monochromatization schemes and beamstrahlung

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monochromatization - history

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A. Faus-Golfe and J. Le Duff, "Versatile DBA and TBA Lattices for a **Tau-Charm Factory** with and without Beam Monochromatization", Nucl. Instr. Methods A 372 (**1996**) 6–18.

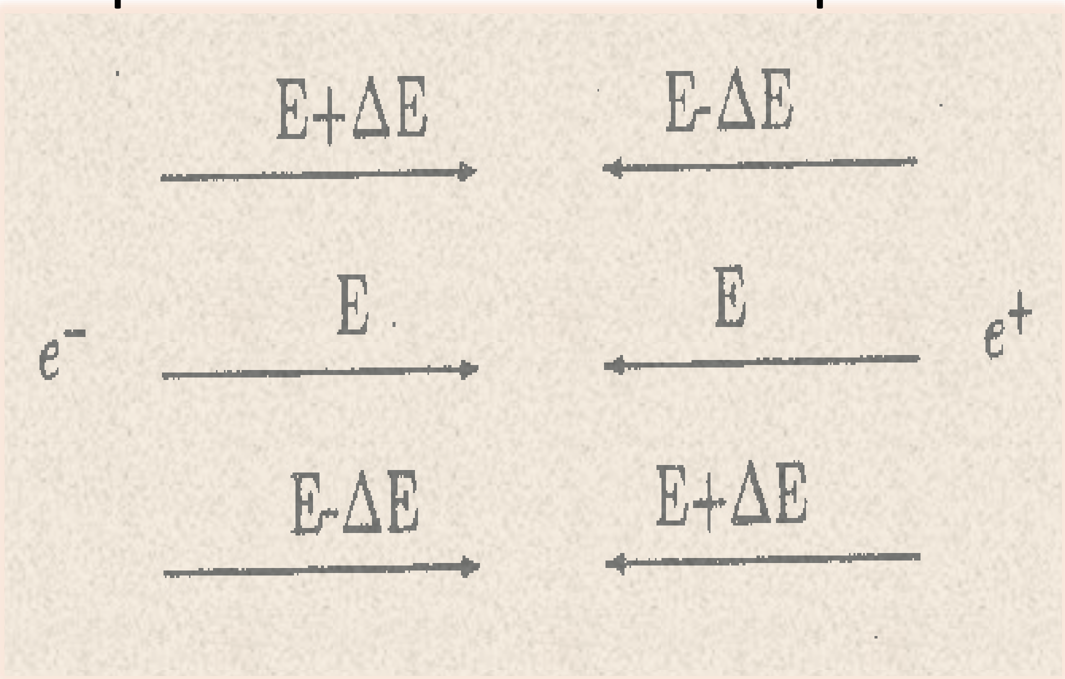
A. Faus-Golfe, M. A. Valdivia Garcia, and F. Zimmermann, "Towards a Monochromatization Scheme for Direct Higgs Production at FCC-ee", IPAC2016 Conference, Busan, Korea (**2016**)

A. Bogomyagkov and E. Levichev, "Collision Monochromatization in e+e− Colliders", Phys. Rev.

several studies, but
never used in any real machine;
new feature for FCC: beamstrahlung

mono-chromatization for direct Higgs production $e^+e^- \rightarrow H$ at FCC-ee

one concept: introduce antisymmetric dispersion at the collision point



rel. collision energy spread for standard conditions

$$\left(\frac{\sigma_W}{W}\right)_{\text{standard}} = \frac{\sigma_\delta}{\sqrt{2}}$$

rel. collision energy spread w. monochromatization

$$\left(\frac{\sigma_W}{W}\right)_{\text{m.c.}} = \frac{\sigma_\delta}{\sqrt{2}}\frac{1}{\lambda}$$

monochromatization factor

$$\lambda = \sqrt{\frac{D_x^{*2}\sigma_\delta^2}{\epsilon_x\beta_x^*} + 1}$$

in LEP(-1) bunch train operation created unwanted antisymmetric vertical dispersion (G. Wilkinson, Rome), ε_y~400 pm, β_y*=50 mm, σ_δ=0.07%, D_y*~2 mm:→ λ~1.05

effect of beamstrahlung (BS) on transverse emittance

BS : synchrotron radiation emitted during collision

- blow up of energy spread and bunch length
- in particular: $D_x^* \neq 0 \rightarrow \Delta\varepsilon > 0$

two coupled nonlinear equations determine equilibrium emittance and energy spread:

$$\varepsilon_{x,tot} = \varepsilon_{x,SR} + \frac{\tau_{x,SR} n_{IP}}{4T_{rev}} \{n_\gamma \langle u^2 \rangle\} \mathcal{H}_x^*$$

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

nonlinear function of $\sigma_{\delta,tot}$ and $\varepsilon_{x,tot}$

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

$$n_\gamma \langle u^2 \rangle \propto \frac{N_b^3 \gamma^2}{\sigma_z^2 \sigma_x^3}$$

https://arxiv.org/abs/1911.03420

M.A. Valdivia Garcia
F. Zimmermann

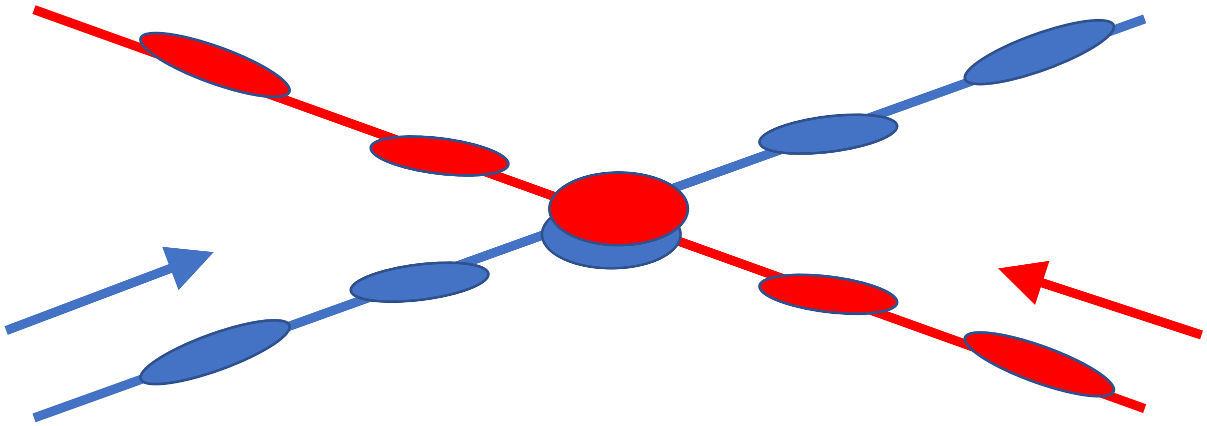
baseline monochromatization scheme for FCC-ee

