Monochromatization for future circular colliders and possible experimental implementation

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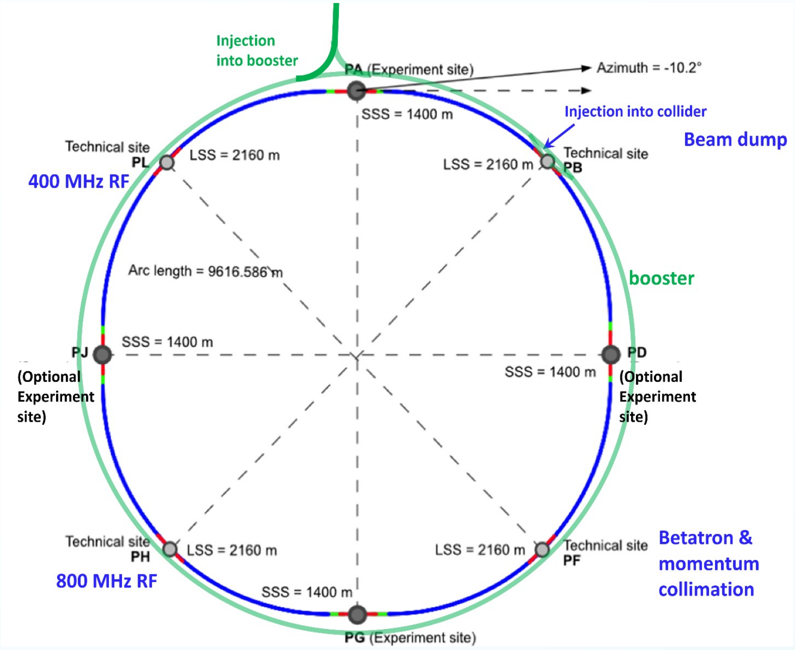
Outline

- Introduction and motivation
- Monochromatization Principle
- FCC-ee Monochromatization IR Optics Design
- Analytical performance optimization and simulation results
- Performance Check and Comparison of FCC-ee MonochroM Optics
- Summary and outlook

Introduction: Physics Requirements

- **FCC-ee modes:**
  - The FCC-ee standard modes:
    - Four different energy operation modes:

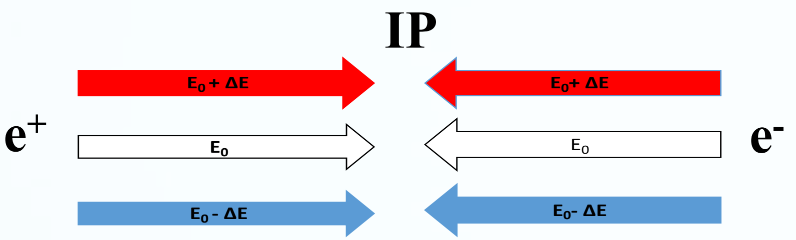
      $\boldsymbol{Z}$, $\boldsymbol{W^{\pm}}$, $\boldsymbol{Zh}$ **and** $\boldsymbol{t\bar{t}}$
  - The optional fifth mode: ***s***-channel Higgs production mode
    - The measurement of the electron Yukawa coupling, in dedicated runs at 125 GeV with center-of-mass (CM) energy spread (5-10 MeV). But the 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)

Monochromatization Principle

Standard



$D^*_{x,y}=0$

correlation between transverse spatial position and energy deviation

CM energy

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

Spread of the CM energies

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

Monochromatization factor

$$\lambda = 1$$

Luminosity

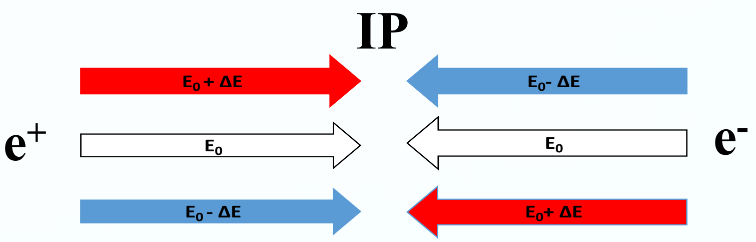
$$L_0 = \frac{k_b f_r N_+ N_-}{4\pi\sigma^*_{x\beta}\sigma^*_{y\beta}}$$

betatronic beam sizes at the IP

$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y}\epsilon_{x,y} + \left(D^*_{x,y}\sigma_\delta\right)^2}$$

dispersive beam size at the IP

Monochromatization



$D^*_{x+} = - D^*_{x-} = D^*_x$

$D^*_{y+} = - D^*_{y-} = D^*_y$

Opposite correlations between transverse spatial position and energy deviation

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

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

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

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

Enhancement of energy resolution, and sometimes an increase in the relative frequency of events at the center of the distribution, but with luminosity loss.

Monochromatization in High-energy Colliders

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

$D^*_{x,y}=0$

Monochromatization BS

$D^*_{x+} = - D^*_{x-} = D^*_x$
$D^*_{y+} = - D^*_{y-} = D^*_y$

Coupled system to be solved numerically

Energy spread

Standard BS:

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

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

Monochromatization BS:

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

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

$$\mathcal{H}^*_{x,y} = \frac{\left(\beta^*_{x,y}D'^*_{x,y} + \alpha^*_{x,y}D^*_{x,y}\right)^2 + \left(D^*_{x,y}\right)^2}{\beta^*_{x,y}}$$

Horizontal emittance

Standard BS:

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

Monochromatization BS:

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

Bunch length

Standard BS:

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

Monochromatization BS:

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

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

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

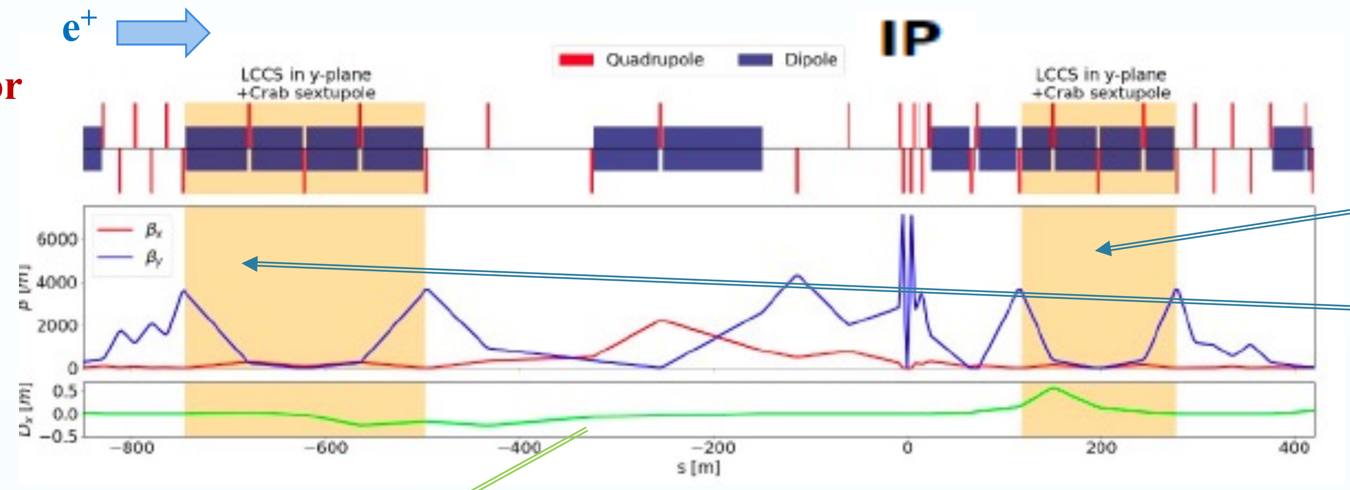
M. A. Valdivia García, F. Zimmermann, Towards an optimized monochromatization for direct Higgs production in future circular e+ e- Colliders, in CERN-BINP Workshop for Young Scientists in e+e- Colliders, pp. 1–12 (2017)

Monochrom Implementation in FCC-ee GHC IR

Despite the **simplicity** of the **monochromatization concept**, the **creation** and the **control** of the necessary **H/V dispersion** function of opposite signs at the IP could be **rather difficult to implement**.

Monochromatization factor

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



IR GHC: Local Chromaticity Correction Section (LCCS) with Crab Sextupoles (CS) in the vertical to produce a crab waist collision

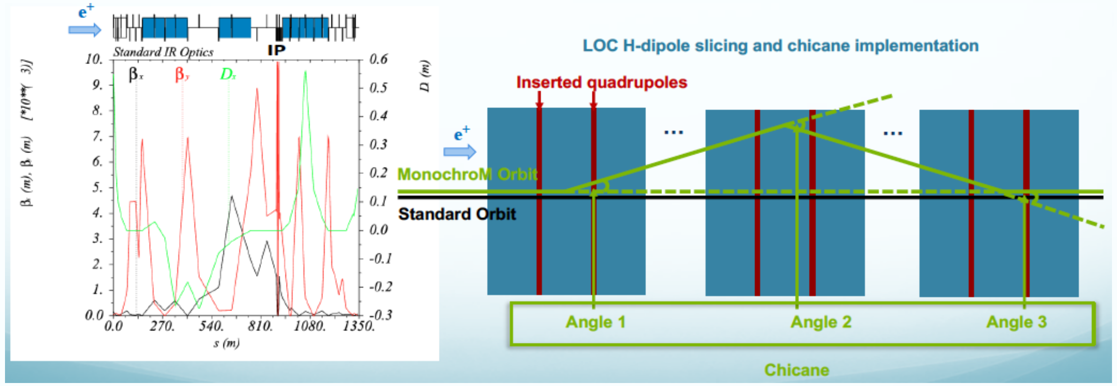
➢ $D^*_x \neq 0$ generation at the IP

In FCC-ee IR region, the **large crossing angle of 30 mrad** in the H-plane and the **local chromaticity correction system (LCCS)** are achieved using **H-dipoles** at both sides of the IP, creating some **H-dispersion** D^*_x ($D_x \neq 0$ in the LCCS and $D_x = 0$ close to the IP for high-luminosity). $D^*_x \neq 0$ can be generated **(~10 cm)** by intentionally **mismatching D_x** in the LCCS.

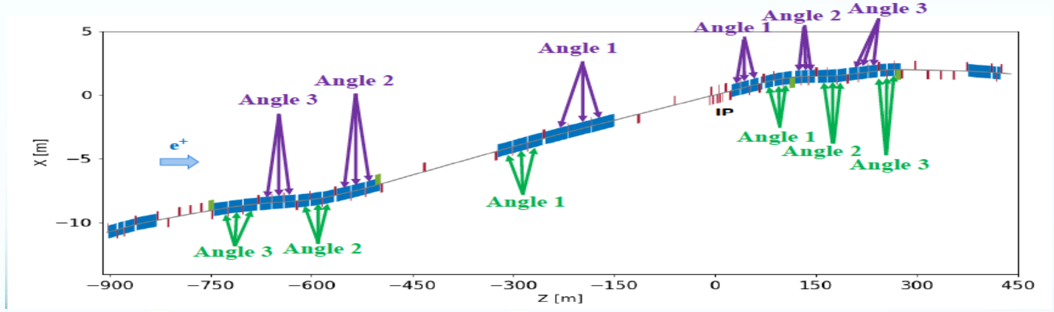
➢ $D^*_y \neq 0$ generation at the IP

Because $\sigma^*_{y\beta} \lll \sigma^*_{x\beta}$, about **100 times smaller D^*_y (~mm)** is needed to get the same monochromatization factor. Therefore, **$D^*_y \neq 0$** could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located where the chromatic sextupole (CS) pairs are located in the LCC system.

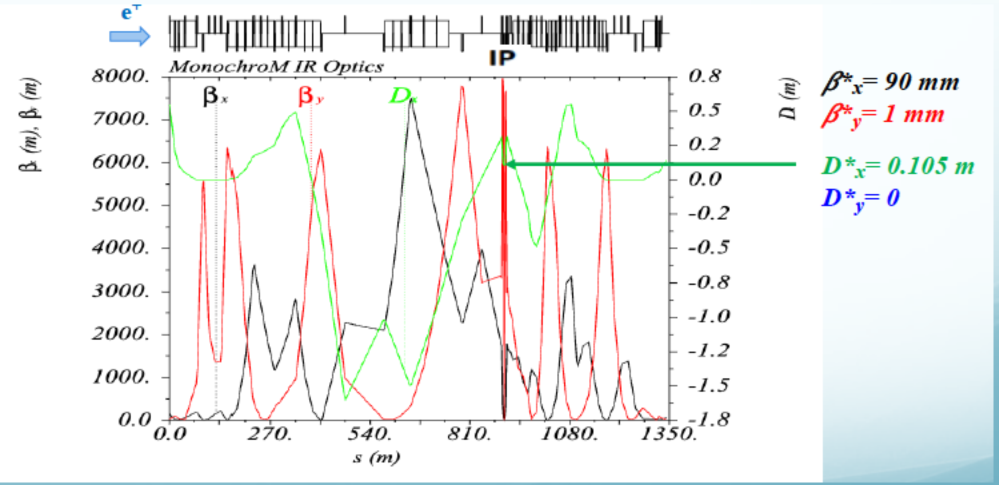
H-Monochrom Implementation in FCC-ee GHC IR (I)



Step 1: All LCCS H-dipoles (blue) are virtually cut into three pieces, and quadrupoles (red) are inserted between them for matching flexibility. Additional chicanes are implemented in each upstream and downstream LCCS H-dipole to create the dispersion at the IP while keeping the orbit.



