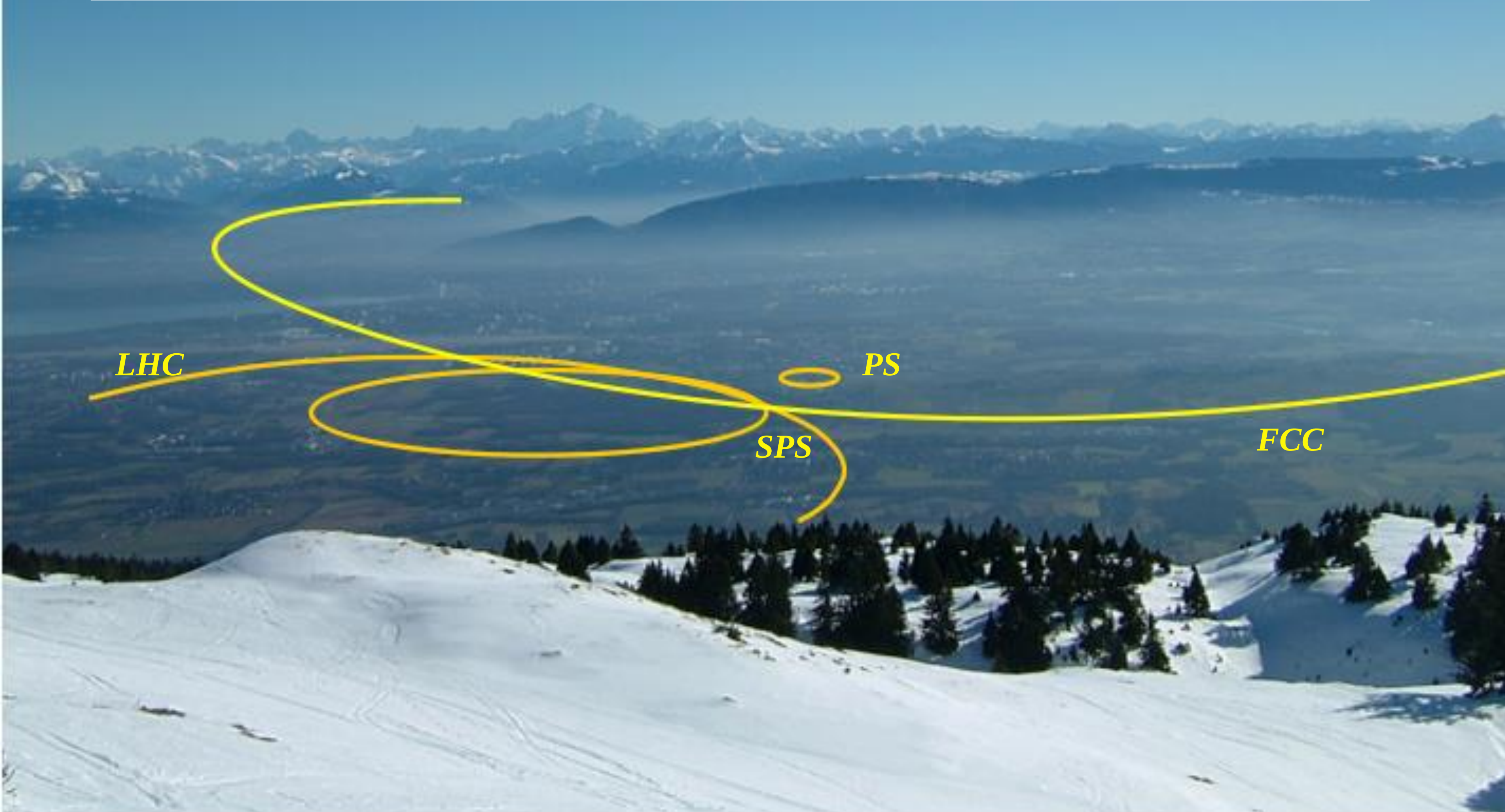
FCC-ee

A Study for the next Generation High Energy e+/- Collider

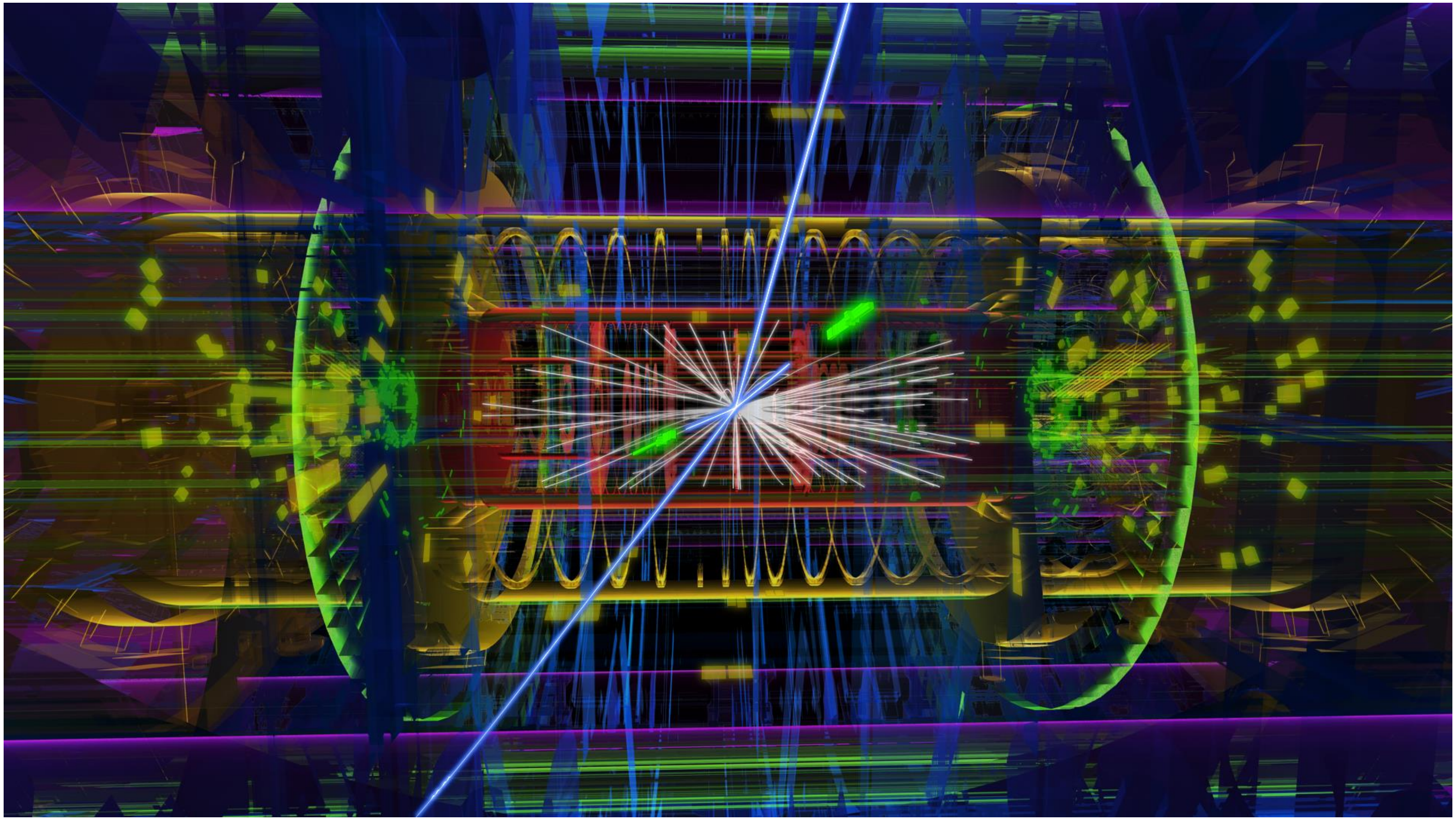
Bernhard Holzer for the FCC-ee study group



