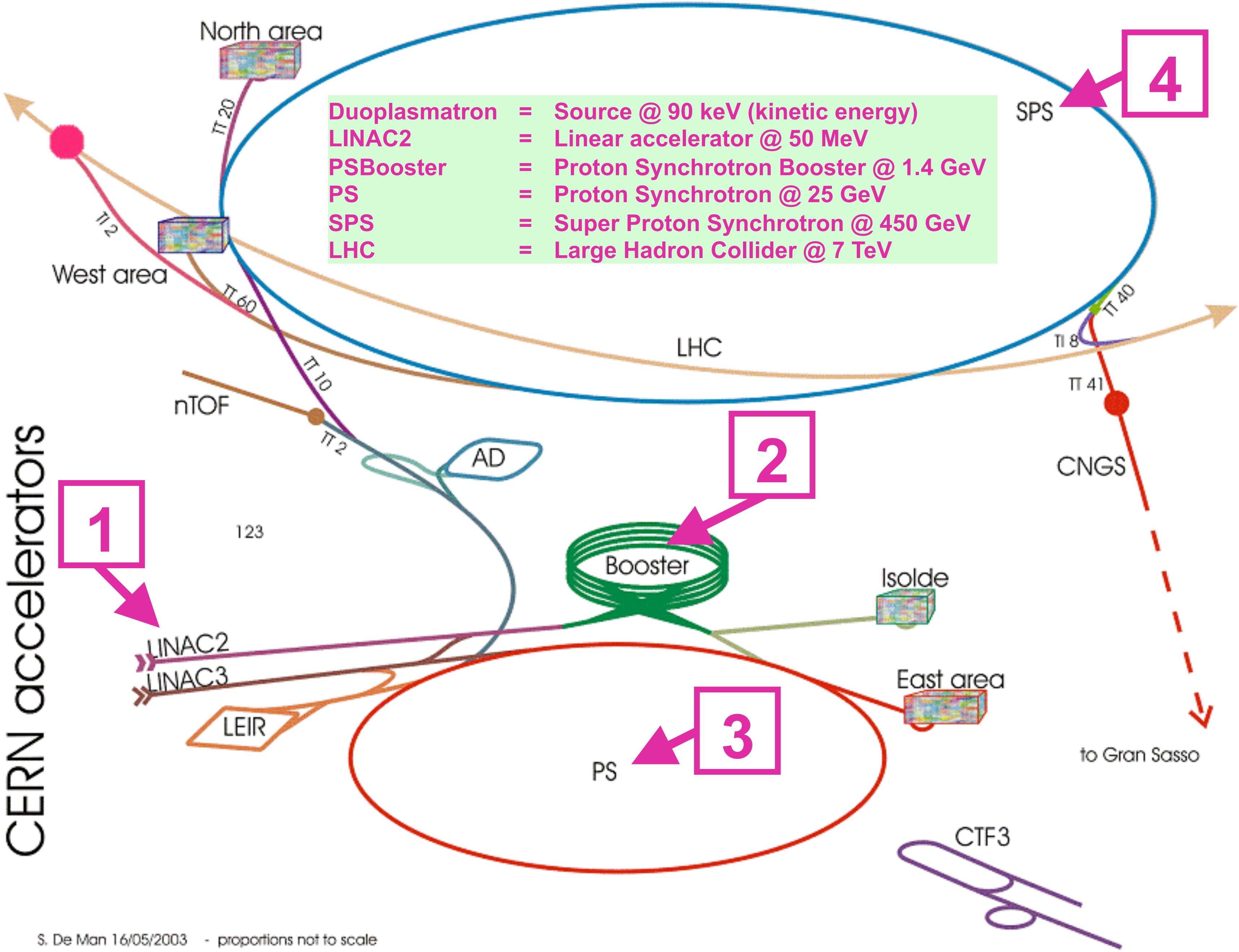
COLLECTIVE EFFECTS IN THE LHC AND ITS INJECTOR COMPLEX

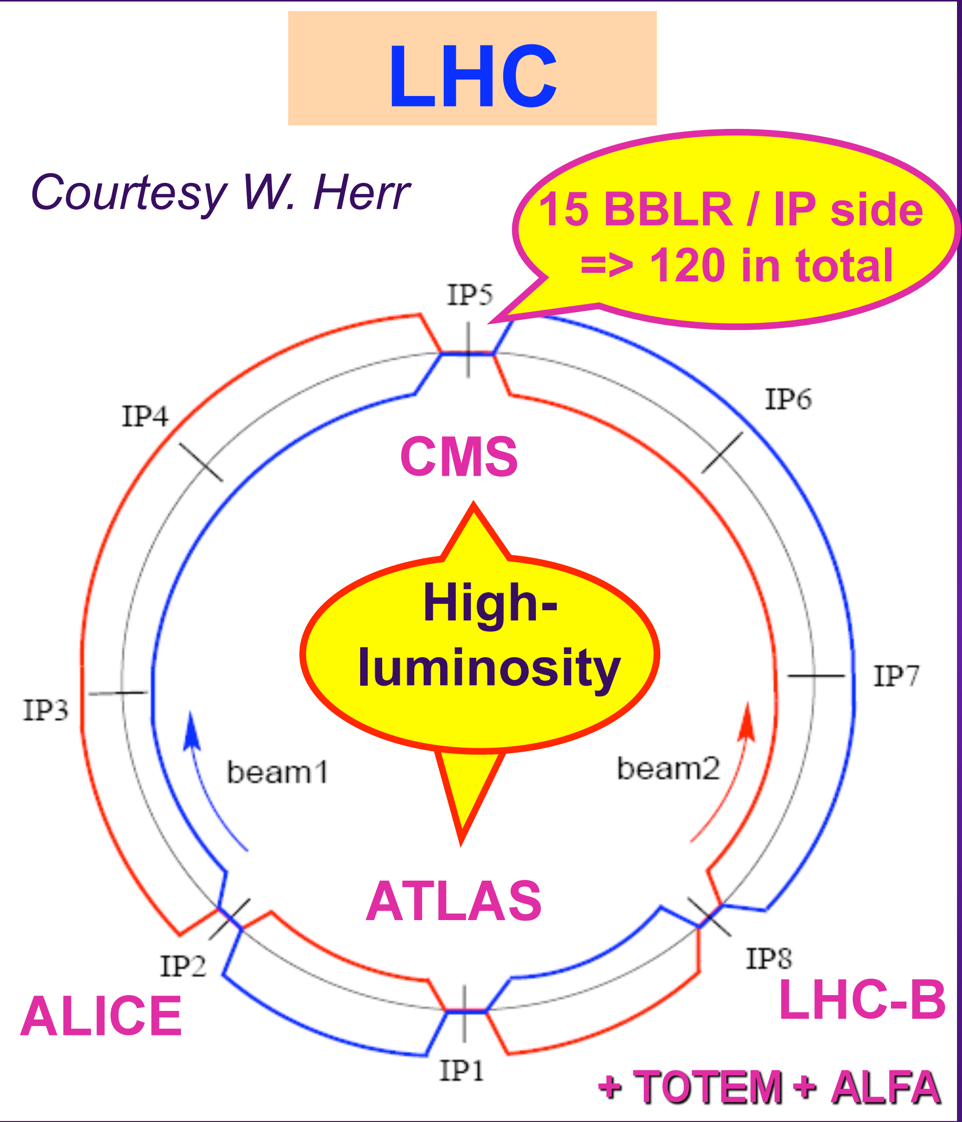
Elias Métral (Invited talk, THYB03, 25 + 5 min, 26 slides)

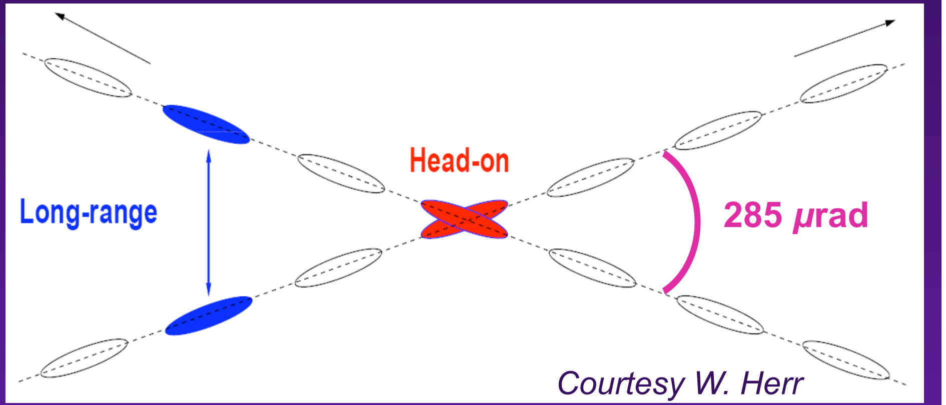
Dedicated to Dieter Möhl (my PHD thesis director) who passed away last night. Many thanks for all!

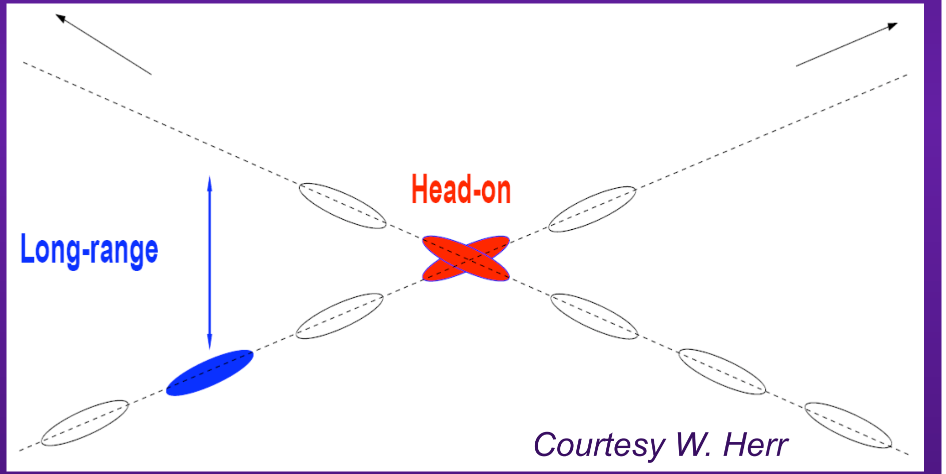
- **Introduction and main challenges**
- **Best results so far and main limitations from collective effects**
  - **LHC INJECTORS: LINAC2 (4), PSB, PS, SPS** **TUXA02 (R. Garoby)**
  - **LHC** **MOXBP01 (S. Myers), THPPP020**
- **Some (nice) pictures**
- **Conclusion and outlook**
- **APPENDIX: Some (more) pictures and results**



LHC injector chain







=> PACMAN bunches
(# integrated beam-beam effect)

INTRODUCTION AND MAIN CHALLENGES (1/4)

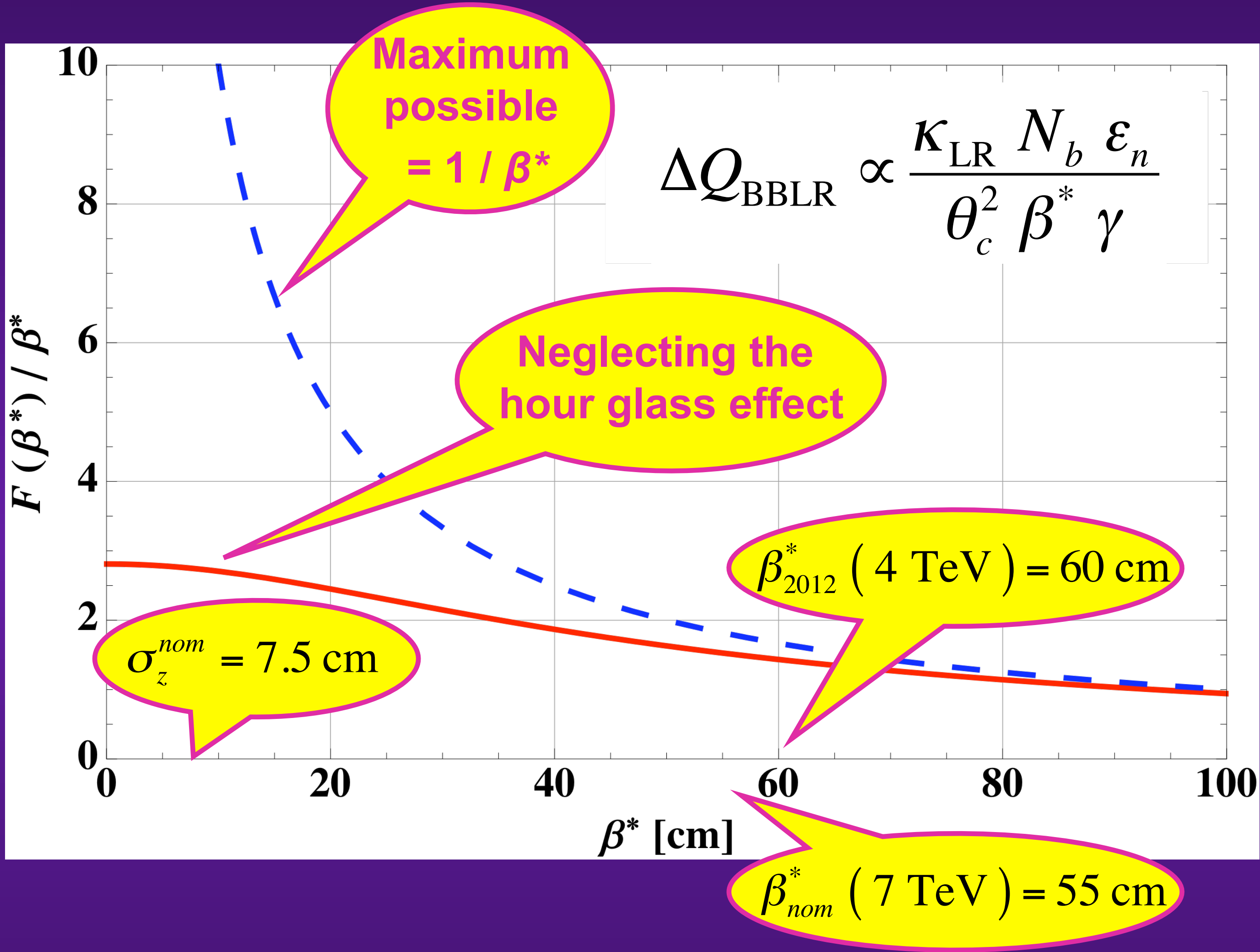
- **2 MAIN CHALLENGES FOR LHC => Very high *B* (2-in-1 SC magnets + superfluid helium at 1.9 K) and very high *Lumi***
- **PEAK LUMINOSITY**

Round beam

$$L_{peak} = \left(\frac{e\, c^2}{8\, \pi^2\, E_0} \right) \left(B \, \frac{\rho}{R} \right) \left(\frac{N_b}{\varepsilon_n} \right) \left(N_b \, M \right) \frac{F\left(\theta_c \,, \sigma_z \,, \beta^* \,, \varepsilon_n / \gamma \right)}{\beta^*}$$

  - **1st term: constant**
  - **2nd term: Magnetic field (8.33 T ⇔ 7 TeV proton energy)**
  - **3rd term: Bunch brightness => SC, BBHO, IBS, TCBI of higher head-tail modes (-1) to be stabilized by Landau octupoles**
  - **4th term: Total beam current => RF heating, TCBI of mode 0 to be stabilized by transverse damper, TMCI, e-cloud, BBLR, cryogenic load, collimation system (large impedance)…**
  - **5th term: Lattice (high gradient quadrupole lenses and interaction region geometry), BBLR, RF voltage (bunch length)…**

INTRODUCTION AND MAIN CHALLENGES (2/4)



=> Future upgrades with smaller β^*: crab cavities, smaller bunch length (additional RF system), flat beams, BBLR compensation…

MOPPC027, TUPPR027, WEPPC027, TUPPR077

INTRODUCTION AND MAIN CHALLENGES (3/4)

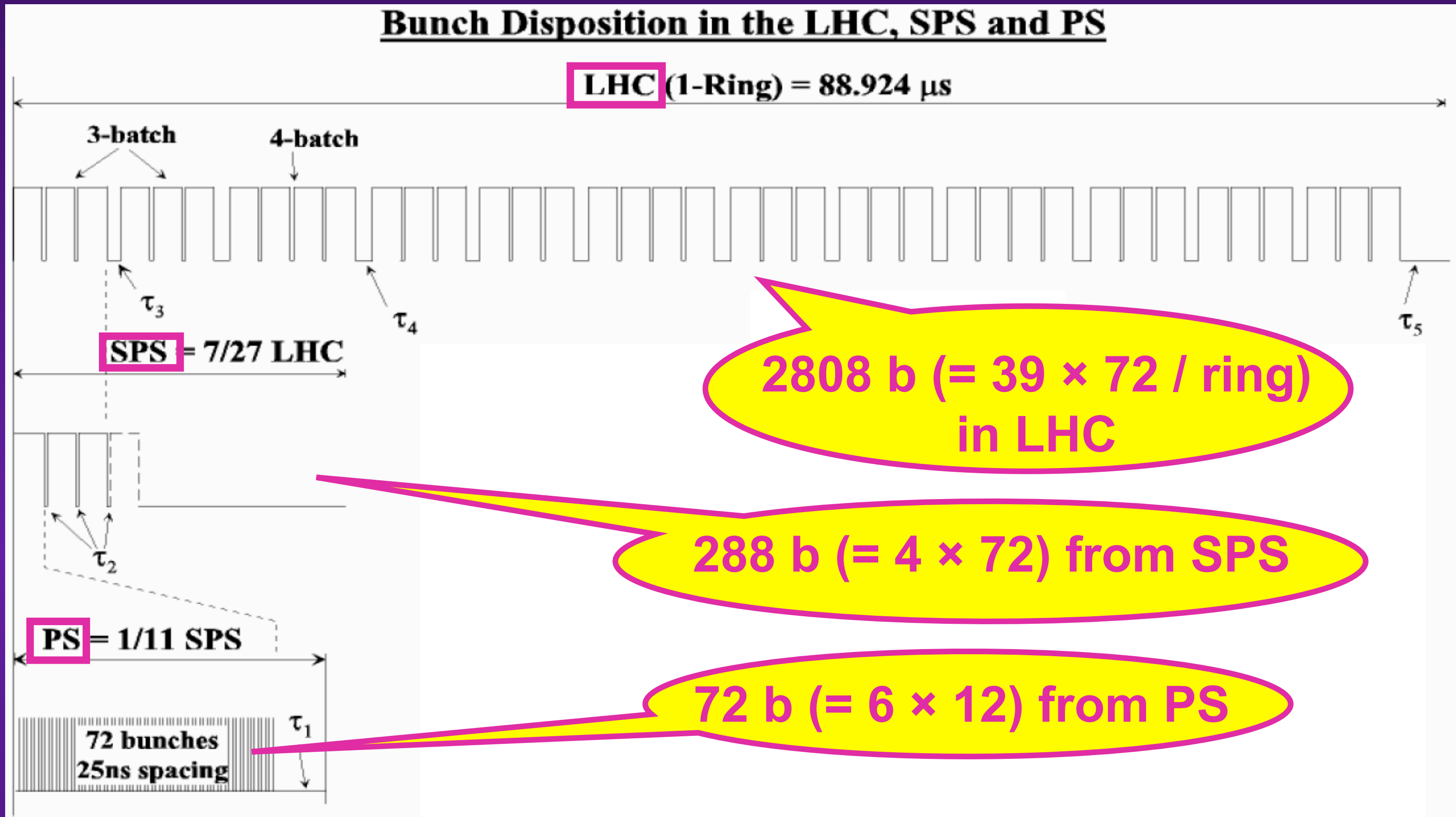
- **2 MAIN CHALLENGES FOR THE LHC INJECTORS**
  - **Preservation of transverse emittance => High brightness**
  - **Generation of longitudinal structure (25 ns bunch spacing)**
    - **Very long bunches (~ 180 ns at 4σ) at PSB-PS transfer**
    - **Very short bunches (~ 1-1.5 ns at 4σ) at SPS extraction**

