



ICFA mini-workshop on  
"Beam-Beam Effects in Hadron Colliders"  
March 18th to 22nd, 2013



# Beam-beam studies in the LHC and new projects

T. Pieloni for the  
LHC and HL-LHC Beam-Beam Teams



ÉCOLE POLYTECHNIQUE  
FÉDÉRALE DE LAUSANNE

# BB effects and luminosity

Pushing for luminosity means stronger beam-beam effects

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

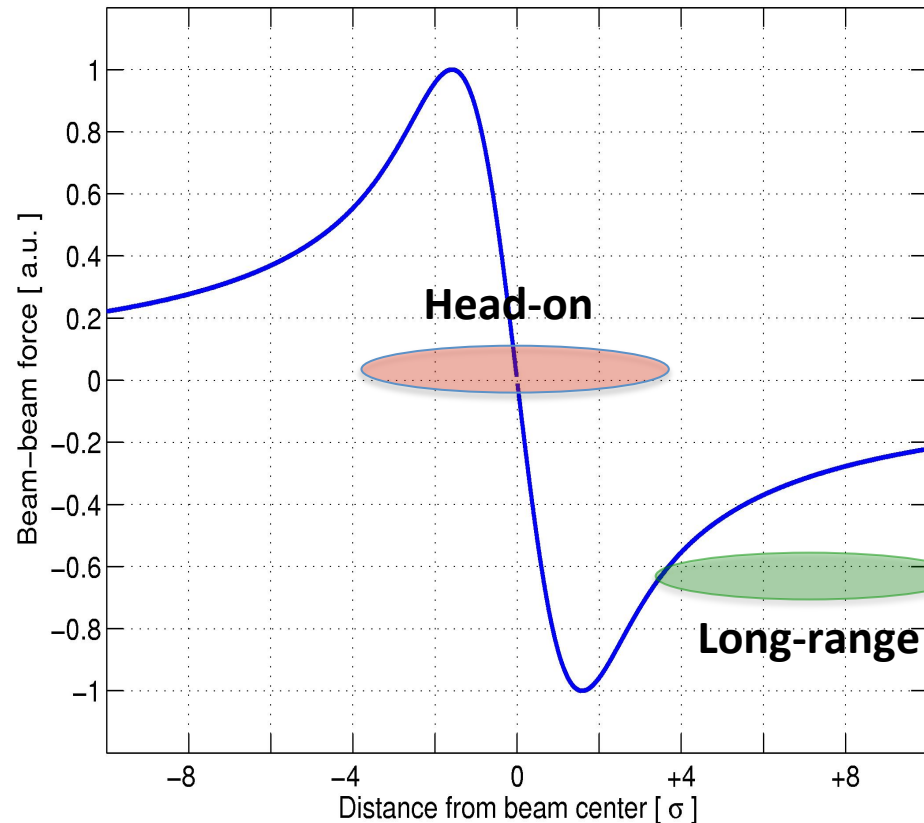
$$\xi_{x,y} = \frac{N r_0 \beta_{x,y}^*}{2\pi \gamma \sigma_{x,y} (\sigma_x + \sigma_y)}$$

Different Effects Head-on and Long-range...

Two main questions:

What happens to a single particle?  
What happens to the whole beam?

Beam-beam force



# Layout

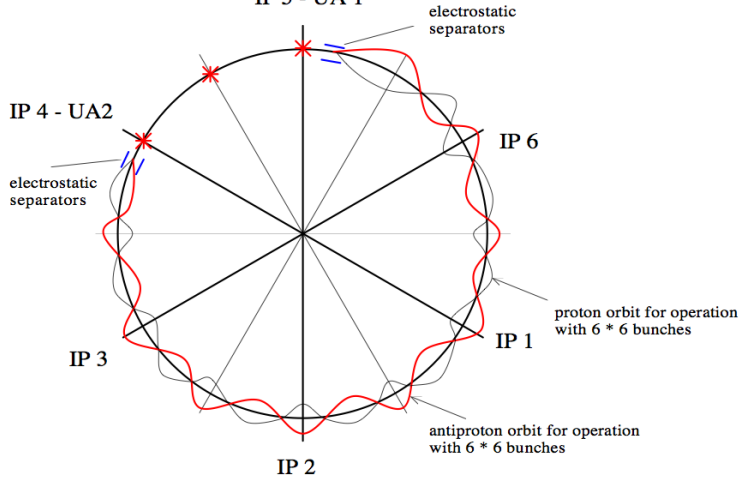
- Experience from other colliders (p-p, e-e, e-p)
- LHC BB experiences foreseen and un-foreseen
- Beam-beam studies for LHC after LS1
- HL-LHC beam-beam studies
- Beam-beam compensations (e-lens, wire compensation)
- Summary

# Experience and observations from hadron colliders

SPS collider: 6 bunches

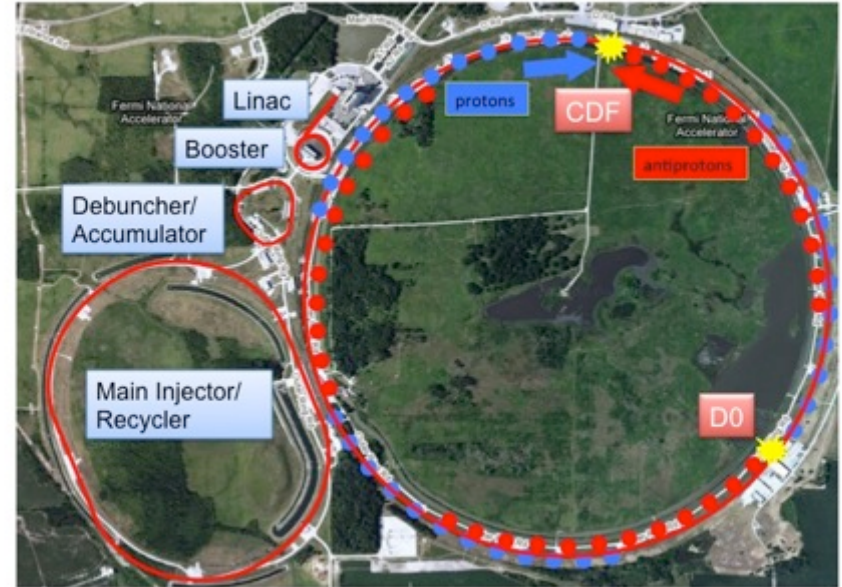
3 HO and 9 LR

IP 5 - UA 1



RHIC: 110 bunches

2 BBIs Head-on

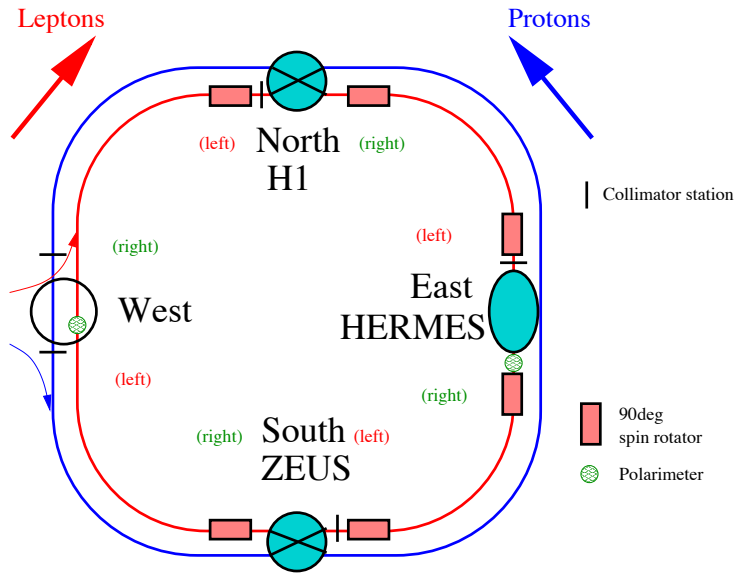


Tevatron: 36 bunches

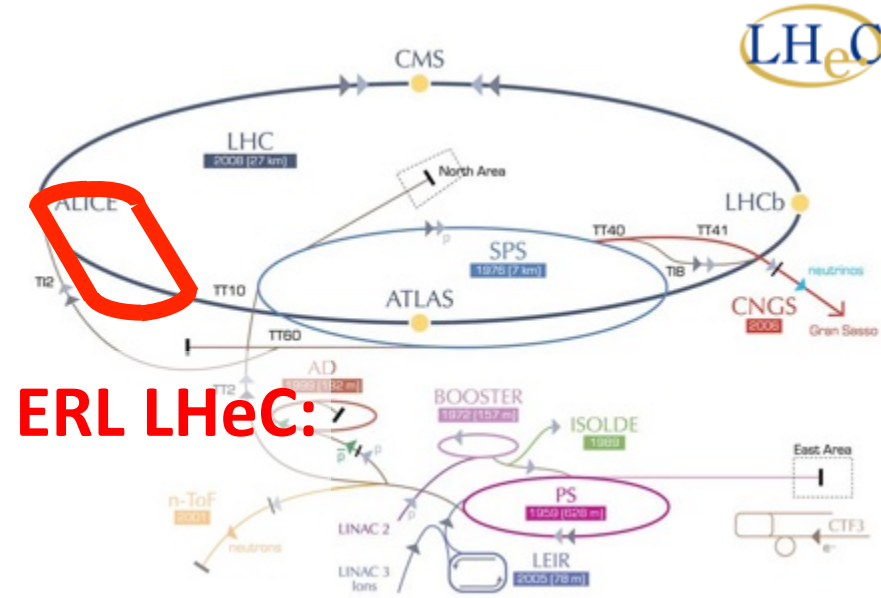
2 BBIs Head-on and 72 Long-range

- K. Cornelis, "Experience with beam-beam effects in the SPS collider"
- V. Shiltsev, "Beam-beam observations in the Tevatron"
- V. Shiltsev, "Experience with long range beam-beam effects in the Tevatron"
- Y. Luo, "Beam-beam observations in RHIC"

