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Monochromatization for Direct Higgs Production in Future Circular e+e- Colliders

M. Alan Valdivia G.
valdivia@fisica.ugto.mx

RADPyC'17, CINVESTAV,
Mexico City, 250517

Outline

- Motivation
- Objectives
- Introduction: Accelerator Physics
- Standard Monochromatization
- Radiation Effects In FCC
- Optimized Monochromatization
- Conclusion
- Discussion

Motivation

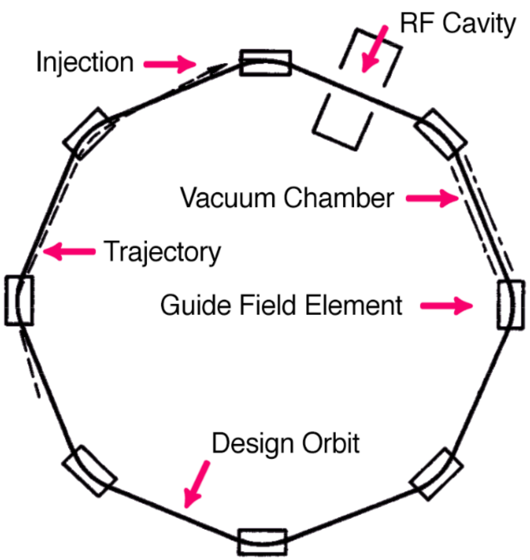
- Questions still unanswered about Higgs boson properties
- Post-LHC high energy resolution requirements
- Upcoming radiation Effects
- FCCe+e- proposal opportunity

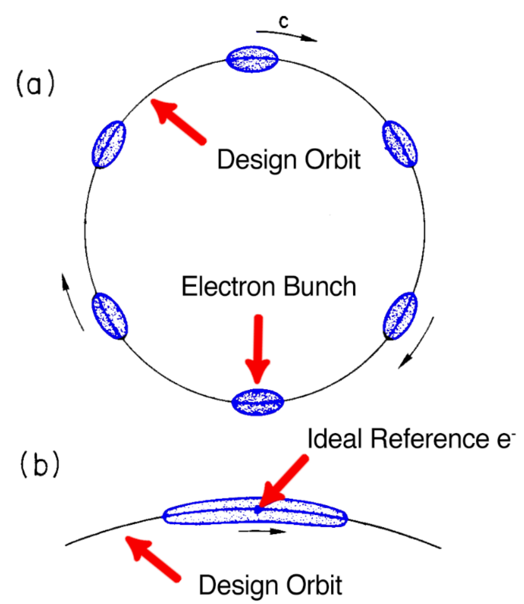
Objectives

- Characterize the radiation effects at the FCCe+e-
- Quantify the IP parameters modification due to the radiation effects.
- Define the IP parameters to produce monochromatization
- Develop an optimized monochromatization scheme for the FCCe+e-

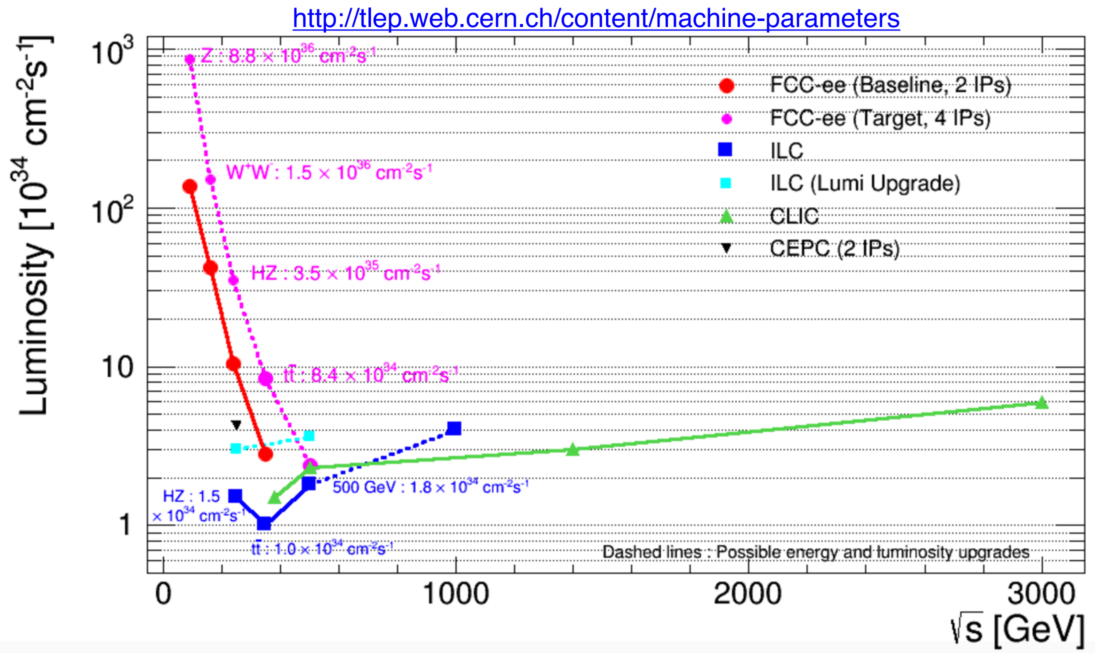
Colliding Particles A Qualitative Description

- Particles are produced at the **source**
- Particles are injected into the **vacuum chamber**
- Stored particles loss energy by **radiation**, compensated by the **RFS**
- Particles are focused by guiding fields toward a **designed orbit**
- Accelerating field collects particles into circulating **bunches**
- Amplitud **damping** occurs due to energy loss by radiation
- Amplitude **excitation** occurs as a quantum effect
- Between damping and excitation a **balance** is reached
- Collision are produced at defined **interaction points**





