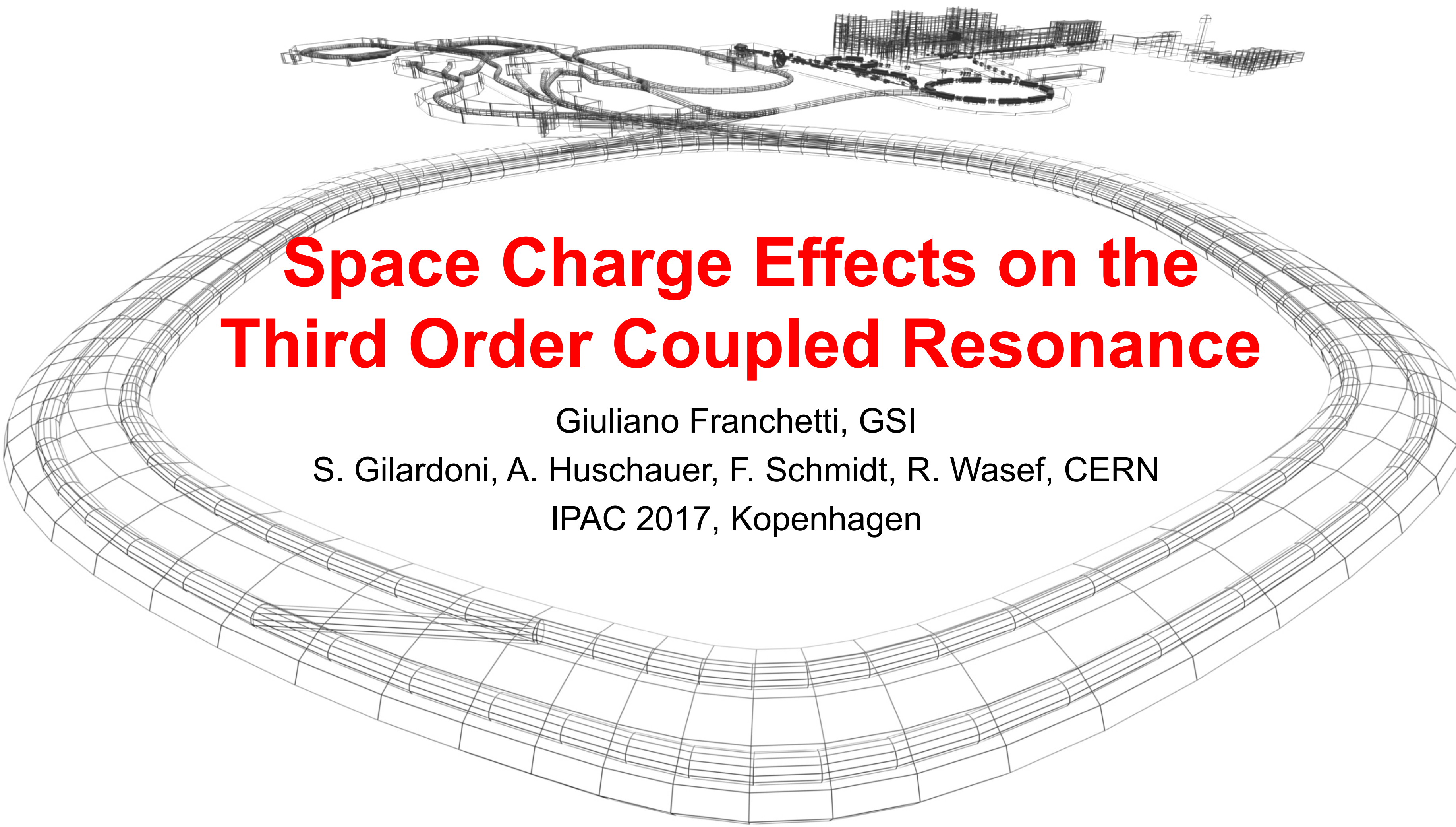
GSI Helmholtzzentrum für Schwerionenforschung GmbH



Space Charge Effects on the Third Order Coupled Resonance

Giuliano Franchetti, GSI

S. Gilardoni, A. Huschauer, F. Schmidt, R. Wasef, CERN

IPAC 2017, Kopenhagen

Acknowledgments

GSI	O. Choriny, W. Bayer, O. Boine-Frankenheim, C. Omet, B. Franczak, P. Forck, T. Giacomini, I. Hofmann, F. Kesting, M. Kirk, H. Kollmus, T. Mohite, A. Parfenova, P. Schuett, P. Spiller
CERN	H. Bartosik, E. Benedetto, C. Carli, R. Cappi, M. Giovannozzi, S. Gilardoni, A. Huschauer, M. Martini, E. Metral, R. Steerenberg, G. Rumolo, F. Schmidt, R. Wasef, F. Zimmermann
ITEP	P. Zenkevich, A.Bolshakov, V. Kapin
Univ. Loughborough	A.I. Neishtadt
Univ. Bologna	G. Turchetti, C. Benedetti, A. Bazzani

Overview

The case for accelerators and projects

Space charge effect in nonlinear rings

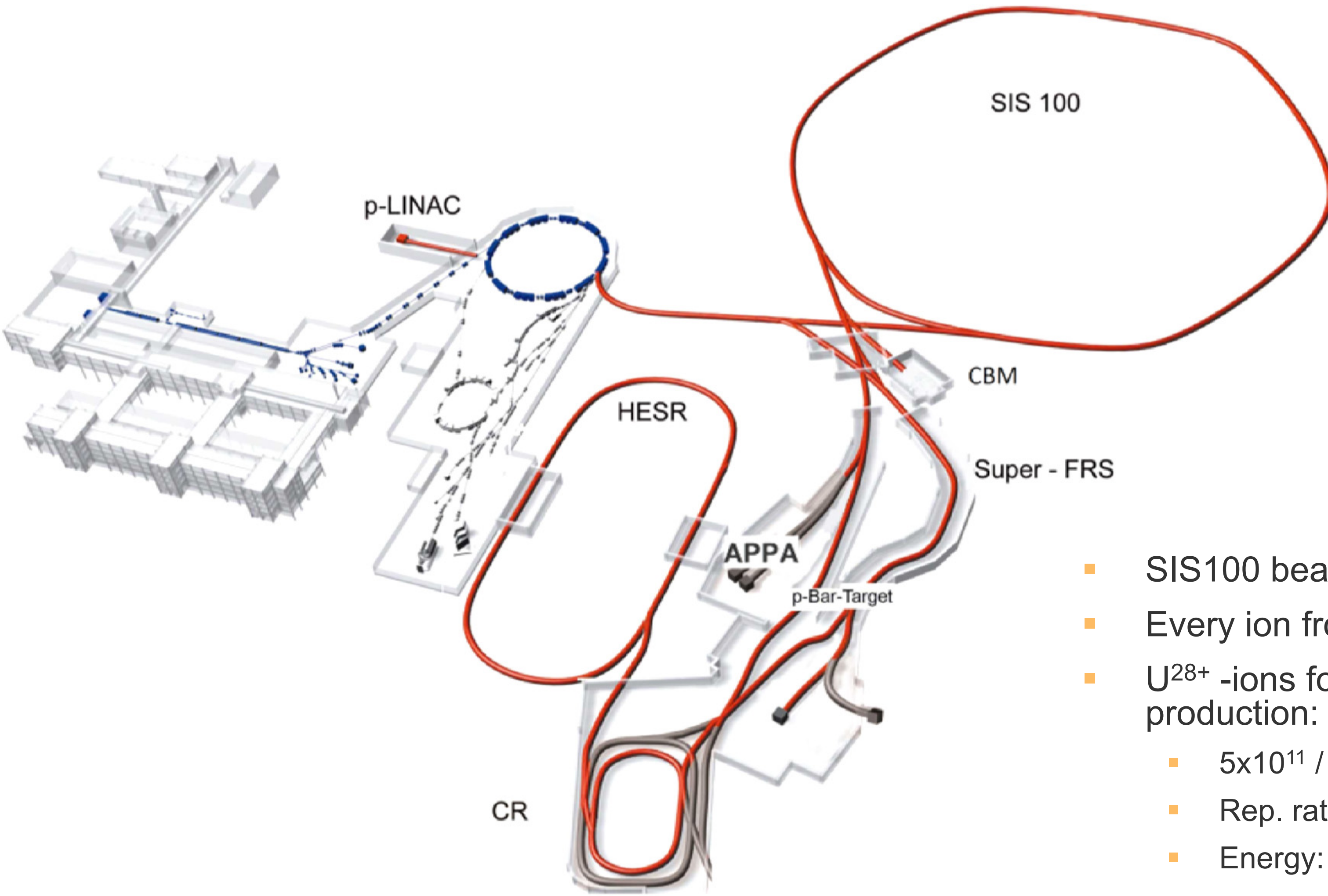
One dimensional resonances

The coupled resonances

Experiment and simulations

Conclusion / Outlook

Motivation: the FAIR project



- SIS100 beam parameters:
- Every ion from p to U
- U^{28+} -ions for RIB production:
  - $5x10^{11}$ / cycle
  - Rep. rate: 0.5 Hz
  - Energy: 400–2715 MeV/u

Motivation: the FAIR project

FAIR @ IPAC 2017

GSI

Winfried A. Barth - TUPVA055 Further Investigations for a Superconducting cw-LINAC at GSI
Lars Bozyk - TUPVA056 Ionization Loss and Dynamic Vacuum in Heavy Ion Synchrotrons
Stephanie Deveaux - MOPIK127 FAIR Risk Management as a Proactive Steering Tool for the Large Scale Multi Project
Manuel Heilmann - MOPVA054 High Power RF Coupler for the CW-Linac Demonstrator at GSI
Manuel Heilmann - TUPVA057 Design Study for a Prototype Alvarez-Cavity for the Upgraded Unilac
Egbert Fischer - WEOCB2 Superconducting Magnets at FAIR
Michael Frey - THPIK015 Prototype Results of the ESR Barrier-Bucket System
Carl M. Kleffner - TUPVA058 The Status of the FAIR pLinac
Harald Klingbeil - THPIK016 Status of the SIS100 RF Systems
Sergio Mauro - THPIK017 Field Uniformity Preservation Strategies for the ESS DTL: Approach and Simulations
Carsten Omet - WEPVA029 SIS100 Tunnel Design and Status
David Ondreka - TUPVA059 Overcoming the Space Charge Limit: Development of an Electron Lens for SIS18
Thomas Reichert - MOPAB034 SIS-100 BPM System: Design and Realization
Stephan Reimann - THPAB096 Automatized Optimization of Beam Lines Using Evolutionary Algorithms
Anna Rubin - THPVA003 Status of the Beam Dynamics Design of the New Post-Stripper DTL for GSI-FAIR
Mariusz Sapinski - TUPVA060 Upgrade of GSI Hades Beamline in Preparation for High Intensity Run
Marcus Schwickert - MOPAB035 Status of Beam Diagnostics for SIS100Bernd
Robert Schlei - TUPIK045 Closed Orbit Feedback for FAIR - Prototype Tests at SIS18
Peter J. Spiller - WEPVA030 FAIR SIS100 - Features and Status of Realisation
Ralph Jeffrey Steinhagen - TUPIK046 Beam-Based Feedbacks for FAIR - Prototyping at the SIS18
Markus Vossberg - TUPIK047 FAIR Control Centre (FCC) - Concepts and Interim Options for the Existing GSI Main Control Room
Natalya Winters - MOPIK128 Integrated Project Planning as a Central Steering Tool for the Large Scale Multi Project FAIR
Stepan Yaramyshev - TUPVA061 Beam Dynamics Study for the HIM&GSI Heavy Ion sc cw-Linac

TUD

Alexander Andreev - THPAB097 Phase Calibration of Synchrotron RF Signals
Jens Harzheim - WEPVA047 Input Signal Generation for Barrier Bucket RF Systems at GSI
Erika Kazantseva - WEPAB026 SUSPSIK049 BRho-Dependent Taylor Transfer Maps for Super-FRS Dipole Magnets
Benjamin Frederic Reichardt - TUPIK048 Longitudinal Beam Stabilization at FAIR by Means of a Derivative Estimation
Thibault Ferrand - THPVA041 Progress in the Bunch-to-Bucket Transfer Implementation for FAIR
Herbert De Gersem - THPIK018 Simulating Cross-Magnetization Effects in Combined-Function Accelerator Magnets
Kerstin Gross - THPAB098 Test Setup for Automated Barrier Bucket Signal Generation
Nicolai Schweizer - THPVA042 Modular Robot for Visual Inspection of the Vacuum Beamline of a Particle Accelerator
William Stem - THPVA004 Pushing the Space Charge Limit:Electron Lenses in High-Intensity Synchrotrons?
Dinu Mihailescu Stoica - THPAB100 On the Impact of Empty Buckets on the Ferrite Cavity Control Loop Dynamics in High Intensity Hadron Synchrotrons

IAP-Frankfurt

Ali Mohammad Almomani - TUPVA064 Updated Cavities Design for the FAIR p-Linac
Markus Baschke - TUPAB147 The Final RF-Design of the 36 MHz-HSI-RFQ-Upgrade at GSI
Daniel Koser - THPIK021 SUSPSIK091 Structural Mechanical Analysis of 4-Rod RFQ Structures in View of a Newly Revised CW RFQ for the HLI at GSI

ITEP

Sergey Markovich Polozov - TUPAB013 Beam Dynamics Study and Electrodynamics Simulations for the CW RFQ

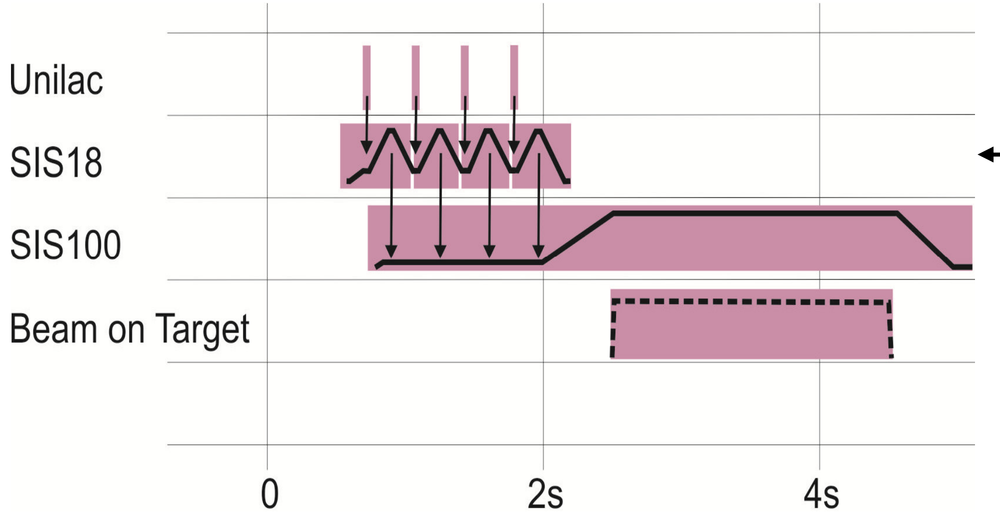
eters:

MeV/u

GSI Anschluss FAIR

Intensity Requirements in SIS18 for FAIR

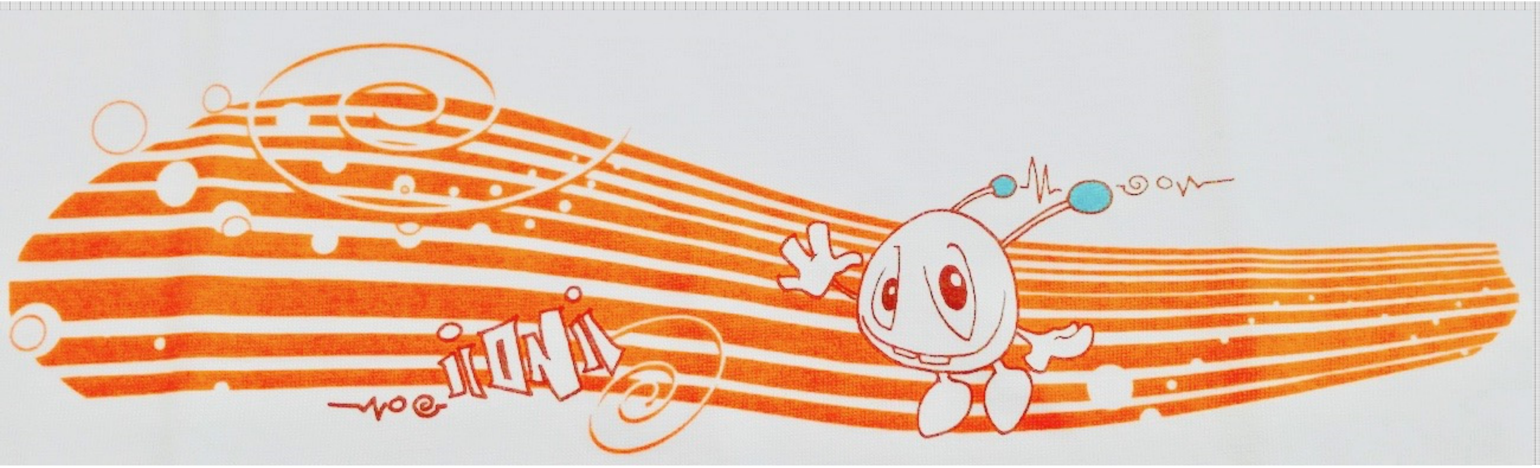
FAIR stage	Today	Stage 0 (Existing Facility after upgrade)	Stage 1 (Existing Facility supplies Super FRS, CR, [HESR])	Stage 2 (SIS100 Booster)
Reference Ion	U^{73+}	U^{73+}	U^{73+}	U^{28+}
Maximum Energy	1 GeV/u	1 GeV/u	1 GeV/u	0.2 GeV/u
Maximum Intensity	$4x10^{9}$	$2x10^{10}$	$2x10^{10}$	$1.5x10^{11}$
Repetition Rate	0.3 - 1 Hz	1 Hz	1 Hz	2.7 Hz



