

BEAM-BEAM EFFECTS AT THE FCC-ee

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for the beam-beam working group, with special thanks to:

H. Burkhardt, C. Carli, F. Carlier, M. Hofer, D. Schulte, M. Seidel, D. Shatilov, D. Zhou

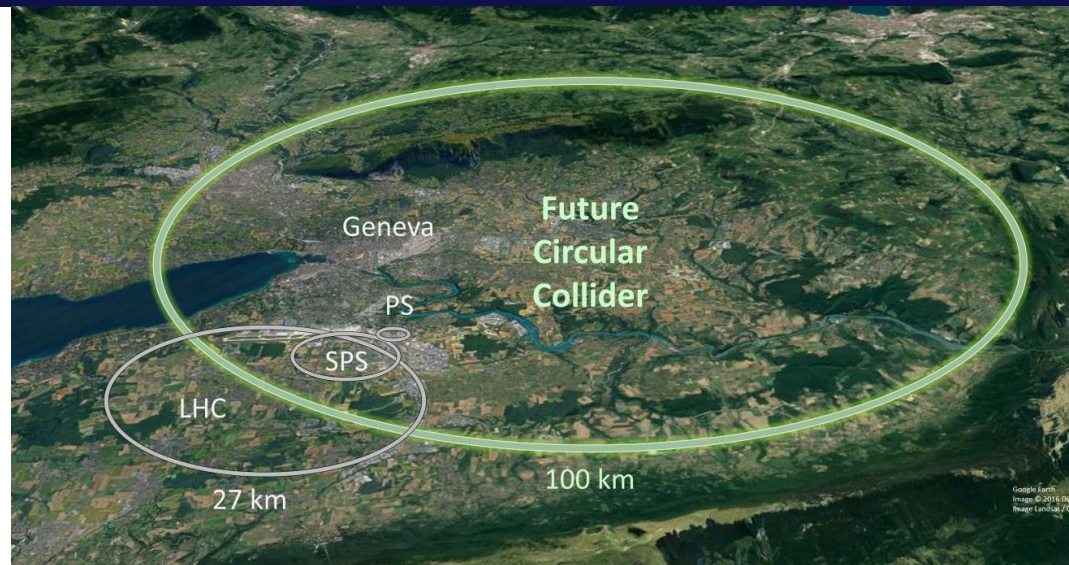
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FCC-ee

- Beam dynamics shaped by interplay of various effects: **impedances**, **machine errors**, **corrections**, **collimation**, **lattice nonlinearities**
- Presence of beam-beam collisions further complicates beam dynamics
- Self-consistent simulations are challenging



High precision
measurement
of Standard
Model particles






Next milestone:
feasibility study
report by
March 2025

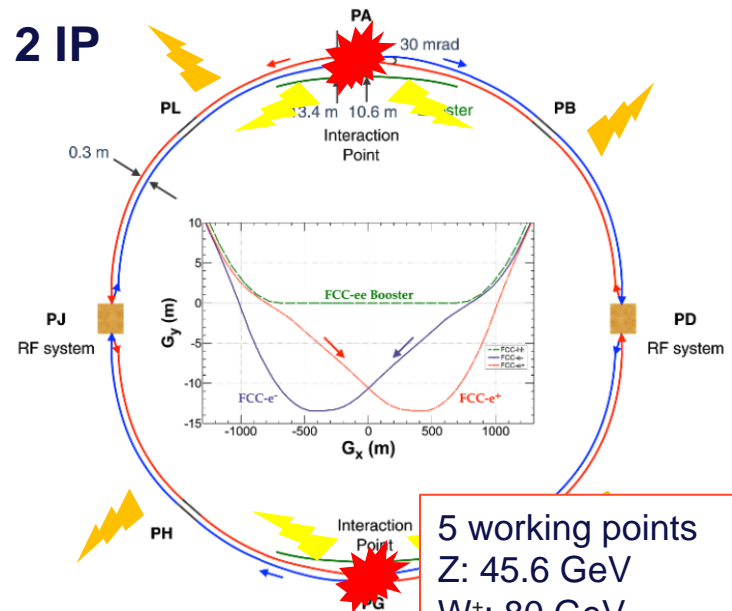


Decision on
approval:
~2028

FCC-ee design

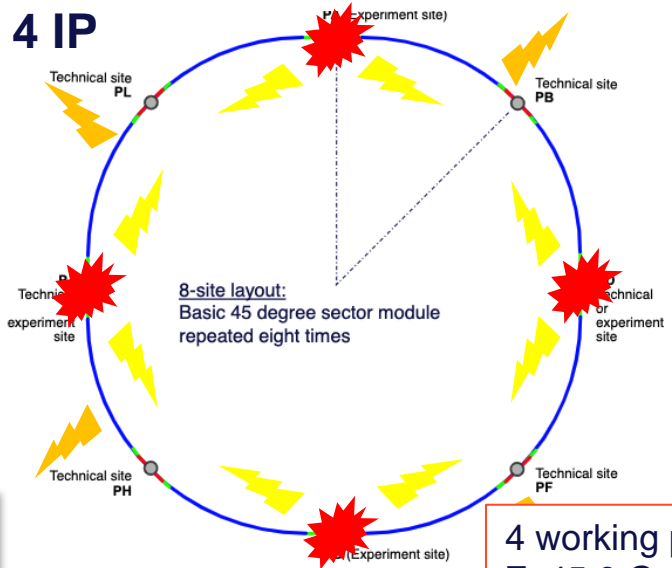
-  Interaction point (IP)
-  Synchrotron radiation
-  Beamstrahlung + radiative Bhabha scattering

2 IP



5 working points
 Z: 45.6 GeV
 W $^\pm$: 80 GeV
 ZH: 120 GeV
 ttbar 1: 175 GeV
 ttbar 2: 182.5 GeV

4 IP



4 working points
 Z: 45.6 GeV
 W $^\pm$: 80 GeV
 ZH: 120 GeV
 ttbar: 182.5 GeV

Design studies so far

- Design strategy: balancing several effects
 - Past studies on parameter optimization [1,2]
 - Increase luminosity by keeping lifetime long enough & avoid instabilities
- Constraint on beam current: 50 MW synchrotron radiation power supply
 - Constrains beam parameters at IP
- In general: high energy & charge density



beamstrahlung limited
non-Gaussian tails
reduced beam lifetime

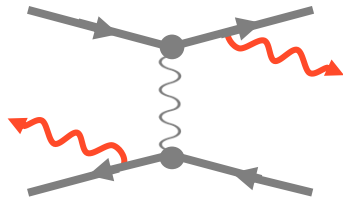
$$\langle \Upsilon \rangle = \frac{5}{6} \frac{Nr_e^2 \gamma}{\alpha(\sigma_x + \sigma_y)\sigma_z}$$

	LEP	SuperKEKB	FCC-ee	CLIC
Avg. BS parameter	$\langle Y \rangle \sim 10^{-5}$ [3]	$\langle Y \rangle \sim 10^{-6}$ [4]	$\langle Y \rangle \sim 10^{-4}$ [5]	$\langle Y \rangle > 10^{-1}$ [6]
Beam lifetime	~5 hours [7]	~10 minutes [8]	~20 minutes [5]	-

