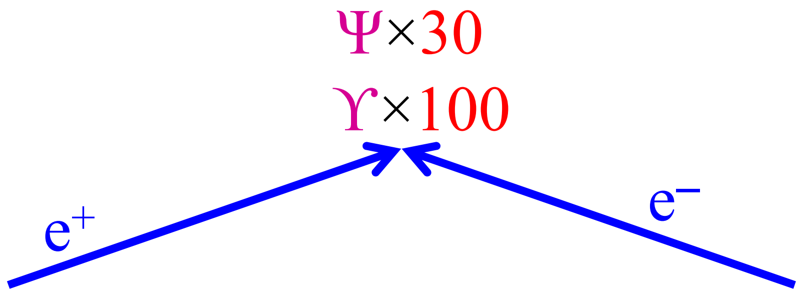

A new method of monochromatization e+e- collisions

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A natural energy spread at circular e+e- colliders

Due to synchrotron radiation (for uniform ring) $\frac{\sigma_E}{E} \approx 0.86\times 10^{-3}\frac{E[\mathrm{GeV}]}{\sqrt{R[\mathrm{m}]}}.$

	VEPP-2000	BEPC-II	SuperKEKB	FCC-ee
E_0, GeV	1	~ 2	4-7	62.5
$2\pi R$, km	0.024	0.24	3	100
$\sigma_E/E, 10^{-3}$	~ 0.6	~ 0.5	0.7	0.6 (w/o BS)

The invariant mass spread $\frac{\sigma_W}{W} = \frac{1}{\sqrt{2}}\frac{\sigma_E}{E} \approx (0.35-0.5)10^{-3}.$

The collider mass spread is much larger than the width of $c\bar{c}, b\bar{b}, H$ resonances

	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$H(125)$	$\mathcal{T}_1(\tau^+\tau^-)$
m, GeV/c^2	3.097	3.686	9.460	10.023	10.355	125	3.554
Γ, keV	93	300	54	32	20.3	4200	2.3×10^{-5}
$\Gamma/m, 10^{-5}$	3	8	0.57	0.32	0.2	3.4	6.5×10^{-7}
$2.36\sigma_W/\Gamma$	$\sim$35	$\sim$13	$\sim$180	$\sim$310	$\sim$500	$\sim$30	$\sim 1.8\times 10^8$

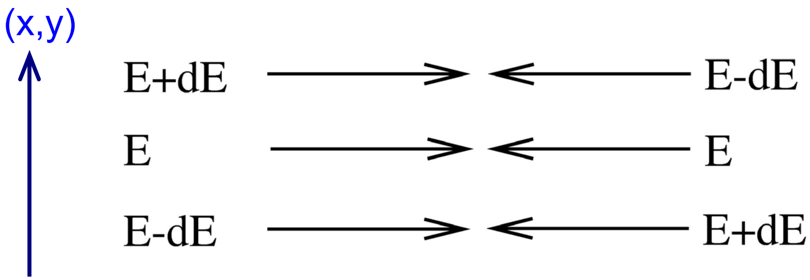
Decreasing σ_W/W increases the number of produced resonances $N_R \propto 1/\sigma_W$.

To observe a resonance at high backgrounds

$$S/\sqrt{B} \propto \sqrt{Lt}/\sigma_W = \text{const} \quad \Rightarrow Lt \propto 1/\sigma_W^2 \;!$$

Existing method of monochromatization (A. Rinieri, 1975)

Energy dispersion at the interaction point in horizontal or vertical directions:

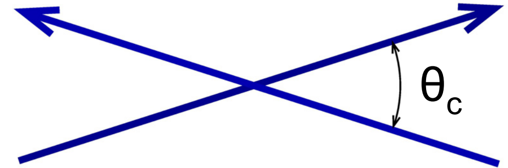


$$W = 2\sqrt{(E+dE)(E-dE)} \approx 2E - (dE)^2 / E \approx 2E$$

This method was actively discussed in 1980-2000 for J/Ψ, charm-τ, B-factories, (Rinieri(1975), Protopopov, Skrinsky and A. A. Zholents (1979), Avdienko et al.(1983), Wille and Chao(1984), Jowett(1985), Alexahin, Dubrovin, Zholents (1990), Faus-Golfe and Le Du(1996)), but was never implemented. The KEKB and PEP-II factories operated at a wide ϒ(4S) resonance where monochromatization was not required; high luminosity was more important.

