Beam-Beam Effects in colliders

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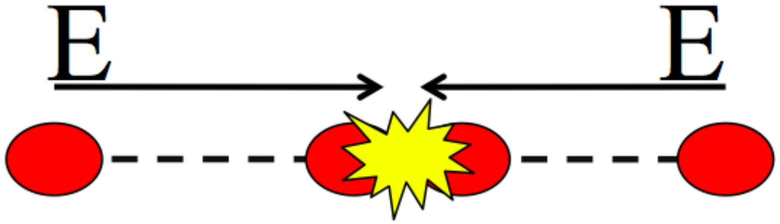
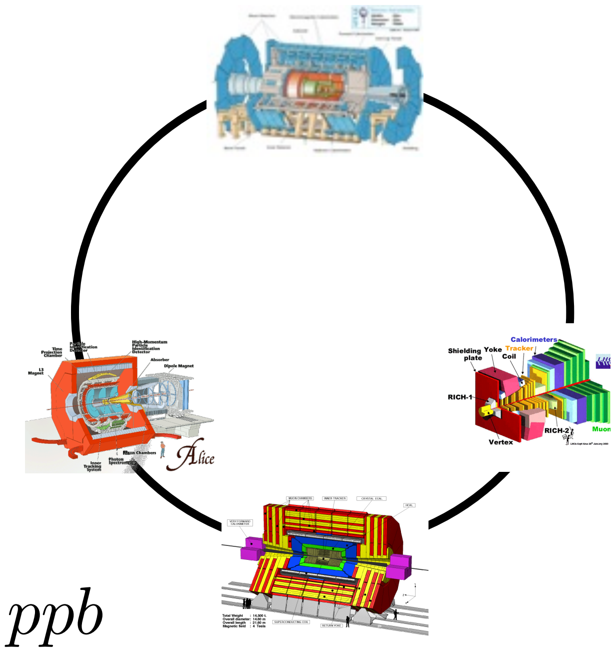
…with material from X. Buffat and W. Herr

Hadron Colliders



$$E^* \approx 2 \times E$$



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

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

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

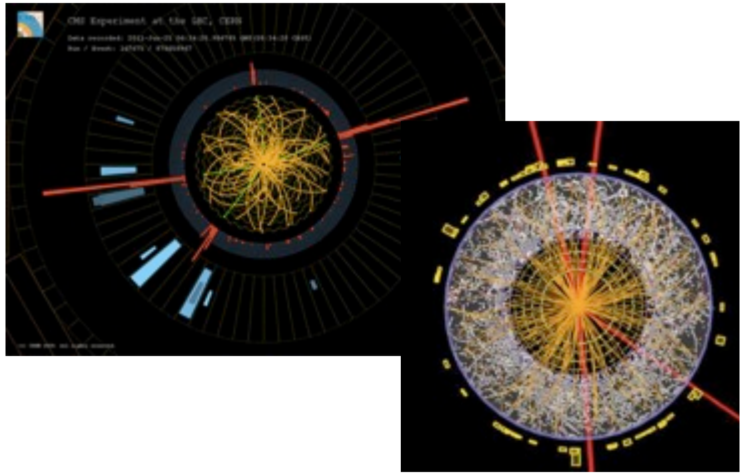
Number of bunches $1370 - 2808$

Revolution frequency $11\ kHz$

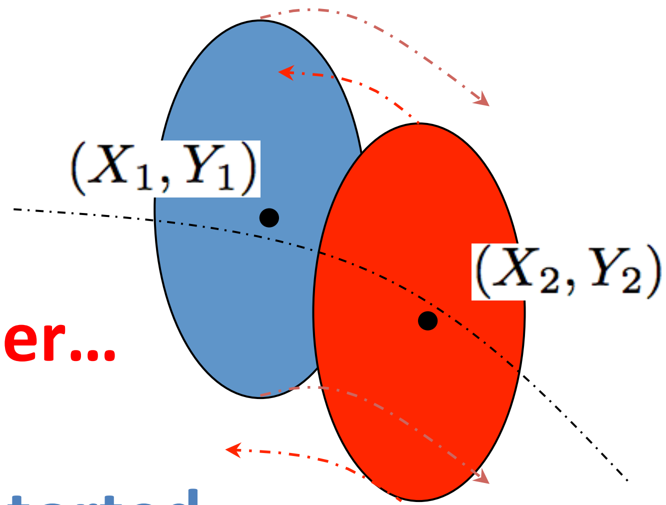
Physics fill lasts for many hours

What are 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**

Beam-beam effects

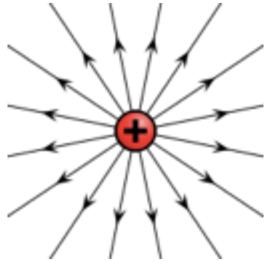
- **Circular Colliders**: interaction occurs at every turn
  - Many effects and problems
  - Try to understand some of them

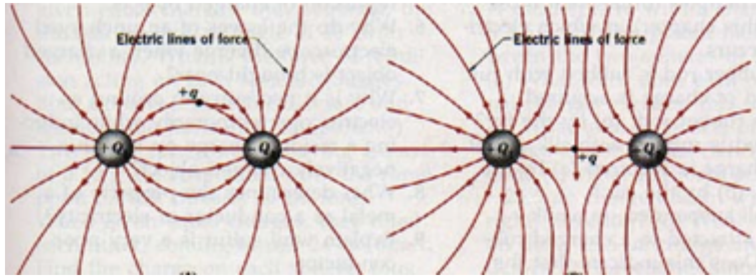
Two main questions:
What happens to a single particle?
What happens to the whole beam?

- Overview of selected effects
- Qualitative and physical picture of effects
- Mathematical derivations and more info in References [] or
  Beam-beam webpage http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/

Beam-beam effects

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



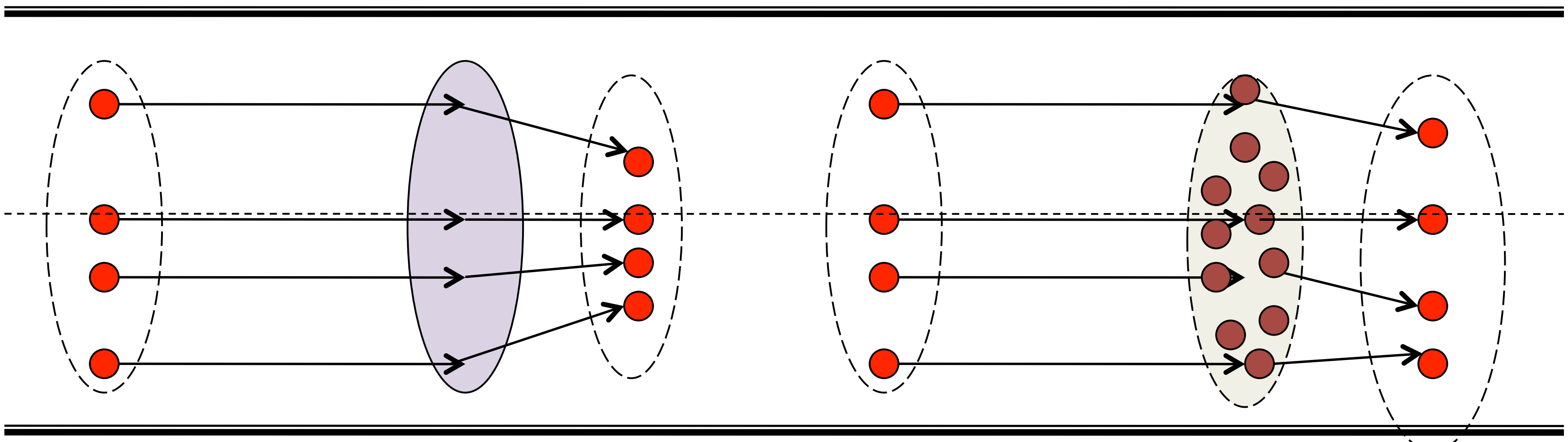


Force on itself (**space charge**) and opposing beam (**beam-beam effects**)

Single particle motion and whole bunch motion distorted

Focusing quadrupole

Opposite Beam



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

Short Beam-beam Mathematics

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

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

Derive potential from Poisson equation for beam with distribution ρ

Solution of Poisson equation

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

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

Then compute the fields

$$\overrightarrow{F} = q(\overrightarrow{E} + \overrightarrow{v} \times \overrightarrow{B})$$

From Lorentz force one calculates the force acting on test particle with charge q

Making some assumptions we can simplify the problem:

Round Gaussian distribution:

Gaussian distribution for charges:
Round beams:
Very relativistic, Force has only radial component :

$$\sigma_x = \sigma_y = \sigma$$

$$\beta \approx 1 \qquad r^2 = x^2 + y^2$$

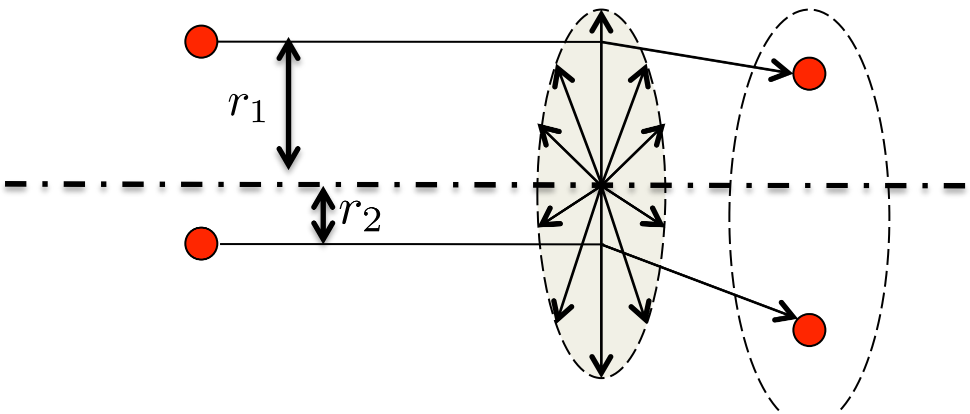
$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

Beam-beam Force

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

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

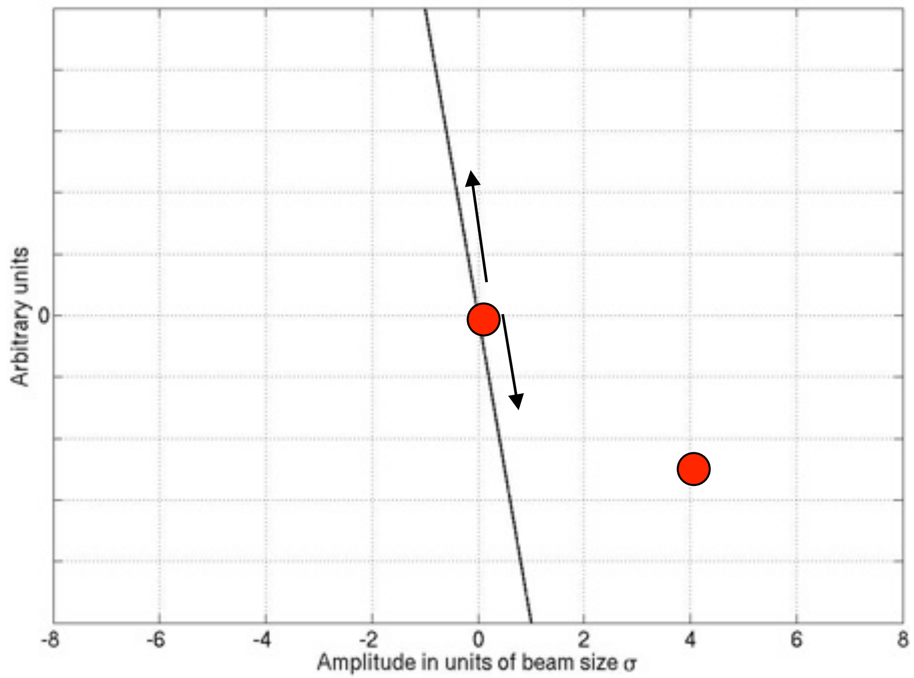
Beam-beam kick obtained integrating the force over the collision (i.e. time of passage)



How does this force looks like?

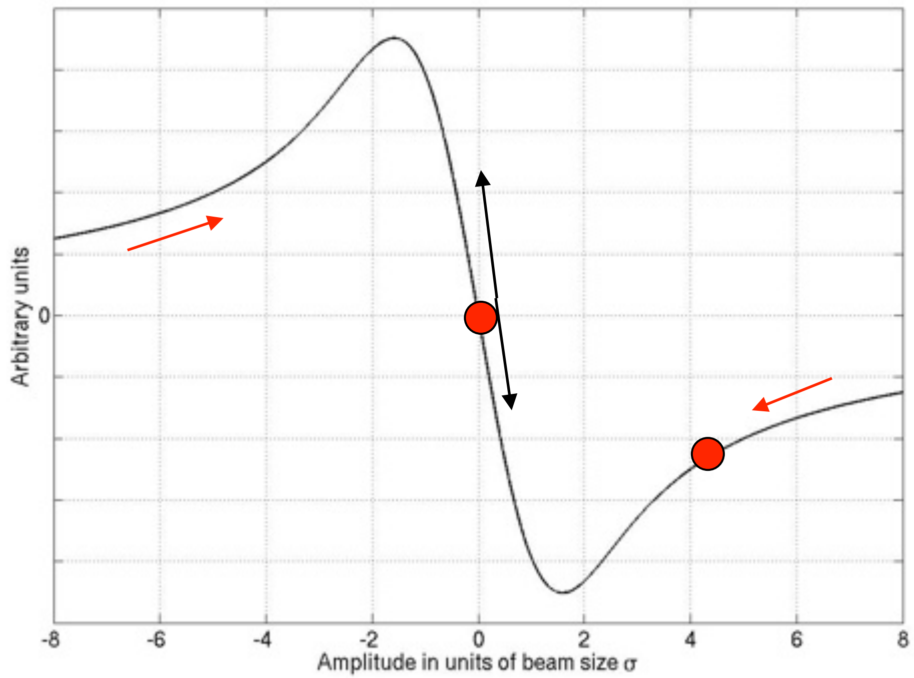
Beam-Beam Force

Lattice defocusing quadrupole



$$F = -k \cdot r$$

Beam-beam force



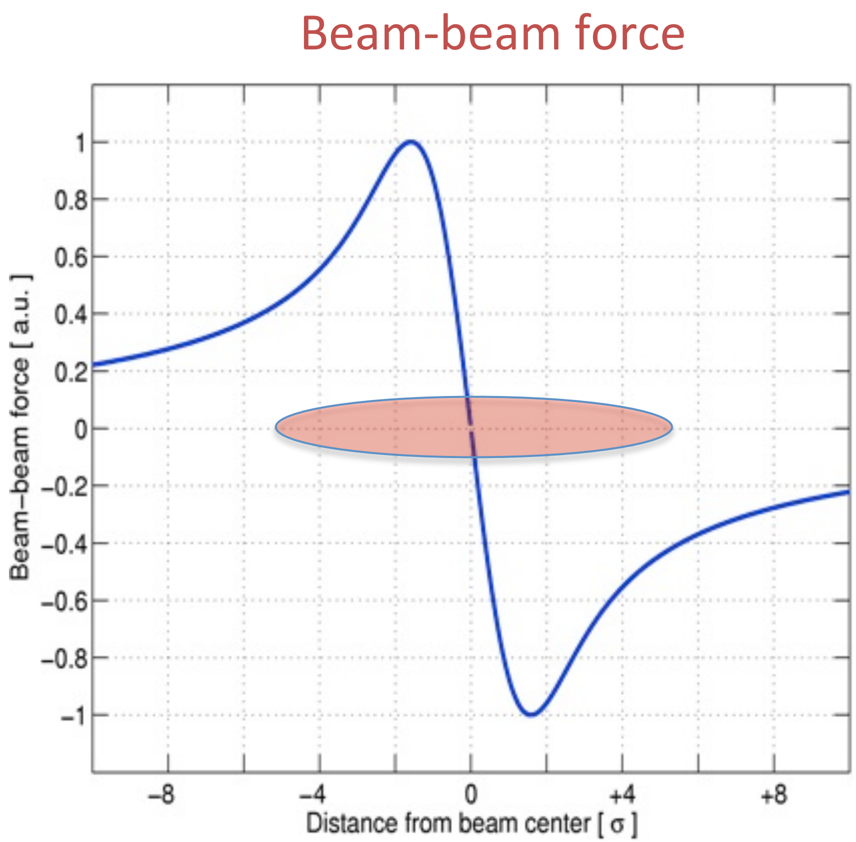
$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

For small amplitudes: linear force

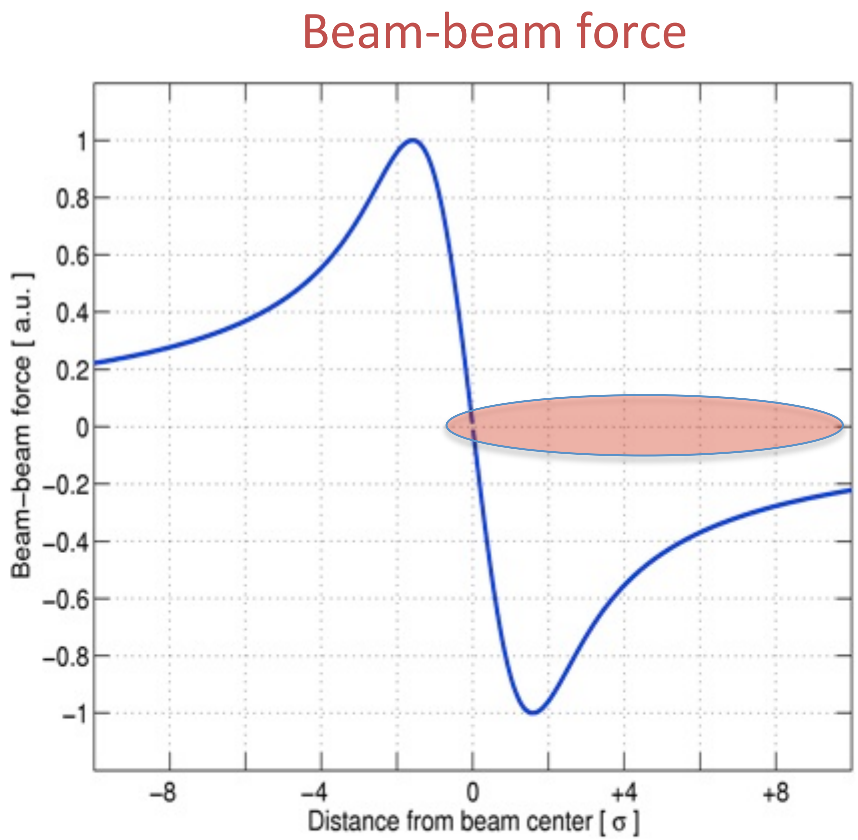
For large amplitude: very non-linear

YOU CANNOT AVOID!

