Simulations of beam-beam effects

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Acknowledgements:

the SuperKEKB team

2nd SuperKEKB Beam Dynamics Mini-Workshop

Sep. 20, 2019, KEK

1. Introduction

➤ Phase 3-1 machine parameters

- A few examples of parameter sets observed in the control room

	2019.06.25		2019.07.01		2019.07.01(op1)		2019.07.01(op2)		2019.07.01(op3)	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.05	0.03	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
# bunch	789		1576		1576		1576		1576	
ε_x (nm)	4.466	1.64	4.49	1.93	4.49	1.93	4.49	1.93	4.49	1.93
ε_y (pm)**	16.2	6.05	16.2	6.05	**40**	**6.05**	**16.2**	**40**	**40**	**40**
β_x (mm)	80	80	80	80	80	80	80	80	80	80
β_y (mm)	2	2	2	2	2	2	2	2	2	2
σ_z (mm)	5.05	4.66	5.5	5.2	5.5	5.2	5.5	5.2	5.5	5.2
σ_y (nm)	180	110	180	110	283	110	180	283	283	283
ν_x	45.5345	44.542	45.53	44.542	45.53	44.542	45.53	44.542	45.53	44.542
ν_y	43.5835	46.606	43.583	46.605	43.583	46.605	43.583	46.605	43.583	46.605
ν_s	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349
ξ_y(Geom.)	0.0073	0.012	0.088	0.089	0.057	0.089	0.034	0.089	0.034	0.057
$\mathcal{L}$(Geom.)	1.95E+32		3.78E+34		2.63E+34		2.38E+34		1.99E+34	

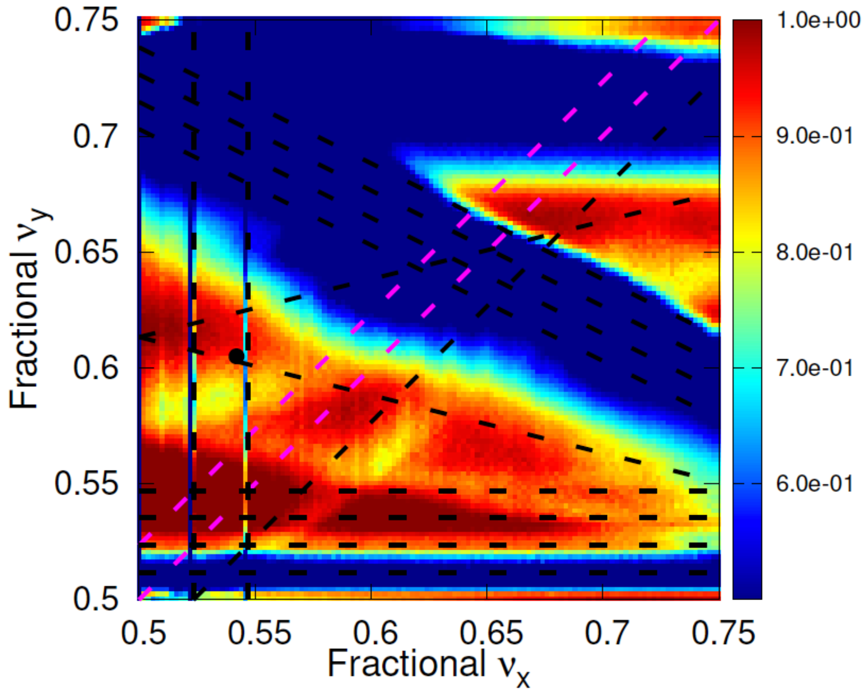
**Single beam emittance estimated from XRM data

2. BBWS simulation: Tune scan

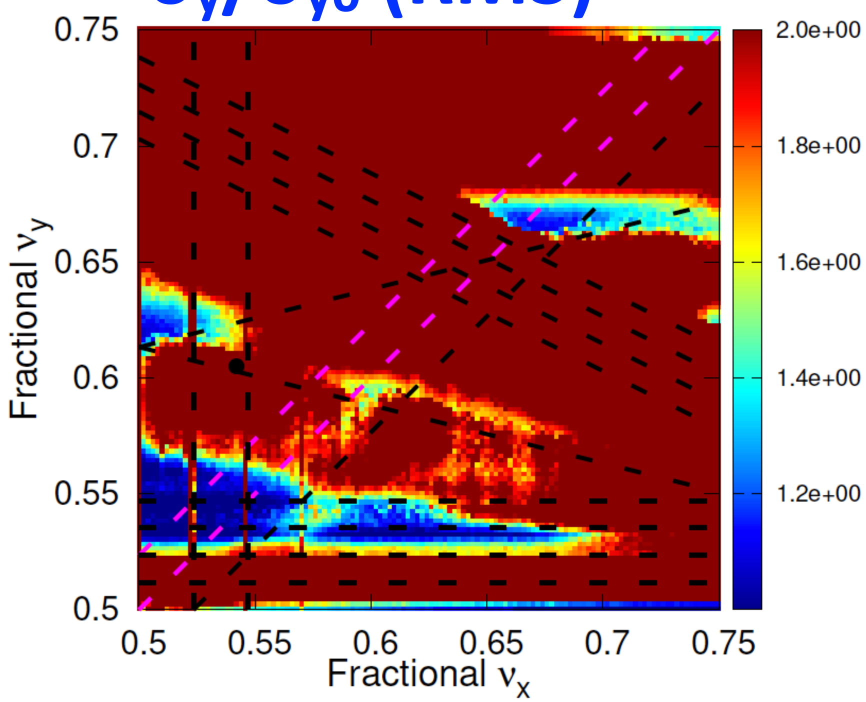
➤ Parameter set (2019.07.01)

e+(W)e-(S)

Lum. (L/L_0)

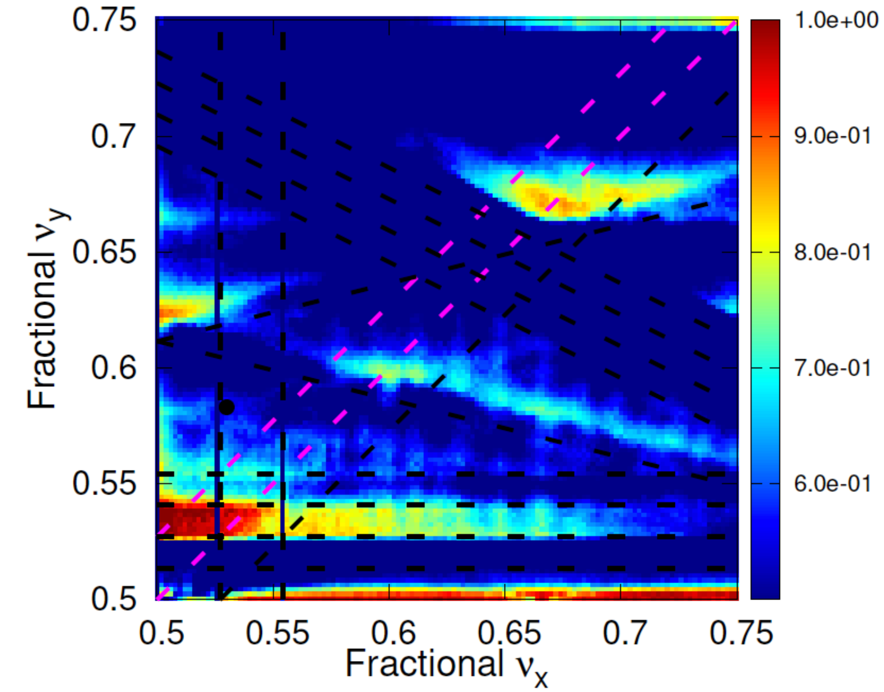


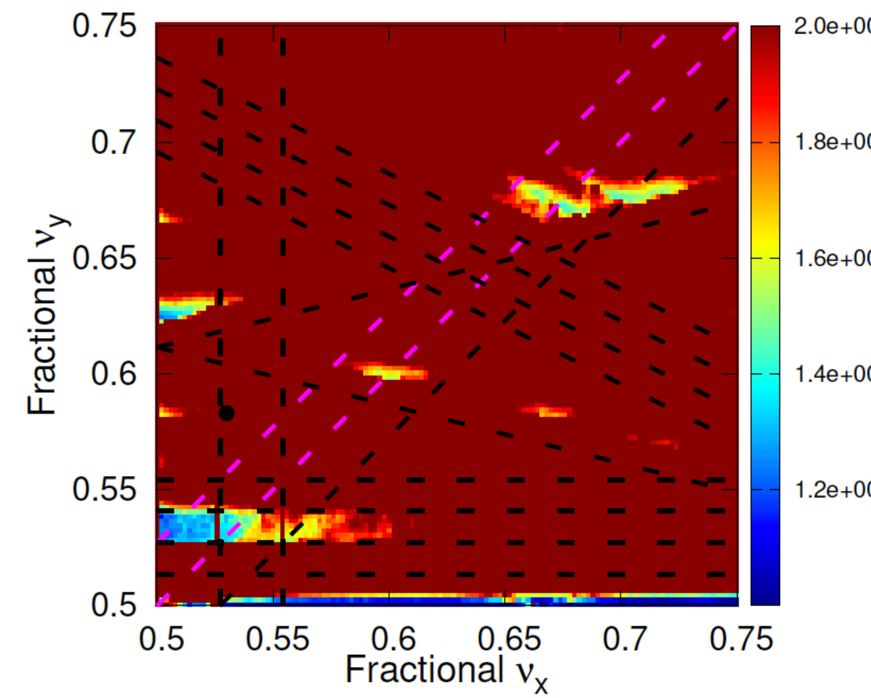
σ_y/σ_{y0} (RMS)



NOTE:
With small single beam vertical emittance, the challenge is the beam-beam tune shift is too large
=> It is too hard to find good working point for both beams
=> Both beams will blow up easily

e+(S)e-(W)



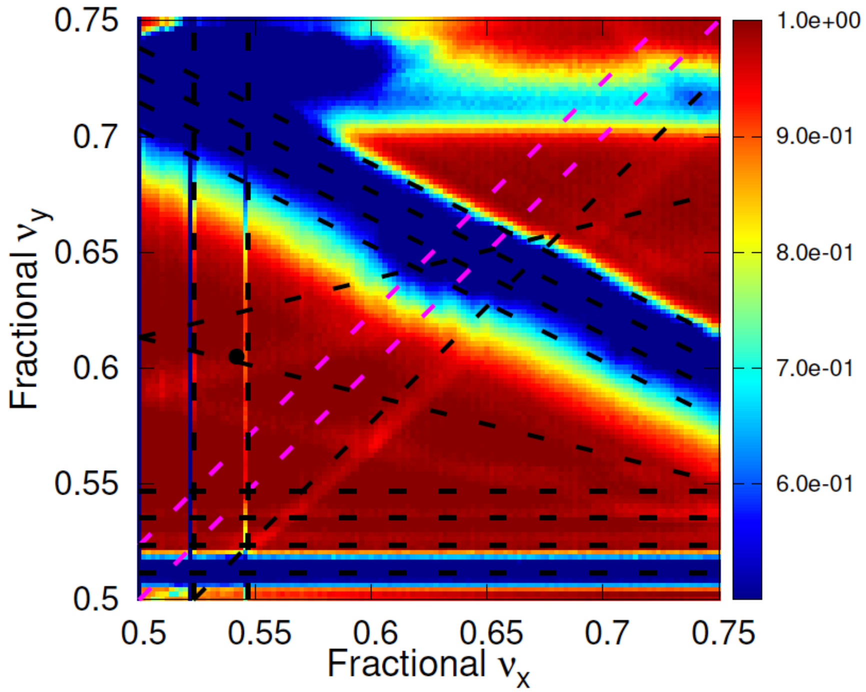


2. BBWS simulation: Tune scan

➤ **Parameter set (2019.07.01, op1 and op2)**

e+(W)e-(S)

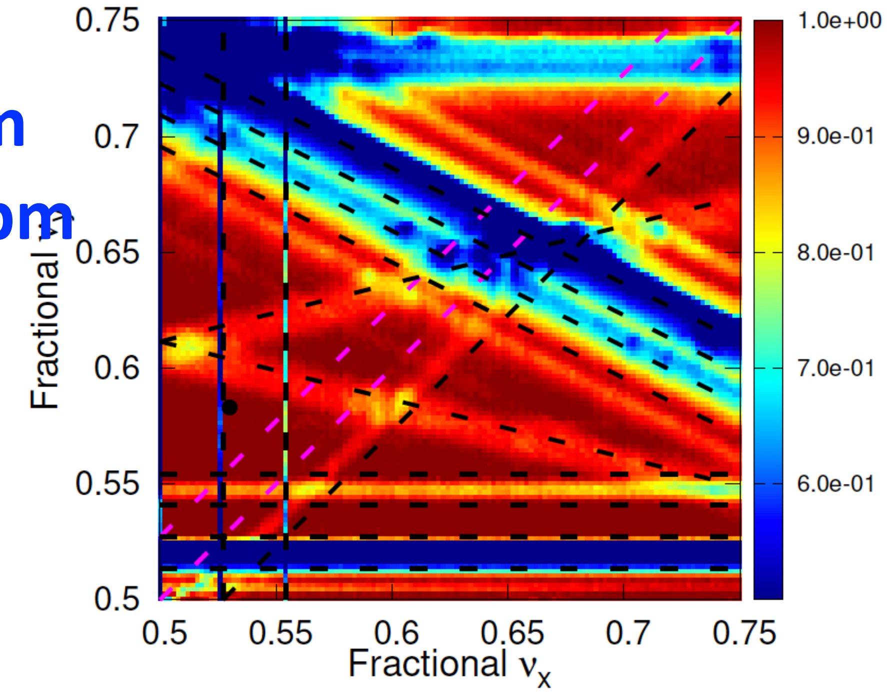
Lum. (L/L_0)



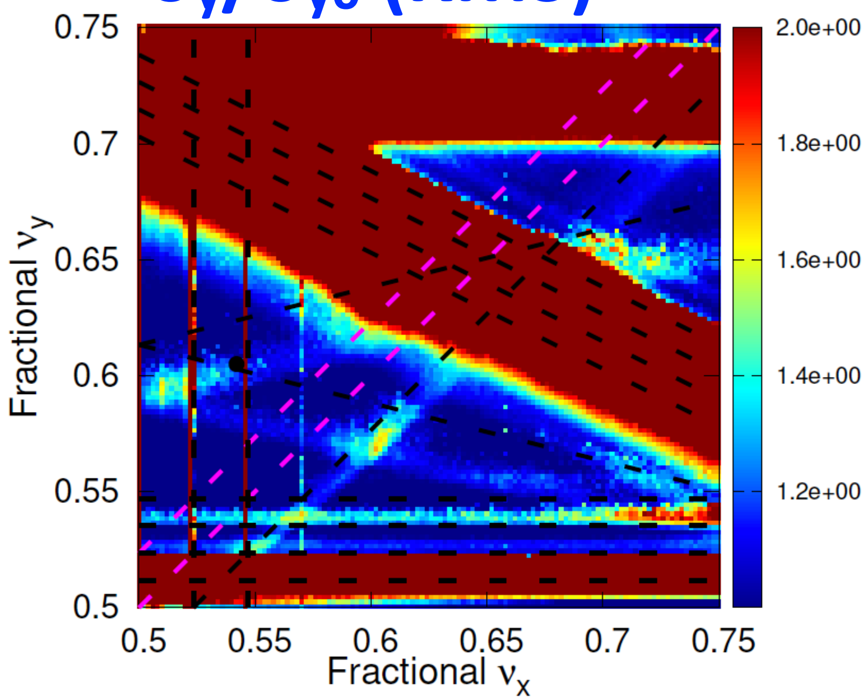
op1:
ε_{e+}=6.05 pm
ε_{e-}=40 pm

op2:
ε_{e+}=40 pm
ε_{e-}=16.2 pm

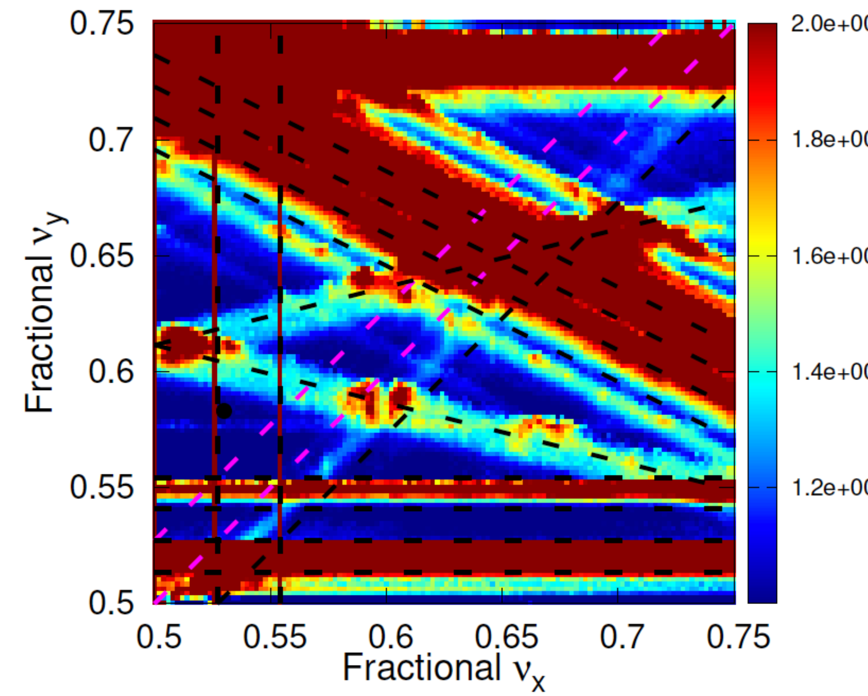
e+(S)e-(W)



σ_y/σ_{y0} (RMS)



NOTE:
Increasing emittance of the strong beam is similar to emittance knob control
=> It relaxes the beam-beam force felt by the opposite beam

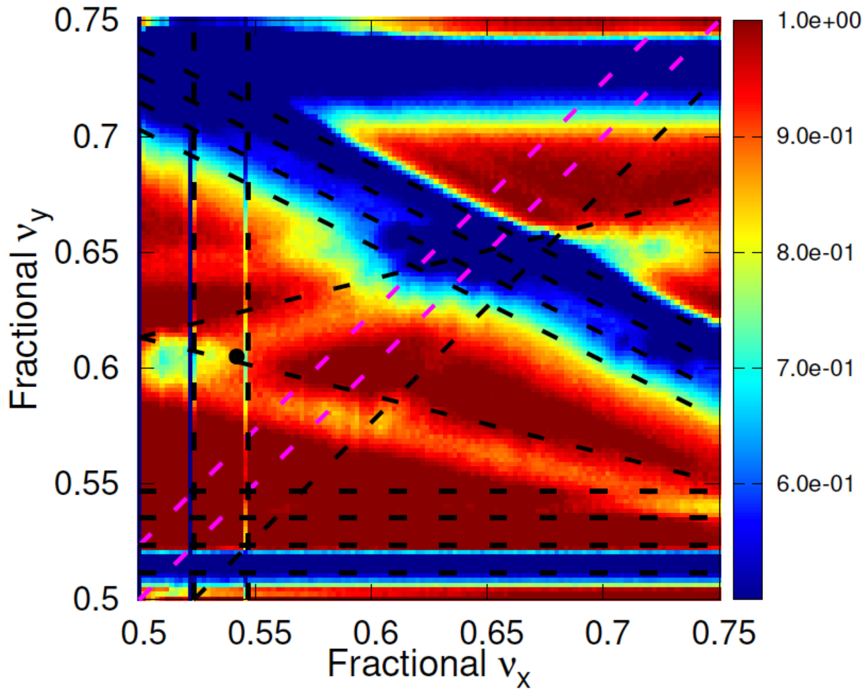


2. BBWS simulation: Tune scan

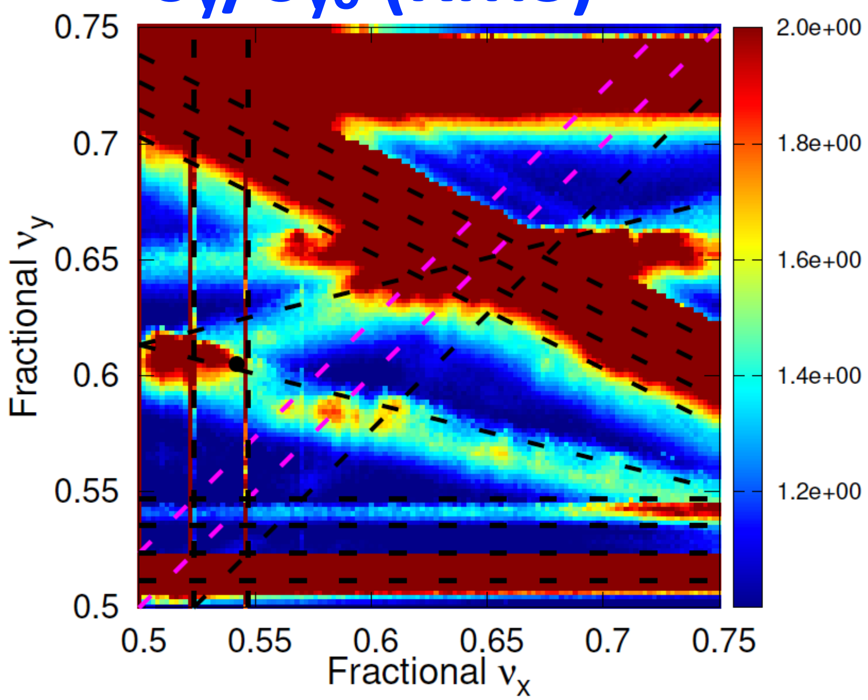
➤ Parameter set (2019.07.01(op3))

e+(W)e-(S)

Lum. (L/L_0)

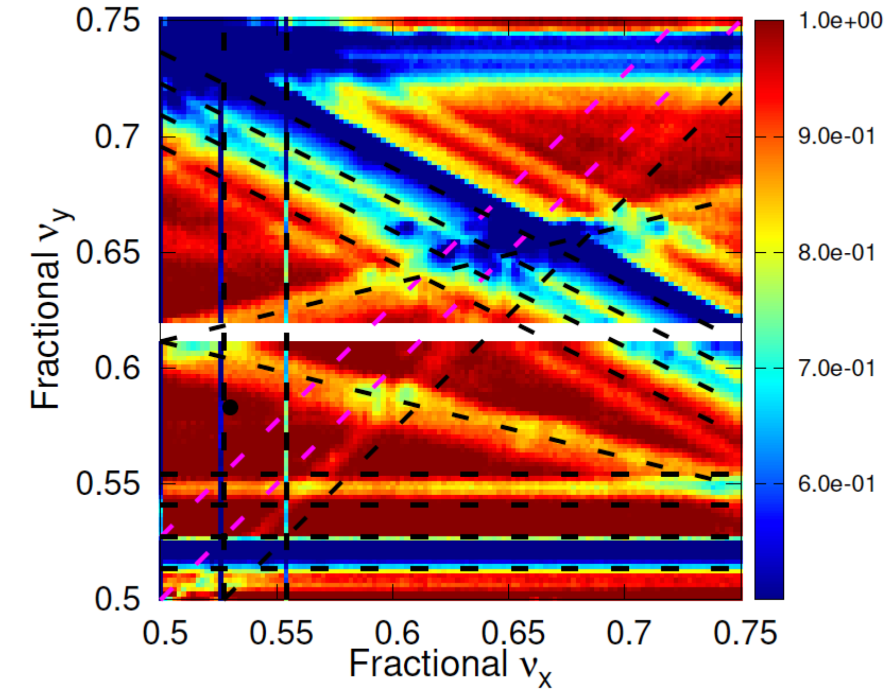


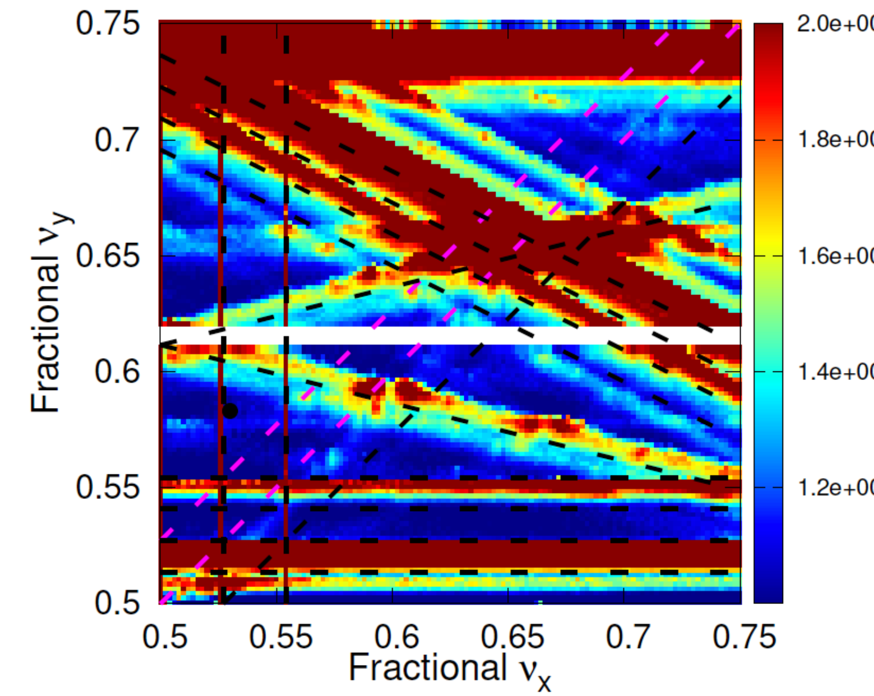
σ_y/σ_{y0} (RMS)



NOTE:
How about increasing the vertical emittance fo the two beam simultaneously?
=> The large-amplitude particles of the weak beam feel stronger nonlinear beam-beam forces
=> Beam-beam resonances coupled to y-motion become outstanding

e+(S)e-(W)





