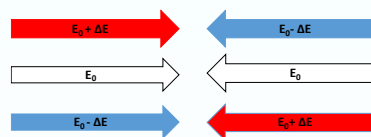




# Monochromatization in $e^+e^-$ colliders FCC-ee case

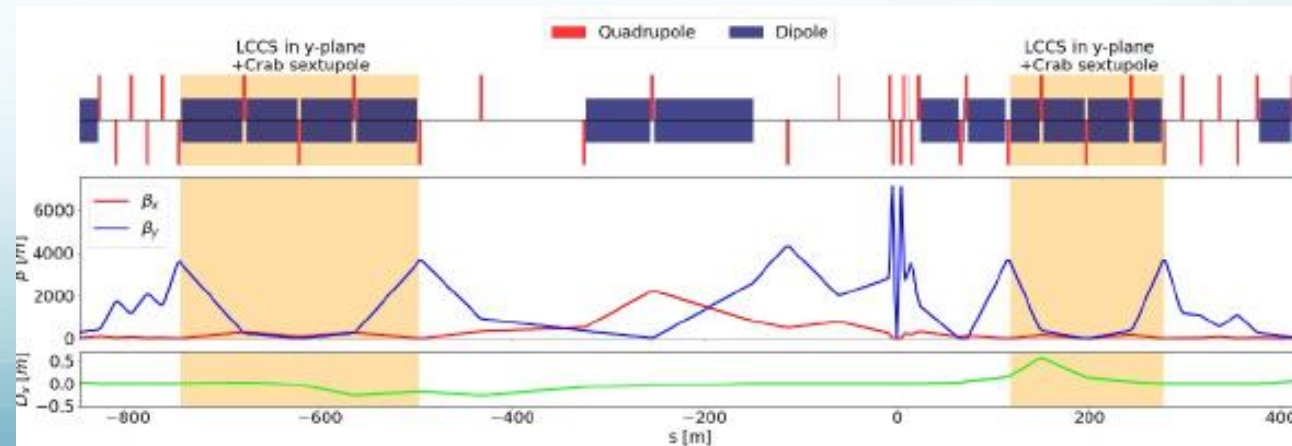
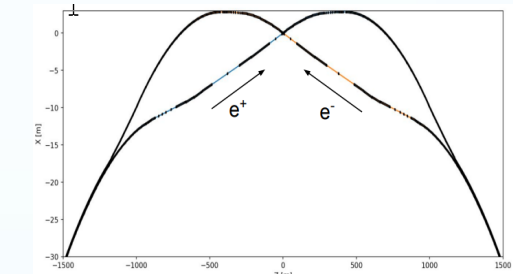
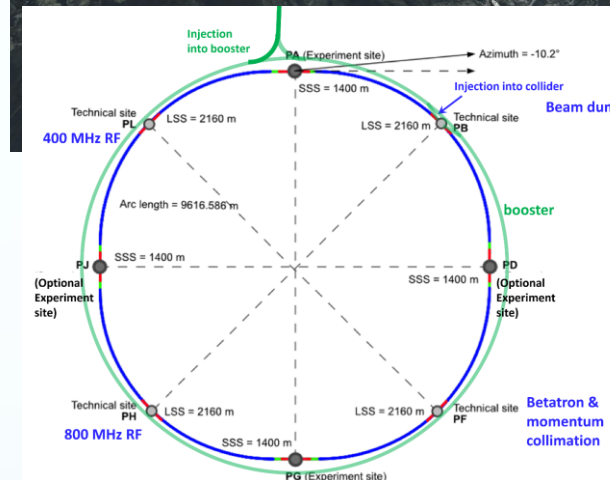
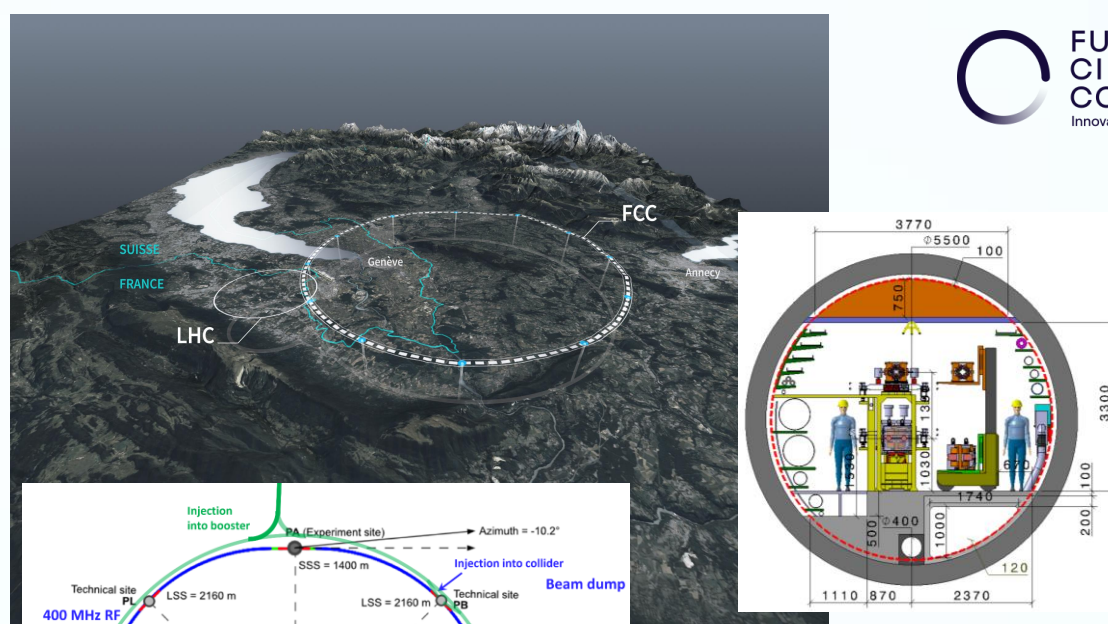
**A. Faus-Golfe**

