Monochromatization and large crossing angle

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Introduction

Direct s-channel H production in e^+e^- collisions, with a collision energy around 125 GeV, allows the measurement of the Hee Yukawa coupling, provided that the centre-of-mass energy spread, σ_M, can be reduced to about 6–10 MeV to be comparable to the width of the standard model Higgs boson $\Gamma_H = 4.2$ MeV.

FCC-ee: The Lepton Collider : Future Circular Collider Conceptual Design Report Volume 2

FCC Collaboration: A. Abada (CNRS, France) et al.

Eur.Phys.J.ST 228 (2019) 2, 261-623

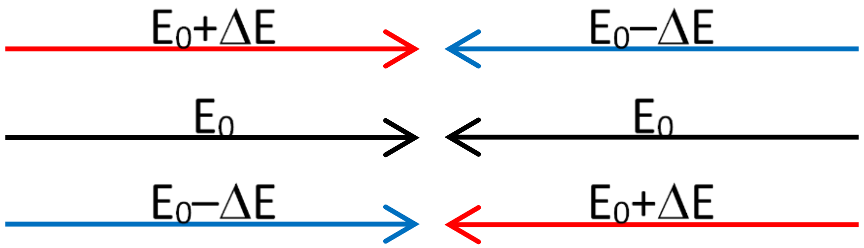
Objectives:

- Beam energy $E = 62.5\ \mathrm{GeV}$
- $\sigma_M = 6 \div 10$ MeV
- Maximum luminosity

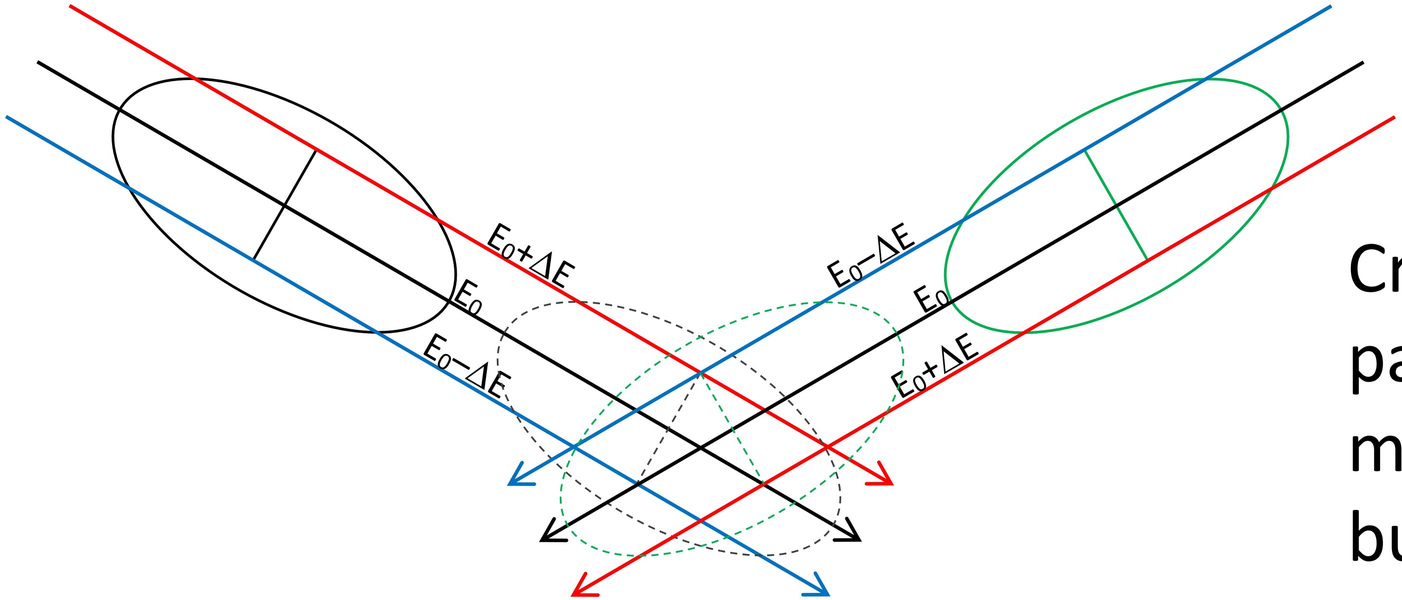
Conditions and Assumptions

- Coupling $\varepsilon_y = 0.0037\varepsilon_x$ (CDR value)
- Parameters $(\varepsilon_x, \sigma_\delta, U_0)$ from CDR Z-lattice scaled with E_{beam}
- Beamstrahlung considered analytically