SIS100:
$5x10^{11}$ U^{28+} ions per cycle
$3x10^{11}$ U^{28+} ions per second

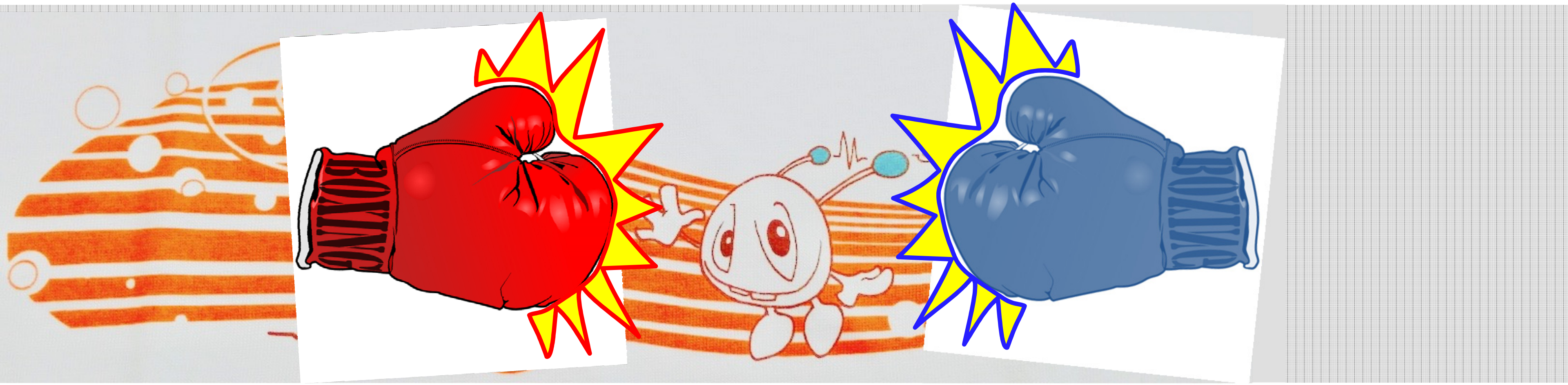
Accelerator case

High intensity bunch stored for many turns



Accelerator case

High intensity bunch stored for many turns



Particles subject to
Space charge

Space charge tune-shift
Amplitude dependent detuning

Structure resonances
Collective effects
impedances

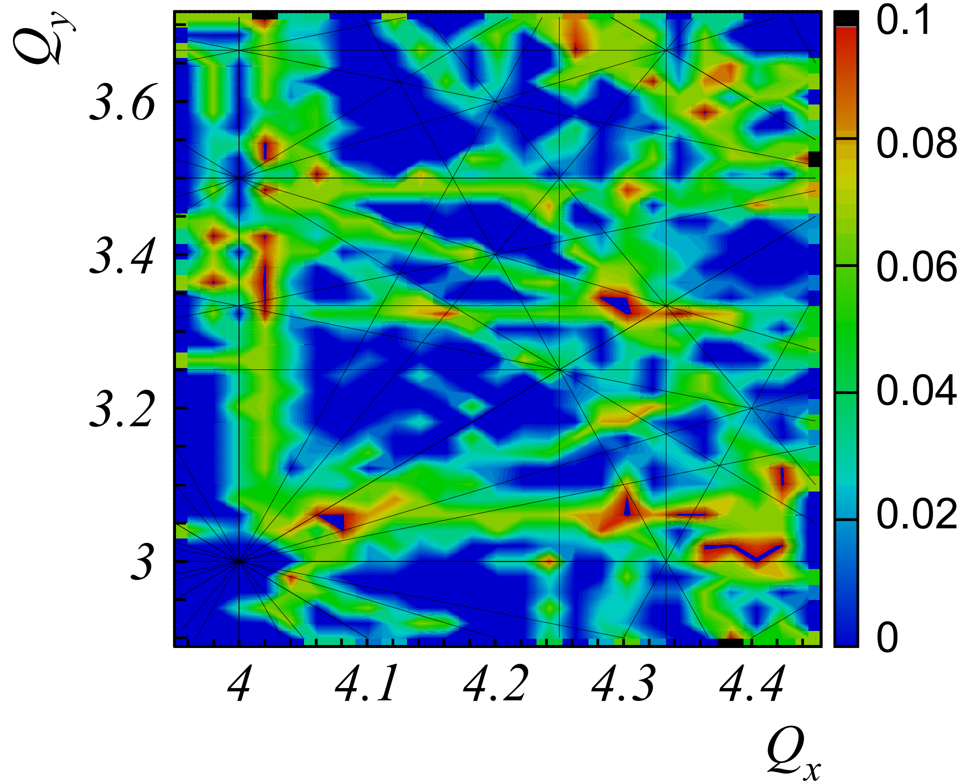
Particles are subject to the
nonlinear motion

Error and structure resonances
Dynamic aperture

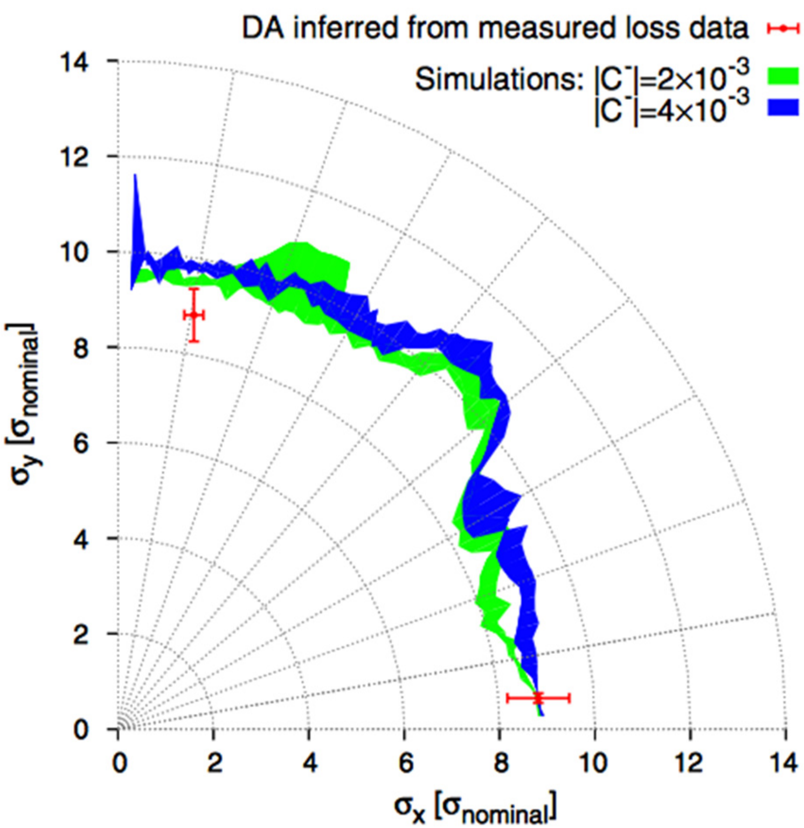
Chromatic effects

Single particle nonlinear dynamics

Error / Structure Resonances
SIS18



Dynamic Aperture: LHC



Lattice induced nonlinear resonances

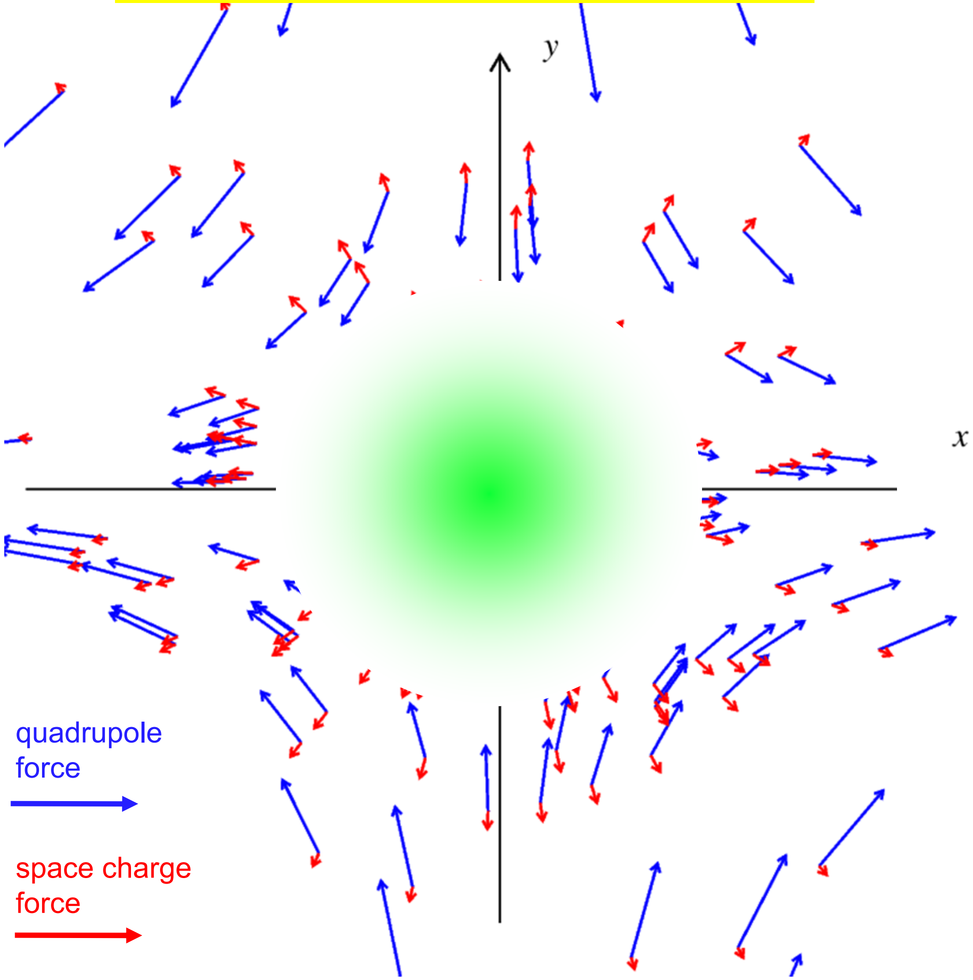
$$n_x Q_{x0} + n_y Q_{y0} = m$$

G. Guignard, CERN 78-11, (1978); A. Bazzani et al., CERN94-02 (1994).

E. H. Maclean, R. Tomás, F. Schmidt, and T. H. B. Persson
Phys. Rev. ST Accel. Beams **17**, 081002

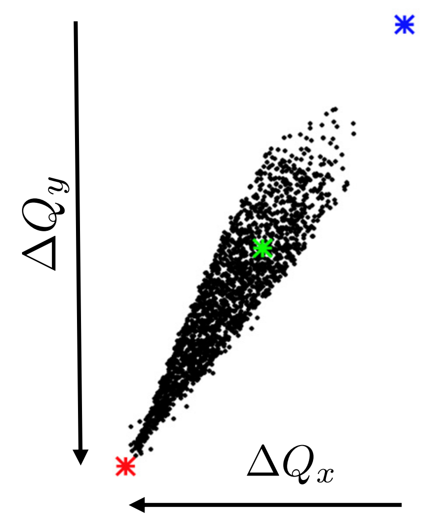
Space charge vs. magnets force

Example in a focusing quadrupole



Space charge tune-spread

Gaussian distribution

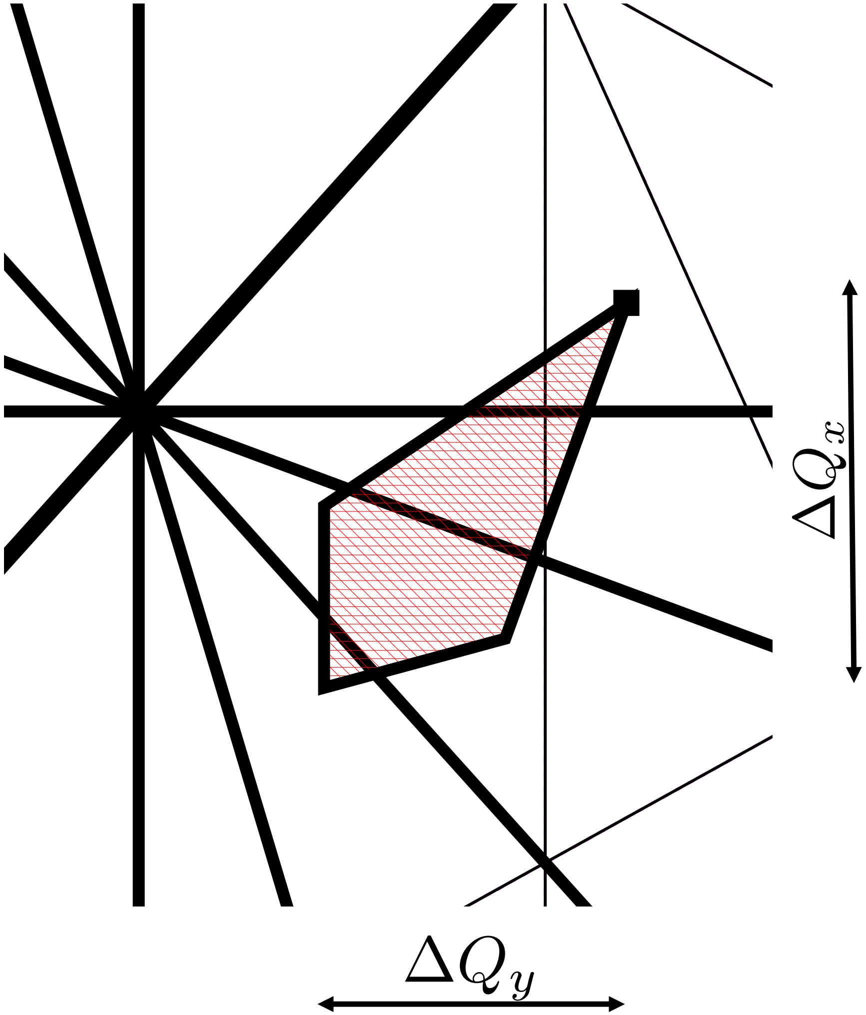


SIS100

$\Delta Q_x \sim -0.2$

$\Delta Q_y \sim -0.3$

The space charge limit

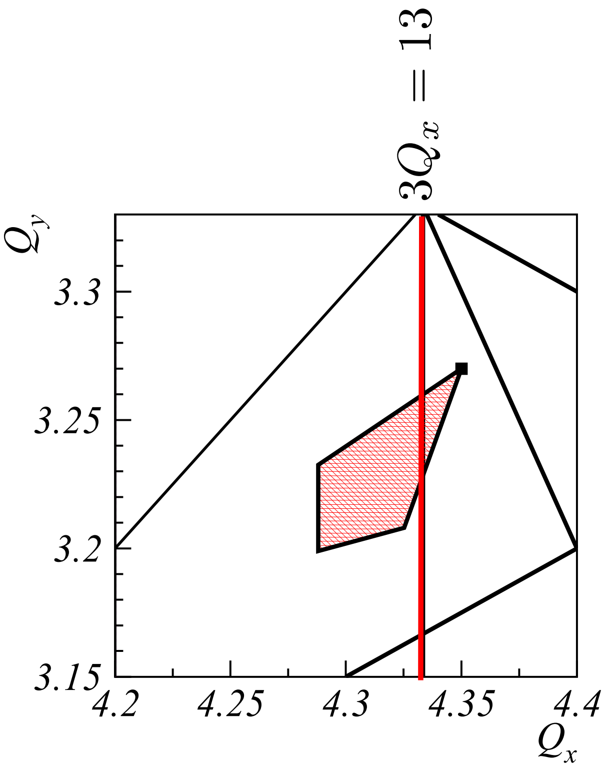


Tolerable space charge tune-shift in order not to overlap with resonances

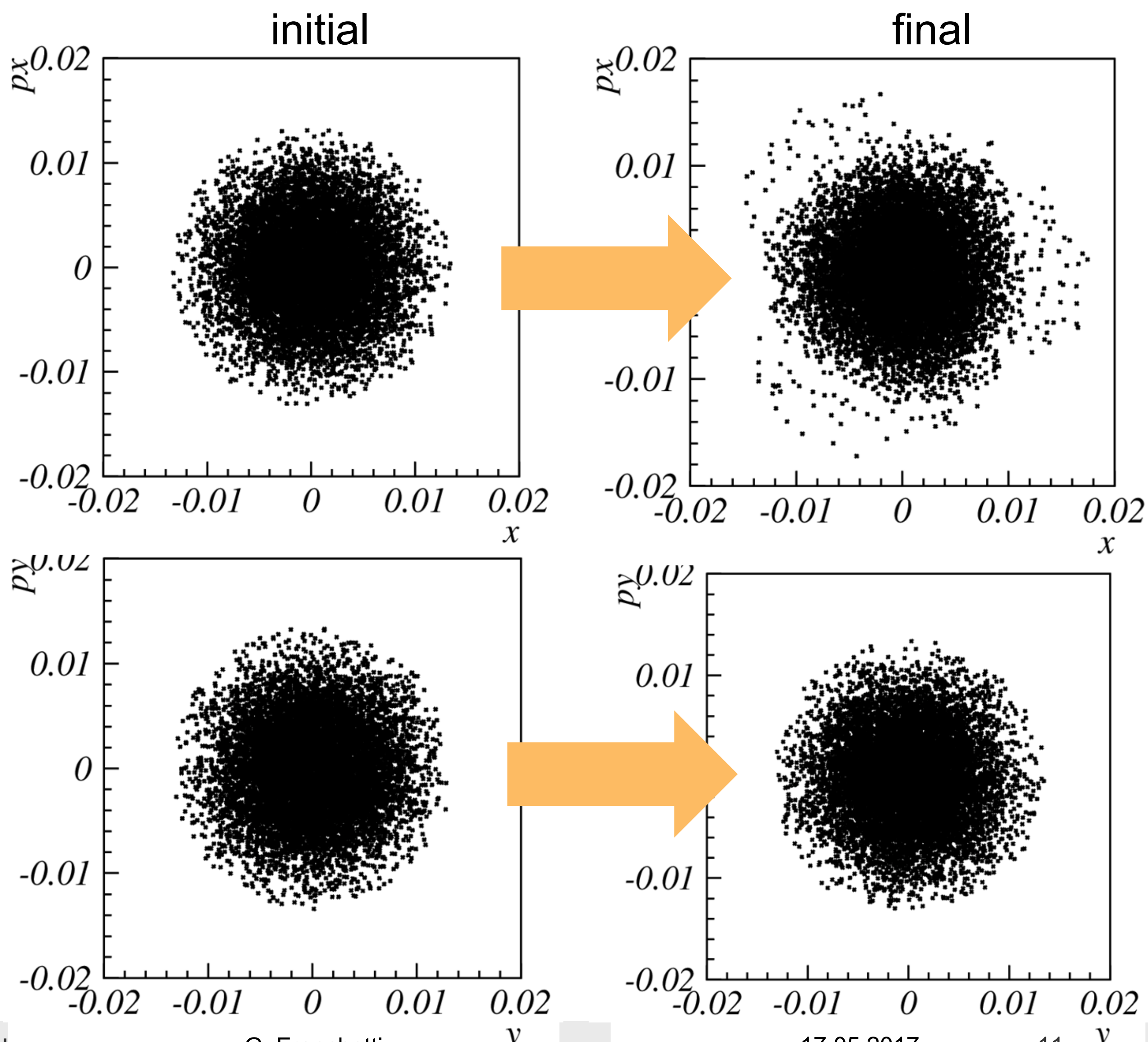
If resonances are too many, or the incoherent tune-shift is too large there is always a resonance overlapping

What happens if space charge tune-spread overlaps a resonance?