# Monochromatization



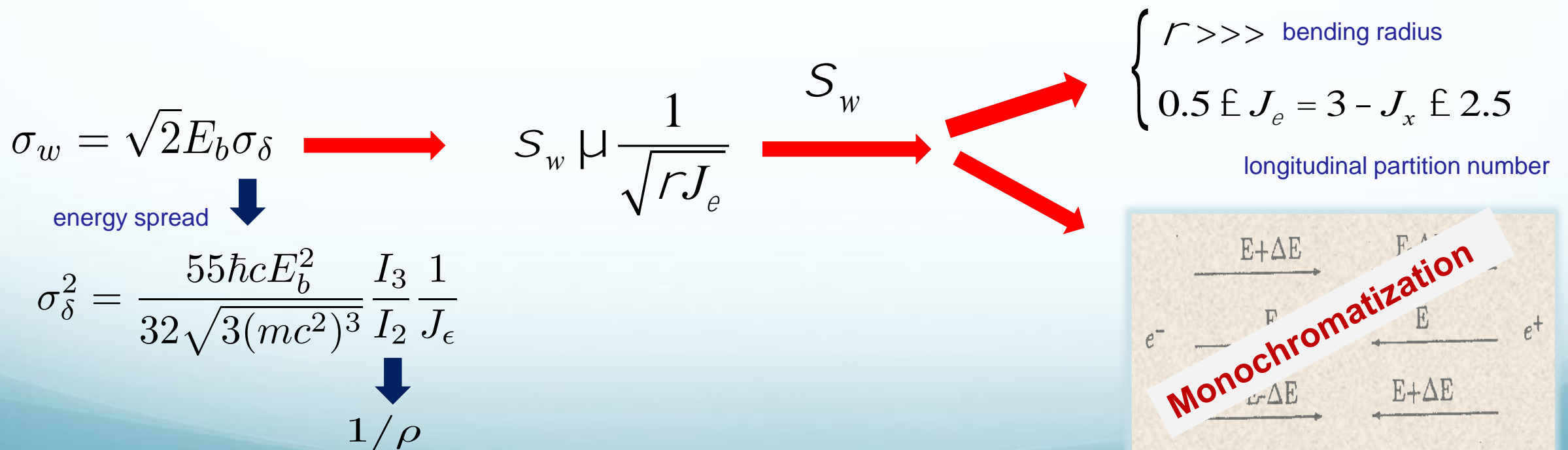
# Outline

- Monochromatization concept
- Monochromatization parameters for FCC-ee
- Monochromatization schemes and implementation in FCC-ee
- Summary and Perspectives



# Energy resolution in colliders

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

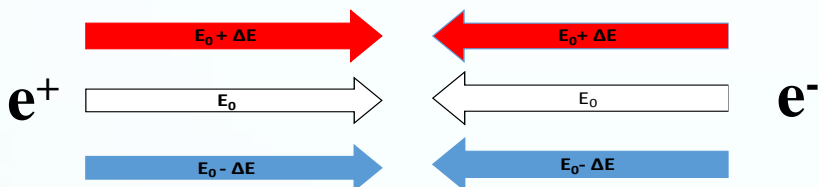


# Monochromatization principle

**Standard**

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

**IP**



$$w = 2(E_b + \epsilon)$$

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

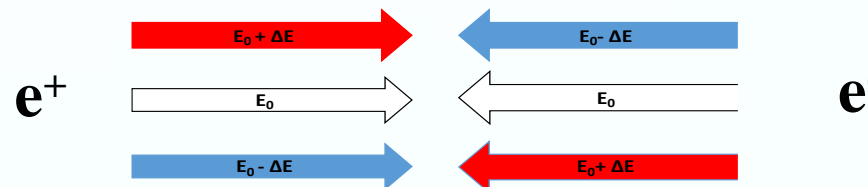
$$L_0 = \frac{k_b f_r N_+ N_-}{4\pi\sigma_{x\beta}^* \sigma_{y\beta}^*}$$

**Monochromatization**

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

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

**IP**



$$w = 2E_b + 0(\epsilon)^2$$

**Monochromatization factor**

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

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

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

Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.

