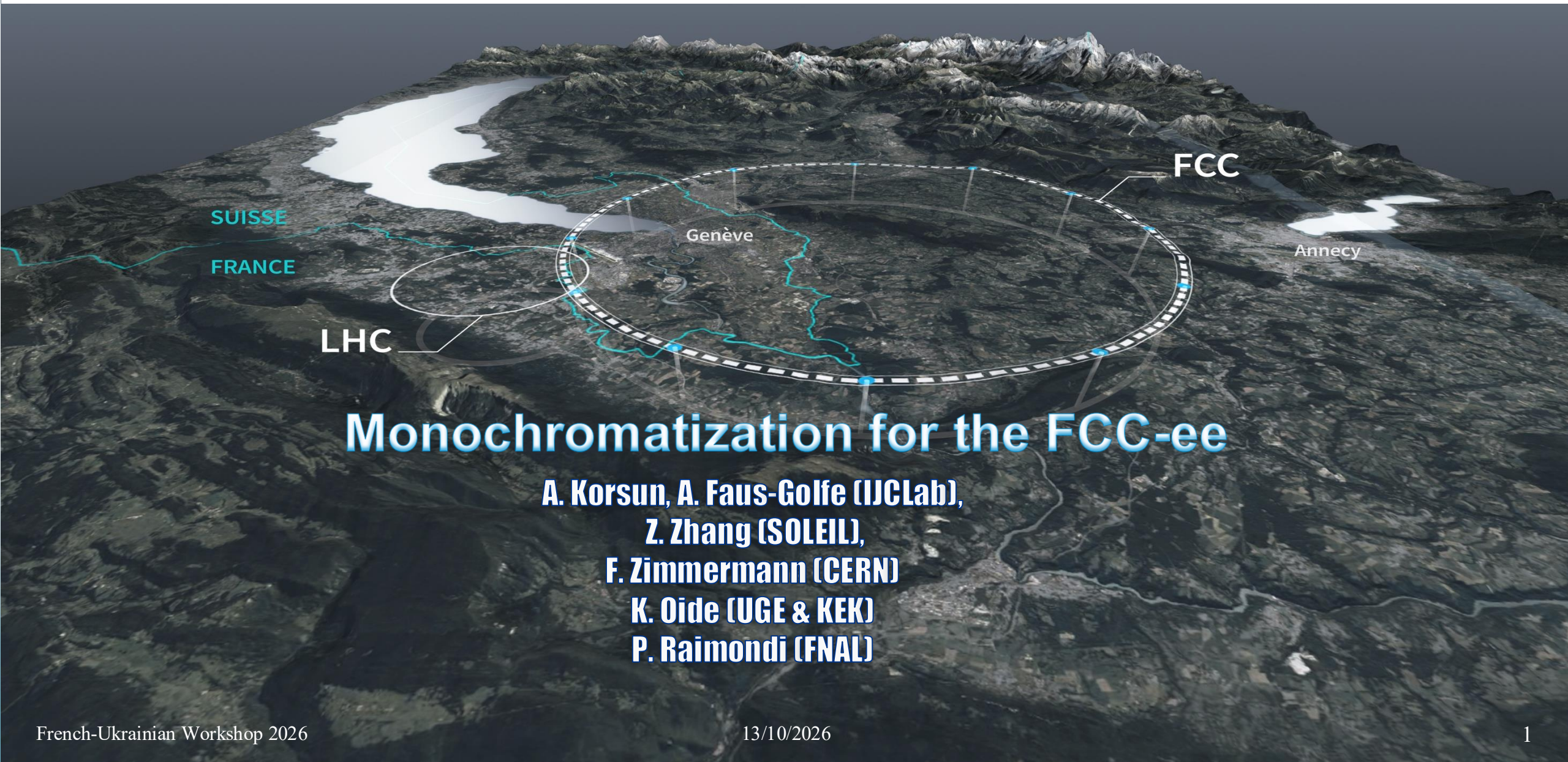




Monochromatization for the FCC-ee

**A. Korsun, A. Faus-Golfe (IJCLab),
Z. Zhang (SOLEIL),
F. Zimmermann (CERN)
K. Oide (UGE & KEK)
P. Raimondi (FNAL)**

Outline

- ☐ Introduction and motivation
- ☐ Transverse Monochromatization Principle
- ☐ FCC-ee Monochromatization Optics Design
- ☐ Parametric optimization
- ☐ Beam-beam effects studies
- ☐ Summary and Outlook

Introduction: Physics Requirements

□ FCC-ee modes:

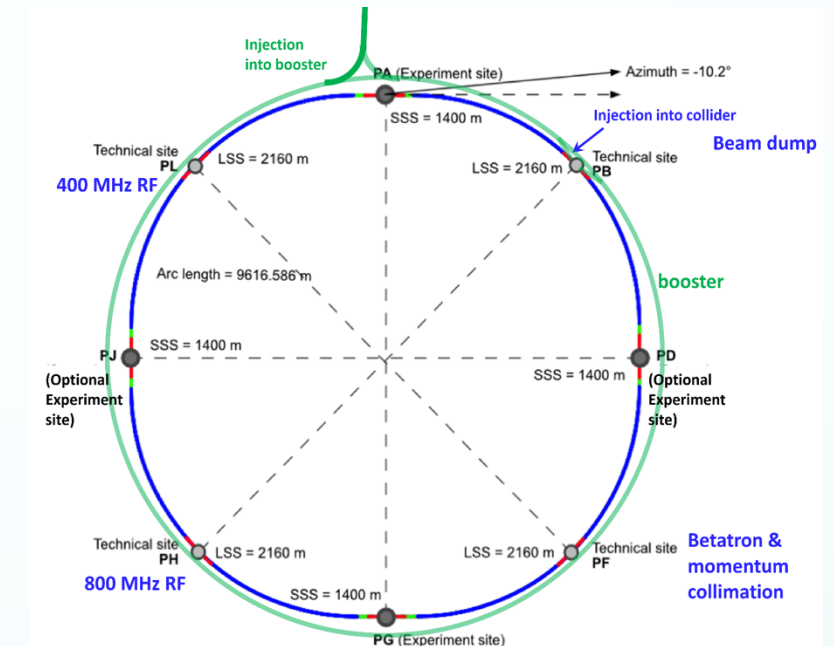
□ The FCC-ee standard modes:

- Four different energy operation modes:

Z , $W^\pm$, Zh and $t\bar{t}$

□ The optional fifth mode: s -channel Higgs production mode

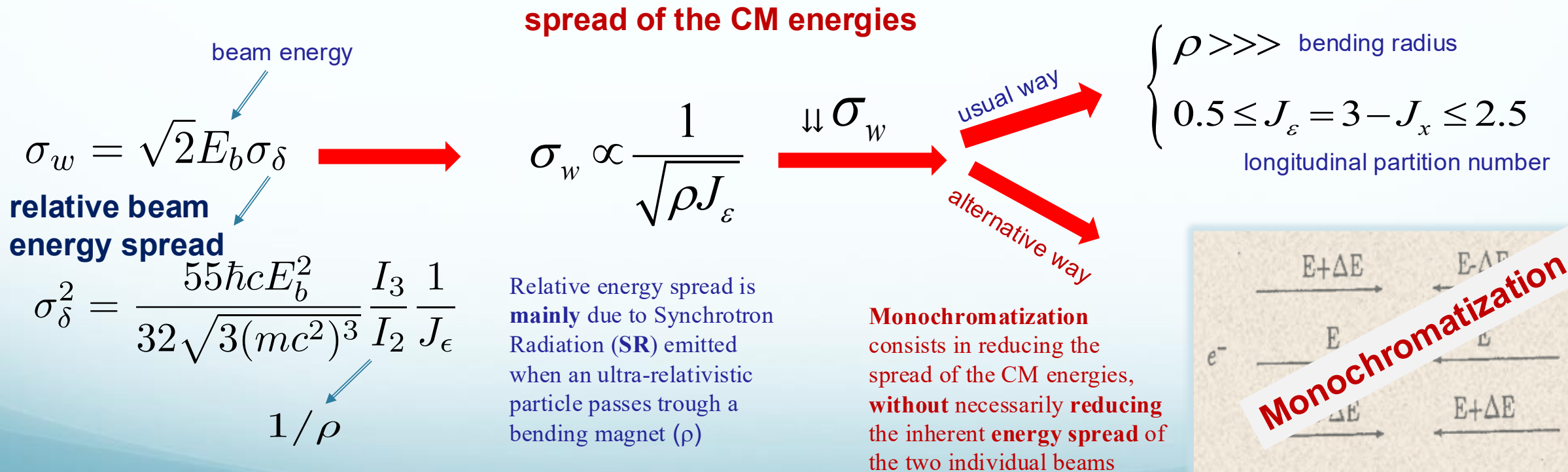
- The measurement of the electron Yukawa coupling, in dedicated runs at **125 GeV** with center-of-mass (CM) energy spread (**5-10 MeV**). But the natural collision energy spread, due to the synchrotron radiation, is about **50 MeV**.