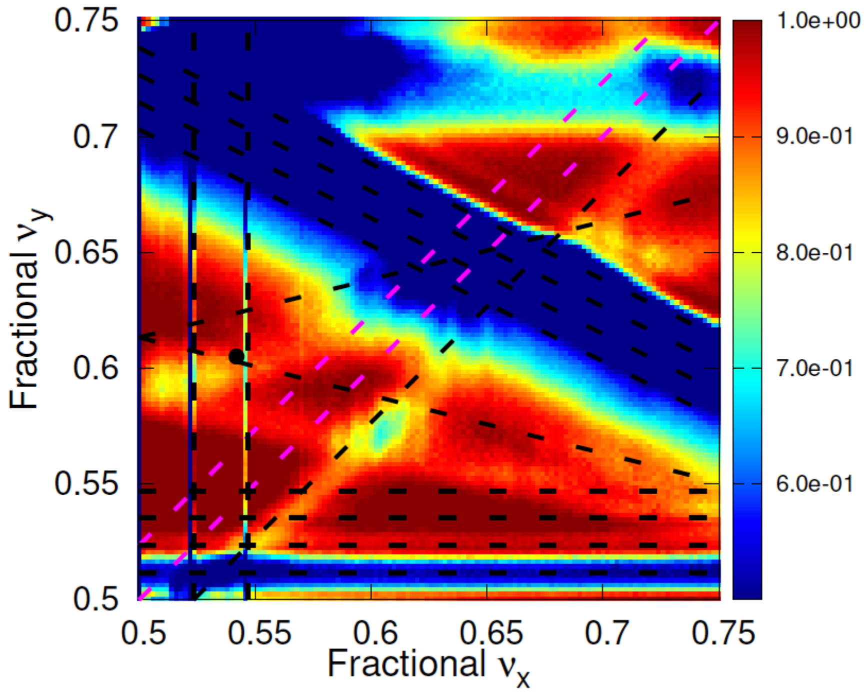
2. BBWS simulation: Tune scan

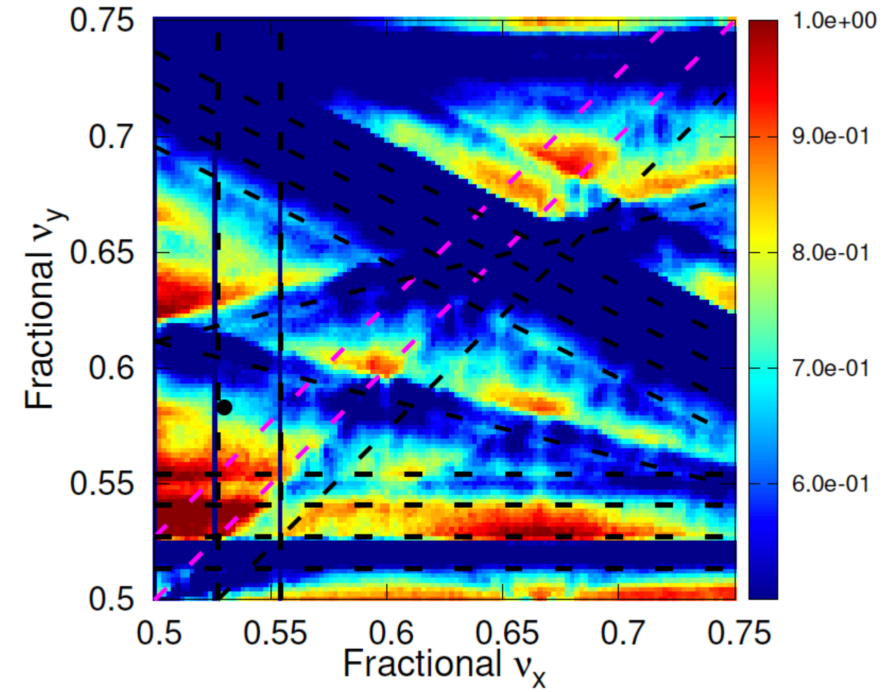
➤ **Parameter set (2019.07.01, with β_x^* = 80 mm and β_y^* = 1 mm)**

e+(W)e-(S)

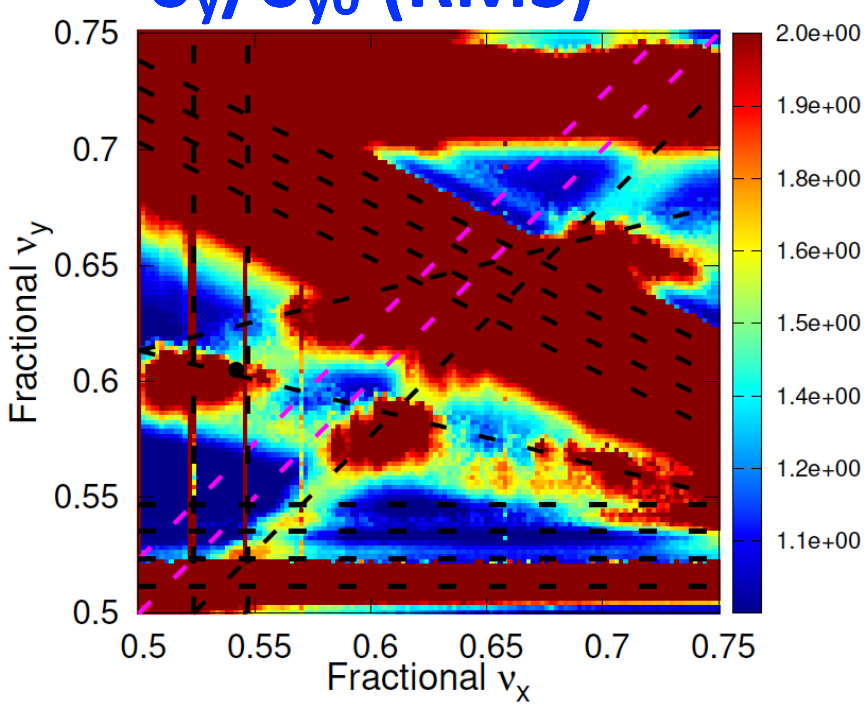
e+(S)e-(W)

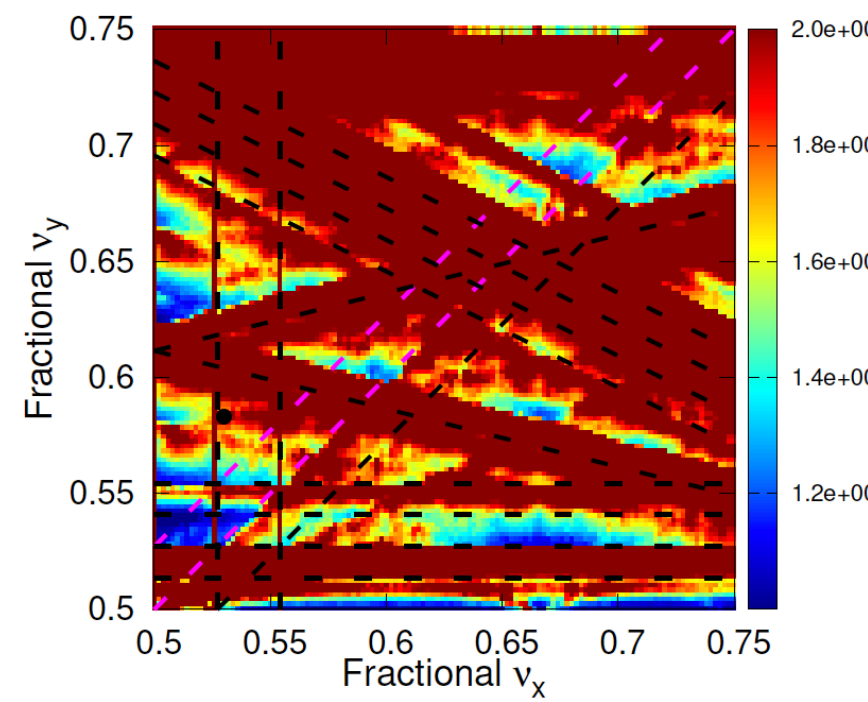
Lum. (L/L_0)





σ_y/σ_{y0} (RMS)





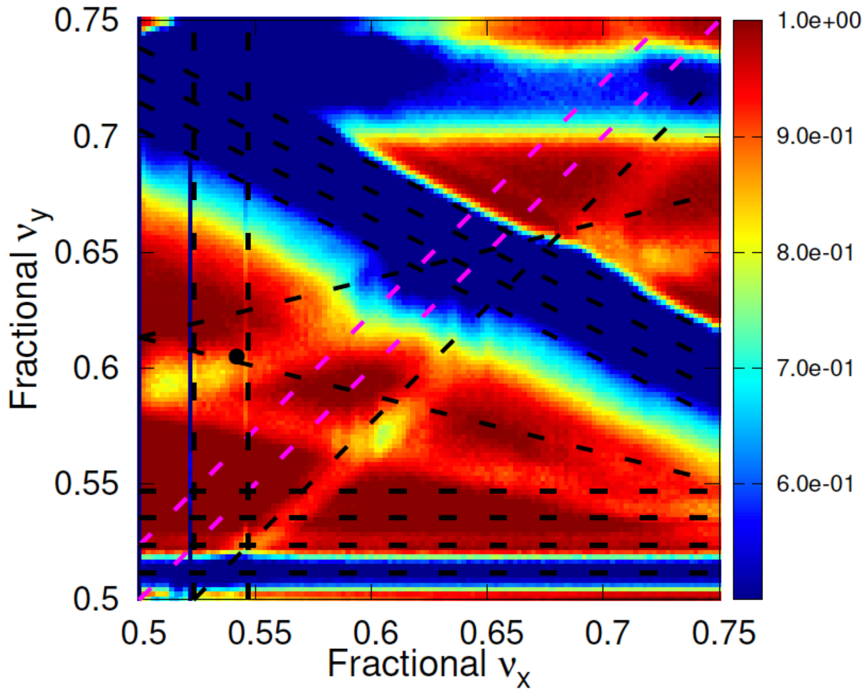
NOTE:
The gain of squeezing β_y^* is obvious: significantly reduce vertical beam-beam tune shift
=> Relax beam-beam instability a lot

2. BBWS simulation: Tune scan

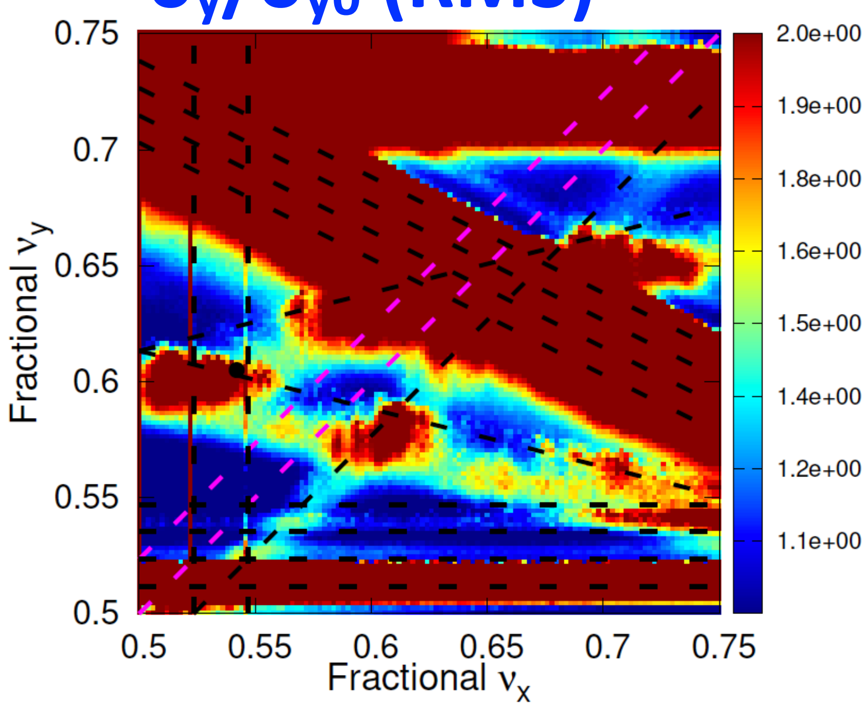
➤ **Parameter set (2019.07.01, with $\beta_x^* = 50$ mm and $\beta_y^* = 1$ mm)**

e+(W)e-(S)

Lum. (L/L_0)

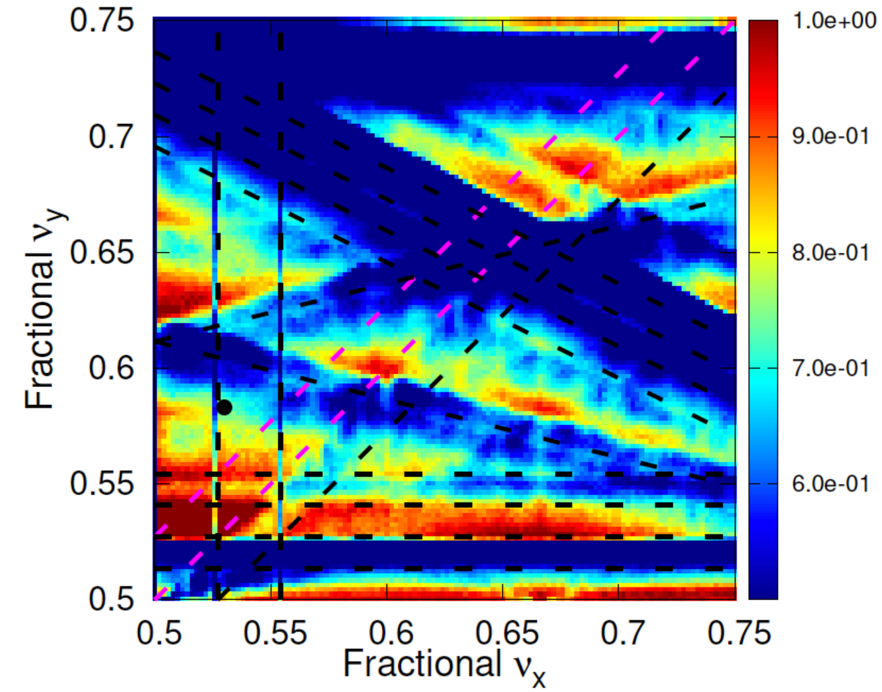


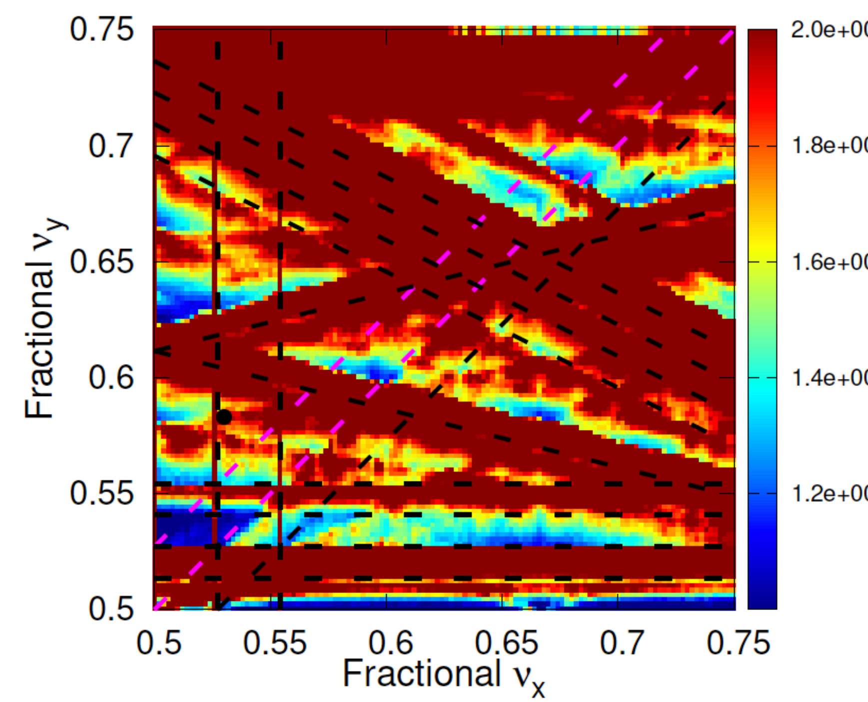
σ_y/σ_{y0} (RMS)



NOTE:
The gain of squeezing β_x^* is NOT very obvious: Because horizontal beam-beam tune shift is already small
=> But it is still important: It suppresses beam-beam driven synchro-betatron X-Z resonances
=> This would help a lot in commissioning when we consider machine errors

e+(S)e-(W)





3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations

- Closed orbit: DX(hor. offset), DPX(hor. crossing angle), DY(vert. offset), DPY(vert. crossing angle), DZ(RF phase)
- Waist(alpha function)
- Linear couplings:
  X-Y: R_1, R_2, R_3, R_4
  X-Z: η_x, η_x', ζ_x, ζ_x'
  Y-Z: η_y, η_y', ζ_y, ζ_y'
- Nonlinear couplings:
  Chromatic Twiss functions(X-Y and X-Z: Tune, alpha function, beta function)
  Chromatic X-Y-Z couplings: R1', R2', R3', R4'
  Third-order geometric aberrations: $p_x^2 p_y$, etc.
- Impedance effects

➤ Only DY* and DPY* will be discussed in this talk

3. Tolerances of IP aberrations with lattice

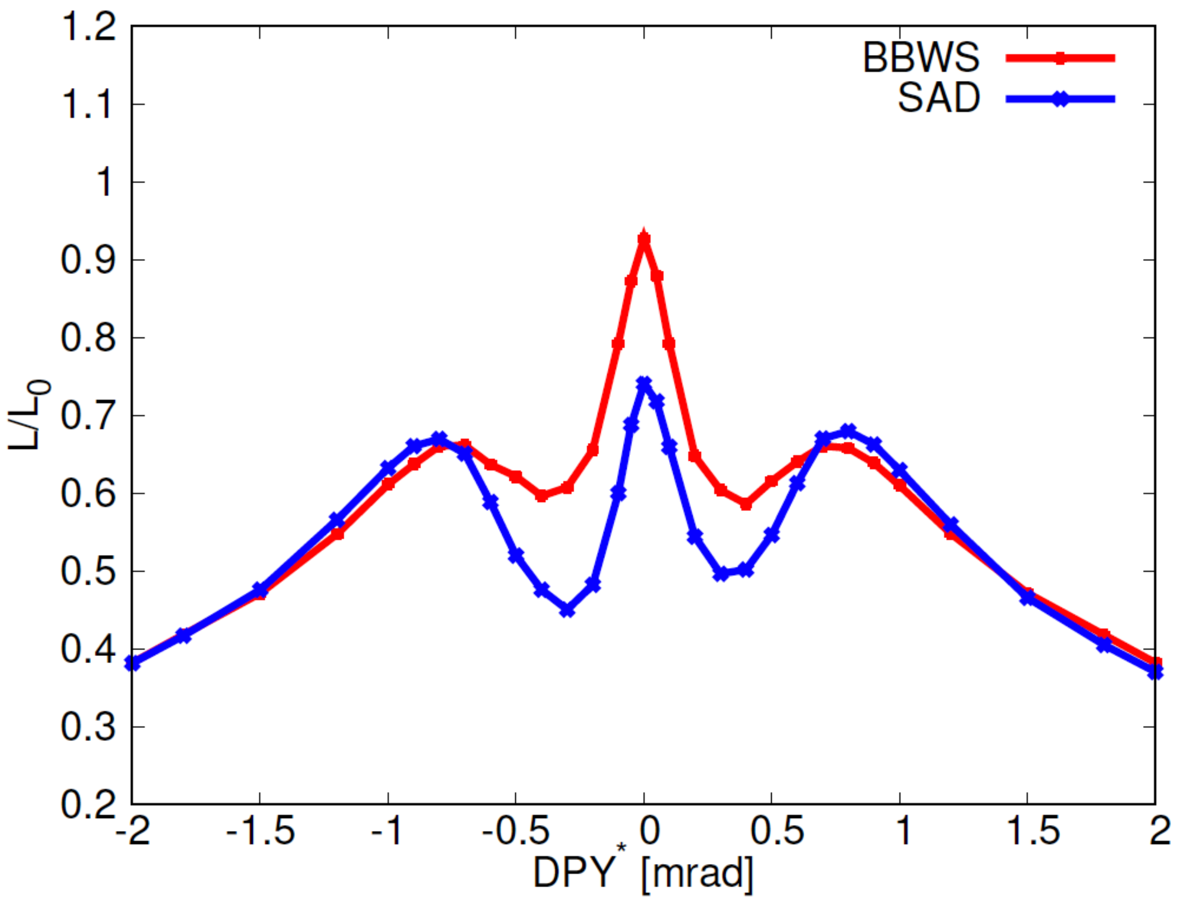
➤ Various IP aberrations: the case of e+ beam

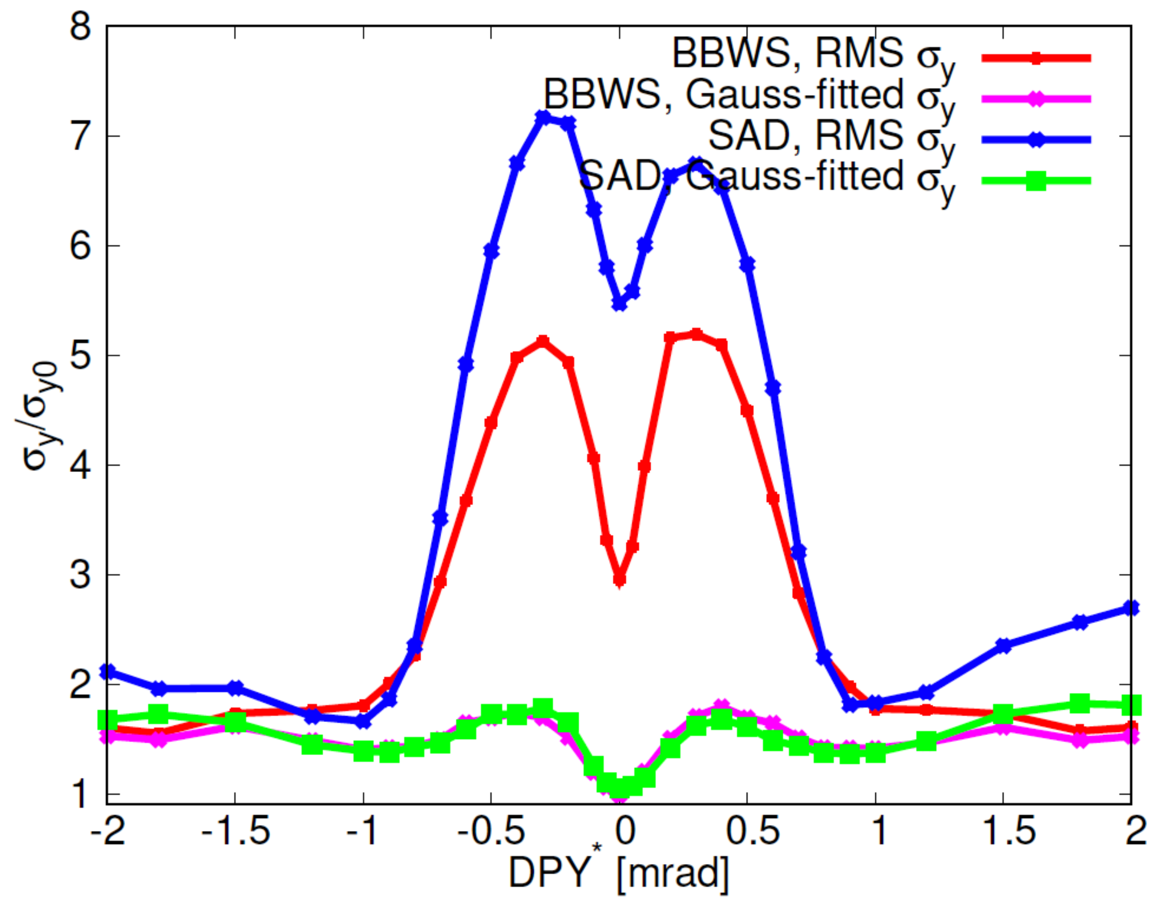
- DPY* (vert. crossing angle) with parameter set of 2019.07.01

  ** Luminosity becomes very sensitive to DPY* at very small vertical emittance.

  ** Luminosity drops faster around DPY*=0 because of additional blowup due to nonzero v-angle

  ** With lattice, large amplitude particles (beam-beam tail) pick up more nonlinear forces from the final focus system





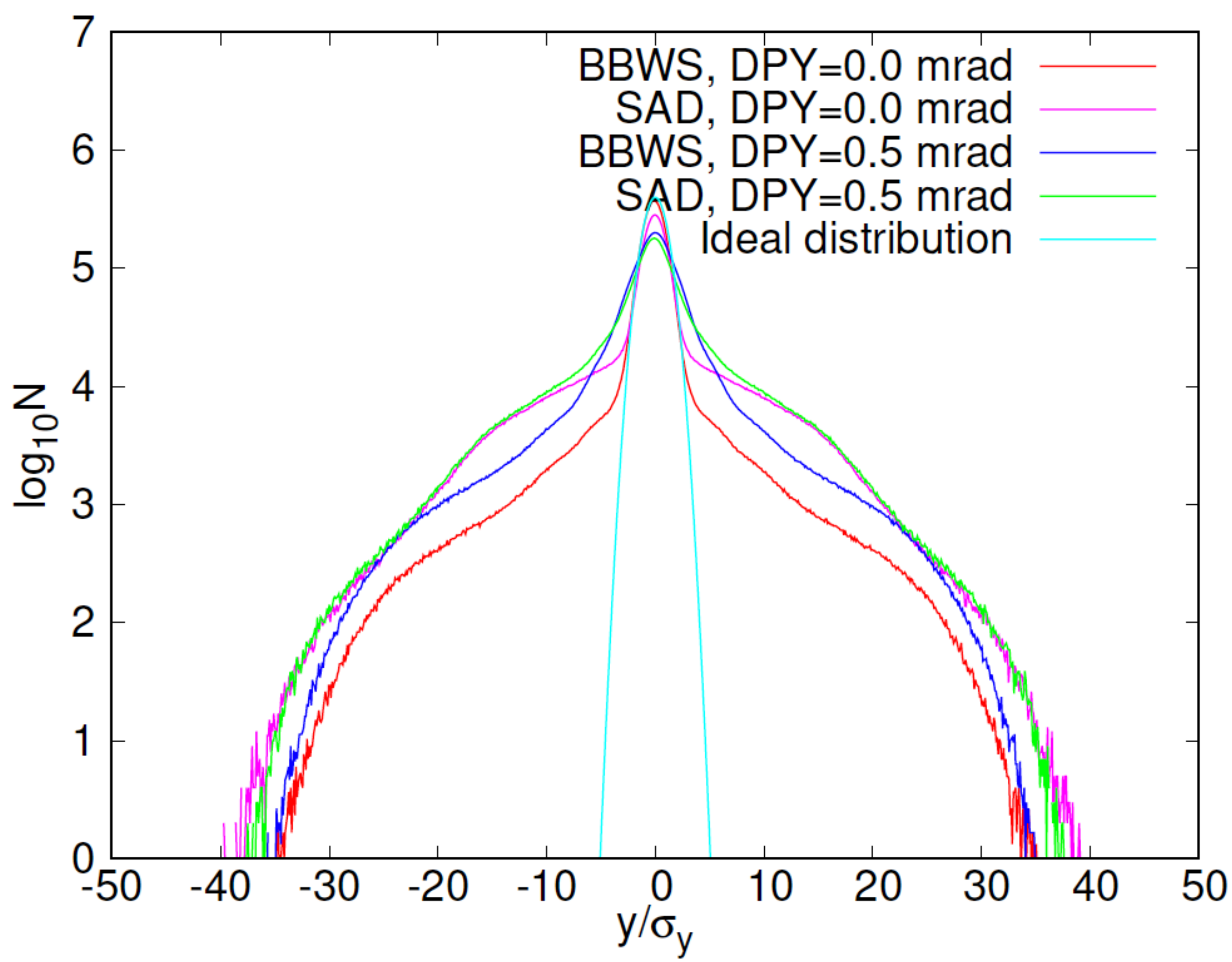
3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- **DPY* (vert. crossing angle) with parameter set of 2019.07.01**