# Monochromatization principle

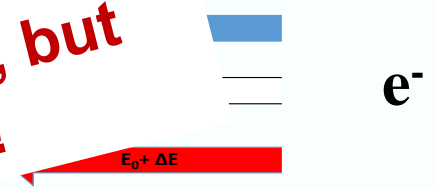
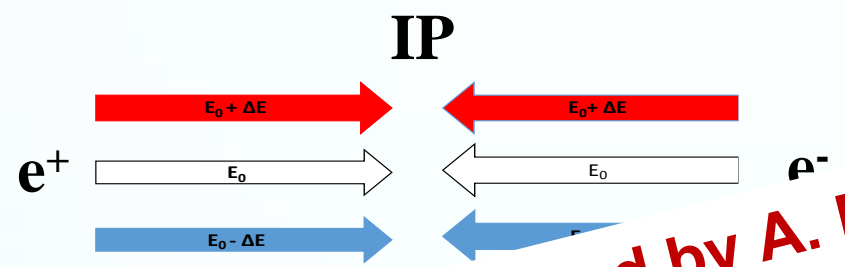
**Standard**

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

**Monochromatization**

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

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



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

$$w =$$

$$w = 2E_b + 0(\epsilon)^2$$

**Monochromatization factor**

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

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

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

Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.



A. Renieri. Possibility of Achieving Very High-Energy Resolution in electron-Positron Storage Rings. LNF Report, LNF-75/6-R, 2 (1975)

# Monochromatization principle

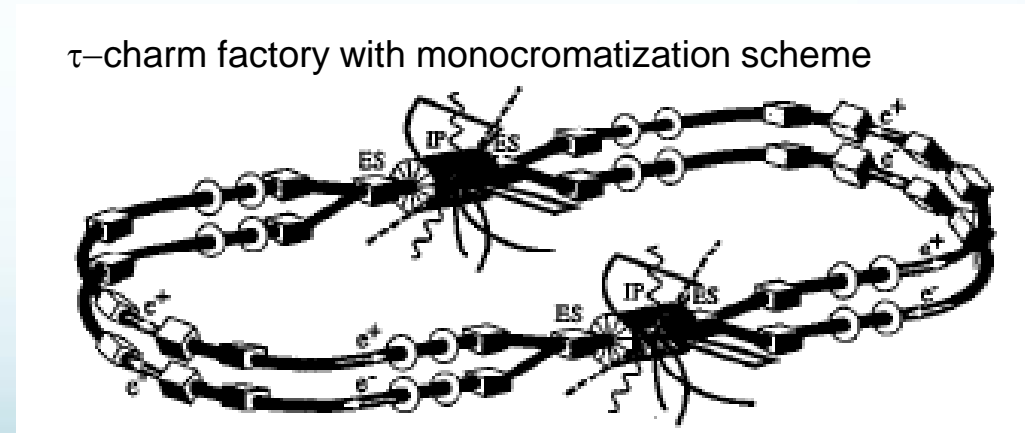
At **low-energy**  $e^+e^-$  colliders, with **flat beam schemes** ( $\sigma_y^* \ll \sigma_x^*$ ) and where the energy spread is mainly due to SR and “beamstrahlung”(BS) **is not important:**

$$\sigma_y^* \ll \ll \sigma_x^* \quad \text{with} \quad \begin{cases} \beta_y^* \ll \beta_x^* \\ \varepsilon_y^* \ll \varepsilon_x^* \end{cases} \quad \longrightarrow \quad \begin{cases} D_{x+}^* = D_{x-}^* = 0 \\ D_{y+}^* = -D_{y-}^* = D_y^* \end{cases} \quad \longrightarrow \quad \begin{cases} \xi_x = \xi_{\max} \\ \text{with low } \varepsilon_x^* \end{cases} \quad L \simeq \frac{I\gamma}{2er_e} \frac{\xi_x}{\beta_x^*}$$

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

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

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



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)

