Beam-beam effects

(an introduction)

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(http://cern.ch/lhc-beam-beam/talks/Daresbury_beambeam.pdf)

BEAMS: moving charges

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

→ Forces on itself (space charge) and opposing beam (beam-beam effects)

→ Main limit in past, present and future colliders

→ Important for high density beams, i.e. high intensity and/or small beams:
for high luminosity !

Beam-beam effects

Remember:

$$\Longrightarrow \quad \mathcal{L} = \frac{N_1 N_2 f n_B}{4\pi \sigma_x \sigma_y} \quad = \quad \frac{N_1 N_2 f n_B}{4\pi \cdot \ \sigma_x \sigma_y}$$

- **Overview: which effects are important for present and future machines (LEP, PEP, Tevatron, RHIC, LHC, ...)**
- **Qualitative and physical picture of the effects**
- **Mathematical derivations in: Proceedings, Zeuthen 2003**

Beam-beam effects

- **A beam acts on particles like an electromagnetic lens, but:**
  - **Does not represent simple form, i.e. well defined multipoles**
  - **Very non-linear form of the forces, depending on distribution**
  - **Can change distribution as result of interaction (time dependent forces ..)**
- **Results in many different effects and problems**

Fields and Forces (I)

- **Need fields $\vec{E}$ and $\vec{B}$ of opposing beam.**
- **In rest frame only electrostatic field: $\vec{E}'$, $\vec{B}' \equiv 0$**
- **Derive potential U(x, y, z) from Poisson equation:**

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

- **The electrostatic fields become:**

$$\vec{E}' = -\nabla U(x, y, z)$$

Fields and Forces (II)

- **Transform into moving frame and calculate Lorentz force $\vec{F}$ on particle with charge $q = Z_2$ e**

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

$$\vec{F} = q(\vec{E} + \vec{\beta} \times \vec{B})$$

- **Example Gaussian distribution:**

$$\rho(x, y, z) = \frac{N Z_1 e}{\sigma_x \sigma_y \sigma_z \sqrt{2\pi}^3} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right)$$

Simple example: Gaussian

- **For 2D case the potential becomes (see proceedings):**

$$U(x, y, \sigma_x, \sigma_y) = \frac{N Z_1 e}{4\pi\epsilon_0}\int_0^\infty \frac{\exp(-\frac{x^2}{2\sigma_x^2+q} - \frac{y^2}{2\sigma_y^2+q})}{\sqrt{(2\sigma_x^2+q)(2\sigma_y^2+q)}}dq$$

- **Can derive $\vec{E}$ and $\vec{B}$ fields and therefore forces**
- **For arbitrary distribution (non-Gaussian): difficult (or impossible, numerical solution required)**

Simple example: Gaussian

- **Round beams:** $\sigma_x = \sigma_y = \sigma$, $\quad Z_1 = -Z_2 = 1$
- **Only components** E_r **and** B_Φ **are non-zero**

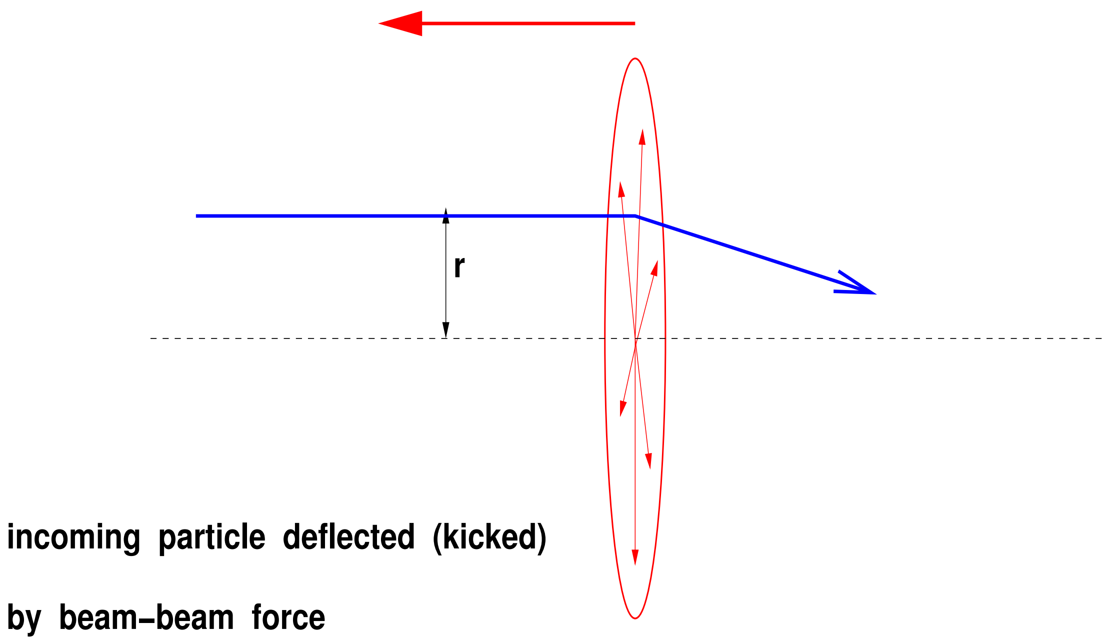
→ **Force has only radial component, i.e. depends only on distance r from bunch centre**

(where: $r^2 = x^2 + y^2$*)* (see proceedings)

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

Beam-beam kick:

➡ **We need the deflection (kick) of the particle:**



Beam-beam kick:

- **Kick ($\Delta r'$): angle by which the particle is deflected during the passage**
- **Derived from force by integration over the collision (assume: m_1=m_2 and $Z_1 = -Z_2 = 1$):**

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

$$\text{with Newton's law :} \qquad \Delta r' = \frac{1}{mc\beta\gamma}\int_{\infty}^{\infty} F_r(r, s, t)dt$$

Beam-beam kick:

➡ **Using the classical particle radius (implies $Z_1 = \pm Z_2$):**

$$r_0 = e^2/4\pi\epsilon_0 mc^2$$

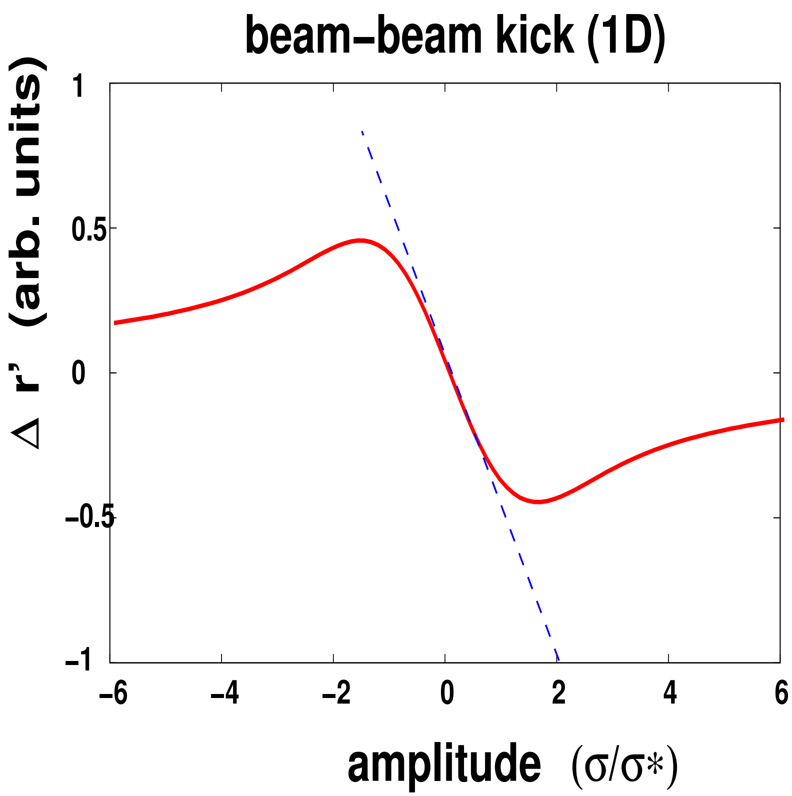
we have (radial kick and in Cartesian coordinates):

$$\Delta r' = -\frac{2Nr_0}{\gamma} \cdot \frac{r}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

$$\Delta x' = -\frac{2Nr_0}{\gamma} \cdot \frac{x}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

$$\Delta y' = -\frac{2Nr_0}{\gamma} \cdot \frac{y}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

Beam-beam force/kick



- For small amplitudes: linear force
  - amplitude independent tune change (like quadrupole)
- For large amplitudes: very non−linear
  - amplitude dependent tune change (like non−linear fields)

Can we quantify the beam-beam strength ?

- **Try the slope of force (kick $\Delta r'$) at zero amplitude**
- **This defines: beam-beam parameter ξ**
- **For head-on interactions and round beams ($\beta^* = \beta^*_x = \beta^*_y$) we get:**

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

LEP - LHC

	LEP (e^+e^-)	LHC (pp)
Beam sizes	160 - 200μm $\cdot$ 2 - 4μm	16.6μm $\cdot$ 16.6μm
Intensity N	4.0 $\cdot$ 10^{11}/bunch	1.15 $\cdot$ 10^{11}/bunch
Energy	100 GeV	7000 GeV
$\beta_x^* \cdot \beta_y^*$	1.25 m $\cdot$ 0.05 m	0.55 m $\cdot$ 0.55 m
Crossing angle	0.0	285 μrad
Beam-beam parameter(ξ)	(+) 0.0700	($-$) 0.0034

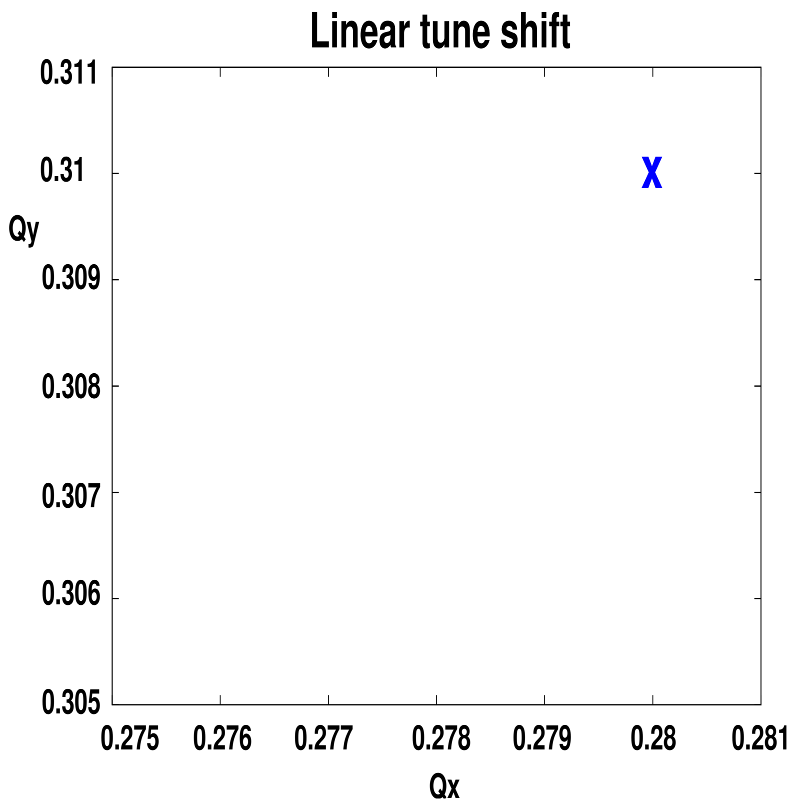
Can we quantify the beam-beam strength ?

