# A few topics on the optics design for FCC-ee

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Many thanks to M. Benedikt, D. El Khechen, F. Zimmermann

*April 1, JLEIC Collaboration Meeting @ JLab*

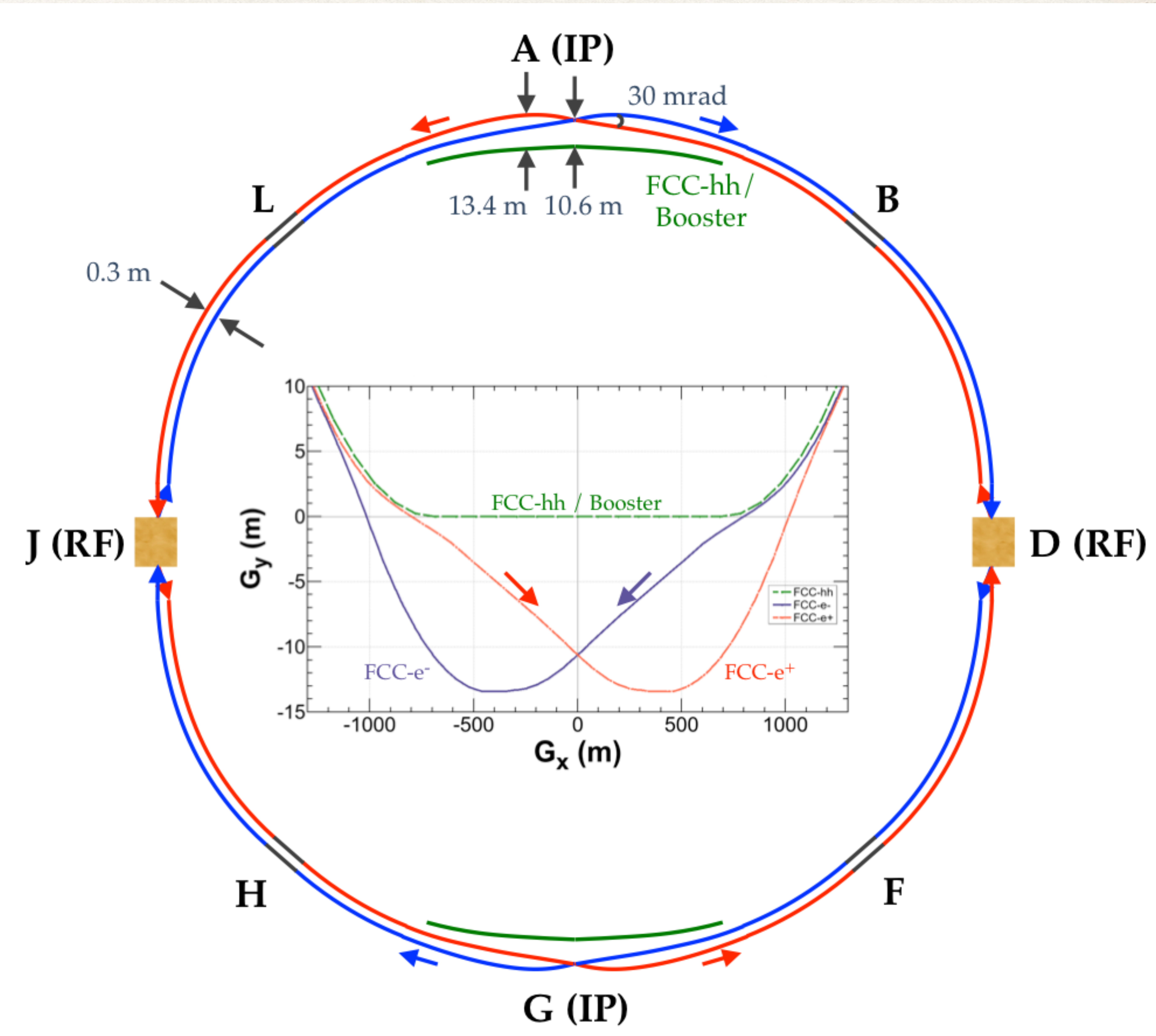
# FCC CDR

https://fcc-cdr.web.cern.ch

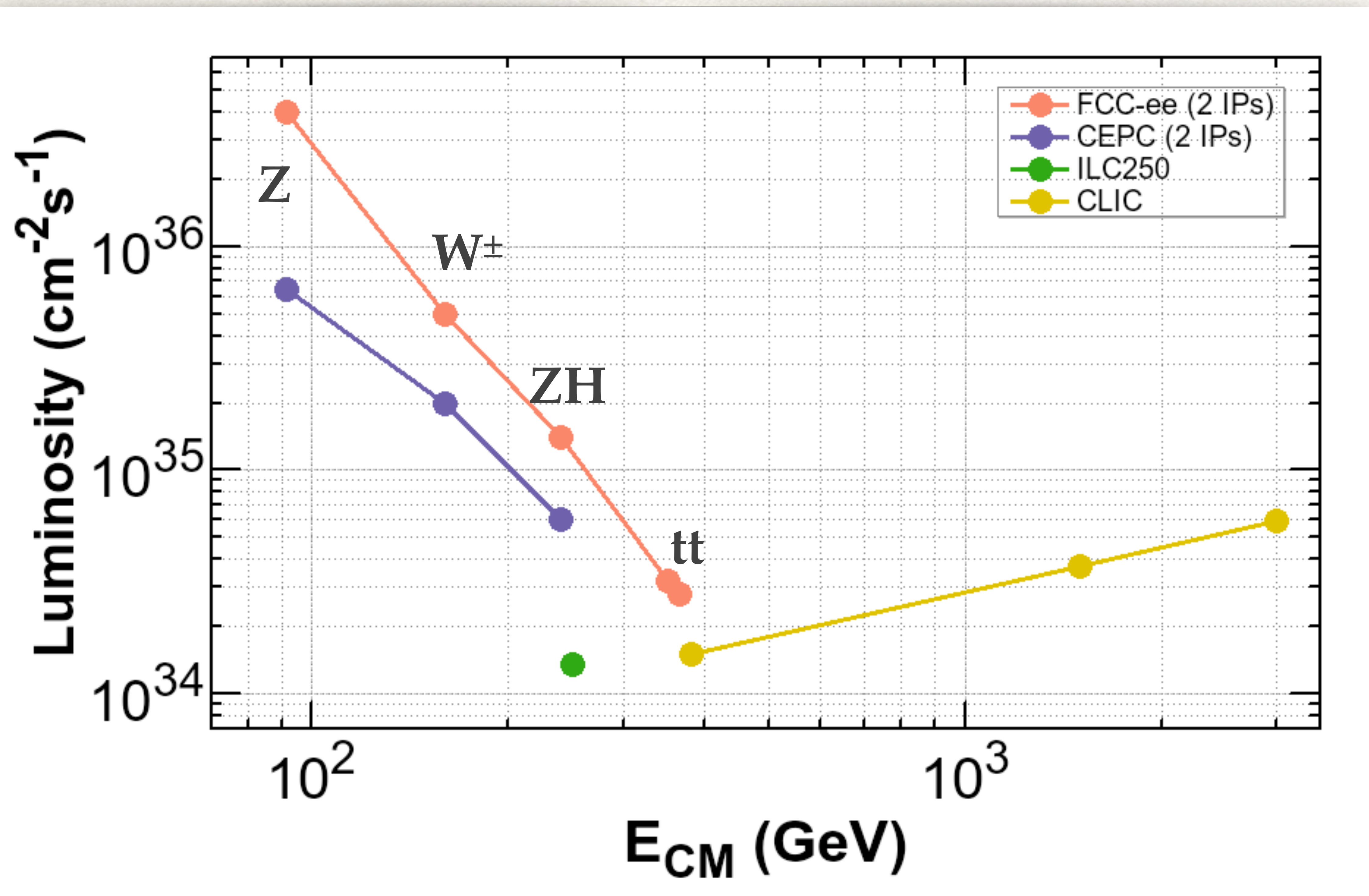
- Published in Jan. 2019. Volume 2 for FCC-ee. Appearing on EPJ.
- “The most effective and comprehensive approach to thoroughly explore the open questions in modern particle physics is a staged research programme, **integrating in sequence lepton (FCC-ee) and hadron (FCC-hh) collision programmes**, to achieve an exhaustive understanding of the Standard Model and of electroweak symmetry breaking, and to maximize the potential for the discovery of phenomena beyond the Standard Model. The project would rely on a shared and cost effective technical and organizational infrastructure, **as was the case with LEP followed by LHC**.”
- “**FCC-ee** will be a general precision instrument for the continued in-depth exploration of nature at the smallest scales, optimised to study with high precision the **Z, W, Higgs and top particles**, with samples of **5·10^12 Z bosons, 10^8 W pairs, 10^6 Higgs bosons and 10^6 top quark pairs**. FCC-ee offers unprecedented sensitivity to signs of new physics, appearing in the form of small deviations from the Standard Model, of forbidden decay processes or of production of new particles with very small couplings.”
- “This collider will be **implemented in stages**, successively spanning the entire energy range from the Z pole over the WW threshold and H production peak to the $t\bar{t}$ threshold. **Most of the infrastructure** (e.g. underground structures, surface sites, electrical distribution, cooling & ventilation, RF systems) **can be directly reused for a subsequent energy-frontier hadron collider (FCC-hh**, see FCC conceptual design report volume 3), serving the world-wide particle-physics community in a highly synergetic and cost-effective manner throughout the 21st century.”

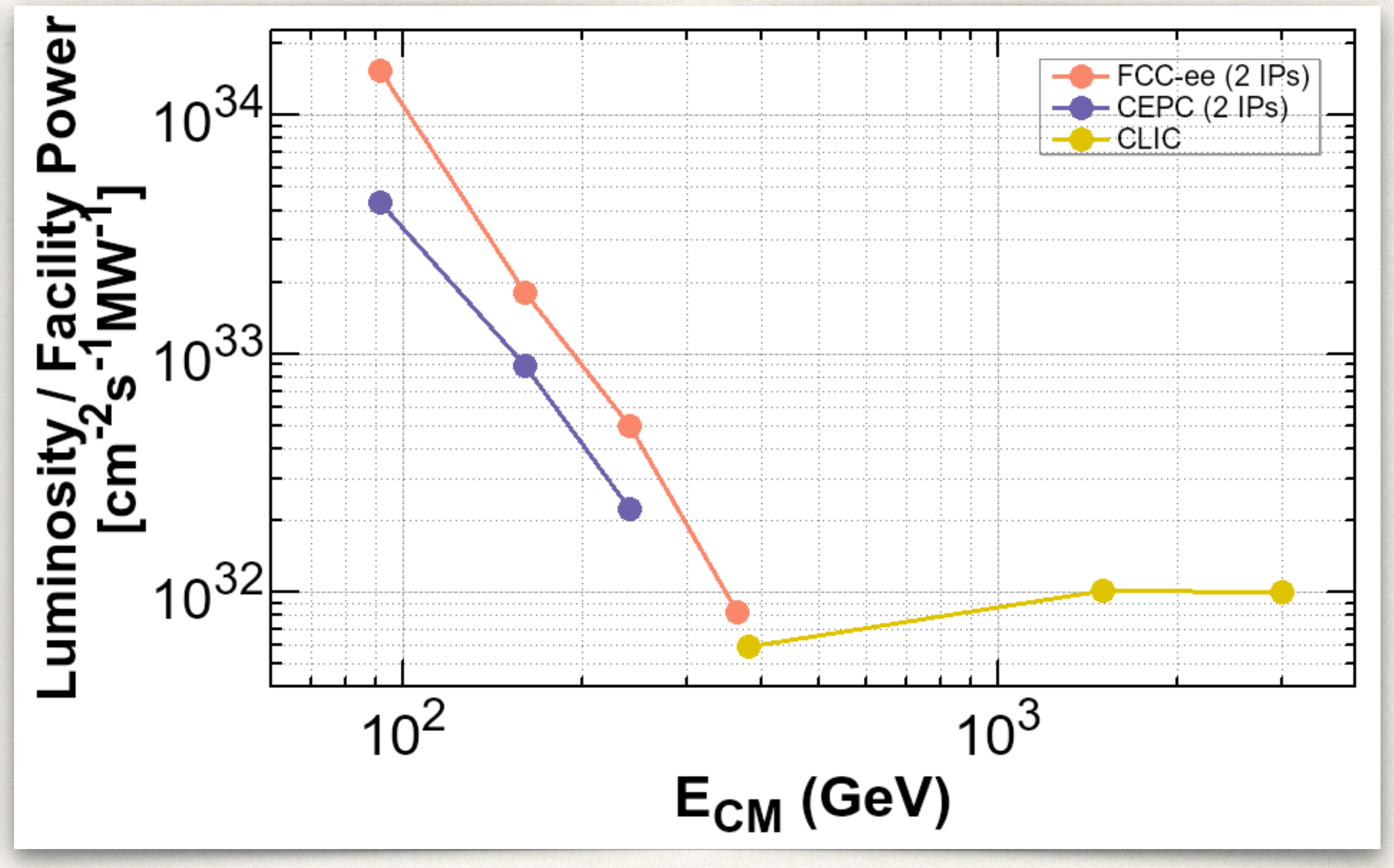
# FCC-ee basic design choices

- Double ring $e^+e^-$ collider ~100 km
- Follows footprint of FCC-hh, except around IPs
- Asymmetric IR layout & optics to limit synchrotron radiation towards the detector
- Presently 2 IPs (alternative layouts with 3 or 4 IPs are under study), large horizontal crossing angle 30 mrad, crab-waist optics
- Synchrotron radiation power 50 MW/beam at all beam energies
- Top-up injection scheme; requires booster synchrotron in collider tunnel



# Future e+e- colliders (CEPC, FCC-ee, CLIC)





- Circular colliders have advantage in luminosity up to 400 GeV CM. At Z, they have 2-3 orders higher luminosity than LCs.
- The steep falls in the luminosity of circular colliders are due to constraints to keep the synchrotron radiation power constant over energies.
- Beyond 400 GeV, LCs take over, and there is no chance for circular e+e- machines (for 100 km circumference & 50 MW/beam).
- More exotic energies, such as the s-channel Higgs production, may be possible at circular colliders.

**FCC-CDR**

**CEPC CDR**

UPDATED BASELINE FOR A
STAGED COMPACT LINEAR
COLLIDER, CERN–2016–004

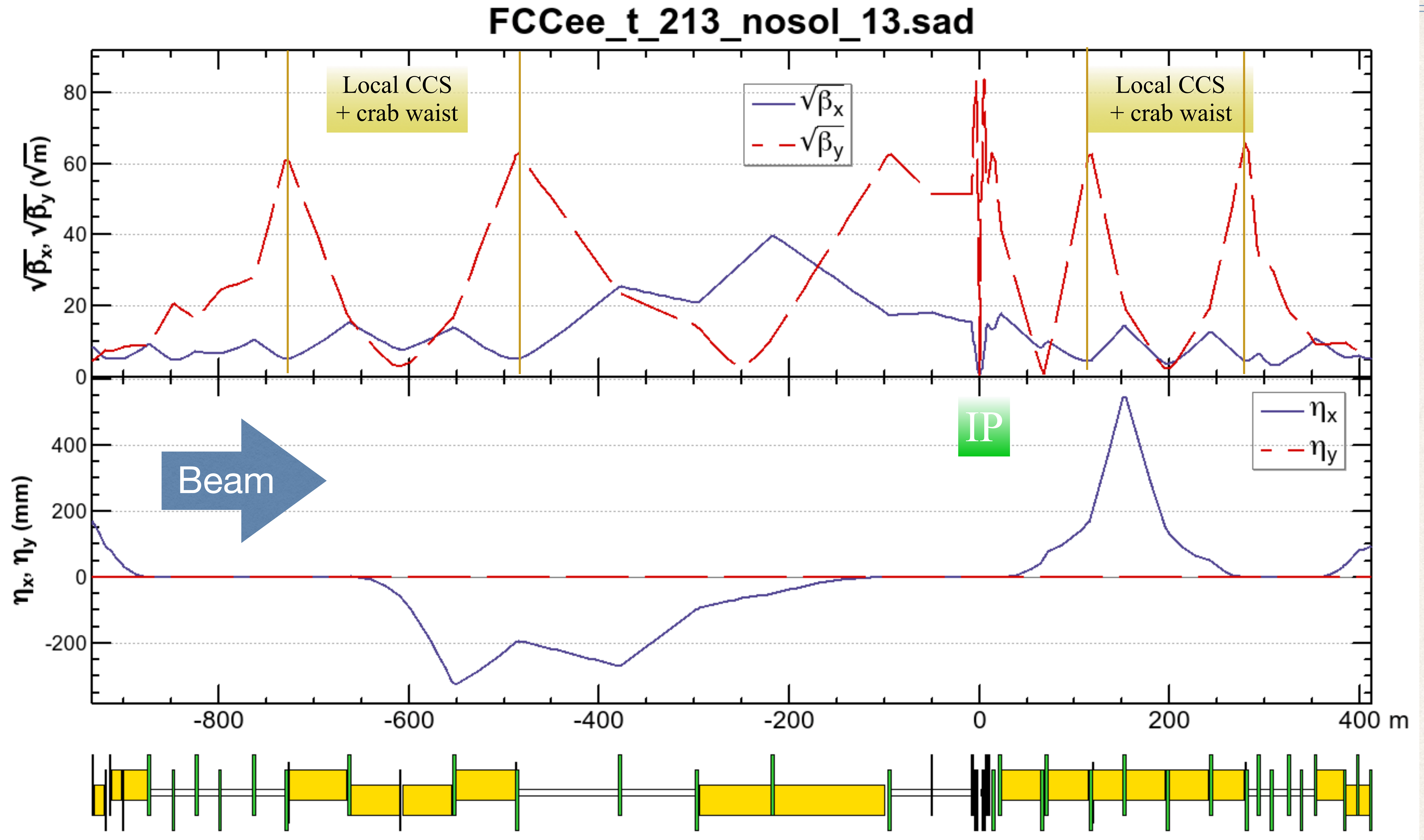
http://newsline.linearcollider.org/
2018/04/05/the-ilc-at-250-gev-an-
overview-of-options/

# FCC-ee collider parameters

| Parameter | Z | WW | H (ZH) | ttbar |
|---|---|---|---|---|
| Circumference [km] | 97.756 | | | |
| Beam energy [GeV] | 45 | 80 | 120 | 182.5 |
| SR loss / turn / beam [MW] | **50** | | | |
| SR energy loss / turn [GeV] | 0.036 | 0.34 | 1.72 | 9.21 |
| Beam current [mA] | 1390 | 147 | 29 | 5.4 |
| Bunches/beam | 16640 | 2000 | 393 | 48 |
| Bunch intensity [$10^{11}$] | 1.7 | 1.5 | 1.5 | 2.3 |
| Total RF voltage [GV] | 0.1 | 0.44 | 2.0 | 10.9 |
| Long. damping time [turns] | 1281 | 235 | 70 | 20 |
| Horizontal beta* [m] | 0.15 | 0.2 | 0.3 | 1 |
| Vertical beta* [mm] | 0.8 | 1 | 1 | 1.6 |
| Horiz. geometric emittance [nm] | 0.27 | 0.28 | 0.63 | 1.46 |
| Vert. geom. emittance [pm] | 1.0 | 1.7 | 1.3 | 2.9 |
| Bunch length with SR / BS [mm] | 3.5 / **12.1** | 3.0 / **6.0** | 3.3 / **5.3** | 2.0 / **2.5** |
| Luminosity per IP [$10^{34}$ $cm^{-2}s^{-1}$] | **>200** | **>25** | **>7** | **>1.4** |
| Beam lifetime rad Bhabha / BS [min] | 68 / >200 | 49 / >1000 | 38 / 18 | 40 / 18 |