like the classical Renieri scheme, but with dispersion in *x*, not *y*;
larger *x*-size helps reduce beamstrahlung, & preserves *y* emittance;

we try to maintain (or modify as little as possible)
the IR geometry; physics operation also requires many bunches;
→ keep 30 mrad crossing angle

implementing this scheme requires crab cavities

RF crab cavities (KEKB, HL-LHC, EIC…) rotate bunches so that they collide effectively head on

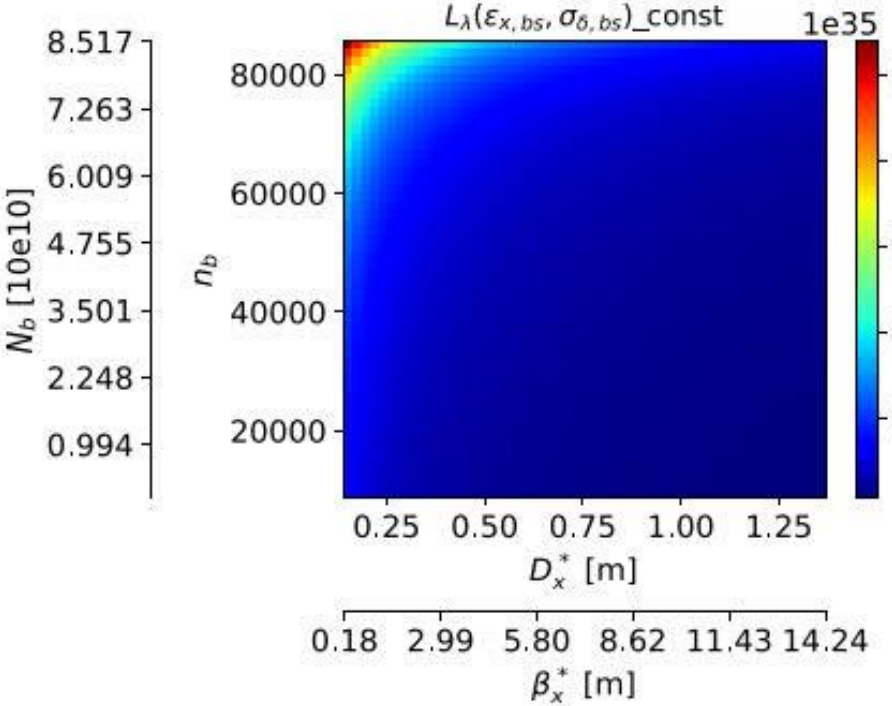


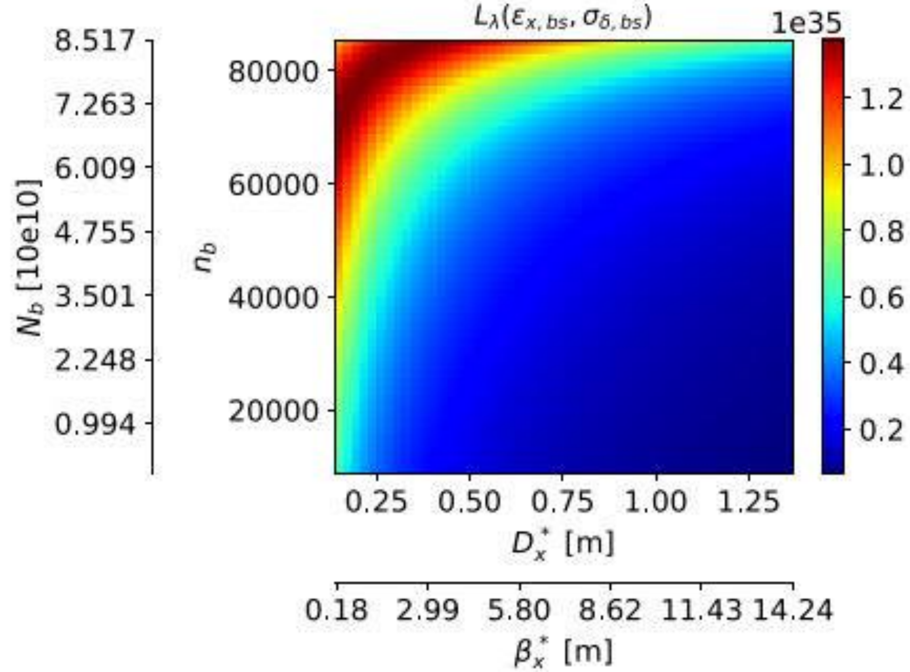
dispersion at IP, D_x^*, increases the horizontal IP beam size and ensures monochromatization;
we need to determine optimum way to generate D_x^* (incl. impact geometry)

optimization, different assumptions on vert. emittance

scan two parameters S & T: $D_x^* = S \times D_{x,0}^*$, $\beta_x^* = S^2 \times \beta_{x,0}^*$, $n_b = n_{b,0} \times T$, $N_b = N_{b,0}/T$