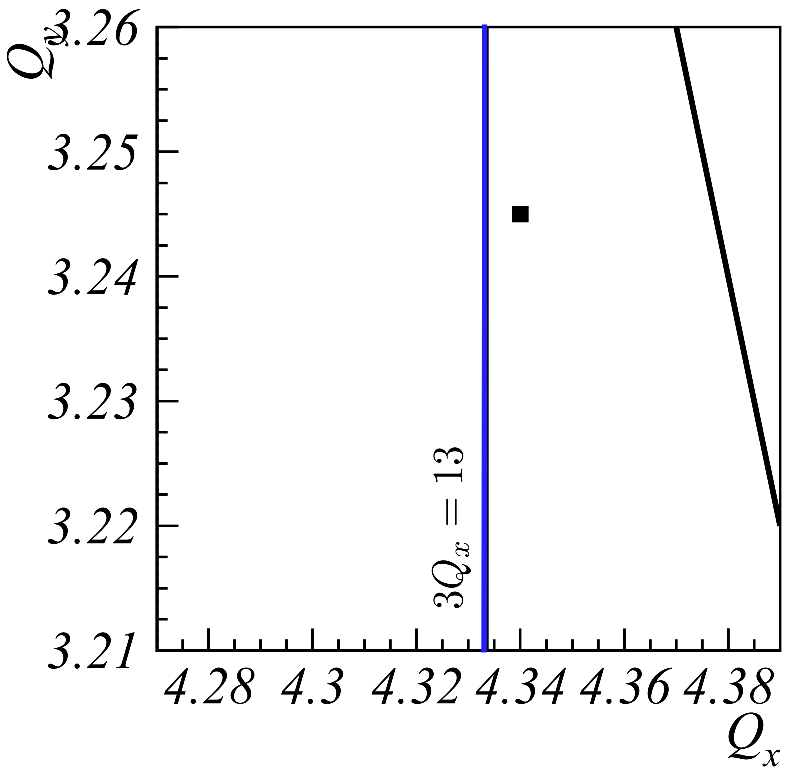
Example: Coasting beam and 1D resonance

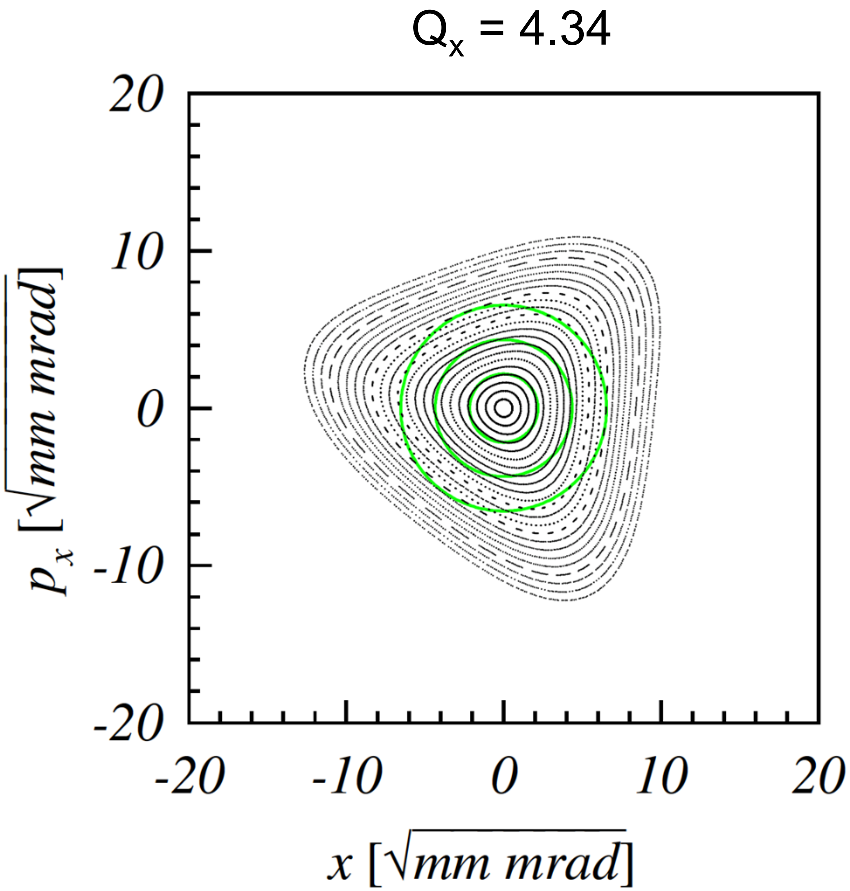


PIC simulation

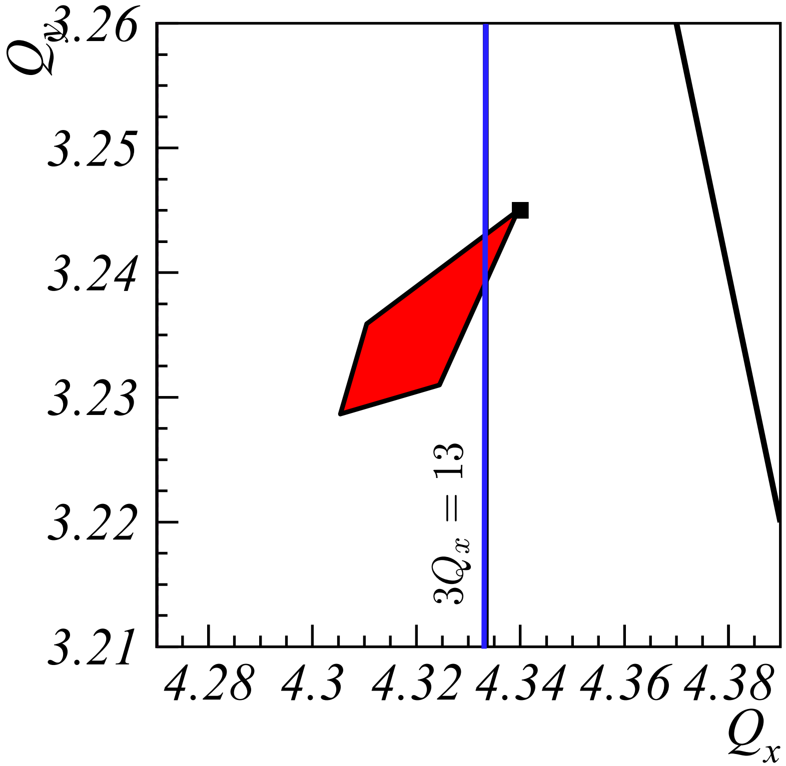


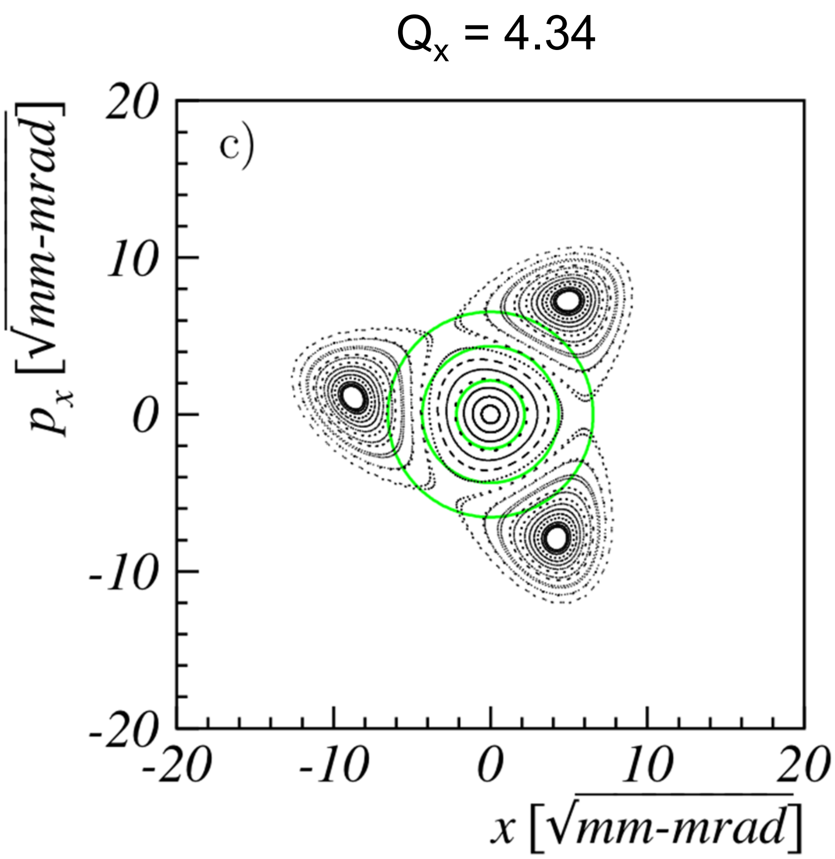
Intrepretation





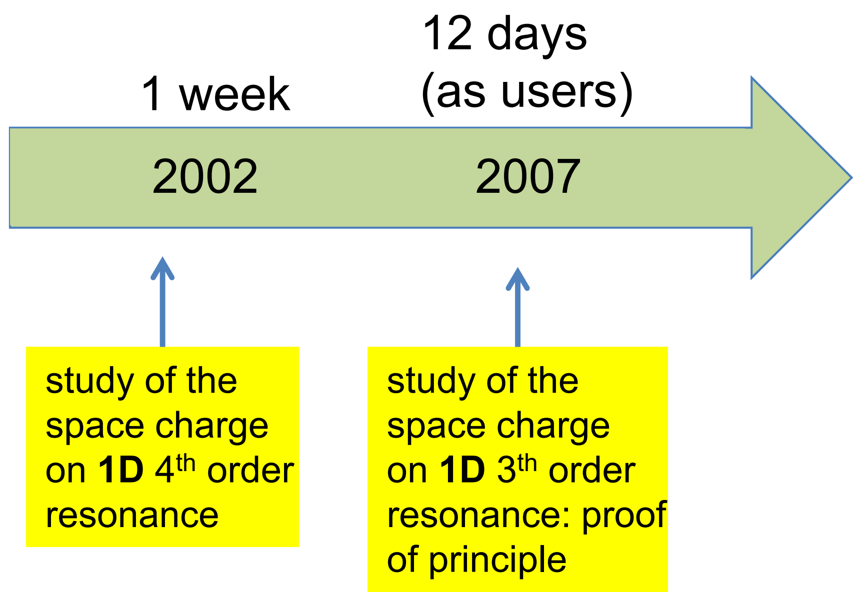
Interpretation





Above the resonance: Large stable 3rd order islands are created

The quest of the incoherent effects of space charge

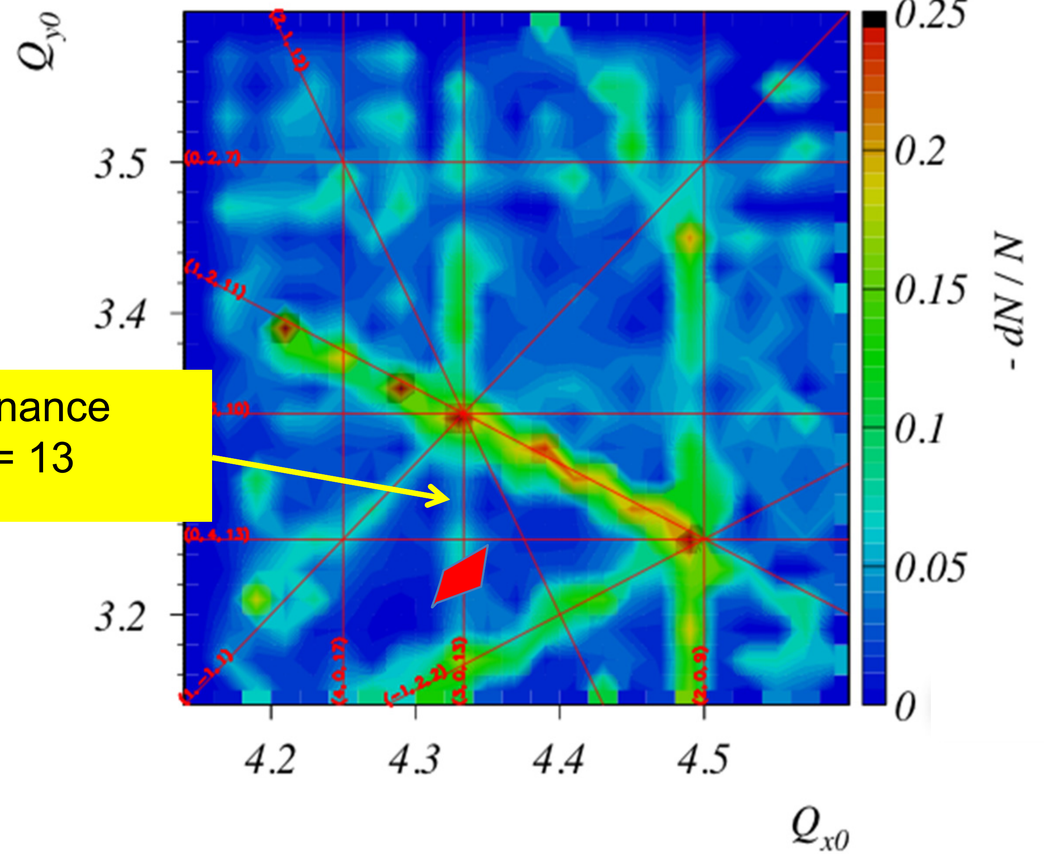


PS

SIS18

1D third order resonance

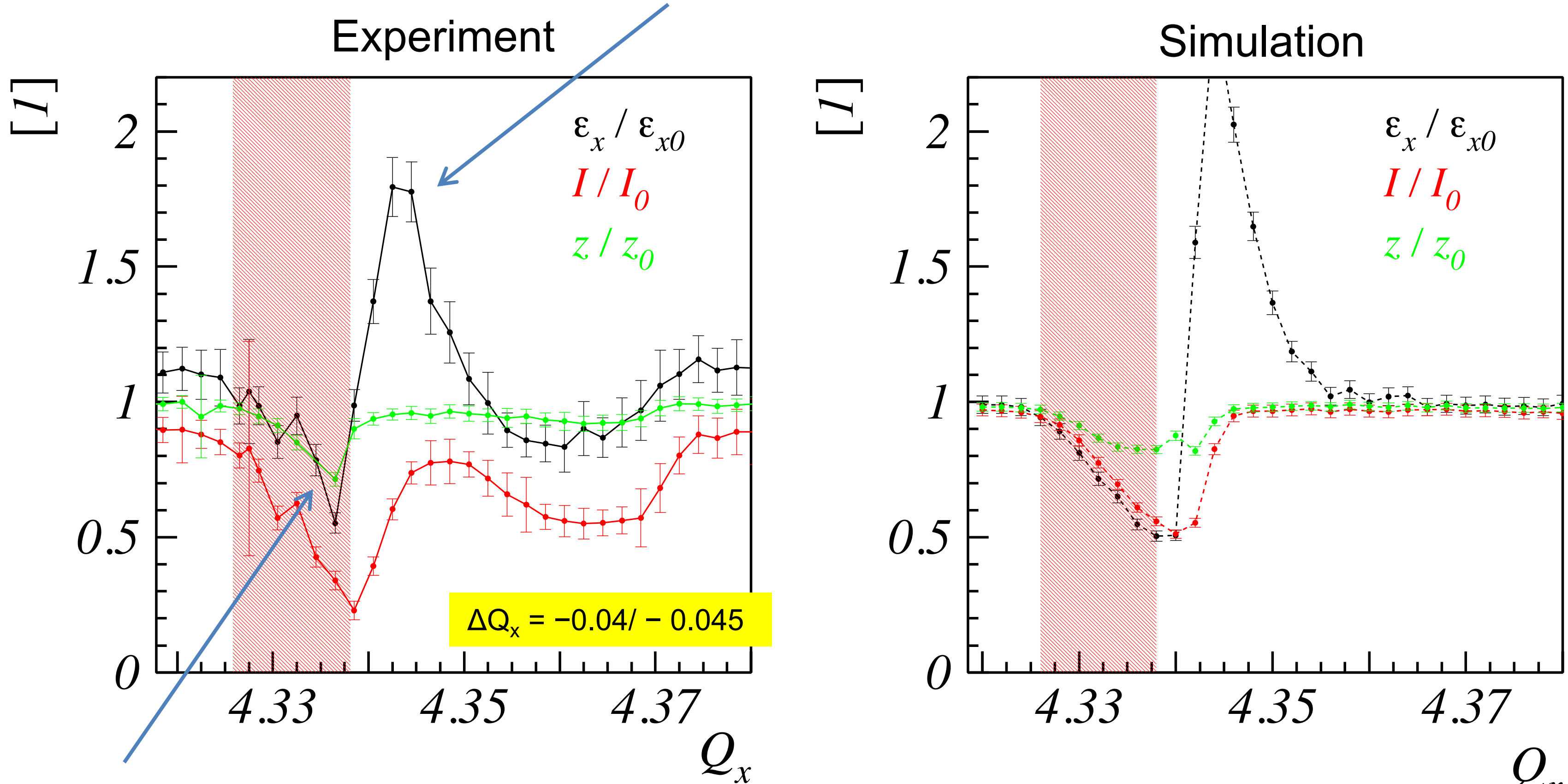
Experiment



Resonance
$3\ Q_x = 13$

Bunched beam at high intensity

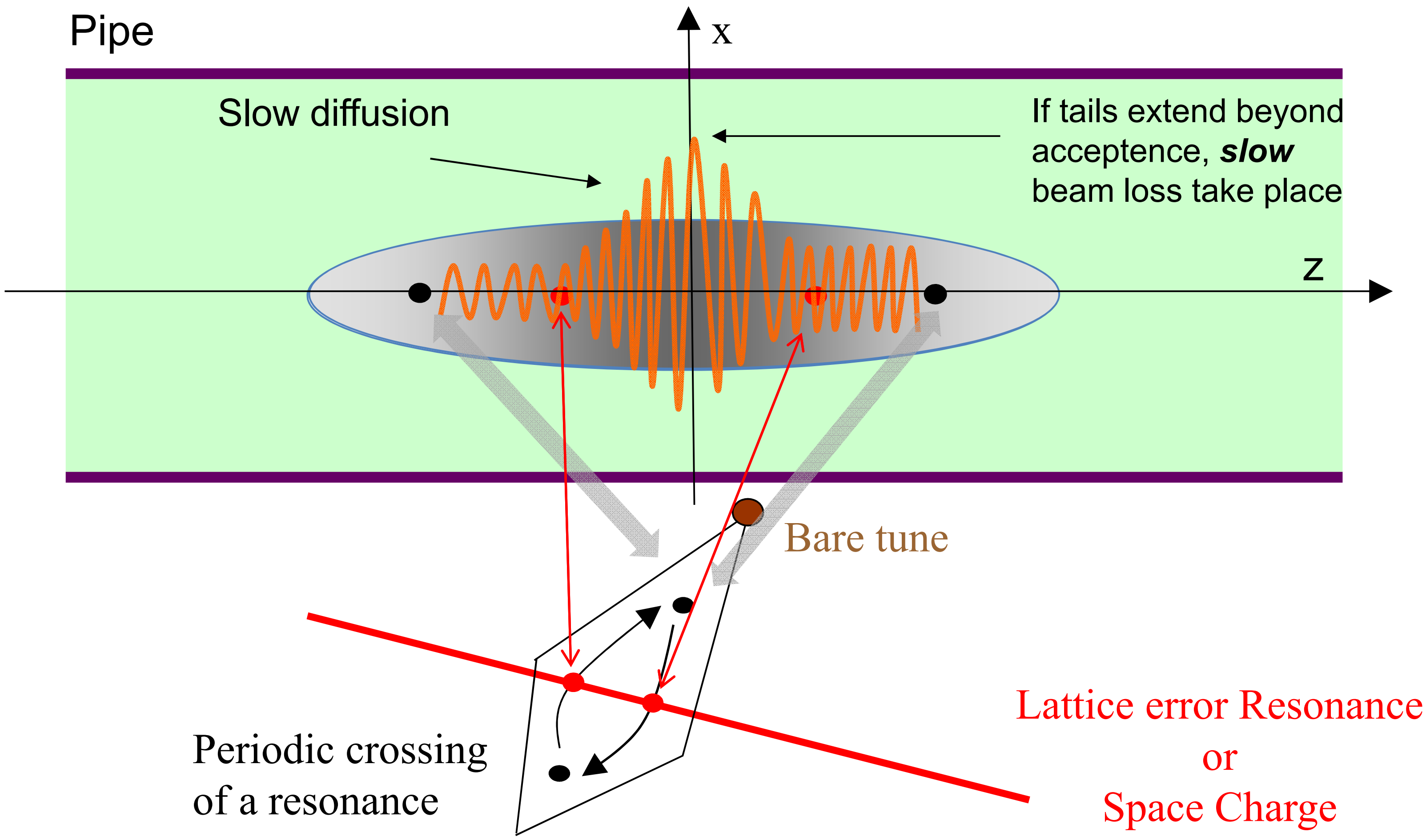
Large emittance growth



The bunch is shorter !

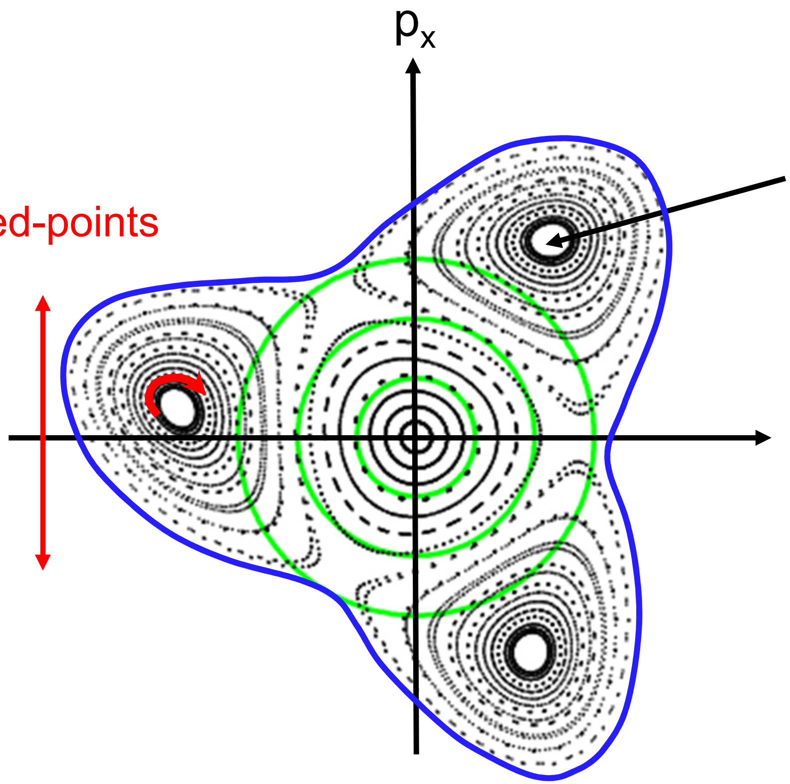
G. Franchetti, O. Chorniy, I. Hofmann, W. Bayer, F. Becker, P. Forck,T. Giacomini, M. Kirk, T. Mohite, C. Omet, A. Parfenova, P. Schuett
Phys. Rev. ST Accel. Beams **13**, 114203 (2010).

Space charge and resonances



1D resonance and space charge
Summary (2000 – 2010)

Resonance strength:
- Island size
- Tunes around fixed-points



Determined by

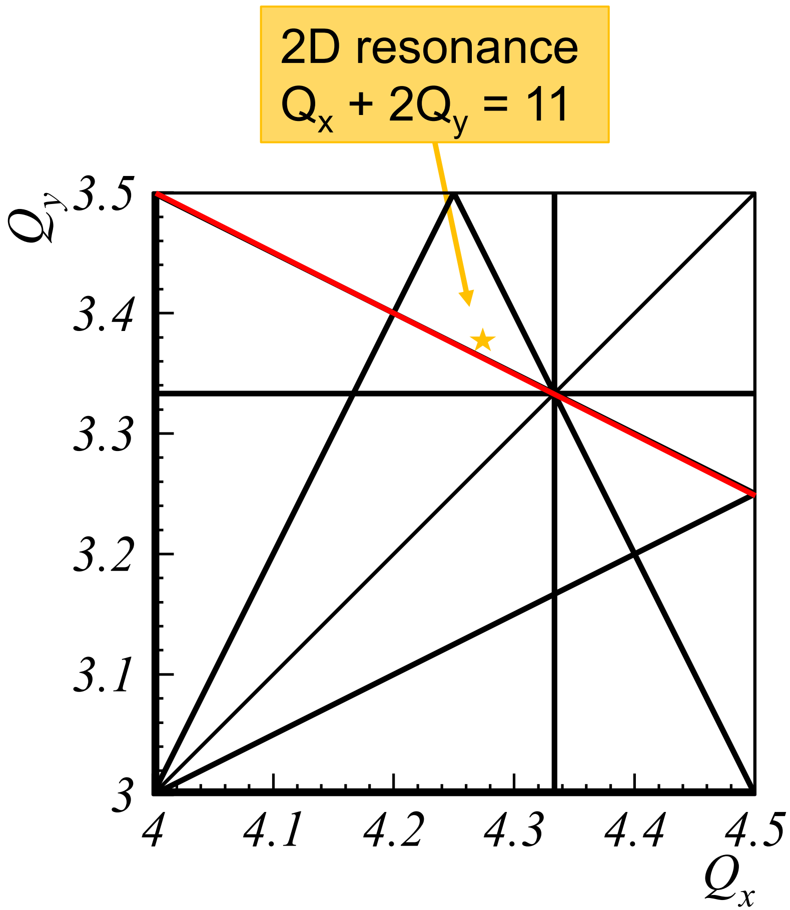