# Experience and observations from HERA e/p

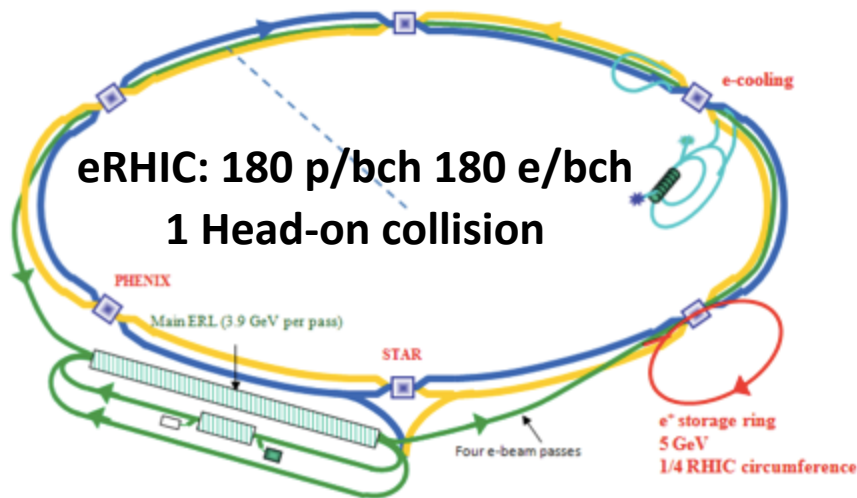


**HERA: 180 p/bch 182e/bch**  
**2 Head-on collisions**



**ERL LHeC:**

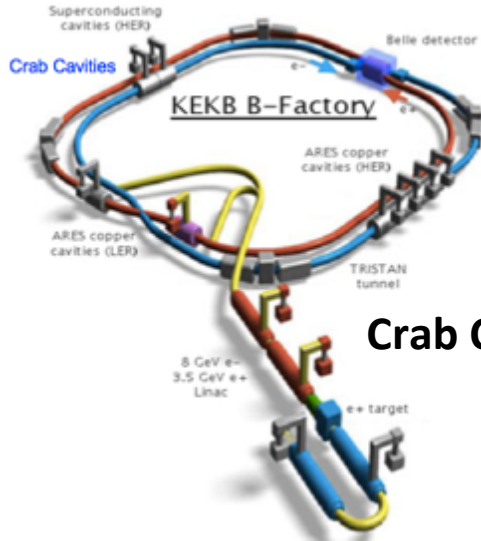
**LHeC: Nominal LHC with p-p collisions**  
**and 1 Head-on collision e-p**



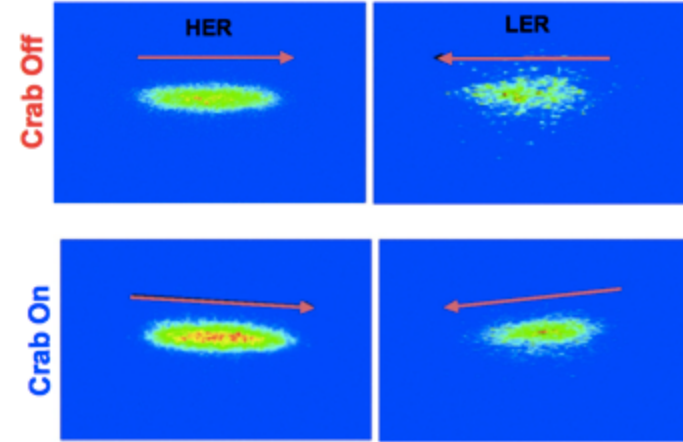
**eRHIC: 180 p/bch 180 e/bch**  
**1 Head-on collision**

- M. Vogt, "Beam-beam Effects in HERA"
- D. Schulte, "Beam-beam effects in the LHeC"
- Y. Hao, "Beam-beam study of the ERL based e-RHIC"

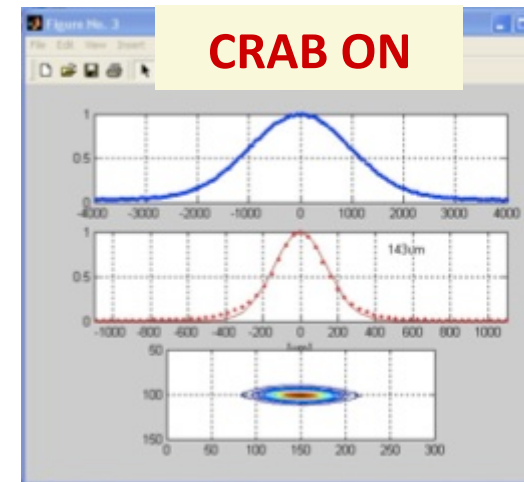
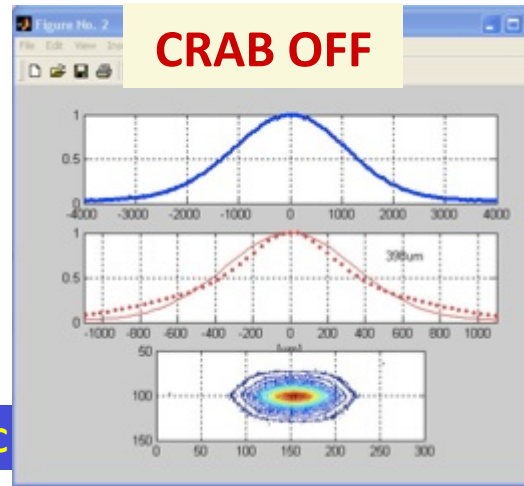
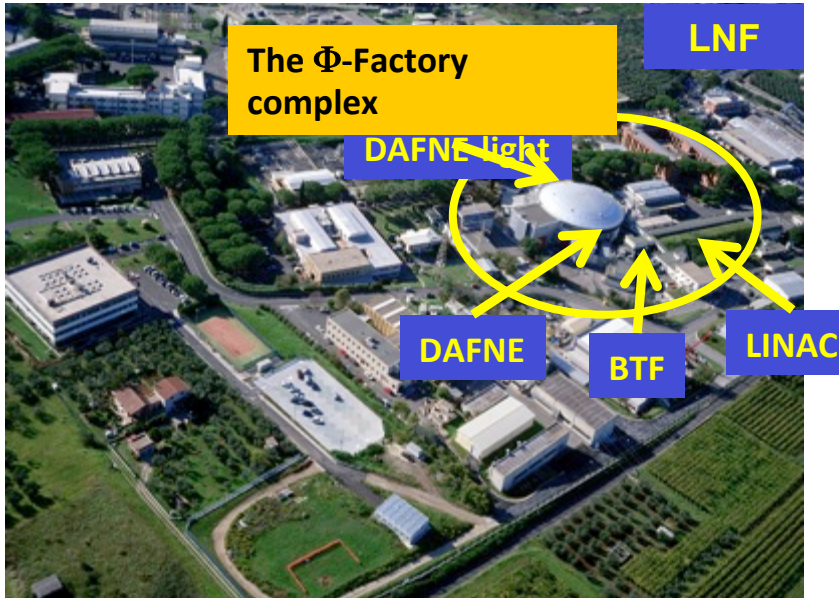
# Lepton colliders experiences relevant for LHC



Crab Cavity Experience from KEKB

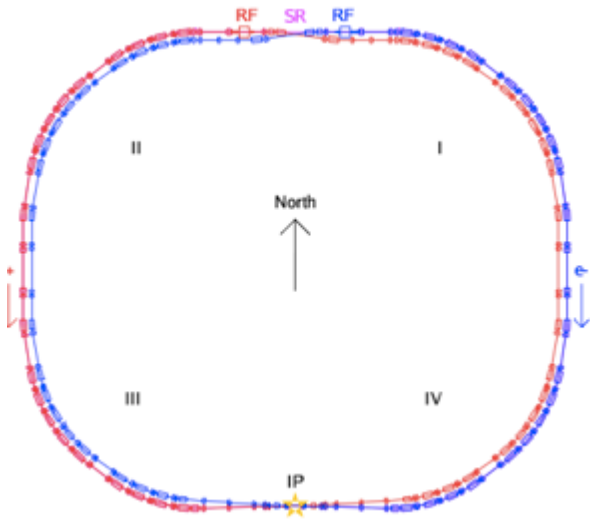


## LPA and crabbed waist

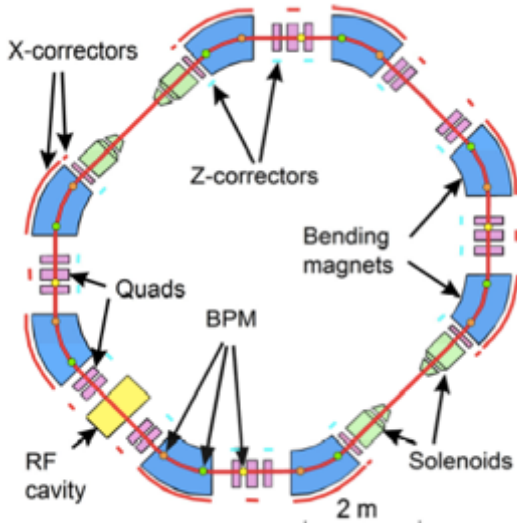
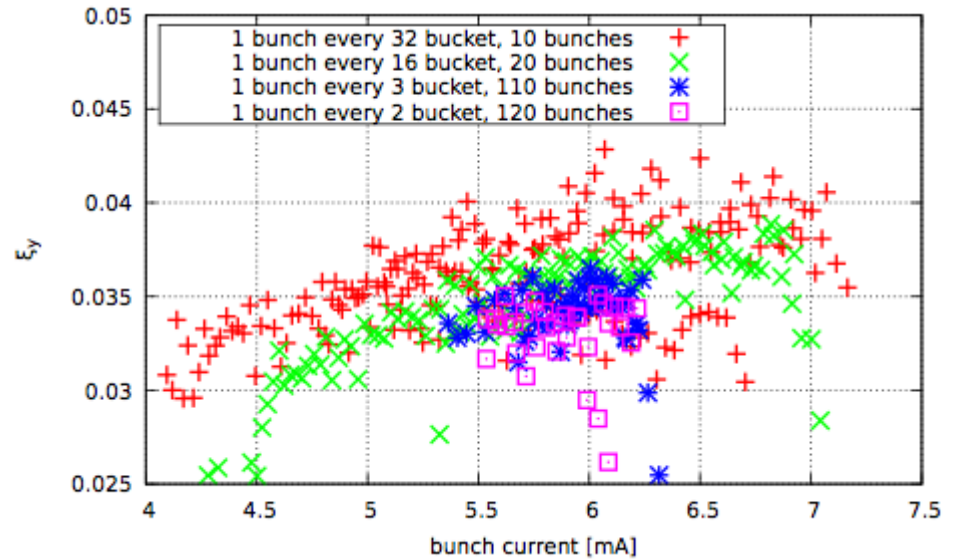


