Beam-beam predictions for SuperKEKB and Large Crossing angle

K. Ohmi (KEK)

Beam-beam workshop at CERN

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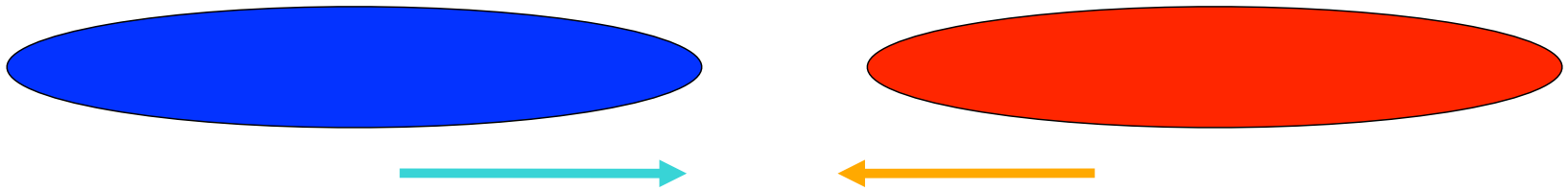
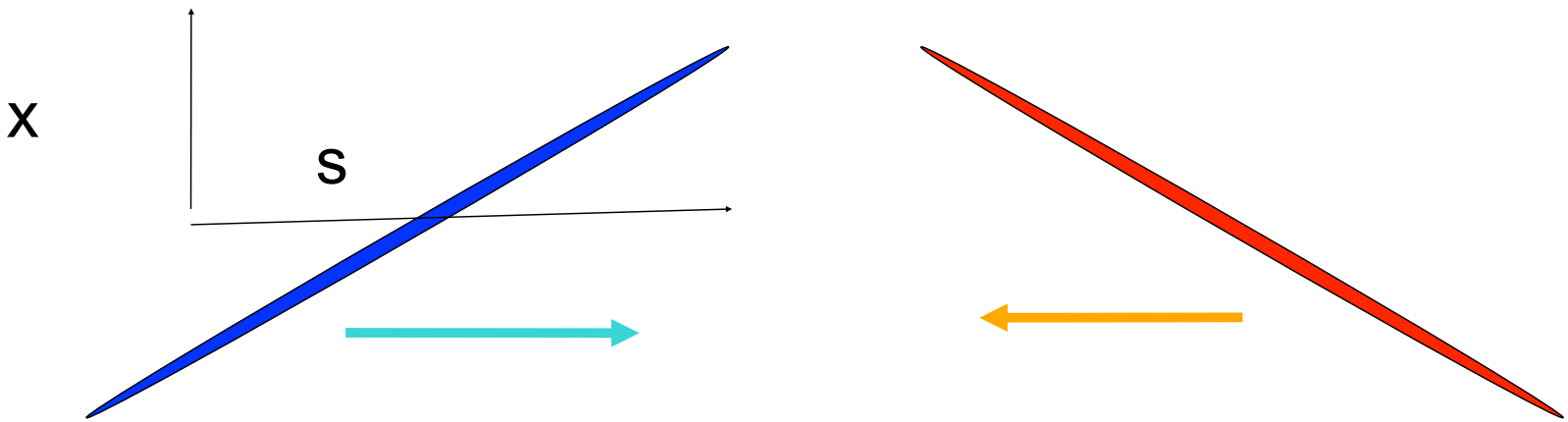
Thanks: KEKB/SuperKEKB term, E. Levichev, P. Piminov, E. Perevedentsev, P. Raimondi, D. Shatilov, F. Zimmermann, M. Zobov

Two approach toward high luminosity

- High current, high beam-beam parameter.



- Low emittance, low beta, low current, so-called super bunch collision



Comparison of two approach

High curent $\frac{\sqrt{\varepsilon_x \beta_x}}{\theta \sigma_z} > 1$ or $\theta = 0$

$$L \sim \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\varepsilon_x}$$

$$\xi_y \sim N \sqrt{\frac{\beta_y}{\varepsilon_x \beta_x \varepsilon_y}}$$

$$\beta_y > \sigma_z$$

θ: half crossing angle

Low emittance $\frac{\sqrt{\varepsilon_x \beta_x}}{\theta \sigma_z} < 1$

Overlap factor

$$L \sim \frac{N^2}{\theta \sigma_z \sqrt{\varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\theta \sigma_z} \sqrt{\frac{\beta_x}{\varepsilon_x}}$$

$$\xi_y \sim \frac{N}{\theta \sigma_z} \sqrt{\frac{\beta_y}{\varepsilon_y}}$$

$$\beta_y > \frac{\sqrt{\varepsilon_x \beta_x}}{\theta}$$

ξ_x is smaller due to cancellation of tune shift along bunch length

High current approach

$$L \sim \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\varepsilon_x}$$

$$\xi_y \sim N\sqrt{\frac{\beta_y}{\varepsilon_x \beta_x \varepsilon_y}}$$

$$\beta_y > \sigma_z$$

Keep ε_x, β_x and $\sqrt{\frac{\beta_y}{\varepsilon_y}}$.

$$\varepsilon_y \beta_y \to 0$$

$$L \to \infty$$

$\beta_y > \sigma_z$ limits luminosity

- High current, Small coupling
- Choice of operating point

$$\nu_x \to +0.5 \qquad \xi_y \to \infty \qquad N \to \infty$$

θ=0 $\qquad L \to \infty$

Why ξ_y can be large

- $\nu_x \rightarrow 0.5$, the horizontal motion is integrated independent of y, because horizontal beam-beam force weakly depends on y.

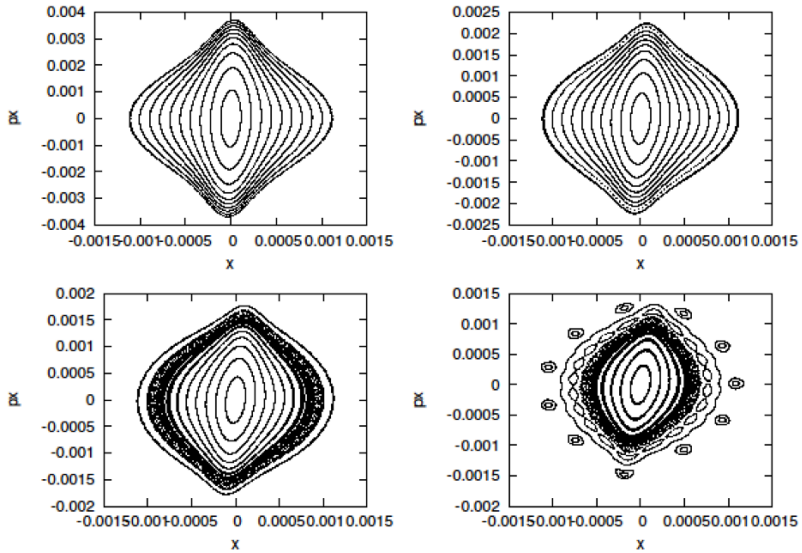
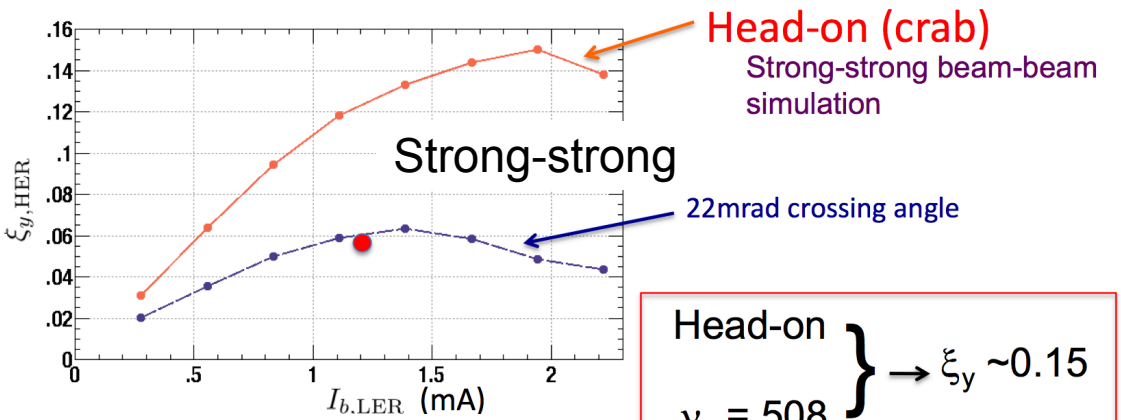
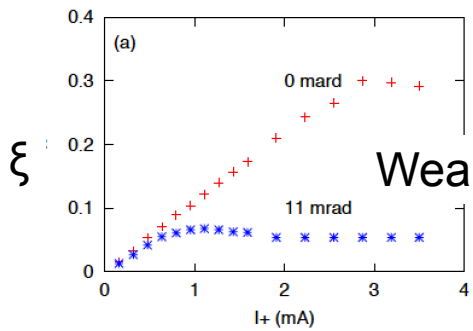


Figure 3: Phase space plot in $x - p_x$. $y_0 = 2\mu$ m$\approx 3\sigma_y$. plots (a), (b), (c) and (d) is given for ν_x =0.503,0.51,0.52 and 0.54, respectively.

- z independent for θ_c=0.
- Nonlinear y motion (1 dim) is slowly modulated by x motion (externally).



Head-on
ν_x =.508 } → ξ_y ~0.15



Weak-strong: ξ=0.3

Limitation of crab and $\nu_x \rightarrow 0.5$ scheme

- Dynamic beta in horizontal works demerit.
- Aperture issue appears other place of IR, especially at the crab cavity.
- Low crab β_x requires high crab voltage, while high IR β_x degrades luminosity.
- Crossing angle relaxes the dynamic beta ironically, $\sigma_x=(\varepsilon_x\beta_x+\theta\sigma_z^2)^{1/2}$.
- We had to find the middle ground.

- The crab crossing works fairly well, though it is not perfect.

