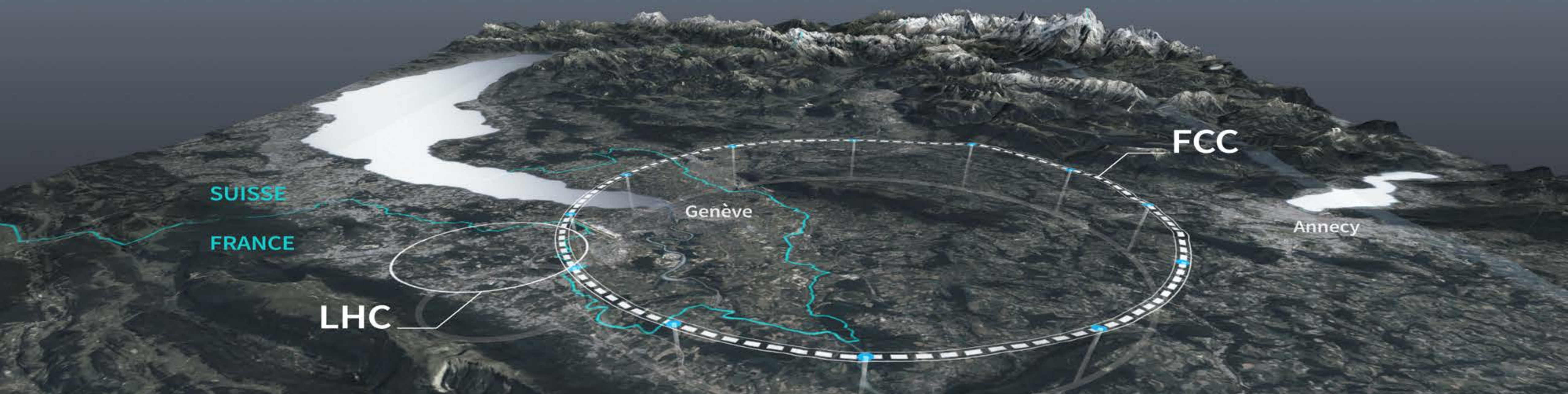
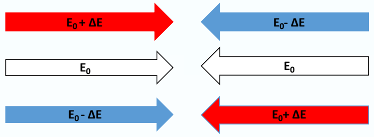
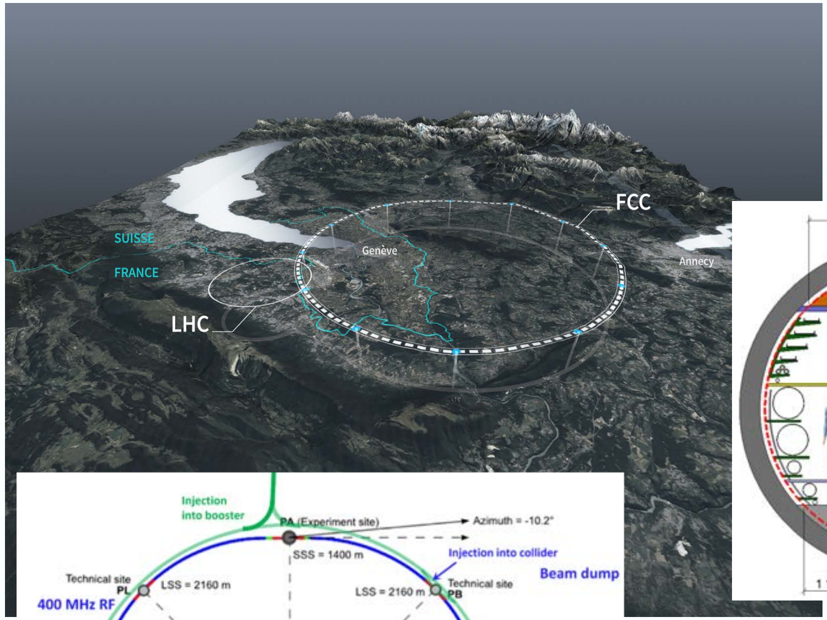


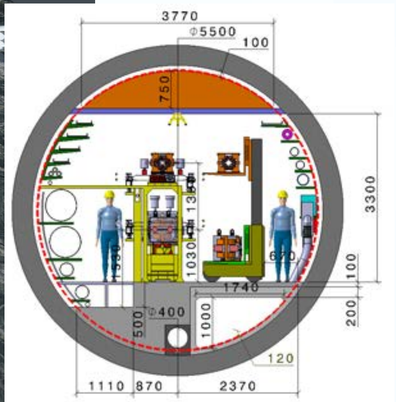
Monochromatization in e^+e^- colliders FCC-ee case