- Y. Kunakoshi, "Operational experience with crab cavities at KEK"
- M. Zobov, "Experience with Large Piwinski Angle and Crabbed Waist"

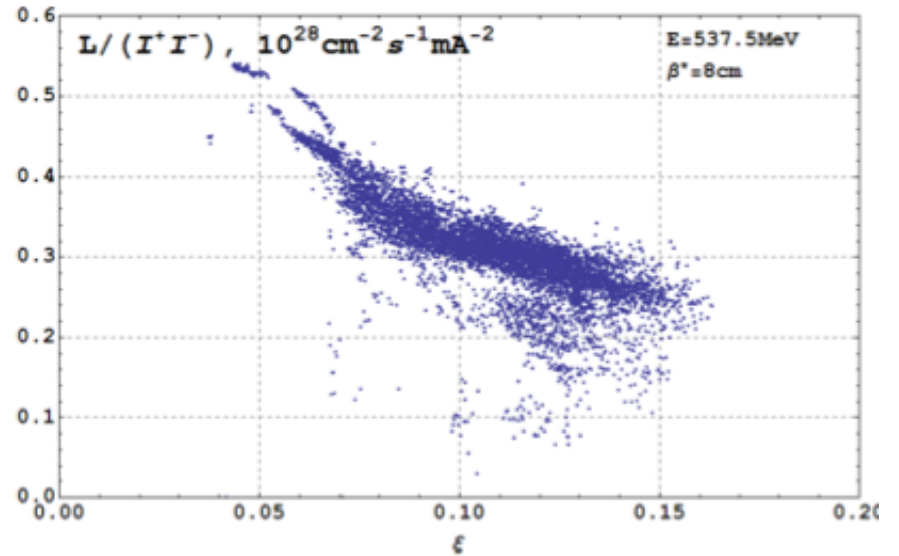
# Lepton colliders experiences



**BEPCII: 1 head-on collision  $e^+e^-$**   
**Max  $\xi_{bb} = 0.04$  few bunches**

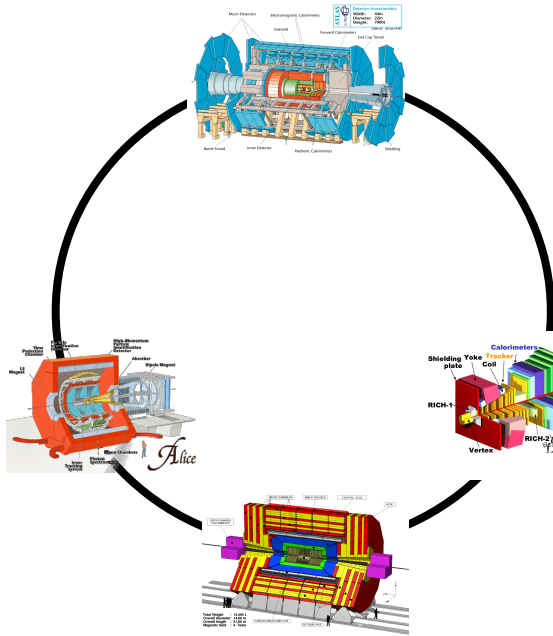


**VEPP2000: 2 head-on collision  $e^+e^-$**   
**Max  $\xi_{bb} = 0.13$**

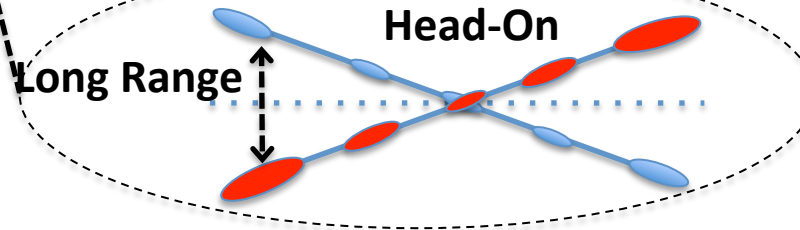


-Y. Zhang, " Beam-beam effects in BEPC-II"  
 -D. Schwartz, " Recent beam-beam effects at VEPP-2000 and VEPP-4 "

# LHC collider and BB effects



- pp collisions
- High number of bunches (2808/beam) in train structures
- Crossing angle operation
- Pronounced Pacman effects (LR 40-120)
- 4 Experiments (3/4 Head-on collisions)
- $\xi_{\text{HO}} = 0.0036$  per Interaction Point



72 bunches

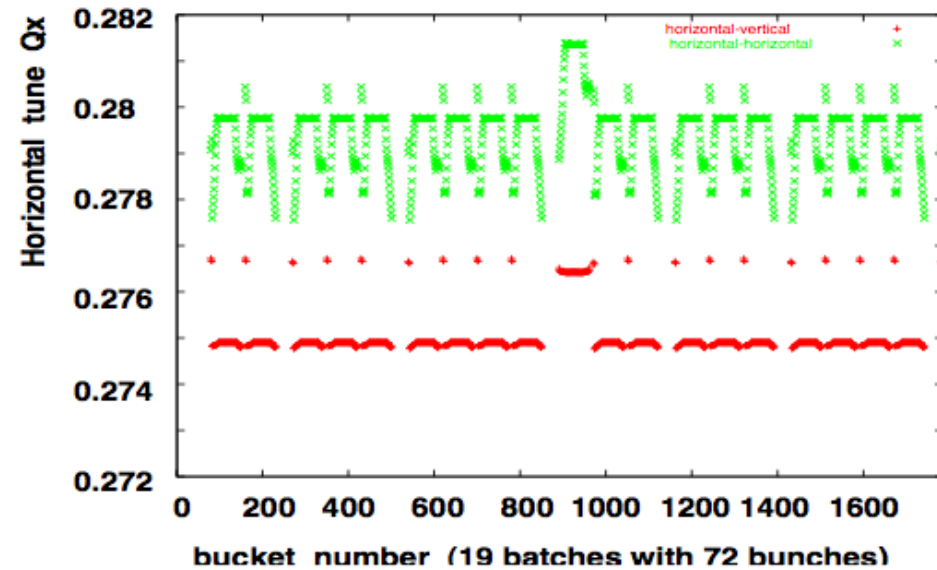
||||| ....

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

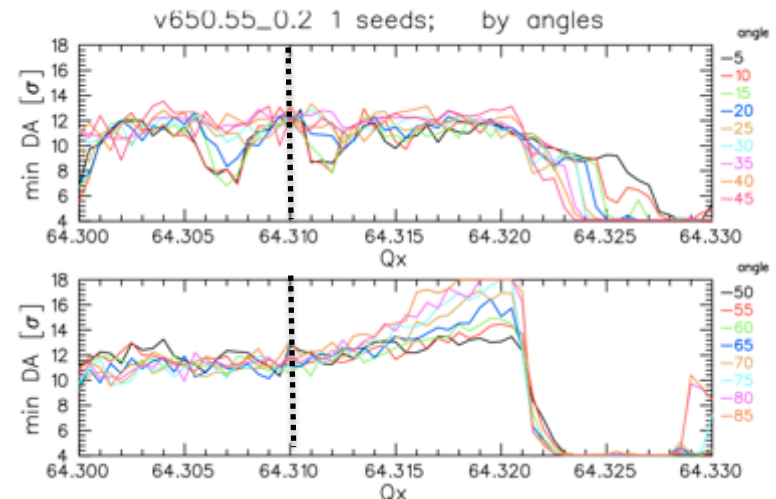


# Nominal LHC BB strategy I

- **ATLAS and CMS alternating crossing: passive compensation** of PACMAN effects worked well mitigating Q, Q' Long Range effects visible in lifetime
- **LHCb and ALICE Long-range should be kept in the shadow** (larger Long-Rang separations), no passive compensation possible
- **Working point (64.31, 59.32)** showed to host well the BB tune spreads for nominal from DA studies



IP 2 and IP8  $b^* = 11$  m

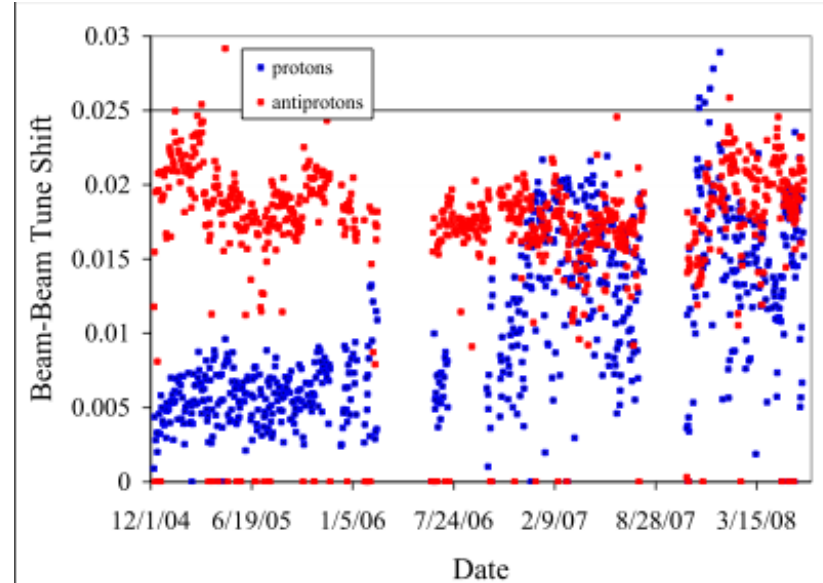


# Nominal LHC BB strategy II

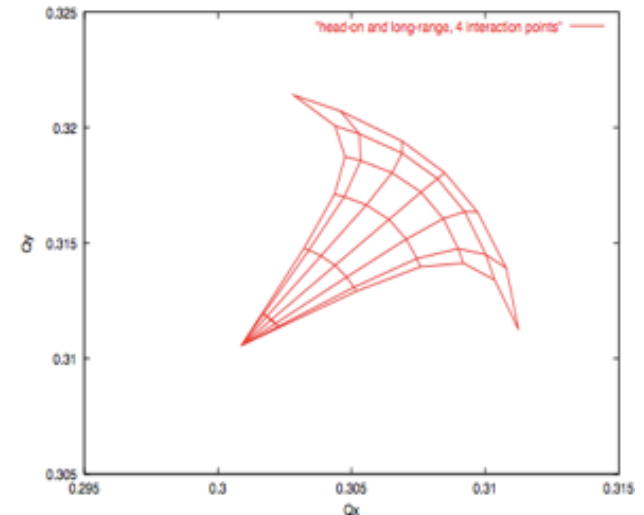
- **Consolidated**  $\xi_{bb}$  based on Tevatron and SppS experience maximum 0.015 total tune shift, 0.01 allocated to beam-beam effects head-on and long-range