FCC-ee:

A Study for the next Generation High Energy e+/- Collider

High Light of the HEP-Year 2013



ATLAS event display: Higgs => two electrons & two muons

Future Projects

Recommendations from European Strategy Group

#1 c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide*

#2 d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

→*Proton –Proton Colliders* **=> *e+/e- colliders***

LHC / HL-LHC, FCC-pp ***CLIC / FCC-ee***

FCC-ee: e+ / e- Ring Collider
The „global“ view

	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	16700	4490	1360	98
Bunch population [10^{11}]	1.8	0.7	0.46	1.4
Transverse emittance e -Horizontal [nm] -Vertical [pm]	 29.2 60	 3.3 7	 0.94 1.9	 2 2
Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP -Horizontal [m] -Vertical [mm]	 0.5 1	 0.5 1	 0.5 1	 1 1
Beam size at IP s* [mm] -Horizontal -Vertical	 121 0.25	 26 0.13	 22 0.044	 45 0.045
Bunch length [mm] -Synchr. radiation -Total	 1.64 2.56	 1.01 1.49	 0.81 1.17	 1.16 1.49
Energy loss/turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

design & optimise a lattice
for 4 different energies

Interaction Region layout
for a large number of bunches
Δs = 6m (LHC = 7.5m)

small hor. emittance
increasing with reduced energy
$\varepsilon_y / \varepsilon_x = 10^{-3}$

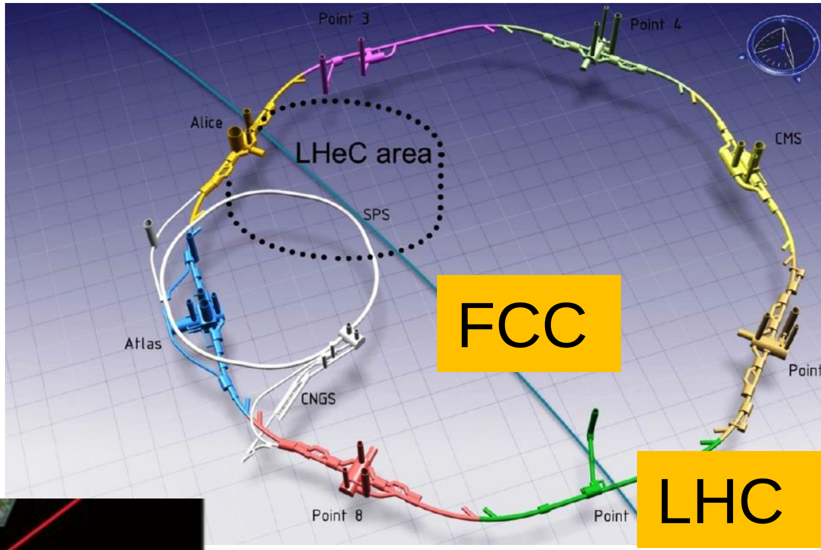
extremely small vert. beta
β_y=1mm
→ *high chromaticity*
→ *challenging dynamic aperture*

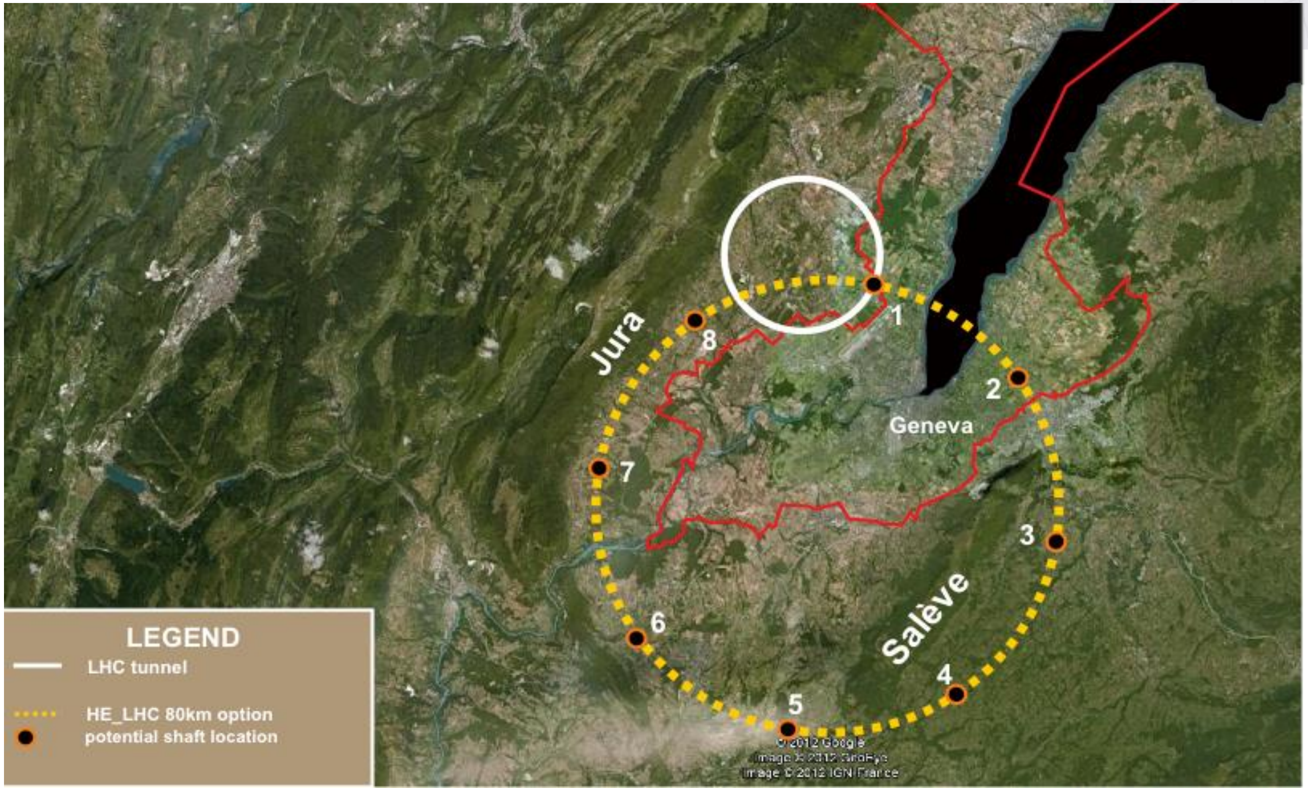
high synchrotron radiation losses
include sophisticated
absorber design in the lattice

FCC-ee: e+ / e- Ring Collider
The „global“ view

Geometric / Geologic Layout considerations

- Detector cavern requirements,
- dump caverns, shielding requirements
- Where & how to dig the tiny tunnel
- E.g. shaft locations