A. Faus-Golfe

Monochromatization

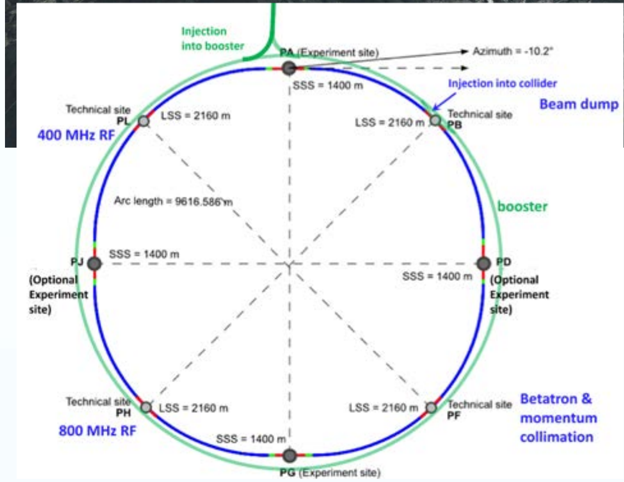


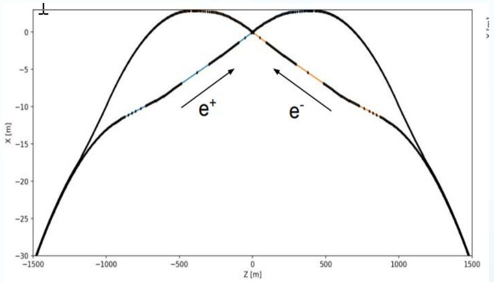


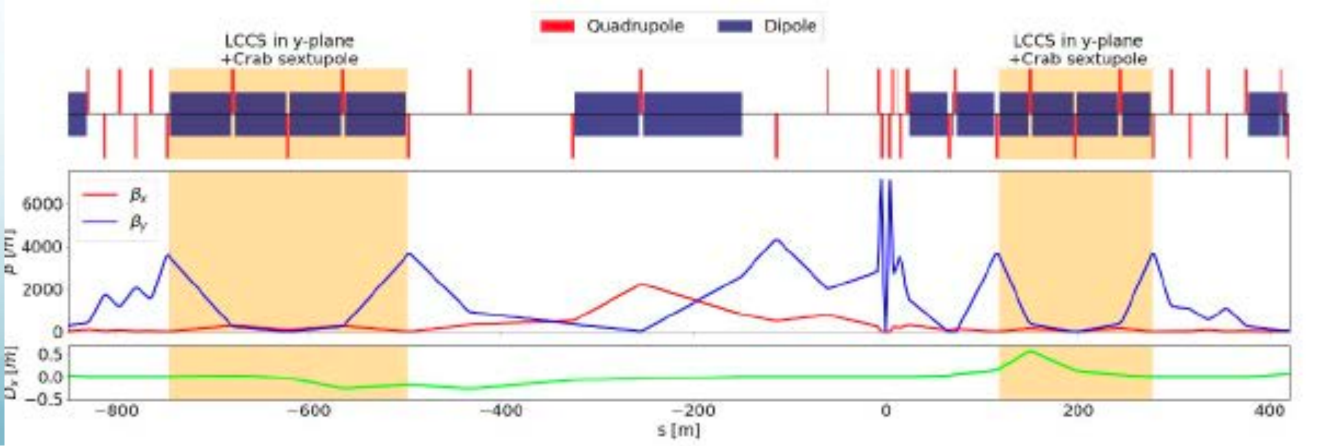


Outline

- 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** (σ_ω) 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.

$$\sigma_w = \sqrt{2} E_b \sigma_\delta \quad \longrightarrow \quad \sigma_w \propto \frac{1}{\sqrt{\rho J_\varepsilon}} \quad \xrightarrow{\sigma_w}$$

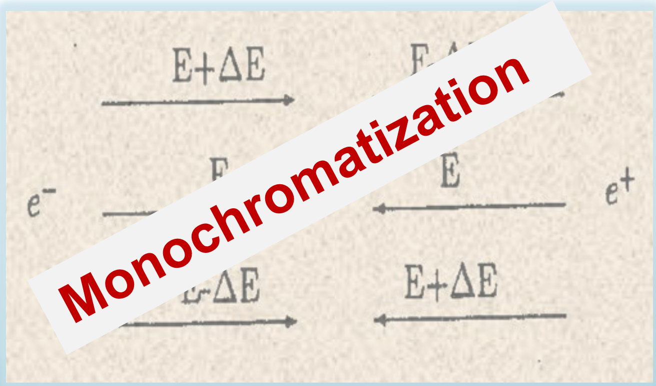
energy spread

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

$$1/\rho$$

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

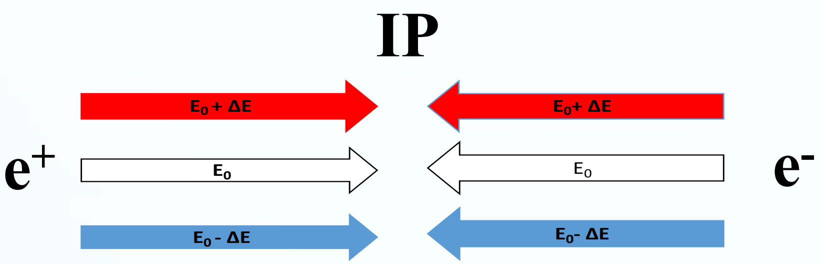
longitudinal partition number



Monochromatization principle

Standard

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



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

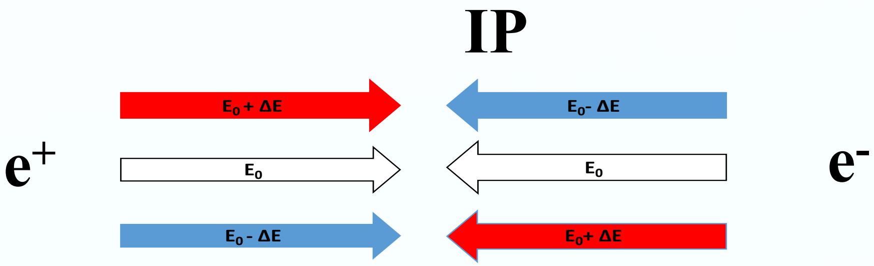
$$\sigma_w = \sqrt{2} E_b \sigma_\delta$$