- **In general for non-round beams ($\beta^*_x \neq \beta^*_y$):**

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

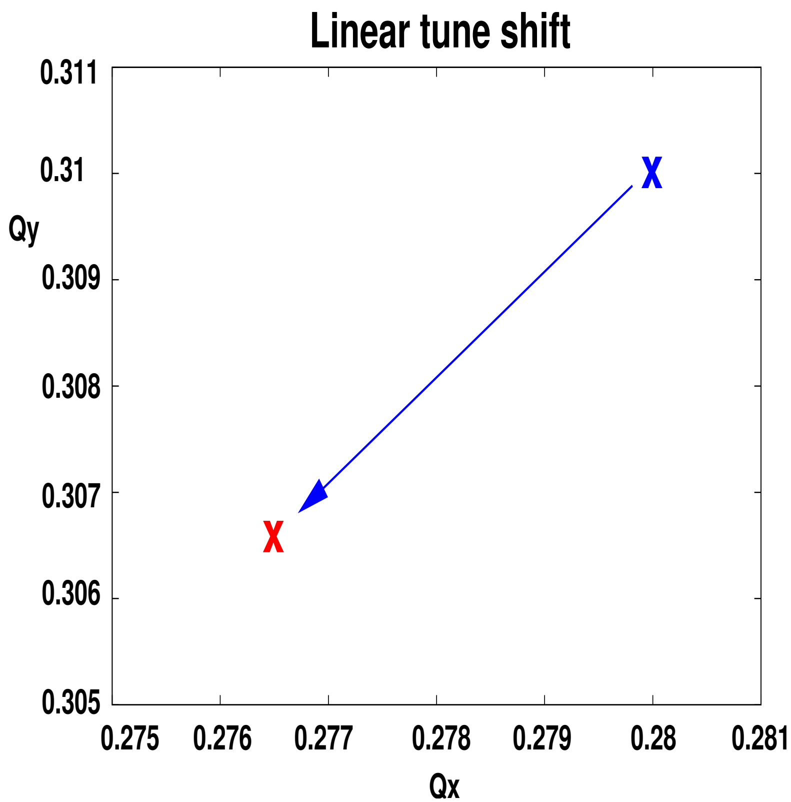
- **Proportional to (linear) tune shift Δ Q$_{bb}$ from beam-beam interaction: $\Delta\, Q_{bb} \propto \pm\, \xi$**
- **Good measure for strength of beam-beam interaction**
- **BUT: does not describe**
  - → **changes to optical functions**
  - → **non-linear part of beam-beam force**

Linear tune shift - two dimensions



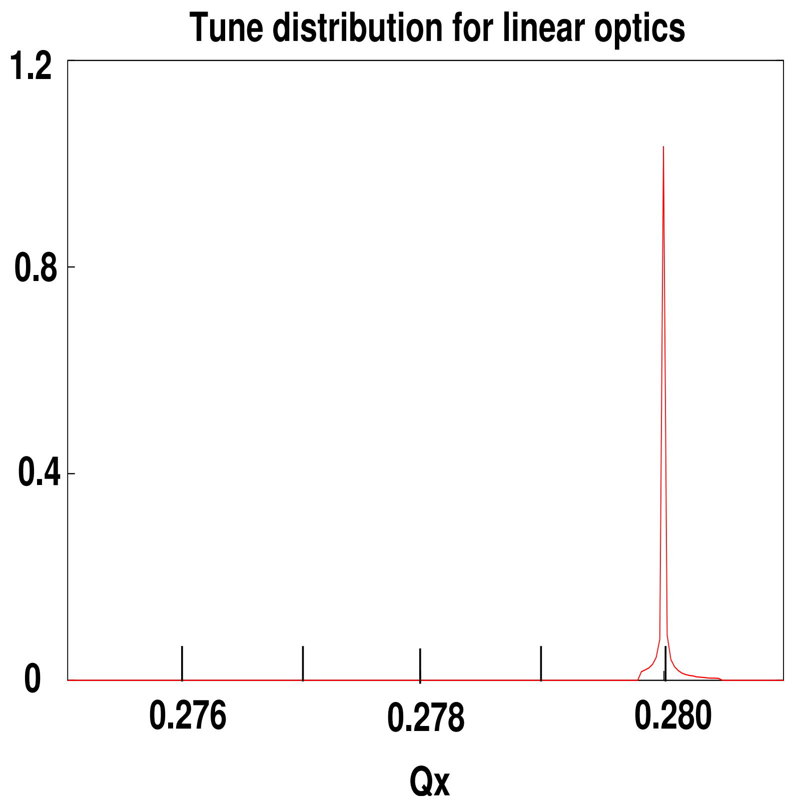
- Start with standard working point
- LHC (equally charged beams)
- Beam–beam shifts tune in both planes

Linear tune shift - two dimensions



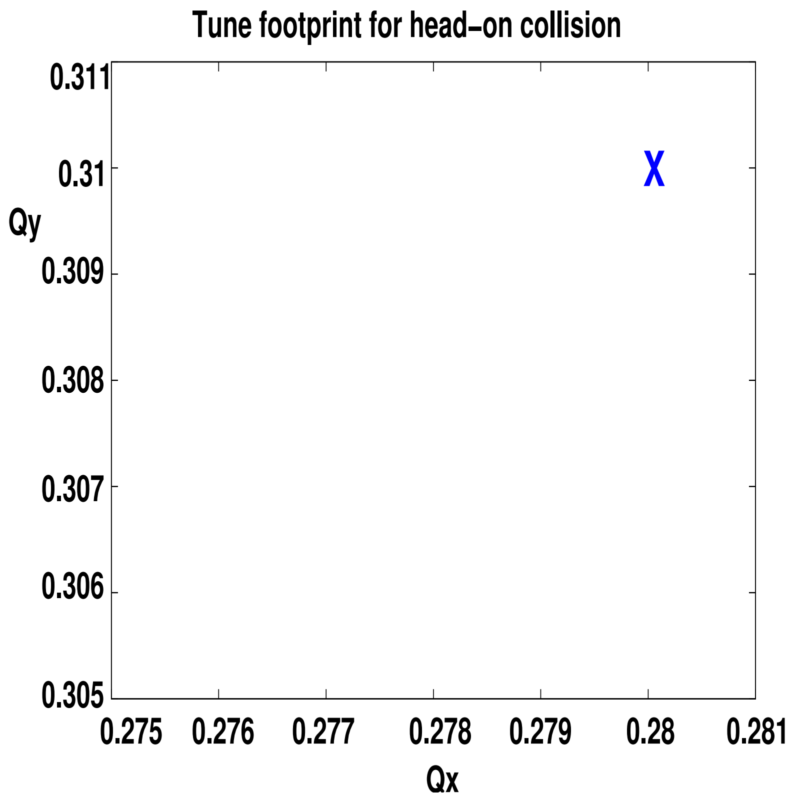
- Start with standard working point
- LHC (equally charged beams)
- Beam–beam shifts tune in both planes

Tune measurement: linear optics



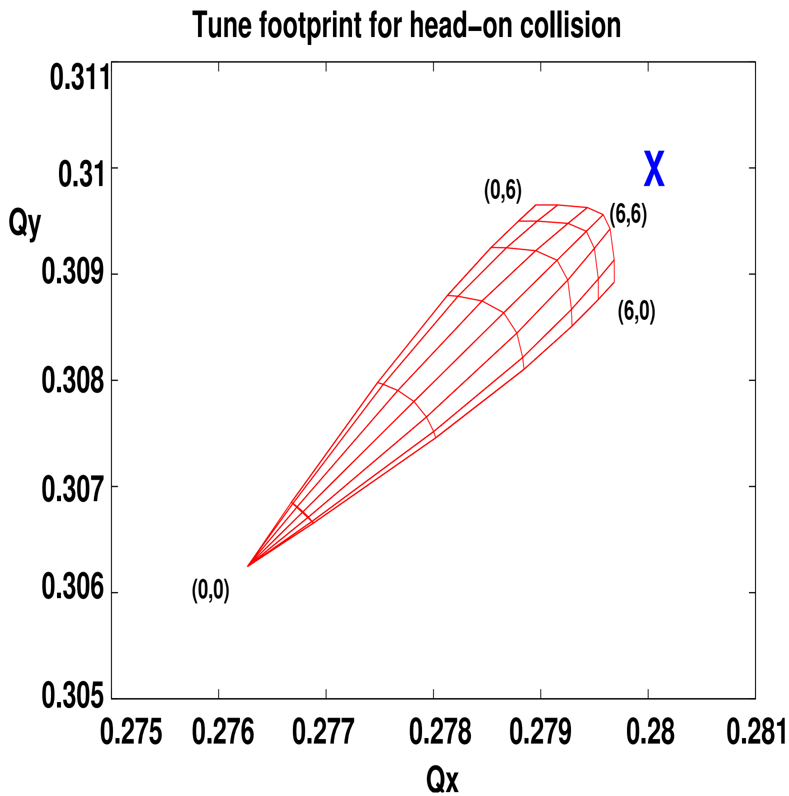
- Linear force: →
- all particles have same tune
- ▶ Only one frequency (tune) visible