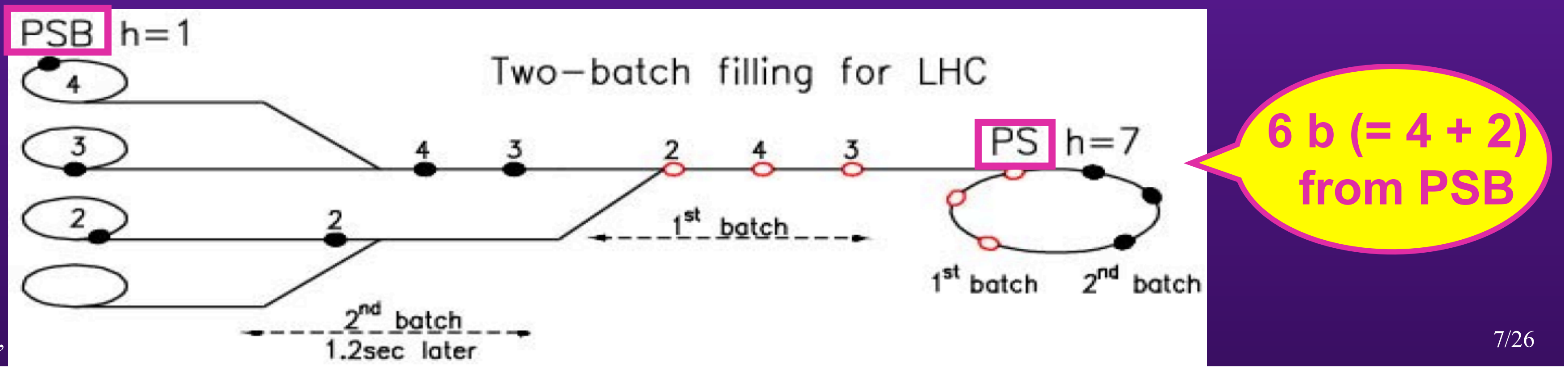
=> Multiple bunch splittings in PS: 12 for 25 ns (and 6 for 50 ns)

=> As PSB could not deliver beams with sufficient brightness, a double-batch scheme was proposed

=> Due to large SC at PS injection, PSB extraction kinetic energy was raised from 1 to 1.4 GeV

INTRODUCTION AND MAIN CHALLENGES (4/4)





BEST RESULTS SO FAR (before end of last week…)

MOPPC005

LHC (in physics)	Achieved (2012)	Nominal	Future High-Lumi LHC	
Proton energy [TeV]	4.0	7		
Bunch spacing [ns]	50	25	25	50
Bunch population [10^{11} p/b]	1.35	1.15	2.2	3.5
Norm. rms.trans. emittance [μm]	~ 2.1	3.75	2.5	3.0
Peak luminosity [10^{34} cm^{-2}s^{-1}]	**~ 0.56**	1		

Injectors **TUXA02**	50 ns		25 ns		Single bunch	
	# p/b [10^{11}]	$(\varepsilon_{nx}+\varepsilon_{ny})$ / 2 [μm]	# p/b [10^{11}]	$(\varepsilon_{nx}+\varepsilon_{ny})$ / 2 [μm]	# p/b [10^{11}]	$(\varepsilon_{nx}+\varepsilon_{ny})$ / 2 [μm]
PSB	See plot PSB emittance vs. bunch intensity				4.0	2.2
PS	1.9	1.9	1.4	3.0	4.0	2.4
SPS nom.	1.6	1.9	1.15	2.6	2.5	2.5
SPS new optics	1.7	?	1.2	2.7	3.0	2.2
LHC	1.45 1.35	~ 2.3 ~ 2.1			1.9 2.4	1.1-1.2 2.5-3.0

MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (1/6)

- **LINAC2-PSB**
  - Space charge: $\Delta Q_{SC} \propto \frac{N_b \, R}{\varepsilon_n \, \beta \, \gamma^2 \, \sigma_z}$
    - "Space charge limit" under investigation (~ - 0.5 already achieved, losses) => Dynamic working point + resonances compensation
    - LINAC4 (160 MeV) will replace LINAC2 (50 MeV) => Factor 2
    - To profit from this in PS => Increase PSB extraction kinetic energy from 1.4 to 2 GeV => Factor 1.6
- **PS**
  - "Space charge limit" under investigation (~ - 0.26 already reached)
  - Horizontal head-tail instability on the long 1.2 s injection flat bottom => No pb with linear coupling. Studies ongoing for 2 GeV

MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (2/6)

- e-cloud build-up (and sometimes instabilities if bunch too small for too long a time) => No pb for the moment but under investigation for future requests **WEPPR010**
- Longitudinal plane
  - Coupled-bunch instabilities during the ramp after transition and on flat-top. Limit at ~ 1.9 10^{11} p/b (for both 25 ns and 50 ns) => Wideband kicker
  - Transient beam loading during bunch splitting => New one-turn delay feedbacks

- **SPS**
  - Fast vertical single-bunch instability at injection (with very low positive chromaticity). Limit at ~ 1.6 10^{11} p/b in good agreement with impedance model (without space charge) but the "clear" mode-coupling could not be observed (maybe indirect measurement of mode-coupling / decoupling)

MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (3/6)

=> New optics with a lower gamma transition (to increase distance from transition). Expected new limit ≥ 3.5 10^{11} p/b **WEPPR078**

- "Space charge limit" under investigation (~ - 0.19 already achieved)
- e-cloud
  - Major problem for many years for nominal LHC beam
  - Beam quality seems to be acceptable since 2011 (which still needs to be fully understood)
  - For higher intensities => Plan to coat large parts of the inside of the SPS vacuum chambers with amorphous carbon
  - New optics should also be better for the e-cloud instability. Detailed studies ongoing
  - High-bandwidth feedback (CERN – US LARP)

MOEPPB015, WEPPP074, WEPPP079, WEPPP080, WEPPR090, WEPPR091

MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (4/6)

- Longitudinal plane
  - Instability during the ramp. Limit at ~ 2 10^{10} p/b at the end of the ramp => 4th harmonic RF system (800 MHz) and controlled longitudinal emittance blow-up. Beneficial effect of new optics under investigation
  - Beam loading => RF power upgrade (for future requests)

- LHC

MOPPC001, WEPPR068, WEPPR076

- e-cloud => Scrubbing (4-fold strategy + some solenoids added) with high chromaticity
- Loss of longitudinal Landau damping => Controlled blow-up
- Transverse coherent instabilities

WEPPR073

  - Mode 0 => Transverse damper. Rise-times measured close to predictions at 450 GeV and maybe factor 2-3 faster at 3.5 TeV
  - Mode – 1 => Landau octupoles (single- and coupled-bunch). 2 dedicated measurements close to predictions

MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (5/6)

- **Transverse impedance**
  - Large transverse (imaginary) impedance from collimators can lead to a loss of transverse Landau damping => Increase Landau octupoles' current. Ongoing studies to fully understand the larger than predicted current in operation
  - Larger than predicted transverse (imaginary) impedance could lead to TMCI. Current thresholds: ~ 9 10^{11} p/b (450 GeV) and ~ 4 10^{11} p/b (4 TeV, 2012 with tight collimators setting) => In case of problem, increase chromaticity, high-bandwidth FB, reduce imp. …

$$\Delta Q_{\mathrm{BBHO}} \propto \frac{\kappa_{\mathrm{HO}} N_b}{\varepsilon_n}$$

$$\tau_{IBS} \propto \frac{\varepsilon_n^2 \varepsilon_l}{N_b} G_{IBS}$$

- **Beam-beam**
  - HO: ξ ~ 0.034 achieved for 2 collision points (IP1 and IP5), i.e. ~ 0.017 / IP (nominal value was ~ 0.0035) => Small emittance!
  - PACMAN => Alternating crossing scheme to compensate for the tunes (orbits can only be minimized)

MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (6/6)

- Coherent beam-beam modes => With few bunches only. Tune split if needed (but should not with many bunches)
- Leveling (by transverse offsets) => For IP2 and IP8 (in operation since 2011)
- Coherent instabilities observed when crossing angle too small or transverse offsets between ~ 1 and 2 σ in IP1 and IP5 or ? => Under investigation

- RF heating (real part of the longitudinal impedance)
  - Injection kickers **WEPPR071**
  - Injection protection collimator **WEPPR068**
  - RF fingers => Task force in 2012

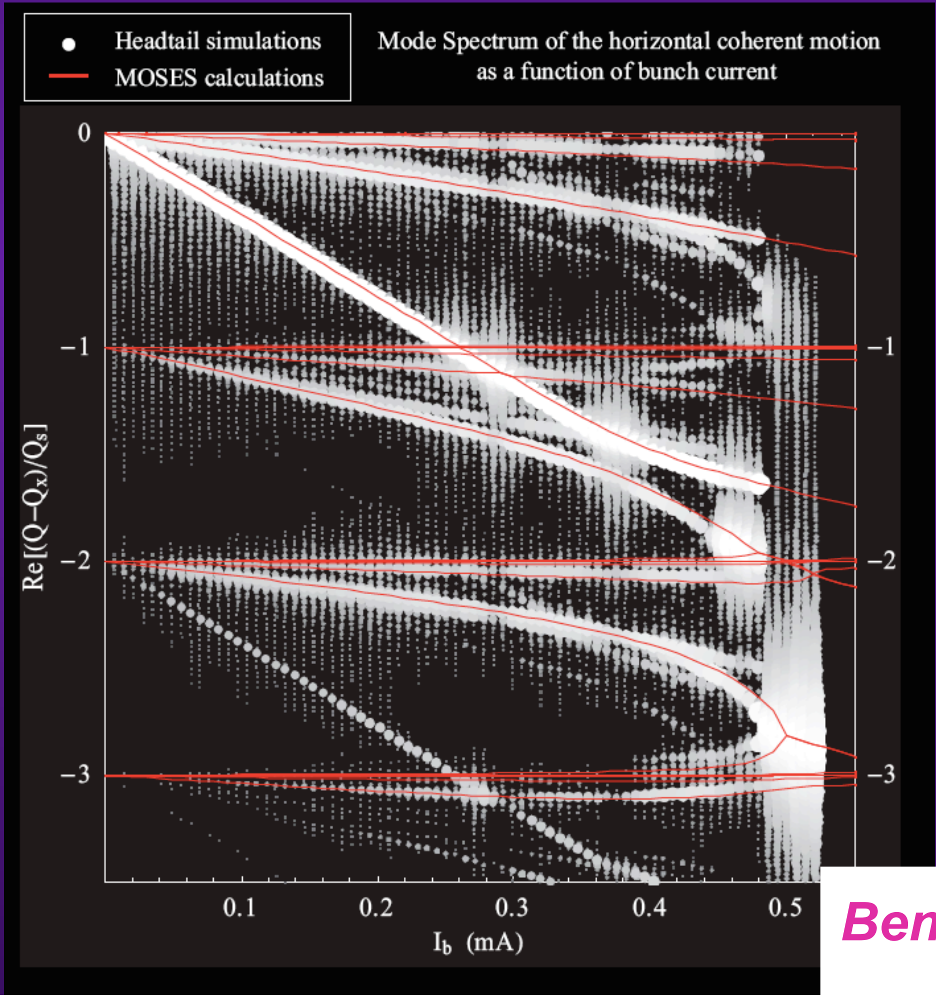
  => Longer bunch usually better (10 cm rms used in 2012 vs. 7.5 cm nominal)

- UFOs (Unidentified Falling Objects) **THPPP086**

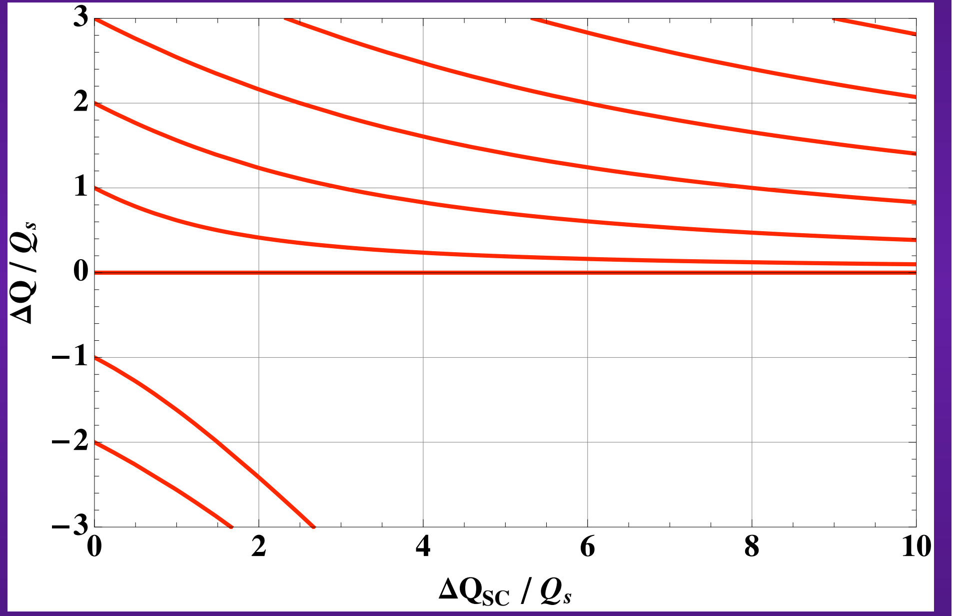
SOME (NICE) PICTURES (1/11)

- **SPS TMCI**

1st: Broad-Band impedance model WITHOUT SC



SC ONLY (square-well air-bag, Blaskiewicz1998)

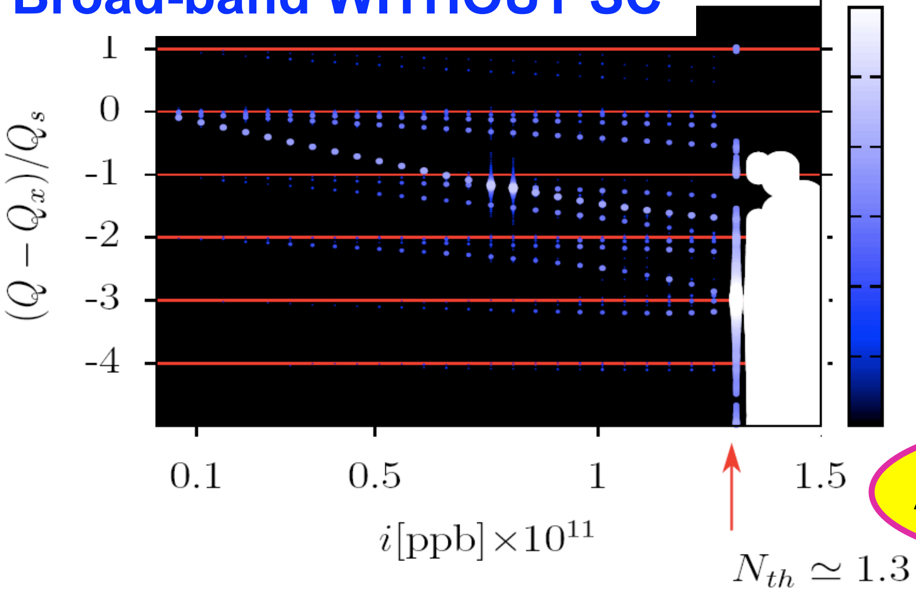


Benoit Salvant

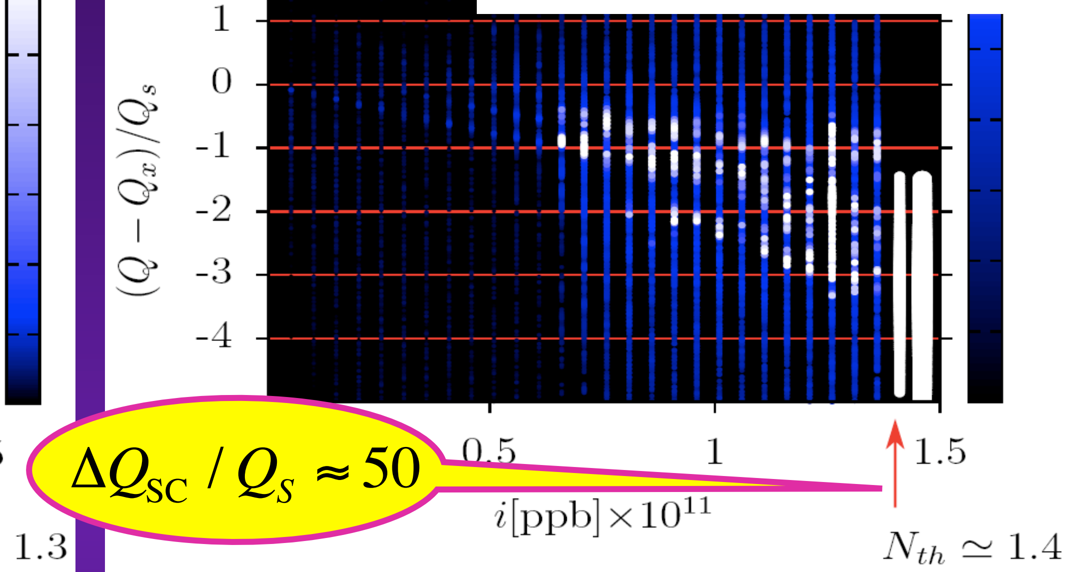
SOME (NICE) PICTURES (2/11)