Step 2: To mitigate the horizontal emittance blowup, 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 LCCS H-dipole.

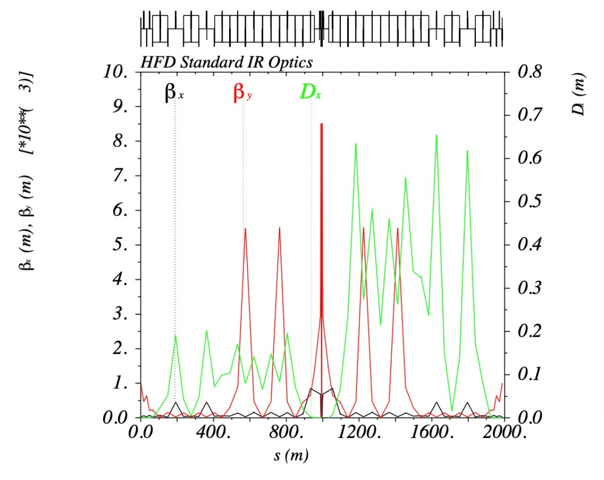


Step 3: The IP beam parameters are matched to FCC-ee Monochrom self-consistent parameters* while keeping the beam parameters at the entrance and exit of the IR similar to those of standard mode, including phase advances between sextupoles and crab sextupoles.

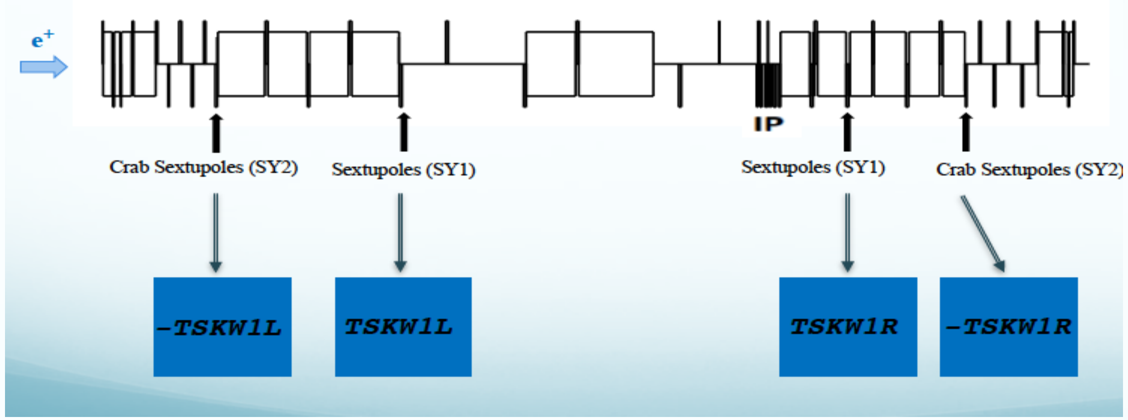
*A. Faus-Golfe, M. Valdivia Garcia, F. Zimmermann, The challenge of monochromatization Direct s-channel Higgs production: e+e− → H, Eur. Phys. J. Plus (2022) 137:31, https://doi.org/10.1140/epjp/s13360-021-02151-y

V-Monochrom Implementation in FCC-ee GHC IR

Step 1: The $\mathbf{D^*_y \neq 0}$ could be generated by implementing **skew quadrupoles** around IP.

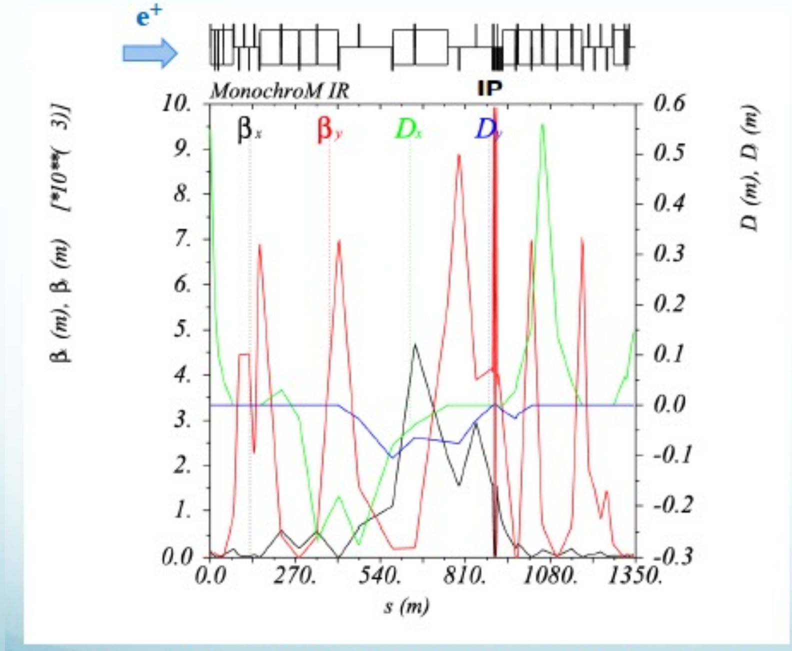


Inspired in **Local Chromaticity Correction** (LCC) IR optics solenoid compensation scheme



