Simulations of beam-beam effects

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Acknowledgements:

the SuperKEKB team

SuperKEKB mini-optics meeting

Aug. 08, 2019, KEK

1. Introduction

➤ Phase-3 (Early stage) machine parameters

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

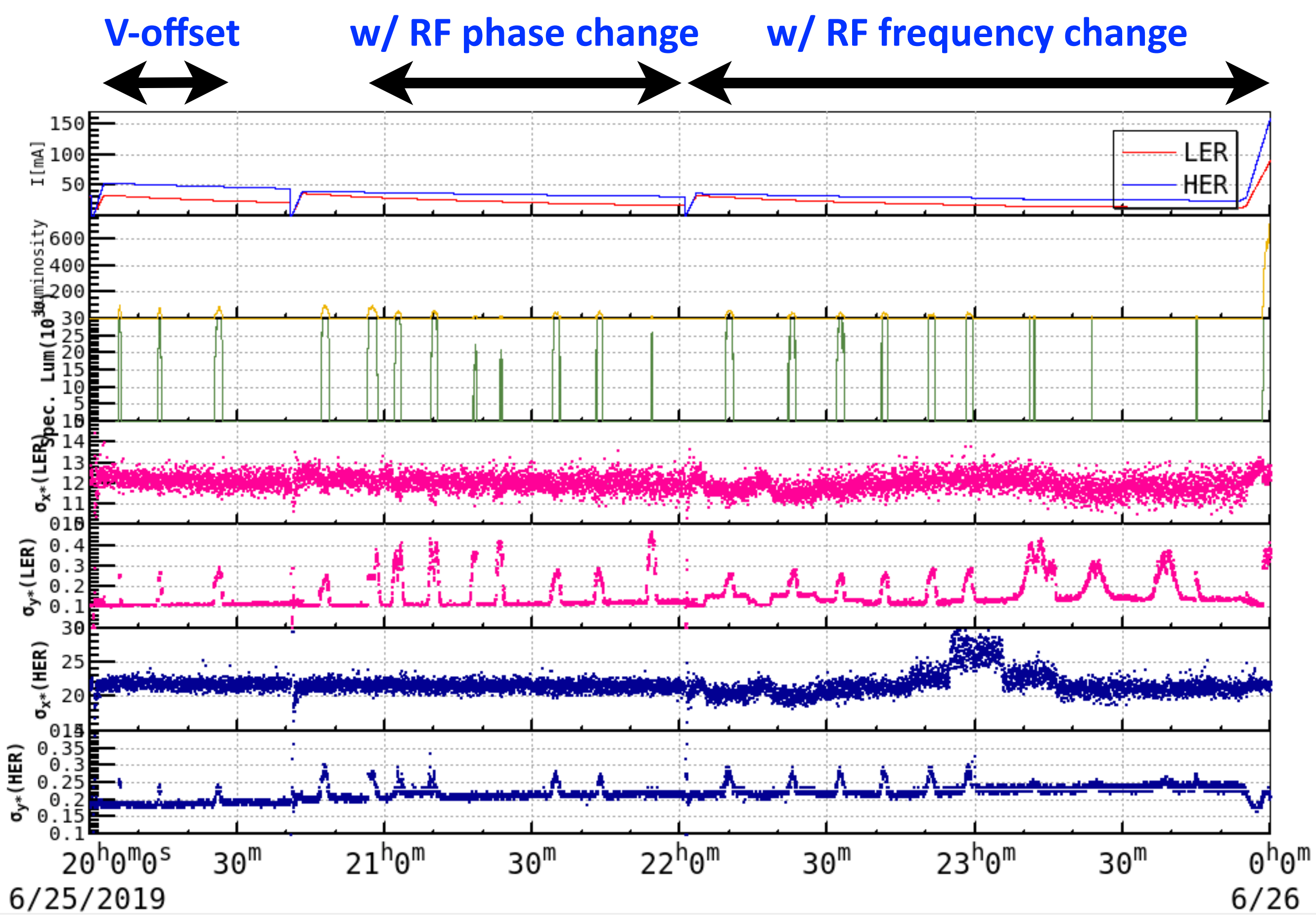
	2019.06.25		2019.07.01		2019.07.01(op1)		2019.07.01(op2)		2019.07.01(op3)	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.05	0.03	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
# bunch	789		1576		1576		1576		1576	
ε_x (nm)	4.466	1.64	4.49	1.93	4.49	1.93	4.49	1.93	4.49	1.93
ε_y (pm)**	16.2	6.05	16.2	6.05	40	6.05	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	

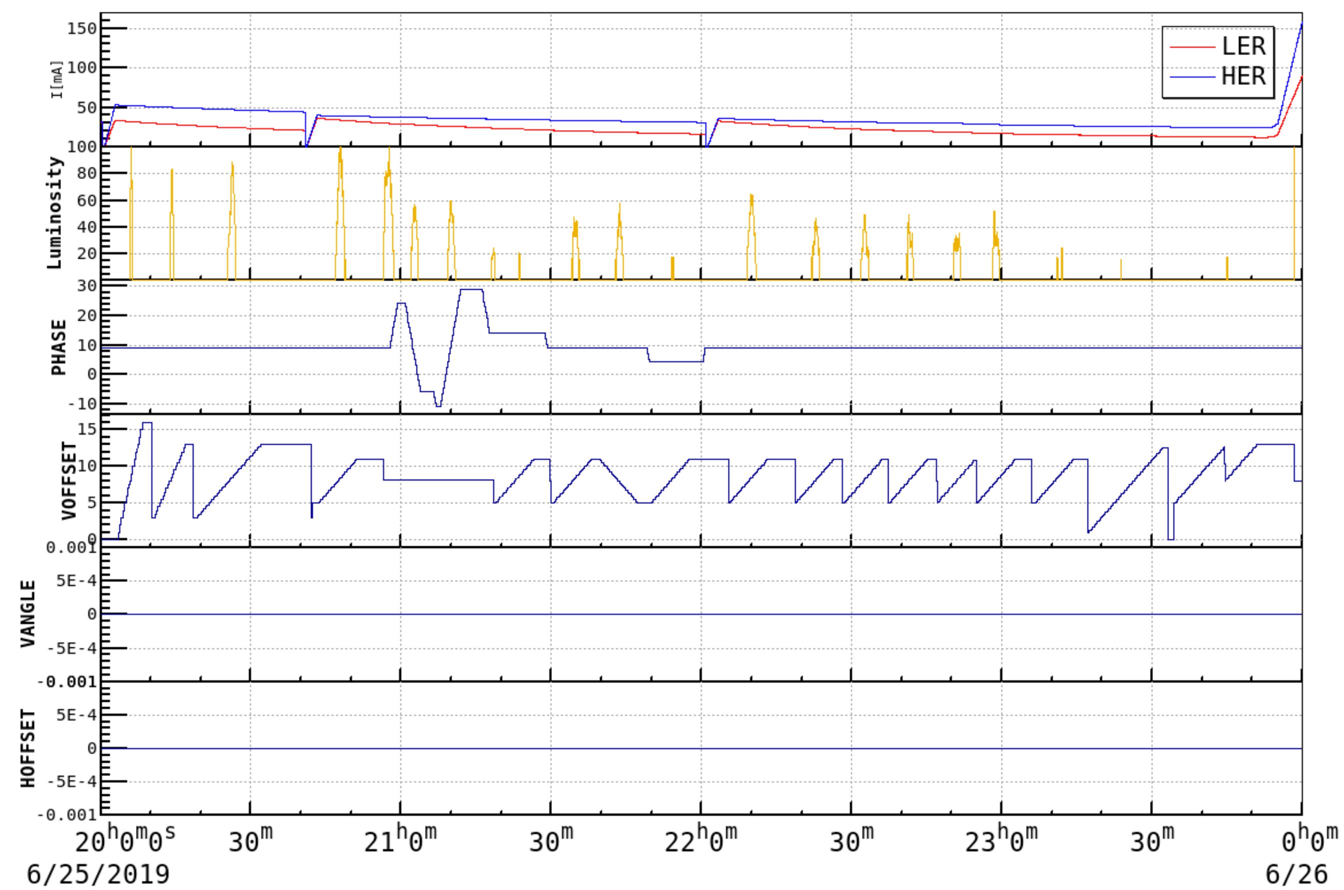
**Single beam emittance estimated from XRM data

1. Introduction

➤ 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**



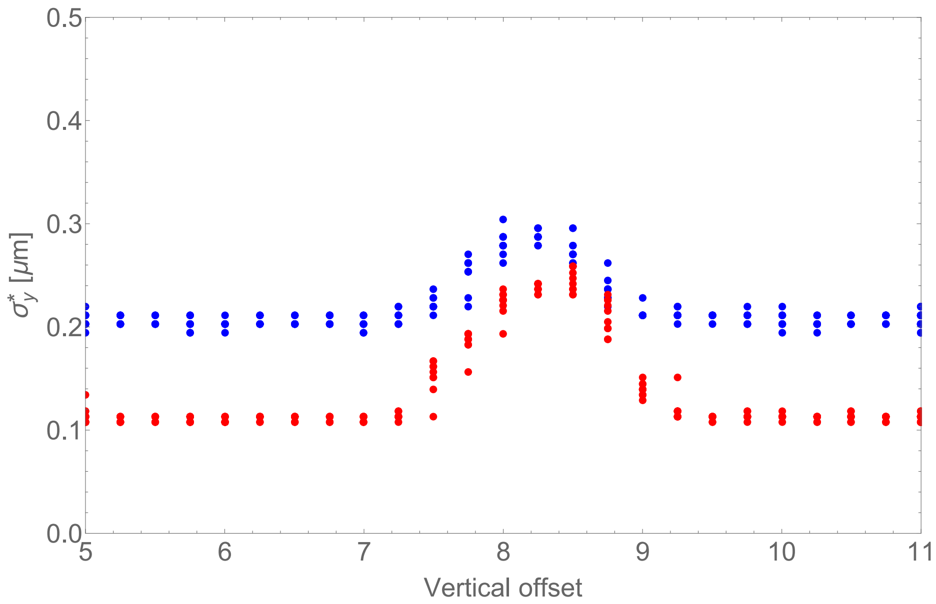


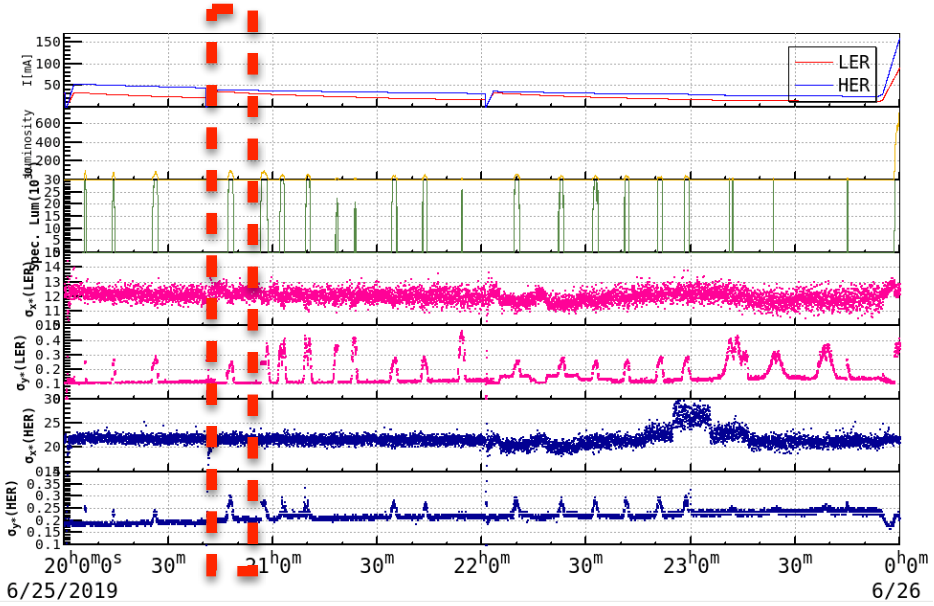
Ref. A. Morita, KCG shift report and Y. Funakoshi, Machine study report on Jun. 25, 2019

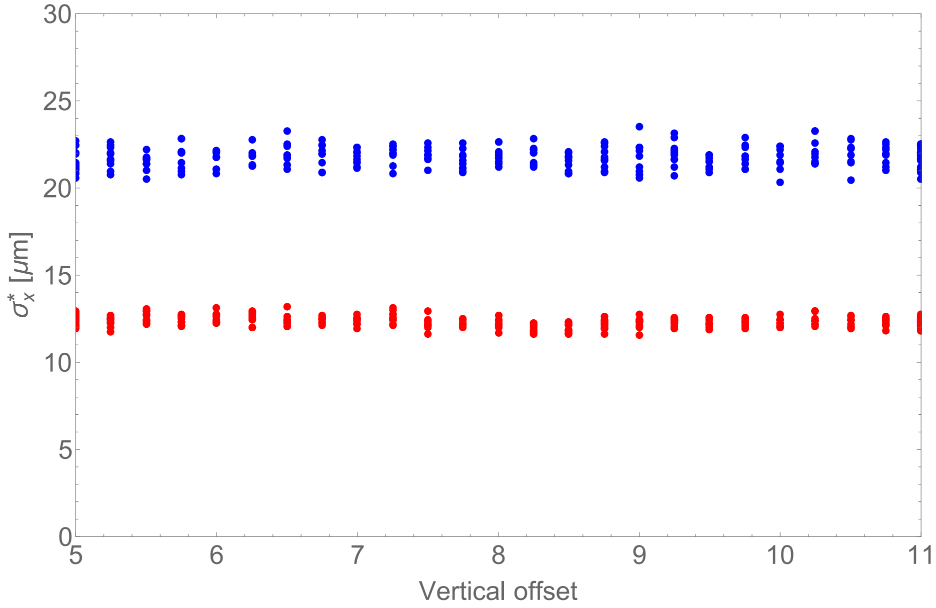
1. Introduction

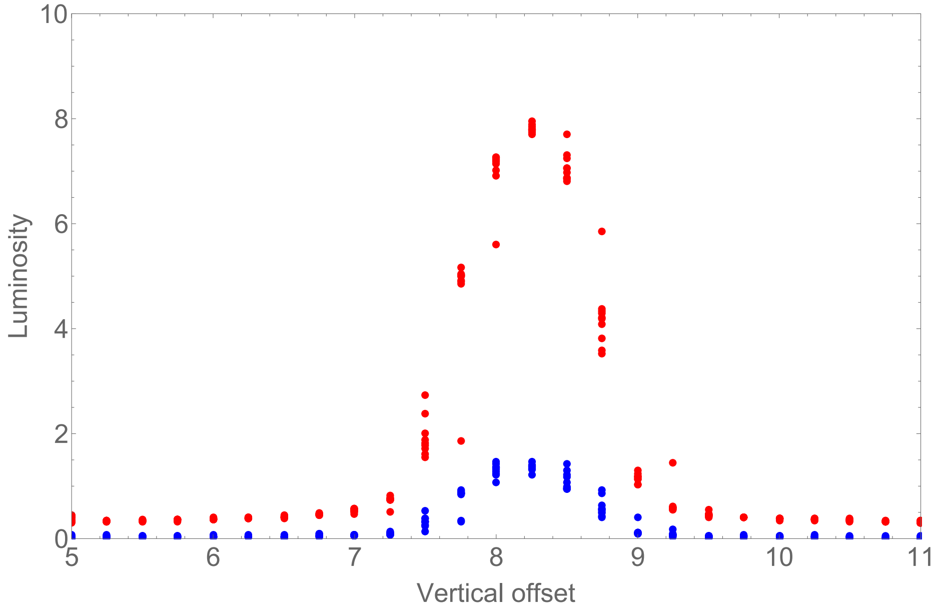
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

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





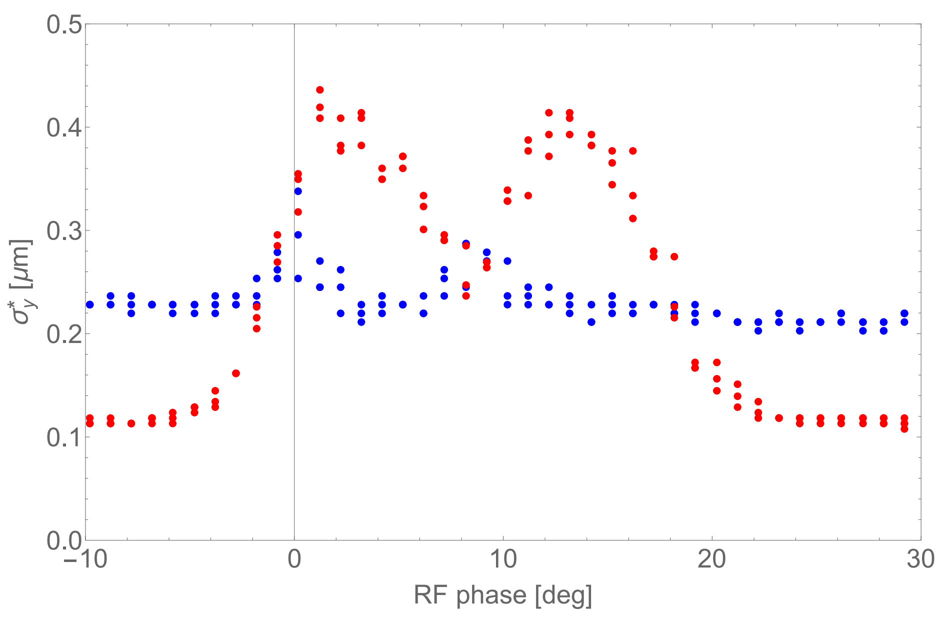


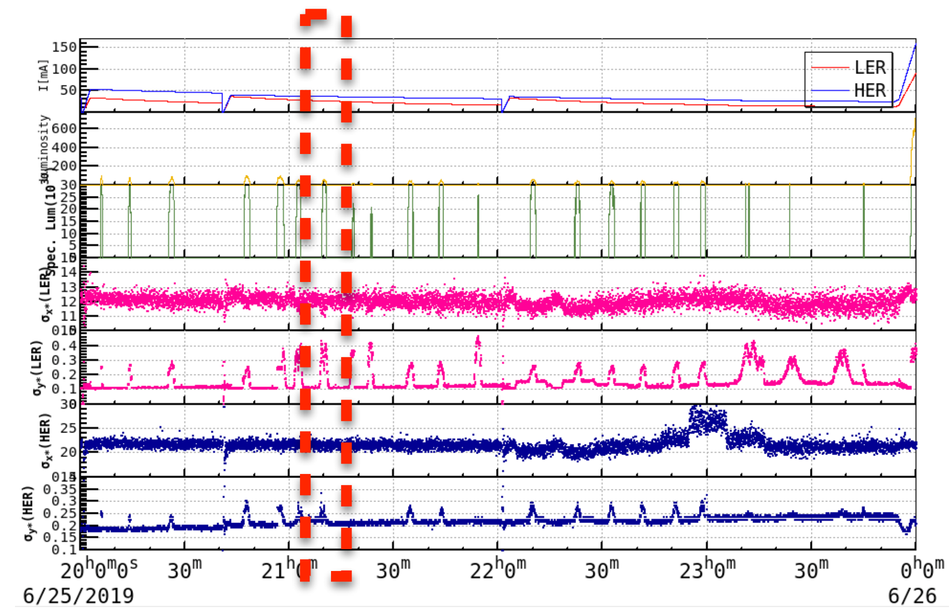


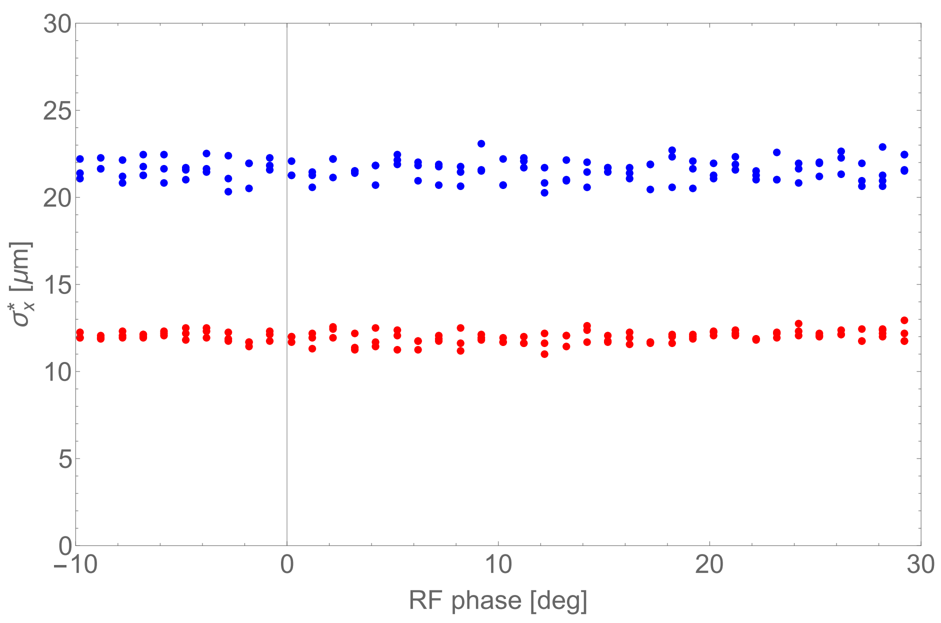
1. Introduction

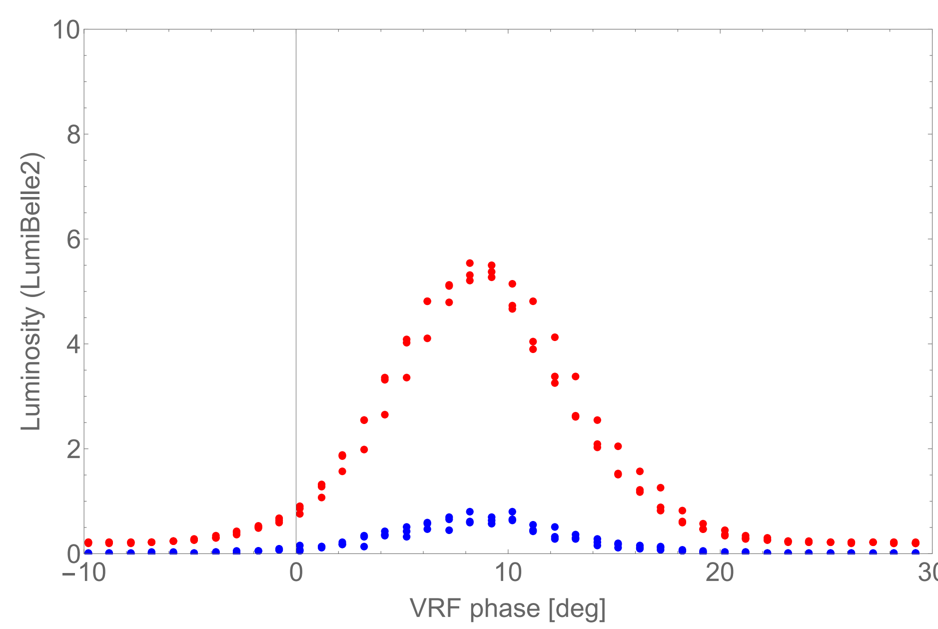
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- 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





