Recent results of beam-beam simulations for SuperKEKB

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Acknowledgements:

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2nd SuperKEKB beam dynamics workgroup meeting

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Outline

- Introduction
- Recent simulation results using BBWS and BBSS codes
- Summary

1. Introduction

➤ Luminosity formula for SuperKEKB (Nano-beam scheme)

- **Beam stability is sensitive (because of large crossing angle) to σ_x^*, though lum. is not (to be demonstrated in this talk).**
- **Lum. is sensitive to σ_z, which is determined by impedance budget.**
- **Lum. is most sensitive to σ_y^*, which is sensitive to many factors.**

$$\mathcal{L} = \mathcal{L}_0 \cdot R_\theta \qquad \mathcal{L}_0 = \frac{N_{\rm p} N_{\rm e} f N_{\rm b}}{2\pi \sqrt{\sigma_{\rm xp}^{*2} + \sigma_{\rm xe}^{*2}} \sqrt{\sigma_{\rm yp}^{*2} + \sigma_{\rm ye}^{*2}}}$$

$$R_\theta \approx \frac{1}{\sqrt{1 + \frac{\sigma_{\rm zp}^{*2} + \sigma_{\rm ze}^{*2}}{\sigma_{\rm xp}^{*2} + \sigma_{\rm xe}^{*2}} \tan^2 \frac{\theta}{2}}}$$

← **Hourglass effect negligible**

$$\theta_{\rm PW} = \sqrt{\frac{\sigma_{\rm zp}^{*2} + \sigma_{\rm ze}^{*2}}{\sigma_{\rm xp}^{*2} + \sigma_{\rm xe}^{*2}}} \tan \frac{\theta}{2}$$

← **Proper definition of Piwinski angle(?)**

$$\theta_{\rm PW} \gg 1 \longrightarrow \mathcal{L} \approx \frac{N_{\rm p} N_{\rm e} f N_{\rm b}}{2\pi \sqrt{\sigma_{\rm yp}^{*2} + \sigma_{\rm ye}^{*2}} \sqrt{\sigma_{\rm zp}^{*2} + \sigma_{\rm ze}^{*2}} \tan \frac{\theta}{2}}$$

1. Introduction

➤ Beam-beam tune shift formula for SuperKEKB (Nano-beam scheme)

- **Assumption: Hourglass effect negligible.**

$$\xi_{\mathrm{xe0}} = \frac{N_{\mathrm{p}} r_{\mathrm{e}} \beta^*_{\mathrm{ye}}}{2\pi\gamma_{\mathrm{e}}\sigma^{*2}_{\mathrm{xp}}} \frac{1}{\sqrt{\left(\frac{\sigma^*_{\mathrm{zp}}}{\sigma^*_{\mathrm{xp}}}\tan\frac{\theta}{2}\right)^2+1}\left(\sqrt{\left(\frac{\sigma^*_{\mathrm{zp}}}{\sigma^*_{\mathrm{xp}}}\tan\frac{\theta}{2}\right)^2+1}+\frac{\sigma^*_{\mathrm{yp}}}{\sigma^*_{\mathrm{xp}}}\right)}$$

$$\xi_{\mathrm{ye0}} = \frac{N_{\mathrm{p}} r_{\mathrm{e}} \beta^*_{\mathrm{ye}}}{2\pi\gamma_{\mathrm{e}}\sigma^*_{\mathrm{xp}}\sigma^*_{\mathrm{yp}}} \frac{1}{\sqrt{\left(\frac{\sigma^*_{\mathrm{zp}}}{\sigma^*_{\mathrm{xp}}}\tan\frac{\theta}{2}\right)^2+1}+\frac{\sigma^*_{\mathrm{yp}}}{\sigma^*_{\mathrm{xp}}}}$$

$$\xi_{\mathrm{ye0}} \propto \frac{N_{\mathrm{p}} \beta^*_{\mathrm{ye}}}{\gamma_{\mathrm{e}}\sigma^*_{\mathrm{yp}}\sigma^*_{\mathrm{zp}}}$$

1. Introduction

➤ Beam-beam simulations

- **Weak-strong (BBWS):**

  *** Tune scan to search for “sweat area” in tune space**

  *** Tune scan to identify dangerous beam-beam resonances**

  *** Tune scan to correlate the strengths of BB resonances with machine parameters**

- **Strong-strong (BBSS):**

  *** Local tune scan (small area in tune space) to detect coherent beam-beam instability**

  *** Refine tune choosing**

  *** Luminosity performance**

1. Introduction

➤ Phase-2 (Last stage) and Phase-3 machine parameters (Early stage)

	1		1(op1)		1(op2)		2019.03.30		2019.04.02		2018.07.13(11AM)	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.2	1.0	1.2	0.21	0.26	0.17	0.22	0.158	177
# bunch	1576		1576		1576		789		789		395	
ε_x (nm)	4.6	2.0	4.6	2.0	4.6	2.0	4.728	1.731	4.537	1.641	4.6	2.0
ε_y (pm)	368	160	160	160	160	160	122.5	40	53.33	13.33	42.4	43.2
β_x (mm)	100	100	100	230	80	80	200	200	100	200	100	200
β_y (mm)	3	3	3	3	3	3	4	4	3	3	3	3
σ_z (mm)	6	6	6	6	6	6	6	6	6	6	6	6
σ_y (nm)	1051	693	693	693	693	693	700	400	400	200	357	360
ν_x	45.57	44.57	45.57	44.57	45.57	44.57	45.564	44.571	45.5439	44.5568	45.542	44.559
ν_y	43.61	46.61	43.61	46.61	43.61	46.61	43.603	46.610	43.6082	46.618	43.6072	46.603
ν_s	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0256	0.0219	0.02576	0.02205	0.0258	0.0225
ξ_y(Geom.)	0.0272	0.0262	0.0272	0.0397	0.0272	0.0397	0.0272	0.0220	0.0345	0.0233	0.0309	0.0486
$\mathcal{L}$(Geom.)	1.06E+34		1.36E+34		1.37E+34		1.50E+33		1.85E+33		2.46E+33	
$\mathcal{L}$(BBSS)	1.00E+34		9.30E+33		1.34E+34		1.25E+33		1.39E+33		2.43E+33	

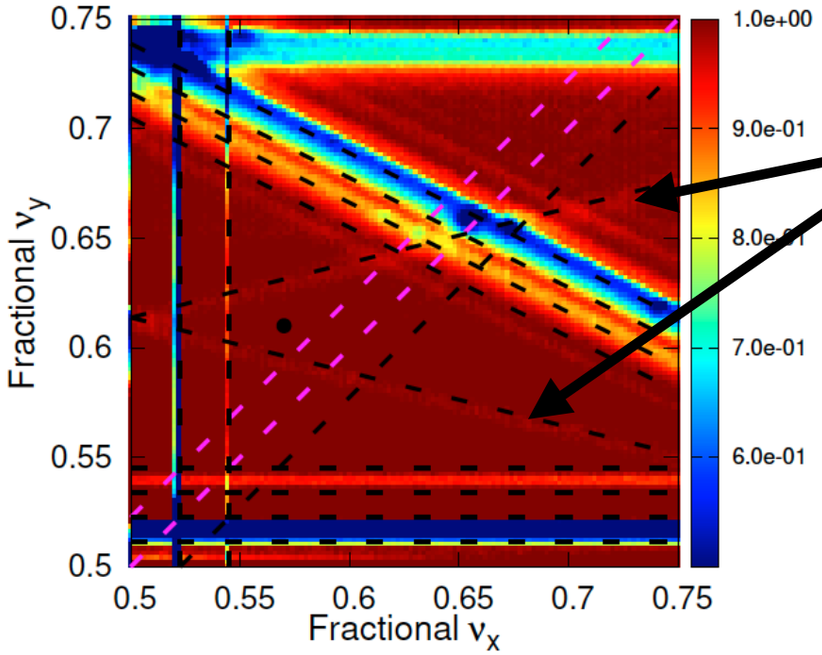
2017.07.13(11AM): Ref. S. Di Carlo's talk in the 1st SKB-BD meeting, Mar. 6, 2019.

2. BBWS simulation: Tune scan

➤ Parameter set (1)

e+(W)e-(S)

Lum. (L/L_0)



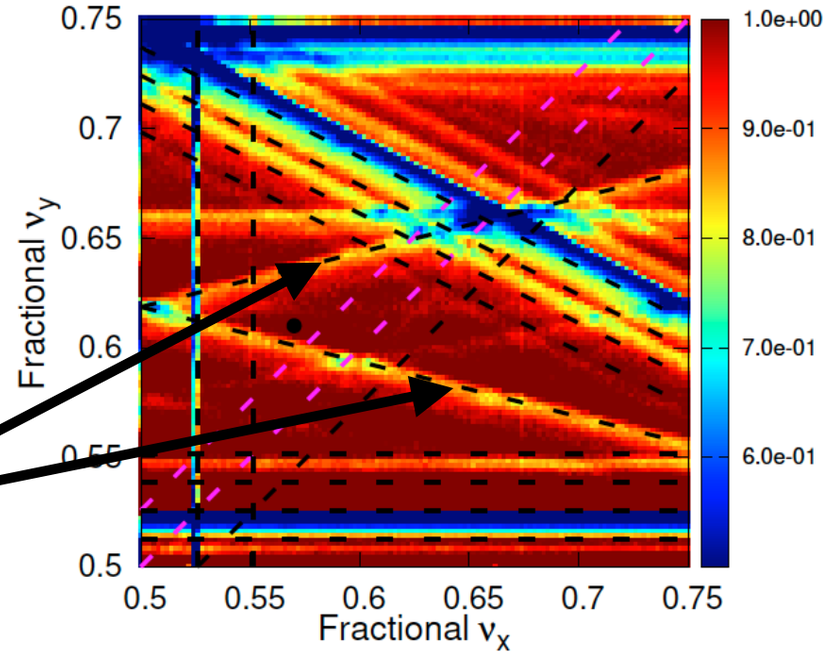
$\pm\nu_x+4\nu_y+\alpha=N$

set $\alpha=2\nu_s$

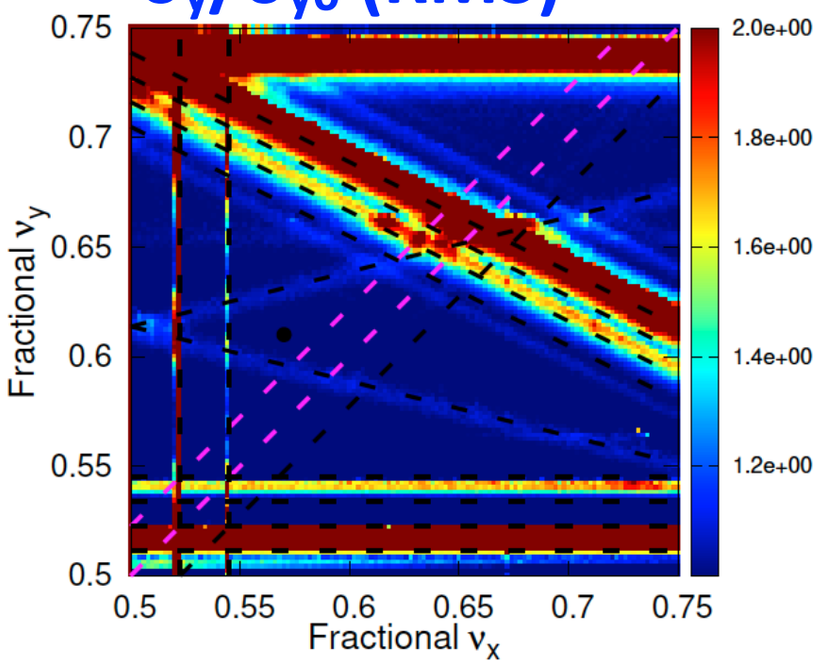
$\pm\nu_x+4\nu_y+\alpha=N$

set $\alpha=\nu_s$

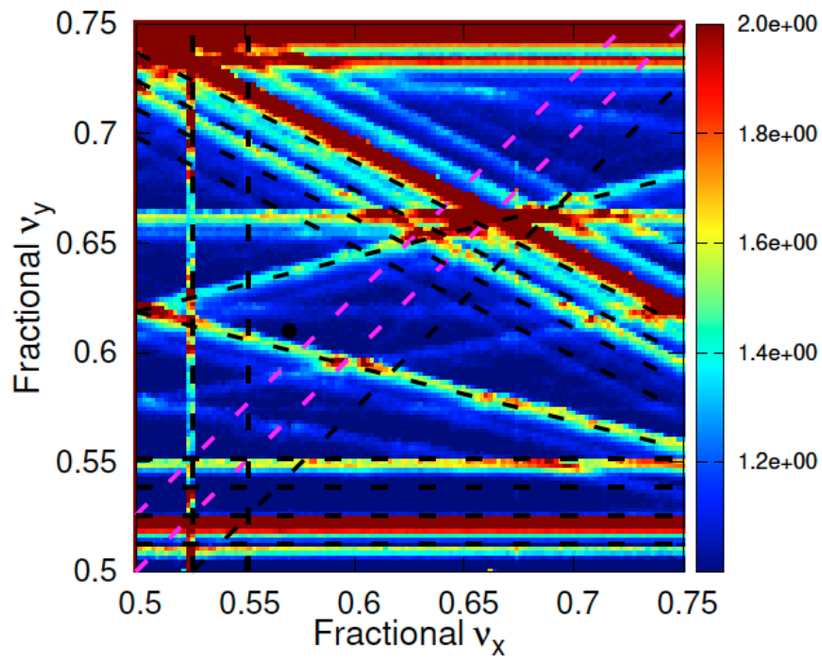
e+(S)e-(W)



σ_y/σ_{y0} (RMS)



NOTE: The plots of normalized quantities show the sensitivity of the machine to beam-beam effects!

