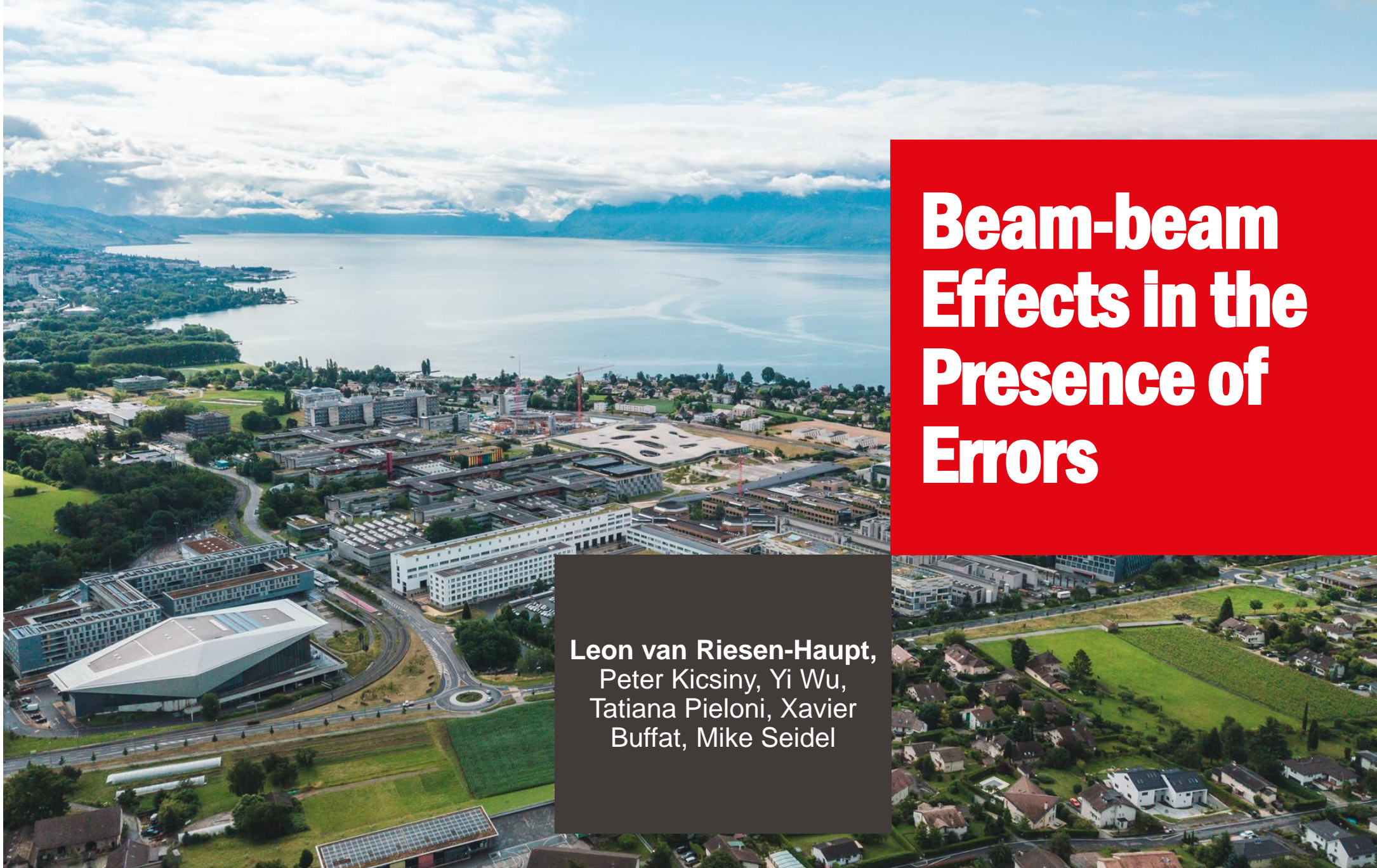


**EPFL**



Swiss Accelerator  
Research and  
Technology



# Beam-beam Effects in the Presence of Errors

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# Introduction and Aims

- FCC pushes both **energy** and **luminosity** frontier
  - Sensitive to **errors**
  - Dynamics strongly impacted by synchrotron **radiation**
  - Strong **beam-beam** forces
- Ensure that performance (**luminosity**) targets are met
  - Minimise **emittance**
  - Accurate **optics** control
  - Sufficient **lifetime**
- Accurately simulate FCC under **realistic conditions**
  - Understand impact of individual effects and their **interplay**
  - Inform and develop **mitigation strategies**