  ** More beam-beam tail with lattice

  ** With lattice, large amplitude particles (beam-beam tail) pick up more nonlinear forces from the final focus system

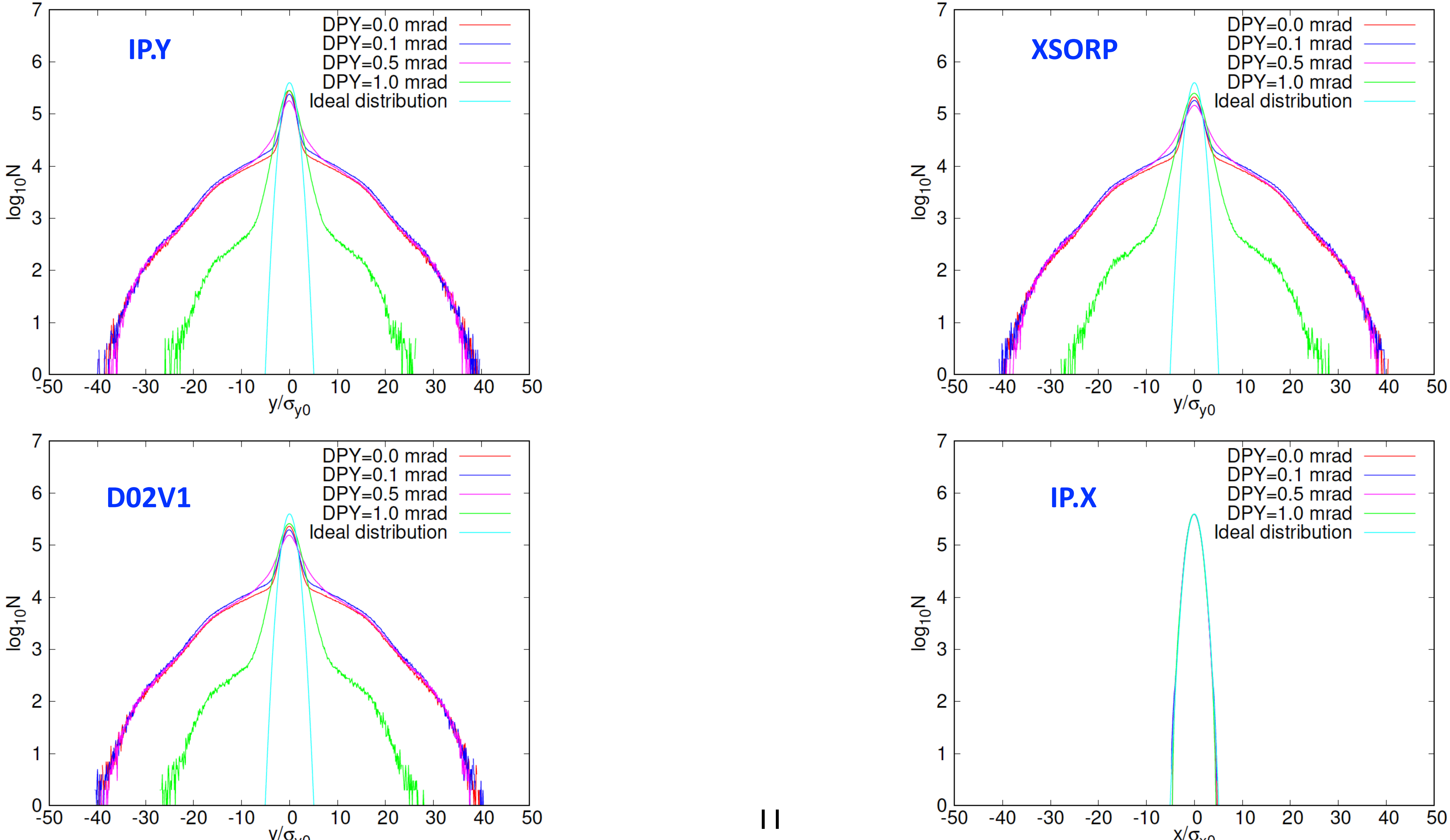


3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- DPY* (vert. crossing angle) with parameter set of 2019.07.01

  ** Similar beam-beam vertical tail distribution at IP, D02V1 and XSORP

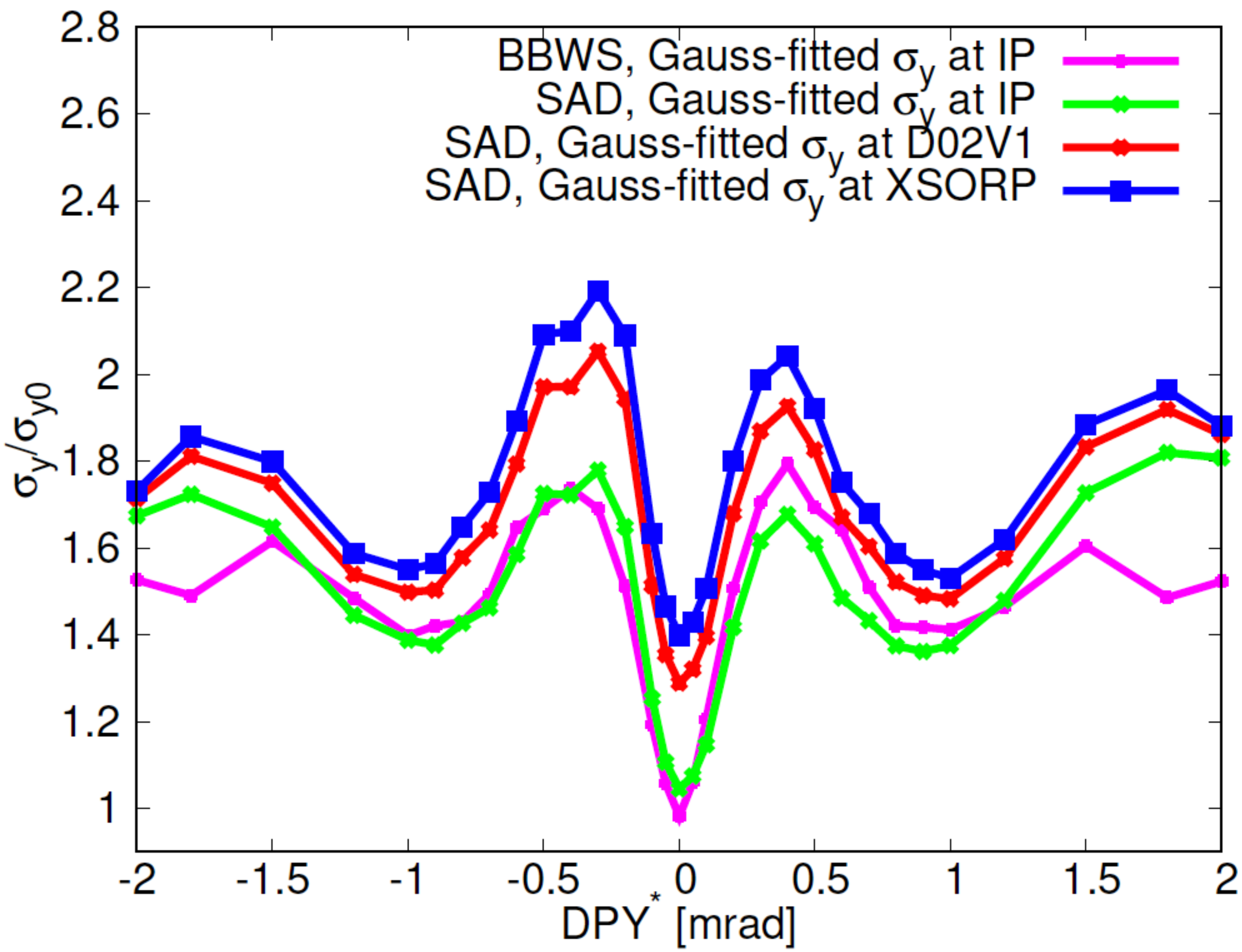


3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- **DPY* (vert. crossing angle) with parameter set of 2019.07.01**

**** Because of dynamic beam-beam effects, simple translation (only use lattice information) of beam size from XRM to IP is not enough**



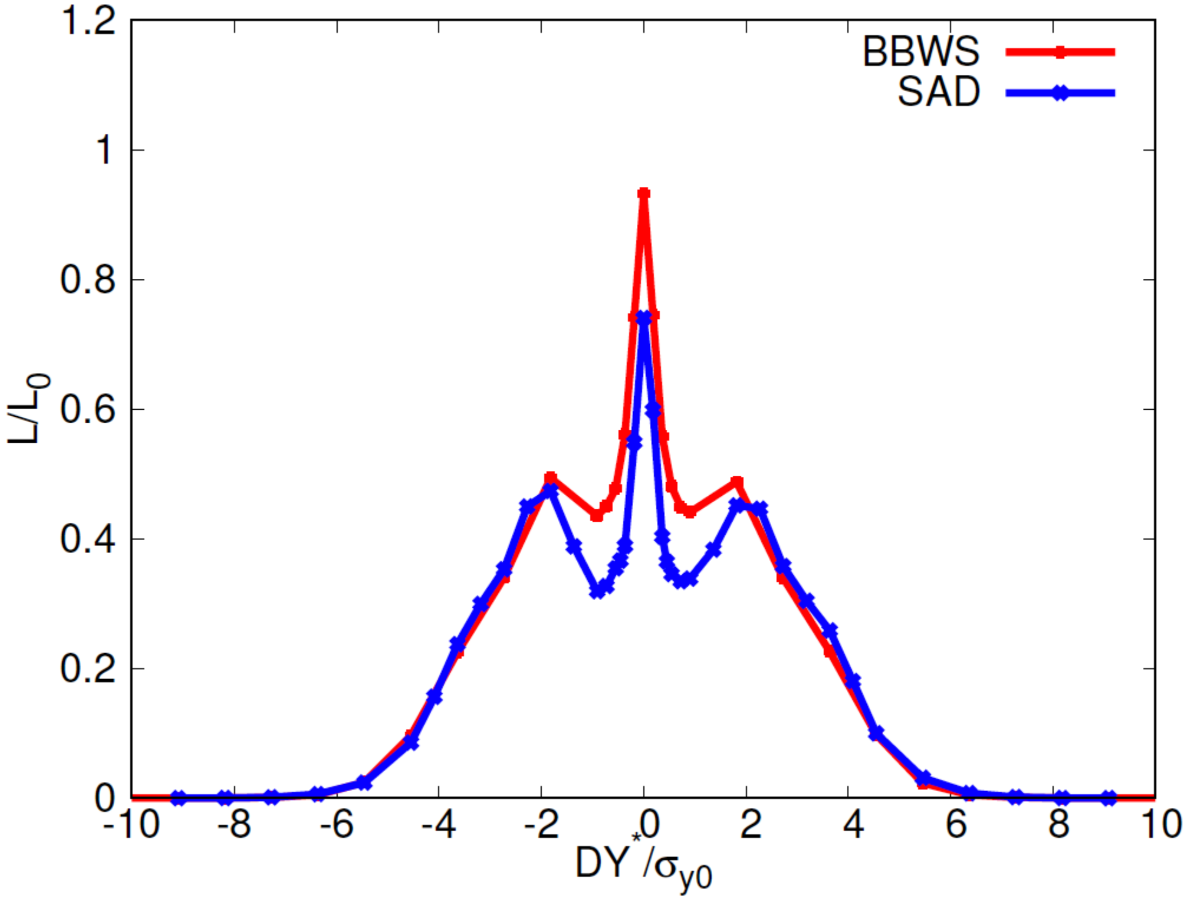
3. Tolerances of IP aberrations with lattice

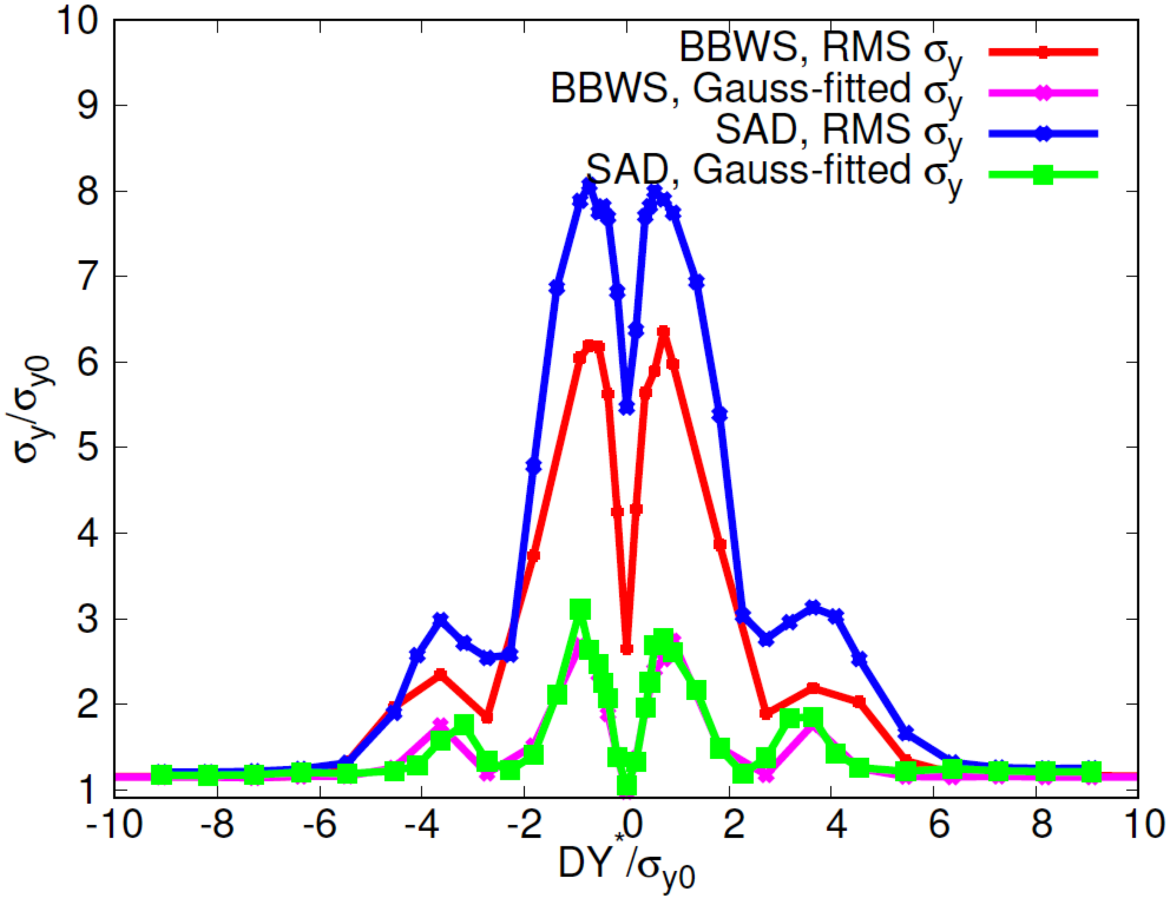
➤ Various IP aberrations: the case of e+ beam

- **DY* (Vertical offset) with parameter set of 2019.07.01**

  **** Luminosity drops faster around DY*=0 because of additional blowup due to nonzero v-offset**

  **** With lattice, large amplitude particles (beam-beam tail) pick up more nonlinear forces from the final focus system**





3. Tolerances of IP aberrations with lattice

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  ** More beam-beam tail with lattice

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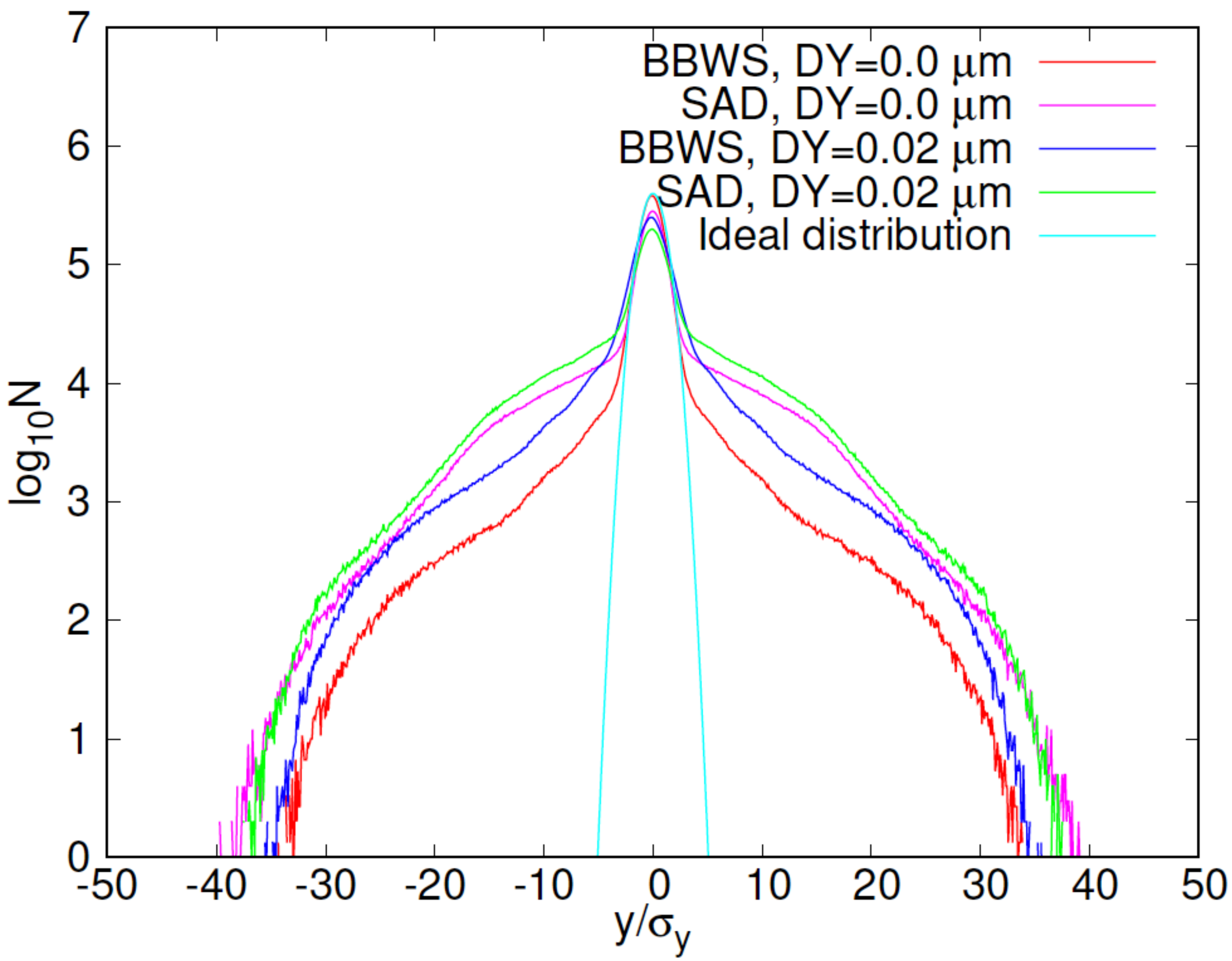
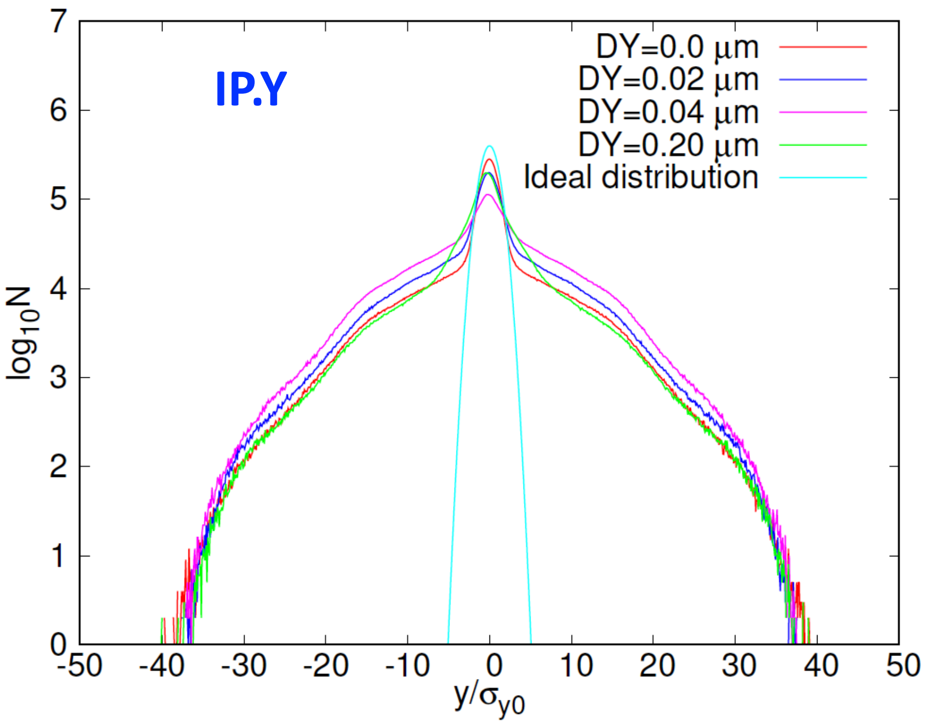


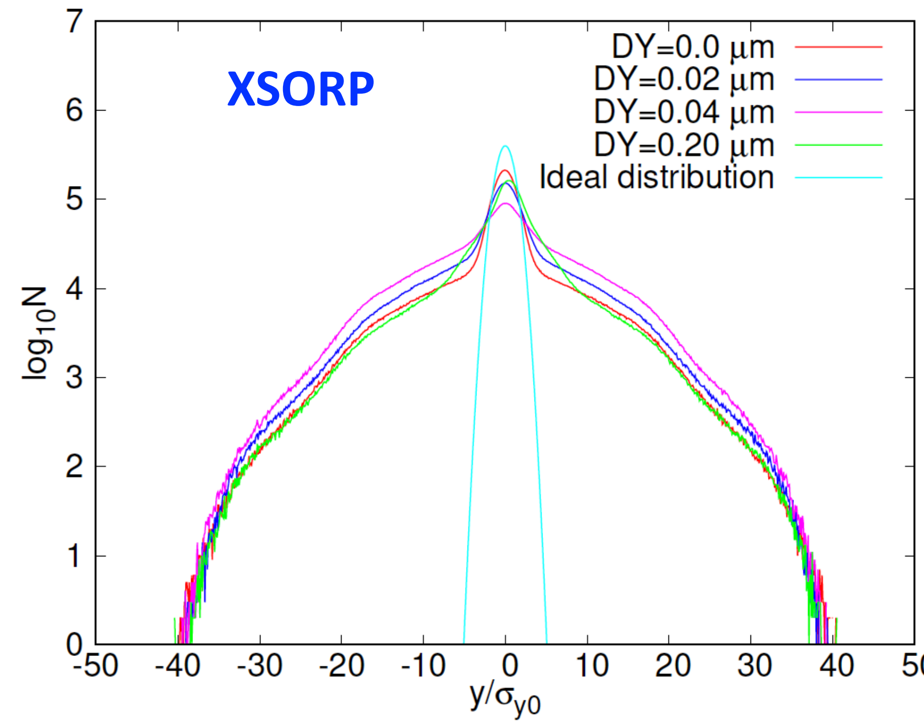
3. Tolerances of IP aberrations with lattice

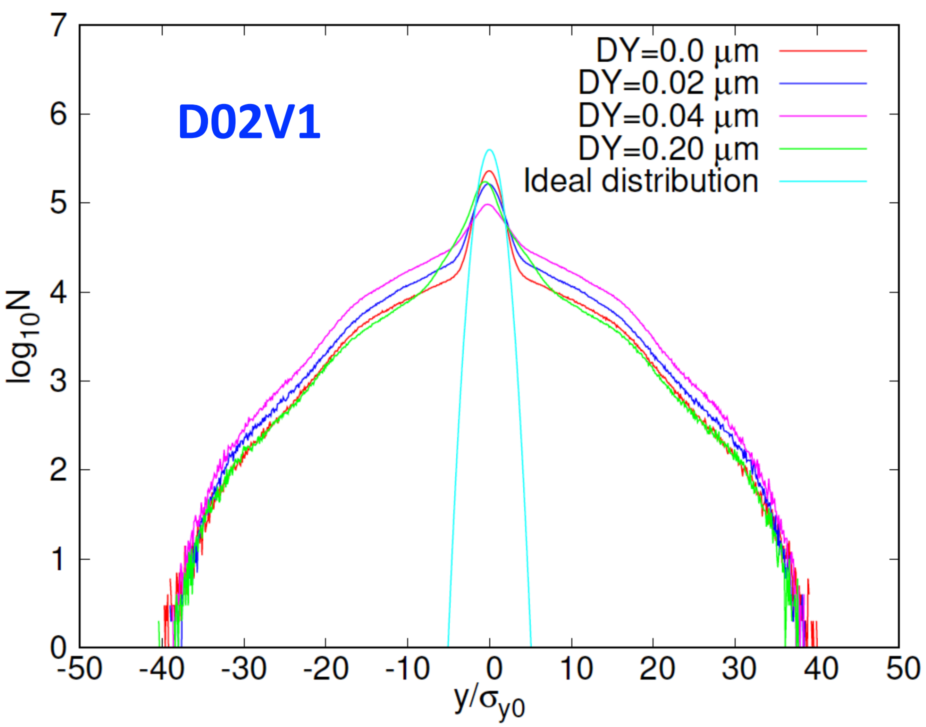
➤ Various IP aberrations: the case of e+ beam

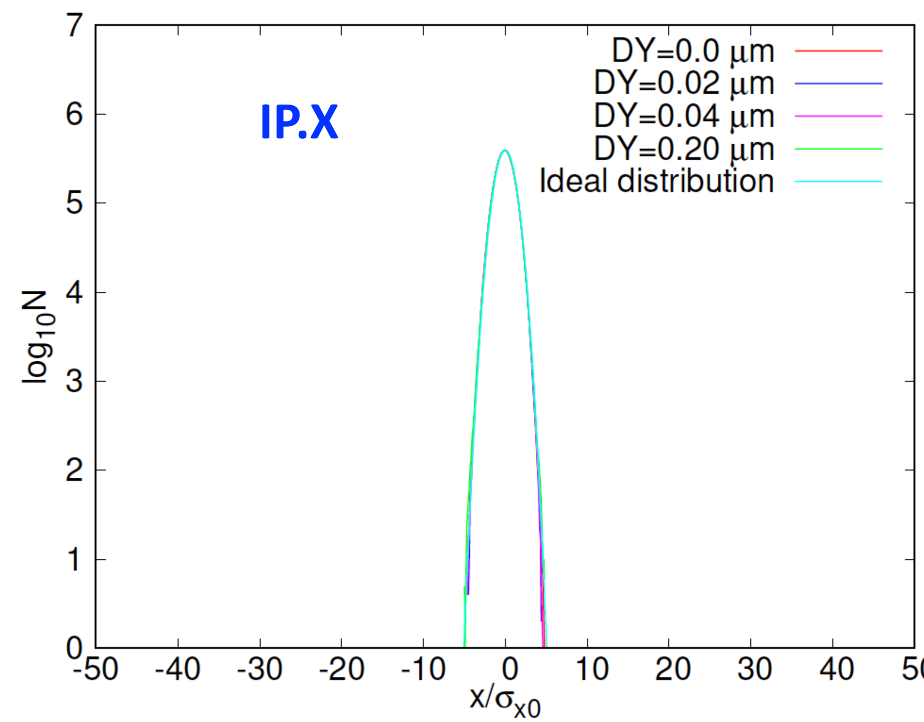
- **DY* (Vertical offset) with parameter set of 2019.07.01**

