Updates on the GHC lattice

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Incremental changes on the GHC lattice, since Nov. 2023 (or MTR)

- Items applied and adapted:

Items	changes	remarks
higher bunch charge at Zh	1.69×10^{11} from 1.32×10^{11}	19% higher luminosity
momentum acceptance at Z/W, Zh	±1.0% from ±0.9% (Z/W) ±1.9% from ±1.6% (Zh)	required by on-axis injection (Y. Dutcheil) better lifetime (Zh)
types of dipoles in a section of the IR straight (BG2 - BGA)	reduced from 9 to 2 types	each bending angle is still different
β* At tt	(0.9 m, 1.4 mm) from (0.8 m, 1.5 mm)	better lifetime
Fine placement of sextupoles in the outer arc	a mistake in the spacing between dipole and sext was corrected	pointed out by C. Garcia, R. Tomas

- Items tried, but not adapted:

Items	changes	remarks
sextupole thickness/strengths	reduced from 1.3 m to 1.2 m/segment	860 T/m² @ tt (unfinished 800 T/m2)
types and angles of dipoles in the IR straight (BG2 - BGA, BL*, BS*)	reduced the types of lengths and angles	optics was possible, but seemed to have higher local chromaticity
higher dispersion at SY*	0.189 m to 0.2 m	
RF distribution for 2 LLSSs	800 MHz / 400 MHz	Special care is necessary for the **tapering of quadrupoles around the RF cavities**

Parameters

FCC-ee collider parameters for the GHC lattice as of May 29, 2024.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658728			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.369	1.86	9.94
SR power / beam	[MW]	50			
Beam current	[mA]	1283	135	26.8	5.0
Colliding bunches / beam		11200	1852	300	64
Colliding bunch population	$[10^{11}]$	2.16	1.38	1.69	1.48
Hor. emittance at collision ε_x	[nm]	0.70	2.16	0.66	1.51
Ver. emittance at collision ε_y	[pm]	1.9	2.0	1.0	1.36
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.87	1.20	0.57	0.94
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	29.2nx		7.52	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		218.158 / 222.220	218.185 / 222.220	398.150 / 398.220	398.148 / 398.215
Chromaticities $Q'_{x/y}$		0 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.110	0.069 / 0.105	0.102 / 0.176	0.152 / 0.184
Bunch length (SR/BS) σ_z	[mm]	5.57 / 15.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.32
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.09 / 0	2.1 / 9.20
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.787129			
Synchrotron tune Q_s		0.0289	0.0809	0.0334	0.0881
Long. damping time	[turns]	1171	218	65.4	19.4
RF acceptance	[%]	1.06	3.32	2.06	3.06
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0022 / 0.0977	0.013 / 0.129	0.0108 / 0.130	0.065 / 0.136
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.6	3.6	6.6	0.94
Lifetime (q + BS + lattice)	[sec]	11800	4500	6000	7700
Lifetime (lum) [b]	[sec]	1330	960	600	670
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	143	20	7.5	1.38

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section, no beam size effect.

- compared to Jul. 2023:
  - higher bunch charge, higher luminosity @Zh.
  - lower bunch charge @$W/t\bar{t}$ for better lifetime.
  - longer lifetime than MTR at all energies.
  - ±1.0% momentum acceptance@Z/W.
- At each energy, parameter with slightly higher luminosity is possible by increasing the bunch charge and ξ_y, in sacrifice of the lifetime.
- The crab waist ratio is subject to optimize further, see slides below.

Previous parameters (July 2023 almost for MTR)

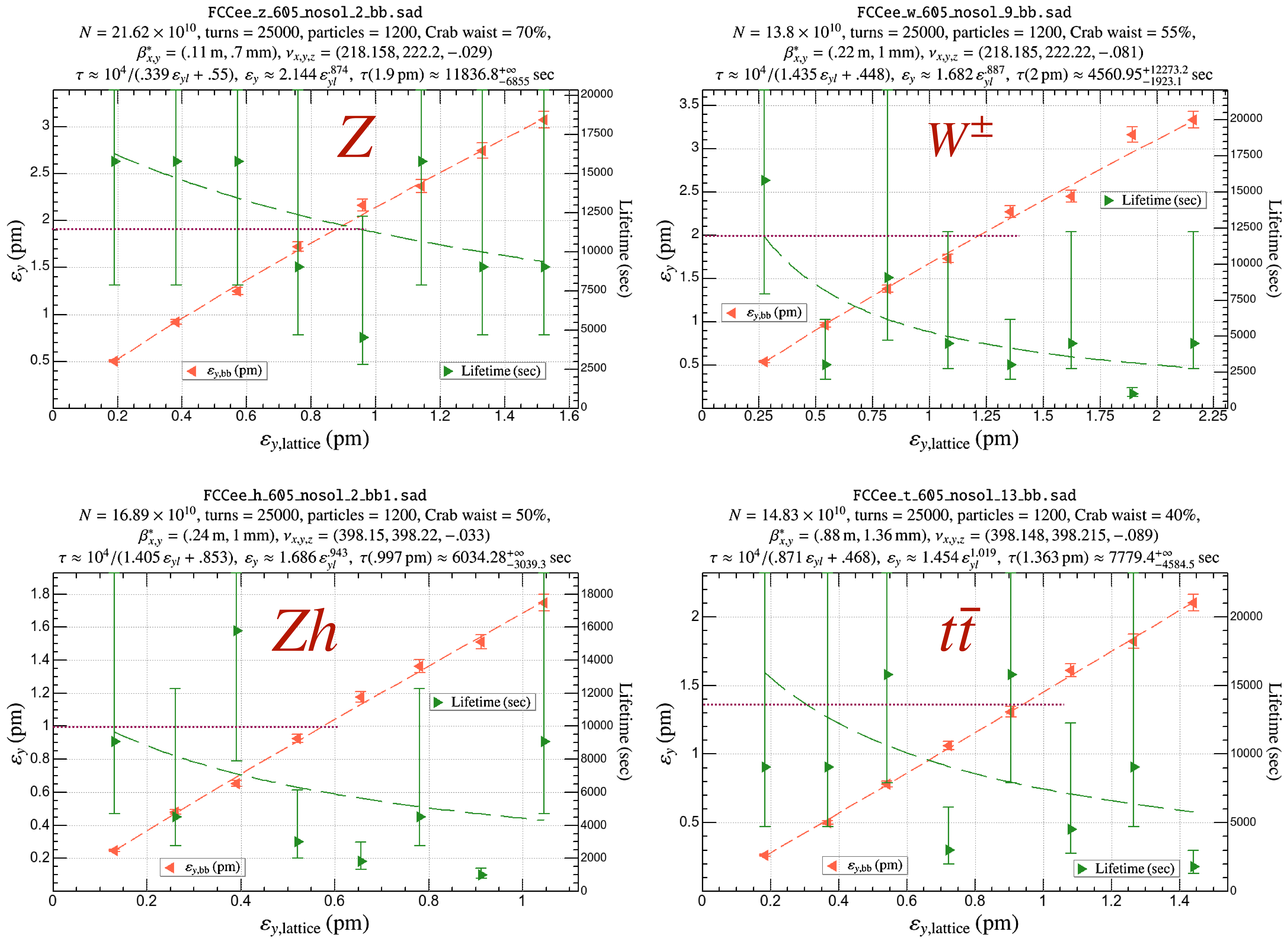
FCC-ee collider parameters as of July 30, 2023.

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 freqeuncy (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
Piwinski angle $(\theta_x \sigma_{z,\text{BS}})/\sigma^*_x$		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	$[10^{34}/\text{cm}^2\text{s}]$	141	20	6.3	1.38
Luminosity / IP (CDR)	$[10^{34}/\text{cm}^2\text{s}]$	230	28	8.5	1.8

