Beam-beam limit vs. number of IP's and energy

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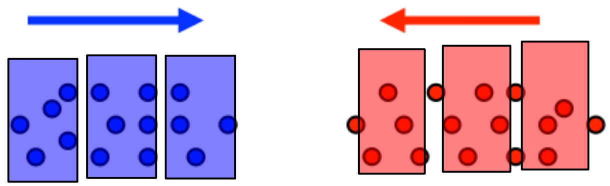
Thanks to Y. Funakoshi

3D beam-beam interaction



Strong-strong

- A bunch is divided into several slices which contain many macro-particles.
- Potential of colliding beam is evaluated by Particle in Cell method using 2D mesh. $F_{x(y)} = -\frac{\partial \phi_{PIC}}{\partial x(y)}$
- Collision is calculated slice by slice.

$$\prod_{i=1}^{N_{sl,-}} \exp\left[- : V_{0,+}^{-1}(s_{-,i})\phi_{-,i}(+, s_{-,i})V_{0,+}(s_{-,i})\Delta s :\right]$$

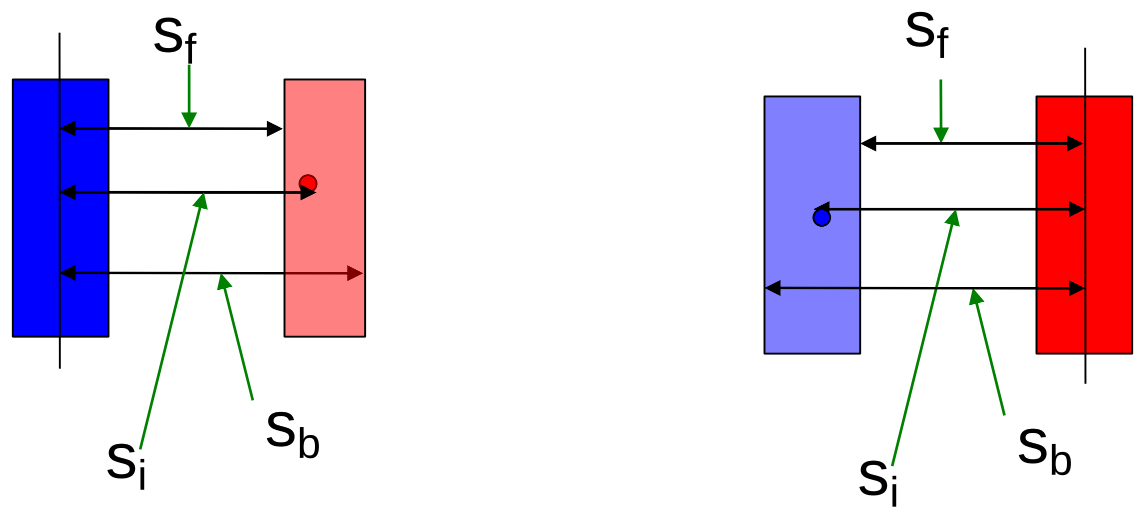
$$\prod_{j=1}^{N_{sl,+}} \exp\left[- : V_{0,-}^{-1}(s_{+,j})\phi_{+,j}(-, s_{+,j})V_{0,-}(s_{+,j})\Delta s :\right]$$

drift between slices

$$V_0(s) \equiv V_0(s,0) = S \exp\left[- : \int_0^s H_0 ds :\right] = \prod_{i=\pm} \exp\left[- : \frac{p_{x,i}^2 + p_{y,i}^2}{2} s :\right],$$

3D symplectic integrator for slice-by-slice collision

- Potential is calculated at s_f and s_b.
- Potential is interpolated to s_i between s_f and s_b.

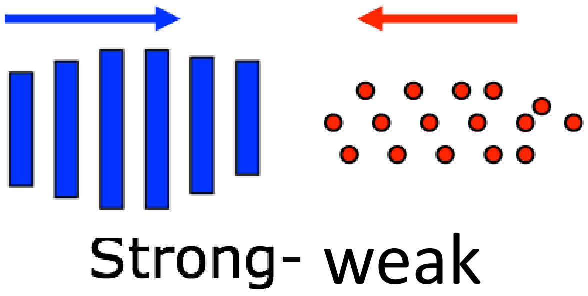


- Since the interaction depends on z, energy kick should be taken into account $d\phi/dz$.
- We repeat the same procedure exchanging particle and slice.

Weak-strong simulation

- Strong beam is sliced. Macro-particles in weak beam collide with the strong beam.

$$\prod_{i=1}^{N_{sl}} \exp[-V_0^{-1}(s_i)\,\phi_{G,i} V_0(s_i)]$$



$$\frac{dp_x}{ds} = -\frac{\partial \phi_G}{\partial x} = -\frac{4n_e r_e}{\gamma} F_x$$

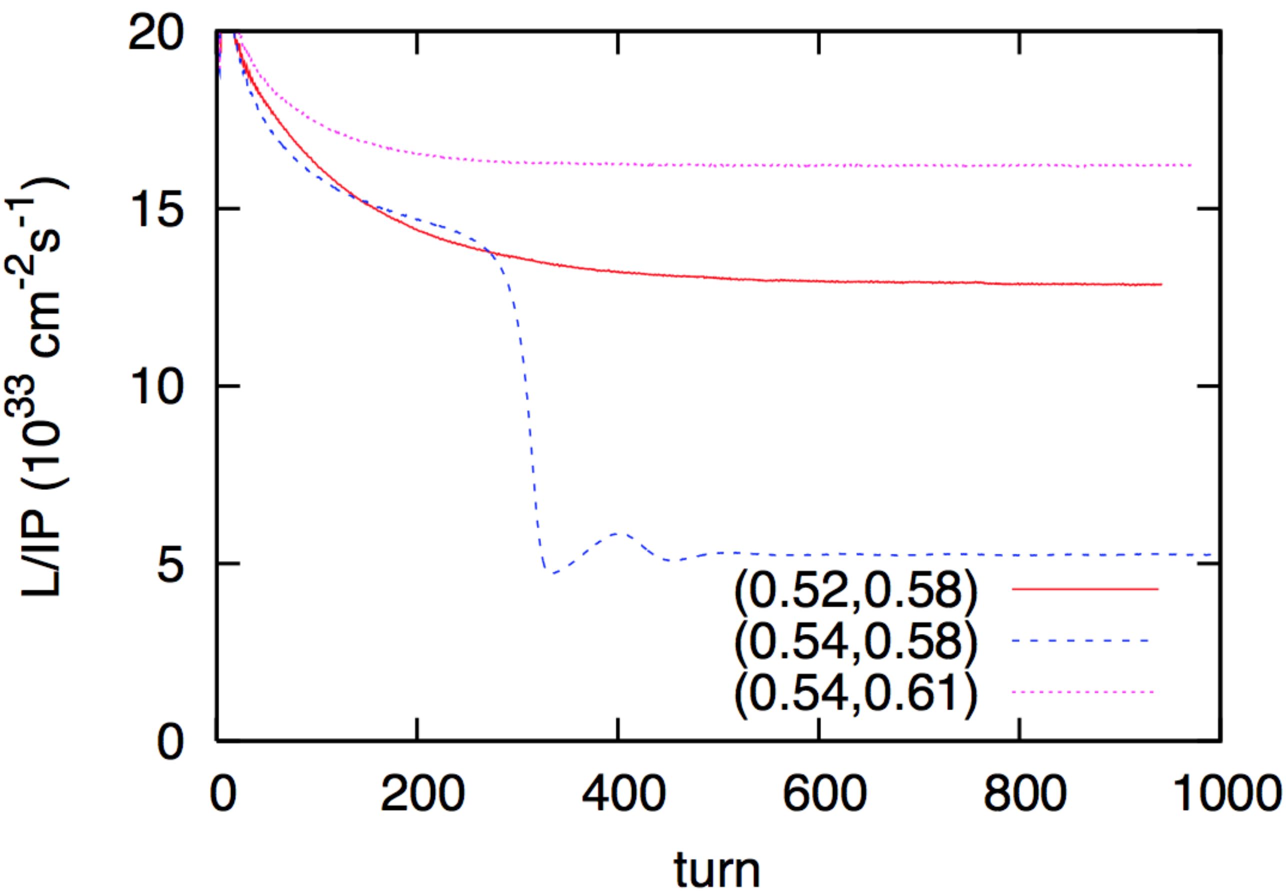
$$F_y + iF_x = \sqrt{\frac{\pi}{2(\sigma_x^2 - \sigma_y^2)}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) w\left(\frac{(\sigma_y/\sigma_x)x + i(\sigma_x/\sigma_y)y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

$$\frac{d\delta}{ds} = -\frac{\partial \phi_G}{\partial z} = -\frac{2n_e r_e}{\gamma} G$$

$$G = \frac{1}{2(\sigma_x^2-\sigma_y^2)}\left\{\frac{d\sigma_x^2}{ds}\left[xF_x + yF_y + \frac{\sigma_y}{\sigma_x} exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) - 1\right] - \frac{d\sigma_y^2}{ds}\left[xF_x + yF_y + \frac{\sigma_x}{\sigma_y} exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) - 1\right]\right\}$$