This method of monochromatization is associated with an increase of the transverse bunch size (σ_y in the case of the vertical dispersion), which leads to decrease of luminosity as $L \propto \sigma_W$. This loss of luminosity can be only partially compensated for by reducing the horizontal beam size.

Crab-waist (c-w) collision scheme



New generation of e^+e^- circular colliders (DAFNE, Super-KEKB, charm-tau …) use so called "Crab-waist" (c-w) scheme (P. Raimondi, 2006), where beams collides at some horizontal crossing angle θ_c~20-80 mrad.

The luminosity at storage rings is restricted by the beam-beam turn shift, as result

$$L_{\mathrm{h}} \approx \frac{Nf\gamma\xi_y}{2r_e\sigma_z} \quad \text{for head-on collisions} \qquad \xi_y \approx \frac{Nr_e\sigma_z}{2\pi\gamma\sigma_x\sigma_y}$$

$$L_{\text{c-w}} \approx \frac{Nf\gamma\xi_y}{2r_e\beta_y} \quad \text{for crab-waist collisions, where } \beta_y \approx \sigma_x/\theta_c << \sigma_z. \qquad \xi_y \approx \frac{Nr_e\beta_y}{\pi\gamma\sigma_y\sigma_z\theta_c}$$

As result, attainable $L_{\text{c-w}} \geq 20L_{\mathrm{h}}$ is possible. To obtain this gain the beams should have very small transverse emittances, especially the vertical one.

It is very attractive to have simultaneously good monochromatization and a very high luminosity provided by e^+e^- colliders with crab-waist collisions!

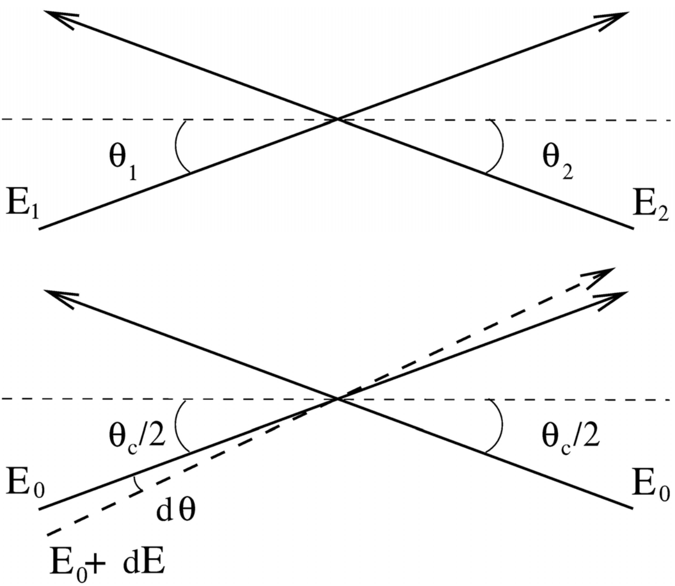
However, due to the crossing angle the existing monochromatization scheme does not work for the horizontal dispersion at the IP. Monochromatization with the vertical dispersion is possible, but it will lead to unacceptable degradation of the vertical emittance (due to synch. rad.) Also the luminosity will decrease as $L \propto \sigma_W$ due to the increase of the vertical beam size. This loss of luminosity can't be compensated for by a decrease of the horizontal beam size (because L does not depend on σ_x).

Resume: the existing monochromatization method is not suitable for colliders with c-w.

A new method of monochromatization

(for collisions at large crossing angle)

The invariant mass of colliding particles depends both on energies and angles:



$$W^2 = (P_1 + P_2)^2 = 2m^2 + 2(E_1 E_2 - \vec{p}_1 \vec{p}_2) \approx$$

$$\approx 2E_1 E_2 (1 + \cos(\theta_1 + \theta_2)). \qquad (1)$$

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

One can provide the beams with an angular dispersion such that a beam particle arrives to the IP with a horizontal angle that depends on its energy: the higher the energy, the larger the angle.