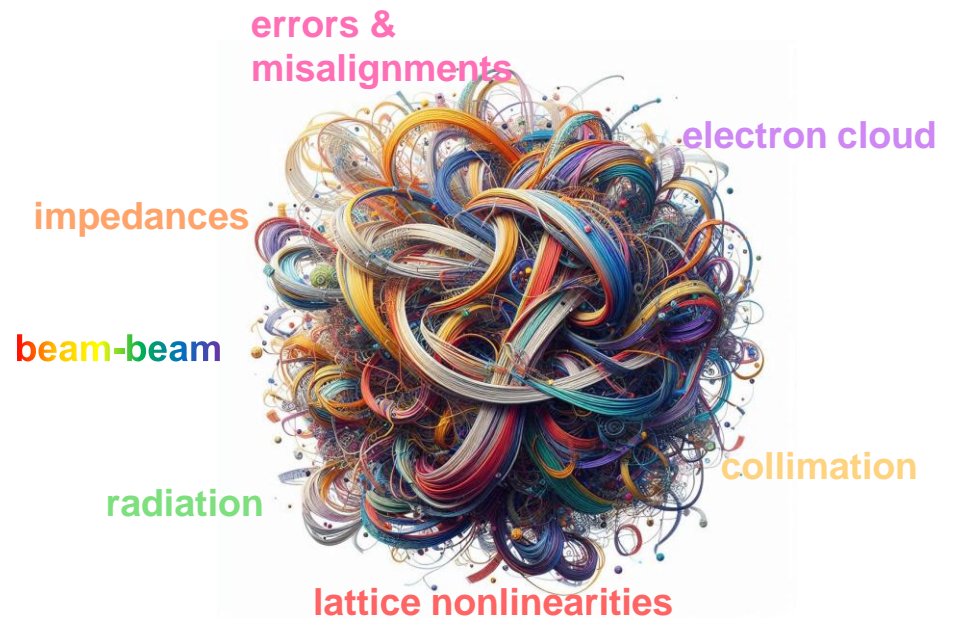
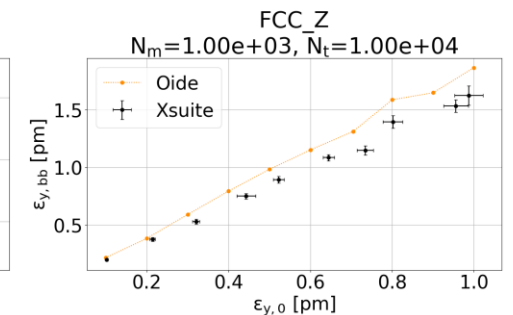
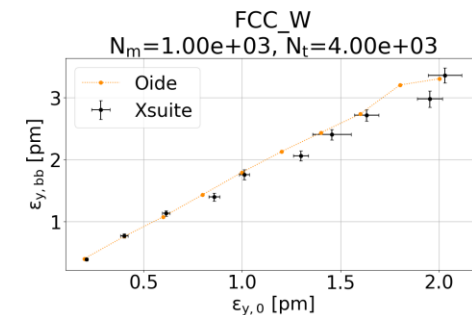
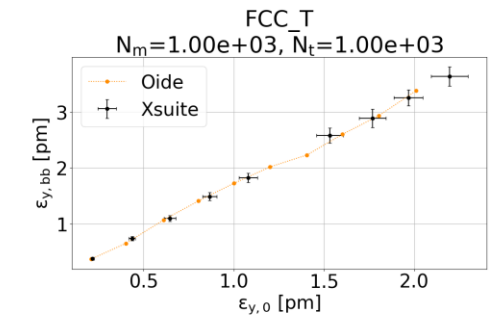
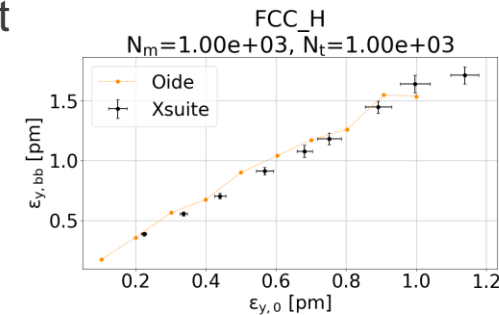
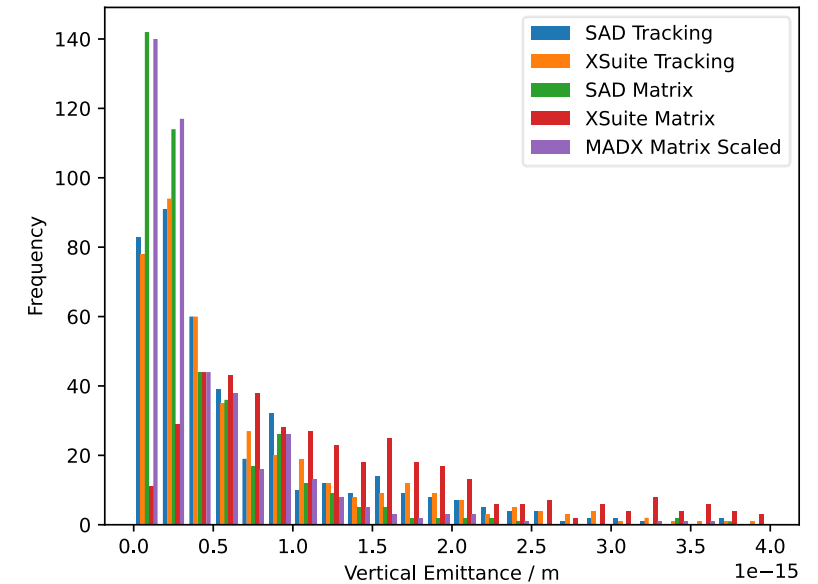