Non-linear tune shift - two dimensions



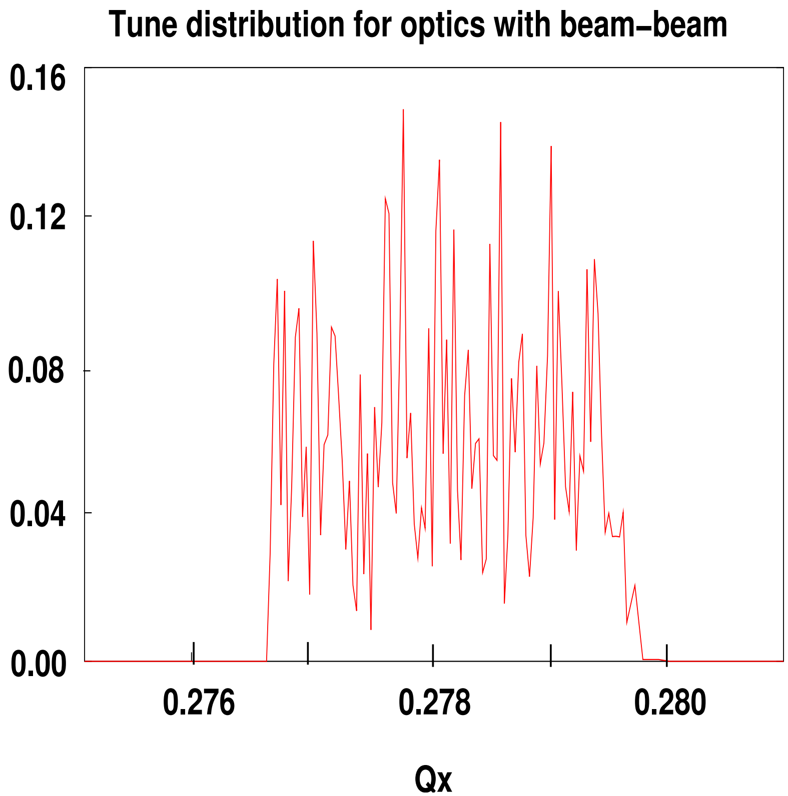
- Tunes depend on x and y amplitudes
- No single tune in the beam
- Compute and plot for every amplitude (pair) the tunes in both planes
- In 2 dimensions:
  plotted as footprint

Non-linear tune shift - two dimensions



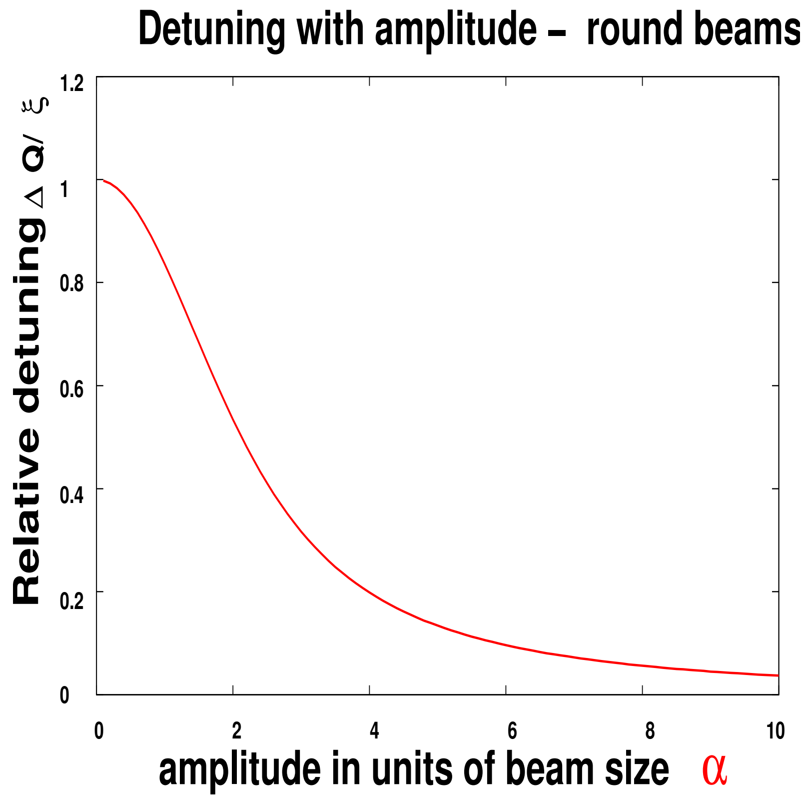
- **Tunes depend on x and y amplitudes**
- **No single tune in the beam**
- **Compute and plot for every amplitude (pair) the tunes in both planes**
- **In 2 dimensions: plotted as footprint**

Tune measurement: with beam-beam



- **Non−linear force:** →
- **particles with different amplitudes have different frequencies (tunes)**
- **We get frequency (tune) spectra**
- **Width of the spectra: about ξ**

Amplitude detuning



- Non-linear force: → tune depends on amplitude
- Largest effect for small amplitudes
- Calculation in the proceedings

→ with $\alpha = \frac{\sigma}{\sigma_*}$ we get: $\Delta Q/\xi = \frac{4}{\alpha^2}\left[1 - I_0(\frac{\alpha^2}{4}) \cdot e^{\frac{-\alpha^2}{4}}\right]$

Weak-strong and strong-strong

- **Both beams are very strong (strong-strong):**
  - → Both beam are affected and change due to beam-beam interaction
  - → Examples: LHC, LEP, RHIC, ...
- **One beam much stronger (weak-strong):**
  - → Only the weak beam is affected and changed due to beam-beam interaction
  - → Examples: SPS collider, Tevatron, ...

Incoherent effects

(single particle effects)

- **Single particle dynamics: treat as a particle through a static electromagnetic lens**
- **Basically non-linear dynamics**
- **All single particle effects observed:**

  $\rightarrow$ **Unstable and/or irregular motion**

  $\rightarrow$ **beam blow up or bad lifetime**

Observations hadrons

- Non-linear motion can become chaotic

  $\rightarrow$ reduction of "dynamic aperture"

  $\rightarrow$ particle loss and bad lifetime

- Strong effects in the presence of noise or ripple
- Very bad: unequal beam sizes (studied at SPS, HERA)
- Evaluation is done by simulation

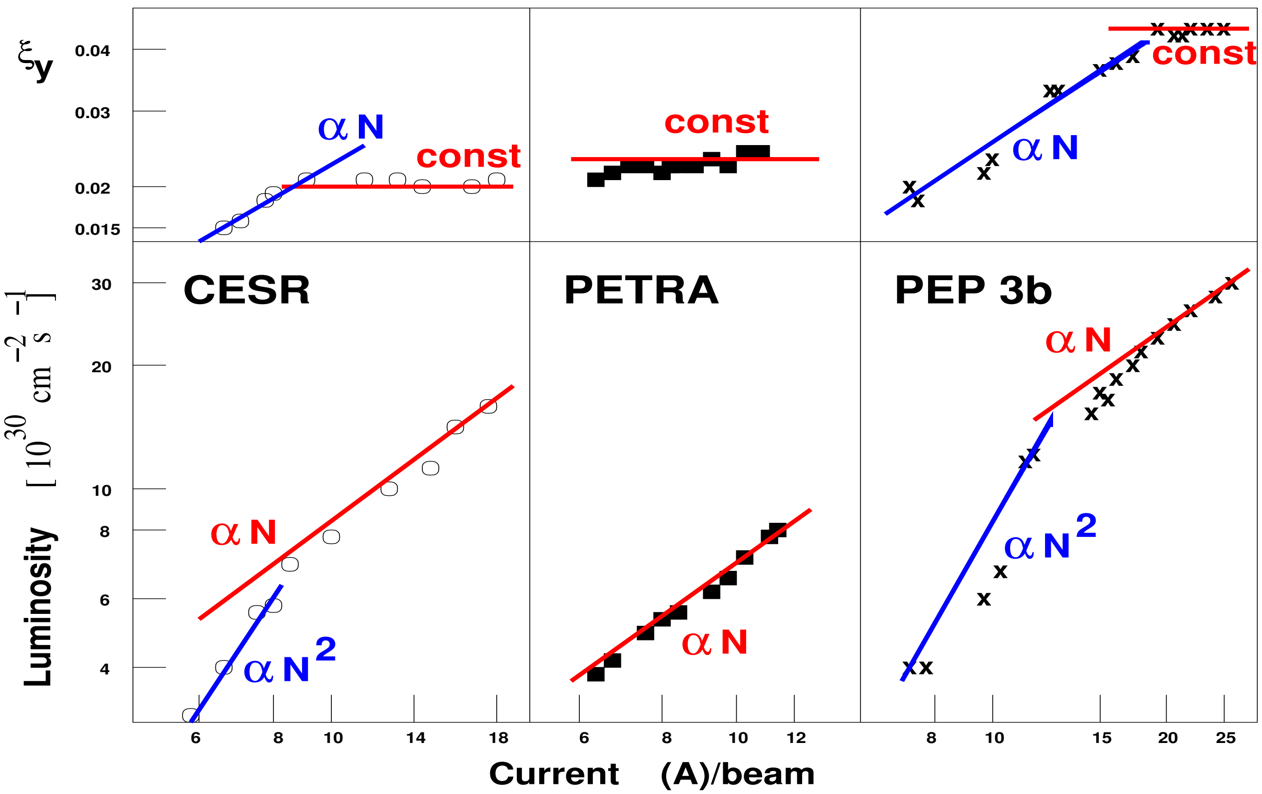
Observations leptons

Remember:

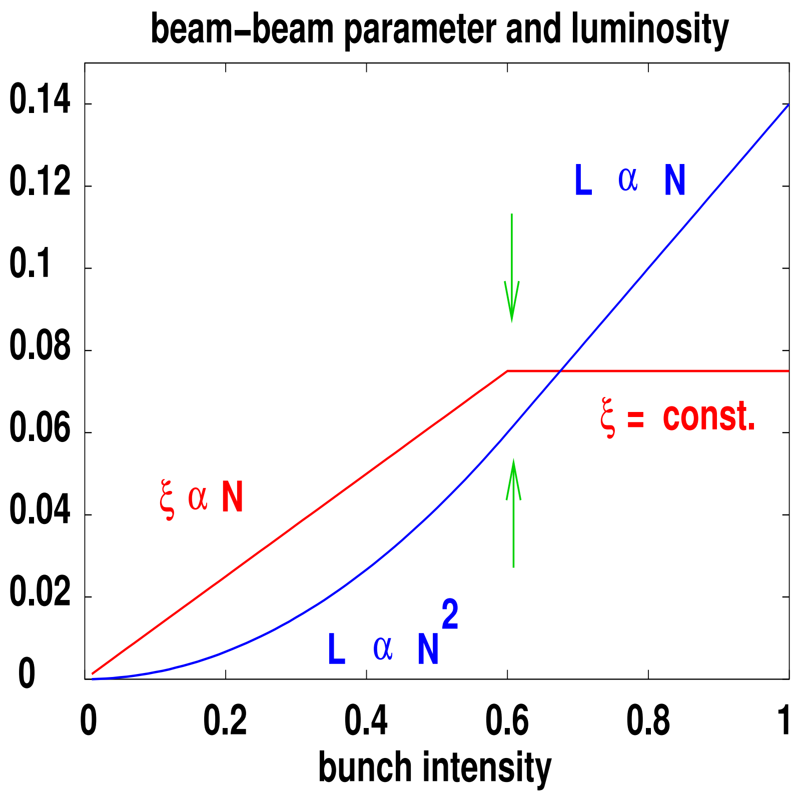
$$\Longrightarrow \quad \mathcal{L} = \frac{N_1 N_2 f n_B}{4\pi\sigma_x\sigma_y}$$