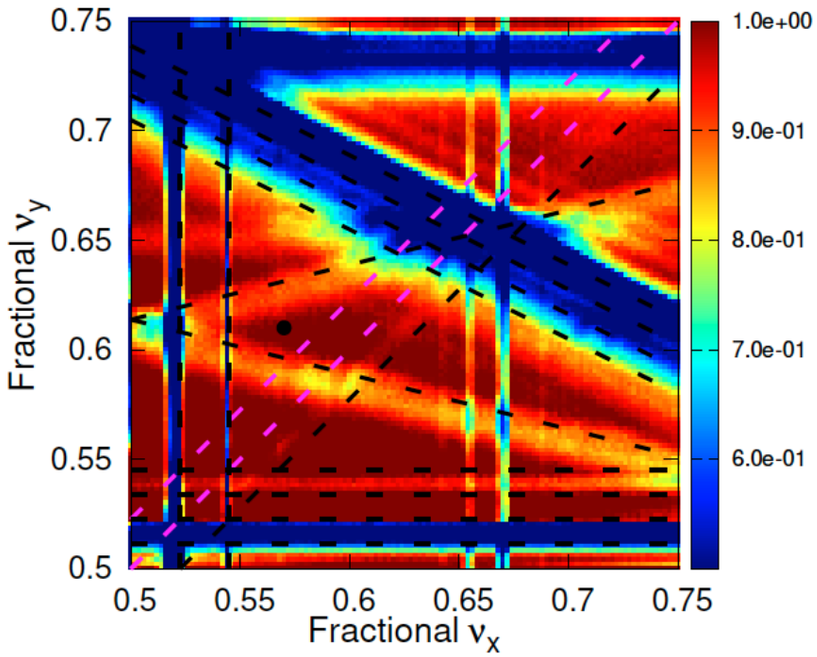


2. BBWS simulation: Tune scan

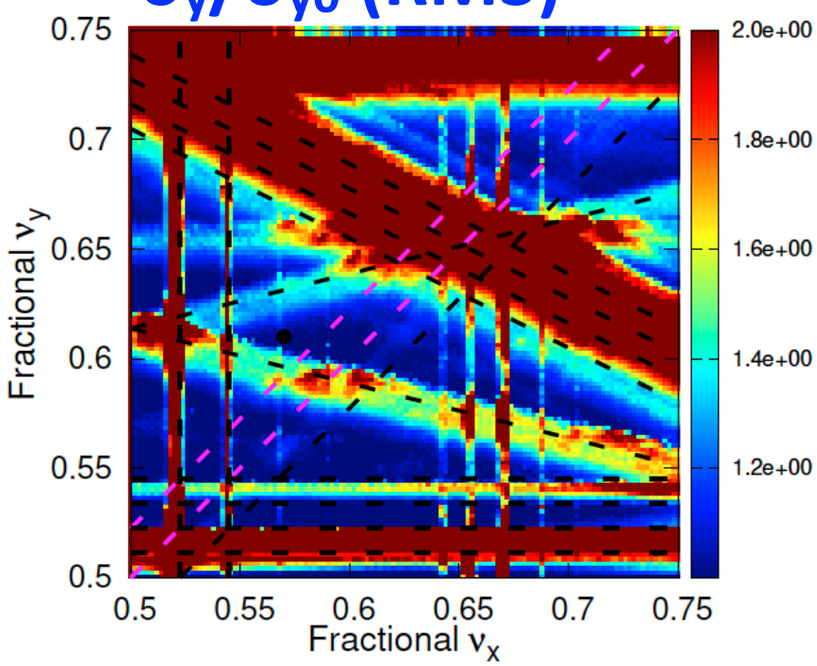
➤ Parameter set (1(op1))

e+(W)e-(S)

Lum. (L/L_0)

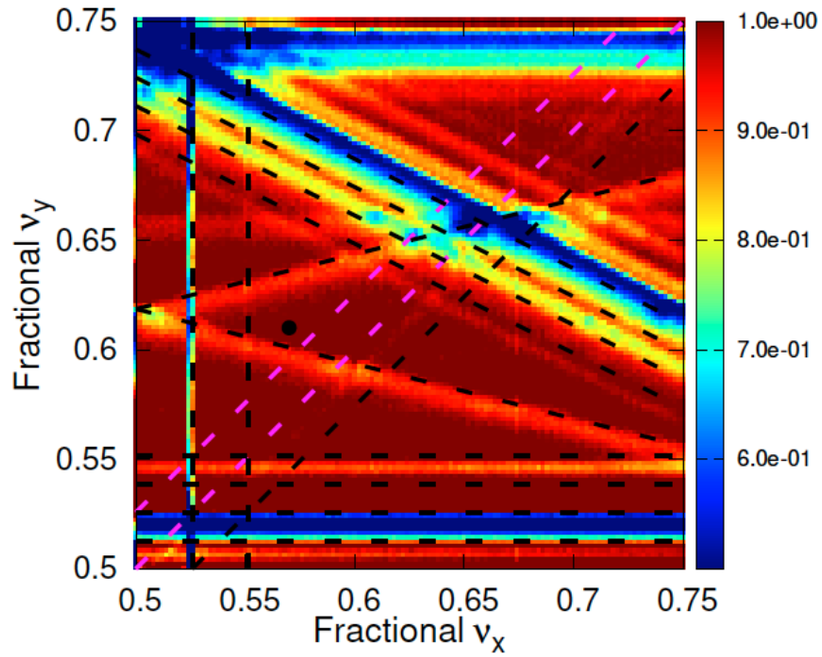


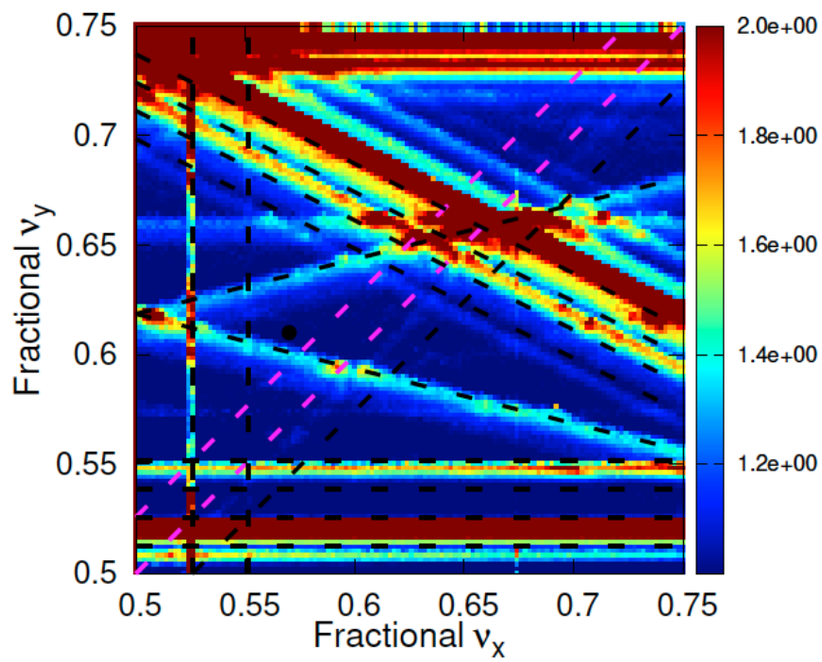
σ_y/σ_{y0} (RMS)



	1		1(op1)	
	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.2
# bunch	1576		1576	
ε_x (nm)	4.6	2.0	4.6	2.0
ε_y (pm)	368	160	160	160
β_x (mm)	100	100	100	230
β_y (mm)	3	3	3	3
σ_z (mm)	6	6	6	6
σ_y (nm)	1051	693	693	693
ν_x	45.57	44.57	45.57	44.57
ν_y	43.61	46.61	43.61	46.61
ν_s	0.0258	0.0225	0.0258	0.0225
ξ_y(Geom.)	0.0272	0.0262		
$\mathcal{L}$(Geom.)	1.06E+34		1.36E+34	
$\mathcal{L}$(BBSS)	1.00E+34		9.30E+33	

e+(S)e-(W)



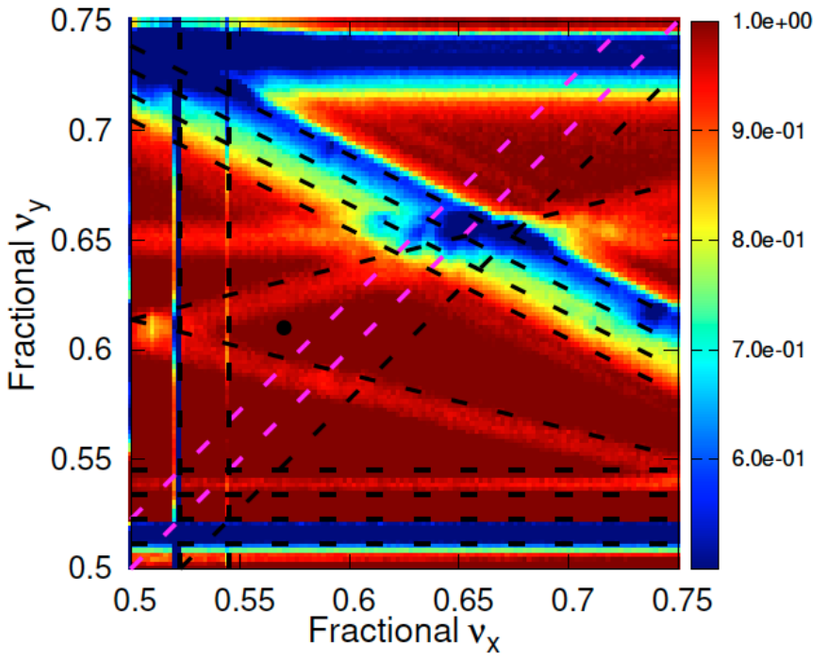


2. BBWS simulation: Tune scan

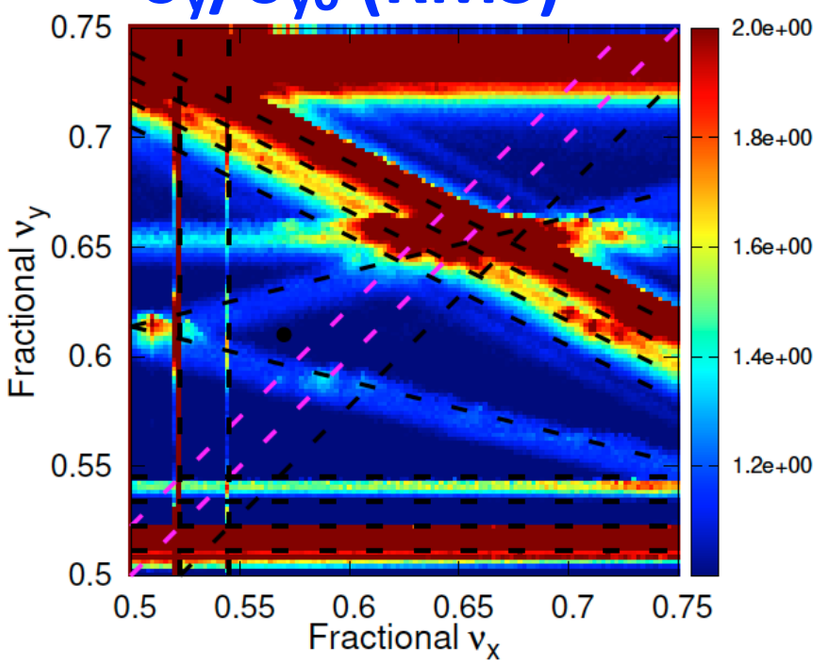
➤ Parameter set (1(op2))

e+(W)e-(S)

Lum. (L/L_0)

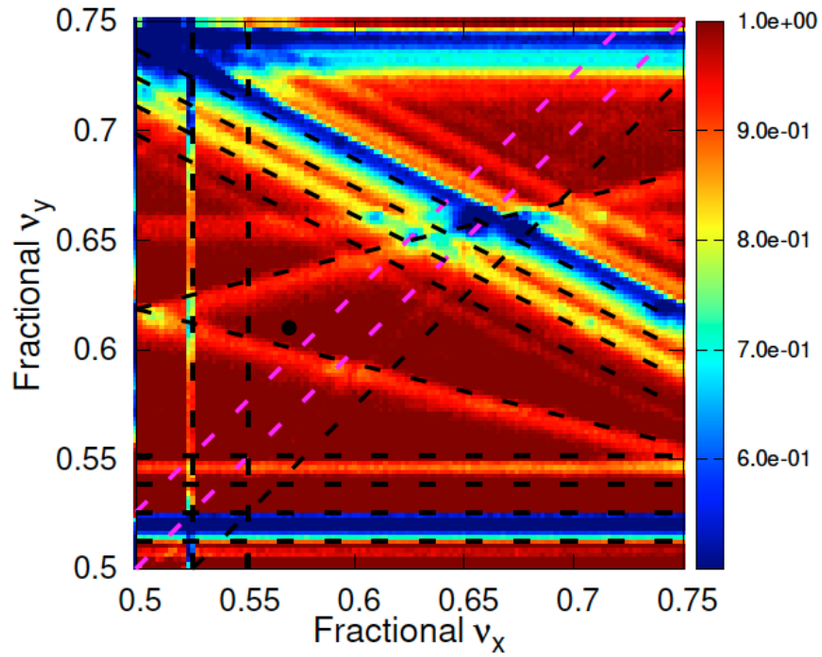


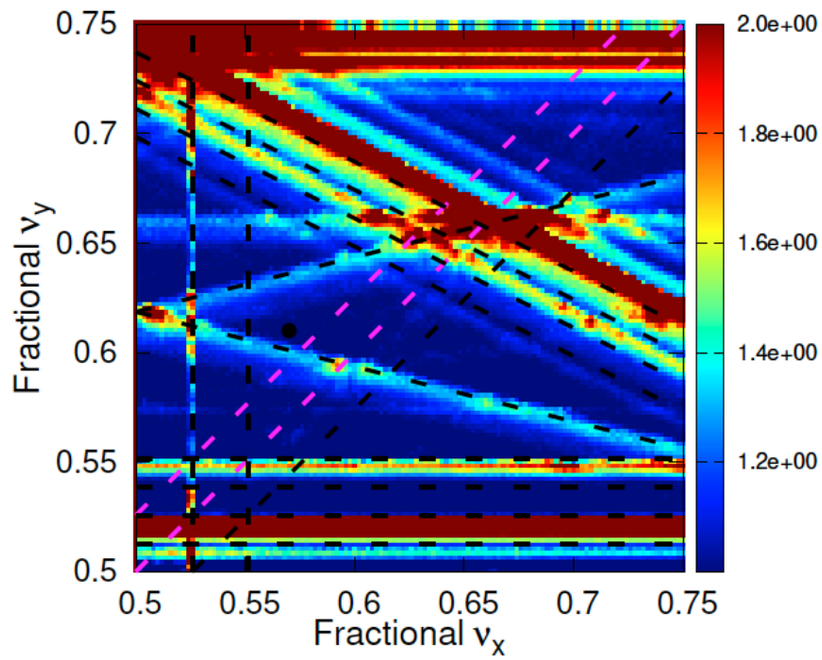
σ_y/σ_{y0} (RMS)