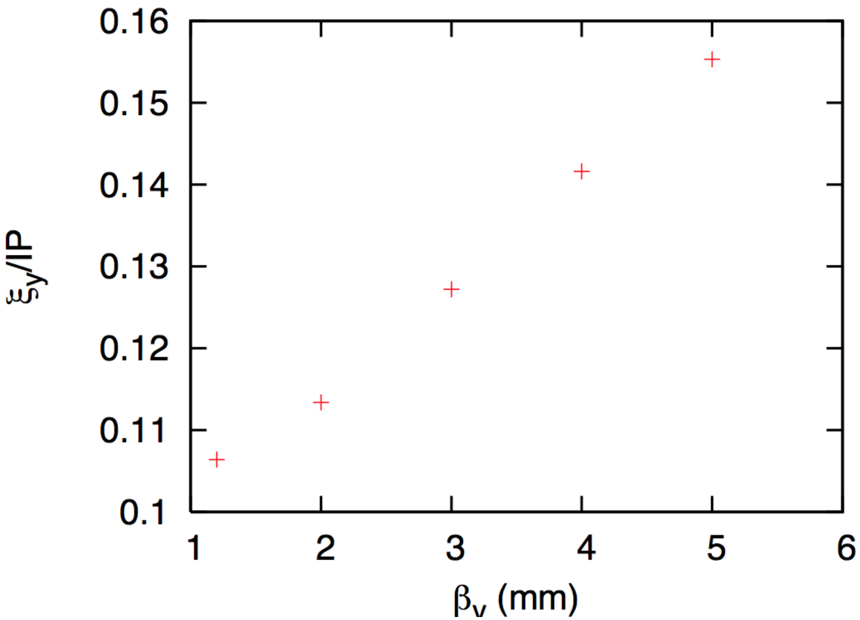
Strong-strong simulation for CEPC

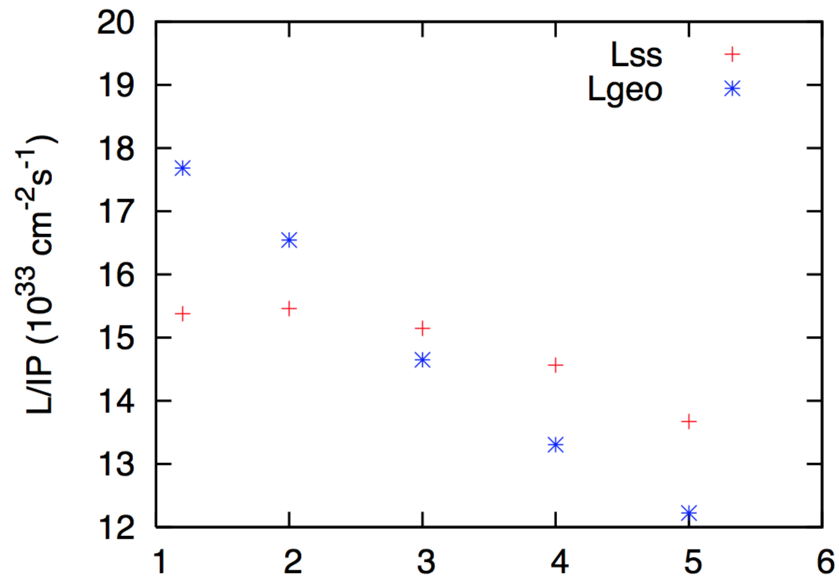
- Luminosity behavior depends on tune operating points.



Dependence on β_y* (CEPC)

- Tune shift including bunch length due to beamstrahlung, σ_z~2.8mm
- Simulated luminosity as function of β_y*.
- β_y*=2mm is better.

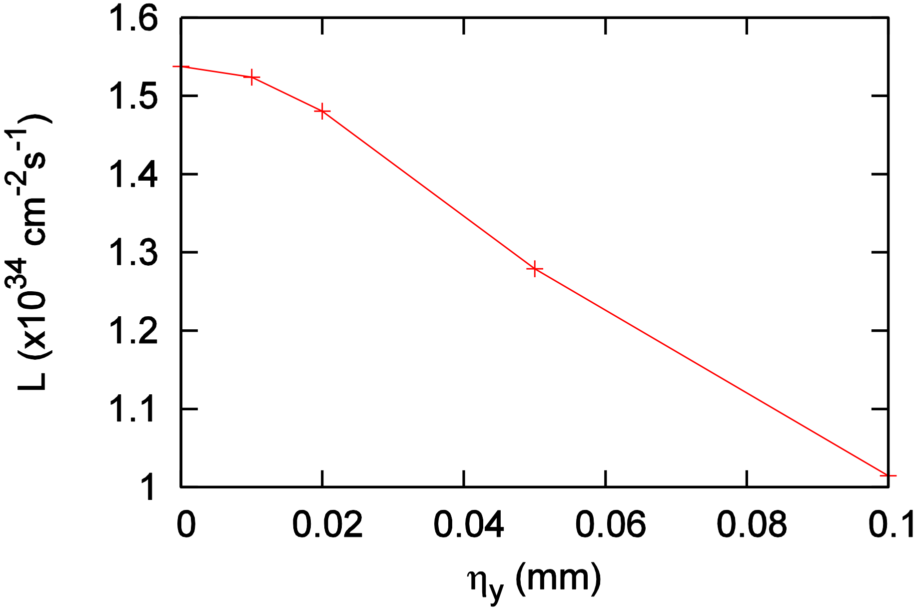




Tolerance for Vertical dispersion at IP in CEPC

$\sigma_y = 0.16\ \mu m$ $\sigma_\delta = 0.16 - 0.17\ \%$

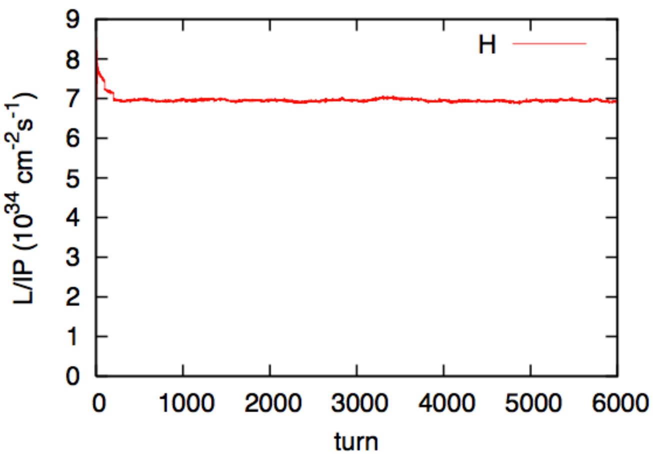
$$\eta_{y,tol} \ll \frac{\sigma_y}{\sigma_\delta} = 0.1\ mm$$



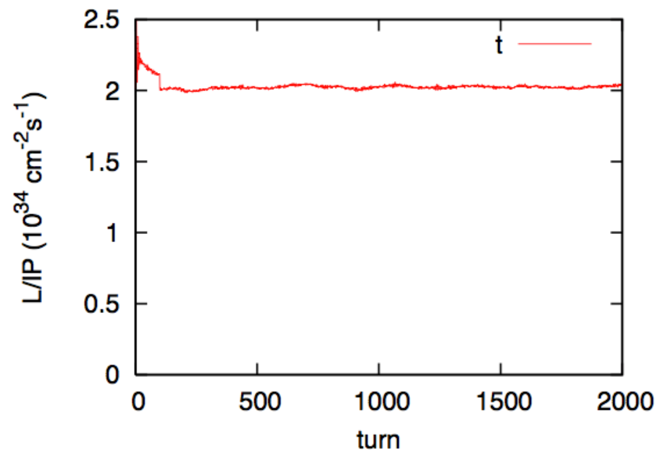
Luminosity degradation is visible for $\eta_{y,tol} > 0.02mm$

