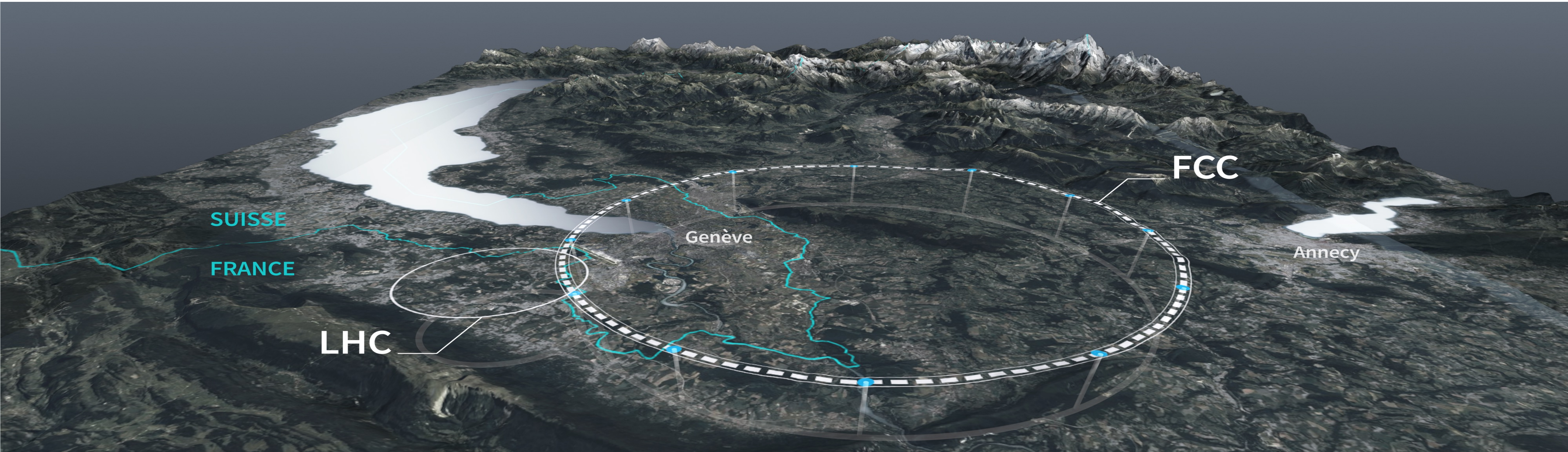


# FCC-ee monochromatization issues

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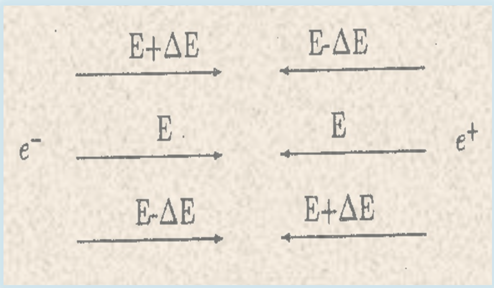
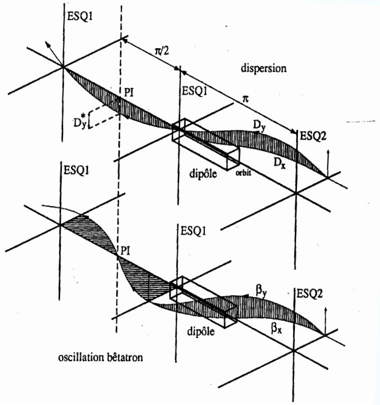
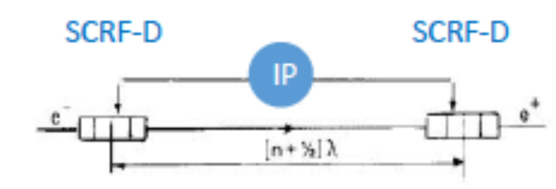
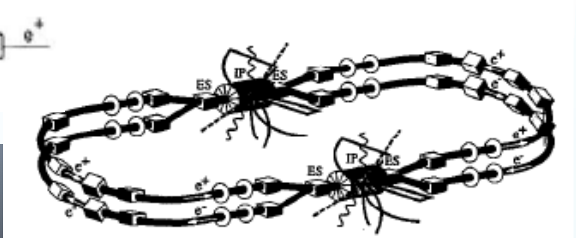
# Outline

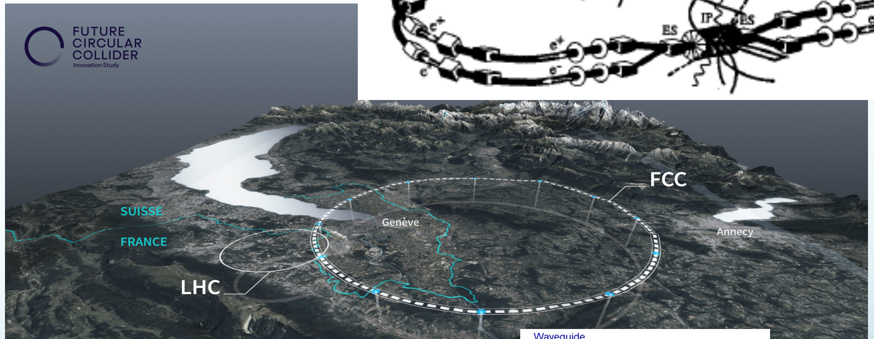
- Monochromatization concept in $e^+e^-$ colliders
  - Low-energy
  - High-energy: FCC-ee
- FCC-ee monochromatization physics motivation and parametric studies
- FCC-ee monochromatization schemes and implementation studies
- Conclusions and Perspectives

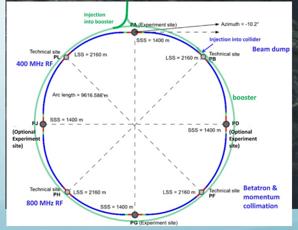


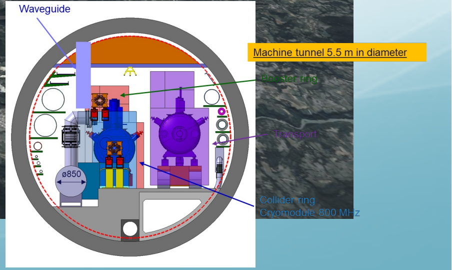







# CM Energy Resolution in Colliders

**Reducing** the **spread of the centre-of mass (CM) energies** ($\sigma_W$) 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.

**spread of the CM energies**

beam energy

$$\sigma_W = \sqrt{2} E_0 \sigma_\delta$$

**relative beam energy spread**

$$\sigma_\delta^2 = \frac{55 \hbar c E_0^2}{32\sqrt{3(mc^2)^3}} \frac{I_2}{I_3} \frac{1}{J_\varepsilon}$$

$1/\rho$

$$\sigma_W \propto \frac{1}{\sqrt{\rho J_\varepsilon}}$$

$\downdownarrows \sigma_W$

usual way

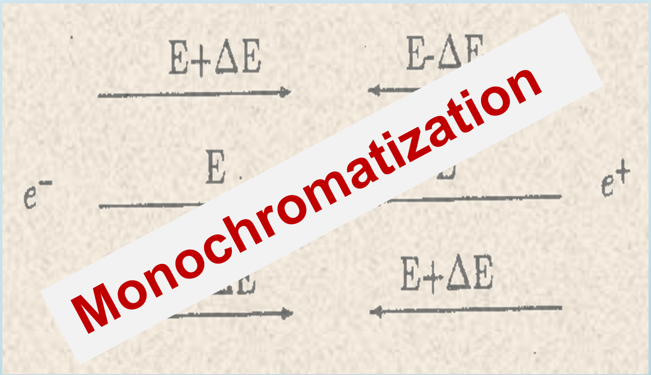
$$\begin{cases} \rho >>> & \text{bending radius} \\ 0.5 \le J_\varepsilon = 3 - J_x \le 2.5 \end{cases}$$

longitudinal partition number

alternative way

Relative energy spread is **mainly** due to Synchrotron Radiation (**SR**) emitted when an ultra-relativistic particle passes through a bending magnet ($\rho$)

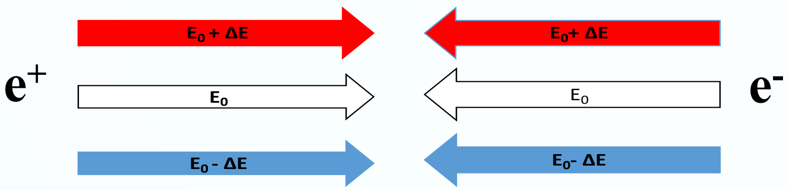
**Monochromatization** consists in reducing the spread of the CM energies, **without** necessarily **reducing** the inherent **energy spread** of the two individual beams



# Monochromatization Principle

## Standard

IP




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

correlation between transverse spatial position and energy deviation

$$W = 2(E_0 + \Delta E)$$

$$\sigma_W = \sqrt{2} E_0 \sigma_\delta$$

$$\lambda = 1$$

$$\mathcal{L}_0 = \frac{n_b f_r N_+ N_-}{4\pi \sigma^*_{x\beta} \sigma^*_{y\beta}}$$

betatronic beam sizes at the IP

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

dispersive beam size at the IP

**CM energy**

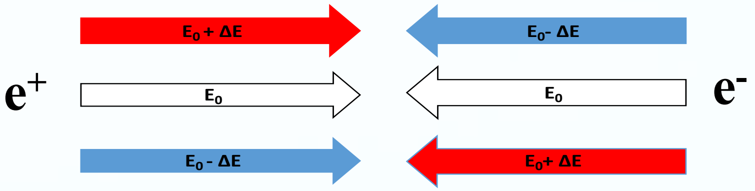
**Spread of the CM energies**

**Monochromatization factor**

**Luminosity**

## Monochromatization

IP




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

Opposite correlations between transverse spatial position and energy deviation

$$W = 2E_0 + O(\Delta E)^2$$

$$\sigma_W = \frac{\sqrt{2} E_0 \sigma_\delta}{\lambda}$$

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

$$\mathcal{L} = \frac{\mathcal{L}_0}{\lambda}$$

**Enhancement of energy resolution,** and sometimes increase of the relative frequency of the events at the center of of the distribution but **luminosity loss !!!!**

# Monochromatization Principle

## Standard

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

IP


correlation between

$e^+$

**Proposed by A. Renieri in 1975 for ADONE. Smart idea, conceptually very simple, but never tested experimentally !!!!!!**

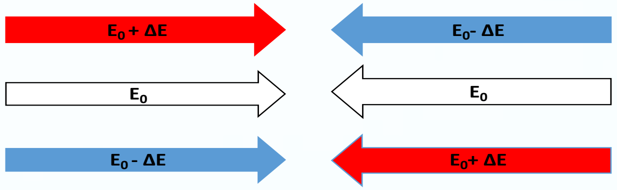
betatronic beam sizes at the IP

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

dispersive beam size at the IP

## Monochromatization

IP




$e^-$

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

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

Opposite correlations between transverse spatial position and energy deviation

$W = 2E$ ...

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

$$\mathcal{L} = \frac{\mathcal{L}_0}{\lambda}$$

**Enhancement of energy resolution,** and sometimes increase of the relative frequency of the events at the centre of of the distribution but **luminosity loss !!!!**

# Monochromatization in Low-energy Colliders

At **low-energy $e^+e^-$ colliders**, with **flat beam schemes** ($\sigma_y^* <<< \sigma_x^*$) and where the energy spread is meanly due to SR ("beamstrahlung"(BS) is not important), **we could optimize this scheme by playing with the beam-beam parameters and the emittances to avoid luminosity losses:**

$$\sigma_y^* <<< \sigma_x^*$$

with $\begin{cases} \beta_y^* <<< \beta_x^* \\ \varepsilon_y <<< \varepsilon_x \end{cases}$

beam emittances

→

$$D_{x+}^* = D_{x-}^* = 0$$
$$D_{y+}^* = -D_{y-}^* = D_y^*$$

Vertical dispersion different from zero

→

$$\sigma_y^* \simeq \sigma_\varepsilon D_y^*$$
$$\xi_y << \xi_x \simeq \xi_{\max}$$

beam-beam parameter

$$\xi_{x,y} = \frac{N_b r_e \beta_{x,y}^*}{2\pi\gamma\sigma_{x,y}^*\left(\sigma_x^* + \sigma_y^*\right)}$$

→

$$L \simeq \frac{I\gamma}{2er_e}\frac{\xi_x}{\beta_x^*}$$

$$\frac{2\pi\gamma}{N_b r_e}\varepsilon_x \xi_x \frac{\beta_y^*}{\beta_x^*} \leq 1$$

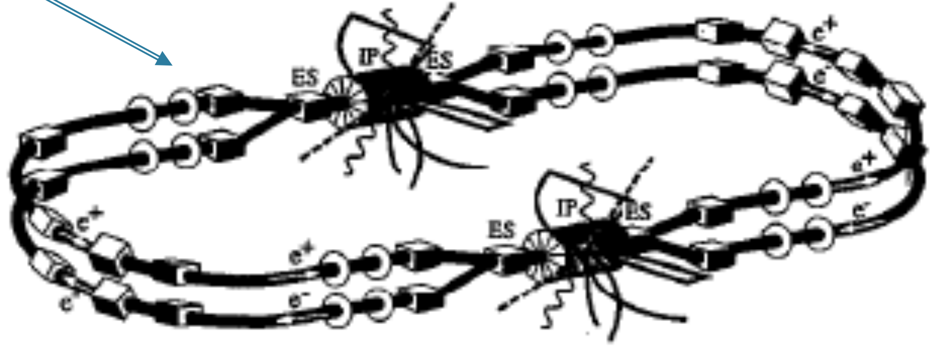
with low-horizontal emittance

we could **gain** in **energy resolution keeping** the **luminosity** constant and the **beam-beam** in the **standard** limits !!!!!!

