Interplay of the beam-beam effect and the lattice nonlinearity

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Acknowledgements:

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Outline

➤ **Introduction**

- **Background**
- **Simulation codes**

✳ **BBWS (K. Ohmi): Weak-strong beam-beam(BB) + Ideal crab-waist(CW) map + Beamstrahlung(BS) + Linear one-turn map + Lumped radiation(RAD) damping/excitation**

✳ **SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation**

➤ **Beam-beam simulation results for FCC-ee**

- **tt_{bar} threshold [175GeV]**
- **Z pole [45.6GeV]**

➤ **Summary**

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➤ **Summary**

1. Introduction

➤ **Luminosity of a lepton collider**

$$L = L_0 R_{H\theta}$$

$$L_0 = \frac{N_e N_p f_0 N_b}{2\pi\sqrt{\sigma_{xe}^{*2} + \sigma_{xp}^{*2}}\sqrt{\sigma_{ye}^{*2} + \sigma_{yp}^{*2}}} \qquad R_{H\theta} \approx \frac{1}{\sqrt{1 + \frac{\sigma_{ze}^2 + \sigma_{zp}^2}{\sigma_{xe}^2 + \sigma_{xp}^2} \tan^2 \frac{\theta}{2}}}$$

➤ **Trends of modern colliders**

- **To increase beam current**
- **To decrease emittance and/or to squeeze beam sizes at IP**

➤ **Growing demand for luminosity results in**

- **Stronger nonlinearity in beam-beam collision**
- **Stronger nonlinearity in lattice, especially in IR**

1. Introduction

- ➤ **Experiences of interplay of beam-beam effect and lattice nonlinearity(LN) in colliders**
  - **Cubic nonlin. at DAΦNE [e.g. C. Milardi, EPAC2000]**
  - **Chromatic coupling at KEKB [e.g. Y. Funakoshi, PTP 2009]**
  - **Amplitude-dependent nonlin. at SuperKEKB [e.g. D. Zhou, IPAC'15]**
  - **… …**
- ➤ **The motivation for FCC-ee**
  - **Low emittance, large crossing angle, and small $\beta^*_{x,y}$**
  - **Crab-waist lattice to mitigate beam-beam effects**
  - **Unavoidable beamstrahlung effects**
  - **Radiation effects**
  - **Others … … [Ref. K. Oide, This conference]**
- ➤ **Evaluations via simulations are necessary**

1. Introduction

➤ The idea via BBWS and SAD

- Simulation codes developed for KEKB and SuperKEKB
- One-turn map:

$$M = M_{\mathrm{RAD}} \circ M_{\mathrm{BB}} \circ M_0$$

- The IP-to-IP one-turn map M_0: linear matrix or realistic element-by-element maps from a design lattice w/ or w/o crab waist
- The beam-beam map M_{BB}: Symplectic weak-strong model w/ or w/o beamstrahlung
- Radiation damping/excitation map M_{RAD}: lumped or distributed
- Observables: luminosity, DA, beam tail, particle loss, etc.

1. Introduction: Machine parameters(for half ring)

	Z	$t\bar{t}$
C (km)	49990.9	49990.9
E (GeV)	45.6	175
Number of IPs	1	1
N_b	90300	78
$N_p(10^{11})$	0.33	1.7
Full crossing angle(rad)	0.03	0.03
ε_x (nm)	0.09	1.3
ε_y (pm)	1	2.5
β_x^* (m) [optional]	1 [0.5]	1 [0.5]
β_y^* (mm) [optional]	2 [1]	2 [1]
σ_z (mm)^{SR}	2.7	2.1
$\sigma_\delta(10^{-3})^{SR}$	0.37	1.4
Fractional betatron tune ν_x/ν_y	.55/.57	.54/.57
Synch. tune ν_s	0.0075	0.0375
Damping rate/turn (10^{-2}) [x/y/z]	0.019/0.019/0.038	1.1/1.1/2.2
Lum./IP(10^{34}cm^{-2}s^{-1})	90	1.3

Ref. F. Zimmermann, FCC-ee design meeting, Dec. 9, 2015, and K. Oide, this conference

Note: Minor difference from the latest parameter table

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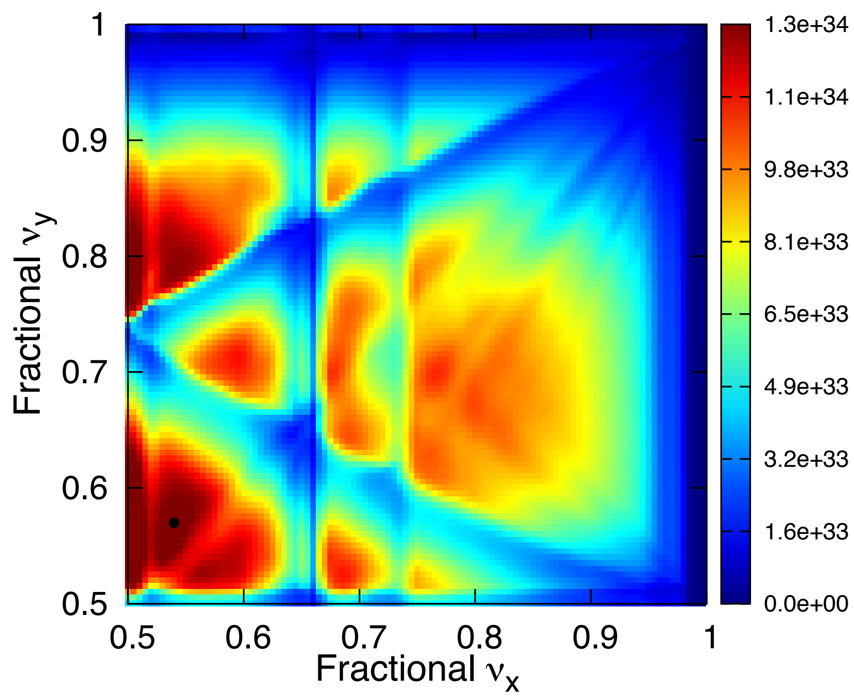
    - SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation
- **Beam-beam simulation results for FCC-ee**
  - **tt_{bar} threshold [175GeV]**
  - Z pole [45.6GeV]
- Summary

2. Simulations: BBWS: tt_{bar}

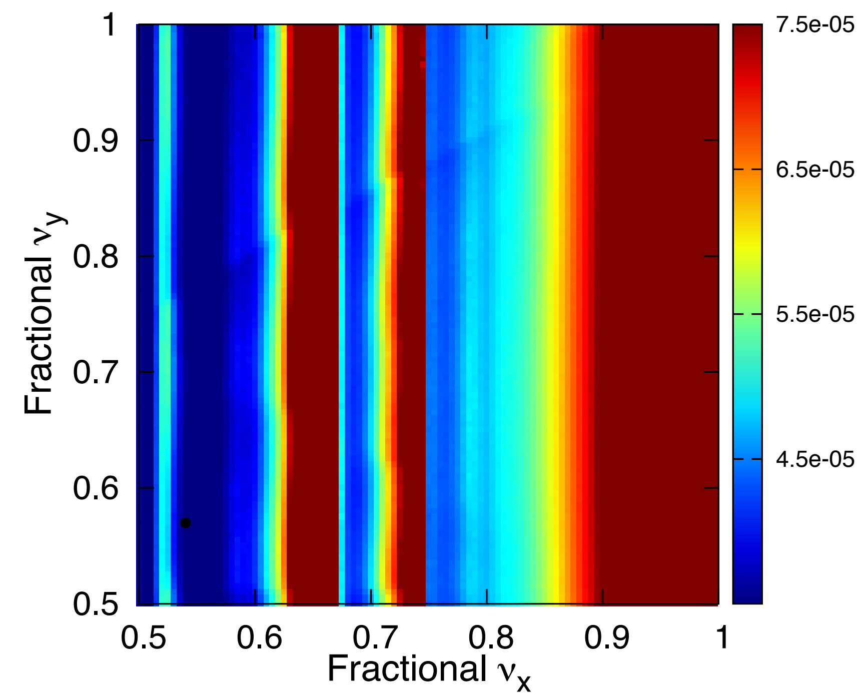
➤ Lum. tune scan w/o CW w/ BS

- **BB+BS: Coupled x-y-z motions**

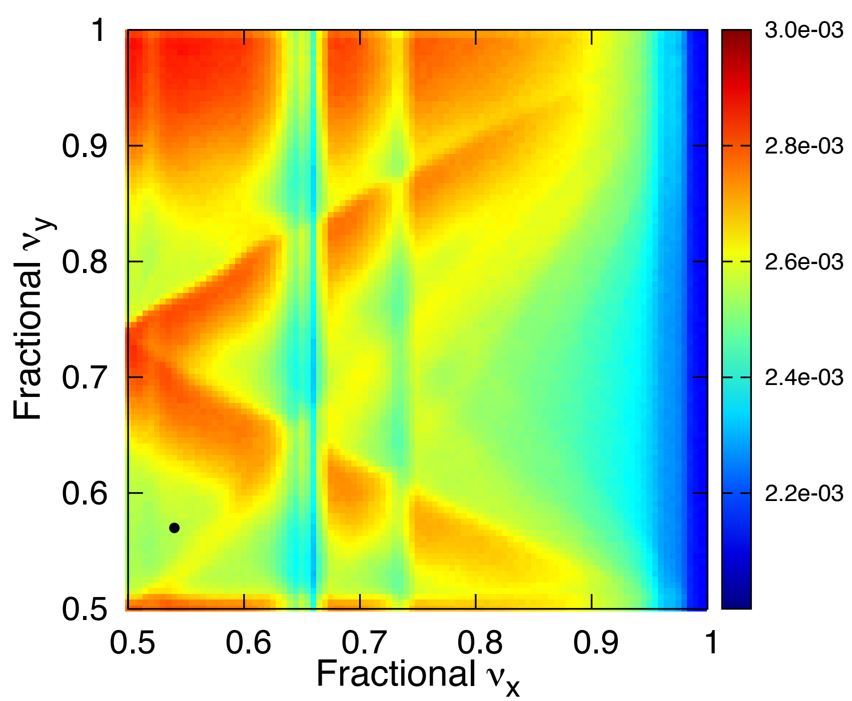
Lum.