	1(op1)		1(op2)	
	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.2
# bunch	1576		1576	
ε_x (nm)	4.6	2.0	4.6	2.0
ε_y (pm)	160	160	160	160
β_x (mm)	100	230	80	80
β_y (mm)	3	3	3	3
σ_z (mm)	6	6	6	6
σ_y (nm)	693	693	693	693
ν_x	45.57	44.57	45.57	44.57
ν_y	43.61	46.61	43.61	46.61
ν_s	0.0258	0.0225	0.0258	0.0225
ξ_y(Geom.)				
$\mathcal{L}$(Geom.)	1.36E+34		1.37E+34	
$\mathcal{L}$(BBSS)	9.30E+33		1.34E+34	

e+(S)e-(W)



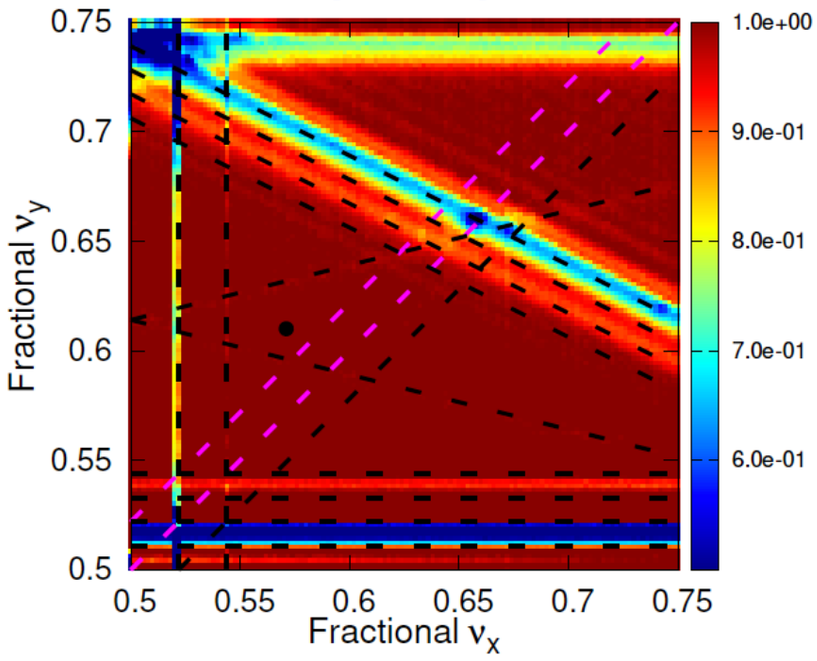


2. BBWS simulation: Tune scan

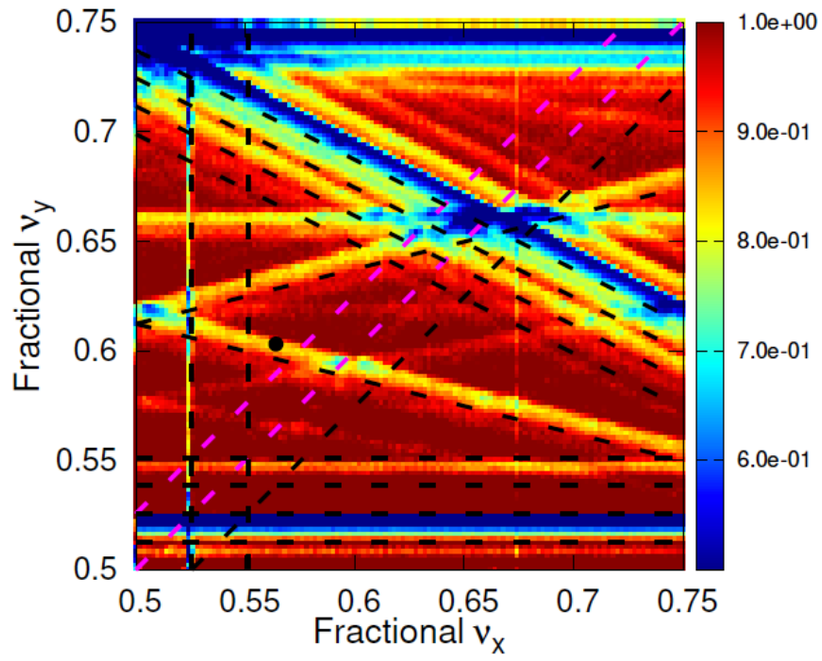
➤ **Parameter set (2019.03.30)**

e+(W)e-(S)

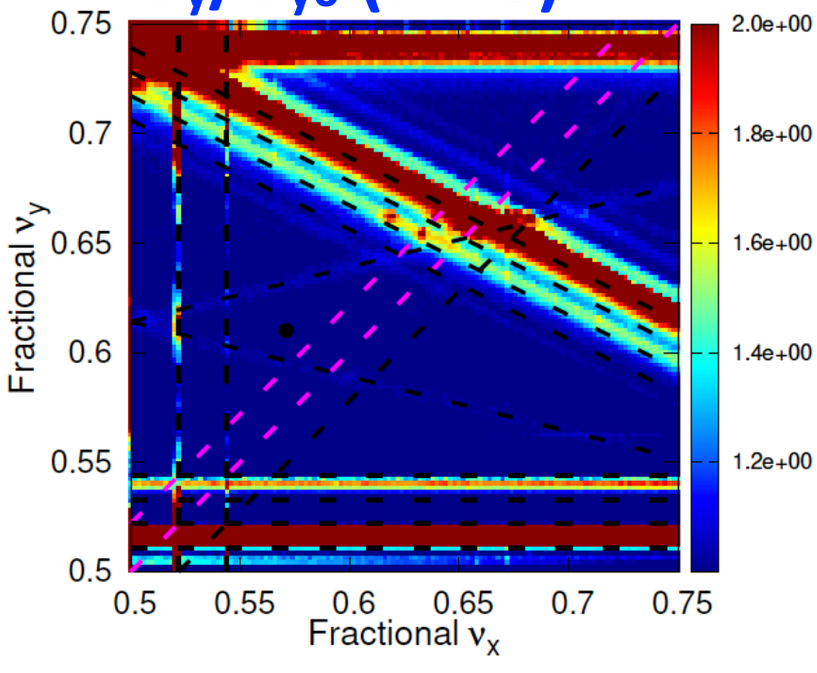
Lum. (L/L_0)

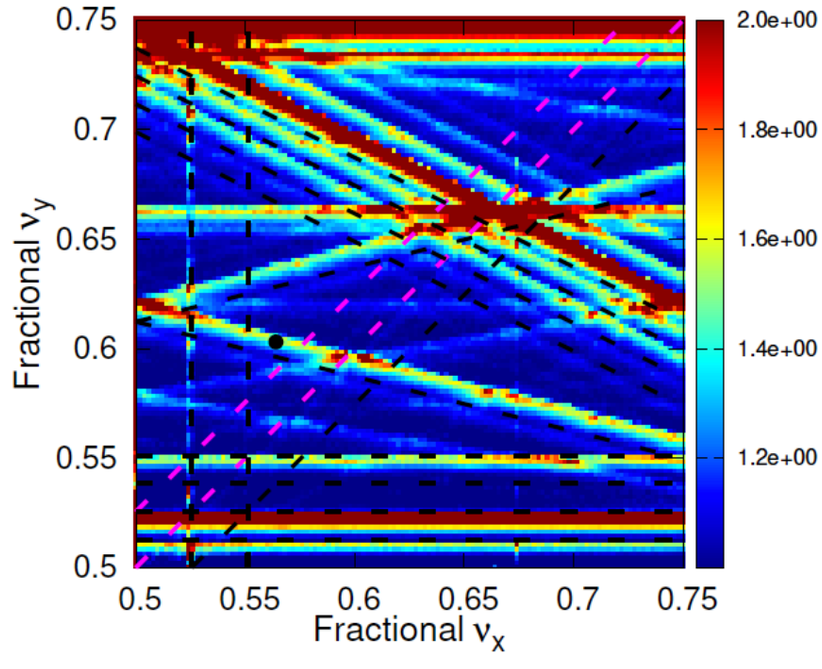


e+(S)e-(W)



σ_y/σ_{y0} (RMS)



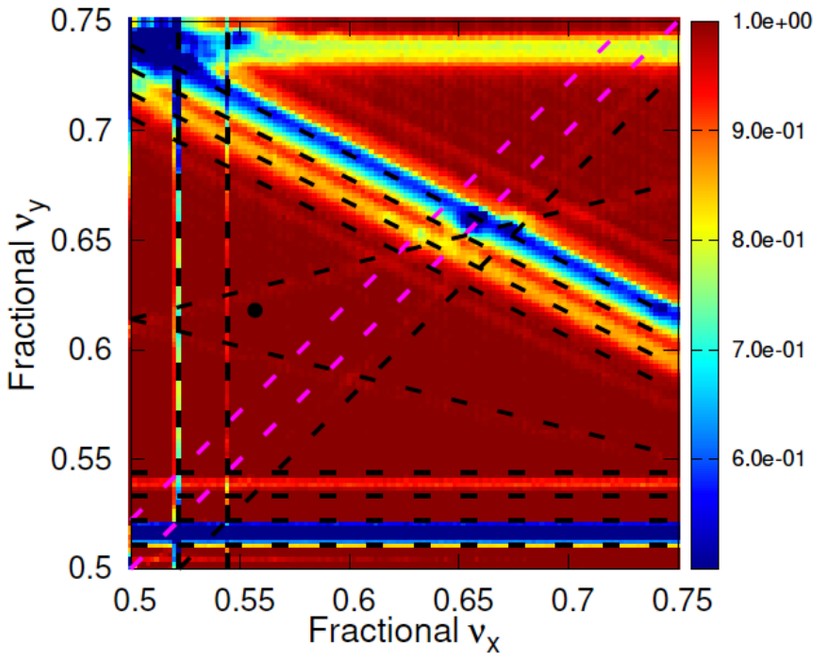


2. BBWS simulation: Tune scan

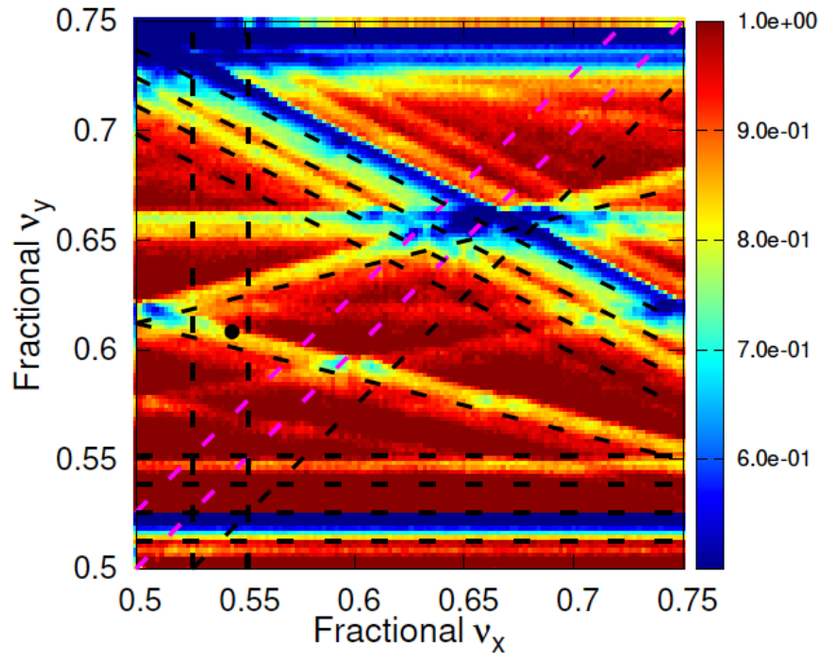
➤ **Parameter set (2019.04.02)**

e+(W)e-(S)

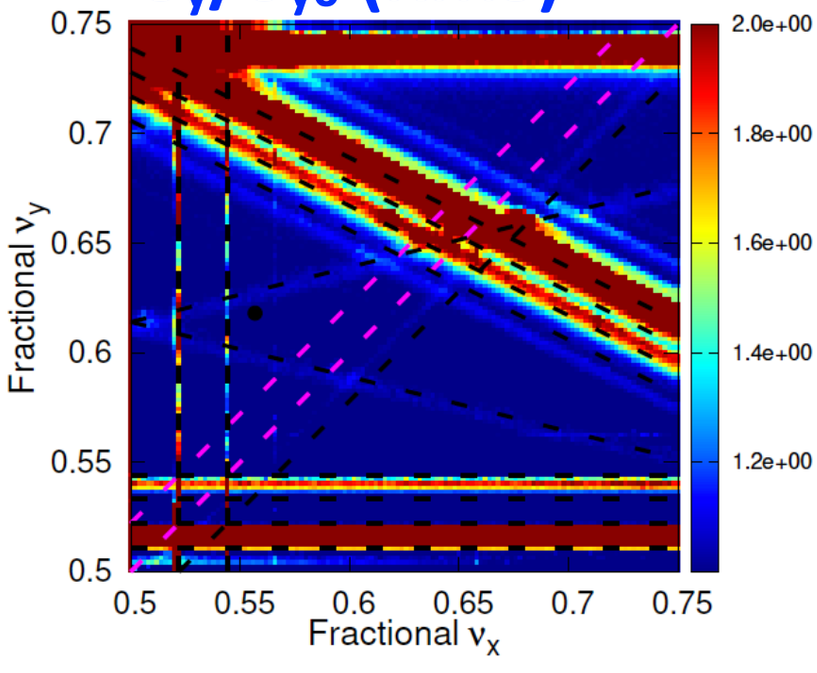
Lum. (L/L_0)