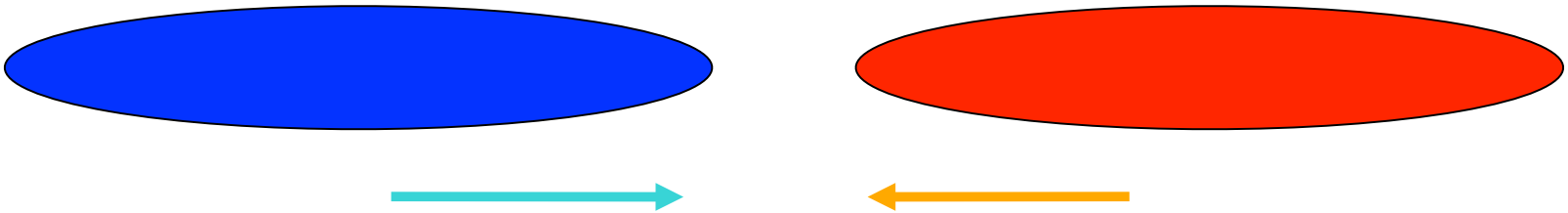
Machine parameters (before/after crab)

Date	Nov.15 2006 before crab		Jun. 17 2009 with crab		
	LER	HER	LER	HER	
Current	1.65	1.33	1.64	1.19	A
Bunches	1389		1584		
Bunch current	1.19	0.96	1.03	0.750	mA
spacing	2.10		1.84		mA
emittance ε_x	18	24	18	24	nm
β_x^*	59	56	120	120	cm
β_y^*	6.5	5.9	5.9	5.9	mm
σ_x @IP	103	107	147	170	μm
σ_y @IP	1.8	1.8	0.94	0.94	μm
ν_x	45.505	43.509	45.506	44.511	
ν_y	44.534	41.565	43.561	41.585	
ν_s	-0.0246	-0.0226	-0.0246	-0.0209	
beam-beam ξ_x	0.117	0.070	0.127	0.102	
beam-beam ξ_y	0.108	0.058	0.129	0.090	
Luminosity	17.6		21.08		$10^{33}cm^{-2}s^{-1}$

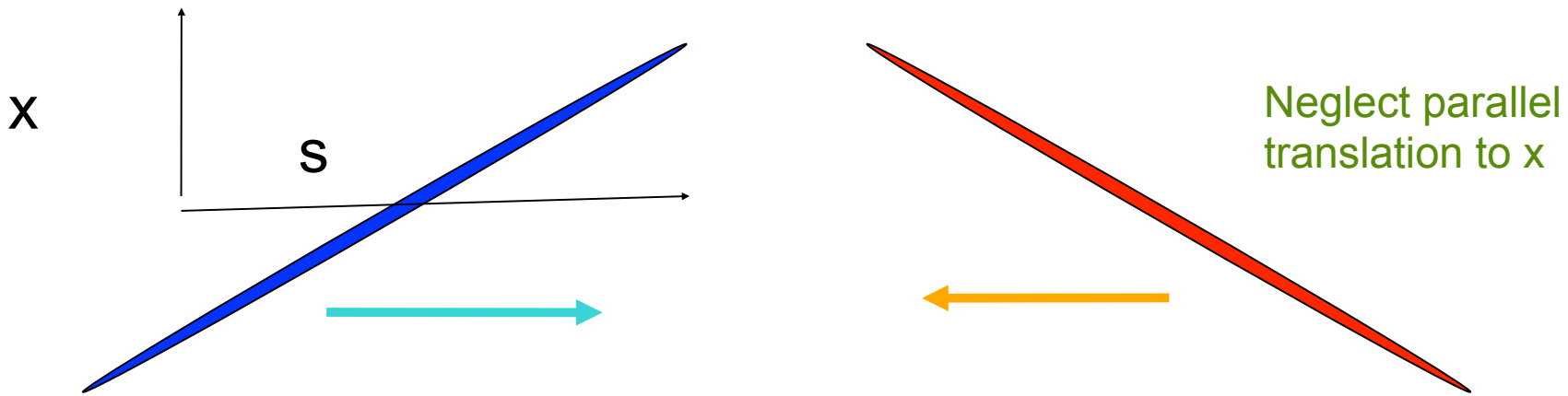
KEKB chooses mutation not evolution.

Nano-beam scheme

- KEKB with crab cavity targeted a high beam-beam parameter >0.1.



- SuperKEKB goes toward Low emittance, low beta, moderate beam-beam parameter <0.1



Low emittance approach

Φ: half crossing angle

$$\sigma_x/\phi < \sigma_z$$

$$\boxed{\sigma_x/\phi < \beta_y}$$

$$L \propto \frac{N^2}{\phi\sigma_z\sqrt{\varepsilon_y\beta_y}}$$

$$\xi_x \propto \frac{N\beta_x}{(\phi\sigma_z)^2}$$

$$\boxed{\xi_y \propto \frac{N}{\phi\sigma_z}\sqrt{\frac{\beta_y}{\varepsilon_y}}}$$

Keep $\sqrt{\frac{\beta_y}{\varepsilon_y}}$ and σ_x/β_y

Then take limit $\varepsilon_y\beta_y \to 0$

$$L \to \infty$$

- Bunch length is free.
- Small beta and small emittance are required.

Super KEKB

ε_x=3/5 nm, ε_y=3/5 pm

β_x=32/25 mm, β_y=0.3mm

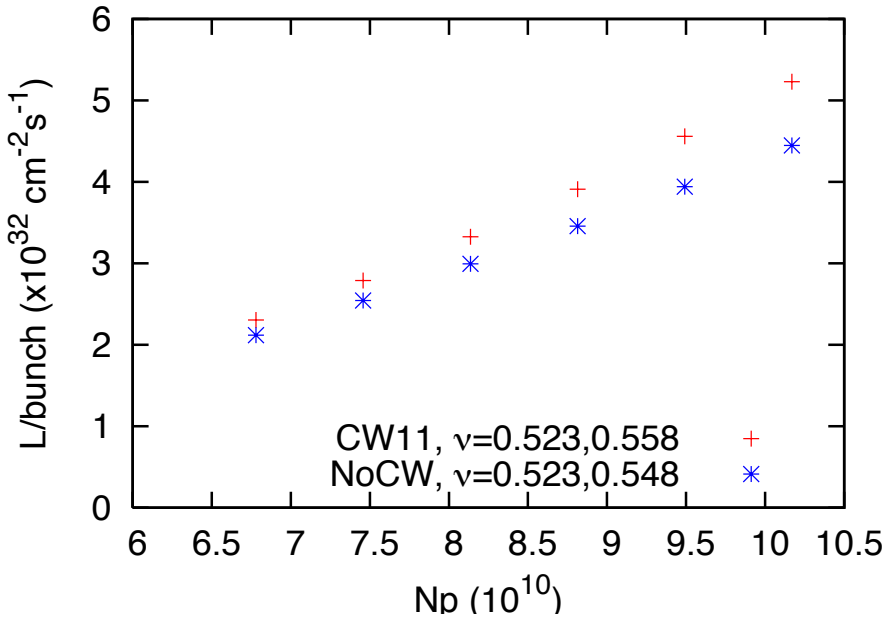
Machine Parameters

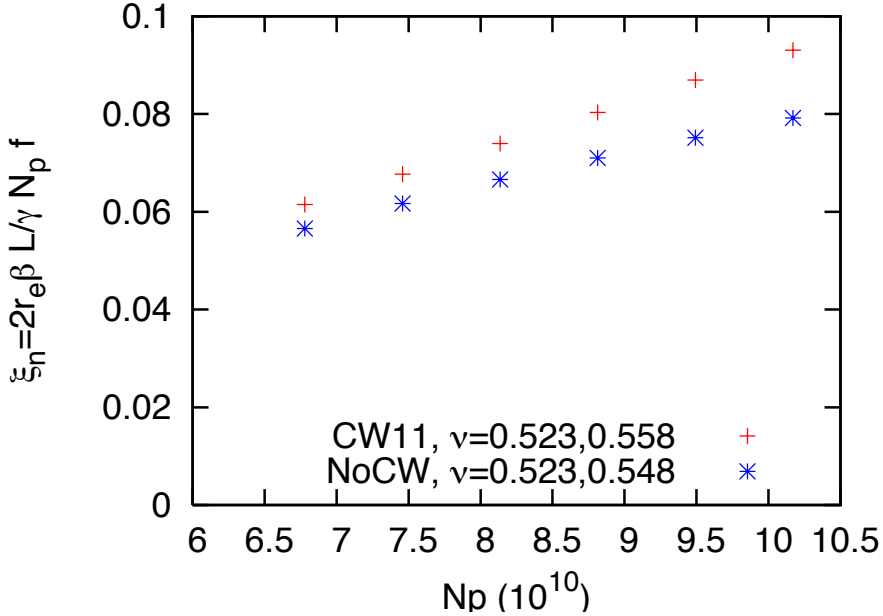
2011/July/20	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/11.5(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.25×10^{-4}	4.55×10^{-4}		
σ_δ	$8.08(7.73)\times10^{-4}$	$6.37(6.31)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0247	-0.0280		
ν_x/ν_y	44.53/44.57	45.53/43.57		
U_0	1.87	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.1/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

Current dependence of L and ξ

given by a weak-strong simulation

- Nano beam collision is reliable for small ξ<0.1 without Crab Waist.
- The gain of CW remarkably appear higher beam-beam parameter.



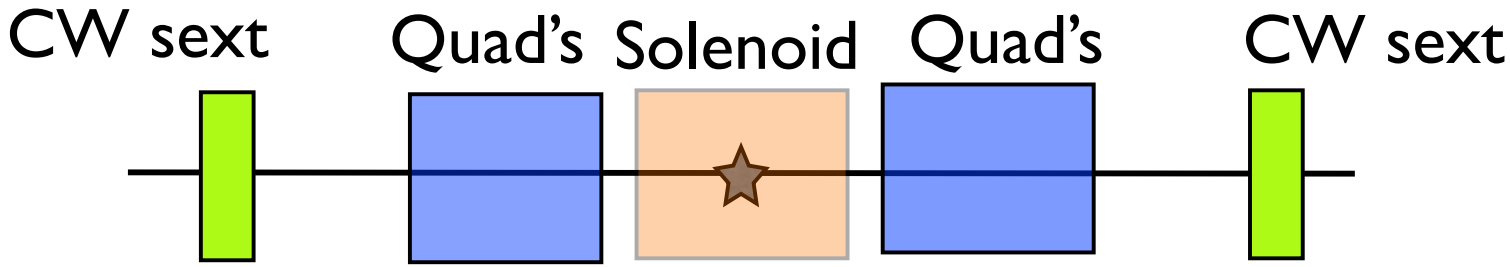


νs=0.012

Strong-strong was performed.
No serious difference.

Crab waist is base line of SuperB.
Beam particles collide with the other beam at their waist using sextupole magnets both side of IP.

Crab waist and IR nonlinearity



$$\mathcal{M}_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2}$$

crab waist sext

crab waist sext

$\neq$

ideal crab waist

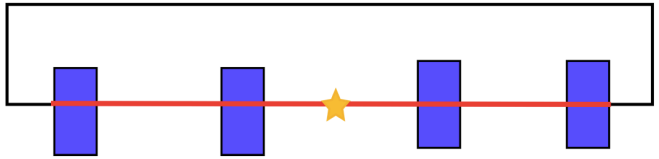
ideal crab waist

$$e^{-H_{Q's}} e^{-H_{Sol}} e^{-xp_y^2/2\phi} e^{-H_{BB}} e^{-xp_y^2/2\phi} e^{-H_{Sol}} e^{-H_{Q's}}$$

- Strong dynamic aperture degradation is seen by crab sextupole installation (H. Koiso).
- We do not know how to handle the nonlinear terms of Q's and Solenoid located at very high β.
- Crab waist is an option in (the) future for Super KEKB.

