NUMERICAL TOOLS FOR BEAM-BEAM STUDIES

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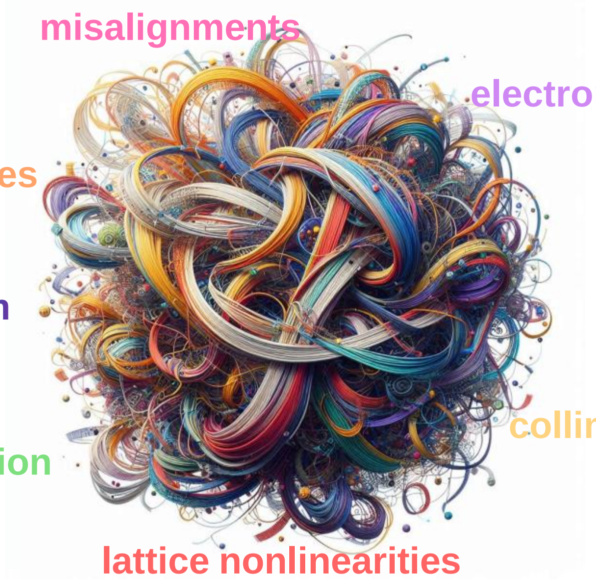
Research and Technology (CHART)

Overview

- FCC-ee will be a highly complex machine
- Interplay of various effects
- Presence of beam-beam collisions further complicates beam dynamics
- Self-consistent simulations are challenging



Tools

	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Open source	Runs on GPU
GUINEA-PIG [1]	🟨	⬛	⬛	🟨	🟨	🟨	⬛	⬛	⬛	⬛	🟨	⬛
COMBI [2]	🟨	🟨	🟨	🟨	⬛	⬛	🟨	⬛	🟨	⬛	🟨	⬛
BBWS [3]	🟨	⬛	⬛	⬛	🟨	⬛	🟨	🟨	🟨	🟨	⬛	⬛
BBSS [4]	⬛	⬛	🟨	🟨	🟨	⬛	🟨	🟨	🟨	⬛	⬛	⬛
SCTR [5]	⬛	⬛	🟨	🟨	🟨	⬛	🟨	🟨	🟨	🟨	⬛	🟨
IBB [6]	⬛	⬛	🟨	⬛	🟨	⬛	🟨	🟨	🟨	⬛	⬛	⬛
LIFETRAC [7]	🟨	🟨	⬛	⬛	🟨	⬛	⬛	⬛	🟨	🟨	⬛	⬛
BeamBeam3D [8]	🟨	⬛	🟨	🟨	🟨	⬛	🟨	⬛	🟨	⬛	🟨	⬛
Xsuite [9]	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

🟨 Available ⬛ Not available

- Different beam-beam codes exist, with different features
- FCC-ee: self-consistent & fast modeling needed including many effects
- Xsuite: development driven by needs for FCC-ee

G. Iadarola talk @ this conference

Transition to Xsuite

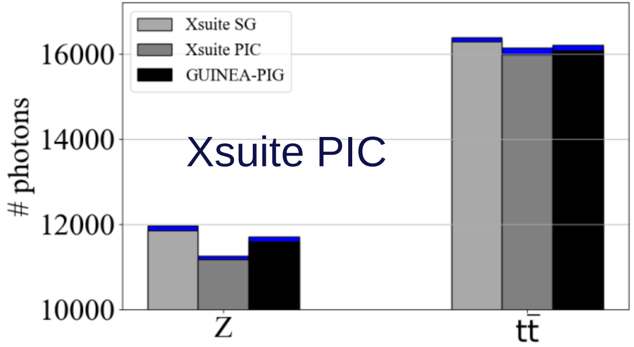
- Phase out legacy codes

  COMBI, SixTrack [1], GUINEA-PIG, PyHEADTAIL [2]

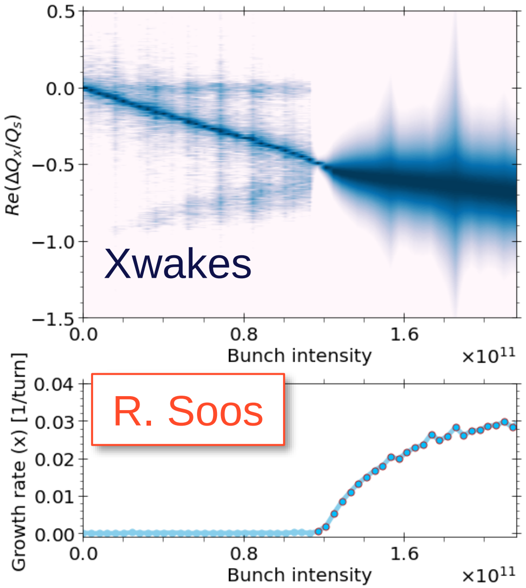
- Integrate their features into Xsuite

- Thorough benchmark of features

- Xsuite advantages:
  - Self contained
  - Maintenance & user support
  - Growing community
  - Python based



Xsuite PIC



Xwakes

R. Soos

Studies made possible by Xsuite beam-beam [1]

Lattice optimization

- Luminosity and beam lifetime [2]
- Footprint & FMA
- Lattice interplay with beam-beam (e.g. emittance) [1]
- Dynamic aperture (DA) / momentum acceptance (MA) [3]
- Errors & corrections
- Top-up injection [4]

Collective effects and instabilities

- 3D flip-flop [5, 6]
- Incoherent and coherent X-Z instability [6, 7]

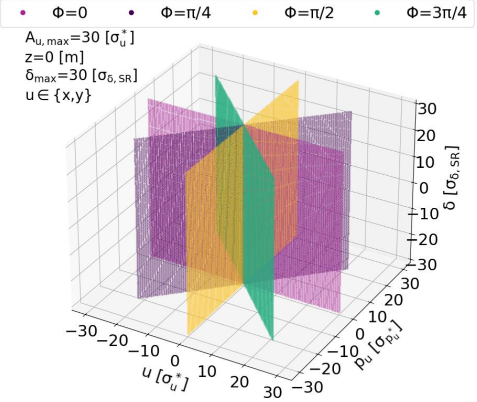
Collimation and MDI

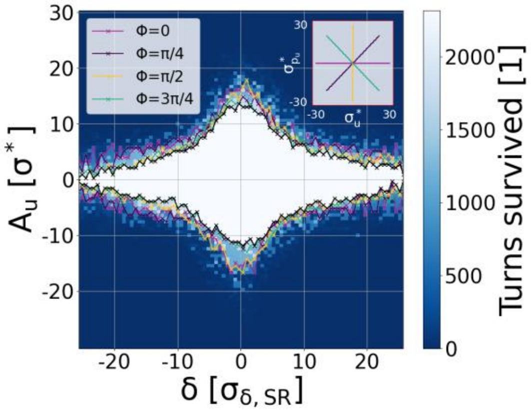
- Loss maps
- Detector background
- IP tuning & feedback