  **** Similar beam-beam vertical tail distribution at IP, D02V1 and XSORP**







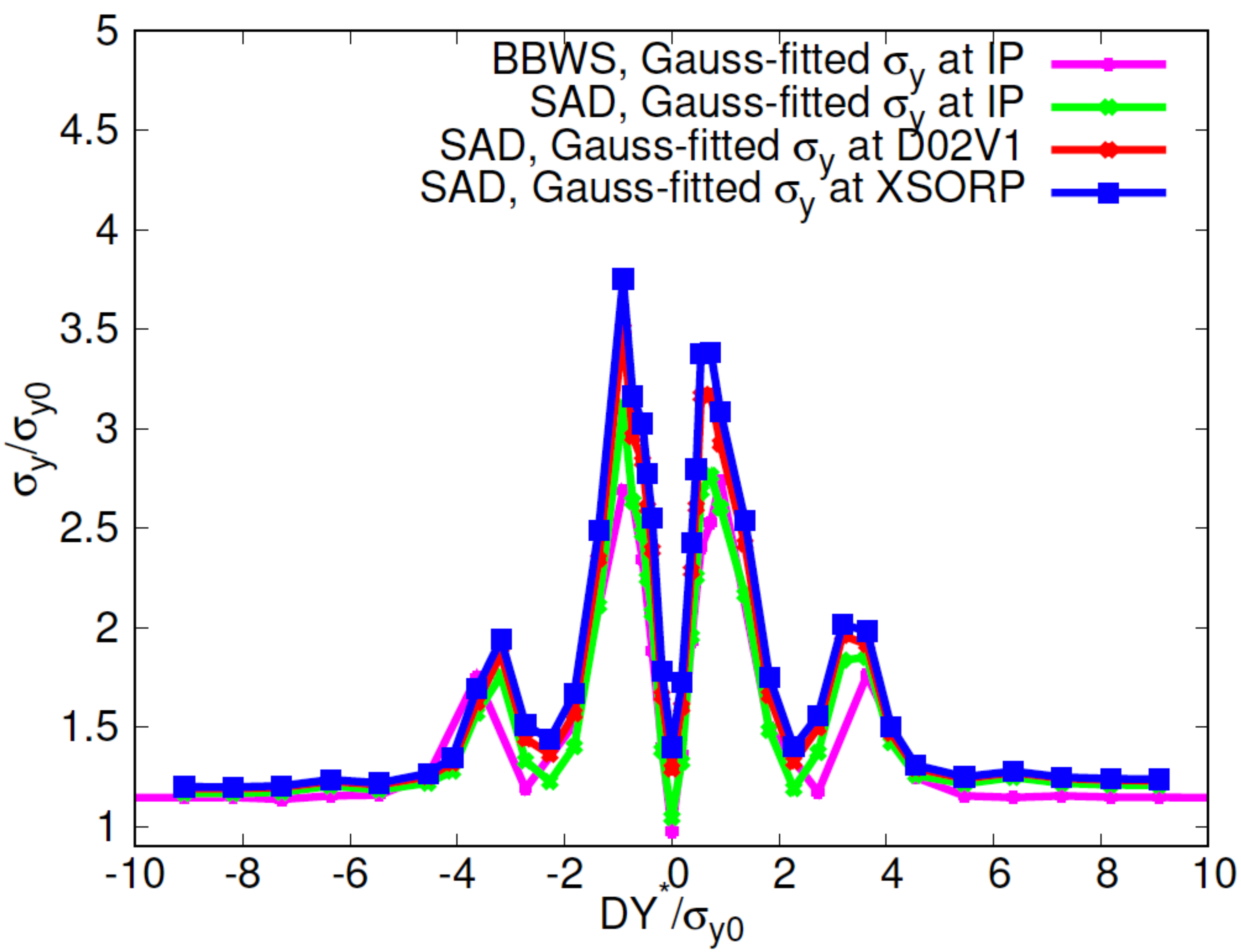


3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- **DY* (Vertical offset) with parameter set of 2019.07.01**

**** Because of dynamic beam-beam effects, simple translation (only use lattice information) of beam size from XRM to IP is not enough**



3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

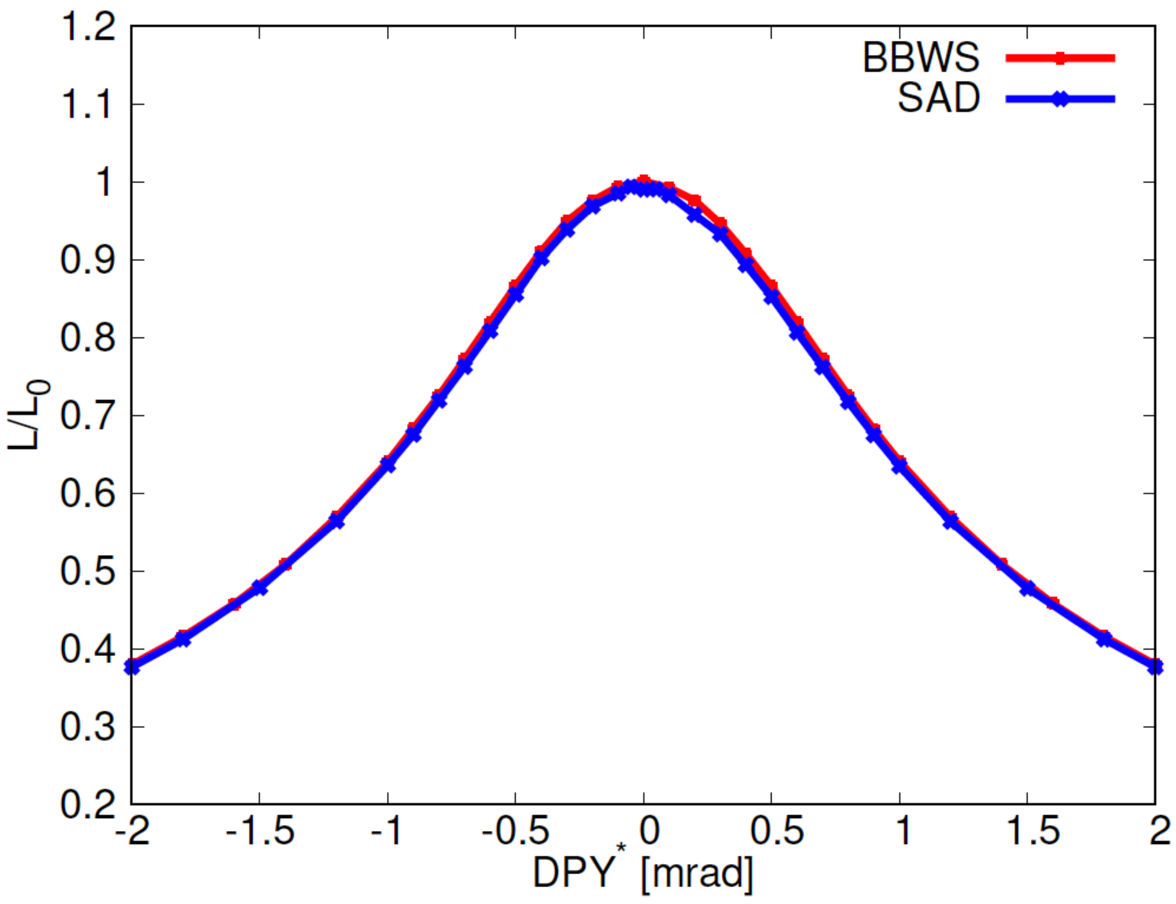
- DPY* (vert. crossing angle) with parameter set of 2019.06.25

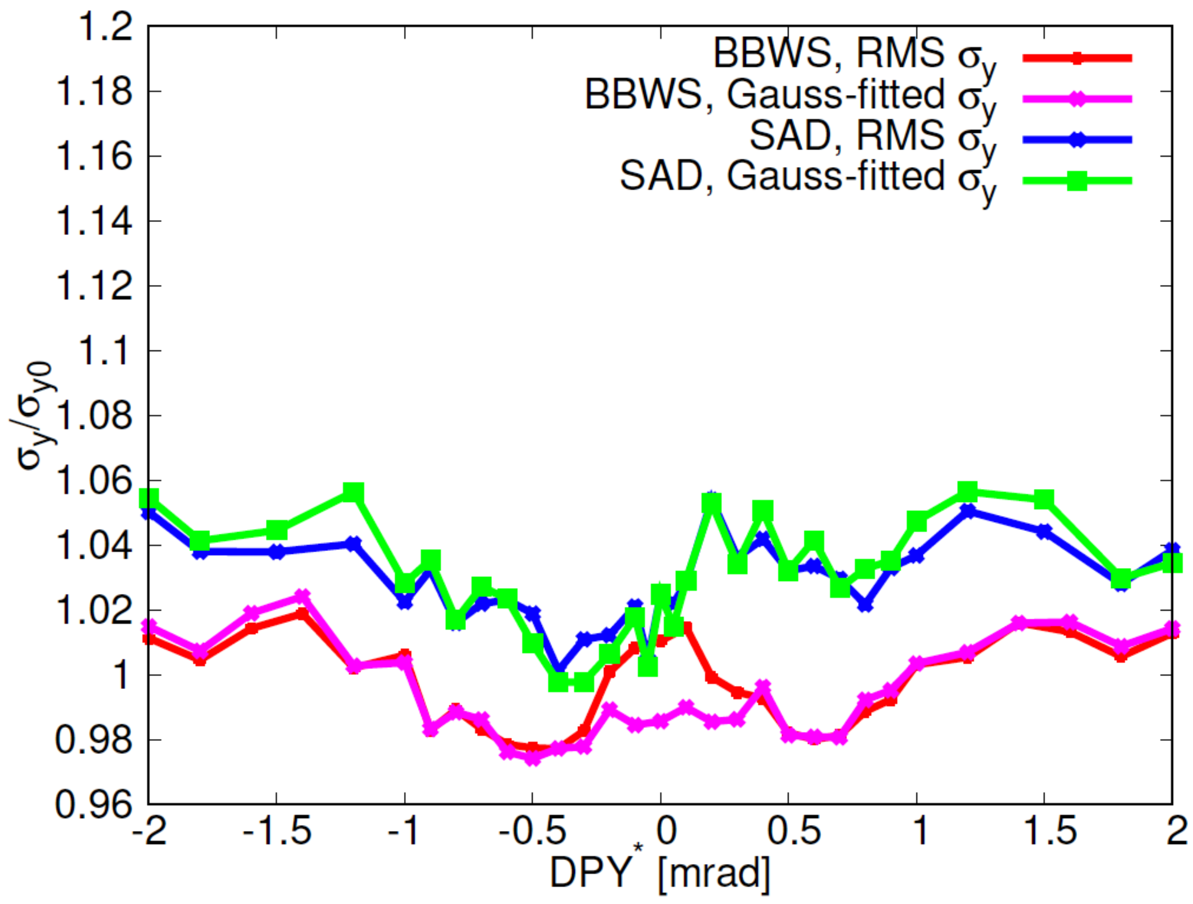
** Luminosity and beam size are very insensitive to DPY*. This is very different from experiments.

** BBWS: ε_y = 6.05 pm

** SAD: ε_y = 6.05 + 0.194 pm with 0.194 pm from ideal lattice

** The difference in luminosity and beam size between SAD and BBWS is mainly attributed to nonzero vertical emittance of the ideal lattice

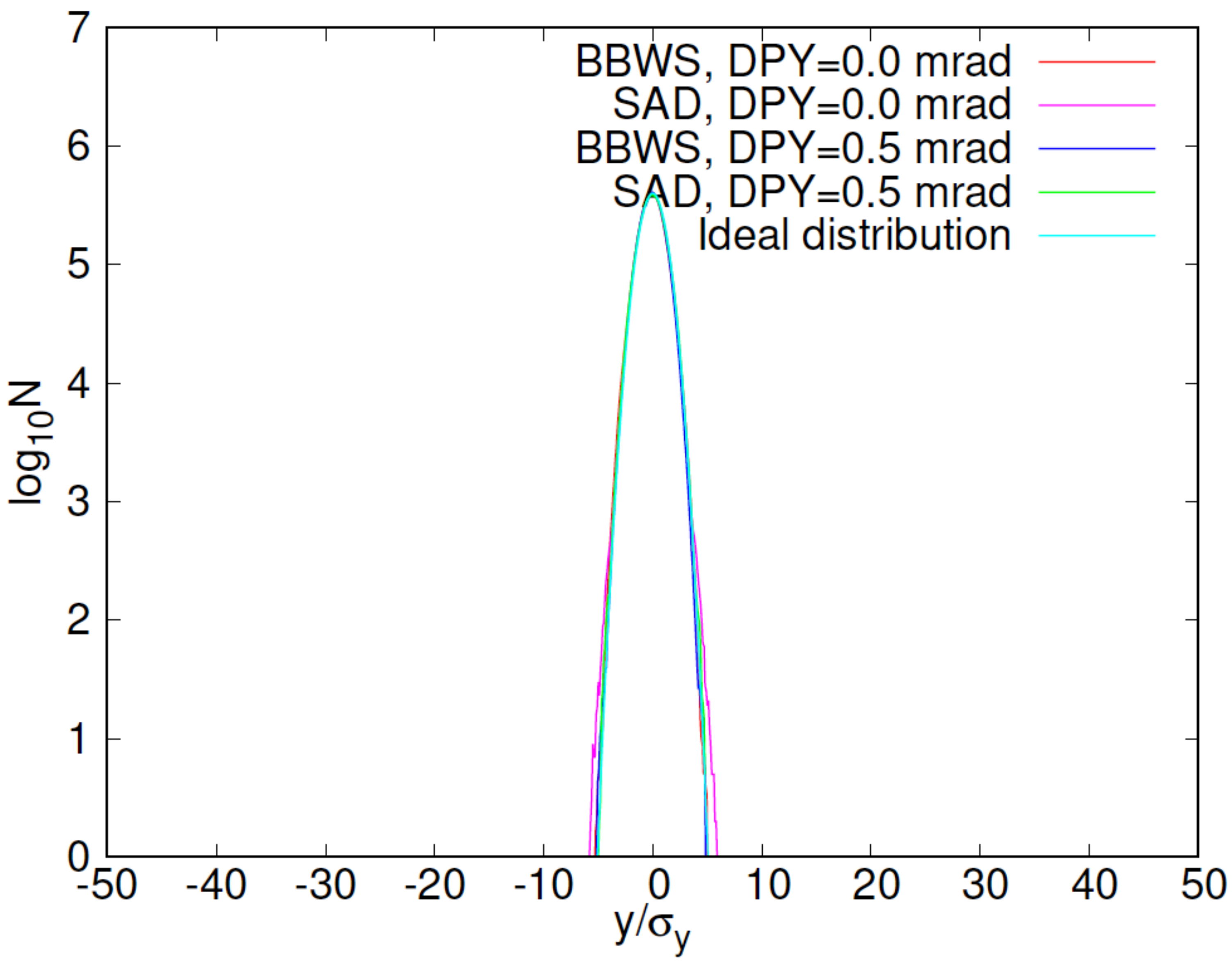




3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- **DPY* (vert. crossing angle) with parameter set of 2019.06.25**
  **** There is small difference in the beam tail**
  **** With lattice, a little more tail can be seen**

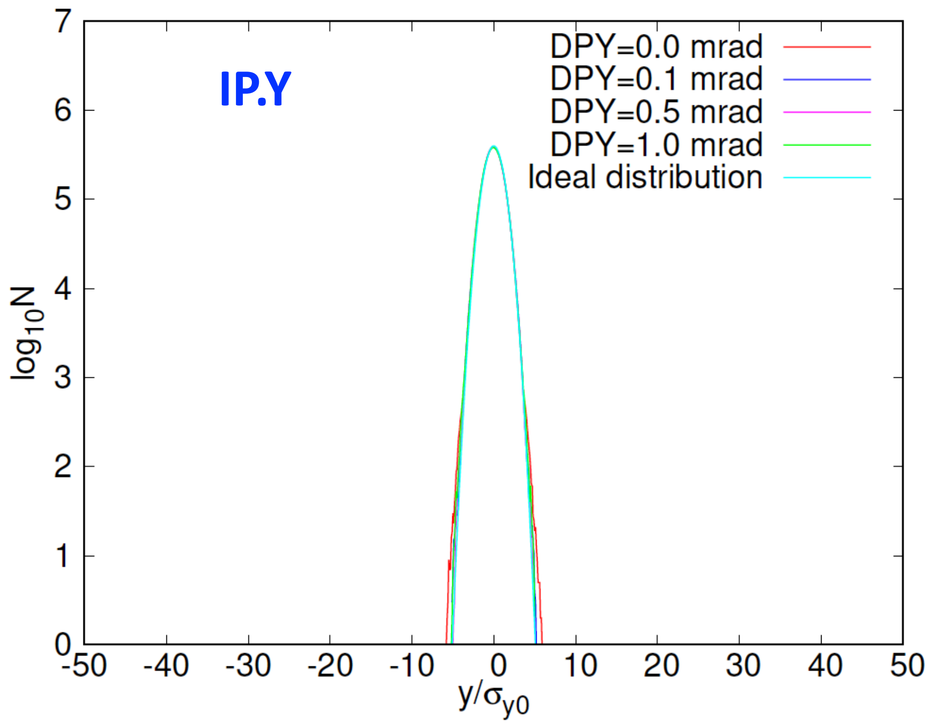


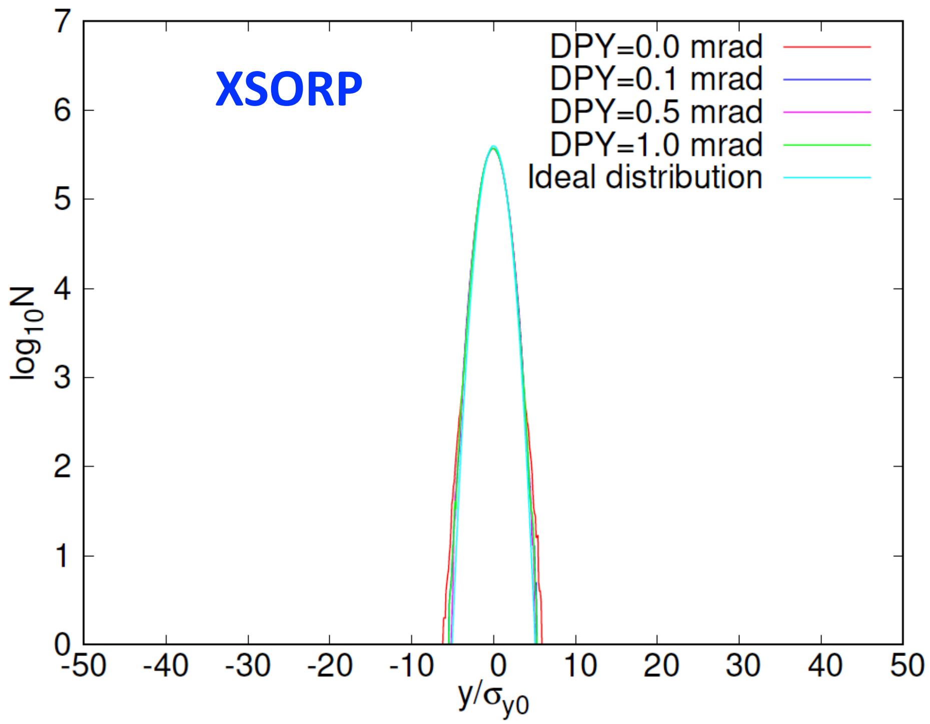
3. Tolerances of IP aberrations with lattice

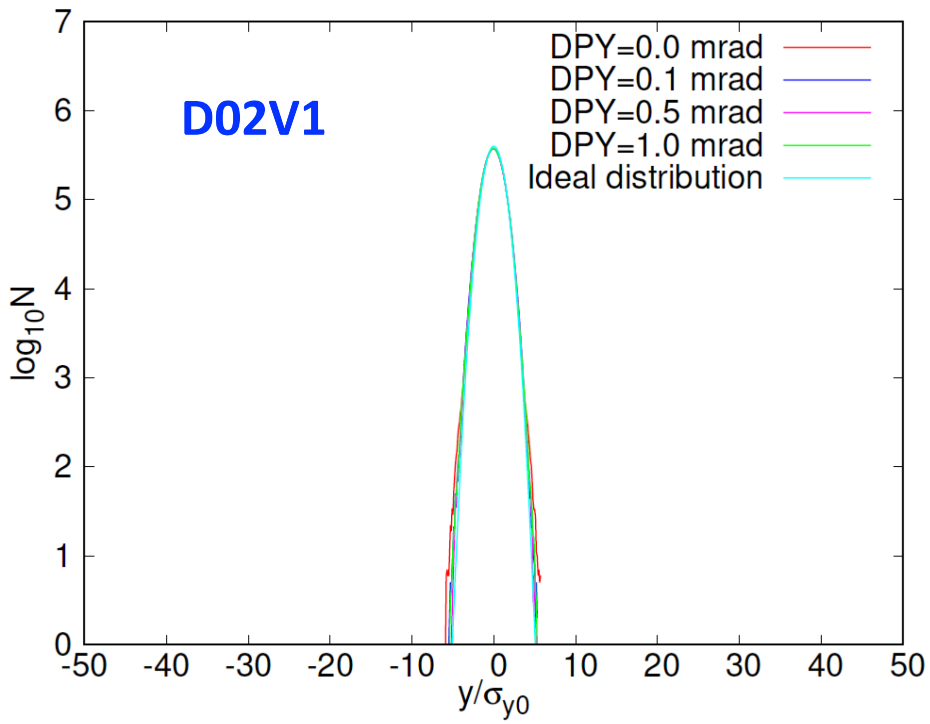
➤ Various IP aberrations: the case of e+ beam

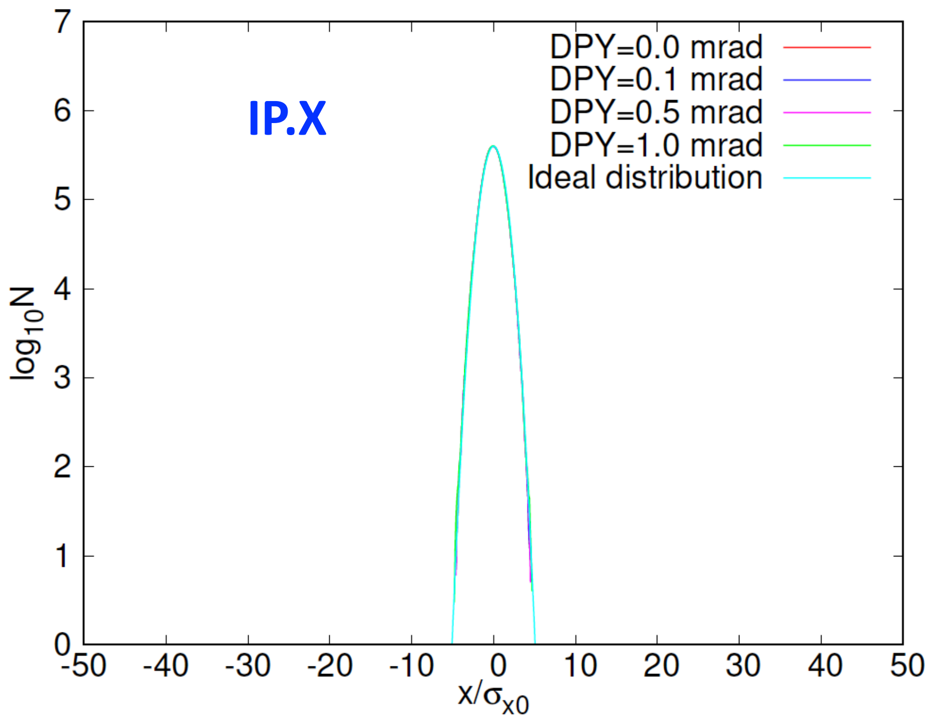
- **DPY* (vert. crossing angle) with parameter set of 2019.06.25**

  ** Similar beam-beam vertical tail distribution at IP, D02V1 and XSORP









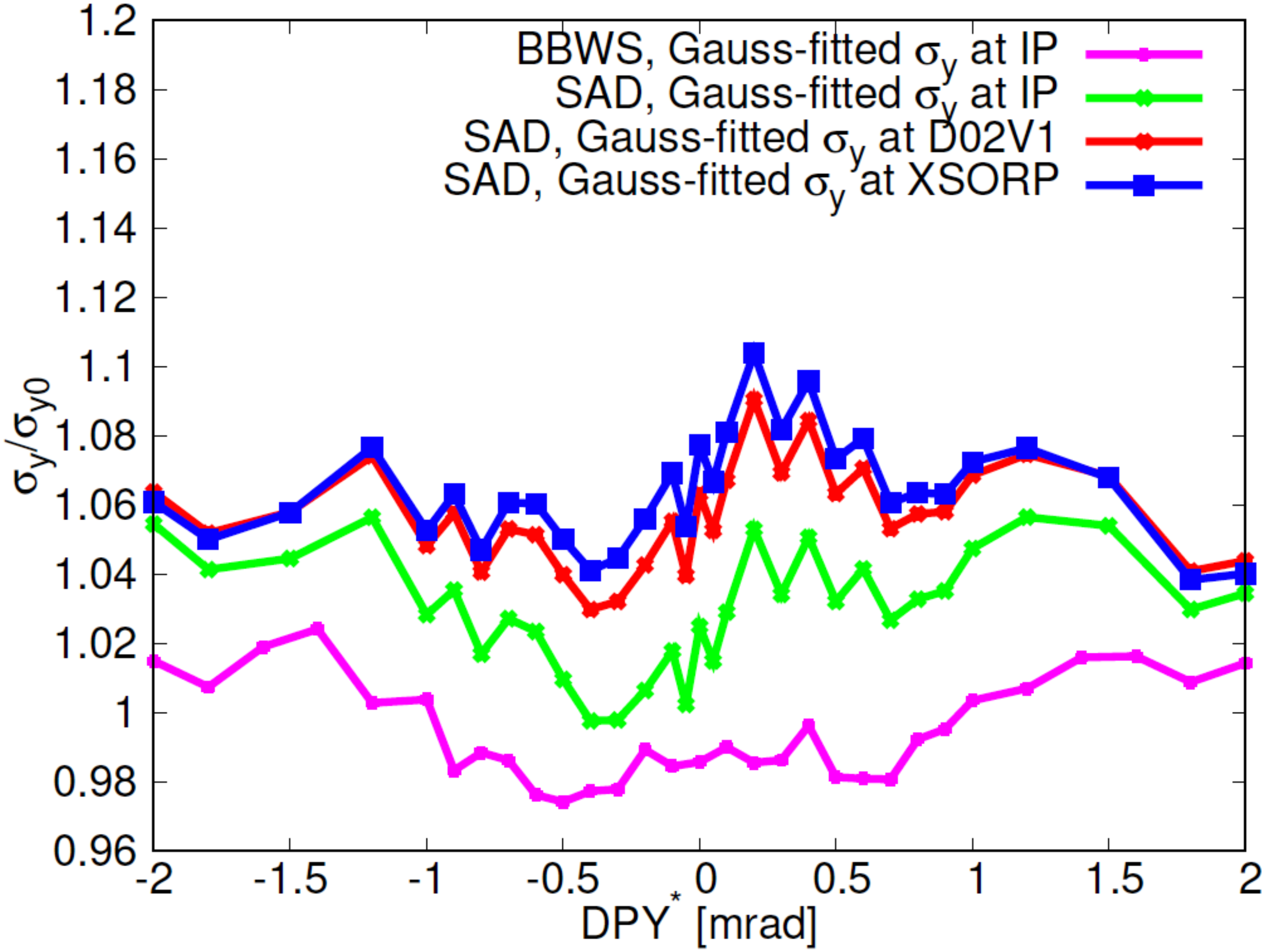
3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- DPY* (vert. crossing angle) with parameter set of 2019.06.25

  ** The difference between SAD and BBWS can be understood: small emittance from ideal lattice

  ** The difference between beam size at IP, D02V1 and XSORP is from dynamic beam-beam effects? I am not quite sure right now. Need to be confirmed.