### Monochromatization Design Studies for low-energy e⁺e⁻ colliders:

- VEPP4: one ring, electrostatic quads ($\tau$ – charm)
- SPEAR: one ring, electrostatic quads, $\lambda$~8
- LEP: one ring, electrostatic quads (limited strength) and alternative RF magnetic quads, $\lambda$~3 (optics limitations)
- B-factory: Superconducting RF resonators
- $\tau$ – charm factory: two rings, vertical dipoles, $\lambda$~7.5

$\tau$ – charm factory with monochromatization scheme



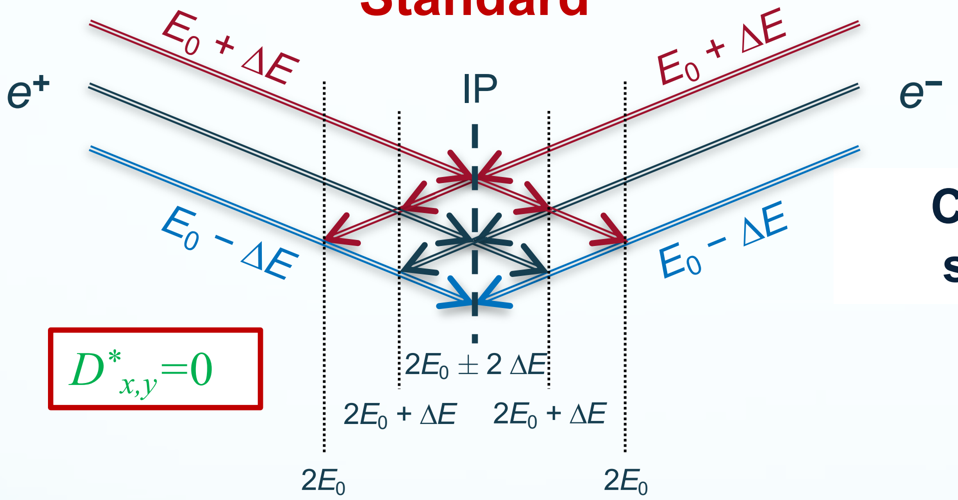

A. Faus-Golfe, J. Le Duff, Versatile DBA and TBA lattices for a tau charm factory with and without beam monochromatization. Nucl. Instrum. Methods A 372, 6–18 (1996)

# Monochromatization in High-energy Colliders (I)

The new generation of circular $e^+e^-$ colliders use the "crab-waist" collision scheme. Recent studies have revisited and extended the concept of monochromatization in the context of $e^+e^-$ colliders in crossing-angle collision configuration.

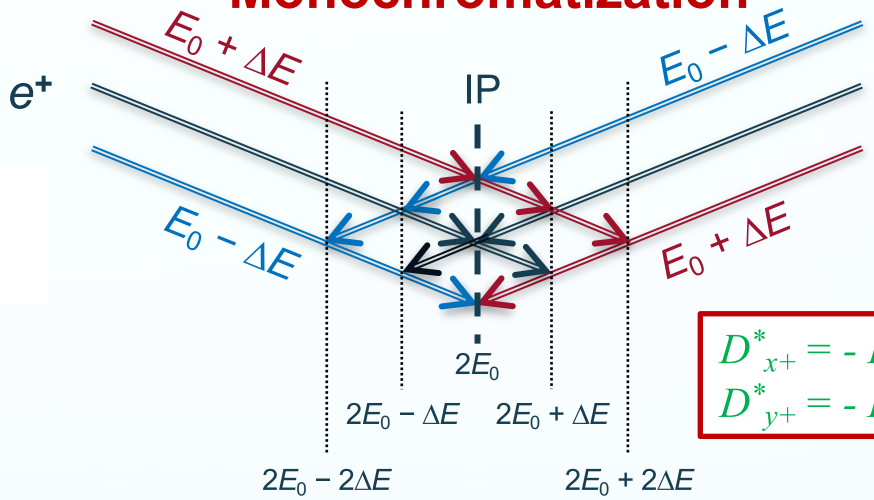
## Collision scheme

### Standard




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

### Monochromatization




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

## Spread of the CM energies

Standard:

$$\sigma_W = \sqrt{2}E_0\sqrt{(\sigma_\delta \cos(\theta_c/2))^2 + \left(\sigma^*_{x'} \sin(\theta_c/2)\right)^2}$$

Monochromatization:

$$\sigma_W = \sqrt{2}E_0\sqrt{\left(\frac{\sigma_\delta \cos(\theta_c/2)}{\lambda}\right)^2 + \left(\sigma^*_{x'} \sin(\theta_c/2)\right)^2}$$

## Monochromatization factor

Standard:

$$\lambda = 1$$

Monochromatization:

$$\lambda = \sqrt{1 + \sigma_\delta^2\left(\frac{D_x^{*2}}{\varepsilon_x\beta_x^*(1+\varphi^2)} + \frac{D_y^{*2}}{\varepsilon_y\beta_y^*}\right)}$$

**Piwinski Angle**

$$\varphi = \frac{\sigma_z}{\sigma_x^*}\tan\frac{\theta_c}{2}$$

## Luminosity

Standard:

$$\mathcal{L}_0 = \frac{n_b f_r N_+ N_-}{4\pi\sigma_x^*(1+\varphi^2)\sigma_y^*}$$

Monochromatization:

$$\mathcal{L} = \frac{\mathcal{L}_0}{\lambda}$$


A. Bogomyagkov, E. Levichev, Collision monochromatization in e+e− colliders, Phys. Rev. Accel. Beams 20.5 (2017). [Erratum: Phys. Rev. Accel. Beams 21, 029902(2018)], p. 051001. doi:10.1103/PhysRevAccelBeams.20.051001. arXiv:1702.03634[physics.acc-ph].

# Monochromatization in High-energy Colliders (II)

In the previous case for low-energy circular $e^+e^-$ colliders, the **relative energy spread** is mainly given by **SR** in the collider arcs ($\sigma_\delta = \sigma_{\delta,\mathrm{SR}}$). Alternatively in **high-energy circular $e^+e^-$** colliders, we must consider 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 $\sigma_z$ the bunch length).

**Coupled system to be solved numerically**

**Energy spread**

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

**(Self-consistency)**

**Horizontal emittance**

$$\varepsilon_{x,\mathrm{tot}} = \varepsilon_{x,\mathrm{SR}} + \frac{2V\mathcal{H}_x^*}{\sigma_{\delta,\mathrm{tot}}^2 \sigma_{x,\mathrm{tot}}^{*3}}$$

**Vertical emittance**

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

**Bunch length**

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

**Head-on** $$V \approx \frac{55\pi^2}{3\sqrt{3}} \left(\sqrt{\frac{2}{\pi}}\right)^3 \frac{n_{\mathrm{IP}} \tau_{E,\mathrm{SR}} Q_s^2 r_e^5 \gamma^2 N_b^3}{T_{\mathrm{rev}} \alpha_{\mathrm{C}}^2 C^2 \alpha} \times 0.7183$$

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

**Dispersion invariant**

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

**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 $D_x^*=0$.

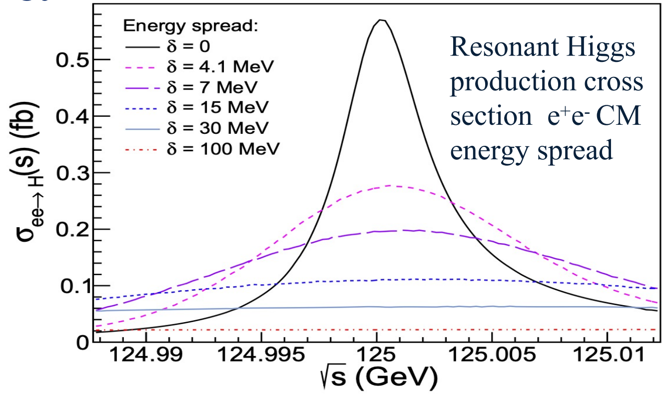
M. A. Valdivia García, F. Zimmermann, Beam blow up due to Beamstrahlung in circular e+e− colliders, Eur. Phys. J. Plus 136.5 (2021), p. 501. doi:10.1140/epjp/s13360-021-01485-x. arXiv:1911.03420 [physics.acc-ph]

# FCC-ee MonochroM Physics Motivation

## ➢ Physics motivation: measuring the electron Yukawa couplings.

- Impossible to measure at hadron colliders: **tiny branching fraction** of the $\mathrm{H} \to e^{+}e^{-}$ decay: $\mathcal{B}(\mathrm{H} \to e^{+}e^{-}) = 5.22{\times}10^{-9}$, **swamped by the Drell-Yan dielectron continuum**.
- **Integrated luminosity ($\mathcal{L}_{int}$)** of ~10 $ab^{-1}$ per year, achievable at the future high-energy circular $e^{+}e^{-}$ collider **FCC-ee**, at a CM energy of **~125 GeV**.
- Potential to observe the **resonant *s*-channel Higgs production**: $e^{+}e^{-} \to \mathrm{H}$.

S. Jadach, R.A. Kycia, Phys. Lett. B 755, 58 (2016. DOI: 10.1016/j.physletb.2016.01.065

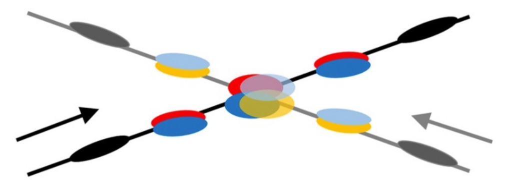



## ➢ Theoretical studies: measurement of resonant *s*-channel Higgs production

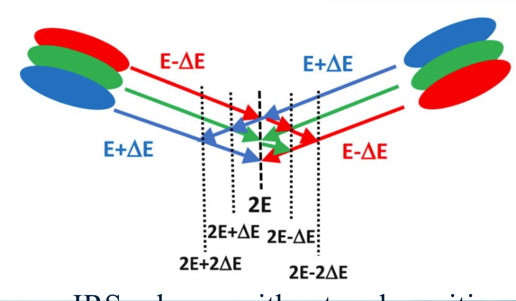
D. d'Enterria, A. Poldaru, G. Wojcik, Measuring the electron Yukawa coupling via resonant *s*-channel Higgs production at FCC-ee, arXiv:2107.02686v1 [hep-ex] 6 Jul 2021

## ➢ Accelerator studies: renewed interest in monochromatization

- Much facilitated if the **CM energy spread** can be reduced to a level comparable with the natural width of the **Higgs boson $\Gamma_H$ = 4.1 MeV.**
- In a conventional collision scheme, the natural CM energy spread at 125 GeV is **~50 MeV** (**~70 MeV** with BS).
- Monochromatization implementation at FCC-ee first proposed in 2016.
- Two possible FCC-ee **monochromatization schemes**: **Crab Crossing (CC) scheme** with crab cavities and **Integrated Resonances Scan (IRS) scheme** without crab cavities.



CC scheme with crab cavities (head-on collision configuration)




IRS scheme without crab cavities (crossing-angle collision configuration)

M. A. Valdivia García, A. Faus-Golfe, F. Zimmermann, Towards a Monochromatization Scheme for Direct Higgs Production at FCC-ee, in: Proc. 7th International Particle Accelerator Conference, Busan, South Korea, 2016, p. WEPMW009. doi:10.18429/JACoW -IPAC2016-WEPMW009.

# FCC-ee MonochroM Parametric Studies

- **Preliminary FCC-ee self-consistent parametric studies** at **125 GeV** has been realized to identify the best scenario with $D^*_x \neq 0$.
  - **Beamstrahlung** impact: **considered** advanced scripts developed in Python to for optimizing all the beam parameter in **self-consistent coupled system**.
  - **Hourglass** effect: **not considered** $R_{\text{hg}}$ ~0.3 optimization feasibility: $\beta^*_y \to 4$ mm, $R_{\text{hg}} \to 0.8$
  - **Preliminary Target** IP beam parameters for monochromatization optics design consider only the horizontal plane.

$$\boldsymbol{\beta^*_{x,y} = 90, 1\ \text{mm}, D^*_x = 0.105\ \text{m}}$$

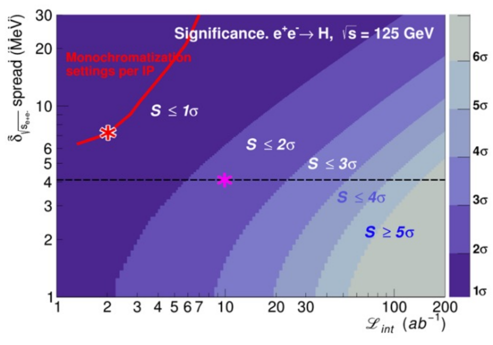
A. Faus-Golfe, M. Valdivia Garcia, F. Zimmermann, The challenge of monochromatization Direct *s*-channel Higgs production: e+e− → H, Eur. Phys. J. Plus (2022) 137:31, DOI: 10.1140/epjp/s13360-021-02151-y

| Parameters | Unit | Value |
|---|---|---|
| CM energy $W$ | [GeV] | 125 |
| Horizontal, vertical RMS emittance with (without) BS $\varepsilon_{x,y}$ | [nm] | 2.5 (0.51), 0.002 |
| Relative RMS beam energy spread $\sigma_\delta$ | % | 0.052 |
| RMS bunch length $\sigma_z$ | [mm] | 3.3 |
| Horizontal dispersion at the IP $D^*_x$ | [m] | **0.105** |
| Betaron function at the IP $\beta^*_{x,y}$ | [mm] | **90, 1** |
| RMS beam size at the IP $\sigma^*_{x,y}$ | [$\mu$m] | 55, 0.045 |
| Full crossing angle $\theta_c$ | [mrad] | 30 |
| Vertical beam-beam tune shift $\xi_y$ | | 0.106 |
| Beam current $I$ | [mA] | 395 |
| Bunch population $N_b$ | [$10^{10}$] | 6 |
| Bunches per beam $n_b$ | | 13420 |
| Luminosity (without crab cavities) per IP $\mathcal{L}$ | [$10^{34}$cm$^{-2}$ s$^{-1}$] | 26 (23) |
| RMS CM energy spread (without crab cavities) $\sigma_W$ | [MeV] | 13 (25) |

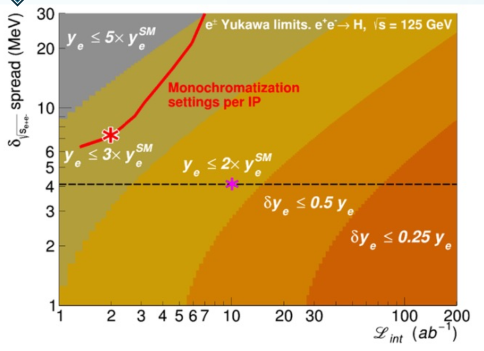
- Associated **upper limits contours** (95% CL) on the **electron Yukawa coupling** ($y_e$) has been calculated.

Red curves show the range of parameters presently reached in self-parametric FCC-ee monochromatization studies. The red star indicates the best signal strength monochromatization point in the plane (the pink star over the $\delta_{\sqrt{s}} = \Gamma_{\text{H}} = 4.1$ MeV dashed line, indicates the ideal baseline point assumed in default analysis). All results are given per IP and per year.

D. d'Enterria, A. Poldaru, G. Wojcik, Measuring the electron Yukawa coupling via resonant *s*-channel Higgs production at FCC-ee, arXiv:2107.02686v1 [hep-ex] 6 Jul 2021



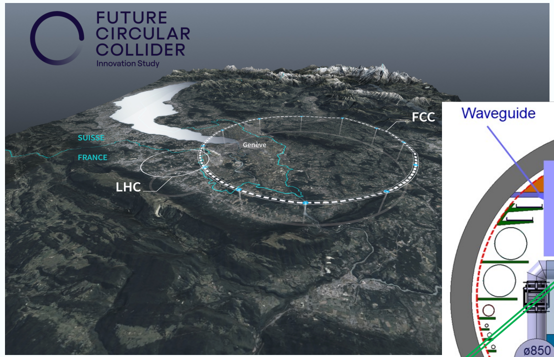

Significance contours in the $\delta_{\sqrt{s}}$ vs. $\mathcal{L}_{\text{int}}$ plane for $\sigma_{ee\to H}$ cross section at $\sqrt{s} = m_{\text{H}}$.