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

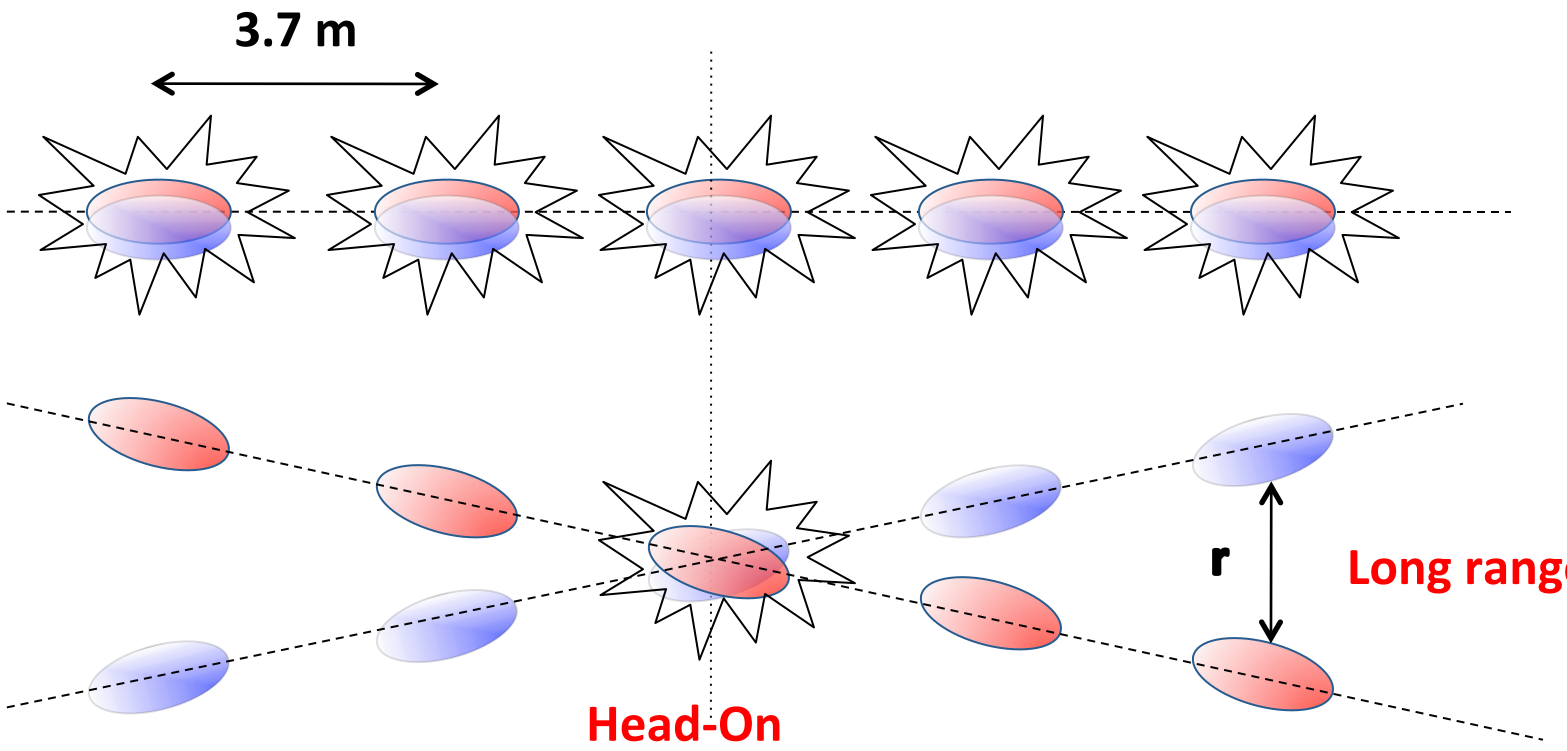
Different particles will see different force

Multiple bunch Complications

MANY INTERACTIONS

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

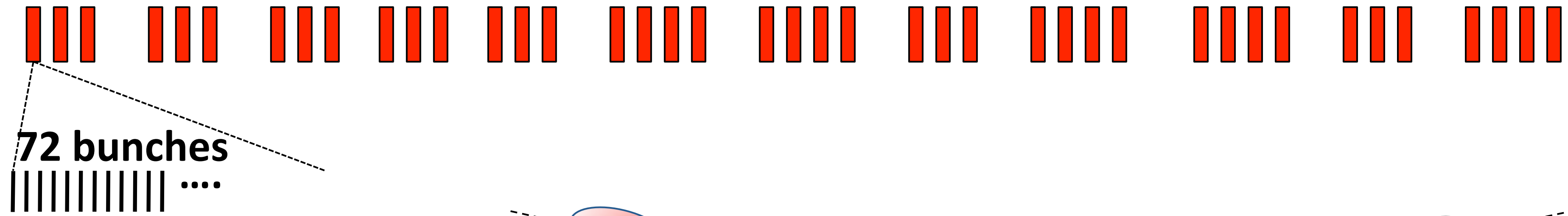
Num. of bunches : $n_b = 2808$

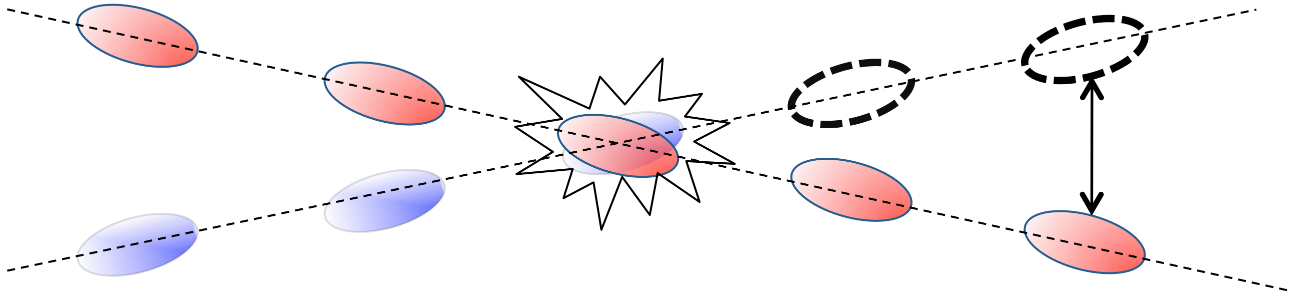


For 25ns case 124 BBIs per turn: 4 HO and 120 LR

LHC Complications

PACMAN and SUPER PACMAN bunches

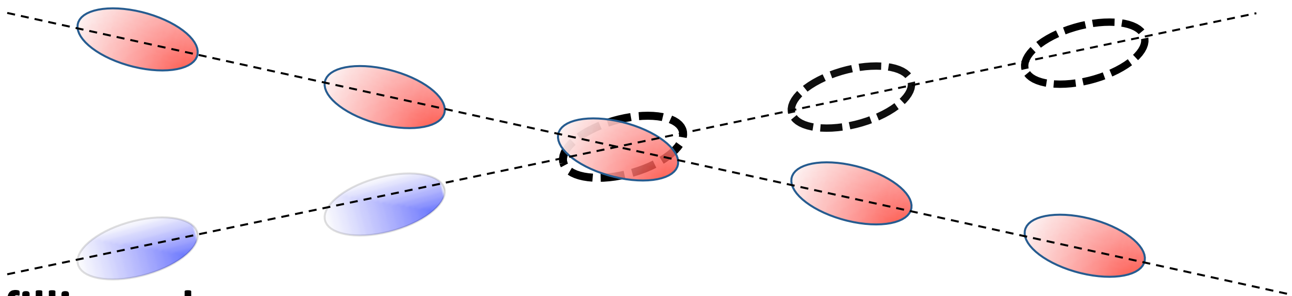




Pacman:

miss long range BBI

(120-40 LR interactions)



Super Pacman:

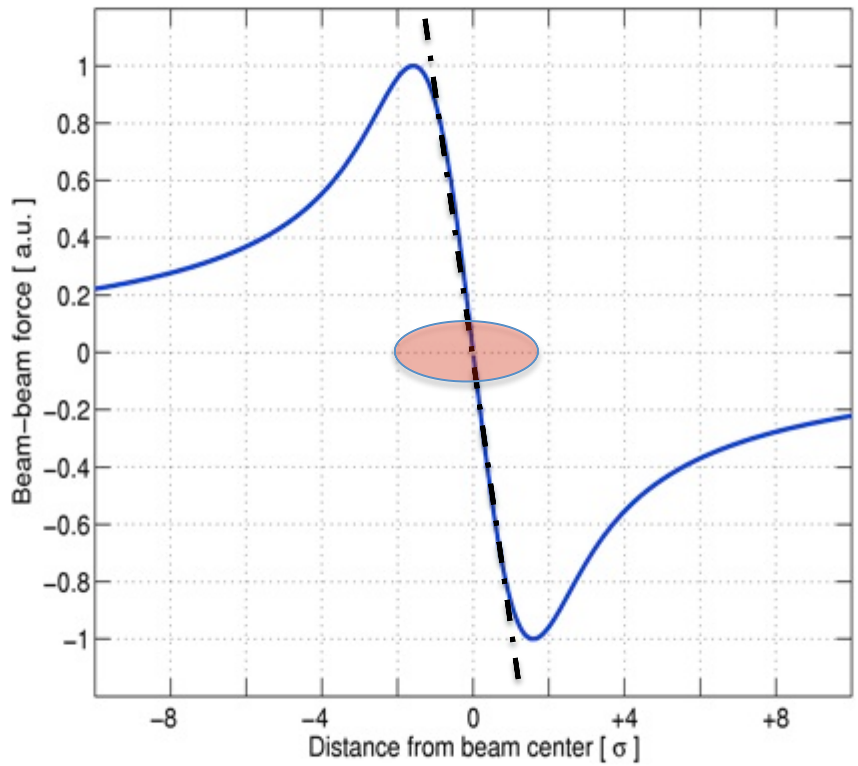
miss head-on BBI

IP2 and IP8 depending on filling scheme

Different bunch families: Pacman and Super Pacman

Can we quantify the beam-beam strenght?

Beam-beam force



For small amplitudes: linear force

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

$$\Delta r' = \frac{2Nr_0}{\gamma}\frac{1}{r}[1-(1-(\frac{r^2}{2\sigma^2})+\ldots)]$$

For round beams:

$$\xi = \frac{\beta^*}{4\pi}\cdot\frac{\delta(\Delta r')}{\delta r} = \frac{Nr_0\beta^*}{4\pi\gamma\sigma^2}$$

For non-round beams:

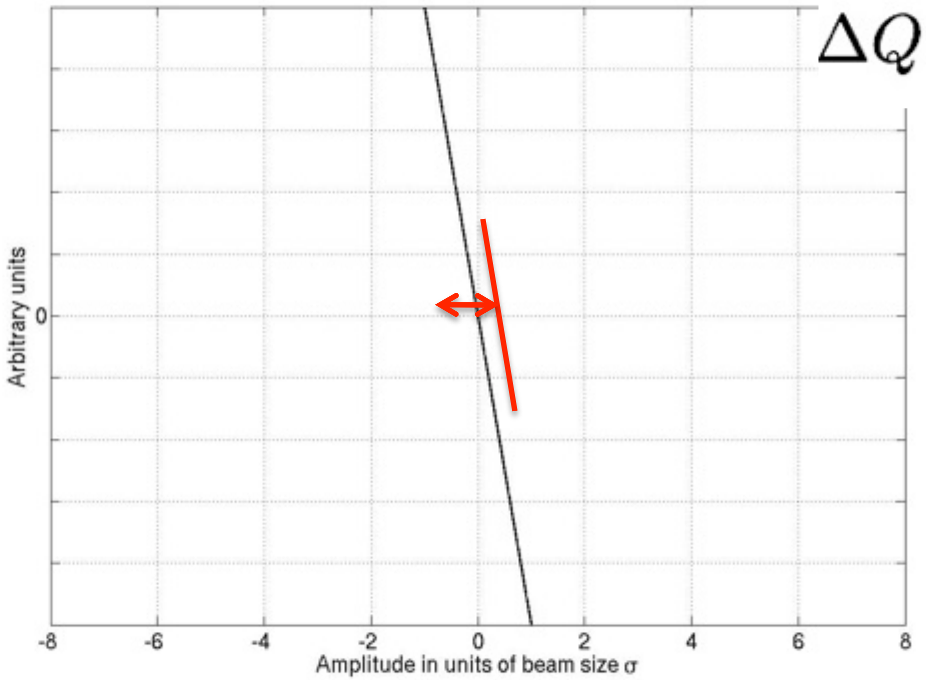
$$\xi_{x,y} = \frac{Nr_0\beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$

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

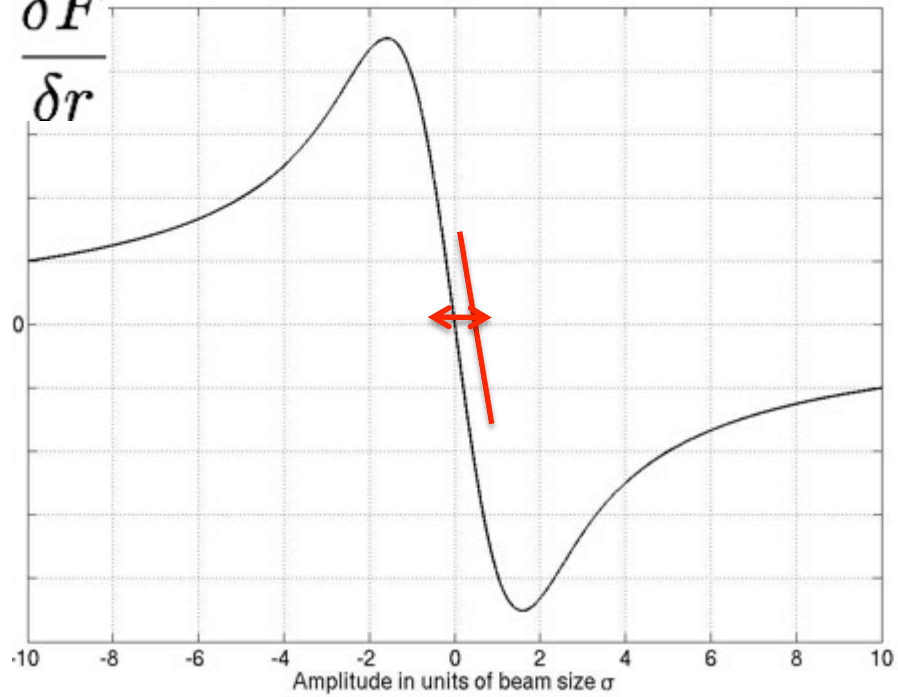
Detuning with Amplitude for head-on

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

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



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



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

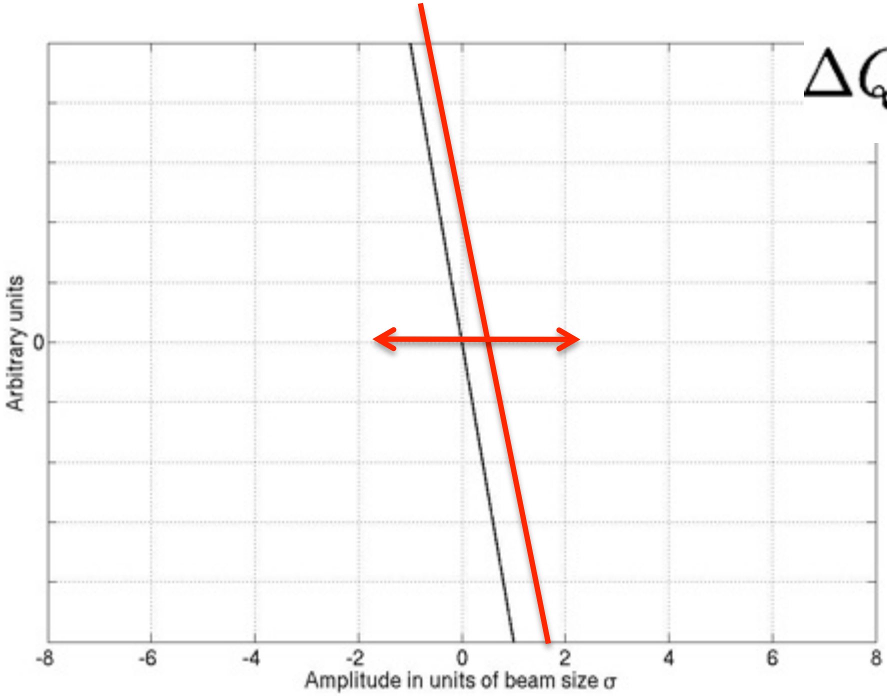
For small amplitude test particle linear tune shift

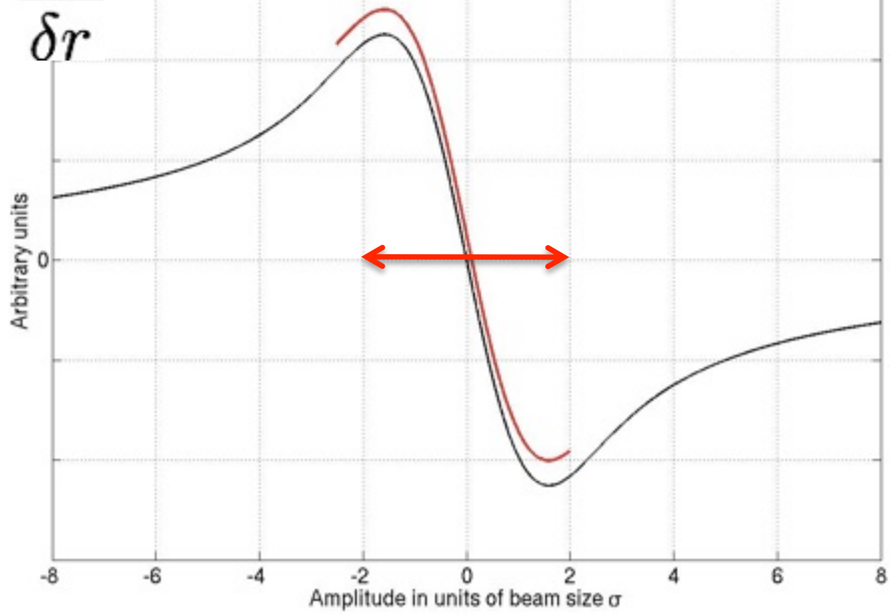
$$\lim_{r\to 0} \Delta Q(r) = -\frac{N r_0 \beta^*}{4\pi\gamma\sigma^2} = \xi$$

Detuning with Amplitude for head-on

Beam with many particles this results in a tune spread

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





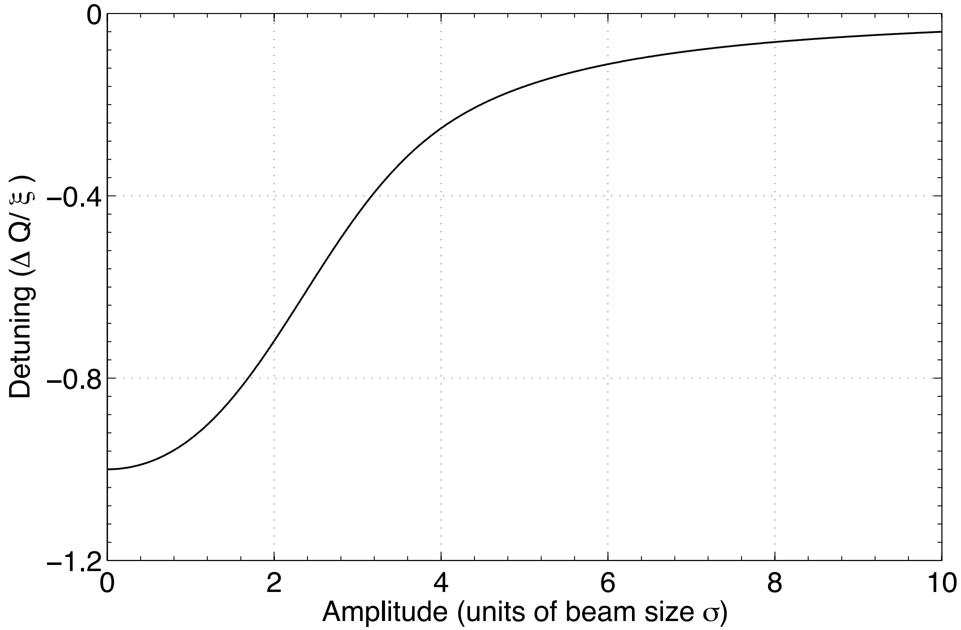
$$\Delta Q_{quad} = const \qquad \Delta Q_{bb} \neq const$$

