Beam-Beam Effects in CEPC

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Berkeley, CA, USA, February 05-07, 2018

Outline

- Introduction
- Codes
- Single-Ring Scheme
- Double-Ring Scheme
- Summary

CEPC

Phase 1: **e^+e^- Higgs (Z) factory** **two detectors, 1M ZH events in ~10yrs**

Circular Electron Positron Collider (CEPC)

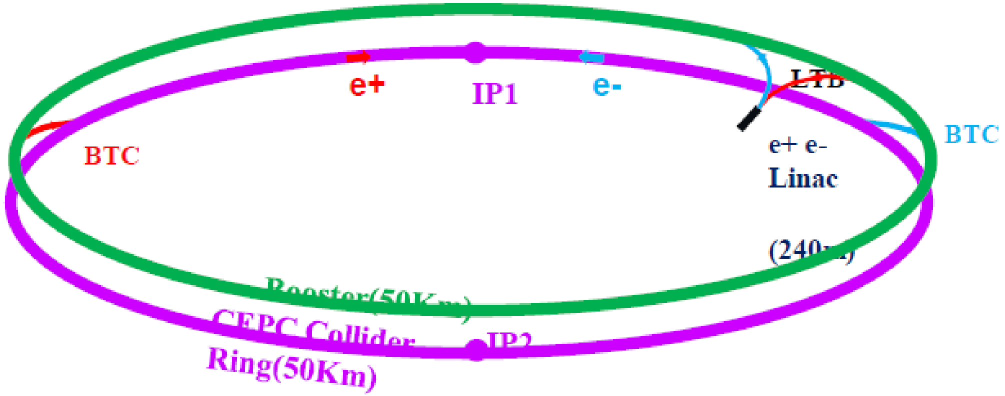
$E_{cm} \approx 240$GeV, luminosity $\sim 2\times10^{34}$ $cm^{-2}s^{-1}$, can also run at the Z-pole

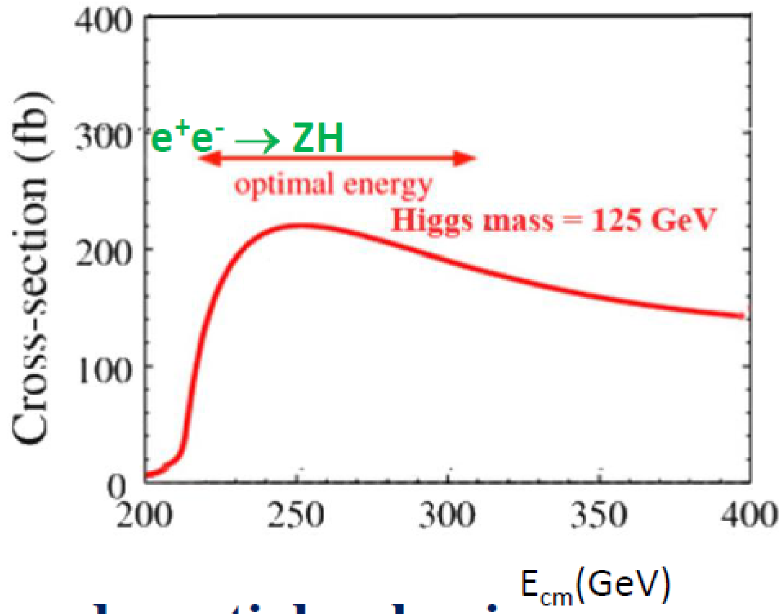
Precision measurement of the Higgs boson (and the Z boson)

Both goals be satisfied by the same collider layout and hardwares

Phase 2: **a discovery machine**; pp collision with $E_{cm} \approx$ 50-100 TeV; ep, HI options

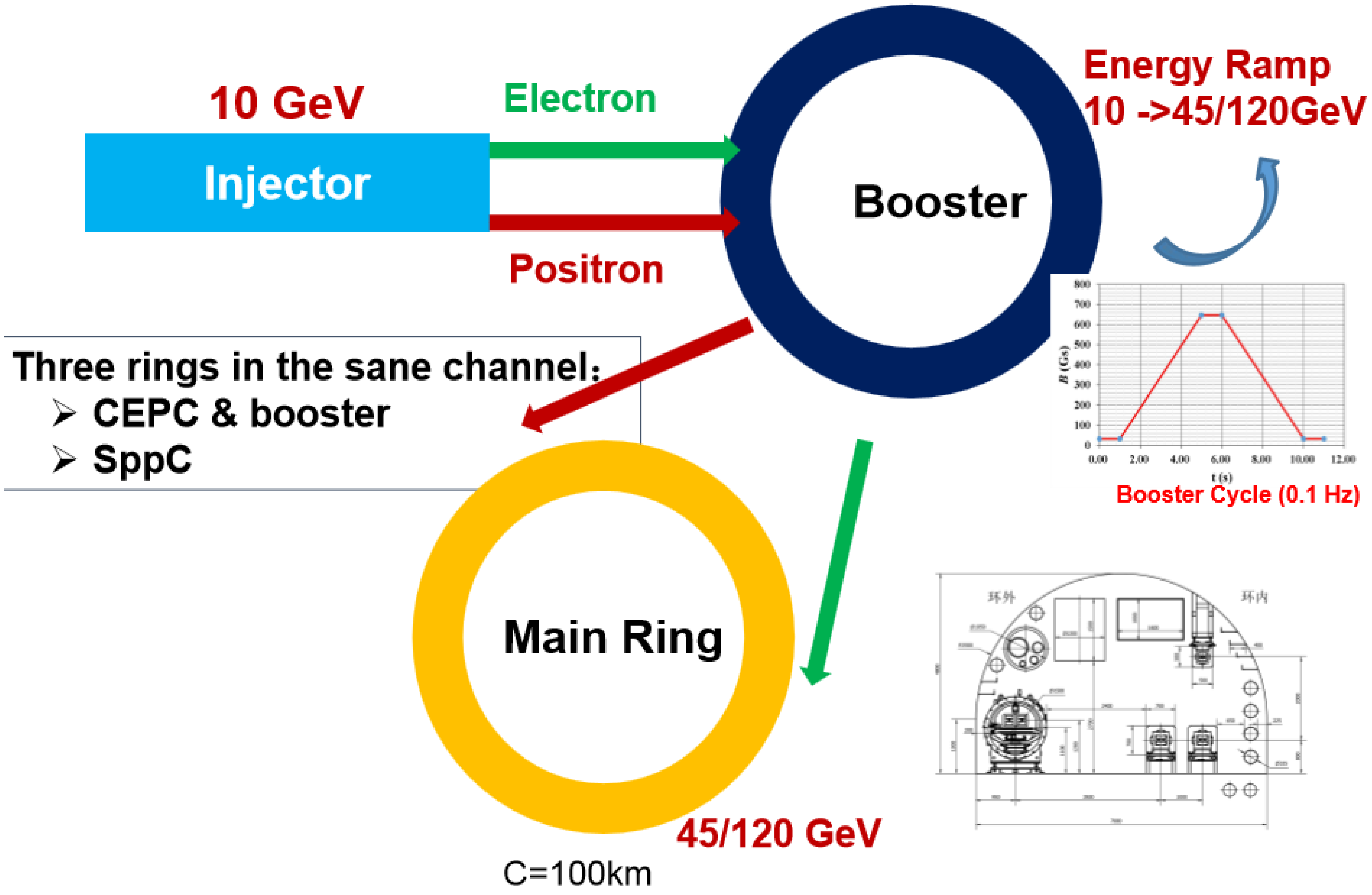
Super proton-proton Collider (SppC)



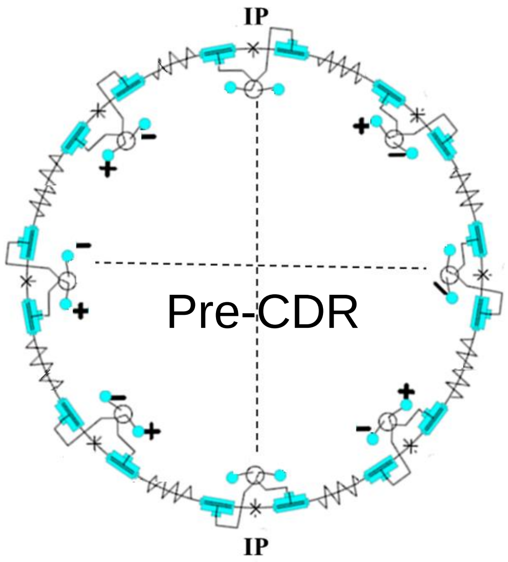


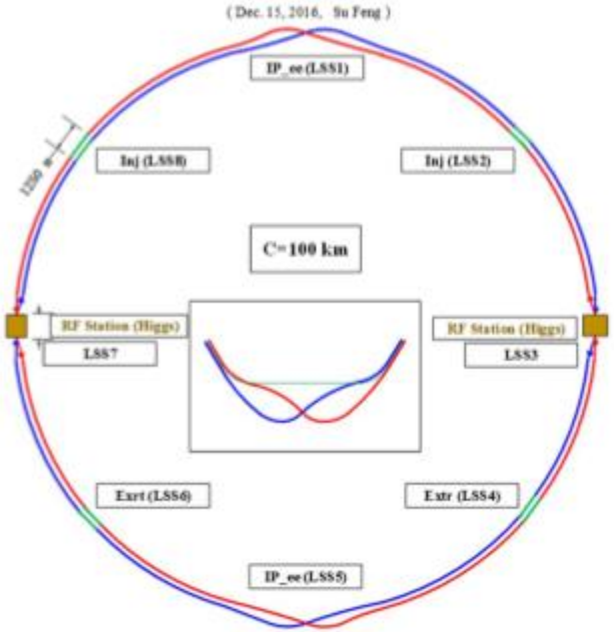
favored post BEPCII accelerator based particle physics program in China

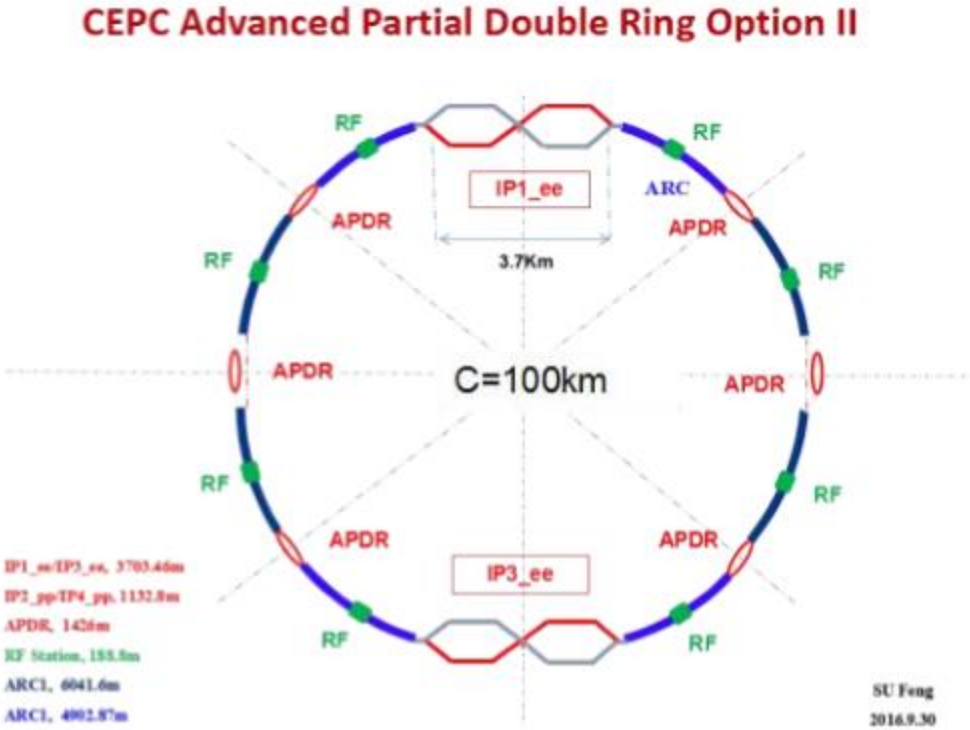
CEPC CDR Accelerator Chain



CEPC CDR Baseline and Alternative Design







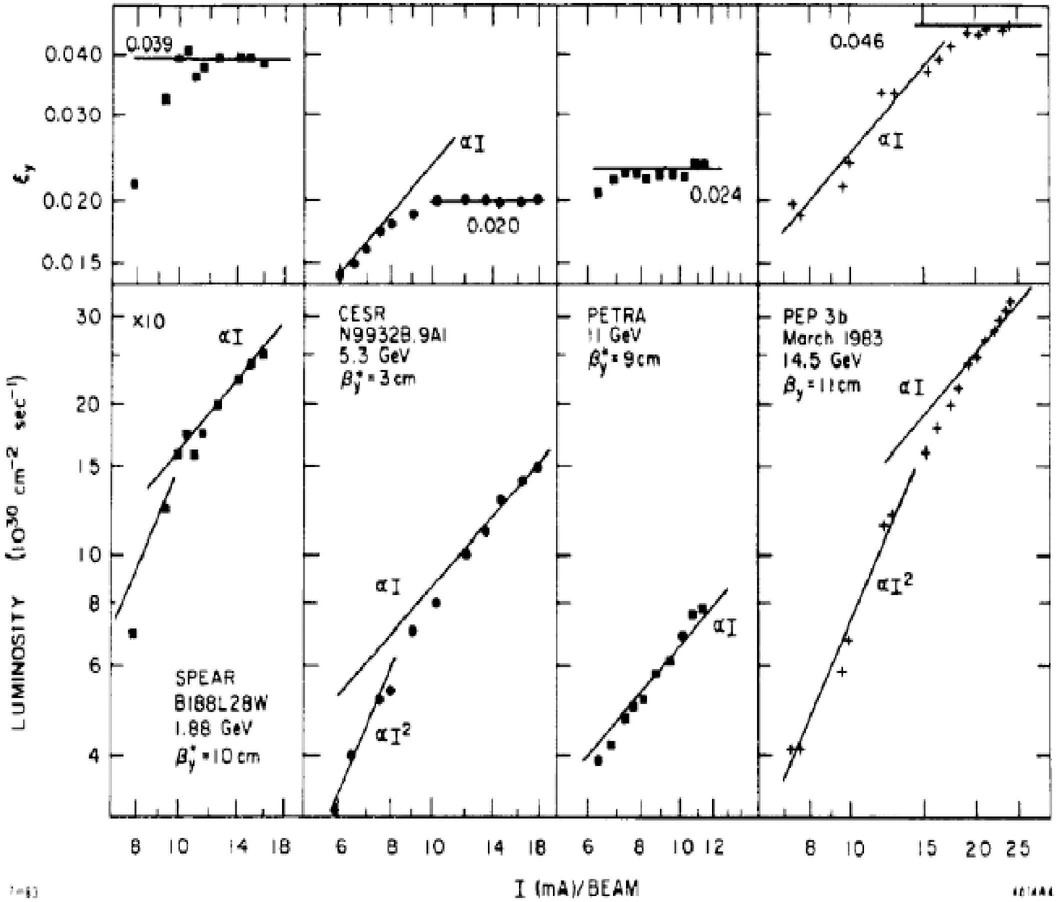
CEPC Baseline Design

Better performance for Higgs and Z compared with alternative scheme, without bottle neck problems, but with higher cost

CEPC Alternative Design

Lower cost and reaching the fundamental requirement for Higgs and Z luminosities, under the condition that sawtooth and beam loading effects be solved

Beam-beam parameter in early machines

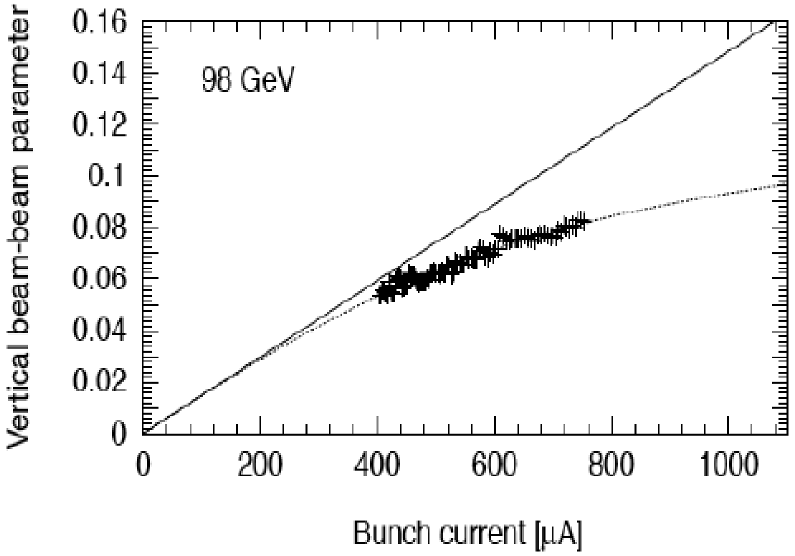


J. Seeman, “Observations of the beam–beam interaction”, 1985

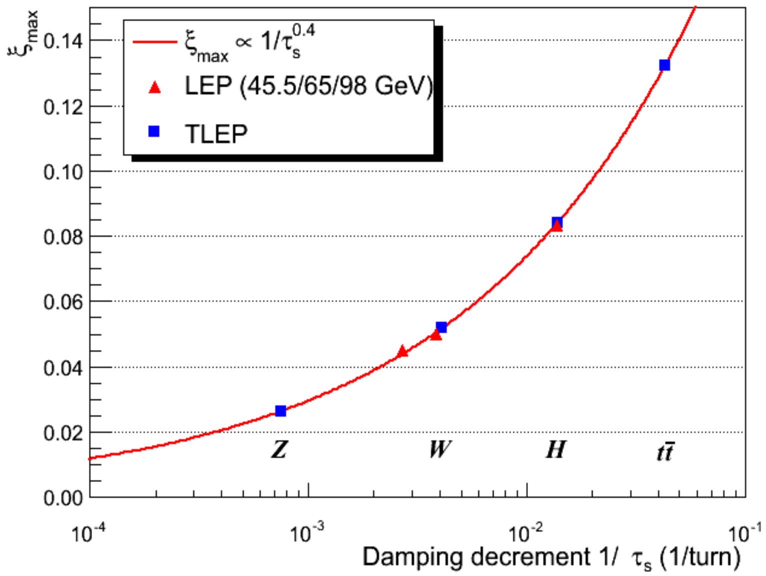
Collider	Energy (GeV)	ξ_v	Nb of IP
VEPP-2M	0.5	0.050	2
DCI	0.8	0.041	2
ADONE	1.5	0.070	6
SPEAR	1.2	0.018	2
	1.9	0.056	2
	2.1	0.055	2
BEPC	1.6	0.035	2
DORIS-2	5.3	0.026	2
VEPP-4	5.0	0.050	1
KEK-AR	5.0	0.030	2
	5.0	0.045	1
CESR	4.7	0.018	2
	5.0	0.022	2
	5.3	0.026	2
	5.5	0.028	2
	5.4	0.020	2
	5.4	0.035	1
PEP	14.5	0.045	6
	14.5	0.065	2
	14.0	0.050	1
PETRA	7.0	0.014	4
	11.0	0.024	4
	17.0	0.040	4
TRISTAN	30.4	0.034	4
LEP	45.6	0.035	4