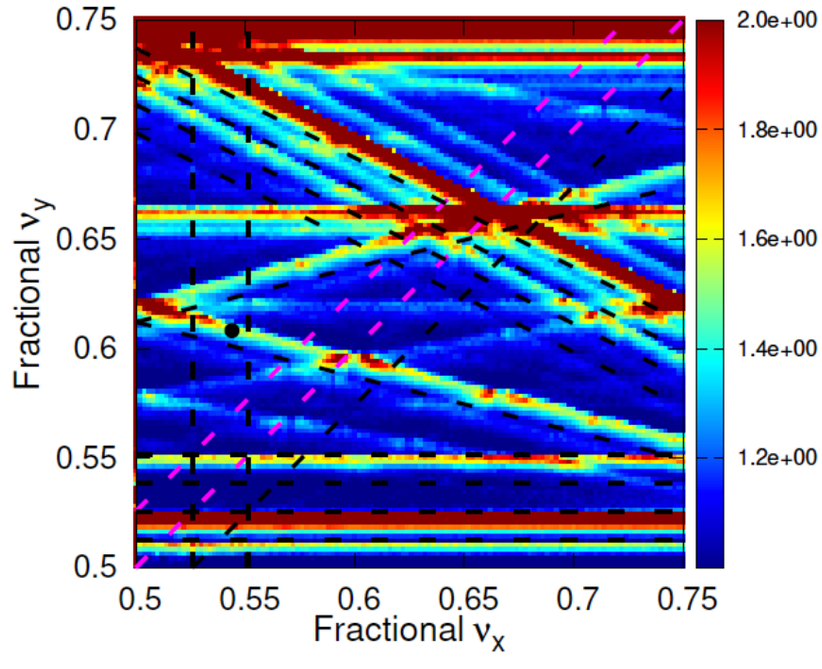


e+(S)e-(W)



σ_y/σ_{y0} (RMS)



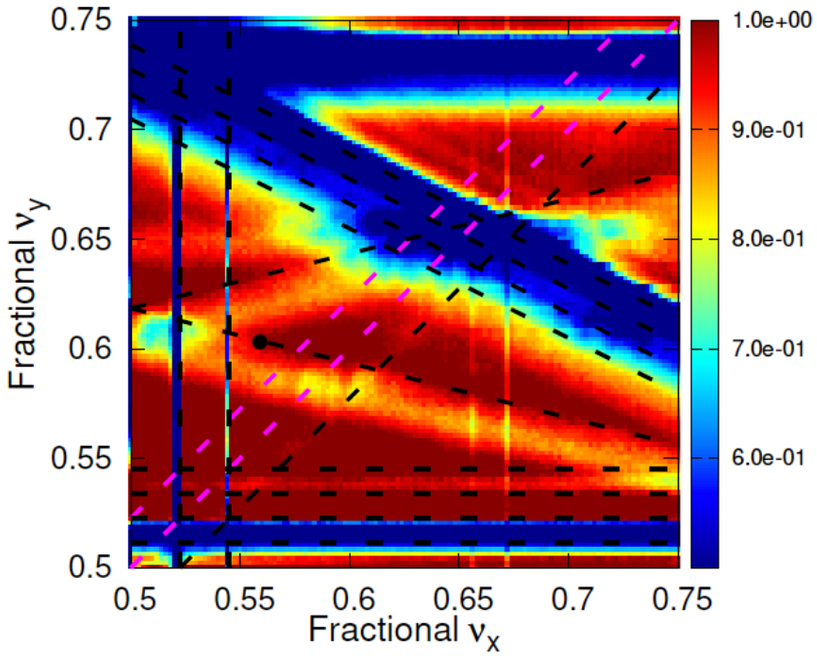


2. BBWS simulation: Tune scan

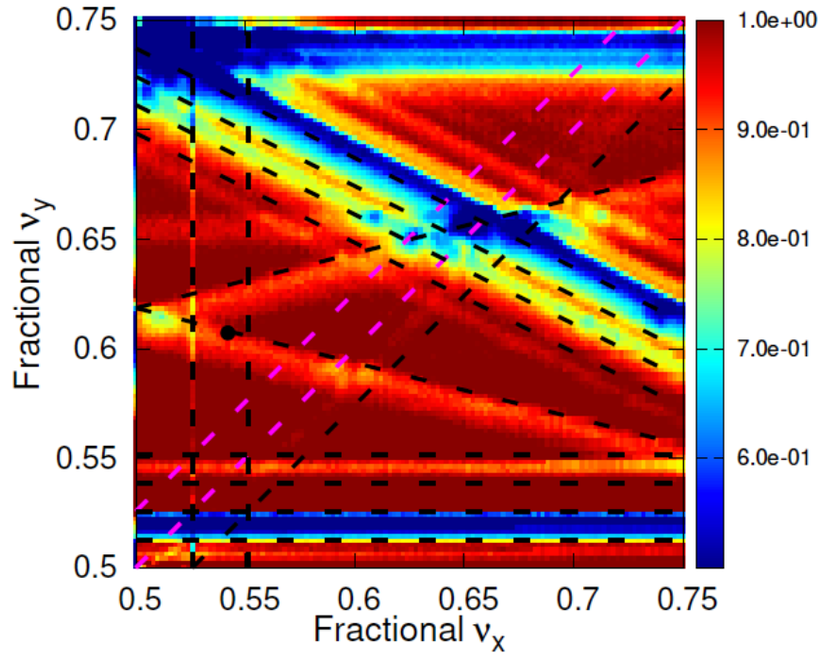
➤ **Parameter set (2018.07.13, 11:00 AM)**

e+(W)e-(S)

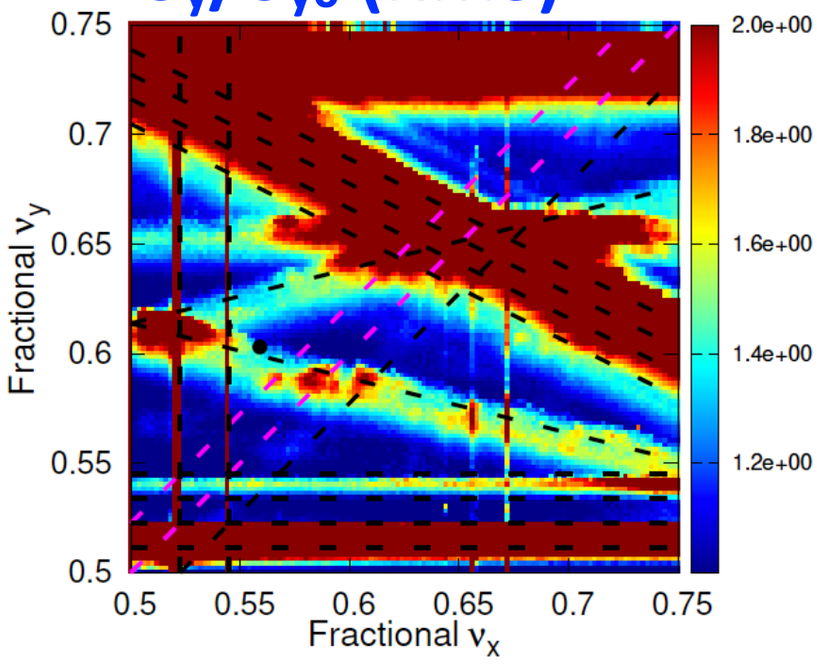
Lum. (L/L_0)

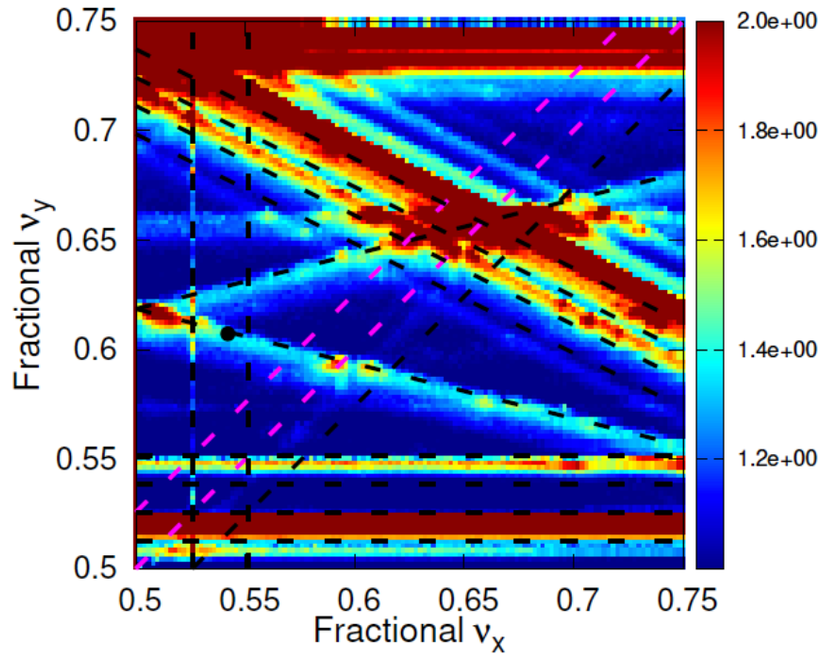


e+(S)e-(W)



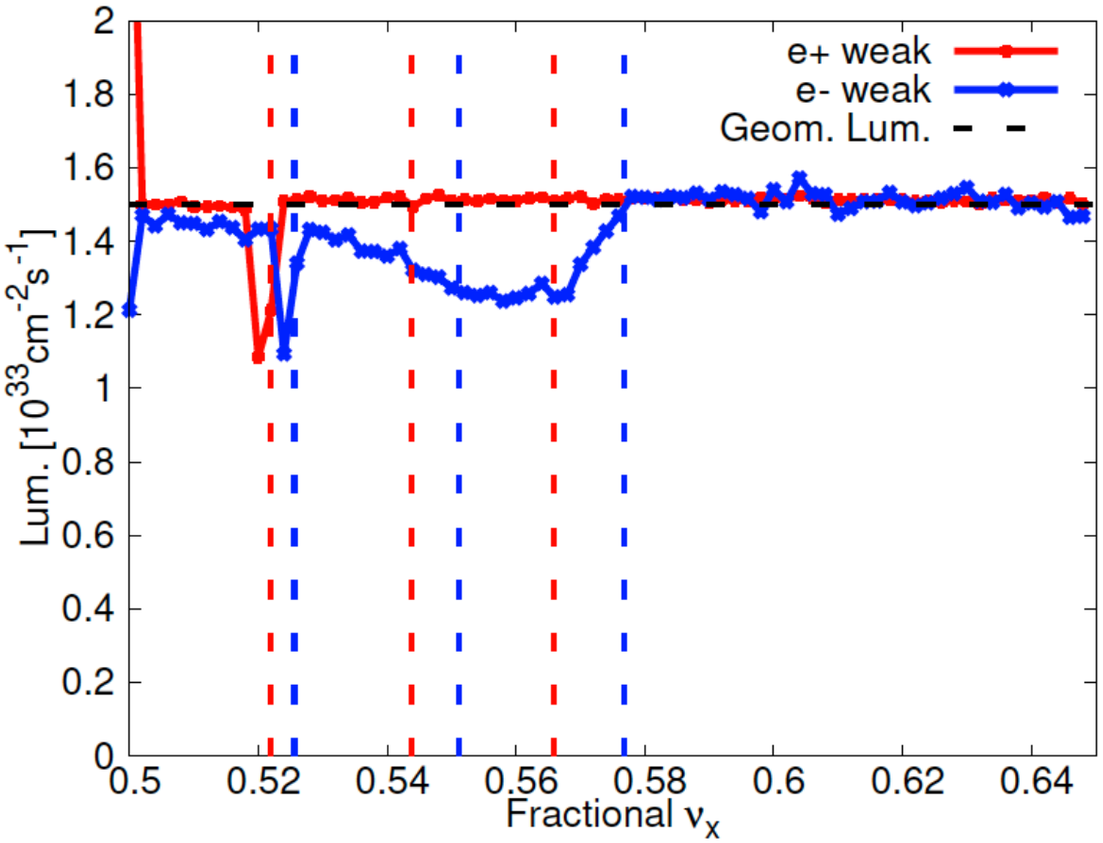
σ_y/σ_{y0} (RMS)