□ Requirements:

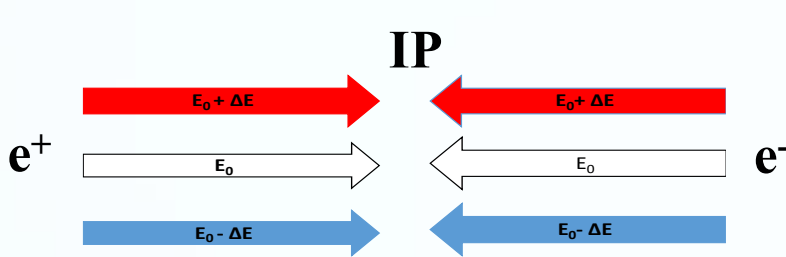
- Reduce the CM energy spread from **50 MeV** to **5 MeV**, which is comparable to the resonant width of the standard model Higgs Boson itself (**4.2 MeV**)

Reducing the spread of the centre-of mass (CM) energies (σ_w) of colliding beams is a way to **increase** the **collision energy resolution**, that is of particular interest when operating the collider on a **narrow particle resonance** or at the threshold of its pair production.



Monochromatization Principle

Standard



$D_{x,y}^* = 0$
 correlation between
 transverse spatial
 position and energy
 deviation

$$w = 2(E_b + \Delta E)$$

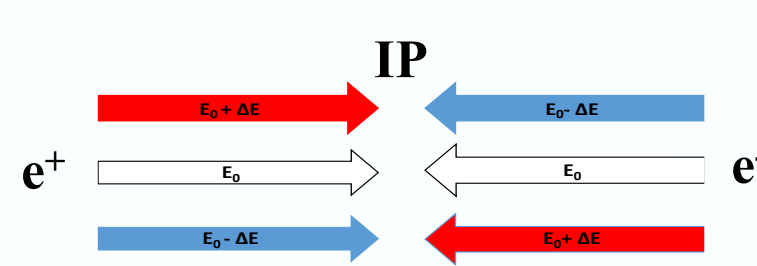
$$\sigma_{x,y}^* = \sqrt{\beta_{x,y}^* \epsilon_{x,y}}$$

$$\sigma_w = \sqrt{2} E_b \sigma_\delta$$

$$\lambda = 1$$

$$L_0 = \frac{k_b f_r N_+ N_-}{4\pi \sigma_{x\beta}^* \sigma_{y\beta}^*}$$

Monochromatization



$D_{x+}^* = -D_{x-}^* = D_x^*$
 $D_{y+}^* = -D_{y-}^* = D_y^*$
 Opposite correlations
 between transverse spatial
 position and energy deviation

$$w = 2E_b + O(\Delta E)^2$$

$$\sigma_{x,y}^* = \sqrt{\beta_{x,y}^* \epsilon_{x,y} + (D_{x,y}^* \sigma_\delta)^2}$$

$$\sigma_w = \frac{\sqrt{2} E_b \sigma_\delta}{\lambda}$$

$$\lambda = \left(1 + \sigma_\delta^2 \left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}} \right) \right)^{1/2}$$

$$L = \frac{L_0}{\lambda}$$

CM energy

Beam size

CM Energy spread

Monochromatization factor

Luminosity

Monochromatization principle

To give an example on FCC-ee, let's assume that only synchrotron radiation is present, with no crossing angle.

Because the vertical beam size at the IP is much smaller than the horizontal beam size, proportionally smaller vertical dispersion is needed to get the same monochromatization factor compared with the horizontal one.

Monochromatization factor

$$\lambda = \left(1 + \sigma_{\delta}^2 \left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}} \right) \right)^{1/2}$$

Parameters	Unit	Horizontal Dispersion	Vertical Dispersion
Beam energy(E)	GeV	62.5	
Horizontal, vertical emittance($\epsilon_{x,y}$)	nm	2700, 1.3	
Energy spread(σ_{δ})	%	0.052	
IP Beta function($\beta_{x,y}^*$)	mm	90, 0.7	
IP RMS beam size ($\sigma_{x,y}$)	μm	11.02, 0.043	
IP Dispersion ($D_{x,y}^*$)	m	0.3	0.001
Monochromatization factor (λ)	/	12	10
Instant Luminosity (L)	cm ⁻² s ⁻²	2 x 10 ³⁵	2.3 x 10 ³⁵

In the previous case for low-energy e^+e^- colliders, the **relative energy spread** is mainly given by **SR** in the colliders arcs ($\sigma_\delta = \sigma_{\delta,SR}$). Alternatively in **high-energy e^+e^-** , we have to take into account also the **SR** created by the strong opposing EM field during collision or “**beamstrahlung**”(BS) ($N_\gamma \propto 1/\sigma_z (\sigma_x^* + \sigma_y^*)$, with σ_z the bunch length).

Standard BS

$$D_{x,y}^* = 0$$

$$\sigma_{\delta,tot} = \sqrt{\frac{1}{2} \sigma_{\delta,SR}^2 + \sqrt{\frac{1}{4} \sigma_{\delta,SR}^4 + A \frac{\sigma_{\delta,SR}^2}{\sigma_{z,SR}^2}}}$$

$$A = \frac{275}{36 \pi^{\frac{3}{2}}} \frac{n_{IP} \tau_E r_e^5 N_b^3 \gamma^2}{4 T_{rev} \alpha \sigma_{x,SR}^3}$$

$$\epsilon_{x,tot} \approx \epsilon_{x,SR}$$

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

BS at high-energy with $D_x^* = 0$, has more **impact** on **energy spread** in standard mode than in monochromatization mode.

Monochromatization BS

$$D_{x+}^* = -D_{x-}^* = D_x^*$$

$$D_{y+}^* = -D_{y-}^* = D_y^*$$

Coupled system to be solved numerically

Energy spread

$$\sigma_{\delta,tot}^2 = \sigma_{\delta,SR}^2 + \frac{V}{\sigma_{\delta,tot}^2 \sigma_{x,tot}^3}$$

$$V \approx \frac{55\pi^2}{3\sqrt{3}} \left(\sqrt{\frac{2}{\pi}} \right)^3 \frac{n_{IP} \tau_{E,SR} Q_s^2 r_e^5 \gamma^2 N_b^3}{T_{rev} \alpha_c^2 C^2 \alpha} \times \frac{0.77562}{\varphi}$$

$$\mathcal{H}_{x,y}^* = \frac{(\beta_{x,y}^* D_{x,y}'^* + \alpha_{x,y}^* D_{x,y}^*)^2 + (D_{x,y}^*)^2}{\beta_{x,y}^*}$$

Horizontal emittance

$$\epsilon_{x,y,tot} = \epsilon_{x,y,SR} + \frac{2V \mathcal{H}_{x,y}^*}{\sigma_{\delta,tot}^2 \sigma_{x,tot}^3}$$

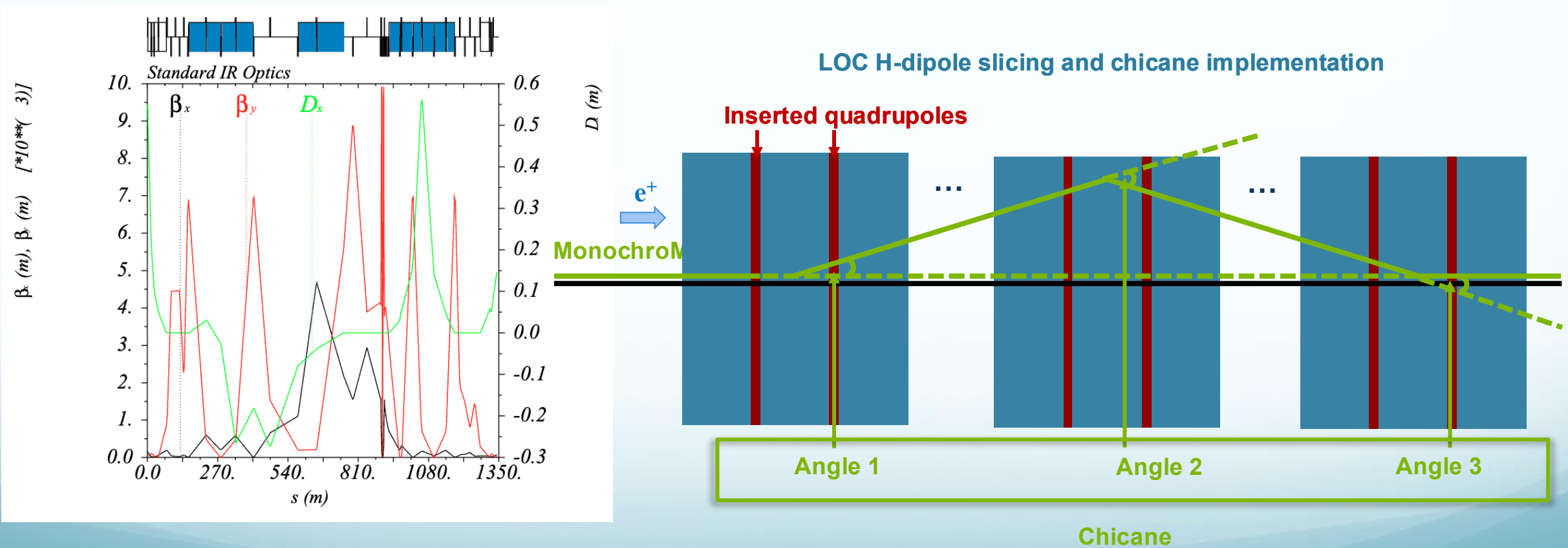
Bunch length

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

BS with monochromatization at high-energy, avoids the blow up of the relative beam energy spread, which is significant in standard mode with $D_x^* = 0$.