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

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

Head-on detuning with amplitude and footprints

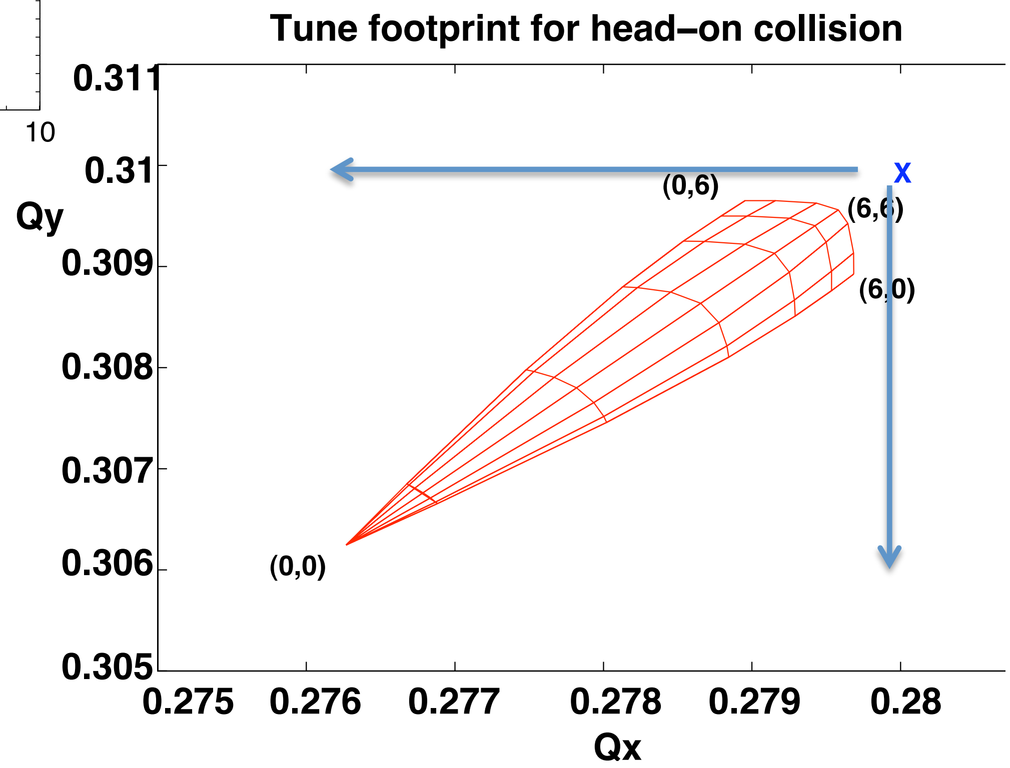
1-D plot of detuning with amplitude



And in the other plane?

THE SAME DERIVATION

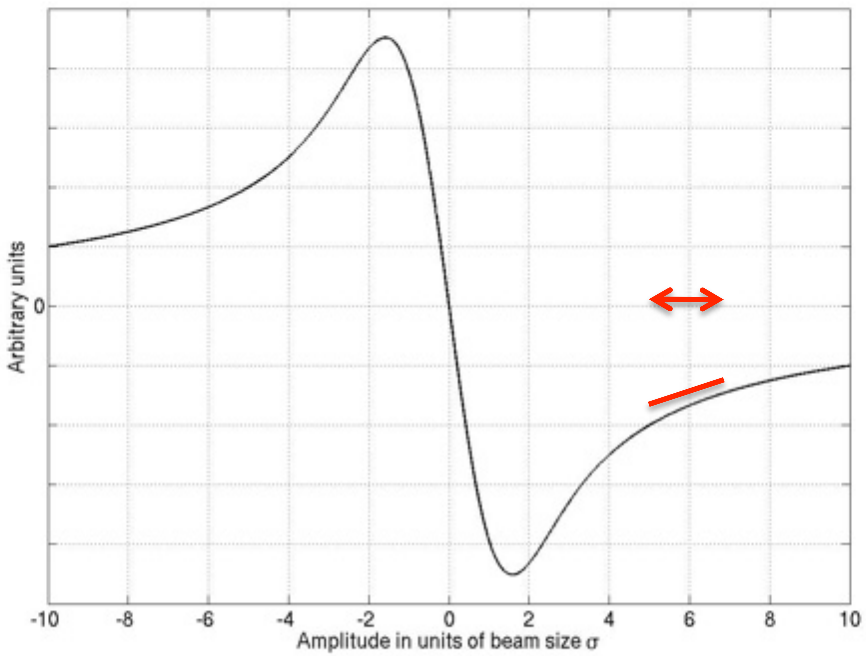
same tune spread



FOOTPRINT

2-D mapping of the detuning with amplitude of particles

And for long-range interactions?

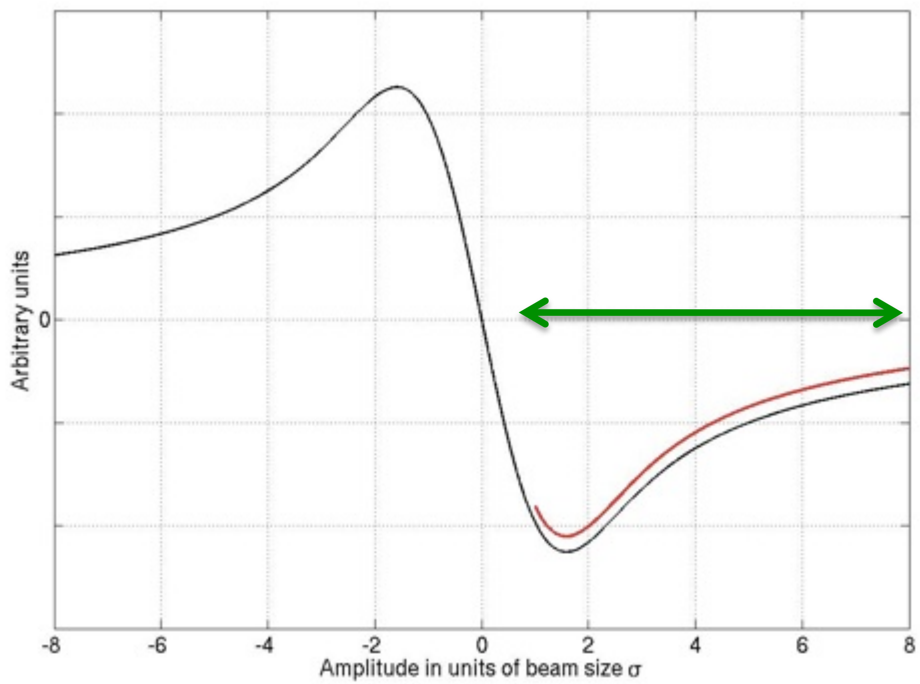


Second beam centered at d (i.e. 6σ)

- Small amplitude particles **positive tune shifts**
- Large amplitude can go to **negative tune shifts**

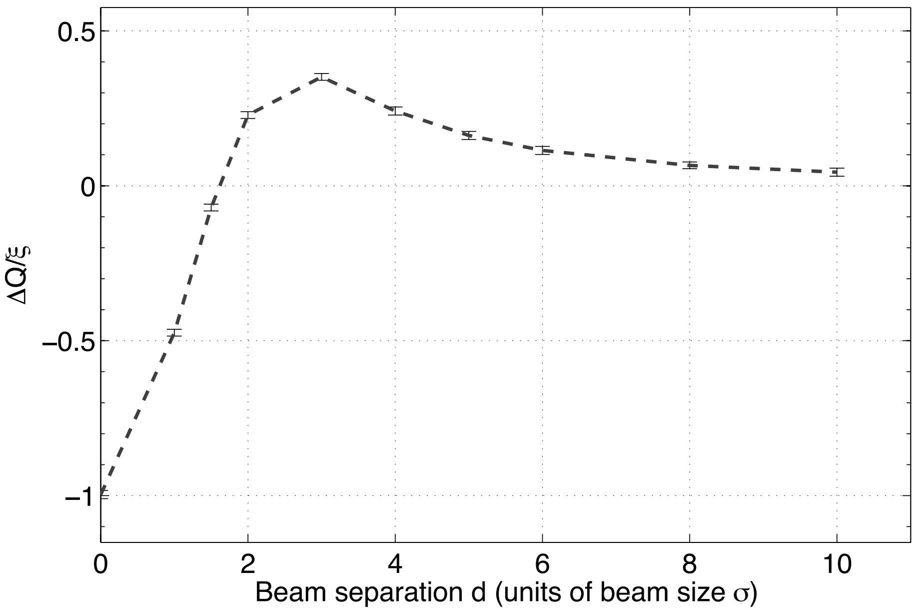
Long range tune shift scaling for distances $d > 6\sigma$

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



Long-range footprints

ΔQ_y

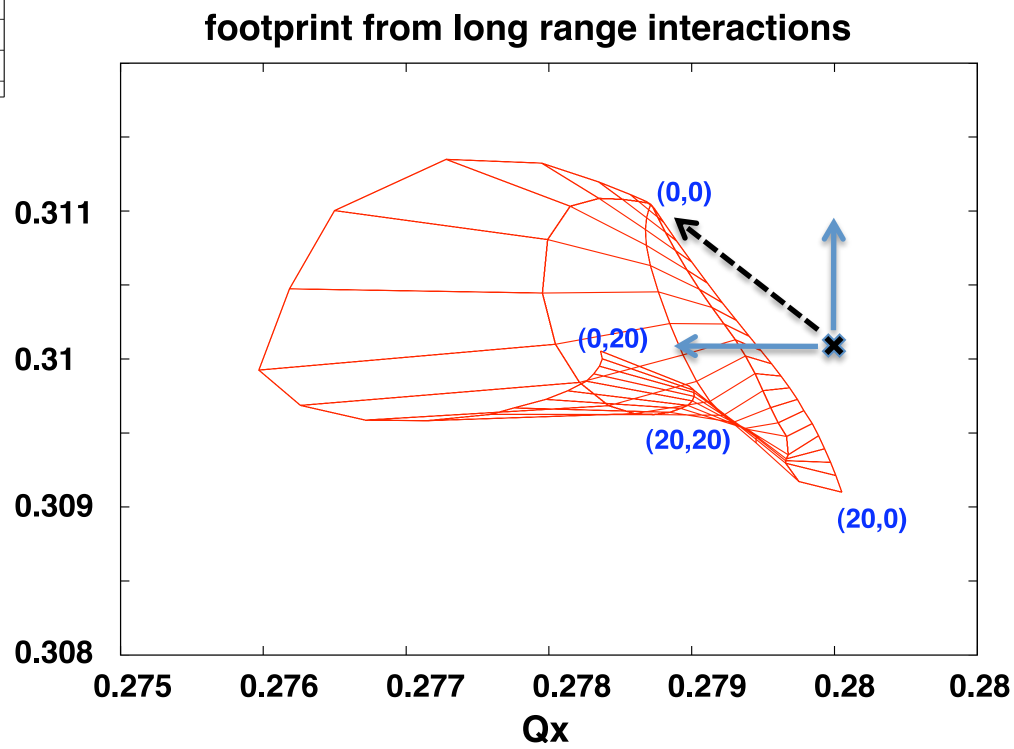


Separation in vertical plane!

And in horizontal plane?

The test particle is centered with the opposite beam

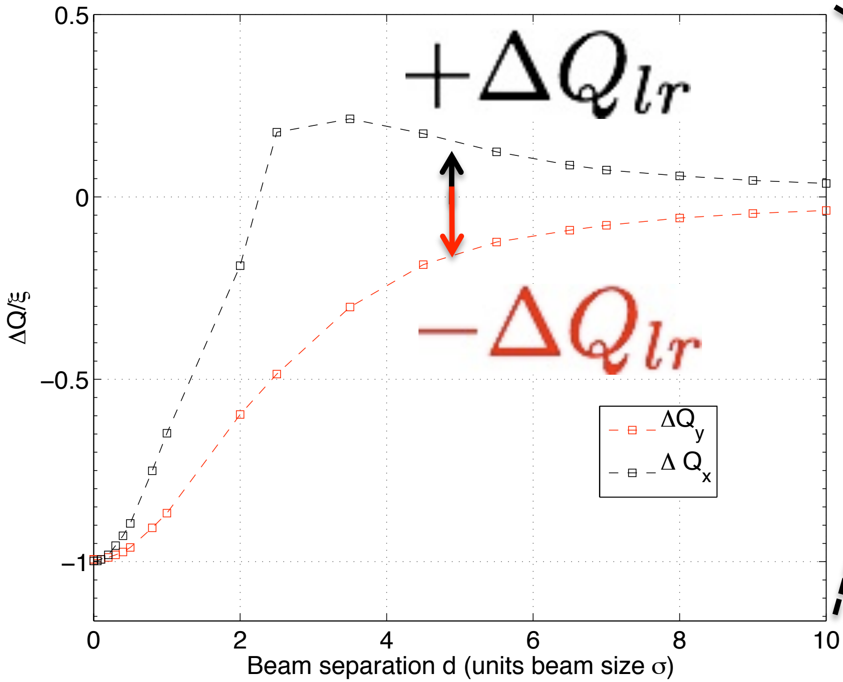
tune spread more like for head-on at large amplitudes



The picture is more complicated

now the LARGE amplitude particles see the second beam and have larger tune shift

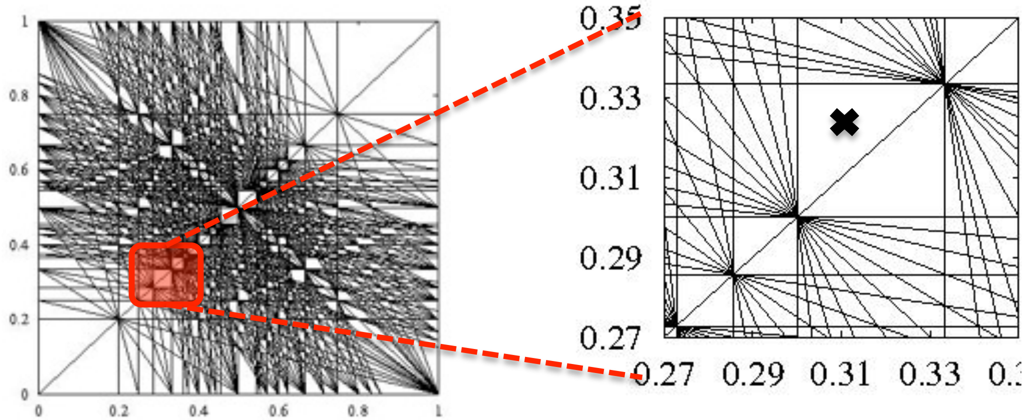
Beam-beam tune shift and spead: 1HO + 1LR

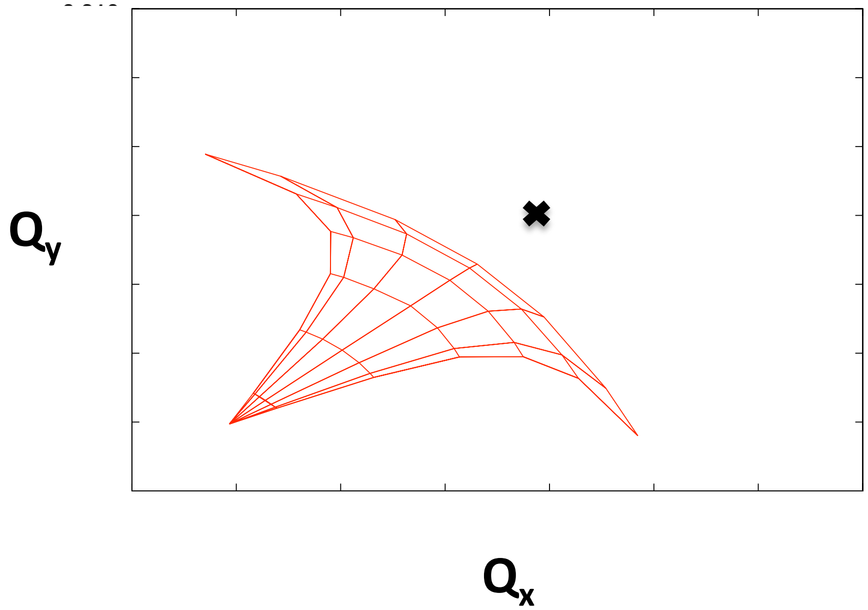


IP5 Head-on + LR with HORIZONTAL separation
HO tune footprint +
In the **horizontal** plane **long range tune shift**
In the **vertical** plane **head-on tune shift**

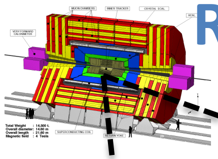
IP1 Head-on + VERTICAL separation
The opposite of IP5
PASSIVE COMPENSATION