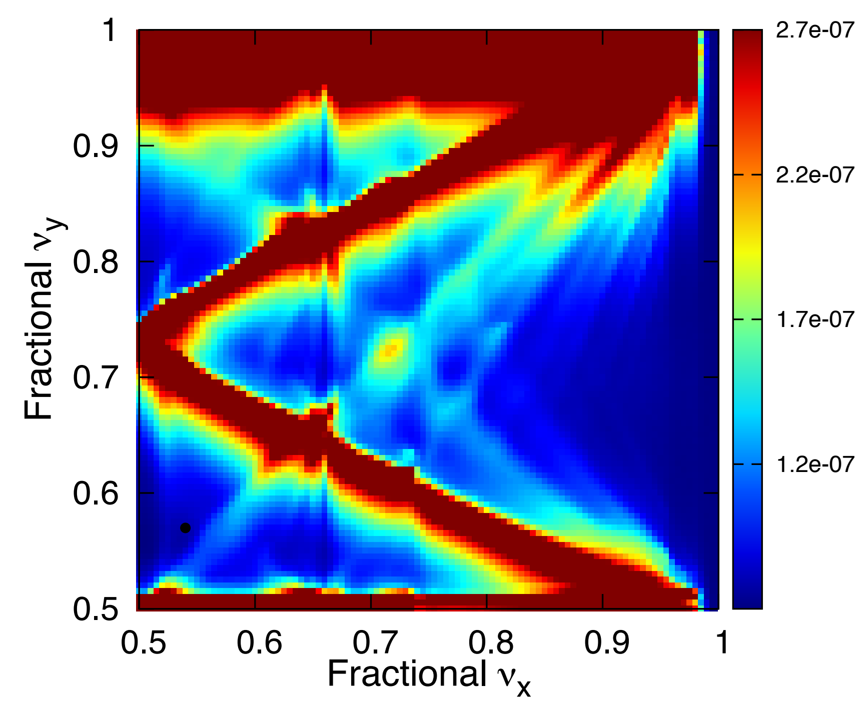
σ_x



σ_z



σ_y

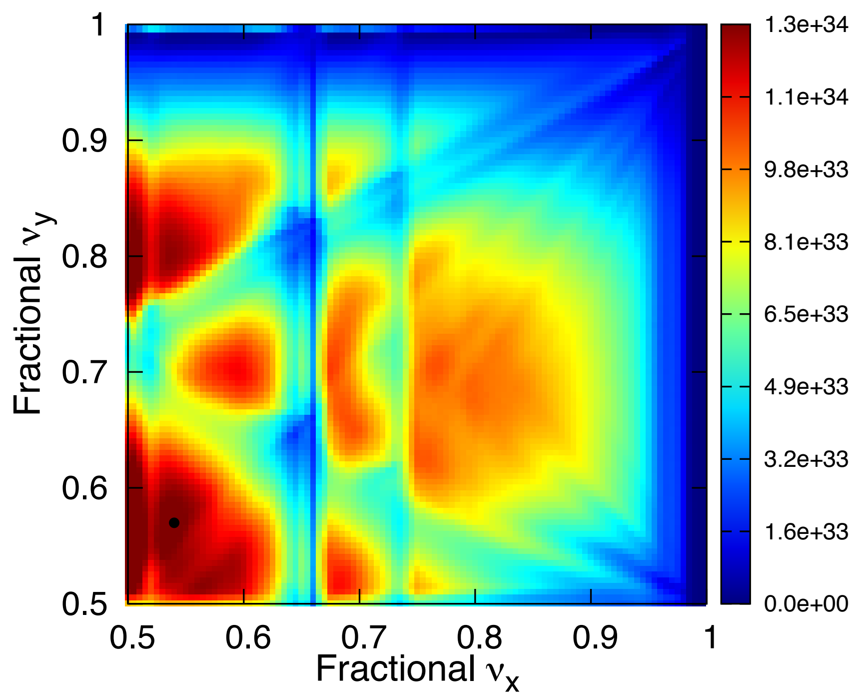


2. Simulations: BBWS: tt_{bar}

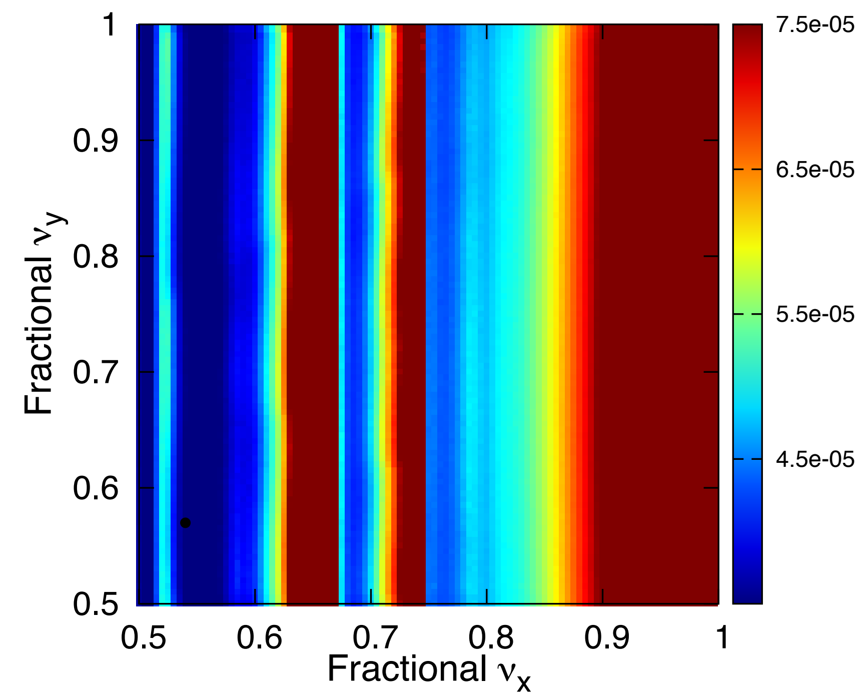
➤ Lum. tune scan w/ CW w/ BS

- Optimal working point: [.54,.57]/IP
- CW's gains: not luminosity but beam-tail suppression

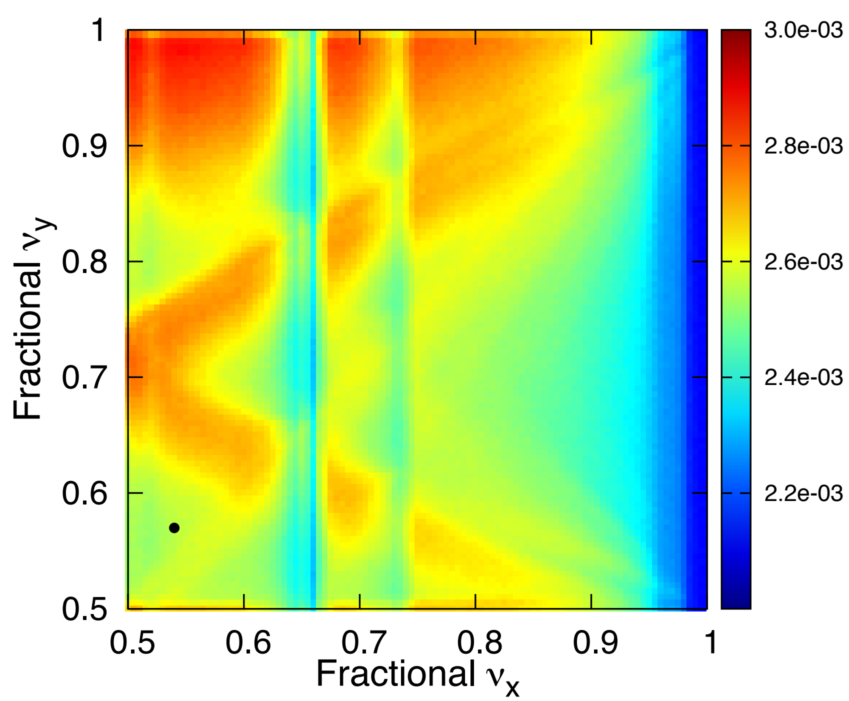
Lum.



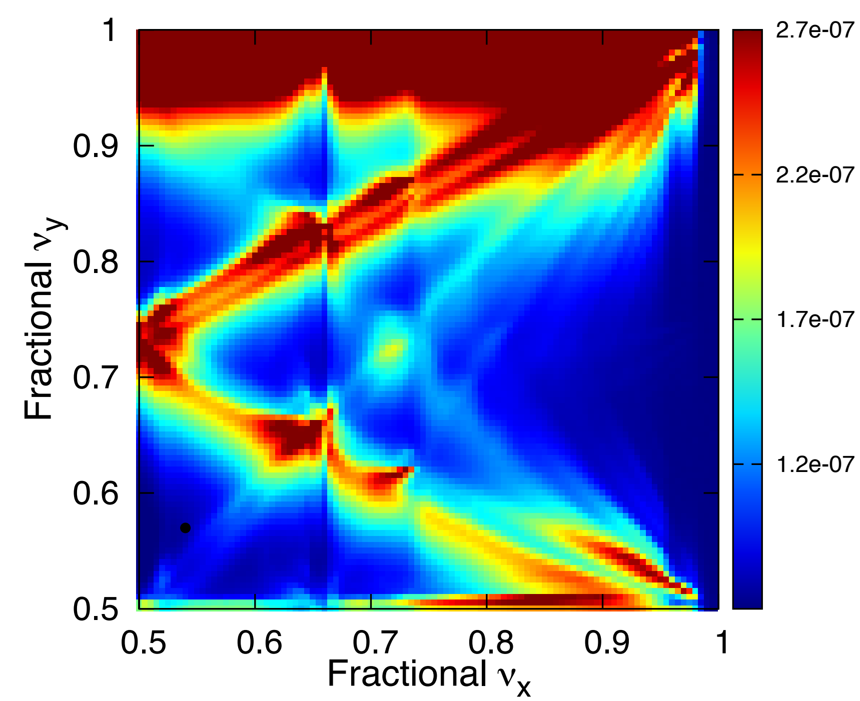
σ_x



σ_z



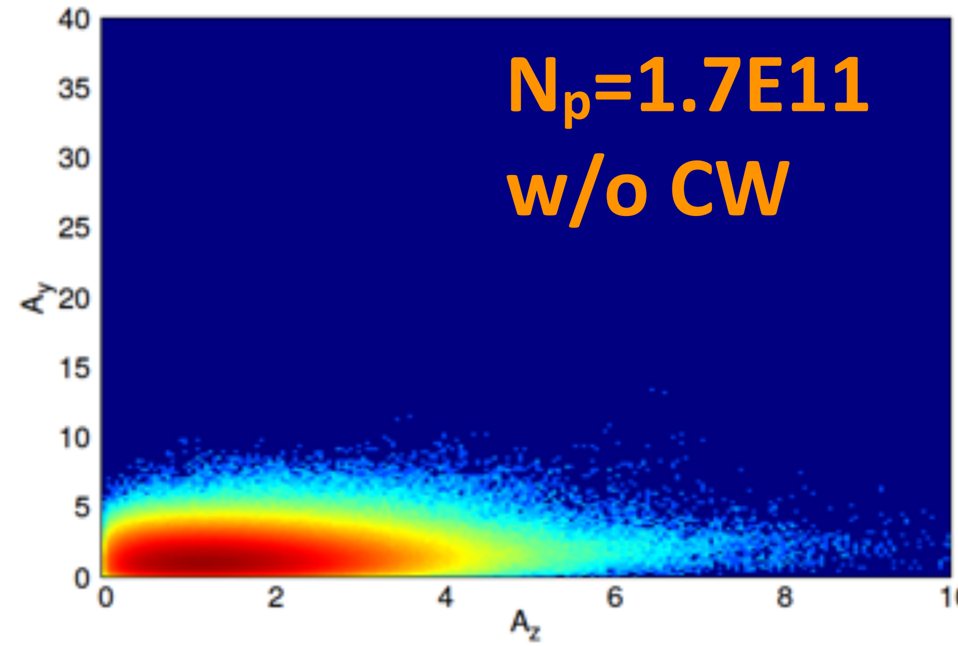
σ_y

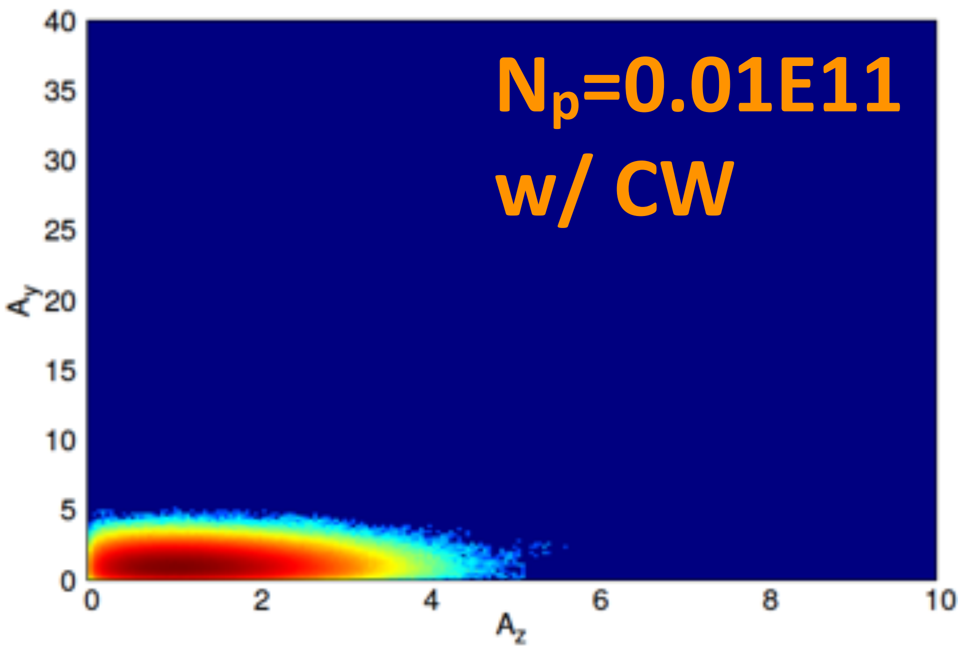


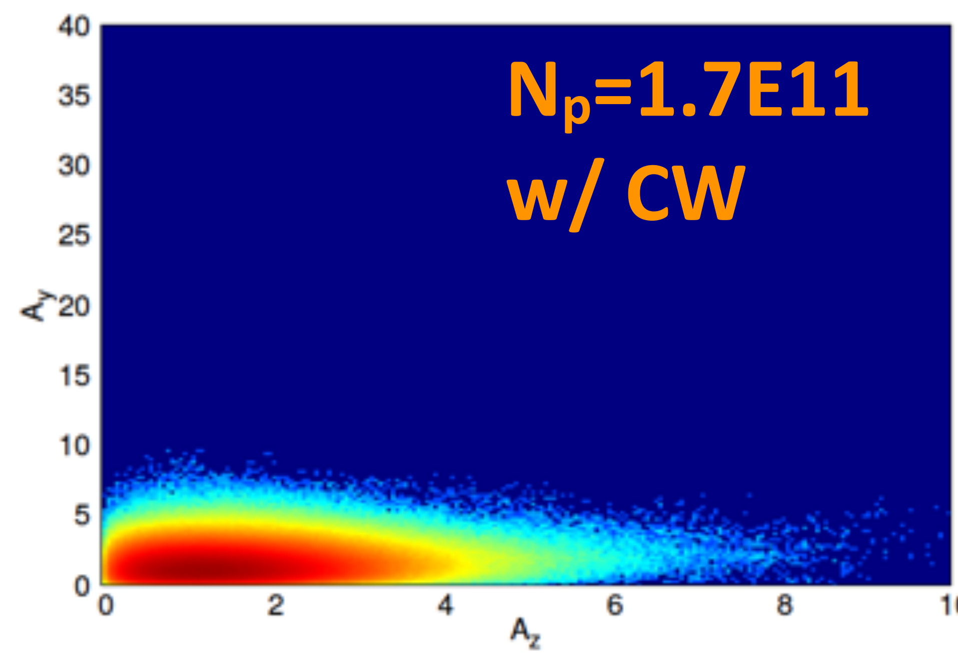
2. Simulations: BBWS: $t\bar{t}$

➤ Beam distribution in y-z plane w/ BS

- Working point: [.54,.57]/IP
- CW suppresses vertical beam-tail
- BS drives long. tail