Weak-strong simulation for TLEP

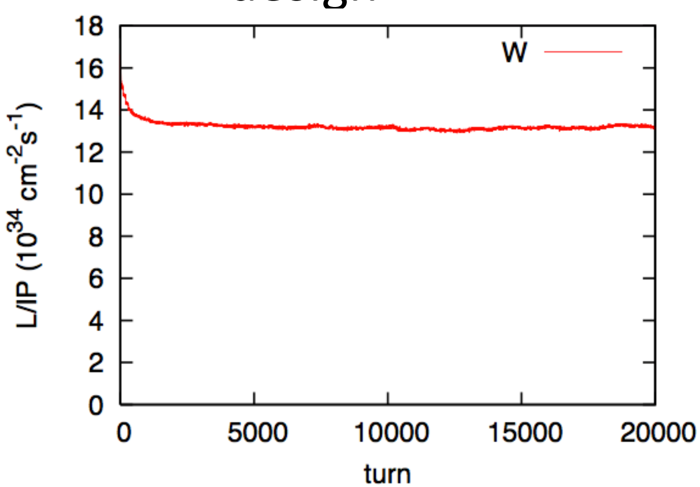
- H L_{design}=6x10^{34}



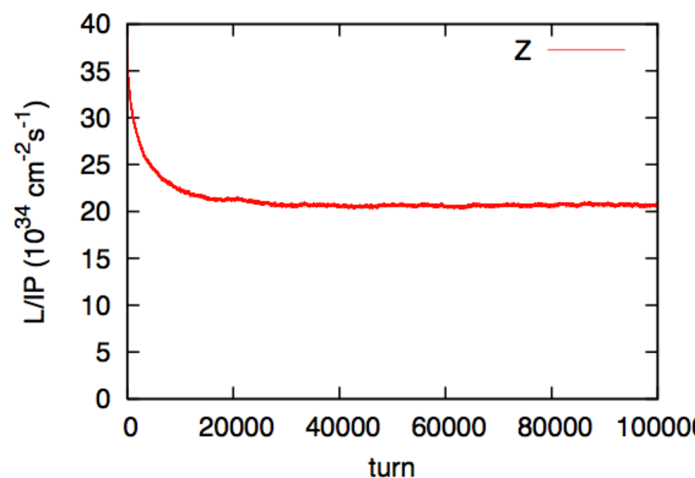
t L_{design}=1.8x10^{34}



- W L_{design}=12x10^{34}



Z L_{design}=28x10^{34}



Crab waist option for TLEP-Z

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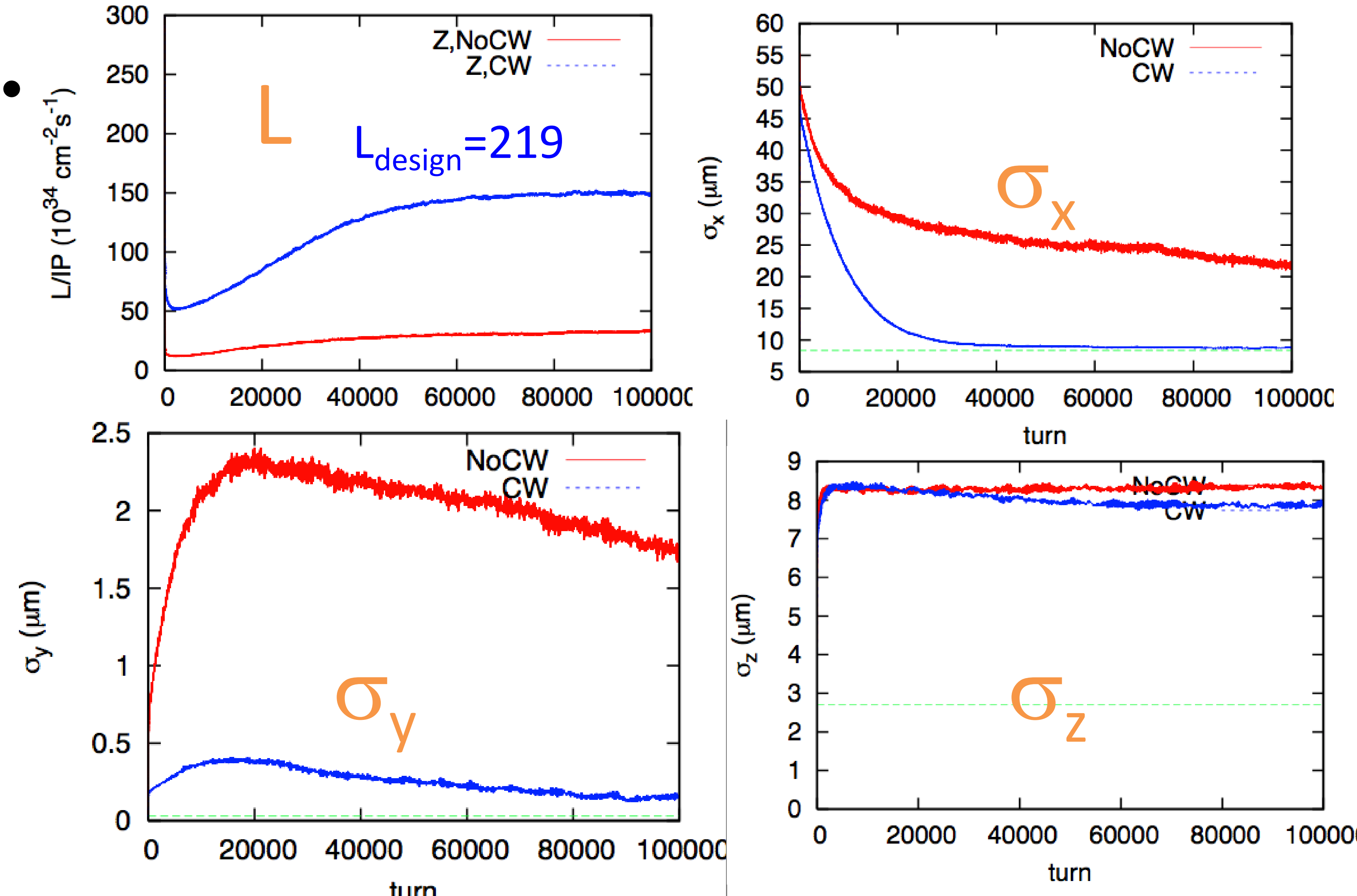
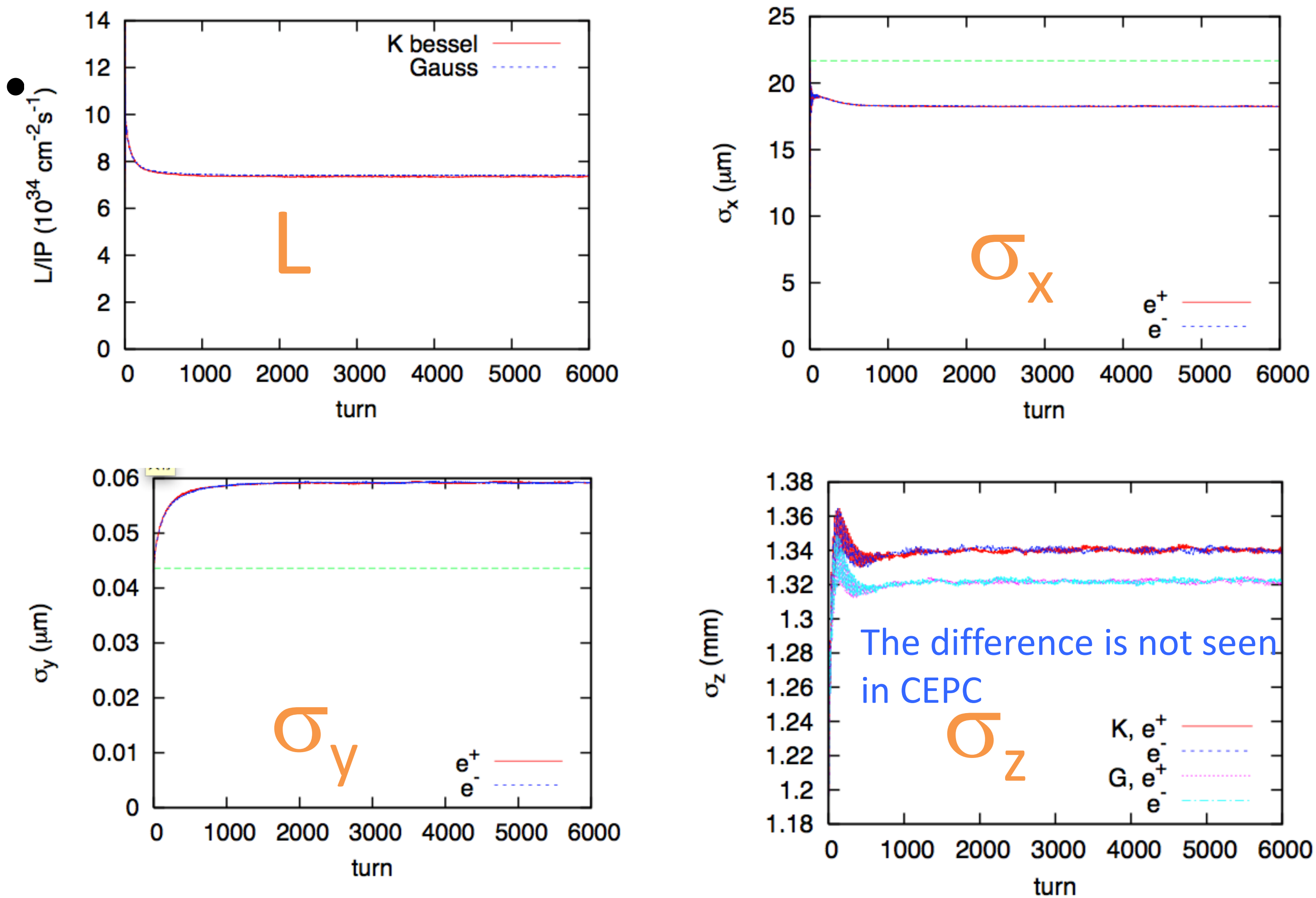
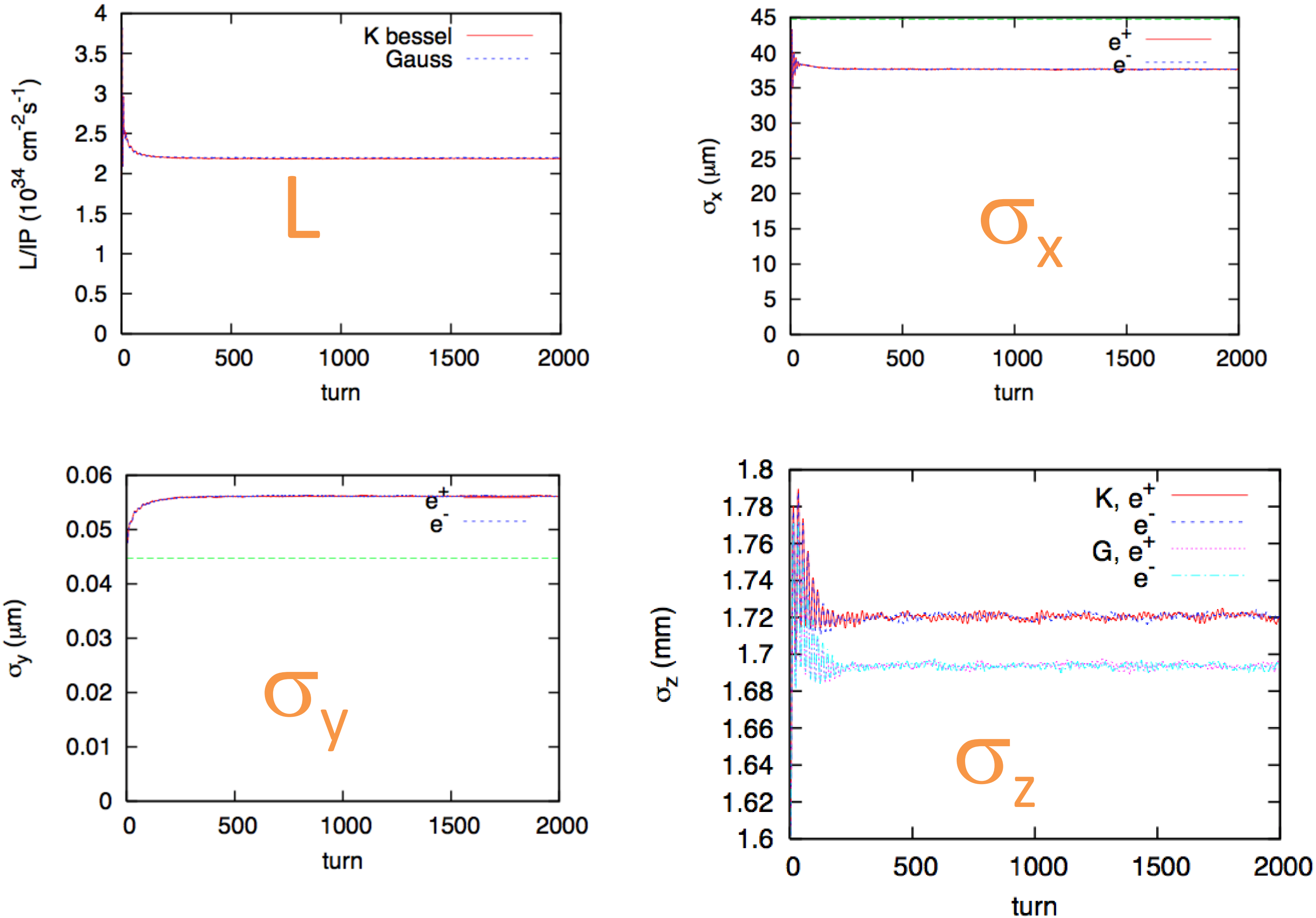


Strong-strong simulation for TLEP-H



Strong-strong simulation for TLEP-t



Summary of luminosity simulation

Table 1: Calculated luminosity and bunch length.