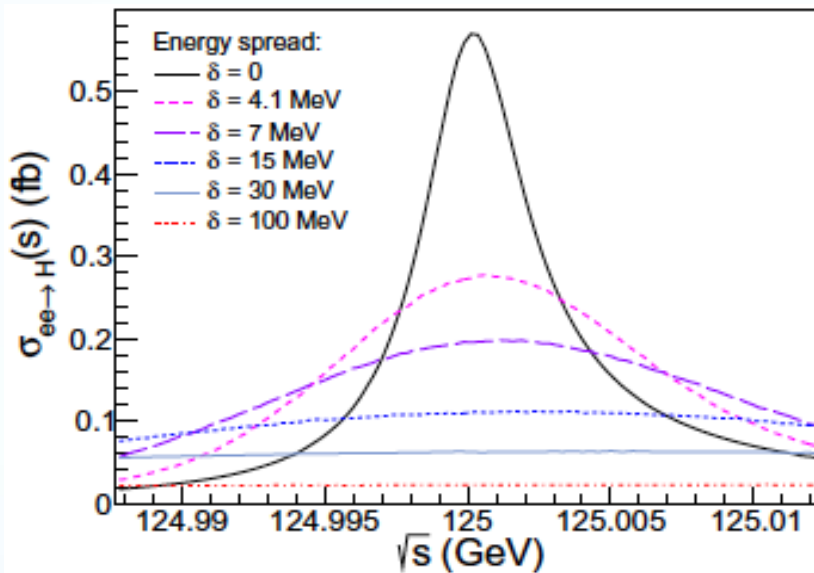
# Monochromatization in FCC-ee

In the previous case for low-energy  $e^+e^-$  colliders, in  $\lambda$  definition, we may take  $\sigma_\delta$  to mean the energy spread without collision so that  $\sigma_\delta = \sigma_{\delta,SR}$ , where  $\sigma_{\delta,SR}$  denotes the natural relative momentum spread due to SR in the collider arcs. Alternatively in high-energy  $e^+e^-$ , it is recommended to take into account the fact that monochromatization avoids the blow up of the relative RMS beam energy spread to a larger value of  $\sigma_{\delta,coll}$  due to the additional contribution from BS, which is significant in collisions with  $D_x^* = 0$ . To this end, we introduce the effective monochromatization factor  $\lambda_{eff}$ , that compares the true **collision energy spread without and with monochromatization** (mc):

$$\lambda_{eff} = \frac{\sigma_{w,D^*=0}}{\sigma_{w,mc}} = \frac{\sigma_{\delta,coll}}{\sigma_{\delta,SR}} \left( \frac{D_x^{*2} \sigma_{\delta,SR}^2}{\epsilon_x \beta_x^*} + 1 \right)^{1/2}$$

In FCC-ee,  $\lambda_{eff}$  is more than two times larger than  $\lambda$ .

# Monochromatization in FCC-ee



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.

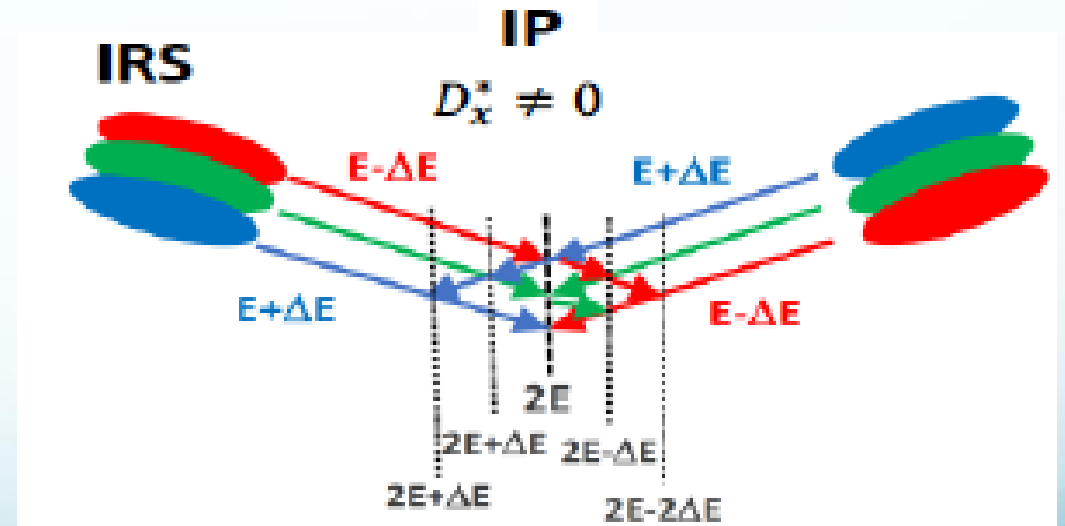
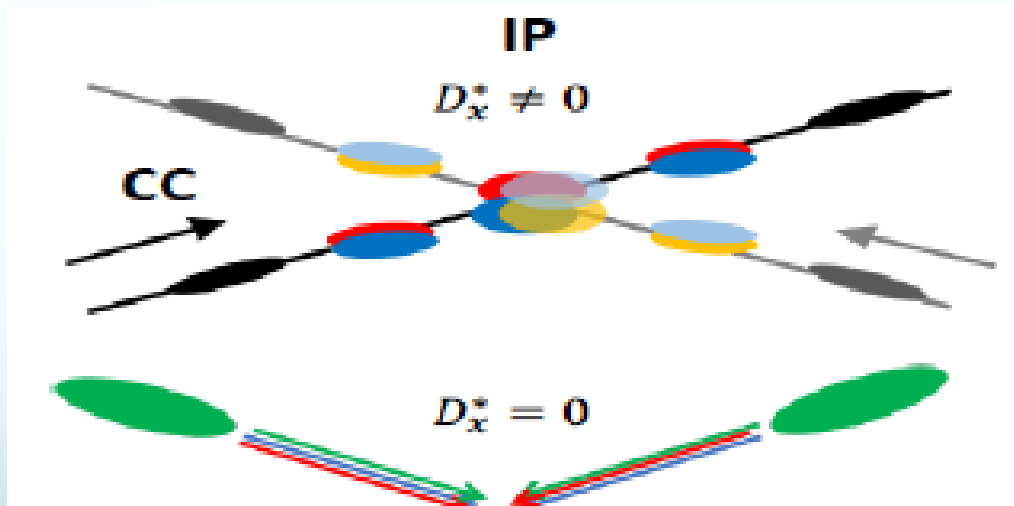
In recent years interest in **monochromatization** has been renewed, as **FCC-ee** could directly produce the Higgs boson in s-channel annihilation  $e^+e^- \rightarrow H$ . This production mode is only possible if the default collision energy spread ( $\sim 50$  MeV) can be reduced to a level comparable with the natural width of the **Higgs boson**  $\Gamma_H = 4.2$  MeV, offering the only known path to measuring the **electron-Yukawa coupling**.