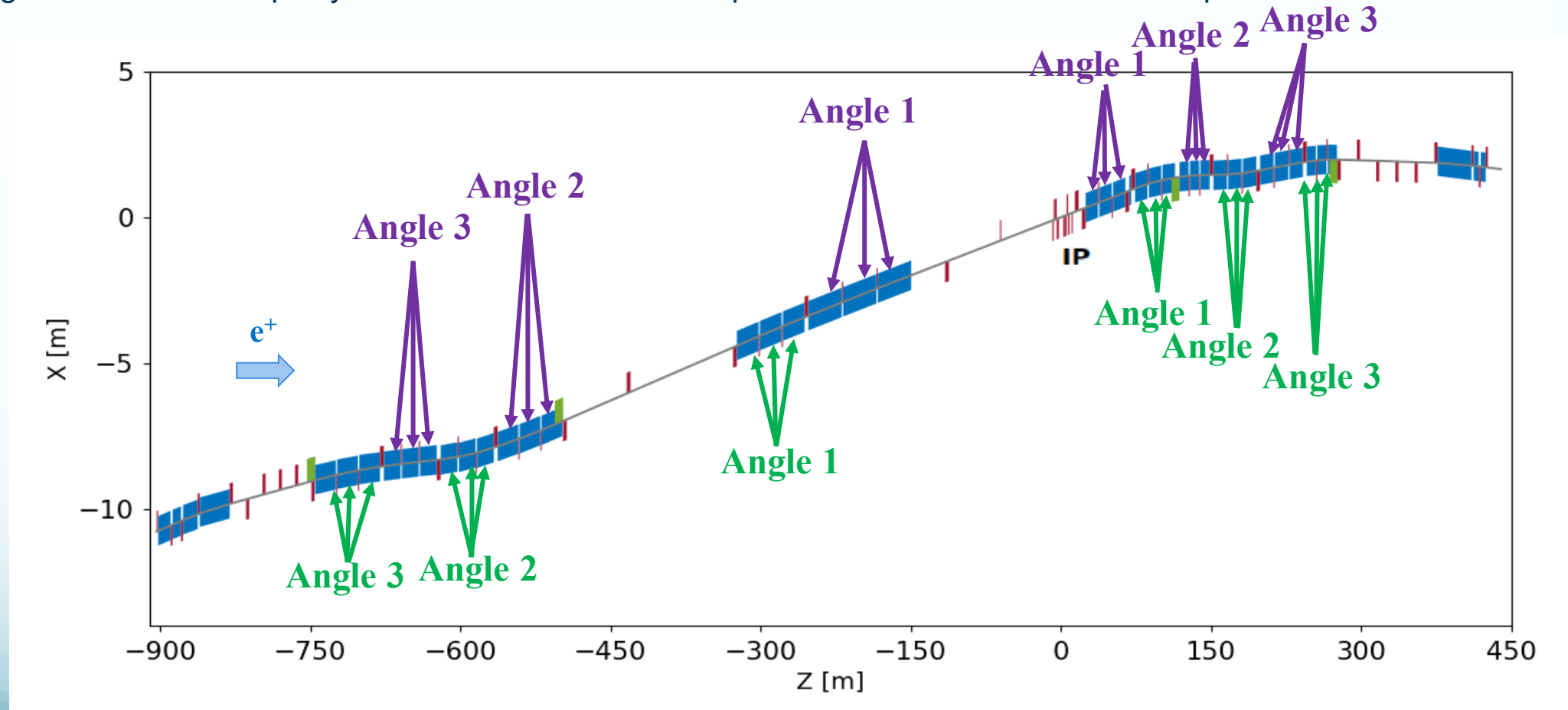
□ Scheme for Horizontal Dispersion Generation at the IP

All local vertical chromaticity horizontal dipoles (LOC H-dipole) (blue) in standard IR Optics are cut into three pieces, and quadrupoles (red) are inserted between them. Additional chicanes are implemented LOC H-dipole in each upstream and downstream to create the dispersion at the IP while keeping the orbit.



□ Scheme for Horizontal Dispersion Generation at the IP

To mitigate horizontal emittance blowup^[3], two long chicanes are implemented to each upstream and downstream. And each angle of chicane is equally distributed to all the three pieces of each LOC horizontal dipole.

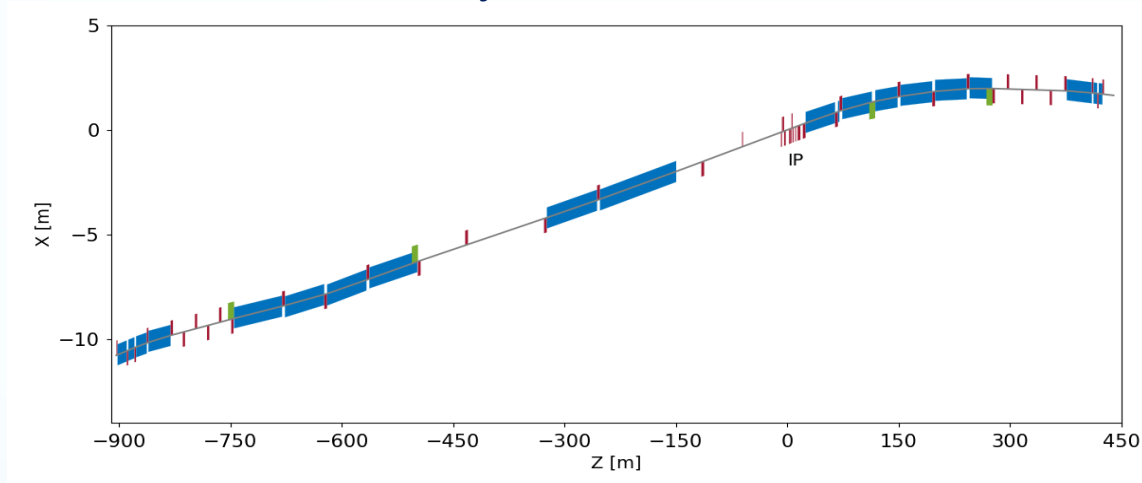


[3] Z.Zhang, A. Faus-Golfe, F. Zimmermann et al. "Monochromatization optics for FCC-ee lattices", CEPC Workshop 2023, <https://indico.ihep.ac.cn/event/19316/contributions/142896/>

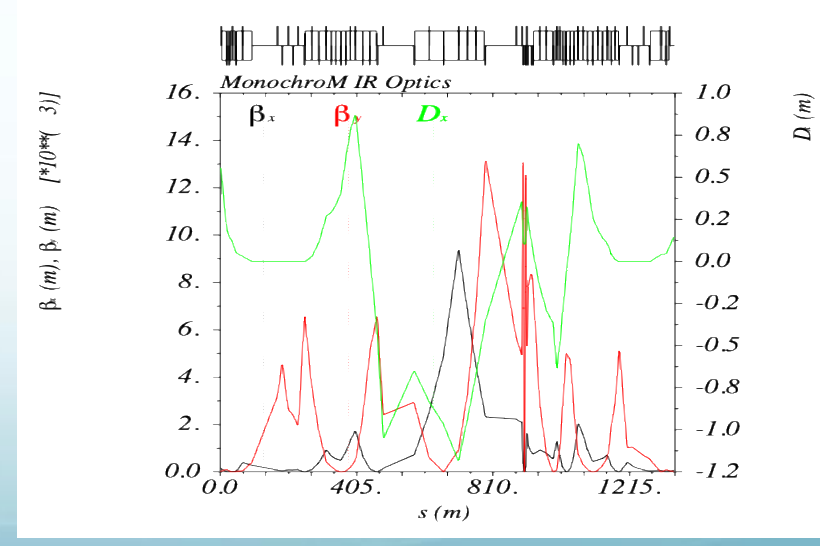
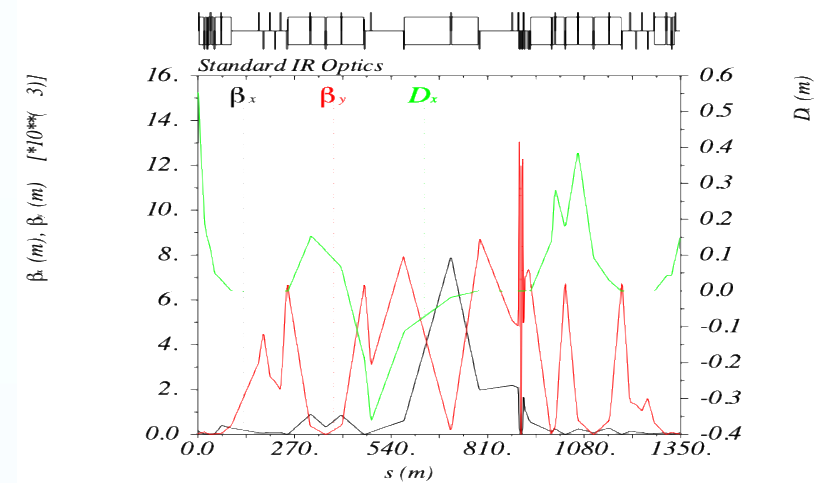
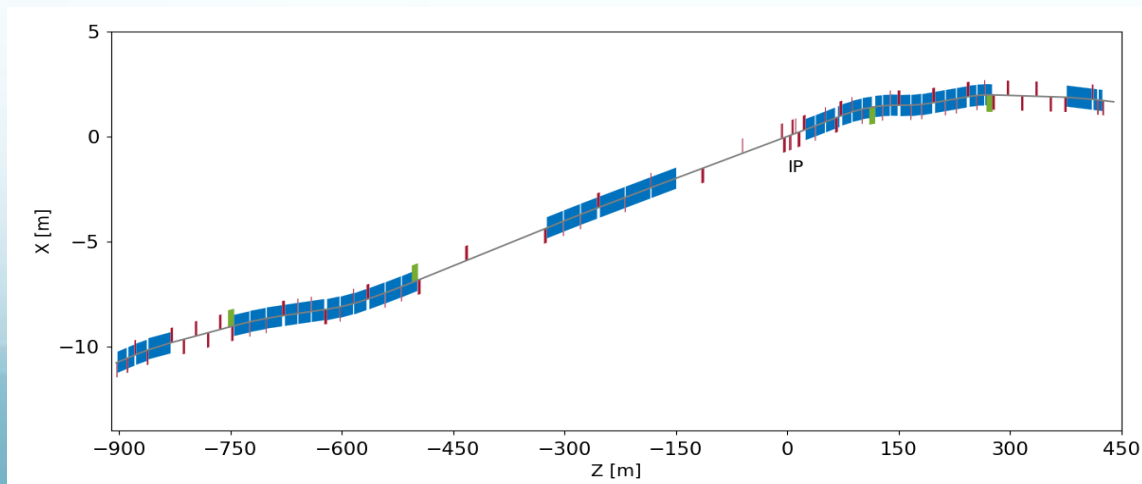
FCCEE Monochromatization optic design