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

Monochromatization

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

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



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

Monochromatization factor

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

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

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

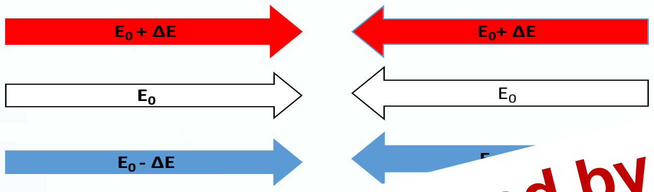
Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.

Monochromatization principle

Standard

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

IP



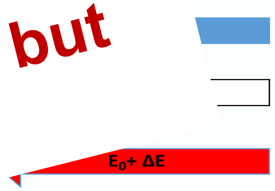
e^+ e^-

$w =$

Monochromatization

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

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



e^-

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

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

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

At **low-energy** e^+e^- colliders, with **flat beam schemes** ($\sigma^*_y <<< \sigma^*_x$) and where the energy spread is meanly due to SR and "beamstrahlung"(**BS**) **is not important**:

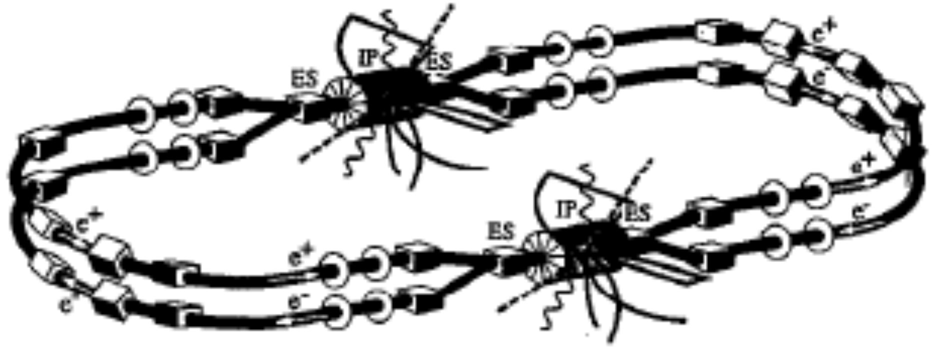
$$\sigma^*_y <<< \sigma^*_x \quad \text{with} \begin{cases} \beta^*_y <<< \beta^*_x \\ \varepsilon^*_y <<< \varepsilon^*_x \end{cases} \Rightarrow \begin{matrix} D^*_{x+} = D^*_{x-} = 0 \\ D^*_{y+} = -D^*_{y-} = D^*_y \end{matrix} \Rightarrow \begin{matrix} \xi_x = \xi_{max} \\ \text{with low } \varepsilon^*_x \end{matrix} \qquad L \simeq \frac{I\gamma}{2er_e}\frac{\xi_x}{\beta^*_x}$$

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

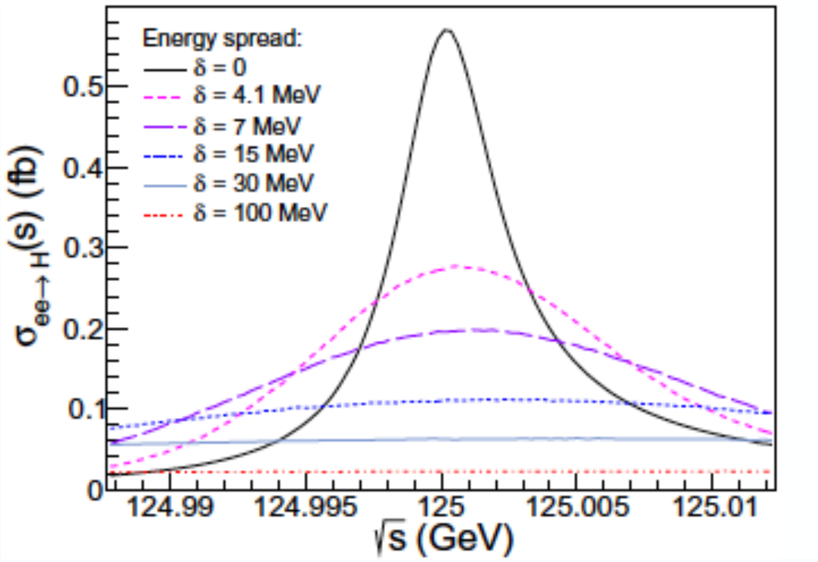
Monocromatization Design Studies for low-energy e+e- colliders:

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

τ–charm factory with monocromatization scheme



Monochromatization in FCC-ee



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

In comparison to the **previous monocromatization 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 ($\mathbf{D_x^*}$). Wide σ_x^* **reduce** the **BS** while preserve small σ_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