Radiation at FCC-ee collisions

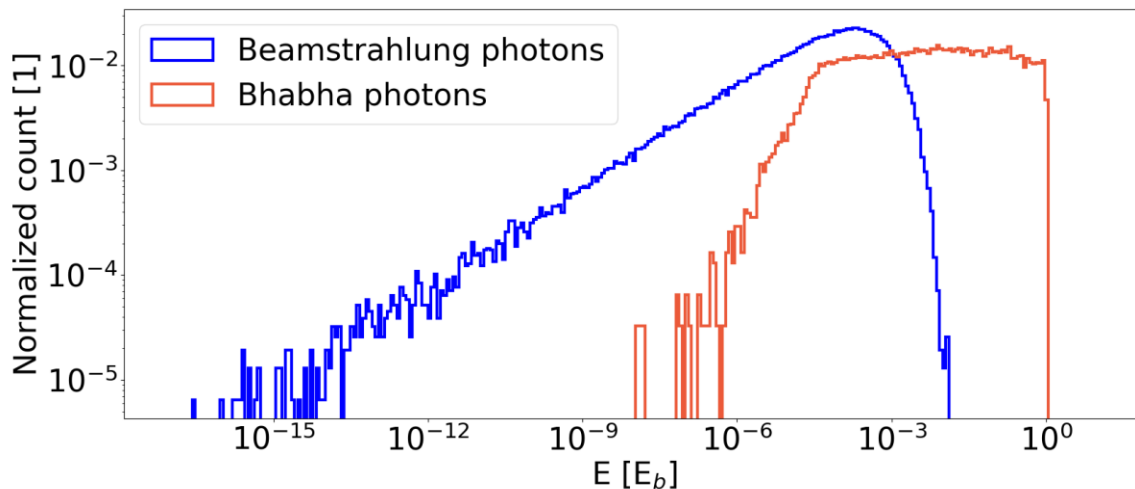
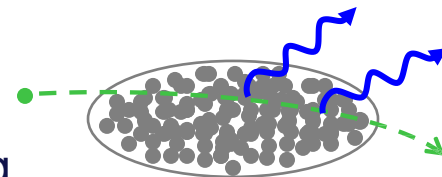
Incoherent

- Radiative Bhabha scattering
- Deflection in field of single particle of opposite bunch



Collective

- Beamstrahlung
- Deflection in collective field of opposite bunch



- Radiation particle losses

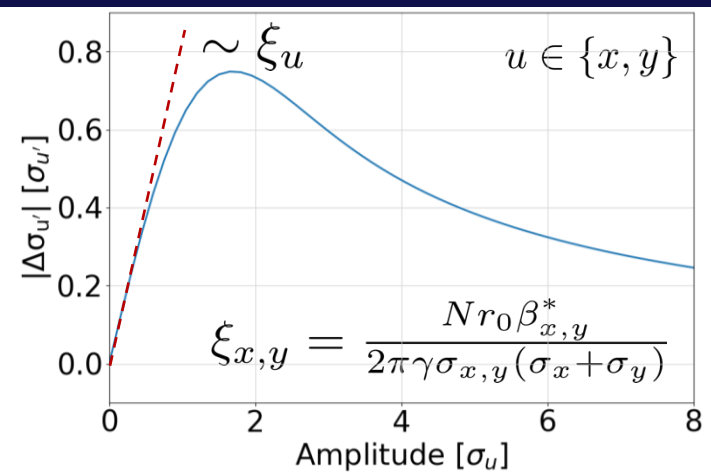
$$\tau \mathcal{L} \Downarrow \quad \sigma_z \sigma_\delta \Uparrow$$

Beamstrahlung + radiative Bhabha dominate beam lifetime @ FCC-ee

Beam-beam force

High lumi  strong beam-beam force

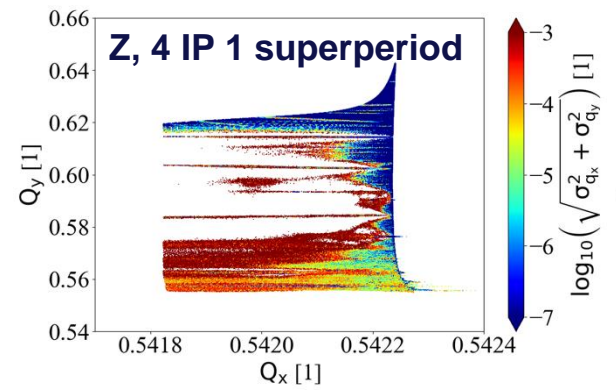
$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot} \xi_y}{\beta_y^*} \cdot R_{hg}$$



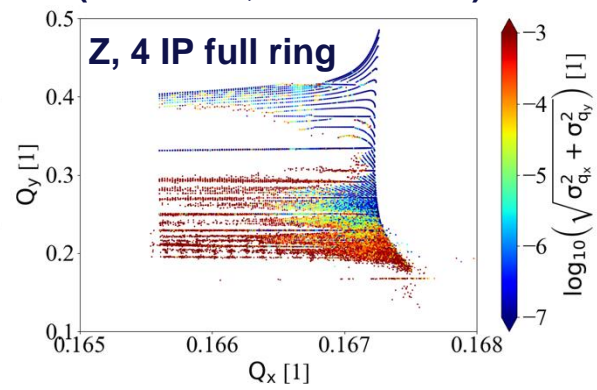
Consolidation...

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

linear model
(no errors, no radiation)



full lattice
(no errors, no radiation)



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

	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 [9]	Available	Not available	Not available	Available	Available	Not available	Not available	Not available	Not available	Available	Not available	Not available
COMBI [10]	Available	Available	Available	Not available	Not available	Available	Not available	Available	Not available	Available	Not available	Not available
BBWS [11]	Available	Not available	Not available	Available	Not available	Available	Available	Available	Available	Not available	Not available	Not available
BBSS [12]	Not available	Not available	Available	Available	Available	Available	Available	Available	Not available	Not available	Not available	Not available
SCTR [13]	Not available	Not available	Available	Available	Not available	Available	Available	Available	Available	Not available	Available	Not available
IBB [14]	Not available	Not available	Available	Not available	Available	Available	Available	Available	Not available	Not available	Not available	Not available
LIFETRAC [15]	Available	Available	Not available	Available	Not available	Not available	Available	Available	Available	Not available	Not available	Not available
BeamBeam3D [16]	Available	Not available	Available	Available	Not available	Available	Not available	Available	Not available	Available	Not available	Not available
Xsuite [17]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available