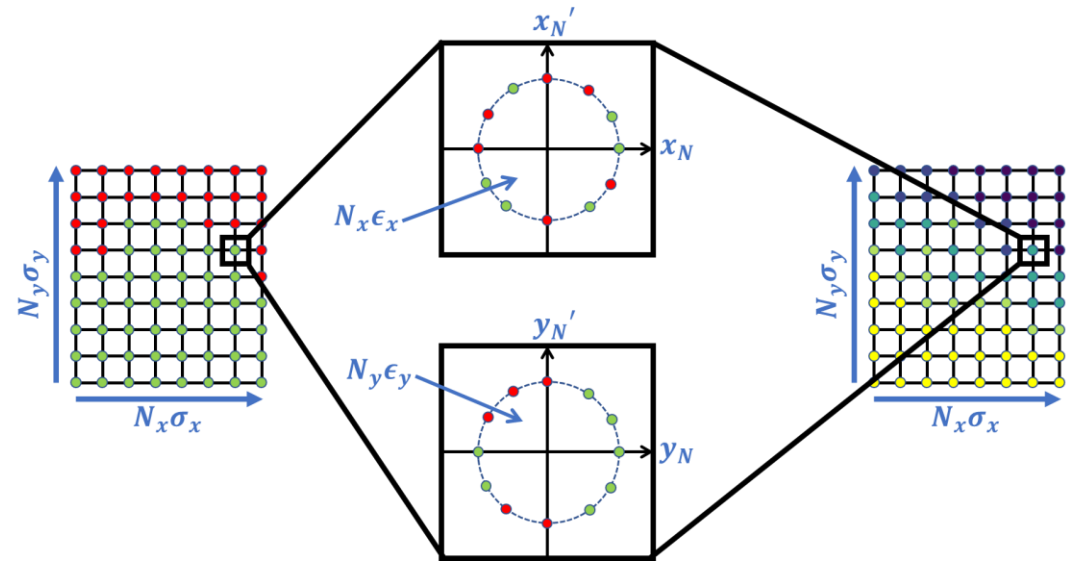
Image by P Kicsiny

- Comprehensive simulations made possible by **Xsuite** *Talk by G Iadarola*
  - Allows simulation of multiple effects
  - Development in **close exchange with FCC-ee team**
    - Beam-beam module developed as CHART effort
- Thorough **benchmarking** campaign ensuring accurate simulation of
  - Radiation (vs SAD and MADX)
  - Lattice errors (vs SAD and MADX)
  - Beam-beam effects
- Needs expert input and experience talk by *P Kicsiny*
  - Set up** meaningful simulations with **perturbations**
  - Compute **performance indicators** from tracking data
  - Interpret** results



# Observables and Indicators

- Some indicators directly describe the performance
  - **Luminosity** and **Lifetime**
  - Often computationally **intensive**
- Others relate to and are **indicative** of the performance
  - **Optics** – especially at interaction point
  - Equilibrium **emittances**
  - **Dynamic aperture**
  - **Momentum acceptance**
- **New methods** needed to describe highly damped system
- Computing **time varies** largely (seconds – days)
  - Use **fast(er)** indicators during design and optimisation
  - Requires solid understanding of **predictive power** of indicators