Tune footprint, combined head–on and long range

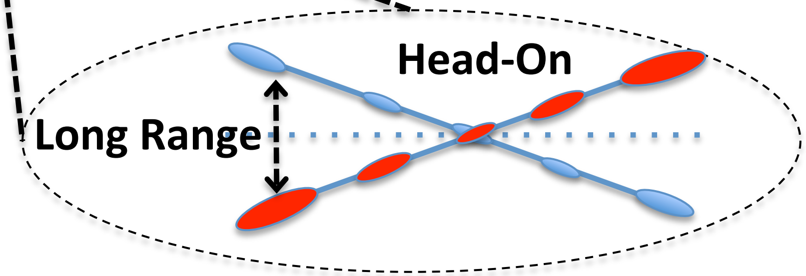


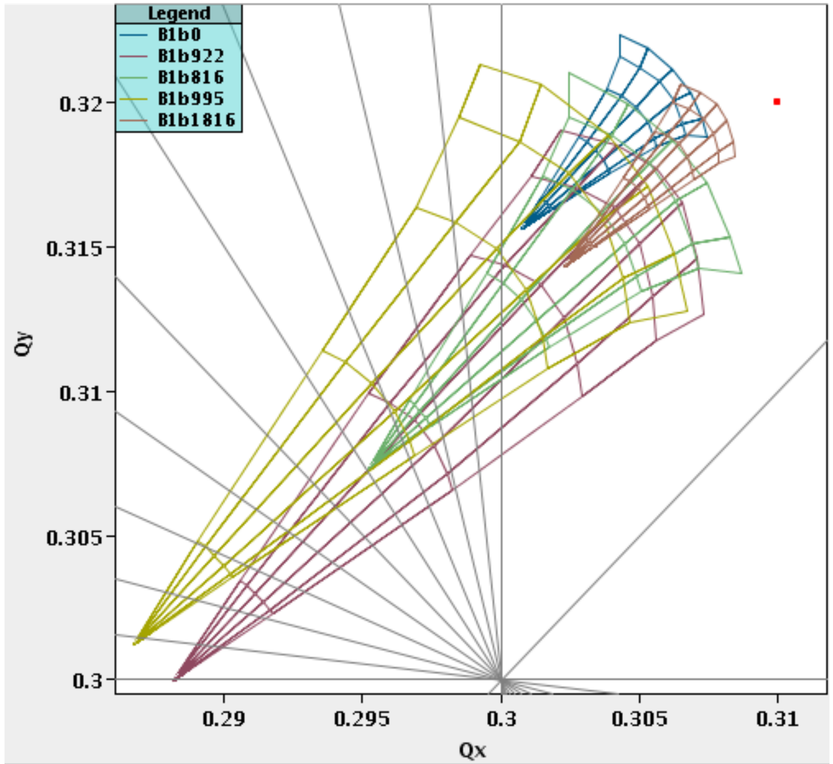


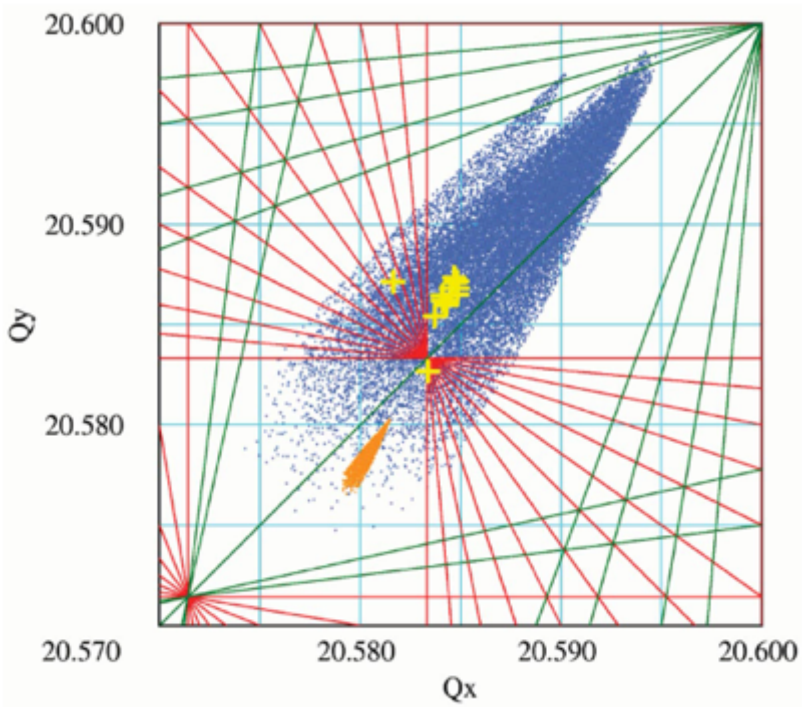
Reminder: Pacman and Super-pacman



Remember 1374 bunches and 64 interactions per turn





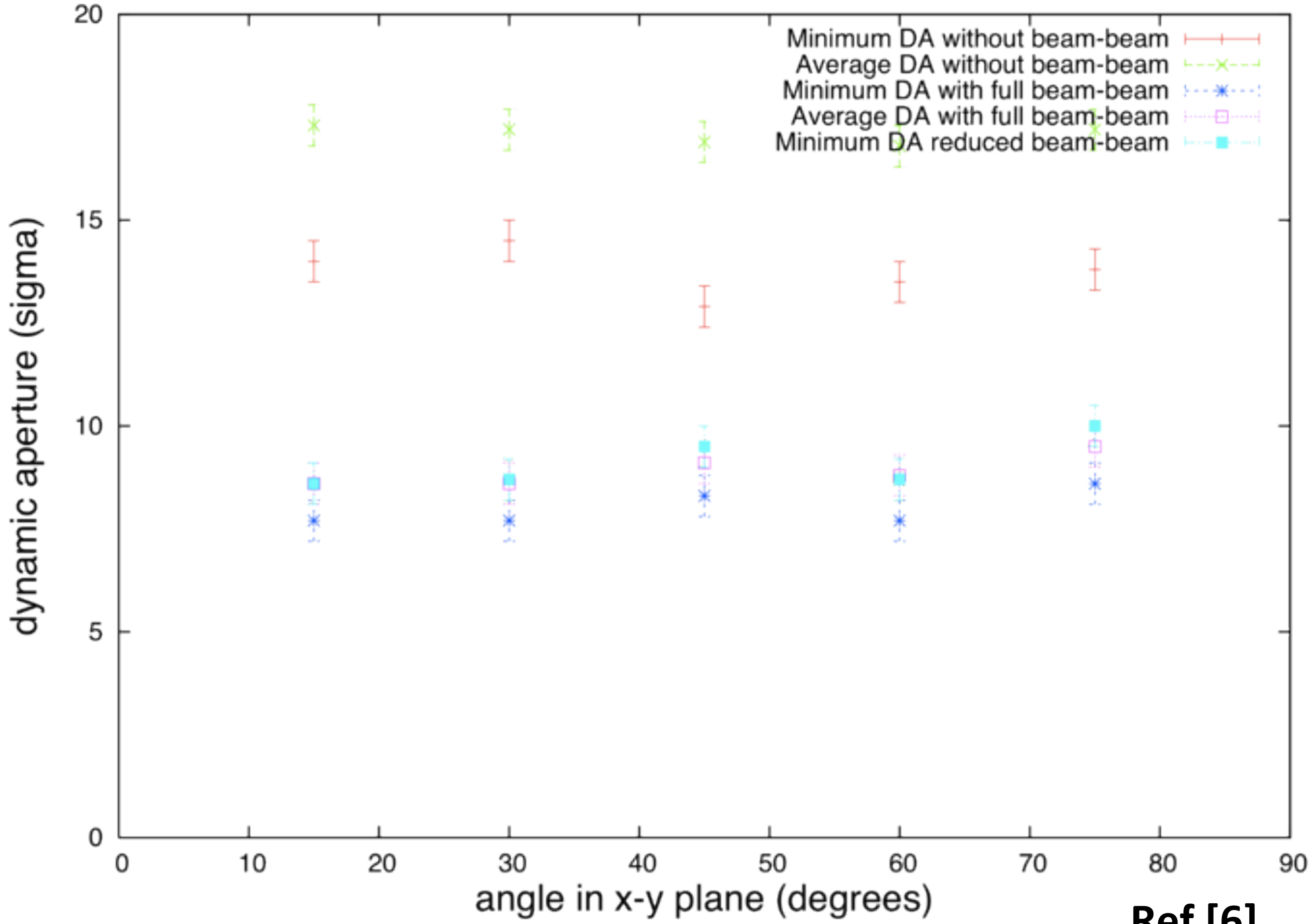


Tevatron Footprints

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

Dynamic Aperture

Dynamic Aperture: area in amplitude space with stable motion



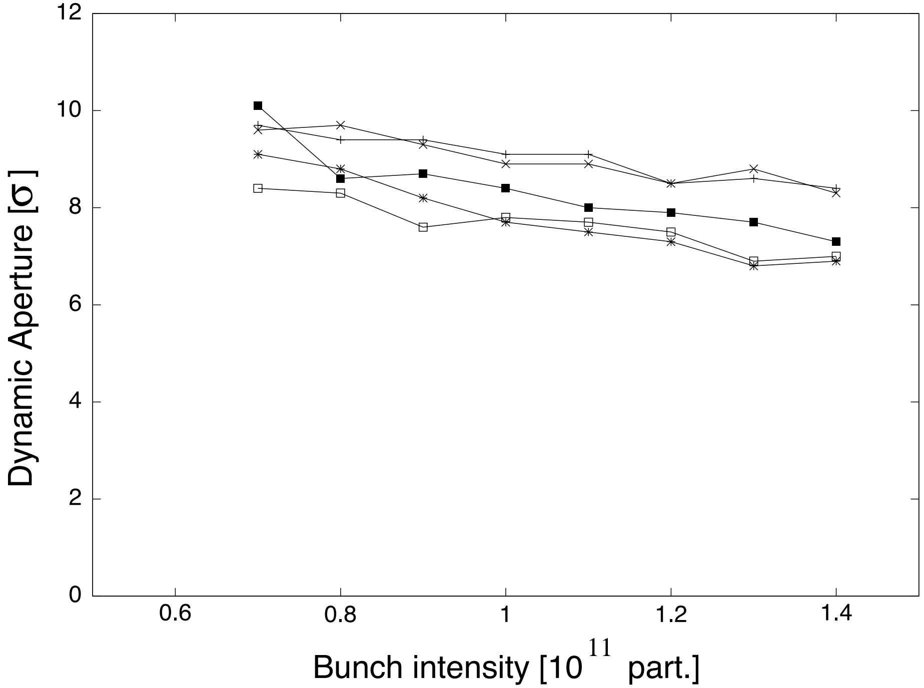
Ref [6]

Stable area reduced by beam-beam interactions resulting in losses and bad lifetime

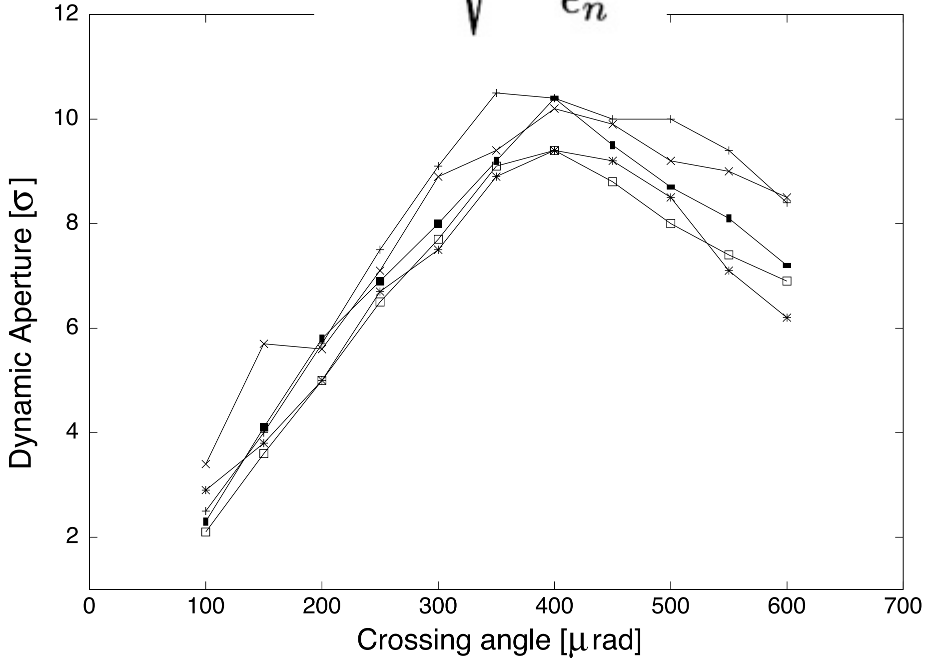
Dynamic Aperture

Dynamic Aperture depends on beam intensity and crossing angle

$$F_{bb} \propto N_p$$



$$d_{lr} \propto \sqrt{\frac{\beta^* \alpha^2 \gamma}{\epsilon_n}}$$

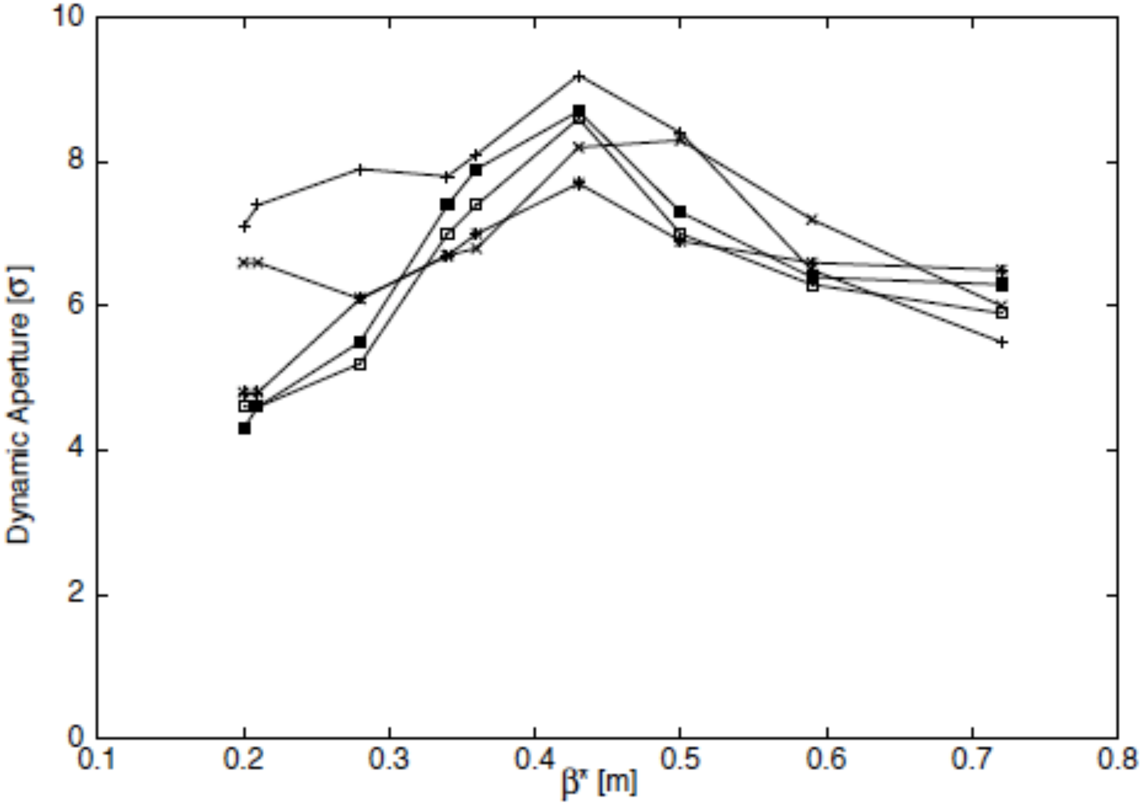


Ref [6]

Stable area depends on beam-beam interactions therefore the choice of running parameters is the result of careful study of different effects

Dynamic Aperture

Dynamic Aperture depends on beta at the IP



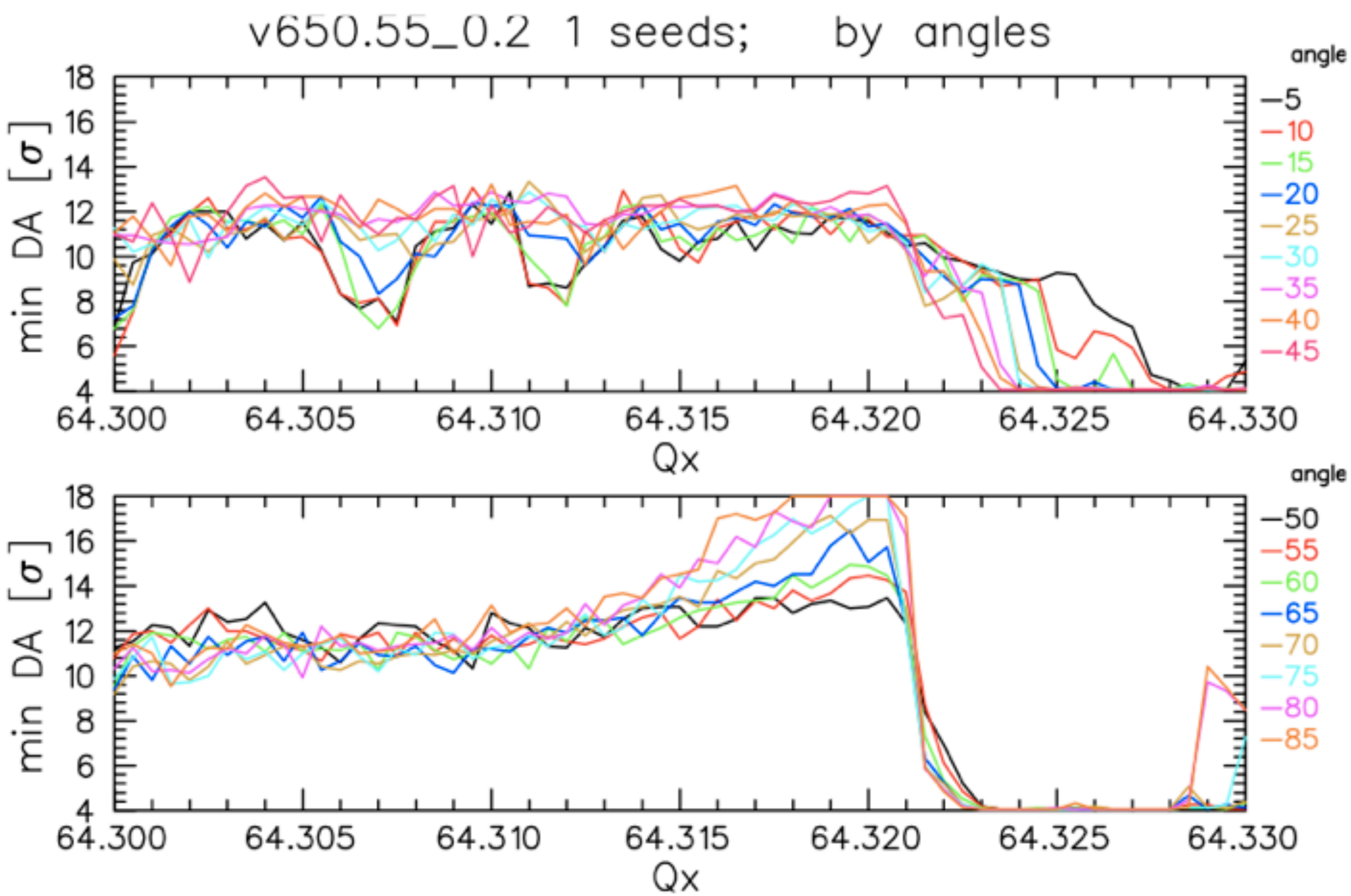
$$d_{lr} \propto \sqrt{\frac{\beta^* \alpha^2 \gamma}{\epsilon_n}}$$

Ref [6]

Interplay of different parameters to reduce losses as for not reducing DA

Dynamic aperture reduction vs tune

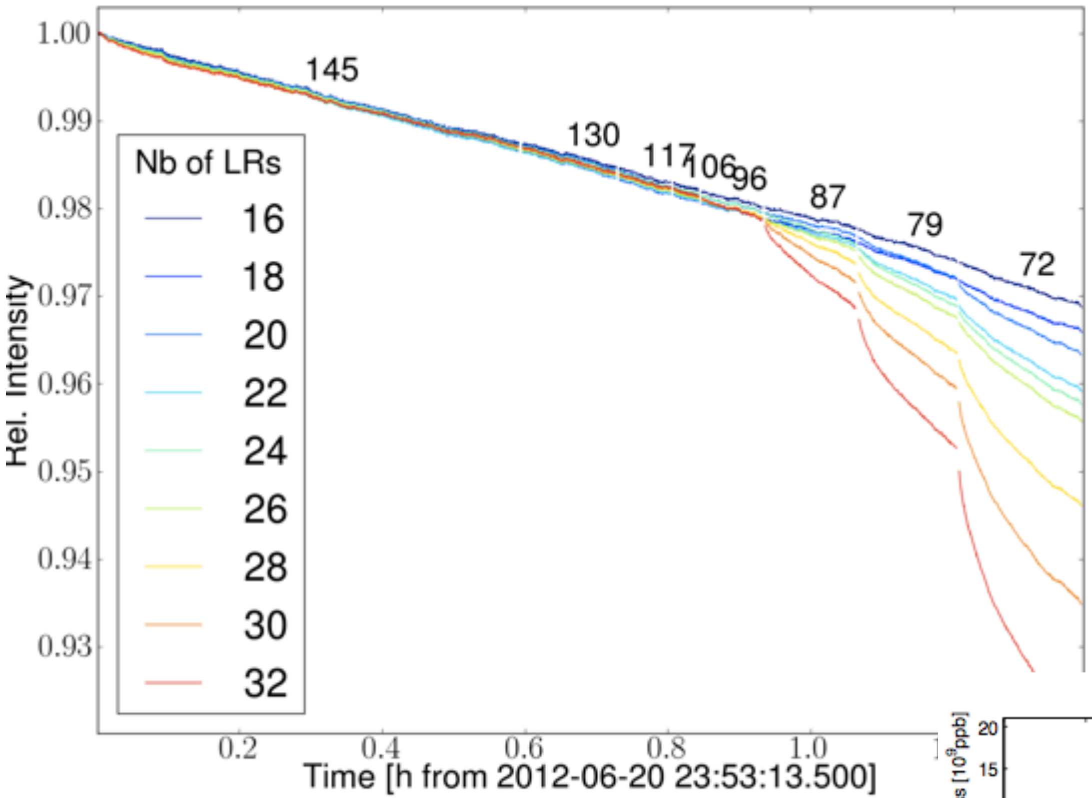
Dynamic Aperture depends on the working point



Ref [8]

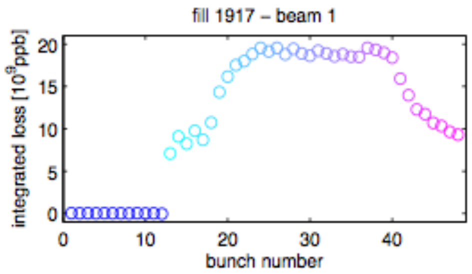
Working point choice comes from careful study of tracking studies with beam-beam to avoid resonances

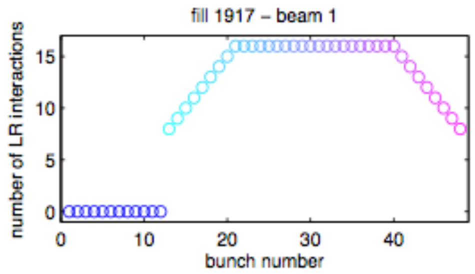
DO we see the effects of LR in the LHC?



