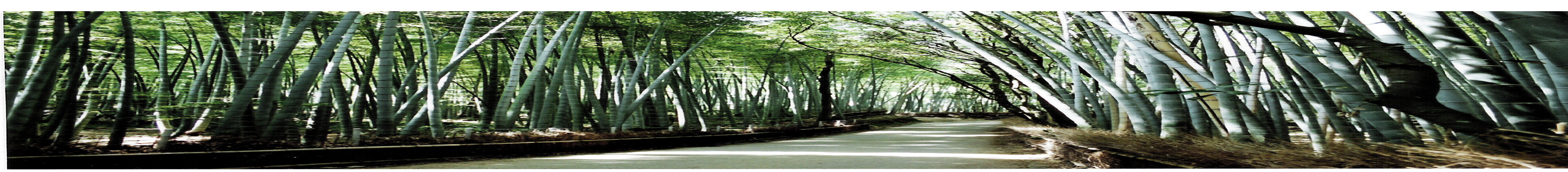
Beam-Beam Effects in Circular Hadron Colliders

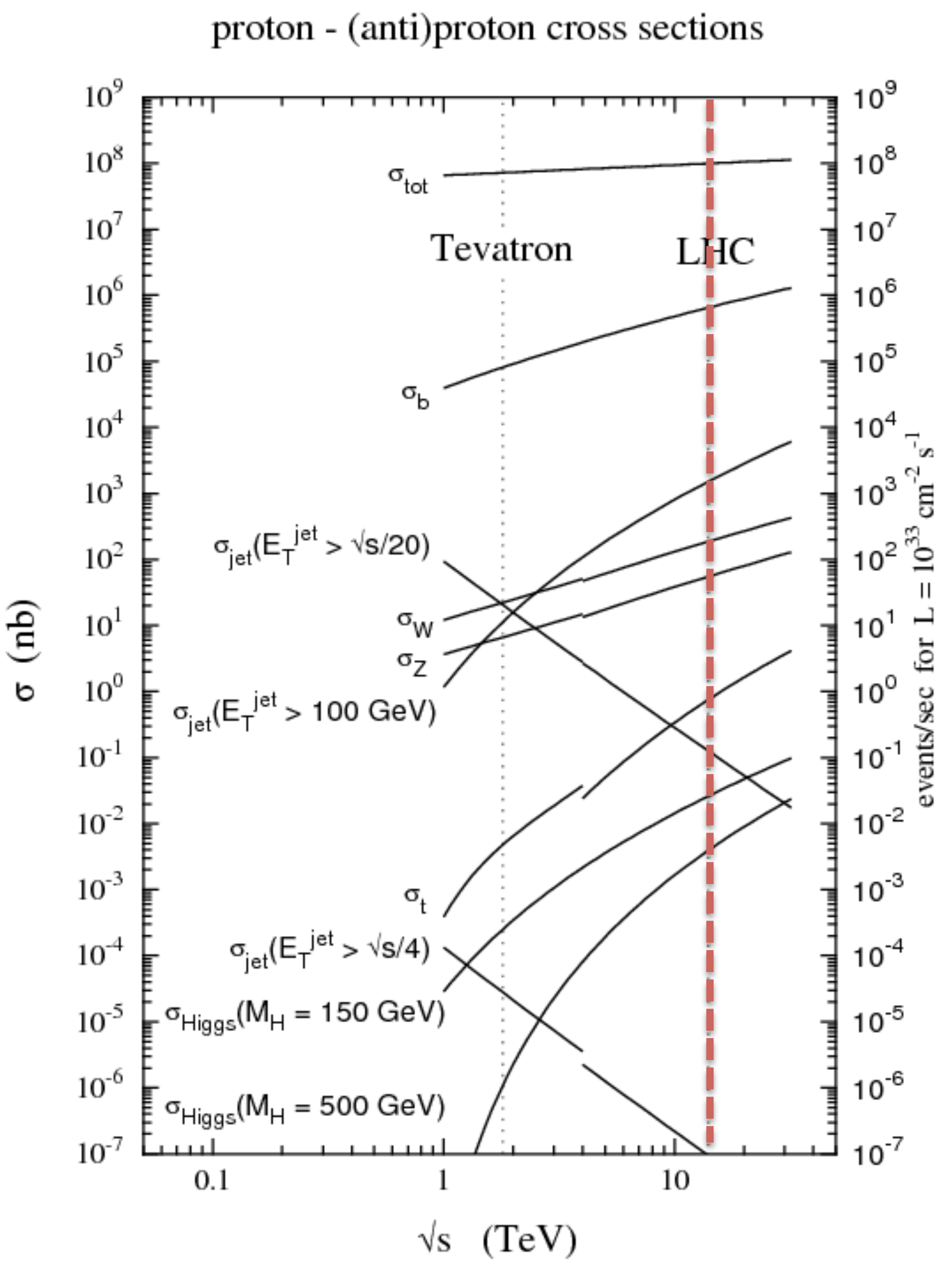
Tatiana Pieloni
CERN Beam Department



Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

High Energy, high luminosity hadron colliders?



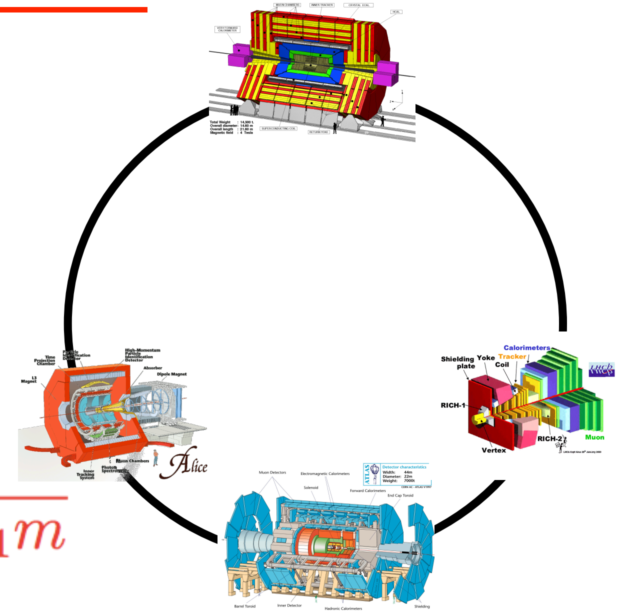
Hadrons (protons, ions):
heavy particles (strong force) made of quarks
Used when mass energy not yet identified

Discovery particles!

High Energy → higher cross section
→ Higher number of events per second
→ **COLLIDER**

Luminosity
→ **CIRCULAR COLLIDER**
machine parameter which relates the event rate and the cross section

High Energy: colliders



Two beams: $E_1, \vec{p_1}, E_2, \vec{p_2}, m_1 = m_2 = m$

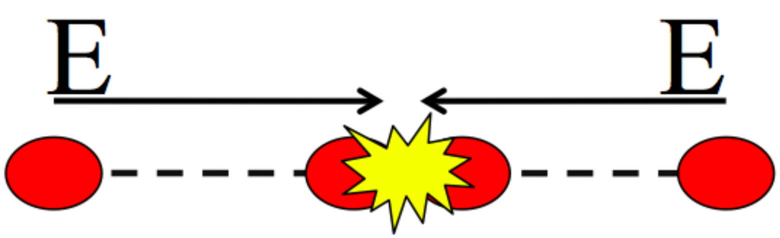
$$E_{cm} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2}$$

Collider versus fixed target:

Fixed target: $\vec{p_2} = 0$ ➜ $E_{cm} = \sqrt{2m^2 + 2E_1 m}$

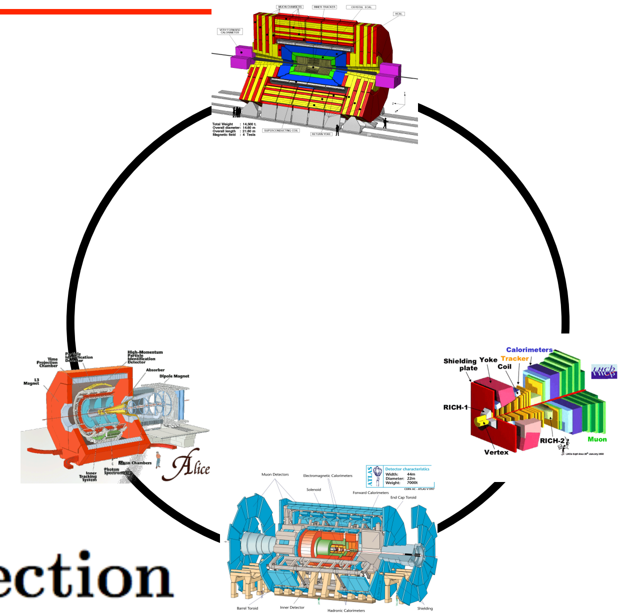
Collider: $\vec{p_1} = -\vec{p_2}$ ➜ $E_{cm} = E_1 + E_2$

LHC (pp): **14000 GeV versus $\approx$ 115 GeV**



$$E_{CM} = 2 \cdot E_{beam}$$

High Luminosity: circular colliders



$$\boxed{N_{event/s} = L \cdot \sigma_{event}}$$

Proportionality factor between cross section σ_p and number of interactions per second $\frac{dR}{dt}$

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p \qquad (\rightarrow \quad \text{units}: \ \text{cm}^{-2}\text{s}^{-1})$$

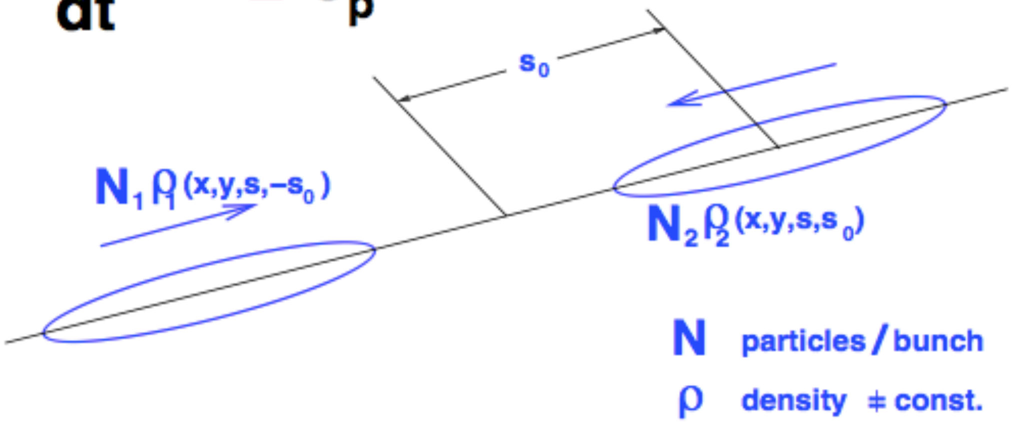
➡ **Independent of the physical reaction**

➡ **Reliable procedures to compute and measure**

Luminosity in a collider

Luminosity per bunch crossing

$$\frac{dR}{dt} = L\, \sigma_p$$



$$\mathcal{L} \propto K N_1 N_2 \int\int\int\int_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)\,dx\,dy\,ds\,ds_0$$

$\mathbf{s_0}$ **is "time"-variable:** $\mathbf{s_0} = c \cdot \mathbf{t}$

Kinematic factor: $K = \sqrt{(\vec{v_1} - \vec{v_2})^2 - (\vec{v_1} \times \vec{v_2})^2/c^2}$

Luminosity formula

- **Assume uncorrelated densities in all planes**

→ **factorize:** $\rho(x, y, s, s_0) = \rho_x(x) \cdot \rho_y(y) \cdot \rho_s(s \pm s_0)$

- **For head-on collisions ($\vec{v_1} = -\vec{v_2}$) we get:**

$$\mathcal{L} = 2 \cdot N_1 N_2 \cdot f \cdot n_b \cdot \int\int\int\int_{-\infty}^{+\infty} dx dy ds ds_0$$
$$\rho_{1x}(x)\rho_{1y}(y)\rho_{1s}(s - s_0) \cdot \rho_{2x}(x)\rho_{2y}(y)\rho_{2s}(s + s_0)$$

- **In principle: should know all distributions**

→ **Mostly use Gaussian ρ for analytic calculation (in general: it is a good approximation)**

Luminosity

Simplest case assumptions:

- Gaussian distributions
- Equal Beams
- No dispersion at the collision point
- Head-on collision

$$\mathcal{L} = \frac{2 \cdot N_1 N_2 f n_b}{(\sqrt{2\pi})^6 \sigma_s^2 \sigma_x^2 \sigma_y^2} \int\int e^{-\frac{x^2}{\sigma_x^2}} e^{-\frac{y^2}{\sigma_y^2}} e^{-\frac{s^2}{\sigma_s^2}} e^{-\frac{s_0^2}{\sigma_s^2}} dx dy ds ds_0$$

Equal Transverse beams

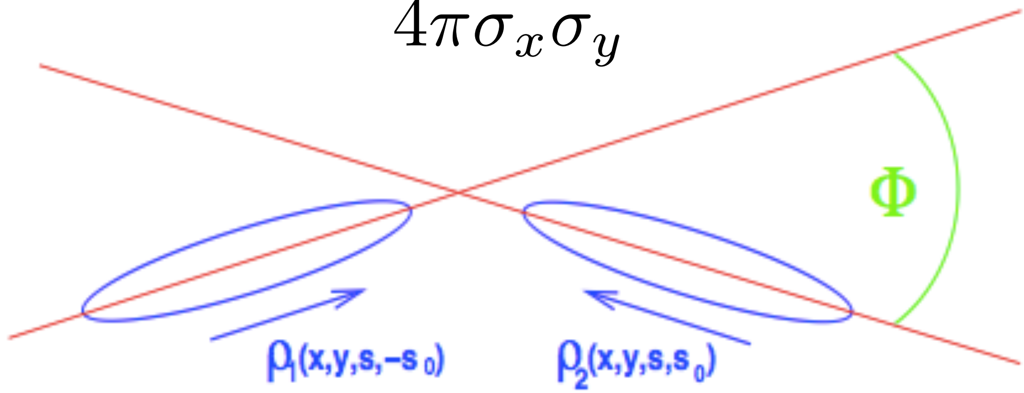
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} \qquad \sigma_{x,y} = \sqrt{\epsilon \cdot \beta^*_{x,y}}$$

UnEqual Transverse beams

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} \left(\mathcal{L} = \frac{N_1 N_2 f n_b}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} \right)$$

Crossing angle effect

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot S$$



S is the geometric reduction factor
For small crossing angle $\sigma_s >> \sigma_{x,y}$

$$S \approx \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

Examples: LHC (7 TeV): ϕ = 285 μrad, σ_x = 17 μm, σ_s = 7.5 cm, **S=0.84**
HL-LHC (7 TeV) ϕ=590 μrad, σ_x = 7 μm, σ_s = 7.5 cm, **S=0.3**

70% loss of luminosity if not compensated

Luminosity in Circular Colliders

	Energy (GeV)	$\mathcal{L}_{max}$ $cm^{-2}s^{-1}$	rate s^{-1}	σ_x/σ_y $\mu m/\mu m$	Particles per bunch
SPS ($p\bar{p}$)	**315x315**	$6\ 10^{30}$	$4\ 10^{5}$	**60/30**	$\approx 10\ 10^{10}$
Tevatron ($p\bar{p}$)	**1000x1000**	$100\ 10^{30}$	$7\ 10^{6}$	**30/30**	$\approx 30/8\ 10^{10}$
HERA ($e^{+}p$)	**30x920**	$40\ 10^{30}$	**40**	**250/50**	$\approx 3/7\ 10^{10}$
LHC (pp)	**7000x7000**	$10000\ 10^{30}$	10^{9}	**17/17**	$\approx 11\ 10^{10}$

Luminosity in Circular Colliders

	Energy (GeV)	$\mathcal{L}_{max}$ $cm^{-2}s^{-1}$	rate s^{-1}	σ_x/σ_y $\mu m/\mu m$	Particles per bunch
SPS ($p\bar{p}$)	315x315	$6\ 10^{30}$	$4\ 10^{5}$	60/30	$\approx 10\ 10^{10}$
Tevatron ($p\bar{p}$)	1000x1000	$100\ 10^{30}$	$7\ 10^{6}$	30/30	$\approx 30/8\ 10^{10}$
HERA ($e^{+}p$)	30x920	$40\ 10^{30}$	40	250/50	$\approx 3/7\ 10^{10}$
LHC (pp)	7000x7000	$10000\ 10^{30}$	10^{9}	17/17	$\approx 11\ 10^{10}$

Highest ENERGY and Highest LUMINOSITY

HL-LHC is aiming to factor 10 higher luminosity

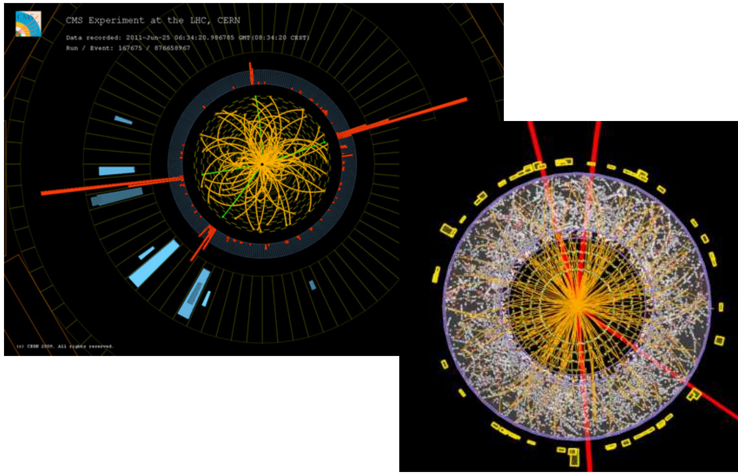
Several projects for larger hadron colliders (China, CERN…)

Outline

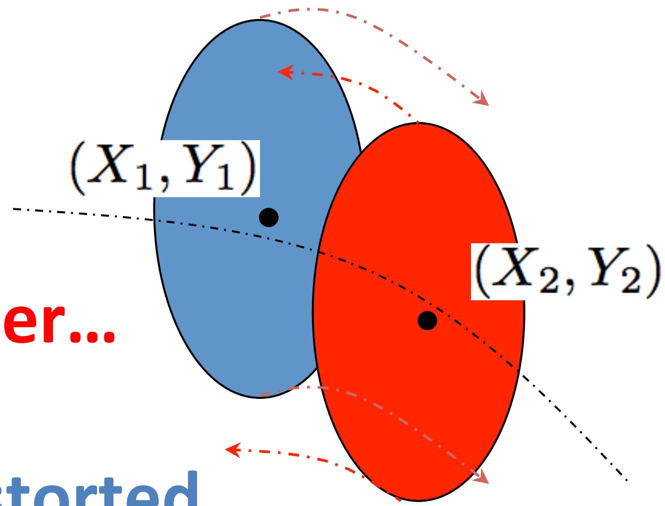
- High Energy and High Luminosity
- Beam-Beam Force
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

When do we have beam-beam effects?

- They occur when two beams get closer and collide



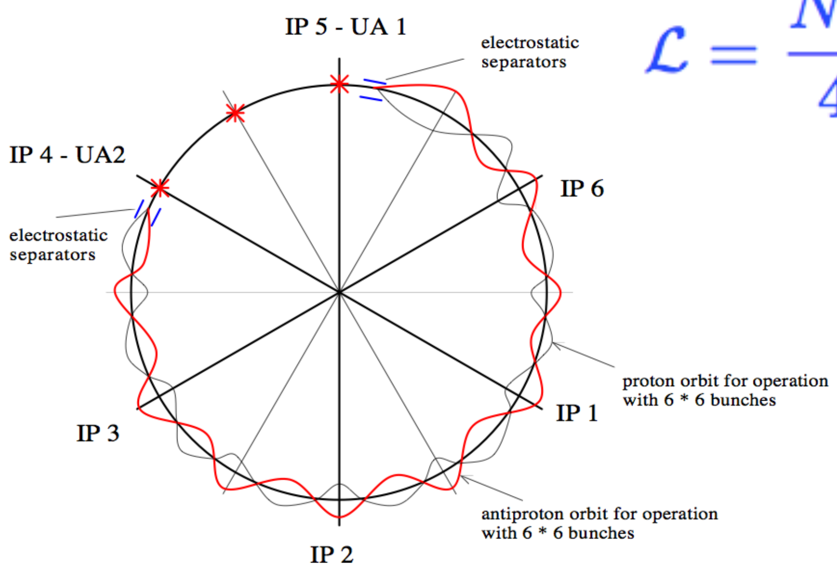
- Two types
  - High energy collisions between two particles (wanted)
  - Distortions of beam by electromagnetic forces (unwanted)



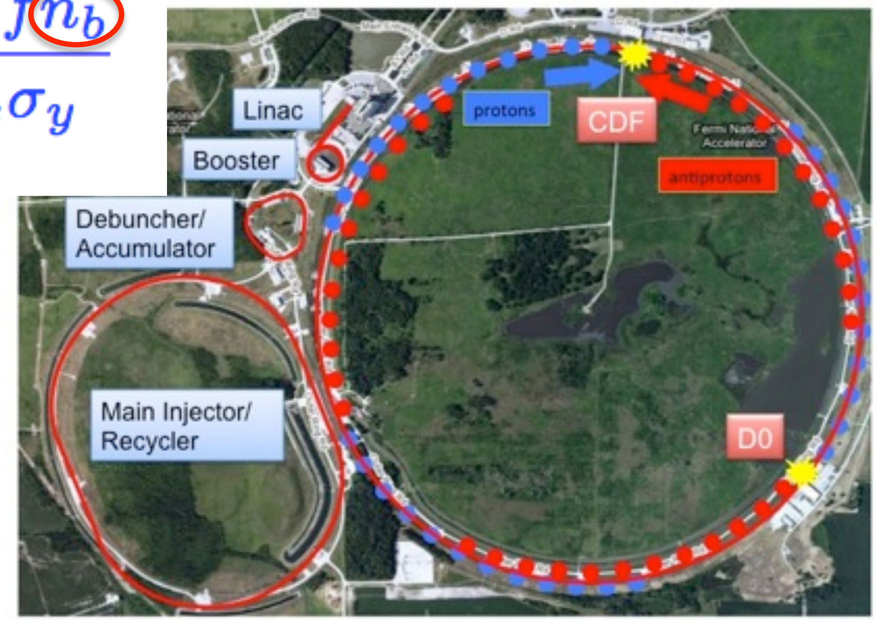
- **Unfortunately: usually both go together…**
- **0.001% (or less) of particles collide**
- **99.999% (or more) of particles are distorted**

Hadron colliders: Pretzel Scheme

Common magnets particles have opposite charge



$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$



SPPS collider (CERN) p anti-p

- 6 bunches = n_b
- 2 Experiments for Physics
- 9 points beams meet each other

Tevatron (FermiLab) p anti-p

- 36 bunches = n_b
- 2 Experiments for physics
- 72 points the beams meet each other

Hadron colliders 2 rings

Opposite field magnets particles have same cl

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

Relativistic Heavy Ion Collider (RHIC) p-p, ion-ion, p-ion)

- 110 bunches per beam = n_b
- 2 Experiments for physics

The Large Hadron Collider (LHC) p-p, ion-ion

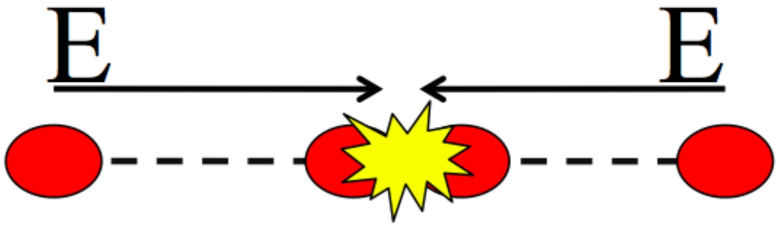
- 2808 bunches per beam = n_b
- 4 Experiments for physics
- 120 locations beams meet each other

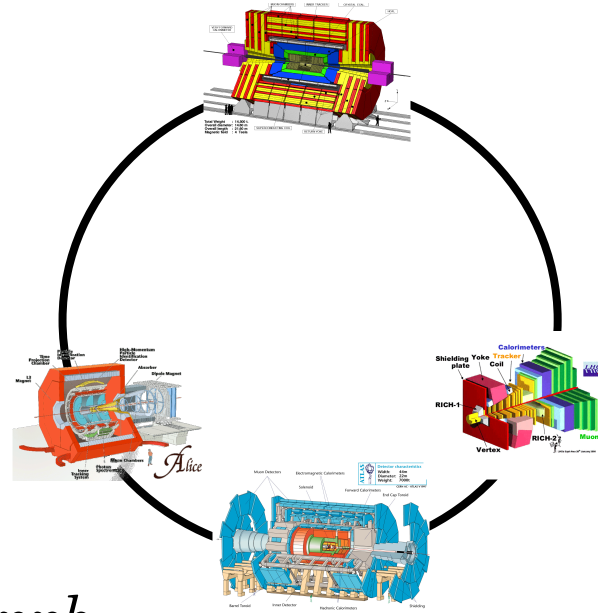
Hadron Circular Colliders

$$E_{CM} = 2 \cdot E_{beam}$$

$$N_{event/s} = L \cdot \sigma_{event}$$

$$L \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b \cdot f_{rev}$$





Bunch intensity: $N_p = 1.15 - 1.65 \cdot 10^{11}\ ppb$

Transverse Beam size: $\sigma_{x,y} = 16 - 30\ \mu m$

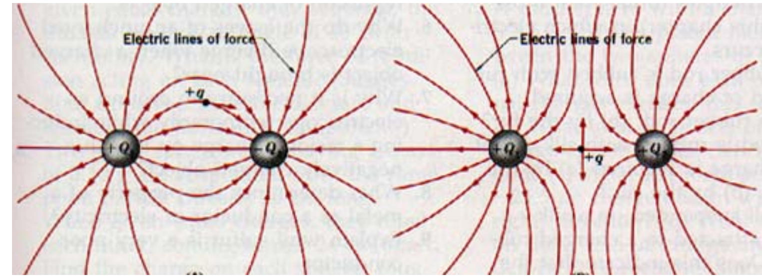
Number of bunches $1370 - 2808$

Revolution frequency $11\ kHz$

L = 10^{34} cm^{-2}s^{-1}

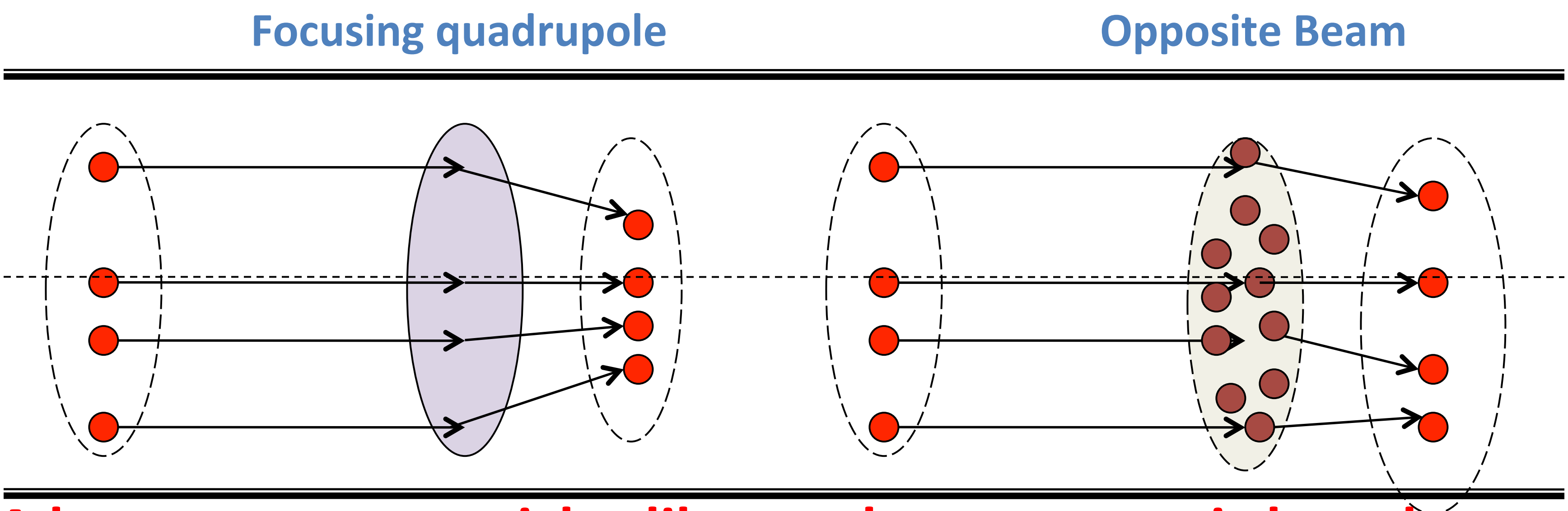
Beams Electro Magnetic potential

- Beam is a collection of charges
- Beam is an electromagnetic potential for other charges



Force on itself (space charge) and opposing beam (beam-beam effects)

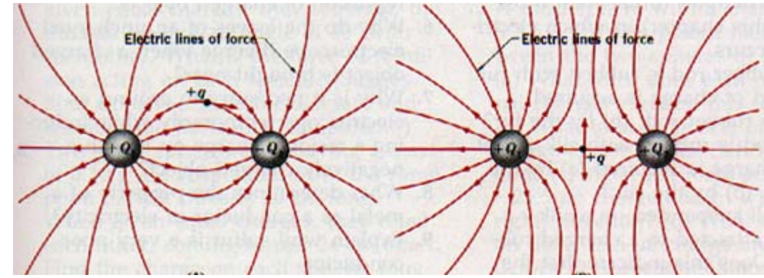
Single particle motion and whole bunch motion distorted



A beam acts on particles like an electromagnetic lens, but…

Beams Electro Magnetic potential

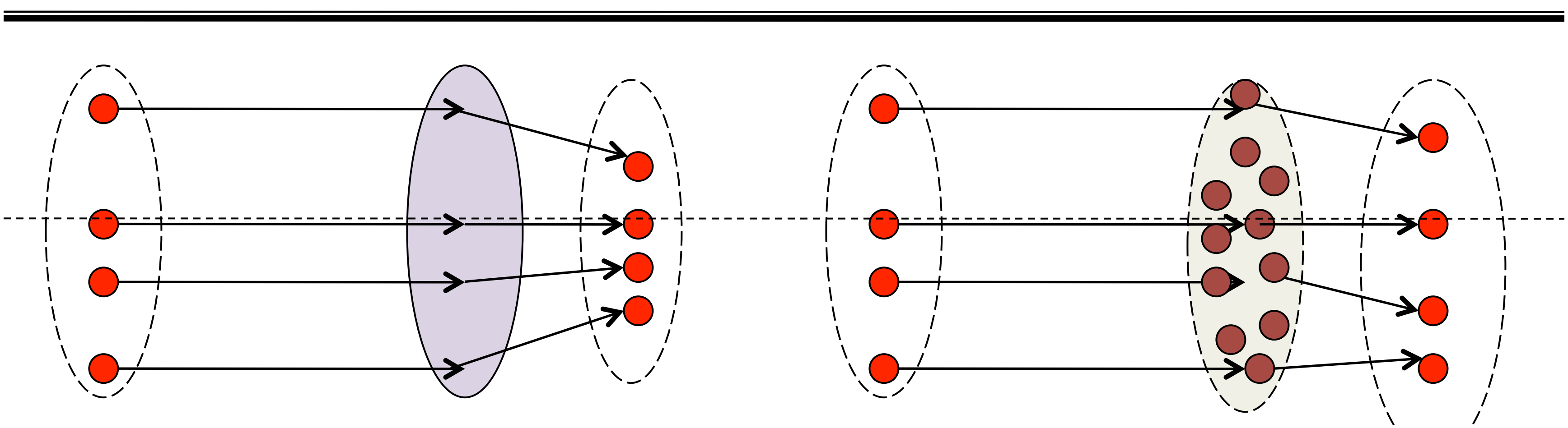
- Beam is a collection of charges
- Beam is an electromagnetic potential for other charges



Force on itself: **space charge** effects goes with $1/\gamma^2$ factor for high energy colliders this contribution is negligible
(i.e. force scales LHC $1/\gamma^2 = 1.8\ 10^{-8}$)

Focusing quadrupole

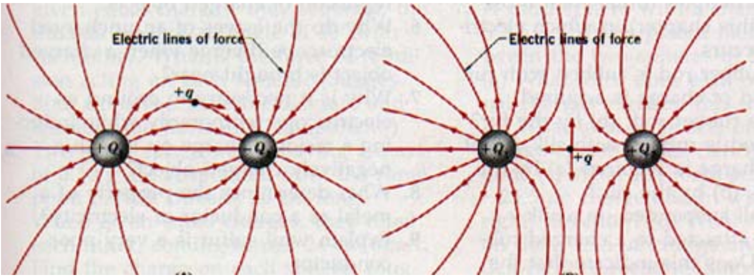
Opposite Beam



A beam acts on particles like an electromagnetic lens, but…

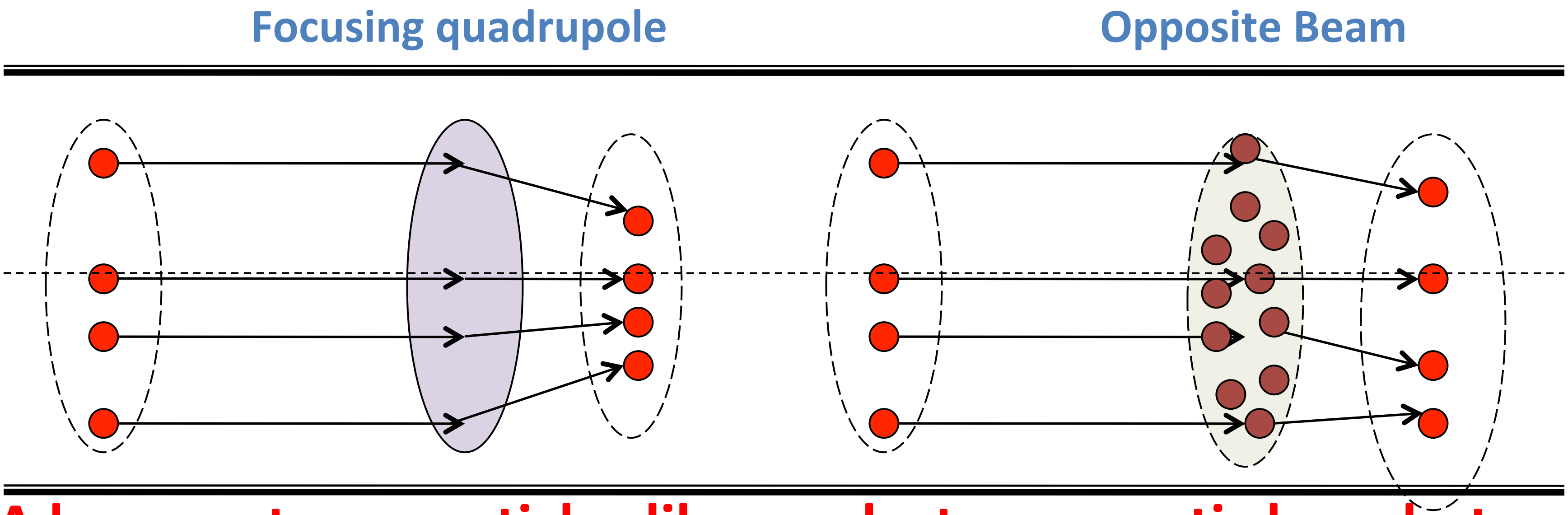
Beams Electro Magnetic potential

- Beam is a collection of charges
- Beam is an electromagnetic potential for other charges



Electromagnetic force from opposing beam (beam-beam effects)

Single particle motion and whole bunch motion distorted



A beam acts on particles like an electromagnetic lens, but…

From the potential of charge beam to the Beam-beam Force

We need to calculate the field E and B of opposing beam

In rest frame only electrostatic field: $\vec{E} \neq 0, \vec{B} = 0$

We can derive the electrostatic field

In the lab frame the electric and magnetic fields can be obtained:

$$E_{\parallel} = E'_{\parallel}, \quad E_{\perp} = \gamma \cdot E'_{\perp} \quad \text{with :} \quad \vec{B} = \vec{\beta} \times \vec{E}/c$$

Lorentz force gives: $\vec{F} = q(\vec{E} + \vec{\beta} \times \vec{B})$

Ultra-relativistic case $F_r = qE_{\perp}(1 + \beta^2)$

Beam-Beam Effect is mainly a TRANSVERSE EFFECT

Beam-beam potential and force

General approach in electromagnetic problems Reference[5]
already applied to beam-beam interactions in Reference[1,3, 4]

We need to calculate the field E and B of opposing beam

In rest frame only electrostatic field: $\vec{E} \neq 0, \vec{B} = 0$

$$\Delta U = -\frac{1}{\epsilon_0}\rho(x, y, z)$$

Scalar Potential can be derived from Poisson equation which relates the potential to the charge density ρ

$$\overrightarrow{E} = -\nabla U(x, y, z, \sigma_x, \sigma_y, \sigma_z)$$

Then compute the Electric Field from Gauss Law

Then back to the Lab frame we can compute the force

Lorentz force gives: $\vec{F} = q(\vec{E} + \vec{\beta} \times \vec{B})$

Beam-beam potential

In the case of Gaussian Beam density distribution we can factorize the density distribution

$$\rho(x_0, y_0, z_0) = \rho(x_0) \cdot \rho(y_0) \cdot \rho(z_0)$$

$$\rho(x_0, y_0, z_0) = \frac{Ne}{\sigma_x \sigma_y \sigma_z \sqrt{2\pi}^3} e^{\left(-\frac{x_0^2}{2\sigma_x^2} - \frac{y_0^2}{2\sigma_y^2} - \frac{z_0^2}{2\sigma_z^2}\right)}$$

N is the number of particles in bunch

The poison equation can be formally solved using the Green's function G(x,y,z,x0,y0,z0) method [25]

Solution of Poisson equation

$$U(x, y, z) = \frac{1}{\epsilon_0} \int G(x, y, z, x_0, y_0, z_0) \cdot \rho(x_0, y_0, z_0) dx_0 dy_0 dz_0$$

The potential get's the form:

$$U(x, y, z, \sigma_x, \sigma_y, \sigma_z) = \frac{1}{4\pi\epsilon_0} \frac{Ne}{\sigma_x \sigma_y \sigma_z \sqrt{2\pi}^3} \int\int\int \frac{e^{\left(-\frac{x_0^2}{2\sigma_x^2} - \frac{y_0^2}{2\sigma_y^2} - \frac{z_0^2}{2\sigma_z^2}\right)} dx_0 dy_0 dz_0}{\sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}}$$

This is difficult to solve but following [29] we can solve the diffusion equation.

