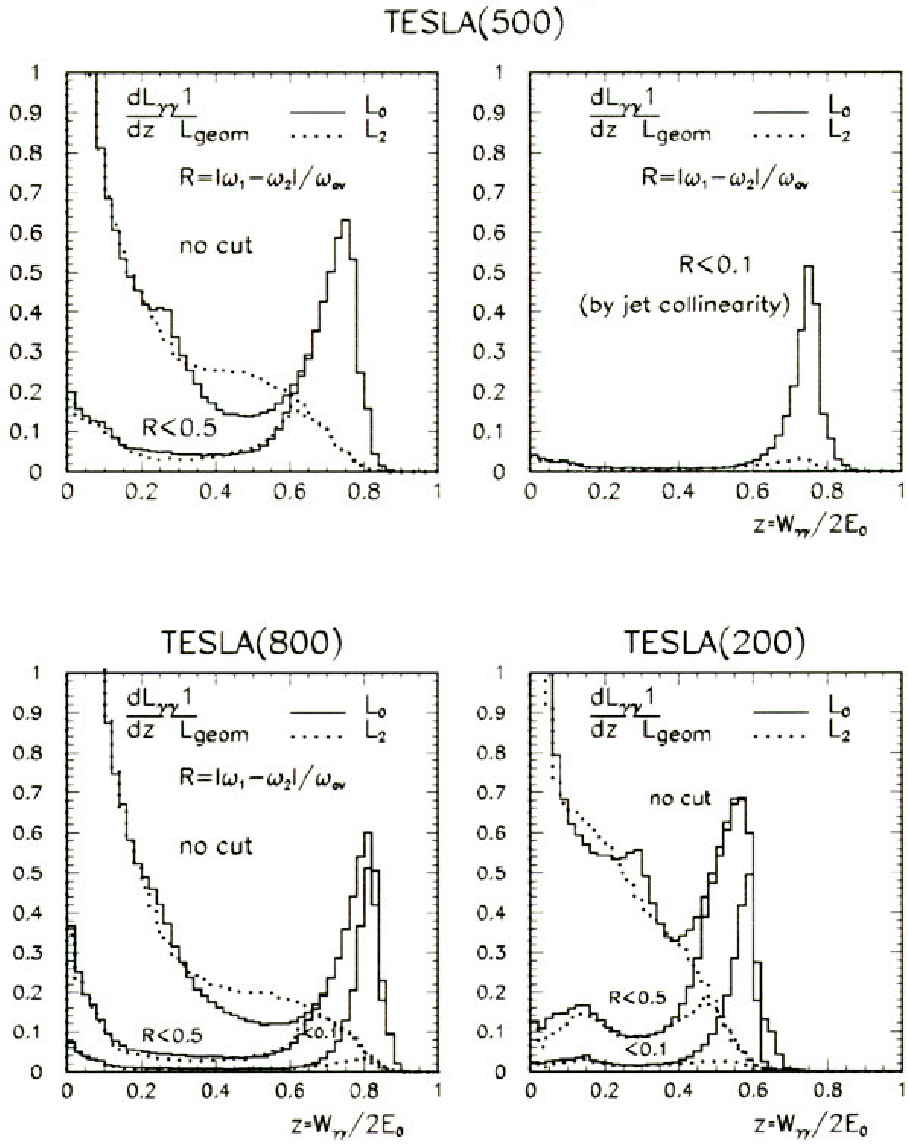


(γe collisions are optimized, γe conversions for one beams, $b = 1.05$ cm)

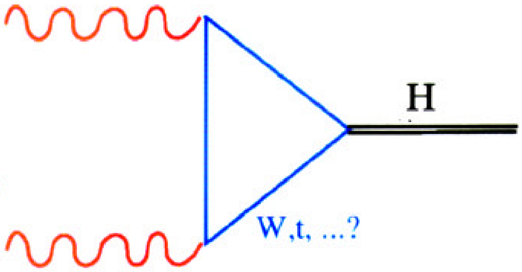


$\gamma\gamma$ luminosity spectra

with various cuts on the longitudinal momentum;
0 and 2 are the total helicities of colliding photons