Collaboration with BINP

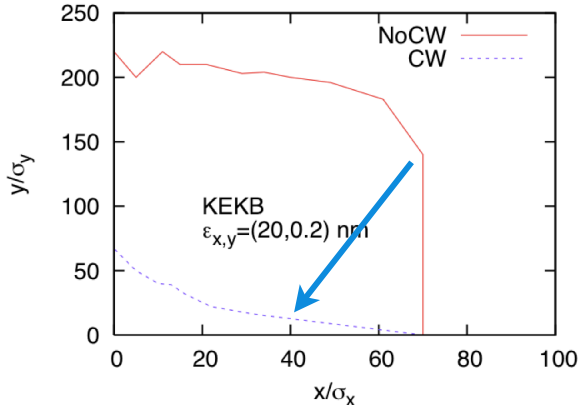
Study with a simple model

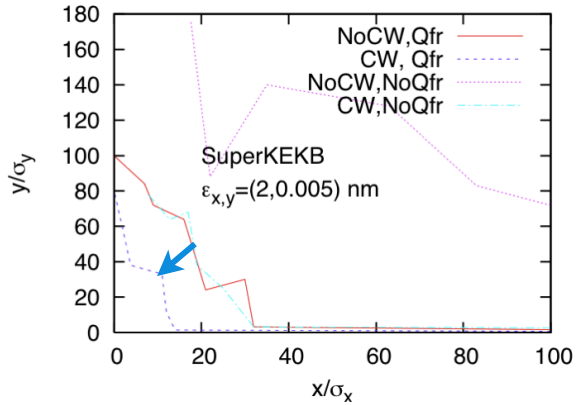


- Strong nonlinearity in drift space, chromatic effects.
- Quadrupole edge at very high β

$$\mathcal{M}_{IR} = e^{-H_{QF}} e^{-H_{L1}} e^{-H_{QD}} e^{-H_{L0}} e^{-H_{L0}} e^{-H_{QD}} e^{-H_{L1}} e^{-H_{QF}}$$

$$\mathcal{M}_{rev} = \mathcal{M}_{IR} \mathcal{M}_{arc}$$

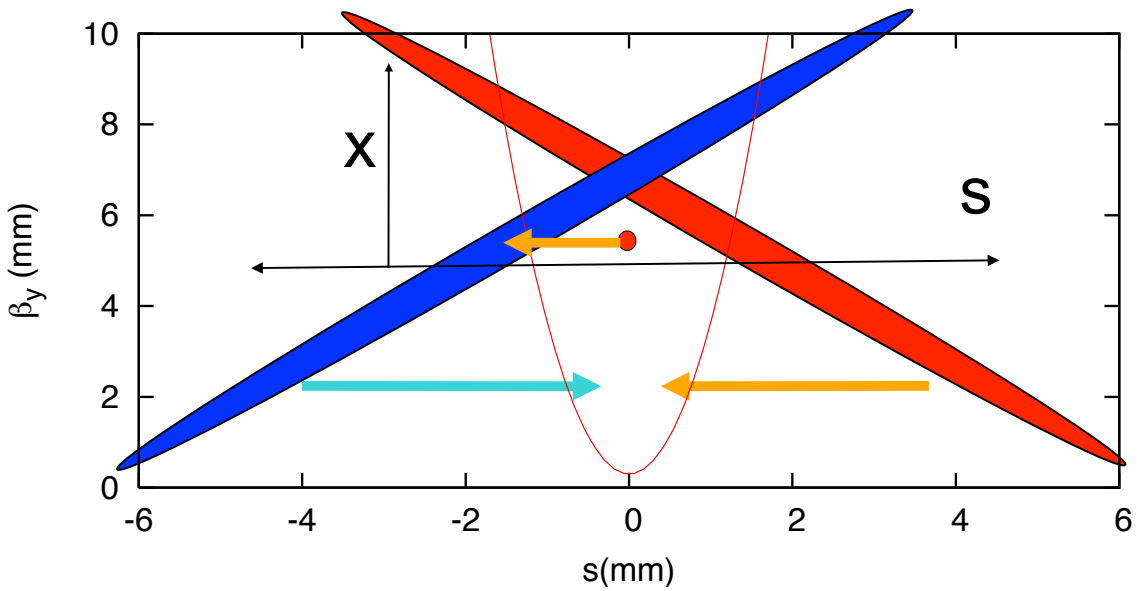




- Dynamic aperture is strongly degraded by installation of crab waist sextupoles.
- More nonlinear components in IR actually.

Characteristics of the collision

- βy is small only interaction area
  - Beam particles with a large horizontal amplitude collide high beta region
  - Issues on injection, collision offset, Touschek ....
  - Crab waist recovers the issues, but



Neglect parallel translation to x

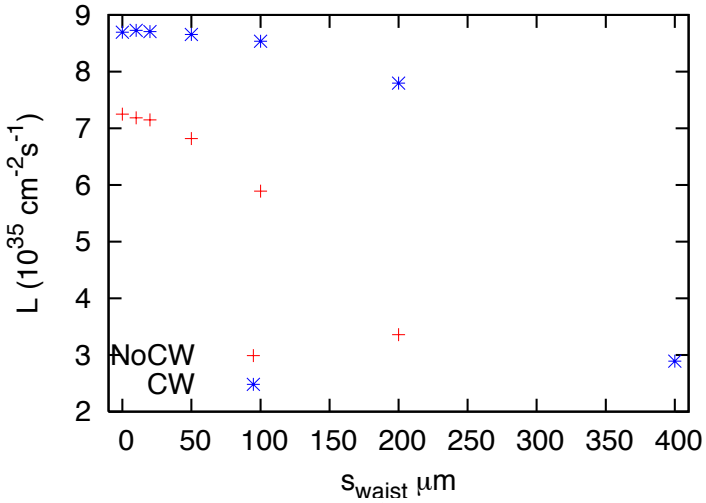
Error tolerance

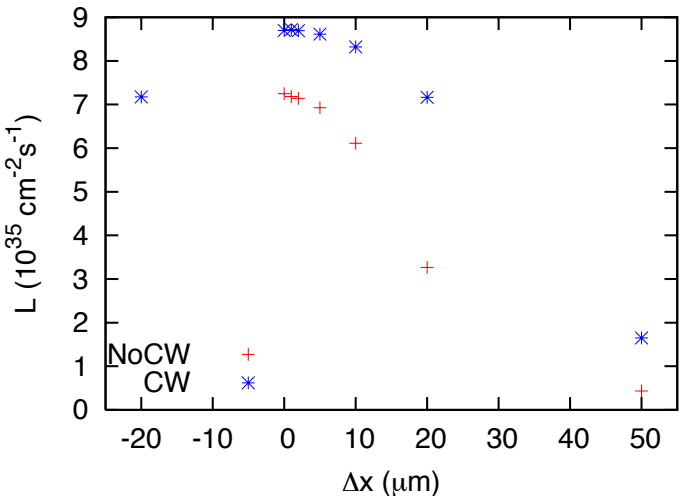
- Collision offset
- x-y coupling at the collision point
- dispersion at the collision point
- Their chromaticity

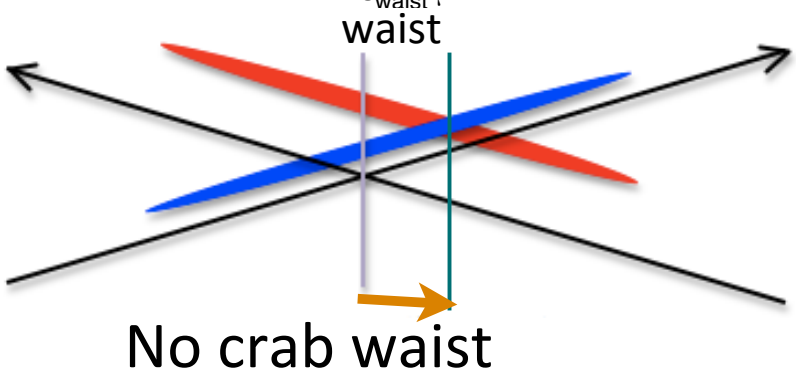
- Correction of these errors was essential to achieve the high performance in KEKB. It should be important also in SuperKEKB.

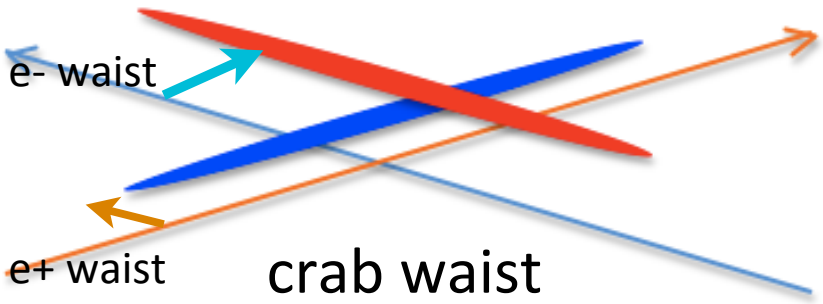
Tolerance of collision condition
Horizontal collision offset and waist

- Horizontal offset and waist are related to each other.
- The cross point of the waist is only one in x-z plane for the crab waist scheme.



