Strong-Strong Beam-Beam effects in Hadron Colliders

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Overview

- Introduction
  - Hadron colliders, Luminosity and Beam-Beam Interactions
  - Motivations and goals of the study
- Models and simulation tool developed
  - Analytical linear method
  - Simplified rigid Gaussian bunch model
  - Self-consistent multi-particle multi-bunch simulation code
- Simulations Limitations and solutions
- What can we learn from RHIC?
- Conclusions

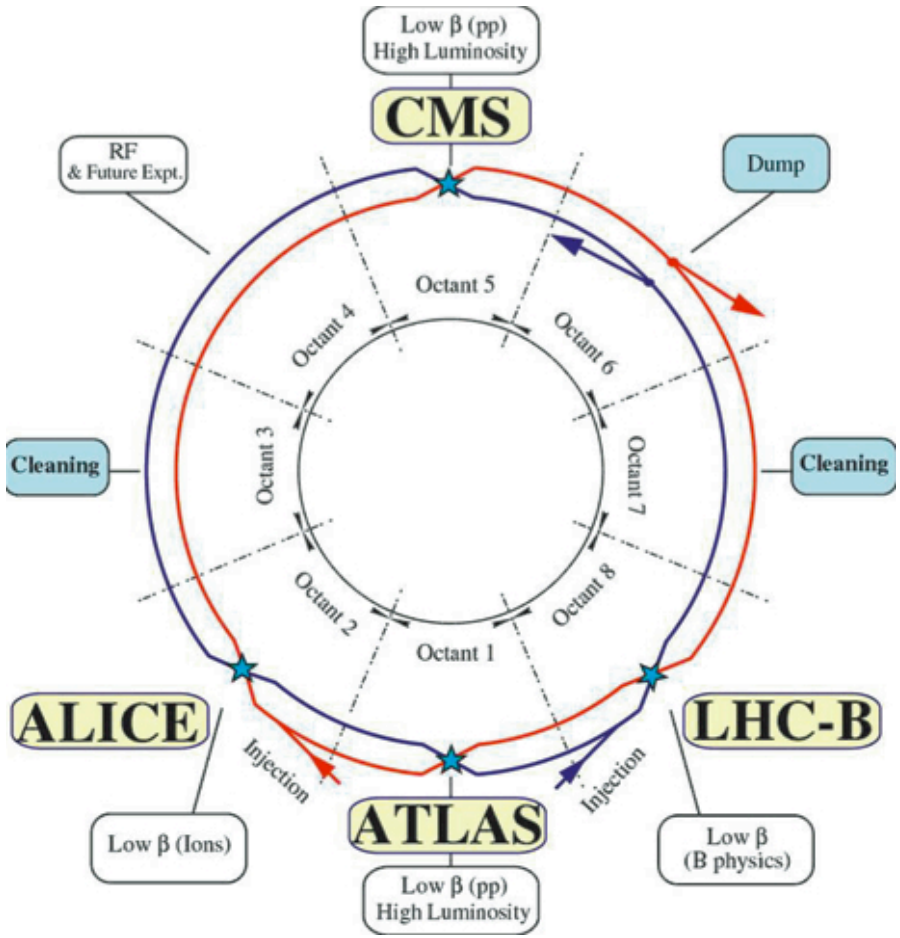
Hadron colliders

- Physics events:

$$N_{event}[sec^{-1}] = L\sigma_{event}$$

- Luminosity:

$$L = \frac{N_1 N_2 f_{rev} N_b}{4\pi\sigma_x\sigma_y}$$



LHC parameters to reach $L=10^{34}$ $cm^{-2}sec^{-1}$

σ_x ,σ_y = 16.7 μm

$N_1 = N_2$ = 1.15 10^{11} protons/bunch

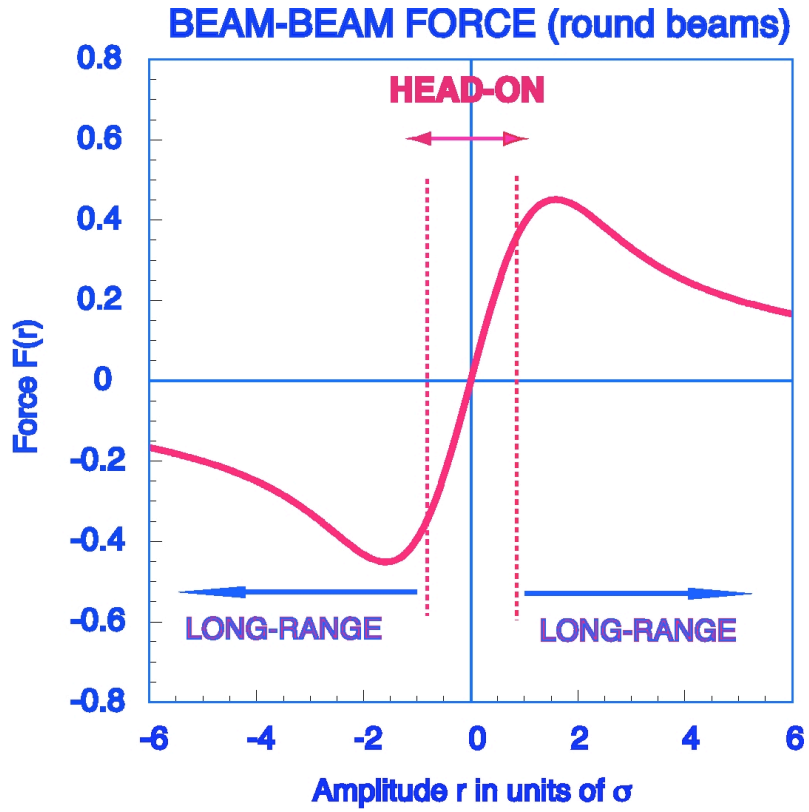
N_b= 2808 bunches/beam

f_{rev}=11.245 kHz

Beam-Beam Interactions

Beam-beam interaction: electromagnetic interaction of two beams colliding in the IRs

$$F_{bb}(r) \approx \frac{N_1 e^2}{r\sigma_x\sigma_y} e^{\frac{-r^2}{2\sigma_x\sigma_y}}$$

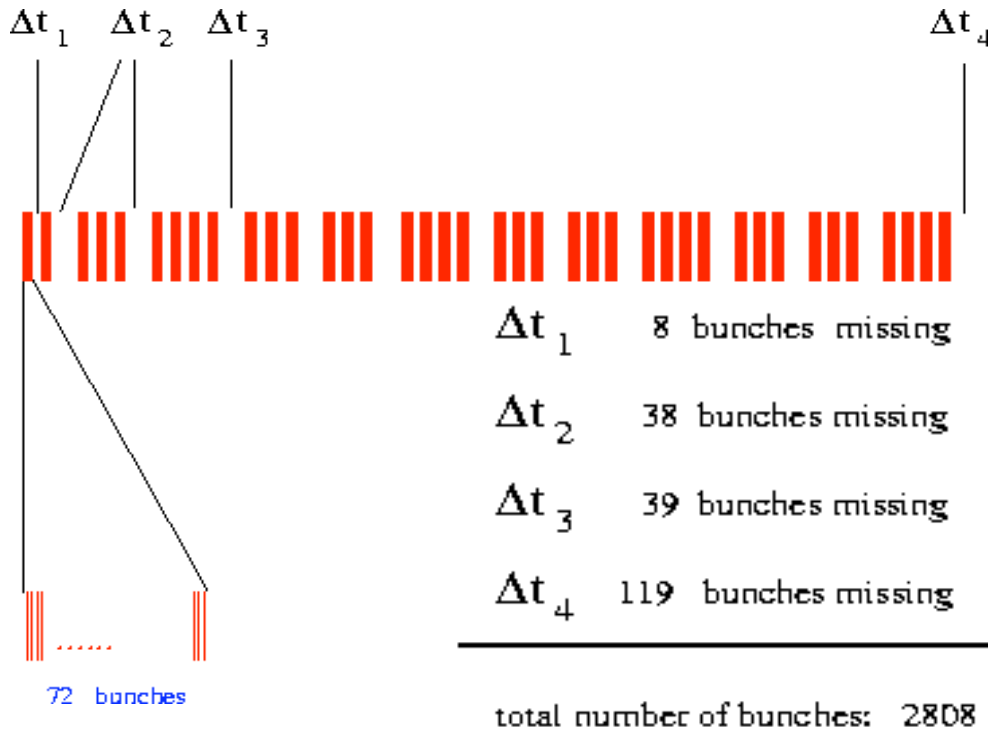


- **Non-linear force** depends on particle distribution
- **Time dependent** change distribution as result of interaction

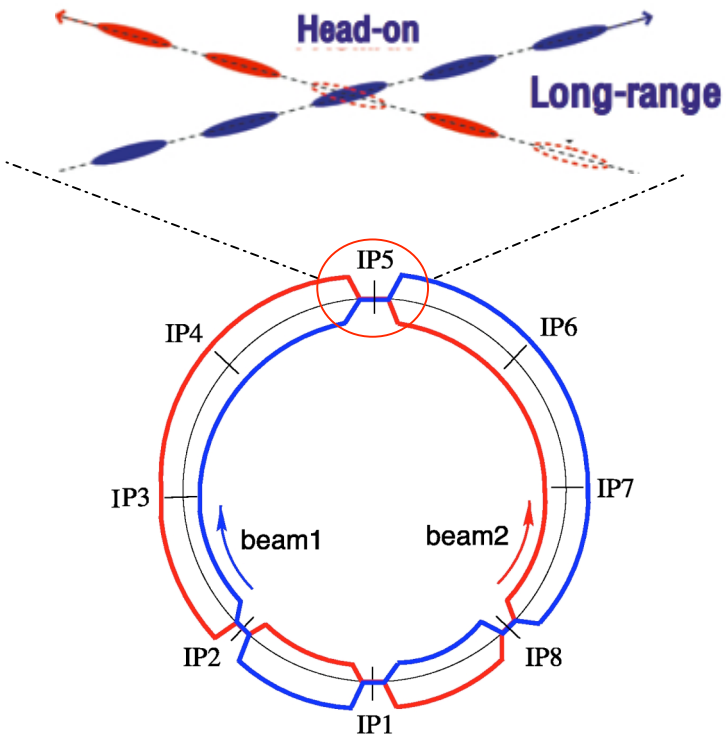
High Luminosity = Strong beam-beam

The LHC special case

Time structure of the LHC beam



Collision with crossing angle:
- Up to 4 head-on collisions
- Up to 120 parasitic interactions



PACMAN bunch: miss long range interactions

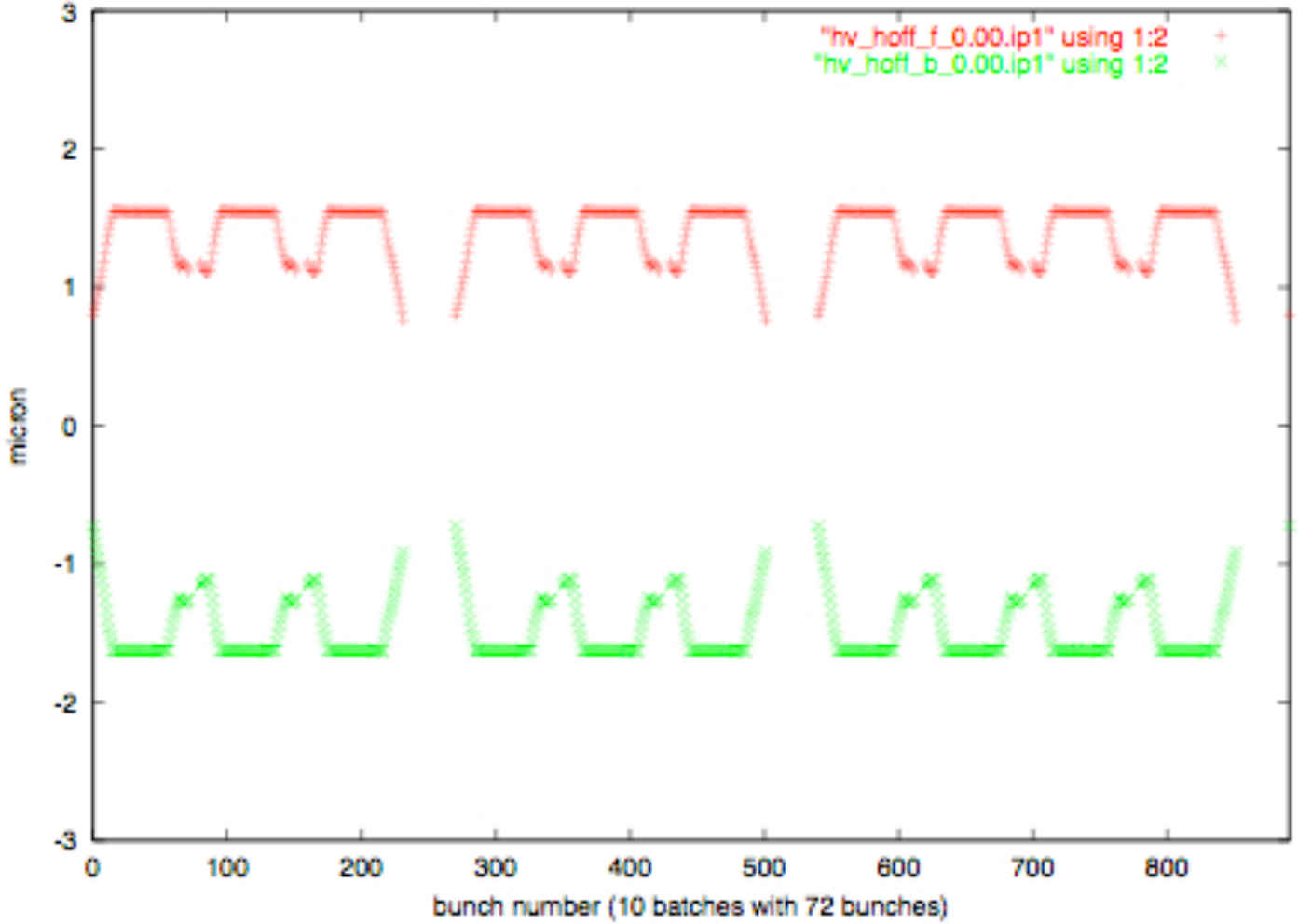
Super PACMAN bunch: miss head-on collision