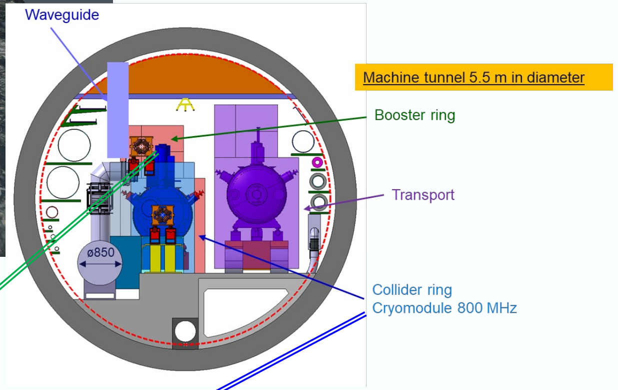


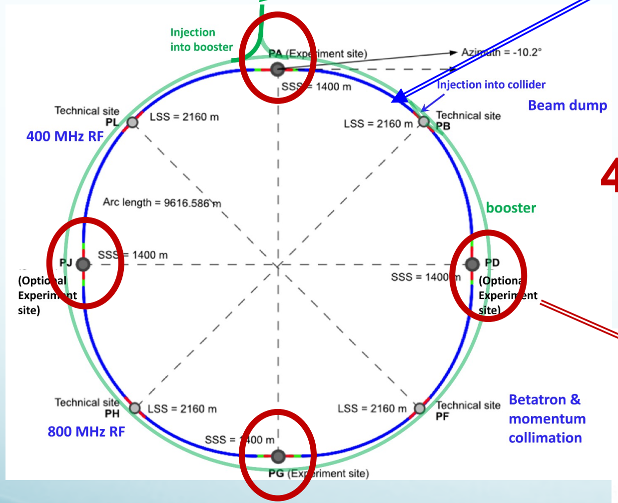

Upper limits contours (95% CL) on the $y_e$.

# The FCC-ee GHC Standard Lattice & Performances

## (Global Hybrid Correction)

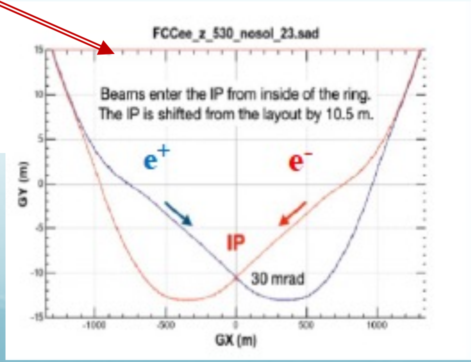



**4 IPs**

Long weak dipoles and antisymmetric IR to avoid SR




Large crossing angle ($\theta_c$=30 mrad) at IP are required to separate the two beams to harmful effects of parasitic collisions

**4 operation modes: *Z, WW, ZH, ttbar***

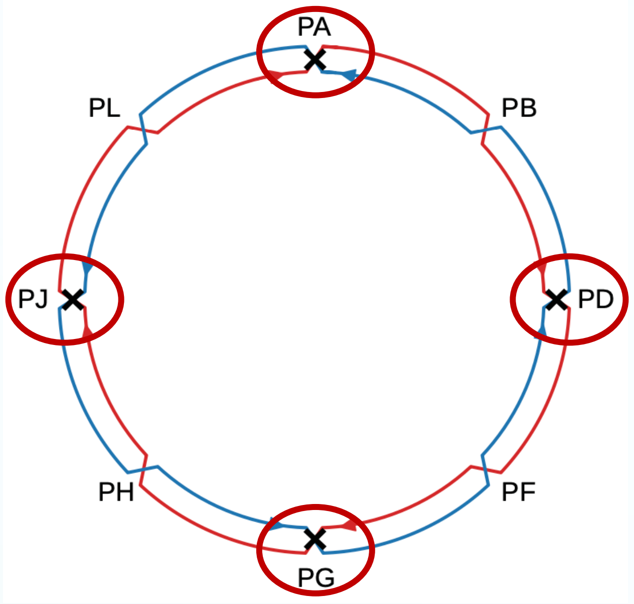
FCC-ee GHC Version 2022 (V22) Performance Table

| Beam energy | [GeV] | 45.6 | 80 | 120 | 182.5 |
|---|---|---|---|---|---|
| Layout | | PA31-1.0 | | | |
| # of IPs | | 4 | | | |
| Circumference | [km] | 91.174117 | | 91.174107 | |
| Bending radius of arc dipole | [km] | 9.937 | | | |
| Energy loss / turn | [GeV] | 0.0391 | 0.370 | 1.869 | 10.0 |
| SR power / beam | [MW] | 50 | | | |
| Beam current | [mA] | 1280 | 135 | 26.7 | 5.00 |
| Bunches / beam | | 10000 | 880 | 248 | 40 |
| Bunch population | [$10^{11}$] | 2.43 | 2.91 | 2.04 | 2.37 |
| Horizontal emittance $\varepsilon_x$ | [nm] | 0.71 | 2.16 | 0.64 | 1.49 |
| Vertical emittance $\varepsilon_y$ | [pm] | 1.42 | 4.32 | 1.29 | 2.98 |
| Arc cell | | Long 90/90 | | 90/90 | |
| Momentum compaction $\alpha_p$ | [$10^{-6}$] | 28.5 | | 7.33 | |
| Arc sextupole families | | 75 | | 146 | |
| $\beta^*_{x/y}$ | [mm] | 100 / 0.8 | 200 / 1.0 | 300 / 1.0 | 1000 / 1.6 |
| Transverse tunes/IP $Q_{x/y}$ | | 53.563 / 53.600 | | 100.565 / 98.595 | |
| Energy spread (SR/BS) $\sigma_\delta$ | [%] | 0.038 / 0.132 | 0.069 / 0.154 | 0.103 / 0.185 | 0.157 / 0.221 |
| Bunch length (SR/BS) $\sigma_z$ | [mm] | 4.38 / 15.4 | 3.55 / 8.01 | 3.34 / 6.00 | 1.95 / 2.75 |
| RF voltage 400/800 MHz | [GV] | 0.120 / 0 | 1.0 / 0 | 2.08 / 0 | 2.5 / 8.8 |
| Harmonic number for 400 MHz | | 121648 | | | |
| RF freuqency (400 MHz) | MHz | 399.994581 | | 399.994627 | |
| Synchrotron tune $Q_s$ | | 0.0370 | 0.0801 | 0.0328 | 0.0826 |
| Long. damping time | [turns] | 1168 | 217 | 64.5 | 18.5 |
| RF acceptance | [%] | 1.6 | 3.4 | 1.9 | 3.0 |
| Energy acceptance (DA) | [%] | ±1.3 | ±1.3 | ±1.7 | -2.8 +2.5 |
| Beam-beam $\xi_x/\xi_y$[a] | | 0.0023 / 0.135 | 0.011 / 0.125 | 0.014 / 0.131 | 0.093 / 0.140 |
| Luminosity / IP | [$10^{34}$/cm$^2$s] | 182 | 19.4 | 7.26 | 1.25 |
| Lifetime (q + BS + lattice) | [sec] | 840 | – | < 1065 | < 4062 |
| Lifetime (lum) | [sec] | 1129 | 1070 | 596 | 744 |

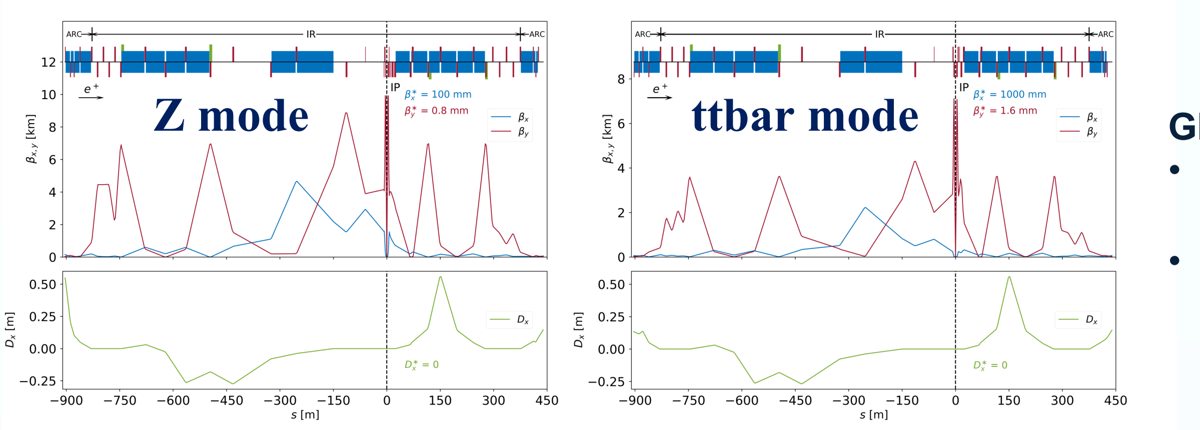
[a] incl. hourglass.

# FCC-ee GHC V22 Standard Optics

## Two types: Z mode lattice and ttbar mode lattice




### IR Lattice with Crab waist transformation: PA, PD, PG, PJ

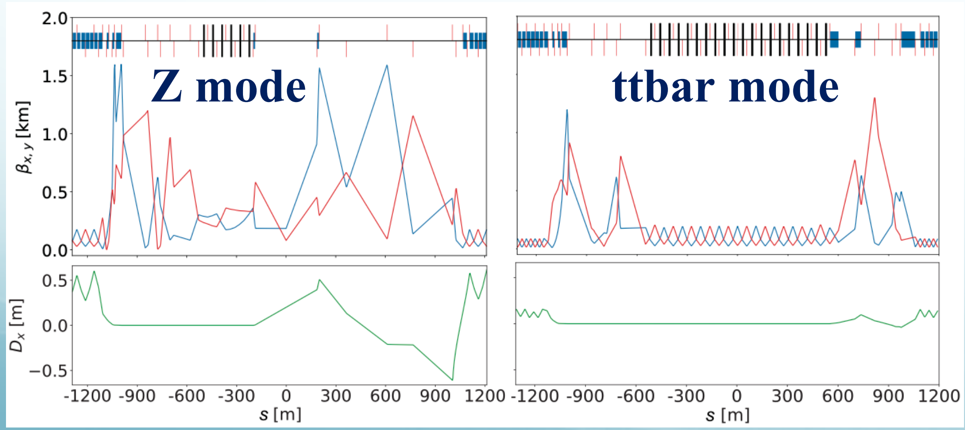



Highly asymmetric IR lattice around the IP to mitigate the SR impact

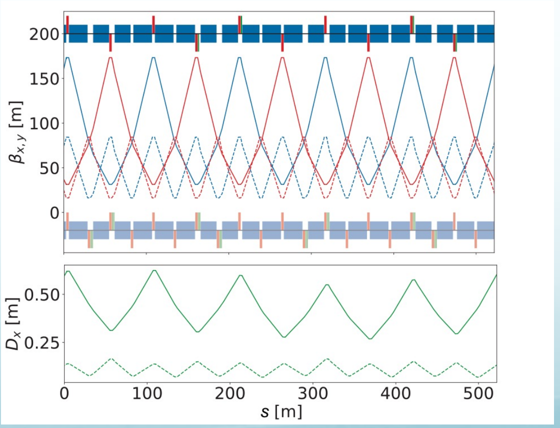
**Global Hybrid Correction:**

- Local chromaticity correction only in vertical plane
- Global chromaticity correction for the both plane.

### Technical site: PB, PF, PH, PL




### Arc: FODO cell with a transverse phase advance of 90°




**Z mode: $E_0$=45.6 GeV**
**Long 90/90 arc cell: 100 m**
**$\varepsilon_x$=0.71 nm, $\varepsilon_y$=1.42 pm**

**ttbar mode: $E_0$=182.5 GeV**
**90/90 arc cell: 50 m**
**$\varepsilon_x$=1.49 nm, $\varepsilon_y$=2.98 pm**

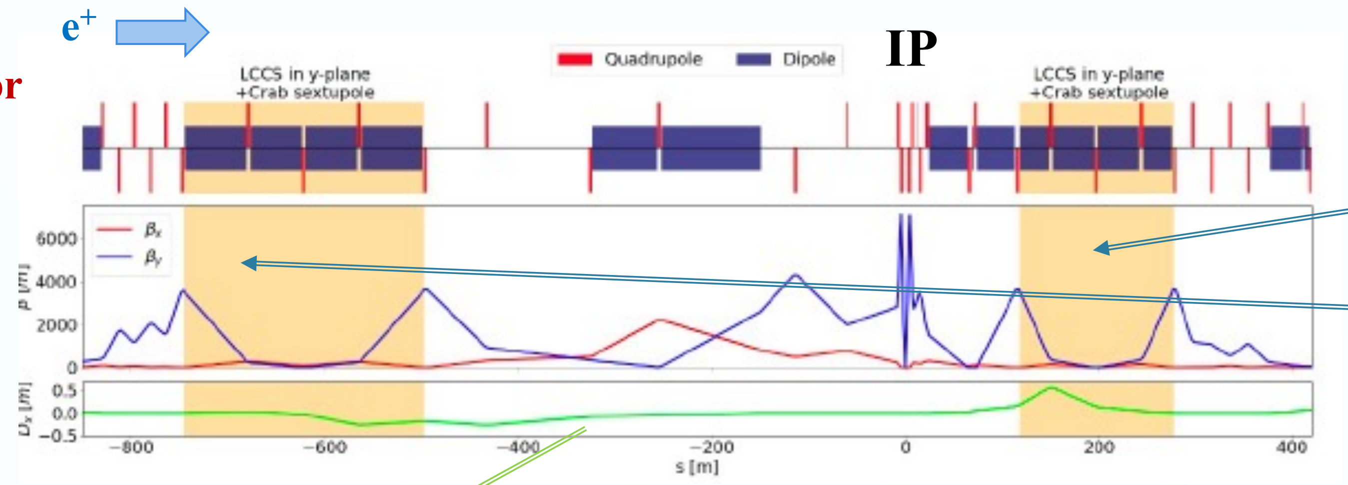
J. Keintzel, A. Abramov, M. Benedikt, M.Hofer, K.Oide et al. "FCC-ee lattice design", eeFACT2022, doi:10.18429/JACoW-eeFACT2022-TUYAT0102

# 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**

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




**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

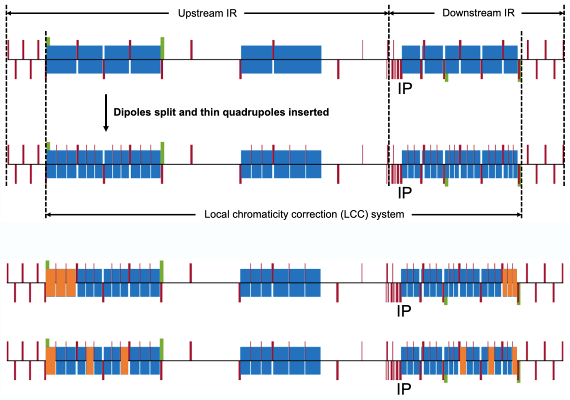
In FCC-ee IR region, the **large crossing angle of 30 mrad** in the H-plane and the **LCCS** is made possible with **H-dipoles** at the two sides of the IP creating some **H-dispersion** $D^*_x$ ($D_x \neq 0$ in the LCCS and $D_x = 0$ close to the IP for high-luminosity). $D^*_x \neq 0$ could be generated **(~10 cm)** by **mismatching** $D_x$ in the LCCS.

