Combined effect of Beam-Beam and Impedance

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FCCIS Workshop 2022

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Outline

- Overview of Study with Longitudinal Impedance (ZL)
- Simulation(Analysis) with Transverse Impedance (ZT)
  - FCCee
  - Other Machines (CEPC/SuperKEKB)
  - Mitigation
- Summary

P. Raimondi , *2nd SuperB Workshop, March 2006*
M. Zobov et al., PRL 104, 174801 (2010)

Crab-waist collision

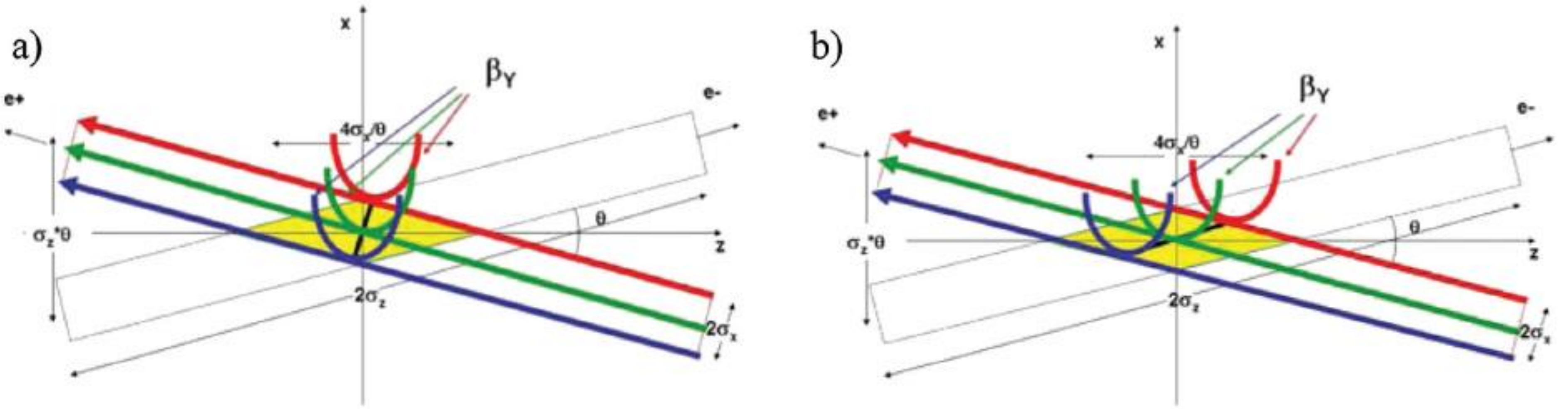


FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

$$L \propto \frac{N\xi_y}{\beta_y^*}; \qquad \xi_y \propto \frac{N\sqrt{\beta_y^*/\varepsilon_y}}{\sigma_z\theta}; \qquad \xi_x \propto \frac{N}{(\sigma_z\theta)^2},$$

$$\varphi = \frac{\sigma_z}{\sigma_x}\tan\left(\frac{\theta}{2}\right) \approx \frac{\sigma_z}{\sigma_x}\frac{\theta}{2}.$$

$$\beta_y^* \approx \frac{\sigma_x}{\theta} \ll \sigma_z.$$

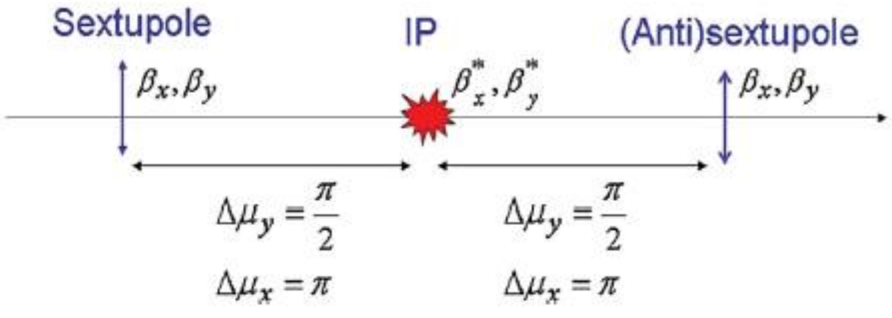
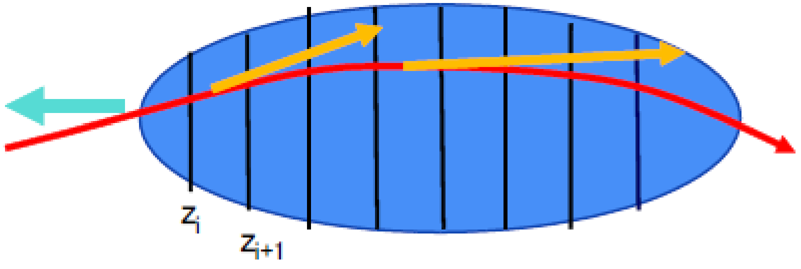


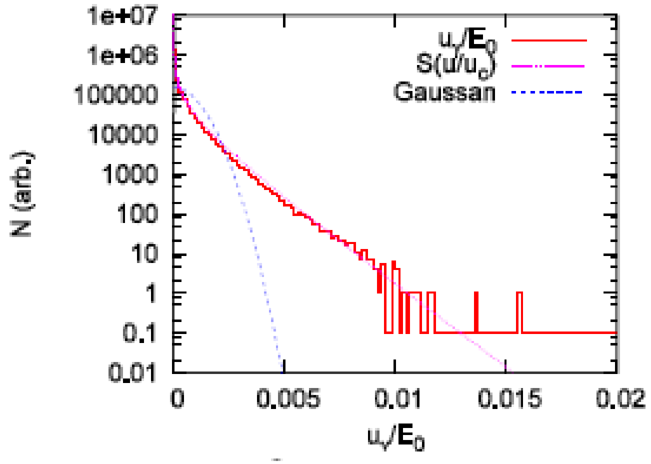
FIG. 2 (color). Crab sextupole locations.

V. I. Telnov, PRL 110, 114801 (2013)
A. Bogomyagkov et al., Phys. Rev. ST Accel. Beams 17, 041004 (2014)
D. Shatilov, ICFA Beam Dyn. Newslett. 72, 30 (2017).

Beamstrahlung Effect & 3D flip-flop

- Synchrotron radiation during beam-beam interaction
- High energy photon -> Momentum acceptance -> Lifetime
- Longer bunch length and Higher energy spread
- Beam blowup: 3D flip-flop





Coherent Beam-Beam Instability with a Large Crossing Angle

K. Ohmi, Int. J. Mod. Phys. A, 31, 1644014 (2016).
K. Ohmi and et al., PRL 119, 134801 (2017)
N. Kuroo et al, PHYS. REV. ACCEL. BEAMS 21, 031002 (2018)
K. Ohmi, eeFACT 2018

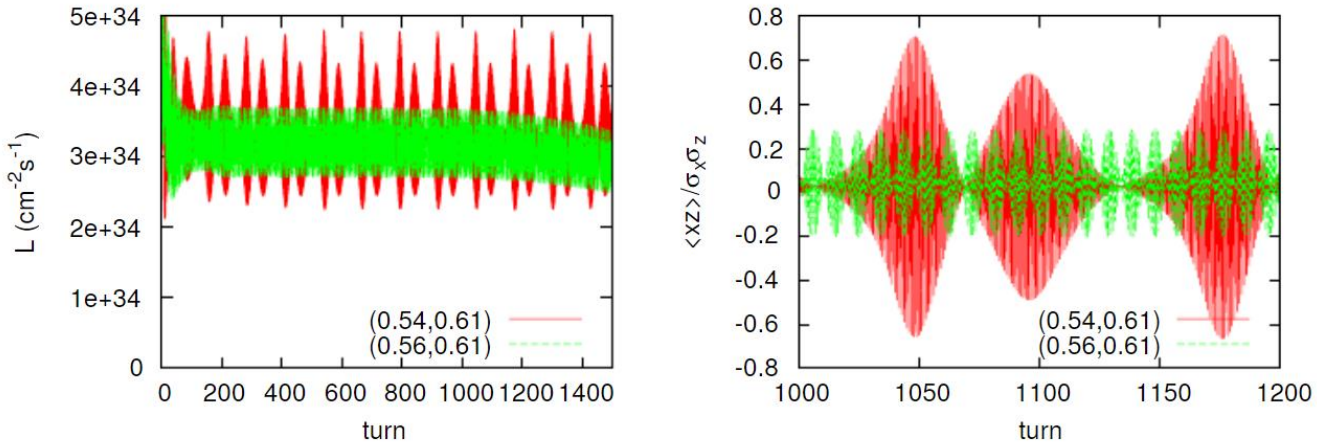


Fig. 5. Luminosity and $\langle xz\rangle$ evolutions given by a strong–strong simulation using BBSS code.

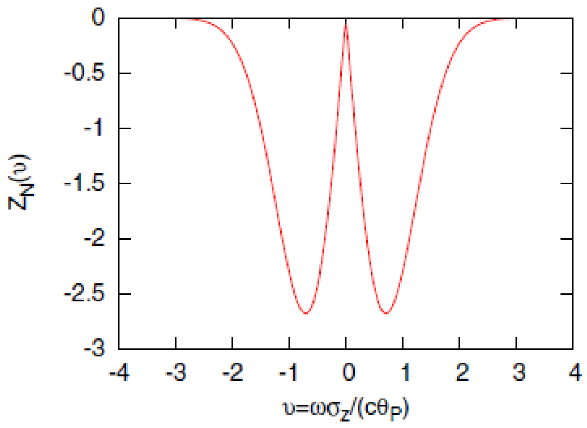


FIG. 3. Imaginary part of normalized cross impedance, where $\upsilon = \omega\bar{\sigma}_z/(c\theta_P)$.

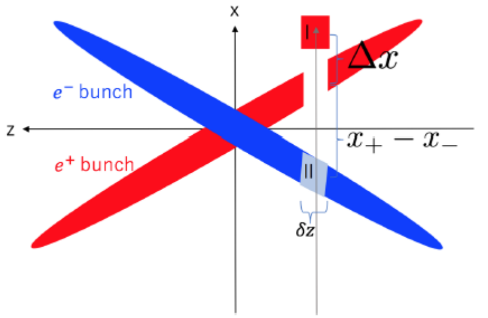


FIG. 1. Illustrative representation of the evaluation of the cross-wake force.

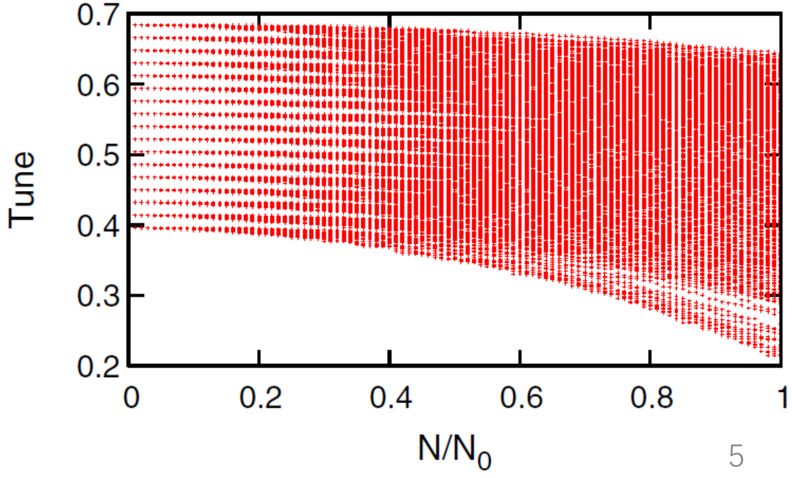
- Usual wake force gives correlation between bunch head to tail. Head-tail instability is induced by synchrotron motion

$$\Delta p_x(z) = -\int_z^{\infty} W(z-z')\rho_x(z')dz'.$$

- Cross wake field gives correlation of two colliding beam by convolution of each dipole moment.

$$\boxed{\Delta p_{x,\mp}(z_\mp)} = -\int_{-\infty}^{\infty} \boxed{W_x^{(\mp)}(z_\mp - z'_\pm)}\boxed{\rho_x^{(\pm)}(z'_\pm)}dz'_\pm$$

- Cross wake force induced by the beam-beam interaction is localized at IP.



Why have we started with the longitudinal impedance and transverse impedance?

1. In the collision scheme with Crab Waist and Large Piwinski Angle the luminosity and tune shifts strongly depend on the bunch length

$$L \propto \frac{N\xi_y}{\beta_y^*}, \quad \xi_y \propto \frac{N\sqrt{\beta_y / \varepsilon_y}}{\sigma_z \theta}, \quad \xi_x \propto \frac{N}{(\sigma_z \theta)^2}$$

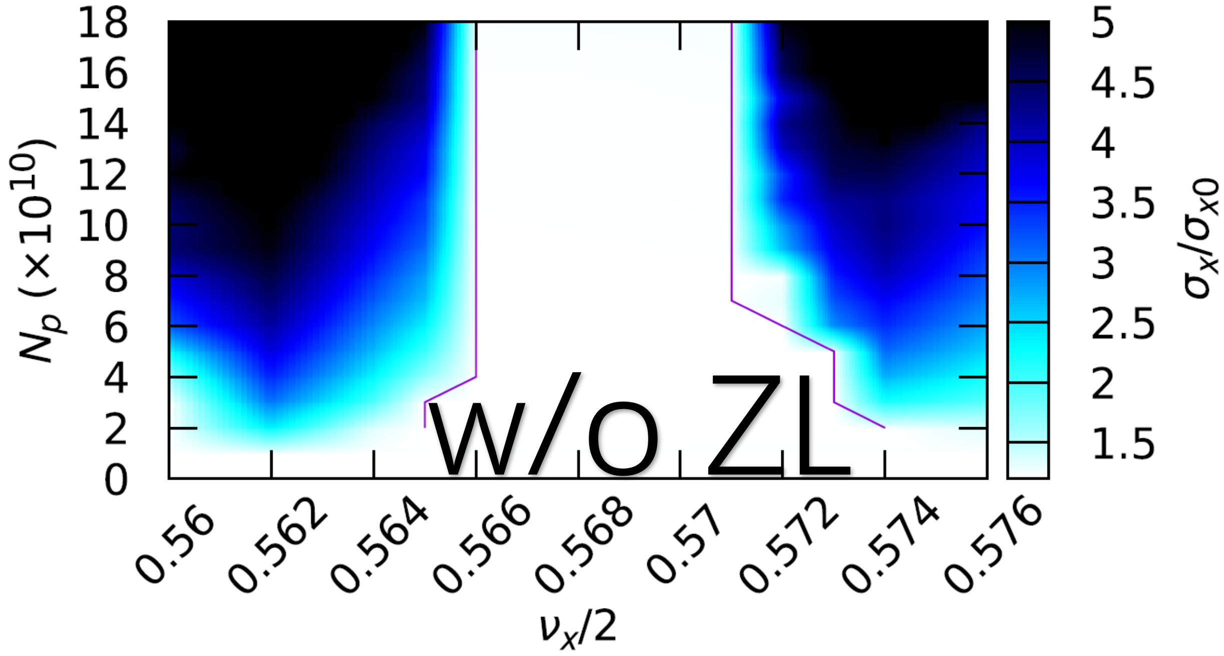
2. For the future circular colliders with extreme beam parameters in collision several new effects become important such as beamstrahlung, coherent X-Z instability and 3D flip-flop. The longitudinal beam dynamics plays an essential role for these effects

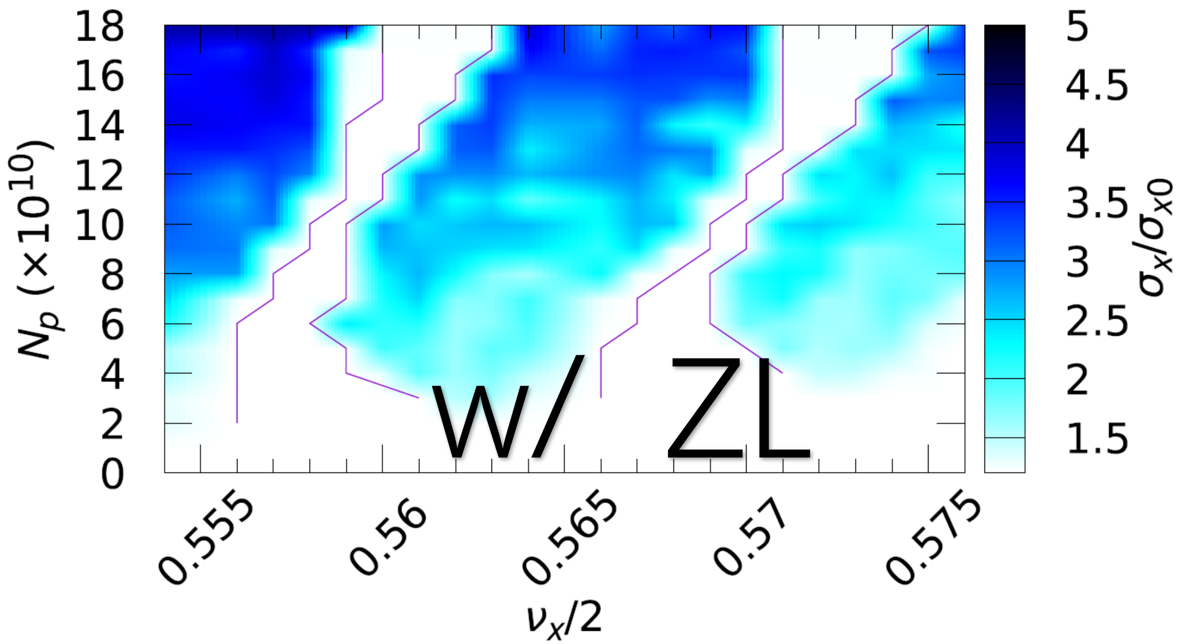
3. Considering transverse impeadance is very natural:

- Why not transverse impedance, since longitudinal impedance is included
- Transverse impedance change the coherent betatron tune

Eur. Phys. J. Plus (2021) 136:1190

	Z
Circumference (km)	97.75 km
Beam energy (GeV)	45.6
Bunch population (10^{11})	1.7
Bunches per beam	16640
RF frequency (MHz)	400
RF Voltage (GV)	0.1
Energy loss per turn (GeV)	0.036
Longitudinal damping time (turns)	1273
Momentum compaction factor 10^{-6}	14.8
Horizontal tune	269.139
Vertical tune	269.219
Synchrotron tune	0.025
Horizontal emittance (nm)	0.27
Verical emittance (pm)	1.0
IP number	2
Nominal bunch length (mm) (SR/BS)*	3.5/12.1
Nominal energy spread (%) (SR/BS)*	0.038/0.132
Piwinski angle (SR/BS)*	8.2/28.5
ξ_x/ξ_y	0.004/0.133
Horizontal β^* (m)	0.15
Vertical β^* (mm)	0.8
Luminosity/IP (10^{34}/cm^{2}s)	230





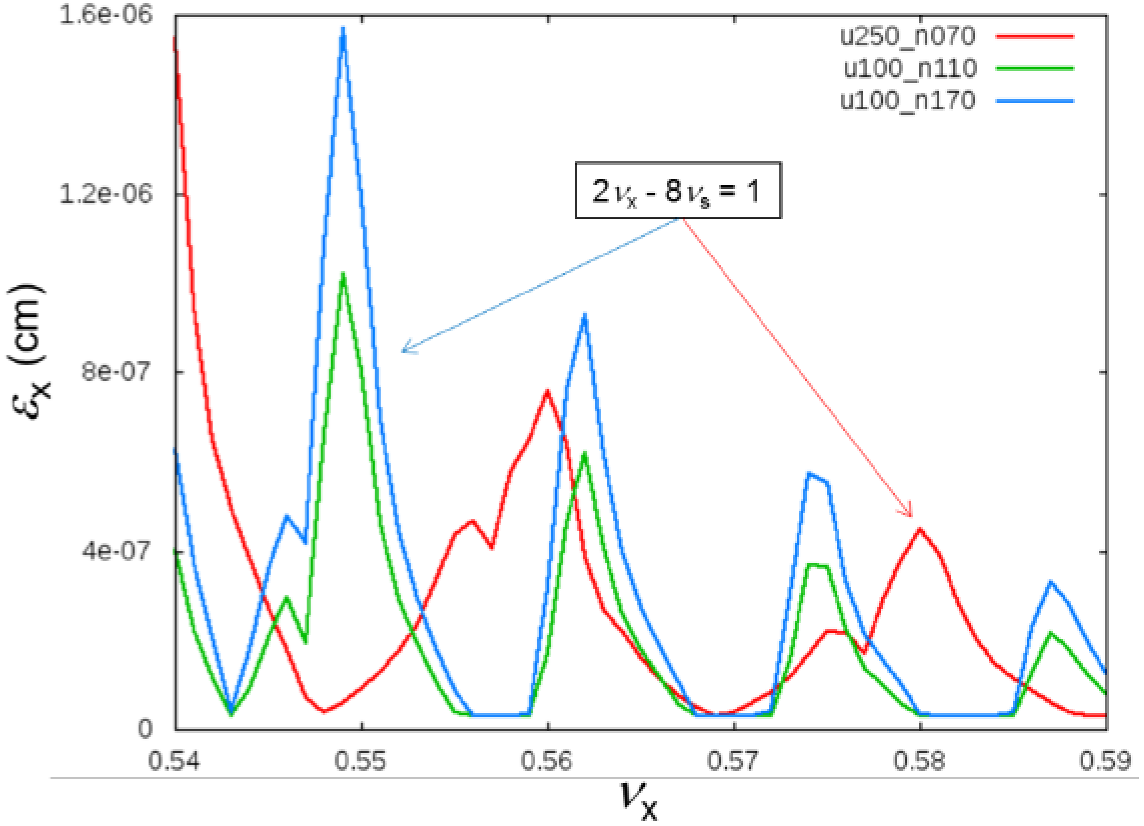
K. Oide, IPAC2017
D. Shatilov, *ICFA Beam Dyn.Newslett.* 72 (2017) 30-41

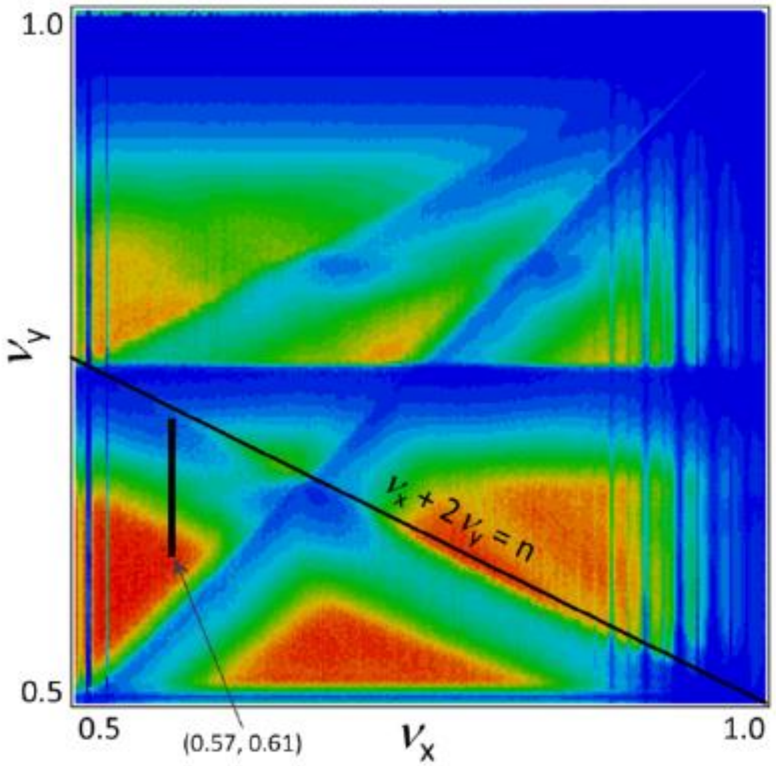
Parameter Optimization

$$\left.\begin{array}{l} N_{th} \propto \dfrac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}, \\ \alpha_p \sigma_\delta \propto \nu_s \sigma_z \\ \xi_x \propto N_p \beta_x^* / \sigma_z^2 \end{array}\right\}$$

Larger ν_s/ξ_x is preferred!

$2\nu_x - 2m \cdot \nu_s = 1$

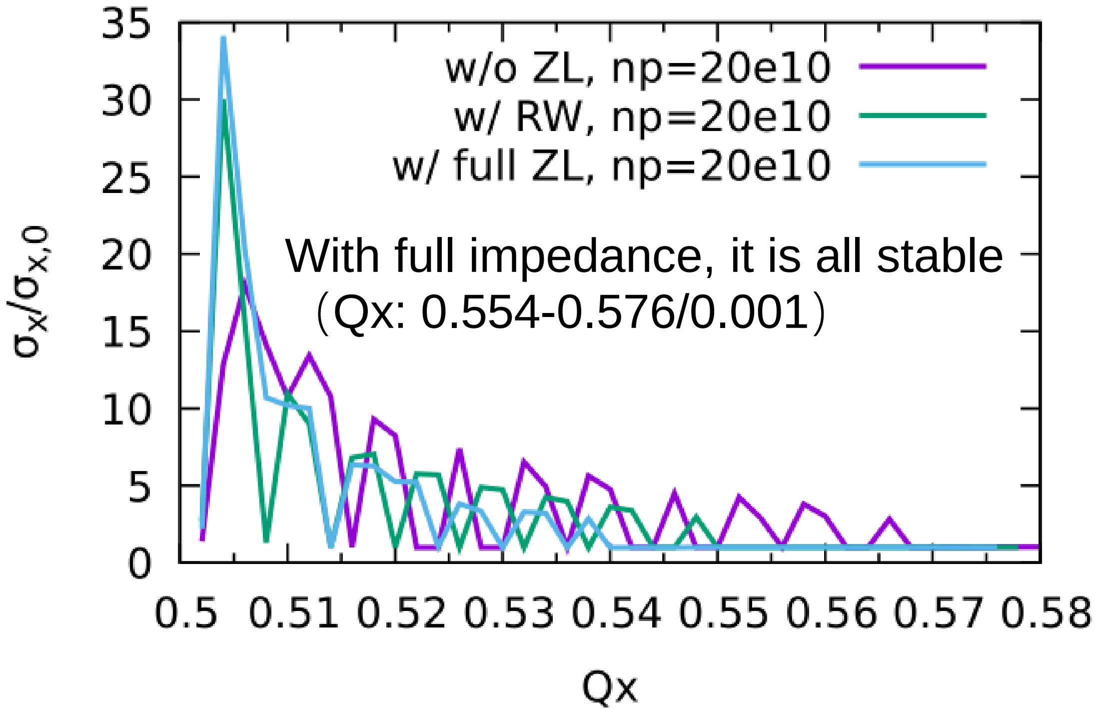




Eur. Phys. J. Plus (2021) 136:1190
doi:10.18429/JACoW-IPAC2021-MOXC01

Idea of using harmonic cavities

- Lower synchrotron tune
- Higher order X-Z resonances
- Landau damping due to higher synchrotron frequency spread
- Longer bunches reduce the horizontal tune shift, which helps in suppressing the X-Z instability.
- Longer bunches in collision result in a smaller energy spread due to beamstrahlung.

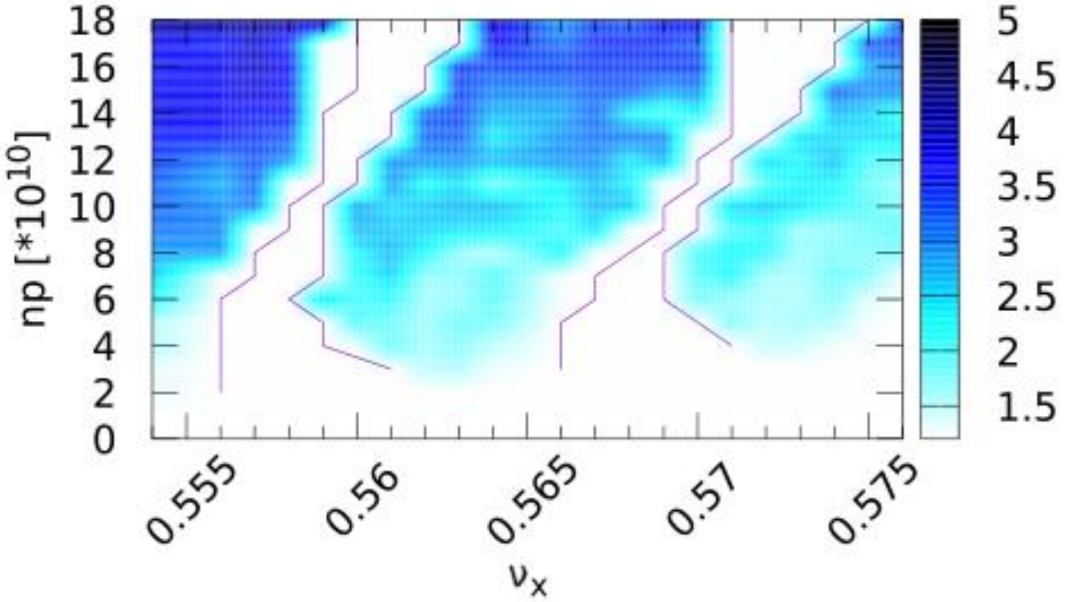


σ_z = 18 mm (CDR: 12 mm)
σ_p = 9.2e-4 (CDR: 13e-4)

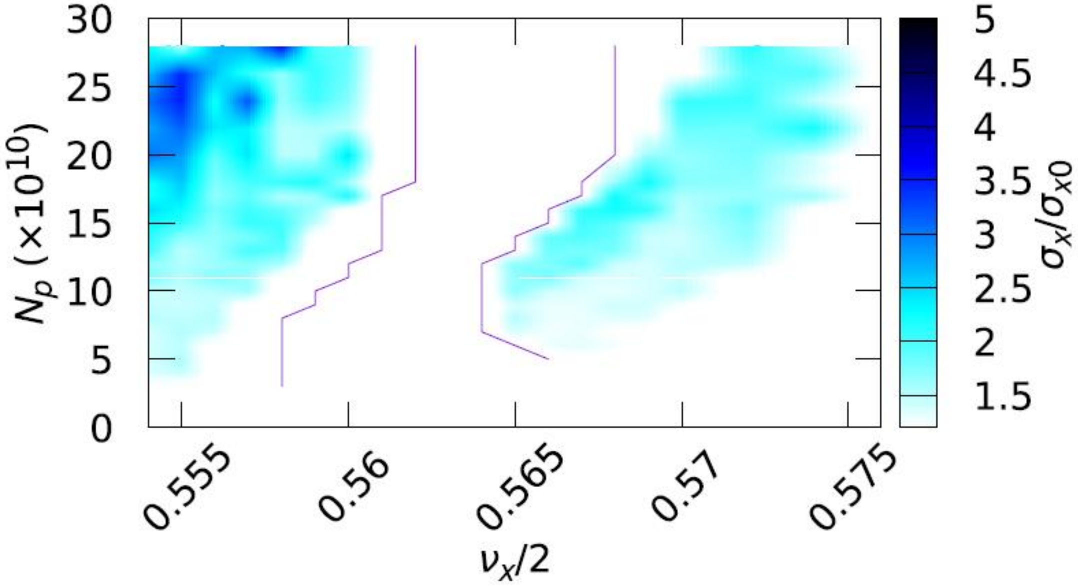
D. Shatilov, 133rd FCC-ee optics design meeting
Eur. Phys. J. Plus (2021) 136:1190
doi:10.18429/JACoW-IPAC2021-MOXC01

Higher Momentum Compaction

- Switching from $60°/60°$ to $45°/45°$ for arc cell lattice has been proposed for FCC-ee Z. To restore the luminosity of CDR, higher bunch population (28e10) has been proposed.