- **Strong effects (high density bunches)**
- **Multiple BBI (124 BBIs)**
- **Non regular pattern (symmetry breaks)**

Strong bch2bch differences

Orbit effects

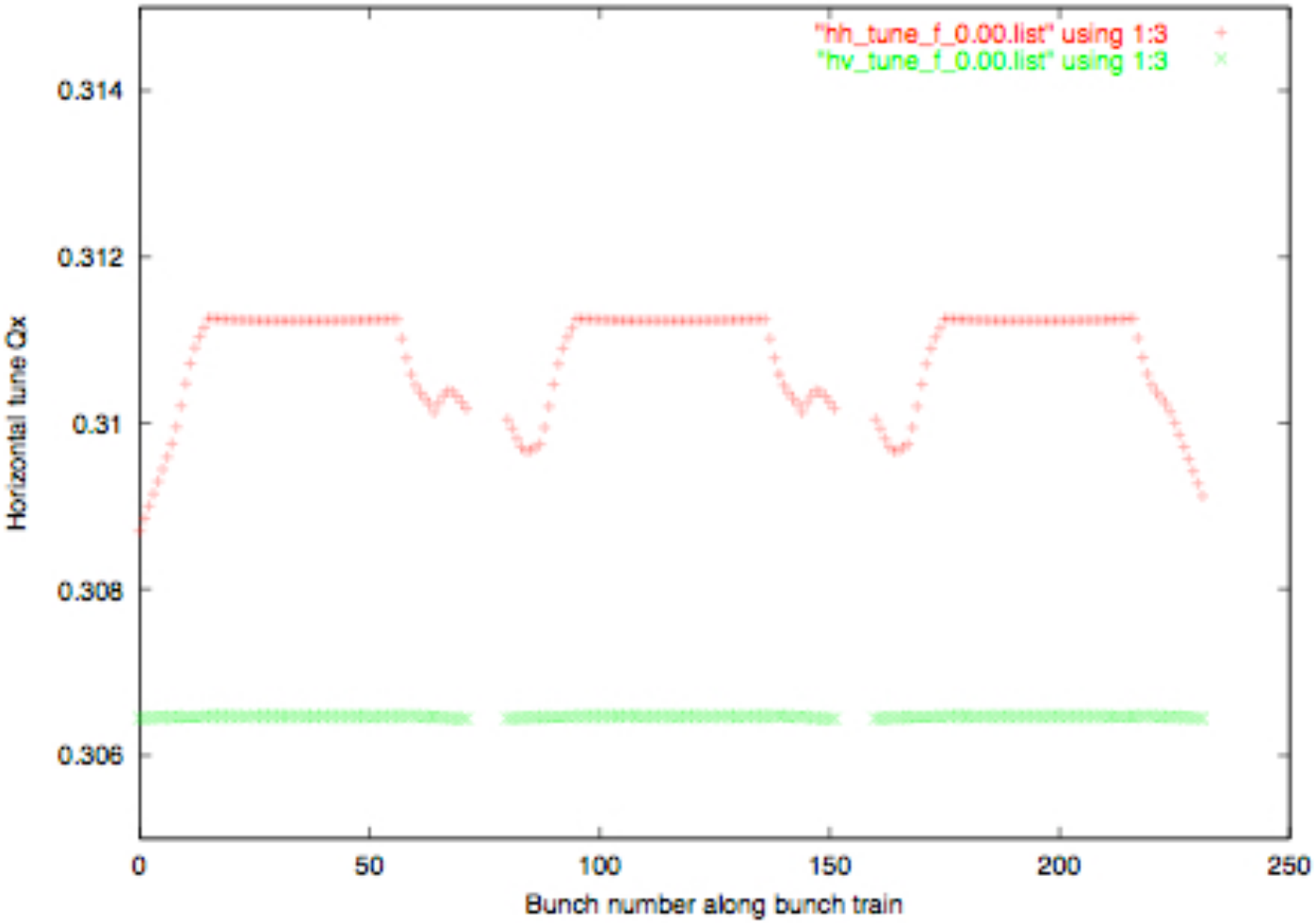
Multiple Long-range interactions lead to offsets in collision



Different offsets into collision

Tune spread

Multiple Long-range interactions lead to tune shifts



Different tunes into collision

Motivations:

Beam-Beam main limiting factor for all past (LEP, SPS collider, HERA) and present (Tevatron, RHIC) colliders: **complete theory does not exist for multiple bunches beam**

Beam-Beam effects still to be addressed

Beam dynamics		**Experiments**
Dipolar coherent oscillation		**offset in collisions**
Emittance growth	→	**lower luminosity**
Beam bad lifetime - halo		**higher background in the IRs**
Bunch to bunch difference		**difficult beam orbit corrections**

GOALS:

*Develop a **BB model*** that **CAN**:

- **Predict** bunch to bunch differences (diagnostic & optimization)
- **Investigate** BB effects for different operational scenarios (optimization)
- **Help understanding** the phenomenon (can lead to possible cures)

How do we proceed?

(1) Simulation type: Strong-Strong

- Only one beam affected **(weak-strong)**:
  - BBIs affect and change only weak beam, strong beam static
  - Examples: SPS collider, Tevatron, HERA…
- Both beam affected **(strong-strong)**:
  - BBIs affect and change both beams
  - Examples: LEP, RHIC, LHC …

How do we proceed?

(2) Methods

- Could solve Vlasov equation **but**:
  - Analytical solution not always possible (perturbation theory needed)
  - Numerical solutions difficult (may not converge)
  - Very difficult to apply to multi bunch beam and multiple interactions

- Numerical simulations: COherent Multiple bunch Beam-beam Interactions code (COMBI) :

Models developed in COMBI:

I. Analytical Linear Model (ALM):

- Beams: system of oscillators coupled through linear BB force
- Solving the eigenvalue problem gives frequency spectra and information on bunch to bunch differences

II. Rigid Bunch Model (RBM):

- Each bunch oscillates as rigid object with fixed RMS
- Each bunch as a whole receives a kick due to interaction
- Fourier analysis of barycentre position gives frequency spectra of the system

III. Multi Particle Simulation (MPS): …strong-strong self consistent multi particle code…

Collider description:

Run parameters:

```
collision:  coll_LHC.in
filling:    fill_ref_1.in  fill_ref_2.in
number of turns: 124000
number of ips:  8 8
bunches to kick: 1015
bunches to measure: 1001 2017
QX0:  63.3200
QY0:  58.3100
beam-beam parameter: 0.0025
```

Collision pattern:

```
#Collision scheme LHC (for filling scheme LHC)
   1  -2   -15  +15
 447   3    8.046    6.940    8.032    6.920
 892  -2   -0    +0
2229   3   23.015  21.821   23.125  21.821
3565   2   -15  +15
4902   3   23.533  20.689   23.533  20.689
6235   2   -0    +0
6684   3    7.716   7.870    7.736    7.820
```

Beam filling scheme:

```
#Bunch filling example LHC
#Number of groups
8
 72 0 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 30 0   0 0
 72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
```

Other action codes:
- 4 only long range interactions
- 5 excitation (white noise, defined kicks)
- 8 BPMs
- 9 AC excitation (for BTFs)

I. Analytical Linear Model

Solve eigenvalue problem of 1 turn map

Beam-Beam Matrix:

$$B = \begin{pmatrix} 1 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\ -b_x & 1 & k & 0 & \dots & b_x & 0 & 0 & 0 & \dots \\ 0 & 0 & 1 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\ k & 0 & -b_y & 1 & \dots & 0 & 0 & b_y & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 1 & 0 & 0 & 0 & \dots \\ b_x & 0 & 0 & 0 & \dots & -b_x & 1 & k & 0 & \dots \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 1 & 0 & \dots \\ k & 0 & b_y & 0 & \dots & 0 & 0 & -b_y & 1 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{pmatrix}$$

$$\begin{array}{c} \text{BEAM 1} \\ \\ \text{BEAM 2} \end{array} \left[\begin{pmatrix} x_{1^{b_1}} \\ x'_{1^{b_1}} \\ y_{1^{b_1}} \\ y'_{1^{b_1}} \\ \dots \\ x_{1^{b_2}} \\ x'_{1^{b_2}} \\ y_{1^{b_2}} \\ y'_{1^{b_2}} \\ \dots \end{pmatrix}_{s_0+C} \right. = M_C \left. \begin{pmatrix} x_{1^{b_1}} \\ x'_{1^{b_1}} \\ y_{1^{b_1}} \\ y'_{1^{b_1}} \\ \dots \\ x_{1^{b_2}} \\ x'_{1^{b_2}} \\ y_{1^{b_2}} \\ y'_{1^{b_2}} \\ \dots \end{pmatrix}_{s_0} \right] \begin{array}{l} \text{bunch1 beam1} \\ \\ \text{bch2, ...} \\ \\ \text{bunch1 beam2} \\ \\ \text{bch2, ...} \end{array}$$

Bunches: Rigid Gaussian distributions

Transfer Matrix:

$$T = \begin{pmatrix} \cos(\Delta\mu_x^{b_1}) & \sin(\Delta\mu_x^{b_1}) & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\ -\sin(\Delta\mu_x^{b_1}) & \cos(\Delta\mu_x^{b_1}) & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\ 0 & 0 & \cos(\Delta\mu_y^{b_1}) & \sin(\Delta\mu_y^{b_1}) & \dots & 0 & 0 & 0 & 0 & \dots \\ 0 & 0 & -\sin(\Delta\mu_x^{b_1}) & \cos(\Delta\mu_y^{b_1}) & \dots & 0 & 0 & 0 & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & \cos(\Delta\mu_x^{b_2}) & \sin(\Delta\mu_x^{b_2}) & 0 & 0 & \dots \\ 0 & 0 & 0 & 0 & \dots & -\sin(\Delta\mu_x^{b_2}) & \cos(\Delta\mu_x^{b_2}) & 0 & 0 & \dots \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & \cos(\Delta\mu_y^{b_2}) & \sin(\Delta\mu_y^{b_2}) & \dots \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & -\sin(\Delta\mu_y^{b_2}) & \cos(\Delta\mu_y^{b_2}) & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{pmatrix}$$

- $\Delta\mu_x^{b_1}$ • Phase advance
- b_x • Linearized HO or LR B-B kick
- k • Coupling factor

One Turn Matrix ➡ $M_C = T_1 * B_1 * T_2 * B_2 * \dots$

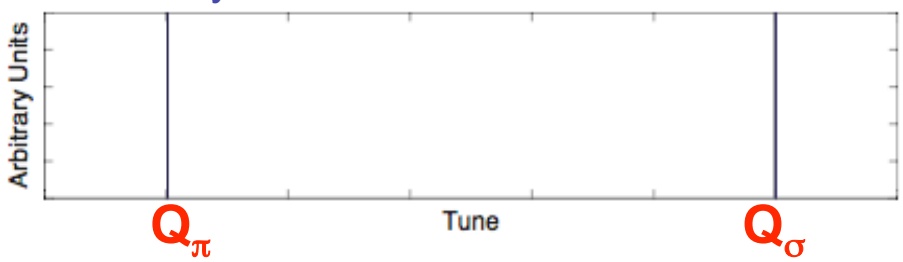
I. Analytical linear model

Solving the eigenvalue problem, like for a system of coupled oscillators:

- **Eigenvalues:** give the system dipolar mode eigen-frequencies (**tune**):

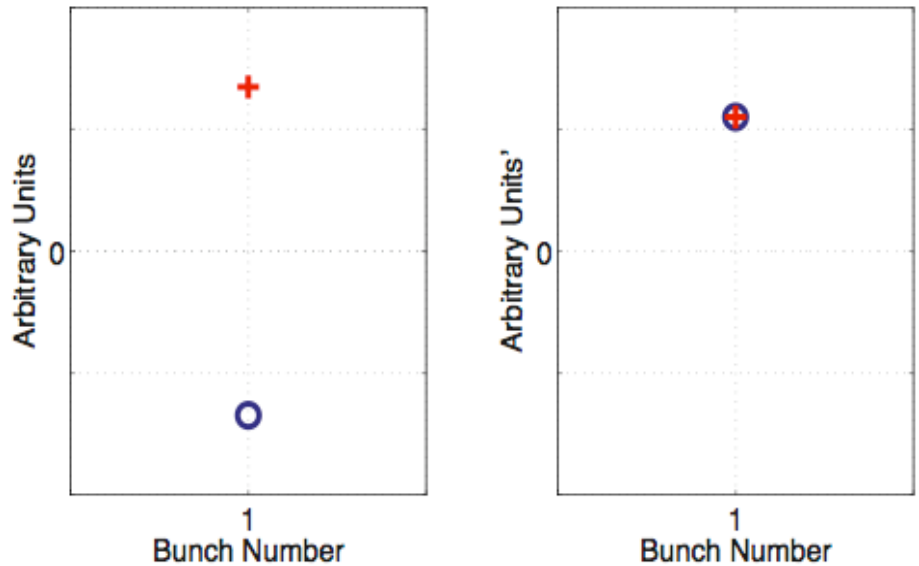
$$Q_i = \frac{\arccos(\lambda_i)}{2\pi}$$

  - Mode frequencies calculations for bunches
  - Stability studies

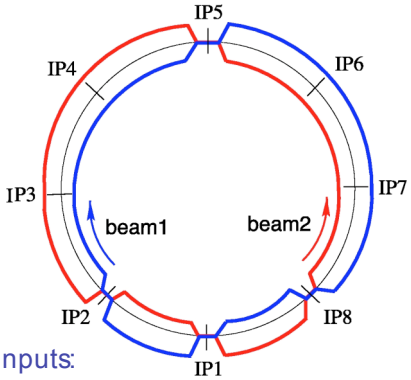


- **Eigenvectors** give the system oscillating patterns:

  - To understand bunches oscillation patterns
  - With other simulations to understand bunch to bunch differences



I. ALM: more bunches



Inputs:

- Beam 1 = 4 equispaced bunches
- Beam 2 = 4 equispaced bunches
- HO collision in IP1-2 and LT

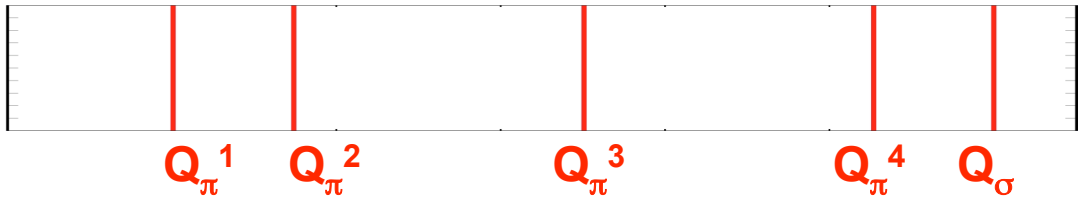
5 different Eigen-values

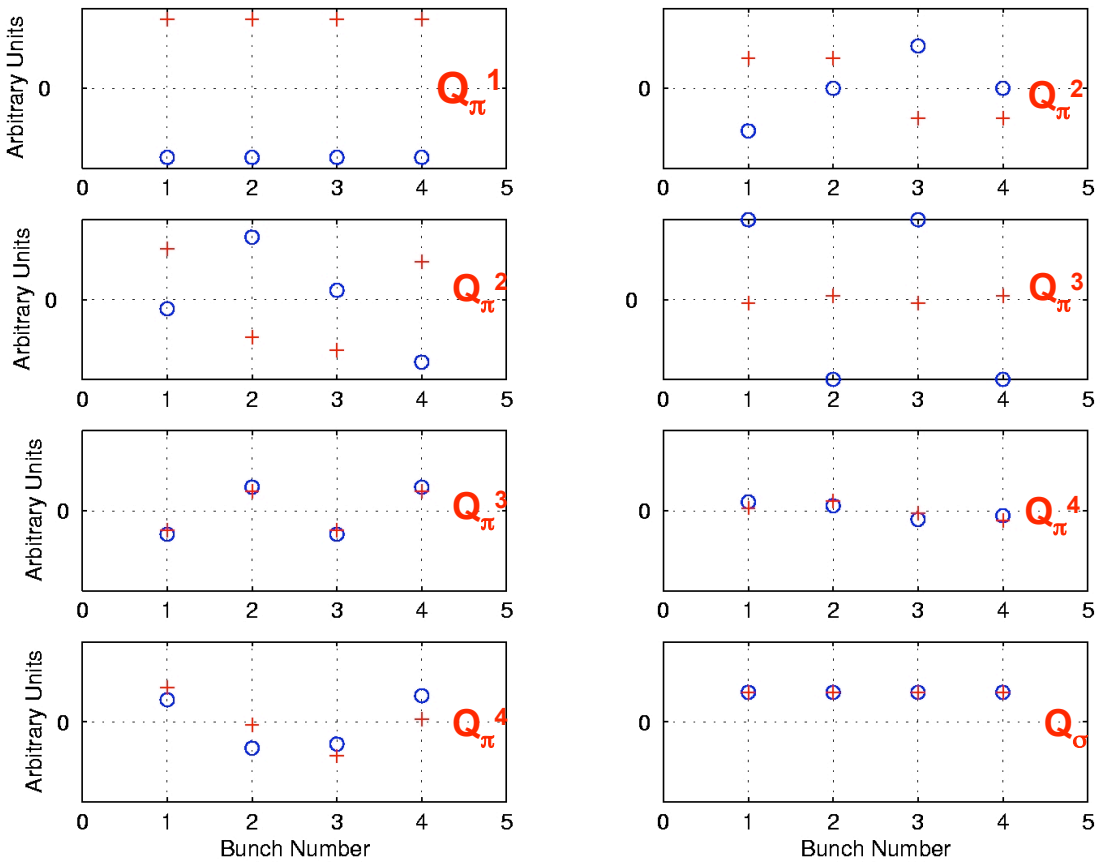
8 different Eigen-vectors

Q_π^1-mode:
all bunches exactly out of phase

$Q_\pi^{2,3,4}$-mode (intermediate modes):

Q_σ-mode:
all bunches exactly in phase





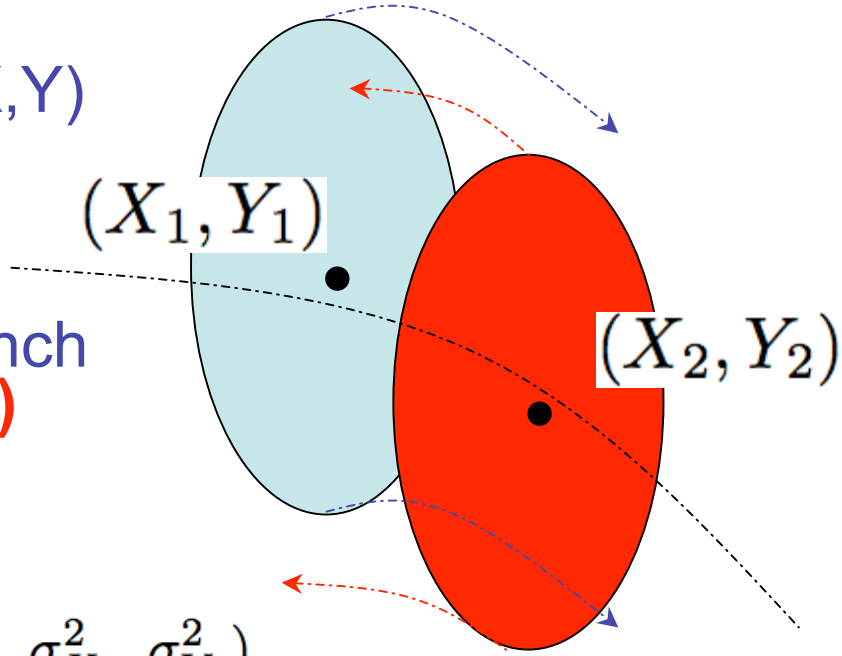
I. ALM: Adv & Disadv

- Advantages:
  - Easy definition of any beam filling scheme and collision patterns
  - Fast calculation speed
  - Get all modes frequencies (eigenvalues)
  - Give information on bunch pattern (eigenvectors)

- Disadvantages:
  - Non-linear terms not treated
  - Landau damping cannot be included
  - Higher order modes cannot be evaluated

II. Rigid Bunch Model

- Bunches: rigid objects assumed Gaussian with varying barycentres (X,Y) and fixed (σ_x,σ_y)



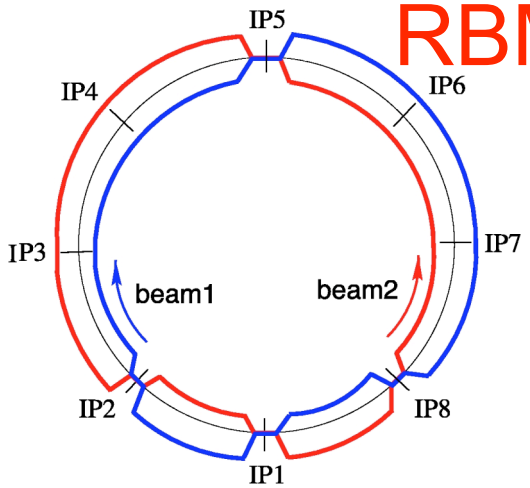
- At BBI bunch at **(X_1,Y_1)** receives a transverse **kick** from the opposite bunch at **(X_2,Y_2)** and transverse sizes **(σ_x,σ_y)** and vice versa

$$\Delta(X_1)' = \frac{2r_p N_p}{\gamma}\frac{\beta_x}{\sigma_{X_2}^2} F_{X_2}(X_1 - X_2, Y_1 - Y_2, \sigma_{X_2}^2, \sigma_{Y_2}^2)$$

- Between BBI: linear transfer (rotation in phase space) and anything else (transverse kick from collimators, kickers…)

- Fourier analysis of the bunch barycentres turn by turn gives the tune spectra of the dipole modes

RBM vs ALM: **multi HO BBIs**

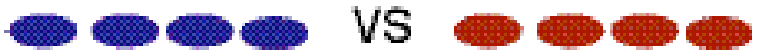


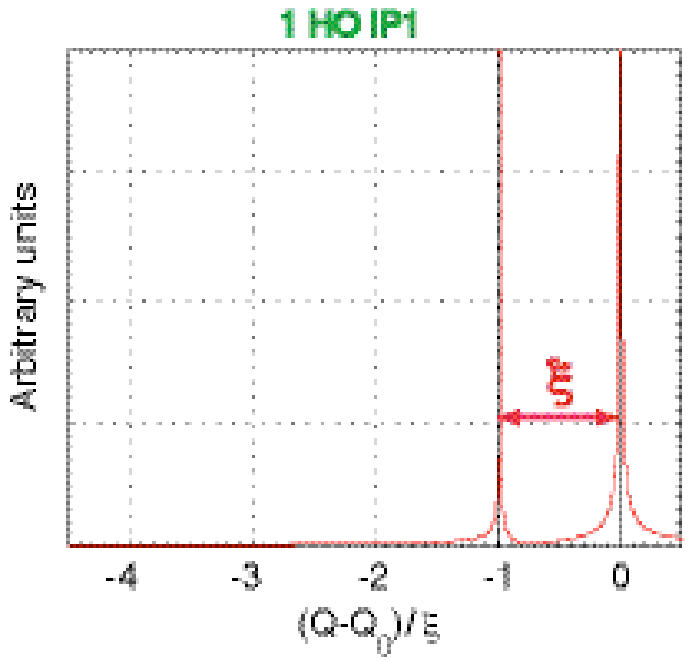
Inputs:

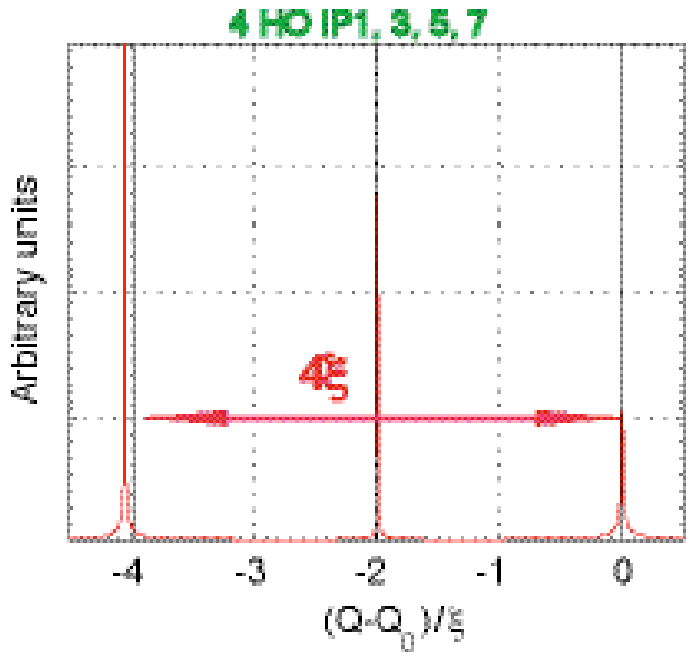
- 4 bch beam1 vs 4 bch beam 2 equi-spaced
- Different collision schemes (only HO)

$$\Delta Q_{bb}^{max} = N_{IPs} * \xi_{bb}$$

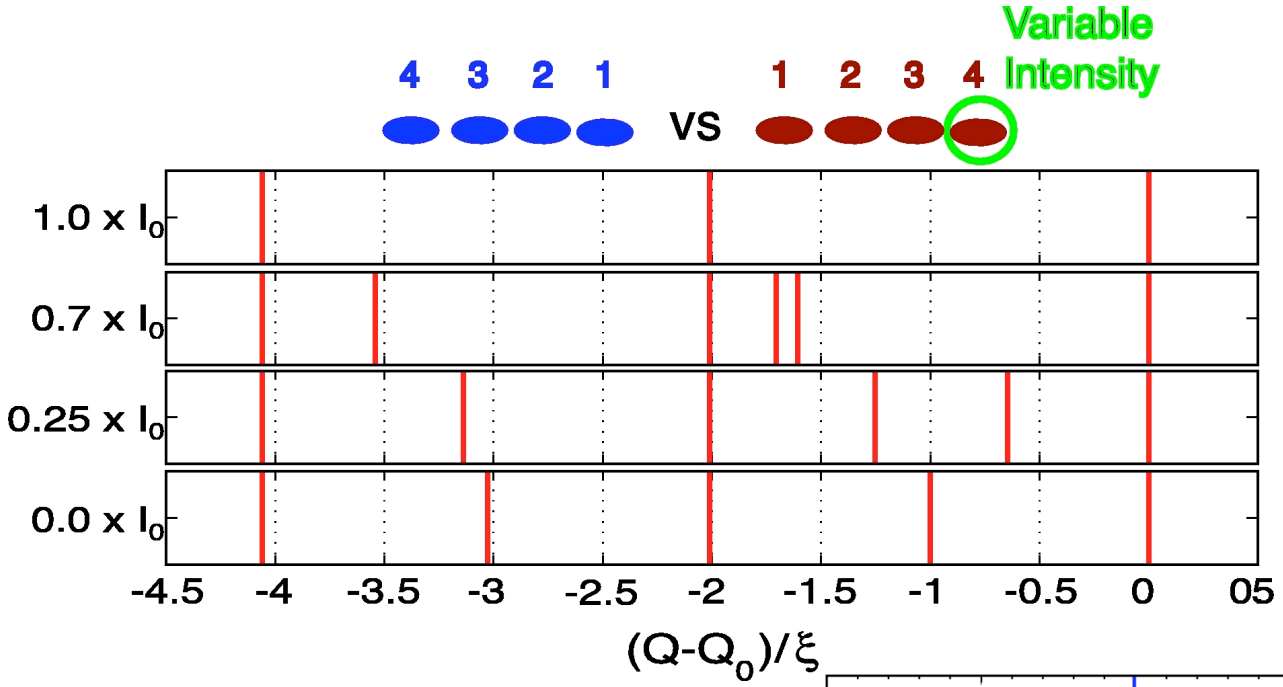
MULTI HO collisions







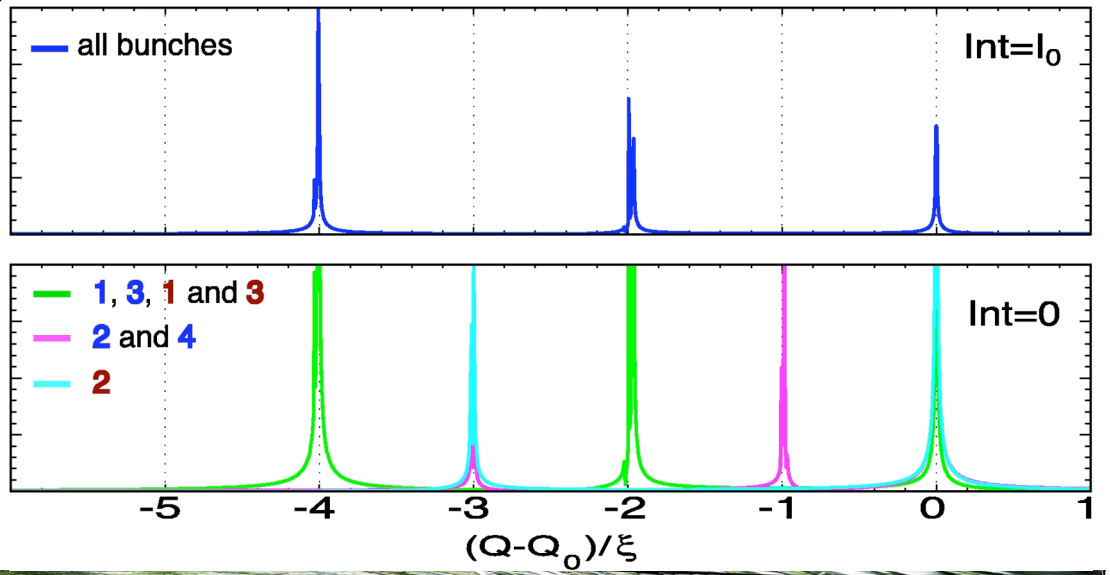
RBM vs ALM: **intensity effects**



Inputs:
- 4 bch vs 4 bch
- HO in IP1, 3, 5 and 7
- intensity variation of b_4

ALM:
- **All modes** visible
- **Degeneracy** break due to symmetry breaking

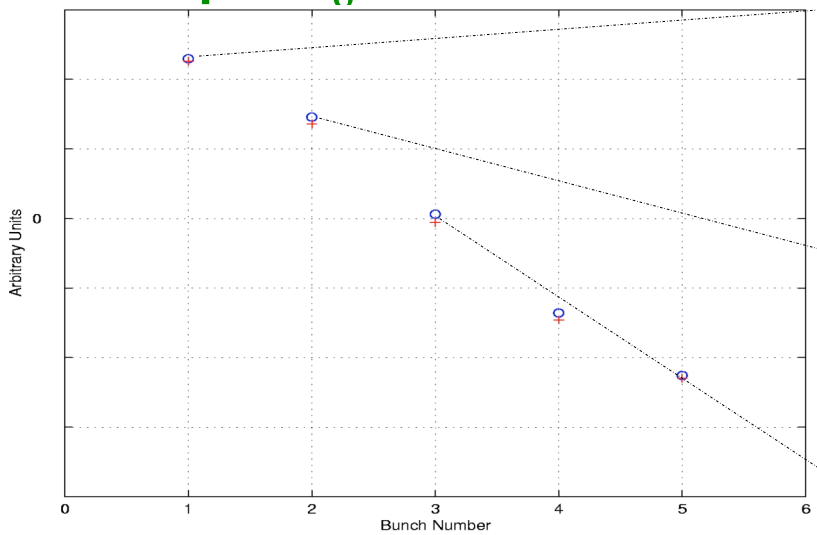
RBM:
- Evidence of **direct and indirect coupling** to b_4
- **Degeneracy breaking of coherent modes** due to missing bunch b_4

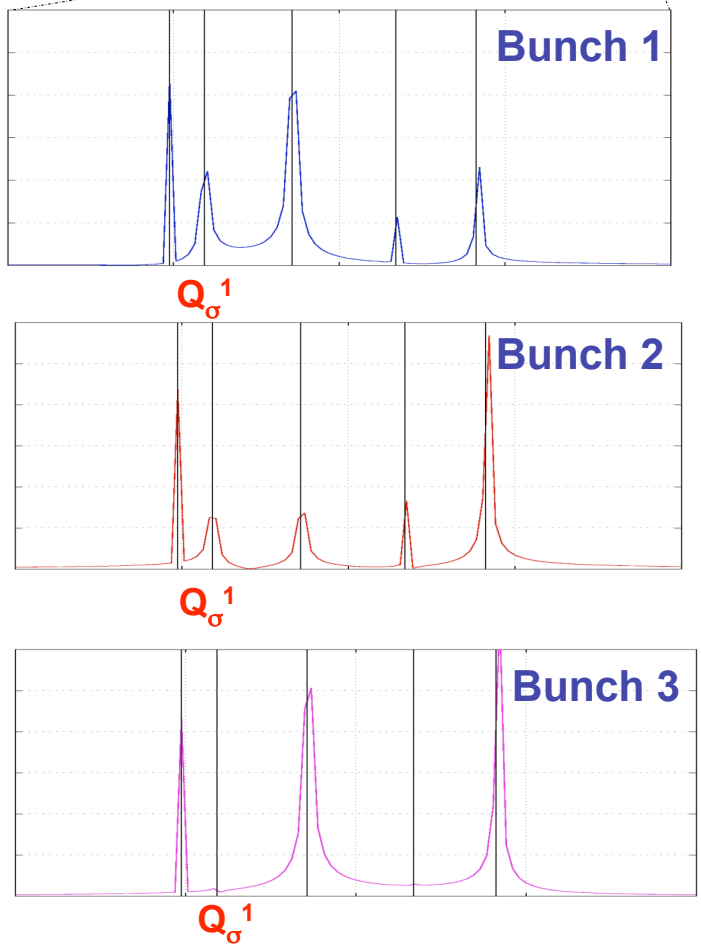


ALM vs RBM: bch to bch differences

Inputs:
- 5 bch trains
- 1 HO + 1 LR

Example Q_σ^1





The eigenvector associated to the Q_σ^1 shows that the total effect on the bunches varies from bunch to bunch depending on **direct and indirect coupling to a PACMAN bunch**

✓ **We can predict bunch to bunch differences in the tune spectra**

RBM: Adv & Disad

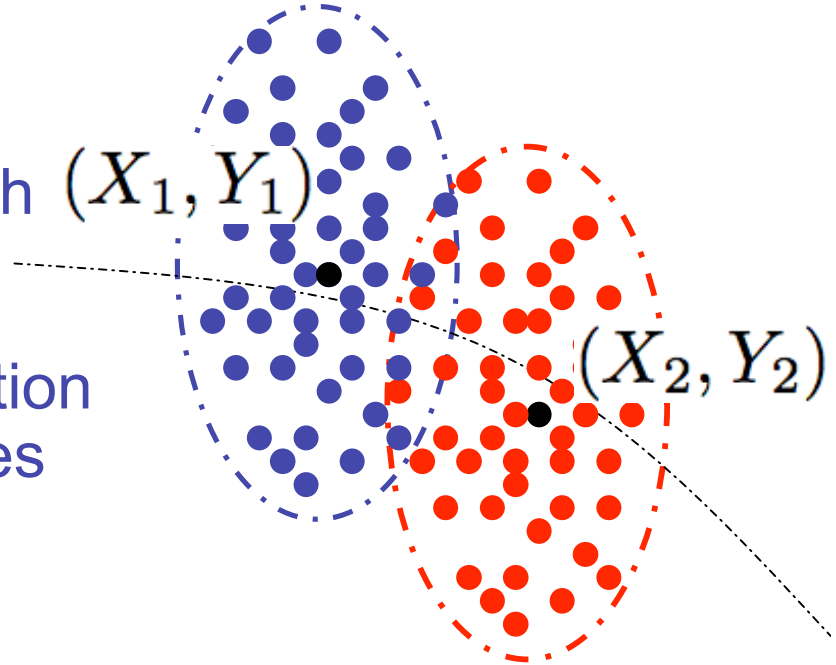
- Advantages:
  - Easy definition of any beam filling scheme and collision pattern
  - Bunch to bunch differences can be predicted
  - Good calculation speed
  - Non-linear effects treated only for Gaussian bunches

- Disadvantages:
  - Non-linear terms partially treated (field calculation not correct)
  - Landau damping cannot be included (rigid bunches)
  - Higher order modes cannot be evaluated

Multi Particle Simulations

- **Bunches: N_{tot} (10^4-10^6)** macro particles

- **BBI:** each particle of bunch **(X_1,Y_1)** receives a transverse **kick** from bunch **(X_2,Y_2)** and vice versa.