luminosity including beamstrahlung effects





$\varepsilon_y = \text{const.}$

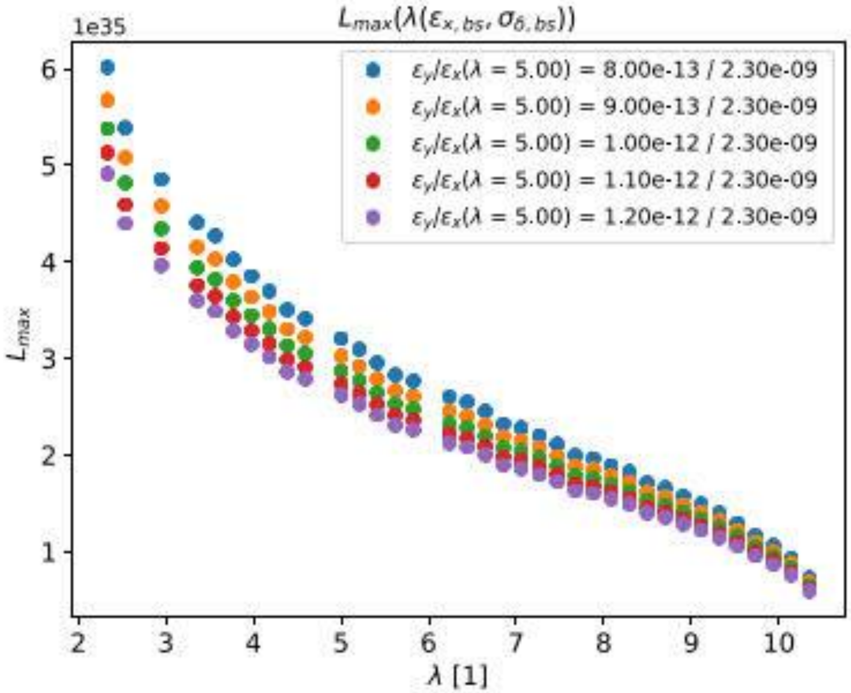
vert. emittance due to residual dispersion or limited by the resolution limit of the available diagnostics, e.g. X-ray interferometer and BPM responses

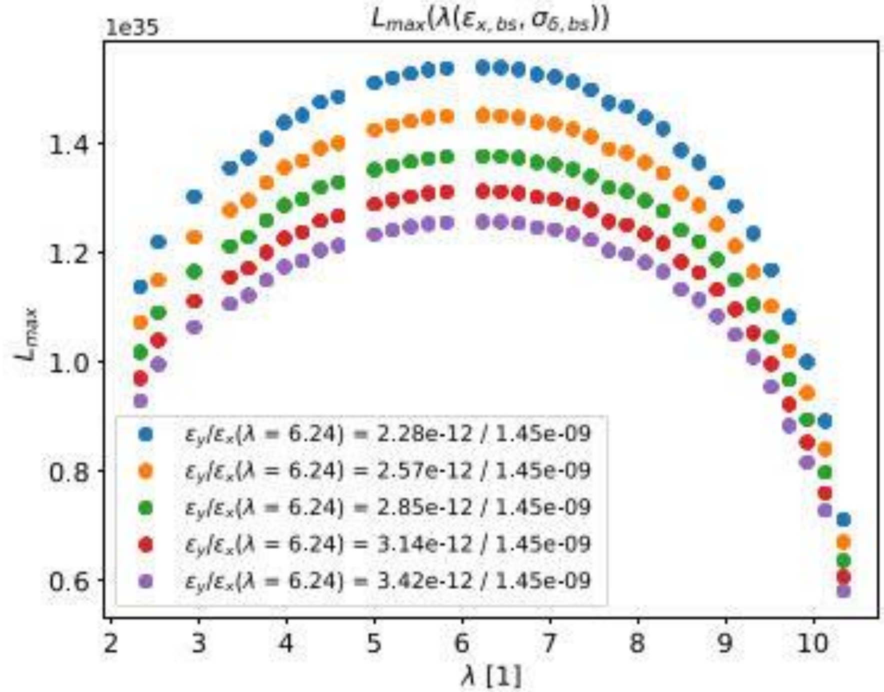
$\varepsilon_y = \kappa_\varepsilon \varepsilon_x$

vertical emittance dominated by residual betatron coupling

M.A. Valdivia, F.Z., IPAC'19

luminosity with beamstrahlung vs λ for the two cases





$\varepsilon_y = \text{const.}$

$\varepsilon_y = \kappa_\varepsilon \varepsilon_x$

example: pick λ~5, $\sigma_W \approx 6\ \text{MeV}$

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optimized monochromatized parameters for $\sigma_W \approx 6\ \mathrm{MeV}$

$\varepsilon_y = 1\ \mathrm{pm} \quad \kappa = 0.2\%$

parameter	case 1	case 2
E_b [GeV]	62.50	62.50
circumference C [km]	97.76	97.76
I_b [mA]	418	418
$n_{b,\mathrm{opt}}$	15950	8700
$N_{b,\mathrm{opt}}$ [10^{10}]	5.33	9.77
$\varepsilon_{x,\mathrm{SR}}$ [nm]	0.51	0.51
$\varepsilon_{x,\mathrm{opt}}$ [nm]	2.30	1.45
$\varepsilon_{y,\mathrm{SR}}$ [pm]	1.00	1.00
$\varepsilon_{y,\mathrm{opt}}$ [pm]	1.00	2.85
α_c [10^{-6}]	14.80	14.80
$\beta^*_{x,\mathrm{opt}}$ [m]	0.24	1.25
β^*_y [mm]	1.00	1.00
$D^*_{x,\mathrm{opt}}$ [m]	0.1624	0.3712