FCC-ee: The tunnel

Rock properties in Geneva Region

Moraines

Glacial deposits comprising gravel, sands silt and clay

Water bearing units

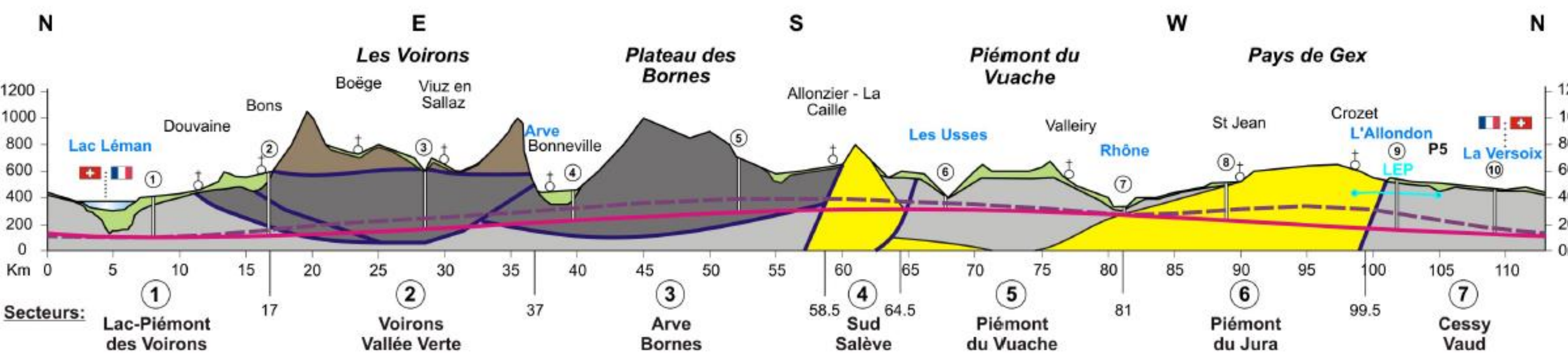
Molasse

Mixture of marls, sandstones, intermediate composition

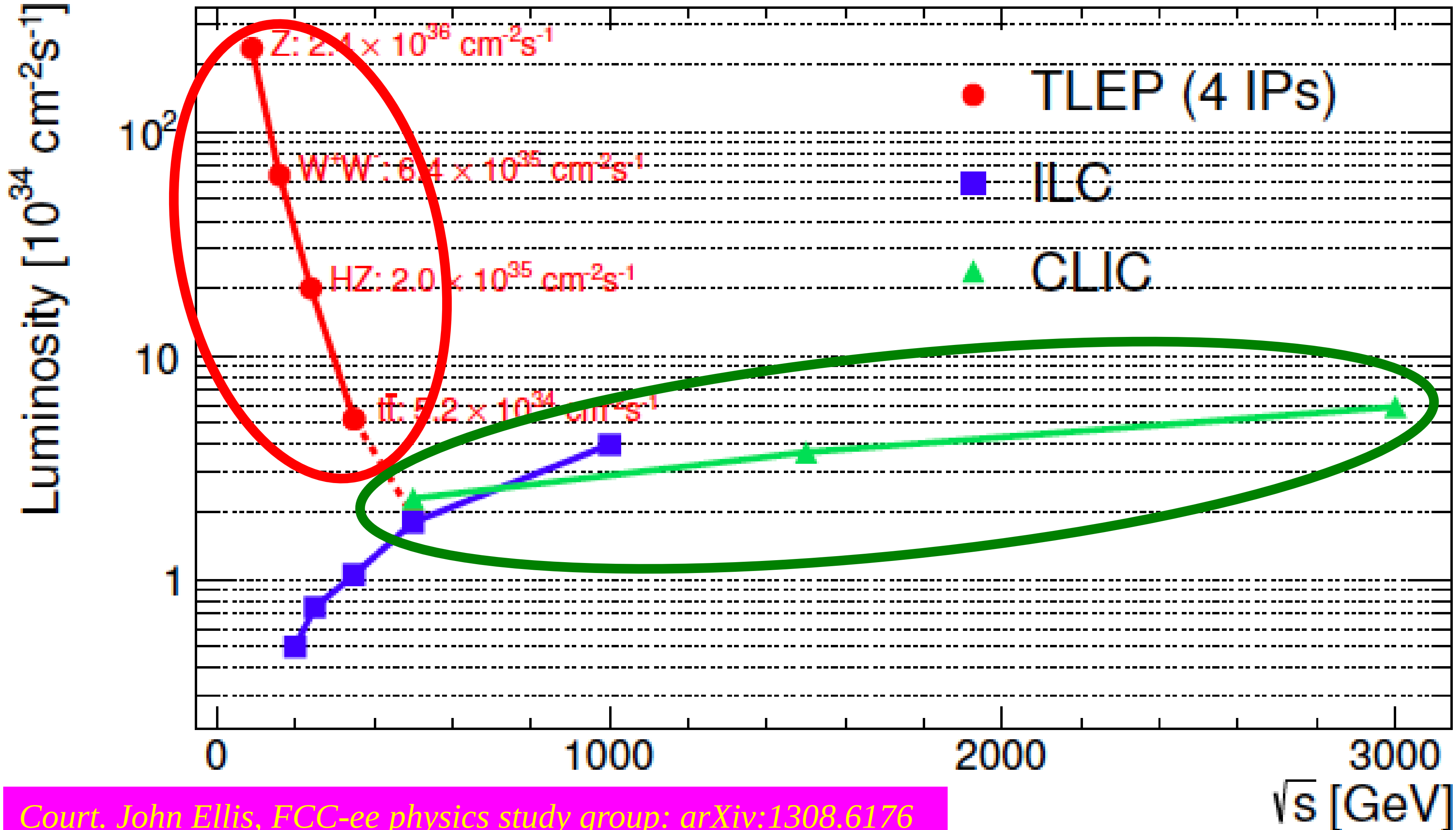
Considered good excavation rock:

Contains layers are zones of weakness, Faulting and fissures

Limestone, etc



The Physics Motivation
Luminosity vs Energy

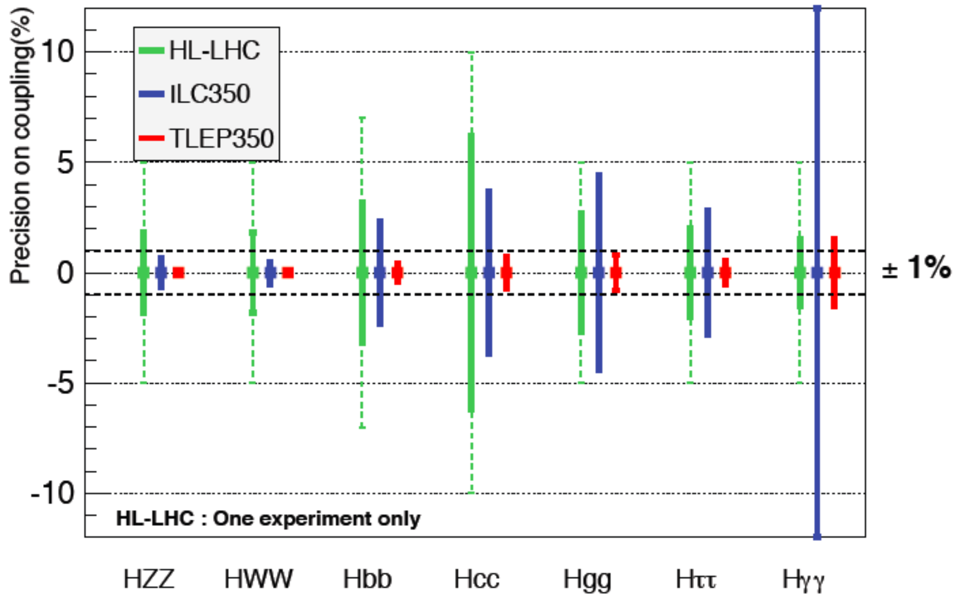


Court. John Ellis, FCC-ee physics study group: arXiv:1308.6176

What Next: A Higgs Factory?