Comparison between Standard Survey and Monochromatization Survey

Standard Survey Plot



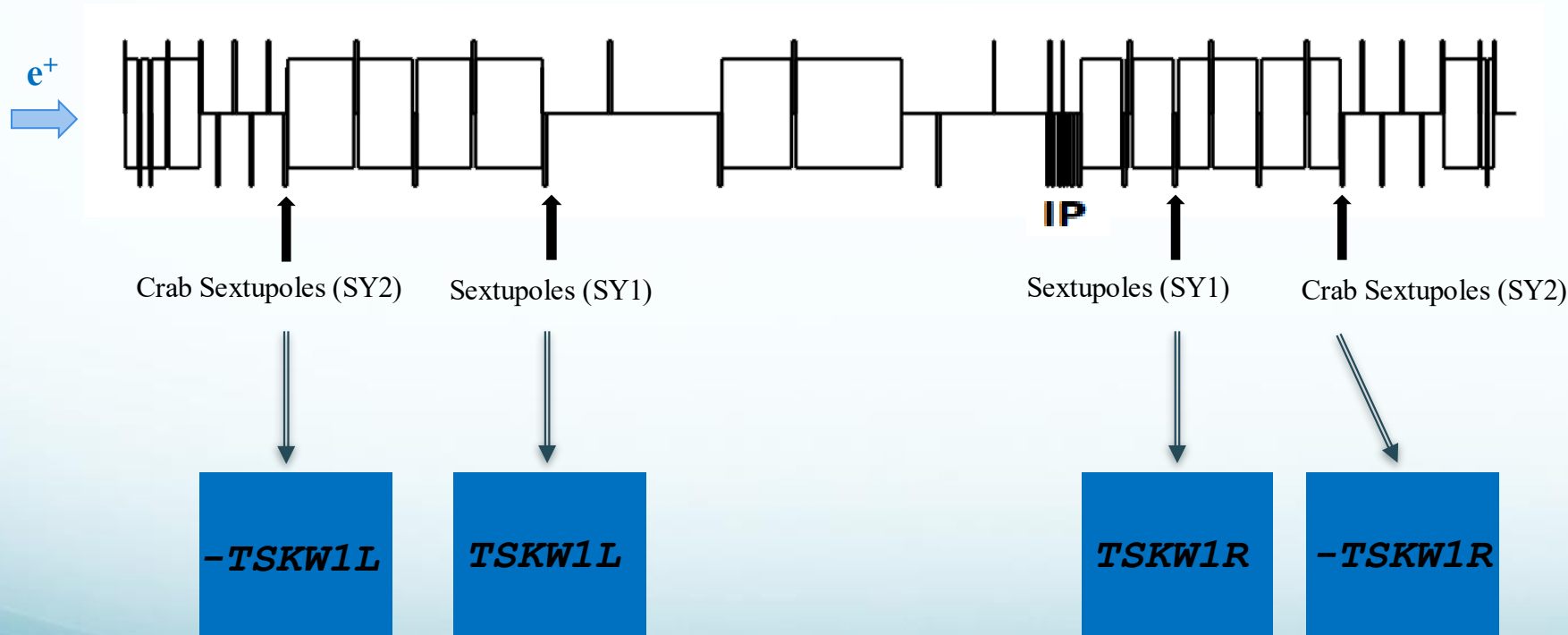
Monochromatization Survey Plot



□ Scheme of Vertical Dispersion Generation at the IP

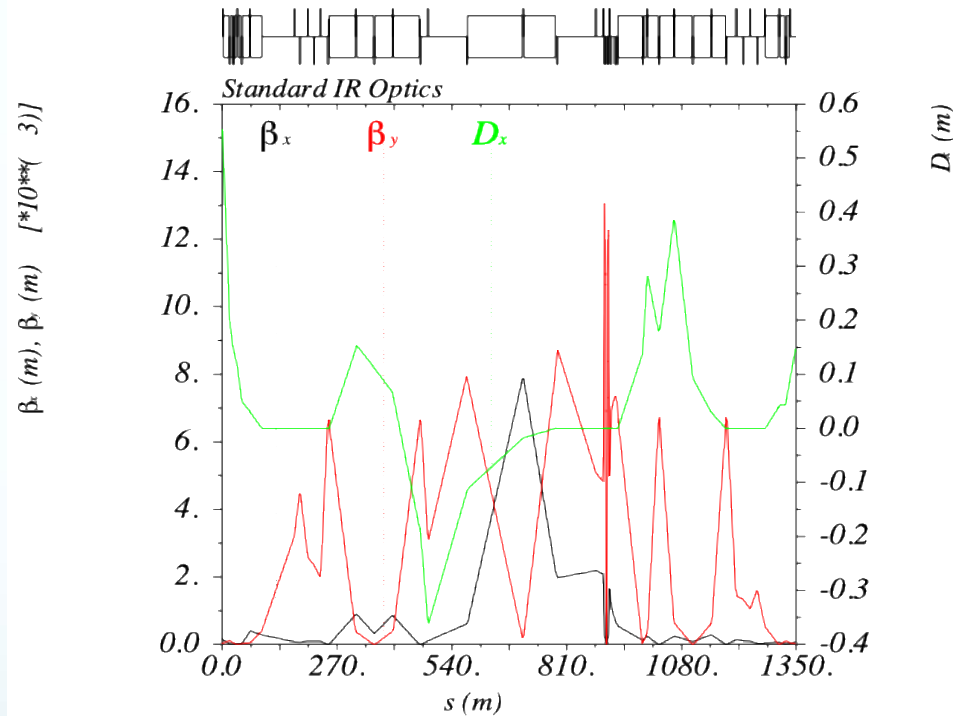
Since the vertical beam size at the IP is much smaller than horizontal beam size, about 100 times smaller vertical dispersion (0.001m) is needed to get the same monochromatization factor compared with the horizontal one.

Creating vertical dispersion by implementing skew quadrupoles around IP. After introducing the vertical dispersion at the IP, match the vertical dispersion back to zero by varying the strength of these 4 skew quadrupoles.