- **BB kick:** solving the Poisson equation for any distribution of charged particles (FMM) or Gaussian approximation:

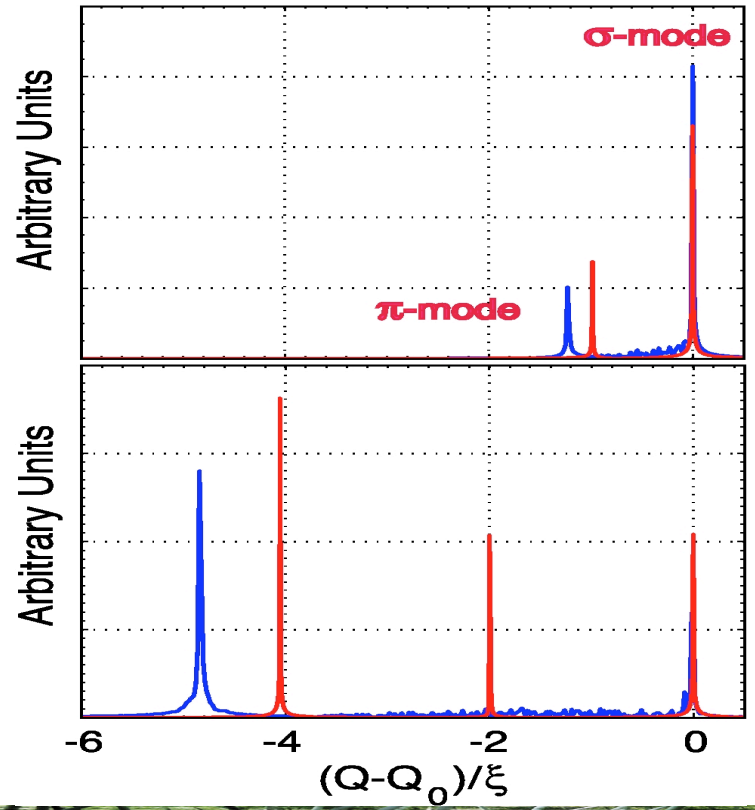
$$\Delta(x_1)' = \frac{2r_p N_p}{\gamma} \frac{\beta_x}{\sigma_{X_2}^2} F_{X_2}(x_1 - X_2, y_1 - Y_2, \sigma_{X_2}^2, \sigma_{Y_2}^2)$$

- **Between the BBIs:** linear transfer (rotation in phase space) and anything else (kickers, collimators, BTF device, etc)

MPS results (I):

❑ Coherent effects:

Fourier analysis bunch barycentres turn by turn gives frequency spectra of dipolar modes



Effects of:

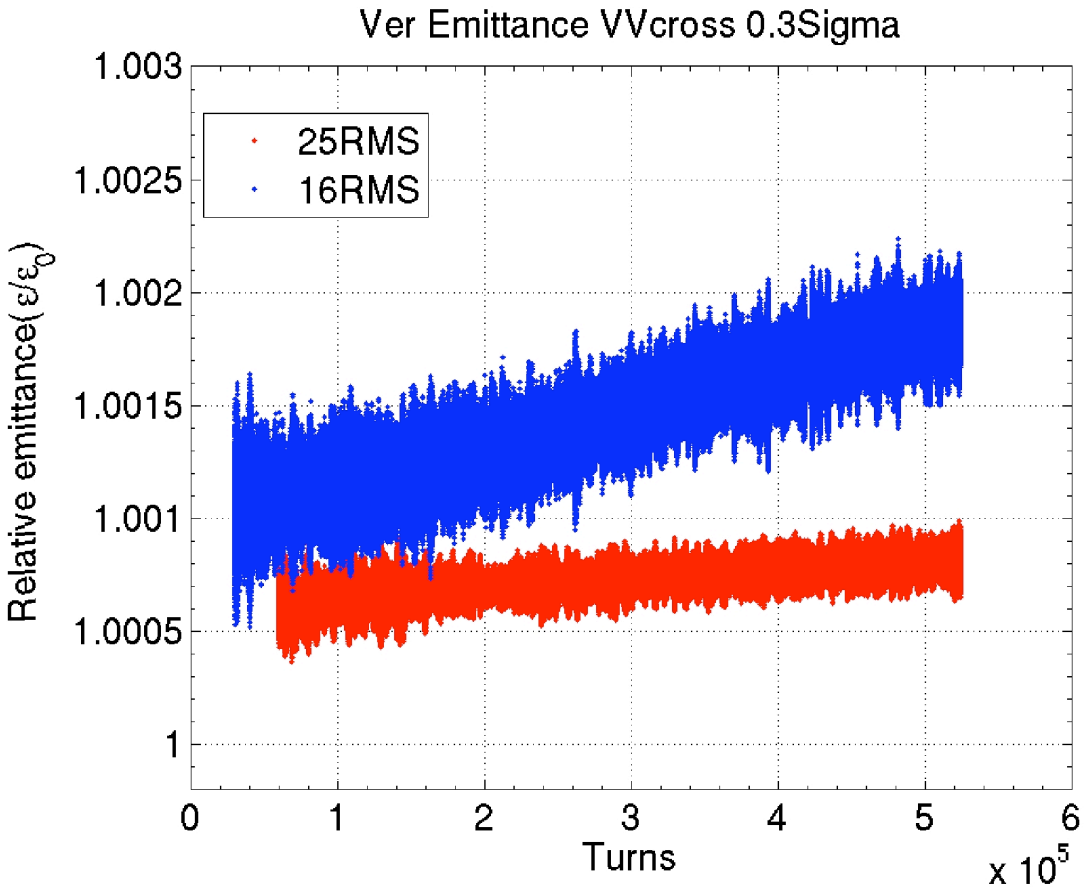
- ❑ **Landau damping**
- ❑ Symmetry breaking in collision scheme and phase advance
- ❑ Intensity fluctuations
- ❑ Bunch to bunch differences
- ❑ Beam instabilities
- ❑ Higher order modes

Inputs
- 4 bunches 10^5 macroparticles
- 2-4 HO collisions
- Run of 32000 turns

MPS results (II):

- Incoherent effects:

studies of "emittance" (beam sizes) behaviour:



Effects of:

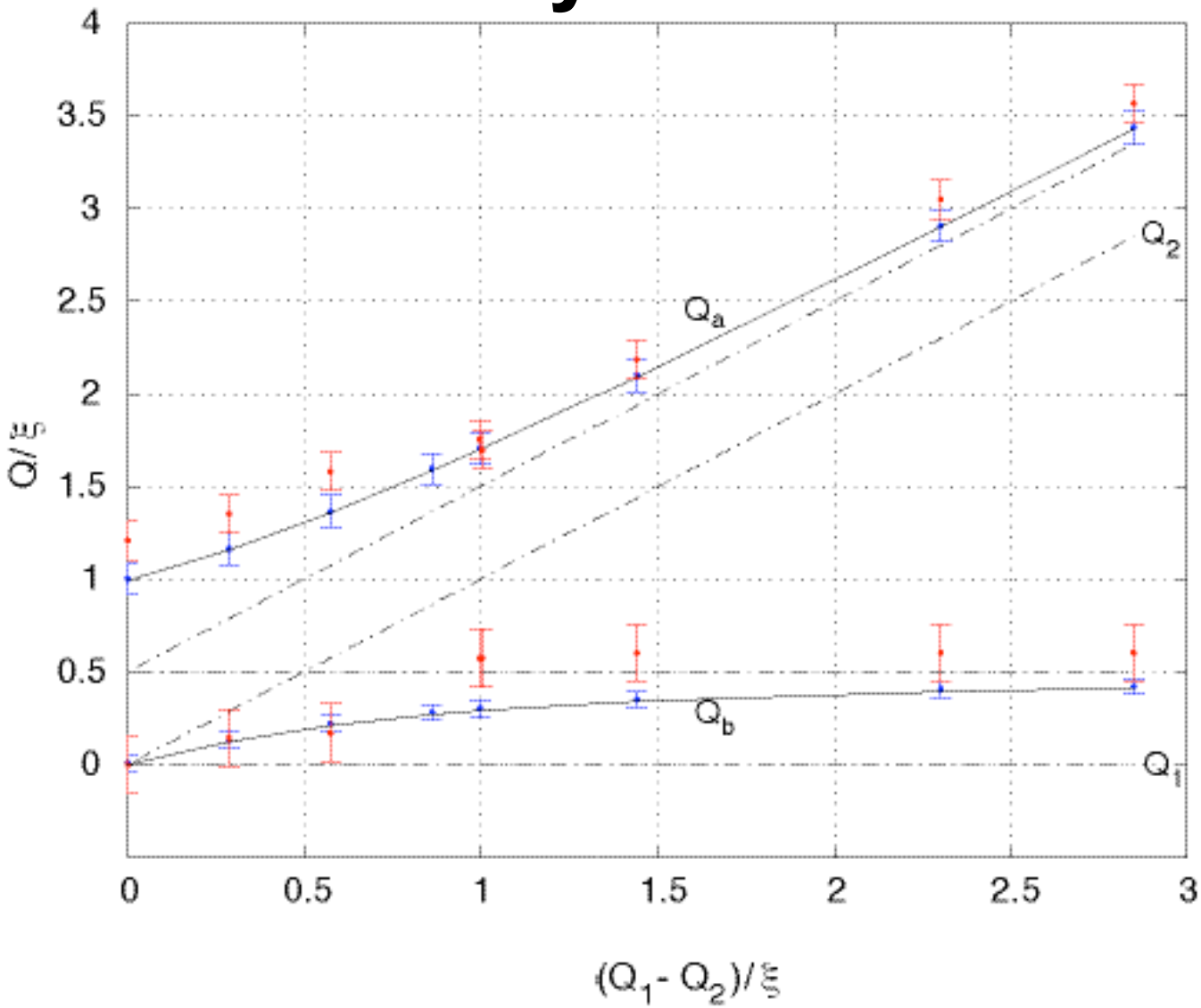
- Different crossing planes
- Noise due to equipment
- Offsets in collision

- 3 independent studies
- 3 different codes (J.Qiang,W.Herr-F.Jones, COMBI)

RBM vs MPS vs Analytical solutions

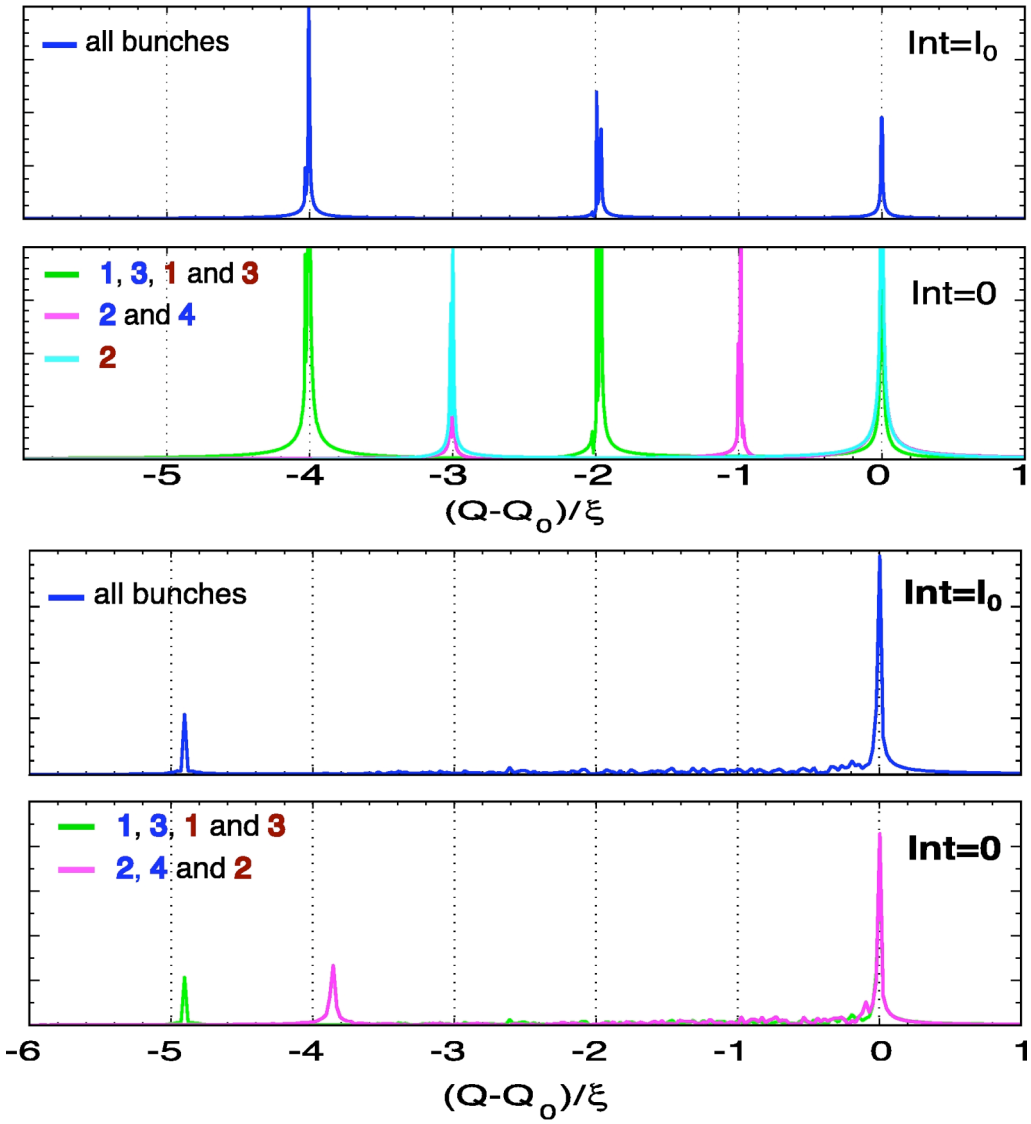
Inputs:

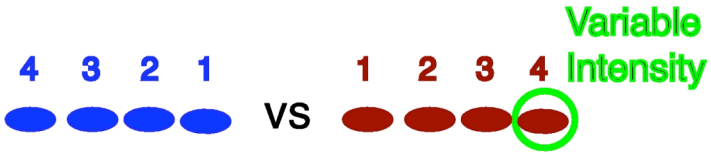
- 1 bunch beams 10^5 macroparticles
- 1 Head-on collision, 1 LT
- $Q_{beam1} \neq Q_{beam2}$
- Run of 32000 turns



✓ **Benchmark with analytical solutions when possible**

RBM vs MPS: Super-pacman bunches





Inputs:

- 4 bch vs 4 bch
- same collision scheme
- intensity variation of b_4

RBM:

- Evidence of **direct and indirect coupling** to b_4 ⇒ **different tune spectra**
- **Different frequencies** and **sliding of coherent modes** with b_4 intensity variations
- **Landau damping** of bunch modes inside their **different incoherent spread**

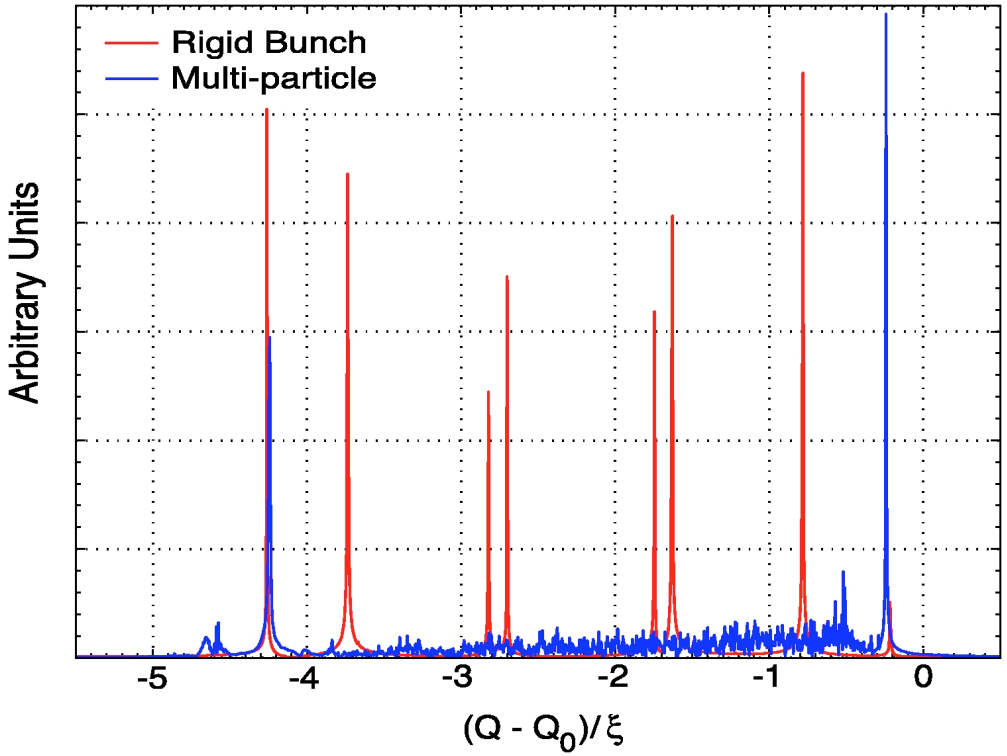
MPS: Adv & Disad

- Advantages:
  - Easy definition of any beam filling scheme and collision patterns
  - Non linear terms properly treated
  - Landau damping can be reproduced
  - Higher order modes can be reproduced
  - Correct field calculation (depending on field solver used)
  - Incoherent effects can be studied (emittance growth, beam lifetime

- Disadvantages:
  - Does not give all mode frequencies due to damping
  - **Time consuming**

The LHC…

Simplified LHC example….



Inputs:
- **36 bunches** per beam each $\mathbf{N_{tot}=10^4}$
- **4** Head-on collisions per turn
- **64000** turns run (only 5-6 s of LHC)

Effects of:

- ❑ Symmetry breaking of the phase advance through IPs
- ❑ "Landau damping" of modes which fall inside the incoherent spectrum

More than 10 days CPU time and still….

- ❑ **Few bunches** and only 10^4 macroparticles
- ❑ **No parasitic** interactions included
- ❑ Only **5-6 sec of LHC** (not enough for emittance studies)

Only with parallel computing…

- Need to simulate up to 124 BBIs simultaneously
- Need at least 10^4 macroparticles per bunch
- All interactions are independent

At each beam-beam interaction we must solve Poisson equation

Time consuming

Need of minimum 124 CPUs:

High communications through processors

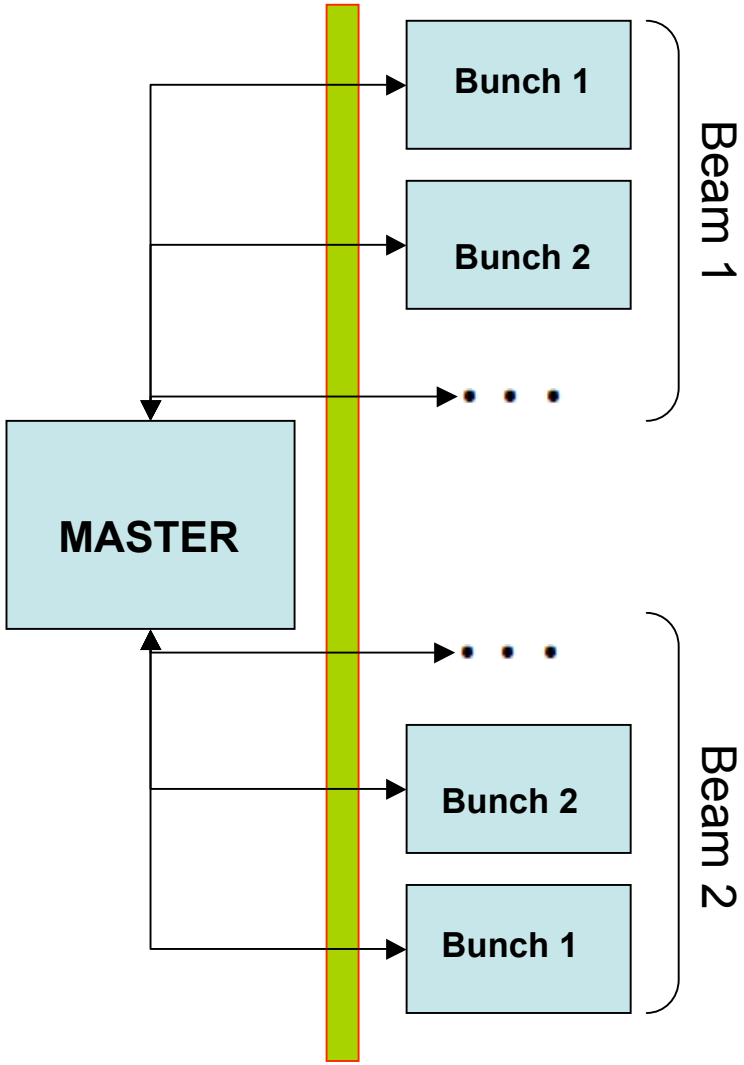
as many CPUs as bunches:

Processors communications at minimum

COMBI MPS to Parallel mode

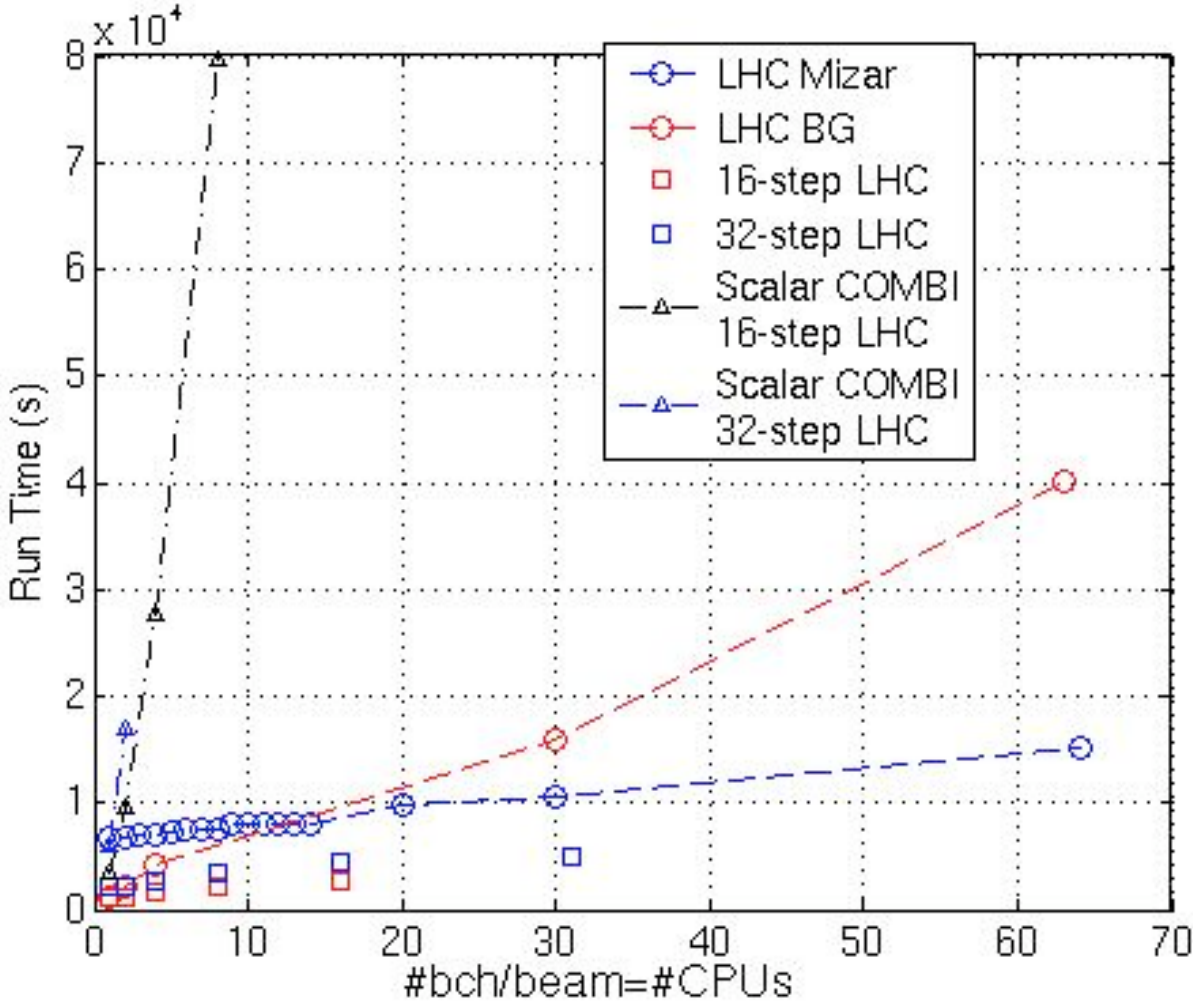
- MPI-protocol
- Master/Slave Architecture
- Clusters: EPFL MIZAR (448 CPUs) and EPFL BlueGene (8000 CPUs)

- MASTER:
  - Controls propagation of the bunches
  - Controls the calculation for the interactions of bunches
- Slaves:
- **Store the macro-particle parameters** and **perform calculation** when an action is required from the MASTER :
  - **Single bunch action**: do not need information from opposite bunch
  - **Double bunch action**: need information barycentre and field from opposite bunch.