To study the 'Higgs' in detail:

- The LHC
  - Consider LHC upgrades in this perspective
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV



- **A circular e^+e^- collider?**

Wait for results from LHC @ 13/14 TeV

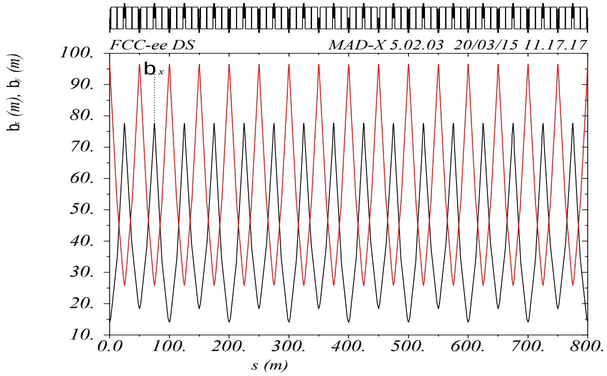
Court. J. Ellis

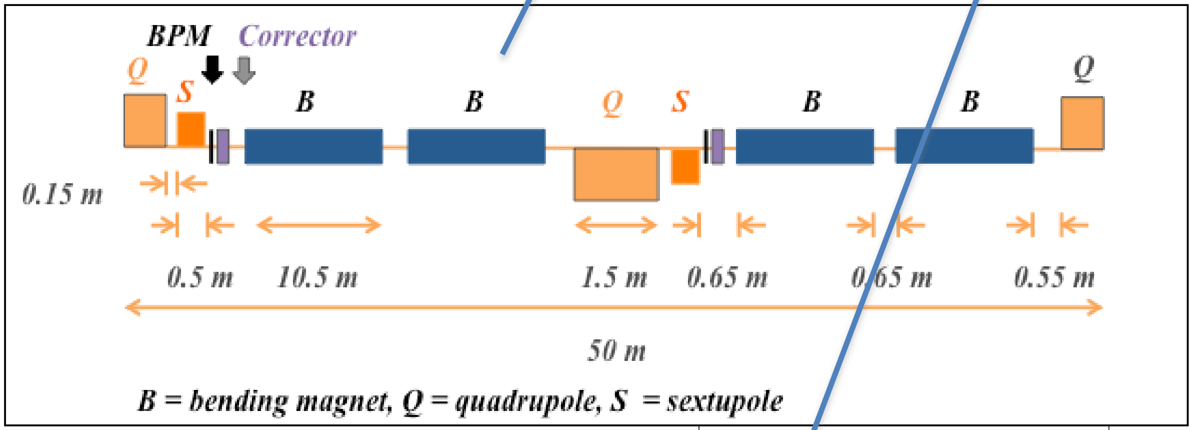
FCC-ee: The Storage Ring

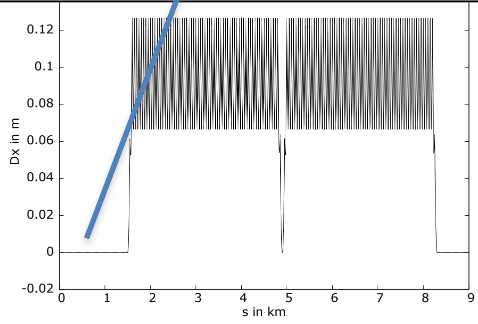
Optics & Cell design in the arcs determine the emittance

$$\varepsilon = \left(\frac{\varphi}{\pi}\right)^2 \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right)$$

$$\hat{D} = \frac{L_{cell}^2}{\rho} \times \left(1 + \frac{1}{2}\sin\left(\frac{\psi_{cell}}{2}\right)\right) \Big/ \sin^2\left(\frac{\psi_{cell}}{2}\right)$$







Basic Cell: $90^0/60^0$ (at present), l=50m
Half Bend dispersion suppressors at 12 (?) straight sections
-> RF, Injection, Extraction, Collimation, Detectors
see Bastian Haerer

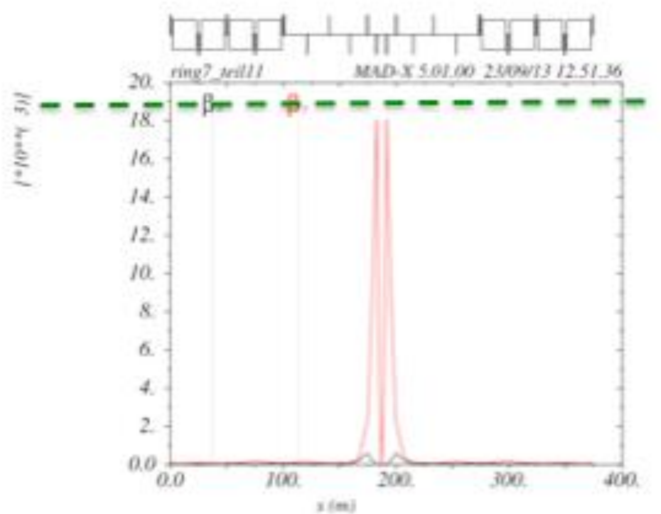
FCC-ee: The Mini-Betas & Chromatic Properties

4 Mini-beta-Insertions :
based on standard doublet structure
matching section / DS

$L^* = 2m)$

$\beta^*_x = 1m, \beta^*_y = 1mm$

$\beta_{max} = 10\ km$



Natural (i.e. uncorrected) Chromaticity

	no IRs	4 IRs	ΔQ (1.5 %)
Q_x	498.85	502.16	
Q_x'	-554.93	-603.80	-9.06
Q_x''	1587.57	-8258.29	-0.93
Q_x'''	-8071.77	-1.4e+08	-79.31
Q_x''''	-3.27e+09	-2.1e+12	-4.43e+03
Q_y	331.24	334.28	
Q_y'	-458.98	-2044.43	-30.67
Q_y''	1086.30	-8.4e+06	-944.12
Q_y'''	-4547.47	-2.0e+11	-1.10e+05
Q_y''''	-3.62e+09	-6.5e+15	-1.37e+07

Required Momentum Acceptance (beam srahlung) $\delta = \Delta p/p \approx \pm 2\%$

$$Q(\delta) = Q_0 + Q'\delta + Q''\delta^2/2 + \ldots$$

→ correction of Chromaticity up to third order required

Court. B. Haerer

Chromaticity

$$j(d) = j_0 + \frac{¶j}{¶d} d + \frac{¶^2 j}{¶j^2} d^2 + \dots$$

The first three orders, as derived by A. Bogomyagkov:

$$\frac{\partial \varphi_y}{\partial \delta} = \frac{1}{2} \int_0^{\Pi} \beta_y (K_1 - K_2 \eta_0) ds \,,$$

$$\frac{\partial^2 \varphi_y}{\partial \delta^2} = -2 \frac{\partial \varphi_y}{\partial \delta} - \int_0^{\Pi} \beta_y K_2 \eta_1 ds + \frac{1}{2} \int_0^{\Pi} \beta_y b_{y,1} (K_1 - K_2 \eta_0) ds \,,$$