Small crossing angle = small separation

If separation of long range too small particles become unstable and get lost





Courtesy G. Papotti

Particle losses follow number of Long range interactions

Nominal LHC will have twice the number of interactions

Orbit Effects

Long Range Beam-beam interactions lead to orbit effects

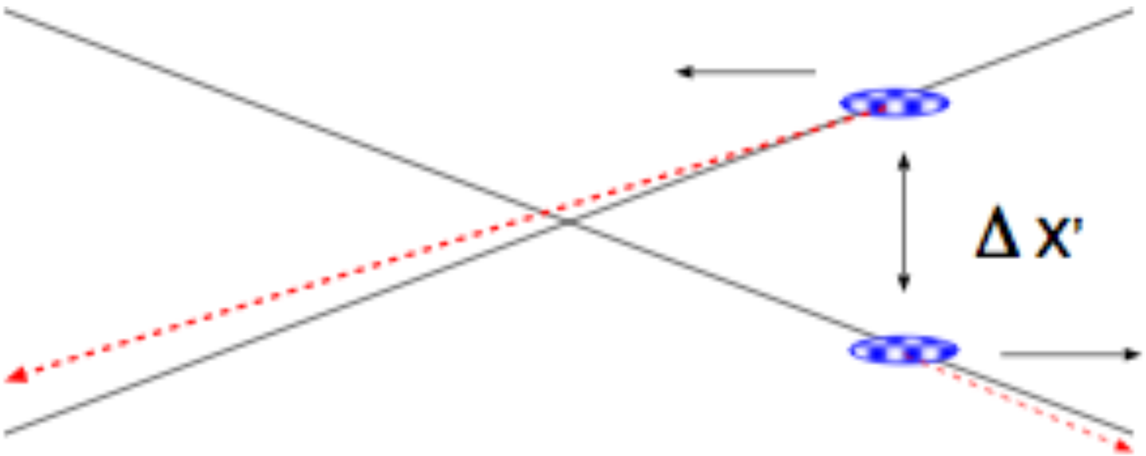
Long range kick

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

For well separated beams $d \gg \sigma$

The force has an amplitude independent contribution: ORBIT KICK

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

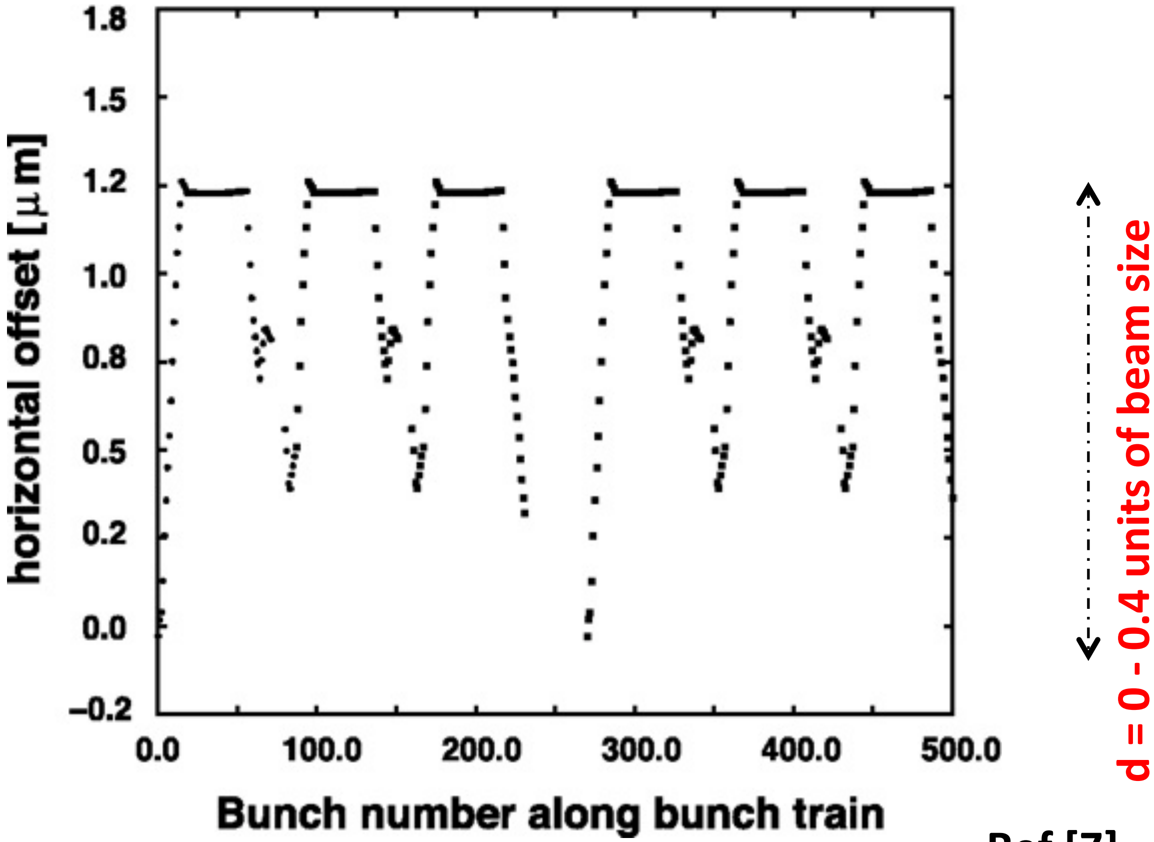


Orbit can be corrected but we should remember PACMAN effects

LHC orbit effects

Orbit effects different due to pacman effects and the many long-range add up giving a non negligible effect

Can be measured and calculated very well self consistent orbit calculations with multiple bunches



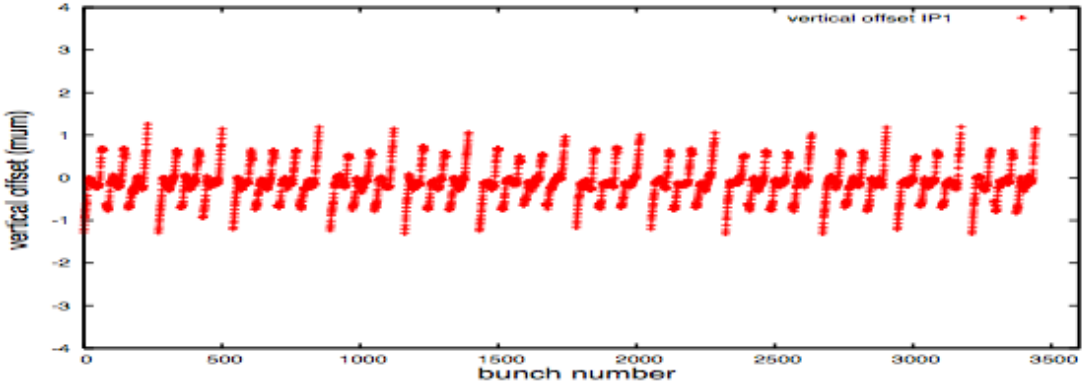
Ref [7]

Moreover can lead to emittance growths

Long range orbit effect

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

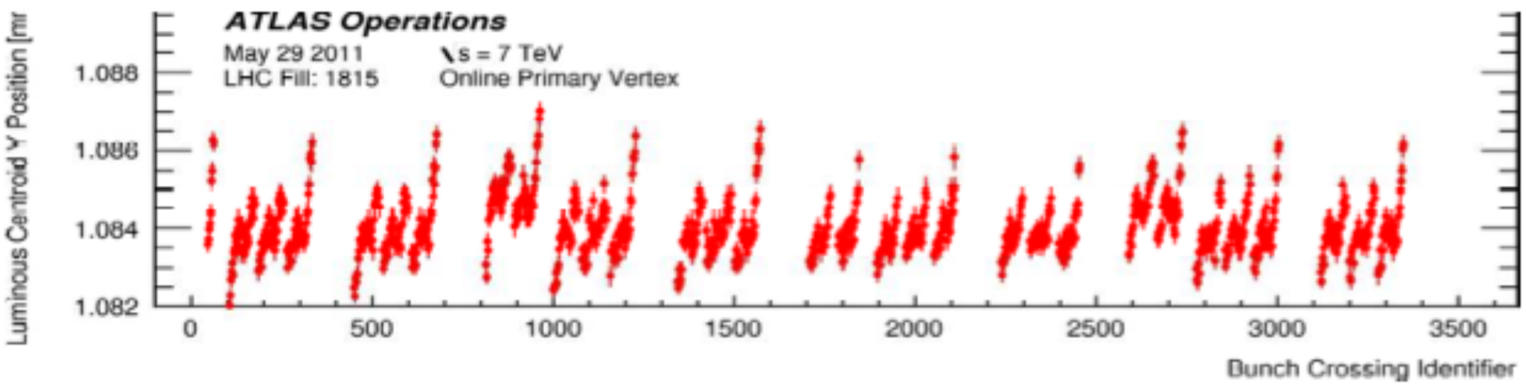
Simulations for LHC 25 ns fillings scheme Ref [7]



2011-07-05

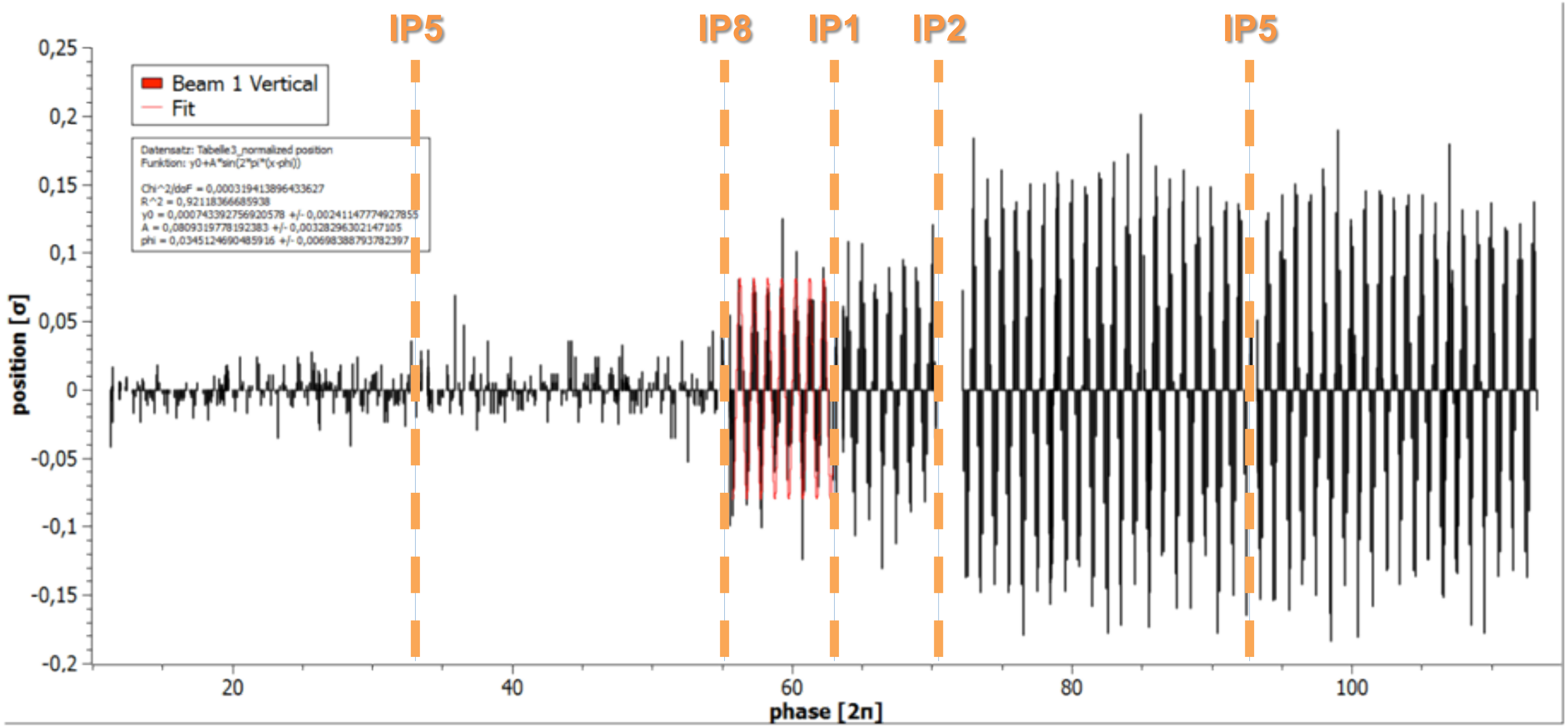
Measurement of the vertex centroid by ATLAS

#1



Effect is already visible with reduced number of interactions

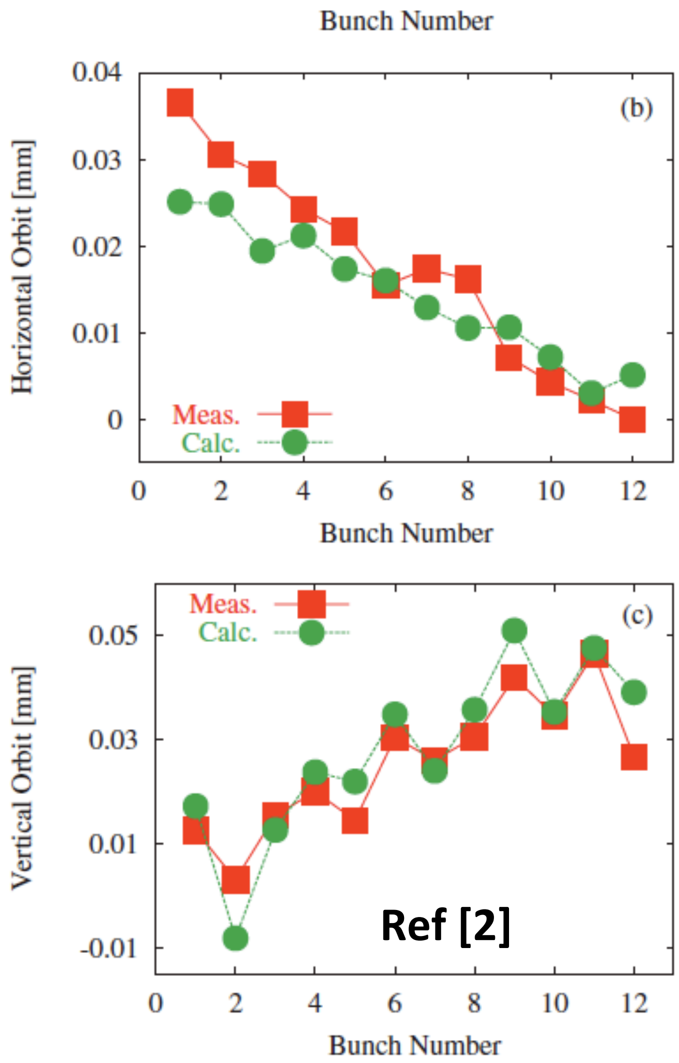
Long range orbit effect observations:



Courtesy T. Baer

Vertical oscillation starts when one beam is missing in IP8
so orbit contribution at IP is missing

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

Coherent dipolar beam-beam modes

Coherent beam-beam effects arise from the forces which an exciting bunch exerts on a whole test bunch during collision

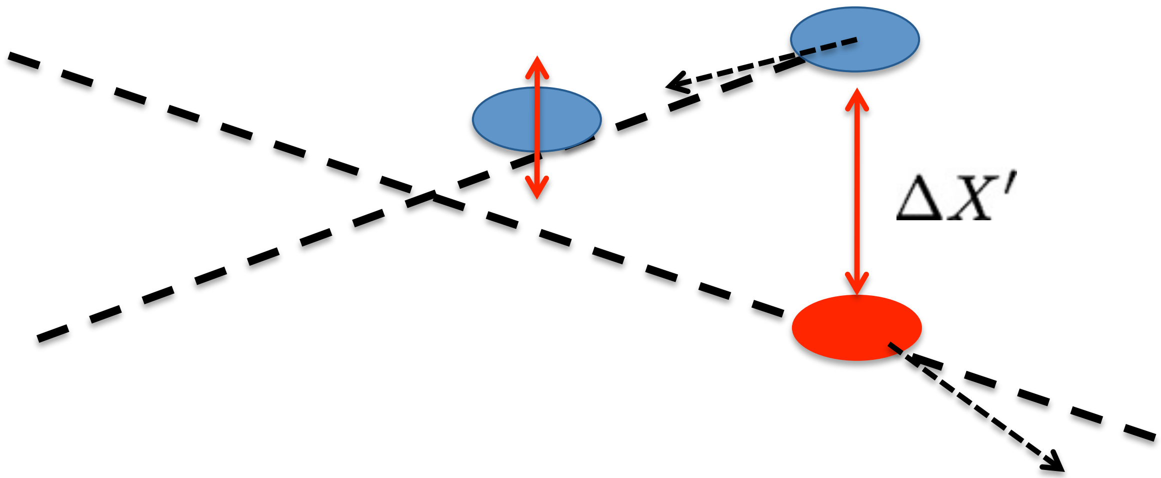
We study the collective behaviour of all particles of a bunch

Coherent motion requires an organized behaviour of all particles of the bunch

Coherent beam-beam force

- Beam distributions $\boldsymbol{\Psi_1}$ **and** $\boldsymbol{\Psi_2}$ mutually changed by interaction
- Interaction depends on distributions
  - Beam 1 Ψ_1 solution depends on beam 2 Ψ_2
  - Beam 2 Ψ_2 solution depends on beam 1 Ψ_1
- Need a self-consistent solution

Coherent beam-beam effects



- Whole bunch sees a kick as an entity (coherent kick)
- Coherent kick seen by full bunch different from single particle kick
- Requires integration of individual kick over particle distribution

- Coherent kick of separated beams can excite coherent dipolar oscillations
- All bunches couple because each bunch “sees” many opposing bunches(LR): many coherent modes possible!