S. Kheifets proposal

From the diffusion equation:

$$\Delta V - A^2 \cdot \frac{\delta V}{\delta t} = -\frac{1}{\epsilon_0}\rho(x,y,z) \qquad (\text{for} \;\; t \geq 0)$$

We obtain the potential U by going to the limit of A → 0 $\quad U = \lim_{A \to 0} V$

Solving the diffusion equation instead of Poisson gives a Green's function of the form:

$$G(x,y,z,t,x_0,y_0,z_0) = \frac{A^3}{(2\sqrt{\pi t})^3} \cdot e^{-A^2/4t \cdot ((x-x_0)^2+(y-y_0)^2+(z-z_0)^2)}$$

We can then compute the potential

$$U(x,y,z,\sigma_x,\sigma_y,\sigma_z)$$

$$\frac{Ne}{\sigma_x\sigma_y\sigma_z\sqrt{2\pi}^3\epsilon_0}\int_0^t d\tau \int\int\int e^{\left(-\frac{x_0^2}{2\sigma_x^2}-\frac{y_0^2}{2\sigma_y^2}-\frac{z_0^2}{2\sigma_z^2}\right)} \frac{A^3 \cdot e^{-A^2/4\tau((x-x_0)^2+(y-y_0)^2+(z-z_0)^2)}}{(2\sqrt{\pi\tau})^3} dx_0 dy_0 dz_0$$

S. Kheifets proposal

From Poisson Equation:

$$U(x,y,z,\sigma_x,\sigma_y,\sigma_z) = \frac{1}{4\pi\epsilon_0}\frac{Ne}{\sigma_x\sigma_y\sigma_z\sqrt{2\pi}^3}\int\int\int \frac{e^{\left(-\frac{x_0^2}{2\sigma_x^2}-\frac{y_0^2}{2\sigma_y^2}-\frac{z_0^2}{2\sigma_z^2}\right)}dx_0dy_0dz_0}{\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2}}$$

From Diffusion equation:

$$U(x,y,z,\sigma_x,\sigma_y,\sigma_z)$$

$$\frac{Ne}{\sigma_x\sigma_y\sigma_z\sqrt{2\pi}^3\epsilon_0}\int_0^t d\tau\int\int\int e^{\left(-\frac{x_0^2}{2\sigma_x^2}-\frac{y_0^2}{2\sigma_y^2}-\frac{z_0^2}{2\sigma_z^2}\right)}\frac{A^3\cdot e^{-A^2/4\tau((x-x_0)^2+(y-y_0)^2+(z-z_0)^2)}}{(2\sqrt{\pi\tau})^3}dx_0dy_0dz_0$$

This allows to avoid the denominator in the integral and to collect the exponential which can be integrated

The potential of charge beam: 2D case

Changing the independent variable τ to q= 4τ/A² and using the three integrations:

$$\int_{-\infty}^{\infty} e^{-(au^2+2bu+c)} du \;=\; \sqrt{\frac{\pi}{a}} e^{\left(\frac{b^2-ac}{a}\right)} \qquad (for: u = x_0, y_0, z_0)$$

Our potential assumes the form of:

$$U(x,y,z,\sigma_x,\sigma_y,\sigma_z) = \frac{1}{4\pi\epsilon_0}\frac{Ne}{\sqrt{\pi}}\int_0^\infty \frac{\exp\left(-\frac{x^2}{2\sigma_x^2+q}-\frac{y^2}{2\sigma_y^2+q}-\frac{z^2}{2\sigma_z^2+q}\right)}{\sqrt{(2\sigma_x^2+q)(2\sigma_y^2+q)(2\sigma_z^2+q)}}dq$$

Since we are interest in the transverse fields, in a two dimensional case

$$\rho(\mathrm{x,y}) = \rho(\mathrm{x}) \cdot \rho(\mathrm{y})$$

$$\rho_u(u) = \frac{1}{\sigma_u\sqrt{2\pi}}\exp\left(-\frac{u^2}{2\sigma_u^2}\right) \text{ where } \; u = x, y$$

2 dimensional problem

The two dimensional potential is then given by:

$$U(x,y,\sigma_x,\sigma_y) = \frac{ne}{4\pi\epsilon_0}\int_0^\infty \frac{\exp(-\frac{x^2}{2\sigma_x^2+q} - \frac{y^2}{2\sigma_y^2+q})}{\sqrt{(2\sigma_x^2+q)(2\sigma_y^2+q)}}dq$$

n is the line density of particles in the beam
e is the elementary charge
ε Is the permittivity of free space

From the potential we can derive the field

$$\vec{E} = -\nabla U(x,y,\sigma_x,\sigma_y)$$

Radial Force

In cylindrical coordinates

$$r^2 = x^2 + y^2$$

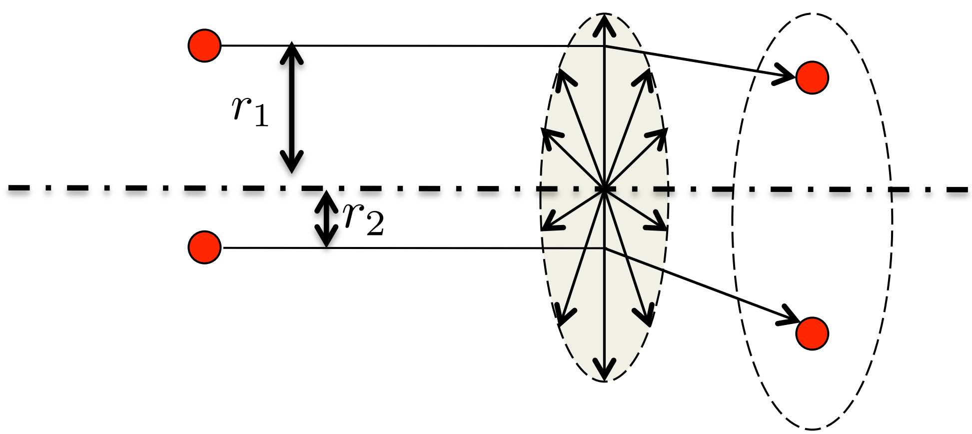
$$E_r = -\frac{ne}{4\pi\epsilon_0} \cdot \frac{\delta}{\delta r} \int_0^\infty \frac{\exp(-\frac{r^2}{(2\sigma^2+q)})}{(2\sigma^2+q)} dq$$

Radial component

$$B_\Phi = -\frac{ne\beta c\mu_0}{4\pi} \cdot \frac{\delta}{\delta r} \int_0^\infty \frac{\exp(-\frac{r^2}{(2\sigma^2+q)})}{(2\sigma^2+q)} dq$$

Azimuthal component

From Lorentz Force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$ **Force has a radial component**



Beam-Beam Force: round beams

For the case of q=-e opposite charges

In cylindrical Coordinates

$$r^2 = x^2 + y^2$$

$$F_r(r) = \frac{ne^2(1+\beta^2)}{2\pi\epsilon_0} \cdot \frac{1}{r} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

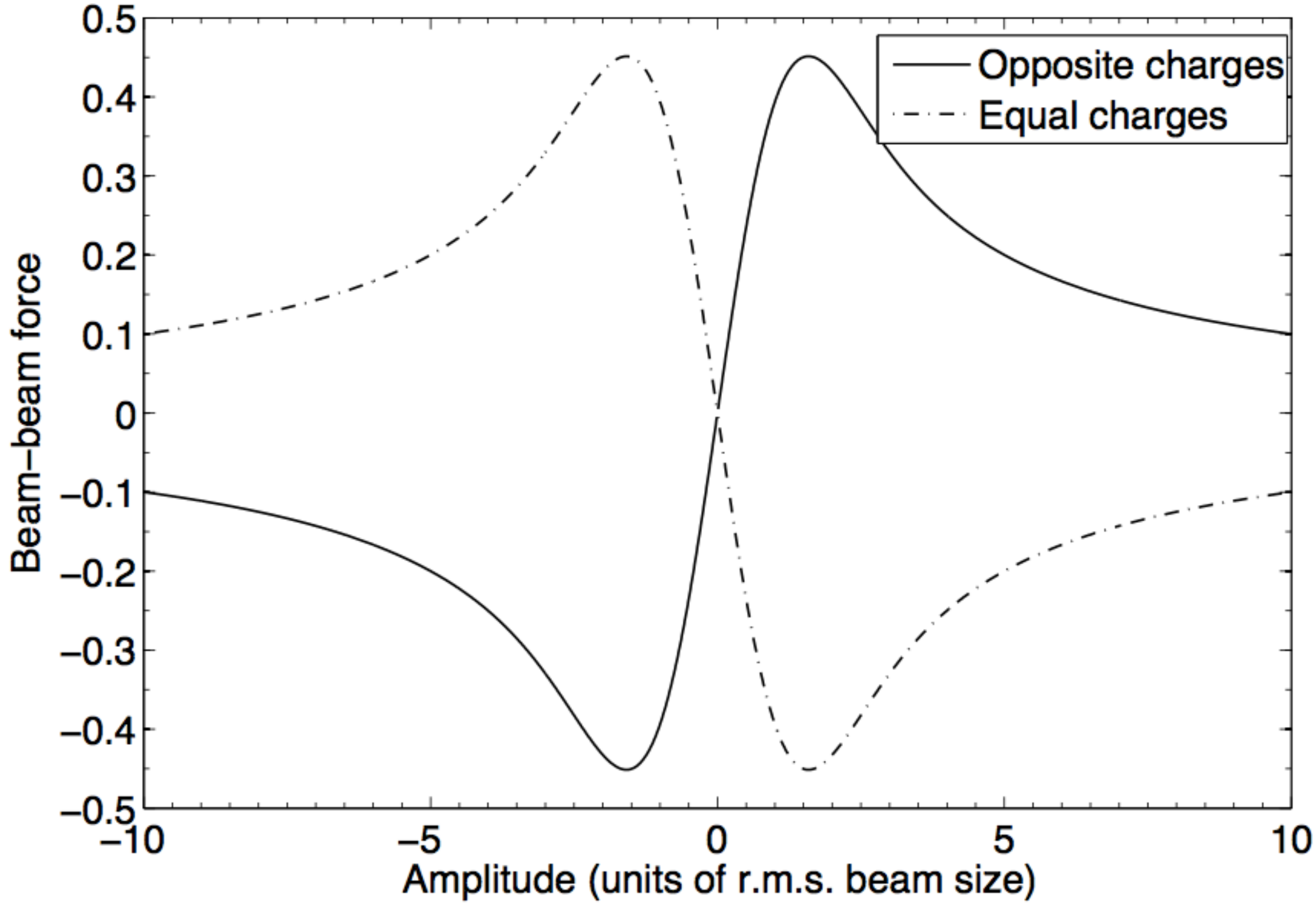
In Cartesian Coordinates:

$$F_x(r) = \frac{ne^2(1+\beta^2)}{2\pi\epsilon_0} \cdot \frac{x}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

$$F_y(r) = \frac{ne^2(1+\beta^2)}{2\pi\epsilon_0} \cdot \frac{y}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

Beam-Beam Force

If we normalize the separations in units of the beam transverse rms size:



$$F_r(r) = \pm \frac{ne^2(1+\beta_{rel}^2)}{2\pi\epsilon_0}\frac{1}{r}[1-\exp(-\frac{r^2}{2\sigma^2})]$$

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

Why do we care?

Pushing for luminosity means stronger beam-beam effects

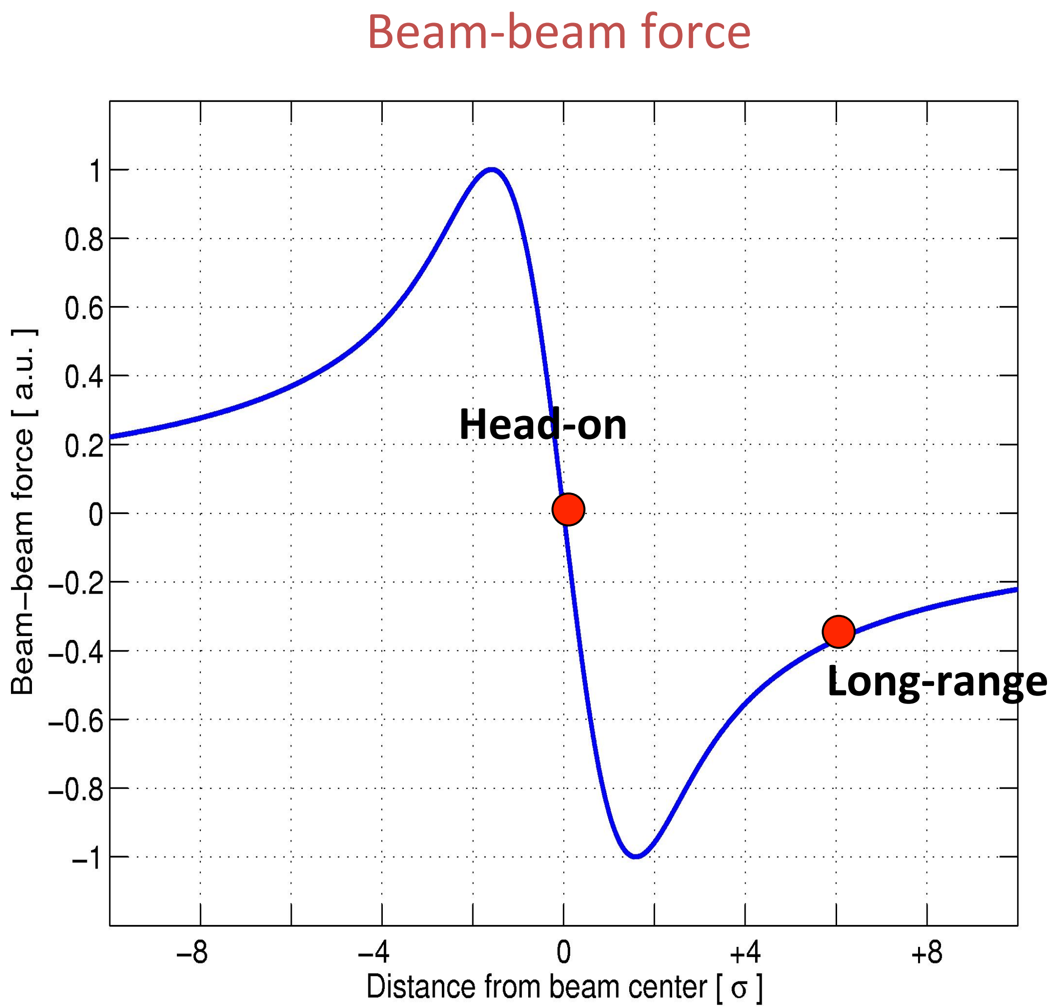
$$\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b$$

$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

Strongest non-linearity in a collider YOU CANNOT AVOID!

Physics fill lasts for many hours 10h – 24h

Head-on and Long-range interactions

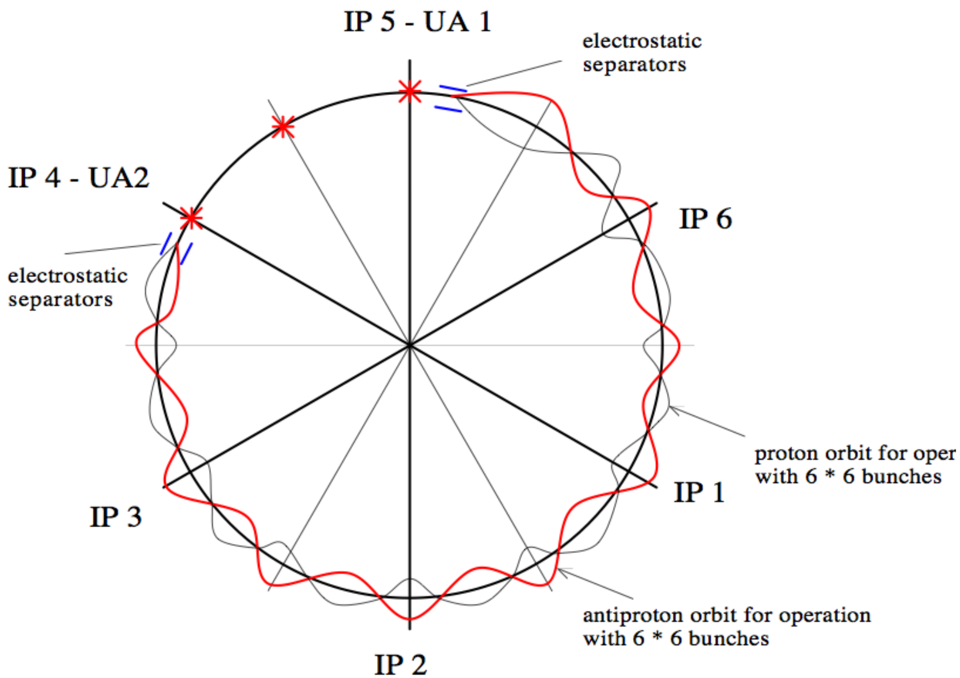


Other beam passing in the center force: HEAD-ON beam-beam interaction

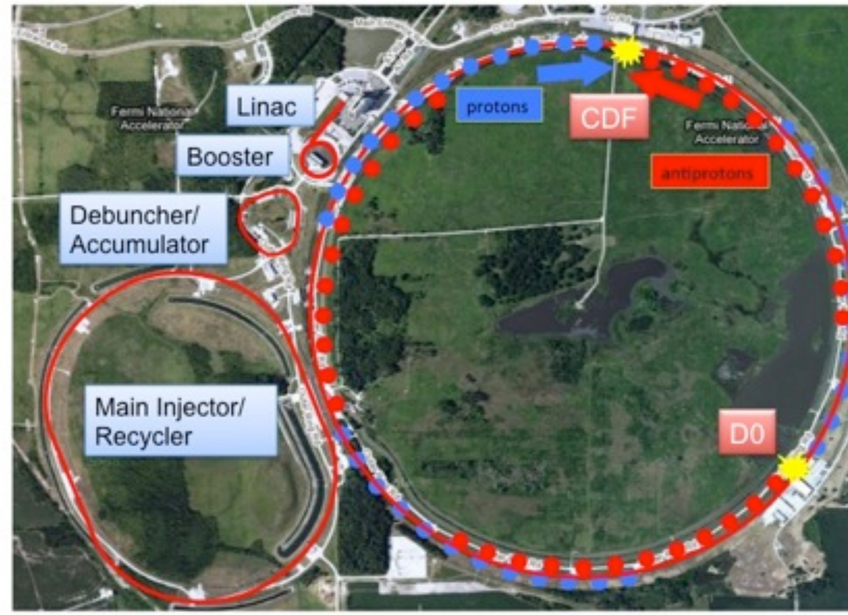
Other beam passing at an offset of the force: LONG-RANGE beam-beam interaction

Circular colliders HO and LR

SPS collider: 6 bunches
3 HO and 9 LR



$$L \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b \cdot f_{rev}$$



Tevatron: 36 bunches
2 BBIs Head-on and 72 Long-range

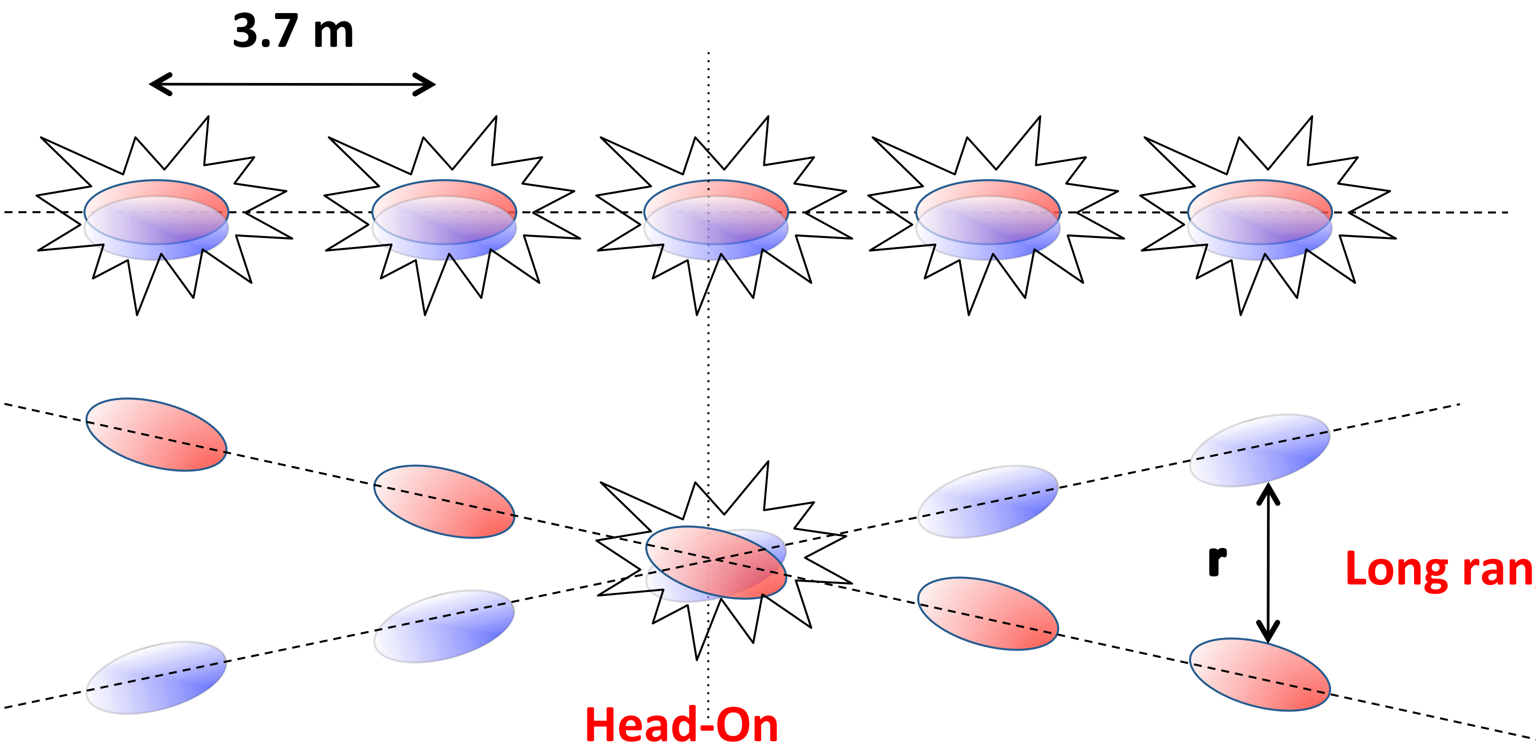
RHIC: 110 bunches
2 BBIs Head-on

Multiple bunch Complications

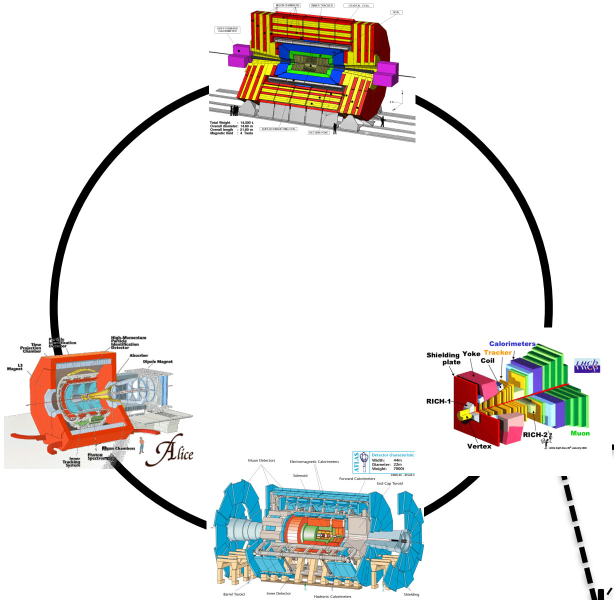
MANY INTERACTIONS

$$\boxed{\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b}$$

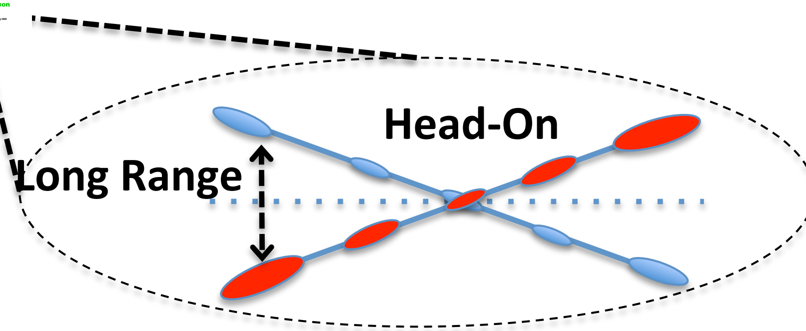
Num. of bunches : $n_b = 2808$



LHC, KEKB... colliders



- Crossing angle operation
- High number of bunches in train structures



72 bunches

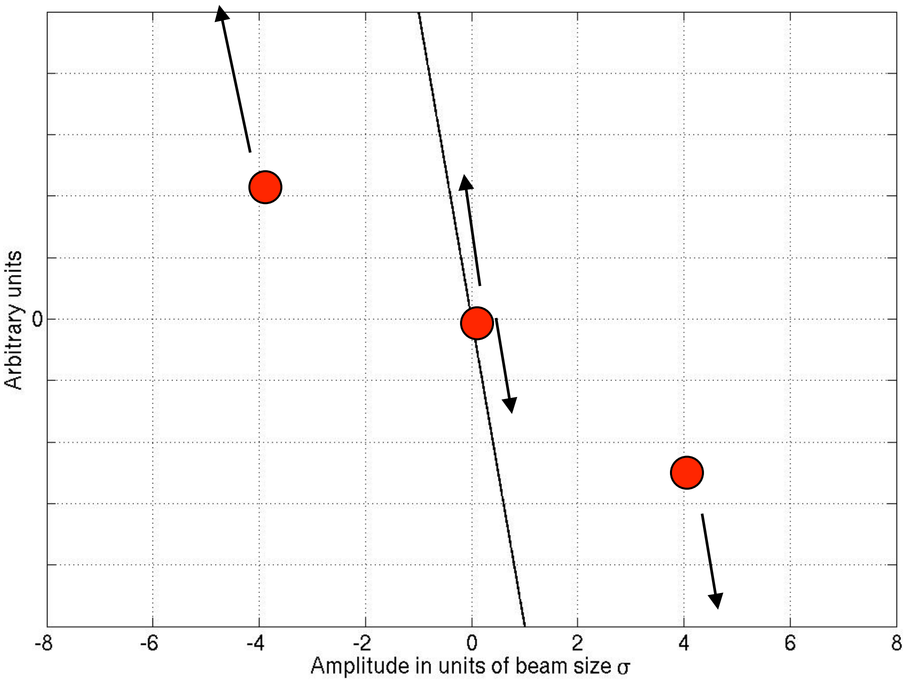
	SppS	Tevatron	RHIC	LHC
Number Bunches	6	36	109	2808
LR interactions	9	70	0	120/40
Head-on interactions	3	2	2	4

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

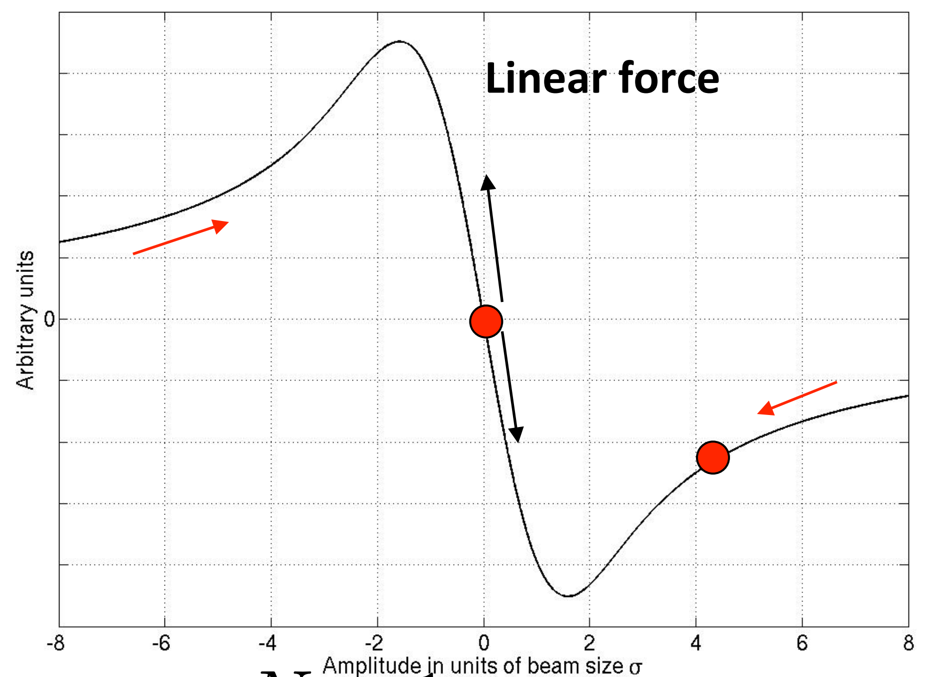
Beam-Beam Force: single particle head-on collision

Lattice defocusing quadrupole



$$F = -k \cdot r$$

Beam-beam force



$$\mathrm{F} \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - \mathrm{e}^{-\frac{r^2}{2\sigma^2}}\right]$$

For small amplitudes: linear force

For large amplitude: very non-linear

The beam will act as a strong non-linear electromagnetic lens!

Beam-Beam transverse kick

Gaussian distribution for charges $\sigma_x = \sigma_y = \sigma$

Round beams:

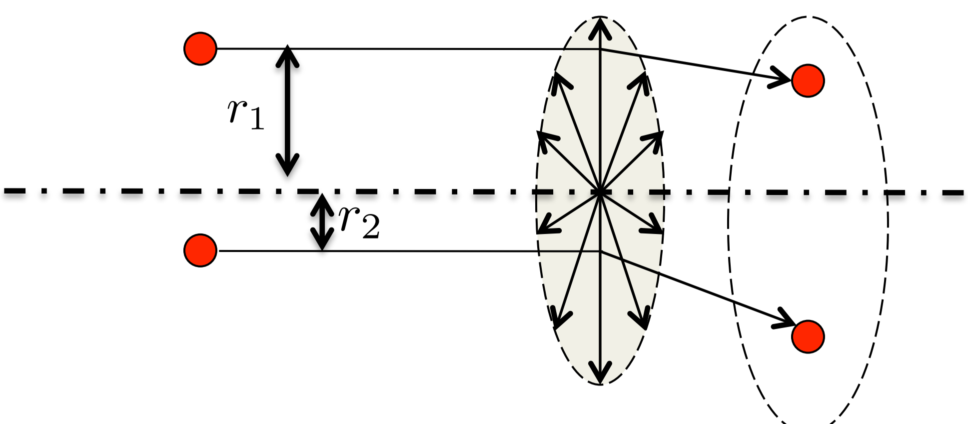
Very relativistic, Force has only radial component : $\beta \approx 1$ $r^2 = x^2 + y^2$

$$F_r(r,s,t) = \frac{Ne^2(1+\beta^2)}{\sqrt{(2\pi)^3}\epsilon_0\sigma_s} \cdot \frac{1}{r} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right] \cdot \left[\exp(-\frac{(s+vt)^2}{2\sigma_s^2})\right]$$

Radial deflection on single particle at r from the center of opposite beams

$$\Delta r' = \frac{1}{mc\beta\gamma} \int F_r(r,s,t)\ dt$$

$$\Delta r' = -\frac{N_p r_0}{r} \cdot \frac{r}{r^2}[1 - e^{-\frac{r^2}{2\sigma^2}}]$$

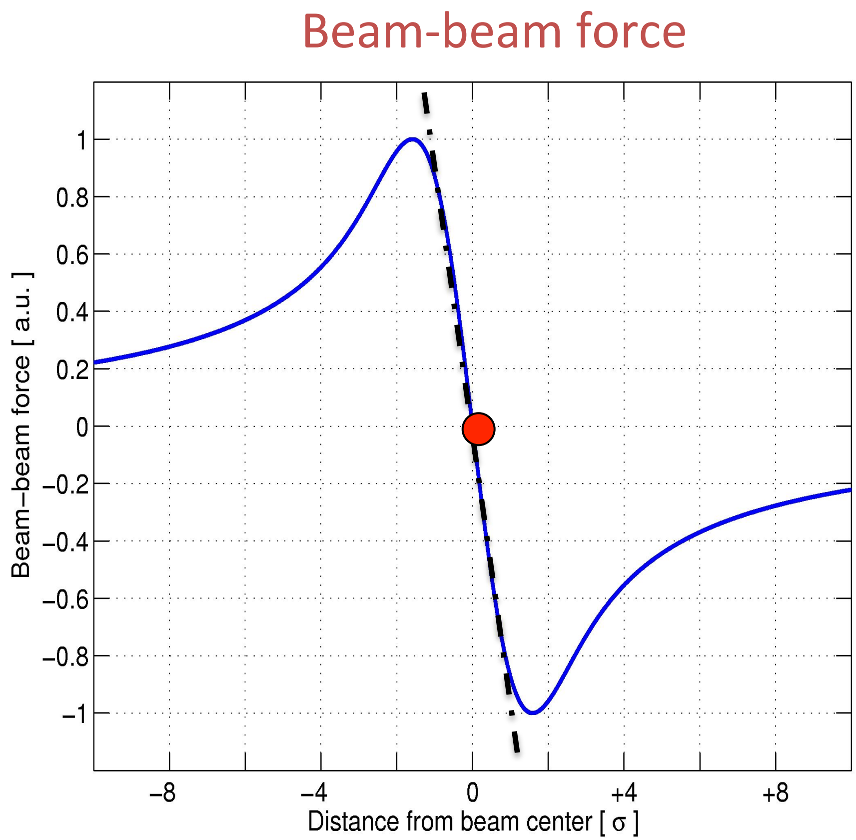


Beam-beam kick obtained integrating the force over the collision (i.e. time of passage)

Only radial component in relativistic case

Can we quantify the beam-beam strenght?