In comparison to the **previous monochromatization designs**, for the first time given the **high-energies** in **FCC-ee** the **BS** become **significant** contributing to **increase the energy spread**. In these conditions is convenient to introduce the dispersion in the horizontal plane ( $D_x^*$ ). Wide  $\sigma_x^*$  **reduce** the **BS** while preserve small  $\sigma_y^*$  for attaining high-luminosity. Furthermore in FCC-ee, horizontal dispersion is created more easily, since the beams are crossed in this plane.



# Monochromatization in FCC-ee

Given the **FCC-ee IR design**, two **monochromatization schemes** are possible. **Crossing angle** monochromatization scheme featuring **IP dispersion of opposite signs** for the colliding beams with **crab crossing (CC)** and without or **integrated resonances scan (IRS)**.

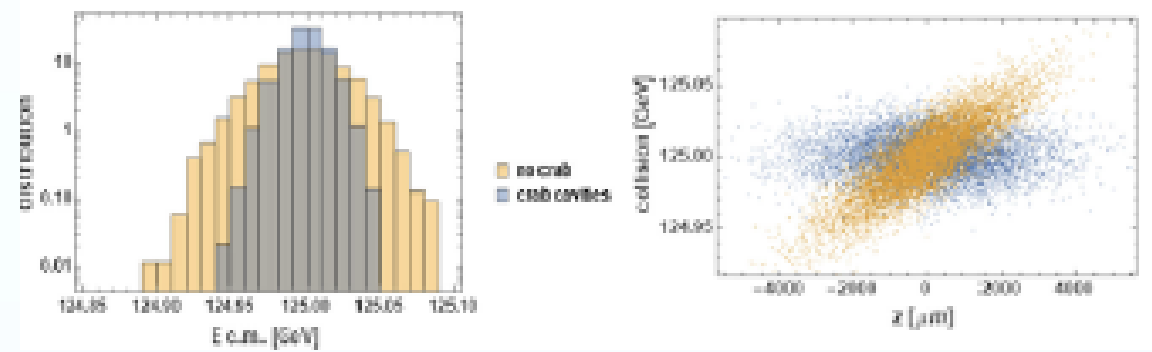


# Monochromatization in FCC-ee

Example IP parameters and performance for typical monochromatization scenario for FCC-ee

Parameter		Units
CM Energy, $W$	125	[GeV]
Horizontal, vertical RMS emittances with (without) beamstrahlung, $\epsilon_{x,y}$	2.5 (0.51), 0.002	[nm]
Relative RMS momentum deviation, $\sigma_\delta$	0.052	%
RMS bunch length, $\sigma_z$	3.3	[mm]
Horizontal dispersion at IP, $D_x^*$	0.105	[m]
Beta functions at the IP, $\beta_{x,y}^*$	90, 1	[mm]
RMS beam size at the IP, $\sigma_{x,y}^*$	55, 0.045	[ $\mu\text{m}$ ]
Full crossing angle, $\theta_c$	30	[mrad]
Vertical beam-beam tune shift, $\xi_y$	0.106	
Total beam current, $I_e$	395	[mA]
Bunch population, $N_b$	$6.0 \times 10^{10}$	
Bunches per beam, $n_b$	13420	
Luminosity (without crab cavities) per IP, $L$	$2.6 (2.3) \times 10^{35}$	[ $\text{cm}^{-2} \text{s}^{-1}$ ]
RMS CM energy spread (without crab cavities), $\sigma_W$	13(25)	[MeV]

## Monochromatization beam-beam simulations



CM distribution with and without crab cavities

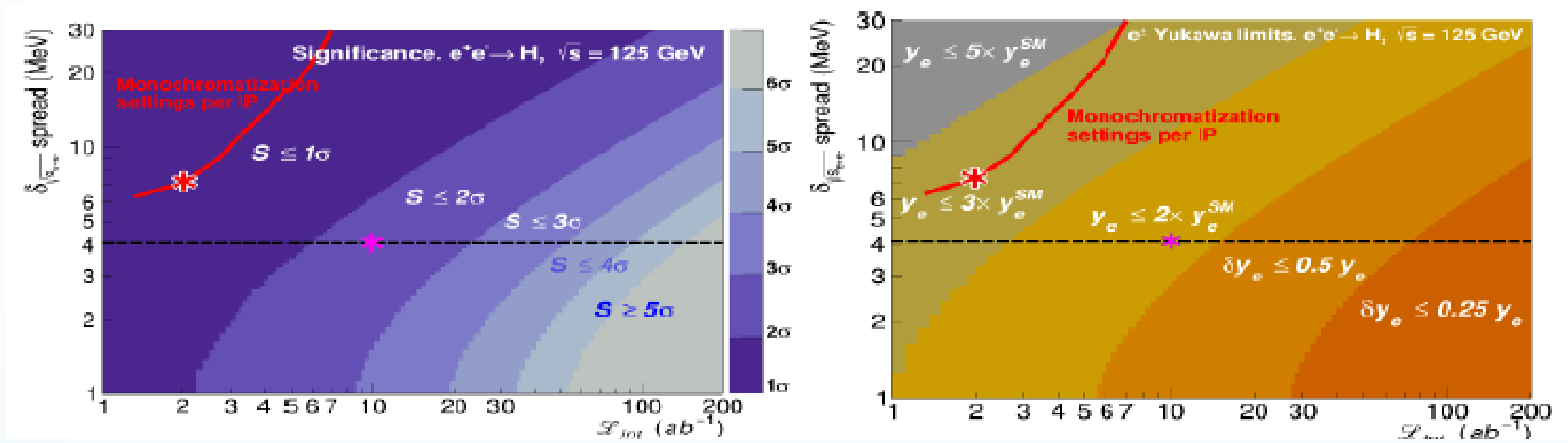
Correlation between collision energy and longitudinal position