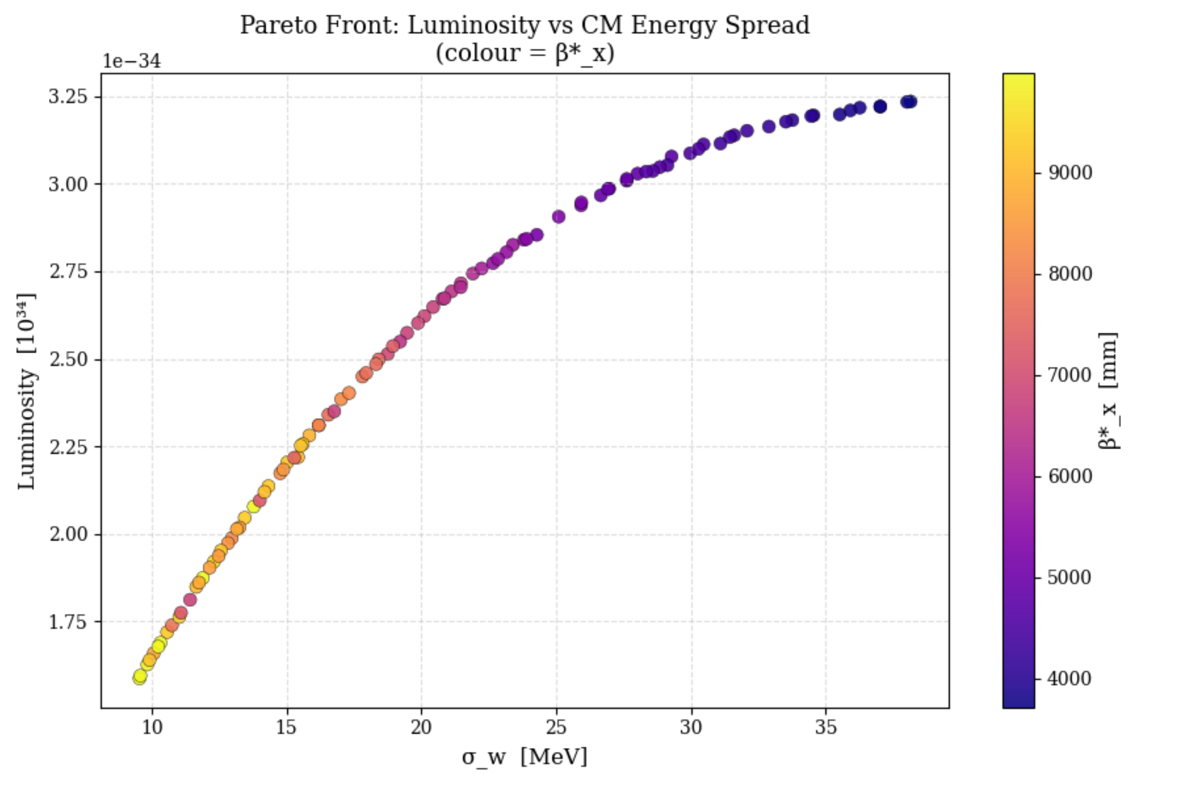
Step 2: IR Monochrom is implemented in the four IPs and global matching:

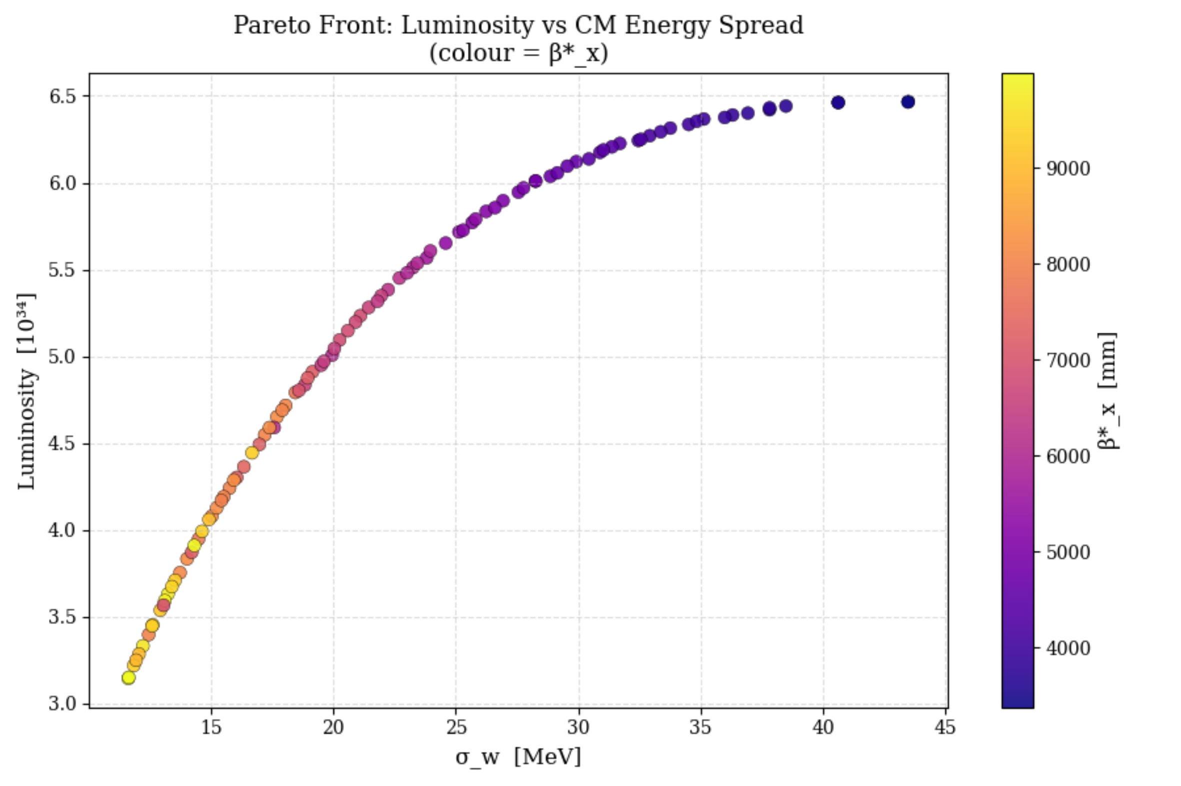
- LCCS chromaticity correction
- Global arc chromaticity correction
- Tune correction
- Emittance checks and SR-RF strategy compensation
- Preliminary Tracking and DA calculations



$\beta^*_x = 100$ mm $\beta^*_y = 0.8$ mm $D^*_x = 0$ $D^*_y = 1$ mm

MonochroM optics based on LCC lattice
Analytical optimization for vertical dispersion





Optimization curve maintaining $D^*_y = 1$ mm

Optimization curve maintaining $D^*_y = 0.5$ mm

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

Optimization is based on a modified MOGA tool, original of which is available on git

Mitigating Emittance Blowup vs. Beam-Beam Limits

- **The Mechanism:** In monochromatization with vertical dispersion, increasing β_x at the IP helps mitigate vertical emittance blowup due to beamstrahlung.

