Beam-beam effects at STCF

Demin Zhou (KEK), Sanya Li, Tao Liu (USTC),
K. Ohmi (KEK/IHEP)
on behalf of STCF collider ring accelerator physics group

Acknowledgements

J.Y. Tang, Y. Zou, L.H. Zhang, T.L. He, W.W. Li (USTC)

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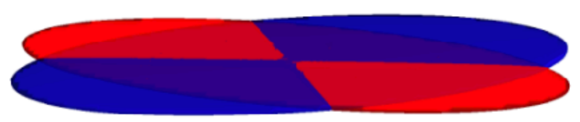
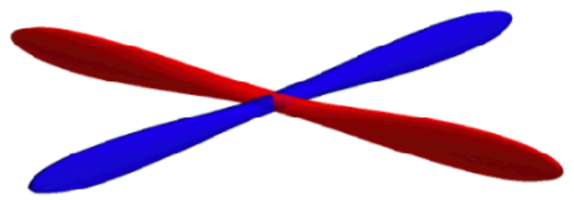
Outline

- Introduction and motivation
- Beam-beam effects in crab-waist colliders
- Beam-beam simulation framework for STCF
- Beam-beam simulation results for STCF (2 GeV)
- Summary

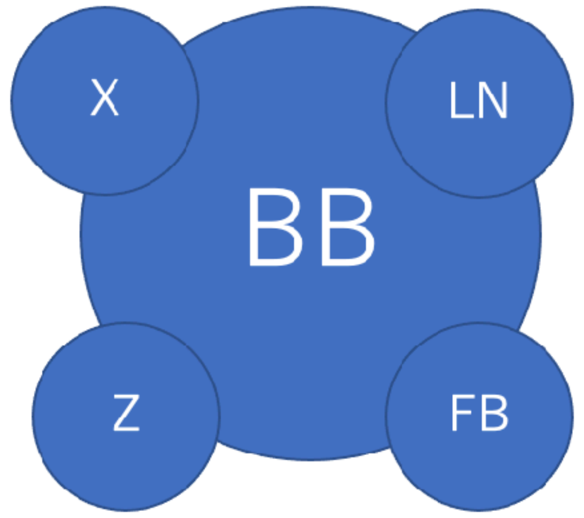
Introduction and motivation

- Role of beam-beam interactions in high-luminosity e+e- colliders
- Importance of evaluating performance limits in the crab-waist collision scheme
- Specific challenges for the Super Tau-Charm Facility (STCF)



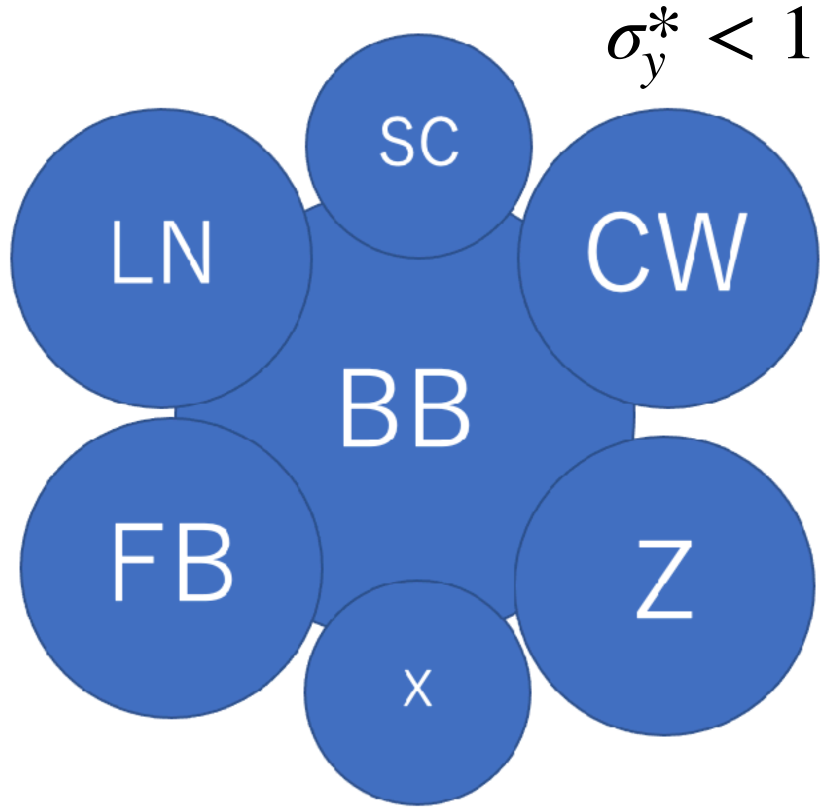


$\sigma_y^* < 1\ \mu m$

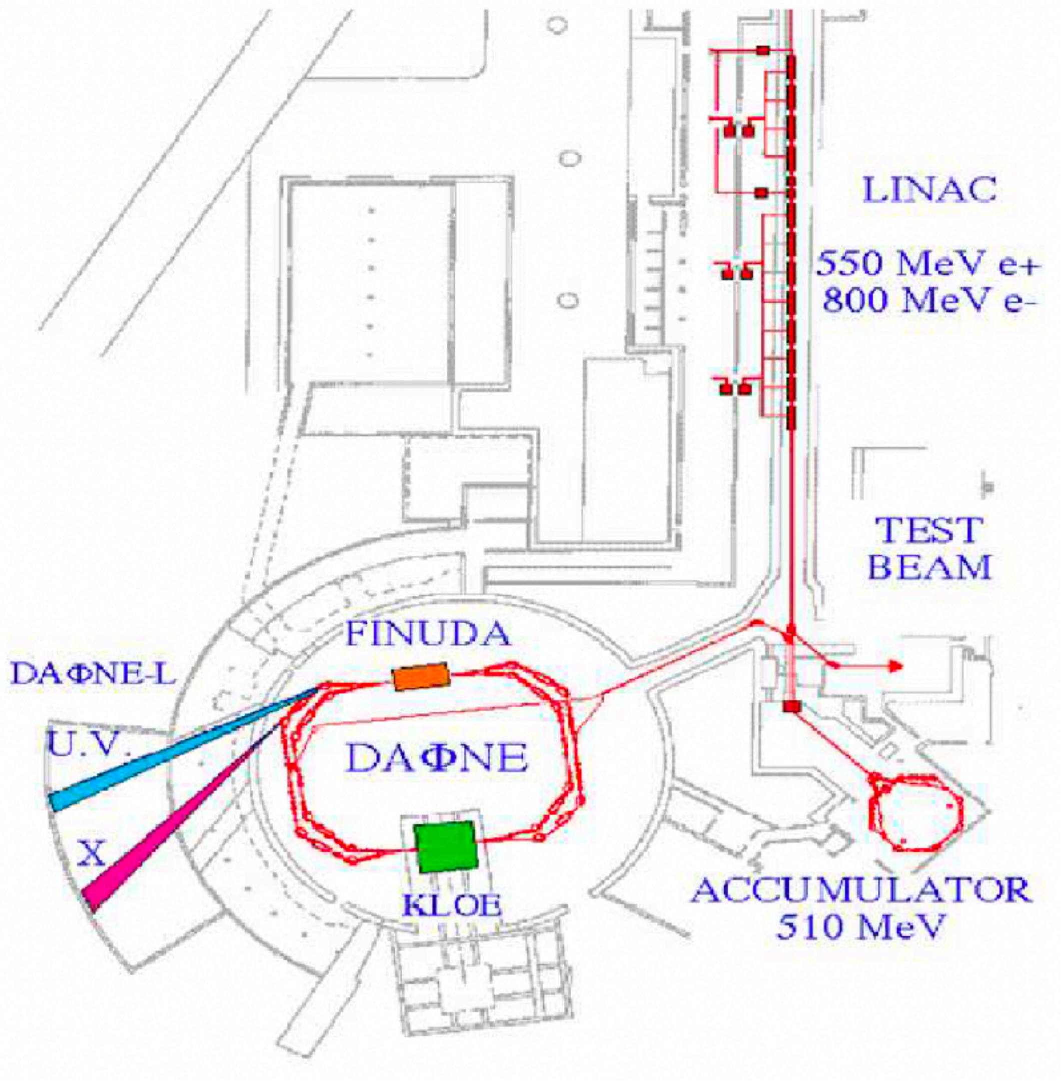


Old colliders

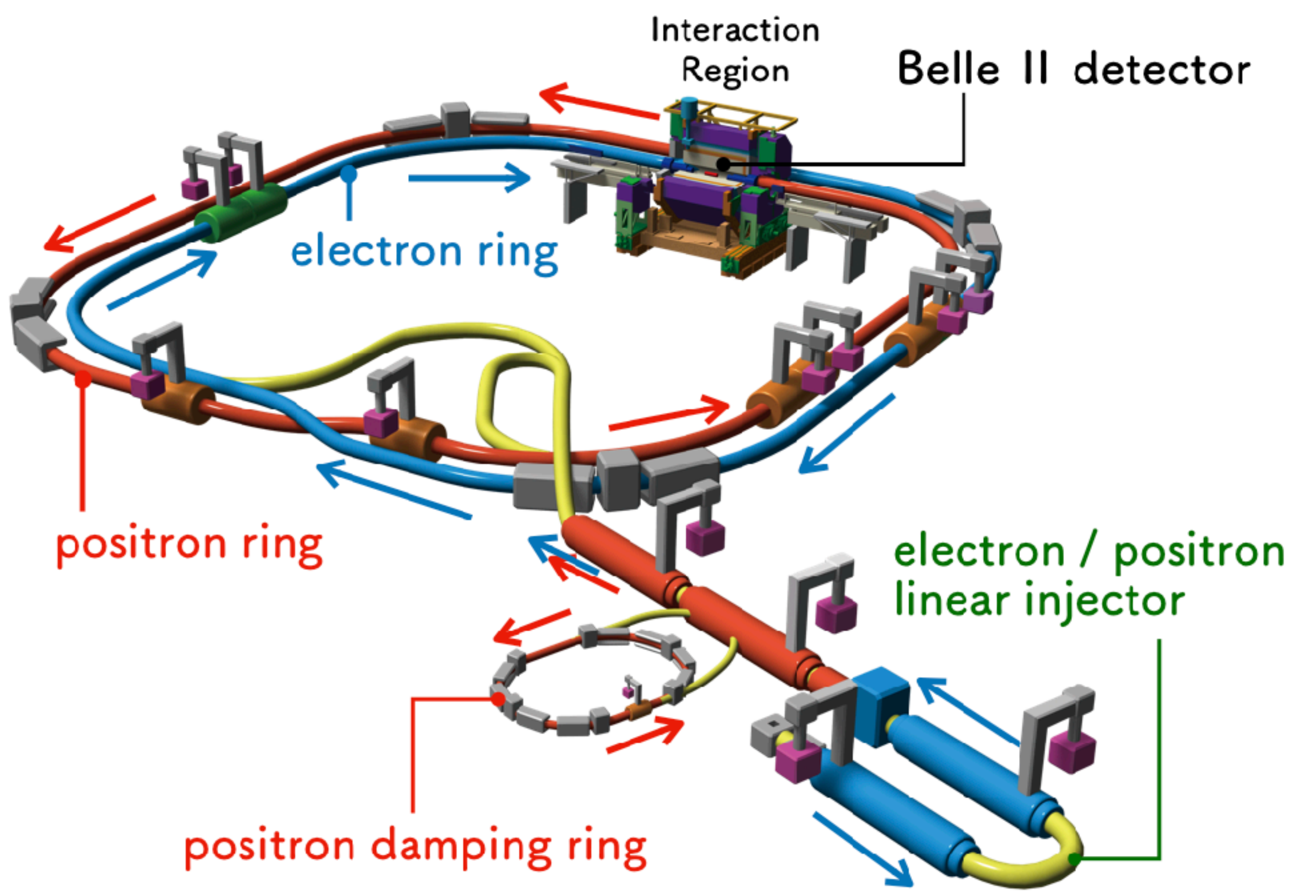
Abbreviations:
BB: Beam-beam
LN: Lattice nonlinearity
Z: Impedance
FB: Feedback
CW: Crab waist
SC: Space charge
X: Unknown factors



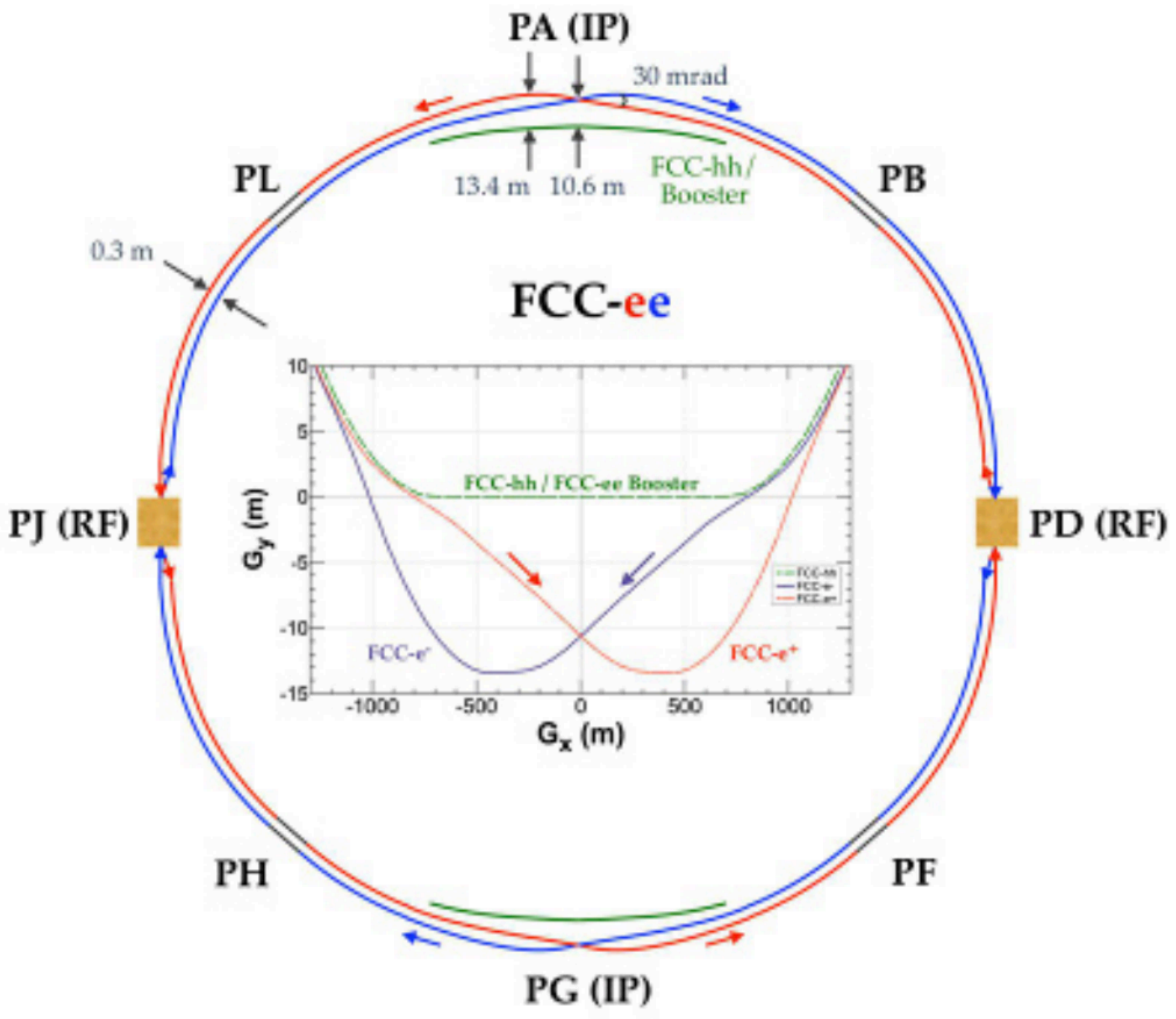
CW colliders



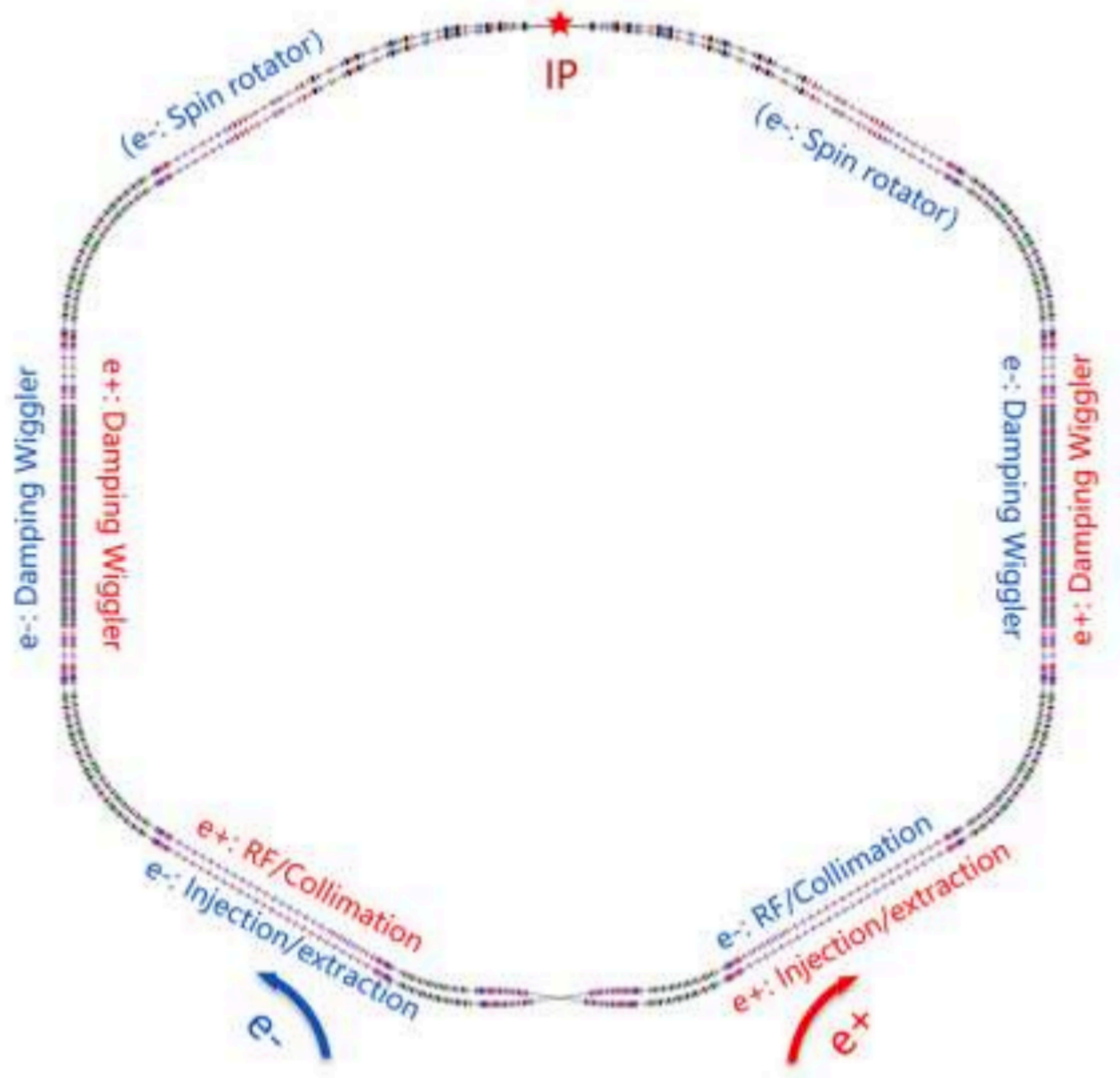
DAFNE (arXiv:1705.06033)



SuperKEKB



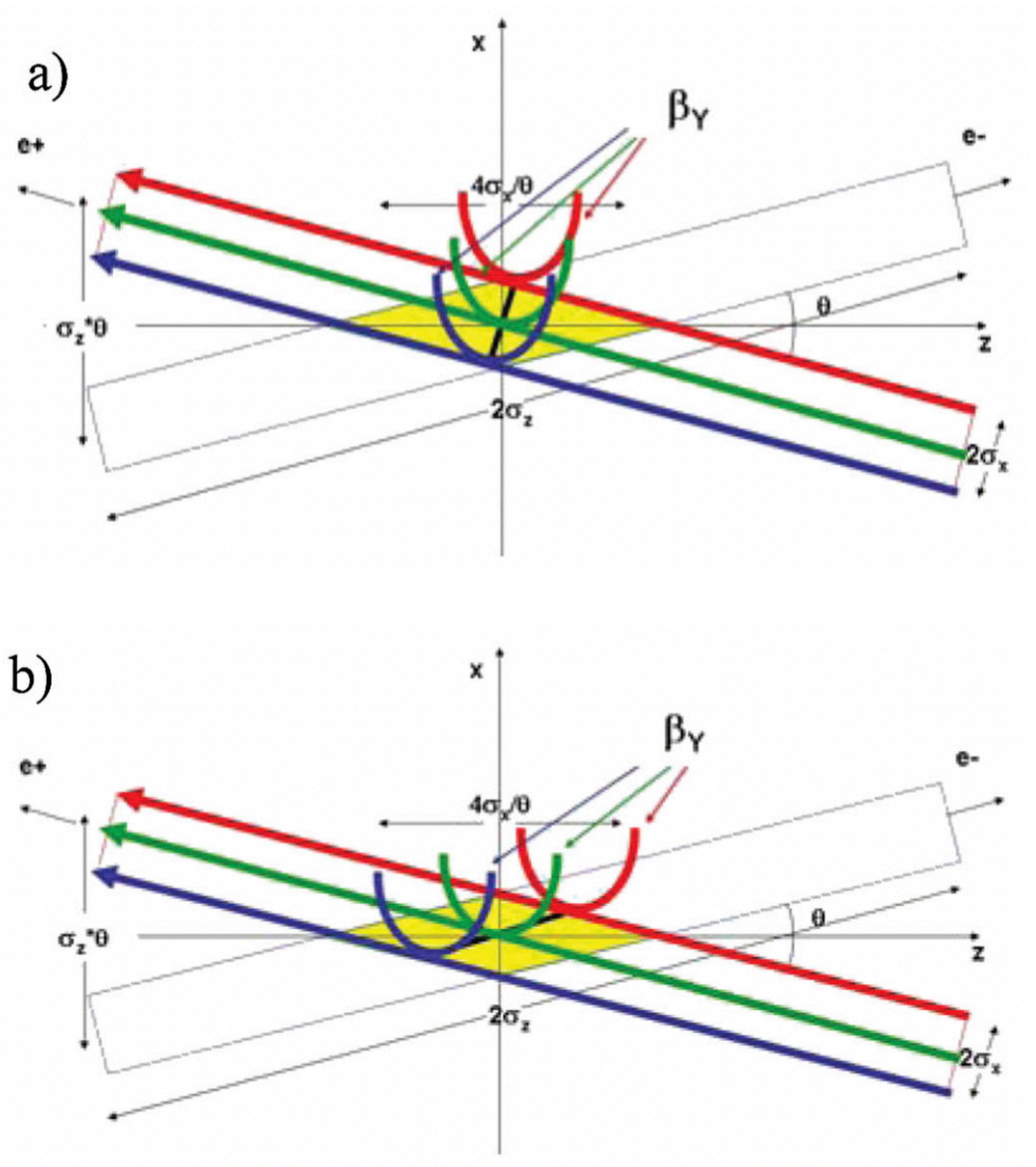
FCC-ee (CDR, 2019)



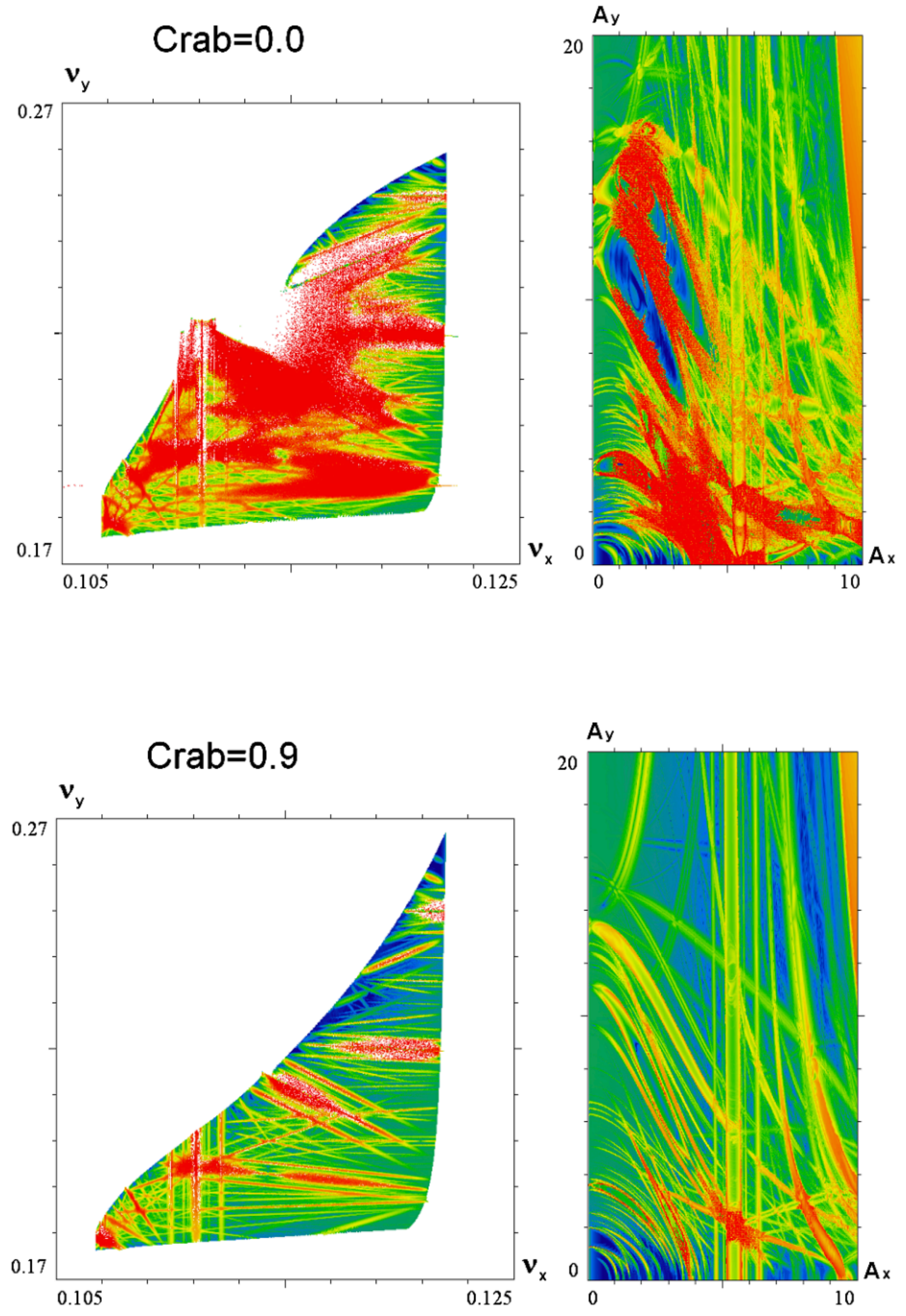
STCF (CDR, 2025)