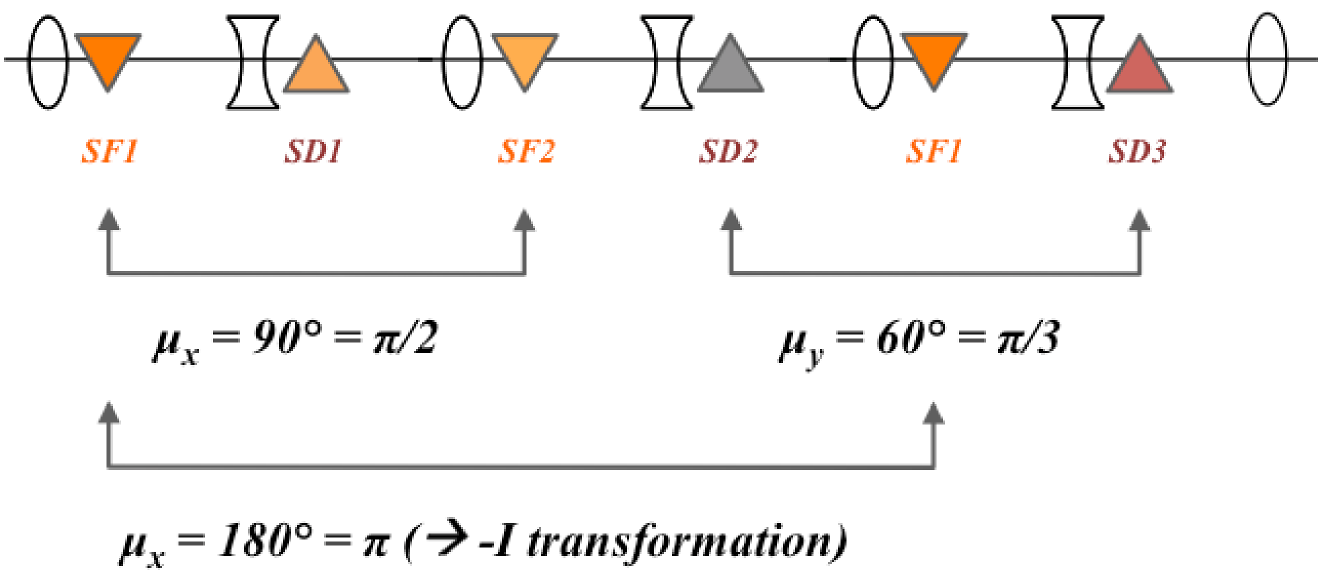
$$\frac{\partial^3 \varphi_y}{\partial \delta^3} = 6 \frac{\partial \varphi_y}{\partial \delta} - \int_0^{\Pi} \beta_y (K_1 - K_2 \eta_0)(a_{y,1}^2 + b_{y,1}^2) ds + $$

$$+ \; 3 \int_0^{\Pi} \beta_y (K_2 \eta_1 - K_2 \eta_2) ds + \frac{3}{2} \int_0^{\Pi} \beta_y b_{y,2} (K_1 - K_2 \eta_0) ds \,.$$

(A. Bogomyagkov: "Crab waist interaction region for FCC-ee and the arc second attempt", presentation in the FCC-ee meeting no. 13, 09 Febuary 2015)

FCC-ee sextupole scheme

Sextupoles grouped in pairs
Phase advance between the couples = π
Multi-Family optimisation



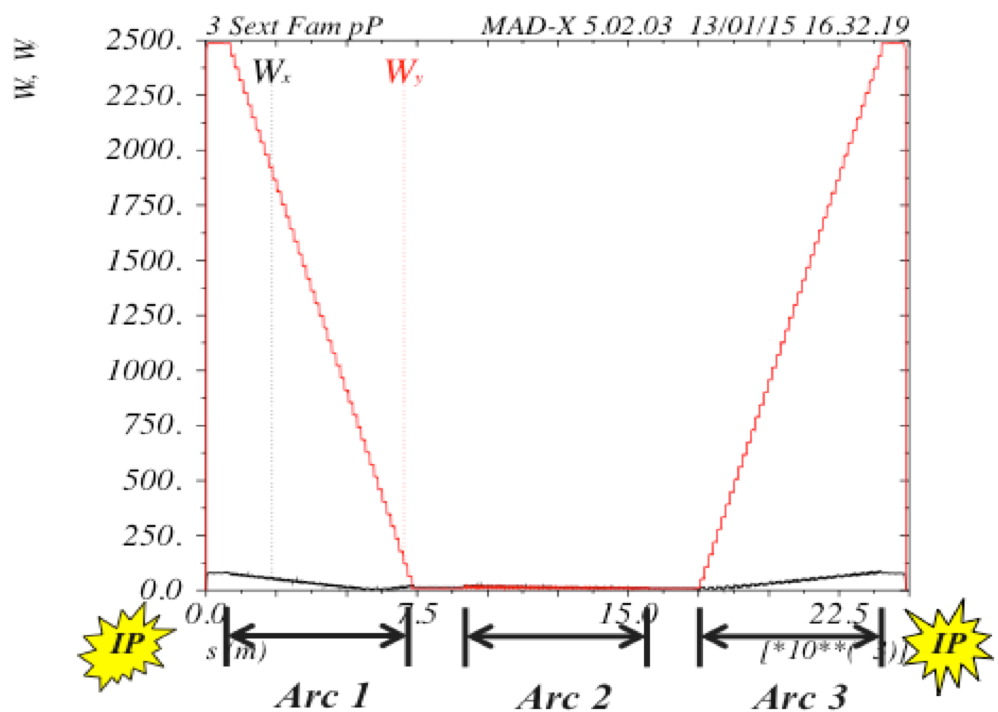
Even number of sextupoles per family!

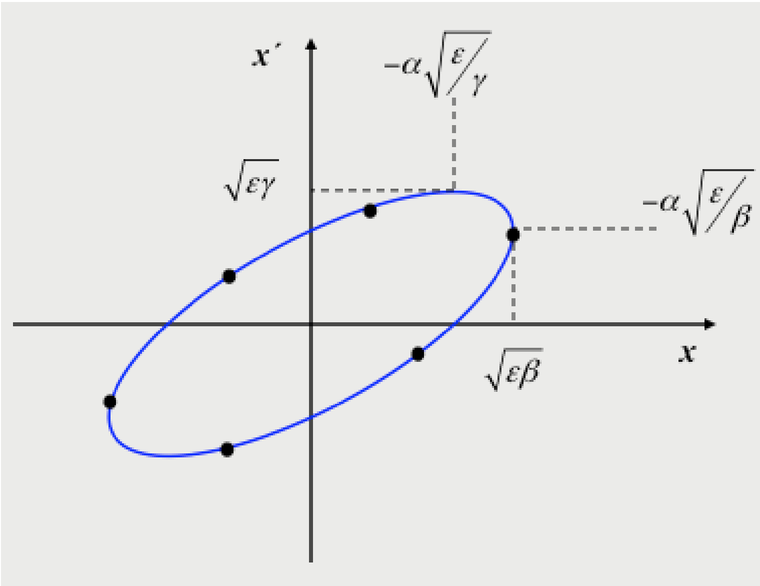
Phd Bastian Haerer

W functions for 1 quarter

Montague Function W describes the detrimental effect of chromaticity to the phase space ellipse

$$B = \frac{1}{\beta}\frac{\partial \beta}{\partial \delta} \qquad A = \frac{\partial \alpha}{\partial \delta} - \frac{\alpha}{\beta}\frac{\partial \beta}{\partial \delta}$$





$$\vec{W} = \frac{1}{2}(B + iA)$$

"Corrected" Chromaticity

	Nat. Chrom.	Corr. Chrom.	ΔQ (+/-5E-4)
Q_x	502.16	502.16	
Q_x'	-603.80	5.7e-05	2.83e-08
Q_x''	-8.3e+03	3.5e+03	4.41e-04
Q_x'''	-1.4e+08	-5.5e+05	-1.14e-05
Q_x''''	-2.1e+12	-8.5e+09	-2.20e-05
Q_y	334.28	334.28	
Q_y'	-2044.43	2.8e-01	1.39e-04
Q_y''	-8.4e+06	-1.2e+04	-1.53e-03
Q_y'''	-2.0e+11	-3.4e+09	-7.00e-02
Q_y''''	-6.5e+15	3.6e+10	9.25e-05