- **The Conflict:**
  - Higher β_x reduces vertical emittance blowup.
  - Higher β_x leads to an increase in the horizontal beam-beam parameter ξ_x.

- **The Constraint: X-Z Instabilities.**
  - Simply increasing β_x very quickly hits stability limits. Unless we reach high enough Piwinski angle to overcome the X-Z instability zone which has to be tested via beam-beam simulations

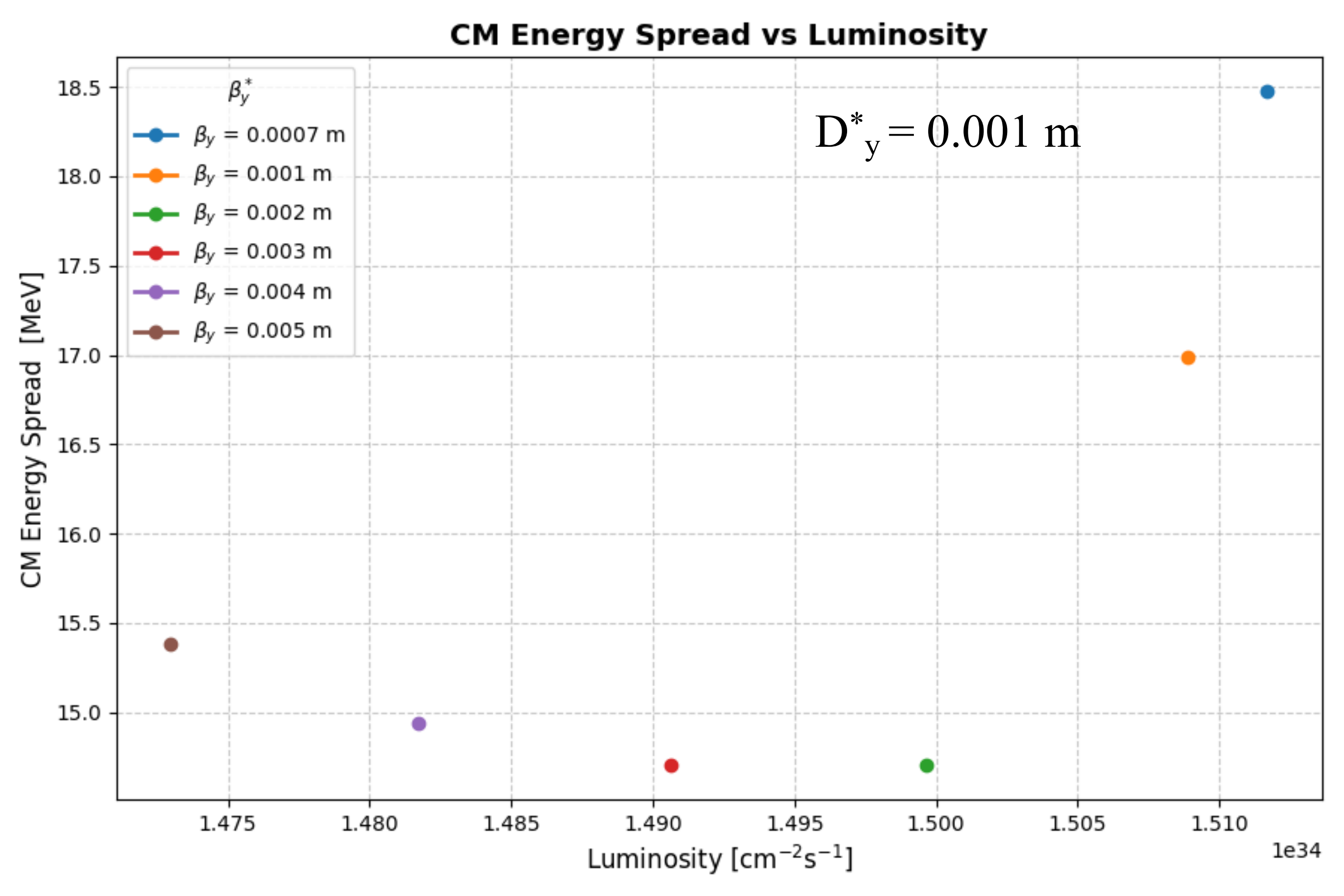
MonochroM optics based on LCC lattice
Analytical optimization for vertical dispersion

Semi-analytical optimization tool allowed to obtain the following parameters.

σ_W [MeV]	L [10^{34} cm^{-2} s^{-1}]	D_y^* [mm]	N_b	β_x^* [mm]	β_y^* [mm]	ξ_x	ξ_x	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