Scalability: preliminary results

- ✓ **Very good results** up to 64 bunches per beam each of 10^4 macroparticles, undergoing up to 64 BBIs and 16 rotations, 124+1 CPUs for runs of 64000 turns
- ✓ Scalability studies on-going

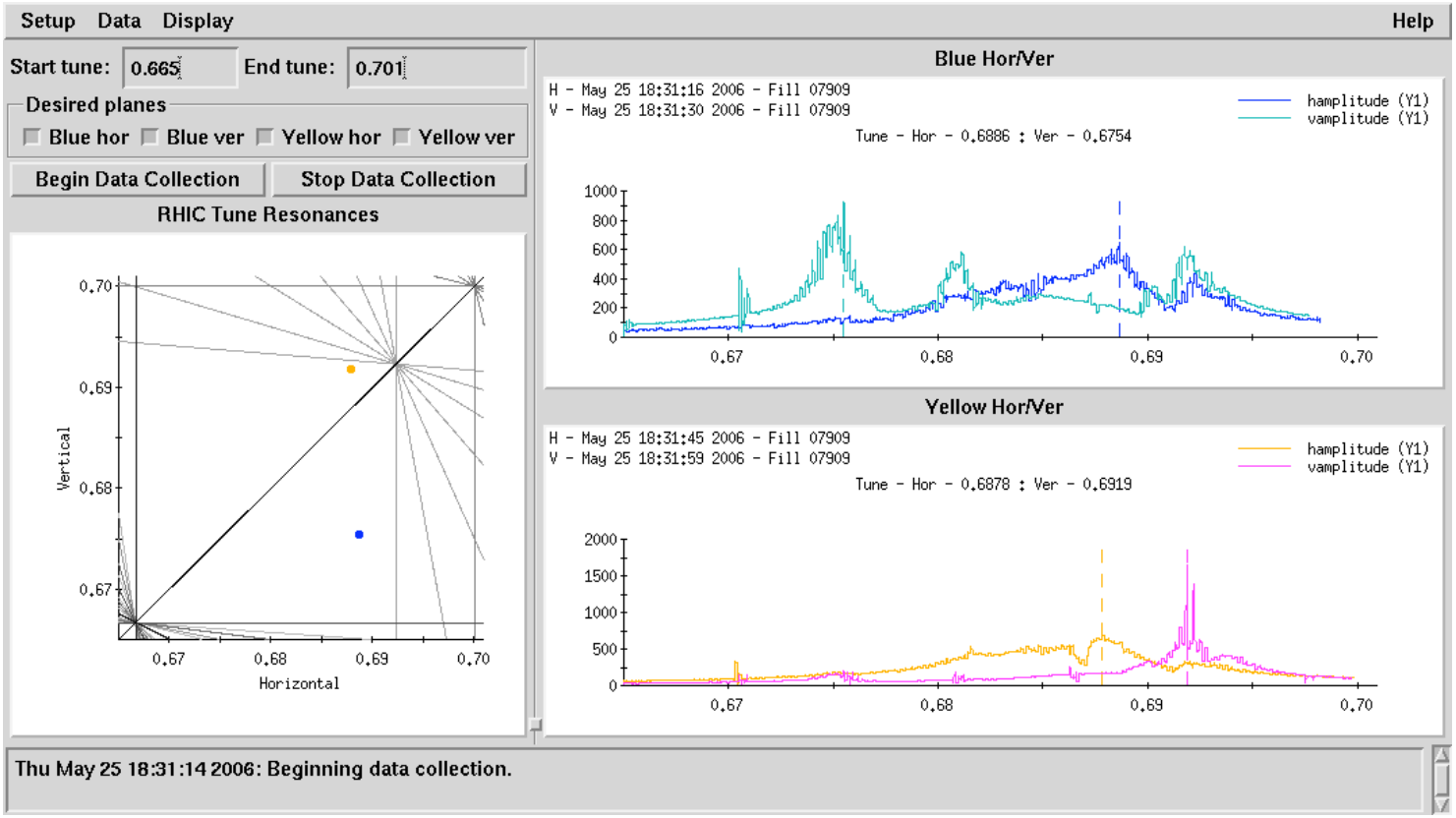


Computing time:

- ➢ Almost independent of bunch number
- ➢ Almost independent of the number of interactions

What can we learn from RHIC?

BTF MEASUREMENT Fill 7909 pp Run06



- Blue Qx=0.6886 and Qy=0.6754
- Yellow Qx=0.6878 and Qy=0.6919
- 2 HO collisions bbparam = 0.01214

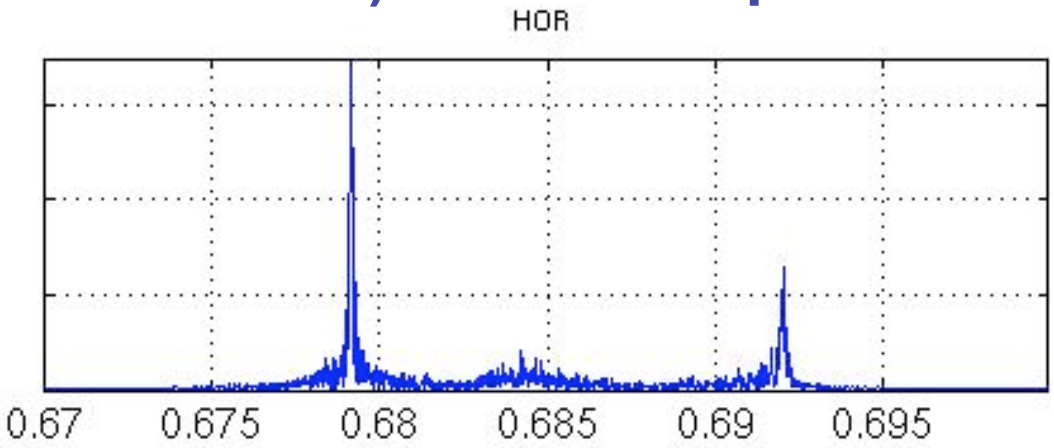
What do we expect:

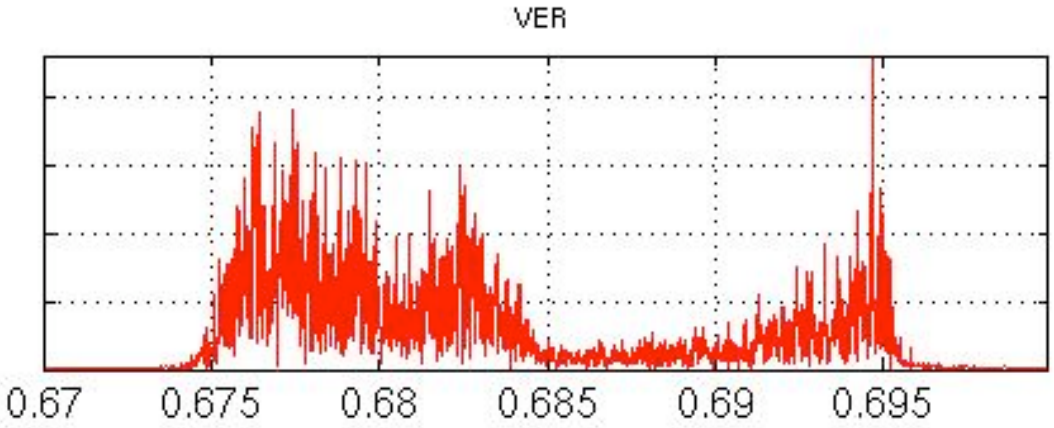
MPS SIMULATIONS (5 bch beams) HOR&VER planes:

- Blue
Qx=0.6886/Qy=0.6754

- Yellow
Qx=0.6878/Qy=0.6919

- 2 HO collisions
I=1.5e11 p/bch

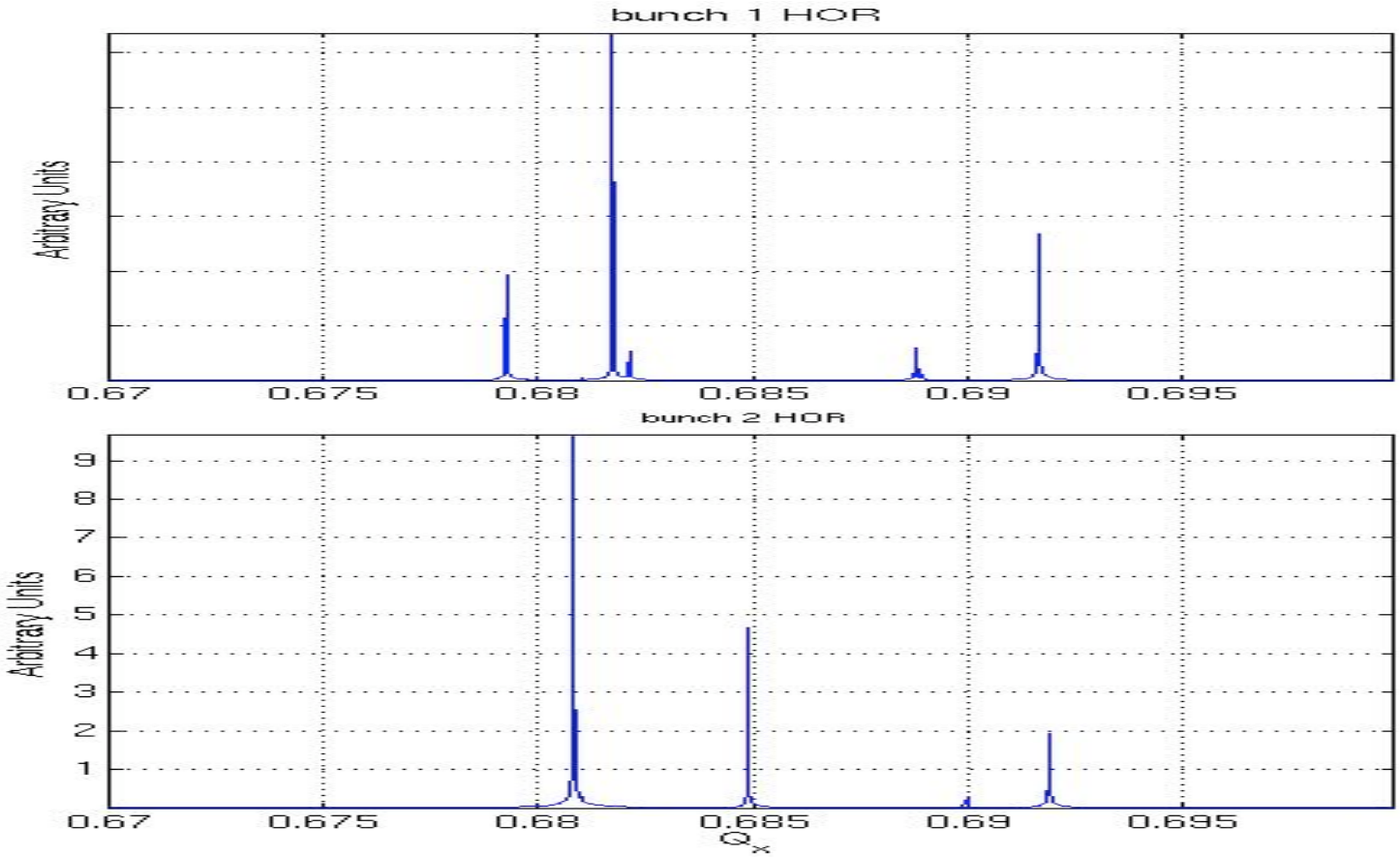




- Horizontal plane coupled system (Qxb1-Qxb2 < bbpar)
- Vertical plane decoupled system with different frequencies

What do we expect:

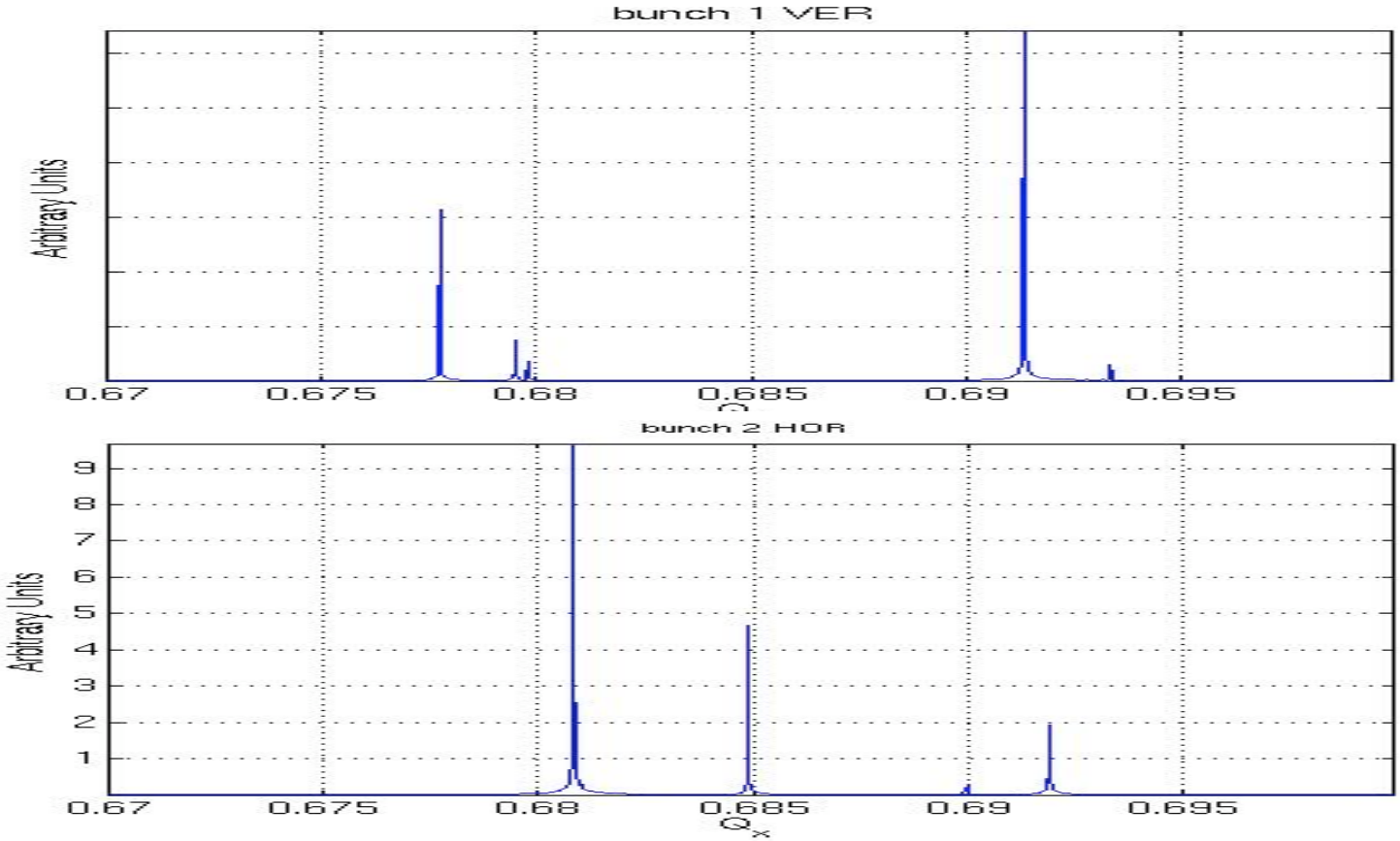
RBM SIMULATIONS (5 bunch beams) HOR plane:



- Super Pacman bunches
- Coupled oscillators with different frequencies

What do we expect:

RBM SIMULATIONS (5 bunch beams) VER plane:



- Super Pacman bunches
- Coupled oscillators with different frequencies

Conclusions:

- Different **beam-beam models** were **developed** to study the effects **for the LHC** but can be applied to any circular collider
- We now have a better **understanding** of **multi bunch effects**
- We are able to **predict bunch to bunch differences**
- Studies of different and optimized operational scenarios of the LHC will lead to **keep detrimental effects under control** and to **propose possible counter-actions**
- **RHIC BTF data** could be evidence of coherent modes excitation?

To be ready for Nominal LHC:

- **Benchmark** of COMBI **with experimental data from RHIC**

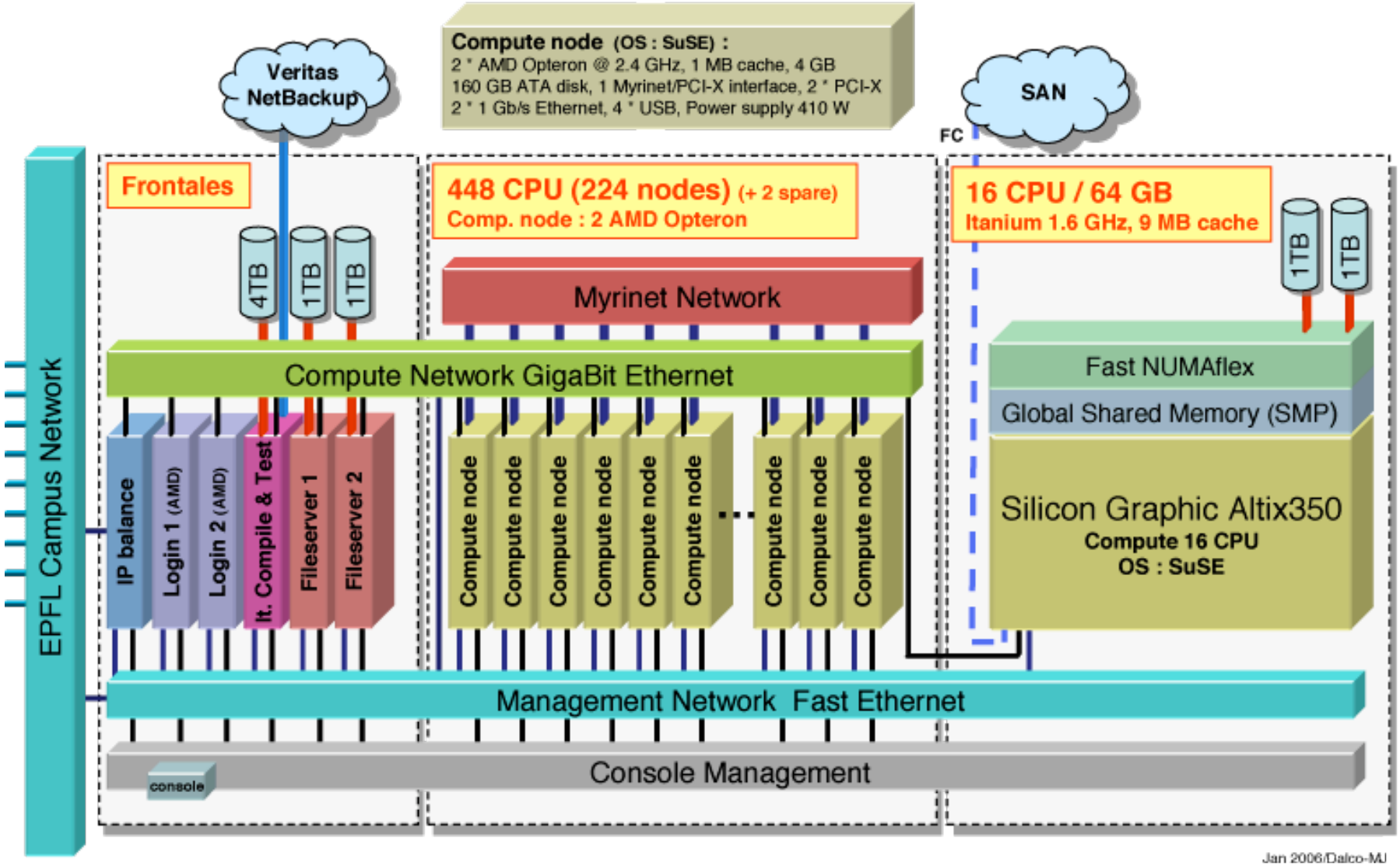
- Simulation campaign **for a more "realistic" LHC scenario (124 BBIs up to 2800 bunchs per beam)**

  - Intensity fluctuation studies
  - Emittance studies for different working points and crossing planes
  - Offsets in collision
  - Effects of collimators, kicker magnets, instrumentation devises.

People and laboratories:

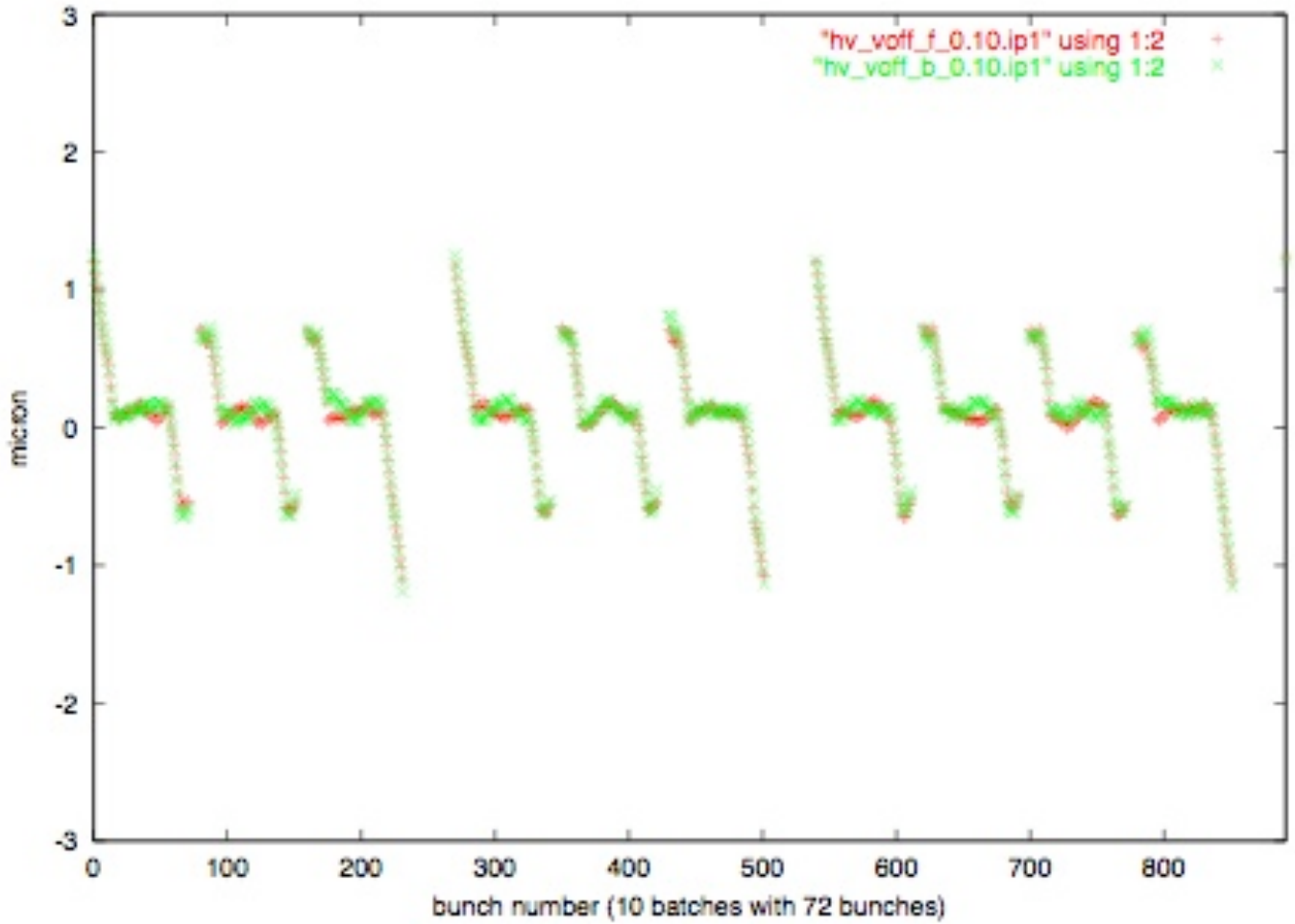
- ☺ CERN: Dr. Werner Herr and LHC Commissioning and Upgrade studies
- ☺ TRIUMF: Dr. Fred Jones
- ☺ Brookhaven NL: M.Blaskiewicy, R.Calaga, P.Cameron, W.Fischer
- ☺ EPFL: Professors A. Bay and L. Rivkin
- ☺ EPFL MIZAR and BG Teams: J. Menu, J.C. Leballeur and C. Clemonce
- ☺ PSI Villigen: Prof. A. Wrulich

Mizar - Central Compute Server



Orbit effects

Multiple Long-range interactions lead to offsets in collision



HV X-ing compensation