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

Lifetime & beam blowup with lattice + beam beam & beamstrahlung

FUTURE CIRCULAR COLLIDER

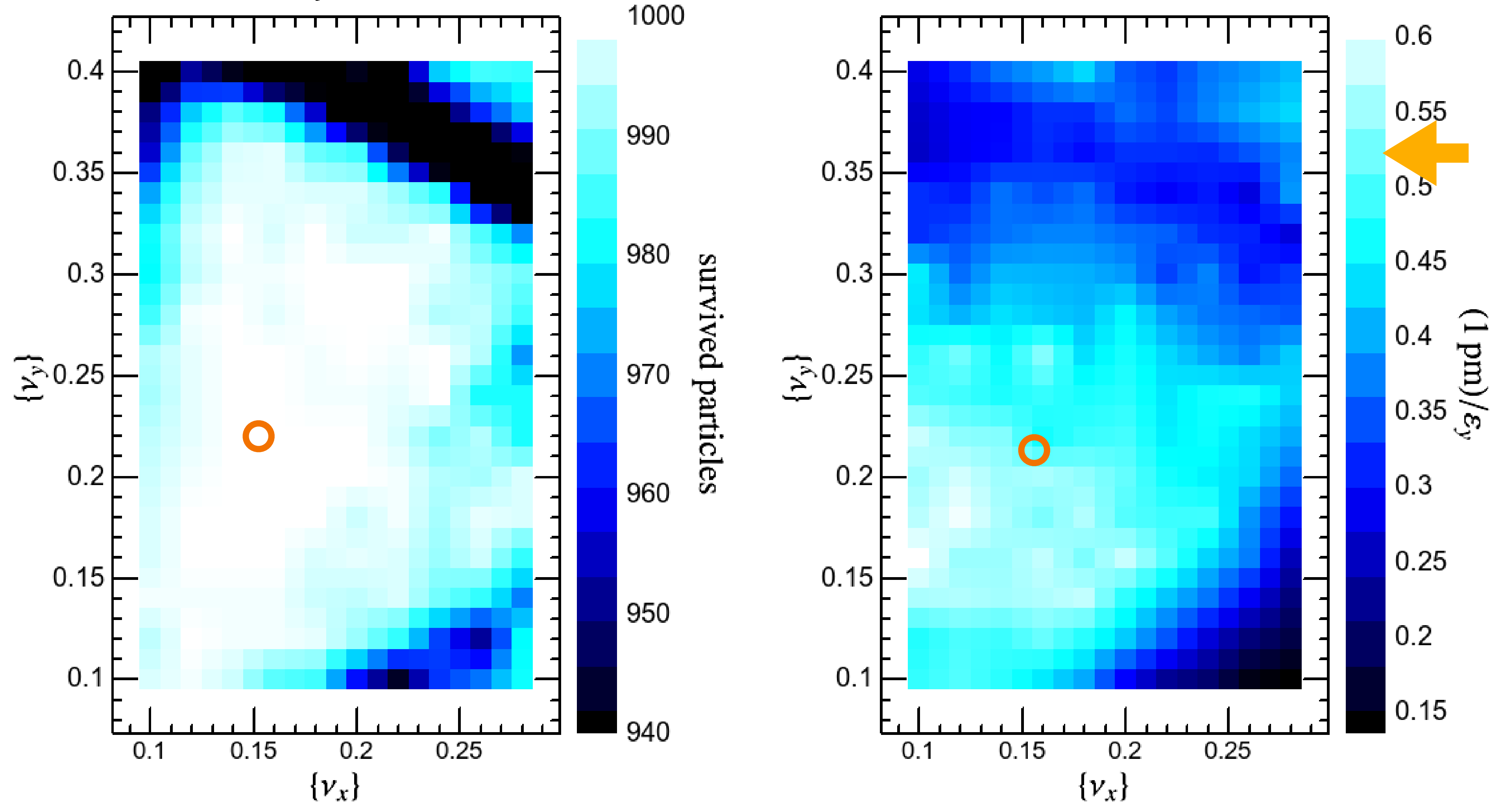


- The vertical emittance after collision (red) and the lifetime (green) against the lattice vertical emittance for each collision energy.
- The purple horizontal dashed line shows the goal vertical emittance at collision, where the vertical emittance of the strong beam is set at.
- SR in all elements, weak-strong beam-beam (BBWS), beamstrahlung are included.
- No machine error is included.
- These results, and also the DA, have been reproduced by independent simulations by P. Kicsiny: https://indico.cern.ch/event/1335891/contributions/5632544/attachments/2745020/4776609/pkicsiny_fccee_optics_meeting_2023_11_02.pdf , **except the lifetime.**
- Using SAD/BBWS on HPC-BATCH. Each plot takes 2 to 3 hours (higher energy needs more time for radiation).

Tune scan (lattice + beam-beam + beamstrahlung with SAD/BBWS)

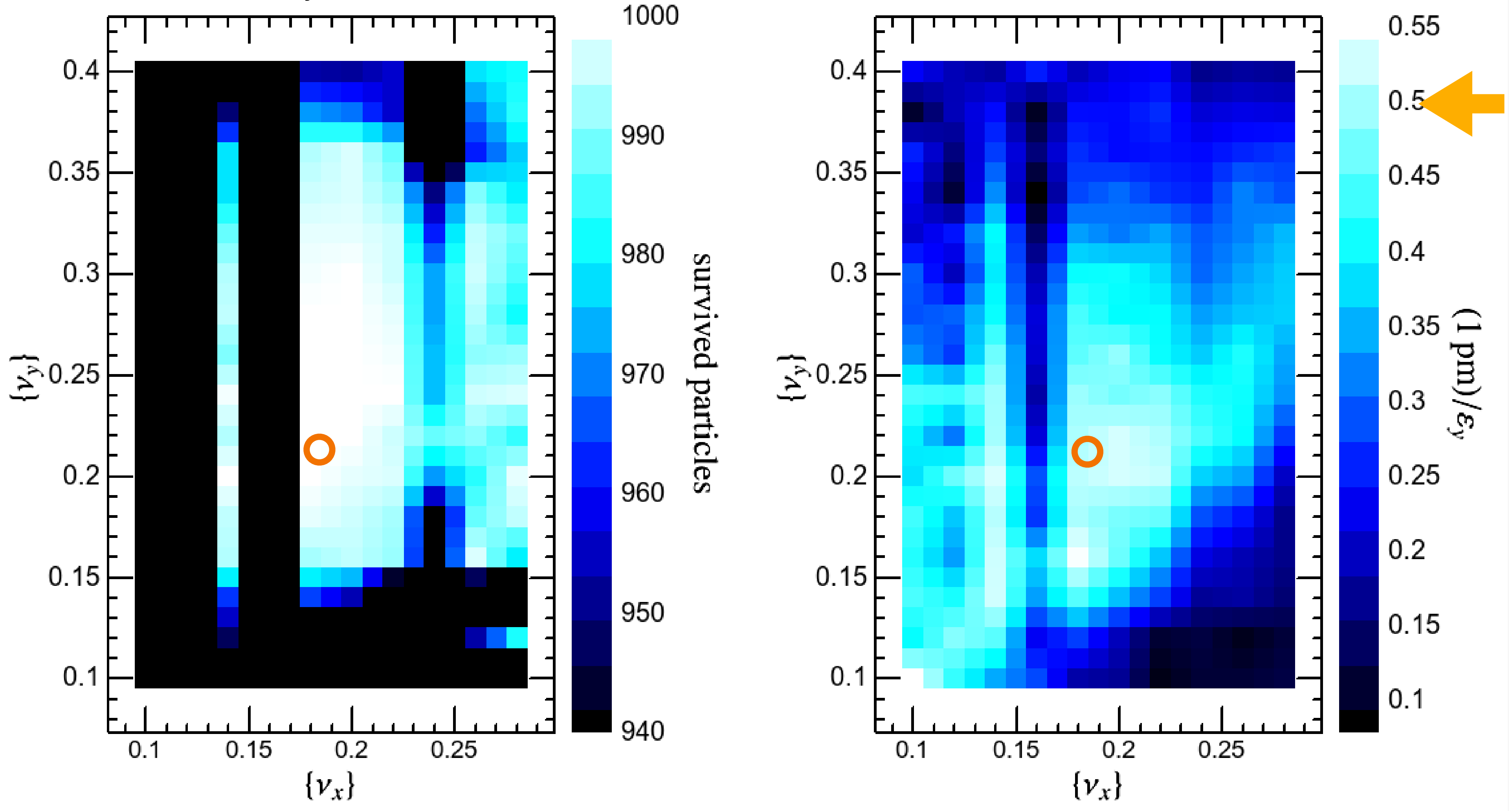
Z

FCCee_z_605_nosol_2_bb_ts.sad
$N = 2.16 \times 10^{11}$, Crab waist = 70%, turns = 4000, particles = 1000,
$\beta^*_{x,y} = \{.11\,\text{m},\ .7\,\text{mm}\}$, $\nu_z = -.0288$, $\varepsilon_{y,\text{lattice}} = .8712\,\text{pm}$