Monochromatization



Head-on collisions by A. Renieri (Adone, 1975)



Crossing angle collisions:
particle with particular energy
meets particles with all energies
but at different densities

Monochromatization: luminosity

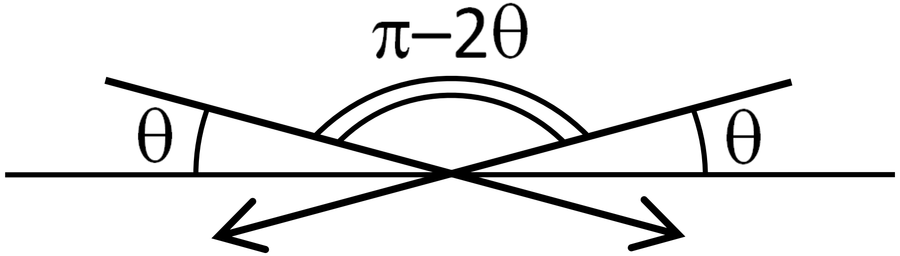
$$L = f_0(1+\cos 2\theta)\int n_1(x,y,s,t,\delta_1)n_2(x,y,s,t,\delta_2)dx\,dy\,ds\,dct\,d\delta_1 d\delta_2$$

$$\frac{\partial^2 L}{\partial\delta_1\partial\delta_2} = \frac{L_0}{2\pi\,\sigma_\delta^2}\exp\left[-\frac{(\delta_1-\delta_2)^2}{4\sigma_\delta^2} - \Lambda^2\frac{(\delta_1+\delta_2)^2}{4\sigma_\delta^2}\right]$$

$$L = \frac{N_1 N_2}{4\,\pi\sigma_x\sigma_y\sqrt{1+\varphi^2}}\frac{1}{\Lambda} = \frac{L_0}{\Lambda}$$

$$\Lambda^2 = 1 + \frac{\psi_x^2\sigma_\delta^2}{\sigma_x^2(1+\varphi^2)}, \qquad \varphi = \frac{\sigma_z\tan\theta}{\sigma_x}, \qquad \sigma_x = \sqrt{\varepsilon_x\beta_x}$$

Monochromatization: invariant mass



$$\langle M^2 \rangle = 4E_0^2 (\cos\theta)^2 - 2E_0^2 \left(\sigma_{x'}^2 + \sigma_{y'}^2\right) \cos 2\theta$$

$$\sigma_M^2 = 2\, E_0^2 \left[\left(\frac{\sigma_\delta \cos\theta}{\Lambda} \right)^2 + (\sigma_{x'} \sin\theta)^2 \right]$$

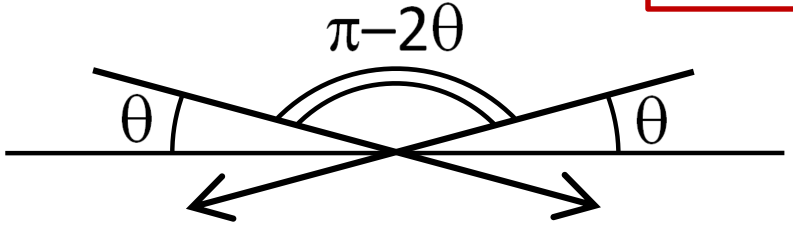
$$\Lambda = \sqrt{1 + \frac{\psi_x^2 \sigma_\delta^2}{\sigma_x^2 (1 + \varphi^2)}}$$