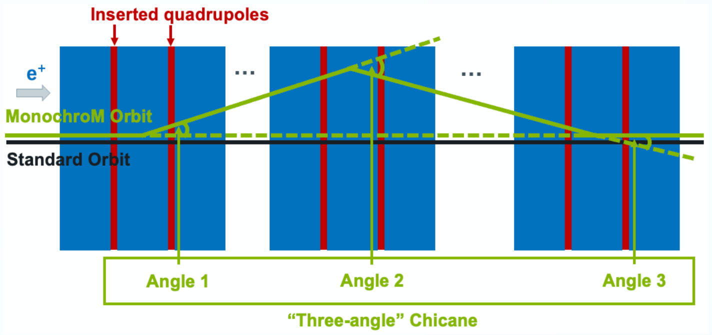
## ➢ $D^*_y \neq 0$ generation at the IP

Because $\sigma^*_{y\beta} <<< \sigma^*_{x\beta}$, 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 CS pairs are located in the LCCS.

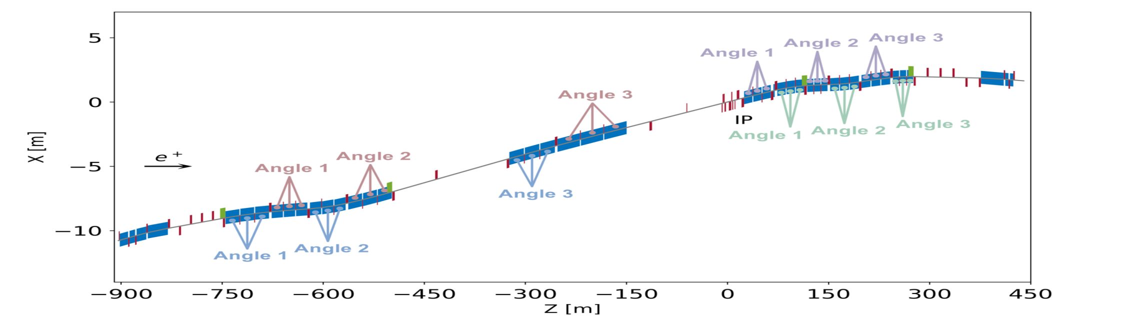
# H-MonochroM Implementation in FCC-ee GHC IR (I)

**Step 1**: All LCCS H-dipoles (blue) are 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.

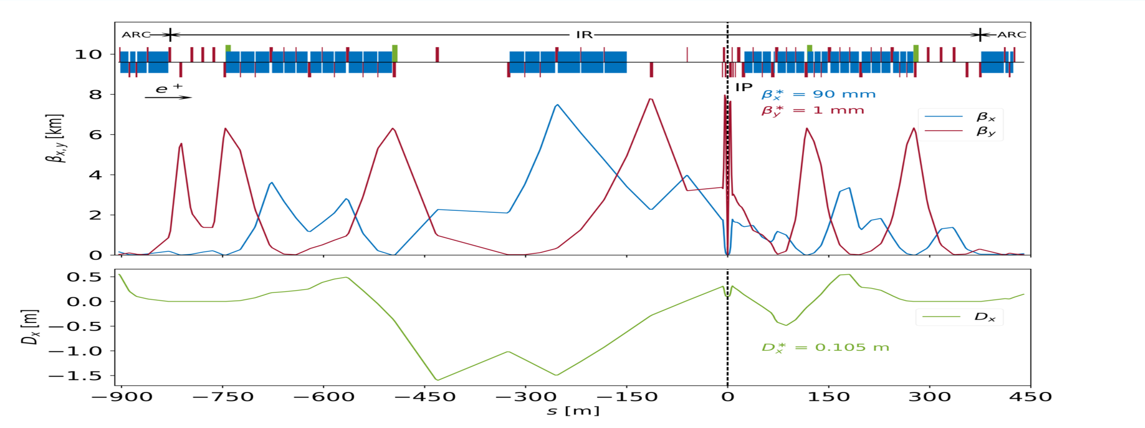



**Step 2**: To mitigate the horizontal emittance blowup, two long chicanes are implemented to each upstream and downstream. And each angle of chicane is equally distributed to all the three pieces of each LCCS H-dipole.



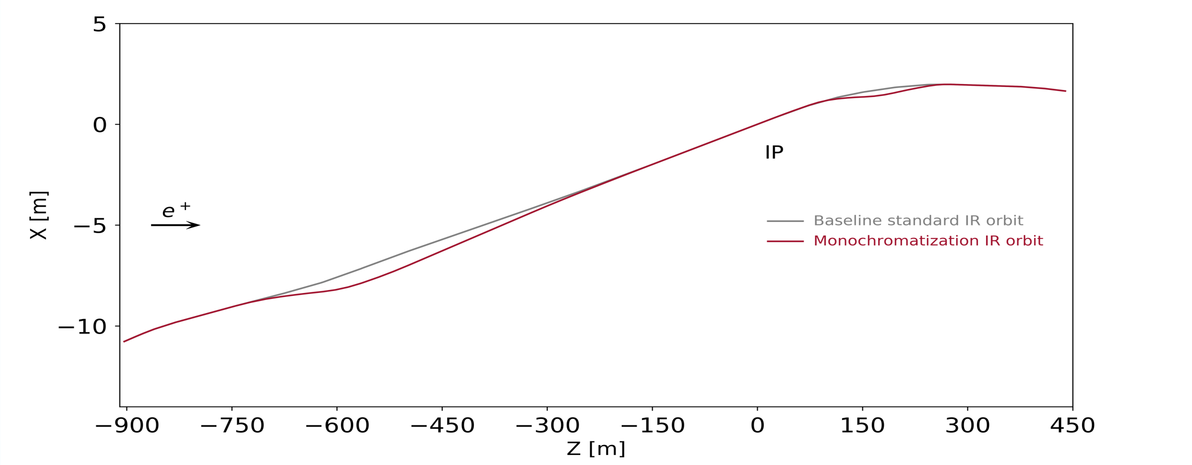

**Step 3:** The IP beam parameters are matched to FCC-ee MonochroM self-consistent parameters* while keeping the beam parameters at the entrance and exit of the IR similar to those of standard mode, including phase advances between sextupoles and crab sextupoles.

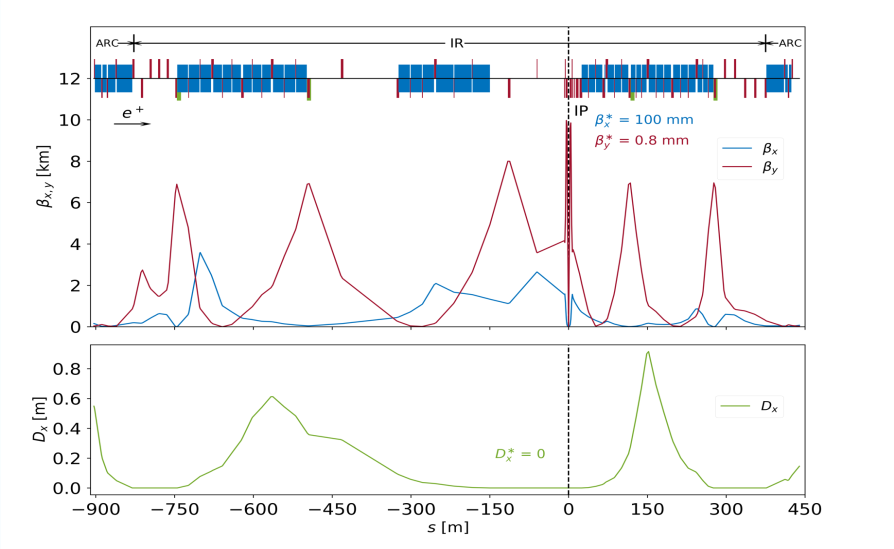



* A. Faus-Golfe, M. Valdivia Garcia, F. Zimmermann, The challenge of monochromatization Direct s-channel Higgs production: e+e− → H, Eur. Phys. J. Plus (2022) 137:31, https://doi.org/10.1140/epjp/s13360-021-02151-y

# H-MonochroM Implementation in FCC-ee GHC IR (II)

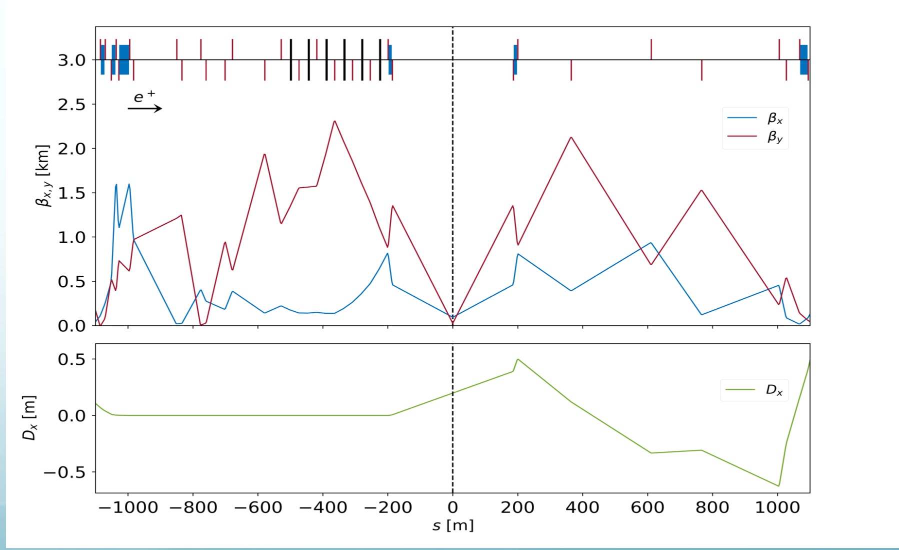
**Step 4:** Orbit compatibility with the standard operation mode with $D_x = 0$.



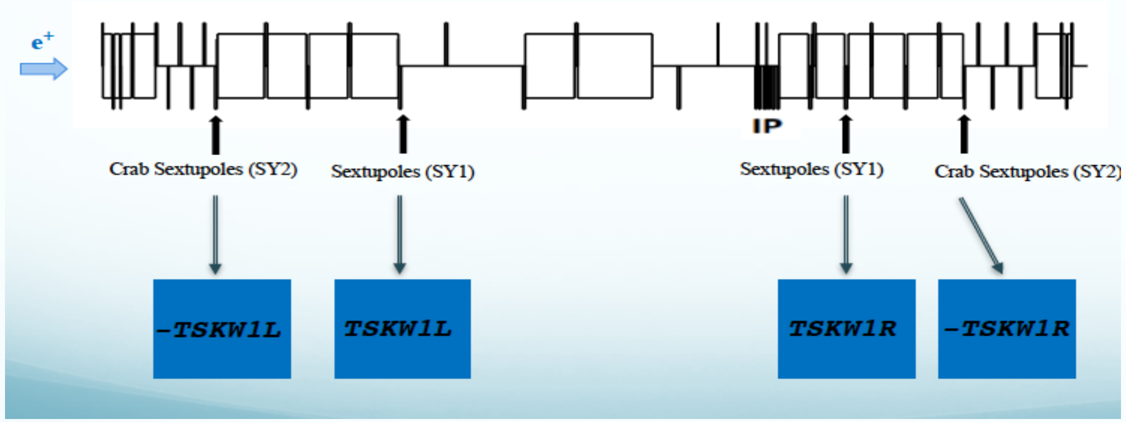

**Step 5:** IR MonochroM is implemented in the four IPs and global matching:

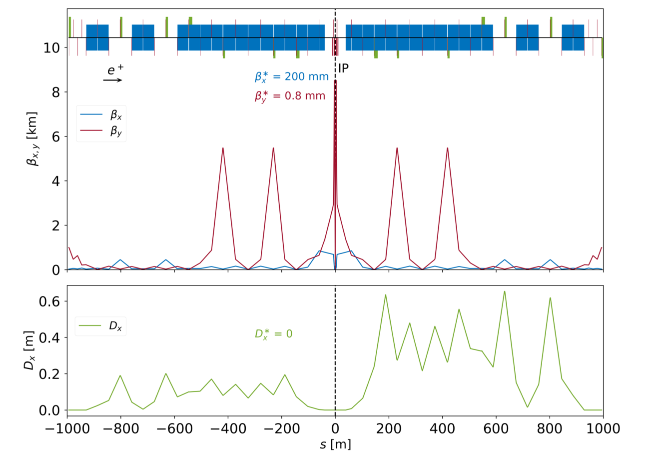
- LCCS chromaticity correction
- Global arc chromaticity correction
- Tune correction
- Emittance checks and SR-RF strategy compensation
- Preliminary Tracking and DA calculations



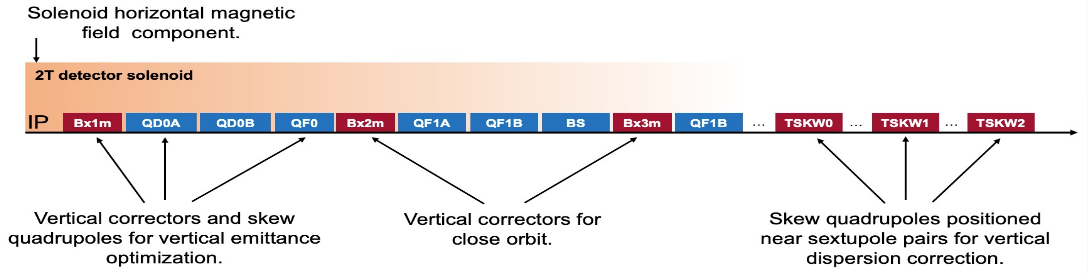
# V-MonochroM Implementation in FCC-ee GHC IR (I)

**Step 1**: Nonzero $D^*_y$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located where the CS pairs are located in the LCC system.