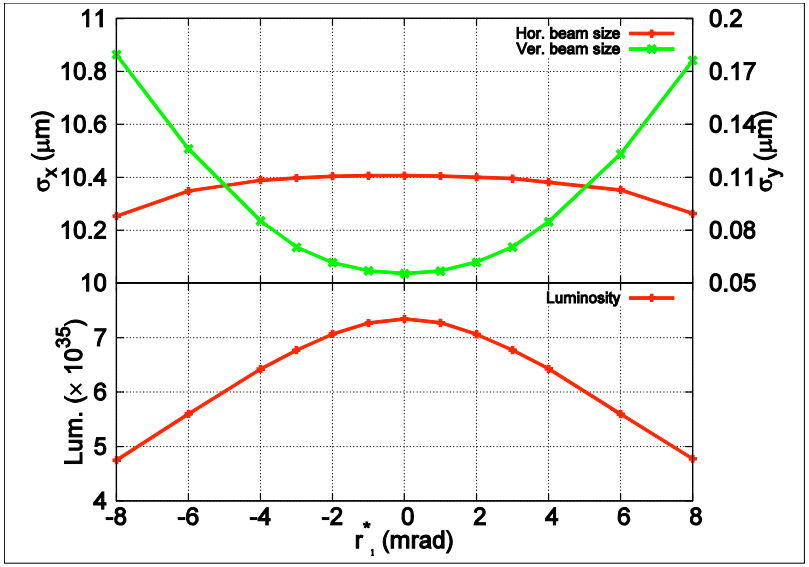


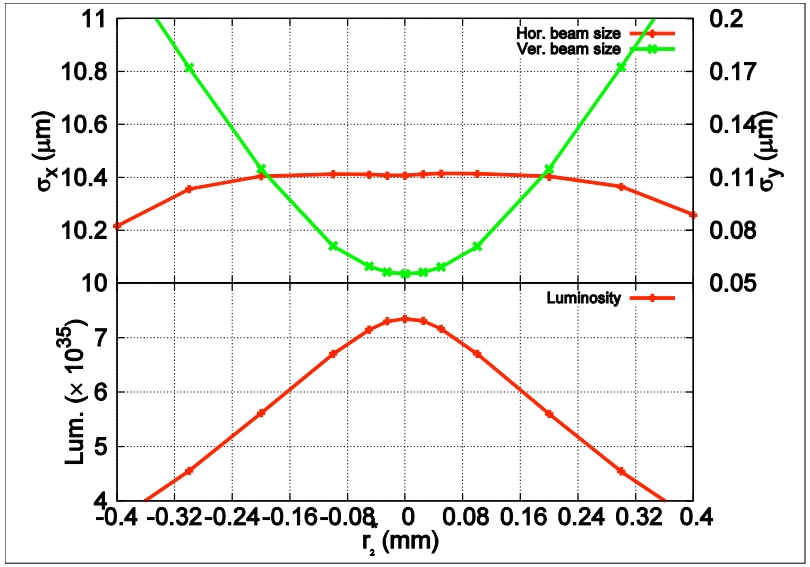


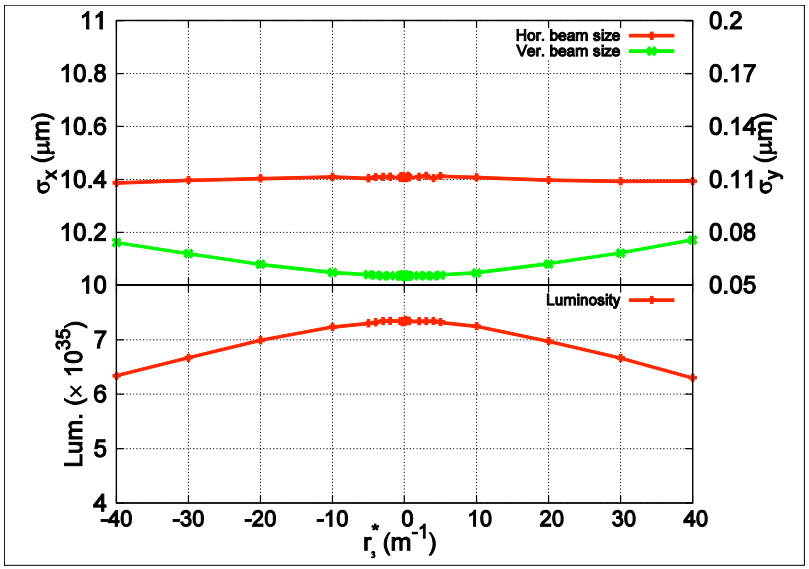


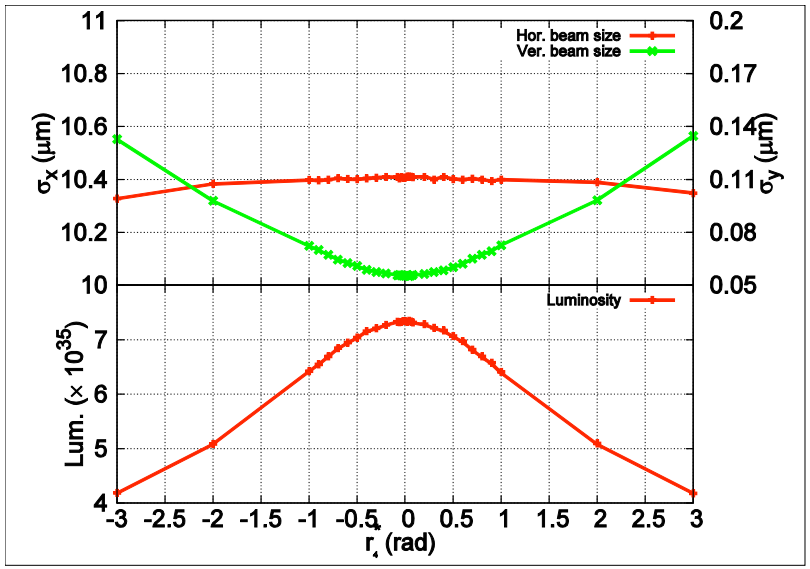
X-Y coupling w/ crab waist

- D. Zhou & K. Ohmi



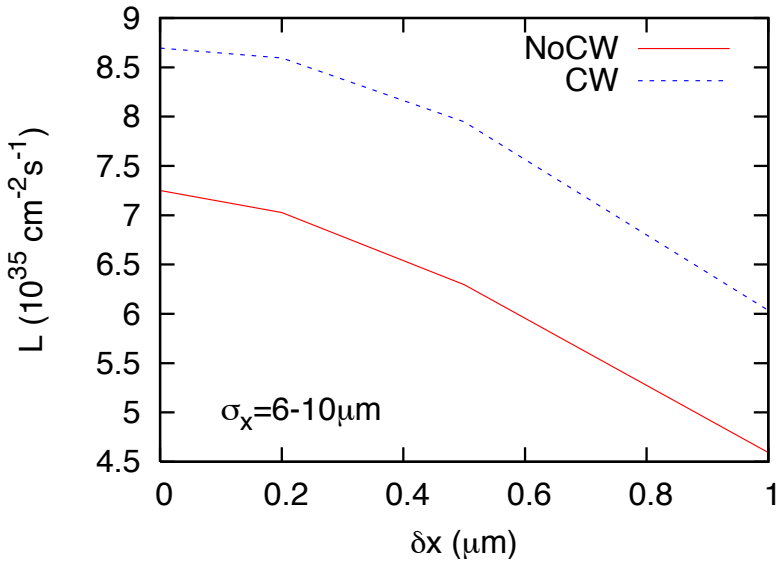


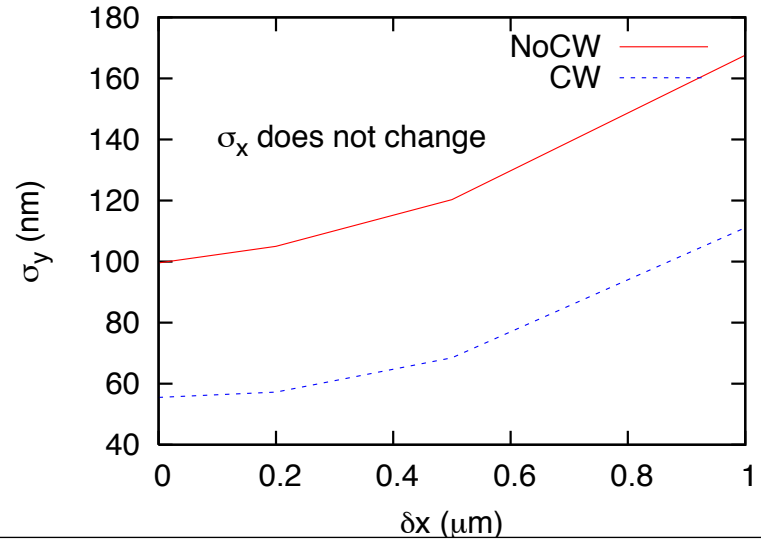




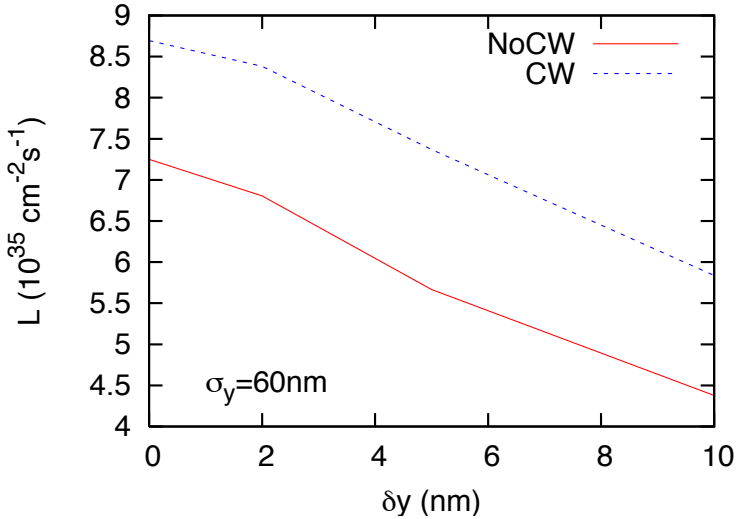
Beam noise

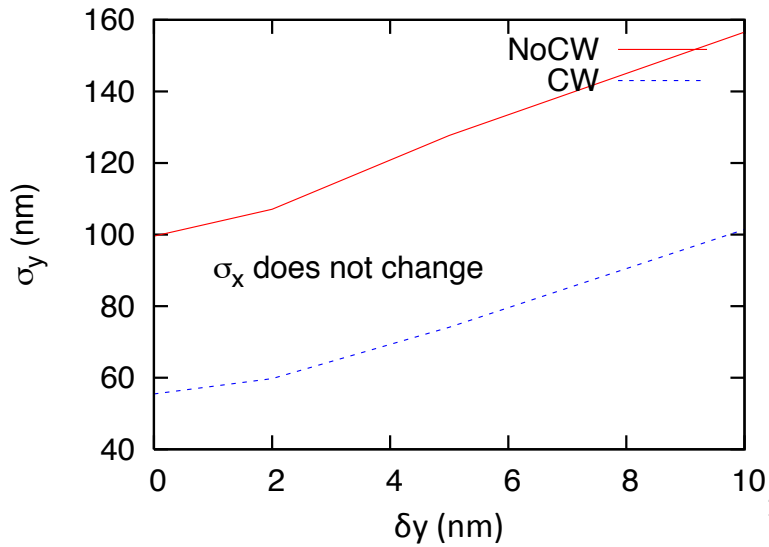
- Turn by turn noise





static offset





Summary – tolerance for parameters with 20% luminosity degradation

Parameter	w/ crab waist	w/o crab waist
r_1^* (mrad)	±5.3	±3.5
r_2^* (mm)	±0.18	±0.13
r_3^* (m^{-1})	±44	±15
r_4^* (rad)	±1.4	±0.4
$\partial r_1^* / \partial \delta$ (rad)	±2.4	±2.1
$\partial r_2^* / \partial \delta$ (m)	±0.086	±0.074
$\partial r_3^* / \partial \delta$ (m^{-1})	$\pm 1.0\times 10^4$	±8400
$\partial r_4^* / \partial \delta$ (rad)	±400	±290
η_y^* (μm)	±62	±31
$\eta_y'^*$	±0.73	±0.23

Δx (μm) collision offset	10	10
Δs (μm) waist error	100	100
Δy,Δy'(μm,μrad) collision offset	0.02 (100)	
δx (μm) turn by turn noise	0.5	0.5
δy (nm)	4	4

The degradation is roughly quadratic

σx=6-10μm σy=50 nm

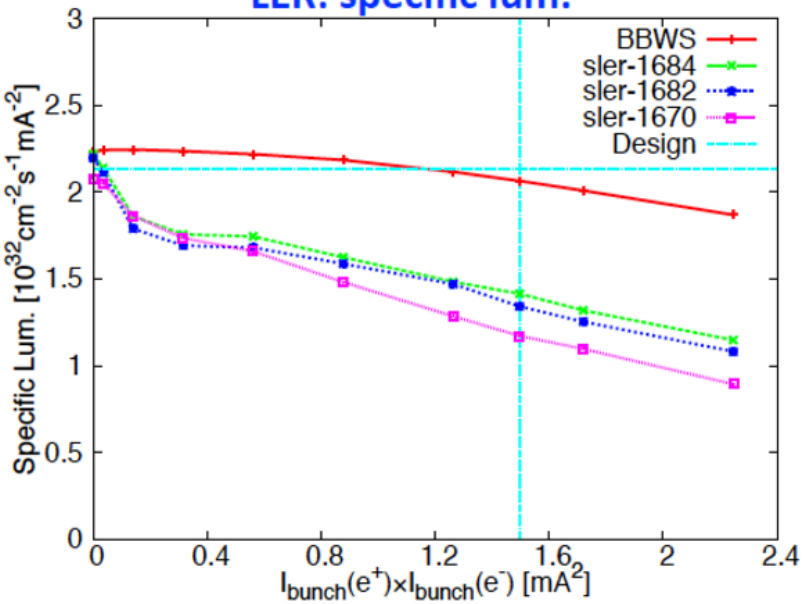
Weak-strong beam-beam simulation considering lattice

D. Zhou

2. Beam-beam: Lattice nonlinearities

- **BB(weak-strong) + LN**
  - Direct vert. emit. growth
  - Current dependent
  - Mechanism not well understood

LER: specific lum.



