Beam-Beam Effects at CEPC

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IAS Program on High Energy Physics (HEP 2023)

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Beam-Beam Related Issues

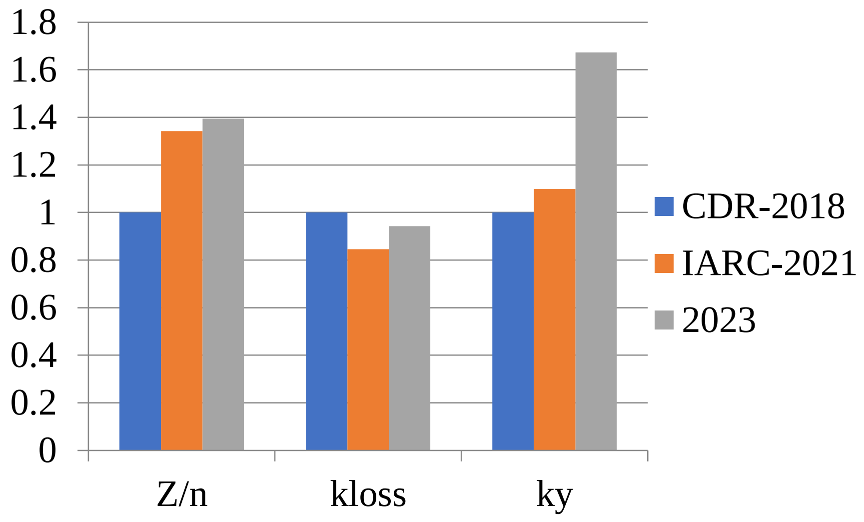
- Beamstrahlung Effect (Luminosity, Lifetime)
- Coherent head-tail instability (X-Z instability)
  - Influenced by Potential Well Distortion due to longitudinal impedance (ZL)
- TMCI-like instability in vertical(horizontal) direction with transverse impedance (ZT)
- Combined effect of Beam-Beam Interaction and realistic lattice
- …

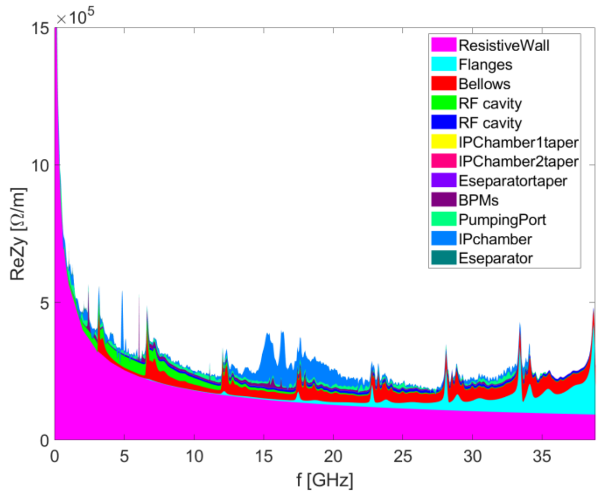
Impedance development

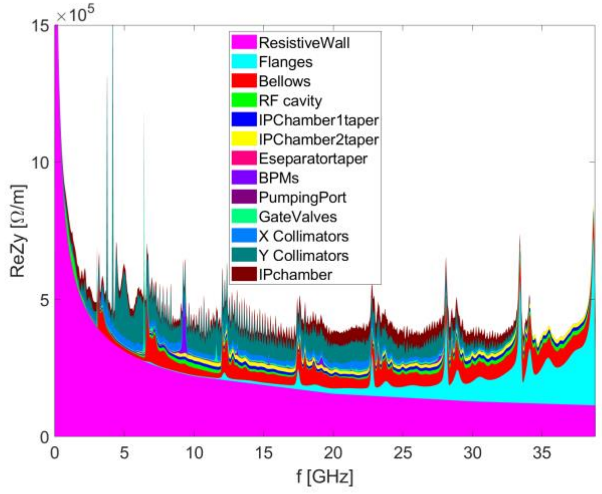
Na Wang

- Continuously updating along with the development of the hardware designs

Naturally increase with more elements included.

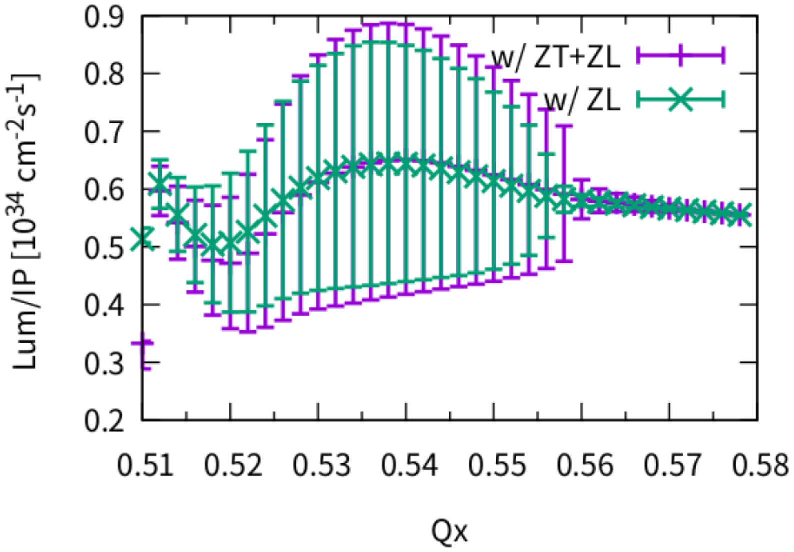


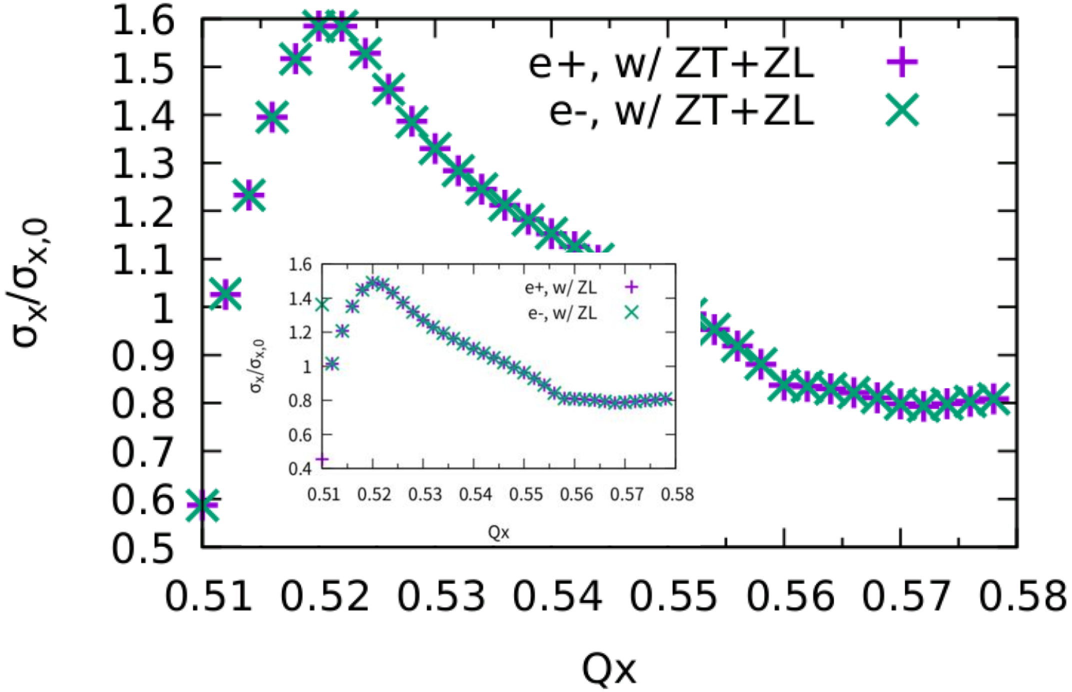


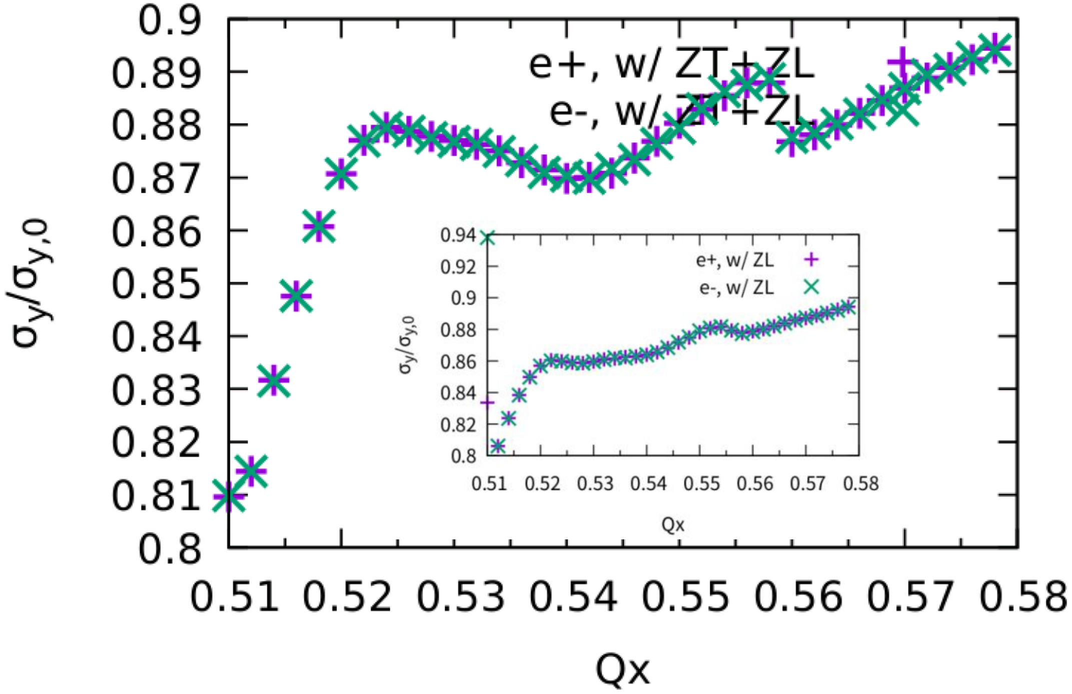


ttbar, w/ZT (2022)

No clear effect from transverse impedance.
Optimized Qx~0.570







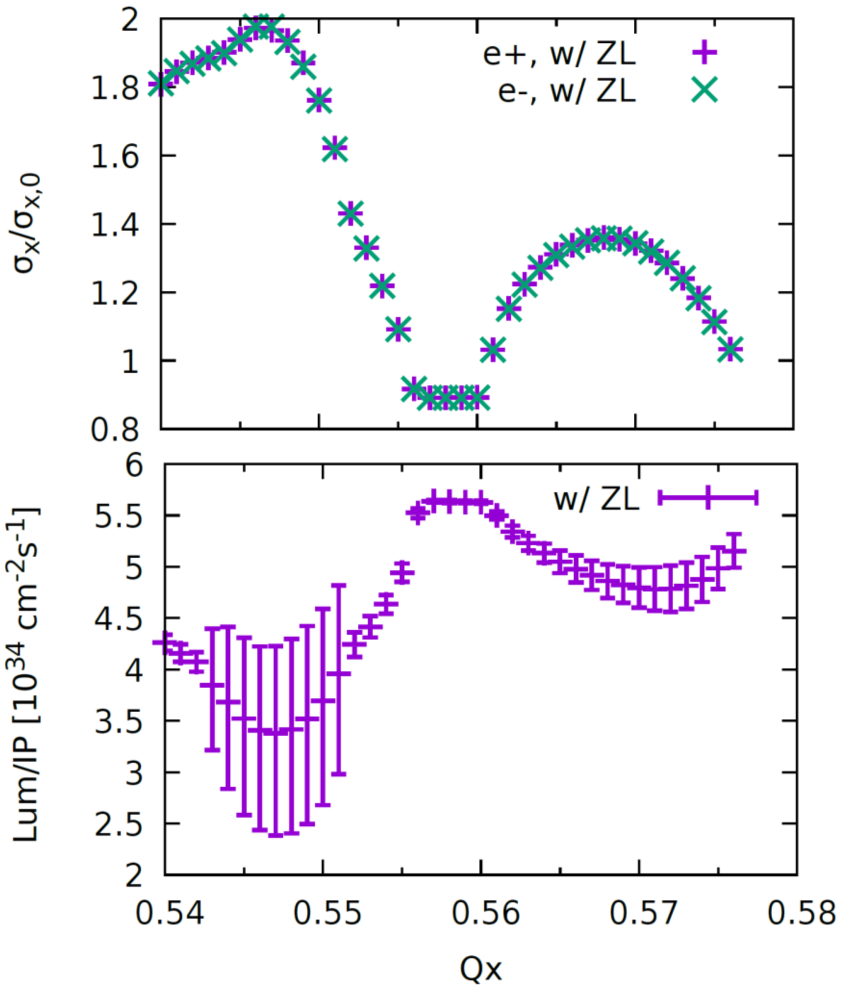
$\beta_x^* = 0.33$ m, Np = 14e10

Higgs: σ_x & Lum versus Horizontal tune

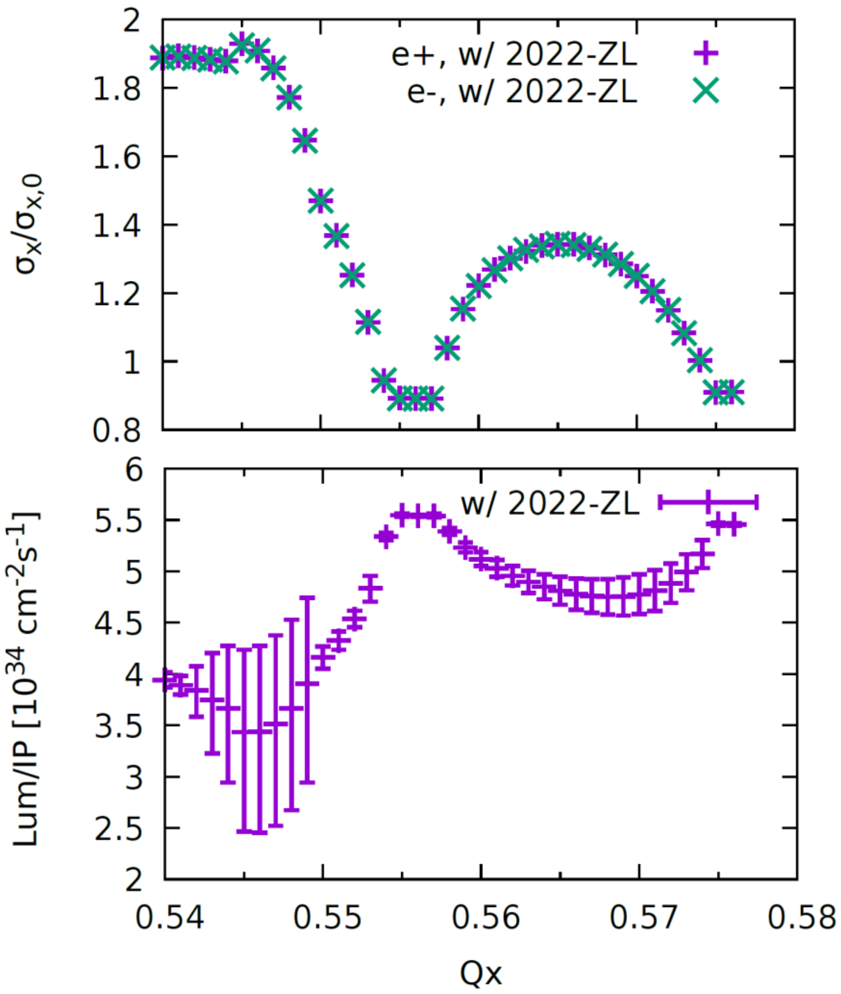
Stable tune area is too limited

Piwinski Angle: 6

CDR Impedance



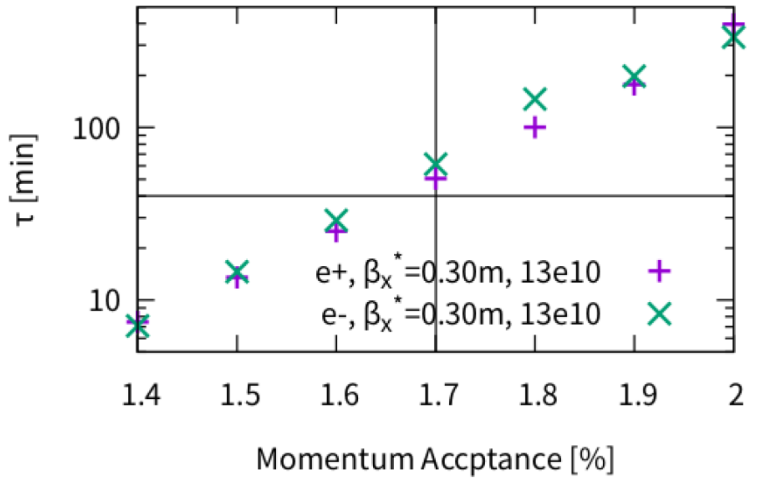
2022



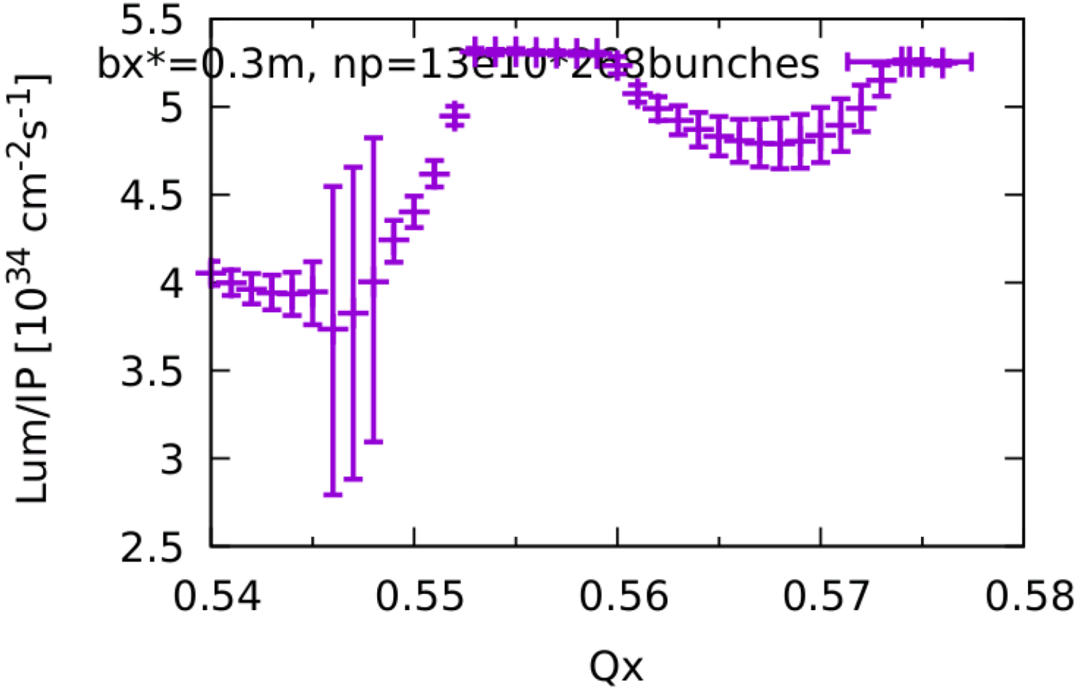
Old: β_x^* = 0.33 m, Np = 14e10

Higgs: β_x^* =0.3 m, Np=13e10

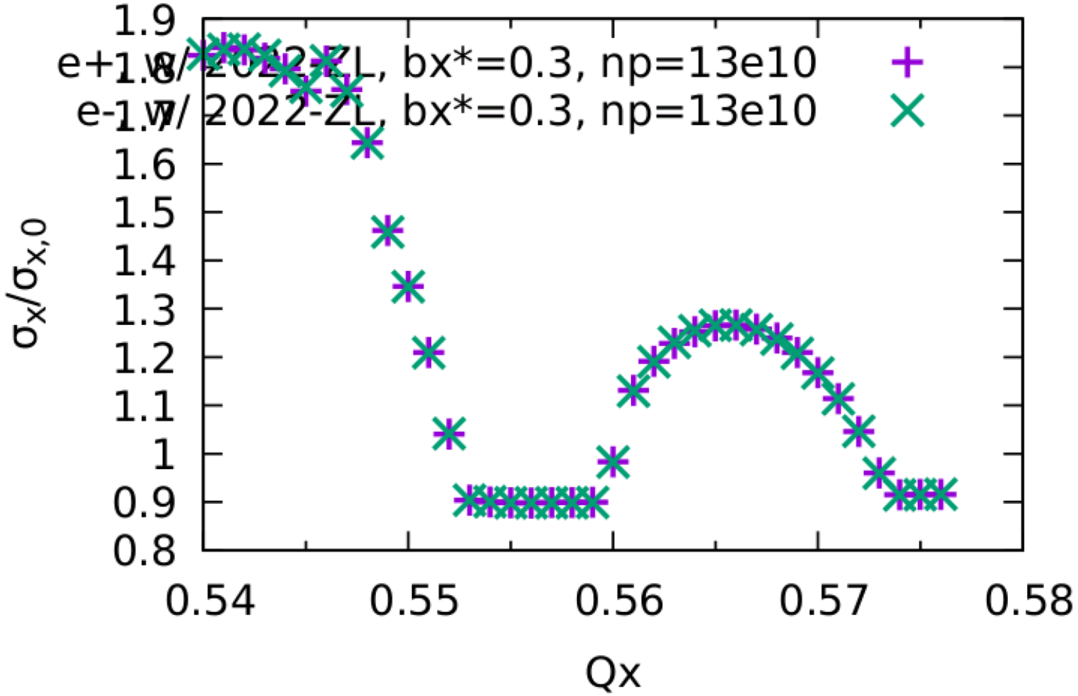
- Width of stable tune area: 0.006
- Lum ~ 5e34
- Beamstrahlung Liftime ~ 50min with MA=1.7%