- **Luminosity should increase** $\propto \ N_1 N_2$
  - → **for:** $N_1 = N_2 = N$ → $\propto \ N^2$
- **Beam-beam parameter should increase** $\propto \ N$
- **But:**

Examples: beam-beam limit



Beam-beam limit (schematic)



- Beam−beam parameter increases linearly with intensity
- Saturation above some intensity

- Luminosity increases linearly
- So−called **beam−beam limit**

What is happening ?

we have $$\xi_y = \frac{N r_0 \beta_y}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)} \overset{(\sigma_x \gg \sigma_y)}{\approx} \frac{r_0\beta_y}{2\pi\gamma(\sigma_x)} \cdot \frac{N}{\sigma_y}$$

and $$\mathcal{L} = \frac{N^2 f n_B}{4\pi\sigma_x\sigma_y} = \frac{N f n_B}{4\pi\sigma_x} \cdot \frac{N}{\sigma_y}$$

- **Above beam-beam limit: σ_y increases when N increases to keep ξ constant ➡ equilibrium emittance !**
- **Therefore: $\mathcal{L} \propto N$ and $\xi \approx$ constant**
- **ξ_{limit} is NOT a universal constant !**
- **Difficult to predict**

The next problem

Remember:

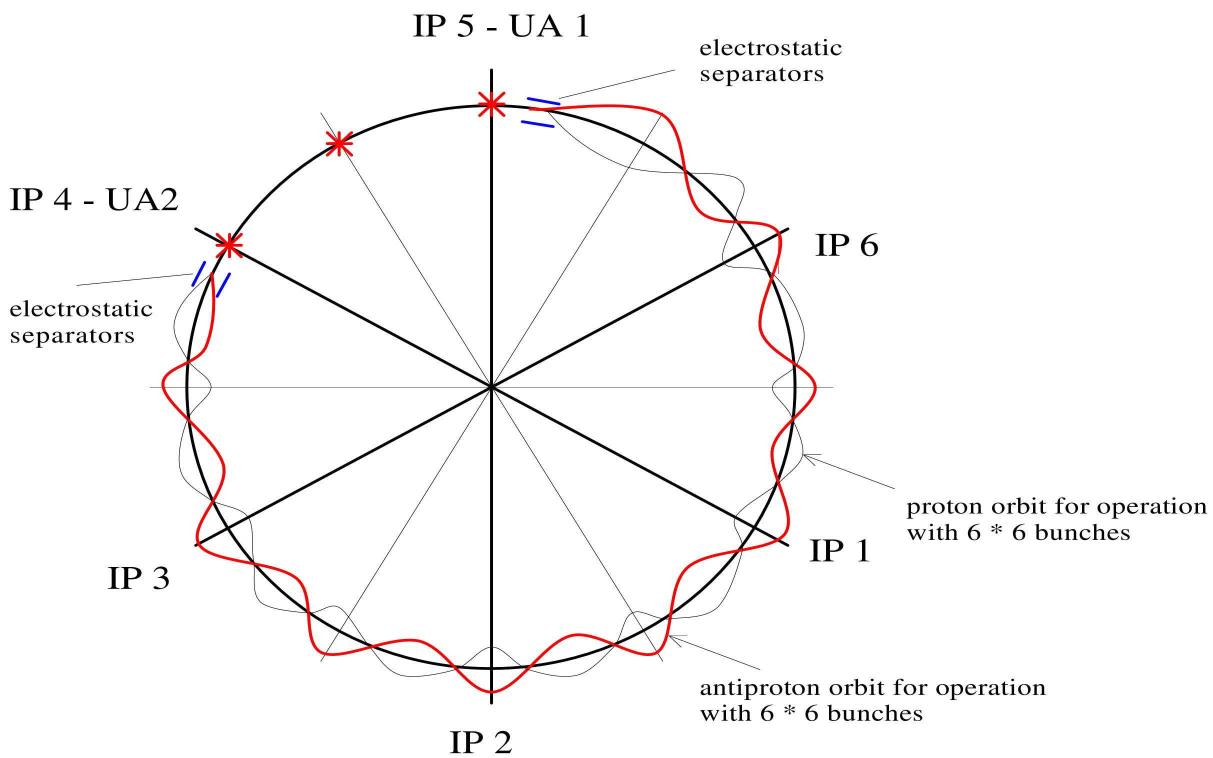
$$\Longrightarrow \quad \mathcal{L} = \frac{N_1 N_2 f \cdot n_B}{4\pi\sigma_x\sigma_y}$$

- **How to collide many bunches (for high $\mathcal{L}$) ??**
- **Must avoid unwanted collisions !!**
- **Separation of the beams:**
  - **Pretzel scheme (SPS,LEP,Tevatron)**
  - **Bunch trains (LEP,PEP)**
  - **Crossing angle (LHC)**

Separation: SPS

- $\Rightarrow$ **Few equidistant bunches**
  (6 against 6)
- **Beams travel in same beam pipe**
  (12 collision points !)
- **Two experimental areas**
- **Need global separation**
- **Horizontal pretzel around most of the circumference**

Separation: SPS



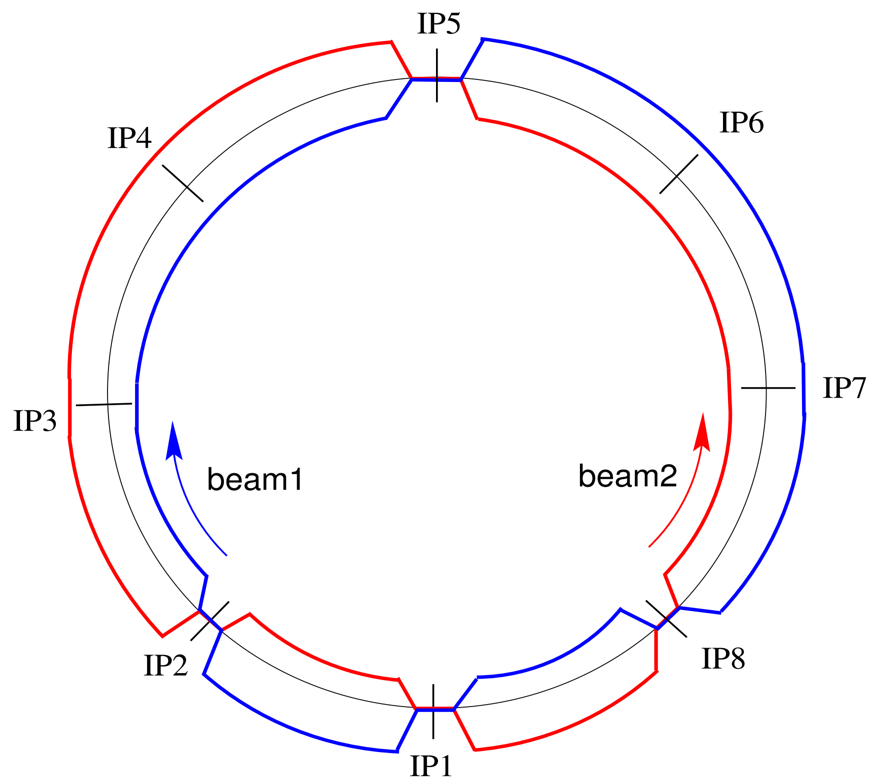
Separation: LHC

- $\Rightarrow$ **Many equidistant bunches**

- **Two beams in separate beam pipes except:**
  - **Four experimental areas**
  - **Need local separation**

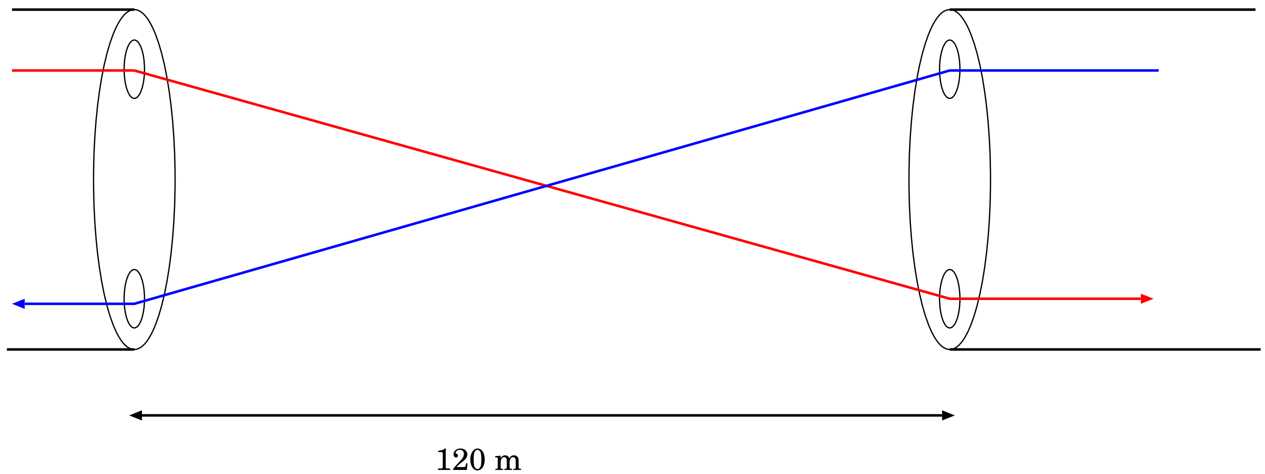
- **Two horizontal and two vertical crossing angles**