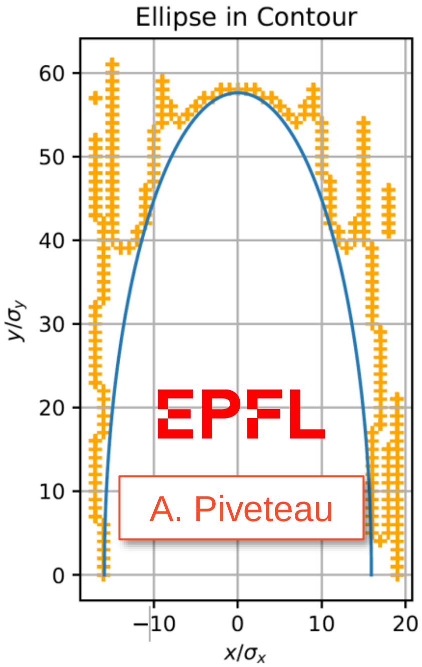
G. Broggi, talk @ this conference

J. Salvesen talk & V. Gawas poster @ this conference

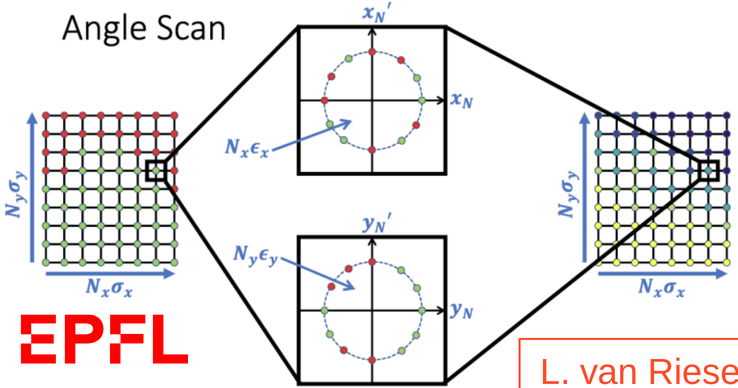
Standardizing performance evaluation: DA/MA



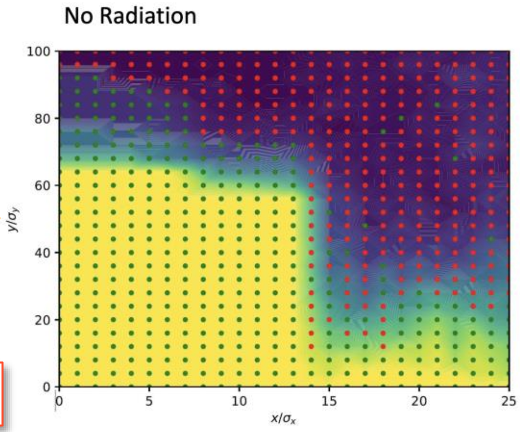




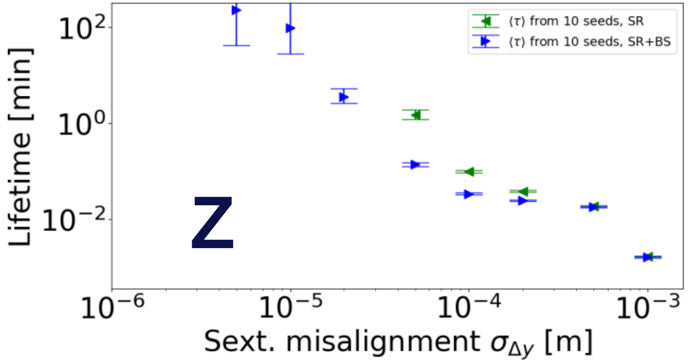
A. Piveteau



L. van Riesen-Haupt

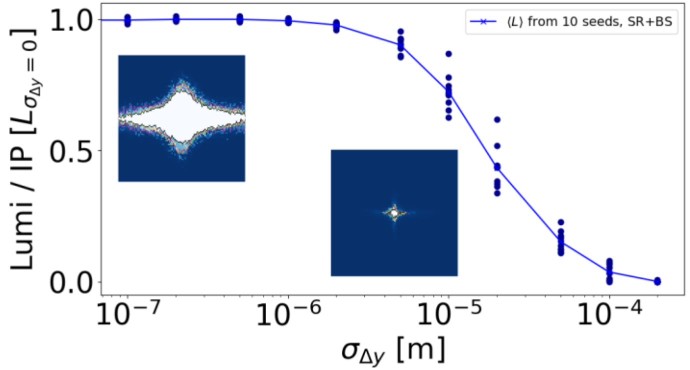


Standardizing performance evaluation: correlations



- Main FCC-ee metrics: luminosity and lifetime
- Lattice optimization to be done including beam-beam
- Ongoing studies with errors & corrections
  - Need standardized way to do DA, MA, FMA
- Idea: exploit correlations between various metrics could speed up optimization process
  - E.g. lifetime vs DA studies

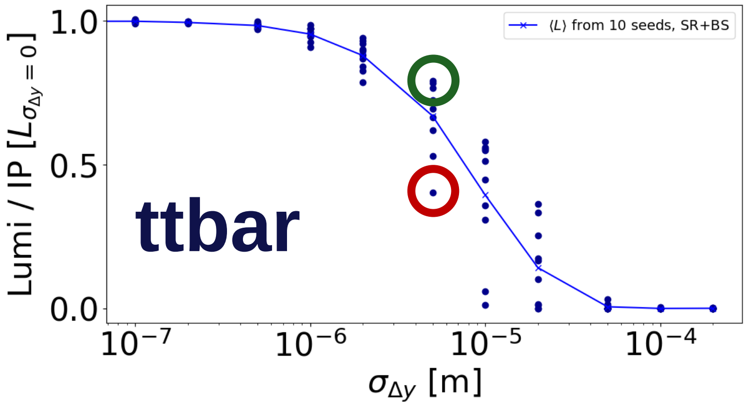
L. van Riesen-Haupt talk @ this conference

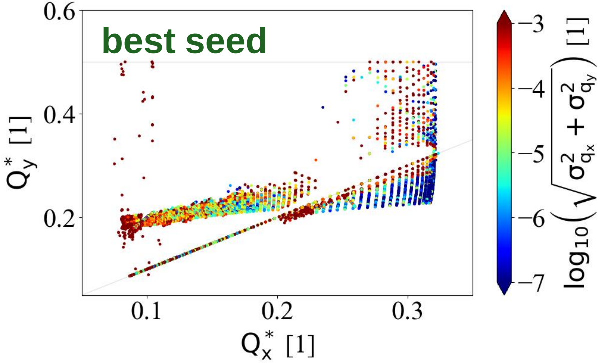


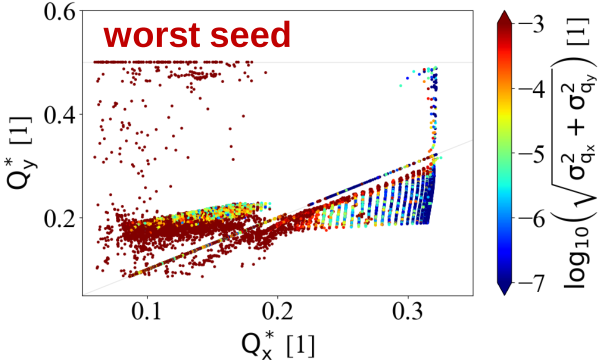
Standardizing performance evaluation: Footprint & FMA