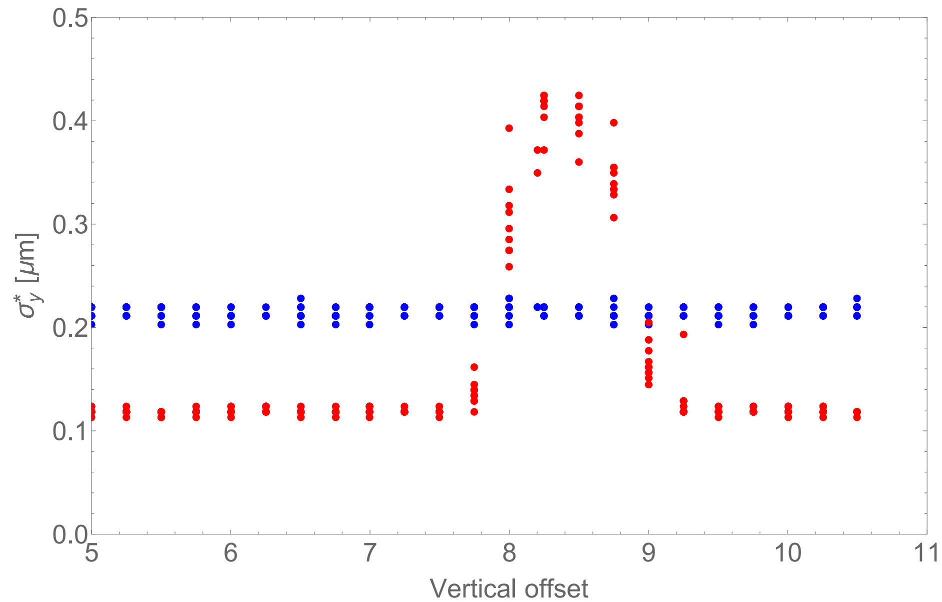


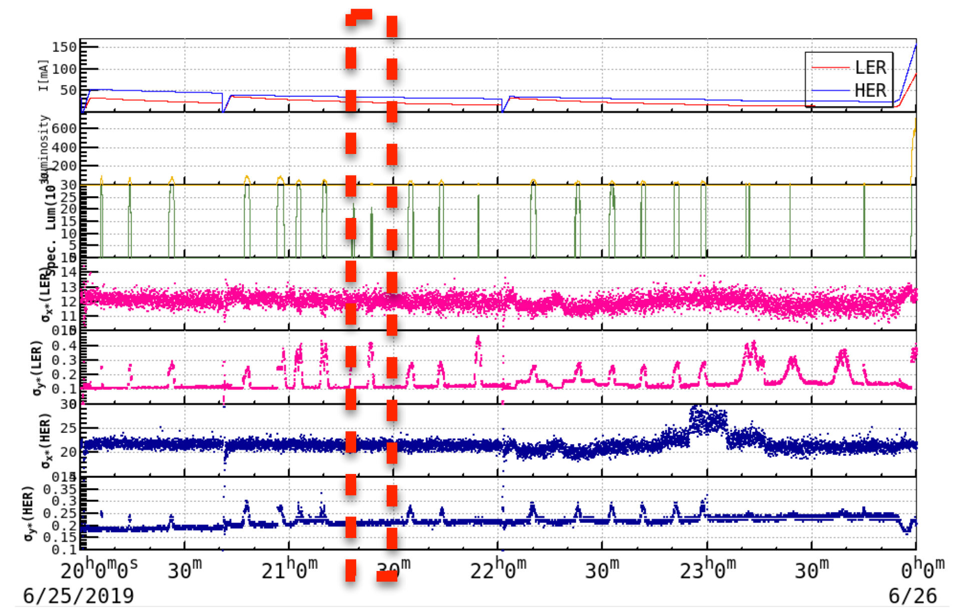


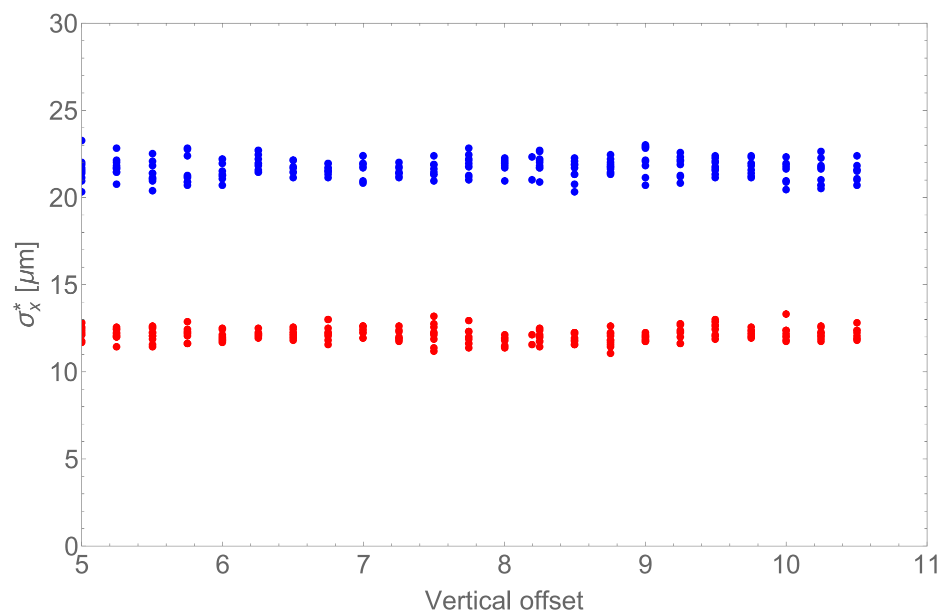
1. Introduction

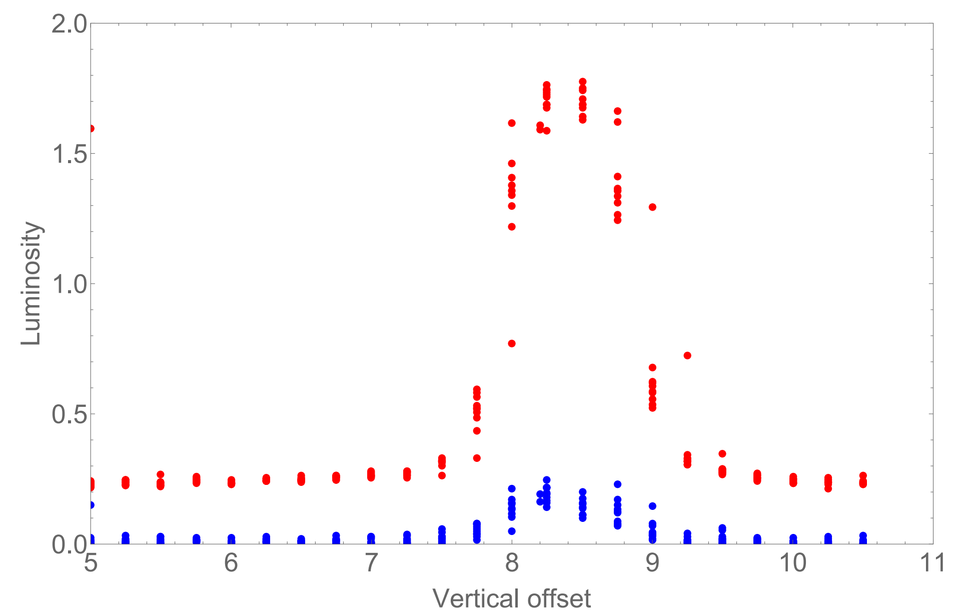
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

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





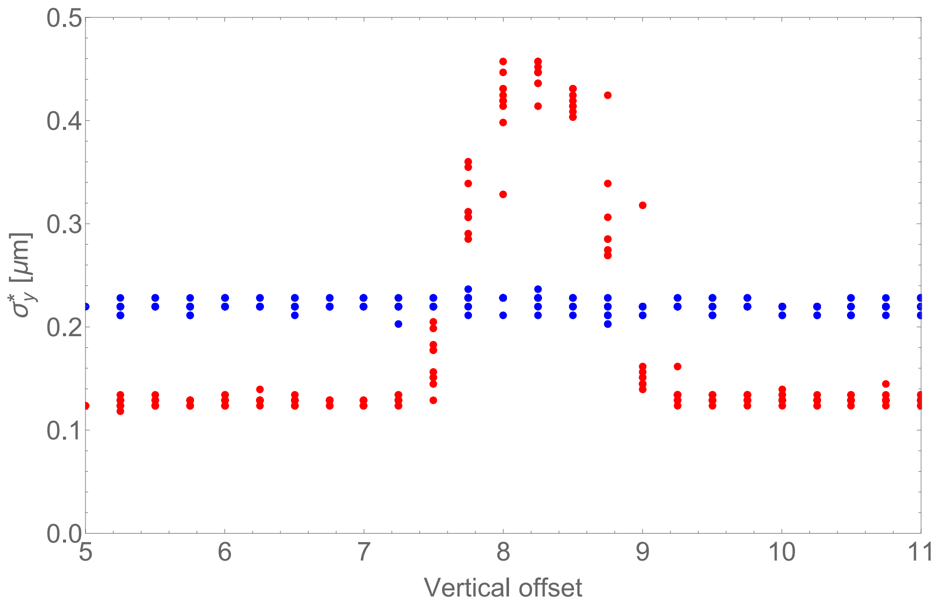


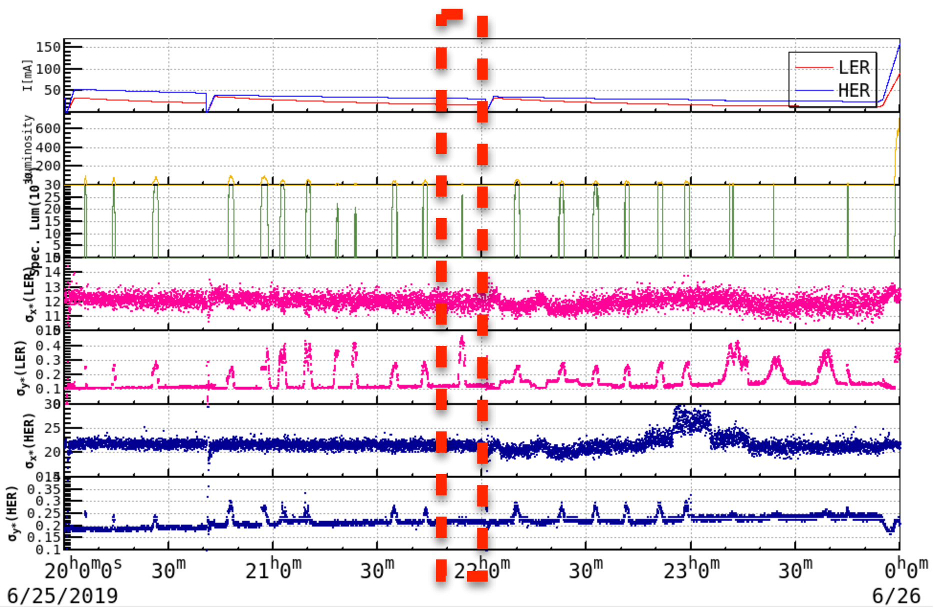


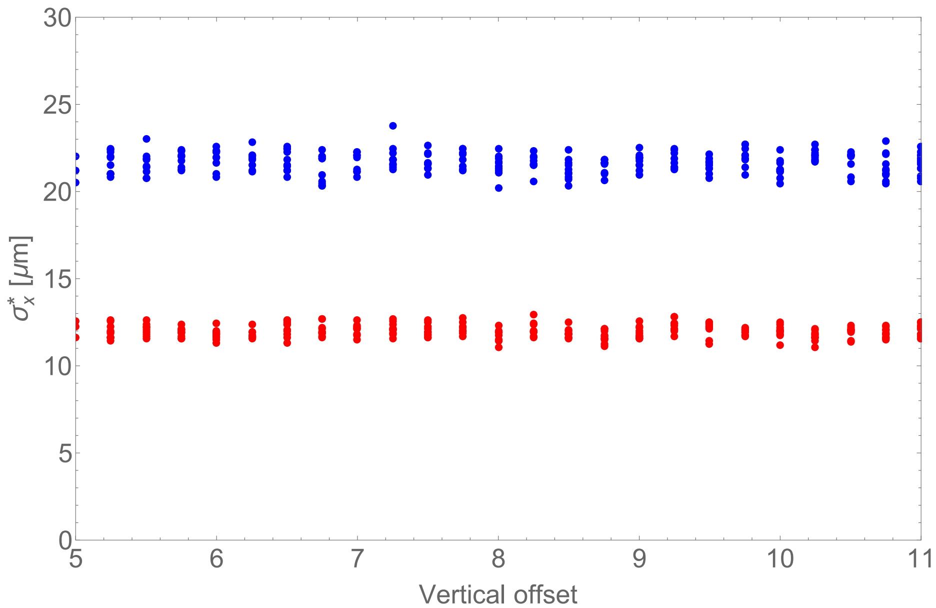
1. Introduction

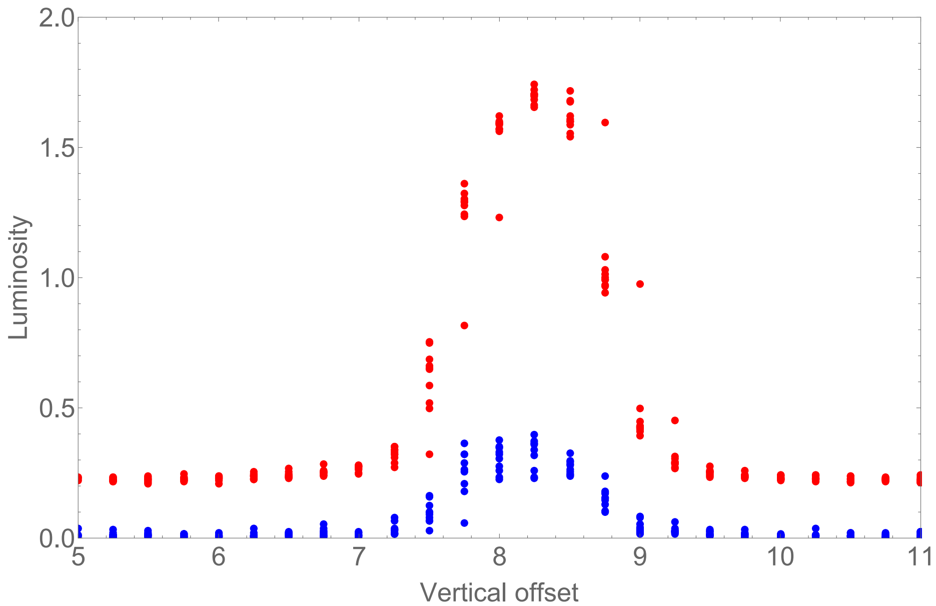
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

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





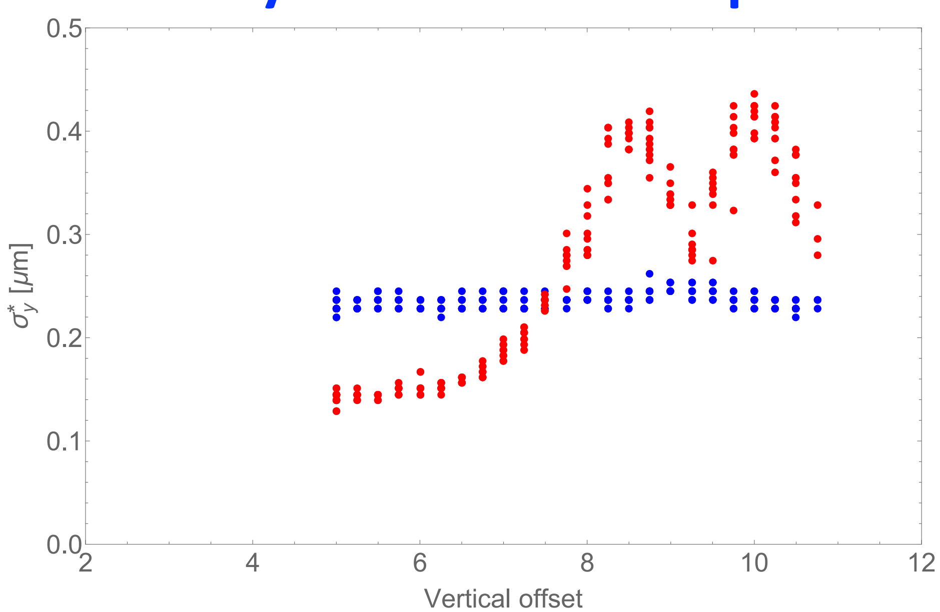


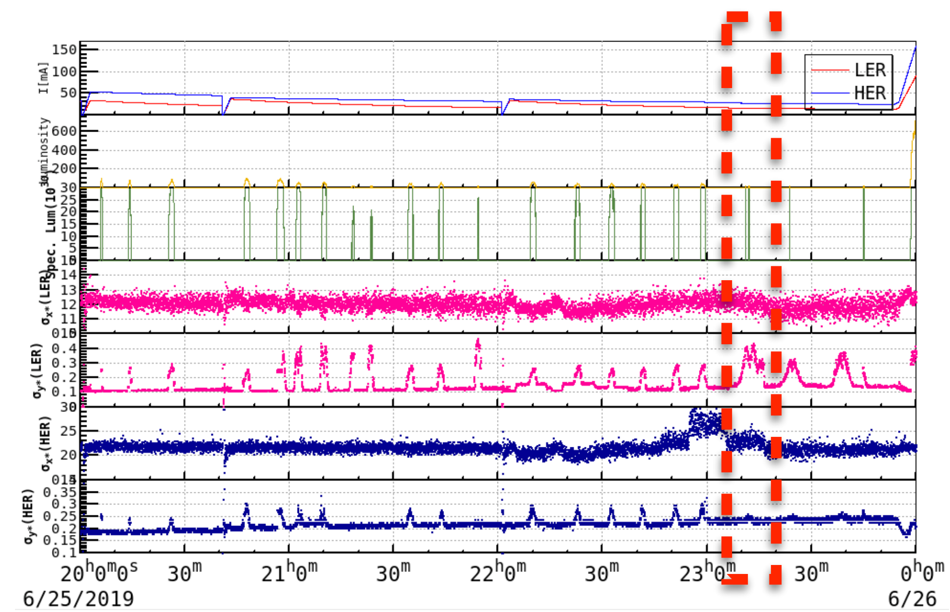


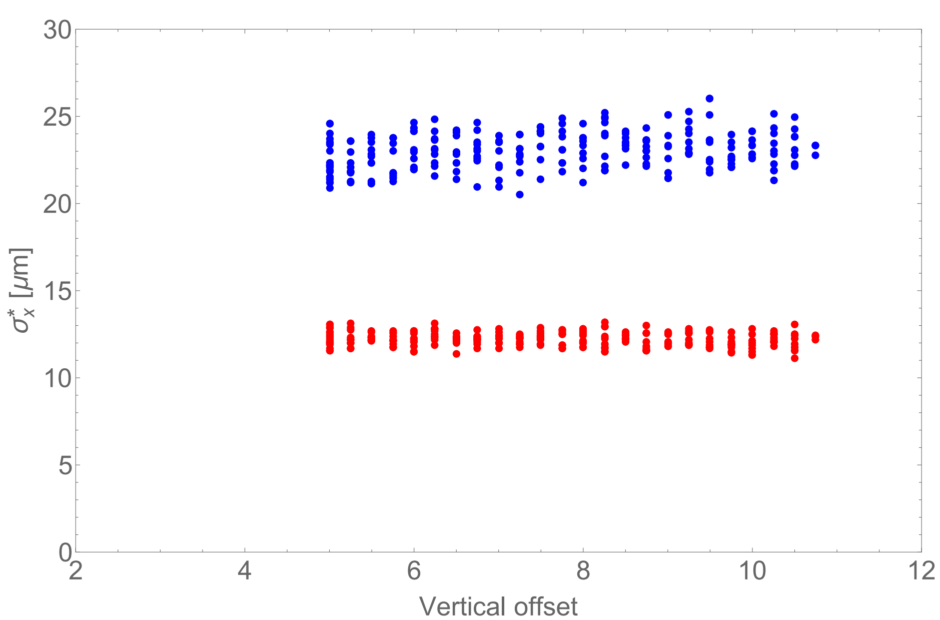
1. Introduction

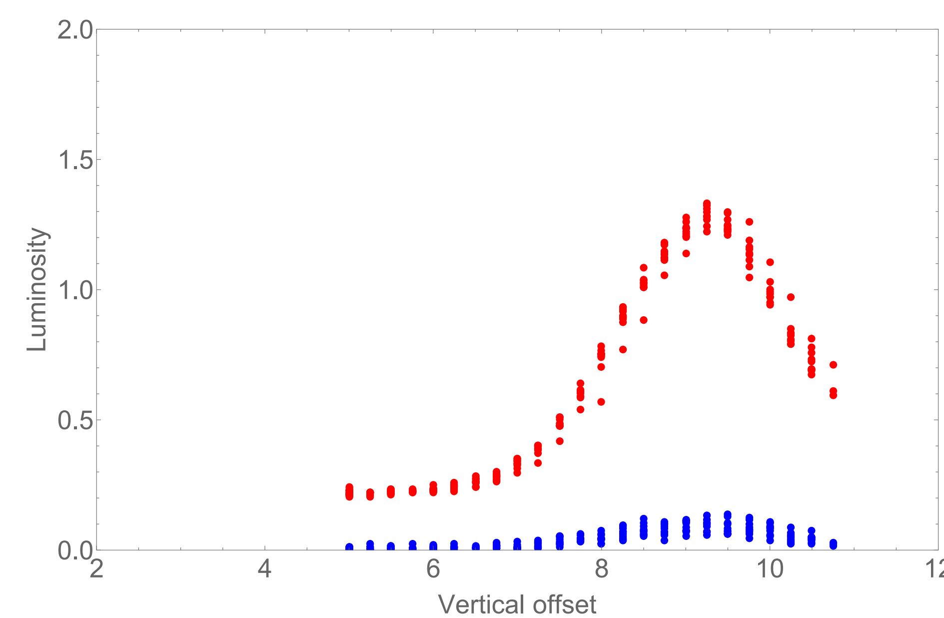
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- 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