Layout of LHC



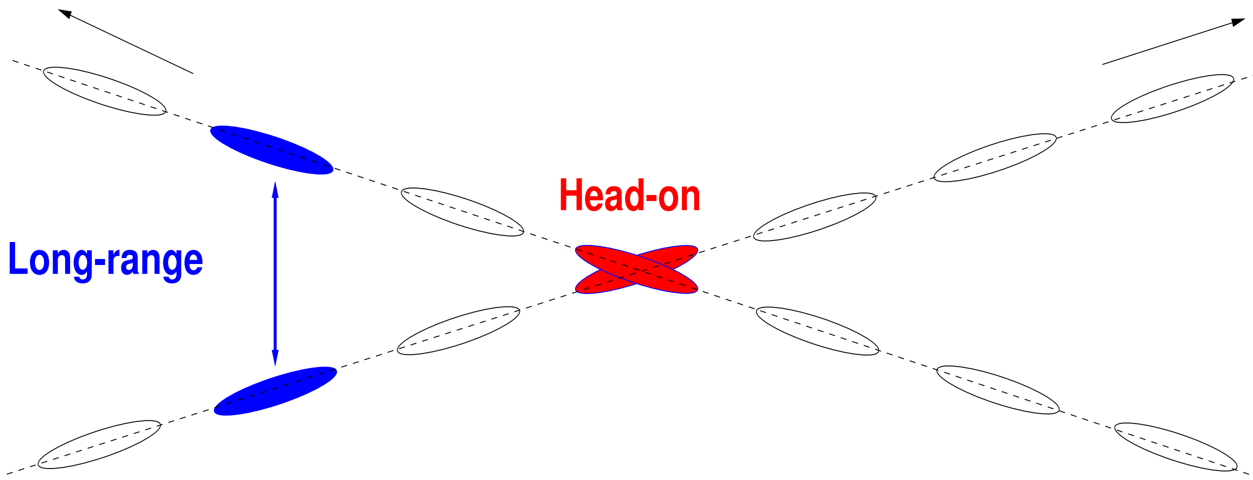
Example: LHC

- **Two beams, 2808 bunches each, every 25 ns**
- **In common chamber around experiments**



- **Over 120 m: about 30 parasitic interactions**

Crossing angles (example LHC)

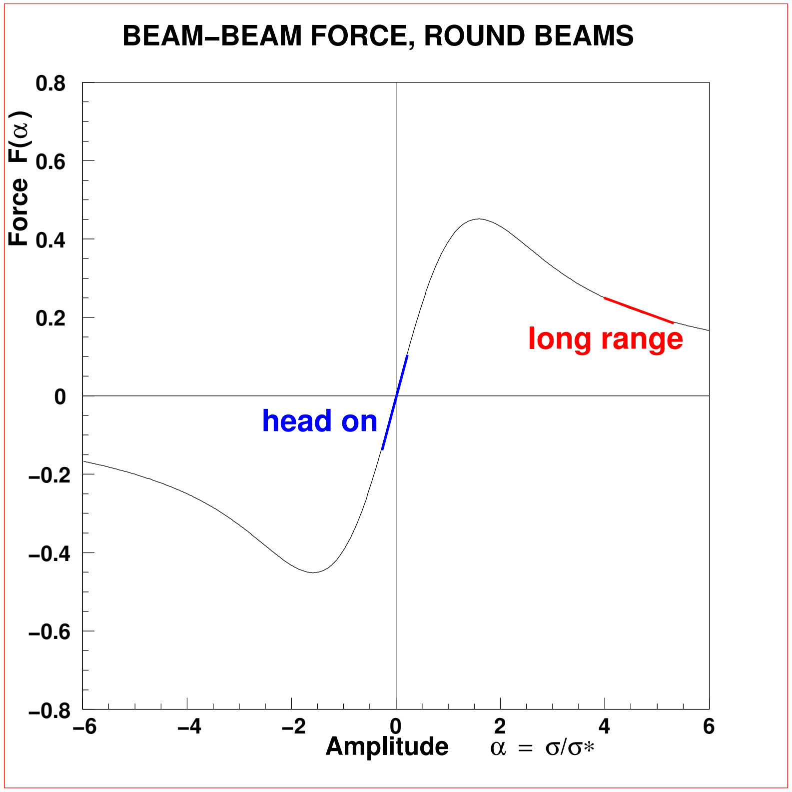


- Particles experience distant (weak) forces
- Separation typically 6 - 12 σ
- → We get so-called long range interactions

What is special about them ?

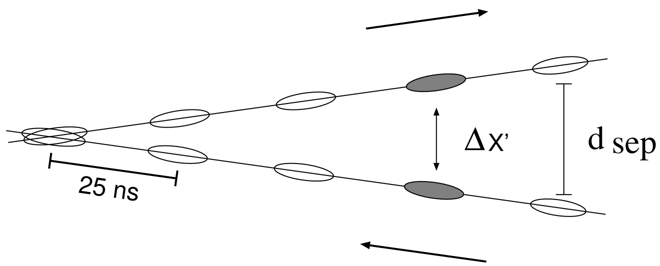
- **Break symmetry between planes, also odd resonances**
- **Mostly affect particles at large amplitudes**
- **Cause effects on closed orbit**
- **PACMAN effects**
- **Tune shift has opposite sign in plane of separation**

Why opposite tuneshift ???



- **Local** slope of force has opposite sign for large separation
- Opposite sign for focusing
- Used for partial compensation

Long range interactions (LHC)

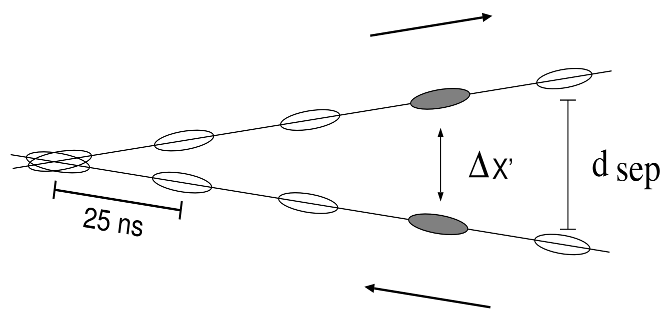


For horizontal separation d:

$$\Delta x'(x+d,y,r) = -\frac{2Nr_0}{\gamma}\cdot\frac{(x+d)}{r^2}\left[1-\exp(-\frac{r^2}{2\sigma^2})\right]$$

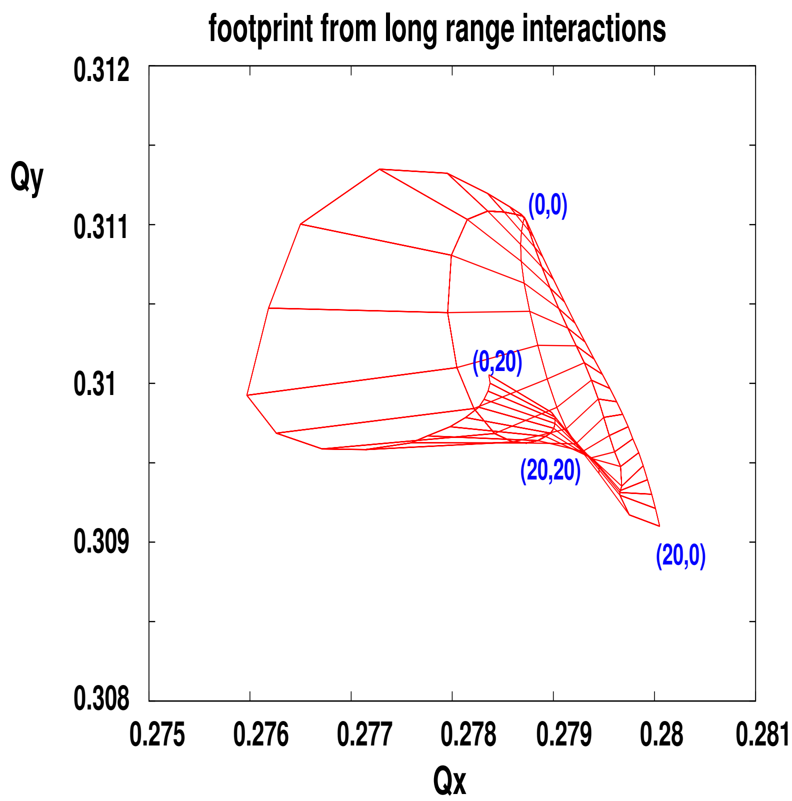
(with: $r^2 = (x+d)^2 + y^2$ ***)***

Long range interactions (LHC)



- **Number of long range interactions depends on spacing and length of common part**
- **In LHC 15 collisions on each side, 120 in total !**
- **Effects depend on separation:** $\Delta Q \propto -\frac{N}{d^2}$ **(for large enough d !)** **footprints ??**

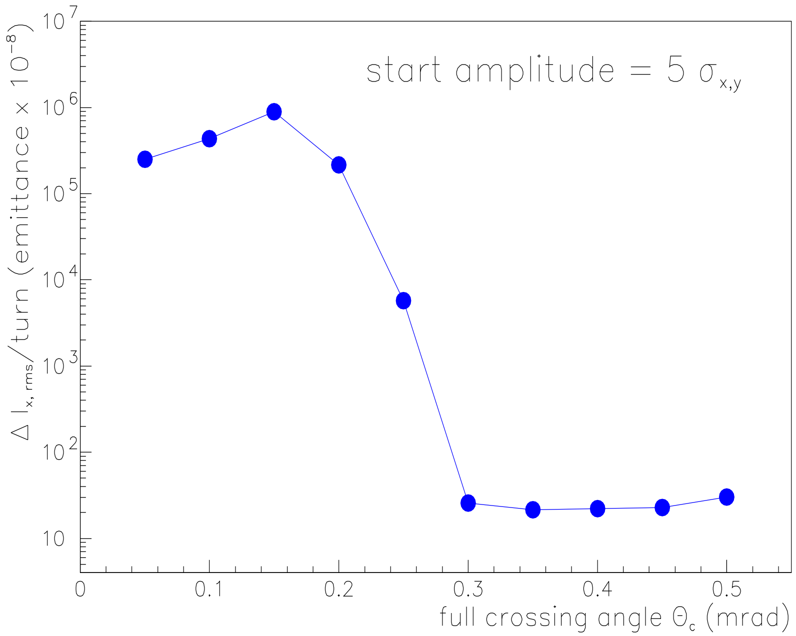
Footprints



- **Large fo largest amplitudes where non–linearities are strong**
- **Size proportional to** $\frac{1}{d^2}$
- **Must expect problems at small separation**
- **Footprint very asymmetric**

Particle losses

- **Small crossing angle $\Longleftrightarrow$ small separation**
- **Small separation: particles become unstable and get lost**



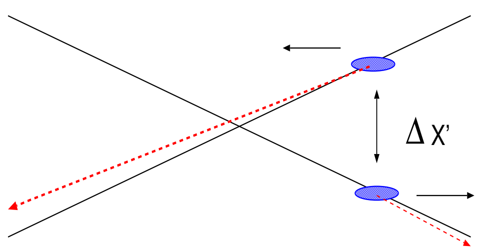
- **Minimum crossing angle for LHC: 285 μrad**

Closed orbit effects

$$\Delta x'(x+d, y, r) = -\frac{2Nr_0}{\gamma} \cdot \frac{(x+d)}{r^2}\left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

For well separated beams ($d \gg \sigma$) the force (kick) has an amplitude independent contribution: → **orbit kick**