Quantifies the strength of the force but does NOT reflect the nonlinear nature of the force



For small amplitudes: linear force

$$F \propto -\xi \cdot r$$

The slope of the force gives you the beam-beam parameter ξ

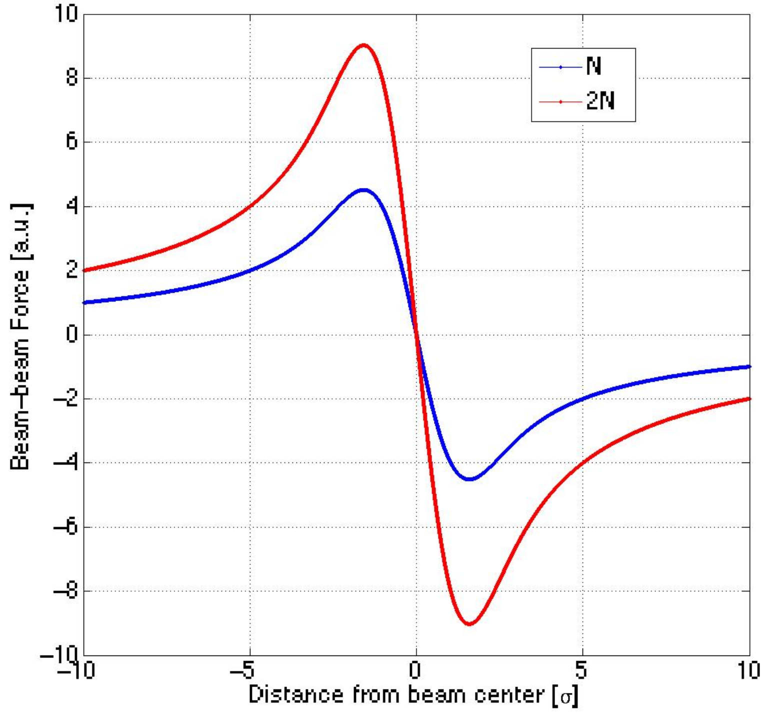
Beam-Beam Parameter

For small amplitudes: linear force

$$\Delta r' = -\frac{N_p r_0}{r} \cdot \frac{r}{r^2} \cdot \left[1 - \mathrm{e}^{-\frac{r^2}{2\sigma^2}}\right]$$

$$\Delta r' = \frac{2N_p r_0}{\gamma} \cdot \frac{1}{r} \cdot \left[1 - \left(1 - \frac{r^2}{2\sigma^2} + \ldots\right)\right]$$

$$\Delta r'|_{r\to 0} = \frac{N r_0 r}{\gamma\sigma^2} = +f \cdot r$$



$$\xi = \frac{\beta^*}{4\pi} \cdot \frac{\delta(\Delta r')}{\delta r} = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

Beam-Beam parameter:

For round beams:

$$\xi = \frac{\beta^*}{4\pi} \cdot \frac{\delta(\Delta r')}{\delta r} = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

For non-round beams:

$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

Examples:

Parameters	LEP (e^+e^-)	LHC(pp)
Intensity $N_{p,e}$/bunch	$4\ 10^{11}$	$1.15\ 10^{11}$
Energy GeV	100	7000
Beam size H	160-200 μm	16.6 μm
Beam size V	2-4 μm	16.6 μm
$\beta_{x,y}$* m	1.25-0.05	0.55-0.55
Crossing angle μrad	0	285
ξ_{bb}	**0.07**	**0.0037**

Beam-Beam parameter:

For round beams:

$$\xi = \frac{\beta^*}{4\pi} \cdot \frac{\delta(\Delta r')}{\delta r} = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

For non-round beams:

$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

Examples:

Parameters	LEP (e^+e^-)	LHC(pp)
Intensity $N_{p,e}$/bunch	$4\ 10^{11}$	$1.15\ 10^{11}$
Energy GeV	100	7000
Beam size H	160-200 μm	16.6 μm
Beam size V	2-4 μm	16.6 μm
$\beta_{x,y}^*$ m	1.25-0.05	0.55-0.55
Crossing angle μrad	0	285
ξ_{bb}	**0.07**	**0.0037**

LHC 2012
$1.7\ 10^{11}$
7000
18 μm
18 μm
0.6-0.6
290
0.009

Linear Tune shift due to head-on collision

For small amplitude particles beam-beam can be approximated as linear force as a quadrupole

$$F \propto -\xi \cdot r$$

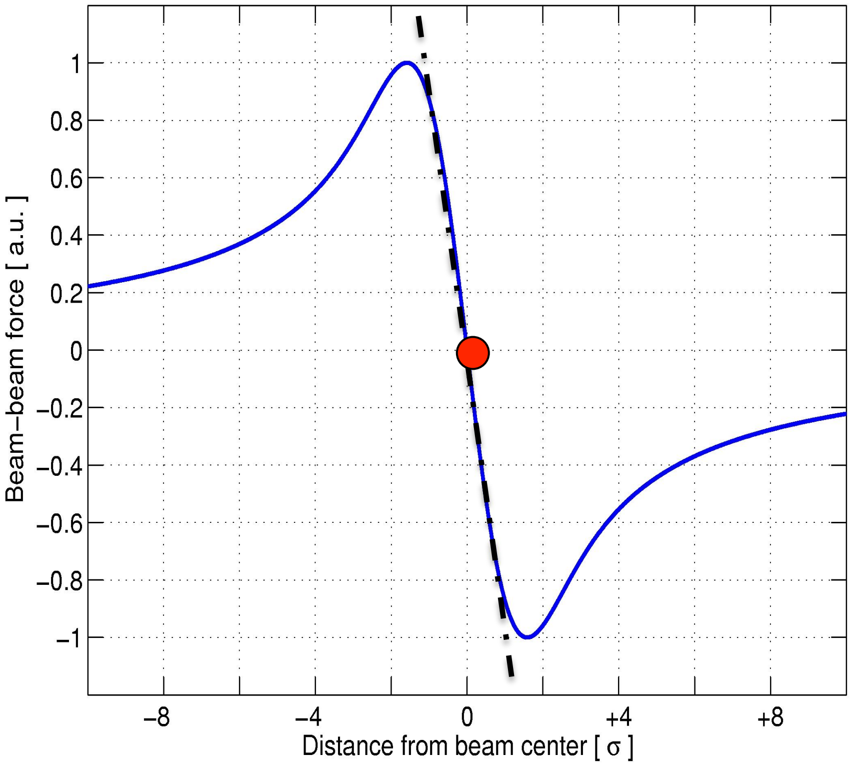
Focal length is given by the beam-beam parameter:

$$\frac{1}{f} = \frac{\Delta x'}{x} = \frac{N r_0}{\gamma \sigma^2} = \frac{\xi \cdot 4\pi}{\beta^*}$$

Beam-beam matrix:

$$\begin{pmatrix} 1 & 0 \\ -\frac{\xi \cdot 4\pi}{\beta^*} & 1 \end{pmatrix}$$

Beam-beam force



Equivalent to tune shift

Perturbed one turn matrix

For small amplitudes beam-beam can be approximated as linear force as a quadrupole

$$F \propto -\xi \cdot r$$

Focal length:

$$\frac{1}{f} = \frac{\Delta x'}{x} = \frac{N r_0}{\gamma \sigma^2} = \frac{\xi \cdot 4\pi}{\beta^*}$$

Beam-beam matrix:

$$\begin{pmatrix} 1 & 0 \\ -\frac{\xi \cdot 4\pi}{\beta^*} & 1 \end{pmatrix}$$

Perturbed one turn matrix with perturbed tune ΔQ and beta function at the IP β*:

$$\begin{pmatrix} cos(2\pi(Q+\Delta Q)) & \beta^* sin(2\pi(Q+\Delta Q)) \\ -\frac{1}{\beta^*} sin(2\pi(Q+\Delta Q)) & cos(2\pi(Q+\Delta Q)) \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix} \cdot \begin{pmatrix} cos(2\pi Q) & \beta_0^* sin(2\pi Q) \\ -\frac{1}{\beta_0^*} sin(2\pi Q) & cos(2\pi Q) \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix}$$

Tune shift and dynamic beta

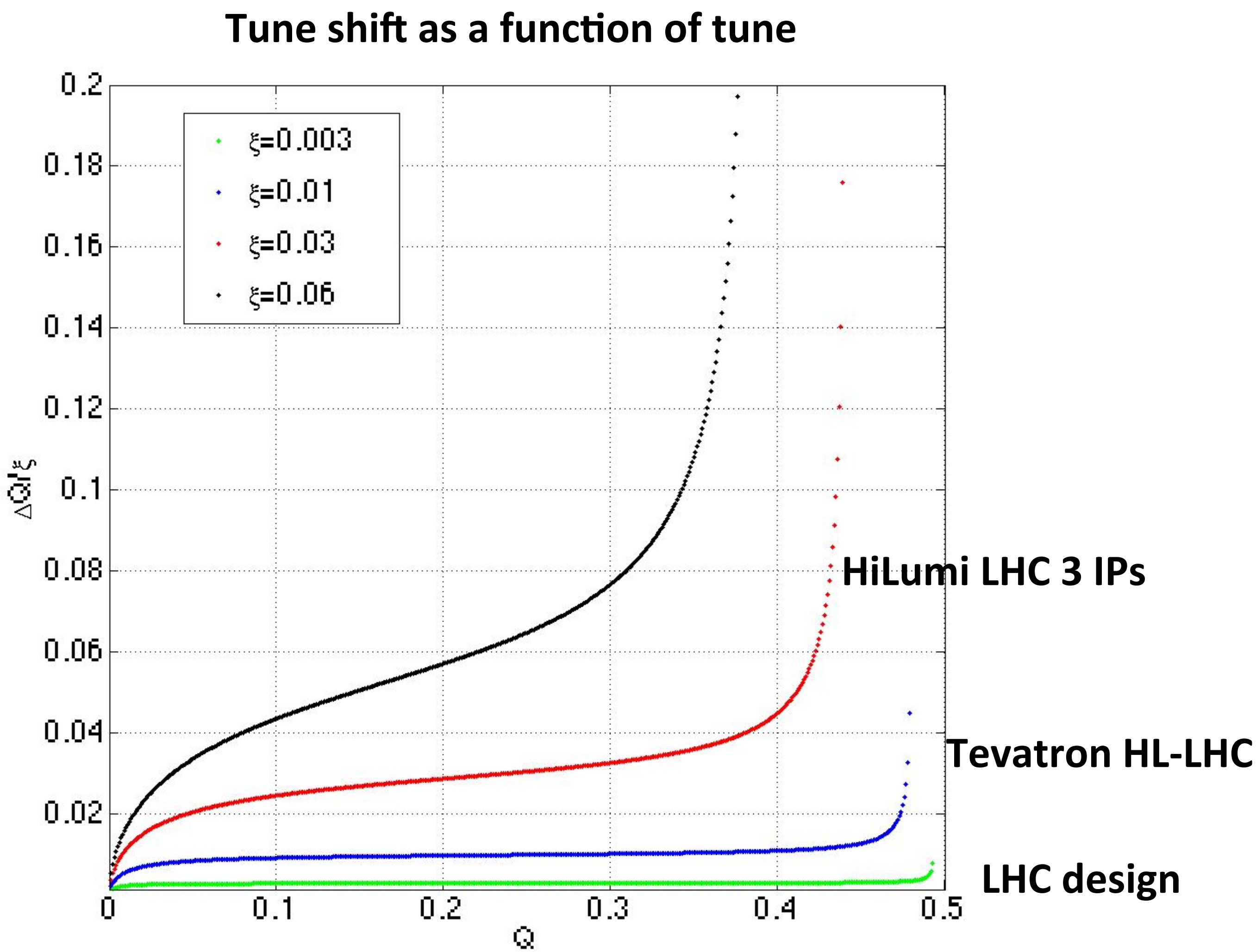
Solving the one turn matrix one can derive the tune shift ΔQ and the perturbed beta function at the IP β*:

Tune is changed

$$cos(2\pi(Q + \Delta Q)) = cos(2\pi Q) - \frac{\beta_0^* \cdot 4\pi\xi}{\beta*} sin(2\pi Q)$$

...how does the tune changes?

Tune shift due to beam-beam interactions

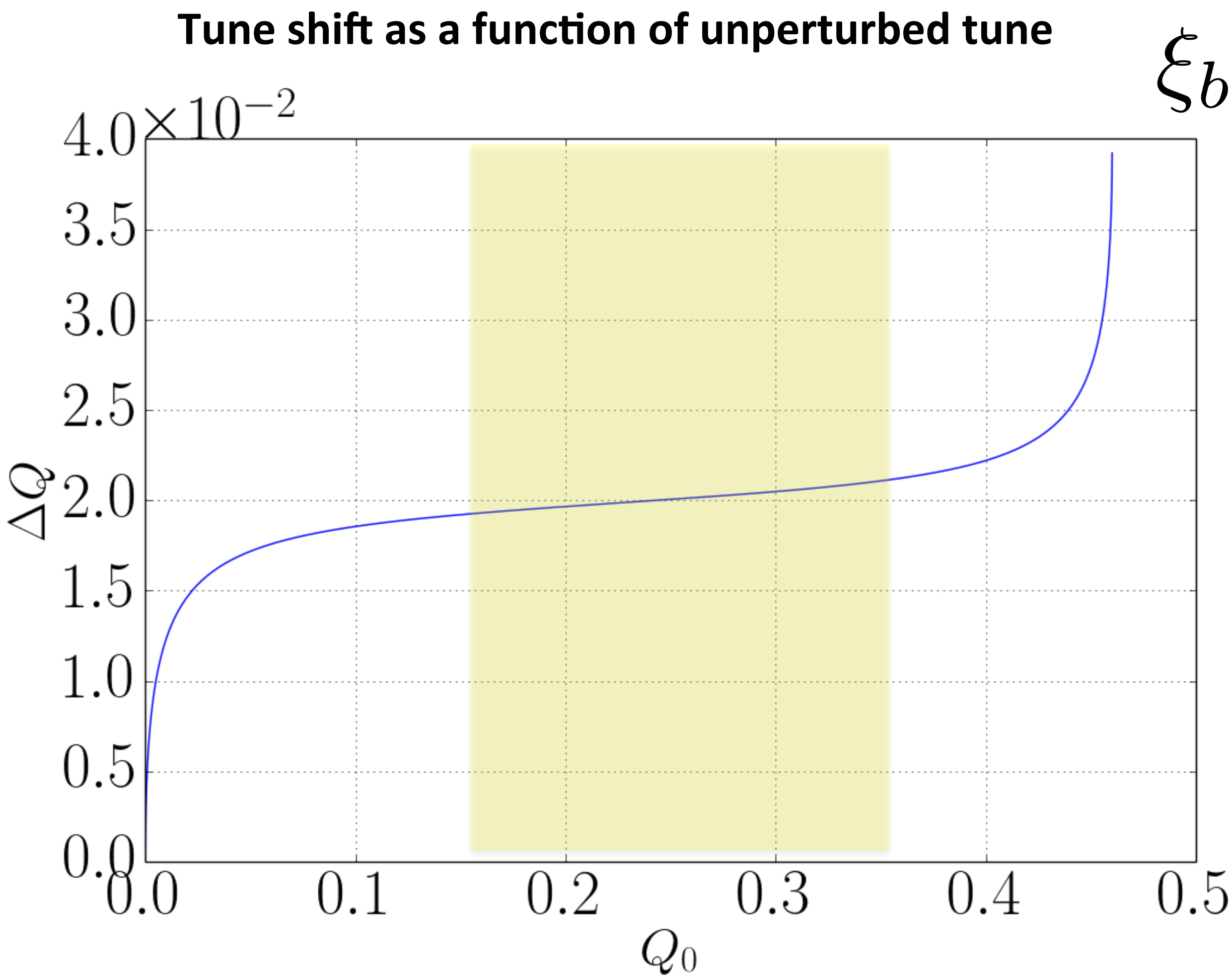


Larger ξ → Strongest variation with Q

Effects of multiple Interaction Points does not add linearly (phase advance between IP..)

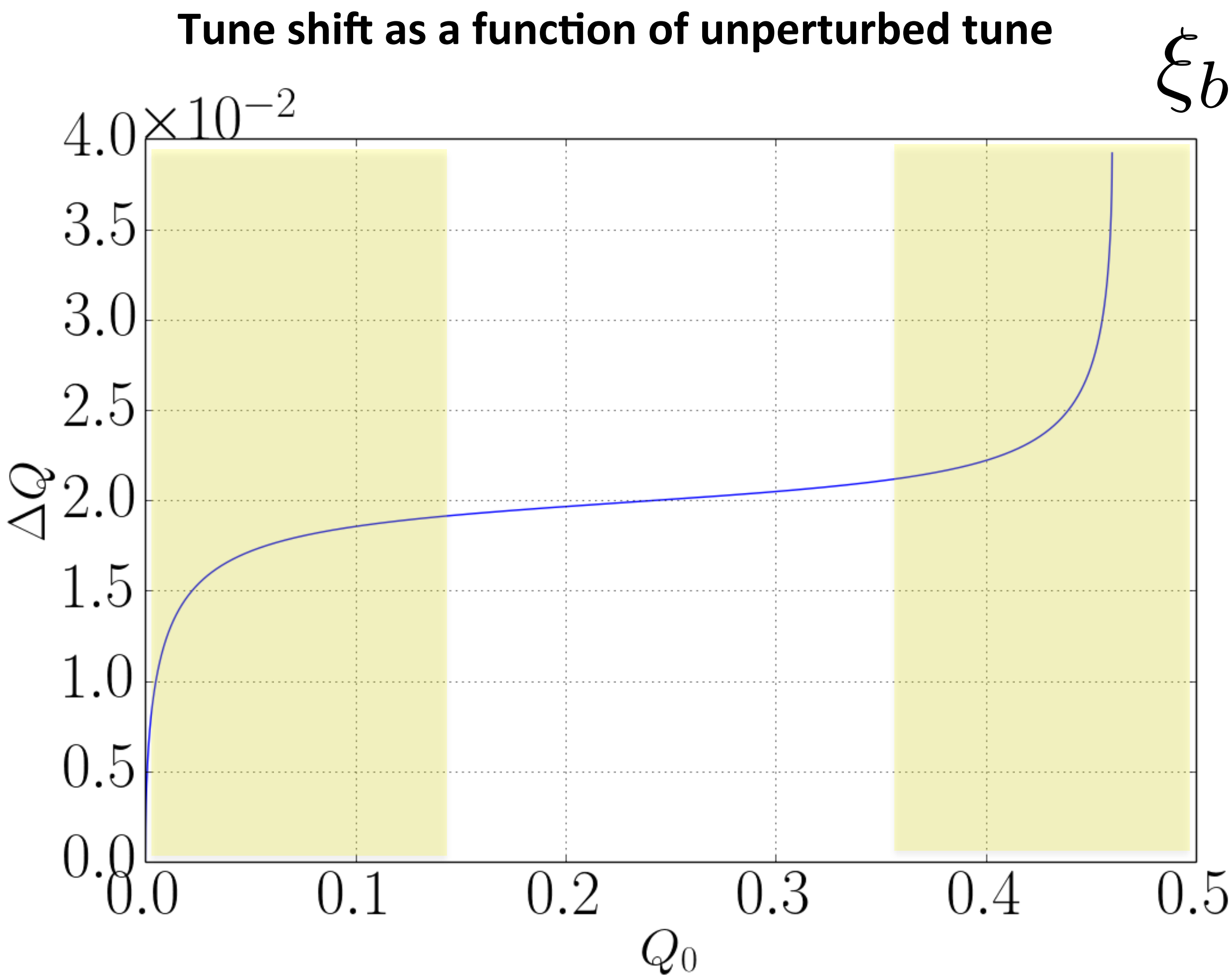
Tune shift due to beam-beam interactions

$$\xi_{bb} = 0.02$$



$$\Delta Q \approx \xi_{bb}$$

Tune shift due to beam-beam interactions

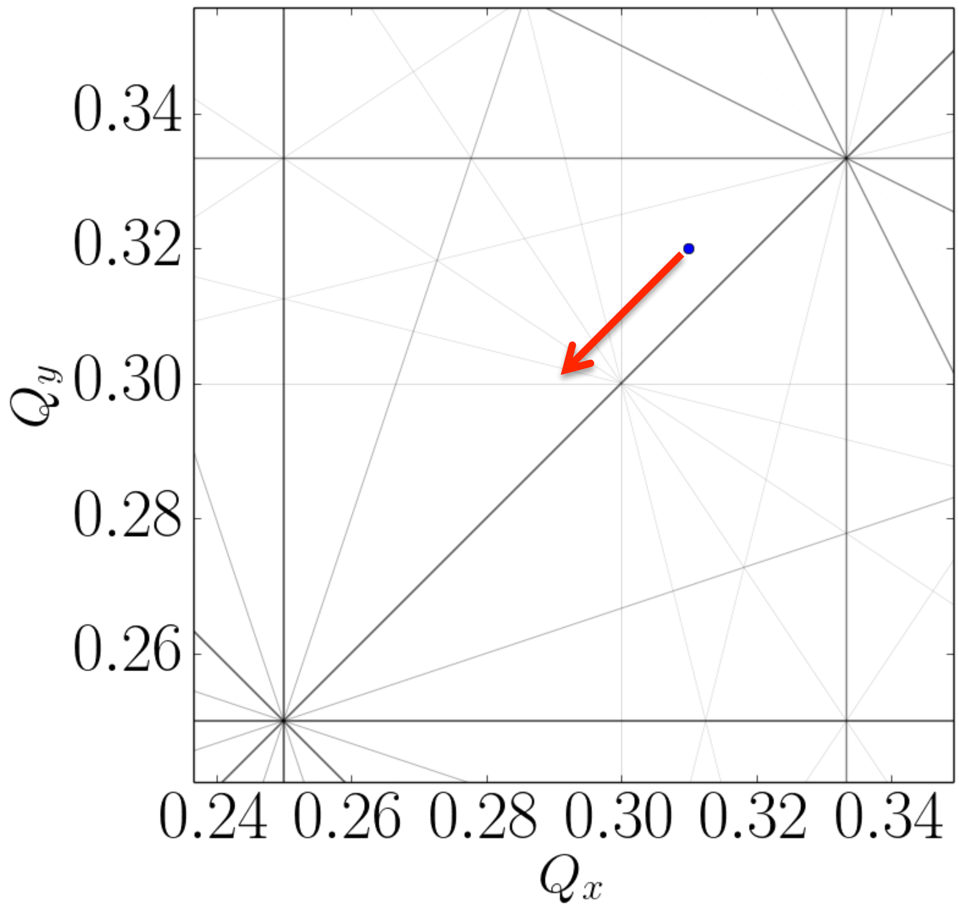


$$\xi_{bb} = 0.02$$

$$\Delta Q \neq \xi_{bb}$$

Linear head-on Tune shift

Tune shift in 2 dimensional case equally charged beams and tunes far from integer and half



$$\xi_{bb} = 0.02$$

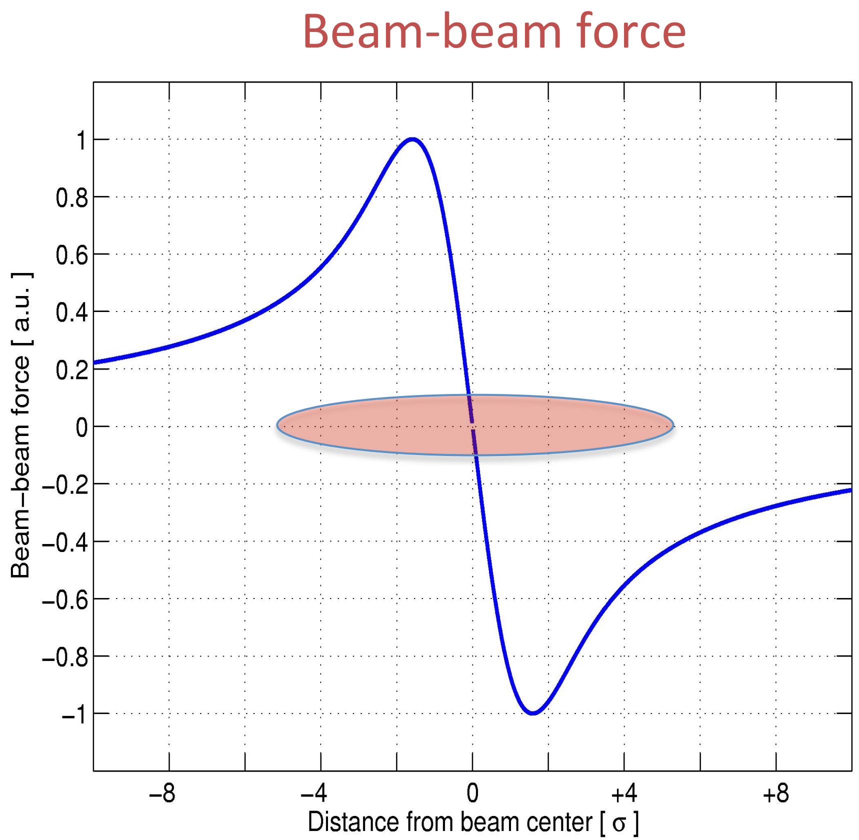
Zero amplitude particle will fill an extra defocusing term

$$\Delta Q \approx \xi_{bb}$$

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

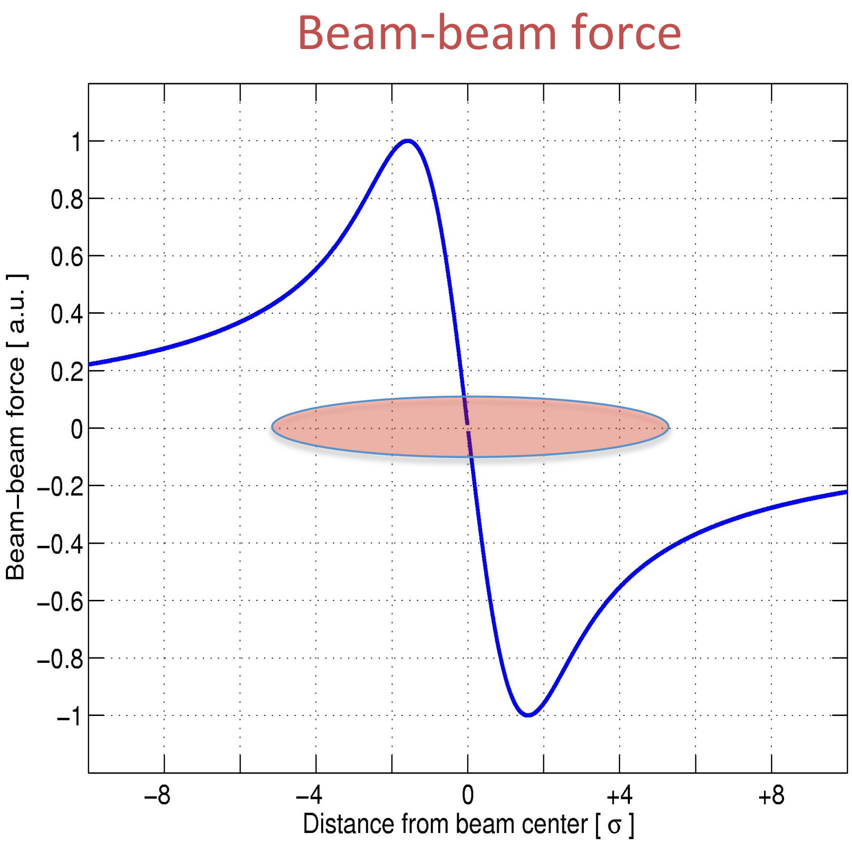
A beam is a collection of particles



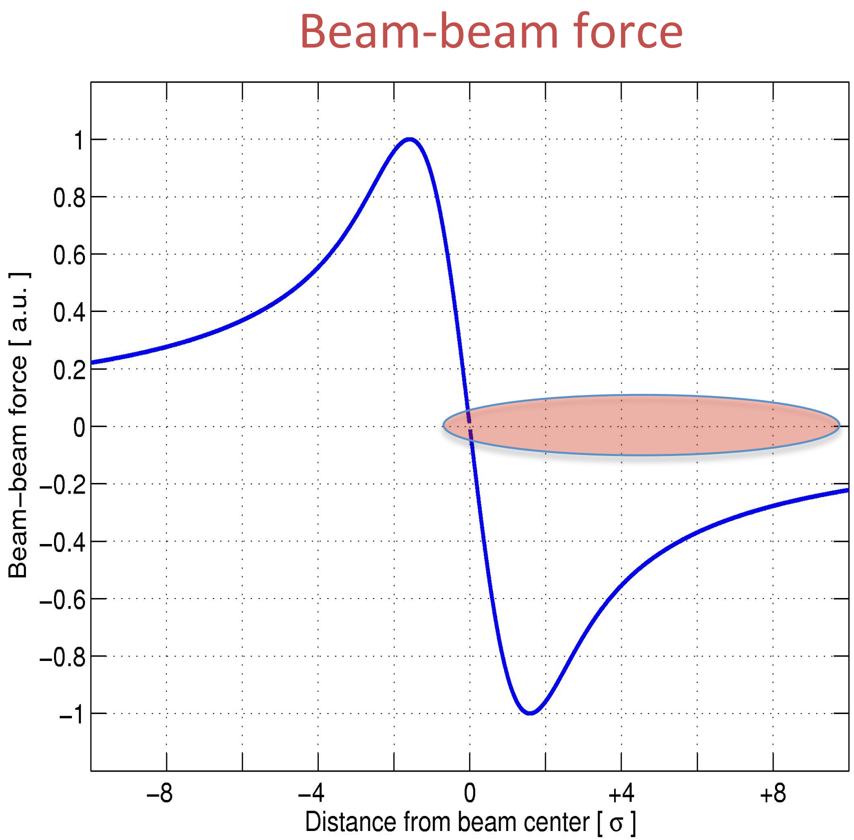
Beam 2 passing in the center of force produce by Beam 1
Particles of Beam 2 will experience different ranges of the beam-beam forces

Tune shift as a function of amplitude (detuning with amplitude or tune spread)

A beam will experience all the force range



Second beam passing in the center
HEAD-ON beam-beam interaction



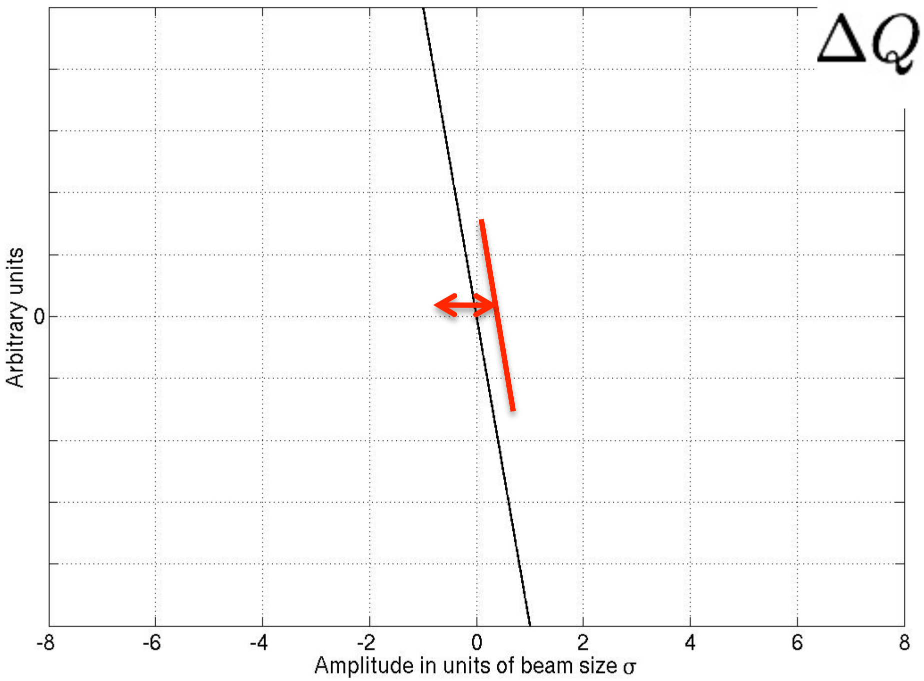
Second beam displaced offset
LONG-RANGE beam-beam interaction

Different particles will see different force

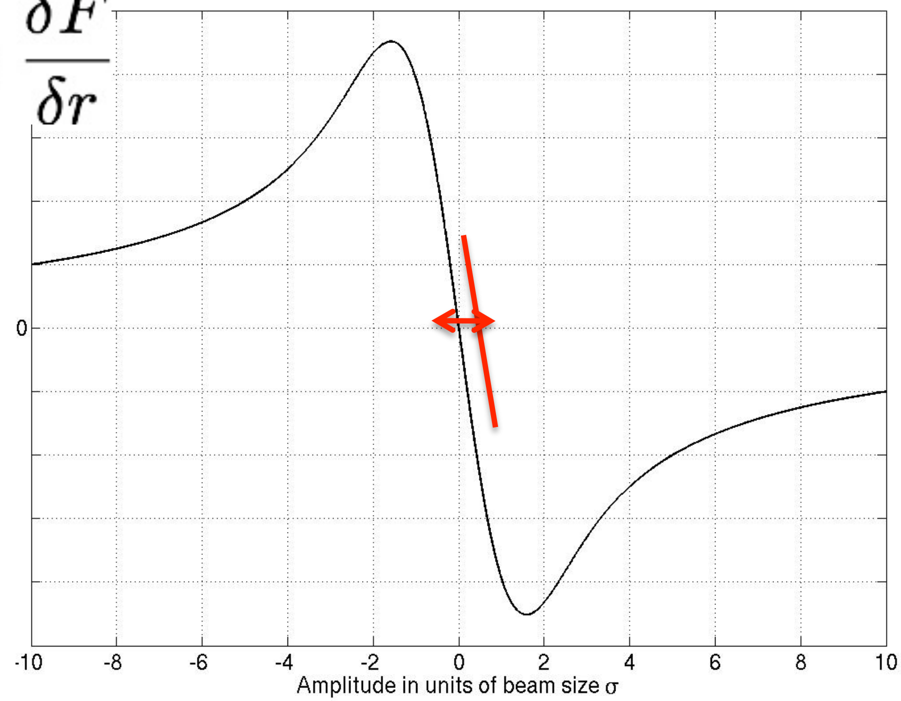
Detuning with Amplitude for head-on

Instantaneous tune shift of test particle when it crosses the other beam is related to the derivative of the force with respect to the amplitude

$$\Delta Q \propto \frac{\delta F}{\delta r}$$



$$\Delta Q_{quad} = const$$



$$\Delta Q_{bb} \approx const$$

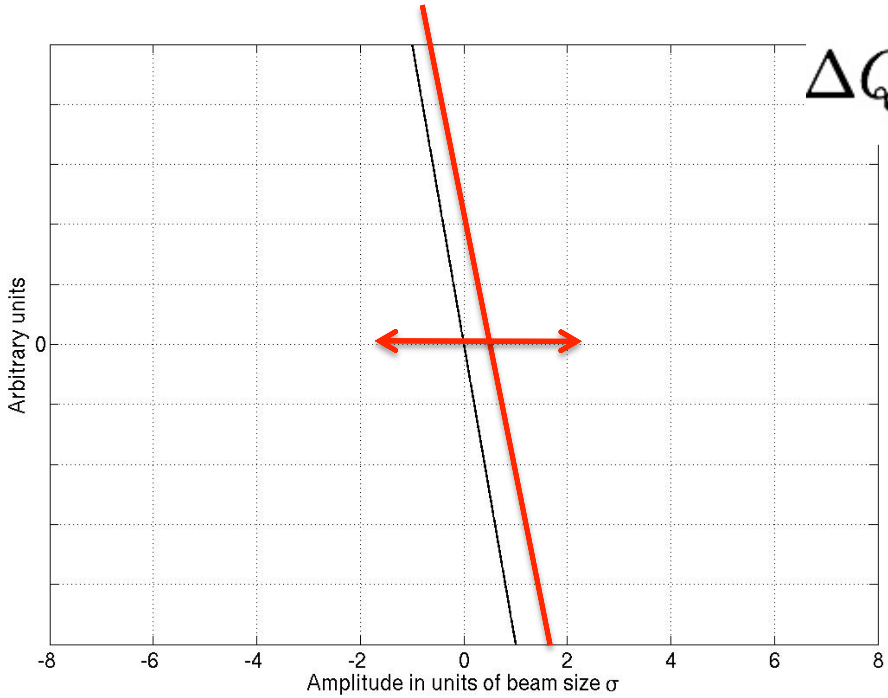
For small amplitude test particle linear tune shift

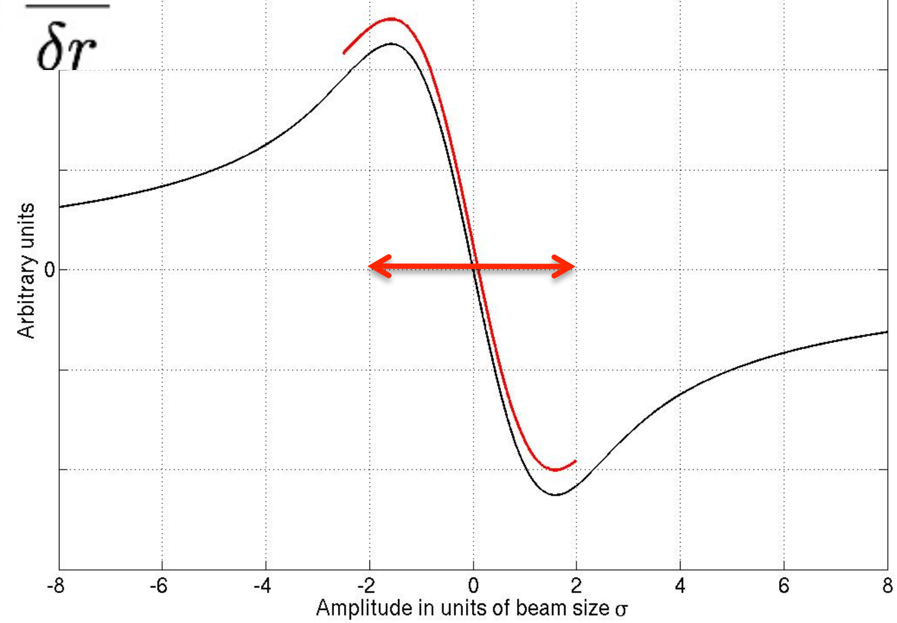
$$\lim_{r \to 0} \Delta Q(r) = -\frac{N r_0 \beta^*}{4\pi\gamma\sigma^2} = \xi$$

Detuning with Amplitude for head-on

Beam with many particles this results in a tune spread

$$\Delta Q \propto \frac{\delta F}{\delta r}$$





$$\Delta Q_{quad} = const \qquad \Delta Q_{bb} \neq const$$

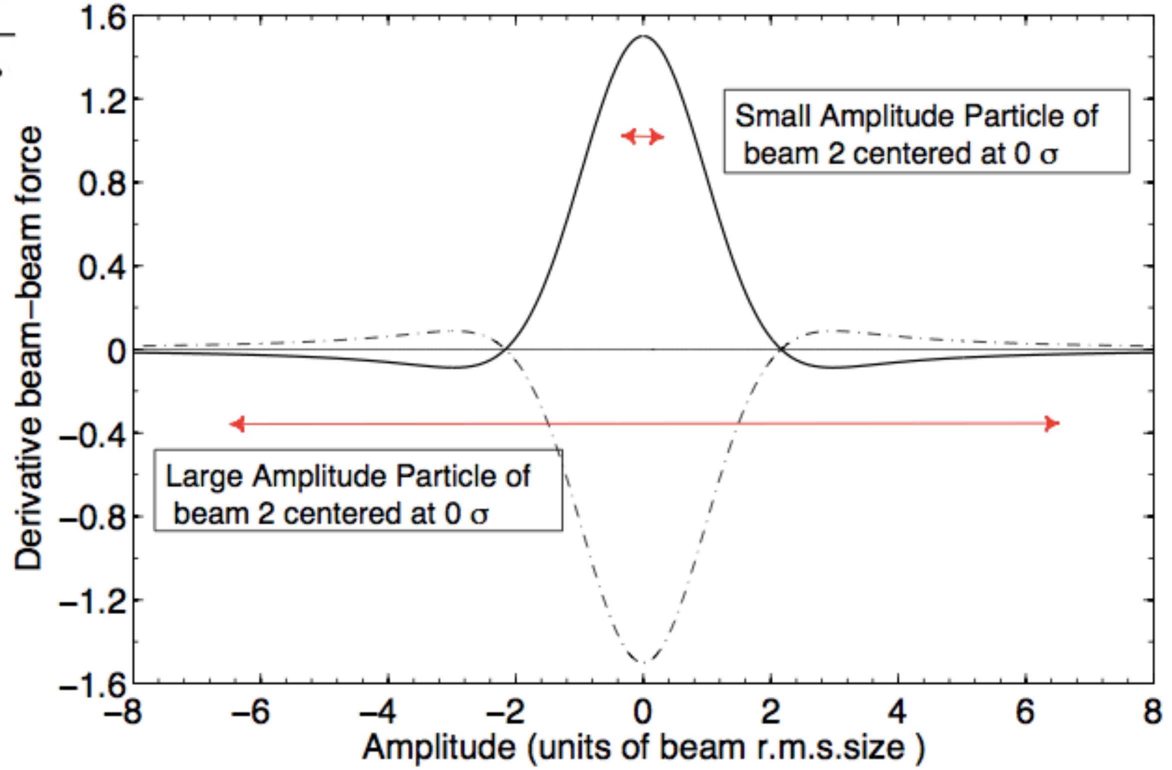
$$\Delta Q(x) = \frac{N r_0 \beta}{4\pi\gamma\sigma^2} \cdot \frac{1}{(\frac{x}{2})^2} \cdot (\exp - (\frac{x}{2})^2 I_0 (\frac{x}{2})^2 - 1)$$

Mathematical derivation in Ref [3] using Hamiltonian formalism and in Ref [4] using Lie Algebra

Head-on detuning with amplitude

1-D plot of detuning with amplitude for opposite and equally charged beams

$$\Delta Q \propto \frac{\delta F}{\delta r}$$

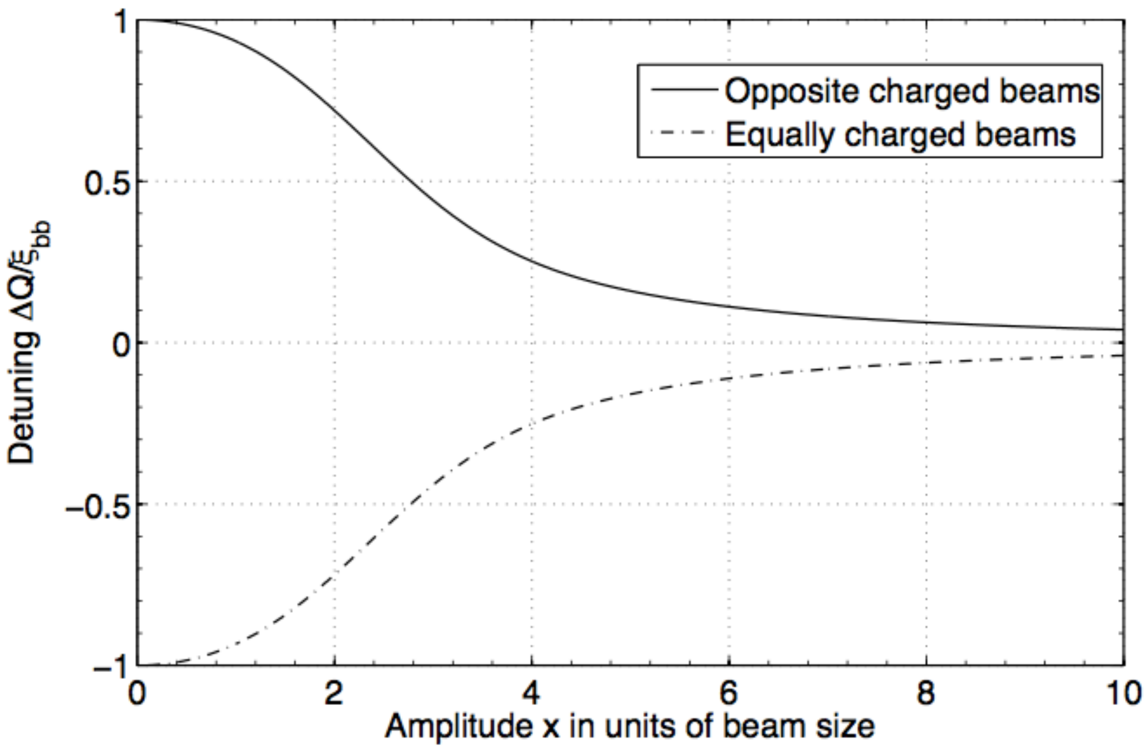


Maximum tune shift for small amplitude particles
Zero tune shift for very large amplitude particles