A proposal Future Circular e+e- Collider



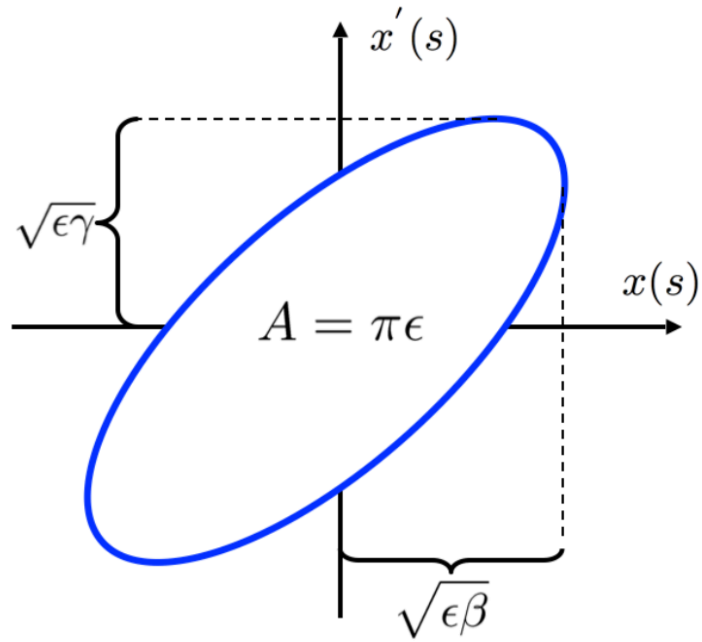
- **Luminosity** is expected of order 10e36
- **Energy** range per beam should be from 40 to 175 GeV
- **Circumference** would be of 100 km
- **Energy Resolution** requires an improvement for direct Higgs production

Hill Differential Equation

$$x'' + K(s)x = 0 \qquad y'' - K(s)y = 0, \qquad K(s) \equiv \frac{1}{(B\rho)}\left(\frac{\partial B_y}{\partial x}\right)(s)$$

$$K(s+C) = K(s)$$

Ansatz $\quad x(s) = A\omega(s)\cos(\phi(x) + \phi_0)$



Courant-Snyder Parameters

$$\beta(s) \equiv \frac{\omega^2(s)}{k} \qquad \alpha(s) \equiv -\frac{1}{2}\beta\prime(s) \qquad \gamma(s) \equiv \frac{1+\alpha^2(s)}{\beta(s)}$$

Emittance

$$\epsilon = \pi\mathcal{W} = \pi[\gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'^2(s)]$$

Size of the Distribution

$$\sigma_{RMS} = \sqrt{\epsilon\beta(s)}$$

Lattice Design Dispersion

Off-Momentum Particles

$$p = p_0(1+\delta)$$

Relative Momentum Deviation

$$\delta \equiv \frac{\Delta p}{p_0}$$

Momentum Contribution

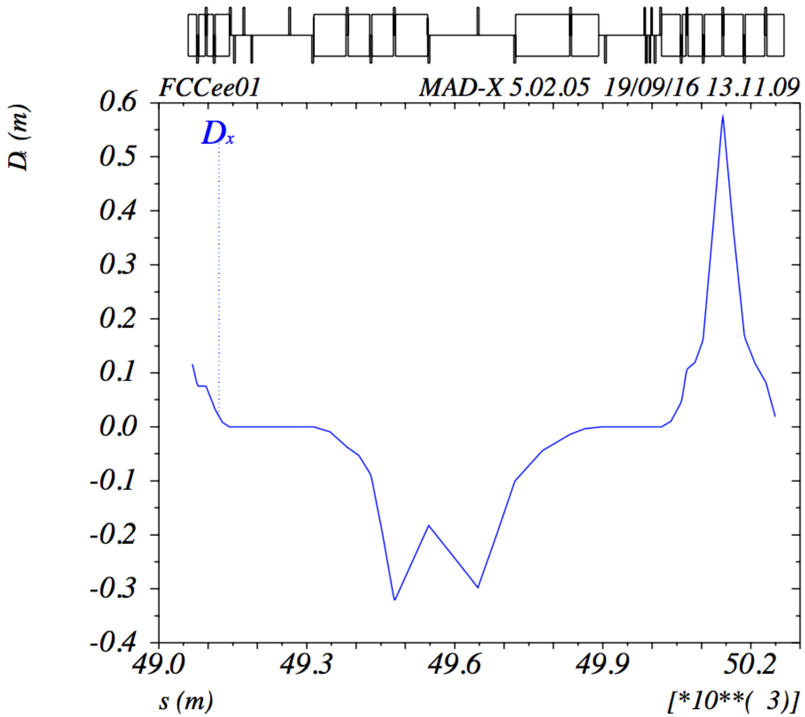
$$x(s) = x_\beta(s) + x_\delta(s)$$

Dispersion Function

$$x_\delta(s) = D(s)\delta$$

Approximations

$$x \ll \rho \qquad \delta \ll 1$$



Dipole Contribution

$$\frac{\partial^2 x}{\partial \theta^2} + (1-n)x = \rho\delta$$

Dispersion Contribution

$$x(\theta) = A\cos\sqrt{1-n}\theta + B\sin\sqrt{1-n}\theta + \frac{\rho}{1-n}\delta$$

General Contribution

$$x'' + K(s)x = \frac{\delta}{\rho(s)}$$

Dispersion Contribution

$$x(s) = C(s)x_0 + S(s)x'_0 + D(s)\delta_0$$

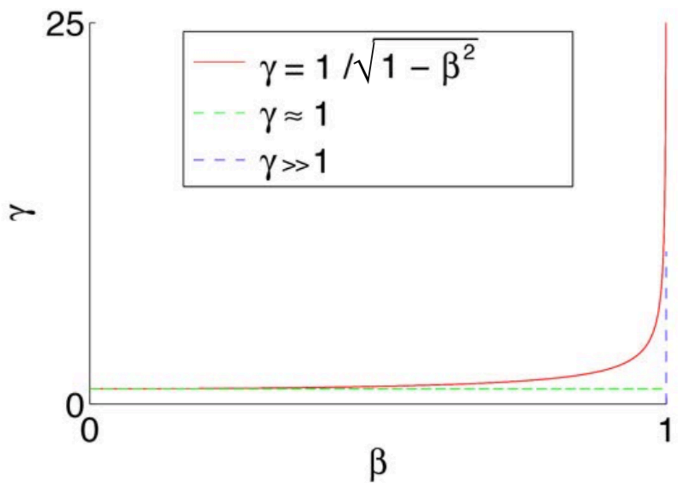
Dispersion Function

$$D(s) = S(s)\int_0^s \frac{C(\tau)}{\rho(\tau)}d\tau - C(s)\int_0^s \frac{S(\tau)}{\rho(\tau)}d\tau$$