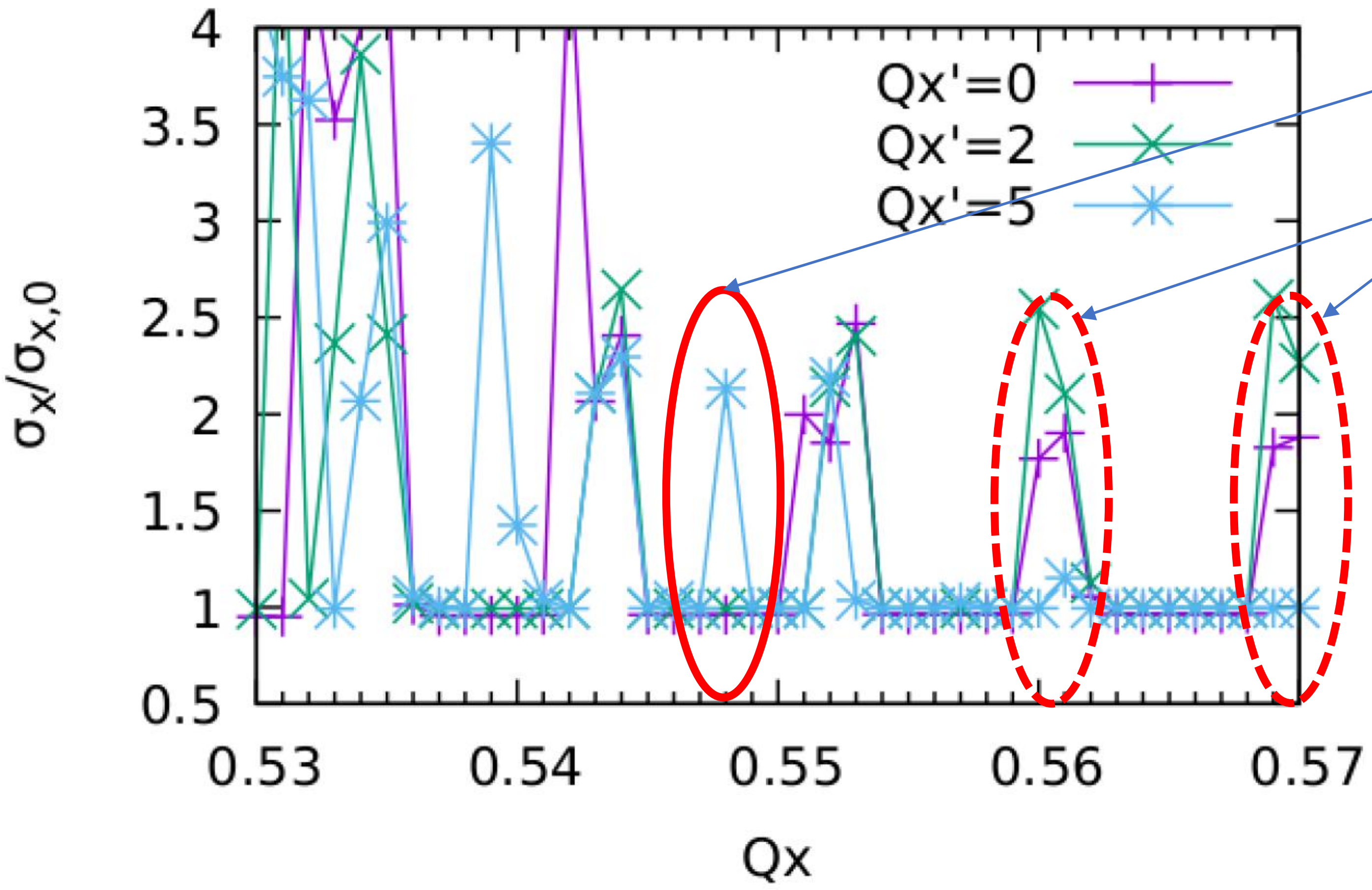
FODO CELL: $60°/60°$



FODO CELL: $45°/45°$

https://doi.org/10.1140/epjti/s40485-022-00084-z
Y. Zhang et al., FCC WEEK 2022

Effect of Chromaticity on X-Z instability



- Non-zero tune chromaticity bring new resonance
- In the high order resonance region (0.5+n*nus), some resonance may be suppressed or weakened

Future work:
- Analysis work considering linear tune chromaticity
- Simulation work considering realistic chromaticity (from lattice model)

C. Lin, K. Ohmi and Y. Zhang, PRAB 25, 011001 (2022)

Analysis with PWD

- Azimuthal Mode Expansion $x(J,\phi) = \sum_{l=-\infty}^{\infty} x_l(J) e^{il\phi}, \quad p_x(J,\phi) = \sum_{l=-\infty}^{\infty} p_l(J) e^{il\phi}$
- Synchro-betatron motion in Arc $\begin{pmatrix} x_l(J) \\ p_l(J) \end{pmatrix} = e^{-2\pi i l \nu_s(J)} \begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix} \begin{pmatrix} x_l(J) \\ p_l(J) \end{pmatrix} \equiv M_0 \begin{pmatrix} x_l(J) \\ p_l(J) \end{pmatrix}$
- Action Discretization we truncate l at $\pm l_{max}$, and discretize J at $J_1, J_2, \ldots, J_{n_J}$.

$$\begin{pmatrix} x_l(J_i) \\ p_l(J_i) \end{pmatrix} = e^{-2\pi i l \nu_s(J_i)} \begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix} \begin{pmatrix} x_l(J_i) \\ p_l(J_i) \end{pmatrix} \equiv M_0 \begin{pmatrix} x_l(J_i) \\ p_l(J_i) \end{pmatrix}$$

For example, $n_J = 40$, $l_{\max} = 8$

- Momentum Kick due to localized Wake force(beam-beam)

$$M_W = \begin{pmatrix} 1 & 0 \\ \beta_x M_{lil'i'} & 1 \end{pmatrix}.$$

$$\Delta p_l(J_i) = \mp \frac{\beta_x}{2\pi} \sum_{l'} \sum_{i'} \Delta J_{i'} W_{ll'}(J_i, J_{i'}) \psi(J_{i'}) x_{l'}(J_{i'}) \equiv \beta_x M_{lil'i'} x_{l'}(J_{i'}).$$

- Stability analysis of $M_0 M_W$

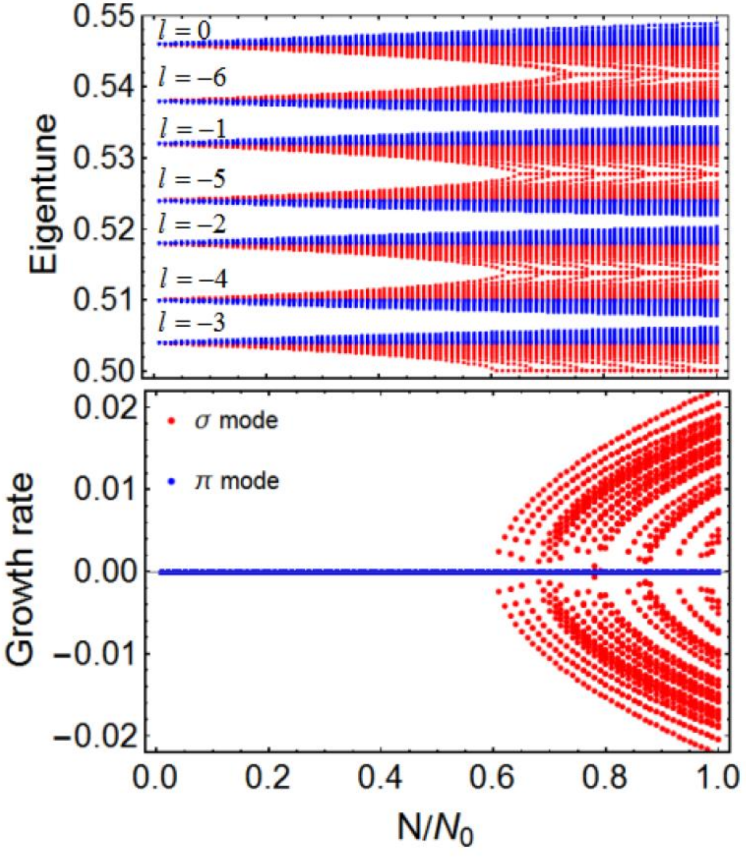
$$W_{ll'}(J_i, J_{i'}) = \sum_j \sum_{j'} e^{-il\phi_j + il'\phi_{j'}} W_x(z(J_i,\phi_j) - z(J_{i'},\phi_{j'})) \Delta\phi_j \Delta\phi_{j'}.$$

C. Lin, K. Ohmi and Y. Zhang, PRAB 25, 011001 (2022)

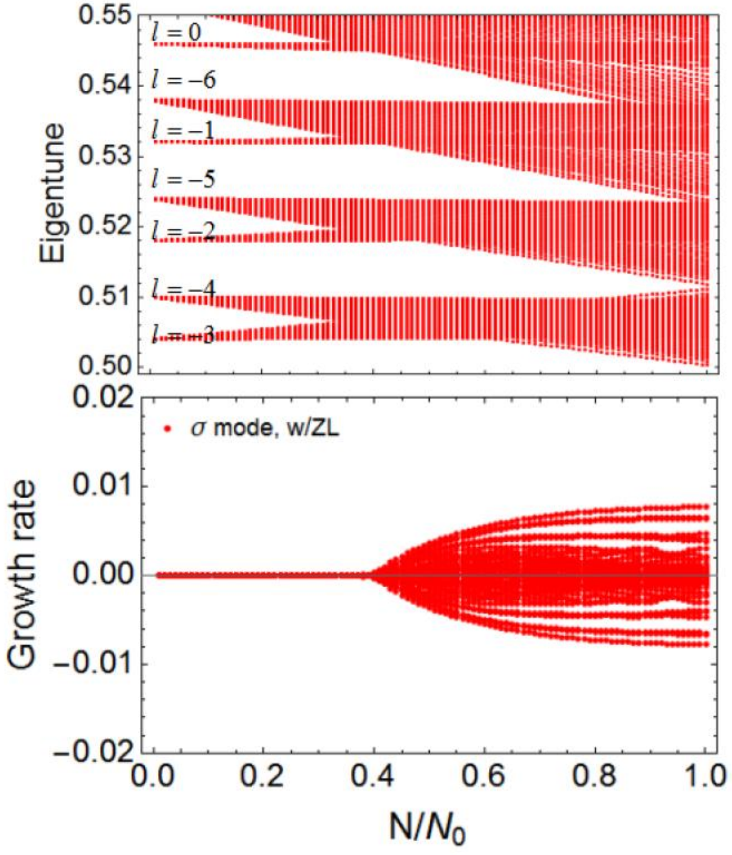
ν_x=0.546, CEPC CDR

Eigen-Mode Analysis w/o and w/ ZL

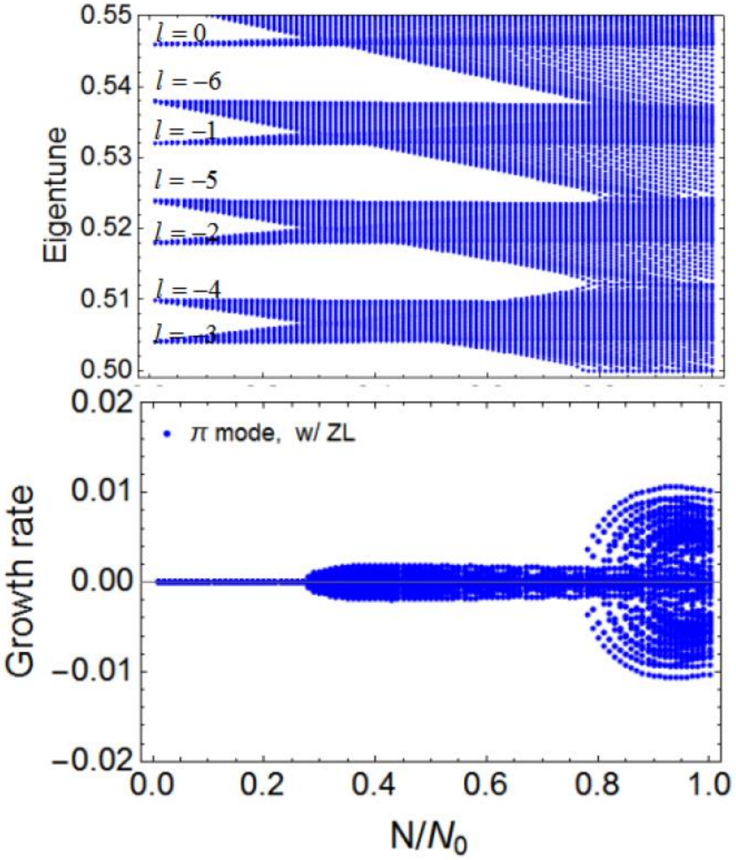
w/o ZL



w/ ZL, σ

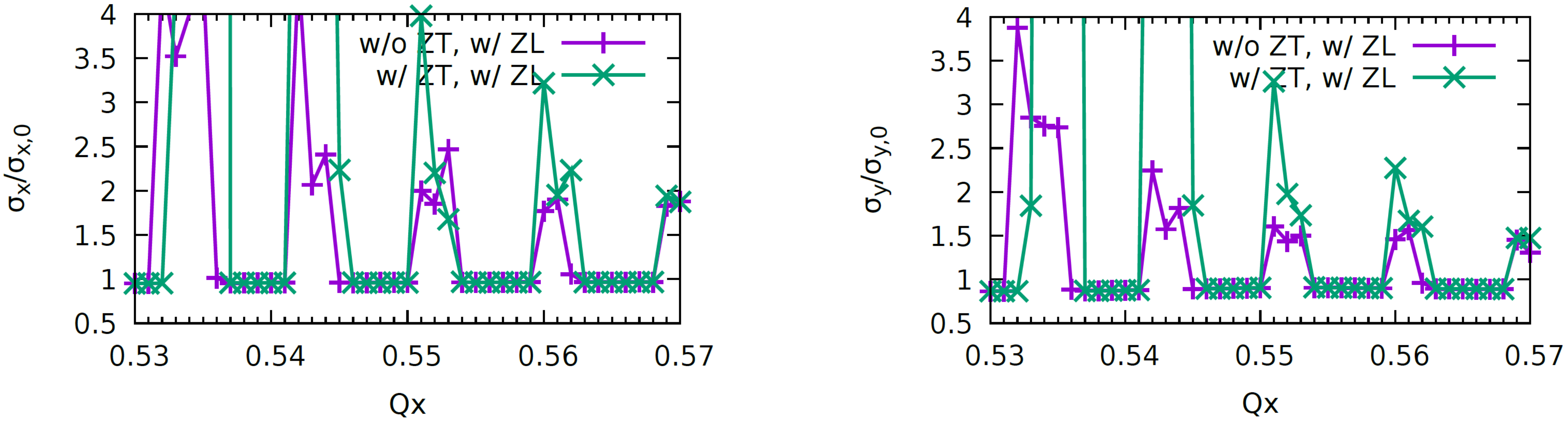


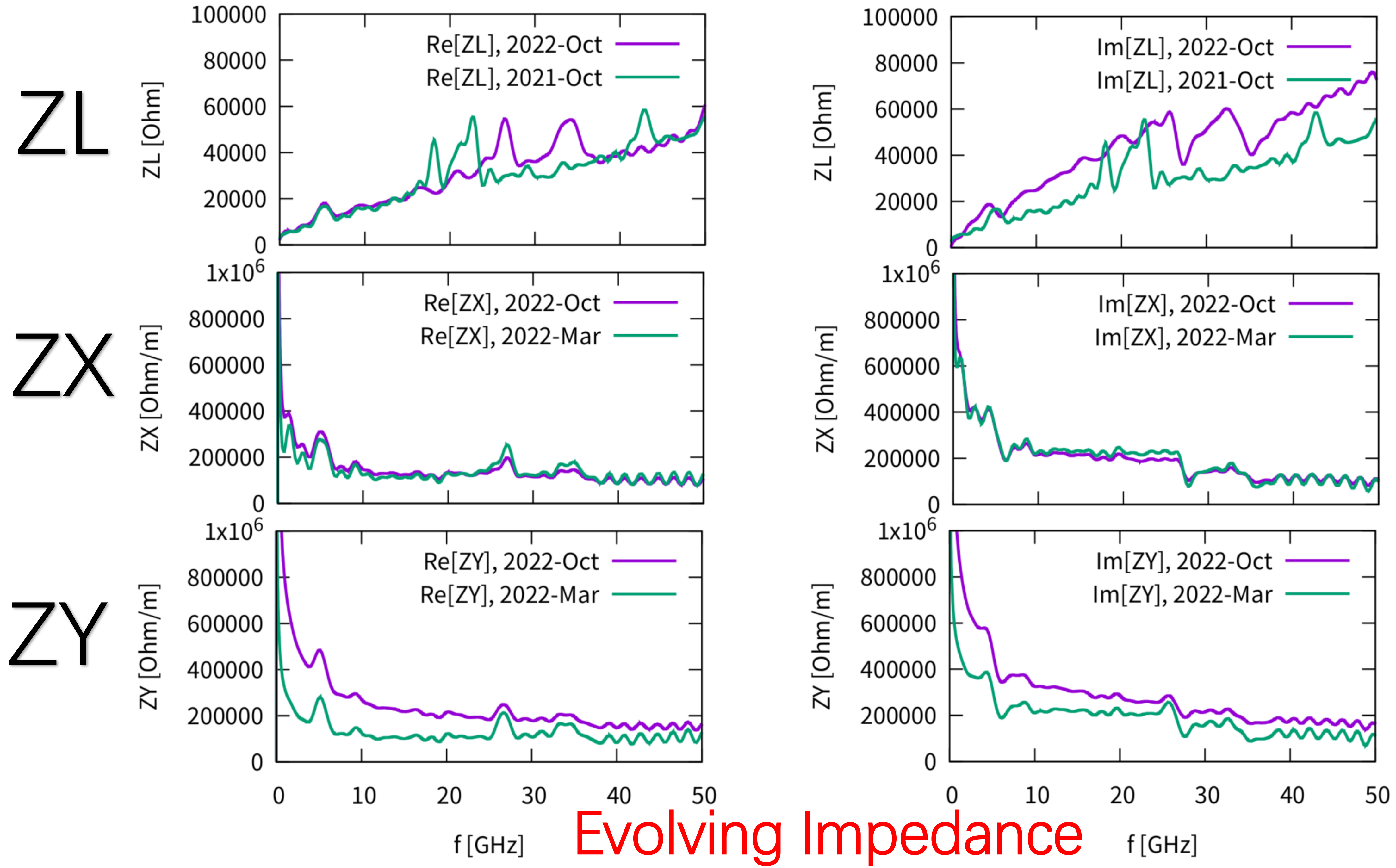
w/ ZL, π



Collision considering ZT (2022-Mar)