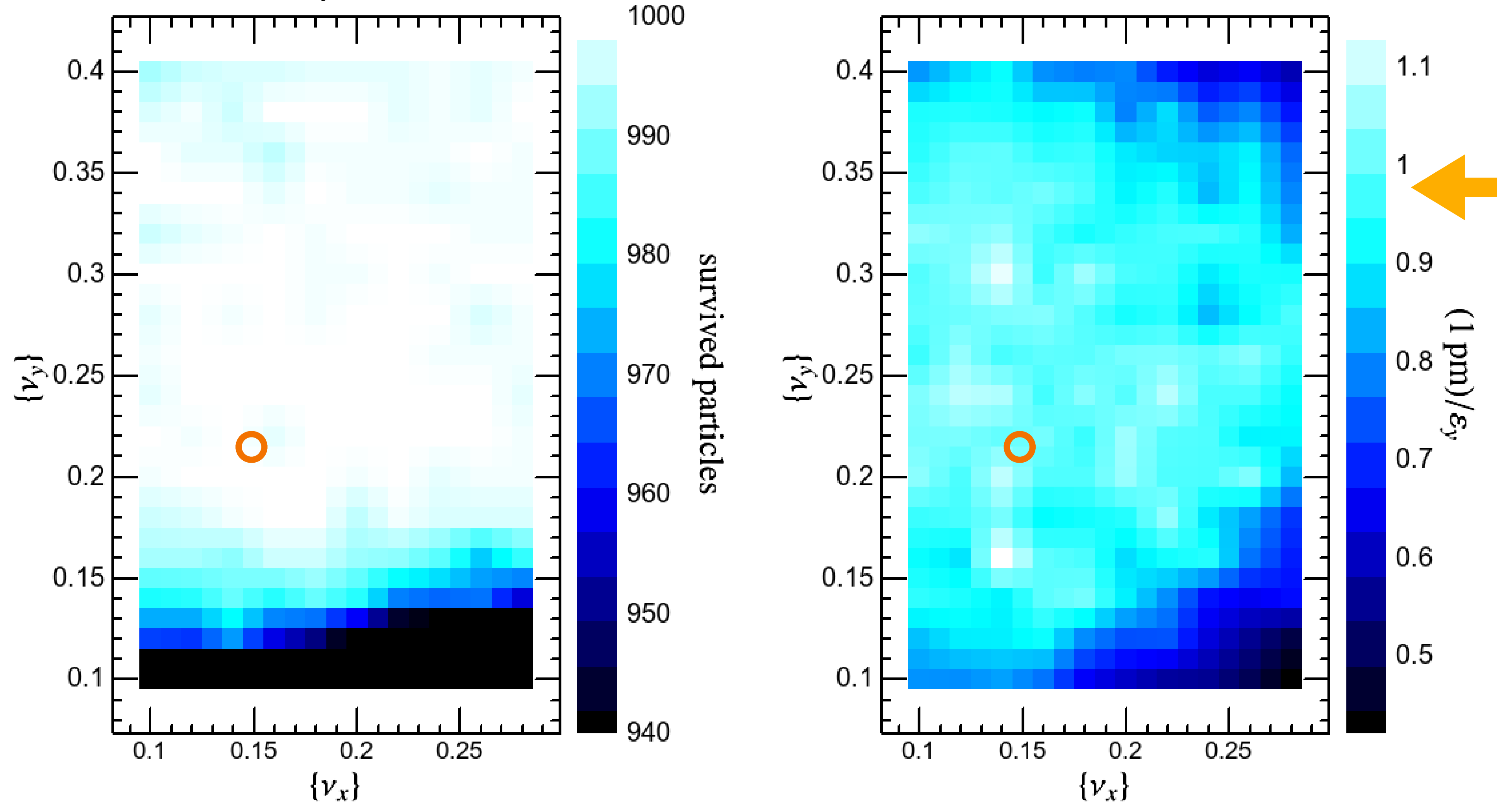
$W^{\pm}$

FCCee_w_605_nosol_9_bb_ts.sad
$N = 1.38 \times 10^{11}$, Crab waist = 55%, turns = 4000, particles = 1000,
$\beta^*_{x,y} = \{.22\,\text{m},\ 1\,\text{mm}\}$, $\nu_z = -.0808$, $\varepsilon_{y,\text{lattice}} = 1.2019\,\text{pm}$



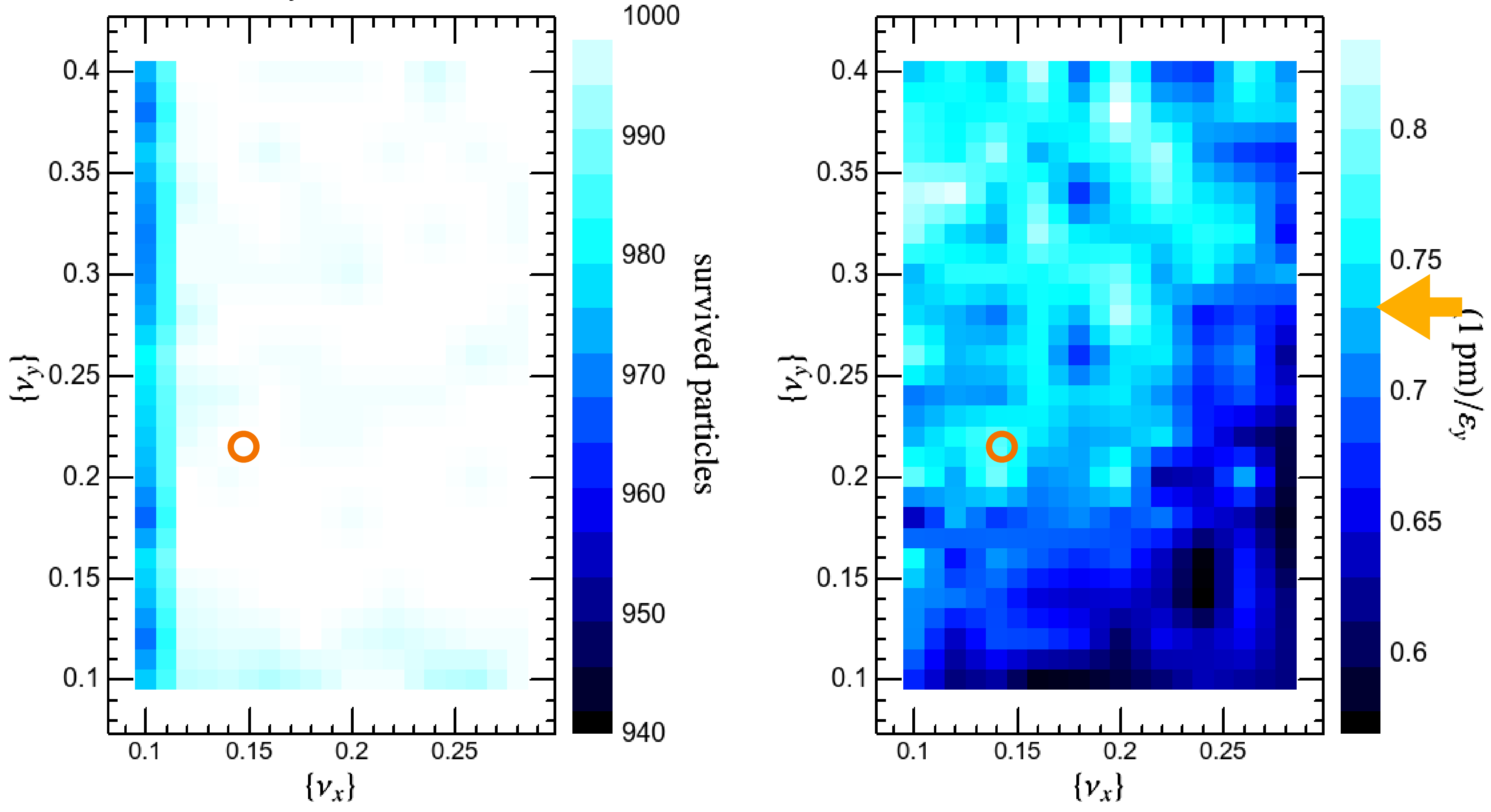
Zh

FCCee_h_605_nosol_2_bb1_ts.sad
$N = 1.69 \times 10^{11}$, Crab waist = 50%, turns = 4000, particles = 1000,
$\beta^*_{x,y} = \{.24\,\text{m},\ 1\,\text{mm}\}$, $\nu_z = -.0327$, $\varepsilon_{y,\text{lattice}} = .5718\,\text{pm}$



