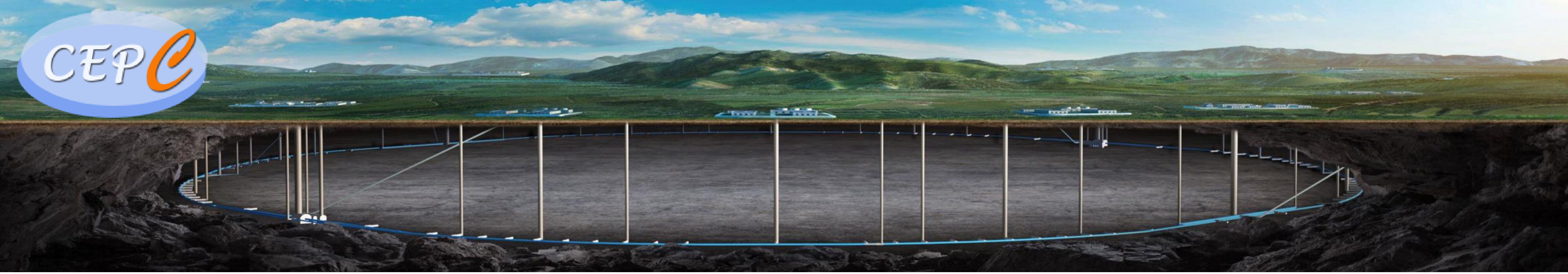

Beam-Beam Effects in CEPC

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Thanks:
D. Shatilov, K. Oide, M. Migliorati

Content

Introduction

- This talk is about Beam-Beam Interaction (sec4.2.2)
- This talk relates to the TDR sec4.1, sec4.2.1, sec4.2.3
- The content relates to the “charge letter” item

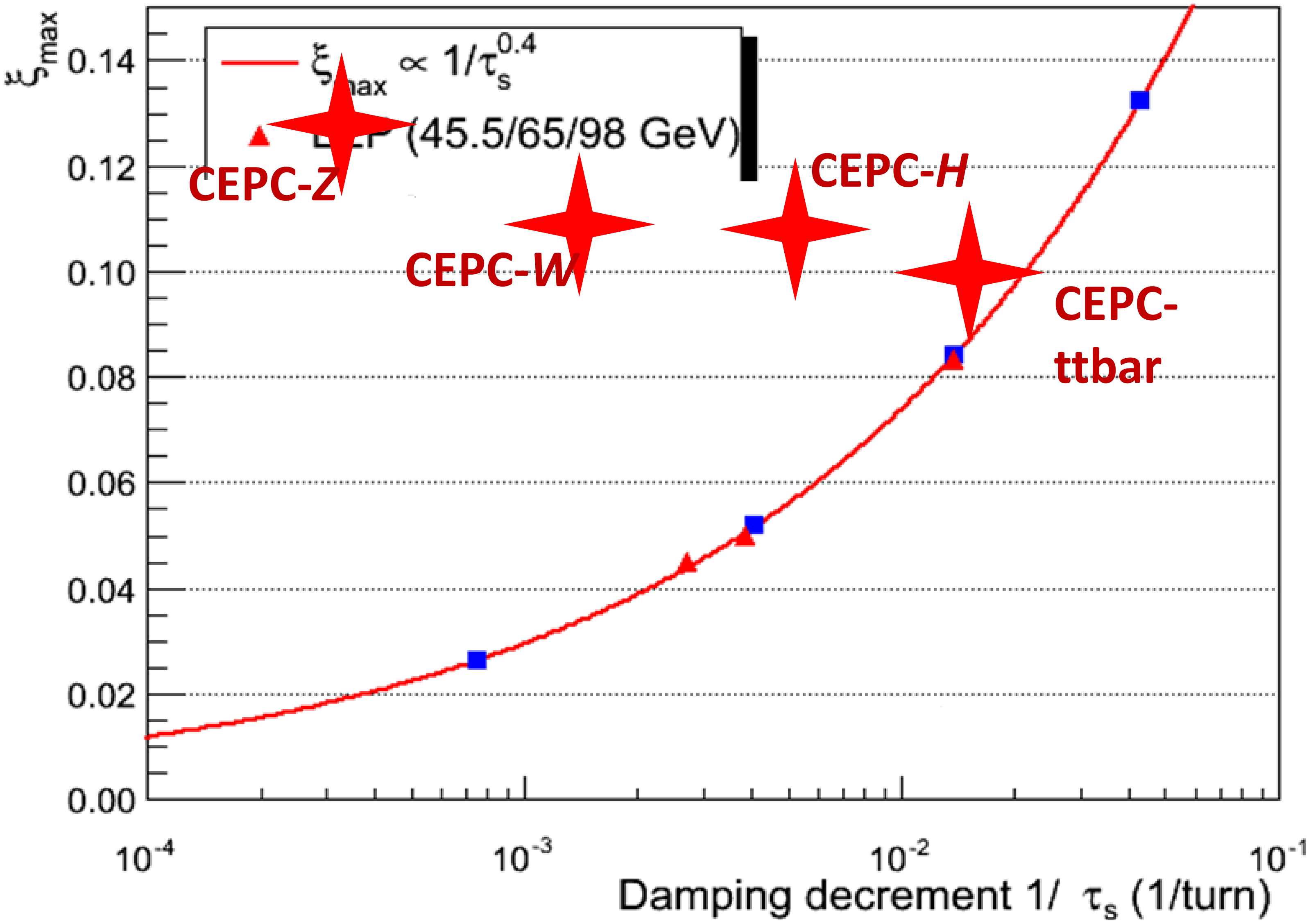
1. Are the accelerator system design goals well defined? Have the goals been reached in the TDR?
2. Are the accelerator physics issues adequately addressed?

Design Parameters

2 IPs, 2x16.5 mrad
100 km

	Higgs	Z	W	ttbar
Beam Energy [GeV]	120	45.5	80	180
Damping Decrement (x/y/z, SR)	0.75/0.75/1.5 $[10^{-2}]$	4/4/8 $[10^{-4}]$	2.2/2.2/4.4 $[10^{-3}]$	2.5/2.5/5 $[10^{-2}]$
β_x^*/β_y^* [m/mm]	0.3/1	0.13/0.9	0.21/1	1.04/2.7
ϵ_x/ϵ_y [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
σ_z (SR/BS) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
σ_p (SR/BS) [%]	0.1/0.17	0.04/0.13	0.07/0.14	0.15/0.2
$\beta_y^*\theta/\sigma_x$	1.2	2.5	1.2	1.2
Piwinski Angle	4.88	24.23	5.98	1.23
ν_s	0.0049	0.035	0.062	0.078
Bunch Population $[10^{10}]$	13	14	13.5	20
ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
Bunch Number	268	11934	1297	35
Luminosity/IP $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	5	115	16	0.5

R. Assmann and K. Cornelis, EPAC'00



Crab-waist collision

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

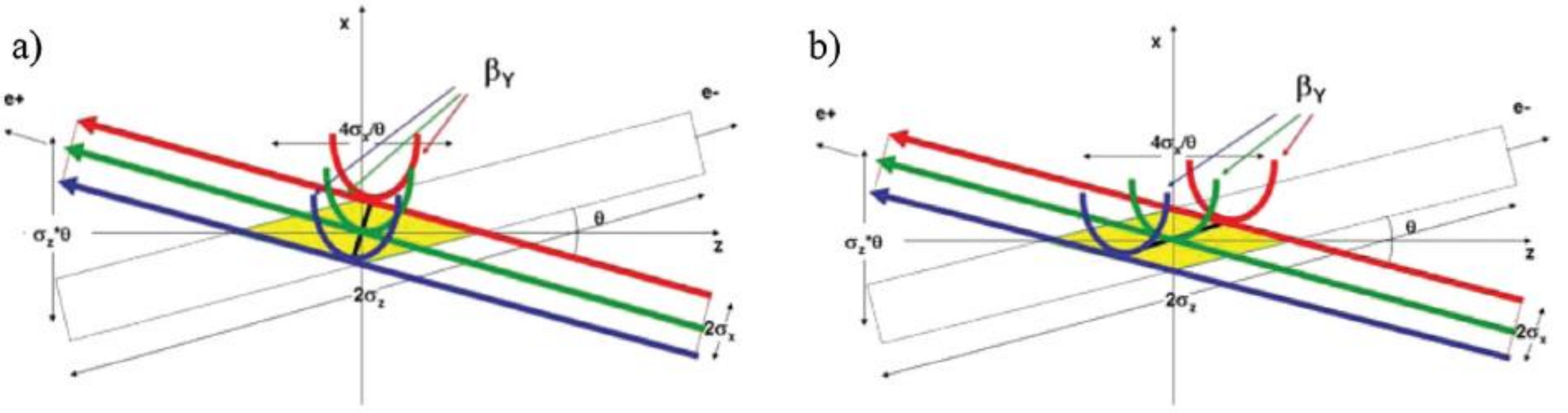


FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

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

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

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

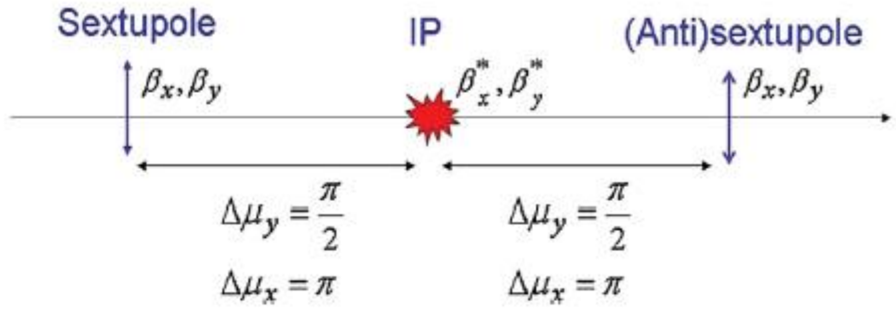
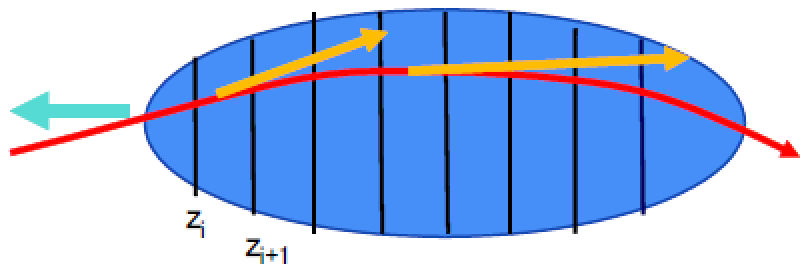


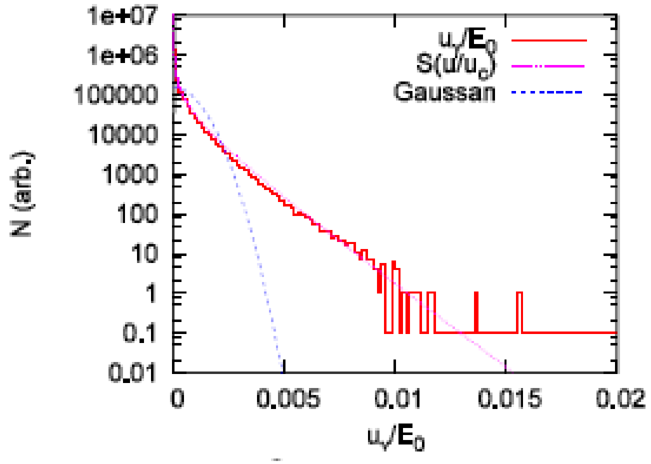
FIG. 2 (color). Crab sextupole locations.

Beamstrahlung Effect & 3D flip-flop

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).

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





Simulation Tool

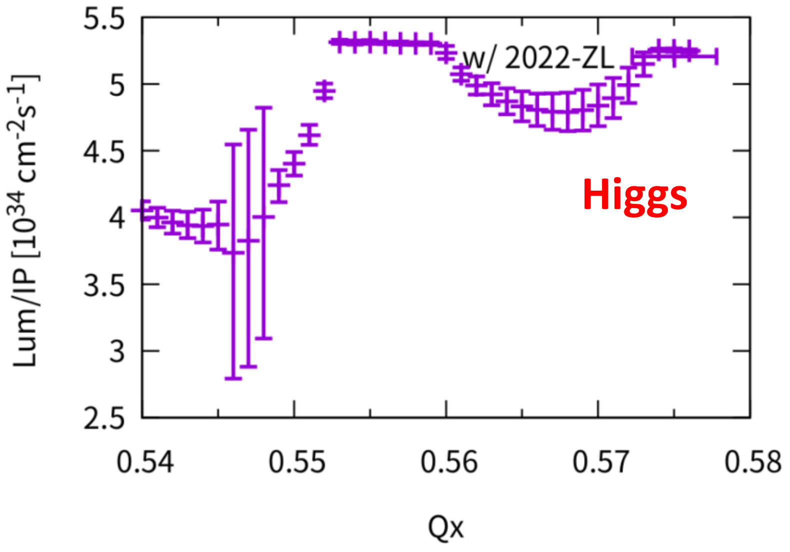
IBB

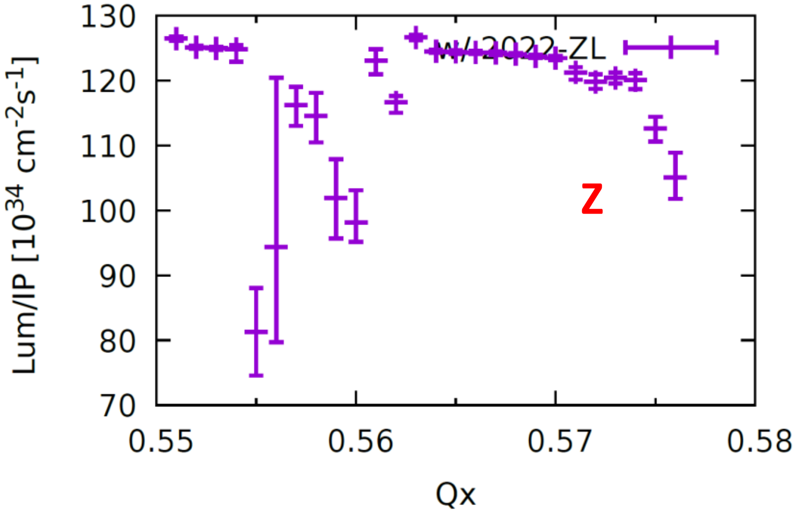
K. Hirata et al., PA 40, 205-228 (1993)
K. Hirata, PRL, 74, 2228 (1995)
Y. Zhang et al., PRST-AB, 8, 074402 (2005)
Y. Seimiya et al., PTP 127, 1099 (2012)
K. Ohmi, IPAC16
Y. Zhang et al., PRAB 23, 104402, (2020)