Luminosity



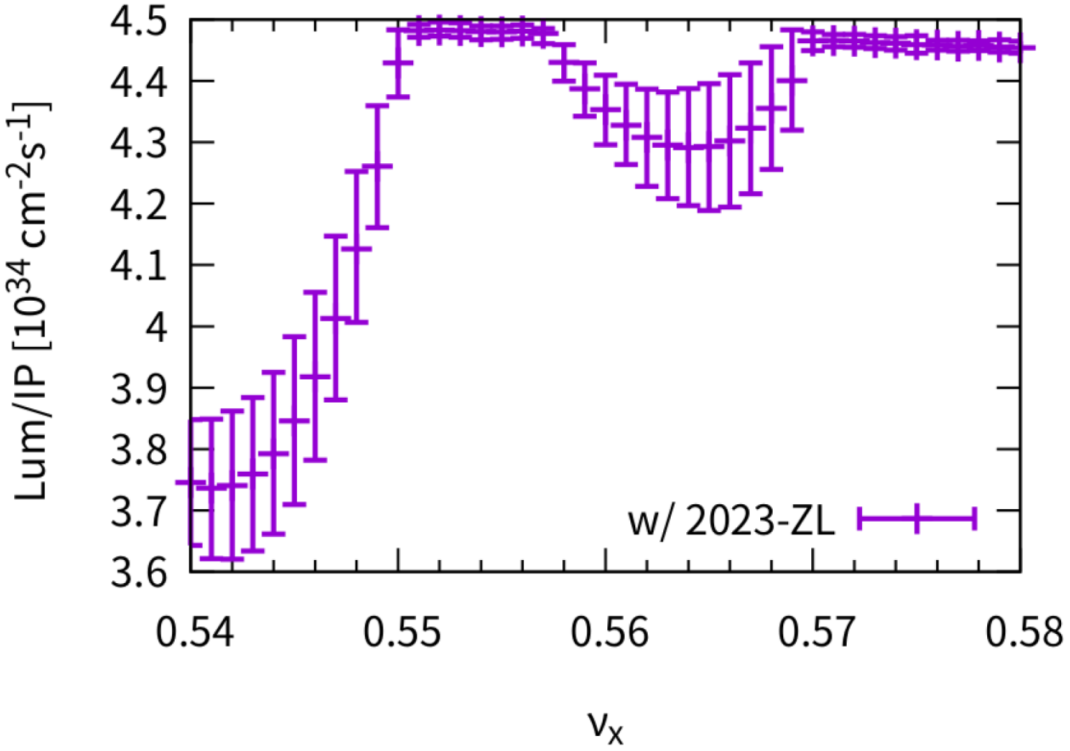
σ_x versus Horizontal tune

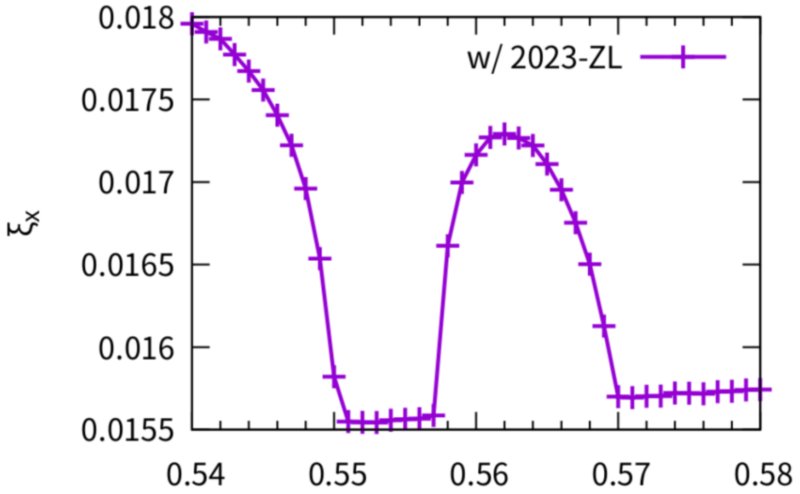


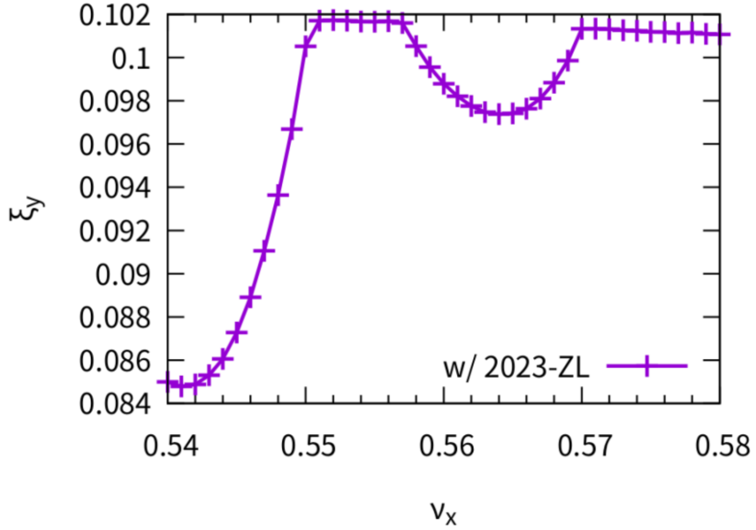
Higgs: 2023-ZL

smooth approximation instead of local RF cavity

- No qualitive difference from 2022-ZL

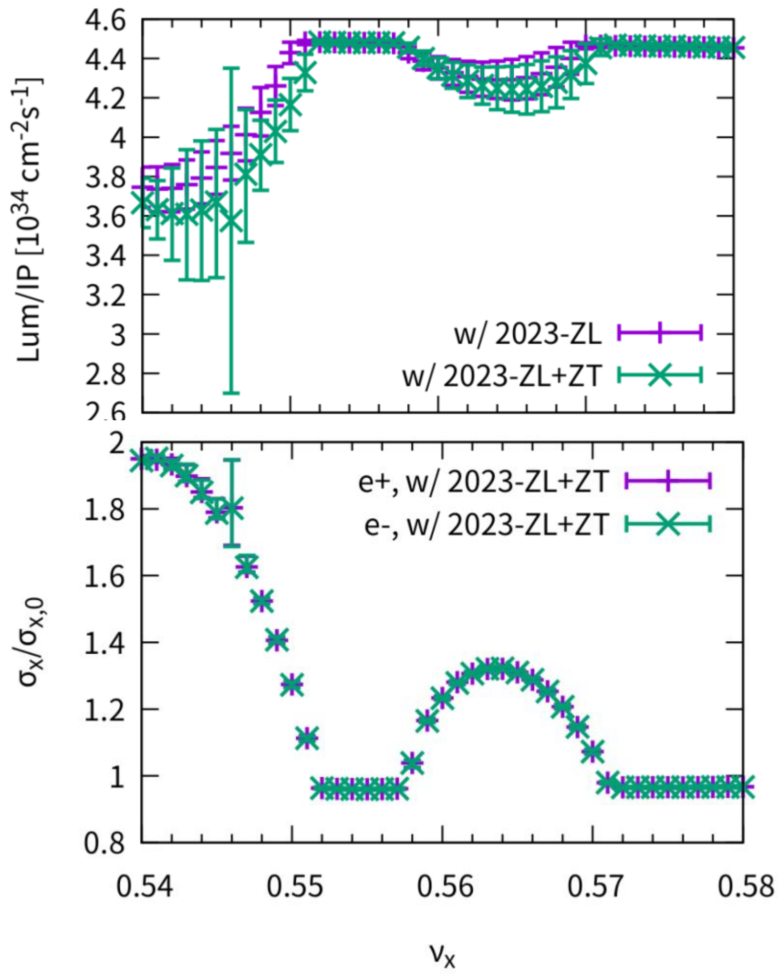


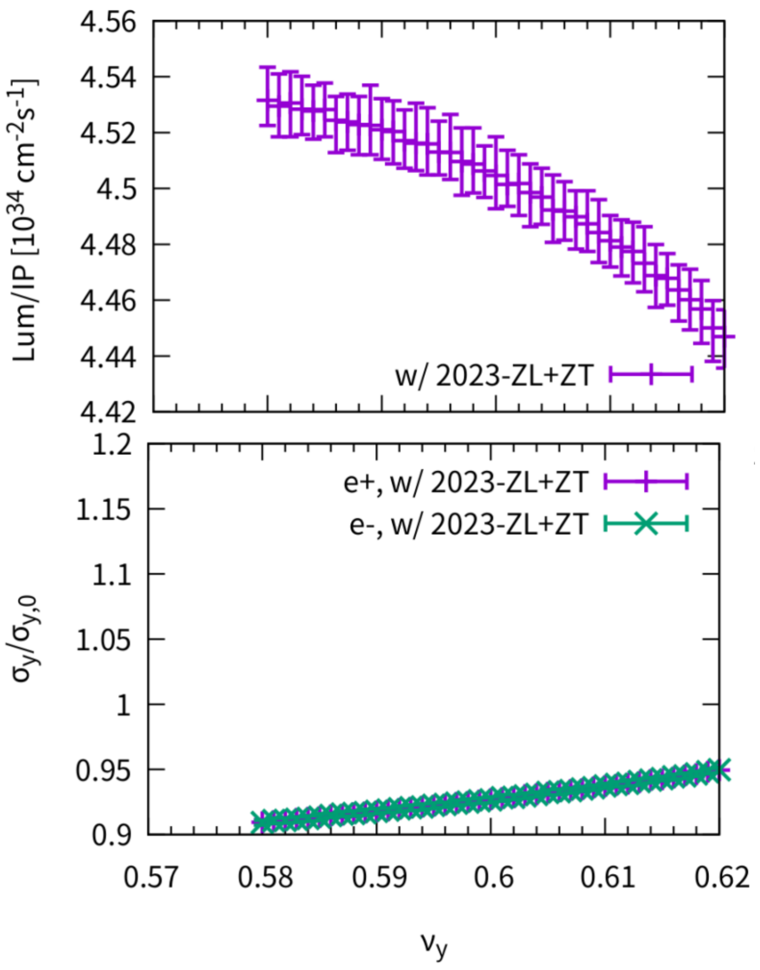




Higgs: 2023-ZT

- Tune scan in both horizontal and vertical direction
- Transverse impedance does not bring clear effect for collision





Realistic lattice w/o beam-beam

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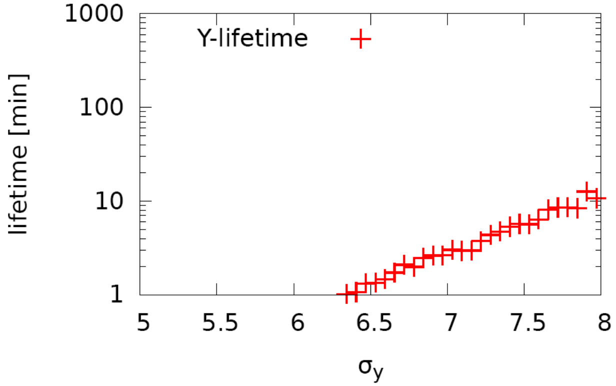
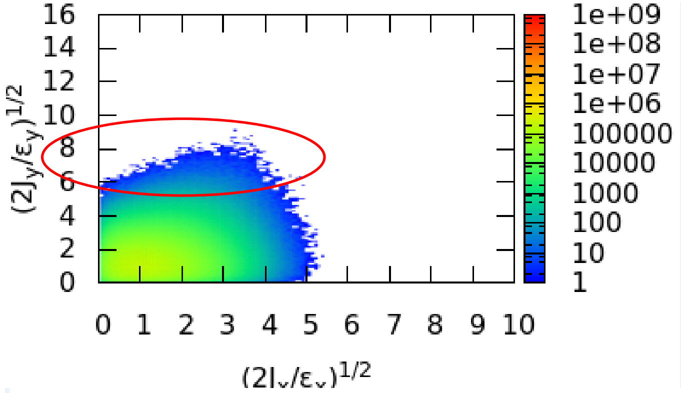
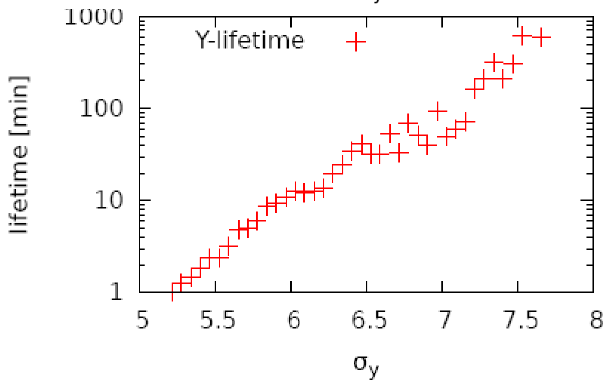
Higgs: Lifetime and equilibrium distribtuion

- 50k turns
- w/o beambeam

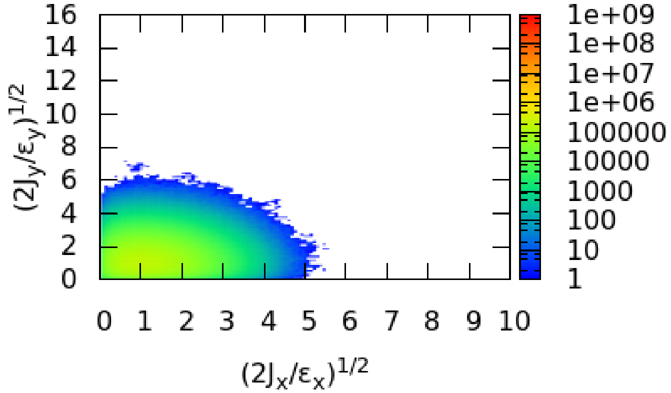


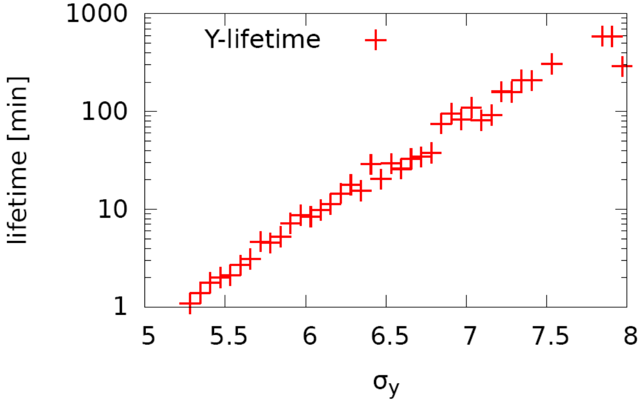
@IP



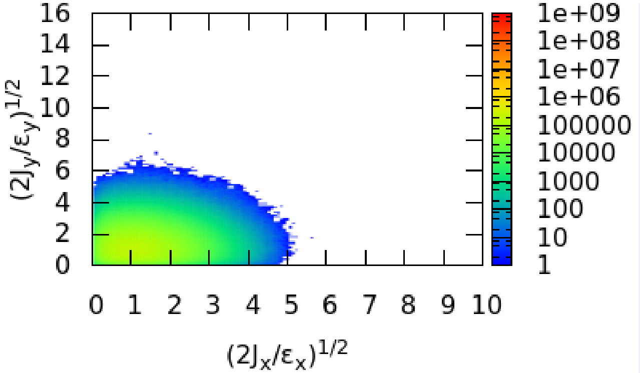


@Injection point





@RF section



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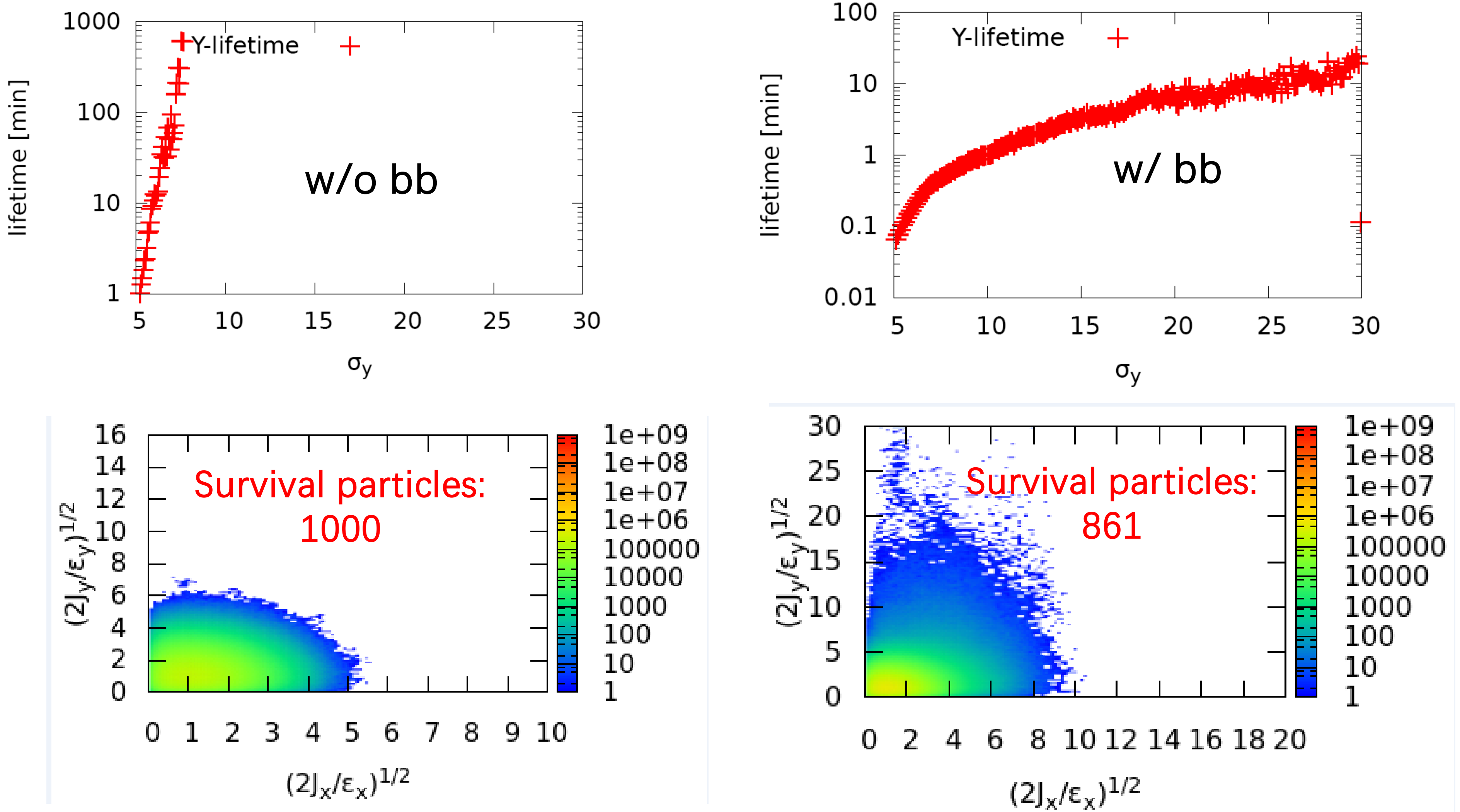
Higgs: Lifetime w/ and w/o beambeam