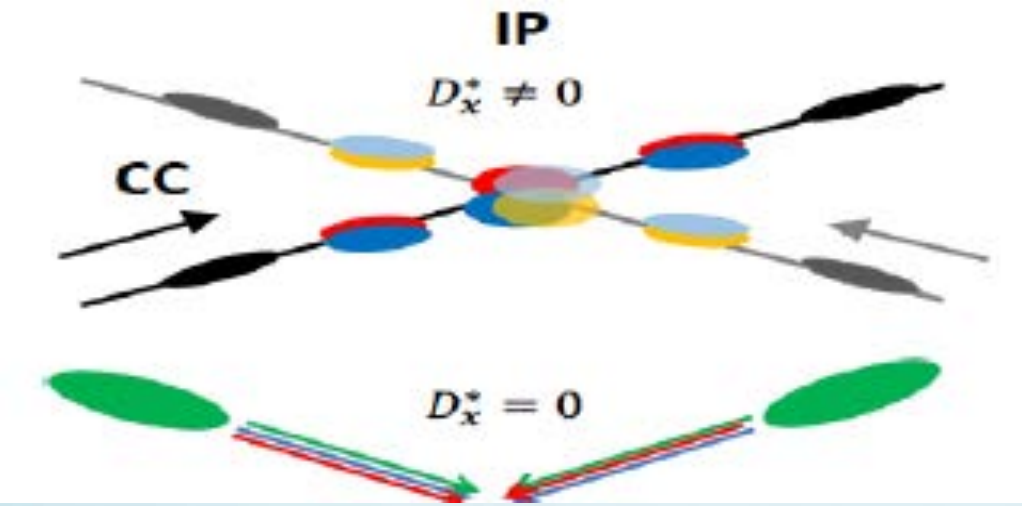
In the previous case for low-energy e^+e^- colliders, in λ definition, we may take σ_δ to mean the energy spread without collision so that $\boldsymbol{\sigma_\delta = \sigma_{\delta,SR}}$, where $\sigma_{\delta,SR}$ denotes the natural relative momentum spread due to SR in the collider arcs. Alternatively 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 $\boldsymbol{\sigma_{\delta,coll}}$ 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 $\boldsymbol{\lambda_{eff}}$, that compares the true **collision energy spread without and with monochromatization** (mc):

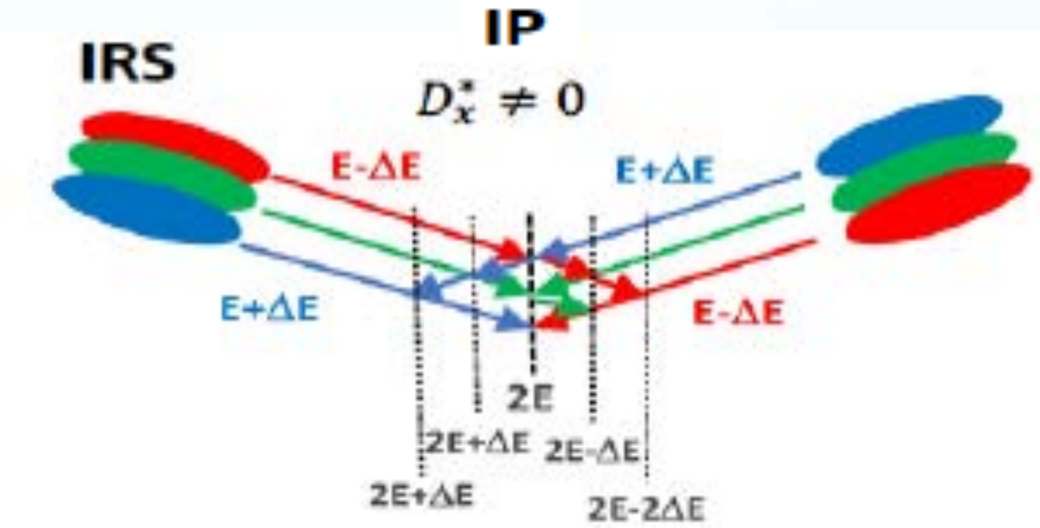
$$\lambda_{eff} = \frac{\sigma_{w,D^*=0}}{\sigma_{w,mc}} = \frac{\sigma_{\delta,coll}}{\sigma_{\delta,SR}} \left(\frac{D_x^{*2}\sigma_{\delta,SR}^2}{\epsilon_x \beta_x^*} + 1 \right)^{1/2}$$

In FCC-ee, λ_{eff} is more than two times larger than λ.

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**).



