Beam-beam interaction

(an introduction)

Werner Herr
CERN, AB Division

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

Colliding beams

- **Beam is a collection of charges**
- **Represent electromagnetic potential for other charges**
- **→ Forces on itself and opposing beam**
- **→ Important for high density beams, i.e. high intensity and/or small beams:**
  for high luminosity !
- **→ Main limit for present and future colliders**

Colliding beams

- **Act on particles like electromagnets etc., BUT:**
- **Do 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**
- **Results in many different effects and problems**

Beam-beam effects

- **Overview of most important effects**
- **Qualitative and physical picture of the effects**
- **Which effects are important for present and future machines (LEP, PEP, KEKB, Tevatron, LHC)**

Fields and Forces

- In rest frame only electrostatic field
- Transform into moving frame and calculate Lorentz force

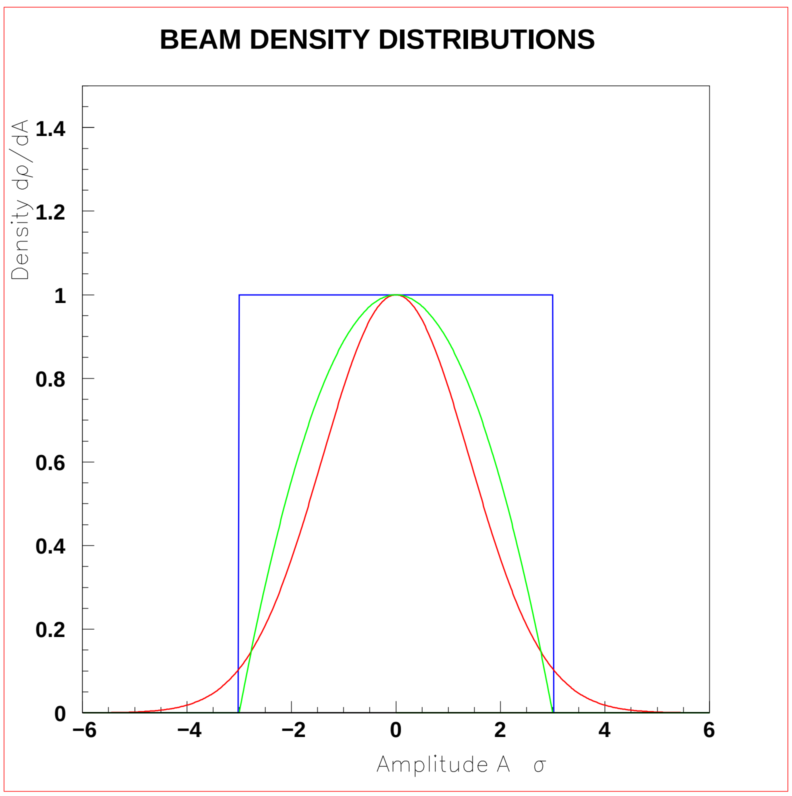
$$F_x = -e(1 + \beta^2)E_x$$
$$F_y = -e(1 + \beta^2)E_y$$

- Integrate over the distribution
- Can be focusing or defocusing

(Remark: The factor is $(1 - \beta^2)$ for the force on the bunch itself, i.e. direct space charge. This results in $1/\gamma^2$ behaviour of space charge effects, always defocussing)

Beam profiles

- Various distributions possible
- Produce different fields (forces)



- For e^-,e^+: most likely Gaussian
- For protons: in principle can be anything

Simple example: Gaussian

- **For 2D case the potential is:**

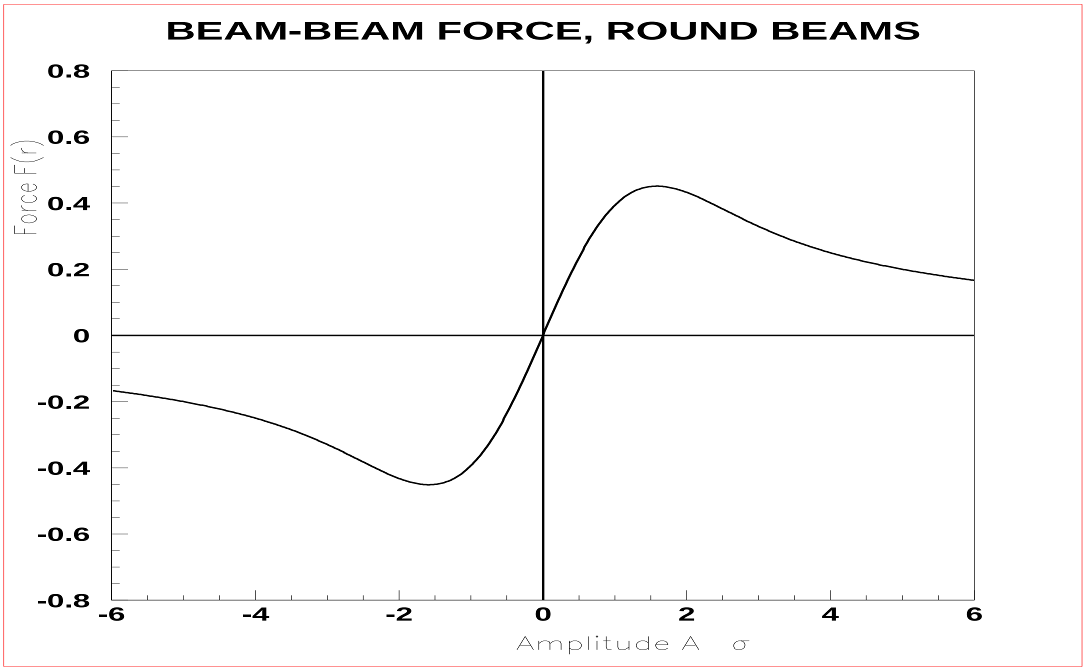
$$U(x,y,\sigma_x,\sigma_y) = \frac{Ne}{4\pi\epsilon_0}\int_0^\infty \frac{exp(-\frac{x^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t})}{\sqrt{(2\sigma_x^2+t)(2\sigma_y^2+t)}}dt$$

- **Can derive $\vec{E}$ and $\vec{B}$ fields and therefore forces**
- **Round beams:** $\sigma_x = \sigma_y = \sigma$
- **Force has only radial component, i.e. depends only on distance r from bunch centre**

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

- **For arbitrary distribution: difficult (or impossible, numerical solution required)**

BEAM-BEAM FORCE



- **Linear for small amplitudes (amplitude independent tune change)**
- **Non-linear for large amplitudes (amplitude dependent tune change, detuning)**
- **All even multipole, ALL even order resonances**

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:**
  - → **Unstable and/or irregular motion**
  - → **beam blow up or bad lifetime**
- **"Weak-strong" approximation (i.e. 'strong' beam is static and not affected by the 'weak' beam)**

Beam-beam parameter

- **Can one measure the strength of beam-beam effects ?**
- **Approximation: beam-beam parameter ξ**
- **For head-on interactions**

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

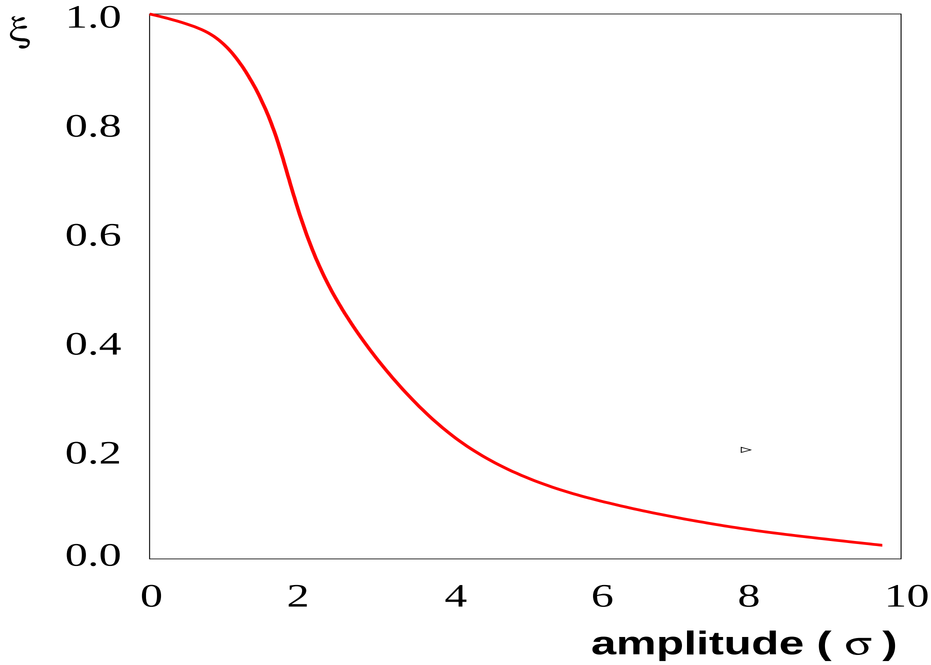
r_0 **is classical particle radius,** (r_e, r_p)

- **Proportional to slope at zero amplitude $\rightarrow$ proportional to (linear) tune shift from beam-beam interaction**
- **BUT: does not describe non-linearity**

LEP - LHC

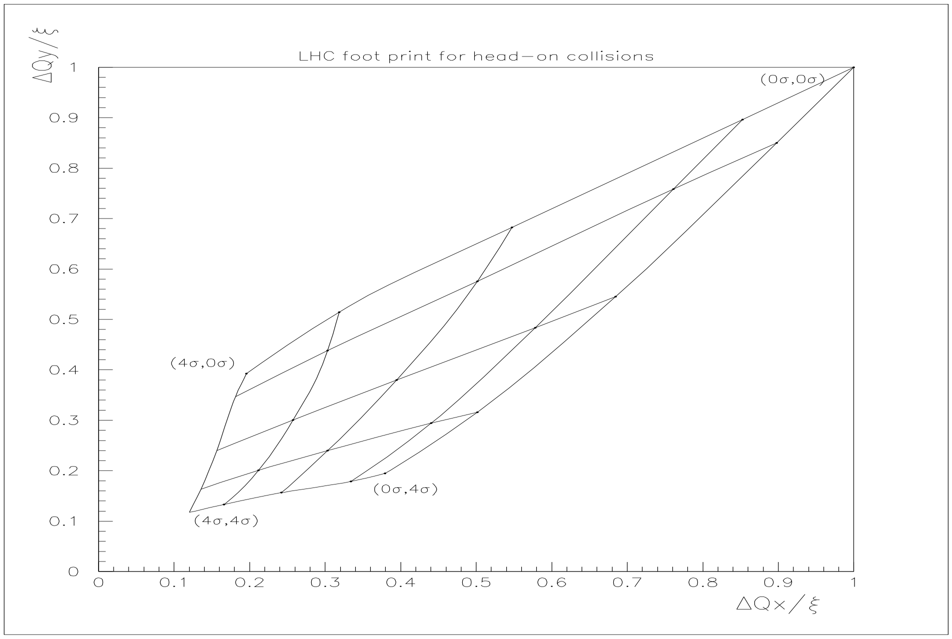
	LEP	LHC
Beam sizes	160μm · 4μm	16.6μm · 16.6μr
Intensity N	4.0 · 10^{11}/bunch	1.15 · 10^{11}/bunc
Energy	100 GeV	7000 GeV
$\beta_x^* \cdot \beta_y^*$	1.25 m · 0.05 m	0.55 m · 0.55 m
Crossing angle	0.0	285 μrad
Beam-beam parameter(ξ)	0.0700	0.0034