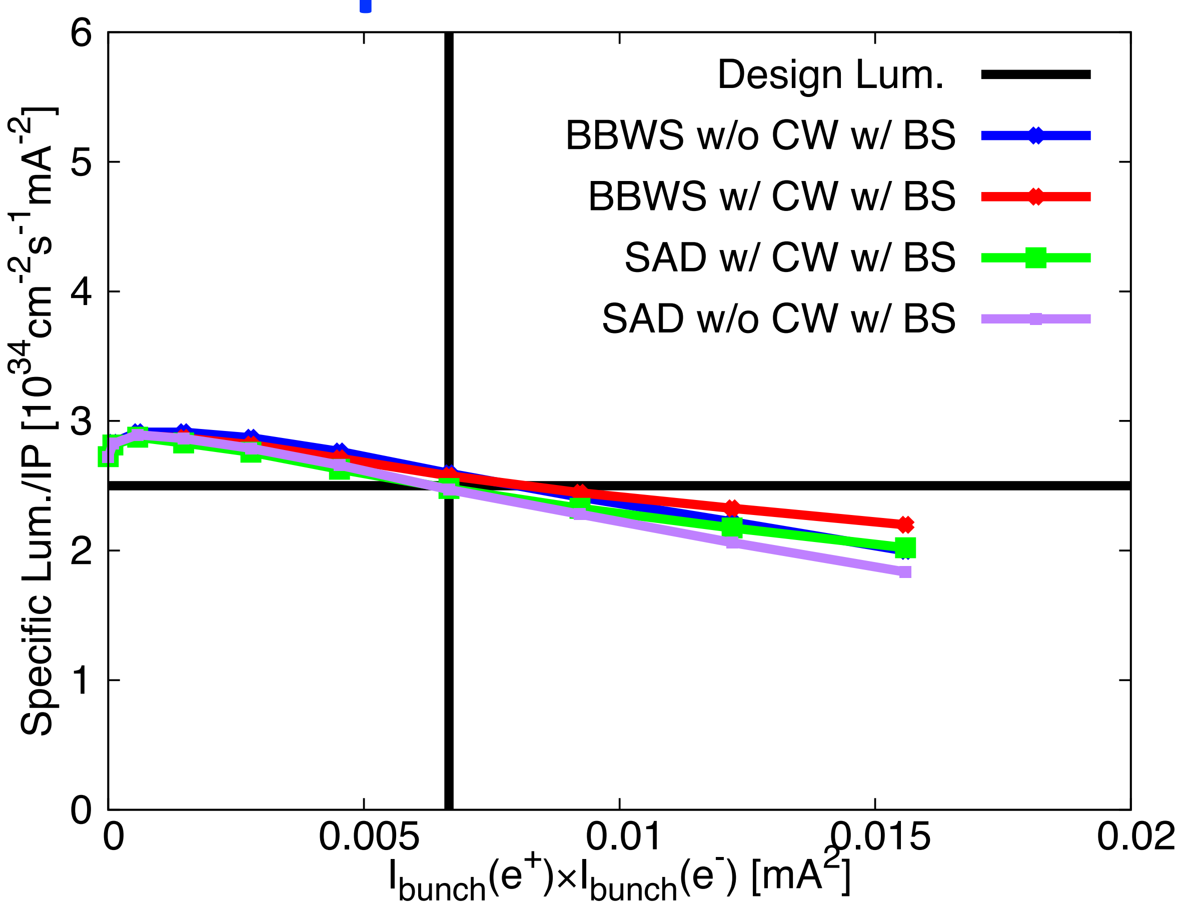
$$A_y = \sqrt{2J_y/\epsilon_y}$$

$$A_z = \sqrt{2J_z/\epsilon_z}$$

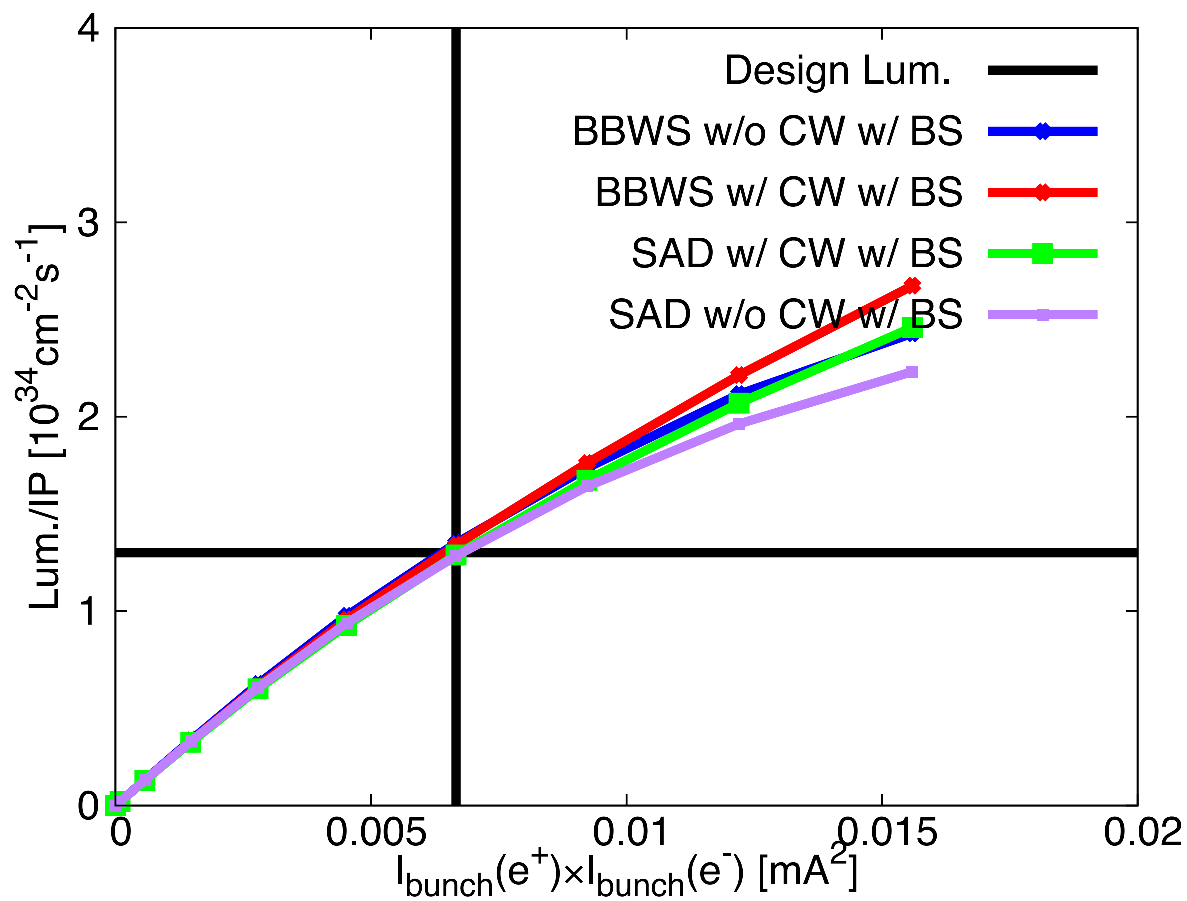
2. Simulations: SAD: tt_{bar}

- **Luminosity for $\beta_x^*=1$m, $\beta_y^*=2$mm**
  - **Lattice ver. FCCee_t_65_26_1_2**
  - **“Invisible” gain from CW**
  - **Small loss(order of a few percents) due to BB+LN**

Specific lum.



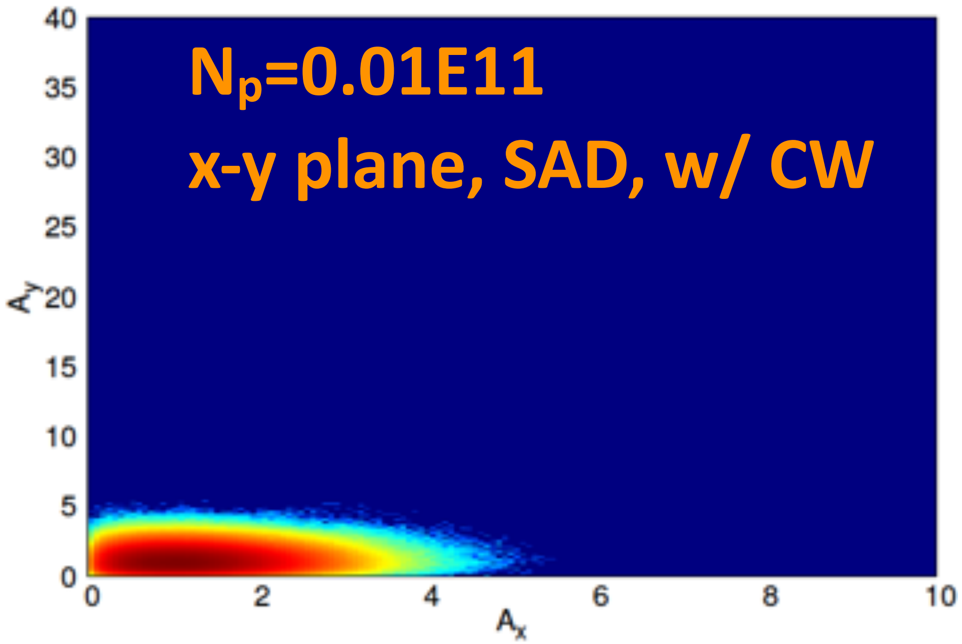
Total lum.