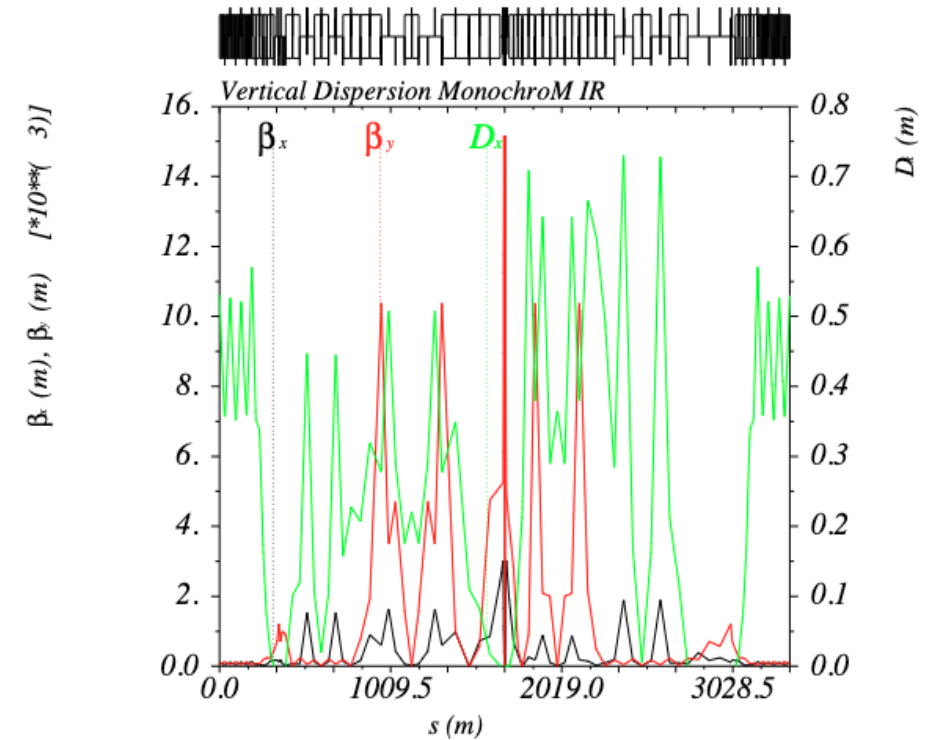
No effect on the beamline or Twiss parameters

FCC-ee Lattice Evolution



Z-mode GHC 2023

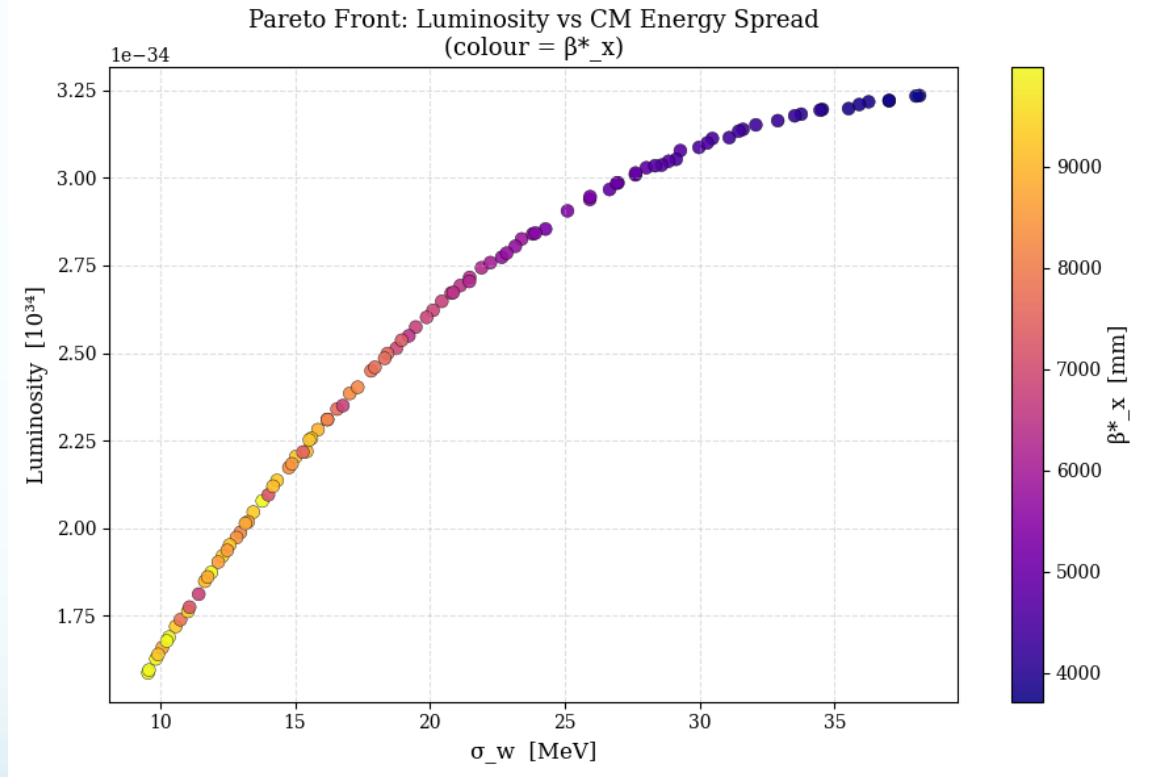
March 2026



Z-mode LCC v105

The baseline FCC-ee lattices experience constant adjustments, so does the monochromatization lattice

Multi-Goal Analytical Optimizer Development



Optimization curve maintaining $D_y^* = 1$ mm

Trade-off between instantaneous luminosity and center-of-mass energy spread with the color scale showing the dependence on the horizontal beta function

Impact on interaction region optics

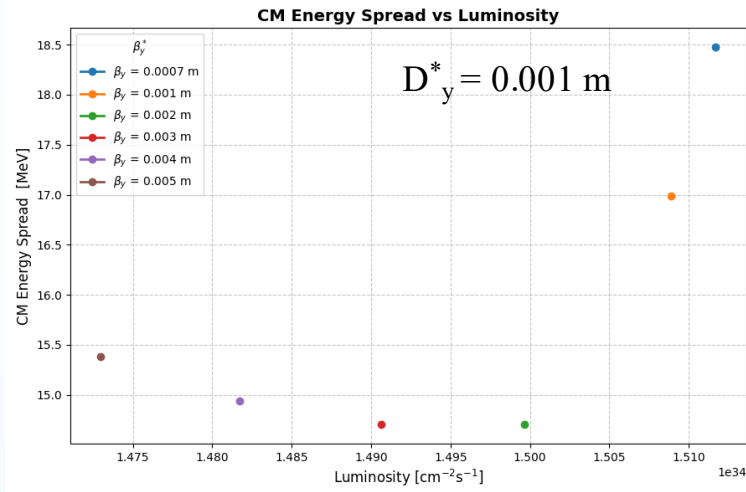
σ_w [MeV]	L [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	D_y^* [mm]	N_b	β_x^* [mm]	β_y^* [mm]	ξ_x	ξ_y	ϵ_y [pm]
63.03	25.28	0	12000	90	0.7	0.001	0.03	2.7
9.097	1.071	1.5	11997	9996.3	0.701	0.1051	0.0014	34.778
9.582	1.543	1.0	11901	9974.2	0.701	0.106	0.002	18.898
11.711	3.191	0.5	11974	9996.2	0.701	0.1057	0.0041	6.519
18.811	7.476	0.25	10668	6859.3	0.7	0.103	0.0096	4.798

But this semi-analytical approach doesn't account for the **hourglass** effect

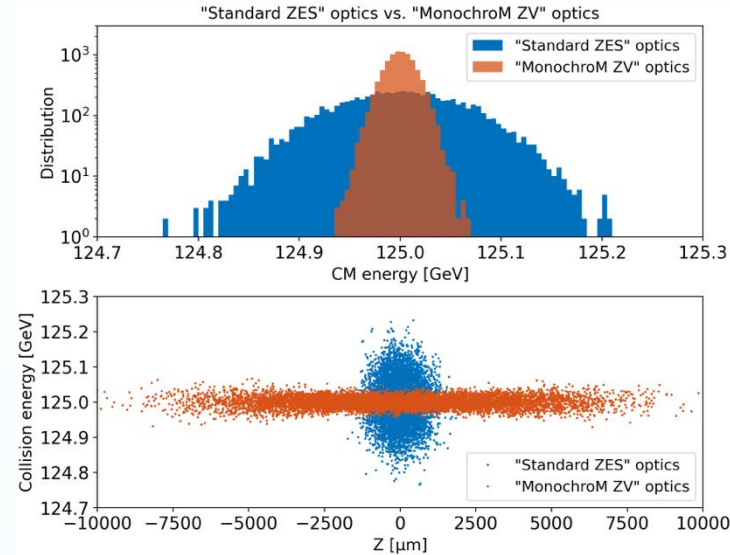
MonochroM Optics Based on LCC Lattice

Simulation-based Parametric Analysis Using Guinea-Pig

Guinea-Pig takes into account BS, hourglass effect, and simplified beam-beam.

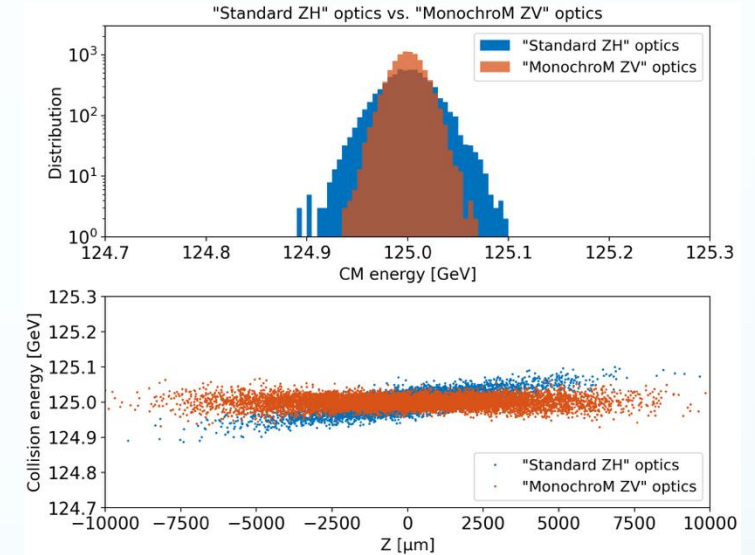


The vertical betatron function β_y^* had to be increased to an optimal value of 2 mm instead of the nominal 0.7 mm to mitigate the **hourglass effect**



Energy distribution in the colliding beams.