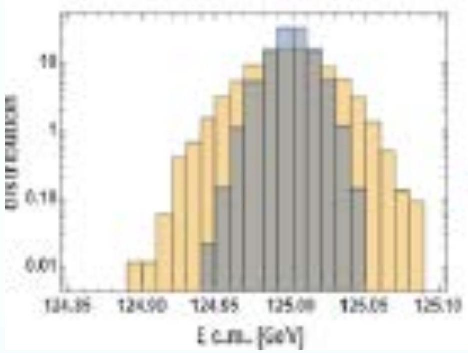


Monocromatization in FCC-ee

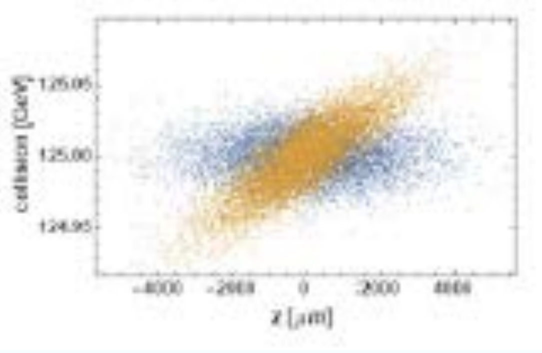
Example **IP parameters and performance** for typical **monochromatization scenario** for **FCC-ee**

Parameter		Units
CM Energy, W	125	[GeV]
Horizontal, vertical RMS emittances with (without) beamstrahlung, ε_{xy}	2.5 (0.51), 0.002	[nm]
Relative RMS momentum deviation, σ_δ	0.052	%
RMS bunch length, σ_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, σ^*_{xy}	55, 0.045	[µm]
Full crossing angle, θ_c	30	[mrad]
Vertical beam-beam tune shift, ξ_y	0.106	
Total beam current, I_e	395	[mA]
Bunch population, N_b	6.0×10^{10}	
Bunches per beam, n_b	13420	
Luminosity (without crab cavities) per IP, L	$2.6\ (2.3) \times 10^{35}$	$[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
RMS CM energy spread (without crab cavities), σ_W	13(25)	[MeV]

Monochromatization beam-beam simulations



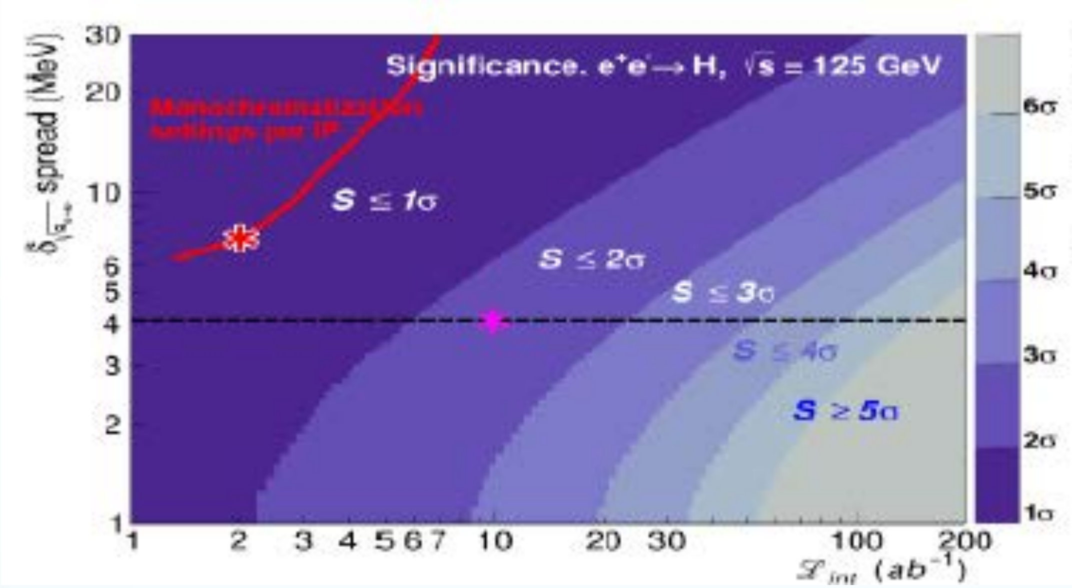
CM distribution with and without crab cavities



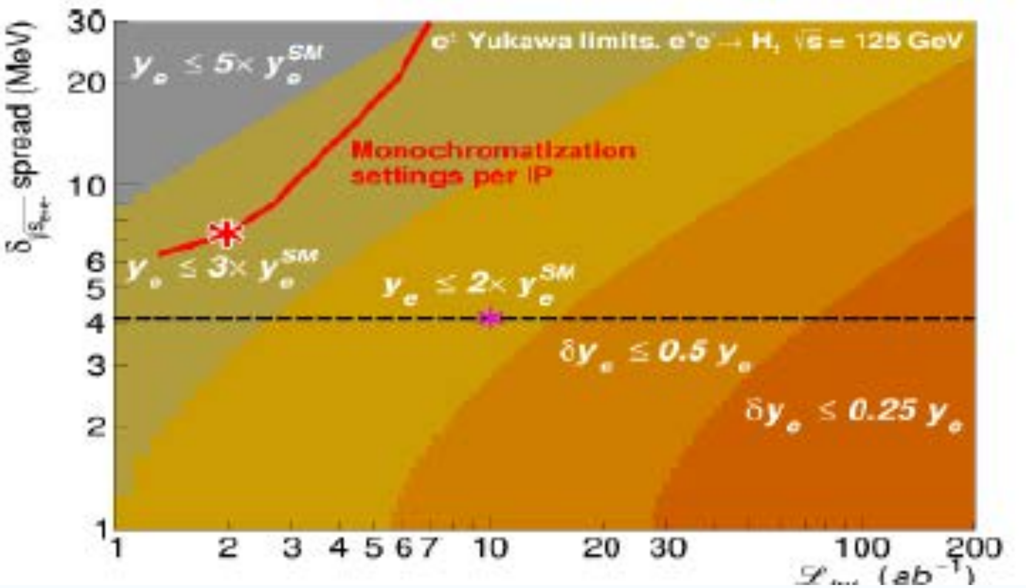
Correlation between collision energy and longitudinal position

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



Significance contours (in std. dev. units σ) in the CM energy spread vs. integrated luminosity plane for the resonant $\sigma_{e+e^-\to H}$ cross section at s = mH.