- 50k turns, 1k macro-particles **@injection point**



Realistic lattice w/ beam-beam

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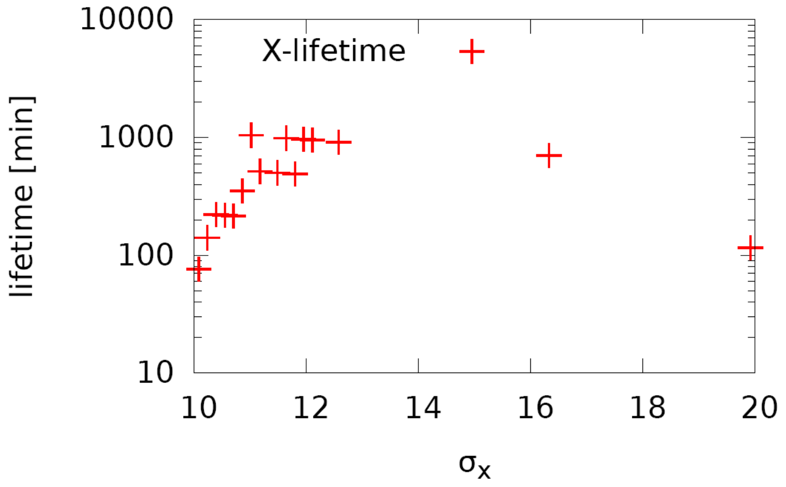
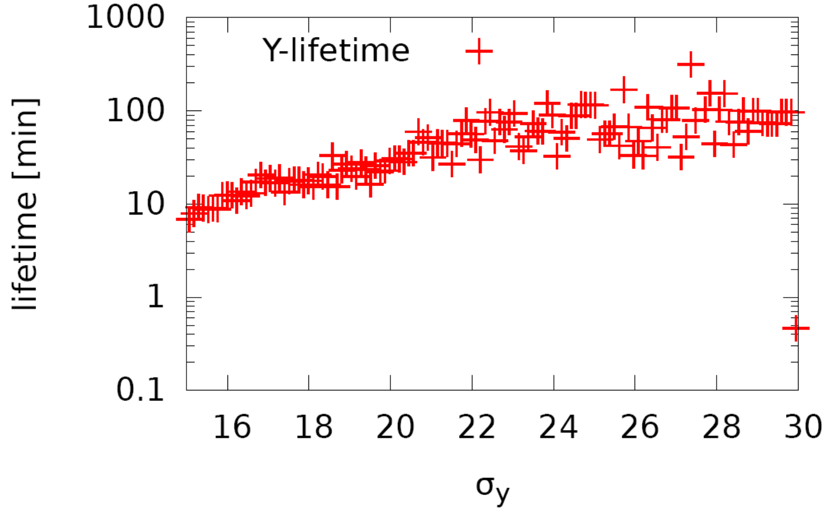
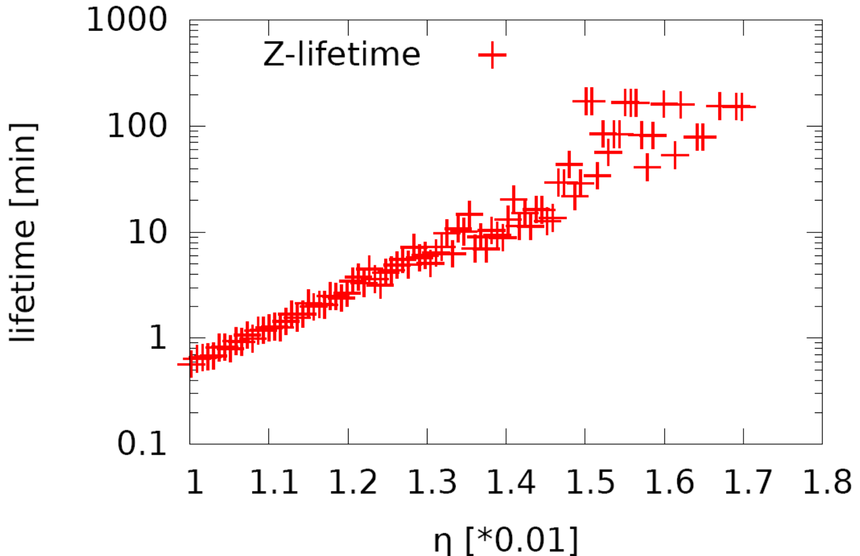
Higgs: Lifetime optimization

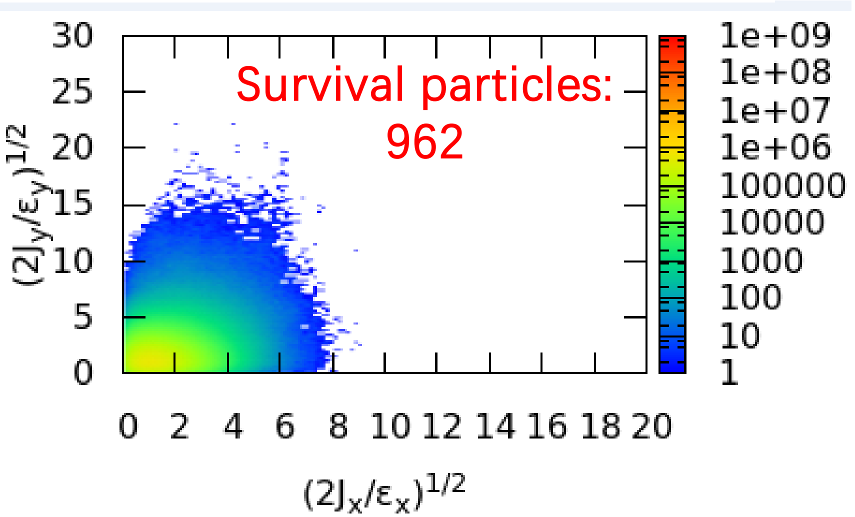
Diffusion Map Analysis

- 50k turns, 1k macro-particles @injection point
- 32 families of sextupoles in Arc







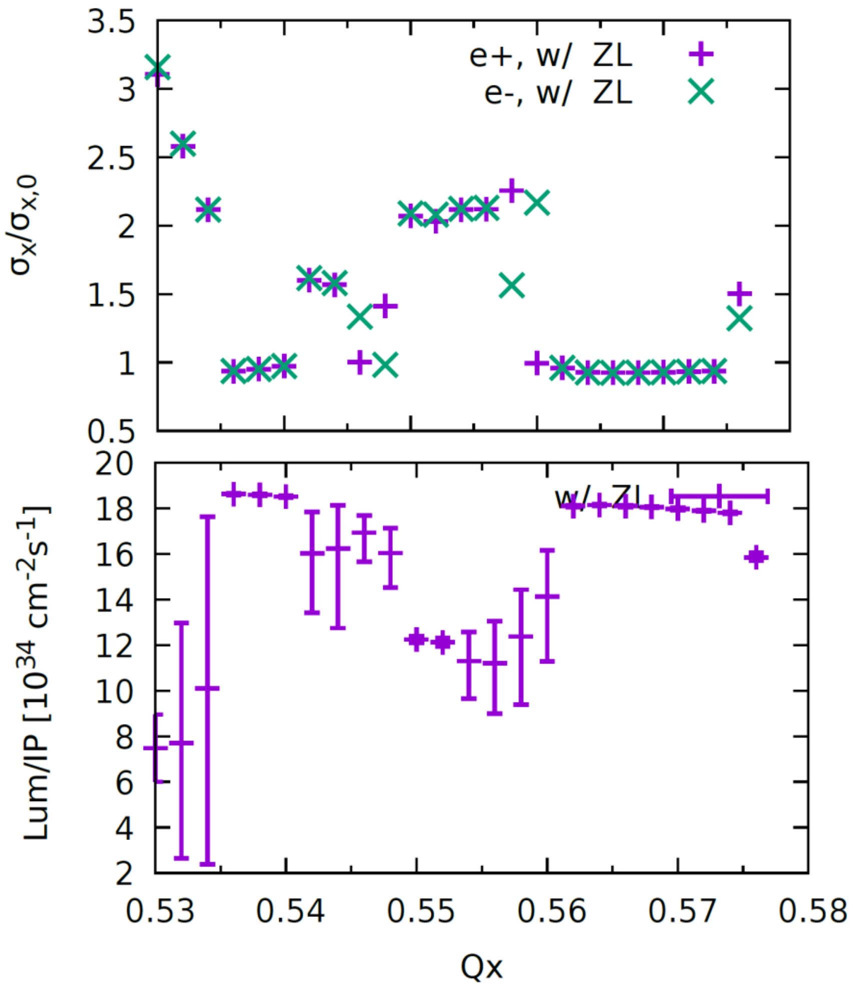


With stronger ZL, Stable tune area is still large enough

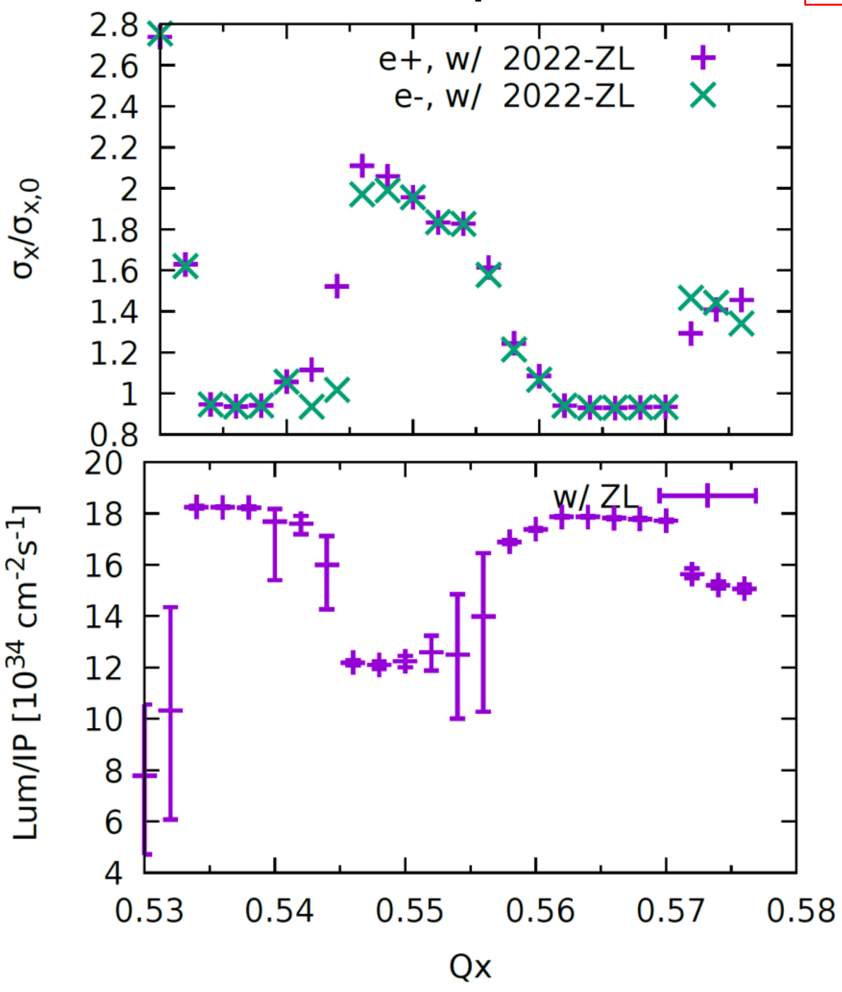
W: σ_x & Lum versus Horizontal tune

Piwinski Angle: 6

CDR Impedance

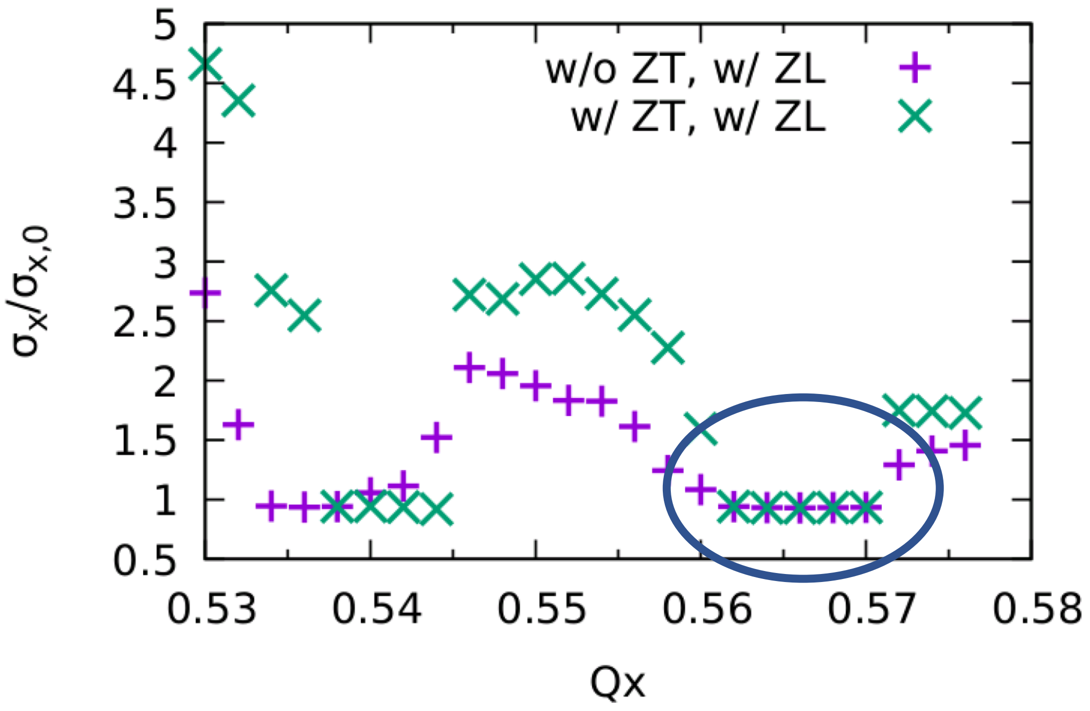


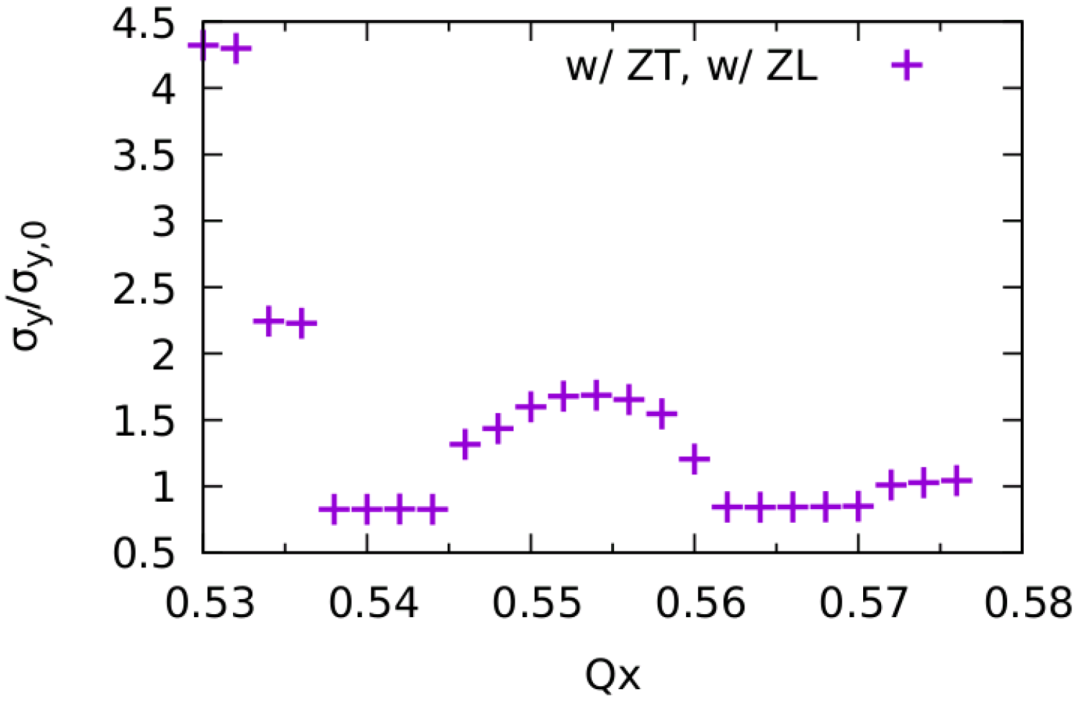
2022 Impedance



W, w/ ZT (2022)

- Only X-Z instability
- stable region is large enough (ZT applied 1 kick)





Only ZL

Piwinski Angle: 24

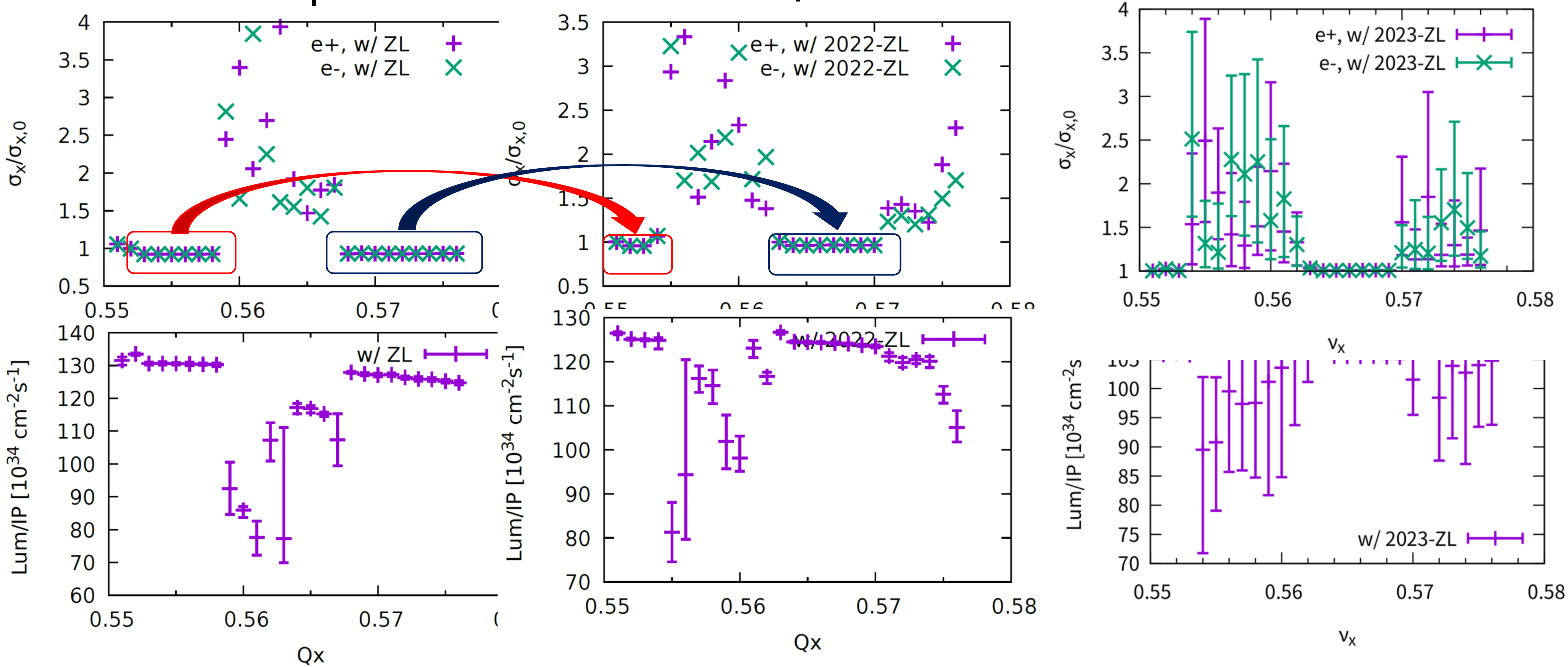
Z: σ_x & Lum versus Horizontal tune

Stable tune area is still large enough, even squeezed.