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

**Monochromatization scheme works well both with and without crab cavities.** In the latter case, the local RMS energy spread at the IP is the same, e.g., 13 MeV, but the total RMS spread is higher and a resonance scan is automatically performed, since the average collision energy  $W$  varies with longitudinal position.

# Monochromatization in FCC-ee

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 std. dev. units  $\sigma$ ) in the CM energy spread vs. integrated luminosity plane for the resonant  $\sigma_{e^+e^- \rightarrow H}$  cross section at  $s = m_H$ .

Associated upper limits contours (95% CL) on the electron Yukawa coupling  $y_e$ .

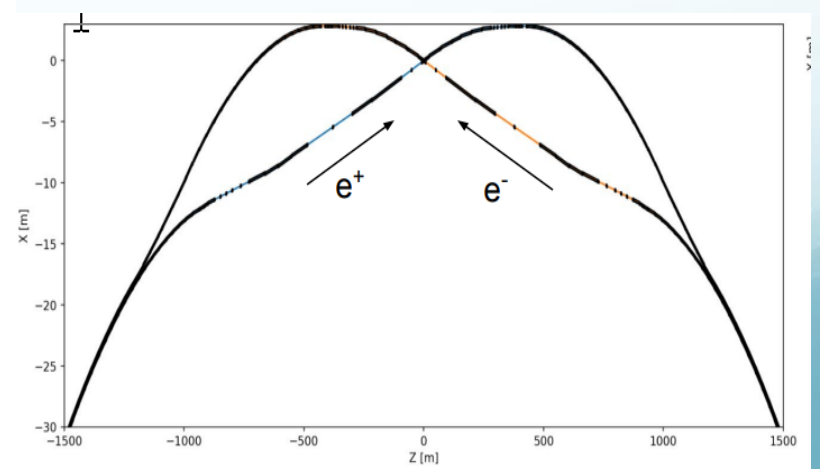
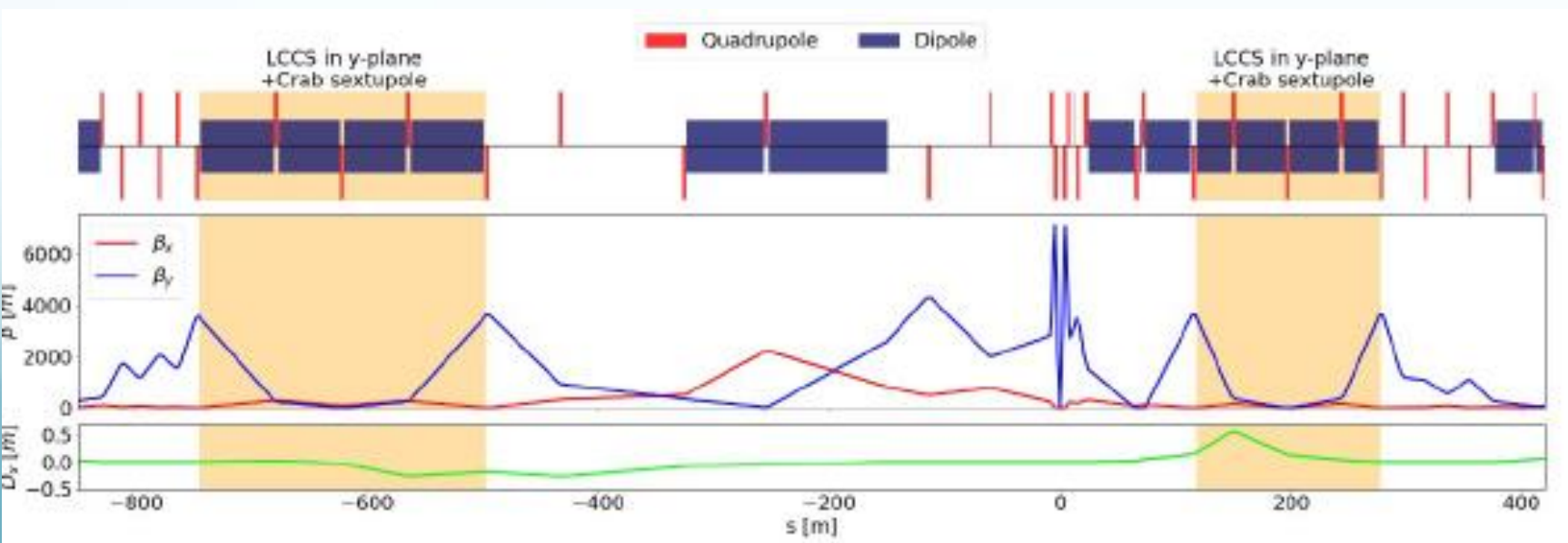
The red curves show the range of parameters presently reached in FCC-ee monochromatization studies. The red star indicates the best signal strength monochromatization point in the plane (the pink star over the  $\delta\sqrt{s} = \Gamma_H = 4.2$  MeV dashed line, indicates the ideal baseline point assumed in default analysis). All results are given per IP and per year.