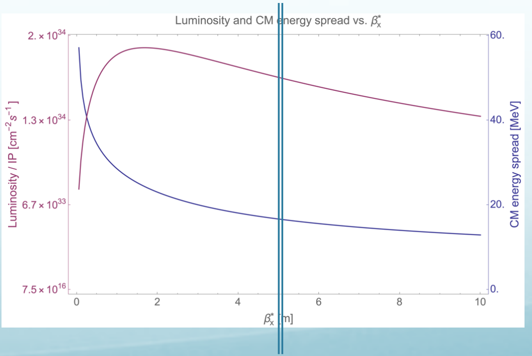

Inspired in FCC-ee **Local Chromaticity Correction** (LCC) optics detector solenoid compensation scheme



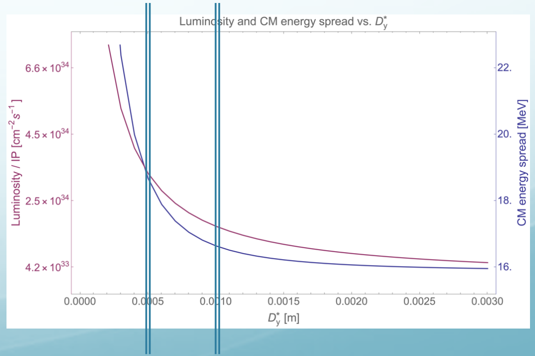

**Step 2: Mitigation of vertical emittance blow-up due to BS**:

$$\varepsilon_{y,\mathrm{tot}} = \varepsilon_{y,\mathrm{SR}} + \frac{2V\mathcal{H}_y^*}{\sigma_{\delta,\mathrm{tot}}^2 \sigma_{x,\mathrm{tot}}^{*3}} \qquad \lambda = \sqrt{1+\sigma_\delta^2\left(\frac{D_x^{*2}}{\sigma_{x\beta}^*}+\frac{D_y^{*2}}{\sigma_{y\beta}^*}\right)} \sim 1$$

Vertical emittance blow-up (~5 pm → ~800 pm) → IP betatronic beam size increases




$\beta_x^*$: 0.1 m → 5 m

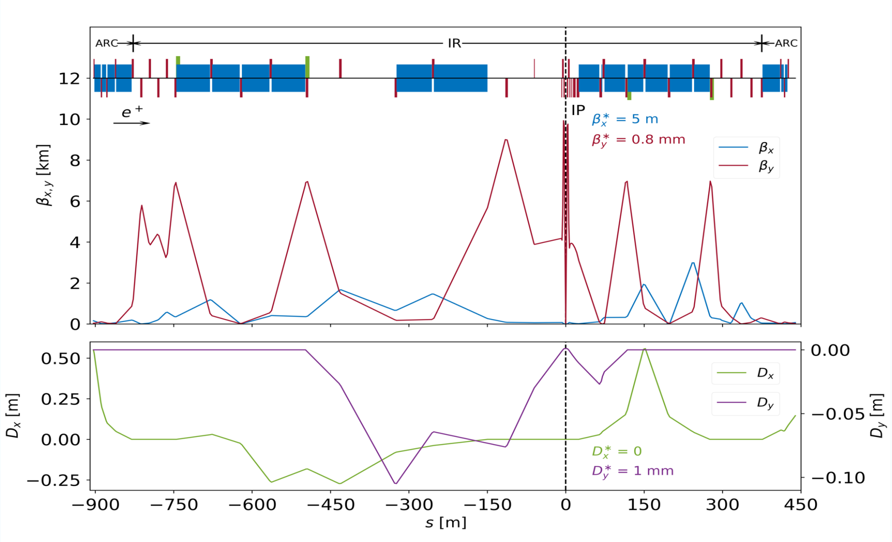



0.5 mm 1 mm

# V-MonochroM Implementation in FCC-ee GHC IR (II)

**Step 3**: MonochroM IR optics design:

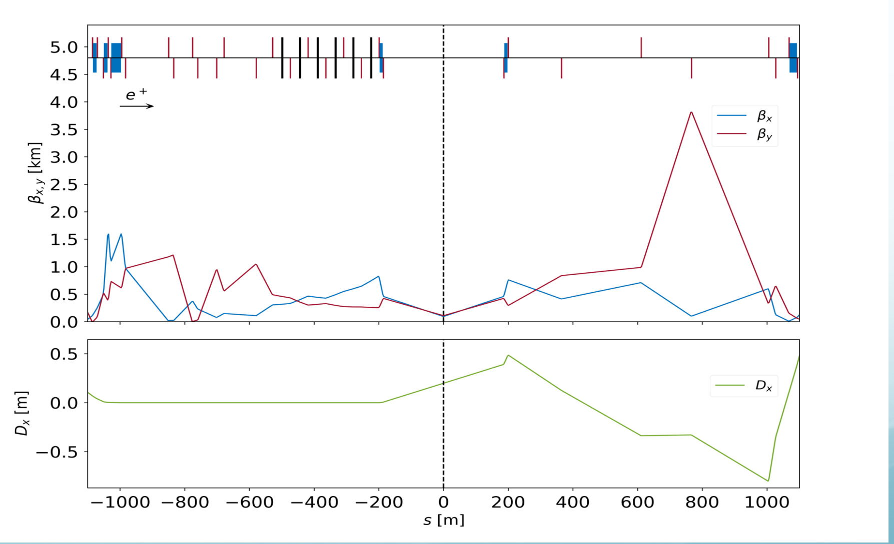
- Matching the increased $\beta_x^*$ using all the quadrupoles in the IR
- Matching the required nonzero $D_y^*$ with the newly implemented skew quadrupoles.




**Compatibility: simpler than the H-MonochroM scheme without alerting the orbit.**

**Step 4:** 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

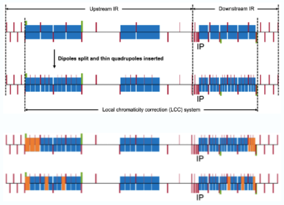


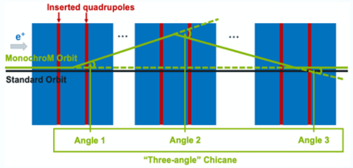
# HV-MonochroM Implementation in FCC-ee GHC IR

**Incorporating skew quadrupoles into the monochromatization IR with nonzero $D_x^*$**

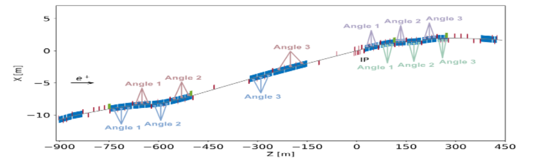
## $D^*_x$

**Step 1**: All LCCS H-dipoles (blue) are 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.



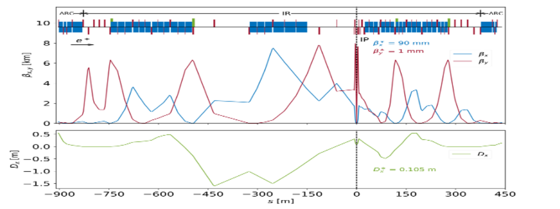




**Step 2**: To mitigate the horizontal emittance blowup, two long chicanes are implemented to each upstream and downstream. And each angle of chicane is equally distributed to all the three pieces of each LCCS H-dipole.



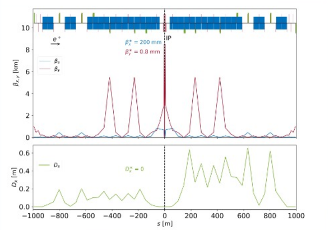

**Step 3:** The IP beam parameters are matched to FCC-ee MonochroM self-consistent parameters* while keeping the beam parameters at the entrance and exit of the IR similar to those of standard mode, including phase advances between sextupoles and crab sextupoles.

* 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

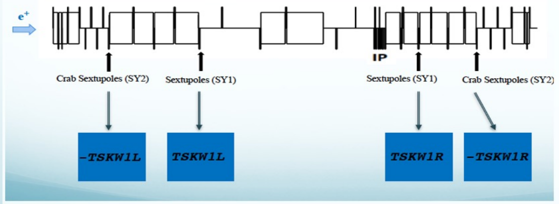


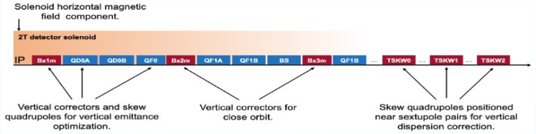
## $D^*_y$

**Step 1**: Nonzero $D_y^*$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located where the CS pairs are located in the LCC system.



Inspired in FCC-ee **Local Chromaticity Correction** (LCC) optics detector solenoid compensation scheme

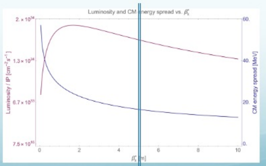


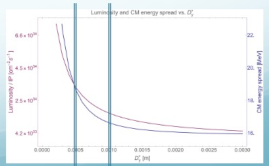



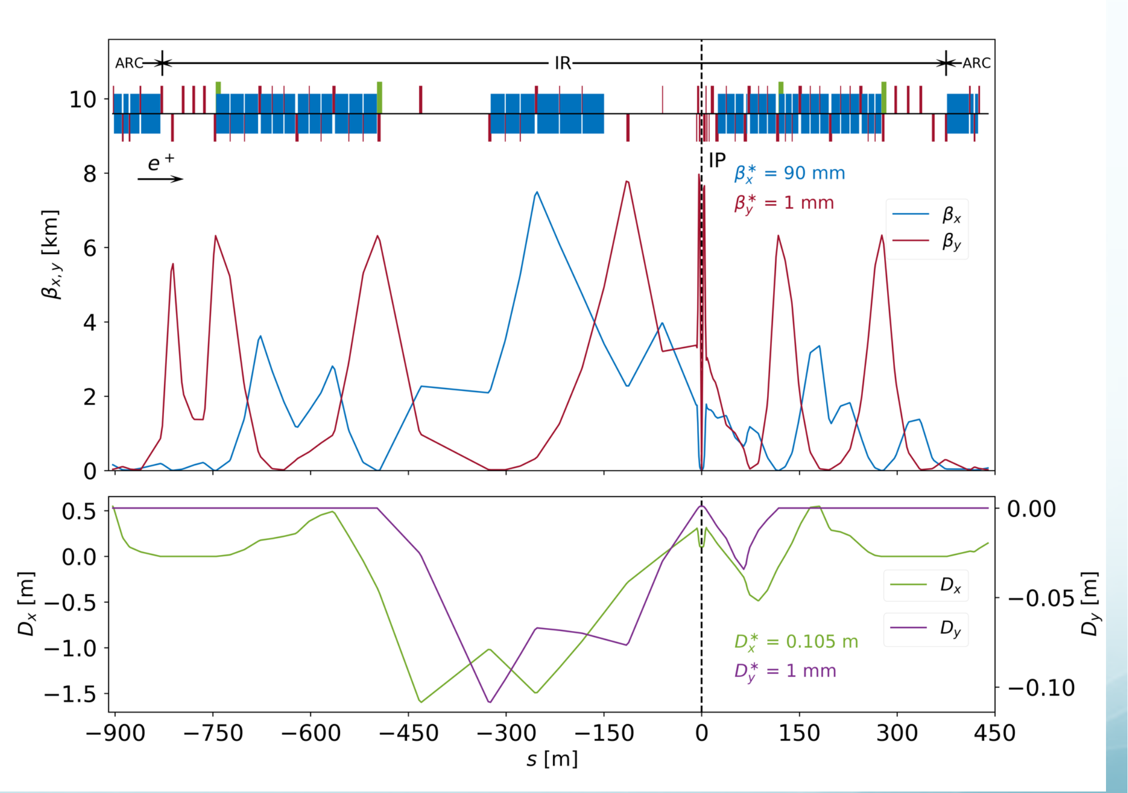

**Step 2: Mitigation of vertical emittance blow-up due to BS**:

$$\varepsilon_{y,\mathrm{tot}} = \varepsilon_{y,\mathrm{SR}} + \frac{2V\mathcal{H}_y^*}{\sigma_{\delta,\mathrm{tot}}^2 \sigma_{x,\mathrm{tot}}^{*3}} \qquad \lambda = \sqrt{1+\sigma_\delta^2\left(\frac{D_x^{*2}}{\sigma_{x\beta}^*}+\frac{D_y^{*2}}{\sigma_{y\beta}^*}\right)} \sim 1$$

Vertical emittance blow-up (~5 nm → ~800 nm) → IP betatronic beam size increases







# FCC-ee GHC MonochroM Lattices

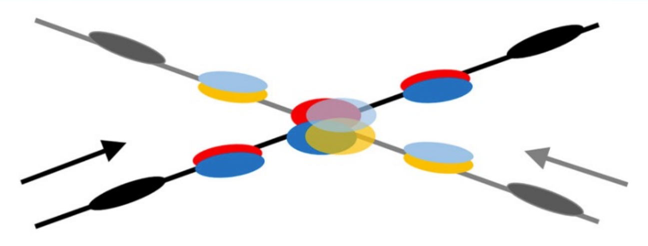
7 kinds of **FCC-ee GHC V22 MonochroM** optics design based on **Z mode** and 7 lattices based on **ttbar mode** has been completed with different possible combination of **H**, **V**, **H/V** dispersions and number of **IPs**.

| FCC-ee GHC | Orbit changed or not | $D^*_x$ | $D^*_y$ |
|---|---|---|---|
| *Standard ZES* | No | 0 | 0 |
| *MonochroM ZH4IP* | Yes | 0.105 m | 0 |
| *MonochroM ZH2IP* | Yes | 0.105 m | 0 |
| *MonochroM ZHS* | Yes | 0 | 0 |
| *MonochroM ZV0.5* | No | 0 | 0.5 mm |
| *MonochroM ZV1* | No | 0 | 1 mm |
| *MonochroM ZHV* | Yes | 0.105 m | 1 mm |

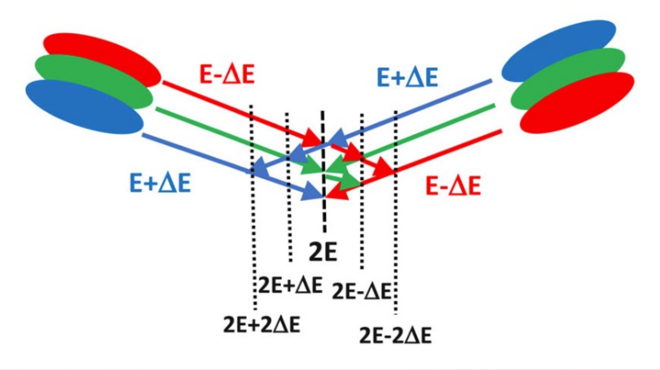
**All transferred from MAD-X version to Xsuite version for further studies.**

MAD-X - Methodical Accelerator Design. http://madx.web.cern.ch/madx/
Xsuite. https://xsuite.readthedocs.io/