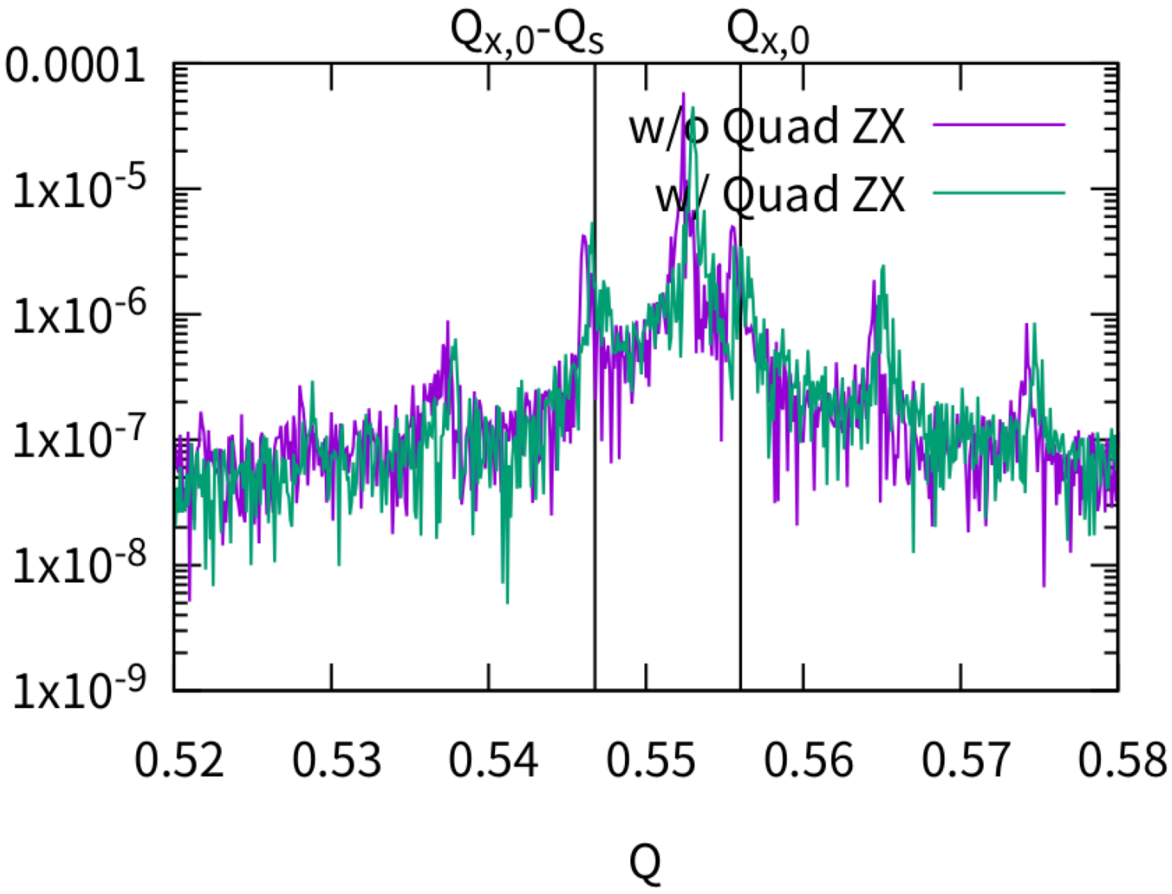
- no clear effect in stability region considering transverse impedance (2022-Mar)

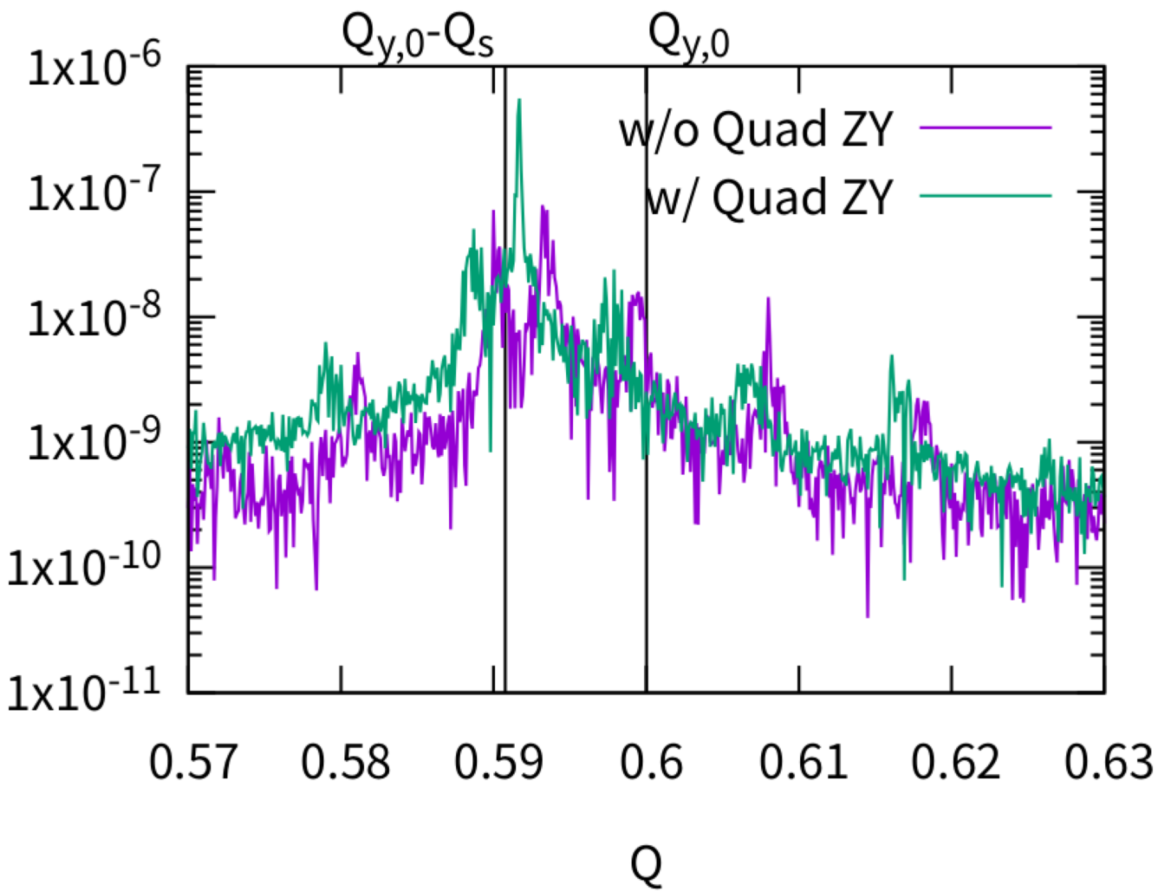




Evolving Impedance

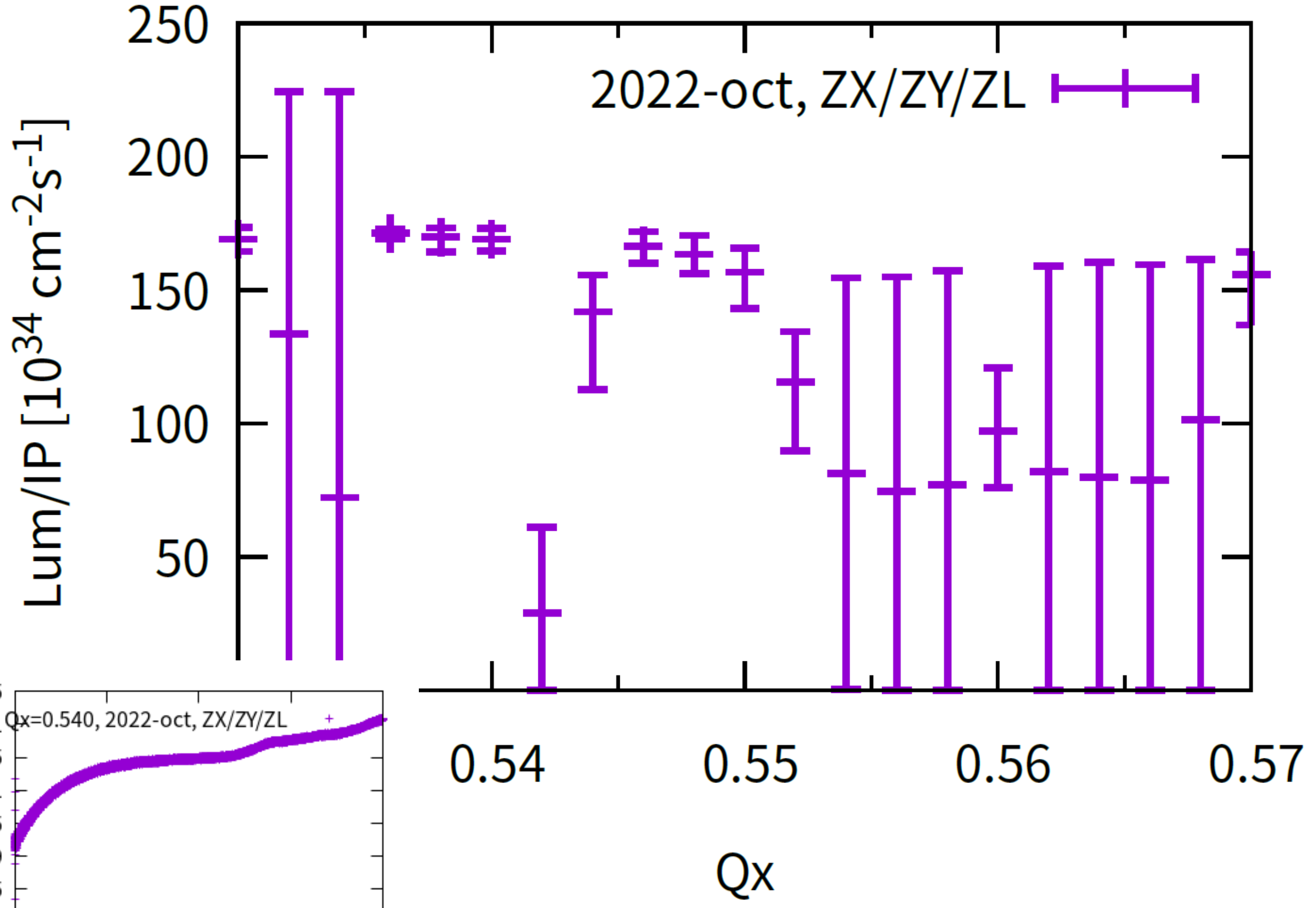
Collison off, but with Beamstrahlung Length

