Possible ML applications for the FCC

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ARIES – iFAST BWS2022, Valencia

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FCC hh ee he · EuroCirCol A key to New Physics · EASITrain · ARIES · FUTURE CIRCULAR COLLIDER Innovation Study · E-JADE

http://cern.ch/fcc

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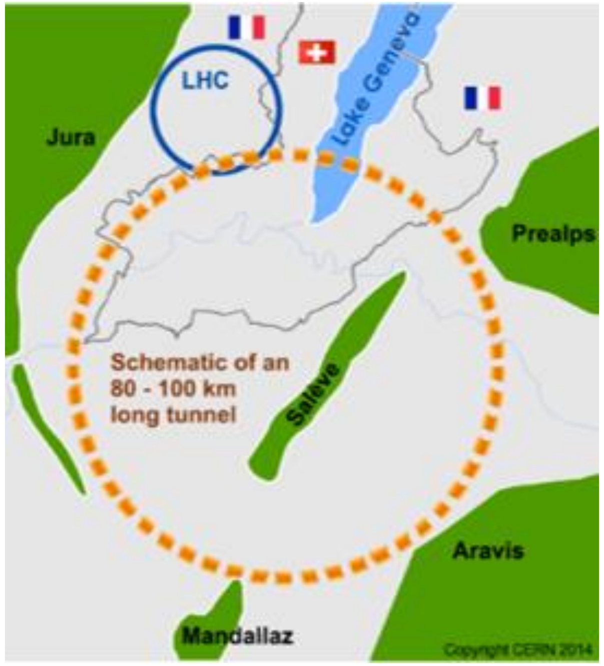
photo: J. Wenninger

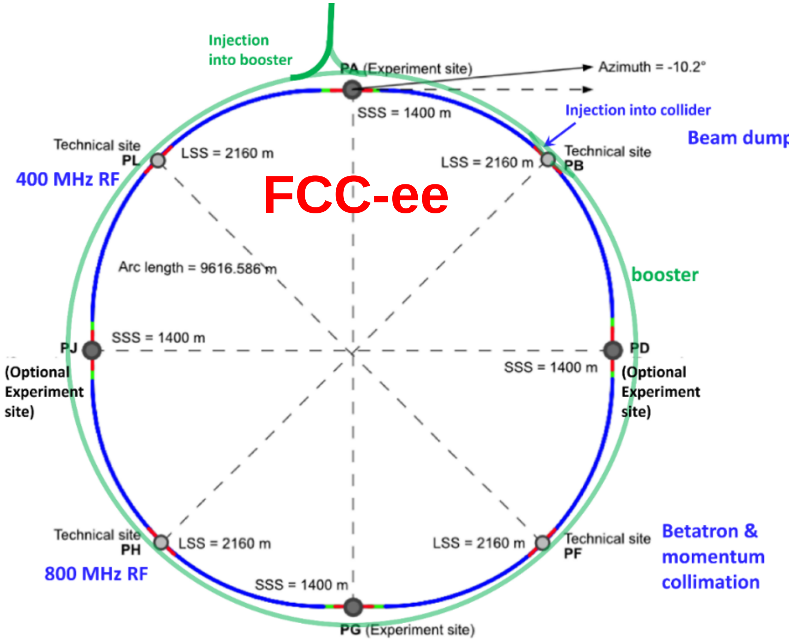
What is FCC?

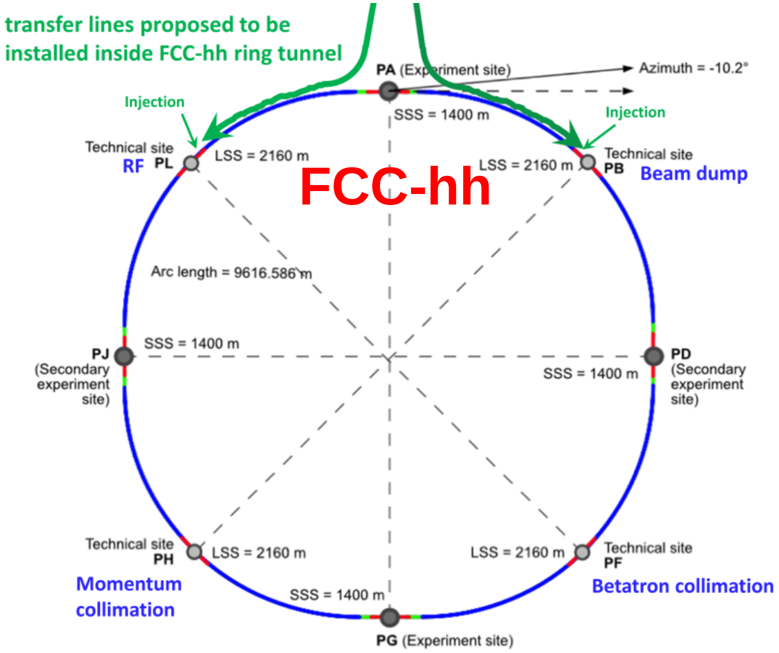
The FCC integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program