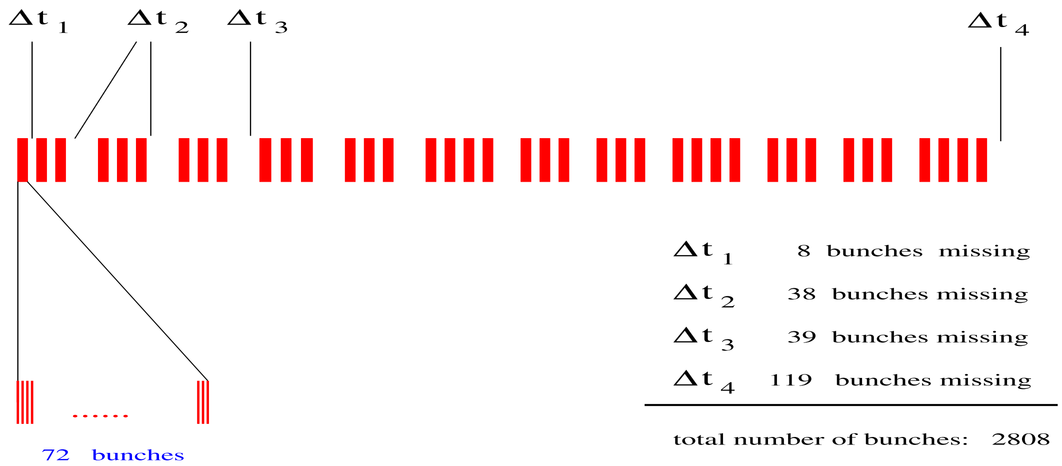
$$\Delta x' = \underbrace{\frac{const.}{d} \cdot [\ 1}\ -\ \frac{x}{d}\ +\ O\left(\frac{x^2}{d^2}\right)\ +\ \ldots$$



Closed orbit effects

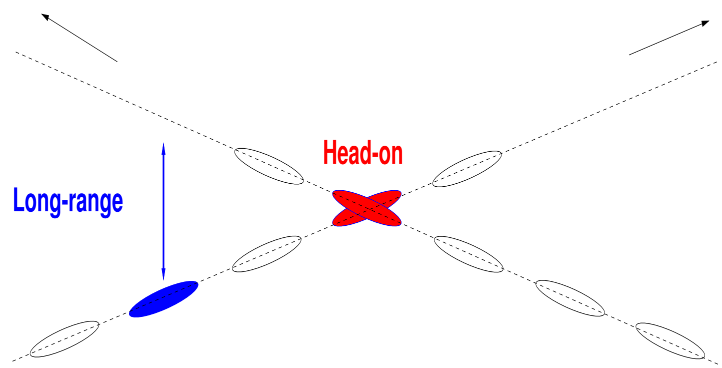
- Beam-beam kick from long range interactions changes the orbit
  - Has been observed in LEP with bunch trains
  - Self-consistent calculation necessary
  - Effects can add up and become important
- Orbit can be corrected, but:

PACMAN bunches



- **LHC bunch filling not continuous: holes for injection, extraction, dump ..**
- **2808 of 3564 possible bunches → 1756 "holes"**
- **"Holes" meet "holes" at the interaction point**
- **But not always ...**

Effect of holes



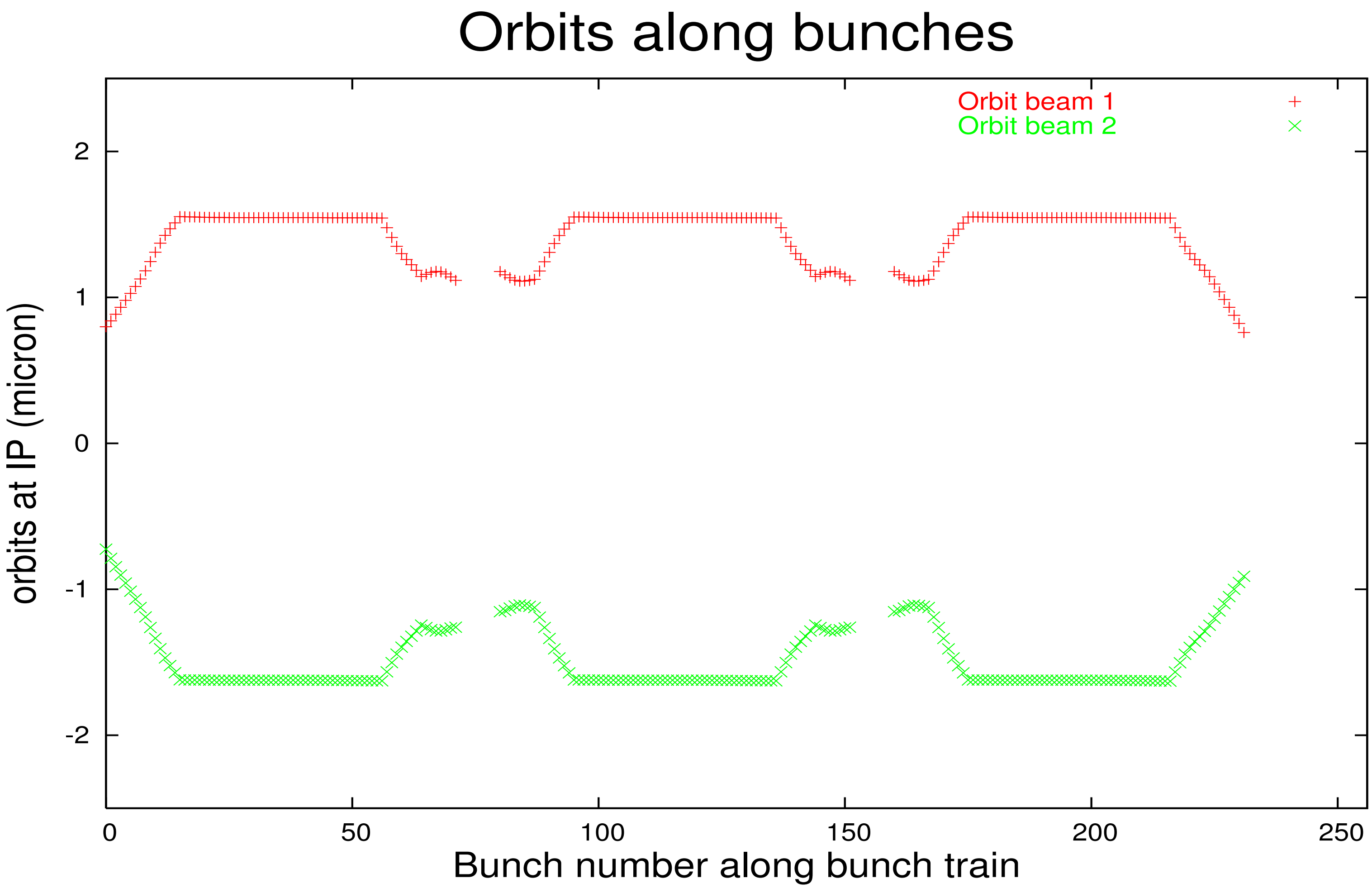
- A bunch can meet a hole (at beginning and end of bunch train)
- Results in left-right asymmetry
- Example LHC: between 120 (max) and 40 (min) long range collisions for different bunches

PACMAN bunches

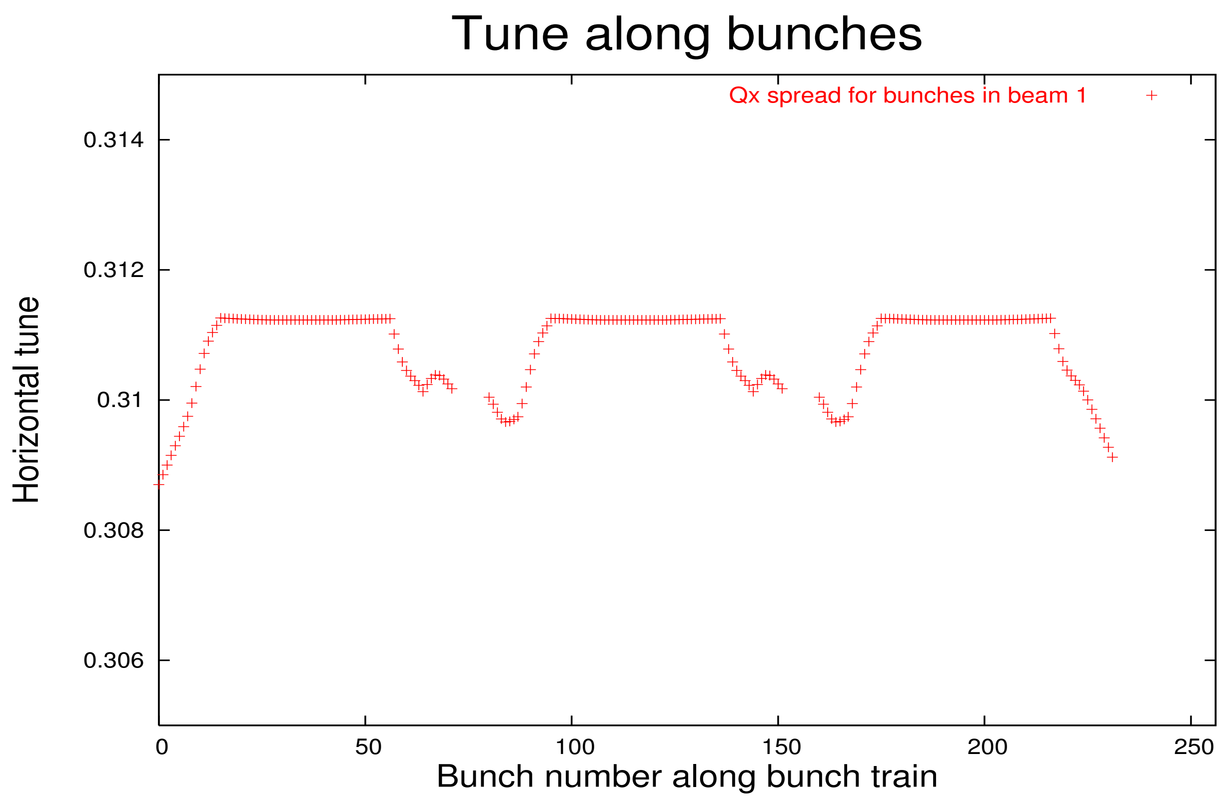
- **When a bunch meets a "hole":**
  - **Miss some long range interactions, PACMAN bunches**
  - **They see fewer unwanted interactions in total**
  - **Different integrated beam-beam effect**
- **In general: when different bunches have different beam-beam effects**
- **Example: orbit and tune effects**