Beam-Beam Parameter at LEP2

- Vertical Beam-Beam Parameter measured at LEP2



http://tlep.web.cern.ch/content/accelerator-challenges



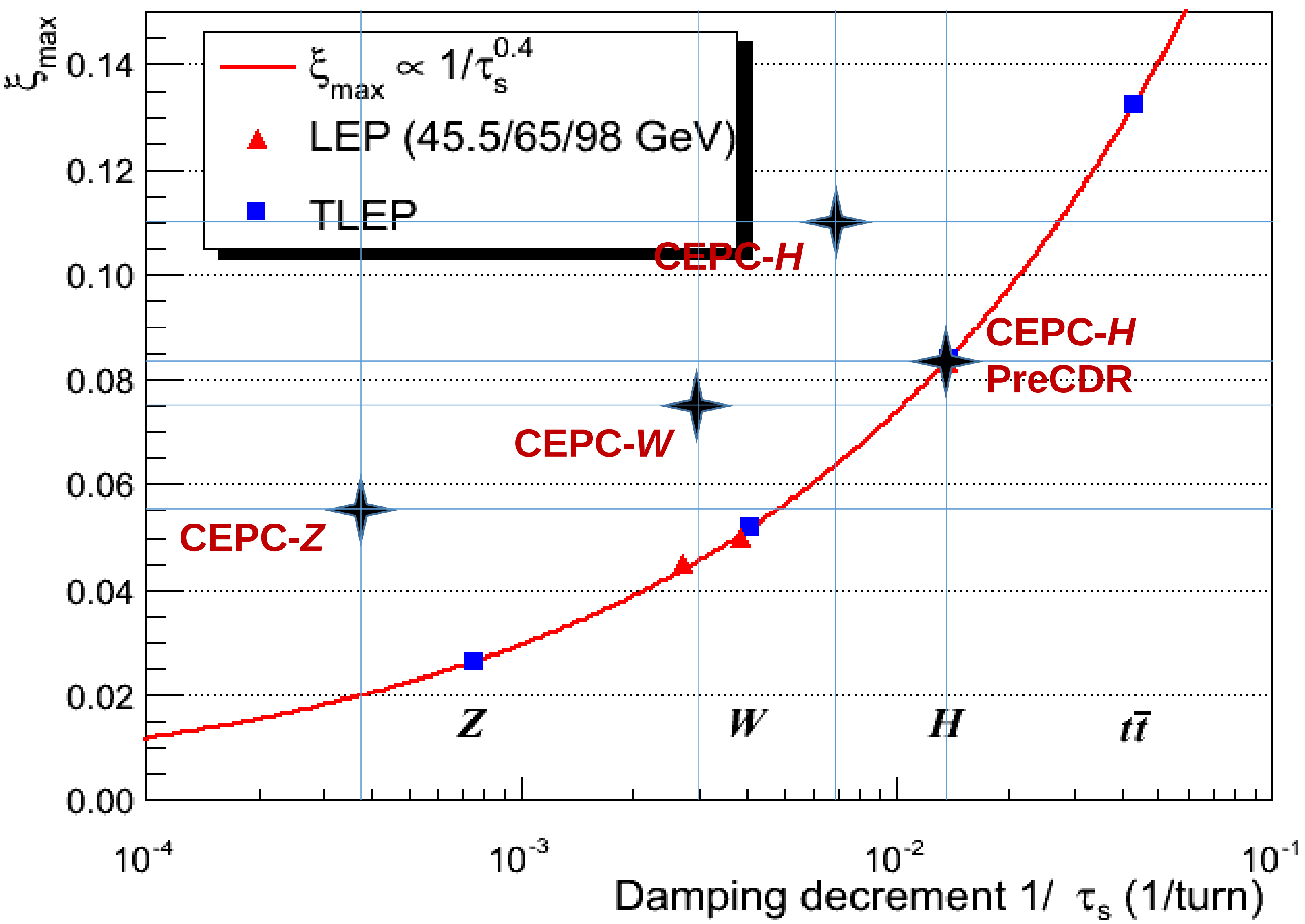
R. Assmann

Machine Parameters of the KEKB (June 17 2009)

	LER	HER	
Circumference	3016		m
RF Frequency	508.88		MHz
Horizontal Emittance	18	24	nm
Beam current	1637	1188	mA
Number of bunches	1584 + 1		
Bunch current	1.03	0.750	mA
Bunch spacing	1.84		m
Bunch trains	1		
Total RF volatage Vc	8.0	13.0	MV
Synchrotron tune ν_s	-0.0246	-0.0209	
Betatron tune ν_x / ν_y	45.506/43.561	44.511/41.585	
beta's at IP β_x^* / β_y^*	120/0.59	120/0.59	cm
momentum compaction a	3.31 x 10^{-4}	3.43 x 10^{-4}	
Estimated vertical beam size at IP from luminosity σ_y^*	0.94	0.94	µm
beam-beam parameters ξ_x / ξ_y	0.127/0.129	0.102/0.090	
Beam lifetime	133@1637	200@1188	min.@mA
Luminosity (Belle CsI)	21.08		10^{33}/cm^2/sec
Luminosity records per day / 7days/ 30days	1.479/8.428/30.208		/fb

$\xi_y \sim 0.1$

	Higgs	*W*	*Z*	***Pre-CDR***
Number of IPs	2			2
Energy (GeV)	120	80	45.5	120
Circumference (km)	100			54
SR loss/turn (GeV)	1.73	0.34	0.036	3.1
Half crossing angle (mrad)	16.5			0
Piwinski angle	2.58	4.29	23.8	0
N_e/bunch (10^{10})	15	5.4	8.0	3.79
Bunch number (bunch spacing)	242 (0.68us)	3390 (98ns)	12000 (25ns+10%gap)	50
Beam current (mA)	17.4	88.0	461	16.6
SR power /beam (MW)	30	30	16.5	51.7
Bending radius (km)	10.6			6.1
Momentum compaction (10^{-5})	1.11			3.4
β_{IP} x/y (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.8/0.0012
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.17/0.004	6.12/0.018
Transverse σ_{IP} (um)	20.9/0.068	13.9/0.049	5.9/0.078	69.97/0.15
ξ_x/ξ_y/IP	0.031/0.109	0.0148/0.076	0.0041/0.056	0.118/0.083
V_{RF} (GV)	2.17	0.47	0.1	6.87
f_{RF} (MHz) (harmonic)	650 (216816)			650
Nature bunch length σ_z (mm)	2.72	2.98	2.42	2.14
Bunch length σ_z (mm)	3.26	3.62	8.5	2.65
HOM power/cavity (kw)	0.54 (2cell)	0.47(2cell)	2.4	3.6
Energy spread (%)	0.1	0.066	0.038	0.13
Energy acceptance requirement (%)	1.35			2
Energy acceptance by RF (%)	2.06	1.47	1.7	6
Photon number due to beamstrahlung	0.29	0.16	0.55	0.23
Lifetime _simulation (min)	100			47
Lifetime (hour)	0.67 (40 min)	2	4	
F (hour glass)	0.89	0.94	0.99	0.68
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.93	7.31	16.6	2.04



the damping rate per beam-beam interaction

Crab-Waist Compensation

Collision with large Φ is not a new idea .....

Crab-Waist transformation is !

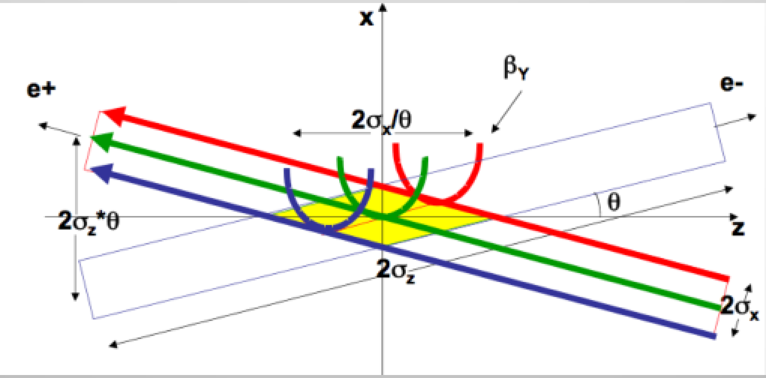
$$y = \frac{xy'}{2\theta}$$

sextupole (anti)sextupole

$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$

- $L_{geometric}$ gain
- x-y synchro-betatron and betatron resonance suppression

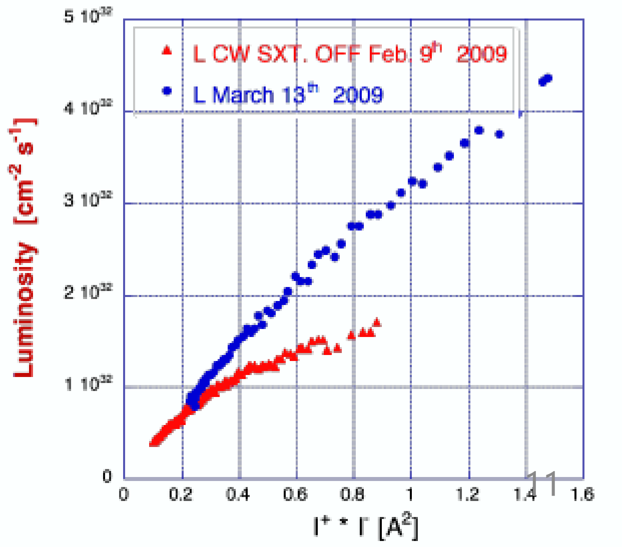
P. Raimondi , 2° *SuperB Workshop, March 2006*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033
C. Milardi et al., Int.J.Mod.Phys.A24, 2009
M. Zobov et al., Phys. Rev. Lett. 104, 2010



DAΦNE Luminosity and Tune Shift

	KLOE (Spt 2005)	FINUDA (Apr 2007)	SIDDHARTA *CW* (Jun 2009)
Luminosity [10^{32} $cm^{-2}s^{-1}$]	1.53	1.6	**4.53** (5.0)
I(ele) [A]	1.38	1.50	1.52
I(pos) [A]	1.18	1.1	1
n_b	111	106	105
ε_x [mm mrad]	0.34	0.34	0.28
β_x [m]	1.5	2.	0.25
β_y [cm]	1.8	1.9	0.9
ξ	0.0245	0.0291	**0.0443 (0.074)**

Luminosity as a function of colliding currents
CW-Sextupole excitation



C. Milardi

Simulation Codes

- LIFETRAC by D. Shatilov (BINP),

Quasi-strong-strong method is used: Self-consistent beam size and dynamic beta/emittance (Gaussian Fit)

- BBWS/BBSS by K. Ohmi (KEK),

Weak-strong simulation with self-consistent σ_z and σ_x, or Strong-strong simulation

- IBB by Y. Zhang (IHEP)
- SAD (KEK)

Simulation of Beamstrahlung

K. Ohmi

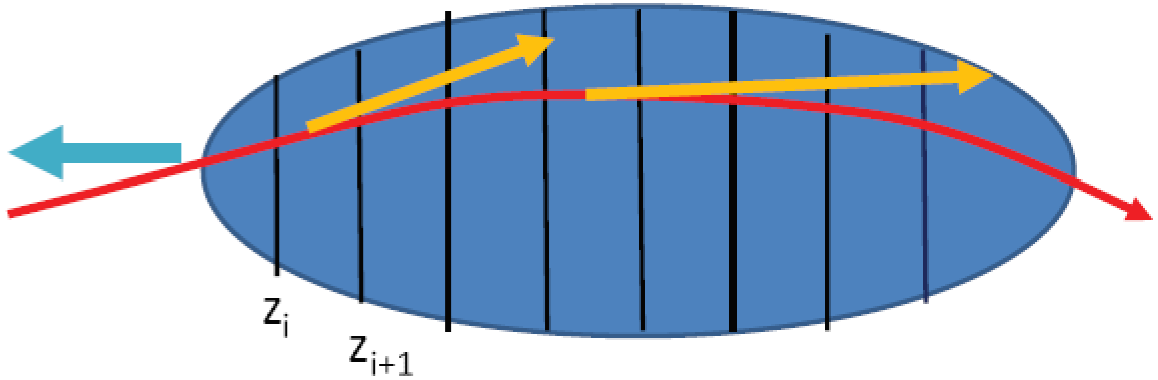
$$\Delta s = (z_i - z_{i+1})/2$$

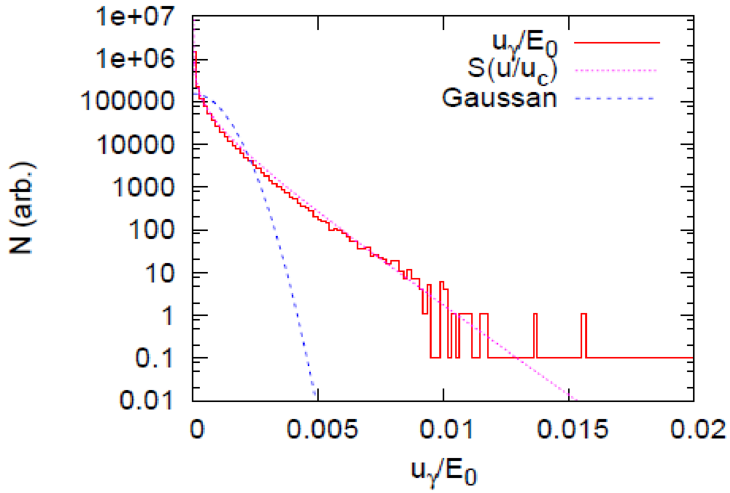
$$\frac{1}{\rho_{xy}} = \frac{\Delta p_{xy}}{\Delta s} \qquad \frac{1}{\rho} = \sqrt{\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2}}$$

$$u_c = \hbar\omega_c = \frac{3\hbar c\gamma^3}{2\rho}$$

$$n_\gamma = \int_0^\infty \frac{dn_\gamma(\omega)}{d\omega} d\omega = \frac{5\sqrt{3}}{6\rho}\Delta s$$

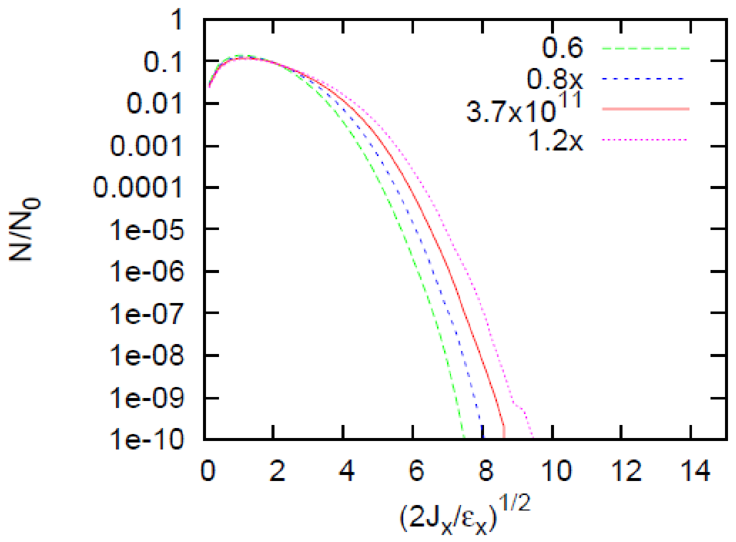
$$\frac{dn_\gamma(\omega)}{d\omega} = \frac{\sqrt{3}\alpha\gamma\Delta s}{2\pi\rho\omega_c} S(\frac{\omega}{\omega_c}) \qquad S(\xi) = \int_\xi^\infty K_{\frac{5}{3}}(y)dy$$

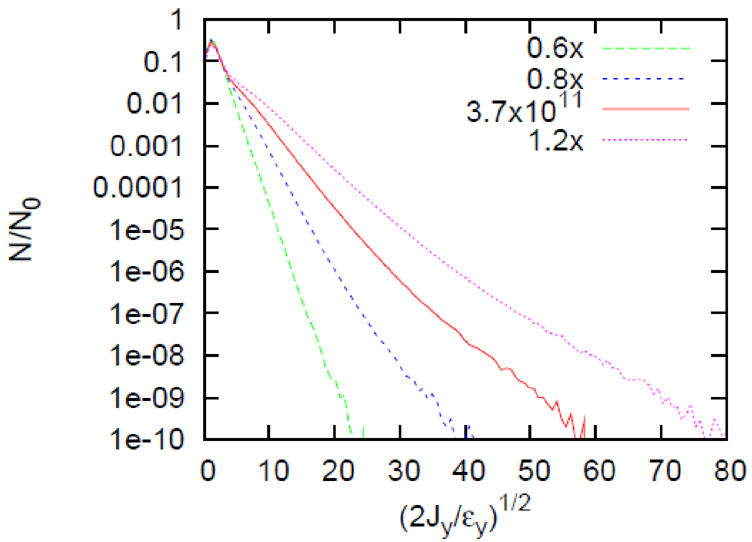




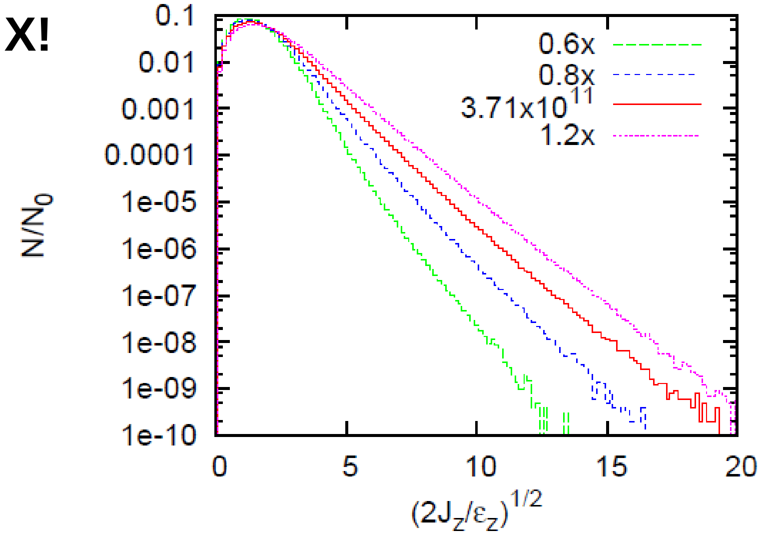
K. Ohmi

Beam halo distribution





There is no long tail in X!

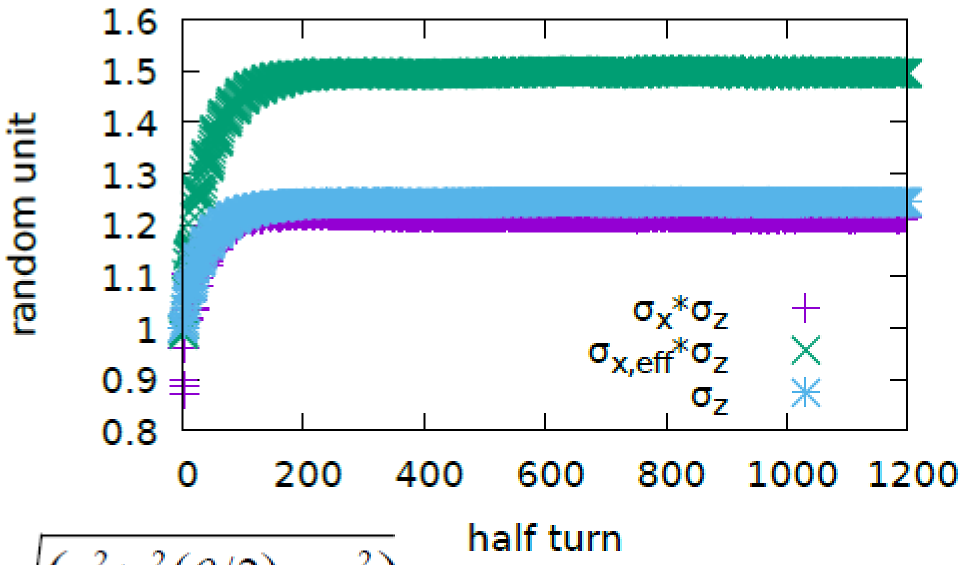


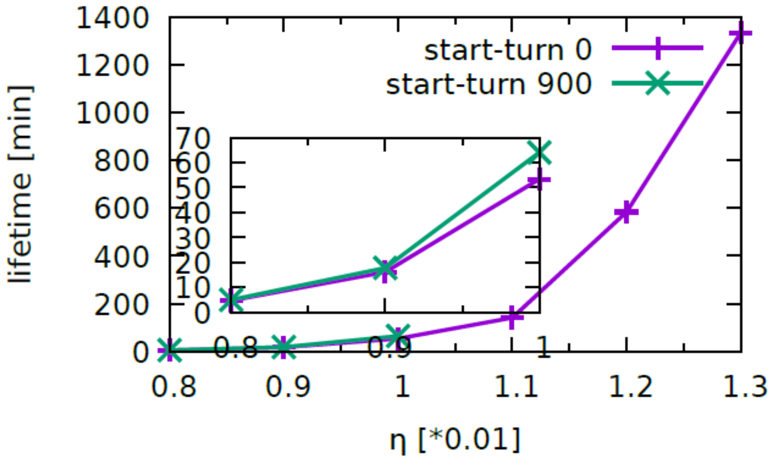
Beamstrahlung lifetime
estimated by the loss particle number