- Different libraries (harpy, nafflib)
    - Same thing, difference in maintenance

- Ongoing work on built-in tool to compute footprint + FMA
    - Linear/nonlinear lattice
    - Compute diffusion
    - Noise or different filters
    - GPU support







Standardizing performance evaluation

Simulation	Number of Particles	Number of Turns	Model	Typical timescale
Optics	~1	~few	full lattice + **WS BB**	**sec**
Emittance – Matrix	~1	~few	linear map + **WS BB**	**sec**
Coarse Dynamic Aperture	~100	~τ_{SR} (50-5000)	full lattice + **WS BB**	**min**
Emittance – Tracking	~1k	~τ_{SR} (50-5000)	full lattice + **WS BB**	**min**
Fine DA / MA	~10k	~τ_{SR} (50-5000)	full lattice + **WS BB**	**min**
Luminosity	~10k	~τ_{SR} (50-5000)	linear map / full lattice + **WS BB**	**hour**
Collective effects	~1M	~τ_{SR} (50-5000)	linear map + **SS BB**	**week**
Footprint + FMA	~10k-1M	~1-10k	linear map / full lattice + **WS BB**	**hour**
Lifetime	~100k	~20k	full lattice + **WS BB**	**day**

Standardizing performance evaluation

Simulation	Number of Particles	Number of Turns	Model	Typical timescale
Optics	~1	~few	full lattice + **WS BB**	**sec**
E				
C A				
E				
F				
L				
C				
Footprint + FMA	~10k-1M	~1-10k	linear map / full lattice + **WS BB**	**hour**
Lifetime	~100k	~20k	full lattice + **WS BB**	**day**

- Currently for most studies weak-strong beam-beam is used
- For longer studies (lifetime) GPUs are necessary but currently not exploited
- For most studies GPUs are not necessary but would boost productivity
- Studies which have to be performed often (lifetime, lumi, emittance) should exploit GPU power

Exploiting hardware infrastructure

CERN cluster (HTCondor)

- ~10^5 CPU cores
- ~100 (modern) GPUs
- Group priority system
- Xsuite GPU capabilities ready, but unexploited by community

INFN Bologna & CERN slurm cluster (slurm)

- ~800 CPU cores
- 4 GPUs
- Designed for many-core CPU jobs (MPI, OpenMP)
- No priority system (first come first served)

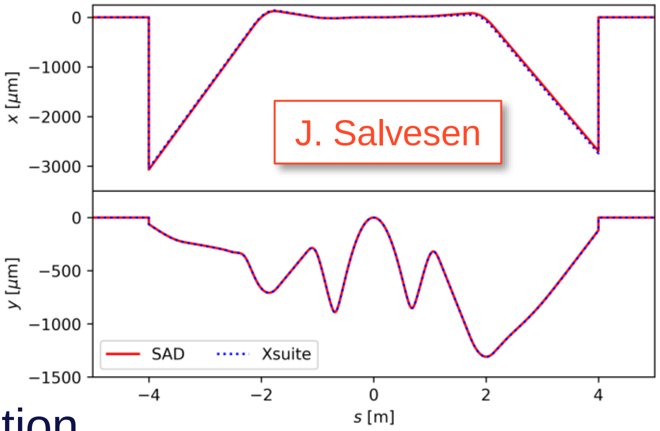
Other resources

- CERN slurm cluster (hpcbatch)
- CEA cluster in France
- Xboinc: volunteer computing
- CSCS: Swiss National Supercomputing Centre

Current priorities

- SAD-like solenoid (coordinates transformed depending on orbit) for polarization studies

Y. Wu, J. Salvesen talk @ this conference



J. Salvesen

- Standardized lattice knobs for IP tuning & correction

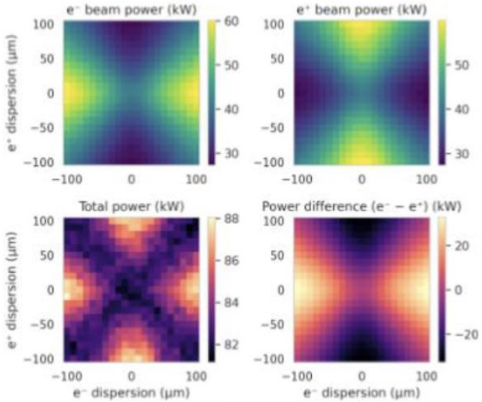
J. Keintzel, S. Jagabathuni, L. van Riesen-Haupt talk @ this conference

V. Gawas poster @ this conference

- Pair production for IP feedback & tuning

- Better structuring of most common simulations with Xutil [1]: example scripts, tutorials

K. Skoufaris talk @ this conference



V. Gawas

Summary

- Xsuite: main tool for self consistent FCC-ee beam dynamics studies
- Most studies use weak-strong beam-beam model
- Longer studies (lifetime) could be replaced by shorter studies (DA)
- Standard setup and submission scripts, DA/MA, FMA evaluation tools are being developed
- GPUs are needed but currently under utilized for FCC-ee studies

Thank you!

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[2] PyHEADTAIL
https://github.com/PyCOMPLETE/PyHEADTAIL

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[5] K. Le Nguyen Nguyen et al., Impact of bunch intensity asymmetry in colliders featuring strong beamstrahlung
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[6] P. Kicsiny et al., Incoherent horizontal emittance growth due to the interplay of beam-beam interaction and longitudinal wakefield in crab-waist colliders
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References slide 12