We can choose such a dispersion that when a particle coming from the left, with energy E_0+dE and angle $\theta = \theta_c/2 + d\theta$, collides with a particle coming from the right with the nominal (average) energy E_0 and angle $\theta_c/2$, they produce the same invariant mass as two colliding particles that both have the nominal energies and angles, E_0 and $\theta_c/2$:

$$(E_0 + \mathrm{d}E)E_0(1 + \cos(\theta_c + \mathrm{d}\theta)) = E_0^2(1 + \cos\theta_c). \qquad (3)$$

In the linear approximation ($\cos(\theta_c + d\theta) \approx \cos\theta_c - \sin\theta_c d\theta$) beam energy spread does not contribute to the W spread when for each of the beams, $dW^2=0$!

$$\boxed{\mathrm{d}\theta_i = \frac{1+\cos\theta_c}{\sin\theta_c}\frac{\mathrm{d}E_i}{E_0}} \qquad (4)$$

The second term in (2) due to the natural stochastic beam angular spread (beam emittance) cannot be avoided.

A new method of monochromatization (continued)

Since the linear on σ_E contribution of the beam energy spread to W is zero, we find the second term of the Taylor series, it gives the quadratic contribution $\propto(\sigma_E)^2$.

For the linear angular dispersion (4), we get

$$\left(\frac{\sigma_W}{W}\right)_E = \frac{\sigma_E^2}{2E^2}\left[\left(1+\frac{1+\cos\theta_c}{\sin^2\theta_c}\right)^2+\left(\frac{1+\cos\theta_c}{\sin^2\theta_c}\right)^2\right]^{1/2}, \qquad (5)$$

also some shift of the average W value exist, quadratic on σ_E:

$$\frac{\Delta W}{W} = \frac{\sigma_E^2}{2E^2}\left(1+\frac{1+\cos\theta_c}{\sin^2\theta_c}\right) \qquad (6)$$

In the case of the best (nonlinear), θ-E correlation (in order to minimize σ_W), we can reach somewhat smaller residual contribution of the beam spread

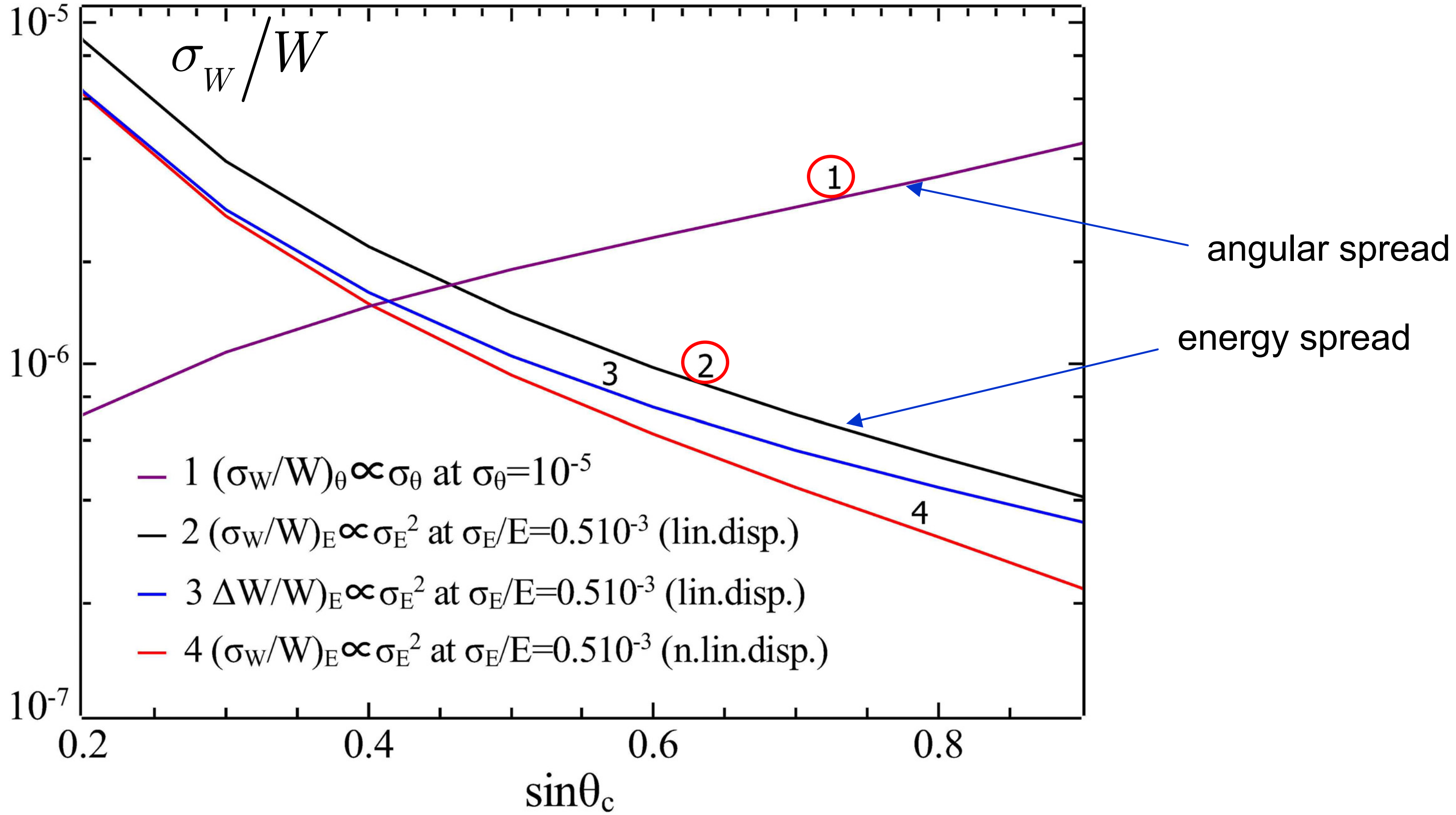
$$\left(\frac{\sigma_W}{W}\right)_E = \frac{\sigma_E^2}{2E^2}\frac{1+\cos\theta_c}{\sin^2\theta_c}, \qquad \frac{\Delta W}{W} = 0 \qquad (7)$$