And in the other plane? THE SAME DERIVATION

Head-on detuning with amplitude

1-D plot of detuning with amplitude for opposite and equally charged beams

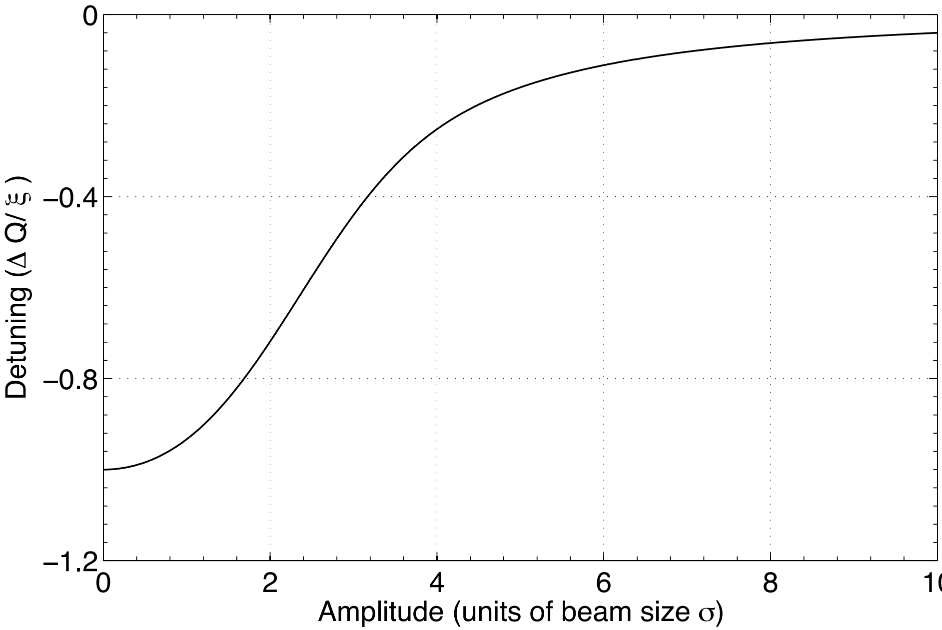


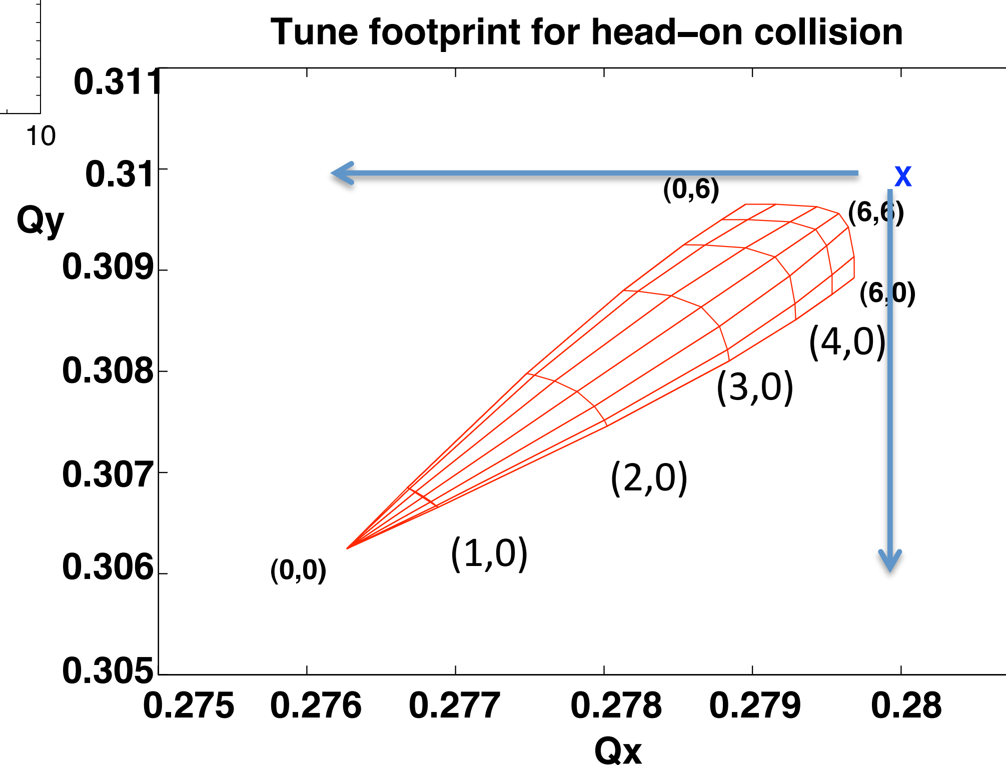
Maximum tune shift for small amplitude particles
Zero tune shift for very large amplitude particles

And in the other plane? THE SAME DERIVATION

Head-on detuning with amplitude and footprints

1-D plot of detuning with amplitude



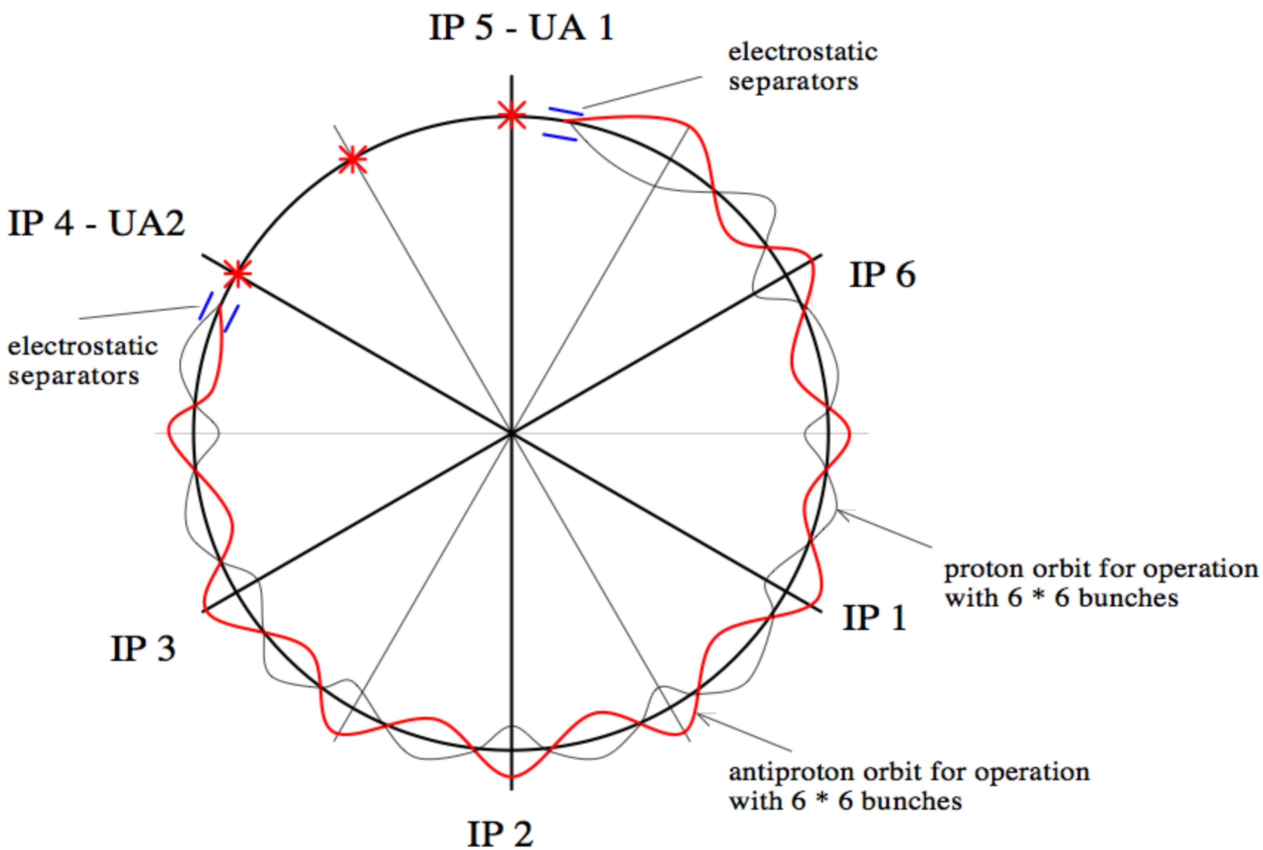


FOOTPRINT

2-D mapping of the detuning with amplitude of particles

Circular colliders Long-Range interactions

SPS collider: 6 bunches
3 Head-On and 9 Long Range



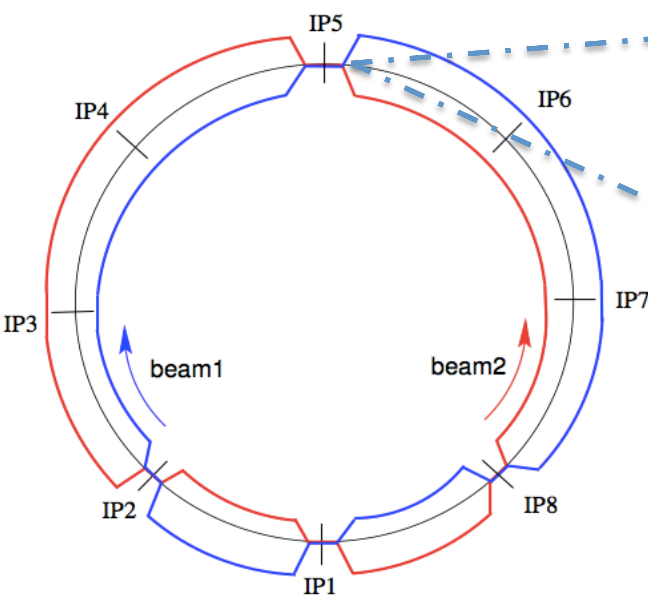
Several distributed long range interactions
Need global separation along circumference

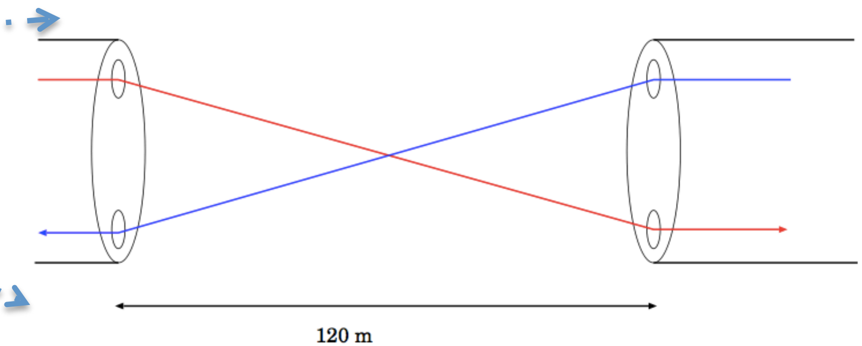
Tevatron: 36 bunches
2 BBIs Head-on and 72 Long-range

Circular colliders Long-Range interactions crossing angle schemes

LHC collider: 2808 bunches

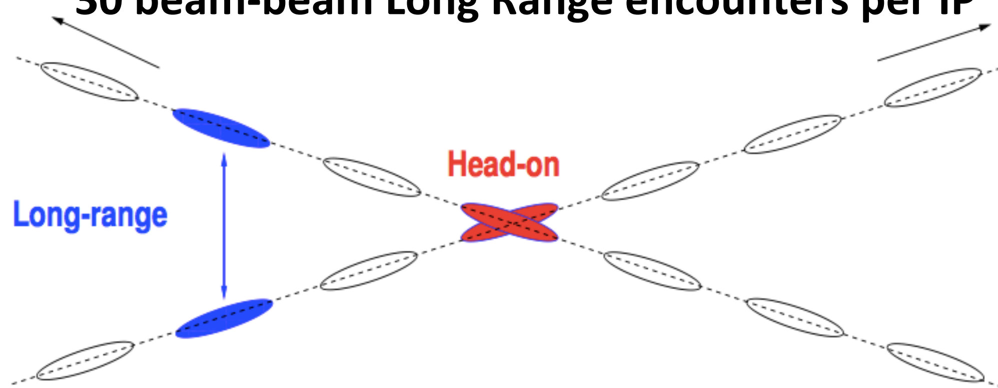
4 Head-On and 120 Long-Range Interactions localized





25 ns bunch spacing → beams will meet every 3.75 m

30 beam-beam Long Range encounters per IP



Separation is typically 6-12 σ

Several localized long range interactions 120

Need local separation (crossing angle)

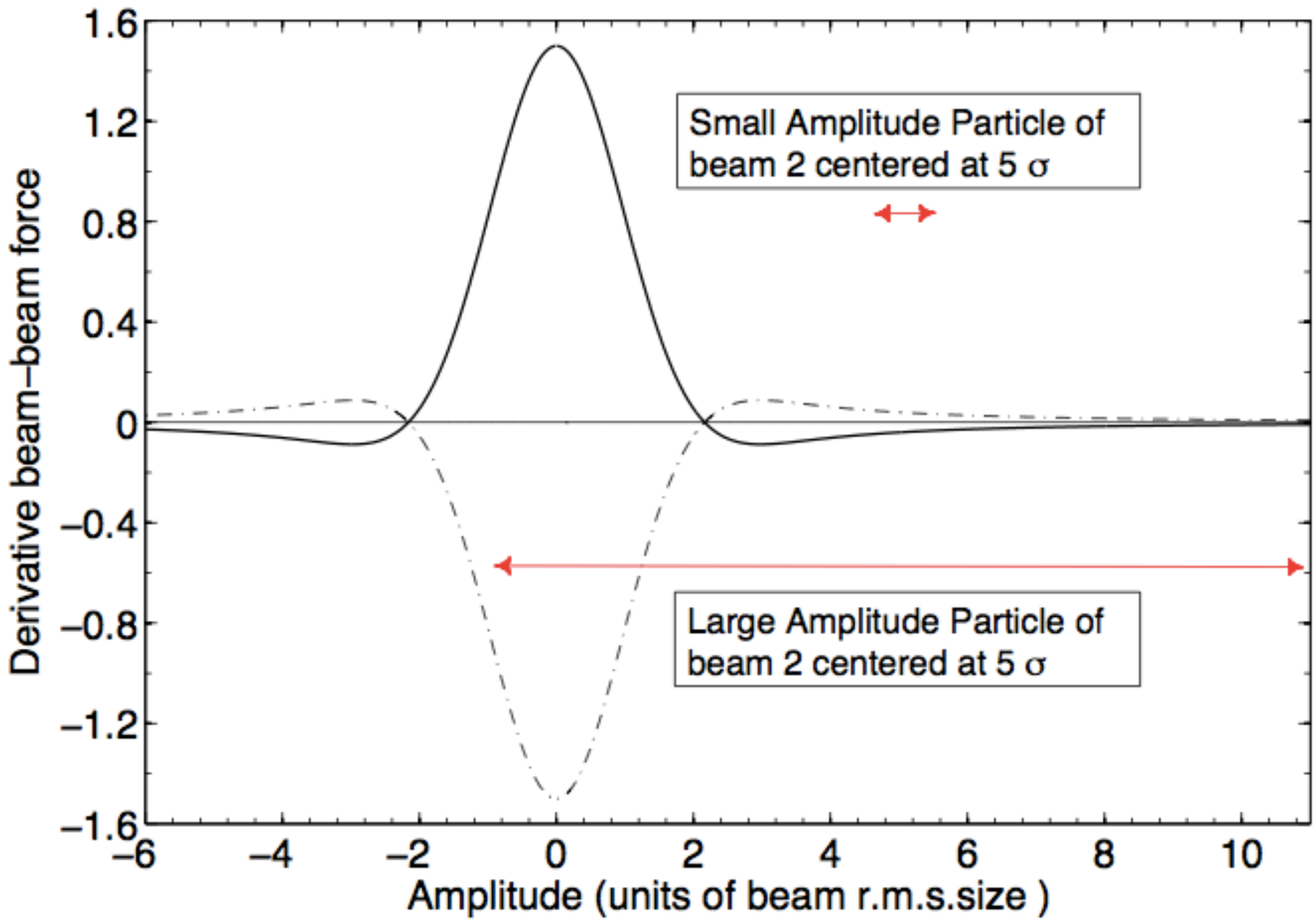
Two horizontal and Two vertical crossing angles

Why do we care?

- Tune shift has opposite sign in plane of separation
- Break the symmetry between the planes, much more resonances are excited
- Mostly affect particles at large amplitude
- Cause effects on closed orbit, tune shift, chromaticity…
- PACMAN effects complicates the picture

Long Range detuning with amplitude

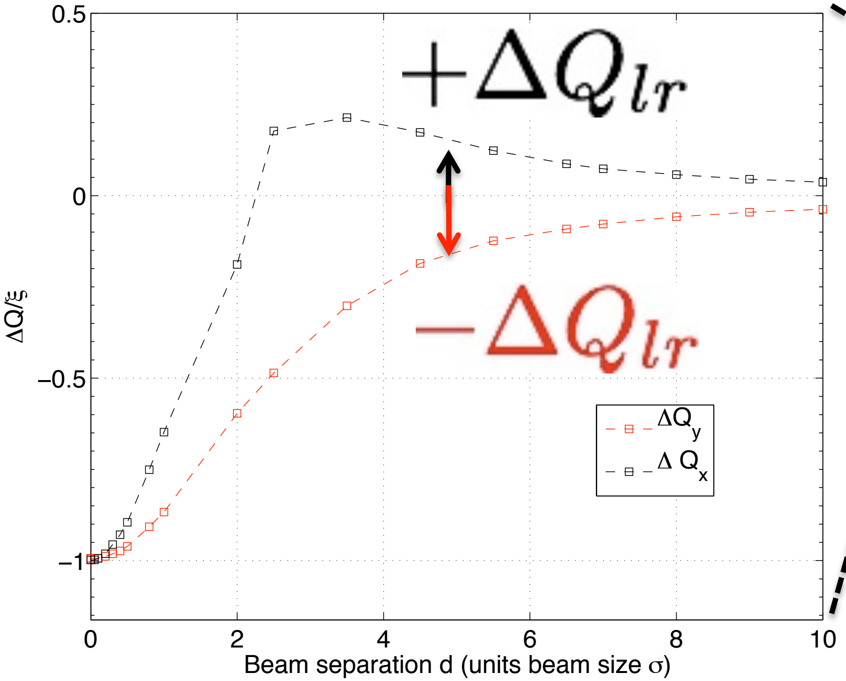
1-D plot of detuning with amplitude for opposite and equally charged beams



Maximum tune shift for large amplitude particles

Smaller tune shift detuning for zero amplitude particles and opposite sign

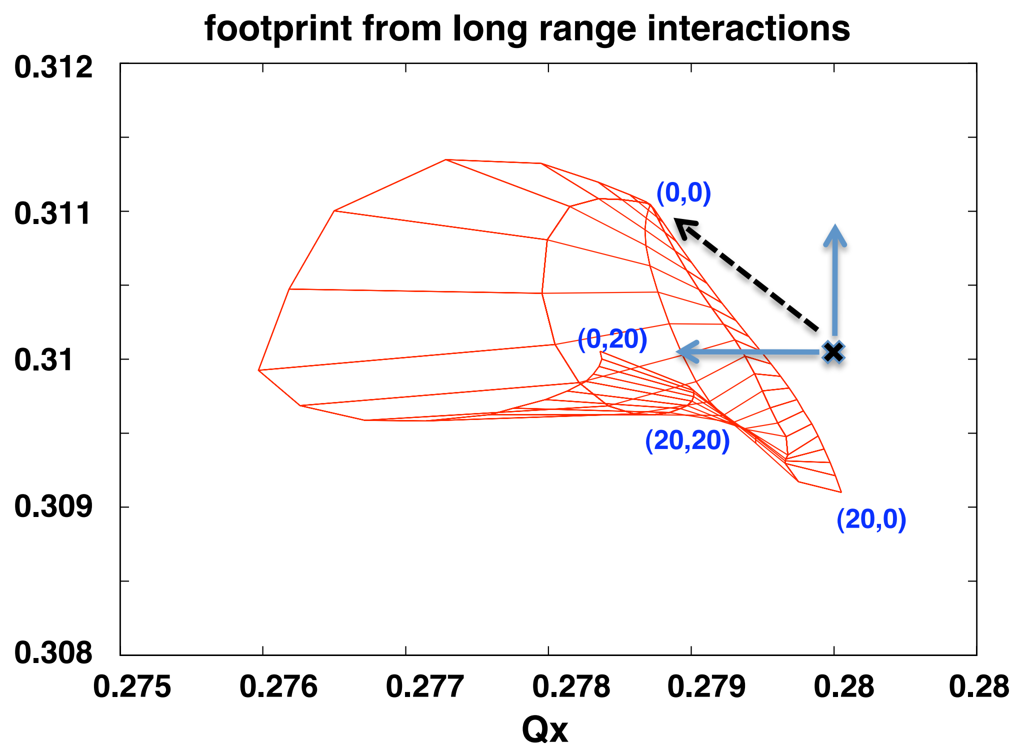
2-D Long Range detuning with amplitude



Tune shift as a function of separation in horizontal plane

In the **horizontal** plane **long range tune shift**

In the **vertical plane opposite sign!**

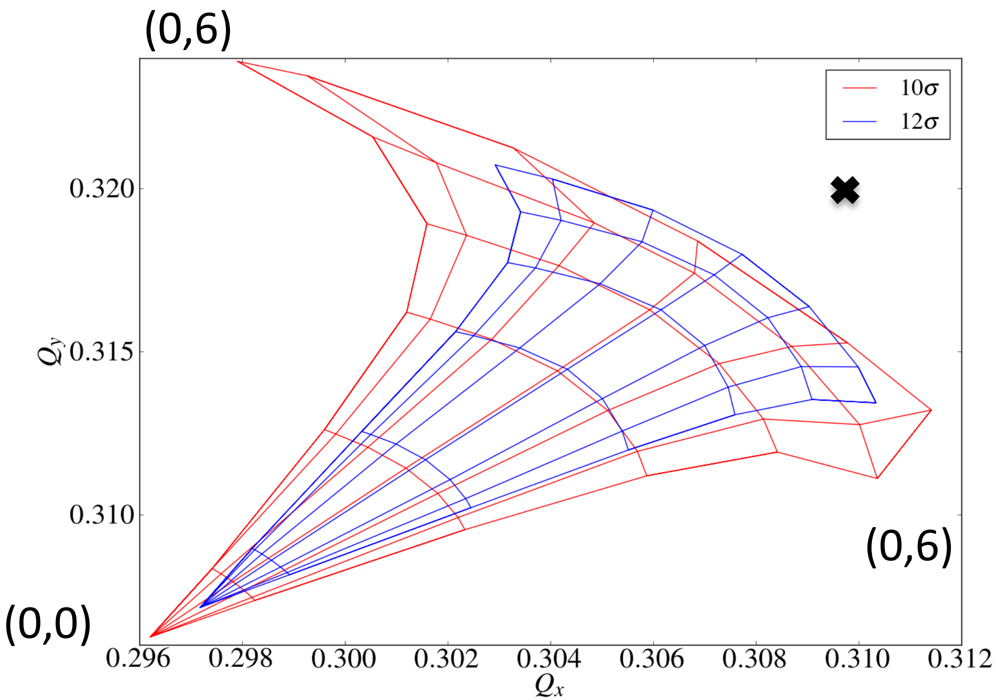


Long range tune shift scaling for distances $d > 6\sigma$

$$\Delta Q_{lr} \propto -\frac{N}{d^2}$$

Beam-beam tune shift and tune spread

Head-on and Long range interactions detuning with amplitude



Footprints depend on:

- number of interactions (124 per turn)
- Type (Head-on and long-range)
- Separation
- Plane of interaction

Very complicated depending on collision scheme

Pushing luminosity increases this area while we need to keep it small to avoid resonances and preserve the stability of particles

Strongest non-linearity in a collider

Outline

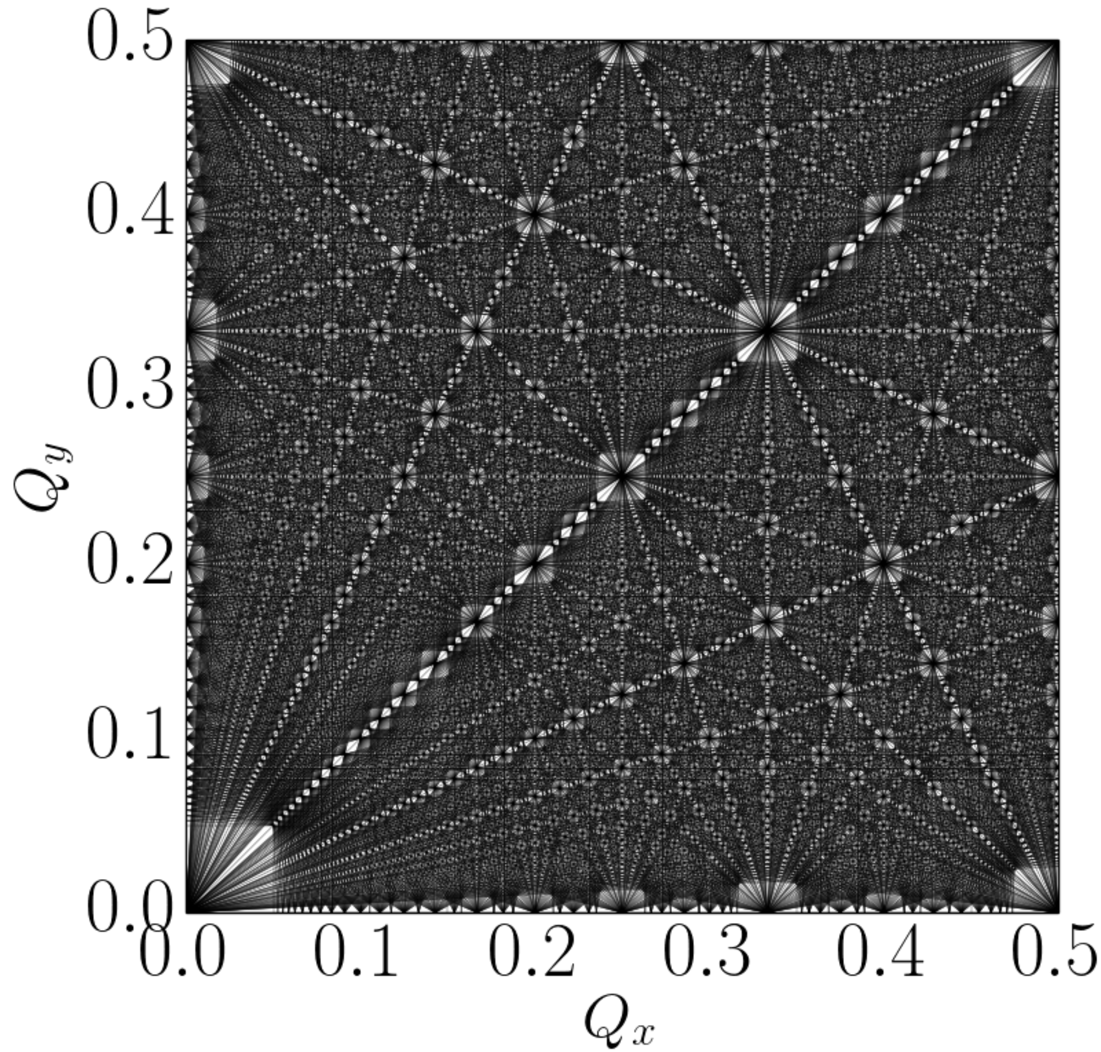
- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

Tune diagram and non-linear effects

Tune diagram resonances up 20^{th} order
…. Fortunately not all resonances matter



Beam-Beam resonances driving terms

$$F(r) = \frac{2Nr_0}{\gamma} \int_0^r \frac{dr}{r/\sigma} \left(1 - e^{\frac{r^2}{2}}\right) = \sum_{n,m} c_{n,m}(J_x, J_y) e^{-in\Phi_x - im\Phi_y}$$

$$c_{n,m}(J_x, J_y) = \iint_0^{2\pi} d\Phi_x d\Phi_y e^{in\Phi_x + im\Phi_y} F\left(r = \sqrt{\beta J_x sin^2(\Phi_x) + \beta J_y sin^2(\Phi_y)}\right)$$

- Details and analytical derivation of the Fourier components in 1D can be found at http://www.slac.stanford.edu/~achao/LieAlgebra.pdf
- For multiple beam-beam interactions, the components might cancel / add up
    - In practice, systematic cancellation/enhancement of resonances by adjusting the phase between the IPs is difficult (W. Herr, D. Kaltchev, LHC project report 1082)

Numerical evaluation of the resonance driving terms

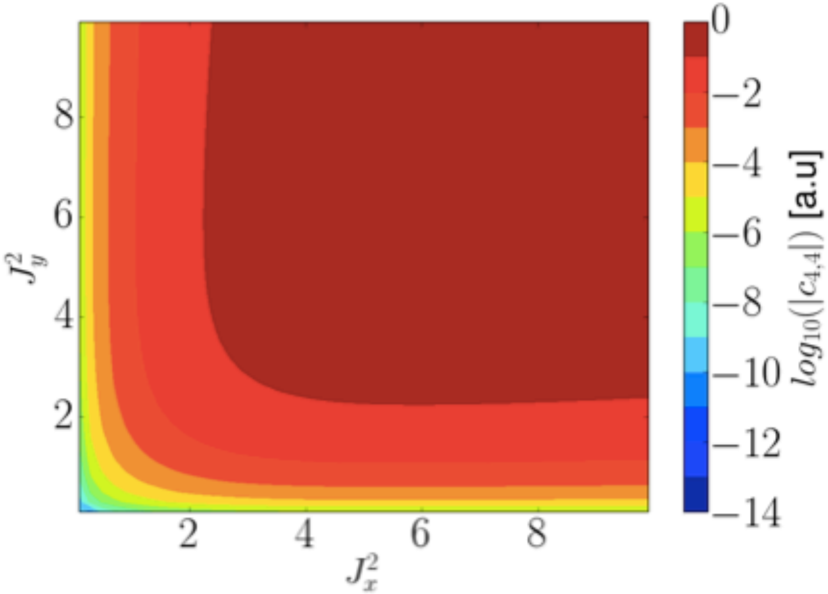
- $|c_{n,m}(J_x,J_y)|$ strongly depend on the oscillation amplitudes
  - → As a figure of merit we take

$$C_{n,m}^{core} = \max_{J_x^2+J_y^2<2} |c_{n,m}(J_x, J_y)|$$

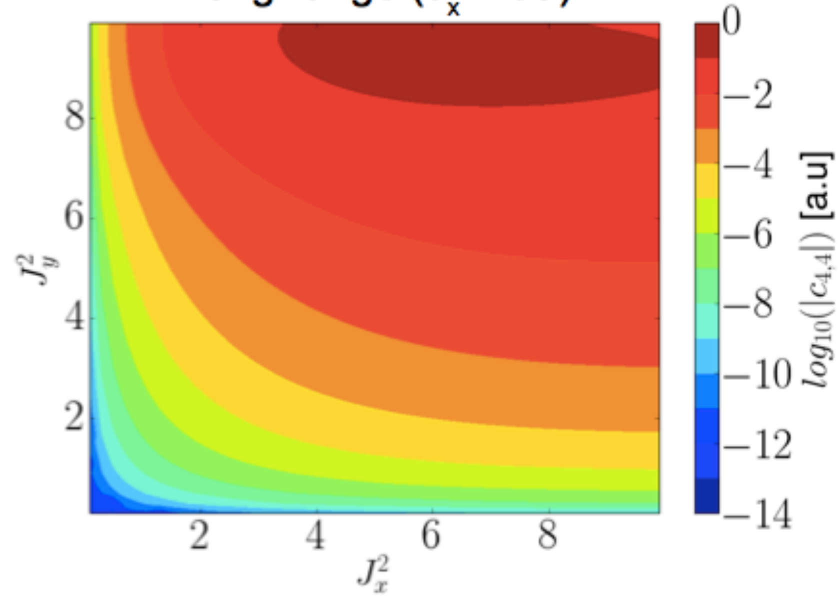
$$C_{n,m}^{tail} = \max_{J_x^2+J_y^2<6} |c_{n,m}(J_x, J_y)|$$

- Example : n=m=4

Head-on

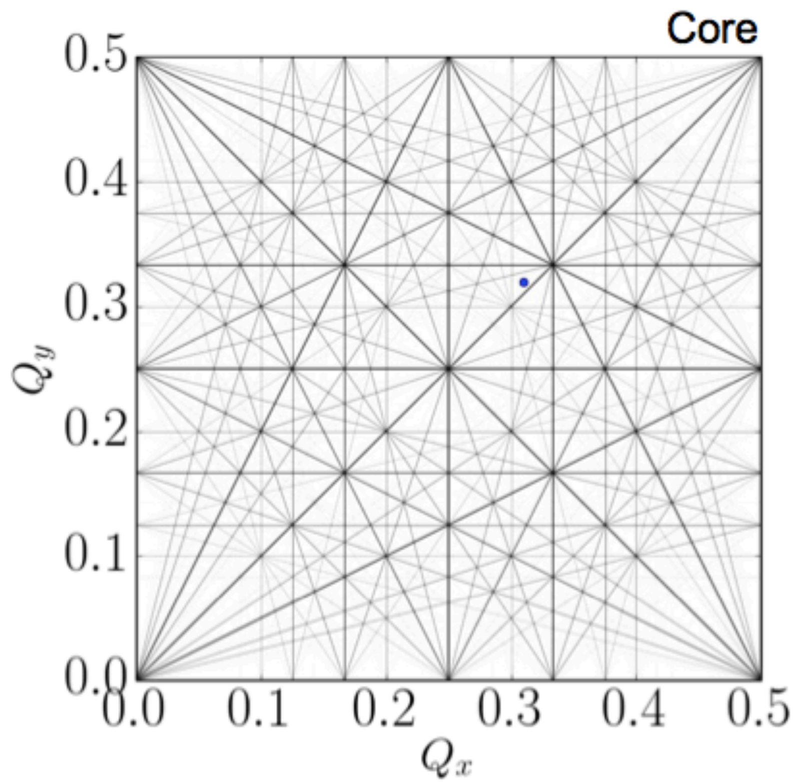


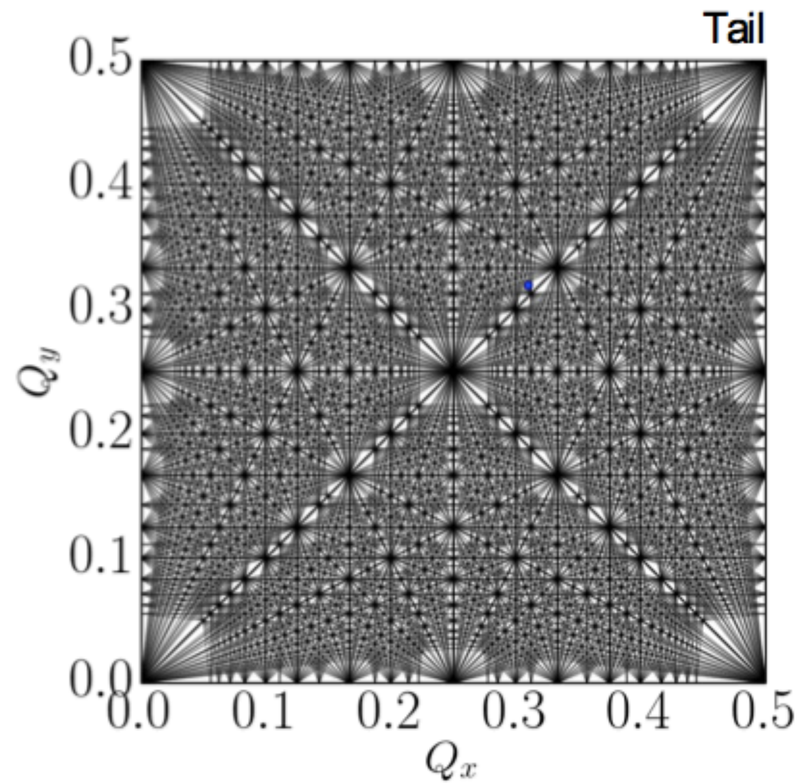
Long-range (d_x=10σ)



Tune diagram

- Tune diagram with line width ~ log $|C_{n,m}|$ for two IPs with head-on and long-range interactions