Beam-beam effects in crab-waist colliders

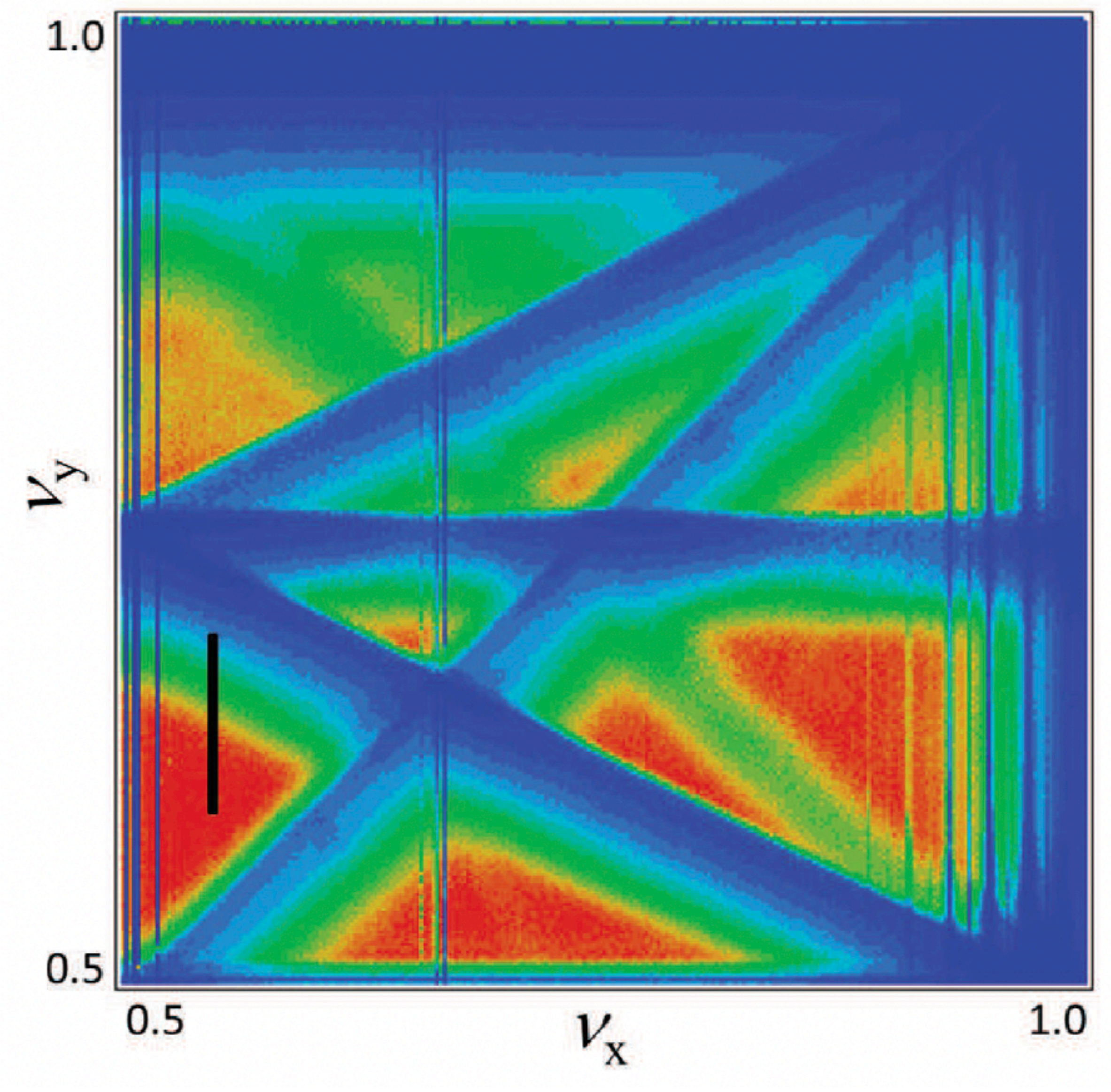
- Fundamental principles of crab-waist scheme (mitigation of incoherent beam-beam effects)



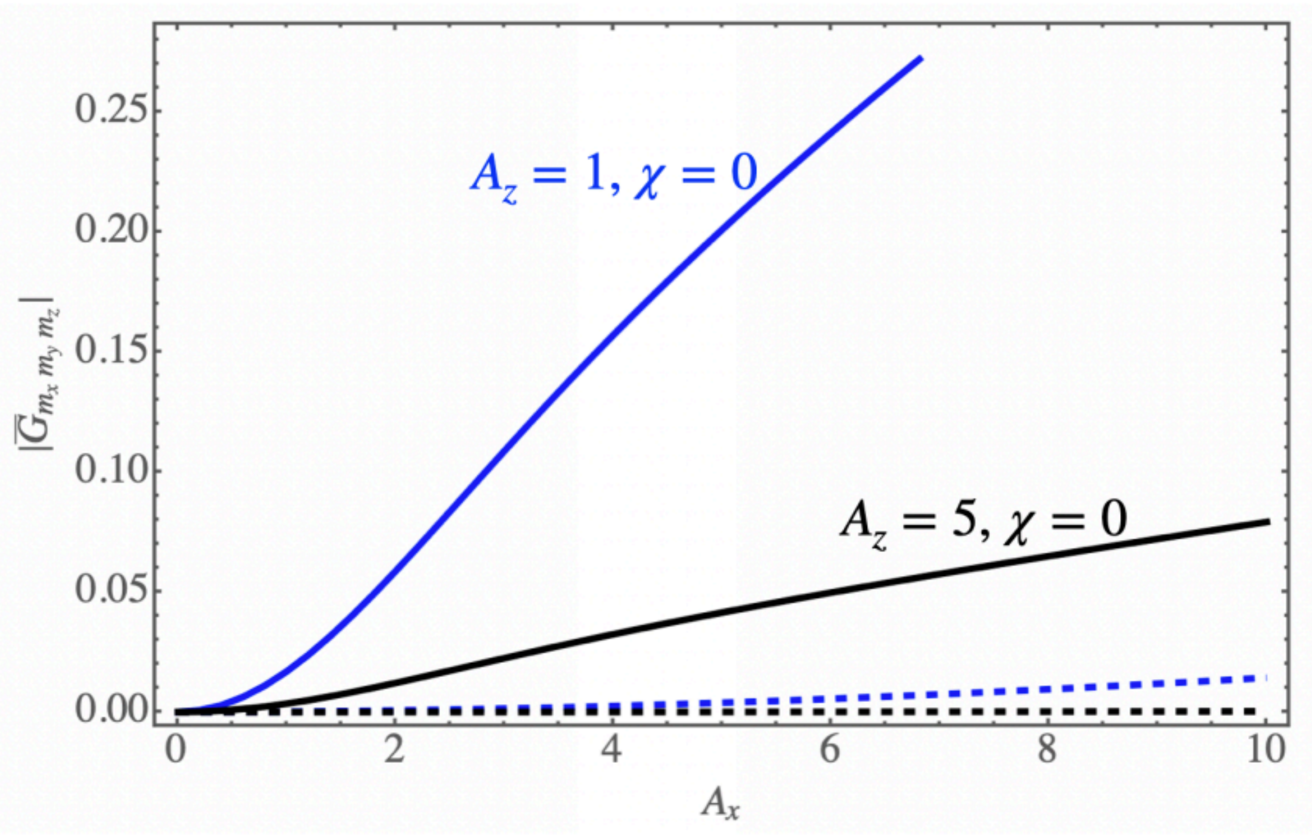
M. Zobov et al., PRL 104, 174801 (2010).



D. Shatilov et al., PRST-AB 14, 014001 (2011).



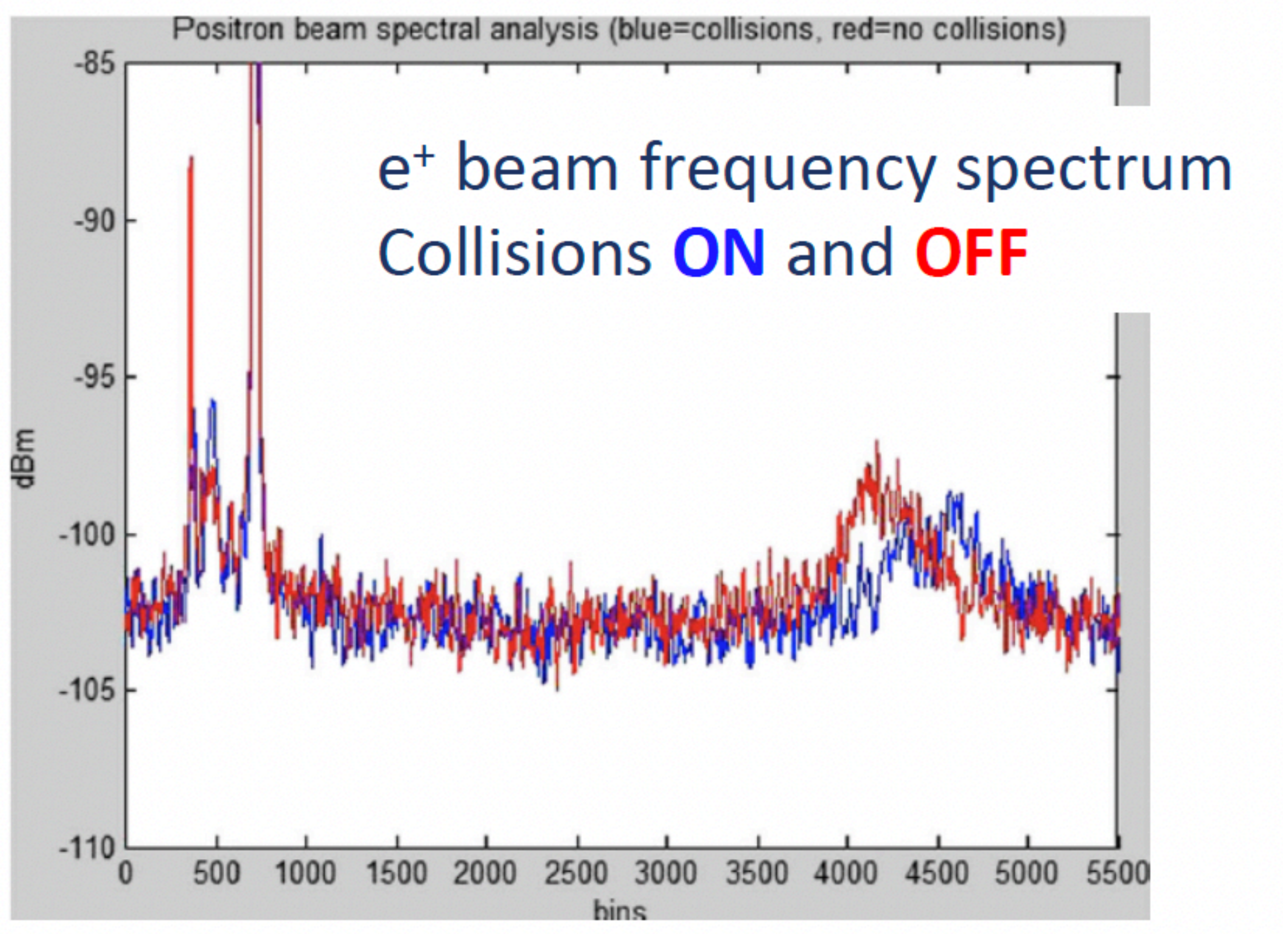
D. Shatilov, Handbook



D. Zhou, BB24, arXiv:2411.10810

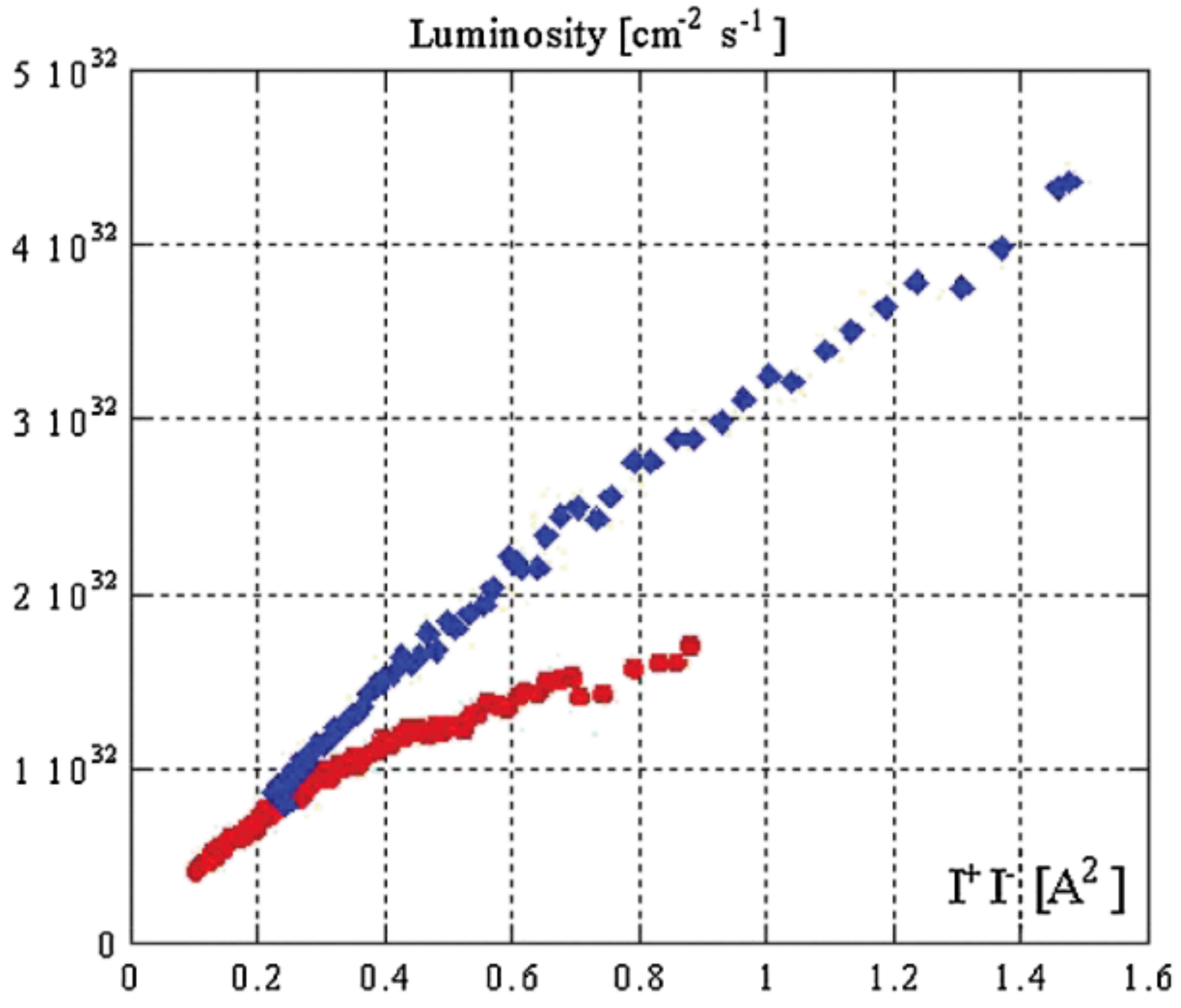
Beam-beam effects in crab-waist colliders

- Accumulated experiences from DAFNE and SuperKEKB (demonstration of CW scheme, interplay of multiple physical processes, etc.)

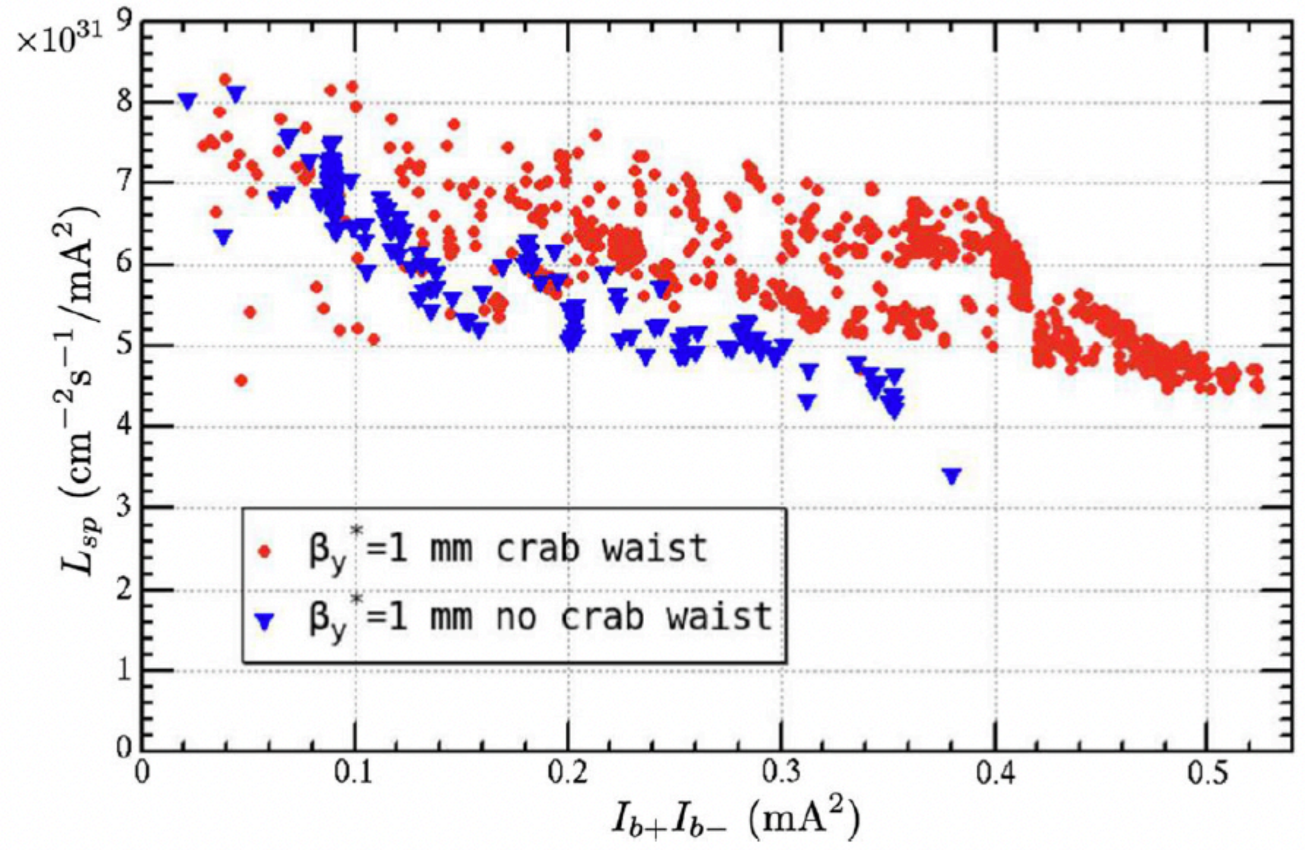


Nonlinear longitudinal kick arising from beam-beam interaction under a large crossing angle

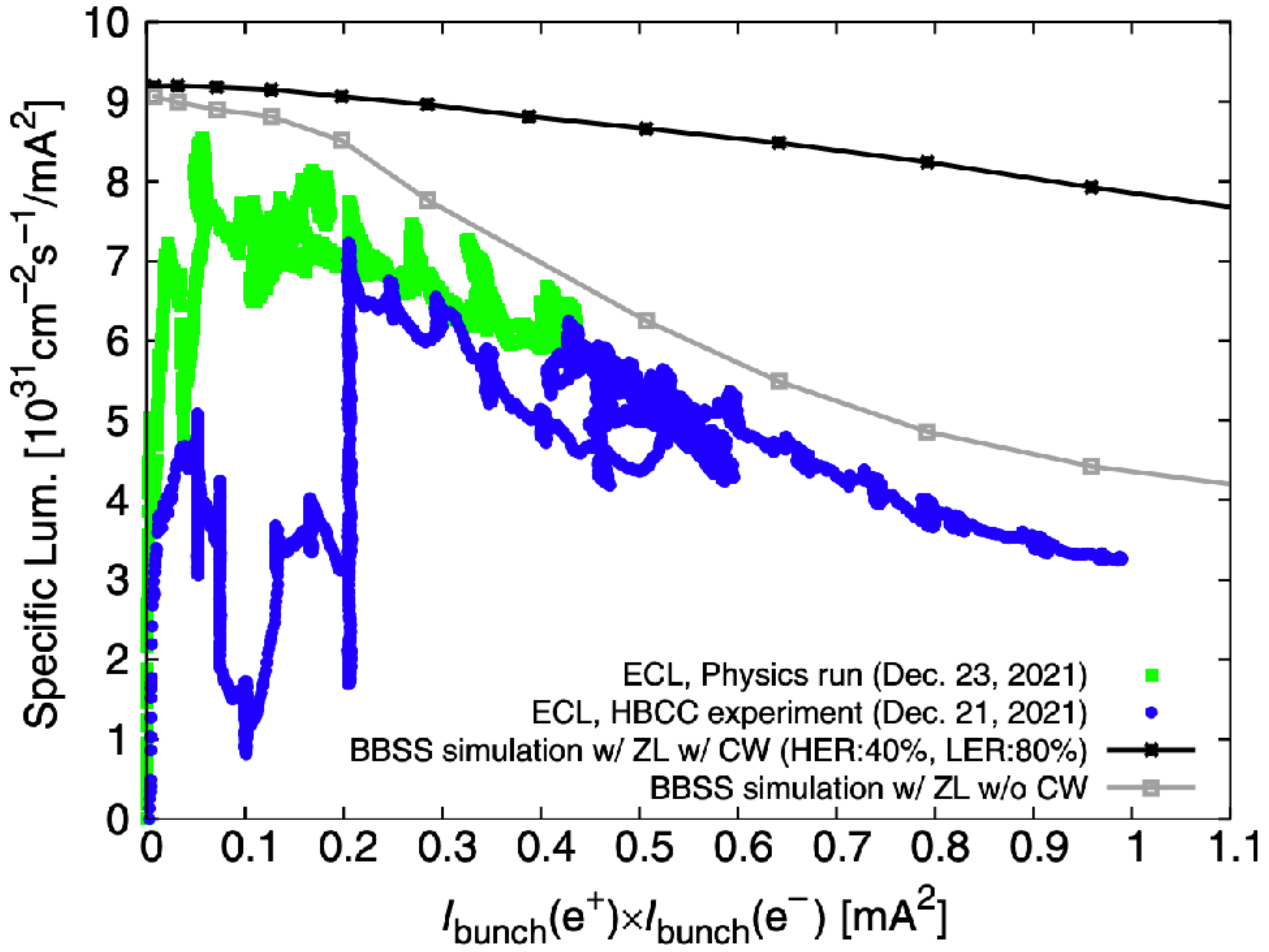
C. Milardi, eeFACT2025



M. Zobov et al., PRL 104, 174801 (2010).



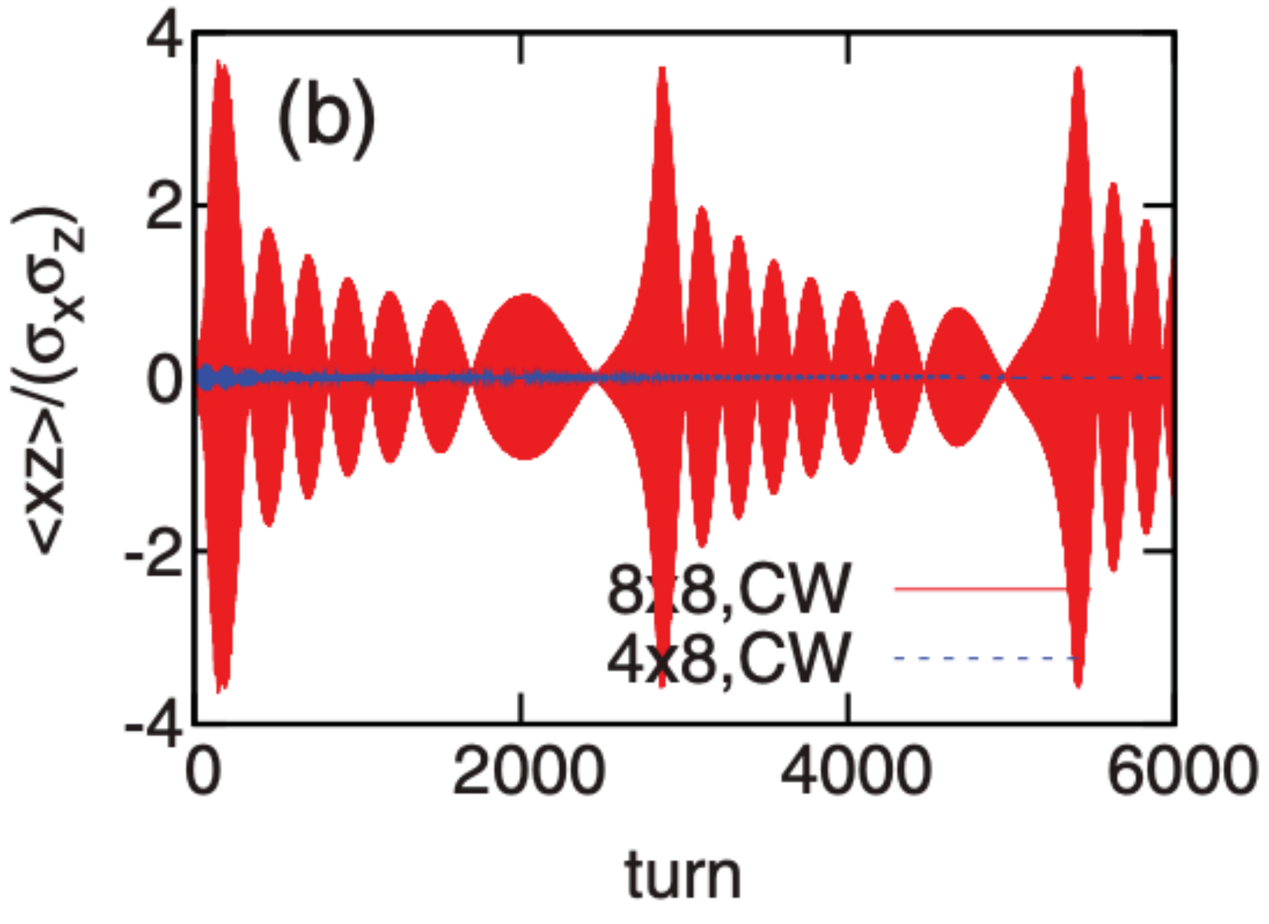
Y. Ohnishi et al., EPJP (2021) 136:1023



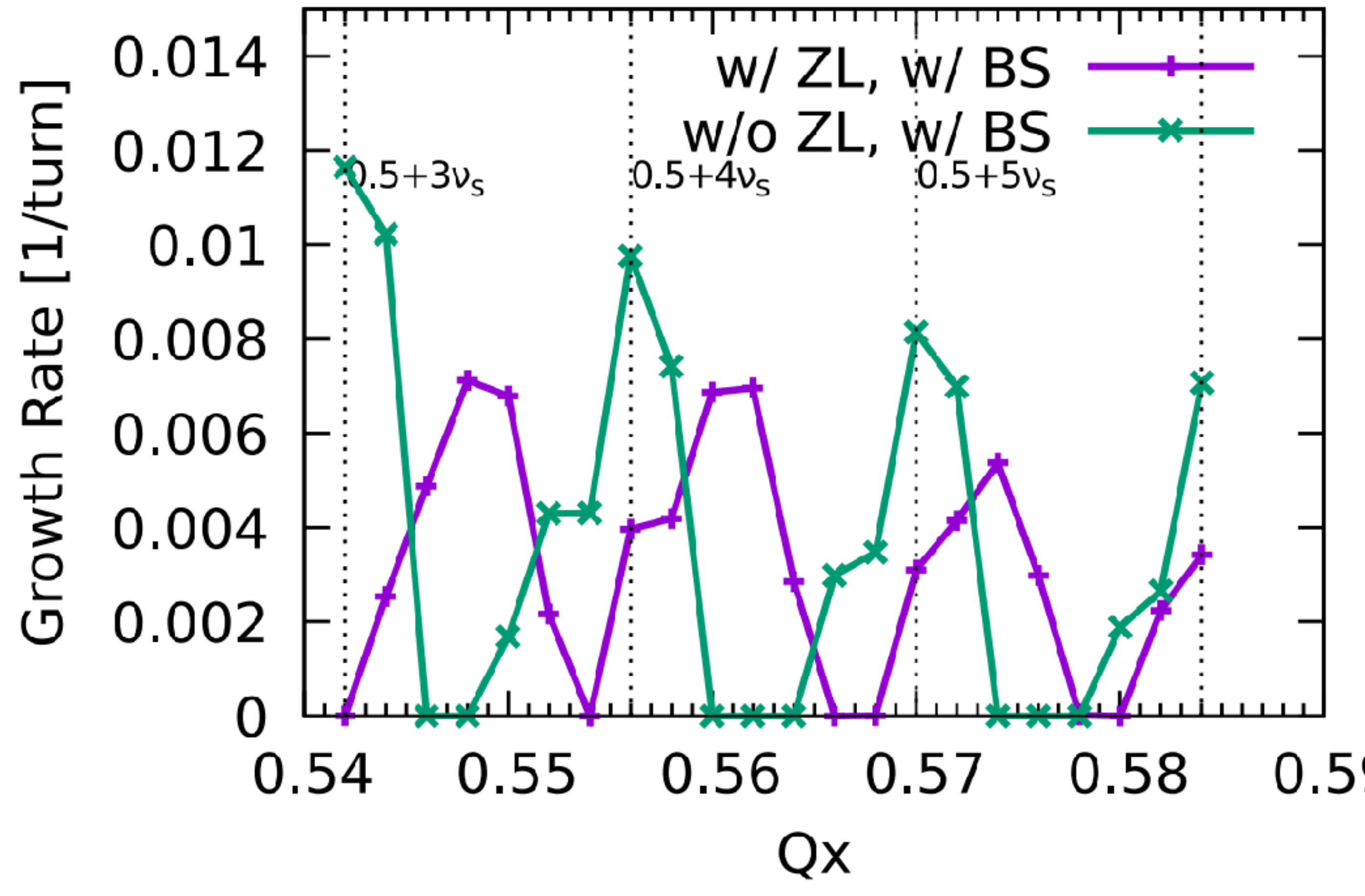
D. Zhou et al., PRAB 26, 071001 (2023)