$$n[q_{x0} + \Delta Q_x(X)] = N$$

Halo size is determined by the outer position of islands

Longitudinal motion and space charge drives islands away too fast

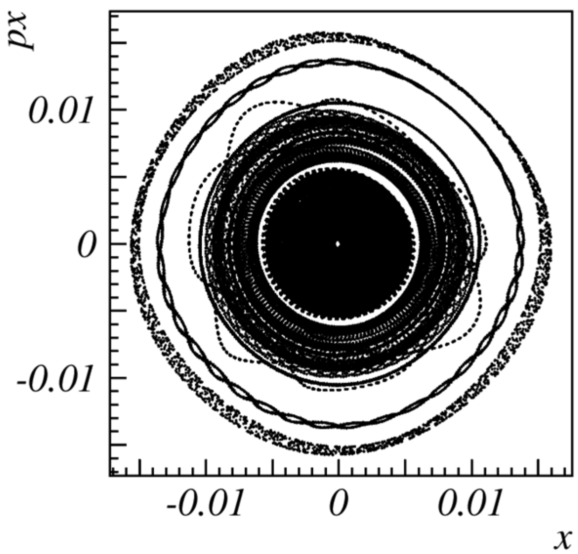
"scattering regime"

The difficulty of the coupled dynamics

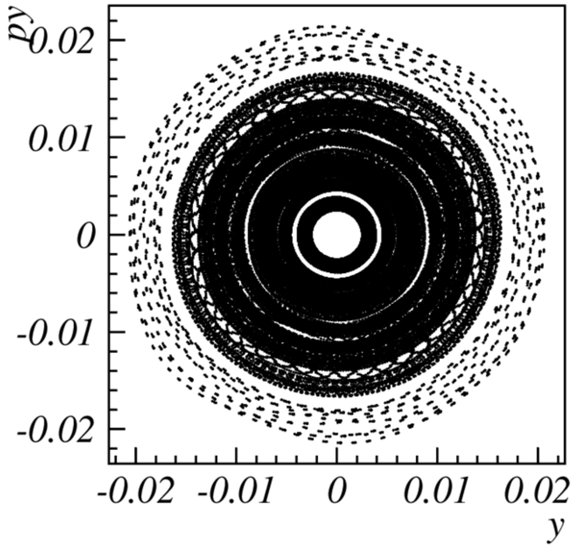


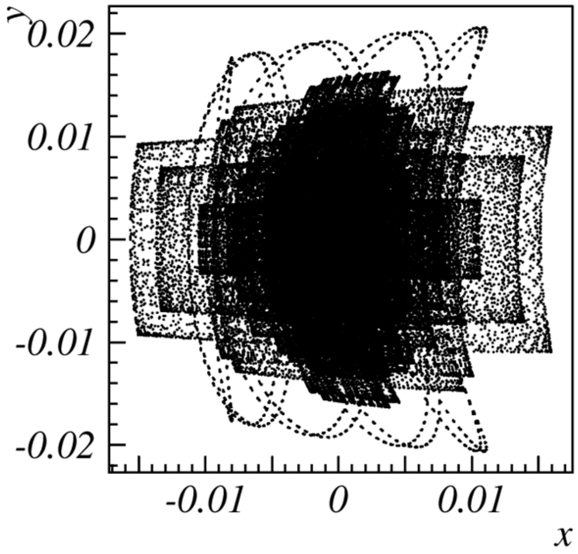
The difficulty of the coupled dynamics

Near the resonance $Q_x + 2\,Q_y = 11$ $Q_x = 4.27,\ Q_y = 3.3575$



Orbits become fuzzy





Very difficult to understand what is going on.

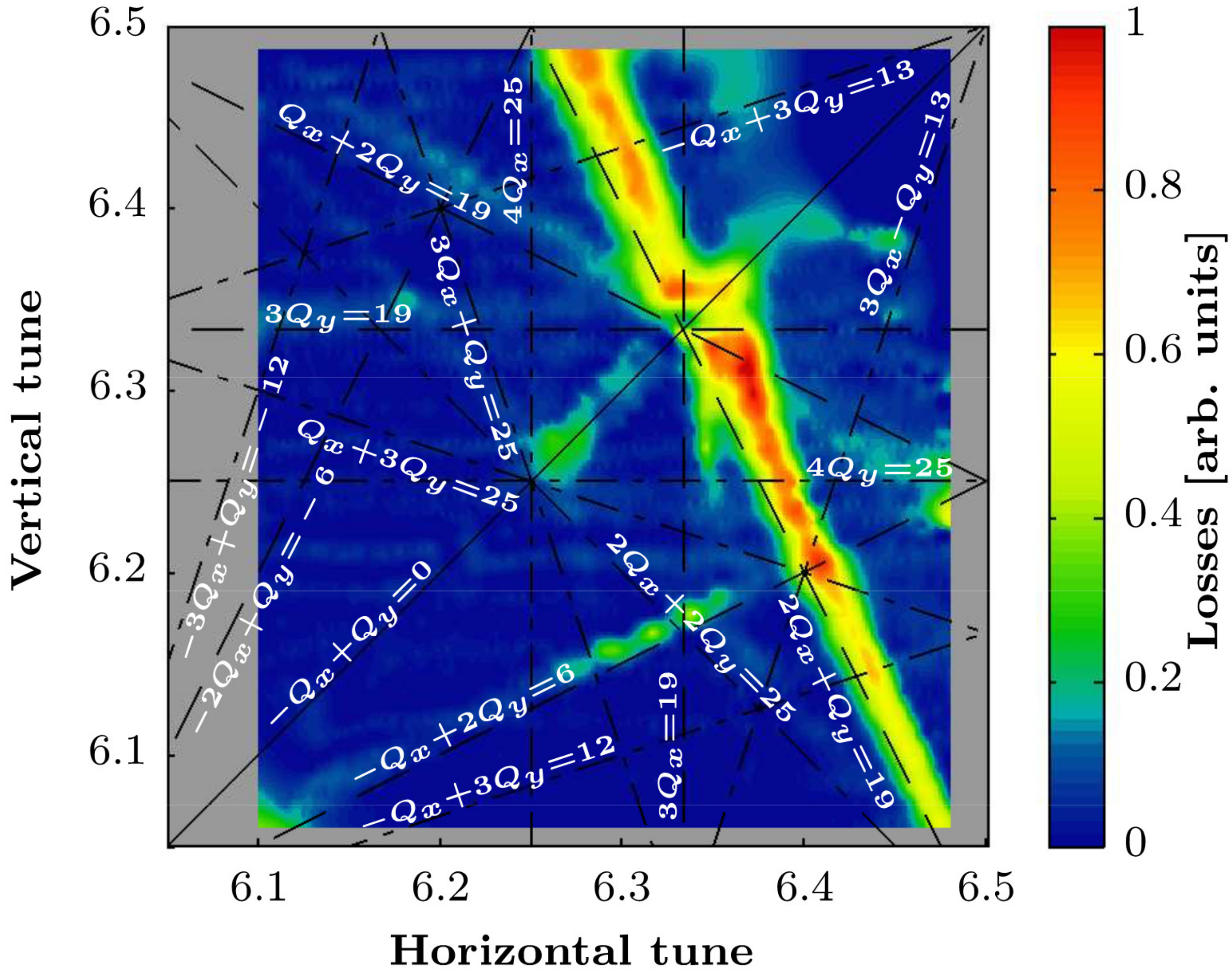
The quest of the incoherent effects of space charge

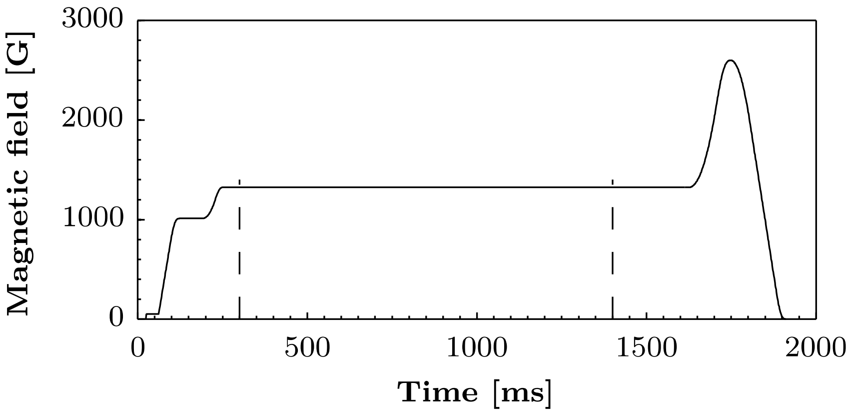
GSI

1 week	12 days (as users)	1 week	~2 days	4 days	
2002	2007	2012	2014	2015	
study of the space charge on **1D** 4th order resonance	study of the space charge on **1D** 3rd order resonance: proof of principle	study of the space charge on **2D** 3rd order resonance	resonance compensation with space charge	Experimental discovery of the fixed-lines	GSI **SIS18, SIS100**
PS CERN	**SIS18** GSI	**PS** CERN	**SIS18** GSI	**SPS** CERN	CERN **PS, SPS, ..**
					Fermilab