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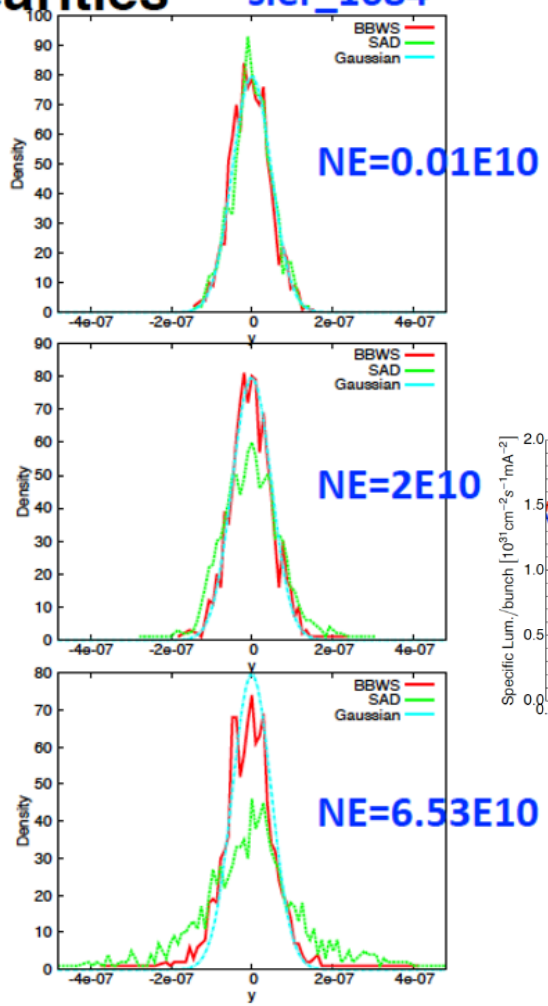
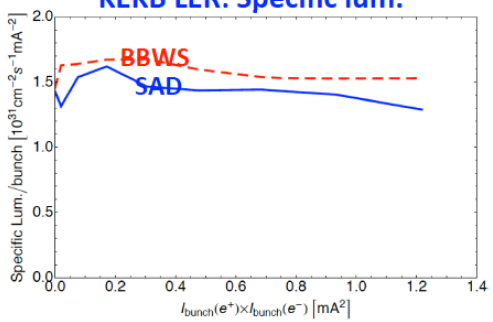


KEKB LER: Specific lum.

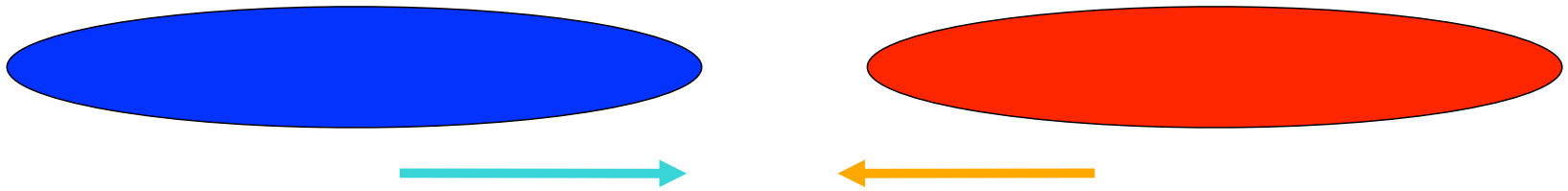


Hadron collider (LHC)

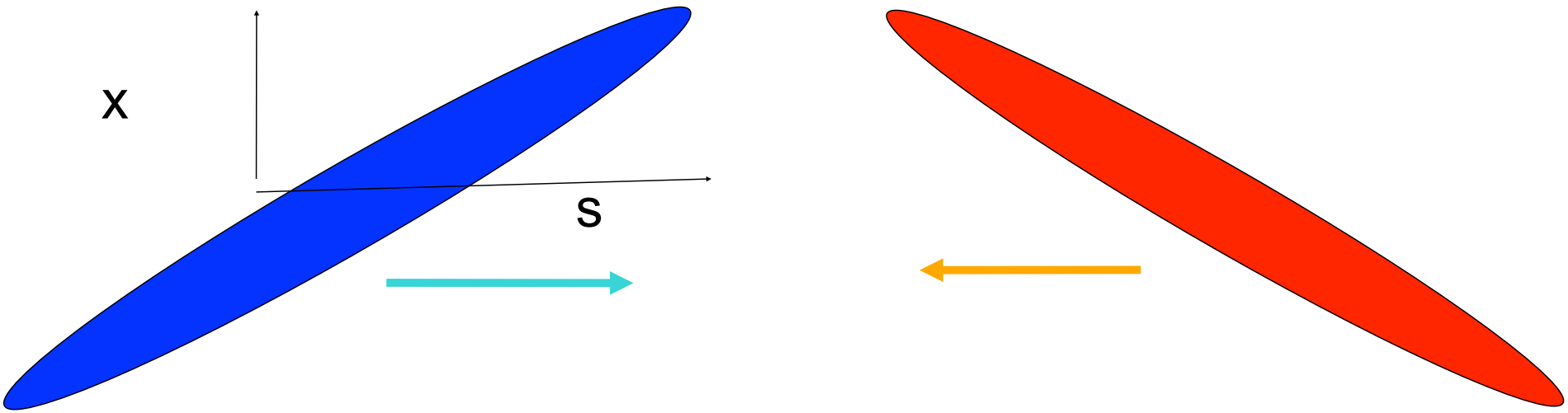
- LHC $\beta^* > \sigma_z$,
- β^*=55cm (design) 15cm(HL-LHC), σ_z=7.5cm
- Hourglass effect does not matter.
- Crossing angle can be used control of the luminosity and beam-beam tune shift.
- Maximum beam-beam tune shift is realized at zero crossing angle in simulations.
- Highest bunch luminosity is limited by event pileup.

Two approach toward high luminosity

- High current, high beam-beam parameter.



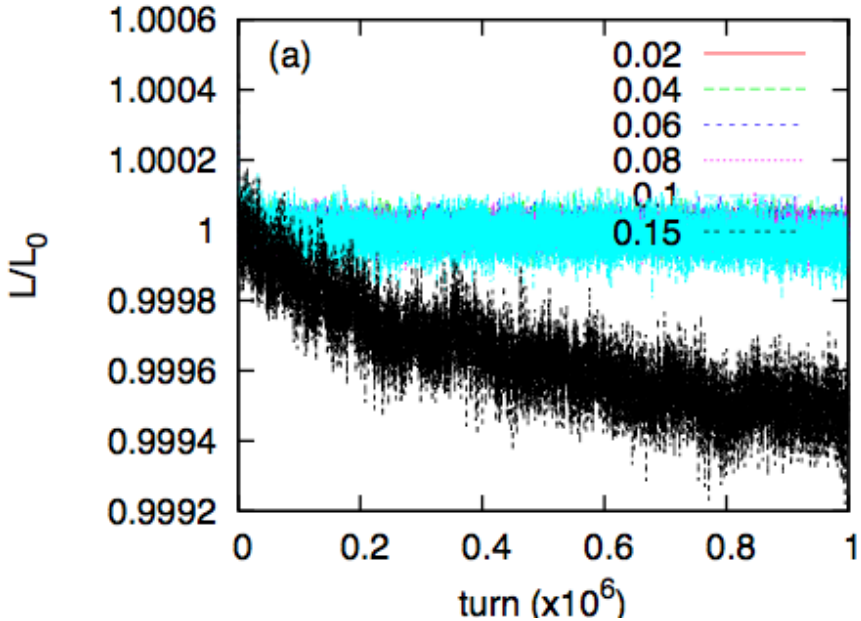
- Low beta, Higher bunch current with long bunch, so-called super bunch collision

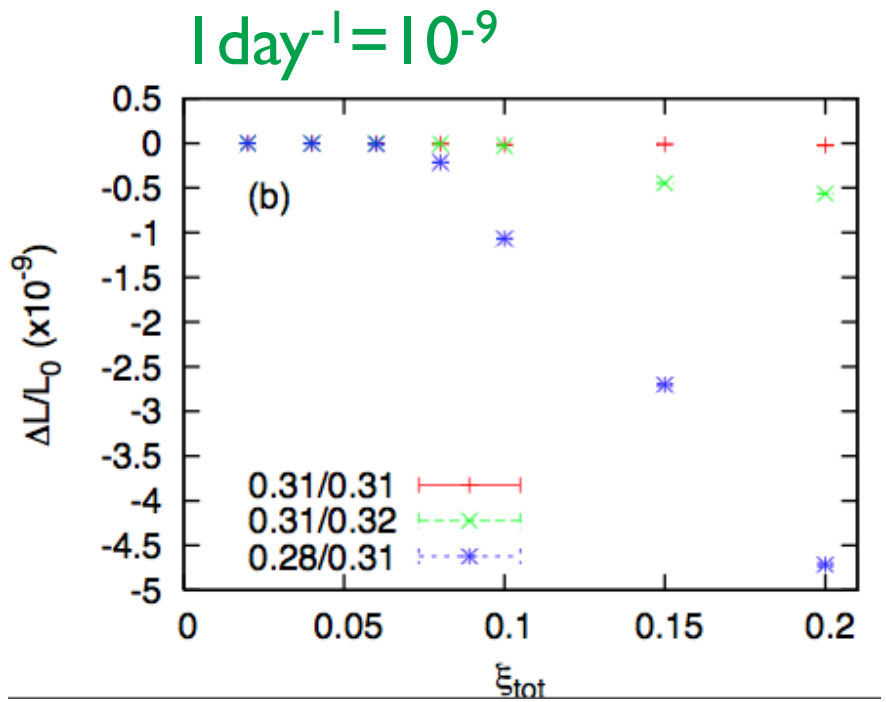


Simulation of luminosity evolution

- Weak-strong model to avoid statistical noise.
- Gaussian beam distribution in transverse and longitudinal directions.
- 2 IP simulation. Horizontal/Vertical crossing.