[1] K. Skoufaris, Xsuite utility toolkit (Xutil)
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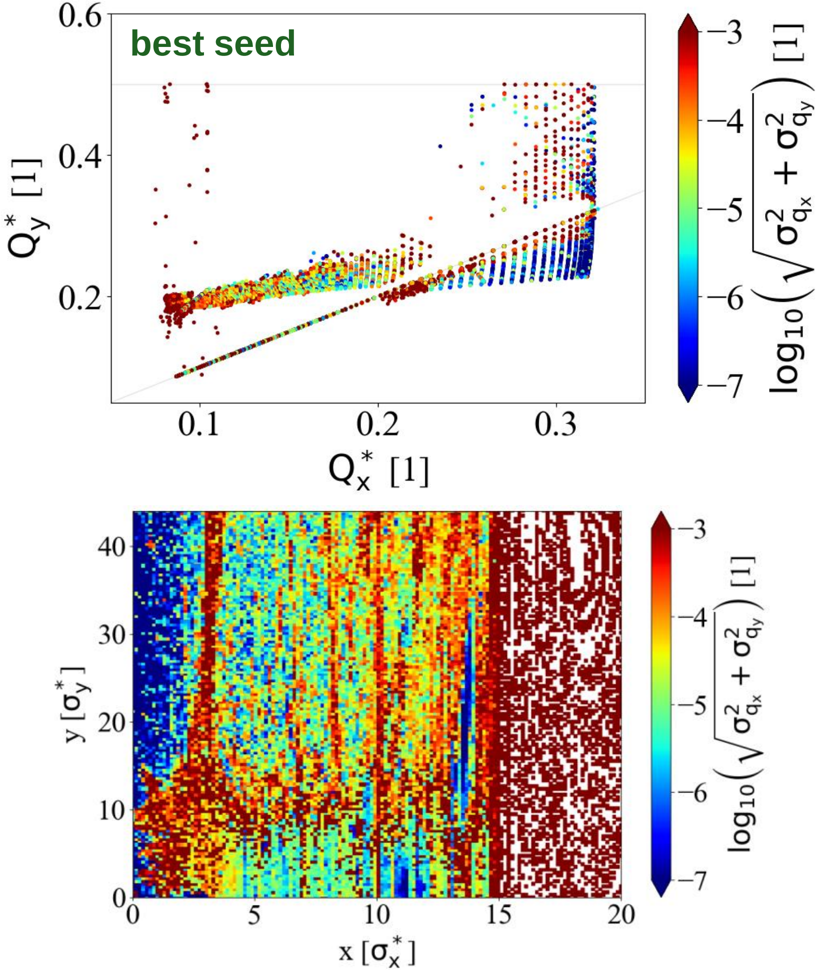
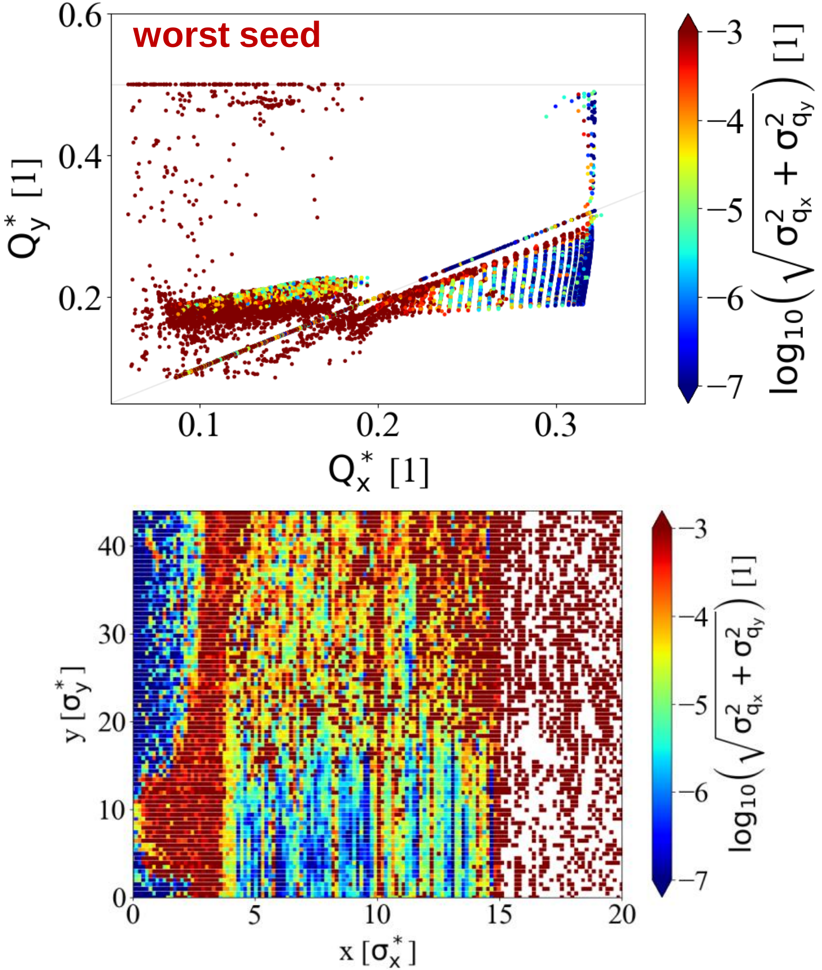
BACKUP

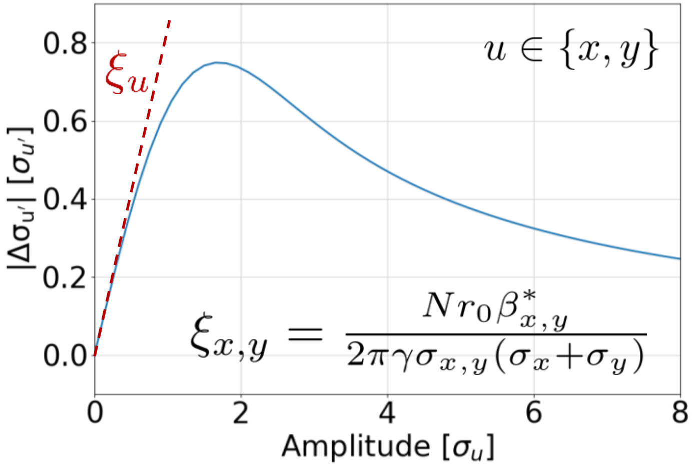

best seed
0.6
0.4
0.2
Q_y^* [1]
0.1
0.2
0.3
Q_x^* [1]
−3
−4
−5
−6
−7
$\log_{10}\left(\sqrt{\sigma_{q_x}^2+\sigma_{q_y}^2}\right)$ [1]
0
10
20
30
40
y [σ_y^*]
0
5
10
15
20
x [σ_x^*]
−3
−4
−5
−6
−7
$\log_{10}\left(\sqrt{\sigma_{q_x}^2+\sigma_{q_y}^2}\right)$ [1]

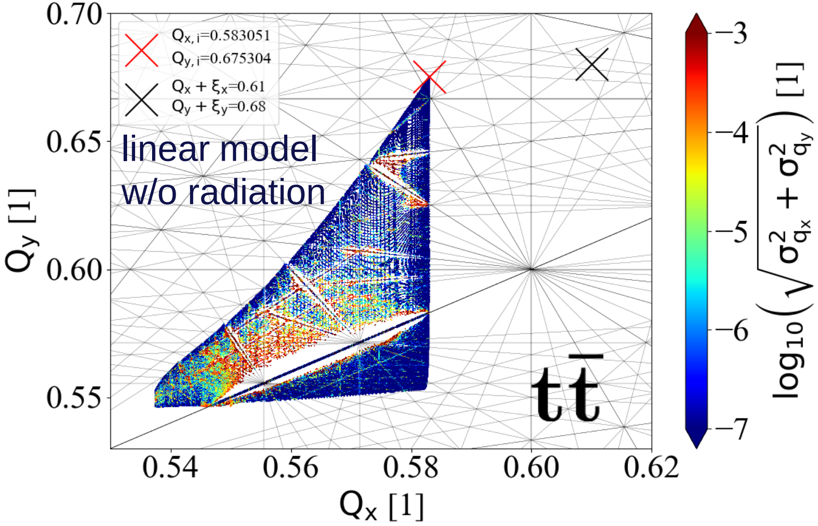

worst seed
0.6
0.4
0.2
Q_y^* [1]
0.1
0.2
0.3
Q_x^* [1]
−3
−4
−5
−6
−7
$\log_{10}\left(\sqrt{\sigma_{q_x}^2+\sigma_{q_y}^2}\right)$ [1]
0
10
20
30
40
y [σ_y^*]
0
5
10
15
20
x [σ_x^*]
−3
−4
−5
−6
−7
$\log_{10}\left(\sqrt{\sigma_{q_x}^2+\sigma_{q_y}^2}\right)$ [1]