2020 - 2040 | **2045 - 2060** | **2065 - 2090**

FCC-ee in a nutshell

- **High luminosity precision study of Z, W, H, and $t\bar{t}$**
  - 2×10^{36} cm^{-2}s^{-1}/IP at Z, 7×10^{34} cm^{-2}s^{-1} at ZH (1.3×10^{34} cm^{-2}s^{-1} at $t\bar{t}$)
  - Unprecedented energy resolution at Z of <100 keV
- **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors
  - R&D on components for improved performance, but no need for "demonstration" facilities
- Infrastructure will support a **century of physics**
  - FCC-ee → FCC-hh → FCC-eh or other options
- **Utility requirements** similar to CERN existing use
- **Strong support** from CERN, partners, and ESPP
- **Detailed design study focused on siting** for 2026 ESPP

FUTURE CIRCULAR COLLIDER

FCC-ee figures of merit – cost & sustainability

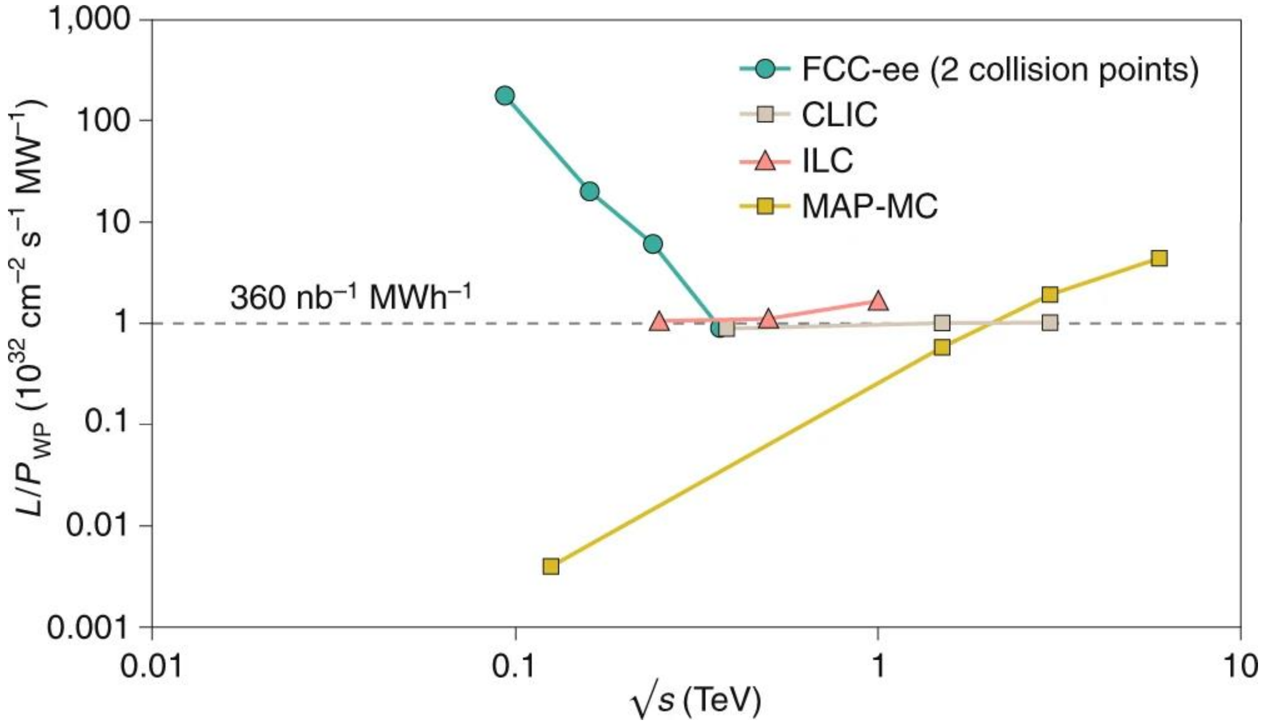
Luminosity vs. capital cost

- for the H running, **with 5 ab^{-1} accumulated over 3 years and 10^6 H produced**, the total investment cost (~10 BCHF) corresponds to
  → **10 kCHF per produced Higgs boson**
- for the Z running with **150 ab^{-1} accumulated over 4 years and $5x10^{12}$ Z produced** (two IPs), the total investment cost corresponds to → **10 kCHF per $5×10^6$ Z bosons** , almost 2x better still with four IPs

This is the number of Z bosons collected by each experiment during the entire LEP programme !

Capital cost per luminosity dramatically decreased compared with LEP !

Luminosity vs. electric power consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

Highest lumi/power of all proposals
Electricity cost ~200 CHF per Higgs boson

M. Benedikt, A. Blondel, P. Janot, et al., **Nature Physics 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

FCC stage 1: infrastructure and FCC-ee project cost estimate and spending profile