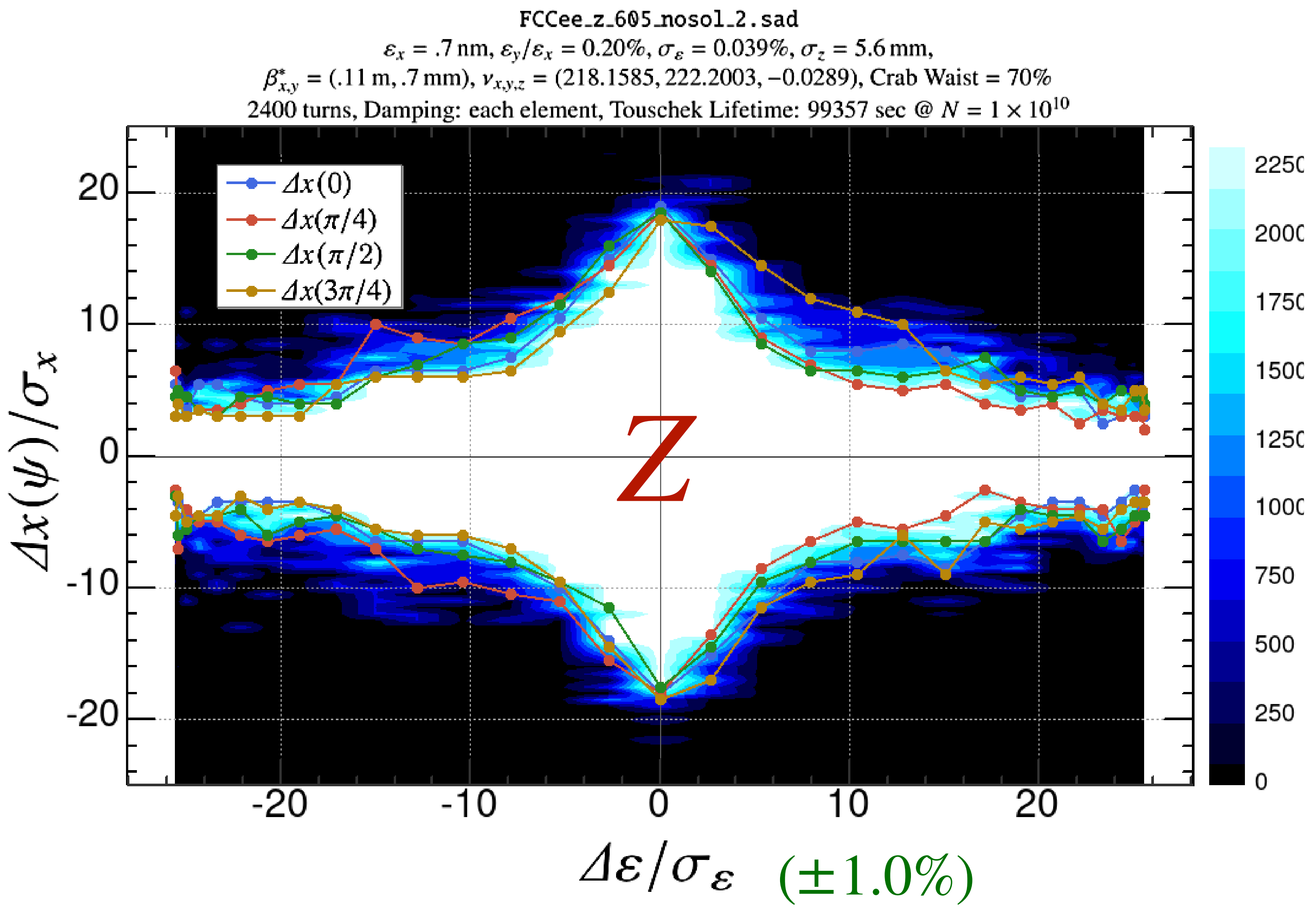
$t\bar{t}$

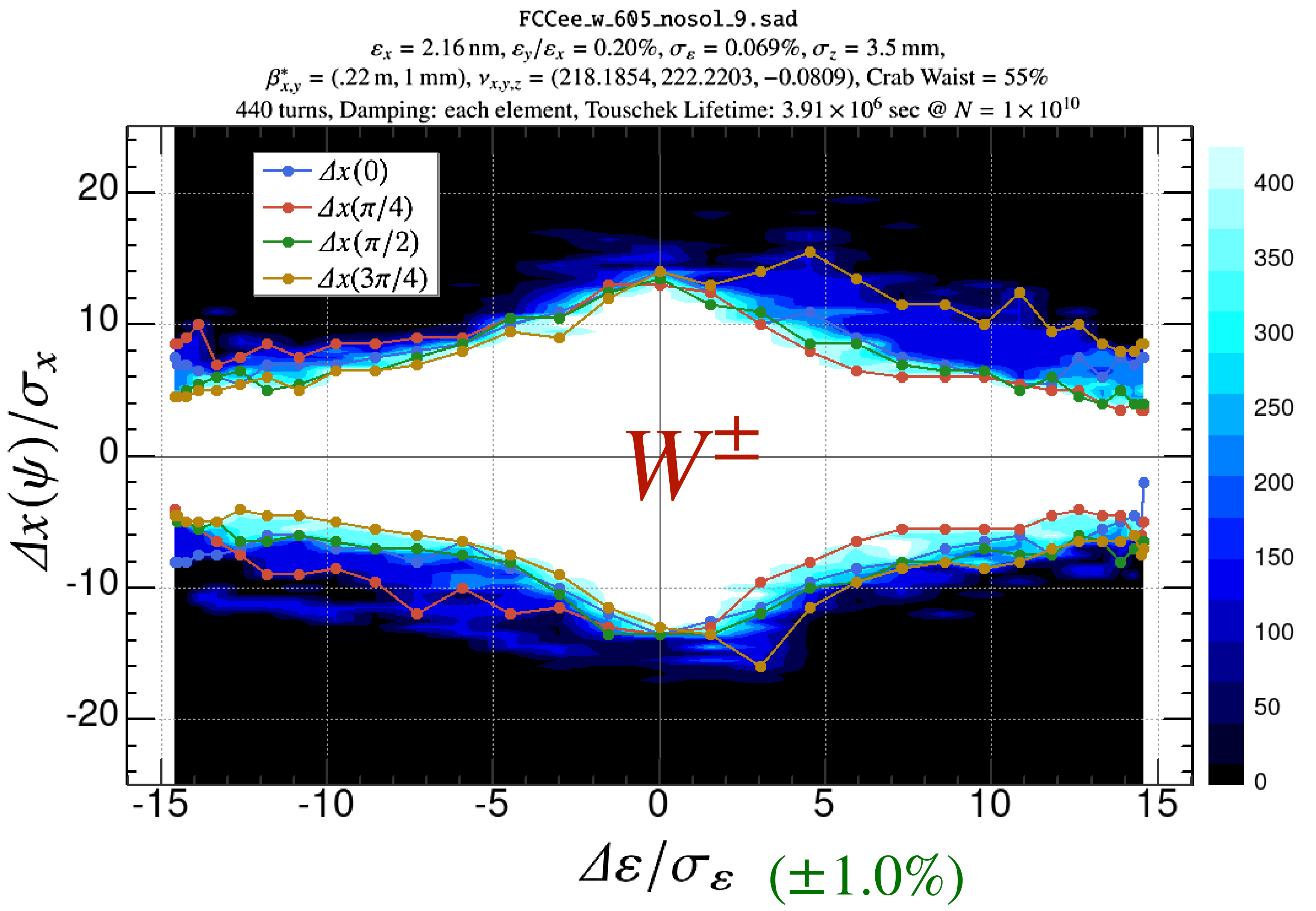
FCCee_t_605_nosol_13_bb_ts.sad
$N = 1.48 \times 10^{11}$, Crab waist = 40%, turns = 4000, particles = 1000,
$\beta^*_{x,y} = \{.88\,\text{m},\ 1.36\,\text{mm}\}$, $\nu_z = -.0872$, $\varepsilon_{y,\text{lattice}} = .9494\,\text{pm}$



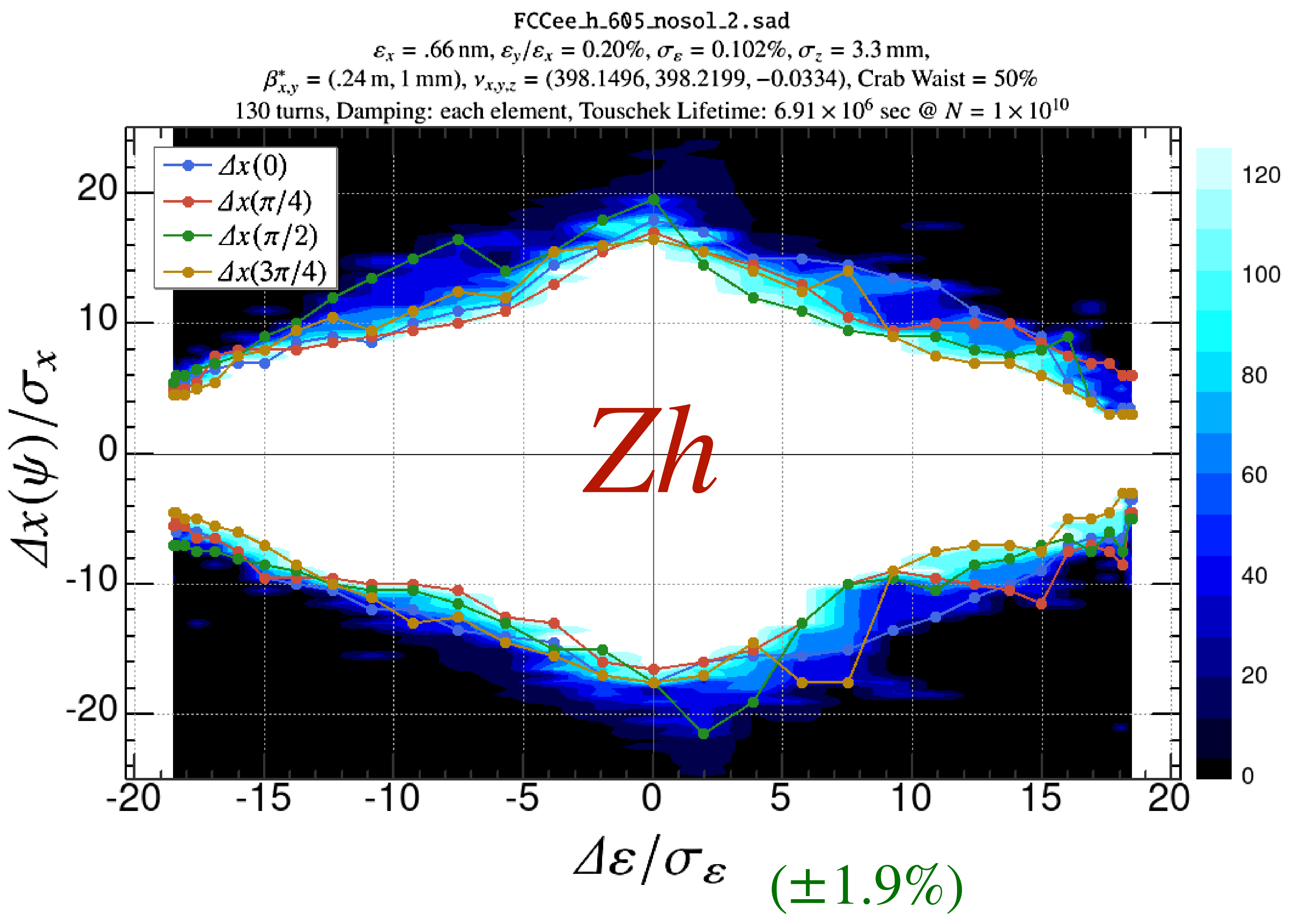
- Each plot shows the particle loss (left) and vert. emittance after collision (right) with each lattice. The circles show the current working point.
  - The gradation of the design emittance is shown by yellow arrow.
- Very strong synchrotron sidebands $\nu_x + n\nu_z = N$, $(n = 1,2,3)$ are seen at $W^{\pm}$.
- A strong "chromatic-crab" resonance line $\nu_x + 2\nu_y - \nu_z = N$ is observed with Z & W lattices. **This resonance strongly depends on the magnitude of the crab waist (see slides later).**
  - At higher energies (Zh, $t\bar{t}$), the chromatic-crab resonance seems weaker or invisible.