This gives  $\xi_{HO} = \mathbf{0.0033/IP}$  (with bunch intensities  $1.15e11$  and transverse emittances  $3.75 \mu\text{m}$ )

- **Nominal LHC 25 ns symmetric filling schemes** guarantees all bunches Landau damping from at least 1 HO collision
- Bunch to bunch **fluctuation in emittances** should be kept within **10%**



Tevatron beam-beam total tune shift

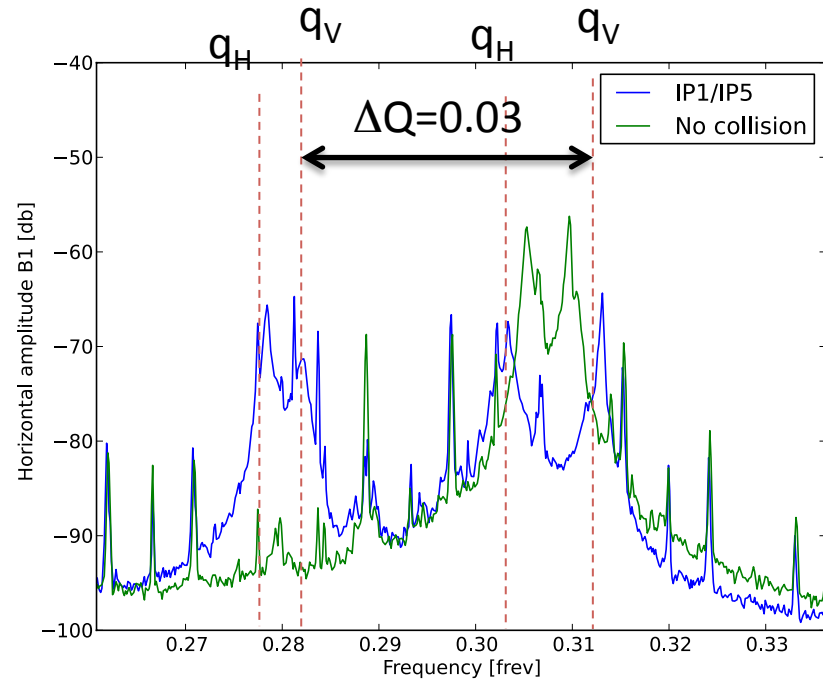
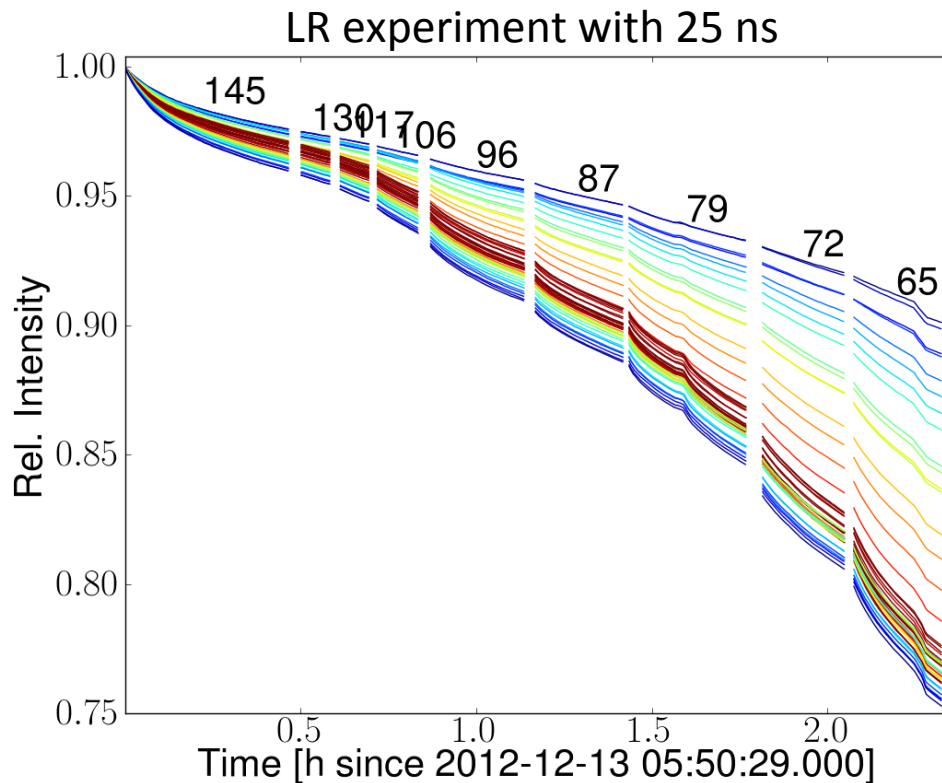


LHC nominal bunch footprint HO+LR beam-beam

**LHC has been anything but Nominal....:O)**

# LHC foreseen and un-foreseen:

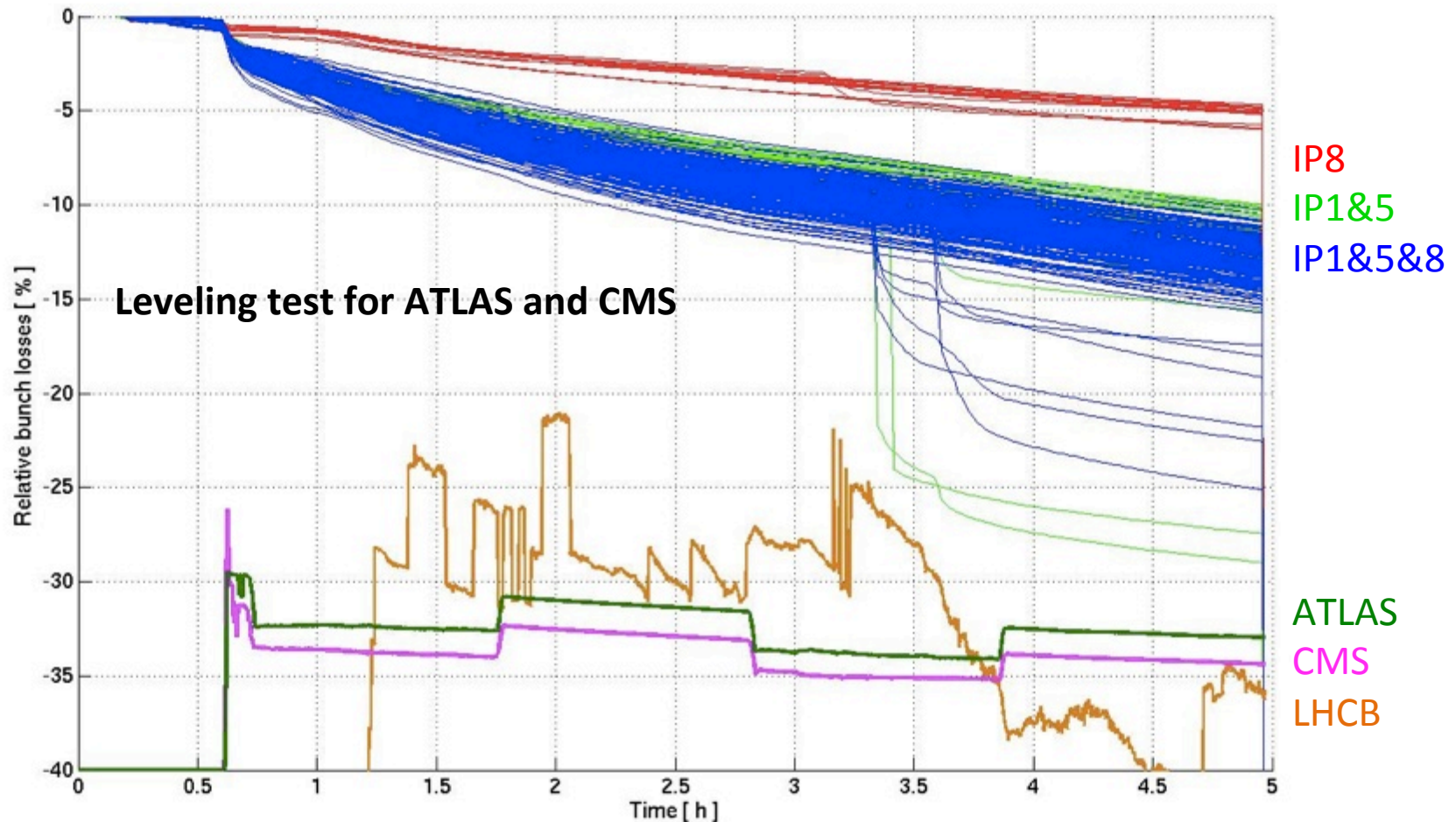
- Long-range effects follows DA studies
- Coherent beam-beam modes observed in MDs
- Long-range effects for 50ns, 25 ns: scaling laws to predict onset of losses due to DA