Beam-beam effects in crab-waist colliders

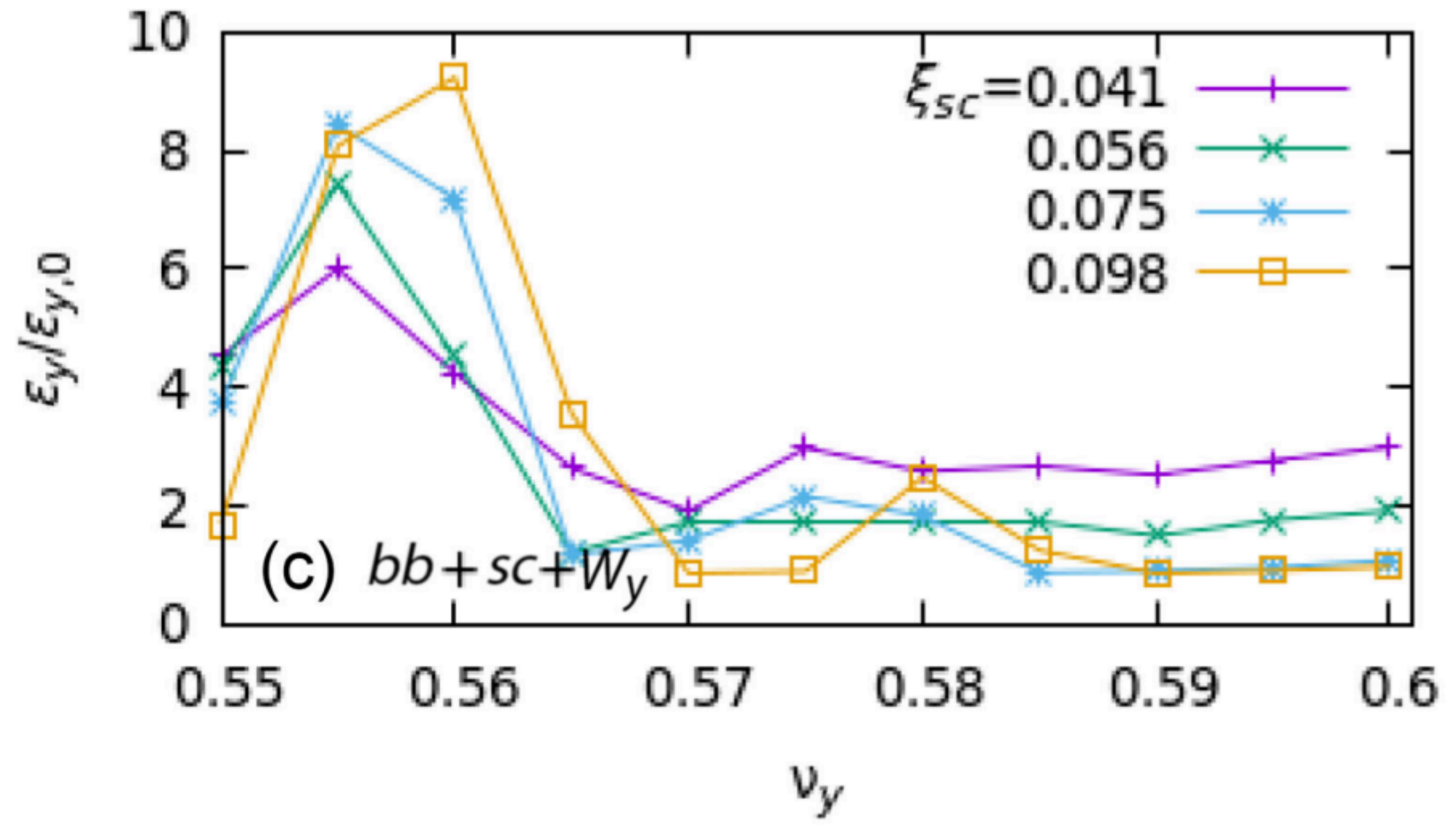
- Key beam-beam phenomena (X-Z instability, Y-Z instability, synchro-betatron resonances, etc.)



K. Ohmi et al., PRL 119, 134801 (2017)



Y. Zhang et al., PRAB 23, 104402 (2020)



K. Ohmi et al., PRAB 27, 101001 (2024)

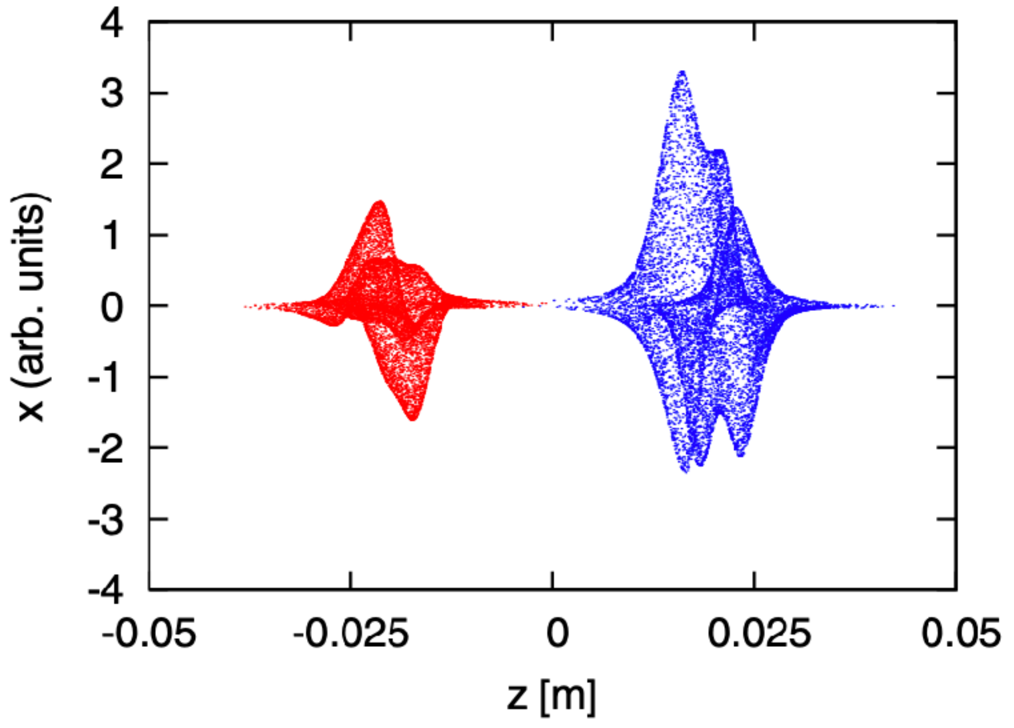
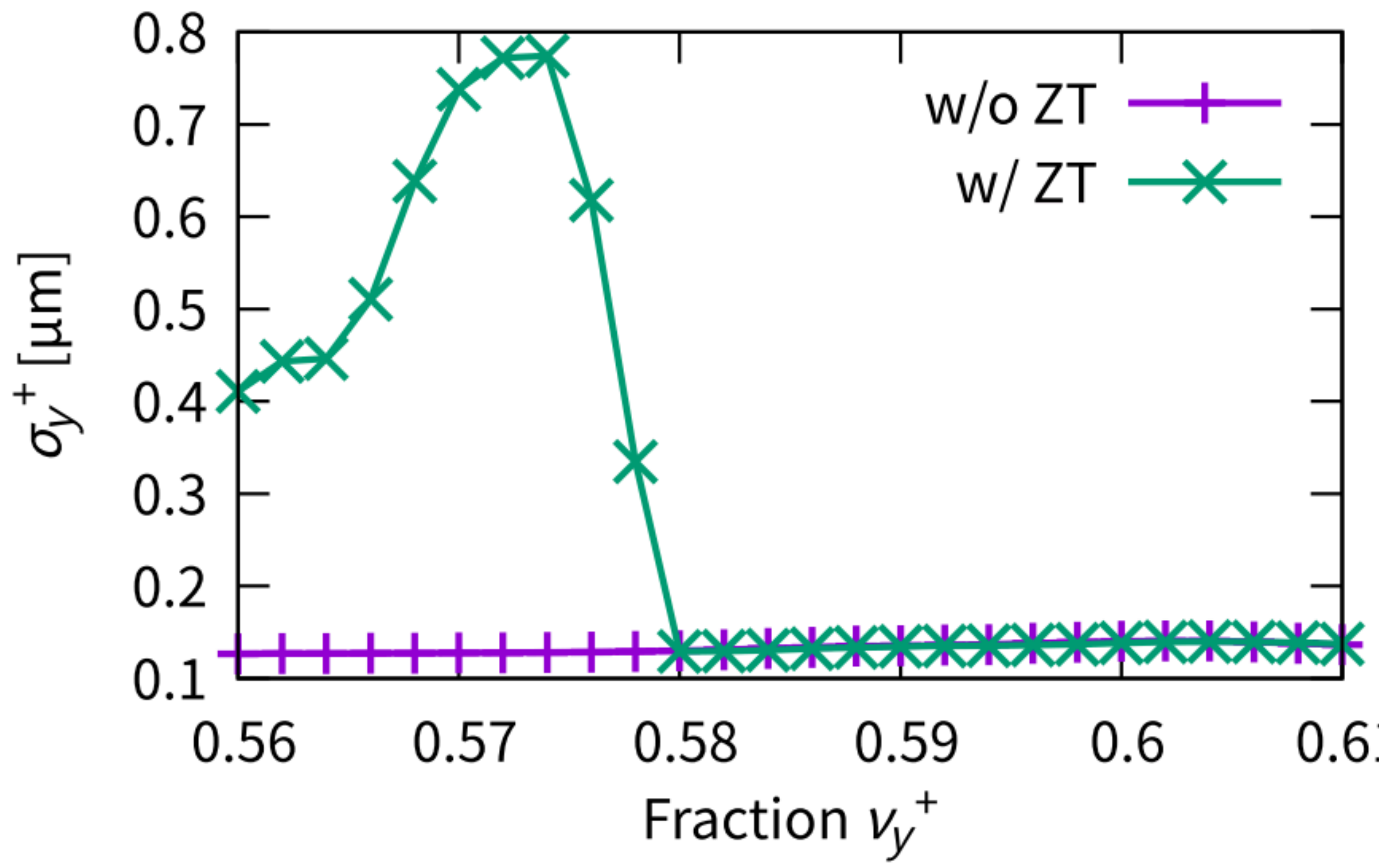
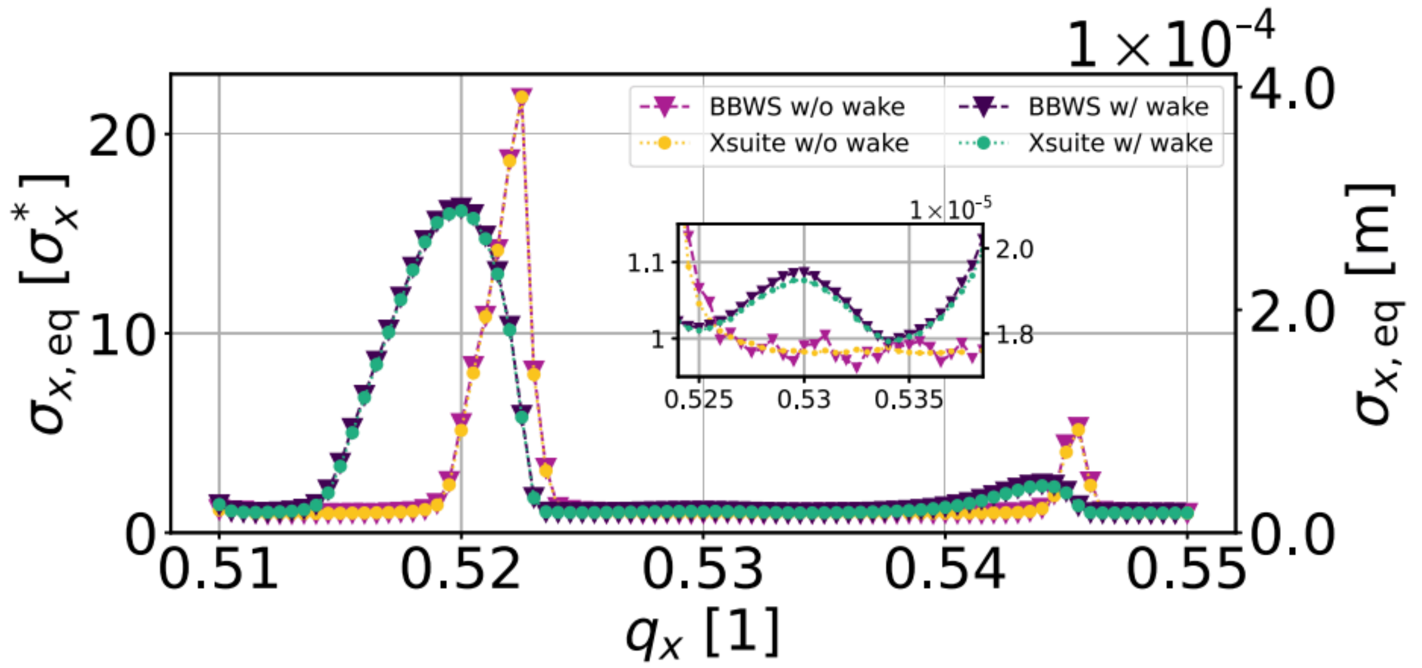


FIG. 11. Beam distribution in the $x-z$ plane at the collision point for $\nu_x^{(-)} = 0.57$ and $\nu_x^{(+)} = 0.53$ (SuperKEKB), where $\theta_P = 8$, $\xi_x^{(+)} = 0.0174$, $\xi_x^{(-)} = 0.0099$, $\nu_z^{(+)} = 0.0244$, and $\nu_z^{(-)} = 0.028$.

N. Kuroo et al., PRAB 21, 031002 (2018)



Y. Zhang et al., PRAB 26, 064401 (2023)



P. Kicsiny et al., PRAB 28, 051002 (2025)

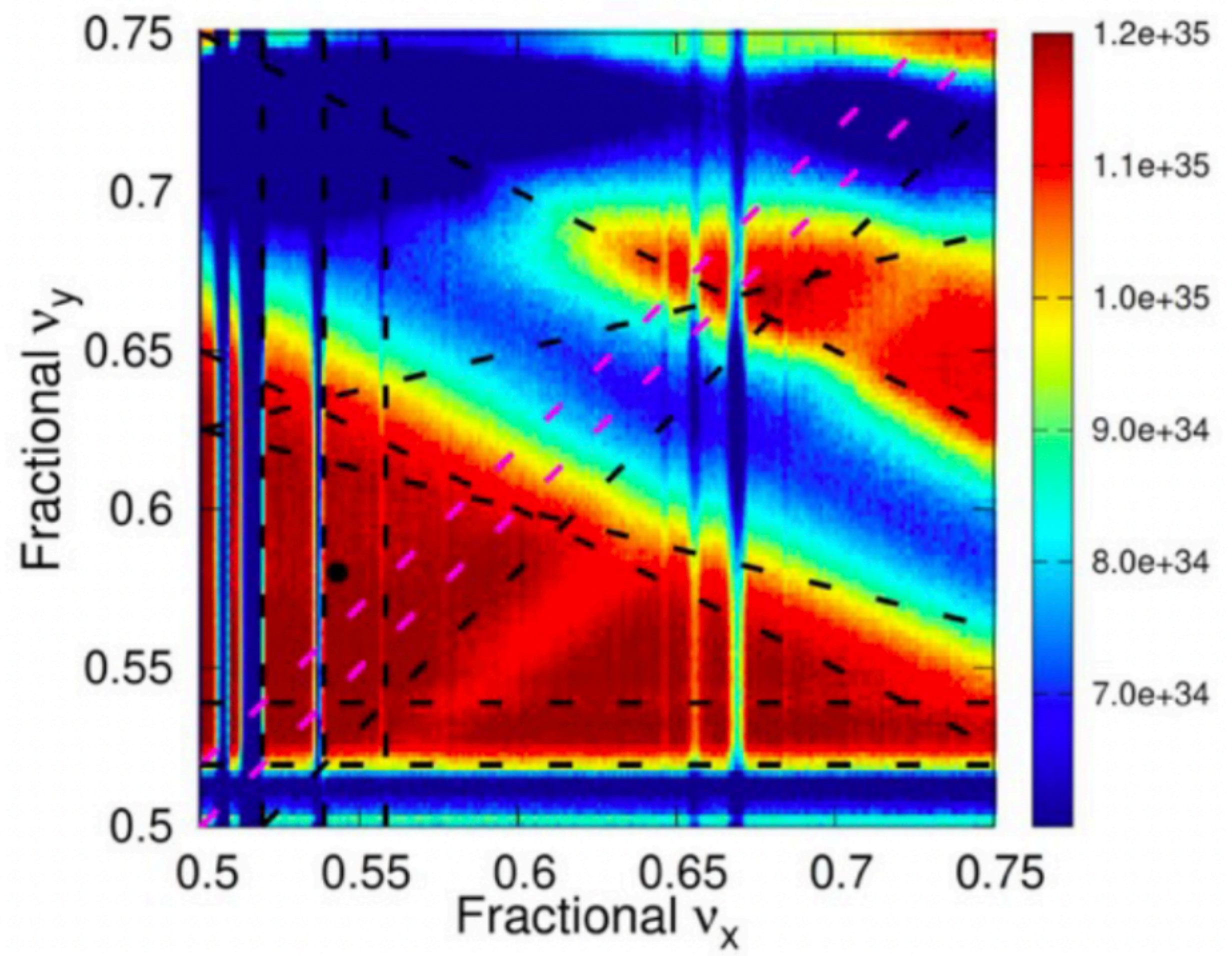
Beam-beam effects in crab-waist colliders

- Implications for STCF parameter regime (The machine design must ensure that the target luminosity is achievable)
  - Beam-beam limit: $\xi_y \approx \xi_y^L \lesssim 0.1$ (account for multi-physics phenomena beyond pure BB effects)
  - Hourglass effects $\zeta_x = \sigma_x^* / (\beta_y^* \tan(2\theta)) \lesssim 0.5$ (smaller ζ_x is desirable but challenging IR optics)
  - Synchro-betatron resonances and coherent X-Z instability: $\nu_s / \xi_x > 3$ (larger ν_s / ξ_x is desirable but challenging ring optics)
  - Horizontal tune: $0.5 + k\nu_s < [\nu_x] < 0.5 + (k+1)\nu_s$ with $k = 2$ or 3 (to be validated via simulations)

$$\xi_x = \frac{N_p r_e \beta_x^*}{2\pi\gamma\sigma_x^{*2}(1+\phi^2)} \approx \frac{N_p r_e \beta_x^*}{2\pi\gamma\sigma_z^2\theta^2}$$

$$\xi_y = \frac{N_p r_e \beta_y^*}{2\pi\gamma\sigma_x^*\sigma_y^*\sqrt{1+\phi^2}} \approx \frac{N_p r_e \beta_y^*}{2\pi\gamma\sigma_y^*\sigma_z\theta}$$

$$L = \frac{\gamma I}{2 e r_e \beta_y^*}\xi_y^L$$

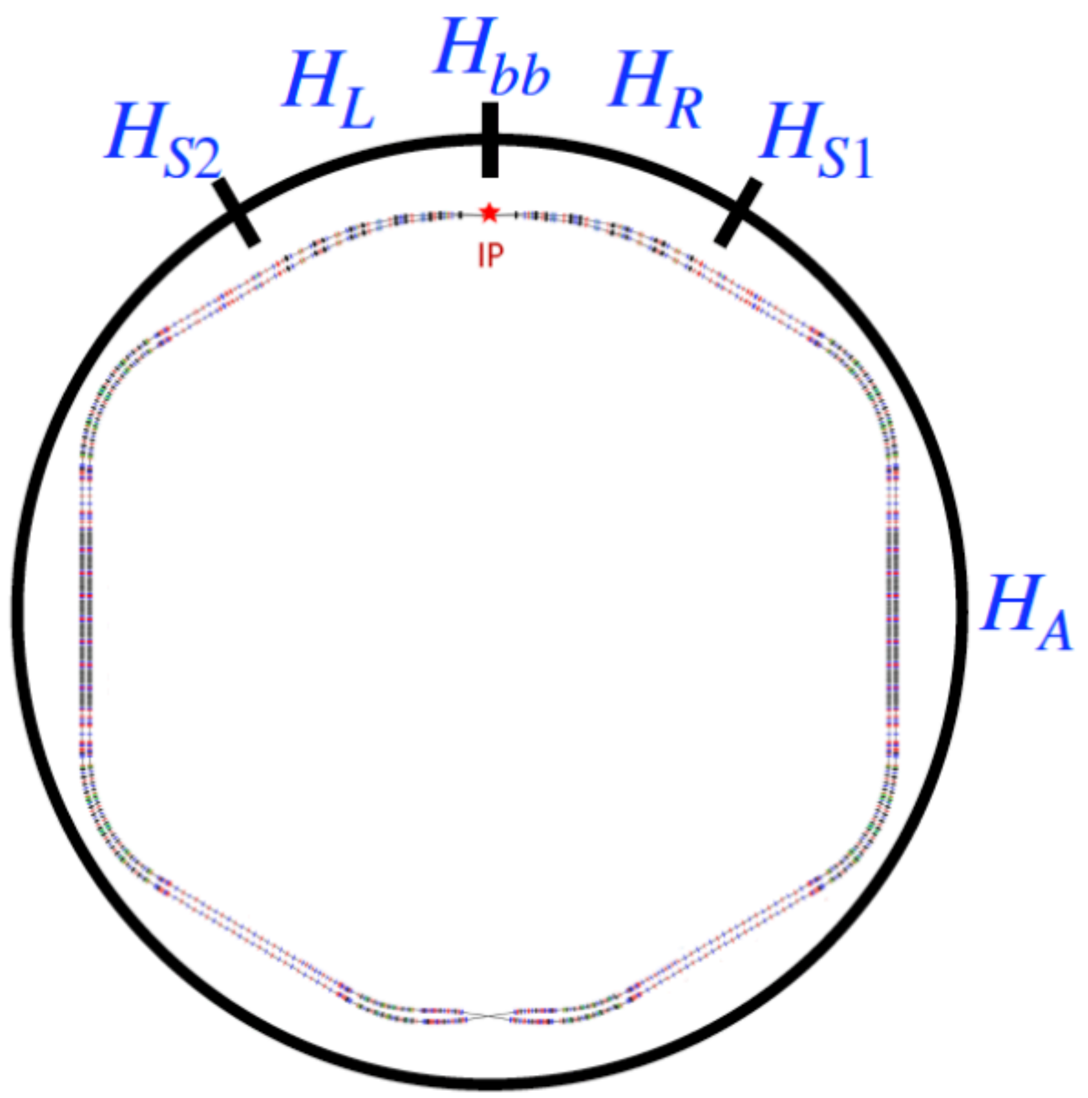


Weak-strong tune scan for STCF

See Y. Zou, L. Zhang, T. Liu's talks on optics design/optimizations

Beam-beam simulation framework for STCF

- Weak-strong model + simple one-turn map: BBWS
  - Incoherent beam-beam effects
- Weak-strong model + full lattice: SAD code
  - Interplay of beam-beam interactions and full lattices (Incoherent effects)
- Strong-strong model + simple one-turn map: BBSS
  - Coherent X-Z and Y-Z instabilities with wakefields
- Strong-strong model + full lattices: BBSCL (old STCR) code
  - Interplay of multiple physical processes (incoherent and coherent effects)
- The codes BBWS/BBSS/BBSCL were developed by K. Ohmi



- Model of a CW collider ring
  - In terms of Lie maps, the one-turn map is

$$M = e^{-:H_R:}e^{-:H_{S1}:}e^{-:H_A:}e^{-:H_{S2}:}e^{-:H_L:}e^{-:H_{bb}:}$$

  - Sequence of elements:
    - H_R, H_L: right and left side of IR
    - H_{S1}, H_{S2}: first and second CW sextupole
    - H_A: arc and straight sections
    - H_{bb}: beam-beam kick at IP
  - The one-turn map of an ideal CW collider ring is

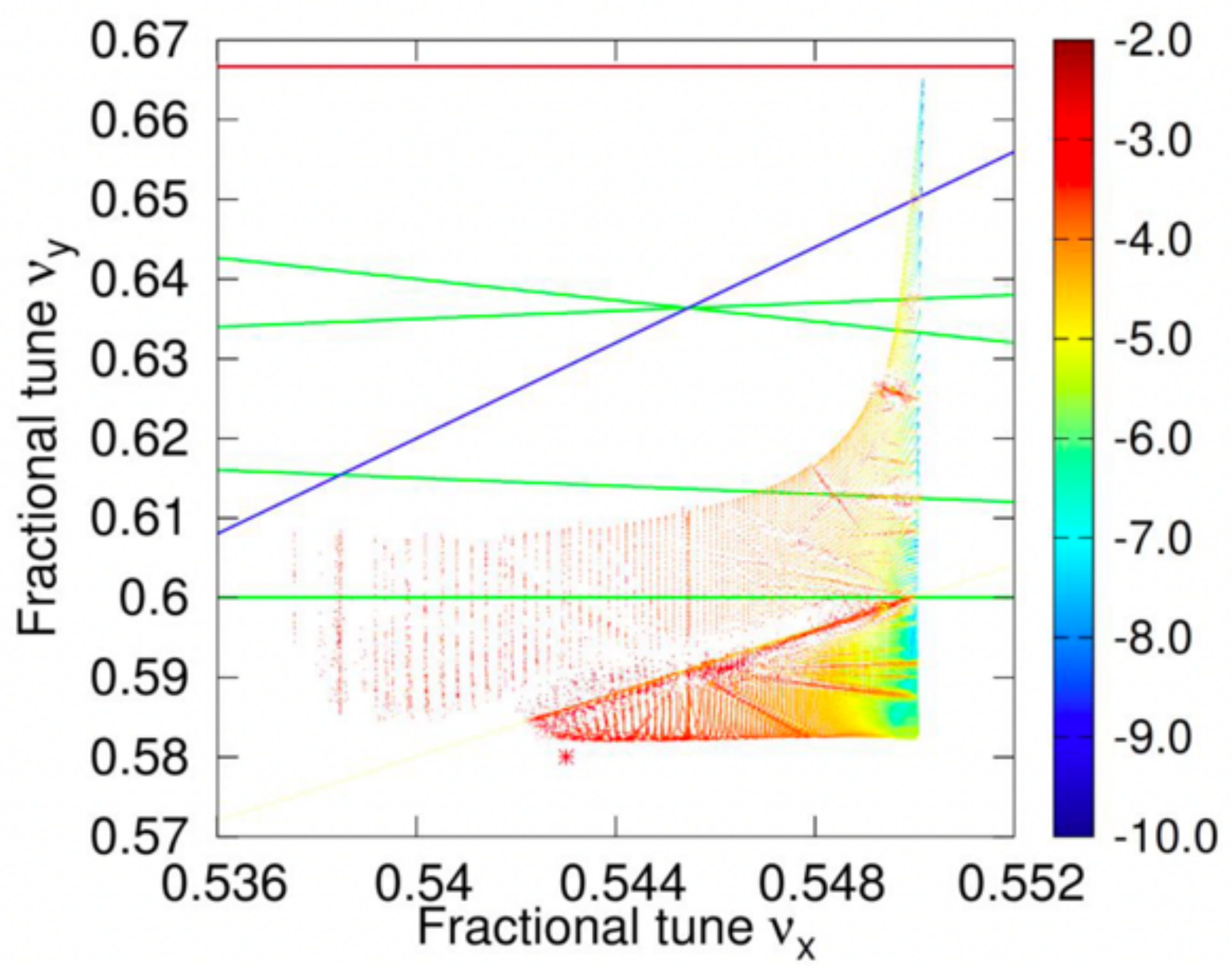
$$M_i = e^{-:H_0:}e^{-:H_{cw}:}e^{-:H_{bb}:}e^{:H_{cw}:} \qquad H_{cw} = \frac{\chi}{2\tan(2\theta_c)}xp_y^2$$