Amplitude detuning



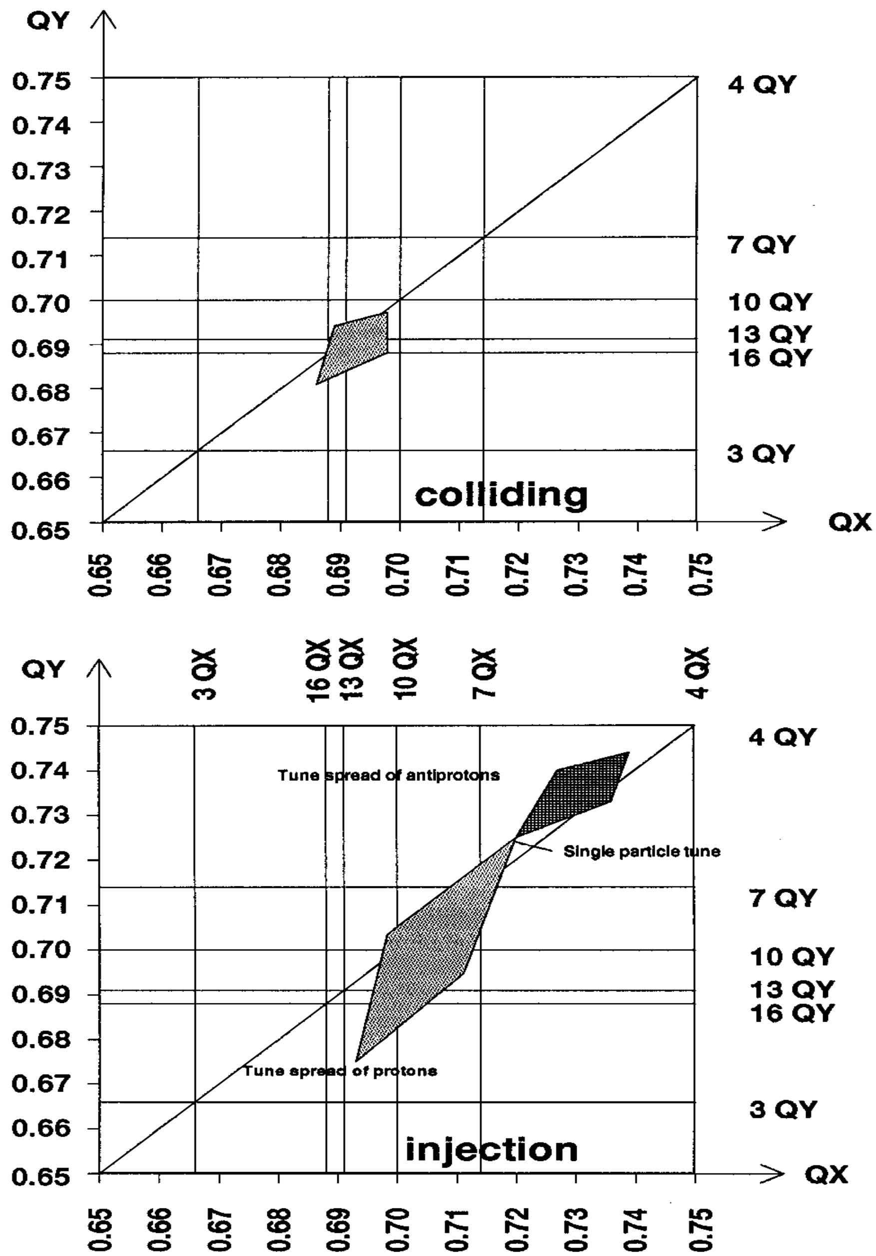
- **Non-linear force: tune change due to beam-beam interaction depends on particle's amplitude**
- **Largest effect for small amplitudes**

Amplitude detuning



- No more single tune (frequency) in the beam
- Tunes depend on x and y amplitude
- In 2 dimensions plotted as "Footprints"
- Particles may cross resonances

Working diagram (SPS)



- "Footprints" cross resonances

Observations hadrons

(head-on interactions)

- **Non-linear motion can become chaotic**

  → **reduction of "dynamic aperture"**

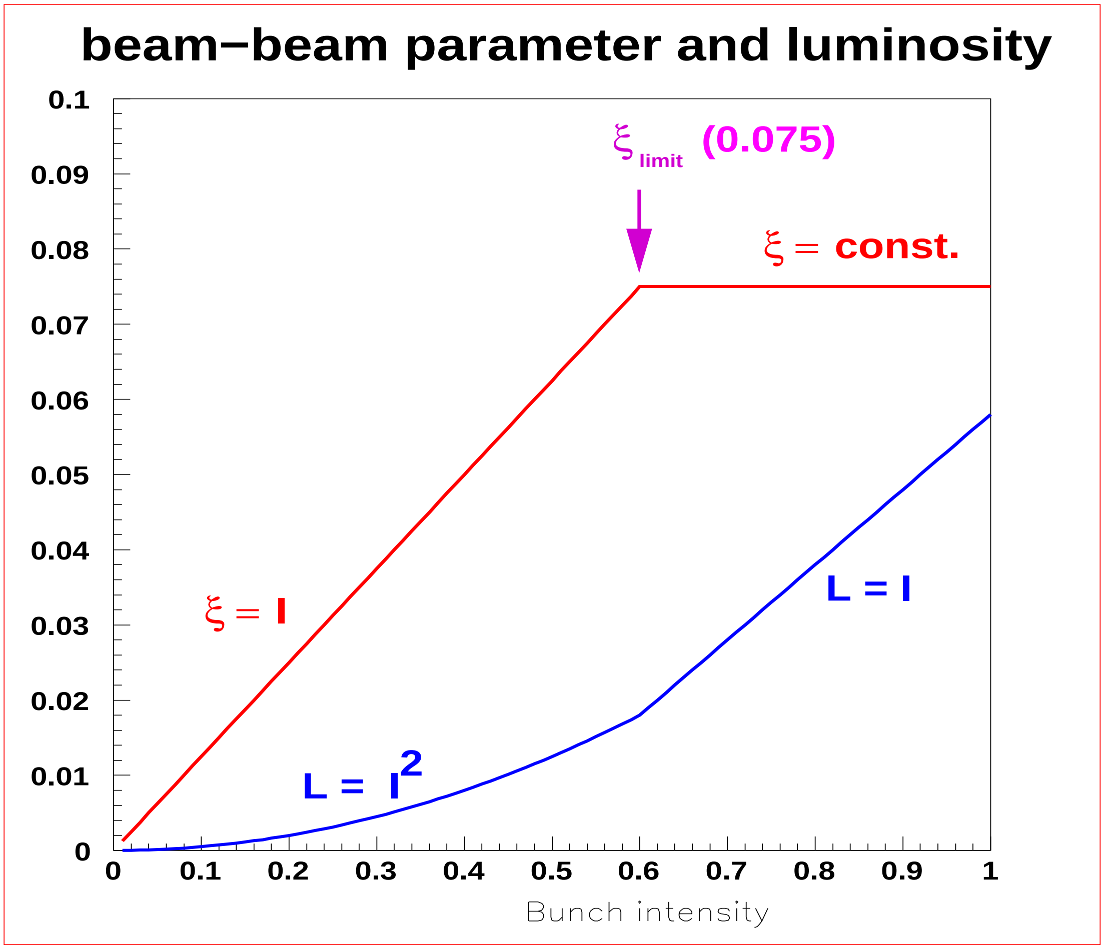
  → **particle loss and bad lifetime**

- **Strong effects in the presence of noise or ripple**
- **Very bad: unequal beam sizes (studied at SPS, HERA)**
- **Very bad: offsets, i.e. collision not exactly head-on (LEP)**
- **Evaluation is done by ~~simulation~~ modelling**

Observations leptons

(head-on interactions)

- Distortion of beam optics: dynamic beta (LEP)
- Vertical blow-up above the so-called beam-beam limit



What is happening ?

- **Beam-beam limit**

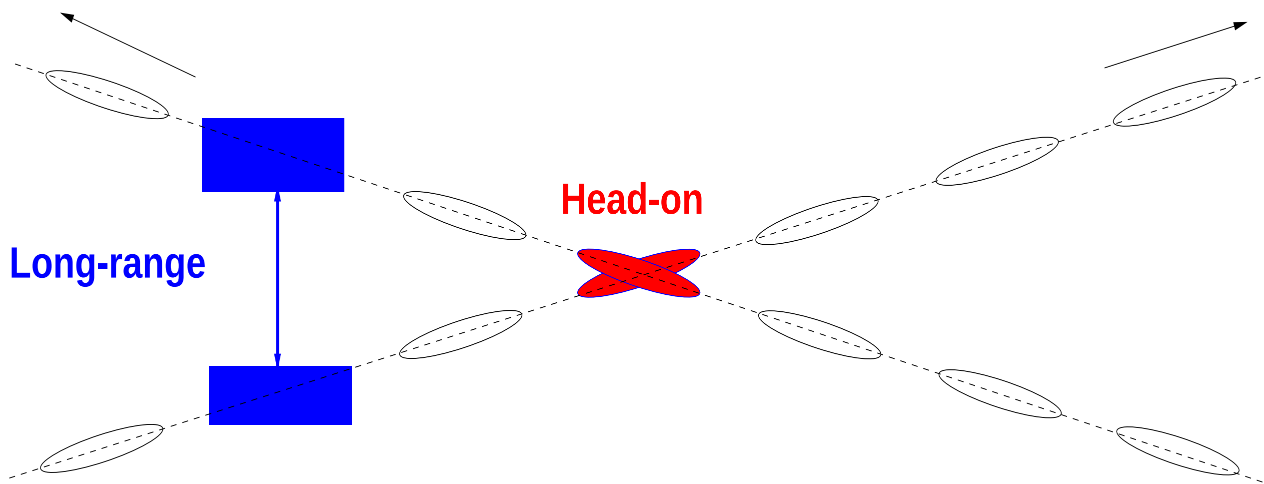
$$\xi_y = \frac{N r_0 \beta_y}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)}$$

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

- **Above beam-beam limit:** σ_y **increases when** N **increases to keep** ξ **constant**
- **Therefore:** $\mathcal{L} \propto N$ **and** $\xi \propto$ **constant**
- ξ_{limit} **is NOT a universal constant !**
- **Can get an idea with tracking (but depends on damping etc.)**

The next threat

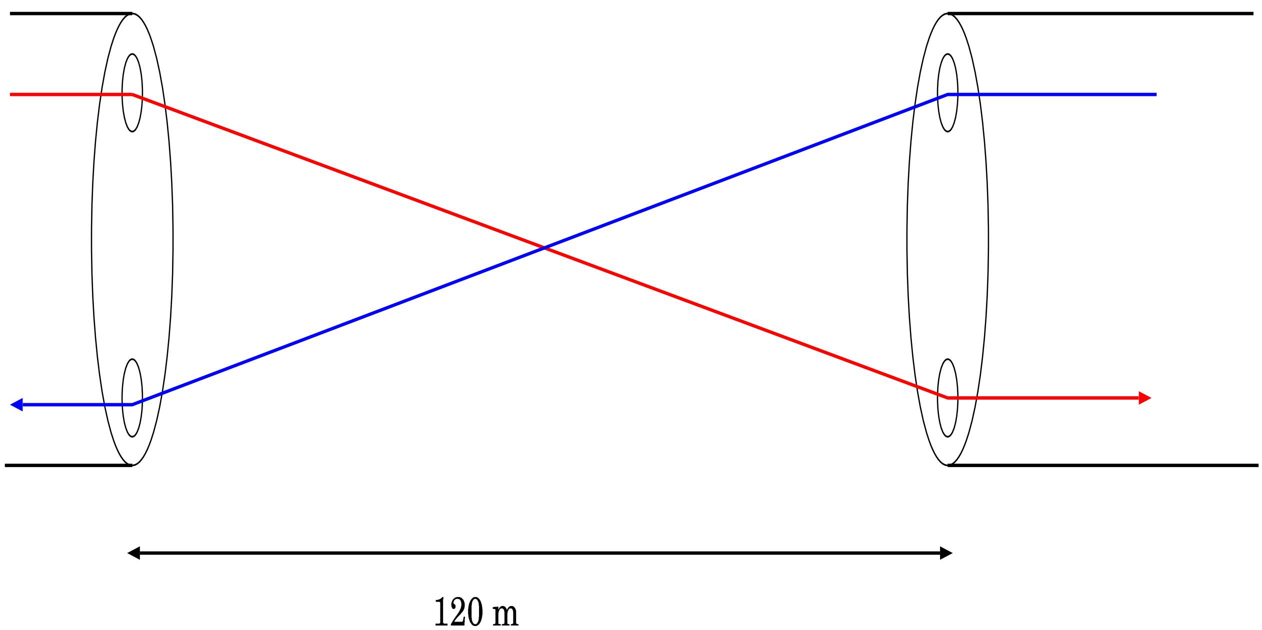
- How to collide many bunches ??
- Must avoid unwanted collisions !!
- E.g. with pretzel scheme (SPS,LEP,Tevatron), bunch trains (LEP,PEP), crossing angle (LHC)