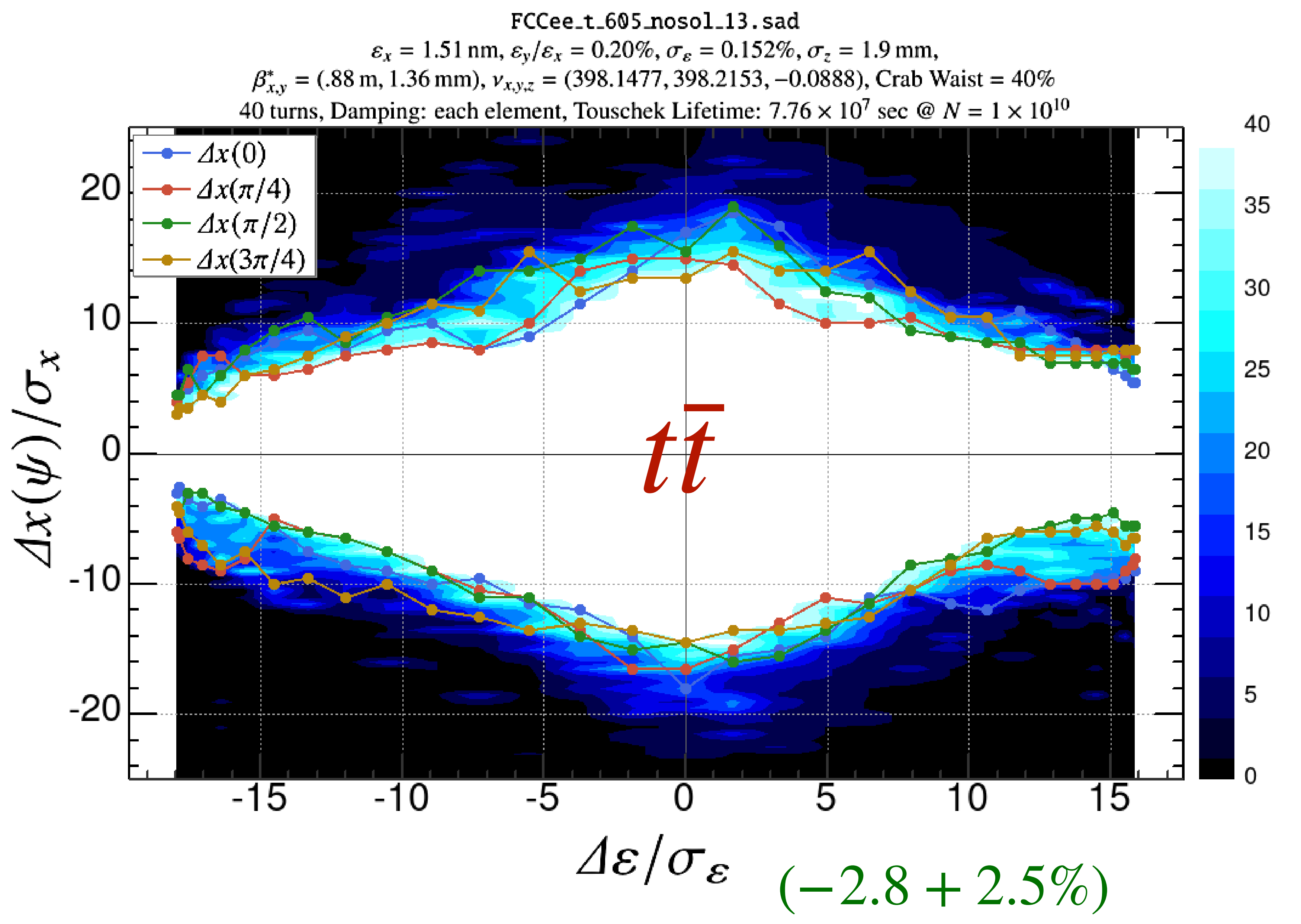
Dynamic aperture (z-x)





- The momentum acceptance is larger than ±1%, which is the minimum requirement for synchrotron injection (following remarks by Y. Dutheil).
- Some DA(MA)s still seem immature, for instance at Z. However, the beam-beam lifetime looks OK.





Significance of horizontal local chromaticity correction (XCCS)

	$t\bar{t}$		Z	
	$\int \gamma_x ds/4\pi$	$\int \gamma_y ds/4\pi$	$\int \gamma_x ds/4\pi$	$\int \gamma_y ds/4\pi$
IP ± 2.2 m	0.32	250.1	3.18	500.2
QC2L2 .. QC2R2	6.45	404.7	48.3	728.7
entire IR (QL6..QS3)	15.3	448.2	63.5	823.9
RF straight	6.08	7.98	12.8	16.23

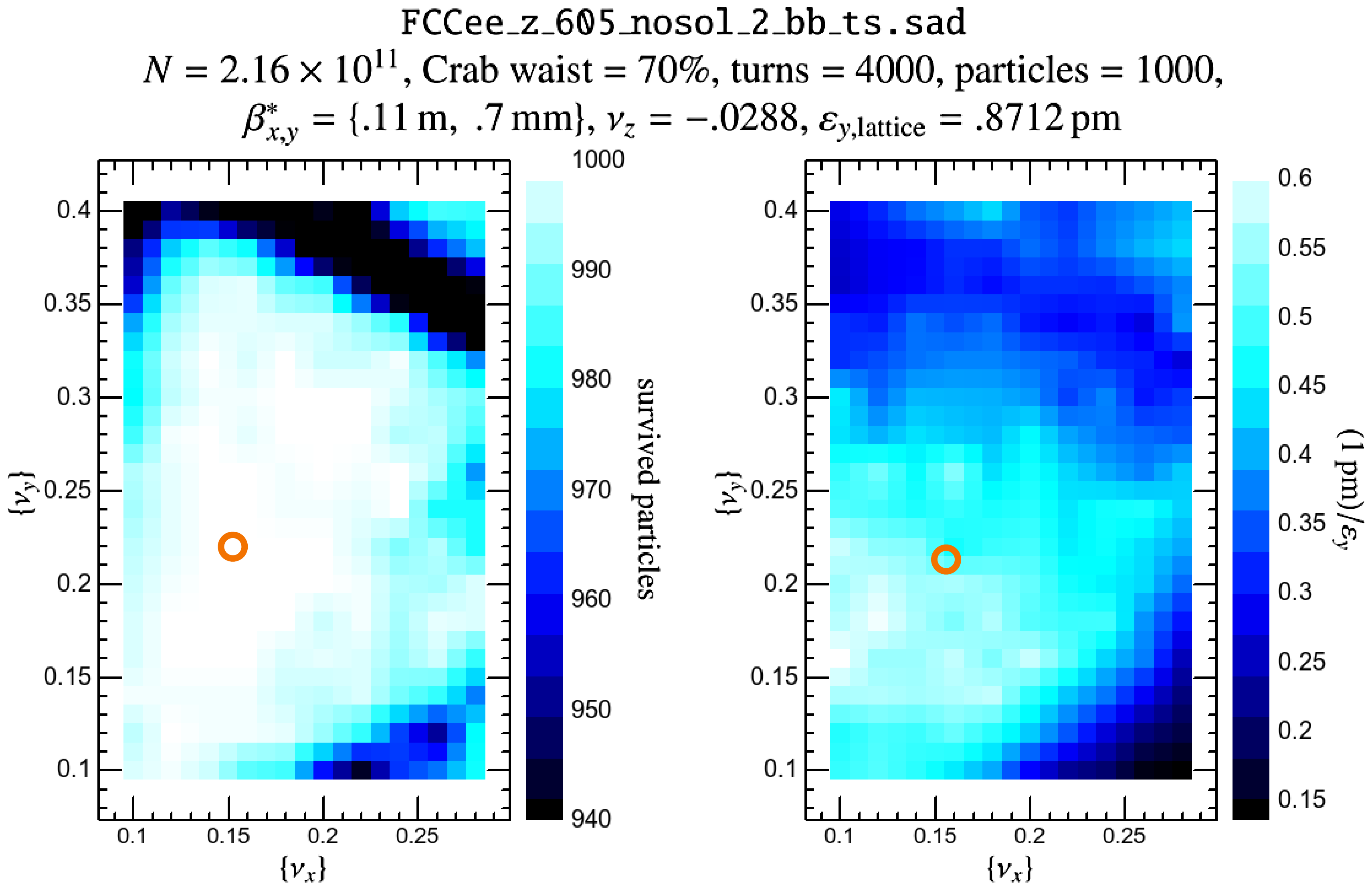
(For optics on May 8, 2024.)