$\varepsilon_y = 1\ \mathrm{pm} \quad \kappa = 0.2\%$

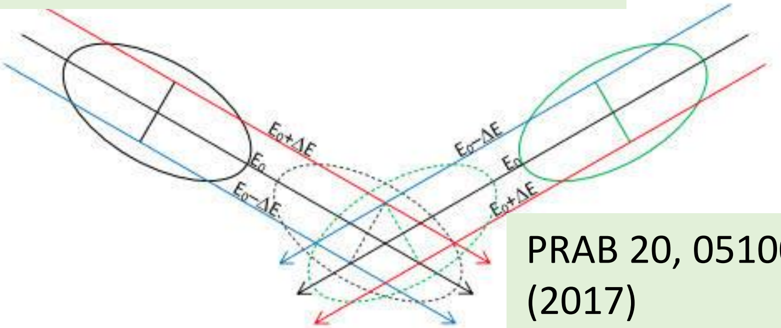
parameter	case 1	case 2
$\sigma_{x,\mathrm{opt}}$ [μm]	119.2	269.5
$\sigma_{y,\mathrm{opt}}$ [nm]	31.6	53.4
$\sigma_{z,\mathrm{SR}}$ [mm]	1.64	1.64
$\sigma_{z,\mathrm{opt}}$ [mm]	1.65	1.65
$\sigma_{\delta,\mathrm{SR}}$ [%]	0.0714	0.0714
$\sigma_{\delta,\mathrm{opt}}$ [%]	0.0720	0.0717
U_0 [GeV]	0.1254	0.1254
V_{rf} [GV]	2.0	2.0
Q_s	0.1002	0.1002
τ_E [ms]	162.5	162.5
$\boxed{L_{\mathrm{opt}}\ [10^{35}\ \mathrm{cm^{-2}s^{-1}}]}$	$\boxed{2.87}$	$\boxed{1.38}$
$\xi_{x,\mathrm{opt}}$	0.0033	0.0062
$\xi_{y,\mathrm{opt}}$	0.0518	0.0249
$\sigma_{w,\mathrm{opt}}$ [MeV]	6.03	6.00

M.A. Valdivia, F.Z., IPAC'19

other monochromatization schemes

crossing angle & opposite IP dispersion

A. Bogomyagkov, V. Levichev, 2017



PRAB 20, 051001 (2017)

FIG. 3. Crossing angle collision with opposite dispersion.

total luminosity (sum of 2 IPs) ~6x10^{34} cm^{-2}s^{-1} with σ_W~6 MeV

strong RF focusing

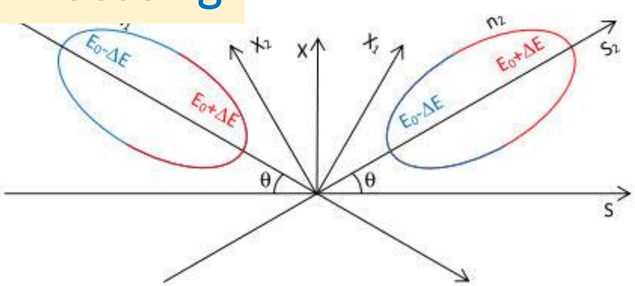


FIG. 6. Monochromatization for crossing angle collision with correlation between particle's energy and longitudinal position.

requires large RF voltage and/or high synchrotron tune, challenging at >5 GeV (?)

angular IP dispersion

V. Telnov, 31 August 2020, arXiv 2008.13668

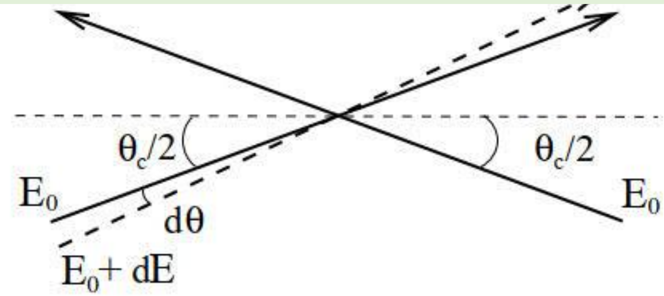


FIG. 3. Collisions with the energy-angle correlation.

$$(E_0 + dE)E_0(1 + \cos(\theta_c + d\theta)) = E_0^2(1 + \cos\theta_c). \quad (3)$$

In the linear approximation this gives the required angular dispersion (same for both particles)

$$d\theta_i = \frac{1 + \cos\theta_c}{\sin\theta_c}\frac{dE_i}{E_0}. \quad (4)$$

requires large crossing angle, may not work >5 GeV (?)

SC cavity upstream of IP

dispersion at RF cavity; true reduction of beam energy spread at IP

TM_{210} cavity

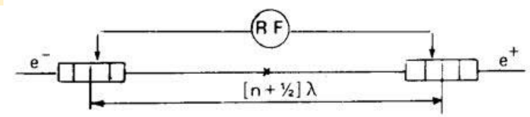


Fig. 4. Schematic view of the two superconducting accelerating rf structures relative to the interaction point used for monochromatization.

another use of crab cavities?

A. Zholents, NIM A 265 (1988) 179

New idea !: Monochromatized Energy Scan*

*Alain Blondel

consider partial monochromatization with integrated resonance scan, by correlating energy with one of the spatial coordinates and exploiting the high detector resolution in *x* or *z* (~3 μm)

such a correlation comes for free in the Bogomyagkov-Levichev collision scheme !