Beam-beam force

High lumi ➡ strong beam-beam force

$$L = \frac{\gamma}{2er_e}\cdot\frac{I_{tot}\xi_y}{\beta_y^*}\cdot R_{hg}$$

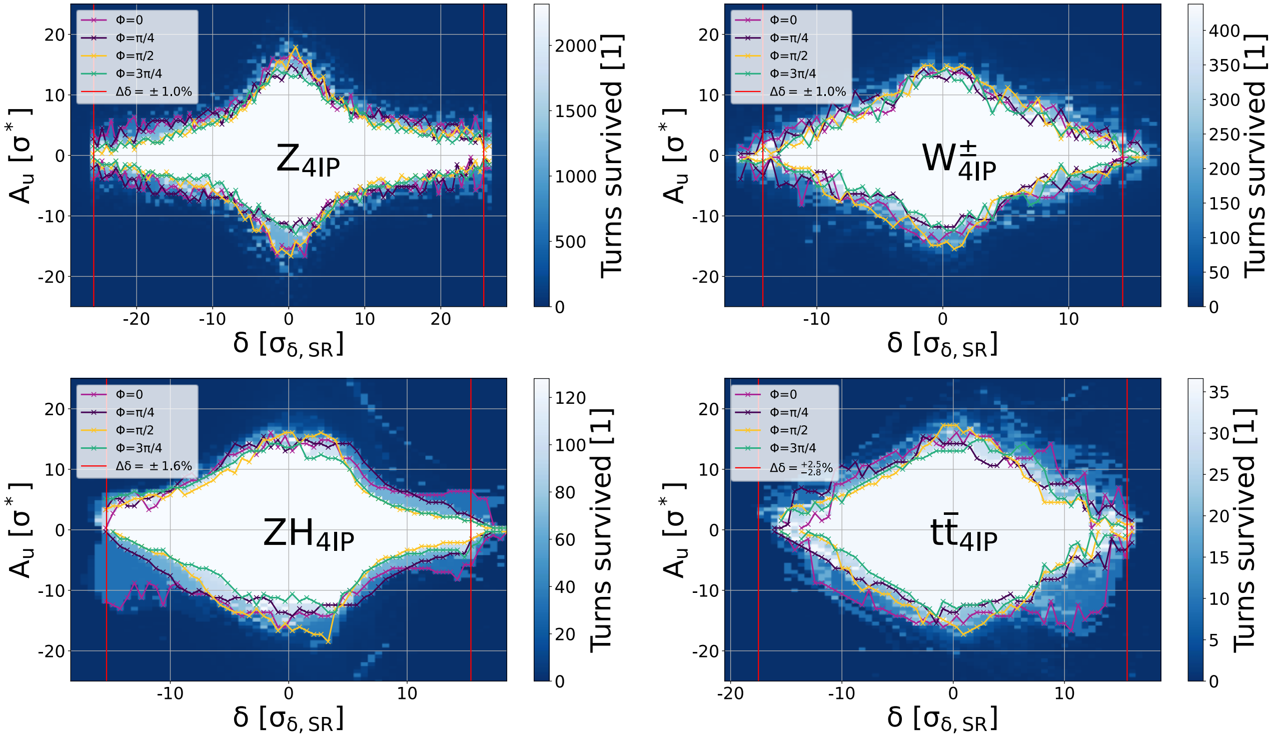




Consolidation...

- Radiation (synchrotron radiation, beamstrahlung, Bhabha)
- IP tuning & feedback
- Beam asymmetries
- Top-up injection

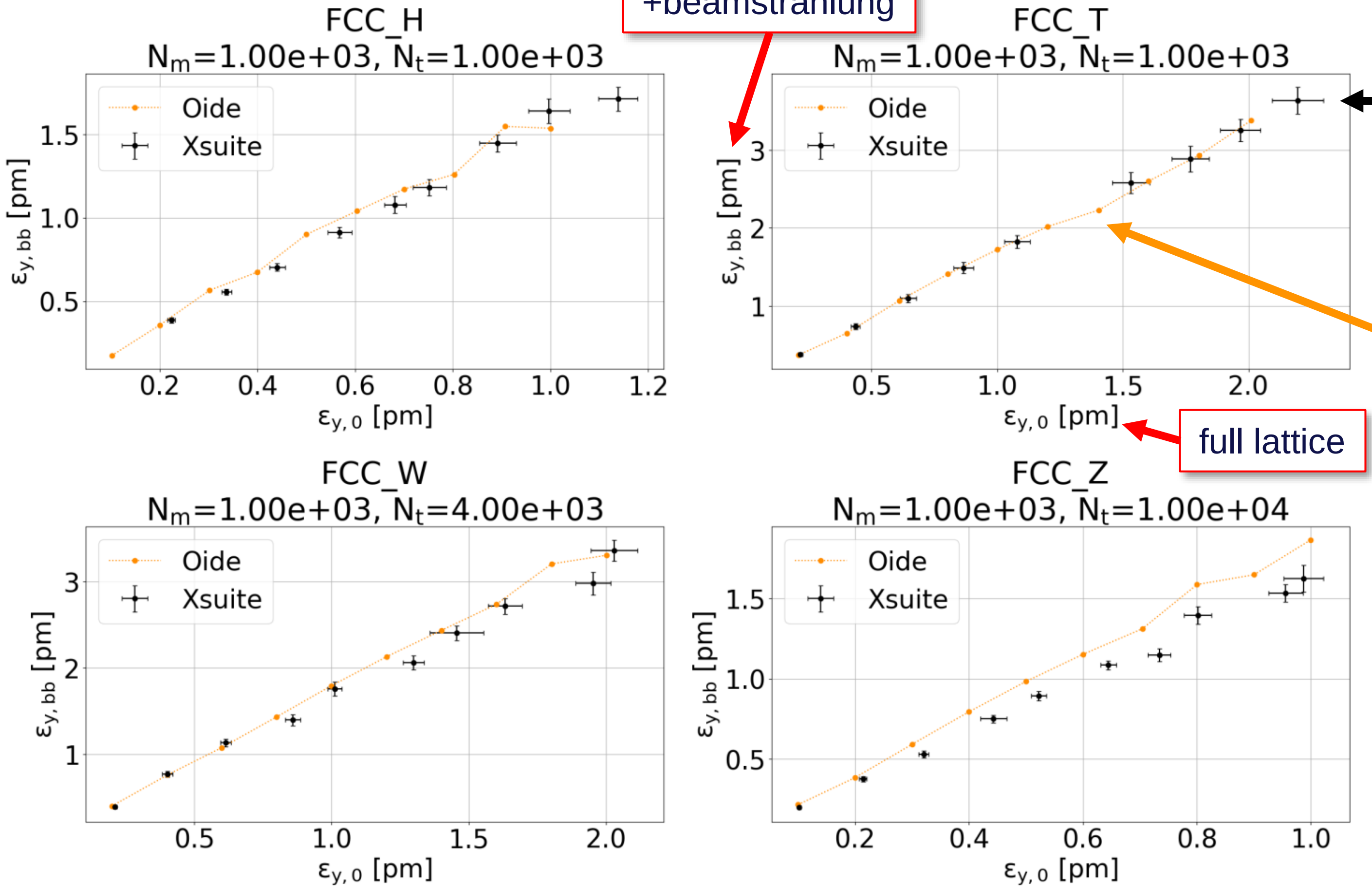
Dynamic aperture with beam-beam



$$A_u = \sqrt{\left(\frac{u}{\sigma_u^*}\right)^2 + \left(\frac{p_u}{\sigma_{p_u}^*}\right)^2}$$