Diego Quatraro

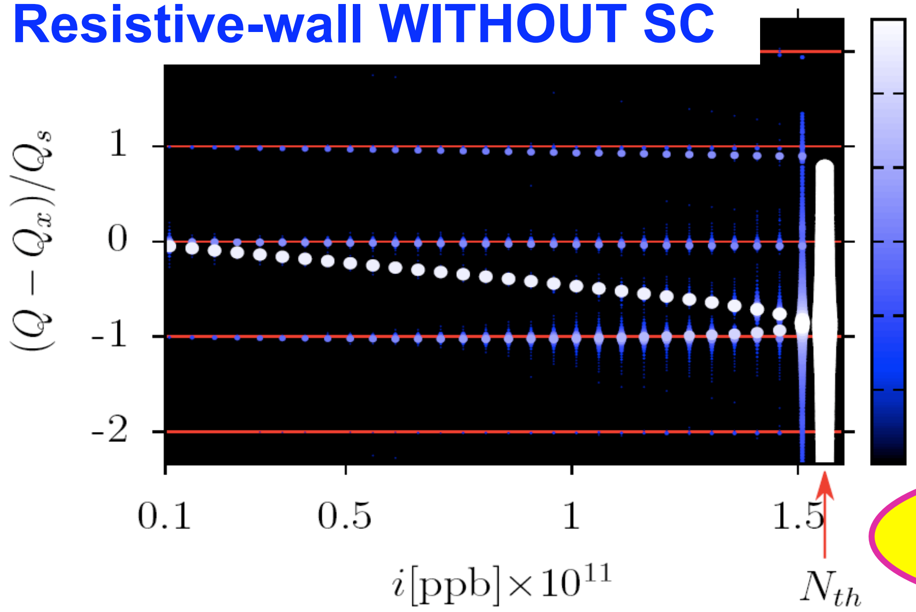
Broad-band WITHOUT SC



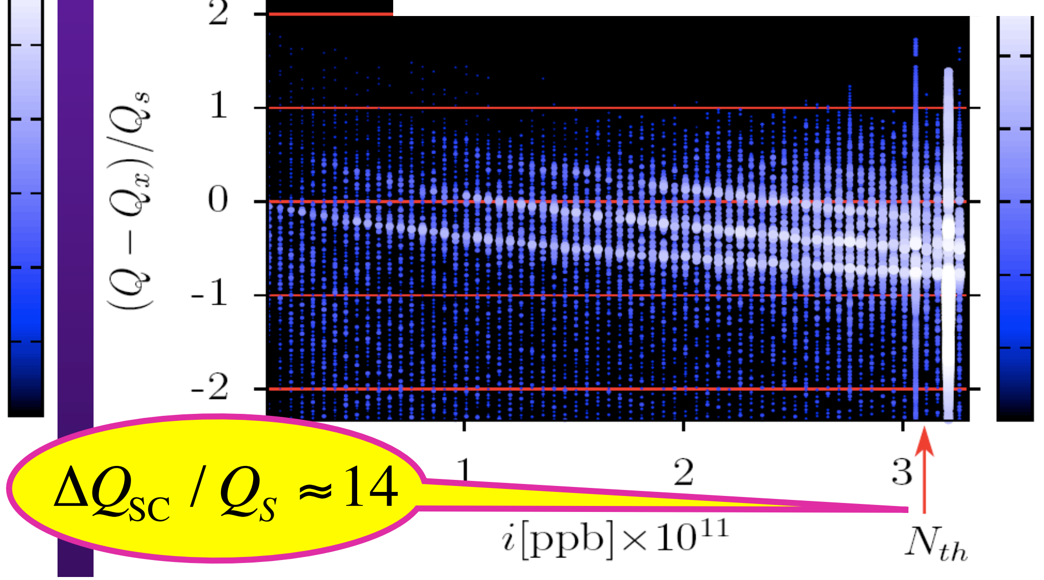
Broad-band WITH SC



Resistive-wall WITHOUT SC

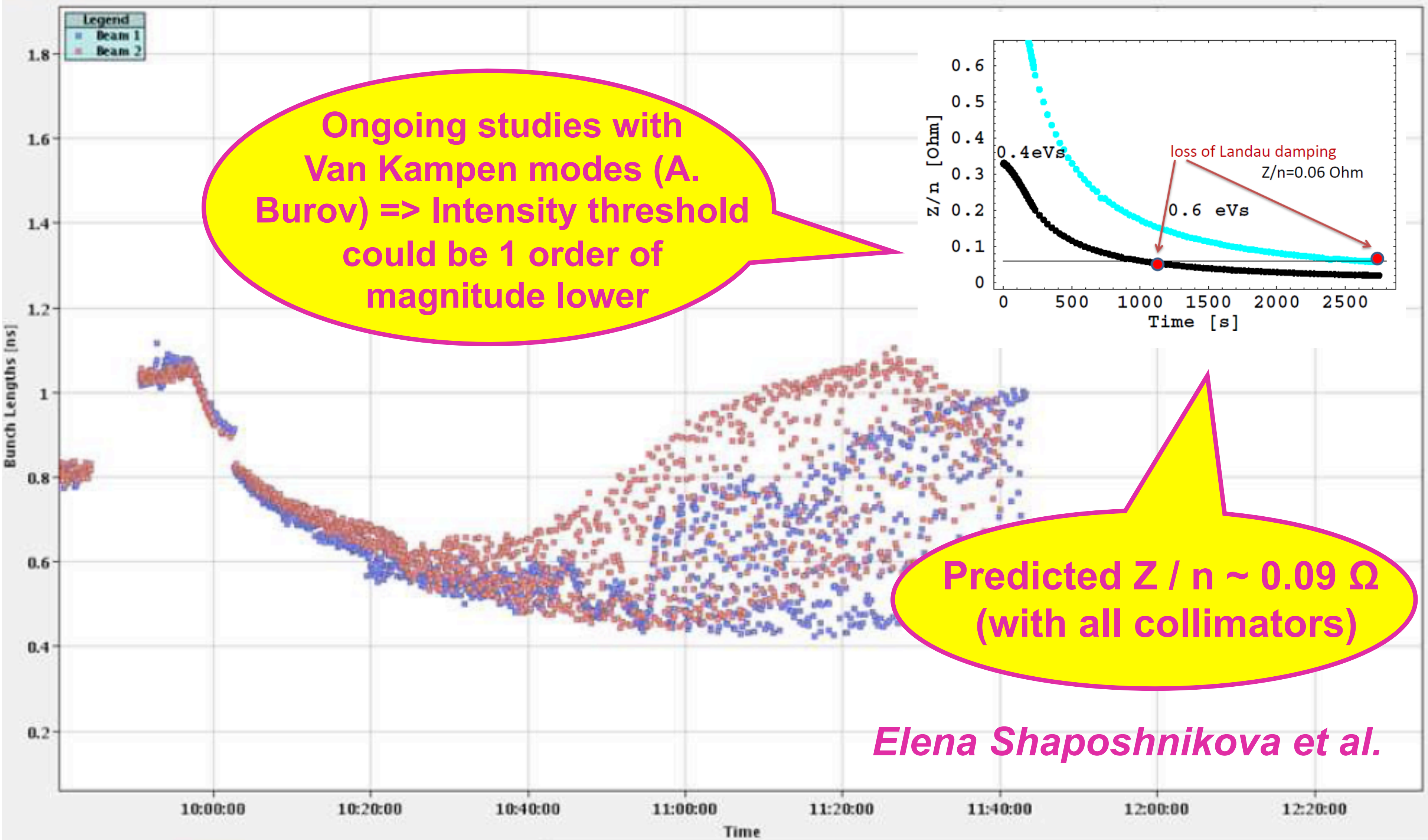


Resistive-wall WITH SC



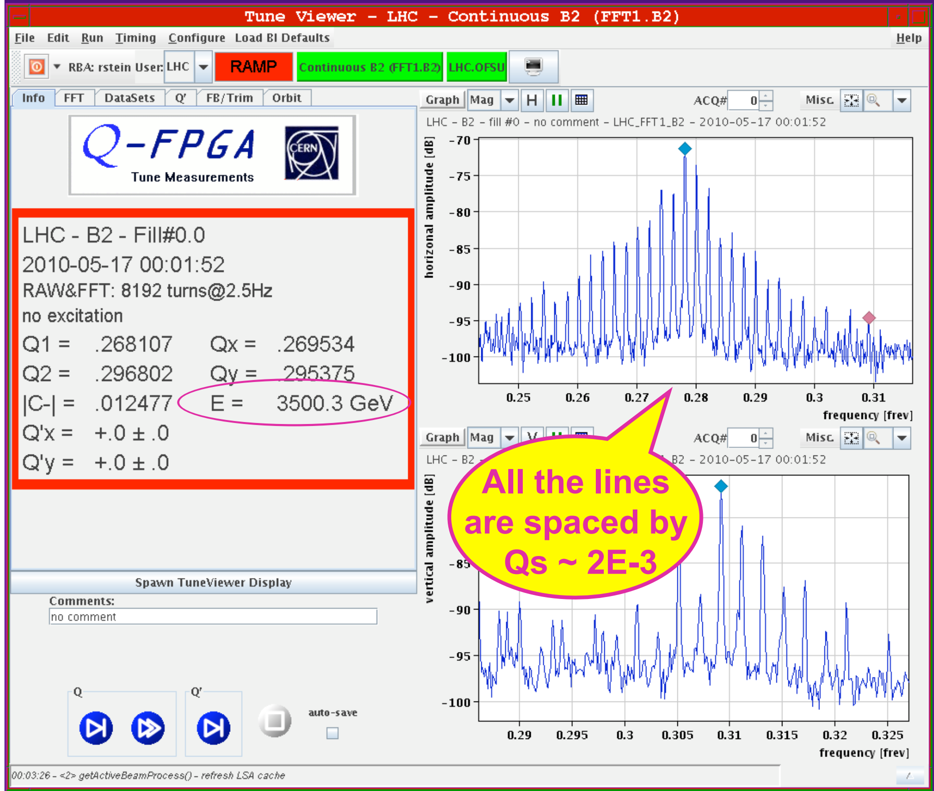
SOME (NICE) PICTURES (3/11)

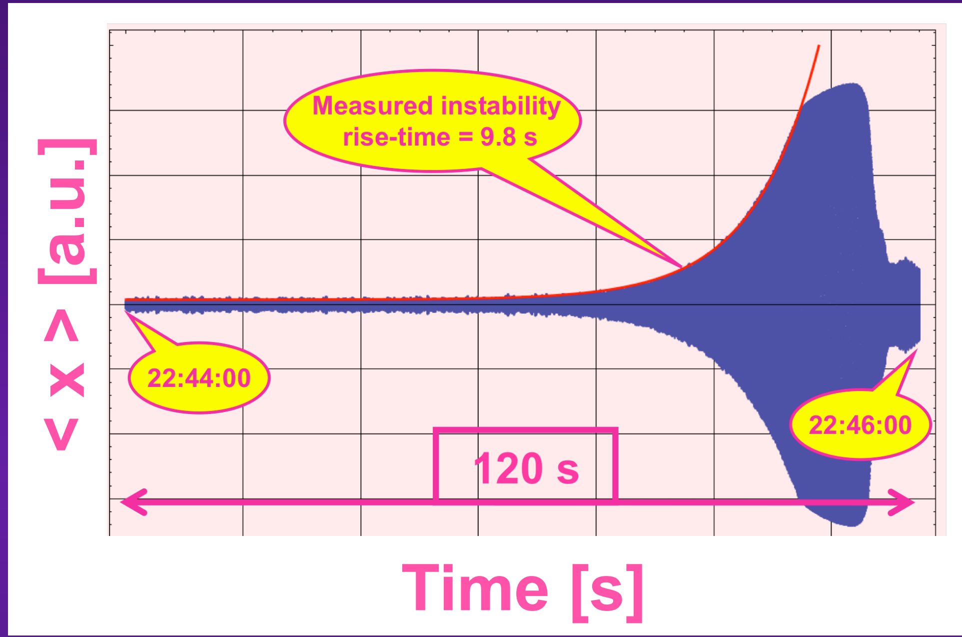
- **Loss of longitudinal Landau damping during LHC acceleration when the longitudinal emittance is too small**

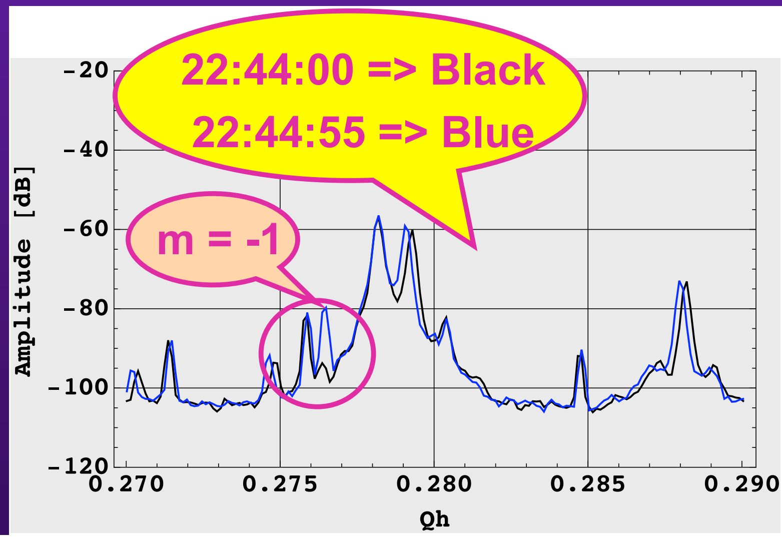


SOME (NICE) PICTURES (4/11)

- Single-bunch head-tail instability m = - 1 without Landau octupoles (for Q' ~ 6) on LHC flat-top



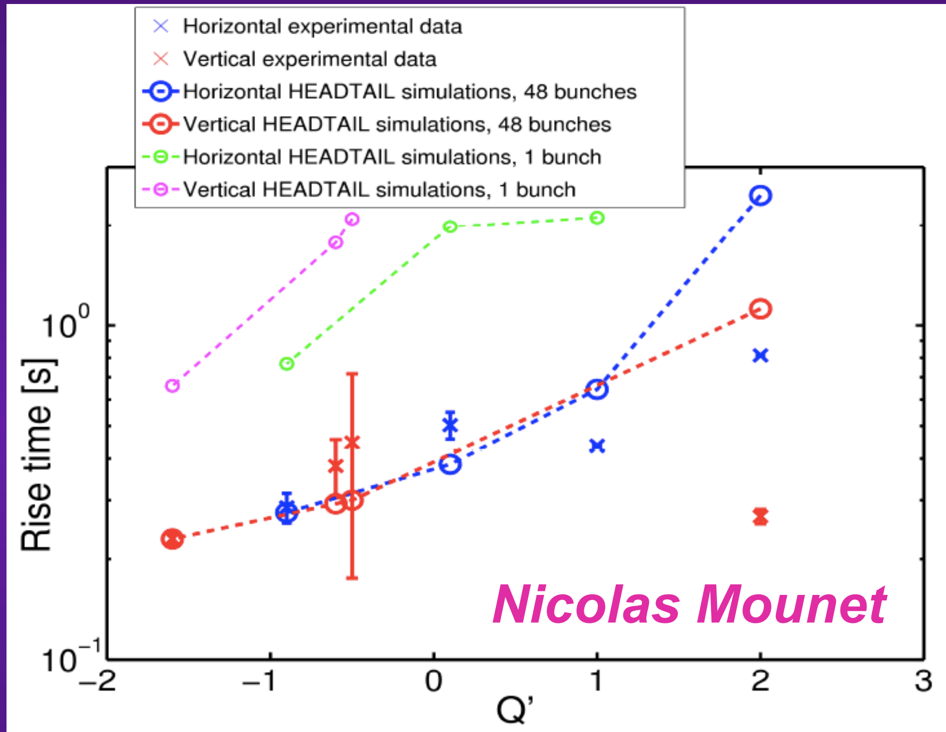




- Rise-time and Landau octupoles' current for stability (between 10 and 20 A) within factor ~ 2 with predictions

SOME (NICE) PICTURES (5/11)

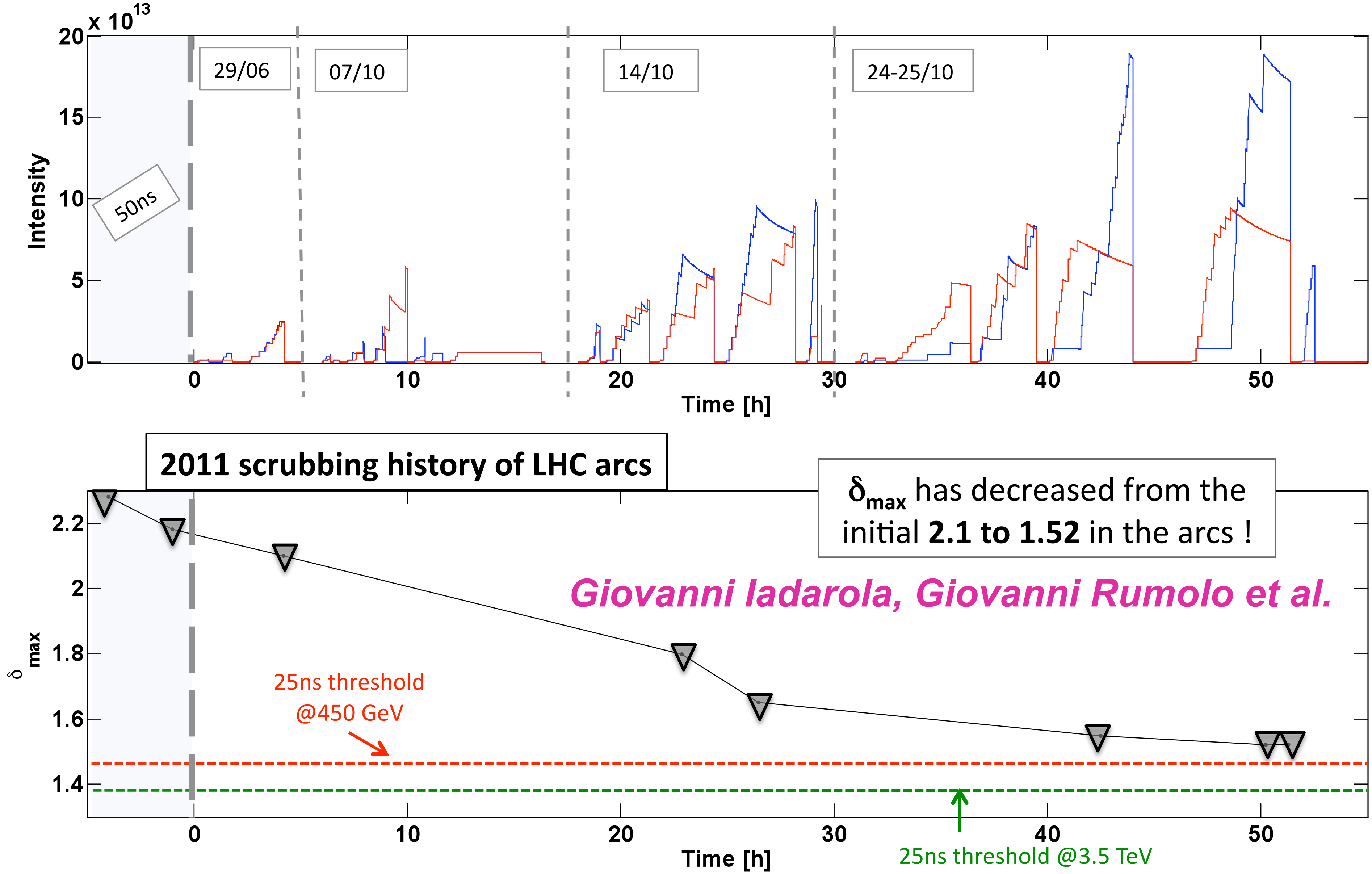
- **TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)**
  - **Good agreement at 450 GeV**