# Monochromatization implementation in FCC-ee

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

**Different schemes are possible:**

- Given the baseline layout of the FCC-ee IR region, that features a **large crossing angle of 30 mrad** in the horizontal plane and a **local chromaticity correction scheme** (with horizontal dispersion created by horizontal dipole magnets at the two sides of the IP where sextupoles are located), the easiest way to generate the necessary dispersion function in the IP ( $D^*x$ ) comes from the use of a set of additional **horizontal dipole magnets in the FFS region**. (More in H. Jiang talk)



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



$$\begin{aligned}
 E_s &= -E_{s0} \sin k_x x \cdot \cos k_z z \cdot \cos(\omega t + \phi), \\
 H_x &= \frac{k_z}{k} E_{s0} \sin k_x x \cdot \sin k_z z \cdot \sin(\omega t + \phi), \quad (1)
 \end{aligned}$$

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

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)

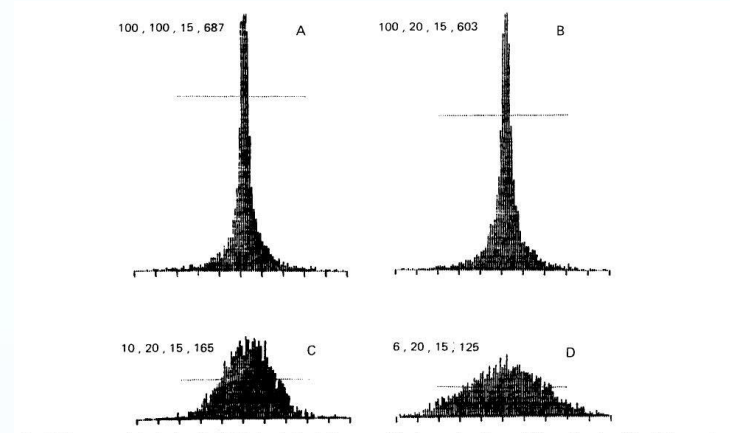


Fig. 5. Histograms of the luminosity distribution in the total energy of electron and positron collisions. The step of the histograms is  $0.01 \sigma_1$ , where  $\sigma_1 = \sqrt{2} a_{E/E}$ , and there are 10 steps between two graduation lines. The parameters of the rf-monochromatization scheme, used in the numerical simulation, are given on each plot in the following order:  $\kappa_0$ ,  $a_x/\sigma_x$ ,  $\lambda/\sigma_1$ . 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.