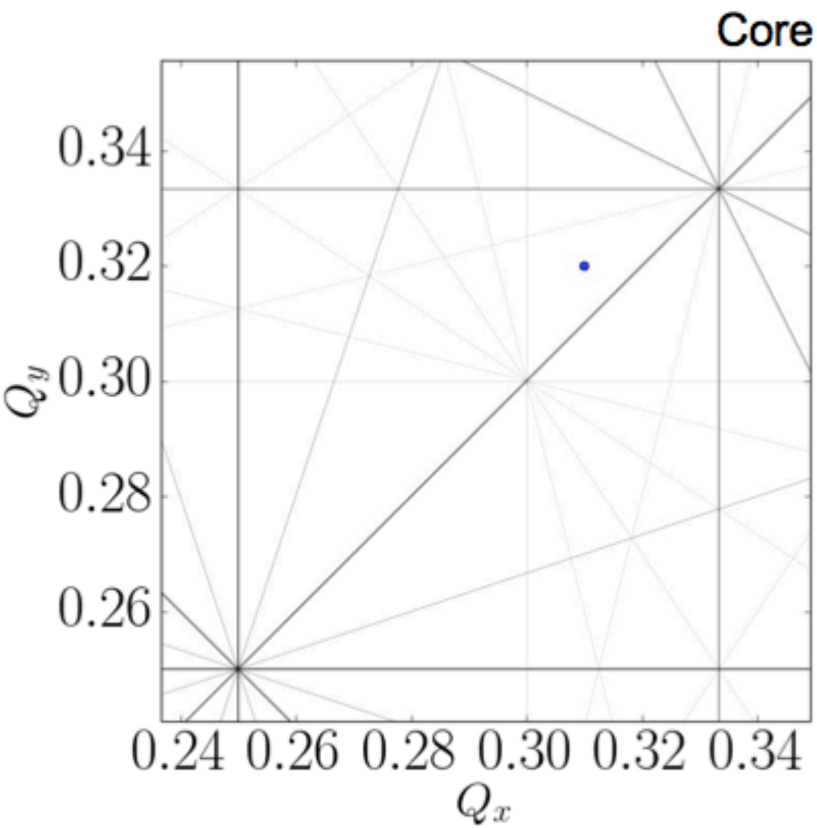


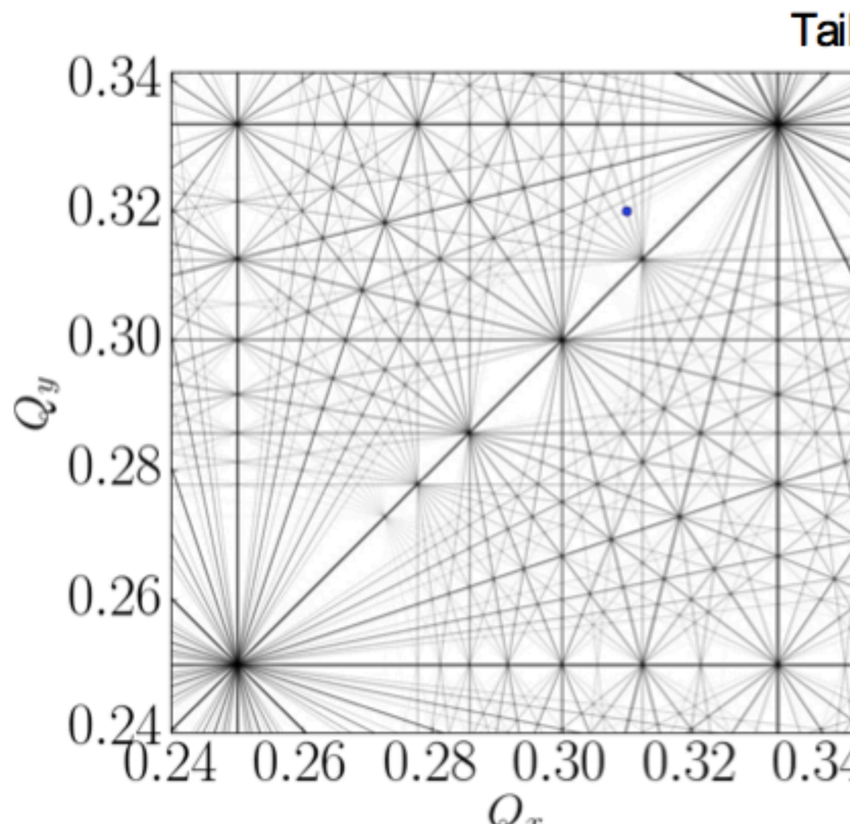
The strength of the resonance depends on the interaction type and on the particle amplitude

They can be very different

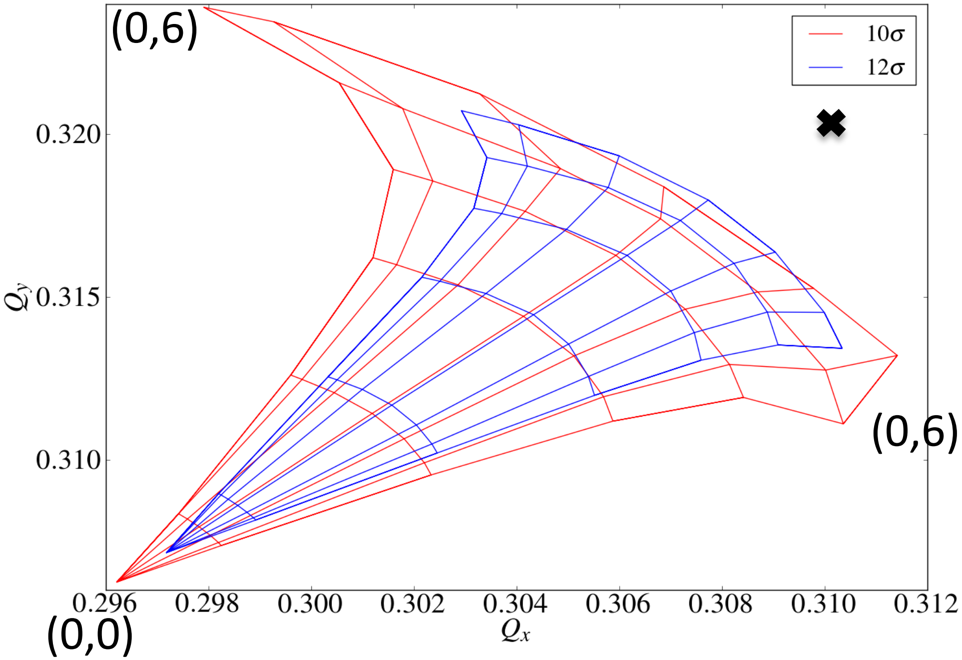
LHC working point

- Profit of the space between 1/3 and ¼
- Nominal beam-beam parameter is 0.0033 per IP
  - Operated with ~0.007 per IP in 2012



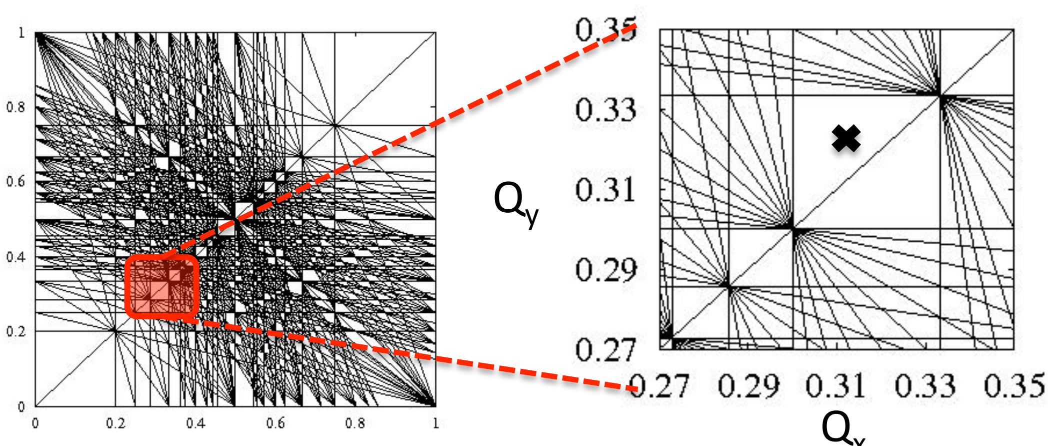


Beam-beam tune shift and spread



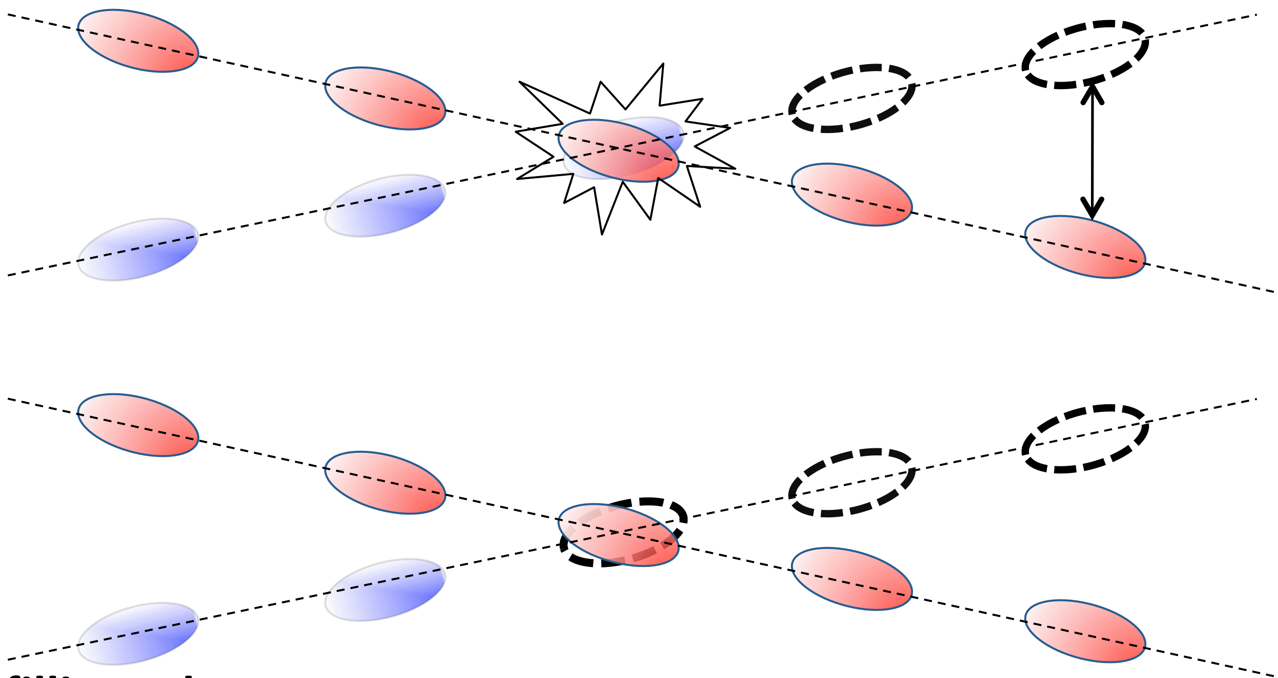
Pushing luminosity increases this area while we need to keep it small to avoid resonances and preserve the stability of particles

The footprint from beam-beam sits in the tune diagram…..
Next step is to set parameters to avoid particle losses which could be driven by resonances…



Complications

PACMAN and SUPER PACMAN bunches



Pacman:

miss long range BBI

(120-40 LR interactions)

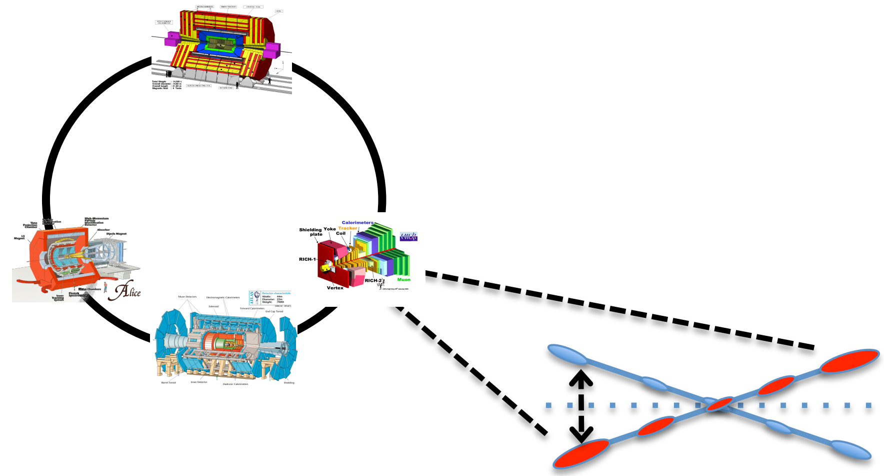
Super Pacman:

miss head-on BBI

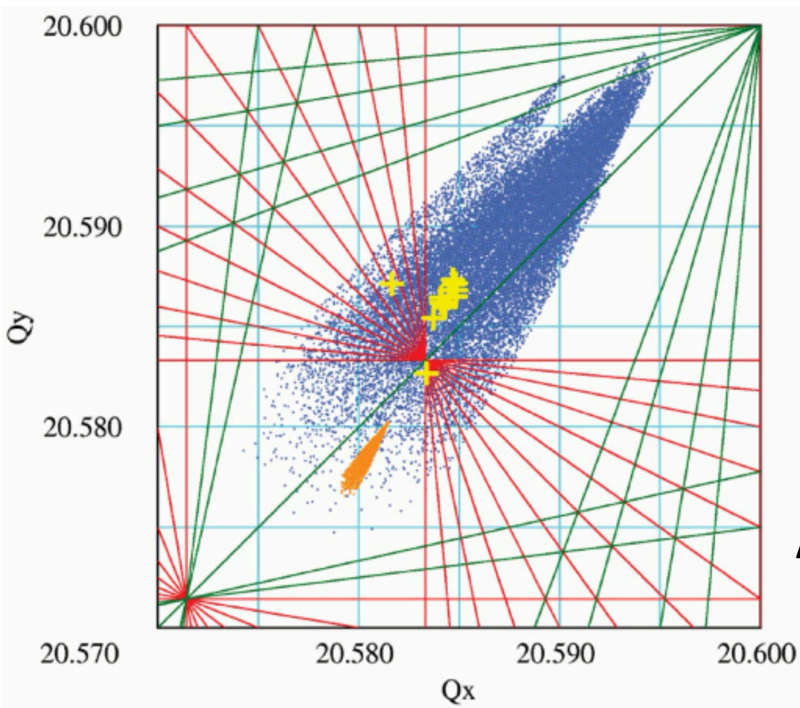
IP2 and IP8 depending on filling scheme

Different bunch families: Pacman and Super Pacman

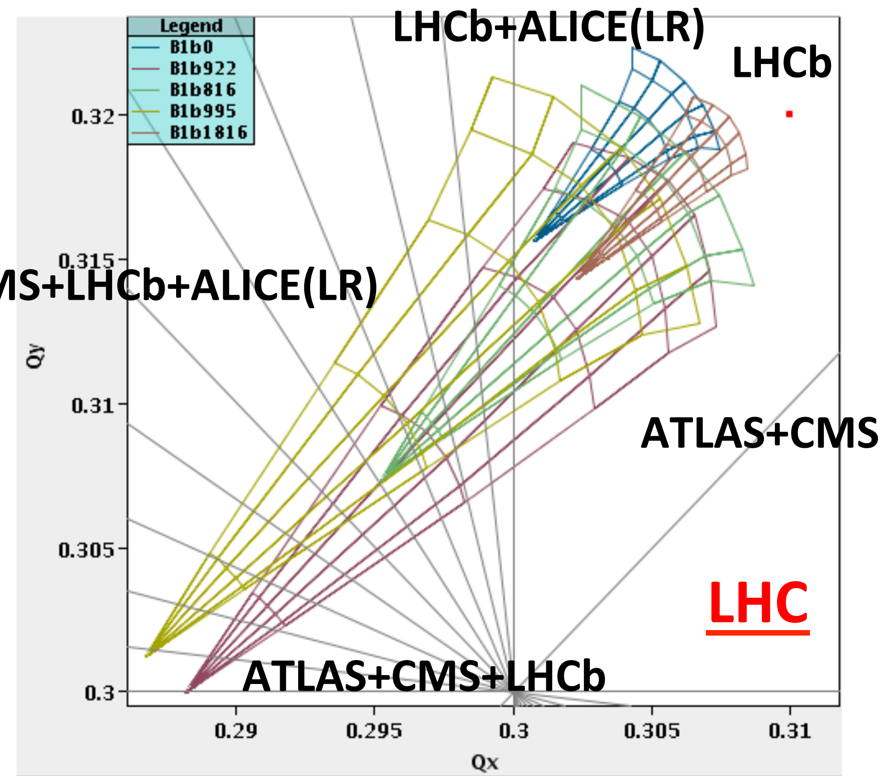
Pacman and Super-pacman



Tevatron



Antiproton bunches footprint (blue)
Proton bunches footprint (orange)



…operationally it is even more complicated!
…intensities, emittances…

Outline

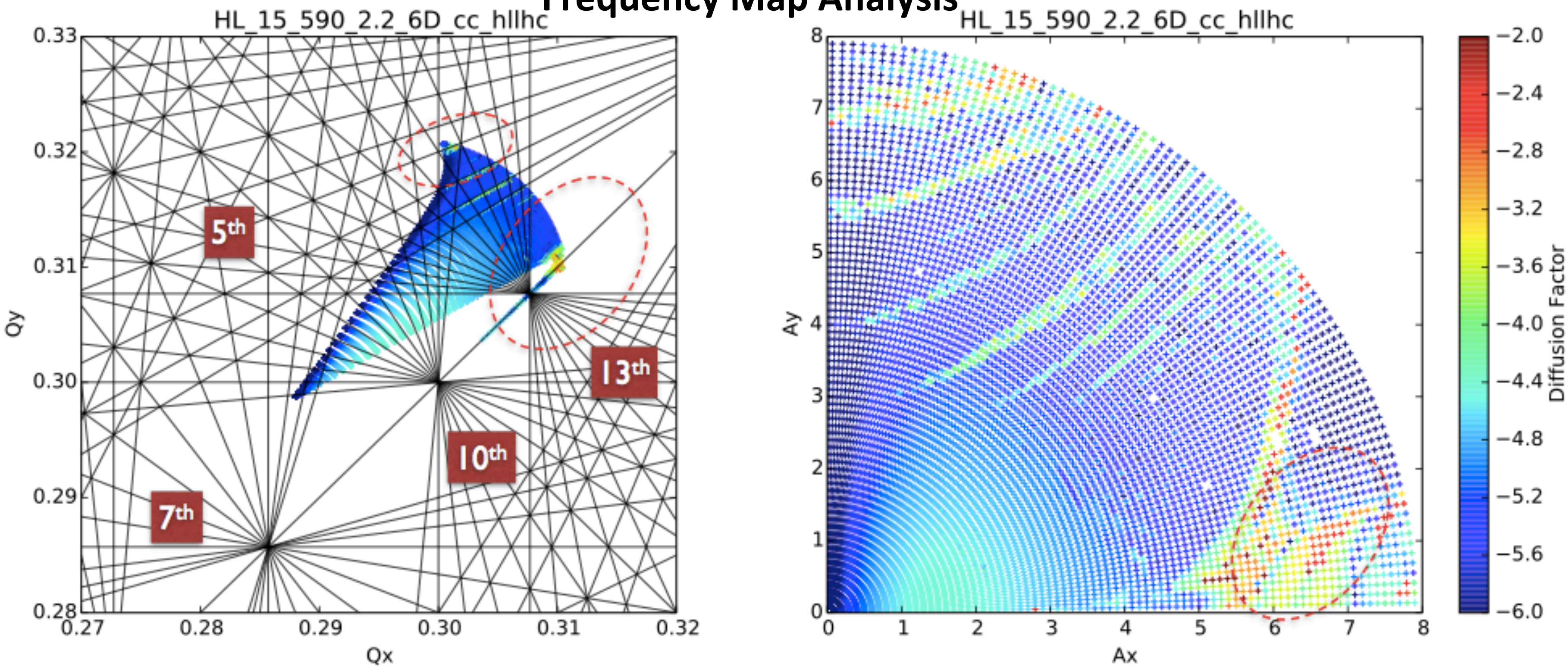
- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects
- Passive compensation of Tune shifts and Chromaticity
- Landau damping

Dynamical Aperture and Particle Losses

Dynamic Aperture: area in amplitude space with stable motion

Stable area of particles depends on beam intensity and crossing angle

Frequency Map Analysis

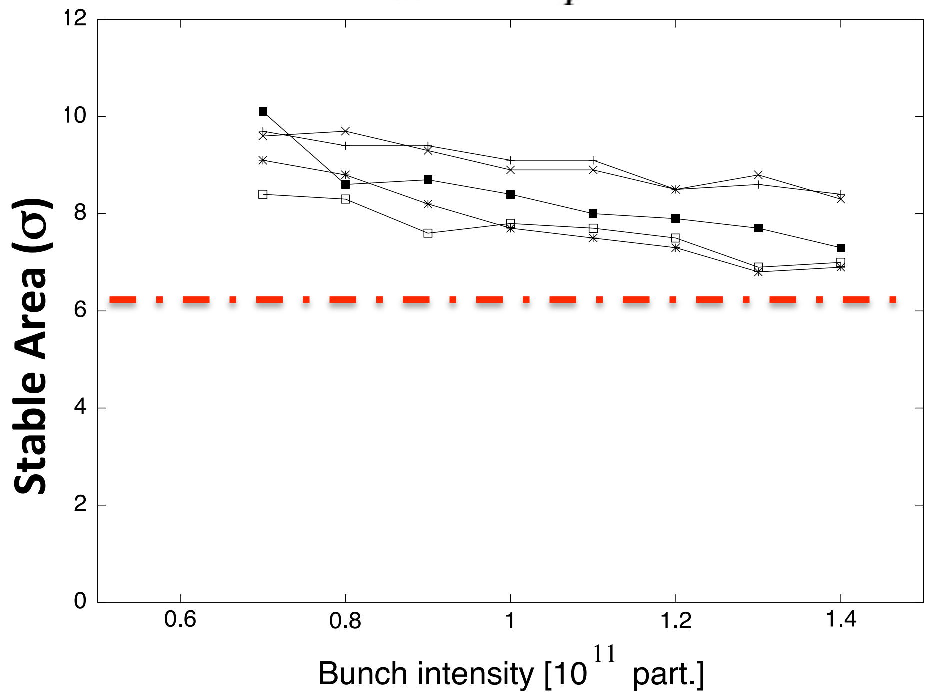


Stable area depends on beam-beam interactions therefore the choice of running parameters (crossing angles, β^*, intensity) is the result of careful study of different effects!

Dynamical Aperture and Particle Losses

Beam-beam linear dependency with Intensity

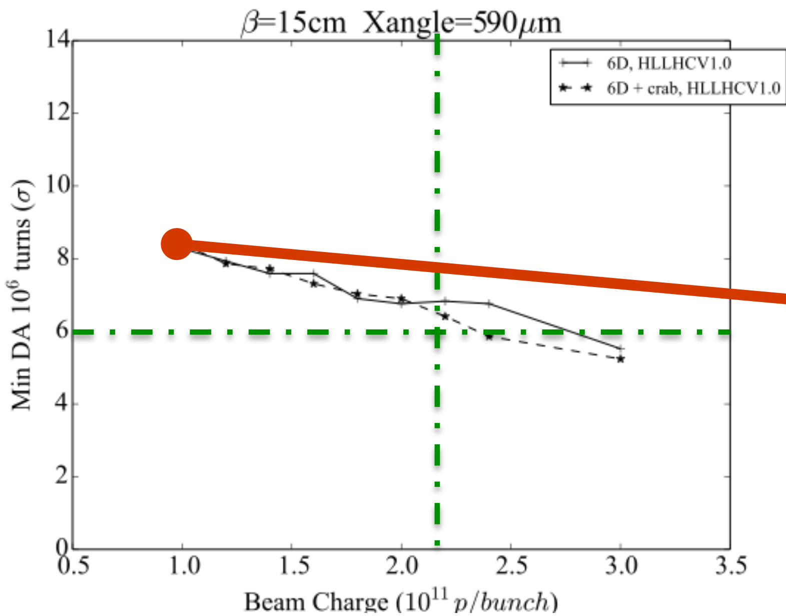
$$F_{bb} \propto N_p$$

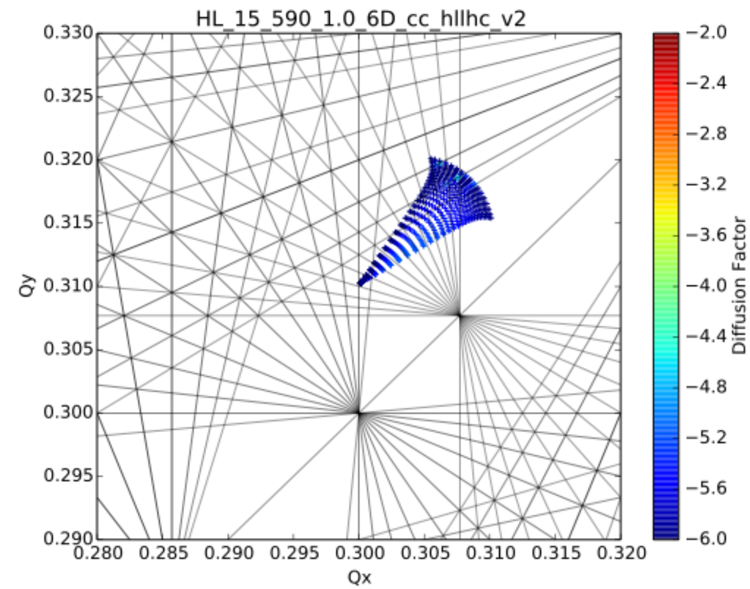


Our goal: keep dynamical aperture above 6 σ → all particles up to 6 σ amplitude not lost over long tracking time (10^6 turns in simulation) equivalent to 1 minute of collider

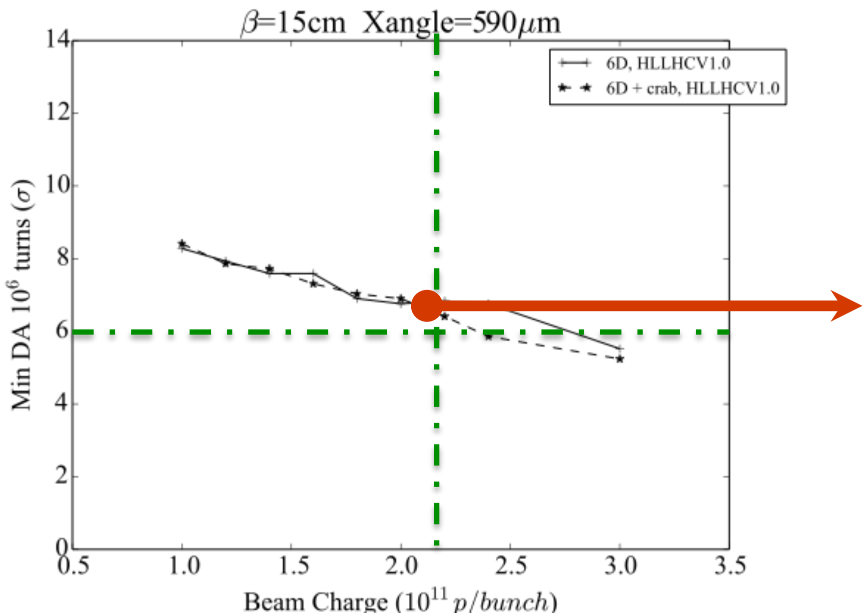
Example collider collision time : 24 hours

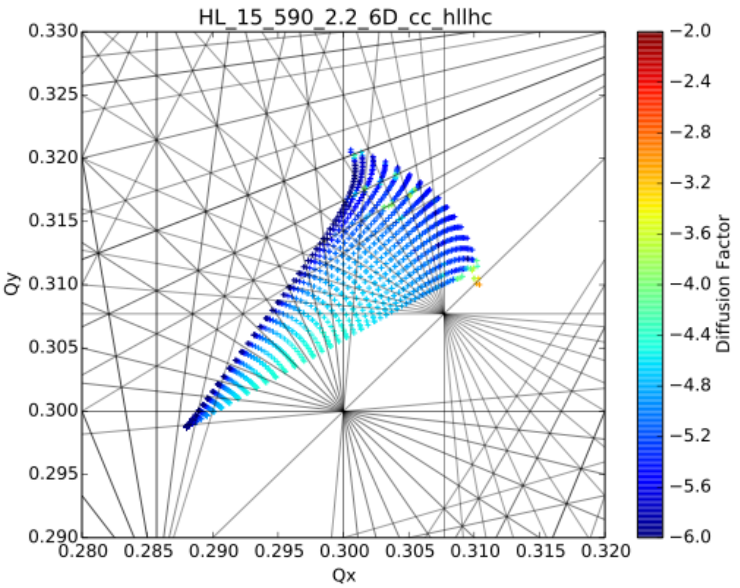
Round optics15 cm, 590µrad: intensity scan



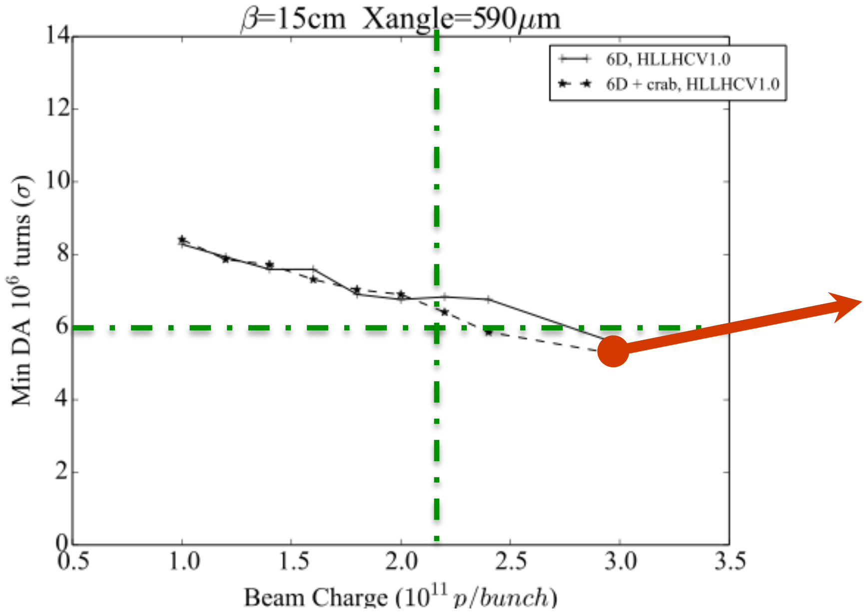


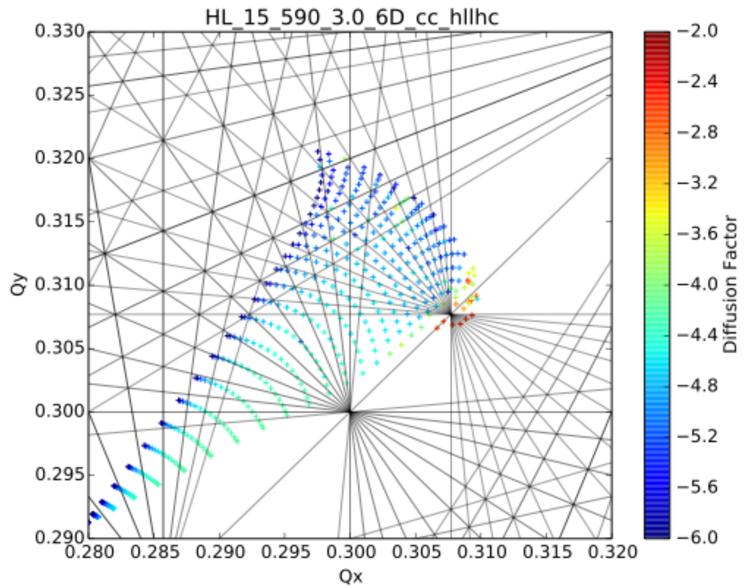
Round optics15 cm, 590μrad: intensity scan





Round optics15 cm, 590μrad: intensity scan

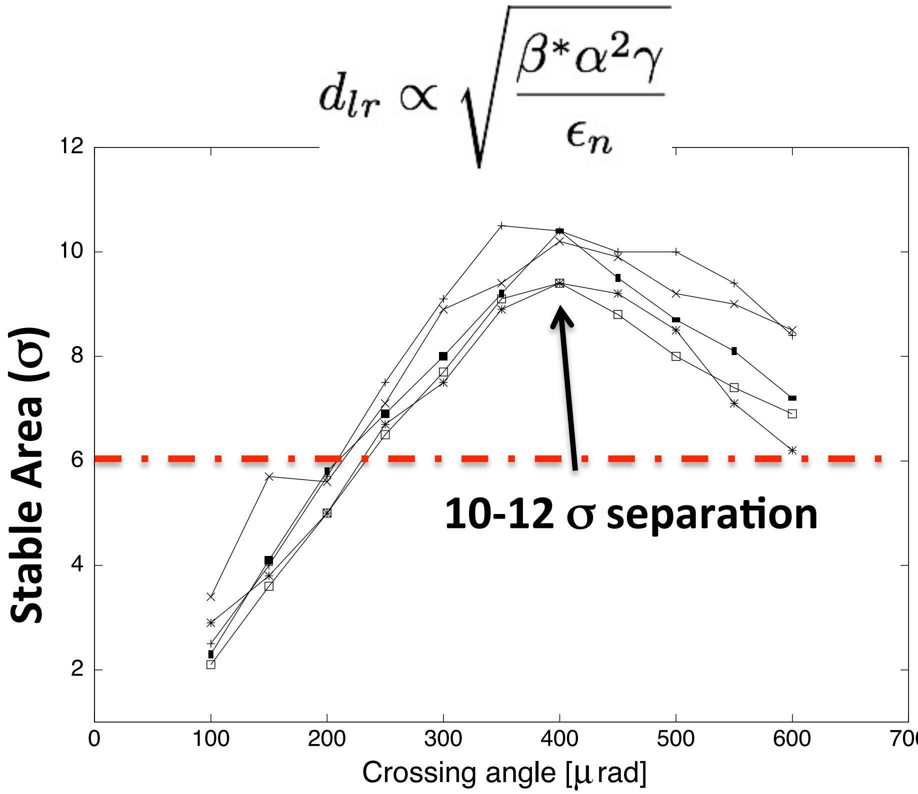




AT high intensity the beam-beam force gets too strong and makes particles unstable and eventually are lost

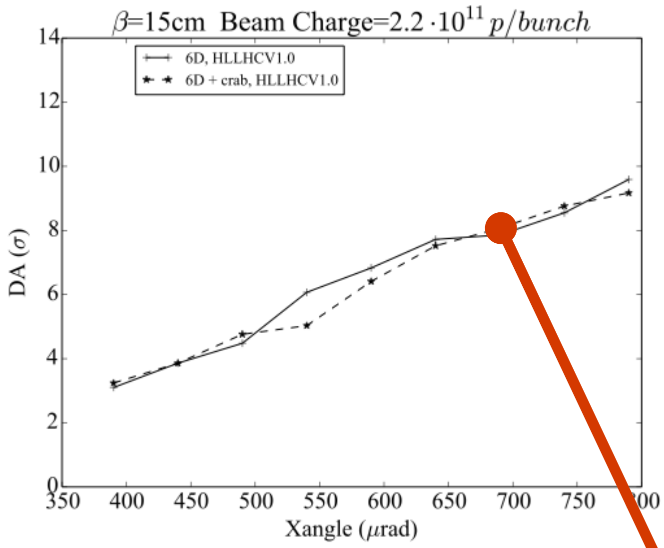
Dynamical Aperture and Particle Losses

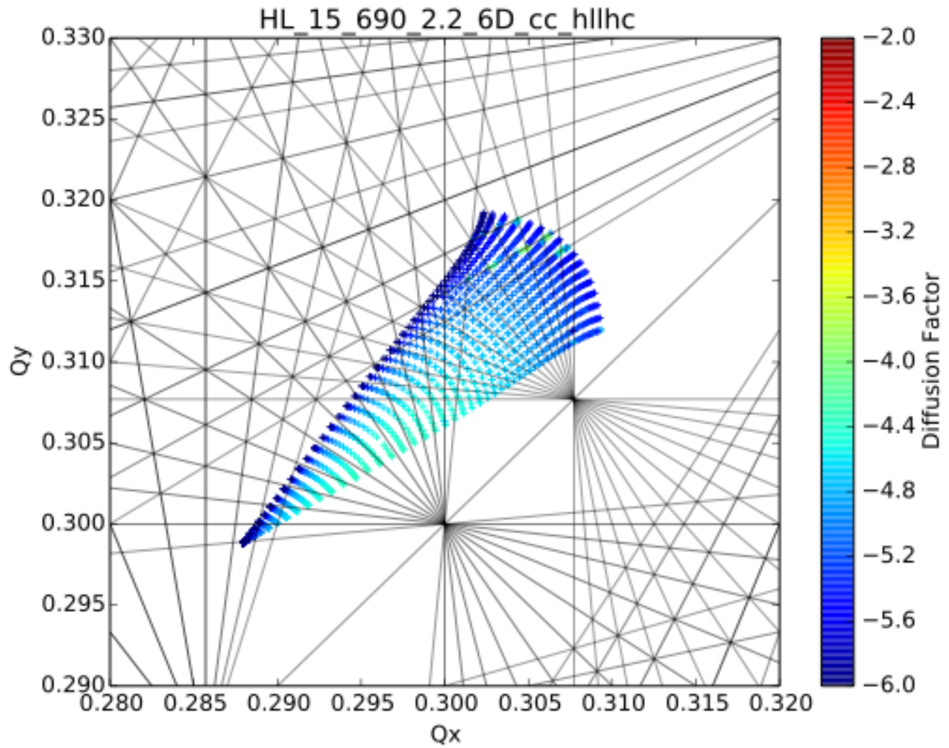
Beam-beam dependency with crossing angle 1/α



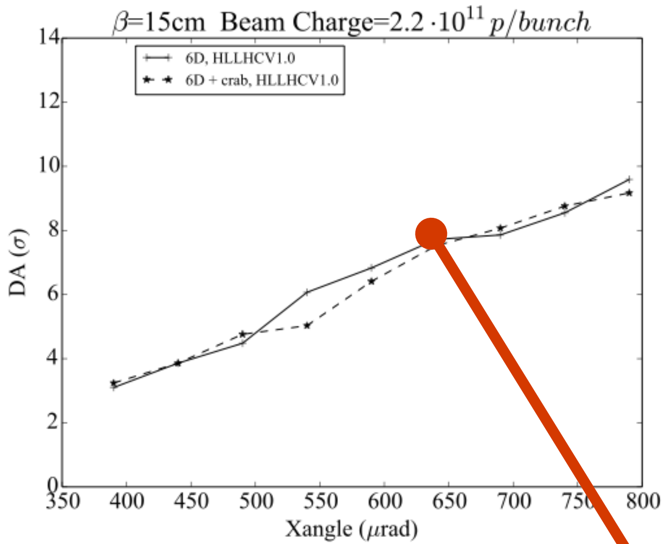
Smaller beam-beam separation at parasitic long-range encounters
stronger non linearities → smaller dynamical aperture