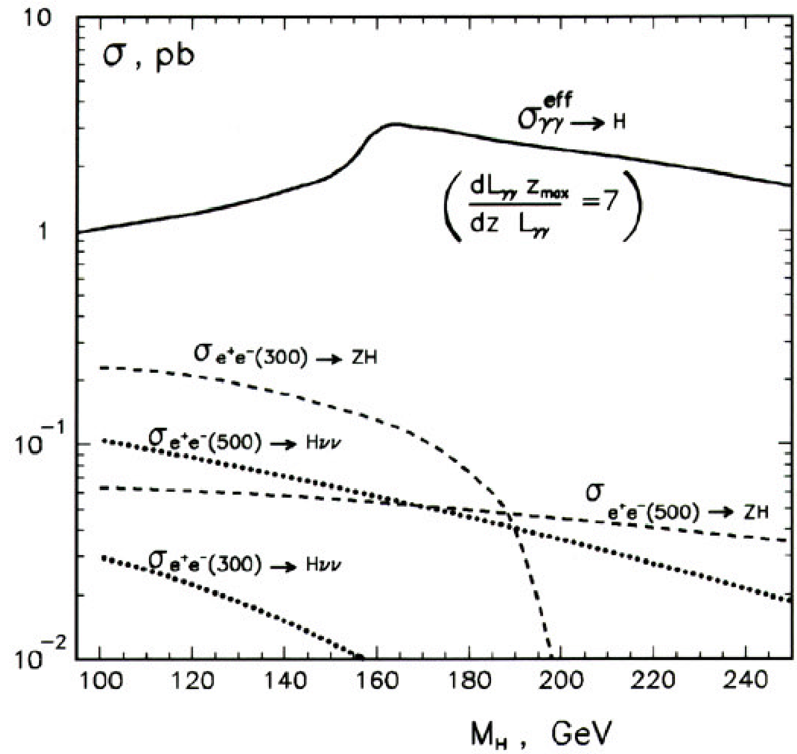


Higgs boson



Very sensitive for $M_? \gg 2E_0$

Cross sections of the Higgs boson production in $\gamma\gamma$ and e^+e^- collisions



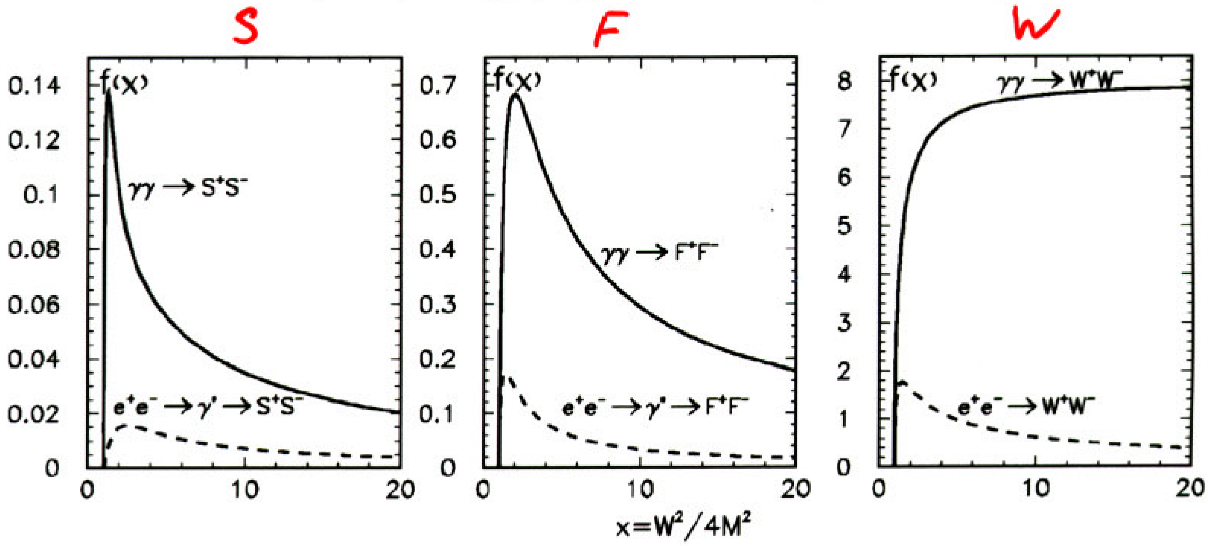
$$\dot{N}_{\gamma\gamma \to h} = L_{\gamma\gamma} \times \frac{dL_{\gamma\gamma} M_h}{dW_{\gamma\gamma} L_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{M_h^3} \equiv L_{\gamma\gamma} \times \sigma^{eff}$$