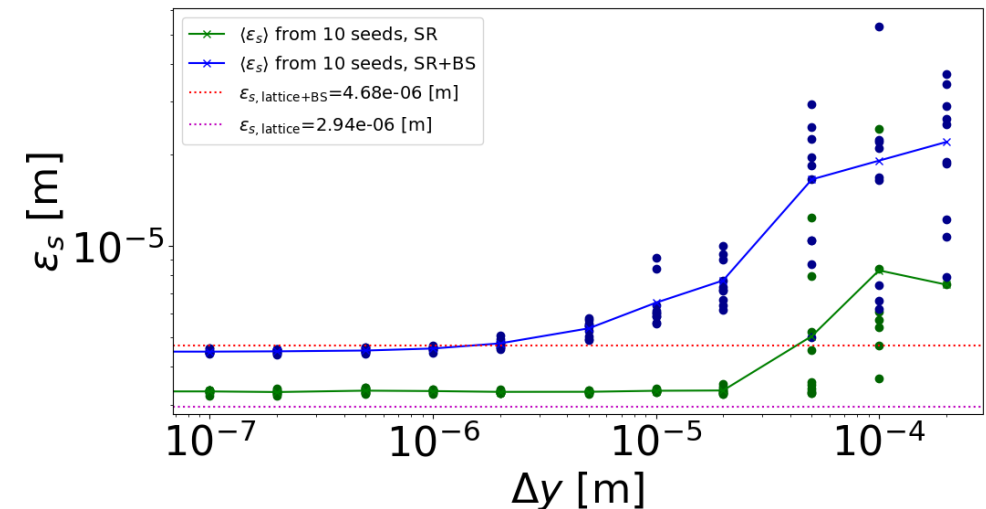
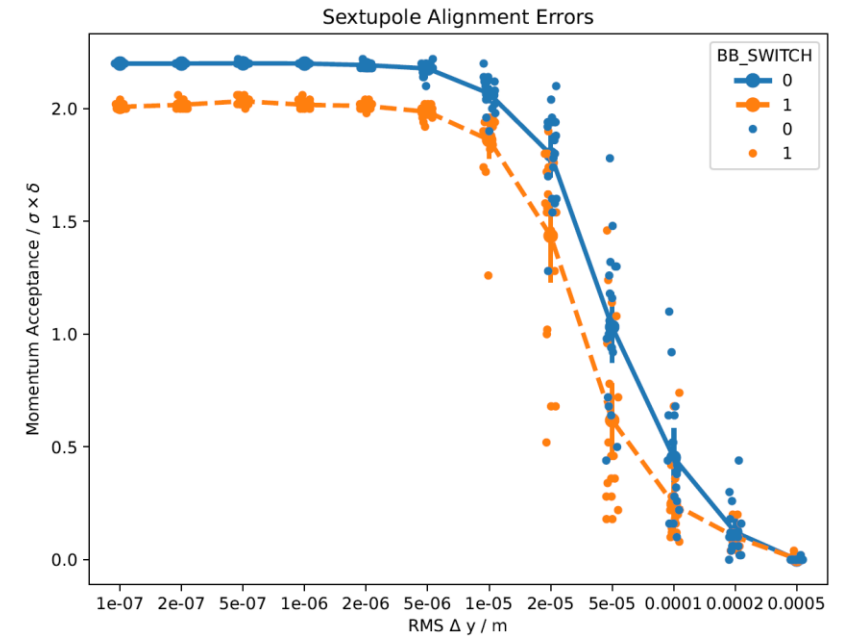


# Lattice Perturbations - Strategy

- Simulation of **beam-beam** with **individual** lattice errors
  - **Misalignments** of magnet groups
  - **Multipole** errors
  - Optics perturbations at the **interaction point**
- Opportunity to introduce **one** type of error **at a time**
  - **Understand** individual interplay with beam-beam effects
- Help **pinpoint** priorities in tolerances and correction strategies
- Develop and test **methods** of lattice setup and performance indicators simulations
  - Ensure implementation of individual perturbations works as **expected** (**benchmark** when possible) before applying all

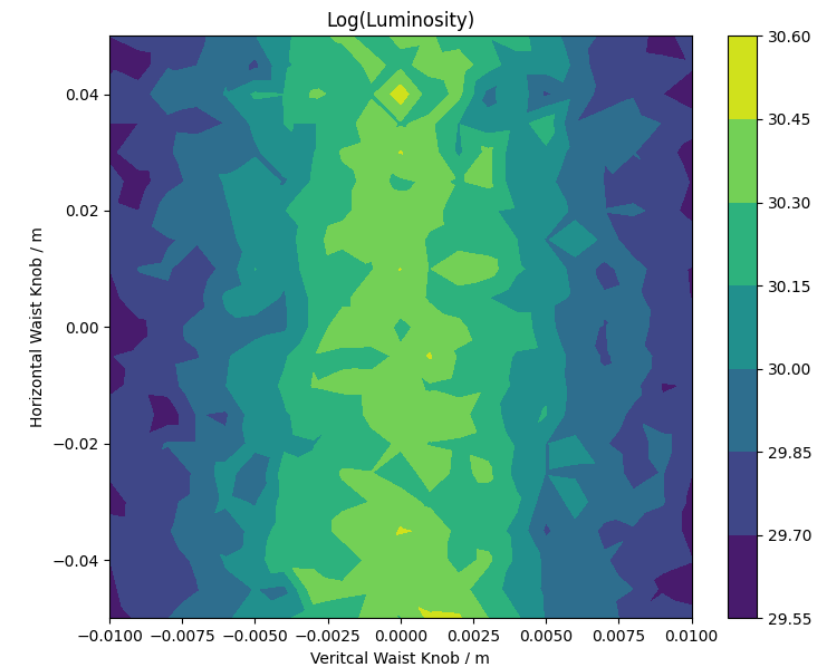
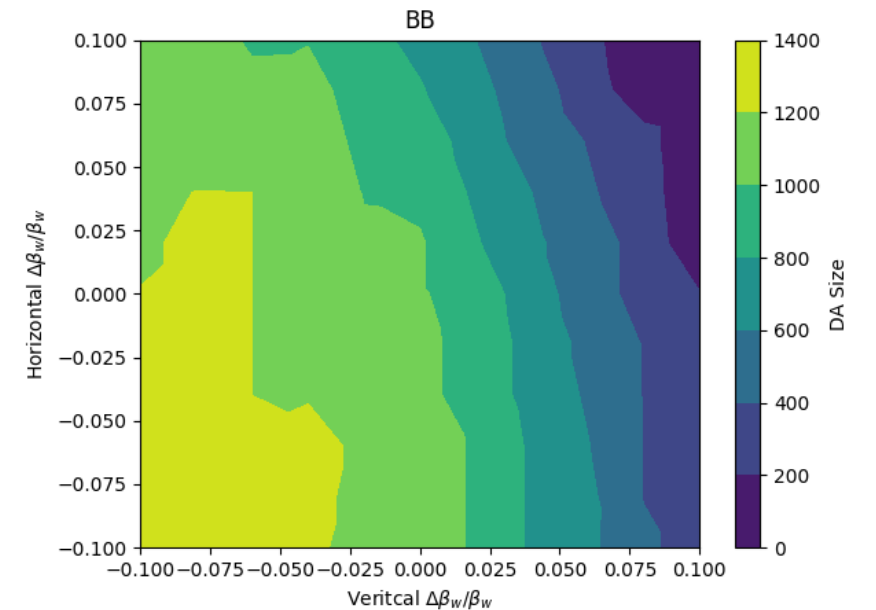
# Lattice Perturbations