- Lifetime is shorter if loss particle number is counted from very beginning

[*V. Telnov, Phys. Rev. Letters 110 (2013) 114801*]

$$\tau_{BS} \approx \frac{1}{n_{IP} f_{rev}} \frac{4\sqrt{\pi}}{3} \sqrt{\frac{\delta_{acc}}{\alpha r_e}} \exp\left(\frac{2}{3}\frac{\delta_{acc}\alpha}{r_e\gamma^2}\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_e N_b}\right) \frac{\sqrt{2}}{\sqrt{\pi}\sigma_z\gamma^2} \left(\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_e N_b}\right)^{3/2}$$





$$\sigma_x \; --> \sqrt{\left(\sigma_z^2 tg^2(\theta/2) + \sigma_x^2\right)}$$

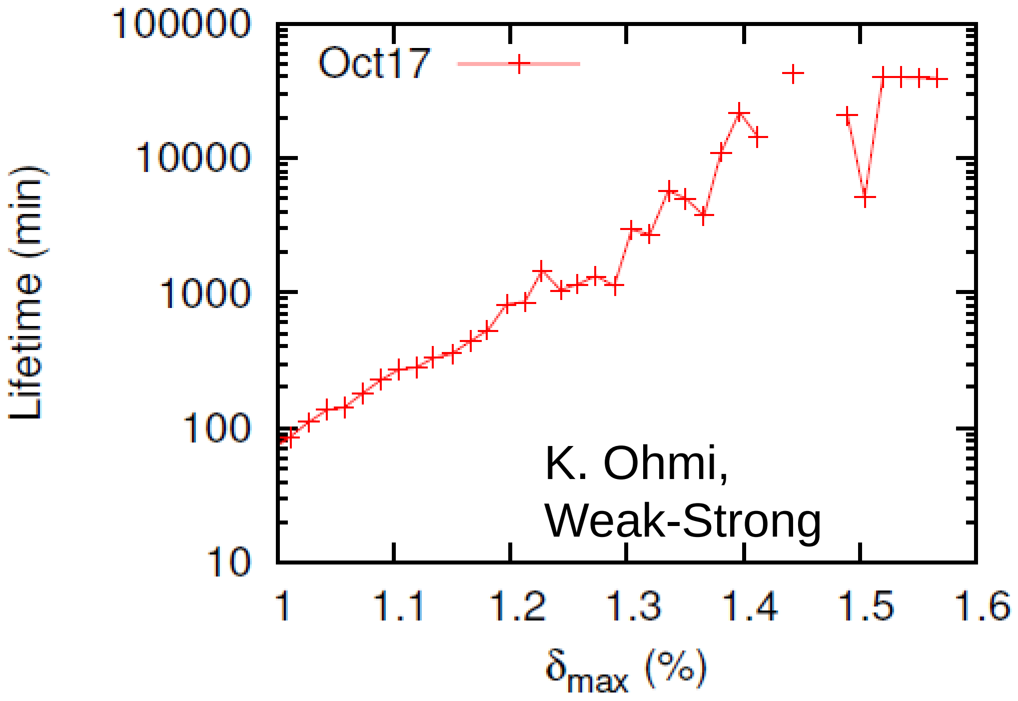
D. Shatilov and M. Zobov, ICFA BD newsletter no. 37, p99

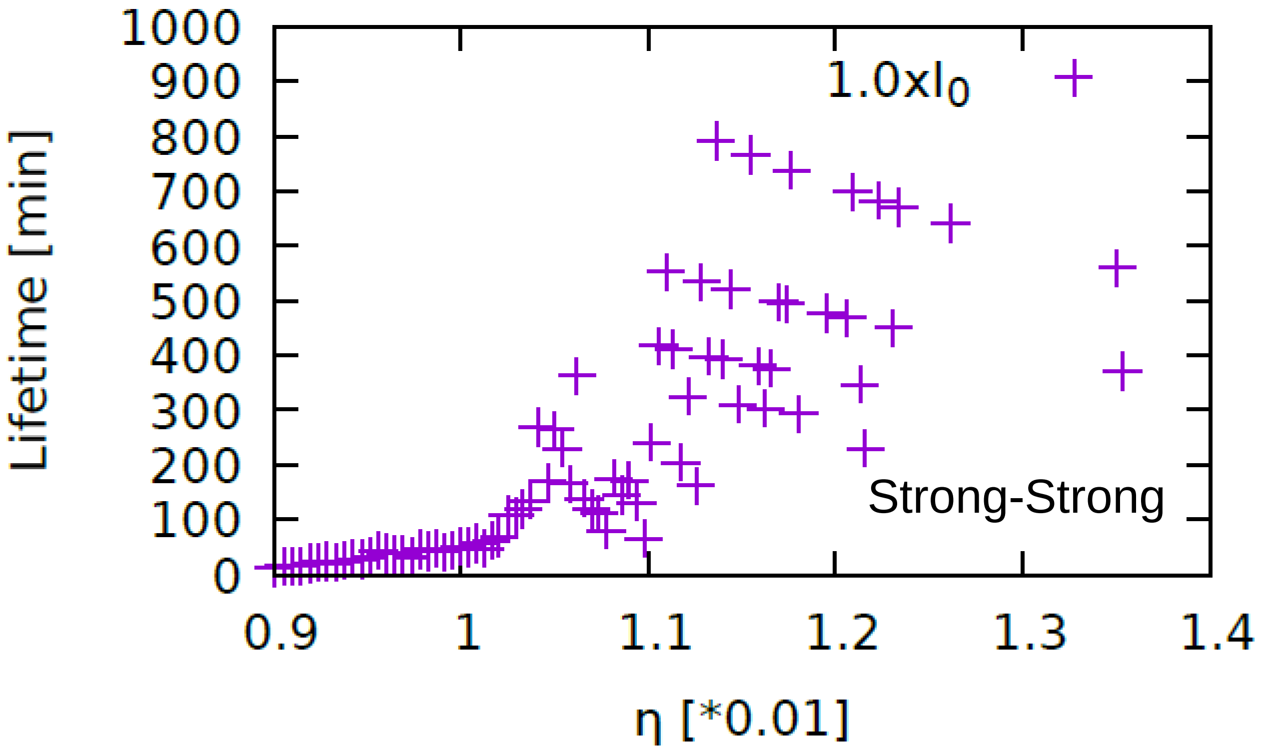
K. Ohmi

Beamstrahlung lifetime
estimated by beam tail

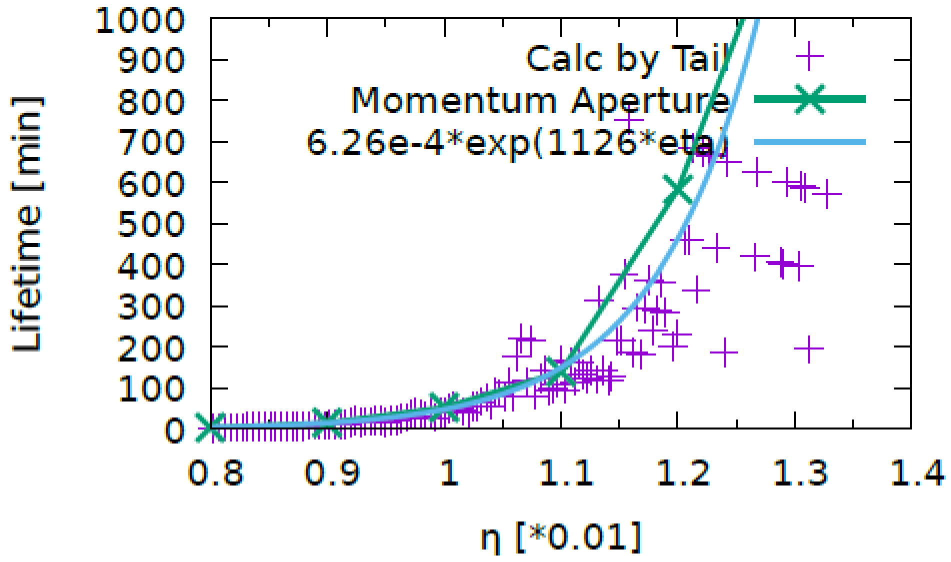
$$\tau_{bs} = \frac{\tau_z}{2Af(A)} \qquad \int_0^\infty dJ\, f(J) = 1$$

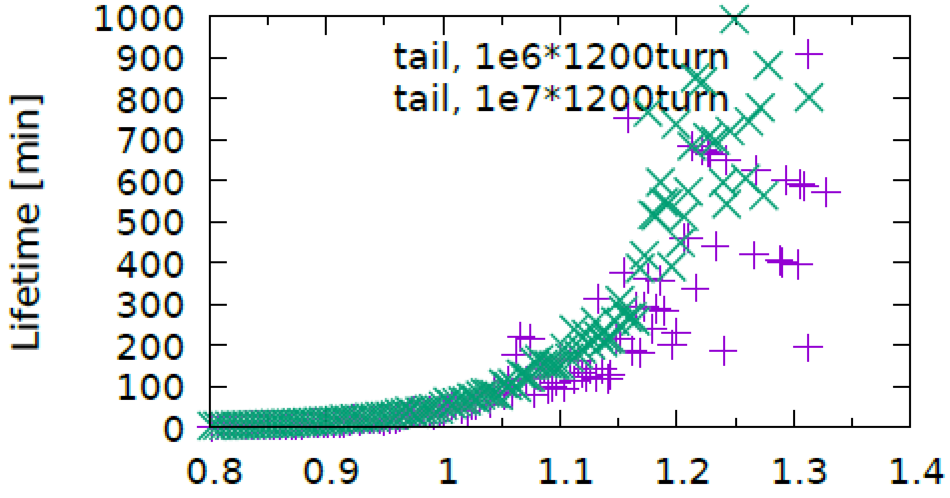
A the boundary of momentum acceptance in action
$f(J)$ the distribution of action with beam-beam
τ_z the longitudinal damping time

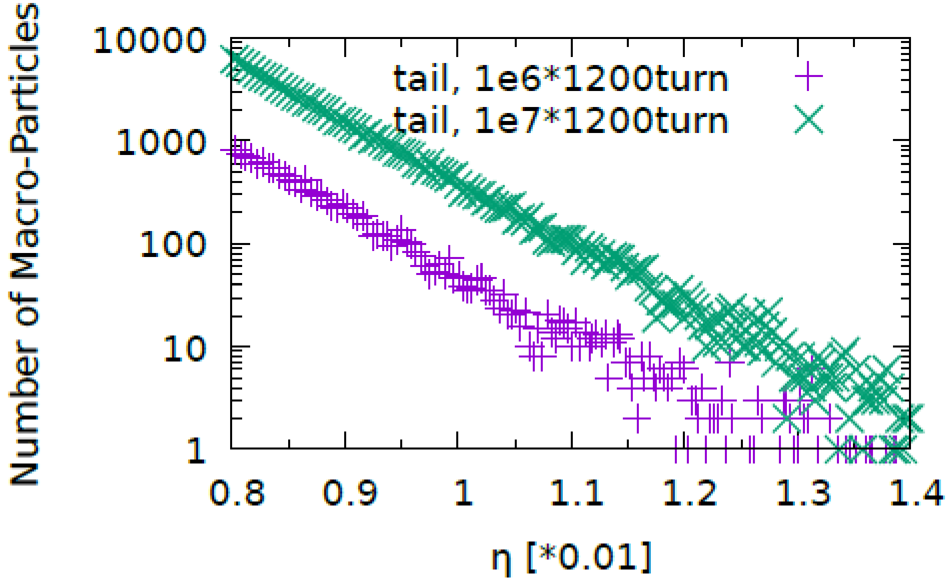




Beamstrahlung lifetime
Comparison of two methods

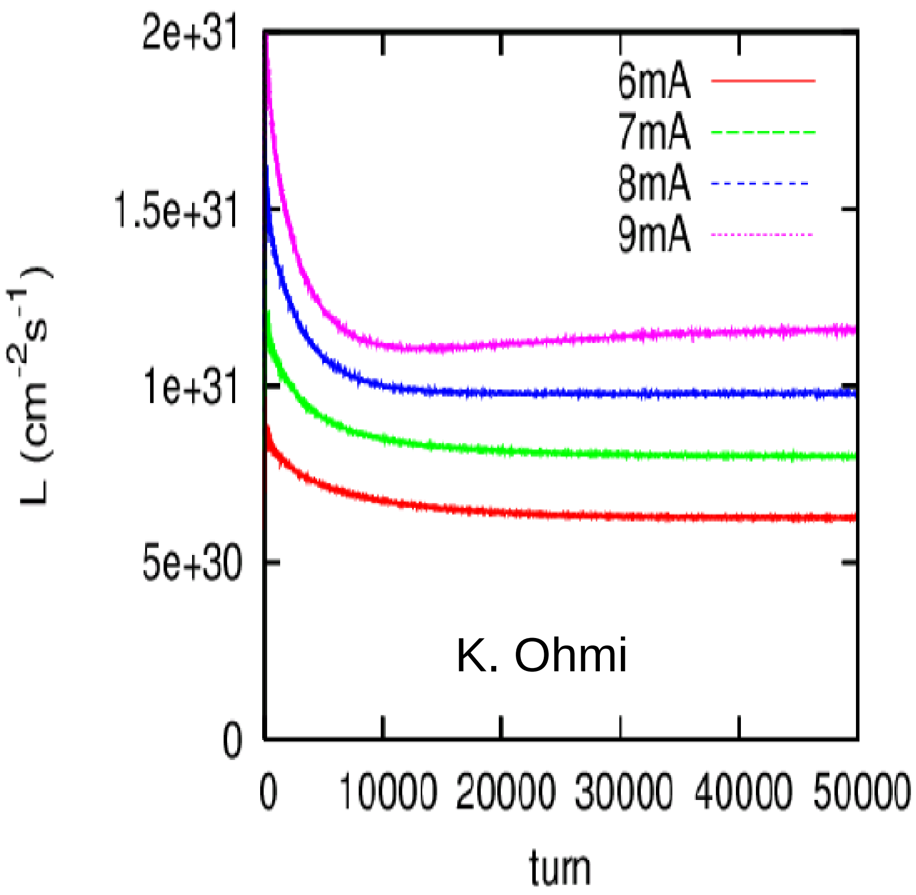


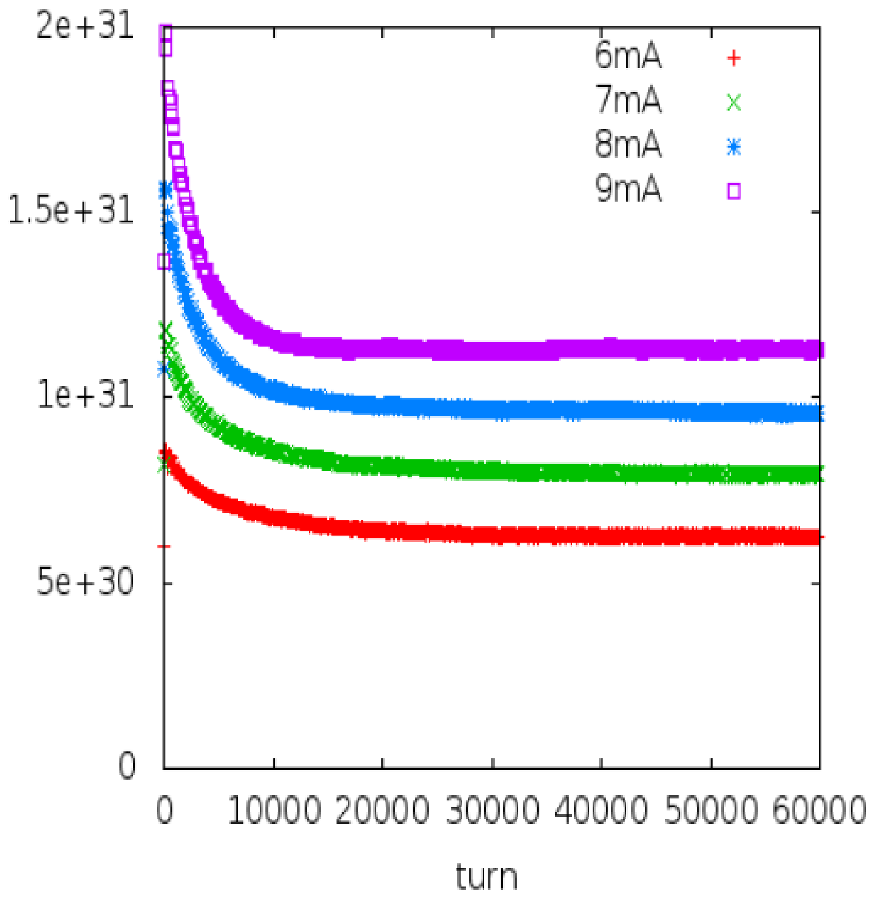




- Two methods coincides well
- 1e6*1200 turn is accurate enough to estimate 100min lifetime by tail

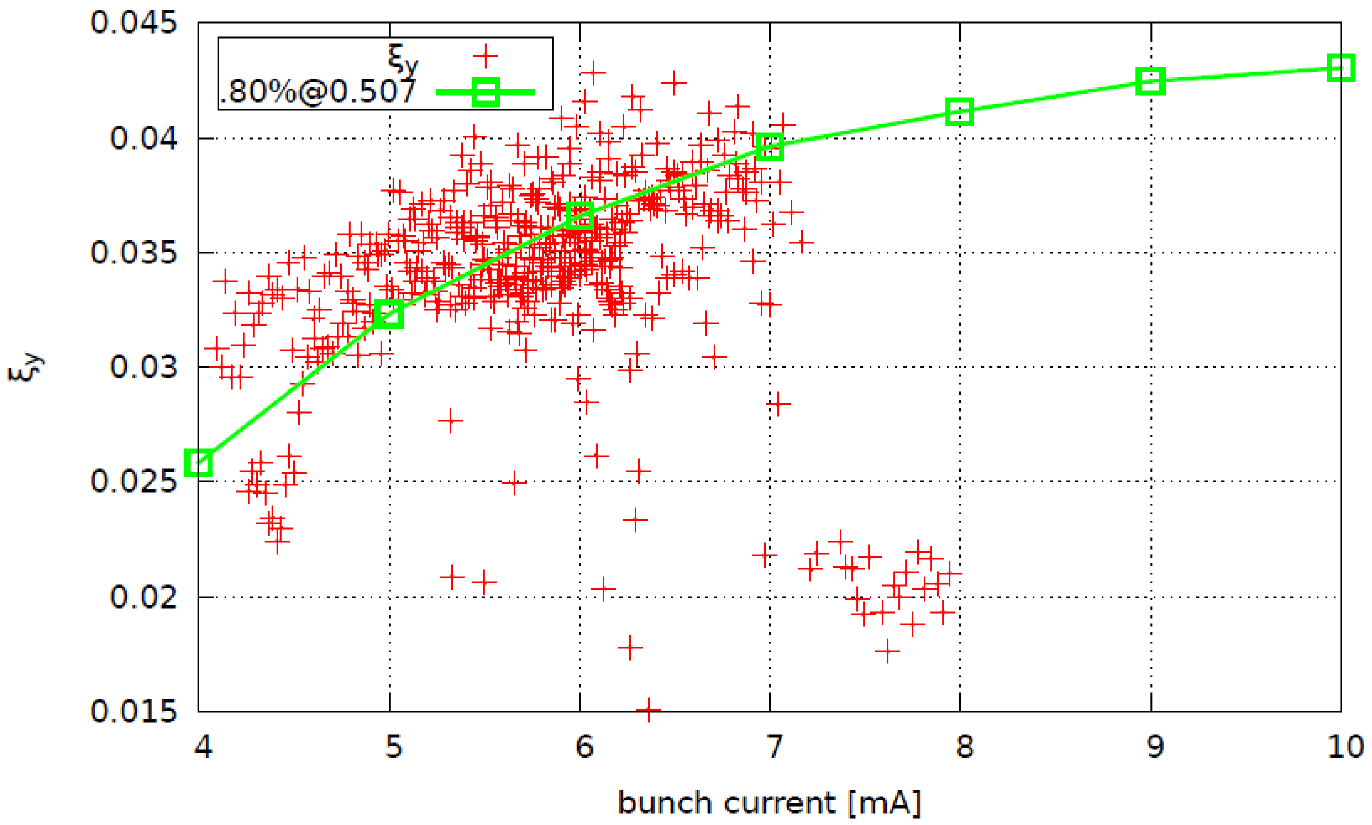
Beam-Beam Code Check – BEPCII (1)