Simple considerations

$$\sigma_M = \sqrt{2}\,E_0\sqrt{\left(\frac{\sigma_\delta\cos\theta}{\Lambda}\right)^2 + (\sigma_{x'}\sin\theta)^2} \approx \sqrt{2}E_0\frac{\sigma_\delta\cos\theta}{\Lambda}$$

$$\sigma_\delta\cos\theta = (5.2\div 12)\times 10^{-4}$$

$$\sigma_{x'}\sin\theta = (6\div 12)\times 10^{-5}\times 0.015$$



$$\Lambda = \sqrt{1+\frac{\psi_x^2\sigma_\delta^2}{\sigma_x^2(1+\varphi^2)}} \approx \frac{\psi_x\sigma_\delta}{\sigma_x}$$

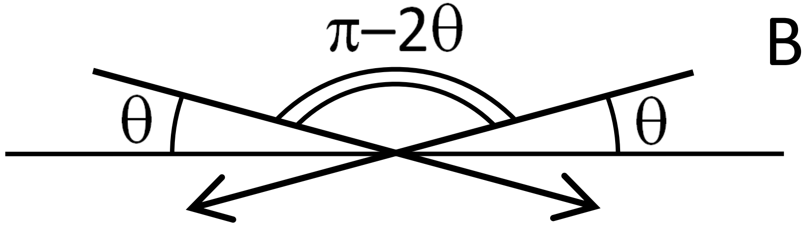
$$\sigma_x \approx \begin{cases} 8.7\times 10^{-6}\mathrm{m}, \psi_x = 0 \\ (2\div 3)\times 10^{-5} m, \psi_x = 0.1\div 1 \end{cases}$$

$$\varphi = \frac{\sigma_z\tan\theta}{\sigma_x} = \begin{cases} 11,\ \psi_x = 0 \\ 0.5\div 1,\ \psi_x = 0.1\div 1 \end{cases}$$

Simple considerations

$$\sigma_M \approx \sqrt{2}E_0\frac{\sigma_x}{\psi_x} \le 10\ \text{MeV} \implies \psi_x \ge 0.08\ \text{m}$$

Depend on ψ_x, N_p



But, beamstrahlung $\sigma_x(\psi_x, N_p), \varepsilon_x(\psi_x, N_p), \sigma_\delta(\psi_x, N_p)$!

$$L = \frac{N_1 N_2}{4\,\pi\sigma_x\sigma_y\sqrt{1+\varphi^2}}\frac{1}{\Lambda}$$

Depend on ψ_x, N_p

Beamstrahlung (simplified)

$$\frac{1}{\rho_x} = \frac{1}{\rho_y} = \frac{N_p r_e}{\gamma \sigma_z \sqrt{\sigma_x^2 + \psi_x^2 \sigma_\delta^2}}, \qquad l = \sqrt{\frac{\pi}{2}} \frac{\sigma_z}{\sqrt{1 + \frac{(\sigma_z \tan\theta)^2}{\sigma_x^2 + \psi_x^2 \sigma_\delta^2}}}$$

$$\frac{1}{\rho^2} = \frac{1}{\rho_x^2} + \frac{1}{\rho_y^2},$$

$$\sigma_\delta \propto \frac{1}{\sqrt{|\rho|}}, \qquad \sigma_x \propto \frac{|\psi_x|}{\sqrt{|\rho|}}$$

Model comparison for Z and WW

	Z CDR	**Z Model**	**WW CDR**	**WW Model**
Beam energy [GeV]	45.6	**45.6**	80	**80**
Energy spread (BS)σ_δ $[10^{-4}]$	13.2	**10**	13.1	**11.7**
Bunch length (BS) σ_z [mm]	12.1	**9.2**	6.0	**5.3**
Piwinski angle (BS) φ	28.5	**22**	7.0	**6.2**
Luminosity / IP $[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	**288**	28	**29.5**