- Two forms of **lattice perturbations** studied
  - Vertical **misalignments**
    - Arc quadrupoles
    - Arc sextupoles
  - Exciting **multipoles** between interaction points
- Simulations performed with and without **beam-beam**
  - Primary aim to **understand** impact beam-beam has in the presence of errors
- Rematching of tune using arcs but no dedicated interaction point corrections
  - Only **coarse indicator** for **tolerances**



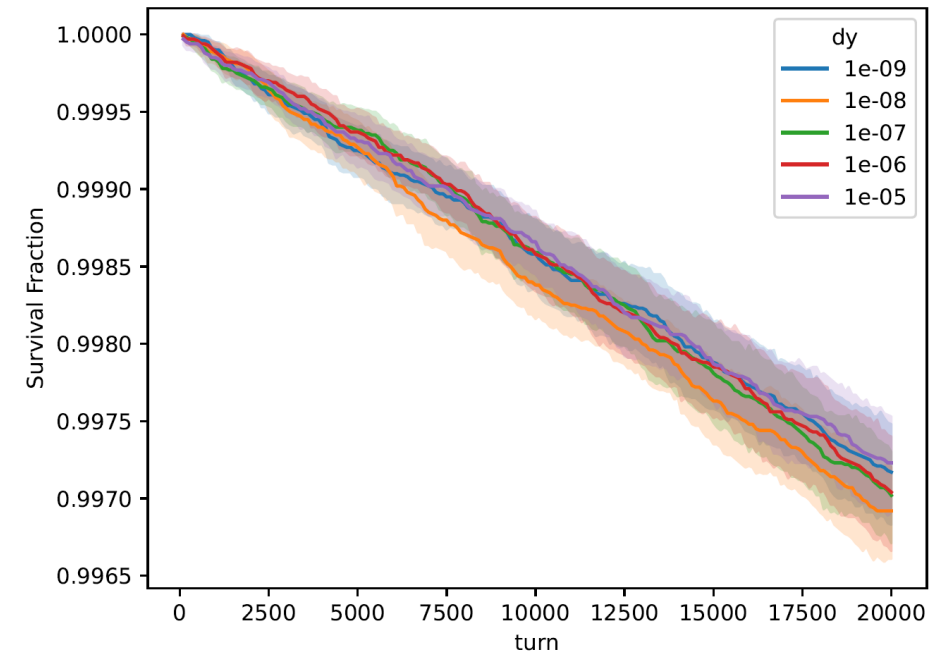
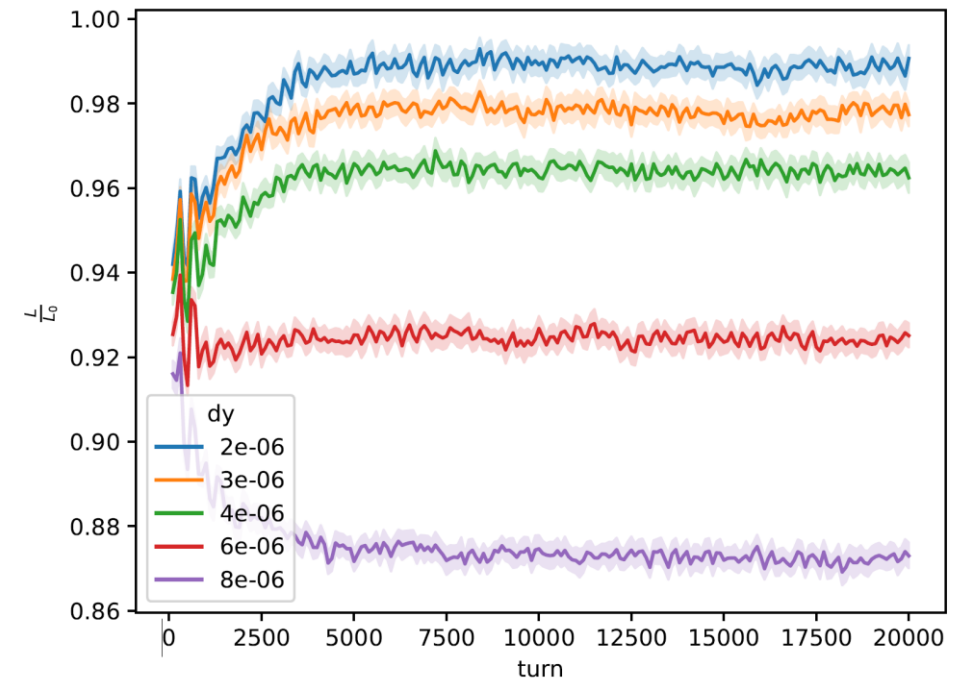
# Insertion Region – Optics Perturbations

