Monochromators for s-channel Higgs production

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IFIC - LAL

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Objectives

In A. Blondel words:

The aim is to monochromatize the FCC-ee beams at E_{CM} = 125.2 GeV for the production of e+e- --> H(125.2) in the s-channel, just like a muon collider, but with hopefully much higher luminosity -- and lower cross-section.

The Higgs width is 4.2 MeV and the FCC-ee energy spread is about 5×10^{-4} at these energies, so one needs to gain a factor 10 in energy spread. We also need to keep the beams polarized to keep track of the beam energy precisely.

It is possible that they don't work for some fundamental reason -- then it is useful to know this, too.

Monochromatization principle

Energy Resolution: $$\sigma_w = \sqrt{2}E_0\sigma_\varepsilon$$

energy spread

$$\sigma_\varepsilon^2 = \frac{55\hbar c E_0^2}{32\sqrt{3}(mc^2)^3}\frac{I_3}{I_2}\frac{1}{J_\varepsilon}$$

$$\sigma_w \propto \frac{1}{\sqrt{\rho J_\varepsilon}}$$

To increase σ_w

$$\begin{cases} \rho >>> \\ 0.5 \le J_\varepsilon = 3 - J_x \le 2.5 \end{cases}$$

bending radius

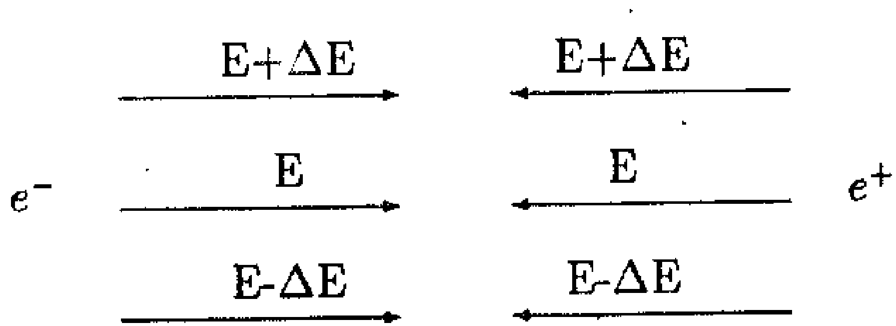
longitudinal partition number

Monochromatization [7]

Monochromatization principle

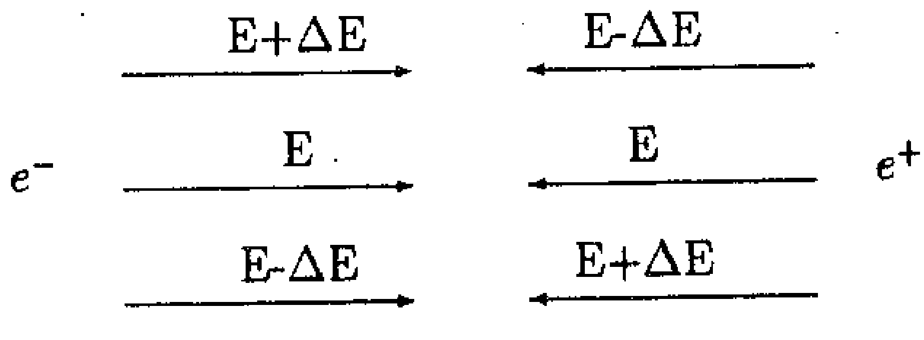
Standard collision:
dispersion has the same sign in the IP

$$w = 2\left(E_0 + e\right)$$



Monochromatization:
dispersion has opposite sign in the IP

$$w = 2E_0 + 0(e)^2$$



Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.