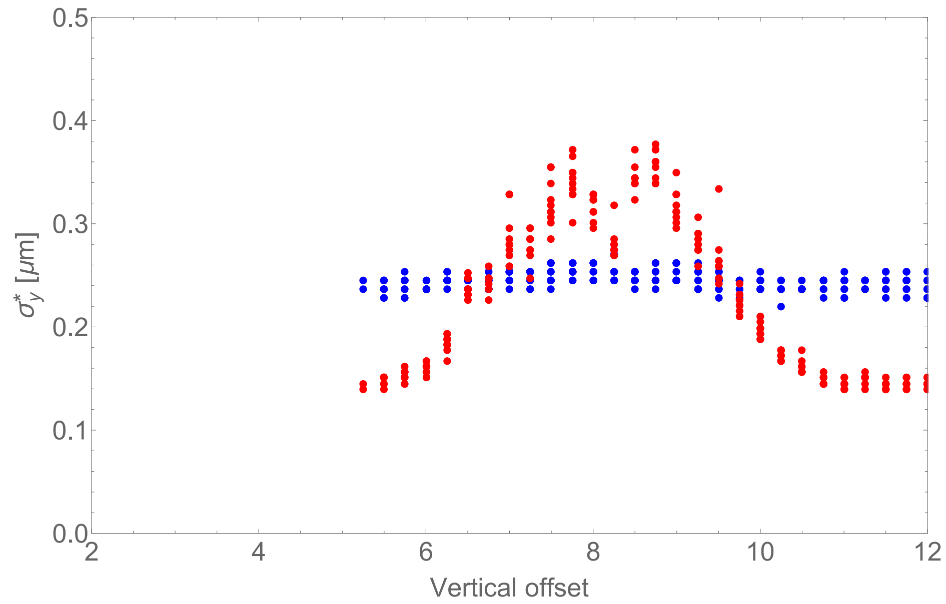


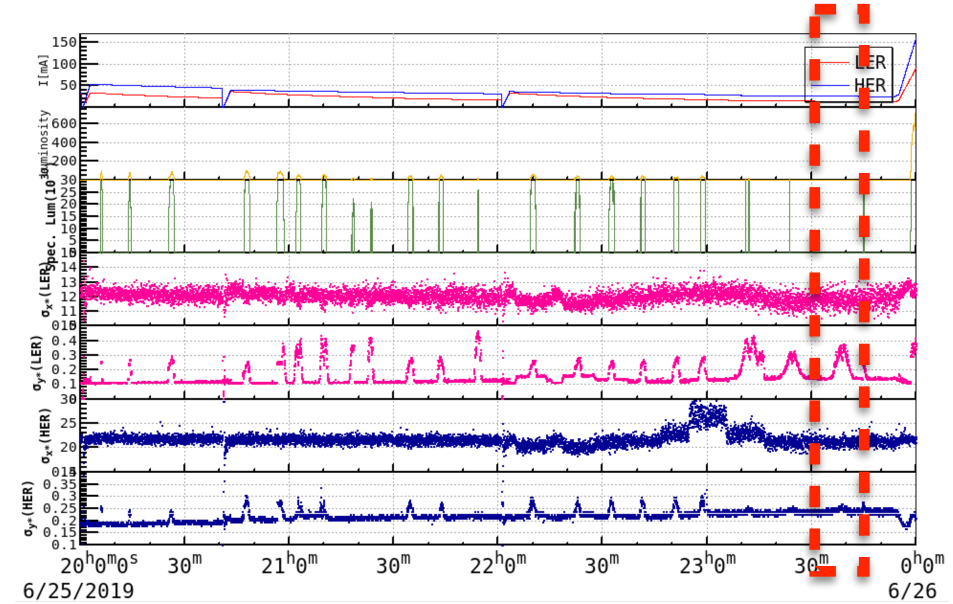


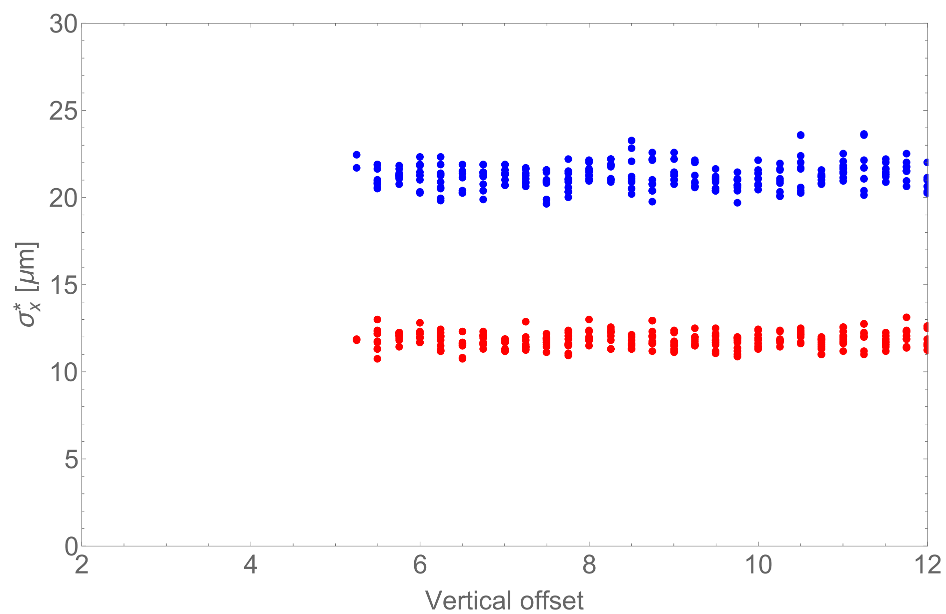
1. Introduction

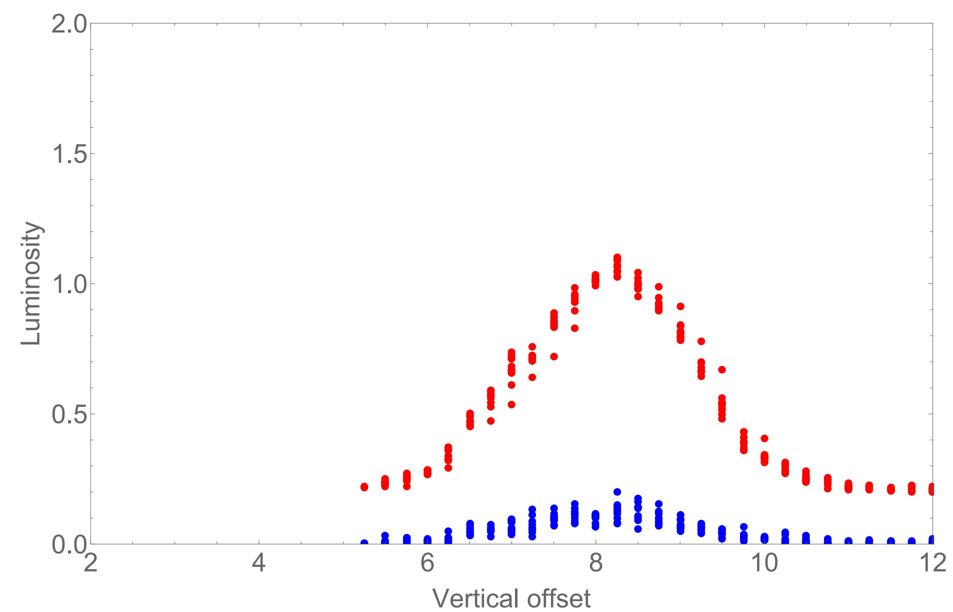
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- 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





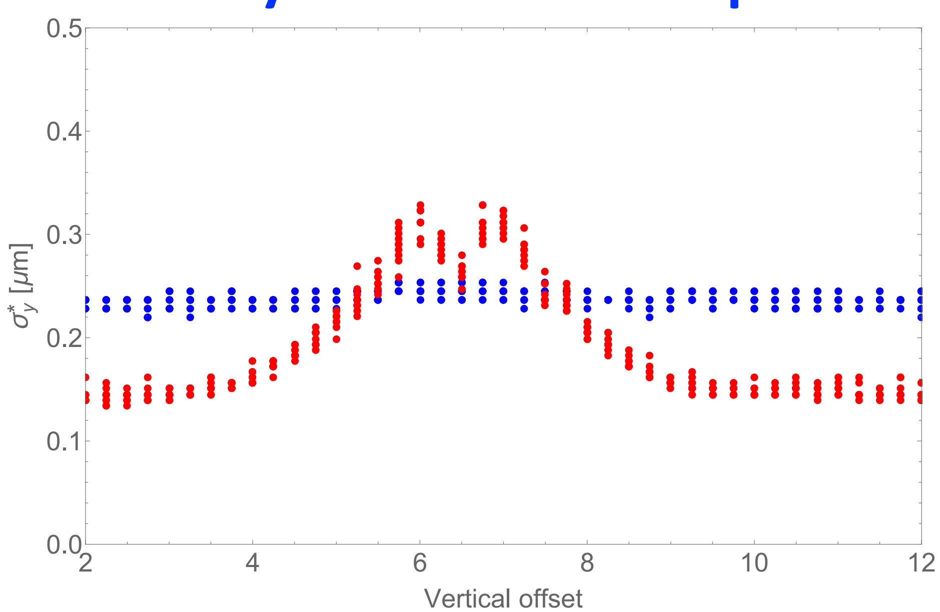


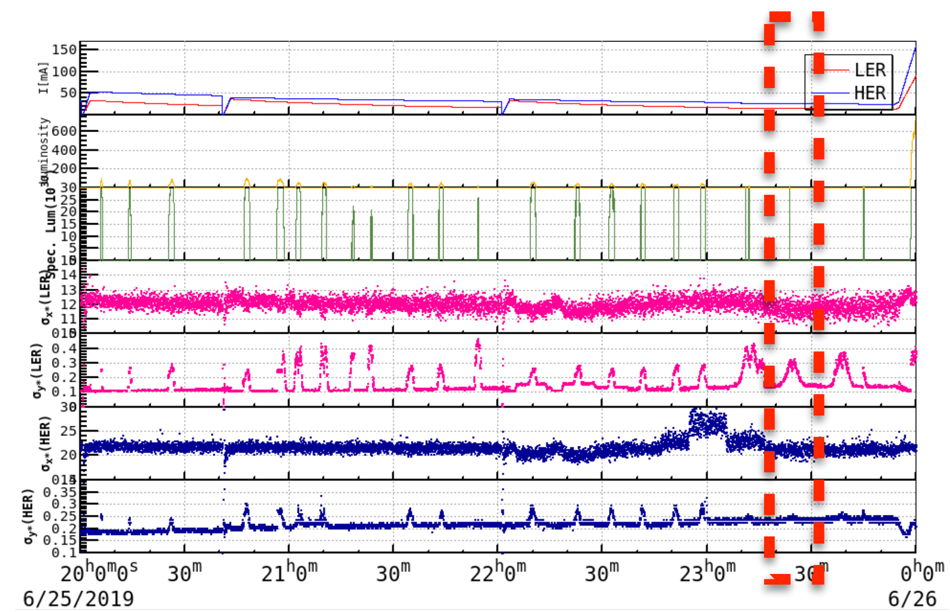


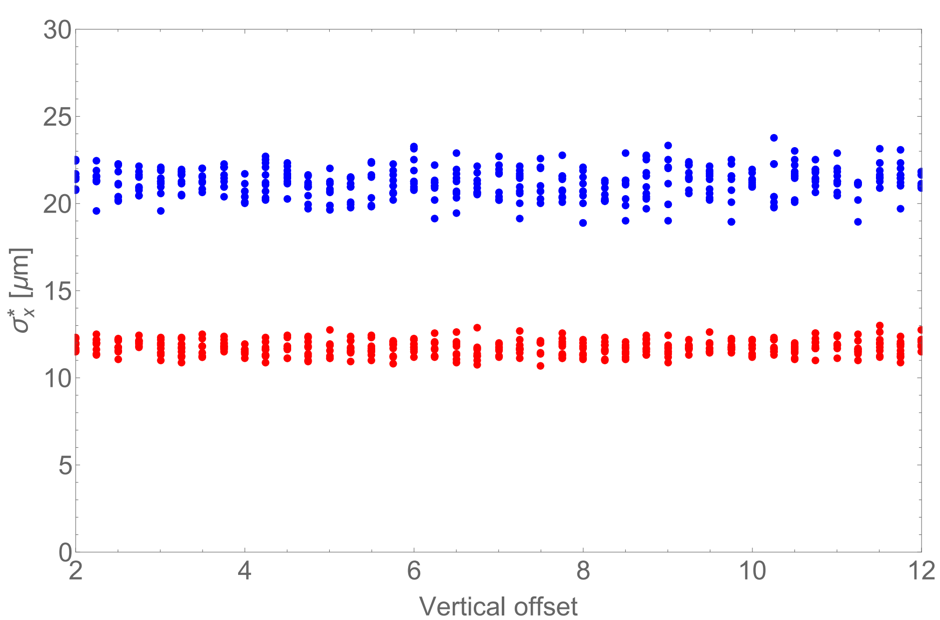
1. Introduction

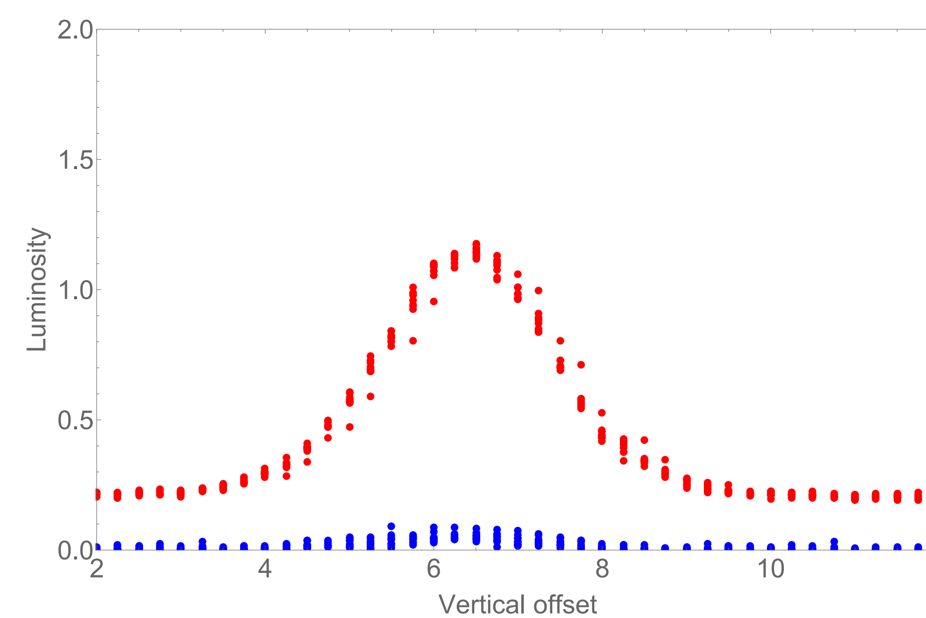
➤ Machine study: Vertical offset scan and RF phase scan (2019.06.25)

- **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**





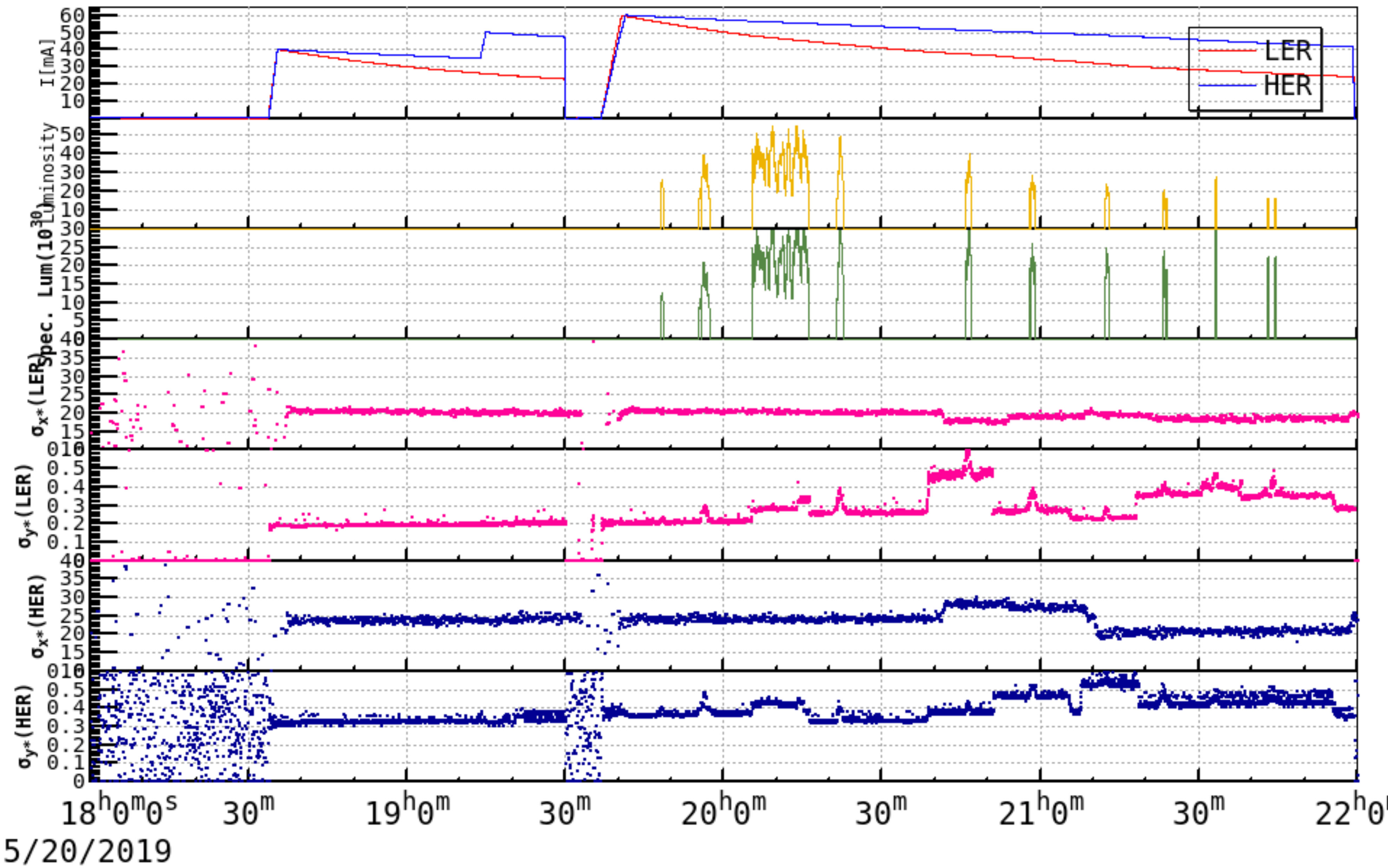




1. Introduction

➤ 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



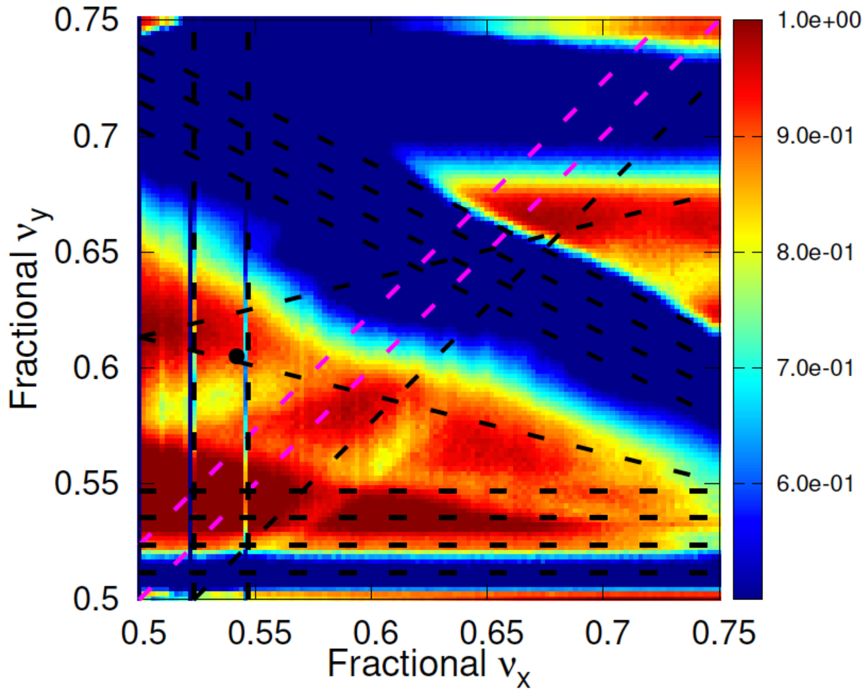
Ref. T. Kobayashi, KCG shift report and K. Ohmi, Machine study report on May. 20, 2019