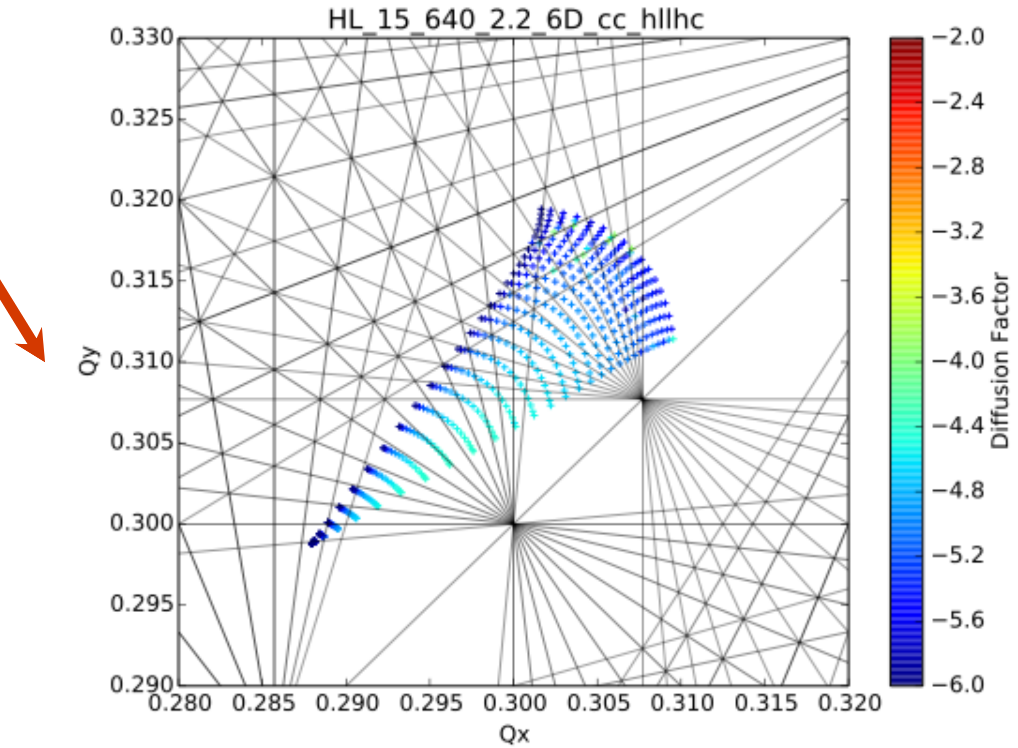
Round 15cm, 2.2E11, 690μrad



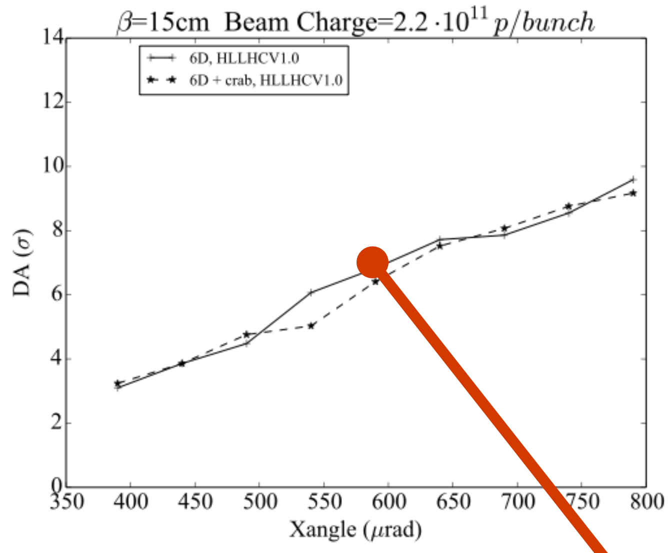


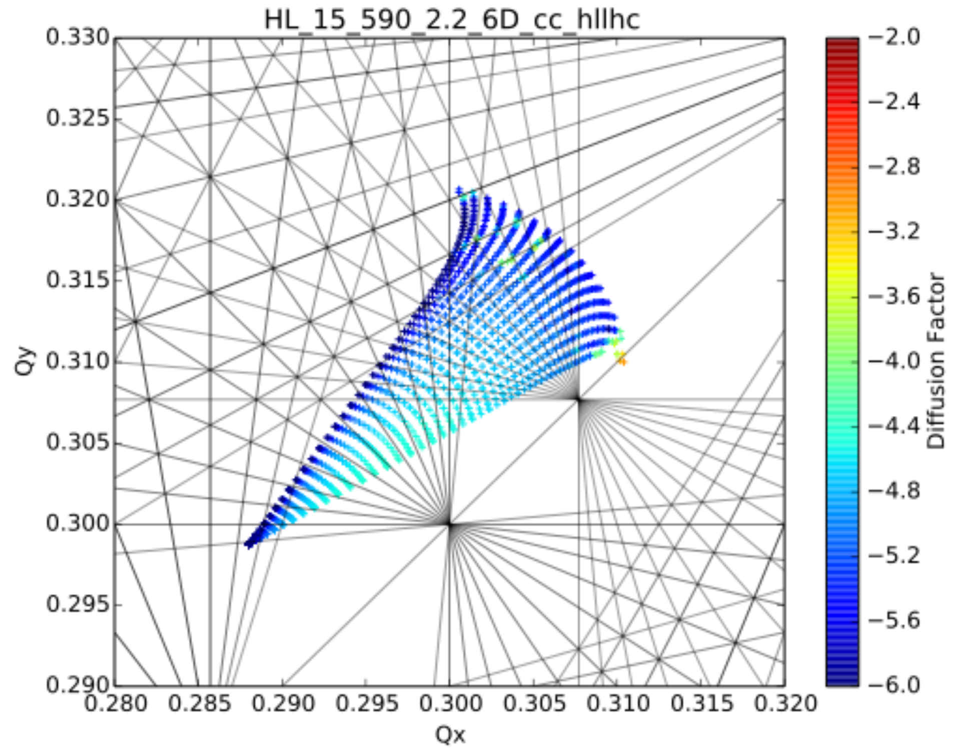
Round 15cm, 2.2E11, 650μrad



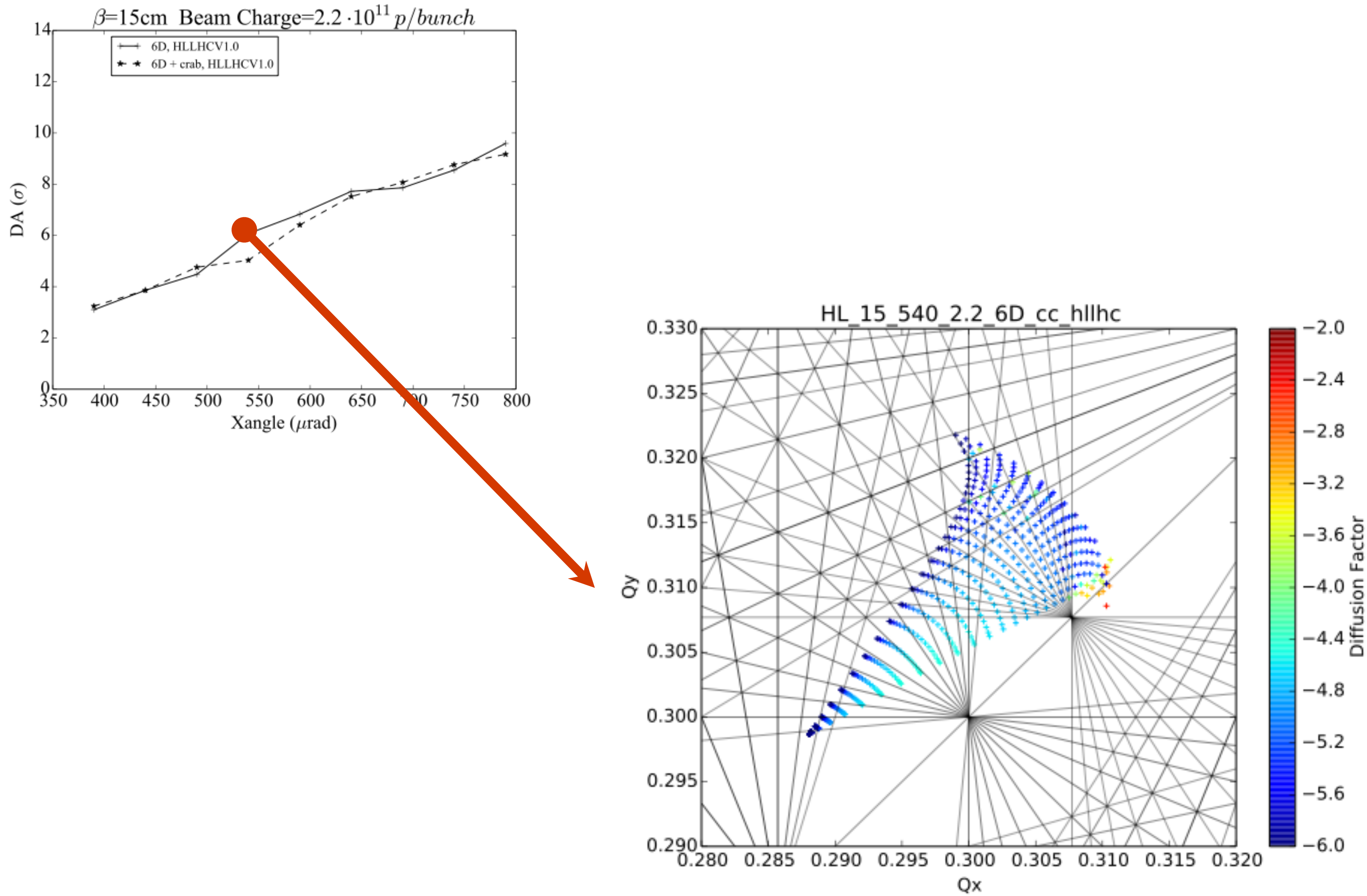


Round 15cm, 2.2E11, 590μrad

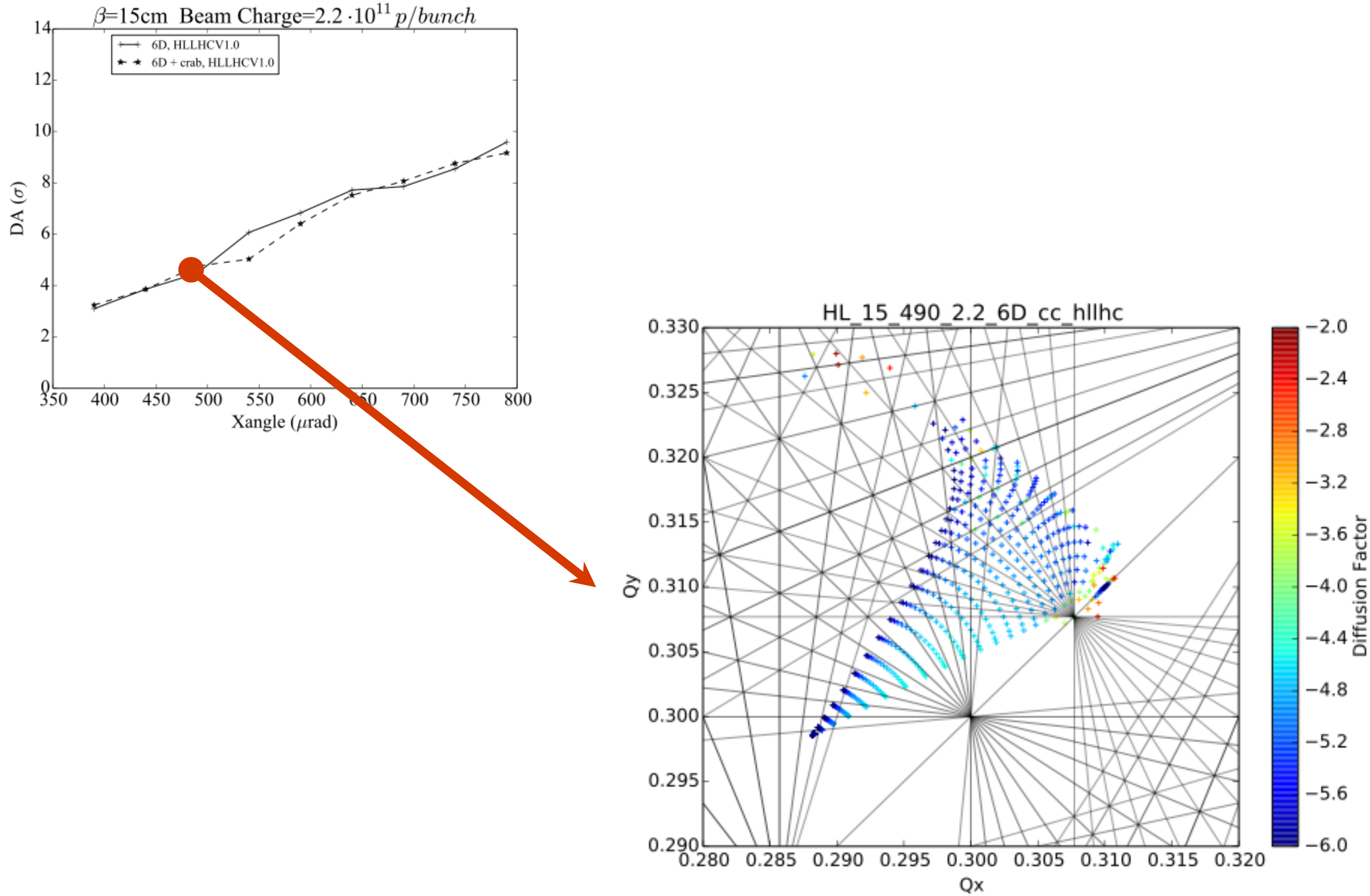




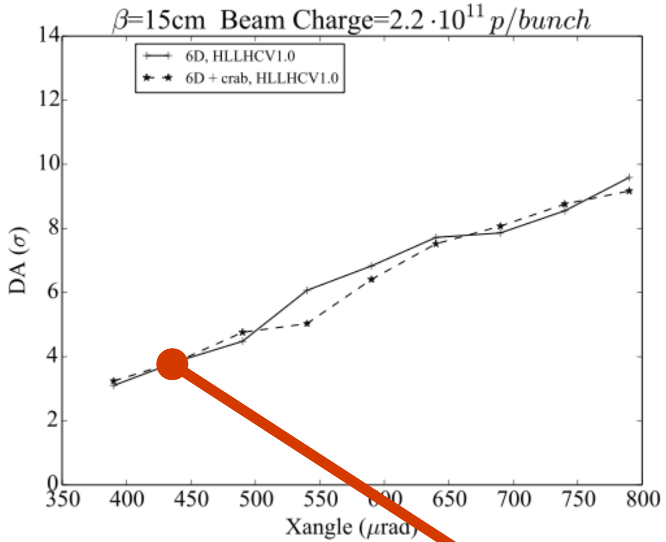
Round 15cm, 2.2E11, 540μrad

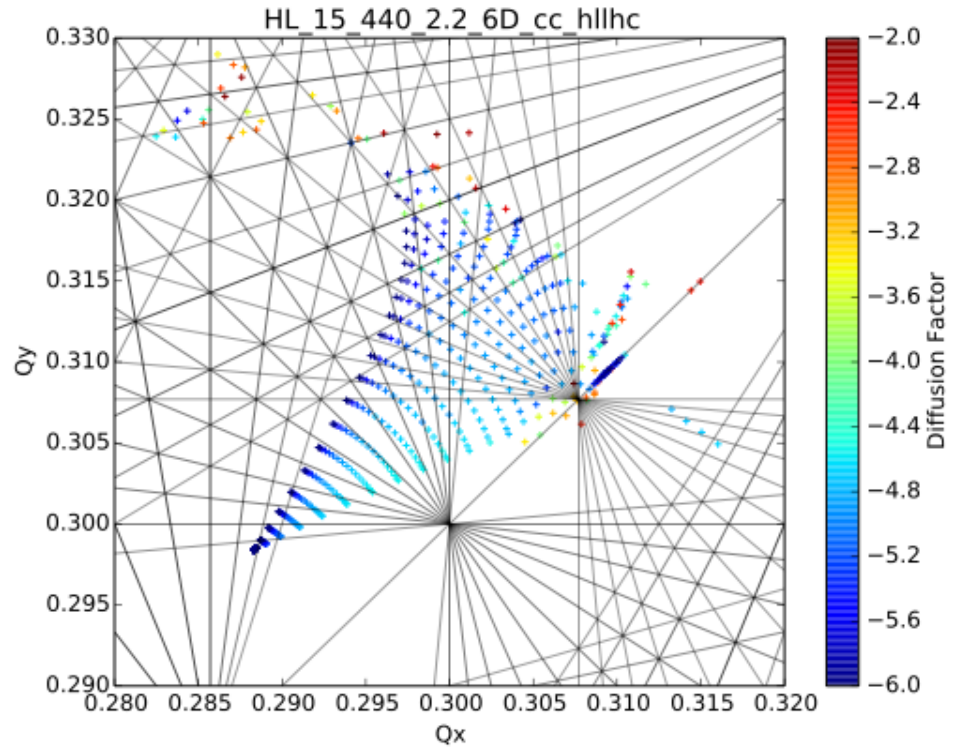


Round 15cm, 2.2E11, 490μrad

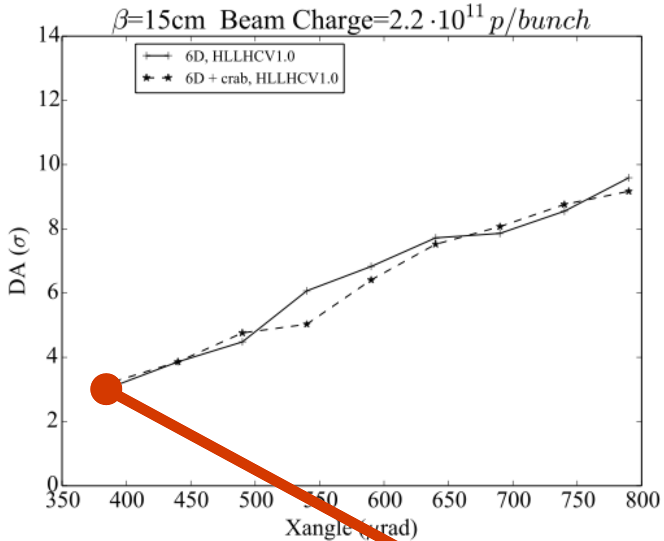


Round 15cm, 2.2E11, 440μrad



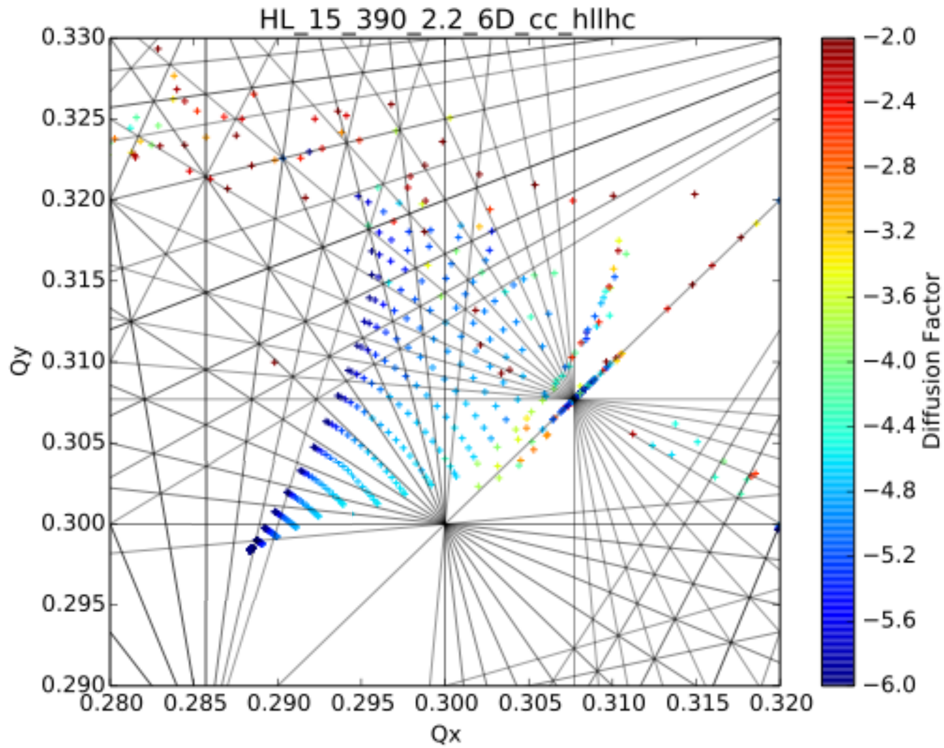


Round 15cm, 2.2E11, 390µrad



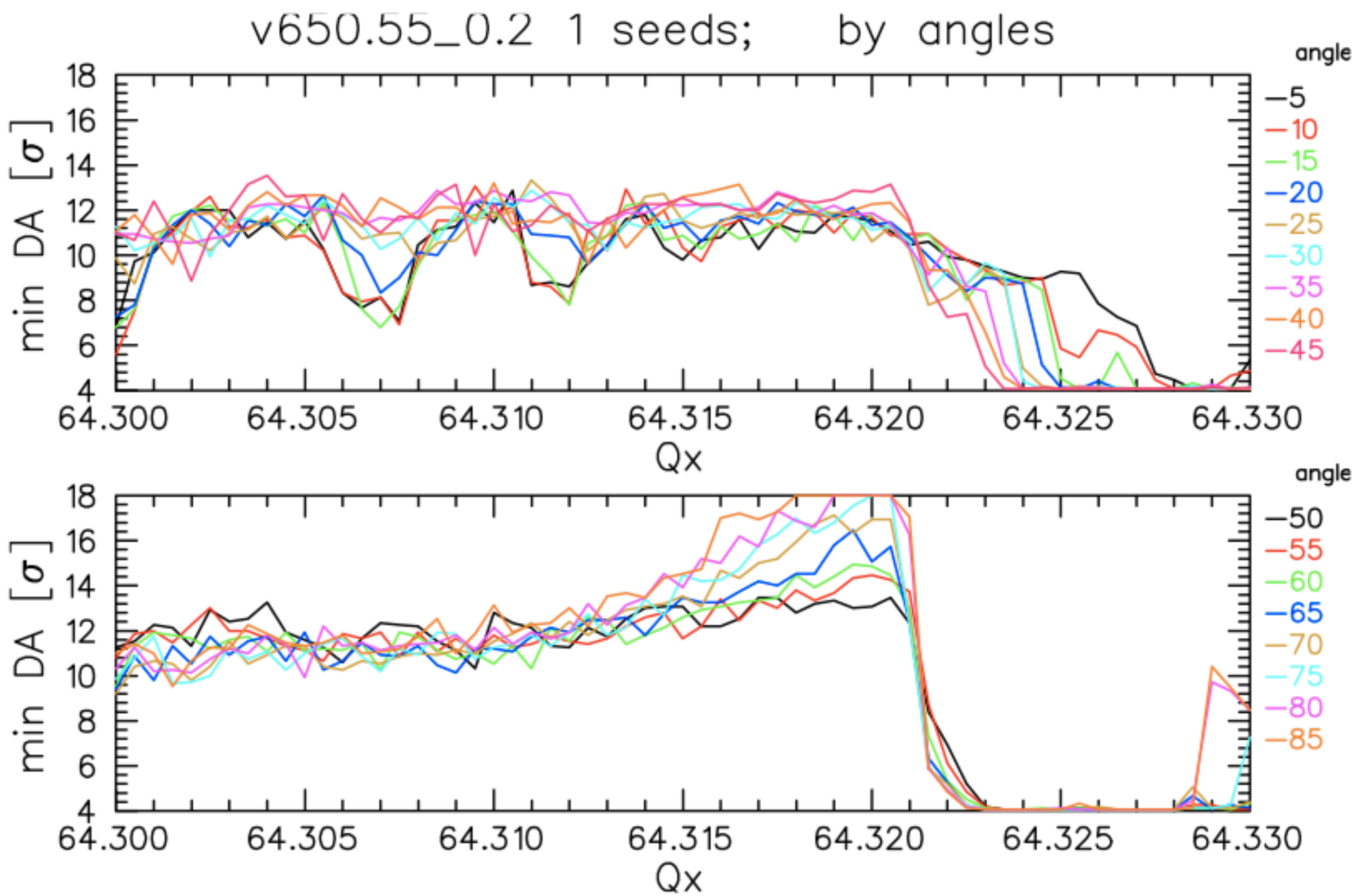
Crossing angle changes the separation and the strength of BB-LR that strongly affect the tails. 0σ particle are almost not affected.

At small separation particles gets unstable and eventually lost



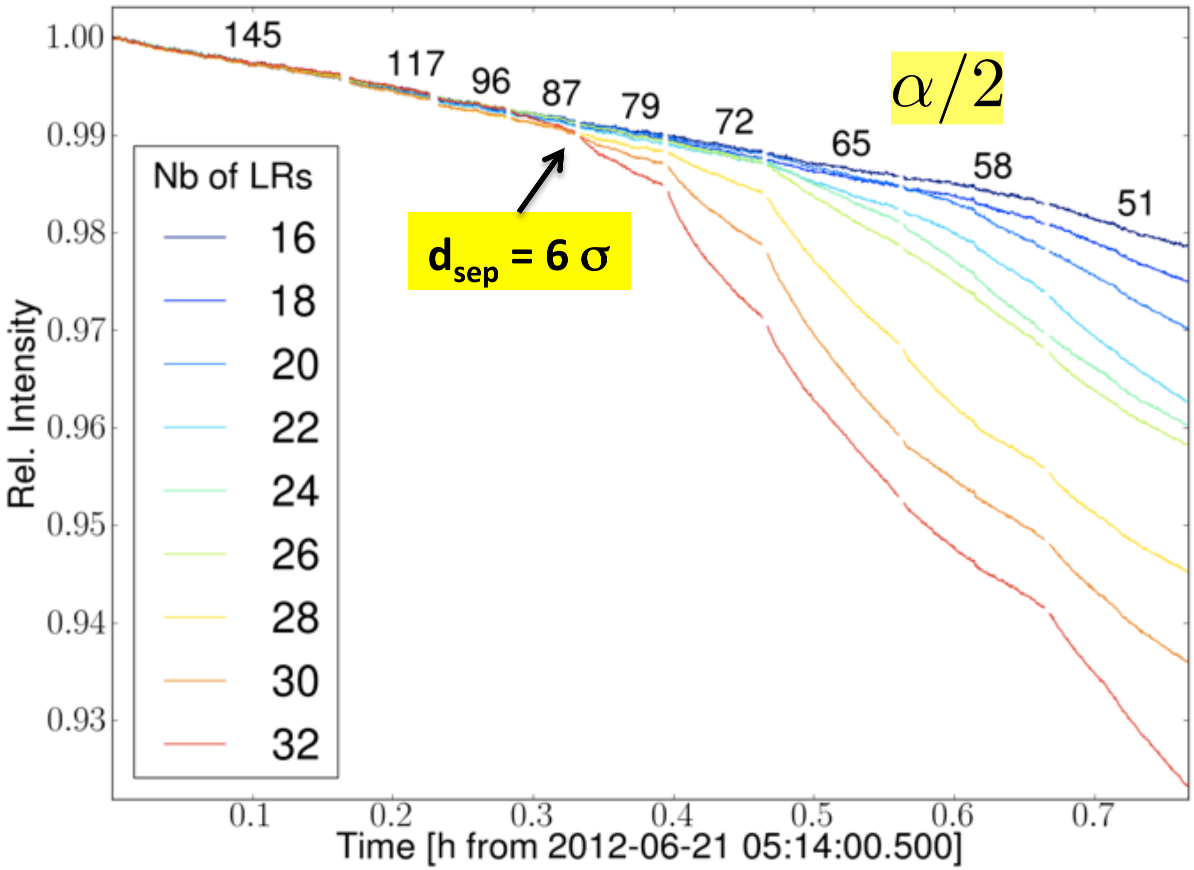
Dynamic aperture reduction vs tune

Dynamic Aperture depends on the working point



Do we see the particle lost in reality?

Dedicated Experiment in the LHC 2012



Beam-Beam separation at first LR

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$

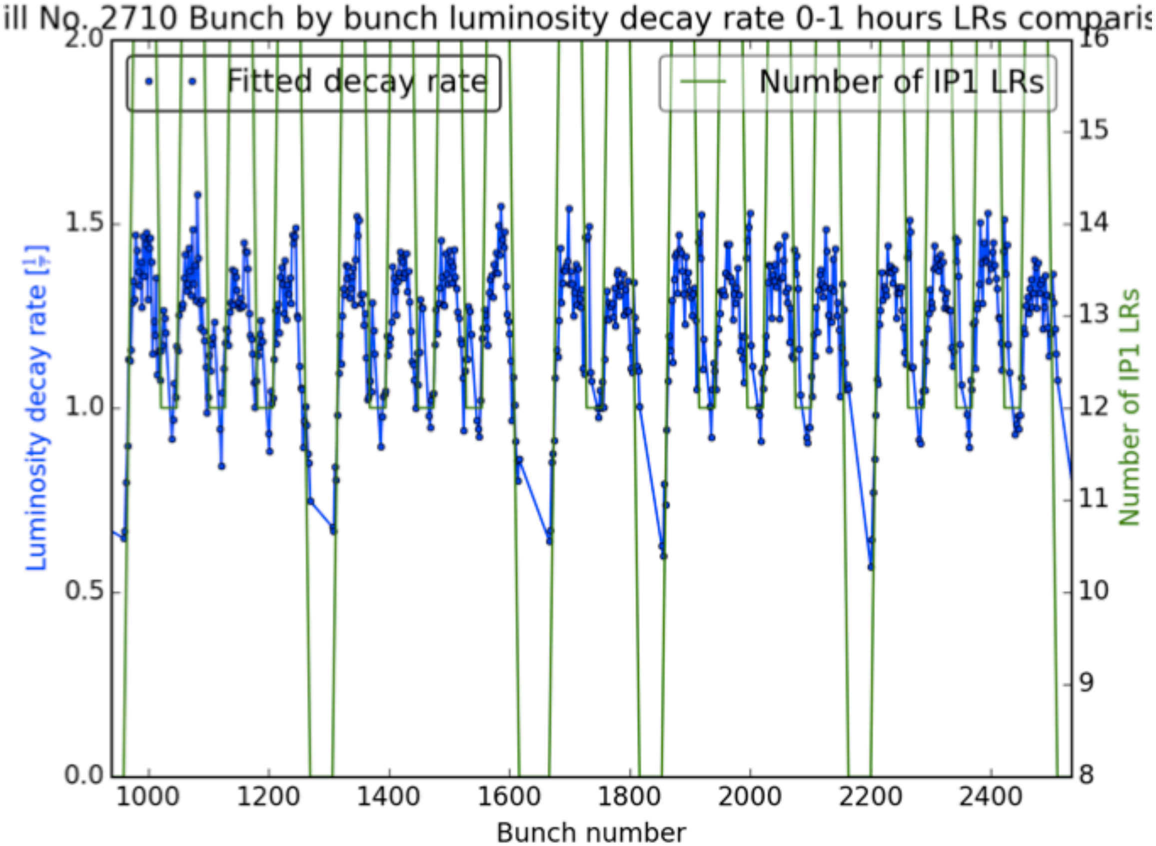
Small crossing angle = small separation

If separation of long range too small particles become unstable and are lost proportionally to the number of long range encounters

Particle losses follow number of Long range interactions

Do we see the particle losses?

Regular Physics Fill of 2012 RUN LHC



Beam-Beam separation at first LR

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$

Small crossing angle = small separation

Luminosity decays following the long range numbers… higher number of long range interactions larger losses

Particle losses follow number of Long range interactions
Machine protection implication and beam lifetimes gets worse…

Best peformance of collider always a trade off between beam-beam and luminosity

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects, Tune shifts, Chromaticity
- Compensation ideas
- Landau damping

Dynamic beta effect and beating

- The beam-beam collision at the experiment changes also the optics of the machine
- This leads to changes in the phase $\Delta\mu$ and to an "optical error" $\Delta\beta^*$
- Source of force at the position s, and the effect at position s_0 in perturbation theory is given by:

$$\Delta\beta(s_0) = -\frac{\beta(s_0)}{2sin(2\pi Q)} \int_{s_1}^{s_1+C} \beta(s)\Delta k(s) cos\left[2(\mu(s)-\mu(s_0))-2\pi Q\right] ds$$

If our case if optics changes → beam-beam force changes → optics changes → beam-beam force changes ...

Self-consistent calculation is required to evaluate the effect

Dynamic Beta effect

In a simple case with one beam-beam interaction and seen as a perturbatio
And taking the effect at the source of the error (s=s_0)

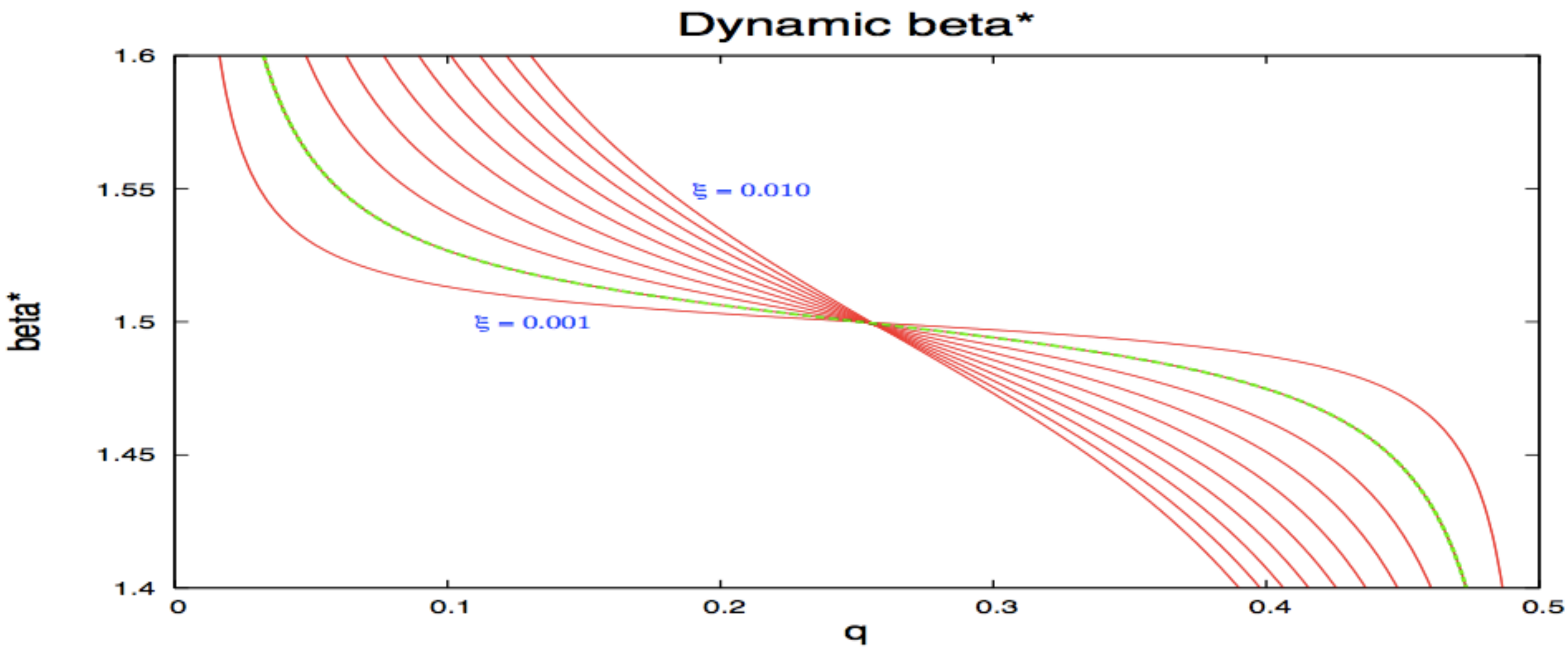
$$\frac{\beta^*}{\beta_0^*} = \frac{sin(2\pi Q)}{sin(2\pi(Q+\Delta Q))} = \frac{1}{\sqrt{1+4\pi\xi cot(2\pi Q) - 4\pi^2\xi^2}}$$

Beam-beam interaction leads to optical distortion at interaction point itself Dynamic beta

Beam-beam interaction leads to optical distortion at all other interaction points Dynamic beating

Expression above not valid during scan or several interaction points $\rightarrow$ needs optics code for calculation

Dynamic Beta effect single Interaction point



$$\frac{\beta^*}{\beta_0^*} = \frac{\sin(2\pi Q)}{\sin(2\pi(Q + \Delta Q))} = \frac{1}{\sqrt{1 + 4\pi\xi \cot(2\pi Q) - 4\pi^2\xi^2}}$$

Sensitive to:

- **Beam-beam parameter: ξ**
- **Tune : Q**
- **Configuration (IPS) and optics (phase advance)**

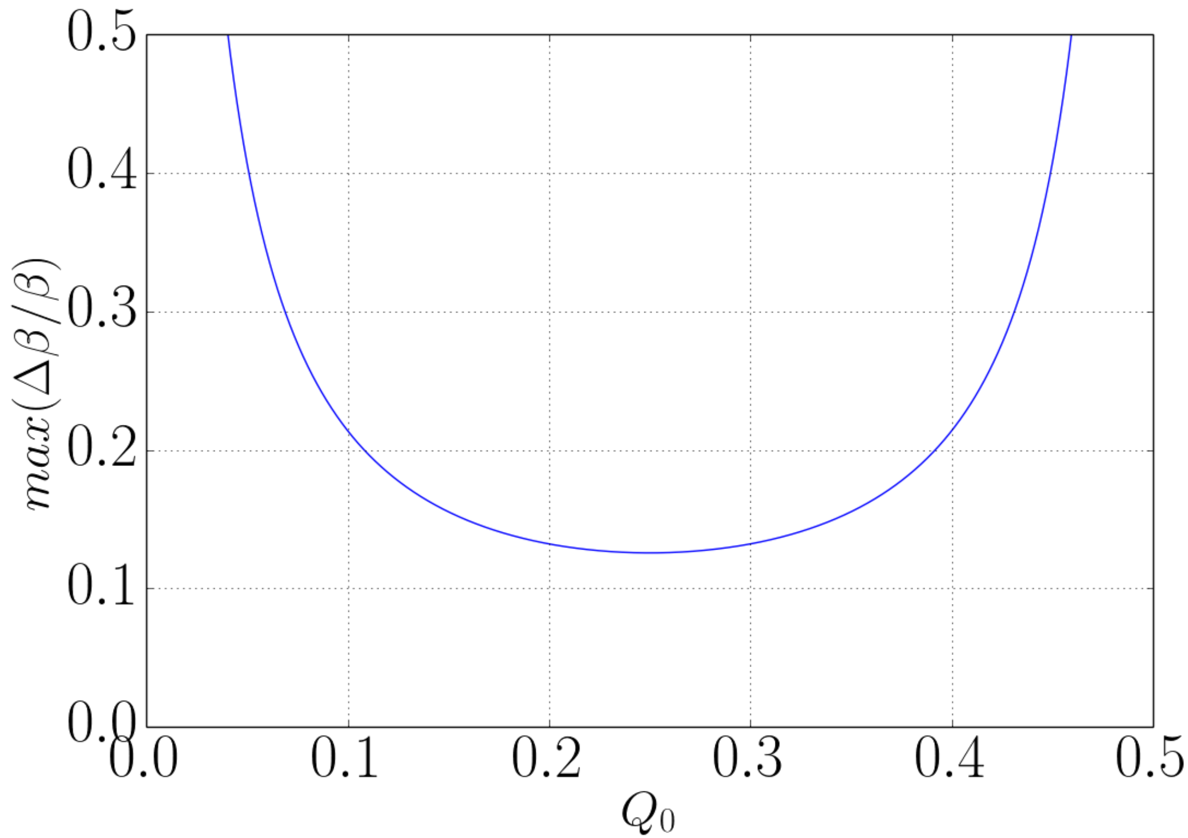
LHC case has 1-2 %
HL-LHC 3-6 %
…or more

Dynamic beta-beating due to beam-beam effects

Maximum beta change as a function of unperturbed tune

$$\max\left(\frac{\Delta\beta}{\beta}\right) = \frac{2\pi\xi}{sin(2\pi Q_0)}$$

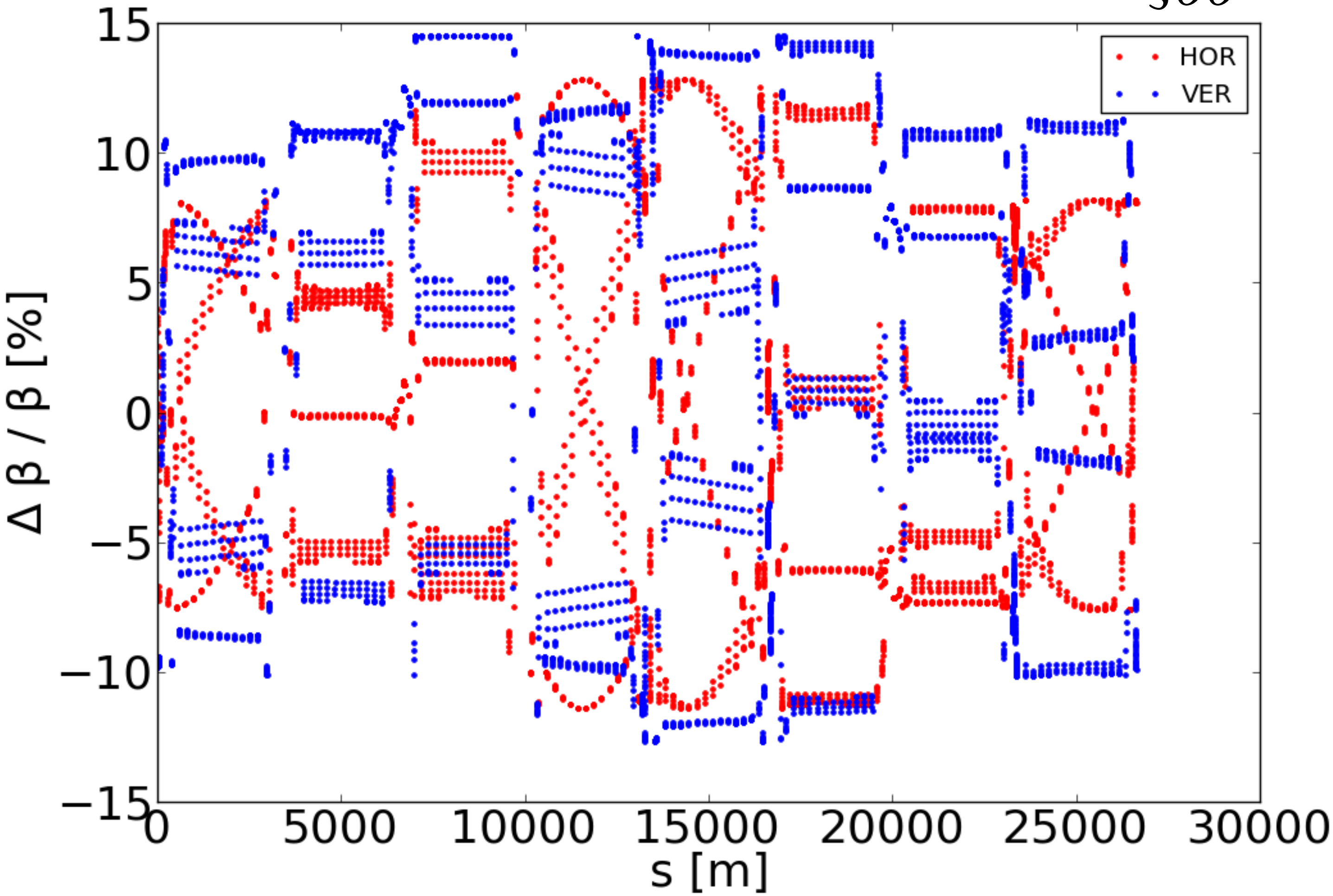
$$\xi_{bb} = 0.02$$



Maximum beating as a function of tune

Dynamic beta-beating due to beam-beam effects

$$\xi_{bb} = 0.02$$



From optics codes beating along the accelerator

How will cleaning efficiency and machine protection deal with such beating?