Longitudinal Motion Energy Deviation Effects

Off-Energy Particles $E = E_0 + \epsilon$

Off-Energy Contribution $x = x_\beta + x_\epsilon$



Ultrarelativistic Limit

$$E \gg mc^2 \qquad p = \frac{1}{c}\sqrt{E^2 - (mc^2)^2} \approx \frac{E}{c}$$

$$\frac{\Delta p}{p_0} = \frac{\Delta E}{E_0} \qquad \delta = \frac{\epsilon}{E_0}$$

Off-Energy Contribution $x_\epsilon = D(s)\epsilon/E_0$

Equation of Motion for Off-Energy Particles

$$x'' = -K_x x + G\left(\frac{\epsilon}{E_0}\right)$$

Radius of Curvature

$$G(s) = \rho^{-1}(s)$$

Dispersion Equation $D''(s) = -K_x D(s) + G(s)$

Beam Parameters Distributions

Transverse Displacement $x = x_\beta + D_x \epsilon_0, \qquad y = y_\beta + D_y \epsilon_0 \qquad \epsilon_0 = \frac{\epsilon}{E_0}$

Phase Space Distribution

$$f^\pm(x,y,\epsilon) = \frac{f^\pm(p_x,p_y,z)}{\sqrt{8\pi^3 \beta_x^* \epsilon_{xc} \beta_y^* \epsilon_{yc} \sigma_\epsilon^2}} \exp\left\{ -\frac{(x_\beta + D_x \epsilon_0)^2}{2\beta_x^* \epsilon_{xc}} - \frac{(y_\beta + D_y \epsilon_0)^2}{2\beta_y^* \epsilon_{yc}} - \frac{\epsilon^2}{2\sigma_\epsilon^2} \right\}$$

Average at the IP $\langle \mathcal{A} \rangle^\pm = \int f^\pm(X^\pm) \mathcal{A}(X^+, X^-) dX^\pm \qquad \langle \mathcal{A} \rangle^* = \left\langle \langle \mathcal{A} \rangle^+ \right\rangle^- = \left\langle \langle \mathcal{A} \rangle^- \right\rangle^+$

Average over distribution

$$\sigma_x^* = \sqrt{\langle x^2 \rangle^\pm} = \sqrt{\beta_x^* \epsilon_{xc} + D_x^{*2} \sigma_\epsilon^2} \qquad \langle x\epsilon_0 \rangle^\pm = D_x^{*\pm} \sigma_\epsilon^2 \qquad \sigma_\epsilon^* = \sqrt{\langle \epsilon_0^2 \rangle^\pm}$$

$$\sigma_y^* = \sqrt{\langle y^2 \rangle^\pm} = \sqrt{\beta_y^* \epsilon_{yc} + D_y^{*2} \sigma_\epsilon^2} \qquad \langle y\epsilon_0 \rangle^\pm = D_y^{*\pm} \sigma_\epsilon^2$$

Notes

- **Relative Momentum Deviation** of particles differs from ideality
- **Dispersion** quantifies the effects on displacement due to off-momentum particles
- **Emittance** is a measure of how far our distribution is from ideal orbit
- **Beta Function** is related to the physical transverse size of bunches

Standard Monochromatization

Monochromatization Colliding Beams

Collision Energy Spread $\sigma_w = \sqrt{2} E_0 \sigma_\epsilon$

Beam Energy Spread $\sigma_\epsilon{}^2 \propto \frac{55 \hbar c E_0{}^2}{32\sqrt{3}(mc^2)^3} \frac{I_3}{I_2} \frac{1}{J_\epsilon}$

Function of radius and J_ϵ $\sigma_w \propto (\rho J_\epsilon)^{-1/2}$. $J_\epsilon \in [0.5, 2.5]$

Typical Options $\left. \begin{array}{l} \rho >> \rho_0 \\ J_\epsilon > J_{0\epsilon} \end{array} \right\} \Rightarrow \sigma_w < \sigma_{0w}$

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Principle of Monochromatization

Monochromatization Factor

$$\lambda \equiv \frac{\mathcal{L}_0}{\mathcal{L}}$$

Baseline Scheme $D^*_{x+} = -D^*_{x-} = 0$ $\mathcal{L} = \mathcal{L}_0$

Monochromatization principle A “simple explanation”

Standard collision Dispersion has the same sign in the IP

$$
\begin{array}{ccccc}
 & \xrightarrow{E+\Delta E} & & \xleftarrow{E+\Delta E} & \\
e^- & \xrightarrow{E} & & \xleftarrow{E} & e^+ \\
 & \xrightarrow{E-\Delta E} & & \xleftarrow{E-\Delta E} &
\end{array}
$$

$$w = 2(E_0 + \epsilon)$$

Monochromatization principle A "simple explanation"

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$$
\begin{array}{ccc}
 & \xrightarrow{E+\Delta E} \quad \xleftarrow{E+\Delta E} & \\
e^- & \xrightarrow{E} \quad \xleftarrow{E} & e^+ \\
 & \xrightarrow{E-\Delta E} \quad \xleftarrow{E-\Delta E} &
\end{array}
$$

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Monochromatization Dispersion has opposite sign in the IP

$$
\begin{array}{ccc}
 & \xrightarrow{E+\Delta E} \quad \xleftarrow{E-\Delta E} & \\
e^- & \xrightarrow{E} \quad \xleftarrow{E} & e^+ \\
 & \xrightarrow{E-\Delta E} \quad \xleftarrow{E+\Delta E} &
\end{array}
$$

$$w = 2E_0 + 0(\epsilon)^2$$

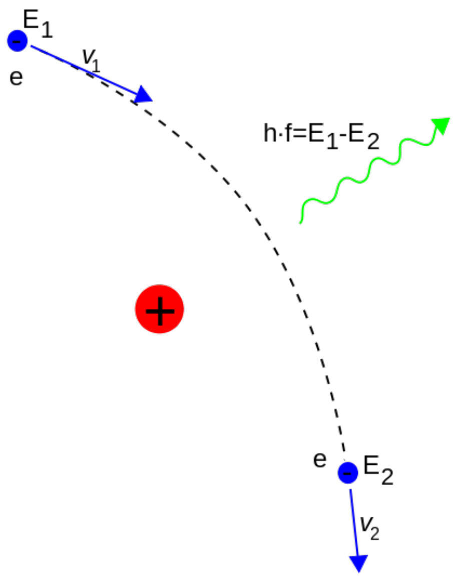
Notes

- **Baseline Parameters** fail to produce the required center-of-mass energy resolution for direct Higgs production at 125 GeV
- **Higgs Width** of ~4.2 MeV requires an improvement in resolution by at least a factor of 10 since baseline produced a ~40 MeV width distribution
- **Double Ring System** of the FCCee may produced dispersion at the interaction point as required for monochromatization.
- **Radiation Effects** could compromise the performance of a monochromatization scheme