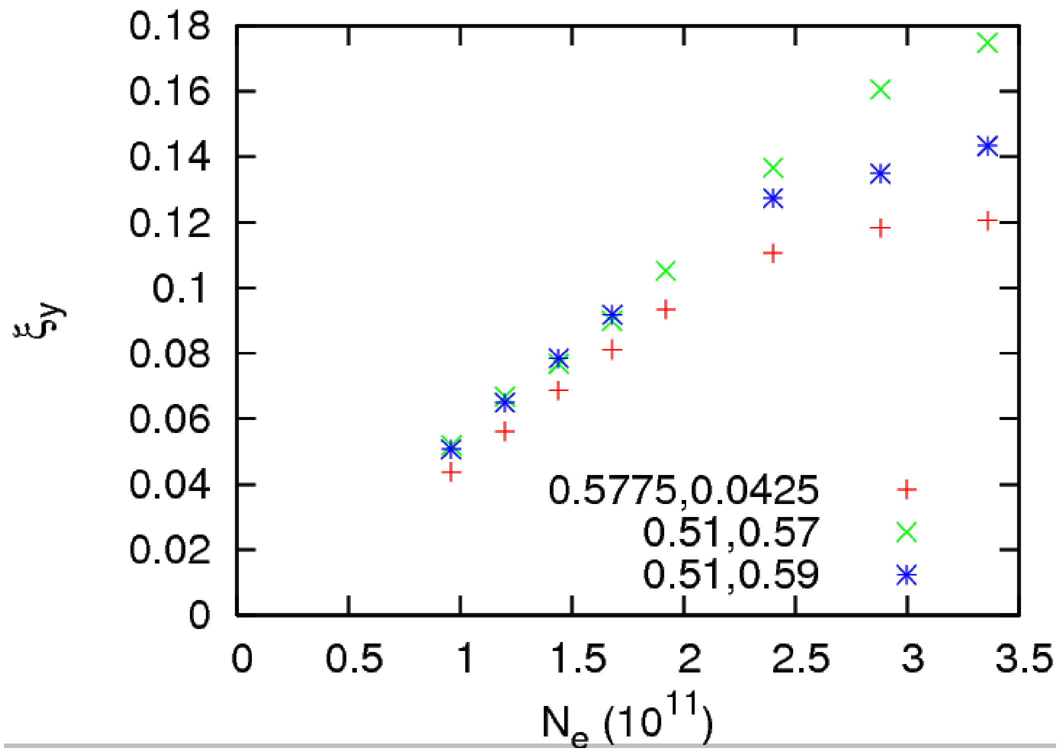
	TLEP/FCC-ee					Ce-
	Z	Z (cr. w.)	W	H	t	pC
	luminosity [10^{34} cm^{-2}s^{-1}]					
analyt.	28	219	12	6.0	1.7	1.8
w-s.	21	150	13	6.9	2.0	1.6
s-strong	—	—	—	7.5	2.2	1.6
	σ_z [mm]					
w/o BS	1.64	1.9	1.01	0.81	1.16	2.3
analyt.	2.56	6.4	1.49	1.17	1.49	2.7
w-s.	2.8	7.9	1.5	1.2	1.6	2.7
s-strong	—	—	—	1.3	1.72	2.9

Systematic study for beam energy LEP experiences

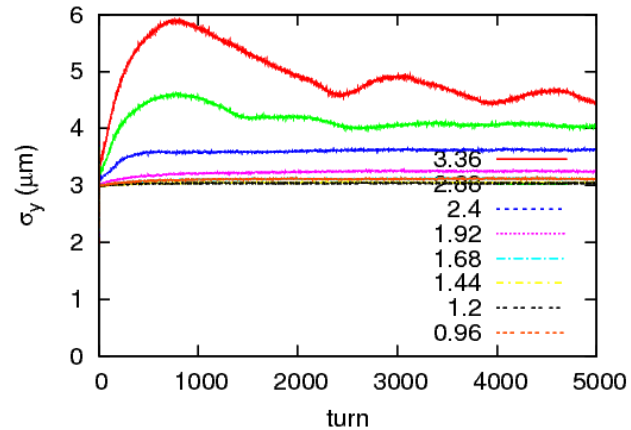
- LEP1: E=45.6 GeV, τ_y/IP=2888 turns, Ne=1.2×10^{10}, ν_x, ν_y=(0.5775,0.0425)/IP,ξ_{y0}=0.044 , ξ_y=0.044
- LEP1.5: E=65 GeV τ_y/IP=1000 turns, Ne=2.0×10^{10}, ν_x, ν_y=(0.5645,0.0415)/IP, ξ_{y0}=0.051 , ξ_y=0.051
- LEP2: E=94.3 GeV τ_y/IP=326 turns, Ne=4.0×10^{10}, ν_x, ν_y=(0.5713,0.0388)/IP, ξ_{y0}=0.075 , ξ_y=0.073
- LEP21: E=97.8 GeV τ_y/IP=293 turns, Ne=4.0×10^{10}, ν_x, ν_y=(0.585,0.045)/IP, ξ_{y0}=0.079 , ξ_y=0.0785

Courtesy of H. Barkhardt

Current dependence of luminosity in LEP1 (strong-strong)



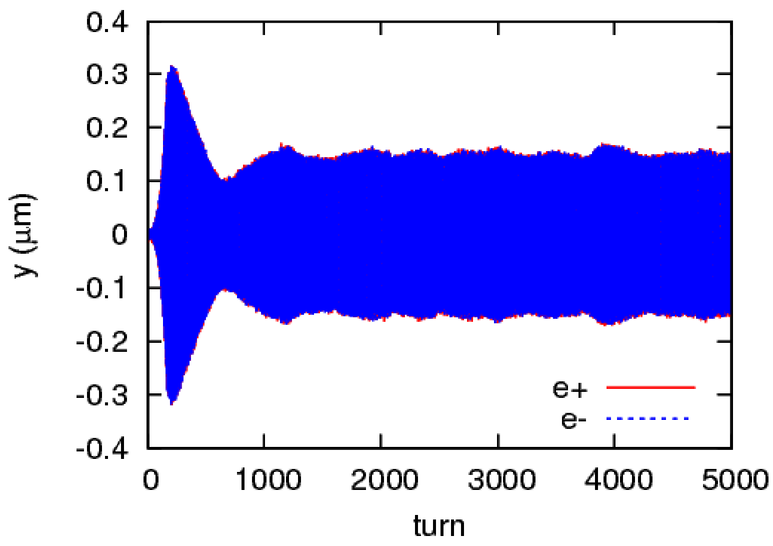
$$\xi_y = \frac{2 r_e \beta_y L}{\gamma N_e f_0}$$

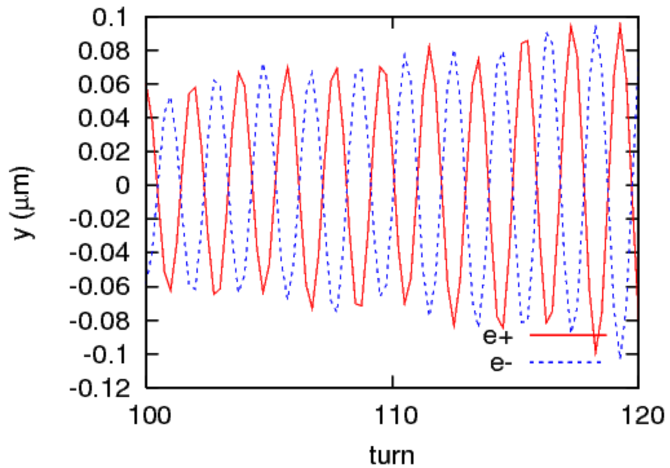


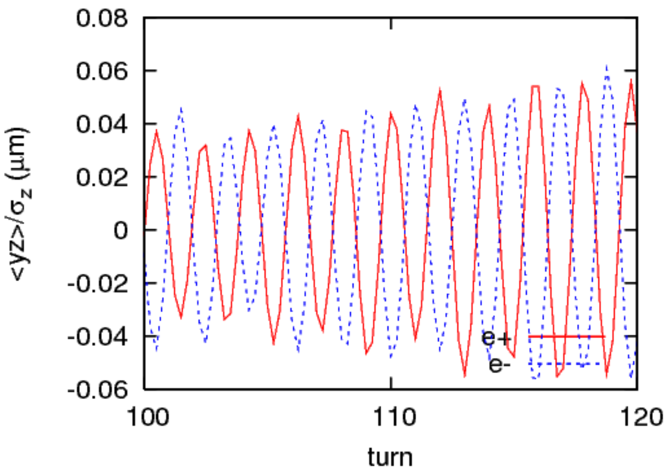
- ξ_y is saturated at 0.12 for ν_x, ν_y=(0.5775,0.0425)

Why is ξ_y saturated

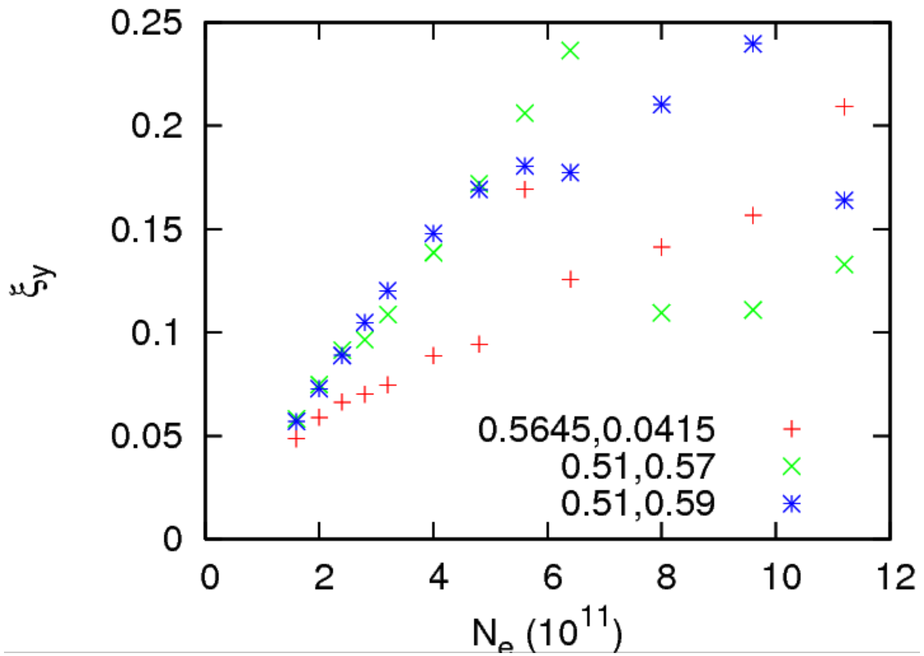
- Vertical synchro-beta coherent motion is seen.