Monochromatization principle Luminosity and Differential Luminosity

Luminosity: $$L = k_b f_r \int f_+(x,y,\varepsilon_+) f_-(x,y,\varepsilon_-) dx dy d\varepsilon_+ d\epsilon_-$$

$$f_\pm(x,y,\varepsilon_\pm) = \frac{N_\pm}{(2\pi)^{3/2}\sigma^*_{x\beta}\sigma^*_{y\beta}\sigma_{\varepsilon_\pm}} exp\left(-\frac{(x-D^*_{x\pm}\varepsilon_\pm)^2}{2\sigma^{*2}_{x\beta}} - \frac{(y-D^*_{y\pm}\varepsilon_\pm)^2}{2\sigma^{*2}_{y\beta}} - \frac{\varepsilon^2_\pm}{2\sigma^2_\varepsilon}\right)$$

with $$\varepsilon = \frac{E}{E-E_0} \qquad \begin{aligned} y_\beta &= y - D_y\varepsilon \\ x_\beta &= x - D_x\varepsilon \end{aligned}$$

Differential Luminosity: Luminosity per unit center of mass energy

$$\begin{aligned} L(w_1,w_2) &= \int_{w_1}^{w_2} \Lambda(w) dw \\ &= k_b f_r \int f_+(x,y,\varepsilon_+) f_-(x,y,\varepsilon_-) \delta(w - 2E_0\sqrt{(1+\varepsilon_+)}\sqrt{(1+\varepsilon_+)}\ ) dx dy d\varepsilon_+ d\varepsilon_- \end{aligned}$$

1) Case with: $D^*_{x,y}=0$

$$L_0 = \frac{k_b f_r N_+ N_-}{4\pi\sigma^*_{x\beta}\sigma^*_{y\beta}} \qquad \Lambda_0(w) = \frac{L_0}{\sqrt{2\pi}\sigma_w} exp\left(-\frac{(w-2E_0)^2}{2\sigma_w^2}\right)$$

2) Case with: $D^*_{x+} = -D^*_{x-} = D^*_x$
$D^*_{y+} = -D^*_{y-} = D^*_y$

enhancement factor

$$\lambda = (1+\sigma_\varepsilon^2(\frac{D_x^{*2}}{\sigma^{*2}_{x\beta}} + \frac{D_y^{*2}}{\sigma^{*2}_{y\beta}}))^{1/2}$$

$$L = \frac{L_0}{\lambda} \qquad \Sigma_w = \frac{\sqrt{2}E_0\sigma_\varepsilon}{\lambda}$$

$$\Lambda(w) = \Lambda_0(2E_0) exp\left(-\frac{1}{2}(\frac{D_x^{*2}}{\sigma^{*2}_{x\beta}} + \frac{D_y^{*2}}{\sigma^{*2}_{y\beta}} + \frac{1}{\sigma_\varepsilon^2})\frac{(w-2E_0)^2}{2\sigma_w^2}\right)$$

with $\Lambda(2E_0) = \Lambda_0(2E_0)$

3) Case with: $D^*_{x+} = D^*_{x-} = D^*_x$
$D^*_{y+} = - D^*_{y-} = D^*_y$

enhancement factor

$$\lambda = (1 + \sigma_\varepsilon^2 \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}})^{1/2}$$

$$L = \frac{L_0}{\lambda(1 + \sigma_\varepsilon^2 \frac{D_x^{*2}}{\sigma_{x\beta}^{*2}})^{1/2}}$$

$$\Sigma_w = \frac{\sqrt{2} E_0 \sigma_\varepsilon}{\lambda}$$

$$\Lambda(w) = \frac{\Lambda_0(2E_0)}{(1 + \sigma_\varepsilon^2 \frac{D_x^{*2}}{\sigma_{x\beta}^{*2}})^{1/2}} exp\left(-\frac{1}{2} (\frac{D_y^{*2}}{\sigma_{y\beta}^{*2}} + \frac{1}{\sigma_\varepsilon^2}) \frac{(w - 2E_0)^2}{2\sigma_w^2} \right)$$

with

$$\Lambda(2E_0) = \frac{\Lambda_0(2E_0)}{(1 + \sigma_\varepsilon^2 \frac{D_x^{*2}}{\sigma_{x\beta}^{*2}})^{1/2}}$$