  - **~ 2-3 faster rise-times observed at 3.5 TeV (but uncertainty on chromaticities)**
  - **Landau octupoles' current for stability at 3.5 TeV within factor ~ 2 with predictions (less than predicted => Studies with Q" ongoing)**

SOME (NICE) PICTURES (6/11)

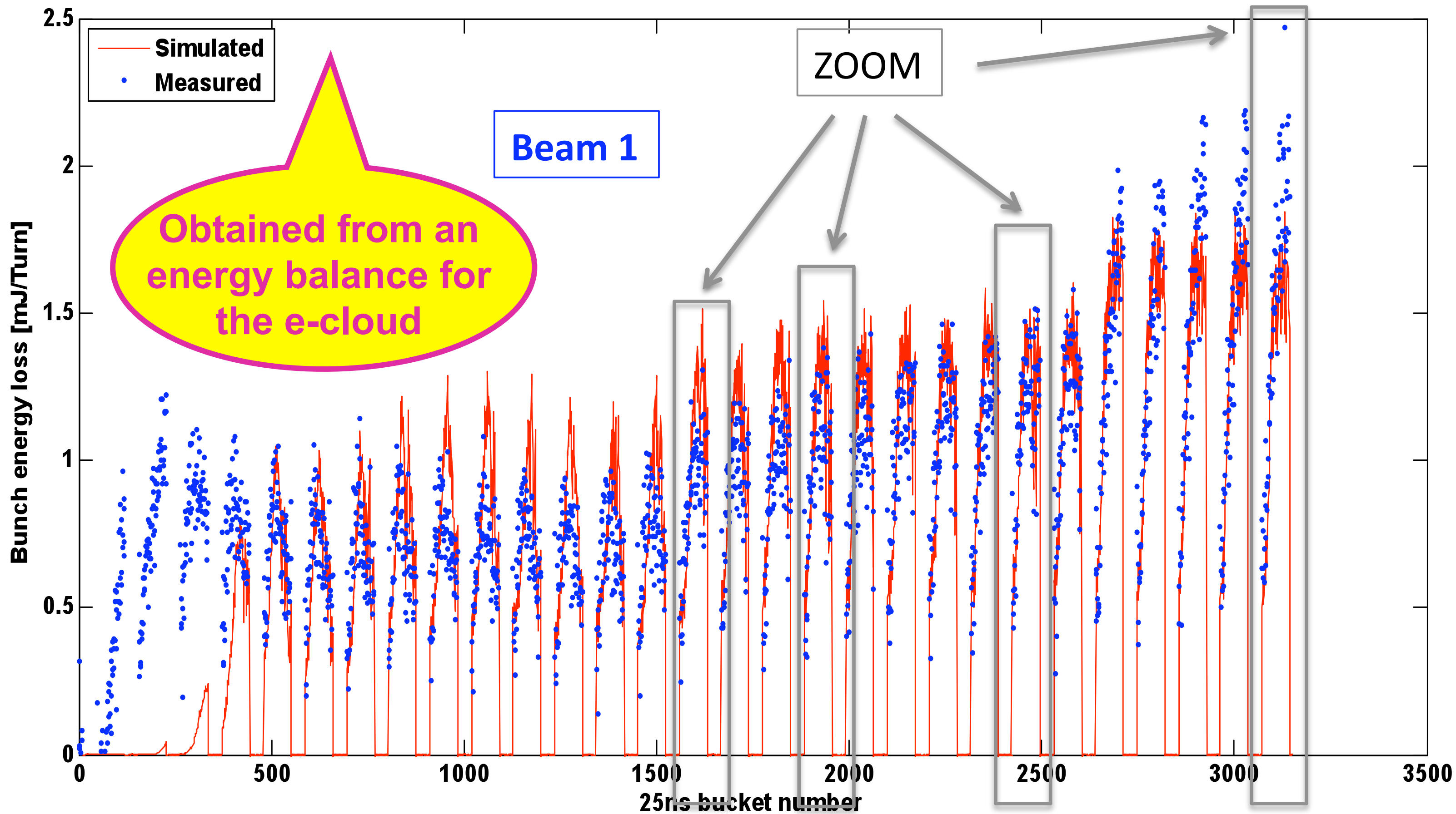
- **ECLOUD studies in the LHC with 25 ns beam**



SOME (NICE) PICTURES (7/11)

Simulations → δ_{max} fixed to **1.5** (added 2e9p$^+$/m uncapt. beam)

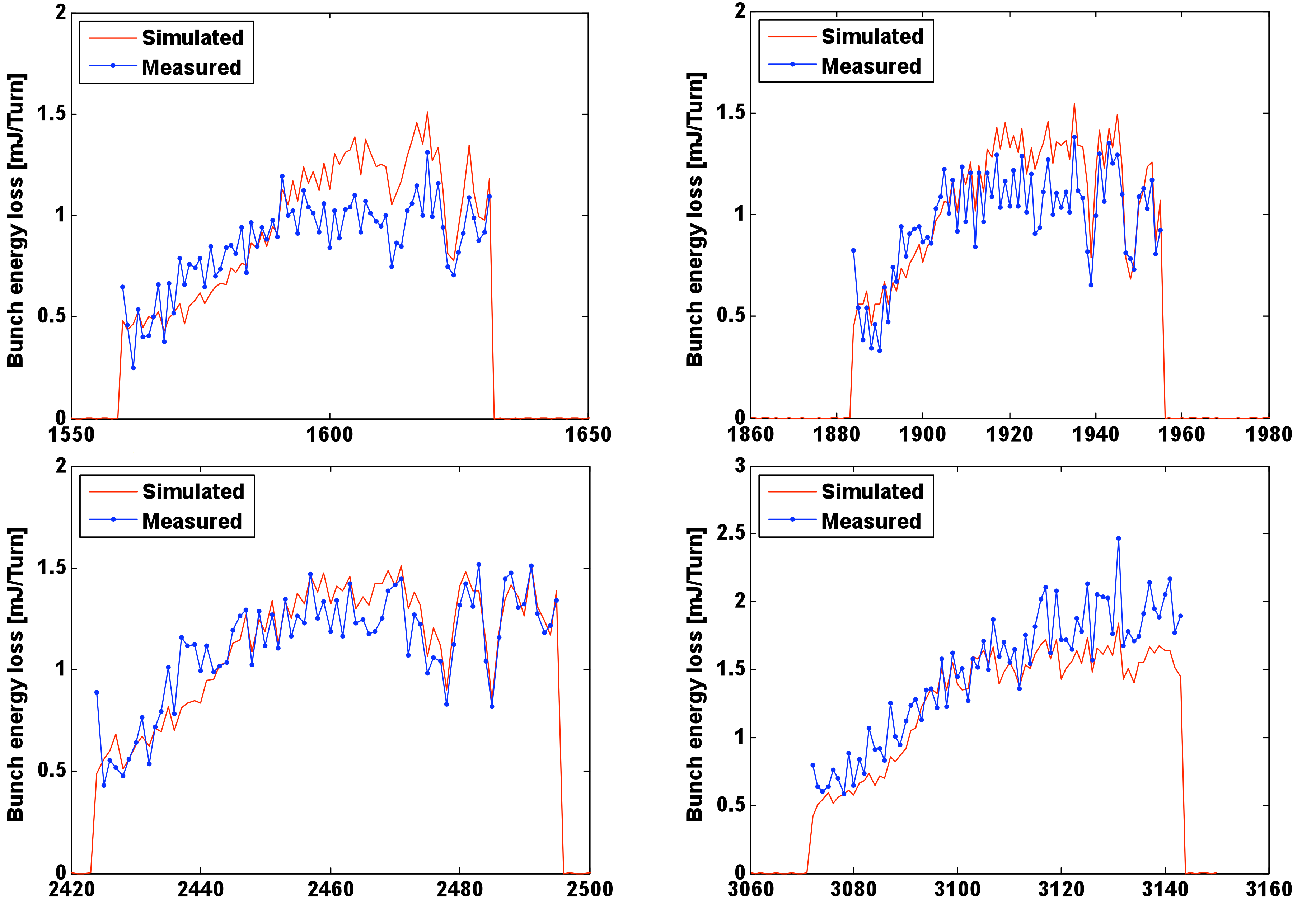
Measurements → the energy loss per bunch is obtained from the stable phase shift



G. Iadarola, G. Rumolo, J.E. Muller, E. Shaposhnikova et al.

SOME (NICE) PICTURES (8/11)

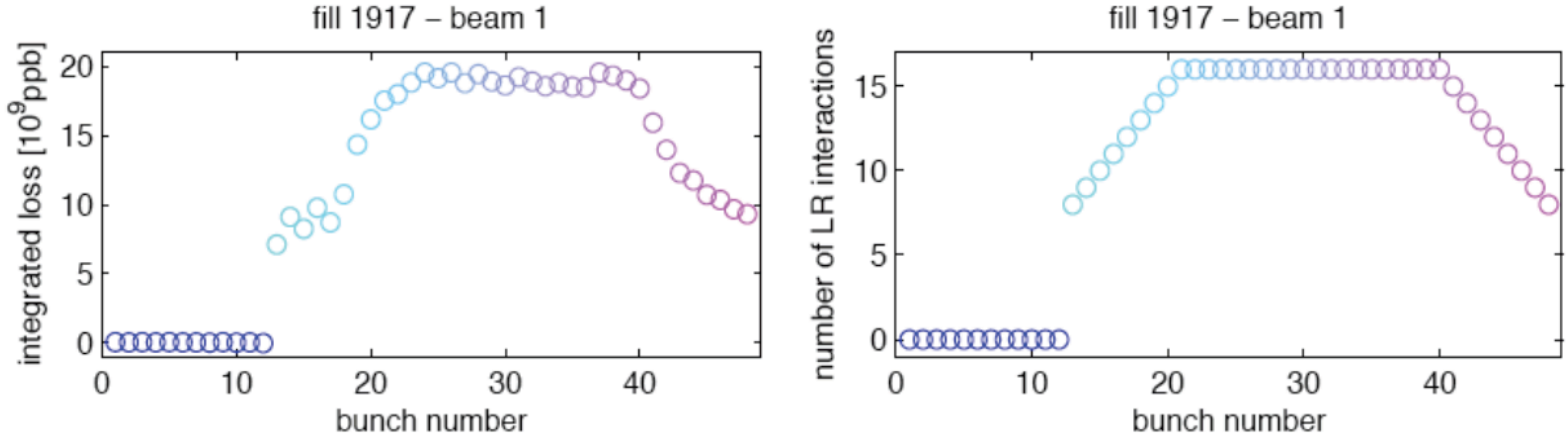
*G. Iadarola, G. Rumolo,
J.E. Muller, E. Shaposhnikova et al.*



SOME (NICE) PICTURES (9/11)

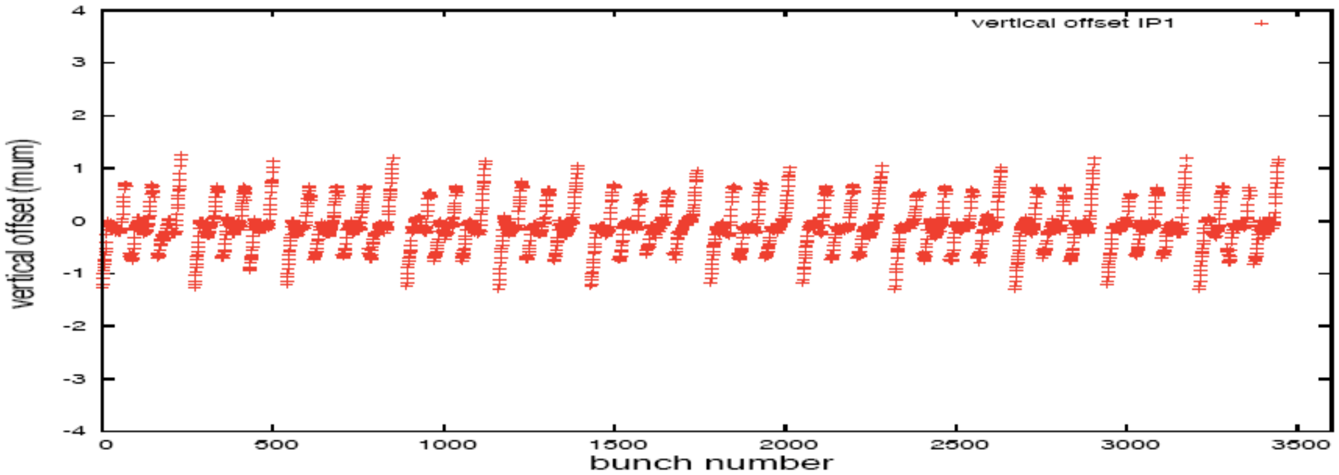
- **Beam-beam**
  - **PACMAN effects clearly visible**

G. Papotti, W. Herr et al.



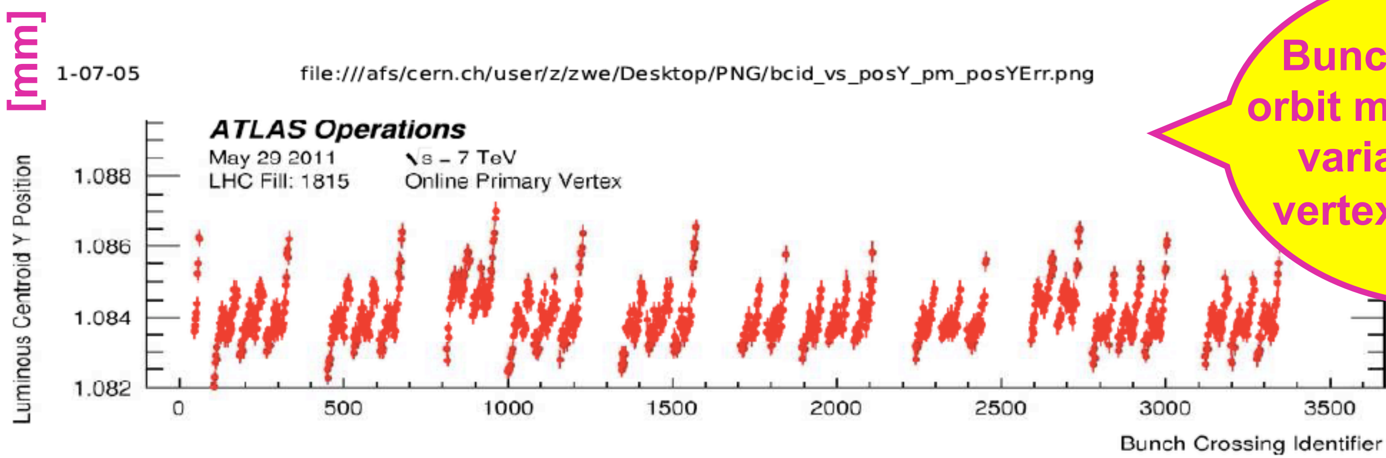
SOME (NICE) PICTURES (10/11)

PACMAN Orbit effects: calculation



W. Herr, R. Bartoldus et al.

PACMAN Orbit effects: observation

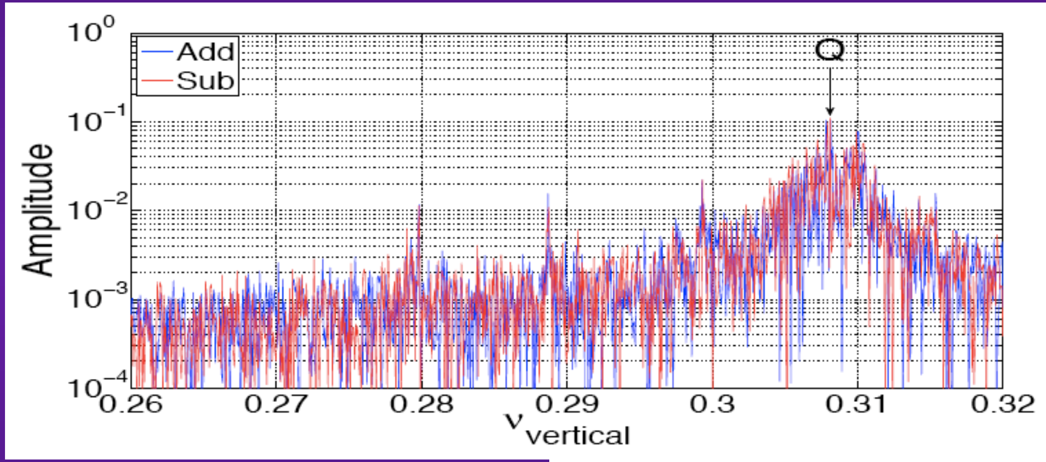


Bunch-by-bunch orbit measurements variation of the vertex centroid in IP1

SOME (NICE) PICTURES (11/11)

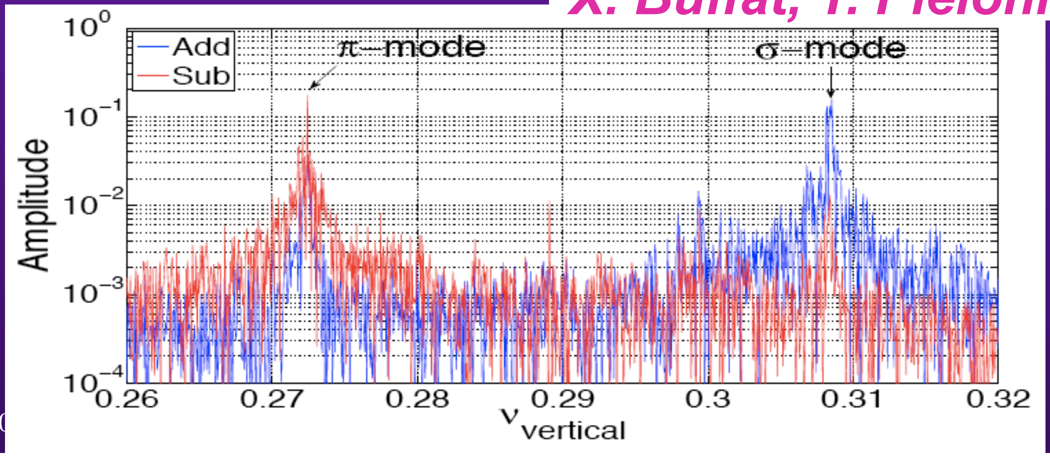
- Coherent beam-beam modes have been observed colliding 2 bunches (demonstrated by analysis of sum and difference of the measured positions of the 2 beams)
- Symmetry breaking suppresses modes as expected

• Without BB collisions



X. Buffat, T. Pieloni et al.

• With BB collisions



CONCLUSION AND OUTLOOK

- **Relatively good understanding of the many collective effects and possible cures**

TUXA02

- **Detailed upgrade plan for the injectors has been clearly defined**
- **In the LHC, the possible limitations should come from**
  - **Loss of Landau damping for the TCBI of head-tail mode - 1**
  - **e-cloud effects for the 25 ns beam**
  - **RF heating**
  - **Beam-beam (with its variety of effects and in particular its interplay with the transverse impedance, Landau damping through octupoles and transverse damper)**
    => Some coherent instabilities observed with too small crossing angle or transverse offsets (~ 1-2 σ) in IP1 and IP5 or ?, with rise-times similar to the predicted ones from the impedance…
  - **… with some perturbations expected from the UFOs**

Still to be fully understood!