- If we calculate the natural chromaticities ($= \int \gamma_{x,y} ds/4\pi$) around the IP, the horizontal one seems not much significant compared to those in other sections, esp. for $t\bar{t}$.
- This is also seen at SuperKEKB, where their XCCS has not been effective so far, as β_x^* is still 4 times larger than the design.
- If above is true, despite the naming, the most important difference between LCC/GHC optics is **not the existence of XCCS**, but in the structures of the arcs, HFD/FODO.

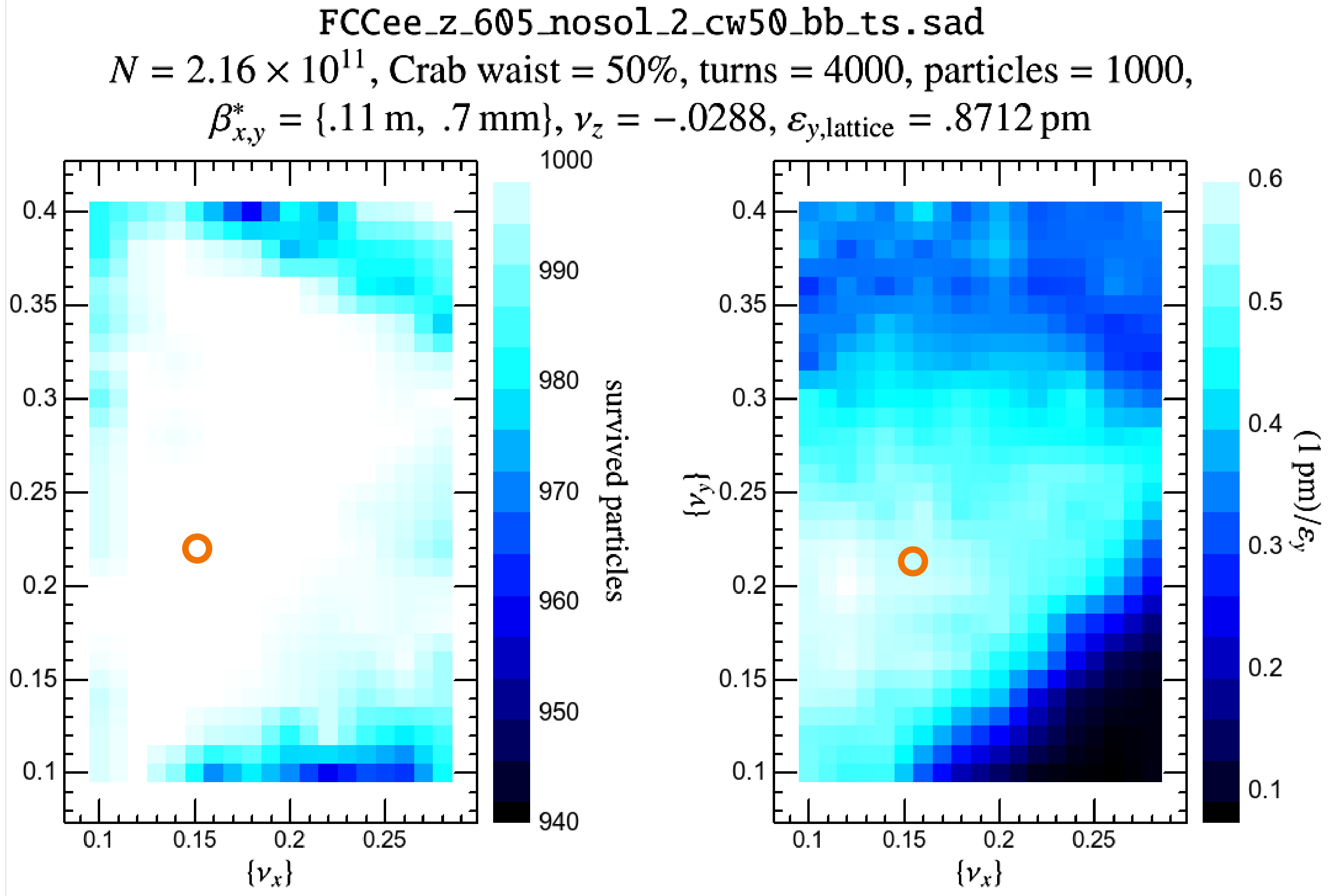
Resonance due to crab waist ratio @Z

Z

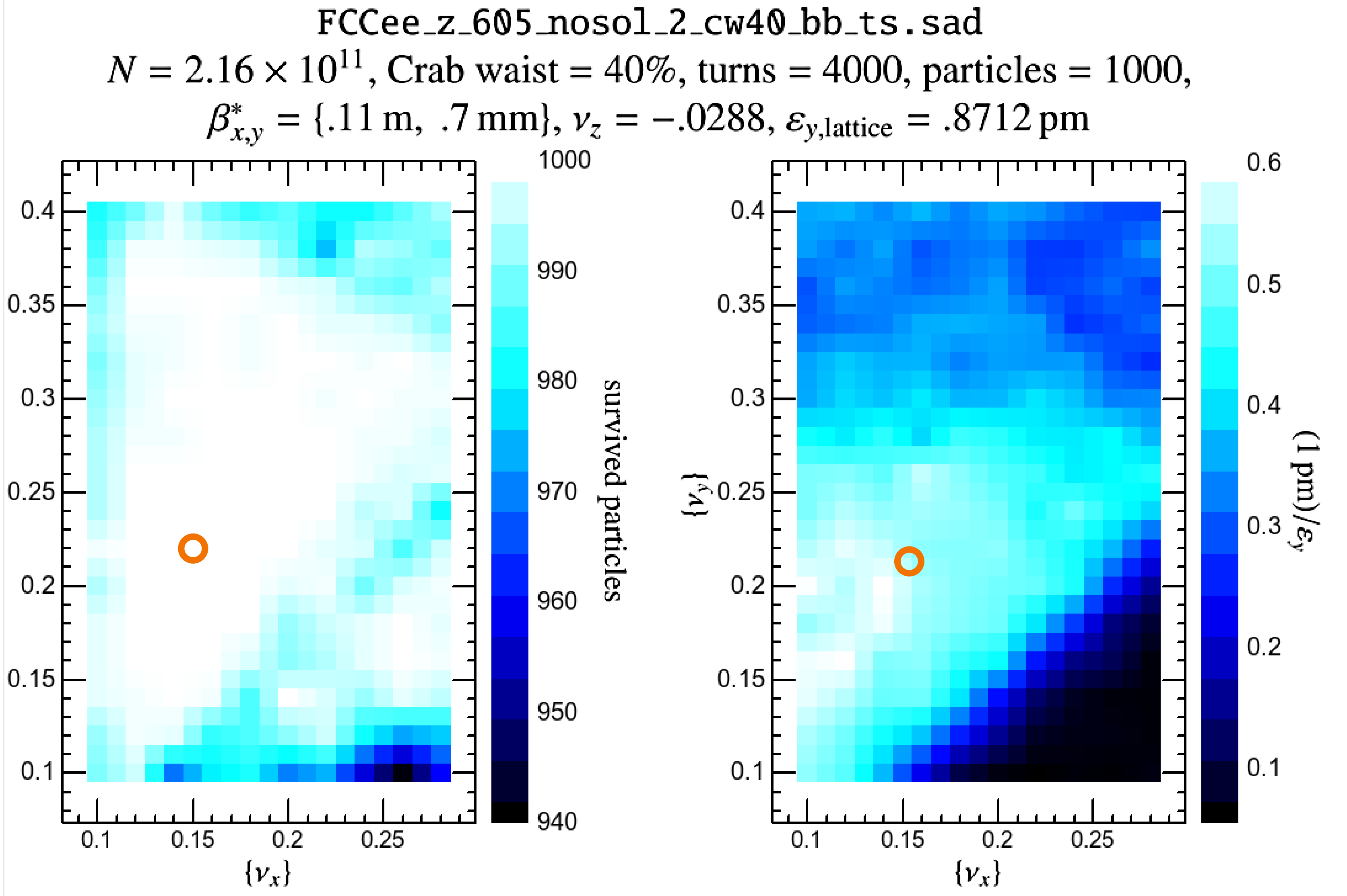
CW = 70%



CW = 50%



CW = 40%



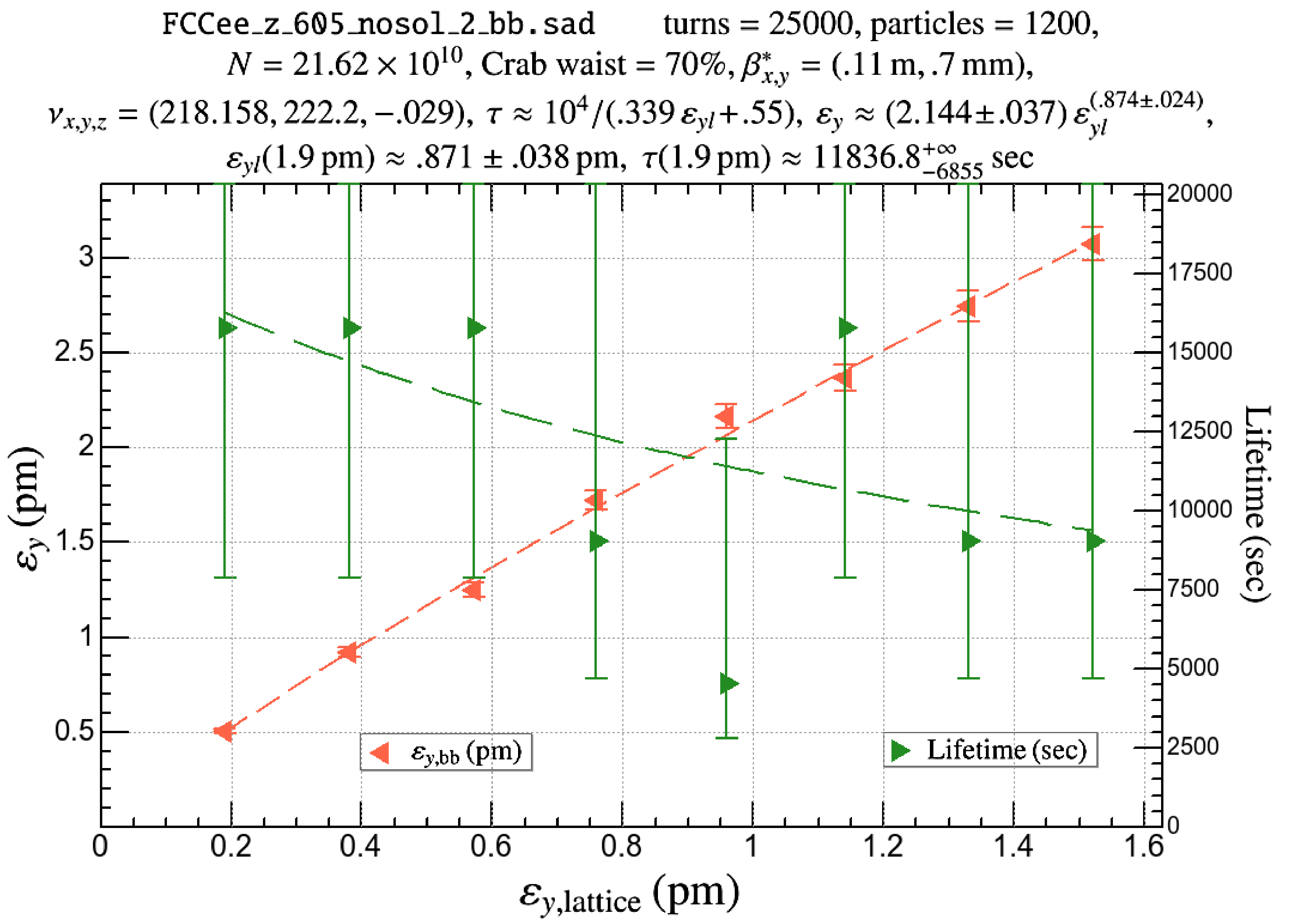
- The resonance line $\nu_x + 2\nu_y - \nu_z = N$ **gets weaker by reducing the crab waist ratio (CW)**.
- Both the lifetime and the emittance blowup by the resonance are affected by the crab waist strength.