At TESLA $\frac{N_{\gamma\gamma \to h}}{N_{e^+e^- \to h+X}} \sim 1-10$ for $M_H = 100-250$ GeV

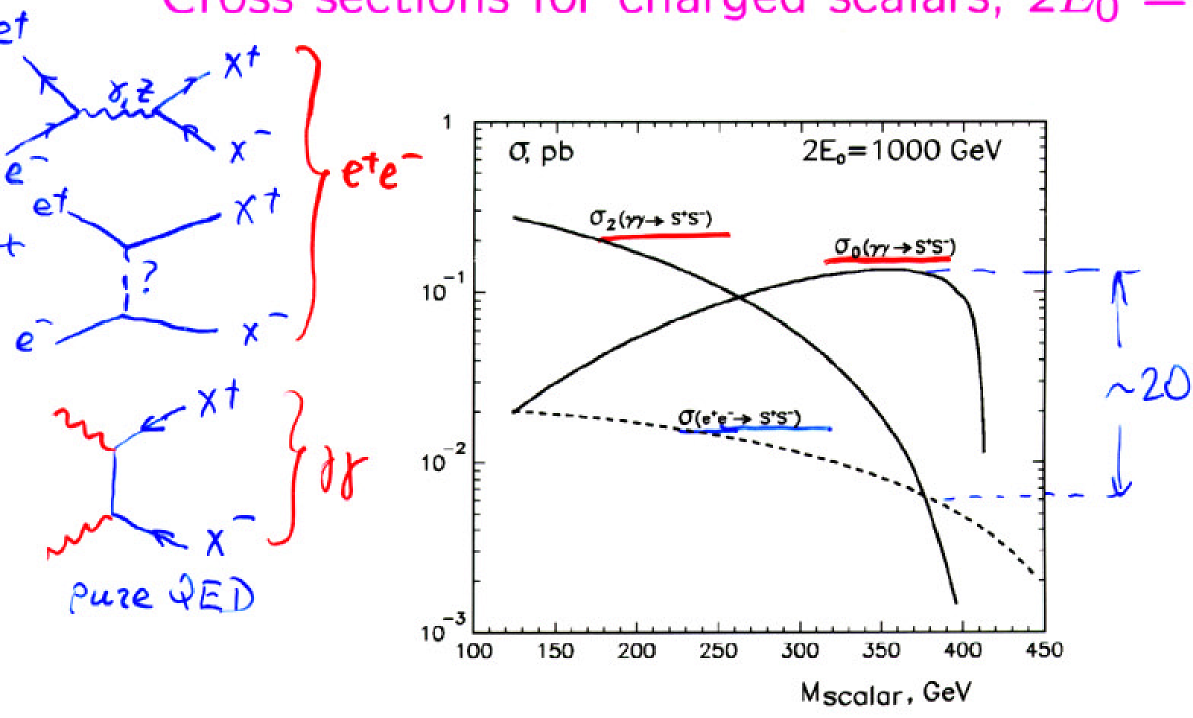
Physics

Charged pair production in e^+e^- and $\gamma\gamma$ collisions.

(S (scalars), F (fermions), W (W-bosons); $\sigma = (\pi\alpha^2/M^2) f(x)$, beams unpolarized)



Cross sections for charged scalars, $2E_0 = 1$ TeV



$\gamma\gamma$ and γe luminosities at TESLA
Summary table

$2E_0$ GeV	200	500	800
λ_L [μm]/x	1.06/1.8	1.06/4.5	1.06/7.2
t_L [λ_{scat}]	1.35	1	1
$N/10^{10}$	2	2	2
σ_z [mm]	0.3	0.3	0.3
$f_{rep} \times n_b$ [kHz]	14.1	14.1	14.1
$\gamma\epsilon_{x/y}/10^{-6}$ [m·rad]	2.5/0.03	2.5/0.03	2.5/0.03
$\beta_{x/y}$ [mm] at IP	1.5/0.3	1.5/0.3	1.5/0.3
$\sigma_{x/y}$ [nm]	140/6.8	88/4.3	69/3.4
b [mm]	2.6	2.1	2.7
L_{ee}(geom) [10^{34}]	4.8	12	19
$L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma})[10^{34}]$	0.43	1.1	1.7
$L_{\gamma e}(z > 0.8 z_{m,\gamma e})[10^{34}]$	0.36	0.94	1.3
$L_{ee}(z > 0.65)[10^{34}]$	0.03	0.07	0.095