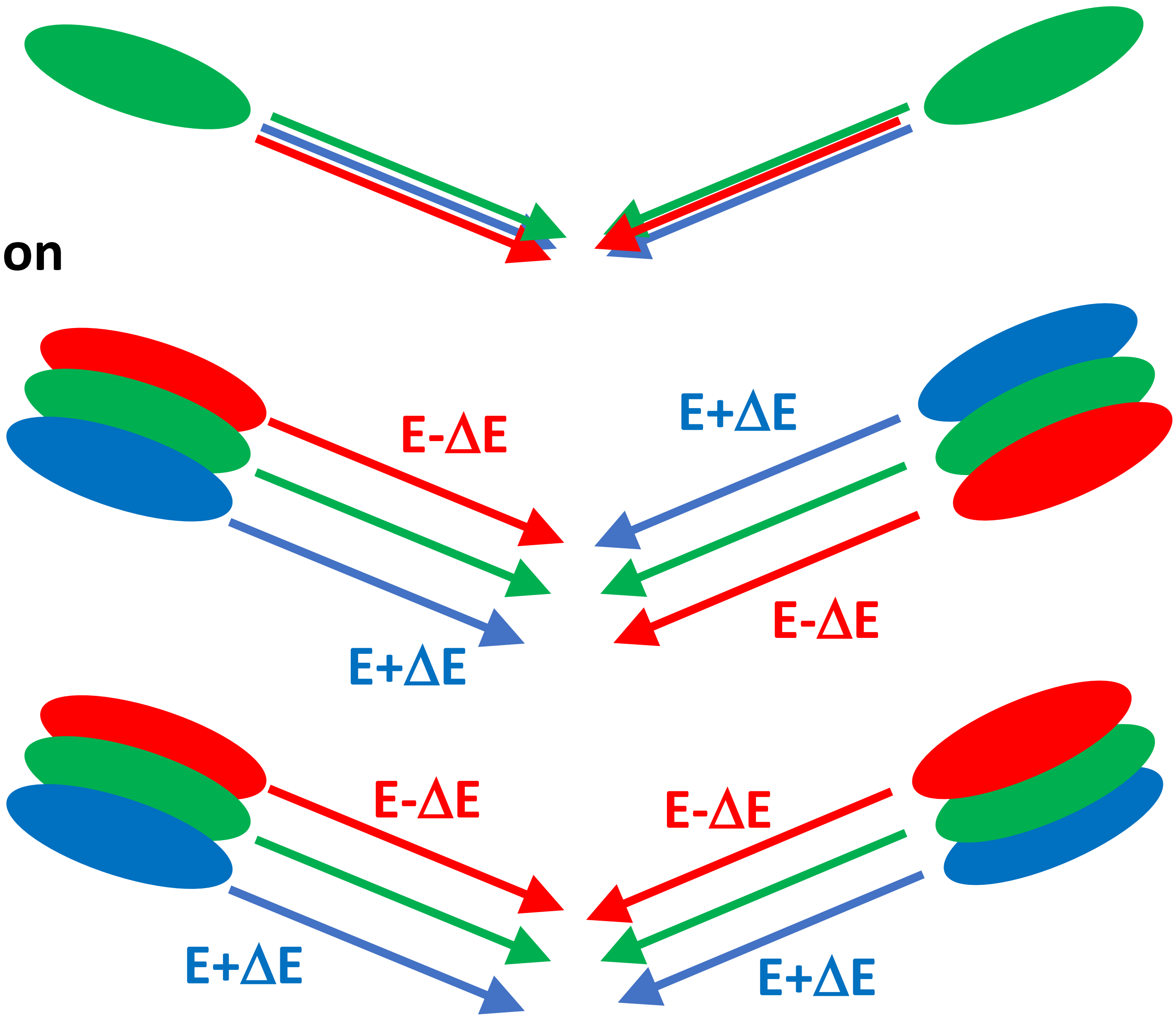
3 cases, all with crossing angle & w/o crab cavity

no dispersion

opposite dispersion (mono-chromatization)

see A. Bogomyagkov, V. Levichev, 2017

equal dispersion



detector resolution Δ=3 μm in x and z; target: $\sqrt{\beta_x^* \varepsilon_{x,\,\mathrm{tot}}} = 5\Delta = 15\ \mu\mathrm{m}$ where $\varepsilon_{x,\mathrm{tot}}$ is the self-consistent emittance with IP dispersion: $\varepsilon_{x,\mathrm{tot}} = \varepsilon_{x,SR} + \Delta\varepsilon_{x,BS}$; emittance from SR $\varepsilon_{x,SR}$ ~ 0.51 nm, addt'l emittance from BS: $\Delta\varepsilon_{x,BS} = 1.8\mathrm{x}10^{-9}/0.11\ (D_x^{*2}/\beta_x^*)$ ignoring crossing angle; σ_δ ~0.0715% from SR ;

$$D_x^* \sigma_\delta \geq 25\,\Delta\ (=5\sqrt{\beta_x^* \varepsilon_{x,\,\mathrm{tot}}}\,) \rightarrow D_x^* \geq 0.105\ \mathrm{m}$$

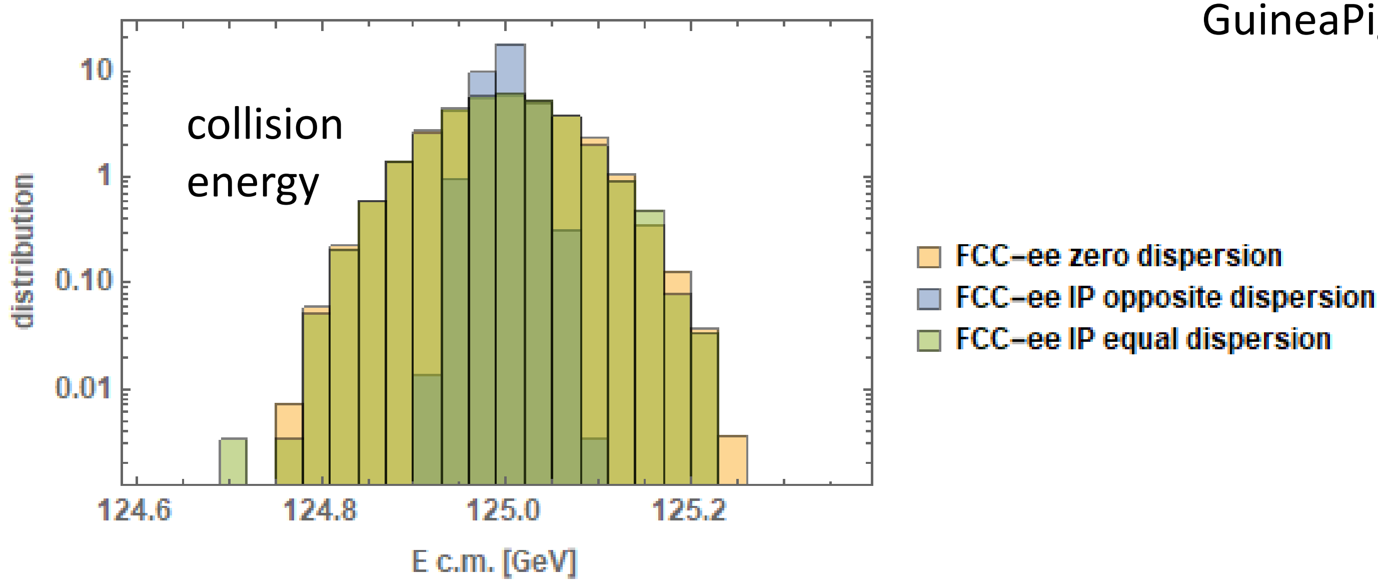
$$\beta_x^* = \left(25\Delta^2 - \beta_x^*\,\Delta\varepsilon_{x,BS}\right)/\varepsilon_{x,SR} = 9\ \mathrm{cm}$$

tentative parameters at 62.5 GeV	
D_x^*	0.105 m
β_x^*	9 cm
σ_δ	0.0715%
$\varepsilon_{x,SR}$	0.51 nm
σ_y	45 nm $(\varepsilon_y = 2\ \mathrm{pm},\ \ \beta_y^* = 1\ \mathrm{mm})$
N_b	$6\mathrm{x}10^{10}$
n_b	14170