BS = beamstrahlung

# Synchrotron radiation toward the IP @ 182.5 GeV

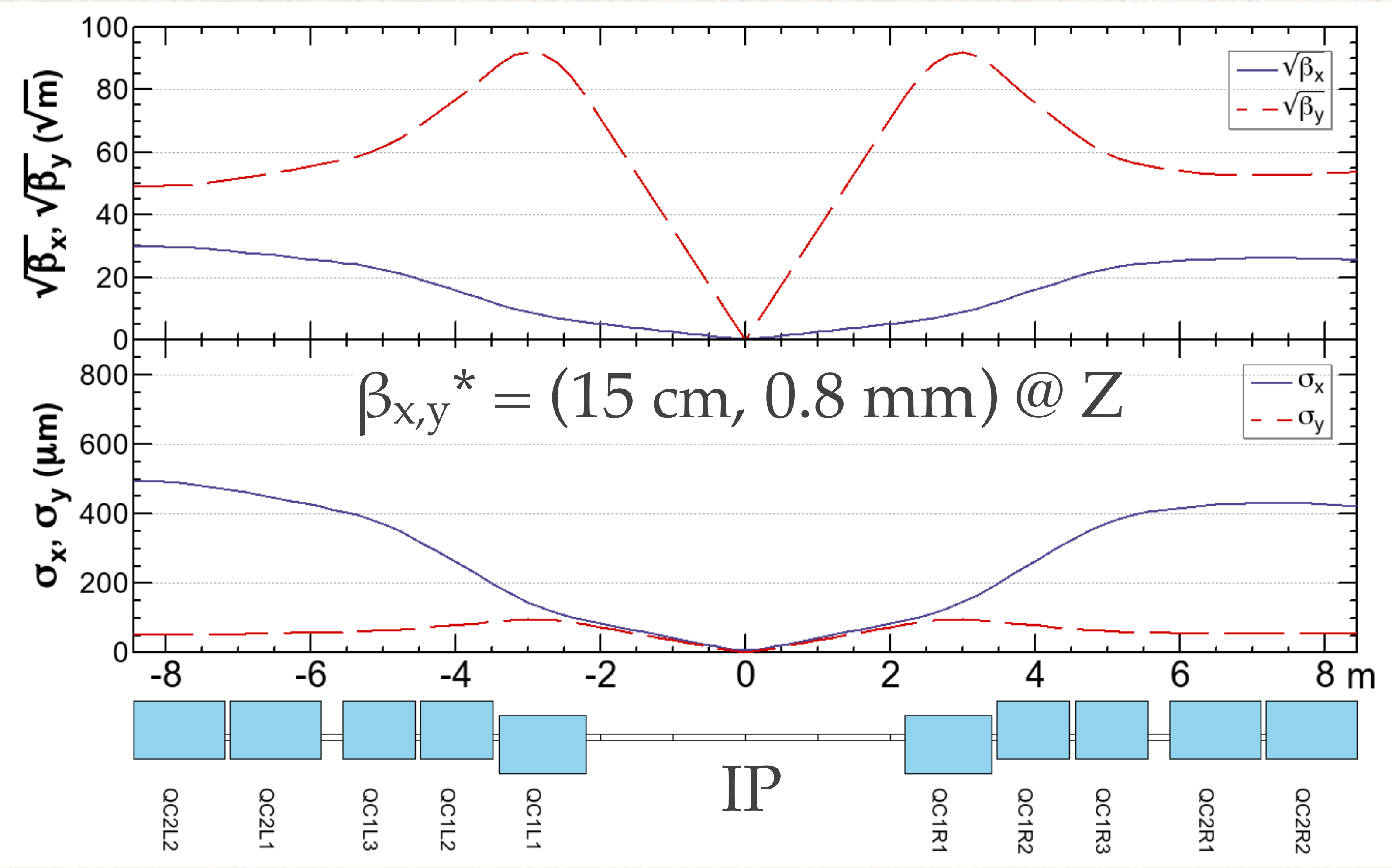


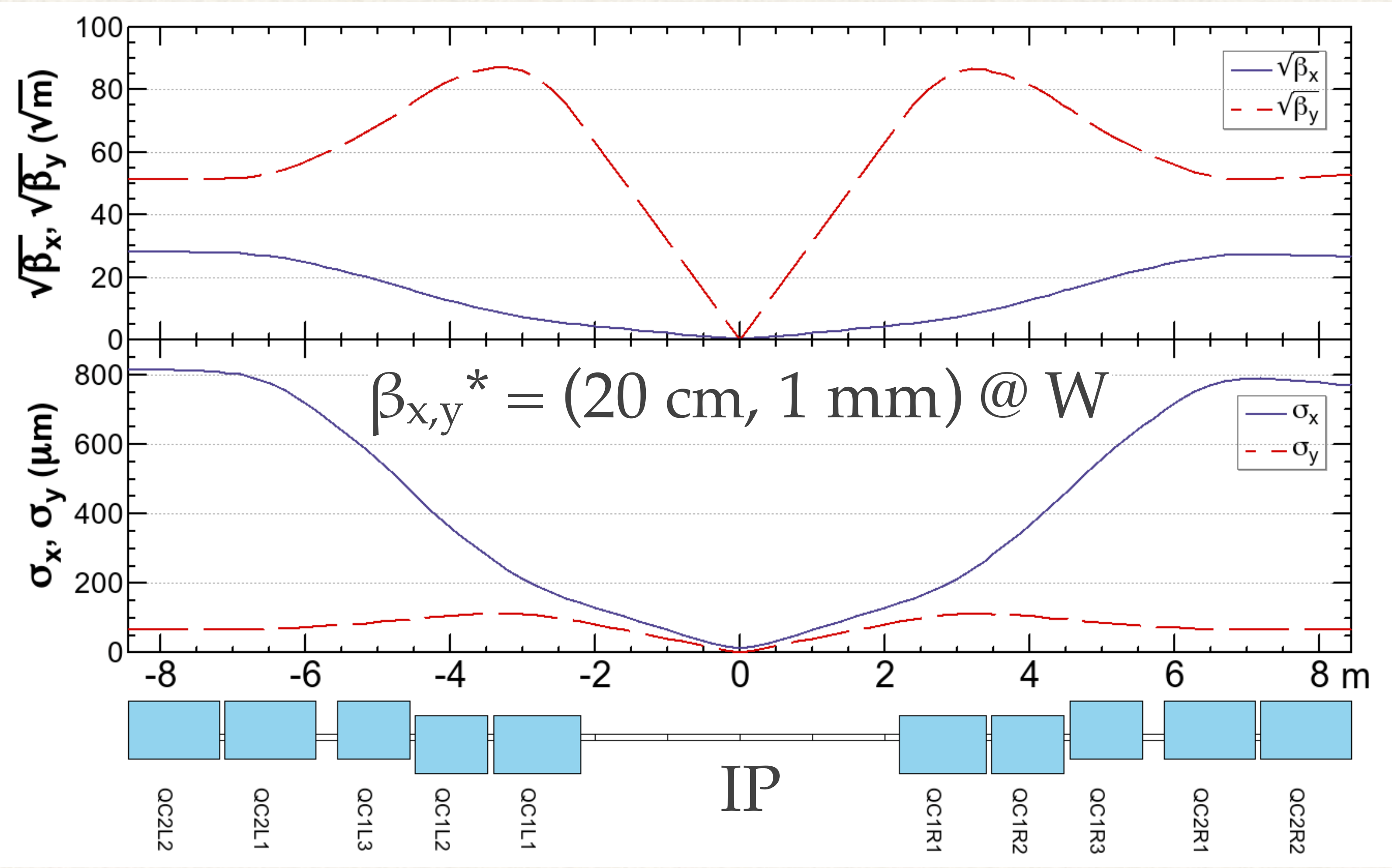
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $u_c$ (keV) | 1470 | 11.9 | 596 | 578 | 224 | 89.2 | 98.9 | 691 | 1434 | 742 | 336 | 972 | … |
| $P_{SR}$ (kW) | 25.0 | 4.0 | 8.4 | 7.9 | 1.5 | 0.28 | 0.53 | 9.0 | 0.74 | 10.7 | 1.64 | 18.0 | … |

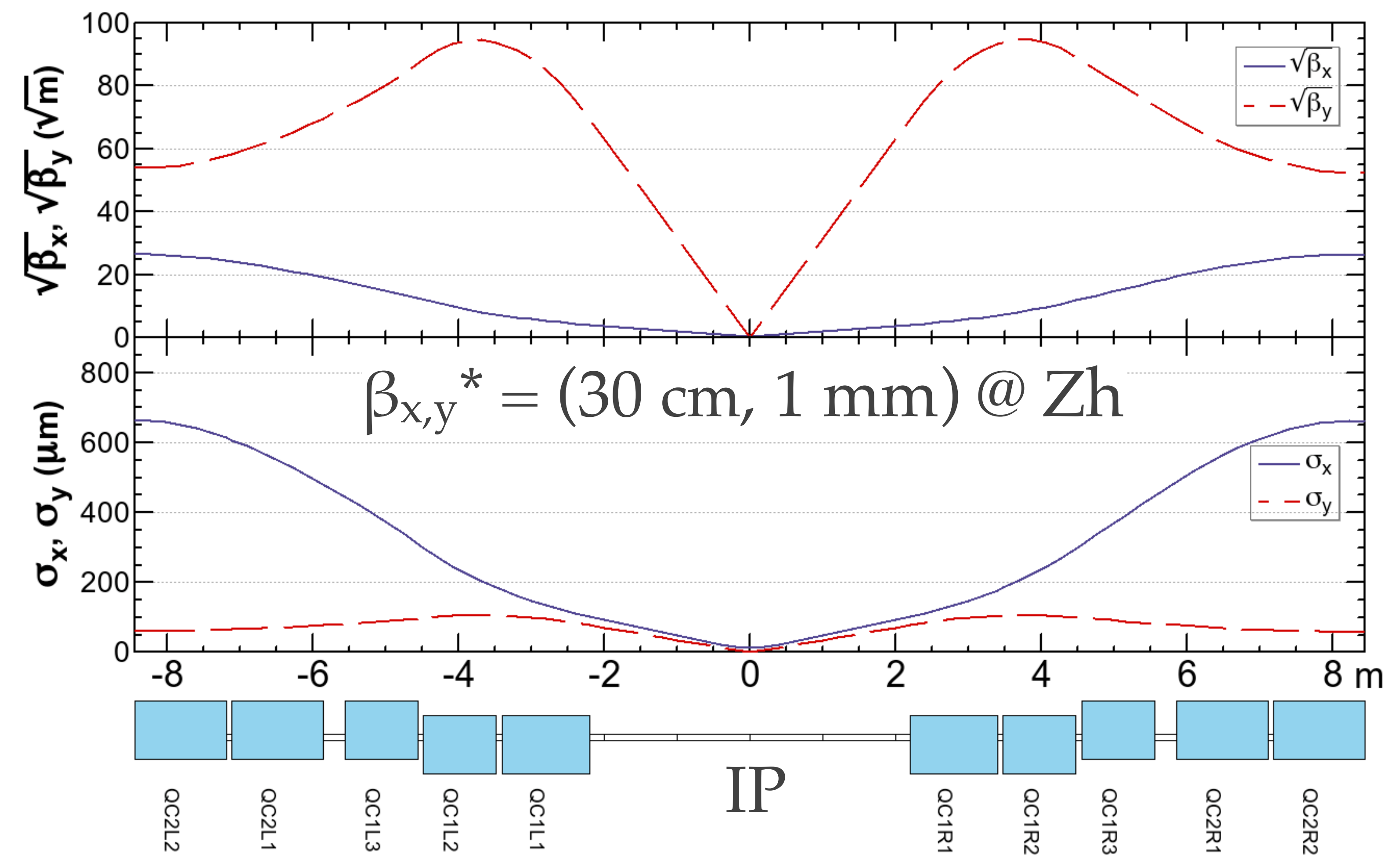
$u_c < 100$ keV up to 480 m from the IP @182.5 GeV.

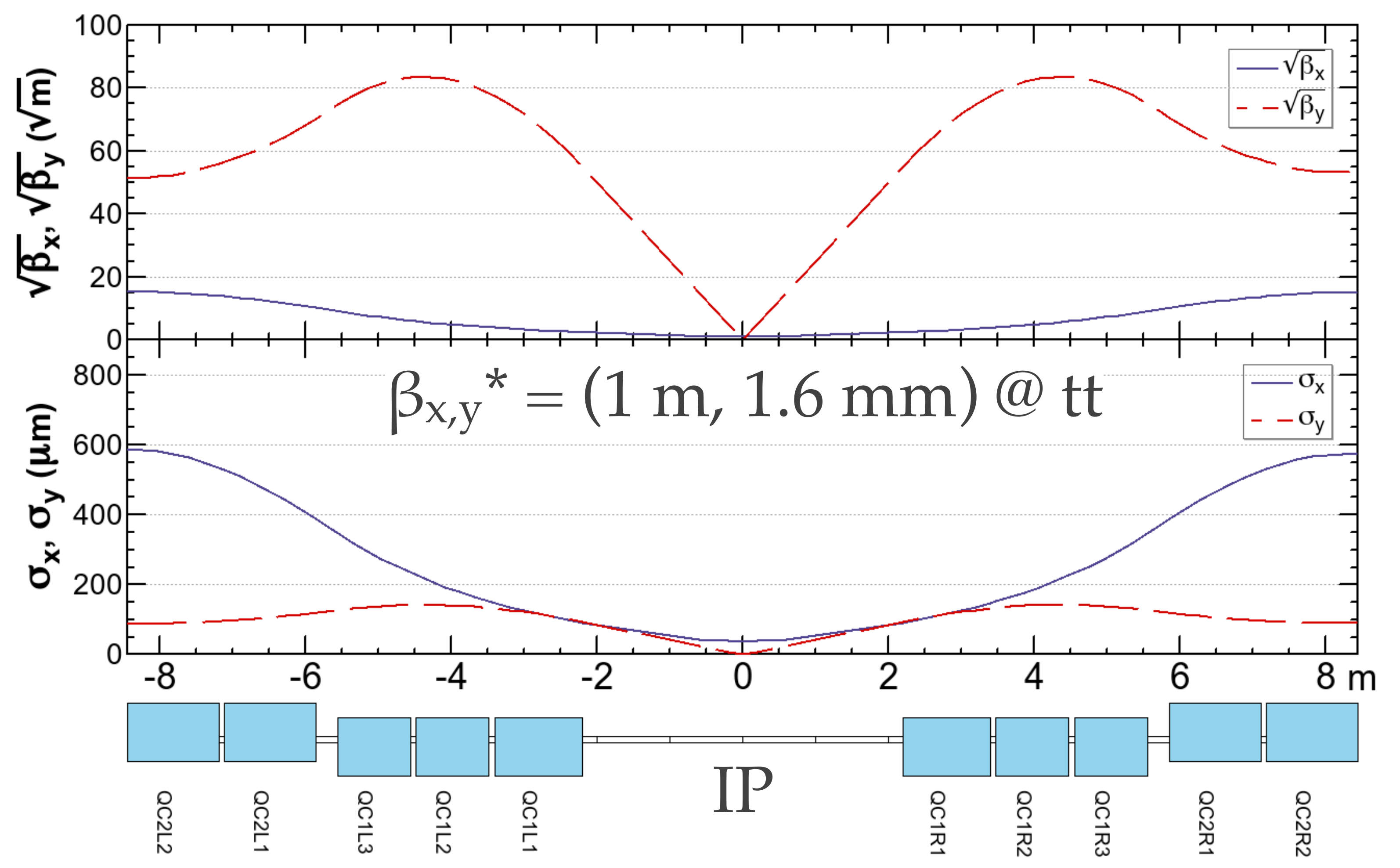
yellow boxes: dipole magnets

# Optics around the IP



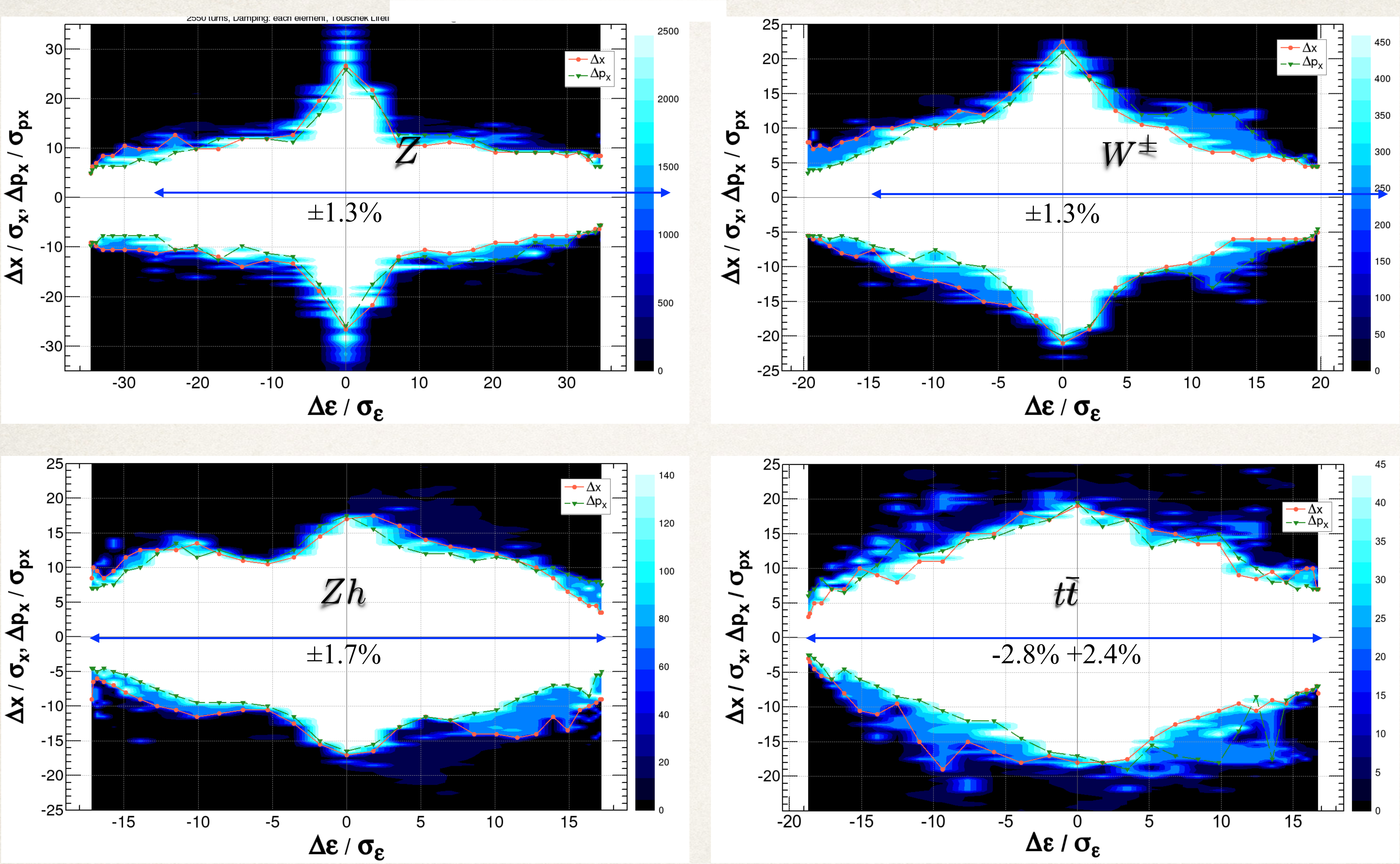






- Divide QC1/2 into 3/2 independent pieces, reversing the polarity at *Z*, *W*, *Zh*.
- By this split, the chromaticity and the peaks of $\beta_{x,y}$ around the IP are suppressed even with the reductions of $\beta_{x,y}^*$.