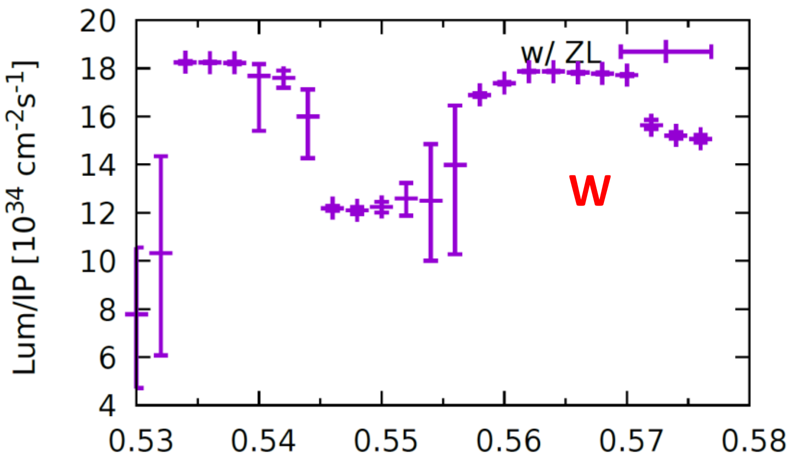
- Linear Arc Map with SR radiation
- One turn map including general chromaticity
- Horizontal crossing angle: Lorentz boost map
- Bunch slice number is about 10 times Piwinski angle
- Slice-Slice collision: Synchro-beam mapping method (or PIC)
- Synchrotron radiation during collision
- Longitudinal wakefield
- Transverse wakefield

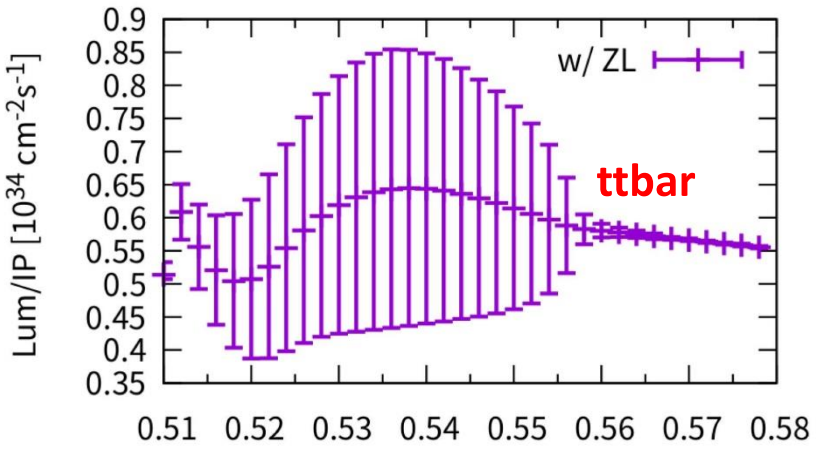
Luminosity versus horizontal tune

The design luminosity could be achieved in the pure beam-beam simulation.



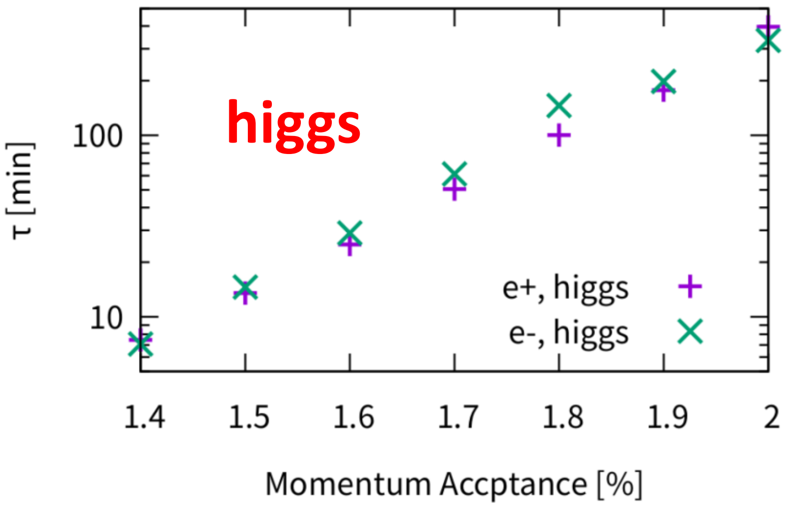


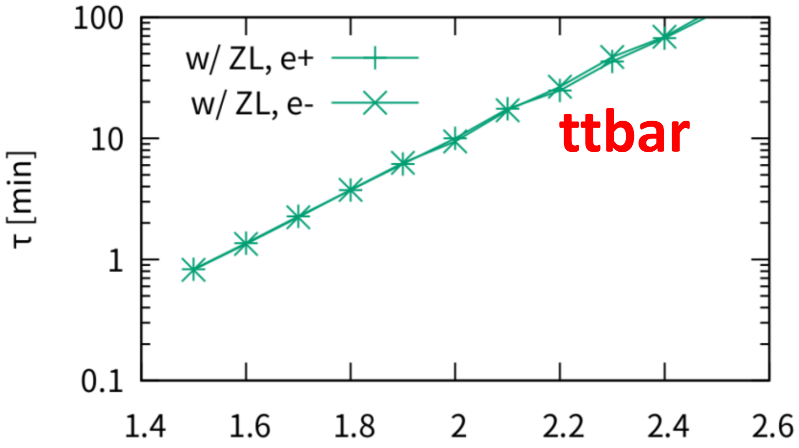


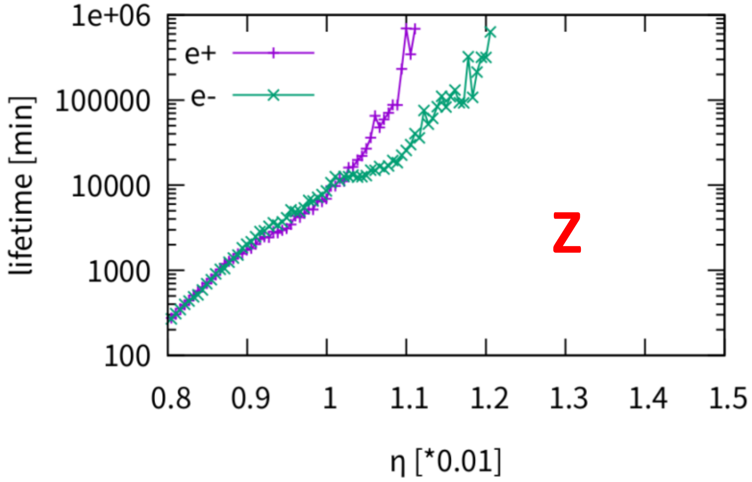


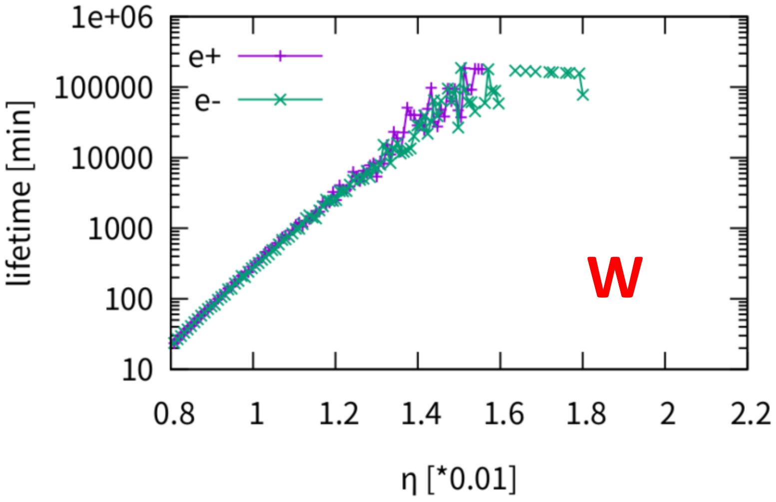
Beamstrahlung Lifetime vs Momentum Acceptance

The pure beam-beam simulation presents a goal value for Lattice optimization.



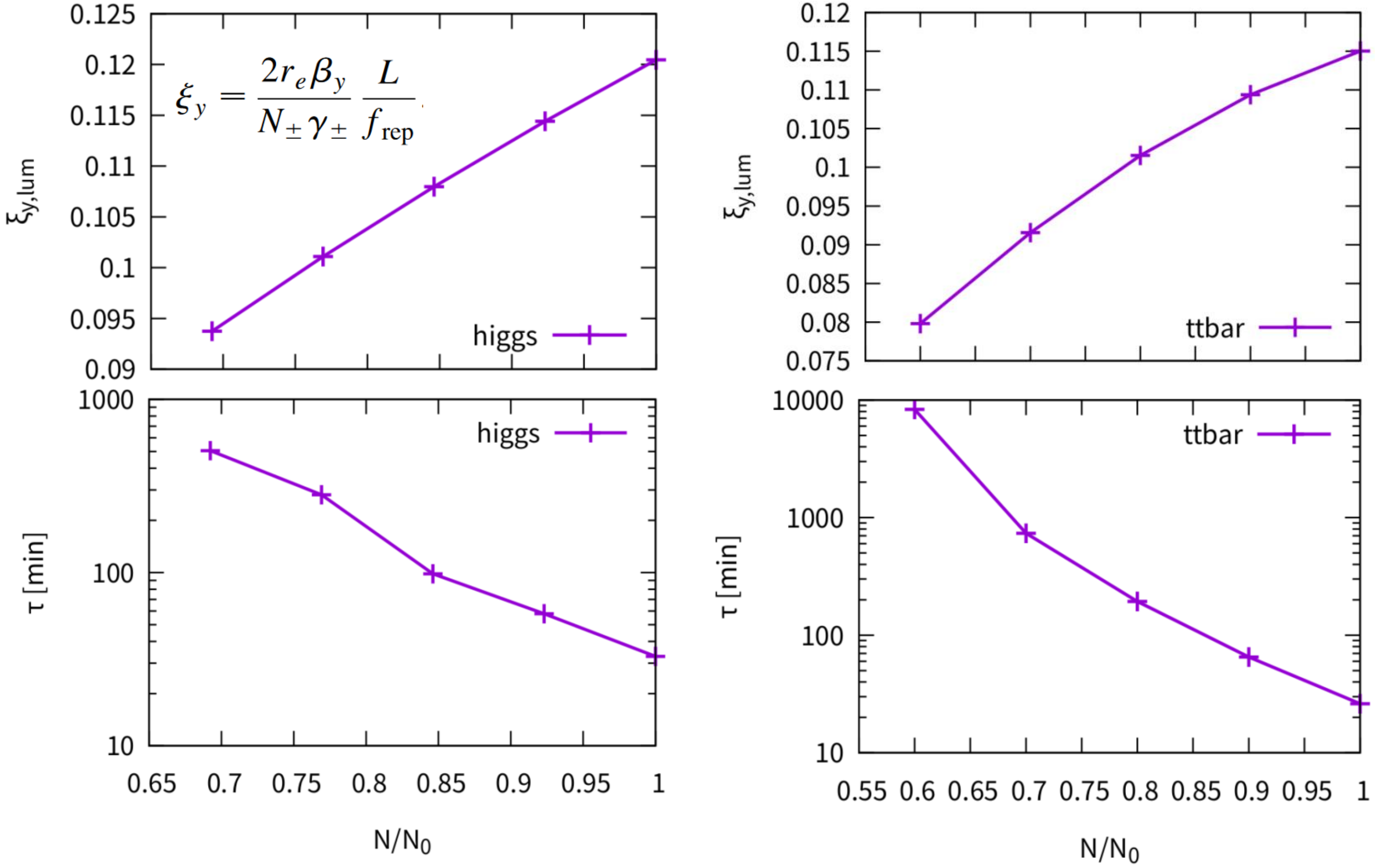






* If particles exceed the momentum acceptance are checked just after collision.

Beam-Beam Performance & Beamstrahlung lifetime vs bunch population (higgs/ttbar)

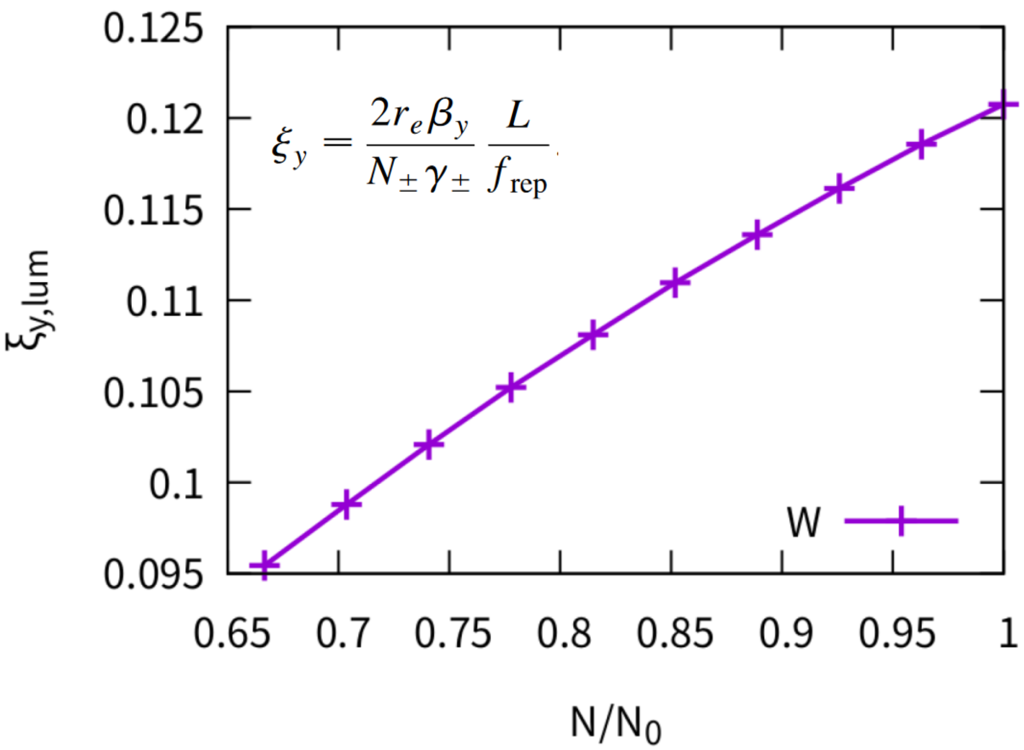


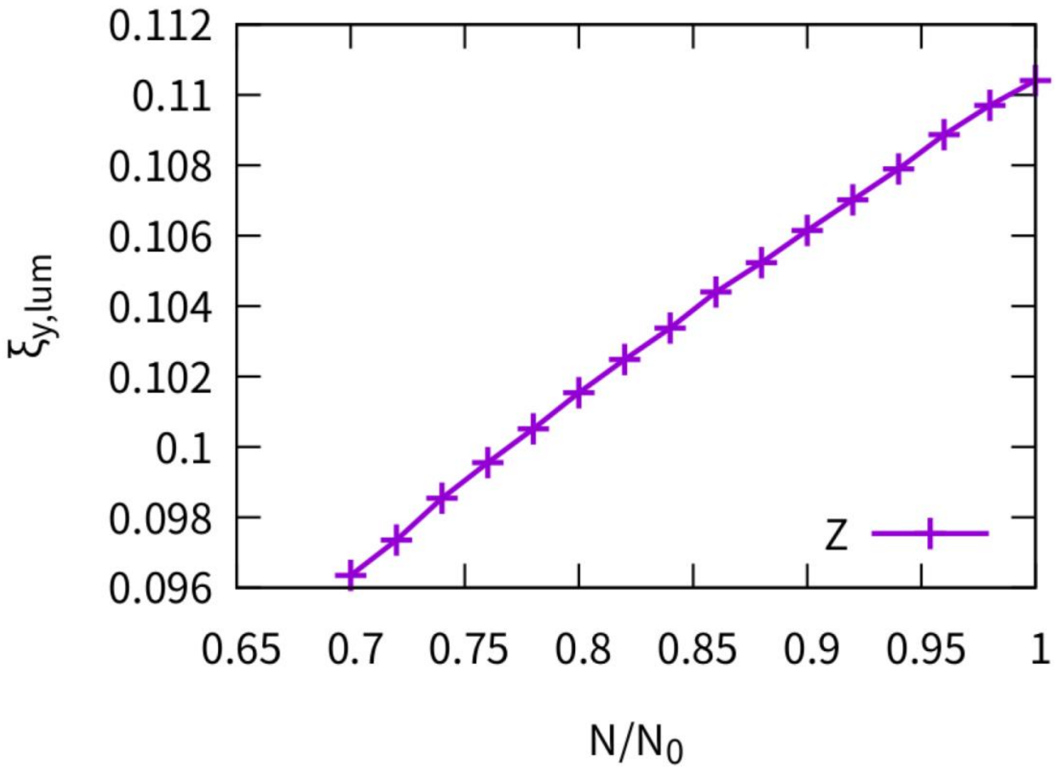
- The beam-beam parameter does not stature at design bunch population
- The beamstrahlung lifetime evaluation shows that it is very sensitive to the bunch population

* If particles exceed the momentum acceptance are checked just after collsion.