Emittance blowup & lifetime dependence on crab waist @Z

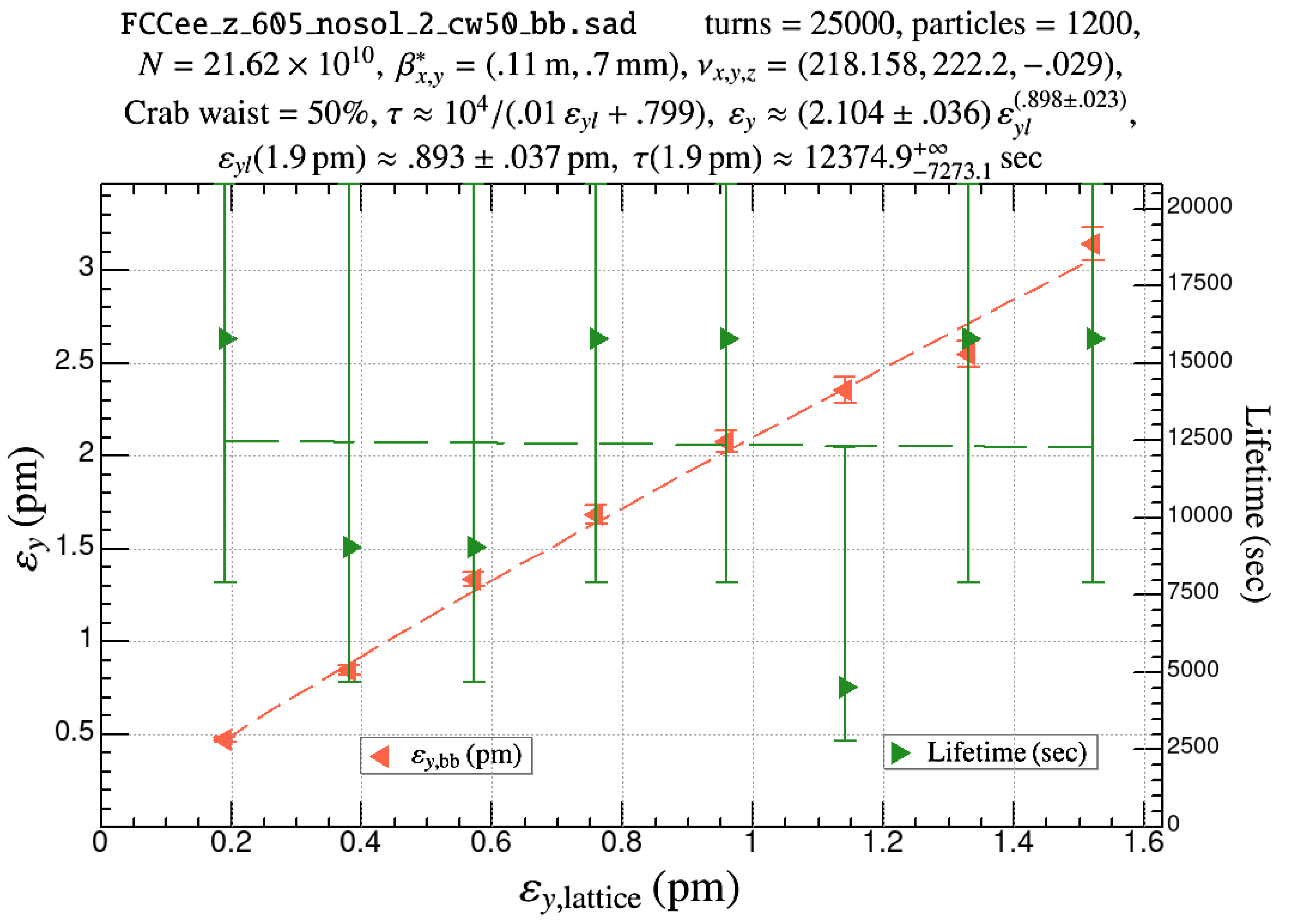
135^{+20}_{-16}

Z

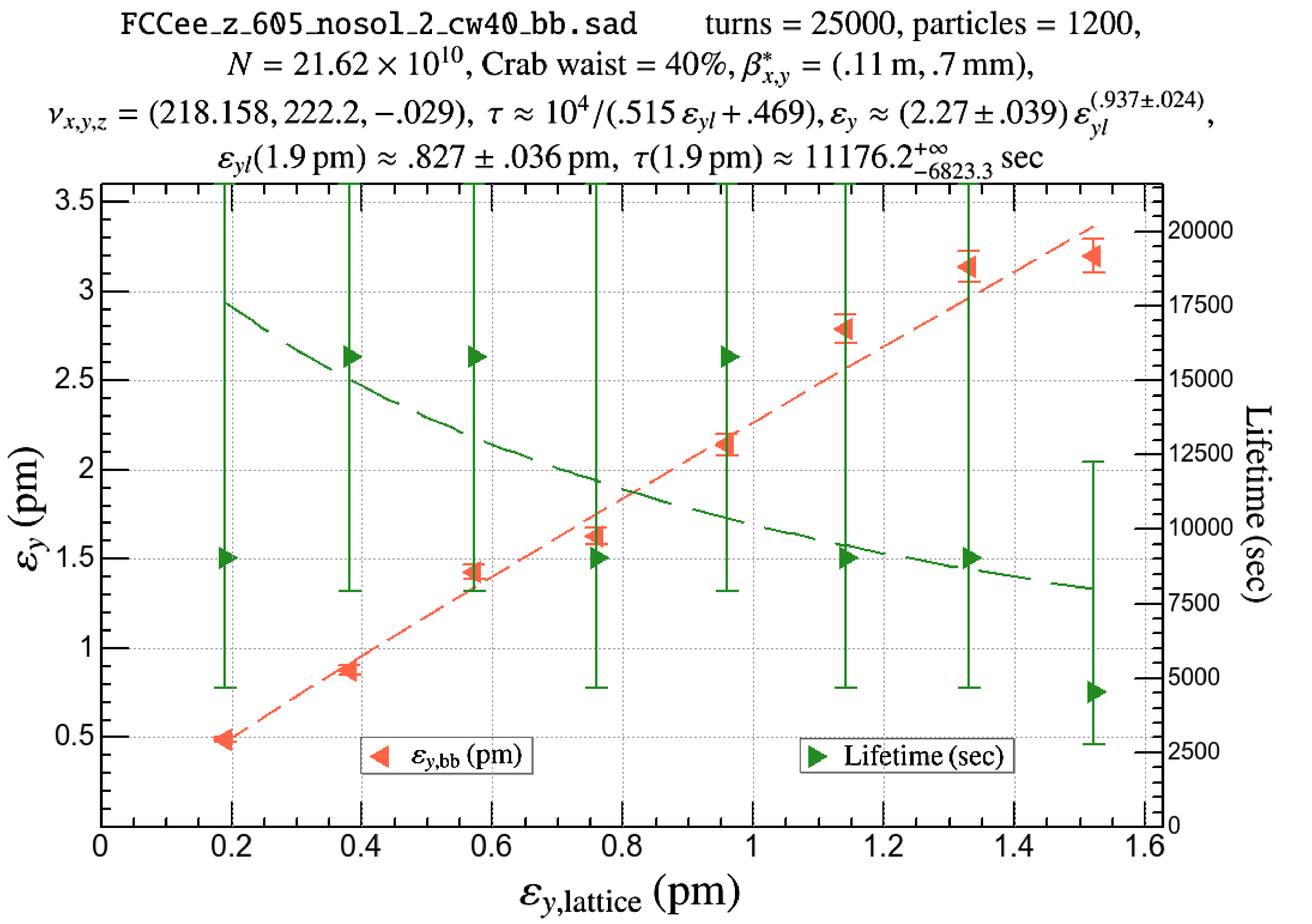
CW = 70%



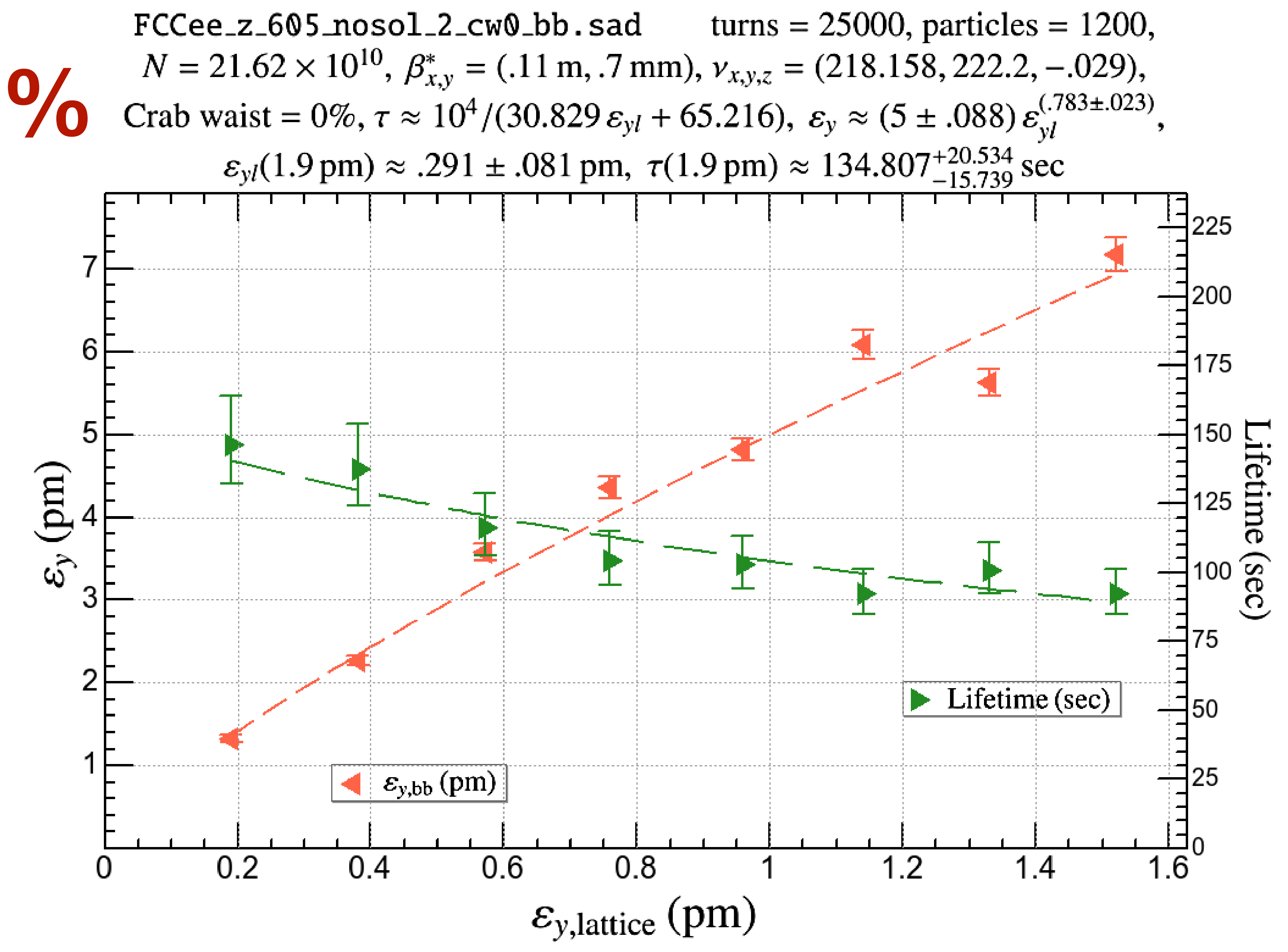
CW = 50%



CW = 40%



CW = 0%



Crab waist (%)	$\varepsilon_{y,\mathrm{lattice}}$ (pm)	τ (sec)
0	0.29 ± 0.08	135^{+20}_{-16}
40	0.83 ± 0.04	$11200^{+\infty}_{-6800}$
50	0.89 ± 0.04	$12400^{+\infty}_{-7300}$
70	0.87 ± 0.04	$11800^{+\infty}_{-6900}$

Optimum crab waist ratio

- According to the simulations above, the optimum crab waist ratio for Z seems to be around 50%.
  - higher CW induces additional resonances due to beam-beam and crab.
  - simulations by the CDR did not take the lattice into account, gave the optimum at nearly 100% for Z.
- ... but what is the reason?
  - Is this lattice-specific?
  - currently the strong beam in BBWS does not take the CW on the beam shape.
  - needs independent simulations, incl. strong-strong model.

Crab waist (%)	$\varepsilon_{y,\mathrm{lattice}}$ (pm)	τ (sec)
0	0.29 ± 0.08	135^{+20}_{-16}
40	0.83 ± 0.04	$11200^{+\infty}_{-6800}$
50	0.89 ± 0.04	$12400^{+\infty}_{-7300}$
70	0.87 ± 0.04	$11800^{+\infty}_{-6900}$

Summary

- Since November 2023 or the MTR, a few incremental changes have been made on the GHC lattice for each energy.
  - Many things remain for further modification:
    - Reduction/regulation of types of dipoles.
    - Insertions for injection/extraction/collimation/polarimeter@PL, etc.
      - The superperiodicity of the lattice will be violated.
      - Separation between two beams needs attention at RF, polarimeter, etc.
    - BPMs, correctors, ...
- The optimum crab waist ratio may be smaller than those has been thought by the CDR.
- An alternative arc lattice will be pursued after this FCCW.
- These lattices are available in the repository, thank to G. Roy.