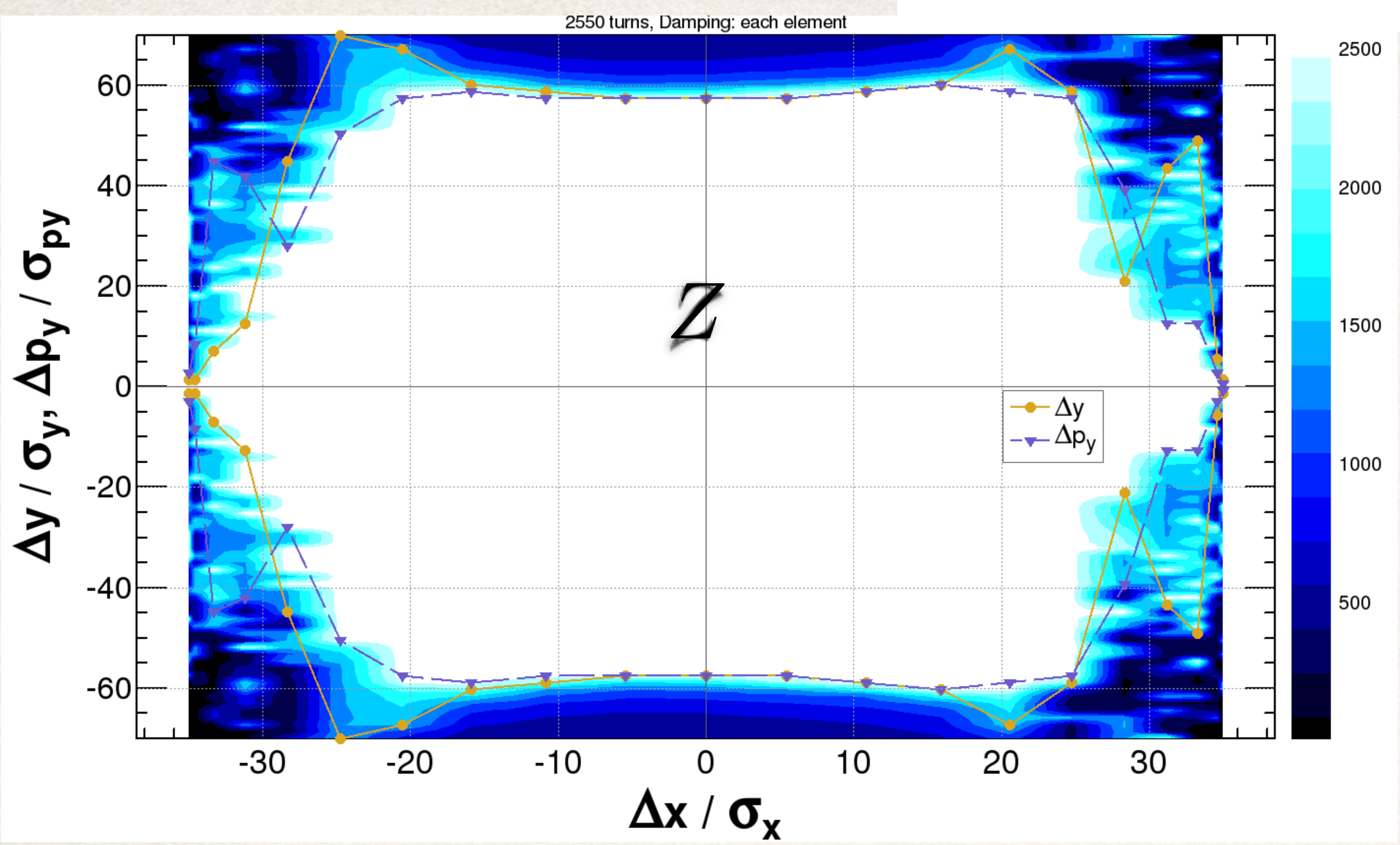
# Dynamic Aperture (Z-X plane)

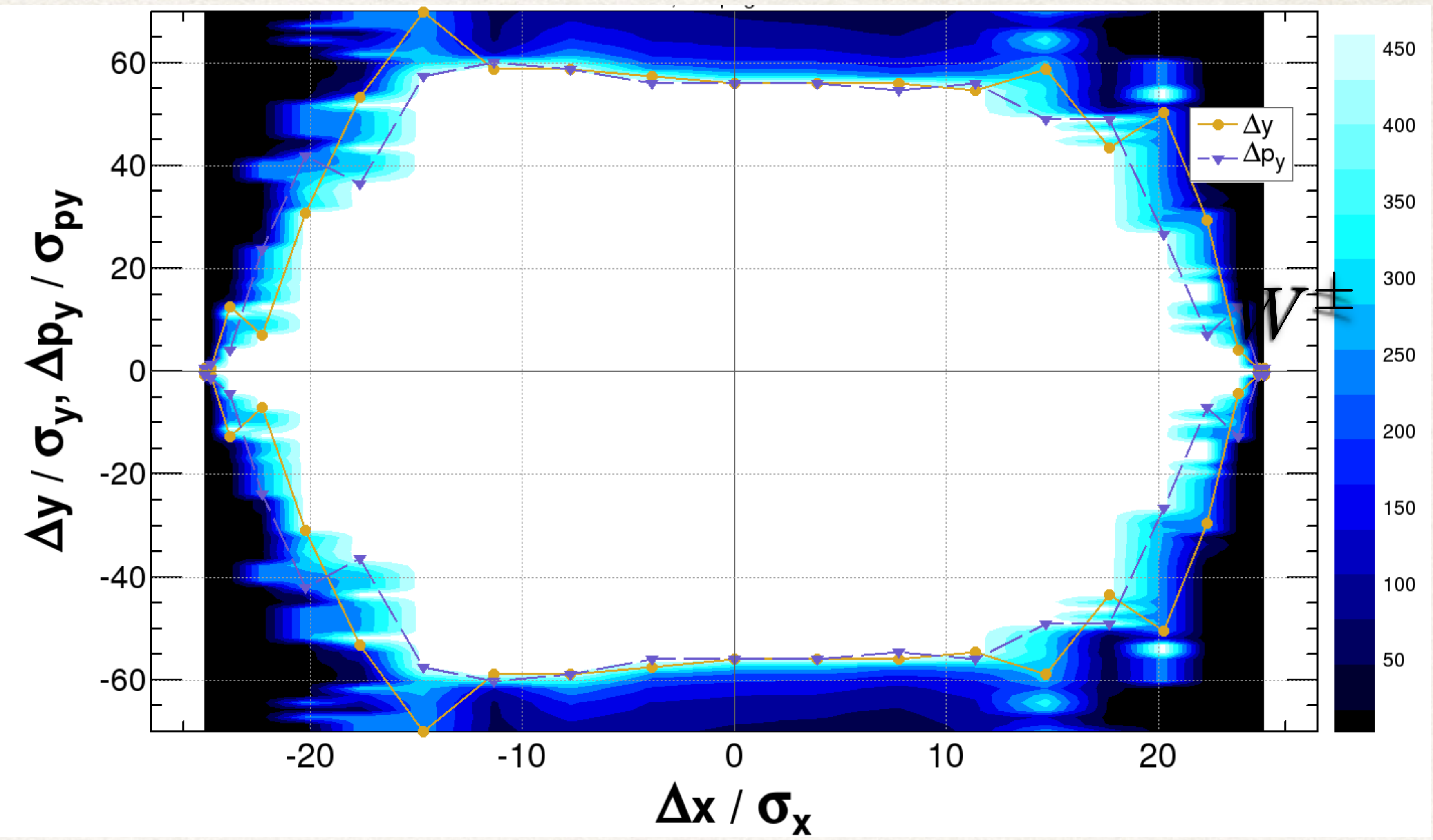


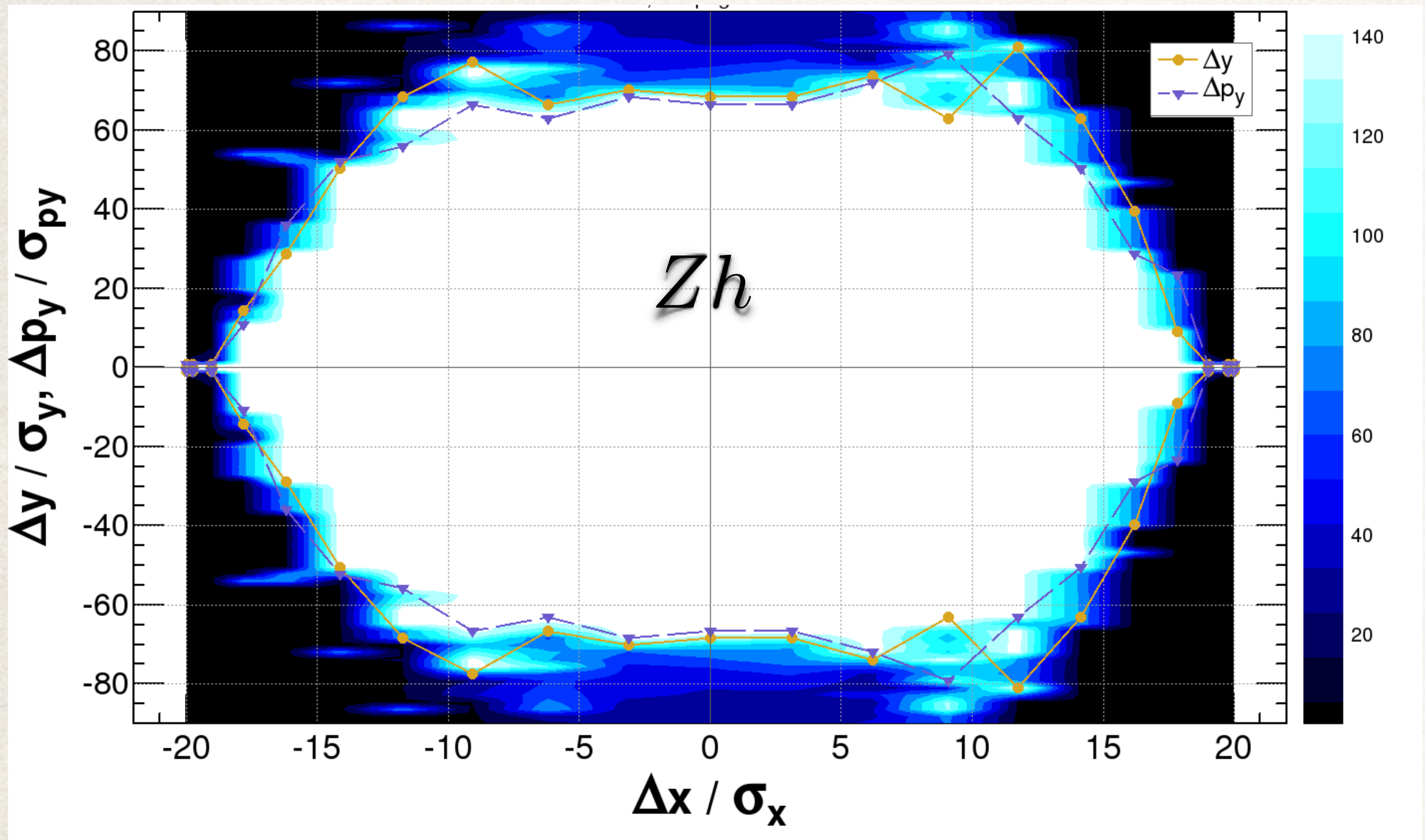
- This is a beamstrahlung-dominated machine: the dynamic momentum acceptance is the crucial parameter to determine the performance.
- The dynamic aperture has been optimized on the Z-X plane by changing 292 (Zh, ttbar) or 208 (Z, W) families of *-I* paired sextupoles.

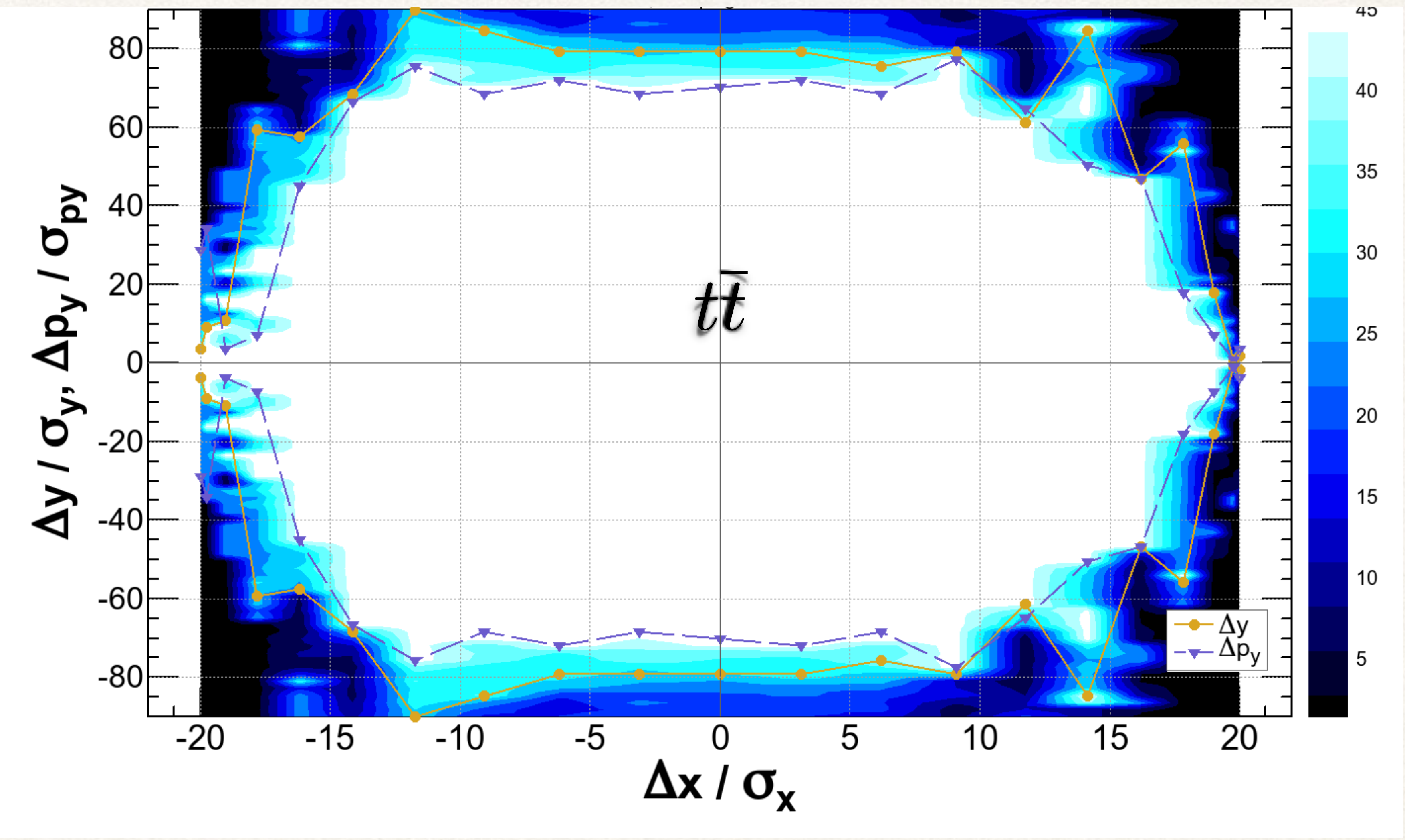
- The dynamic aperture satisfies the requirements by BS and the injection at each energy.

# Dynamic Aperture (on-energy, XY plane)









| Energy | Dynamic | | Physical | |
|---|---|---|---|---|
| | $\Delta x/\sigma_x$ | $\Delta y/\sigma_y$ | $\Delta x/\sigma_x$ | $\Delta y/\sigma_y$ |
| $Z$ | ±35 | ±58 | ±37 | ±170 |
| $W^\pm$ | ±25 | ±55 | ±23 | ±133 |
| $Zh$ | ±18 | ±67 | ±34 | ±144 |
| $t\bar{t}$ | ±19 | ±70 | ±43 | ±107 |

- The dynamic aperture is always smaller than the physical aperture given by the beam pipe at QC1 (15 mm radius).