CDR Impedance

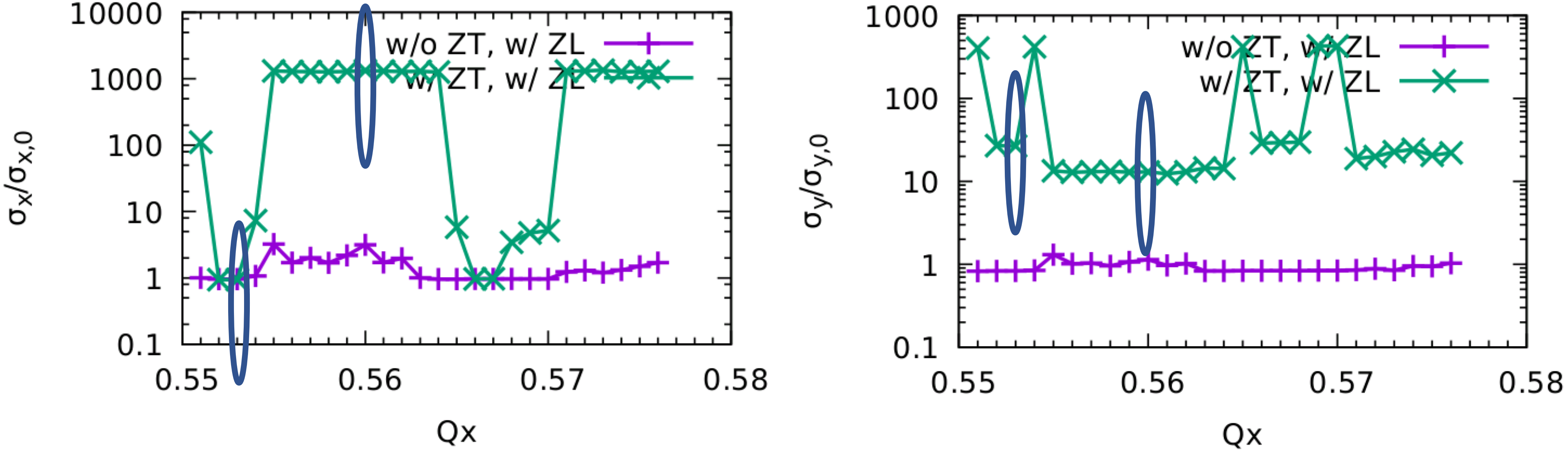
2022 Impedance

2023 Impedance



Z, w/ ZT (2022)

- No stable working points
- There exist very strong blowup in both X/Y direction

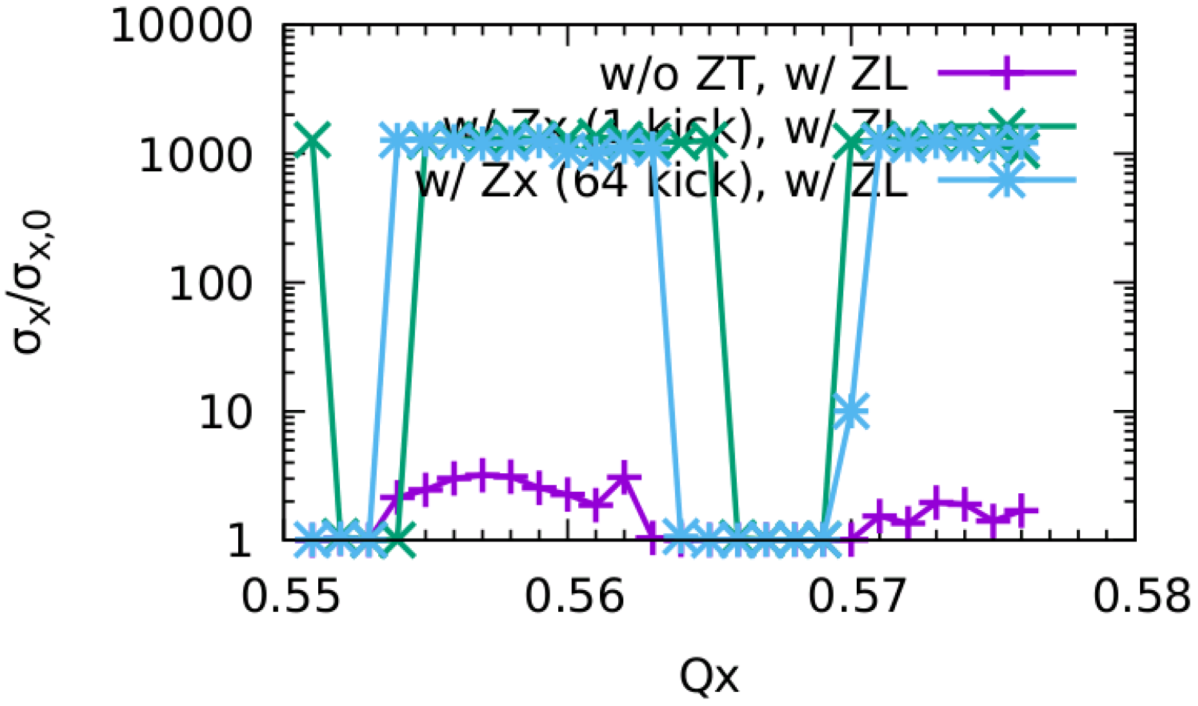


CEPC Only Zx(+ZL) 2022

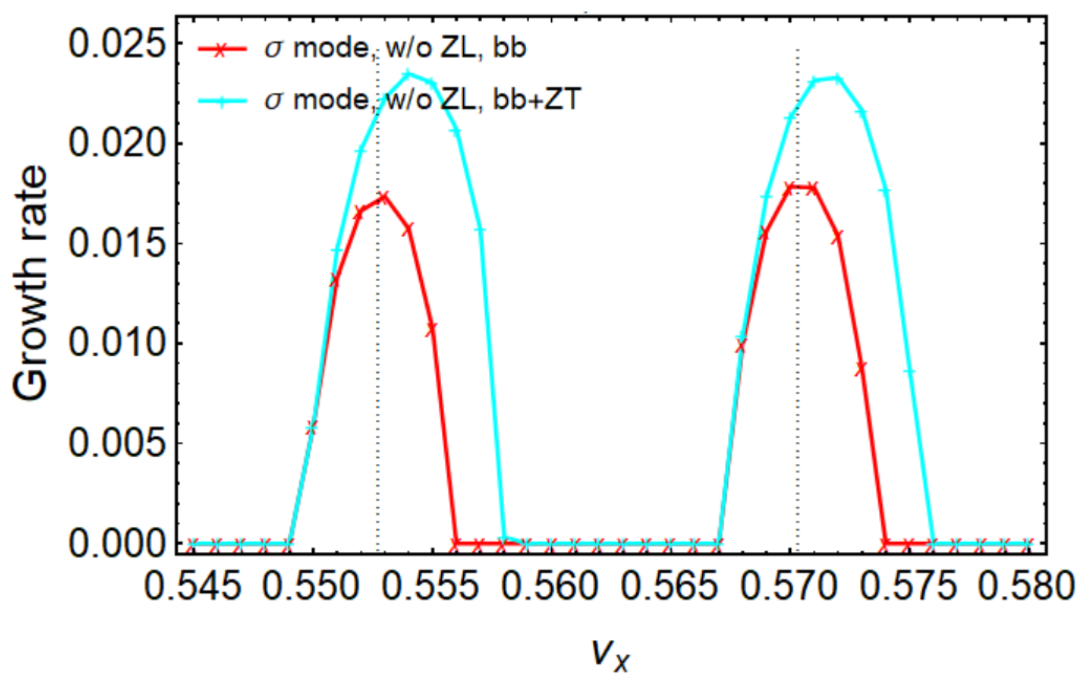
- Stable tune area is large enough (w/ZT)
- Simulation and analysis agrees qualitatively.

Courtesy of Chuntao Lin and Na Wang

Simulation



Analysis, ZT kick applied at IP



Kick number of wake field affect the result

- In horizontal direction, smooth distributed impedance nearly does not squeeze the stable tune area serious
- A very local impedance may squeeze the stable area.

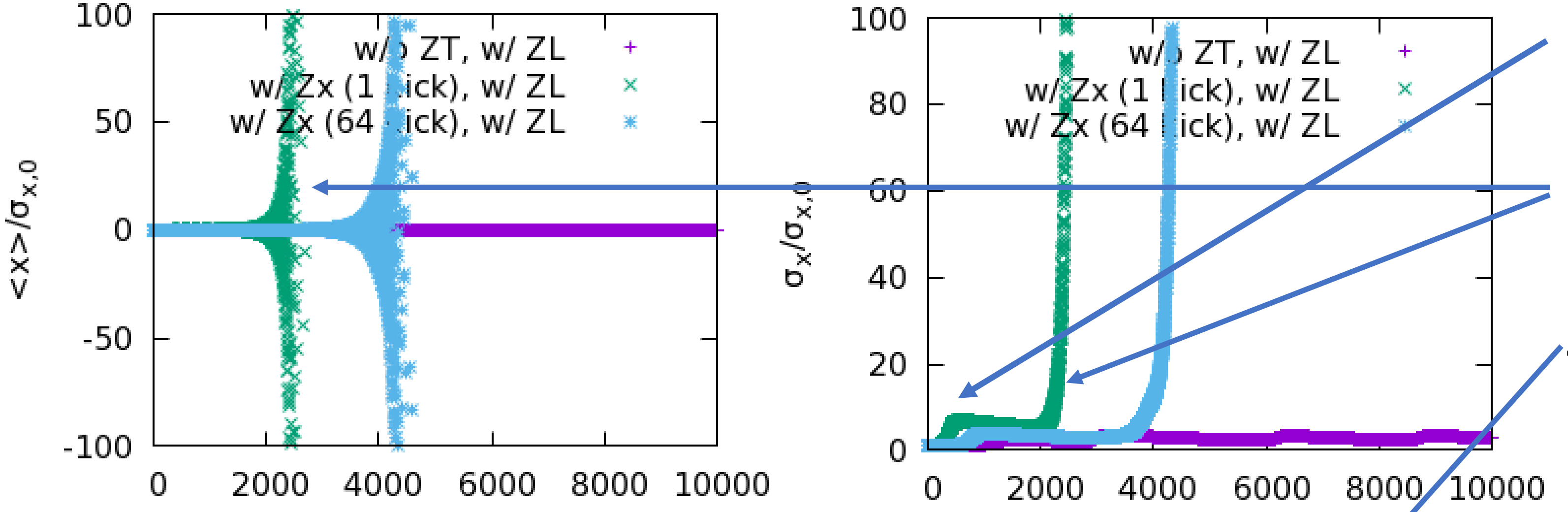
In horizontal direction, considering ZX

- the instability growth rate is faster,
- unstable tune area increases

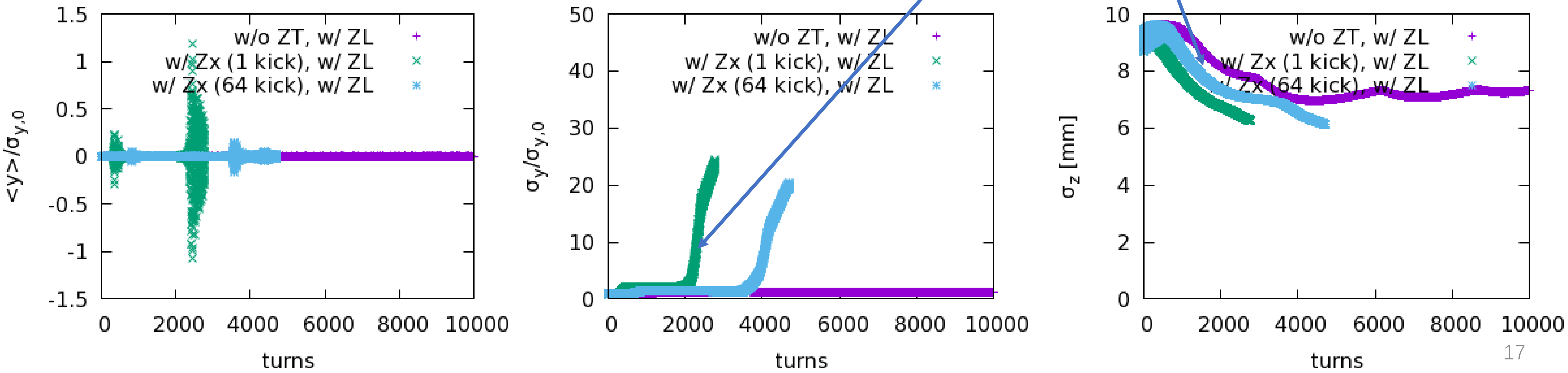
Behavior at unstable working point

CEPC Only Zx(+ZL) 2022 @ Qx=0.562

It has been simulated that w/o BS (but keep same bunch length), the TMCI-like instability would not appear.



1. X-Z instability is first excited
2. Bunch length is shorter
3. X-TMCI-like instability is then excited
4. Y is blowup due to stronger beam-beam interaction

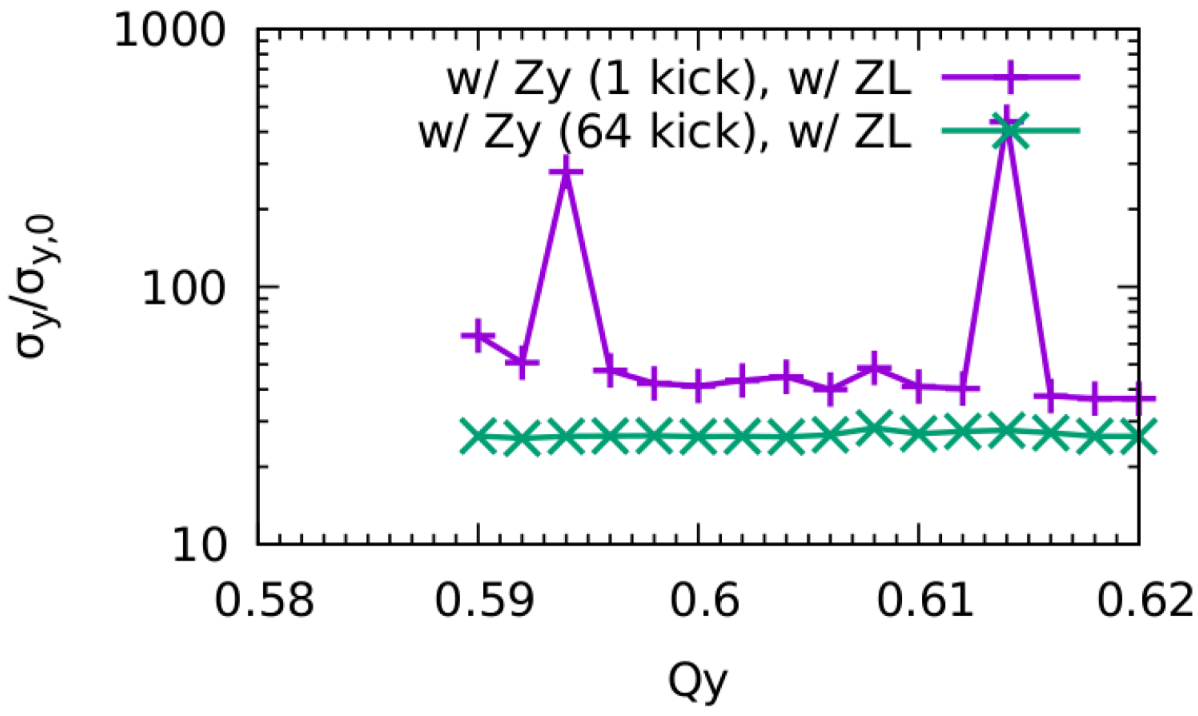


- No stable working point (w/Zy)
- Simulation and analysis agrees qualitatively.