Coherent beam-beam modes during high pile-up MD 2011

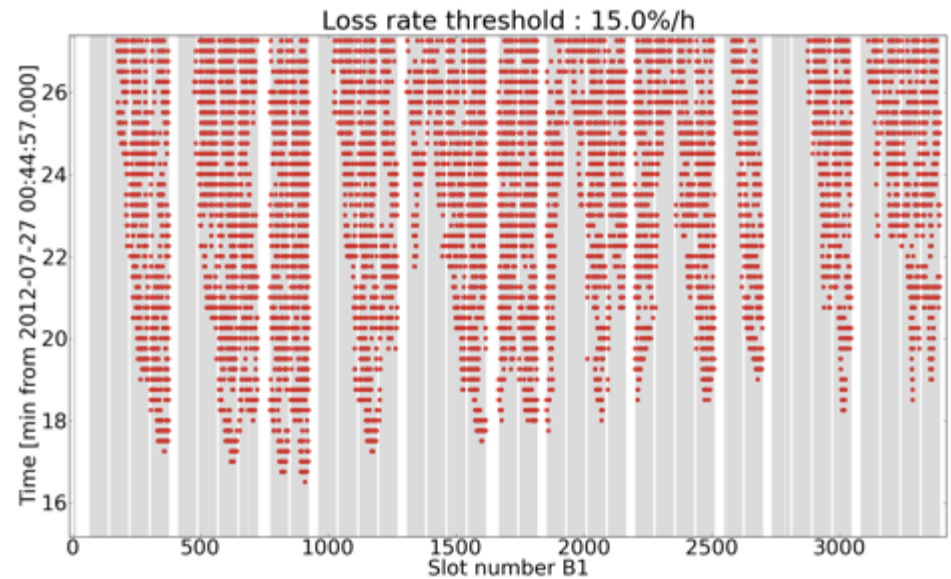
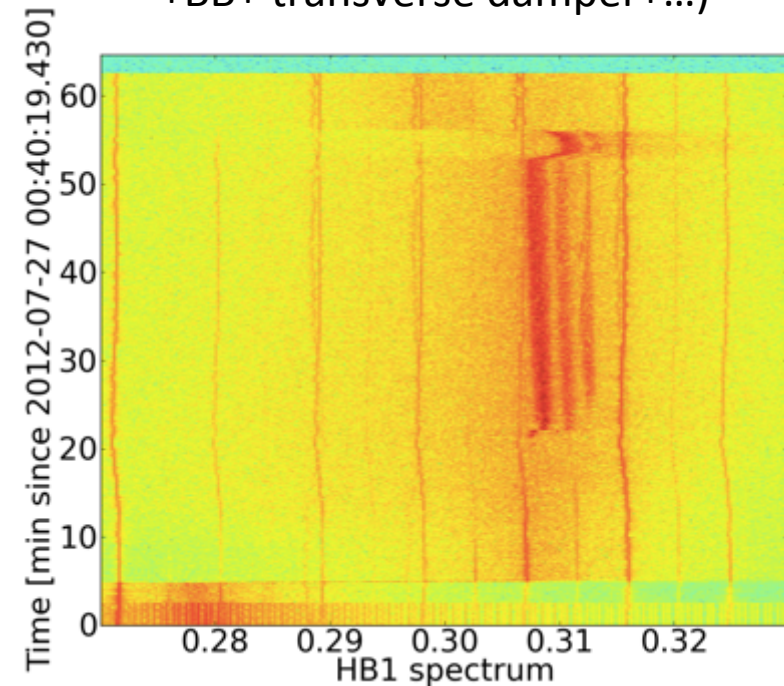
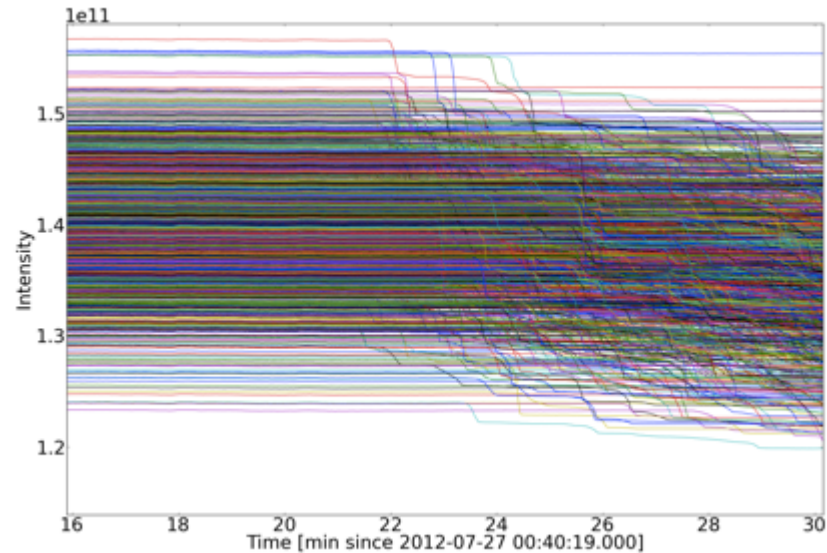
# LHC foreseen and un-foreseen:

- Large  $\xi = 0.017/\text{IP}$  ,  $\xi = 0.03$  for 2 IPs
- Leveling with transverse offset (50 ns requires it!)



# LHC foreseen and un-foreseen:

- 2012 Instabilities, beam-beam is an important ingredient maybe not the driving one (impedance?)
  - Lack of Landau damping IP8 bunches
  - Stability at different stages of beam process
  - Need for multi-effect models (Impedance +BB+ transverse damper+...)



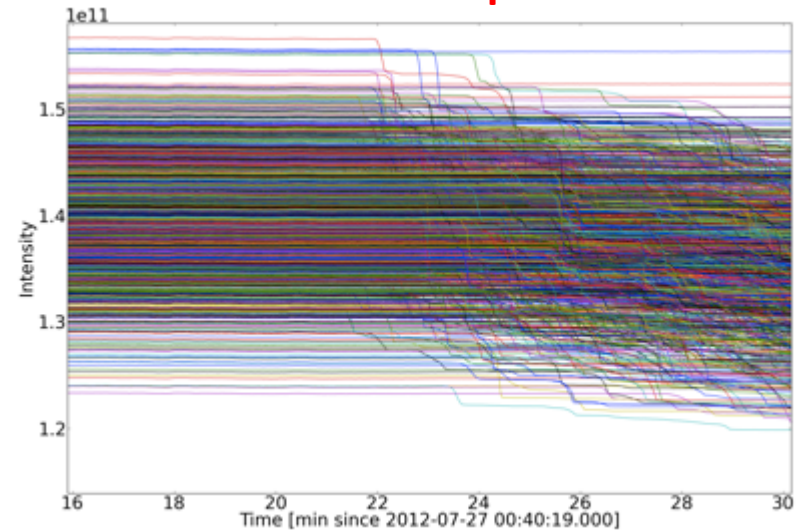
# LHC Studies for after LS1

2012 has been very exciting year

Good surprises



Bad surprises



What have we learned?

- Study beam-beam effects as in normal operation
- Long-range effects should be mitigated where possible
- Collide for stability: collide and squeeze and possibly level luminosity

What we should address?

- Development of simulation tools for multiple effects, to reproduce LHC observations, and flexible for different operational scenarios
- Need observables to benchmark models
- Need to define/study possible operational scenarios for cases (25 ns, 50 ns, emittances)
- Leveling strategies and BB effects, need careful thinking 4 experiments

# Studies for after LS1

## What we should address?

Development of simulation tools for multiple effects, to reproduce LHC observations, and flexible for different operational scenarios

Need observables to benchmark models

Need to define/study possible operational scenarios (25 ns, 50 ns, emittances)

Leveling strategies and BB effects, needs careful thinking 4 experiments

### Simulation and Theory I - II

- M. Vogt, "Analytical and numerical tools for beam-beam studies"
- S. Paret&J. Qiang, "Poisson solvers for self-consistent multi-particle simulations"
- A. Valishev,"Modelling beam-beam in the Tevatron"
- A. Burov, "Beam-beam, impedance and damper"
- X. Buffat, "Stability diagrams of colliding beams"
- C. Montag,"Beam-beam effects in space charge dominated ion beam"

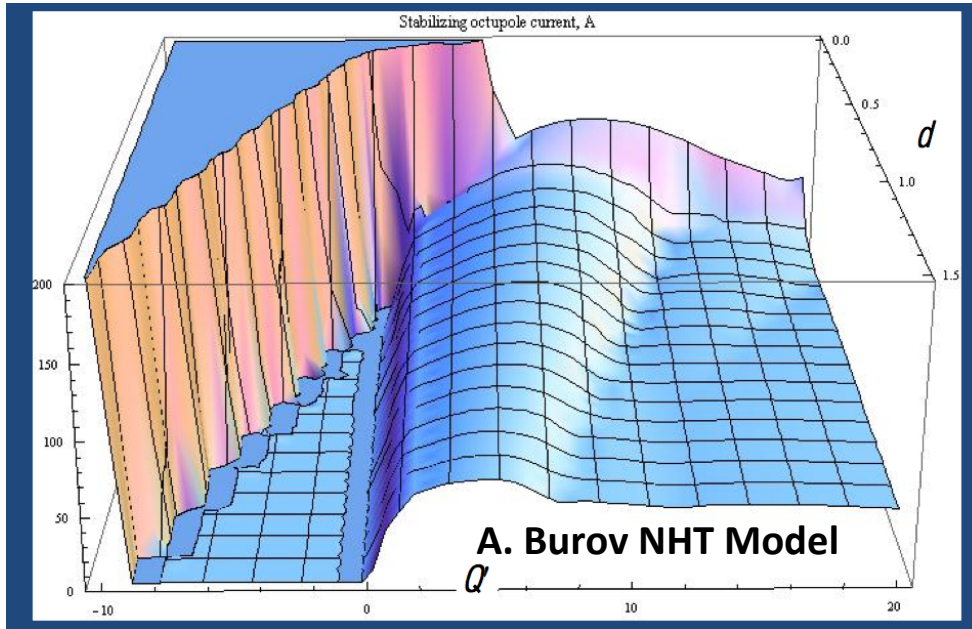
### Strong-Strong and coherent beam-beam effects

- S. White, "Beam-beam and impedance"
- X. Buffat, "Coherent beam-beam modes in the LHC"
- P. A. Goergen,"BTF measurements with beam-beam interactions"

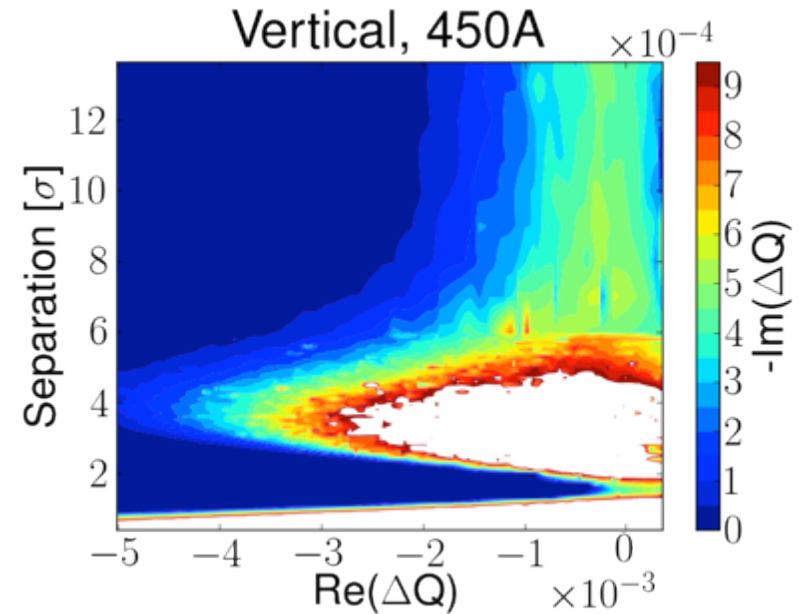
### Operatonal aspects

- R. Giachino, "Diagnostics needs for beam-beam studies and optimization"
- W. Kozanecki, "Luminosity measurements and optimization – consequences for bb effects"