- Particles experience distant (weak) forces
- $\rightarrow$ long range interactions

Example: LHC

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



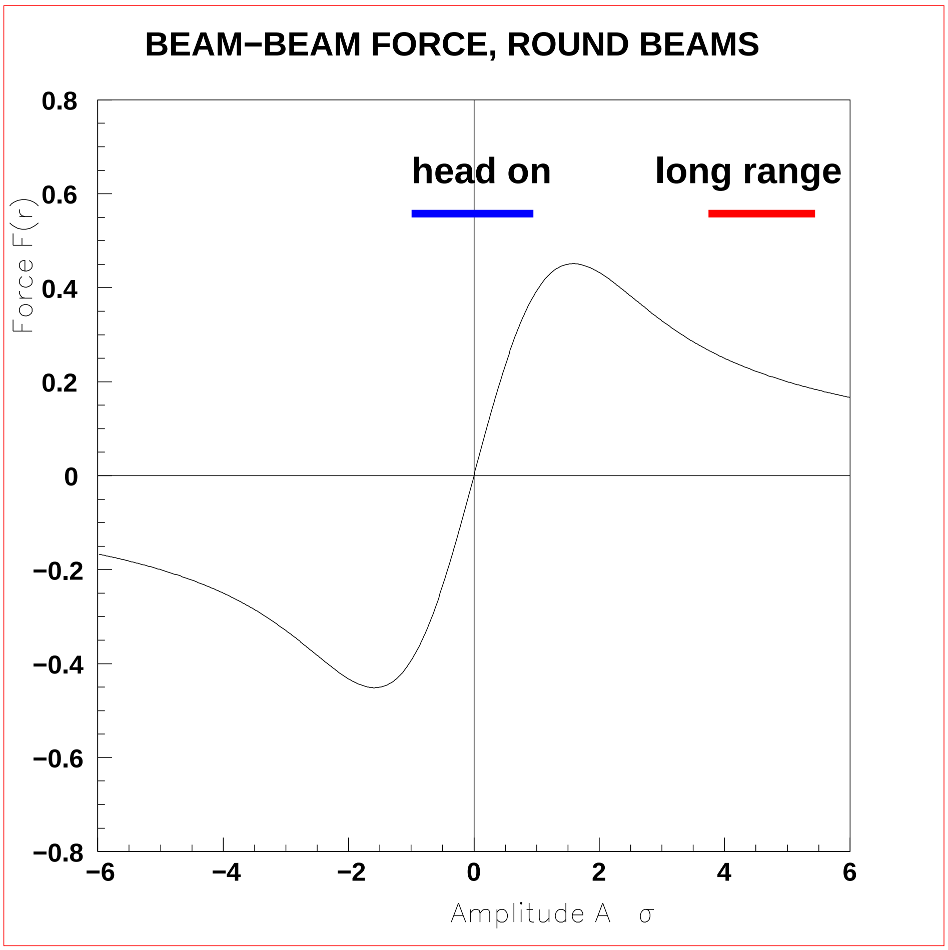
- **Around each IP: 30 (!) long range interactions**
- **Separation typically 6 - 12 σ**

What is special about them ?

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

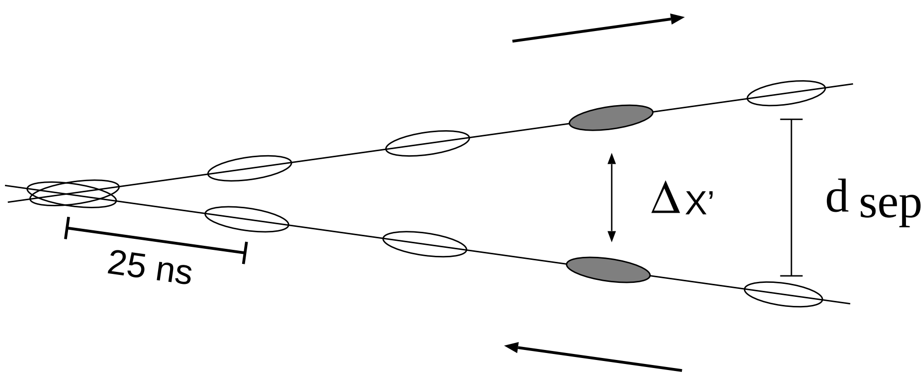
Opposite tuneshift ???

- Slope of force has opposite sign for large separations !
- $\Rightarrow$ opposite sign of focusing !



- Can use for partial compensation

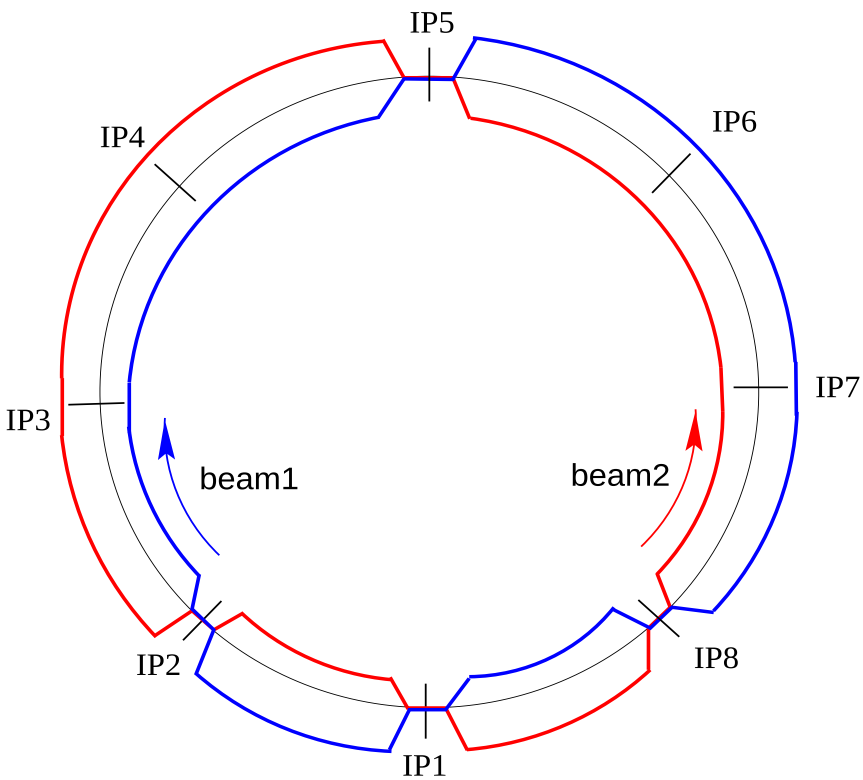
Long range interactions (LHC)



- **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 !)**

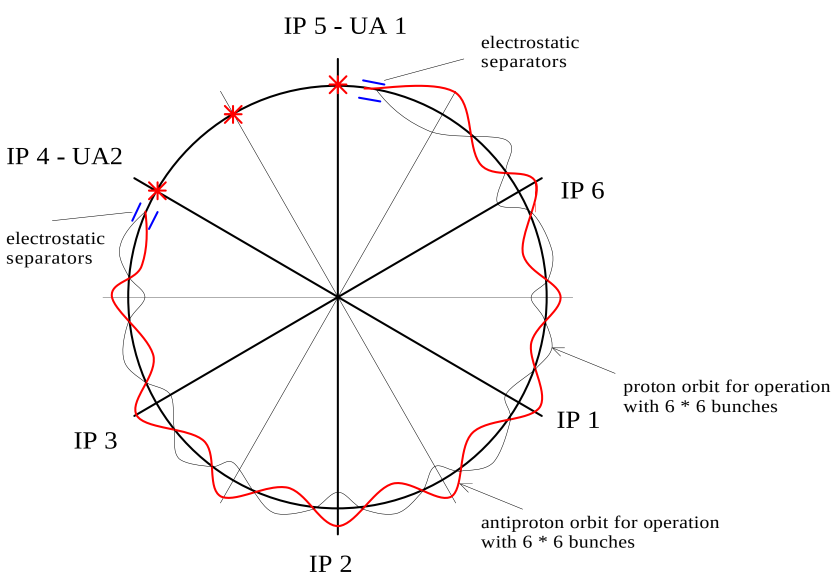
Separation: LHC

- ⇒ **Many equidistant bunches**
- **Four experimental areas**
- **Two horizontal and two vertical crossing angles**



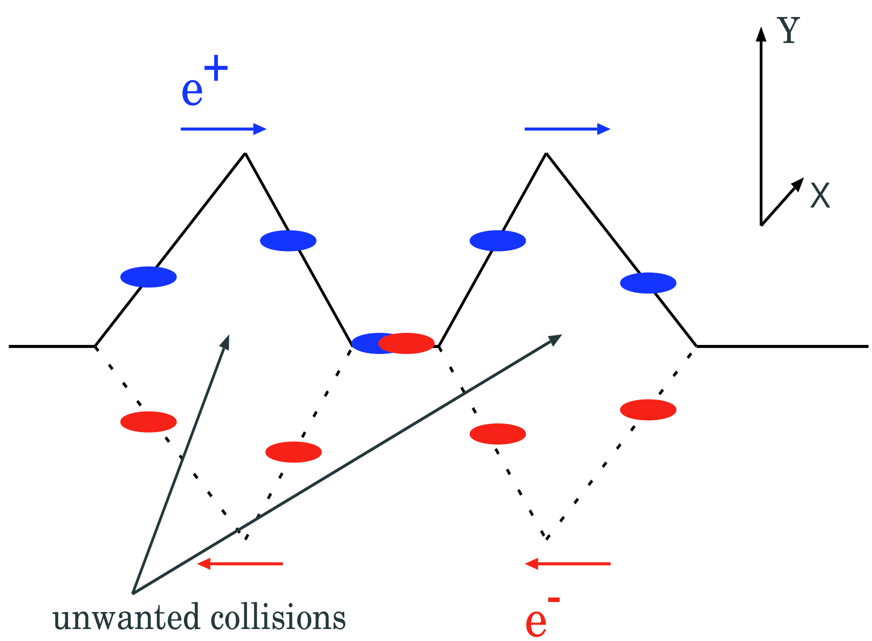
Separation: SPS

- ⇒ Few equidistant bunches
- Two experimental areas
- Horizontal pretzel around most of the circumference