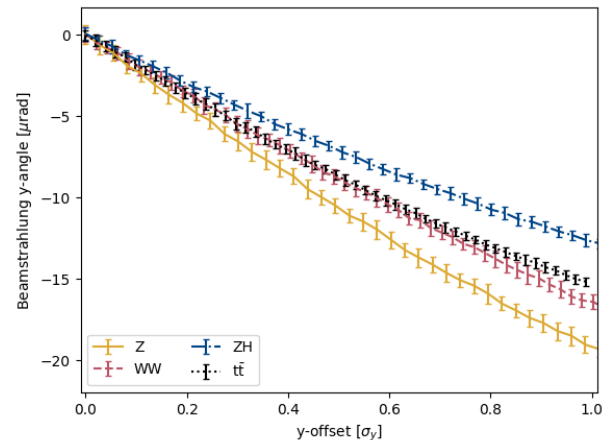
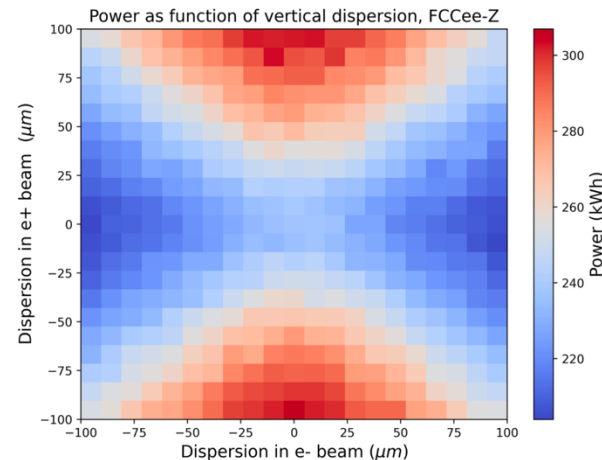
Available
Not available

- 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
 - GPU & multi CPU support

IP tuning & optimization [18, 19]

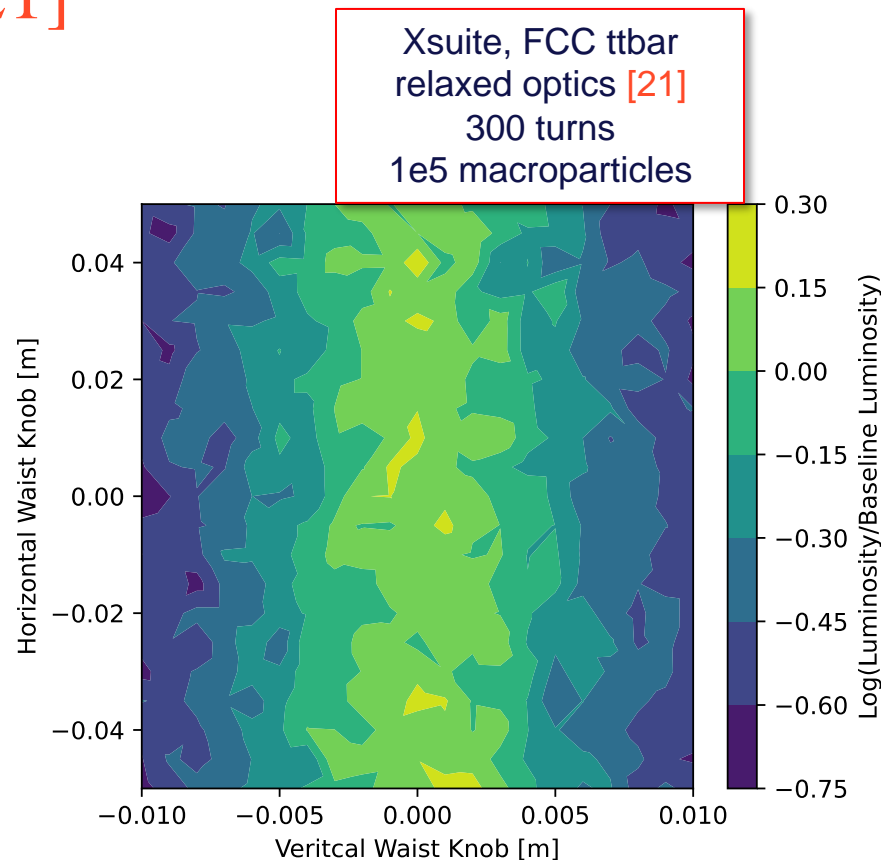
Design schemes to infer and correct for imperfections based on different signals (radiation, orbit measurements, ...)

- Waist & dispersion shifts, beam offsets (fast IP feedback)
- Using GUINEA-PIG (single passage), multiturn effects with Xsuite need to be considered



IP tuning & optimization [20, 21]

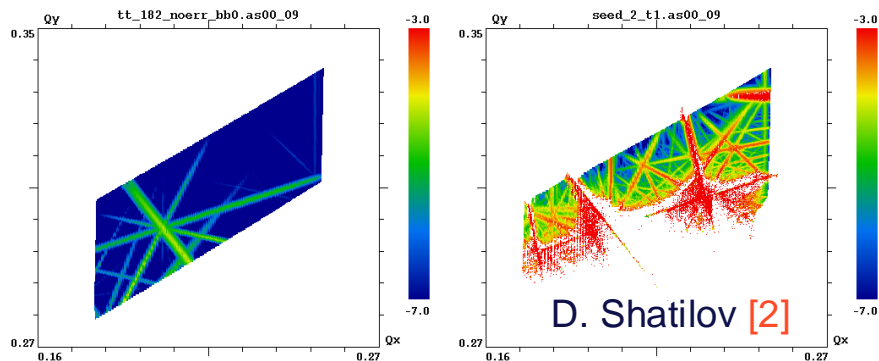
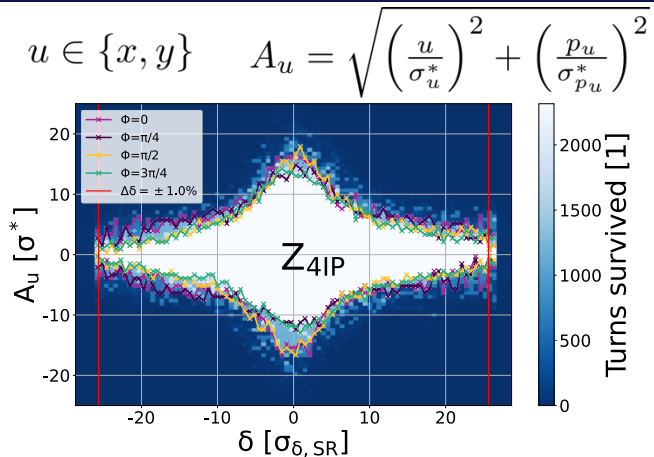
- Development of tuning knobs to vary beam configuration at the IP (waist)
- Determine whether optics can be relaxed for better performance (e.g. easier startup)
- Design experimental methods for waist correction based on luminosity
- Larger sensitivity in luminosity for vertical but smaller in horizontal waist
- Tests with machine errors in progress



Dynamic aperture [22]

w/o errors

- Negligible reduction from beam-beam
- Compares well with SAD results from K. Oide [5]