- Direct input for IP tuning **tolerances**
- Introduce perturbations to insertion region using **optics knobs**
  - Created from response [matrix with SVD](#)
  - Work continued by [S Jagabathuni](#)
  - Adjust minimum  **$\beta$  function** and its location
- Computed various performance **indicators**
  - Dynamic aperture
  - Luminosity



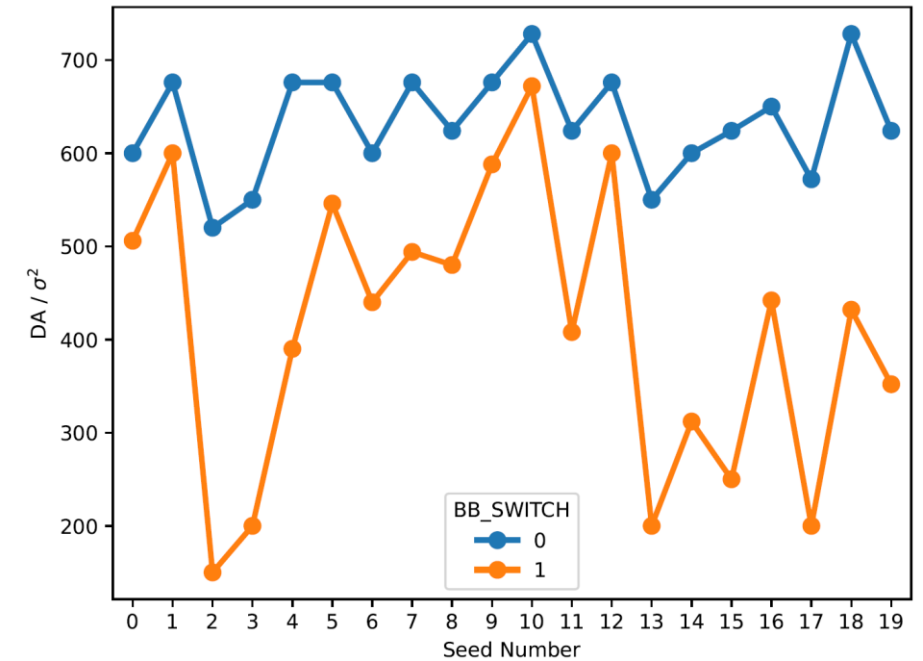
# Insertion Region – Dispersion

- **Vertical dispersion** in interaction point area of interest for tuning team
  - Hard to **measure**
  - Large impact on **luminosity**
  - Potential impact on **lifetime**
- Determine control **target** to achieve luminosity loss of 5%
  - Between 4 – 6  $\mu\text{m}$
- **Survival rates** and momentum acceptance **less affected** at this range