Model accuracy ≤30%

Monochromatization at $E_{beam} = 62.5$ GeV

	0	**1**			
Dispersion ψ_x [m]	0	0			
Bunch population N_p $[10^{11}]$	1.7	0.1			
Bunches per beam	4620	80240			
Horizontal/Vertical β^* [mm]	150/0.8	150/0.8			
RF voltage [GV]	0.4	0.4			
Energy spread (BS)σ_δ $[10^{-4}]$	12.2	5.3			
Bunch length (BS) σ_z [mm]	6.5	2.85			
Λ	1	1			
Invariant mass spread σ_M[MeV]	107	47			
Luminosity / IP $[10^{34}/\mathrm{cm}^2\mathrm{s}]$	79	10			

Monochromatization at $E_{beam} = 62.5$ GeV

	0	**1**	**2**		
Dispersion ψ_x [m]	0	0	0.125		
Bunch population N_p $[10^{11}]$	1.7	0.1	0.1		
Bunches per beam	4620	80240	80240		
Horizontal/Vertical β^* [mm]	150/0.8	150/0.8	50/0.8		
RF voltage [GV]	0.4	0.4	4		
Energy spread (BS)σ_δ $[10^{-4}]$	12.2	5.3	5.2		
Bunch length (BS) σ_z [mm]	6.5	2.85	0.86		
Λ	1	1	4.5		
Invariant mass spread σ_M[MeV]	107	47	10.2		
Luminosity / IP $[10^{34}/\mathrm{cm}^2\mathrm{s}]$	79	10	4.3		

Monochromatization at $E_{beam} = 62.5$ GeV

	0	1	2	3	
Dispersion ψ_x [m]	0	0	0.125	0.25	
Bunch population N_p $[10^{11}]$	1.7	0.1	0.1	0.5	
Bunches per beam	4620	80240	80240	16047	
Horizontal/Vertical β^* [mm]	150/0.8	150/0.8	50/0.8	150/0.8	
RF voltage [GV]	0.4	0.4	4	2	
Energy spread (BS)σ_δ $[10^{-4}]$	12.2	5.3	5.2	5.3	
Bunch length (BS) σ_z [mm]	6.5	2.85	0.86	1.2	
Λ	1	1	4.5	5	
Invariant mass spread σ_M[MeV]	107	47	10.2	9.5	
Luminosity / IP $[10^{34}/\mathrm{cm}^2\mathrm{s}]$	79	10	4.3	6.2	

Monochromatization at $E_{beam} = 62.5$ GeV

	0	**1**	**2**	**3**	**4**
Dispersion ψ_x [m]	0	0	0.125	0.25	0.5
Bunch population N_p $[10^{11}]$	1.7	0.1	0.1	0.5	2
Bunches per beam	4620	80240	80240	16047	4011
Horizontal/Vertical β^* [mm]	150/0.8	150/0.8	50/0.8	150/0.8	450/0.8
RF voltage [GV]	0.4	0.4	4	2	1
Energy spread (BS)σ_δ $[10^{-4}]$	12.2	5.3	5.2	5.3	5.6
Bunch length (BS) σ_z [mm]	6.5	2.85	0.86	1.2	1.84
Λ	1	1	4.5	5	5
Invariant mass spread σ_M[MeV]	107	47	10.2	9.5	9.7
Luminosity / IP $[10^{34}/\text{cm}^2\text{s}]$	79	10	4.3	6.2	7.4

Conclusion

Monochromatization is possible, but

- σ_M enhancement means luminosity drop – is it satisfactory?
- the bunch length is less than 2 mm – is it feasible for collective effects?
- what dispersion does the lattice allow?
- calculations should be checked by beam-beam simulation

References and Disclaimer

Beam-beam effects investigation and parameters optimization for a circular e+e- collider TLEP to study the Higgs boson, A. Bogomyagkov, E. Levichev, D. Shatilov, Phys.Rev.ST Accel.Beams 17 (2014), 041004

Collision monochromatization in e^+e^- colliders, A. Bogomyagkov, E. Levichev, Phys.Rev.Accel.Beams 20 (2017) 5, 051001, Phys.Rev.Accel.Beams 21 (2018) 2, 029902 (erratum)

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