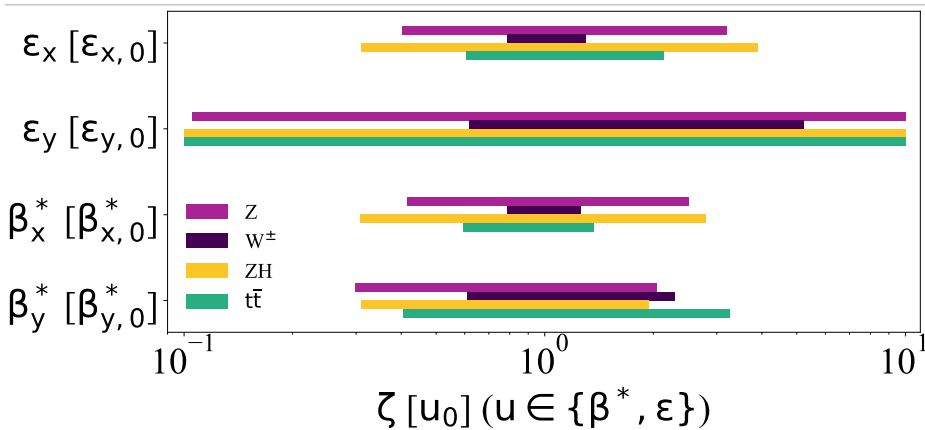
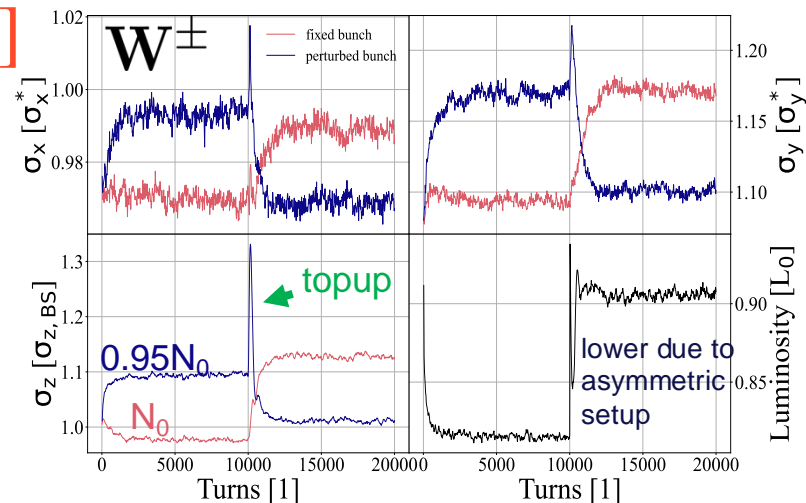
w/ errors & corrections

- More lattice induced resonances are seen with beam-beam due to large amplitude detuning
- Full lattice needs to be optimized with beam-beam included
- Tools are ready, requires work with tuning working group to establish correction strategies [23]

Top-up injection & asymmetry [24]

Longitudinal top-up simulated with Xsuite

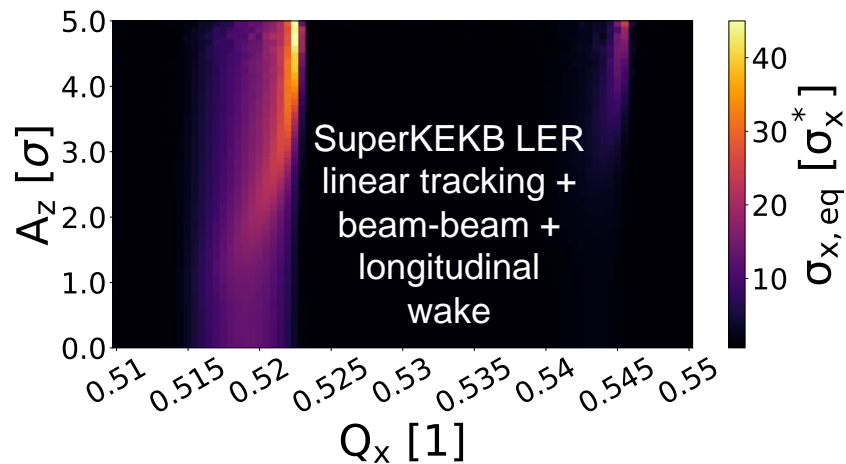
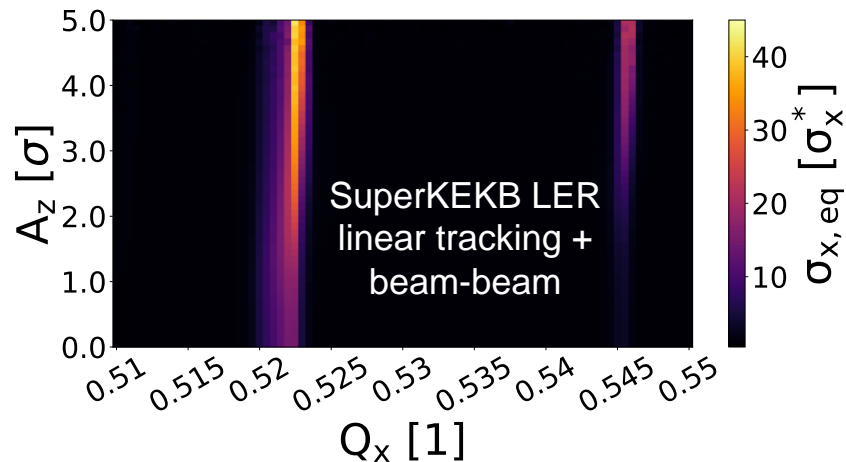
- Perturbed bunch initialized with 95% intensity
- Track till equilibrium & top-up
- Luminosity lower than in symmetric case (L_0) due to vertical blowup
 - Should be avoided (e.g. working point optimization)



- Evaluate asymmetries in emittance/beta leading to 50% vertical blowup
- Derived coarse tolerances for machine tuning
 - Some seem hard to reach e.g. for W
 - Working point needs to be optimized

Case study at the SuperKEKB

- Beam-beam excites synchro-betatron resonances (collective [25], here single particle)
- Interplay with longitudinal wakefield enhances amplitude dependent incoherent x-z resonance
 - Impact on FCC-ee W [26]? (high Q_s)
- Successful Xsuite benchmarks against BBWS, BBSS, PyHEADTAIL
- Crab-waist imperfections [27]
- Transverse impedance + beam-beam @ FCC-ee [28]



Summary

Work so far

- Xsuite beam-beam model developed:
 - Benchmarked against other codes GUINEA-PIG, BBWS, BBSS, PyHEADTAIL, COMBI, BBBREM, SAD, MAD-X
 - Tools are ready to combine beam-beam + lattice / IP + errors & tuning
 - Consolidated tolerances for asymmetries (bunch intensity, emittance, beta)

Lots of work still ahead...

- Errors & misalignments + beam-beam: needed for realistic estimates
- Parameter optimization of FCC-ee W
- IP tuning with multiturn tracking
- Beam-beam + transverse impedances

Thank you!