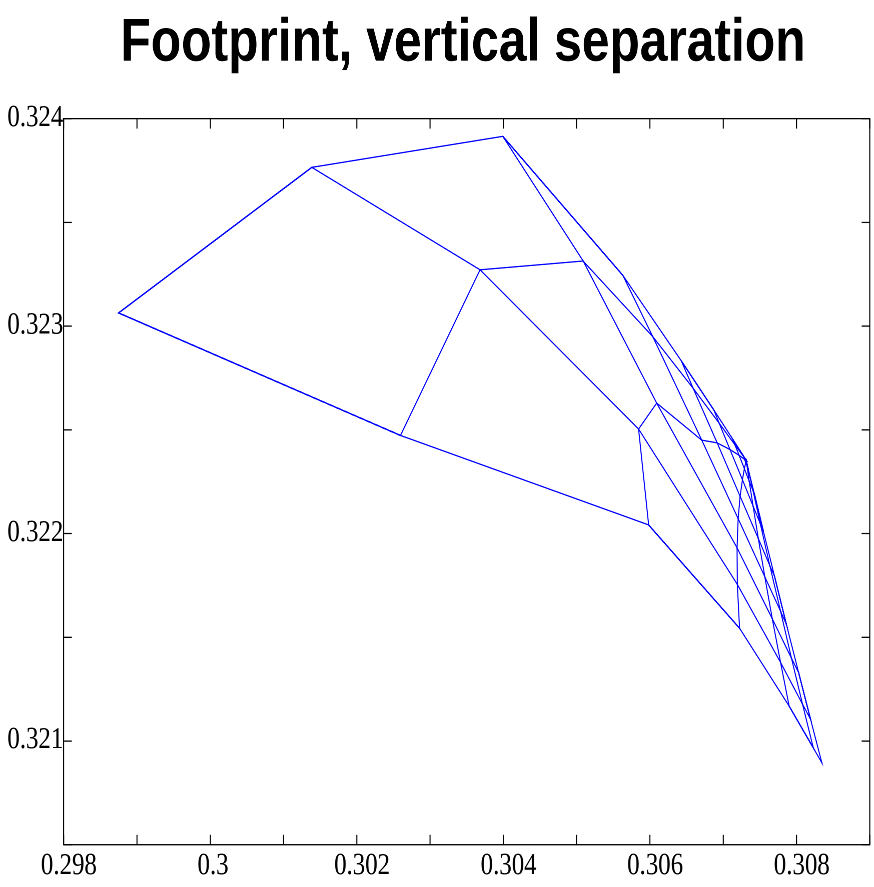
Separation: LEP

- ⇒ Short trains of bunches
- Local separation around interaction points
- No separation between experiments



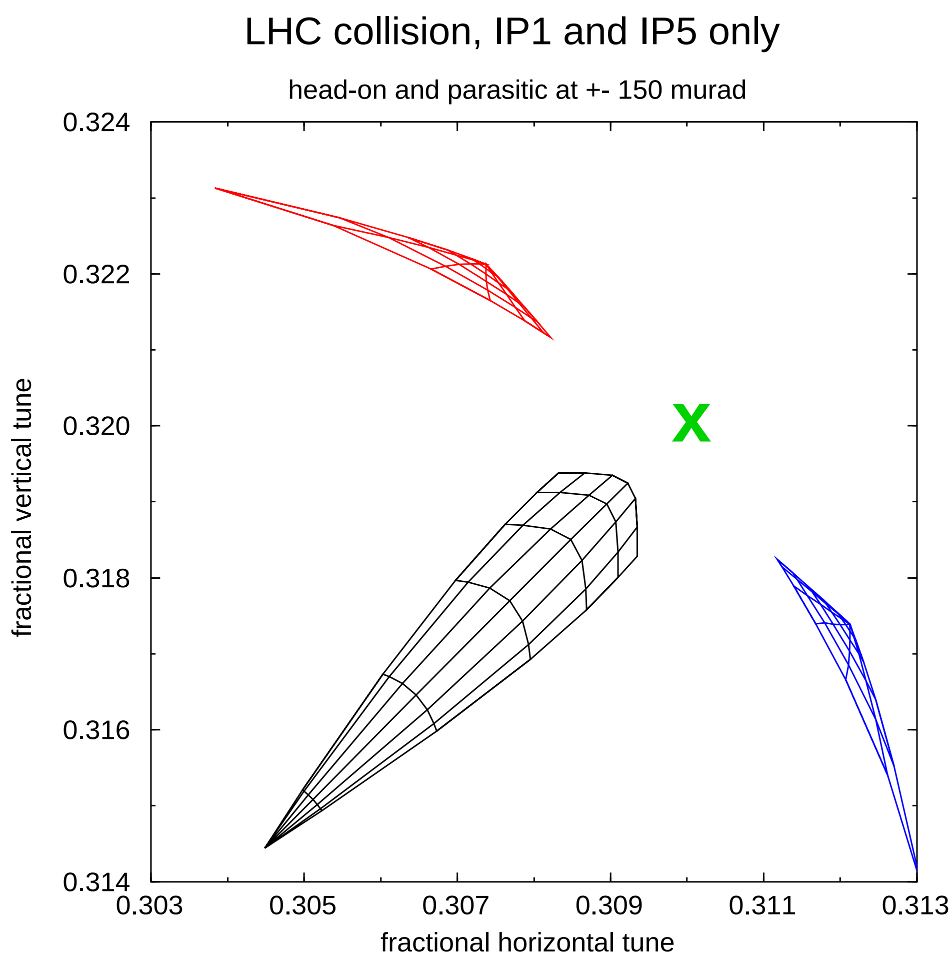
Footprints

- Largest effect for large amplitudes (i.e. where other non-linearities are largest)
- Must expect problems for small separation ($\leq\ 10\ \sigma$)



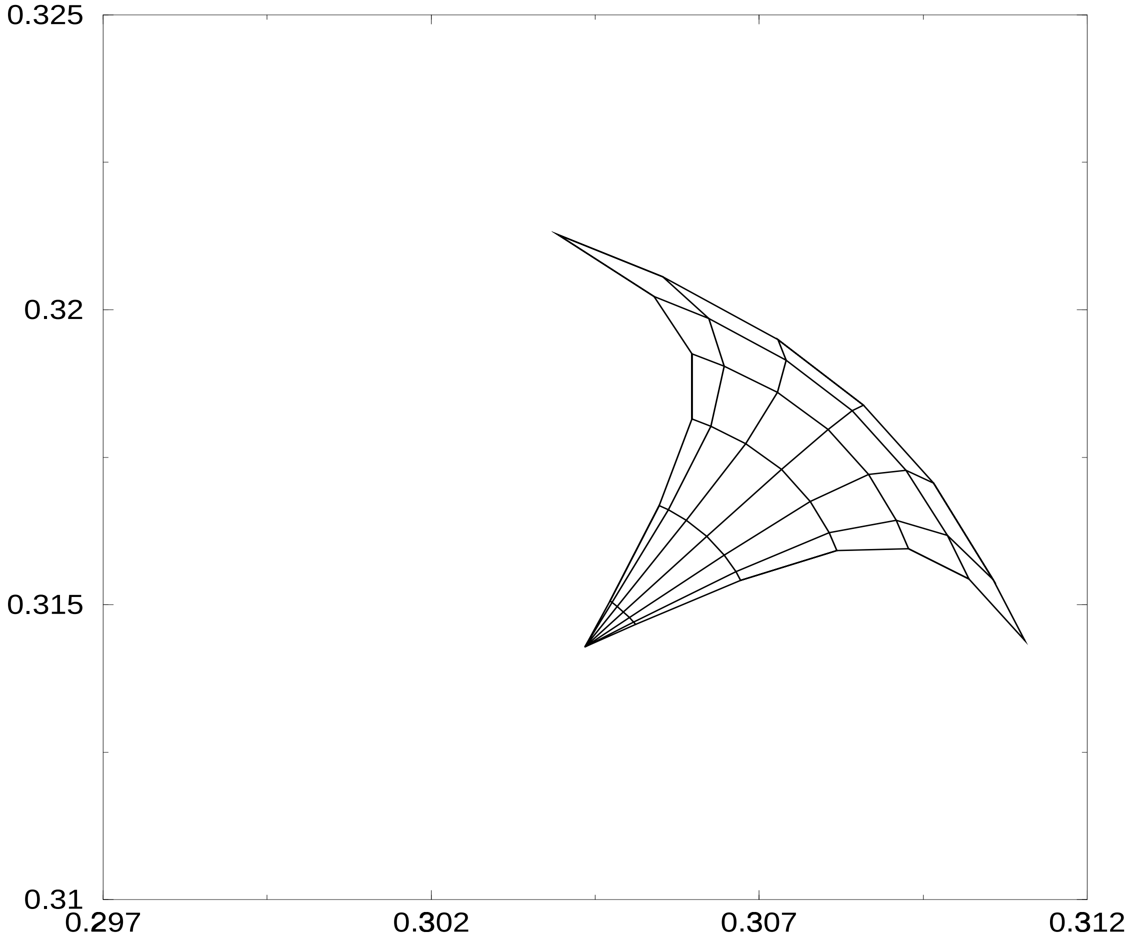
Footprints

- head on interaction
- vertical and horizontal separation



- Exercise: which is horizontal, which is vertical ?

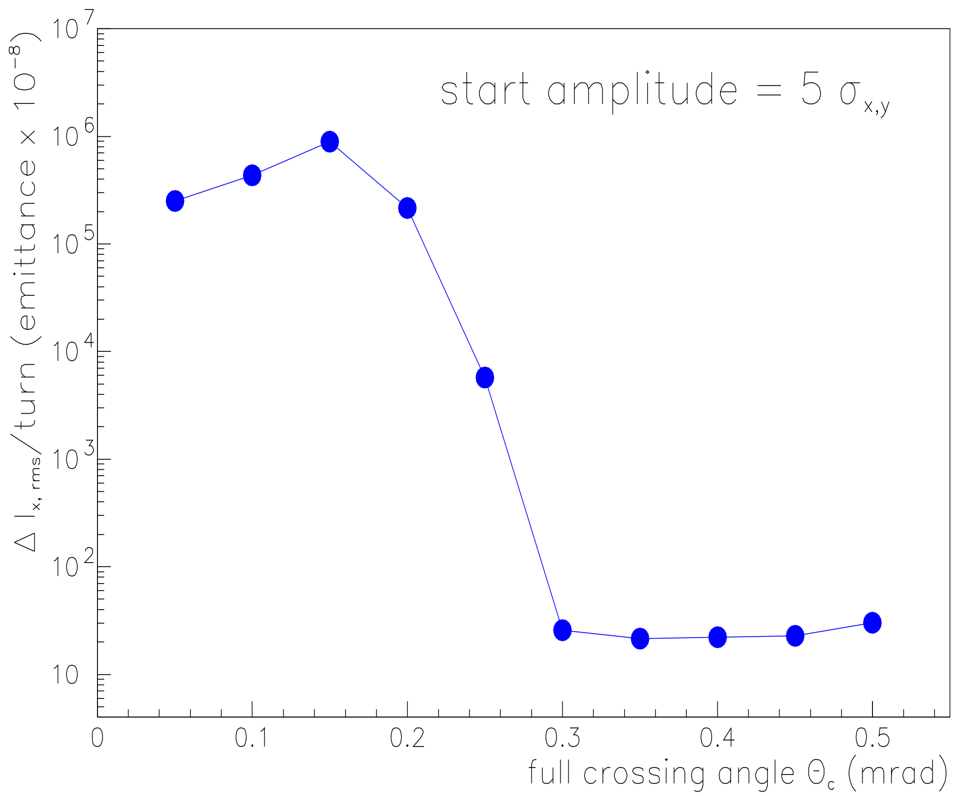
Combined footprint



- **Head-on and long range**
- **Partial compensation between planes very important !**