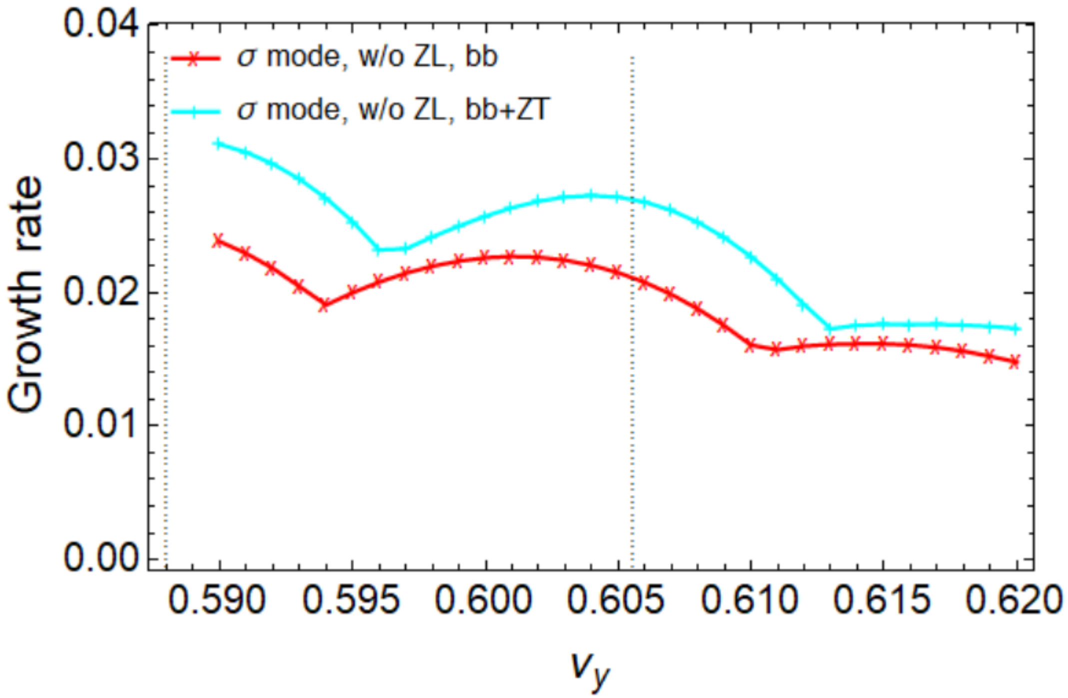
CEPC Only Zy(+ZL) 2022 Qx=0.567

Courtesy of Chuntao Lin and Na Wang

Simulation



Analysis, ZT kick applied at IP



- Kick number of wake field affect the result
- No stable tune area

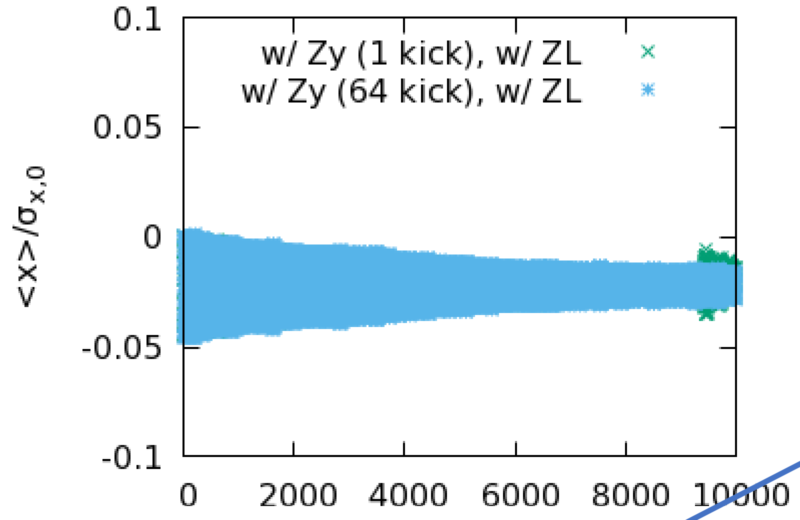
- pure beam-beam is unstable due to ignorance of strong nonlinearity ?
- It is also found enhance of instability when considering ZY

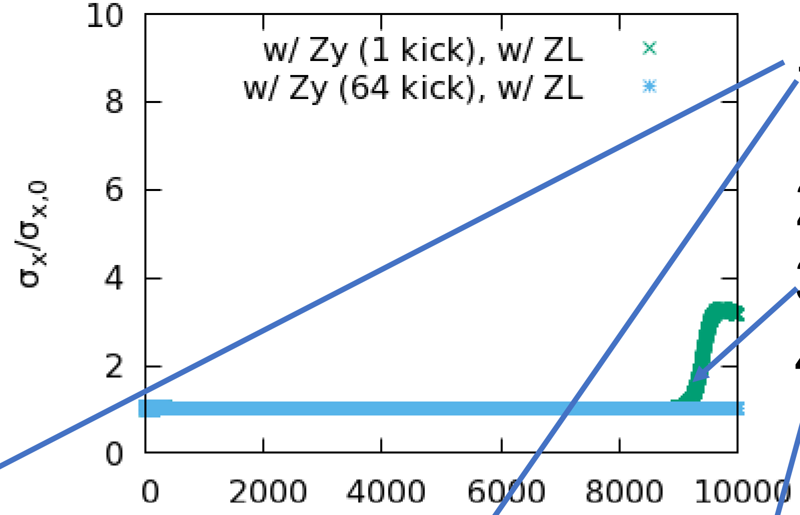
Behavior at unstable working point

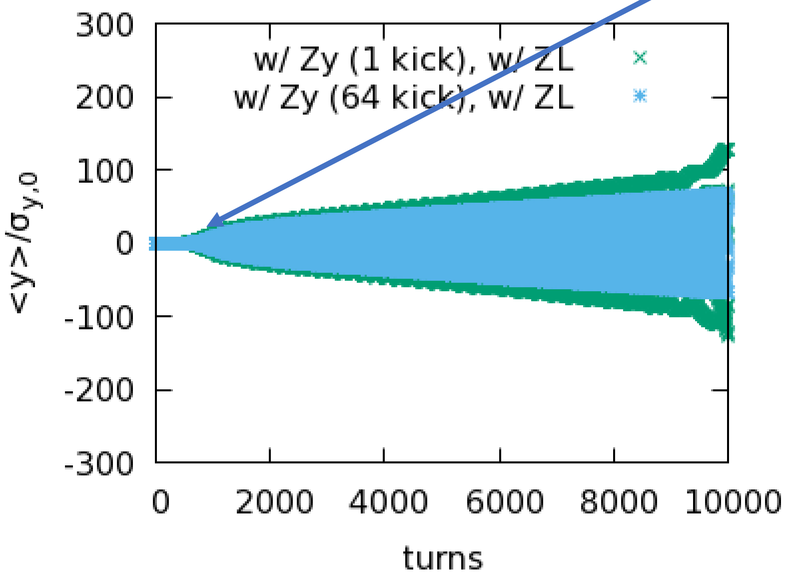
CEPC Only Zy(+ZL) 2022
Qx=0.567

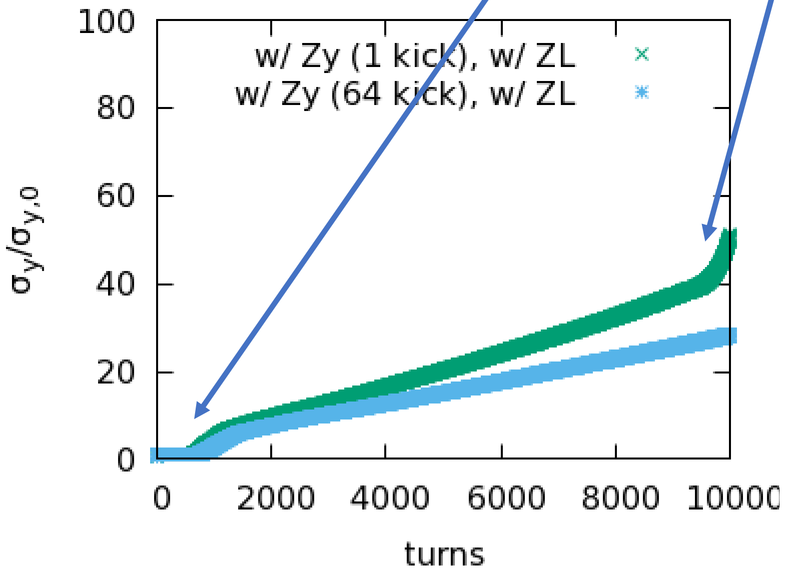
It has been simulated that w/o BS (but keep same bunch length), the X-Z instability would not appear.

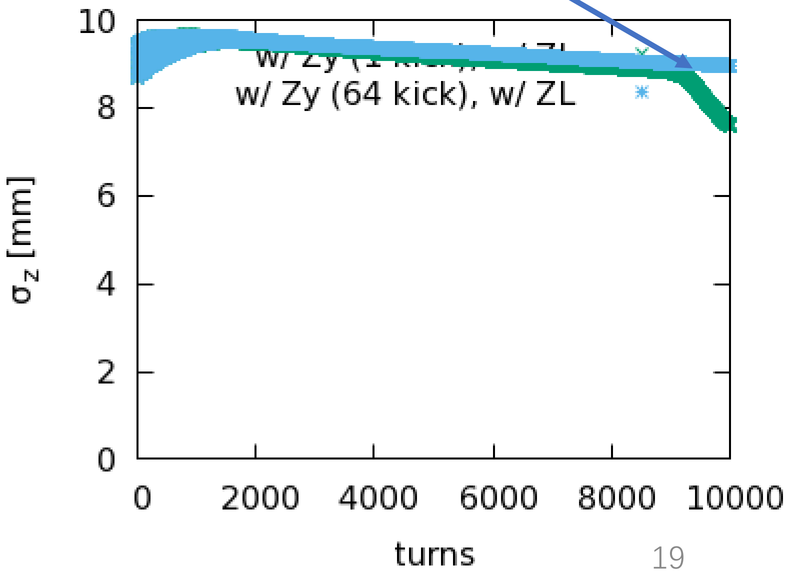
1. Y-TMCI-like instability is first excited
2. Bunch length is shorter
3. X-Z instability is excited
4. Stronger Y blowup due to strong beam-beam











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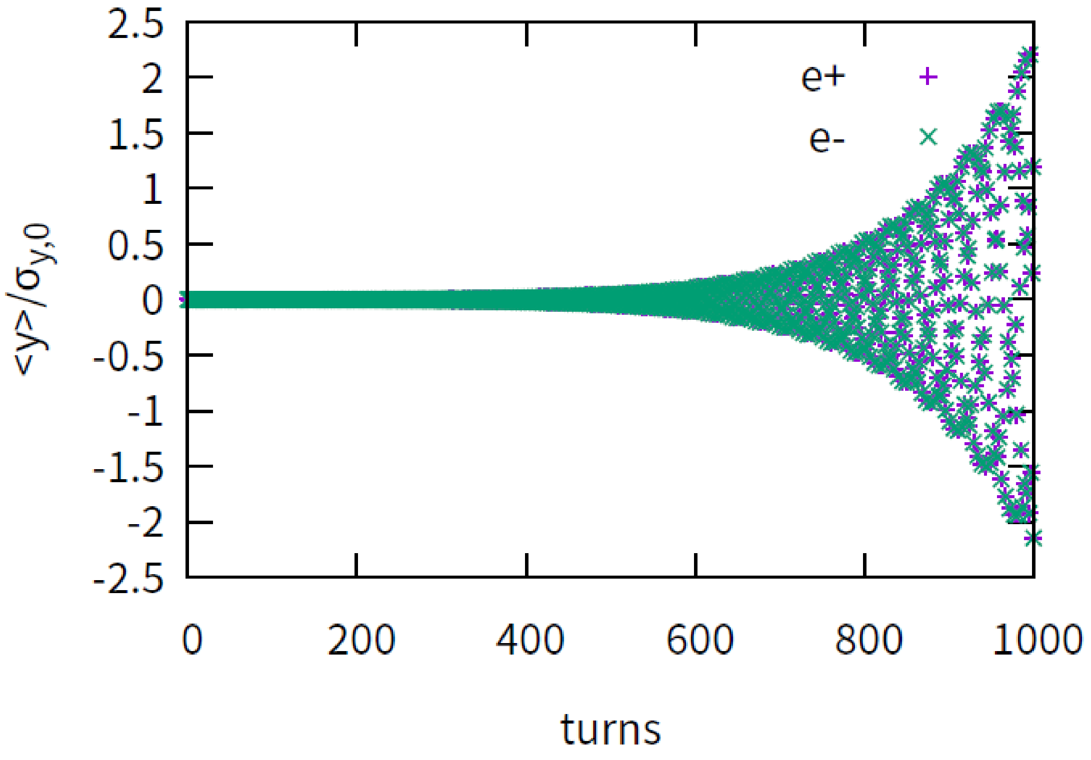
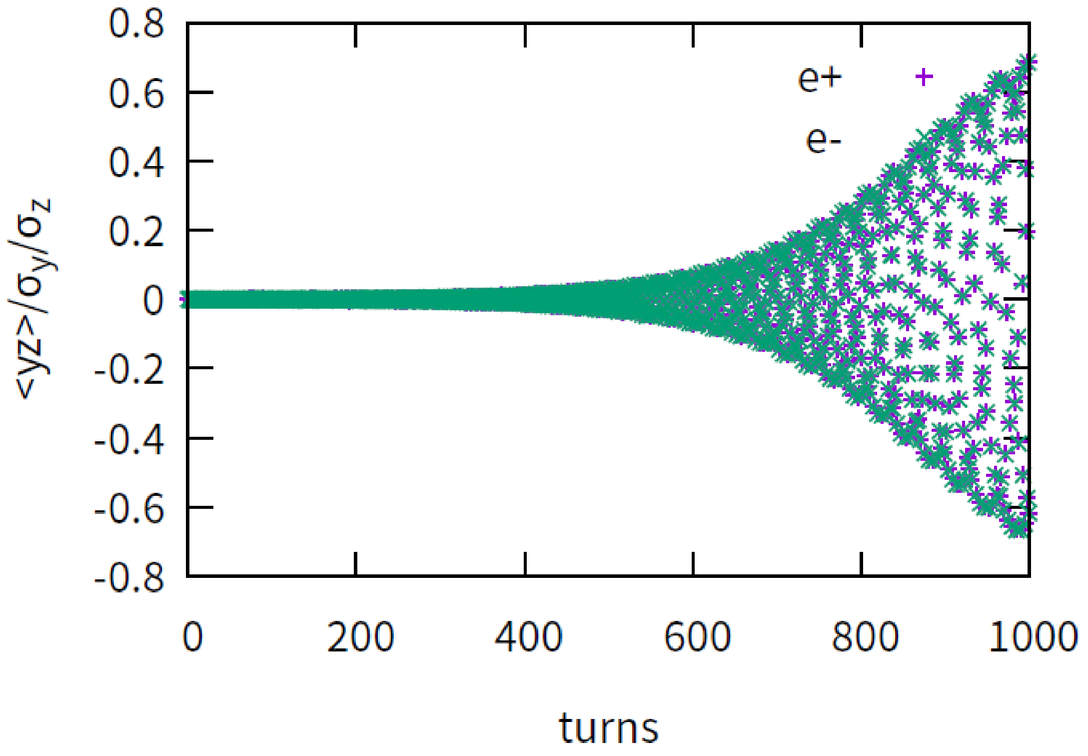
σ mode dominate

Head-tail behavior





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

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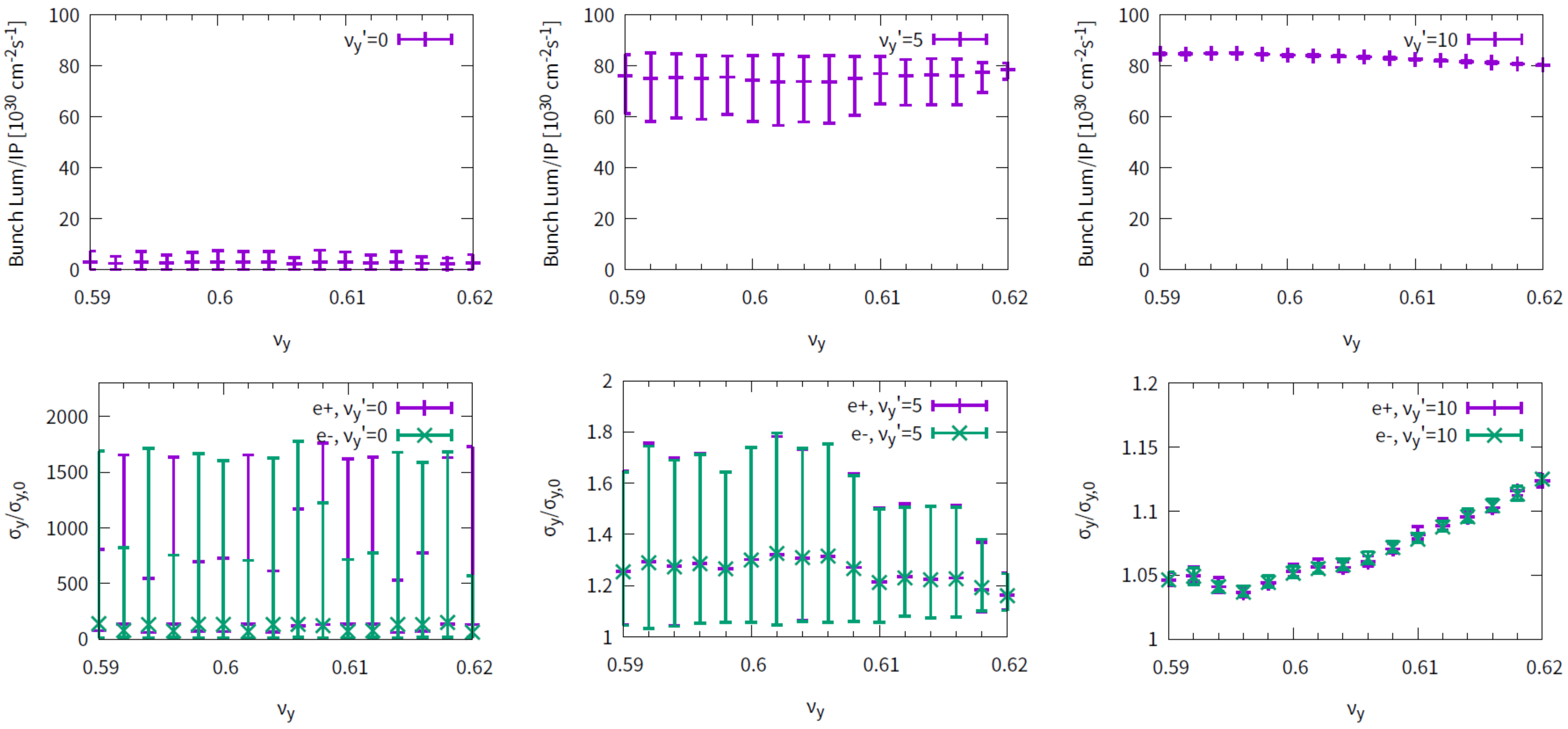
Effect of Vertical Chromaticity (Lum & $\boldsymbol{\sigma_y}$)