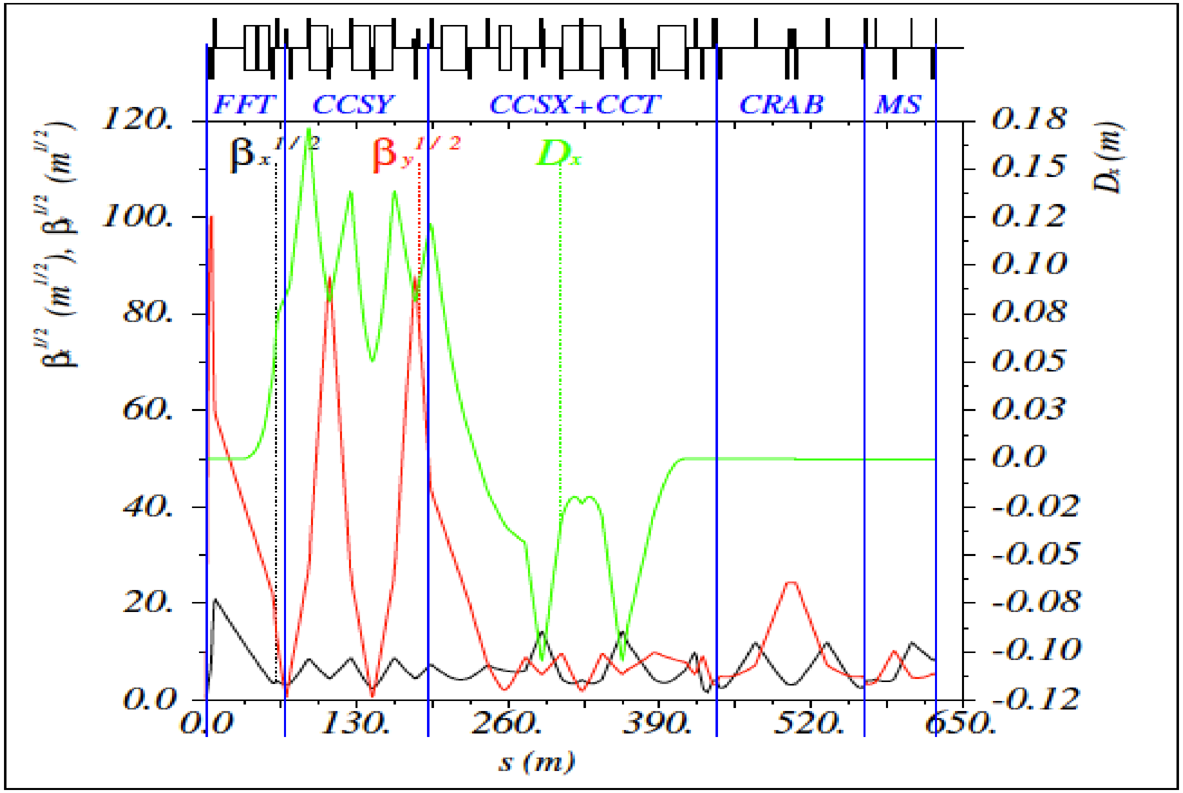
(4 IPs, chromaticity correction with arc sextupoles)

Chromaticity budget too high for a even sophisticated sextupole compensation in the arcs
→ Local Chromaticity compensation needed (ILC/CLIC designs)

The Mini-Beta and local Q' compensation

L=2m*
β^*_x =1m, β^*_y =1mm

Doublet structure combined with local chromaticity compensation scheme
-> create dispersion directly after the IP
-> install sextupoles in order to local suppress the W-function



A. Bogomyagkov et al

Momentum Acceptance

Required momentum acceptance due to beam strahlung:
$\Delta p/p$ = +/- 2%

	no IRs	4 IRs	ΔQ (1.5 %)
Q_x	498.85	502.16	
Q_x'	-554.93	-603.80	-9.06
Q_x''	1587.57	-8258.29	[illegible].93
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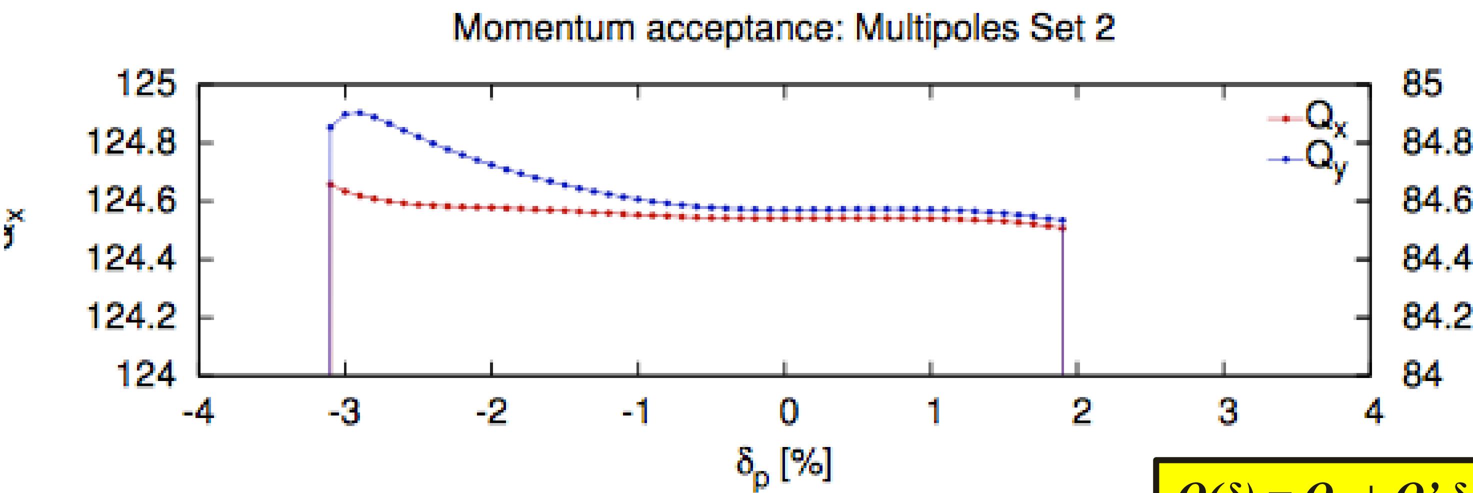
Q_y'''	-4547.47	-2.0e+11	-1.10e+05
Q_y''''	-3.62e+09	-6.5e+15	-1.37e+07

Reminder: uncorrected case

Combining the local chromaticity compensation with the optimised sextupole scheme in the arcs

15 families,
optimisation up to order Q''''



$Q(\delta) = Q_0 + Q'\,\delta + Q''\,\delta^2/2 + \ldots$

WE ARE (NEARLY) THERE !!

The Challenges: Orbit Tolerances & Emittances

required: $\varepsilon_y / \varepsilon_x = 1*10^{-3}$

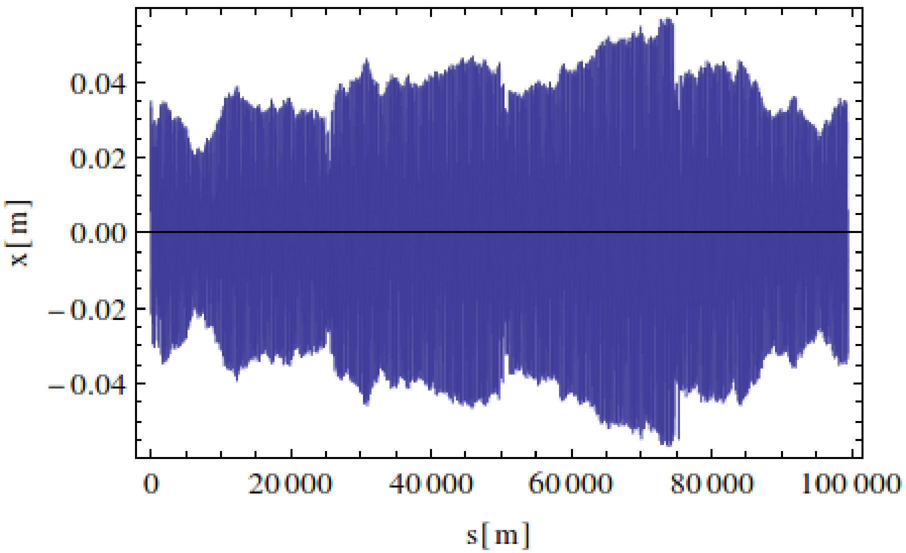
horizontal ... defined by energy, cell length and focusing properties