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BACKUP

Simulation parameters

Slide #	10	11/upper	11/lower	12
Machine setup	FCC 4 IP baseline	FCC 4 IP baseline, W	FCC 4 IP baseline	SuperKEKB LER
Lattice model	nonlinear	linear	linear	linear
Beam-beam model	weak-strong	1 st part: quasi-strong-strong ($f_{\text{update}}=100$), 2 nd part: strong-strong	quasi-strong-strong ($f_{\text{update}}=100$)	strong-strong
# slices in beam-beam	100 (200 for Z)	100	100 (200 for Z)	100
# macroparticles	4e4	1e5	1e5 (1e6 for Z)	1e5
# turns	2x SR damping time	2e4	1e4 (Z, W), 5e3 (H, T)	2e4

Previous parameters (July 2023 almost for MTR)

FCC-ee collider parameters as of July 30, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	[10 ¹¹]	2.14	1.45	1.32	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\text{lattice}}$	[pm]	0.85	1.25	0.65	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10 ⁻⁶]	28.6		7.4	
Arc sext families		75		146	
$\beta_{x/y}^*$	[mm]	110 / 0.7	220 / 1	240 / 1	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.360	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y^a		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Piwnski angle $(\theta_x\sigma_x, \text{BS})/\sigma_x^*$		26.4	3.7	5.4	0.99
Lifetime (q + BS + lattice)	[sec]	10000	4000	3500	3000
Lifetime (lum) ^b	[sec]	1330	970	660	650
Luminosity / IP	[10 ³⁴ /cm ² s]	141	20	6.3	1.38
Luminosity / IP (CDR)	[10 ³⁴ /cm ² s]	230	28	8.5	1.8

^aincl. hourglass.

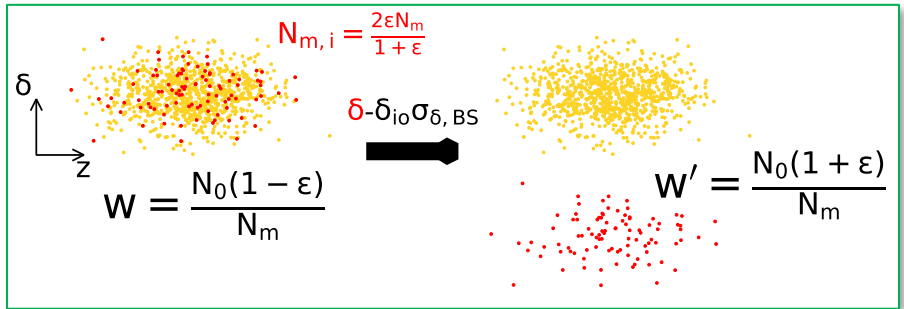
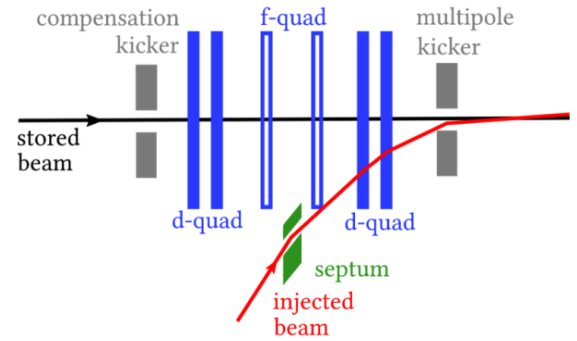
^bonly the energy acceptance is taken into account for the cross section

Top-up injection

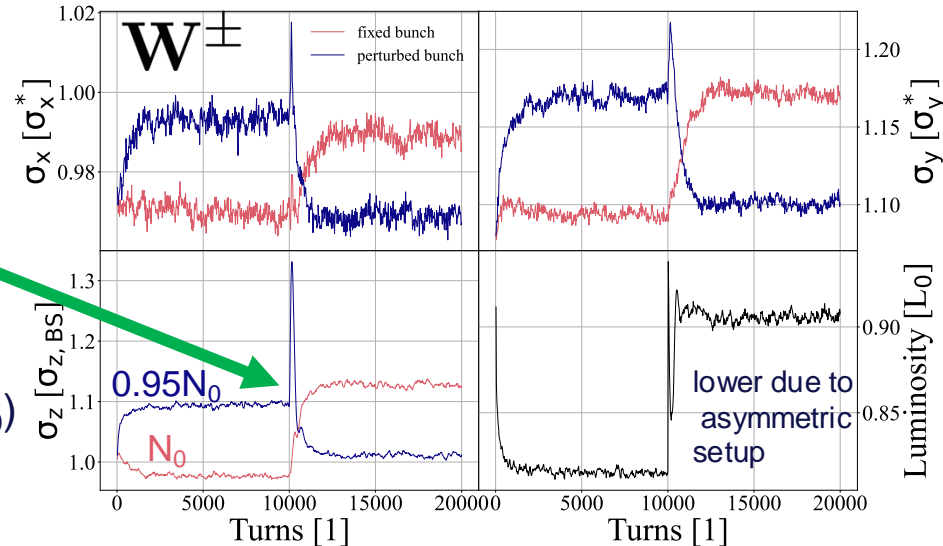
- Maintains luminosity levels & compensates for decreased beam lifetime
- Single booster feeds both beams

Longitudinal top-up simulated with Xsuite

- Perturbed bunch init. with 95% intensity
- Track till equilibrium & top-up



- Luminosity lower than in symmetric case (L_0)
 - This reduction cannot be avoided but currently not taken into account in design

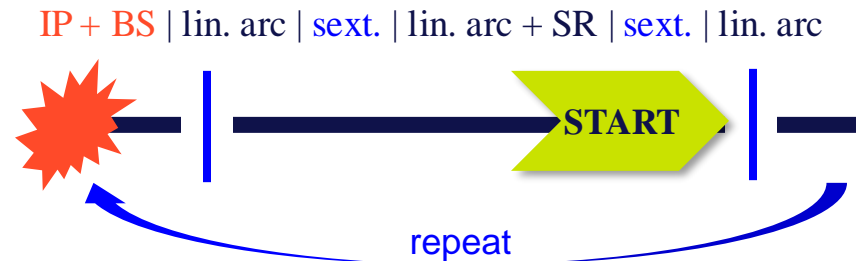


Simplified tracking simulations with Xsuite

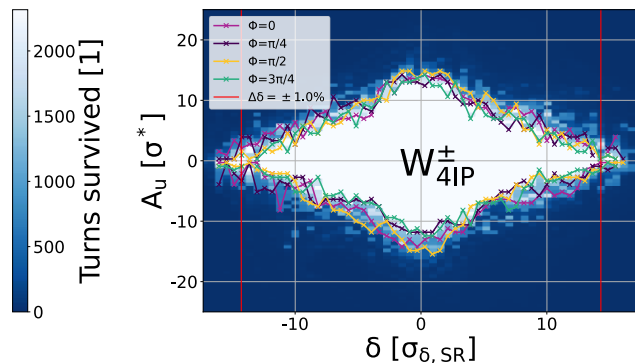
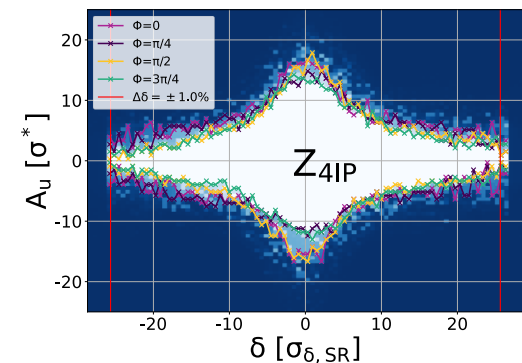
- First studies with 2 IP baseline from CDR
- Recent studies with 4 IP design