Coherent effects

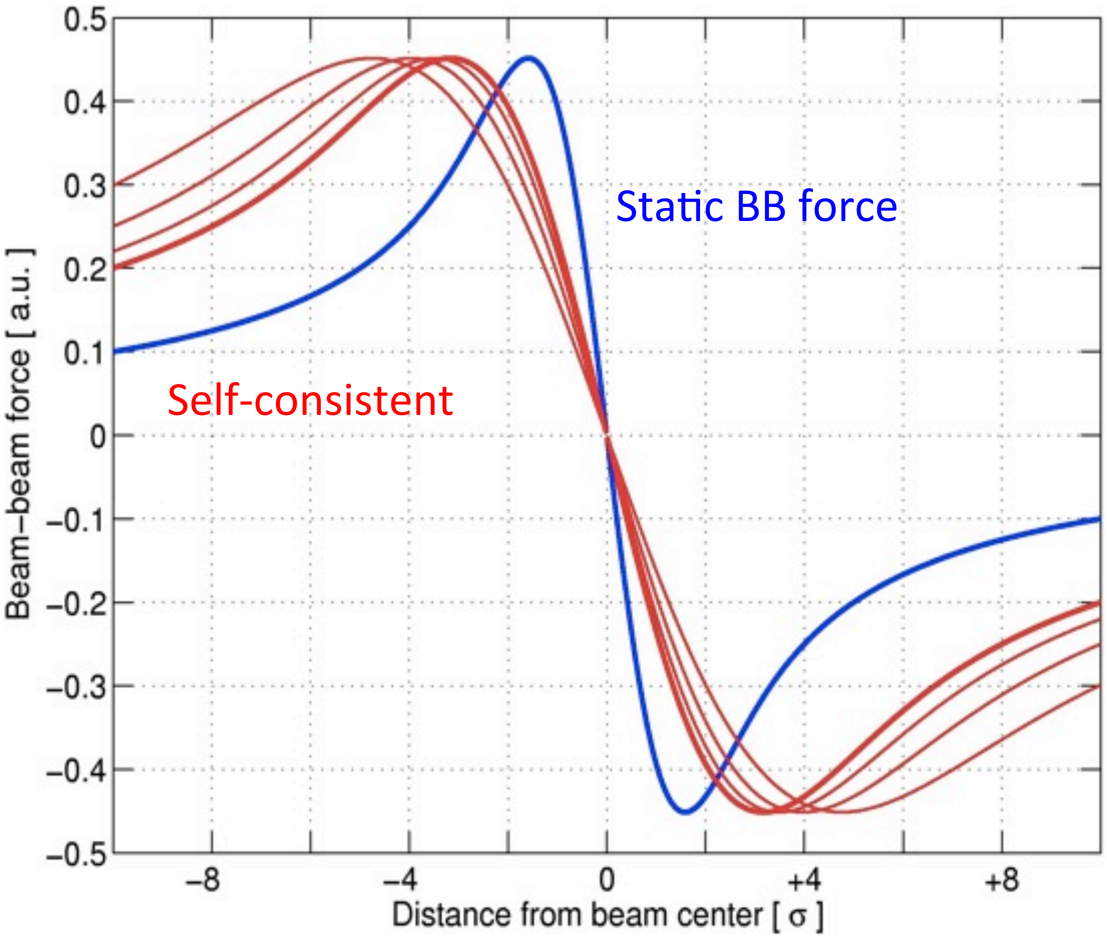
Self-consistent treatment needed

Perturbative methods

static source of distortion:
example magnet

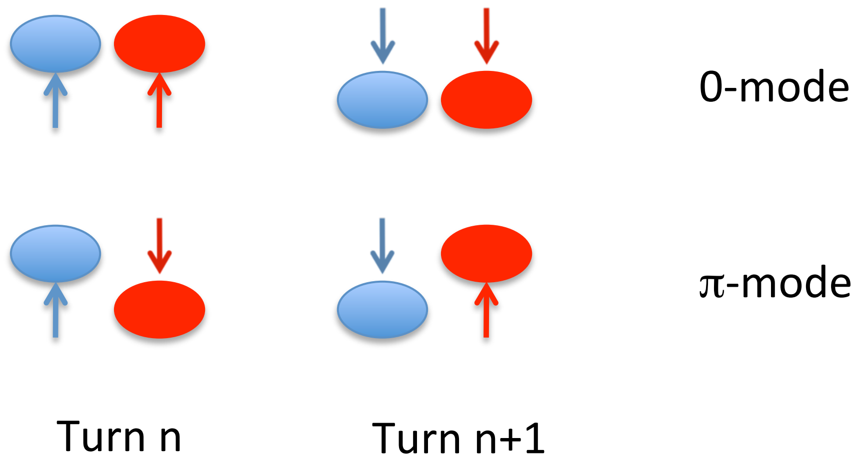
Self-consistent method

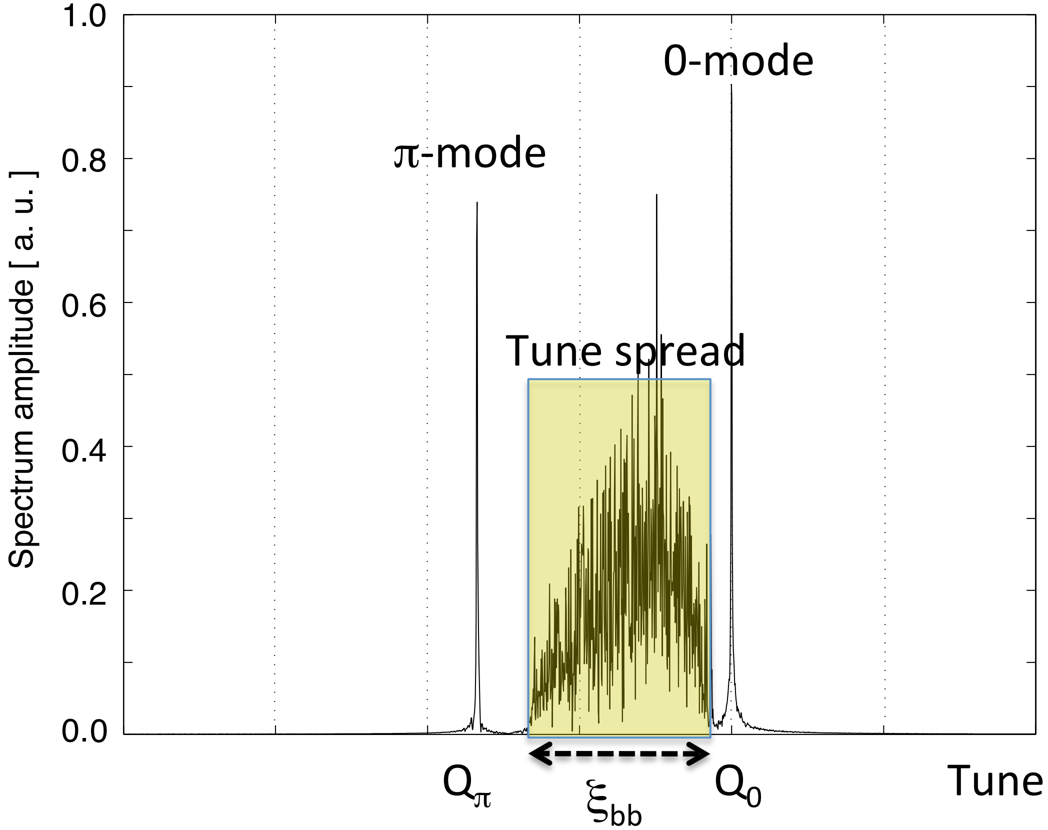
source of distortion changes
as a result of the distortion



For a complete understanding of BB effect for the LHC a self-consistent treatment should be used

Simple case: one bunch per beam





0-mode at unperturbed tune Q_0

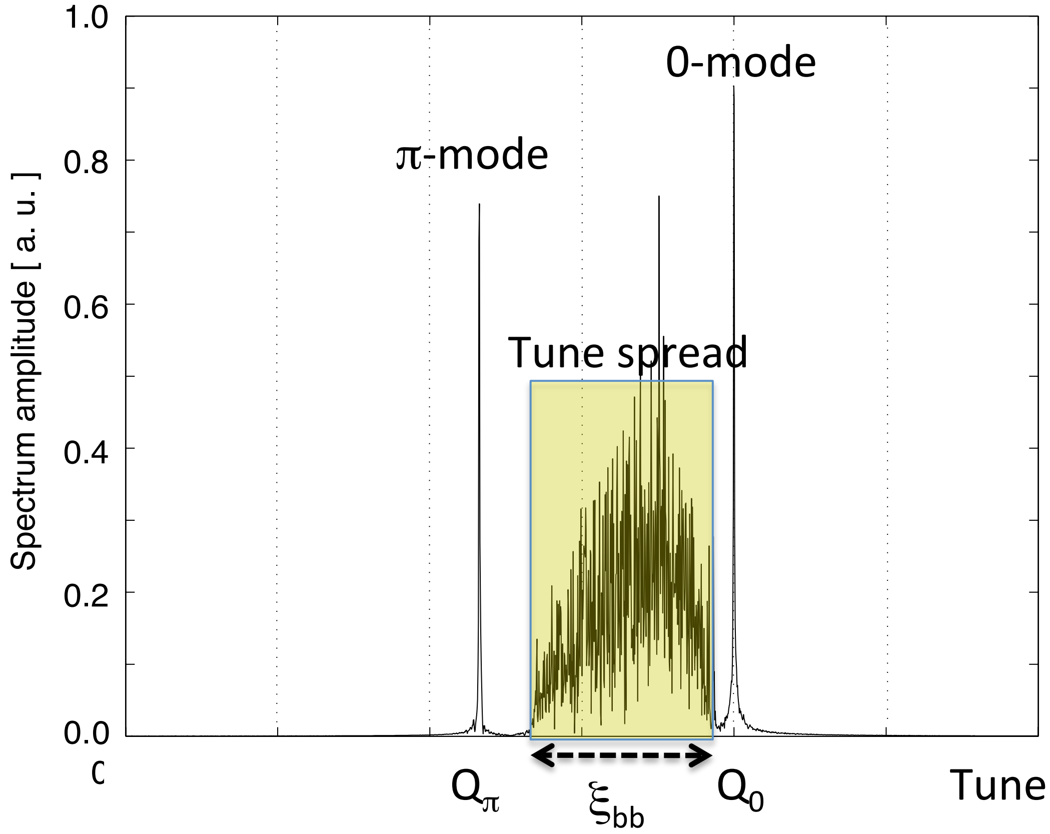
π-mode is shifted at Q_π =1.1-1.3 ξ_{bb}

Incoherent tune spread range [0,-ξ]

$$\Delta Q = Y \cdot \xi$$

- 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)

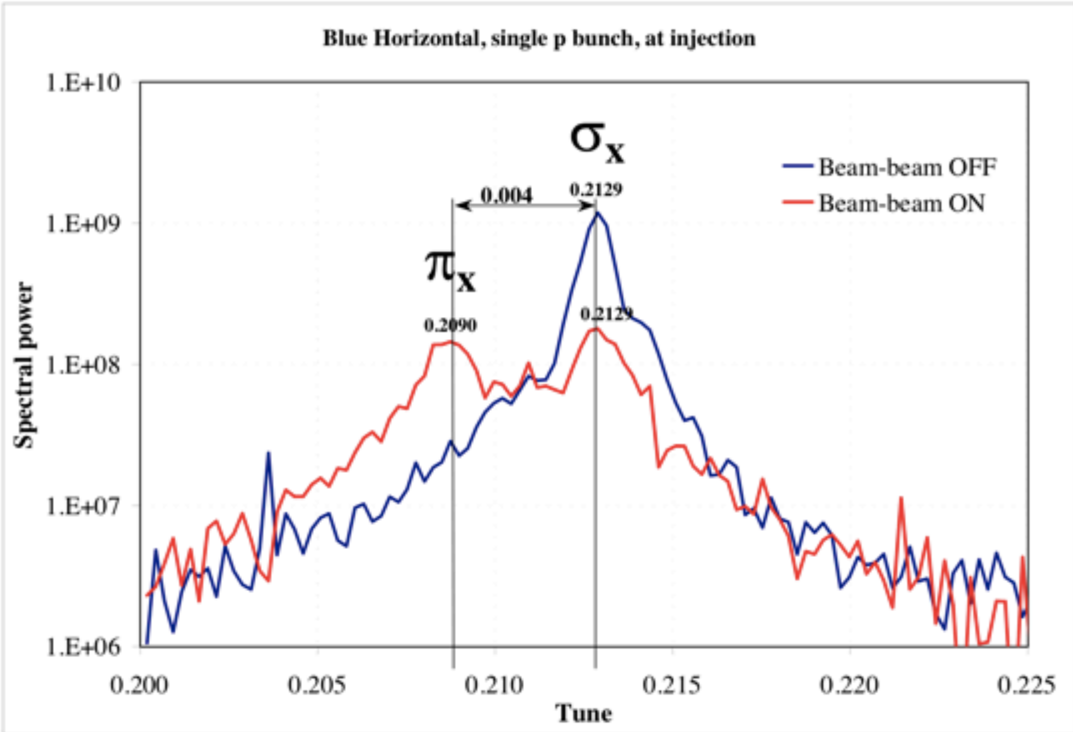
Simple case: one bunch per beam and Landau damping



Incoherent tune spread is the Landau damping region any mode with frequency laying in this range should not develop

- π-mode has frequency out of tune spread

Coherent modes at RHIC

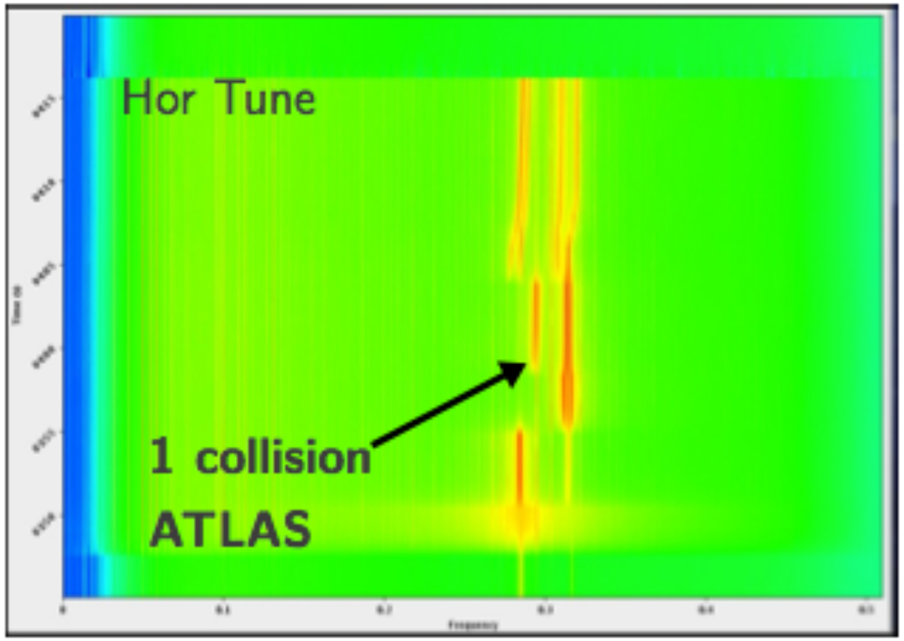


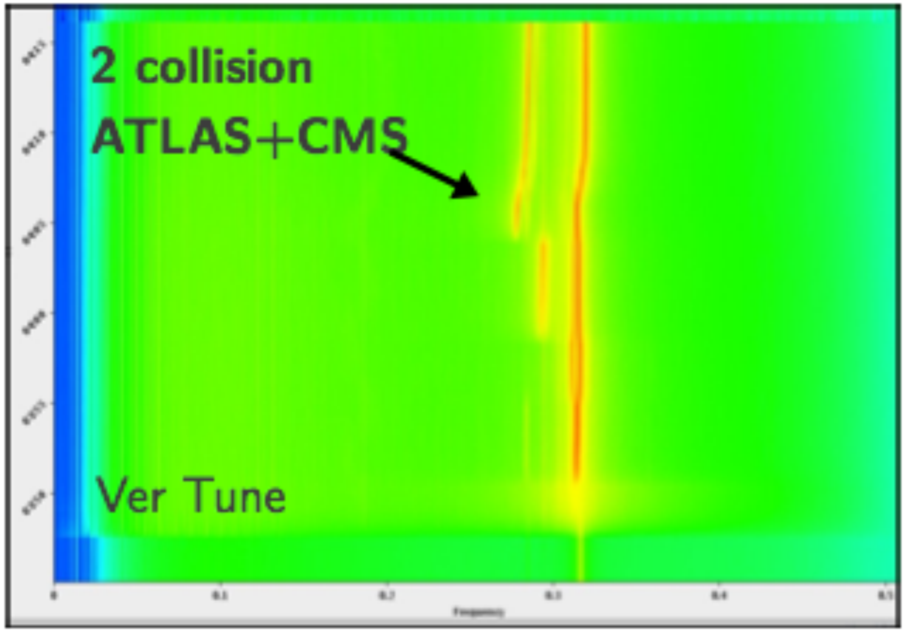
Courtesy W. Fischer (BNL)