$$u \in \{x, y\}$$

Vertical emittance



w/ beam-beam
+beamstrahlung

Xsuite tracking

error bars:
stat. of last 2500 turns

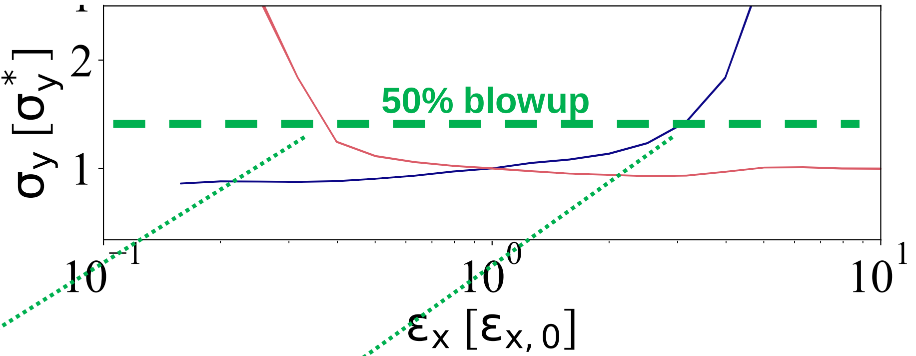
Reference data
by K. Oide

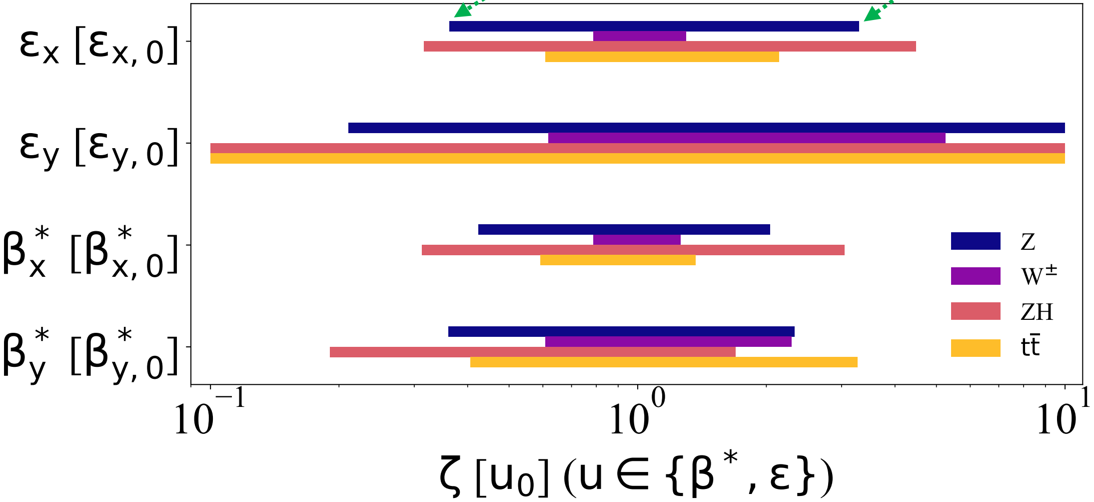
full lattice

- Independent benchmarks with SAD & Xsuite
- Good agreement

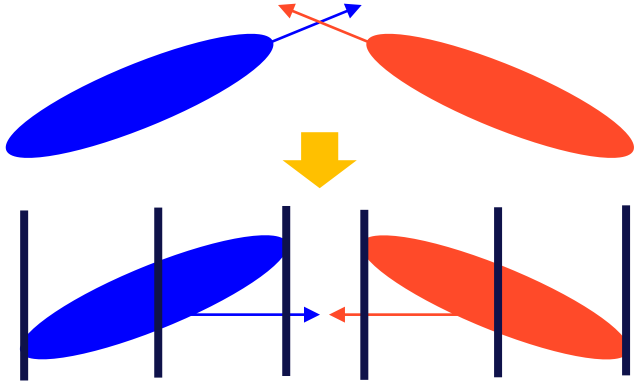
Tolerances to parameter asymmetries

- fixed bunch: init. with nominal parameter u_0
- perturbed bunch: init. with $u=\zeta u_0$ & scan ζ
- Track with linear transfer map until equilibrium
- Tolerance: 50% blowup in σ_y w.r.t. $\zeta=1$ case





Beam-beam in Xsuite



1. Lorentz transform into head-on frame

2. Longitudinal slicing

3. Beam-beam kick in soft-Gaussian approximation [4]

$$\Delta y' + i\Delta x' = \frac{N r_0 \sqrt{2\pi}}{\gamma\sqrt{\sigma_x{}^2-\sigma_y{}^2}}\left(\mathrm{w}\left[\frac{x+iy}{\sqrt{2(\sigma_x{}^2-\sigma_y{}^2)}}\right] - \exp\left[-\frac{x^2}{2\sigma_x{}^2}-\frac{y^2}{2\sigma_y{}^2}\right]\cdot \mathrm{w}\left[\frac{x\frac{\sigma_y}{\sigma_x}+y\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x{}^2-\sigma_y{}^2)}}\right]\right)$$

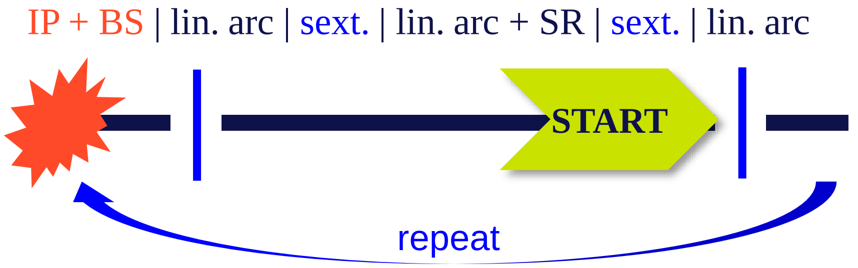
$$x' \leftarrow x' + \Delta x'$$
$$y' \leftarrow y' + \Delta y'$$

$$\mathrm{w}[t] = \exp\left[-t^2\right]\left(1 + \frac{2\mathrm{i}}{\sqrt{\pi}}\int_0^t \exp\left[u^2\right]\mathrm{d}u\right)$$

Simplified tracking simulations with Xsuite

- First studies with 2 IP baseline from CDR [5]
- Recent studies with 4 IP design from [6]

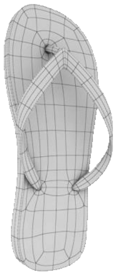
- Xsuite tracking setup:
  - 1 IP + tracking over arc superperiod with linear transfer matrix