- Xsuite tracking setup:

- 1 IP + tracking over arc superperiod with linear transfer matrix
- Arc split into 3 segments
- 2 crab sextupoles between arc segments ($\beta_x=3$ m, $\beta_y=500$ 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**

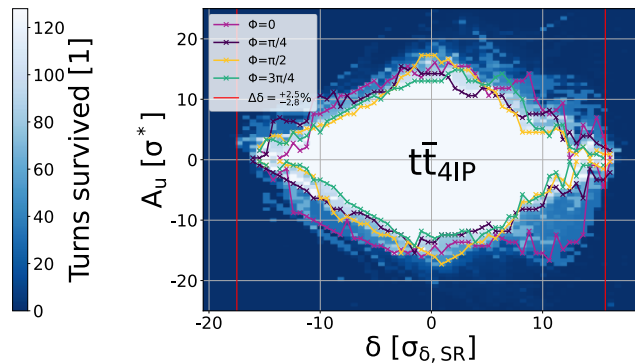
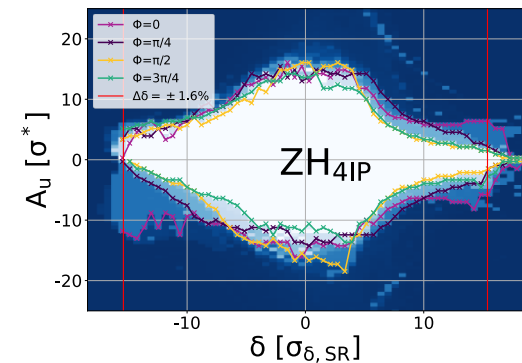


Dynamic aperture with beam-beam

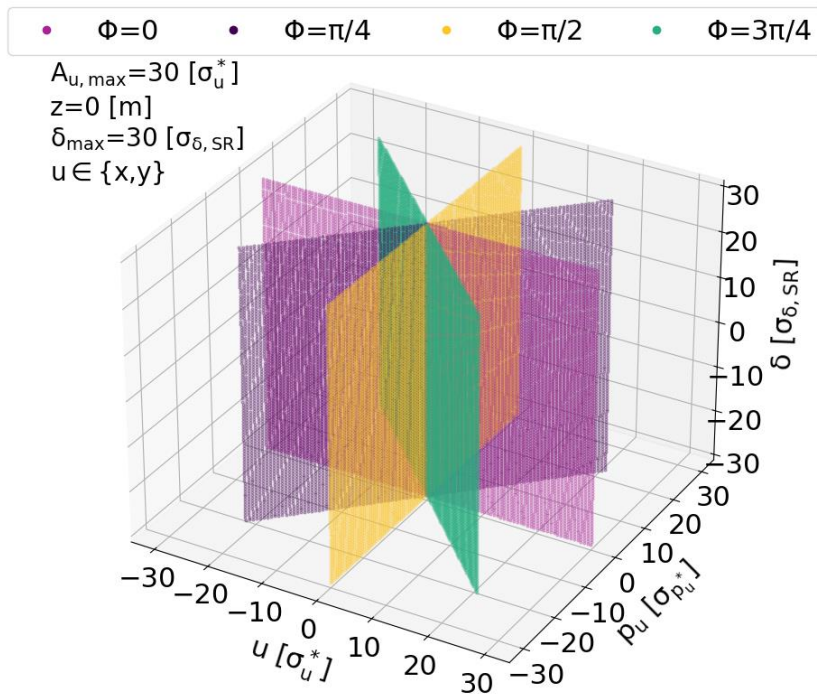


$$A_u = \sqrt{\left(\frac{u}{\sigma_u^*}\right)^2 + \left(\frac{p_u}{\sigma_{p_u}^*}\right)^2}$$

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

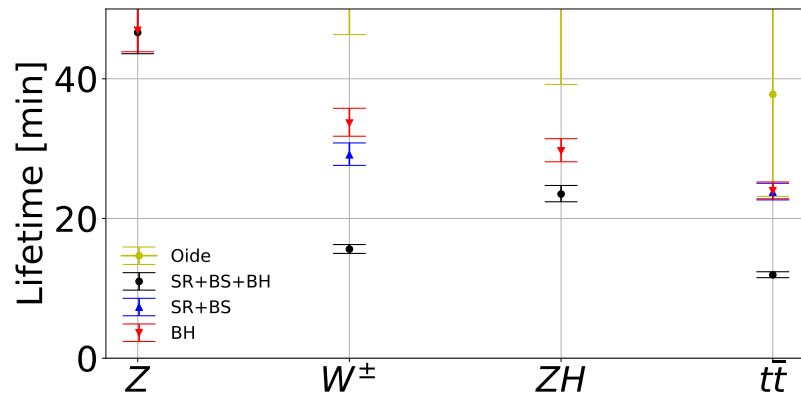
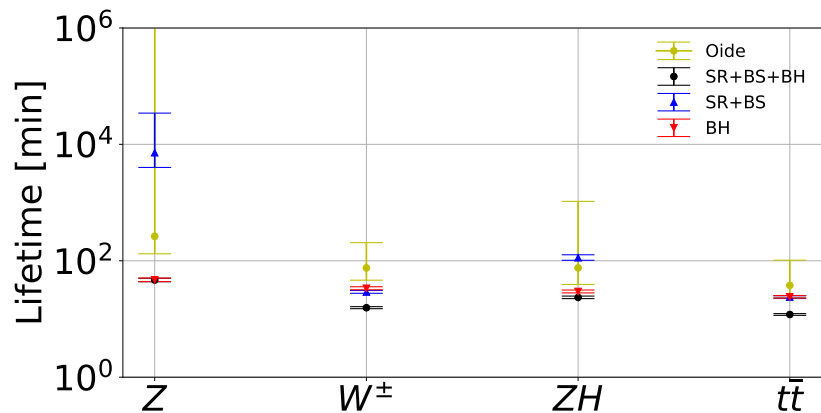