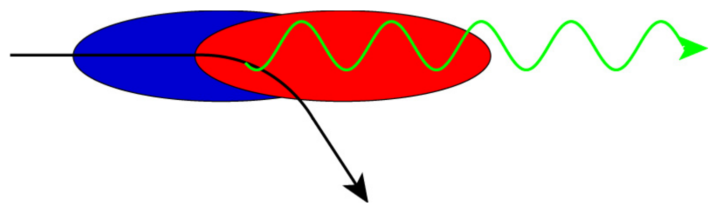
Radiation Effects

Beamstrahlung Sokolov-Ternov Theory

Breamsstrahlung



Beamstrahlung



Lorentz Invariant

$$\Upsilon \equiv \frac{e}{m_e^3}\sqrt{|(F_{\mu\nu}p^\nu)^2|} = \frac{B}{B_c} = \frac{2}{3}\frac{\hbar\omega_c}{E_e}$$

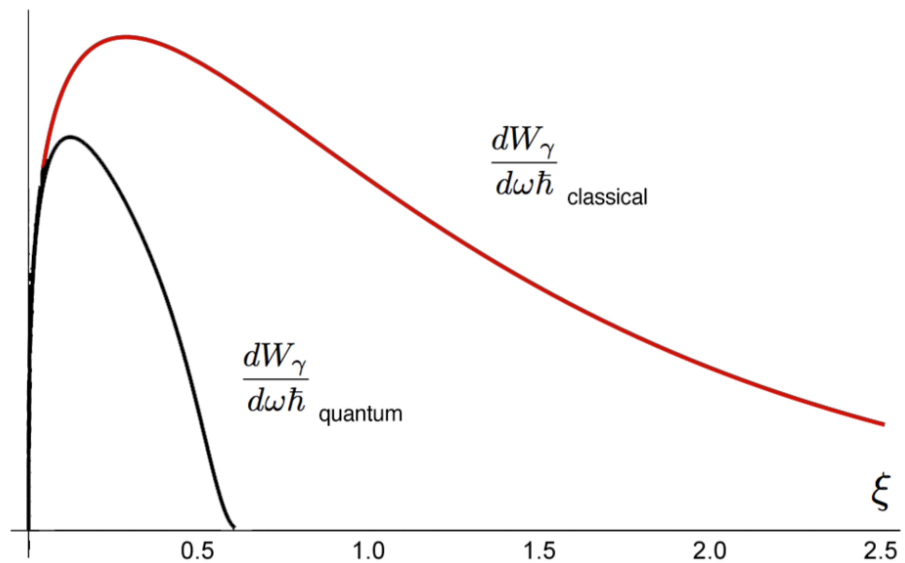
$$\Upsilon_{\mathrm{max}} = 2\frac{r_e^2\gamma N_b}{\alpha\sigma_z(\sigma_x^* + \sigma_y^*)}$$

$$\Upsilon_{\mathrm{ave}} \approx \frac{5}{12}\Upsilon_{\mathtt{max}} = \frac{5}{6}\frac{r_e^2\gamma N_b}{\alpha\sigma_z^*(\sigma_x^* + \sigma_y^*)}$$

Quantum Spectrum Formula

$$\frac{dW_\gamma}{d\omega\hbar} = \frac{\alpha}{\sqrt{3}\hbar\pi\gamma^2}\left(\int_\xi^\infty K_{5/3}(\xi')\,d\xi' + \frac{y^2}{1-y}K_{2/3}(\xi)\right)$$

$$\xi = \frac{2\hbar\omega}{3\Upsilon(E - \hbar\omega)} \qquad\qquad y \equiv \omega/E_e$$



Beamstrahlung Sokolov-Ternov Theory

Relative Energy Loss

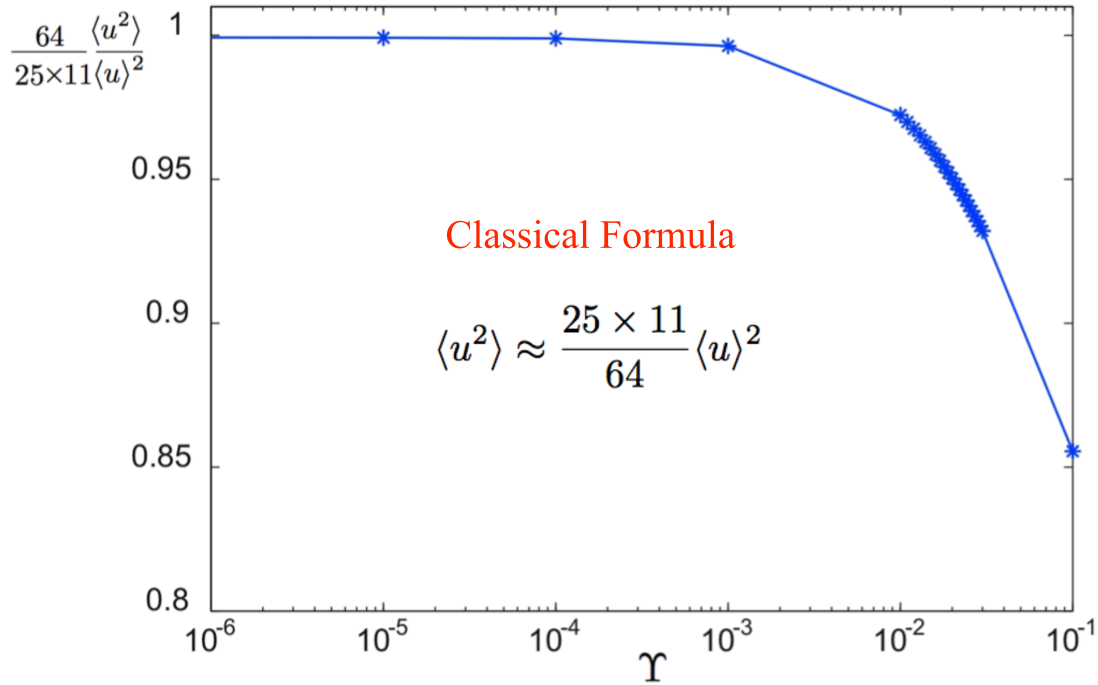
$$\delta_B \approx \frac{24}{3\sqrt{3}\pi^{3/2}} \frac{r_e^3 \gamma N_b^2}{\sigma_z(\sigma_x + \sigma_y)^2} \approx \frac{24}{3\sqrt{3}\pi^{3/2}} \frac{r_e^3 \gamma N_b^2}{\sigma_z \sigma_x^2}$$