In summary:

- Opposite dispersions at the IP enhance energy resolution without detriment of the differential luminosity while dispersion which have the same sign degrade both differential and total luminosity

- When $\sigma^*_y <<< \sigma^*_x$ is more efficient to produce dispersion in the vertical plane trying to keep it zero horizontally

Monochromatization principle "Standard" Scheme

$\sigma^*_y <<< \sigma^*_x$ $\Rightarrow$ $D^*_{x+} = D^*_{x-} = 0$

$D^*_{y+} = -D^*_{y-} = D^*_y$

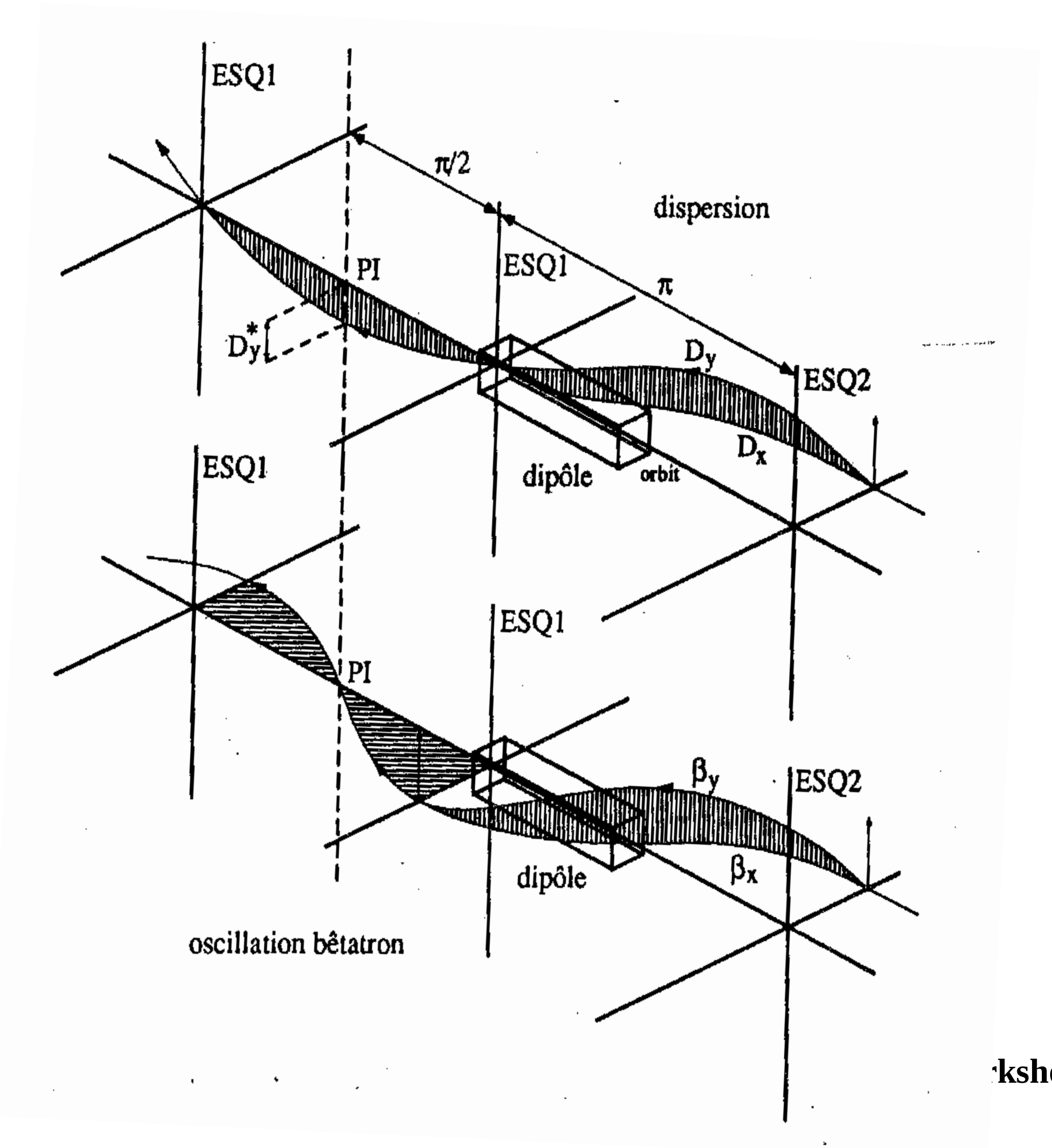
Implementations historical Studies:

- VEPP4: one ring, electrostatic quads [3][12]
- SPEAR: one ring, electrostatic quads, λ~8 [9]
- LEP: one ring, electrostatic quads (limited strength) and alternative RF magnetic quads, λ~3 (optics limitations) [2] [10]
- Superconducting RF resonators [33]

- Tau-Charm factory: two rings, vertical dipoles, , λ~7.5 [3] [4] [6]]8] [11] [13] [32]

Never tested experimentally !!!!!!

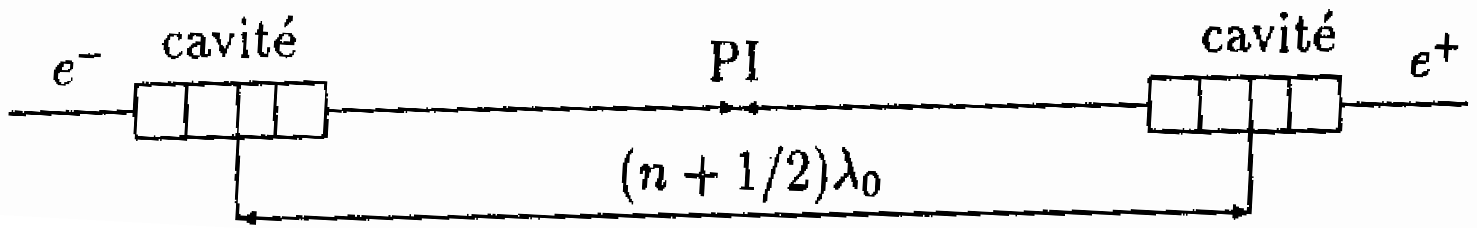
Monochromatization principle "Standard" Scheme



- VEPP4 (one ring), electrostatic quads
- SPEAR (one ring), electrostatic quads, λ~8
- LEP: one ring, electrostatic quads (limited strength) and alternative RF magnetic quads, λ~3 (optics limitations)