For the same energy and TESLA beams

$$L_{\gamma\gamma}(z > 0.8 z_m) \approx \frac{1}{3} L_{e^+e^-}$$

(however cross sections in $\gamma\gamma$ collisions are typicaly larger the in e^+e^- by one order of magnitude)

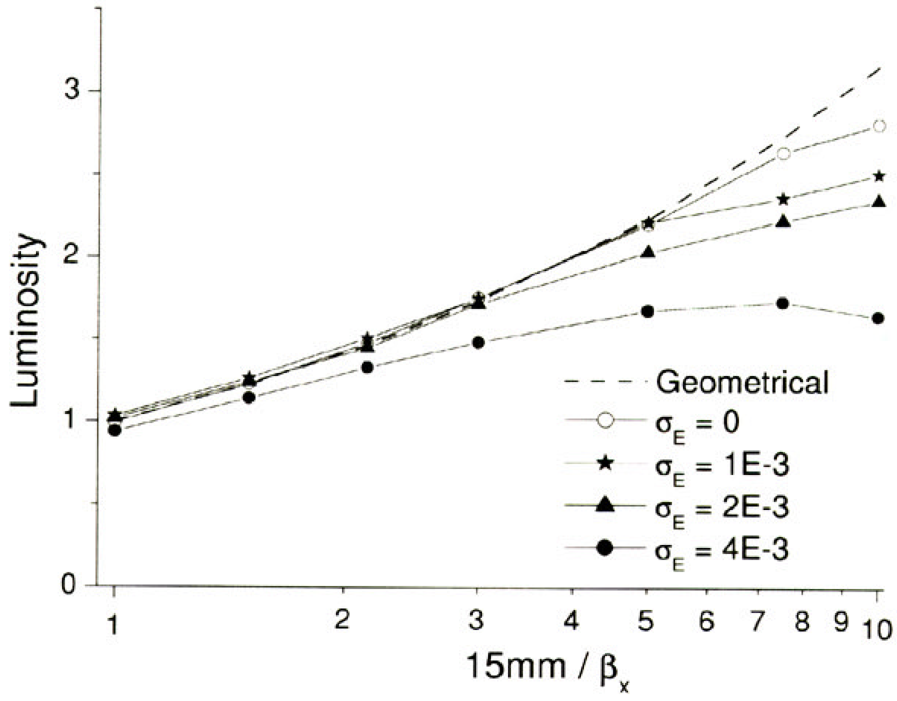
More universal relation (for $k^2 = 0.4$)

$$L_{\gamma\gamma}(z > 0.8 z_m) \approx 0.1 L_{ee}(geom)$$

Chromo-geometric aberrations in the final focus system

Dependence of the geometric e^-e^- luminosity on the horizontal β-function (SLAC design).

For TESLA the $\sigma_E/E \sim 10^{-3}$ (σ_E in the figure)



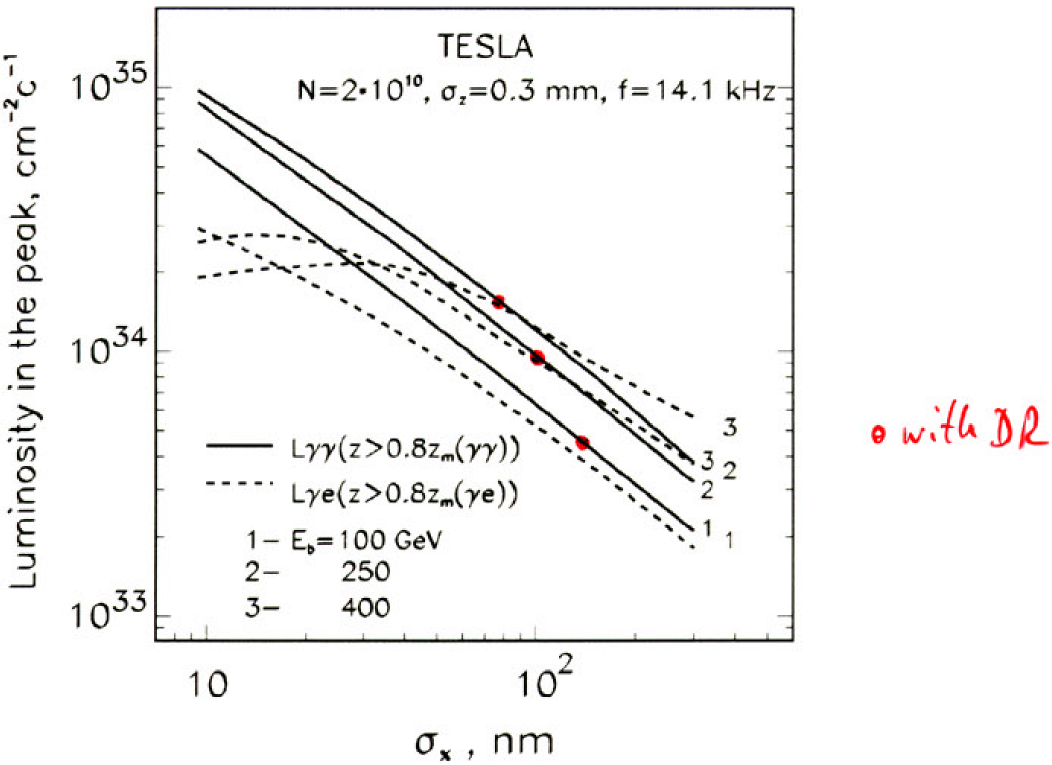
For TESLA $\beta_x = 1.5$ mm, $\beta_y = \sigma_z = 0.3$ mm is assumed.