4. BBWS simulation: Tune scan: Phase 3-2

➤ Phase 3-2 machine parameters

- A few examples of parameter sets observed in the control room

	Phase 3-1		Phase 3-2-1		Phase 3-2-2		Phase 3-2-3	
	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
# bunch	1576		1576		1576		1576	
ε_x (nm)	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0
ε_y (pm)**	**87.4**	**88**	**73.6**	**72**	**59.8**	**60**	**46**	**44**
β_x (mm)	80	80	80	80	80	80	80	80
β_y (mm)	**2**	**2**	**1.5**	**1.5**	**1.2**	**1.2**	**1.0**	**1.0**
σ_z (mm)	6.0	5.5	6.0	5.5	6.0	5.5	6.0	5.5
σ_y (nm)	418	420	332	329	268	268	214	210
ν_x	45.53	44.542	45.53	44.542	45.53	44.542	45.53	44.542
ν_y	43.583	46.605	43.583	46.605	43.583	46.605	43.583	46.605
ν_s	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349
ξ_y(Geom.)	0.0218	0.0353	0.021	0.0335	0.0207	0.0335	0.0221	0.0352
$\mathcal{L}$(Geom.)	1.25E+34		1.57E+34		1.9E+34		2.4E+34	

**Take as single beam emittance

Ref. Y. Ohnishi

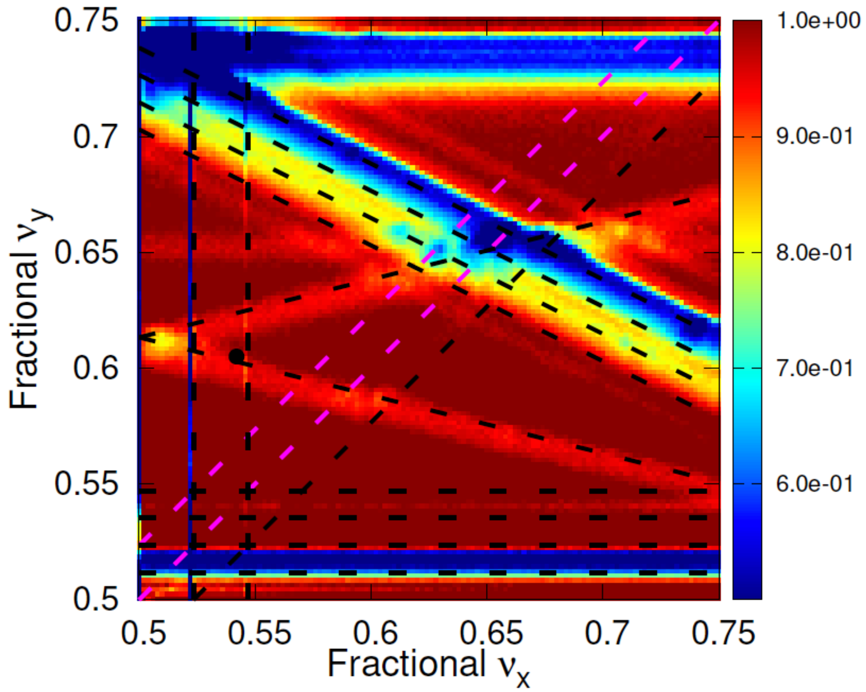
4. BBWS simulation: Tune scan: Phase 3-2

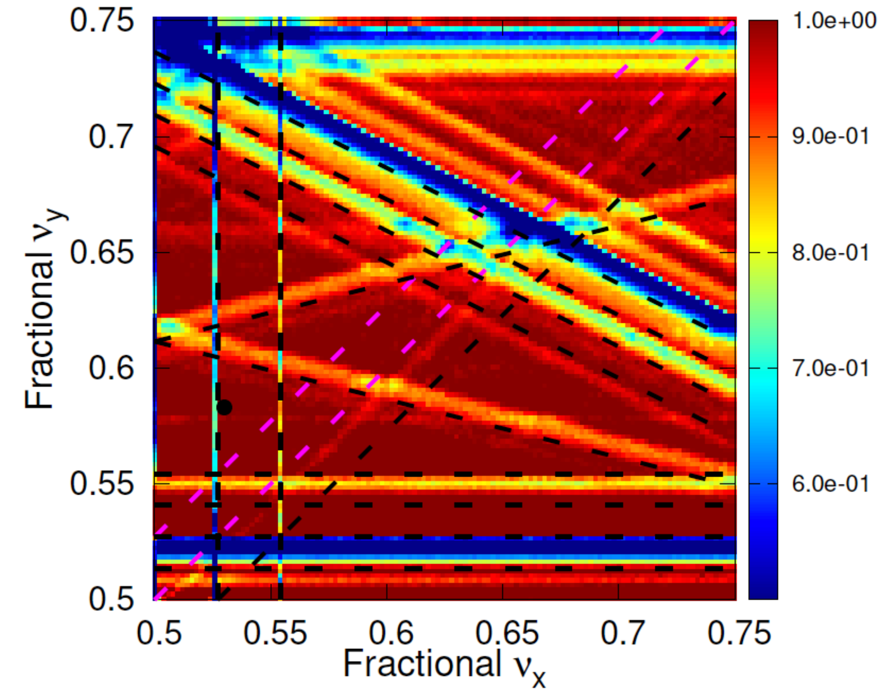
➤ **Parameter set (Phase 3-1: $\beta_y^* = 2.0$ mm)**

e+(W)e-(S)

e+(S)e-(W)

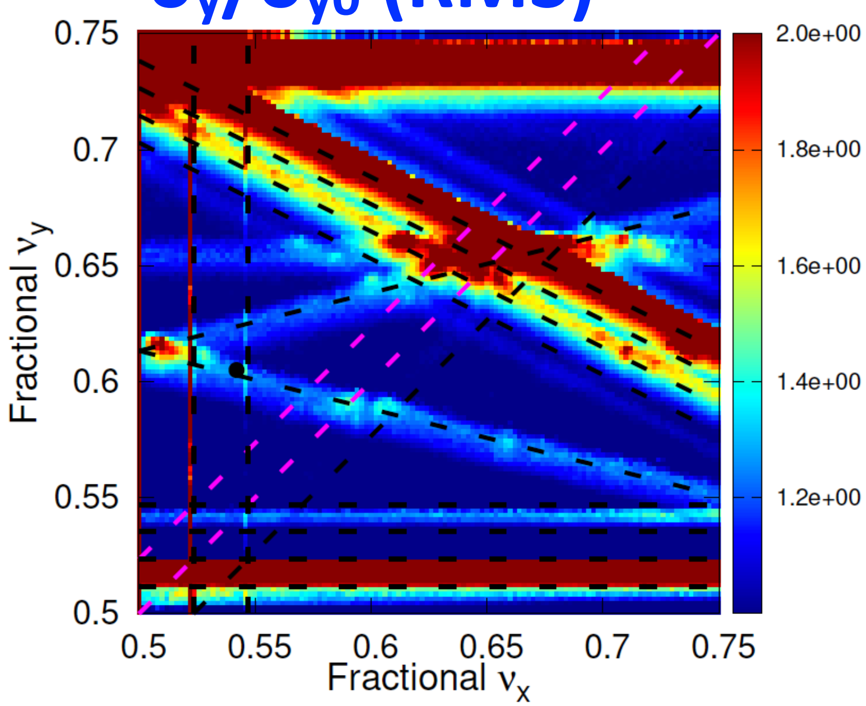
Lum. (L/L_0)

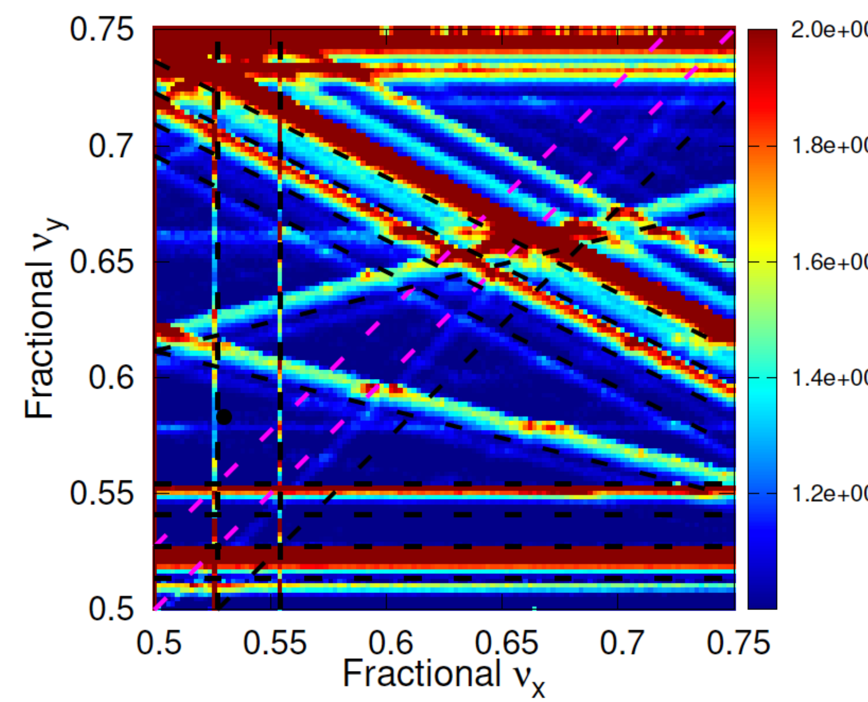




NOTE:
Design working point (.53, .57) is preferred at least from viewpoint of simulations.

σ_y/σ_{y0} (RMS)



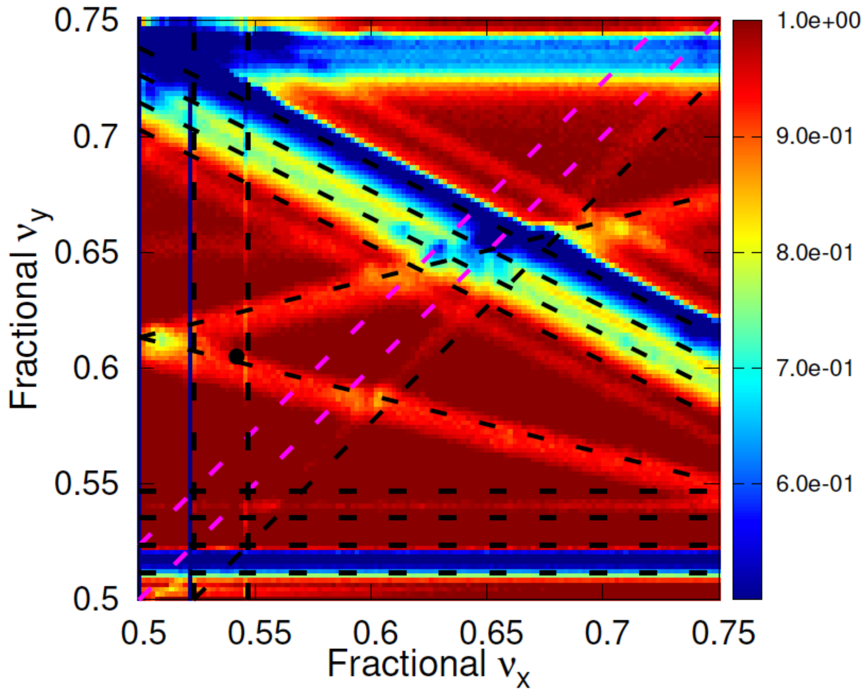


4. BBWS simulation: Tune scan: Phase 3-2

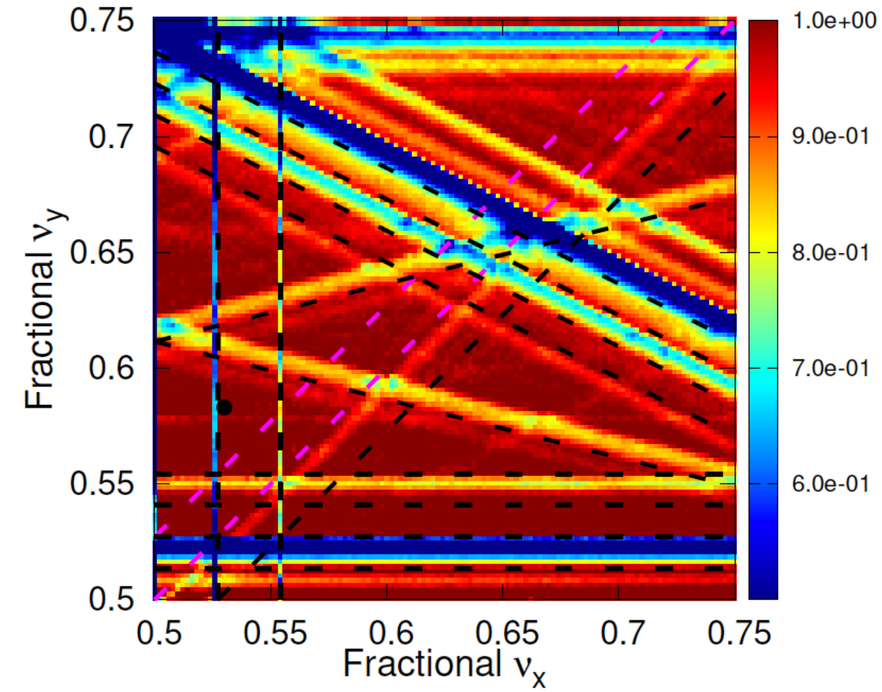
➤ Parameter set (Phase 3-2-1: $\beta_y^* = 1.5$ mm)

e+(W)e-(S)

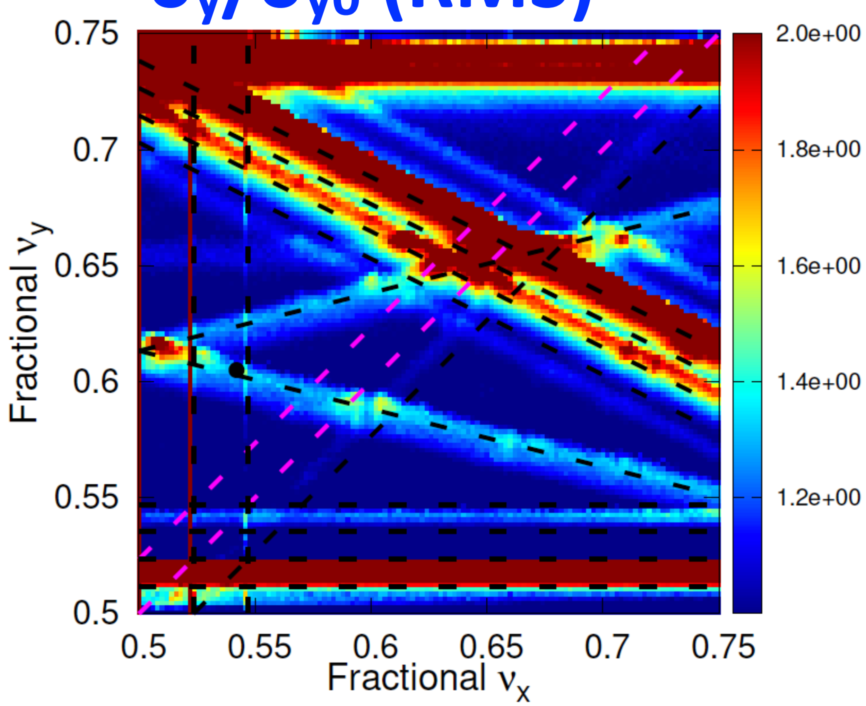
Lum. (L/L_0)



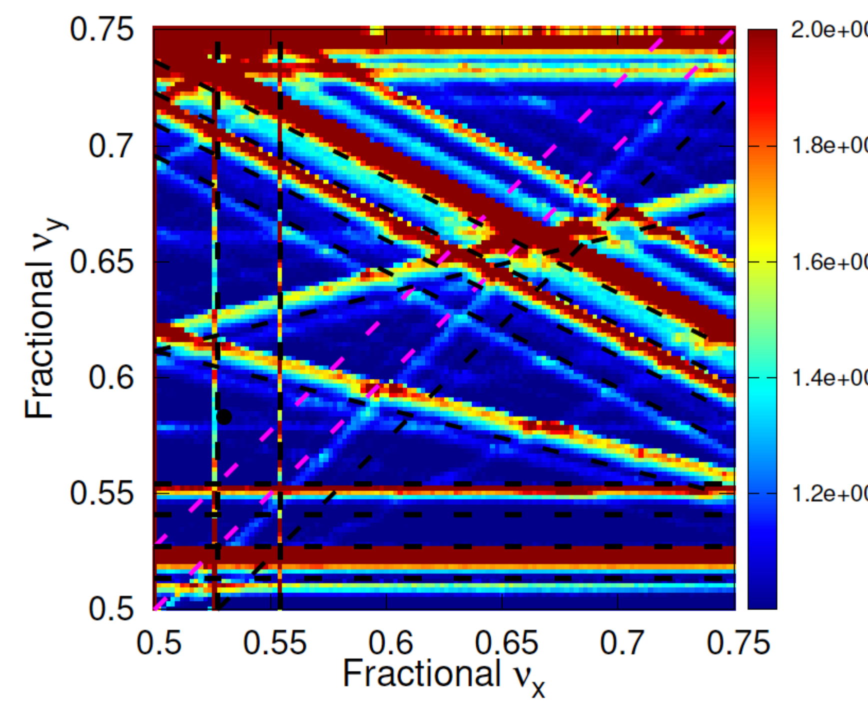
e+(S)e-(W)



σ_y/σ_{y0} (RMS)



NOTE:
Design working point (.53, .57) is preferred at least from viewpoint of simulations.



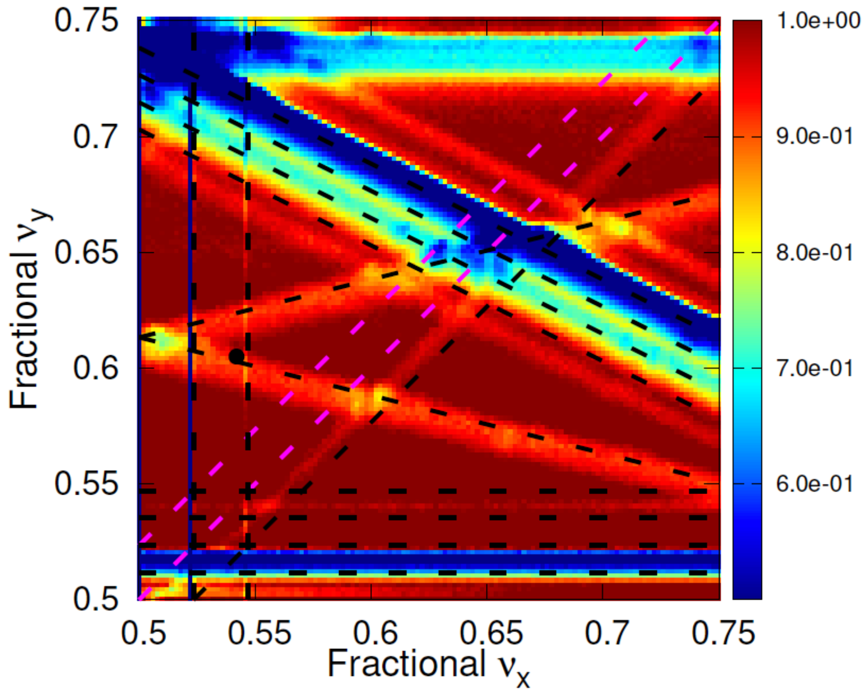
4. BBWS simulation: Tune scan: Phase 3-2

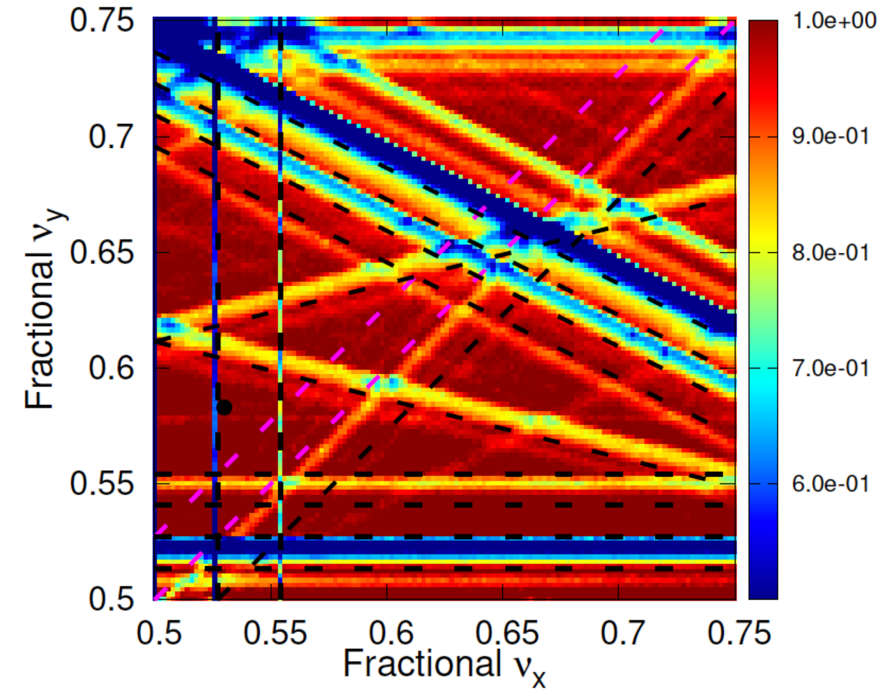
➤ **Parameter set (Phase 3-2-2: $\beta_y^* = 1.2$ mm)**

e+(W)e-(S)

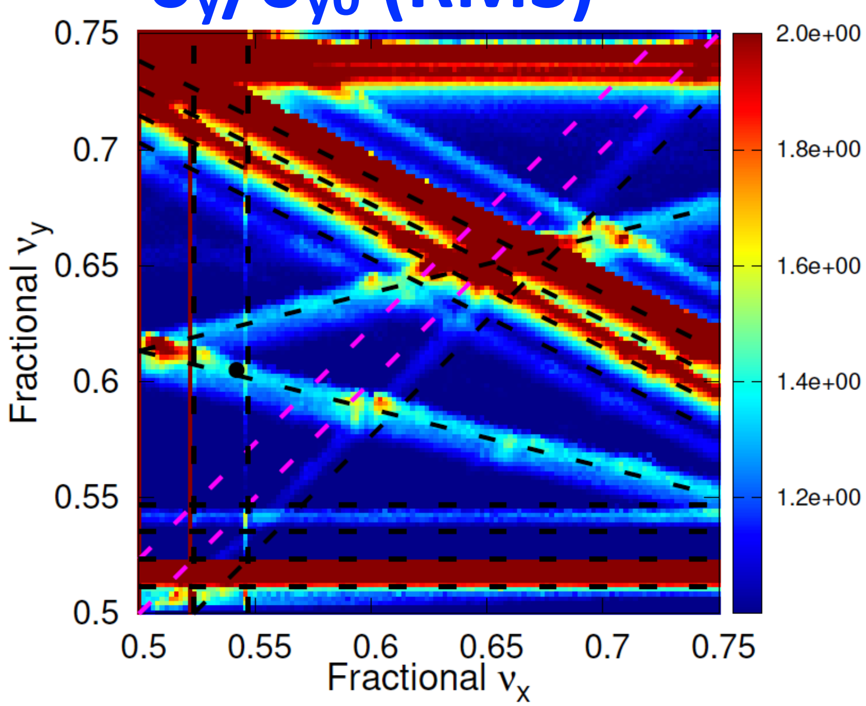
e+(S)e-(W)

Lum. (L/L_0)

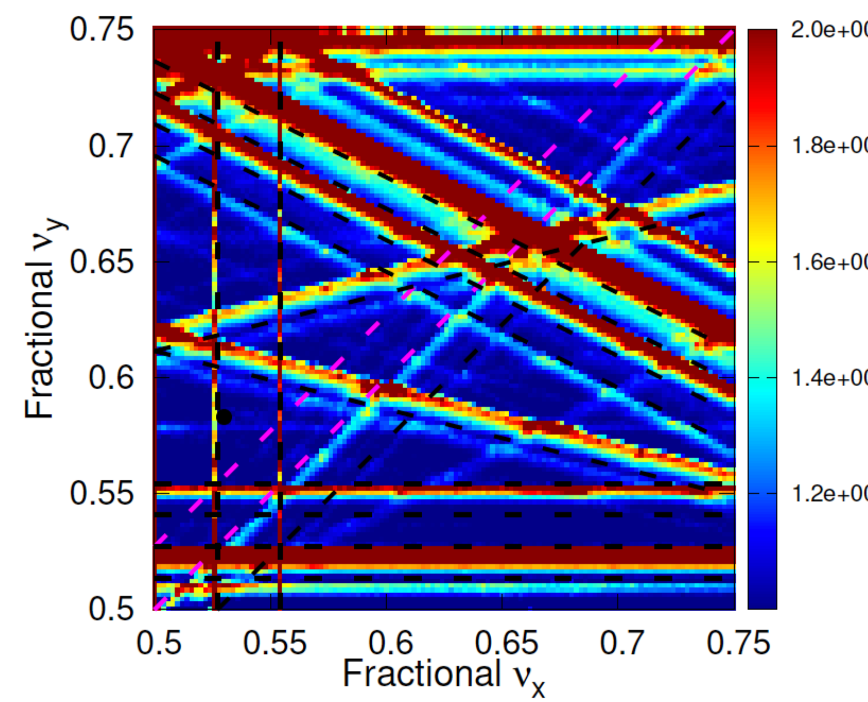




σ_y/σ_{y0} (RMS)



NOTE:
Design working point (.53, .57) is preferred at least from viewpoint of simulations.