Beam-Beam Performance vs bunch population (W/Z)

- The beam-beam parameter does not stature at design bunch population

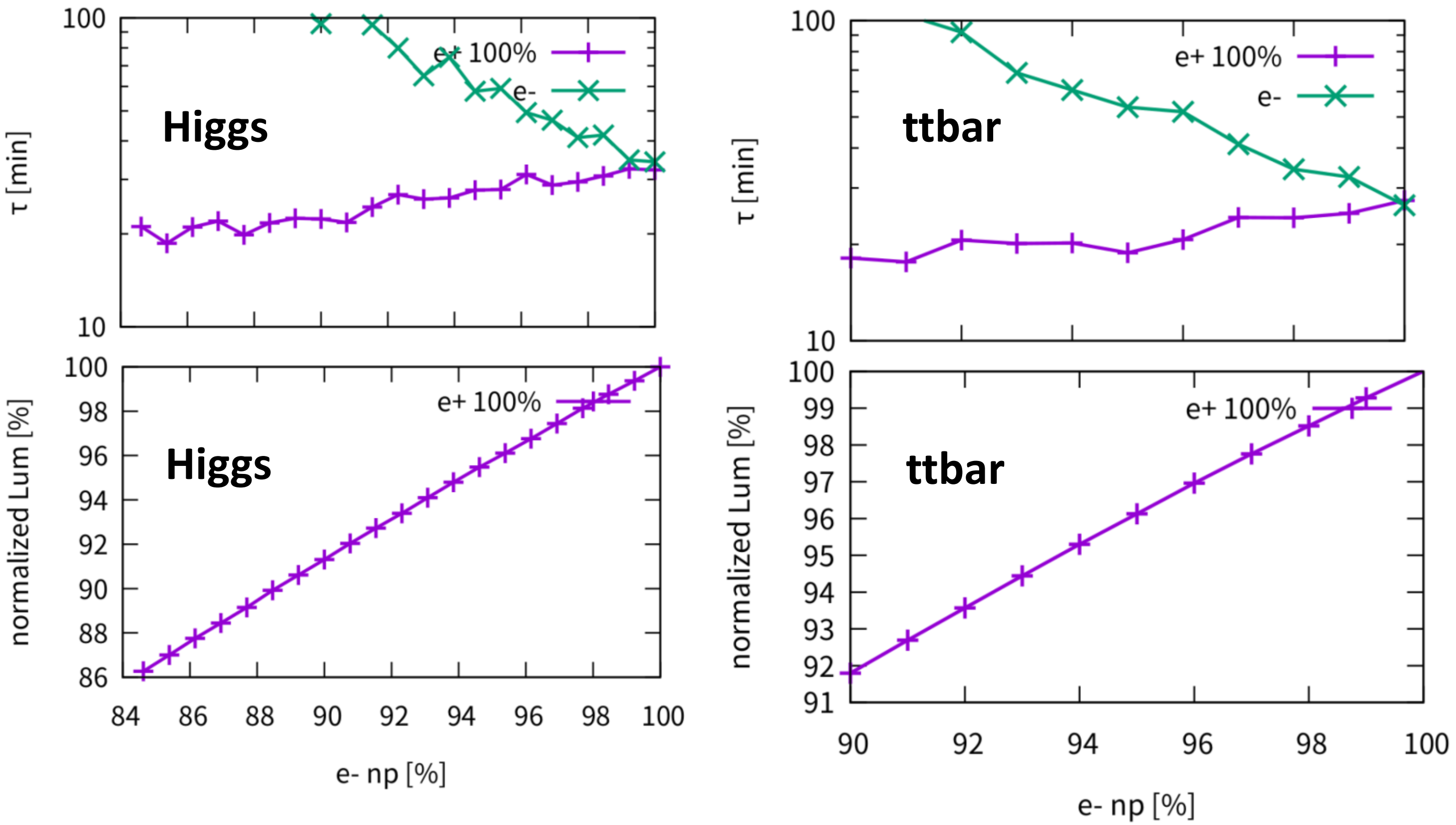




Asymmetric Collision: Higgs/ttbar

Lifetime

Luminosity



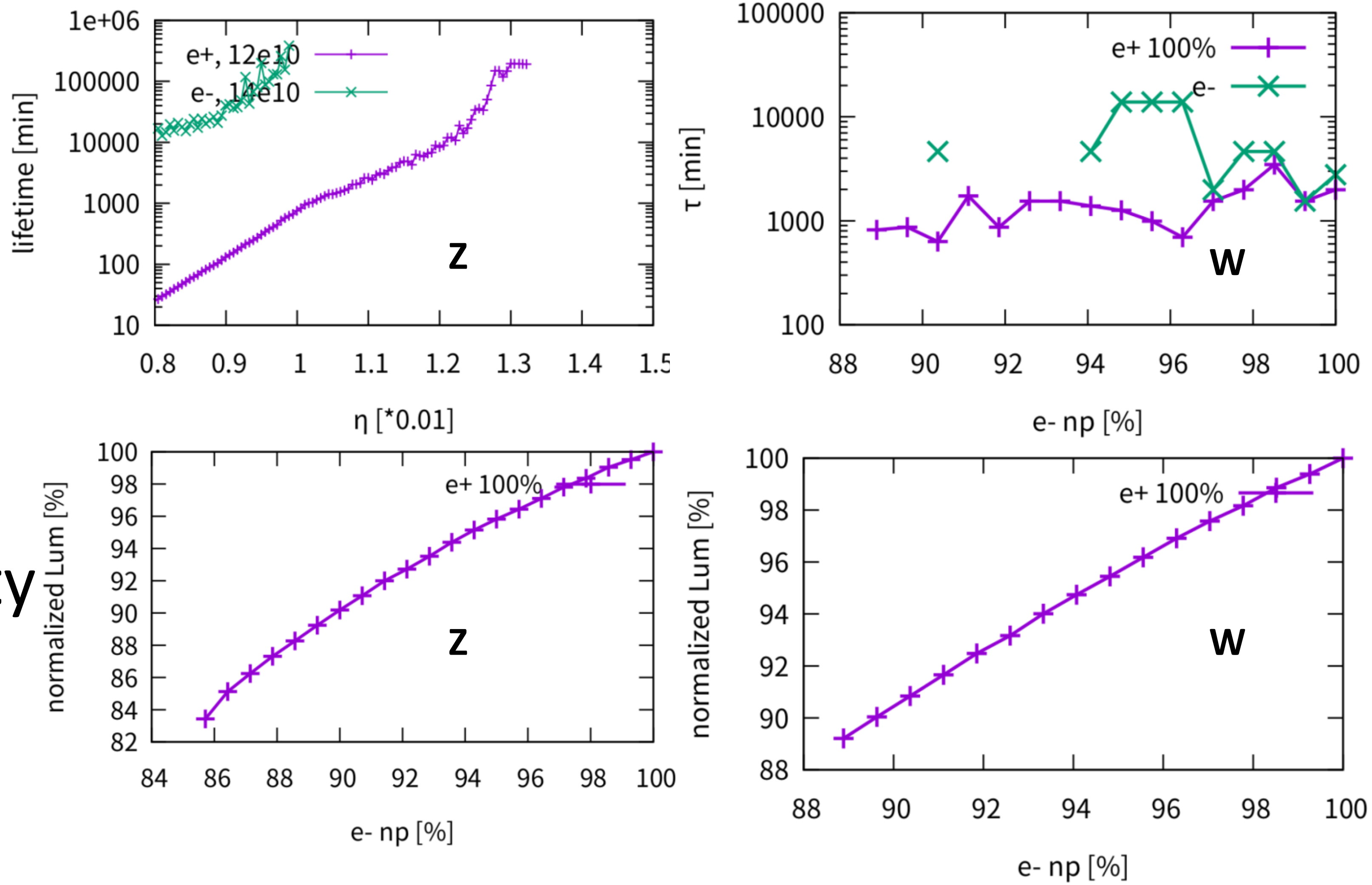
- The weak beam's lifetime would be about only half with collision between 100% vs 90% bunch population. (design 100% vs 97%: ~20% lifetime reduction)
- The luminosity scale linearly with the weak beam's bunch population

* If particles exceed the momentum acceptance are checked just after collision.

Asymmetric Collision: Z/W

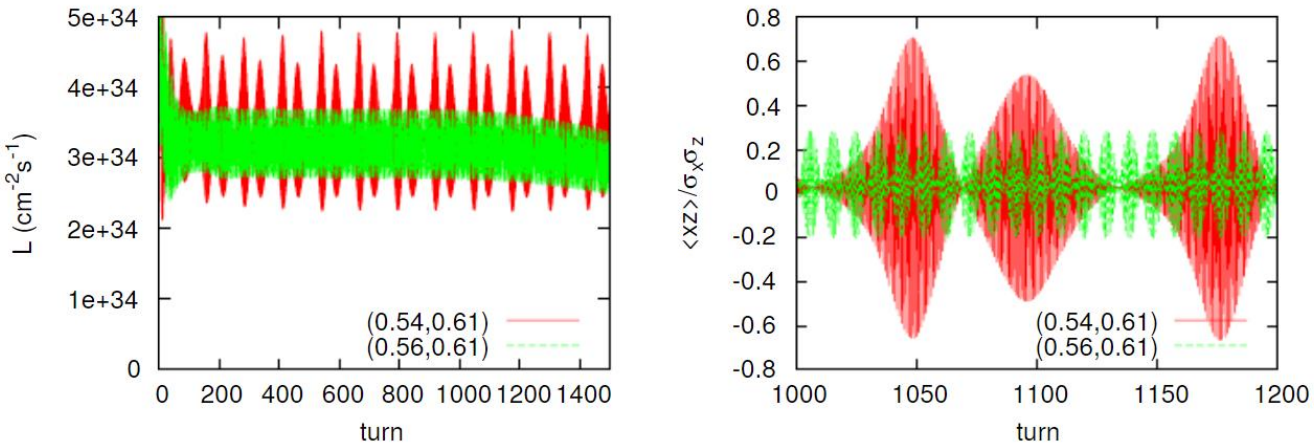
Lifetime

Luminosity



- The beamstrahlung lifetime induced by pure beam-beam interaction would not be a serious issue.
- The luminosity scale linearly with the weak beam's bunch population

Horizontal Coherent Beam-Beam Instability (X-Z instability)



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

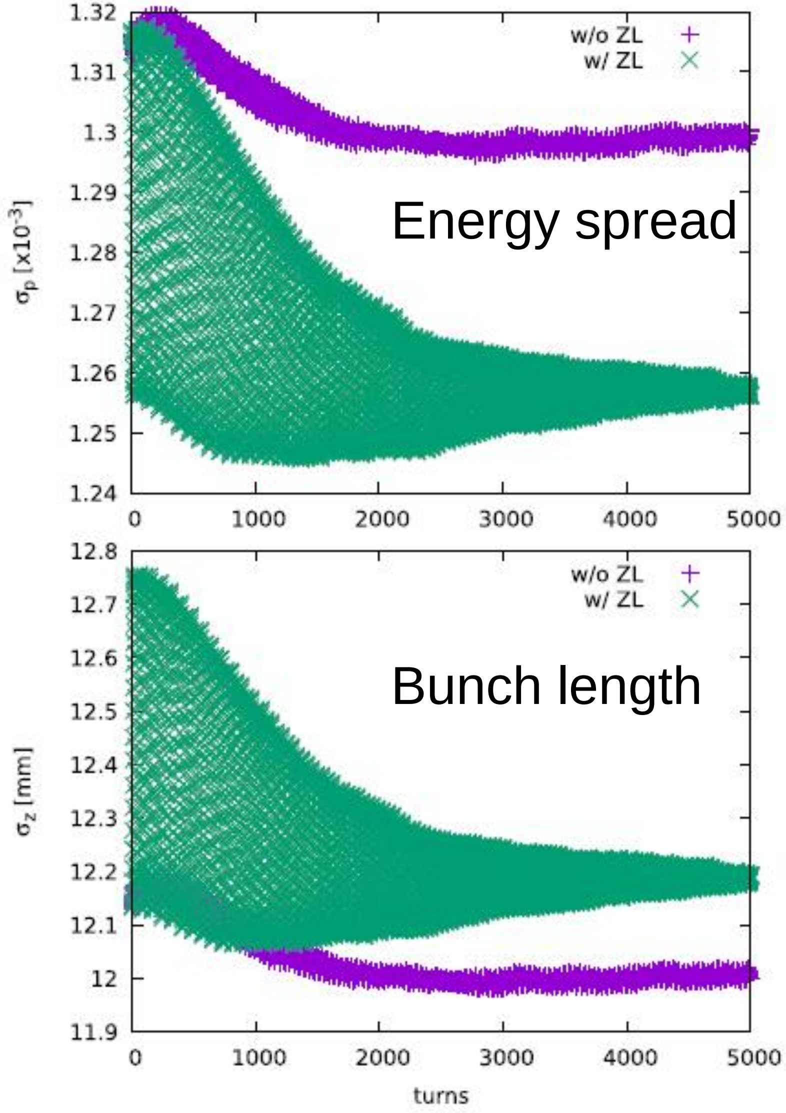
1. In the collision scheme with Crab Waist and Large Piwinski Angle the luminosity and tune shifts strongly depend on the bunch length

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

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

Combined effect of beamstrahlung and longitudinal impedance in stable tune areas

D.Leshenok and et al. PRAB 23, 101003 (2020)
Y. Zhang et al., PRAB 23, 104402, (2020)



Semi-analytical calculations are in reasonable agreement with numerical modeling

TABLE IV. The FCC-ee beam energy spread and length as well as the synchrotron tune parameter due to the combined effect of SR, BS, and PWD.