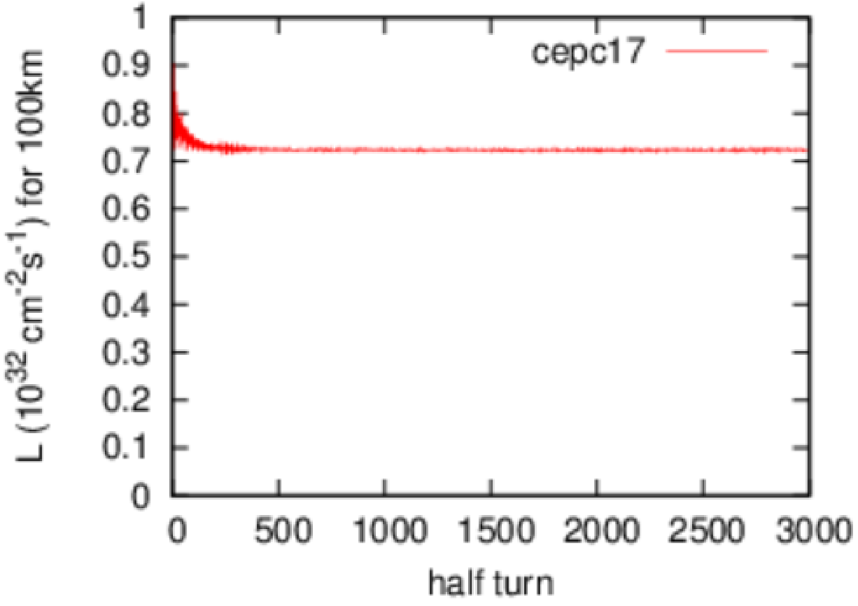


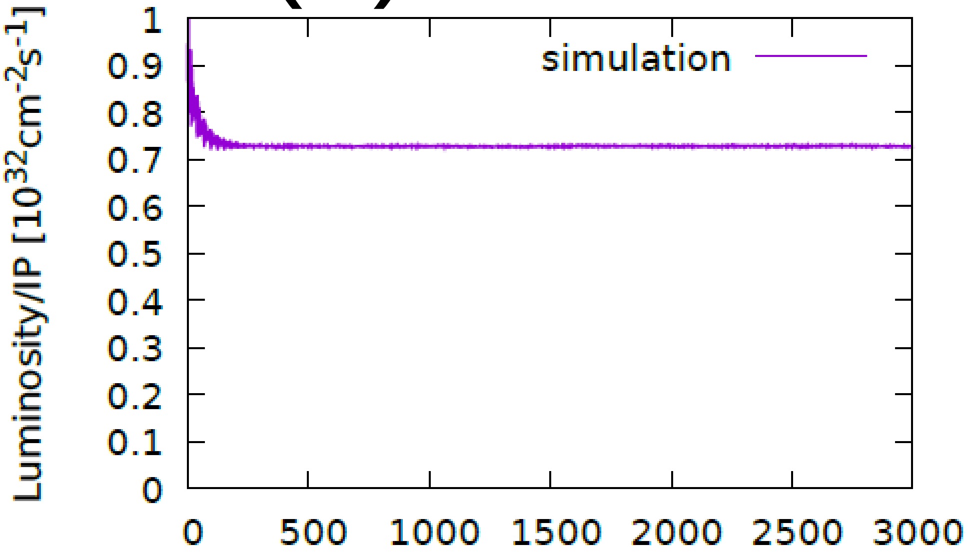
Beam-Beam Code Check (2)

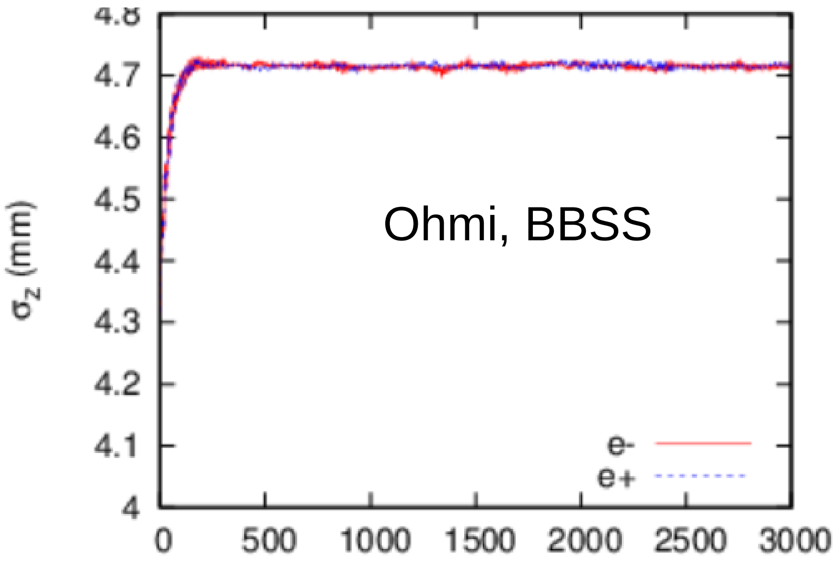
- Beam-Beam Parameter at BEPCII (1.89GeV)