Orbit along LHC batches: beam 1

Orbit along LHC batches: beam 1 and beam 2



Tune along LHC batches

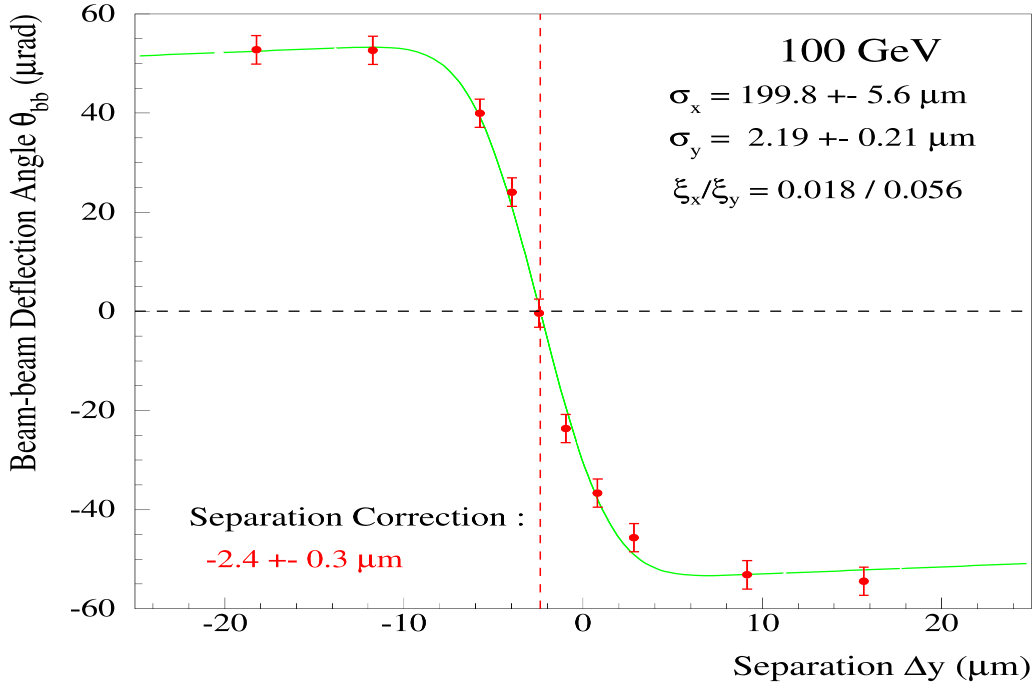


- **Spread is too large for safe operation**

Beam-beam deflection scan

- The orbit effect can be useful when one has only a few bunches, i.e. not PACMAN effects
- Effect can be used to optimize luminosity
- Scanning two beams against each other
- Two beams get a orbit kick, depending on distance

Deflection scan (LEP measurement)

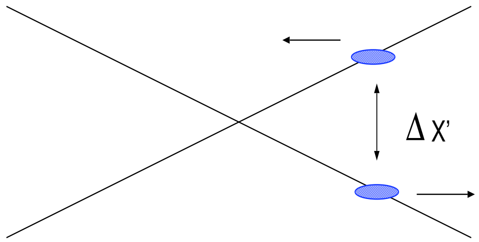


(Courtesy J. Wenniger)

Deflection scan

- Calculated kick from orbit follows the force function
- Allows to calculate parameters
- Allows to centre the beam
- Standard procedure at LEP

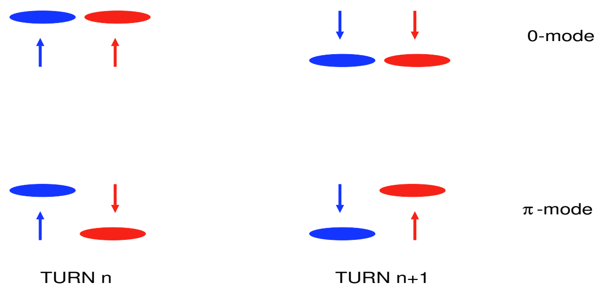
Coherent beam-beam effect



- Whole bunch sees a kick as an entity (coherent kick)
- The coherent kick of separated beams can excite coherent dipole oscillations
- All bunches couple together because each bunch "sees" many opposing bunches: many coherent modes possible !

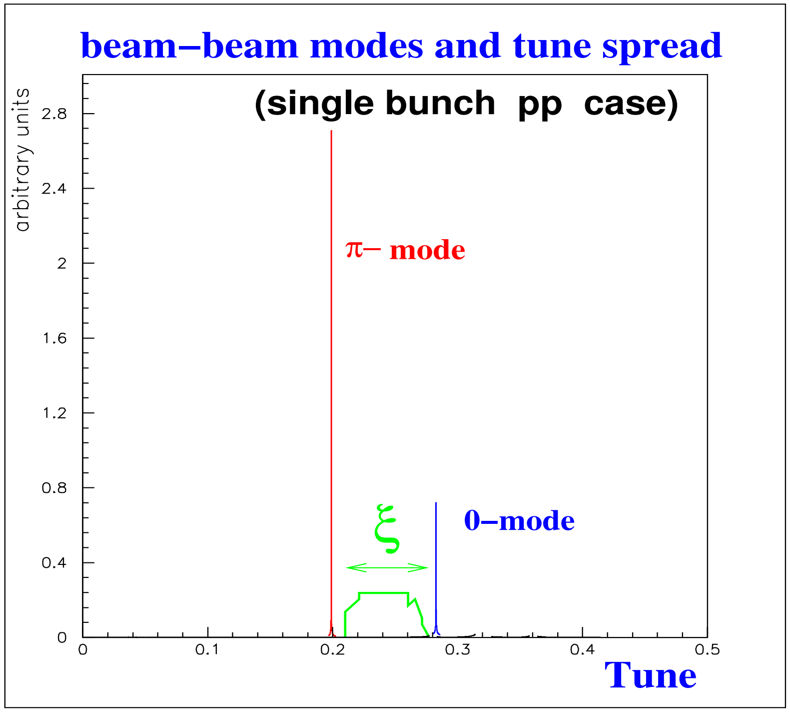
Coherent beam-beam effect

Simplest case: one bunch per beam:



- **Coherent mode: two bunches are "locked" in a coherent oscillation**
- **0-mode is stable (Mode with NO tune shift)**
- **π-mode can become unstable (Mode with LARGEST tune shift)**

Coherent beam-beam frequencies (schematic)

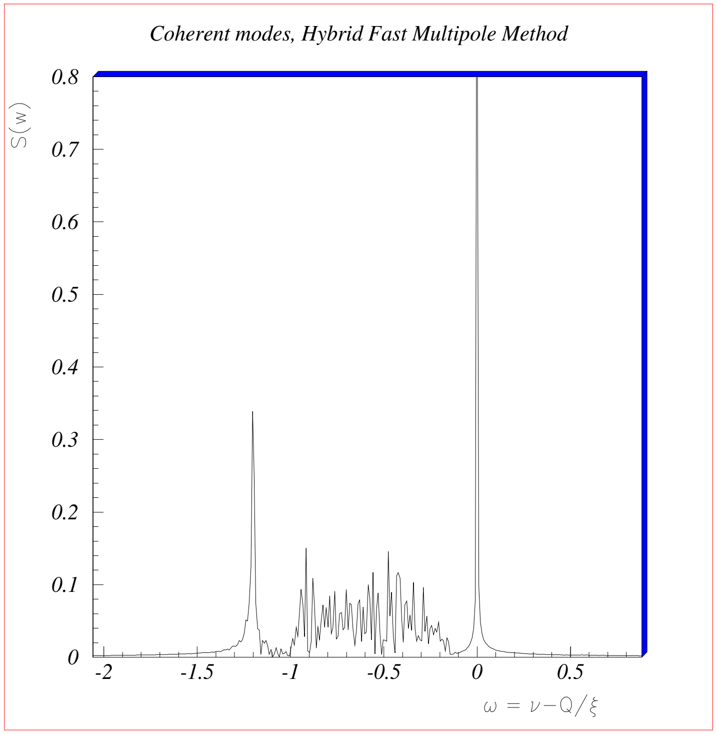


- 0−mode is at unperturbed tune
- π−mode is shifted by 1.1 – 1.3 $\cdot\ \xi$
- Incoherent spread between [0.0,1.0] $\cdot\ \xi$