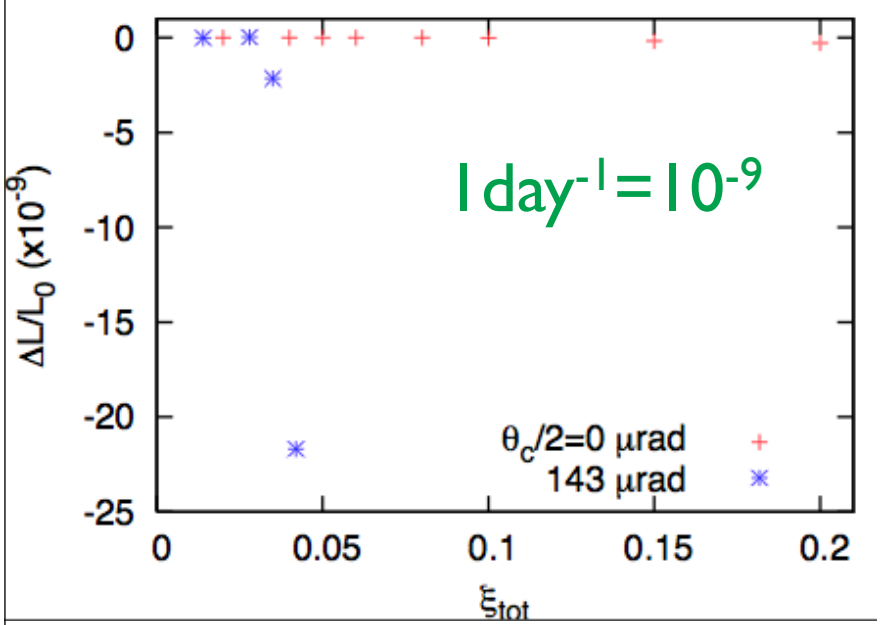
Luminosity degradation in the simulations

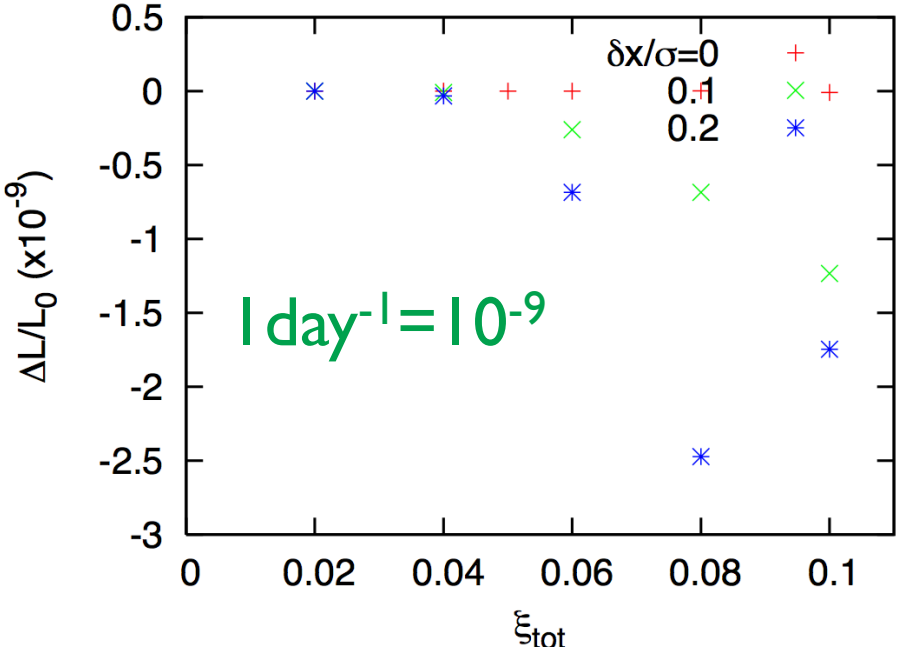




- Very high potential for headon(θ_c=0).
- Especially ξ>0.2-0.3 $\nu_x=\nu_y$, 1dim motion!

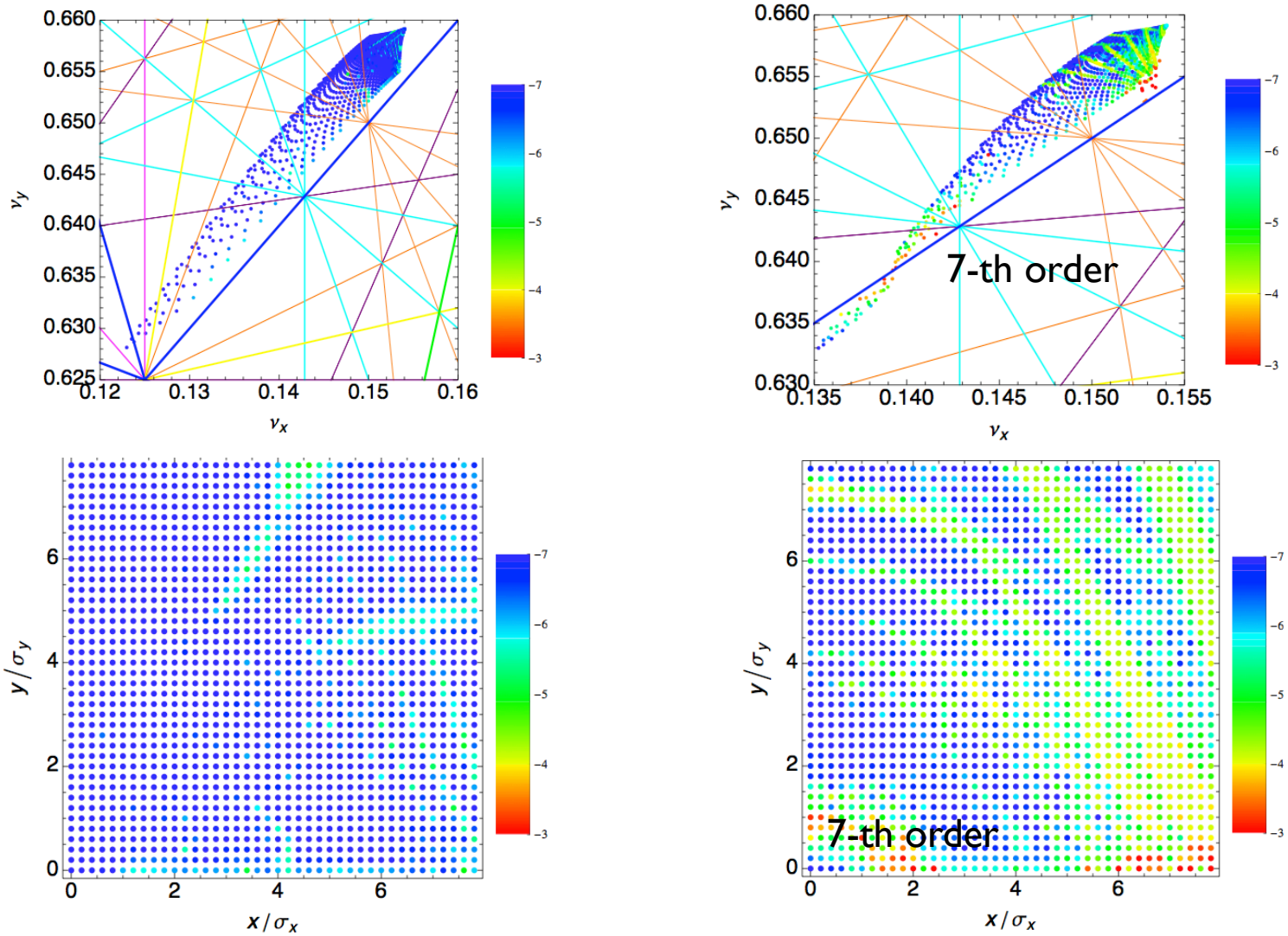
Effect of crossing angle and offset



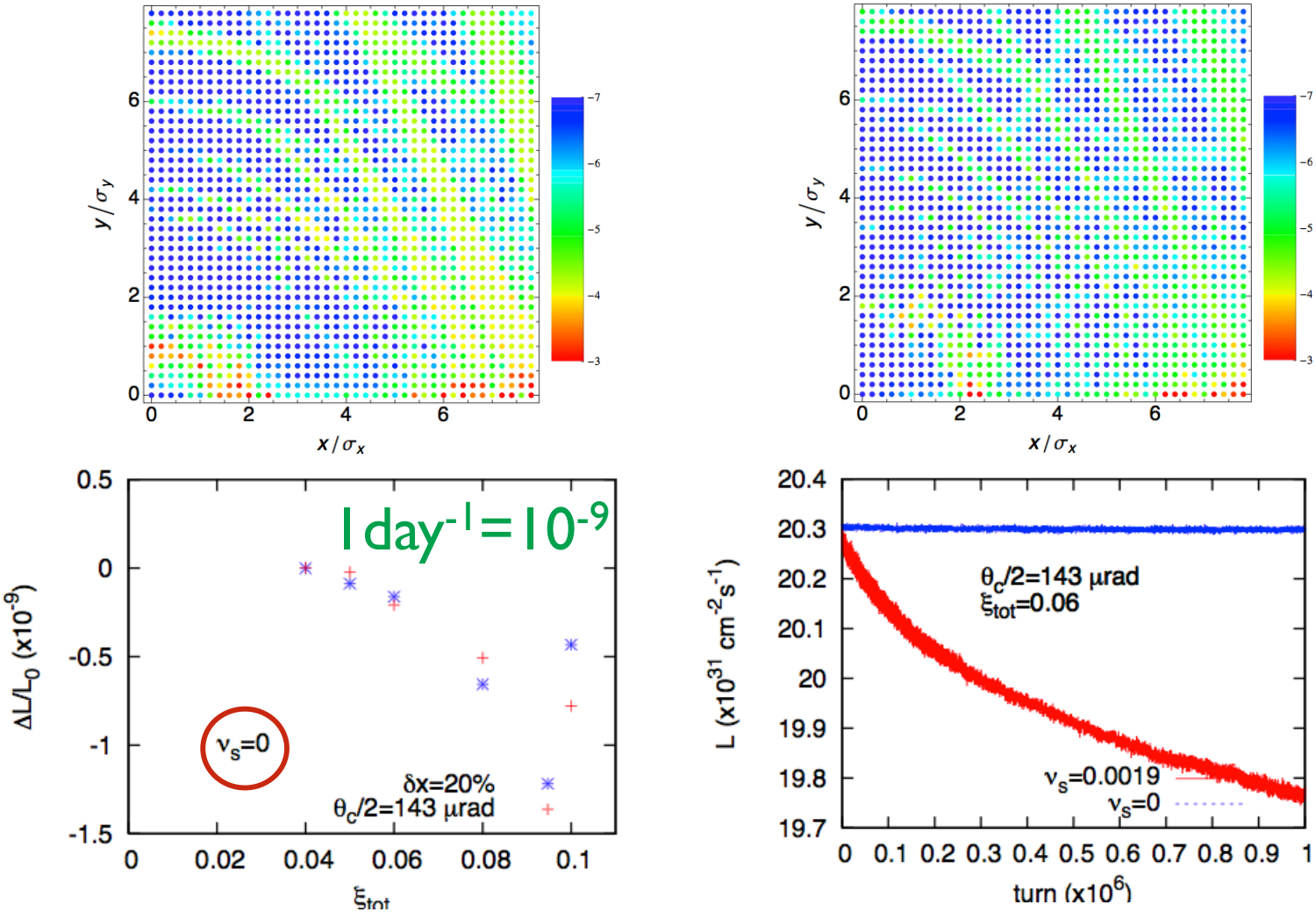


- Zero crossing angle, symmetry, less resonances. $\xi_{tot} > 0.2$
- More resonances appear in collision with crossing angle and with collision offset.
- Tune modulation due to synchrotron motion in the crossing collision. $\xi_{tot} \leq 0.035$

FMA analysis for F=1(θc=0) and F=0.8 (θc=285μrad)