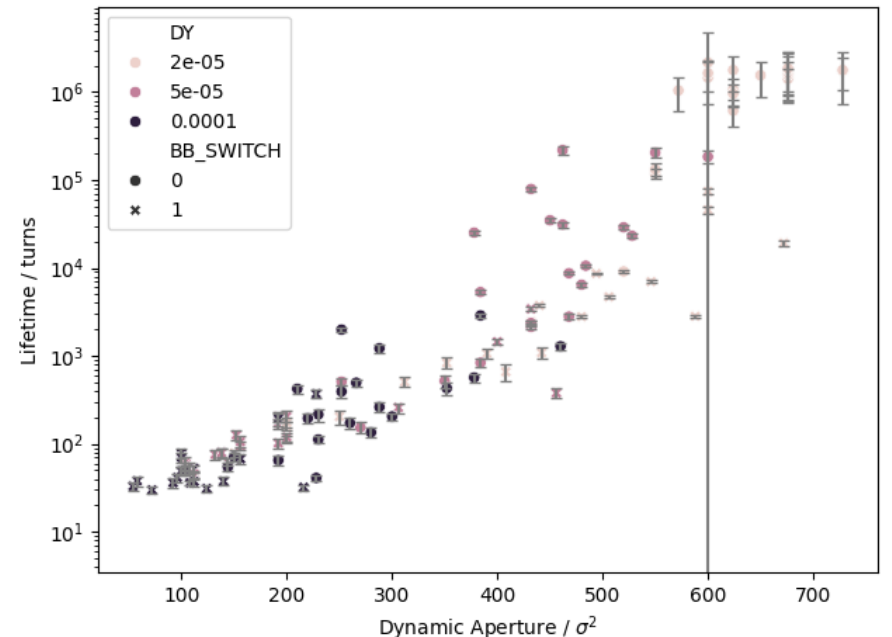
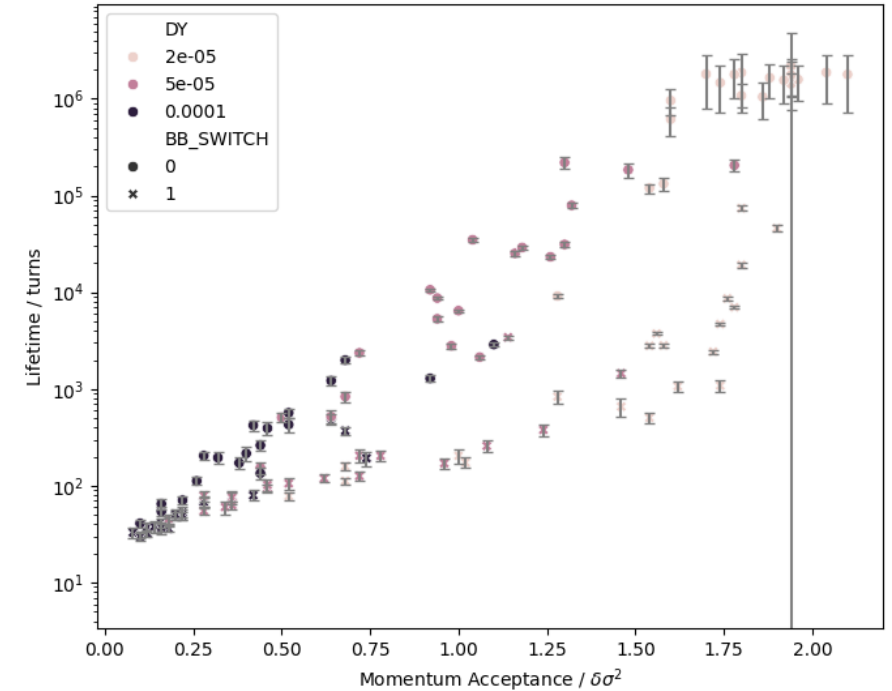
# Correlations and Efficient Indicators

- **Understand correlations** between effects and observables
  - If and how **adding** an **effect** changes indicators evenly
  - How **different indicators** are **correlated**
- Allow for **simplified models** and **predictions**
  - **Save computing time**
- Long-term aim: create **large repository** of simulation setup and results