Comparison between the Standard operation (ZES) and the Vertical Monochromatization mode (ZV) operation.



Energy distribution in the colliding beams.

Comparison between the Horizontal (ZH) and Vertical (ZV) Monochromatization modes.

GHC and LCC lattice performance comparison

- FCC-ee Monochromatization Optics based on GHC Z mode lattice V22*

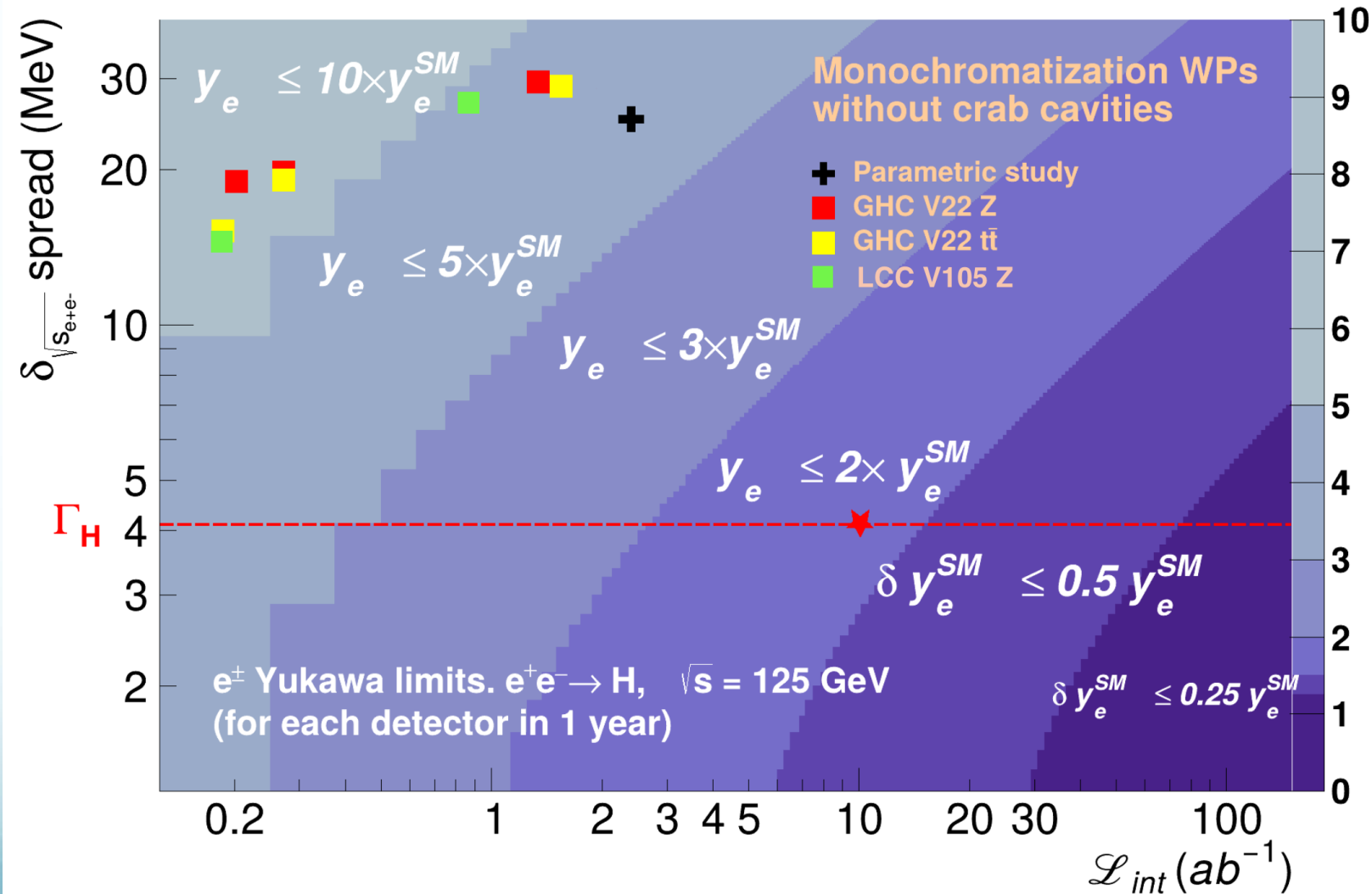
Parameters		Standard ZES V22	MonochroM ZH V22	MonochroM ZV V22
RMS CM energy spread σ_w	[MeV]	68.49	29.77	19.05
Luminosity per IP	[$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	22.1	10.1	1.68
Integrated luminosity/IP/year	[ab^{-1}]	2.65	1.21	0.2

- FCC-ee Monochromatization Optics based on LCC Z mode lattice v105*

Parameters		Standard ZES v105	MonochroM ZH v105*	MonochroM ZV v105
RMS CM energy spread σ_w	[MeV]	63.5	23.8	14.7
Luminosity per IP	[$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	19.4	7.3	1.5
Integrated luminosity/IP/year	[ab^{-1}]	2.3	0.9	0.2

* analytical data, no actual lattice yet developped

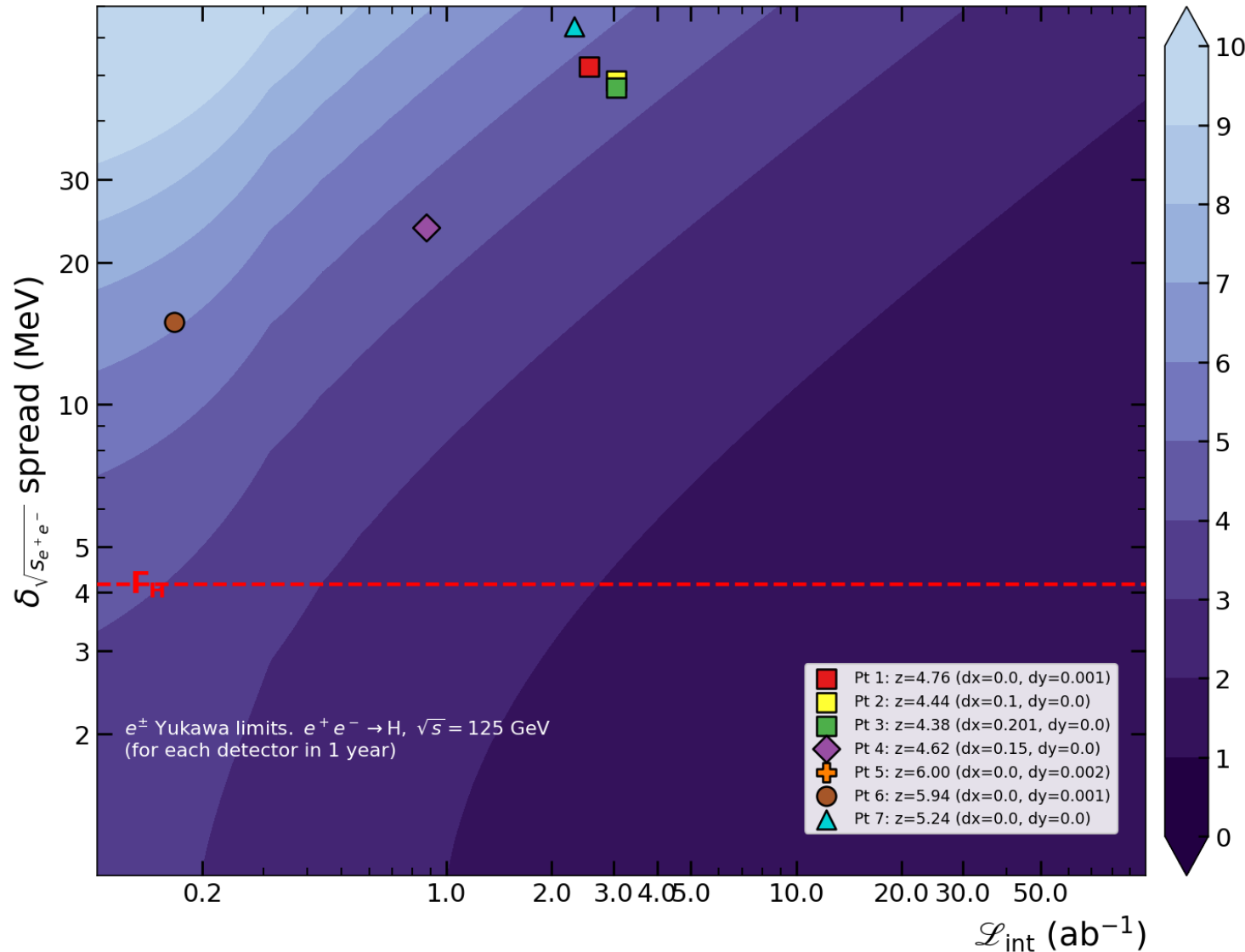
Significance Parameter definition



After discussing the definition of an optimal result, I was provided with the data set of Luminosity versus CME spread and the corresponding Yukawa coupling measurement uncertainty parameter (color in the plot).