Particle losses

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

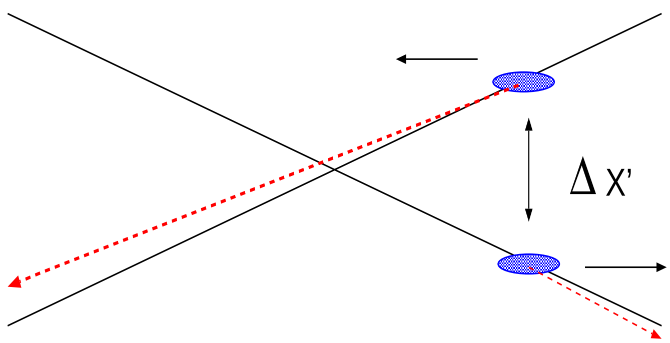


- **From modelling : minimum crossing angle for LHC: 285 μrad**

Closed orbit effects

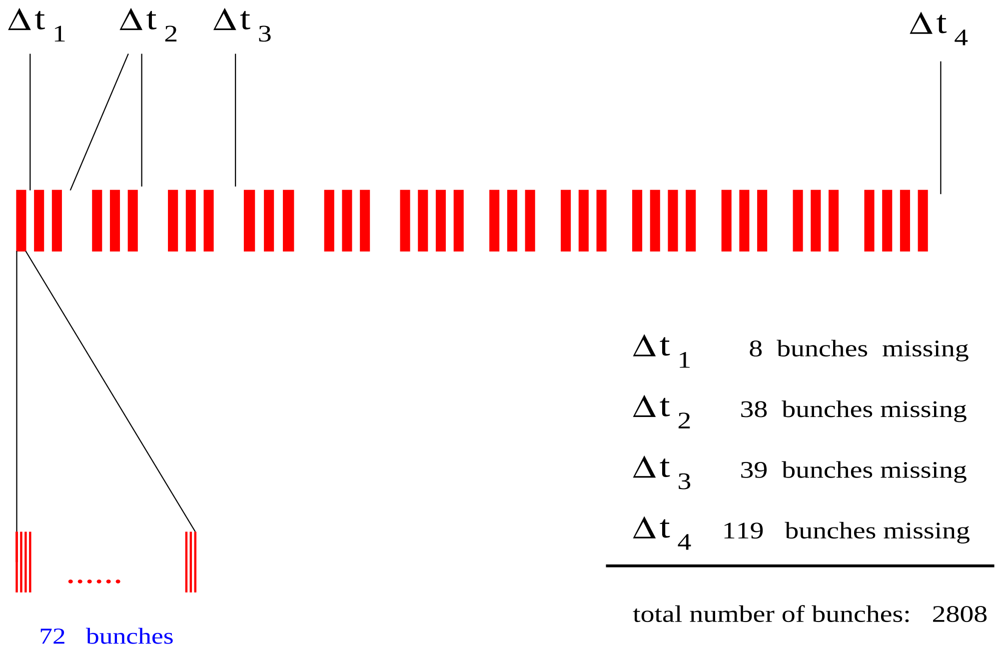
For separated beams the force has a constant contribution: → orbit kick

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



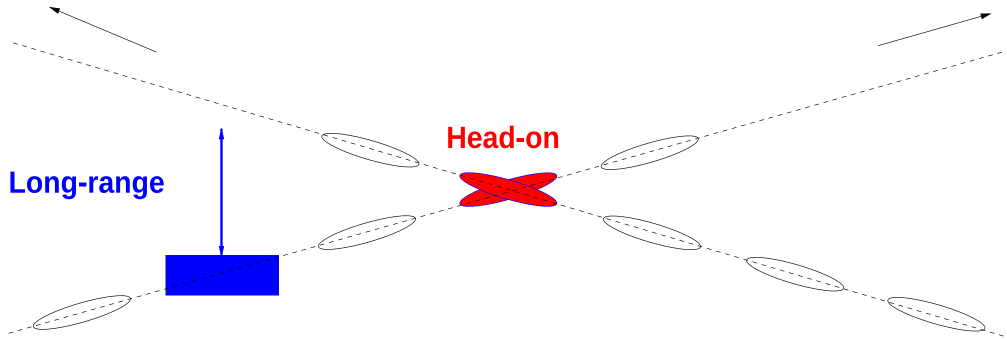
- **Has been observed in LEP with bunch trains**
- **Self-consistent calculation necessary**
- **Effects can add up, but can't we correct the orbit ?!?**

PACMAN bunches



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

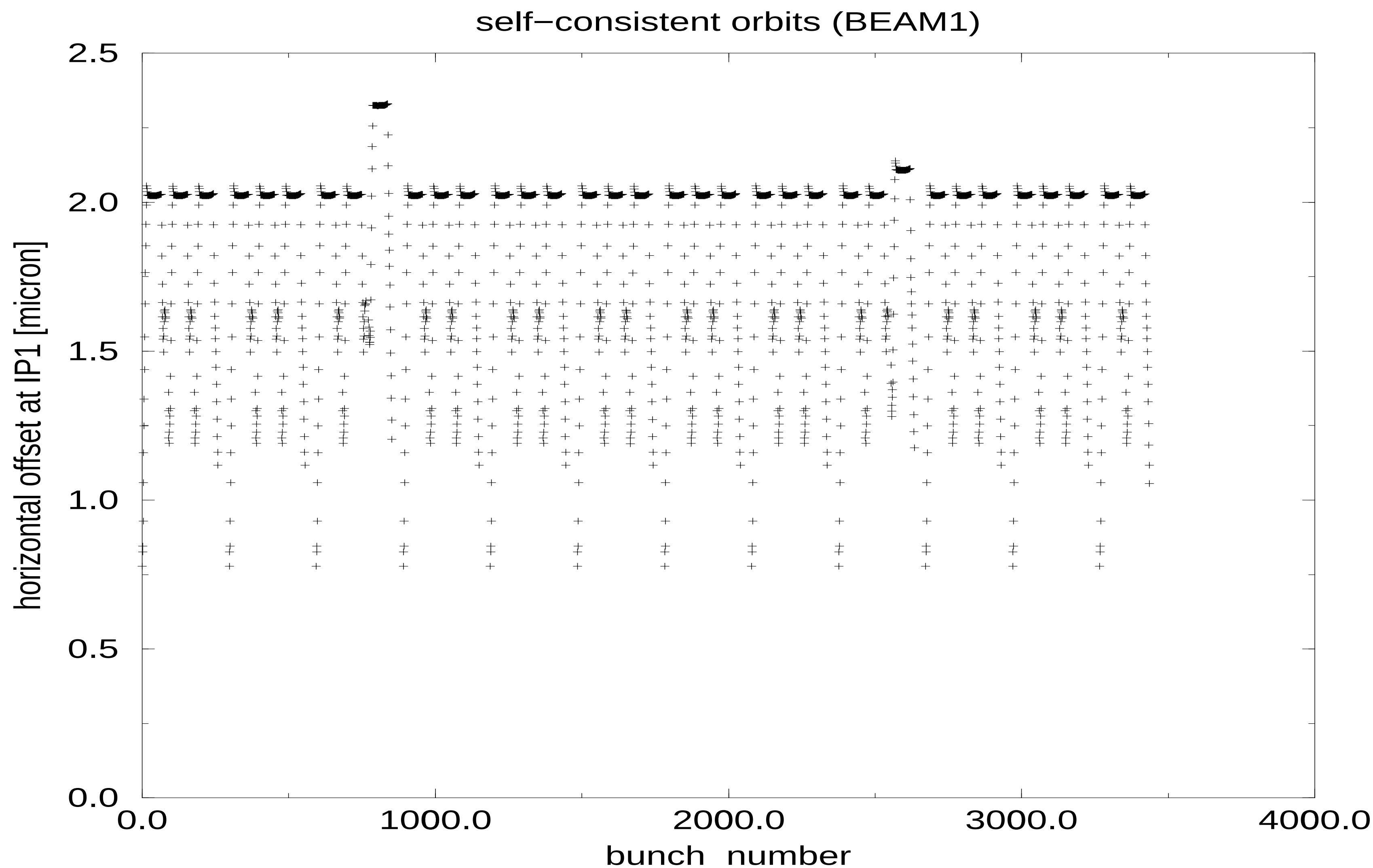
Effect of holes



- Bunches meet holes in common part (at beginning and end of bunch train)
- Cannot be avoided
- Left-right asymmetry
- Worst case: less than half of long range collisions (depends on collision scheme and gaps)

PACMAN bunches

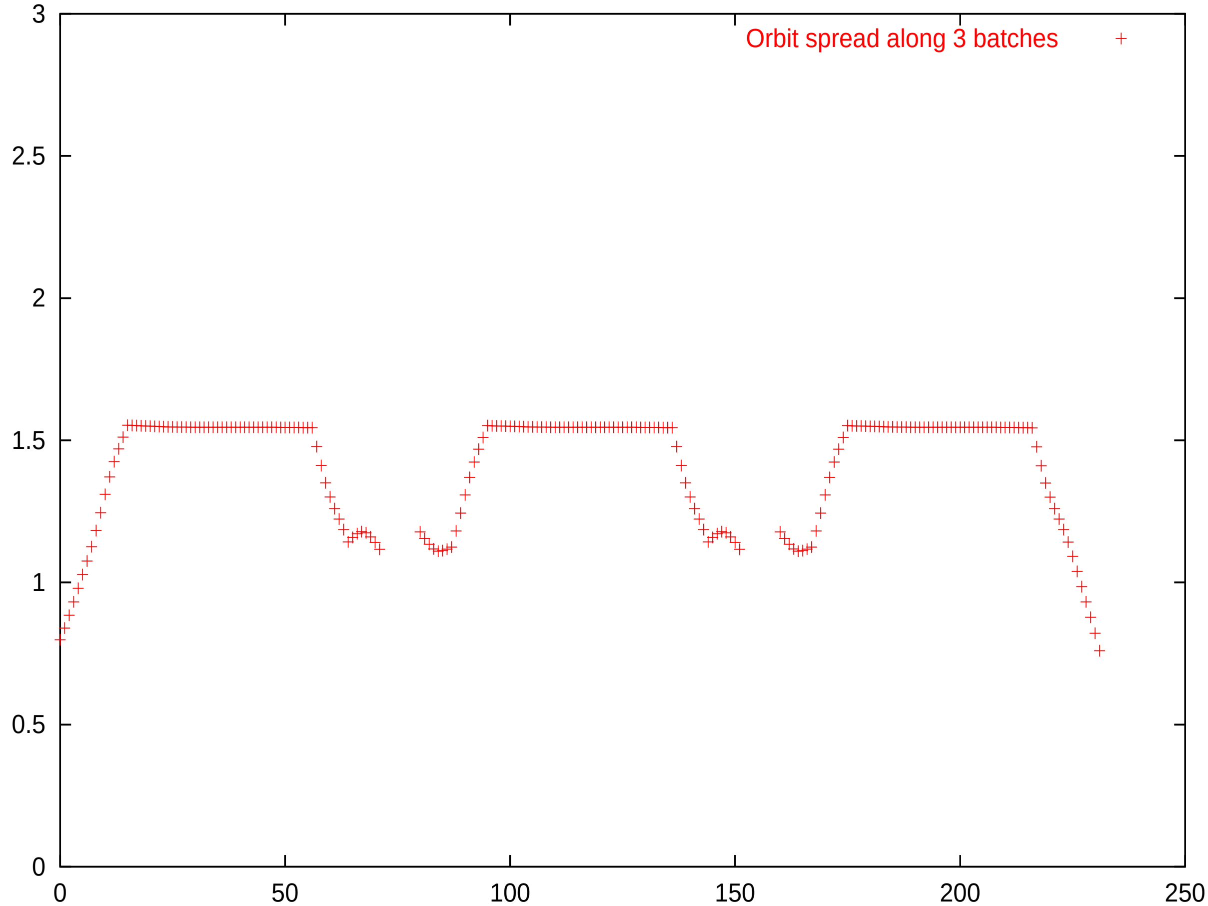
- **When a bunch meets a "hole" in the common part**
  - → **Miss some long range interactions, PACMAN bunches**
  - → **They see fewer unwanted interactions in total**
  - → **Different integrated beam-beam effect**
- **Optimization always for nominal bunches**
- **Edge bunches are lost first**
- **Example: orbit effects**



self−consistent orbits (BEAM1)
horizontal offset at IP1 [micron]
2.5
2.0
1.5
1.0
0.5
0.0
0.0
1000.0
2000.0
3000.0
4000.0
bunch number