**Not part of the baseline collision scheme for FCC-ee!!** → **For comparison and further simulation in Guinea-Pig**



CC scheme with crab cavities
(**head-on collision configuration**)




IRS scheme without crab cavities
(**crossing-angle collision configuration**)

# FCC-ee GHC MonochroM Optical Performance (I)

➤ **FCC-ee GHC MonochroM Optical Performance based on Z mode lattice (IRS) (with or w/o BS effect)**

| Parameters | Units | Standard ZES | MonochroM ZH4IP | MonochroM ZH2IP | MonochroM ZHS | MonochroM ZV0.5 | MonochroM ZV1 | MonochroM ZHV |
|---|---|---|---|---|---|---|---|---|
| Beam Energy $E_0$ | GeV | 62.5 | 62.5 | 62.5 | 62.5 | 62.5 | 62.5 | 62.5 |
| # of IPs $n_{IP}$ | | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Circumference $C$ | km | 91 | 91 | 91 | 91 | 91 | 91 | 91 |
| Energy Loss/turn $U_0$ | MeV | 138 | 143 | 140 | 143 | 138 | 138 | 143 |
| SR power loss $P_{SR}$ | MW | 50 | 50 | 49 | 50 | 50 | 50 | 50 |
| Beam current $I$ | mA | 360 | 350 | 350 | 350 | 360 | 360 | 350 |
| Bunches/beam $n_b$ | | 12000 | 12000 | 12000 | 12000 | 12000 | 12000 | 12000 |
| Bunch population $N_b$ | $10^{11}$ | 0.57 | 0.55 | 0.55 | 0.55 | 0.57 | 0.57 | 0.55 |
| Horizontal emittance (SR/BS) $\varepsilon_x$ | nm | 1.33 / 1.33 | 2.09 / 7.78 | 1.71 / 3.56 | 1.66 / 1.66 | 1.34 / 1.34 | 1.34 / 1.34 | 2.03 / 7.72 |
| Vertical emittance (SR/BS) $\varepsilon_y$ | pm | 2.65 / 2.65 | 4.17 / 4.17 | 3.42 / 3.42 | 3.33 / 3.33 | 2.67 / 13.84 | 2.67 / 47.32 | 4.06 / 50.55 |
| Momentum compaction $\alpha_c$ | $10^{-6}$ | 28.0 | 27.4 | 27.7 | 27.6 | 27.9 | 27.9 | 27.4 |
| $\beta^*_{x/y}$ | mm | 100 / 0.8 | 90 / 1 | 90 / 1 | 100 / 0.8 | 5000 / 0.8 | 5000 / 0.8 | 90 / 1 |
| $D^*_{x/y}$ | m | 0 / 0 | 0.105 / 0 | 0.105 / 0 | 0 / 0 | 0 / 0.0005 | 0 / 0.001 | 0.105 / 0.001 |
| Energy Spread (SR/BS) $\sigma_\delta$ | % | 0.054 / 0.078 | 0.055 / 0.057 | 0.054 / 0.064 | 0.055 / 0.075 | 0.054 / 0.055 | 0.054 / 0.055 | 0.055 / 0.057 |
| Bunch length (SR/BS) $\sigma_z$ | mm | 4.09 / 5.82 | 4.15 / 4.23 | 4.12 / 4.74 | 4.17 / 5.59 | 4.10 / 4.14 | 4.10 / 4.14 | 4.15 / 4.23 |
| Sychrotron tune $Q_s$ | | 0.054 | 0.053 | 0.054 | 0.054 | 0.054 | 0.054 | 0.053 |
| Longitudinal damping time | turns | 453 | 438 | 446 | 438 | 454 | 454 | 438 |
| CM energy spread (SR/BS) $\sigma_W$ | MeV | 47.47 / 68.78 | 15.83 / 26.42 | 14.52 / 20.19 | 48.46 / 66.15 | 8.06 / 17.38 | 4.07 / 16.22 | 5.30 / 15.87 |
| Luminosity (SR/BS) $\mathcal{L}$ | $10^{34}cm^{-2}\ s^{-1}$ | 35.4 / 25.1 | 17.3 / 16.4 | 19.3 / 16.6 | 29.2 / 22.0 | 3.56 / 3.35 | 1.85 / 1.69 | 2.03 / 1.73 |

# FCC-ee GHC MonochroM Optical Performance (II)

➢ **FCC-ee GHC MonochroM Optical Performance based on ttbar mode lattice (IRS) (with or w/o BS effect)**

| Parameters | Units | Standard TES | MonochroM TH4IP | MonochroM TH2IP | MonochroM THS | MonochroM TV0.5 | MonochroM TV1 | MonochroM THV |
|---|---|---|---|---|---|---|---|---|
| Beam Energy $E_0$ | GeV | 62.5 | 62.5 | 62.5 | 62.5 | 62.5 | 62.5 | 62.5 |
| # of IPs $n_{IP}$ | | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Circumference $C$ | km | 91 | 91 | 91 | 91 | 91 | 91 | 91 |
| Energy Loss/turn $U_0$ | MeV | 138 | 143 | 141 | 143 | 138 | 138 | 143 |
| SR power loss $P_{SR}$ | MW | 50 | 50 | 49 | 50 | 50 | 50 | 50 |
| Beam current $I$ | mA | 360 | 350 | 350 | 350 | 360 | 360 | 350 |
| Bunches/beam $n_b$ | | 12000 | 12000 | 12000 | 12000 | 12000 | 12000 | 12000 |
| Bunch population $N_b$ | $10^{11}$ | 0.57 | 0.55 | 0.55 | 0.55 | 0.57 | 0.57 | 0.55 |
| Horizontal emittance (SR/BS) $\varepsilon_x$ | nm | 0.17 / 0.17 | 1.48 / 7.27 | 0.84 / 4.23 | 0.35 / 0.35 | 0.19 / 0.19 | 0.19 / 0.19 | 1.48 / 7.26 |
| Vertical emittance (SR/BS) $\varepsilon_y$ | pm | 0.35 / 0.35 | 2.96 / 2.96 | 1.68 / 1.68 | 0.71 / 0.71 | 0.37 / 4.49 | 0.37 / 18.8 | 2.96 / 50.18 |
| Momentum compaction $\alpha_c$ | $10^{-6}$ | 7.31 | 6.93 | 7.12 | 7.06 | 7.31 | 7.31 | 6.92 |
| $\beta^*_{x/y}$ | mm | 1000 / 1.6 | 90 / 1 | 90 / 1 | 1000 / 1.6 | 50000 / 1.6 | 50000 / 1.6 | 90 / 1 |
| $D^*_{x/y}$ | m | 0 / 0 | 0.105 / 0 | 0.105 / 0 | 0 / 0 | 0 / 0.0005 | 0 / 0.001 | 0.105 / 0.001 |
| Energy Spread (SR/BS) $\sigma_\delta$ | % | 0.054 / 0.076 | 0.055 / 0.057 | 0.054 / 0.057 | 0.055 / 0.068 | 0.054 / 0.055 | 0.054 / 0.055 | 0.055 / 0.057 |
| Bunch length (SR/BS) $\sigma_z$ | mm | 3.86 / 5.49 | 4.05 / 4.20 | 3.95 / 4.12 | 4.09 / 5.07 | 3.86 / 3.95 | 3.86 / 3.95 | 4.05 / 4.20 |
| Sychrotron tune $Q_s$ | | 0.015 | 0.014 | 0.014 | 0.014 | 0.015 | 0.015 | 0.014 |
| Longitudinal damping time | turns | 454 | 436 | 445 | 436 | 454 | 454 | 436 |
| CM energy spread (SR/BS) $\sigma_W$ | MeV | 47.45 / 67.58 | 13.41 / 25.75 | 10.25 / 20.95 | 48.80 / 60.47 | 4.30 / 15.02 | 2.16 / 14.63 | 4.52 / 15.69 |
| Luminosity (SR/BS) $\mathcal{L}$ | $10^{34}cm^{-2}s^{-1}$ | 72.8 / 51.9 | 20.9 / 19.5 | 28.3 / 26.6 | 44.6 / 36.6 | 3.36 / 3.11 | 1.68 / 1.56 | 2.05 / 1.72 |

**Lower CM energy spread compared to Z mode**

# FCC-ee GHC MonochroM Physics Performance (I)

## ➢ Luminosity and CM energy spread calculation in Guinea-Pig

- Two key indicators of the physics performance in collider experiments: CM energy spread $\sigma_W$ and integrated luminosity $\mathcal{L}_{\text{int}}$.
- $\sigma_W$ and $\mathcal{L}$ calculated using **Guinea-Pig**, particle distribution modeled as an ideal Gaussian distribution comprising 40000 particles ($Z = N(0,1)$):

$$E_{\pm} = (Z\sigma_\delta + 1)E_0$$

$$x_{\pm} = \left(Z\sqrt{\varepsilon_x\beta_x^*} + Z\sigma_\delta D_{x\pm}^*\right)\sqrt{1 + \tan\frac{\theta_c}{2}\frac{\sigma_z}{\sqrt{\varepsilon_x\beta_x^* + \sigma_\delta^2 D_{x\pm}^{*2}}}}$$

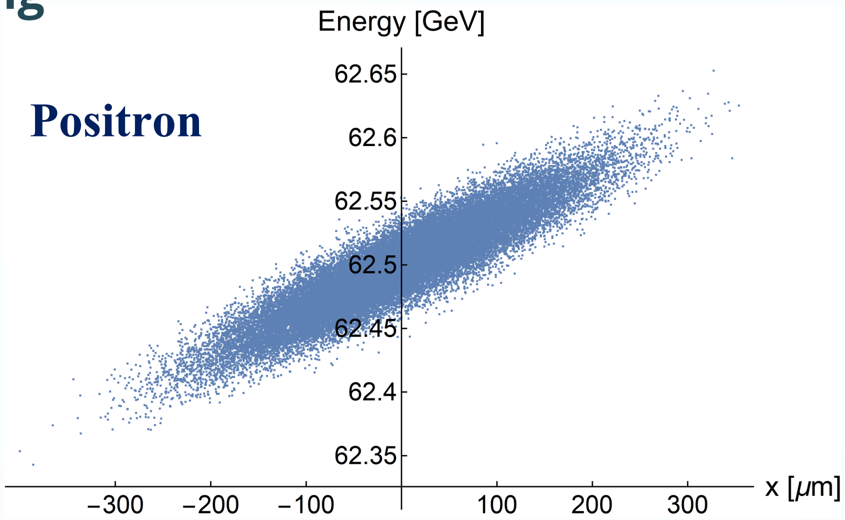
$$y_{\pm} = Z\sqrt{\varepsilon_y\beta_y^*} + Z\sigma_\delta D_{y\pm}^*$$