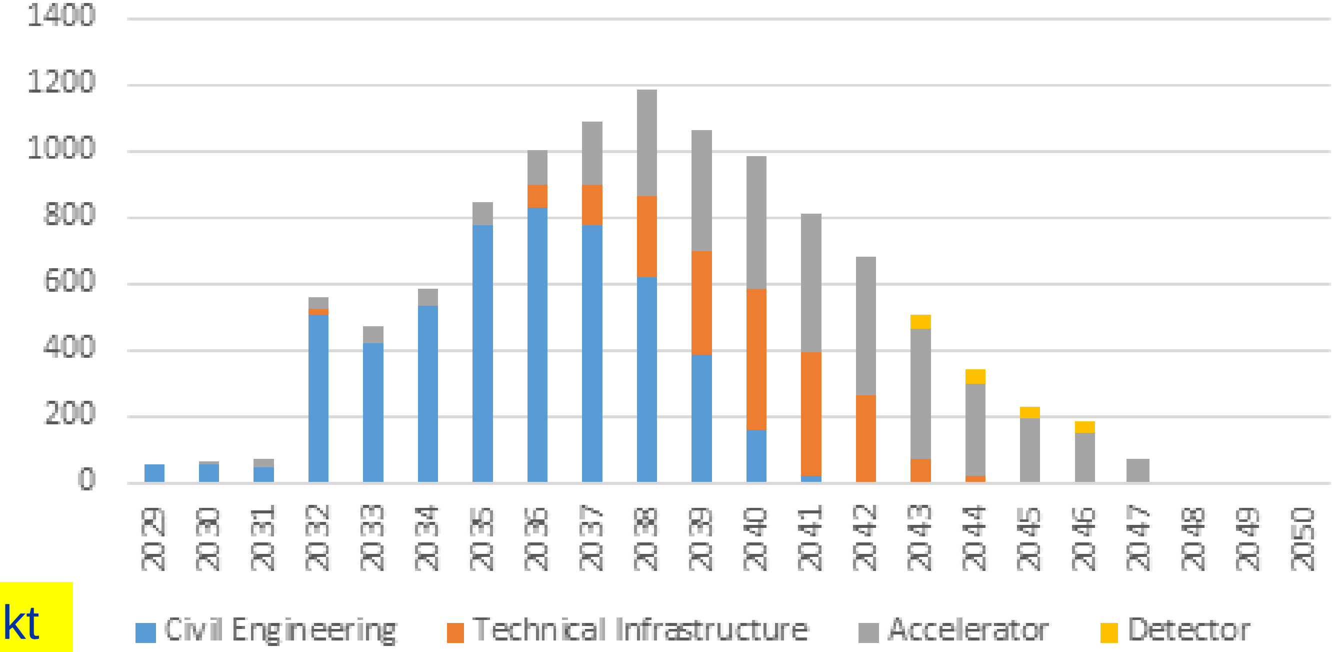
Construction cost estimate for FCC-ee

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

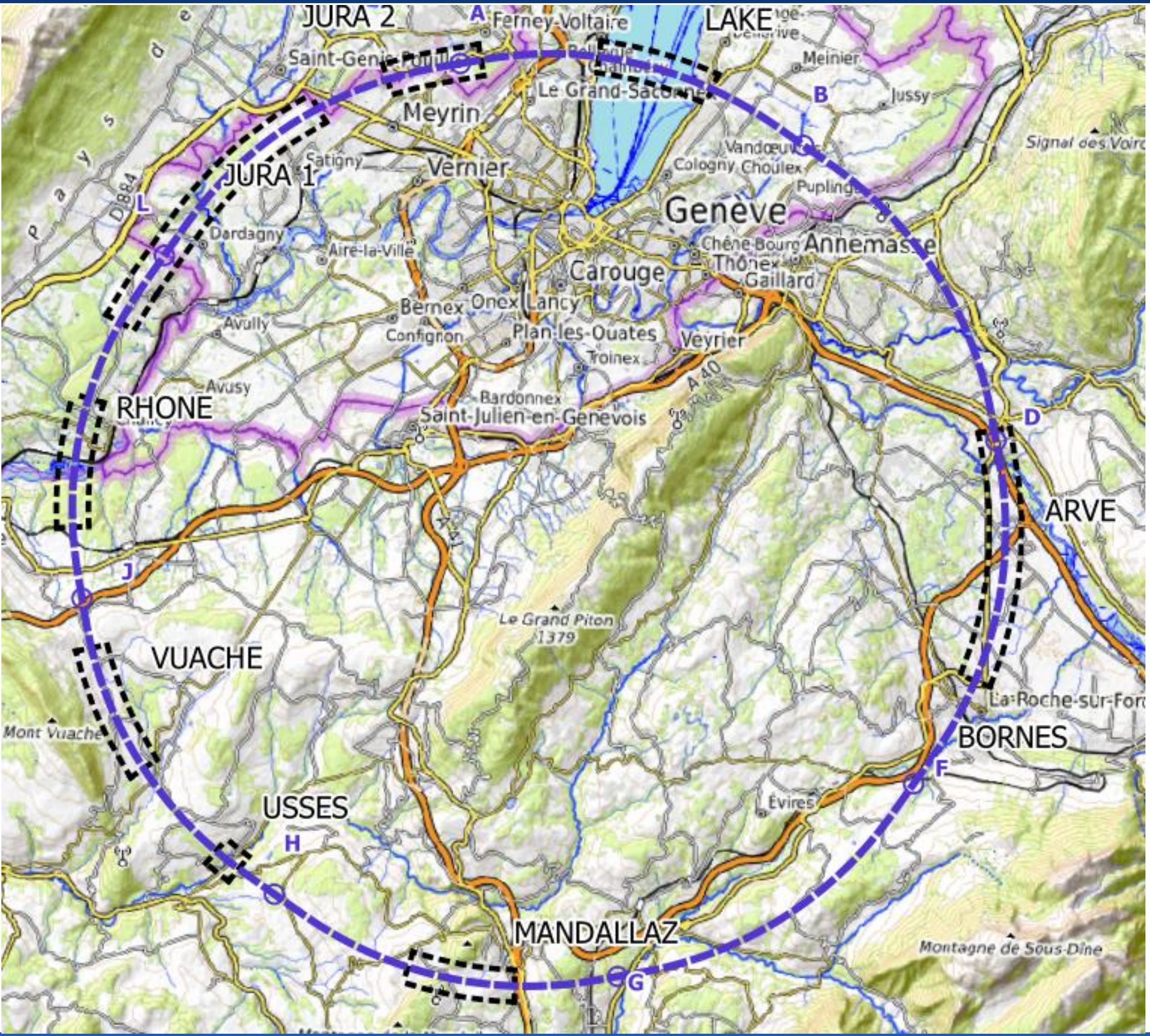
Spending profile for FCC-ee

- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.