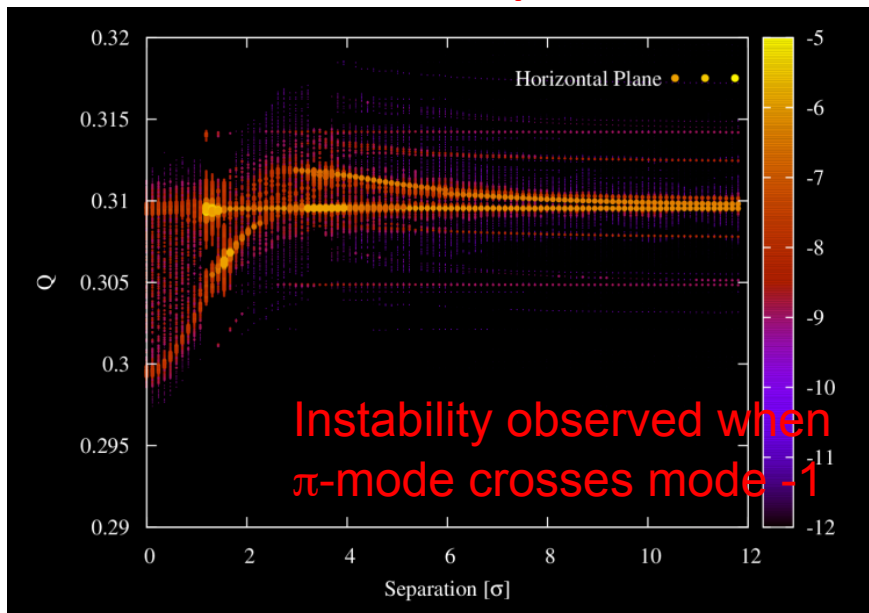
# Studies for after LS1



## Stability diagrams from tracking



## Beam-beam and Impedance



How does beam-beam changes/  
plays with other effects?

Many new models including  
beam-beam, impedance,  
transverse damper for multi  
bunch beams have been  
developed during 2012



# Studies for after LS1

## What we should address?

Development of simulation tools for multiple effects, to reproduce LHC observations

Need for observables to benchmark models

**Need to define/study possible operational scenarios for cases (25 ns, 50 ns, parameters)**

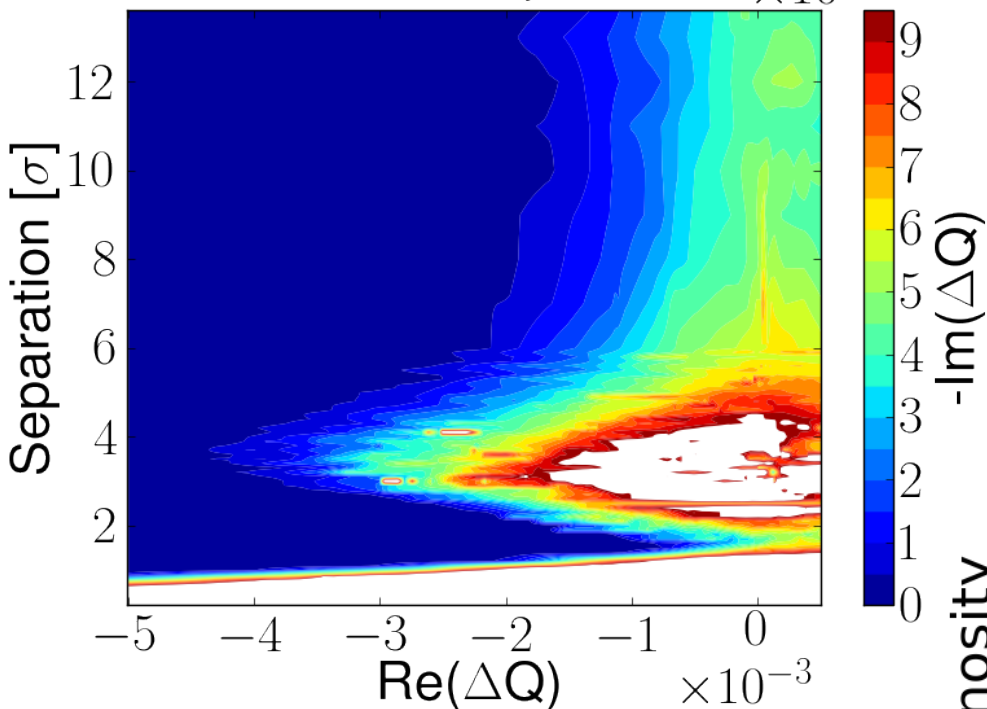
**Leveling strategies and BB effects, needs careful thinking 4 experiments all independent**

### **Operational aspects of beam-beam effects I - II**

- R. Jacobsson, "Needs and requirements from the physics experiments"
- T. Pieloni & B. Muratori, "Luminosity leveling techniques: implications for beam-beam interactions"
- D. Jacquet, "Implementation and experience with luminosity leveling with offset beams"
- R. Giachino, "Diagnostics needs for beam-beam studies and optimization"
- W. Kozanecki, "Luminosity measurements and optimization-consequences for beam-beam effects"
- X. Buffat, "Consequences of missing collisions – beam stability and Landau damping"

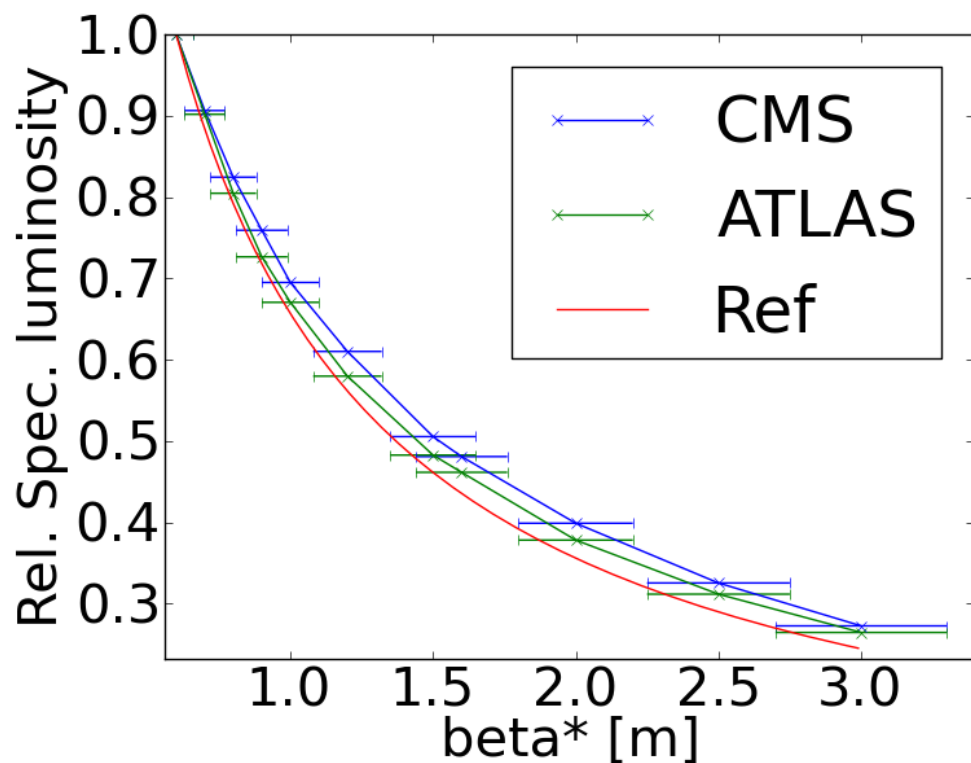
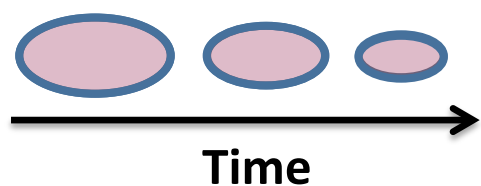
# Studies for after LS1

Horizontal, 450A  $\times 10^{-4}$



**Instabilities cured by:  
Collide&squeeze**

**High pile-up reduced by  
larger  $\beta^*$  then squeeze**



# HL-LHC Project: main parameters and BB view

## ‘Stretched’ Baseline Parameters following 2<sup>nd</sup> HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	<b>2.2E+11</b>	<b>3.5E+11</b>
$n_b$	2808	2808	1404
beam current [A]	0.58	<b>1.12</b>	<b>0.89</b>
x-ing angle [ $\mu$ rad]	300	590	590
beam separation [ $\sigma$ ]	9.9	12.5	11.4
$\beta^*$ [m]	0.55	<b>0.15</b>	<b>0.15</b>
$\varepsilon_n$ [ $\mu$ m]	3.75	2.5	3.0
$\varepsilon_L$ [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	<b>18.5</b>	<b>17.2</b>
IBS longitudinal [h]	61 -> 60	<b>20.4</b>	<b>16.1</b>
Piwinski parameter	0.68	<b>3.12</b>	<b>2.85</b>
geom. reduction*	0.83	<b>0.305</b>	<b>0.331</b>
beam-beam / IP	3.10E-03	<b>3.3E-03</b>	<b>4.7E-03</b>
Peak Luminosity	1 $10^{34}$	<b>7.4 <math>10^{34}</math></b>	<b>8.5 <math>10^{34}</math></b>
Virtual Luminosity	1.2 $10^{34}$	<b>24 <math>10^{34}</math></b>	<b>26 <math>10^{34}</math></b>
Events/crossing	19 /28	<b>207/140</b>	<b>476/140</b>