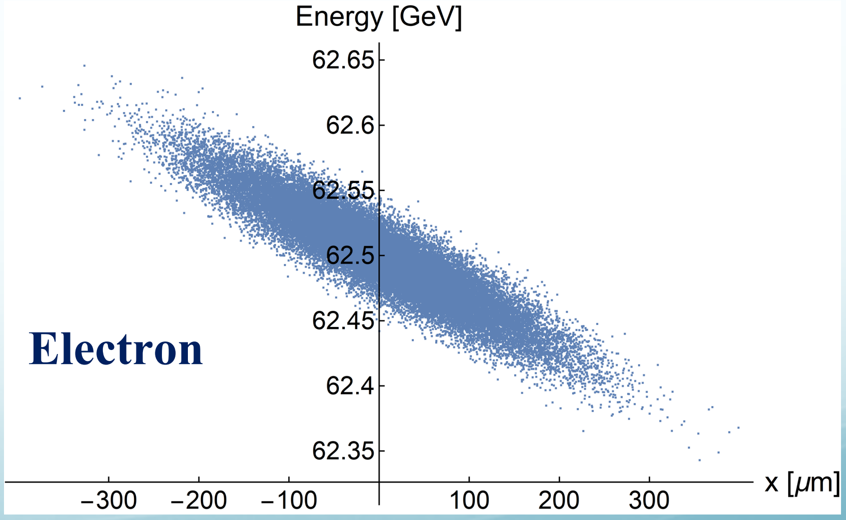
$$z_{\pm} = Z\sigma_z$$

$$x'_{\pm} = Z\sqrt{\frac{\varepsilon_x}{\beta_x^*}} - \frac{\theta_c}{2}$$

$$y'_{\pm} = Z\sqrt{\frac{\varepsilon_y}{\beta_y^*}}$$

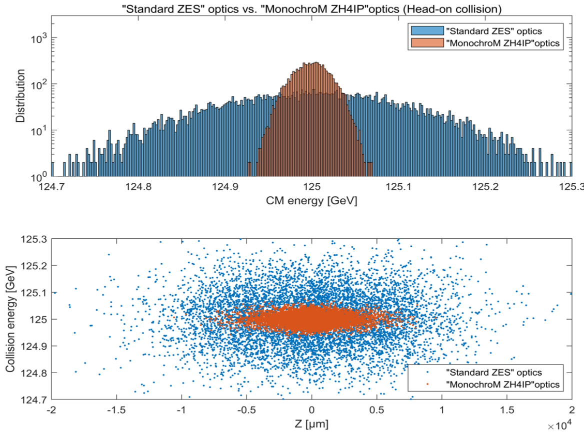
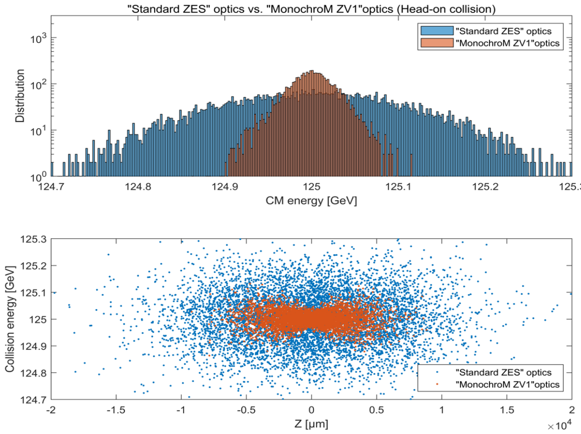
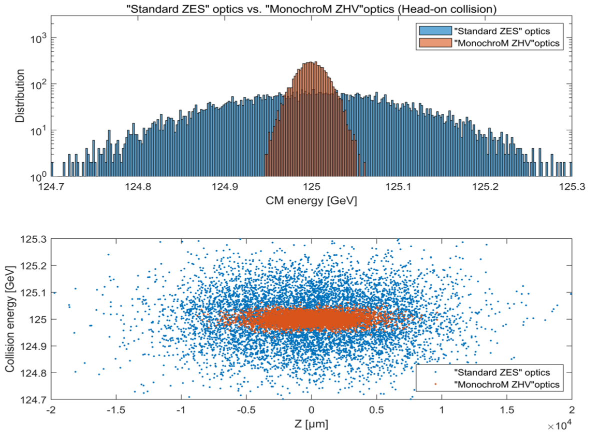
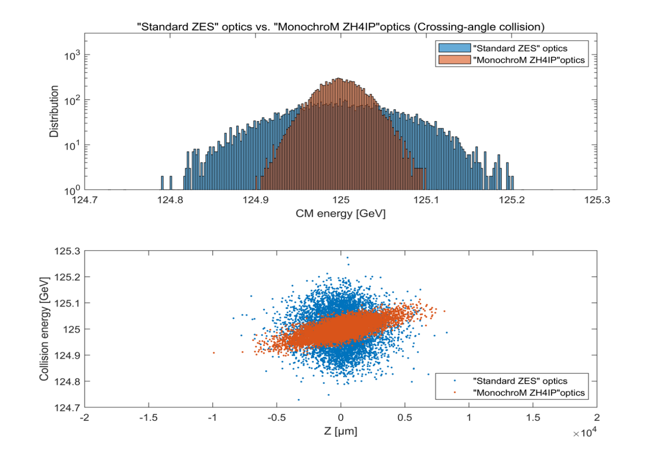
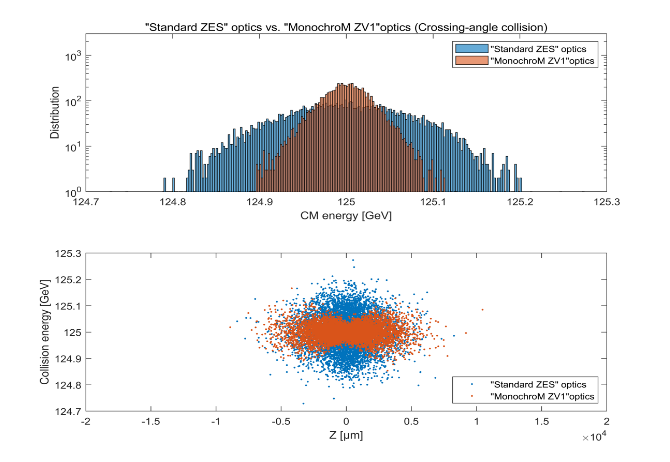
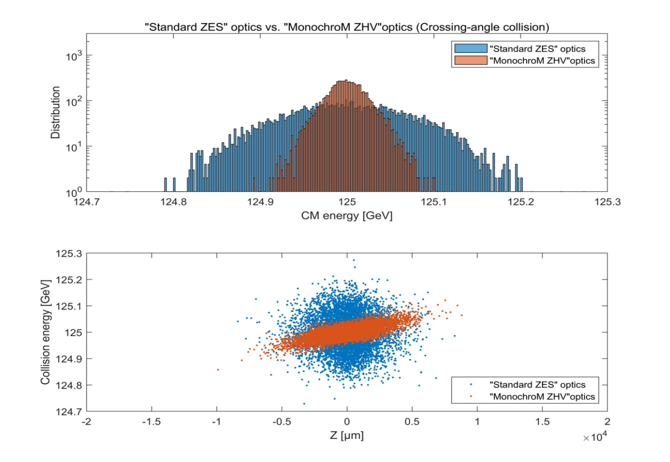
**$N_b$ needs to be adjusted so that the head-on luminosity is align with the analytical result.**



# FCC-ee GHC MonochroM Physics Performance (II)

➢ **Energy distribution calculated using Guinea-Pig**

| | MonochroM ZH4IP | MonochroM ZV1 | MonochroM ZHV |
|---|---|---|---|
| CC scheme |   |   |   |
| IRS scheme |   |   |   |

# FCC-ee GHC MonochroM Physics Performance (III)

➢ $\sigma_W$, $\mathcal{L}$ and $\mathcal{L}_{int}$ of the monochromatization IR optics based on Z mode lattice (CC/IRS)

| Parameters | Units | Standard ZES | MonochroM ZH4IP | MonochroM ZH2IP | MonochroM ZHS | MonochroM ZV0.5 | MonochroM ZV1 | MonochroM ZHV |
|---|---|---|---|---|---|---|---|---|
| CM energy spread (CC/IRS) $\sigma_W$ | MeV | 99.77 / 69.52 | 20.53 / 26.80 | 11.97 / 24.40 | 91.57 / 66.87 | 25.86 / 27.03 | 23.96 / 25.25 | 16.43 / 20.58 |
| Luminosity (CC/IRS) $\mathcal{L}$ | $10^{34}$cm$^{-2}$ s$^{-1}$ | 195 / 44.8 | 23.1 / 15.0 | 18.4 / 18.5 | 147 / 37.7 | 4.32 / 2.92 | 2.18 / 1.46 | 2.46 / 1.42 |
| Integrated luminosity (CC/IRS) $\mathcal{L}_{int}$ | ab$^{-1}$ | 23.4 / 5.38 | 2.77 / 1.80 | 2.21 / 2.21 | 17.6 / 4.52 | 0.52 / 0.35 | 0.26 / 0.18 | 0.30 / 0.17 |

➢ $\sigma_W$, $\mathcal{L}$ and $\mathcal{L}_{int}$ of the monochromatization IR optics based on ttbar mode lattice (CC/IRS)

| Parameters | Units | Standard TES | MonochroM TH4IP | MonochroM TH2IP | MonochroM THS | MonochroM TV0.5 | MonochroM TV1 | MonochroM THV |
|---|---|---|---|---|---|---|---|---|
| CM energy spread (CC/IRS) $\sigma_W$ | MeV | 95.32 / 67.20 | 19.05 / 27.10 | 15.46 / 23.16 | 74.81 / 61.14 | 17.44 / 20.41 | 16.65 / 20.23 | 15.99 / 21.24 |
| Luminosity (CC/IRS) $\mathcal{L}$ | $10^{34}$cm$^{-2}$ s$^{-1}$ | 334 / 71.2 | 27.4 / 17.9 | 37.6 / 24.5 | 155 / 44.3 | 3.78 / 2.72 | 1.89 / 1.37 | 2.45 / 1.42 |
| Integrated luminosity (CC/IRS) $\mathcal{L}_{int}$ | ab$^{-1}$ | 40.1 / 8.54 | 3.29 / 2.15 | 4.51 / 2.94 | 18.6 / 5.32 | 0.45 / 0.33 | 0.23 / 0.16 | 0.29 / 0.17 |

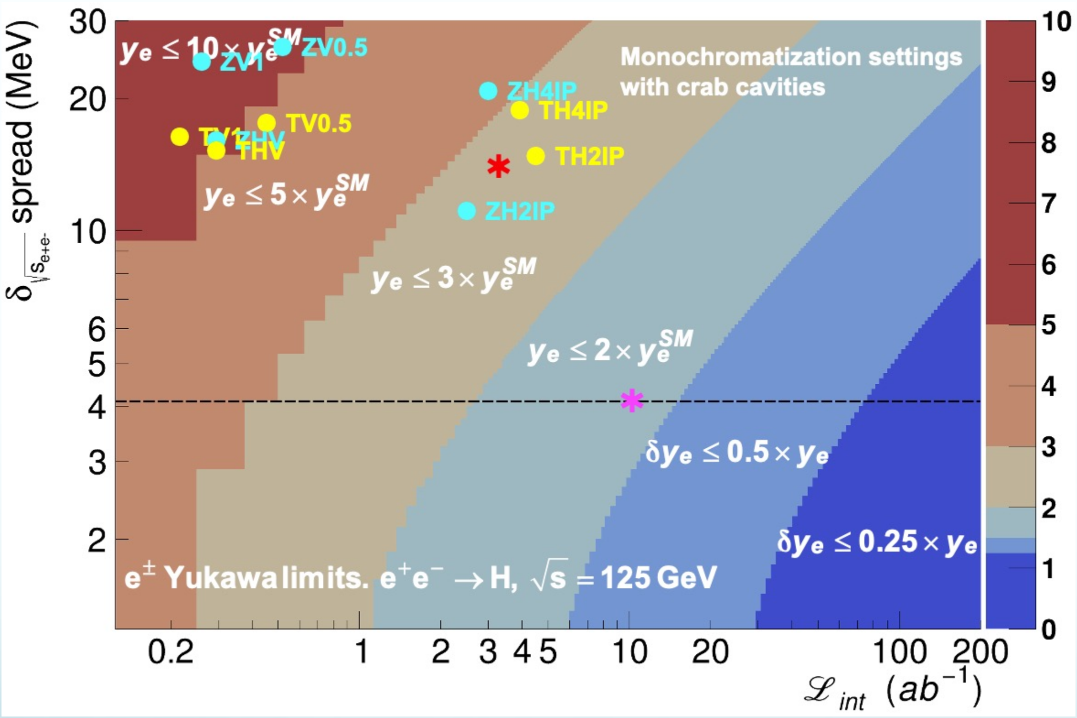
$\mathcal{L}_{\text{int}}$ assumption in FCC-ee CDR (184 physics day and 75% physics efficiency): $10^{35}$ cm$^{-2}$s$^{-1}$ → 1.2 ab$^{-1}$ per IP per year.

# FCC-ee GHC MonochroM Physics Performance (IV)

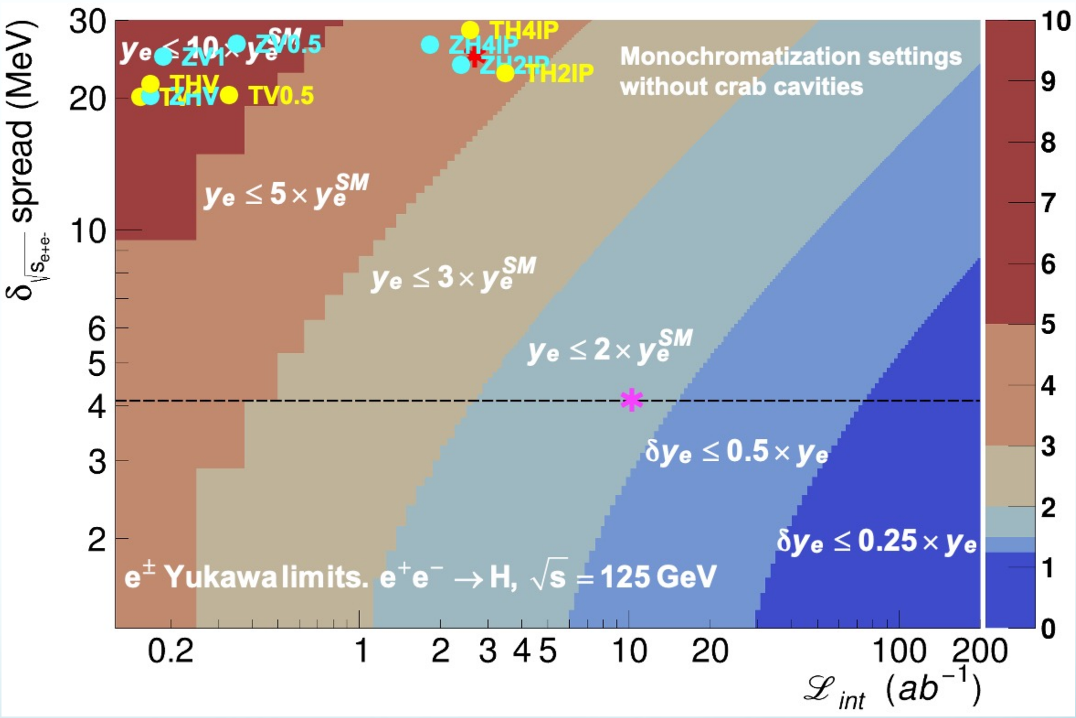
## Physics performance

Physics performance evaluated by establishing the $\delta_{\sqrt{s}}$-$\mathcal{L}_{\text{int}}$ benchmarks in the upper limit contours (95% CL) for $y_e$ couplings.

- Physics performance of the monochromatization IR optics (CC scheme).




- Physics performance of the monochromatization IR optics (IRS scheme).




Pink star: baseline point assumed in the original physics simulation analysis.
Red star: FCC-ee self-consistent parameters.

# Conclusions and Perspectives

- Monochromatization is a **simple conceptual idea** but its practical implementation in a collider is challenging, especially when it is not integrated into the initial IR optics design as a dedicated operational mode.

- Research on monochromatization has **never reached** the stage for full implementation and experimental validation. A flexible lattice with two modes of operation with/without monochromatization is mandatory.

- Different **FCC-ee GHC MonochroM "realistic" optics** lattices has been completed for V22 featuring very promising performances.

- Further studies on FCC-ee GHC MonochroM lattices are needed: to simulate the impact of the **beam-beam with $D^*_{x,y} \neq 0$** after optimizing the dynamic aperture for these new type of operation mode.

- Implementation and comparison with the FCC-ee LCC optics with more symmetric IRs will be carried out.

- MonochroM optics design for CEPC is ongoing (IR more symmetric).

- Experimental proof of monochromatization concept in running $e^+e^-$ low energy colliders are under study for BEPCII (IHEP China), DAFNE and maybe in SuperKEKB.