# Effects included in the optimization of dynamic aperture

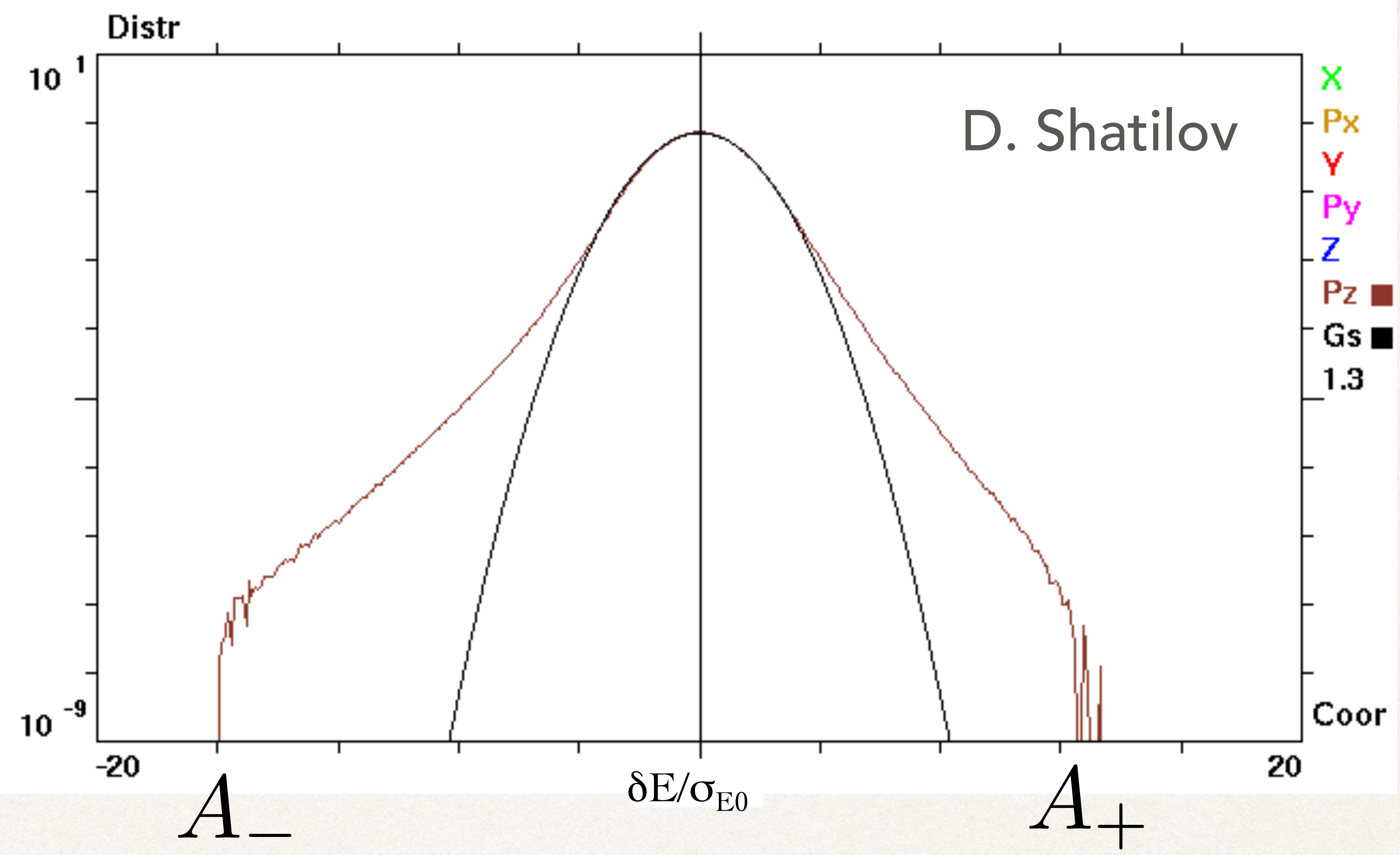
| Effects | Included? | Significance |
|---|---|---|
| Synchrotron motion | Yes | **Essential** |
| Radiation loss in dipoles | Yes | **Essential** – improves the aperture |
| Radiation loss in quadrupoles | Yes | **Essential** – reduces the aperture |
| Tapering | Yes | **Essential** |
| Crab waist | Yes | transverse aperture is reduced by $\sim 20\%$ |
| Maxwellian fringes | Yes | small |
| Kinematical terms | Yes | small |
| Solenoids | Evaluated separately | minimal, if locally compensated |
| Radiation fluctuation | after optimization | **Essential** |
| Beam-beam effects and beamstrahlung for stored beam | after optimization | affects the lifetime |
| Beam-beam effects for injected beam | on going | |
| Higher order fields / errors / misalignments | on going | **Essential**, development of correction/tuning scheme is necessary |

# Asymmetric acceptance (ttbar)

**E = 182.5 GeV**

$\sigma_{E0}$ = 0.00153,  $\sigma_E$ = 0.00193,
Black line: Gauss with $\sigma_E$ = 1.3 $\sigma_{E0}$

Energy acceptance: 2.5% = 16.3 $\sigma_{E0}$



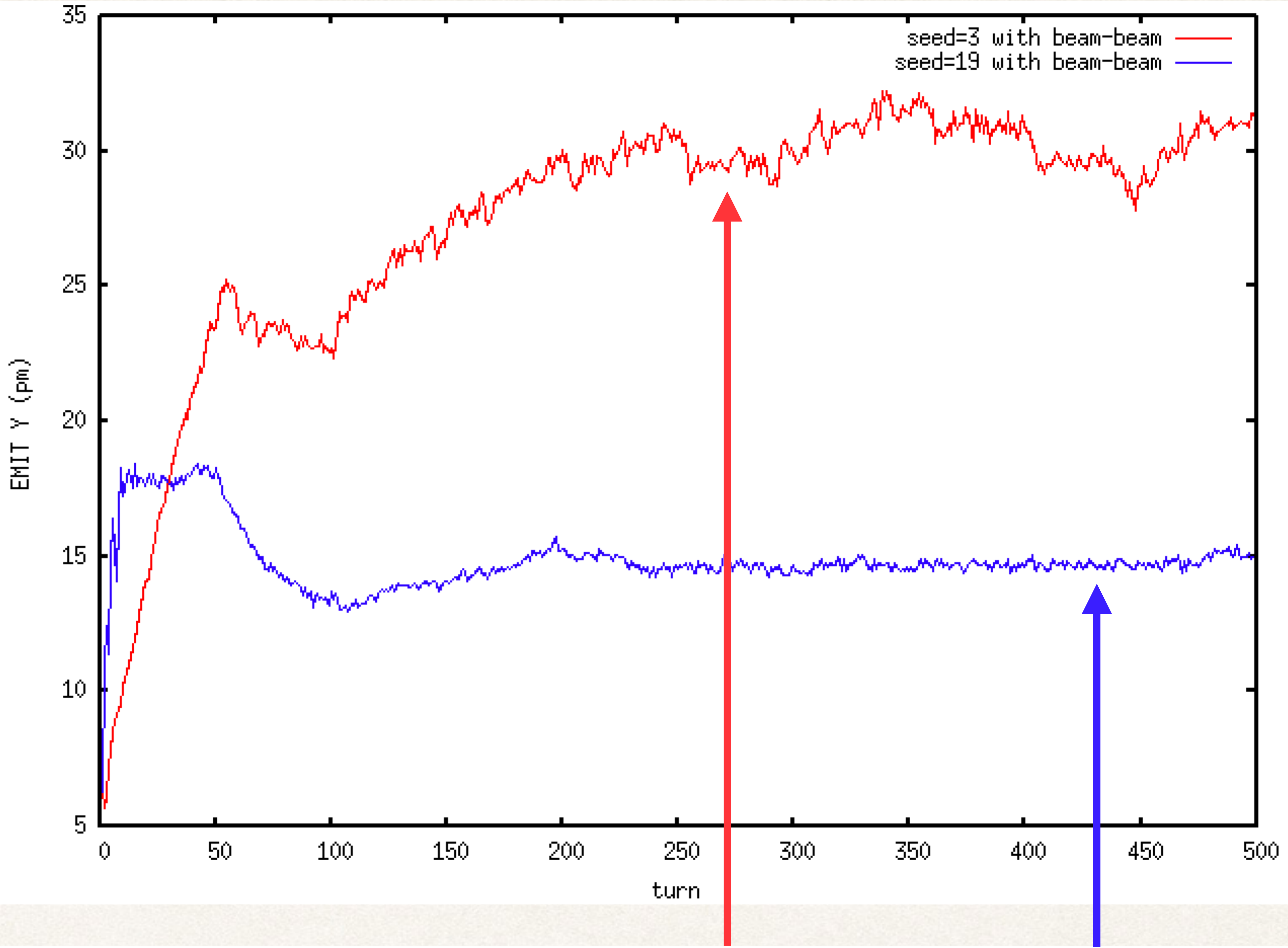
- The expected energy distribution of the beam has asymmetric tail due to beamstrahlung (D. Shatilov, as above).
- Thus the required momentum acceptance should be asymmetric: Wider aperture in the negative side.
- The aperture of the positive side can be expressed as the summation of damping and diffusion terms in a half synchrotron period:

$$A_+ \approx -A_- \exp(-\alpha_z/2\nu_s) + 3\sigma_{\delta,\mathrm{BS}}\sqrt{1-\exp(-\alpha_z/\nu_s)}$$

with the damping rate $\alpha_z$.

# Unexpected beam blowup

- D. El Khechen has observed an unexpected vertical beam blowup in tracking simulations with beam-beam and lattice for FCC-ee ttbar by SAD.
- The vertical (on closed orbit) emittance of the lattice is generated by random misalignments of sextpoles and set to the design (2.9 pm = 0.2%).
- In early simulations with beam beam and lattice without misalignment did not show such blowups (D. Zhou).
- The blowup strongly depends on the random number for strength of skew quads or misalignments of sextupoles to produce the vertical emittance.



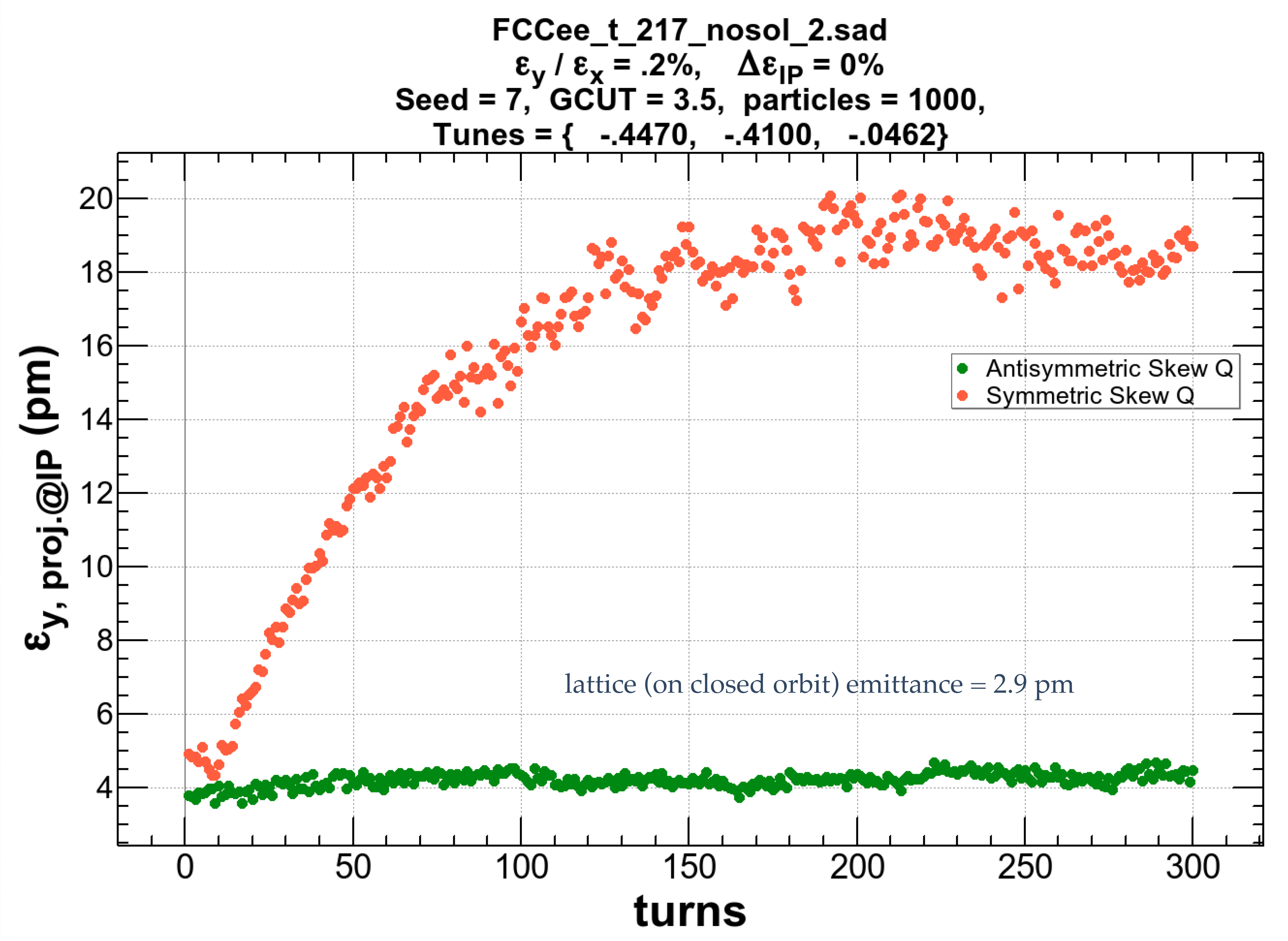
| Coupling (%) | 0.2 | 0.2 |
|---|---|---|
| RMS of sext. Offset () | 11 | 15 |
| Seed | 3 | 19 |
| $\eta_y$ @ (IP.1, IP.2) () | (-5.3, 4.24) | (-8.9,8) |
| $\eta_{py}$ x $\beta_y^*$ @ (IP.1, IP.2) () | (6.8, 1.04) | (35.4,23) |
| R2 parameter | ($1.8x10^{-3}$,$1.8x10^{-3}$) | ($-5.1x10^{-5}$,$-1.8x10^{-4}$) |

lattice emittance on closed orbit = 2.9 pm

D. El Khechen

# Unexpected beam blowup

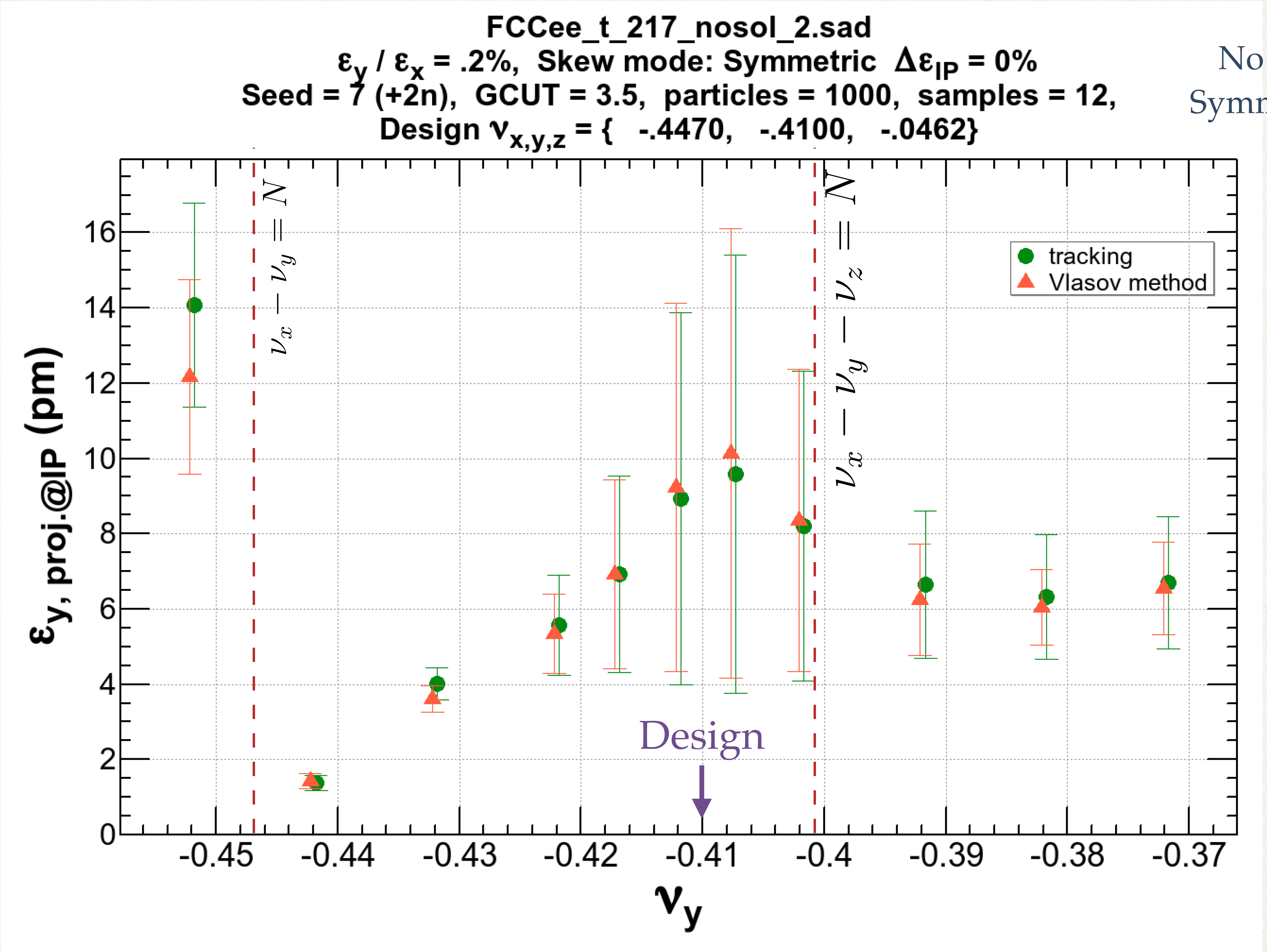
- Then it was found that such a blowup could occur even ***without beam-beam***.
- The blowup depends on how the vertical emittance is generated (between symmetric skew = $x$-$y$ coupling dominated and antisymmetric skew = vertical dispersion dominated).
- The blowup is explained by a Vlasov model for "anomalous emittance" in Ref. [2]. .



lattice (on closed orbit) emittance = 2.9 pm

[2] K. Oide, H. Koiso, ``Anomalous equilibrium emittance due to chromaticity in electron storage rings'', Phys.Rev. E49 (1994) 4474-4479.