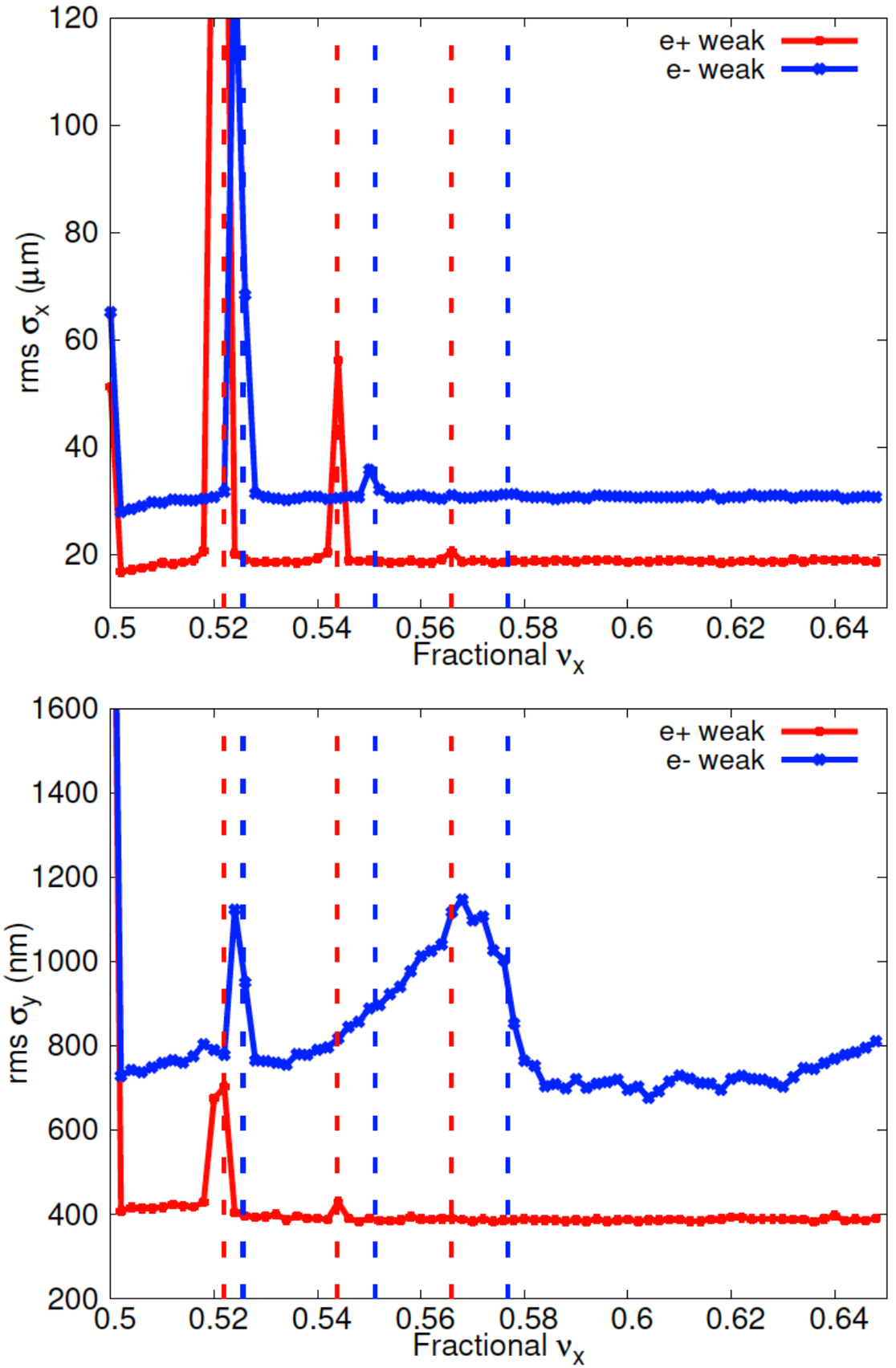




2. BBWS simulation: Tune scan

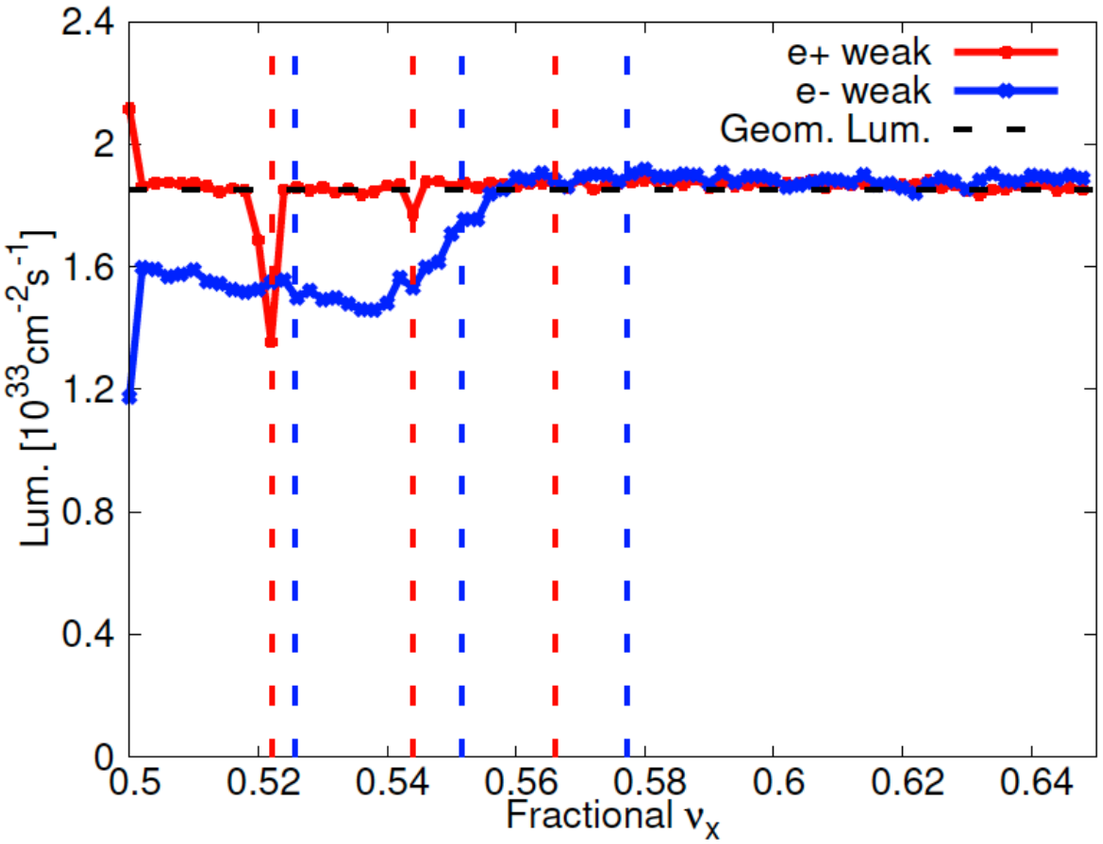
➤ **Parameter set (2019.03.30)**

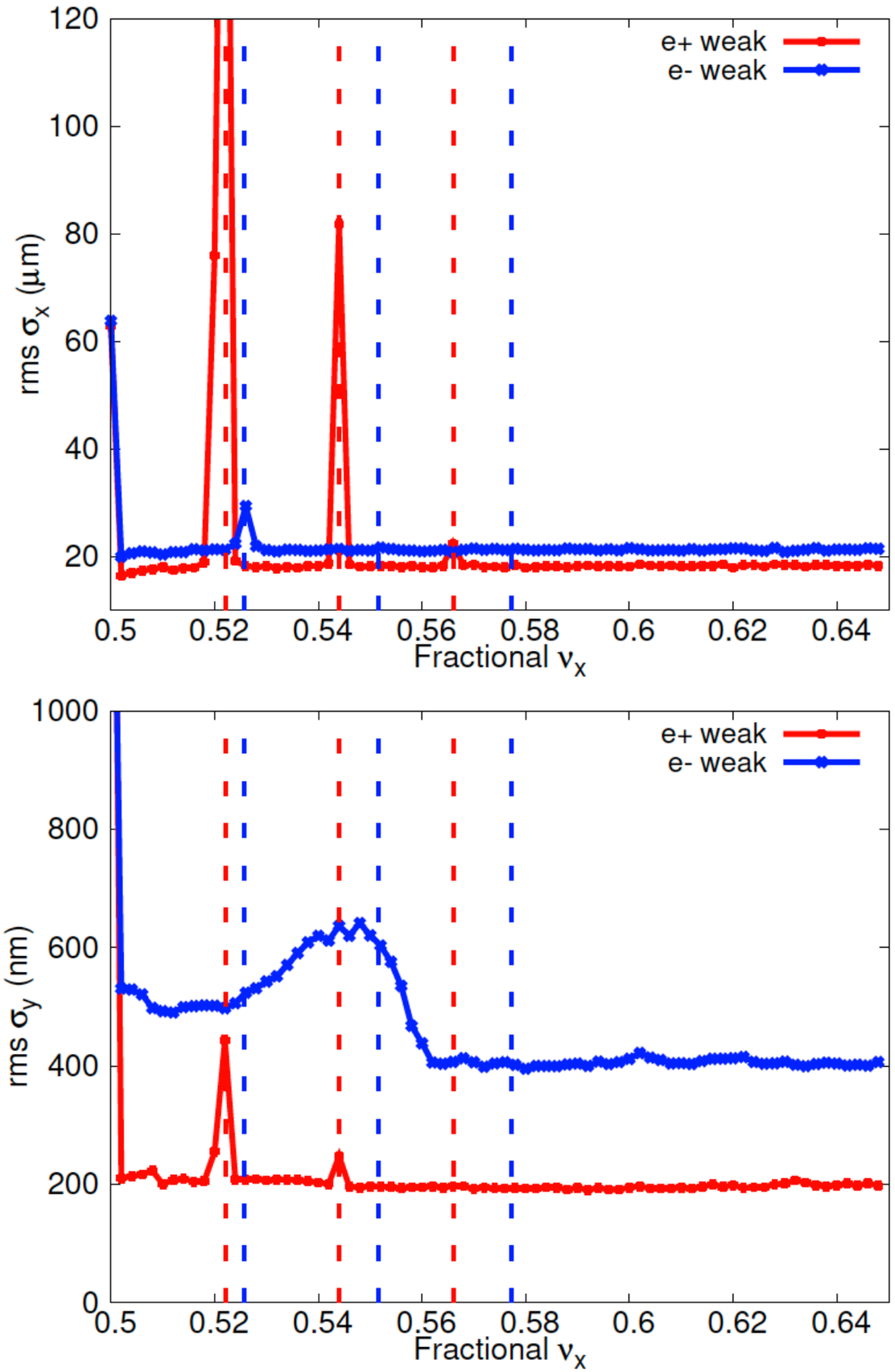




2. BBWS simulation: Tune scan

➤ **Parameter set (2019.04.02)**

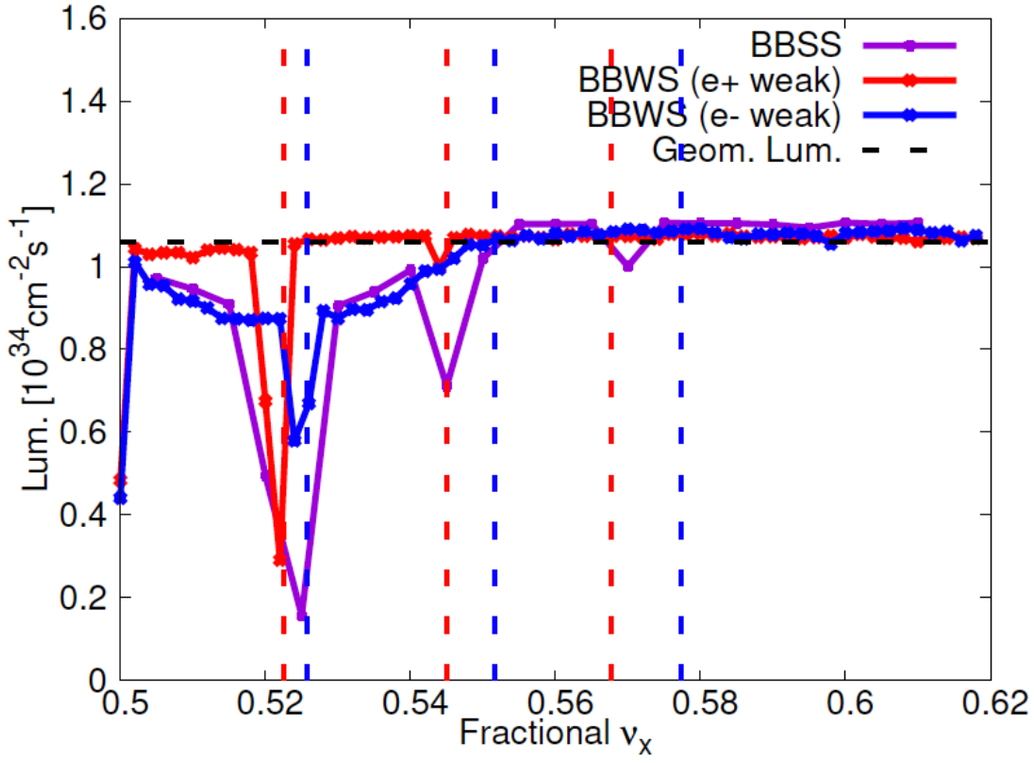


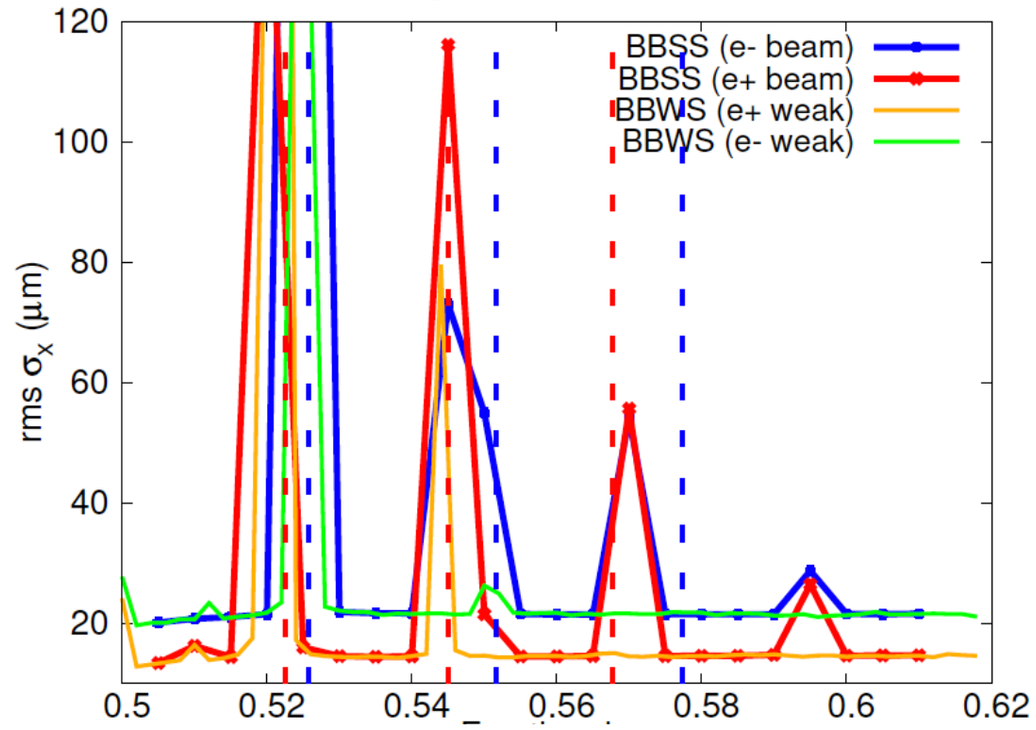


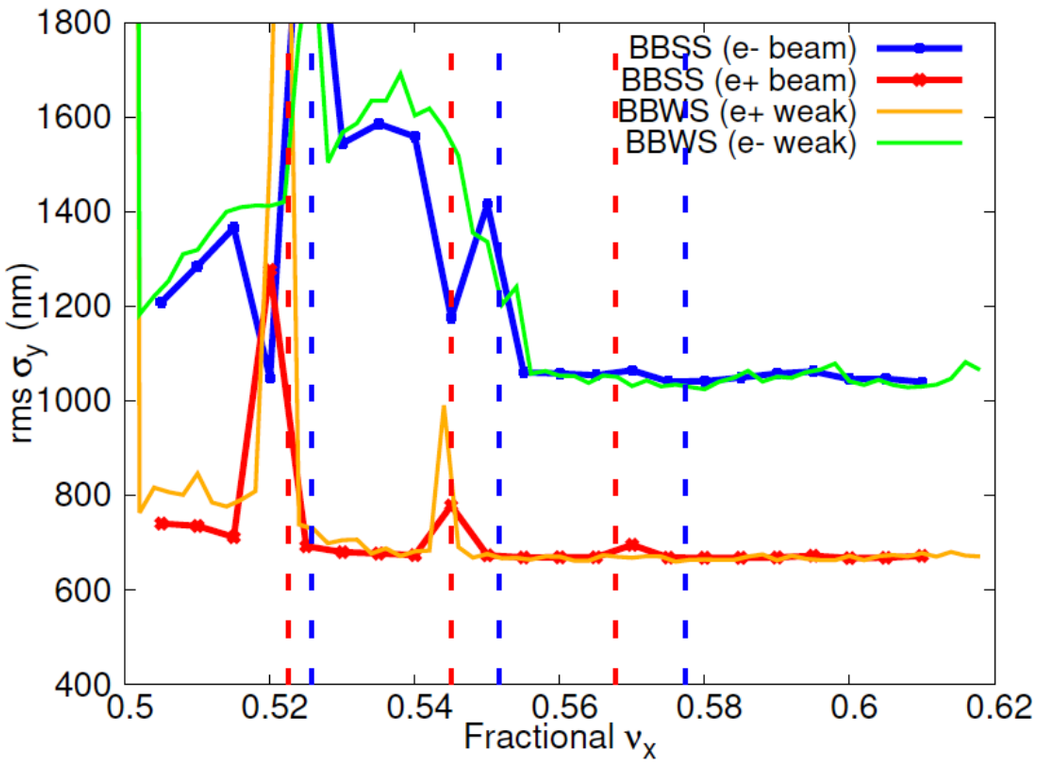
3. BBSS simulation

➤ Parameter set (1): ν_y=*.61