Average Emitted Photons

$$n_\gamma \approx \frac{12}{\pi^{3/2}} \frac{\alpha r_e N_b}{\sigma_x + \sigma_y} \approx \frac{12}{\pi^{3/2}} \frac{\alpha r_e N_b}{\sigma_x}$$

Statistical Properties

$$\langle u \rangle = \frac{\delta_B}{n_\gamma} \approx \frac{2\sqrt{3}}{9} \frac{r_e^2 N_b \gamma}{\alpha \sigma_z \sigma_x}$$



Excitation Term

$$n_\gamma \langle u^2 \rangle \approx 1.4 \frac{r_e^5 N_b^3 \gamma^2}{\alpha \sigma_z^2 (\sigma_x + \sigma_y)^3} \approx 192 \frac{r_e^5 N_b^3 \gamma^2}{\sigma_z^2 \sigma_x^3}$$

Beamstrahlung Self-Consistant Energy Spread

Total Energy Spread $$\sigma_{\rm tot}^2 = \sigma_{\delta,\rm SR}^2 + \sigma_{\delta,\rm BS}^2$$

$$\sigma_{\delta,\rm tot}^2 - \sigma_{\delta,\rm SR}^2 = A\left(\frac{\sigma_{\delta,\rm SR}}{\sigma_{\delta,\rm tot}}\frac{1}{\sigma_{z,\rm SR}}\right)^2$$

$$\sigma_{\delta,\rm tot} = \left[\frac{1}{2}\sigma_{\delta,\rm SR}^2 + \left(\frac{1}{4}\sigma_{\delta,\rm SR}^4 + A\frac{\sigma_{\delta,\rm SR}^2}{\sigma_{z,\rm SR}^2}\right)^{1/2}\right]^{1/2}$$

Bunch Length

$$\sigma_{z,\rm tot} = \frac{\alpha_{\rm C} C}{2\pi Q_s}\sigma_{\delta,\rm tot}$$

Dispersion Invariant

$$\mathcal{H}_x^* \equiv \frac{\left(\beta_x^* D_x'^{\,*} + \alpha_x^* D_x^*\right)^2 + D_x^{*\,2}}{\beta_x^*}$$

Self-Consistent Equations

$$\epsilon_{x,\rm tot} = \epsilon_{x,\rm SR} + \frac{\tau_x n_{\rm IP}}{4T_{\rm rev}}\{n_\gamma < u^2 >\}\mathcal{H}_x^*$$

$$\sigma_{\delta,\rm tot}^2 = \sigma_{\delta,\rm SR}^2 + \frac{n_{\rm IP}\tau_{E,\rm SR}}{4T_{\rm rev}}\{n_\gamma < u^2 >\}$$