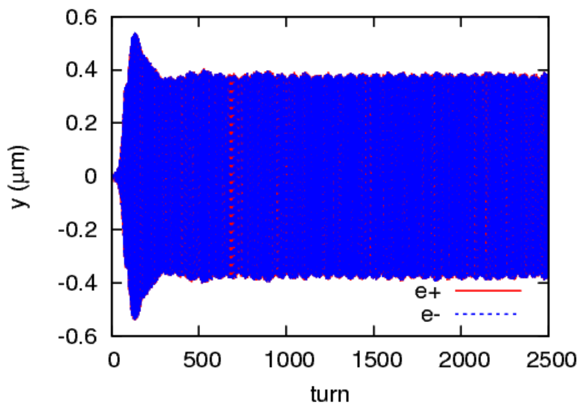


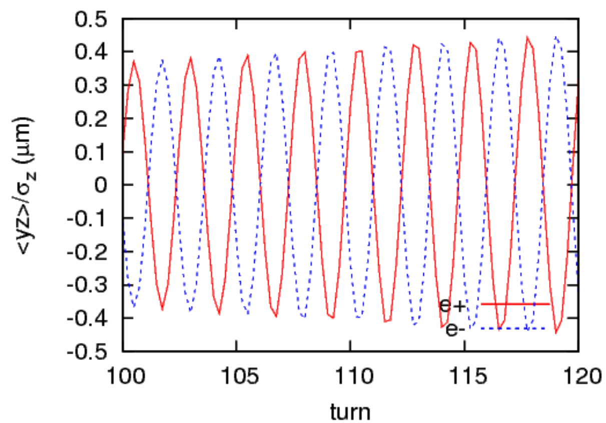




Current dependence of luminosity in LEP1.5 (strong-strong)



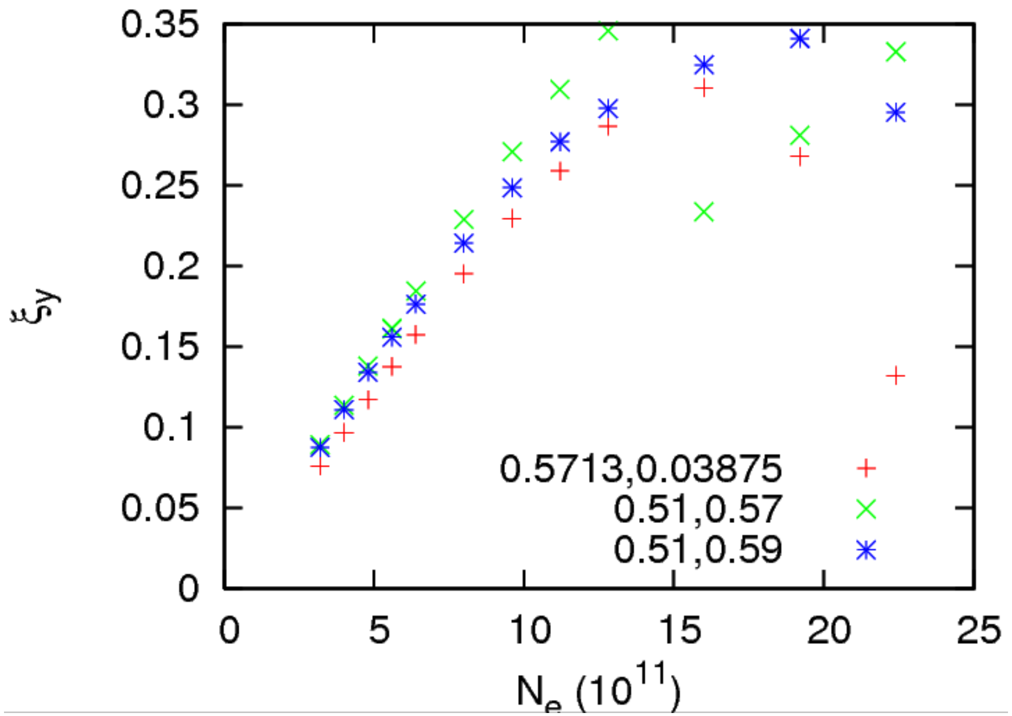


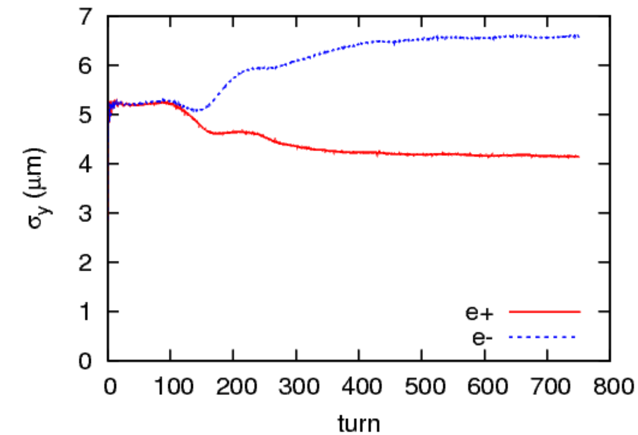


Vertical synchro-beta coherent motion is seen at ξ_y=0.05.

$$\xi_y = \frac{2r_e\beta_y L}{\gamma N_e f_0}$$

Current dependence of luminosity in LEP2 (strong-strong)

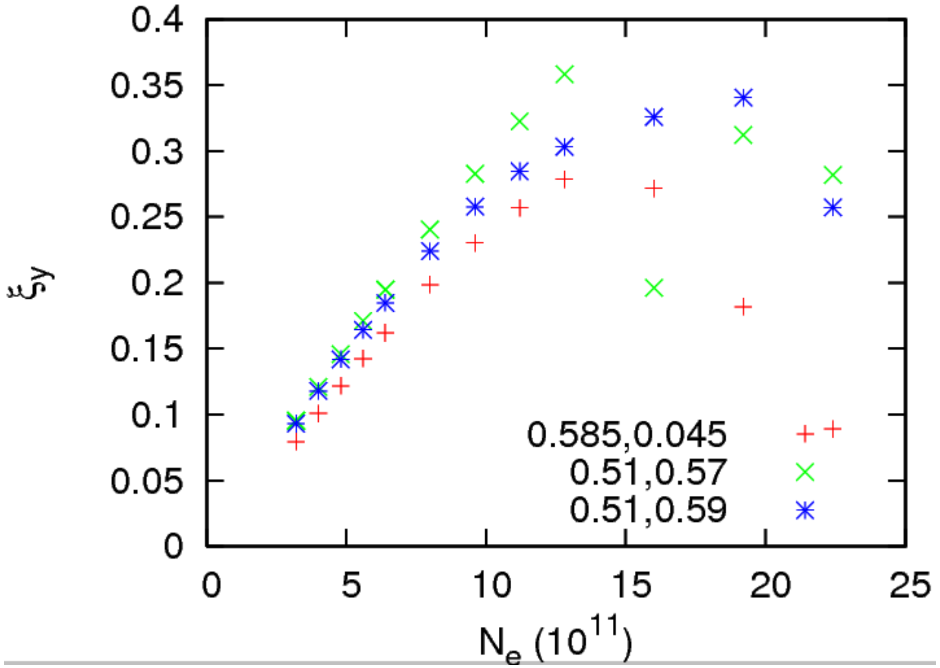


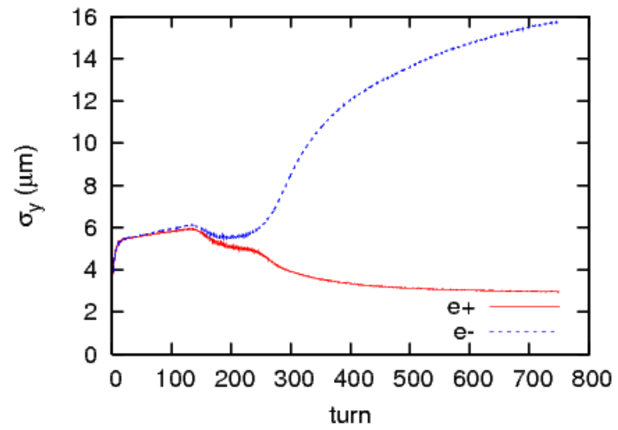


$$\xi_y = \frac{2r_e\beta_y L}{\gamma N_e f_0}$$

- ξ_y limits at 0.3.
- No coherent instability is seen.
- Beam size flip/flop

Current dependence of luminosity in LEP2.1 (strong-strong)