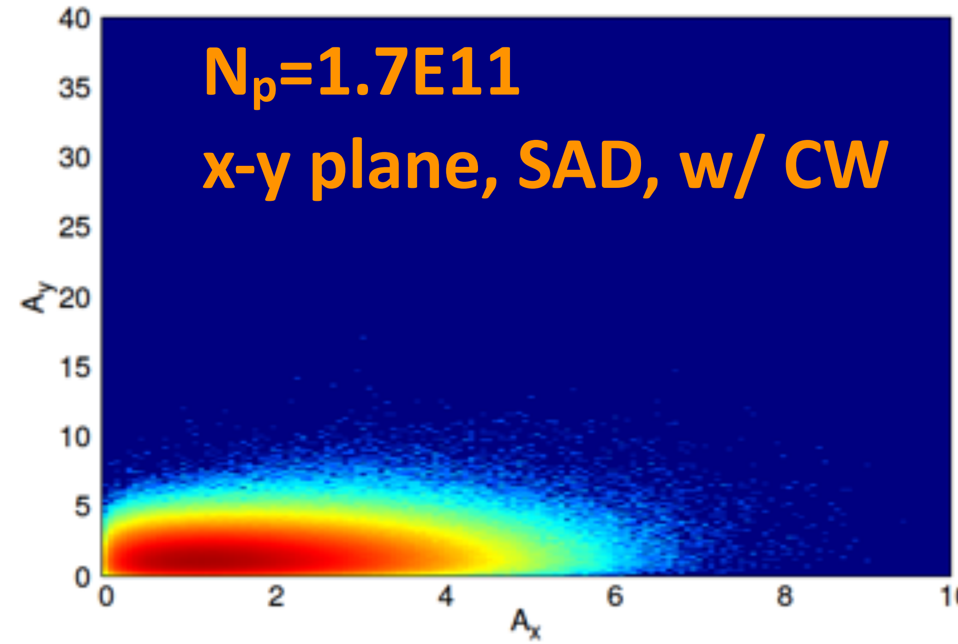


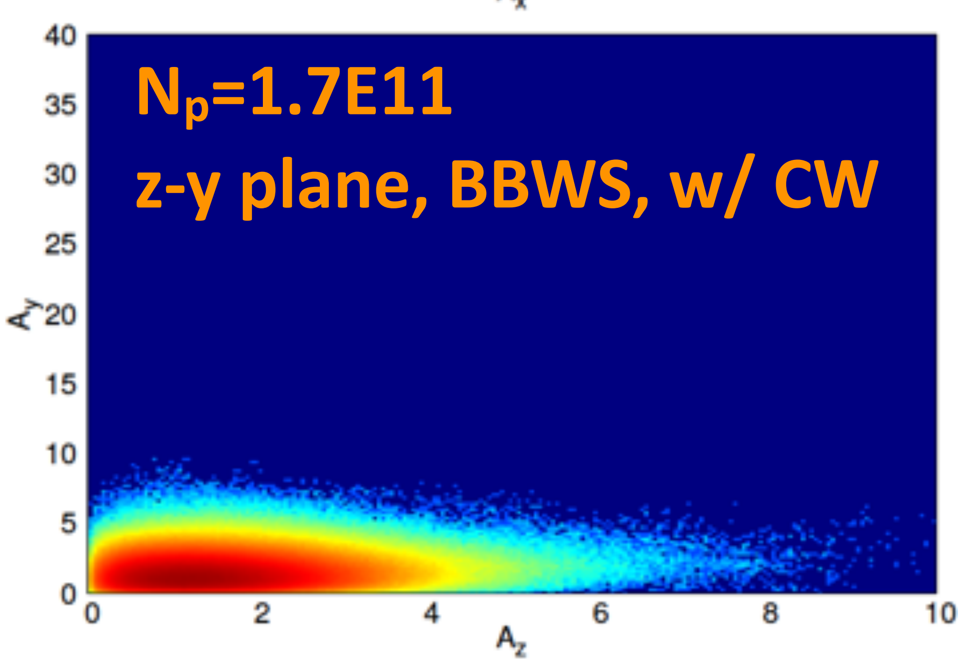
2. Simulations: SAD: $t\bar{t}$

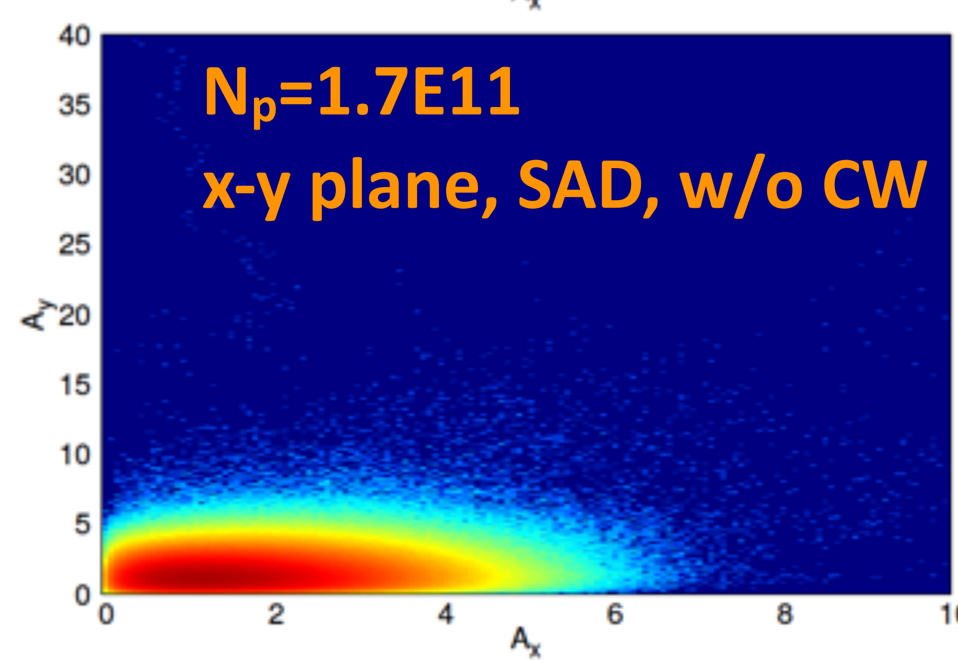
➤ **Beam distribution for β_x^*=1m, β_y^*=2mm**

- Working point: [.54,.57]/IP
- CW suppresses vertical beam-tail
- BB+LN drives beam-tail and causes particle loss [next page]







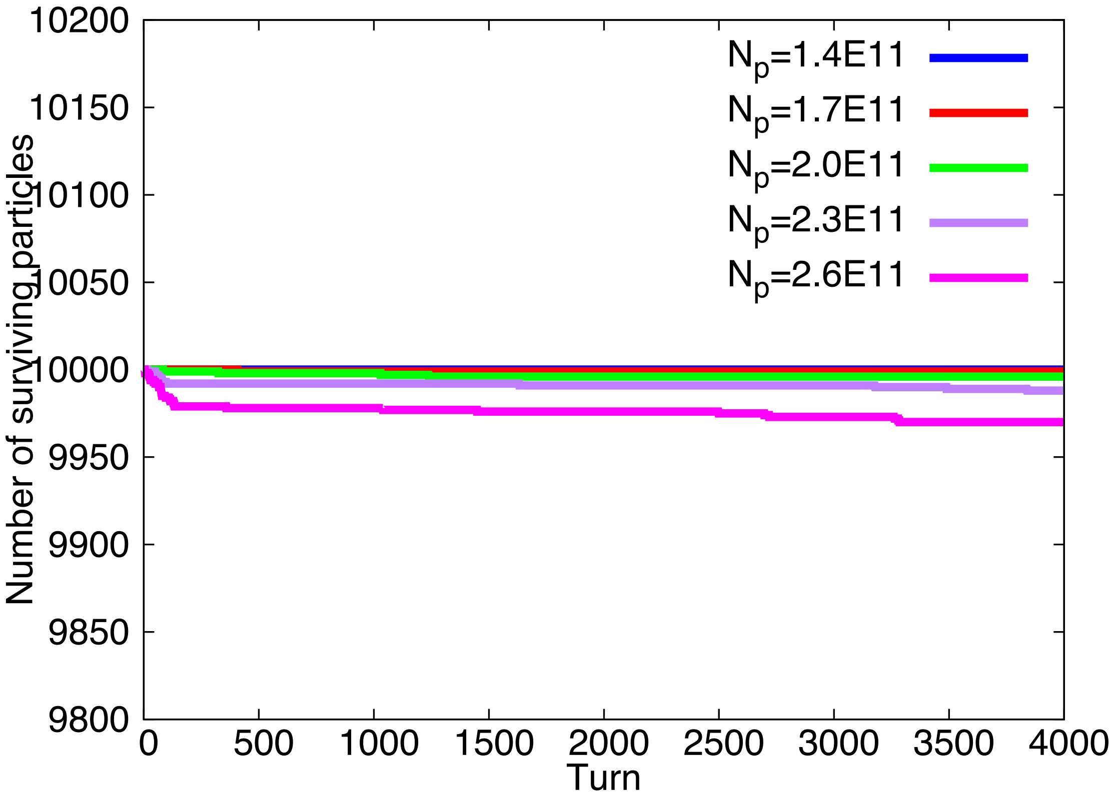


2. Simulations: SAD: tt_{bar}

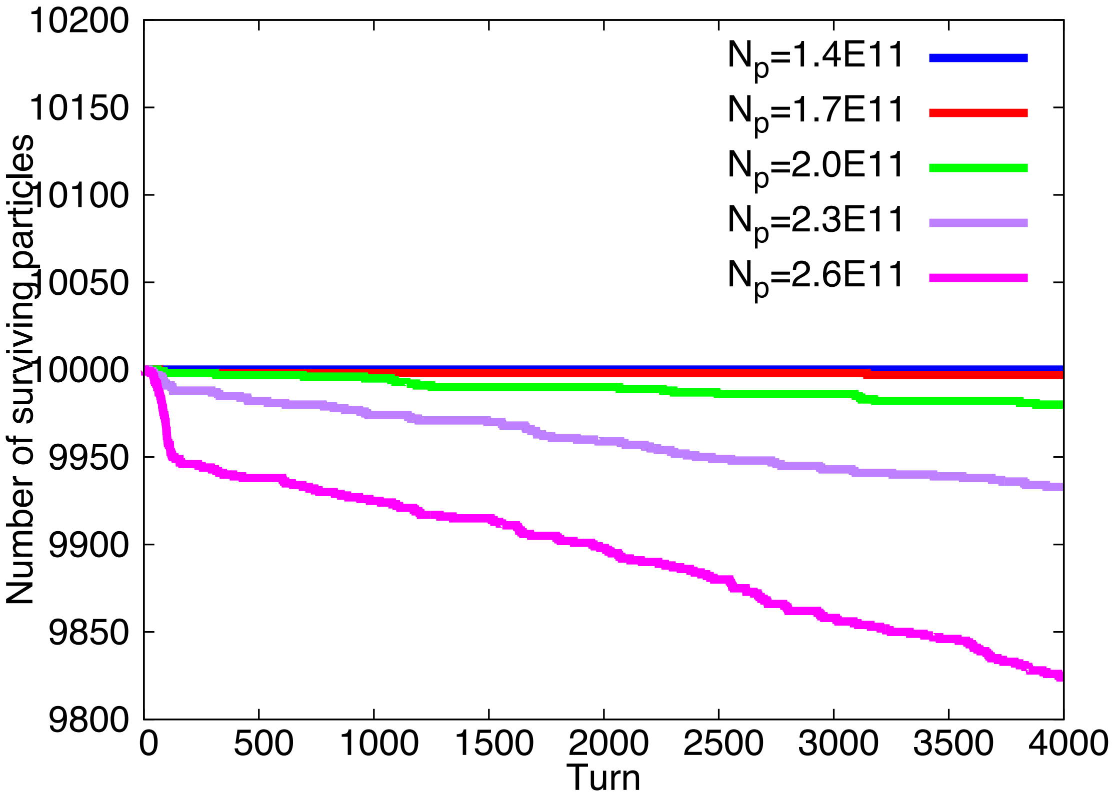
➤ Particle losses in tracking

- Nominal N_p=1.7E11, β_x^*=1m, β_y^*=2mm
- "Instability" threshold observed
- Loss rate depend on $\beta^*_{x,y}$, and DA
- Above threshold particles continuously slip out of DA and RF bucket

FCCee_t_65_26_1_2
w/ CW



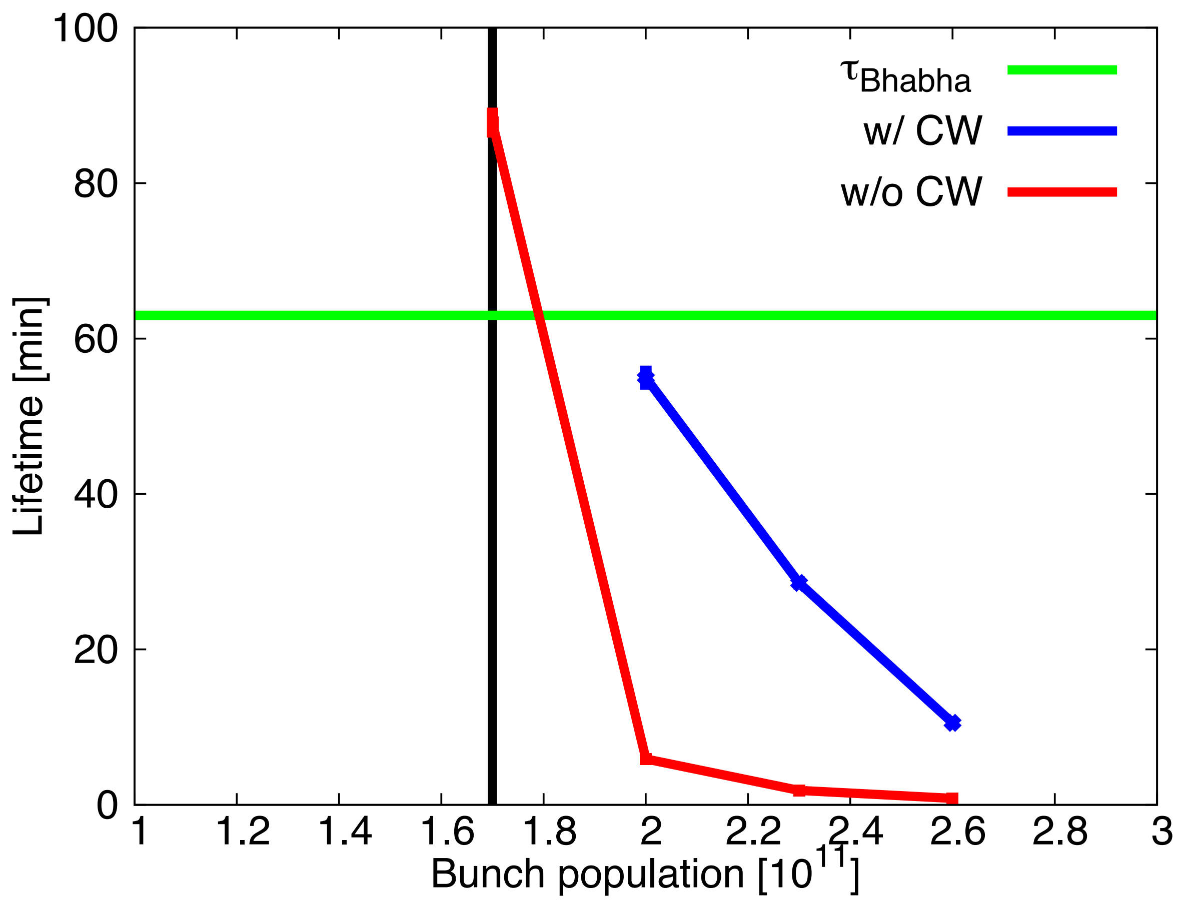
FCCee_t_65_26_1_2_nocw
w/o CW



2. Simulations: SAD: tt_{bar}

➤ Particle losses in tracking

- Nominal N_p=1.7E11, β_x^*=1m, β_y^*=2mm
- Translate loss rate into lifetime [No physical aperture for this calculation]
- Likely CW improves lifetime via suppressing beam tail [Need more careful simulations]