Large  $\xi_{bb}$

DA studies with Working Point optimization & Orbit effects

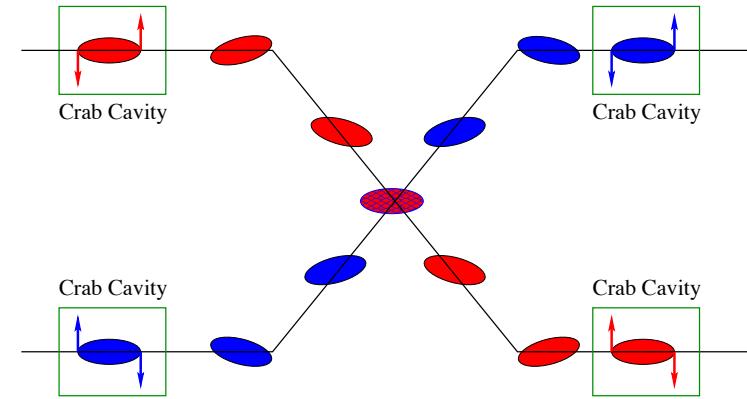
Large crossing angle requires compensation of geometrical factor by CRAB-CAVITIES

High pile-up needs robust strategy for leveling

# HL-LHC

Geometric reduction factor of 70%

$$L = L_0 \frac{1}{\sqrt{1 + \frac{\sigma_{s1}^2 + \sigma_{s2}^2}{\sigma_{u1}^2 + \sigma_{u2}^2} \left(\tan \frac{\phi_u}{2}\right)^2}}$$



- Crab cavities noise on colliding beams to define tolerances
- Operational Experience of crab cavities with proton beams
- Impact of crab cavities and crab noise on DA
- New working points (1/2 integer tunes)? New ideas?

## Studies for Future Projects

- A. Valishev, "Beam-beam studies for the HL-LHC"
- S. Paret, "Simulation of beam-beam induced emittance growth in the HL-LHC with crab cavities"
- K. Ohmi, "Beam-beam predictions for SuperKEKB and Large Crossing Angles"
- A. Burov, "Circular Modes"

## Single Particle effects

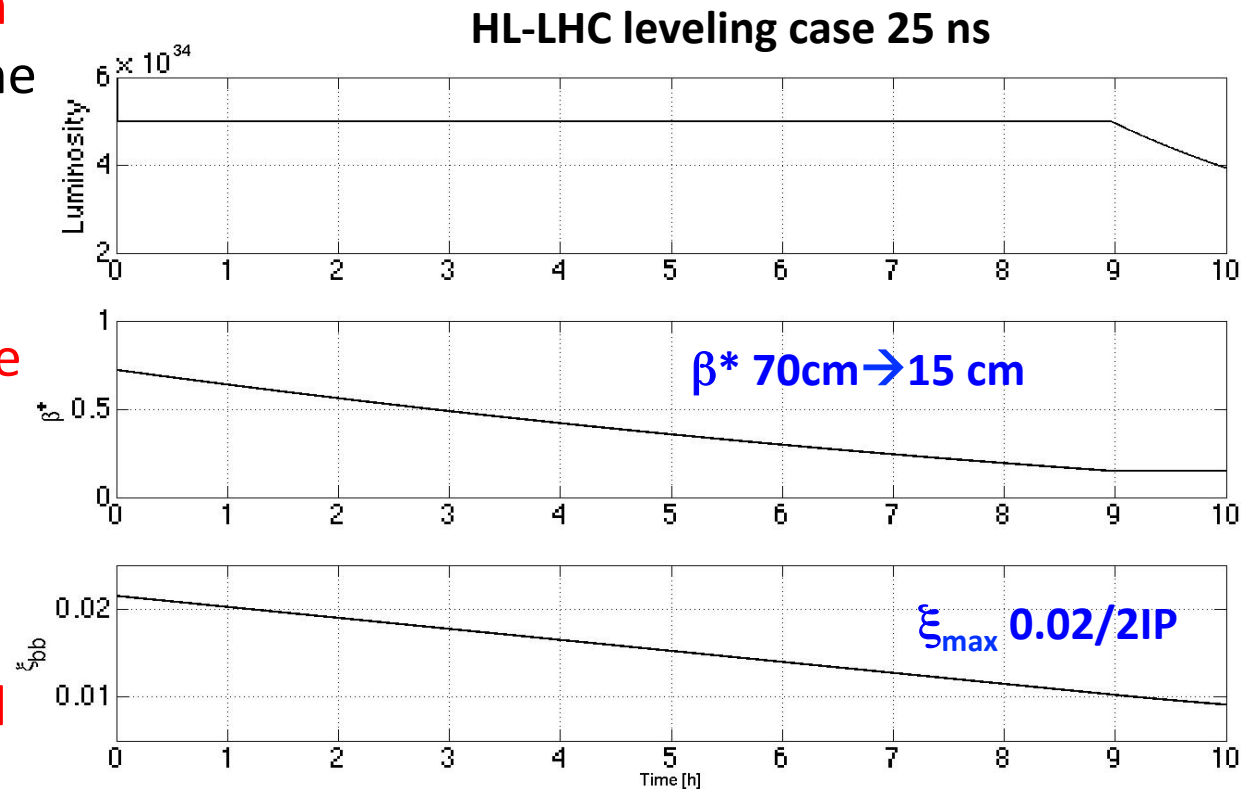
- K. Ohmi, "Beam-beam effects under the influence of external noise"
- G. Stancari, "Measurements of the effect of collisions on transverse beam halo diffusion in the Tevatron and in the LHC"

## Experience in Lepton Colliders

- Y. Kunakoshi, "Operational experience with crab cavities at KEK"

# HL-LHC leveling and $\xi$

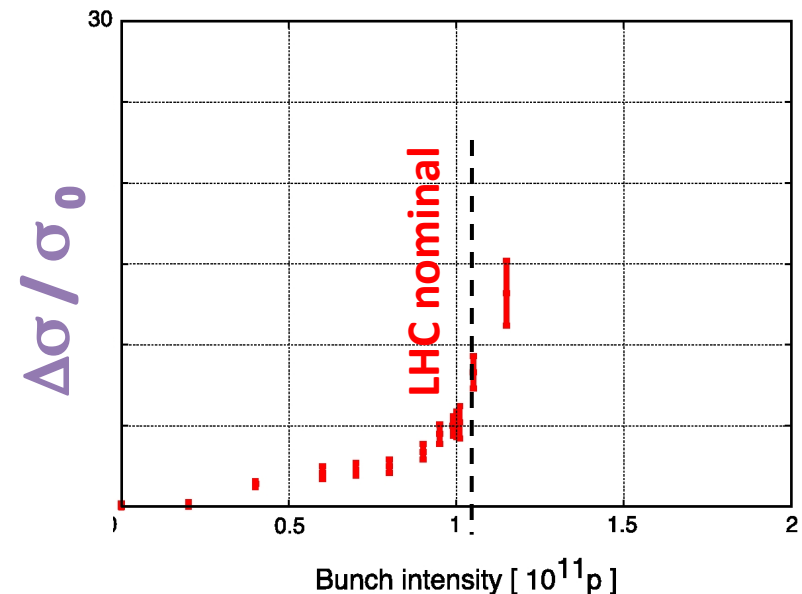
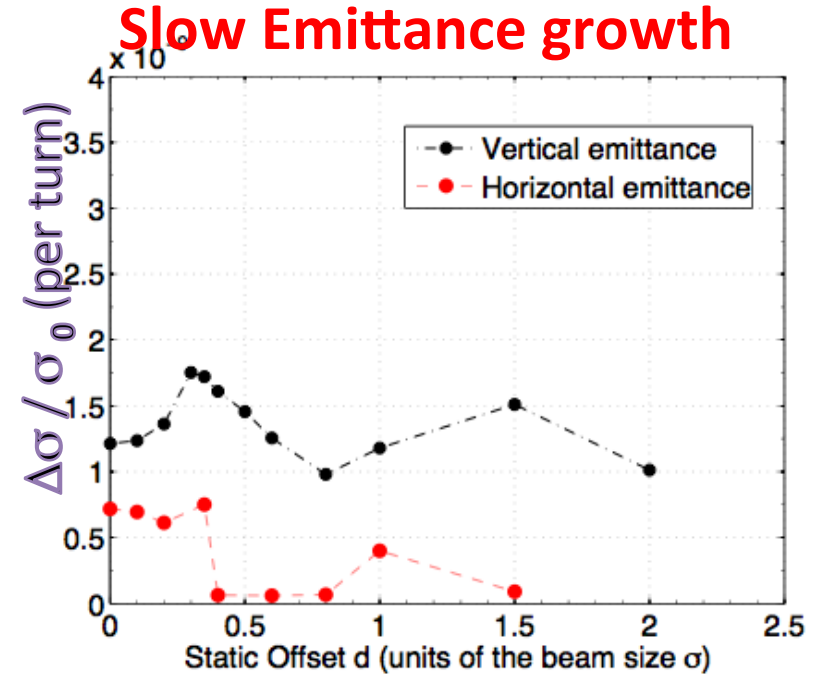
- Leveling **desiderata** from **the experiments** to define strategy
- Crab crossing compensation gives **large  $\xi$**  (specially 50 ns), will **noise of cavities deteriorate it?**
- **$\beta^*$  Leveling fundamental for stability.** Need operational experience in the LHC!