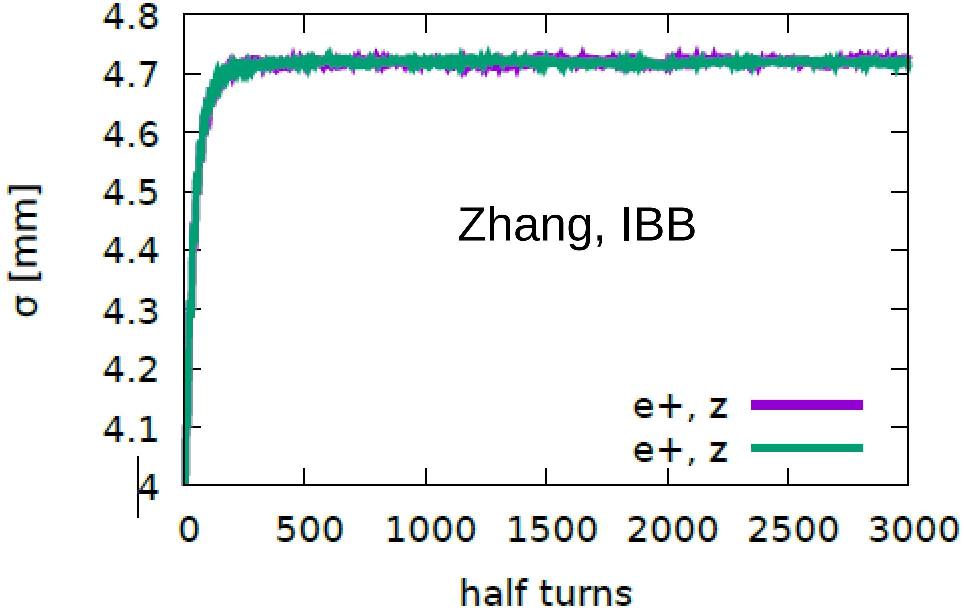


Beam-Beam Code Check (3) - CEPC



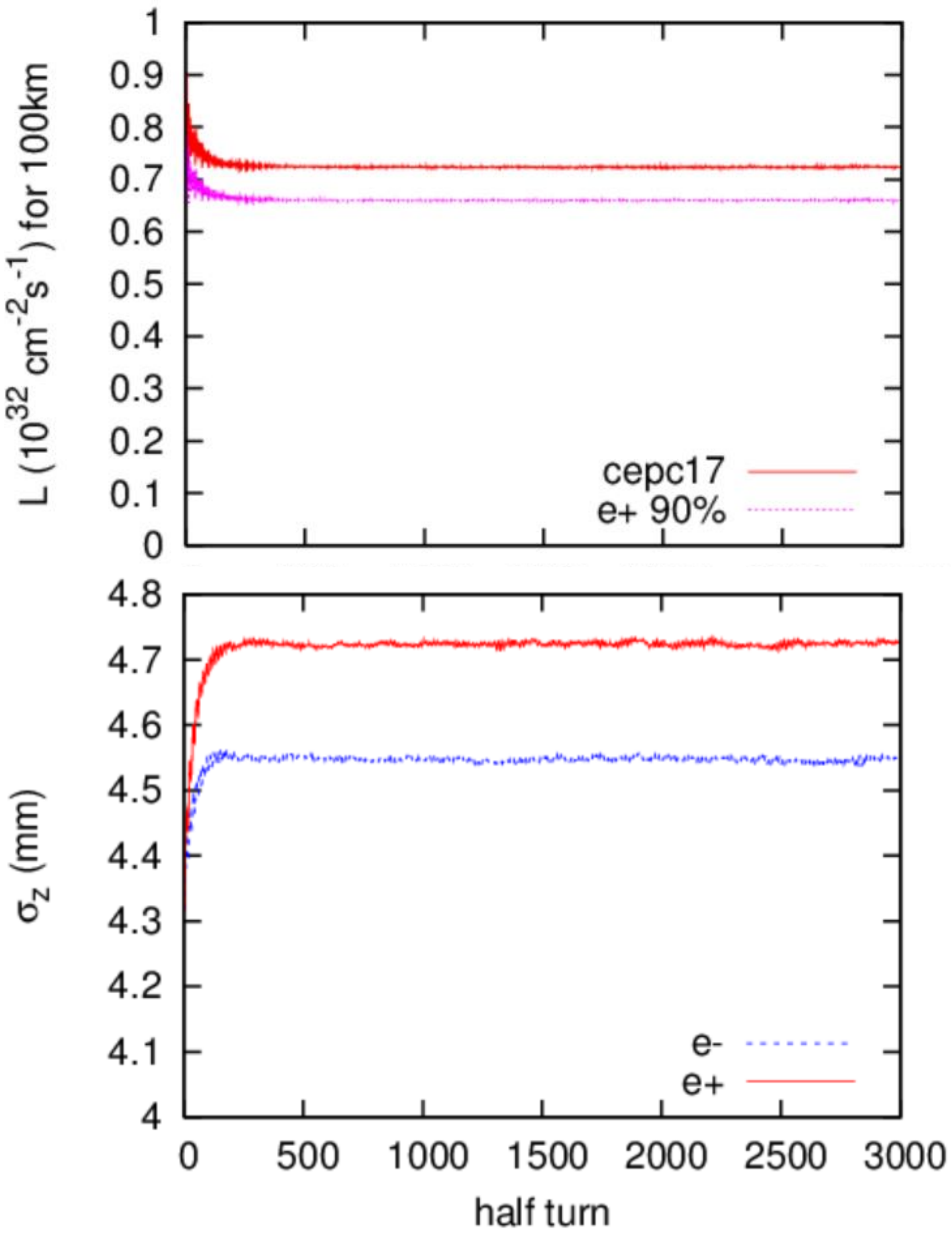




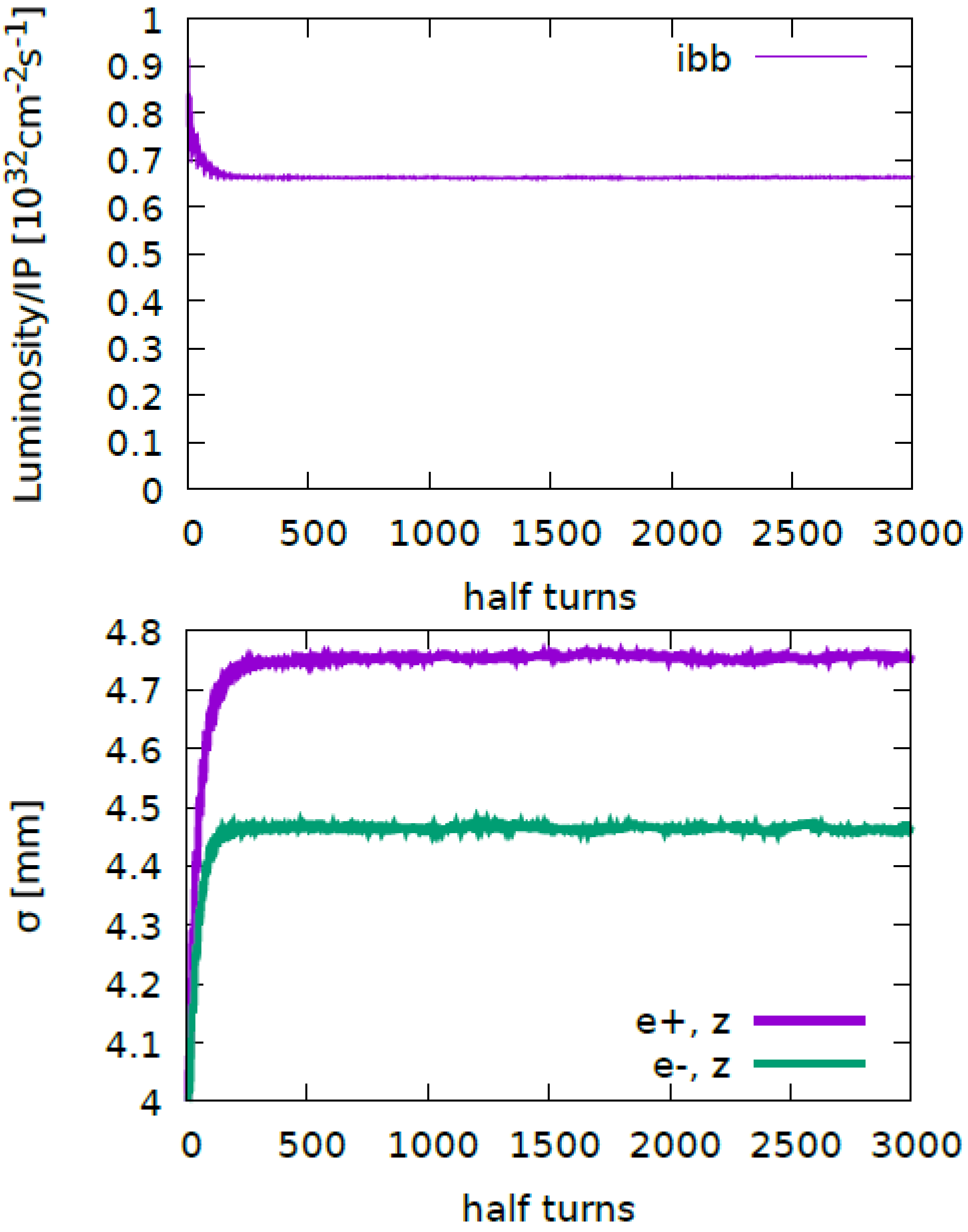


Beam current asymmetry: e+: 90% e-:100%

Ohmi,

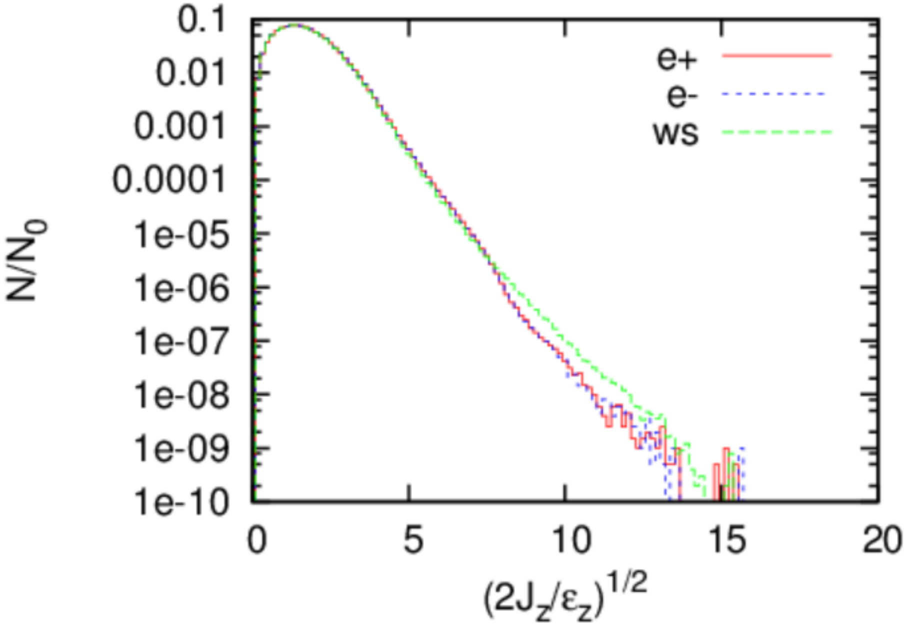


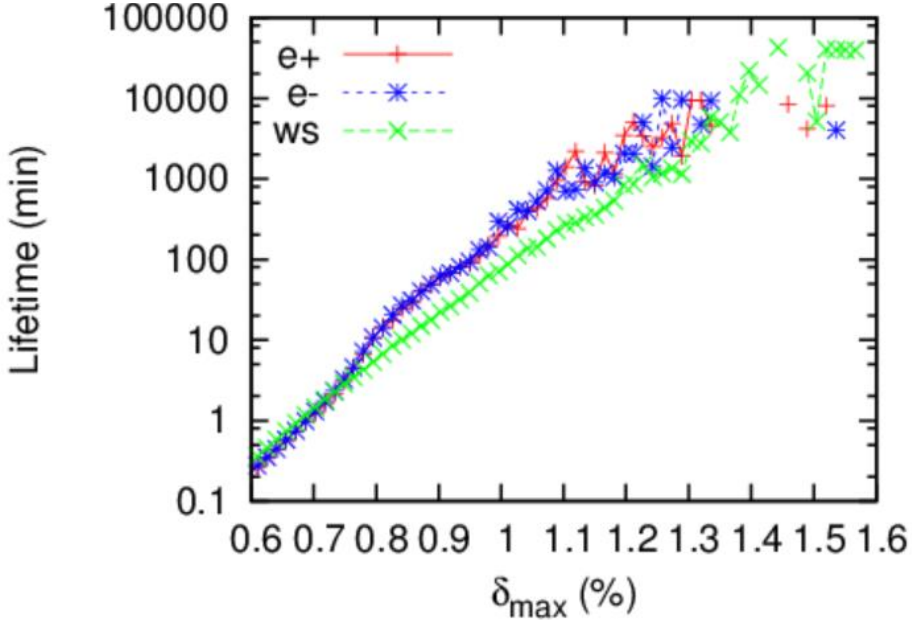
Zhang, IBB



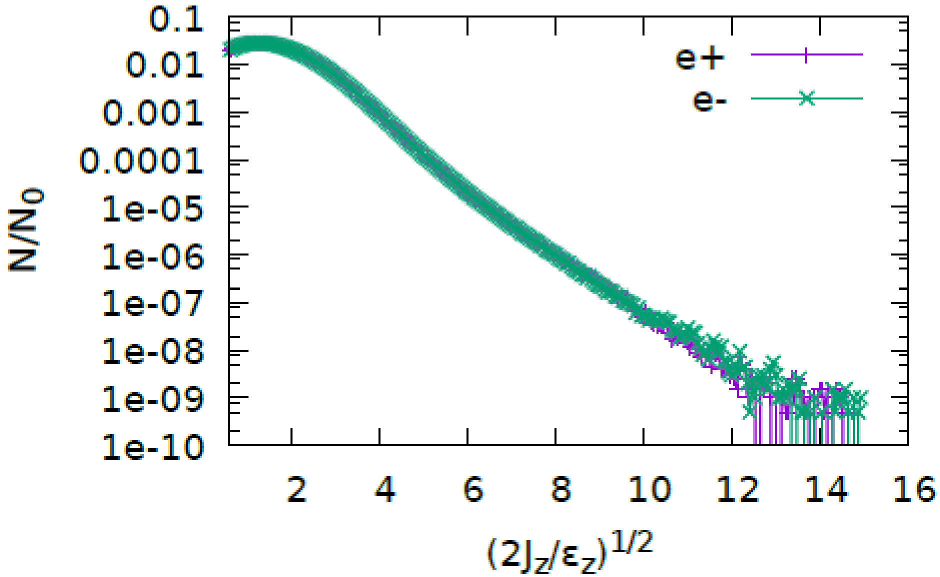
Beam tail distribution and lifetime

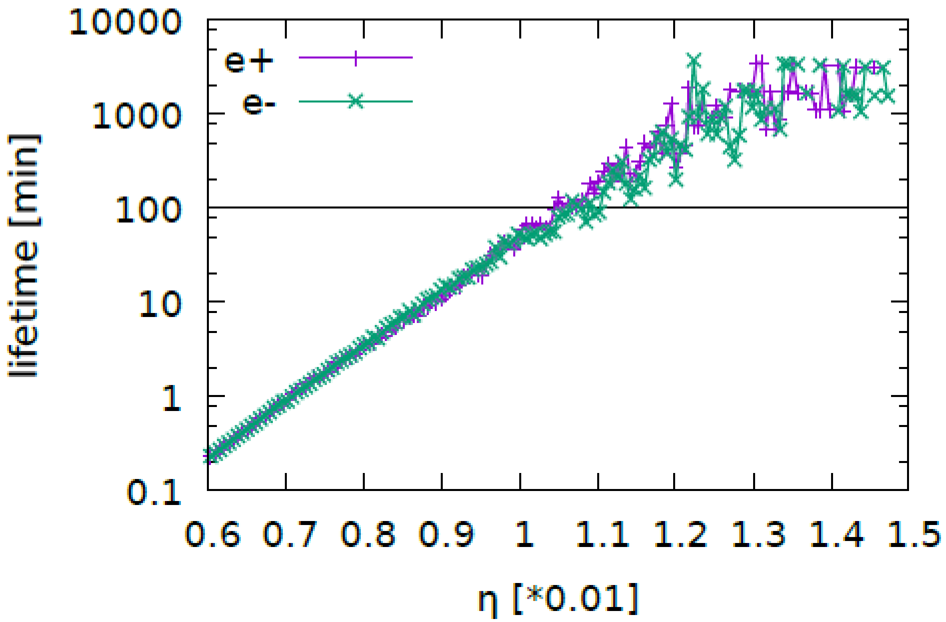
Ohmi





Zhang, IBB

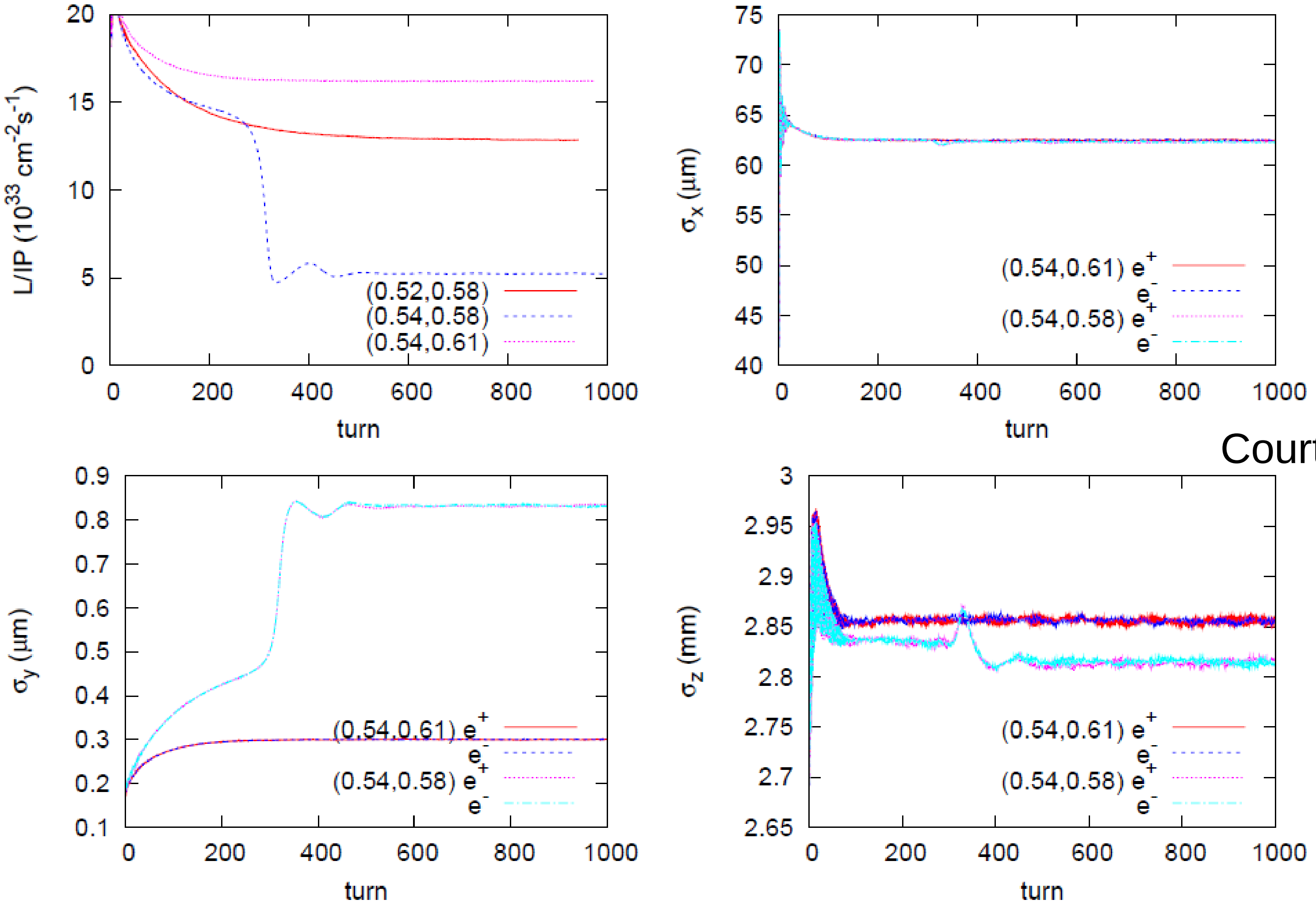




Single Ring Scheme(PRE-CDR)

Luminonisty/Beam Sizes evaluated by Strong-Strong Simulation

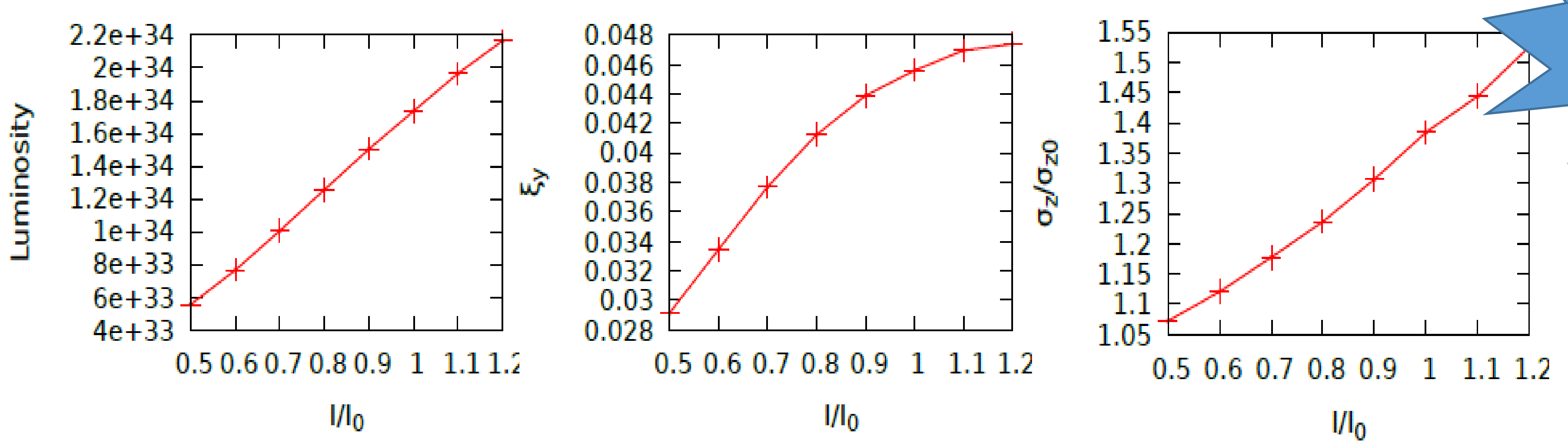
Pre-CDR



Courtesy of K. Ohmi

Luminosity versus bunch current

Pre-CDR



- For flat beam, the achieved beam-beam parameter can be defined as

$$\xi_y = \frac{2 r_e \beta_y^0}{N\gamma} \frac{L}{f_0}$$

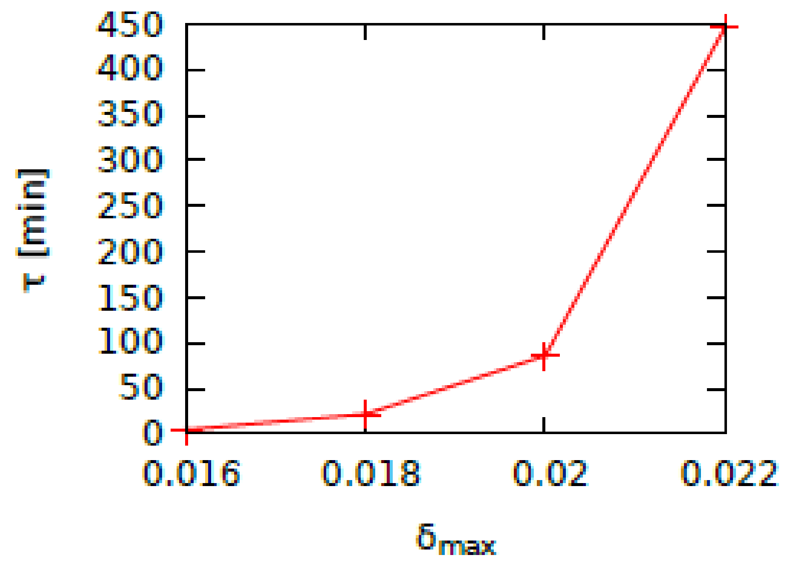
The effective beam-beam parameter is only about 0.045 with design parameters and the saturation is very clear near the design bunch current.

- The bunch length is nearly 3 times of β_y^*, which entails strong hourglass effect.

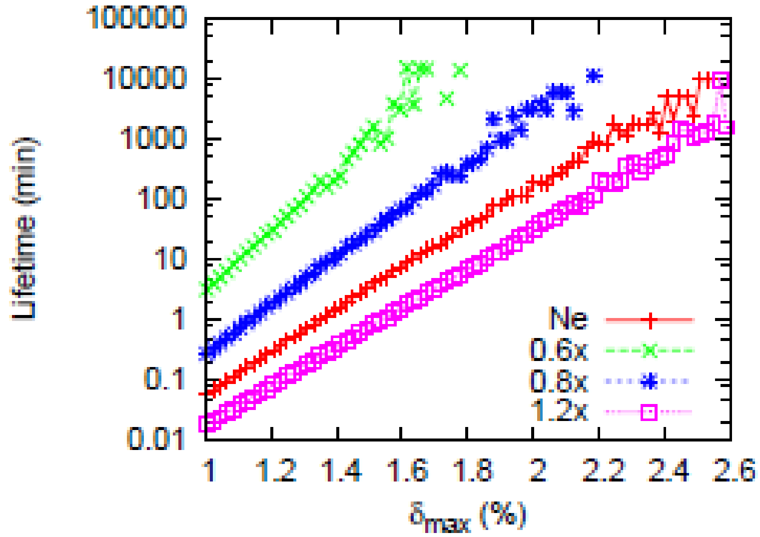
LIFETRAC

Beamstrahlung Lifetime

Pre CDR



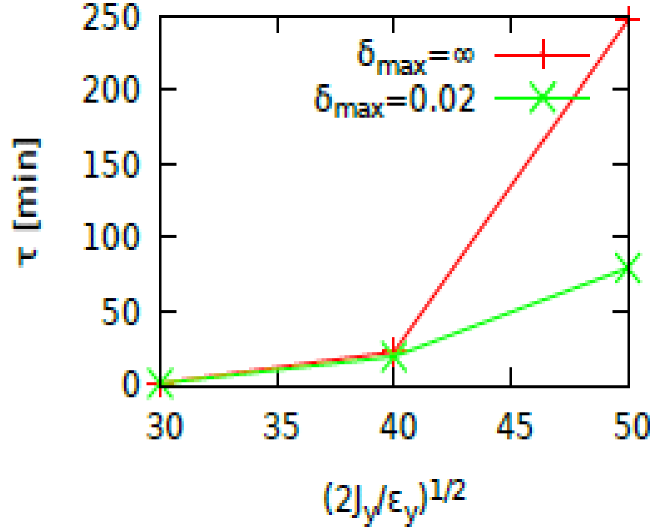
LIFETRAC

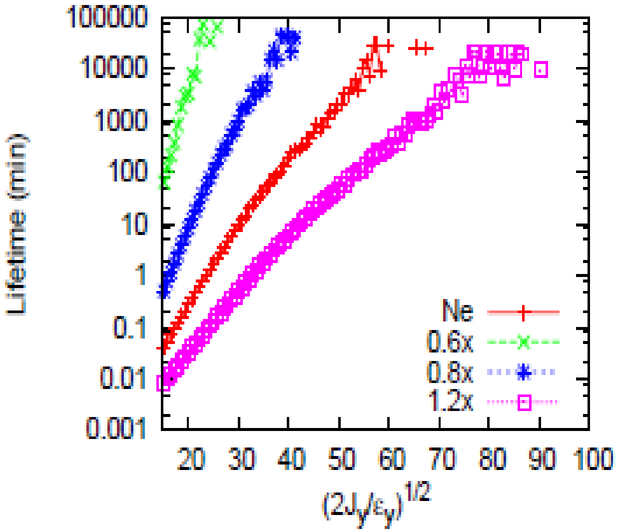


BBWS

- With $\delta_{max} = 0.02$, Beamstrahlung lifetime estimated by LIFETRAC/BBWS is about 85/250min.

Lifetime limited by vertical dynamic aperture





LIFETIME [min]	Aperture by LIFETRAC	Aperture by BBWS
250	$50\sigma_y$	$42\sigma_y$
20	$40\sigma_y$	$32\sigma_y$

Cause of the lifetime difference

- It seems both codes use the quasi-strong-strong model in lifetime simulation. But the details may be different. The strong beam' s parameter is obtained by Gaussian fitting in LIFETRAC. And it is only self-consistent for σ_x and σ_z in BBWS.

Gaussian fit in Lifetrac

	LIFETIME $(\eta = 0.02)$	LIFTIME $(40\sigma_y)$	Luminosity
W/O Gaussian Fit	222 min	202 min	1.5e34
W/ Gaussian Fit	85 min	22 min	1.7e34

Analysis of Dynamic Effect

- In the linear approximation, the dynamics can be treated as 1-D system. If we use the weak-strong picture, it could be found that the new β-function at IP

$$\beta = \frac{\beta_0}{\sqrt{1 + 4\pi\xi_0 \cot\mu_0 - 4\pi^2\xi_0^2}}$$

and the dynamic emittance

$$\epsilon = \frac{(1 + 2\pi\xi_0 \cot\mu_0)\epsilon_0}{\sqrt{1 + 4\pi\xi_0 \cot\mu_0 - 4\pi^2\xi_0^2}}$$

where ξ_0 and β_0 are the nominal values.

- We could estimate the strong-strong picture by iteration.
  - β: 0.8m -> 0.28m; (LIEETRAC: 0.274m, BBSS: 0.38m)
  - ϵ: 6.79nmrad -> 12.1nmrad; (LIFETRAC: 12.5nmrad, BBSS: 10nmrad)
  - ξ_0: 0.10 -> 0.16; (LIFETRAC: 0.165)

Analysis of Dynamic Effect (Cont)

- We've obtained the β just at IP, and could continue to calculate the twiss function just after IP using the transfer matrix of half beam-beam kick map

$$\begin{bmatrix} 1 & 0 \\ -\frac{2\pi\xi_0}{\beta_0} & 1 \end{bmatrix}$$

- It is found that $\alpha_+ = 0.84$ and $\beta_+ = 0.28$m just after IP. That is to say the new waist is about 0.14m away from IP and β is about 0.164m at the waist.
- L^*~1.5m, it could be estimated that the dynamic beam size is about 2.3 times the nominal value. As we've shown there is no long tail in horizontal direction, the aperture should be about $20\sigma_{x,0}$ at the final focus magnet.
- The estimation may be overestimated since the linear model is used and it is valid only for small oscillation particle.

Pretzel scheme

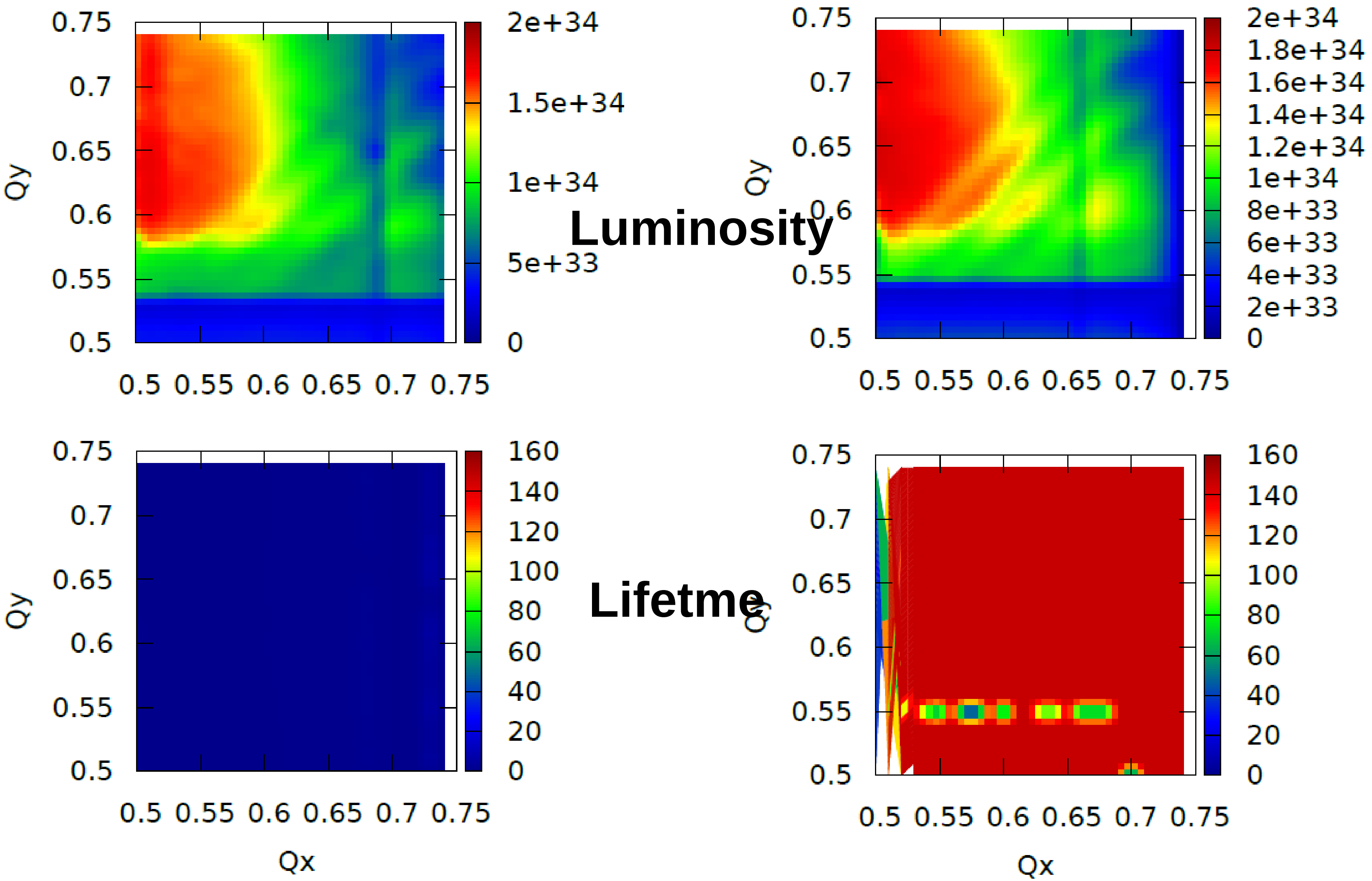
Single Ring

- the phase advance between parasitic crossing point should be a integer number of 2*Pi,
- Designed for 50 bunches/beam, every 4pi phase advance has one collision point
- Horizontal separation is adopted to avoid big coupling
- $10\sigma_x$ separation is assumed in horizontal direction
- 50 bunches per beam, 100 parasitic crossings totally

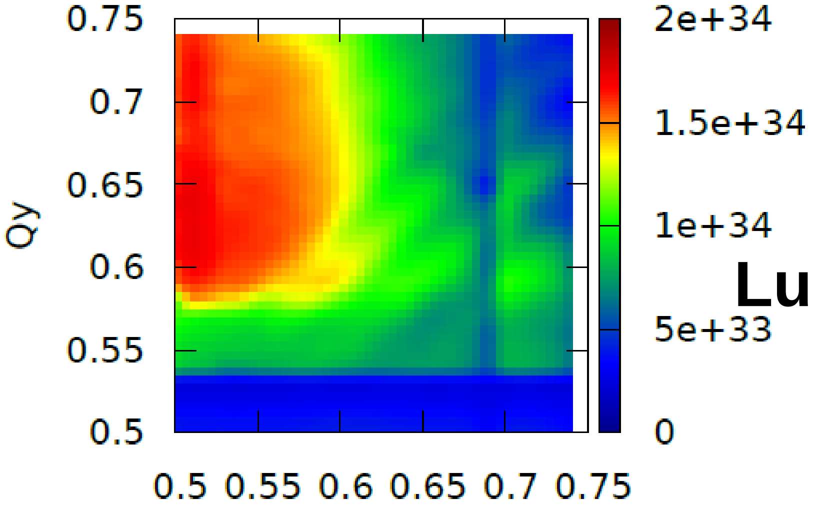
$(\xi_x, \xi_y) = \frac{Nr_e}{2\pi\gamma} \frac{(\beta_x, \beta_y)(x^2 - y^2)}{(x^2 + y^2)^2}$, It could be estimated that

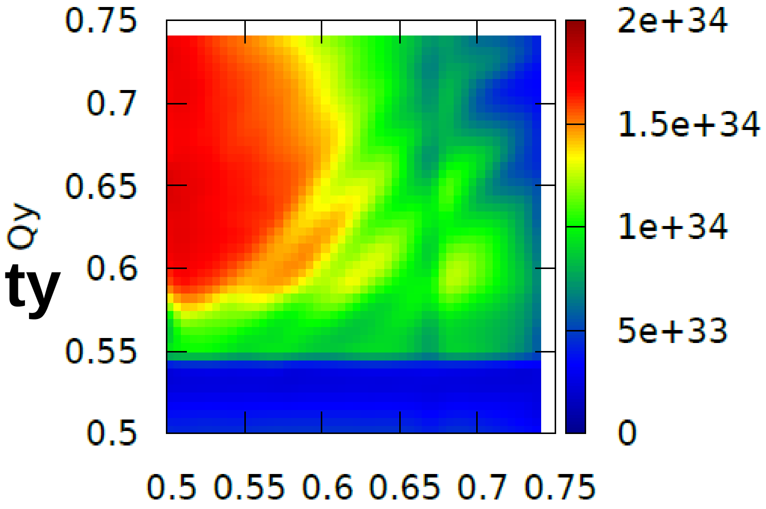
$$\xi_x = 0.0007/pc,\ \xi_{x,total} = 0.07$$