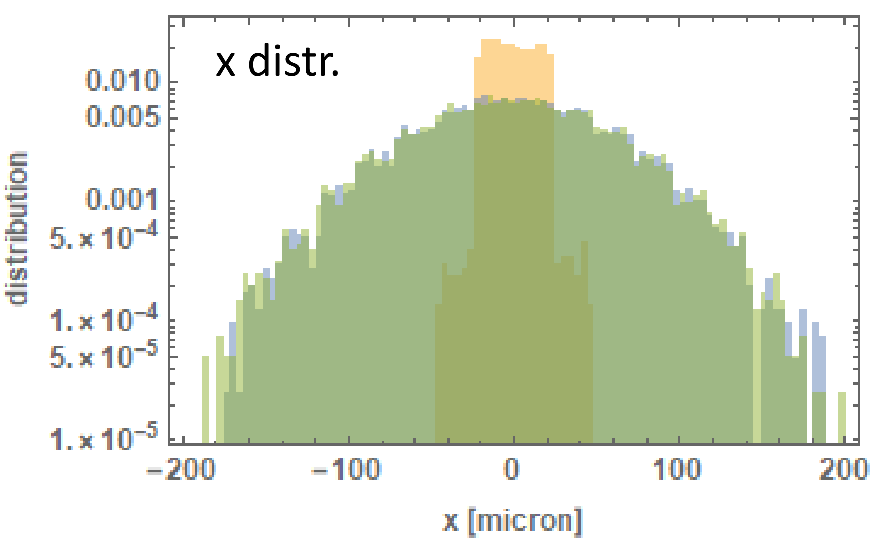
self-consistent simulation w θ_c=30 mrad (total)	
σ_x^*	80 μm (with dispersion)
$\sigma_{x,\beta}^*$	15 μm
$\sigma_{\delta,\mathrm{tot}}$	0.075 %
$\varepsilon_{x,\mathrm{tot}}$	2.5 nm
L	$2.75 \mathrm{~x~} 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
ξ_y	0.061