M. Benedikt

Plans for high-risk area site investigations



JURA, VUACHE (3 AREAS)
Top of limestone
Karstification and filling-in at the tunnel depth
Water pressure

LAKE, RHÔNE, ARVE AND USSES VALLEY (4 AREAS)
Top of the molasse
Quaternary soft grounds, water bearing layers

MANDALLAZ (1 AREAS)
Water pressure at the tunnel level
Karstification

BORNES (1 AREA)
High overburden molasse properties
Thrust zones

Site investigations planned for mid 2023 – mid 2025:
~40-50 drillings, 100 km of seismic lines

M. Benedikt, J. Gutleber, V. Mertens, J. Osborne, T. Watson

Machine learning for FCC-ee

Dynamic & momentum aperture optimisation using PSO

Particle swarm optimiser: an evolutionary algorithm with both cognitive and `social' components, originally influenced by bird flocking behaviour.
PSO can be employed to improve dynami and momentum aperture of FCC with its high number of degrees of freedom.
FCC-ee number of degrees of freedom ma be reduced by keeping -I transform between sextupole pairs, and additionally maintaining the 2-periodicity of the machine. Doing so, 294 degrees of freedo are left.
This number is clearly still out of range for brute force scanning; evolutionary algorithms like PSO are better suited to handle the optimisation.

- population of candidate solutions (called particles) which are moving through the search space
- particles move with each generation according to their position (the current state) and their velocities as

$$\vec{x}_{n+1} = \vec{x}_n + \vec{v}_{n+1} \quad (1)$$

$$\vec{v}_{n+1} = \omega \vec{v}_n + c_c r_1 (\vec{x}_{\text{p-best}} - \vec{x}_n) + c_s r_2 (\vec{x}_{\text{g-best}} - \vec{x}_n) \quad (2)$$

- ω - rigidity of movement, c_c - cognitive factor, c_s - social factor, $\vec{x}_{\text{p-best}}$ - personal best, $\vec{x}_{\text{g-best}}$ - global best, $r_{1,2}$ - random numbers

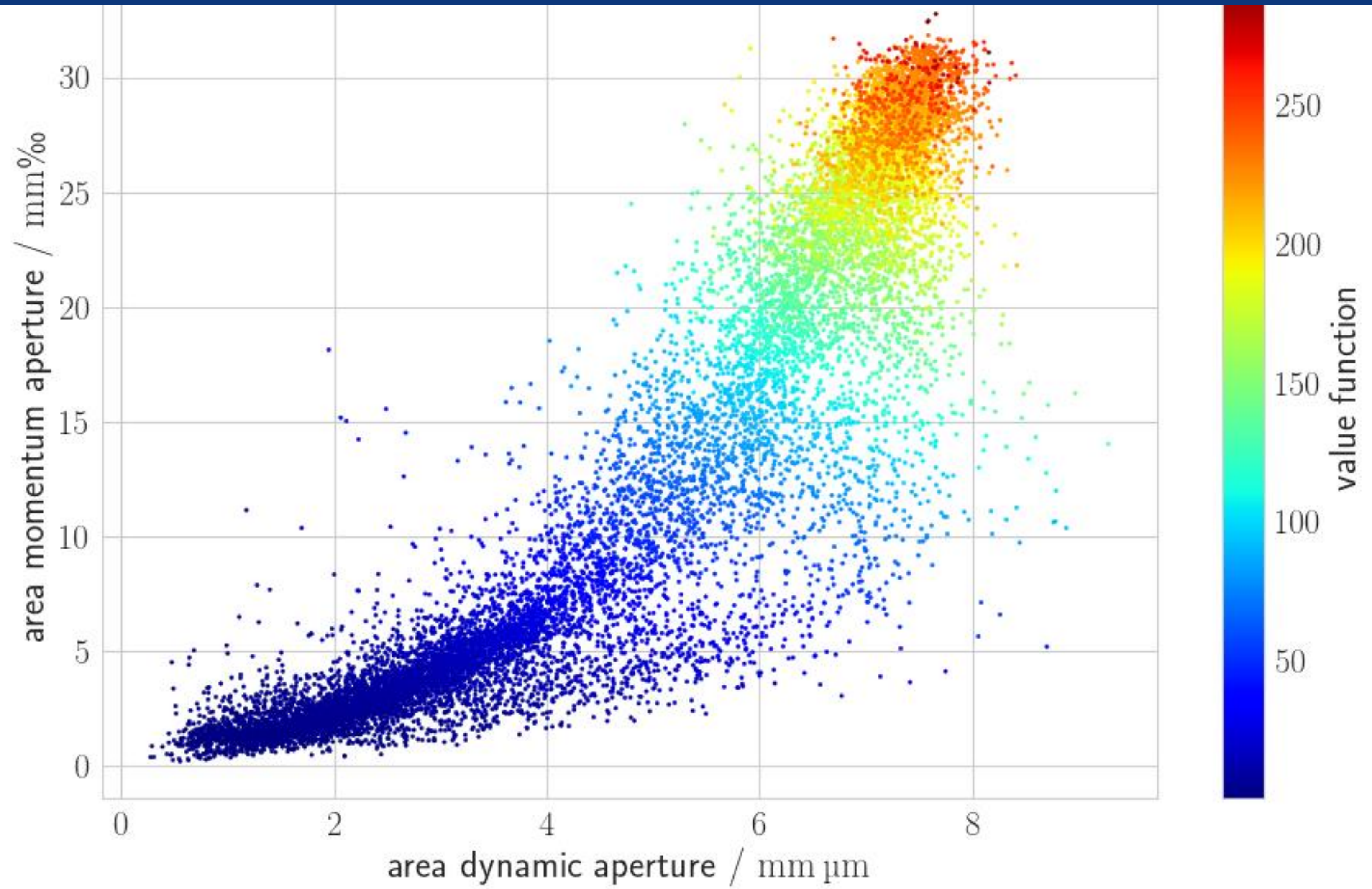
1. each preliminary set sextupole strengths is checked for its impact on chromaticity:
   - $\Delta \frac{\partial \nu_x}{\partial \delta} = \pm \sum_i \frac{1}{4\pi} \eta_x^i \beta_{x,y}^i \Delta k_2^i$
   - $\Delta \frac{1}{\beta_{x,y}} \frac{\partial \beta_{x,y}}{\partial \delta} = \mp \sum_i \frac{\eta_x^i \beta_{x,y}^i}{2 \sin 2\pi \nu_{x,y}} C_{x,y} \Delta k_2^i$
   - $\Delta \frac{\partial \alpha_{x,y}}{\partial \delta} = \mp \sum_i \frac{\eta_x^i \beta_{x,y}^i}{2 \sin 2\pi \nu_{x,y}} (S_{x,y} + \alpha_{x,y} C_{x,y}) \Delta k_2^i$
2. change in chromaticity is corrected using a scipy optimizer including final focus sextupoles
3. resulting sextupole setting is tracked in `MADX/PTC` for dynamic / momentum aperture