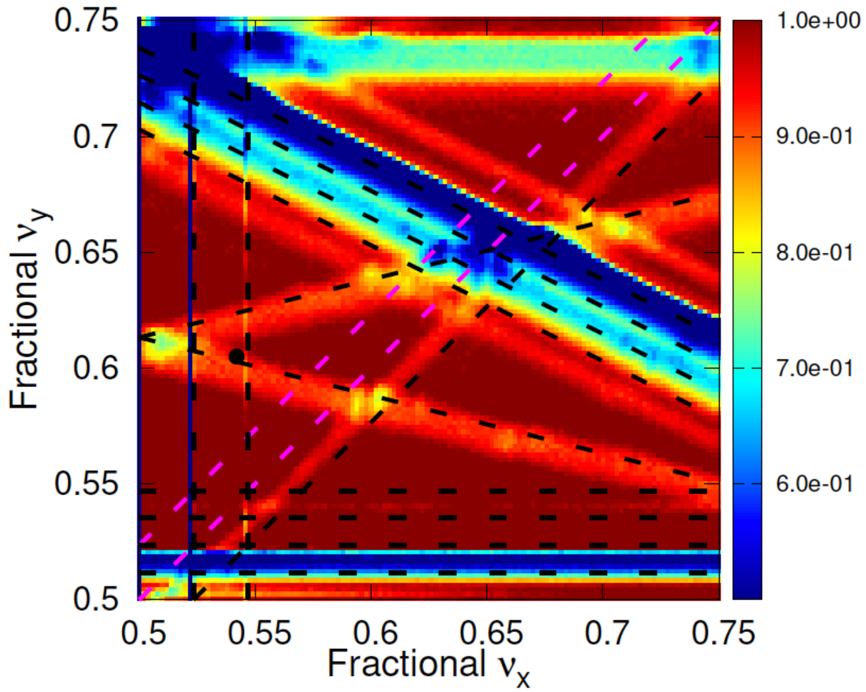
4. BBWS simulation: Tune scan: Phase 3-2

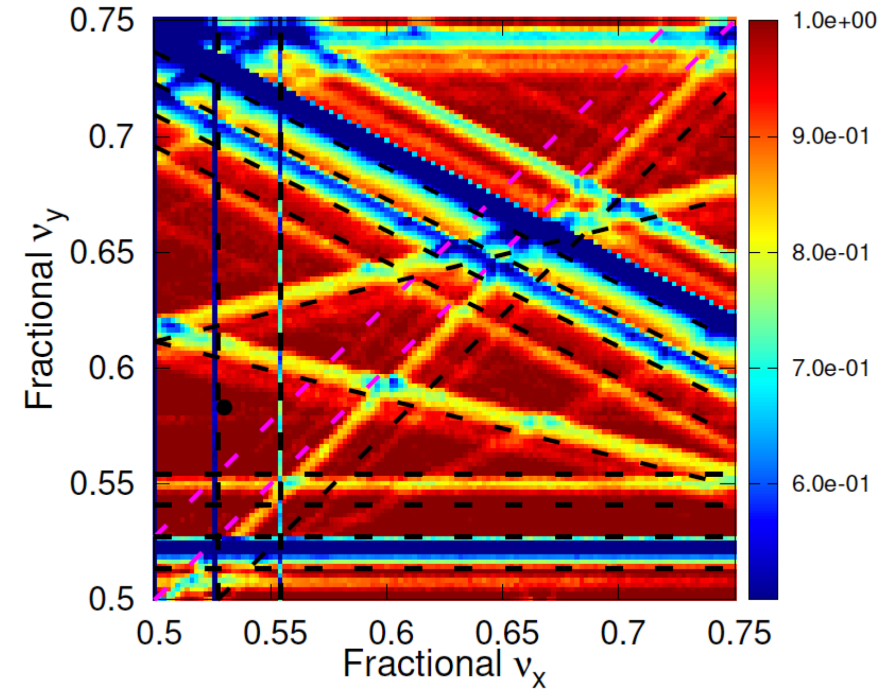
➤ **Parameter set (Phase 3-2-3: $\beta_y^* = 1.0$ mm)**

e+(W)e-(S)

e+(S)e-(W)

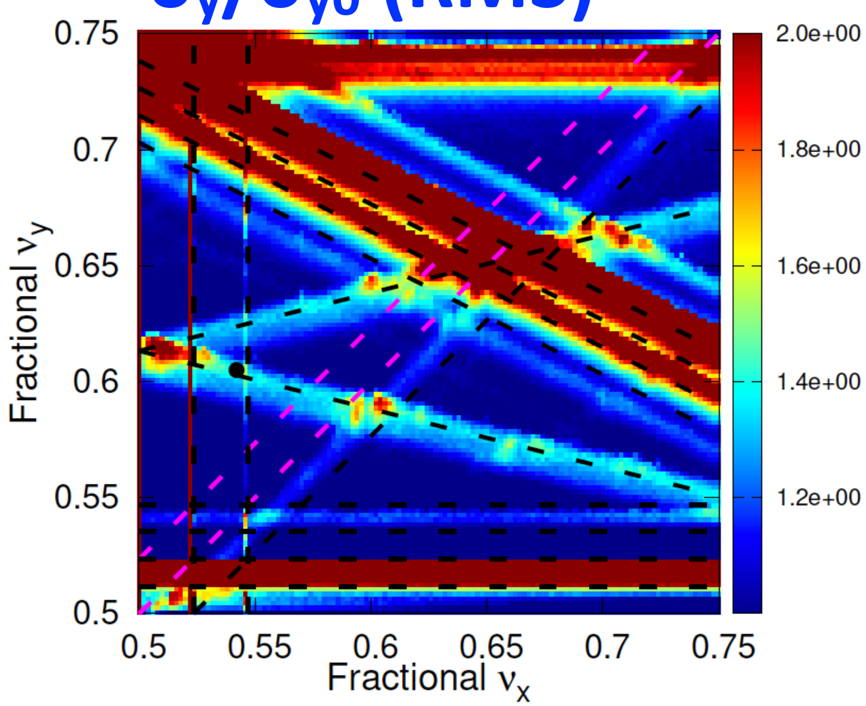
Lum. (L/L_0)

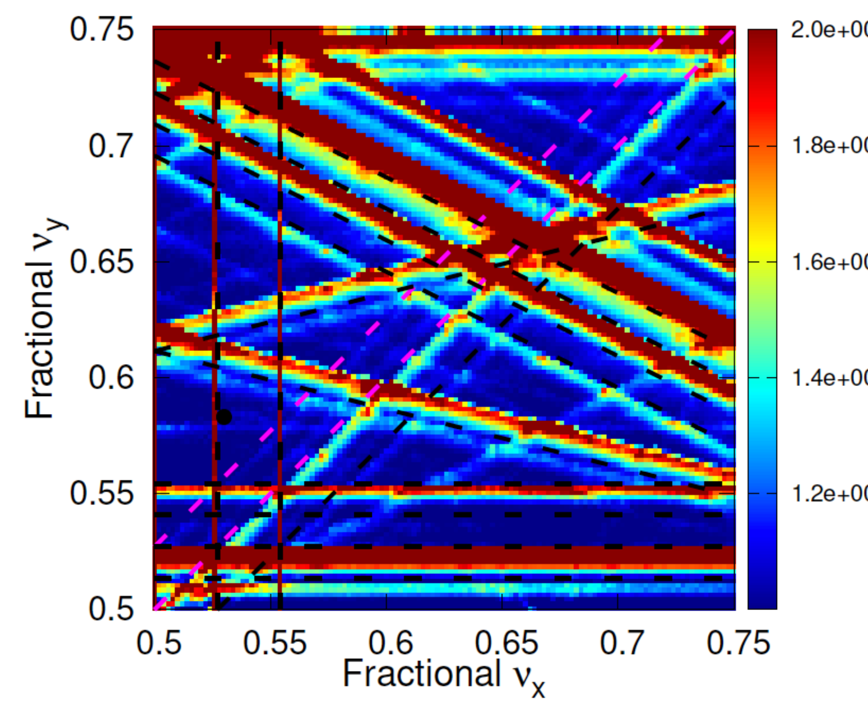




NOTE:
Design working point (.53, .57) is preferred at least from viewpoint of simulations.

σ_y/σ_{y0} (RMS)

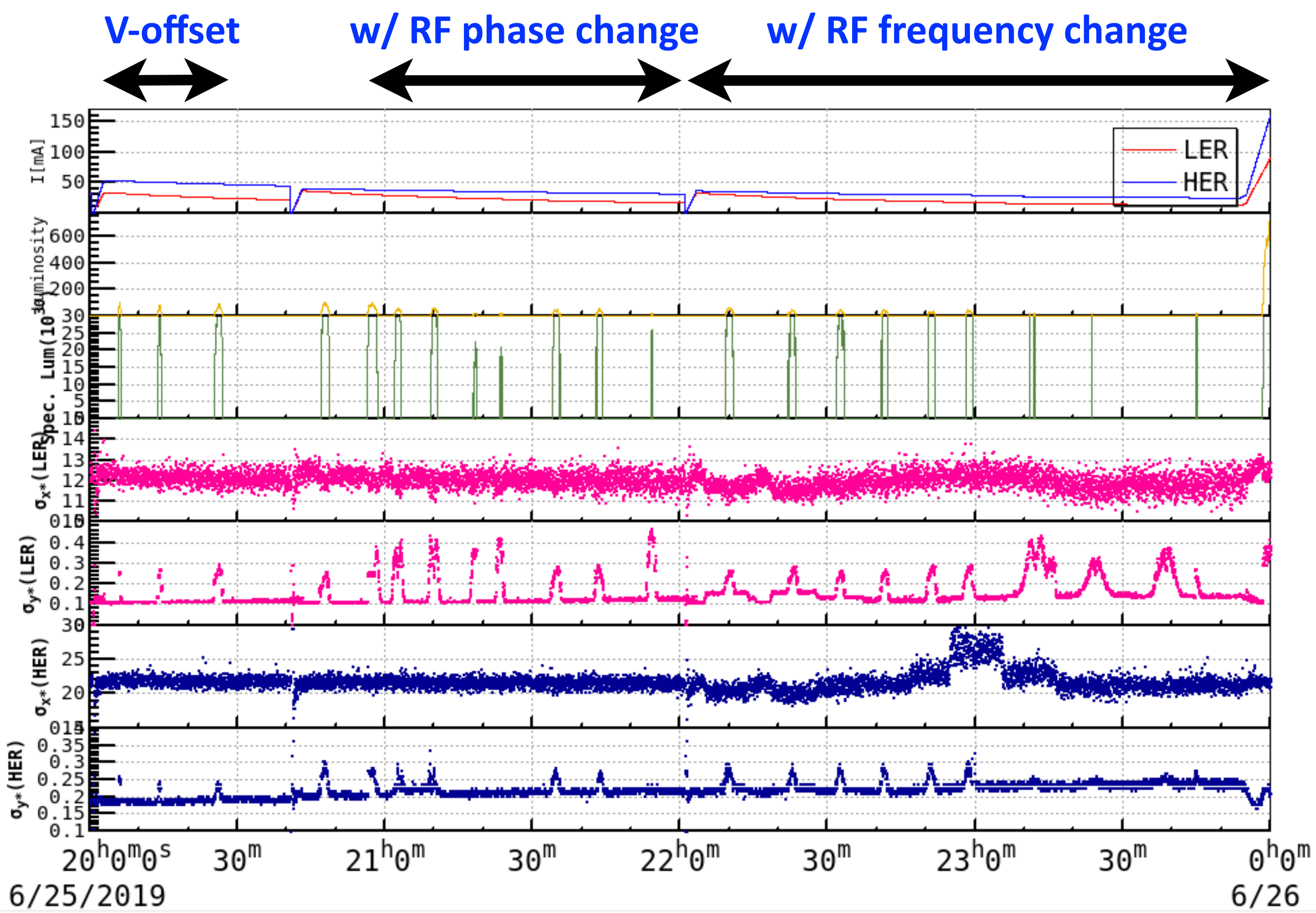


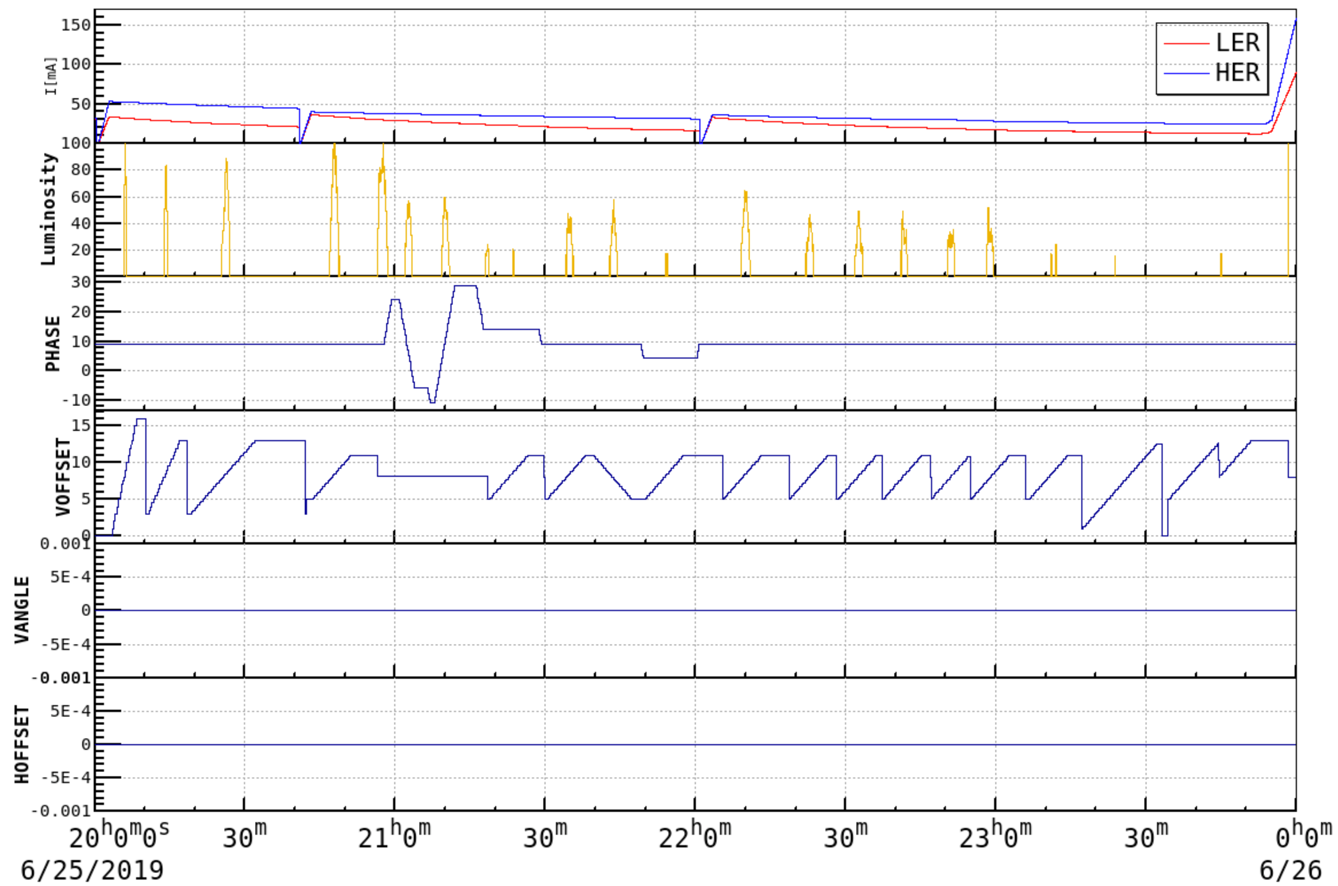


5. Beam blowup at very low bunch currents

➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- **Beam size blowup was clearly seen at very low bunch current**
- **This blowup cannot be explained by beam-beam simulations**



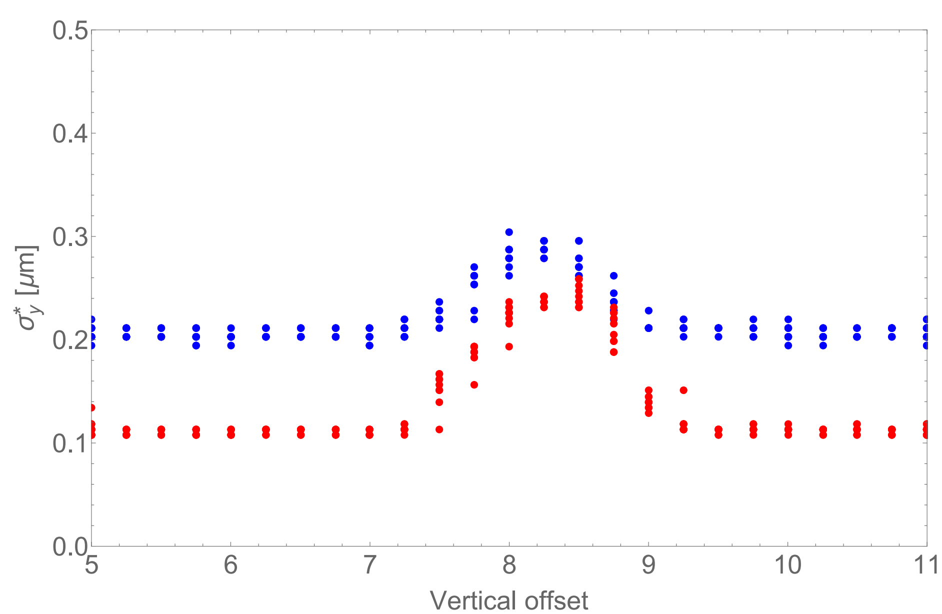


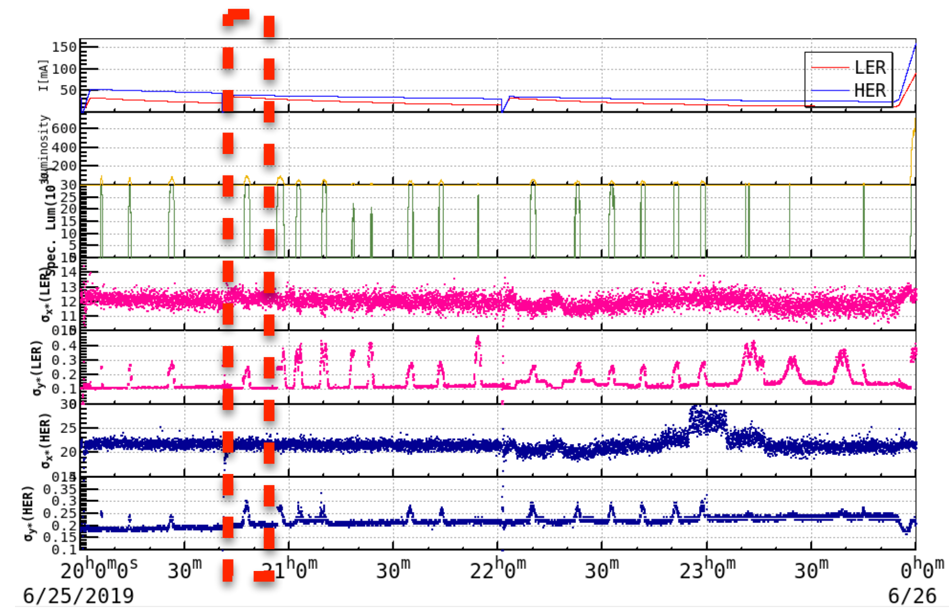
Ref. A. Morita, KCG shift report and Y. Funakoshi, Machine study report on Jun. 25, 2019

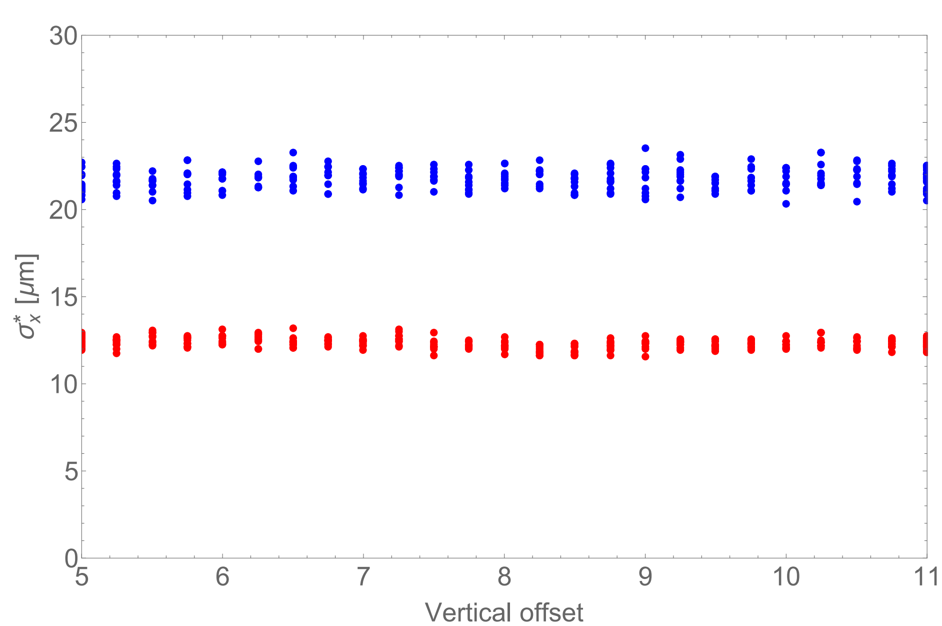
5. Beam blowup at very low bunch currents

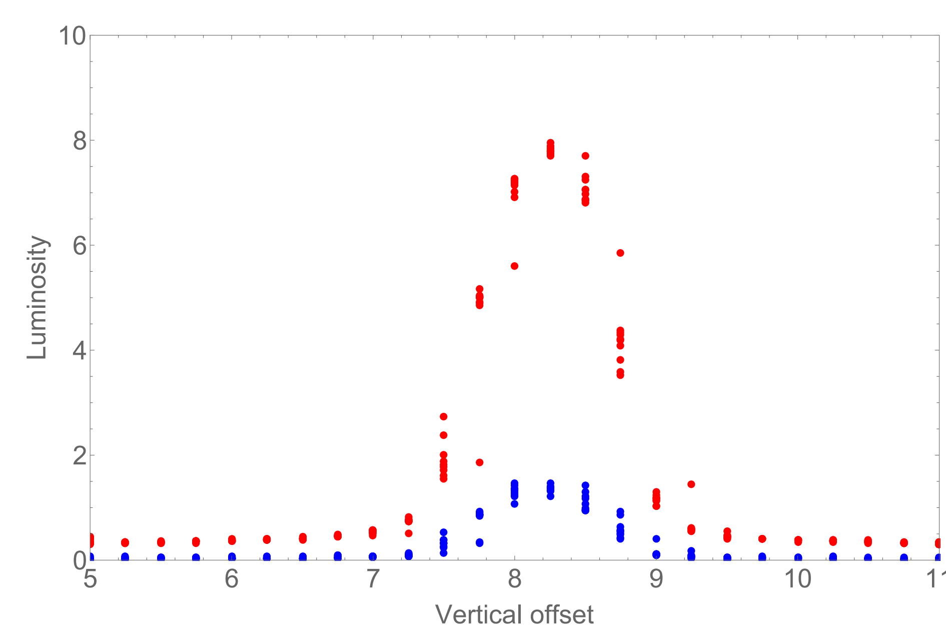
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- **Vertical offset scan with LER RF room phase 9.2 deg**
- **Both e+ and e- beams blow up in vertical direction**





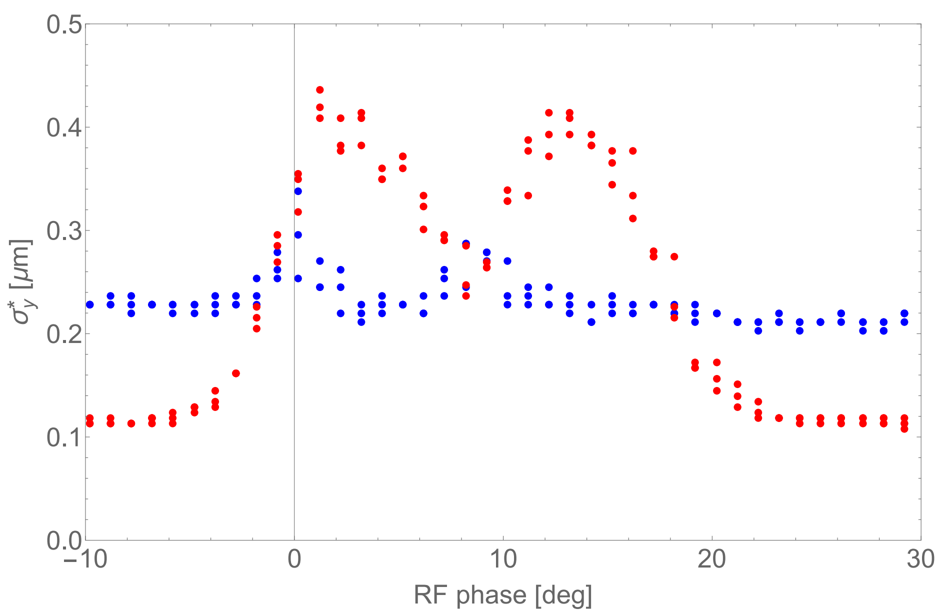


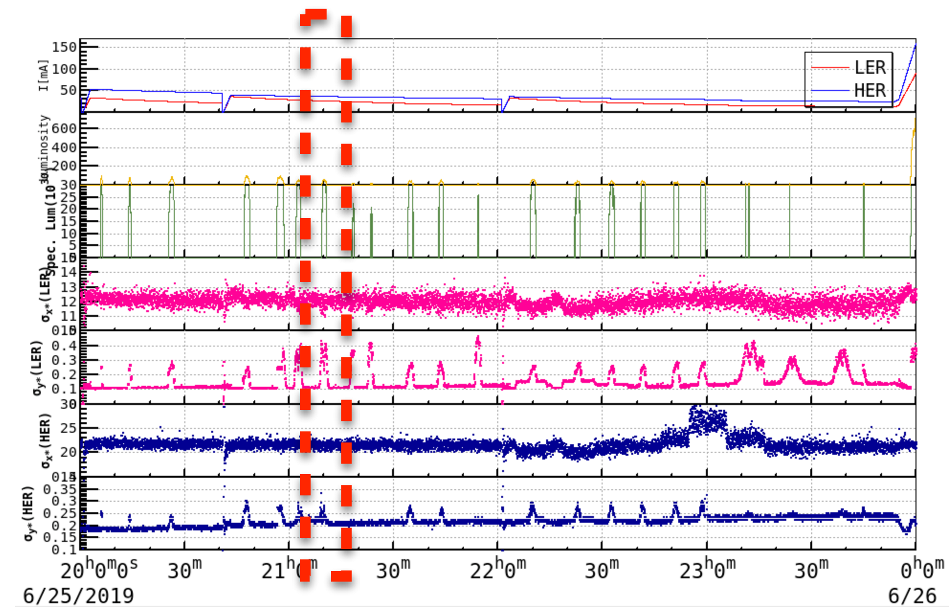


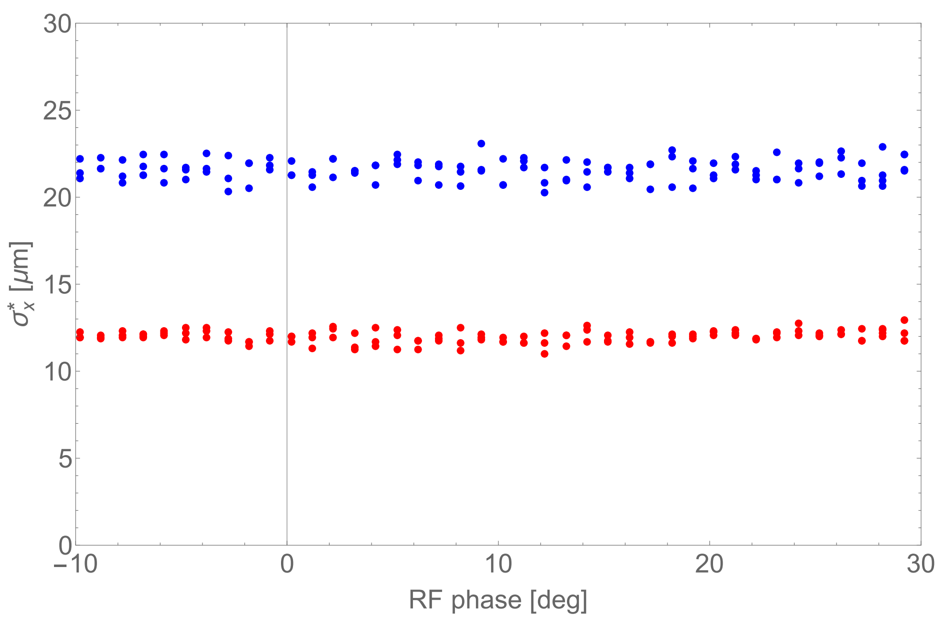
5. Beam blowup at very low bunch currents