Tune spectra before collision and in collision two modes visible

Head-on beam-beam coherent mode

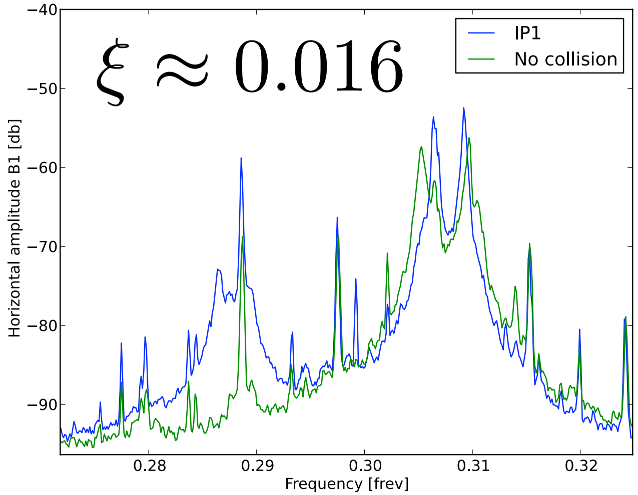
BBQ Signals

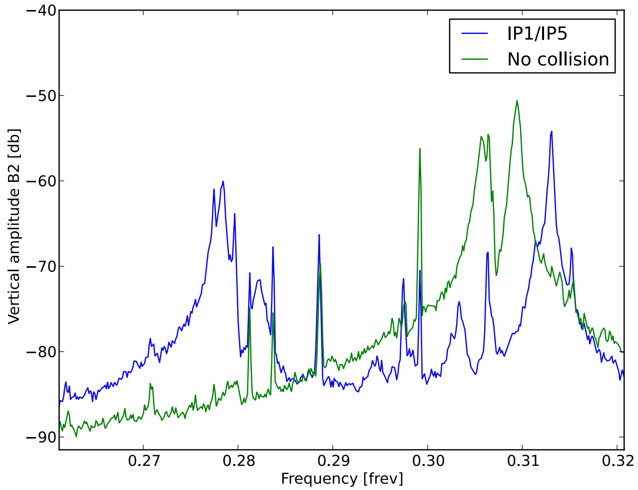




$$\Delta Q = 0.019$$

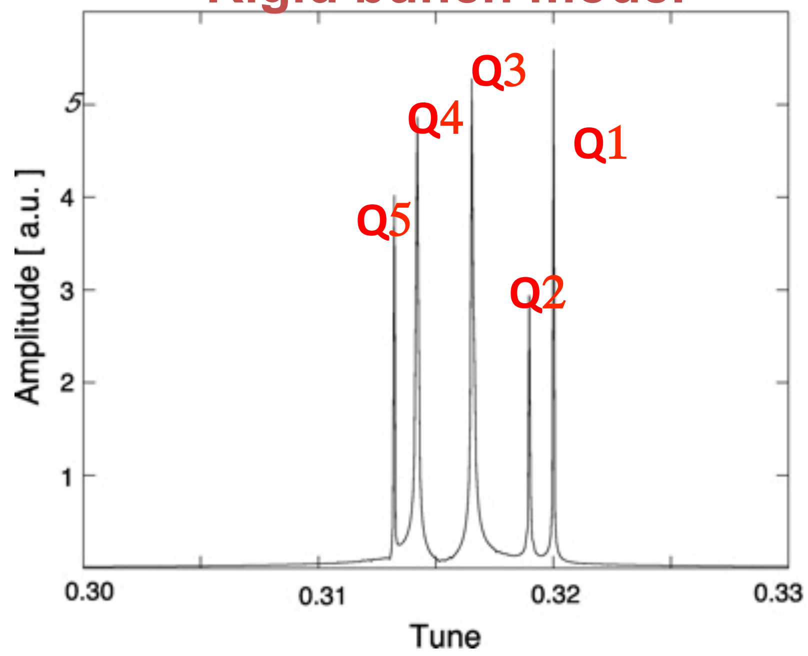
$$\Delta Q = 0.034$$



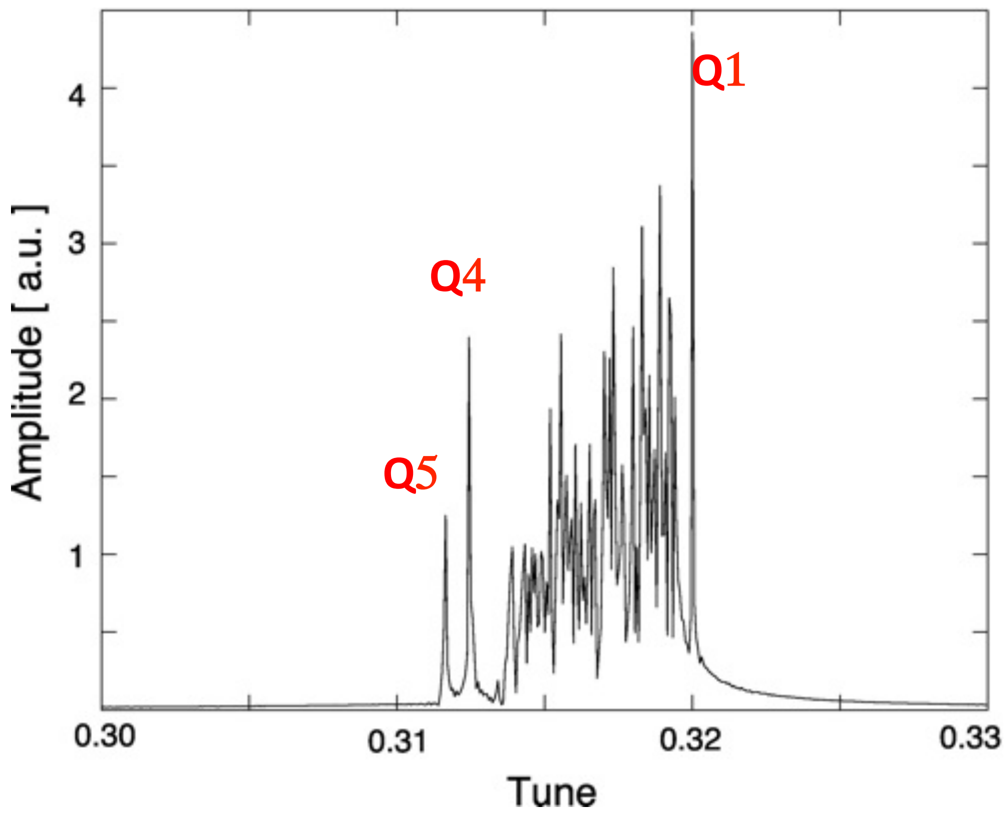


If we have more HO interactions

Rigid bunch model



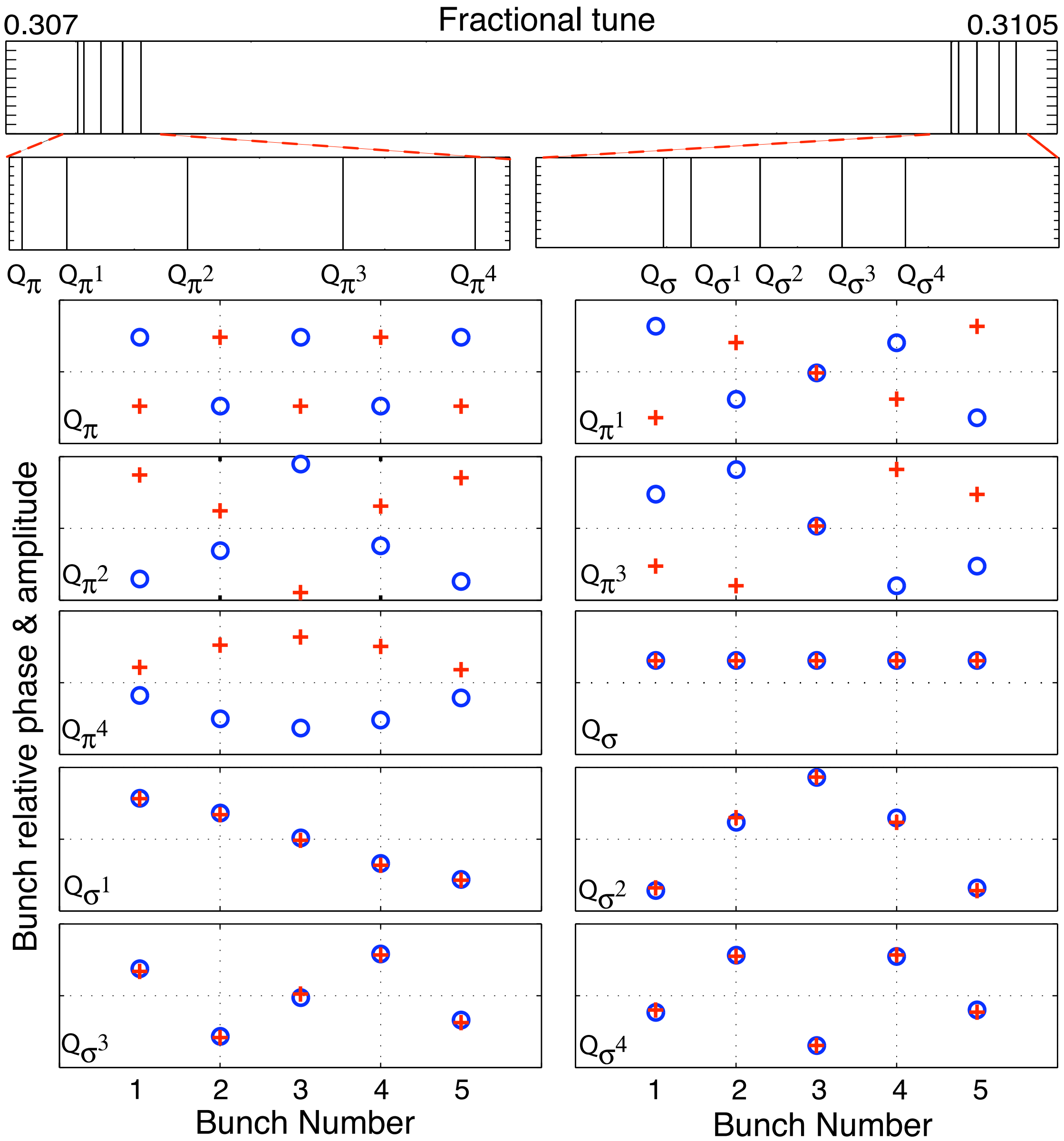
Multi particle simulations



- Bunches couple via the beam-beam interaction
- Additional modes
- Undesirable situation

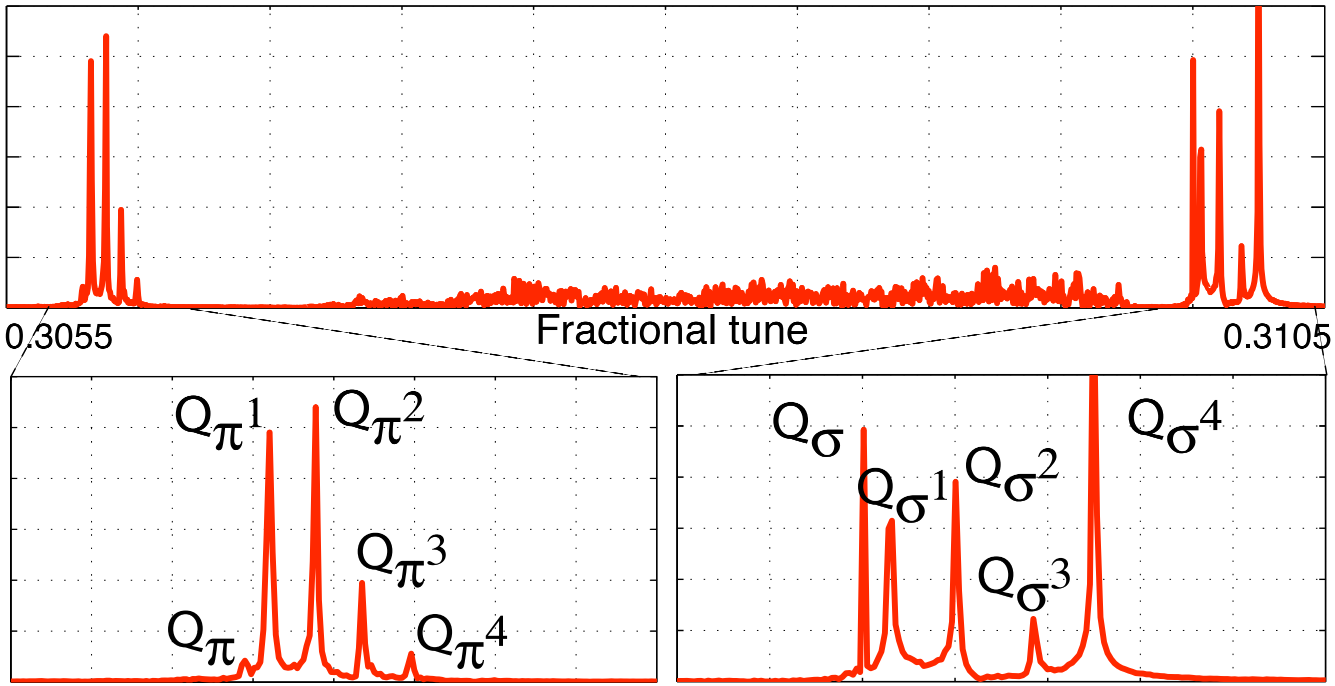
Landau damping of intermediate modes important ingredient

Bunch trains and more interactions



Eigenfunctions of coherent modes

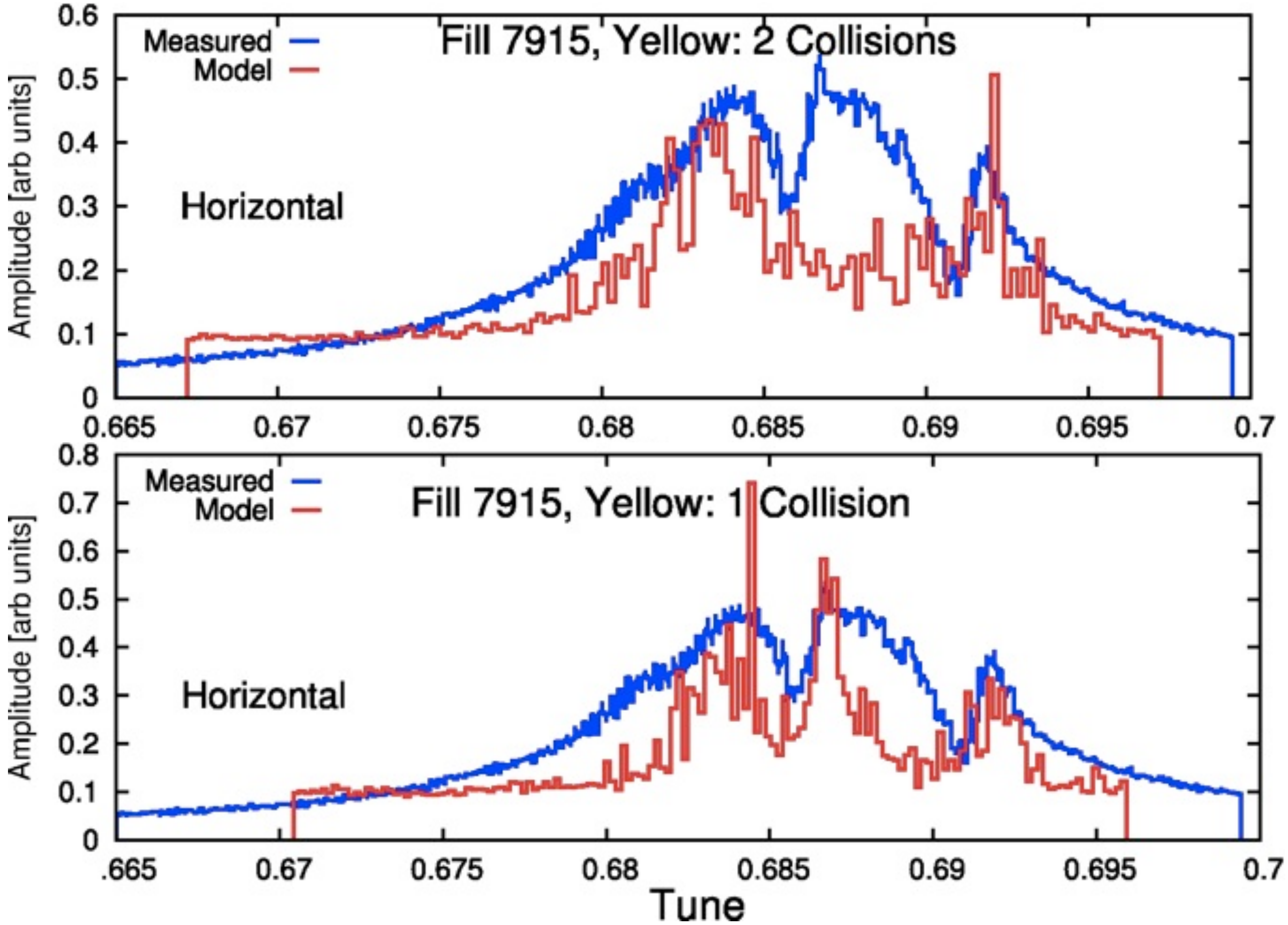
Bunch trains and more interactions



Long-range coherent modes frequencies are sidebands of HO
Pacman bunchhave different number of modes

No Landau damping of long range modes

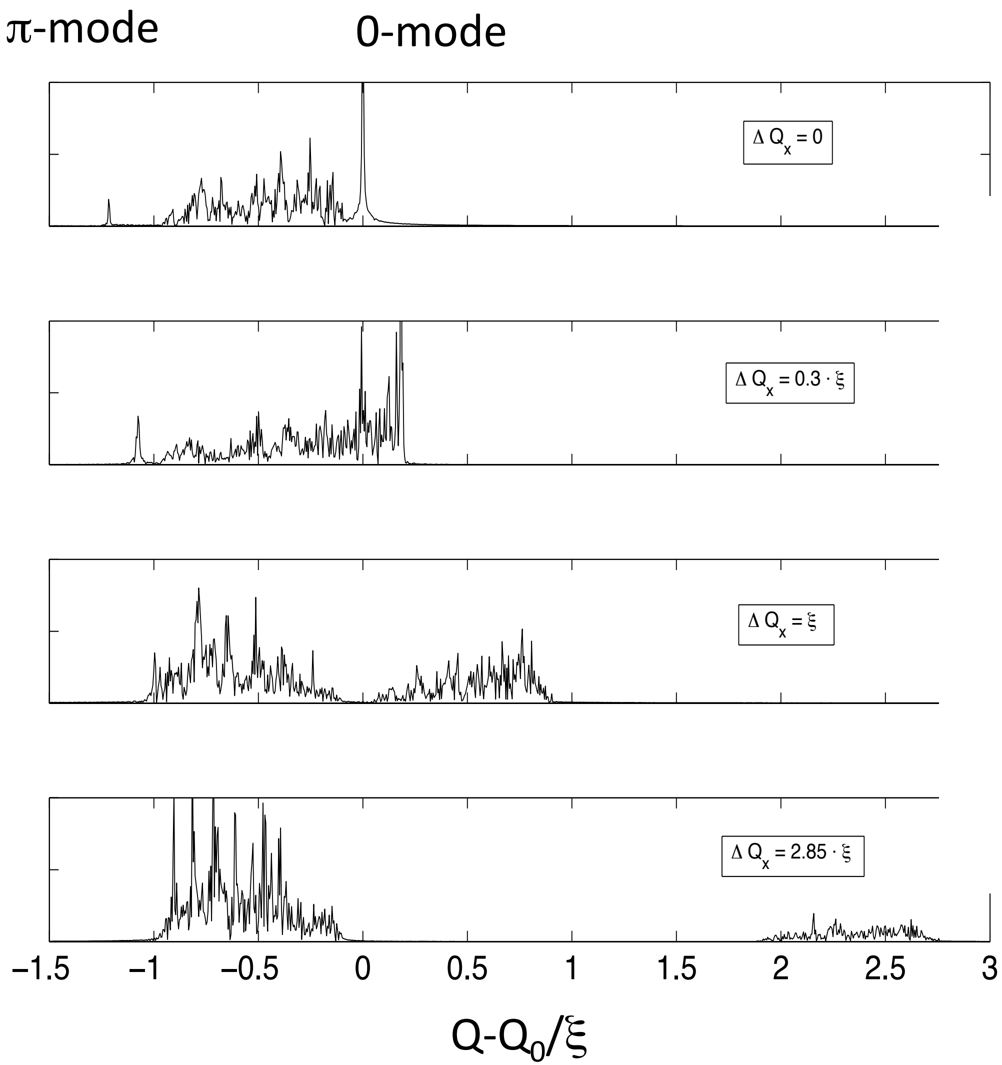
Beam Transfer Function measurements @ RHIC