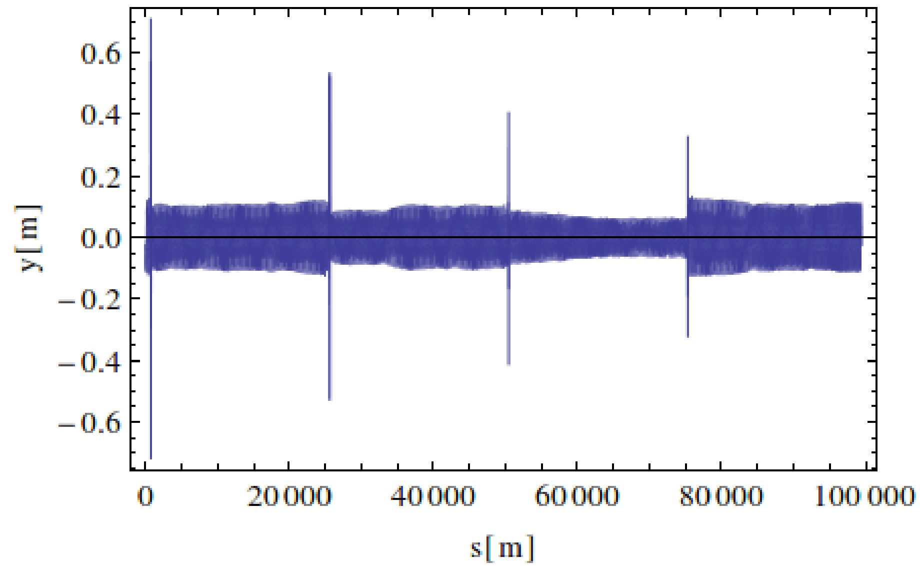
vertical ... defined by orbit tolerances (magnet misalignment & coupling)

assumed magnet alignment tolerance (D. Missiaen) $\Delta x = \Delta y = 150\ \mu m$

Immediate consequence:

This ring needs a Linear Collider like Alignment and stabilisation system





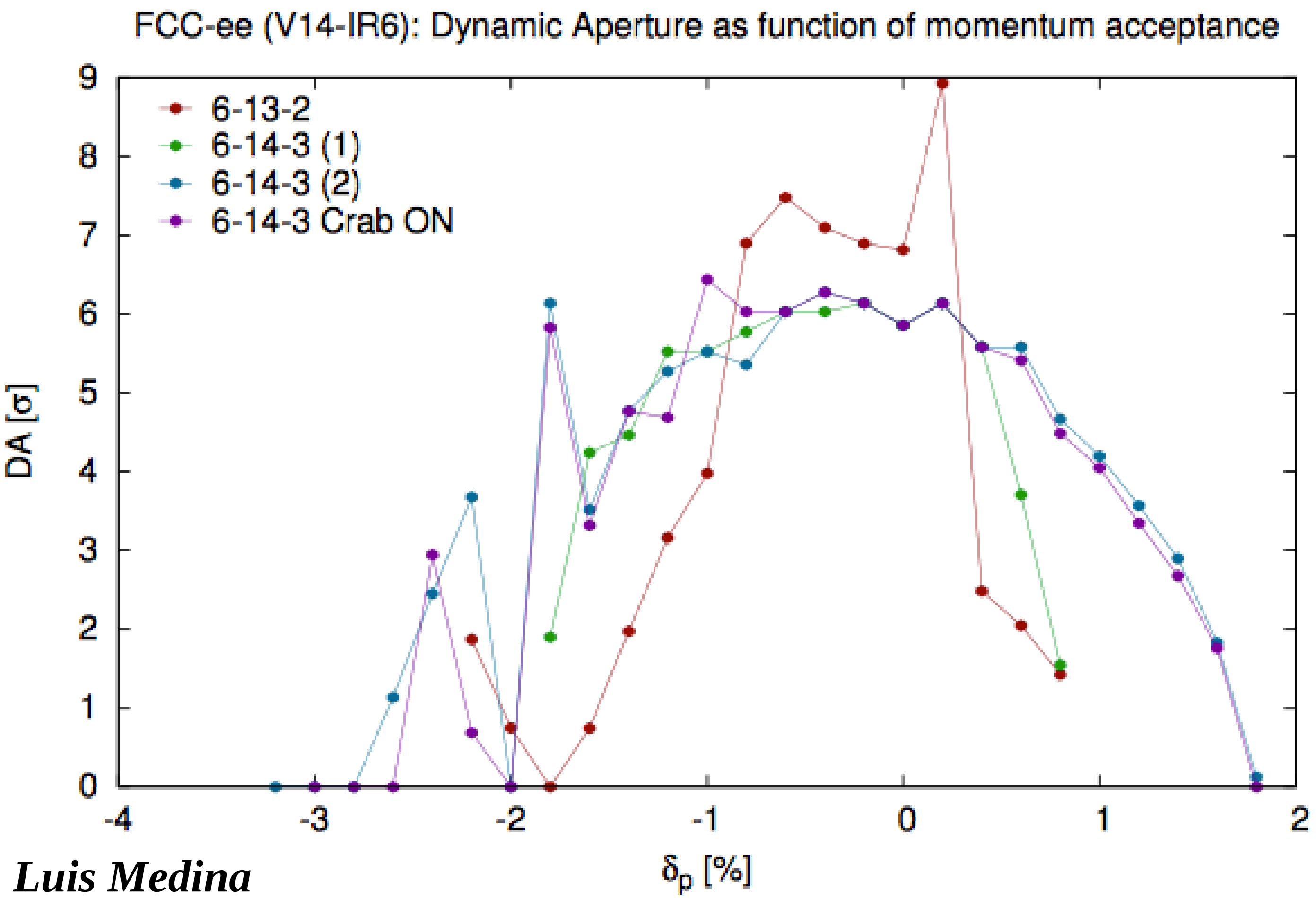
orbit tolerances add up to very large distortions and are amplified by the extreme mini-beta concept