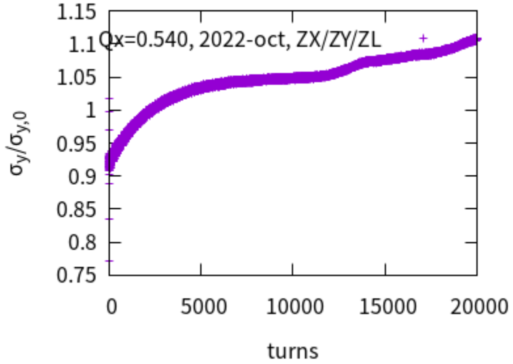


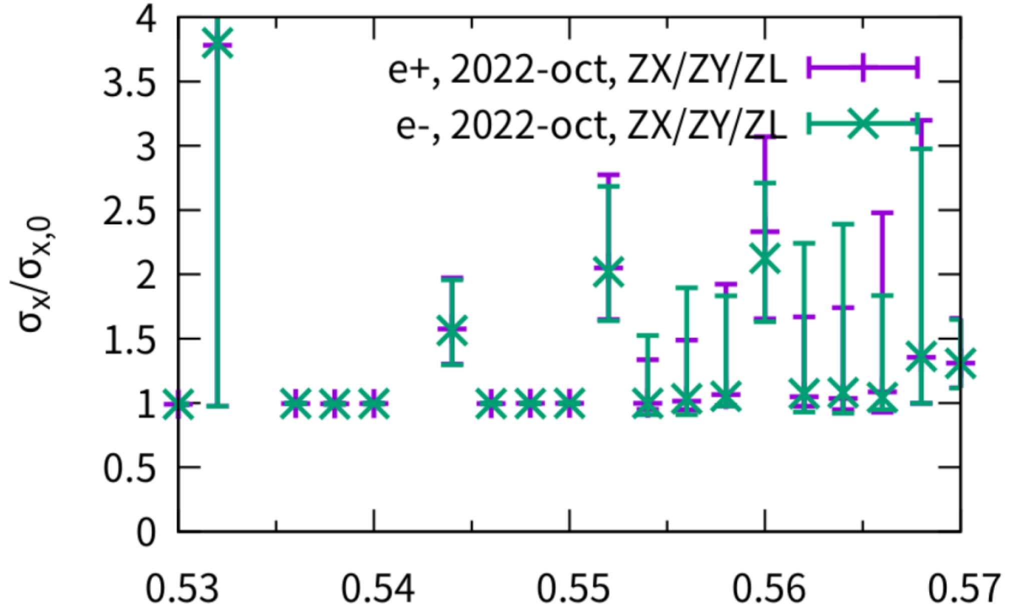


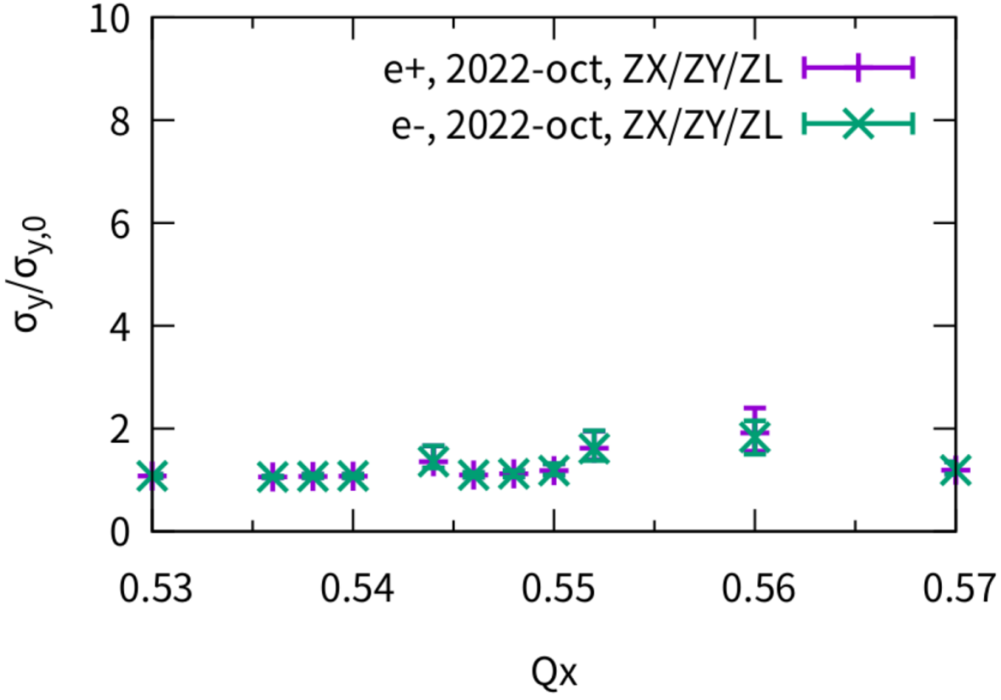
Qy=0.600

Horizontal tune scan



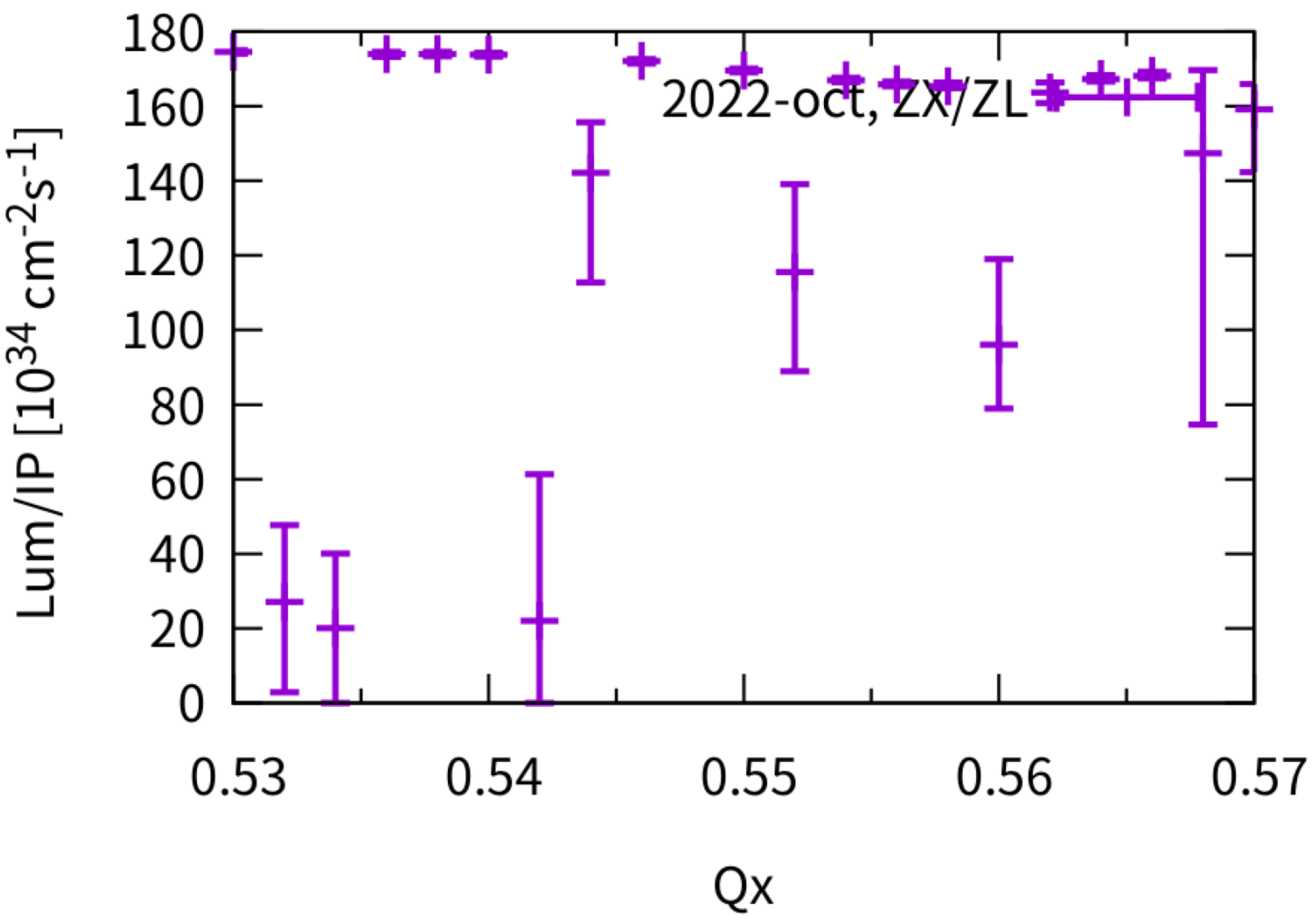


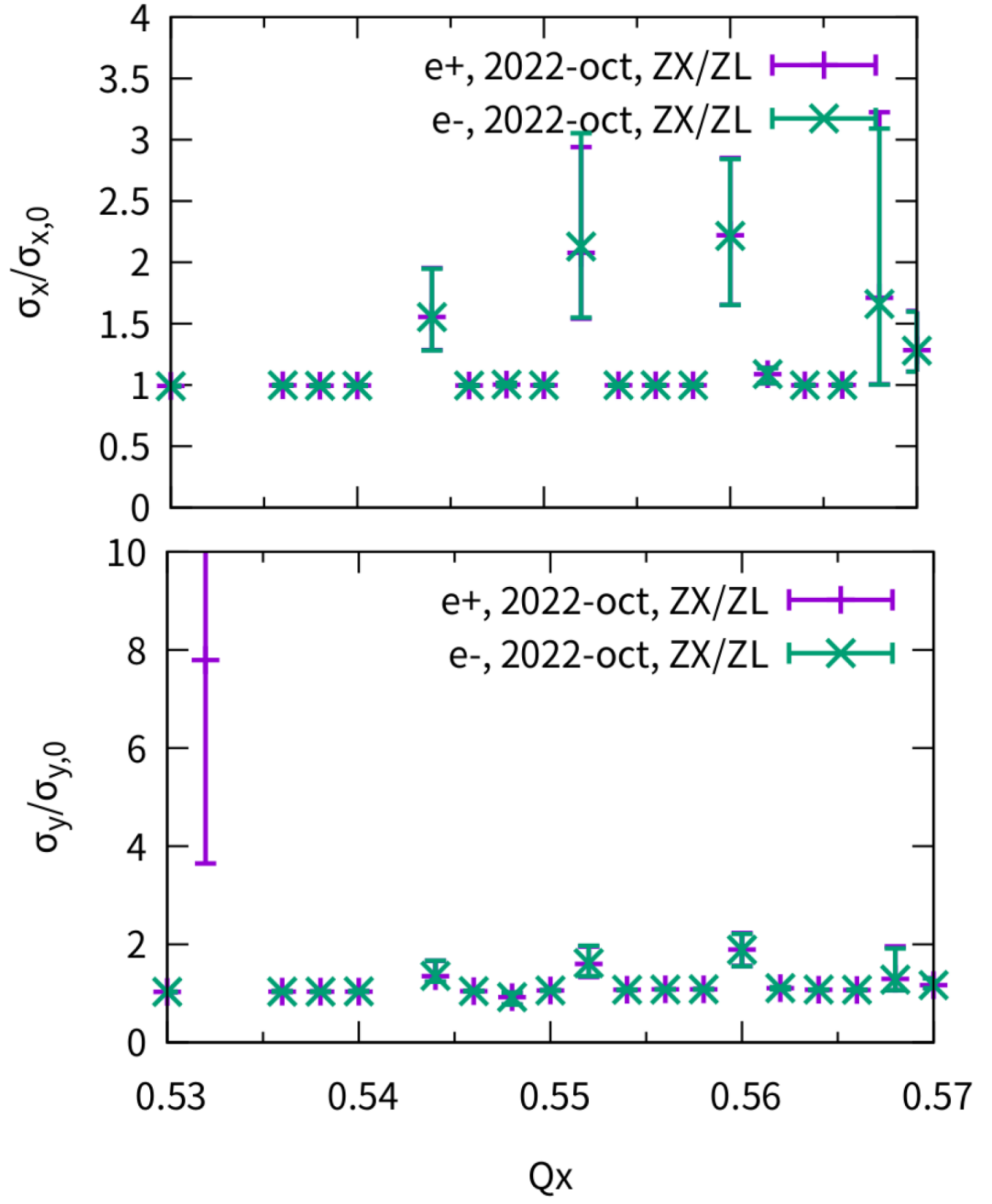




Qy=0.600

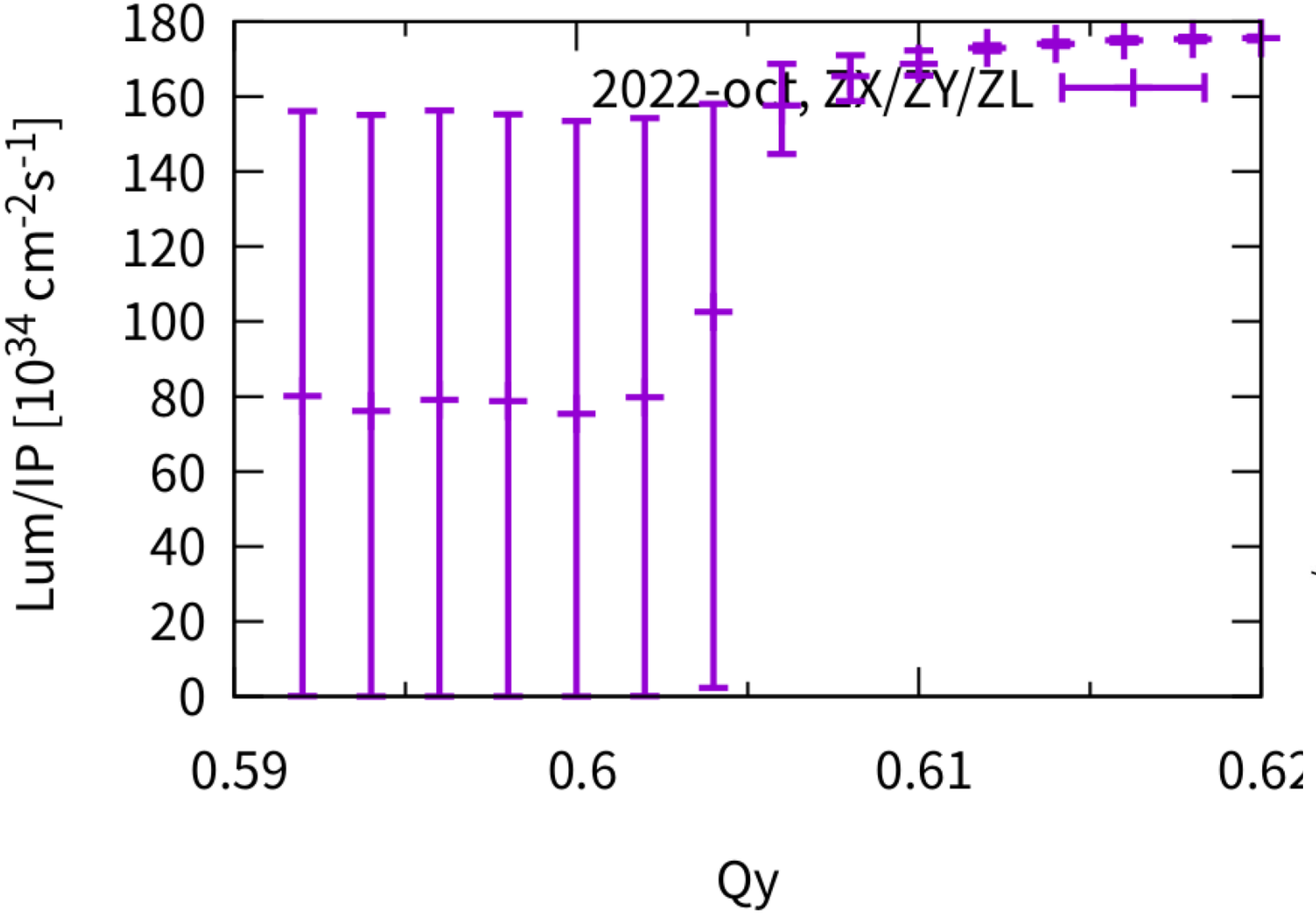
Only horizonal impedance

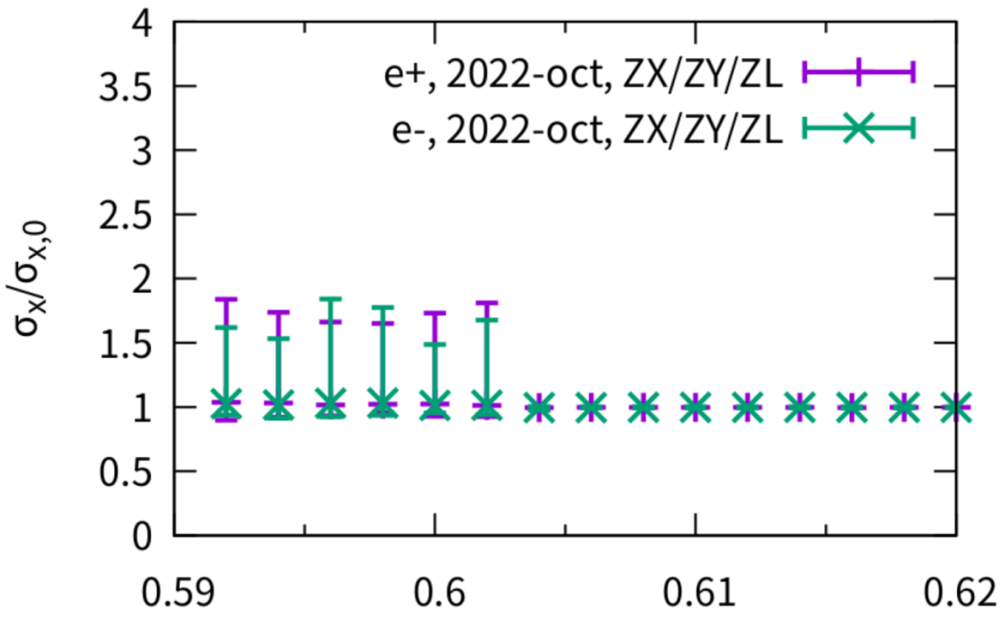


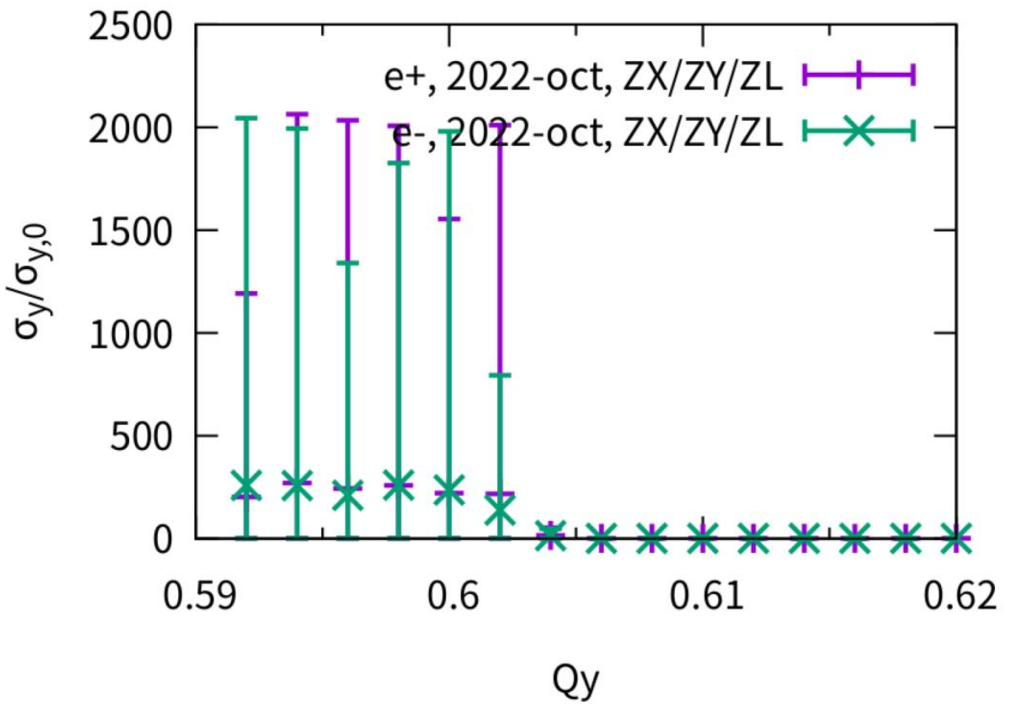