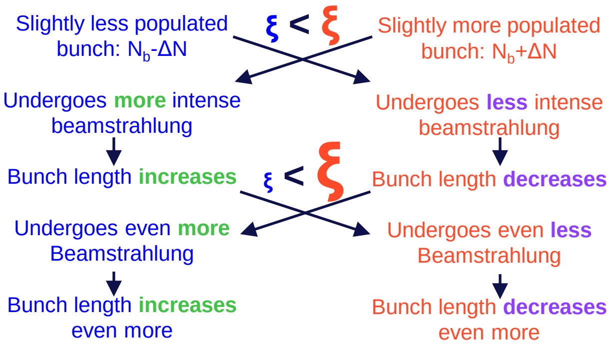
  - Arc split into 3 segments
  - 2 crab sextupoles between arc segments (β_x=3 m, β_y=500 m)
  - Each iteration begins in front of the right sextupole
    - Observation point for coordinates
  - Synchrotron radiation (damping+noise) in **arc**, beamstrahlung+bhabha scattering in **beam-beam element**

Flip-flop

- Flip-flop instability (1D) observed in other colliders (VEPP-2000) [7]



- For FCC-ee: 3D flip-flop - direct consequence of **beamstrahlung**, triggered by an initial asymmetry in **bunch intensity** [8]



Slightly less populated bunch: N_b-ΔN

$\xi < \xi$

Slightly more populated bunch: N_b+ΔN

Undergoes **more** intense beamstrahlung

Undergoes **less** intense beamstrahlung

Bunch length **increases**

$\xi < \xi$

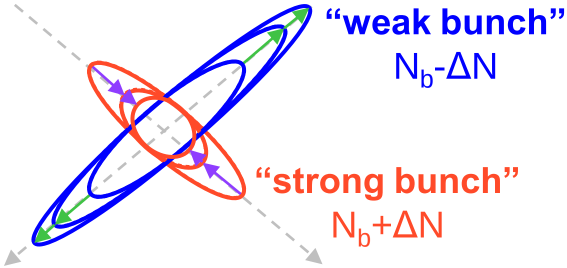
Bunch length **decreases**

Undergoes even **more** Beamstrahlung

Undergoes even **less** Beamstrahlung

Bunch length **increases** even more

Bunch length **decreases** even more



$$\xi \sim \frac{1}{\sigma_z}$$

- Inflation of one bunch → beam loss
- Above a threshold ξ_0 longitudinal blowup drives transverse diffusion → 3D flip-flop
- Relevant for FCC-ee top-up injection

Workflow for emittance scan – everything in Xsuite

Prepare Xtrack line once [6]:

- load MAD-X sequence [7]
- add wigglers
- convert to Xtrack line
- build + twiss 4D
- slice sequence
- build + twiss 4D
- save Xtrack line

Loop over a range of ε_y values:

- load Xtrack line
- add observation point @ RF
- build + twiss 4D
- twiss 6D mean synrad + tapering
- match ε_y
- twiss 6D mean synrad + tapering

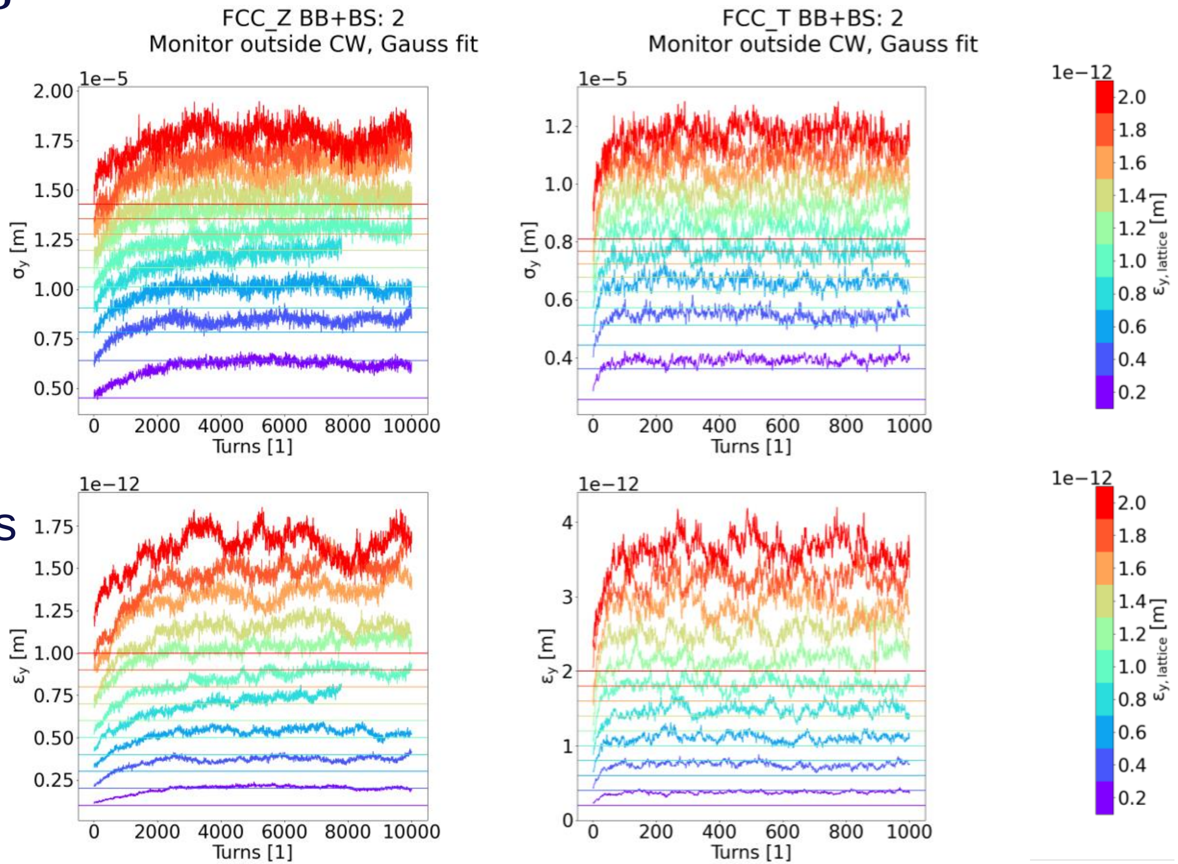
⋮

⋮

- add beam-beam element (optional)
- build
- set quantum synrad
- track
- repeat with next ε_y

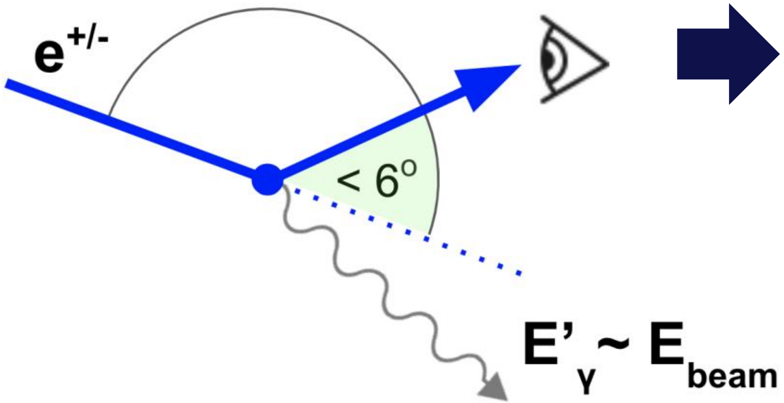
Emittance scan results

- Small discrepancy compared to SAD results
- Xsuite likely not yet converged
- Need more turns to see fully converged emittances