R. Schmidt next Monday

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects, Tune shifts and Chromaticity
- Compensation ideas
- Landau damping

Long-range Beam-Beam effects: orbit

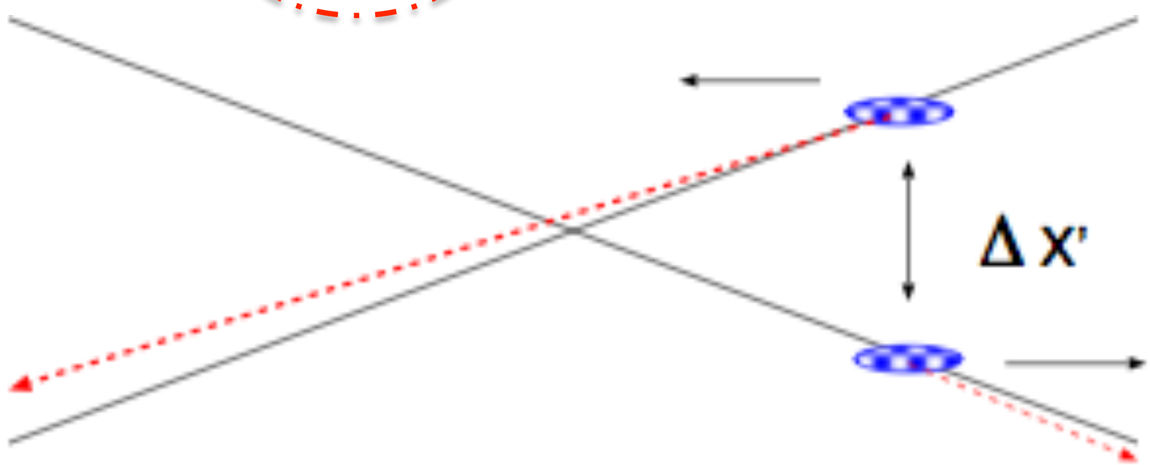
Long Range Beam-beam interactions lead to several effects…

Long range angular kick $\Delta x'(x+d, y, r) = -\frac{2Nr_0}{\gamma}\frac{(x+d)}{r^2}[1-\exp(-\frac{r^2}{2\sigma^2})$

For well separated beams $d \gg \sigma$

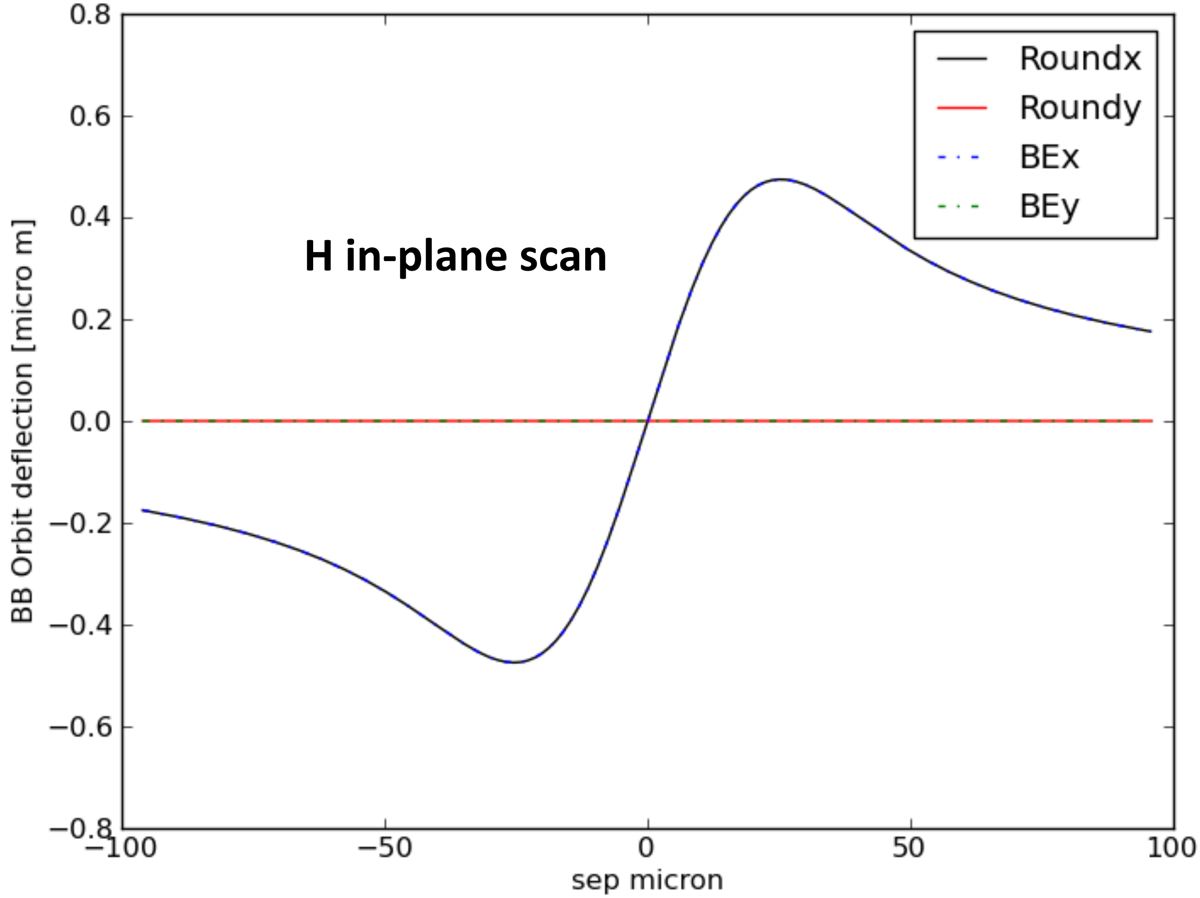
The force has several components at first order we have an amplitude independent contribution: ORBIT KICK

$$\Delta x' = \frac{const}{d}[1 - \frac{x}{d} + O(\frac{x^2}{d^2}) + \ldots]$$



In simple case (1 interaction) one can compute it analytically

Orbit effect as a function of separation



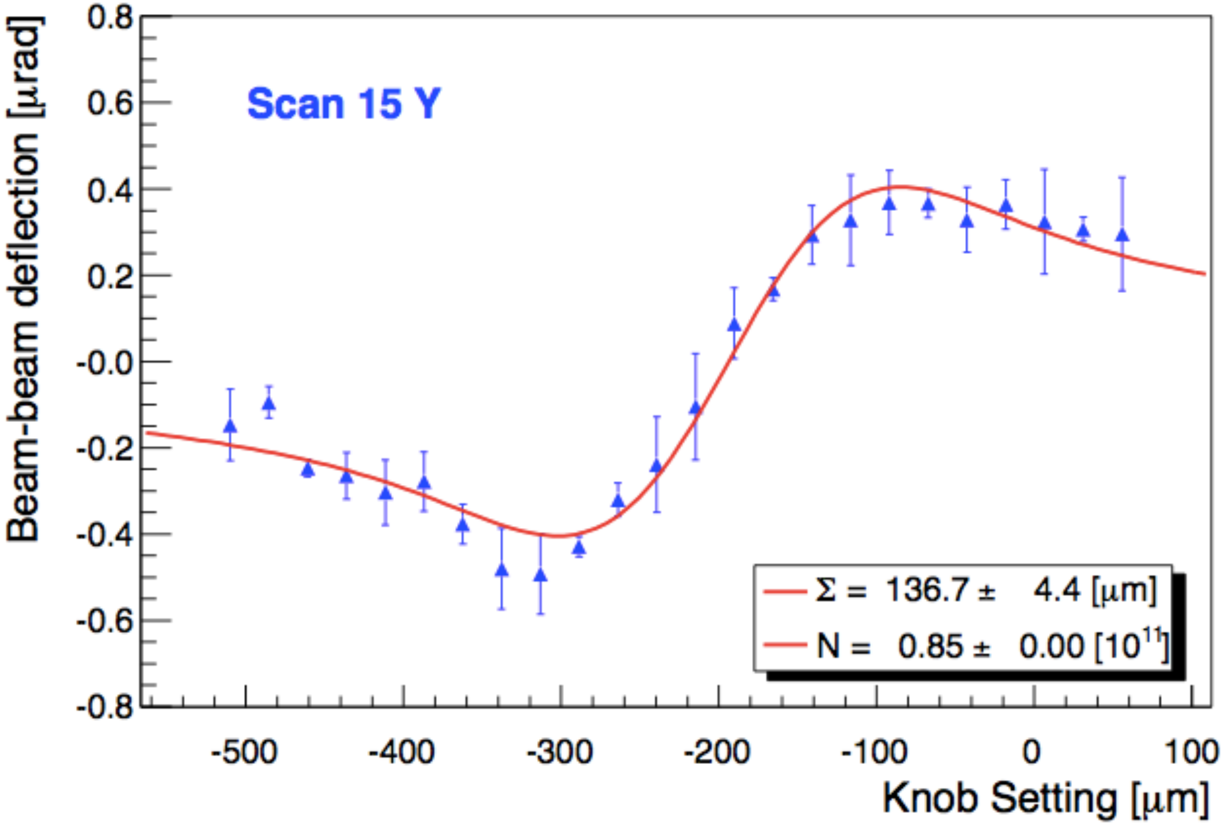
Angular Deflections:

$$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

Closed Orbit effect:

$$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Orbit effect as a function of separation



Angular Deflections:

$$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

Closed Orbit effect:

$$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Orbit can be corrected but we should remember PACMAN effects

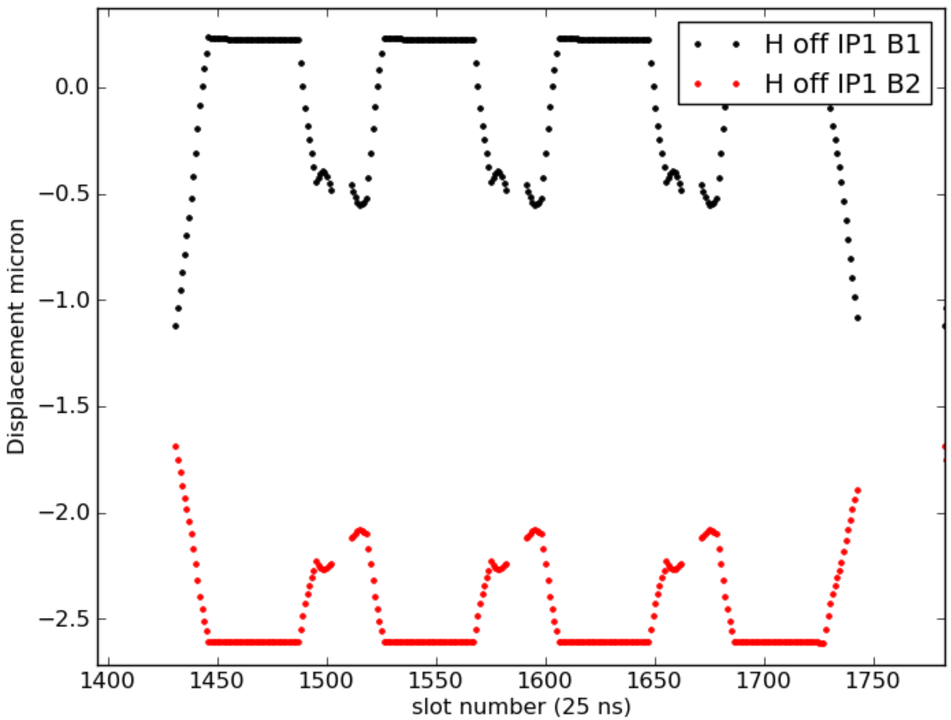
LHC orbit effects

Many long range interactions could become important effect!

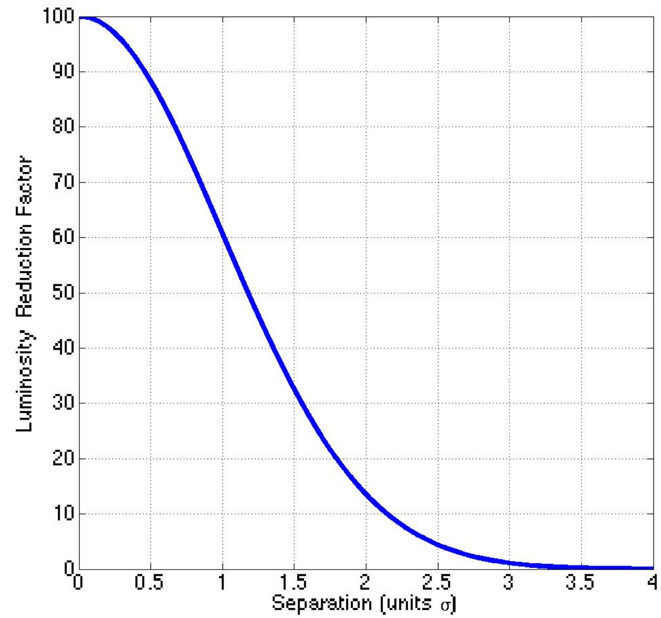
Holes in bunch structure leads to PACMAN effects this cannot be corrected!

$$L = L_0 \cdot e^{-\frac{d^2}{4\sigma_x^2}}$$

Self consistent evaluation



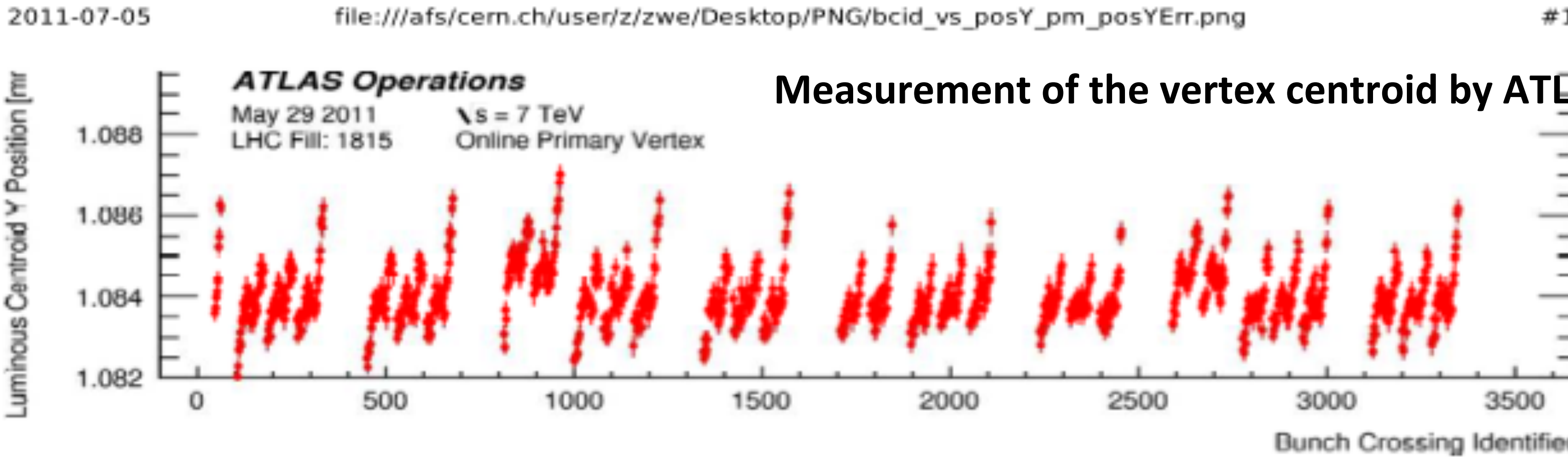
d = 0 – 0.2 units of beam size



Orbit Effect due to PACMAN bunches CANNOT be compensated should be kept SMALL to avoid loss of luminosity!

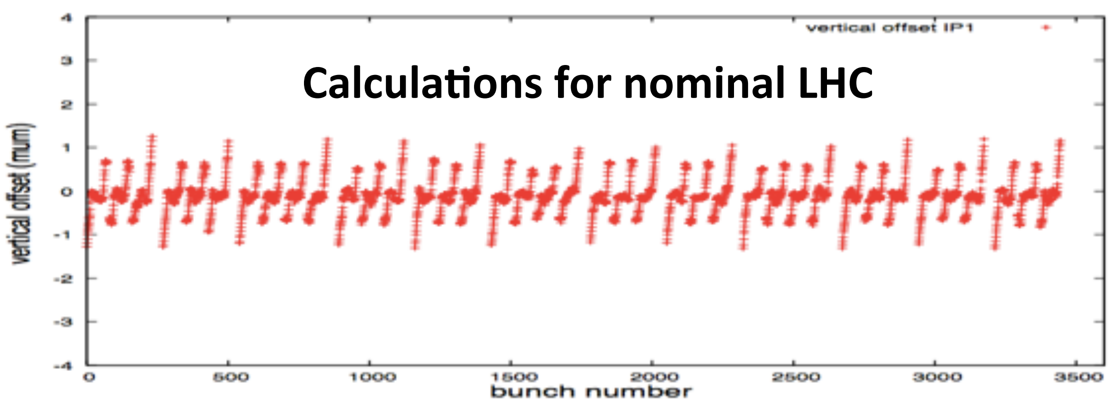
Long range orbit effect

Long range interactions leads to orbit offsets at the experiment a direct consequence is deterioration of the luminosity



Measurement of the vertex centroid by ATLAS

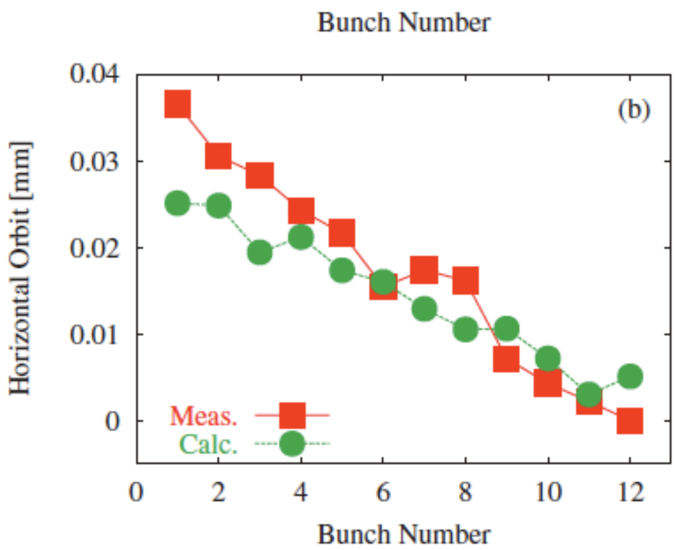
Courtesy W. Kozanecki

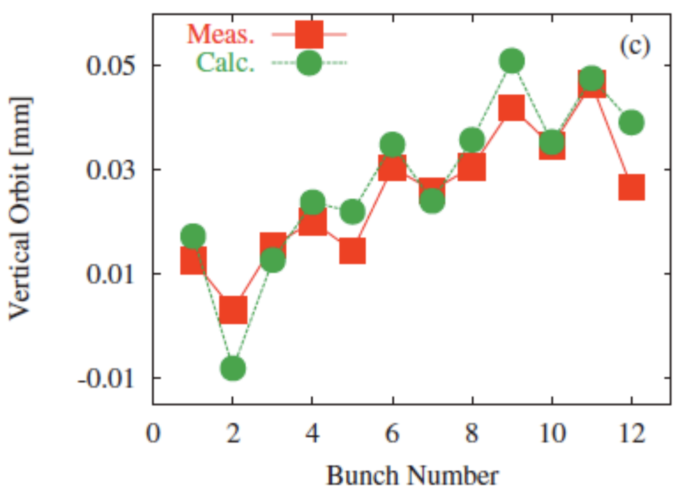


Calculations for nominal LHC

Effect is already visible with reduced number of interactions

Tevatron orbit effects





Beam-beam single bunch orbit can be well reproduced and measured also in LEP

Effects can become important (1 σ offset not impossible)

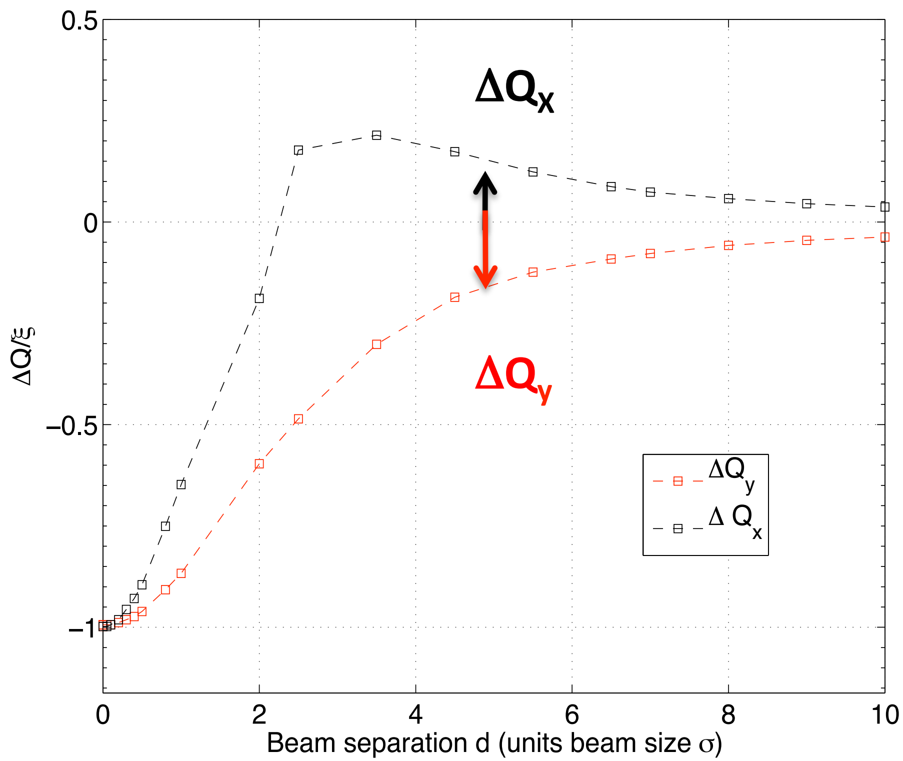
LUMINOSITY Deterioration

Long-range Beam-Beam effects: tune shift

The force has several components : TUNE SHIFT

$$\Delta x' = \frac{const}{d}[1 - \frac{x}{d} + O(\frac{x^2}{d^2}) + \ldots]$$

Zero amplitude particle tune shift when separation in horizontal plane is applied



In plane of separation shift opposite sign respect to non-separated plane

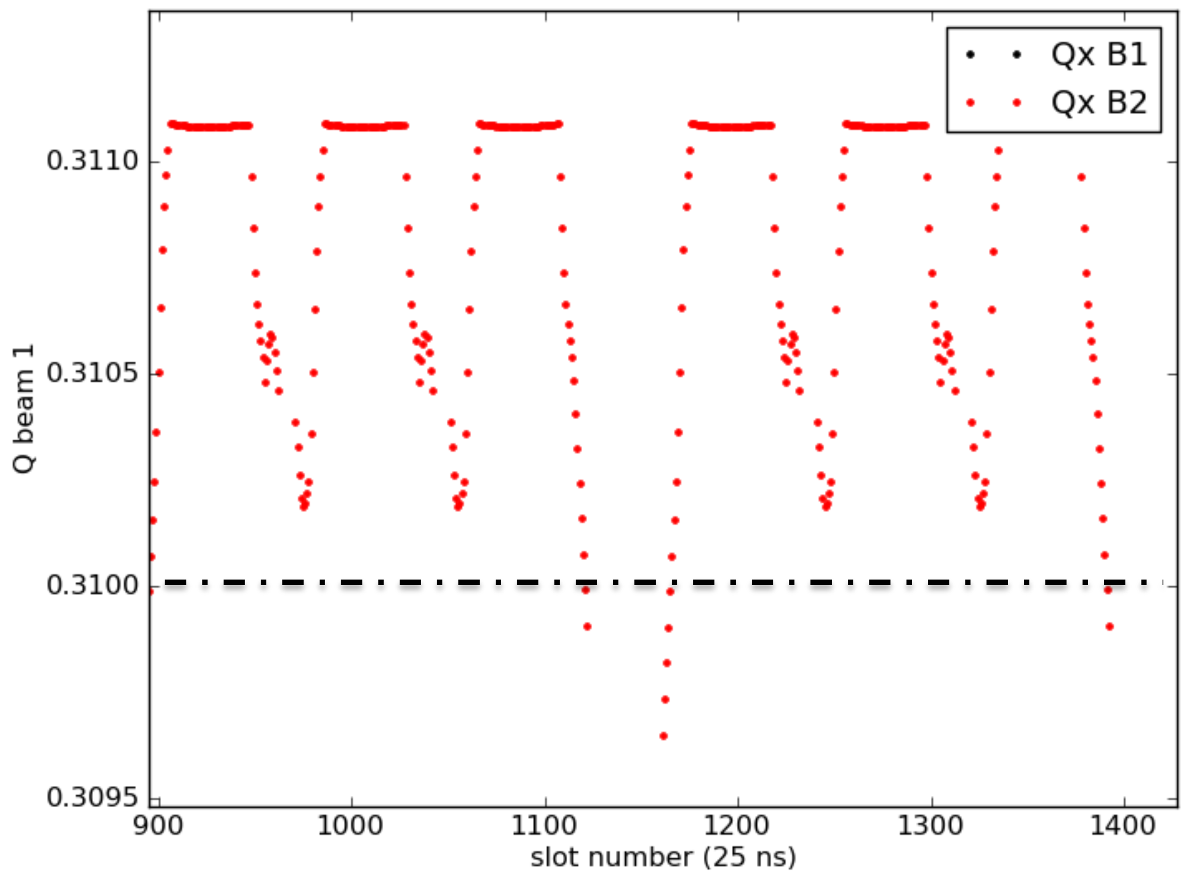
How is it for PACMAN bunches?

Long-range Beam-Beam effects: tune shift

The force has several components : TUNE SHIFT

Need self-consistent treatment to solve the N bunches system

Tune shift from Long range effects

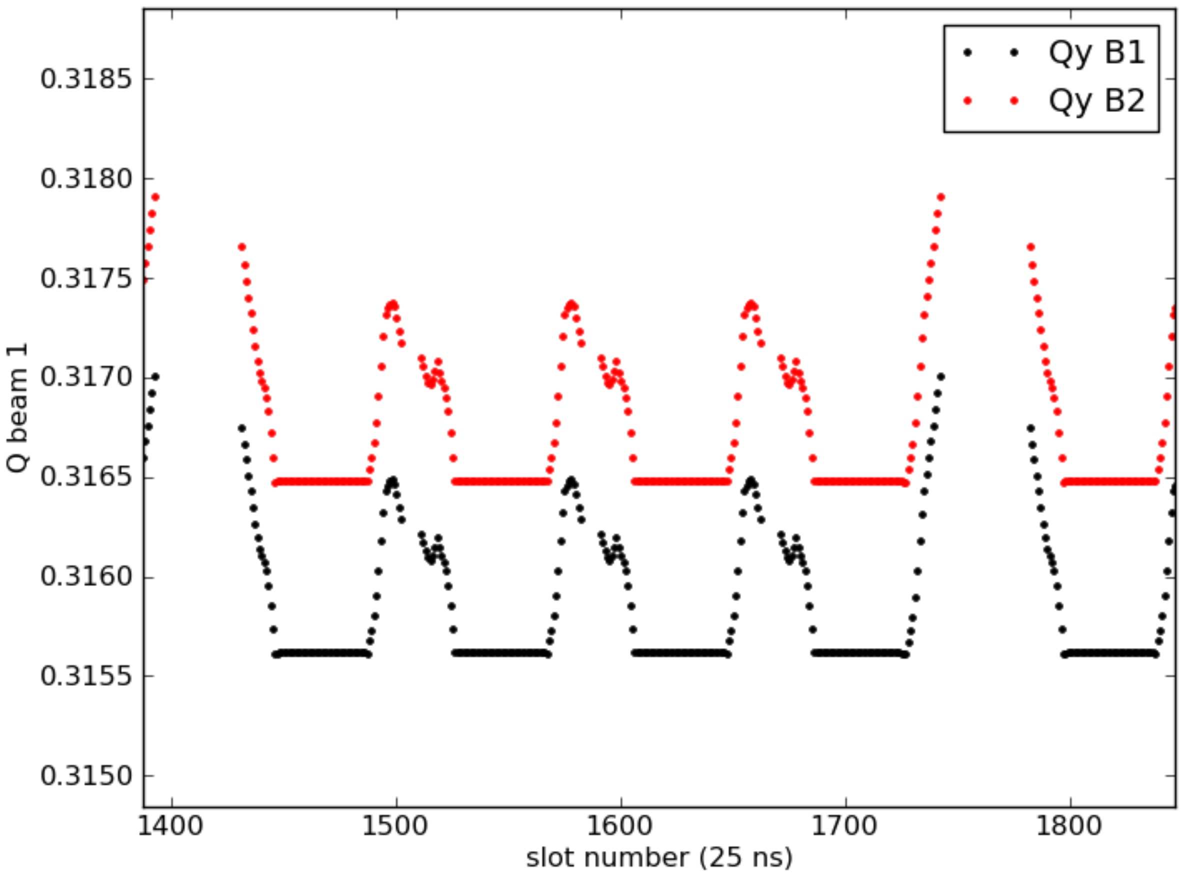


Long-range Beam-Beam effects: tune shift

The force has several components : TUNE SHIFT

Need self-consistent treatment to solve the N bunches system

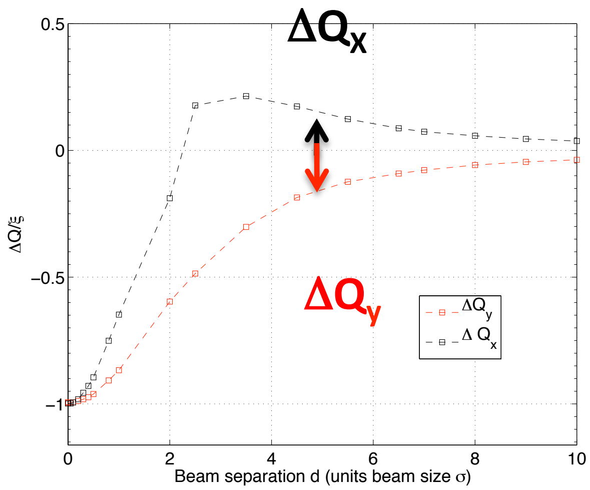
Tune shift in vertical plane from Long range interactions in horizontal plane



Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects, Tune and Chromaticity
- Compensation ideas
- Landau damping

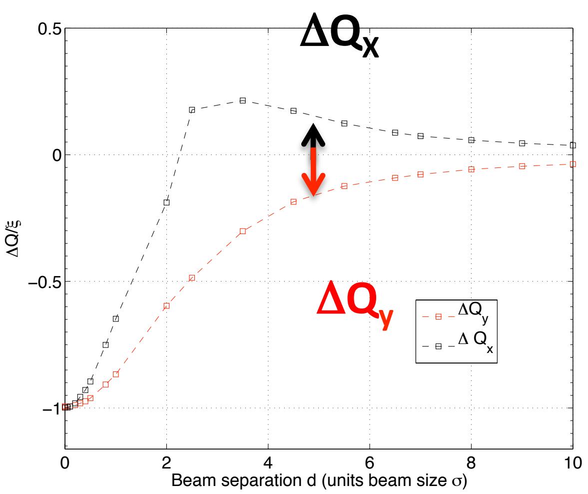
Long-range Beam-Beam effects: tune shift passive compensation



If we have long range interaction in the vertical plane the two curves just swap!

Can we profit of this?

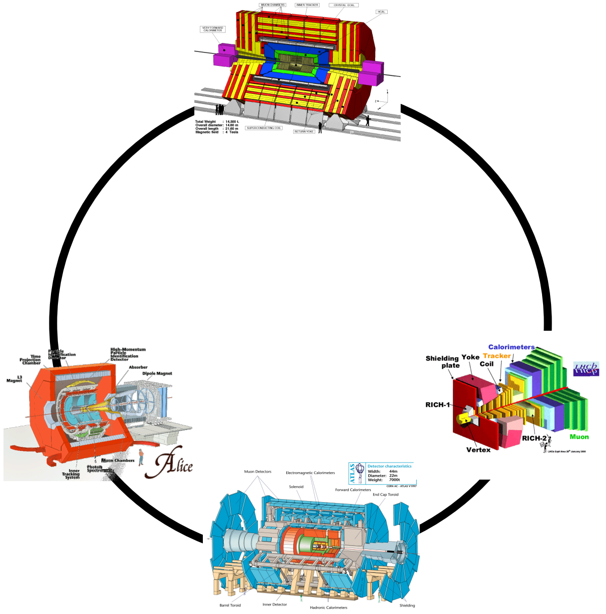
Long-range Beam-Beam effects: tune shift passive compensation



If we have long range interaction in the vertical plane the two curves just swap!

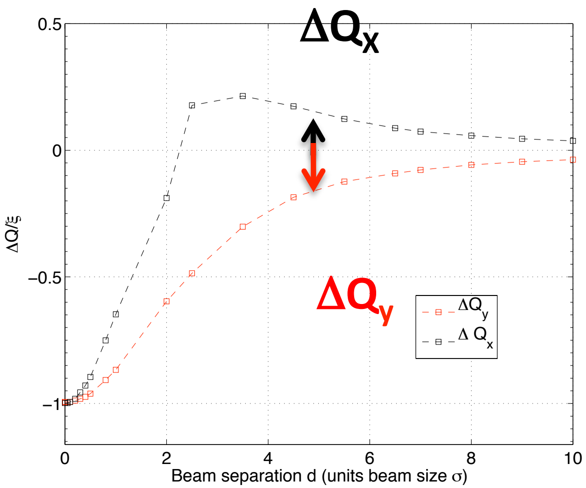
Can we profit of this? YES....