➡ Strong-strong case: π-mode shifted outside tune spread

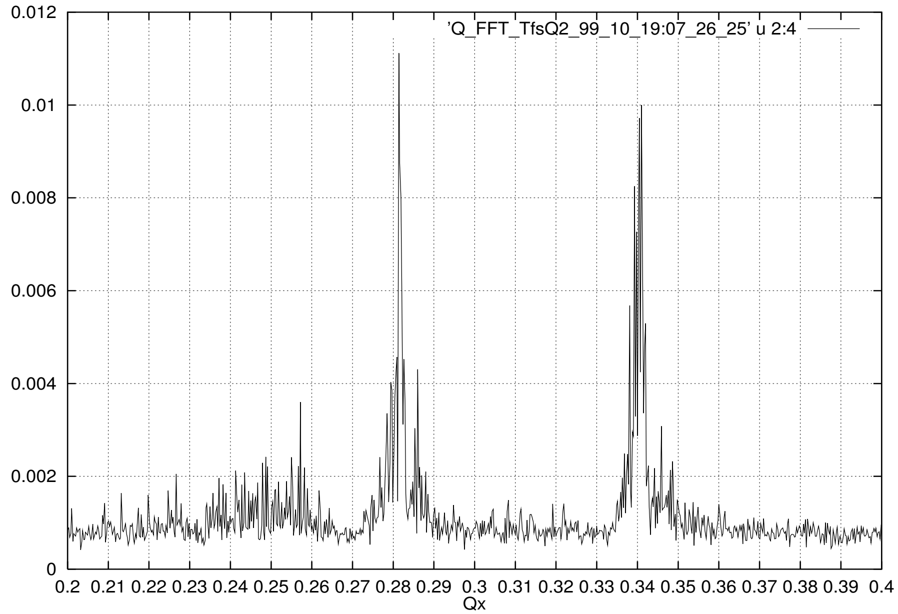
➡ No Landau damping possible

Simulation of coherent spectra



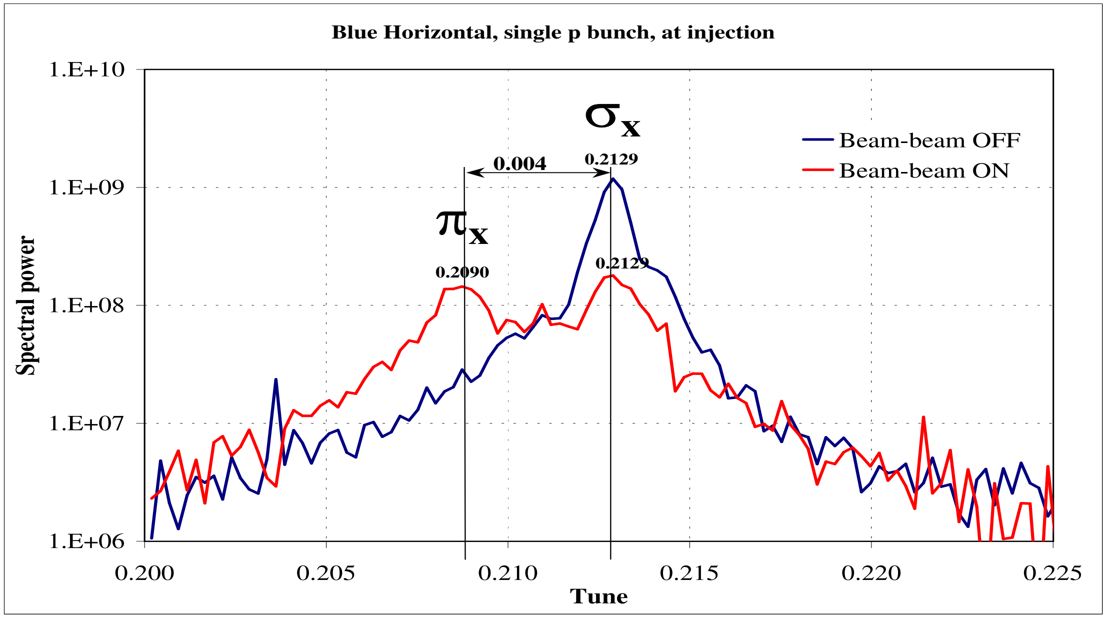
- **Full simulation of both beams required**
- **Use up to 10^8 particles in simulations**
- **Must take into account changing fields**
- **Requires computation of arbitrary fields**

What we measure: LEP



- **Two modes clearly visible**
- **Can be distinguished by phase relation, i.e. sum and difference signals**

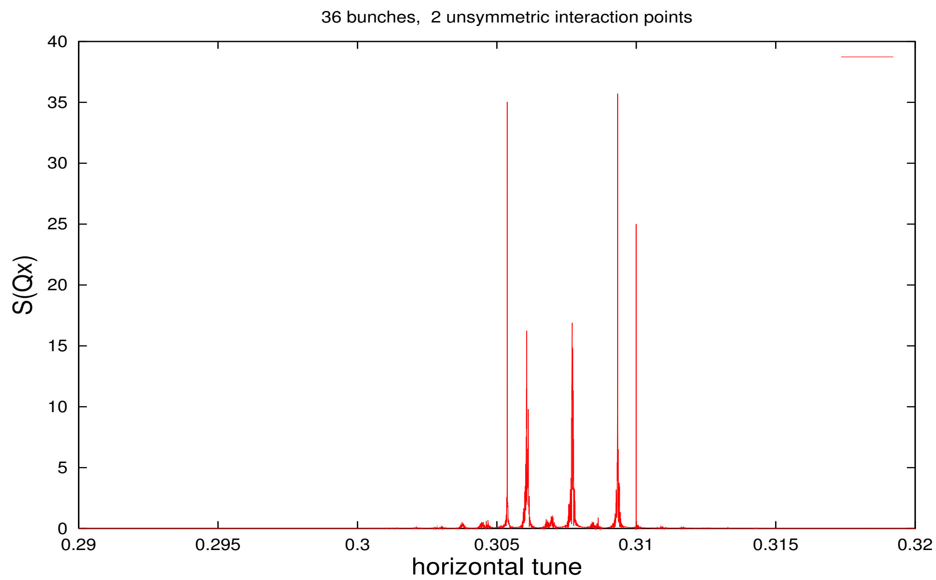
What we measure: RHIC



Courtesy W. Fischer (BNL)

➡ **Compare spectra with and without beams : two modes visible with beams**

Many bunches and more interaction points



- **Bunches couple via the beam-beam interaction**
- **Additional coherent modes become visible**
- **Potentially undesirable situation**

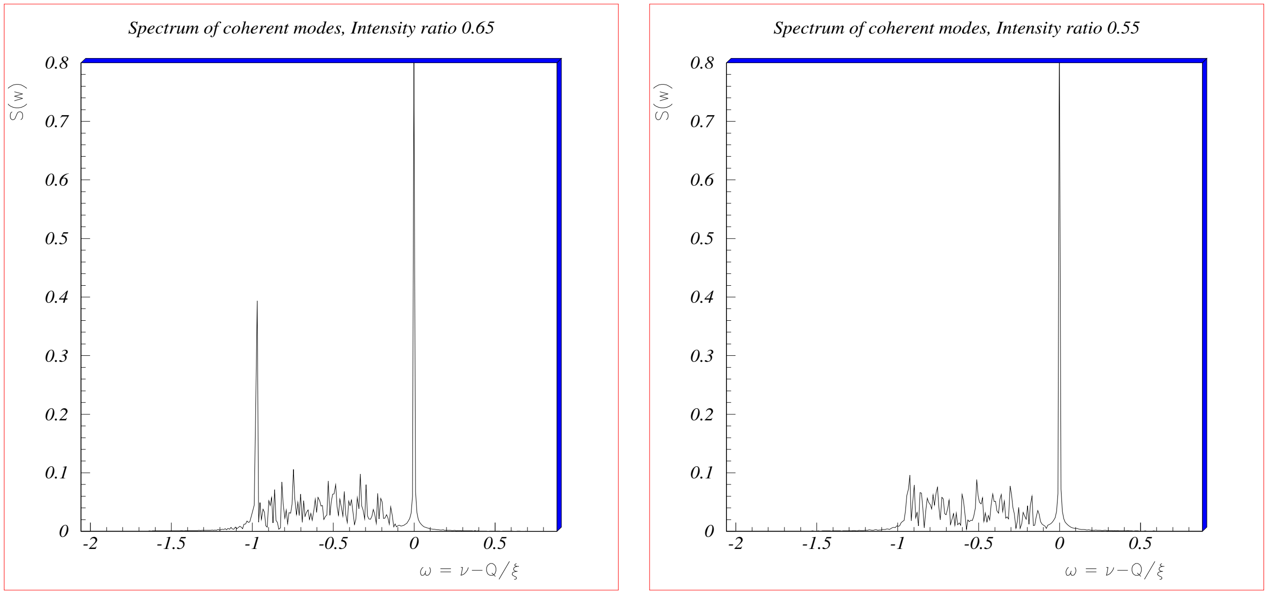
What can be done to avoid problems ?

- Coherent motion requires 'organized' motion of many particles
- Therefore high degree of symmetry required
- Possible countermeasure: (symmetry breaking)

$\rightarrow$ Different bunch intensity

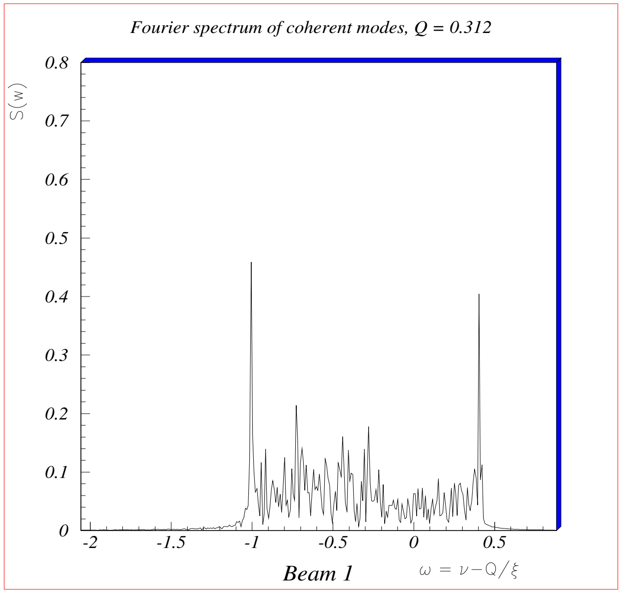
$\rightarrow$ Different tunes in the two beams

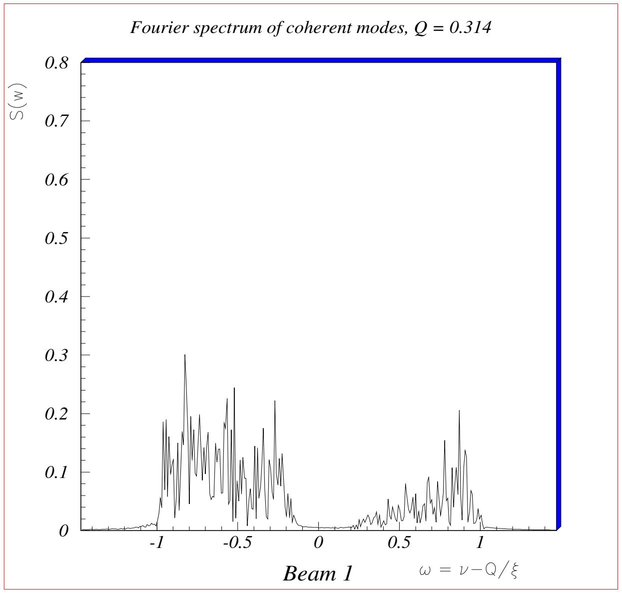
Beams with different intensity



➡ **Bunches with different intensities cannot maintain coherent motion**

Beams with different tunes





→ **Bunches with different tunes cannot maintain coherent motion**

Can we suppress beam-beam effects ?

- **Find 'lenses' to correct beam-beam effects**
  - **Head on effects:**
    - $\rightarrow$ **Linear "electron lens" to shift tunes**
    - $\rightarrow$ **Non-linear "electron lens" to reduce spread**
    - $\rightarrow$ **Tests in progress at FNAL**
  - **Long range effects:**
    - $\rightarrow$ **At very large distance: force is 1/r**
    - $\rightarrow$ **Same force as a wire !**
- **So far: mixed success with active compensation**

Others: Möbius lattice

- **Principle:**
  - $\rightarrow$ **Interchange horizontal and vertical plane each turn**
- **Effects:**
  - $\rightarrow$ **Round beams (even for leptons)**
  - $\rightarrow$ **Some compensation effects for beam-beam interaction**
  - $\rightarrow$ **First test at CESR at Cornell**

Not mentioned:

- Effects in linear colliders
- Asymmetric beams
- Coasting beams
- Beamstrahlung
- Synchrobetatron coupling
- Monochromatization
- Beam-beam experiments
- ... and many more

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