The total invariant mass spread is the sum of the residual contribution of the energy spread (5) or (7)) and the second term of (2), which is due to the beam emittance (without angular dispersion):

$$\left(\frac{\sigma_W}{W}\right)^2 = \left(\frac{\sigma_W}{W}\right)_E^2 + \frac{1}{2}\frac{\sin^2\theta_c}{(1+\cos\theta_c)^2}\sigma_\theta^2 \qquad (8)$$

These contributions for various crossing angles are shown on the next page.

Monochromaticity of collisions vs collision angle



The optimum choice of the crossing angle depends on the achievable horizontal angular spread.

Important: this method requires the horizontal dispersion in the first quadrupole $D_x \approx F \dfrac{1+\cos\theta_c}{\sin\theta_c}$, larger θ_c (smaller D_x) are preferable because:

a) the horizontal spot size in quadrupole $\sigma_x \approx (\sigma_E / E_0) D_x$, synch. radiation (and the increase of the horizontal emittance) is smaller for larger θ_c;

b) easier (smaller length) to obtain the required $D_{x;}$.

With $\sin\theta_c$~0.4-0.5 one can dream about $\sigma_W/W \sim 3 \cdot 10^{-6}$, that is >100 times better than without monochromatization.

First look: achievable σ_W, main problems

Let us take existing SuperKEKb parameters: W~10 GeV, $\varepsilon_x = 4\times10^{-9}$ m, $\sigma_E/E = 0.7\times10^{-3}$, $\sigma_W/W = (1/\sqrt{2})\sigma_E/E = 5\times10^{-4}$.

For monochromatization with $\sin\theta_c = 0.5$ and $\beta_x = 10$ m
(it does not affect L since collisions at large crossing angle)
we get contributions to $\sigma_W/W = 2.75\times10^{-6}$ from σ_E and 3.8×10^{-6} from $\sigma_\theta = 2.5\times10^{-5}$, and together $\sigma_W/W = 4.7\times10^{-6}$.

Improvement 100 times!

Problems

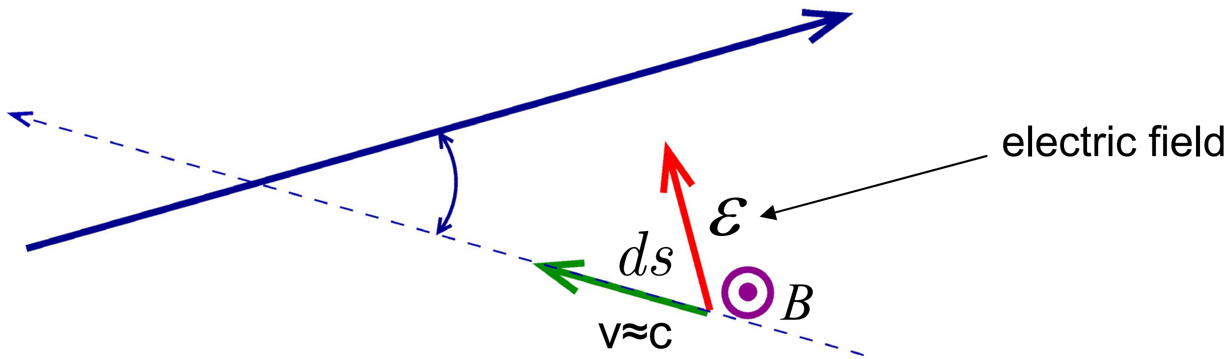
1. Beam attraction which change the collision angle.