- **Scan of ν_x (same fractional part for LER and HER)**



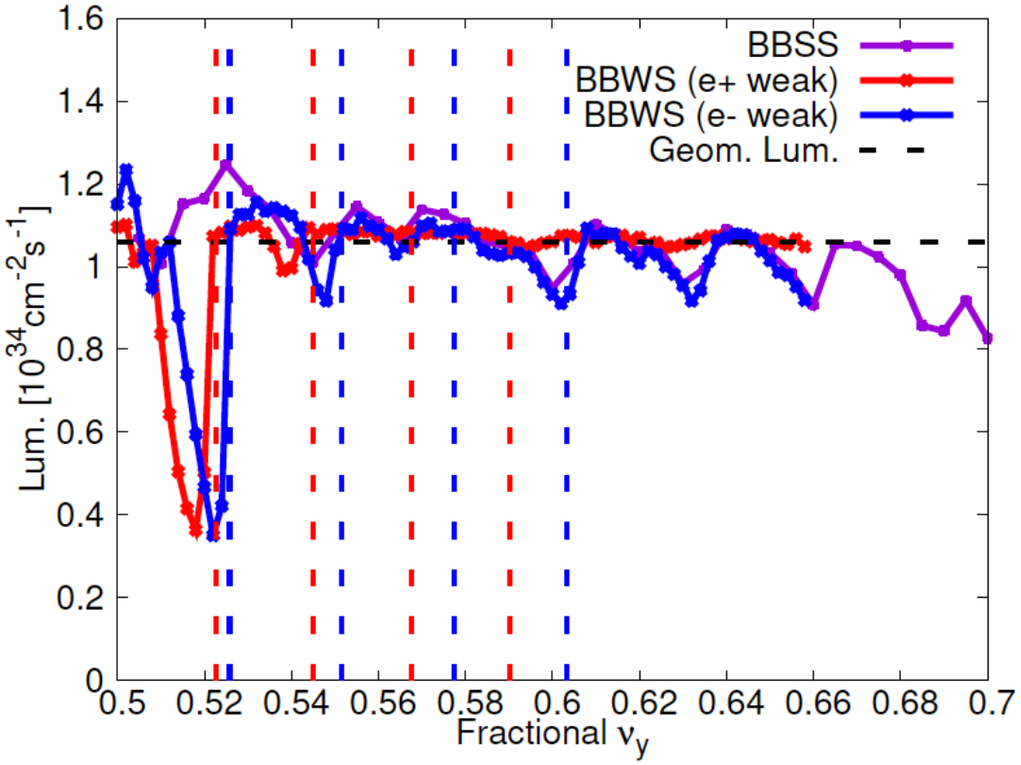


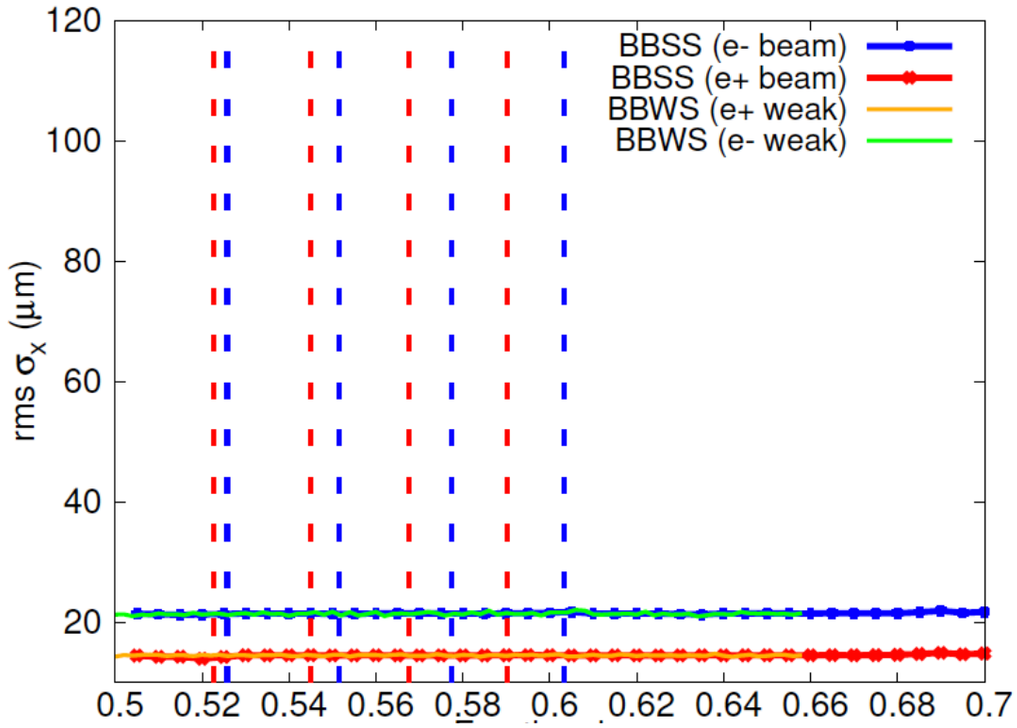


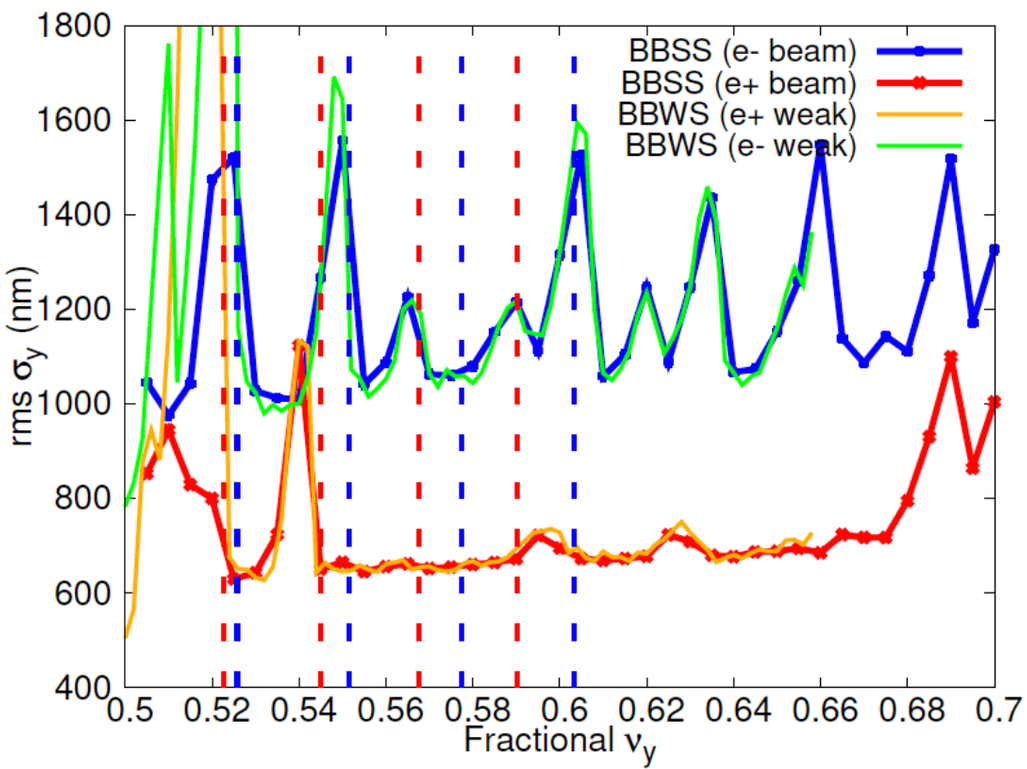
3. BBSS simulation

➤ Parameter set (1): ν_x=*.56

- Scan of ν_y (same fractional part for LER and HER)
- Beam very unstable for ν_y<*.53







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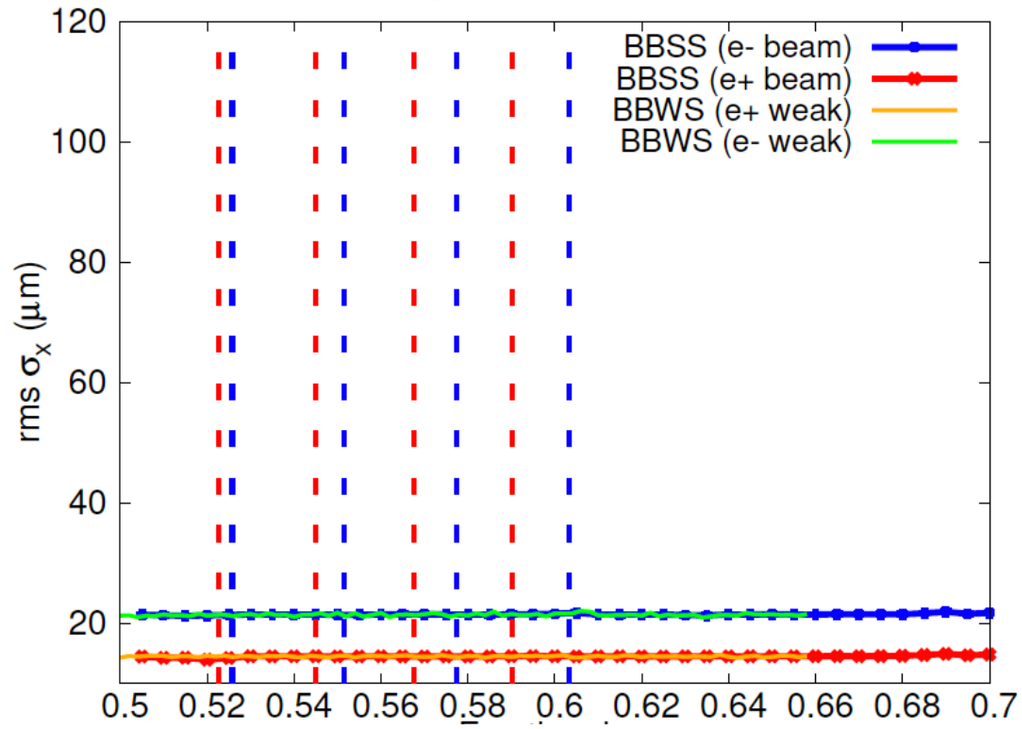
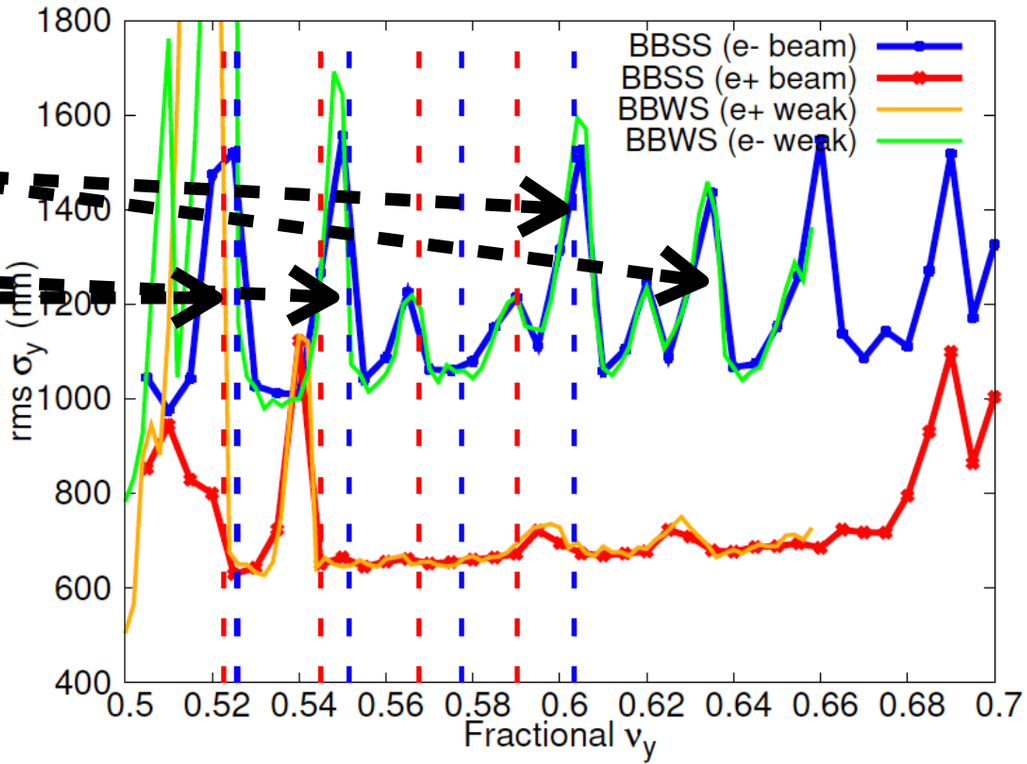
e+(S)e-(W)