IOTA

The 2012 CERN-PS measurement campaign





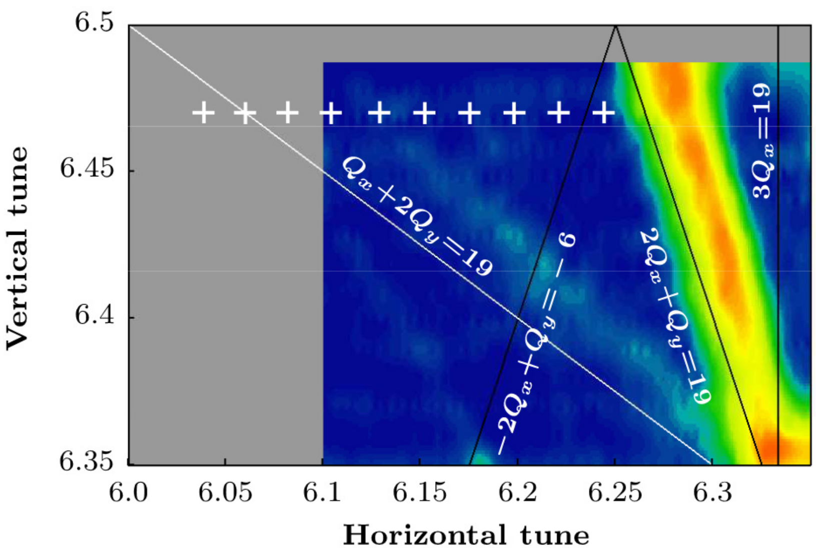


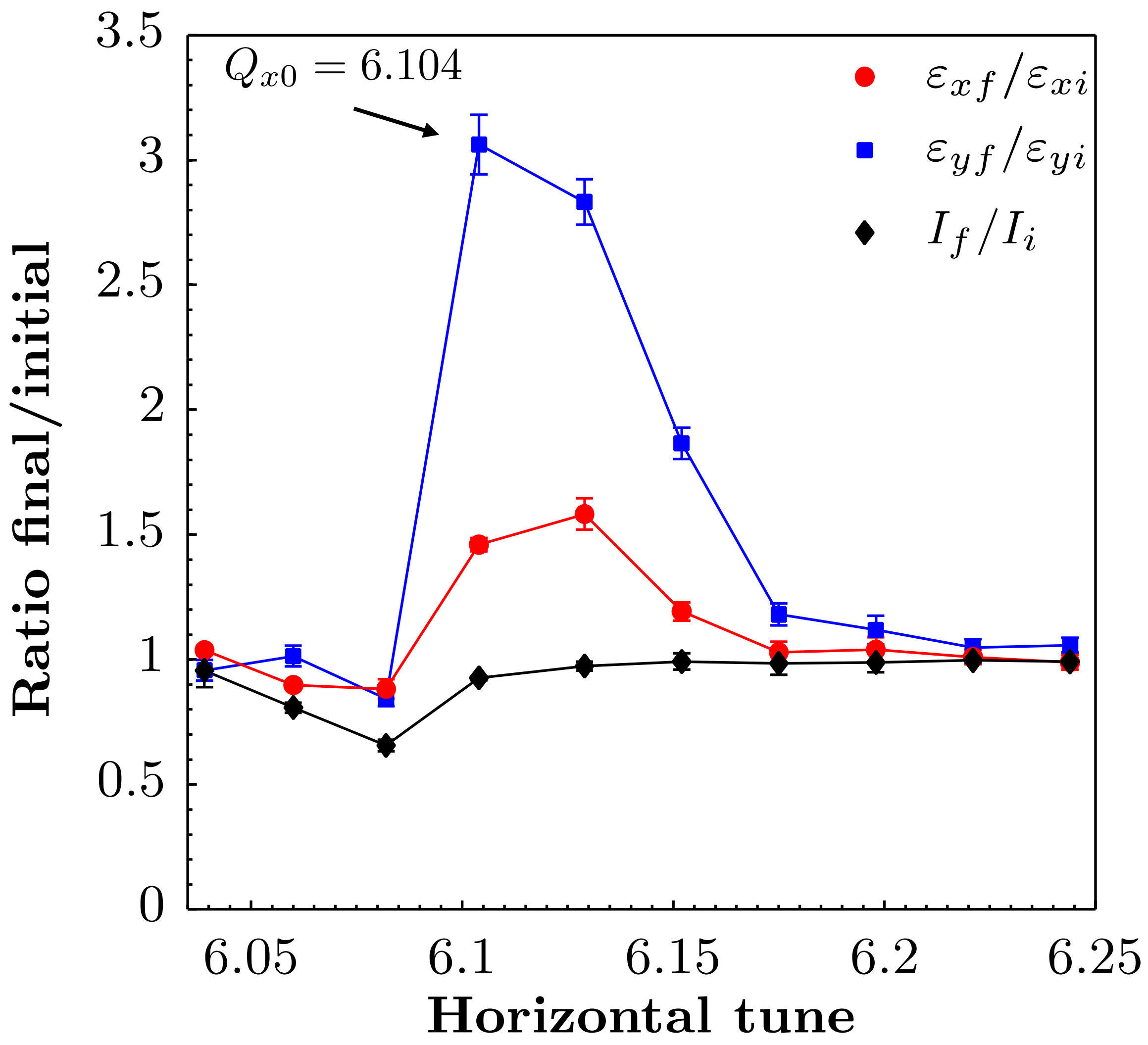
TABLE I. Beam and machine parameters.

Parameter	Value
Intensity N_p [10^{10} p]	55
Normalized horizontal rms emittance ε_x^n [mm mrad]	3.6
Normalized vertical rms emittance ε_y^n [mm mrad]	2.2
Rms bunch length σ_t [ns]	33
Rms momentum spread $\frac{\Delta p}{p}$ [10^{-3}]	0.95
Horizontal maximum tune spread $\Delta Q_{x,\max}$ [a]	-0.05
Vertical maximum tune spread $\Delta Q_{y,\max}$ [a]	-0.071
Sextupole current I_{SX} [A]	2
Harmonic number h	8
RF voltage V_{RF} [kV]	20.5
Horizontal linear chromaticity ξ_x [b]	-0.83
Vertical linear chromaticity ξ_y [b]	-1.12
Energy of stored beam [GeV]	2
Turns stored	497646
Storage time [s]	1.1
Relativistic β	0.948
Relativistic γ	3.14
Synchrotron tune	1163^{-1}
Horizontal flying w. (SS68 at 422.8 m) β_x [m]	12.40
Vertical flying w. (SS64 at 397.7 m) β_y [m]	21.75

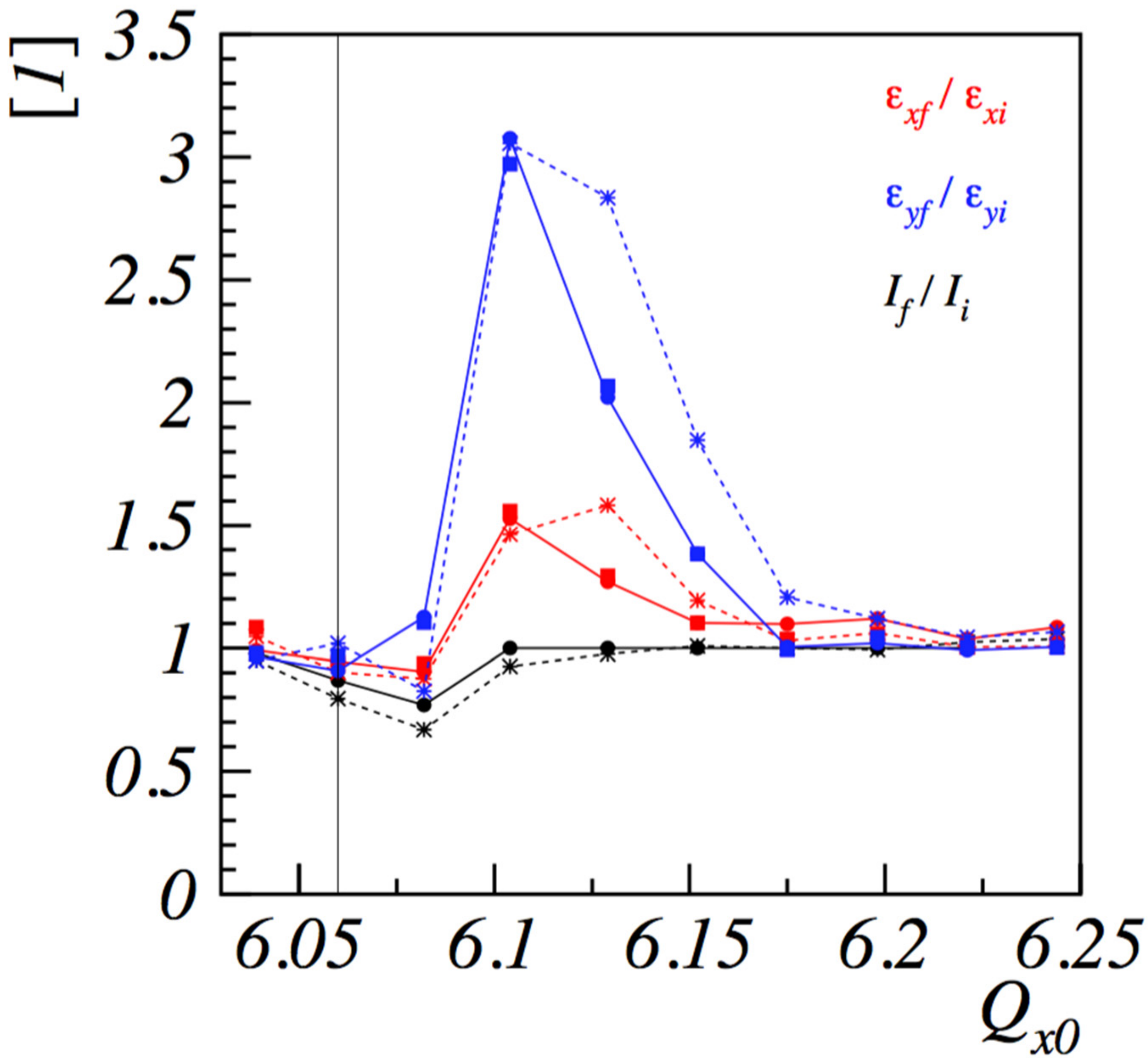
[a] The tune spread is calculated according to Ref. [18].

[b] $\xi_{x,y} = \frac{Q'_{x,y}}{Q_{x,y}} = \frac{\Delta Q_{x,y}/Q_{x,y}}{\Delta p/p}$