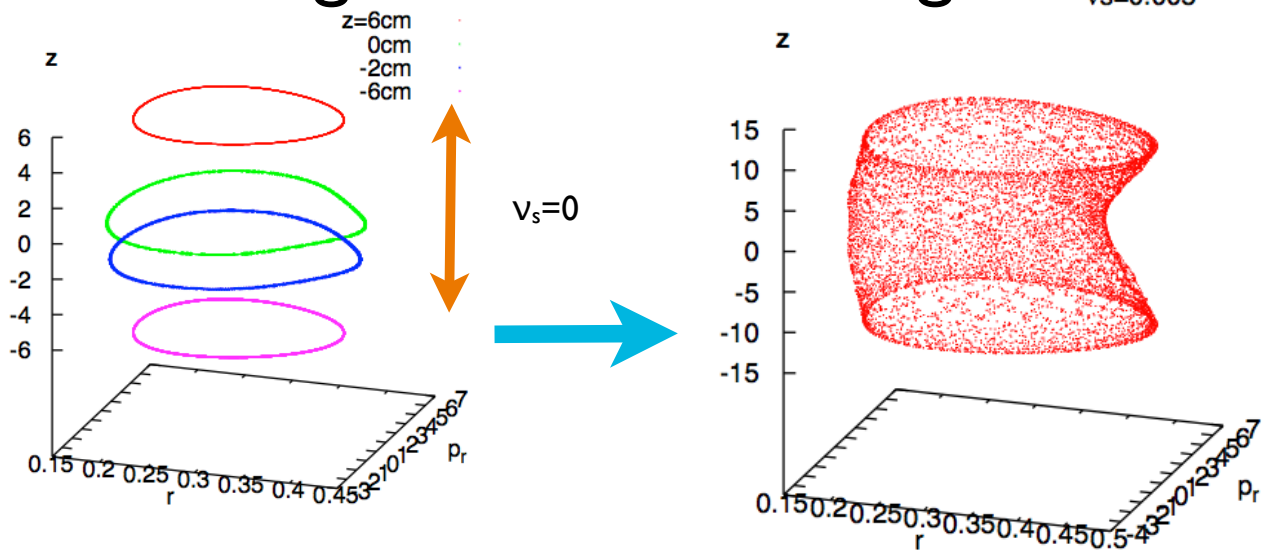
Crossing collision and offset collision



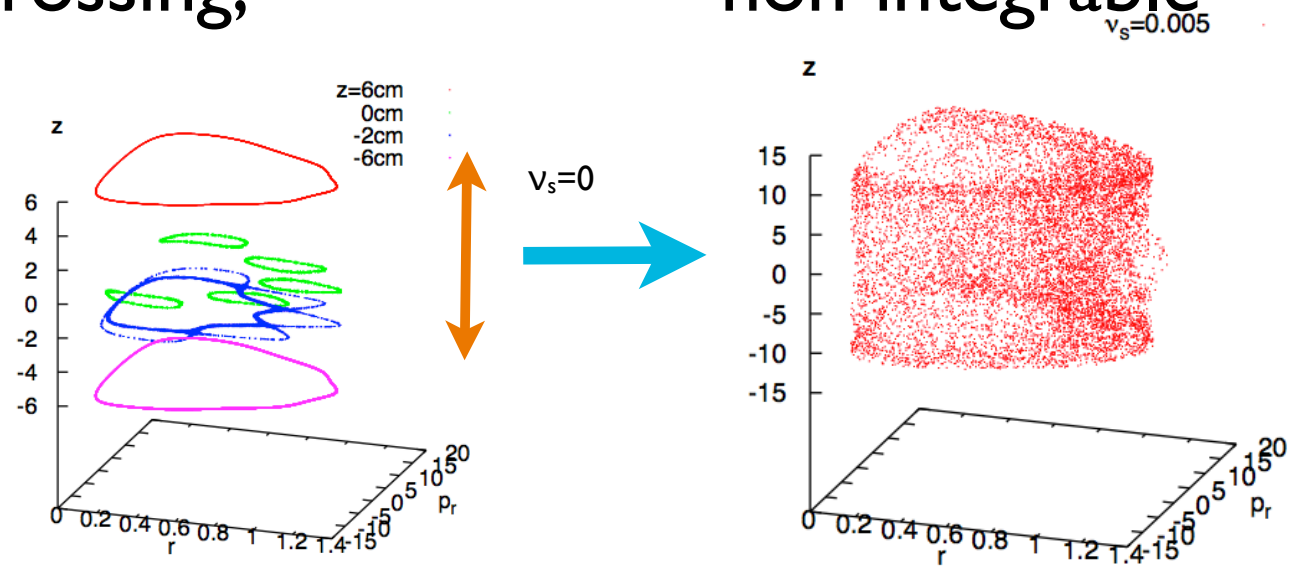
- Similar transverse behavior, but ΔL(crossing)>> ΔL(offset).

Resonance crossing

- No Crossing, integrable

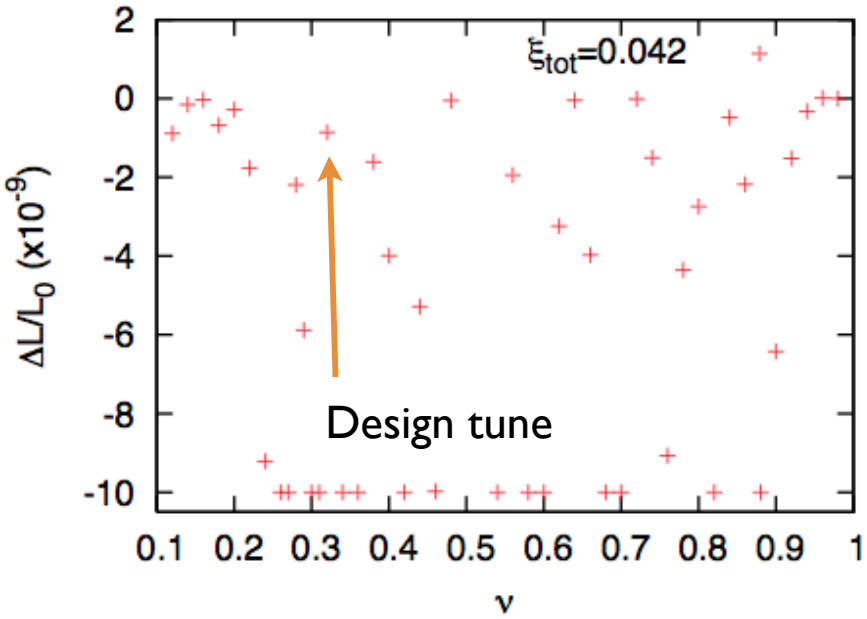


- Crossing, non-integrable



Tune scan

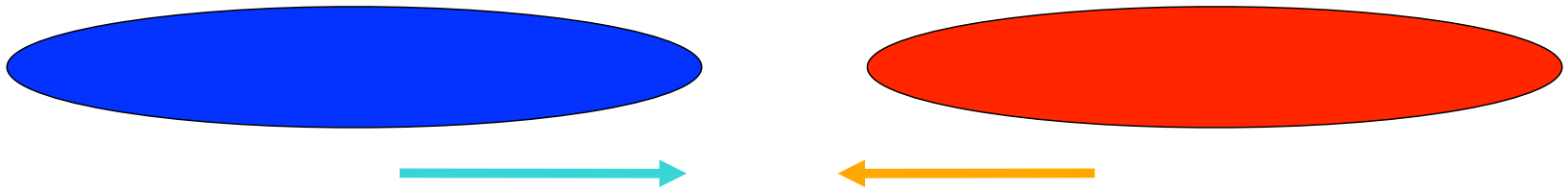
- Nominal parameters but high current, θc=285 μrad, Keeping ν_y-ν_x=0.01.



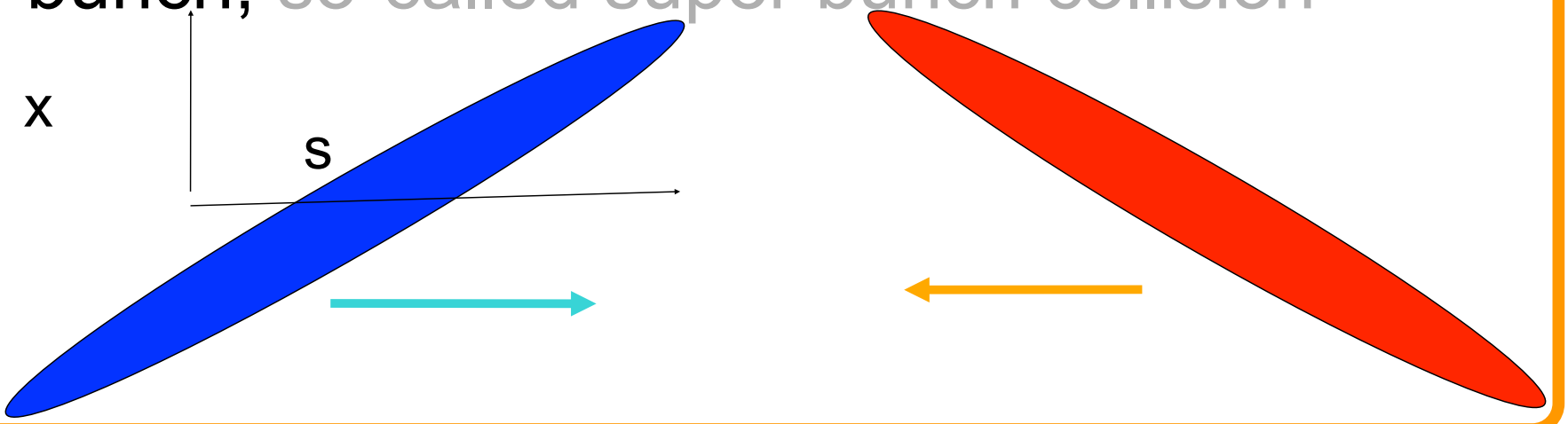
- The present working point is good, but not the best.

Two approach toward high luminosity

- High bunch current, high beam-beam parameter.