Optimized Monochromatization

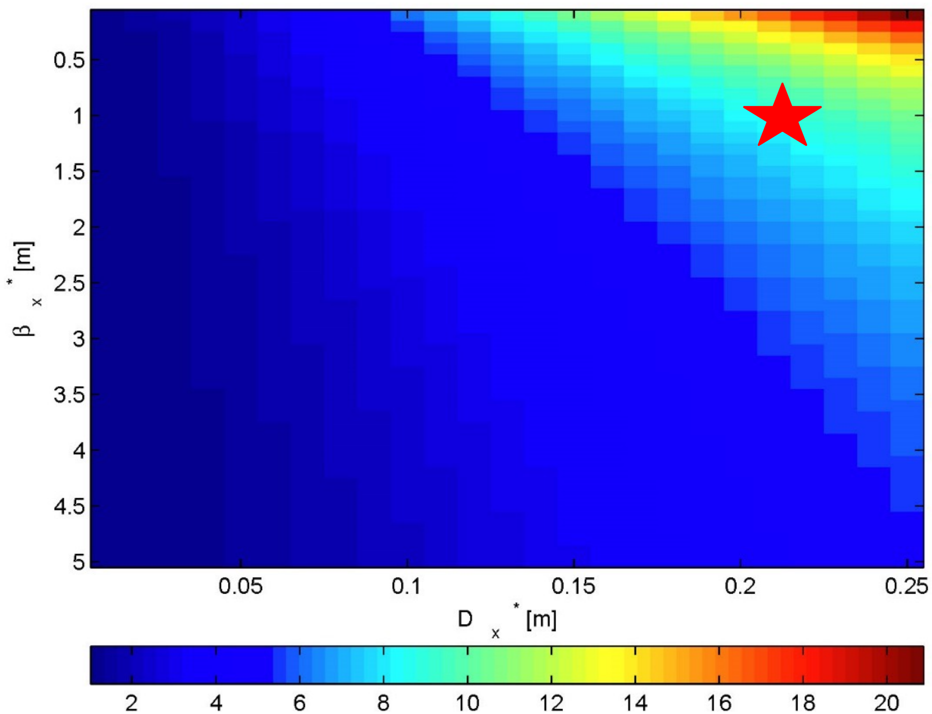
Baseline monochromatization

E_e [GeV]	62.5
scheme	m.c. basel.
I_b [mA]	408.3
N_b [10^{10}]	3.3
n_b [1]	25760
n_{IP} [1]	2
β_x^* [m]	1.0
β_y^* [mm]	2
D_x^* [m]	0.22
$\epsilon_{x,\mathrm{SR}}$ [nm]	0.17
$\epsilon_{x,\mathrm{tot}}$ [nm]	0.21
$\epsilon_{y,\mathrm{SR}}$ [pm]	1
$\sigma_{x,\mathrm{SR}}$ [μm]	132
$\sigma_{x,\mathrm{tot}}$ [μm]	144
σ_y [nm]	45
$\sigma_{z,\mathrm{SR}}$ [mm]	1.8
$\sigma_{z,\mathrm{tot}}$ [mm]	1.8
$\sigma_{\delta,\mathrm{SR}}$ [%]	0.06
$\sigma_{\delta,\mathrm{tot}}$ [%]	0.06
θ_c [mrad]	0
circ. C [km]	100
α_C [10^{-6}]	7
f_{rf} [MHz]	400
V_{rf} [GV]	0.4
$U_{0,\mathrm{SR}}$ [GeV]	0.12
$U_{0,\mathrm{BS}}$ [MeV]	0.01
τ_E/T_{rev}	509
Q_s	0.030
Υ_{max} [10^{-4}]	0.3
Υ_{ave} [10^{-4}]	0.1
θ_c [mrad]	0
ξ_x [10^{-2}]	1
ξ_y [10^{-2}]	4
λ [1]	9.2
L [10^{35} cm^{-2}s^{-1}]	1.0
σ_w [MeV]	5.8

Width of standard model Higgs 4-5 MeV requires $\lambda \geq 10$

$N_b = 3.3\mathrm{x}10^{10}$ $n_b = 25760$ $\beta_y^* = 2$ mm

Monochromatization Factor



★: $\lambda = 9.2$, $L = 1 \times 10^{35}$ cm^{-2}s^{-1}

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θ_c [mrad]	0
ξ_x [10^{-2}]	1
ξ_y [10^{-2}]	4
λ [1]	9.2
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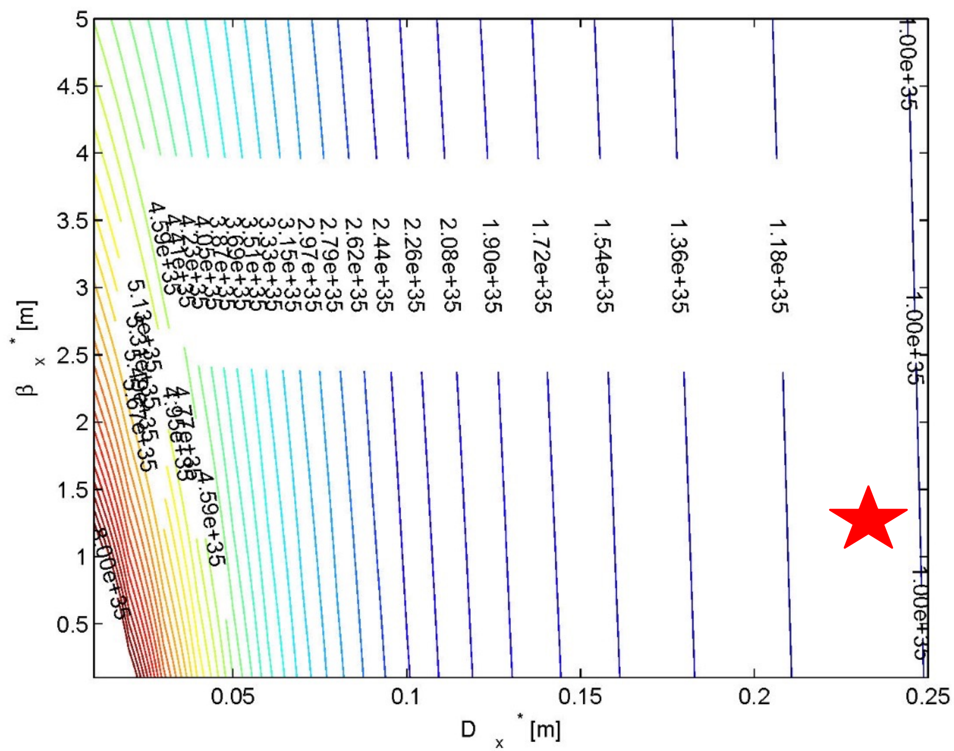
Luminosity contours



★ : $\lambda = 9.2$, $L = 1 \mathrm{~x~} 10^{35}$ cm^{-2}s^{-1}

Optimized Monochromatization Luminosity_max and λ

$S = [\ 0.1\ ,\ 3\ ]$, $T = [\ 0.1\ ,\ 3\ ]$

$\beta_{0x} = 1.0$ m, $\beta_{0y} = 1.0$ mm

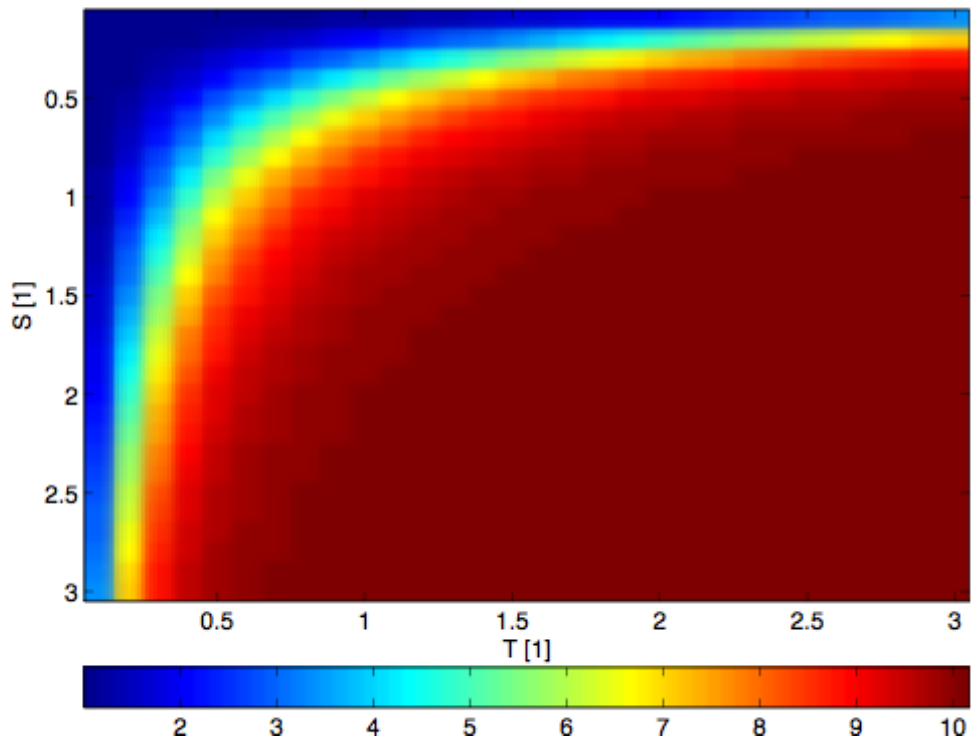
$D_{0x} = 0.22$ m

$N_{0b} = 3.3\mathrm{x}10^{10}$, $n_{0b} = 25760$

$\beta_x = \beta_{0x} * S^2$, $D_x * = D_{0x} * S$

$N_b = N_{0b} / T$, $n_b = n_{0b} * T$

Monochromatization Factor



★ : $\lambda_0 = 10.17321$

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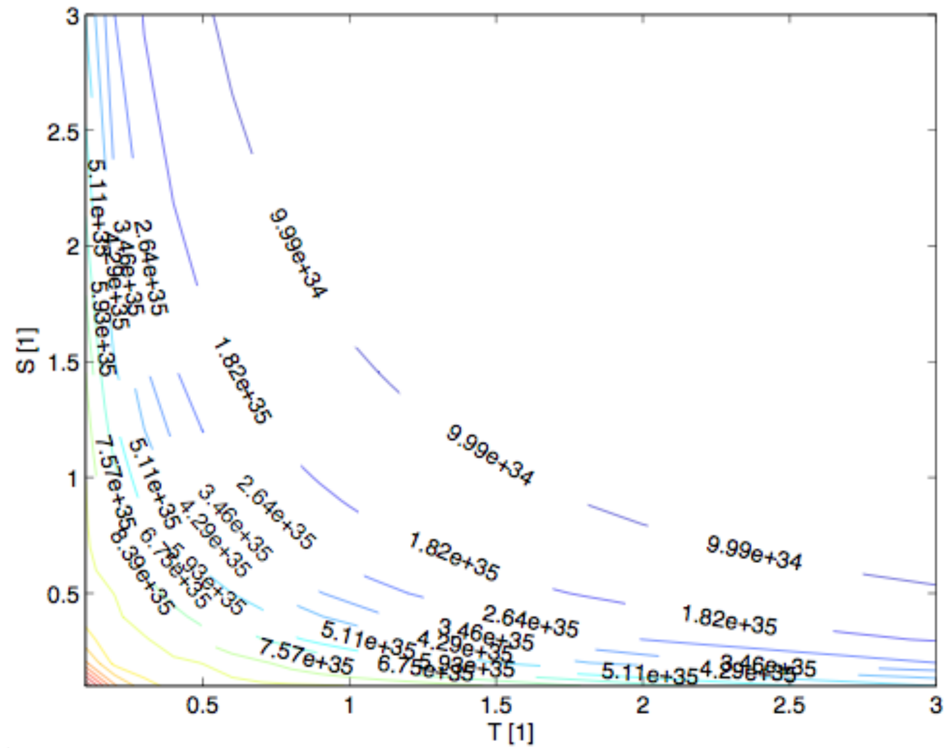

★ : $\lambda_0 = 10.17321$, $L \sim 1 \times 10^{36}$ $cm^{-2}s^{-1}$

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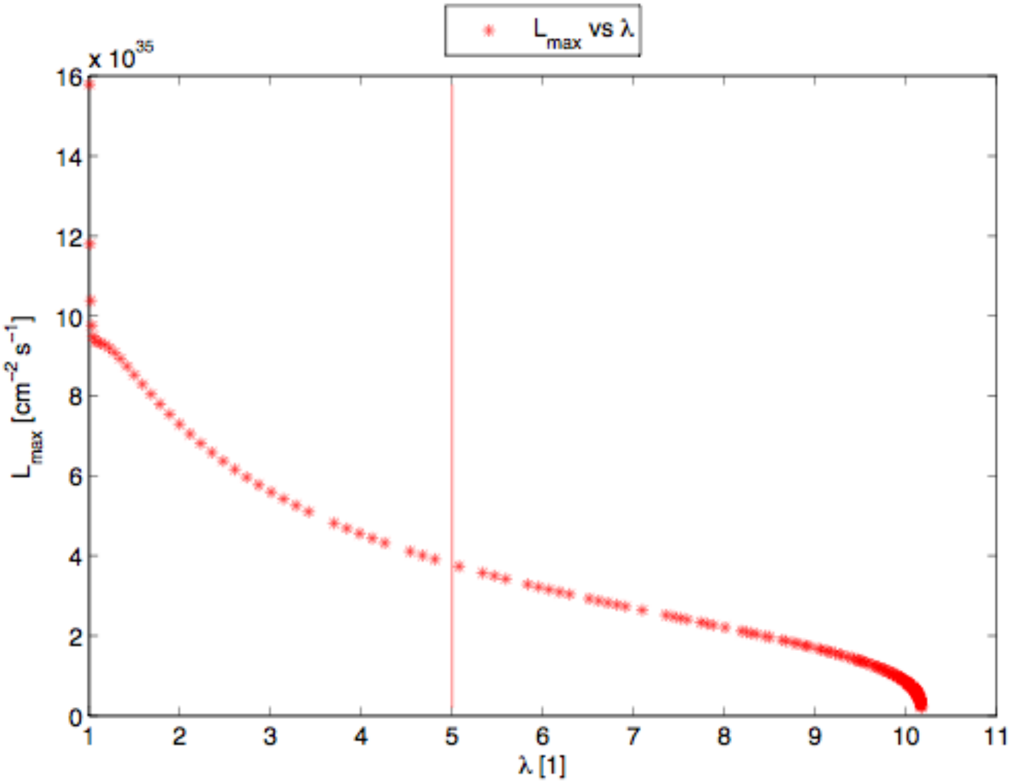