Tune Scan with PCs on/off

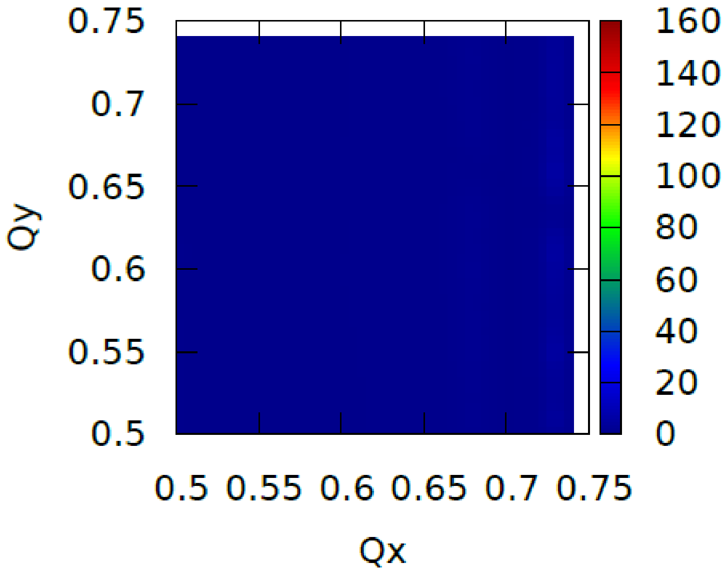


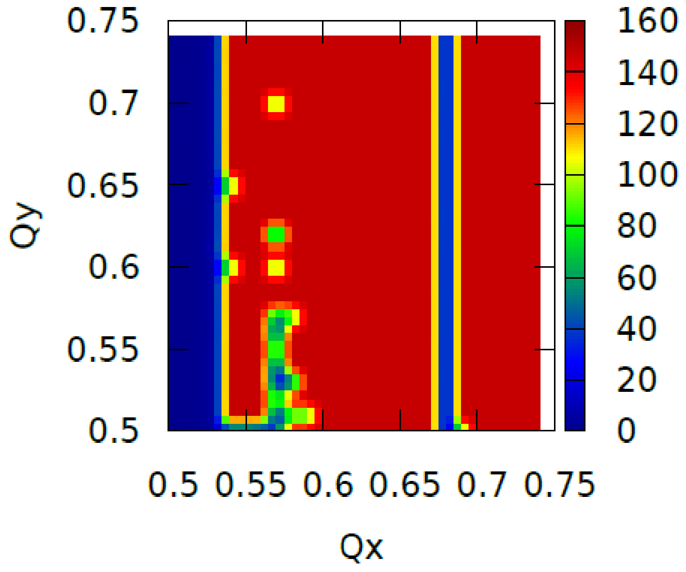
Different Separation: $10\sigma_x$ vs $15\sigma_x$





Luminosity

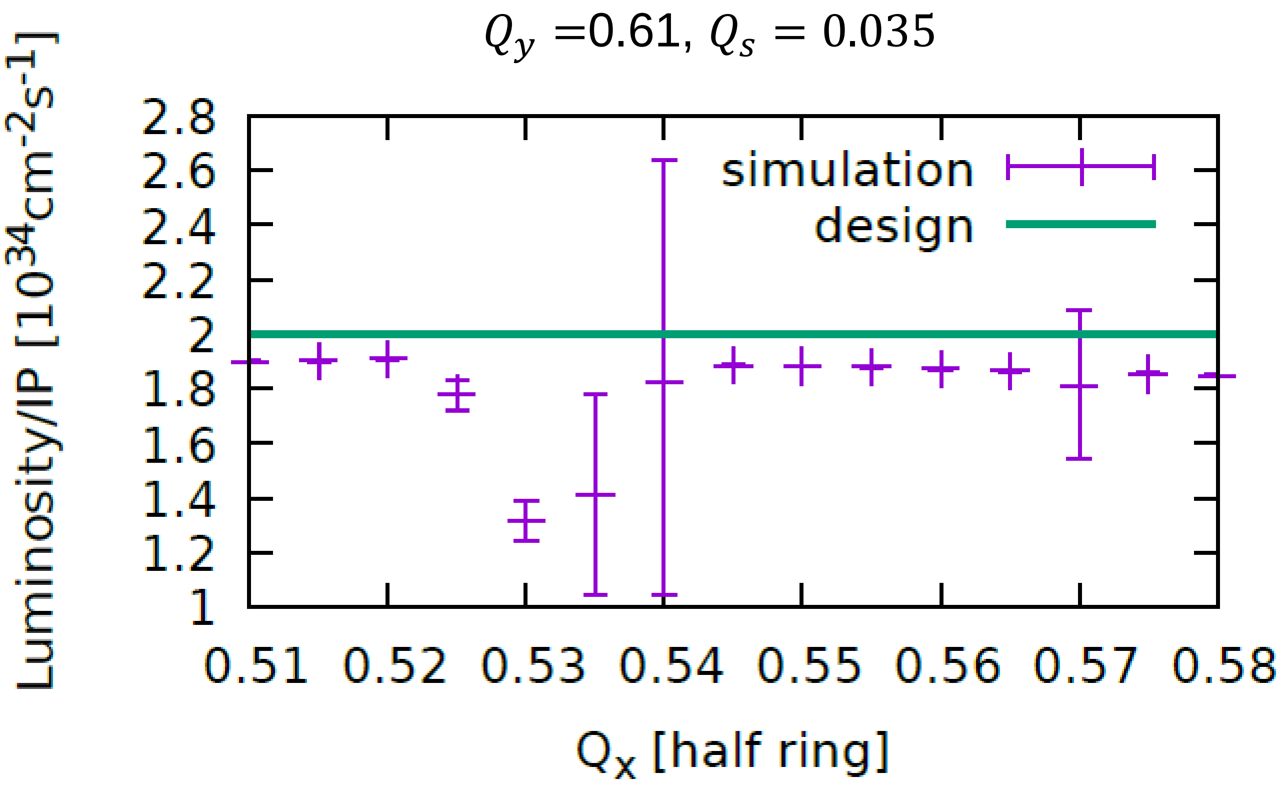




Lifetime

Double Ring Scheme

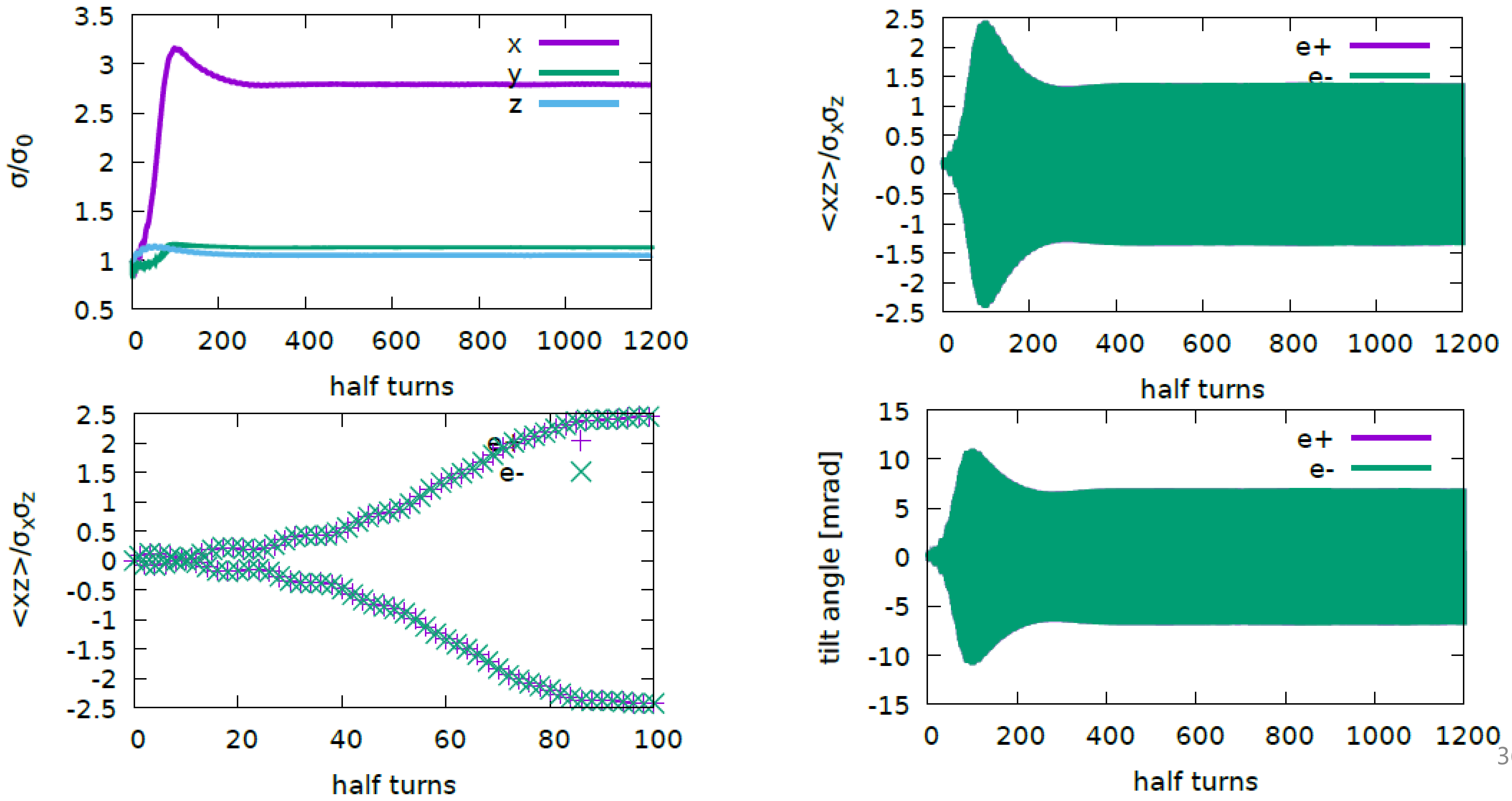
Tune Scan(Higgs)



The error bar shows the turn-by-turn luminosity difference.

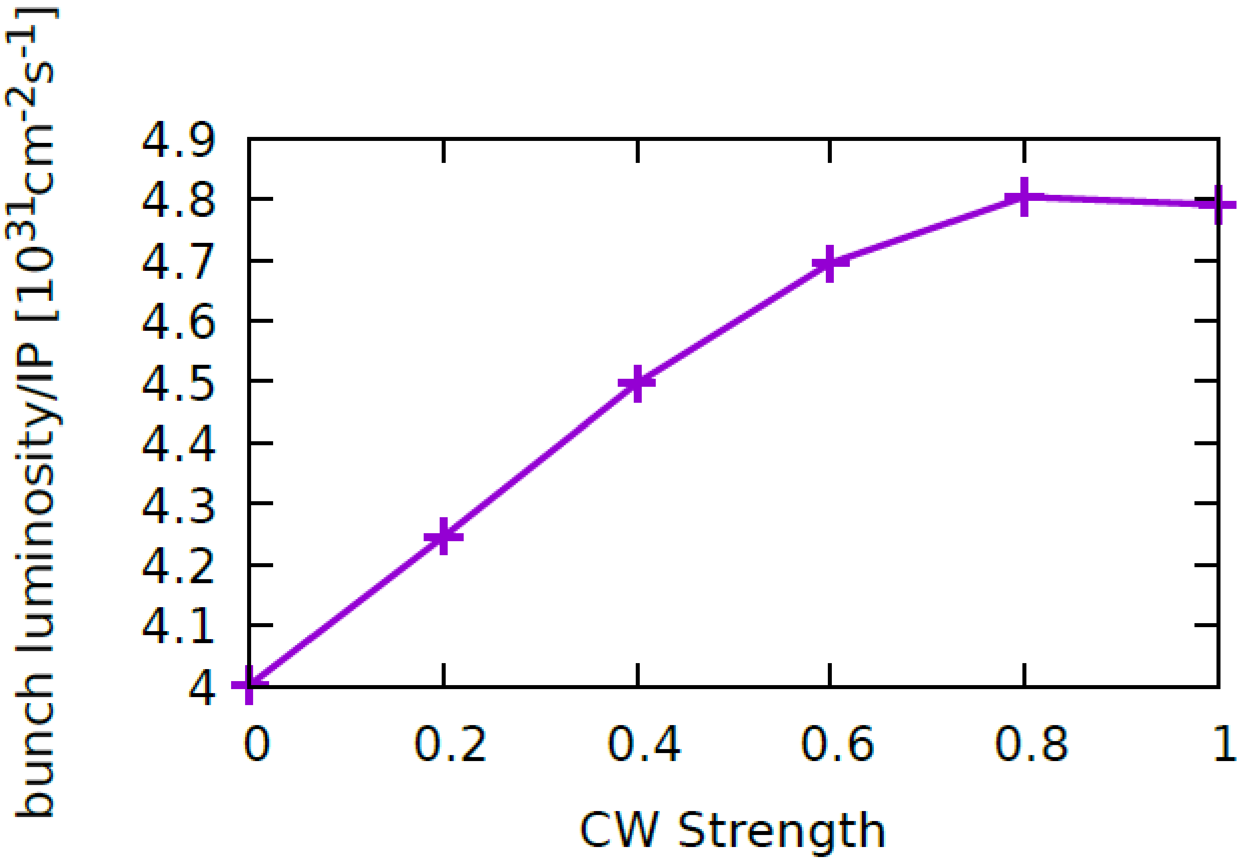
K. Ohmi and etal., DOI:10.1103/PhysRevLett.119.134801

X-Z instability @(0.535,0.61)



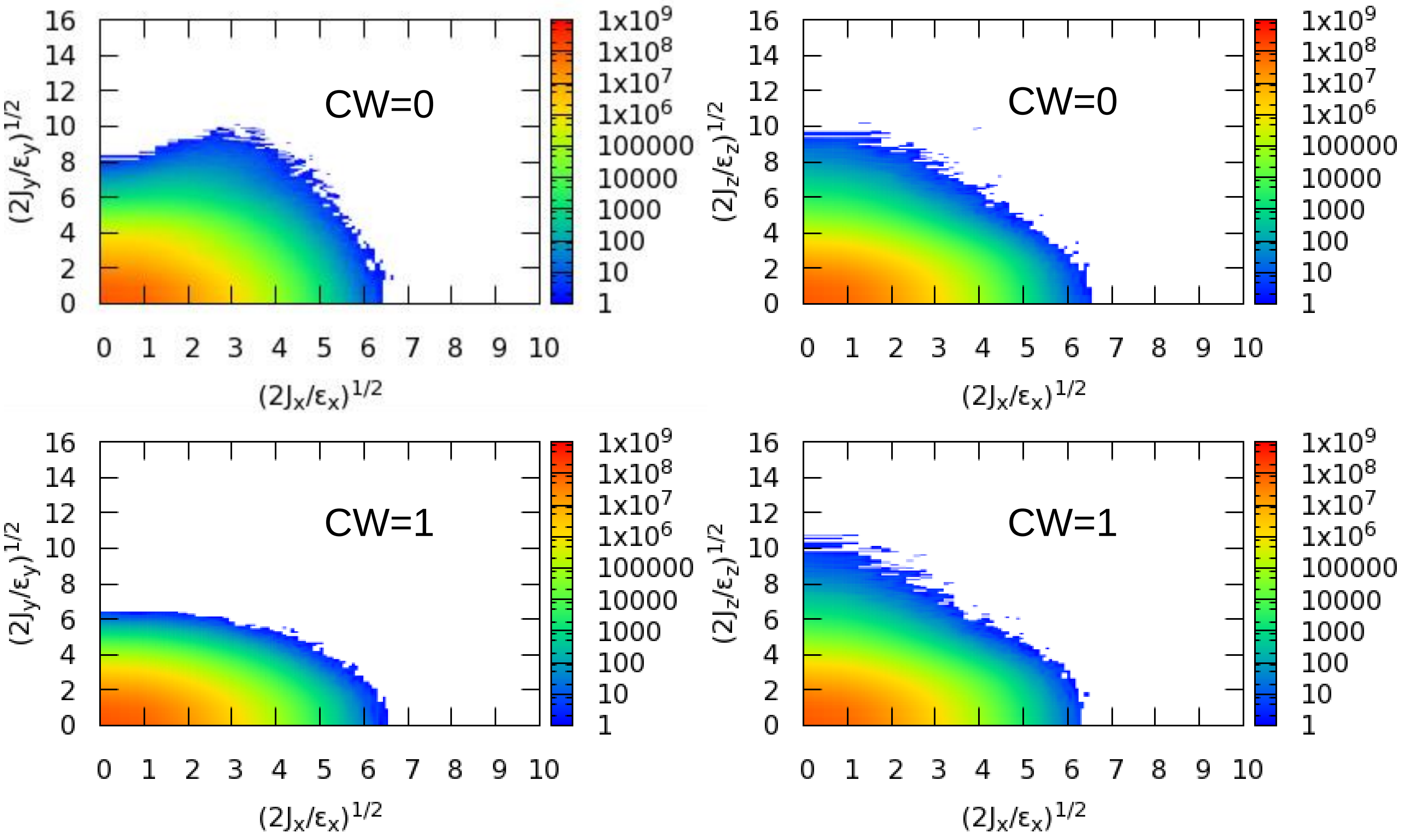
Crab Waist Strength (Higgs)

Piwinski Angle ~ 3



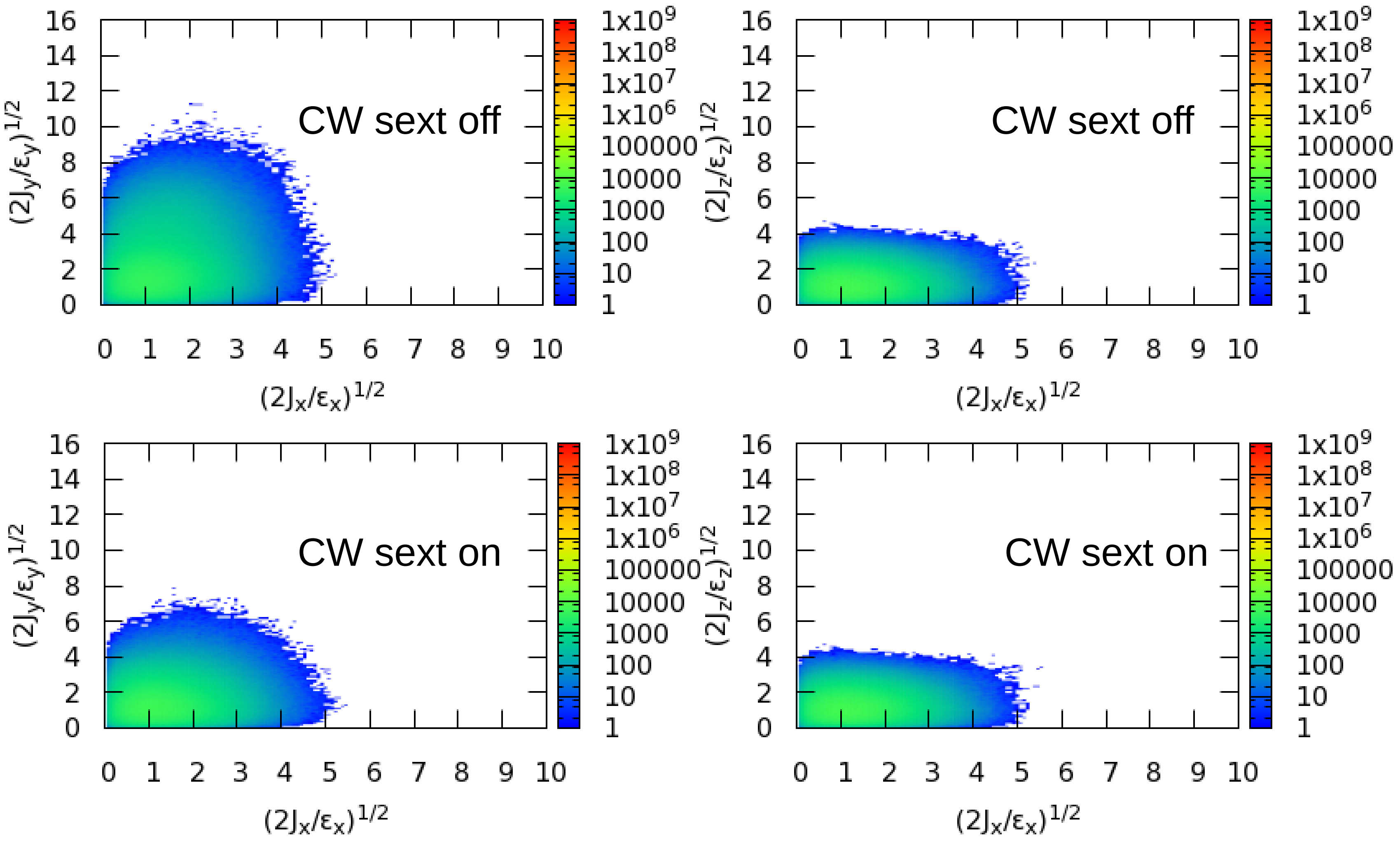
Beam-Distribution: Beam-Beam + Linear Arc