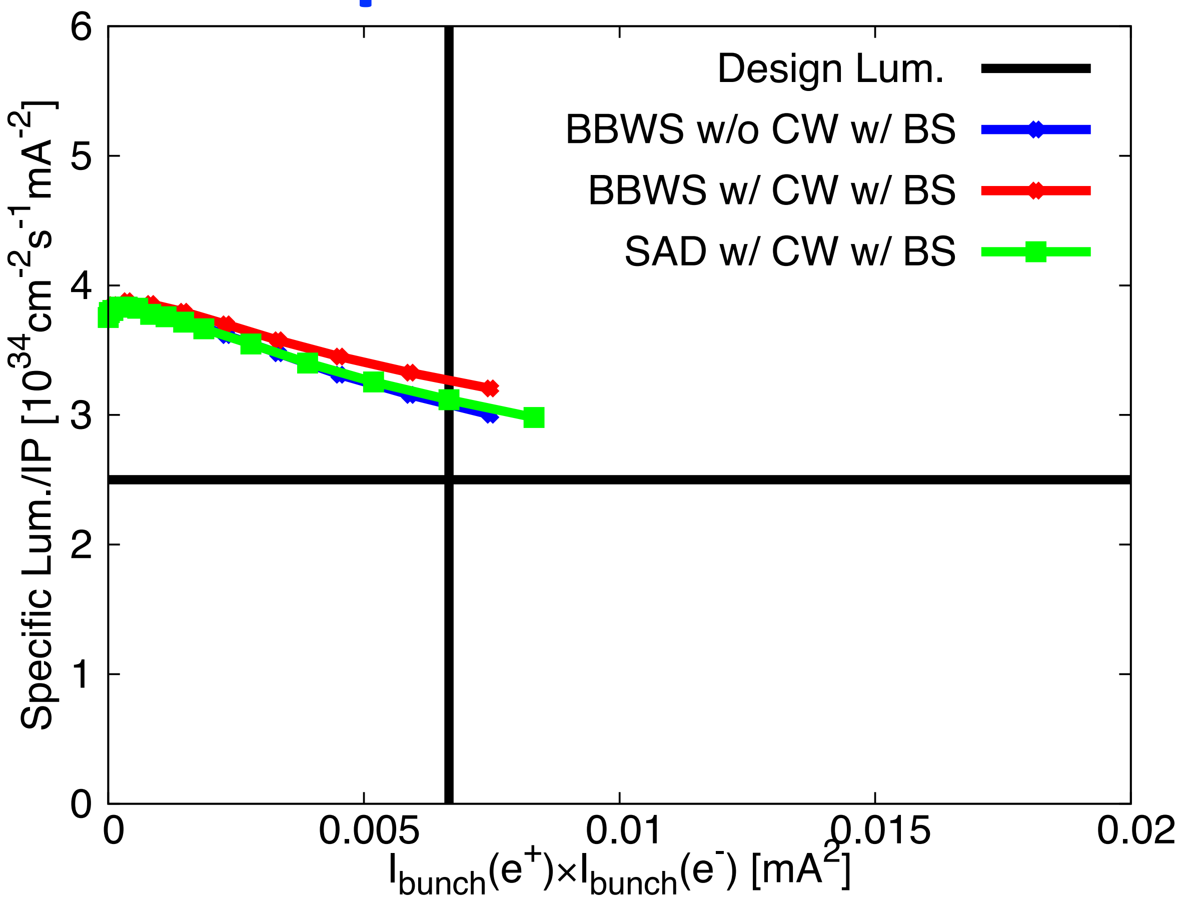


2. Simulations: SAD: tt_{bar}

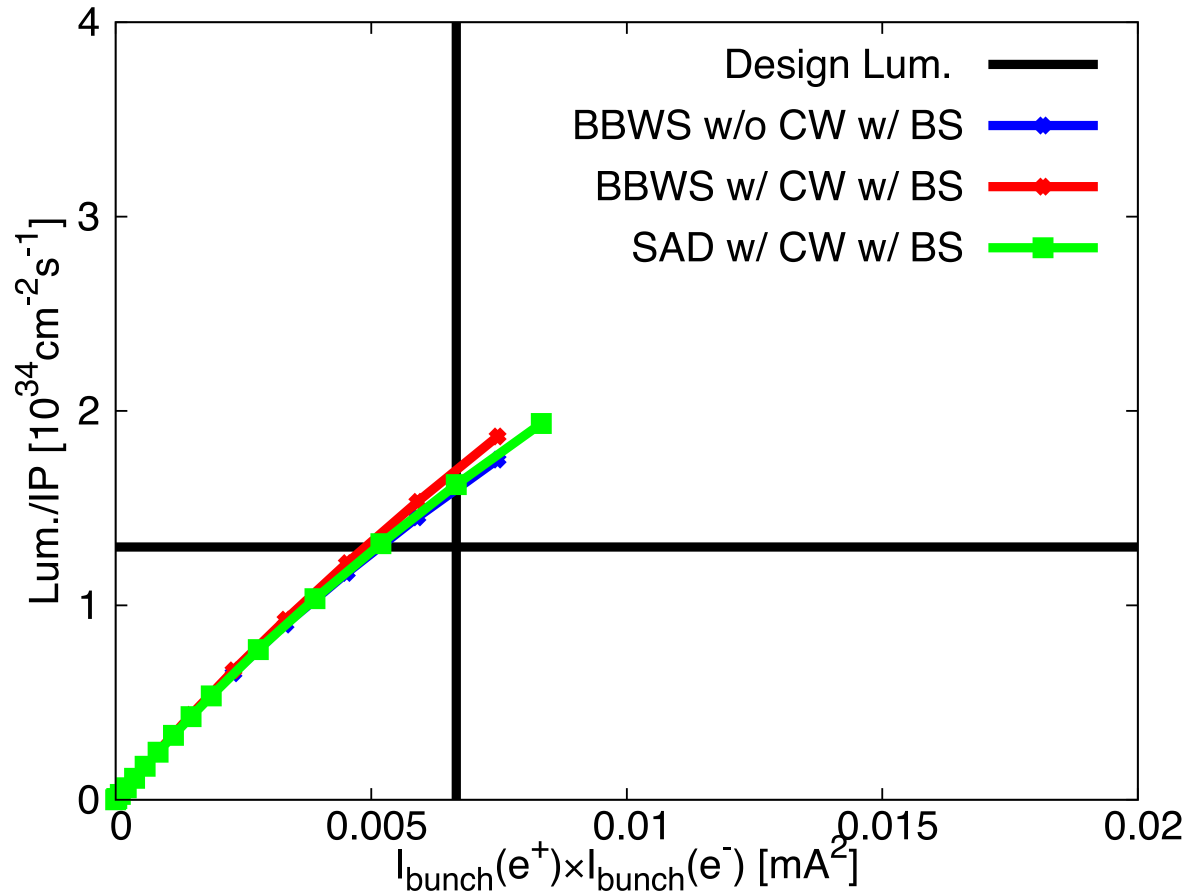
➤ **Luminosity for β_x^*=0.5m, β_y^*=1mm**

- **Lattice ver. FCCee_t_65_26**
- **Small gain from CW**
- **Small loss(order of a few percents) due to BB+LN**
- **Allow lower beam current to achieve the same lum.**

Specific lum.



Total lum.



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➤ **Beam-beam simulation results for FCC-ee**

- tt_{bar} threshold [175GeV]
- **Z pole [45.6GeV]**

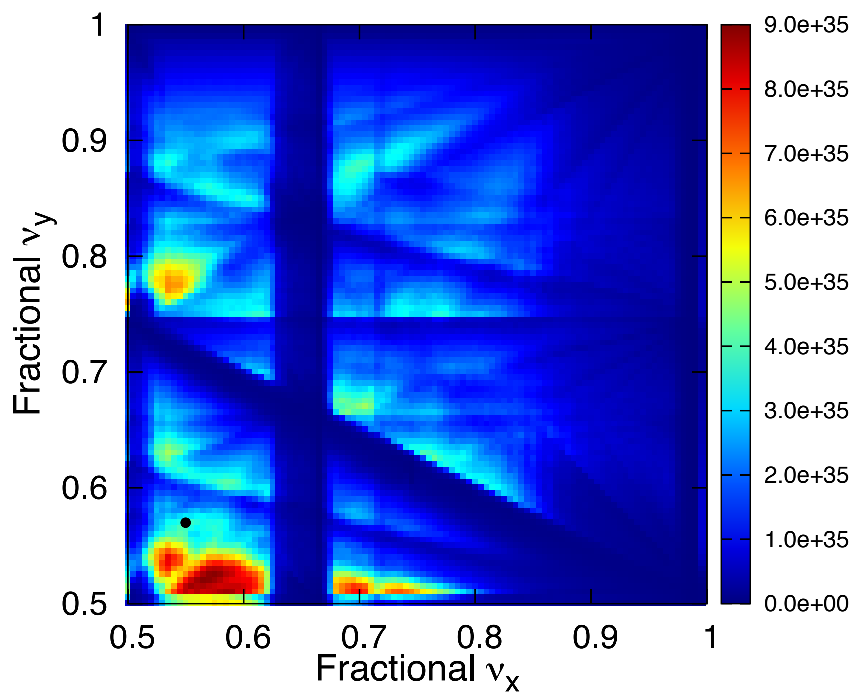
➤ Summary

3. Simulations: BBWS: Z

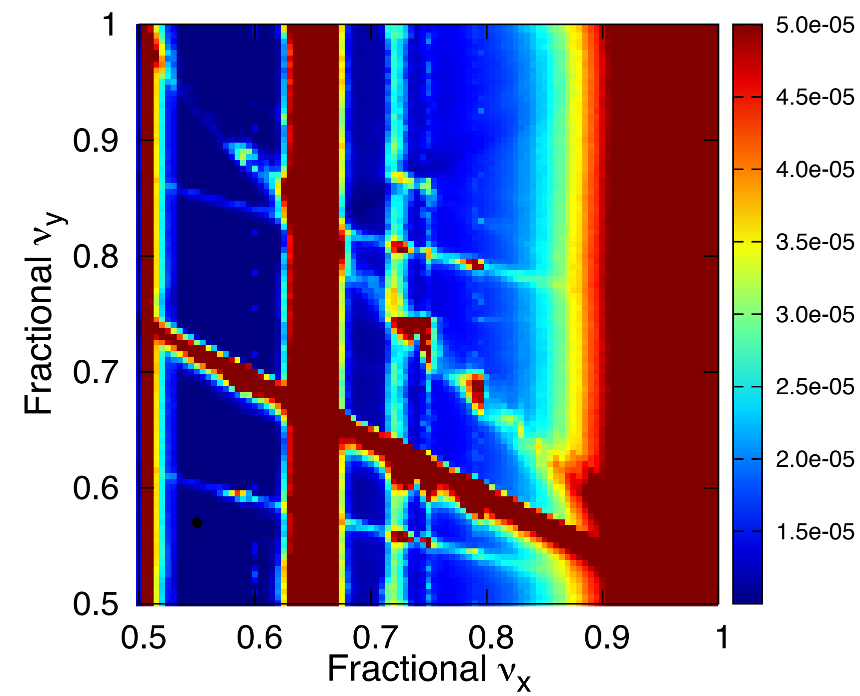
➤ Lum. tune scan w/o CW w/ BS

- BB+BS: Coupled x-y-z motions
- Very small area for good luminosity

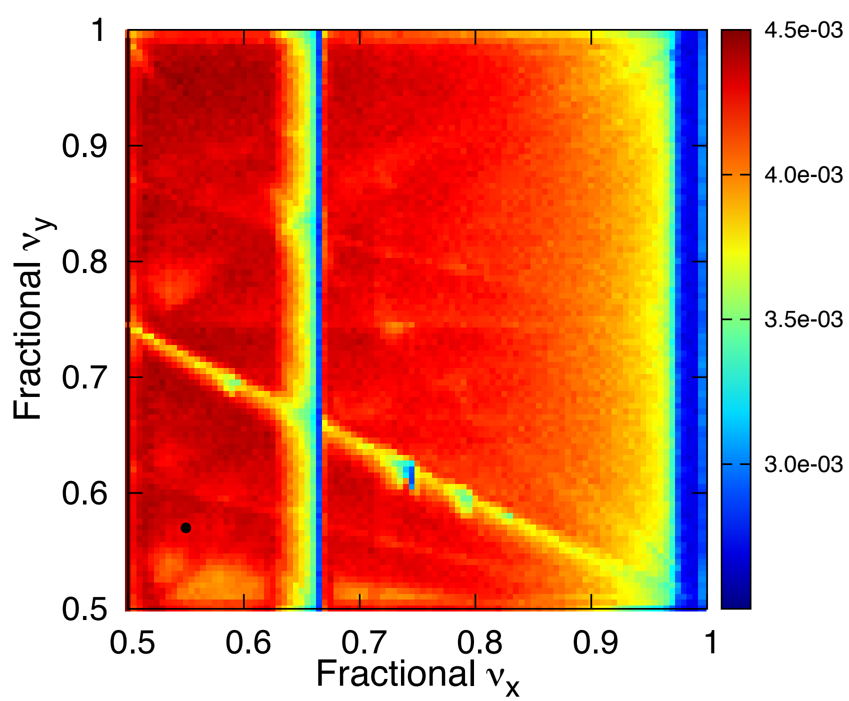
Lum.