CO-AUTHORS

G. Arduini, R. Assmann, H. Bartosik, P. Baudrenghien, T. Bohl, O. Bruning, X. Buffat, H. Damerau, S. Fartoukh, S. Gilardoni, B. Goddard, S. Hancock, W. Herr, W. Hofle, N. Mounet, Y. Papaphilippou, T. Pieloni, G. Rumolo, B. Salvant, E. Shaposhnikova, F. Zimmermann, (CERN, Geneva, Switzerland) and A. Burov (FNAL, Chicago, USA)

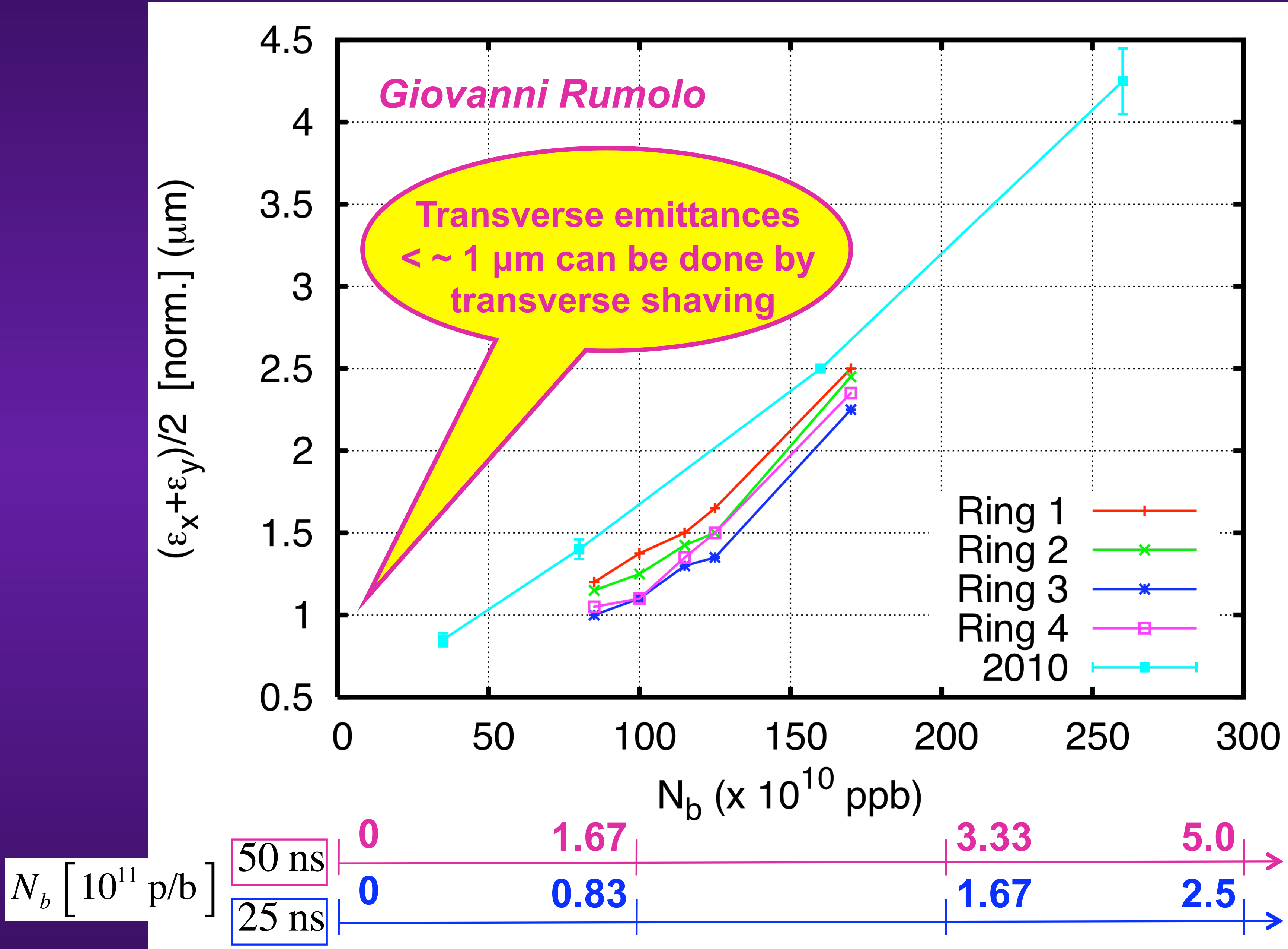
ACKNOWLEDGEMENTS

M. Giovannozzi, many (other) people from CERN (OP team…) and other labs

APPENDIX:

SOME (MORE) PICTURES AND RESULTS

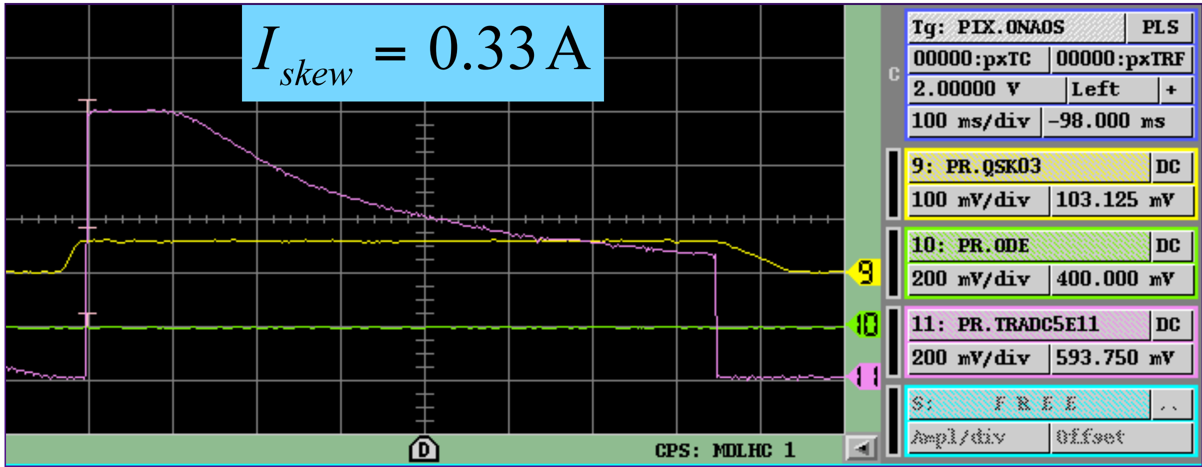
LINAC2-PSB

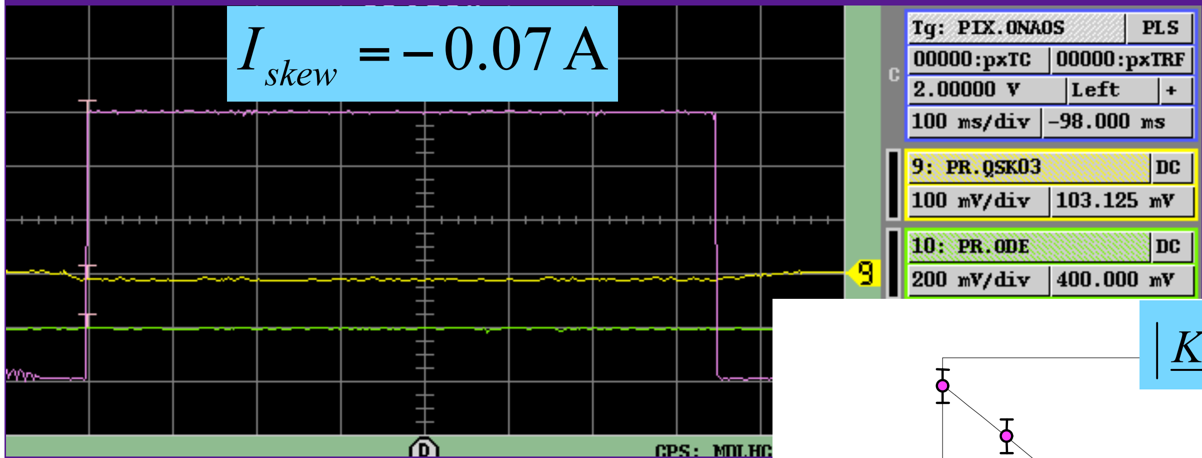


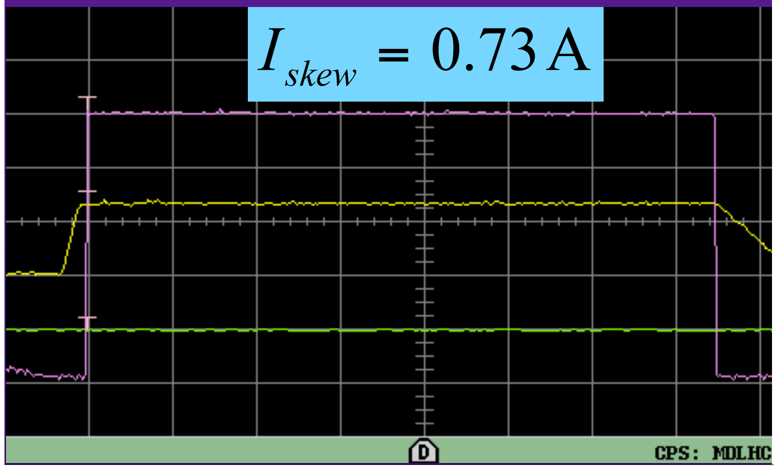
Giovanni Rumolo
Transverse emittances
< ~ 1 µm can be done by
transverse shaving
Ring 1
Ring 2
Ring 3
Ring 4
2010
(εx+εy)/2 [norm.] (µm)
Nb (x 10^10 ppb)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
50
100
150
200
250
300
Nb [10^11 p/b]
50 ns
0
1.67
3.33
5.0
25 ns
0
0.83
1.67
2.5

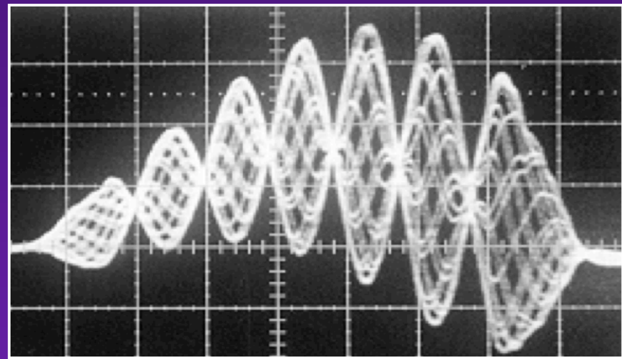
PS (1/5)

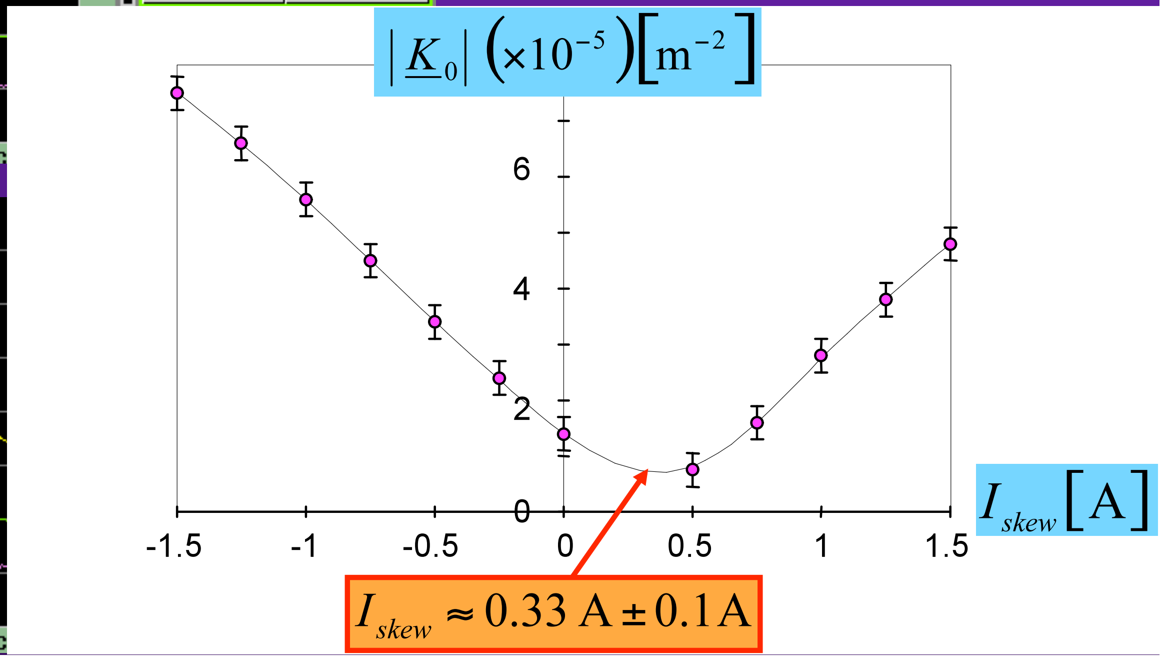
- **Horizontal head-tail instability**





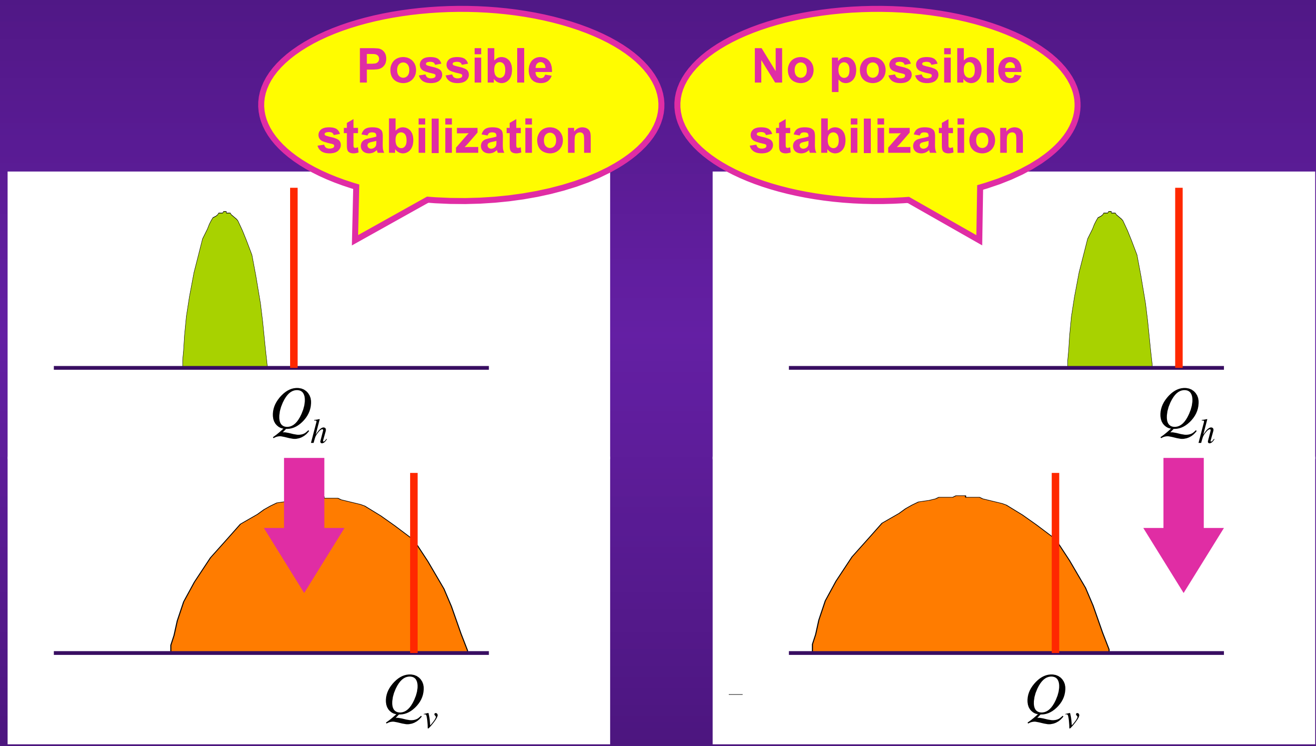






PS (2/5)

- 2 (stabilizing) effects predicted with linear coupling
  - Transfer of instability growth rates
  - Transfer of Landau damping

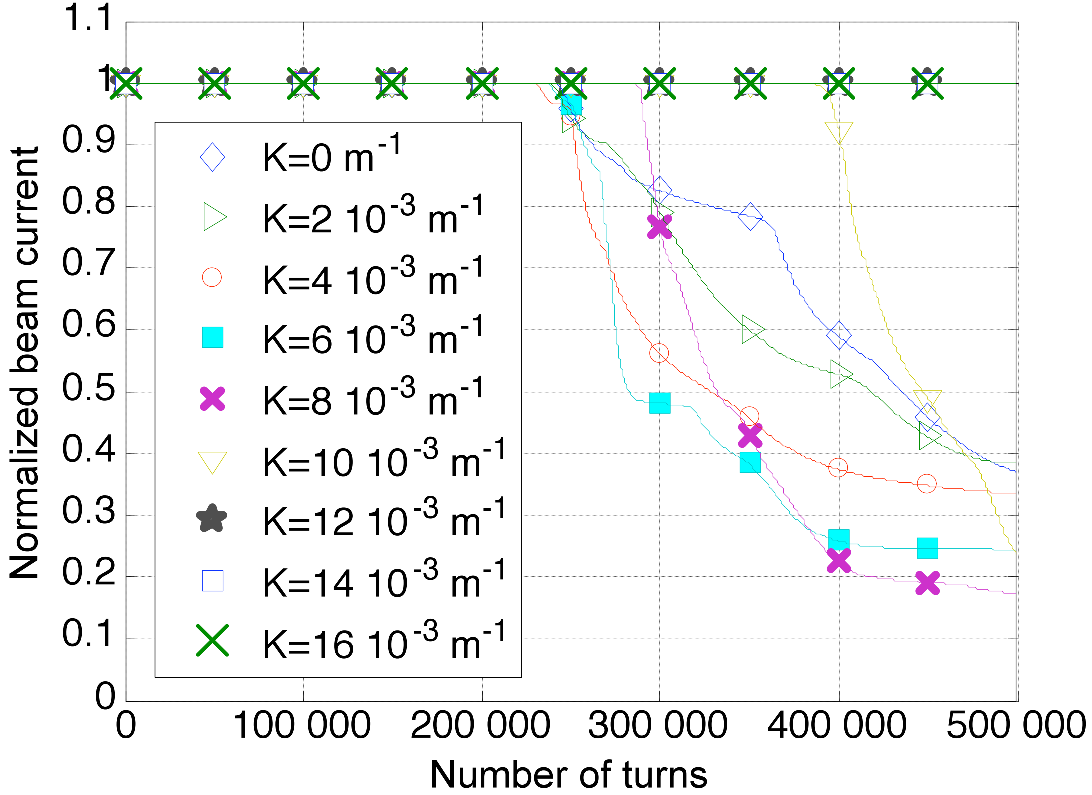


- Measurements in 2011 on a 2 GeV plateau by E. Benedetto seem to be in qualitative agreement (no stability above the diagonal). Ongoing analyses