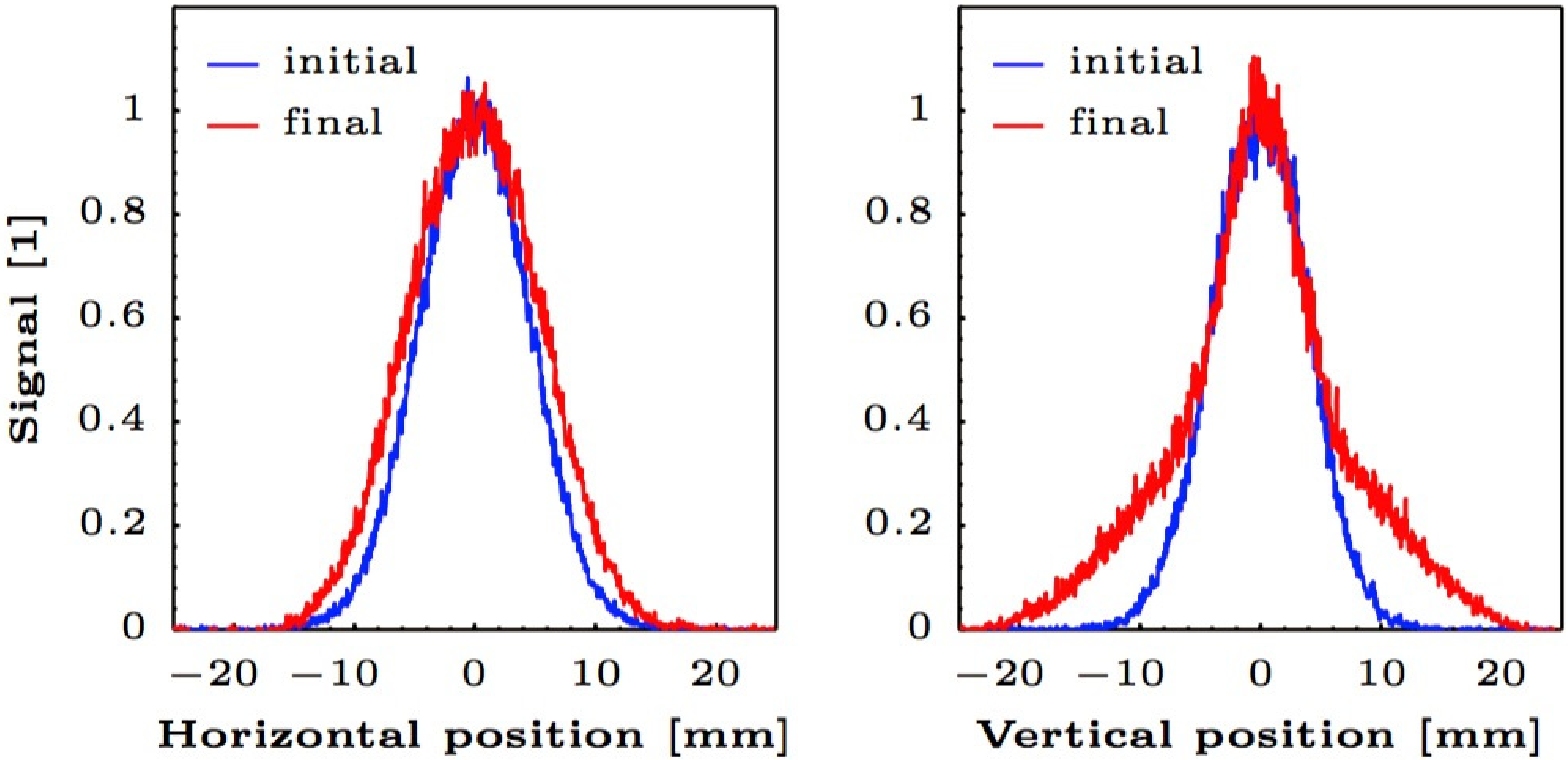
PS campaign results



Comparison with simulations

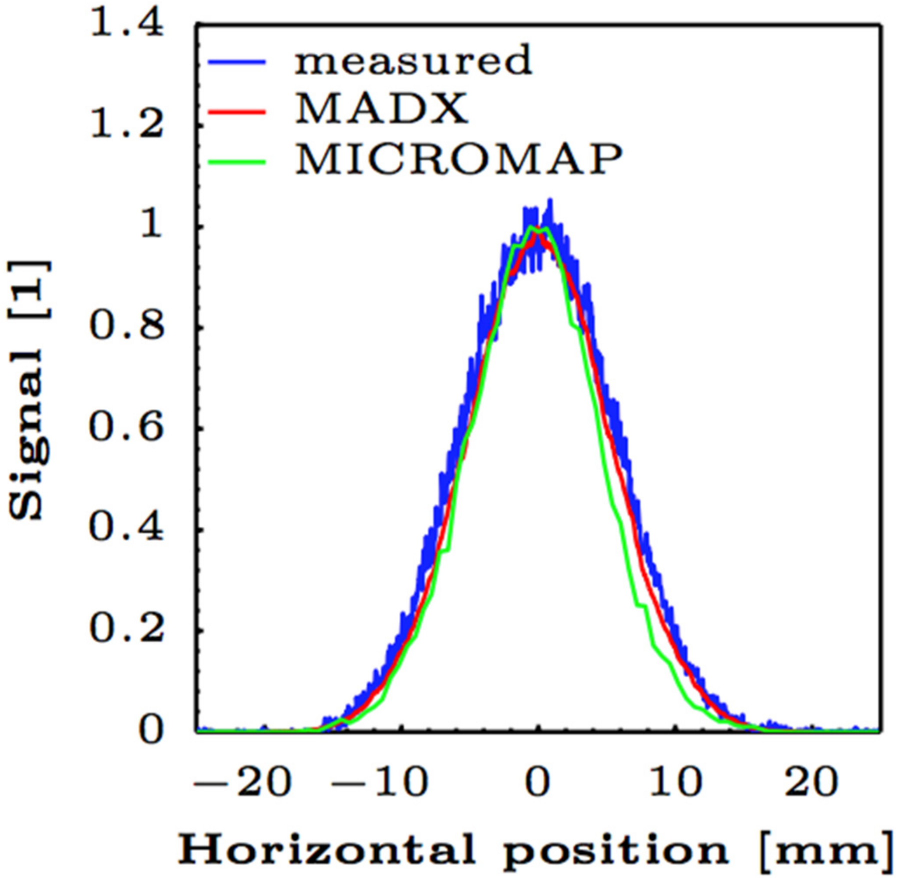


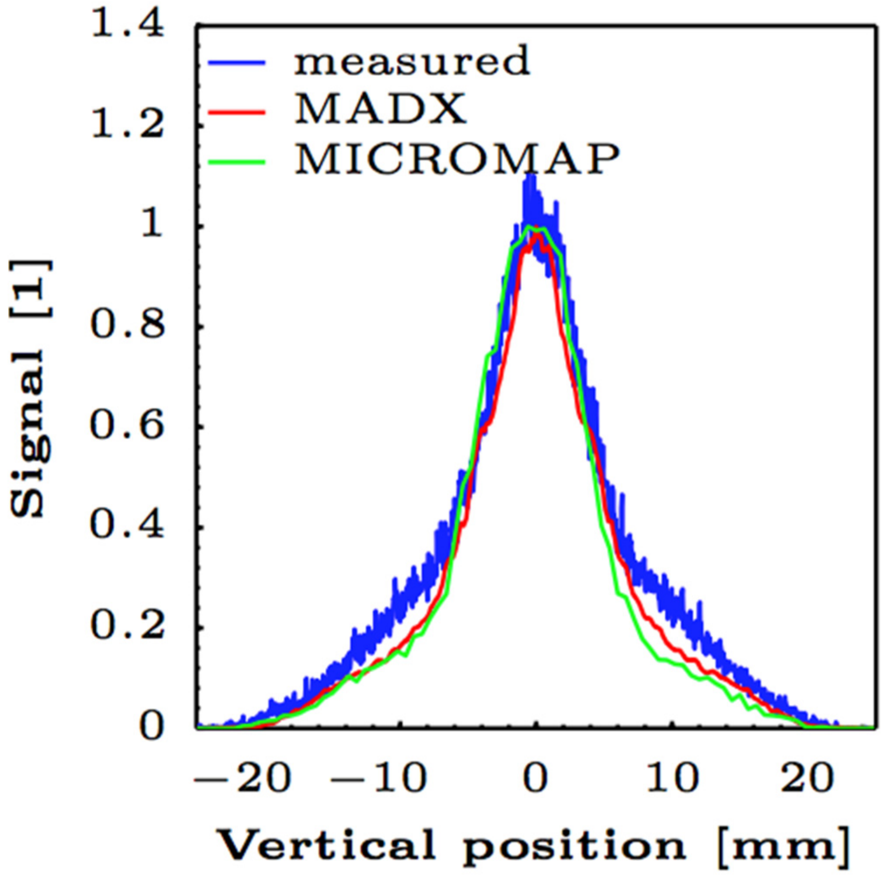
Beam Profiles for $Q_{x0} = 6.104$



Experiment-Code
Beam Profile benchmarking

$$Q_{x0} = 6.104$$





Resonance condition: discussion

No space charge

Distance of the resonance

$$\Delta_{r0} = Q_{x0} + 2Q_{y0} - 19$$

Resonance condition

$$\Delta_{r0} = 0$$

With space charge

Distance from the resonance for one particle at amplitudes X,Y

$$\Delta_r = \Delta_{r0} + \\ + \Delta Q_{sc,x}(X,Y) + 2\Delta Q_{sc,y}(X,Y)$$

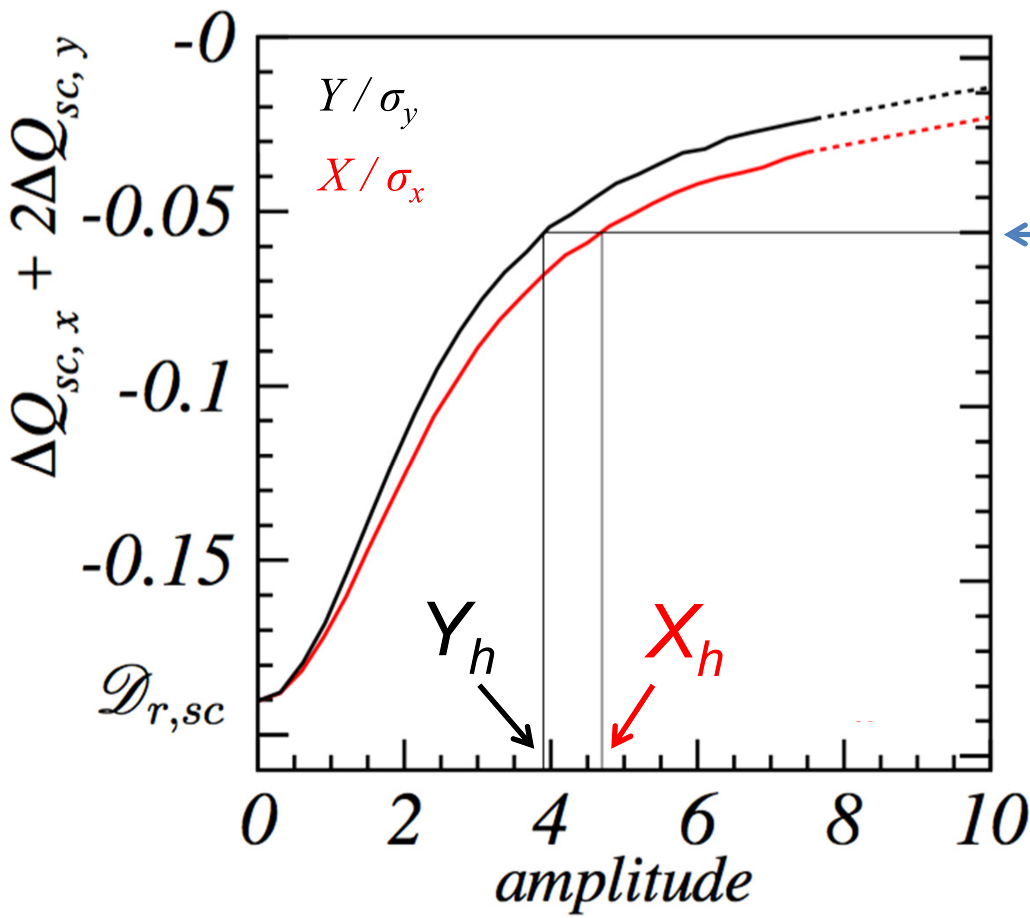
Resonance condition

$$\Delta_r = 0$$

Δ_{r0} may be different from zero

Resonant particles

$$Q_{x0} = 6.104 \Rightarrow \Delta_{r0} = 0.056$$

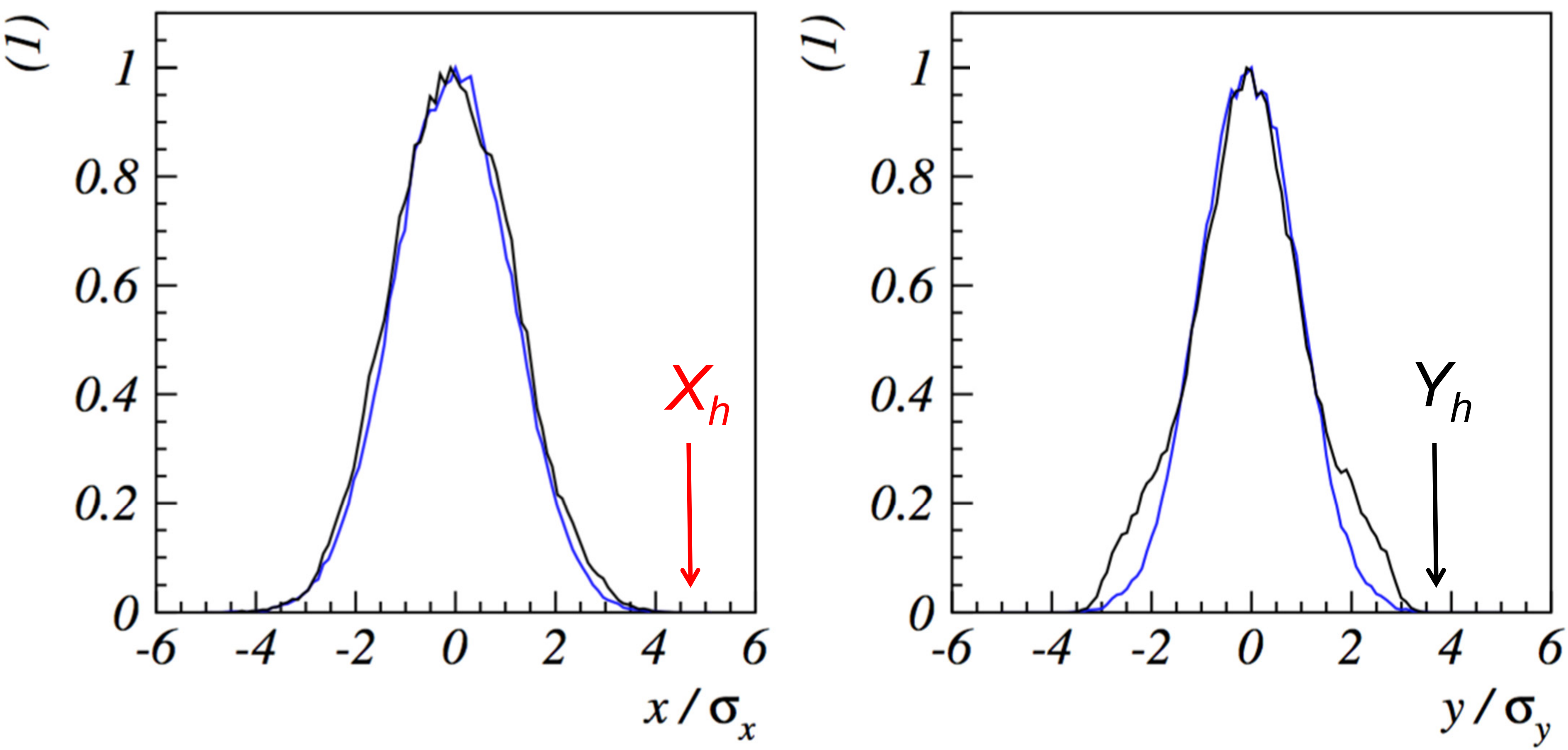


$\Delta_{r0} = 0.056$

"resonant detuning cancel Δ_{r0} and makes particle resonant"

Comparison with simulations without chromaticity

$$Q_{x0} = 6.104$$

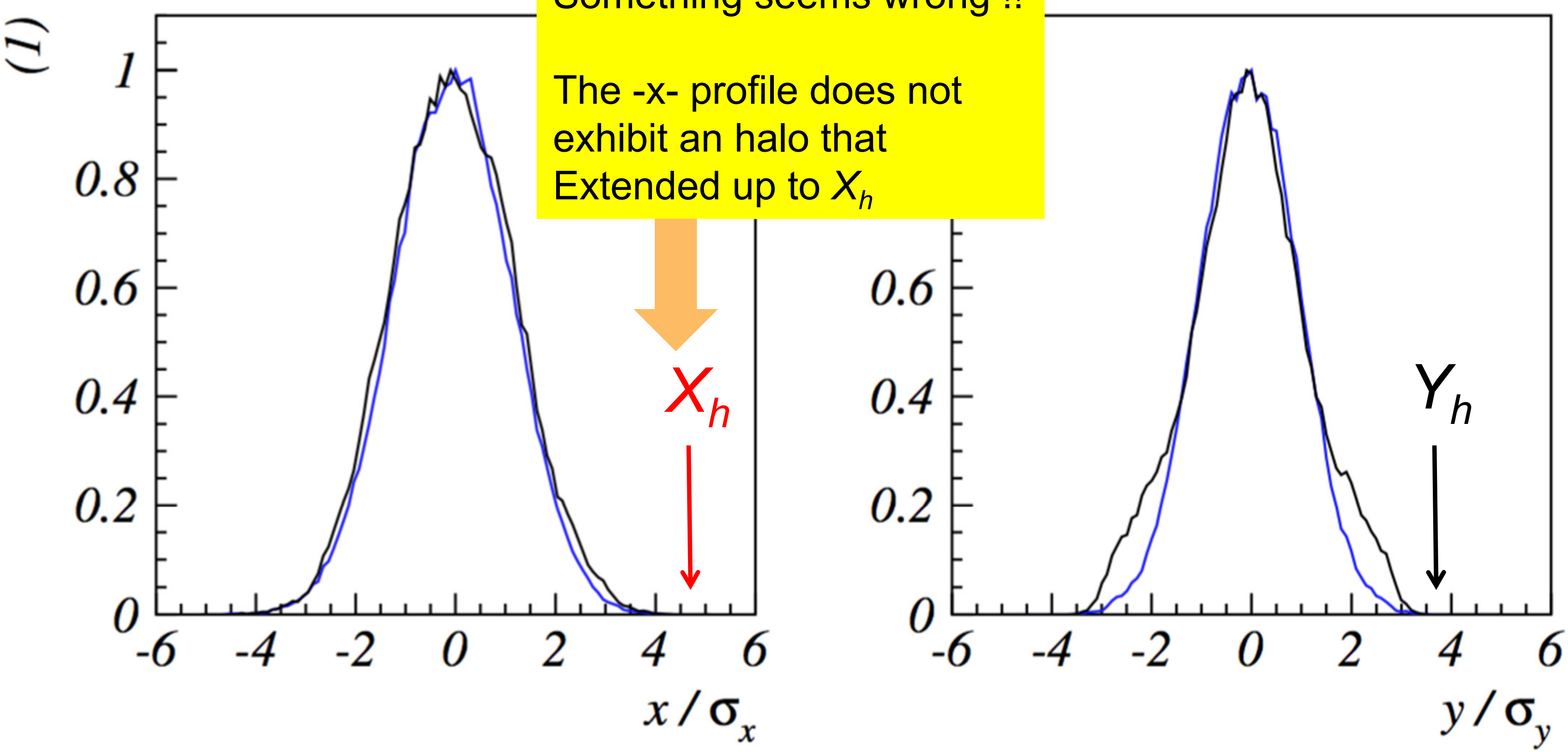


Comparison with simulations without chromaticity

$$Q_{x0} = 6.104$$

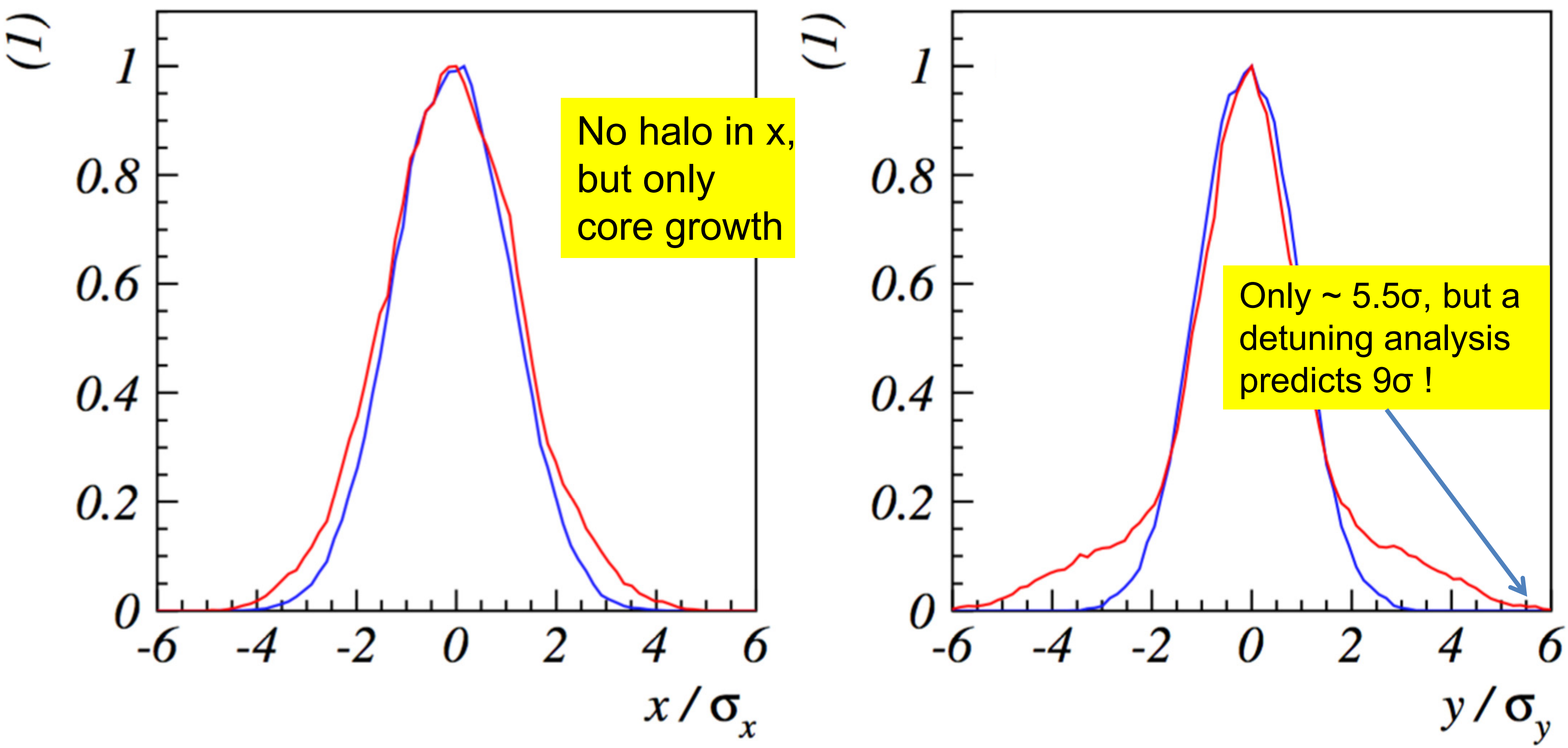
Something seems wrong !!