Monochromatization principle “Standard” Scheme

- Superconducting RF resonators



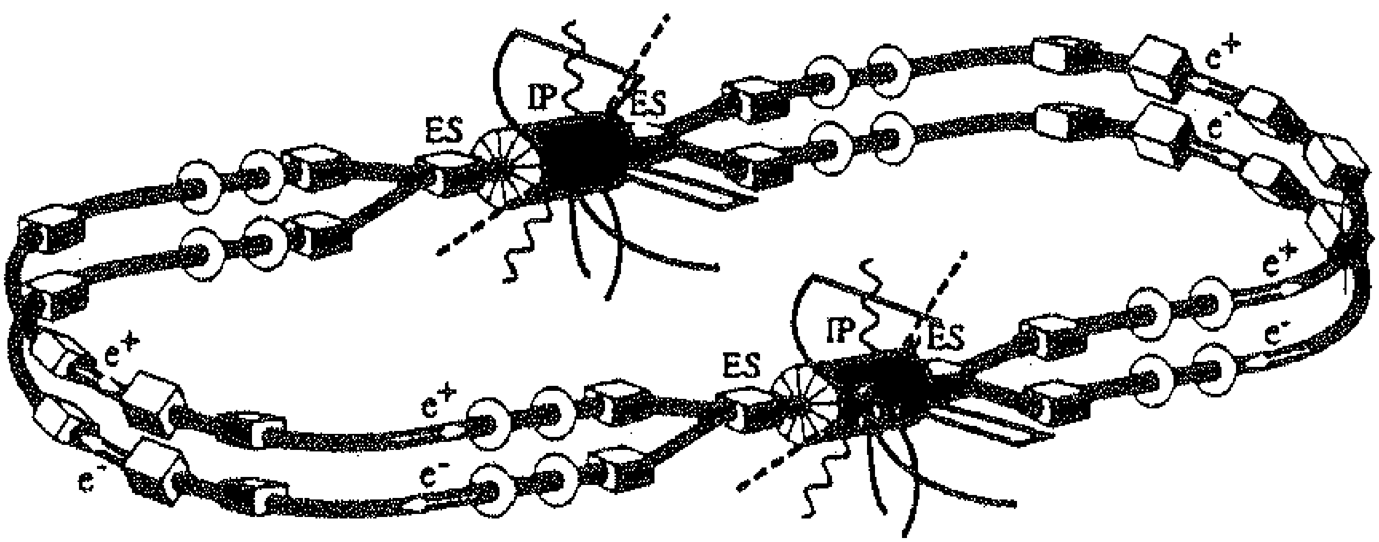
with a large horizontal decomposition of the beam relative energy spread created by a special lattice.
If we have the longitudinal size bigger than the betatron size, the non equilibrium particles with energy deviation have:

$$x = D_x \varepsilon$$

If the mode excited in the cavity could be proportional to x, we could have a gain in energy opposite to the energy deviation.

Monochromatization principle "Standard" Scheme

- Tau-Charm factory: two rings, vertical dipoles, λ~7.5



Monochromatization principle "Standard" Scheme for FCC-ee

Higgs factory:

$$E_0 = 120\ GeV$$
$$N_b = 0.46\ 10^{11}$$
$$I = 0.03\ mA$$
$$\epsilon_x = 0.94\ nm$$
$$\epsilon_y = 1.9\ pm$$
$$\beta_x^* = 0.5\ m$$
$$\beta_y^* = 1.0\ mm$$
$$\sigma_x^* = 22\ \mu m$$
$$\sigma_y^* = 0.044\ \mu m$$
$$\sigma_\varepsilon = 0.001$$
$$\sigma_b = 1.17\ mm$$
$$L_0 = 6.0\ 10^{34}\ cm^{-2}s^{-1}$$

choosing

$$D_y^* = 0.367\ m$$
$$D_x^* = 0.0$$

$\Rightarrow$

Enhancement factor

$$\lambda = (1 + \sigma_\varepsilon^2 \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}})^{1/2} = 8.4$$

Luminosity

$$L = \frac{L_0}{\lambda} = 7.14\ 10^{33}\ cm^{-2}s^{-1}$$

Standard deviation of w

$$\Sigma_w = \frac{\sqrt{2}E_0\sigma_\varepsilon}{\lambda} = \frac{0.17}{8.4} = 0.02\ GeV$$

Optimizing the beam parameters we could gain in energy resolution keeping the Luminosity constant and the beam-beam in the standard limits !!!!!!

Rewriting some formulas:

$\sigma^*_y <<< \sigma^*_x$ → $D^*_{x+} = D^*_{x-} = 0$, $D^*_{y+} = -D^*_{y-} = D^*_y$

$$\frac{\sigma_\varepsilon^2 D_y^{*2}}{\sigma_{y\beta}^{*2}} >> 1$$

$$\Sigma_w \simeq \sqrt{2} E_0 \sqrt{\frac{\epsilon_y}{H_y^*}}$$

with $H_y^* = \frac{D_y^{*2}}{\beta_y^*}$ vertical invariant dispersion

$$\xi_{xy} = \frac{N_b r_e \beta^*_{xy}}{2\pi\gamma\sigma^*_{xy}(\sigma^*_x + \sigma^*_y)} \rightarrow L = \frac{I\gamma}{2er_e}\left(\frac{\xi_x}{\beta^*_x} + \frac{\xi_y}{\beta^*_y}\right)$$

with $\sigma^*_y \simeq \sigma_\varepsilon D^*_y$ → $\xi_y << \xi_x \simeq \xi_{max}$