T. Tydecks,
FCC-ee CDR

value function in DA / MA space

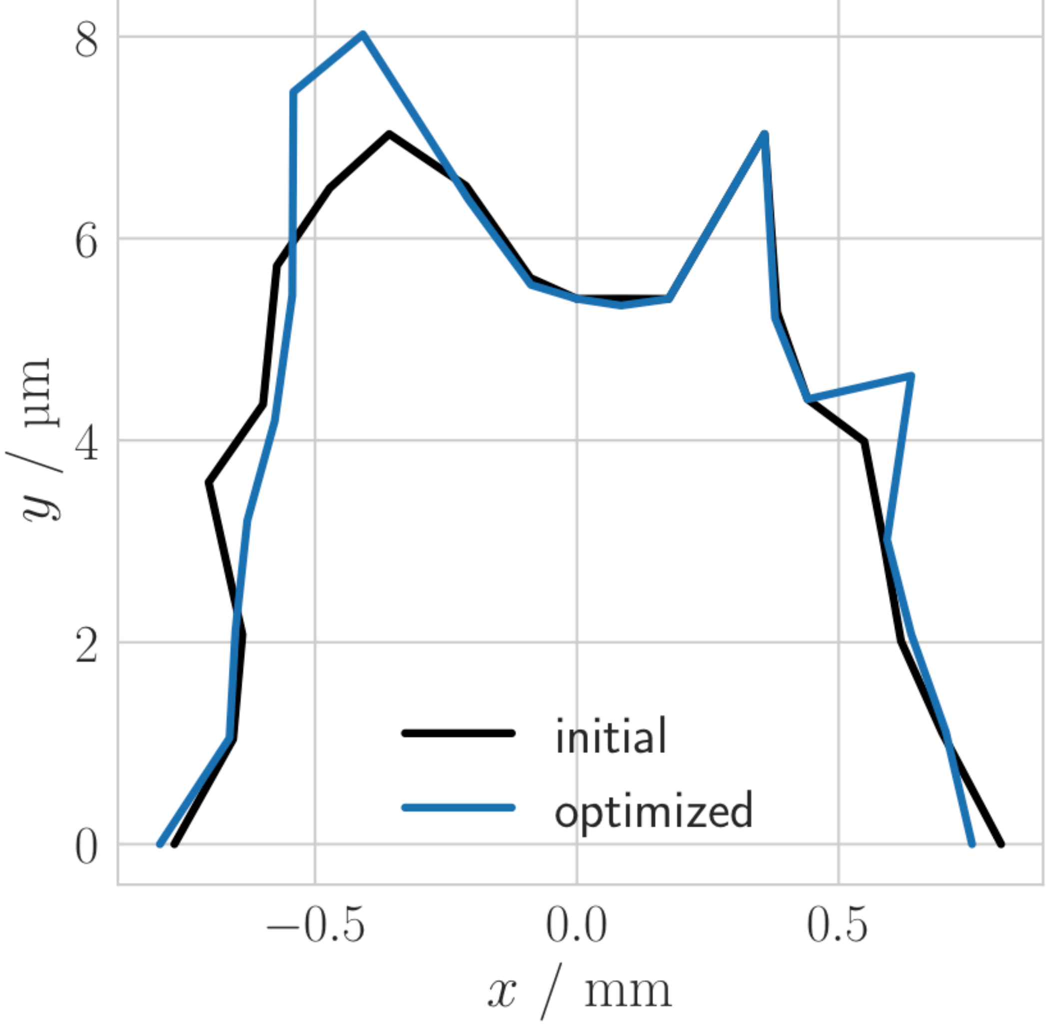
T. Tydecks, FCC-ee CDR

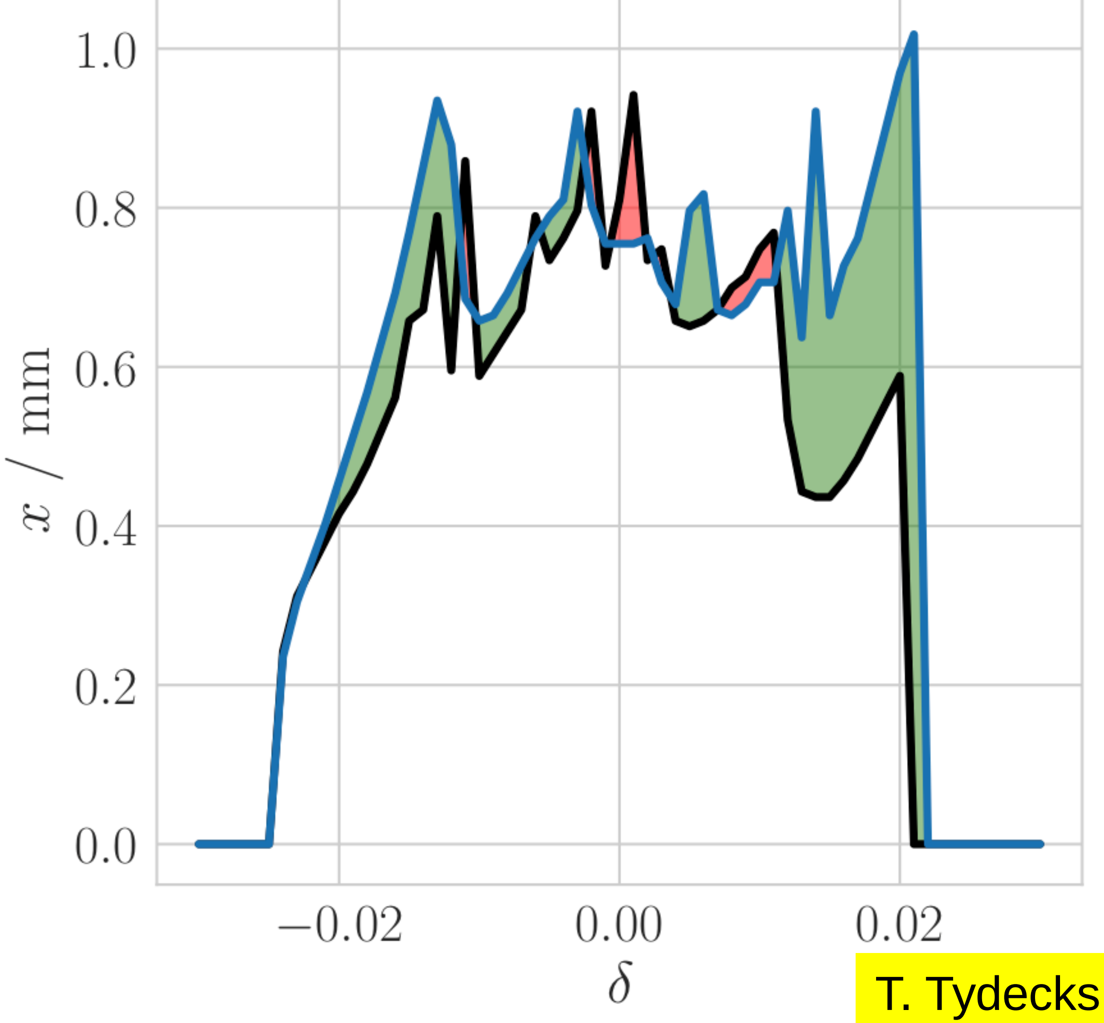
The European Physical Journal Special Topics volume 228, pages261–623 (2019



Value function as a function of area of momentum aperture and area of dynamic aperture for all solutions of the PSO algorithm.