E [GeV]	45.6
σ_E	0.00126[a]
	0.00132[b]
σ_z [mm]	12.2[a]
	12.6[b]
ν_s/ν_{s0}	0.964[b]

[a]Beam-beam simulation [21].
[b]Semianalytical model (SR + BS + PWD).

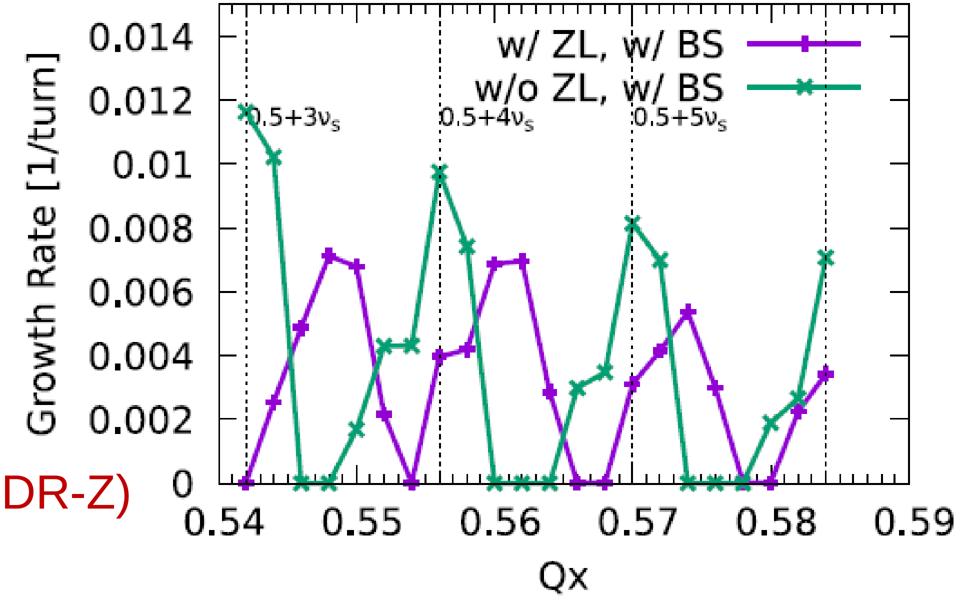
Longitudinal Impedance induces
- Longer bunch length
- Lower energy spread
- Lower incoherent synchrotron tune

X-Z instability with and without beam coupling impedance

Y. Zhang etal., PRAB 23, 104402, (2020)
C. Lin etal.,, PRAB 25, 011001 (2022)

By including the impedance stable areas become narrower and are shifted

(CEPC-CDR-Z)

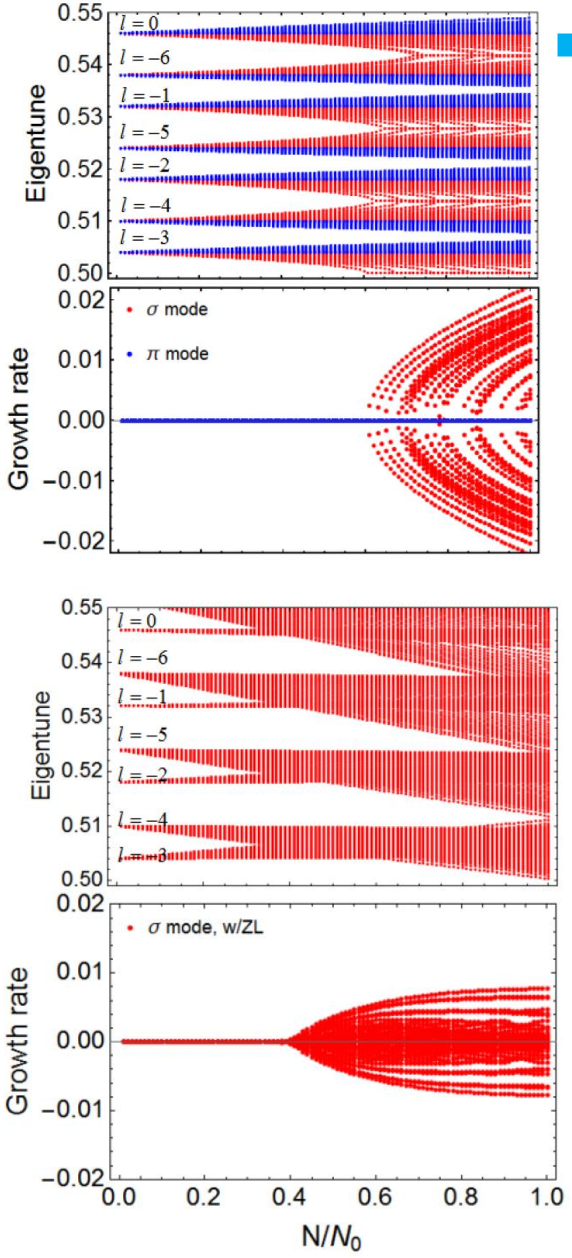


After the horizontal beta function reduction from 0.2 m down to 0.15 m

FIG. 3. The horizontal beam size growth rate versus horizontal tune with and without longitudinal coupling impedance (ZL). Beamstrahlung (BS) effect is turned on.

w/o ZL

w/ ZL, σ mode



Parameter Optimization for X-Z instability

K. Oide， IPAC2017
D. Shatilov, *ICFA Beam Dyn.Newslett.* 72 (2017) 30-41
Y. Zhang et al., PRAB 23, 104402, (2020)

$$N_{th} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*},$$

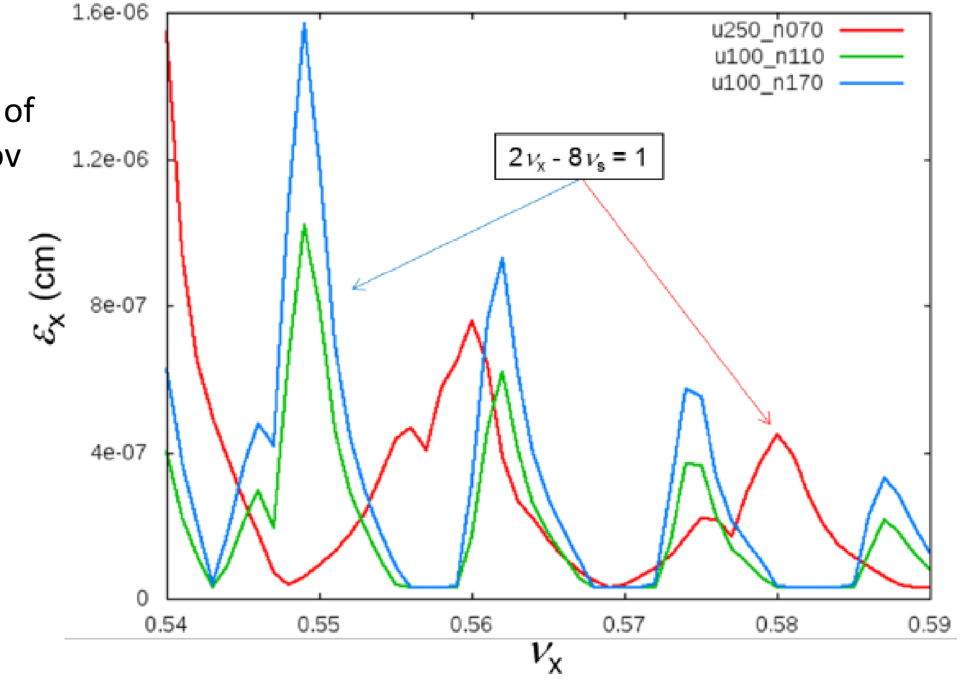
$$\alpha_p \sigma_\delta \propto \nu_s \sigma_z$$

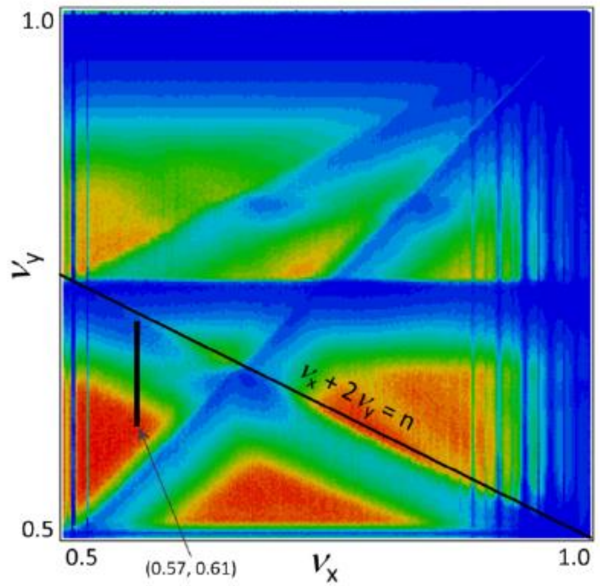
$$\xi_x \propto N_p \beta_x^* / \sigma_z^2$$

Larger ν_s/ξ_x is preferred

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

Courtesy of D. Shatilov





Courtesy of D. Shatilov

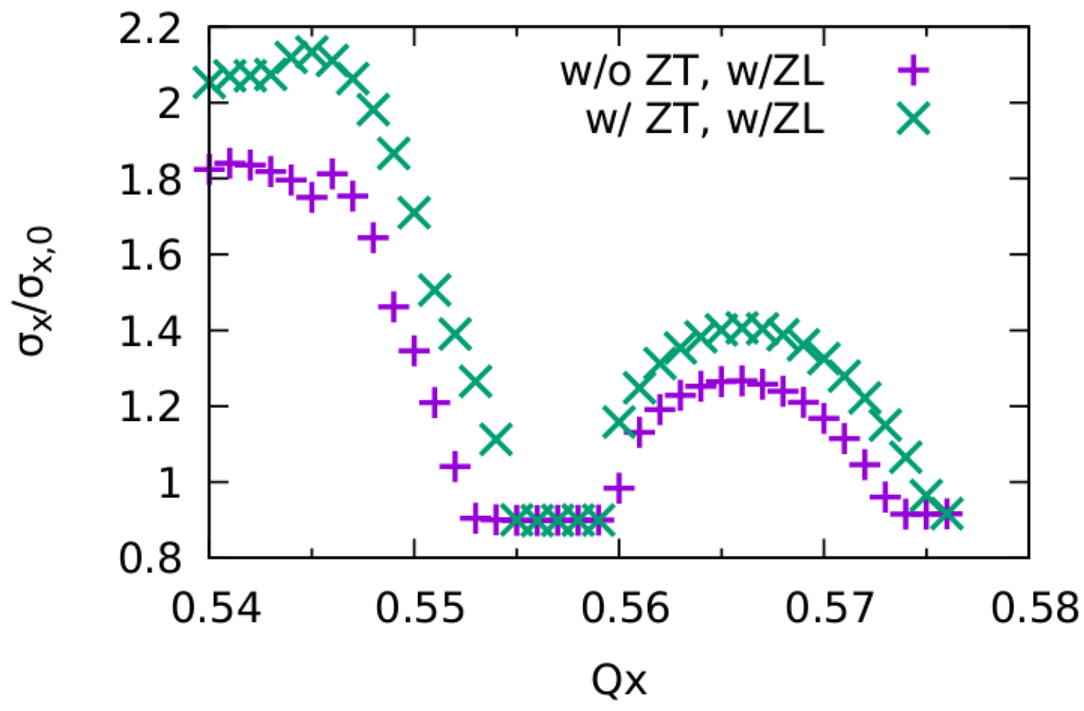
Different modes of CEPC has been well optimized to mitigate the X-Z instability

w/ transverse impedance (ZT): Higgs/ttbar

Higgs:

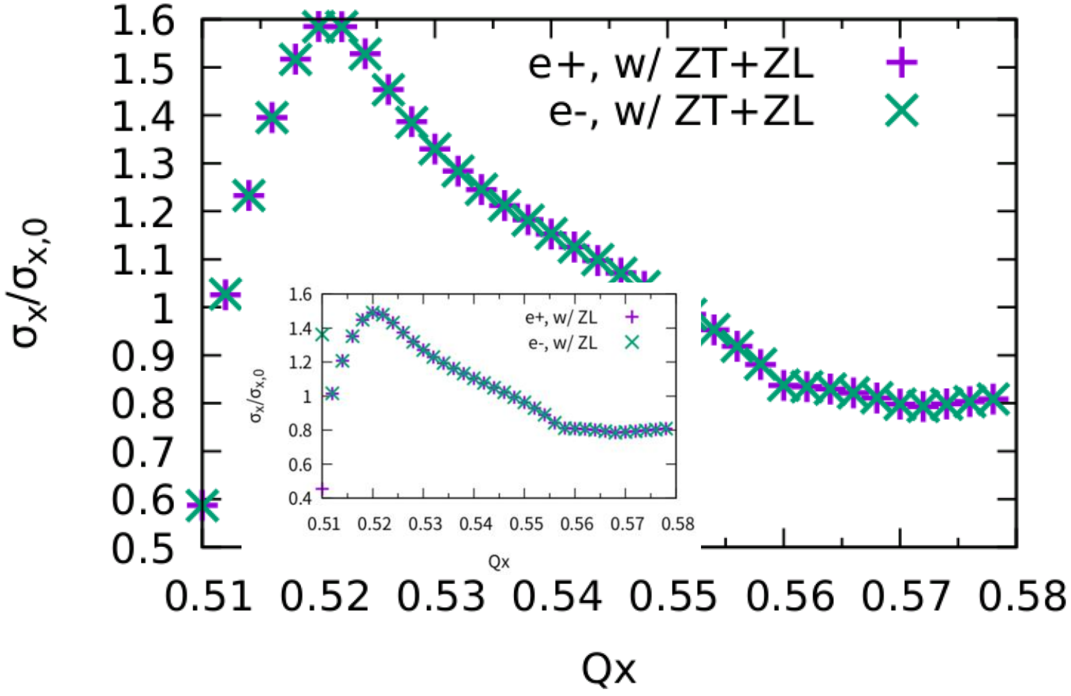
Only X-Z instability

Stable area width is reduced a little (ZT only applied 1 kick)



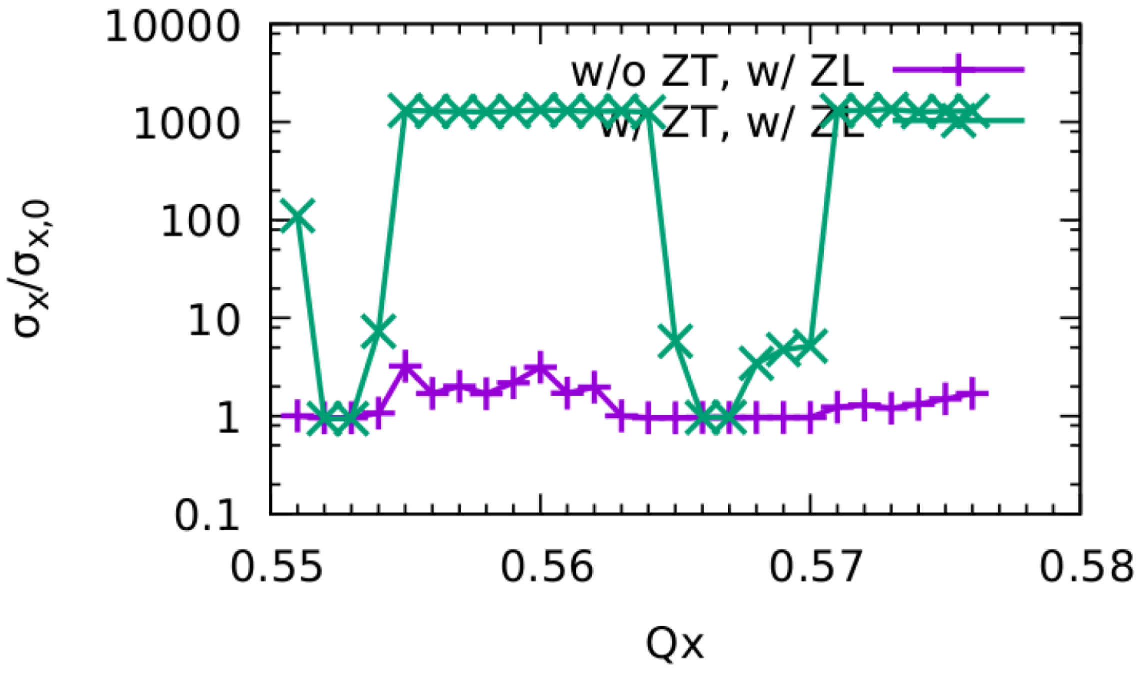
ttbar:

No clear effect from transverse impedance.