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

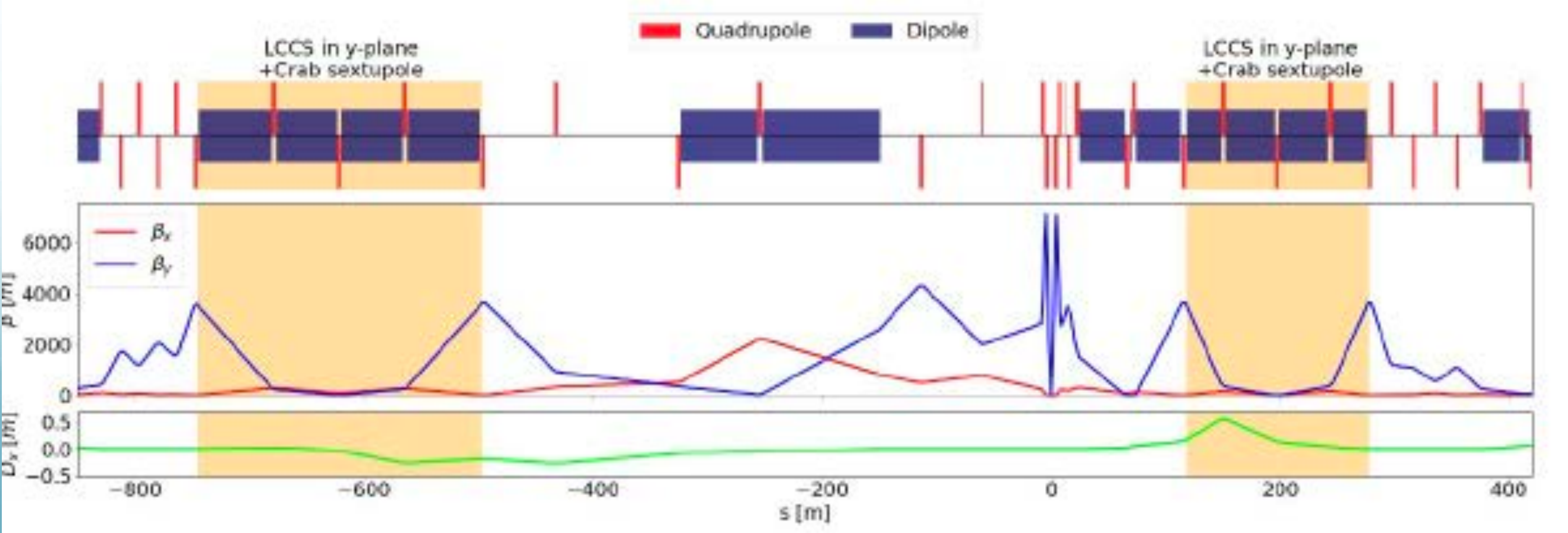
The red curves show the range of parameters presently reached in FCC-ee monochromatization studies. The red star indicates the best signal strength monochromatization point in the plane (the pink star over the $\delta\sqrt{s} = \Gamma H = 4.2$ MeV dashed line, indicates the ideal baseline point assumed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

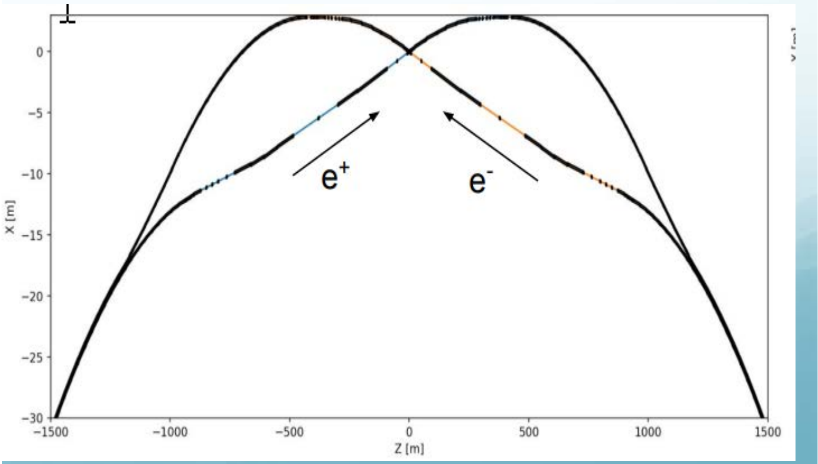
Monochromatization implementation in FCC-ee

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**.