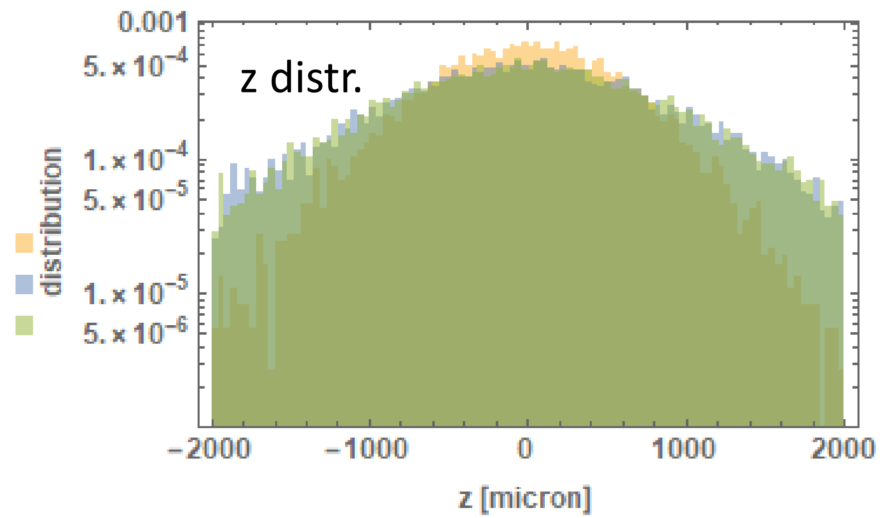
spreads of luminosity events compared

GuineaPig simulations



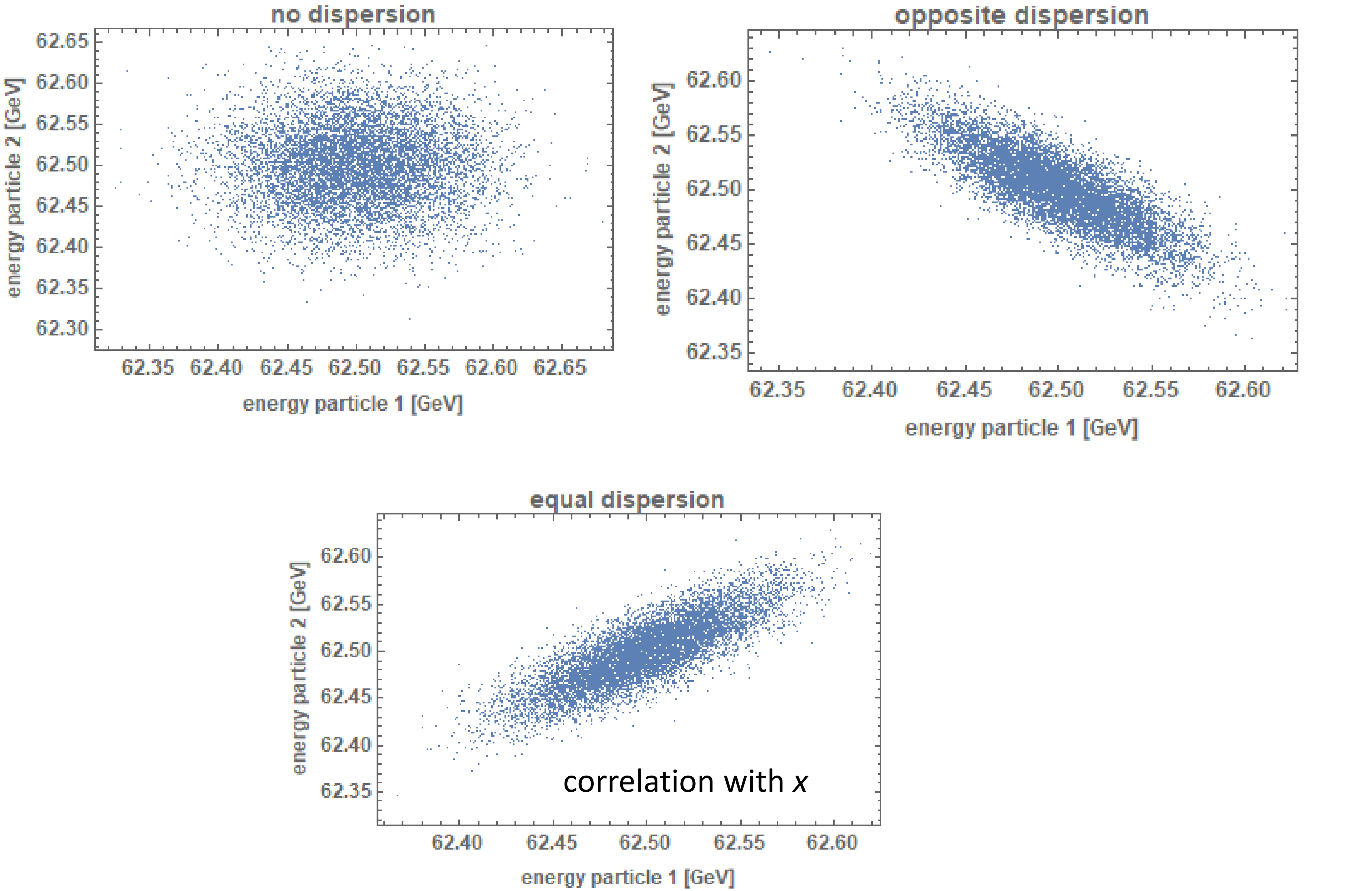
σ_W~66 MeV
σ_W~20 MeV
σ_W~65 MeV



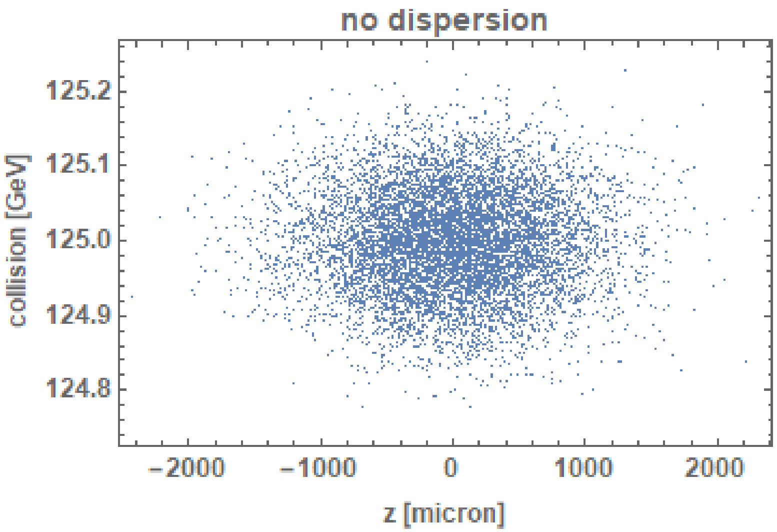


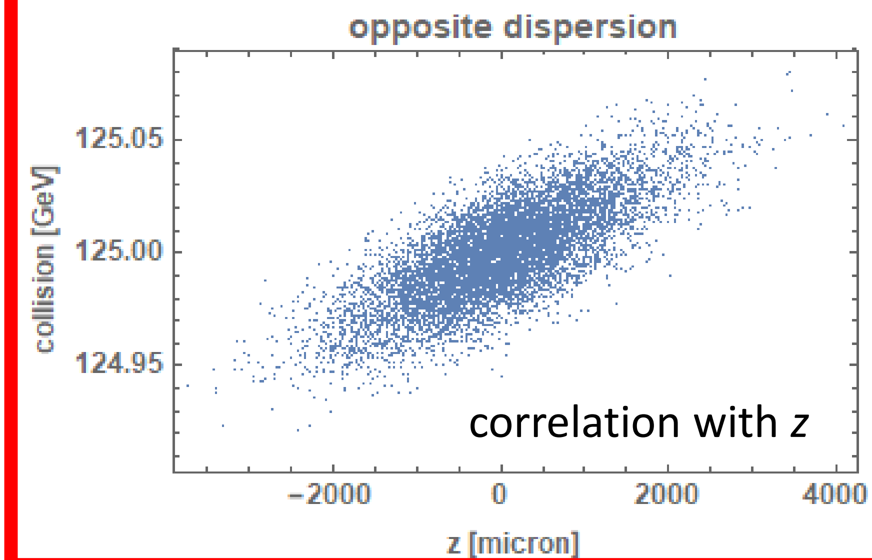
with help from C. Rimbault et al.