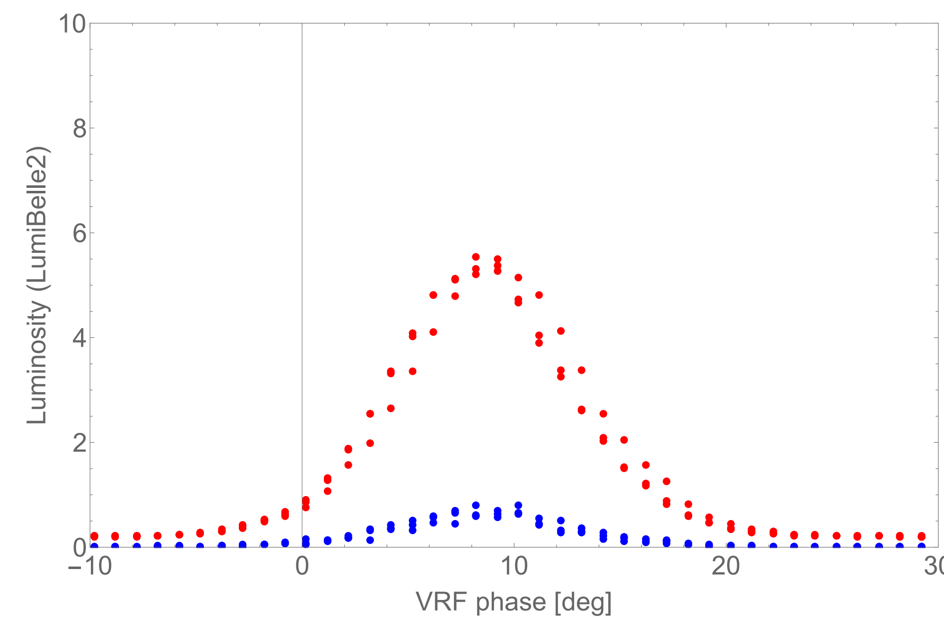
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- LER RF room phase scan with optimum vertical offset target 8.2 μm
- Both e+ and e- beams blow up (and double peaks) in vertical direction





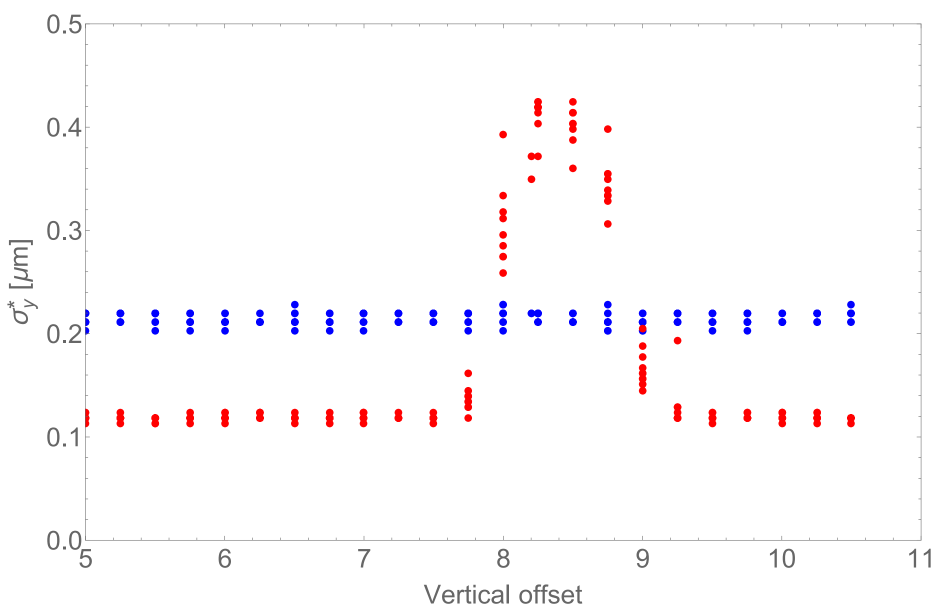


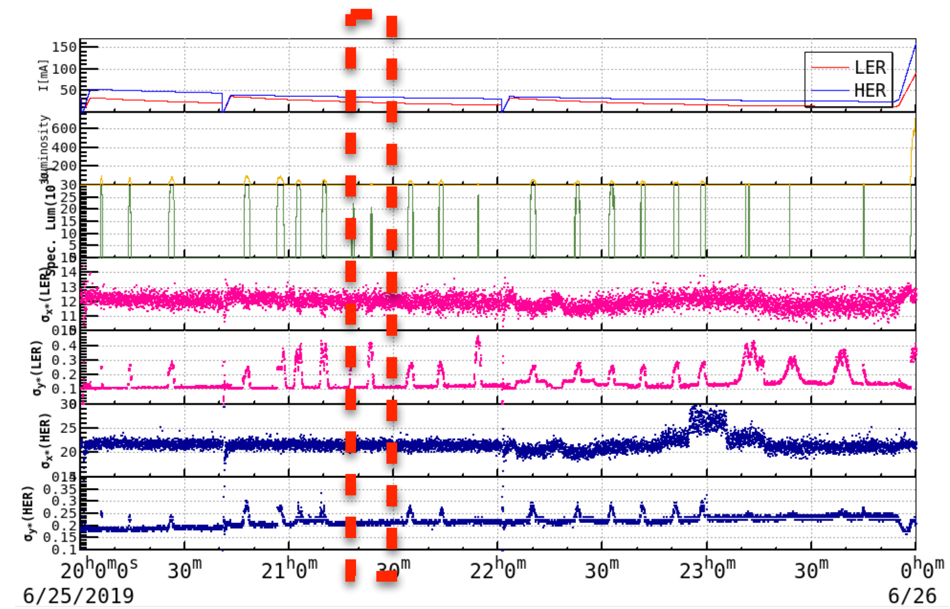


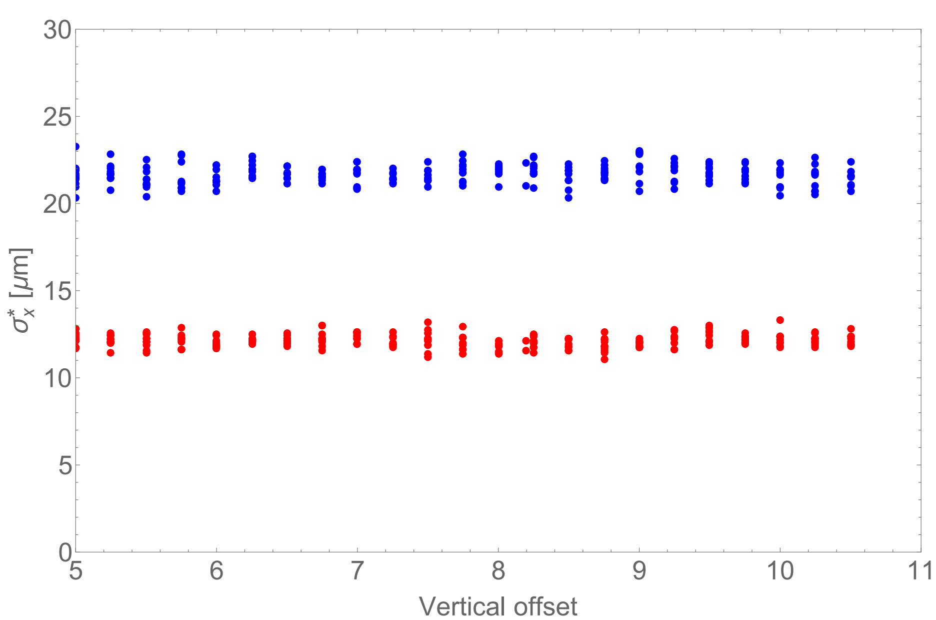
5. Beam blowup at very low bunch currents

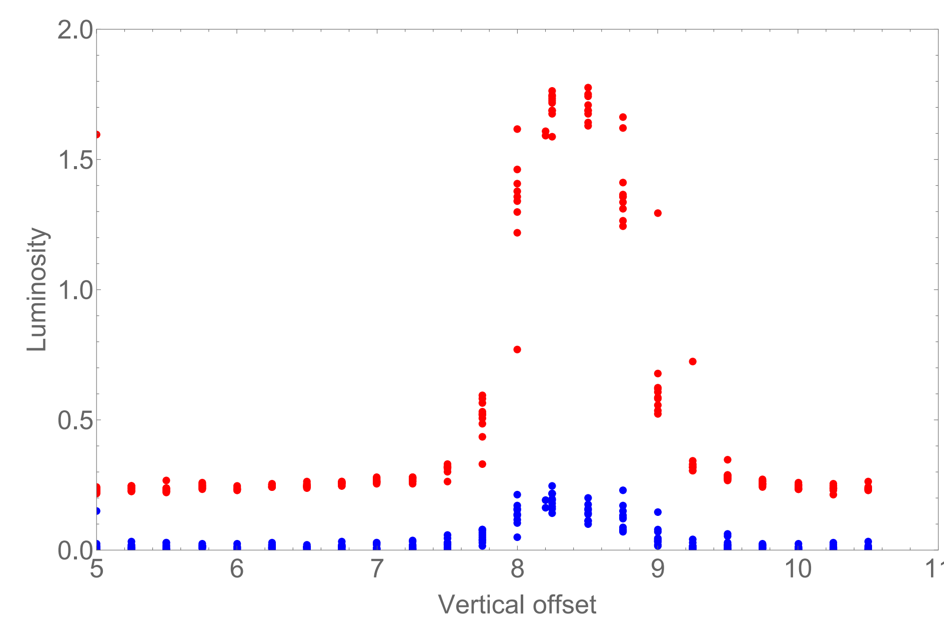
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- **Vertical offset scan with LER RF room phase 14.2 deg**
- **Only e+ beam blow up in vertical direction**





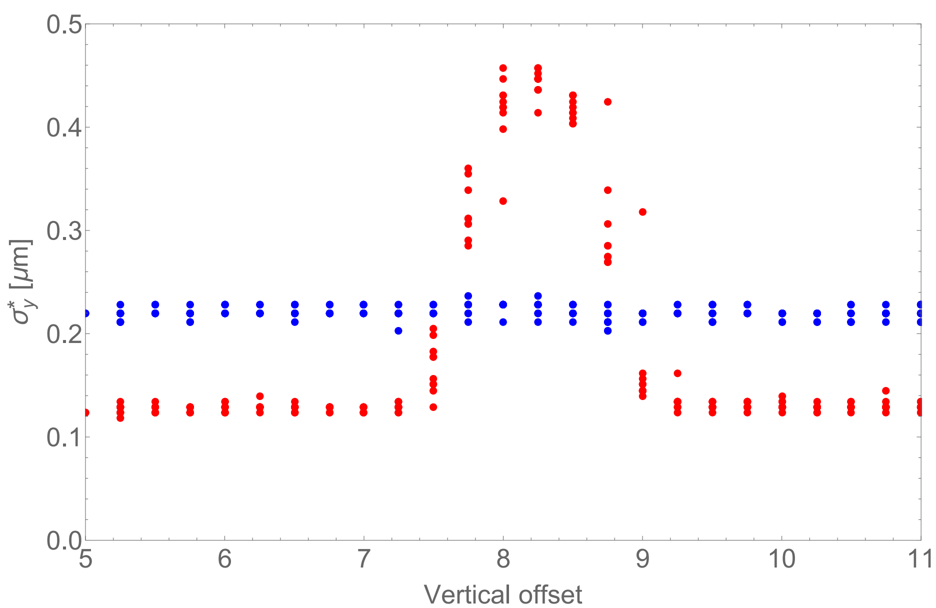


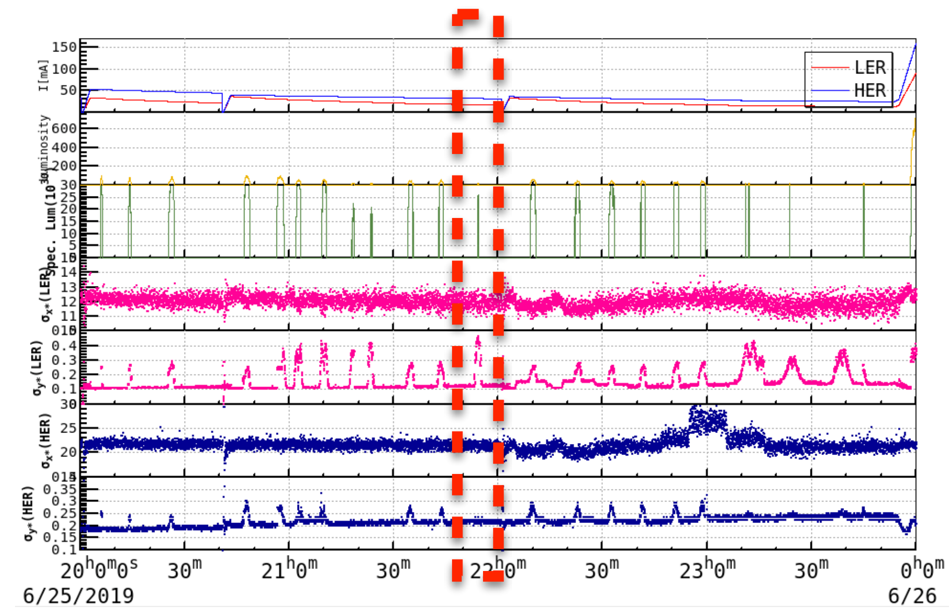


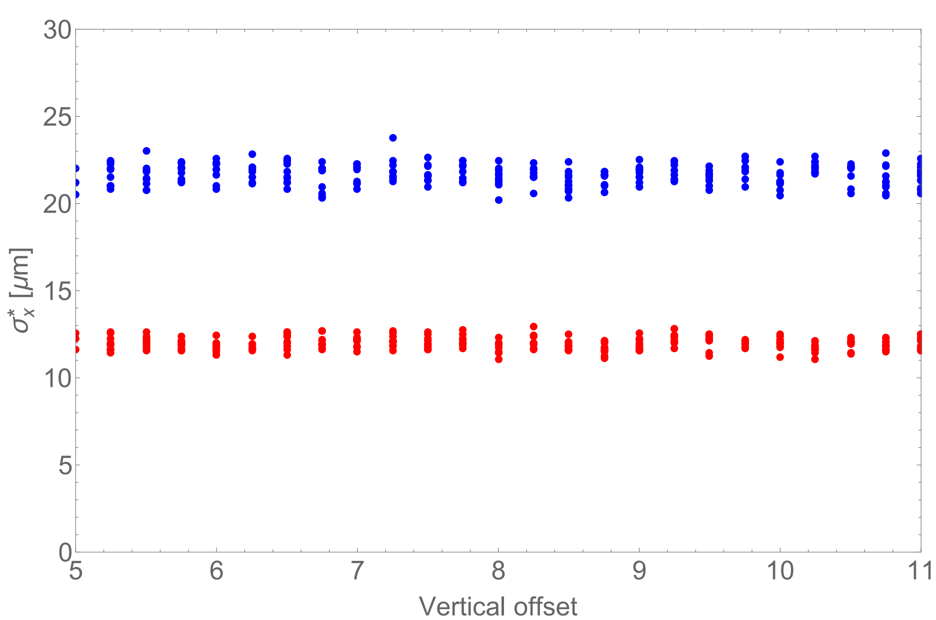
5. Beam blowup at very low bunch currents

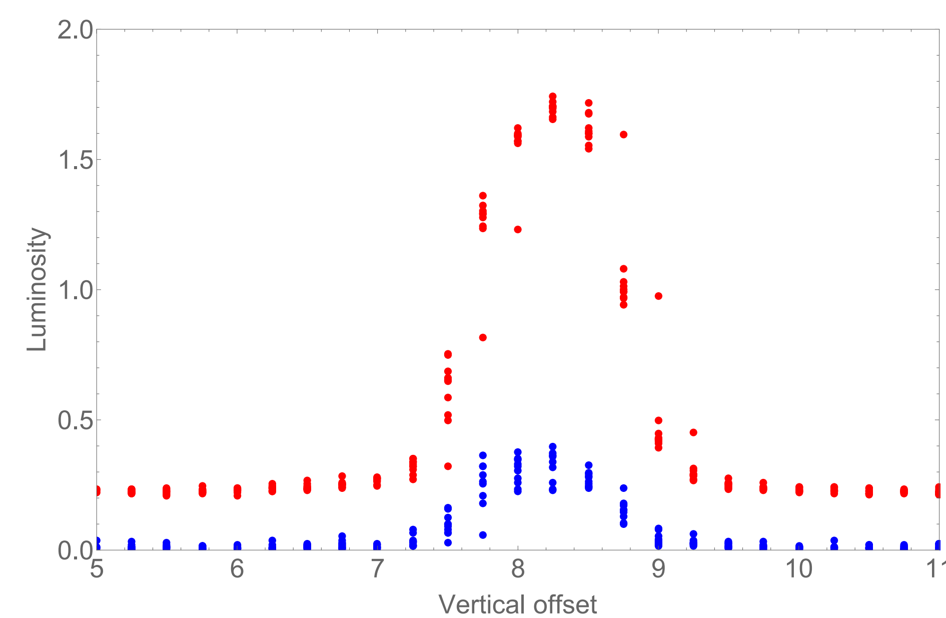
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- Vertical offset scan with LER RF room phase 4.2 deg
- Only e+ beam blow up in vertical direction





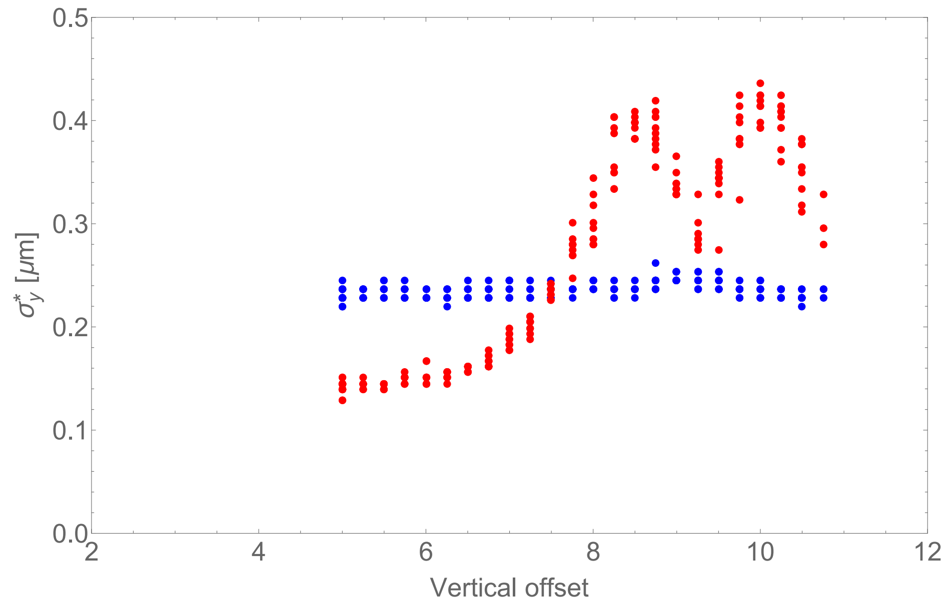


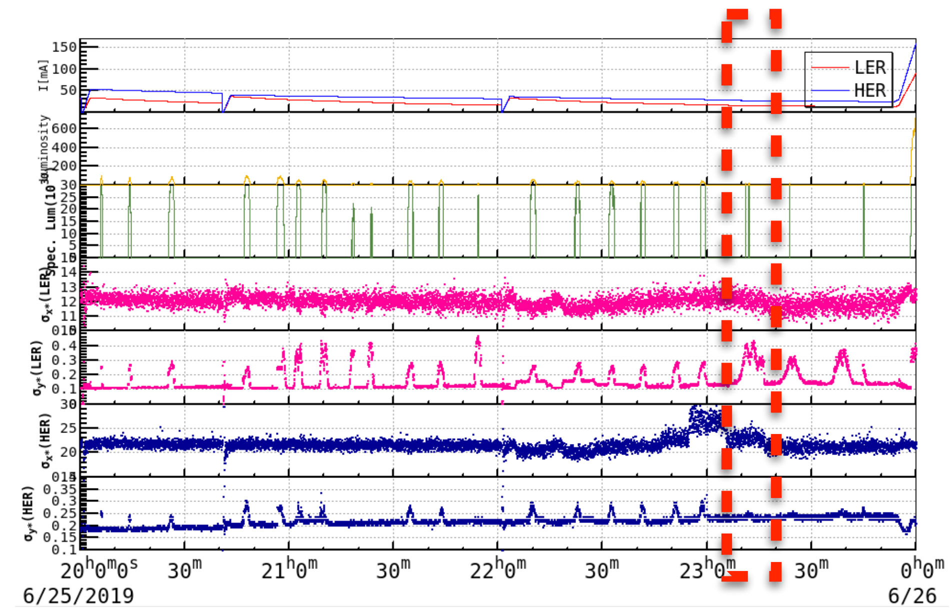


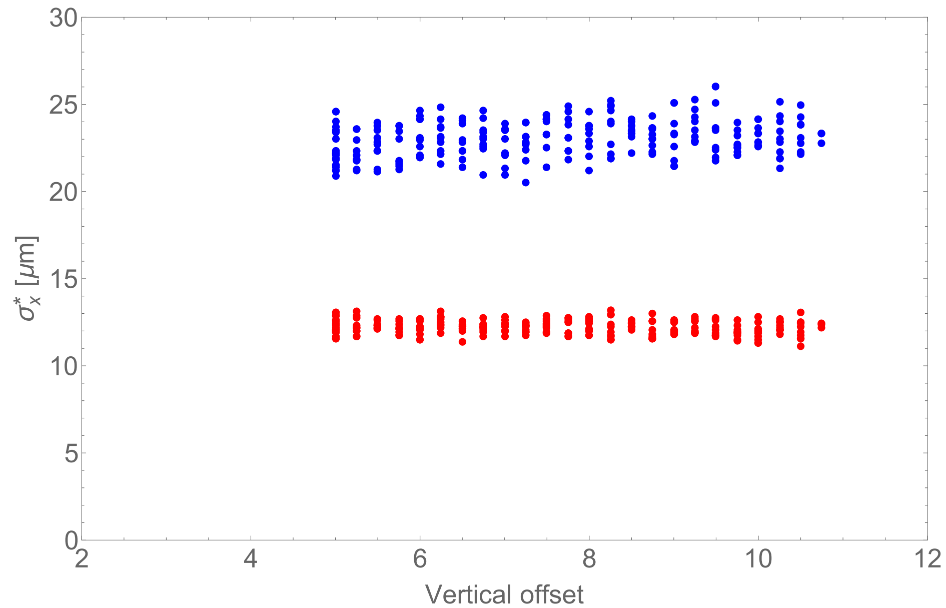
5. Beam blowup at very low bunch currents

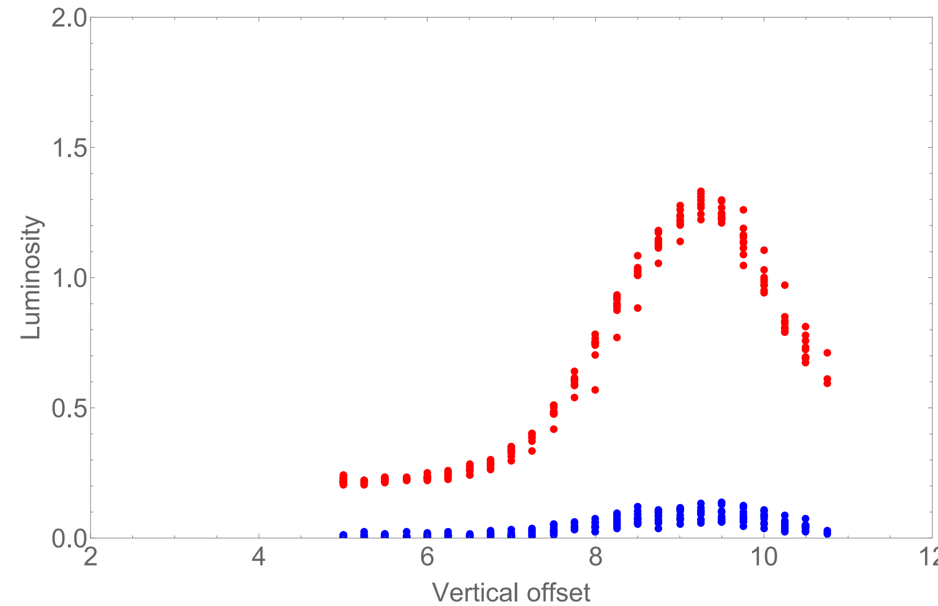
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- Vertical offset scan with LER RF room phase 9.2 deg, RF frequency Δf=-200 Hz, and LER IP dispersion $\xi_y^* = +1$ mm
- Only e+ beam blow up in vertical direction