This changed my approach to optimization.

Monochromatization Performances



My optimization was changed to a simulation-based approach rather than an analytical one because the analytical approach didn't account for the hourglass effect, which was significant in monochrom modes.

The optimization is still ongoing.

We aim to go under $Z=4$.

Attempt to include the hourglass effect analytically

High computational costs motivated us to incorporate an hourglass correction in the monochromatization case [1].

$$D_x^* \neq 0, D_y^* = 0$$

$$\mathcal{L}_1 = \frac{f_{rev} n_b N_b^2}{4\pi \sigma_{x\beta}^* \sigma_{y\beta}^*} \frac{\beta_y^*}{\sigma_z \sqrt{\pi}} \frac{1}{\sqrt{1 + \frac{\sigma_\delta^2 D_x^{*2}}{\sigma_{x\beta}^{*2}}}} \exp(t_1) K_0(t_1)$$

$$t_1 = \frac{\beta_y^{*2}}{2 \sigma_z^2} \left(1 + \frac{\sigma_{x\beta}^2 \varphi^2}{\sigma_x^{*2}} \right)$$

$$K_0(t_1) = \int_0^\infty \frac{\cos(t_1 t)}{\sqrt{t^2 + 1}} dt$$

$$D_y^* \neq 0, D_x^* = 0$$

$$\mathcal{L}_2 = \frac{f_{rev} n_b N_b^2}{4\pi \sigma_{x\beta}^* \sigma_{y\beta}^*} \frac{\beta_y^*}{\sigma_z \sqrt{\pi}} \exp(t_2) K_0(t_2)$$

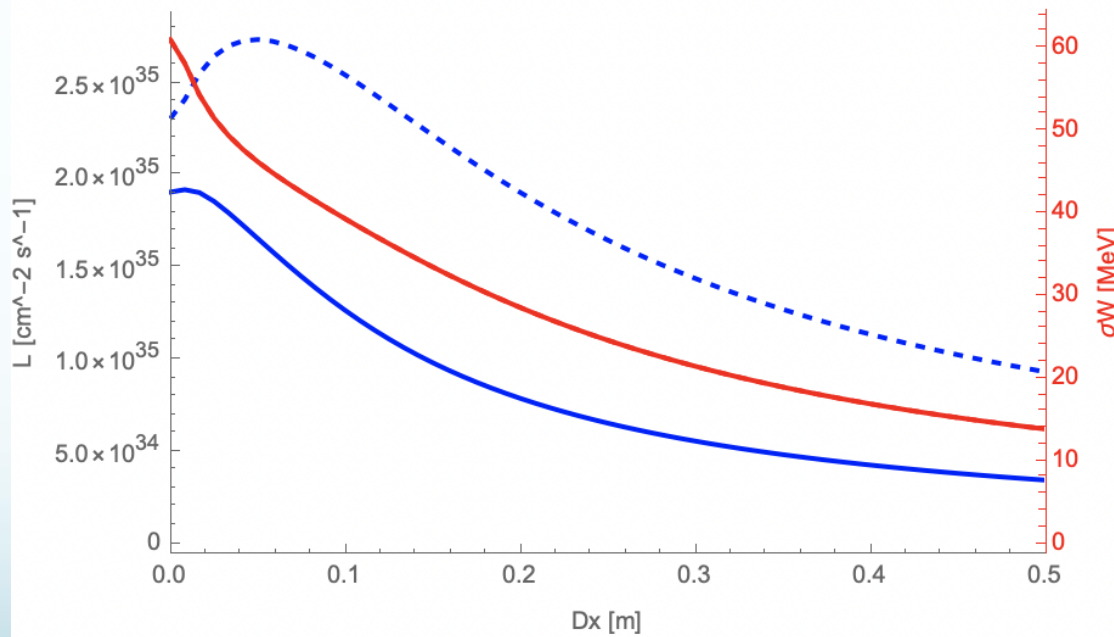
$$t_2 = \frac{\beta_y^{*2}}{2 \sigma_z^2} (1 + \varphi^2) \left(1 + \frac{\sigma_\delta^2 D_y^{*2}}{\sigma_{y\beta}^{*2}} \right)$$

[1] A. Bogomyagkov, E. Levichev, Collision monochromatization in e⁺e⁻ colliders, Phys. Rev. Accel. Beams 20, 051001 (2017).

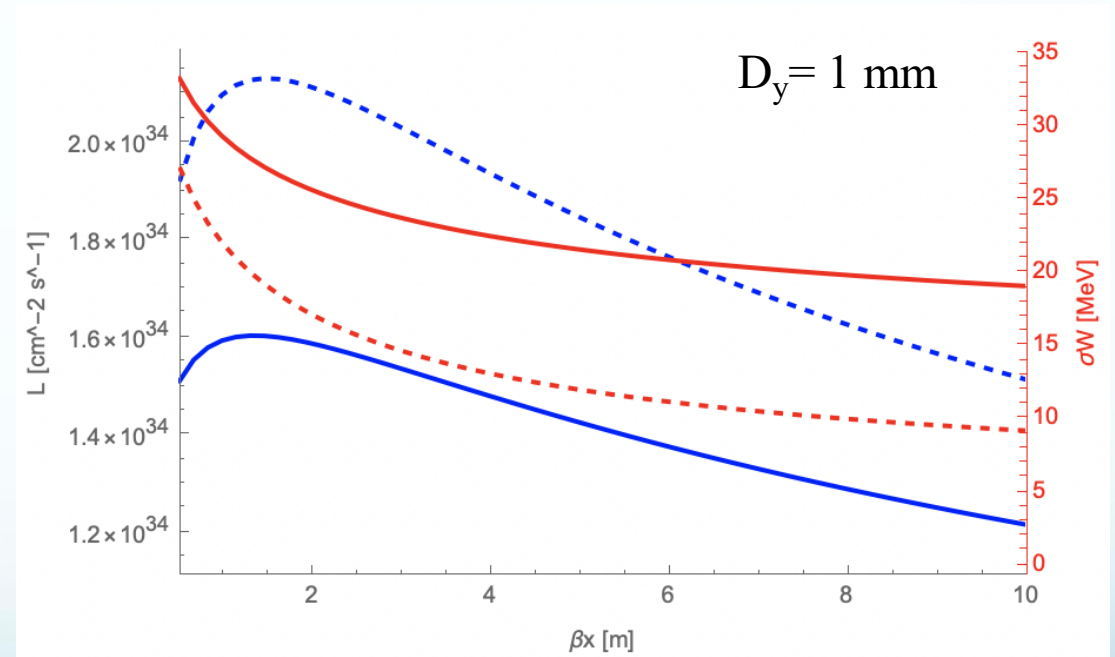
Attempt to include the hourglass effect analytically