- Low beta, Higher bunch current with long bunch, so-called super bunch collision

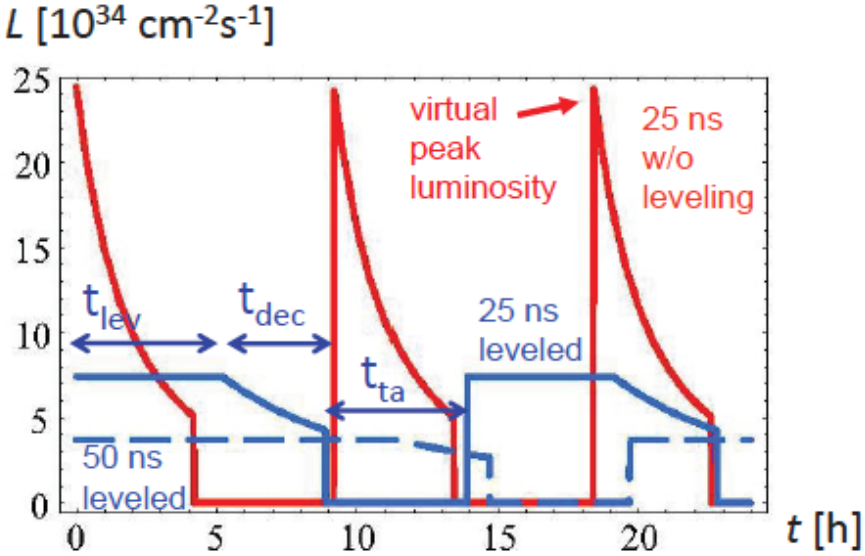


Large crossing angle collision in LHC

HL-LHC

- Luminosity leveling using crab cavity

- Parameter table given by O. Bruning and F. Zimmermann (IPAC12)

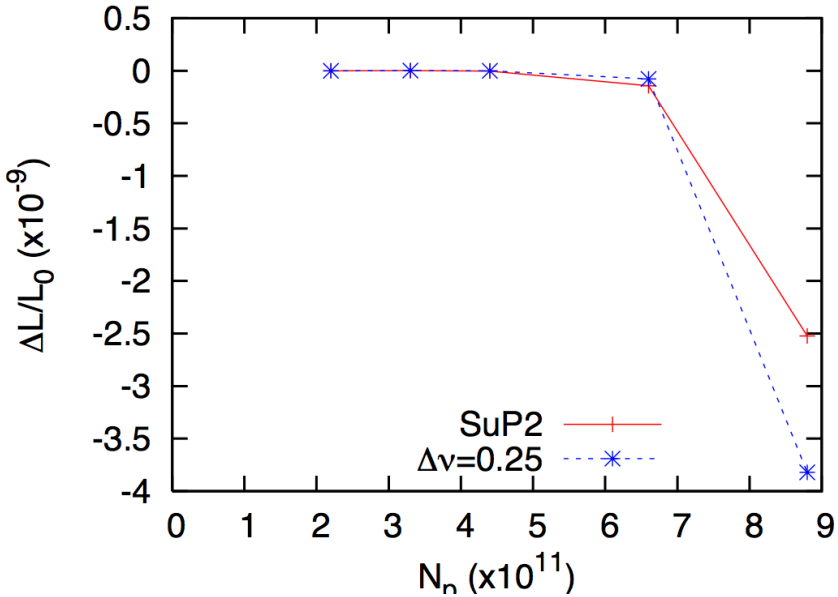


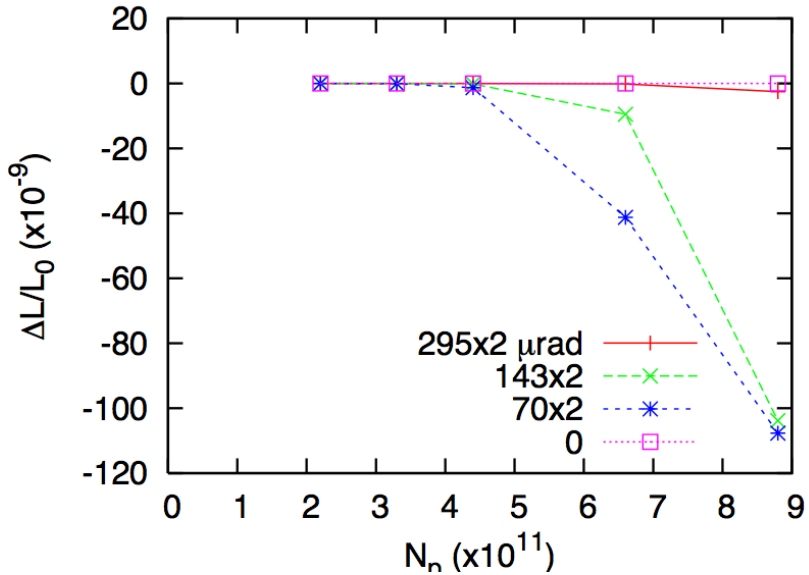
$$F = \left(1 + \left(\frac{\sigma_z \theta_c}{2\sigma_\perp}\right)^2\right)^{-1/2}$$

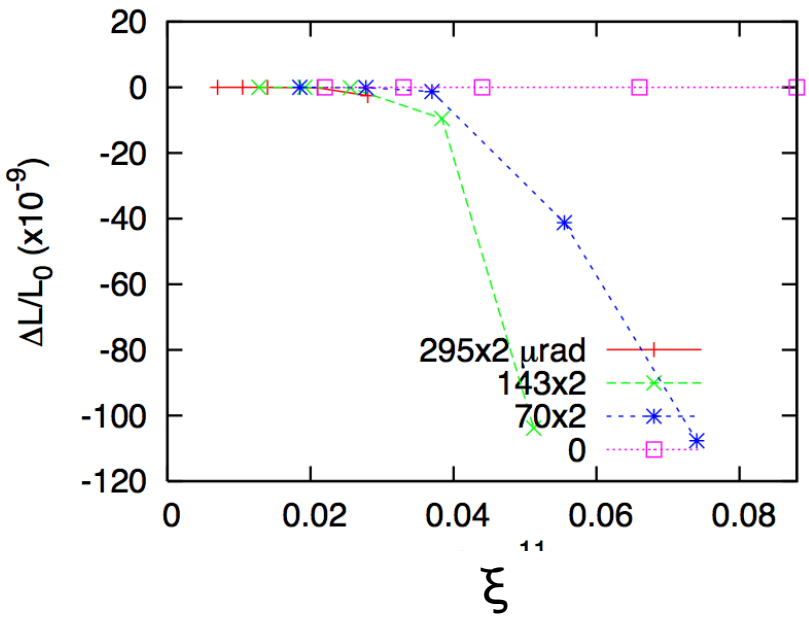
$$\sigma_z = 7.55 \text{ cm}$$

Parameter	nominal	25 ns	50 ns
energy E_b [TeV]	7	7	7
$N_b[10^{11}]$	1.15	2.2	3.5
n_b	2808	2808	1404
I_{beam} [A]	0.58	1.12	0.89
N_{tot} $[10^{14}]$	3.2	6.2	4.9
θ_c [μrad]	285	590	590
b-b sep. [σ]	9.5	12.5	11.4
$\beta^*_{x,y}$ [m]	0.55	0.15	0.15
$\gamma\epsilon_{x,y}$ [μm]	3.75	2.5	3.0
$\tau_{\text{IBS},x}$ [h]	103	15.4	14.3
$\tau_{\text{IBS},z}$ [h]	57	21.0	16.4
F	0.84	0.30	0.33
max. $\Delta Q_{\text{bb,tot}}$ $[10^{-3}]$	11	15	19
$\hat{L}$ $[10^{34}$ cm^{-2}s$^{-1}]$	1.0	24	25
L_{lev} $[10^{34}$ cm^{-2}s$^{-1}]$	1.0	7.4	3.7
ratio k	-	3.3	6.9
pile up	19	140	140
lum. region σ_{lum} [mm]	45	$\geq$20	$\geq$20
τ_{eff} [h]	44.9	11.6	18.4
t_{lev} [h]	-	5.2	11.4
$t_{\text{dec,opt}}$ [h]	-	3.7	2.9
t_{run} [h]	15.0	8.9	14.3
$L_{\text{ave,opt}}$ $[10^{34}$ cm^{-2}s$^{-1}]$	0.56	4.3	2.7
availability A [%]	(50)	45	72
efficiency E [%]	(38)	29	53
L_{int}/year [fb^{-1}]	(37)	250	250

Luminosity degradation in HL-LHC







- ξ_{tot}<0.03-0.035, similar as nominal crossing collision.

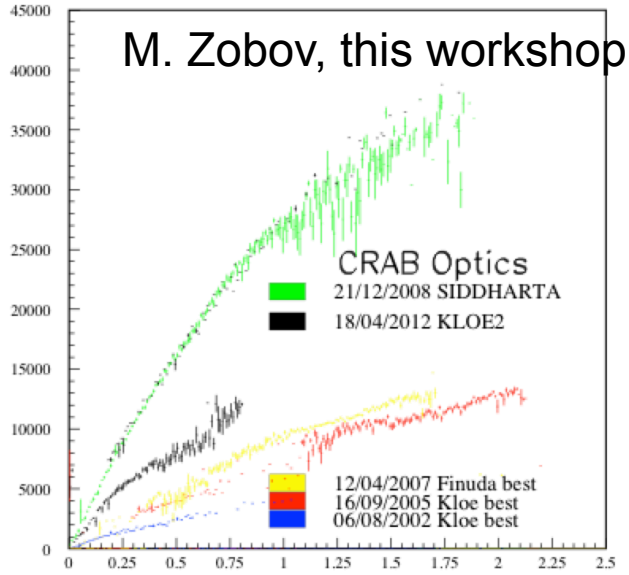
Summary

- Crab crossing and nano-beam (LPA) in KEKB/ SuperKEKB.
- Crab crossing works fairly well. We go to nano-beam for SuperKEKB.
- Dynamic aperture, error tolerance of IR optics are critical issues.
- Crab crossing or LPA in LHC.
- Crab crossing (θ_c=0) showed very high beam-beam parameter as seen in KEKB.
  in this simple model.
- There are no serious problem for single bunch collision in LPA. in this simple model.

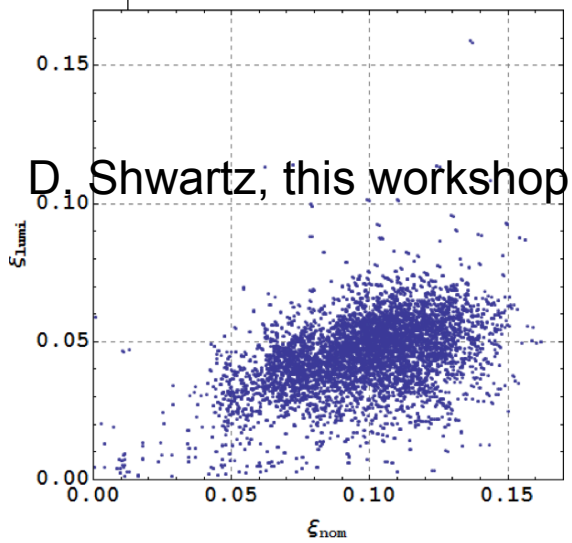
- The difference between θ_c=0 or finte is occurrence of 7-th order resonance. The resonance appear even in offset collision.
- The 7-th order resonance is seen in Tevatron. Small crossing angle or offset?

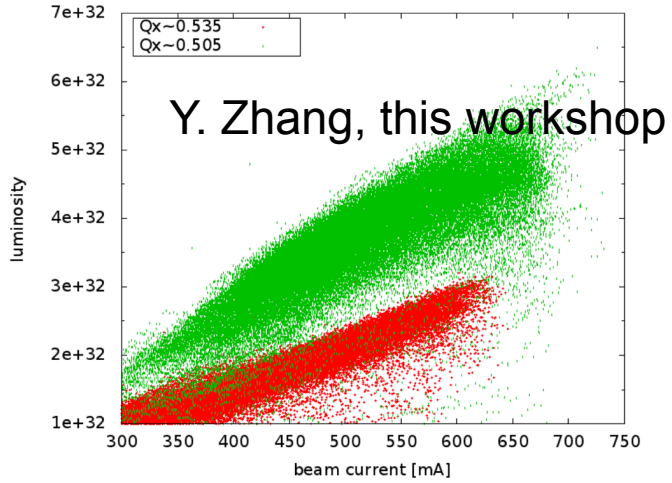
World wide trials toward high luminosity in lepton colliders

Luminosity [10^{28} cm^{-2} s^{-1}]



$$\xi_{lumi} = \frac{N^{-} r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{lumi}}$$





Thank you for your attention