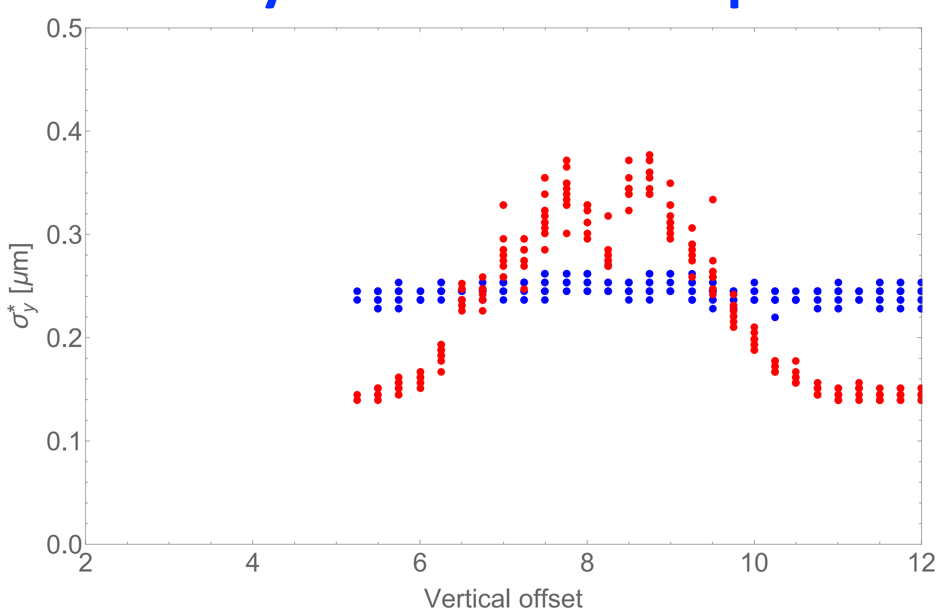


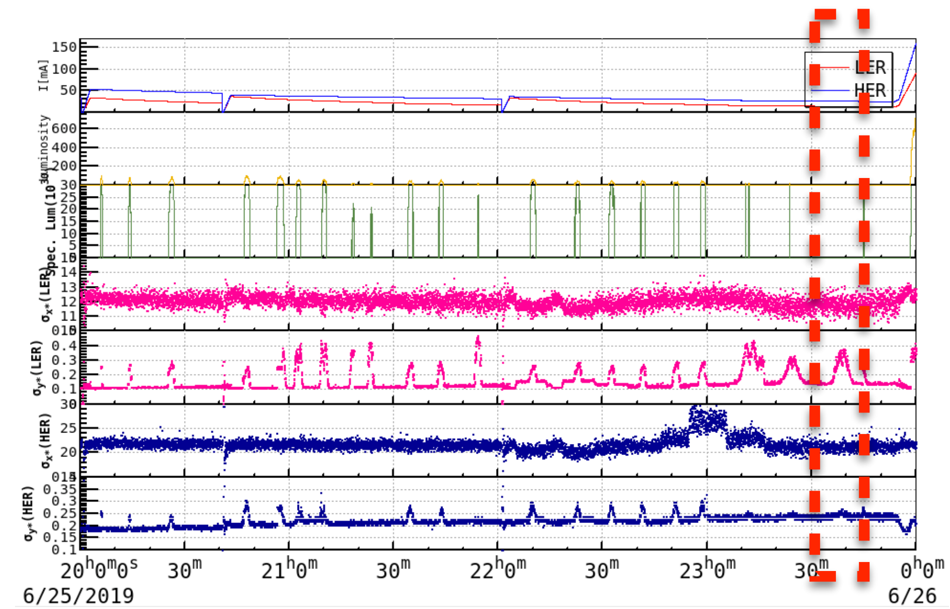


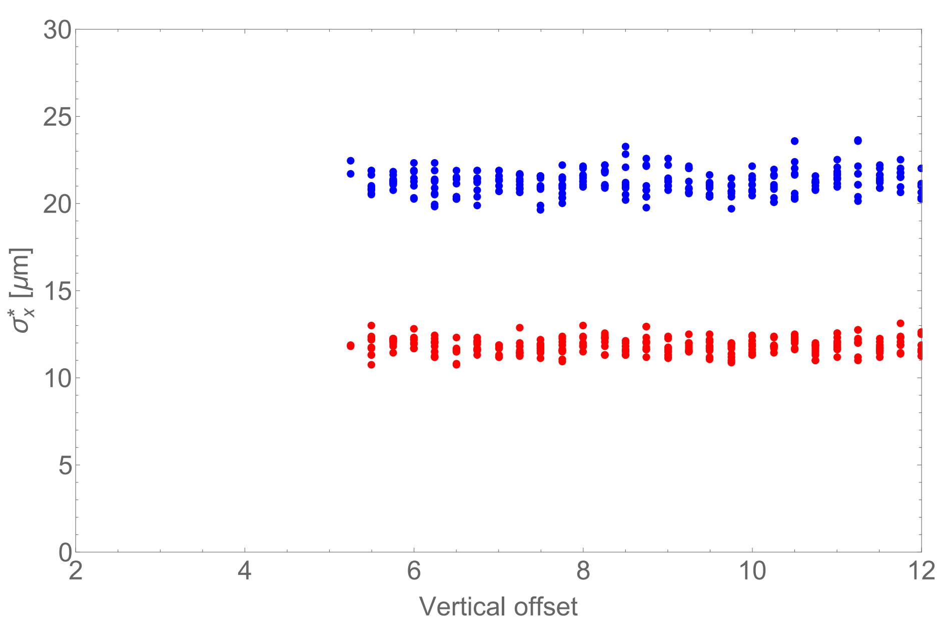
5. Beam blowup at very low bunch currents

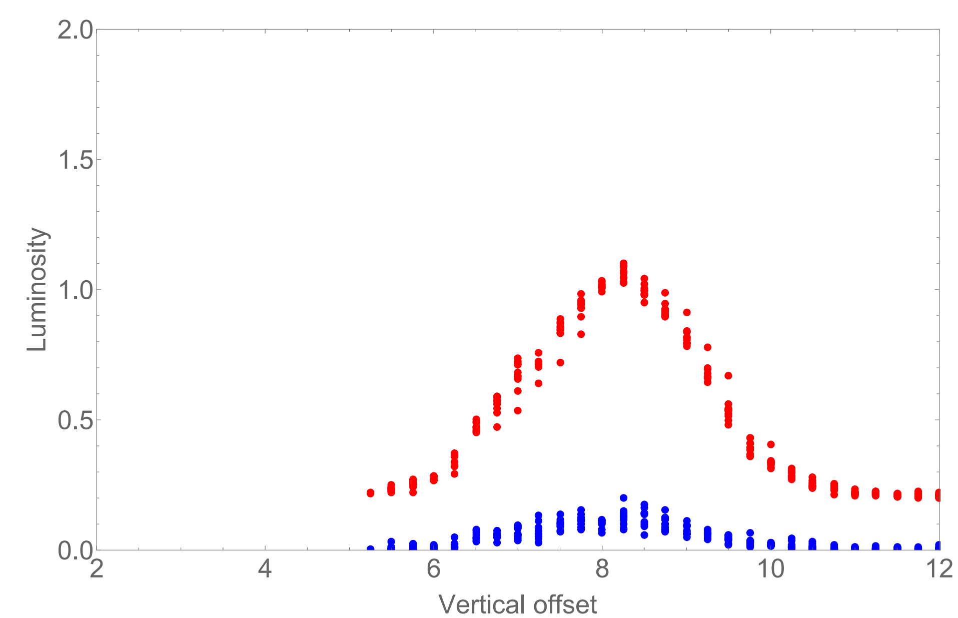
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- **Vertical offset scan with LER RF room phase 9.2 deg, RF frequency Δf=0 Hz, and LER IP dispersion ξ_y^* = +1 mm**
- **Only e+ beam blow up in vertical direction**





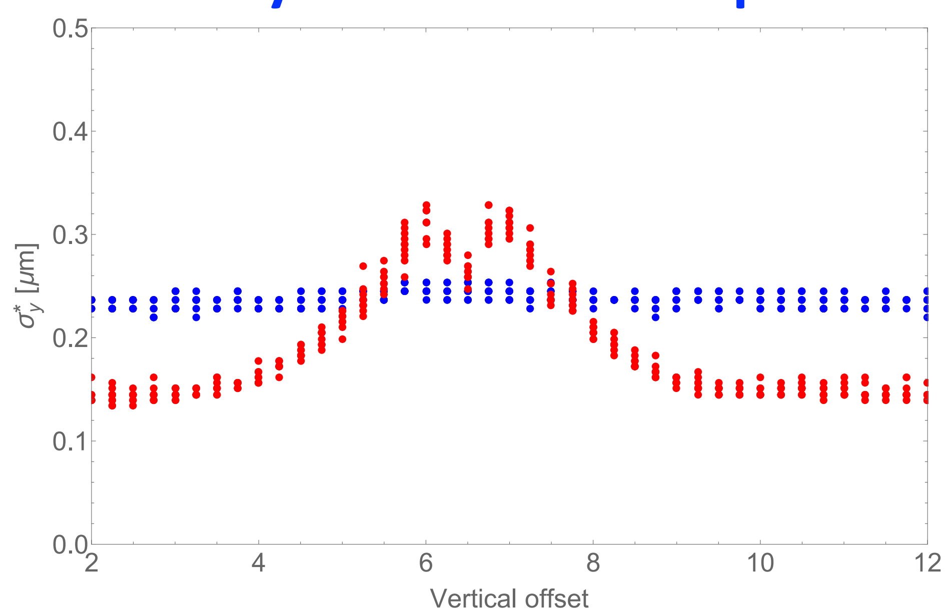


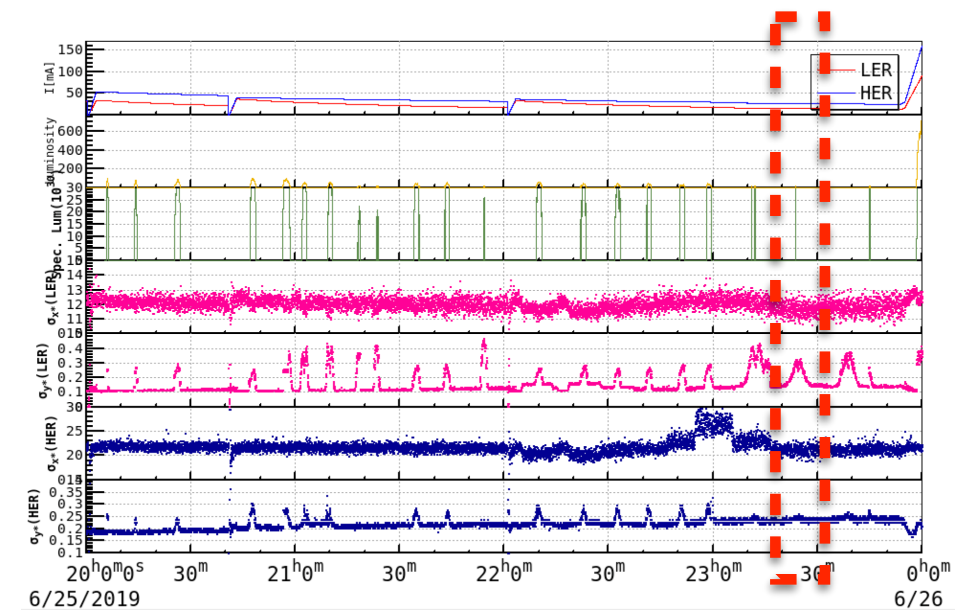


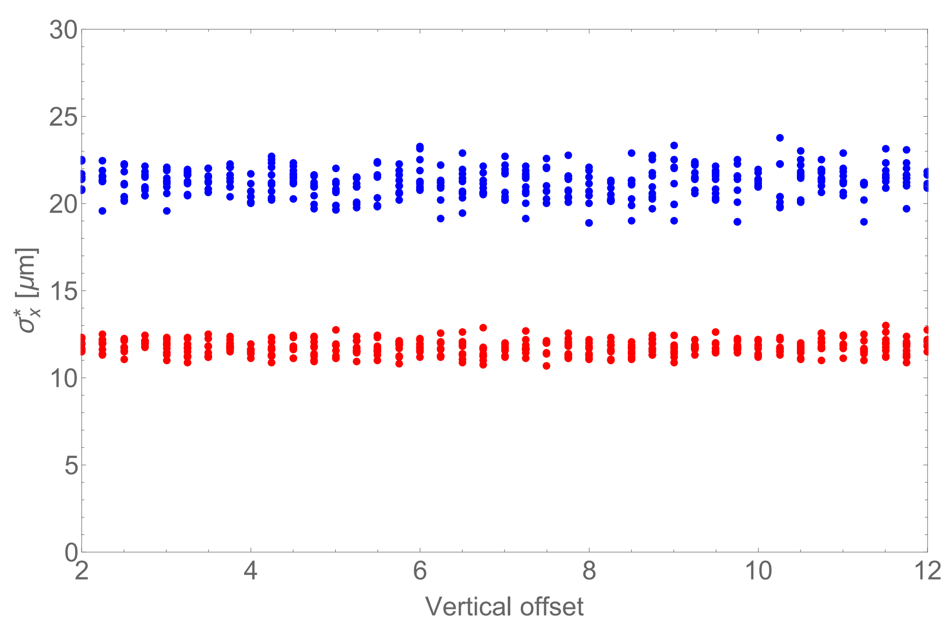
5. Beam blowup at very low bunch currents

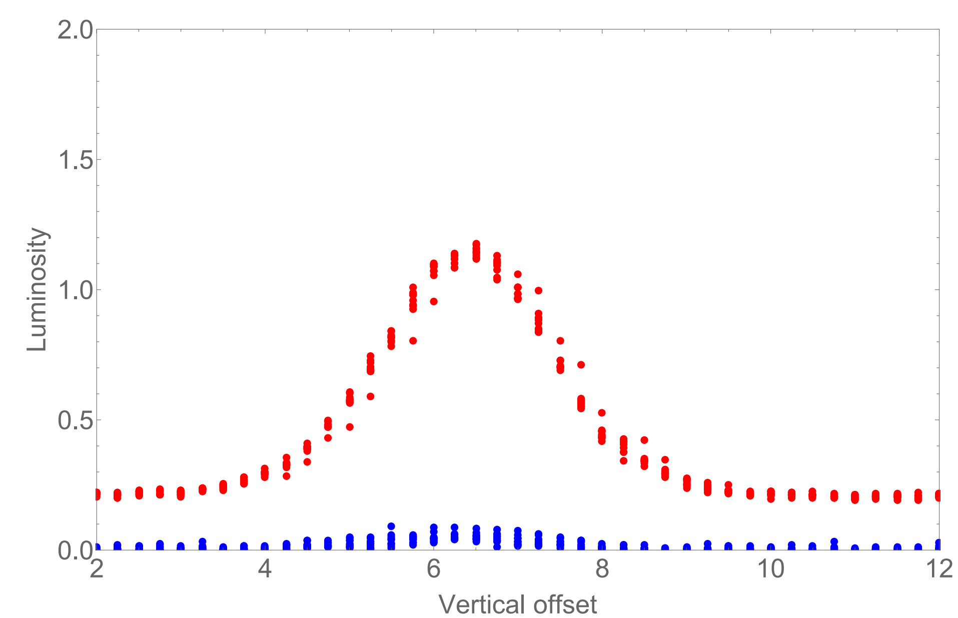
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- **Vertical offset scan with LER RF room phase 9.2 deg, RF frequency Δf=+200 Hz, and LER IP dispersion ξ_y^* = +1 mm**
- **Only e+ beam blow up in vertical direction**





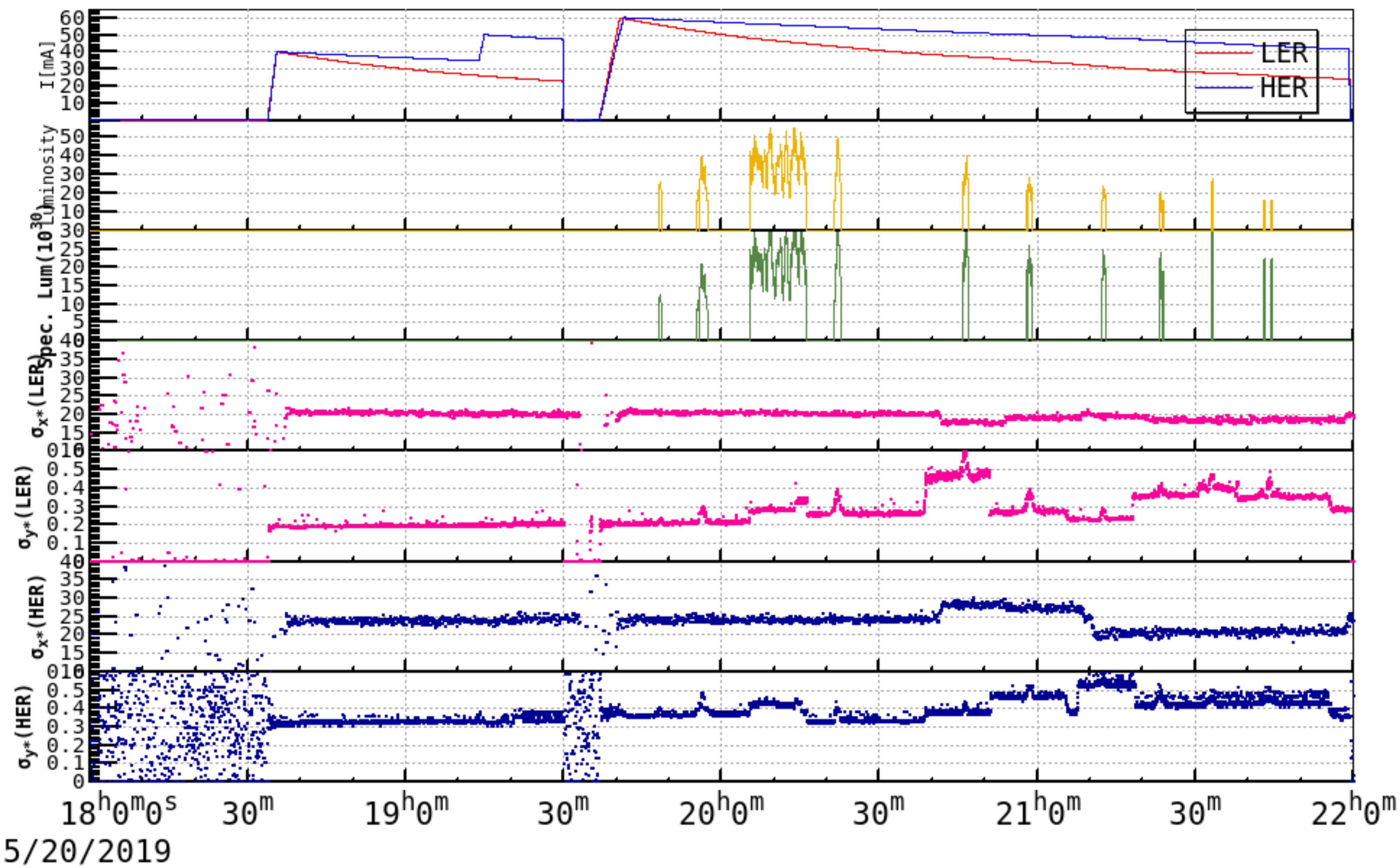




5. Beam blowup at very low bunch currents

➤ Machine study: Vertical offset scan (2019.05.20)

- **Similar beam size blowup was clearly also observed on May. 20, 2019**
- **The single beam beam size was larger than that of Jun. 25, 2019, so the blowup looked not very significant**



Ref. T. Kobayashi, KCG shift report and K. Ohmi, Machine study report on May. 20, 2019

6. Summary

➤ Findings

- **Weak-strong beam-beam simulations**

** How to choose the vertical single beam emittance for collision in SuperKEKB?

*** My opinion: We need control it for both beams using emittance knob. If the single beam emittance is too small (because of good optics corrections), though beam-beam interaction blows up the beams, the machine would be operated with unstable condition

*** Question: Was the vertical single beam emittance controlled at KEKB?

- **Offset scan at low bunch current**

** Experiments showed significant beam-beam related blow up in vertical beam size

** But beam-beam simulations (both BBWS and SAD with ideal lattice) cannot reproduce this phenomenon

** Two possible candidates are under my consideration:

*** The translation of beam size from XRM to IP need to be well understood

*** Machine imperfections: In SAD simulations, I need to take into account

*) the vertical closed orbit as measured with beam

*) the vertical dispersion function along the whole ring as measured with beam

*) other errors, such as misalignment of magnets

I suppose these kind of imperfections might create interplay with beam-beam (even at low bunch currents)

Backup

6. Simple scaling laws

➤ Some derivations of the "magic" variables

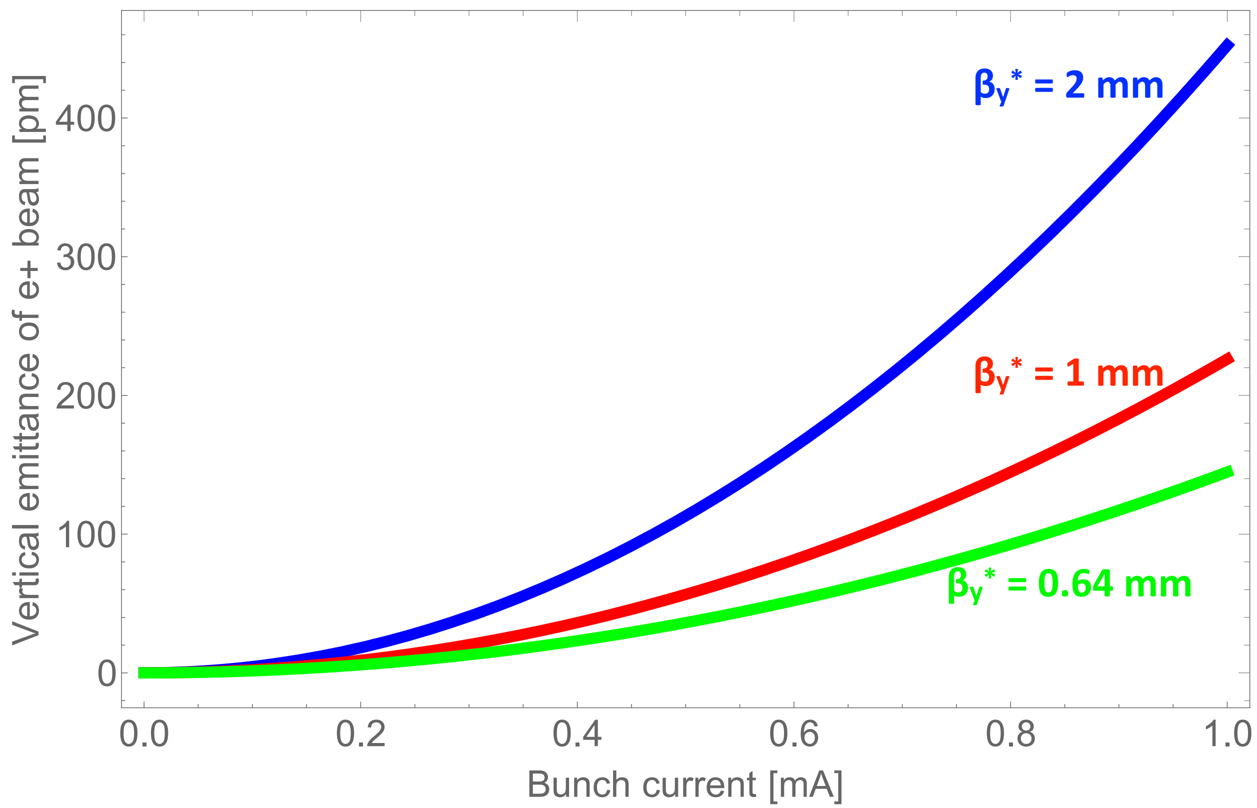
• With given beam-beam limit, the scaling law of emittance control (or beam-beam blowup):

$$\epsilon_{\rm yp} \propto N_{\rm p}^2$$

$$\epsilon_{\rm yp} \propto \beta_{\rm y}^*$$

$$\epsilon_{\rm yp} \propto \frac{1}{\xi_{\rm ye}^2}$$

$$\xi_{\rm ye} = \frac{r_{\rm e}}{2\pi \tan\frac{\theta}{2}} \frac{N_{\rm p}\beta_{\rm ye}^*}{\gamma_{\rm e}\sigma_{\rm zp}\sigma_{\rm yp}^*}$$



NOTE: Assume beam-beam parameter of ξ_{ye}=0.02 from observations of 2019.07.01

**** The vertical emittance can be very large (set challenge to the ECK?) when increasing the bunch current**

**** The only way is to squeeze β_y^*, or to increase the beam-beam limit**

6. Simple scaling laws

➤ Some derivations of the "magic" variables

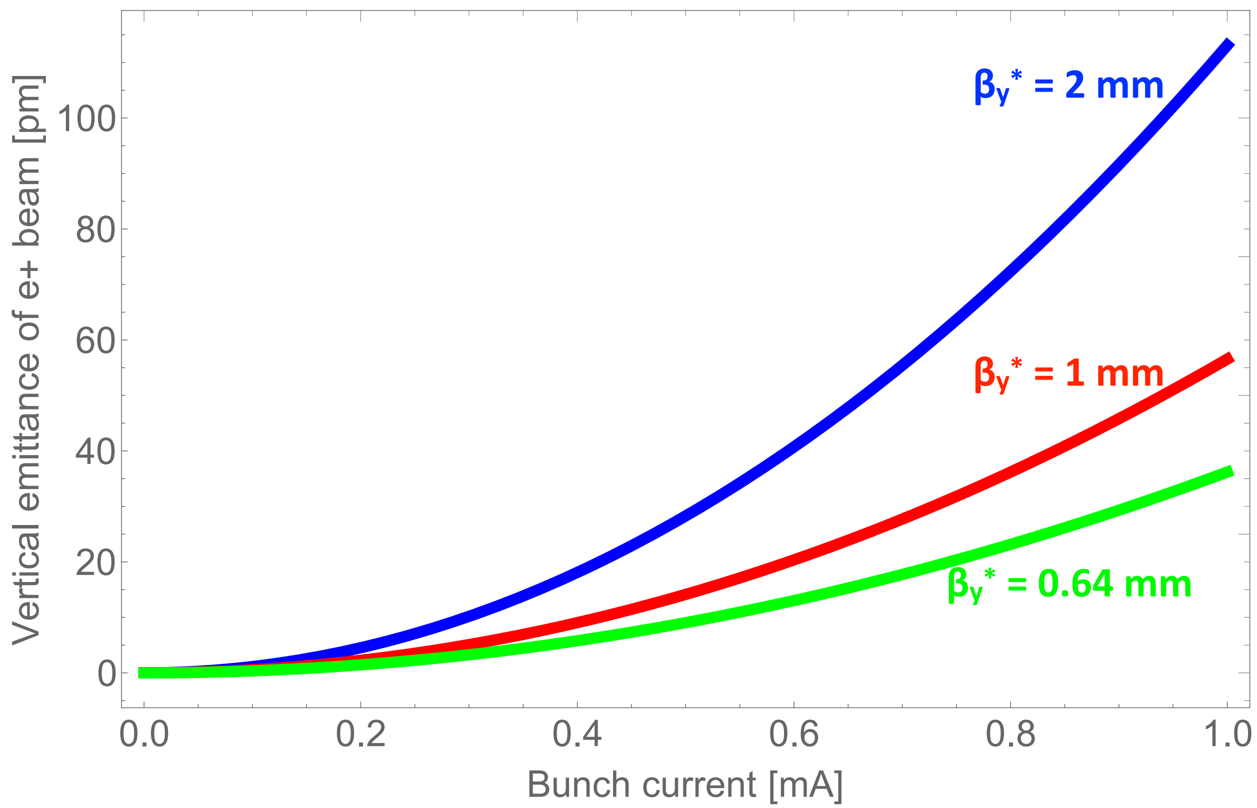
- **With given beam-beam limit, the scaling law of emittance control (or beam-beam blowup):**

$$\xi_{\rm ye} = \frac{r_{\rm e}}{2\pi \tan\frac{\theta}{2}} \frac{N_{\rm p}\beta^*_{\rm ye}}{\gamma_{\rm e}\sigma_{\rm zp}\sigma^*_{\rm yp}}$$

$$\epsilon_{\rm yp} \propto N_{\rm p}^2$$

$$\epsilon_{\rm yp} \propto \beta^*_{\rm y}$$

$$\epsilon_{\rm yp} \propto \frac{1}{\xi^2_{\rm ye}}$$



NOTE: Assume beam-beam parameter of ξ_{ye}=0.04

**** The vertical emittance can be very large (set challenge to the ECK?) when increasing the bunch current**

**** The only way is to squeeze β_y^*, or to increase the beam-beam limit**