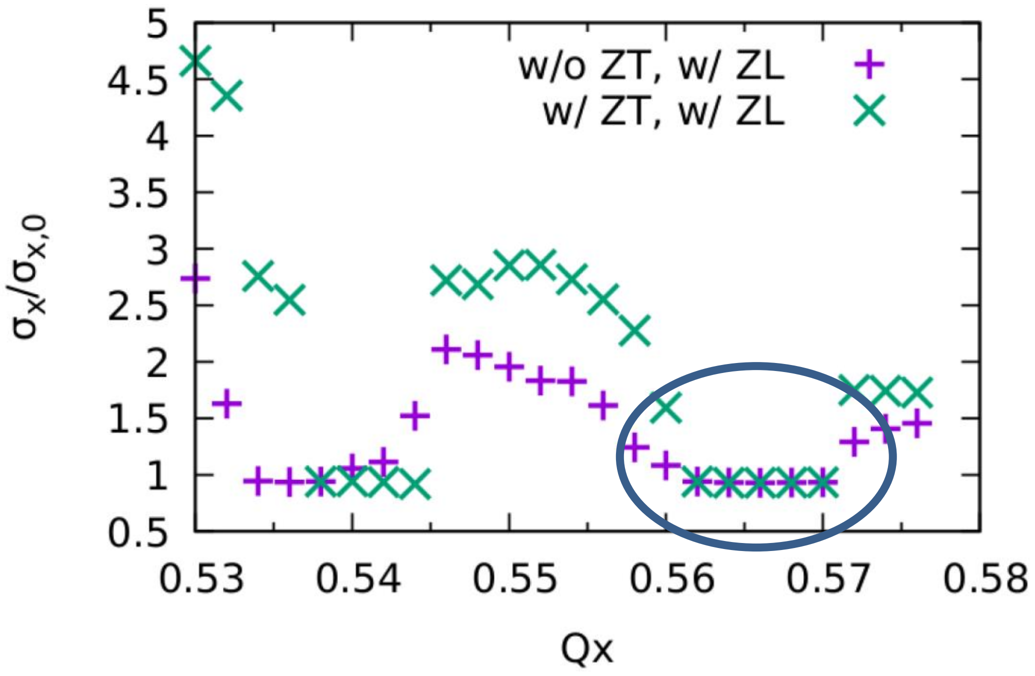


w/ transverse impedance (ZT): Z/W

Z:
No stable working points.
There exist very strong blowup in both X/Y direction



W:
Only X-Z instability
stable area is large enough

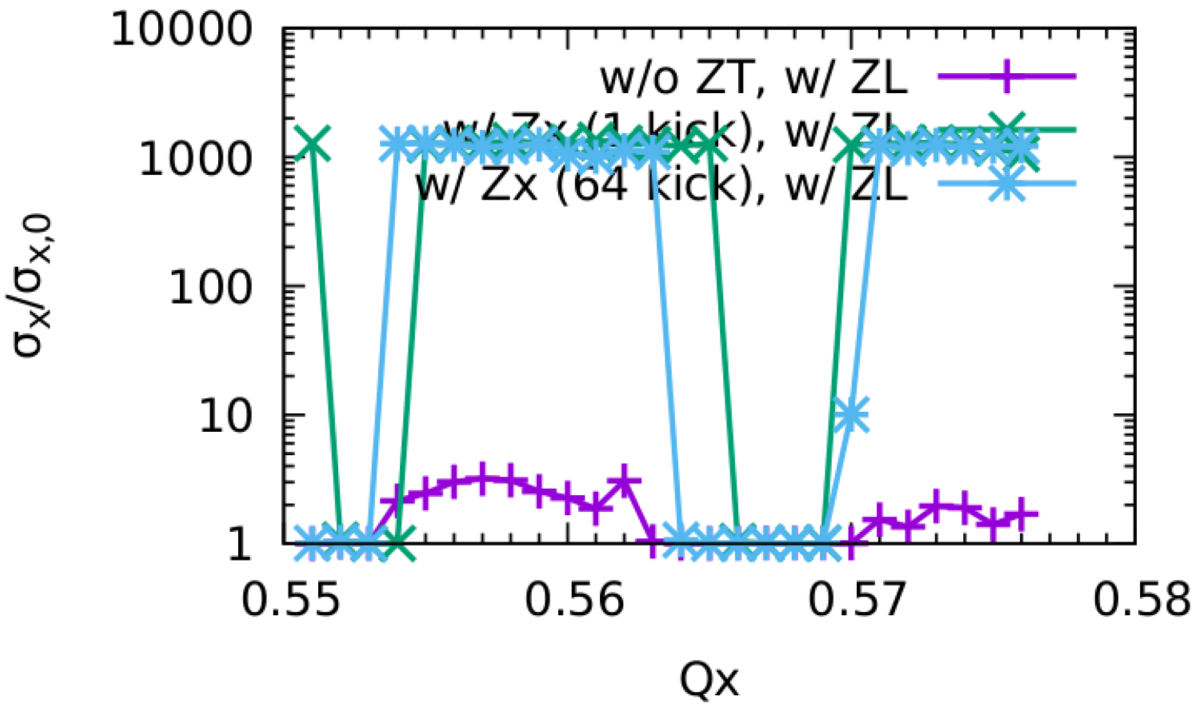


Z: Only horizontal impedance (+ZL)

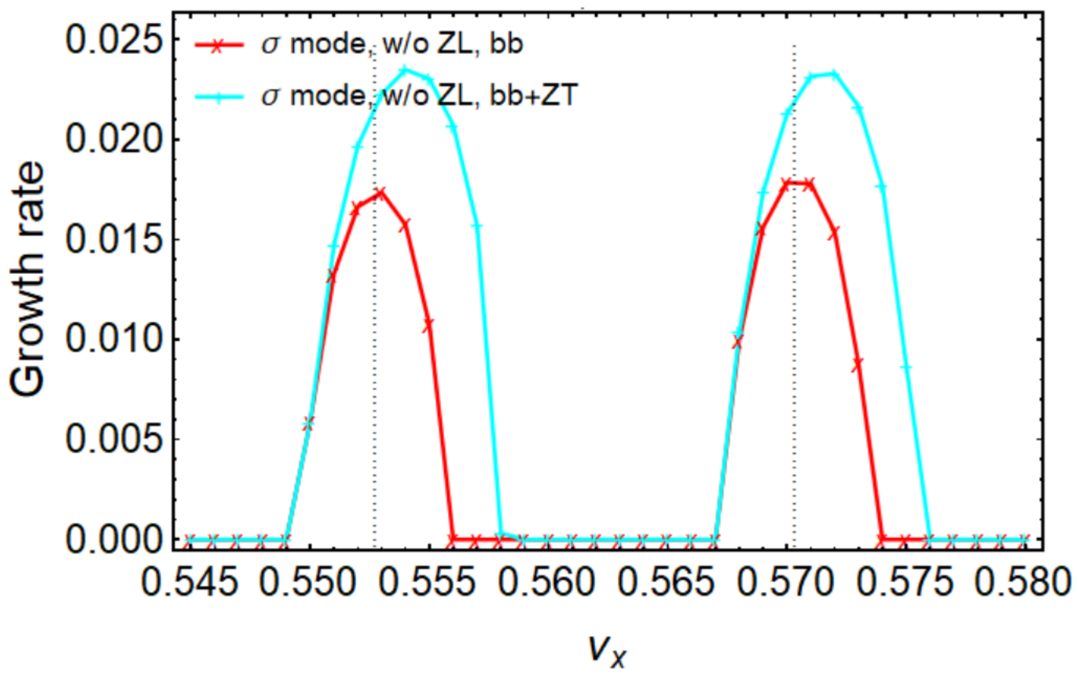
- **Stable tune area is large enough (w/ZX)**
- **Simulation and analysis agree well.**

Courtesy of Chuntao Lin and Na Wang

Simulation



Analysis, ZT kick applied at IP



Kick number of wake field affect the result

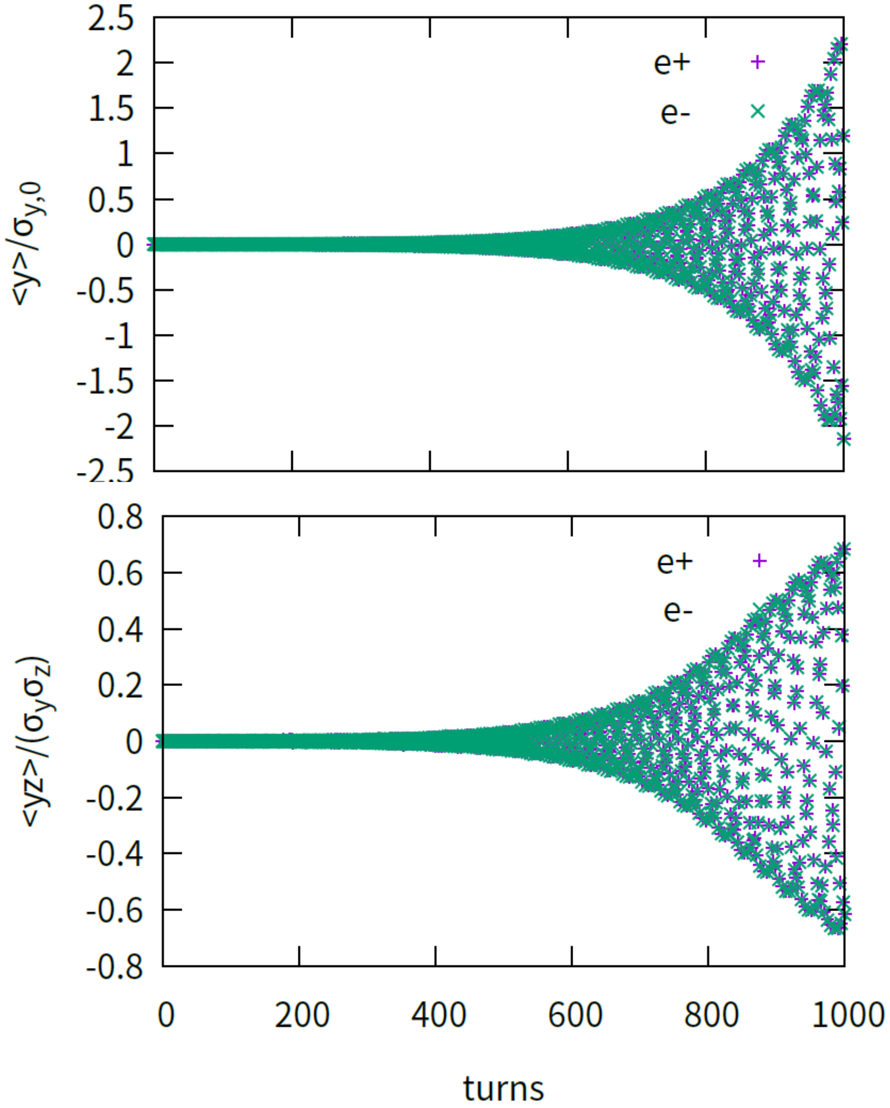
- In horizontal direction, smooth distributed impedance nearly does not squeeze the stable tune area serious
- A very local impedance may squeeze the stable area.