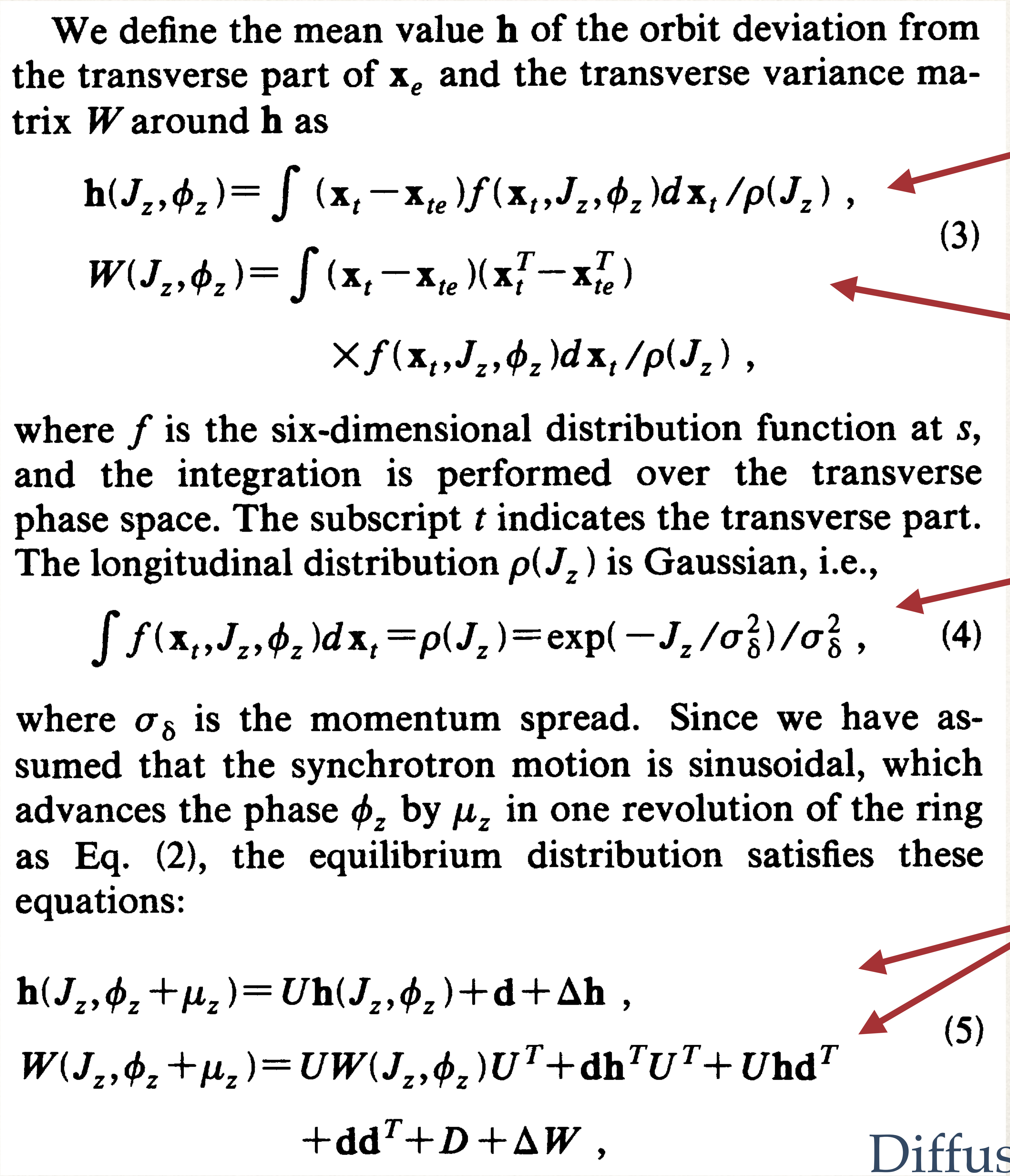
# The Vlasov model agrees with tracking



No beam-beam
Symmetric Skew Q

- The error bars show the variation for 12 samples of skew excitations.
- The most significant resonance is $\nu_x - \nu_y - \nu_z = N$, according to the tune dependence.

# The Vlasov model (in Ref. [2])



We define the mean value **h** of the orbit deviation from the transverse part of $\mathbf{x}_e$ and the transverse variance matrix $W$ around **h** as

$$\mathbf{h}(J_z,\phi_z)=\int(\mathbf{x}_t-\mathbf{x}_{te})f(\mathbf{x}_t,J_z,\phi_z)d\mathbf{x}_t/\rho(J_z)\ ,$$

$$W(J_z,\phi_z)=\int(\mathbf{x}_t-\mathbf{x}_{te})(\mathbf{x}_t^T-\mathbf{x}_{te}^T)\times f(\mathbf{x}_t,J_z,\phi_z)d\mathbf{x}_t/\rho(J_z)\ , \qquad (3)$$

where $f$ is the six-dimensional distribution function at $s$, and the integration is performed over the transverse phase space. The subscript $t$ indicates the transverse part. The longitudinal distribution $\rho(J_z)$ is Gaussian, i.e.,

$$\int f(\mathbf{x}_t,J_z,\phi_z)d\mathbf{x}_t=\rho(J_z)=\exp(-J_z/\sigma_\delta^2)/\sigma_\delta^2\ , \qquad (4)$$

where $\sigma_\delta$ is the momentum spread. Since we have assumed that the synchrotron motion is sinusoidal, which advances the phase $\phi_z$ by $\mu_z$ in one revolution of the ring as Eq. (2), the equilibrium distribution satisfies these equations:

$$\mathbf{h}(J_z,\phi_z+\mu_z)=U\mathbf{h}(J_z,\phi_z)+\mathbf{d}+\Delta\mathbf{h}\ ,$$

$$W(J_z,\phi_z+\mu_z)=UW(J_z,\phi_z)U^T+\mathbf{d}\mathbf{h}^TU^T+U\mathbf{h}\mathbf{d}^T+\mathbf{d}\mathbf{d}^T+D+\Delta W\ , \qquad (5)$$

Closed orbit ($J_z$, $\phi_z$)

Transverse
second moment ($J_z$, $\phi_z$)

The longitudinal
distribution is Gaussian

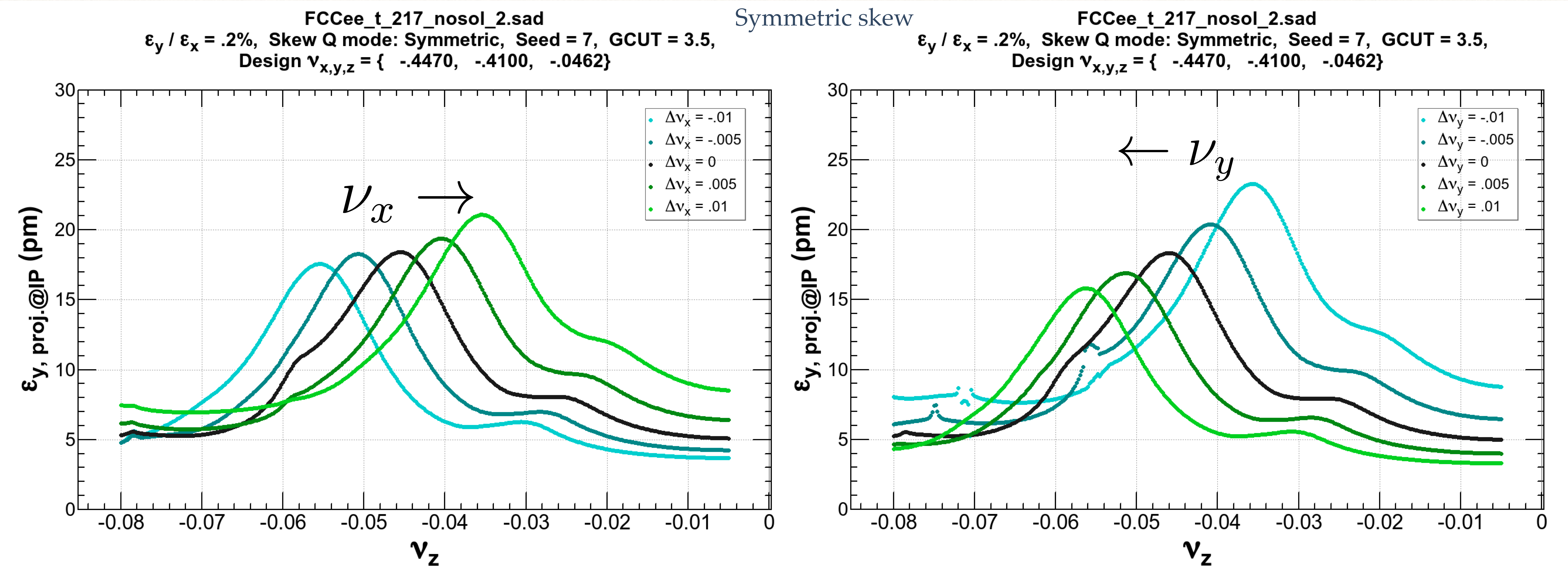
$U=U(\delta)$: momentum
dependent 1-turn xfer matrix

Equilibrium after one
revolution of the ring

Diffusion is also taken into account.

# Tune dependence by Vlasov model

- As the agreement with tracking looks excellent, let us use the Vlasov model hereafter, since it is many orders faster than tracking.
- Scanning the synchrotron tune is just easy in the model, since it is just a parameter and no change in the lattice is necessary.



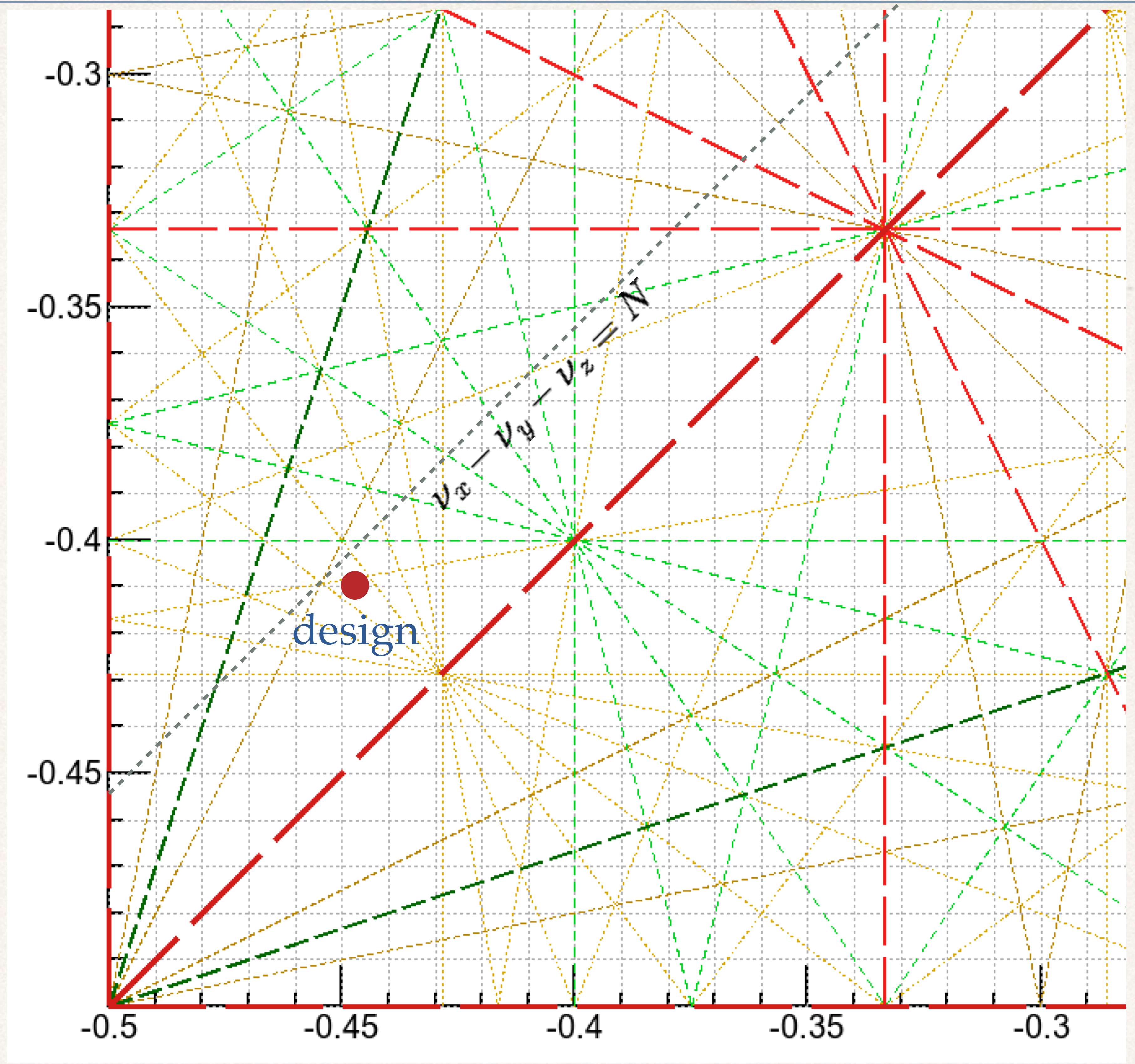
No beam-beam
Symmetric skew

Skew Q is fixed at the design νz
in these figures above.

- The width of resonance ~ damping rate = 1/(40 half turns)

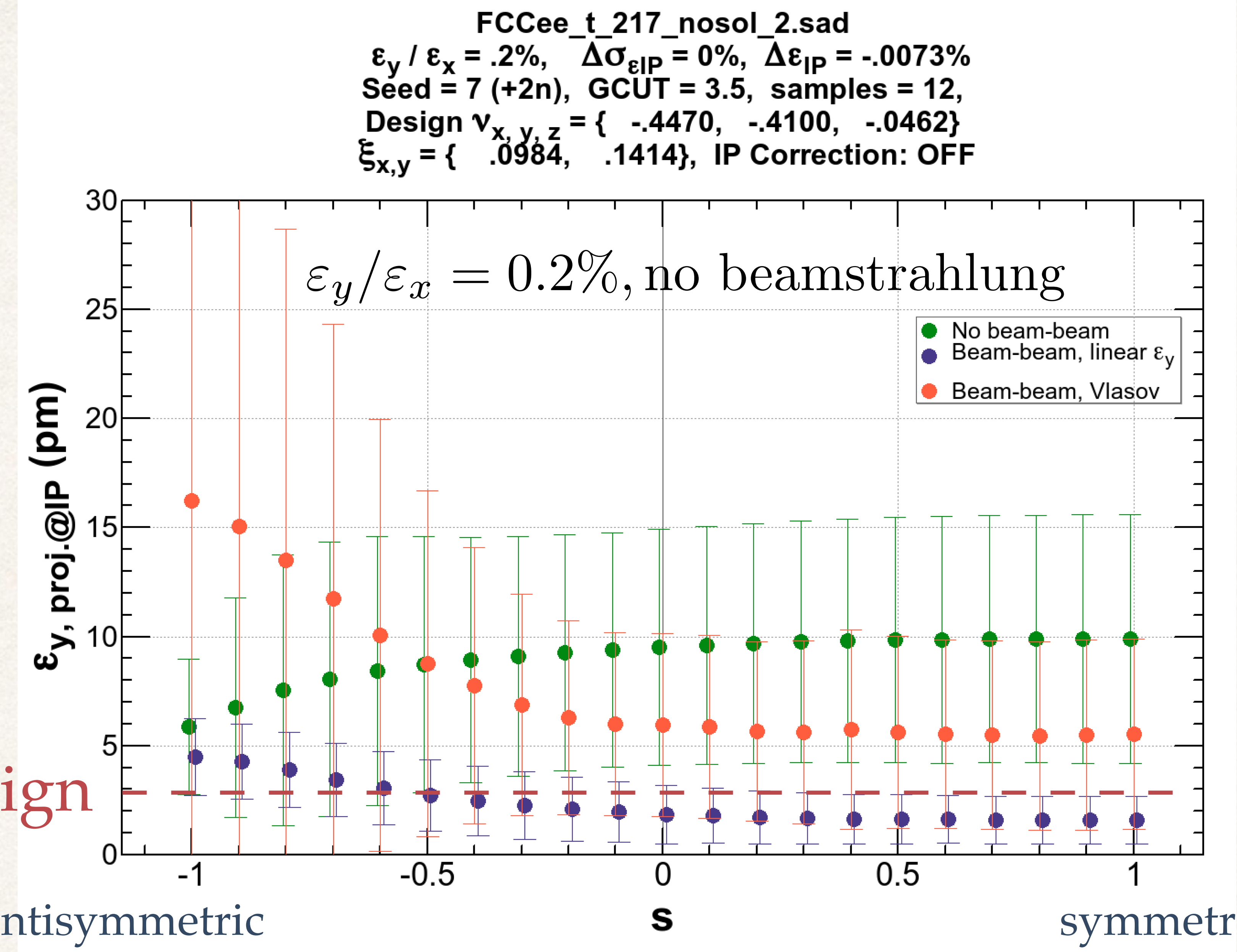
  - According to the tune dependence above, the resonance $\nu_x - \nu_y - \nu_z = N$ is identified as the most relevant one.

# The resonance line



- The design tune point is a little bit off the resonance line — but it has a meaning: the blowup can be larger than on a tune exact at the resonance.