Qx=0.556

Vertical tune scan

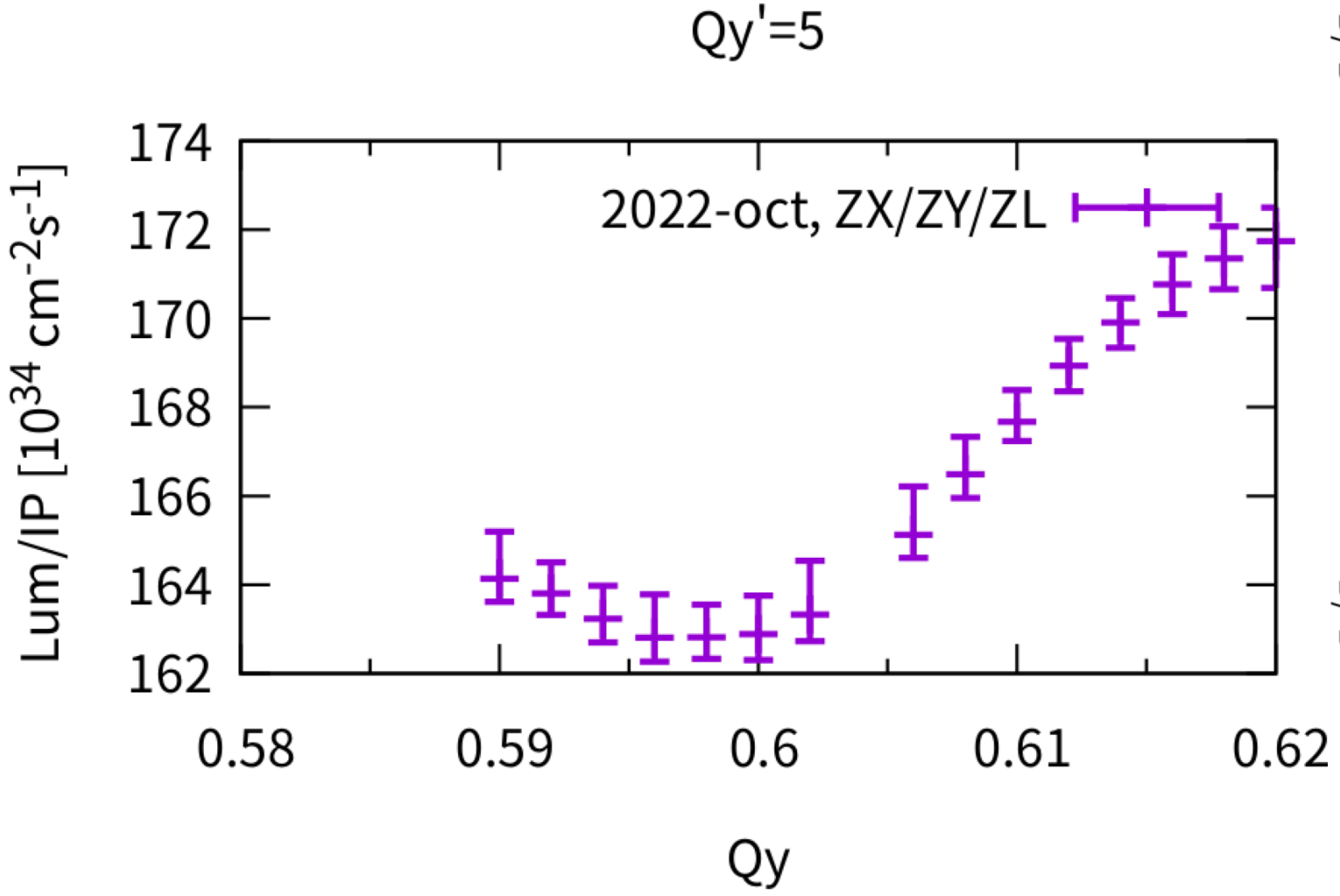


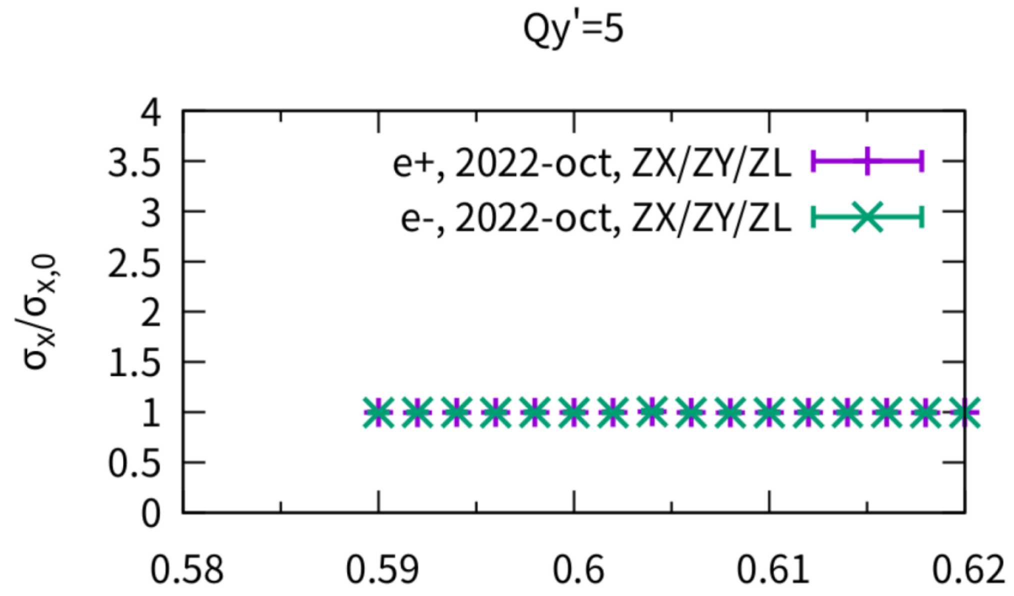


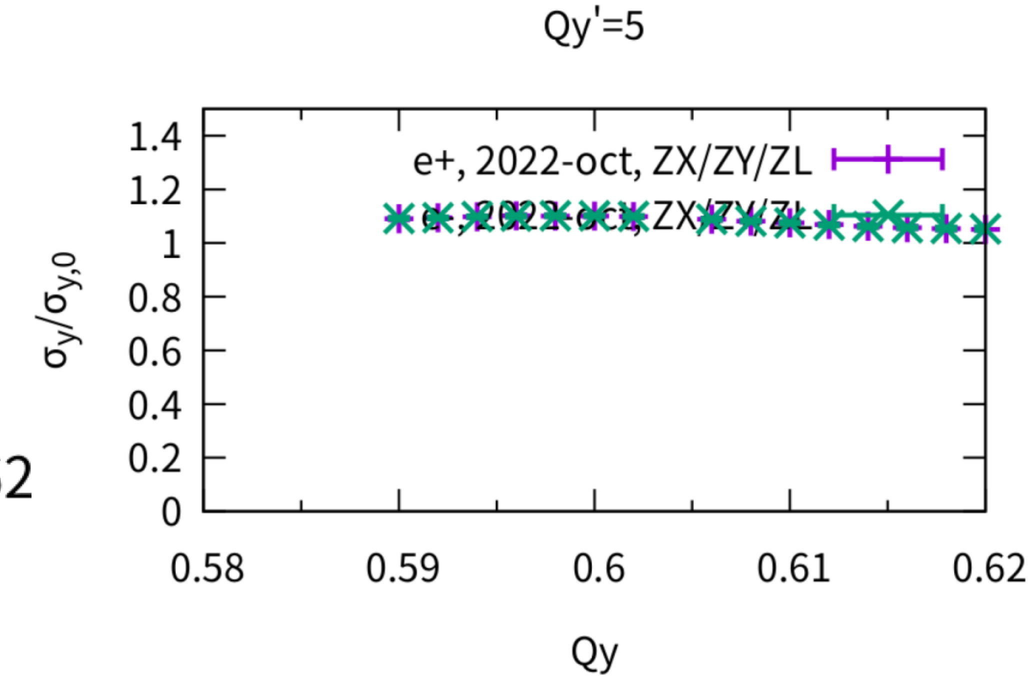


Qx=0.556

Vertical Chromaticity

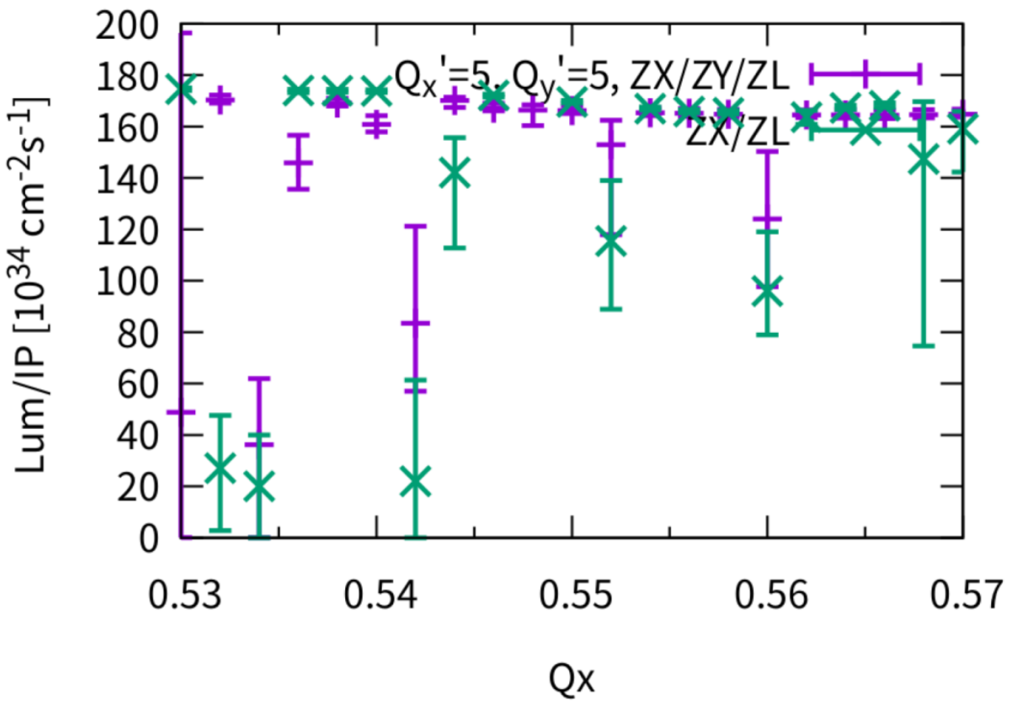


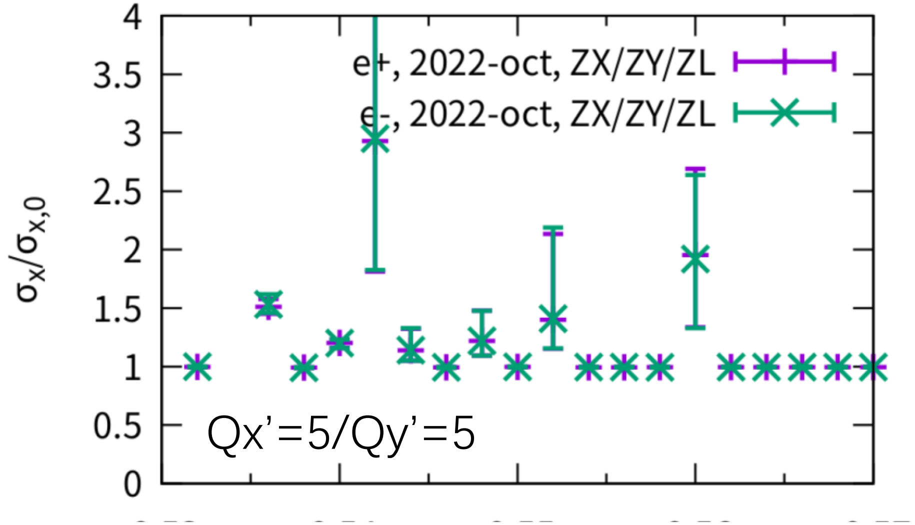


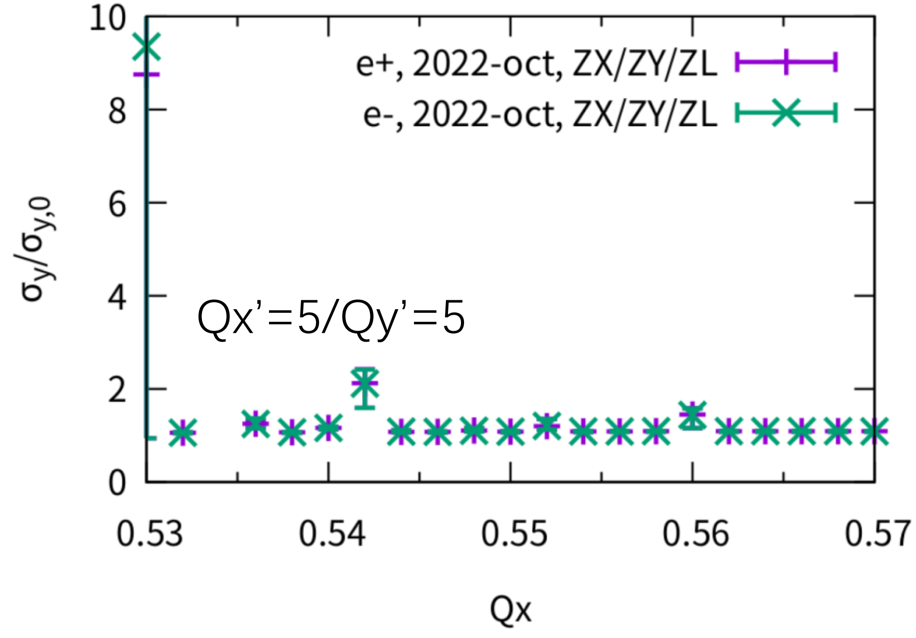


Qx'=5/Qy'=5 (Qy=0.60)

Enlarge stable tune area in （0.56-0.57)