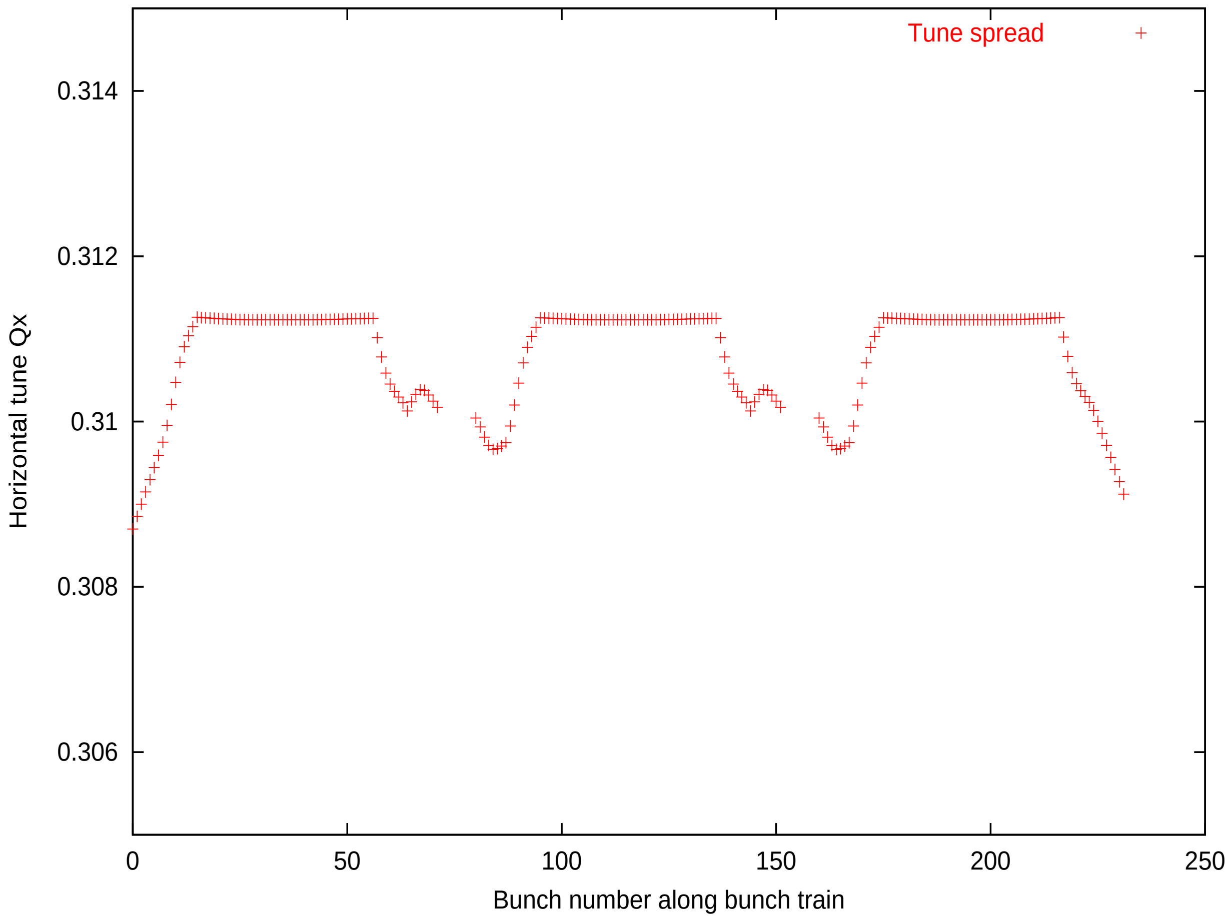

self−consistent orbits (BEAM2)
horizontal offset at IP1 [micron]
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
0.0
1000.0
2000.0
3000.0
4000.0
bunch number

Orbit along batches



- **PACMAN structure clearly visible**

Tune along batches

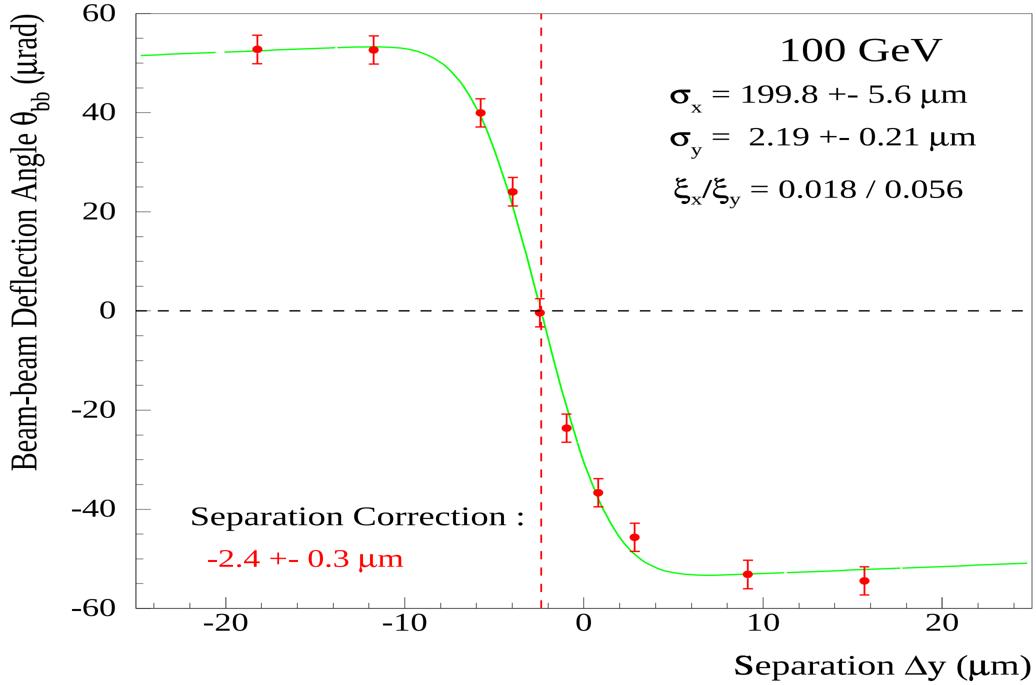


- **PACMAN structure clearly visible**
- **Spread is too large for safe operation**

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

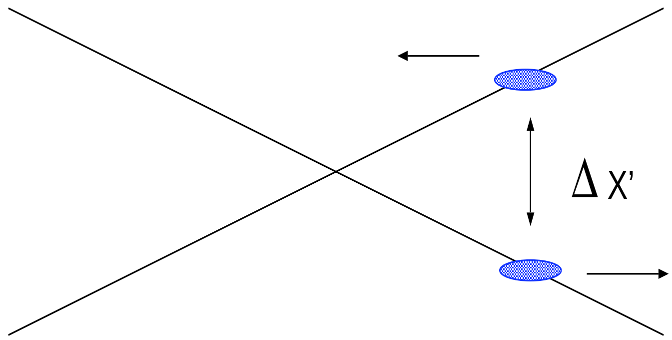
Deflection scan



(Courtesy J. Wenniger)

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

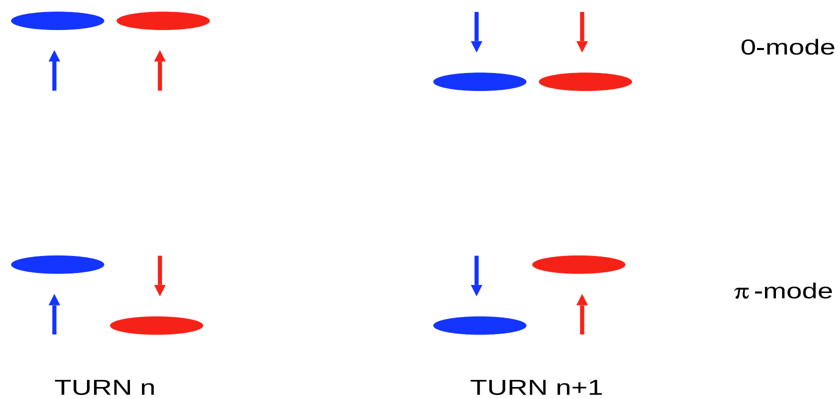
Coherent beam-beam effect



- **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 !**

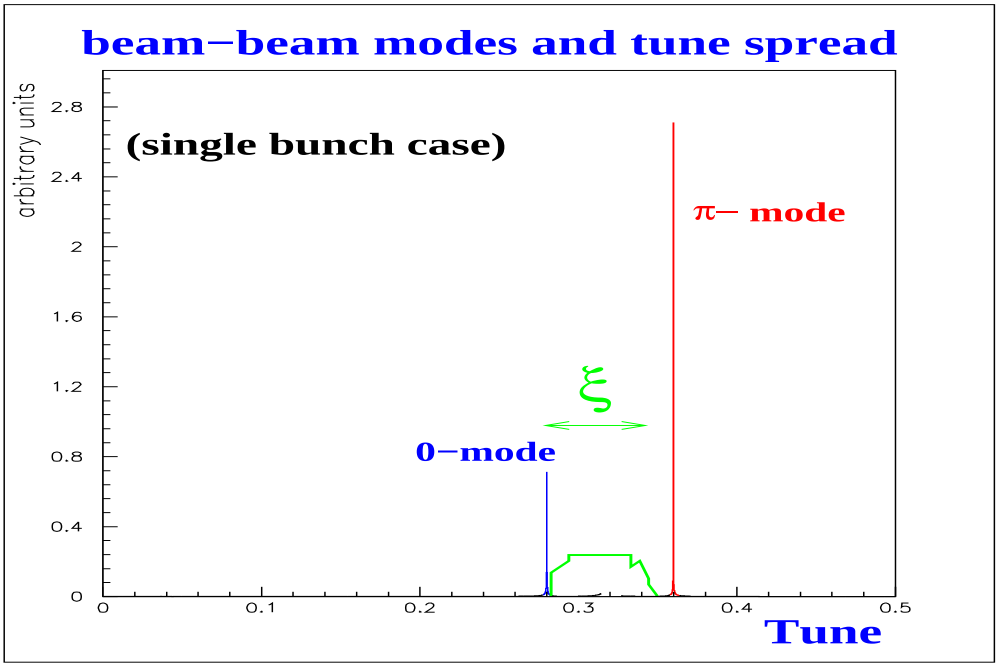
Coherent beam-beam effect

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)**
- **more bunches → more modes**