# Blowup with/without beam-beam

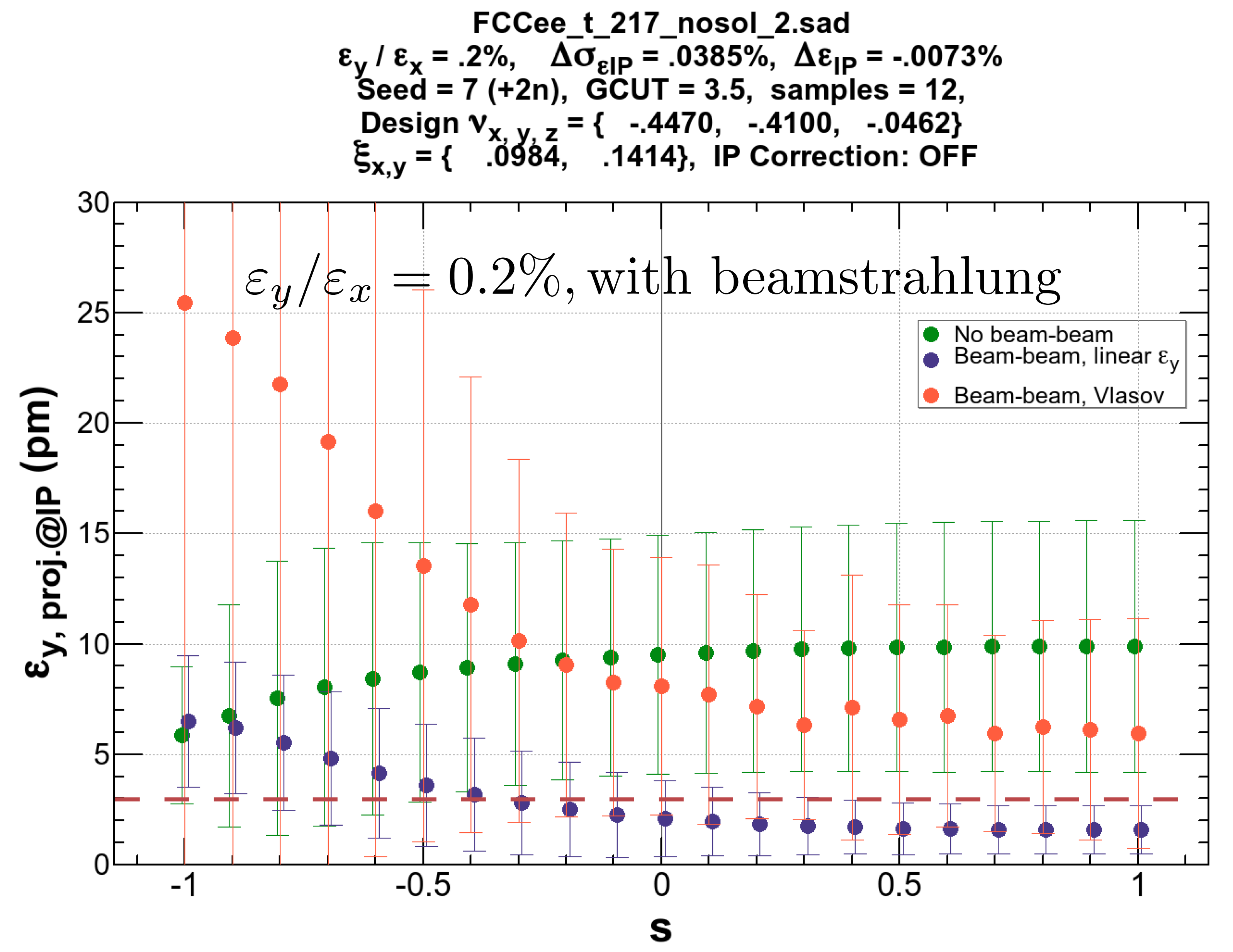


$\varepsilon_y/\varepsilon_x = 0.2\%$, no beamstrahlung

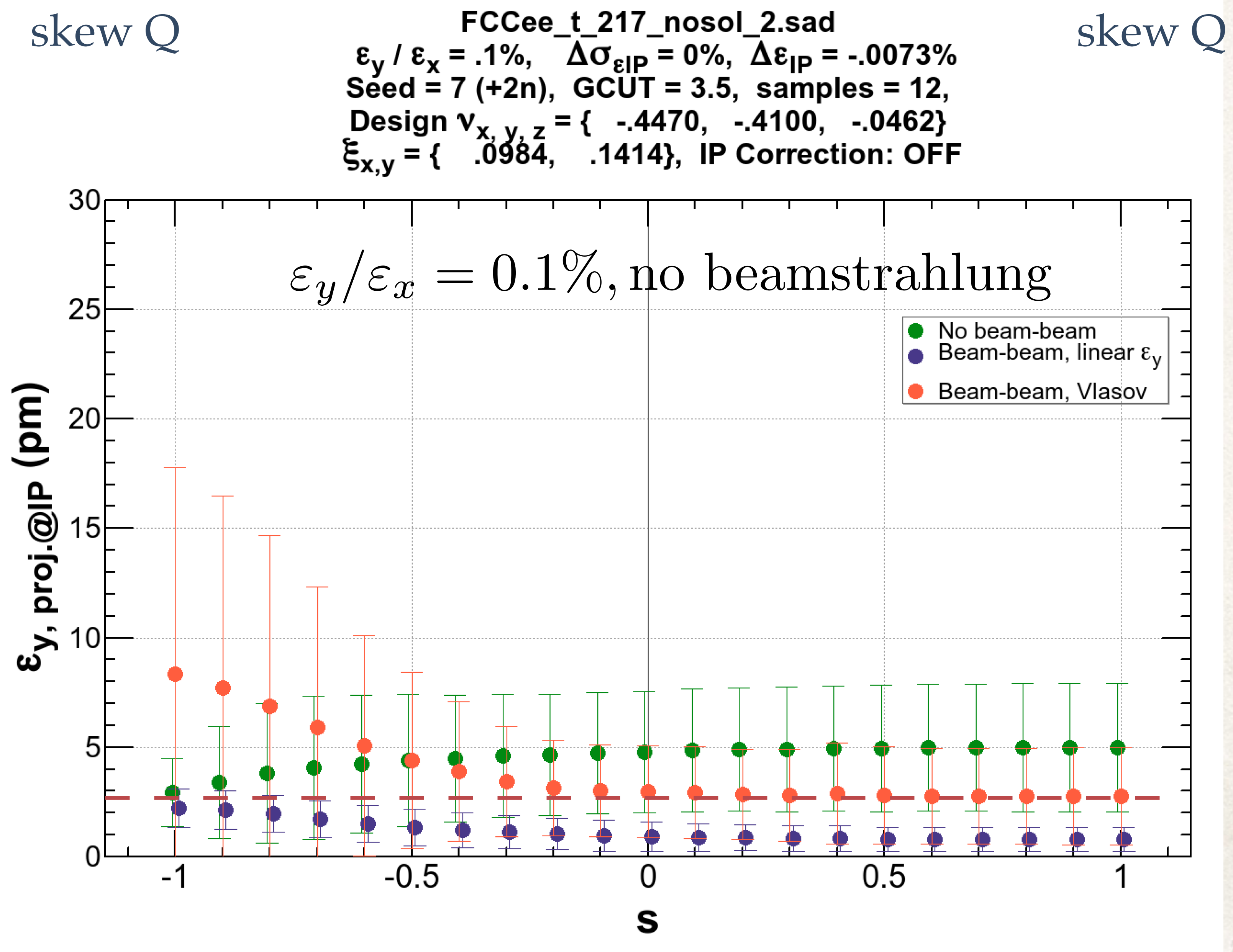
design

antisymmetric
skew Q

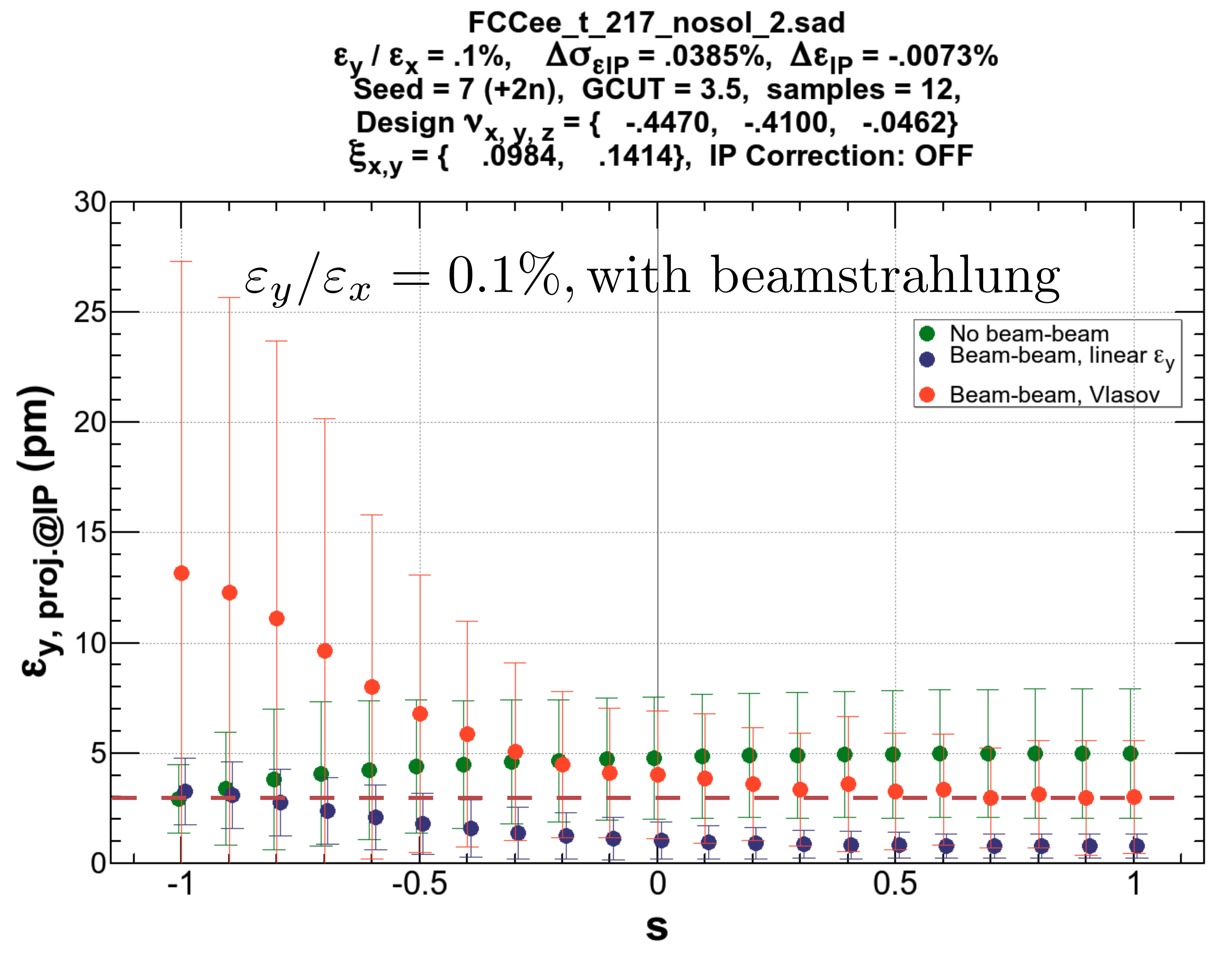
symmetric
skew Q



$\varepsilon_y/\varepsilon_x = 0.2\%$, with beamstrahlung



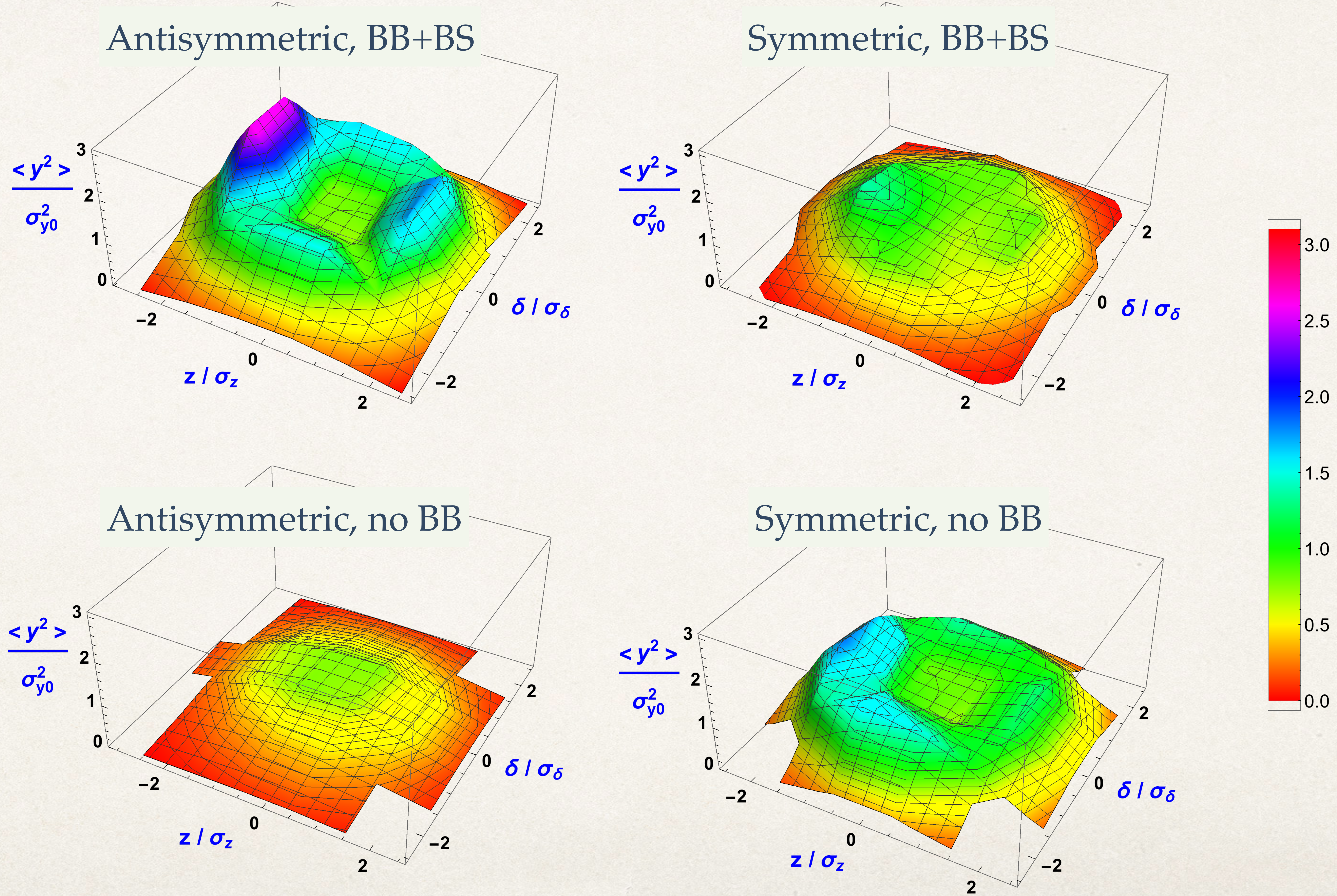
$\varepsilon_y/\varepsilon_x = 0.1\%$, no beamstrahlung



$\varepsilon_y/\varepsilon_x = 0.1\%$, with beamstrahlung

# Comparison of the blowups

in the synchrotron phase space



Antisymmetric, BB+BS

Symmetric, BB+BS

Antisymmetric, no BB

Symmetric, no BB

# Summary

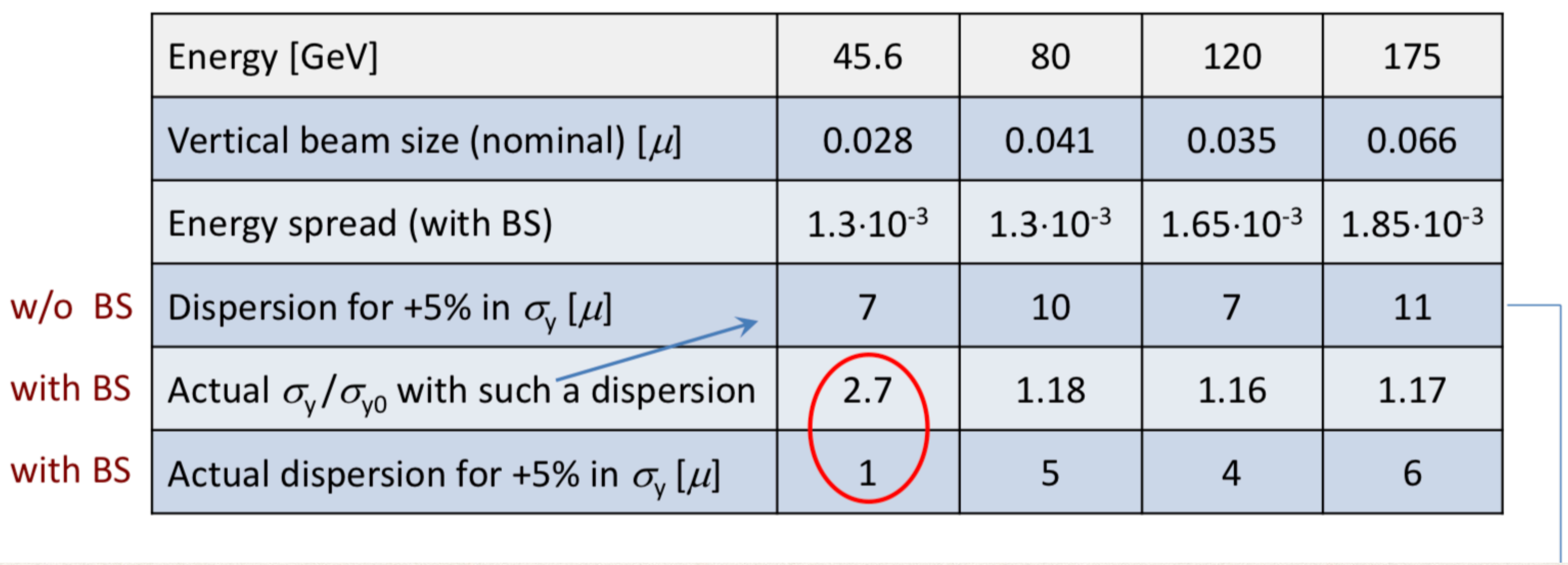
- FCC CDR has been published, identifying FCC-ee as its first step to provide the maximum luminosity as an e+e- collider covering Z, WW, Zh, and tuba physics.
- FCC-ee collider optics has been designed to achieve a large dynamic aperture to match the luminosity and beamstrahlung.
- Several "new" effects on the beam dynamics are expected, such as an anomalous vertical emittance growth by synchrotron-betatron resonances with/without beam-beam.

**Thank you for paying attention!**

# Backups

# Why unexpected?

- This unexpected blowup occurs even when the residual dispersion at the IP is below the criteria given by D. Shatilov with beam-beam simulation with beamstrahlung but without the lattice.

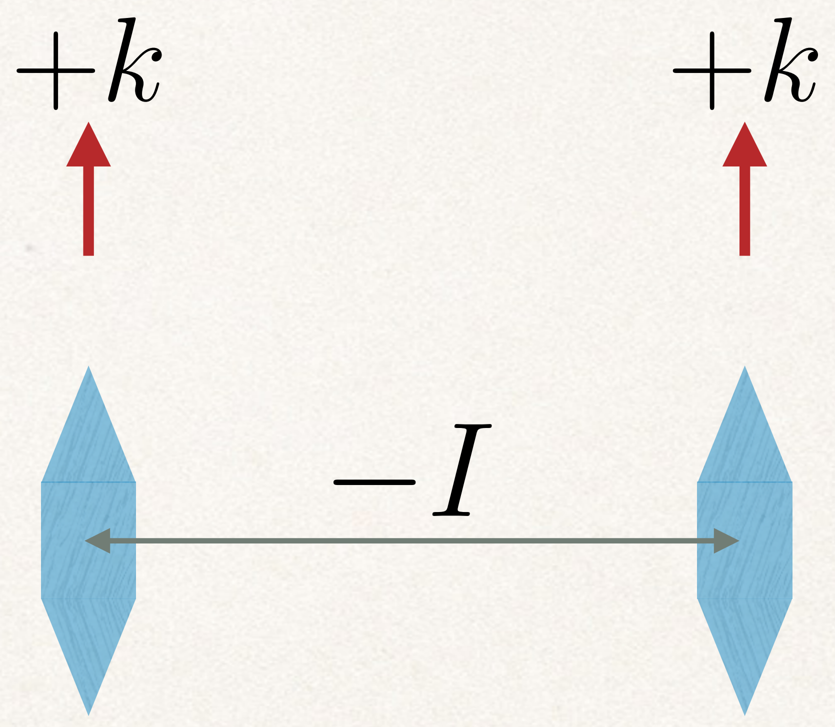


| | Energy [GeV] | 45.6 | 80 | 120 | 175 |
|---|---|---|---|---|---|
| | Vertical beam size (nominal) [$\mu$] | 0.028 | 0.041 | 0.035 | 0.066 |
| | Energy spread (with BS) | $1.3\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $1.65\cdot10^{-3}$ | $1.85\cdot10^{-3}$ |
| w/o BS | Dispersion for +5% in $\sigma_y$ [$\mu$] | 7 | 10 | 7 | 11 |
| with BS | Actual $\sigma_y/\sigma_{y0}$ with such a dispersion | 2.7 | 1.18 | 1.16 | 1.17 |
| with BS | Actual dispersion for +5% in $\sigma_y$ [$\mu$] | 1 | 5 | 4 | 6 |

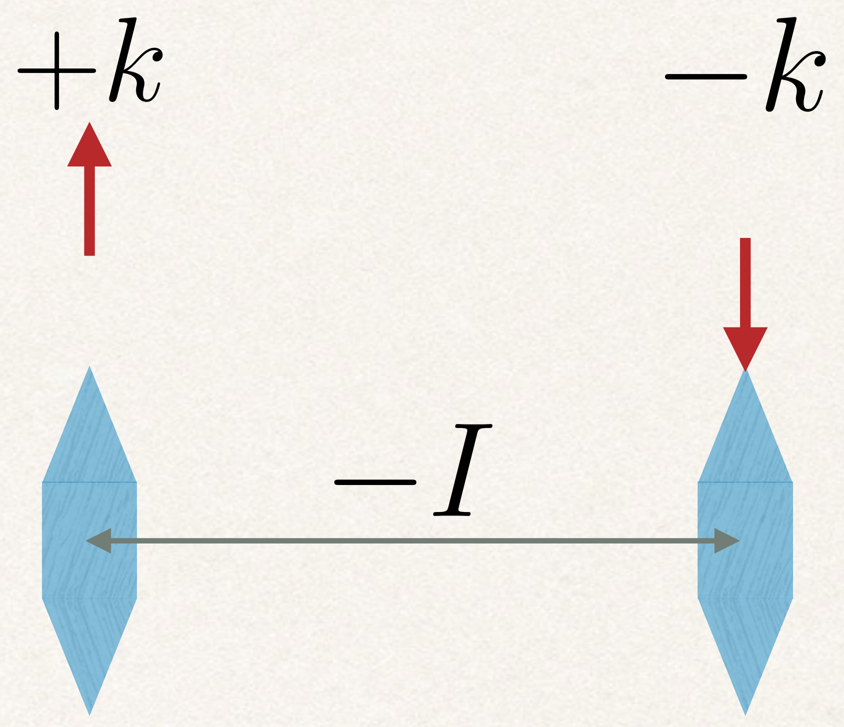
D. Shatilov

# Method

- Lattice: FCCee_t_217_nosol_2.sad, 182.5 GeV, half ring.
- The vertical emittance is given by randomly excited skew quadrupole placed on each sextupole in the arc:



Symmetric: vertical dispersion is confined within the pair, x-y coupling leaks outside.