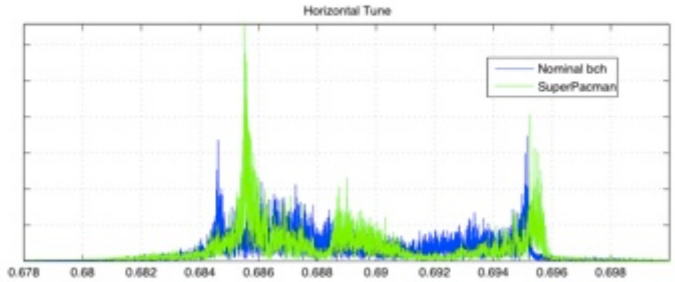
Pacman effect on coherent modes

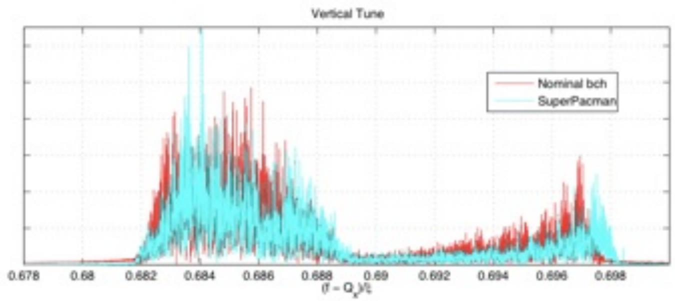
Single bunch diagnostic so important

Different tunes or intensities



RHIC running with mirrored tune for years to break coherent oscillations

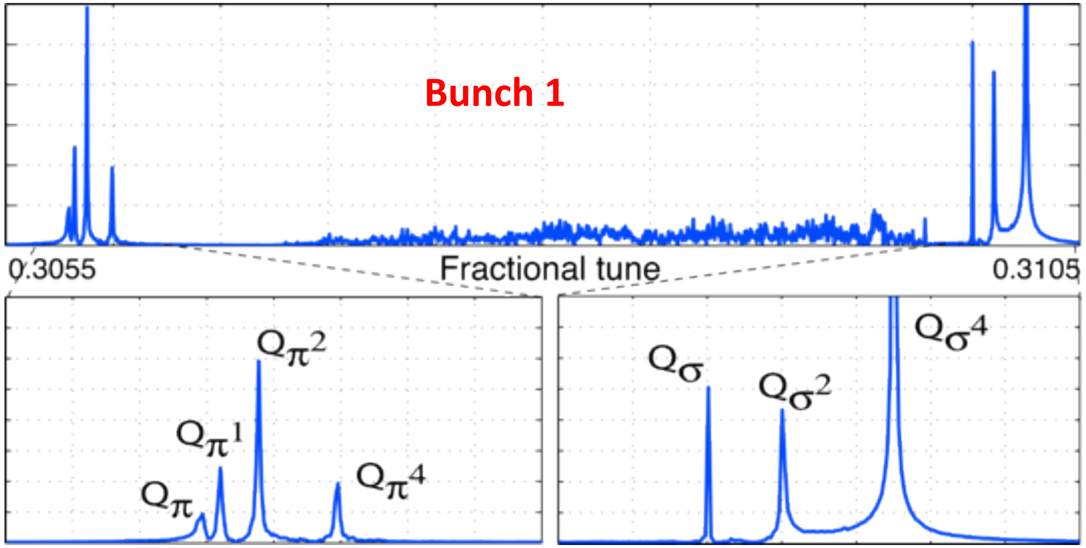


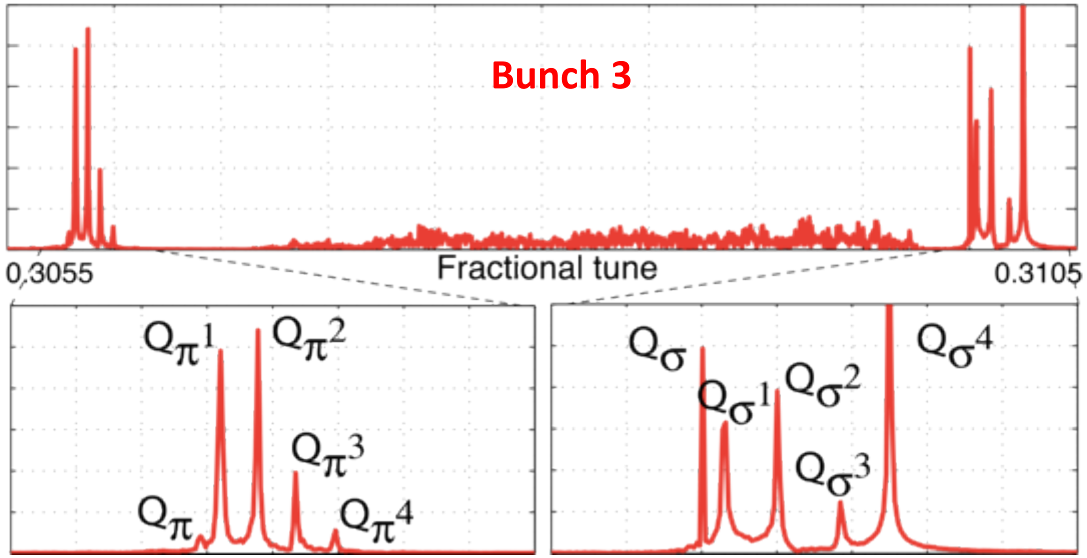


LHC has used a tune split to suppress coherent BB modes

Tune split breaks symmetry and coherent modes disappear Ref [8]

And Long range interactions?





- **Each bunch will have different number of modes and tune spectra**

Single bunch diagnostic can make the difference

…some comments

- **Beam-beam** effects are very important for a collider
- Past **experience** and **studies explain** many **features** and observations but the LHC will still reserve some surprises (PACMAN effects)
- **Single bunch diagnostic** is at the basis of a correct interpretation of the collider performances
- Beam-beam has **many effects** and they depend on different parameters. Improving one can make others worse. That's way a **one solution** to the problem **does NOT** always **exist**!
- Careful choice of **beam parameters** if we know the limits will define the best operating scenario

Some 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.

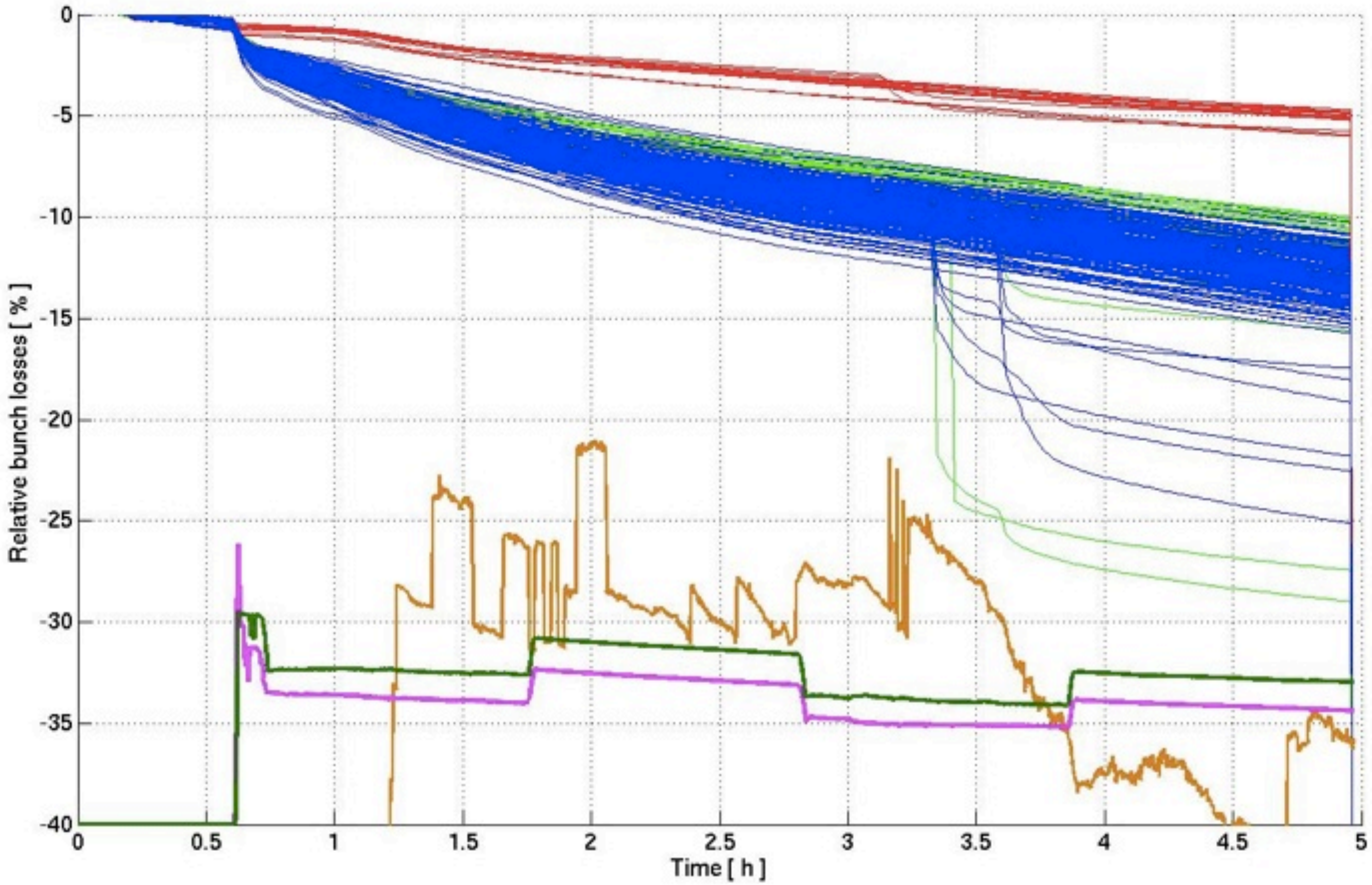
[9]Y. Alexahin,"On the Landau damping and decoherence of transverse dipole oscillations in colliding beams ", Part. Acc. 59, 43 (1996).

[10] K. Cornelis BB workshop 1999

[11] D. Kaltchev and W. Herr, Dynamic Aperture studies

[12] Beam-beam webpage http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/

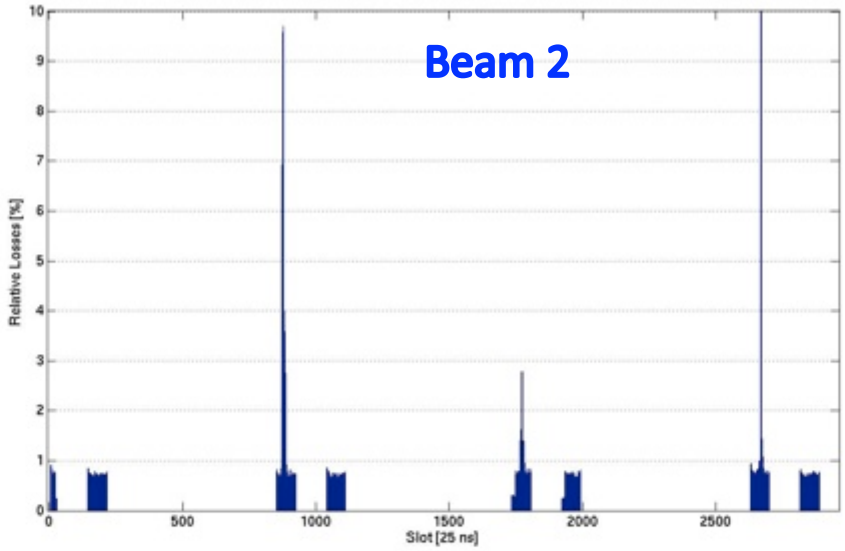
Lack of Landau damping

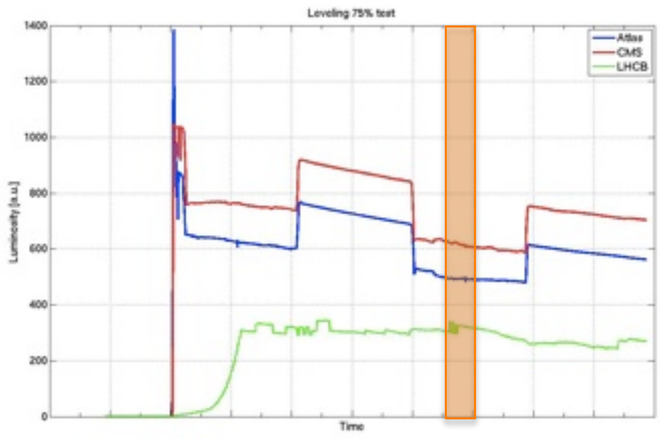


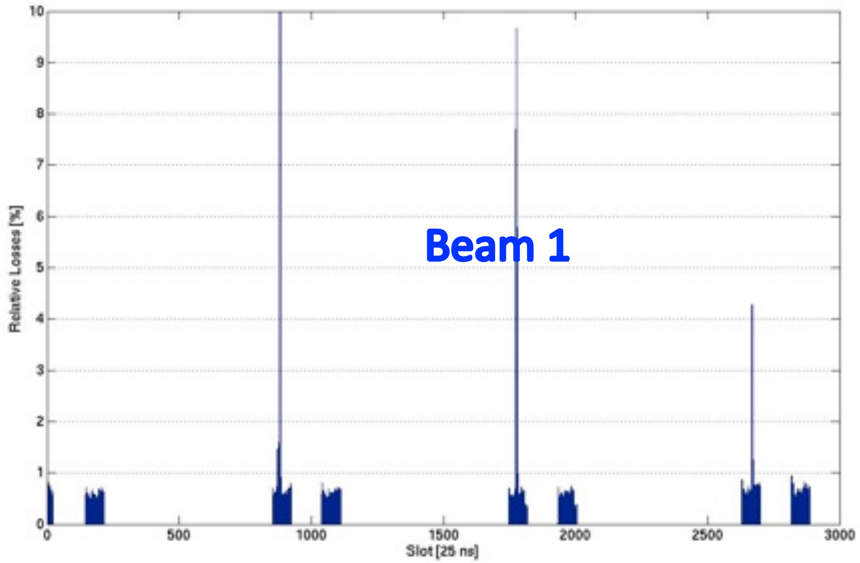
IP8
IP1&5
IP1&5&8

ATLAS
CMS
LHCB

Instability propagates to colliding pairs

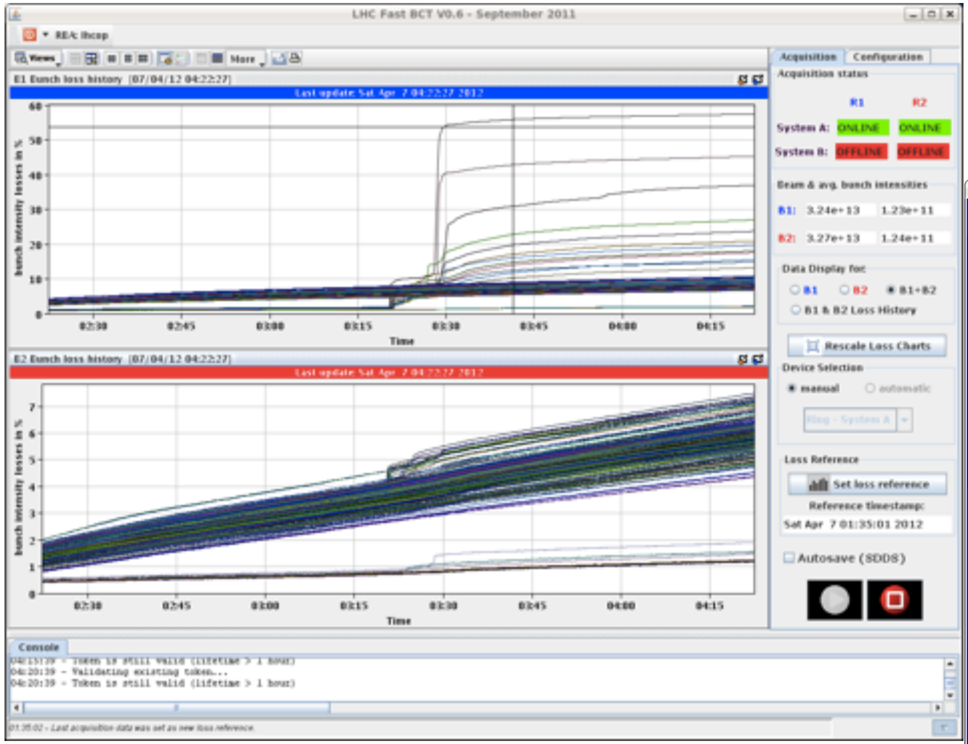


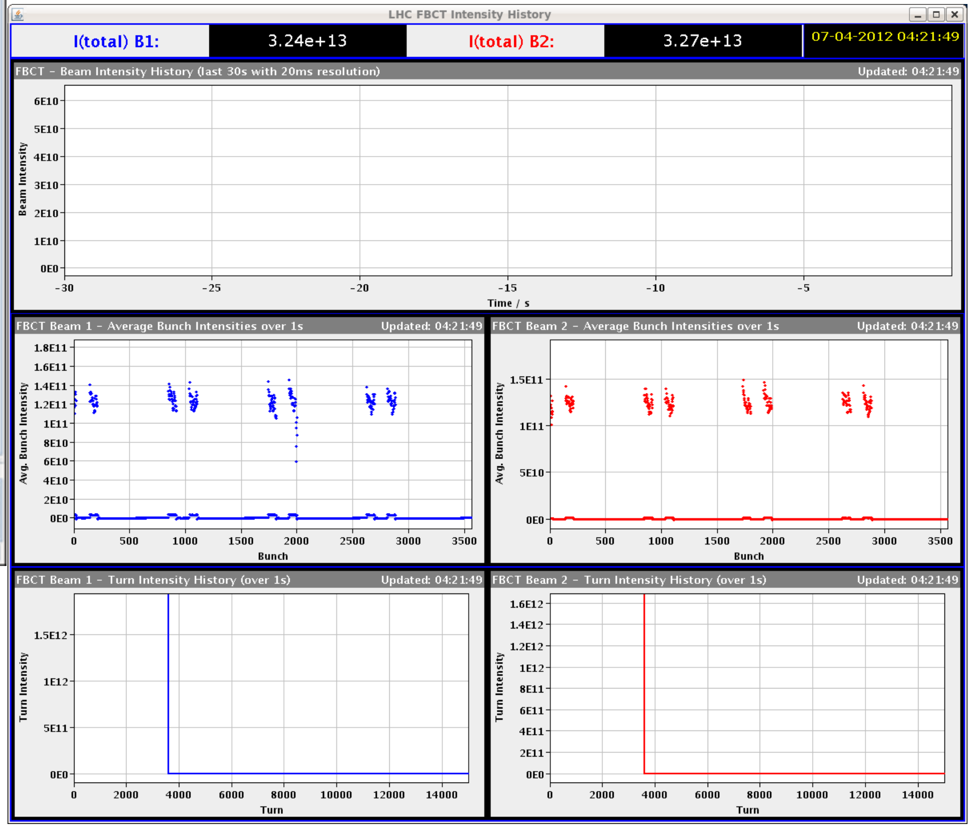




Beam-beam amplifies the instability to many more bunches

Instability due to lack of Landau damping





- Sudden losses observed in some bunches. Patterns being verified (colliding in IP8)

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