2. BBWS simulation: Tune scan

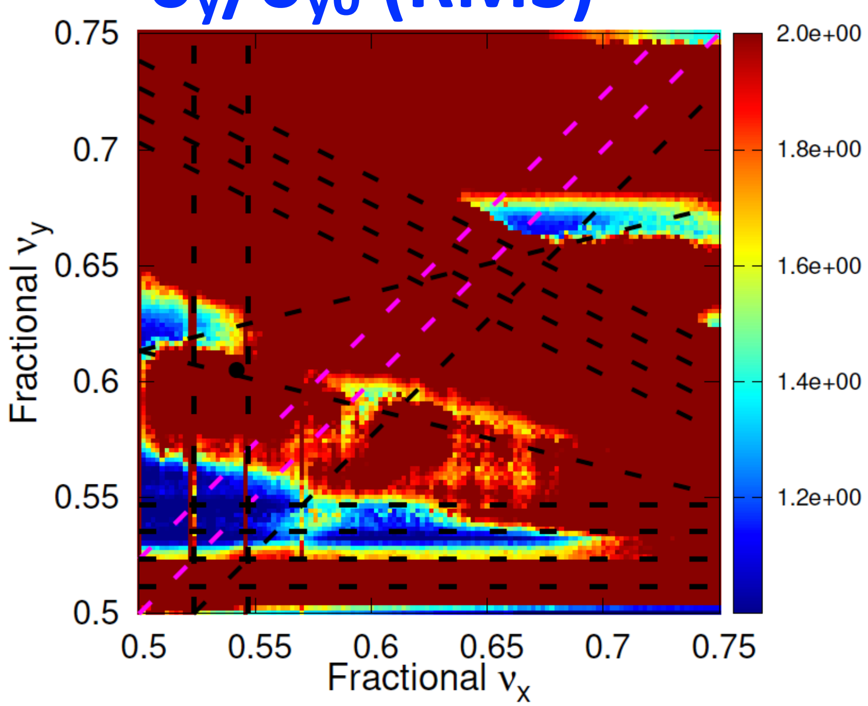
➤ Parameter set (2019.07.01)

e+(W)e-(S)

Lum. (L/L_0)

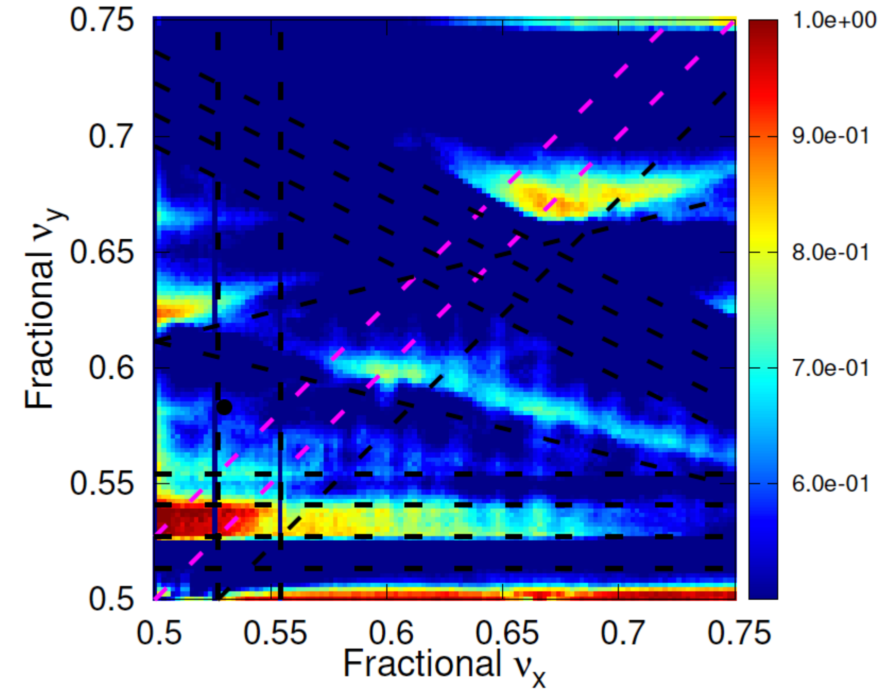


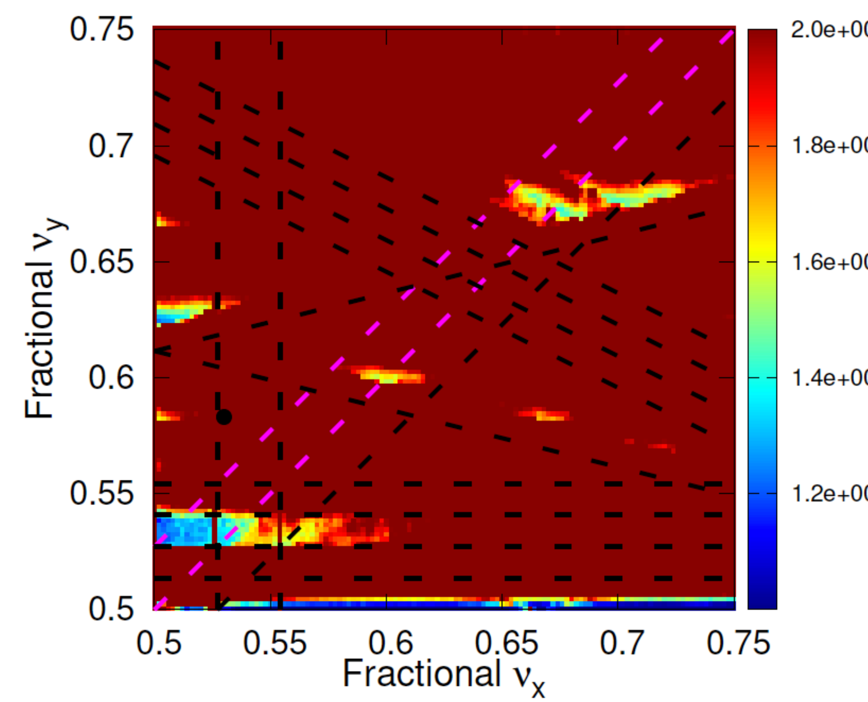
σ_y/σ_{y0} (RMS)



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)





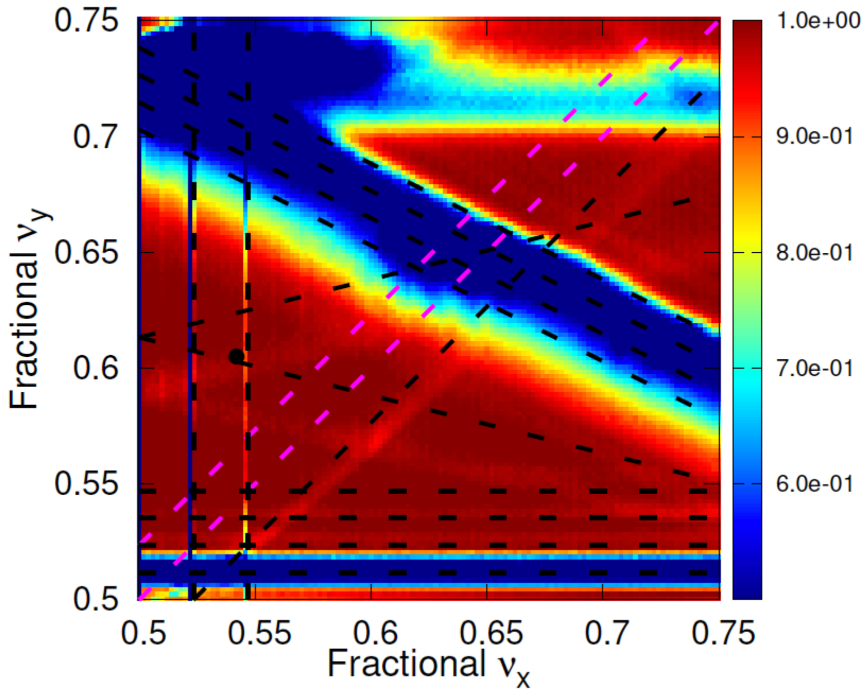
2. BBWS simulation: Tune scan

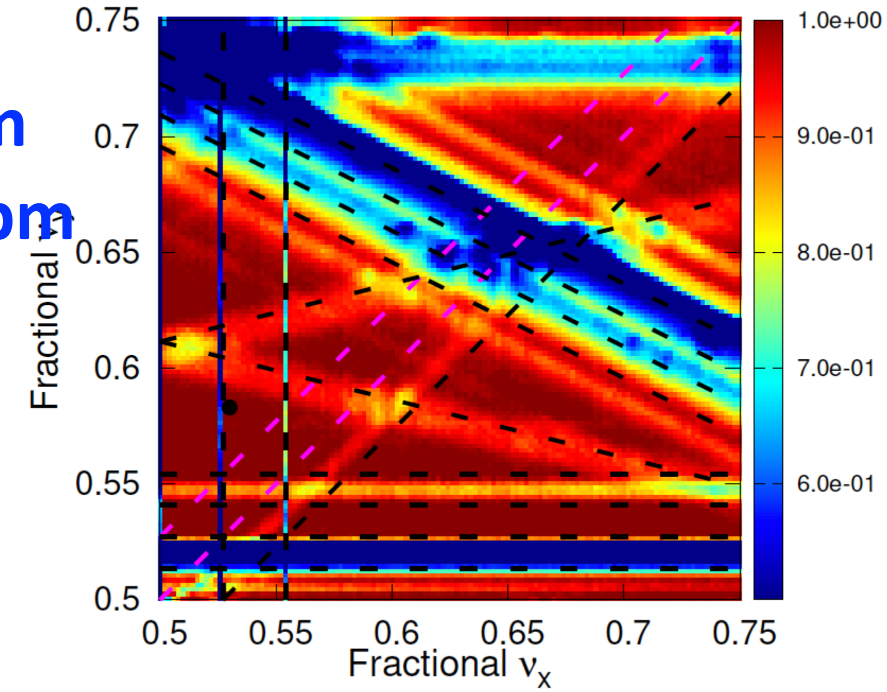
➤ **Parameter set (2019.07.01, op1 and op2)**

e+(W)e-(S)

e+(S)e-(W)

Lum. (L/L_0)

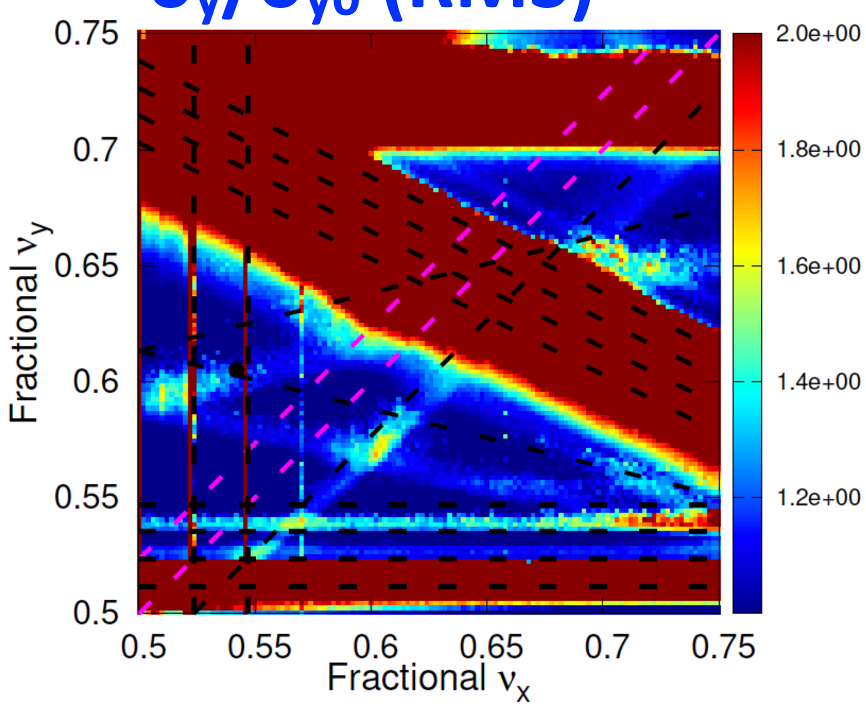




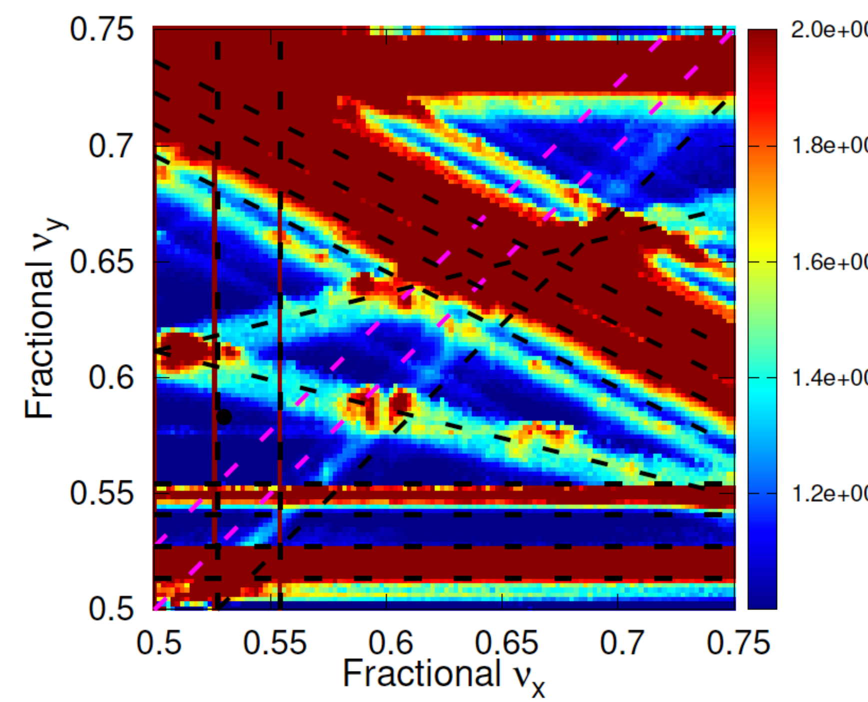
op1:
ε_{e+}=6.05 pm
ε_{e-}=40 pm

op2:
ε_{e+}=40 pm
ε_{e-}=16.2 pm

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

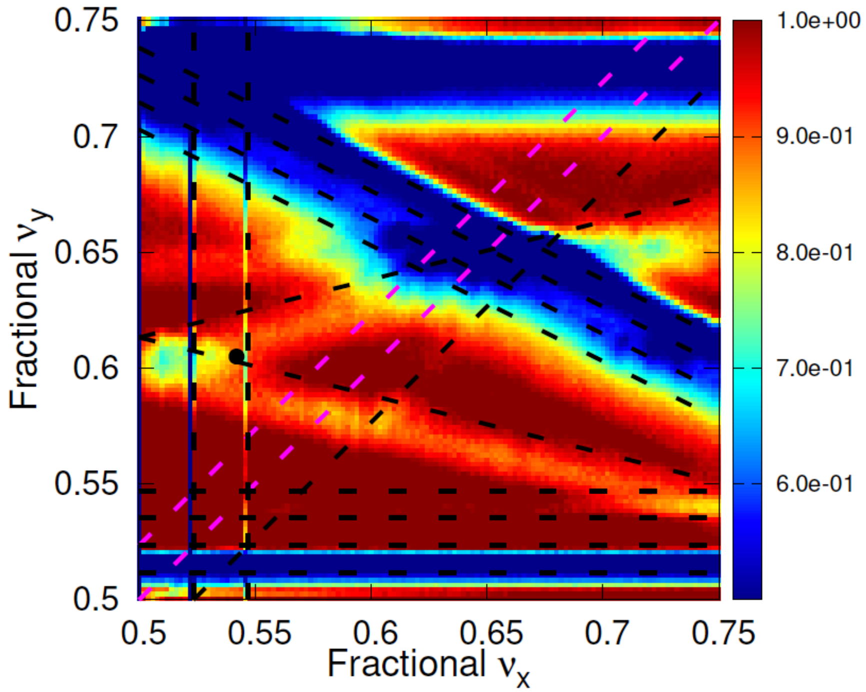


2. BBWS simulation: Tune scan

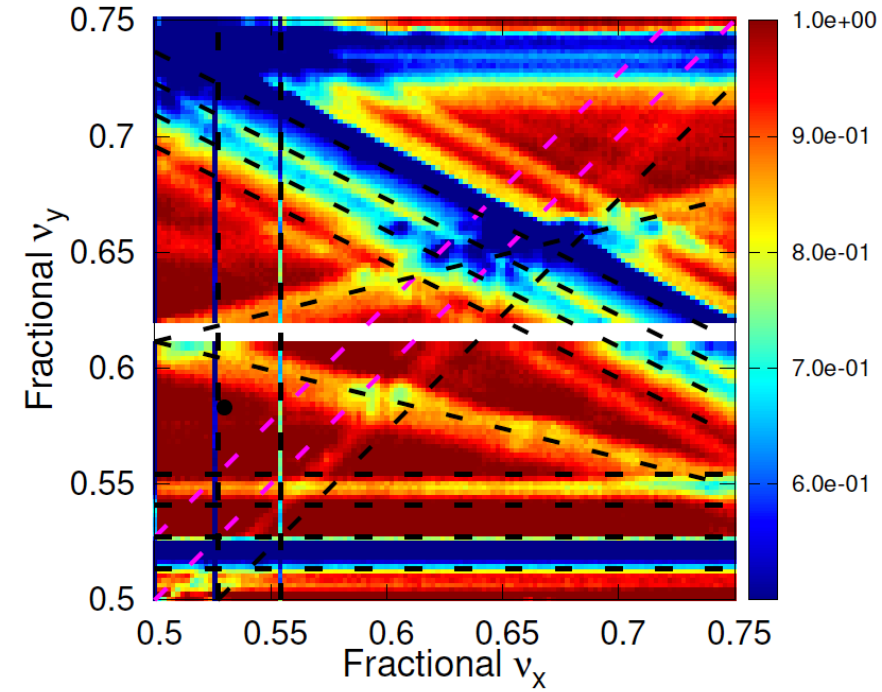
➤ Parameter set (2019.07.01(op3))

e+(W)e-(S)