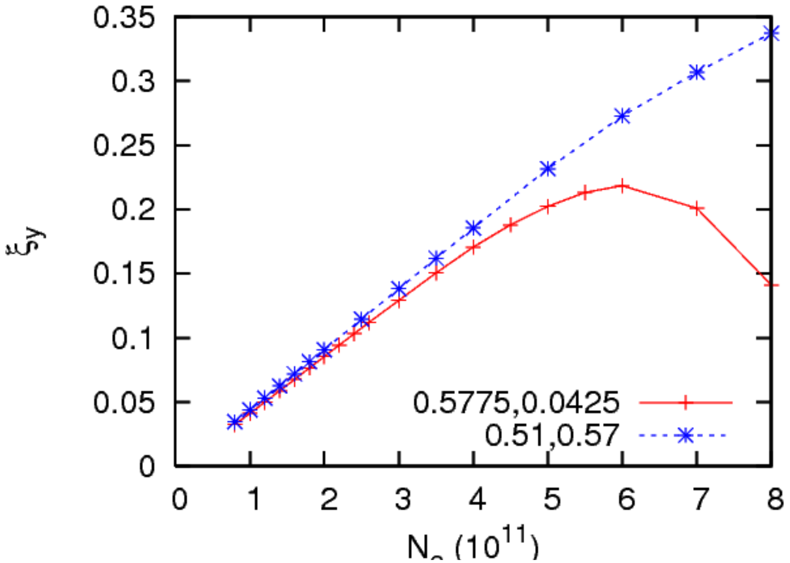
- ξ_y limits at 0.3.
- No coherent instability is seen.
- Beam size flip/flop

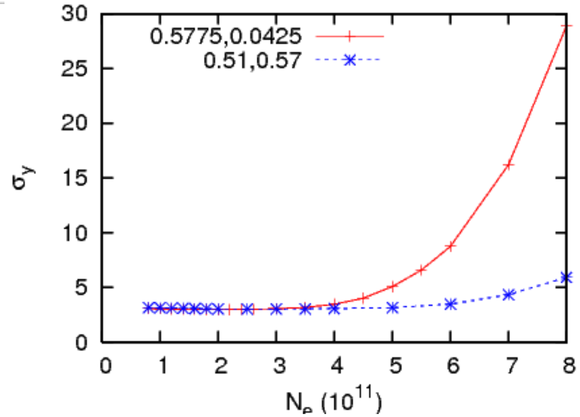
$$\xi_y = \frac{2 r_e \beta_y L}{\gamma N_e f_0}$$

Weak-strong simulation

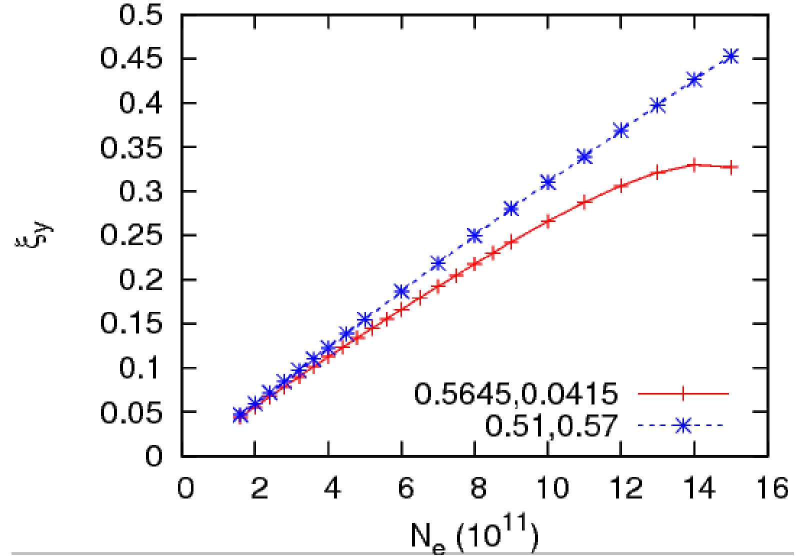
Only incoherent effects can be studied.