The Interaction Region

Collisions effects

Coherent pair creation
Beamstrahlung
Beam-beam repulsion
Depolarization (not important)

Dependence of $\gamma\gamma$ and γe luminosities in the high energy peak on the horizontal beam size



For the TESLA electron beams $\sigma_x \sim 100$ nm at $2E_0 = 500$. Having beams with smaller emittances one could have by one order higher $\gamma\gamma$ luminosity.

γe luminosity in the high energy peak is limited due to the beam repulsion and beamstrahlung

Method of obtaining e^- beams (polarized) with low emittances

1. Damping rings

TESLA ($\gamma\gamma$): $\varepsilon_{nx} = 2.5 \cdot 10^{-6}$ m
$\varepsilon_{ny} = 0.03 \cdot 10^{-6}$ m
$Q = 3$ nC

$L \propto \frac{N P}{\sqrt{\varepsilon_{nx}\varepsilon_{ny}}}$. Limits: space charge for TESLA
IB scattering, SR for others

Many people work in this direction, big progress is not expected

2. Photo-guns (without DR)

Typicaly: $\varepsilon_n \sim 10^{-6}$ m for $Q = 1$ nC

Compared to TESLA DR at photoguns

$\frac{N}{\sqrt{\varepsilon_{nx}\varepsilon_{ny}}}$ is 10 times smaller

Some Progress is possible but still not happend
main problem is space charge.

3. Cooling of electron beams

- Linear cooling in strong wigglers (Mikhailichenko, Dikansky)
- Laser cooling (Telnov, 1996)