Coherent beam-beam effect

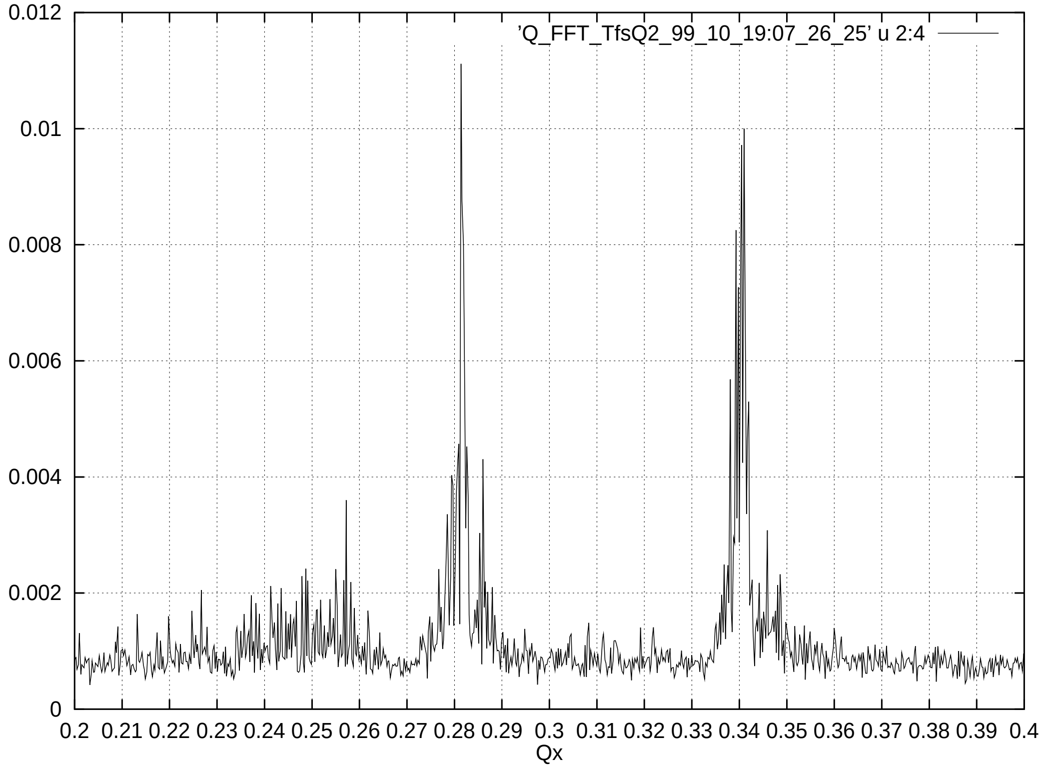


- **0-mode is at unperturbed tune**
- **π-mode is shifted by 1.2-1.3 ξ**
- **Incoherent spread (footprint) between [0.0,1.0] ξ**

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

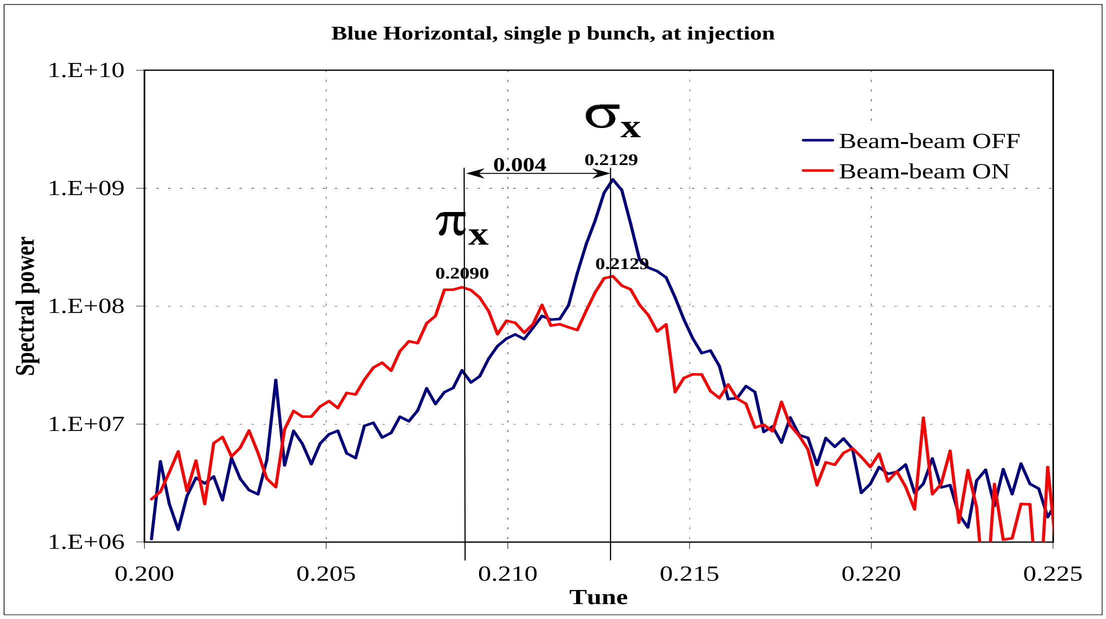
No Landau damping possible

Measurement: LEP



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

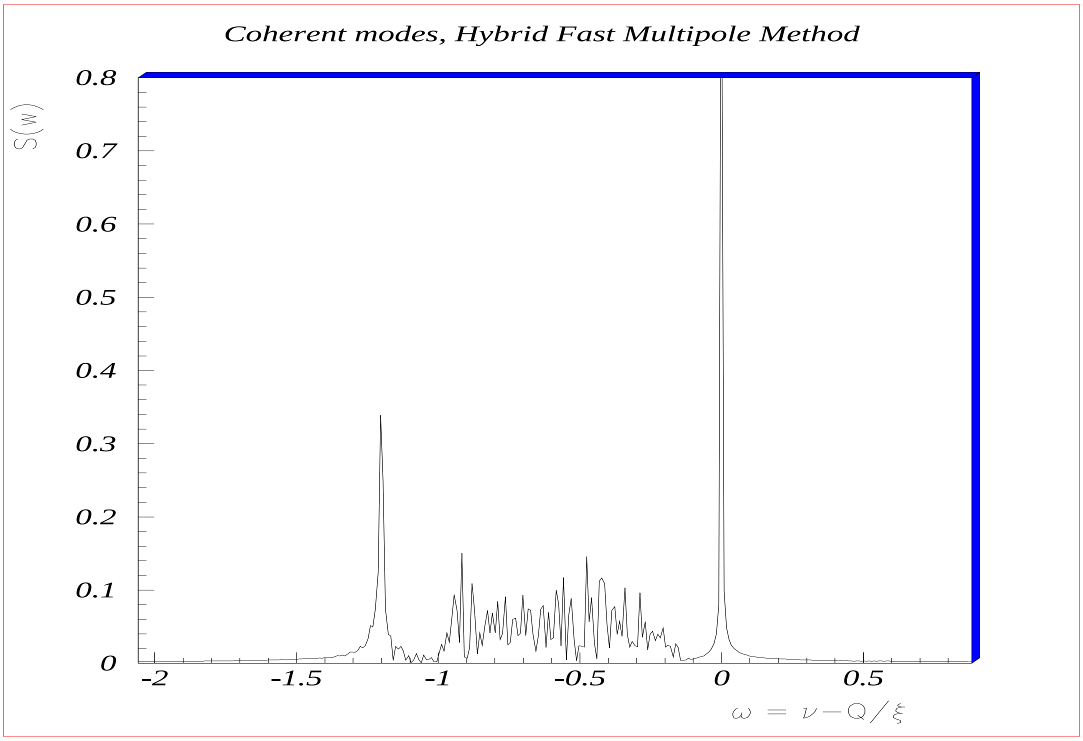
Measurement: RHIC



Courtesy W. Fischer (BNL)

- Compare spectra with and without beams
- Two modes visible with beams
- More difficult to see in hadron machines

~~Simulation~~ Modelling

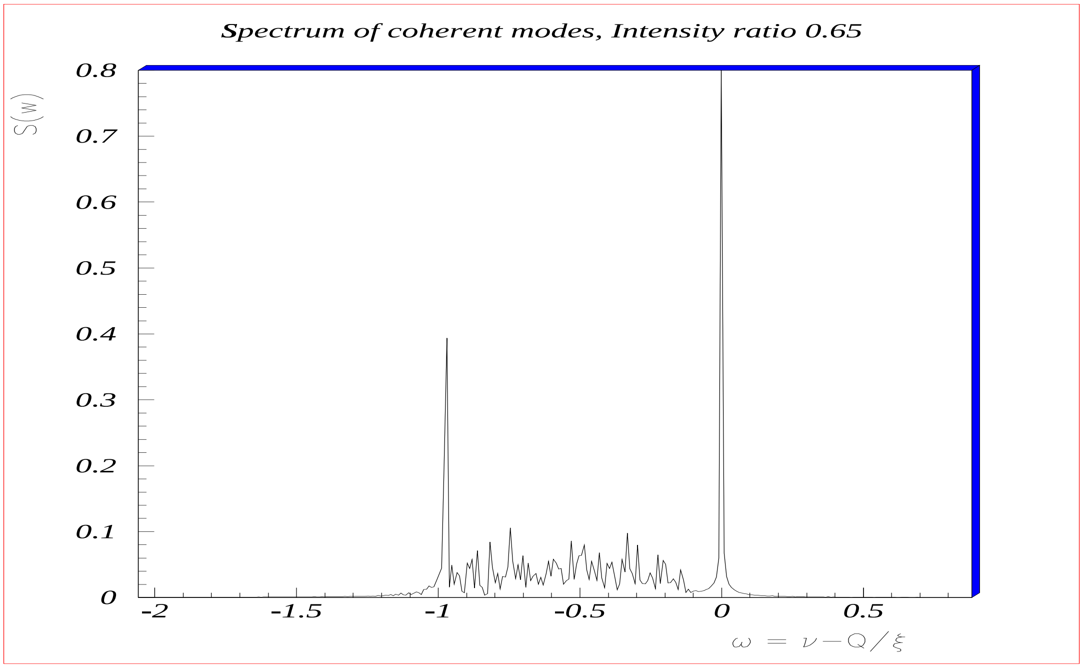


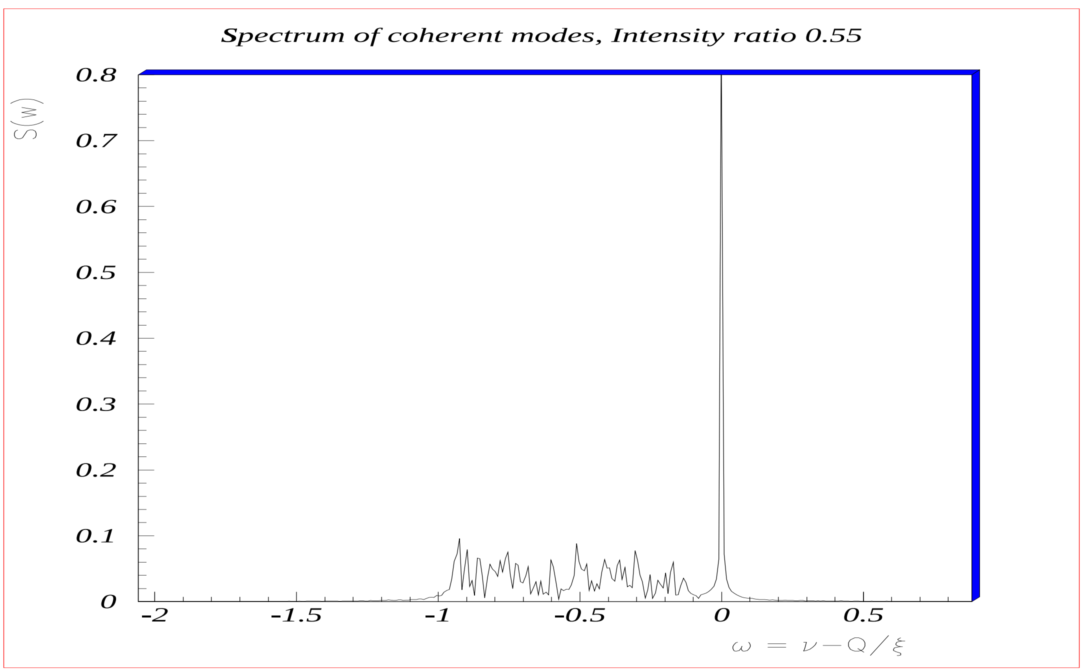
- **Full modelling of both beams**
- **Must take into account changing distributions !**
- **Must calculate forces from arbitrary distributions**

What can we do ?