σ_y/σ_{y0} (RMS)



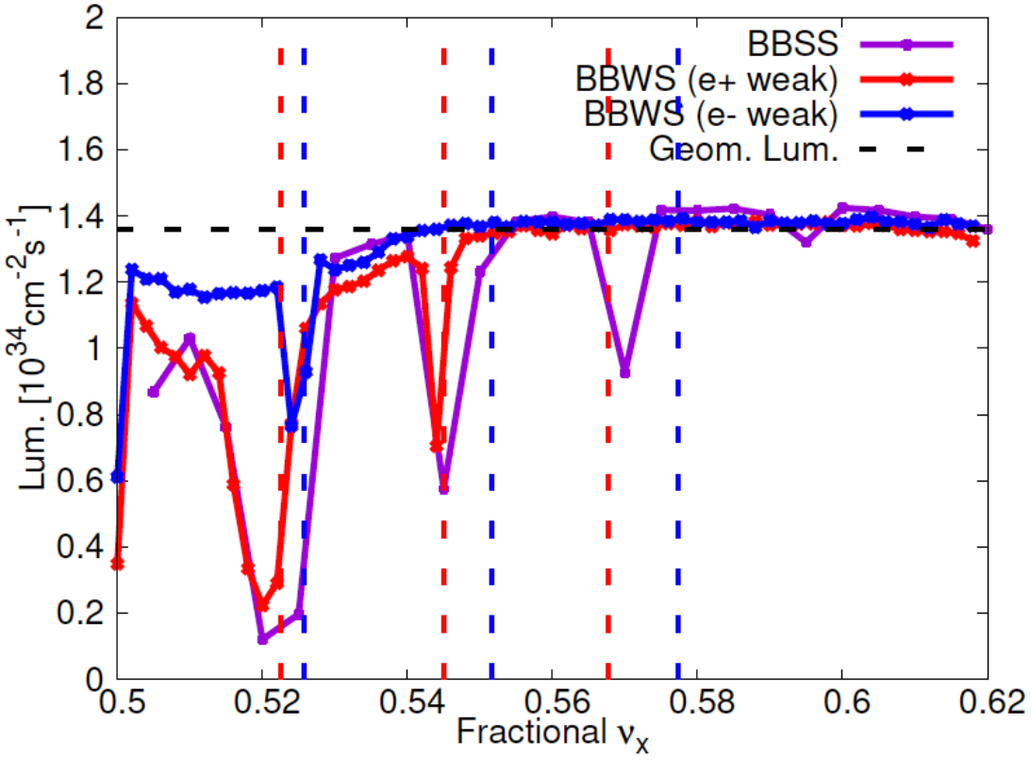


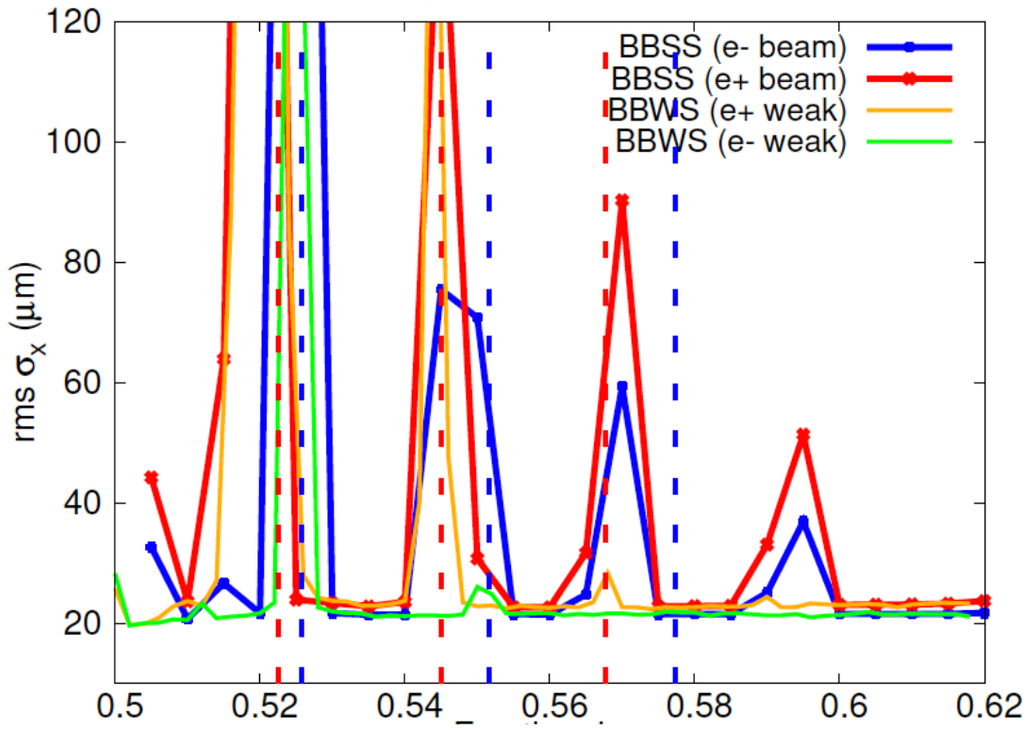
3. BBSS simulation

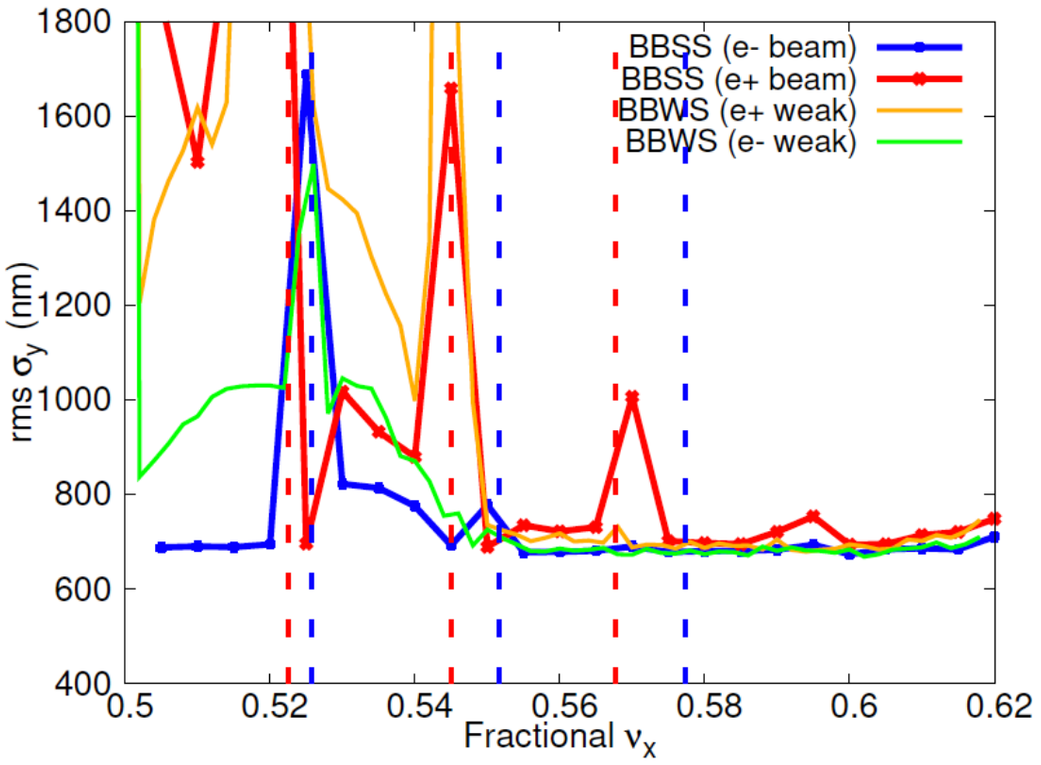
➤ Parameter set (1(op1)): ν_y=*.61

- **Scan of ν_x (same fractional part for LER and HER)**

Change parameters(1 -> 1(op1)):
β^*_{x+}=0.1 m -> 0.23 m (equalize σ^*_x)
ε_{y-}=0.368 nm -> 0.16 m (equalize σ^*_y)







3. BBSS simulation

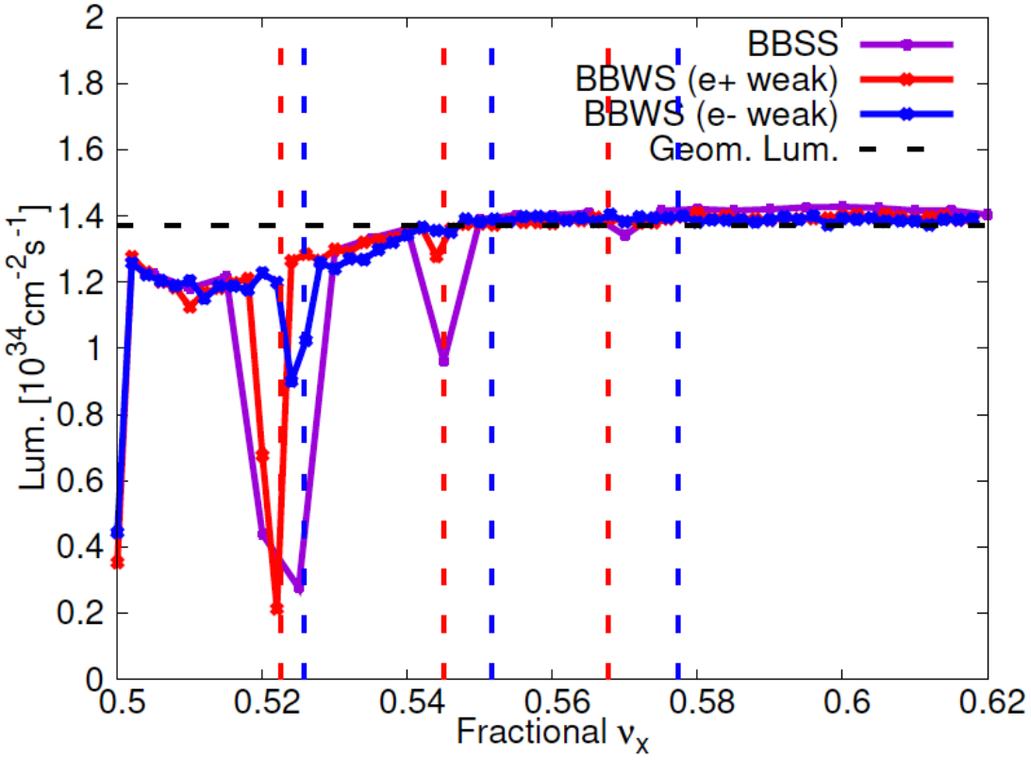
➤ Parameter set (1(op2)): ν_y=*.61

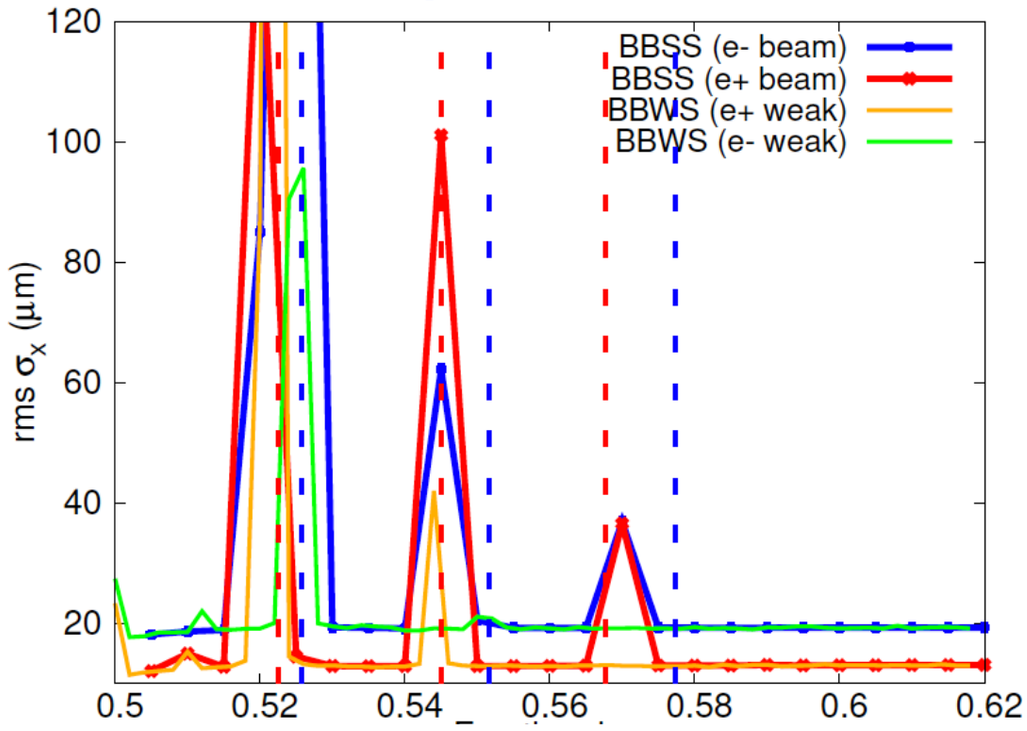
- **Scan of ν_x (same fractional part for LER and HER)**