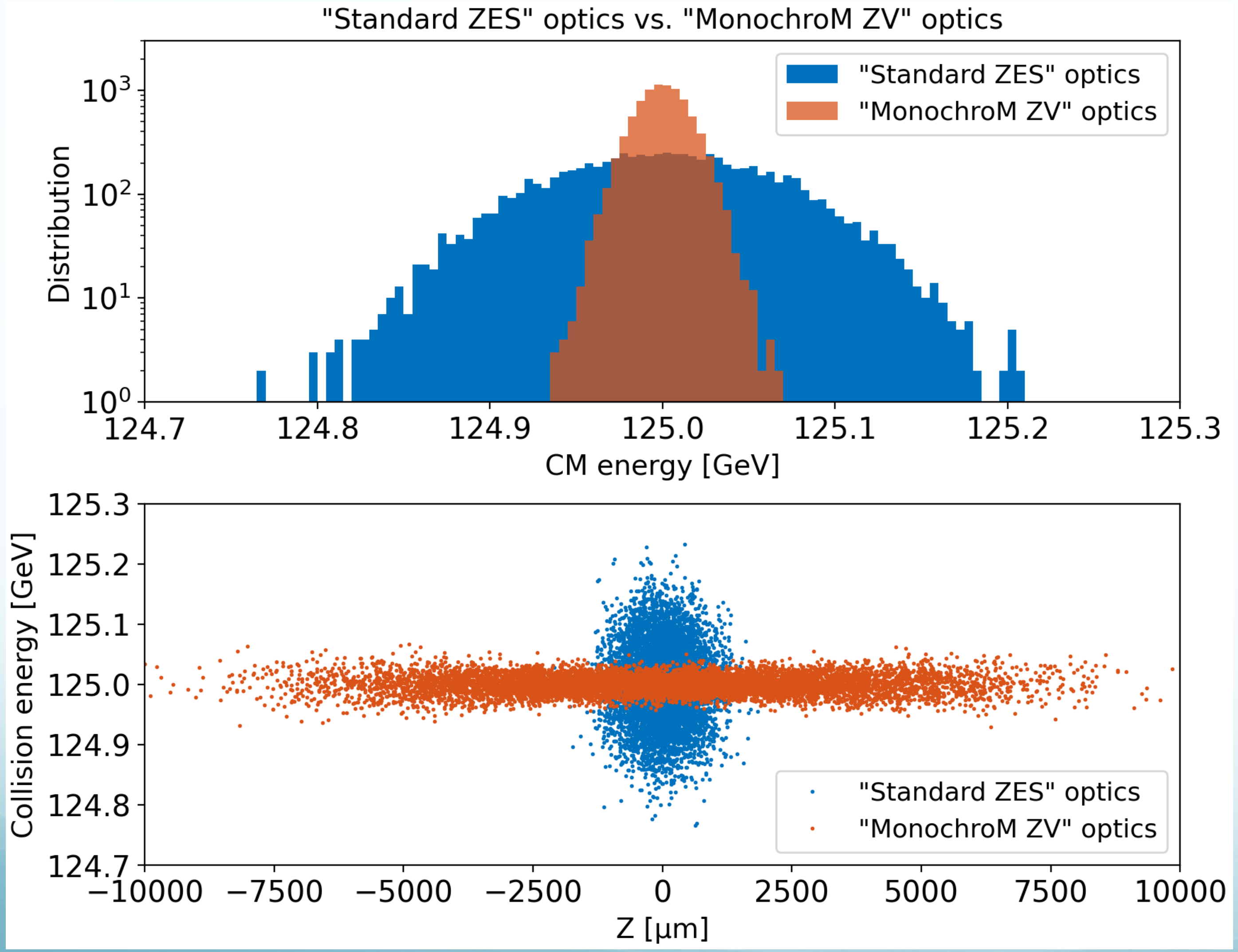
But it doesn’t account for the hourglass effect

MonochroM optics based on LCC lattice
Simulation-based parametric analysis using Guinea-Pig



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

MonochroM optics based on LCC lattice
Guinea-Pig simulation result



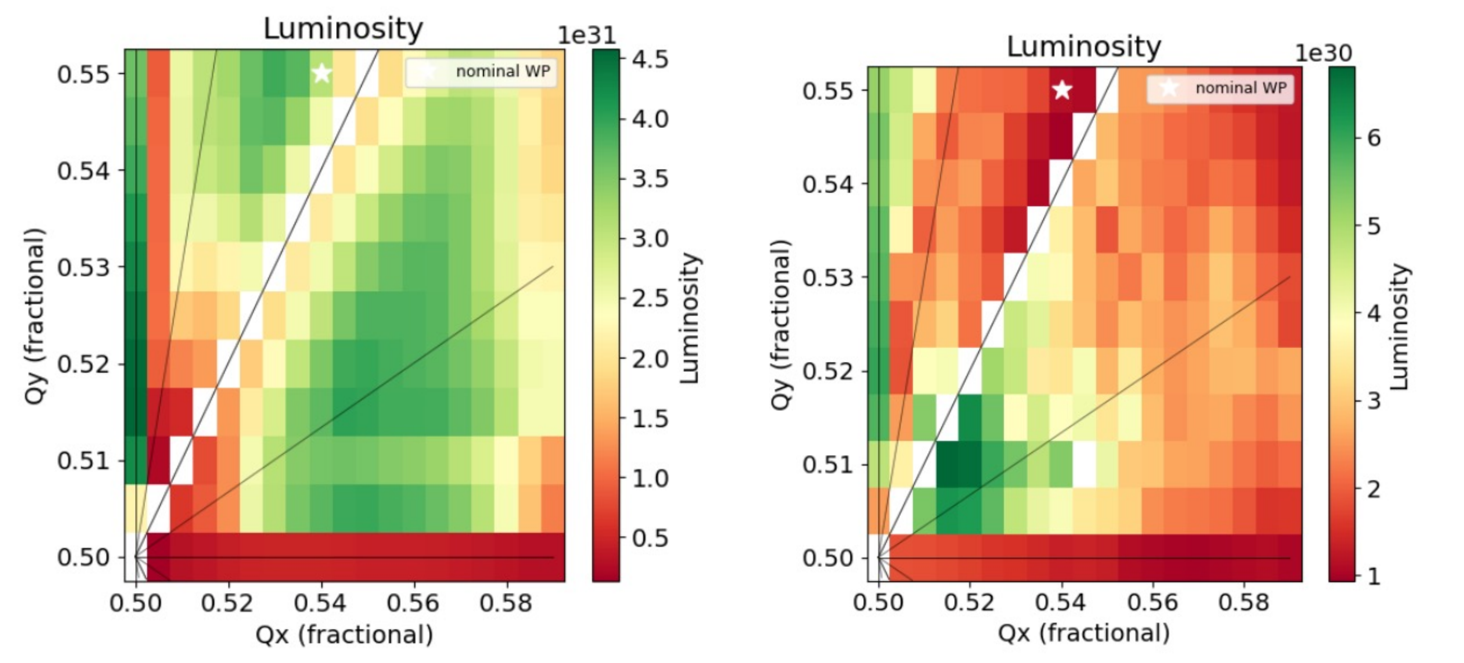
Energy distribution in the colliding beams.