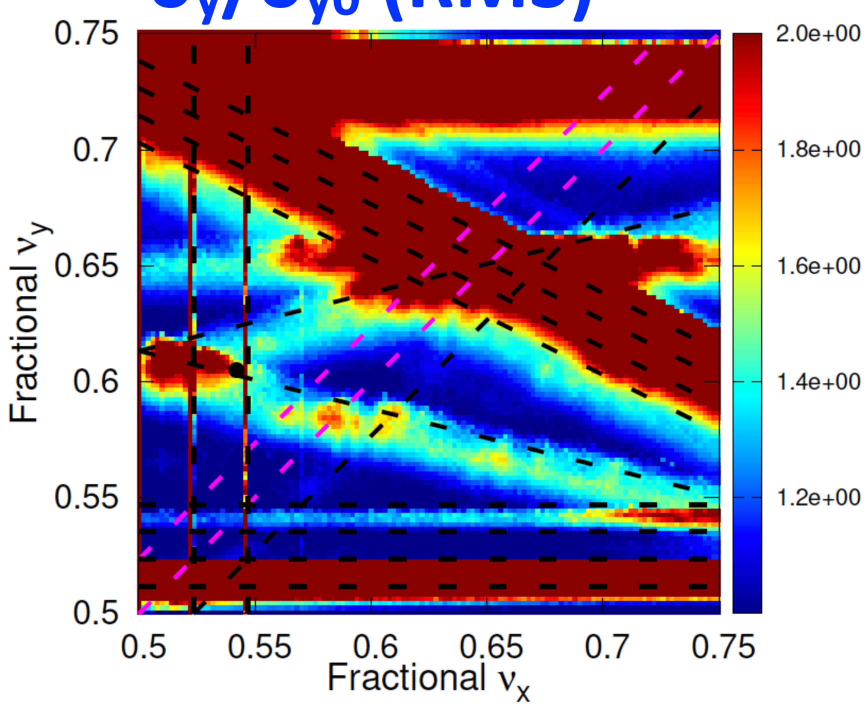
Lum. (L/L_0)

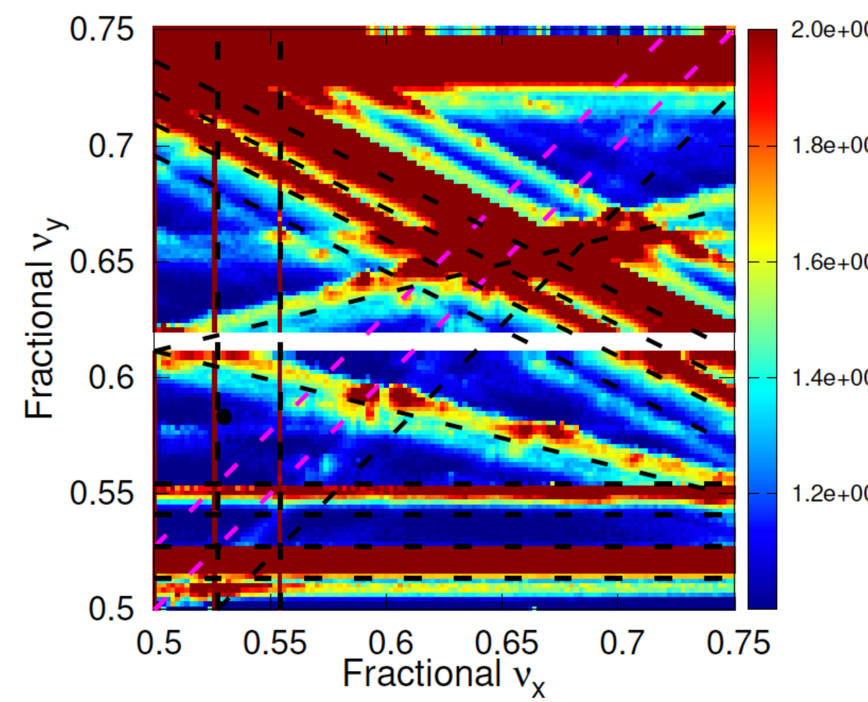


e+(S)e-(W)



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

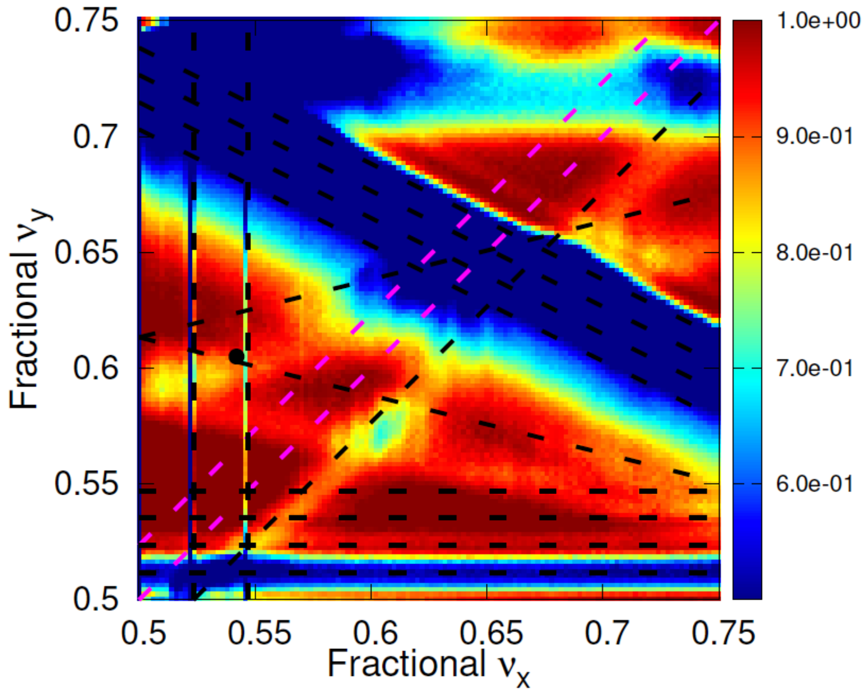
2. BBWS simulation: Tune scan

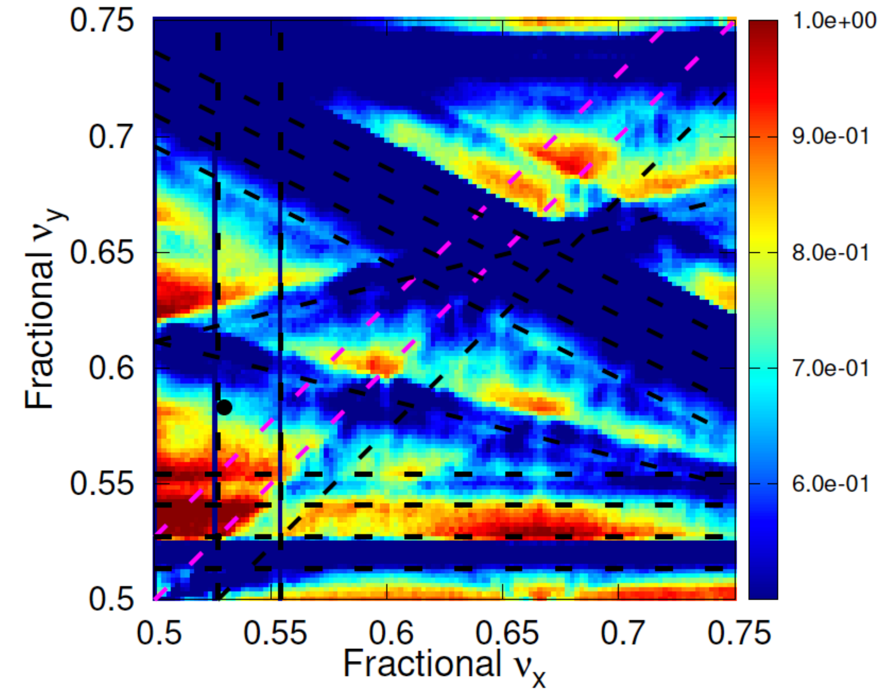
➤ **Parameter set (2019.07.01, with β_x^* = 80 mm and β_y^* = 1 mm)**

e+(W)e-(S)

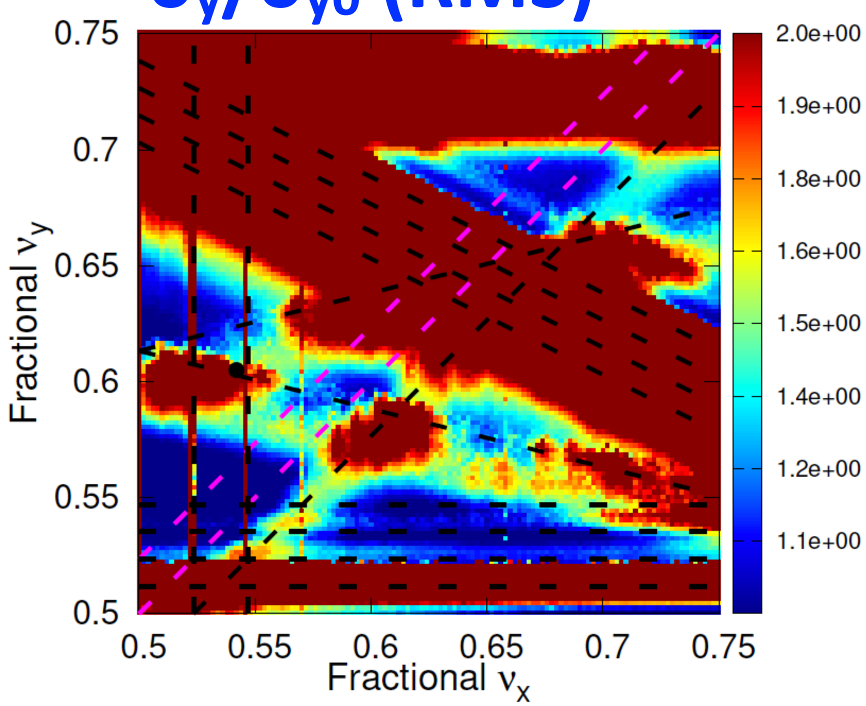
e+(S)e-(W)

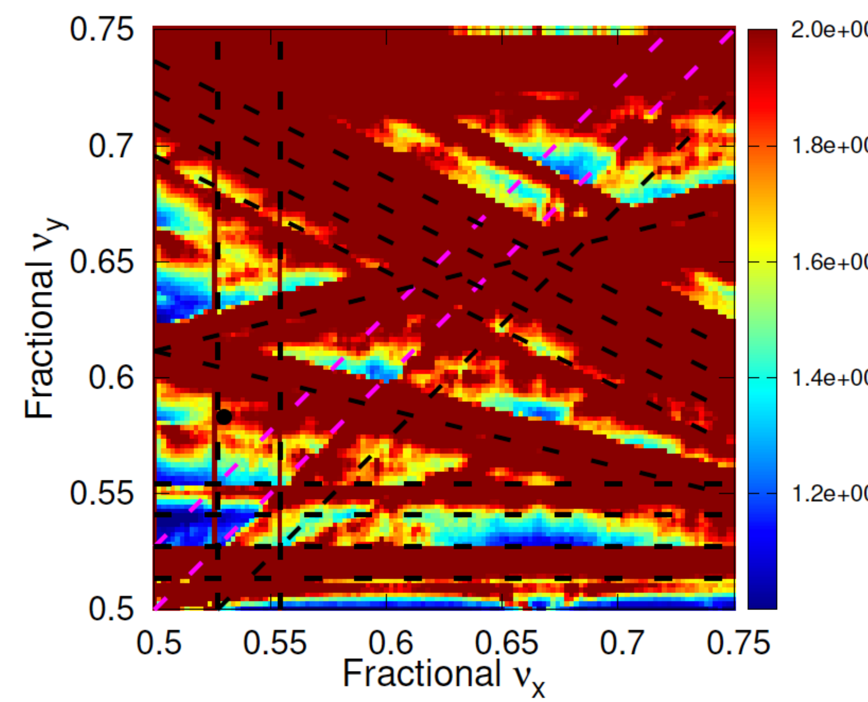
Lum. (L/L_0)





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

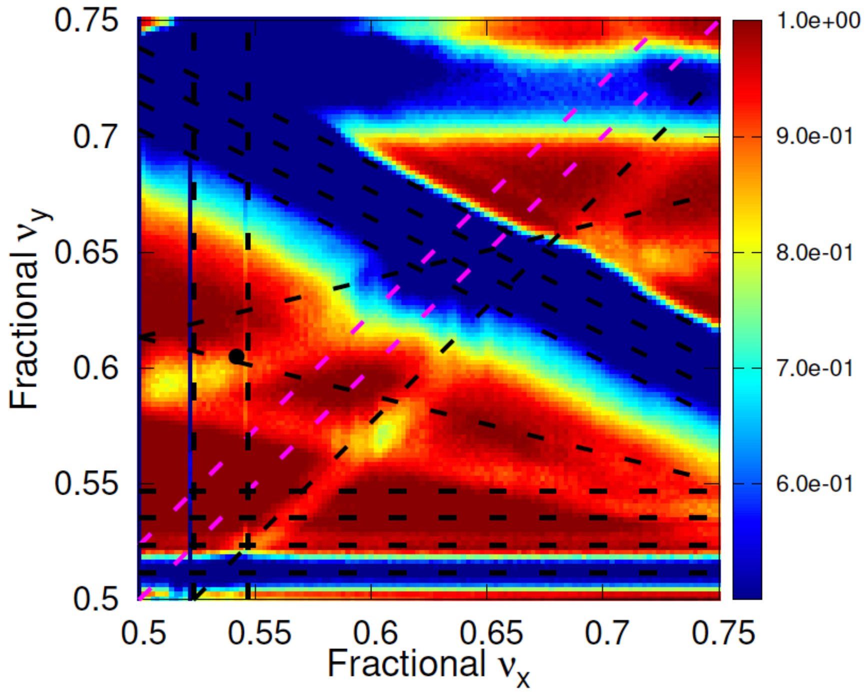
2. BBWS simulation: Tune scan

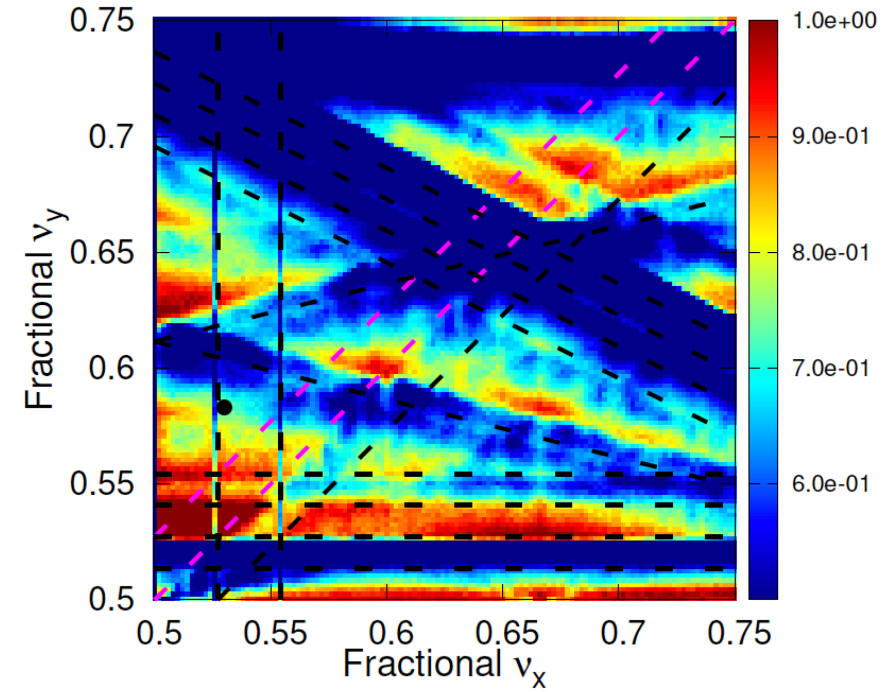
➤ **Parameter set (2019.07.01, with β_x^* = 50 mm and β_y^* = 1 mm)**

e+(W)e-(S)

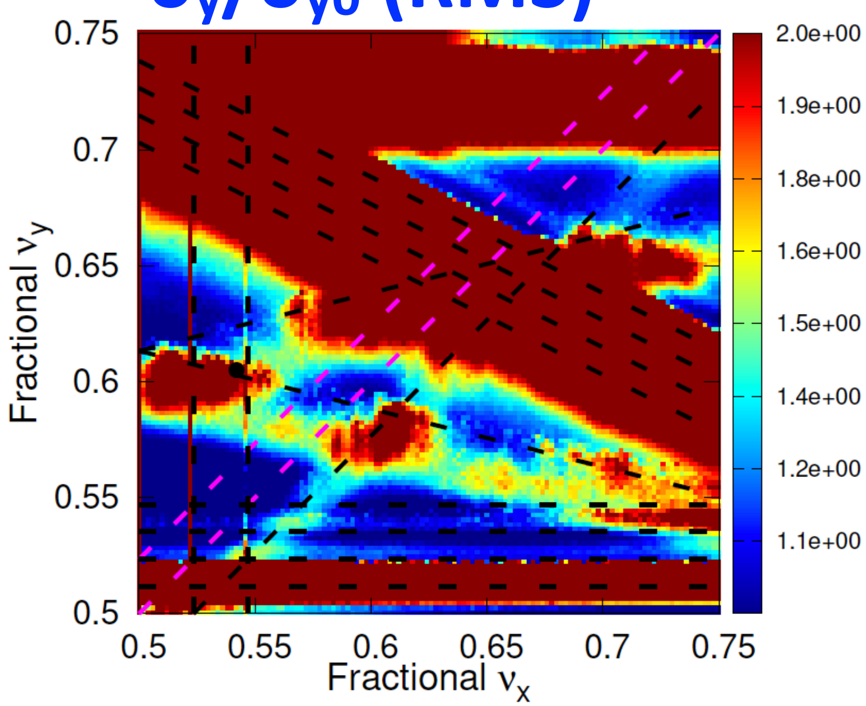
e+(S)e-(W)

Lum. (L/L_0)

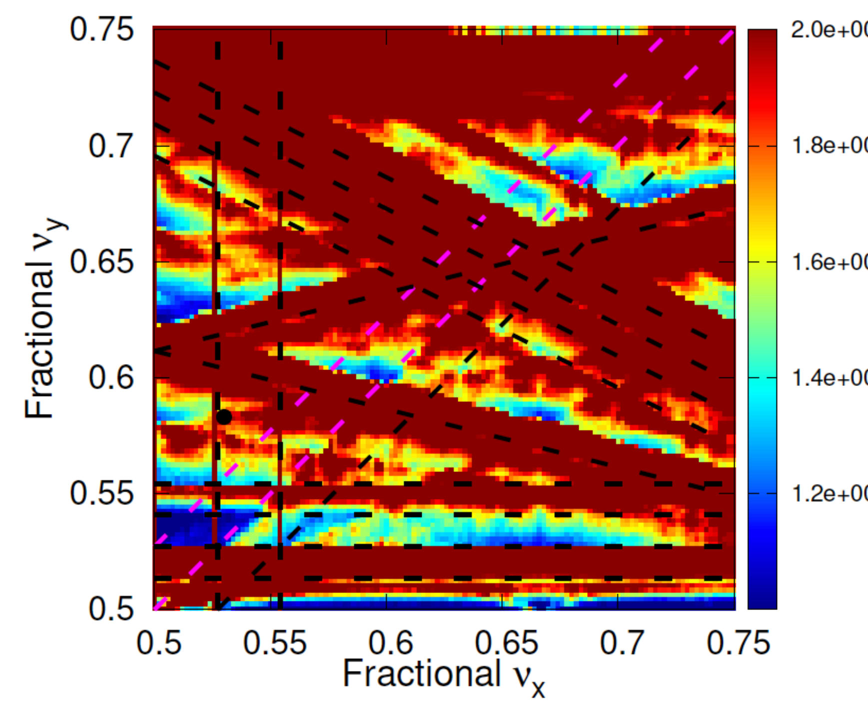




σ_y/σ_{y0} (RMS)



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



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: px^2py, etc.
- Impedance effects

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

3. Tolerances of IP aberrations with lattice

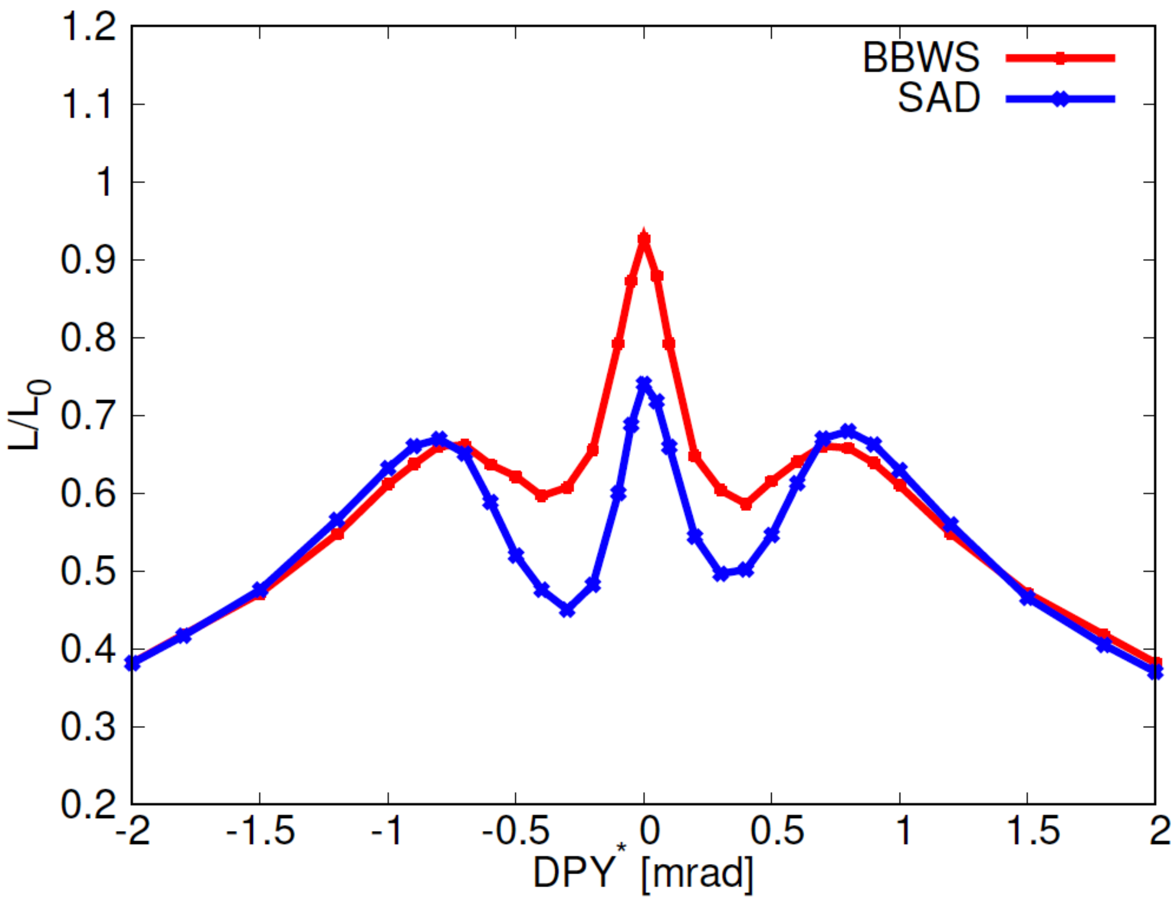
➤ Various IP aberrations: the case of e+ beam