    - χ=1 for full CW strength
    - H_0 is determined only by $\beta^*_{x,y,z}$ and $\nu_{x,y,z}$

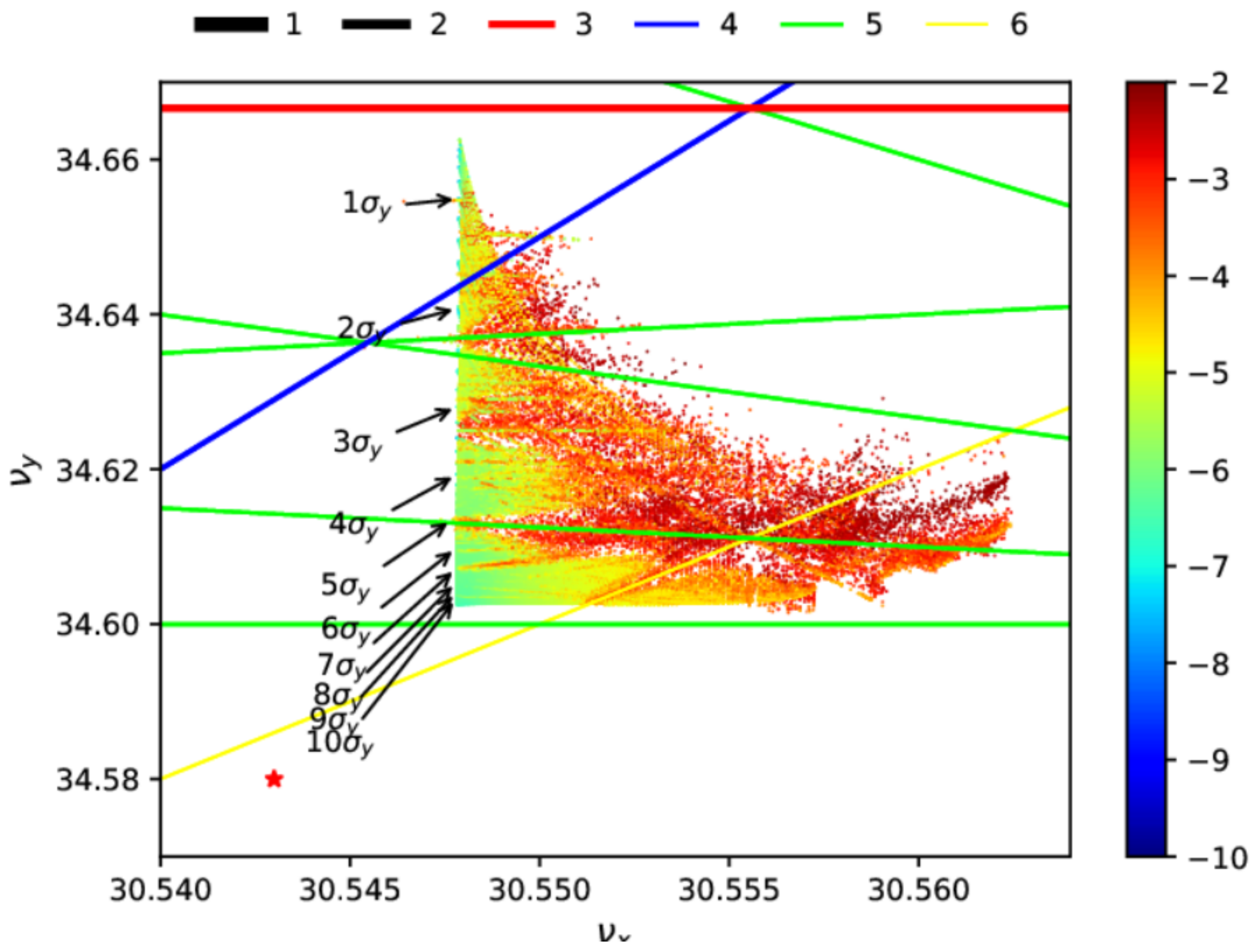
Beam-beam simulation results for STCF (2 GeV)

- Weak-strong simulations using BBWS
  - Tune scan to identify beam-beam resonances and choose optimal working point
- Weak-strong simulations using SAD
  - Interplay of beam-beam and lattice resonances
  - Evaluation/optimization of dynamic aperture and lifetime (see T. Liu's talk)

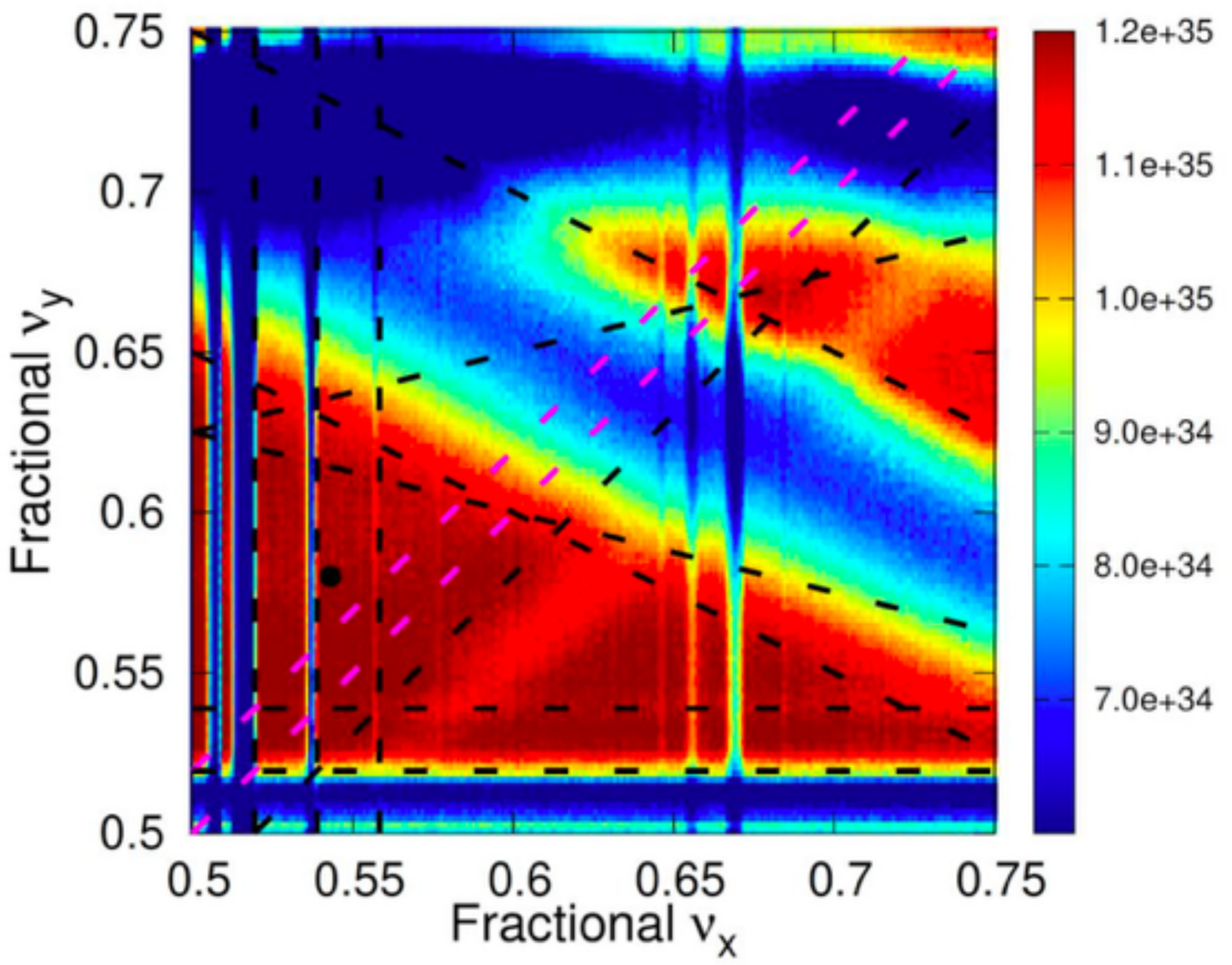
Tune footprint with $\partial \nu_{x,y} / \partial J_{x,y} < 0$



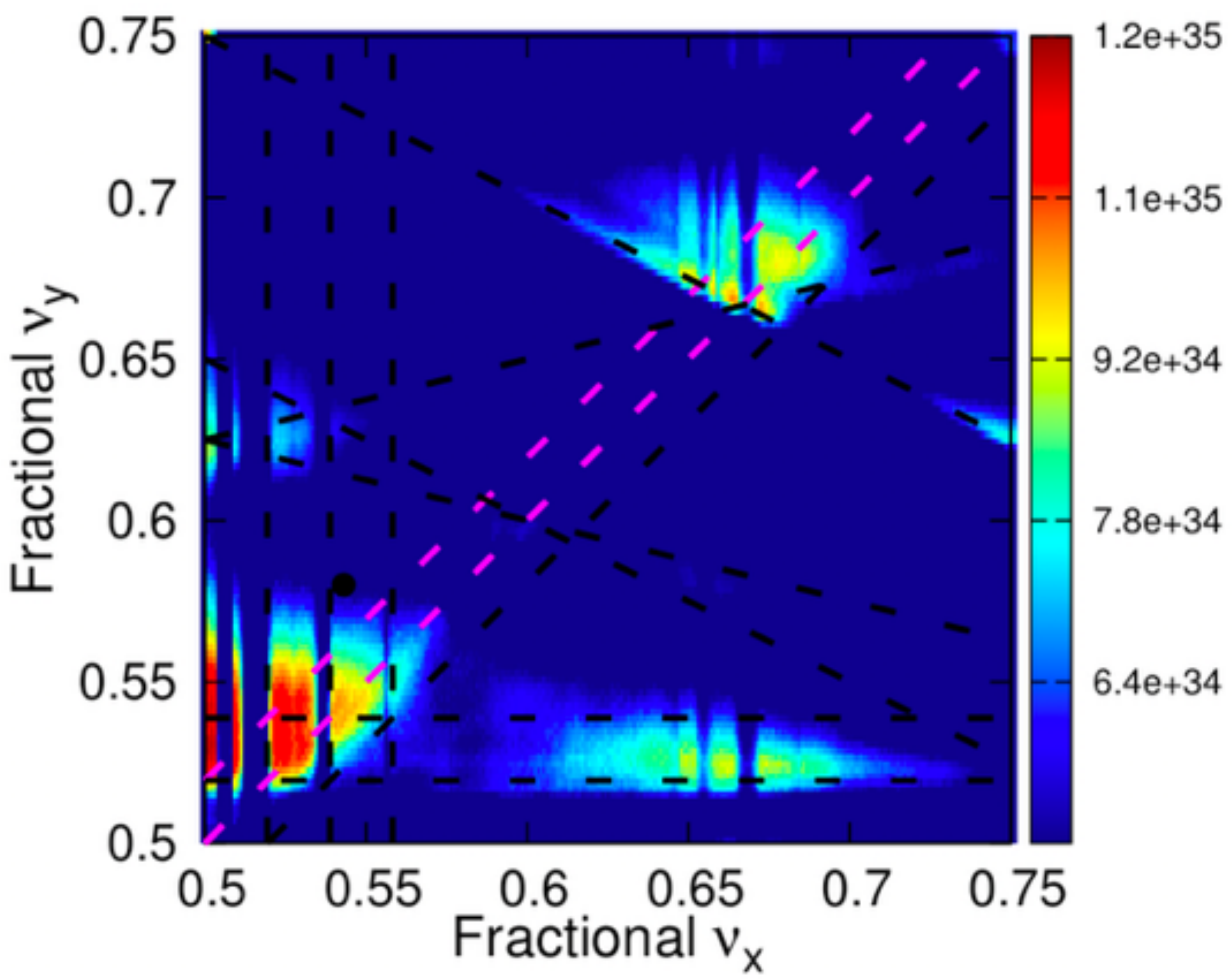
Tune footprint with $\partial \nu_{x,y} / \partial J_{x,y} > 0$



w/ crab waist



w/o crab waist

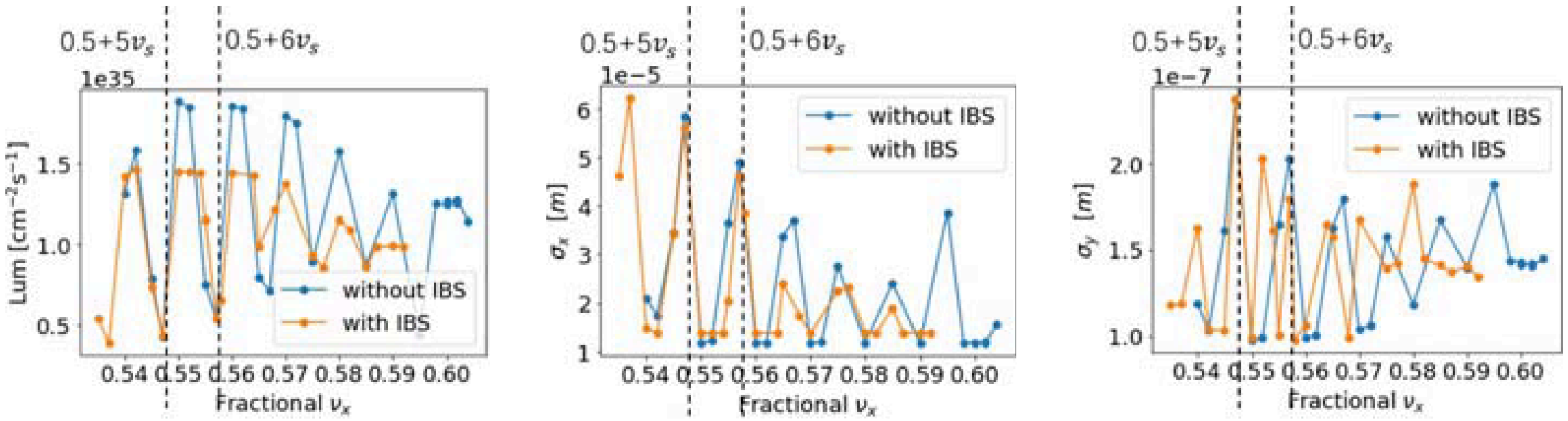


Courtesy of T. Liu

Beam-beam simulation results for STCF (2 GeV)

- Strong-strong simulations using BBSS/IBB
  - Parameter optimizations [ν_s: 0.01→0.02, β_x^*: 60 mm→40 mm (see Y. Zou's talk)] accounting for X-Z instability (and MWI/TMCI)
  - Interplay of beam-beam and impedance effects (see T. He's talk on collective effects)

Strong-strong simulations with ν_s=0.0096

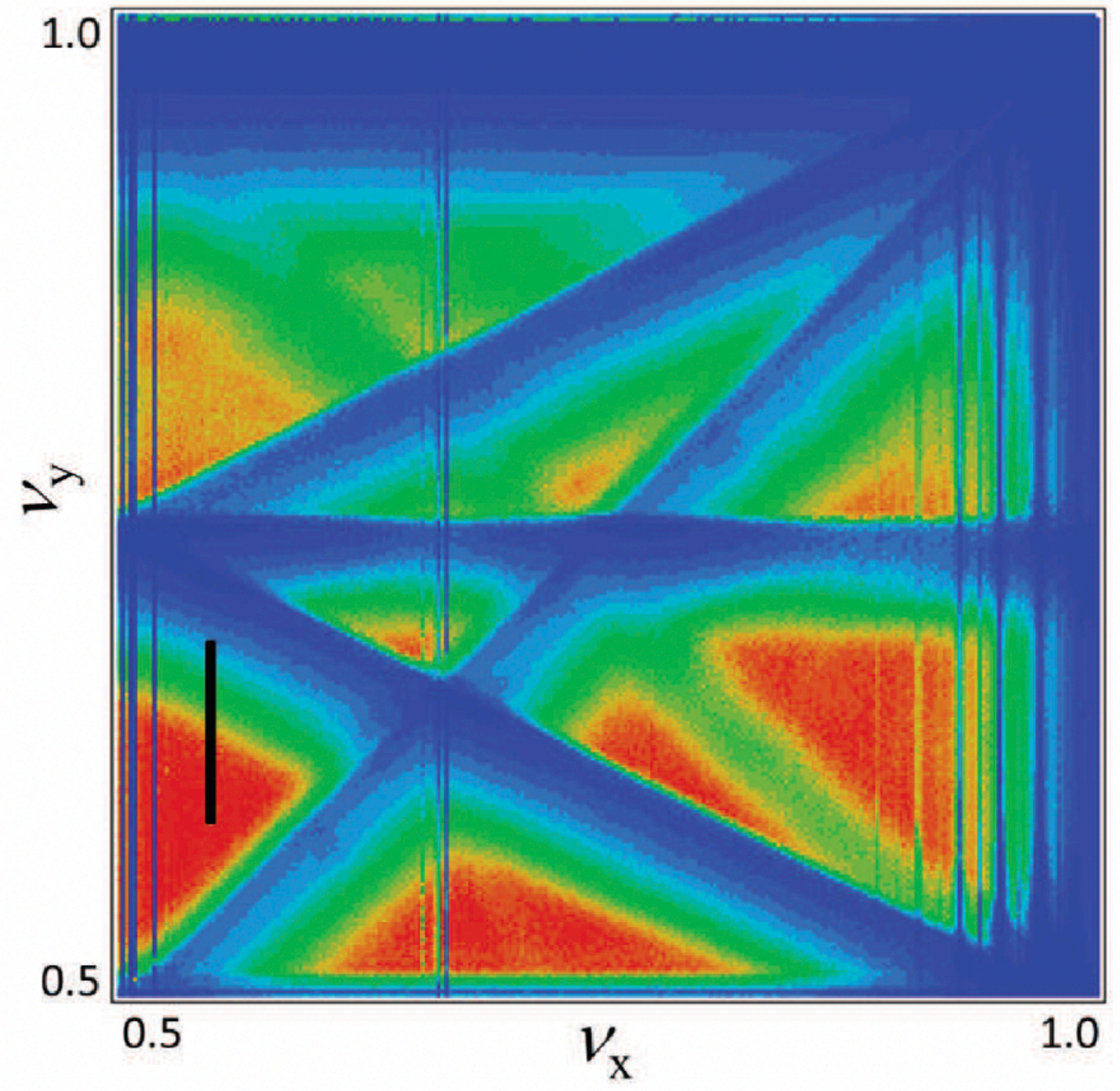


(a) Luminosity (b) Horizontal $\sigma_x{}^*$ (c) Vertical $\sigma_y{}^*$

S. Li et al., MPLA Vol. 39, No. 40 (2024) 2440013

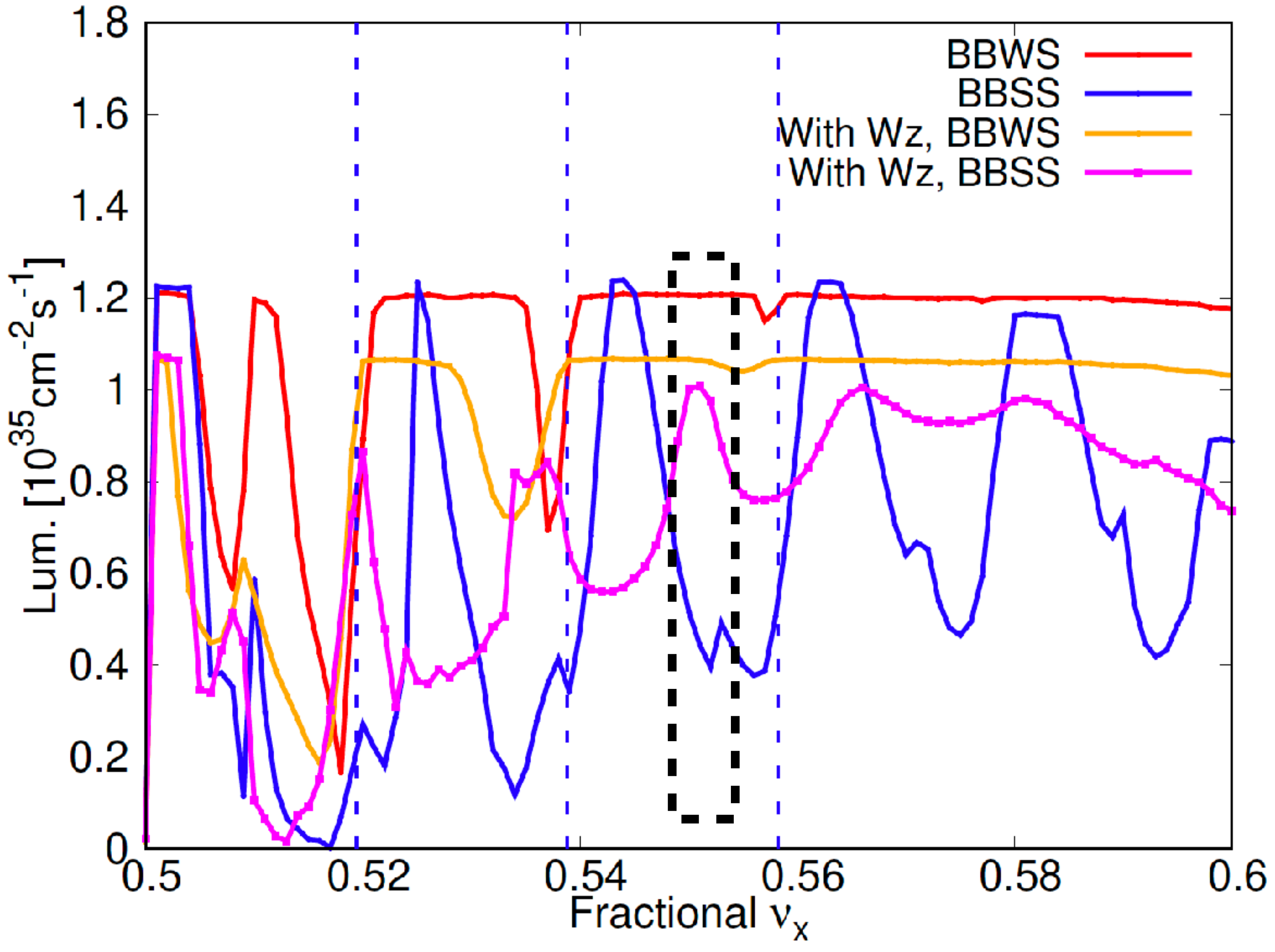
Beam-beam simulation results for STCF (2 GeV)

- Strong-strong simulations with longitudinal impedance using BBSS
  - BBR impedance model used
  - Difficult to operate the machine with $[\nu_x] < 0.5 + 2\nu_s$
  - Maximizing the tune space for good luminosity is preferred from machine operation viewpoint

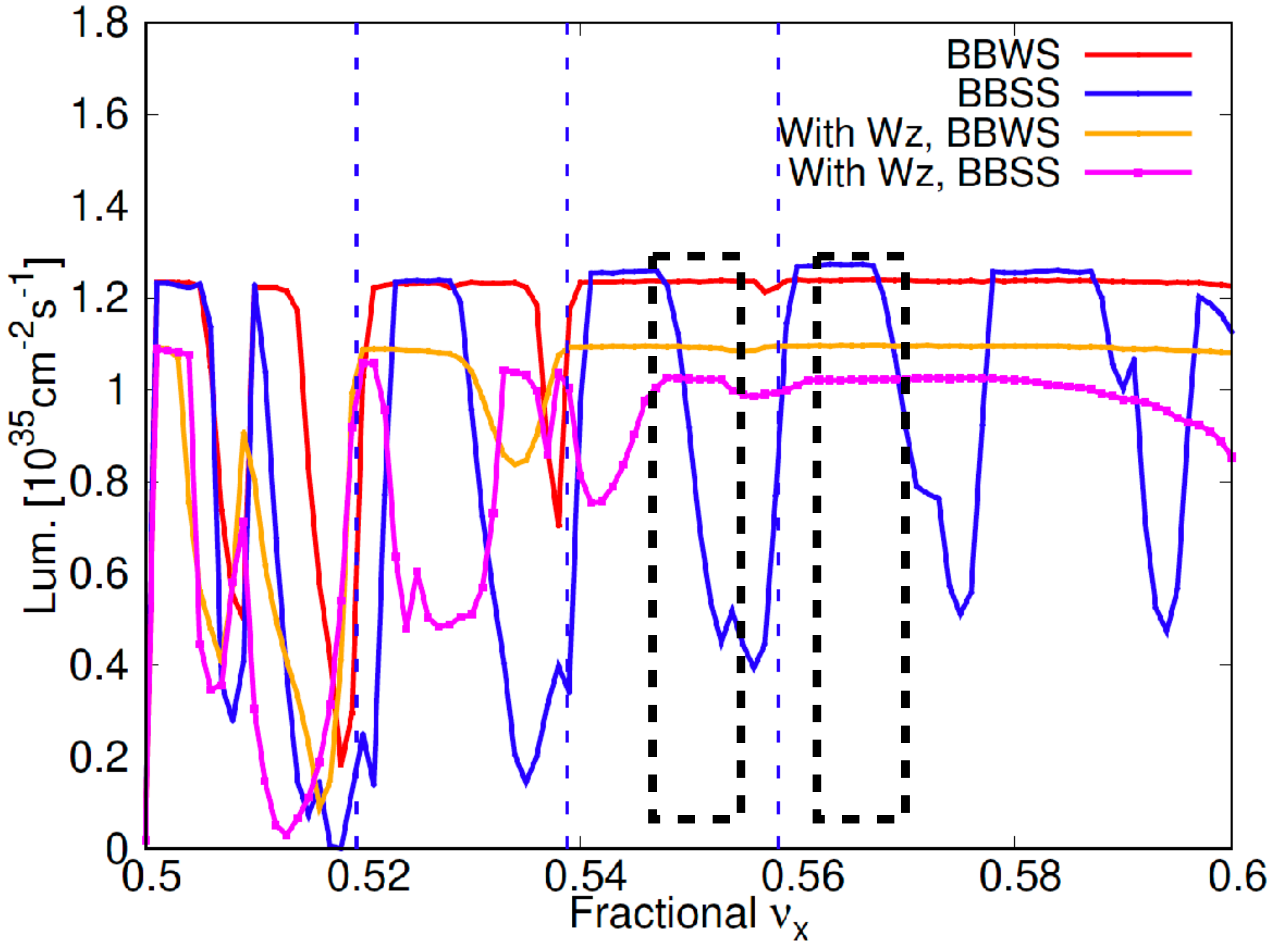


D. Shatilov, Handbook

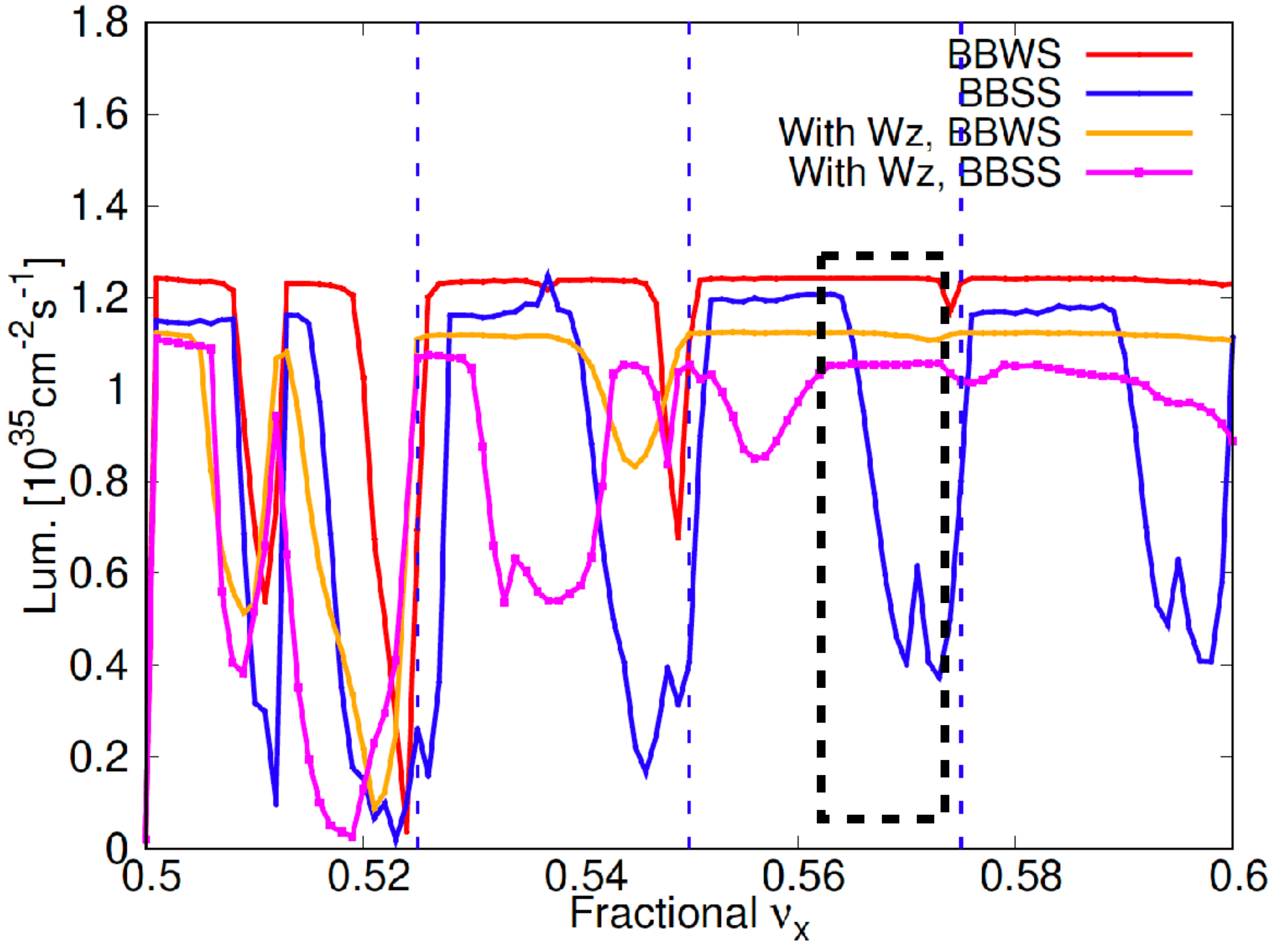
Specific luminosity vs. ν_x (β_x^*=60 mm, ν_s=0.0194)