PS (3/5)

Benoit Salvant

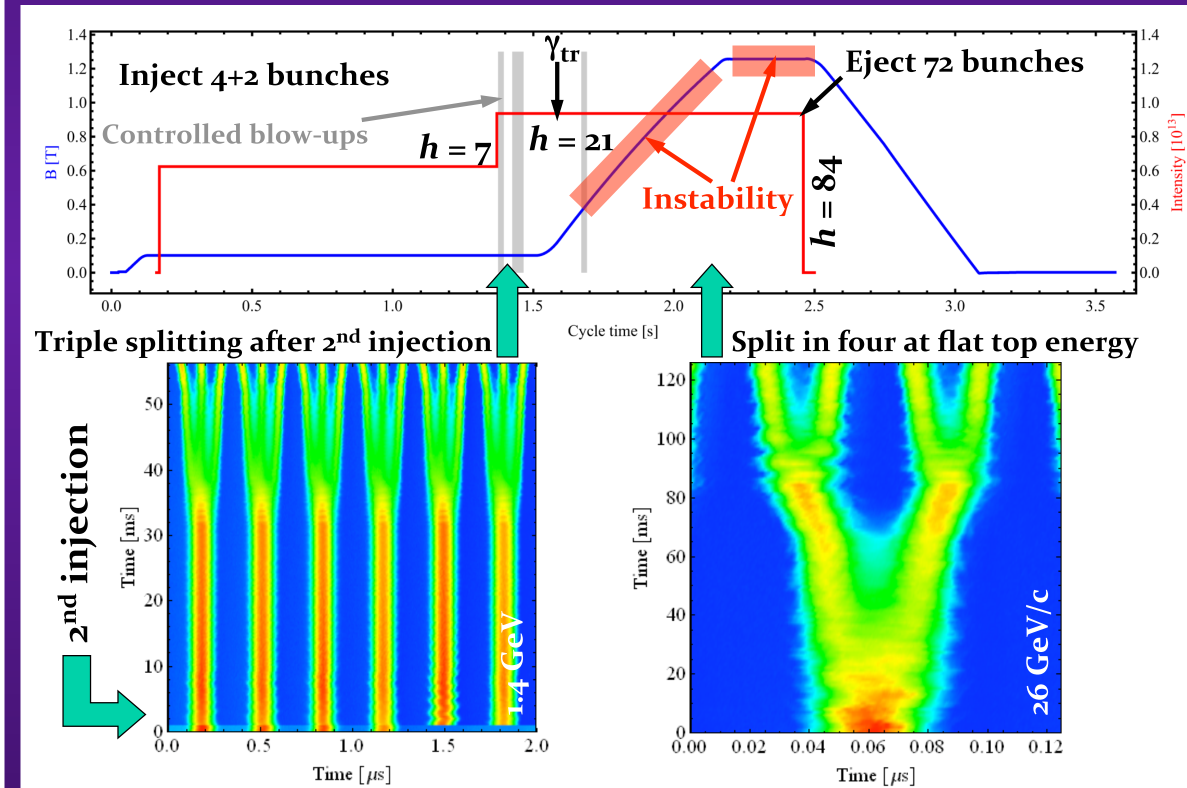
- **HEADTAIL simulations confirmed the transfer of instability growth rates (chromaticity sharing)**



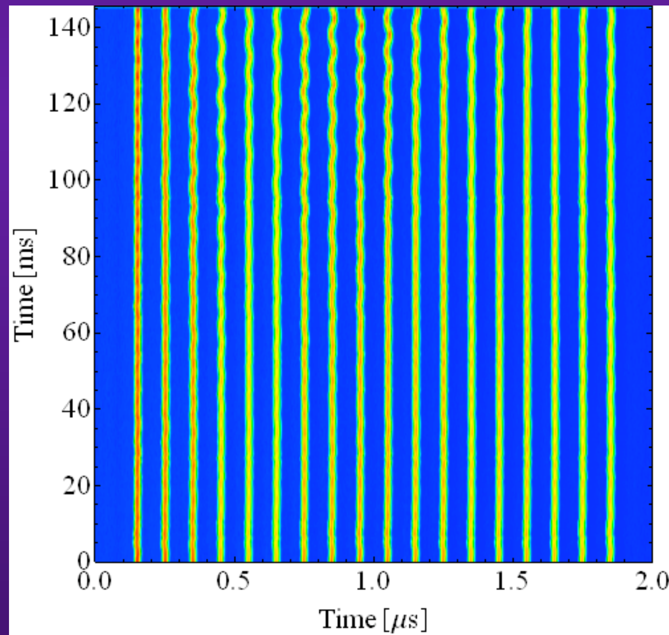
- **Effect of space charge remains to be studied in detail but a lot of progress has been made over the last few years (Burov2009-2011, Balbekov2011, Kornilov-Frankenheim2010) which can explain why space charge has almost no effect =>** $\Delta Q_{SC} / Q_s >> 1 \quad (\sim 150)$

PS (4/5)

- Longitudinal coupled-bunch instability



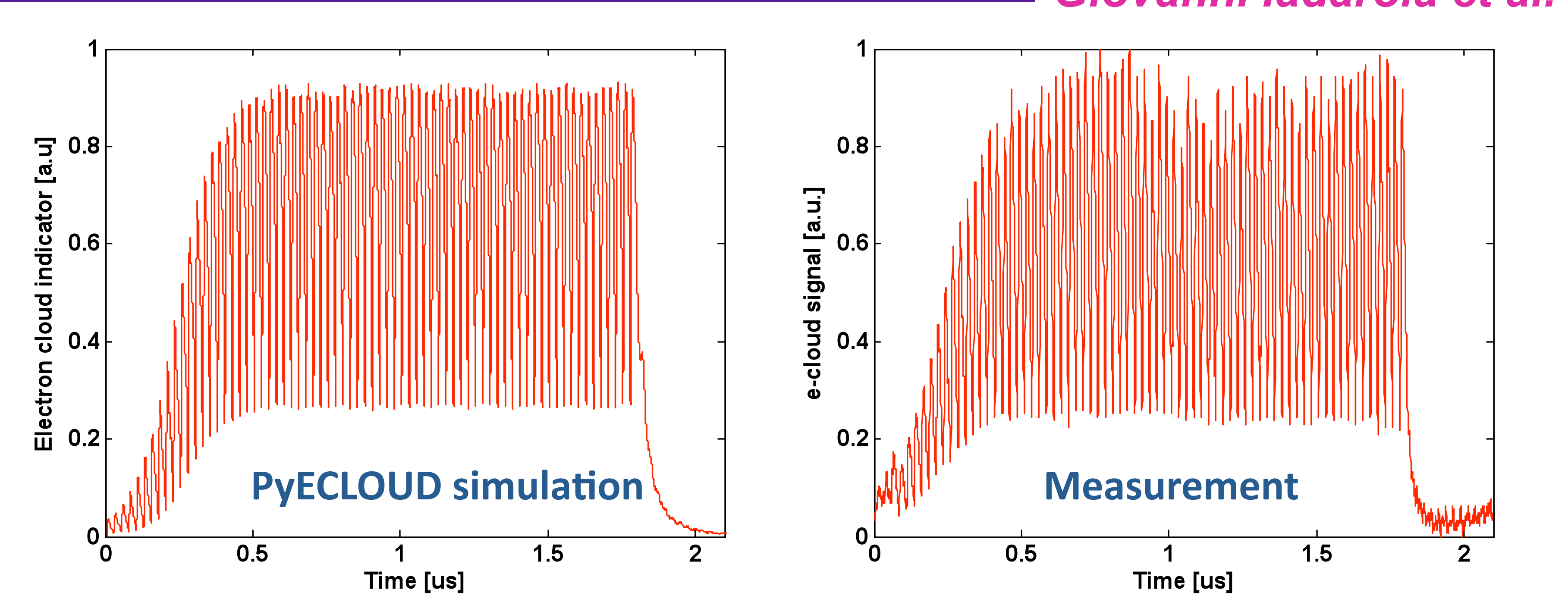
Heiko Damerau



PS (5/5)

- **e-cloud: Appears only in the last stages of the RF gymnastics before extraction. Dedicated experiment (shielded pickup) available**

Giovanni Iadarola et al.



SPS (1/5)

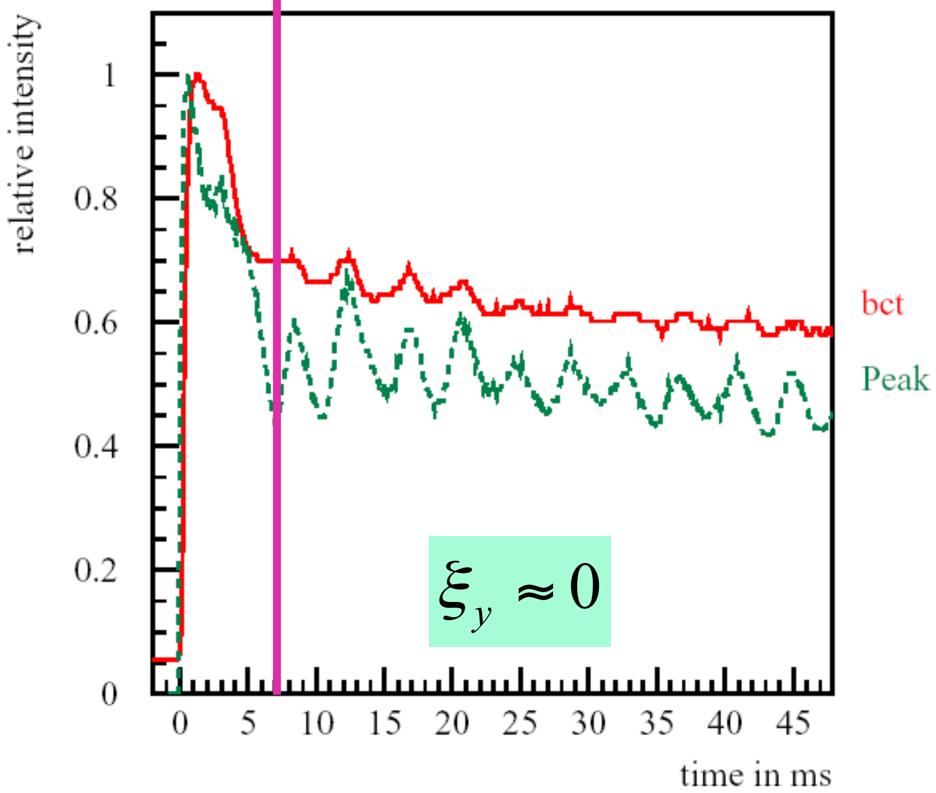
- **A fast vertical single-bunch instability can be observed at injection with very low positive chromaticity (believed to be TMCI)**

H. Burkhardt et al.

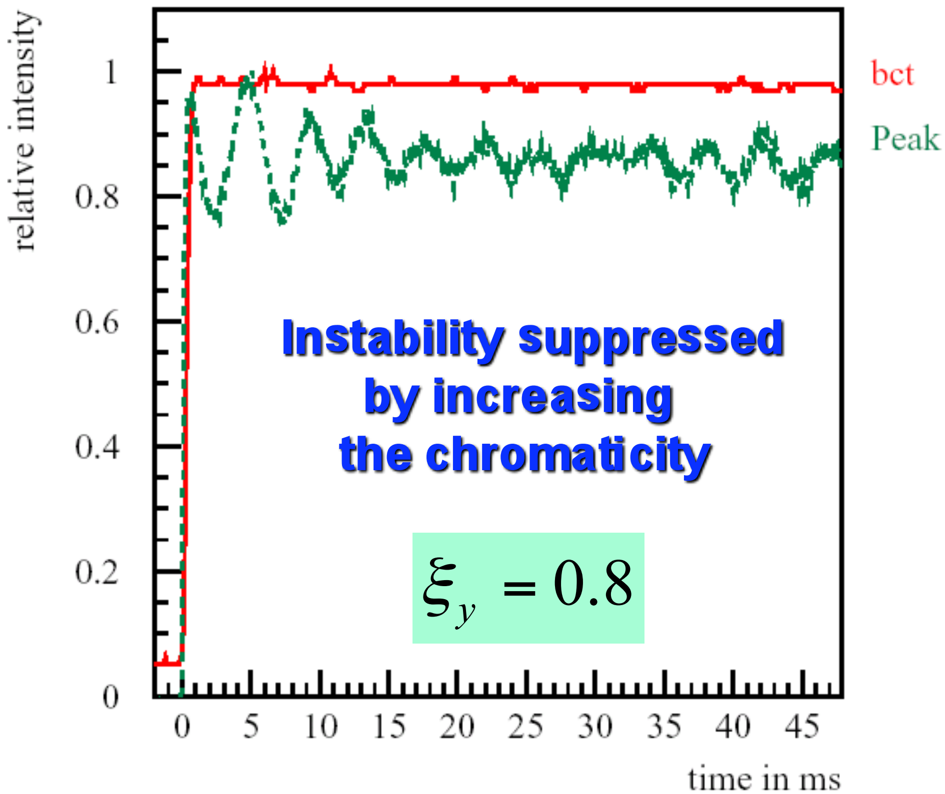
$p = 26$ GeV/c $N_b \approx 1.2\,10^{11}$ p/b

$\varepsilon_l \approx 0.2$ eVs $< \varepsilon_l^{LHC} = 0.35$ eVs

Synchrotron period ≈ 7 ms



$\xi_y \approx 0$



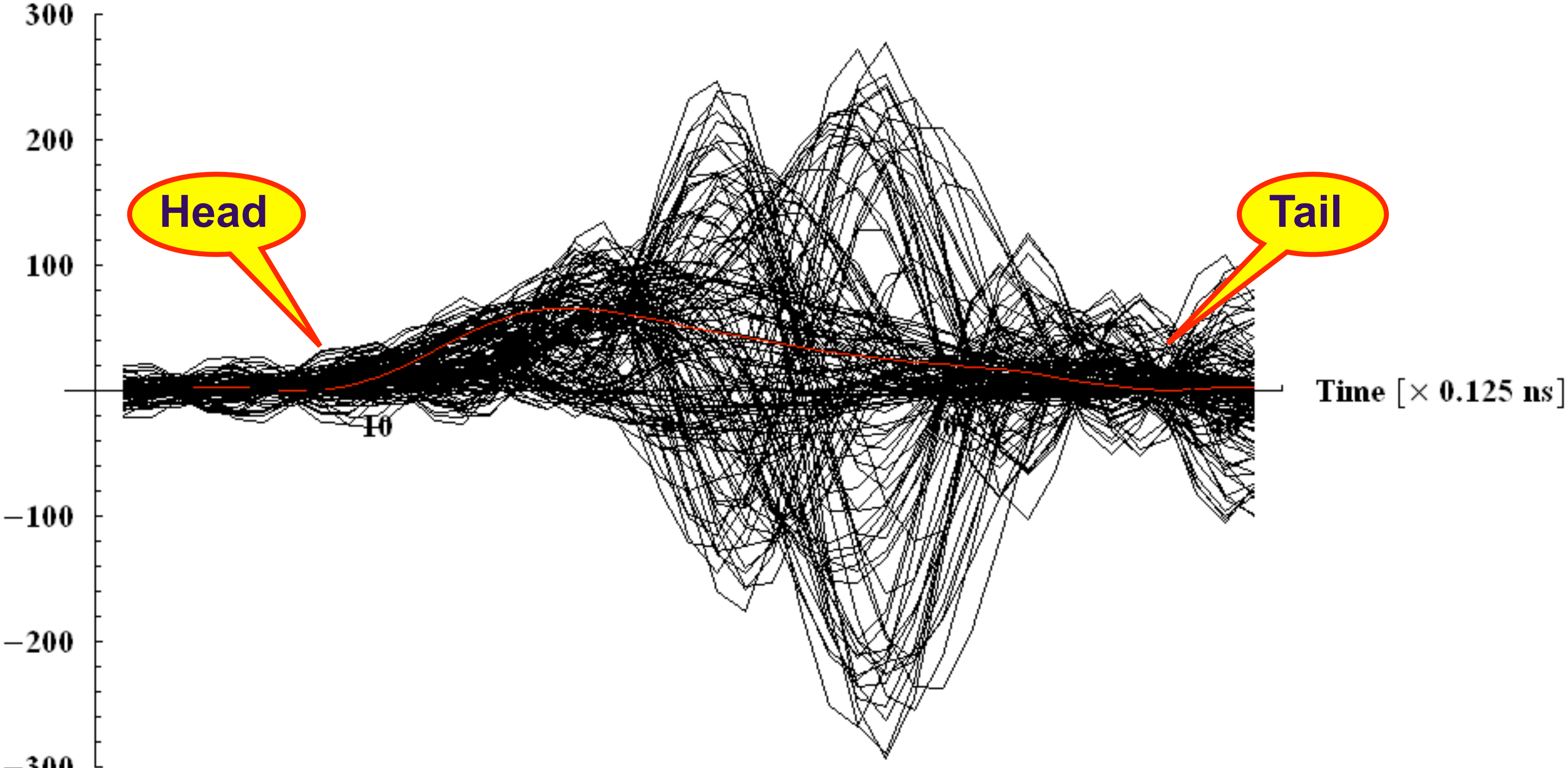
Instability suppressed by increasing the chromaticity

$\xi_y = 0.8$

SPS (2/5)

⇒ **Travelling-wave pattern along the bunch**

$\xi_y = 0.14$



1[st] trace (in red) = turn 2

SPS (3/5)

- **Assuming the coasting-beam formalism with peak values (and a Broad-Band impedance), the intensity threshold scaling (without space charge) is given by**

$$f_{\xi_y} = Q_{y0}\, f_0 \, \frac{\xi_y}{\eta}$$

$$N_b^{th,y} \propto \frac{f_r^{BB}}{\left| Z_y^{BB} \right|} \, \frac{|\eta|}{\beta_y} \, \varepsilon_L \left(1 + \frac{f_{\xi_y}}{f_r^{BB}} \right)$$

- Increase the chromatic frequency
- Chromaticity jump in case transition has to be crossed

Increase the beam longitudinal emittance (when possible)