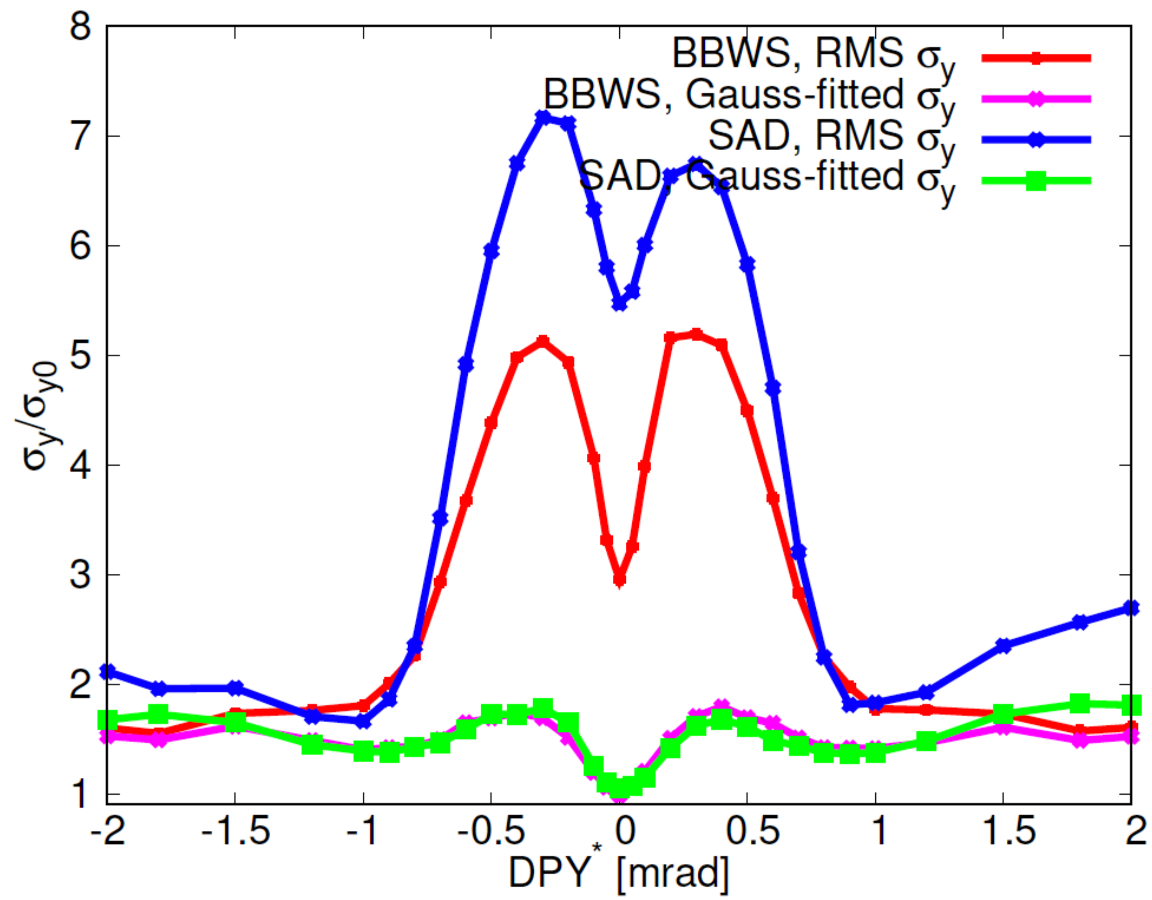
- DPY* (vert. crossing angle) with parameter set of 2019.07.01

  ** 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





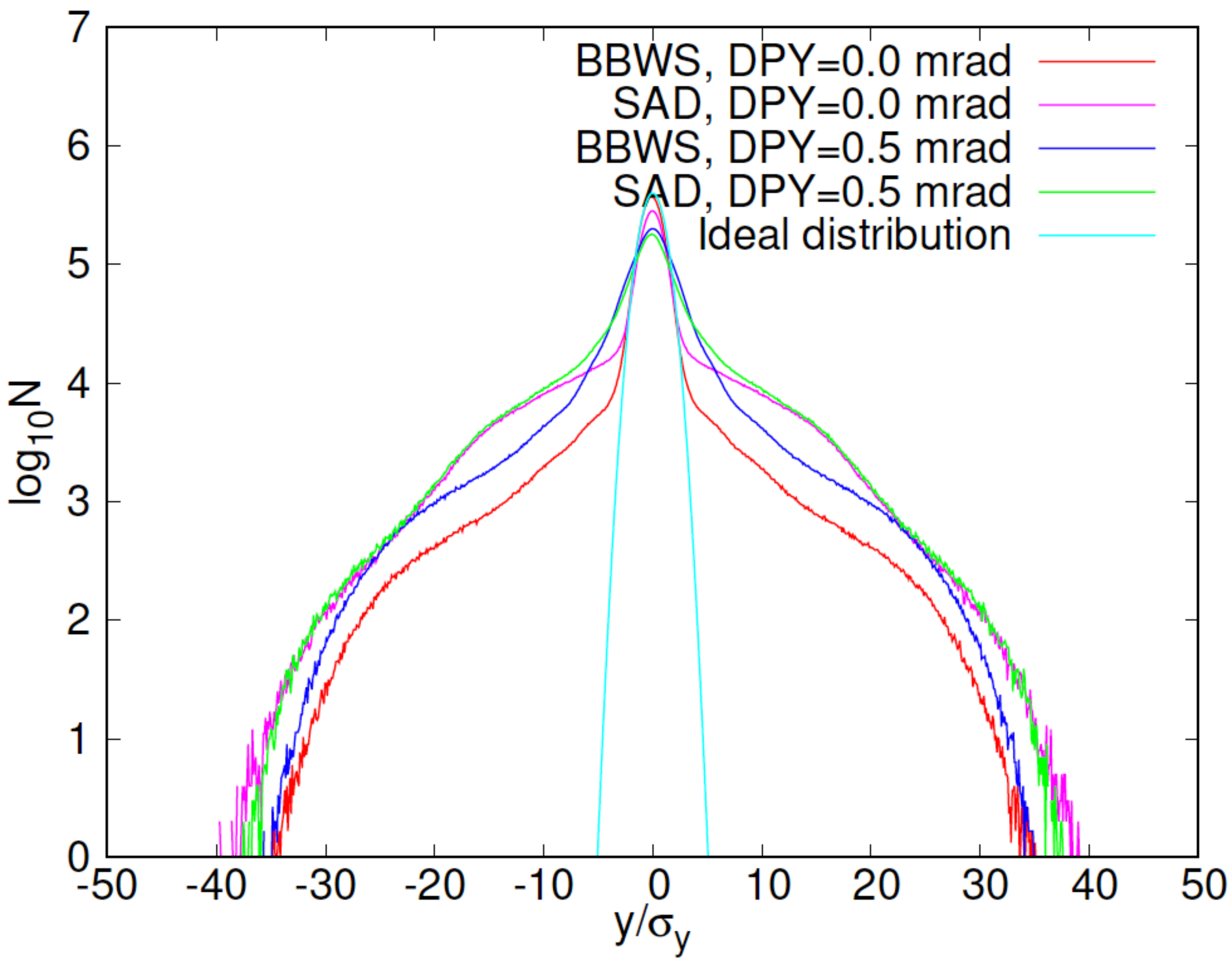
3. Tolerances of IP aberrations with lattice

➤ 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**

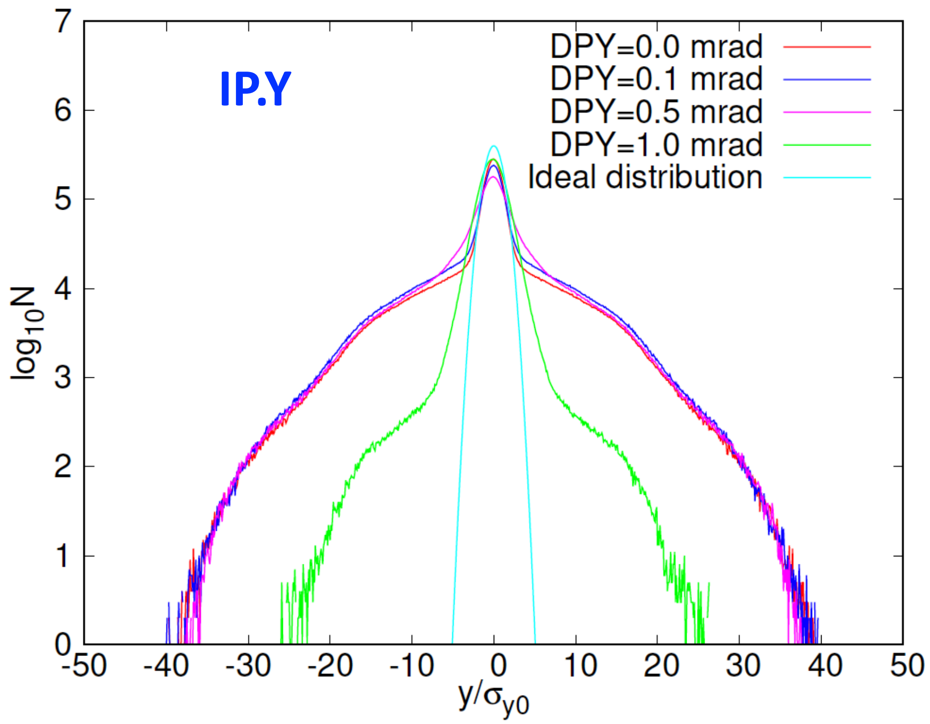


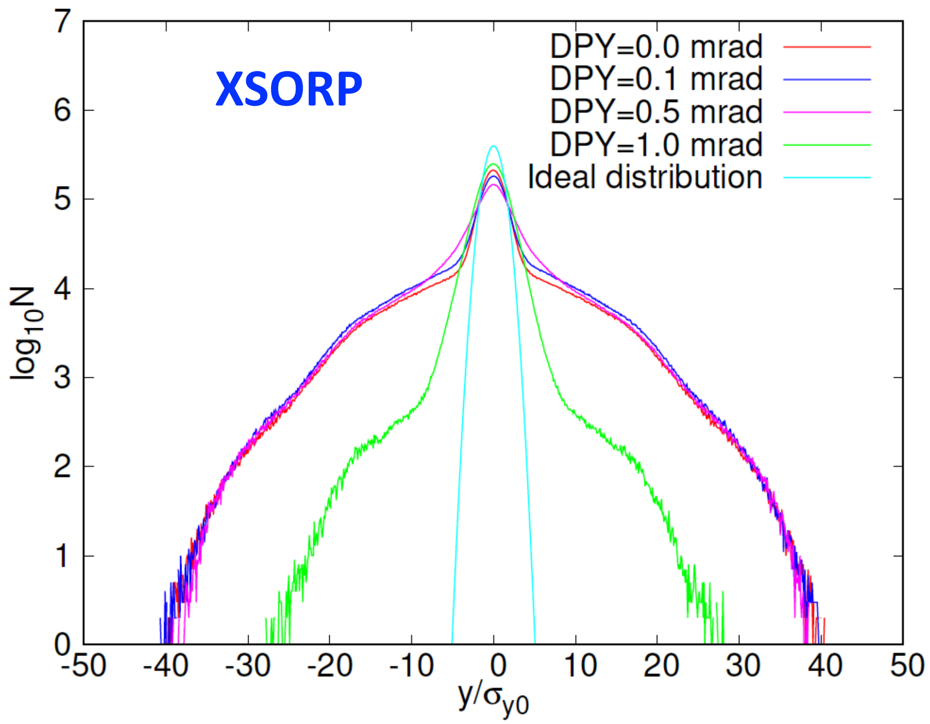
3. Tolerances of IP aberrations with lattice

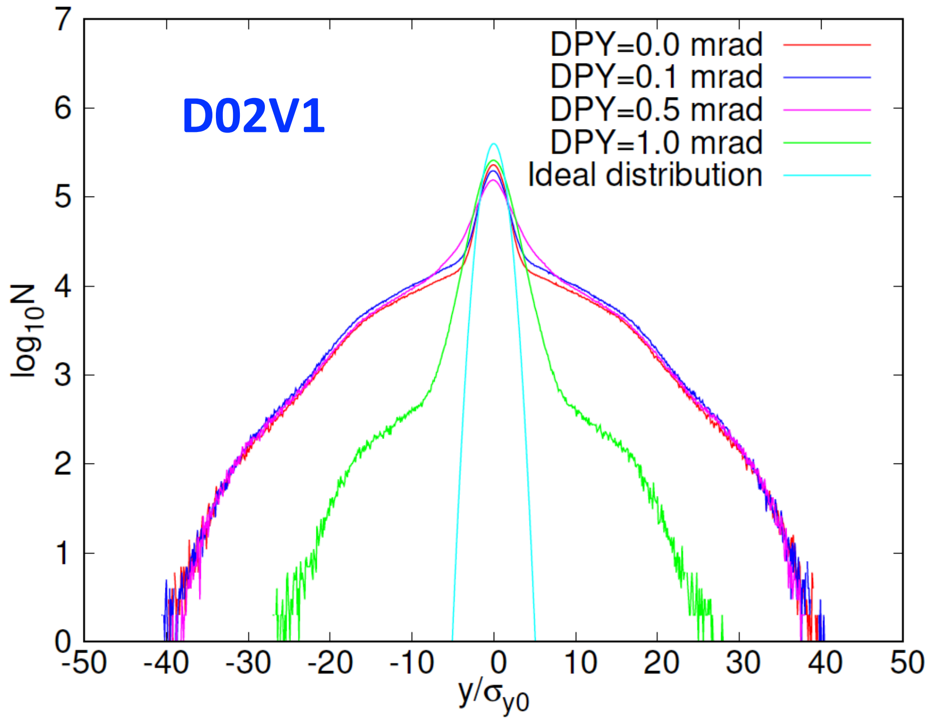
➤ Various IP aberrations: the case of e+ beam

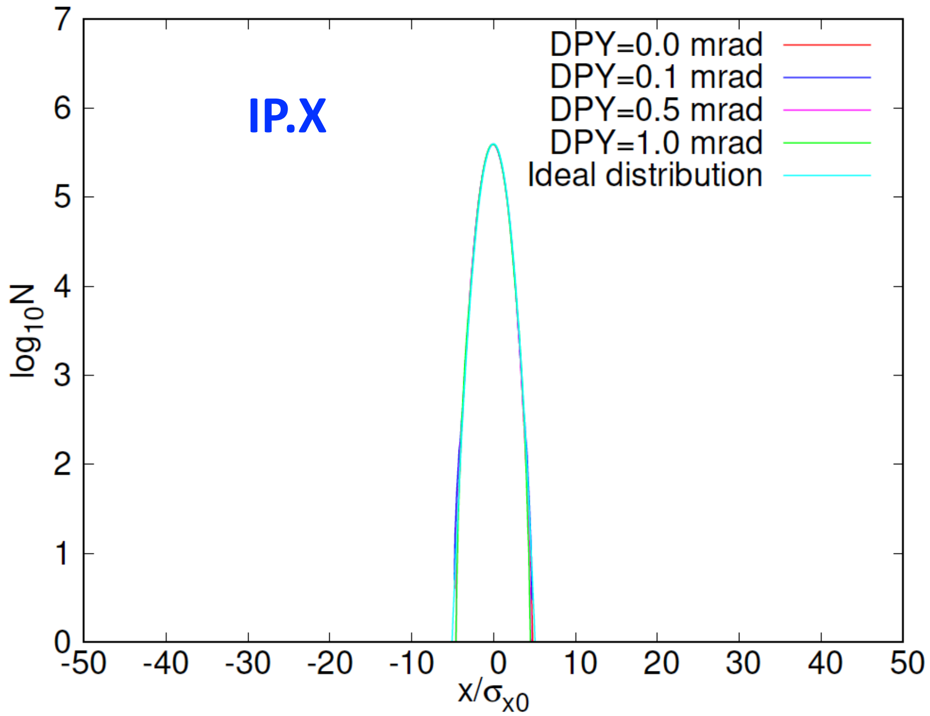
- DPY* (vert. crossing angle) with parameter set of 2019.07.01