Specific luminosity vs. ν_x (β_x^*=40 mm, ν_s=0.0194)



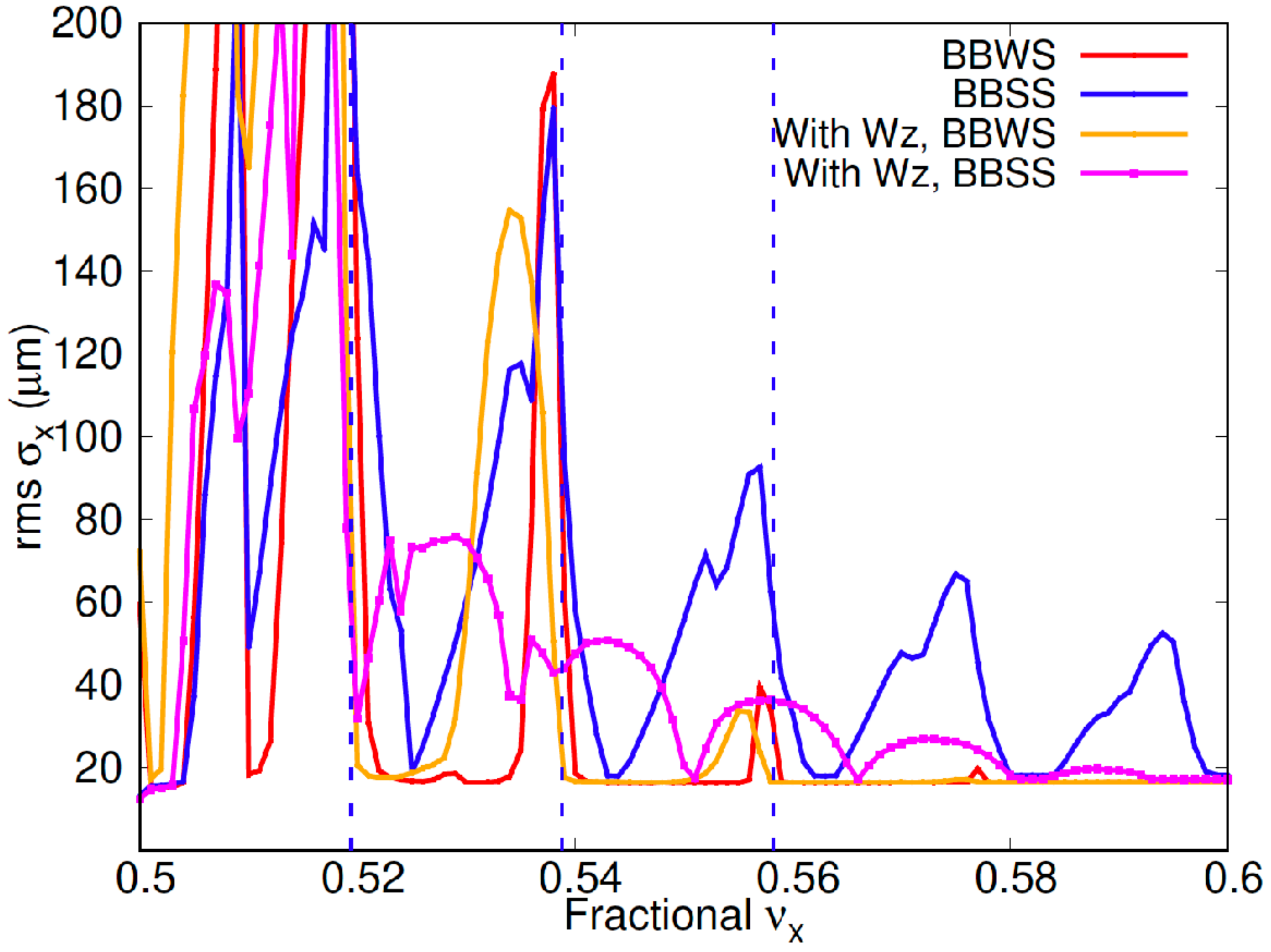
Specific luminosity vs. ν_x (β_x^*=40 mm, ν_s=0.025)



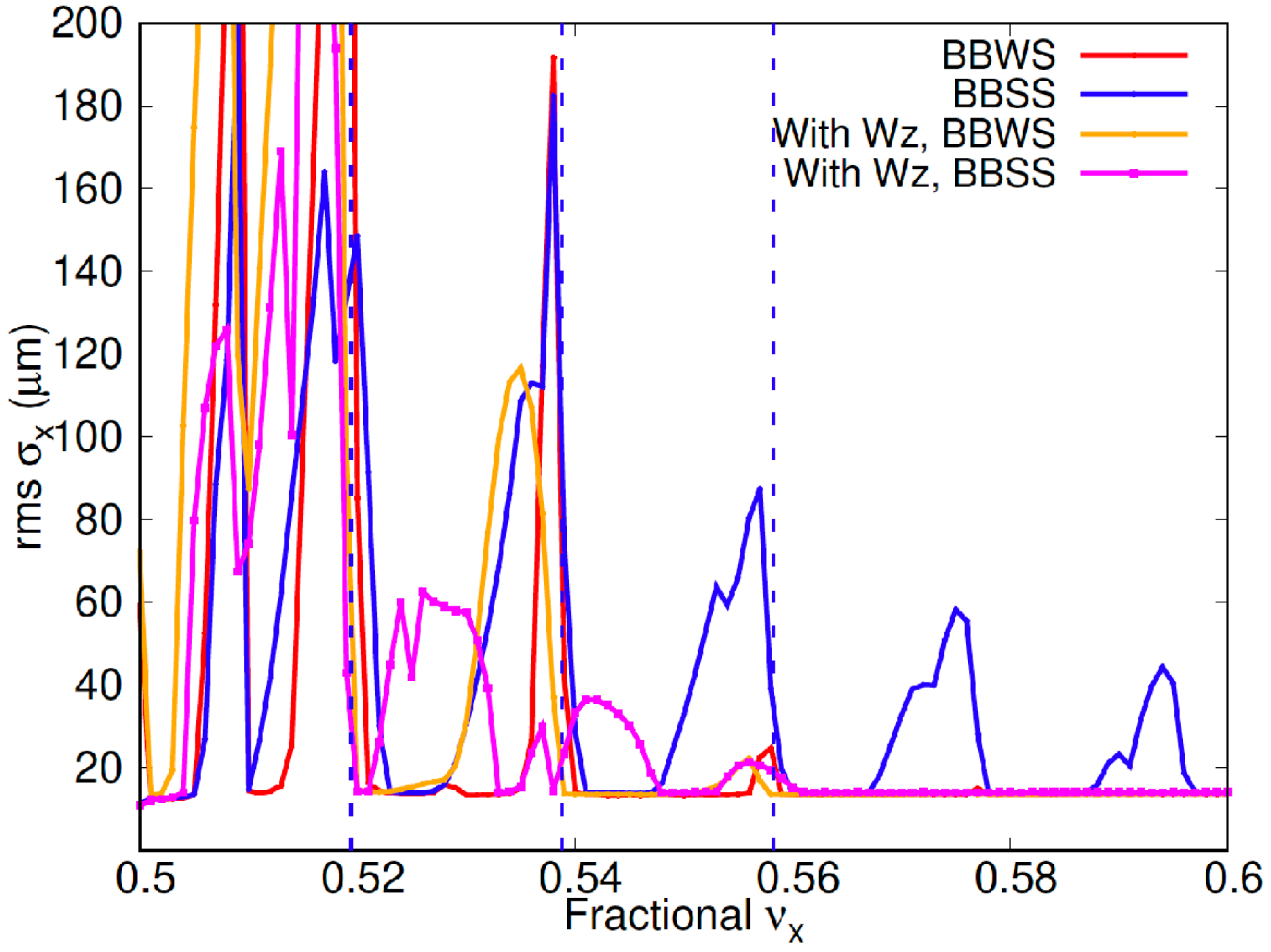
Beam-beam simulation results for STCF (2 GeV)

- Strong-strong simulations with longitudinal impedance using BBSS
  - Impedance effects shift the X-Z instability "peaks" to the left in ν_x axis
  - Impedance effects suppress higher-order X-Z instability through Landau damping

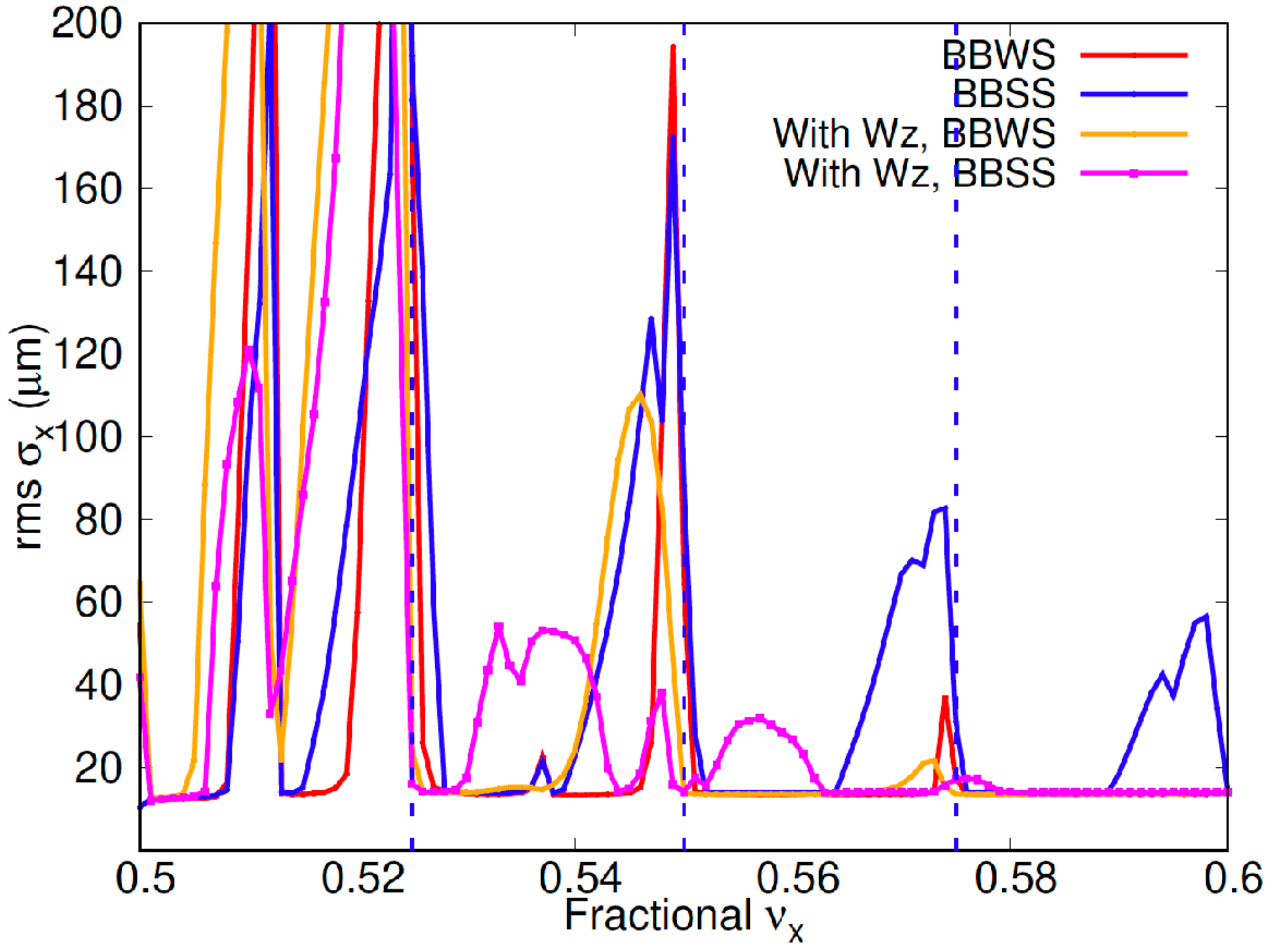
Hor. beam size@IP vs. ν_x (β_x^*=60 mm, ν_s=0.0194)



Hor. beam size@IP vs. ν_x (β_x^*=40 mm, ν_s=0.0194)



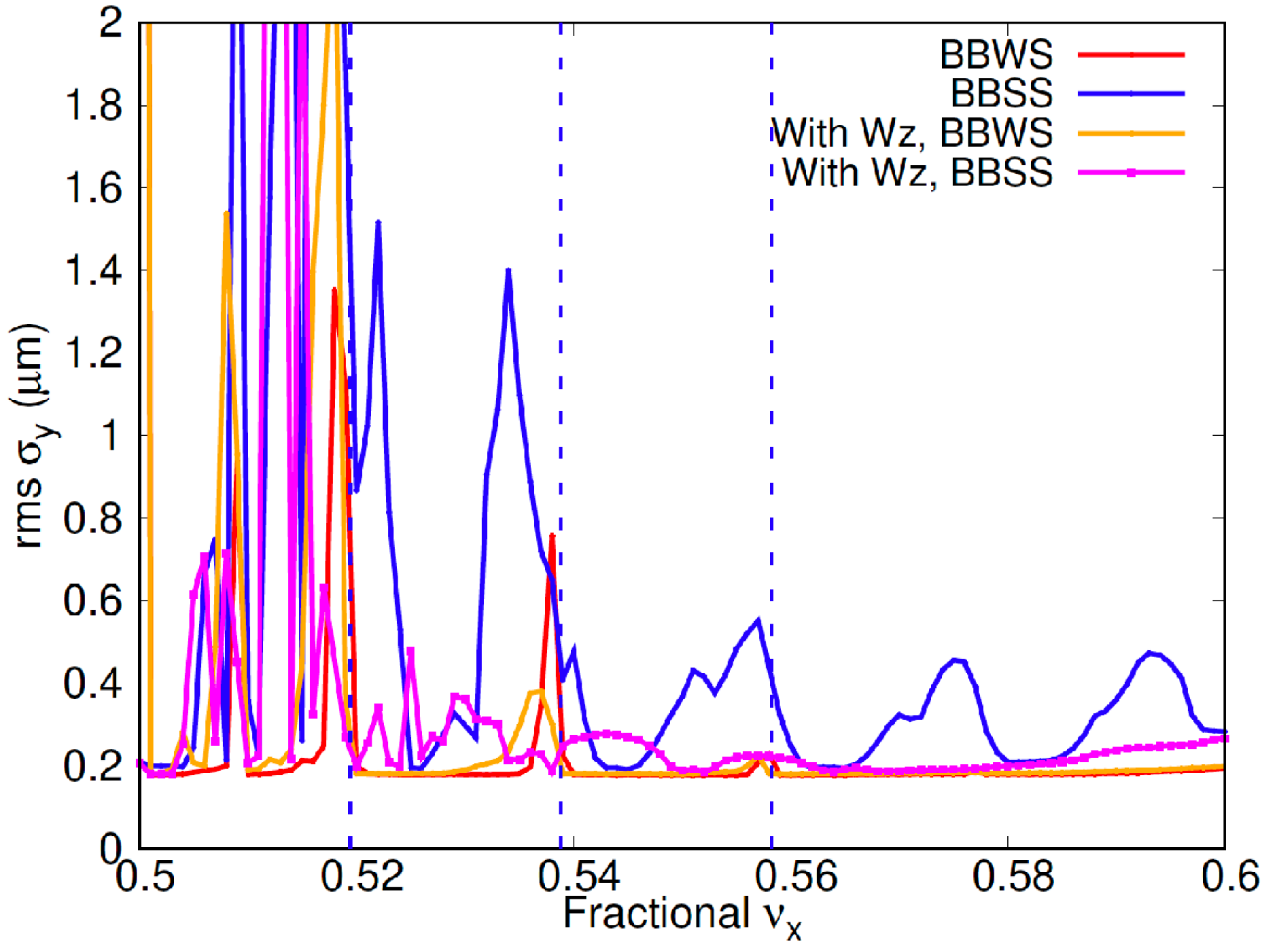
Hor. beam size@IP vs. ν_x (β_x^*=40 mm, ν_s=0.025)



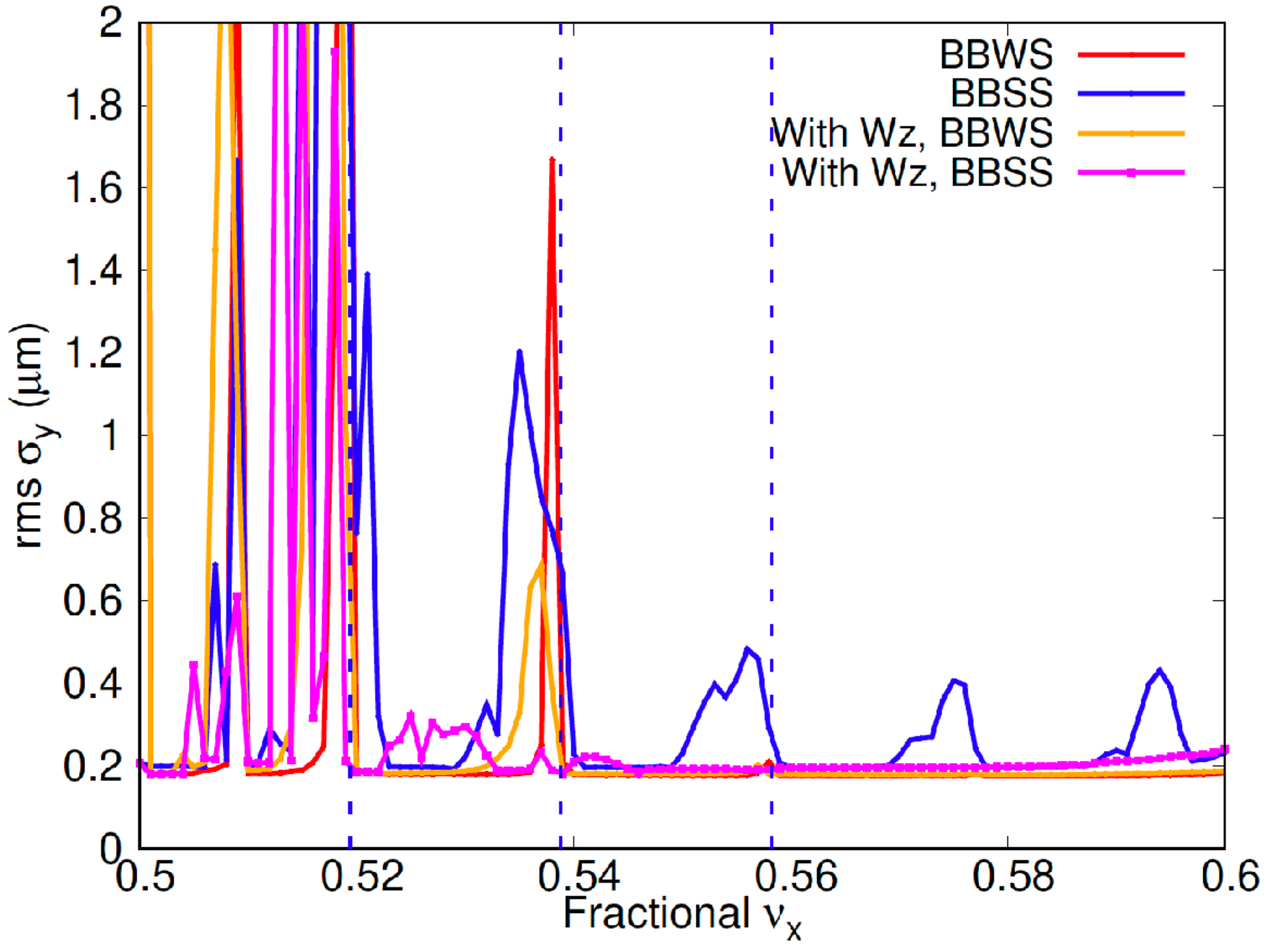
Beam-beam simulation results for STCF (2 GeV)

- Strong-strong simulations with longitudinal impedance using BBSS
  - When X-Z instability appears, σ_y^* also blows up. This suggests that X-Z instability disrupts the crab-waist transformation and must be avoided.

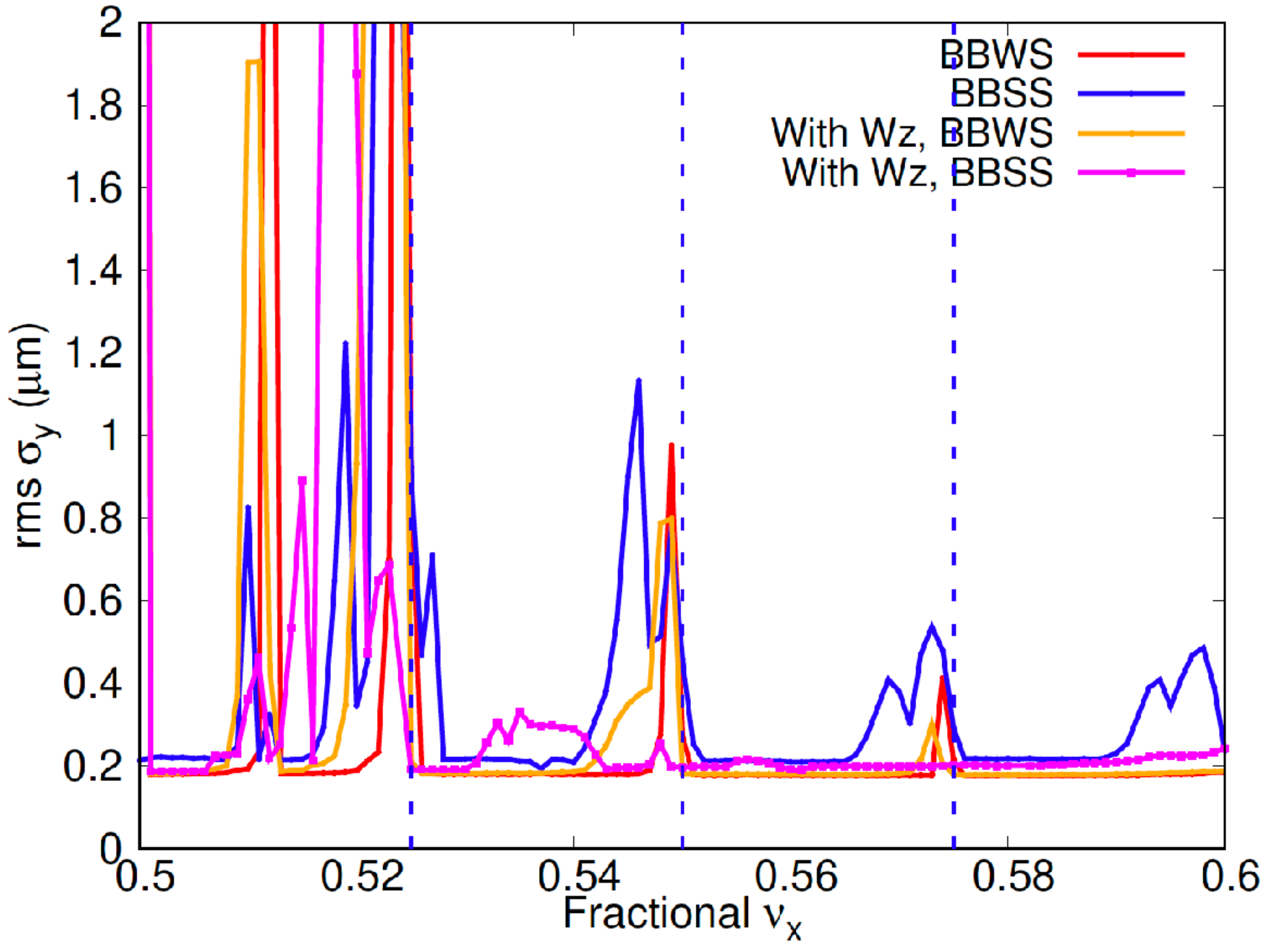
Ver. beam size@IP vs. ν_x
(β_x^*=60 mm, ν_s=0.0194)



Ver. beam size@IP vs. ν_x
(β_x^*=40 mm, ν_s=0.0194)