Small angle Bhabha scattering [6]

- Dominated by t-channel (scattering) process



➡ **luminosity** in lepton colliders

➡ primary particles lost within a turn

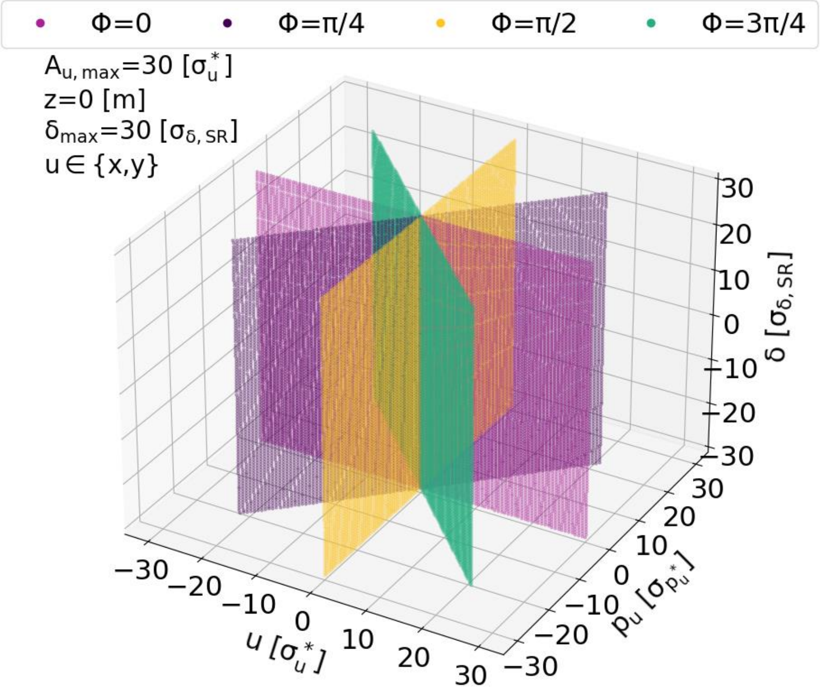
- Main limitation of FCC-ee **beam lifetime** (alongside beamstrahlung)

Bhabha lifetimes

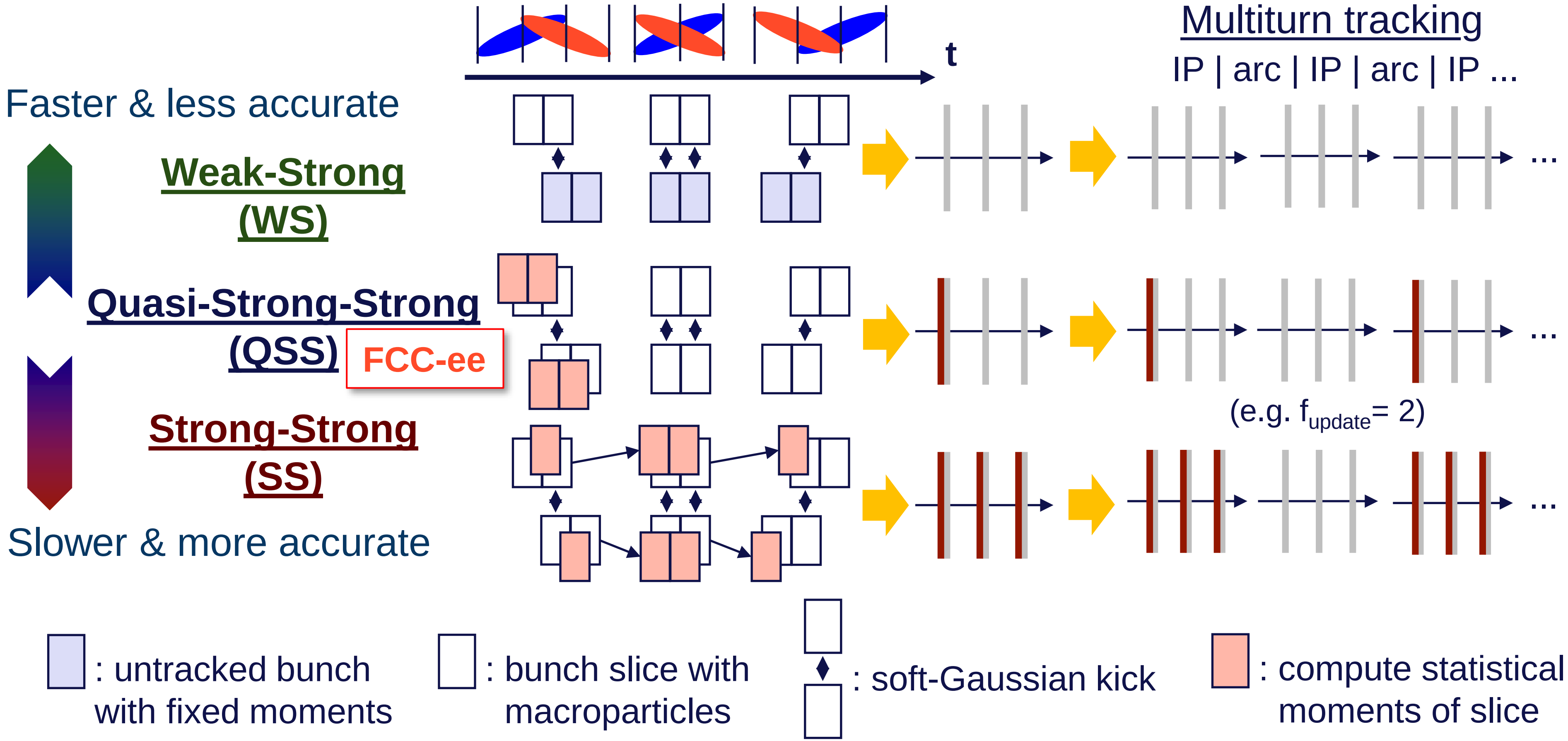
$$\frac{1}{\tau} = \frac{1}{N_b}\frac{dN_b}{dt} = \frac{1}{N_b}\sigma_{Bhabha} L_{inst} \cdot N_{IP} = \frac{1}{N_b} R_b \cdot f_{rev} \cdot N_{IP}$$

- τ: Bhabha lifetime [s]
- N_b: bunch intensity [1]
- σ_{Bhabha}: Bhabha cross section [m^2]
- N_{IP}: number of Ips [1]
- $L_{inst}=L*f_{rev}$: instantaneous lumi of 1 bunch crossing [m^-2 s^-1]
- L: integrated lumi of a single collision (luminosity per bunch crossing) [m^-2]
- f_{rev}: revolution frequency [s^-1]
- $R_b = \sigma_{Bhabha}*L$: number of emitted Bhabha photons with E above mom. acceptance [1]

Dynamic aperture test grid



Beam-beam in Xsuite



Multiturn tracking

IP | arc | IP | arc | IP ...

Faster & less accurate

Weak-Strong (WS)

Quasi-Strong-Strong (QSS)

FCC-ee

Strong-Strong (SS)

Slower & more accurate

(e.g. f_{update}= 2)

: untracked bunch with fixed moments

: bunch slice with macroparticles

: soft-Gaussian kick

: compute statistical moments of slice