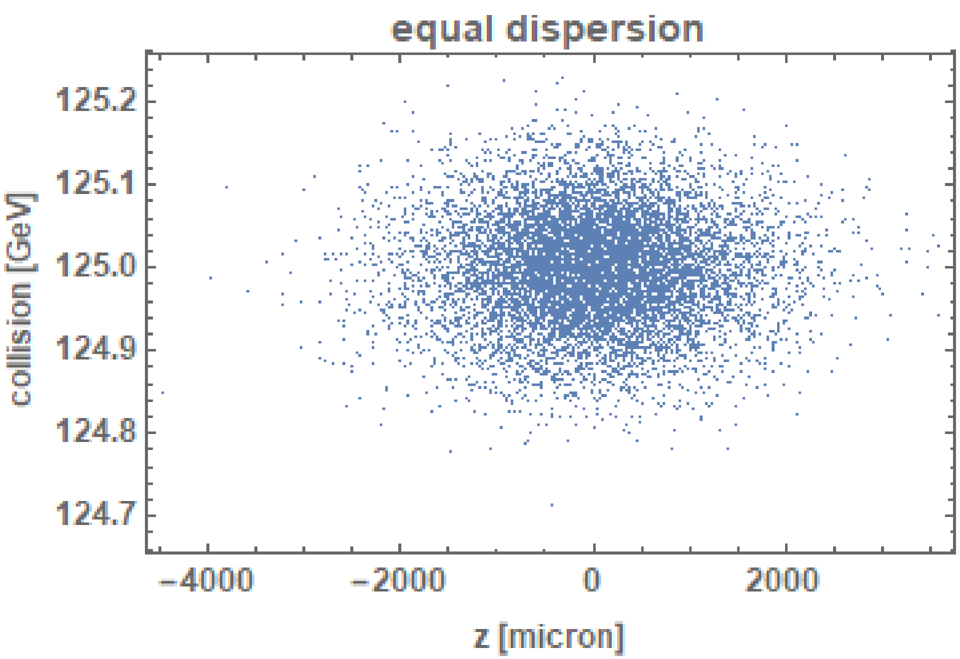
energy correlation of luminosity events



z-E_{cm} correlation of luminosity events

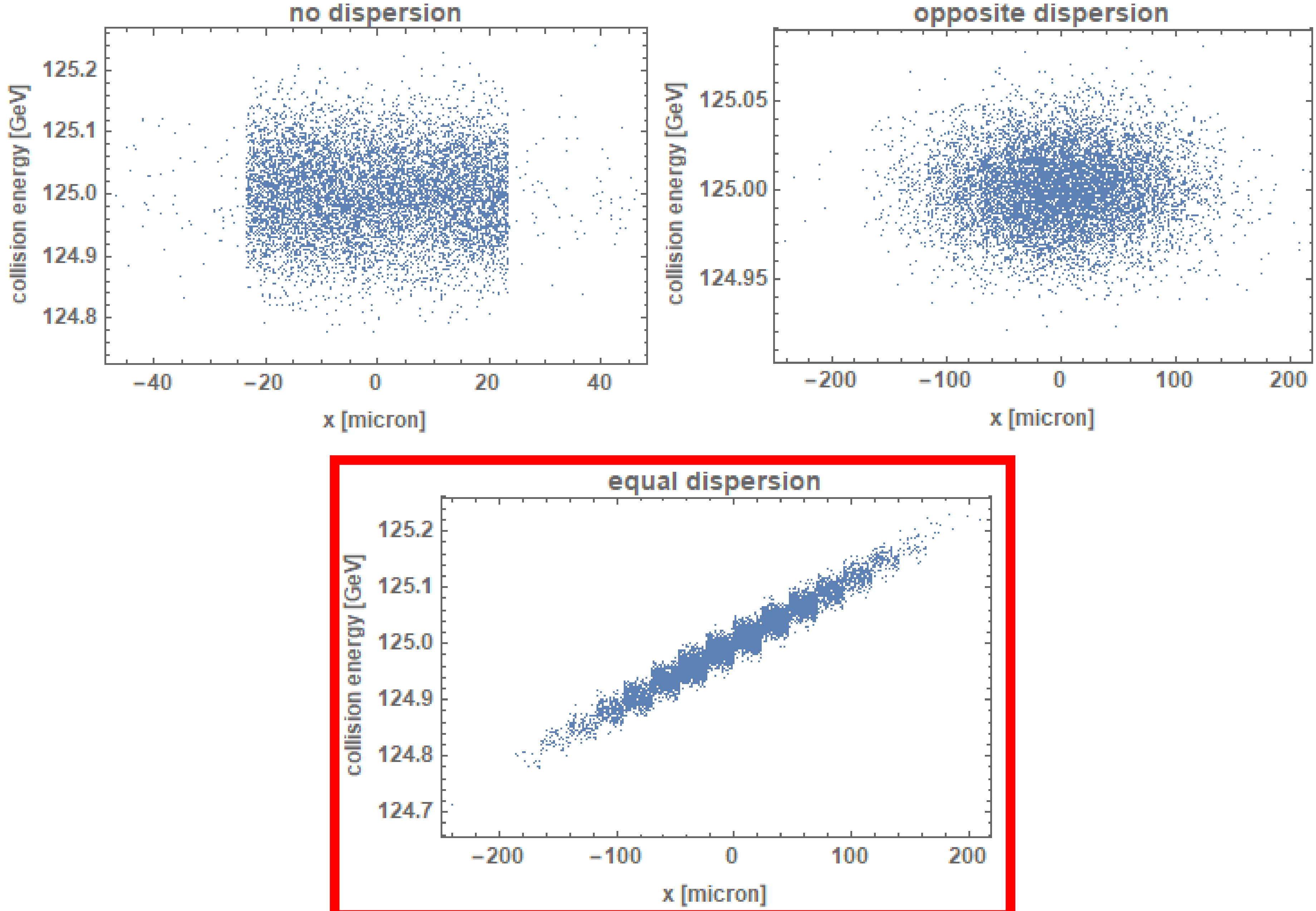






built-in energy scan

x-E_{cm} correlation of luminosity events



a few conclusions

several approaches exist to achieve monochromatized s-channel Higgs production at FCC-ee, with e.g. $L{\sim}10^{35}$ cm^{-2}s^{-1} , or higher, at $\sigma_W{\sim}6$ MeV - is this of interest for physics? how should we optimally trade off luminosity and energy spread?

there are quite a number of monochromatization approaches – new proposals appear roughly every other month

the crab cavities needed in the monochromatization baseline could also be used for the scheme of Zholents et al.; perhaps a combination of these schemes would be optimum

using dispersion and crossing angle for integrated energy scan looks very promising, with, e.g., $L{\sim}3\text{x}10^{35}$ cm^{-2}s^{-1} at $\sigma_W{\sim}20$ MeV ; this eliminates need for crab cavities ; opposite or equal sign dispersion can be used together with resulting *z* and *x* correlation, respectively, depending on the desired scan energy range