Monochromatization principle "Optimized" Scheme

$\frac{\xi_y}{\beta_y^*}$ is not the dominant term and we have a reduction in the luminosity,

but we could keep the luminosity at the same level if we increase the term, $\frac{\xi_x}{\beta_x^*}$ this is possible by reducing the ϵ_x in this case we have:

$$L \simeq \frac{I\gamma}{2er_e}\frac{\xi_x}{\beta_x^*}$$

with

$\beta^*_x <<< \beta^*_y$
$\sigma^*_x <<< \sigma^*_y$

The beam-beam parameter could be maximized in the plane where dispersion is zero, keeping lower value in the plane where dispersion is different from zero

Monochromatization principle "Optimized" Scheme

The new condition for an optimized scheme are:

$D^*_{x+} = D^*_{x-} = 0$
$D^*_{y+} = - D^*_{y-} = D^*_{y}$

with

$$\sigma_x^* << \sigma_y^* \qquad \xi_y < \xi_x$$
$$\beta_x^* << \beta_y^*$$

$$L \simeq \frac{I\gamma}{2er_e}\frac{\xi_x}{\beta_x^*} \qquad \frac{2\pi\gamma}{N_b r_e}\epsilon_x \xi_x \frac{\beta_y^*}{\beta_x^*} \leq 1$$

Higgs factory:

$$E_0 = 120\ GeV$$

$$\sigma_\varepsilon = 0.001$$

$$\sigma_b = 1.17\ mm$$

$$I = 0.045\ /0.026\ mA$$

$$N_b = 6.89\ 10^{10}\ /\ 3.98\ 10^{10}$$

keeping

choosing

$$L_0 = 6.0\ 10^{34}\ cm^{-2}s^{-1}$$

$$\beta_x^* = 1.0\ mm$$

$$\beta_y^* = 0.15\ m$$

$$D_y^* = 0.367\ m$$

$$\xi_x = 0.04\ /0.087$$

$$\xi_y = 0.015$$

$$\epsilon_x \leq 21.92\ /\ 5.82\ pm$$

Standard:

$$\epsilon_x = 0.94\ nm$$

$$\epsilon_y = 1.9\ pm$$

Conclusions

In A. Blondel words:

The aim is to monochromatize the FCC-ee beams at E_{CM} = 125.2 GeV for the production of e+e- --> H(125.2) in the s-channel, just like a muon collider, but with hopefully much higher luminosity -- and lower cross-section.

The Higgs width is 4.2 MeV and the FCC-ee energy spread is about $5x10^{-4}$ at these energies so one needs to gain a factor 10 in energy spread. We also need to keep the beams polarized to keep track of the beam energy precisely.

It is possible that they don't work for some fundamental reason – then it is useful to know this, too.

There is no fundamental reason against monochomatization, but monochomatization has never been tested experimentally these means a flexible lattice with two modes of operation with/without is mandatory.

Implementation of a “standard” sees not so difficult the “optimized” maybe a dream.

Further studies

Drawbacks:

- D_y* gives rise quantum excitation which increase vertical emittance
- D_y* limited strength and difficult implementation
- Residual coupling
- Aperture limitation
- Dynamic Aperture reduction
- Beam-Beam including parasitic crossings
- Estimations of the broad band and the narrow band impedances and the current limits
- Touschek lifetime
- Polarization ring
- Backgound and masking
- For the FCC-ee D_x* different from zero will be a more natural option

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Thanks for your attention