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

Beam-Beam Limits: Selecting a New Working Point

Additionally, strong-strong beam-beam simulations in Xsuite have been performed for different β^*_x

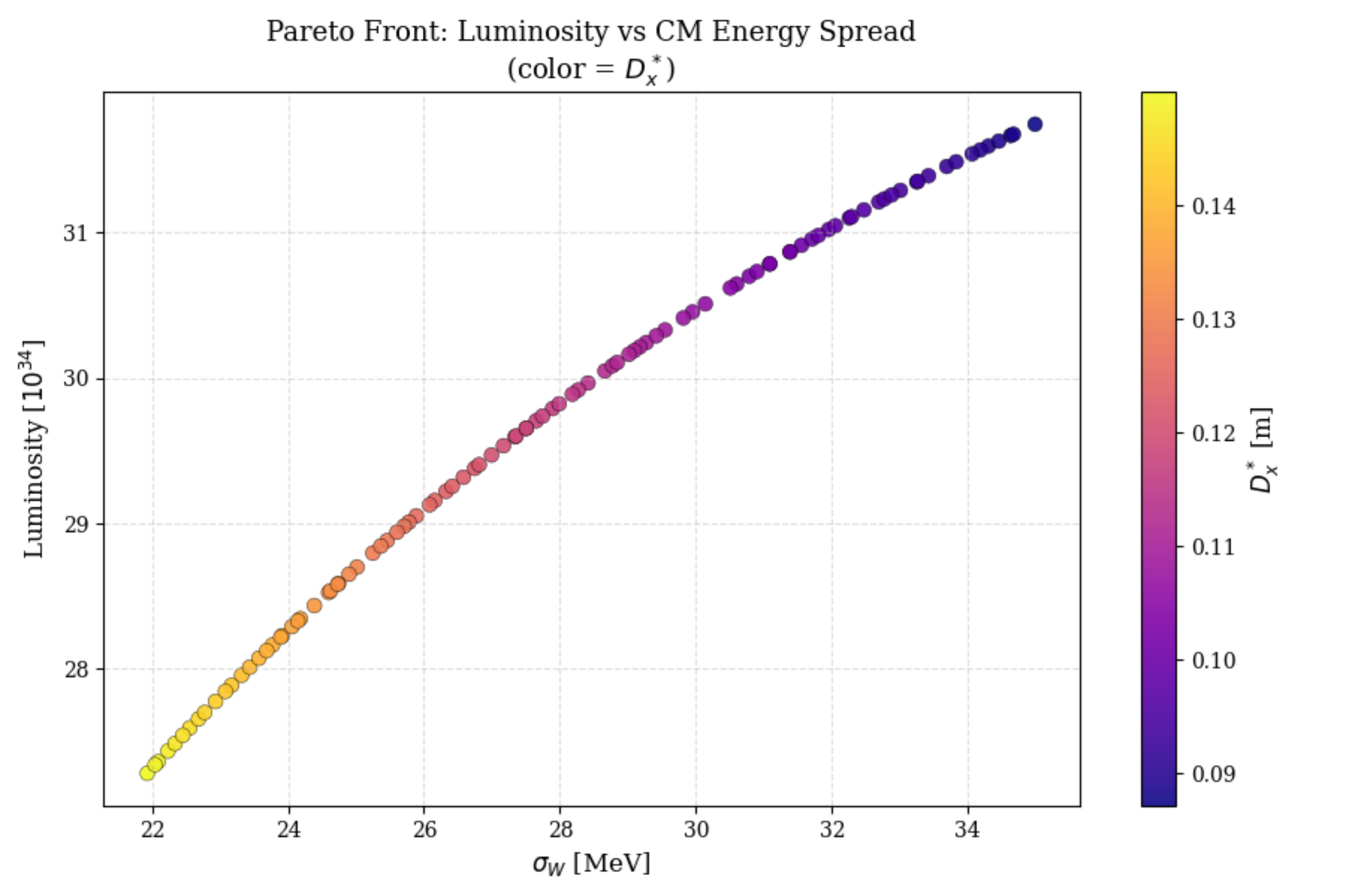
Visible need of change of the working point when increasing the β^*_x



Q-scan at β^*_x=1m

Q-scan at β^*_x=10m

MonochroM optics based on LCC lattice
Analytical optimization for horizontal dispersion