Dynamic aperture test grid



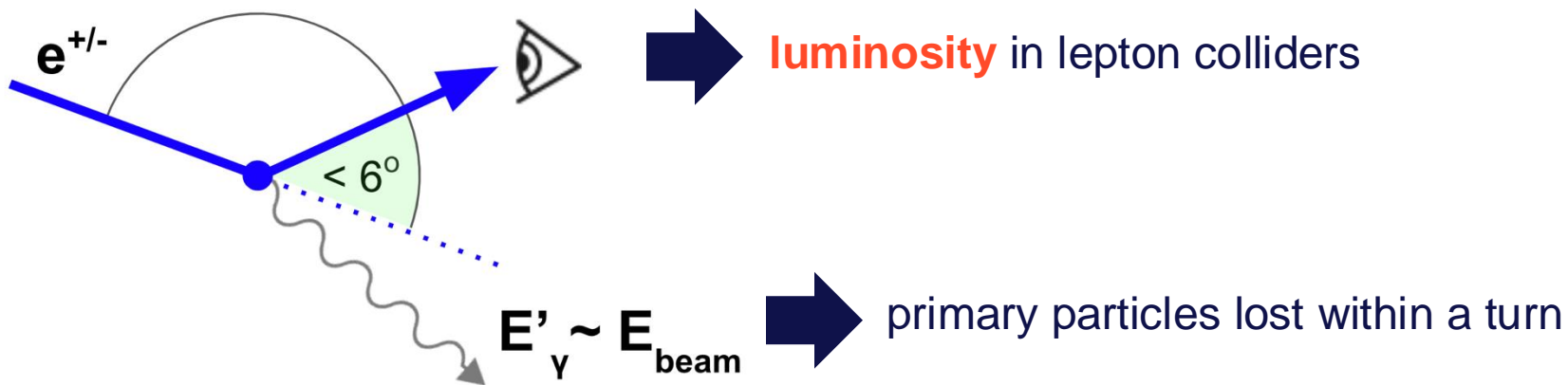
Beam lifetime

- Full lattice tracking
- No errors



Small angle Bhabha scattering

- Dominated by t-channel (scattering) process



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

Bhabha lifetimes

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

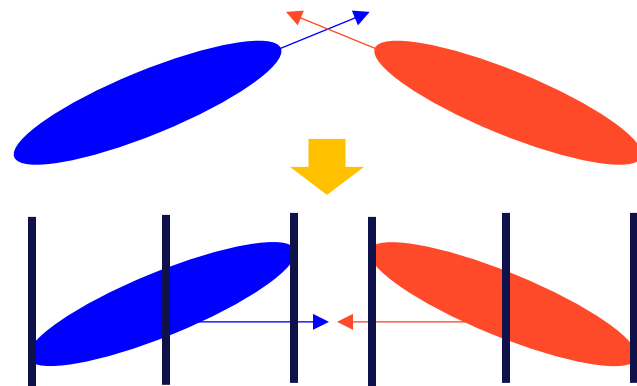
- τ : Bhabha lifetime [s]
- N_b : bunch intensity [1]
- σ_{Bhabha} : Bhabha cross section [m²]
- N_{IP} : number of Ips [1]
- $L_{\text{inst}} = L \cdot f_{\text{rev}}$: instantaneous lumi of 1 bunch crossing [m⁻² s⁻¹]
- L : integrated lumi of a single collision (luminosity per bunch crossing) [m⁻²]
- f_{rev} : revolution frequency [s⁻¹]
- $R_b = \sigma_{\text{Bhabha}} \cdot L$: number of emitted Bhabha photons with E above mom. acceptance [1]

Beam-beam in Xsuite

1. Lorentz transform into head-on frame

2. Longitudinal slicing

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



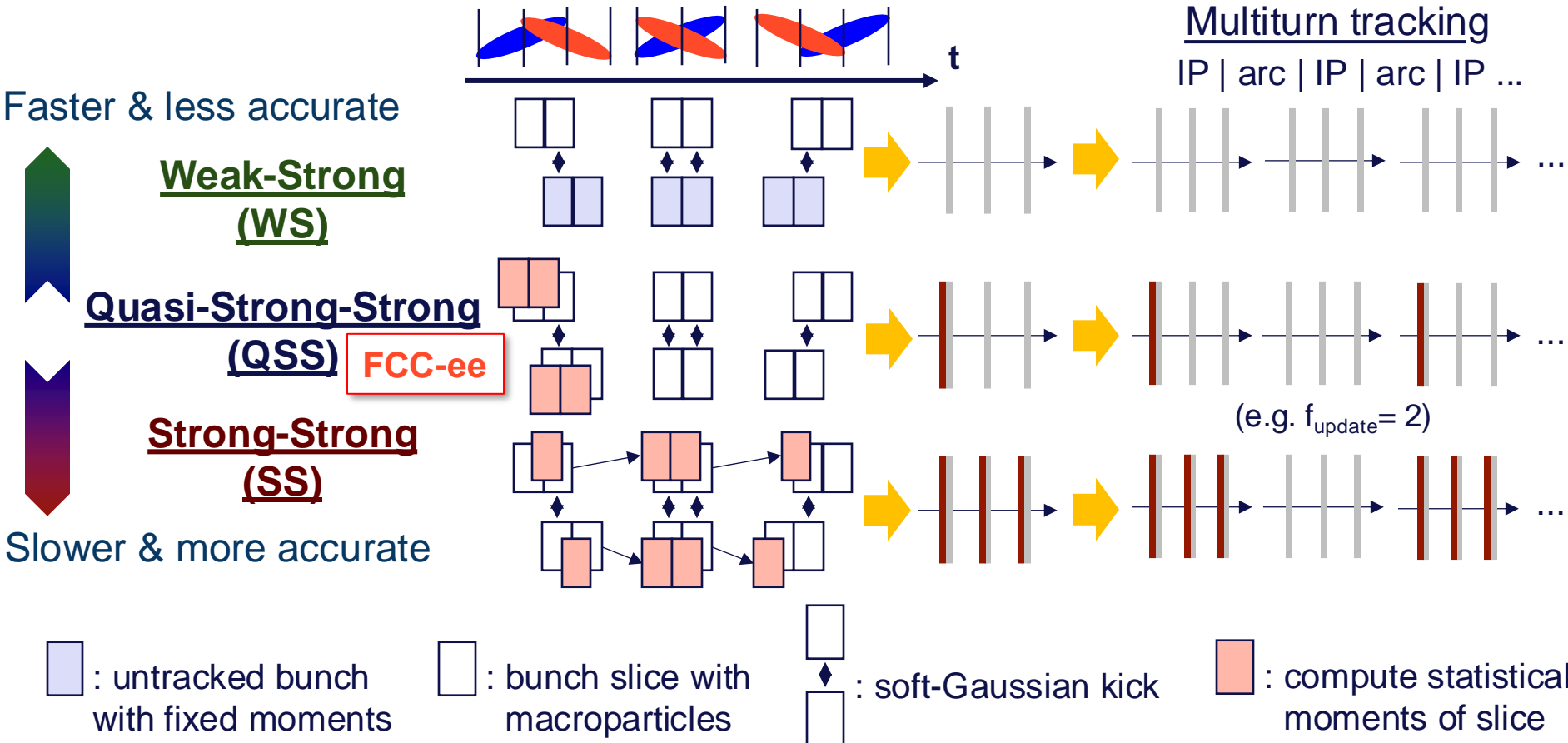
$$\Delta y' + i\Delta x' = \frac{Nr_0\sqrt{2\pi}}{\gamma\sqrt{\sigma_x^2 - \sigma_y^2}} \left(w \left[\frac{x+iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right] - \exp \left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} \right] \cdot w \left[\frac{x\frac{\sigma_y}{\sigma_x} + y\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right] \right)$$