L_{max} vs λ

★ : $\lambda_0 = 10.17321$, $L \sim 1 \times 10^{36}\ cm^{-2}s^{-1}$

Luminosity_max and λ

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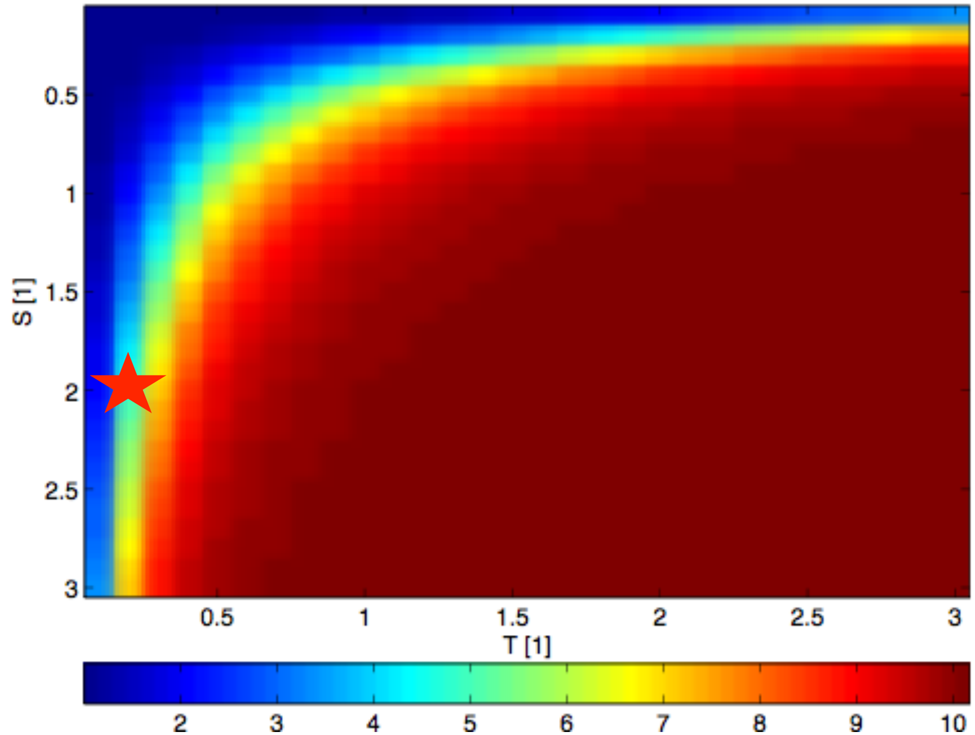
Monochromatization Factor



★ : $\lambda = 5.07$, $\beta = 1.96$ m, $D_x = 0.308$ m, $L = 3.736 \times 10^{35}$ $cm^{-2}s^{-1}$

Conclusions

★ : $\lambda = 5.07$, $\beta = 1.96$ m, $D_x = 0.308$ m, $L = 3.736 \times 10^{35}$ $cm^{-2}s^{-1}$

E_e [GeV]	45.6	62.5	62.5	62.5	80
scheme	CW	h.-o.	m.c. basel.	m.c. opt'd	CW
I_b [mA]	1450.3	408.3	408.3	408.3	151.5
N_b [10^{10}]	3.3	1.05	3.3	11.1	6.0
n_b [1]	91500	80960	25760	7728	5260
n_{IP} [1]	2	2	2	2	2
β_x^* [m]	1	1.0	1.0	1.96	1
β_y^* [mm]	2	2	2	1	2
D_x^* [m]	0	0	0.22	0.308	0
$\epsilon_{x,\mathrm{SR}}$ [nm]	0.09	0.17	0.17	0.17	0.26
$\epsilon_{x,\mathrm{tot}}$ [nm]	0.09	0.17	0.21	0.70	0.26
$\epsilon_{y,\mathrm{SR}}$ [pm]	1	1	1	1	1
$\sigma_{x,\mathrm{SR}}$ [μm]	9.5	9.2	132	185.7	16
$\sigma_{x,\mathrm{tot}}$ [μm]	9.5	9.2	144	188.5	16
σ_y [nm]	45	45	45	32	45
$\sigma_{z,\mathrm{SR}}$ [mm]	1.6	1.8	1.8	1.8	2.0
$\sigma_{z,\mathrm{tot}}$ [mm]	3.8	1.8	1.8	1.8	3.1
$\sigma_{\delta,\mathrm{SR}}$ [%]	0.04	0.06	0.06	0.06	0.07
$\sigma_{\delta,\mathrm{tot}}$ [%]	0.09	0.06	0.06	0.06	0.10
θ_c [mrad]	30	0	0	0	30
circ. C [km]	100	100	100	100	100
α_C [10^{-6}]	7	7	7	7	7
f_{rf} [MHz]	400	400	400	400	400
V_{rf} [GV]	0.2	0.4	0.4	0.4	0.8
$U_{0,\mathrm{SR}}$ [GeV]	0.03	0.12	0.12	0.12	0.33
$U_{0,\mathrm{BS}}$ [MeV]	0.5	0.05	0.01	0.01	0.21
τ_E/T_{rev}	1320	509	509	509	243
Q_s	0.025	0.030	0.030	0.030	0.037
Υ_{max} [10^{-4}]	1.7	0.8	0.3	0.85	4.0
Υ_{ave} [10^{-4}]	0.7	0.3	0.1	0.35	1.7
θ_c [mrad]	30	0	0	0	30
ξ_x [10^{-2}]	5	12	1	2.22	7
ξ_y [10^{-2}]	13	15	4	6.76	16
λ [1]	1	1	9.2	5.08	1
L [10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	9.0	2.2	1.0	3.74	1.9
σ_w [MeV]	58	53	5.8	10.44	113

- **Monochromatization** scheme can be implemented
- **Beamstrahlung** effects may be controlled
- **Simulation** supports predictions
- **Lattice** designed is still in progress and the required modification should be possible
- **Theory** confirmation could be achieved at the FCCe+e-

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L(λ)

Monochromatization for Direct Higgs Production in Future Circular e+e- Colliders

M. Alan Valdivia G.
valdivia@fisica.ugto.mx

RADPyC'17, CINVESTAV,
Mexico City, 250517