The -x- profile does not exhibit an halo that Extended up to X_h



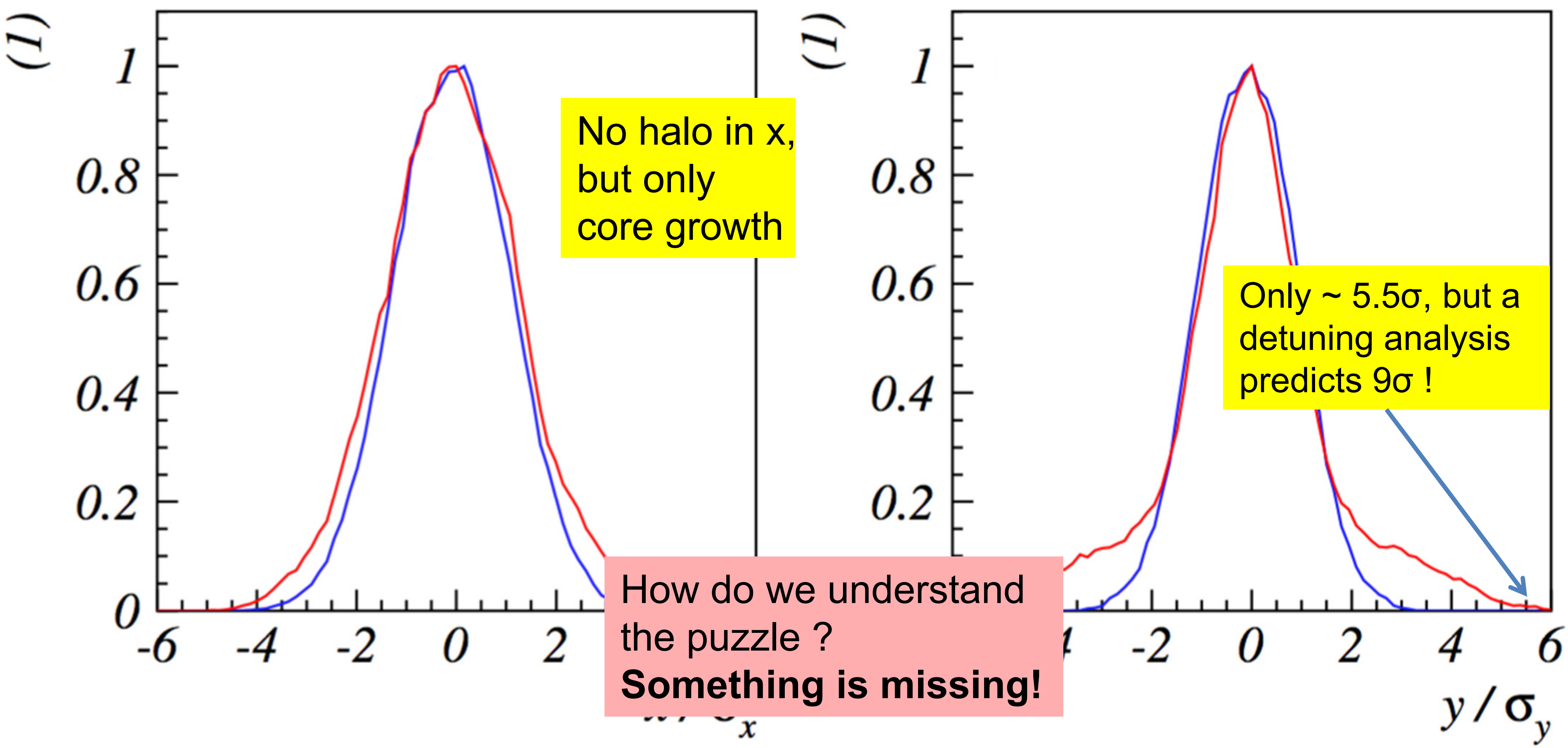
Comparison with simulations including chromaticity

$$Q_{x0} = 6.104$$



Comparison with simulations including chromaticity

$$Q_{x0} = 6.104$$

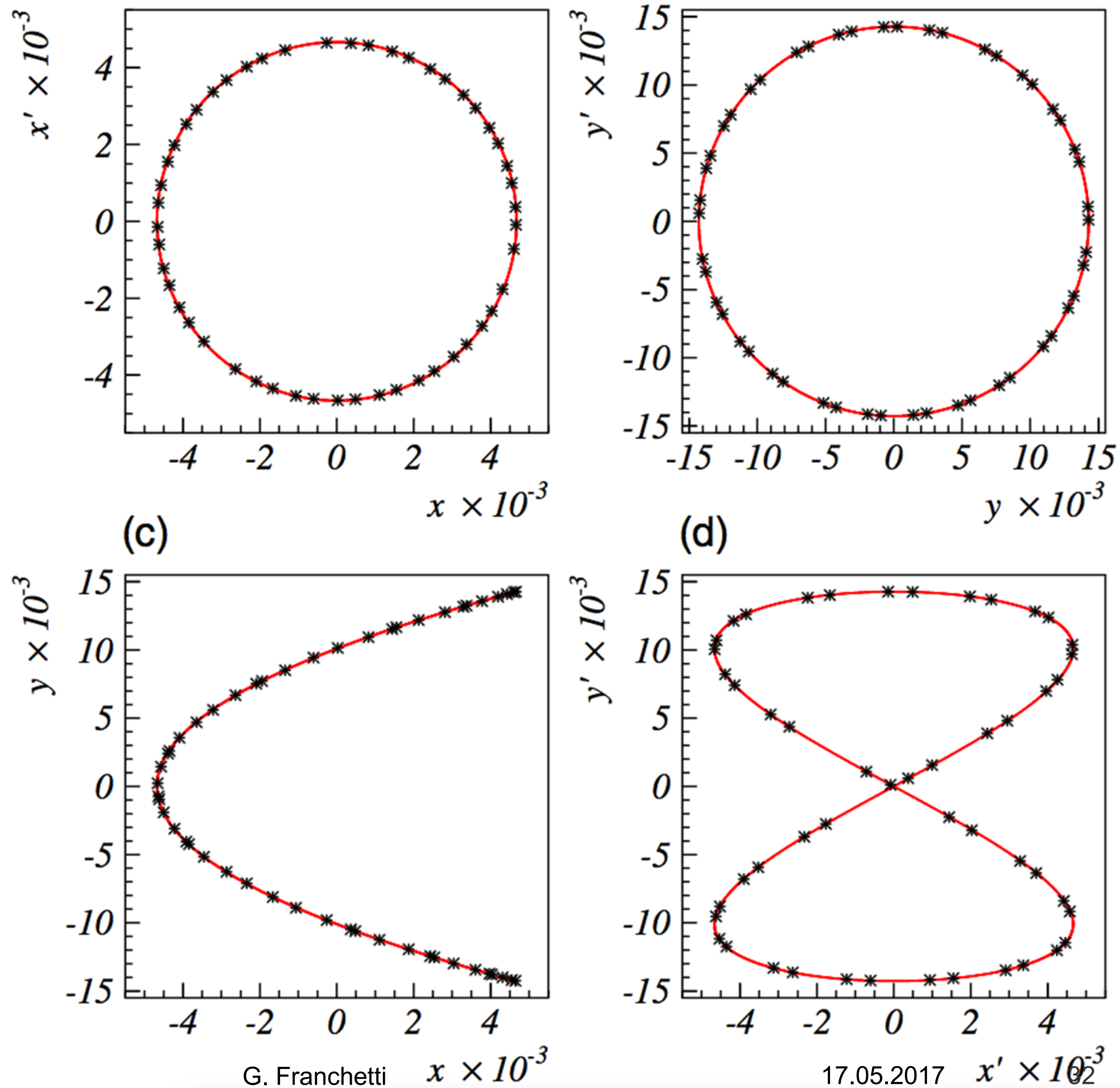


Missing: the coupled dynamics on the resonance

F. Schmidt PhD thesis, *and others*

G. Franchetti and F. Schmidt
Phys. Rev. Lett. **114**, 234801 (2015).

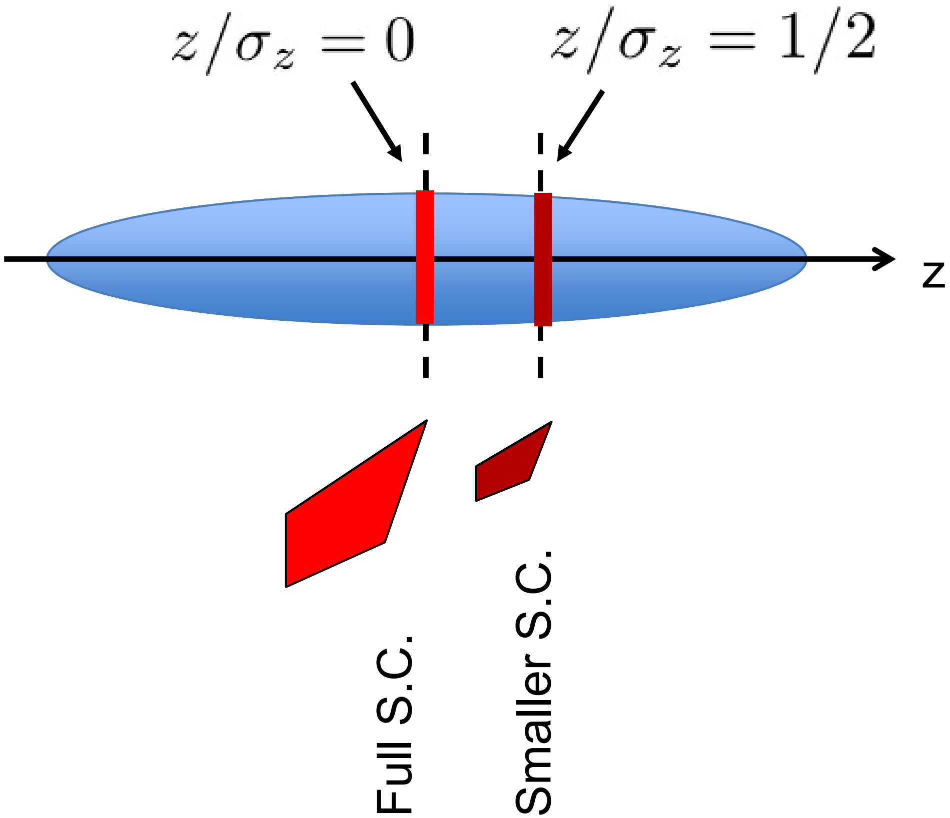
G. Franchetti and F. Schmidt
http://arxiv.org/abs/1504.04389

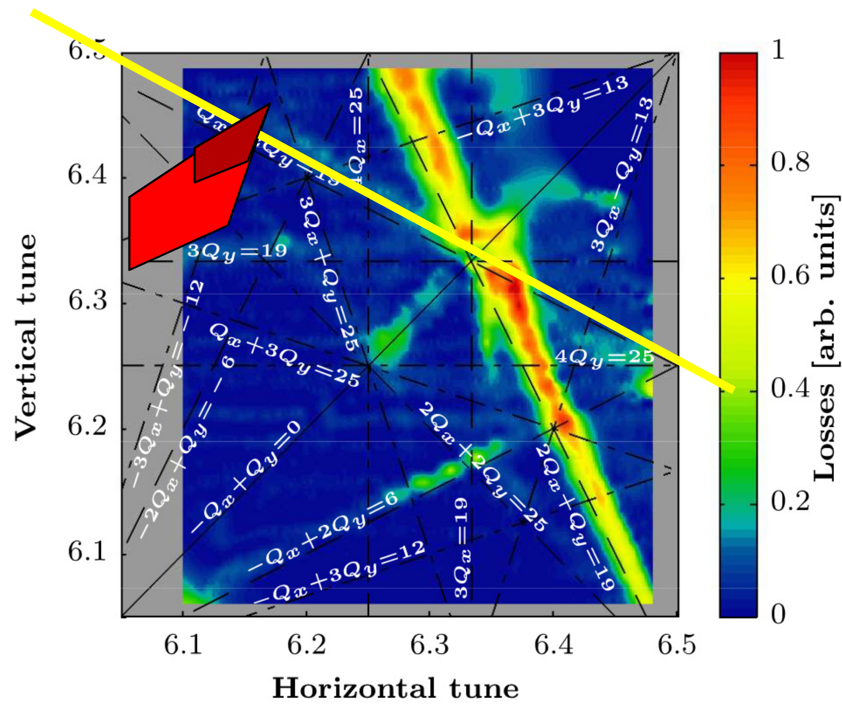


SPS campaign on May 2015

Does fixed-lines play a role with space charge ?

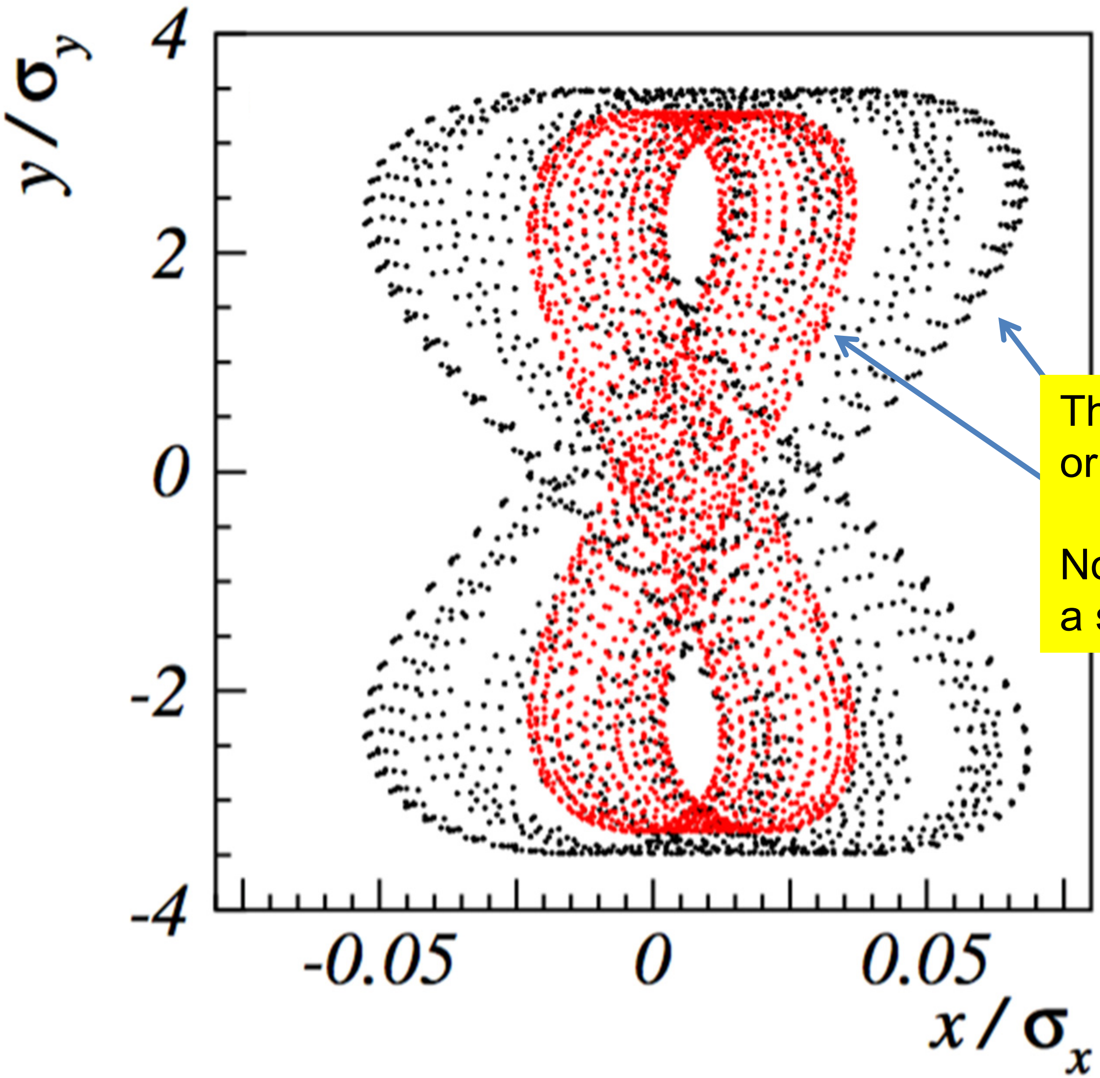
longitudinal motion is kept frozen, so to retrieve Poincare’ section orbits