ZX+ZY+ZL (2022), Qx=0.567



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

Thanks: K. Oide, K. Ohmi

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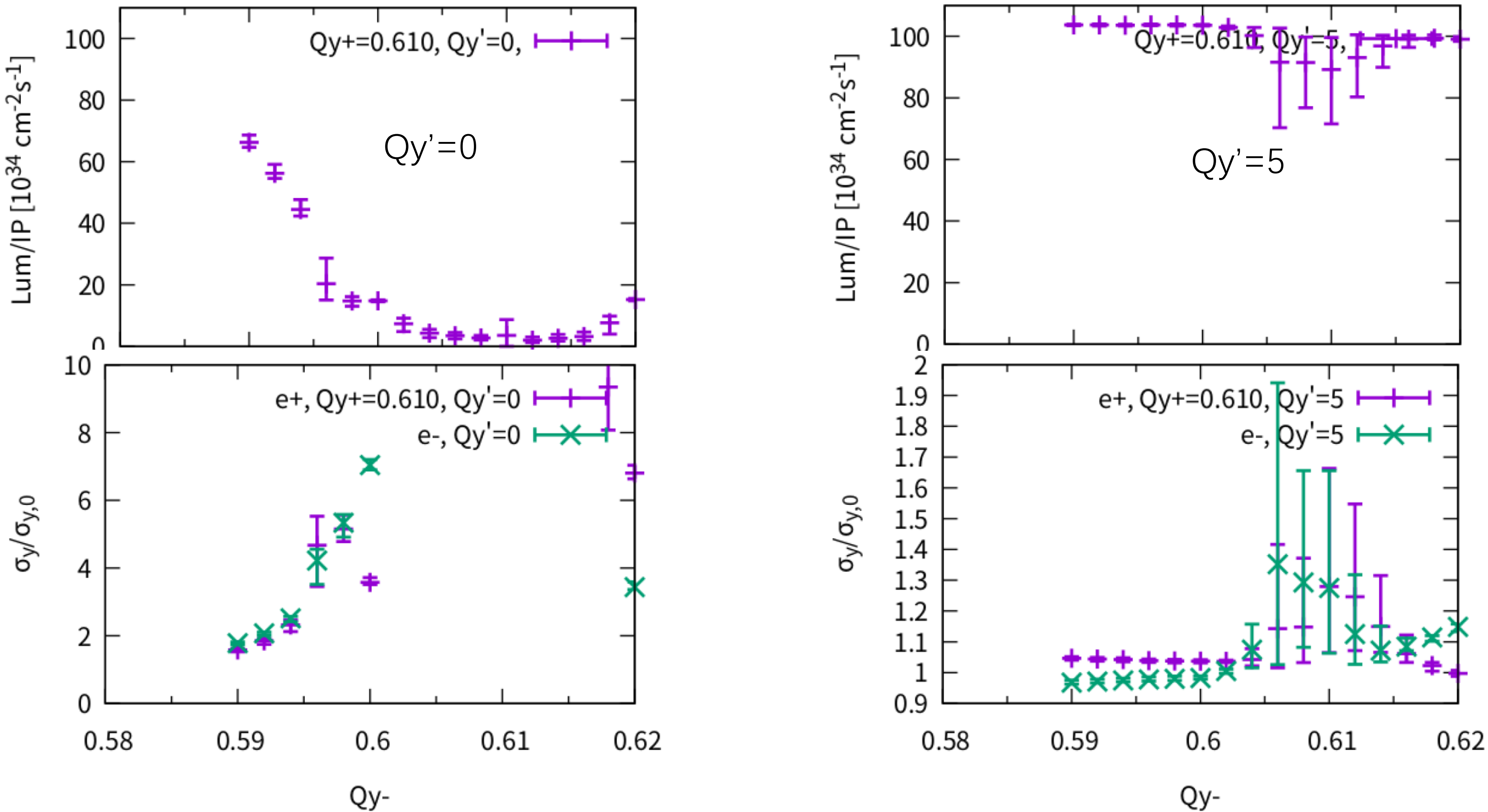
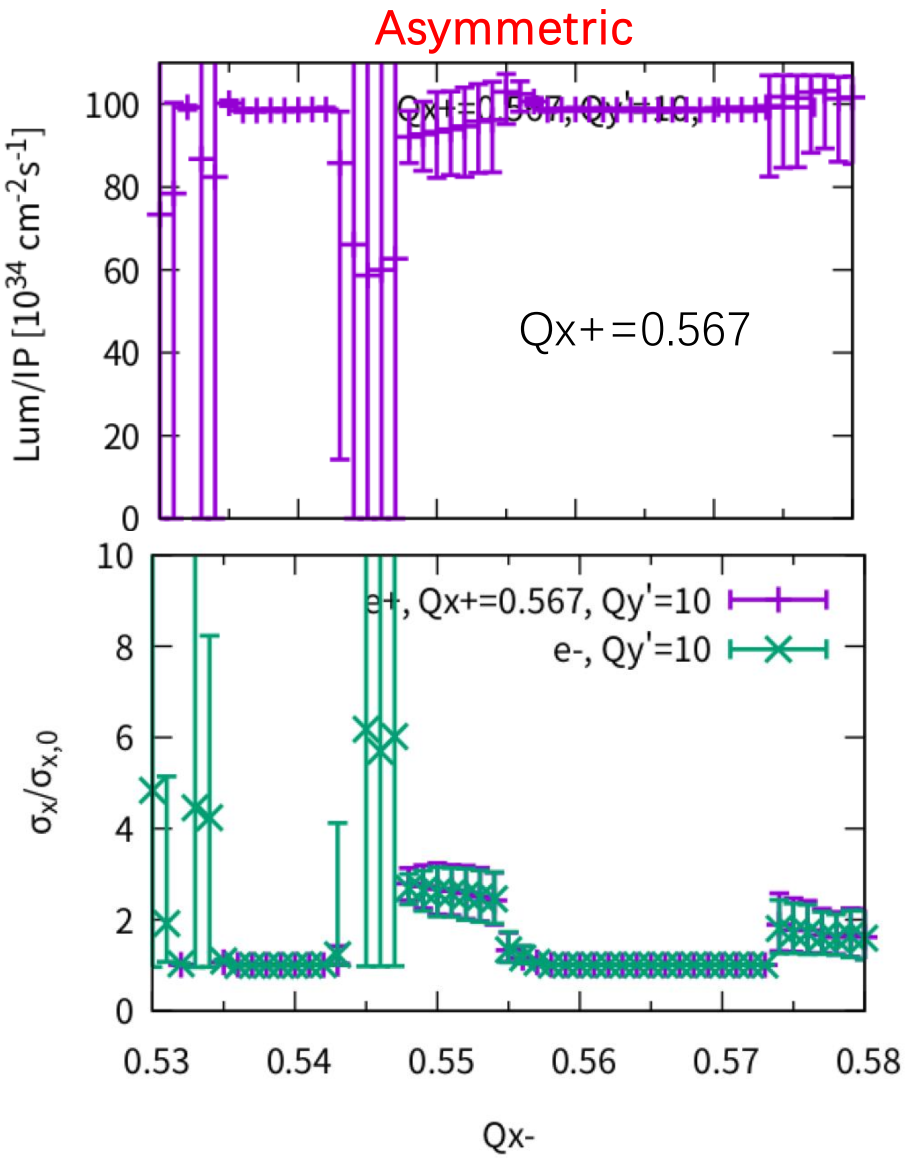
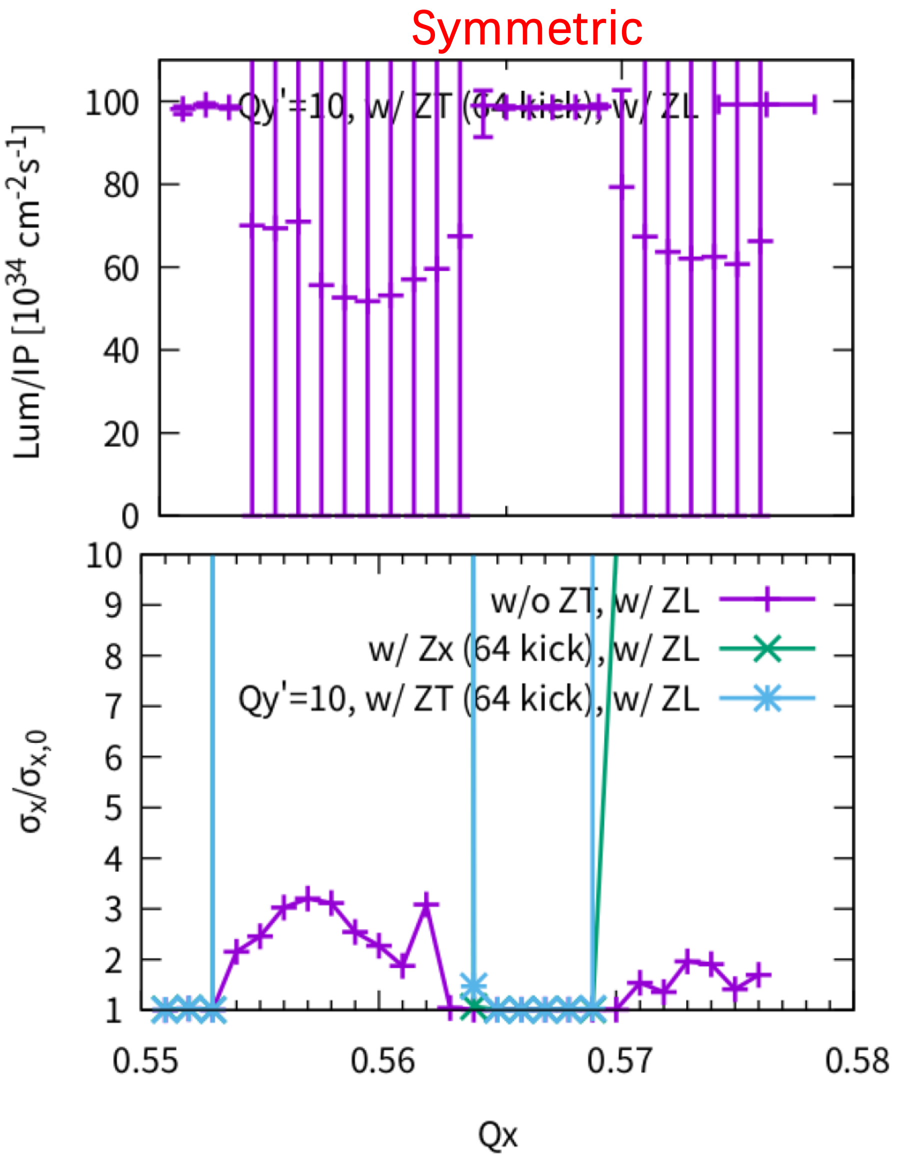
Effect of different vertical tune (Qy+=0.610)



Different Horizontal tune





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K. Ohmi, D. Zhou, T. Ishibashi,
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$$\Delta p_y(z) = \mp \int_{-\infty}^{\infty} W_y(z-z')\rho_y(z')dz,$$

'-' for σ mode beam-beam cross-wake force, which is same sign as ring wake ; '+' for π mode

Beam-Beam cross-wake force

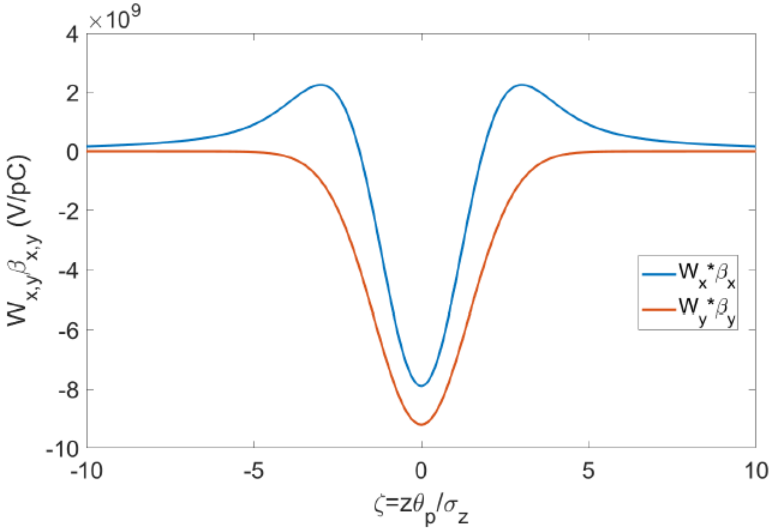

FIG. 1. Comparison of the the horizontal and vertical beam-beam cross-wake function of CEPC which have been weighted by the local beta functions at the IP.

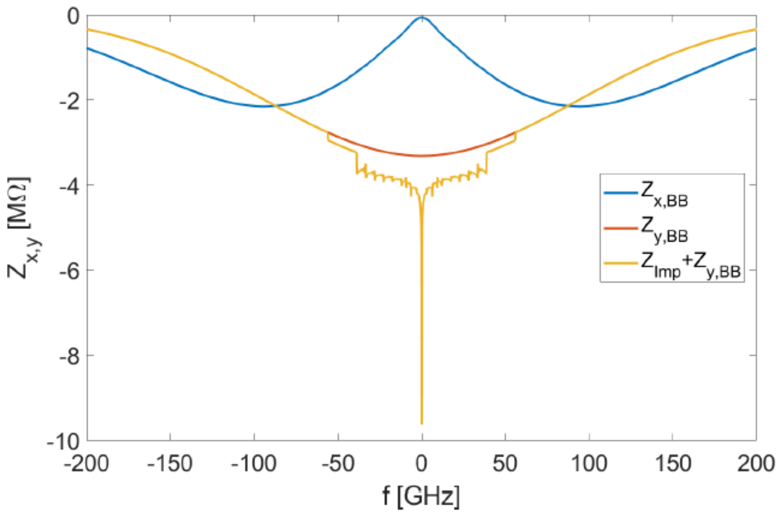

FIG. 2. Comparison of the CEPC ring impedance (imaginary part) with the horizontal and vertical beam-beam impedance, where the impedances have been weighted by the local beta functions.

Ring impedance : 2022

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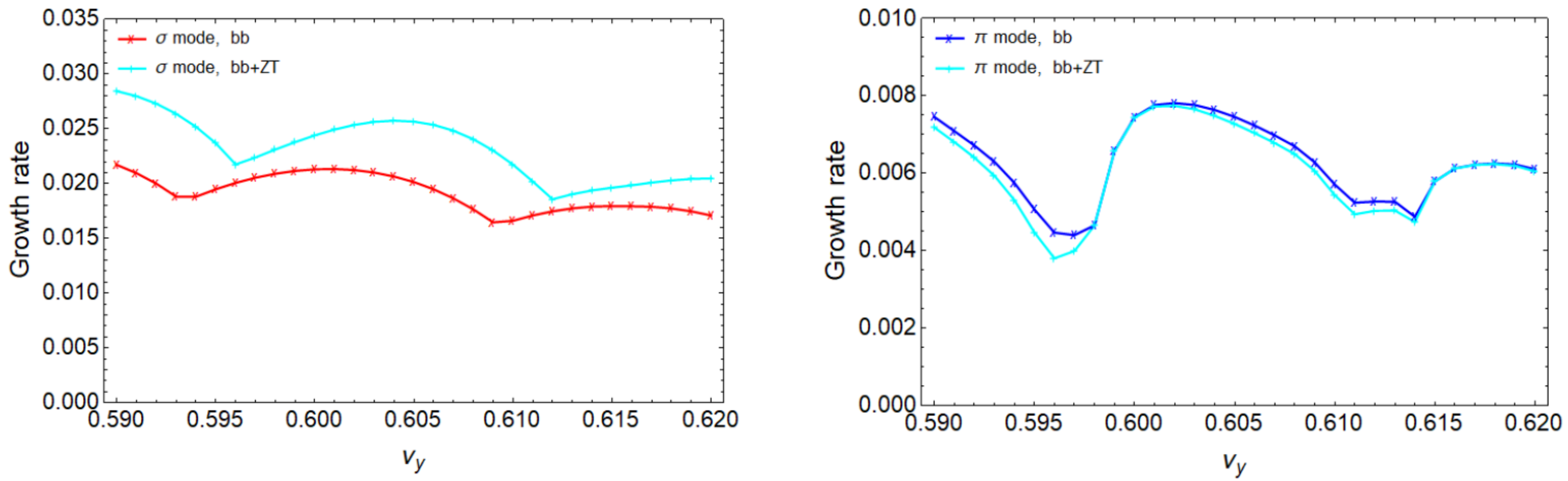
Analysis of vertical coherent instability

- Dipole/Quadrupole beam-beam force is considered
- σ mode is more unstable, which is similar to that in horizontal direction
- σ mode instability is enhanced by ring wakefields.
- π mode is more or less weakened by ring wakefields



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Some analysis results of mitigation method

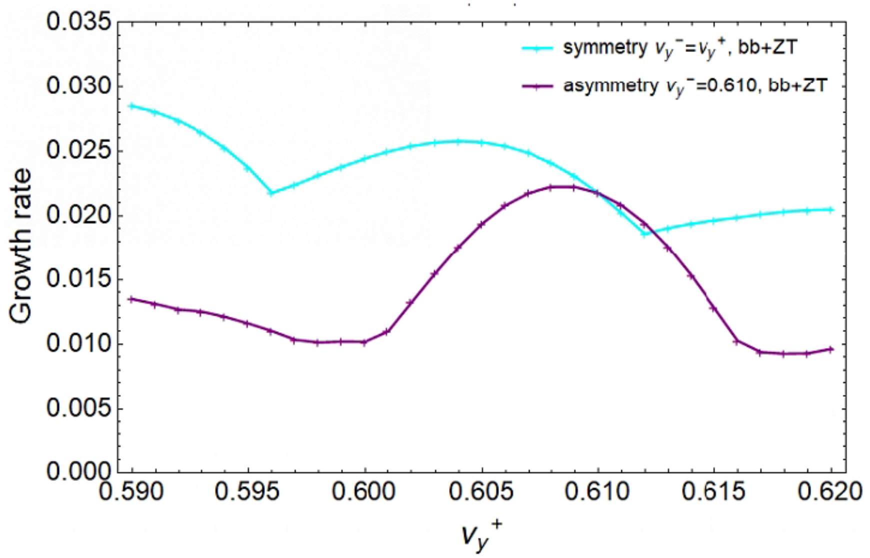


FIG. 6. Vertical instability growth rate versus tune in case of symmetric and asymmetric tunes. In the asymmetric case, one beam's vertical tune is fixed at 0.61, and the other beam's vertical tune is scanned. For the symmetric case, the two beams' vertical tunes are the same and scanned together. Ring impedance is considered.

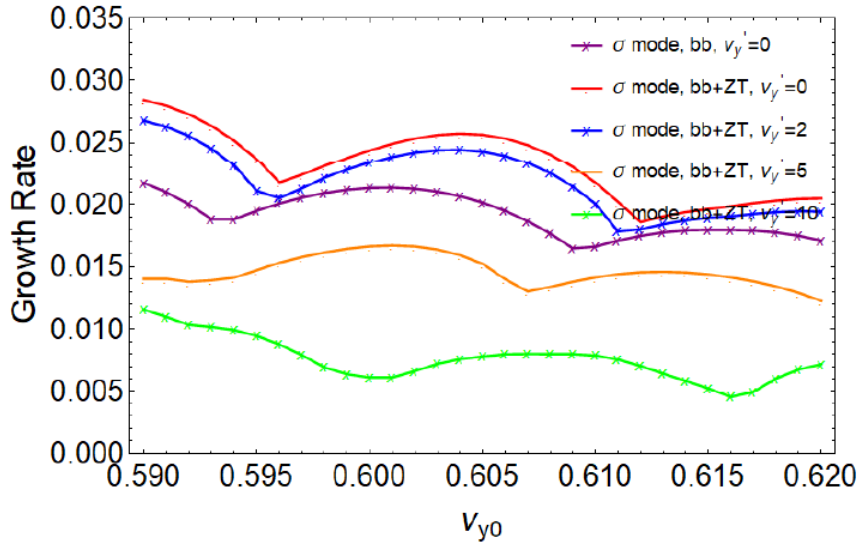


FIG. 7. The growth rate of vertical σ-mode instability with finite chromaticity at different tune.

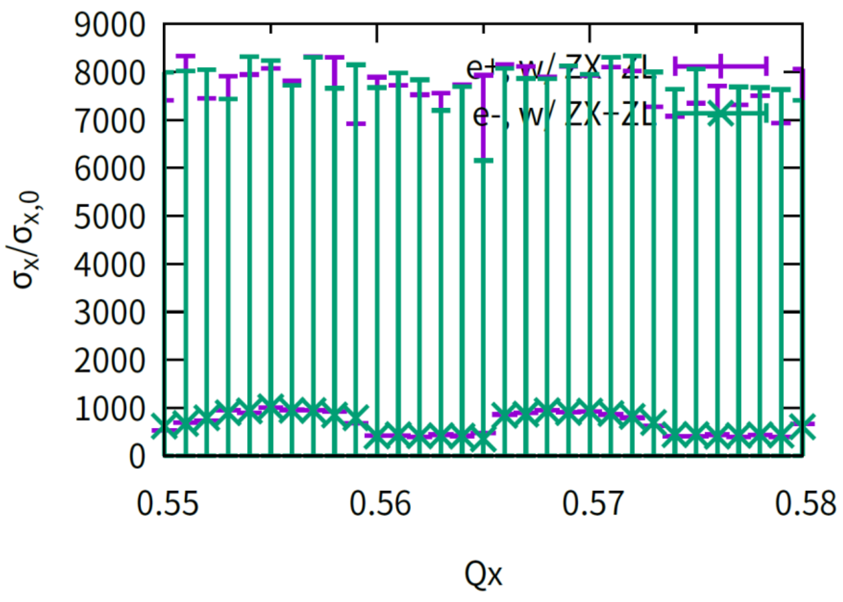
Z: More challenging: 30MW->50MW bunch population: 14e10->21e10

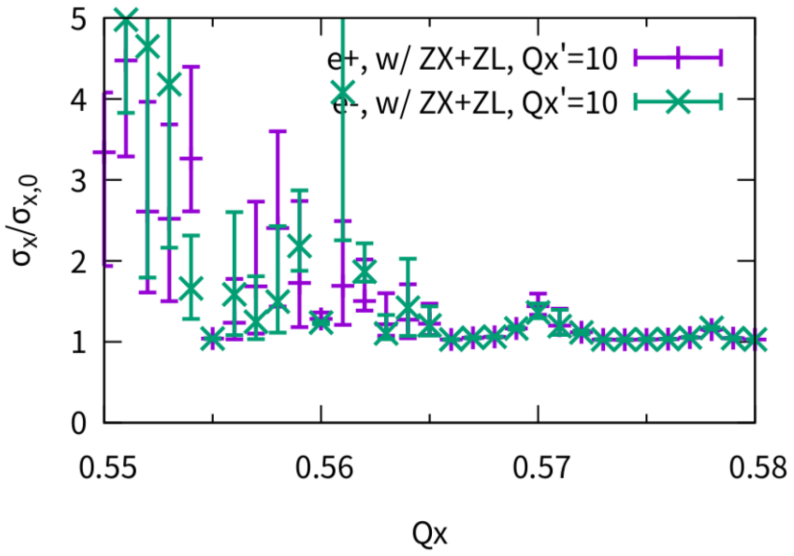
Single Bunch TMCI threshold ~ 21e10 considering beamstrahlung length without beam-beam interaction

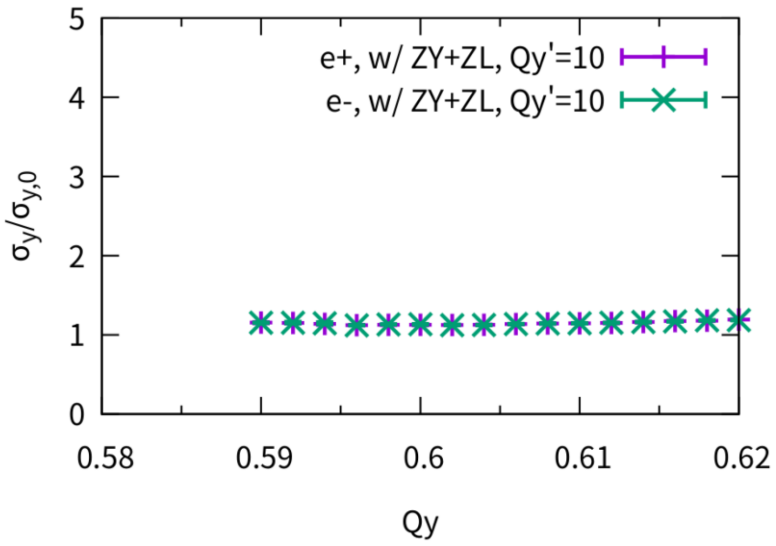
Qx'=5 does not help
Qx'=5 + diffnux does not help
Qx'=10 help suppress the instability

2022 impedance

Only ZX, Qx'=0, Symmetrical

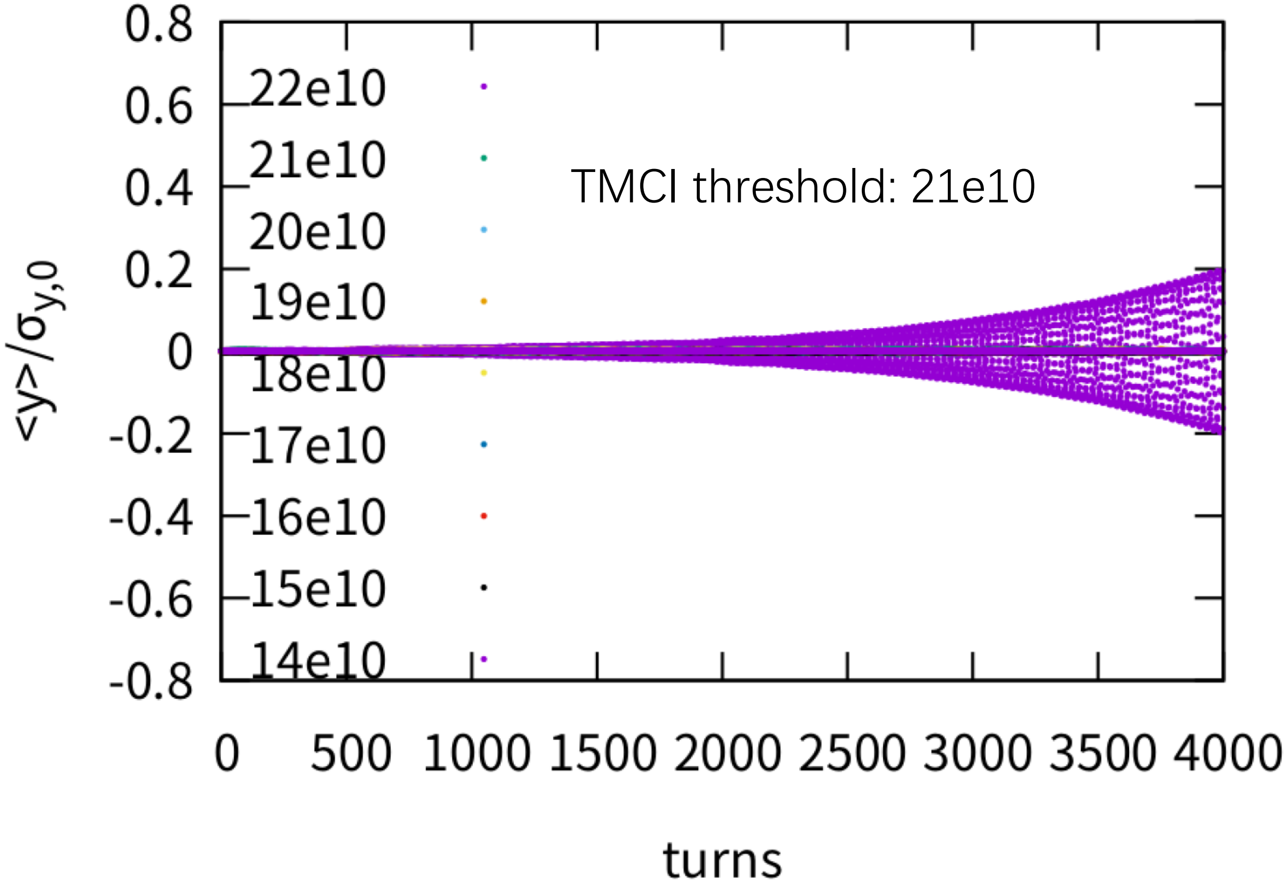




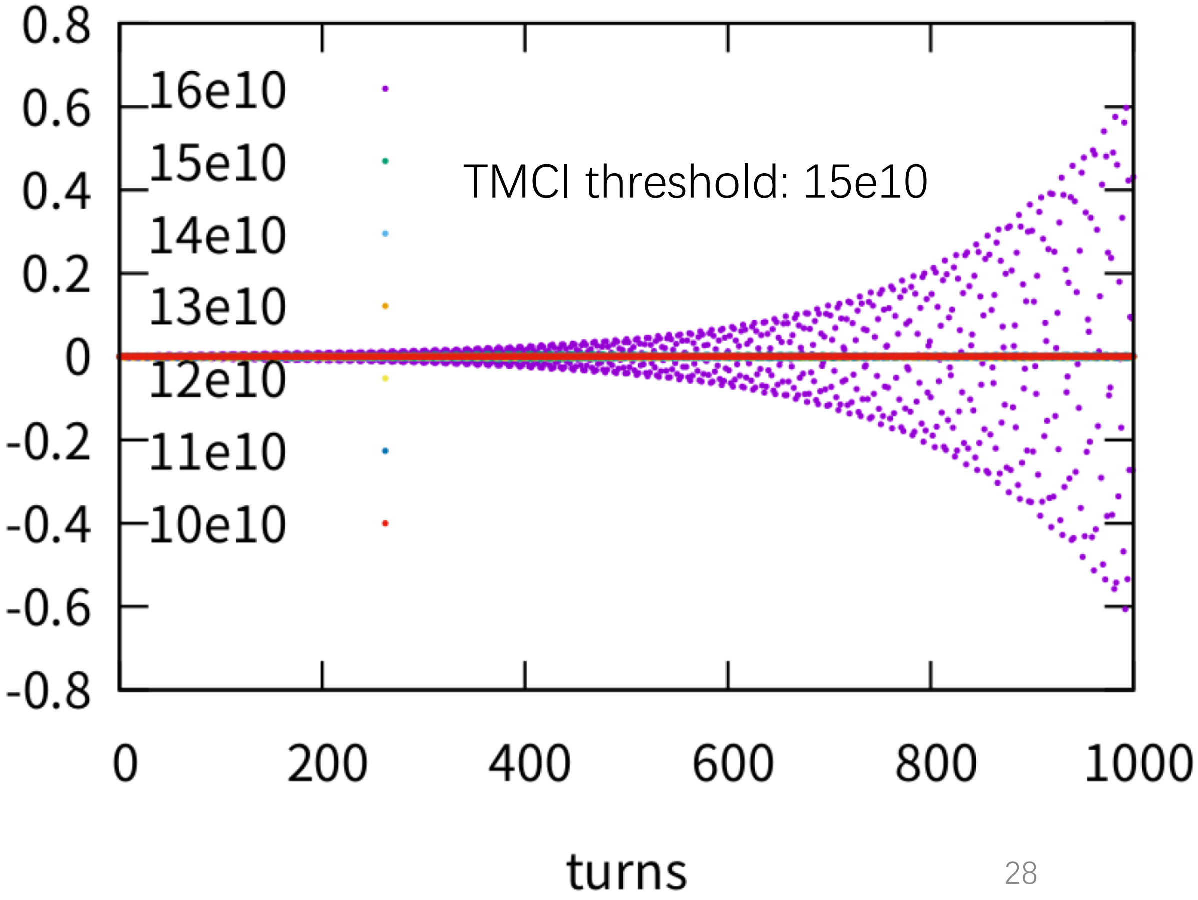


TMCI –THRESHOD: 2022 VS 2023 impedance

2022-ZT
+ beamstrahlung length and energy spread @14e10 (with ZL)



2023-ZT
+ beamstrahlung length and energy spread @14e10 (with ZL)



- Thanks: M. Zobov, M. Migliorati
- PRAB 24, 041003 (2021)

Could expected strong feedback system help? (Off-collision)

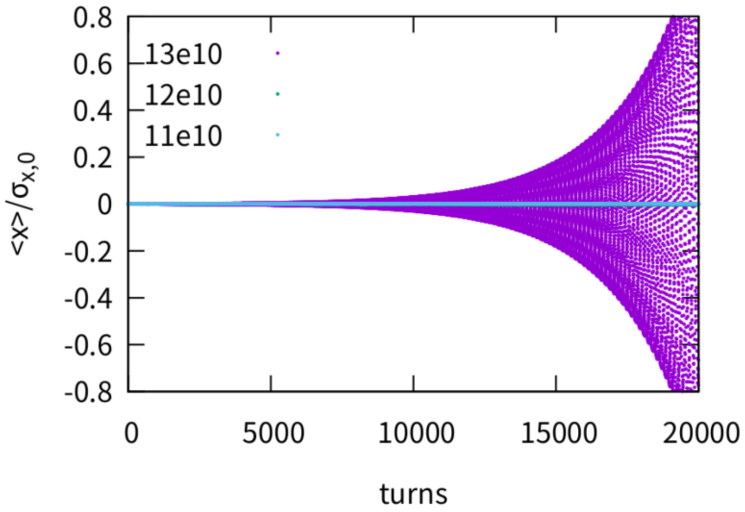
$\nu_s = 0.0176$

A simplified resistive damper is used:

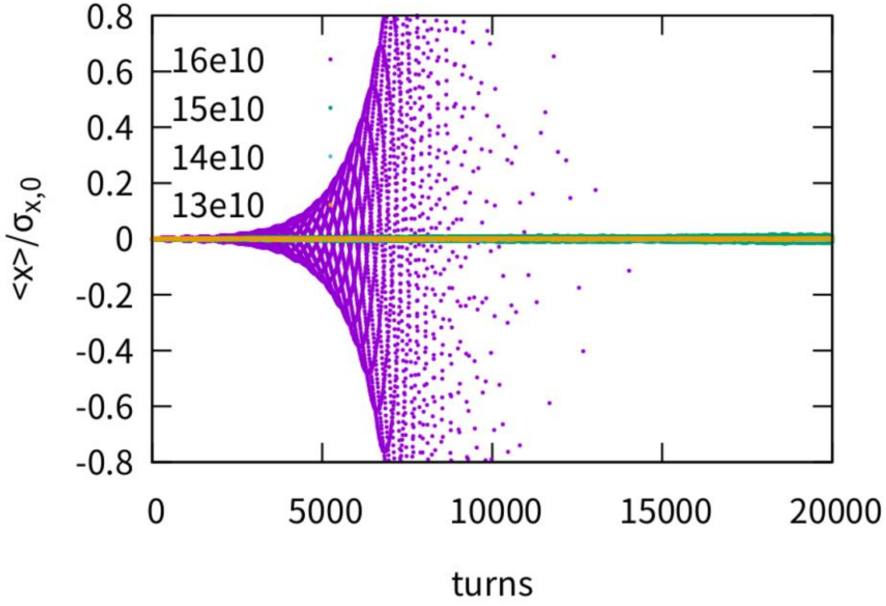
$$\Delta p_i = -2d_p p_i$$

It is fountd stronger damper reduce the TMCI threshold.

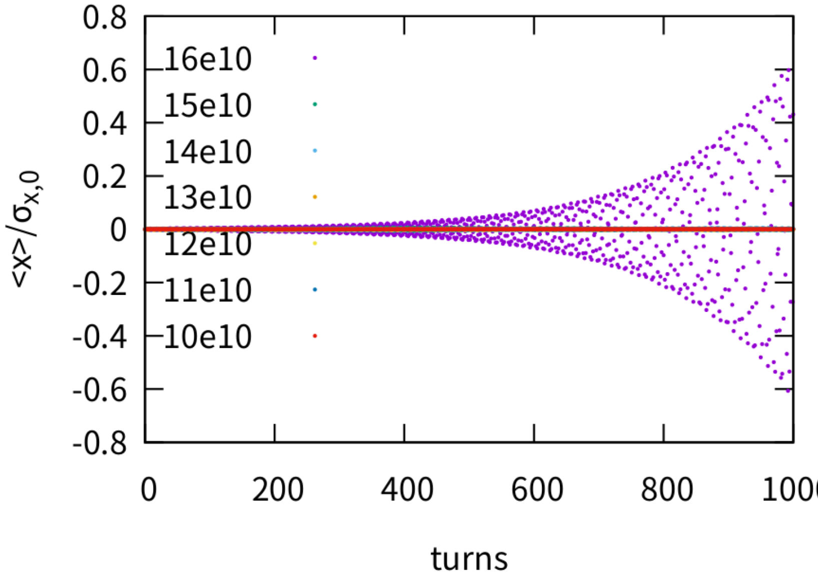
- Dp=0.1, threshold ~ 12e10.



- Dp=0.01, threshold ~ 15e10.



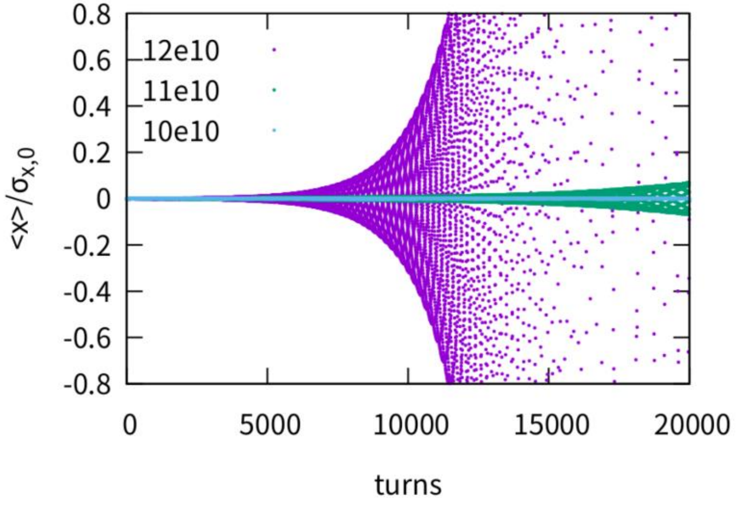
- Dp=0, threshold ~ 15e10.