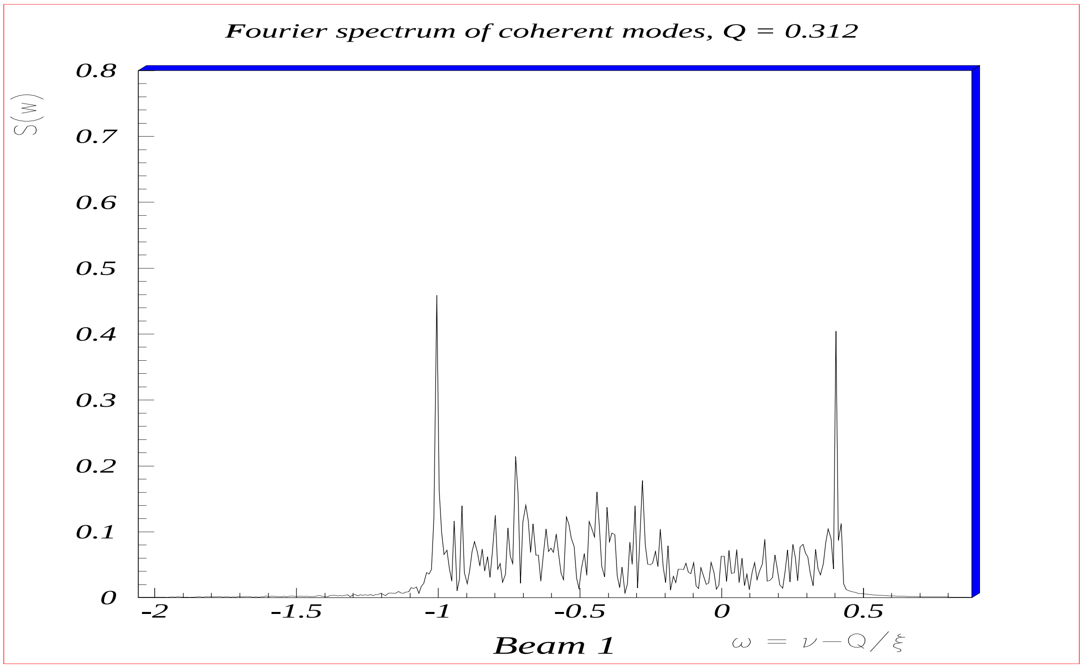
- Coherent motion requires 'organized' motion of many particles
- Therefore high degree of symmetry required
- Possible countermeasure (symmetry breaking):
  - → Different bunch intensity
  - → Different tunes in the two beams

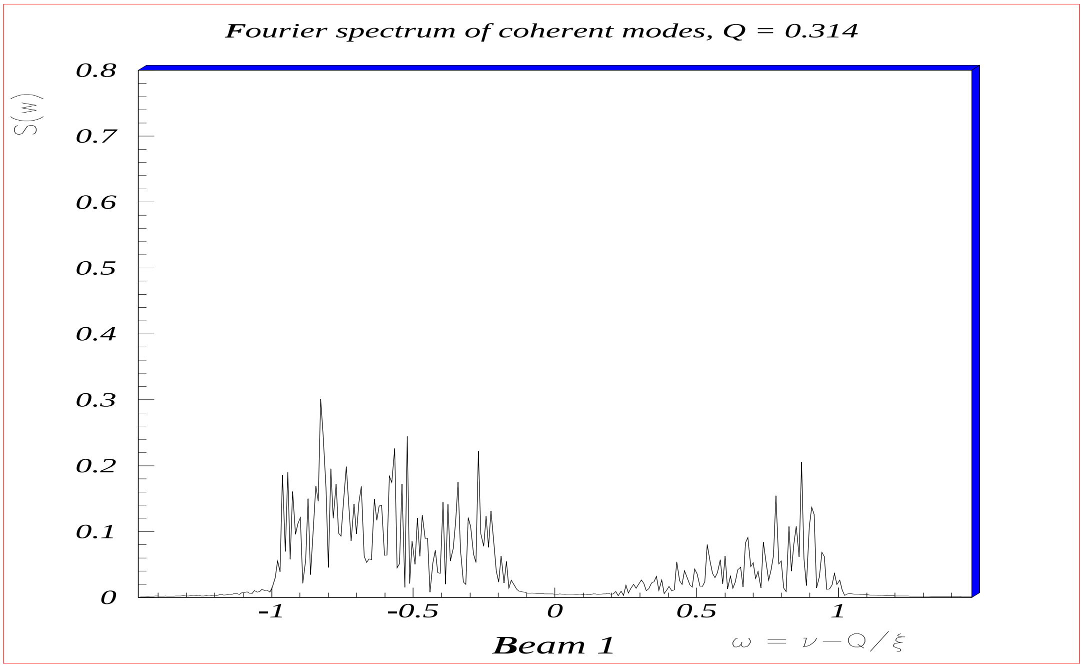
Beams with different intensity





Beams with different tunes





Can we suppress beam-beam effects ?

- **Find 'lenses' to correct beam-beam effects**
- **Head on effects:**

  $\rightarrow$ **Electron lenses**

  $\rightarrow$ **Linear lens to shift tunes**

  $\rightarrow$ **Non-linear lens to decrease tune spread**

  $\rightarrow$ **Tests in progress at FNAL**
- **Long range effects:**

  $\rightarrow$ **At large distance: force is 1/r**

  $\rightarrow$ **Same force as a wire !**

Others: Möbius lattice

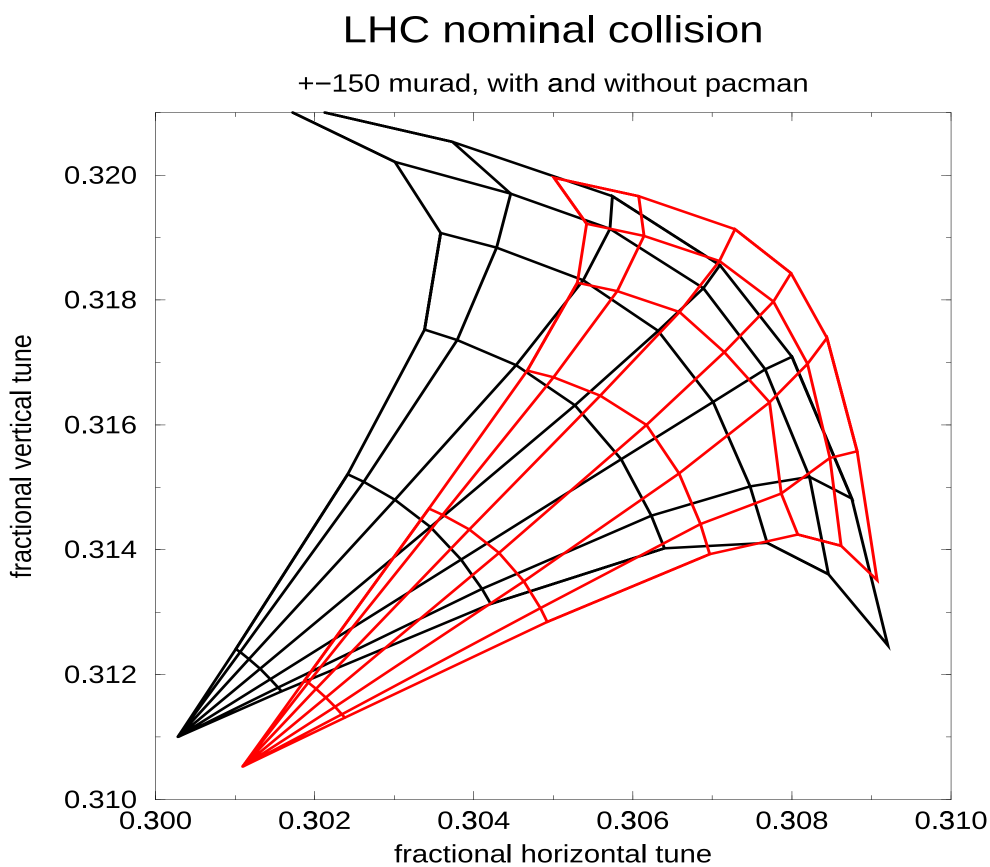
- **Principle:**
  - → **Interchange horizontal and vertical plane each turn**
- **Effects:**
  - → **Round beams (even for leptons)**
  - → **Some compensation effects for beam-beam interaction**
  - → **First test at CESR at Cornell**

Not mentioned:

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

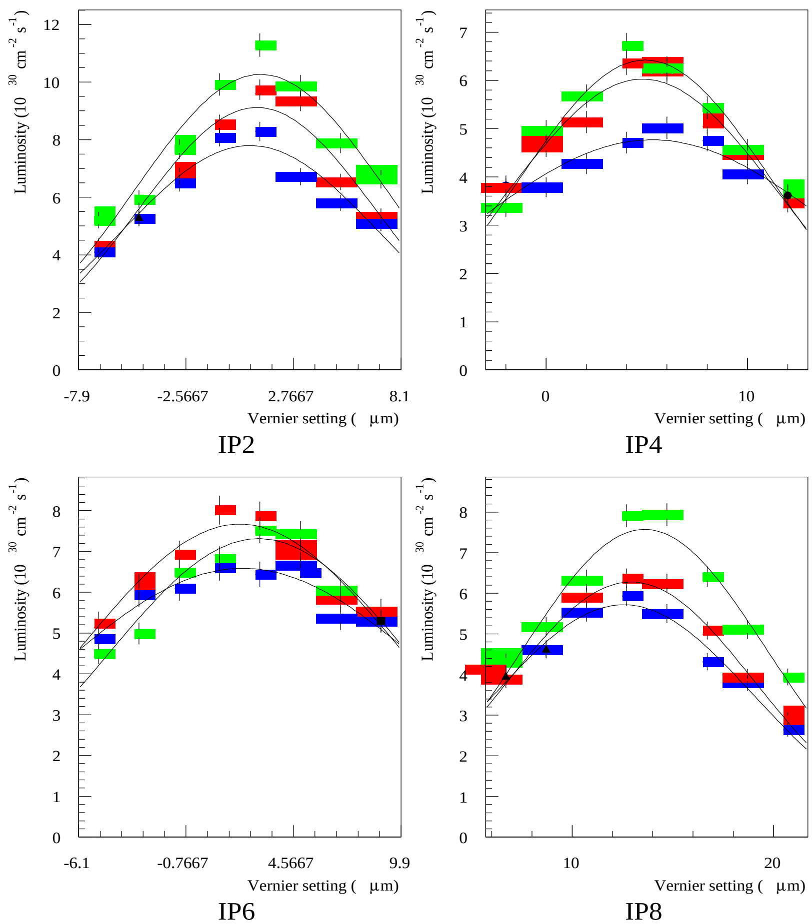
Some bibliography in the hand-out

Footprints PACMAN bunches



- **"Footprints" of PACMAN bunches are shifted**

Scan of offsets in lep



Families

a **b** **c**

IP2 Scan .9 μm

Offset a 0.96+- 0.13 $(\chi^2/_{dof}= 2.3)$
Offset b 1.13+- 0.15 $(\chi^2/_{dof}= 2.1)$
Offset c 0.61+- 0.17 $(\chi^2/_{dof}= 1.7)$

IP4 Scan 5.0 μm

Offset a 4.79+- 0.17 $(\chi^2/_{dof}= .7)$
Offset b 4.93+- 0.15 $(\chi^2/_{dof}= 1.0)$
Offset c 5.26+- 0.35 $(\chi^2/_{dof}= 1.1)$

IP6 Scan 2.3 μm

Offset a 1.91+- 0.25 $(\chi^2/_{dof}= 1.2)$
Offset b 2.84+- 0.23 $(\chi^2/_{dof}= 1.2)$
Offset c 2.05+- 0.30 $(\chi^2/_{dof}= .8)$

IP8 Scan 13.1 μm

Offset a 12.92+- 0.15 $(\chi^2/_{dof}= 1.0)$
Offset b 13.59+- 0.13 $(\chi^2/_{dof}= .9)$
Offset c 12.55+- 0.18 $(\chi^2/_{dof}= .8)$

- **LEP beam with 3 bunches per train**
- **Confirms self-consistent calculation**

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