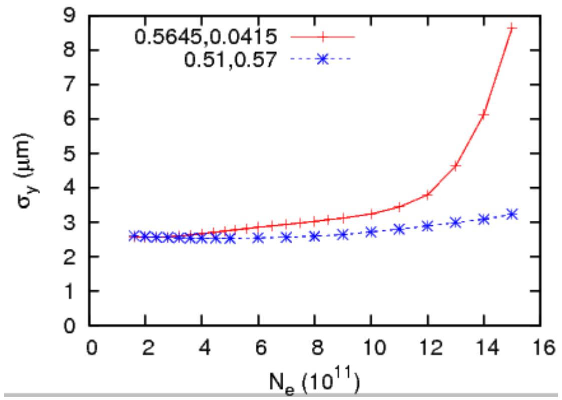
LEP1 $\xi_{y,max}$=0.22





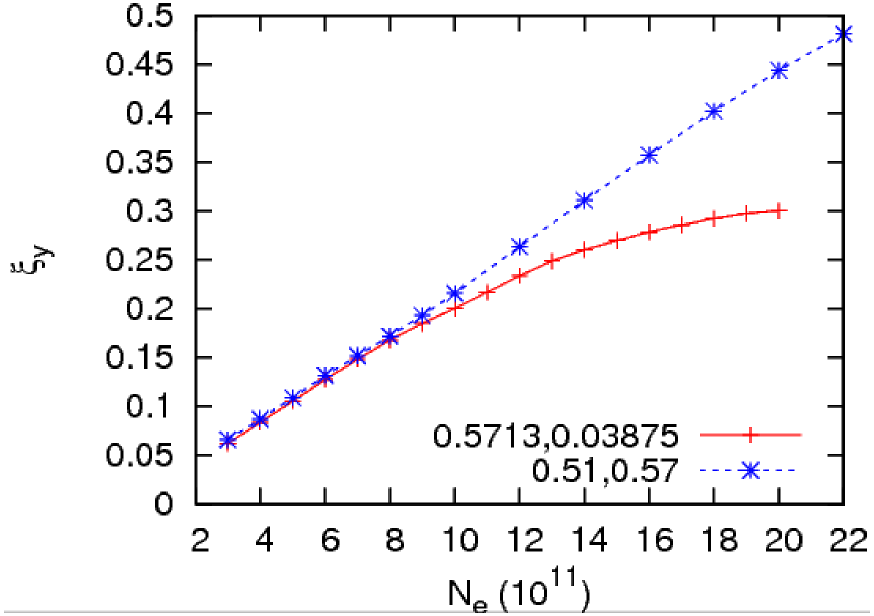
LEP1.5 $\xi_{y,max}$=0.33

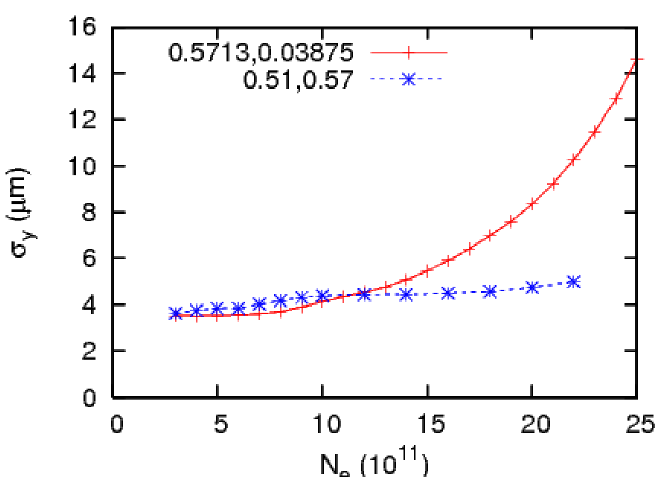




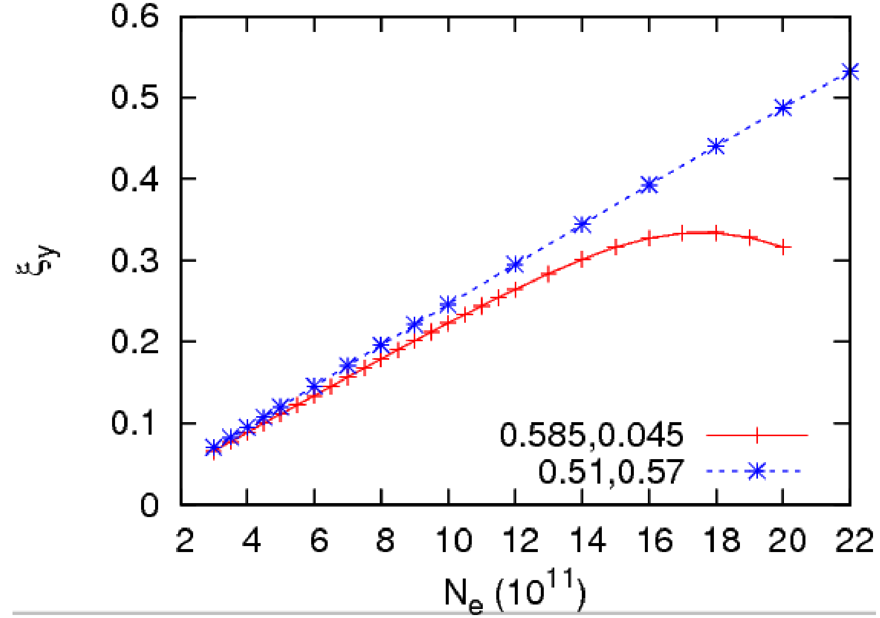
Weak-strong simulation

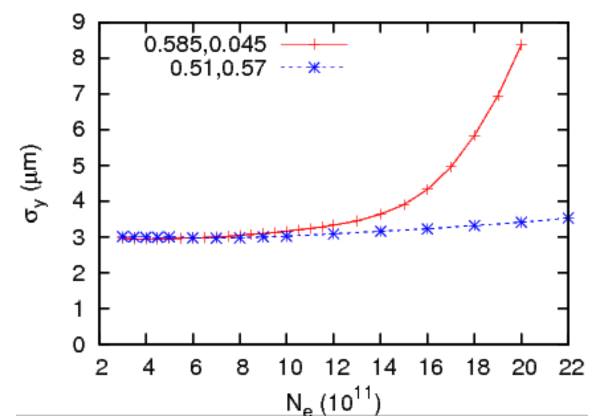
LEP2 $\xi_{y,max}$=0.3





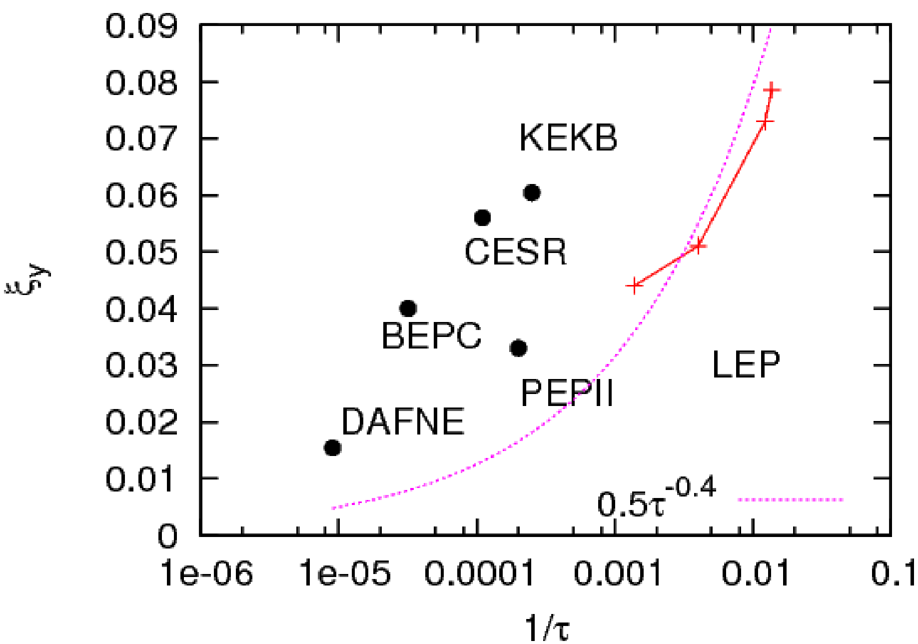
LEP1.5 $\xi_{y,max}$=0.34

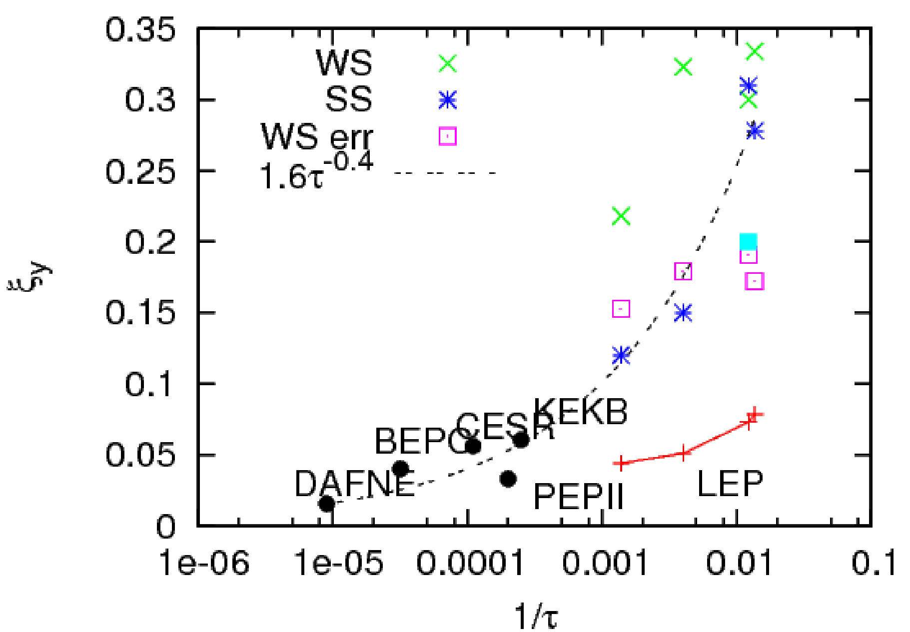




Damping rate

- Beam-beam tune shift evaluated by luminosity $\xi_y = \frac{2 r_e \beta_y L}{\gamma N_e f_0}$
- Simulation shows very high tune shift.





Number of IP

- When the super-periodicity is perfect, simulations using IP phase difference are correct.
- Betatron phase between IP's modulates.
- IP Twiss parameters, β, x-y coupling, η are not equal in every IP's.
- IP offset also shifts in each IP.

Vertical betatron Phase modulation

A sample

(1) $\Delta\phi_{12},\Delta\phi_{23},\Delta\phi_{34}$=0.01, 0.02, 0.01,

(2) $\Delta\phi_{12},\Delta\phi_{23},\Delta\phi_{34}$=0.02, 0.04, 0.01,

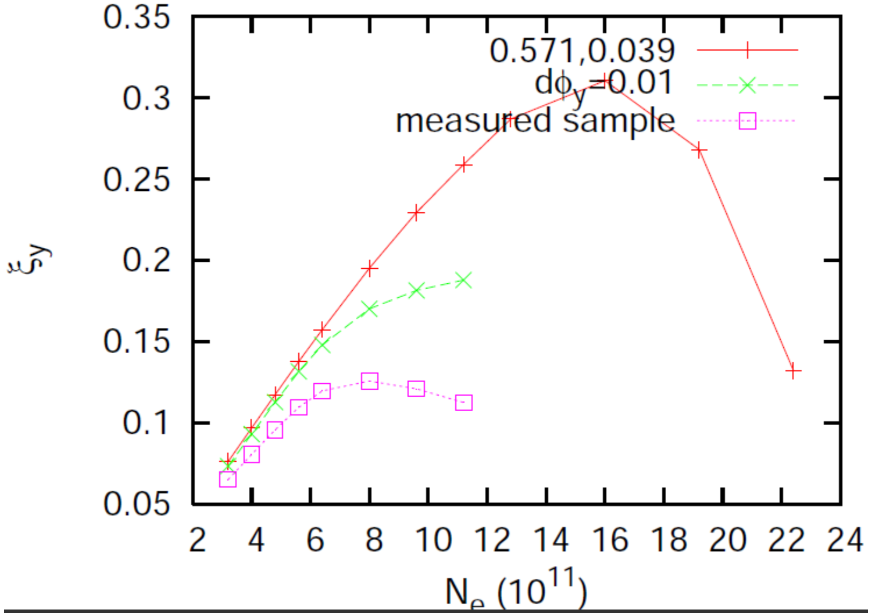
(3) $\Delta\phi_{12},\Delta\phi_{23},\Delta\phi_{34}$=0.0417, -0.02, -0.01

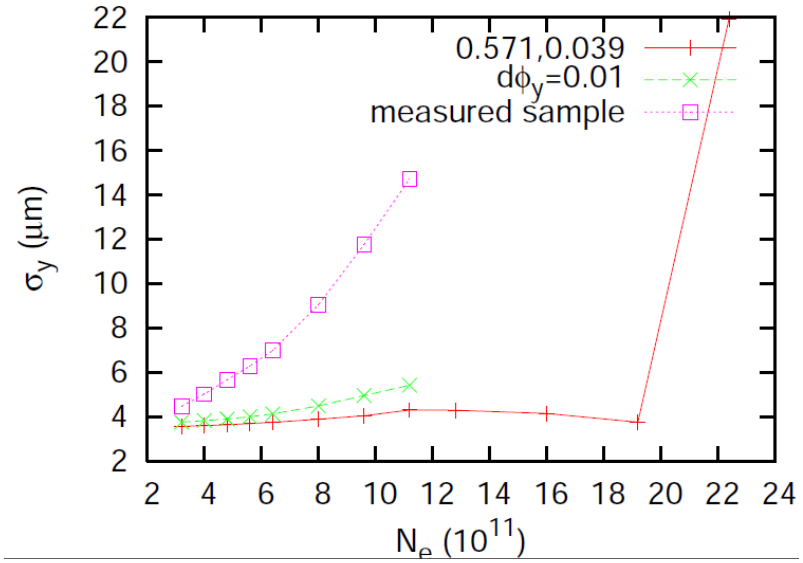
$\Delta N_e=0.1N_e$

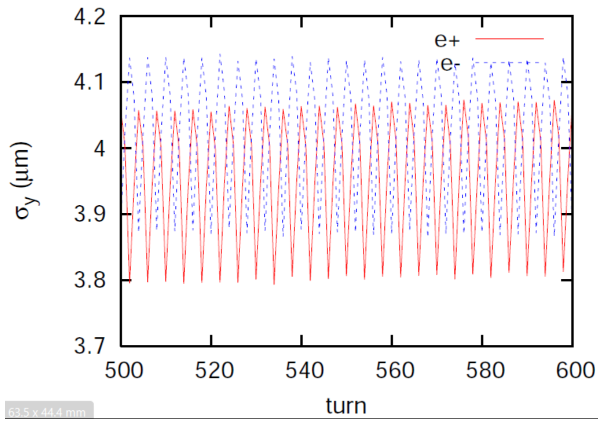
r_2=0.0024, -0.0024,0.0048,-0.0024 (KEKB level)