Crab waist mainly helps to suppress the vertical blowup

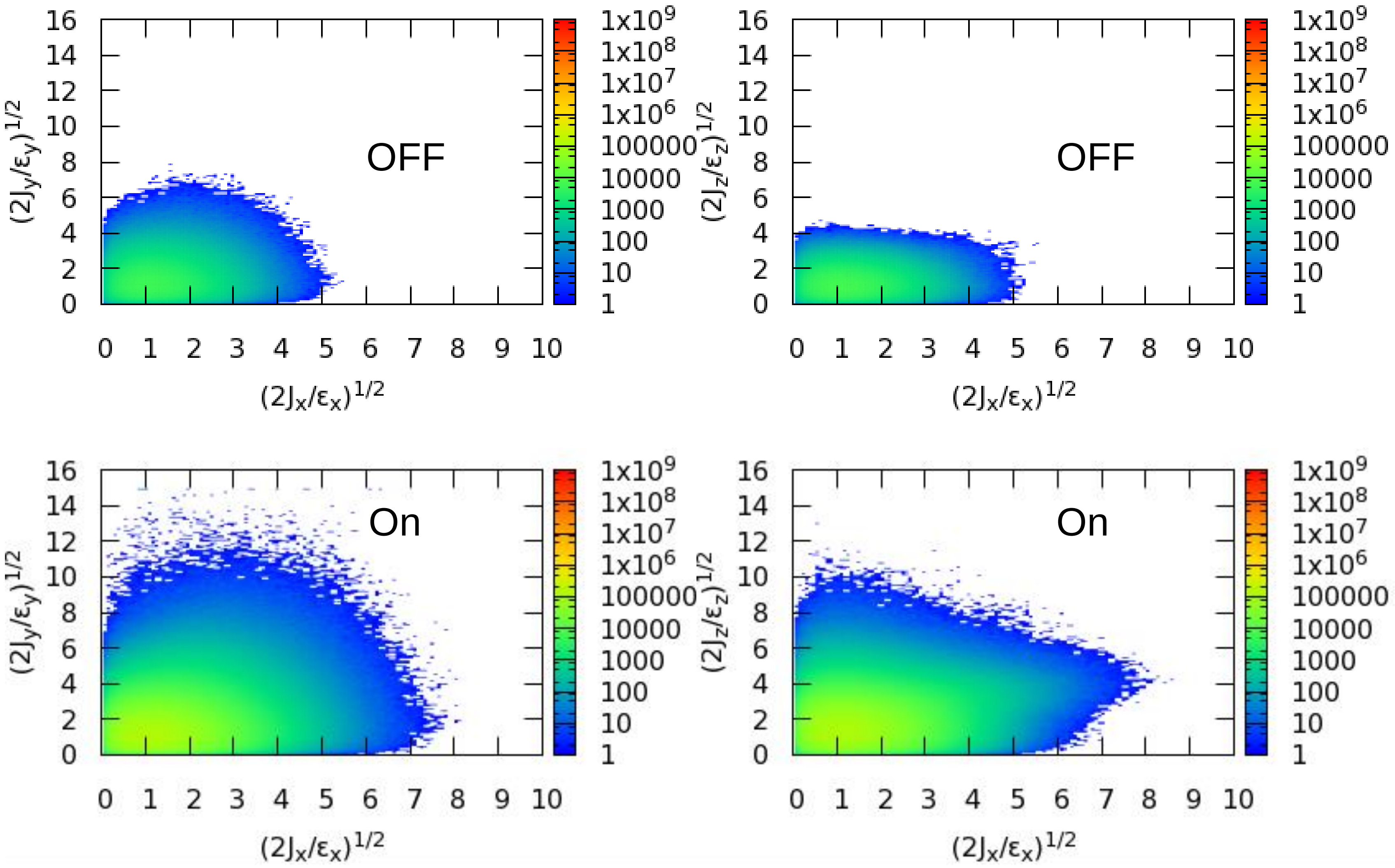


BB@IP with real Lattice

1000 particles
5000 half-turn



BB@IP with real Lattice : Beamstrahlung

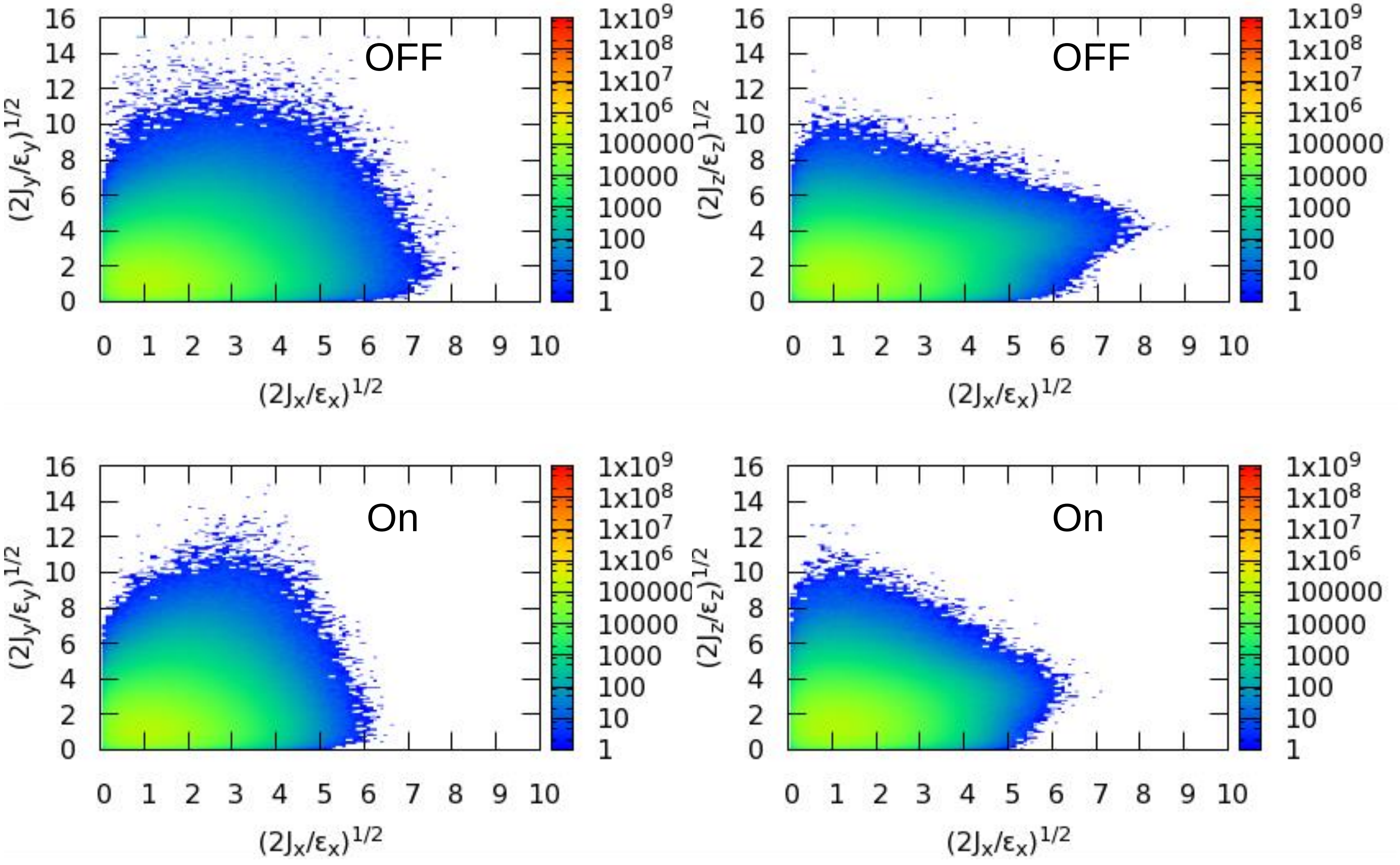


1000 particles
5000 half-turn

1e3 particles
1e5 half-turn

BB@IP with real Lattice : Beamstrahlung , SR in Magnet(B/Q…)

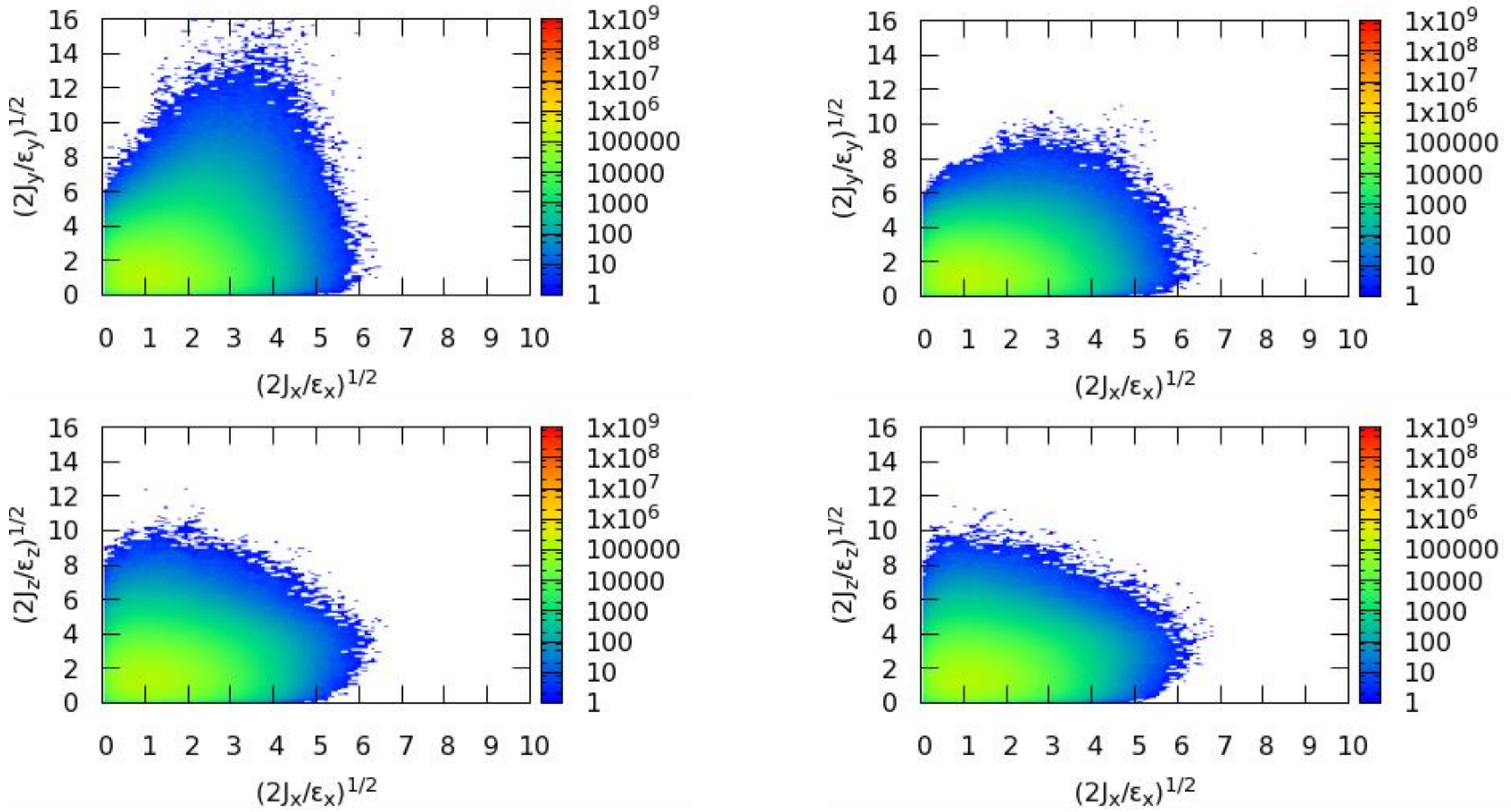
1e3 particles
1e5 half-turn



SR at IP

Different Observation Point

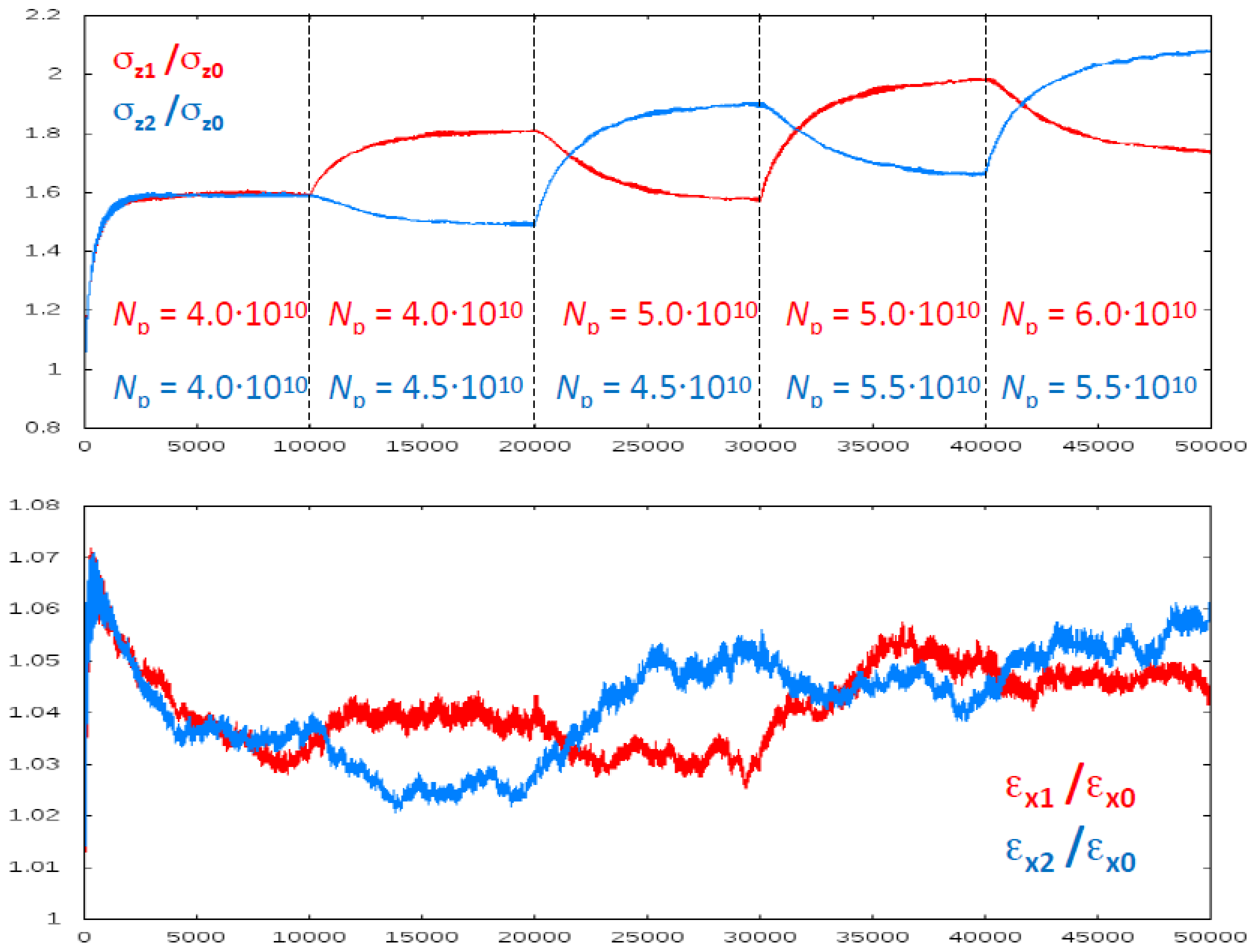
IP **INJ**



Bootstraping

D. Shatilov

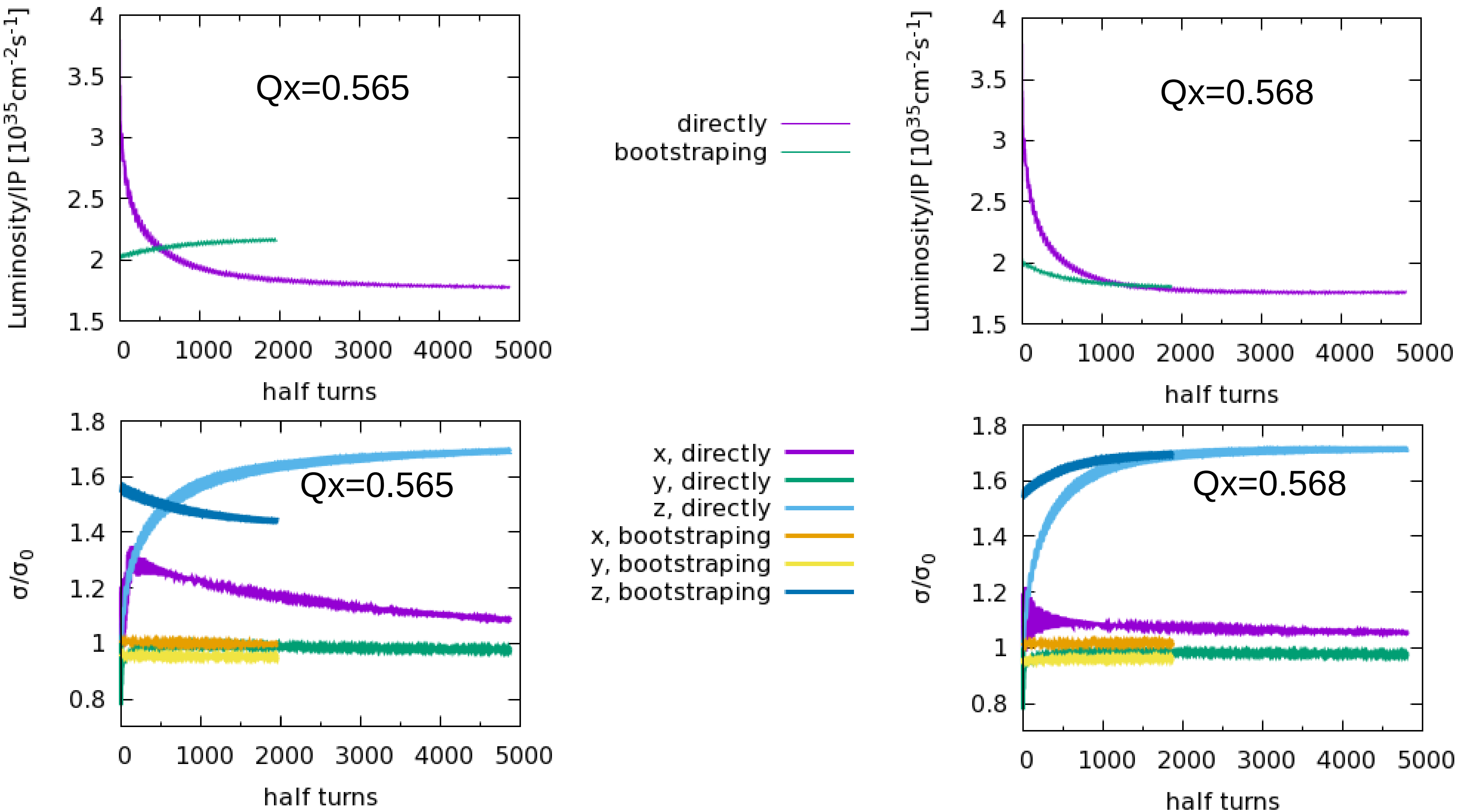
Np $\propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}$ (K. Oide)



- The maximum bunch charge is determined considering the balance of beamstrahlung, momentum acceptance, and the capability of injector.