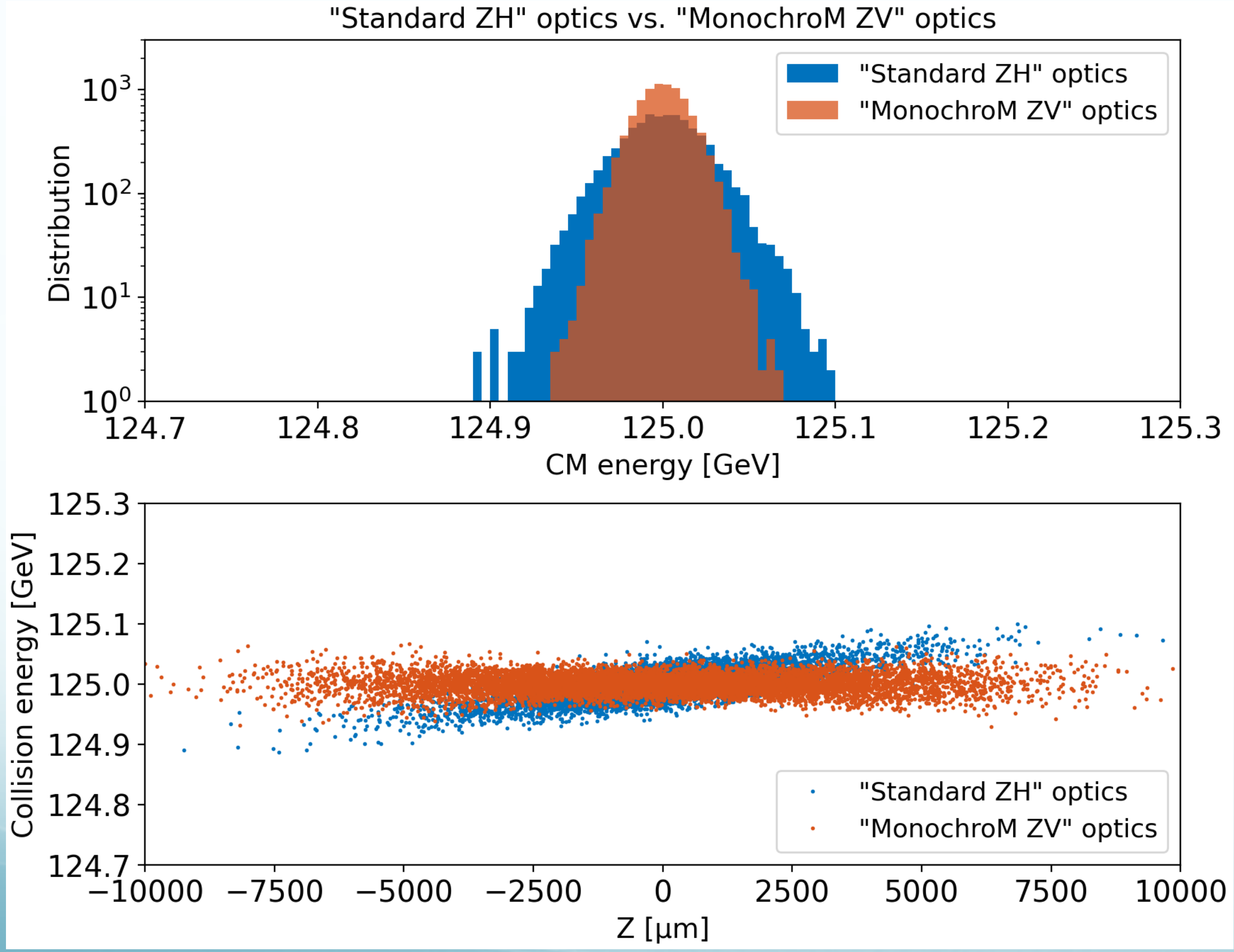


Horizontal dispersion offers lower achievable CM energy spread but higher luminosity.

CM energy spread reduction efficiency mostly dependent on the magnitude of D^*_x.

No need for drastic IP parameters change but implementation may cause certain change in the beamline.

MonochroM optics based on LCC lattice
Guine-Pig simulation for horizontal dispersion



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*

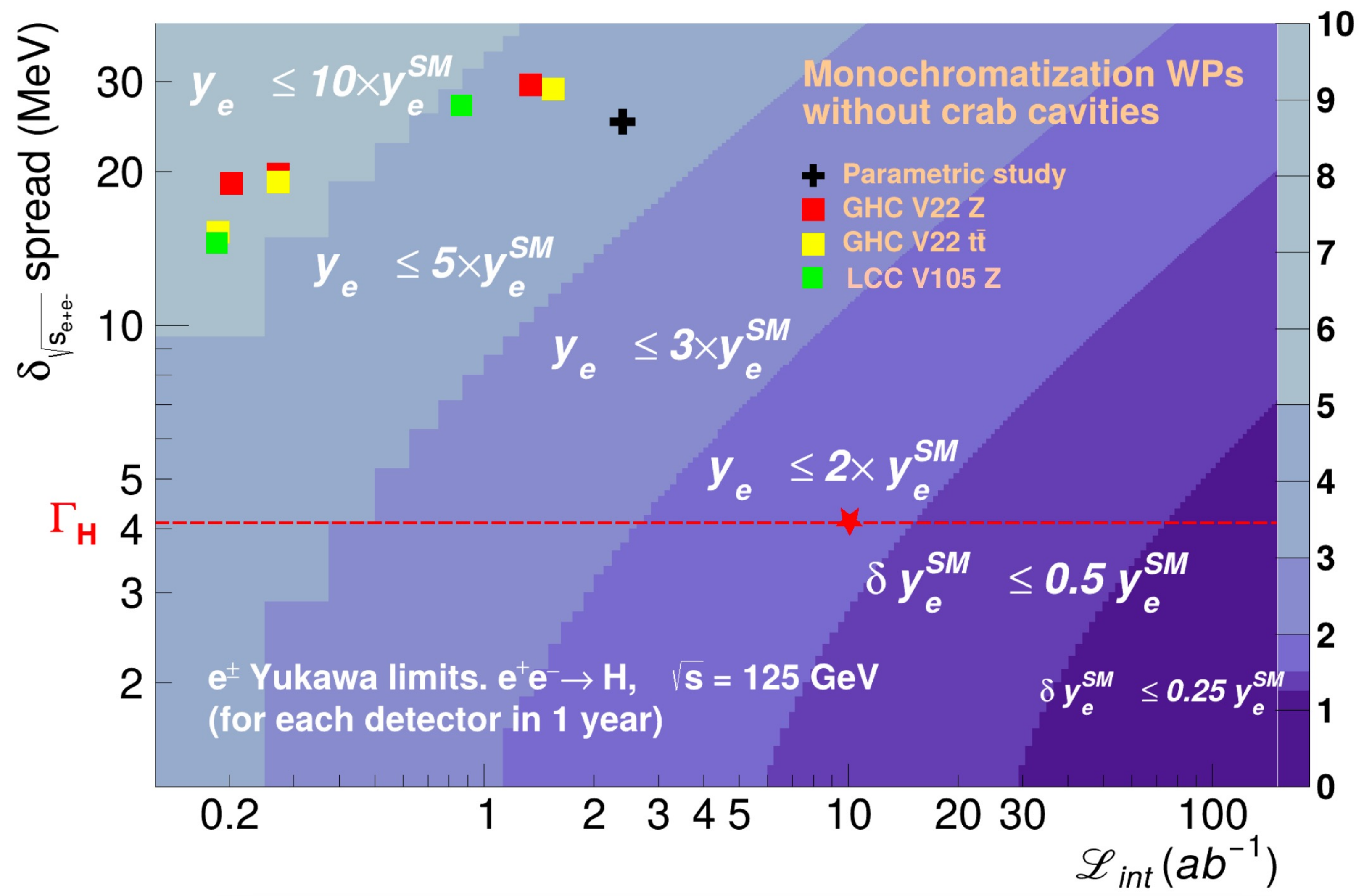
Parameters		Standard ZES V22	MonochroM ZH V22	MonochroM ZV V22
RMS CM energy spread σ_w	[MeV]	68.49	29.77	19.05
Luminosity per IP	[$10^{34}cm^{-2}s^{-1}$]	22.1	10.1	1.68
Integrated luminosity/IP/year	[ab^{-1}]	2.65	1.21	0.2

- *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	[$10^{34}cm^{-2}s^{-1}$]	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

GHC and LCC lattice performance comparison



Summary and Outlook

- Monochromatization is a **simple conceptual idea** but not easy to implement in a collider, if not integrated from the beginning in the optics IR design as a dedicated operation mode.
- Parametric optimization is still ongoing adjusting to the lattice updates and physical needs.
- **Experimental PoC monochromatization in running e+e- low energy colliders is possible at BEPCII-U (IHEP China) and SuperKEKB (KEK Japan).**
- Further steps:
  - Finalize and analyse strong-strong beam-beam simulations to validate the stability regimes.
  - Finalize the working point (Qx, Qy) for the high βx regime where horizontal effects dominate.
  - Design a lattice for horizontal MonochroM mode and confirm its feasibility through simulations

Thanks for you attention!