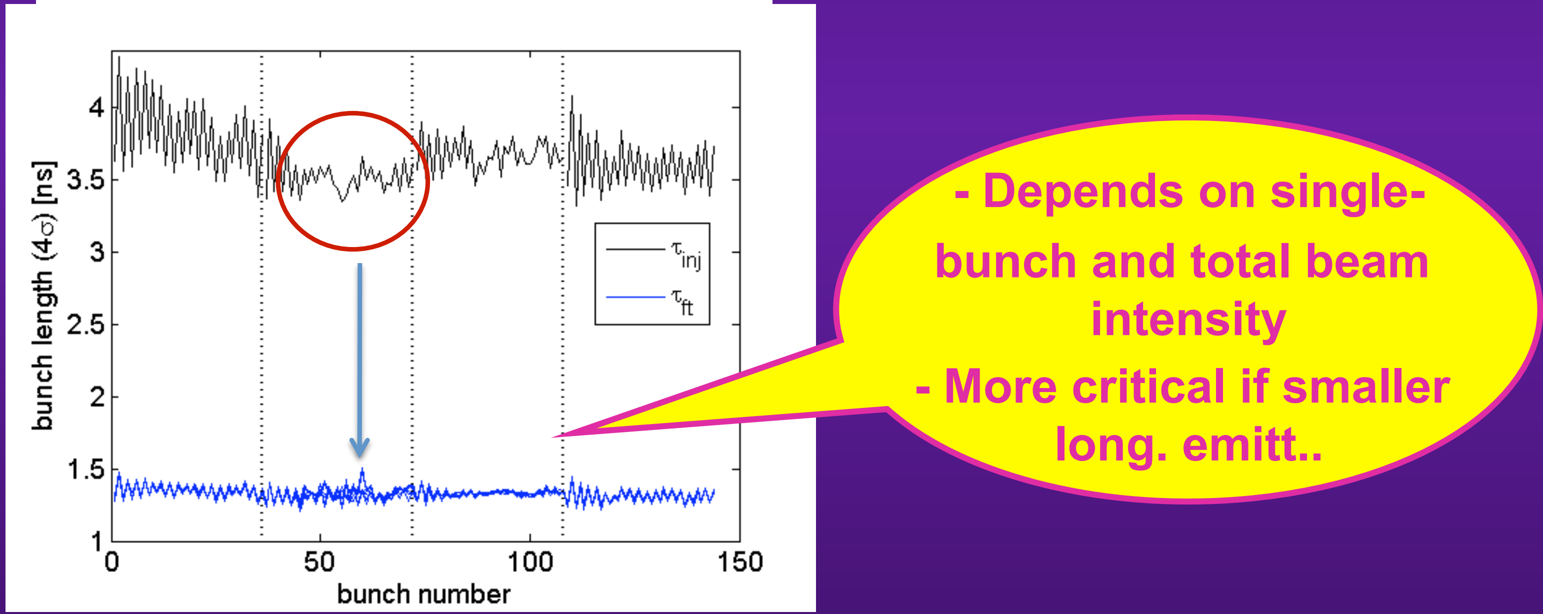
Try to decrease the impedance and/or increase the resonance frequency => Impedance reduction campaign

Change the optics to decrease the betatron function and/or go further away from transition => New optics studied

SPS (4/5)

- **Longitudinal instabilities**

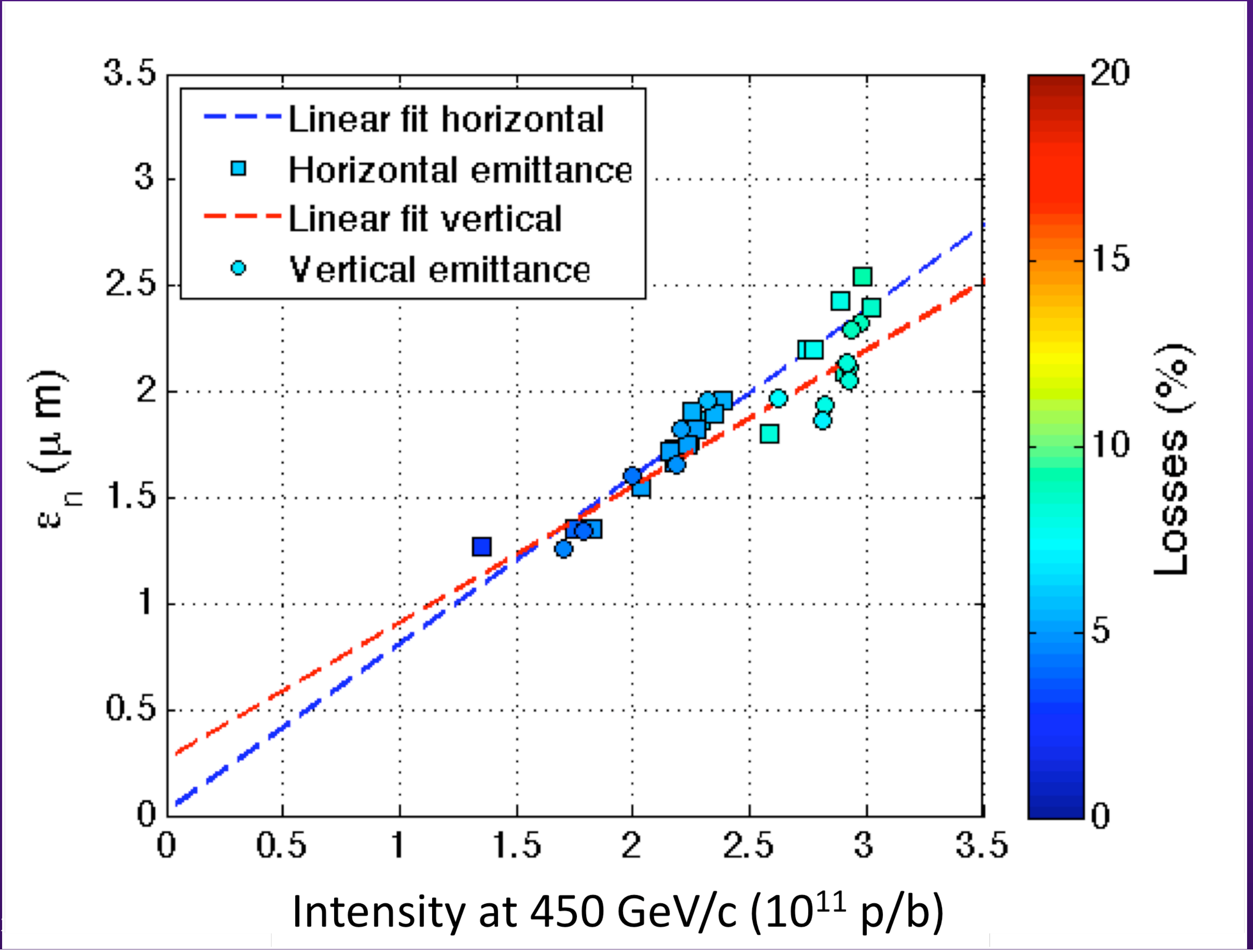
Elena Shaposhnikova et al.



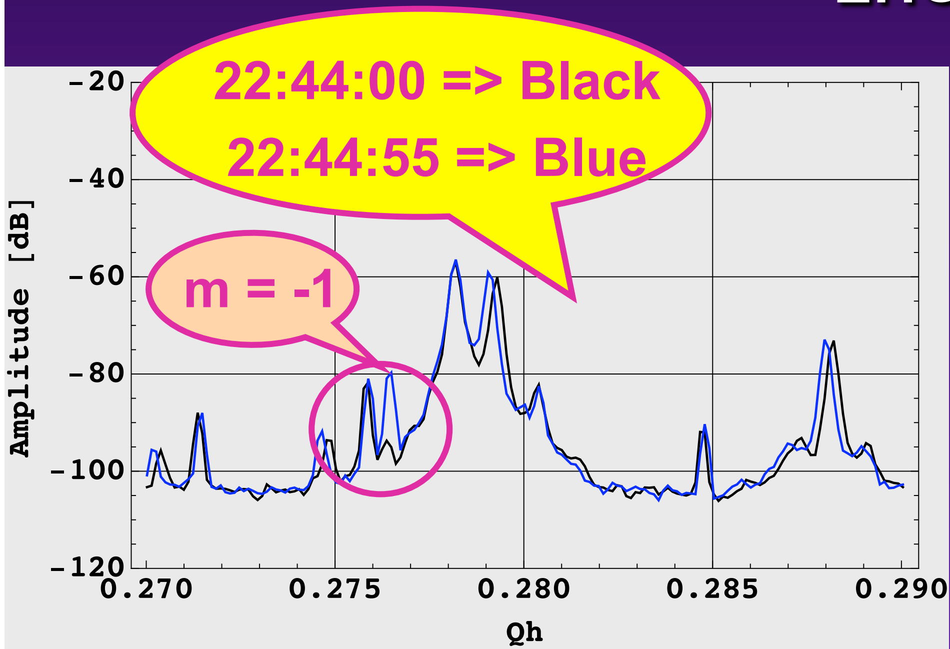
SPS (5/5)

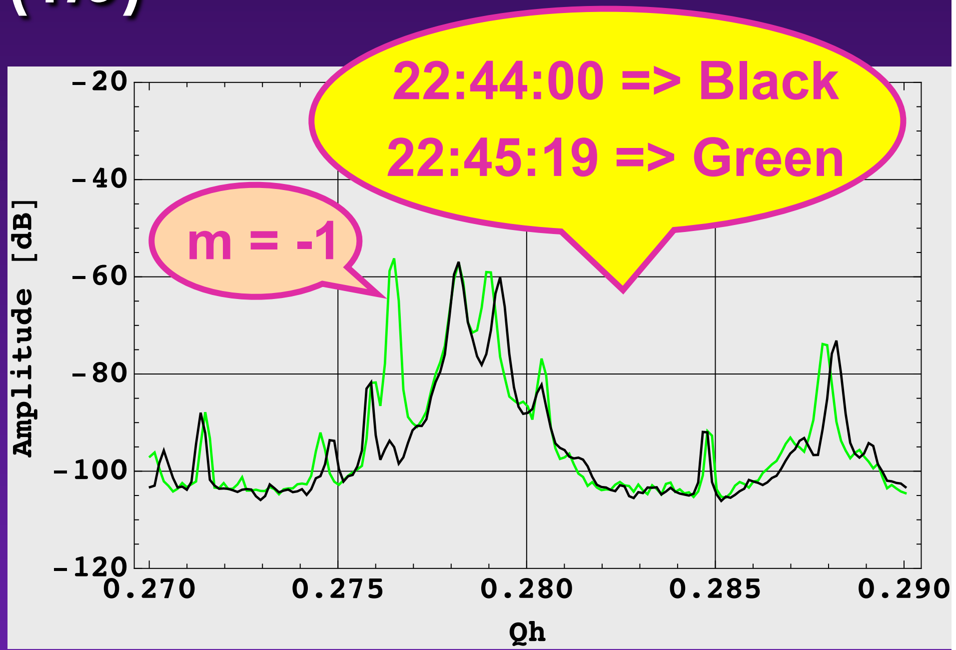
- Space charge studies

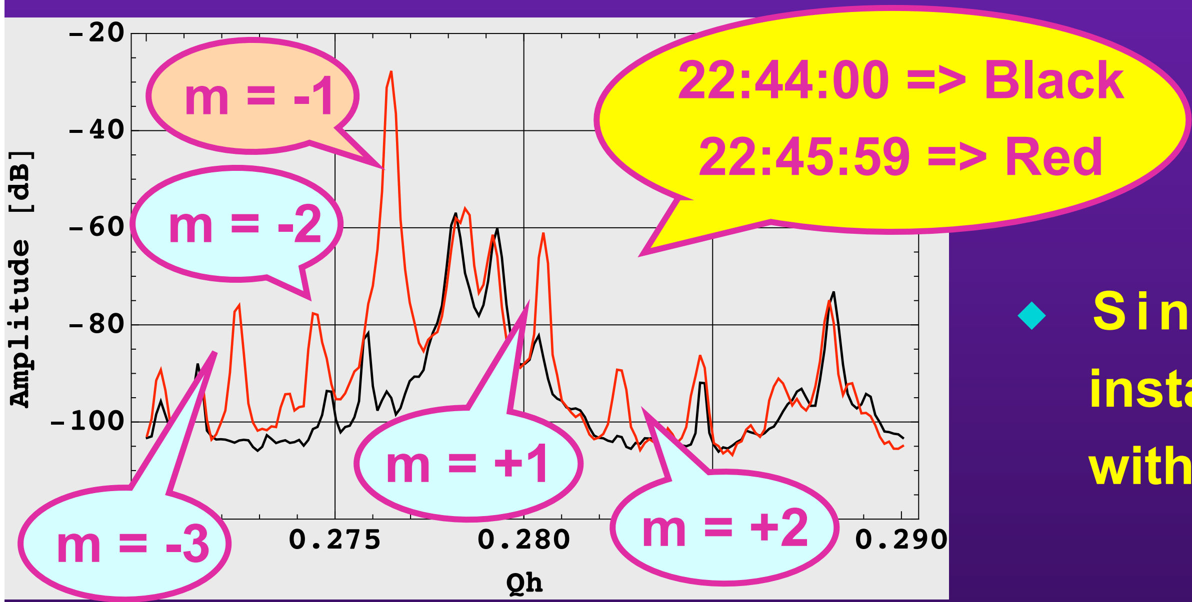
Hannes Bartosik et al. (new optics)



LHC (1/9)

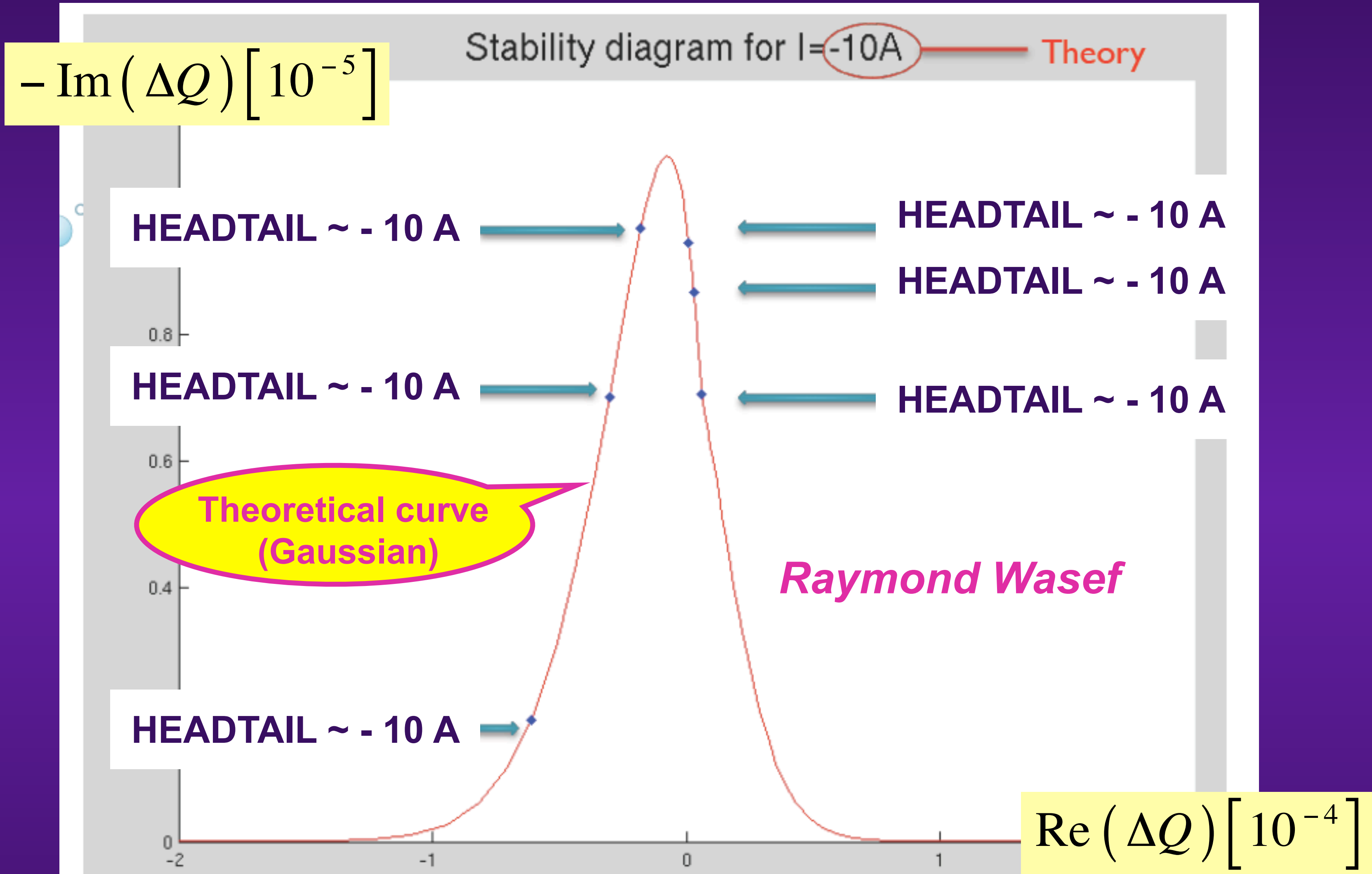






- **Single-bunch head-tail instability m = - 1 at 3.5 TeV without Landau octupoles**

LHC (2/9)



Benchmark between HEADTAIL and theoretical stability diagram (Berg-Ruggiero1996)

LHC (3/9)

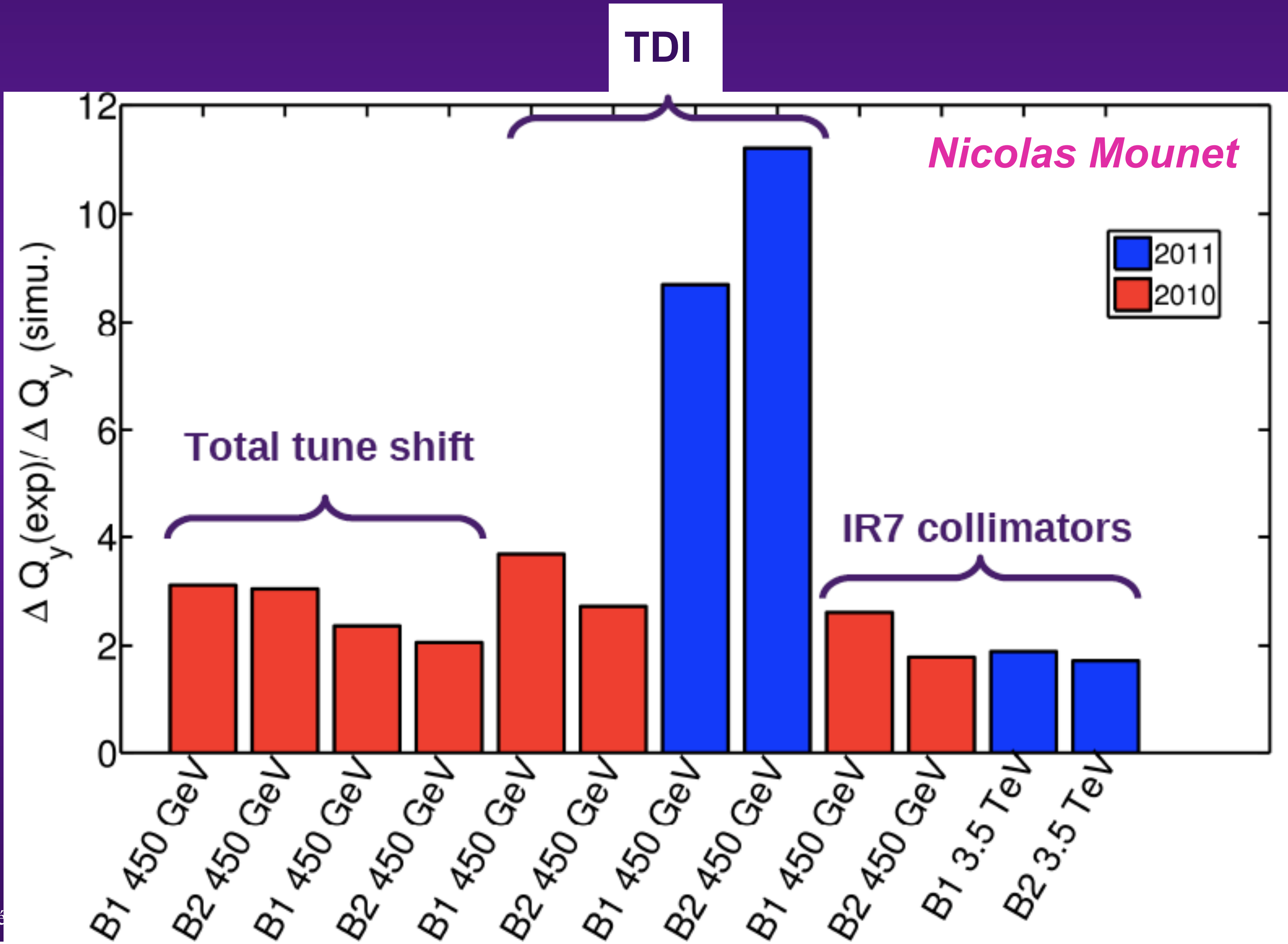
- **TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)**
  - **Landau octupoles used at 3.5 TeV to stabilize the beam**