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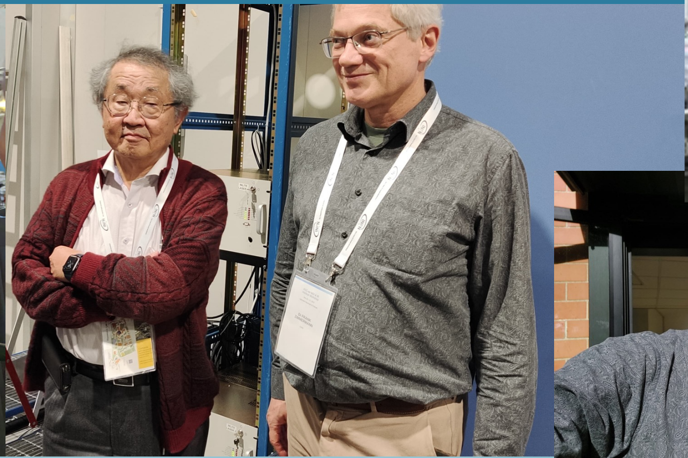
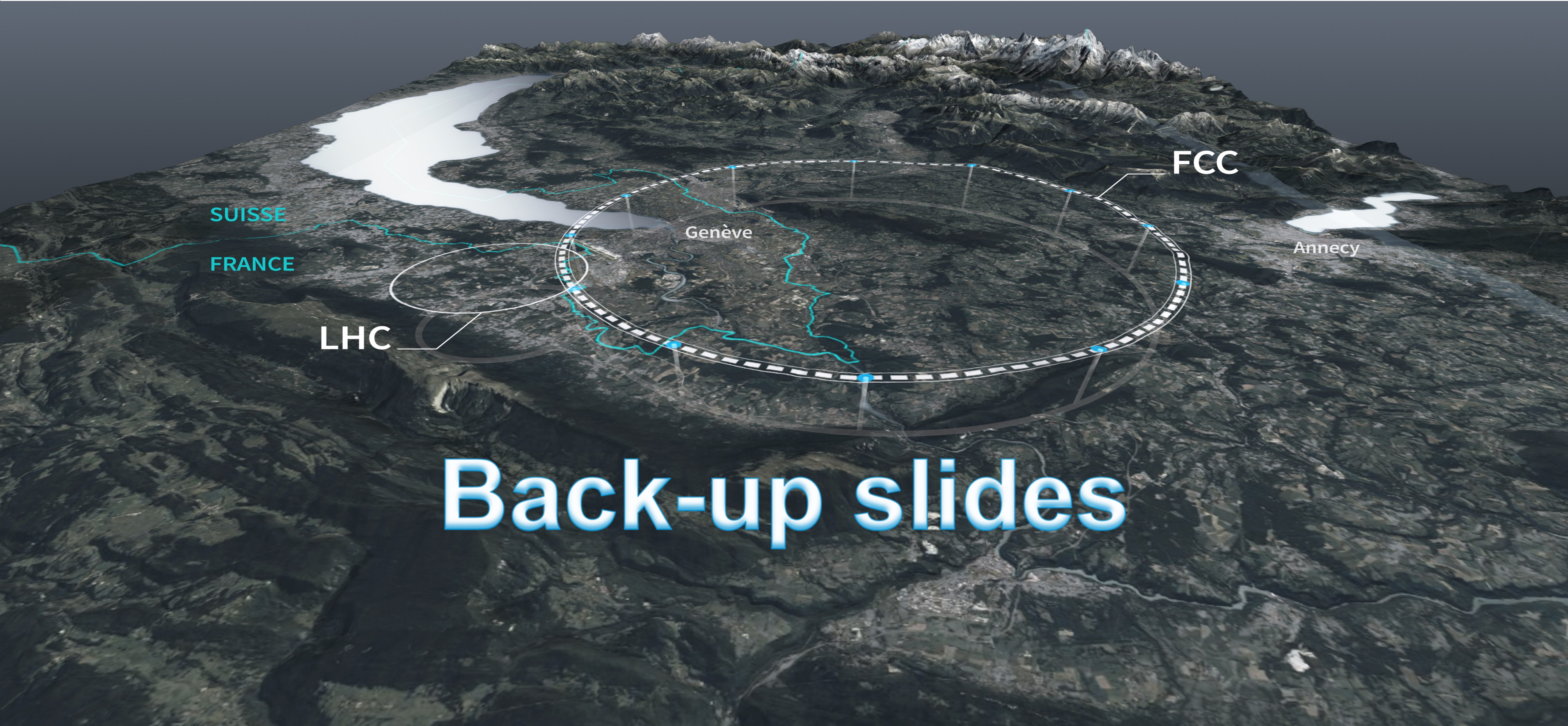
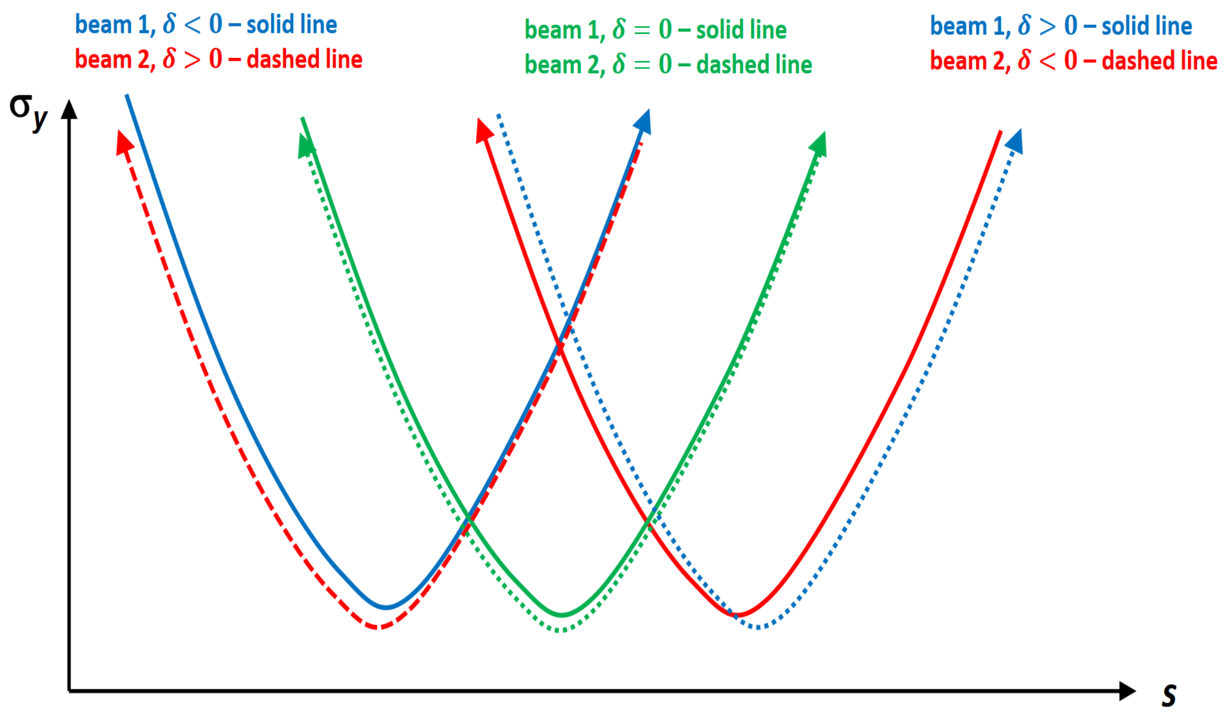





# Back-up slides

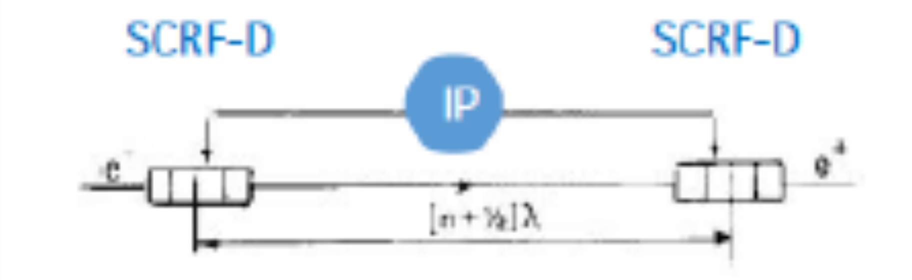
Monochromatization could be obtained by operating with a **residual nonzero local vertical chromaticit**y (RLC). This enables the focal length of the final quadrupoles to change with the momentum deviation of a beam particle, and establishes a dependence between the vertical beam size waist and momentum offset. An effective monochromatization could be obtained, without adding any new hardware. The resulting monochromatization factor will be enhanced for smaller $\beta_y^*$, but limited $\lambda$ possible.




Waist location for beam 1 with momentum offset δ, can be made to coincide with the waist location for beam 2 with momentum offset -δ, leading to an effective monochromatization, without adding any new hardware.

P. Raimondi, F. Zimmermann, private communication

Monochromatization with **dispersion inside the deflecting RF cavities (SCRF-D)** on either side of the collision point.




$$E_s = -E_{s0} \sin k_x x \cdot \cos k_z z \cdot \cos(\omega t + \phi),$$

$$H_x = \frac{k_z}{k} E_{s0} \sin k_x x \cdot \sin k_z z \cdot \sin(\omega t + \phi), \qquad (1)$$

$$H_z = -\frac{k_x}{k} E_{s0} \cos k_x x \cdot \cos k_z z \cdot \sin(\omega t + \phi),$$

where $E_{s0}$ is the amplitude of electric field; $\omega$, $\phi$ are the frequency and phase of oscillations; $k_x = 2\pi/a_x$, $k_z = \pi/a_z$, $k^2 = k_x^2 + k_z^2$.

A.A. Zholents, Sophisticated accelerator techniques for colliding beam experiments. Nucl. Instrum. Methods A 265, 179–185 (1988)

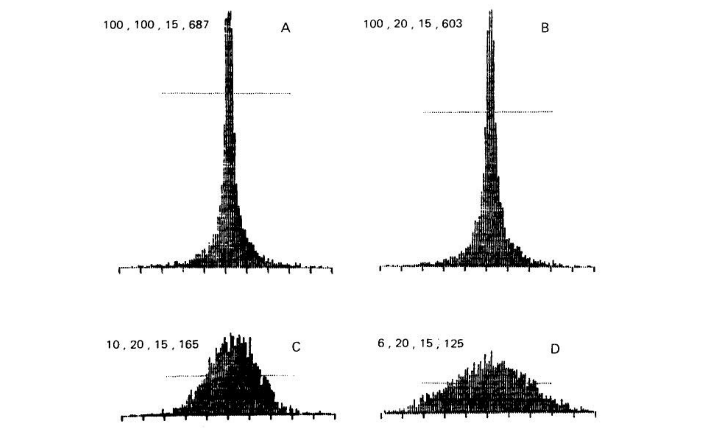



Fig. 5. Histograms of the luminosity distribution in the total energy of electron and positron collisions. The step of the histograms is 0.01 $\sigma_t$, where $\sigma_t = \sqrt{2}\sigma_{\Delta E/E}$ and there are 10 steps between two graduation lines. The parameters of the rf-monochromatization scheme, used in the numerical simulation, are given on each plot in the following order: $\kappa_0$, $a_x/\sigma_{xs}$, $\lambda/\sigma_1$. The fourth number shows the number of particles in the peak. The upper parts of the first two histograms lying above a certain level are not shown on the plot. An additional horizontal line on all the plots shows the half height of the peak.

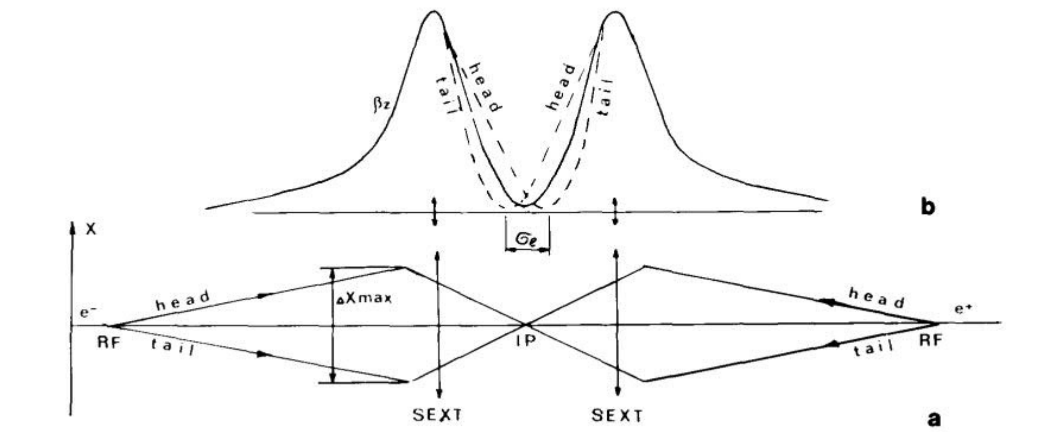



Fig. 6. a) The trajectories of the head and the tail of the bunch in the region between AS. b) The behaviour of $\beta_z$-function.

# Monochromatization IR Global Implementation

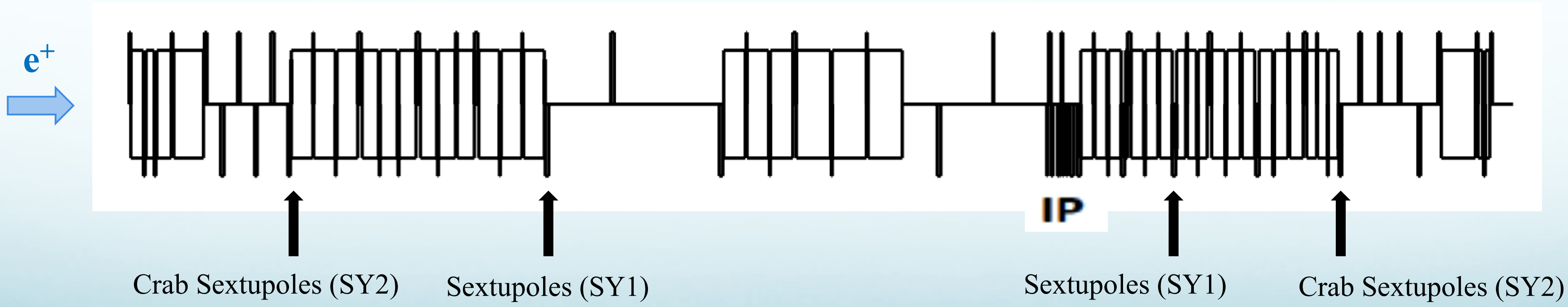
- **Local Chromaticity Correction**
  - Load monochromatization ring lattice, and extract sequence from IP to crab sextupoles.
  - Turned off all the sextupoles including crab sextupoles SY2.
  - Match the vertical chromaticity from IP to crab sextupoles to 0 using the sextupoles SY1.
  - Calculate the strength of crab sextupoles (SY2) with the following formula:

$$K2SY2 = K2SY1 \pm crab_{factor} \cdot crab_{strength}$$

The crab strength is given by:

$$crab_{strength} = \frac{1}{L_{SY2} * \theta_{CROSS} * BY_{IP} * BY_{CS}} * \sqrt{\frac{BX_{IP}}{BX_{CS}}}$$

The crab factor is determined from Beam-beam studies, at Z it's 97%, W 87%, so ~90% for Higgs mode seems a good starting guess.




K. Oide, M. Aiba, S. Aumon, M. Benedikt, A. Blondel et al. "Design of beam optics for the future circular collider e+e- collider rings", Physical Review Accelerators and Beams, 19, 111005 (2016)

# Monochromatization IR Global Implementation

- **Global Chromaticity Correction**

With the matched strength of the SY1 and the strength of SY2 calculated by the formula, the global chromaticity correction is done by matching the strength of all the sextupoles in the arc.

There are two kinds of sextupoles in the arc, focus sextupoles and defocus sextupoles. The strength of all the focus sextupoles is multiplied by the coefficient kn_sf, while the strength of all the defocus sextupoles is multiplied by the coefficient kn_sd.

The horizontal chromaticity (DQ1) and vertical chromaticity (DQ2) are matched to 5 with the two coefficient, because positive chromaticity is benefit for the beam stability.

- **Tune Correction**

By varying the strength of quadrupoles around the RF cavities in the arc, the horizontal tune Q1 and vertical tune Q2 are matched to be same with the standard mode while keeping the beam parameters at the IRs.

- **Emittance Check**

Switching on the RF cavities and considering the energy loss due to synchrotron radiation, the longitudinal energy difference (*pt*) are matched to zero by varying the voltage and the phase of the RF cavities in tapering twiss model.