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







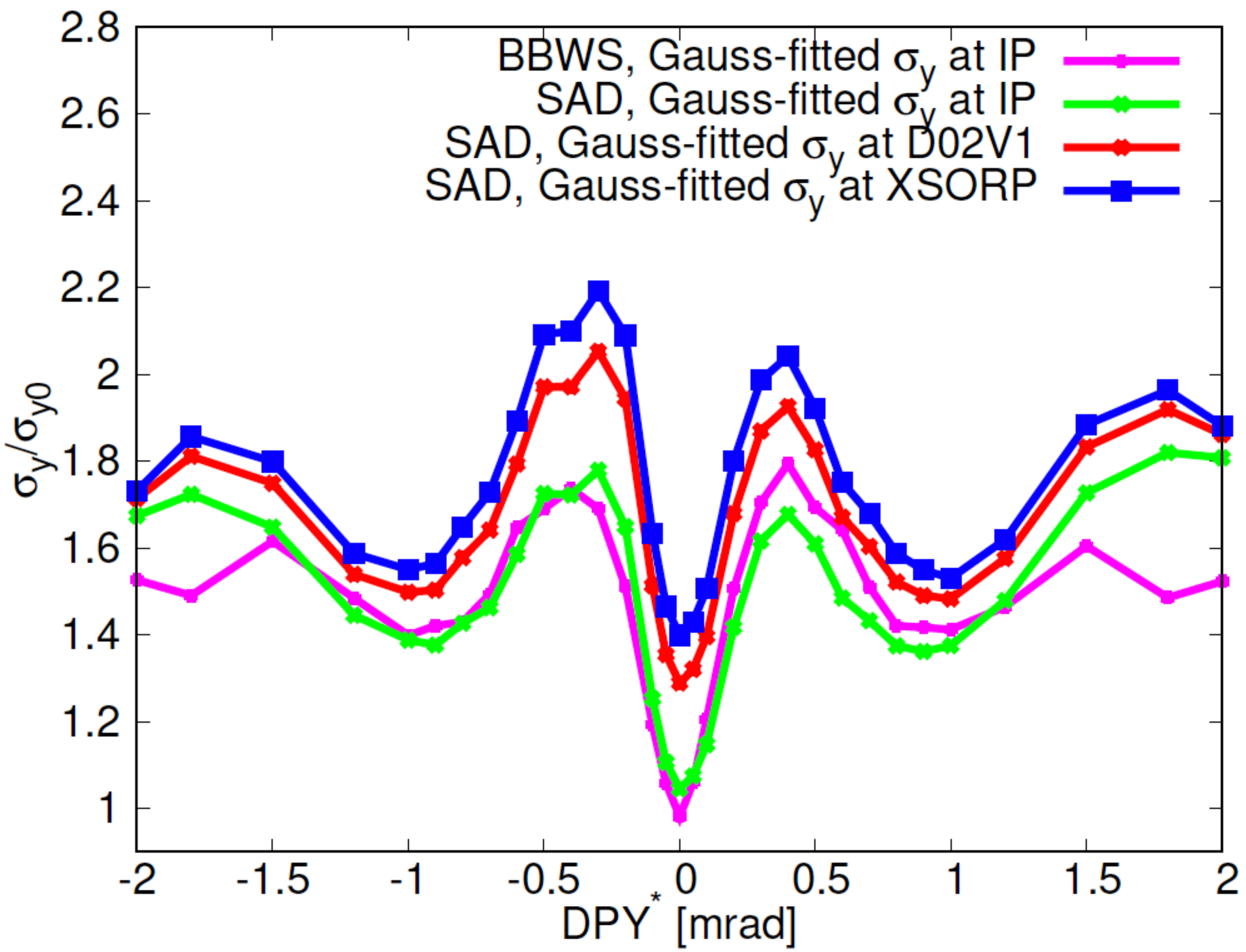


3. Tolerances of IP aberrations with lattice

➤ 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



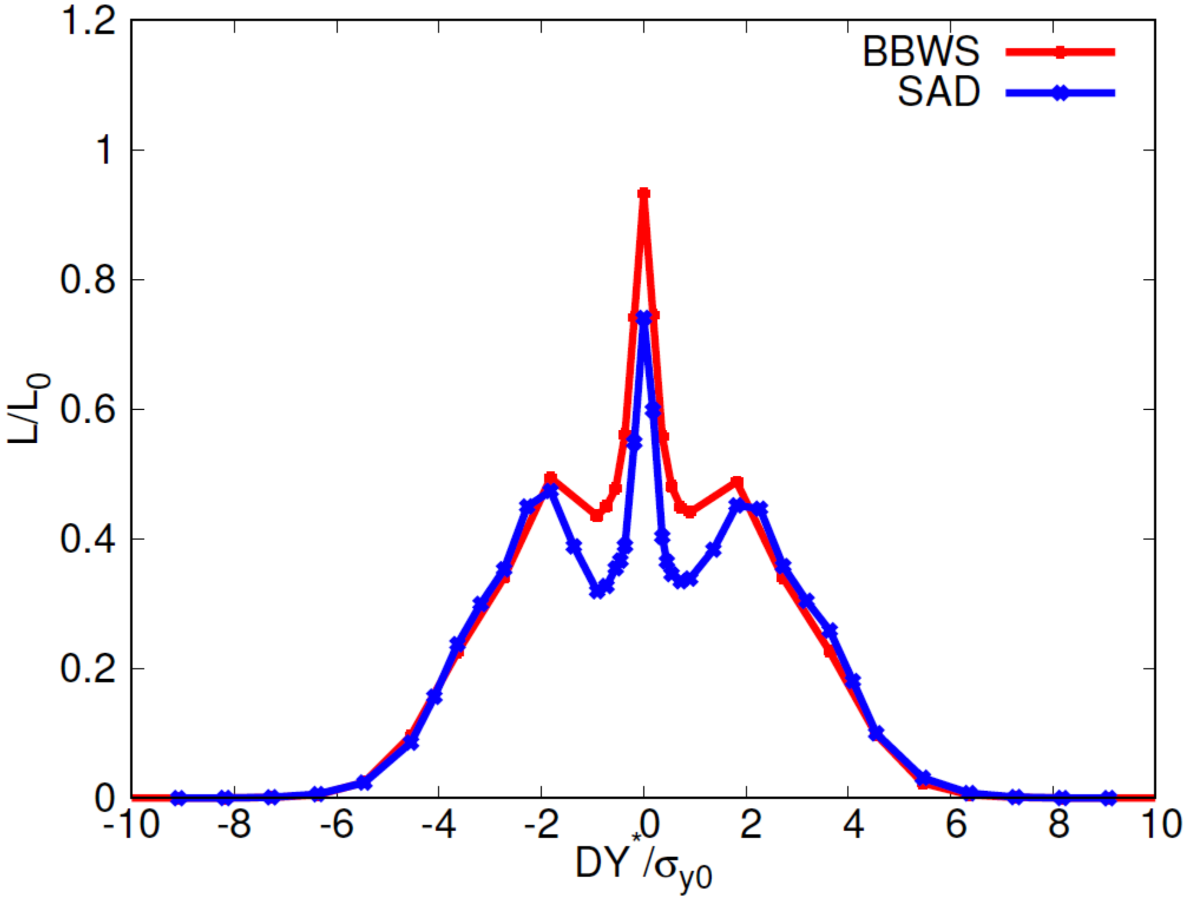
3. Tolerances of IP aberrations with lattice

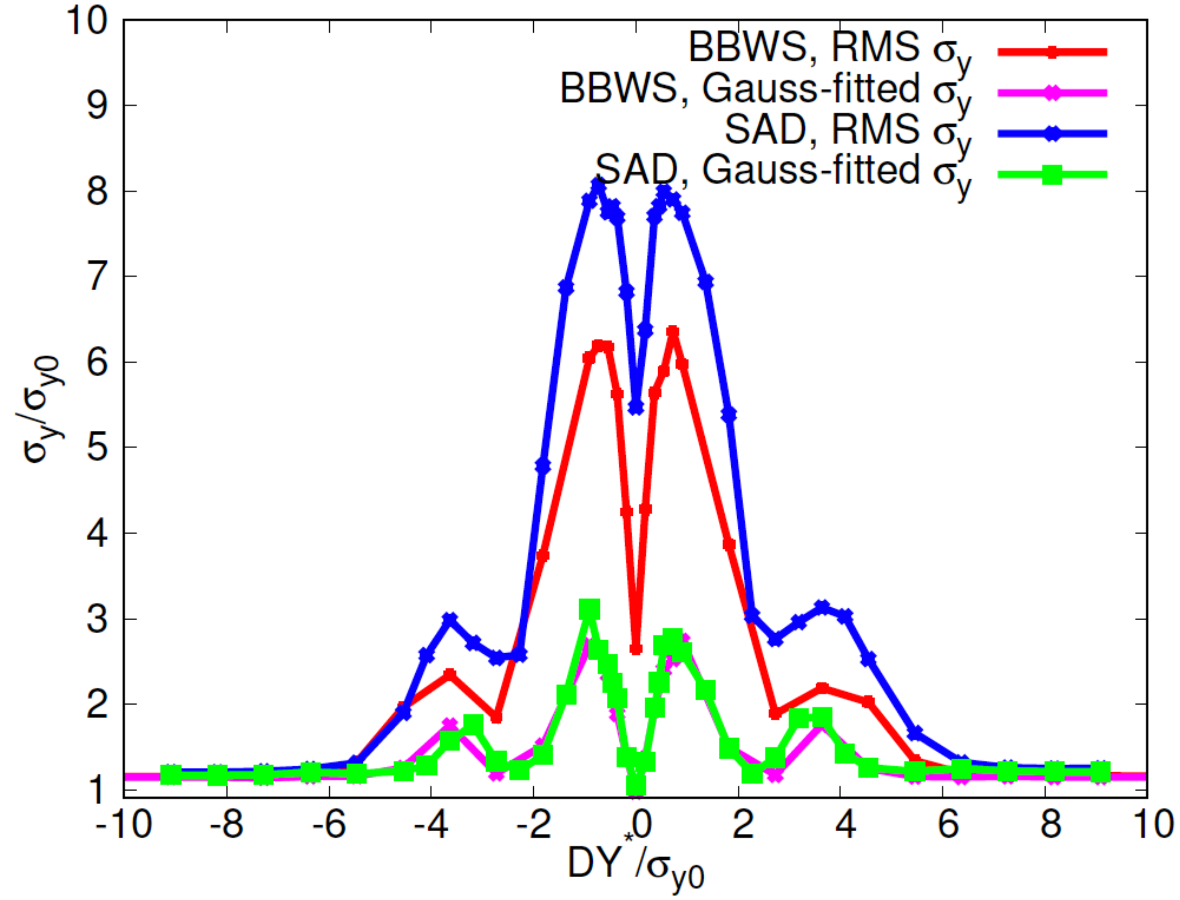
➤ Various IP aberrations: the case of e+ beam

- 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





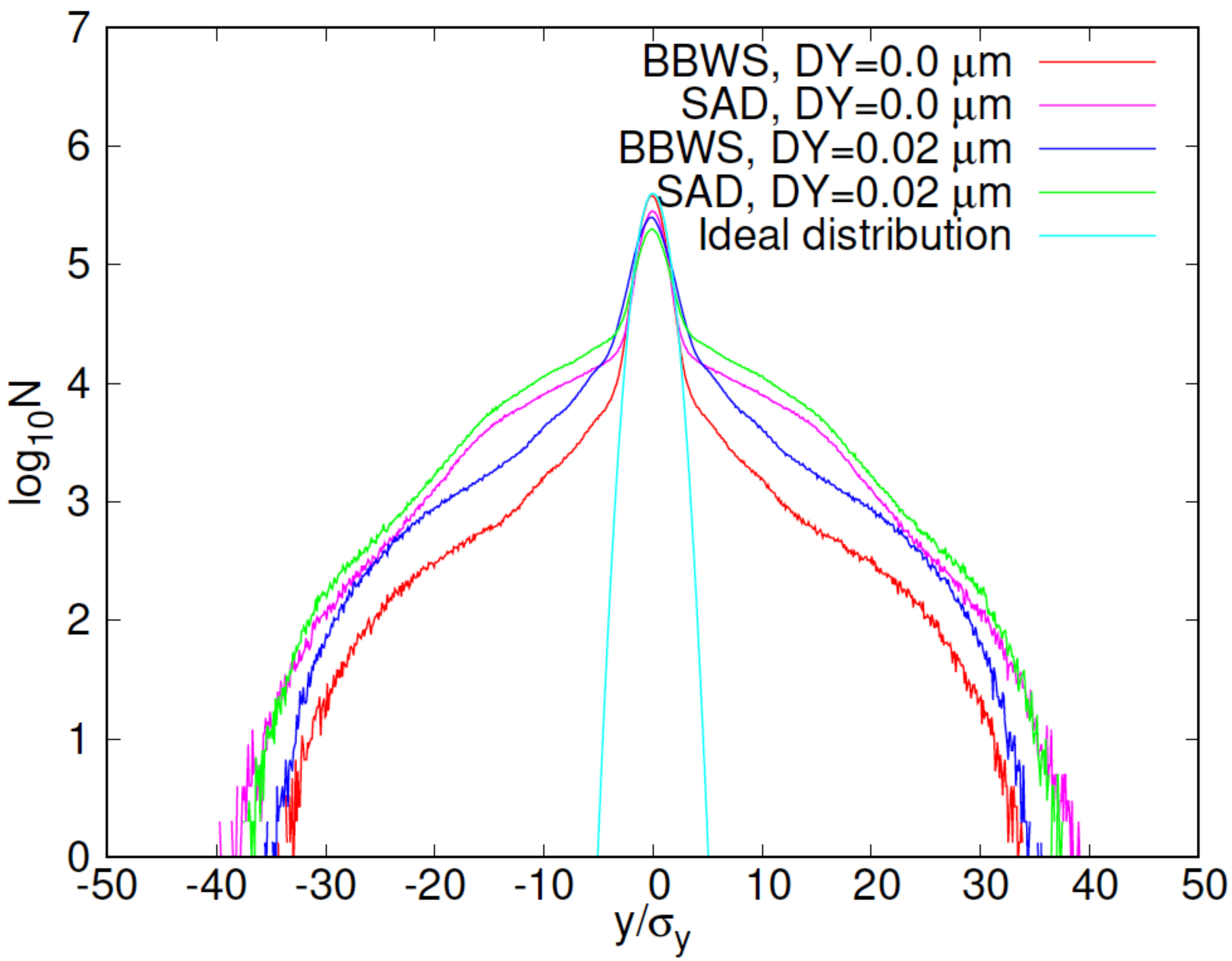
3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- DY* (Vertical offset) 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

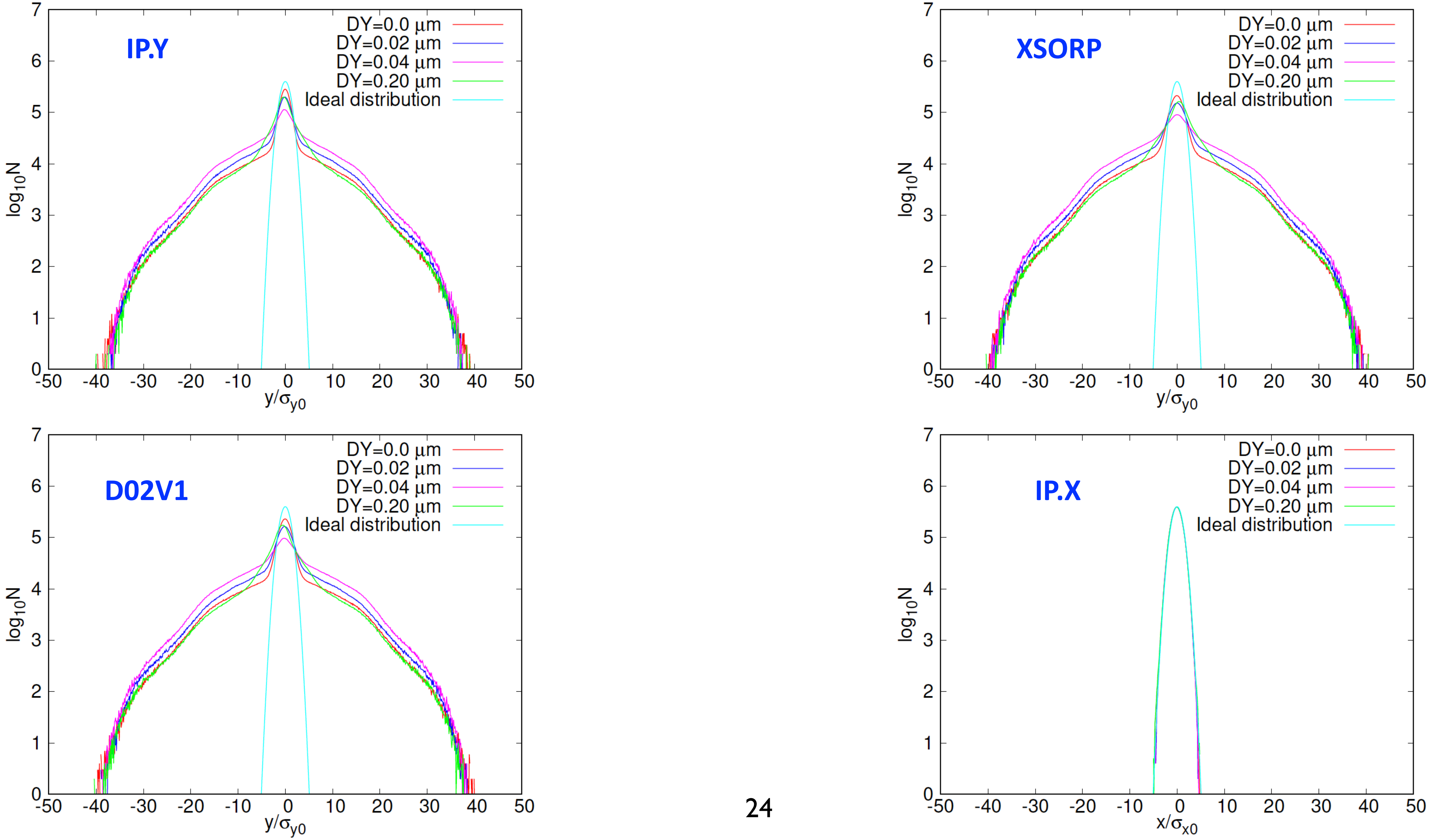


3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

- **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**

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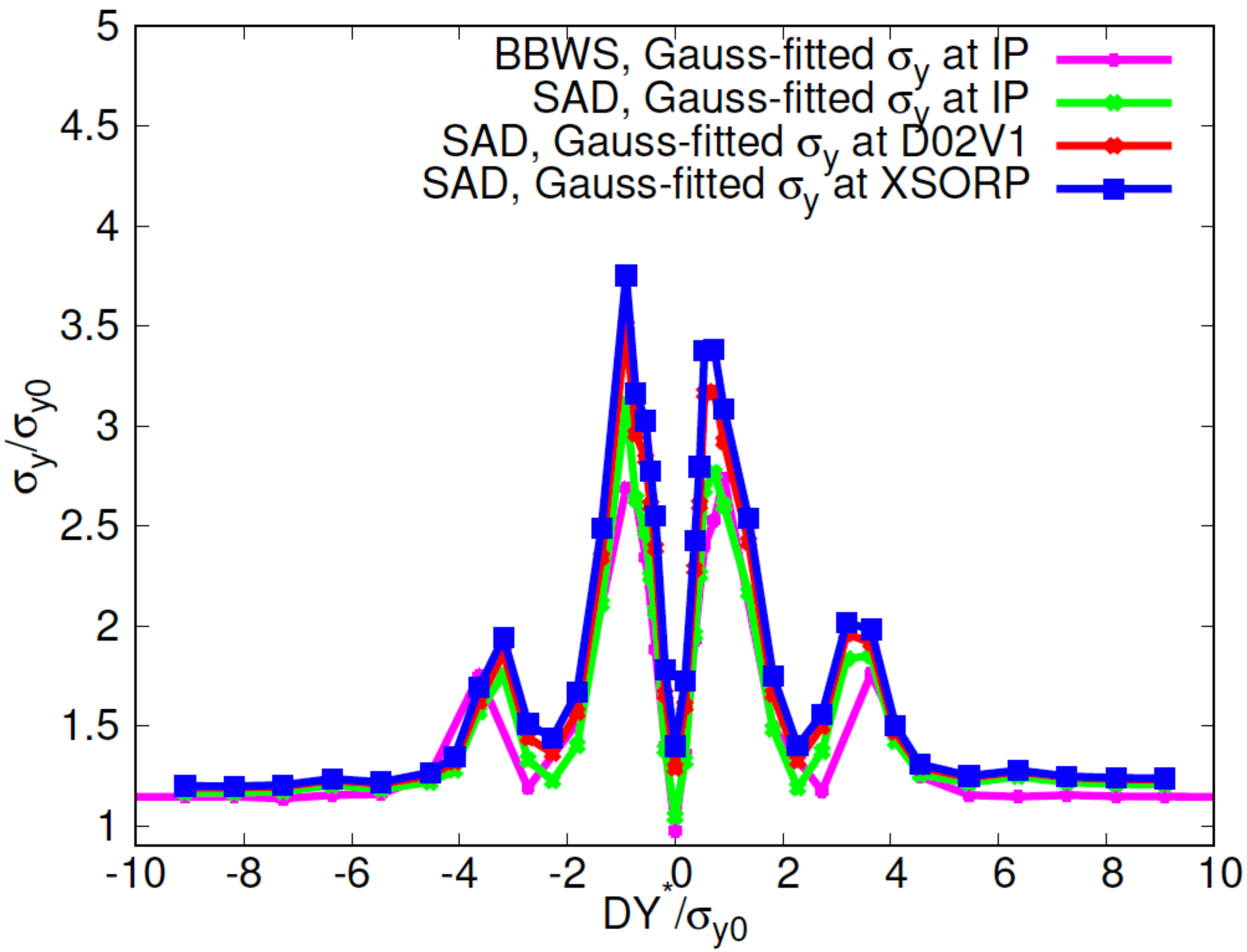


3. Tolerances of IP aberrations with lattice

➤ Various IP aberrations: the case of e+ beam

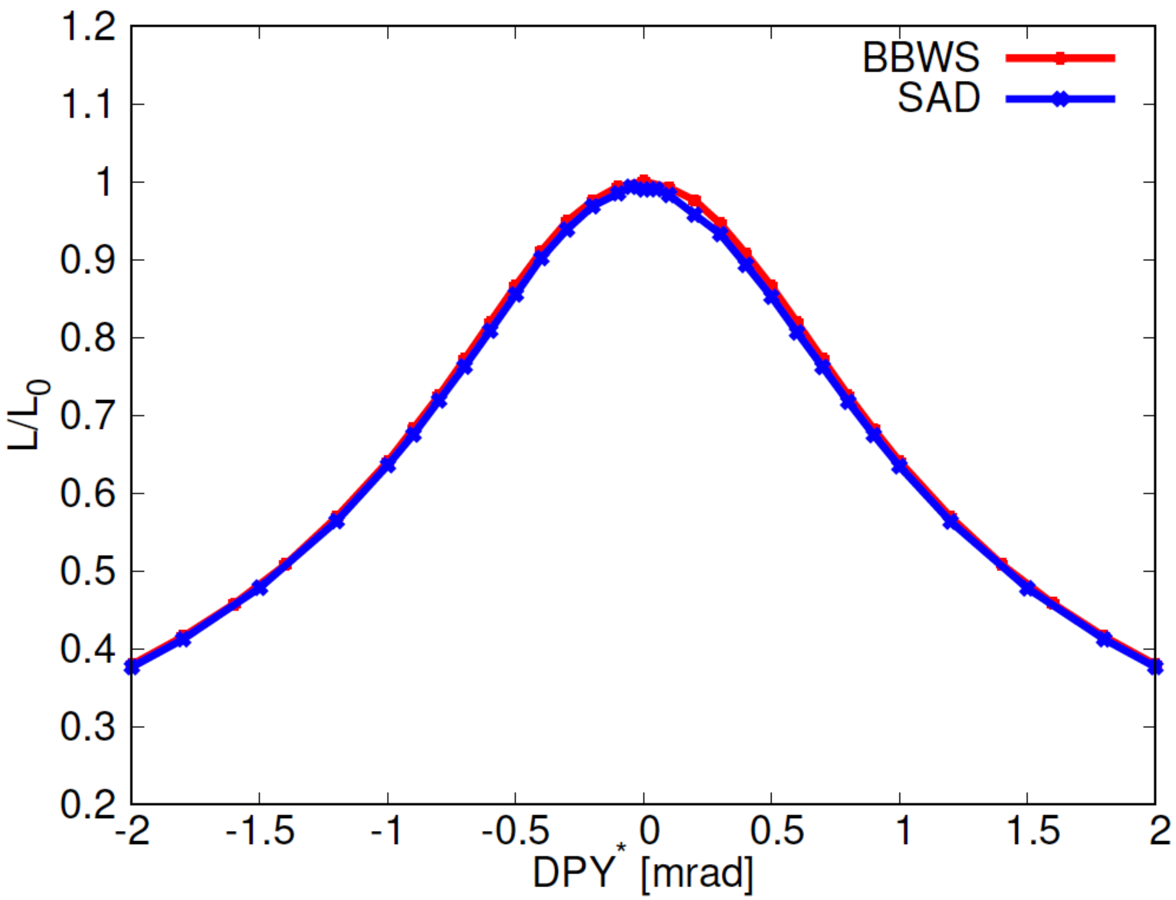
- DPY* (vert. crossing angle) with parameter set of 2019.06.25