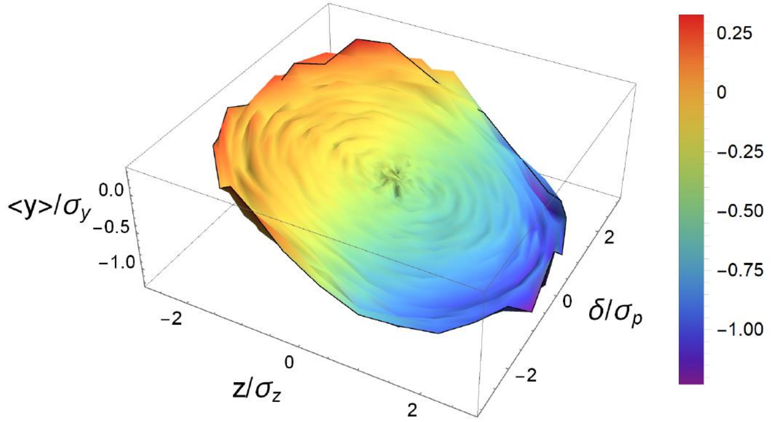
In horizontal direction, considering ZX

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

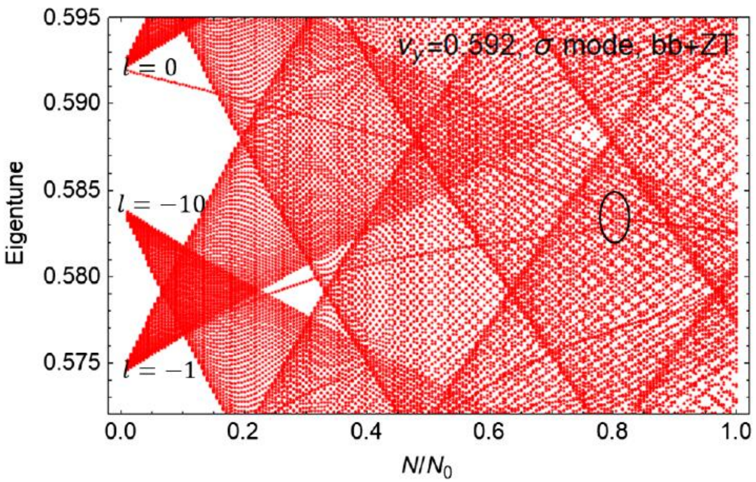
Vertical mode coupling with ZT(σ-mode)

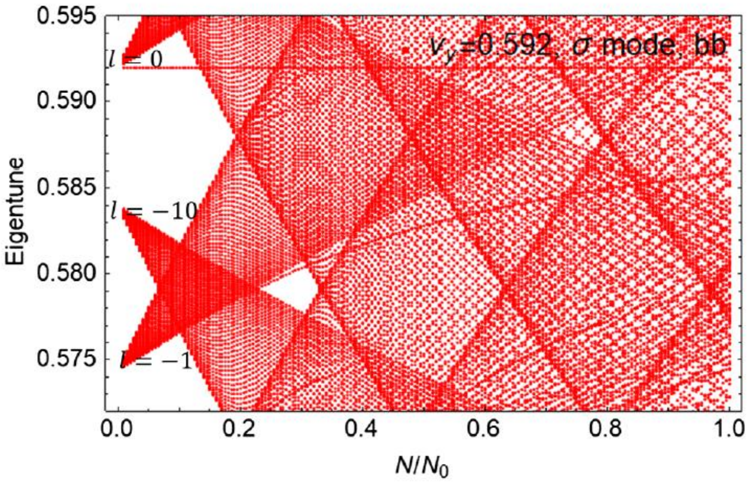
Accepted by PRAB





TMCI threshold is reduced from about 21e10 to 11e10

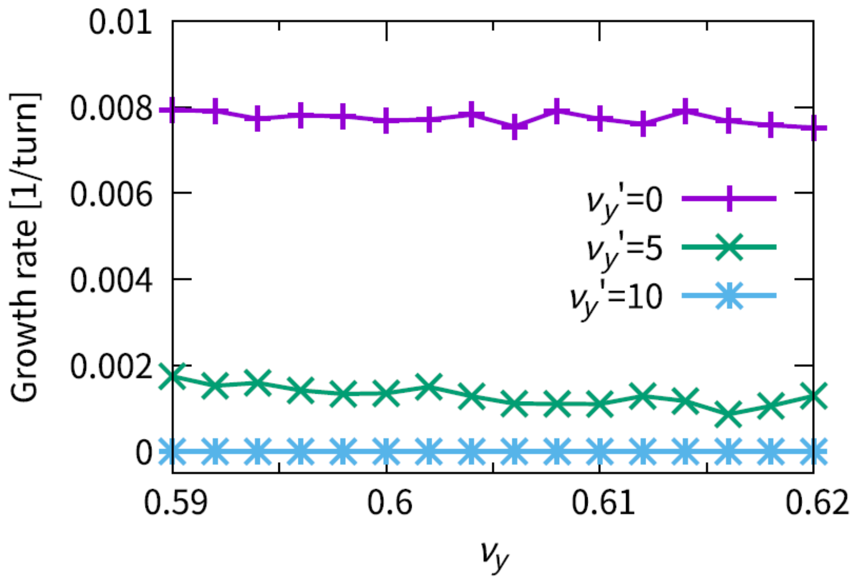




Mitigation of Vertical TMCI (BB+ZT)

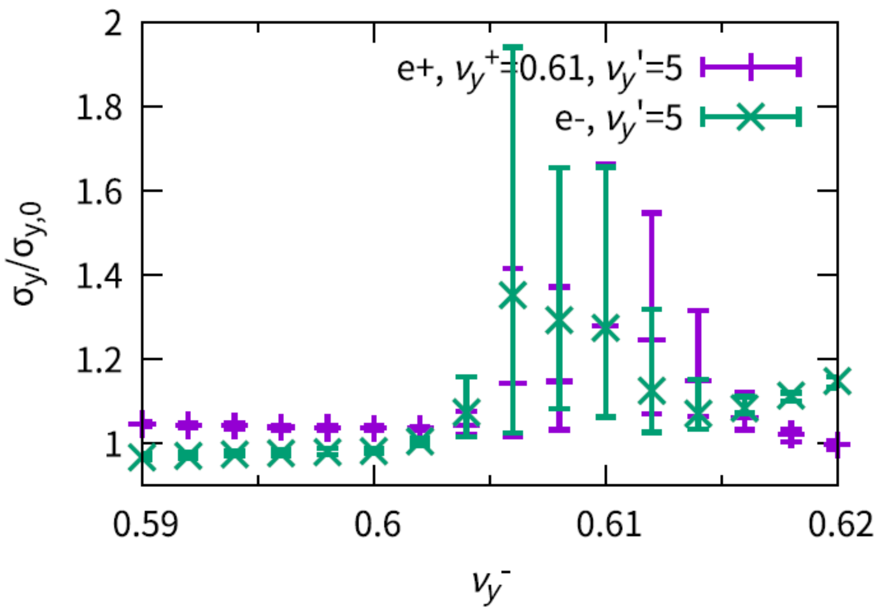
Accepted by PRAB

Chromaticity



Growth rate of vertical centroid versus tune with different vertical chromaticity. Both transverse and longitudinal impedance are considered.

Asymmetrical Tunes + Chromaticity



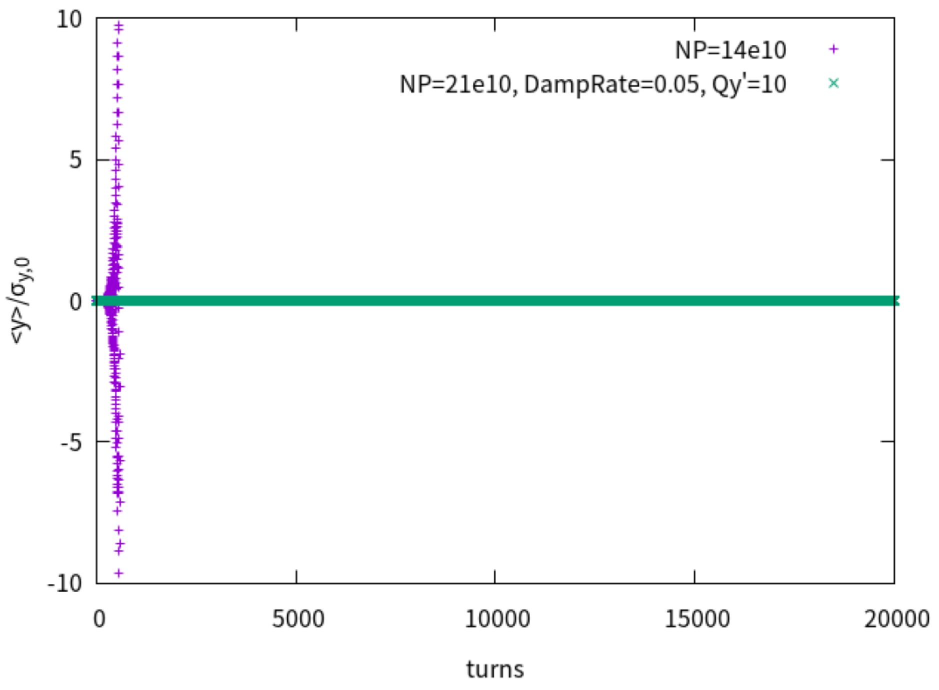
vertical beam size versus asymmetric vertical tunes with different vertical chromaticity. Both transverse and longitudinal impedance are considered. One beam's vertical working point is fixed at 0.610.

More measures to suppress vertical TMCI

Y. Zhang, HK-IAS, 2023
K. Ohmi et al., submitted to PRAB

Feedback + Chromaticity

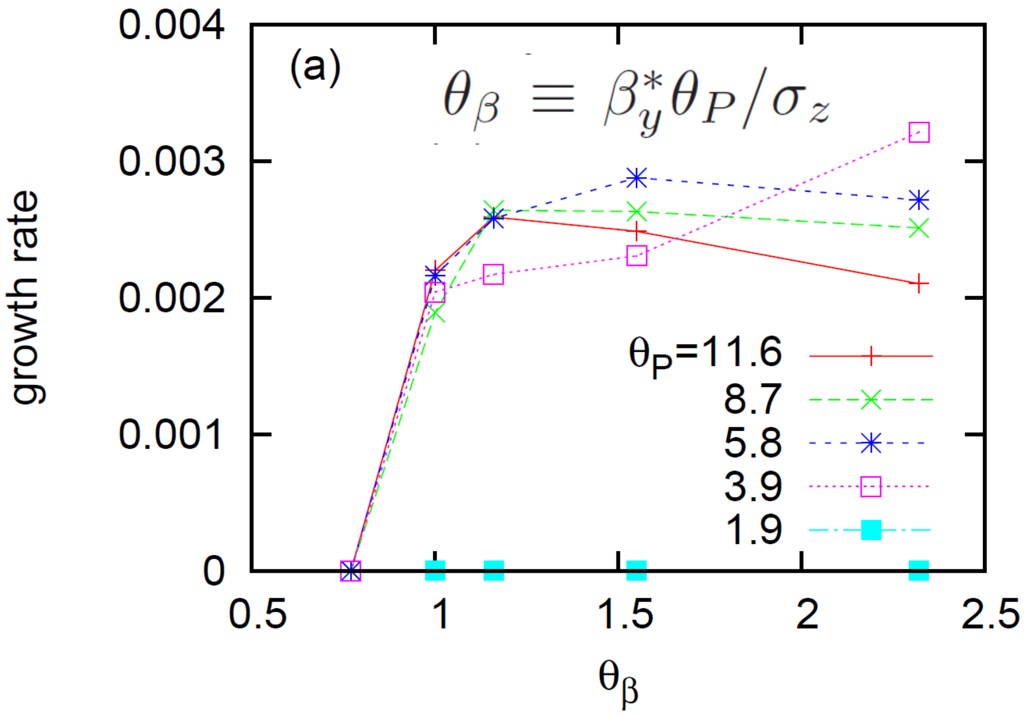
- Resistive feedback, damp rate=0.05 + Qy'=10
- np=21e10 is stable with 1.5 times higher transverse impedance



Hourglass effect

- $\beta_y^* < \sigma_x/\theta$ (K. Ohmi)

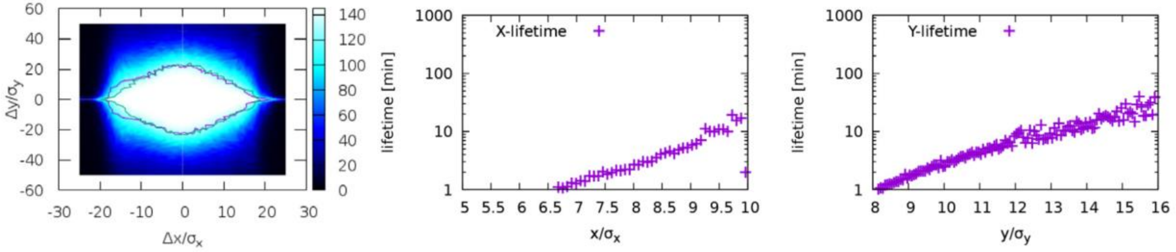
Courtesy of K. Ohmi



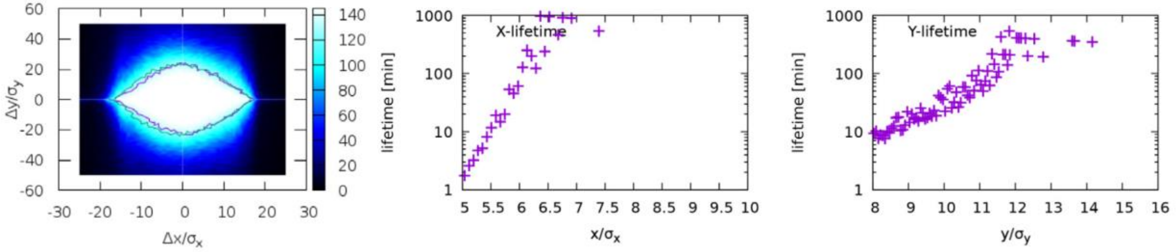
J. Wu et al., NIMA 959 (2020) 163517

Combined effect considering realistic lattice

Case (a) has a larger DA but a shorter beam lifetime, while case (b) is opposite.



(a)



)

$$ai \equiv \sqrt{\frac{2J_i}{\varepsilon_i}}\,(i = x, y, z)\,,$$

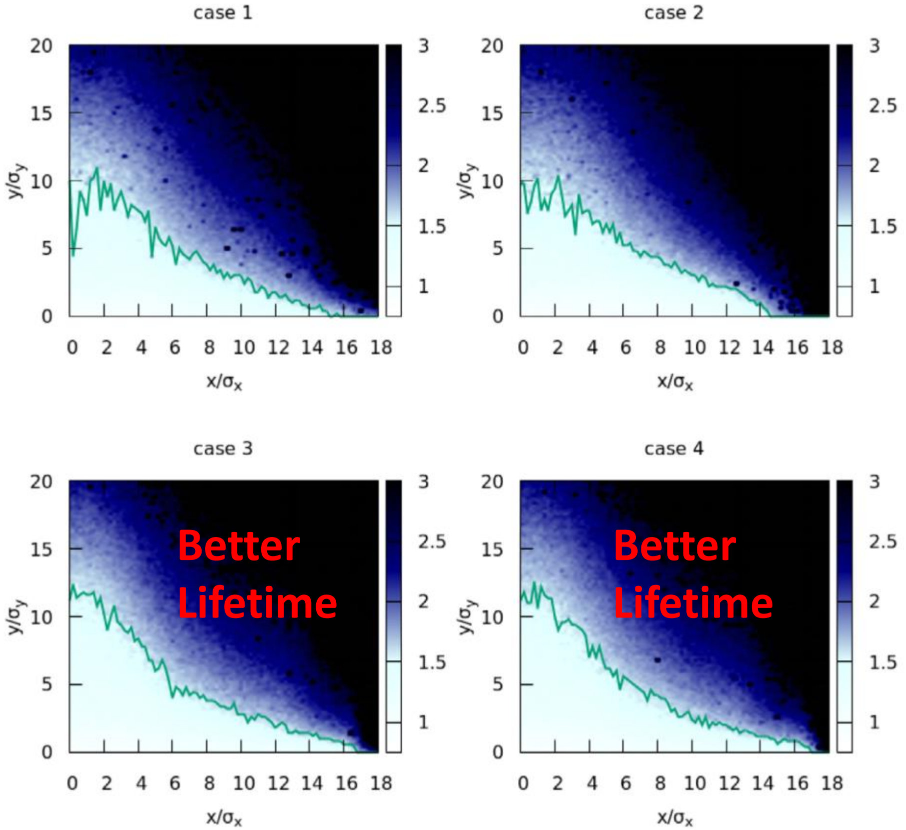
$$\sigma_a \stackrel{\text{def}}{=} \sqrt{\sigma_{ax}^2 + \sigma_{ay}^2 + \sigma_{az}^2}.$$