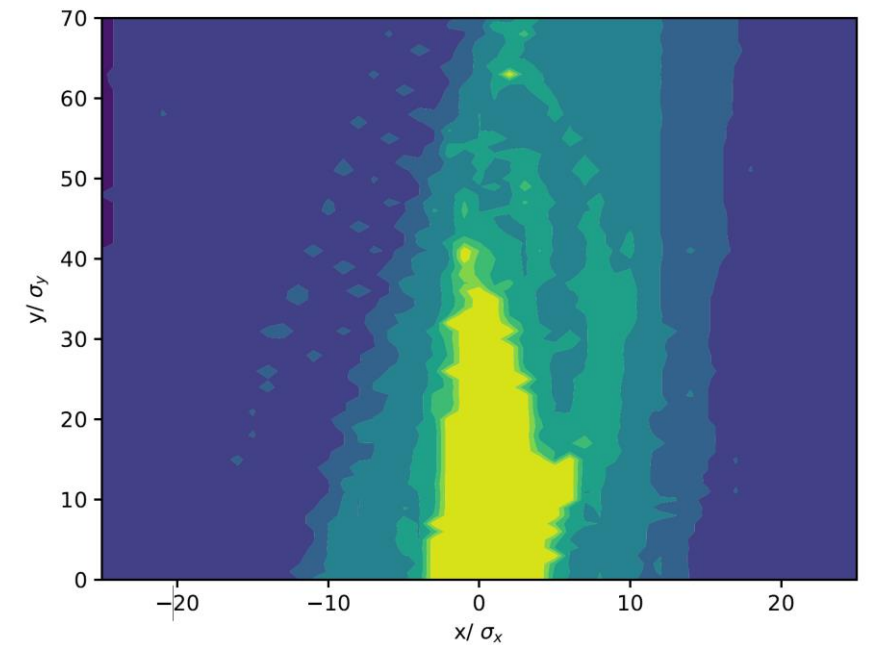
# Dynamic Aperture vs Lifetime

- **Lifetime** simulations significantly **slower** than computing **DA/MA**
  - Traditionally optimise these with aim to maximise lifetime
- Simulation with various **sextupole misalignment** seeds and amplitudes
  - Compute DA, MA and lifetime
- Clear **trend** between DA/MA and lifetime
  - **Additional variance** by an order of magnitude
  - **Additional or better indicators needed** to fully describe lifetime

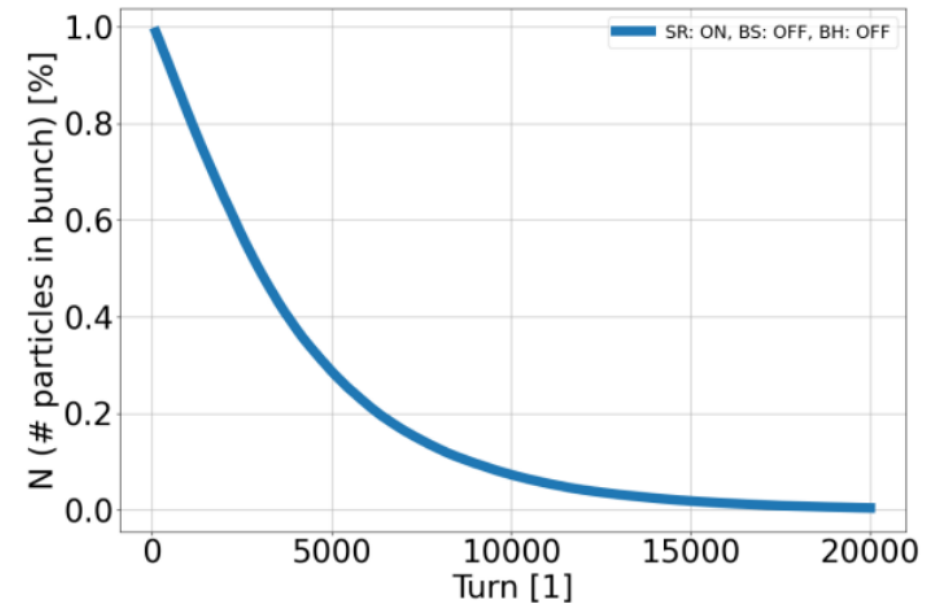


# Errors and Correction

- Applied beam-beam perturbations to lattices with **global errors** and **corrections**
- Lattice with **arc errors** and **corrections** provided by [Yi Wu](#)
  - Errors applied and thorough global correction applied in **MADX**
    - **Interleaved optics and orbit corrections**
    - **Ramping of sextupoles**
  - Acceptable dynamic aperture but only 2 seconds lifetime
- Aim to test on **lattices corrected using LOCO** by [E Musa et al.](#)
- Aim to create more targeted correction approaches
  - From knowledge gained by sensitivity studies
  - Using faster metrics during optimisation steps



FCC z  $N_m=1.00e+05$



- Possibility for **comprehensive studies unlocked** in recent years
  - Developments in **simulation tools**
  - Comprehensive **benchmarking** and **testing**
- **First simulations** to probe behaviour under **combined effects**
  - Introduction of individual effects to study and understand behaviour
    - Misalignments, multipole errors, IP perturbations
  - First indications for **tolerances** and **input** for **tuning** teams
- Explore **dynamic indicators**
  - Define **new** and explore established **indicators** to describe dynamics
  - First exploration of **correlations**
- Long term target to add **all effects** in dedicated **tuned lattices**

- Further studies introducing **more effects**
  - **Non-linearities** in the interaction point
  - Exciting **resonance** driving terms
  - **Multiple errors** at the same time
- Improved understanding of **correlations** between indicators
  - Compute more **indicators** at more **configurations**
    - Create **extensive repository** to analyse
  - Find combination of faster indicators that **explain variation** in lifetime
- **Inform and contribute** to **tuning** efforts
  - Set tolerance **targets**
  - **Create tuning tools** and **test tuned lattices** with beam-beam effects
  - Increase **tuning speed** using **faster indicators**