CMS Horizontal crossing angle→long ranges shift like in plot



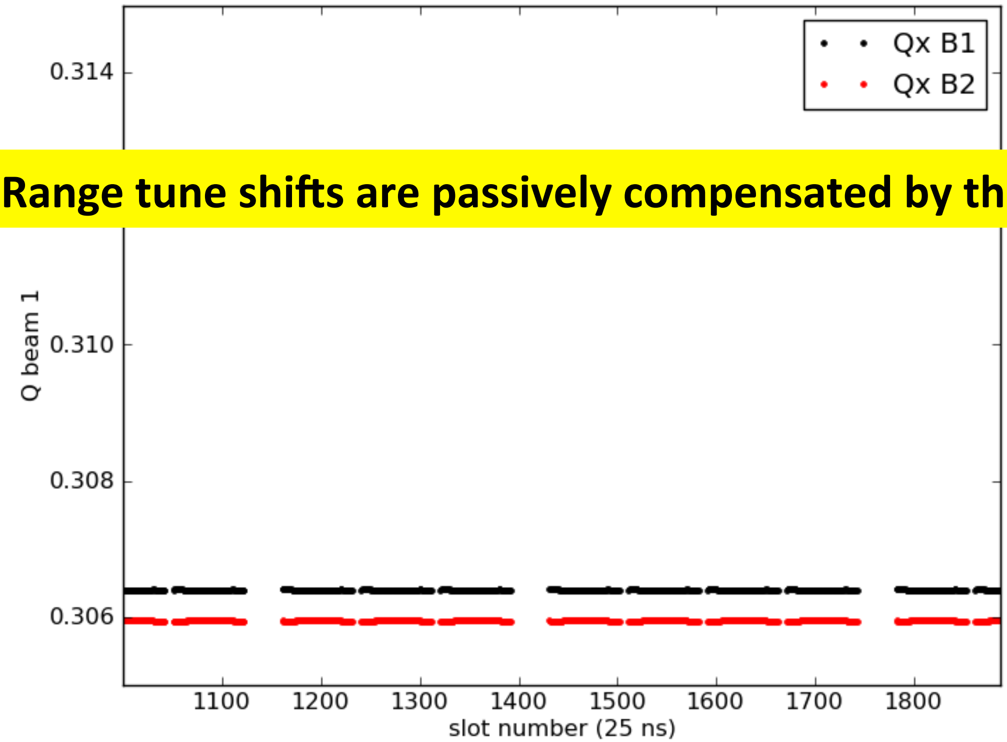
ATLAS Vertical crosing angle→long ranges shift opposite than plot

Long-range Beam-Beam effects: tune shift passive compensation



If we have long range interaction in the vertical plane the two curves just swap!

Can we profit of this? YES….



Long Range tune shifts are passively compensated by this trick!

Long range effects: chromaticity

The Long Range interaction also change chromaticity
How???

Here some examples on how to compensate passively these effects

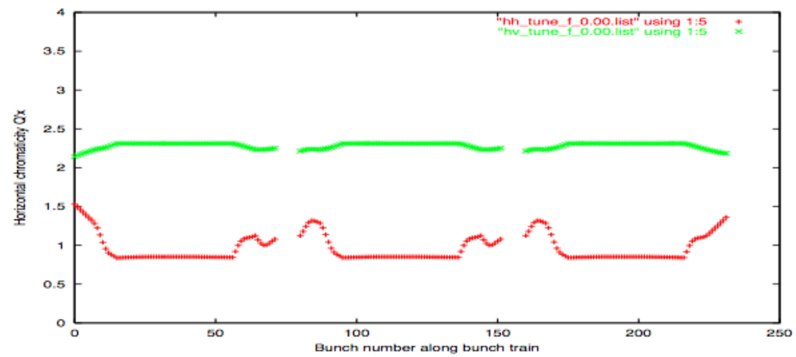
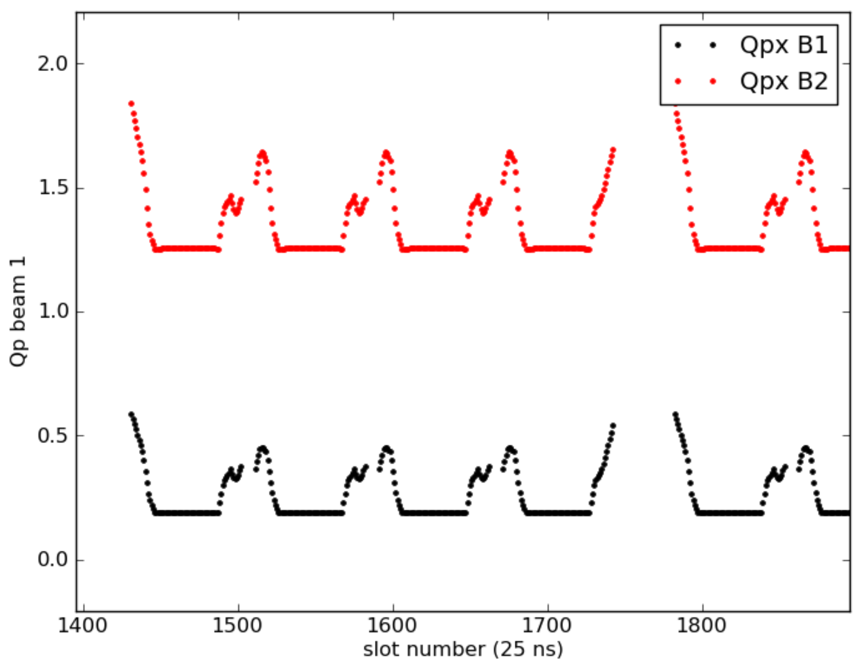


Figure 36: Horizontal chromaticity variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.

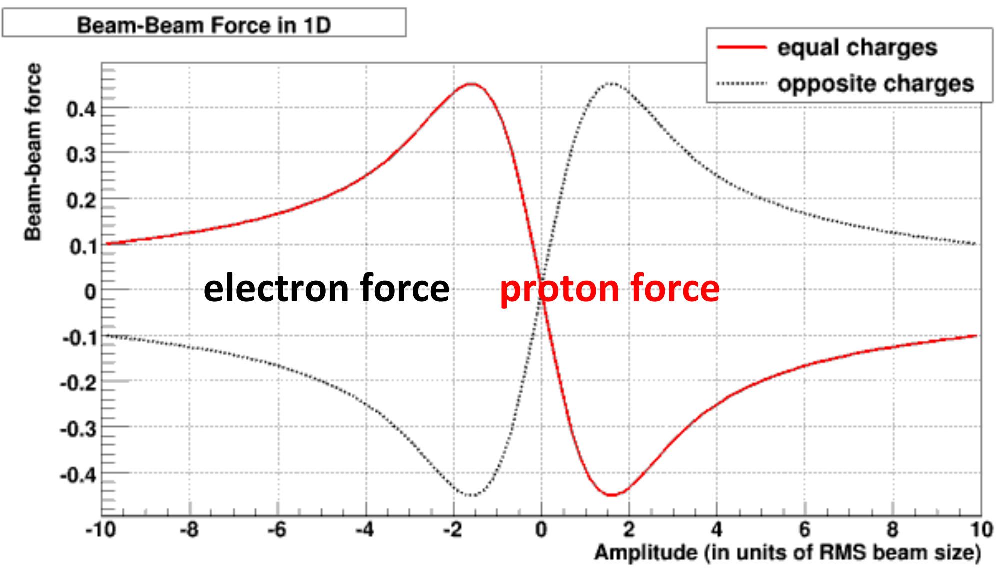


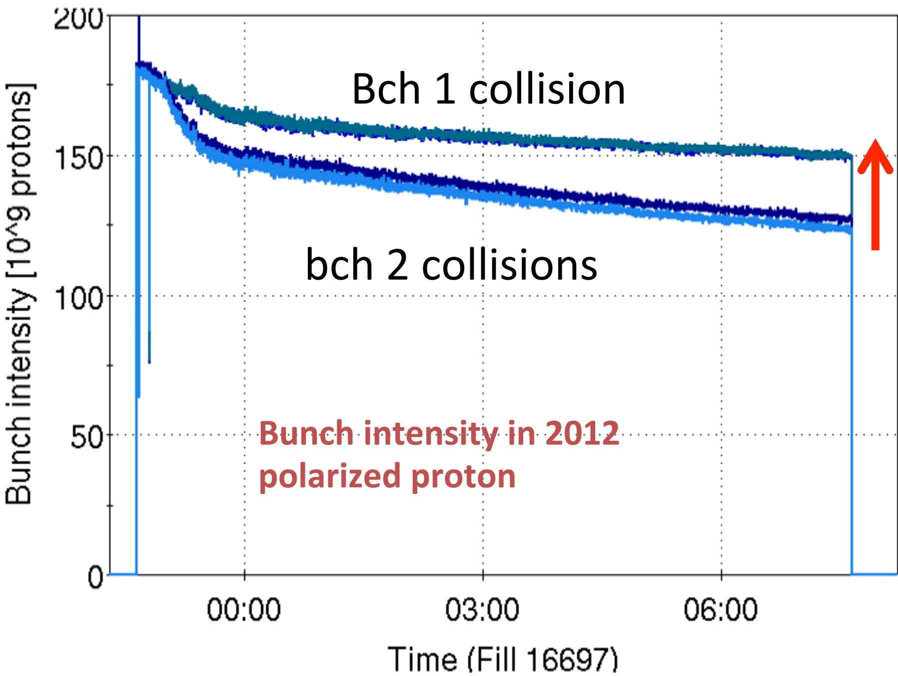
Long Range chromaticity shifts are passively compensated by this trick!

Beam-beam compensations:

Head-on

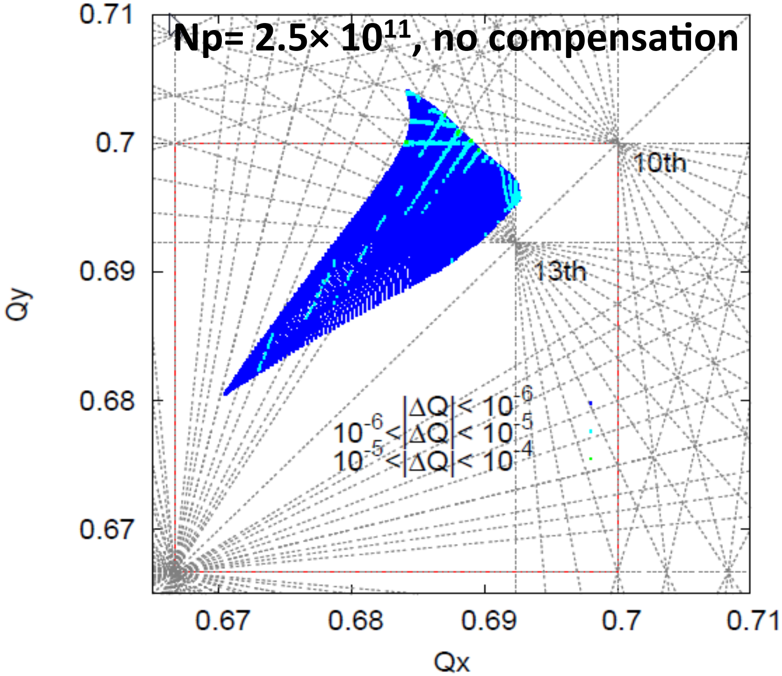
- Linear e-lens, suppress shift
- Non-linear e-lens, suppress tune spread

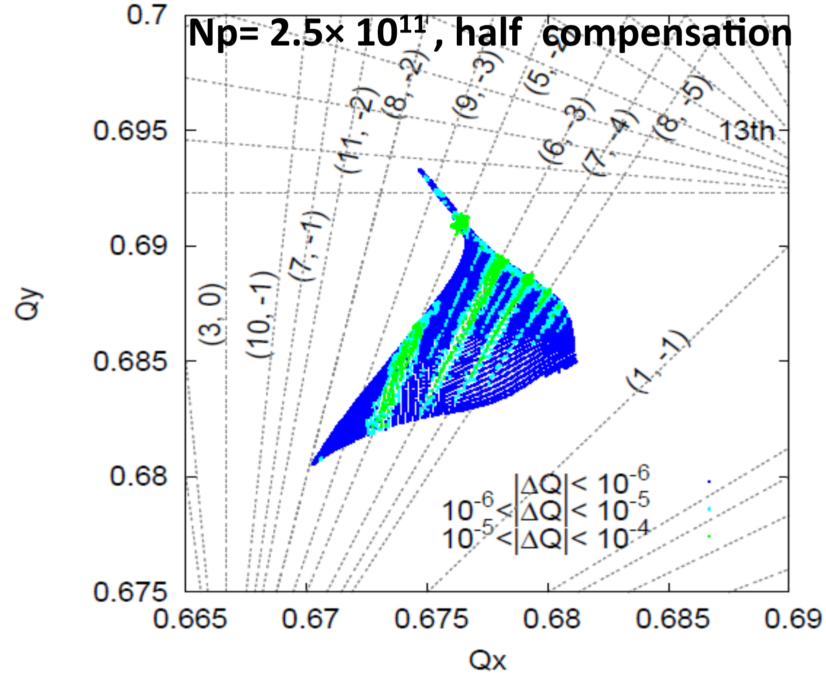


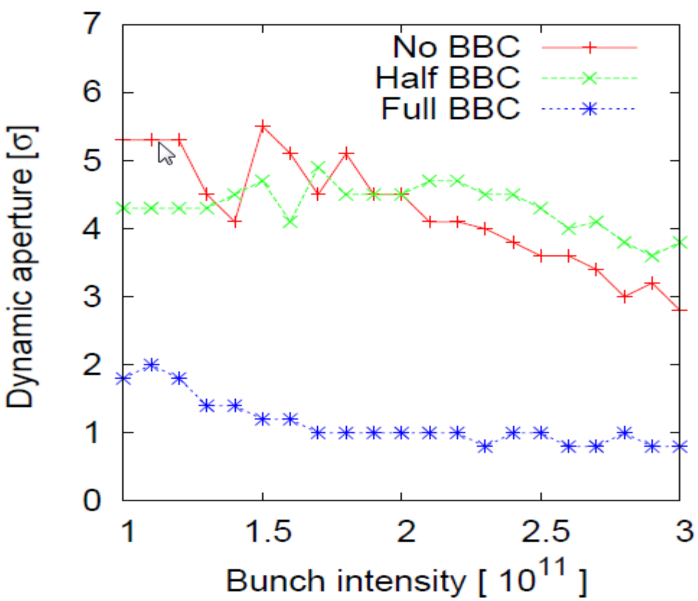


Past experience: at Tevatron linear and non-linear e-lenses, also hollow….

RHIC HO compensation strategy





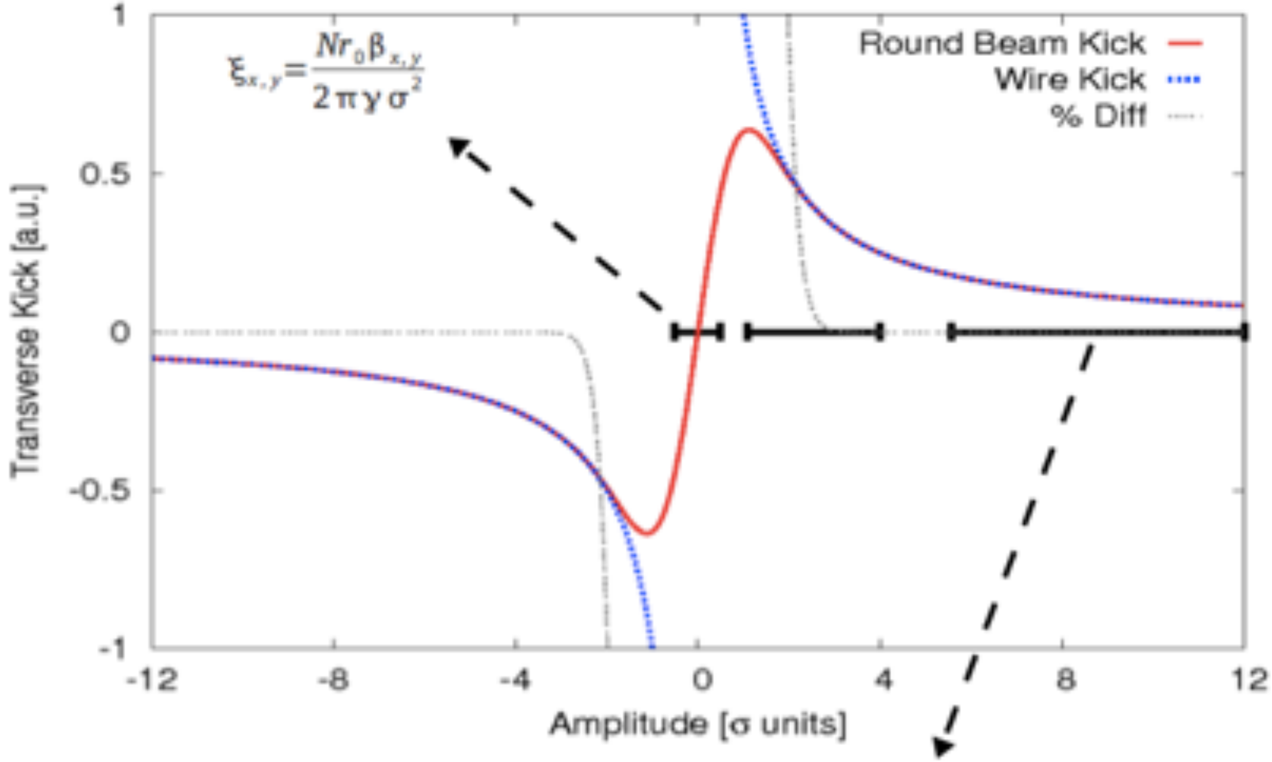


Calculated dynamic aperture and particle loss rate show that **half beam-beam compensation** improves proton beam's beam lifetime.

Fully commissioned and operational at RHIC with factor 2 luminosity increase…

Beam-beam compensations: long-range

Beam-beam wire compensation

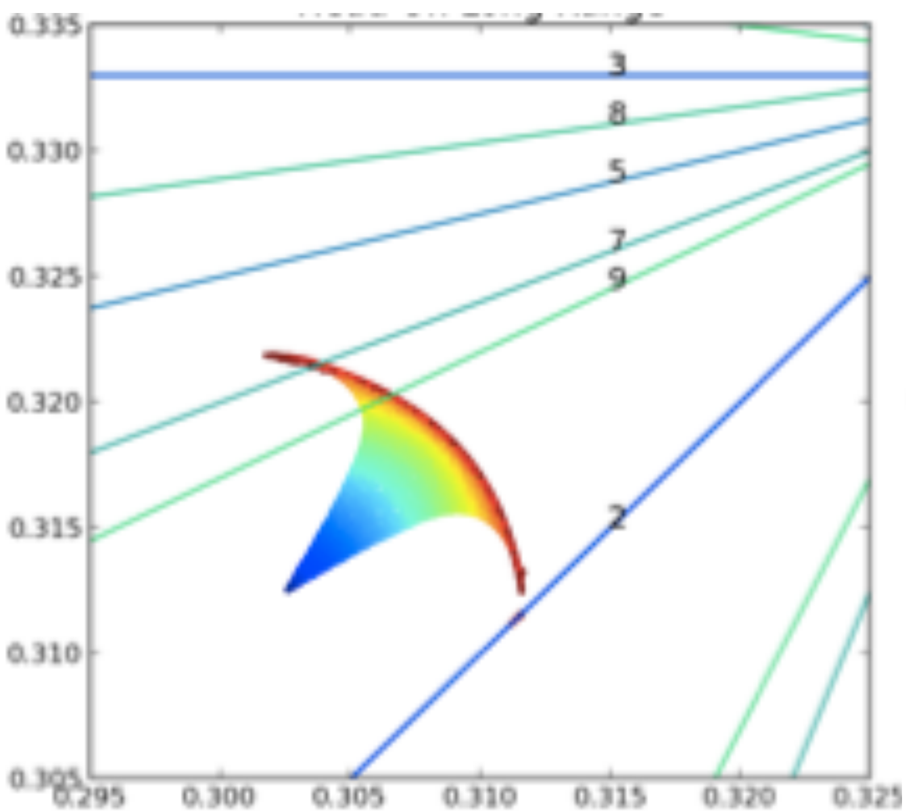


σ << d: $\Delta x'(x,d) = -\frac{K}{d}.(1 + \frac{x}{d} + \frac{x^2}{d^2} + \ldots)$

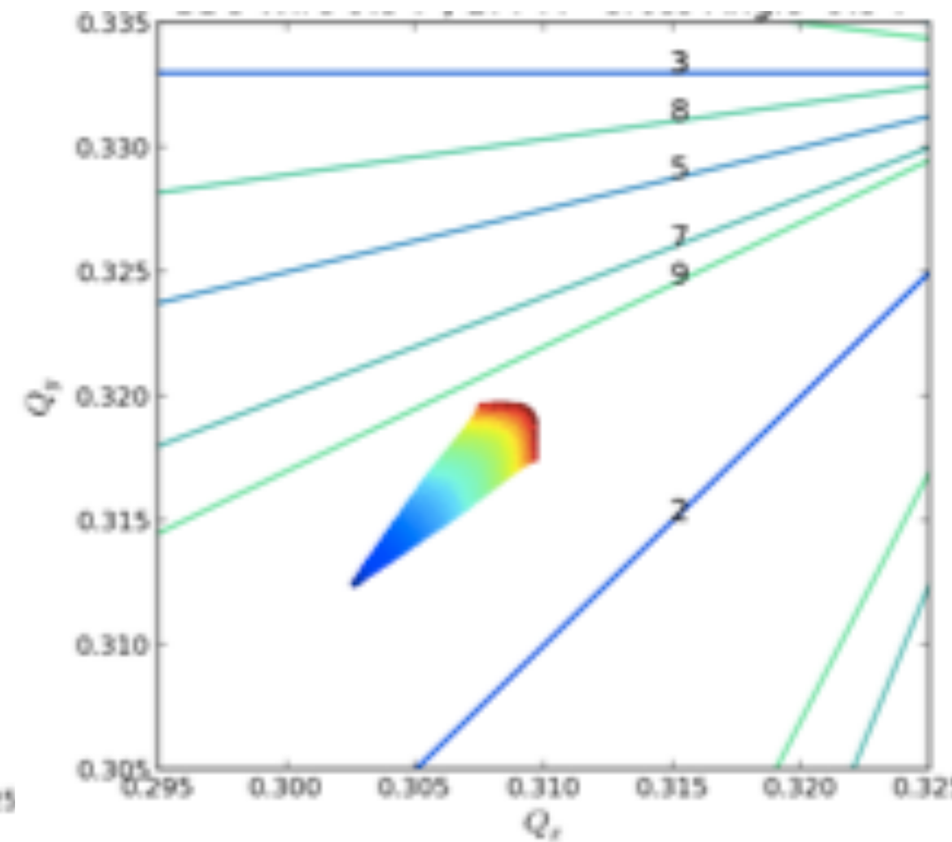
Past experience with beams: at RHIC several tests till 2009…

Study case for the LHC

Head-on and Long-Range



Head-on and Long-Range + WIRE



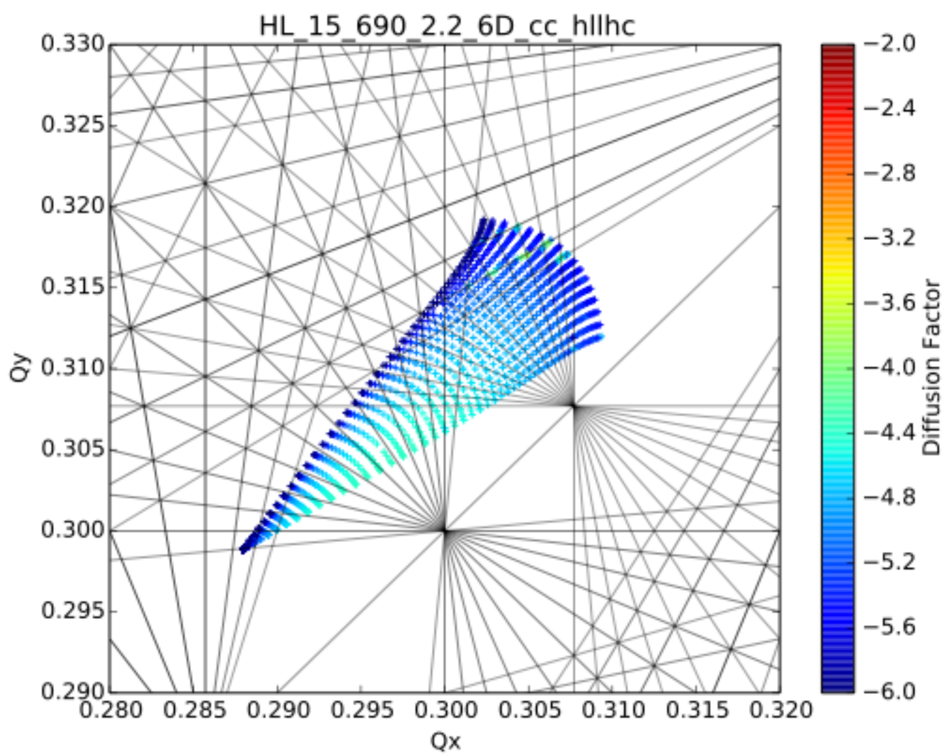
Present: simulation studies on-going for possible use in HL-LHC…

Outline

- High Energy and High Luminosity
- Beam-Beam Force
- Head-on and Long Range
- Linear Tune shift and beam-beam parameter
- Detuning with amplitude
- Resonance driving terms
- Dynamical Aperture and particle losses
- Dynamic beta and beating
- Orbit Effects, Tune and Chromaticity
- Compensation ideas
- Landau damping

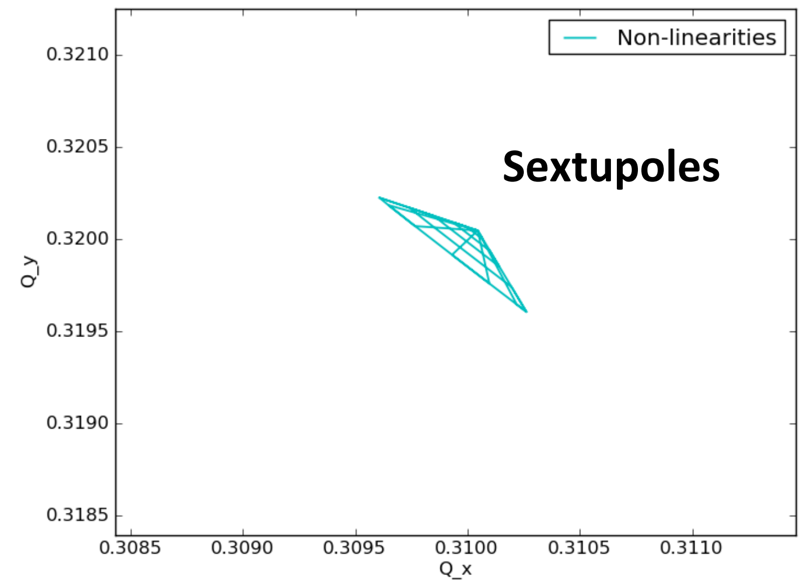
Beam-Beam spread and Landau Damping

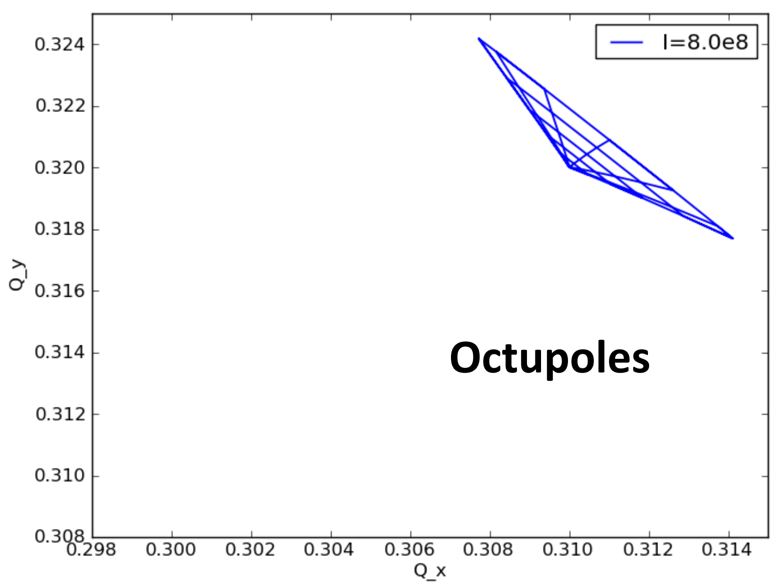
Non-linearities produce a tune/frequency spread
Larger the spread stronger the Landau damping
Which is now the strongest non-linearity in the collider?

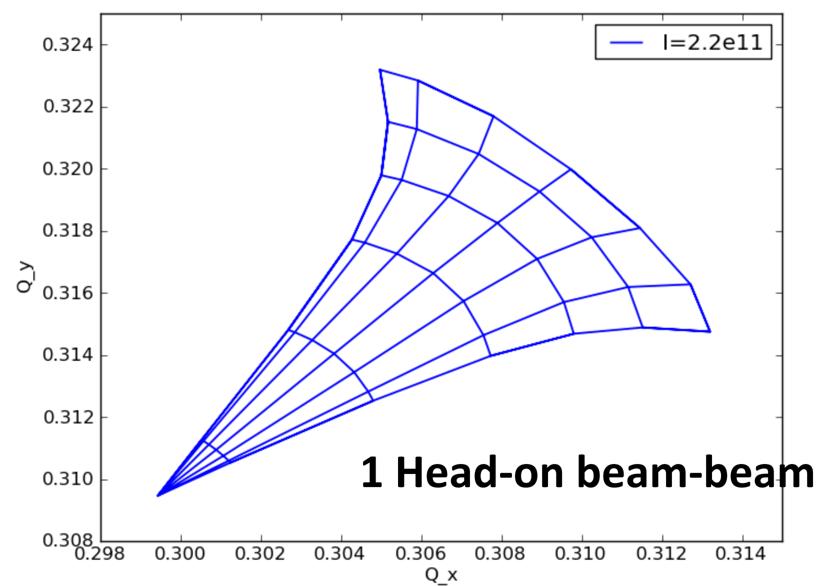


Beam-Beam spread and Landau Damping

Non-linearities produce a tune/frequency spread
Beam-Beam is the strongest non-linearity in a colliders







Frequency spread means Landau damping

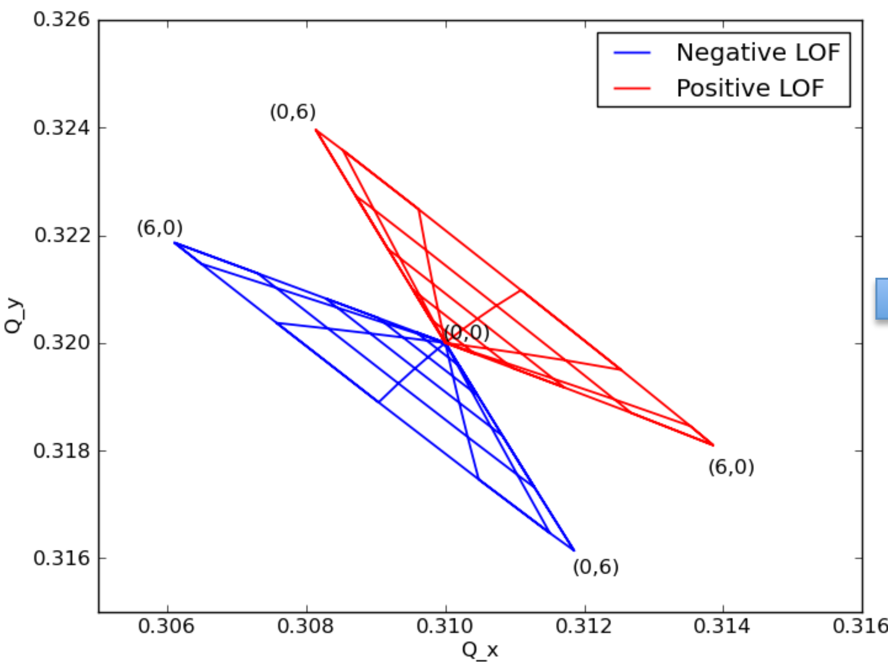
Larger frequency spread → Stronger Landau damping

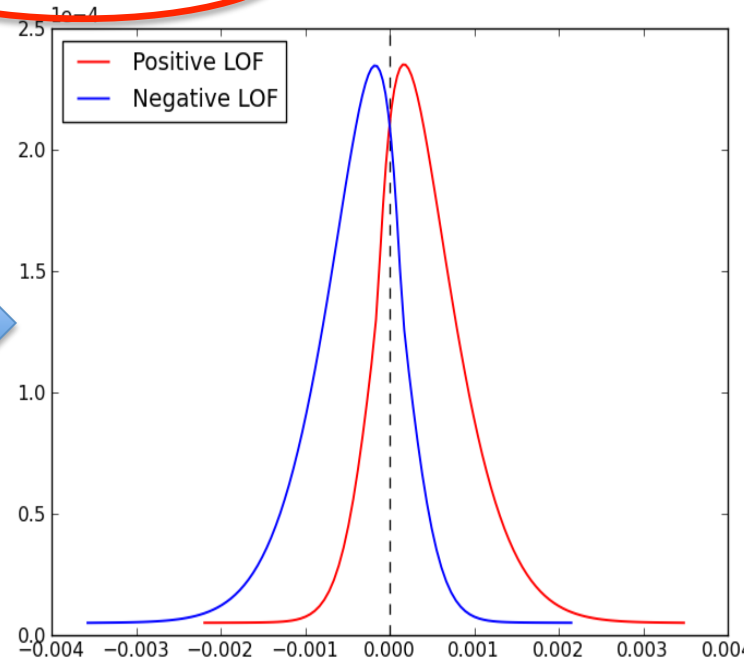
A. Chao

A way to quantify the Landau damping is by use of the Stability Diagram

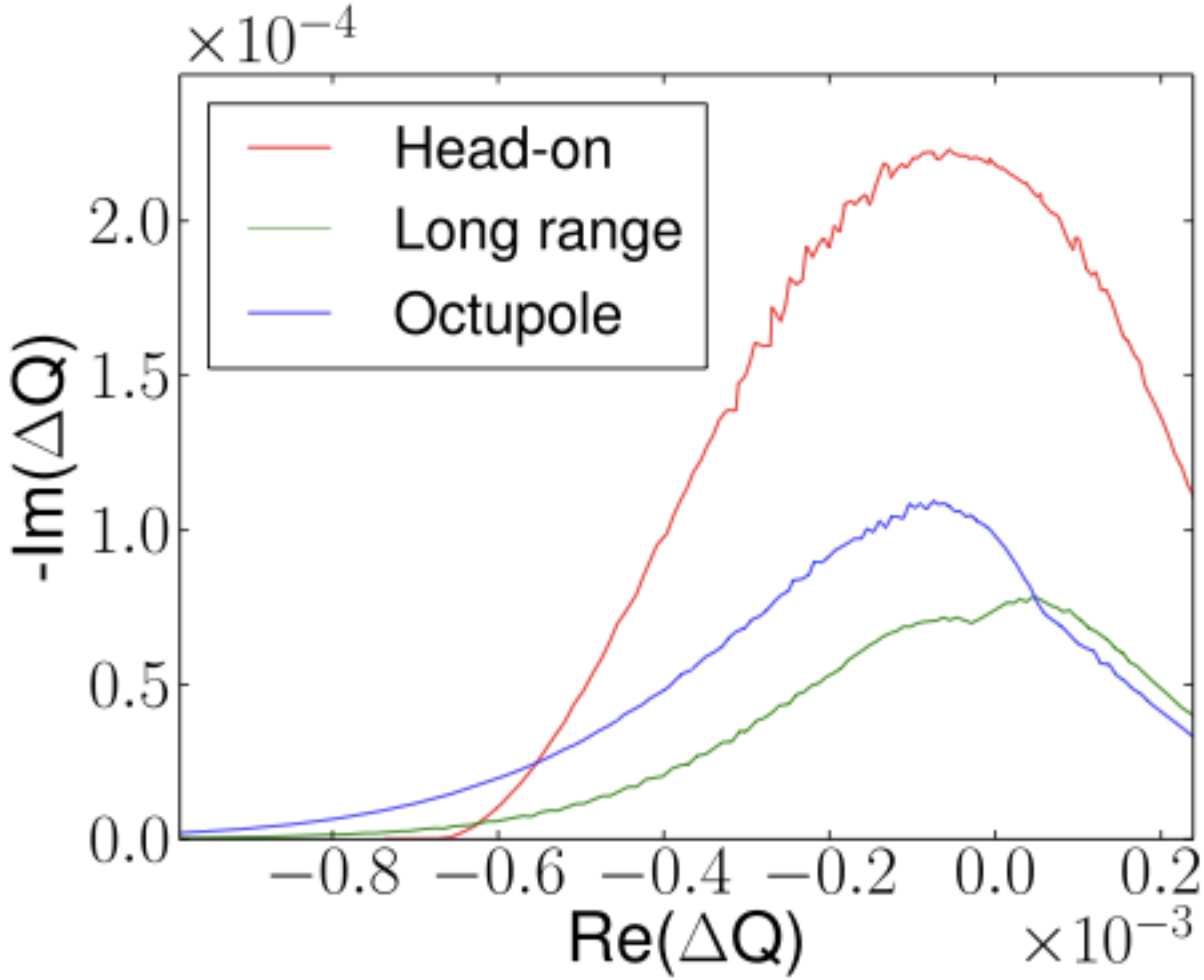
V. Kornilov

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$





Frequency spread means Landau damping



Larger Stability area (Landau Damping) doesn't mean always more stability

X. Buffat

…not covered here…

- *Asymmetric beams effects*
- *Coasting beams*
- *Synchro-betatron coupling*
- *Beam-beam coherent effects*
- *Beam-beam and impedance* **X. Buffat**
- *Noise on colliding beams*
- *Lepton colliders* **K. Milardi**
- *Linear colliders* **D. Schulte**
- *…*

Thank you!

Questions?

References:

[1] http://cern.ch/Werner.Herr/CAS2009/proceedings/bb_proc.pdf

[2] V. Shiltsev et al, "Beam beam effects in the Tevatron", Phys. Rev. ST Accel. Beams 8, 101001 (2005)

[3] Lyn Evans "The beam-beam interaction", CERN 84-15 (1984)

[4] Alex Chao "Lie Algebra Techniques for Nonlinear Dynamics" SLAC-PUB-9574 (2002)

[5] J. D. Jackson, "Classical Electrodynamics", John Wiley & Sons, NY, 1962.

[6] H. Grote, F. Schmidt, L. H. A. Leunissen,"LHC Dynamic Aperture at Collision", LHC-Project-Note 197, (1999).

[7] W. Herr,"Features and implications of different LHC crossing schemes", LHC-Project-Note 628, (2003).

[8] A. Hofmann,"Beam-beam modes for two beams with unequal tunes", CERN-SL-99-039 (AP) (1999) p. 56.

[9] Y. Alexahin, "On the Landau damping and decoherence of transverse dipole oscillations in colliding beams ", Part. Acc. 59, 43 (1996).

*[10] R. Assmann et al., "*Results of long-range beam-beam studies - scaling with beam separation and intensity "

…much more on the LHC Beam-beam webpage:

http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/