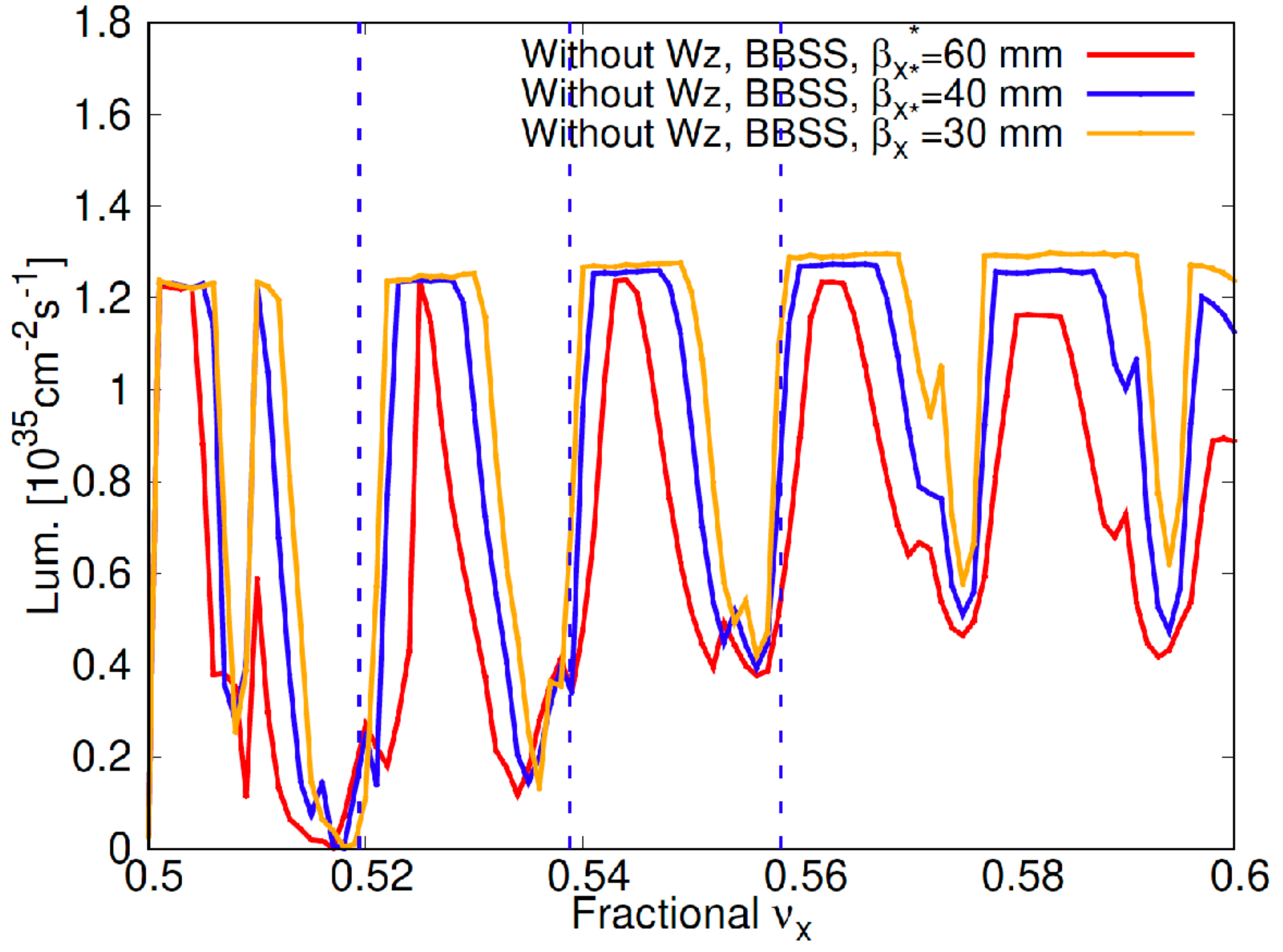
Ver. beam size@IP vs. ν_x
(β_x^*=40 mm, ν_s=0.025)



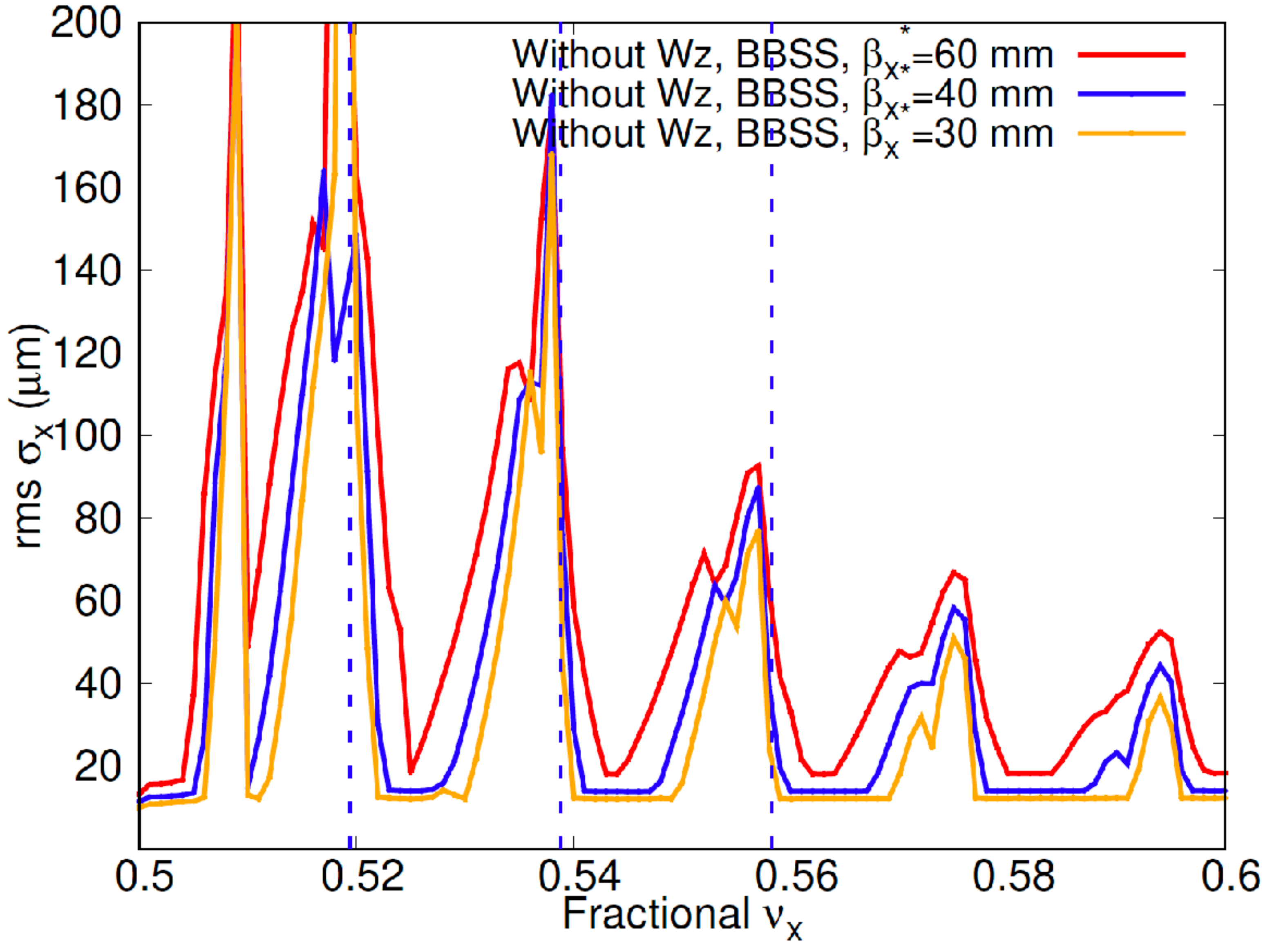
Beam-beam simulation results for STCF (2 GeV)

- BBSS simulations with varied β_x^* (fixed ν_s=0.0194) w/o longitudinal wake
  - Smaller β_x^* leads better performance

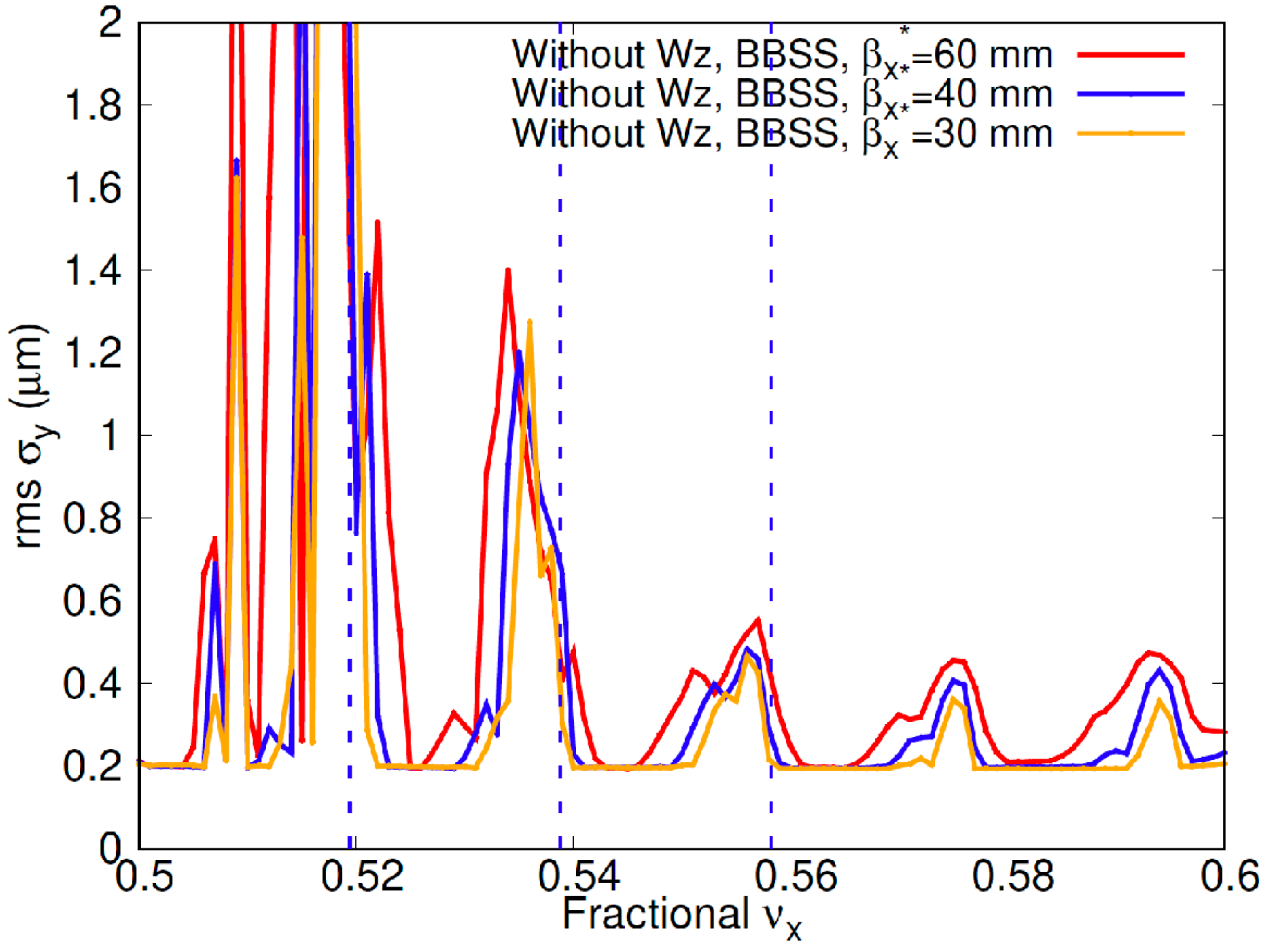
Specific lum. vs. ν_x



σ_x^* vs. ν_x



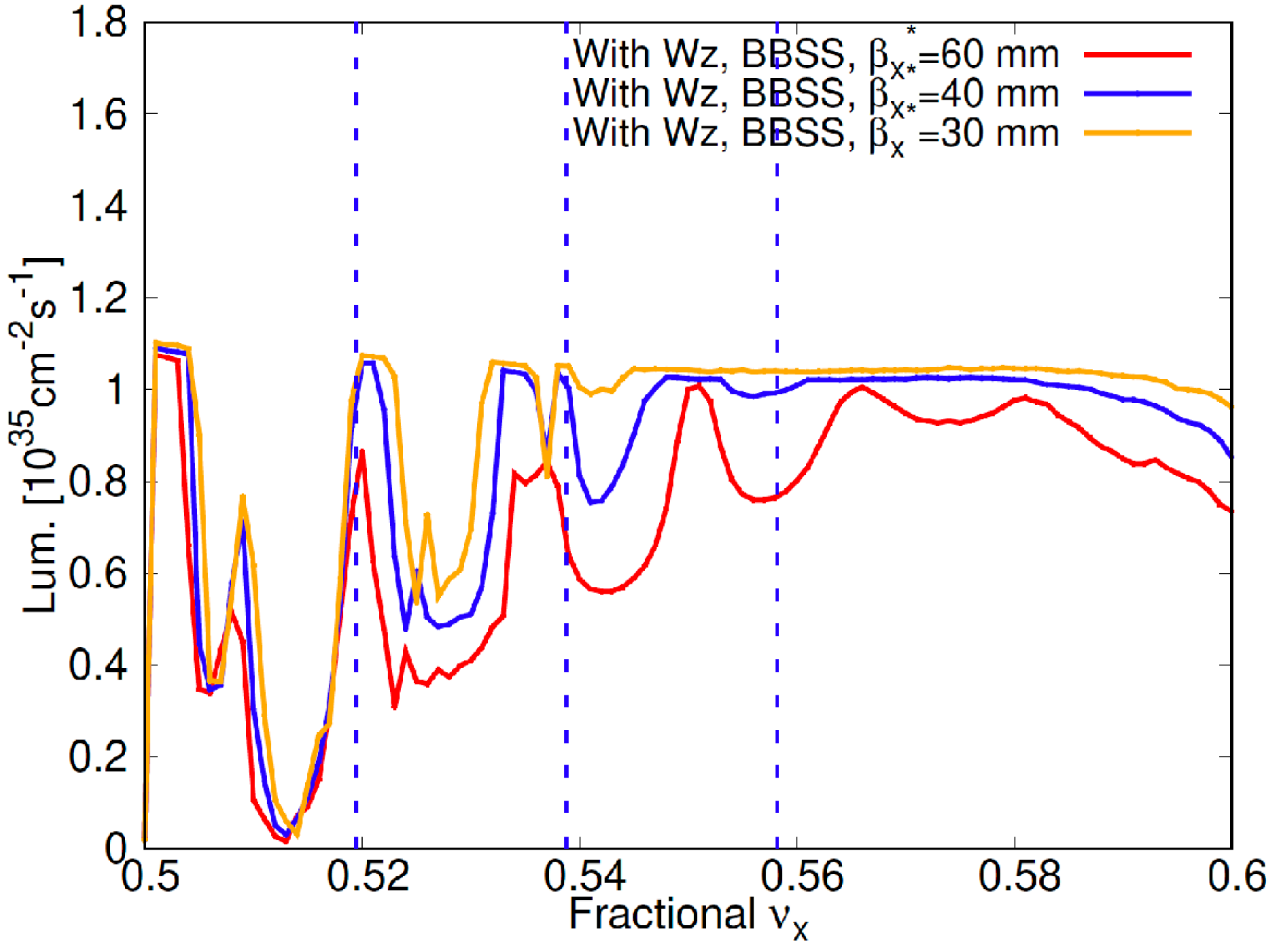
σ_y^* vs. ν_x



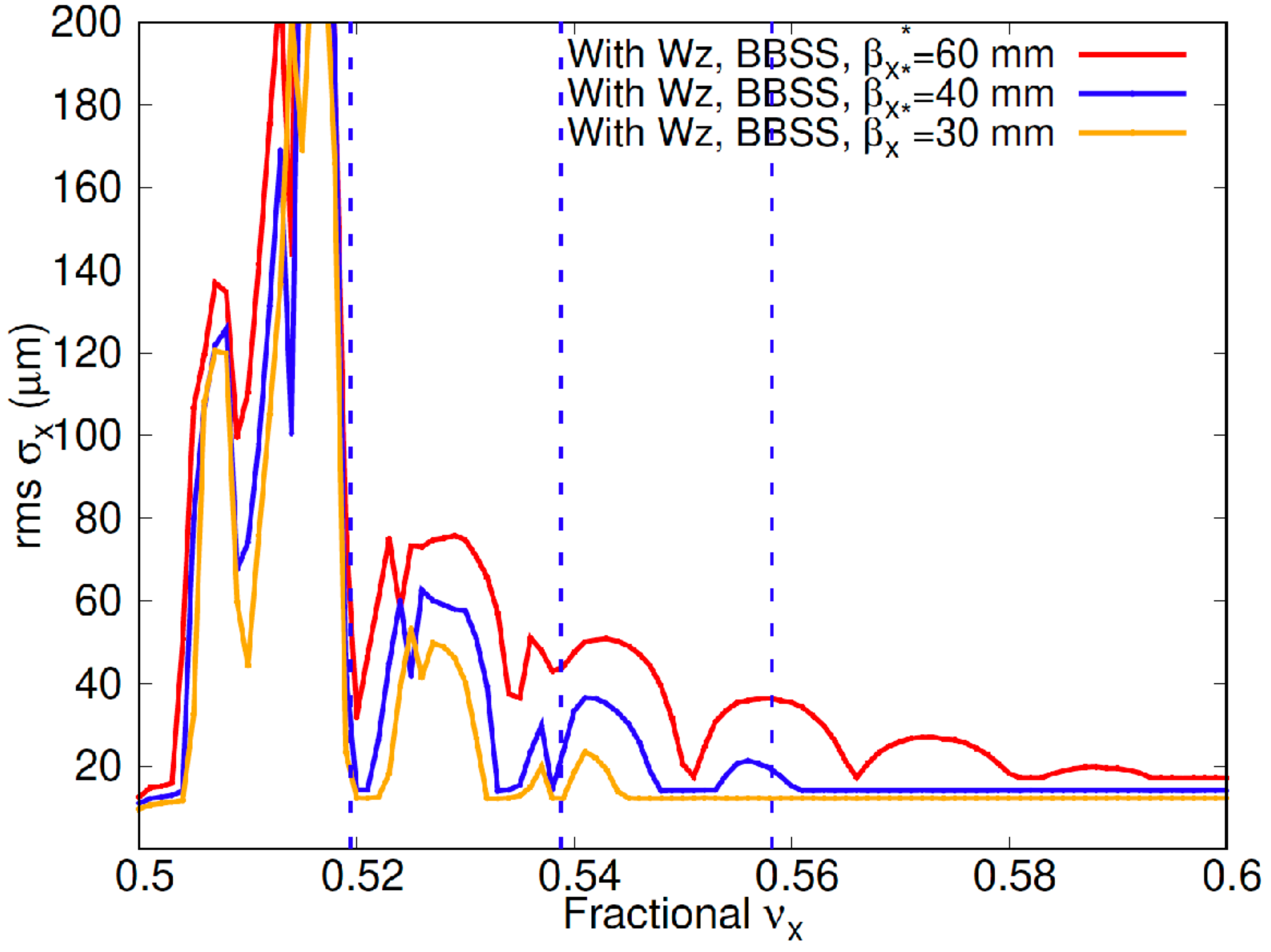
Beam-beam simulation results for STCF (2 GeV)

- BBSS simulations with varied β_x^* (fixed ν_s=0.0194) w/ longitudinal wake
    - Smaller β_x^* leads better performance (Latest STCF V5 lattice adopts β_x^*=40 mm)

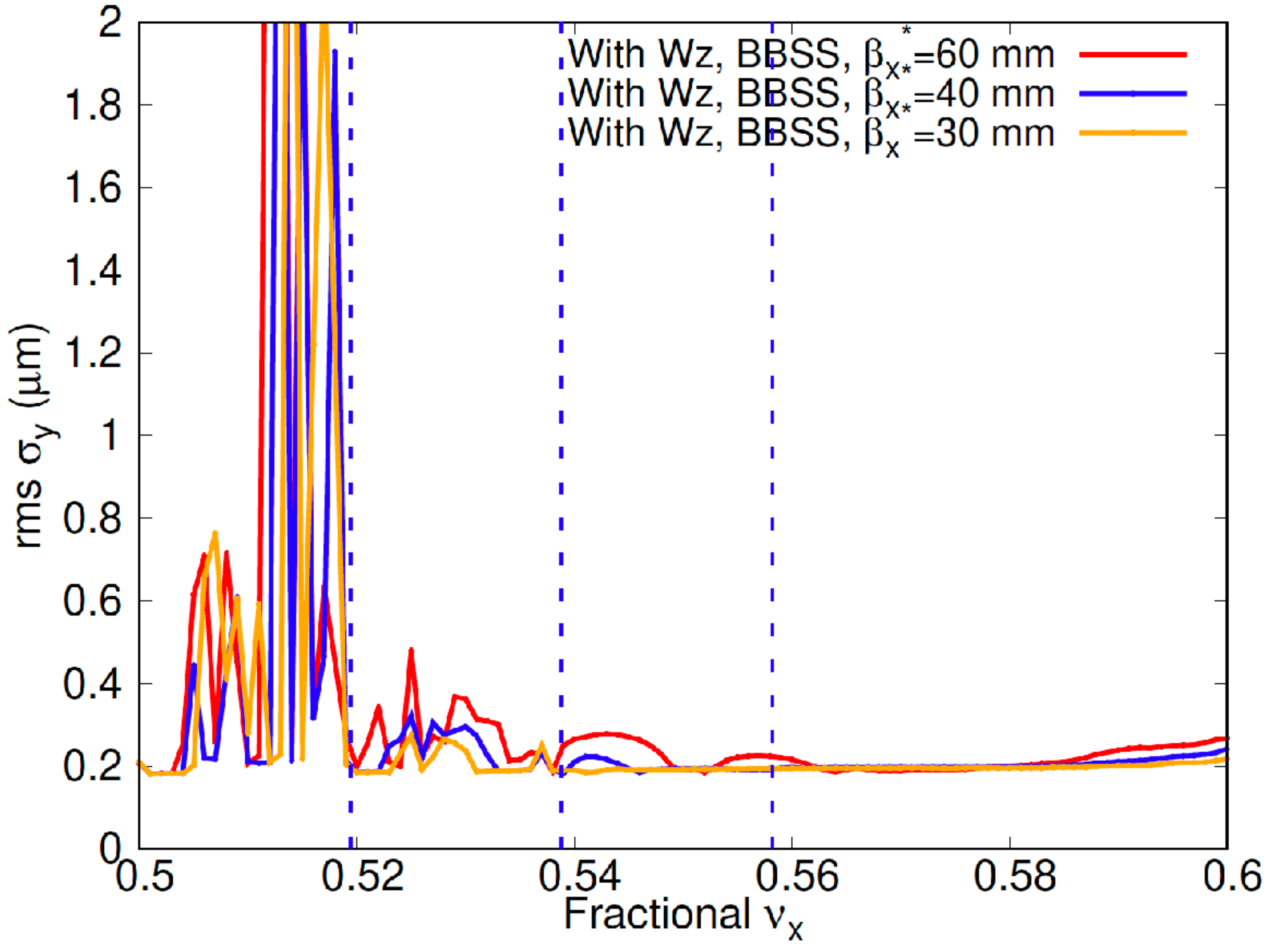
Specific lum. vs. ν_x



σ_x^* vs. ν_x



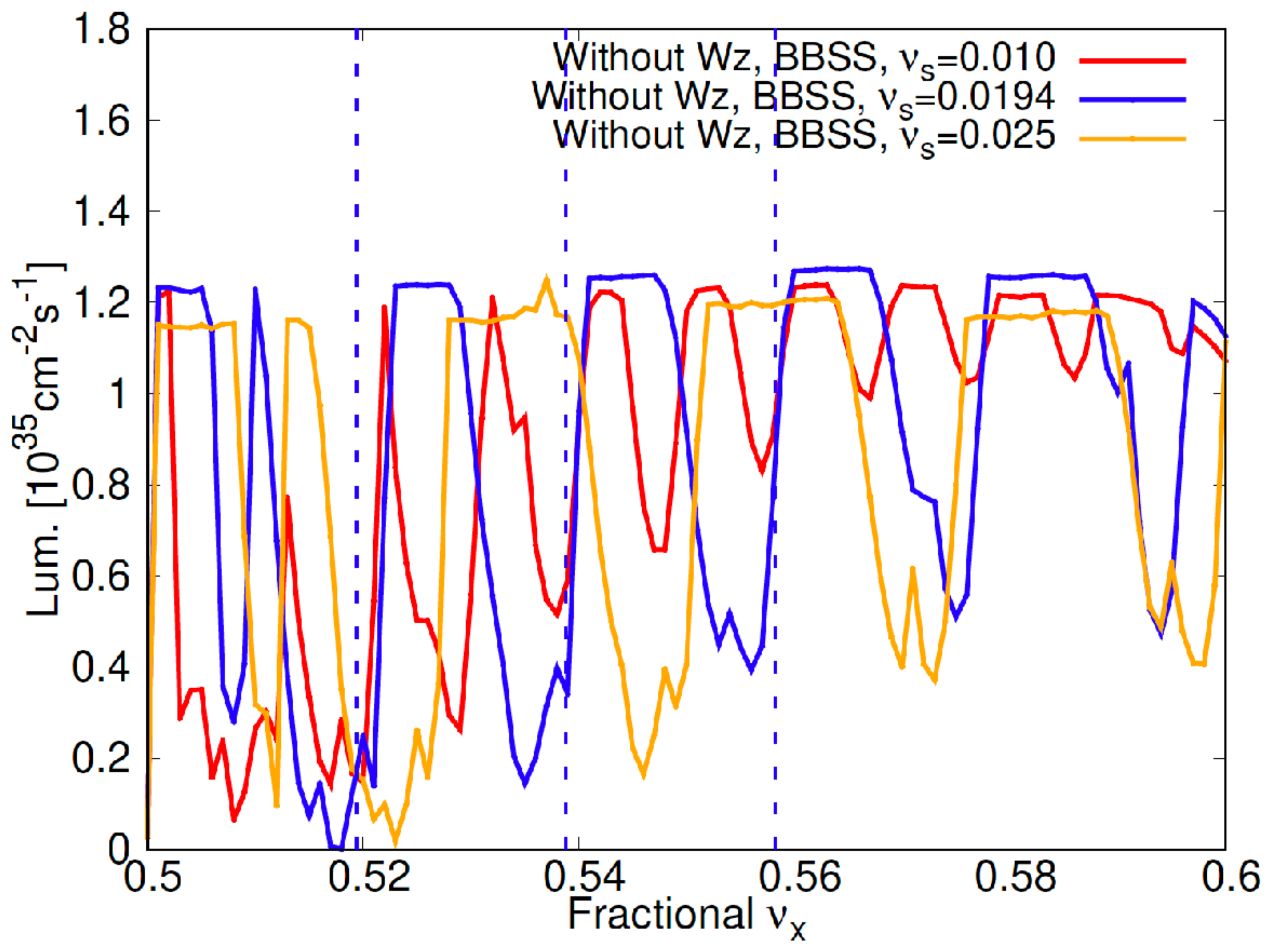
σ_y^* vs. ν_x



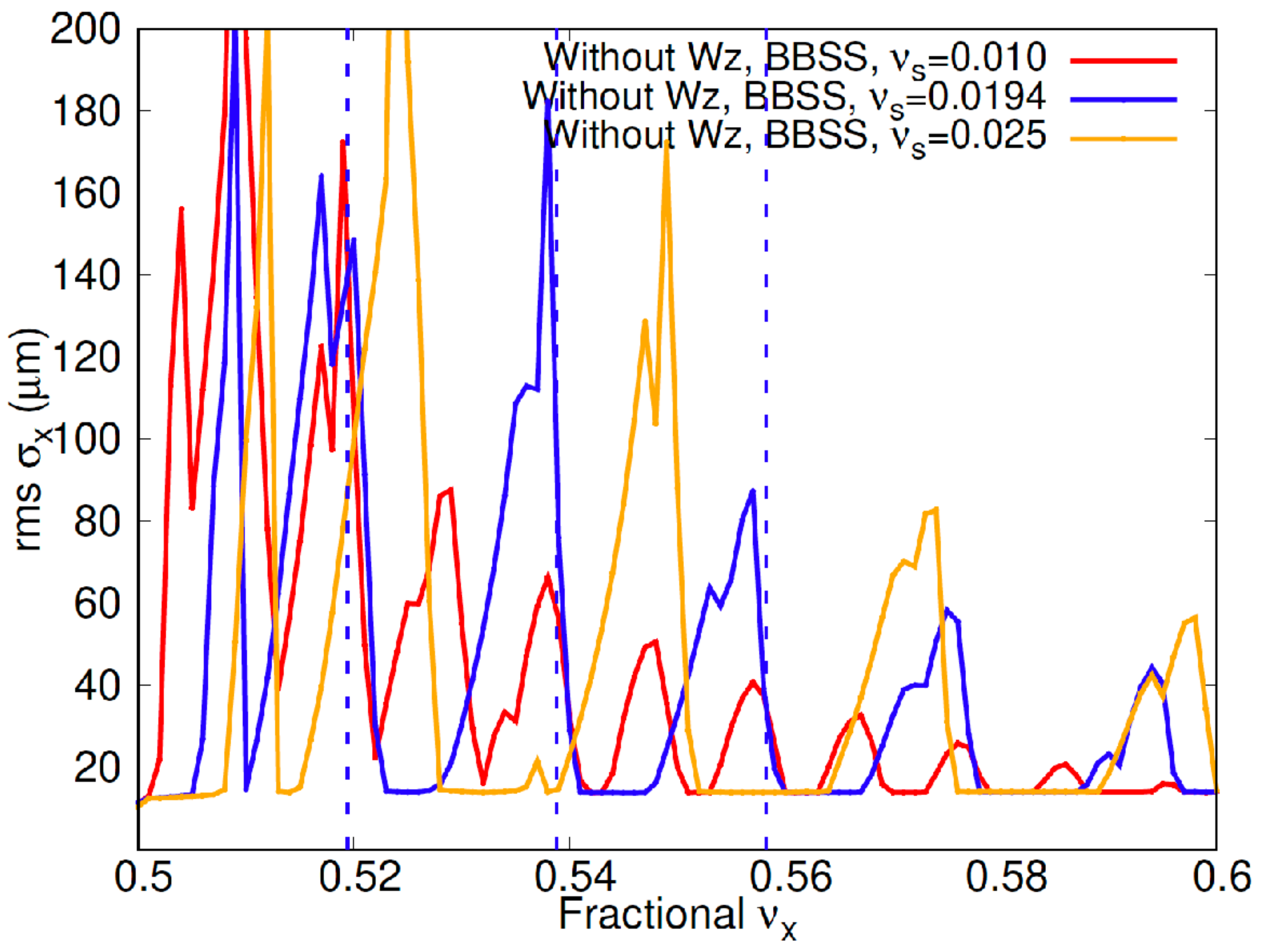
Beam-beam simulation results for STCF (2 GeV)