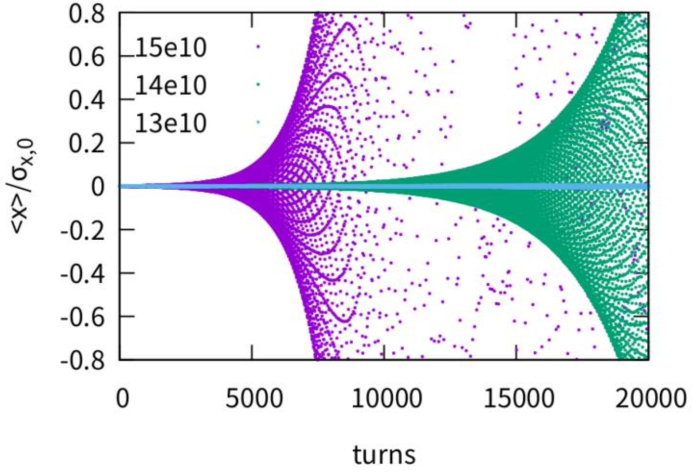
Threshold increase with the damper strength

Resistive feedback + Qx’=5 (off collision)

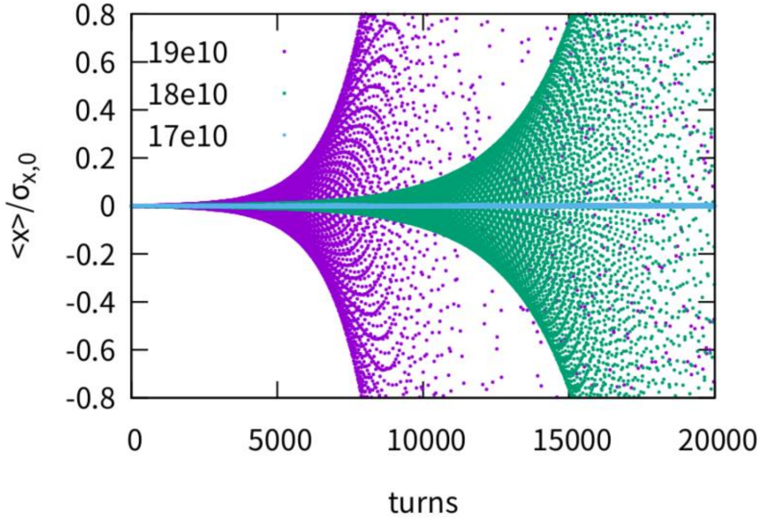
Dp=0.01, threshold~10e10



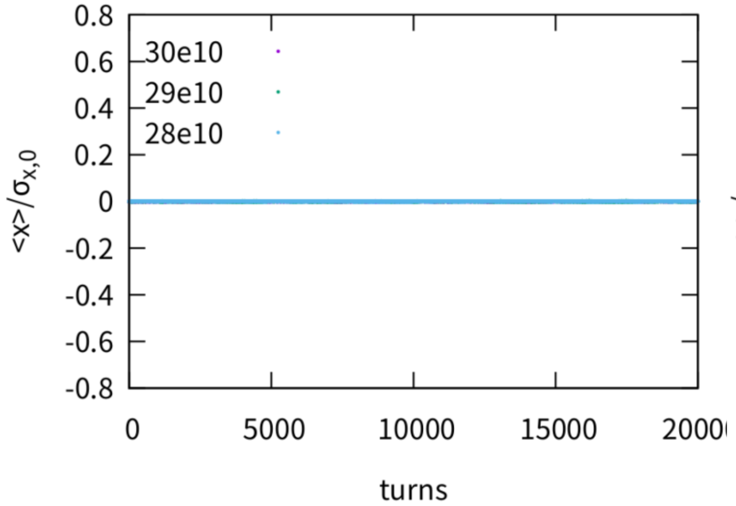
Dp=0.02, threshold~13e10

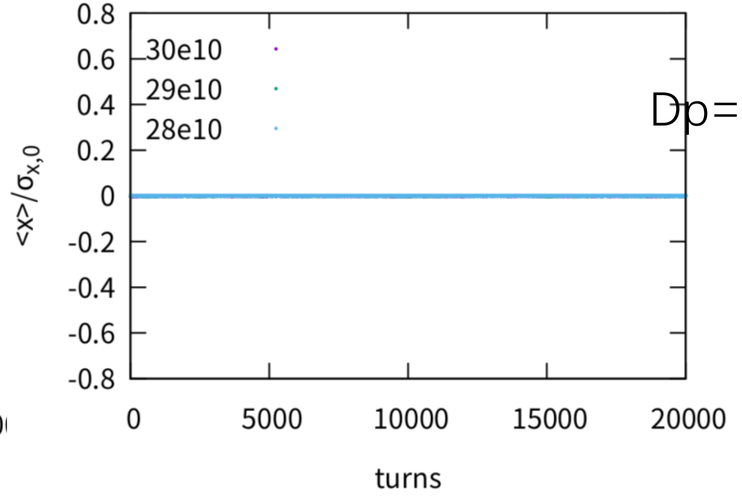


Dp=0.03, threshold~17e10



Dp=0.04, threshold~30e10

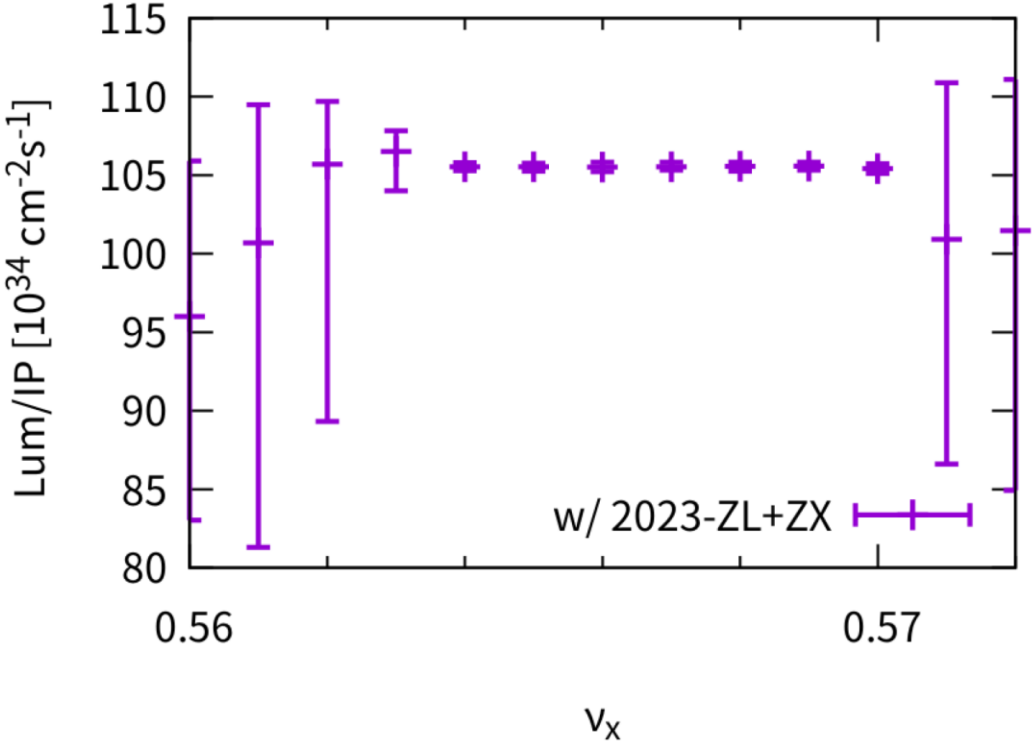


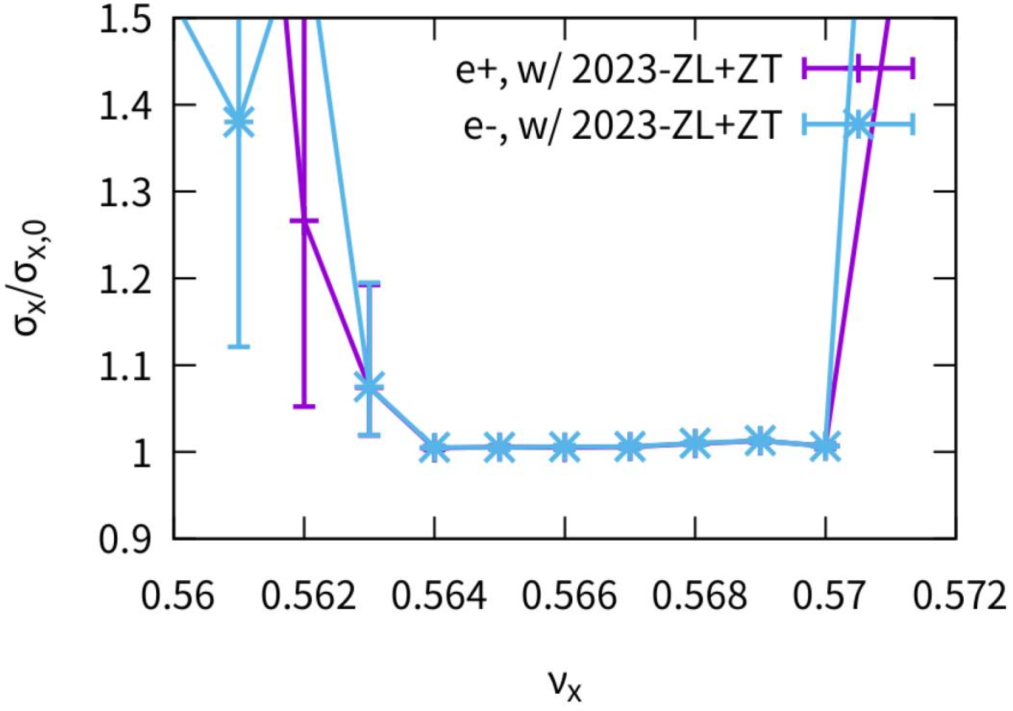


Dp=0.05, threshold~30e10

ZX+ZL, resistive feedback dp=5e-2 (Qx'=5)

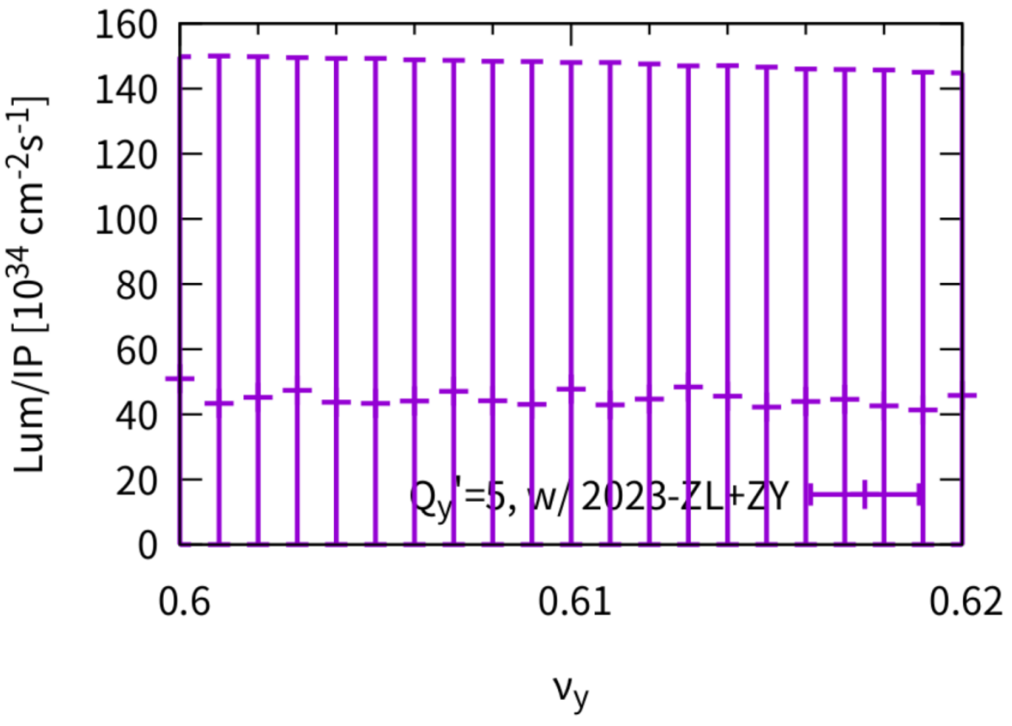
- Np=14e10, 30MW (stable)

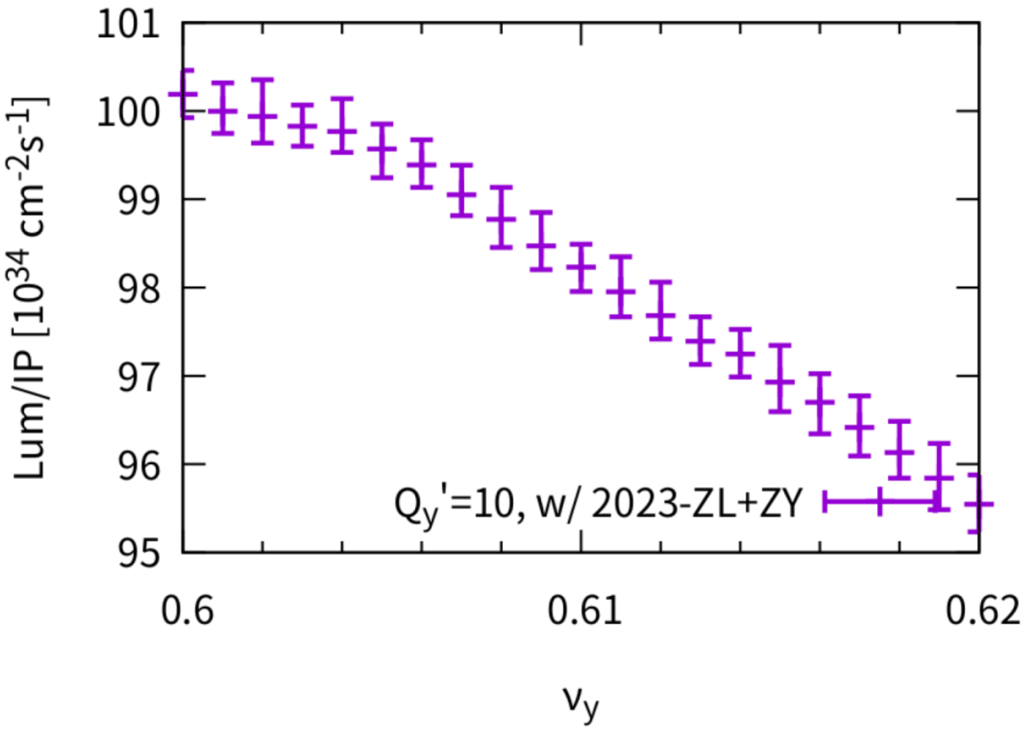




ZY+ZL, resistive feedback dp=5e-2

- Np=14e10, Qy’=10 is stable, Qy’=5 unstable

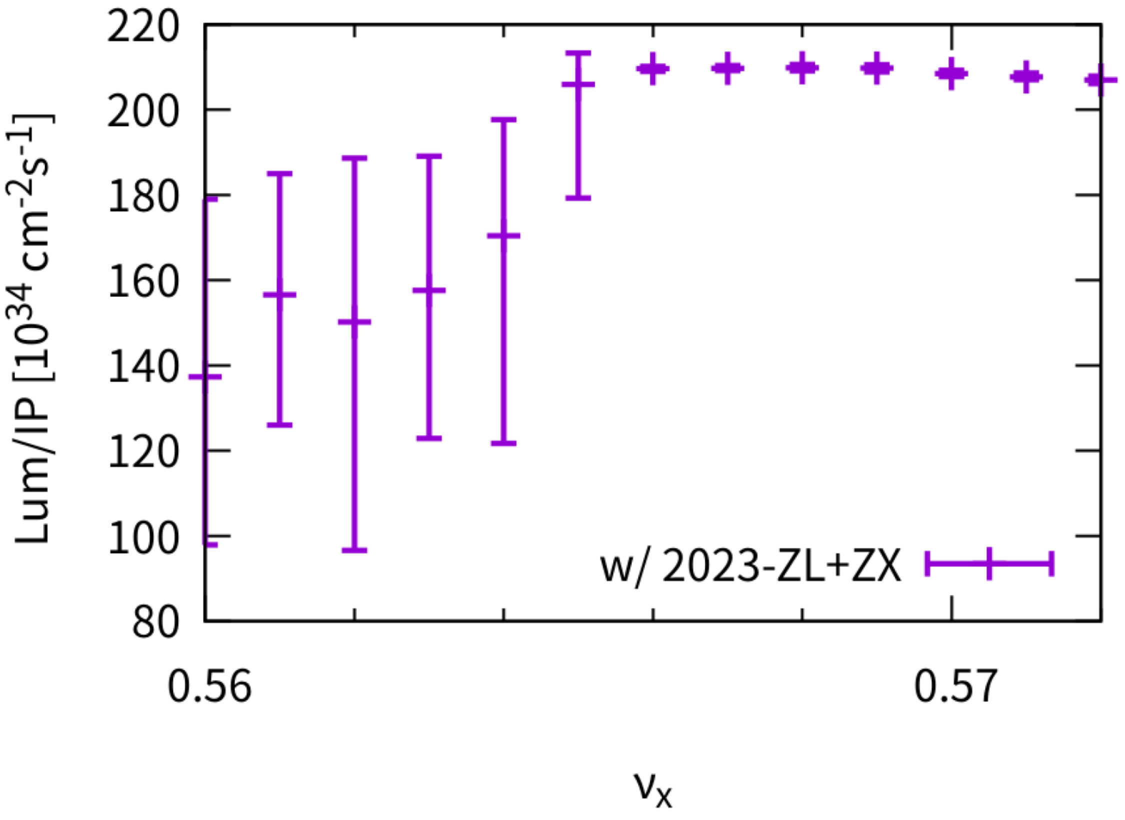




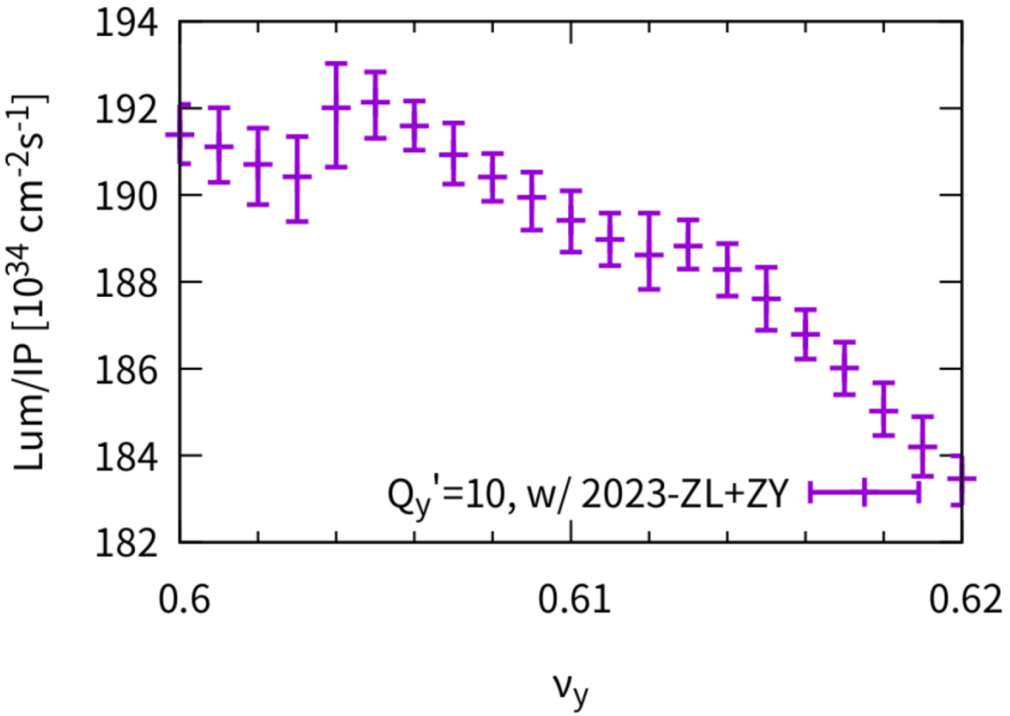
Stable!

resistive feedback dp=5e-2, np=21e10

- Qx'=5, Zx+ZL



Qy'=10, Zy+ZL



Summary & Outlook

- It is important to consider both ZL+ZT at CEPC
- The transverse impedance does not bring harmful effect for ttbar/Higgs/W
- Combined effect of beam-beam interaction and transverse impedance may induce strong head-tail instability in vertical direction at Z mode
- The chromaticity and asymmetrical tunes could help mitigate the instability induced by beam-beam with impedance
- With newest impedance, 30MW(np=14e10) could not work. Strong damper+Chromaticiy may help, however strong feedback is challenging and complicated (future work)