Antisymmetric: x-y coupling is confined within the pair, vertical dispersion leaks outside.

- The vertical invariant emittance is always set to 2.9 pm ($\varepsilon_y / \varepsilon_x = 0.2\%$).
- Synchrotron radiation in all magnets.
- Tapering.
- Optionally, simplified beam-beam effects and beamstrahlung can be applied.
- 1000 particles up to 300 half-turns.

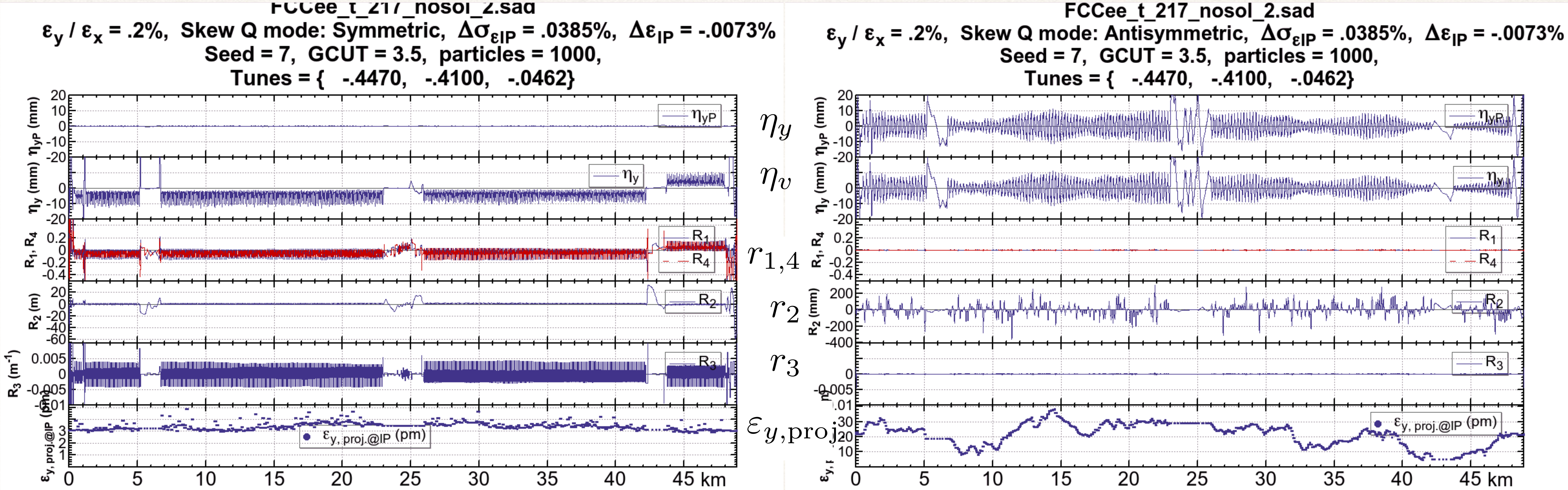
# Optics by different excitations of skew quads

## Symmetric Skew Quads

Vertical dispersion is confined within the pair, x-y coupling leaks outside.

## Antisymmetric Skew Quads

X-y coupling is confined within the pair, vertical dispersion leaks outside.



definition of x-y coupling parameter:

$$\begin{pmatrix}u\\p_u\\v\\p_v\end{pmatrix} = \mathrm{R}\begin{pmatrix}x\\p_x\\y\\p_y\end{pmatrix} = \begin{pmatrix}\mu & . & -r_4 & r_2\\ . & \mu & r_3 & -r_1\\ r_1 & r_2 & \mu & .\\ r_3 & r_4 & . & \mu\end{pmatrix}\begin{pmatrix}x\\p_x\\y\\p_y\end{pmatrix},$$

betatron coordinate

physical coordinate

The skew quads on a sextupole pair can be represented by two random numbers $k_{1,2}$ and a parameter $-1 \le s \le 1$ as $(k_1 + sk_2, k_2 + sk_1)$. Then

$s = 1$ : perfect symmetric

$s = -1$ : perfect antisymmetric

$s = 0$ : : simply random

# Implementation of simplified beam-beam

- The beam-beam tune shift and beamstrahlung can be implemented in the Vlasov model, by introducing a thin kick

$$\Delta p_{x,y} = -k\frac{\partial U}{\partial(x,y)} \,, \tag{1}$$

where $U$ is a potential by a gaussian charge distribution.

- The associated transfer matrix is

$$M_{\mathrm{BB}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -k\frac{\partial^2 U}{\partial x^2} & 1 & -k\frac{\partial^2 U}{\partial x \partial y} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -k\frac{\partial^2 U}{\partial x \partial y} & 0 & -k\frac{\partial^2 U}{\partial y^2} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} , \tag{2}$$

where $k$ and $U$ are chosen to the matrix be consistent with beam-beam parameters $\xi_{x,y}$.

- Beamstrahlung is simplified by an excitation matrix

$$\Delta\Sigma_{\mathrm{BB}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Delta\sigma_\varepsilon^2 \end{pmatrix} , \tag{3}$$

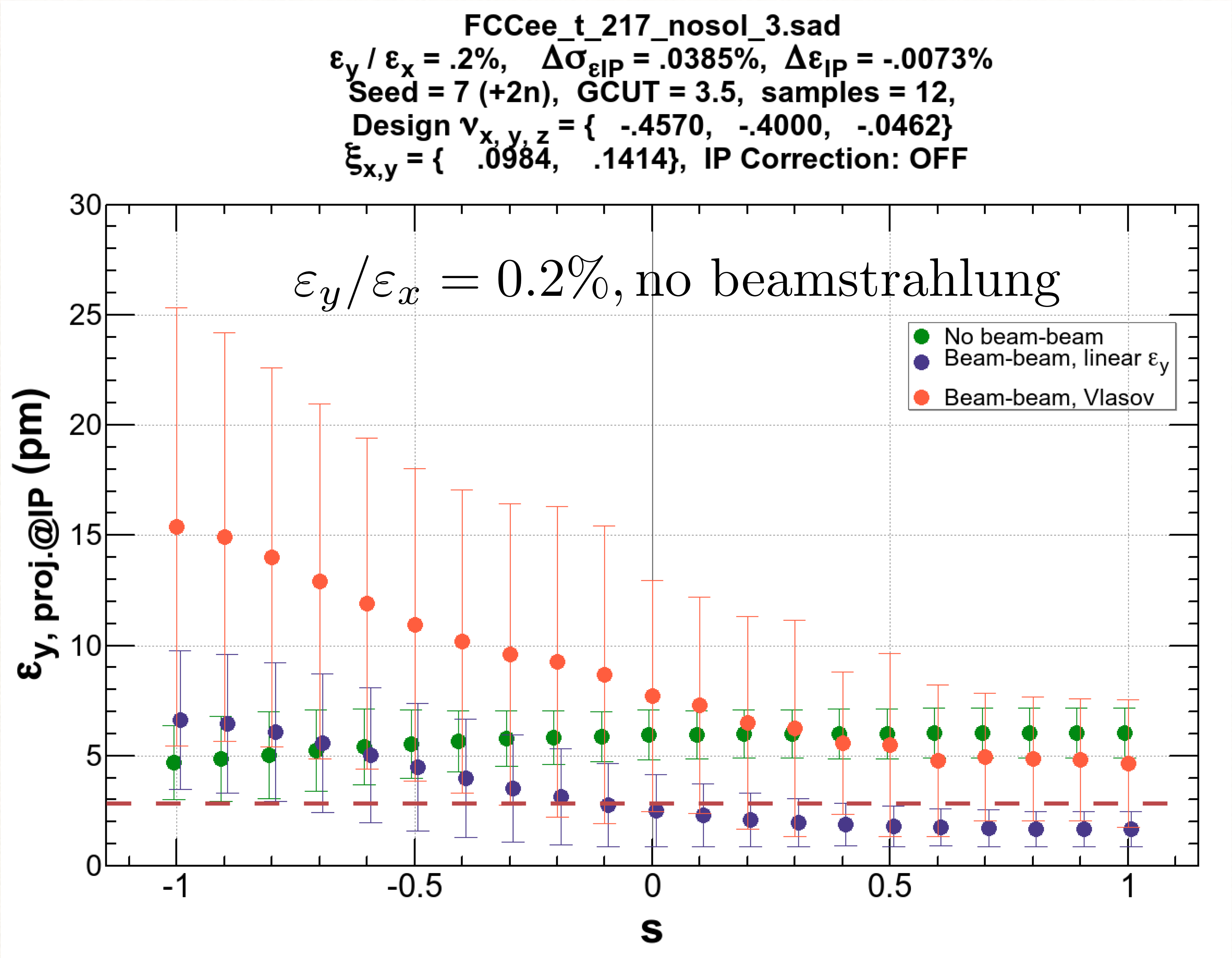
where $\sigma_\varepsilon$ is the single-pass energy spread due to beamstrahlung.

The damping due to BS is also implemented in a similar way.

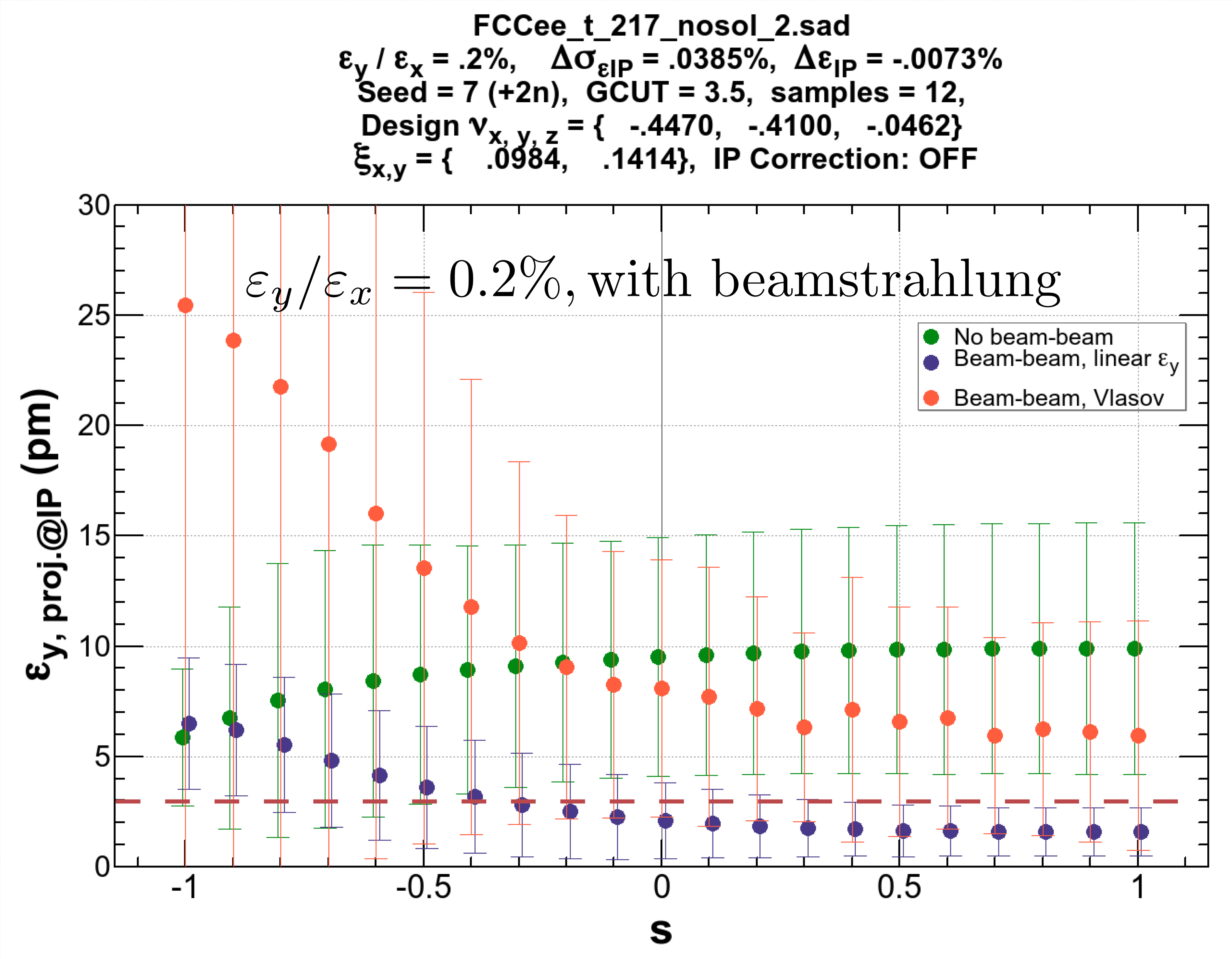
- In the case of FCC-ee@182.5 GeV, $\xi_{x,y} = (0.0984, 0.1414)$ and $\sigma_\varepsilon = 3.85 \times 10^{-4}$.