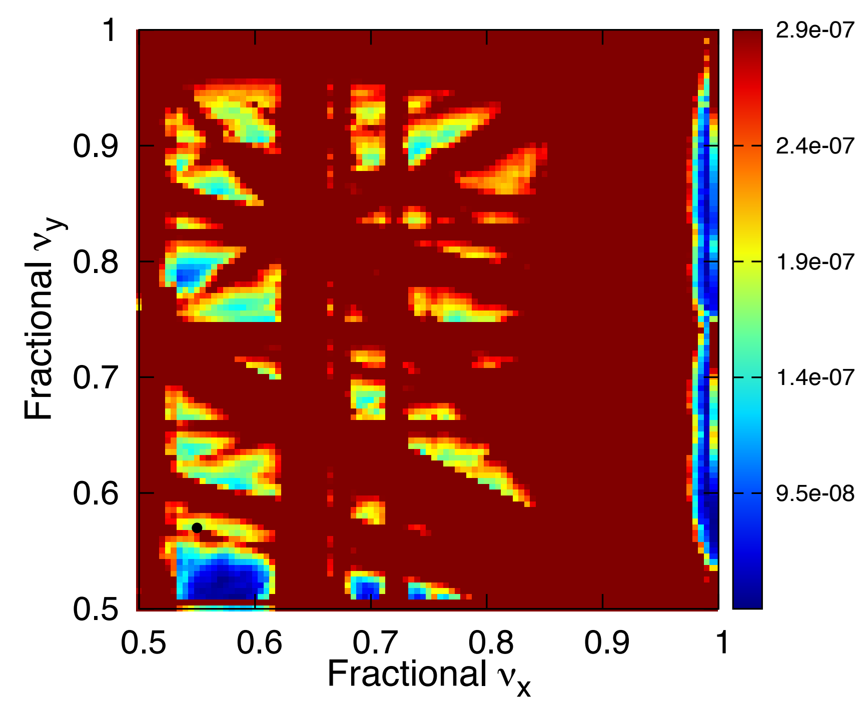
σ_x



σ_z



σ_y

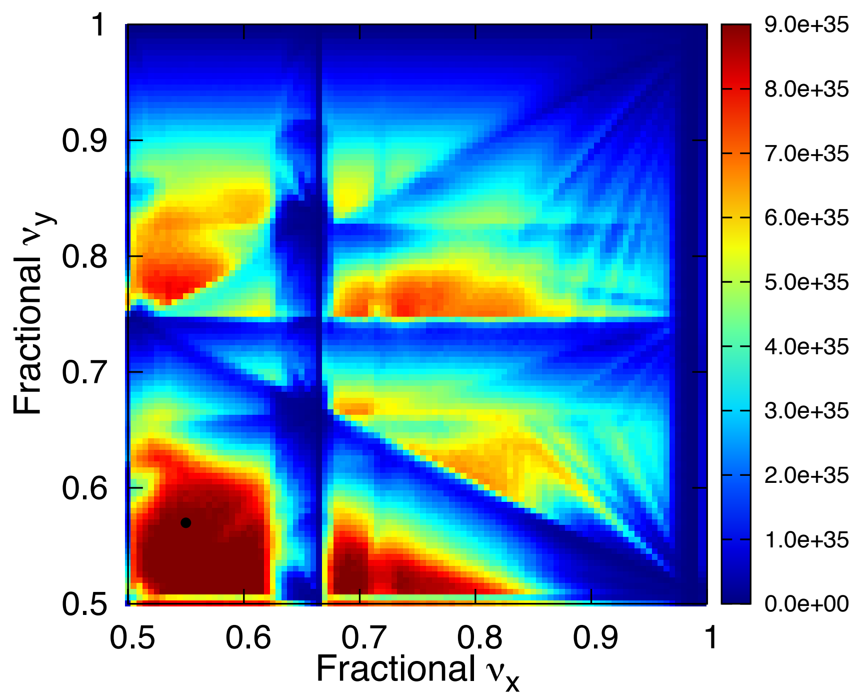


3. Simulations: BBWS: Z

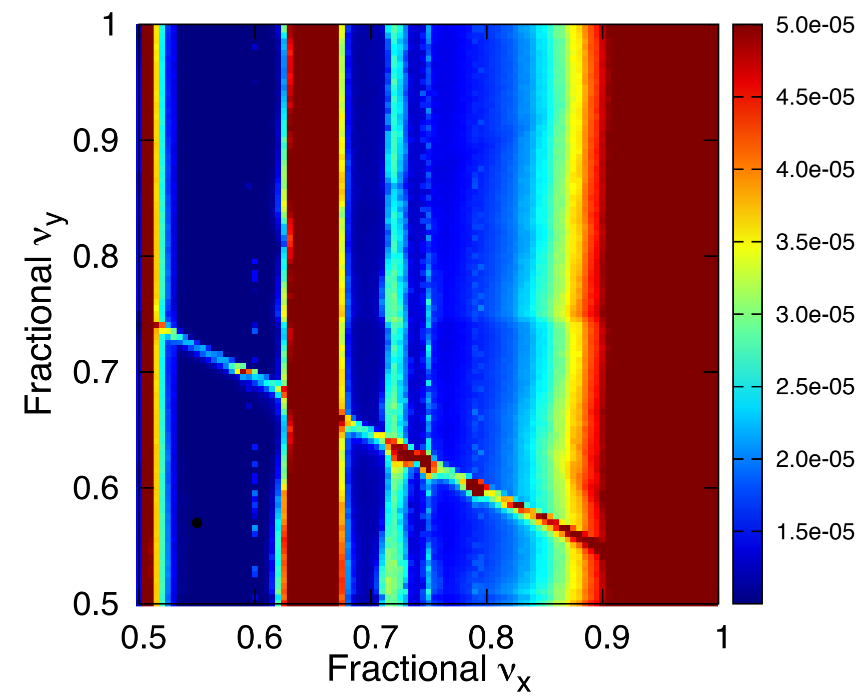
➤ **Lum. tune scan w/ CW w/ BS**

- **Optimal working point: [.55,.57]/IP**
- **CW's gains: both luminosity and beam-tail suppression**

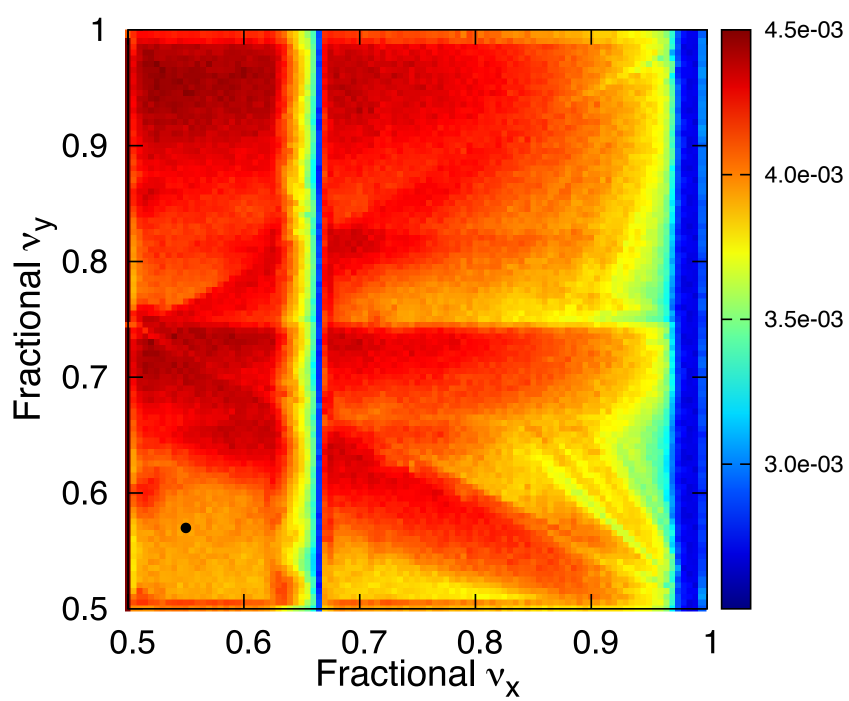
Lum.