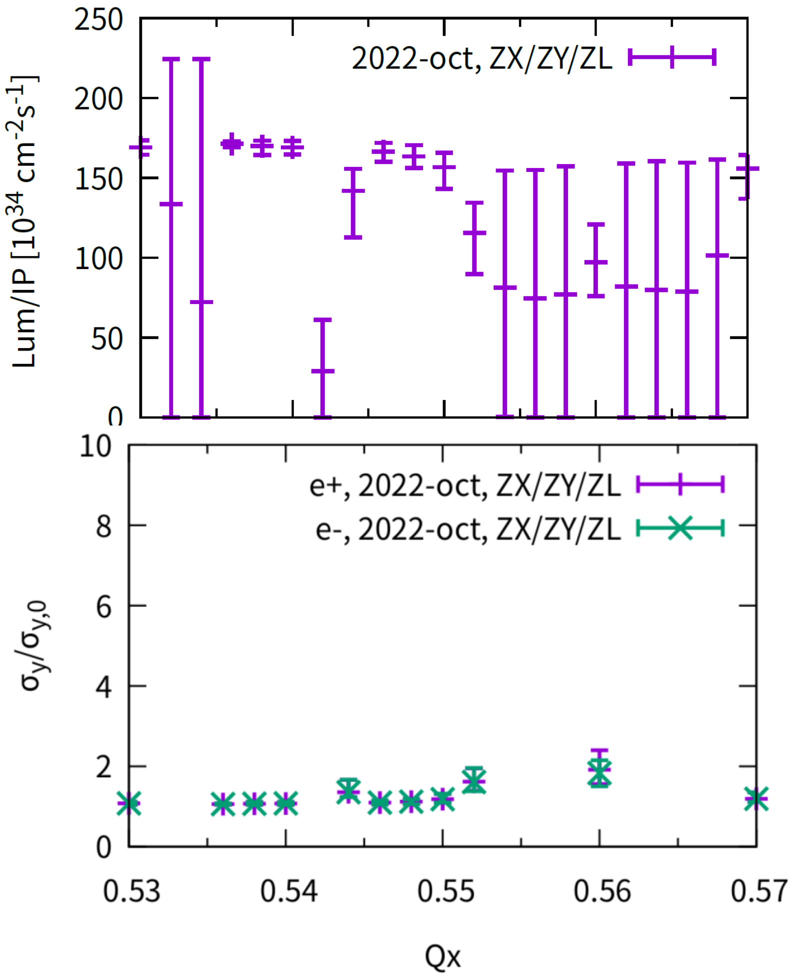




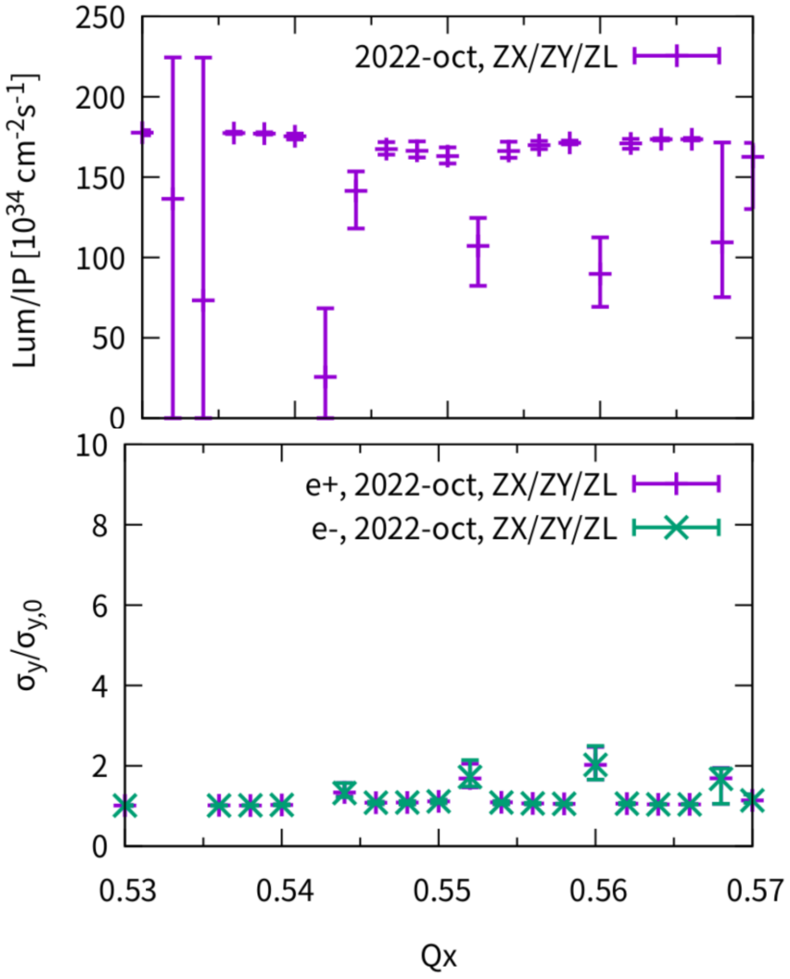


Horizontal scan at different Qy

Qy=0.60



Qy=0.61



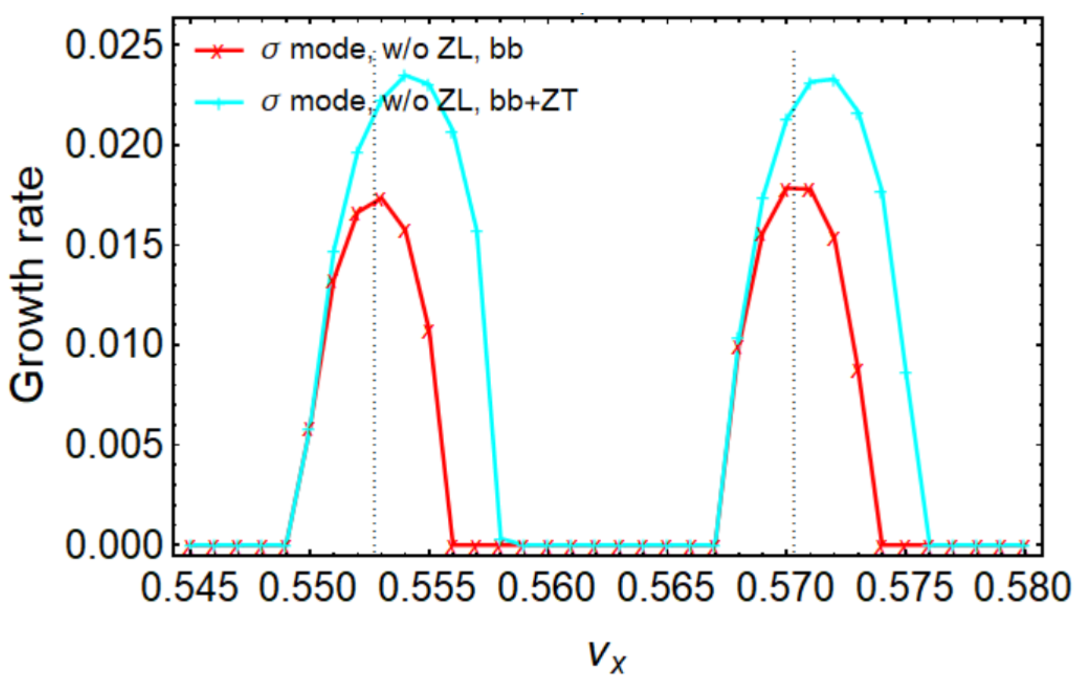
Chuntao Li and Na Wang

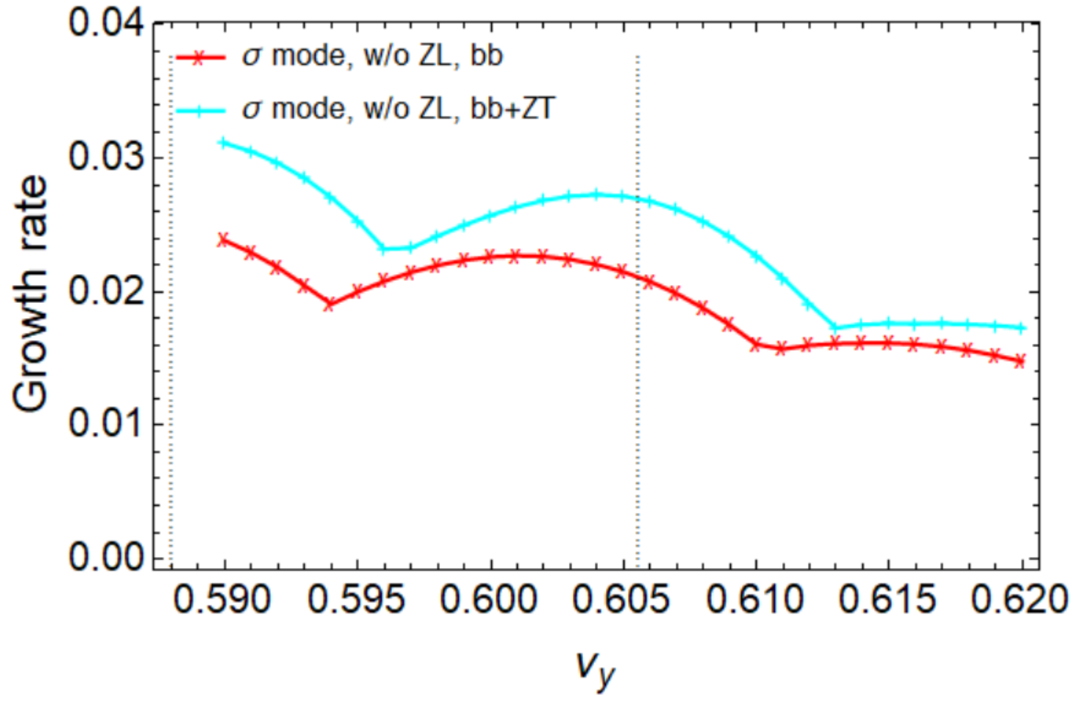
Some Analysis - Local Beam-Beam Model

- In horizontal direction, considering ZX
  - the instability growth rate is faster,
  - unstable tune area increases
- In vertical direction,
  - pure beam-beam is unstable due to ignorance of strong nonlinearity
  - It is also found enhance of instability when considering ZY

CEPC

Pi mode is not sensitive to ZT



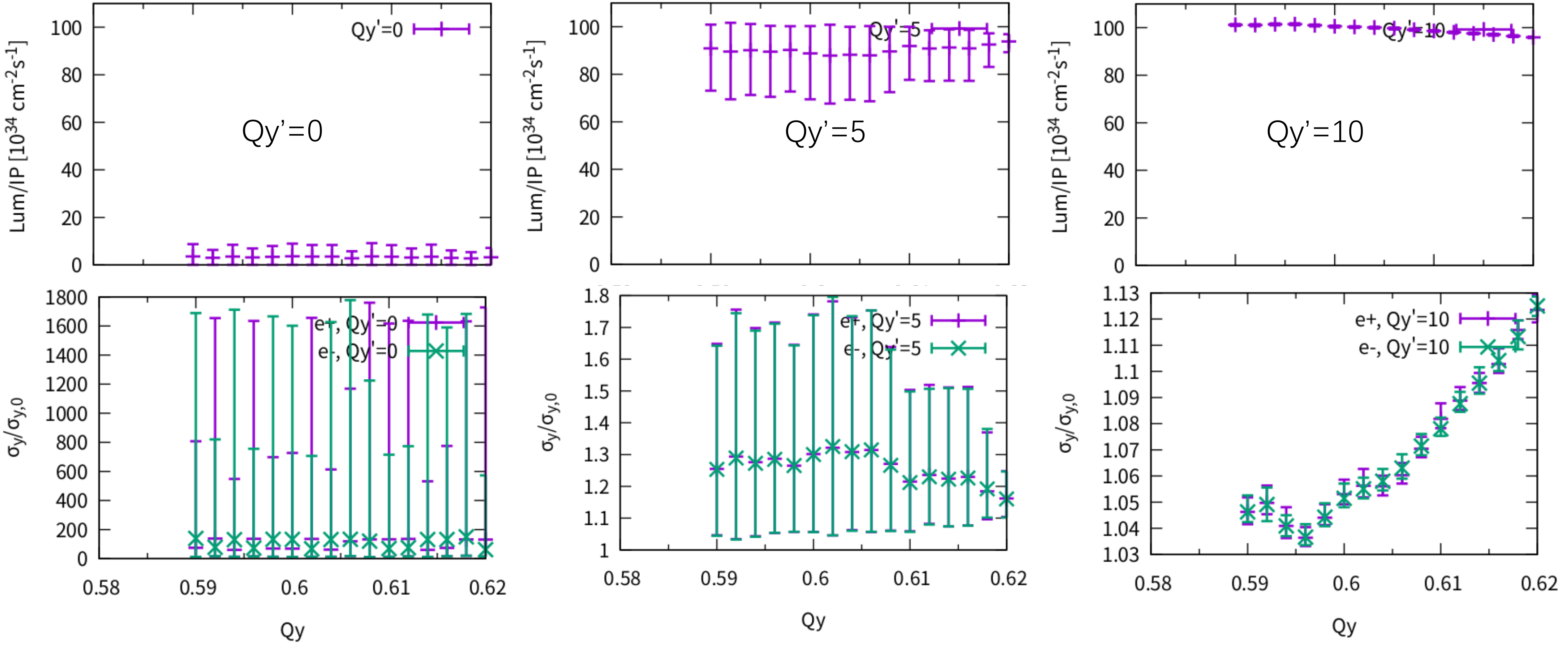


Qy'~10 could help suppress the strong TMCI-like instability induced by BB+ZT

Effect of Vertical Chromaticity (Lum & σ_y)

CEPC

ZX+ZY+ZL, Qx=0.567

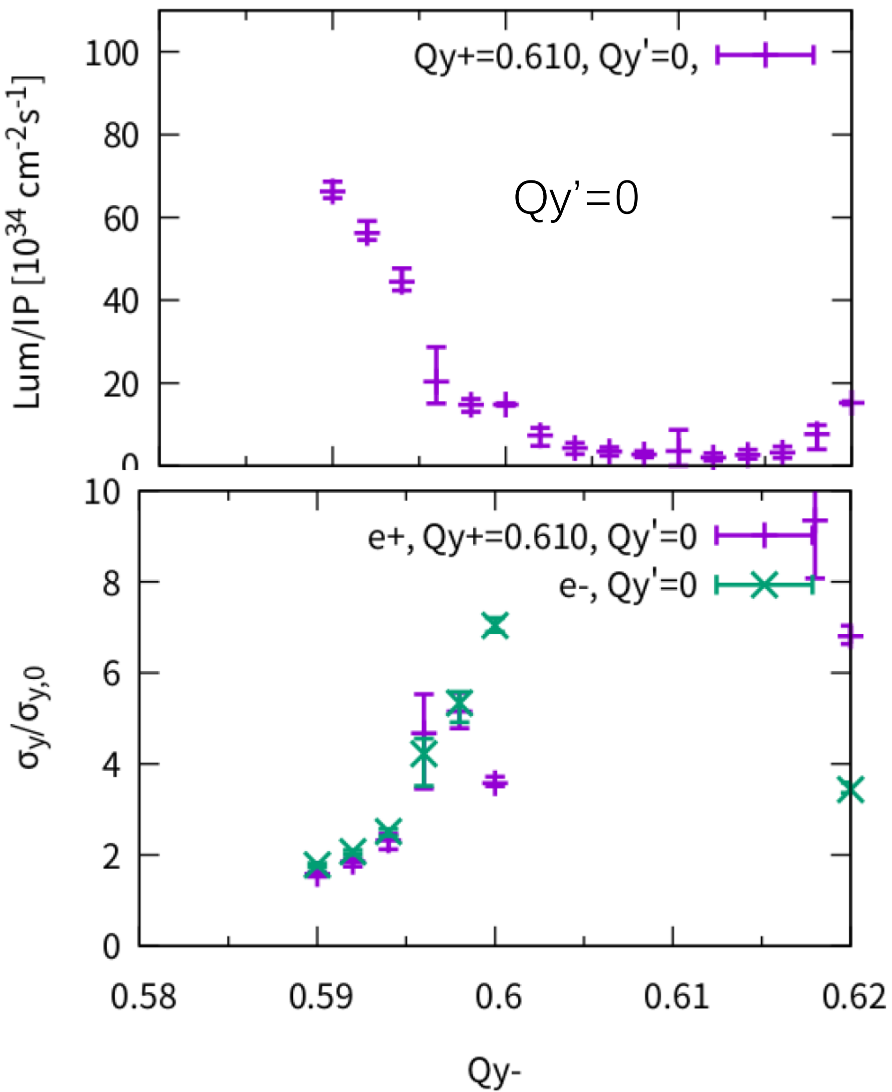


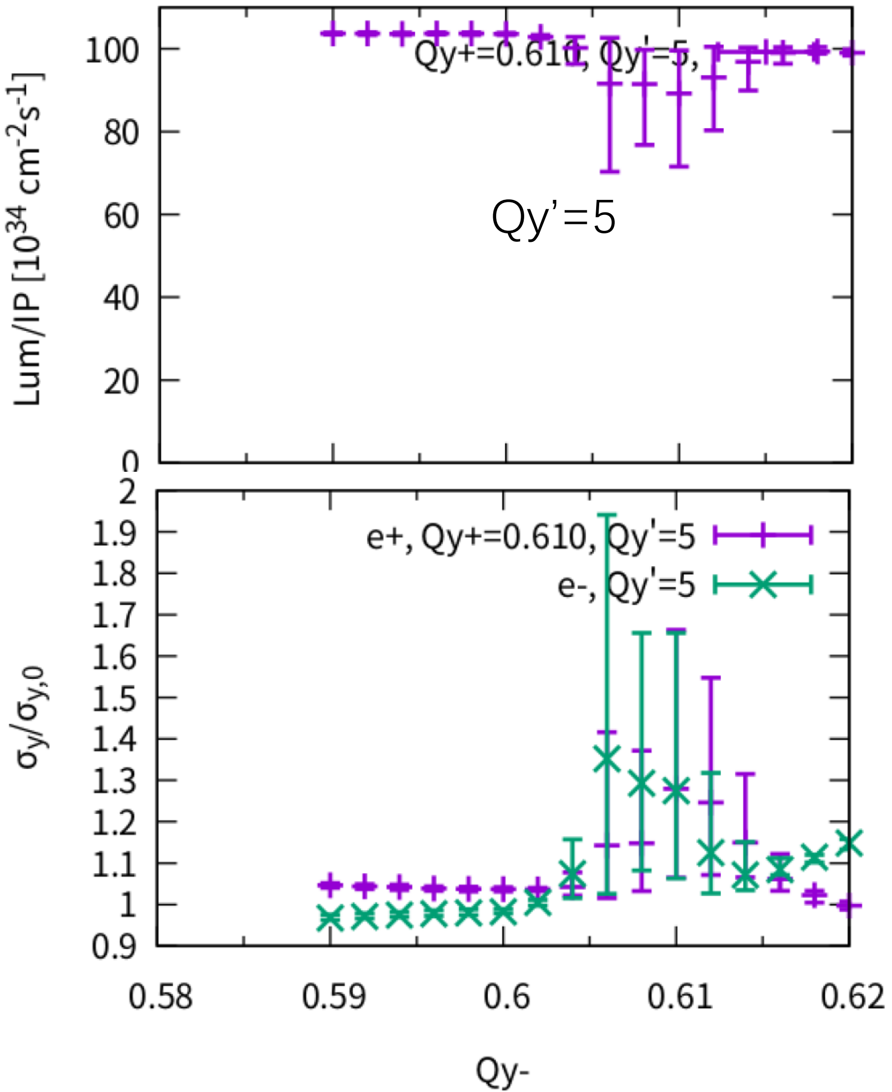
Qy Difference > 0.01 could help suppress instability with Qy'=5

Thanks: K. Oide, K. Ohmi

CEPC

Effect of different vertical tune (Qy+=0.610)