Diffusion Map:

$$f(ax, ay) \equiv \log_{10}\left(\sum_{turn} \sigma_a^2\right).$$

- **lattice nonlinearity**
- **strong synchrotron radiation**
- **Beam-beam interaction**
- **beamstrahlung effect**

Diffusion Map Analysis of Four Cases



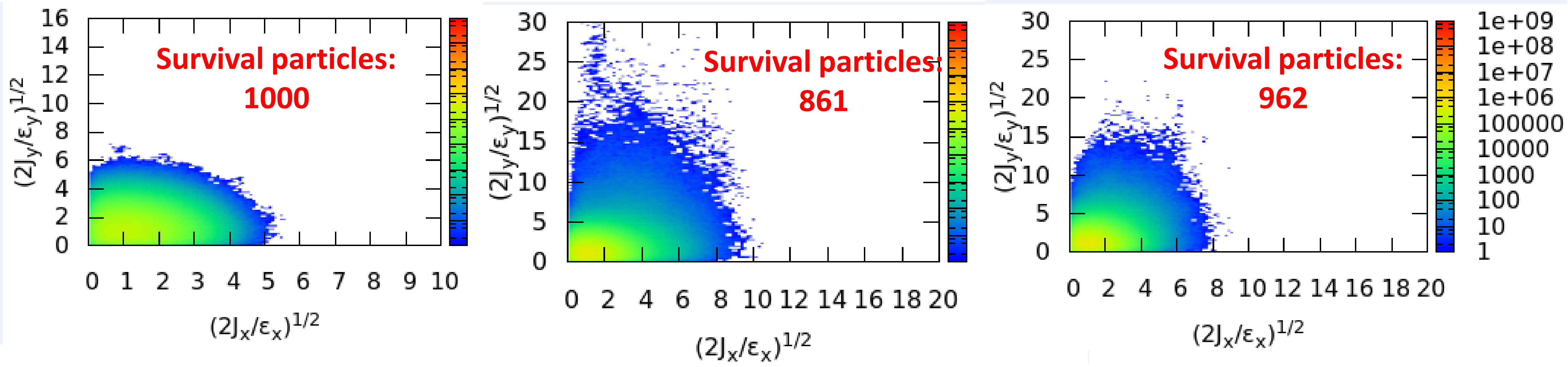
A lifetime optimization sample

Huiping Geng, Yiwei Wang

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

- **w/ BB and BS**
- 32 families of sextupoles in Arc
- Optimization of diffusion

w/o BB and BS **w/ BB and BS**



Code development for future work

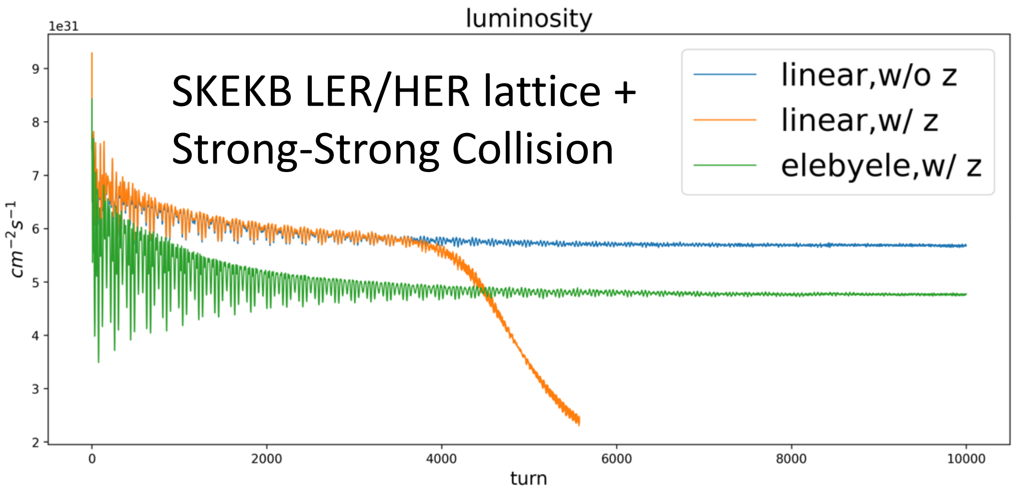
Zhiyuan Li, K. Ohmi and Demin Zhou

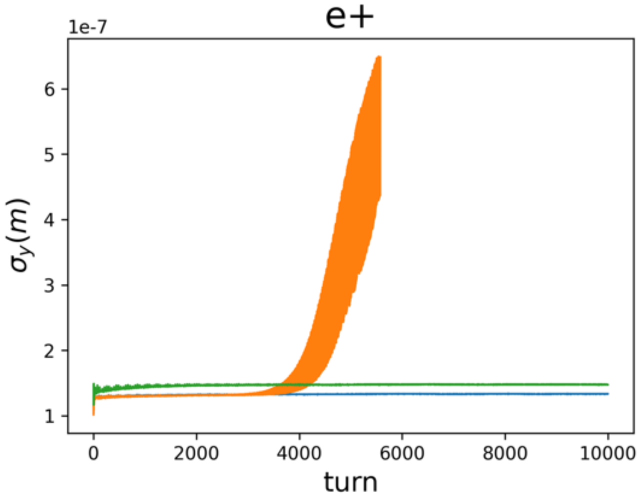
- Tracking with realistic lattice + **Strong Beam-Beam**
- Based on SAD,
  - Supports element: DRIFT, BEND, QUAD, SEXT, MULT, SOL, CAVIT, APERT
  - Support lattice generated by SAD
  - Lattice error could be included
- CPU and GPU.
  - MPI or CUDA to parallelize multi-particle tracking
- Collective effects (MPI) could be included

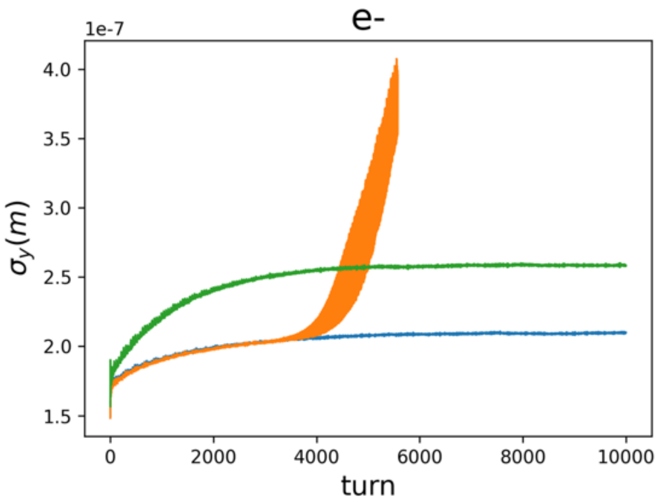
GPU:NVIDIA A100 FP64： 9.746 TFLOPS (1:2)
CPU: Intel(R) Xeon(R) Gold 6348 CPU @ 2.60GHz

SuperKEKB lattice was used:
The acceleration ratio for particle tracking：
- GPU /CPU(single core) ≈ 250

- Some initial benchmark comparing with SAD has been done







Summary

- Machine parameters are evaluated by strong-strong simulation
- X-Z instability is well suppressed even considering longitudinal impedance
- Strong vertical instability exist at Z with transverse impedance. Simulation and analysis has helped understanding the physics. Mitigation schemes have been studied.
- Disagreement between dynamic aperture and lifetime have been found. Diffusion analysis method is presented to optimize the lifetime. (lattice+beambeam+beamstrahlung)
- More self-consistent simulation code is being developed for future study
- Error effects and necessary luminosity tuning knob are still not yet studied.

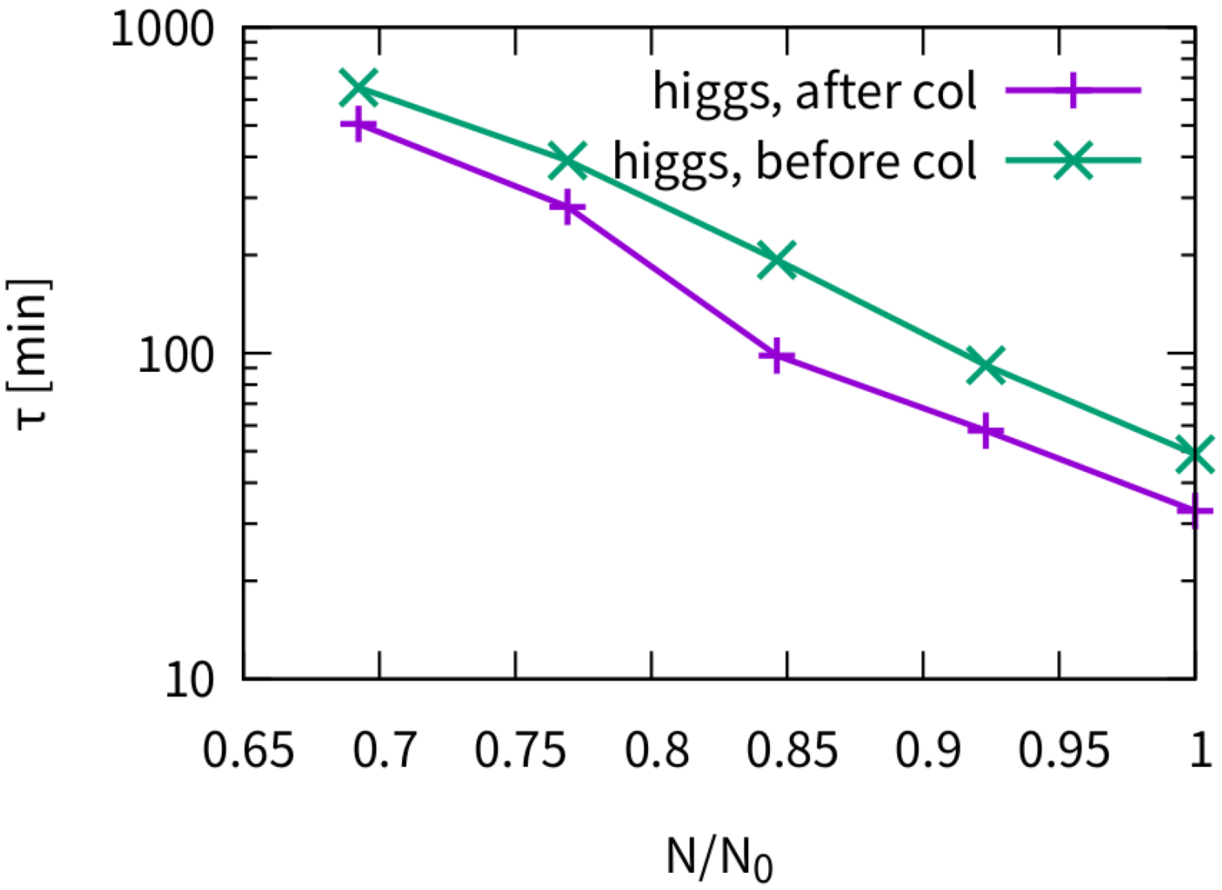
- BACKUP

Main Parameters

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.7	1.2/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	39/40	82/2800	60/700	81/23
Beam lifetime (min)	20	80	55	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5

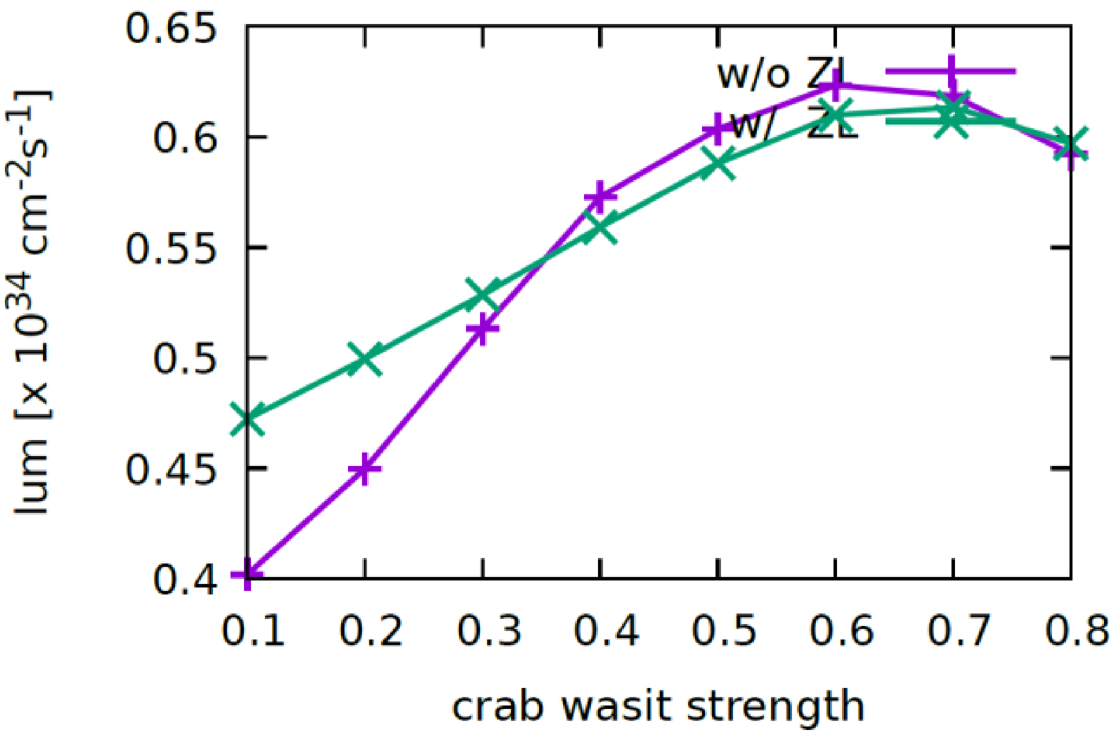
Lifetime evaluation (pure beam-beam interaction)

- Watch Point before vs after IP

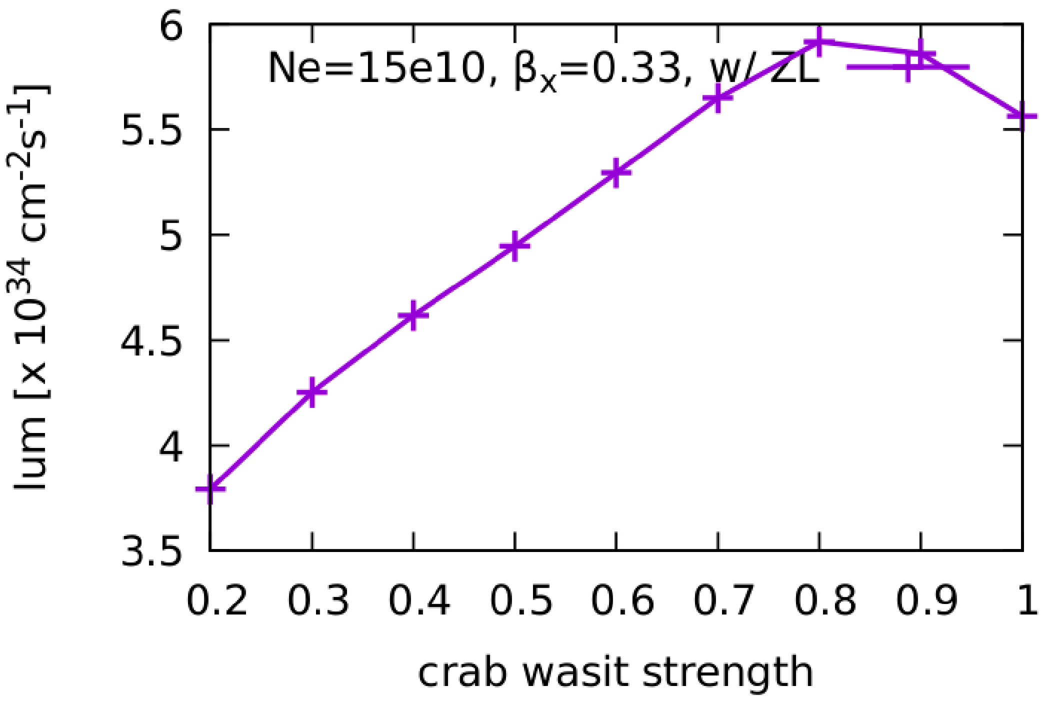


Crab Waist strength

ttbar

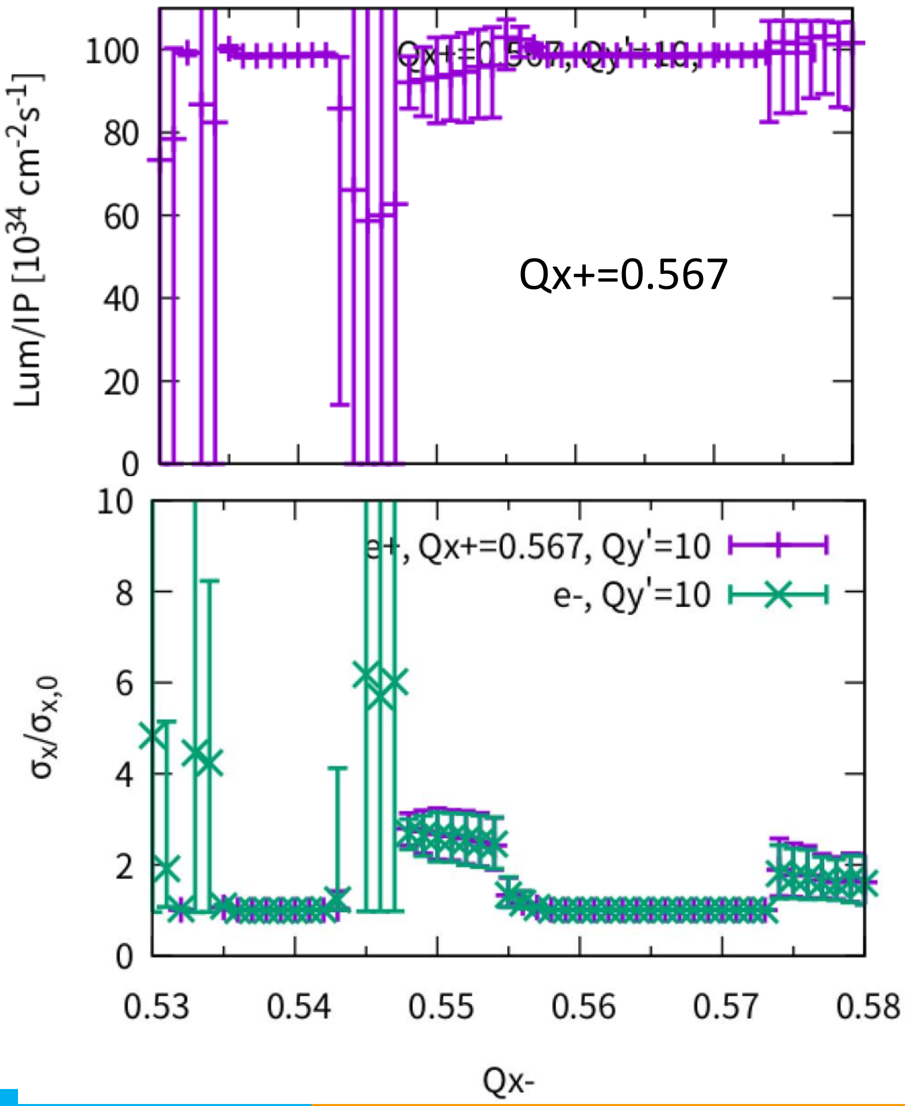


Higgs

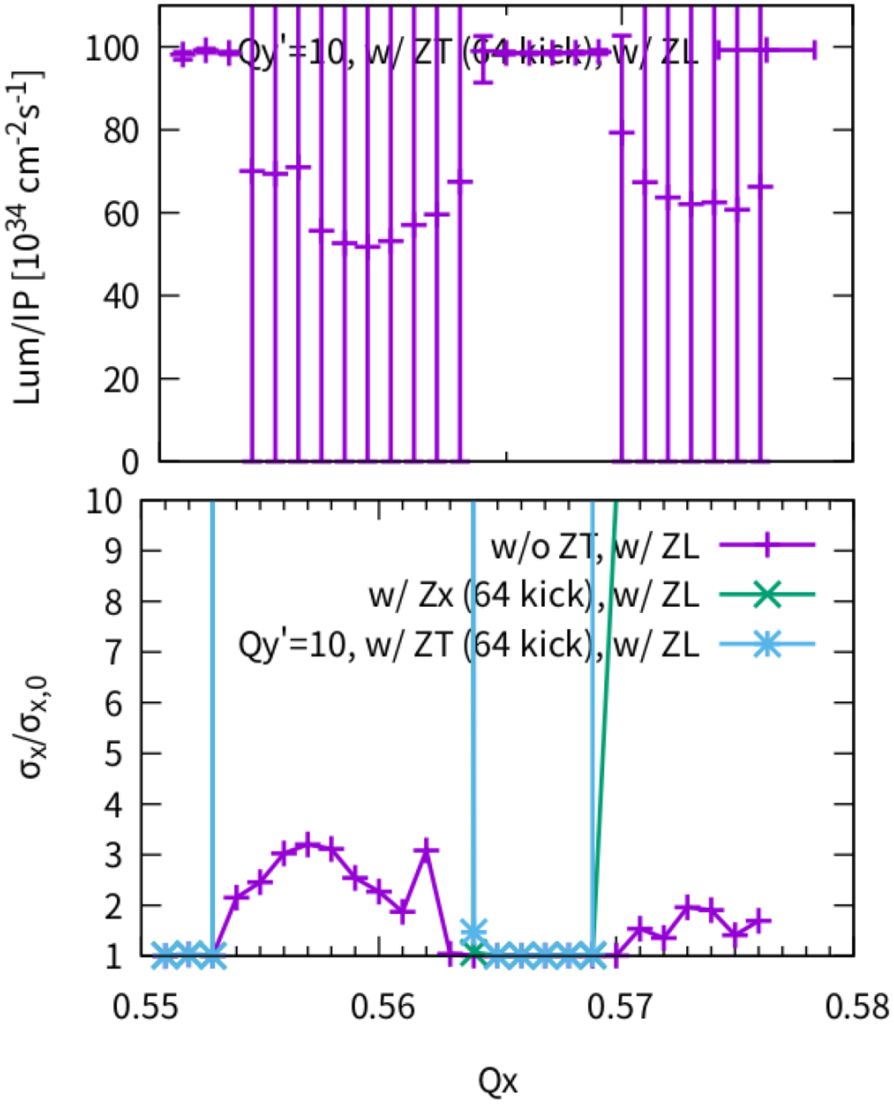


Different Horizontal tune

Asymmetric



Symmetric

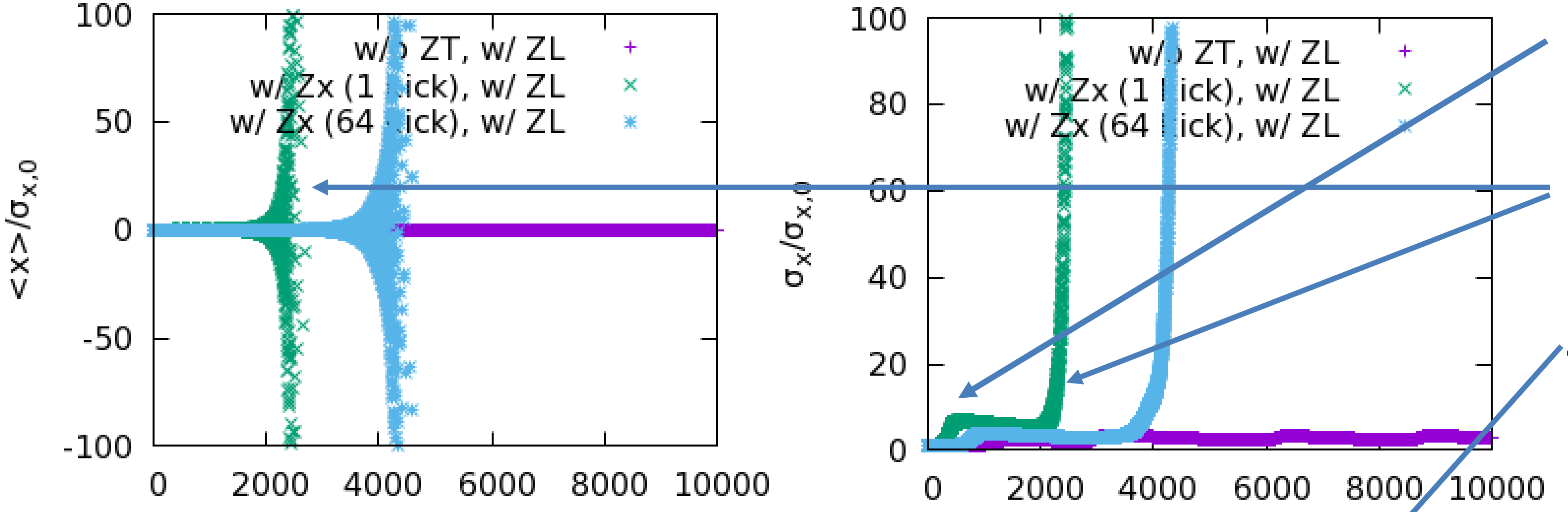


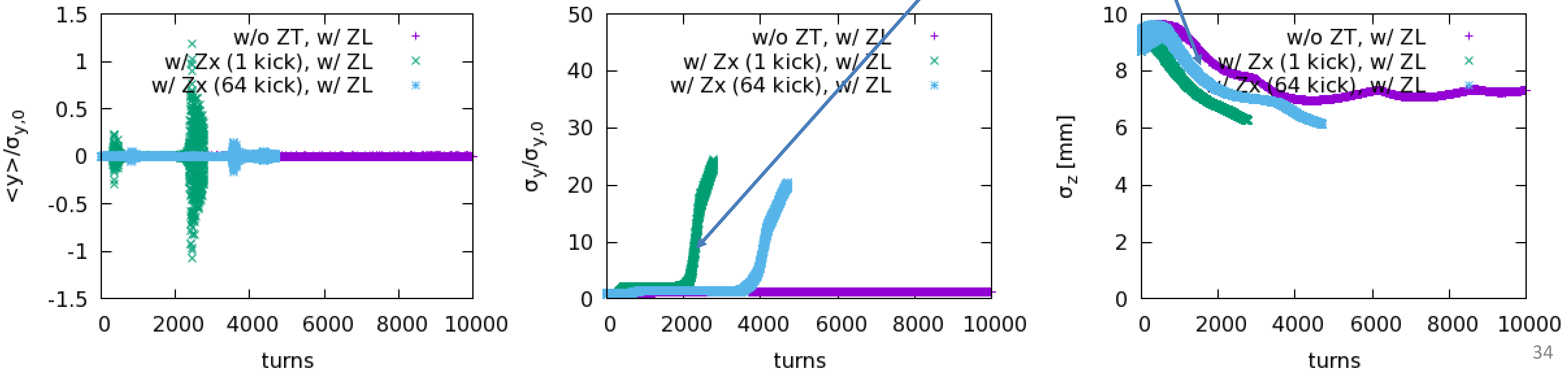
Behavior at unstable working point

CEPC Only Zx(+ZL) @ 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



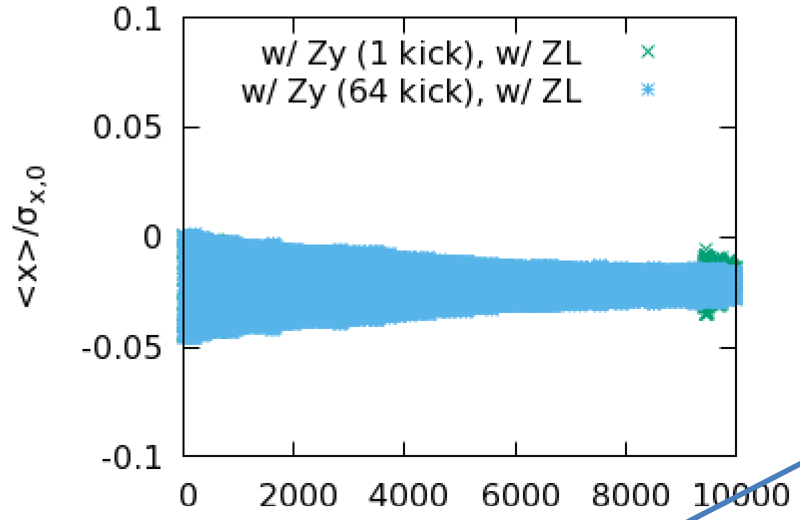


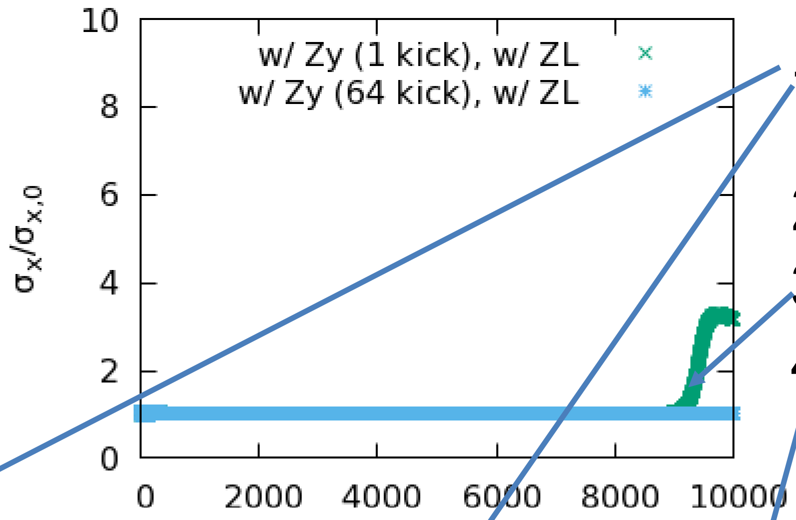
CEPC Only Zy(+ZL) Qx=0.567

Behavior at unstable working point

σ mode

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