optimized DA & MA

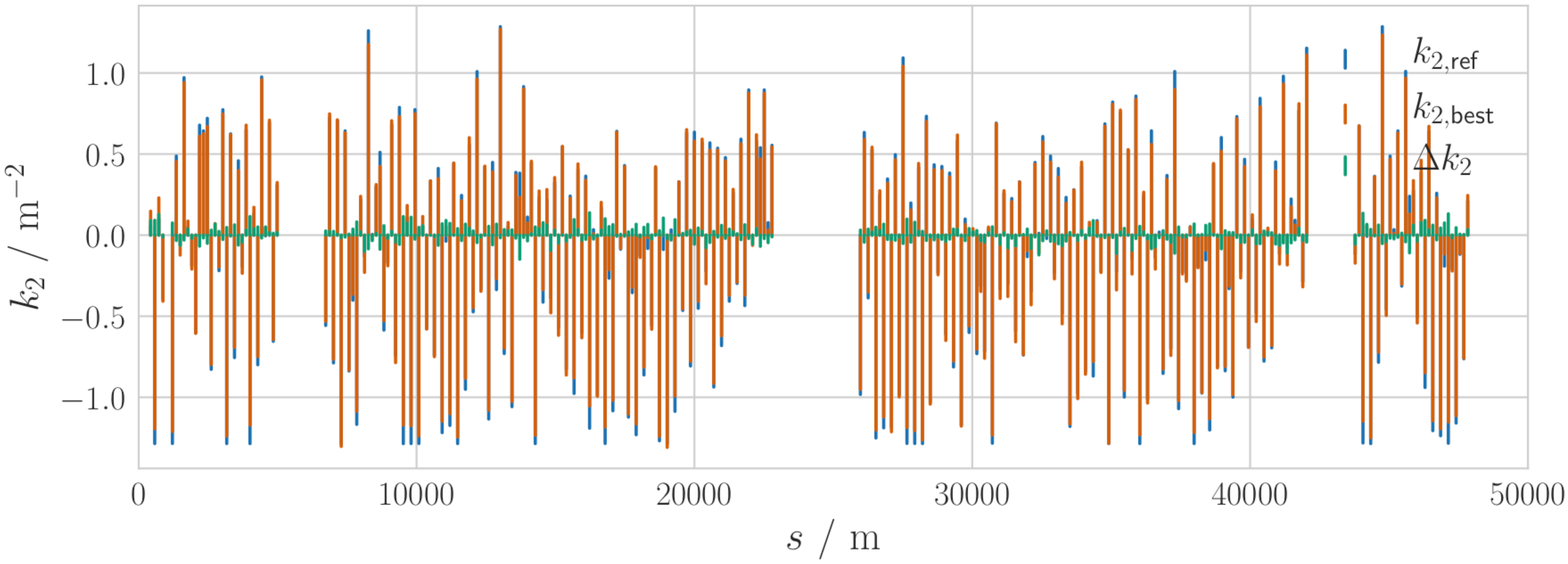




T. Tydecks, FCC-ee CDR

Dynamic aperture (left) and momentum aperture (right) for reference lattice (black) and optimised lattice (blue). The area of dynamic aperture is improved by 3.1% while area of momentum aperture is increased by 18%.

change in sextupole strength

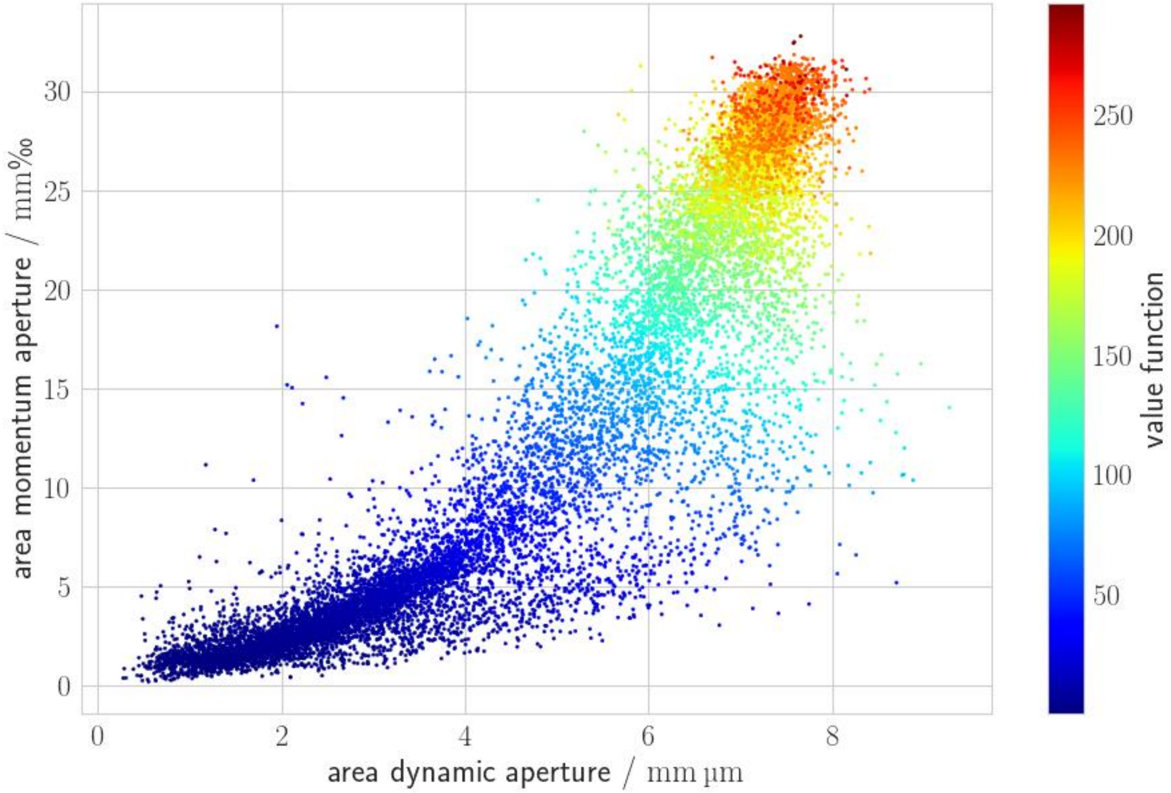


Change in sextupole strengths (green) between optimised solution (red) and reference solution (blue) for one half ring.