Landau octupole current [A]	Beam 1	Beam 2
HEADTAIL predictions (Gaussian bunch)	120	100
Measurements	60	70

- **Simulations are more critical (but uncertainty on chromaticities)**
- **Remaining difference could maybe be explained by the Q" effect introduced by the octupoles (ongoing analyses)**

LHC (4/9)

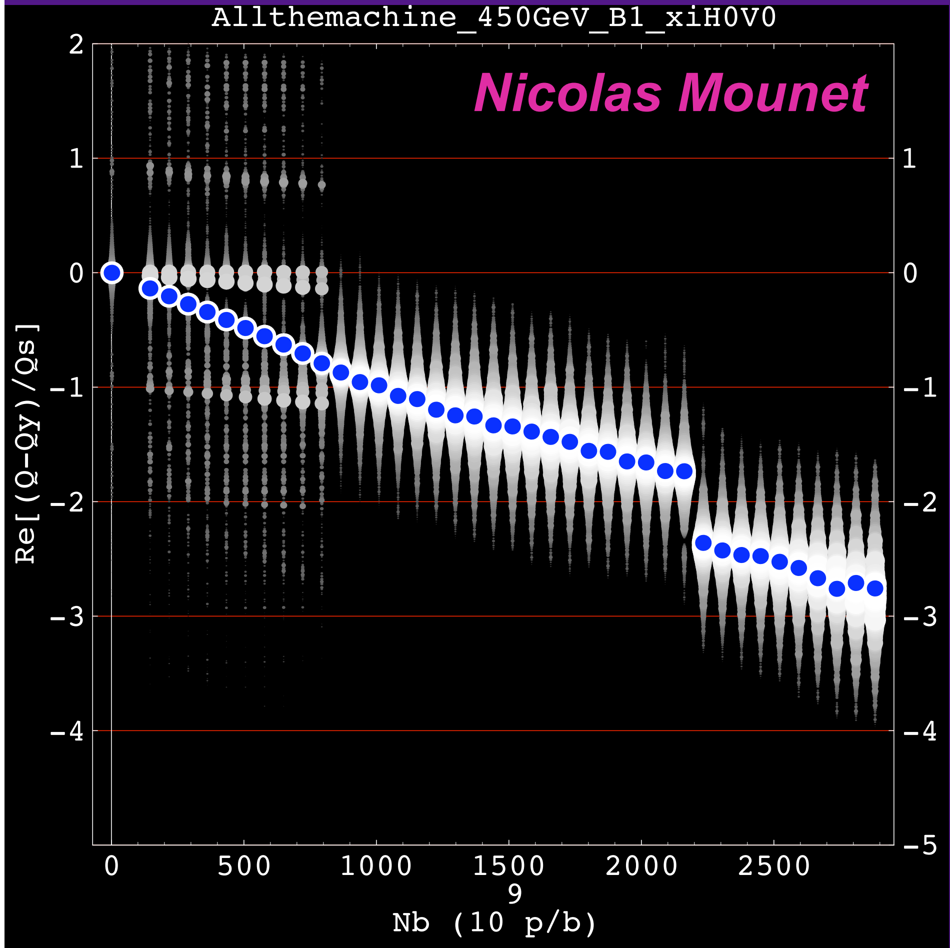
- **Transverse (real) coherent tune shift measurements**



LHC (5/9)

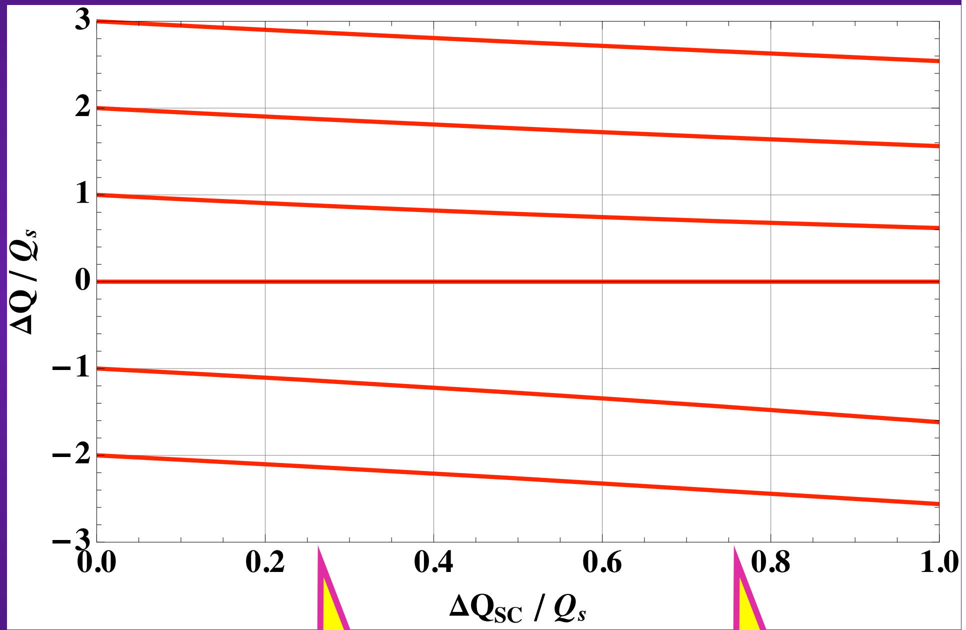
- **TMCI at injection**

WITHOUT SC



SC ONLY

(square-well air-bag, Blaskiewicz1998)

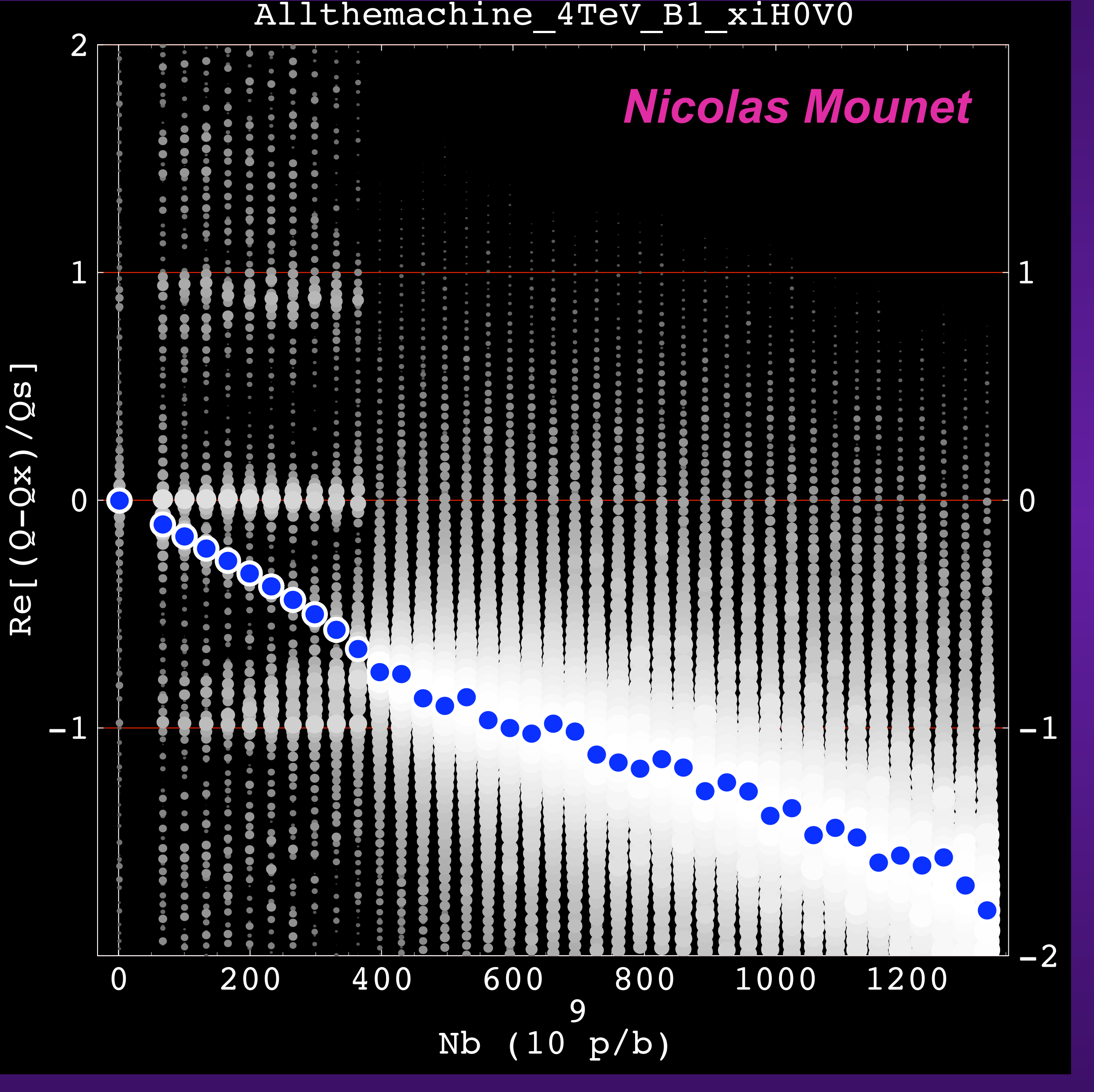


~ 0.26 (LHC inj. nominal)

~ 0.77 (LHC inj. 2012)

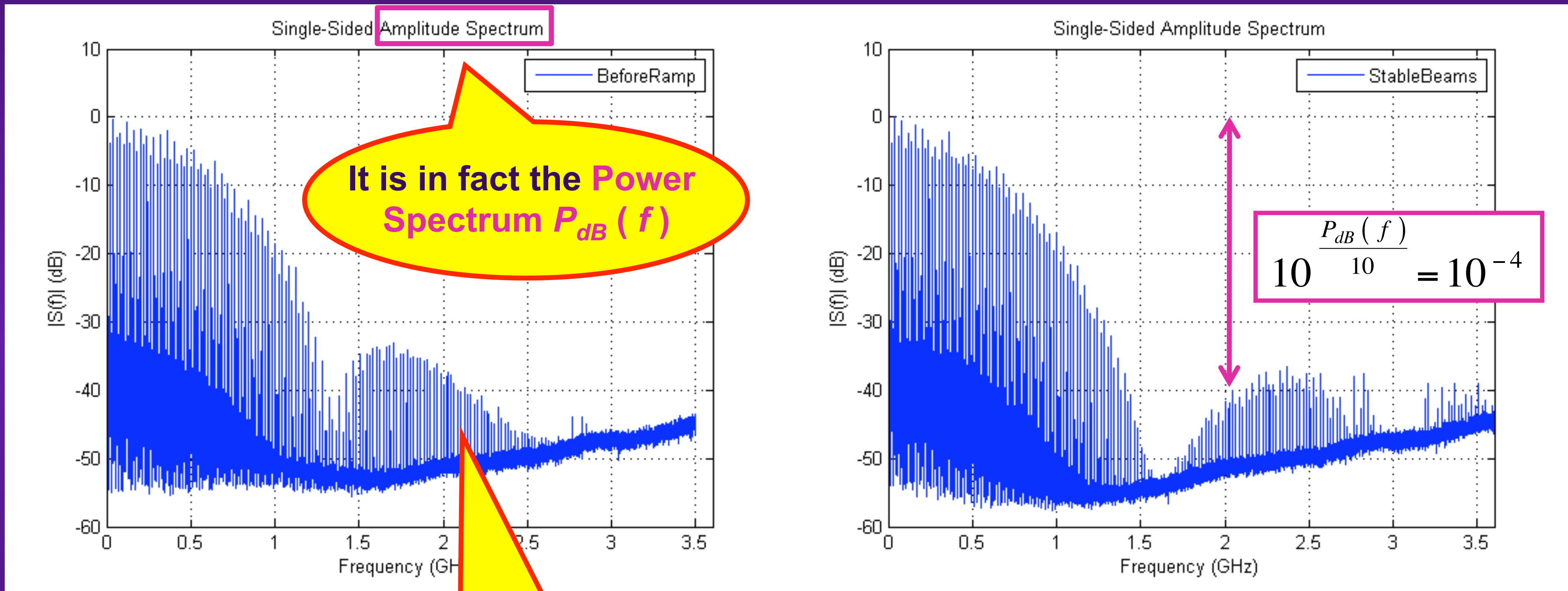
LHC (6/9)

- **TMCI at 4 TeV**



LHC (7/9)

- **RF HEATING**



It is in fact the Power Spectrum $P_{dB}(f)$

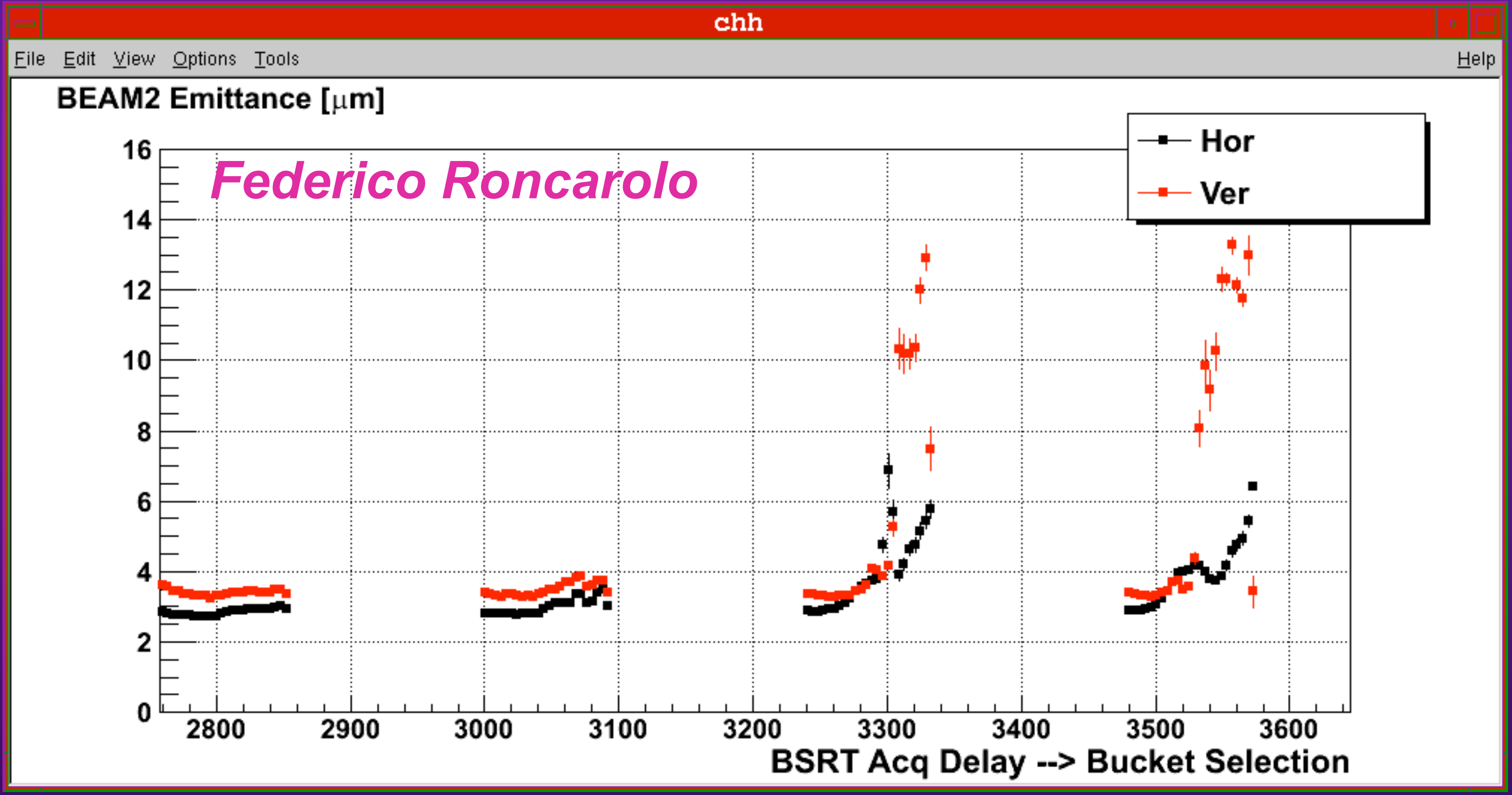
$$10^{\frac{P_{dB}(f)}{10}} = 10^{-4}$$

Coupled-bunch lines spaced by $M f_0$ ~ 20 MHz (for 50 ns bunch spacing) => It would be ~ 40 MHz for 25 ns

Themis Mastoridis and Philippe Baudrenghien

LHC (8/9)

- **e-cloud**
  - **Pressure rise, heat load in the arcs, beam instability, emittance growth and synchronous phase shift**
  - **Successful dedicated scrubbing run for physics operation in 2011**



LHC (9/9)

- **e-cloud summary (at the end of 2011)**

	Uncoated straight section	**Arc dipoles**
Estimated $\delta_{\max}$	1.35	1.52
Threshold $\delta_{\max}$ (25ns, 450 GeV)	1.25	1.45
Threshold $\delta_{\max}$ (25ns, 3.5 TeV)	1.22	1.37
Threshold $\delta_{\max}$ (50ns, 450 GeV)	1.63	2.2
Threshold $\delta_{\max}$ (50ns, 3.5 TeV)	1.58	2.1

- **Prediction for the scrubbing time needed for 25 ns physics operation: ~ 20 h of beam time (i.e. ~ 2 weeks)**