$\Delta y/\sigma_y$=0, 0.25, 0.5,-0.25

Effect of phase error in strong-strong simulation for LEP2

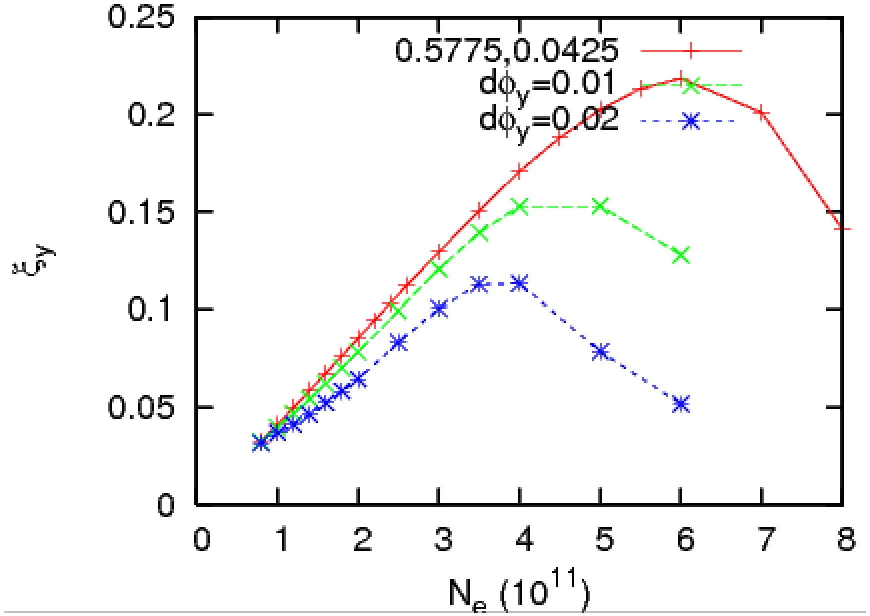




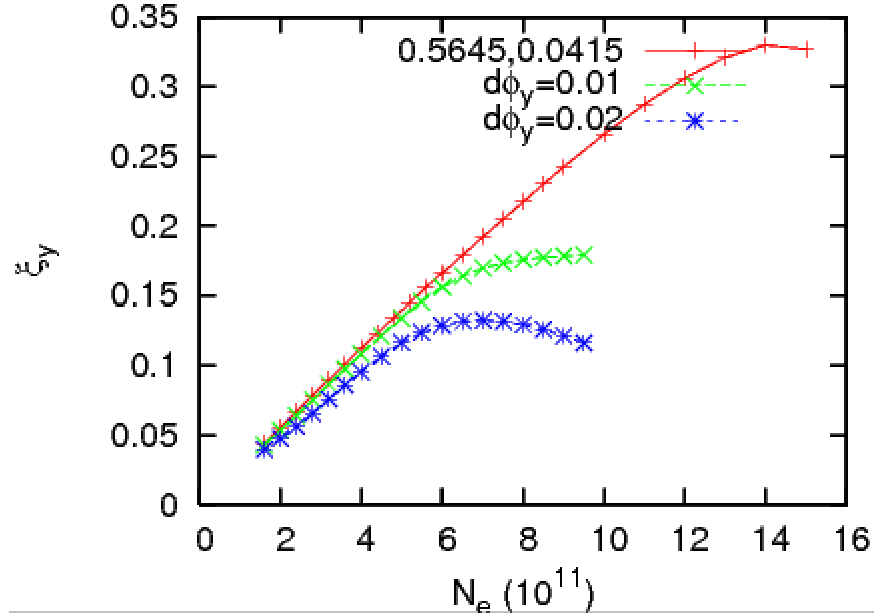


Effect of phase error in weak-strong simulation

LEP1



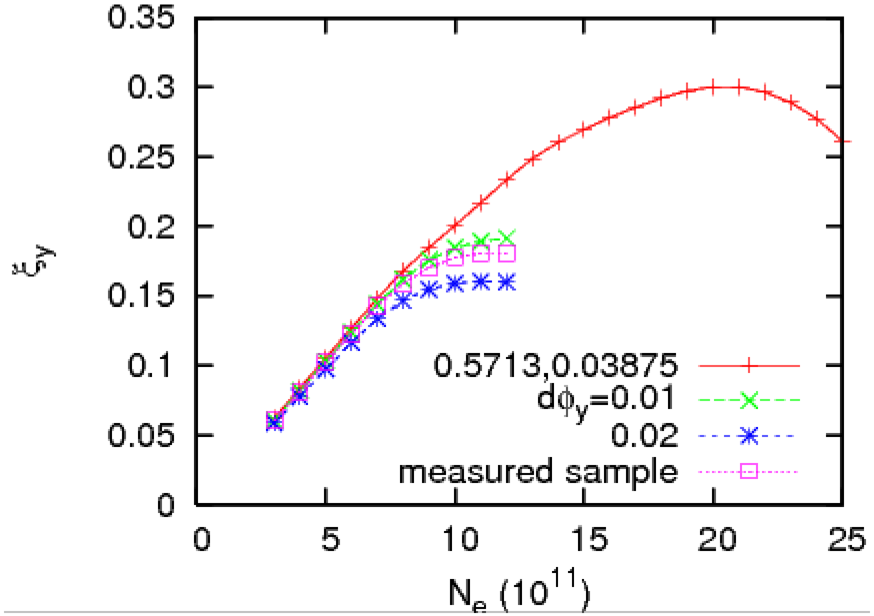
LEP15



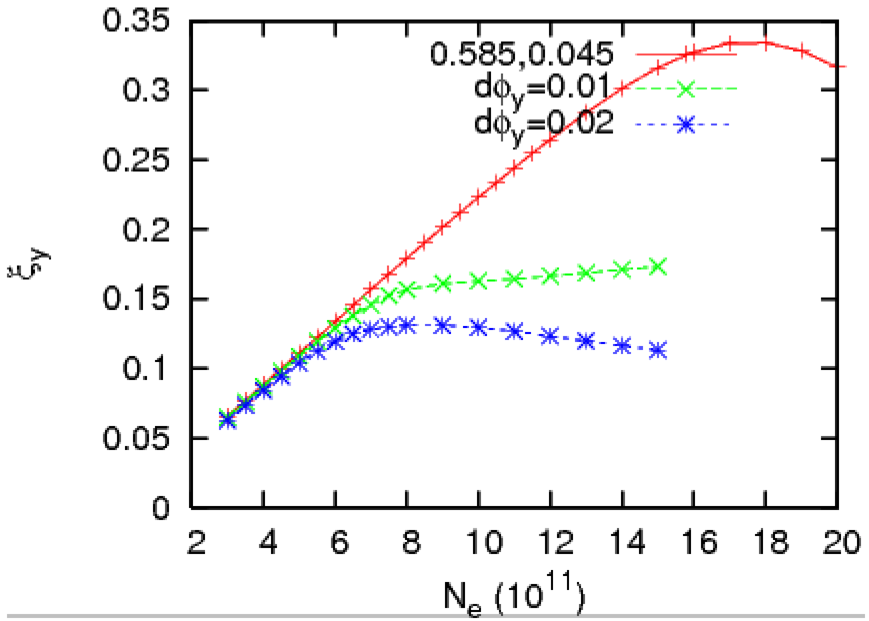
$\xi_{y,max}$ degrades drastically.

Effect of phase error in weak-strong simulation

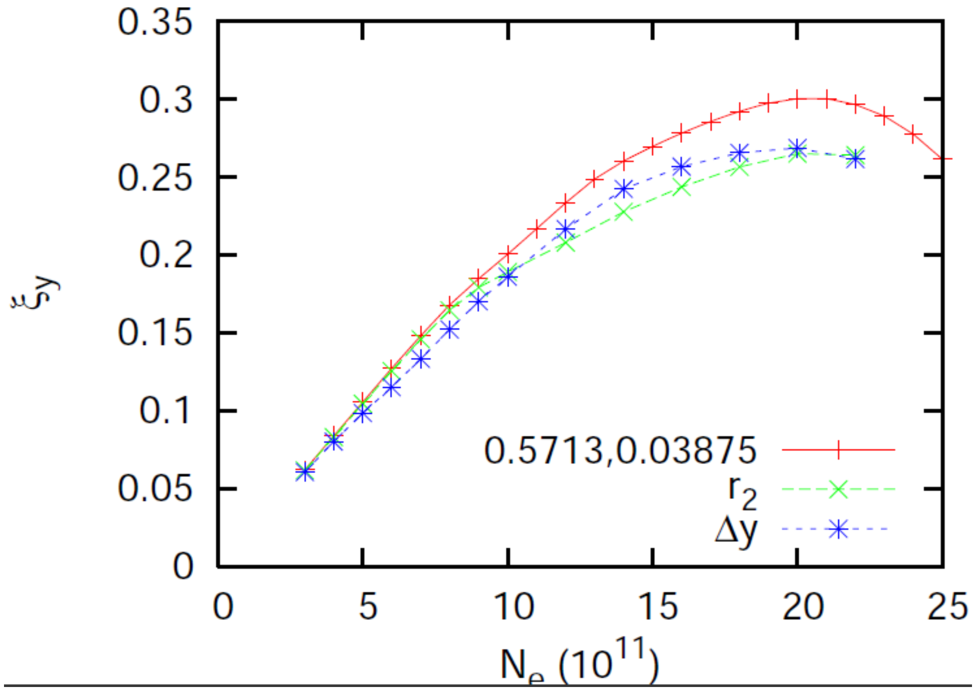
LEP2



LEP21

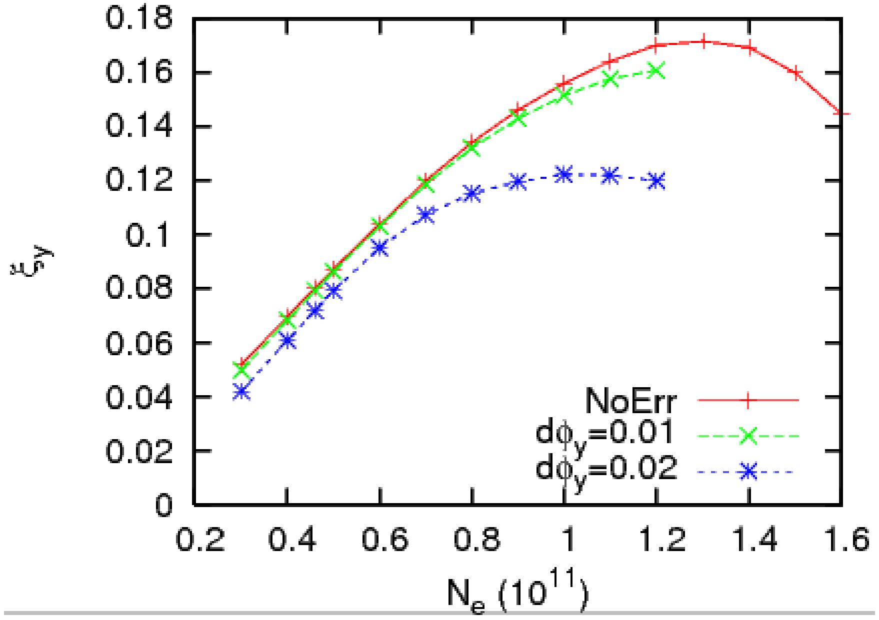


x-y coupling, collision offset



Effect of phase error in weak-strong simulation

- TLEP



Summary

- Luminosity simulation has been performed for TLEP, CEPC and LEP using weak-strong and strong-strong model.
- Design luminosity can be achievable for TLEP and CEPC in the simulations.
- Effects of energy and number of IP's have been studied using LEP parameters.
- The beam-beam limit in simulation is much higher than LEP experiments.
- Erros, for example betatron phase error between IP's affect the beam-beam performance.
- Which is correct scaling for the bam-beam parameter.

$$\xi_y = 0.5\tau^{-0.4} \text{ or } 1.6\tau^{-0.4}$$