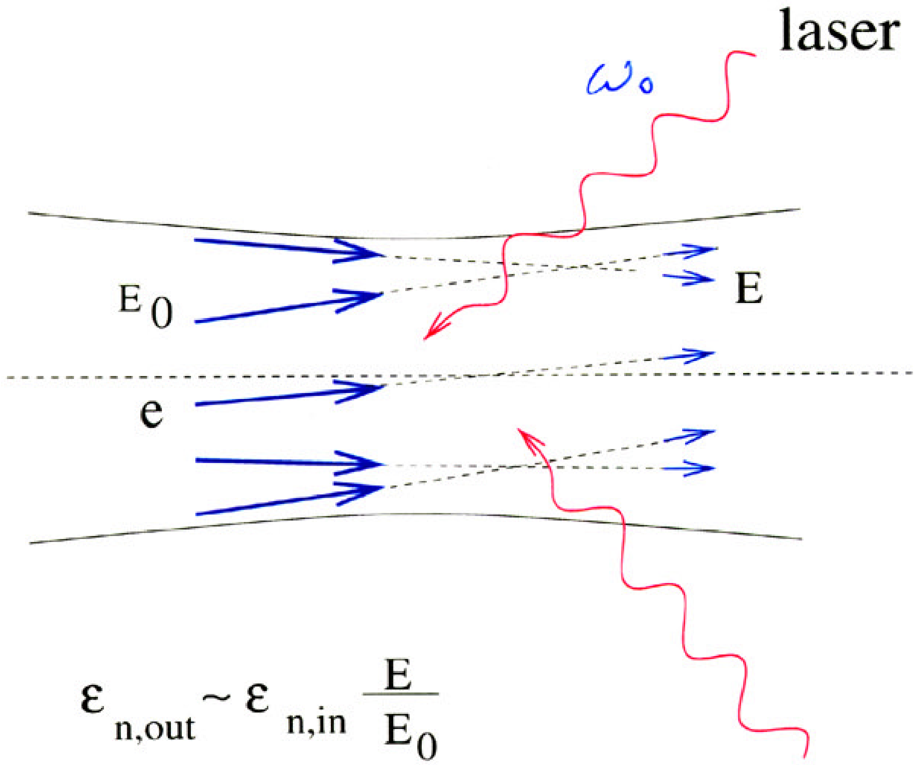
Laser cooling

T.V.I. Phys. Rev. Lett 78 (1997) 4757
NIM (2000)

$$\frac{p^2}{m} \sim \gamma \omega_0 \qquad \frac{p_t}{\gamma m c} = \sqrt{\frac{\varepsilon_n}{\gamma \beta}}$$

$$\Rightarrow \varepsilon_n \sim \frac{\lambda_c}{\lambda} \beta \qquad \left(\varepsilon_{ni} = \frac{3\pi}{5} \frac{\lambda_c}{\lambda} \beta_i \right) \qquad \lambda_c = \frac{\hbar}{mc}$$

valid for Compton scat. and undulators



$$\varepsilon_{n,out} \sim \varepsilon_{n,in} \frac{E}{E_0}$$

For „wiggler" case

$$\varepsilon_{nx} \simeq \varepsilon_{nx}(\text{undul}) \cdot \xi^3$$
$$\varepsilon_{ny} \simeq \varepsilon_{ny}(\text{undul}) \cdot \xi$$

Why lasers? May be simple undulators?

1) $\frac{dE}{dx} = -\frac{2}{3}\frac{e^4 \overline{B^2} E^2}{m^4 c^8}$

In the case of damping with reacceleration

$\frac{d\varepsilon_n}{\varepsilon_n} = e^{-x/\lambda}$ $\quad \lambda = \frac{3}{2}\frac{m^2c^4}{2e^2\overline{B^2}E} = \frac{7.7\,km}{E(GeV)\left(\frac{B}{10^5}\right)^2}$

$\sqrt{\overline{B^2}} = 75\,kG$, $E = 20\,GeV \Rightarrow \lambda = 0.7\,km$

if $\Delta z = 4\lambda$, Then $\Delta z \sim 3km + \frac{80\,GeV}{G} \sim 6\,km$

That is ~max what can be accepted.

2) However, emittance

$\varepsilon_{nx} = \frac{11 e^3 \hbar c \lambda^2 B_0^2 \beta_x}{24\sqrt{3}\pi^3 (mc^2)^4} = 7.3 \cdot 10^{-8} cm \left(\frac{B_0}{10^5}\right)^3 \beta_x(cm) * \lambda^2(cm)$

$B_0 = 105\,kG$, $\beta_x \sim 300\sqrt{20} = 1340\,cm$, $\lambda = 10\,cm$

$\Rightarrow \varepsilon_{nx} = 0.01\,cm$, too large

even at $\lambda = 1\,cm$ (impossible for a such field)

$\varepsilon_{nx} \sim 10^{-4}\,cm$, as with DR

Resume: linear cooling in undulators-wigglers can not provide desirable emittance.

Laser cooling

1. $\varepsilon_{n,\,min} \sim \frac{3\pi}{5}\frac{\lambda_c}{\lambda}\beta \simeq \frac{7.2\cdot 10^{-10}\,\beta(mm)}{\lambda(\mu m)}$ m rad

If $\lambda = 1\mu m$, $\varepsilon_{nx} = 10^{-8}\cdot 3m$ (as ε_{ny} in DR) then $\beta_x = 4cm$.

To have add. cool. on y $\beta_y < 0.5cm$ is required.

2. Problem: energy spread

For $E_0 \rightarrow 1/10\,E_0$, $E_0 = 5\,GeV$, $E_f = 0.5\,GeV$

$\frac{\sigma_E}{E} \simeq 12\%$

There is problem of matching small β in cooling region with large β in accelerator.