8.0e10 * 8.0e10

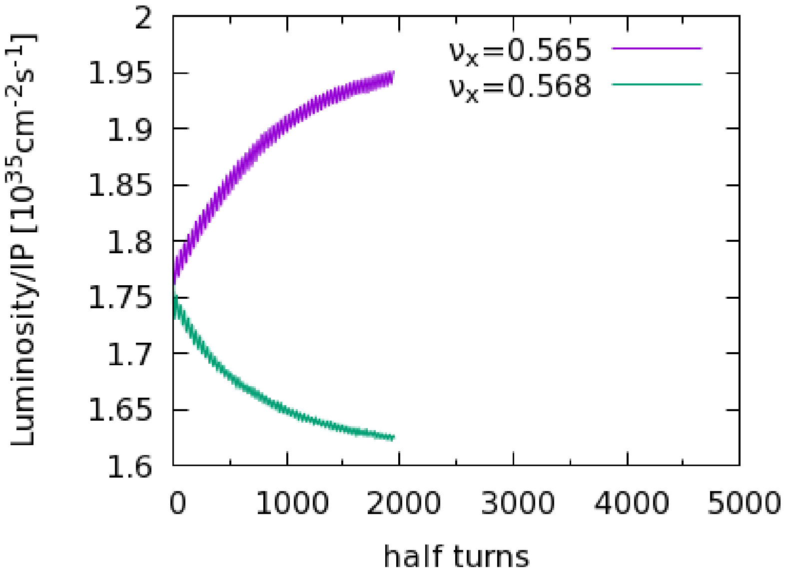
Z: different collision path

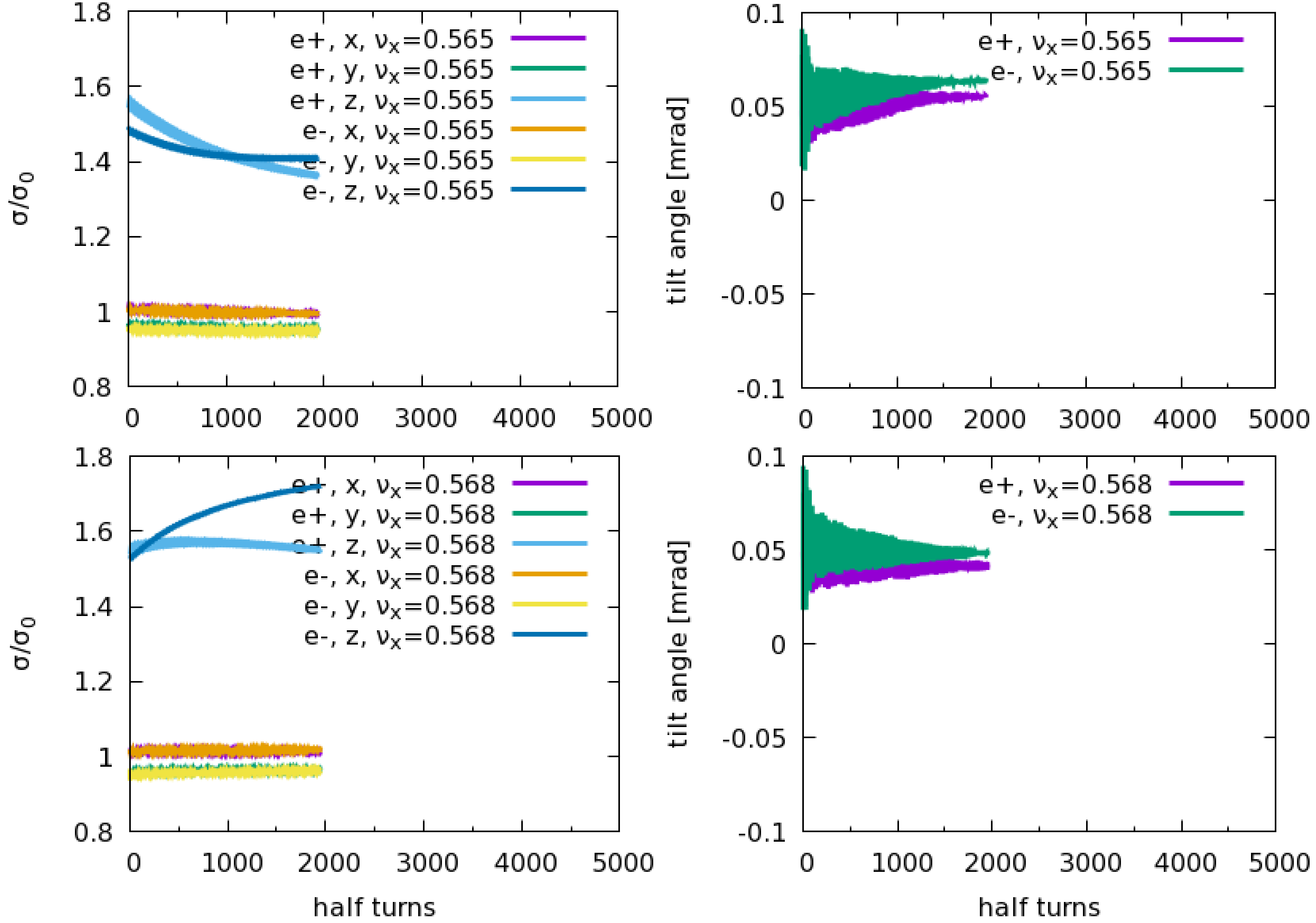


Z: Asymmetric Bunch Current Collison

10% difference

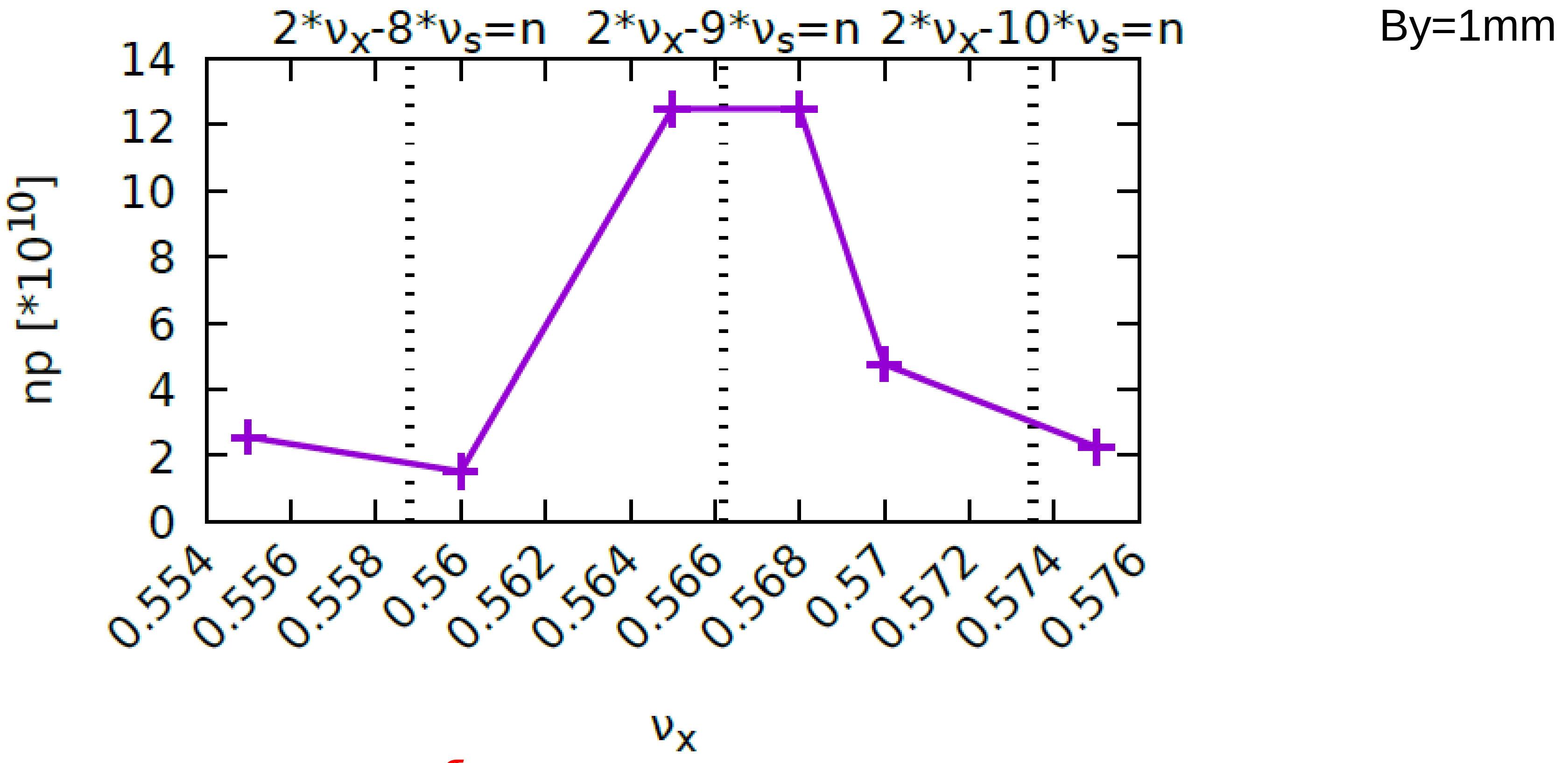
8.0e10 * 7.0e10





Z: bunch current limit using bootstrapping

Width of safe Qx ~ 0.003



blowup of $\frac{\sigma_x}{\sigma_0}$ <1.1, Limit of bunch population

Summary

- Beam-beam code has been developed and cross checked for large Piwinski angle collision and beamstrahlung effect
- Single Ring Scheme: Large momentum acceptance requirement and DA requirement, complicated Pretzel Scheme …… ($20\sigma_x \times 50\sigma_y \times 0.02$)
- The beam-beam effect is evaluated by comparing with built machines and is considered reasonable
- Crosstalk between lattice & BB is studied at Higgs Energy
- Limit of bunch population by beam-beam interaction
  - Beamstrahlung lifetime
  - If X-Z instability is suppressed
  - If Asymmetric Collision is OK
  - If there exist large enough stable working point space

Backup Slides

Main Parameters of CEPC (ver. 140416)

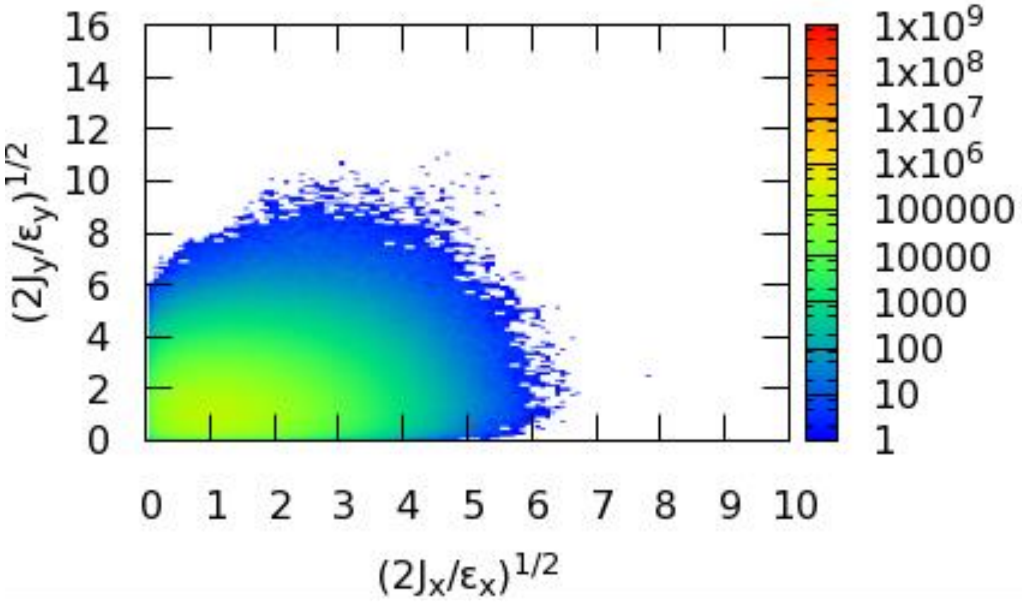
Pre-CDR

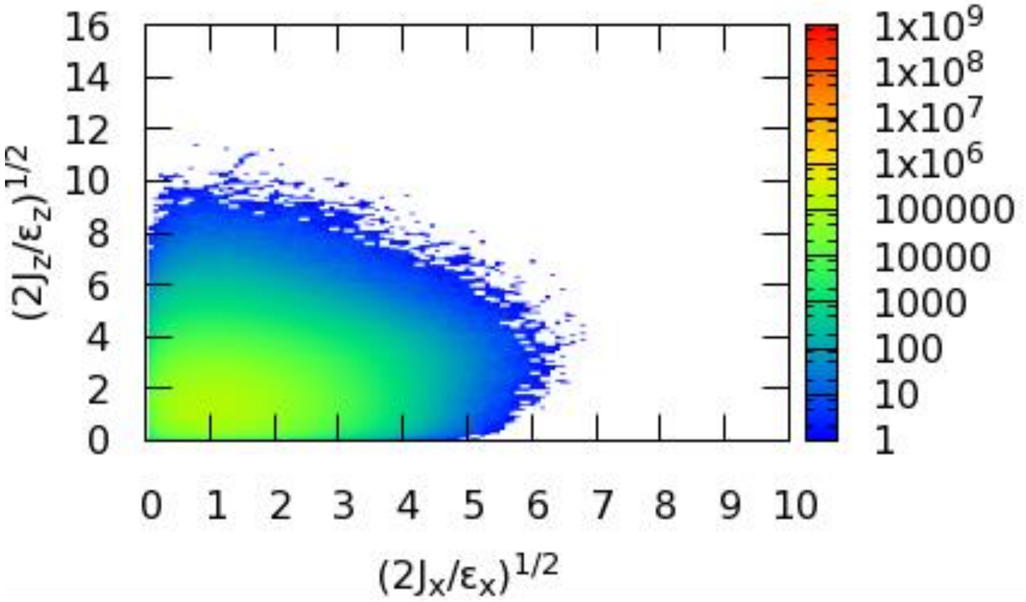
Main parameters

Beam energy [E]	GeV	120	Beam length SR [$\sigma_{s.SR}$]	m	0.00226
Circumference [C]	km	53.6	Betatron function at IP-vertical [β_{y}	m	0.0012
Luminosity [L]	$cm^{-2}s^{-1}$	1.82E+34	Betatron function at IP-horizontal	m	0.8
SR power/beam [P]	MW	50	Beam-beam parameter [ξ_x]		0.104
N_{IP}		2	Beam-beam parameter [ξ_y]		0.074
n_B		50	RF voltage [V_{rf}]	GV	6.87
momentum compaction factor [α_p]		4.15E-05	RF frequency [f_{rf}]	GHz	0.7
Energy acceptance Ring[η]		0.02	Synchrotron oscillation tune [ν_s]		0.206
Beam current [I]	mA	16.60	SR loss/turn [U_0]	GeV	3.01
Bunch population [N_e]		3.71E+11	Energy spread SR [$\sigma_{\delta.SR}$]	%	0.13
emittance-horizontal [ε_x]	m·rad	6.79E-09	Transverse damping time [n_x]	turns	79.70
coupling factor [κ]		0.003	Longitudinal damping time [n_ε]	turns	39.85

Higgs

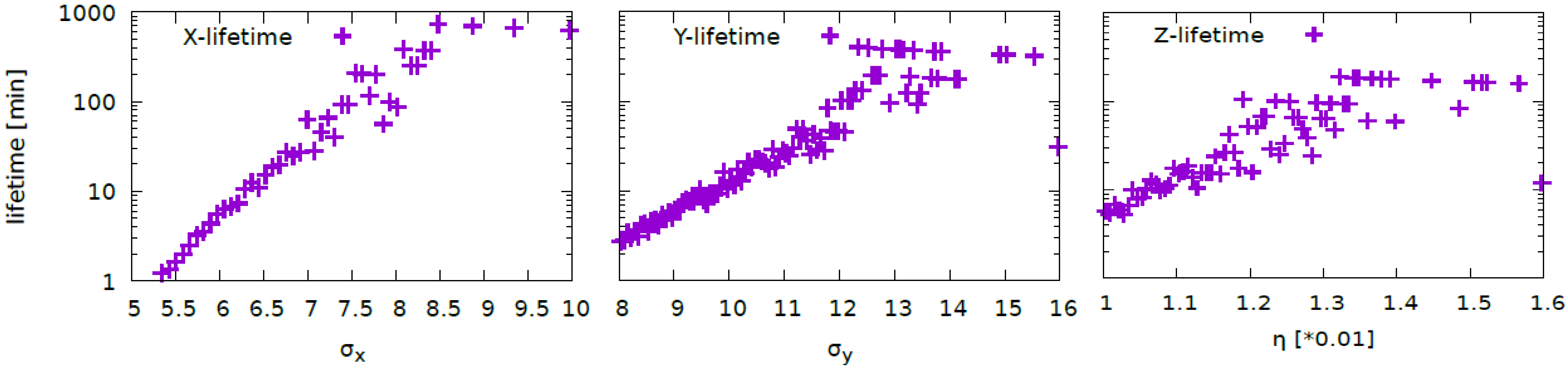
Beam Distribution: by=1.5mm
Lattice + Beamstrahlung + SR Fluctuation





Higgs

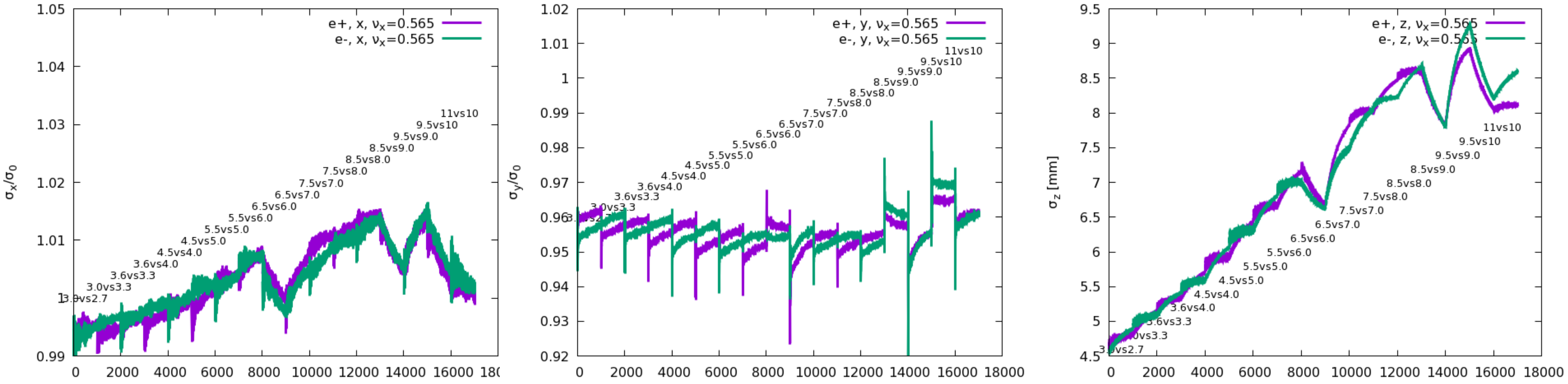
Beam Lifetime: by=1.5mm
Lattice + Beamstrahlung + SR Fluctuation



100min, DA requirement: 7.5σ_x,   12.5σ_y,   0.0135

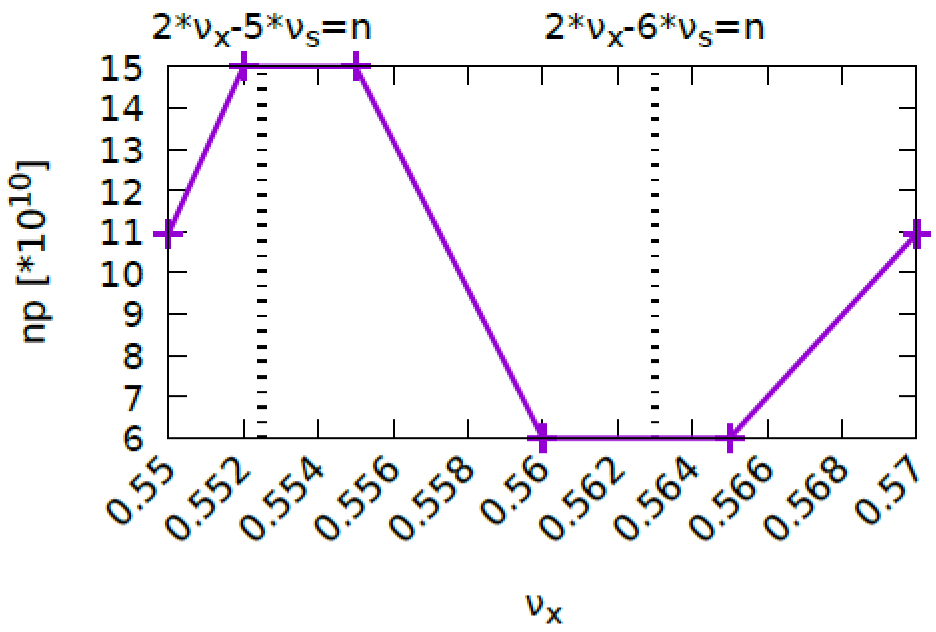
Achieved DA: ~15σ_x,   ~15σ_y,   ~0.015

By=1mm, 100MV, Z-Bootstraping



W:

- bootstraping



W: 15.0vs15.0 (*e10)