2. Possible increase of the horizontal emittance due to emission of synchrotron radiation and intrabeam scattering in region with high dispersion function (final quads, chromatic generation section, magnetic field of the detector).

3. Possible increase of the energy spread.

So far, there are only some estimates of critical effects:

1) Beam attraction. During the collision the horizontal angle θ_x of the particle changes due to attraction to the opposing beam, what is the variation of the invariant mass W?



At a distance ds, the particle receives the energy $dE = e\mathcal{E}\sin\theta_c ds \approx eB\sin\theta_c ds$

and the additional angle $d\theta \approx (e\mathcal{E}\cos\theta_c + eB)ds/E \approx eB(1+\cos\theta_c)ds/E$.

From the expression (1) for W^2 we have $dW^2 = 2EdE(1+\cos\theta_c) - 2E^2\sin\theta_c d\theta$.

Substituting dE and $d\theta$ we get $dW^2 = 0$. No problem!

This is wonderful and unexpected result, but not so surprising, in the theory of the relativity W^2=const in collisions.

2) Possible increase of the horizontal emittance ...

To date, only effects of synchrotron radiation have been estimated which dominate at high energies (at low energies IBS is more important).

Results:

a) most critical place are final quads where due to huge dispersion the beams have large σ_x and particles emit SR in strong magnetic field which leads to the increase of the horizontal emittance. This effect makes it impossible to use this monochromatization method at FCC-ee (where it is very desirable for study of Higgs coupling to the electron in the process $e^+e^- \to H$). It works well at W<10 GeV, where most of the narrow resonances are located (especially interesting are very narrow Υ-mesons). In J/Ψ region IBS should be taken into account.

b) the section for creating dispersion must be long enough (100-200 m for Υ-region) to preserve the emittance.

c) the detector is situated in the region with large dispersion, due to large crossing angles particles experience a strong magnetic field $B_s \sin(\theta_c/2)$, which causes the increase of the emittance. One should use antisolenoids of magnetic field configuration without B in the beam region.

3) Additional energy spread - not important

Conclusion

- New method of monochromatization is proposed which works at large crossing angles where e^+e^- colliders can provide an ultimate luminosity due to crab-waist scheme.

- This method of monochromatization does not require an increase of the spot size at the IP, therefore the luminosity may be lower only due to larger crossing angle (~6×θ_c(Super-KEKB)), that can be compensated partially by an increase of N: $L \propto N^2 f / \sigma_z \sigma_y \theta_c$

- This method works well in the region of very narrow resonances

$$J/\psi,\ \psi', \Upsilon, \Upsilon', \Upsilon'', \Upsilon''', \mathrm{T}(\tau^+\tau^-)$$

can increase their production rate 30-100 times, that opens a great opportunity to search for new physics in $10^{13\text{-}14}$ decays of these resonances.

- HEP directions:
  - energy frontiers
  - intensity frontiers: high L → high L+monochromatization

One example

	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$H(125)$	$\mathcal{T}_1(\tau^+\tau^-)$
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The integrated luminosity for observation (5σ) of Tauonium-binding state of tau-leptons in the process $e^+e^- \to \mathrm{T}_1 \to \mu^+\mu^-$

$$\int L\,dt \approx 4.3 \times 10^{36} \sigma_W^2 (\mathrm{keV})$$

При $\sigma_W = 35$ keV $(\sigma_W/W = 10^{-5})$ и $L = 10^{33}$ (moderate)

the scanning time t ≈ 2 month ($\propto$ 1/L).

Such collider needs careful detailed study, it is not easy, and, if all is OK,

this could be a great next e+e project for BINP !