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

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

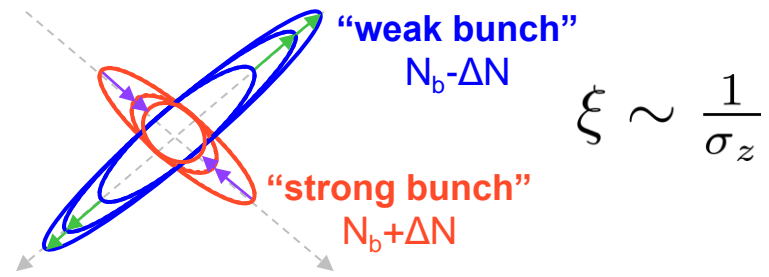
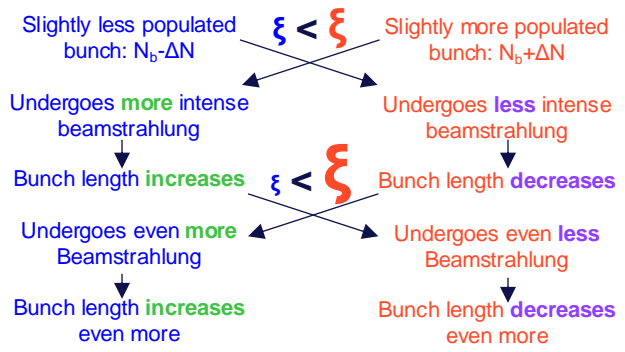
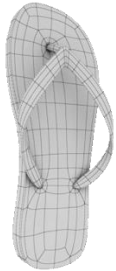
$$w[t] = \exp[-t^2] \left(1 + \frac{2i}{\sqrt{\pi}} \int_0^t \exp[u^2] du \right)$$

Beam-beam in Xsuite



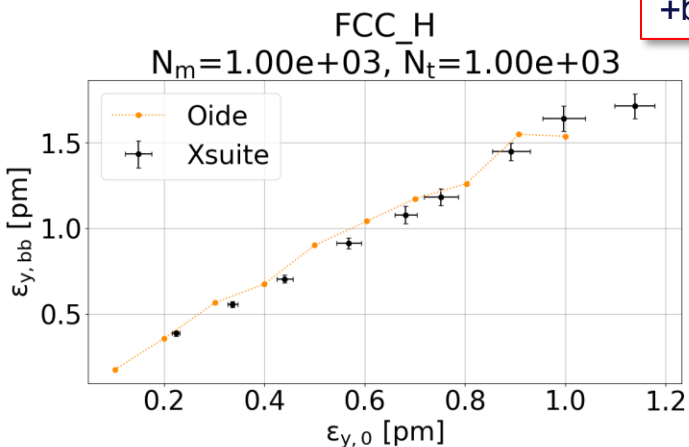
Flip-flop

- Flip-flop instability (1D) observed in other colliders (VEPP-2000)
- For FCC-ee: 3D flip-flop - direct consequence of **beamstrahlung**, triggered by an initial asymmetry in **bunch intensity**

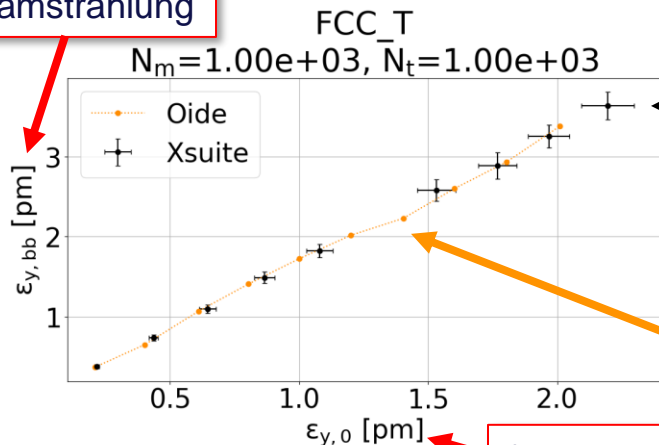


- Inflation of one bunch \Rightarrow beam loss
- Above a threshold ξ_0 longitudinal blowup drives transverse diffusion \Rightarrow 3D flip-flop
- Relevant for FCC-ee top-up injection

Vertical emittance



w/ beam-beam
+beamstrahlung

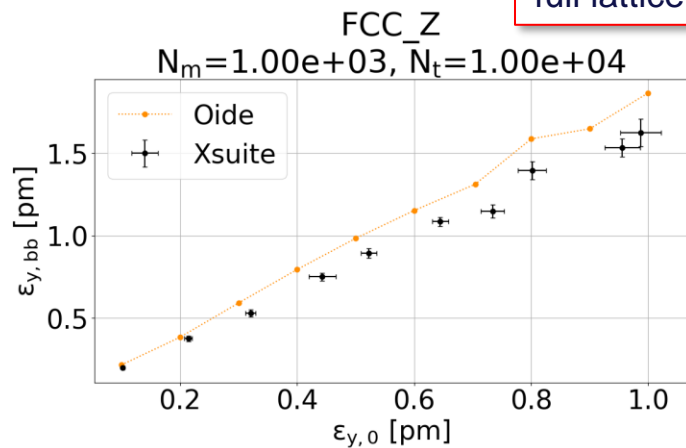
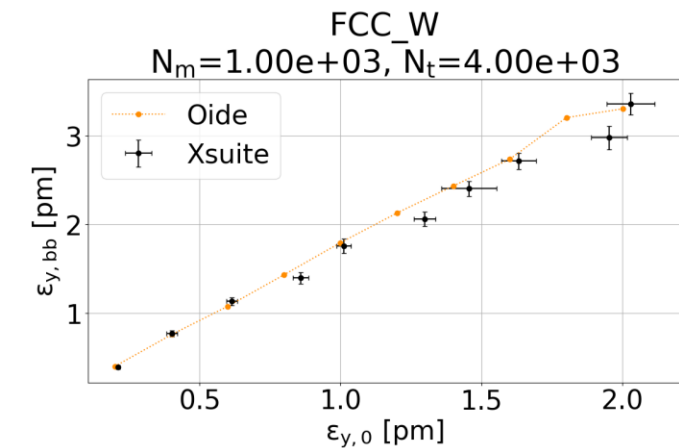


Xsuite tracking

error bars:
stat. of last 2500 turns

Reference data
by K. Oide

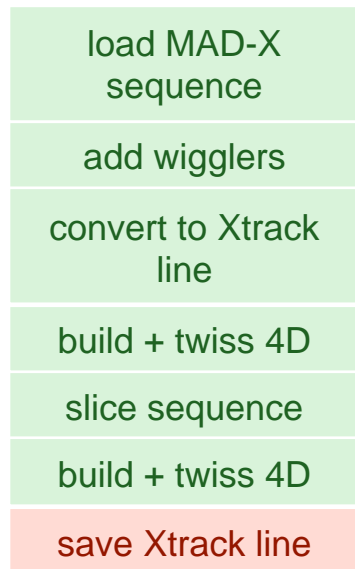
full lattice



- Independent benchmarks with SAD & Xsuite
- Good agreement

Workflow for emittance scan – everything in Xsuite

Prepare Xtrack line once:



Loop over a range of ϵ_y values:

