Letter of Interest for Snowmass 2021

Monochromatization of e^+e^- colliders with a large crossing angle

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The relative center-of-mass energy spread σ_W/W at e^+e^- colliders is $\mathcal{O}(10^{-3})$, which is much larger than the widths of narrow resonances produced in the s-channel in e^+e^- collisions. This circumstance greatly lowers the resonance production rates of J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$. Thus, a significant reduction of the center-of-mass energy spread would open up great opportunities in the search for new physics in rare decays of narrow resonances, the search for new narrow states with small $\Gamma_{e^+e^-}$, the study of true muonium and tauonium, etc. The existing monochromatization scheme is only suitable for head-on collisions, while e^+e^- colliders with crossing angles (the so-called Crab Waist collision scheme) can provide significantly higher luminosity due to reduced collision effects. In the paper [1] a new monochromatization method for colliders with a large crossing angle was proposed. The contribution of the beam energy spread to the spread of the center-of-mass energy is canceled by introducing an appropriate energy–angle correlation at the interaction point; $\sigma_W/W \sim (3\text{–}5)\times 10^{-6}$ appears possible. Limitations of the proposed method are also considered. This monochromatization scheme is attractive for collider energies $\lesssim 10$ GeV, the energy is limitted by the increase of the emittance due to radiation in quads places in the place with a high dispersion.

The point-like nature of the electron and a narrow energy spread are important advantages of e^+e^- colliders. The energy spread occurs due to synchrotron radiation (SR) in rings, as well as beamstrahlung at the IP (important for Z and H factories). The c.m.s. energy spreads for existing and planed e^+e^- rings $\sigma_W/W=(1/\sqrt{2})\sigma_E/E \sim (0.35\text{–}0.5)\times 10^{-3}$. This collision mass spread is much larger than the widths of narrow e^+e^- resonances J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and the Higgs boson, see Table I. The resonance width Γ is the width at the half of maximum, so one should compare Γ/m and 2.36 $\sigma_W/W \approx (0.8\text{–}1.2)\times 10^{-3}$.

TABLE I. Width of some narrow e^+e^- resonances

	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	H(125)
m, GeV/c^2	3.097	3.686	9.460	10.023	10.355	125
Γ, keV	93	300	54	32	20.3	4200
$\Gamma/m, 10^{-5}$	3	8	5.7	0.32	0.2	3.4

If one manages to decrease σ_W by some factor (and if σ_W is still larger than the width of the resonance), the production rate of narrow resonances for the same luminosity would increase by the same factor, while the rate of continuum-background processes would not change. In the case of a large continuum background, the signal-to-noise ratio $S/\sqrt{B} \propto \sqrt{Lt}/\sigma_W$, therefore the integrated luminosity required to observe a rare decay of a known resonance (or to observe a narrow resonance with a very small $\Gamma_{e^+e^-}$) $Lt \propto (1/\sigma_W)^2$. For $\Upsilon(3S)$ this would be equivalent to increase of the effective luminosity by a factor of $(400)^2$=160,000!

The first considerations of e^+e^- collision monochromatization date back to mid-1970s [2]. In the proposed scheme beams collide head-on and have horizontal or vertical energy dispersion at the IP, opposite for e^+ and e^- beam. As a result, the particles collide with opposite energy deviations $E_0+\Delta E$ and $E_0-\Delta E$, and their invariant mass $W \approx 2\sqrt{E_1E_2} \approx 2E_0-(\Delta E)^2/E_0$ is very close to $2E_0$. This monochromatization scheme was considered by many authors in 1980s-1990s for c-τ and B-factory projects but since the luminosity significantly decreased in all schemes, these monochromatization ideas were not implemented.

The new generation of e^+e^- ring colliders (DaΦNE, Super-KEKB, c-τ, FCC-ee, CEPC) use the so called "crab-waist" scheme of beam collisions. In this scheme the beams collide at an angle $\theta_c \gg \sigma_x/\sigma_z$. It allows for higher luminosity by a factor of 20–40. The crossing angle θ_c in existing designs varies between 30 mrad (FCC-ee) and 83 mrad (Super-KEKB). In [1] we adopted this scheme but significantly modified to obtain monochromatization.

In the standard scheme with the crossing angle the relative mass spread

$$\left(\frac{\sigma_W}{W}\right)^2 = \frac{1}{2}\left(\frac{\sigma_E}{E}\right)^2 + \frac{1}{2}\frac{\sin^2\theta_c}{(1+\cos\theta_c)^2}\sigma_\theta^2, \qquad (1)$$

where σ_E is the beam energy spread and σ_θ is the beam angular spread at the interaction point (IP). For head-on collisions the mass resolution is determined by the beam energy spread, the contribution of the second term is negligible. The beam energy spread also makes a dominant contribution in the aforementioned colliders with the crab-waist scheme as well.

Our idea of monochromatization [1] is based on the fact that the invariant mass depends on both the particle energies and their angles. We prepare beams with angular dispersion so that particles come to the IP with the hor-

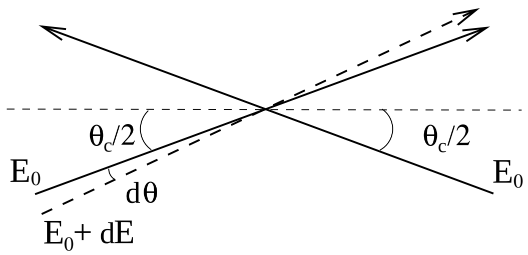

FIG. 1. Collisions with the energy-angle correlation[1].

izontal angle depending on the energy: higher energy – larger angle, Fig. 1. We can choose such a dispersion that when the left particle with the energy $E_0 + dE$ and the angle $\theta = \theta_c/2 + d\theta$ collides with the right one with the nominal(average) energy E_0 and the angle $\theta_c/2$ and they produce the same invariant mass as in the case when they both have average energies and angles. The required angular dispersion

$$d\theta_i = \frac{1+\cos\theta_c}{\sin\theta_c}\frac{dE_i}{E_0}. \tag{2}$$

In this case the contribution of the beam energy spread to the spread of the center-of-mass energy σ_W/W is canceled, only a term proportional $(\sigma_E/E)^2 \sim 10^{-6}$ left. The required dispersion is unacceptably large at small collision angles, therefore $\sin\theta_c \geq 0.5$ is desirable.

The dependence of the invariant mass spread on the collision angle is shown in Fig. 2.

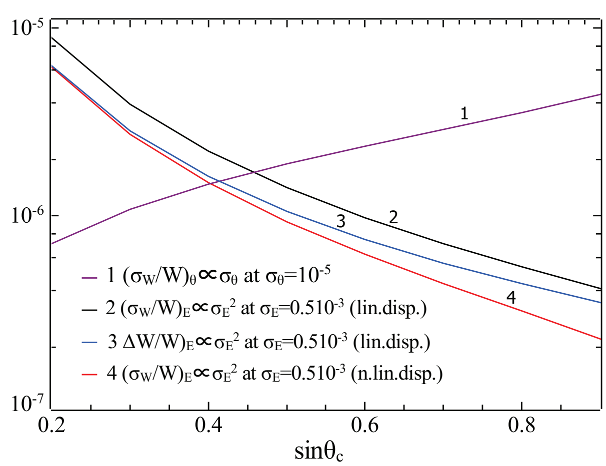

FIG. 2. Monochromaticity of collisions vs collision angle [1].

From Fig. 2 we see that for an equal contribution of the residual energy spread and horizontal angular spread (only due to emittance) the latter should be about $\sigma_\theta < 10^{-5}$ for $\sin\theta_c = 0.5$. Horizontal angular spread at the IP $\sigma_\theta = \sqrt{\varepsilon_x/\beta_x^*}$, where β_x^* is the horizontal β-function at the IP. The horizontal emittance at the 7(4) GeV KEK Super-B factory is $\varepsilon_x = 4.8(3.3)\cdot 10^{-9}$ m. Specialized synchrotron sources have and are planning $\varepsilon_x < 10^{-10}$ m at energies $E < 6$ GeV. The maximum value of β_x^* is limited by the distance between the IP and final quad which is about 1 m. So, $\sigma_\theta = \sqrt{10^{-10}/1} \sim 10^{-5}$ can be thought of as a possible ultimate target that gives the mass resolution $\sigma_W/W \approx 2.5 \cdot 10^{-6}$, which is about 150-200 times smaller than that at e^+e^- storage rings.

Main limitations of this method are connected with the increase of the horizontal emittance due synchrotron radiation in the final focus quads, in the detector field and in the part of the ring where dispersion is created [1]. Most severe is the first one, it makes this monochromatization scheme inapplicable for FCC-ee and CEPC.

A few words about the possible loss of luminosity due to monochromatization. The only difference from the KEK Super-B factory is the larger crossing angle, about 500 mrad instead of 90 mrad. The luminosity $L \propto N(Nf)/(\sigma_z\sigma_y\theta_c)$. For the same beams, an increase of the crossing angle by 6 times means a loss of luminosity by the same amount. However, the collision effects become weaker and you can partially compensate for the loss by increasing N and decreasing σ_z. There are other limitations here and, possibly, the resulting luminosity will be lower, may be 2–3 times. We can agree with such losses, since monochromatization increases the effective luminosity very significantly.

In conclusion, the new method of monochromatization of e^+e^- collisions at large crossing angle ($\theta_c \gtrsim 0.5$ rad) allows high luminosities (as in the crab-waist collision scheme). The contribution of the beam energy spread to the invariant mass is compensated by introducing the energy-angle correlation at the interaction point. The main problem of this method is the increase of the horizontal emittance due to synchrotron radiation in quads, which limits the maximum energies to $2E_0 \approx 10$ GeV. The achievable spread of the invariant mass is $\sigma_W/W \sim$ (3–5)10^{-6}, which is about 100 times better than at existing e^+e^- storage rings. There are two main directions in high energy physics: higher energies or relatively low energies with very high luminosity (factories). Monochromatization is a very natural next step in the development of the second direction. It can increase the effective luminosity 10000 times in studying rare decays or looking for narrow state with small $\Gamma_{e^+e^-}$. The full potential of this method can be realized at very narrow $\Upsilon(nS)$ resonances, and there are many other interesting problems at lower energies. The next step towards realistic project requires the efforts of accelerator designers.

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[1] V. I. Telnov, Monochromatization of e^+e^- colliders with a large crossing angle, arXiv:2008.13668.

[2] A. Renieri, Laboratori Nazionali di Frascati Report No. LNF-75/6(R).