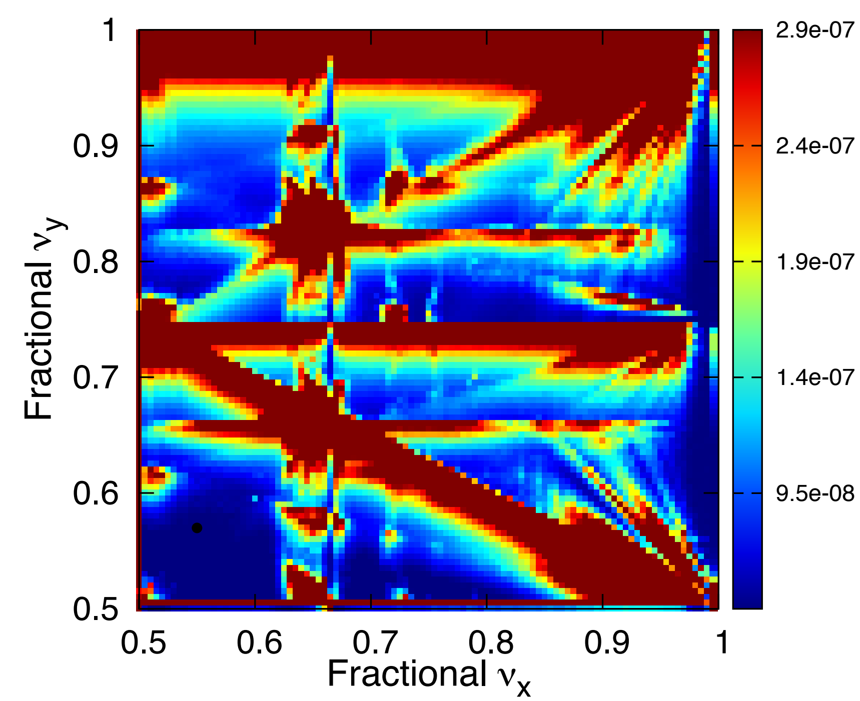
σ_x



σ_z



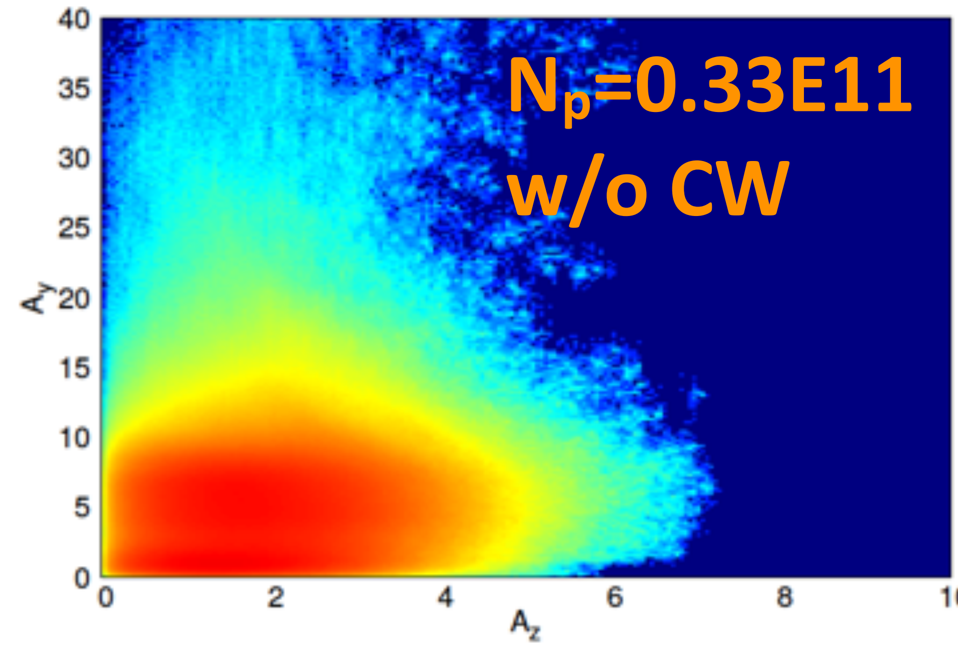
σ_y

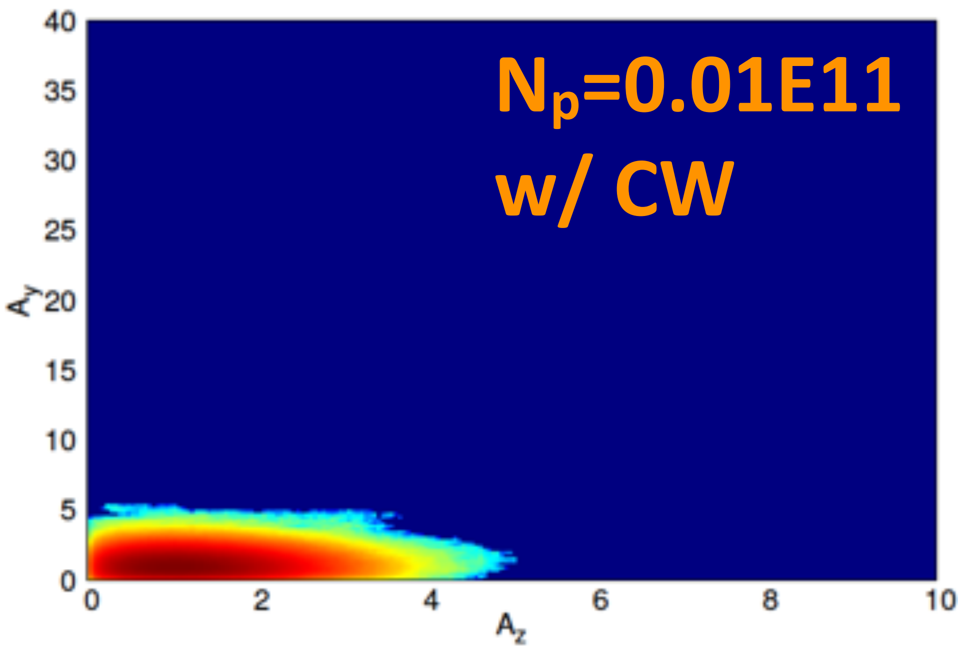


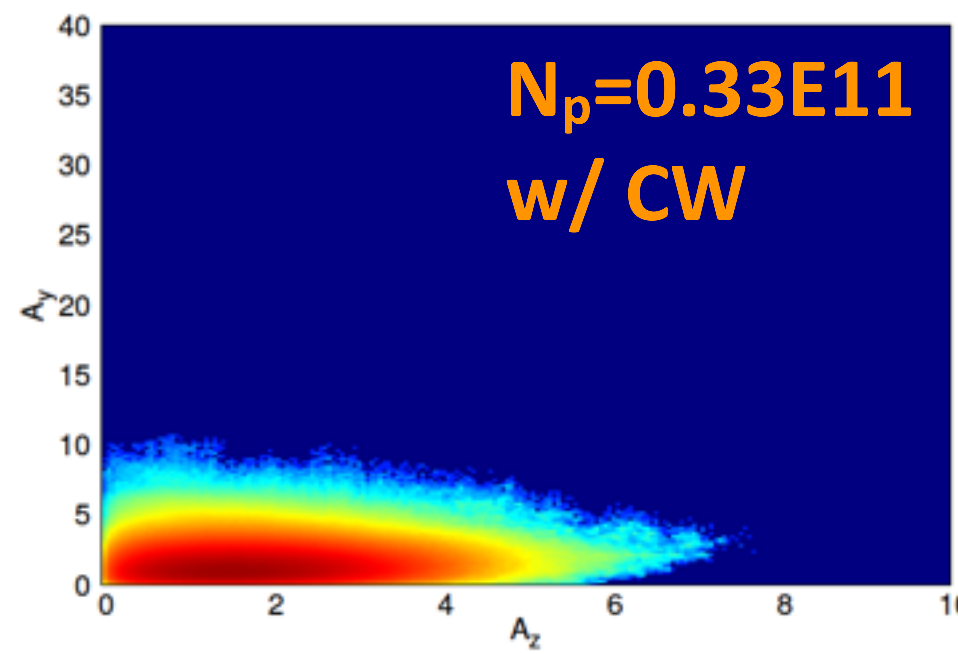
3. Simulations: BBWS: Z

➤ **Beam distribution in y-z plane w/ BS**

- Working point: [.55,.57]/IP
- CW suppresses vertical beam-tail
- CW is a must for FCC-ee Z pole(?)







$$A_y = \sqrt{2J_y/\epsilon_y}$$

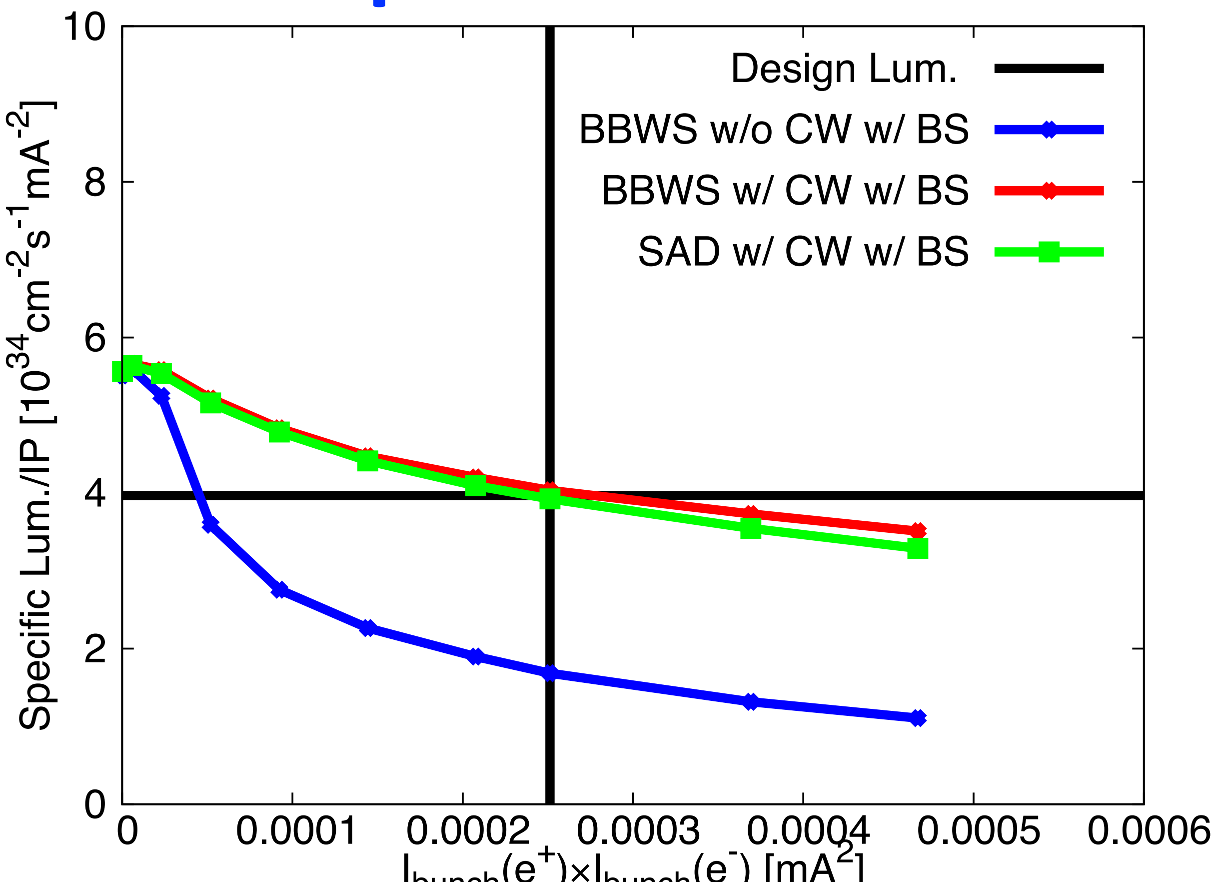
$$A_z = \sqrt{2J_z/\epsilon_z}$$

3. Simulations: SAD: Z

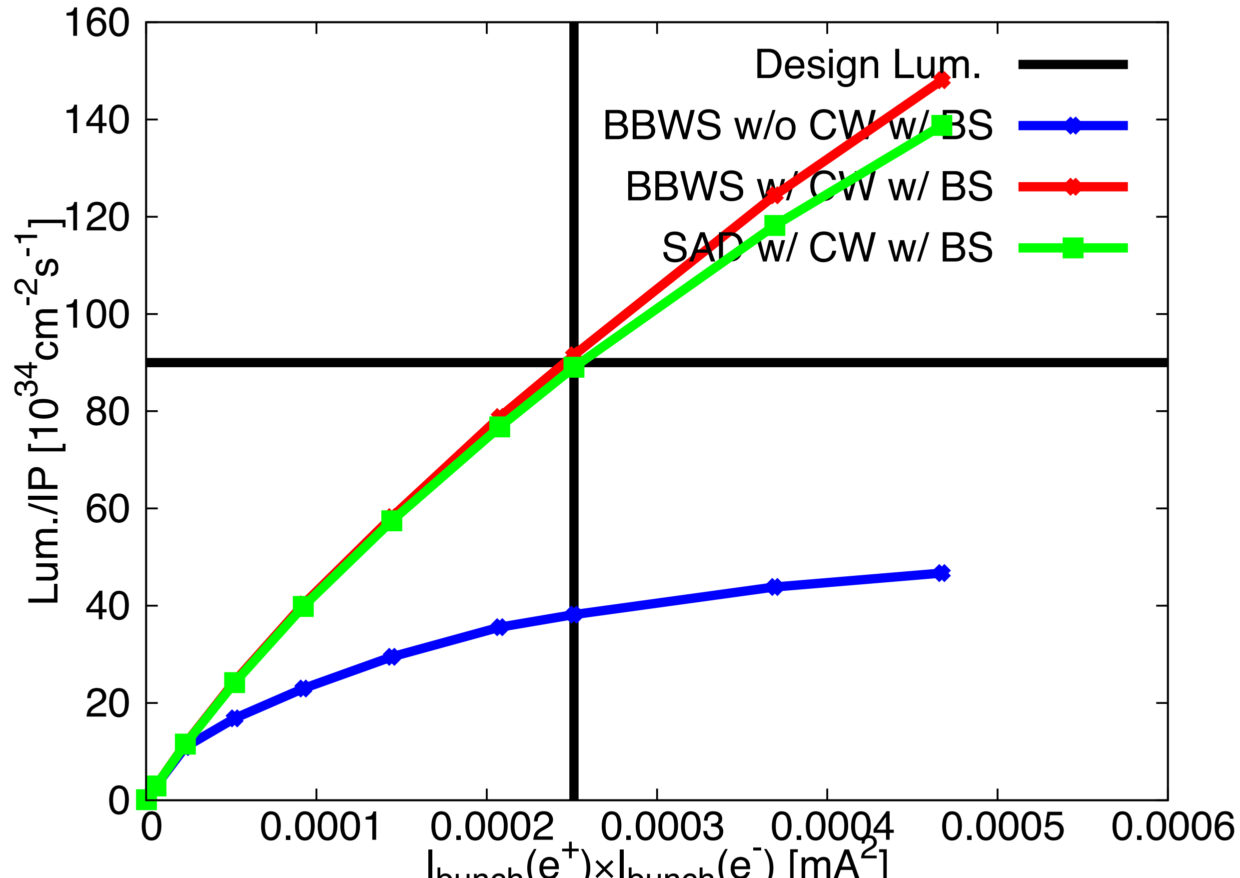
➤ **Luminosity for $\beta_x^*=1$m, $\beta_y^*=2$mm**

- **Lattice ver. FCCee_z_65_36**
- **Significant gain from CW**
- **Small loss(order of a few percents) due to BB+LN**

Specific lum.