- R. Jacobson, "Needs and requirements from the physics experiments"
- T. Pieloni & B. Muratori, "Luminosity leveling techniques: implications for beam-beam interactions"

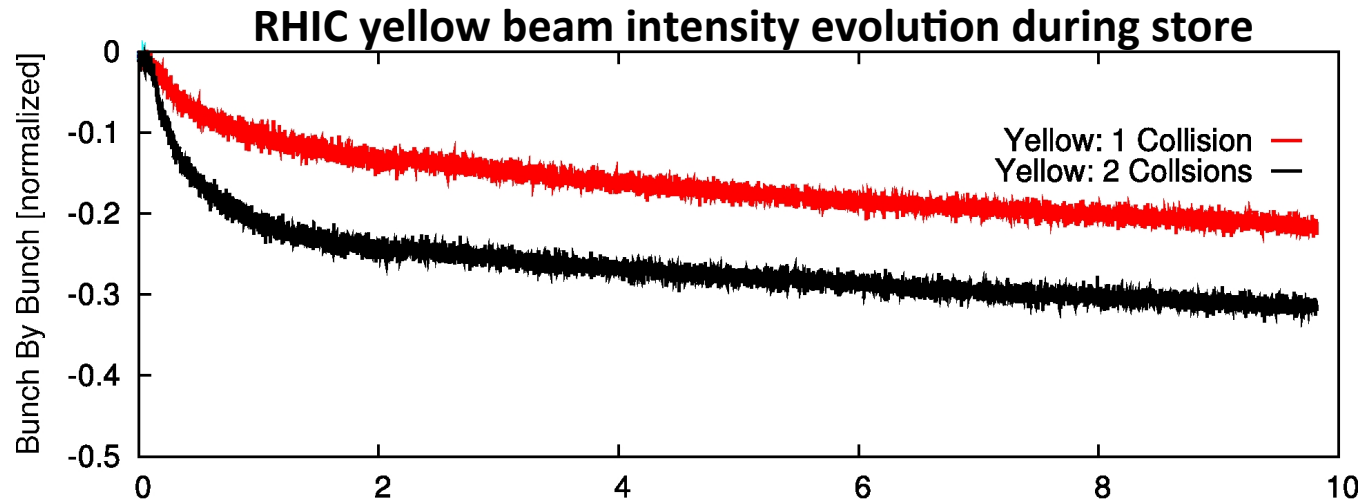
# HL-LHC transverse offsets and emittance growth

- Leveling with transverse offset still option for HL-LHC
- Long range interactions will give orbit effects at the IPs. How large the effect?
- Emittance growth is induced by small offsets at collision and has intensity threshold! Is HL-LHC safe?
- 2012 LHC test not conclusive



# Beam-beam compensation

Head-on compensation by use of an electron beam



- Can head-on be partially compensated by an electron beam (RHIC)?
- What can we learn from Tevatron experience?

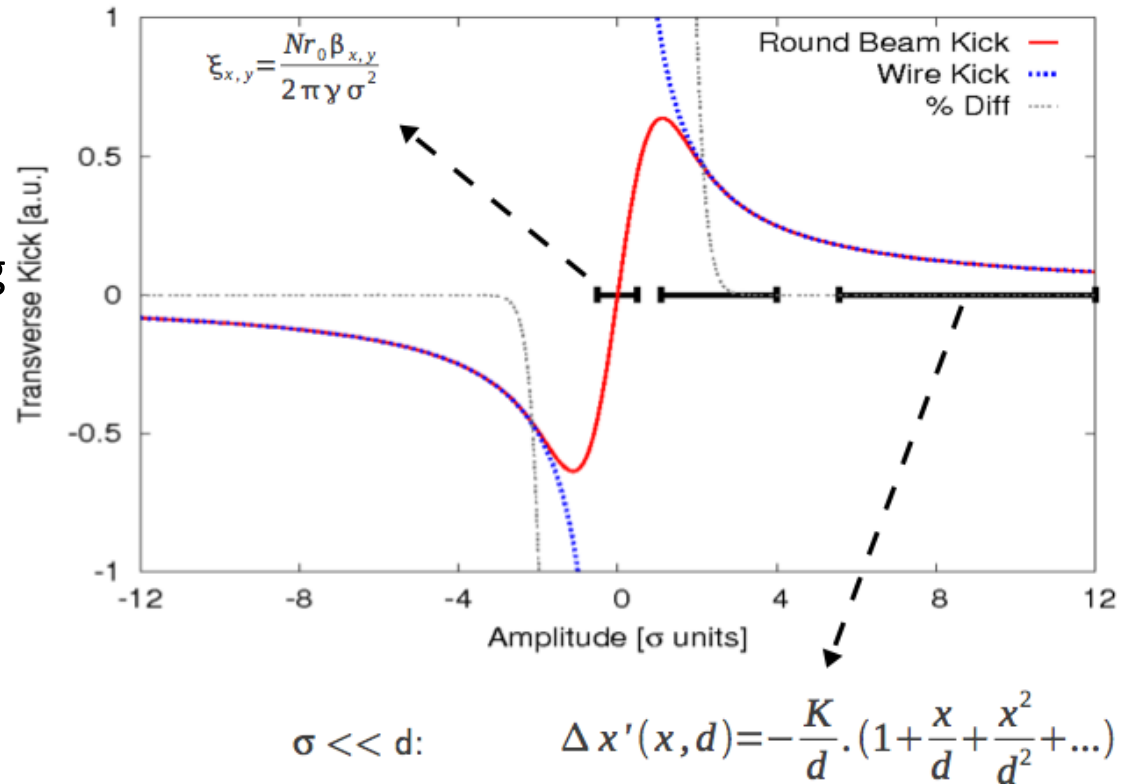
## Studies for Future Projects

- W. Fischer, "Status of head-on compensation in RHIC"
- G. Stancari, "Beam-beam compensation studies in the Tevatron"
- Y. Luo, "Six-dimensional weak-strong simulations of head-on compensation in RHIC"
- S. White, "Coherent beam-beam effects in experiments and implications for head-on compensation"

# Long range Beam-beam compensation

Long-range compensation by use of a wire

- Can we **reduce crossing angle for HL-LHC** by partially compensating long-range effects?
- Which are the **difficulties of a beam test**?
- What is **operational experience from RHIC**?

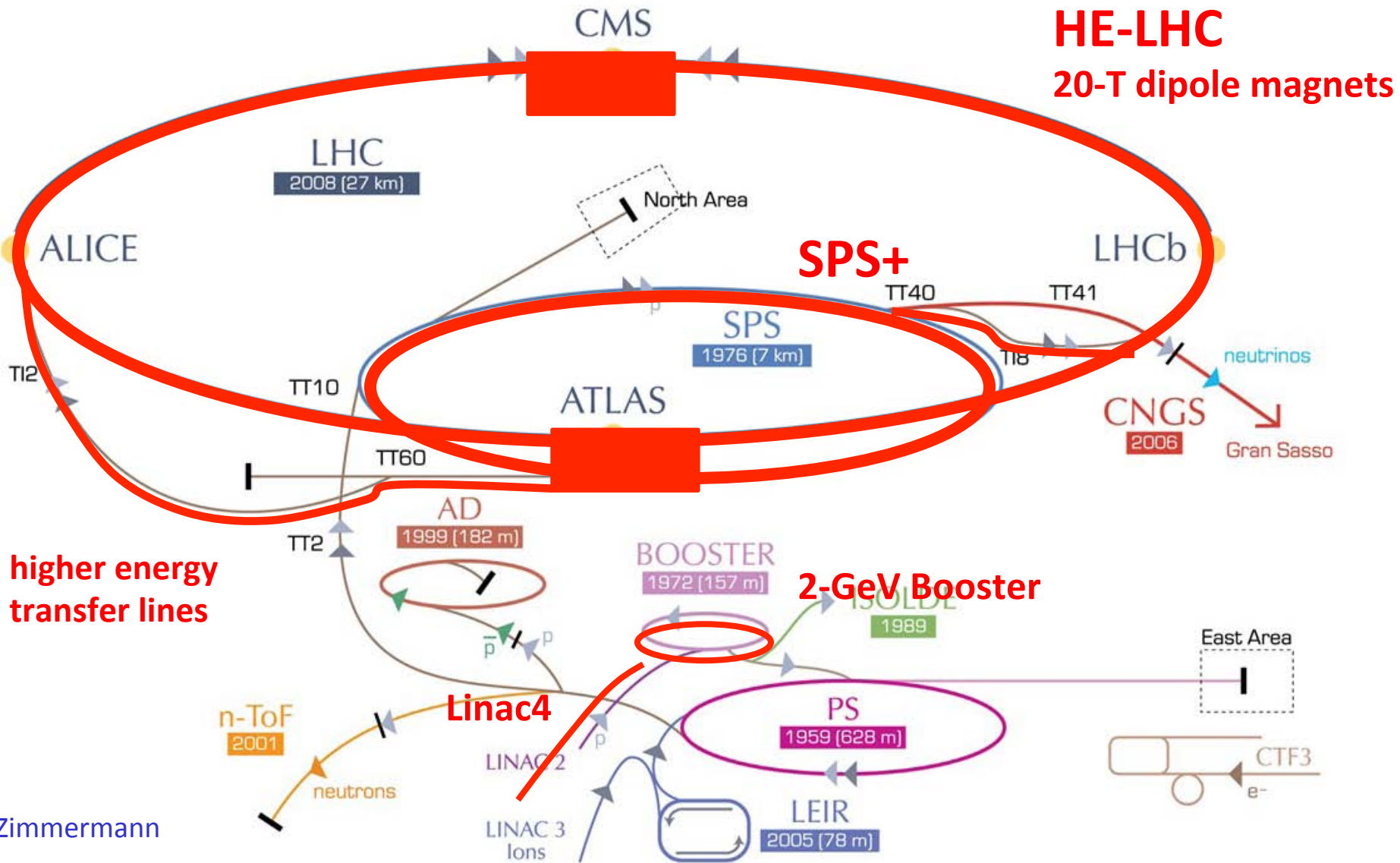


## Studies for Future Projects

- R. Calaga, “Long-range experiments in RHIC”
- T. L. Rijoff, “Simulation of long range compensation in the LHC with a wire”
- F. Zimmermann, “10 years of wire excitation experiments in the CERN SPS”



# ...and in the future HE-LHC?....



F. Zimmermann

...no talks at this workshop hopefully at the next BB workshop...!

# Summary:

- The LHC Beam-beam strategy has not yet been tested, **we are not at nominal**
- 2011/2012 experience has shown **foreseen and un-foreseen beam-beam effects** (leveling needs, large  $\xi_{bb}$ , instabilities, Long-range scaling laws)
- **LHC after LS1** needs new scenarios and beam-beam studies to prepare for:
  - Cure the 2012 instabilities by **collide&squeeze**
  - **Leveling strategies** among the experiments desiderata ( $b^*$ , offset, how?, when?)
  - **Study multi effects in the LHC** to reproduce observables (BB, impedance, transverse damper)
  - Need to push for bunch by bunch and special diagnostics (BTF?)
- **HL-LHC** opens new exciting issues:
  - Full and complete study of general **noise on colliding beams**, need experimental studies in LHC
  - **DA study** for optimizing working point and parameters with and without crab cavities
  - Study **effect of crab cavities noise** on colliding beams
  - **Leveling strategy** fundamental
  - Effect of small offsets on emittance growth studies
- **HE-LHC**...no talks at this workshop maybe at the next one....other projects?

Thank you !