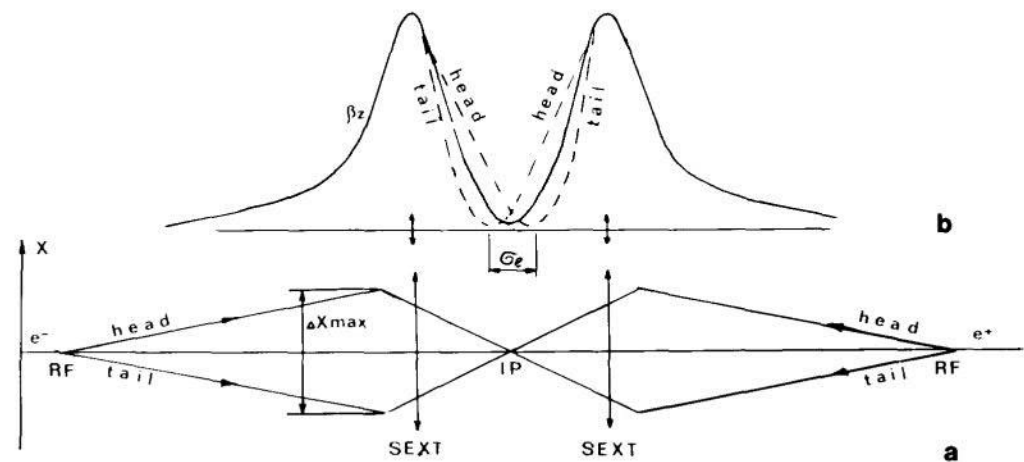
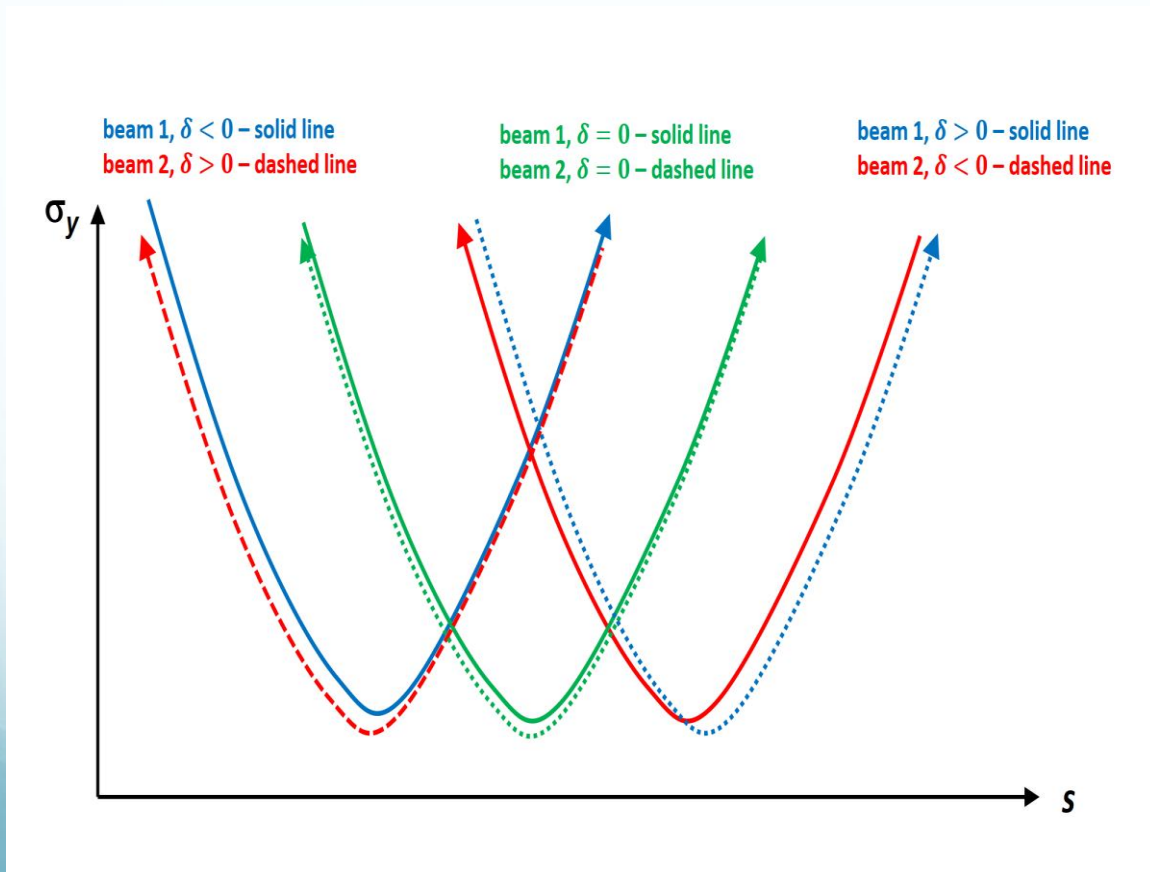


Fig. 6. a) The trajectories of the head and the tail of the bunch in the region between AS. b) The behaviour of  $\beta_z$ -function.

- Monochromatization could be obtained by operating with a **residual nonzero local vertical chromaticity** (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  $\mathcal{R}_y^*$ , but limited  $\lambda$  possible.



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

P. Raimondi, F. Zimmermann, private communication

# Summary and perspectives

- 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.
- Given the fact monochromatization has never been tested experimentally, a flexible lattice with two modes of operation with/without monochromatization is advisable.
- Monochromatization optics with IR LOC Dipoles is ongoing.
- New ideas are being investigated.

# Summary and perspectives

Further studies are need on:

- Beam performance and main physics self-consistent parameters for monochromatized collisions.
- Linear optics design studies for monochromatization ( $D_x^*$  limitations) and compatibility with baseline mode.
- Non-linear beam dynamics studies including BS and SR issues.
- Feasibility study of crab cavities for monochromatization.
- Alternative modes of monochromatization and combinations.
- .....



# WG5: Monochromatization

## Tuesday 20 Sep 2022 - Parallel WG5

	Talk	Speaker
15:30	Requirements on Monochromatization (Physics & run)	D. Enterria
15:55	Measurement of monochromatization parameters	A. Blondel - P. Janot

## Wednesday 21 Sep 2022 - Parallel WG5

	Talk	Speaker
15:30	Towards monochromatization optics	A. Faus-Golfe
15:55	First draft optics	H. Jiang
16:20	Monochromatization with chromatic waist shift	P. Raimondi

## Thursday 29 Sep 2022 - Parallel WG4 and WG5

15:30	Final discussion and wrap up	all
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**Thanks for your attention  
and specially to  
F. Zimmermann, K. Oide, A. Blondel,  
P. Raimondi and A. Zholents.**