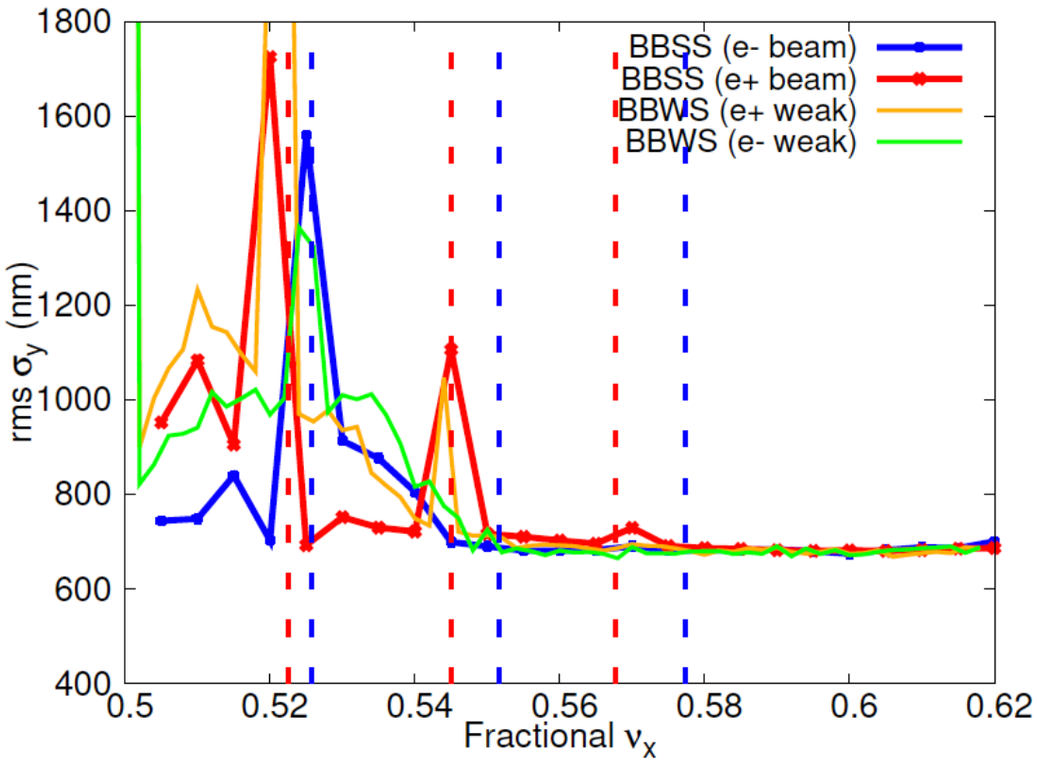
Change parameters(1 -> 1(op2)):

$\beta^*_{x-}=\beta^*_{x+}$=0.1 m -> 0.08 m (squeeze σ^*_x)

ε_{y-}=0.368 nm -> 0.16 m (equalize σ^*_x)



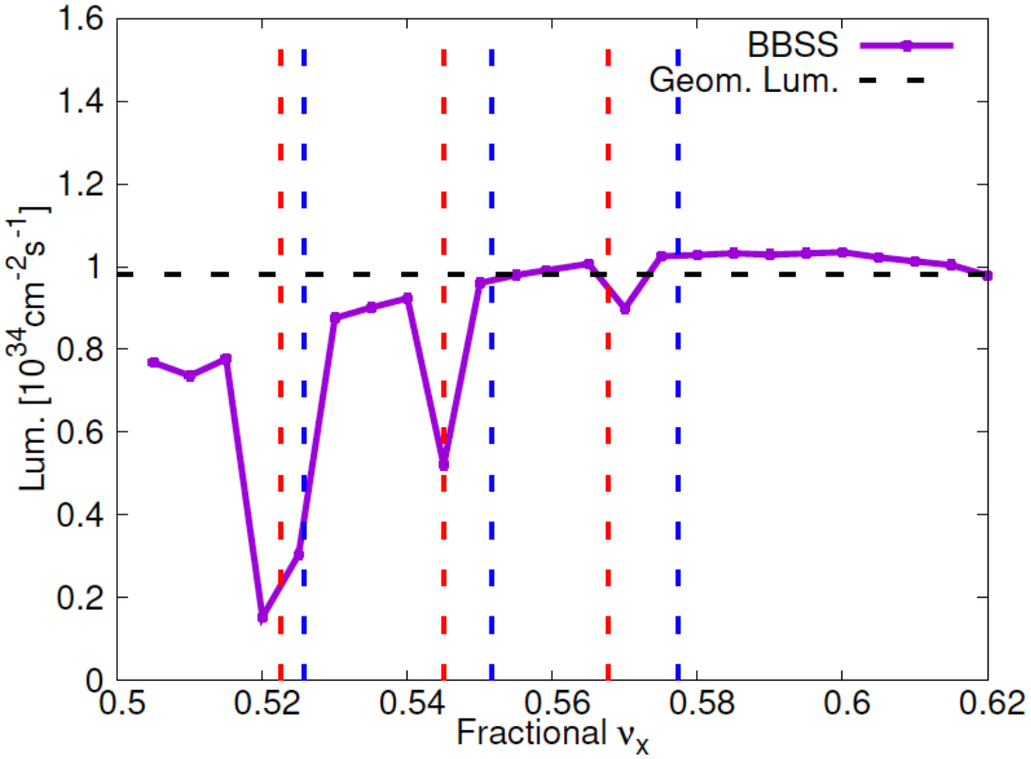


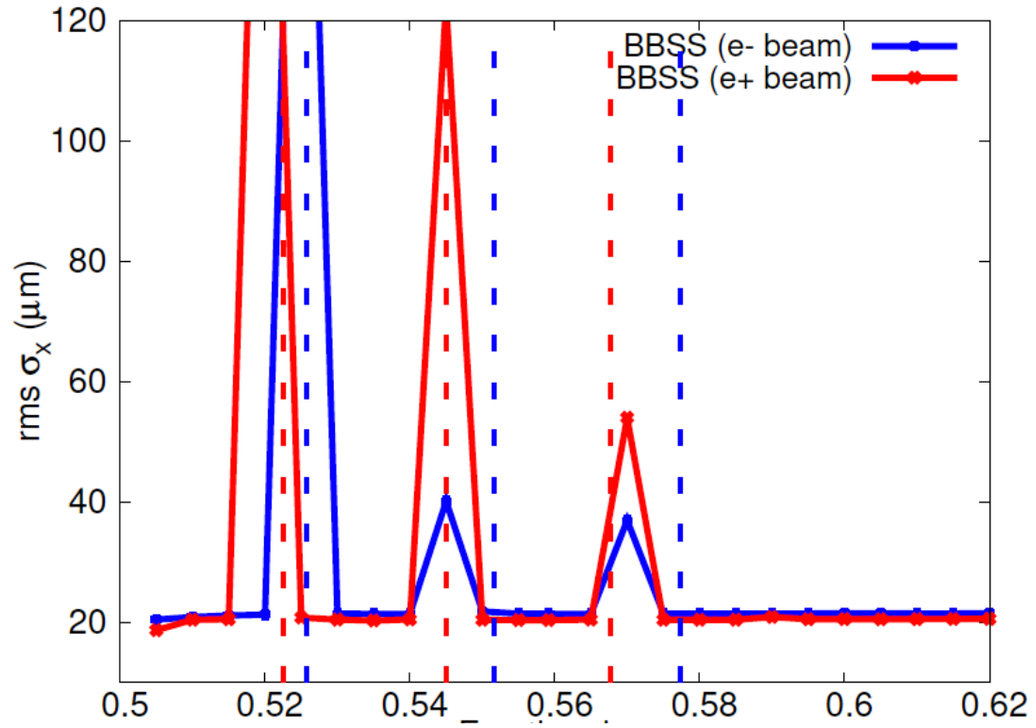


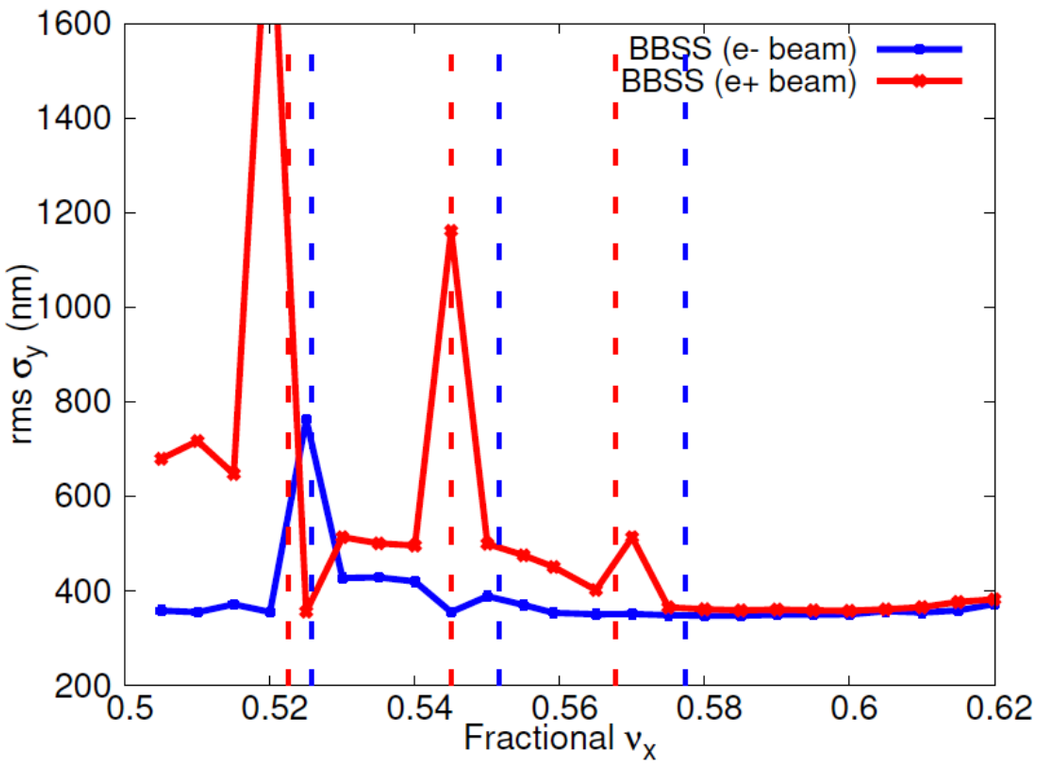
3. BBSS simulation

➤ Parameter set (2018.07.13, 11:00 AM): $\nu_y \approx *.605$

- **Scan of ν_x (same fractional part for LER and HER)**







4. Summary

➤ **Findings from beam-beam simulations**

- **The luminosity and beam stability of SuperKEKB suffer from beam-beam driven resonances:**
  - * ν_x-{1,2,3,4}ν_s=N/2
  - * {+-}ν_x+4ν_y+α=N (Observed with beams, K. Ohmi, 2019.03.31)
- **General agreements found between BBSS and BBWS**
- **Coherent beam-beam instability or emittance growth needs strong-strong simulations (BBSS)**

4. Summary

➤ "Crab waist" scheme

- **The crab waist Hamiltonian: H=a*x*p_y^2**

$$K \propto \frac{\sqrt{\beta_x^*}}{\beta_y^*}$$

- **Implications of weakening beam-beam resonances:**

*** To Squeeze β_x^* : No loss of luminosity (ε_x is almost a given constant, only depending on optics design)**

*** To increase β_y^* (similar to blowing up ε_y): Decease of blow-up ratio σ_y/σ_{y0}, but with direct loss of luminosity**

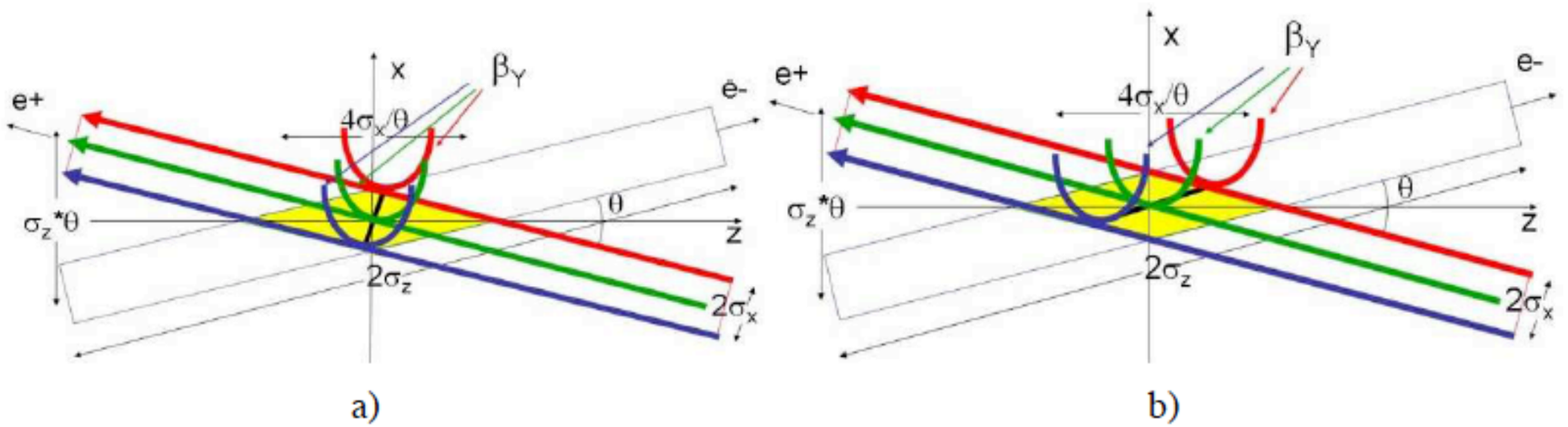


Figure 1. Crab Waist collision scheme: a) crab sextupoles OFF; b) crab sextupoles ON.

Ref. M. Zobov, arXiv:1608.06150 [physics.acc-ph]

4. Summary

➤ Personal comments

- Squeezing βx* is essential in suppressing beam-beam resonances:
  * ν_x-{1,2,3,4}ν_s=N/2
  * ν_x{+-}4ν_y+α=N
- Need to look at the analytical theory of beam-beam resonances