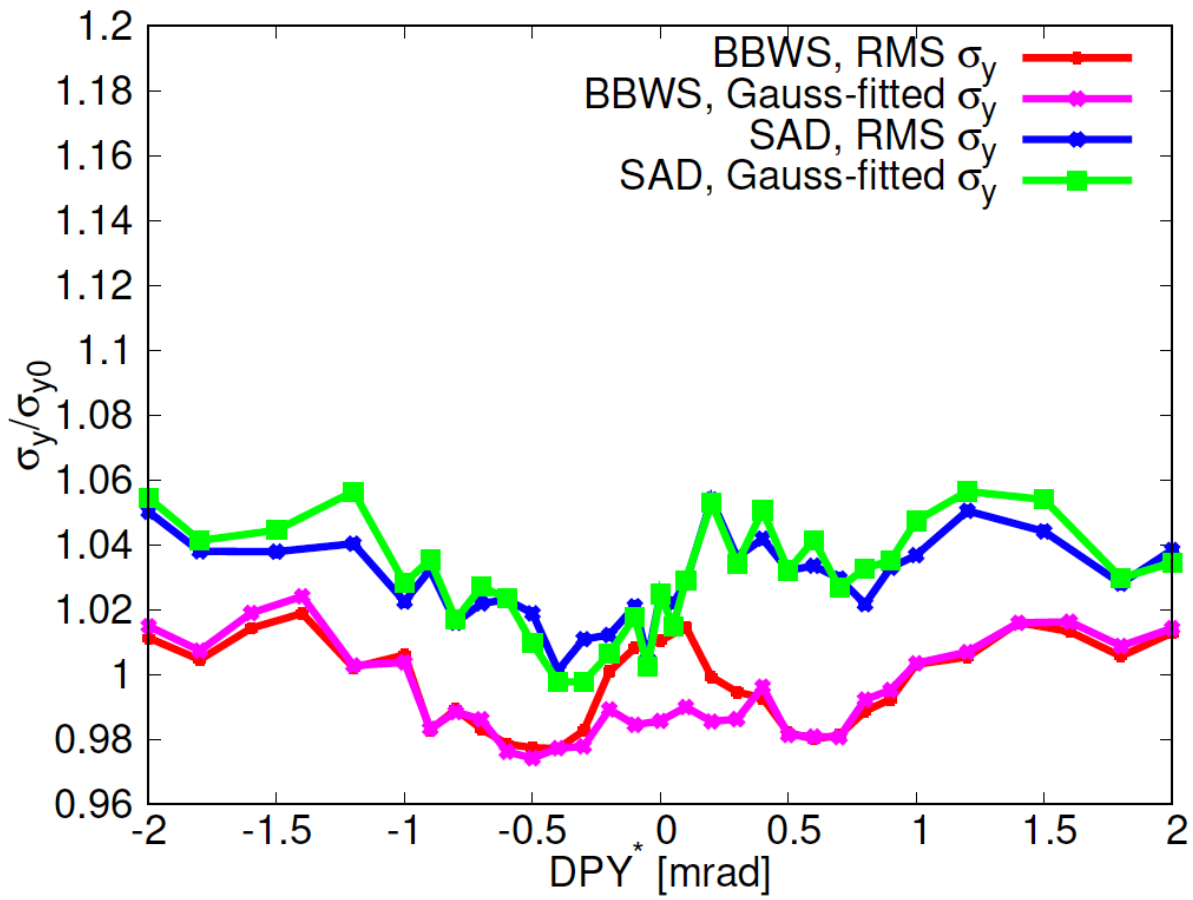
** Luminosity and beam size are very insensitive to DPY*. This is very different from experiments.

** 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





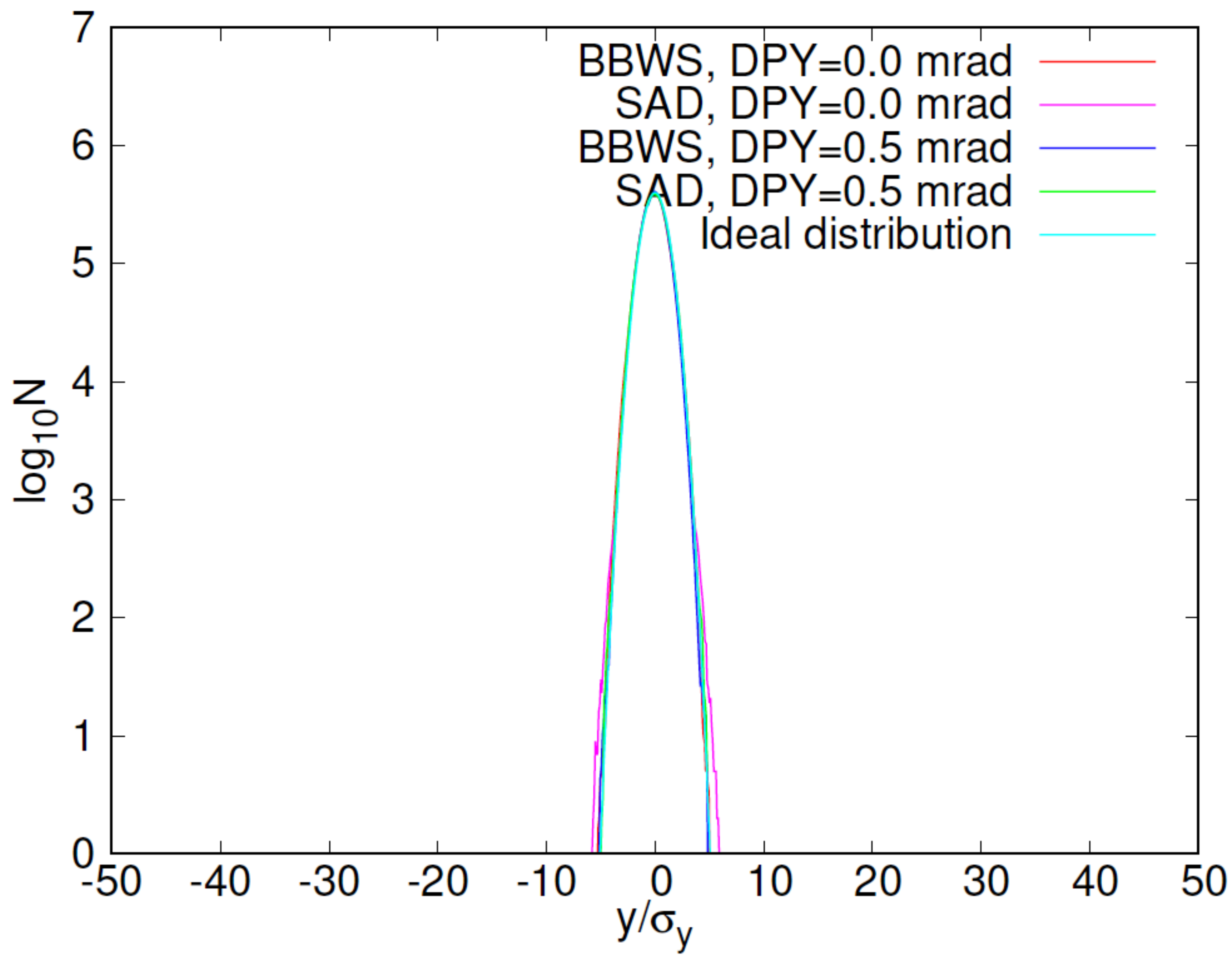
3. Tolerances of IP aberrations with lattice

➤ 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**

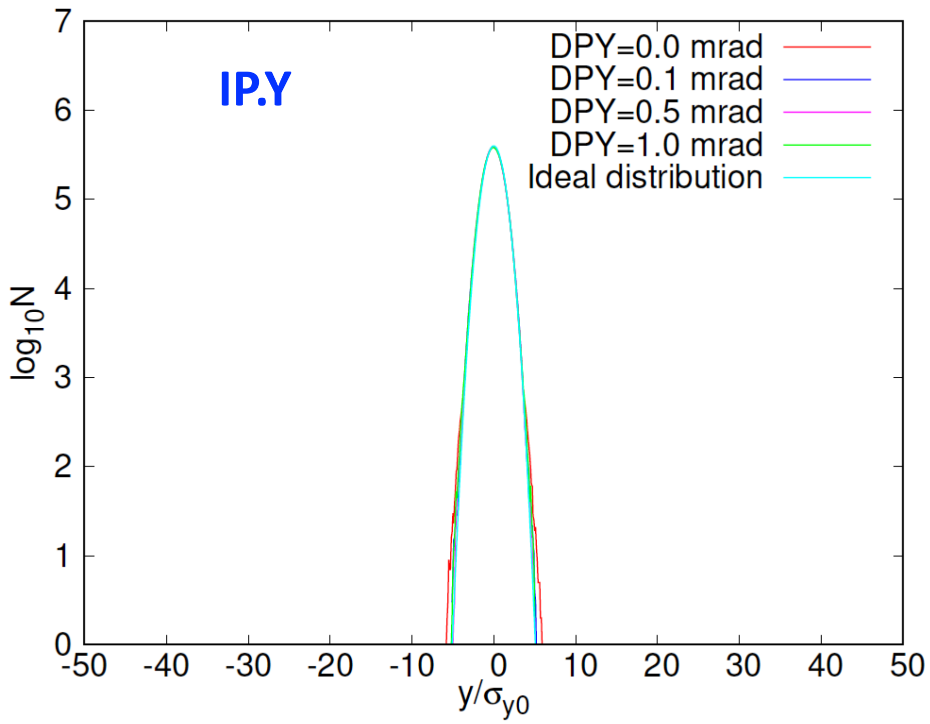


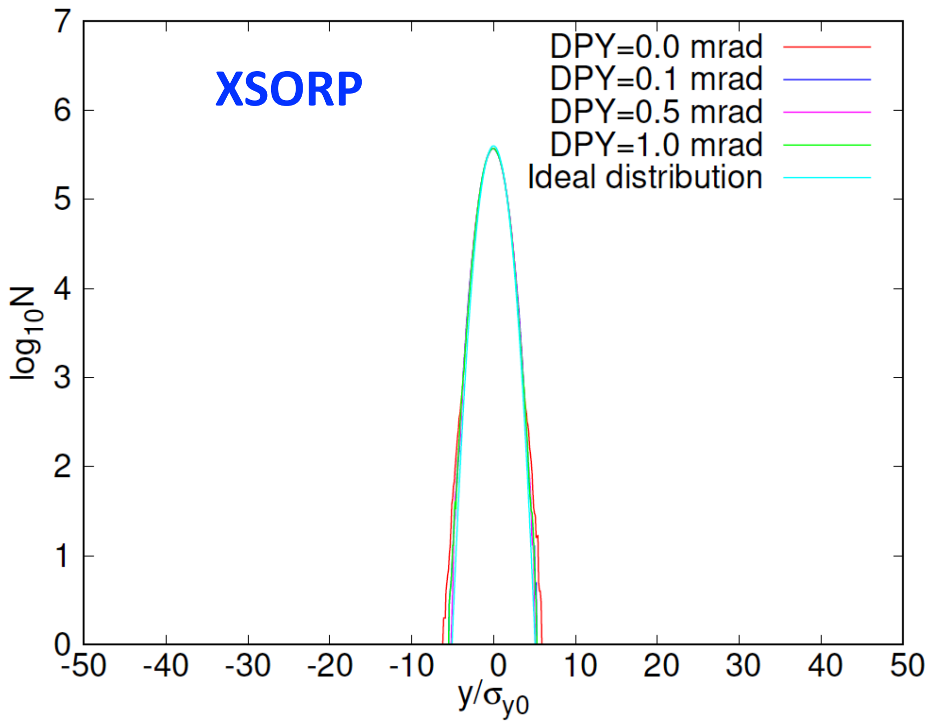
3. Tolerances of IP aberrations with lattice

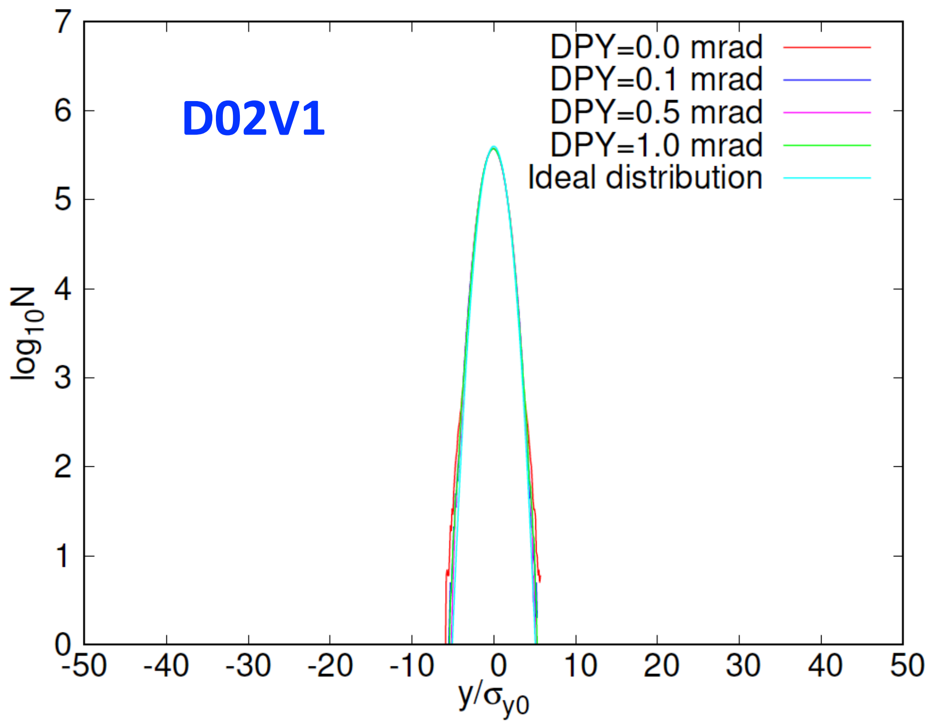
➤ Various IP aberrations: the case of e+ beam

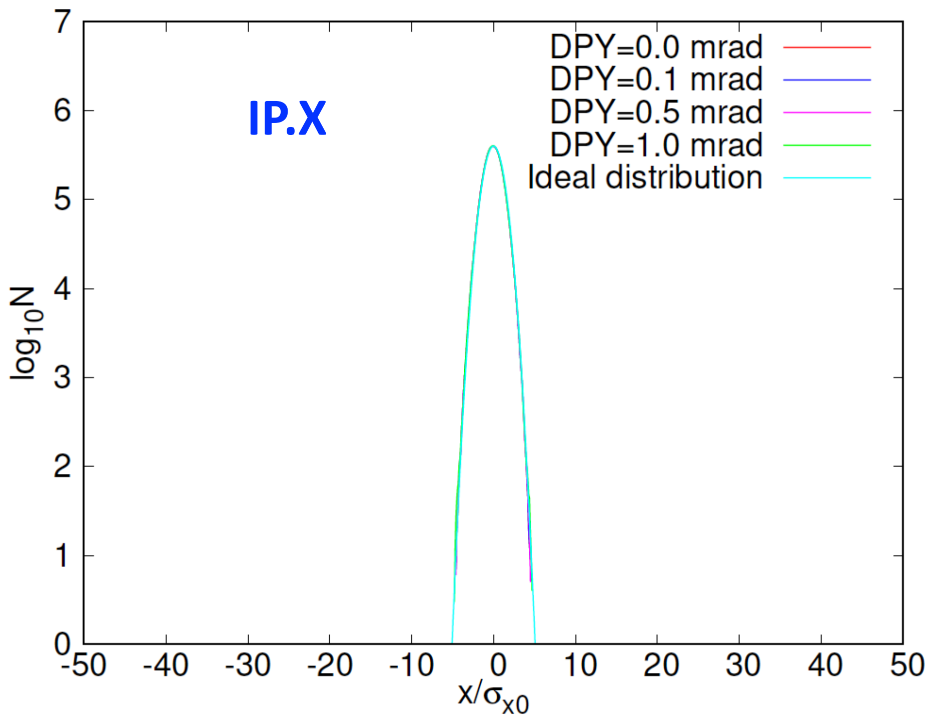
- DPY* (vert. crossing angle) with parameter set of 2019.06.25

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









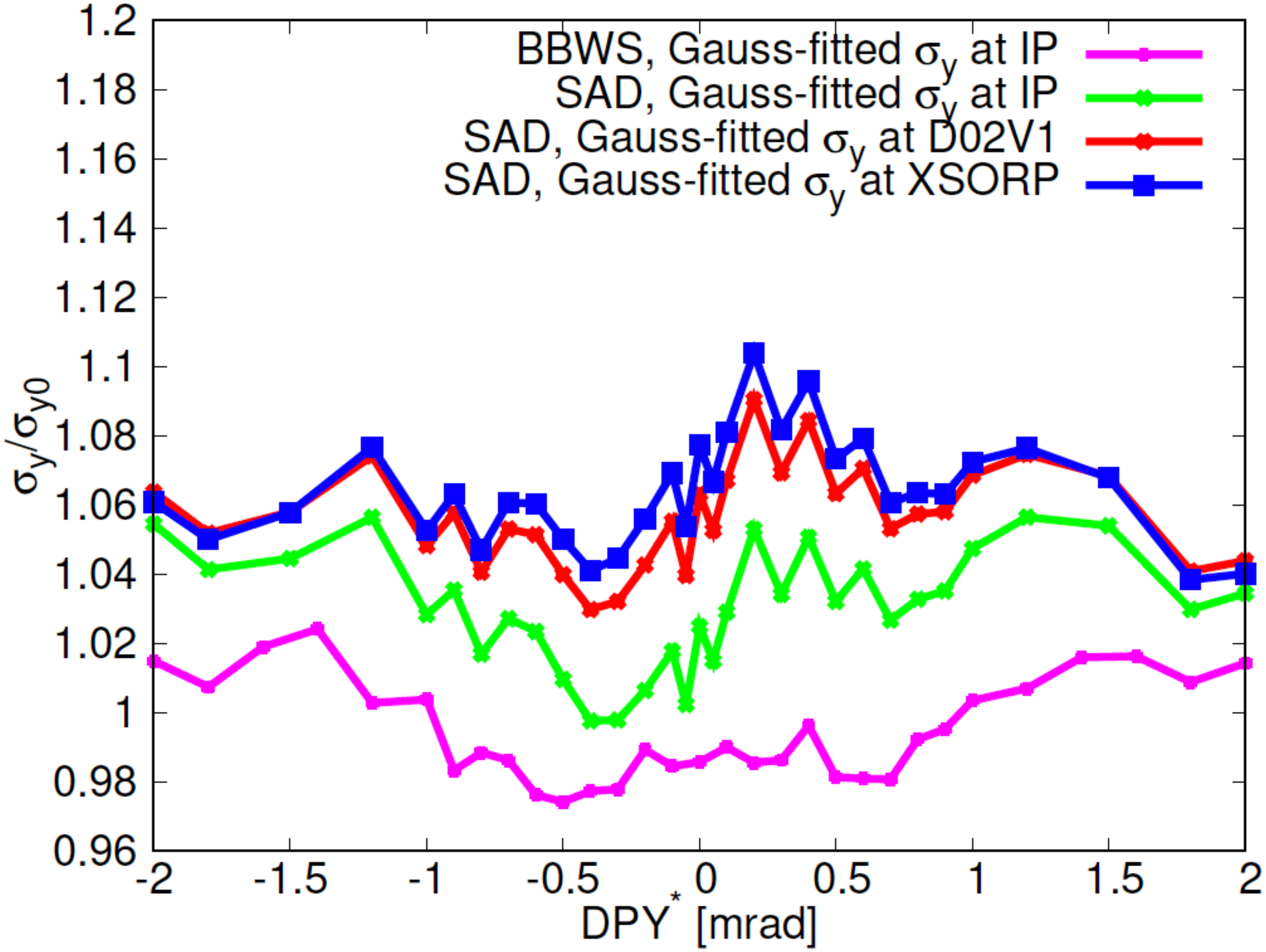
3. Tolerances of IP aberrations with lattice

➤ 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. Summary

➤ Findings

- **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)

- **Beam-beam effects at high currents (or strong beam-beam effects as the final design)**

  ** I think the dynamic beam effects (both linear and nonlinear) will make it difficult to estimate the beam size using XRM data. The translation needs to take into account beam-beam effects

  ** I propose to prepare another method to estimate beam sizes at IP, such as LABM