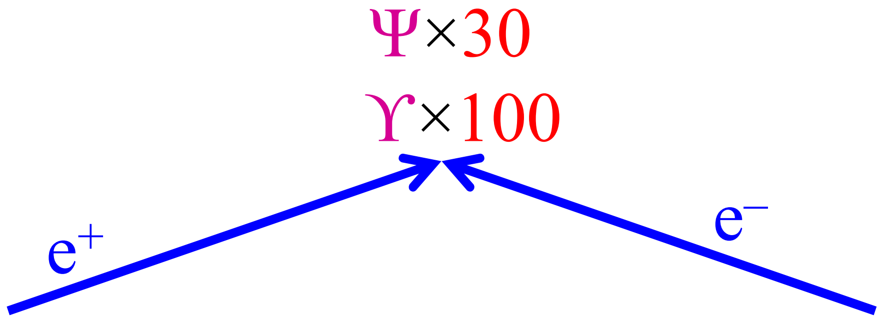

Monochromatization of e+e- colliders with a large crossing angle

Valery Telnov

Budker INP and Novosibirsk Univ.

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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}
$2.36\sigma_W/\Gamma$	~35	~13	~180	~310	~500	~30	$\sim 1.8 \times 10^8$

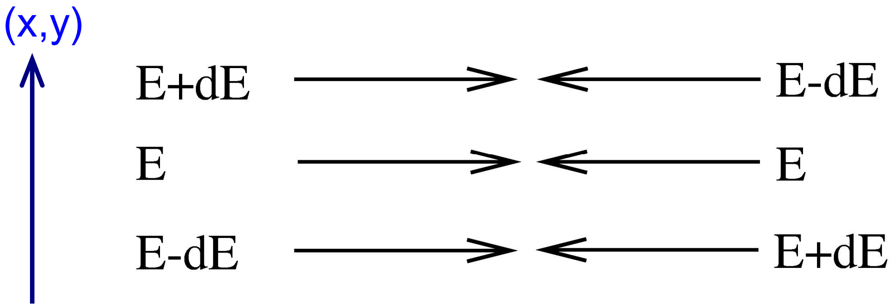
Decreasing σ_W/W increases the number of produced resonances $N_R \propto 1/\sigma_W$.

To observe a resonance at high backgrounds

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

Existing method of monochromatization (A. Rinieri, 1975)

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

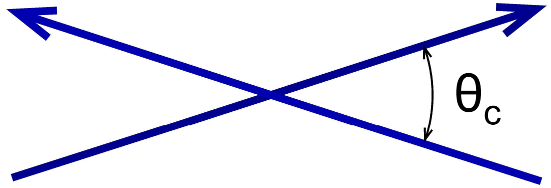


$$W = 2\sqrt{(E+dE)(E-dE)} \approx 2E - (dE)^2 / E \approx 2E$$

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!

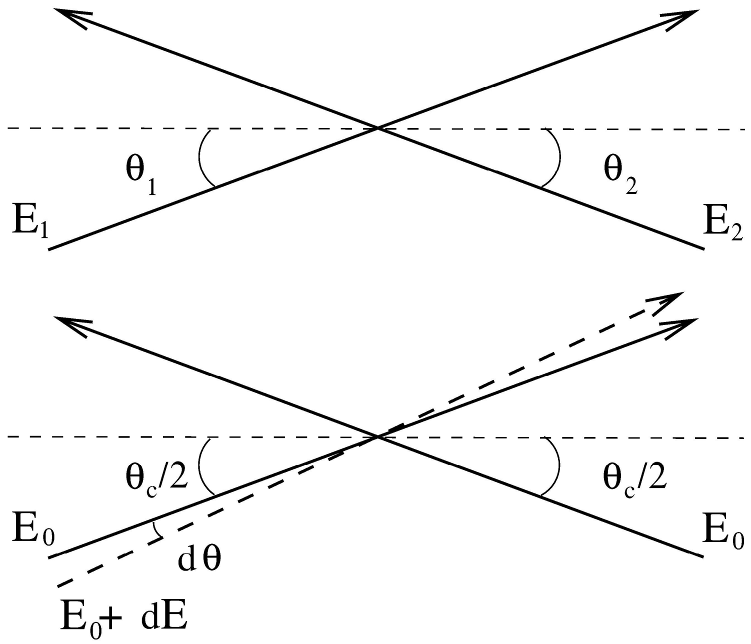
However, due to the crossing angle the existing monochromatization scheme does not work for the horizontal dispersion at the IP. Monochromatization with the vertical dispersion is possible, but it will lead to unacceptable degradation of the vertical emittance (due to synch. rad.) Also the luminosity 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:



$$W^2 = (P_1 + P_2)^2 = 2m^2 + 2(E_1E_2 - \vec{p}_1\vec{p}_2) \approx$$

$$\approx 2E_1E_2(1 + \cos(\theta_1 + \theta_2)). \quad (1)$$

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

One can provide an angular dispersion $d\theta/dE$ 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.