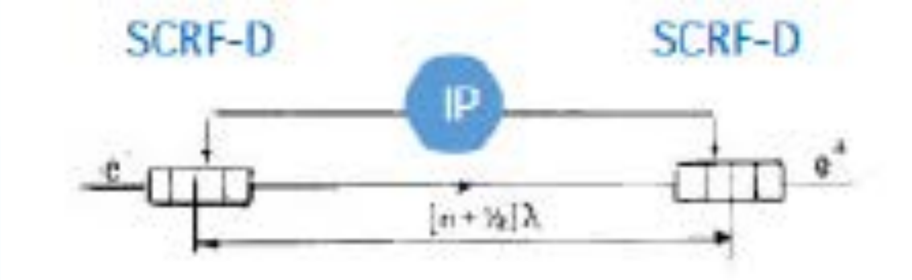
Different schemes are possible:

- 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.



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

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

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

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

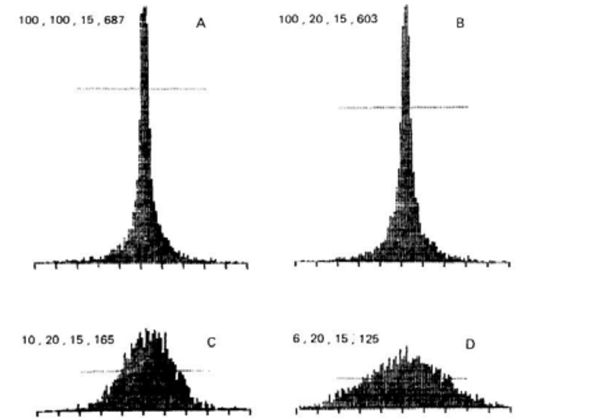


Fig. 5. Histograms of the luminosity distribution in the total energy of electron and positron collisions. The step of the histograms is 0.01 σ_1, where $\sigma_1 = \sqrt{2}\,\sigma_{\Delta E/E}$ and there are 10 steps between two graduation lines. The parameters of the rf-monochromatization scheme, used in the numerical simulation, are given on each plot in the following order: κ_0, a_x/σ_{xs}, λ/σ_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.

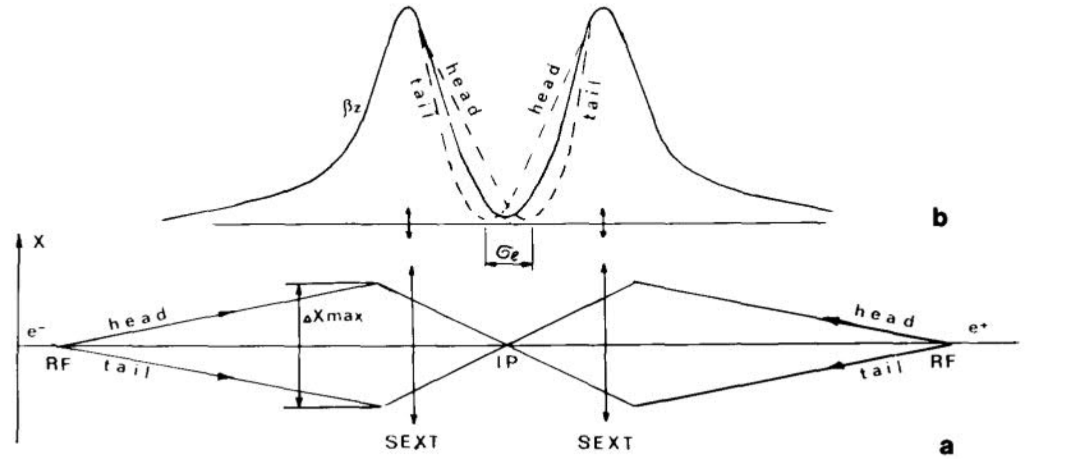
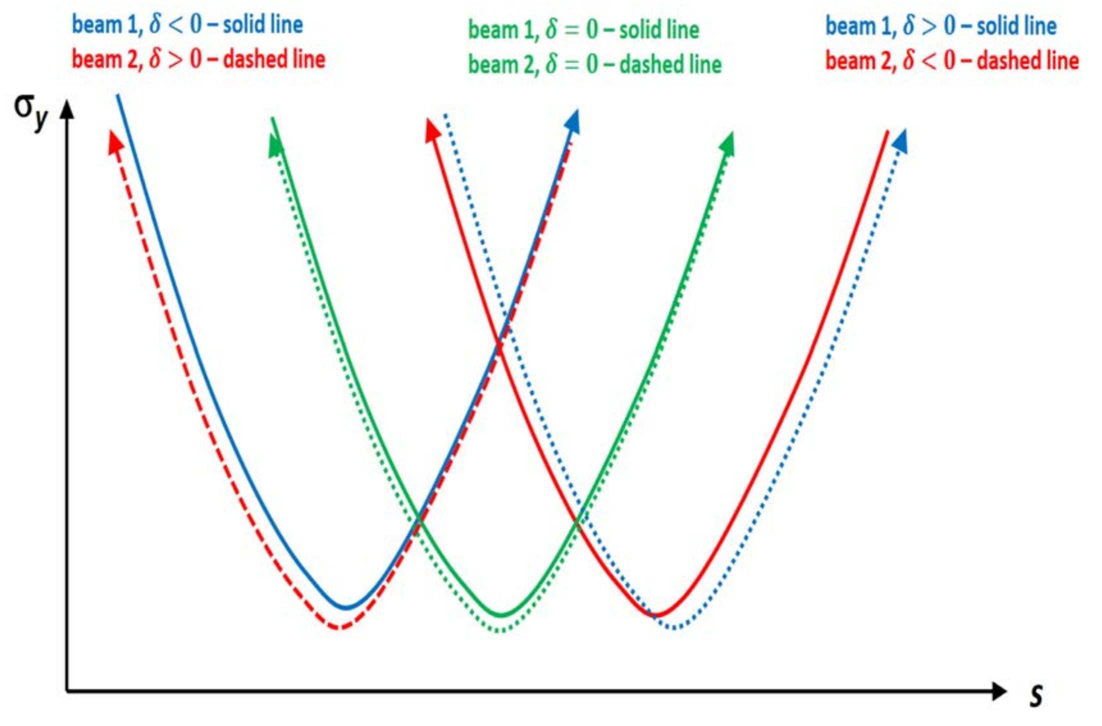