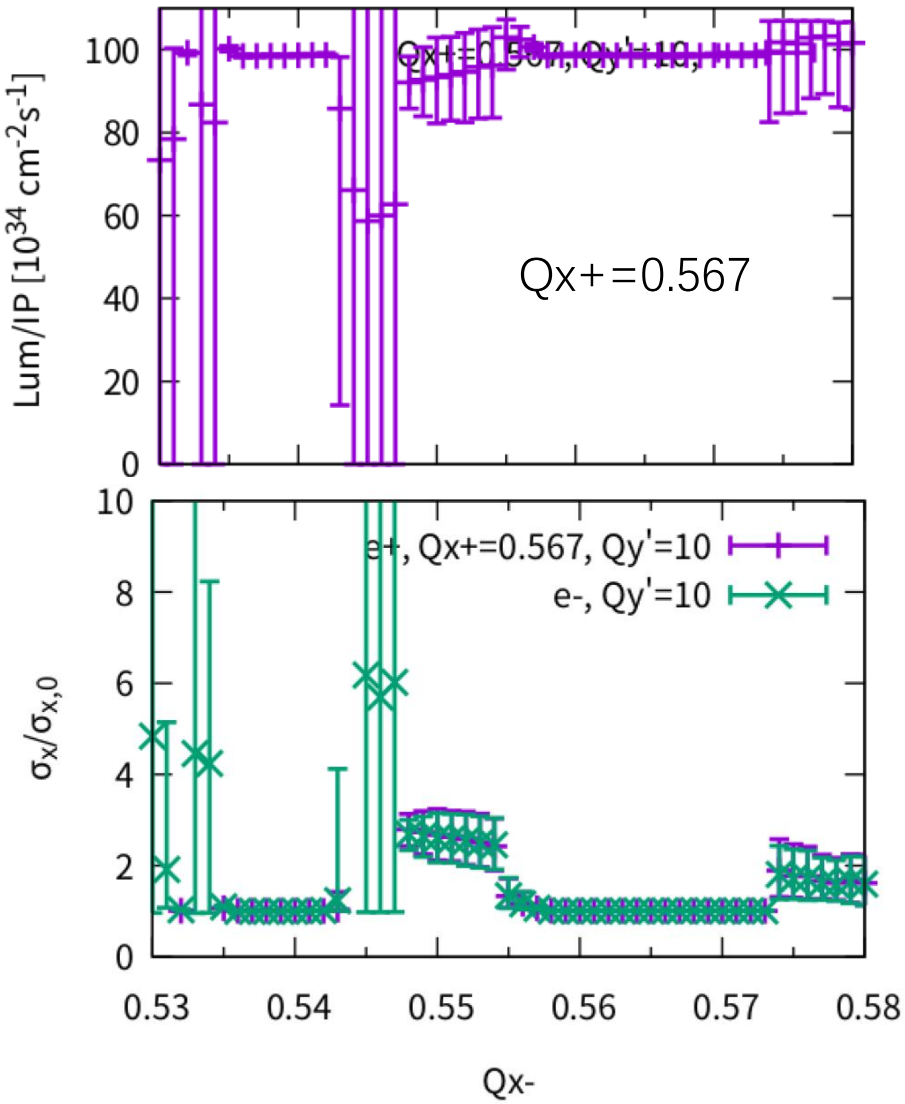




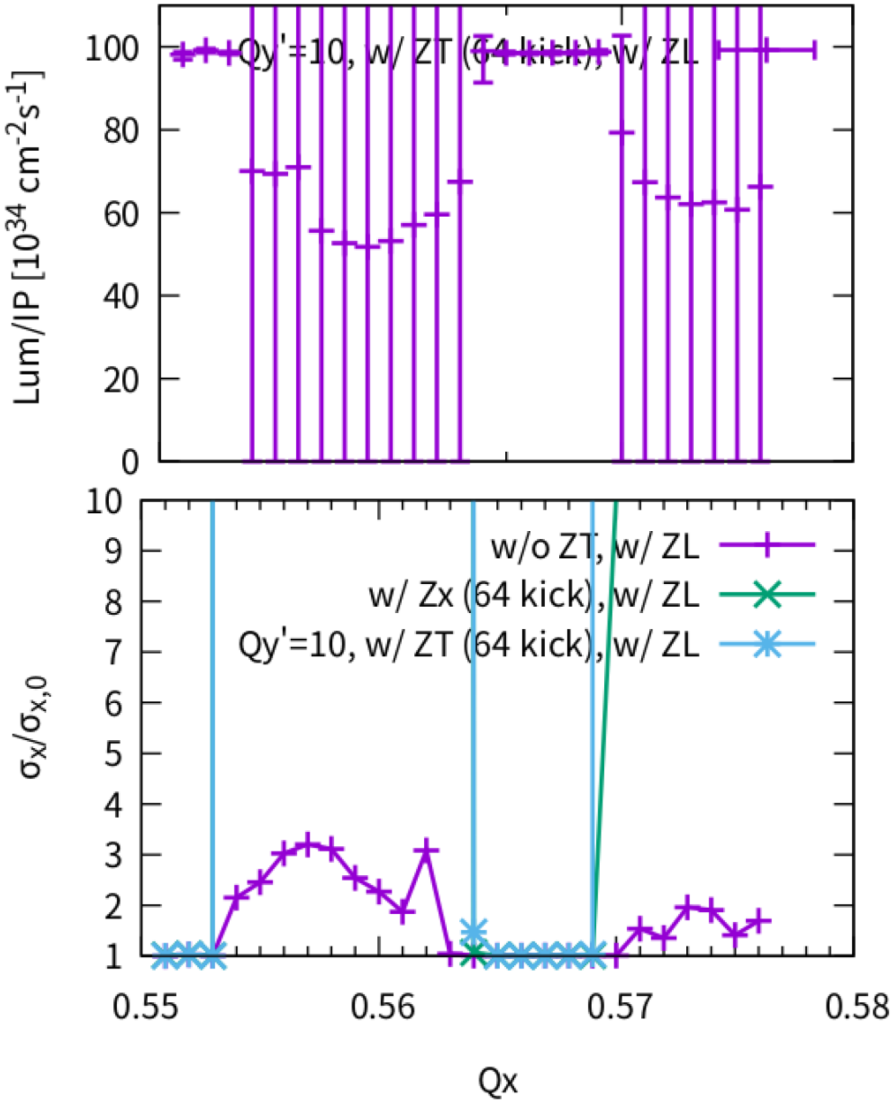
Different Horizontal tune

CEPC

Asymmetric



Symmetric



SKEKB: Machine Parameters & Impedance

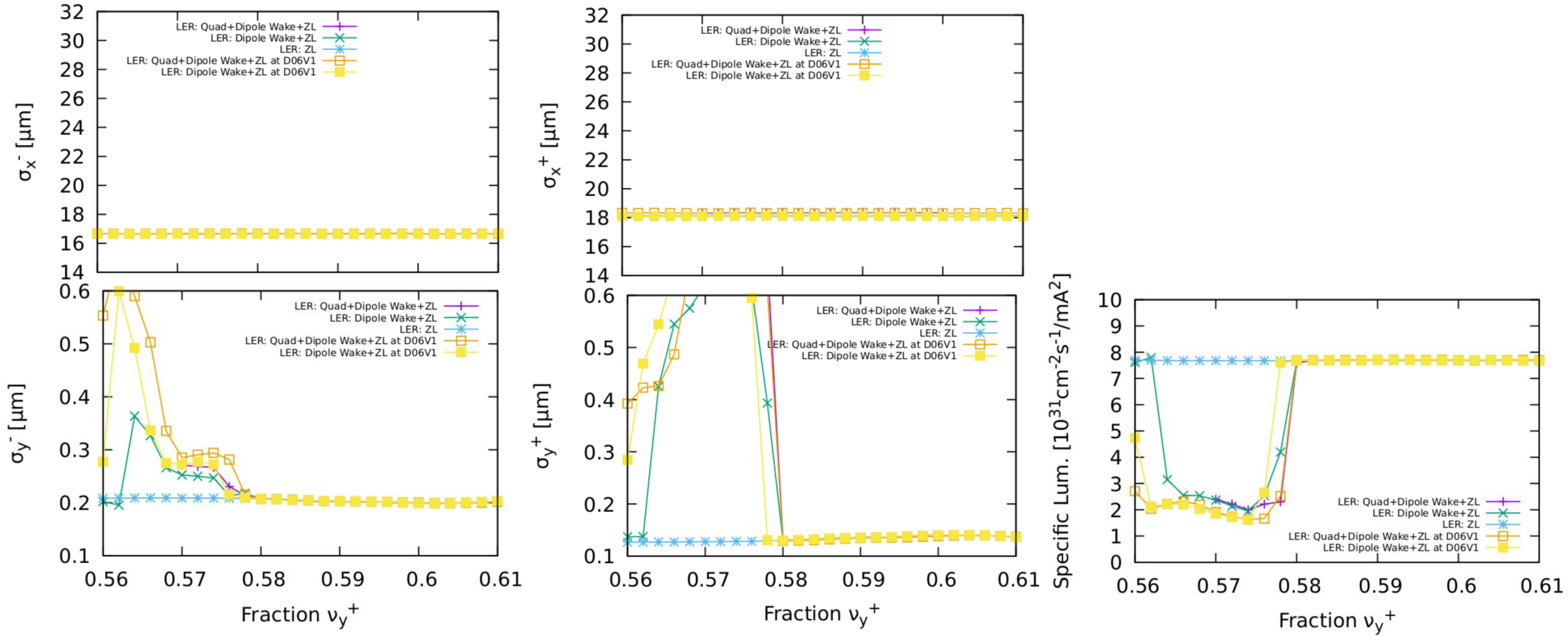
	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	
# bunch	393		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	35	20	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design

- Wake data for TMCI study of 2021.12
- CSR are not included
- **Only LER transverse wake is considered. HER transverse wake not considered.**
- The impedance instead of original wake data is used in simulation

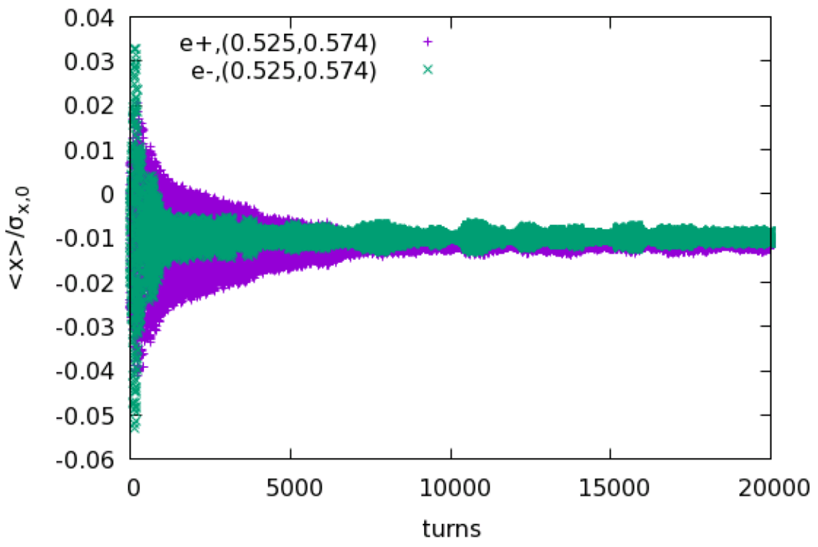
$\nu_{x,0}^{+} = 0.525$

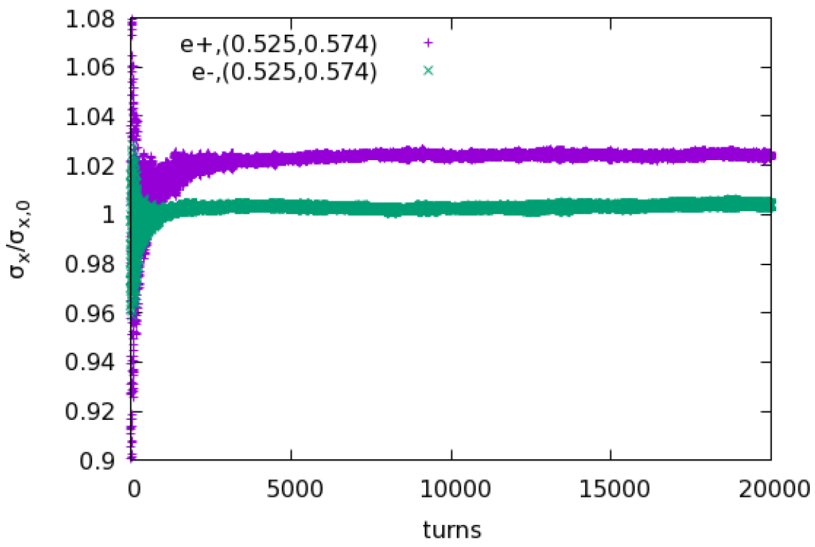
SKEKB Collision versus $\nu_{y,0}^{+}$

- There exist vertical instability when we consider transverse wake.
- It does not matter that the local transverse is put at IP or D06V1.



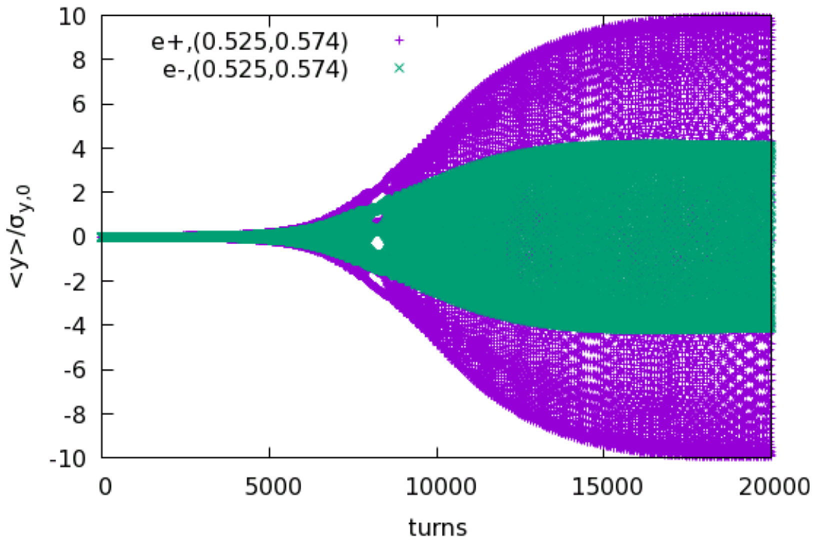
Moment evolution: LER: dipole+quad wake + ZL, HER: ZL

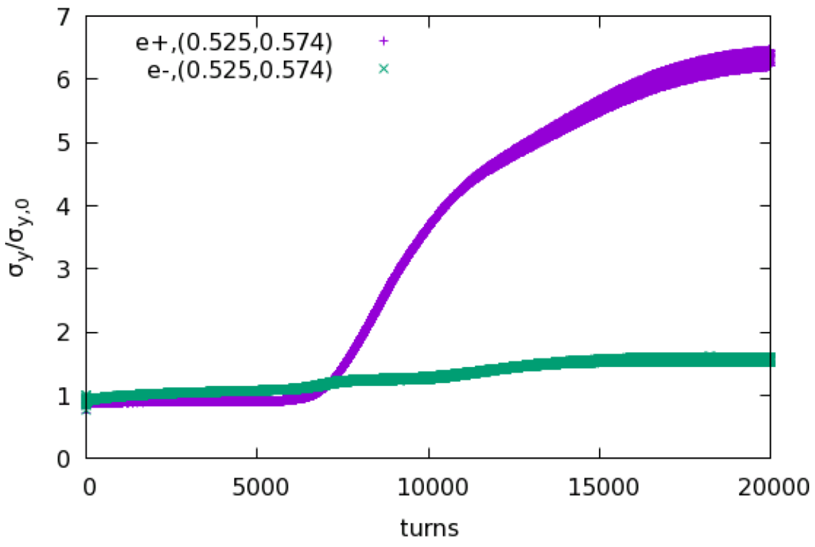


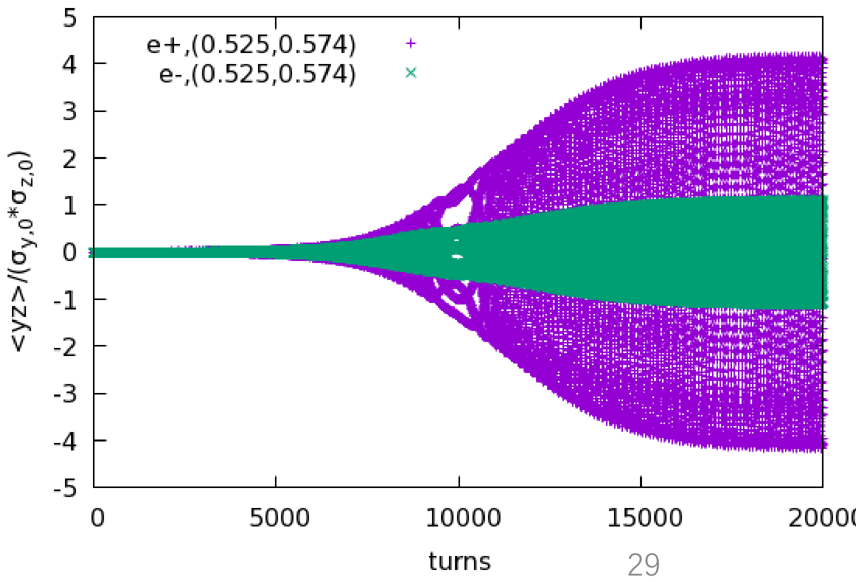


There exist:

- Vertical Dipole oscillation
- Vertical Beam Blowup
- <yz> head-tail oscillation







Summary

- The FCCee (Z) parameters is evolving, and the combined effect of beam-beam and impedance has been studied by simulation.
- The simulation results show that the present parameter could work when both ZL and ZT is considered
- Some mitigation schemes has been studied
- Some analysis work has been done to help understand the physics
- **The interplay between beam-beam and other dynamics effect must be considered in future high performance e+e- colliders**