Differentiation of (1) gives $d(W^2) \approx 2\mathrm{E}_0 \sum_{i=1,2} [(1+\cos\theta_c)dE_i - E_0 \sin\theta_c d\theta_i]$ (3)

For the energy-angle correlation (in each beam) $\mathrm{d}\theta_i = \frac{1+\cos\theta_c}{\sin\theta_c}\frac{\mathrm{d}E_i}{E_0}$ (4)

the beam energy spread does not contribute to the W spread, $d(W^2)=0$!

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 $\sigma_W \propto (\sigma_E)^2$.

For the linear angular dispersion (4)

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

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

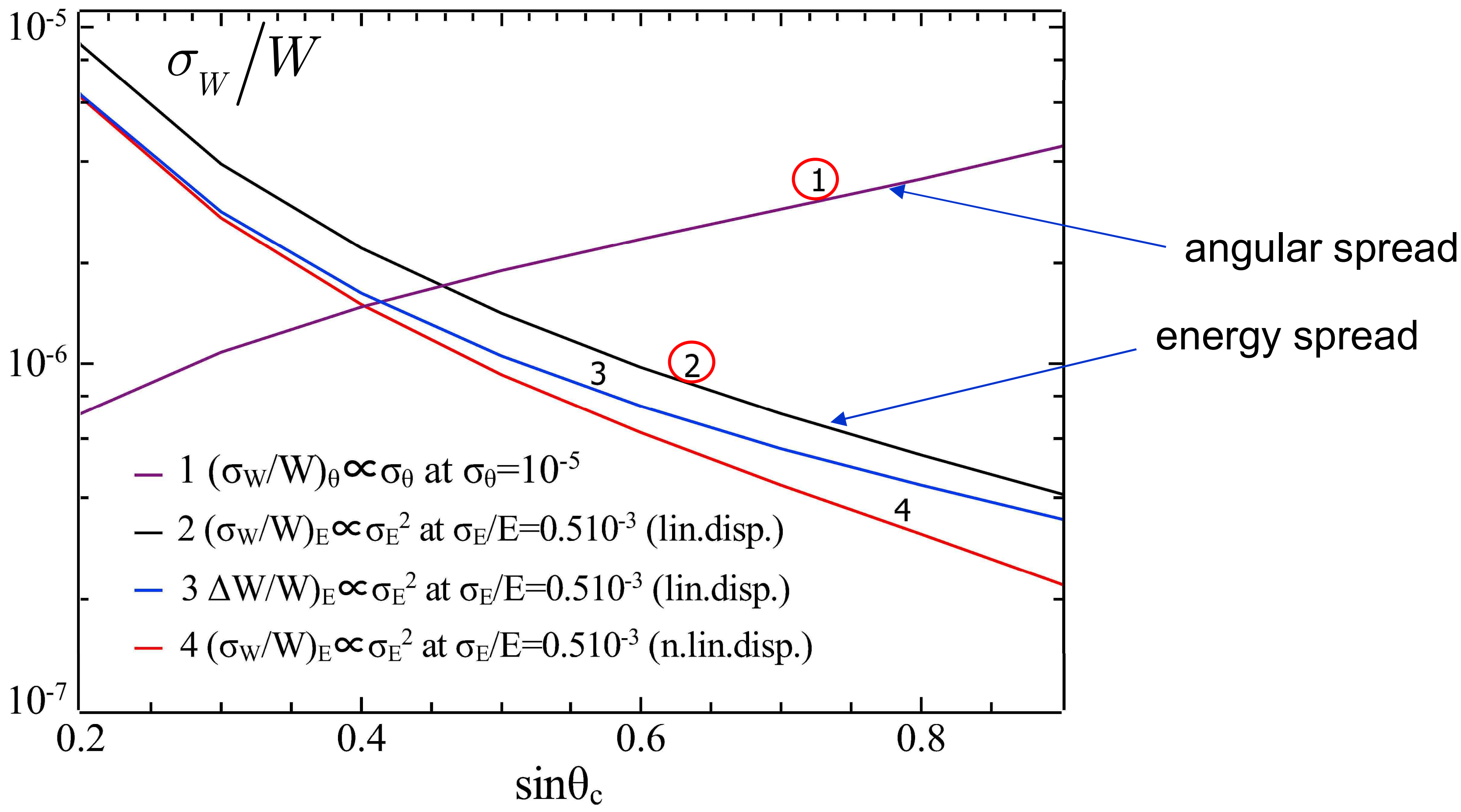
$$\left(\frac{\sigma_W}{W}\right)_E = \frac{\sigma_E^2}{2E^2}\frac{1+\cos\theta_c}{\sin^2\theta_c}, \qquad \frac{\Delta W}{W} = 0 \qquad (7)$$

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.