- BBSS simulations with varied ν_s (fixed β_x^*=40 mm) w/o longitudinal wake
  - The widths of X-Z instability peaks $\nu_x - k\nu_s = N/2$ depend on ξ_y (function of β_x^*), but not on ν_s

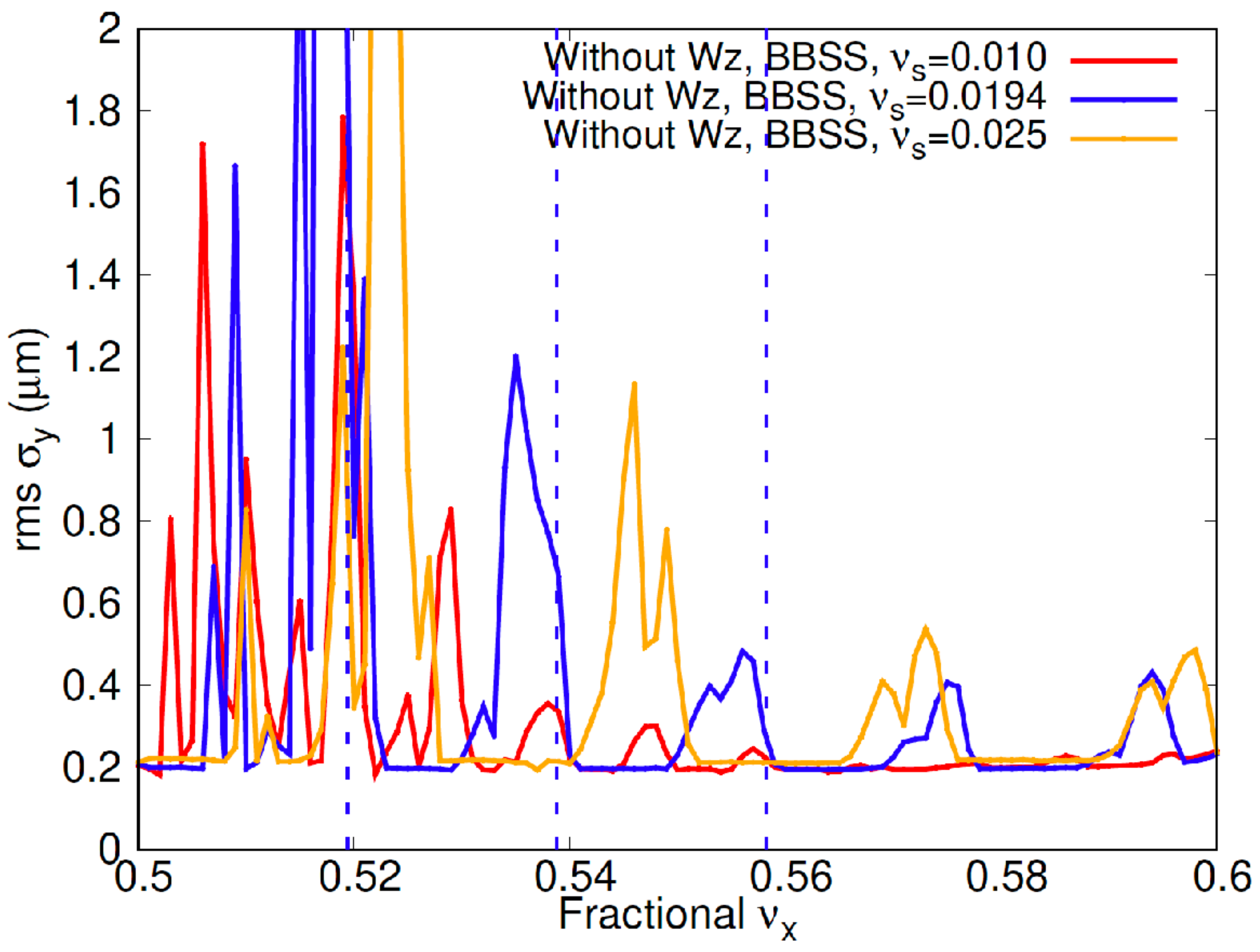
Specific lum. vs. ν_x



σ_x^* vs. ν_x

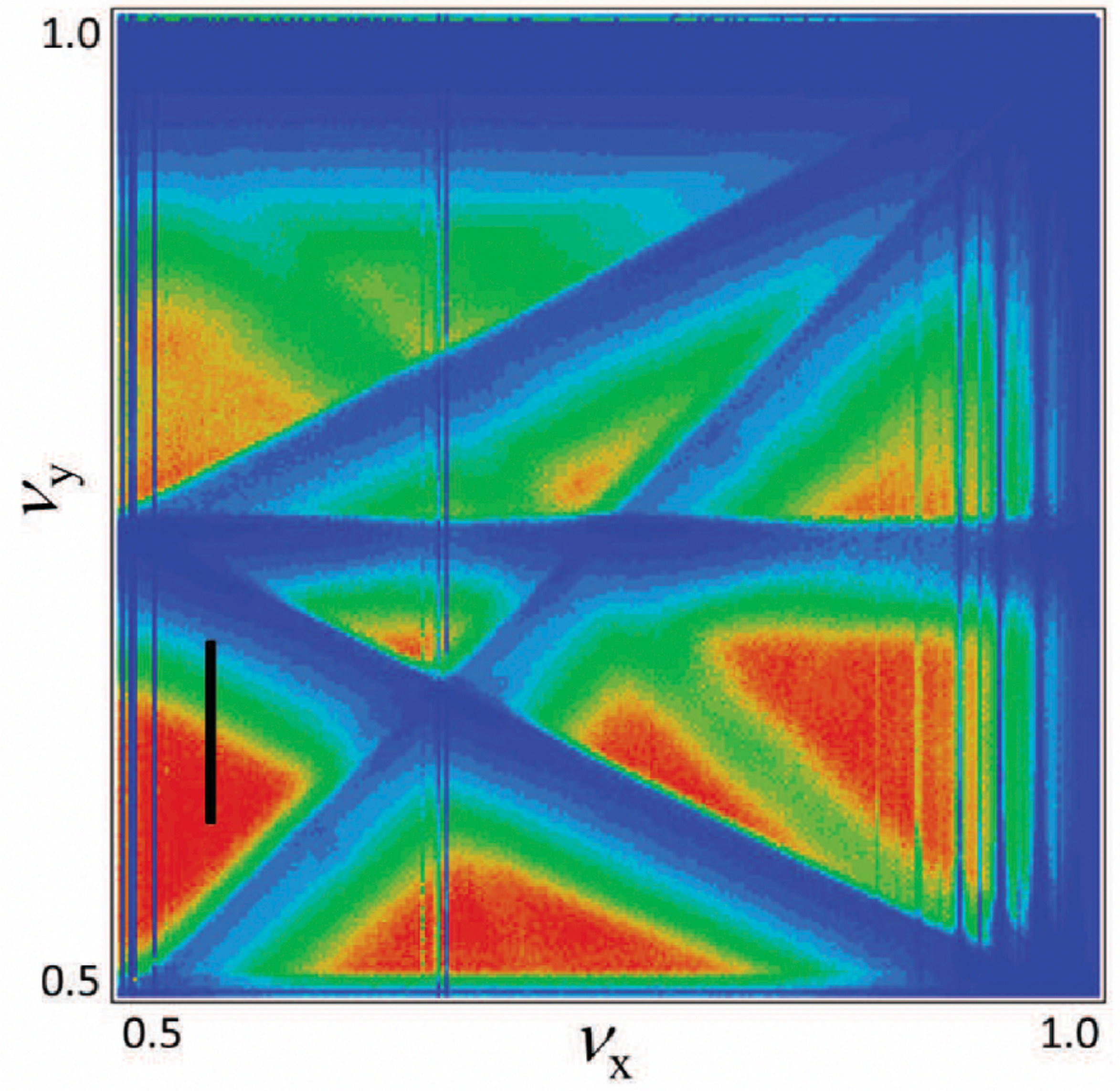


σ_y^* vs. ν_x



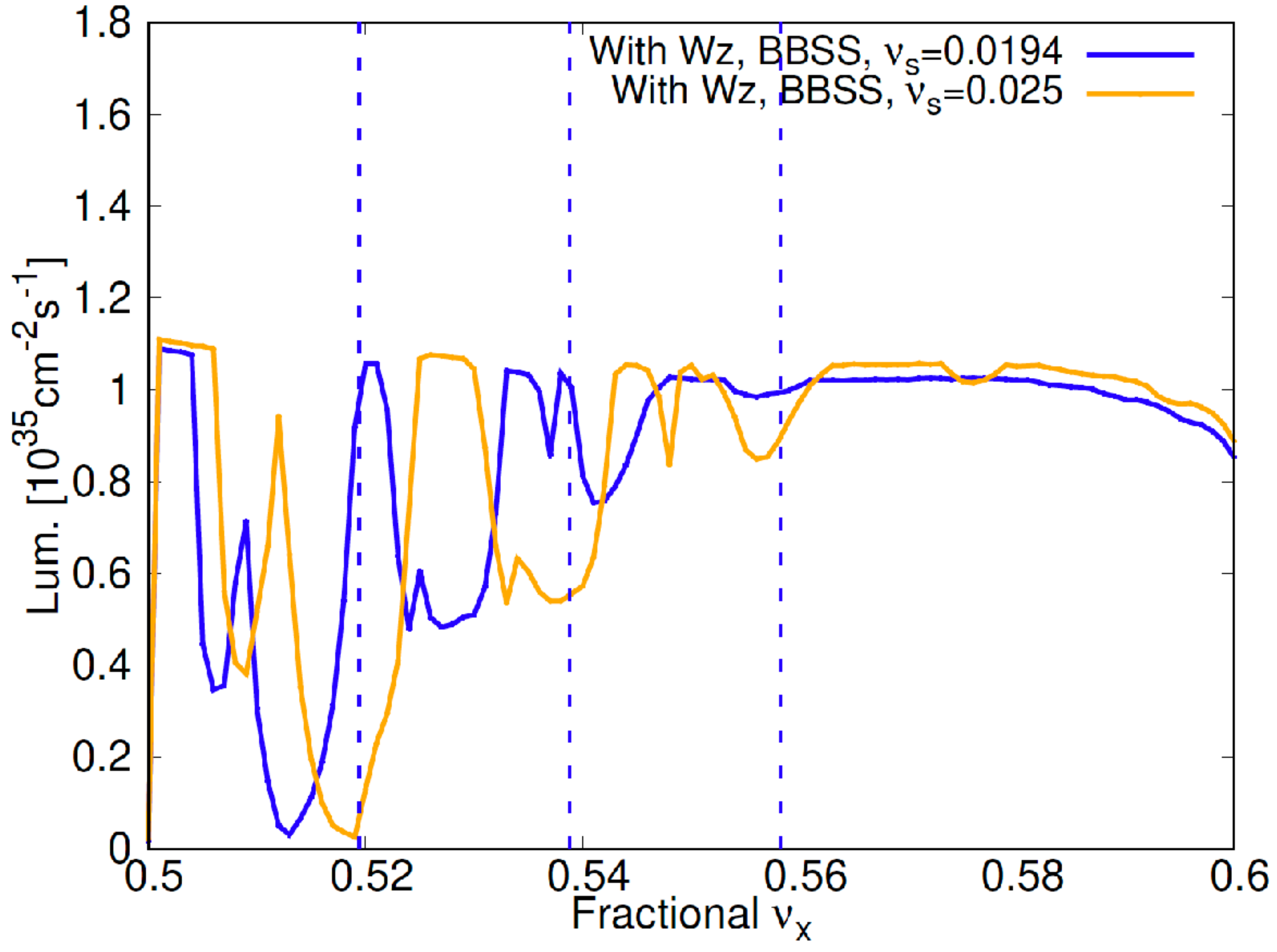
Beam-beam simulation results for STCF (2 GeV)

- BBSS simulations with varied ν_s (fixed β_x^*=40 mm) w/ longitudinal wake
  - Larger ν_s requires larger ν_x
  - With ν_s=0.01, the beam is unstable due to microwave instability

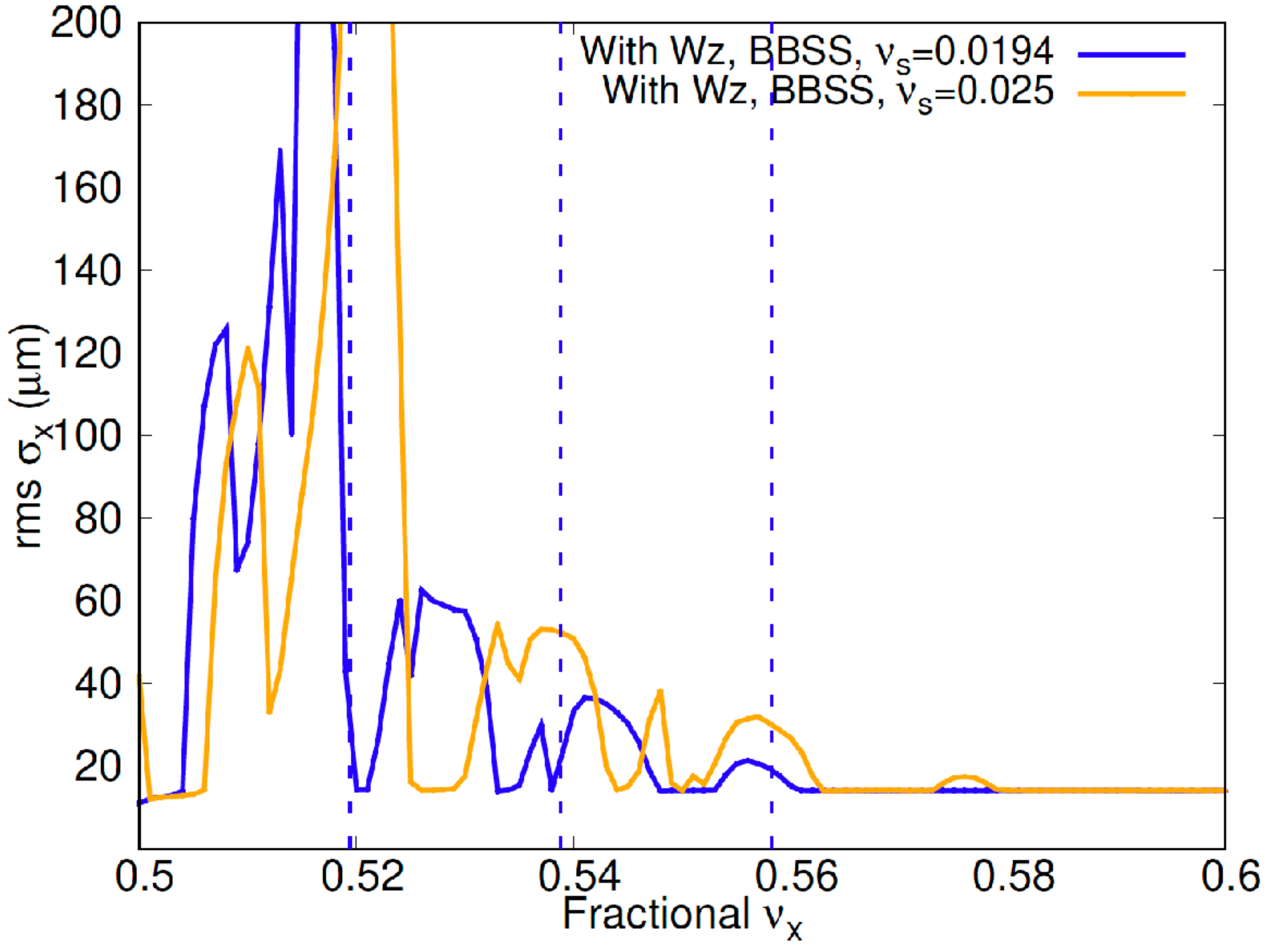


D. Shatilov, Handbook

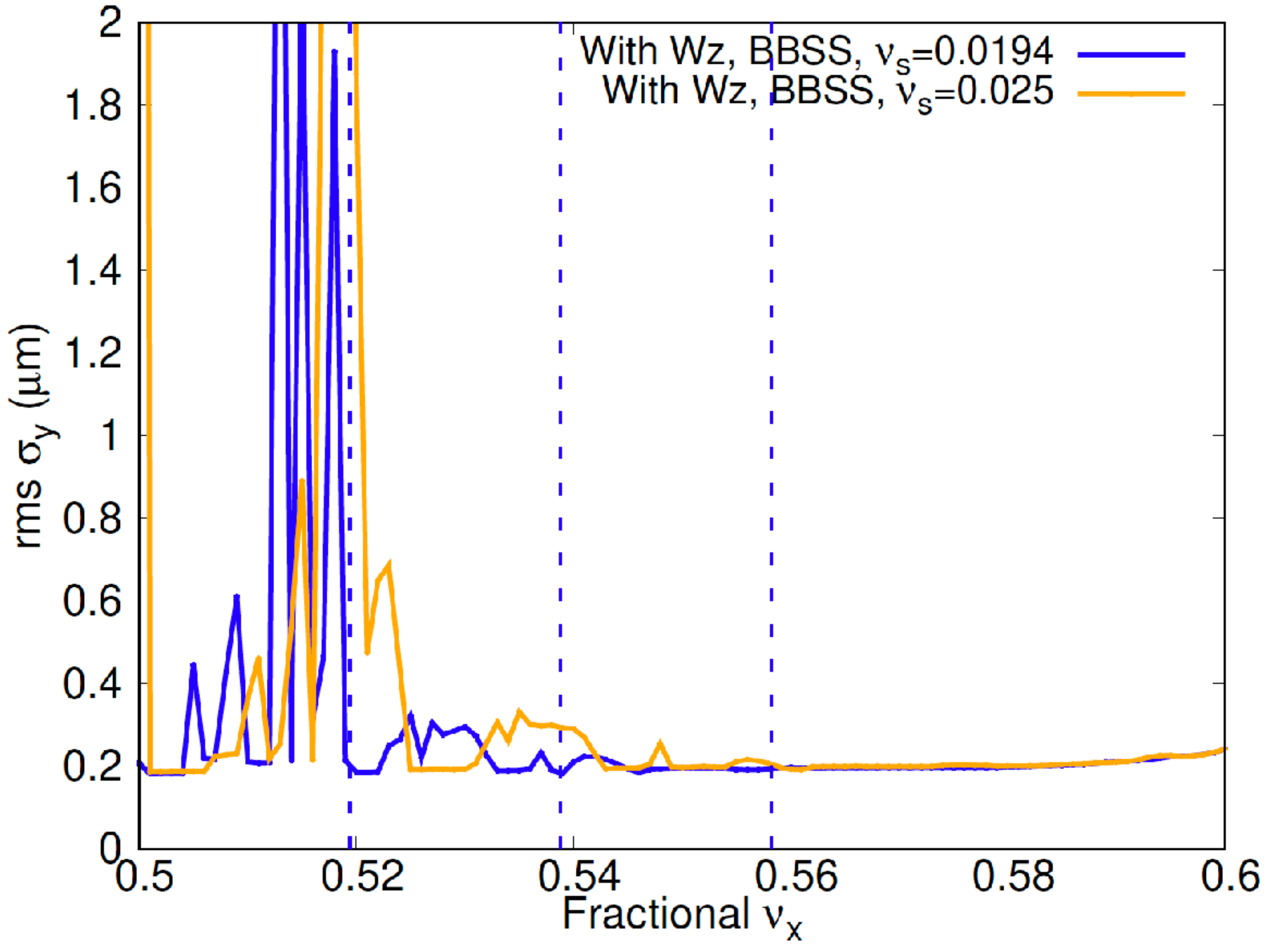
Specific lum. vs. ν_x



σ_x^* vs. ν_x



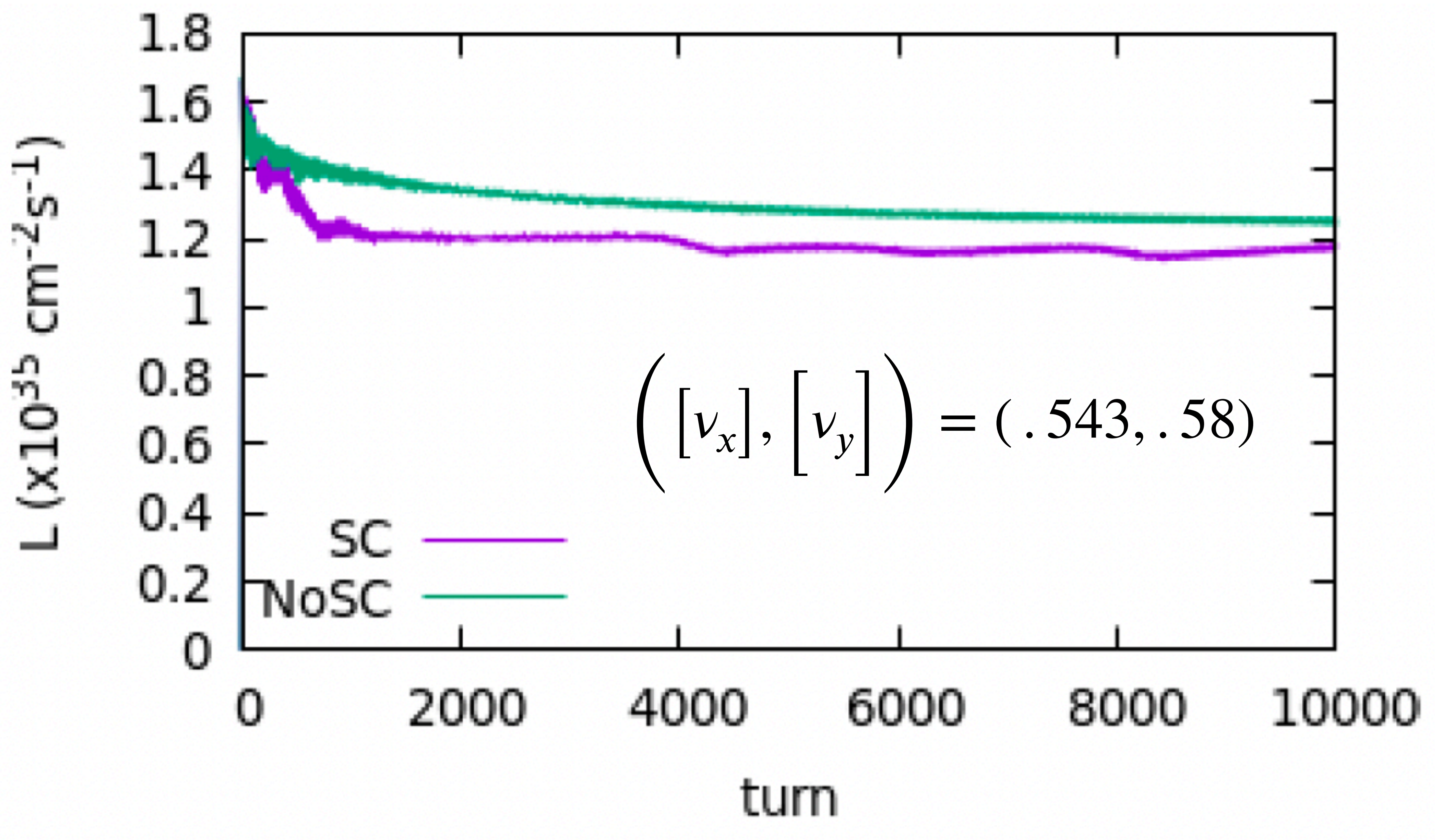
σ_y^* vs. ν_x



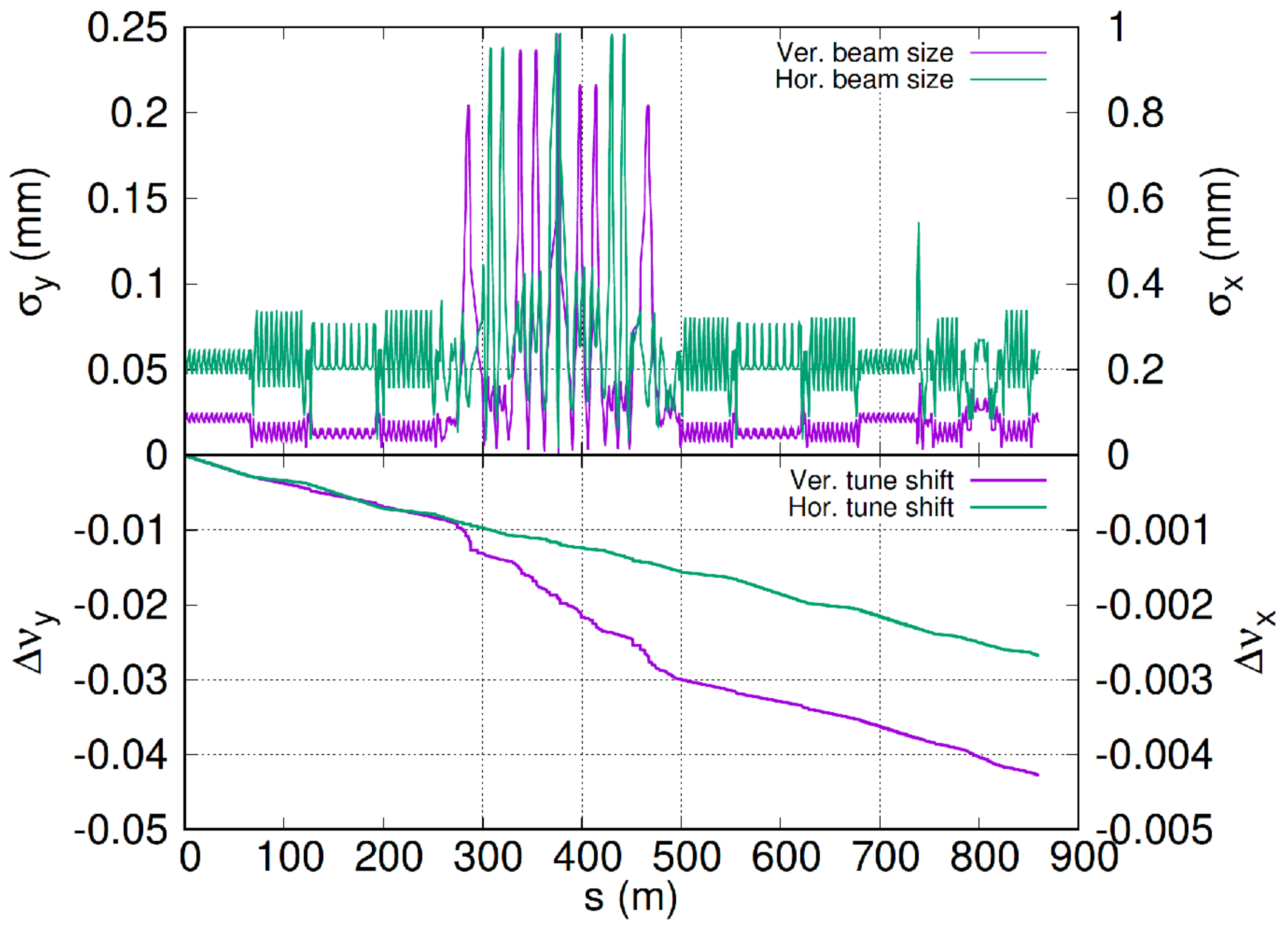
Beam-beam simulation results for STCF (2 GeV)

- Space-charge effects are seen in simulations, but seem not severe (SC tune shifts compared with BB tune shifts: $\Delta\nu_y \approx -\xi_y/2$, $\Delta\nu_x \approx -\xi_x$)