Fig. 6. a) The trajectories of the head and the tail of the bunch in the region between AS. b) The behaviour of β_z-function.

A. Zholents, NIM A 265 (1988) 179

➢ 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 β_y^*, but limited λ 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, private communication.

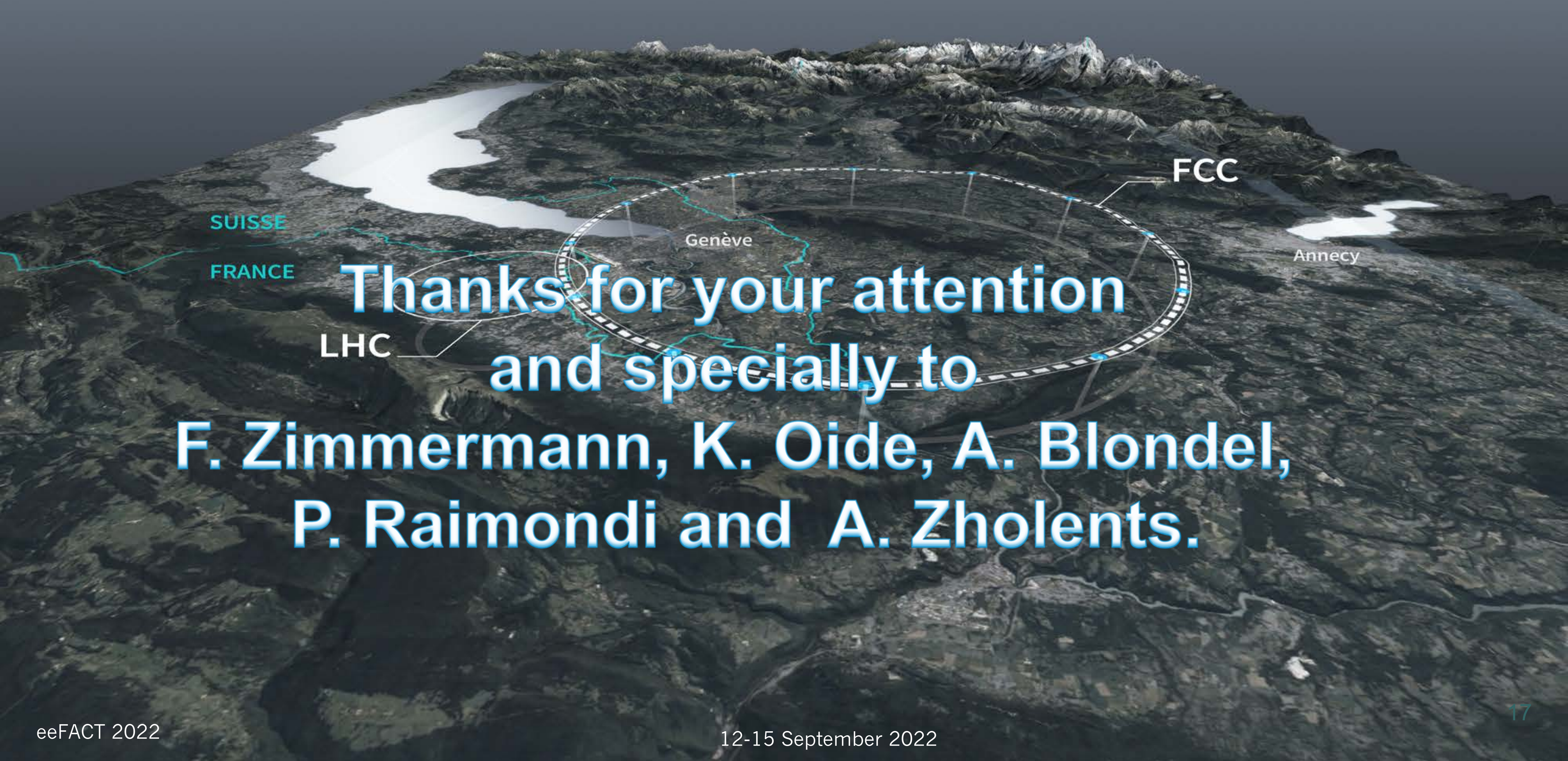
Summary and perspectives

- 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 monochomatization has never been tested experimentally, a flexible lattice with two modes of operation with/without monocromatization is advisable.
- Monocromatization 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 beamstrahlung and SR issues.
- Feasibility study of crab cavities for monochromatization.
- Alternative modes of monochromatization and combinations.
- .....



Thanks for your attention and specially to

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