With $\sin\theta_c$~0.4-0.5 one can dream about $\sigma_W/W \sim 3\cdot10^{-6}$, 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 (σ_x it does not affect L due to 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 up to 50-100 times!

Problems

1. Beam attraction which change the collision angle.

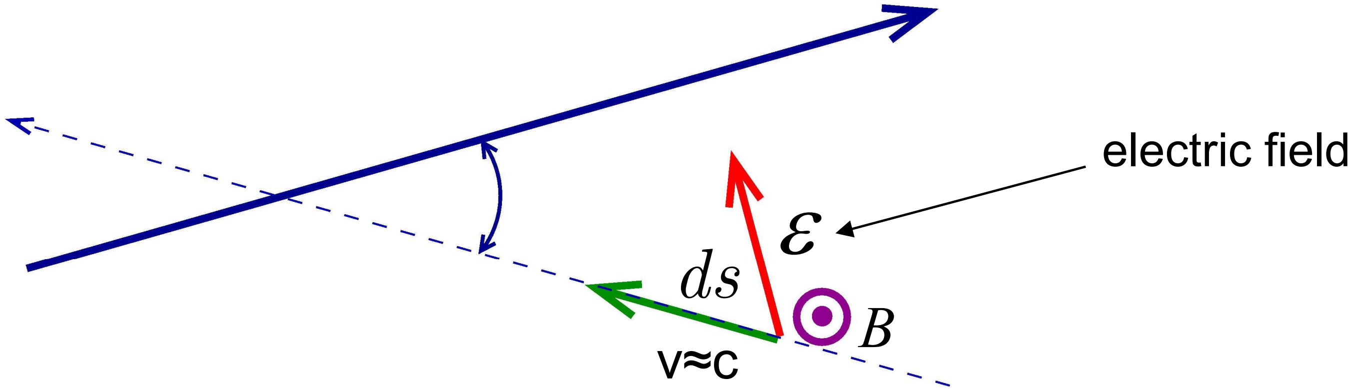
2. High B in final quadrupoles

3. 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.

4. Increase of the vertical emittance in the detector magnetic field.

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 happens only for our special energy-angle correlation

This is interesting and unexpected result

2) A too high magnetic field in final quadrupoles

What is the required maximum magnetic field in the first quadrupole?

There is no design yet, however it can be estimated as follows.

The horizontal angular beam divergence $\sigma_{\theta_x} = \frac{\sigma_E}{E_0} \frac{1+\cos\theta_c}{\sin\theta_c}$.

For $\sigma_E / E_0 \approx 10^{-3}$, $\sin\theta_c = 0.5$ we get $\sigma_{\theta_x} \sim 3.7 \cdot 10^{-3}$

The required angular aperture of the quadrupole $\theta_x \sim 10\sigma_{\theta_x} \sim 3.7 \cdot 10^{-2}$.

The maximum field in the quad of the length *L* may be estimated from $\frac{L}{\rho} \sim \theta_x \rightarrow B_{\max} \sim \frac{E_0 \theta_x}{eL}$

For E_0=2 GeV (c-tau), L=100 cm $B_{\max} \sim 2.5$ kGs.

In reality, it can be larger by 2-3 times, but it is still OK.

So, it seems, this problem is not a stopper for the energy region $2E_0 < 10$ GeV which contains many narrow resonances.

3) 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).

Some preliminary conclusions:

a) Most critical place are final quads where due to huge dispersion the beams have large σ_x , ,particles emit SR in a very 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 monochromtization is very desirable for $e^+e^- \to H$).

This energy region is closed also due to the requirement of unrealistically high field in quadrupoles.

The method works 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. Strong wigglers are needed to damp emittances, although they increase the beam energy spread, should be optimized.

3) Increase of emittances (continue)

b) the section for creating dispersion must be long enough to preserve the horizontal emittance.

4) Increase of emittances in the detector solenoid field

c) the detector is situated in the region with a large horizontal dispersion, due to large crossing angles particles experience a strong magnetic field $B_s \sin(\theta_c/2)$, radiate, which causes the increase of the horizontal as well as vertical emittance (because of vertical dispersion due to the detector field).

So, solenoidal detector field is almost excluded, one should use antisolenoids, or the detector magnetic field configuration without B in the beam region (toroidal field, like in ATLAS muon system).

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 (for ψ-ϒ), that opens a great opportunity to search for new physics in 10^{13-14} 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 $\sigma_W = 35\ \mathrm{keV}\ (\sigma_W/W = 10^{-5})$ и $L = 10^{33}$ (moderate)

the scanning time t ≈ 2 month (~1/L).

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

this could be a great e^+e^- project for Ψ-ϒ energy region !