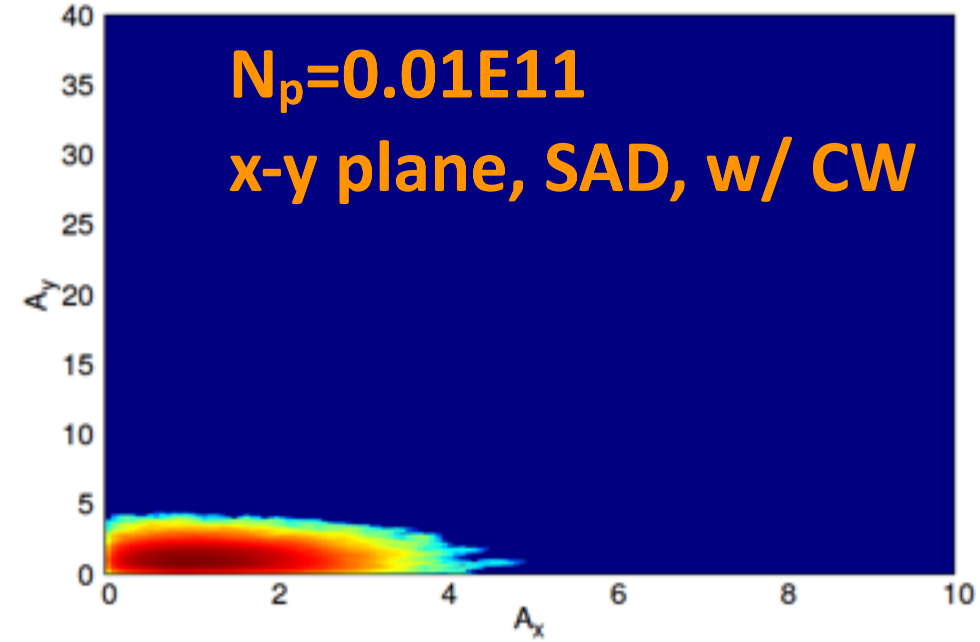


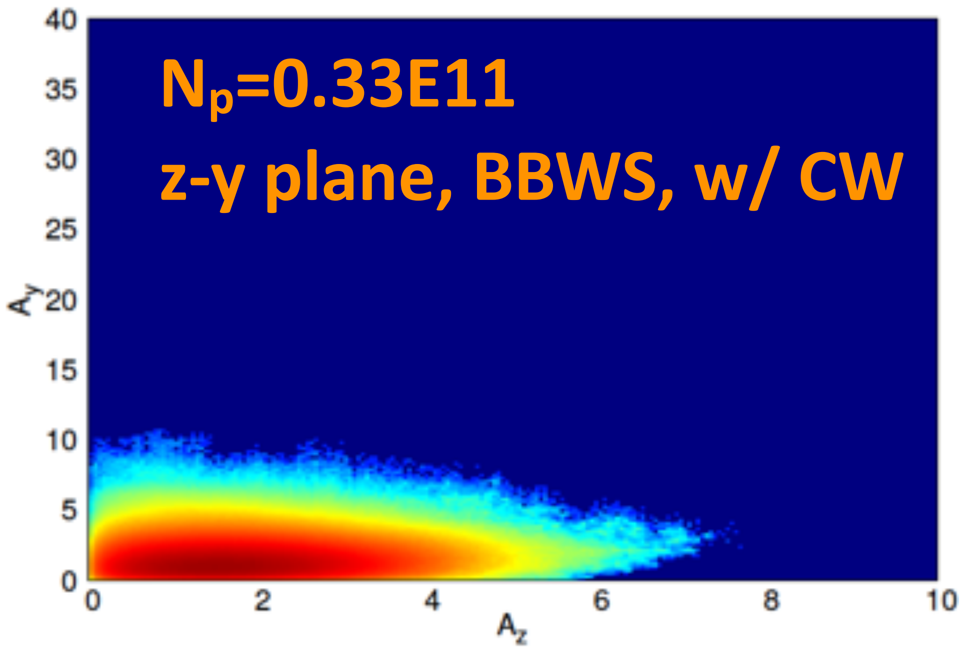
Total lum.

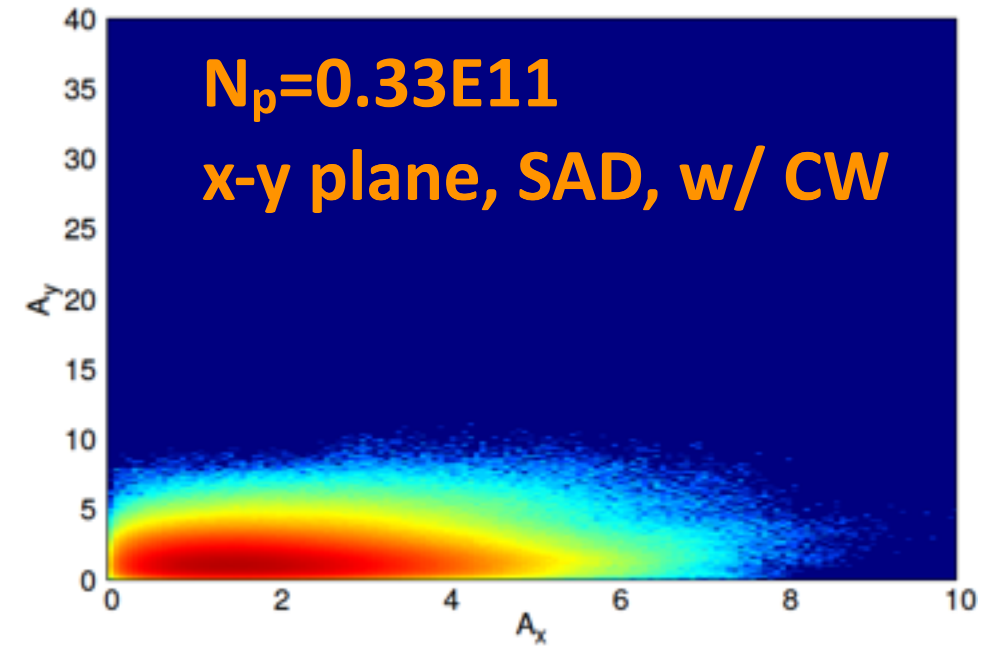


3. Simulations: SAD: Z

- **Beam distribution in for $\beta_x^*=1m$, $\beta_y^*=2mm$**
  - **Working point: [.55,.57]/IP**
  - **CW suppresses vertical beam-tail**
  - **BB+LN drives beam tail, but no particle loss observed**





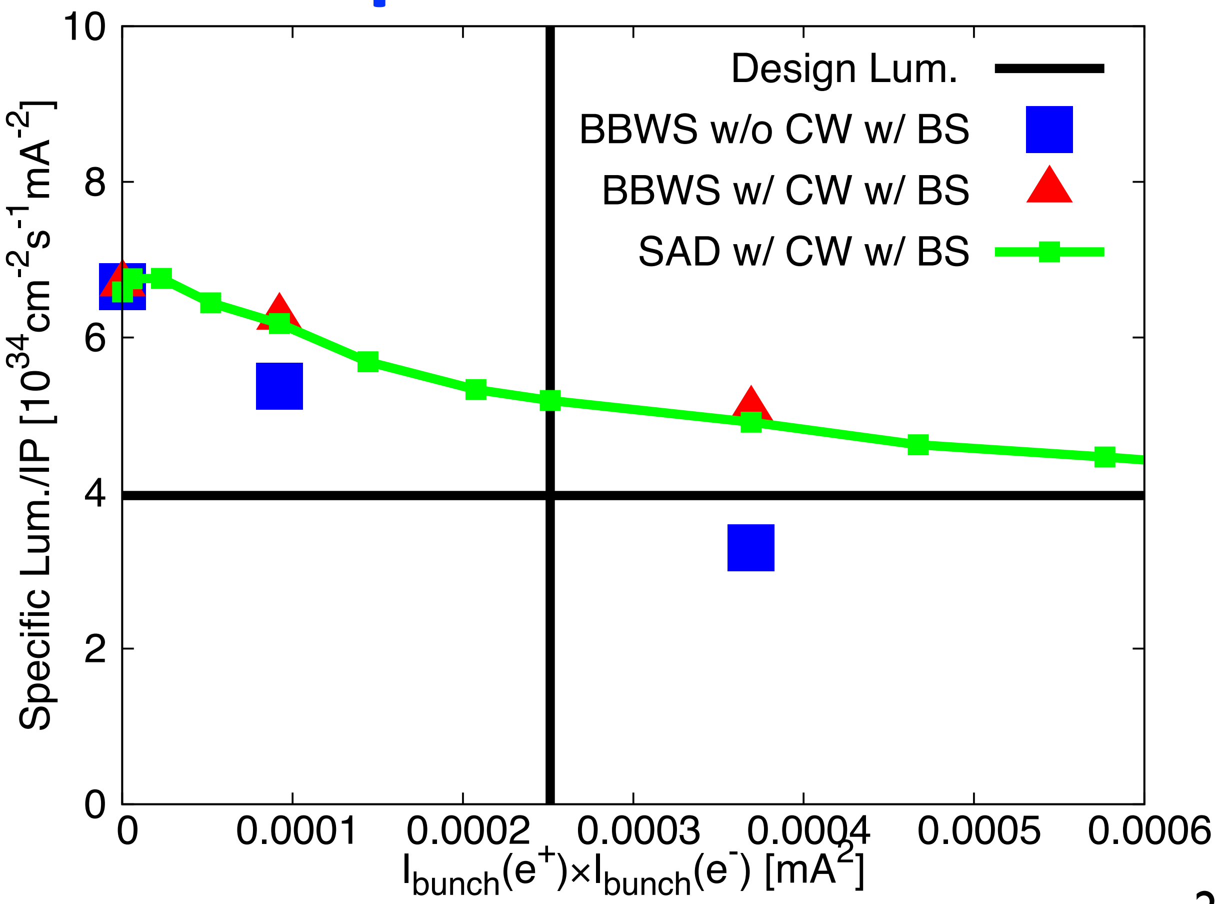


3. Simulations: SAD: Z

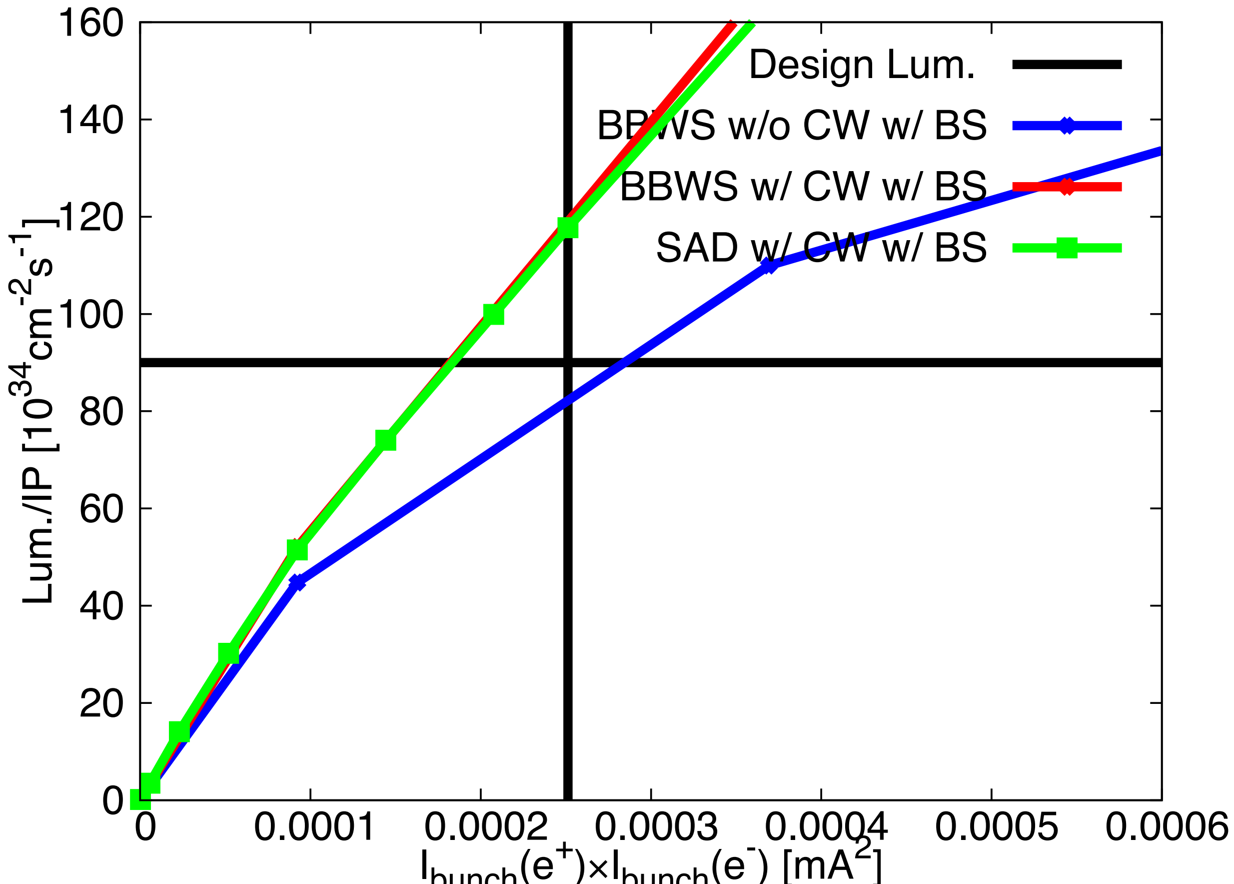
➤ **Luminosity for $\beta_x^*=0.5$m, $\beta_y^*=1$mm**

- Lattice ver. FCCee_z_65_36_by1
- Large gain from CW
- Small loss(order of a few percents) due to BB+LN
- Allow lower beam current to achieve the same lum.

Specific lum.



Total lum.



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    - SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation
- Beam-beam simulation results for FCC-ee
  - tt_{bar} threshold [175GeV]
  - Z pole [45.6GeV]
- **Summary**

4. Summary

- **Crab waist**
  - Work well for FCC-ee
  - Suppress vertical beam tail
  - Lum. gain at lower beam energy region
- **BB+LN**
  - Lum. loss in the order of a few percents given the present designs
  - Particle loss observed in tracking [beamstrahlung + DA + momentum acceptance], depending on optics designs and optimisations of DA
  - Not a concern for the latest designs
- **$(\beta_x^*, \beta_y^*) \rightarrow (0.5, 0.001)$ [m]**
  - No limit from BB+LN
- **Simulations to be periodically updated with**
  - Updates of machine parameters
  - Updates of optics designs
  - Updates of magnet designs, especially in the IR