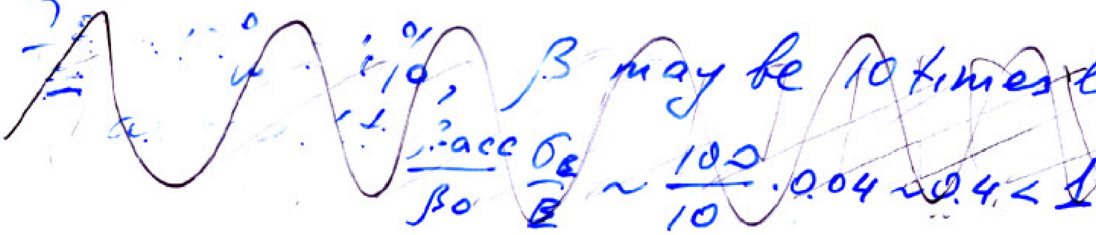
The chromatic factor $\frac{F}{\beta_0}\frac{\sigma_E}{E} \sim \frac{\beta_{acc}}{\beta_0}\frac{\sigma_E}{E}$

$\sim \frac{100cm}{1cm}\cdot 0.12 \sim 10$, system with chromatic corrections is needed.

All attempts (by now) to find solution were unsuccesful!

The solution, may be, is in increase of λ?

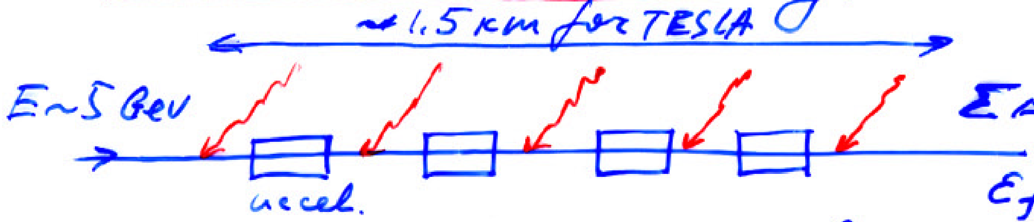
$\lambda = 1\mu m \longrightarrow 10\mu m$



... %, β may be 10 times larger,

$\frac{\beta_{acc}}{\beta_0}\frac{\sigma_E}{E} \sim \frac{100}{10}\cdot 0.04 \sim 0.4 < 1$

Continues laser cooling



$\Sigma \Delta E_e \sim (3-4) E_0$

$\varepsilon_f \sim \varepsilon_{in} e^{-(3-4)}$

- $$\varepsilon_{n,min} \sim \frac{3\pi}{5} \frac{\lambda_c}{\lambda} \beta = \frac{7.2 \cdot 10^{-9} \beta(cm)}{\lambda(\mu m)} \; m \cdot rad \quad (\xi^2 < 1)$$
- $$\left(\frac{\sigma_E}{E}\right)_{equil.} = \sqrt{\frac{7\pi r_e \gamma}{5 \alpha \lambda}} = 0.058 \sqrt{\frac{E(GeV)}{\lambda(\mu m)}}$$

$E = 5$ GeV, $\lambda = 10 \mu m \Rightarrow \sigma_E / E = 0.04$

If $\beta_{x,y} \sim 20$ cm $\quad \varepsilon_{n,min} \sim 1.5 \cdot 10^{-8}$ m.rad

- $\sqrt{\varepsilon_{nx} \cdot \varepsilon_{ny}}$ is 18 times better than with TESLA DR.
- At $E = 100$ GeV $\quad \frac{\sigma_E}{E} = 0.04 \cdot \frac{5}{100} = 0.002$ OK.
- Chromaticity problem

$$\frac{F}{\beta} \frac{\sigma_E}{E} \sim \frac{200}{20} \cdot 0.04 \sim 0.4$$

seems can be solved.

Laser flash energy

The system reminds that developed at KEK for e^+ production, but should be repeated ~30 times (to have e^3 damping)

Σ flash energy $O(300 J)$!

$P \sim 300 \cdot 10^4 \sim 3$ MW!

Using optical cavity (or just multiple use) one can decrease P by 1-2 orders

Not easy, but not impossible

Conclusion

1. The $\gamma\gamma$ luminosity at photon colliders at $2E_0 \le 500$ GeV is determined by geometric luminosity of electron beams (after DR), further decrease of ε_{nx} (100 times) is desirable (ε_{ny} may be also smaller by factor 5).

2. There are no good solutions at the moment.

3. Laser cooling is one of possible ways. Technology is not ready, but may be possible in 10-15 years.

4. New ideas are welcomed!