Strong-strong simulations with full lattices and w/wo space charge
Luminosity loss can be avoided by adjusting ν_x



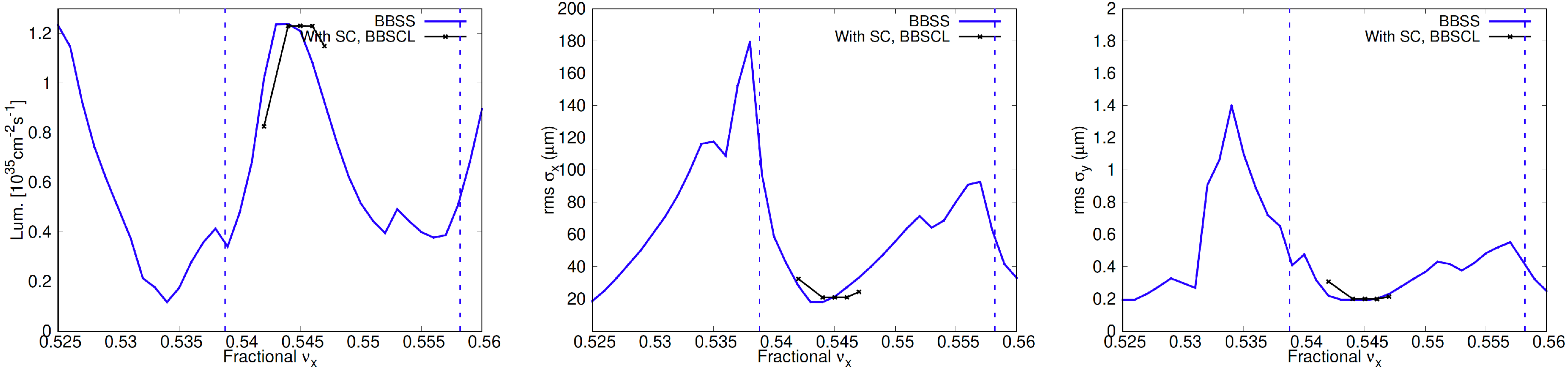
Space-charge tune shift integrated along the ring



Beam-beam simulation results for STCF (2 GeV)

- Space-charge effects are seen in simulations, but seem not severe (SC tune shifts compared with BB tune shifts: $\Delta\nu_y \approx -\xi_y/2$, $\Delta\nu_x \approx -\xi_x$)
  - Slightly shifting ν_x can avoid X-Z instability and luminosity loss
  - Detailed BBSCL simulations for β_x^*=40 mm (current baseline) are ongoing

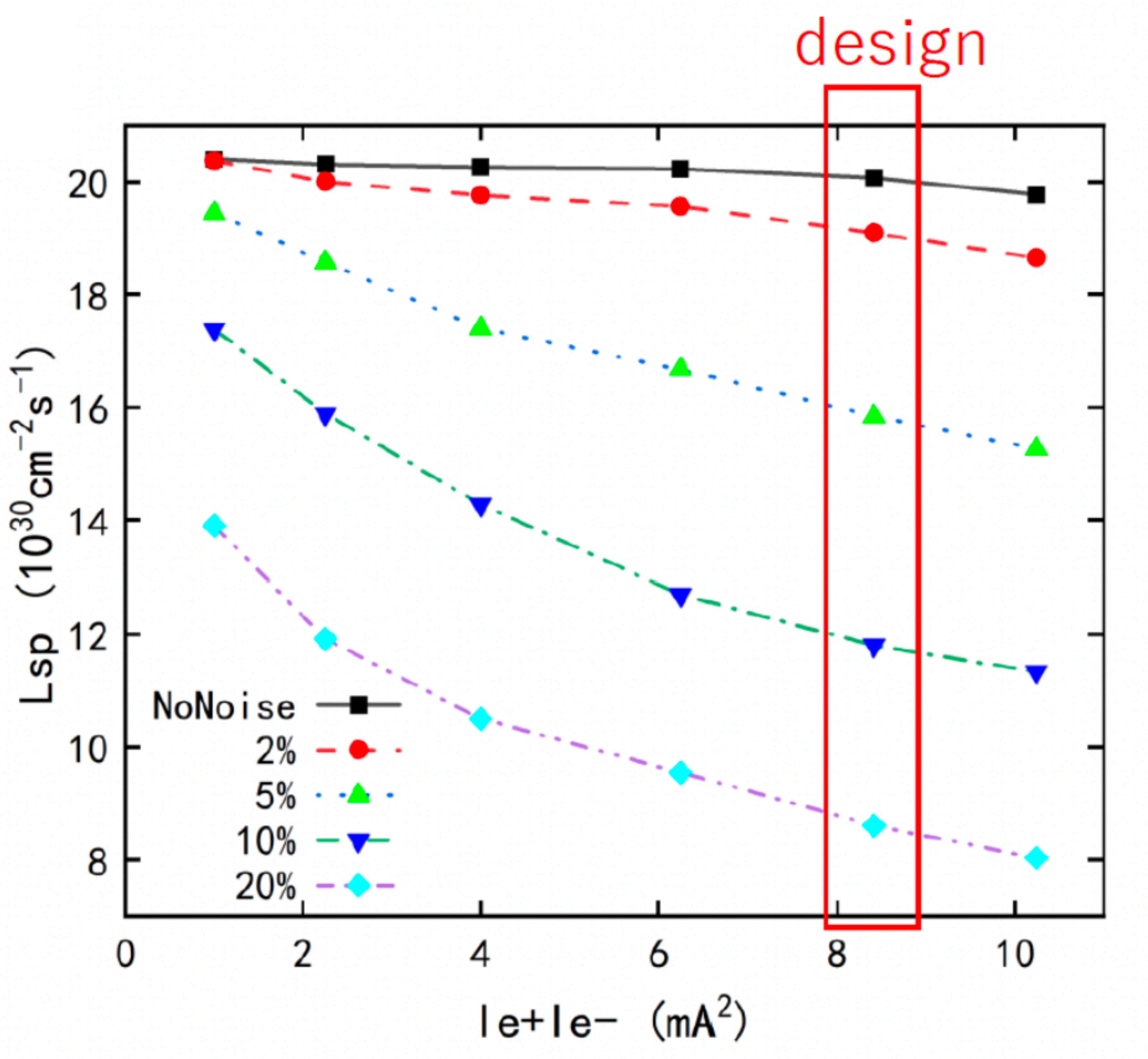
BBSS and BBSCL simulations for β_x^*=60 mm



Beam-beam simulation results for STCF (2 GeV)

- Turn-by-turn noises in the collision offsets are important → Require tight control of the feedback noises

BBSS simulations with T-b-T collision offsets



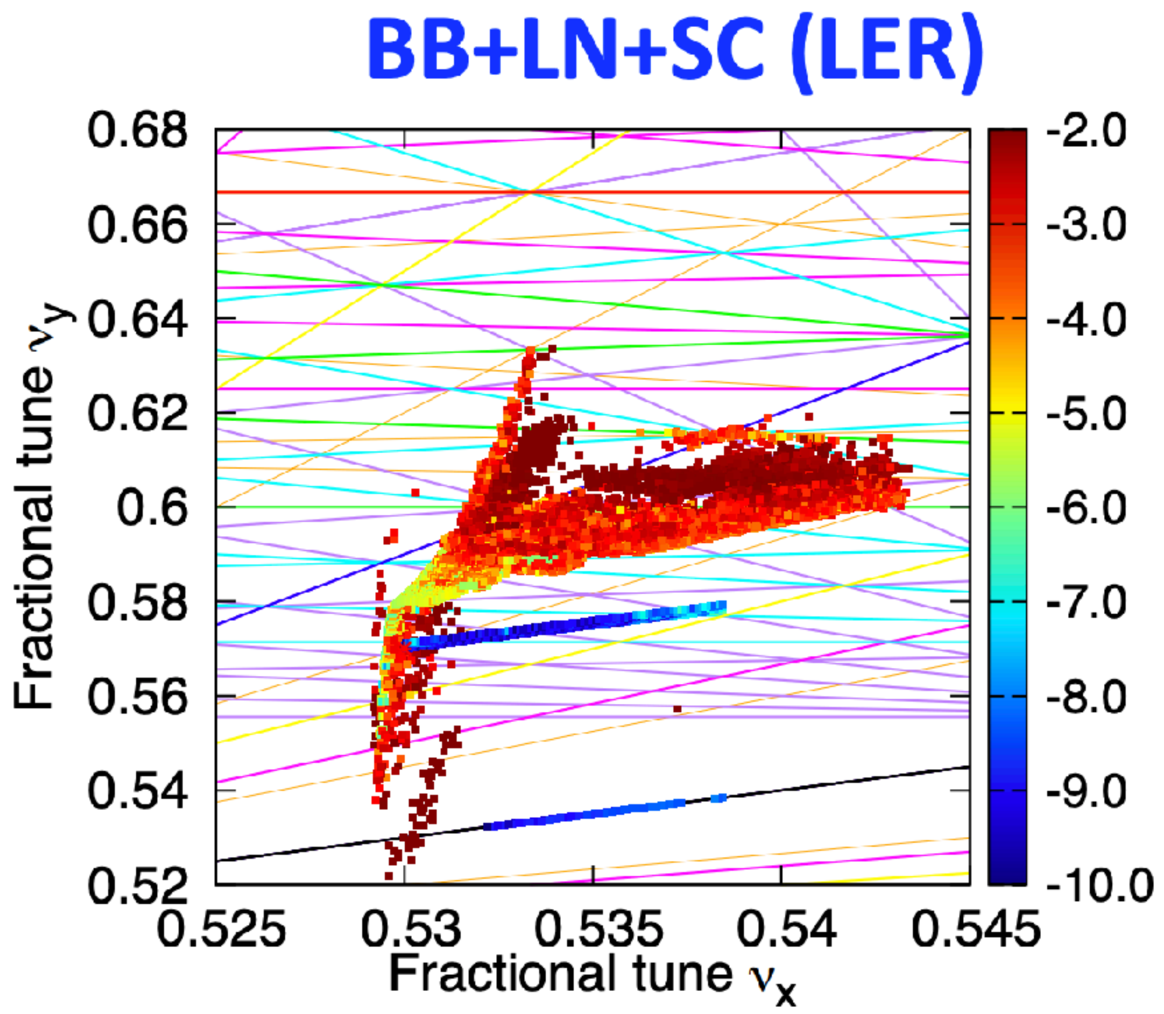
K. Ohmi and Q. Chen

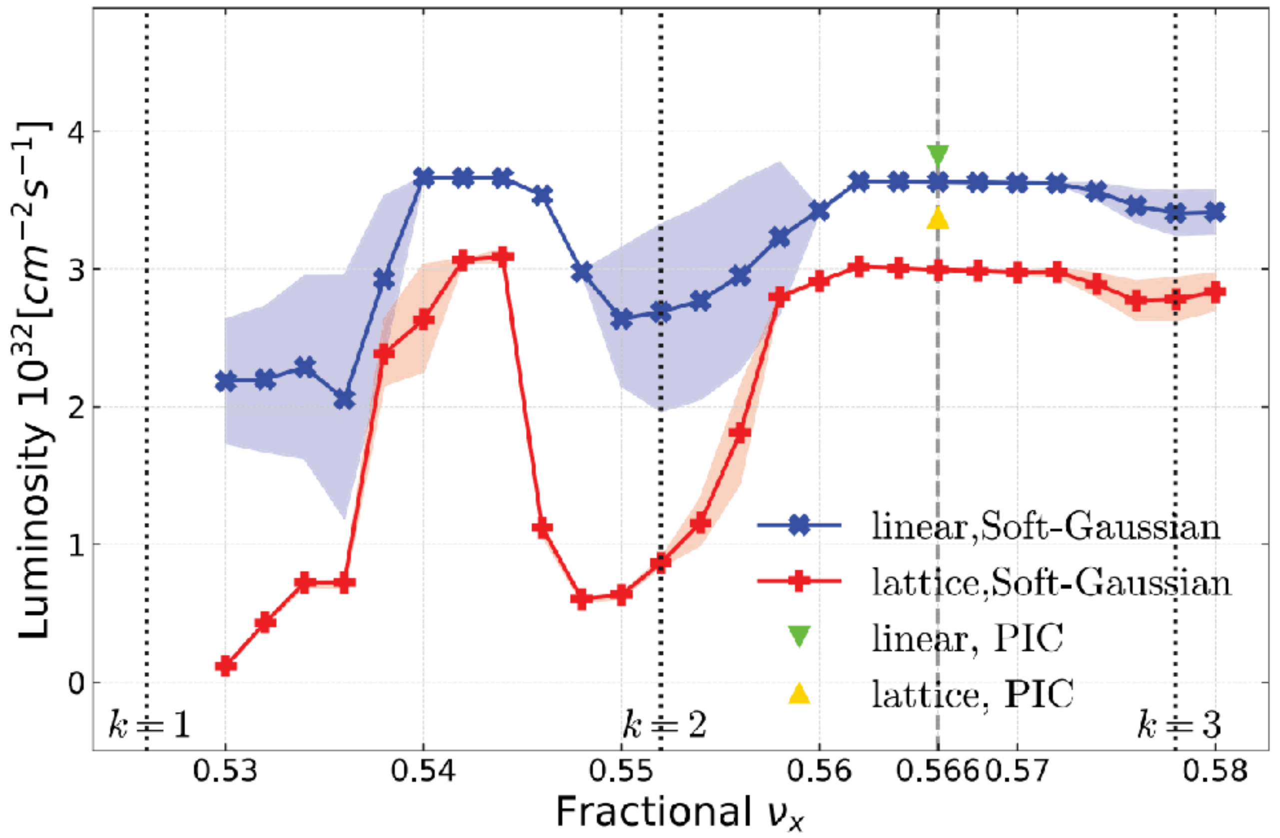
Summary

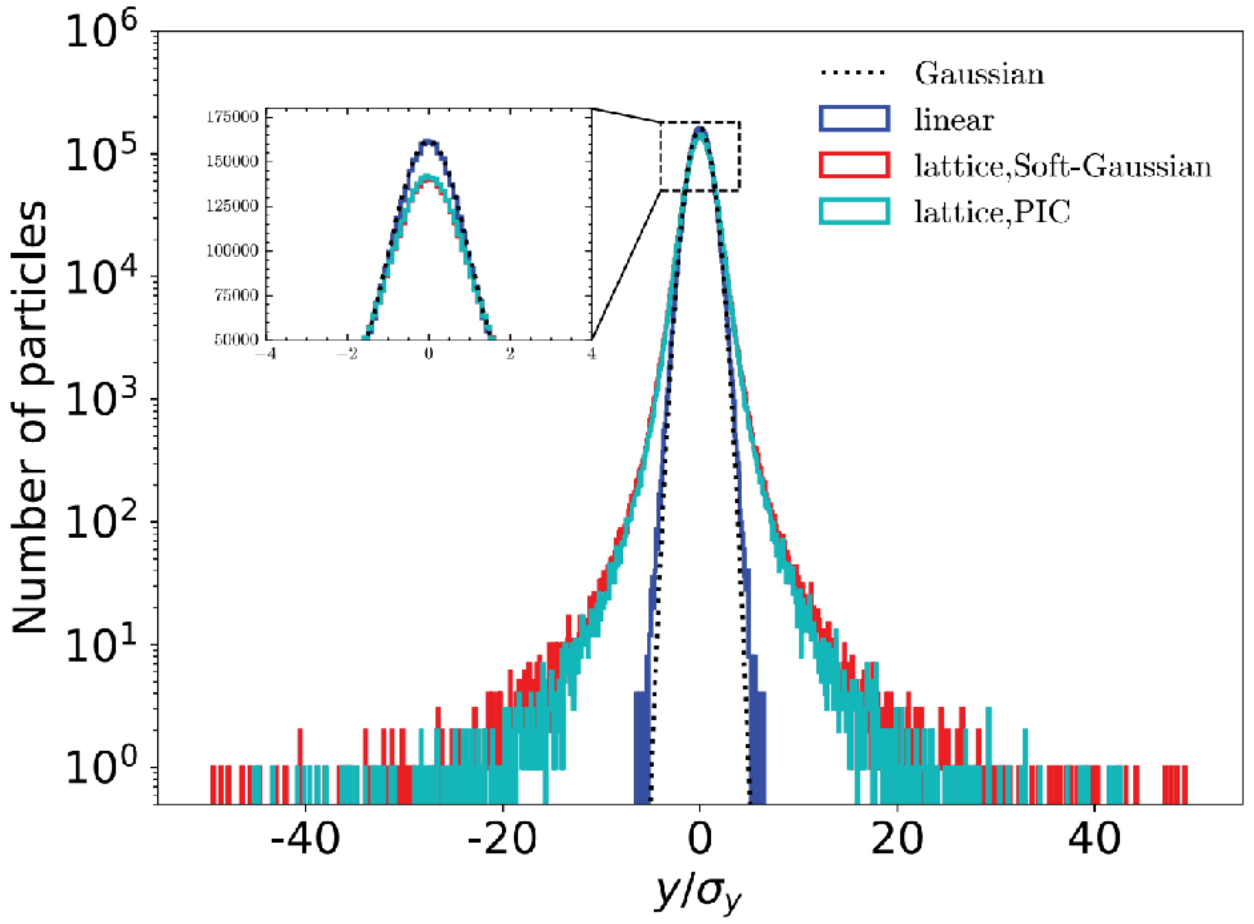
- Beam-beam effects in crab-waist colliders have been extensively studied over the past two decades.
- The STCF design parameters have been optimized using insights from previous crab-waist machines and dedicated beam-beam simulations.
  - With optimized machine parameters and lattices (Ver.5), $L > 10^{35}$ $cm^{-2}s^{-1}$ is achievable at 2 GeV from simulation viewpoint (full lattice, impedance, space charge taken into account).
- GPU-accelerated full beam-beam simulations are now feasible and underway to evaluate their impact on STCF performance.
  - Interplay of multiple physical processes is to be extensively investigated via GPU simulations.

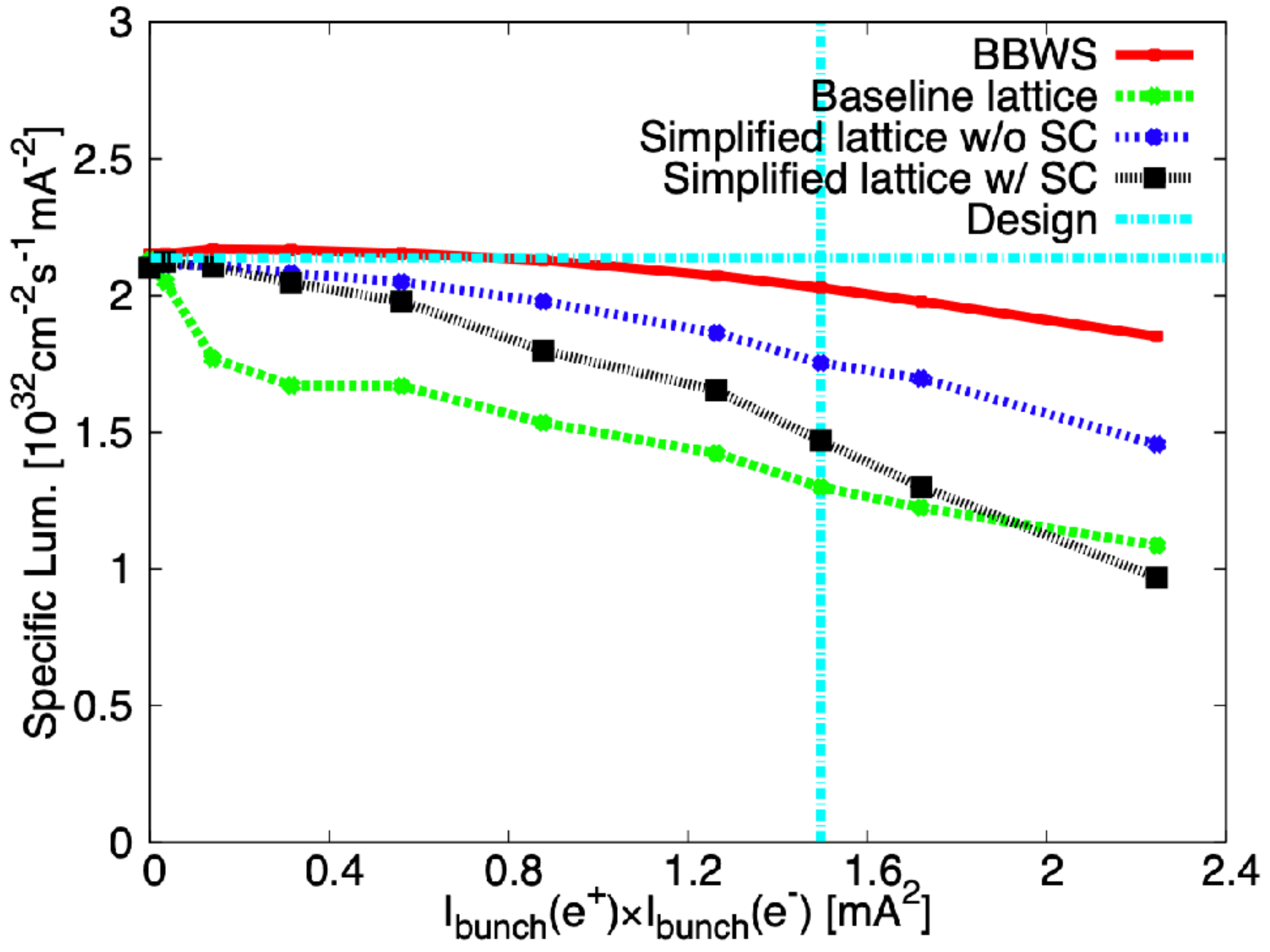
Beam-beam effects in crab-waist colliders

- Key beam-beam phenomena (interplay with full lattices and other physical processes)

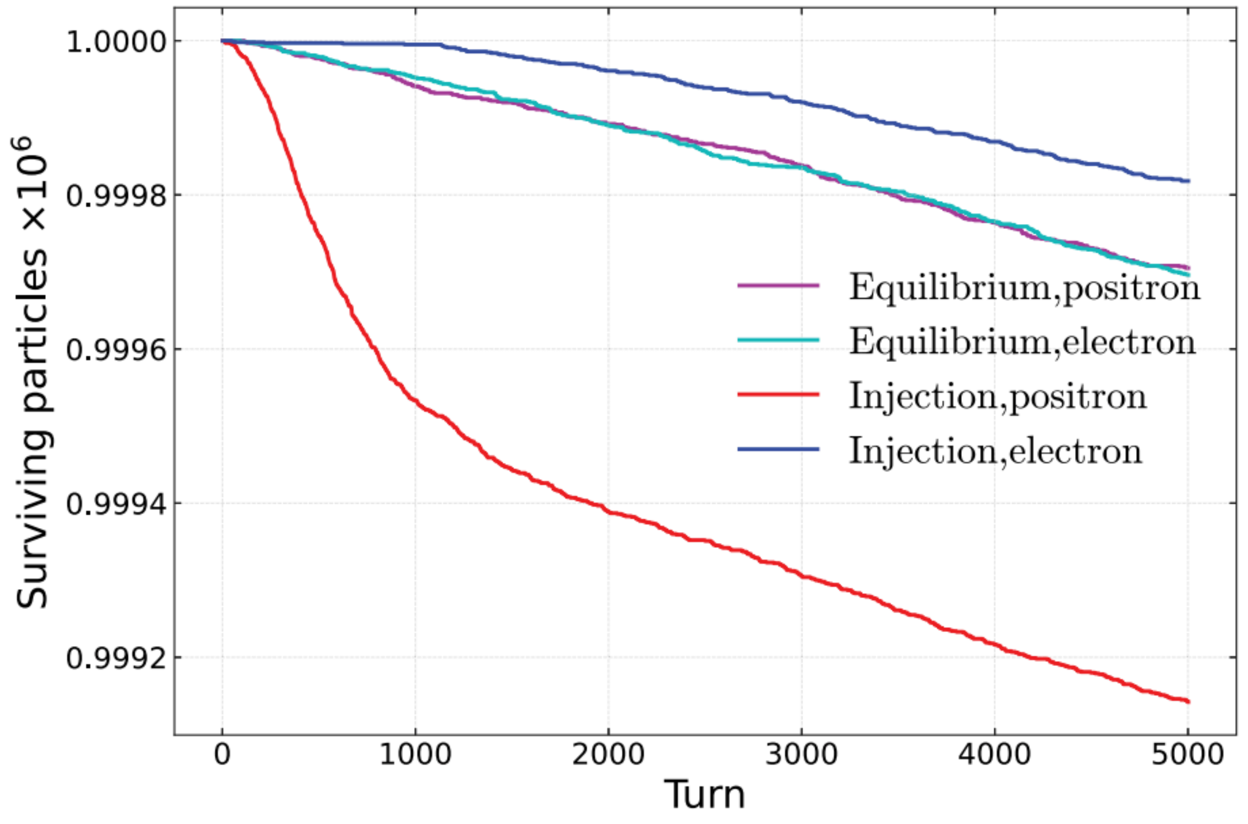


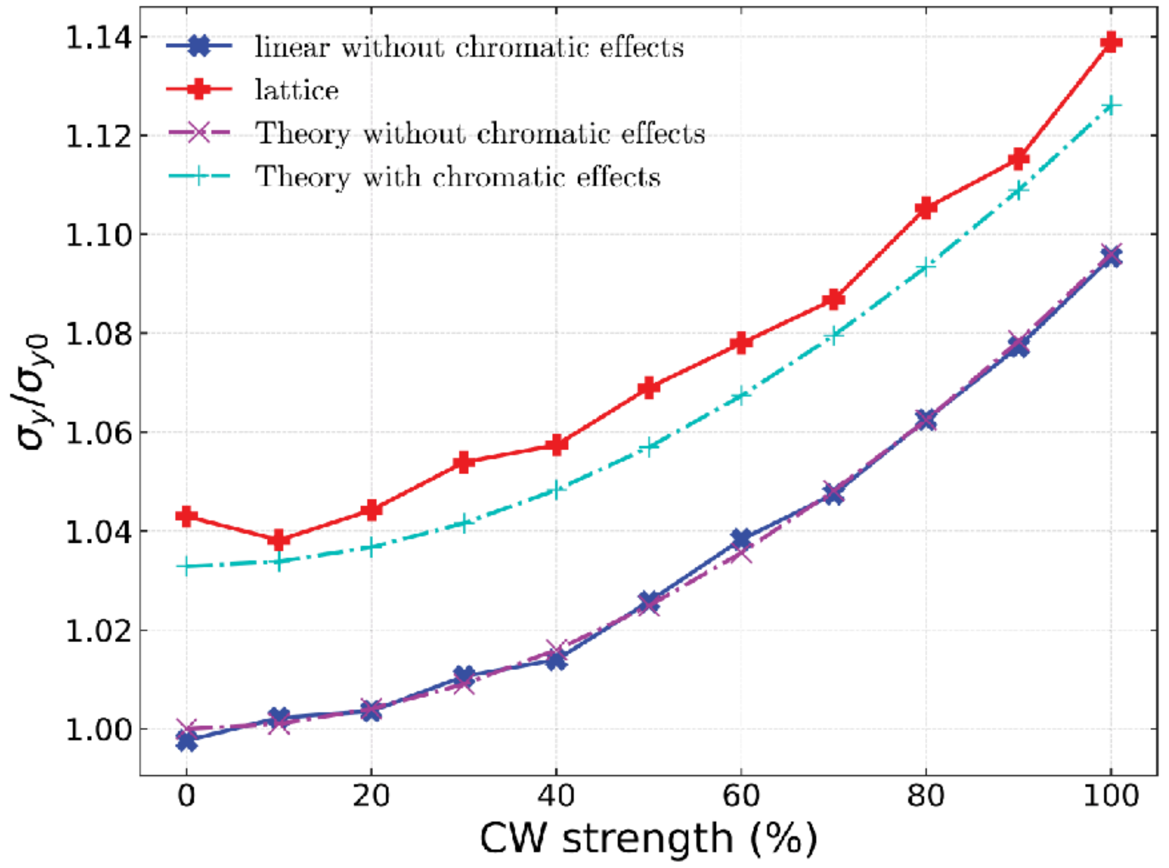






D. Zhou et al., IPAC'15





Z. Li et al., NIMA 1064 (2024) 169386