# An alternative tune

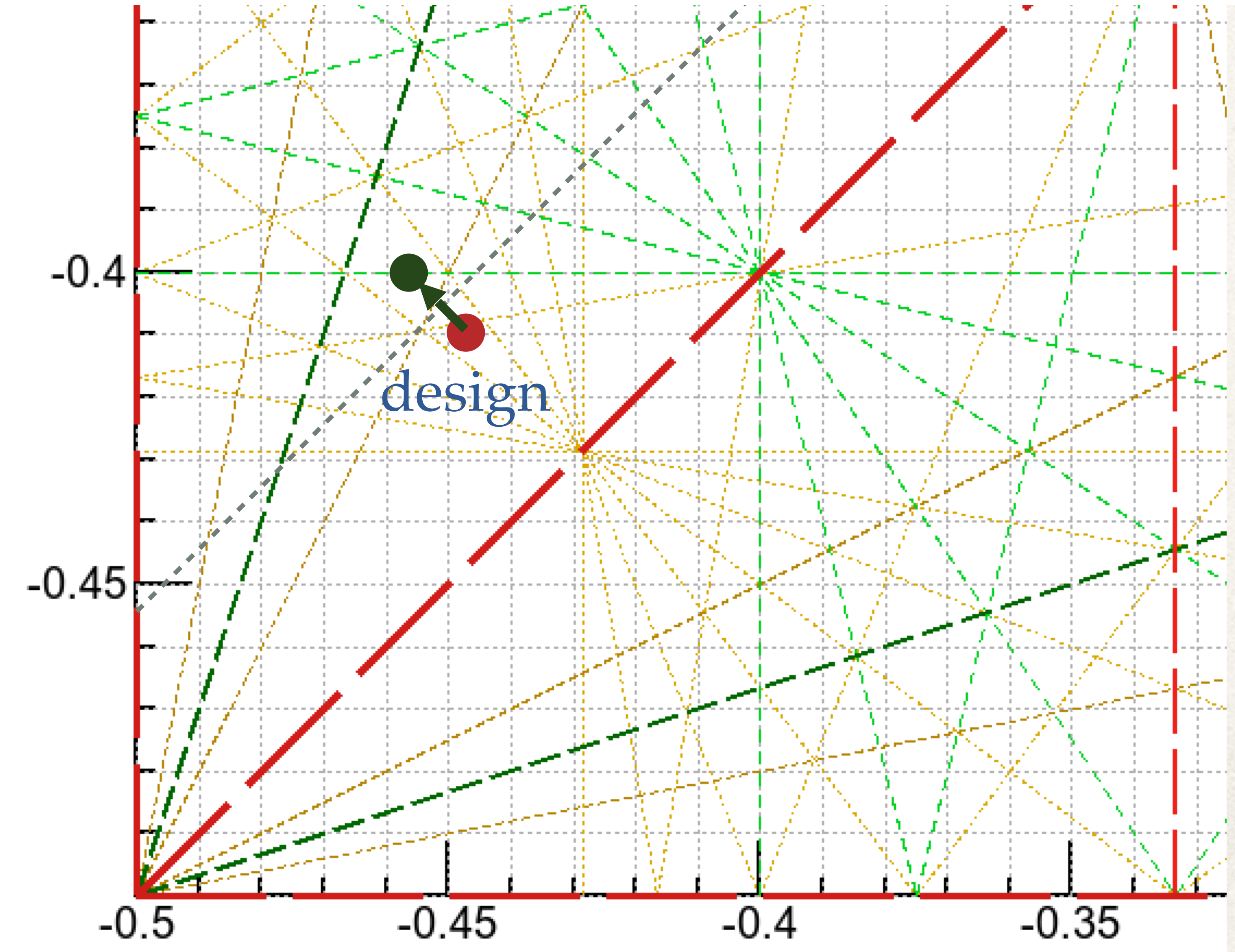
### An alternative tune



### Design tune



des



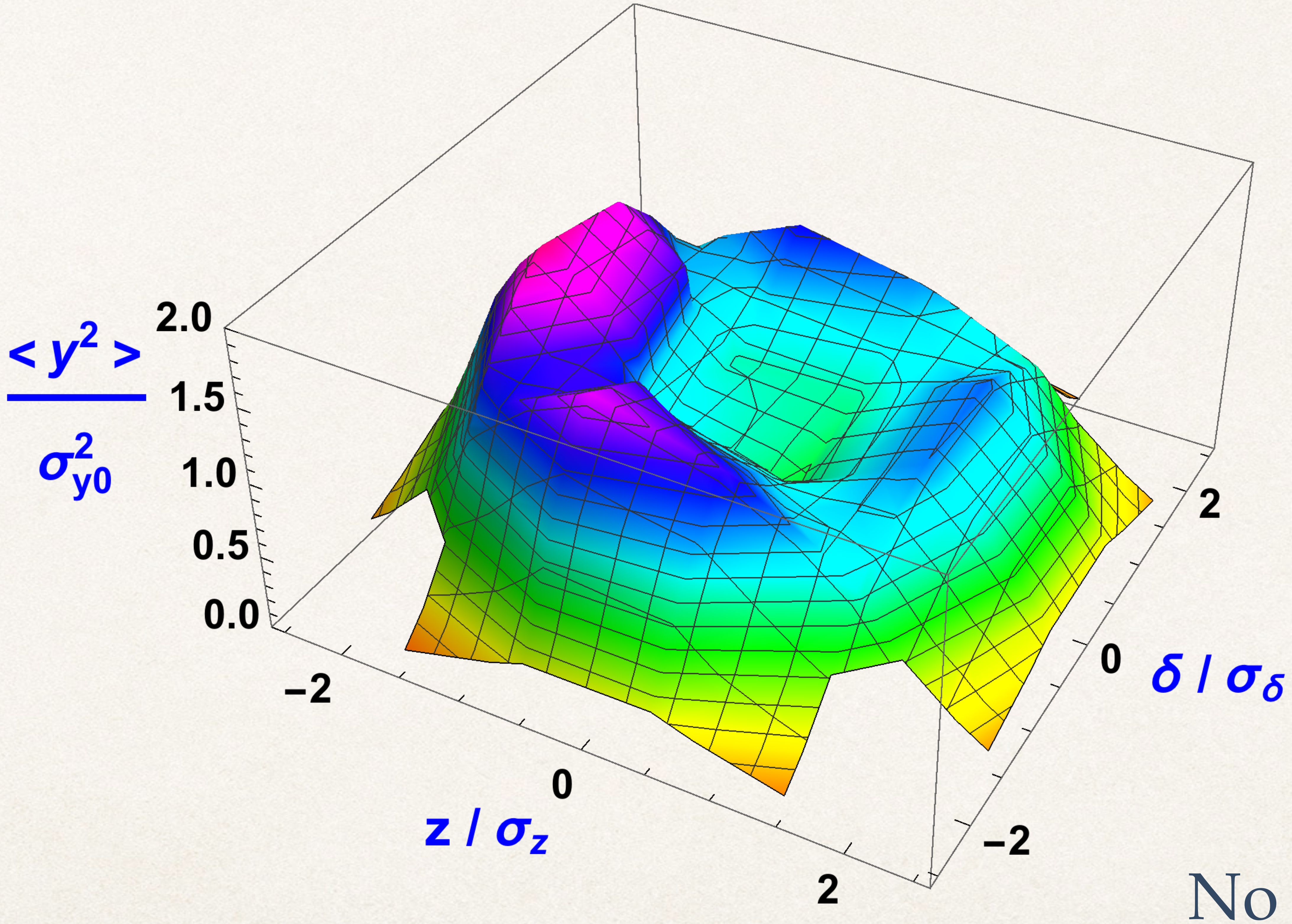
Shifting the tune by $\Delta\nu_{x,y} = (-0.01, 0.01)$ relaxes the blowup. Combining with a lower emittance may reduce the blowup within the design emittance.

# How can we solve the unexpected beam blowup?

- The unexpected (anomalous) emittance blowup sets an additional condition for the machine.
- Not only the luminosity, but beam losses, detector background, quenches of superconducting magnets will be affected.
- Probably the most straight-forward solution is to reduce the lattice (on closed orbit) emittance well below the design. For instance it should be less than 0.1% in the case of FCC-ee ttbar.
- Such a very small emittance is reachable by the emittance tuning method simulated.
- Once such a very small vertical emittance is achieved, a question is how to blowup it to the design value. For that purpose an emittance control knob, which does not affect the anomalous emittance, must be developed.

# The Vlasov model

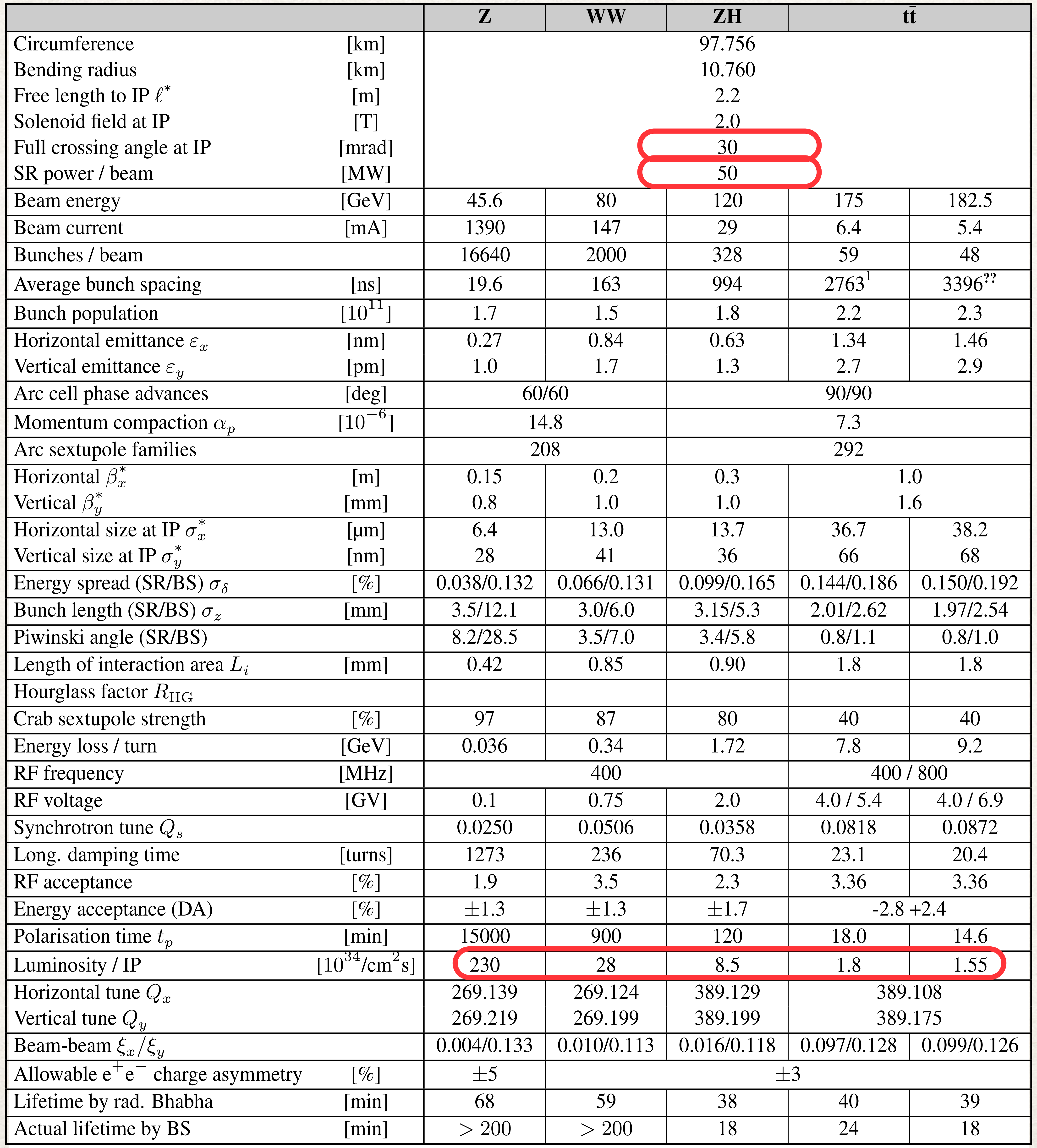
- Near a resonance line, the transfer matrix over one synchrotron period can be on resonance at a certain amplitude of the synchrotron motion. This leads to the anomalous beam blowup.
-



No beam-beam
Symmetric skew

# Luminosity performance

Table 2.1: Machine parameters of the FCC-ee for different beam energies.



| | | Z | WW | ZH | $t\bar{t}$ | |
|---|---|---|---|---|---|---|
| Circumference | [km] | 97.756 | | | | |
| Bending radius | [km] | 10.760 | | | | |
| Free length to IP $\ell^*$ | [m] | 2.2 | | | | |
| Solenoid field at IP | [T] | 2.0 | | | | |
| Full crossing angle at IP | [mrad] | 30 | | | | |
| SR power / beam | [MW] | 50 | | | | |
| Beam energy | [GeV] | 45.6 | 80 | 120 | 175 | 182.5 |
| Beam current | [mA] | 1390 | 147 | 29 | 6.4 | 5.4 |
| Bunches / beam | | 16640 | 2000 | 328 | 59 | 48 |
| Average bunch spacing | [ns] | 19.6 | 163 | 994 | 2763[1] | 3396[??] |
| Bunch population | [$10^{11}$] | 1.7 | 1.5 | 1.8 | 2.2 | 2.3 |
| Horizontal emittance $\varepsilon_x$ | [nm] | 0.27 | 0.84 | 0.63 | 1.34 | 1.46 |
| Vertical emittance $\varepsilon_y$ | [pm] | 1.0 | 1.7 | 1.3 | 2.7 | 2.9 |
| Arc cell phase advances | [deg] | 60/60 | | 90/90 | | |
| Momentum compaction $\alpha_p$ | [$10^{-6}$] | 14.8 | | 7.3 | | |
| Arc sextupole families | | 208 | | 292 | | |
| Horizontal $\beta^*_x$ | [m] | 0.15 | 0.2 | 0.3 | 1.0 | |
| Vertical $\beta^*_y$ | [mm] | 0.8 | 1.0 | 1.0 | 1.6 | |
| Horizontal size at IP $\sigma^*_x$ | [µm] | 6.4 | 13.0 | 13.7 | 36.7 | 38.2 |
| Vertical size at IP $\sigma^*_y$ | [nm] | 28 | 41 | 36 | 66 | 68 |
| Energy spread (SR/BS) $\sigma_\delta$ | [%] | 0.038/0.132 | 0.066/0.131 | 0.099/0.165 | 0.144/0.186 | 0.150/0.192 |
| Bunch length (SR/BS) $\sigma_z$ | [mm] | 3.5/12.1 | 3.0/6.0 | 3.15/5.3 | 2.01/2.62 | 1.97/2.54 |
| Piwinski angle (SR/BS) | | 8.2/28.5 | 3.5/7.0 | 3.4/5.8 | 0.8/1.1 | 0.8/1.0 |
| Length of interaction area $L_i$ | [mm] | 0.42 | 0.85 | 0.90 | 1.8 | 1.8 |
| Hourglass factor $R_{\mathrm{HG}}$ | | | | | | |
| Crab sextupole strength | [%] | 97 | 87 | 80 | 40 | 40 |
| Energy loss / turn | [GeV] | 0.036 | 0.34 | 1.72 | 7.8 | 9.2 |
| RF frequency | [MHz] | 400 | | | 400 / 800 | |
| RF voltage | [GV] | 0.1 | 0.75 | 2.0 | 4.0 / 5.4 | 4.0 / 6.9 |
| Synchrotron tune $Q_s$ | | 0.0250 | 0.0506 | 0.0358 | 0.0818 | 0.0872 |
| Long. damping time | [turns] | 1273 | 236 | 70.3 | 23.1 | 20.4 |
| RF acceptance | [%] | 1.9 | 3.5 | 2.3 | 3.36 | 3.36 |
| Energy acceptance (DA) | [%] | ±1.3 | ±1.3 | ±1.7 | -2.8 +2.4 | |
| Polarisation time $t_p$ | [min] | 15000 | 900 | 120 | 18.0 | 14.6 |
| Luminosity / IP | [$10^{34}$/cm$^2$s] | 230 | 28 | 8.5 | 1.8 | 1.55 |
| Horizontal tune $Q_x$ | | 269.139 | 269.124 | 389.129 | 389.108 | |
| Vertical tune $Q_y$ | | 269.219 | 269.199 | 389.199 | 389.175 | |
| Beam-beam $\xi_x/\xi_y$ | | 0.004/0.133 | 0.010/0.113 | 0.016/0.118 | 0.097/0.128 | 0.099/0.126 |
| Allowable $e^+e^-$ charge asymmetry | [%] | ±5 | ±3 | | | |
| Lifetime by rad. Bhabha | [min] | 68 | 59 | 38 | 40 | 39 |
| Actual lifetime by BS | [min] | > 200 | > 200 | 18 | 24 | 18 |

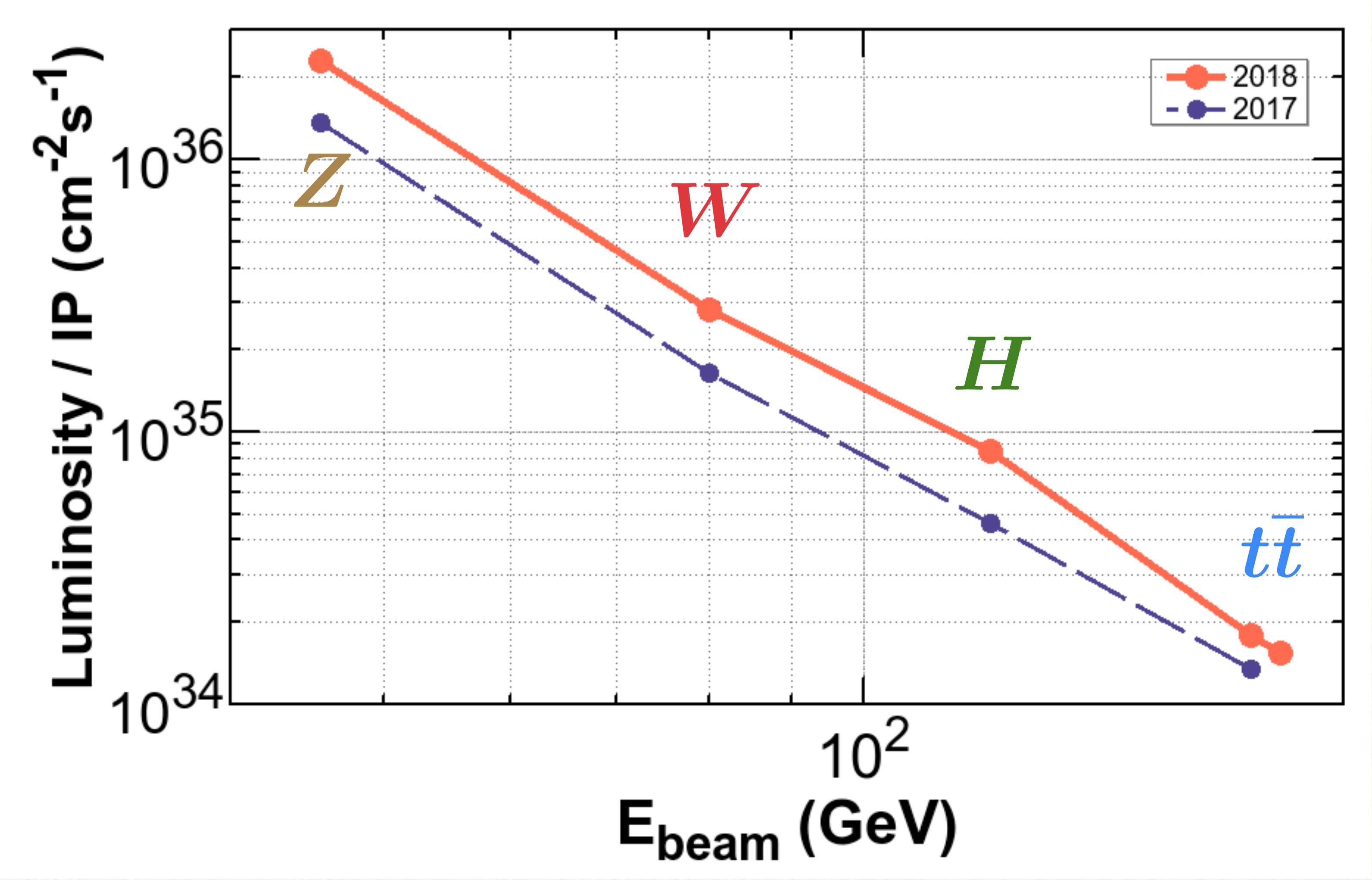
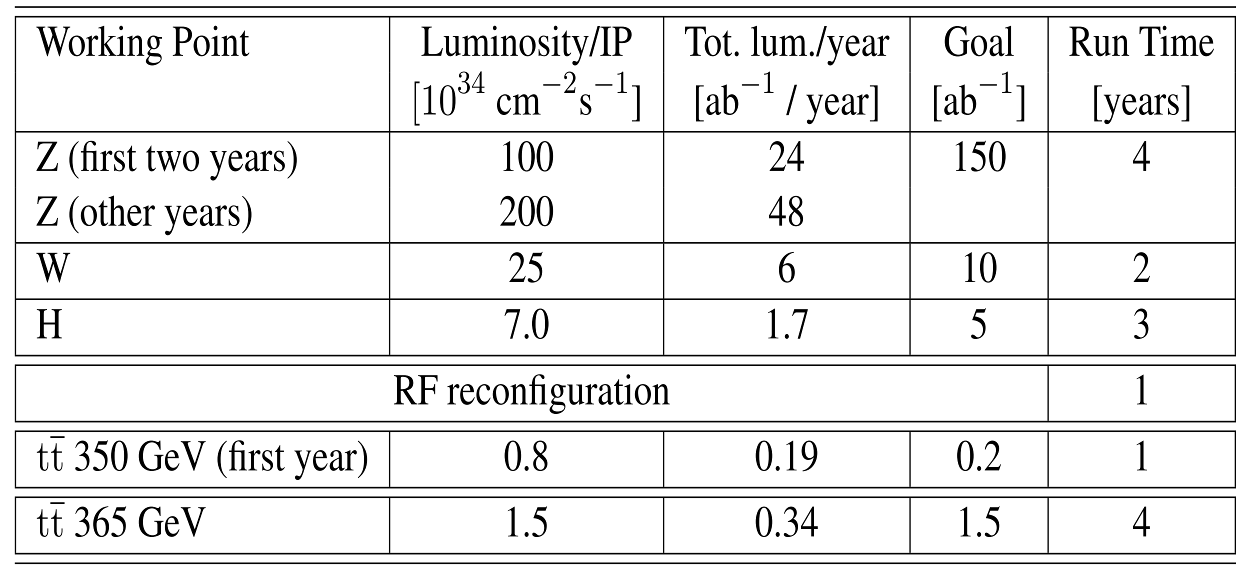


Table 2.10: Peak luminosity per IP, total luminosity per year (two IPs), luminosity target, and run time for each FCC-ee working point.



| Working Point | Luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$] | Tot. lum./year [ab$^{-1}$ / year] | Goal [ab$^{-1}$] | Run Time [years] |
|---|---|---|---|---|
| Z (first two years) | 100 | 24 | 150 | 4 |
| Z (other years) | 200 | 48 | | |
| W | 25 | 6 | 10 | 2 |
| H | 7.0 | 1.7 | 5 | 3 |
| RF reconfiguration | | | | 1 |
| $t\bar{t}$ 350 GeV (first year) | 0.8 | 0.19 | 0.2 | 1 |
| $t\bar{t}$ 365 GeV | 1.5 | 0.34 | 1.5 | 4 |