court. Sandra Aumon

The Challenges: Dynamic Aperture

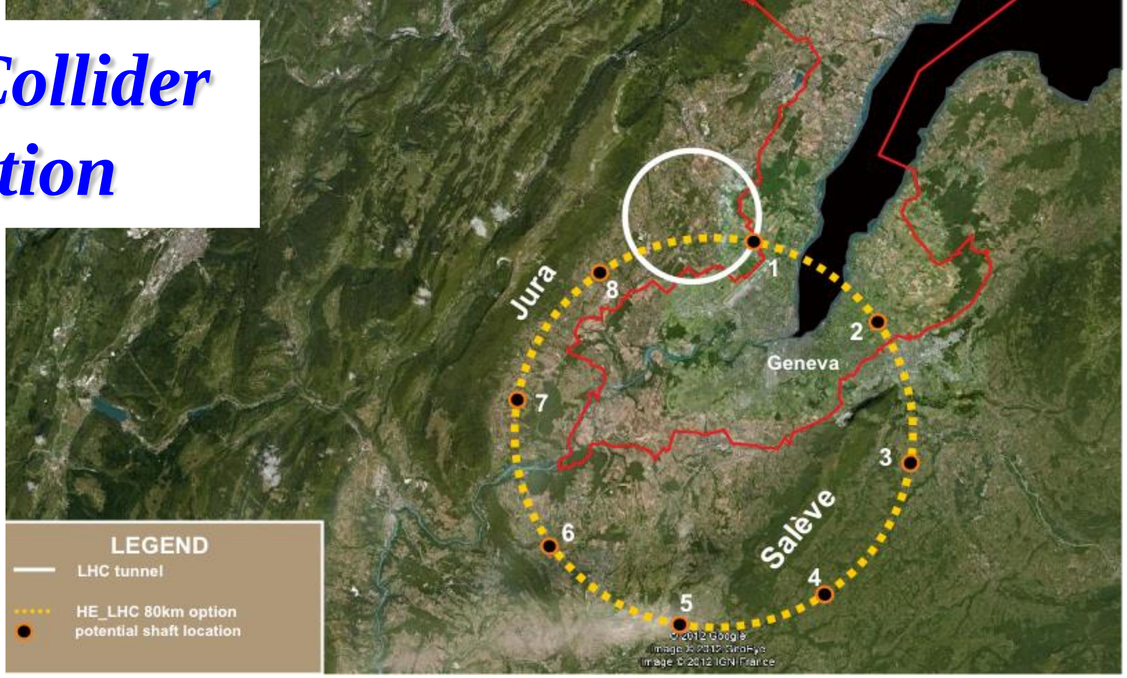
Unprecedented high chromaticity needs strong sextupoles
→ Lead to reduced dynamic aperture

→ Optimisation needed via careful phase adjustment & balance of 6-pole strengths



Court. Luis Medina

FCC-ee: e+ / e- Ring Collider Synchrotron Radiation



Design Parameters FCC-ee

E = 175 GeV / beam
L = 100 km

$$\mathrm{D}U_0(keV) \approx \frac{89 * E^4(GeV)}{r}$$

$$\mathrm{D}U_0 \approx 7.55\, GeV$$

$$\Delta P_{sy} \approx \frac{\Delta U_0}{T_0} * N_p = \frac{10.4 * 10^6 eV * 1.6 * 10^{-19} Cb}{263 * 10^{-6} s} * 9 * 10^{12}$$

$$\Delta P_{sy} \approx 47\ MW$$

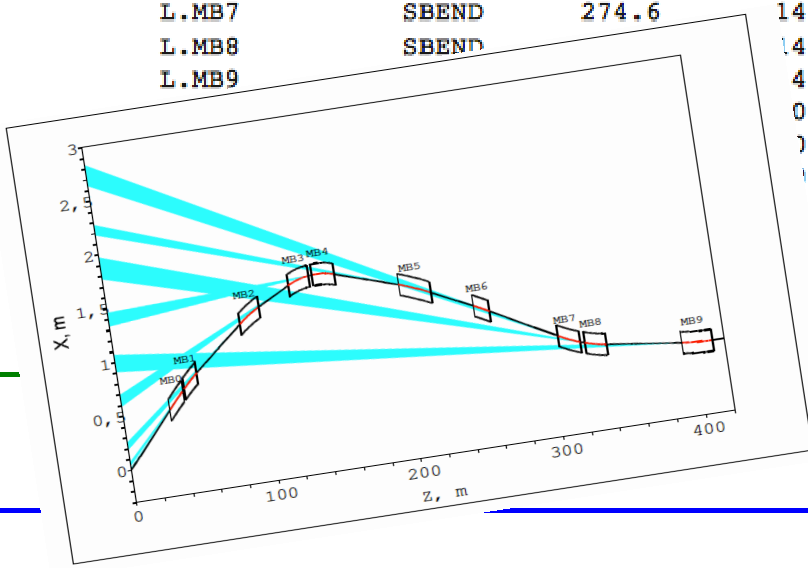
Parameter List is determined by Luminosity needs and synchrotron light losses

The Challenges: Beam Separation & Synchrotron Light

MDISIM output, bends

iele	NAME	KEYWORD	S	L	Angle	Emean	ngamBend	rho	B	BE
			m	m		keV		m	T	
13	L.MB0	SBEND	22.56	10.5	0.001	348.64	3.6071	1.05e+04	0.055594	
15	L.MB1	SBEND	33.66	10.5	0.0037	1290.	13.346	2.84e+03	0.205698	1
39	L.MB2	SBEND	73.68	10.5	0.0037674	1313.5	13.59	2.79e+03	0.209446	7
59	L.MB3	SBEND	107.2	14.5	0.0051804	1307.9	18.686	2.8e+03	0.208551	2
65	L.MB4	SBEND	123.5	14.5	0.0051804	1307.9	18.686	2.8e+03	0.208551	1
91	L.MB5	SBEND	179.7	14.5	0.00063536	160.41	[illegible]	2.28e+04	0.025578	6
105	L.MB6	SBEND	221.5	14.5	0.0002393	60.415	[illegible]	[illegible]06e+04	0.00963366	8
129	L.MB7	SBEND	274.6	14.5	-0.0031537	796.19	[illegible]	[illegible]	-0.126959	8
135	L.MB8	SBEND	[illegible]	14.5	-0.0031537	796.19	[illegible]	[illegible]	[illegible]959	2
161	L.MB9	[illegible]	[illegible]	4.5	-0.0028026	707.57	10.10[illegible]	[illegible]	[illegible]	1
235	[illegible]	[illegible]	[illegible]	0.5	0.0011018	384.13	3.9743	9.5[illegible]	[illegible]	1
241	[illegible]	[illegible]	[illegible]	.5	0.0011018	384.13	3.9743	9.53e+03	[illegible]	2
247	[illegible]	[illegible]	[illegible]	.5	0.0011018	384.13	3.9743	9.53e+03	0.06125[illegible]	7
253	[illegible]	[illegible]	[illegible]	.5	0.0011018	384.13	3.9743	9.53e+03	0.0612522	8
273	[illegible]	[illegible]	[illegible]	.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	3
275	[illegible]	[illegible]	[illegible]	5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	1
282	[illegible]	[illegible]	[illegible]	5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	3
284	[illegible]	[illegible]	[illegible]	5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	7

The local Q' control is based on strong dipoles close to the IP.



Quads, at 1 sigmax, horizontal

iele	Element	s	betx	sigx	divx	K1L	k0	L	x	Angle	Emean
		m	m	mm	mrad	m-2	m-1	m	mm		keV
5	L.MQ0_1	3.8	41.5	0.2709	0.006531	-0.29142	7.8947e-05	1.8	8.6833e-32	0.000142104	289.004
7	L.MQ0_2	5.6	183	0.5684	0.003113	-0.29142	0.00016565	1.8	1.7717e-31	0.000298166	606.395
9	L.MQ1_1	7	393	0.8338	0.002122	0.15977	0.00013321	1	2.5822e-31	0.000133211	487.651
11	L.MQ1_2	8	433	0.8752	0.002022	0.15977	0.00013984	1	2.7024e-31	0.000139835	511.902
17	L.MQ2_1	35.7	7.16	0.1126	0.01571	-0.06095	6.8626e-06	1	5.8903e-20	6.86259e-06	25.1222
19	L.MQ2_2	36.7	5.8	0.1013	0.01747	-0.06095	6.1735e-06	1	7.0102e-20	6.17354e-06	22.5998

Conclusion

FCC-ee is an extremly challenging Storage Ring

flexible layttice needed

to be optimised for (at least) four flat top energies

running at the radiation loss limit

pushing for highest possible luminosity

and accordingly highest chromaticity

combination required between sophisticated storage ring design and linear collider concepts.