Employing machine learning concepts for DA optimisation

Side product of optimisation process: dynamic aperture and momentum acceptance determined for a large number of sextupole settings.

T. Tydecks, FCC-ee CDR



Value function as a function of area of momentum aperture and area of dynamic aperture for all solutions of the PSO algorithm.

These settings can be used to train an artificial neural network (NN) predicting the off-momentum dynamic aperture for different sextupole settings. With such a model, the optimisation process can be significantly accelerated since tracking can be avoided.

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optimisation: proof of principle

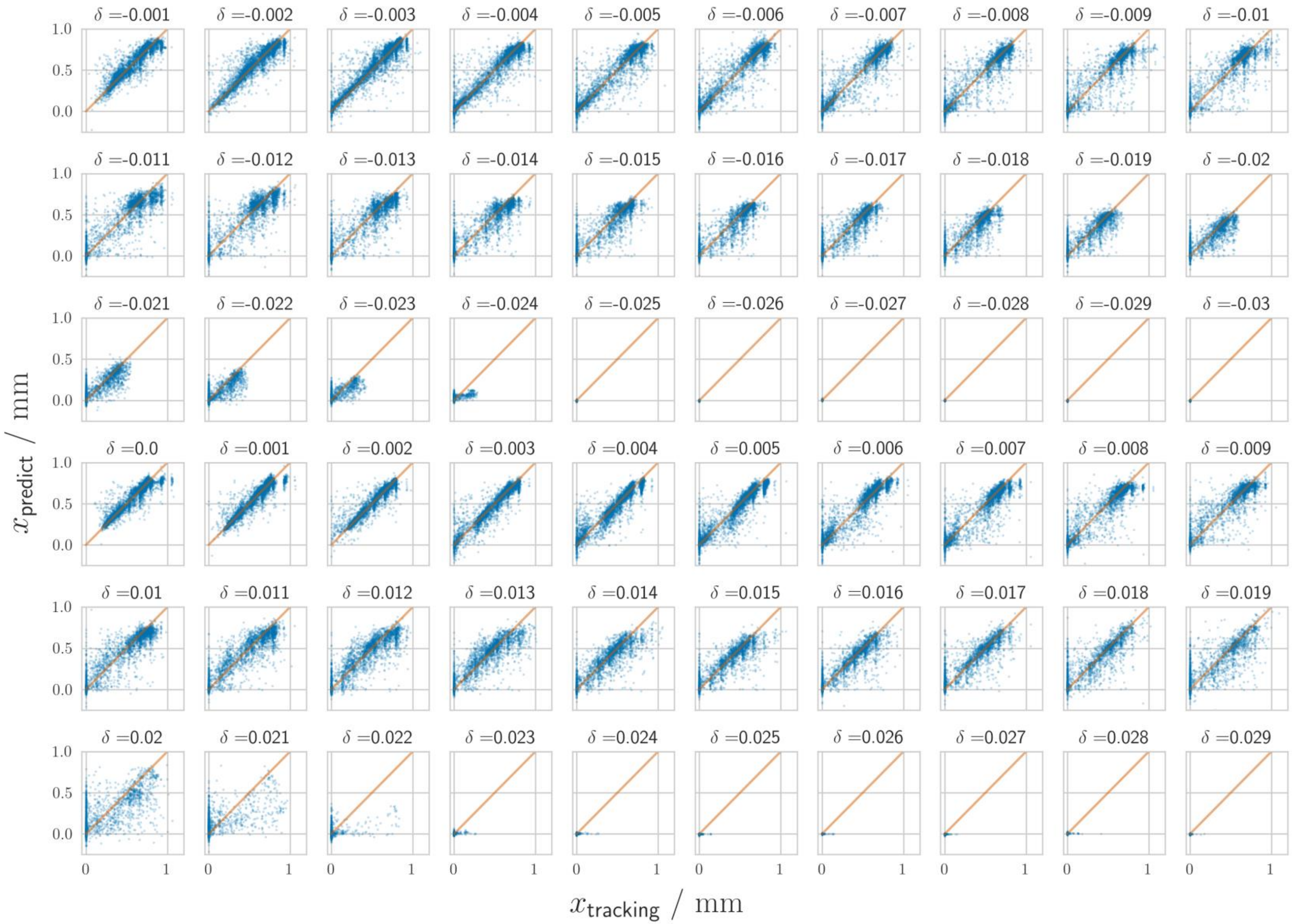
NN containing an input layer, three hidden layers, and an output layer

Input: 298 sextupole strengths including final focus

Hidden layers all accept 300 input values and produce 300 output values

Output layer : 61 horizontal apertures for different energy deviations ranging from -3% to +3% in steps of 0.1%

T. Tydecks, FCC-ee CDR



Aperture predictions for different energy deviations from a trained NN model together with true values from particle tracking, for a test data set, which has been withheld from training.

FCC-ee machine learning - what next ?

Cristobal Garcia
EPFL Global Leaders Program

Challenging Task: “Develop an Expert System that emulates the decision-making ability of a human expert in optics design. Use the developed tools for the design of the FCC-ee.”
– 4 year project

summary

FCC-ee and FCC-hh offer plenty of opportunities for machine learning

we may be watching a real-time revolution in accelerator design