Hourglass adjustment to instant luminosities and CM energy spread

Horizontal Monochrom mode



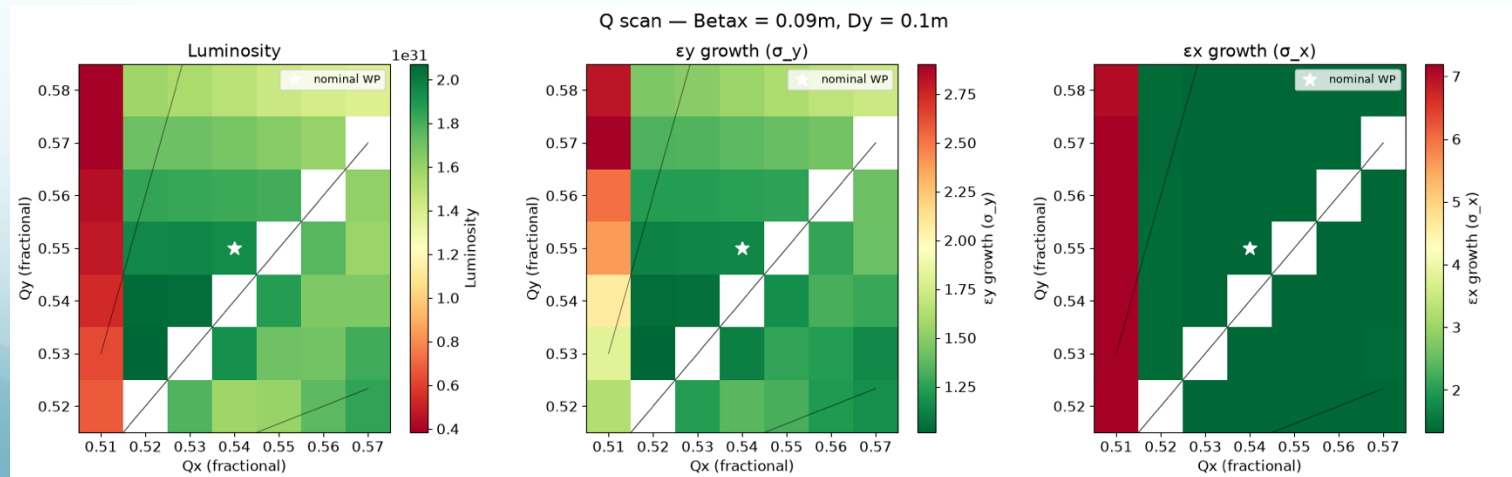
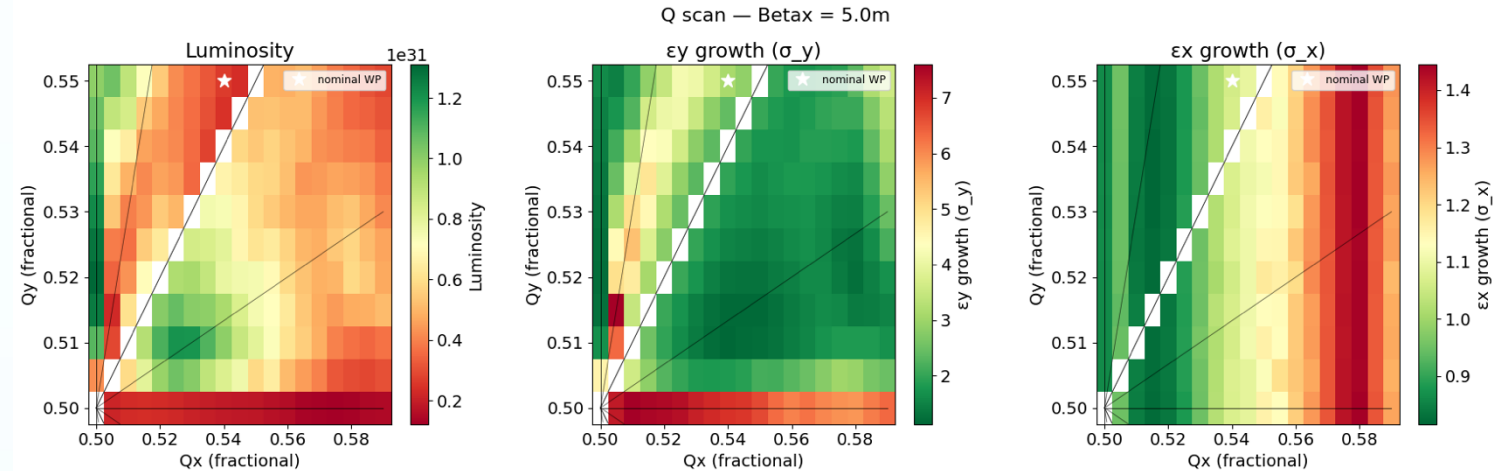
Vertical Monochrom mode



Beam-beam stability studies

Search for a stable working point in the MonochroM mode

Vertical MonochroM mode

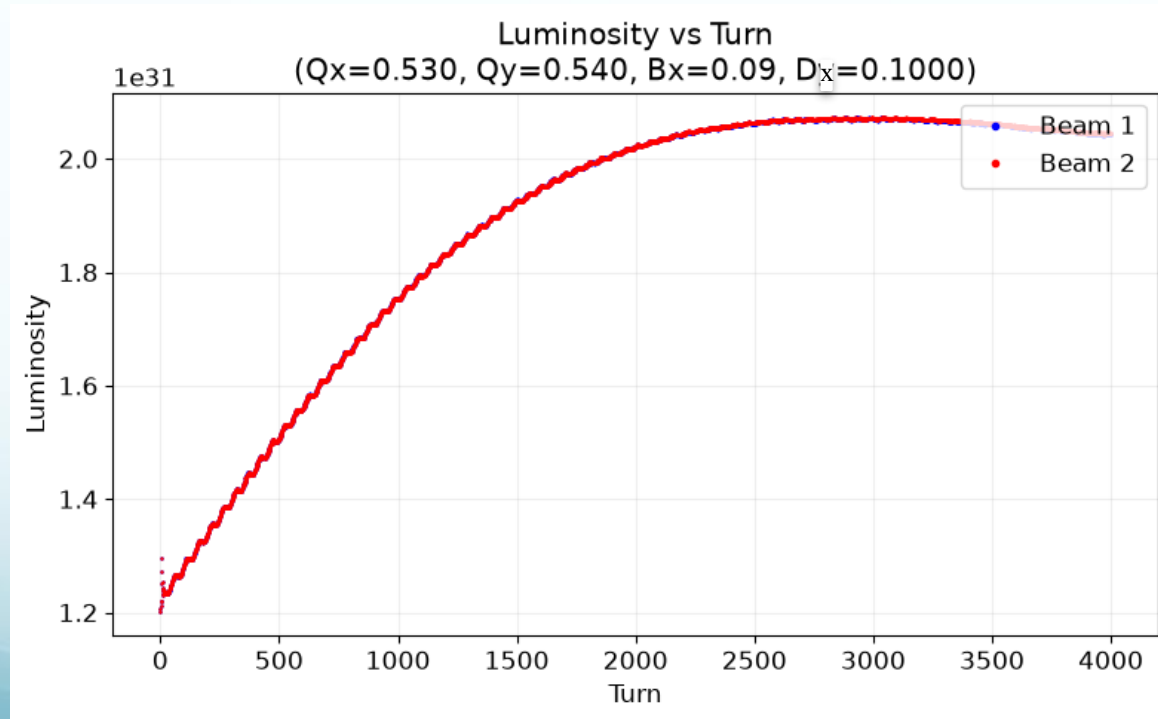


Horizontal MonochroM mode

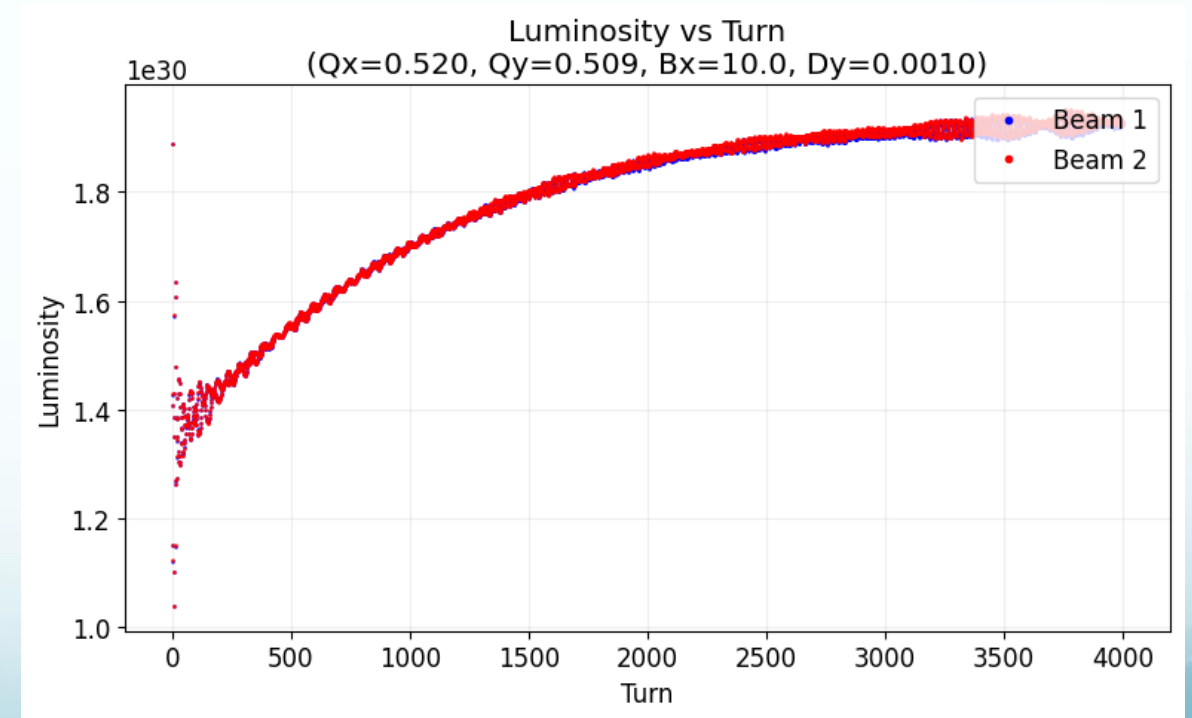
Beam-beam stability studies

Turn-by-turn Xsuite simulations reveal a stable working point for instantaneous luminosity

Horizontal MonochroM mode



Vertical MonochroM mode



Summary and Outlook

- ☐ Monochromatization is a **simple conceptual idea**. However, research on the monochromatization principle has never reached a maturity level that allows **implementation** and **experimental testing**.
- ☐ The parametric studies for the LCC lattice parameters are ongoing. The optimization tools are evolving.
- ☐ Experimental proof of the monochromatization concept in running e^+e^- low-energy colliders is under study for SuperKEKB at the moment.
- ☐ The lattice design for the horizontal MonochroM mode is undergoing.

Thanks for you attention!