Largest resonant orbits at $z/\sigma_z = 0$

No chromaticity

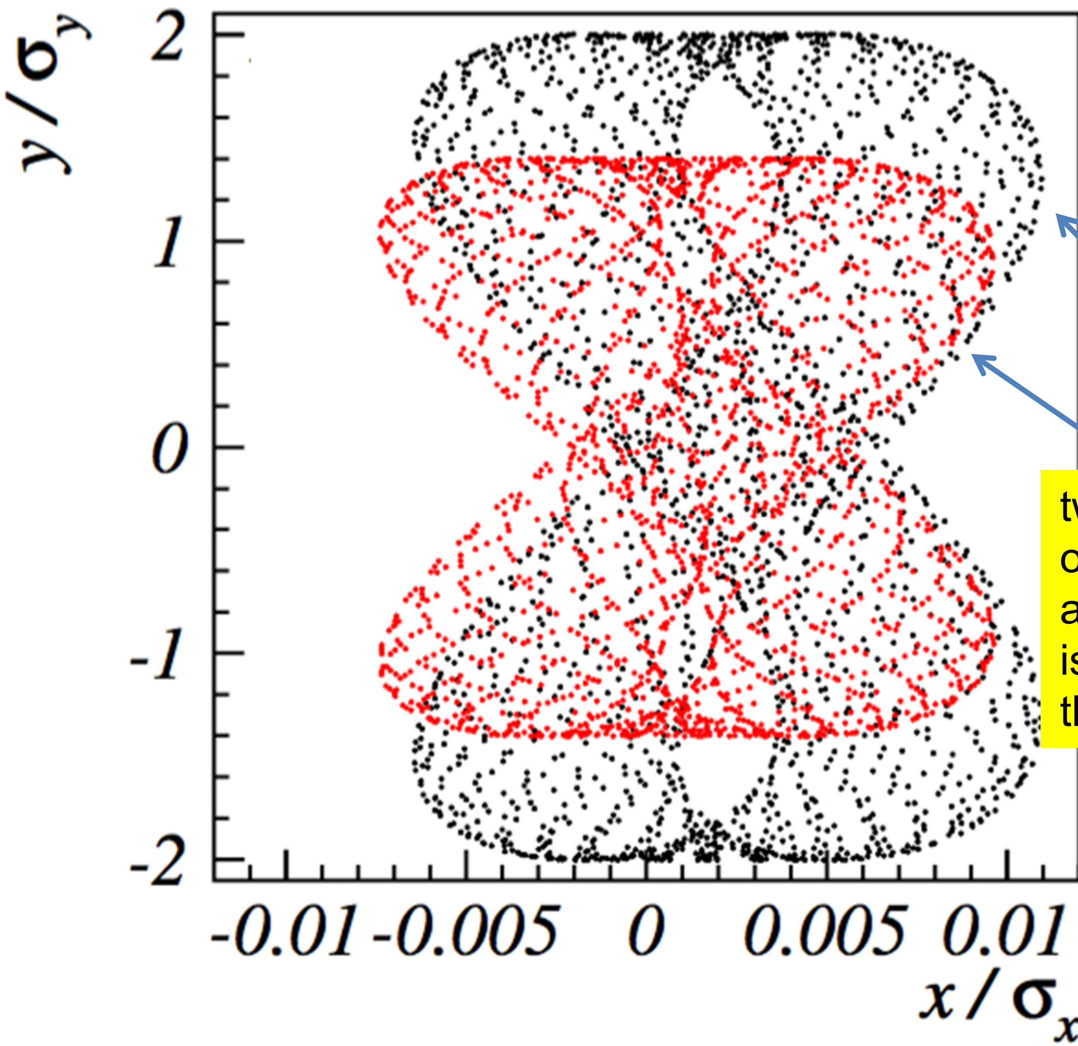


The two larger resonant orbits…

No doubt they have a structure of fixed-lines

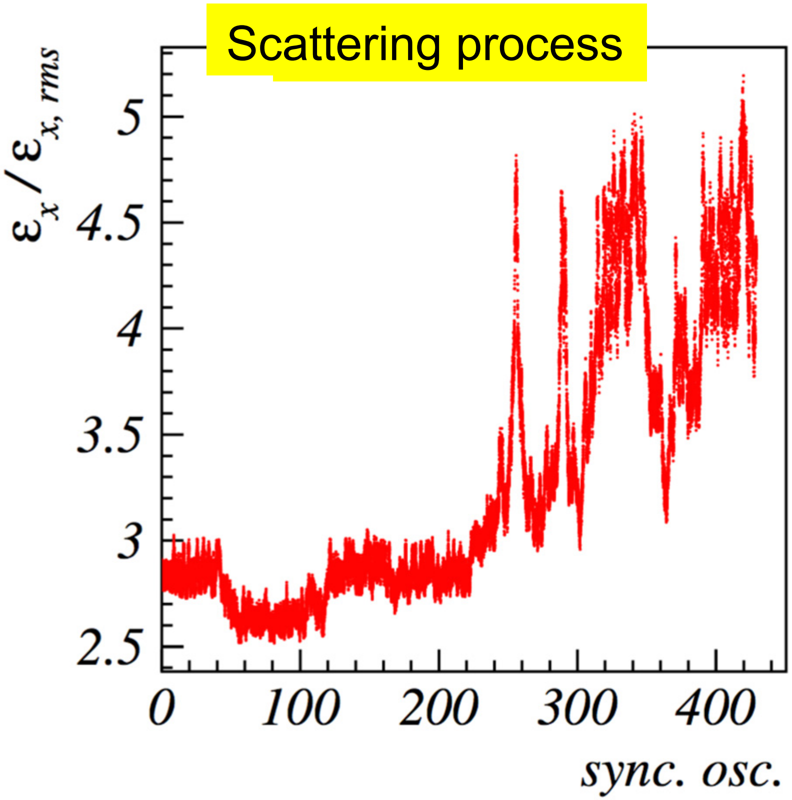
Largest resonant orbits at $z/\sigma_z = 1/2$

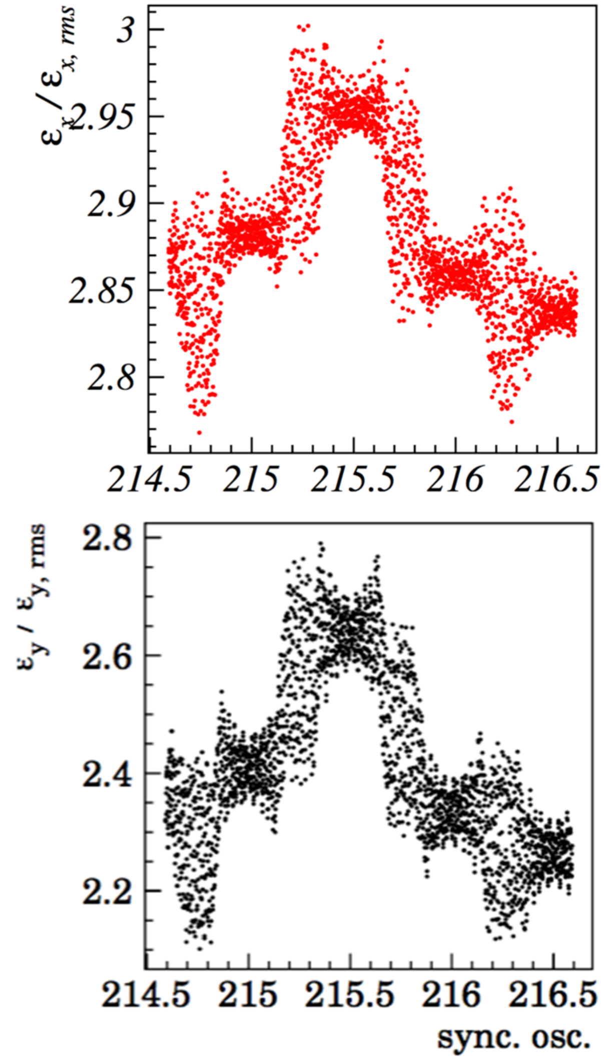
No chromaticity



two larger resonant orbits: now the amplitude of the orbits is smaller, but still have the structure of fixed-lines

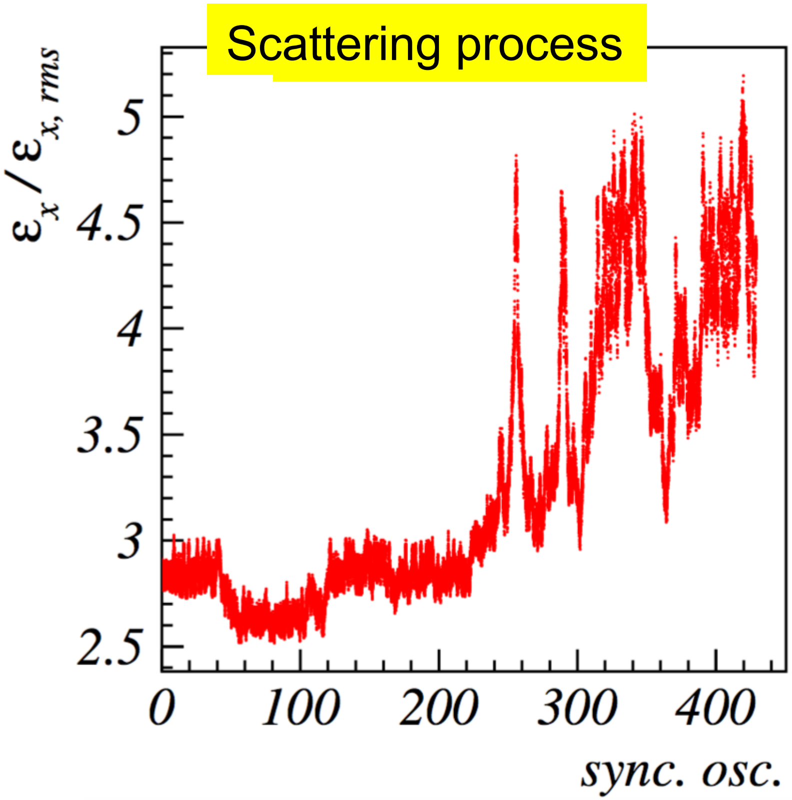
Periodic crossing of fixed-lines

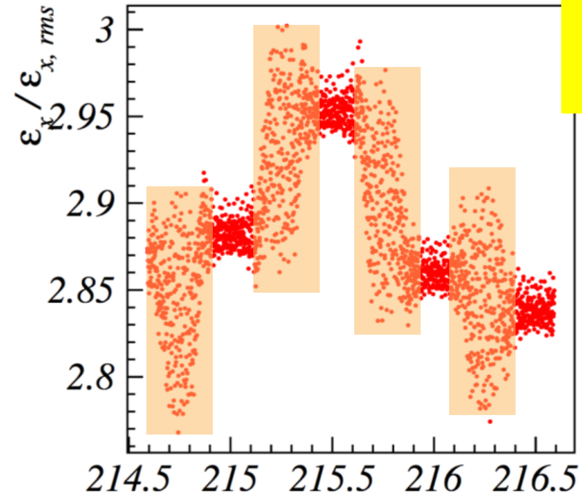


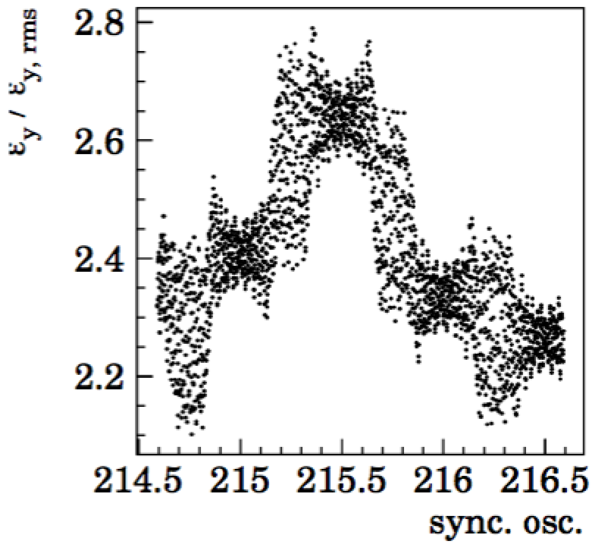


Extended paper to appear in PRAB

Periodic crossing of fixed-lines

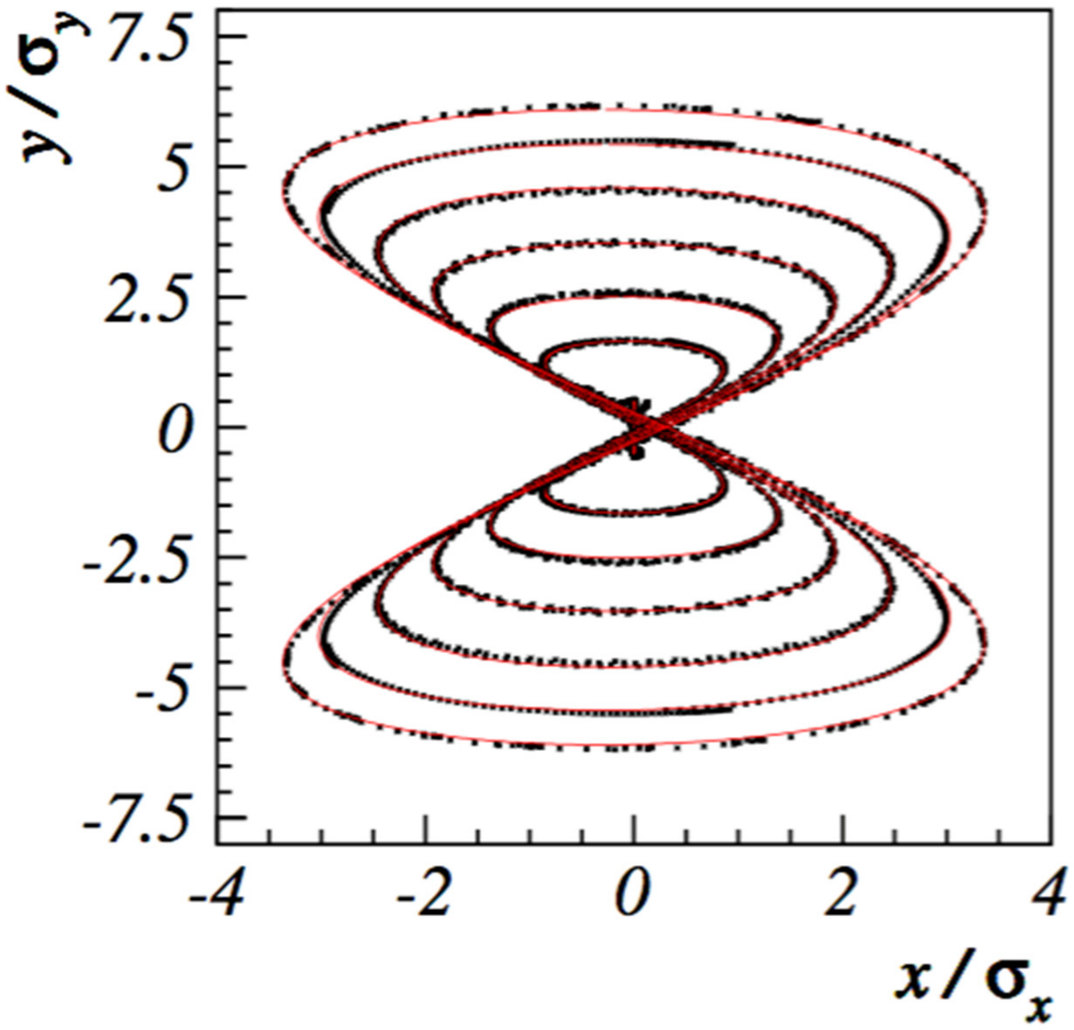






Extended paper to appear in PRAB

Prediction of the halo size: the adiabatic limit



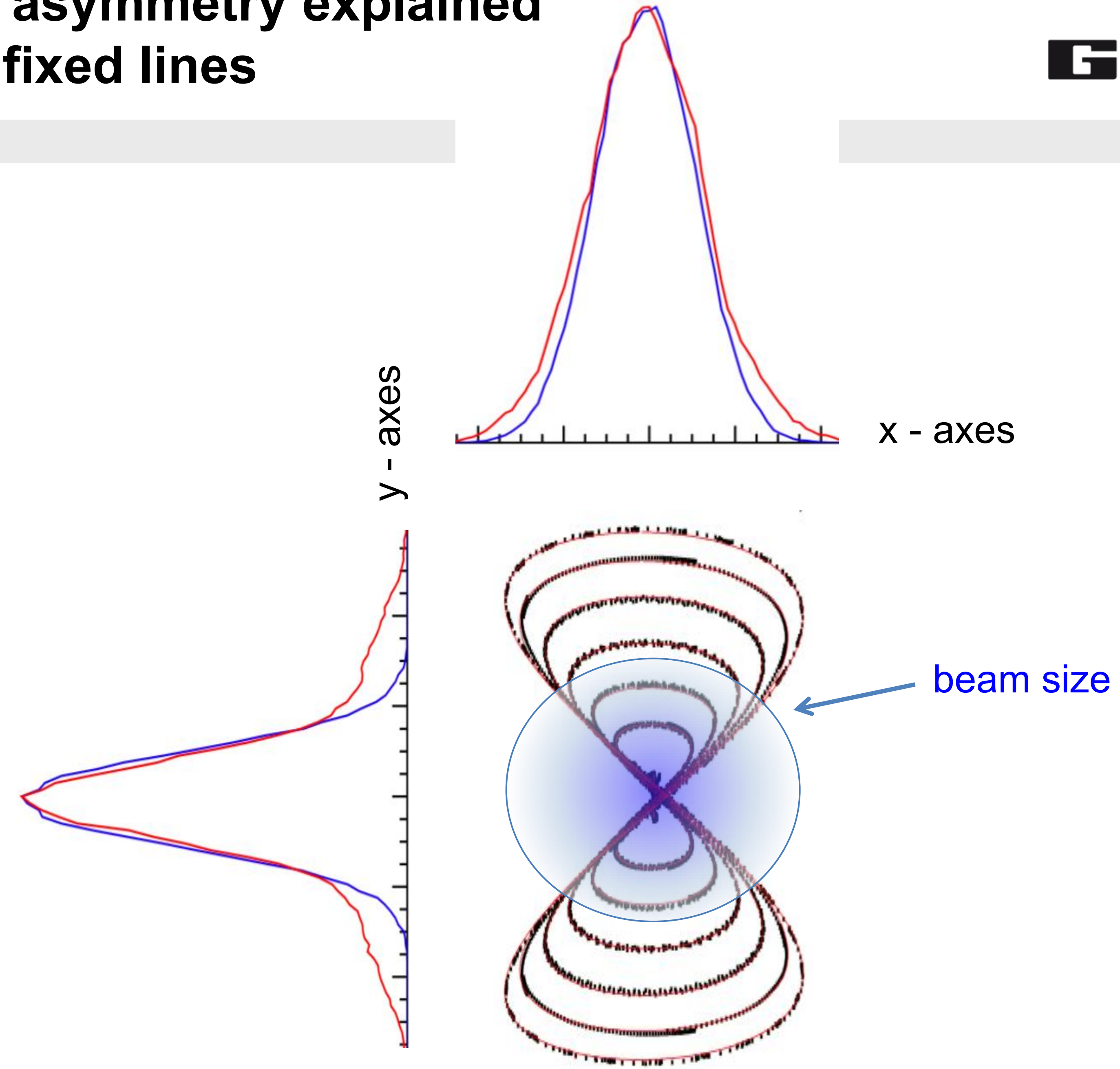
$$x = \sqrt{\beta_x a_x} \cos(-2t - \alpha + \pi M)$$

$$y = \sqrt{\beta_y a_y} \cos(t)$$

For adiabatic synchrotron motion all particles trapped are transported to the “same” fixed-line

The sizes of this fixed-line characterize the halo/core formation

Halo asymmetry explained with fixed lines



Conclusion / Outlook

- A successful experiment-code benchmarking of the beam dynamics on the 3rd order coupled resonance is carried out for the full PS structure.
- Outstanding asymmetric halo is formed well retrieved by the simulations
- Thinking in terms of resonance detuning leads paradoxes
- The "fixed-lines" or tori are the new objects that explain the dynamics of diffusion in a high intensity bunch subject to a coupled resonance
- **"Fixed lines" are experimentally measured in the SPS**
- Simulations show that the periodic crossing of the fixed-lines causes the asymmetric halo as result of fixed lines geometry.
- *Particle seems to diffuse to **"one"** fixed-line → adiabatic limit*
- **The doors are open for massive studies of all coupled resonances and space charge**
- **→ Strategies to mitigate particle diffusion**

Outlook

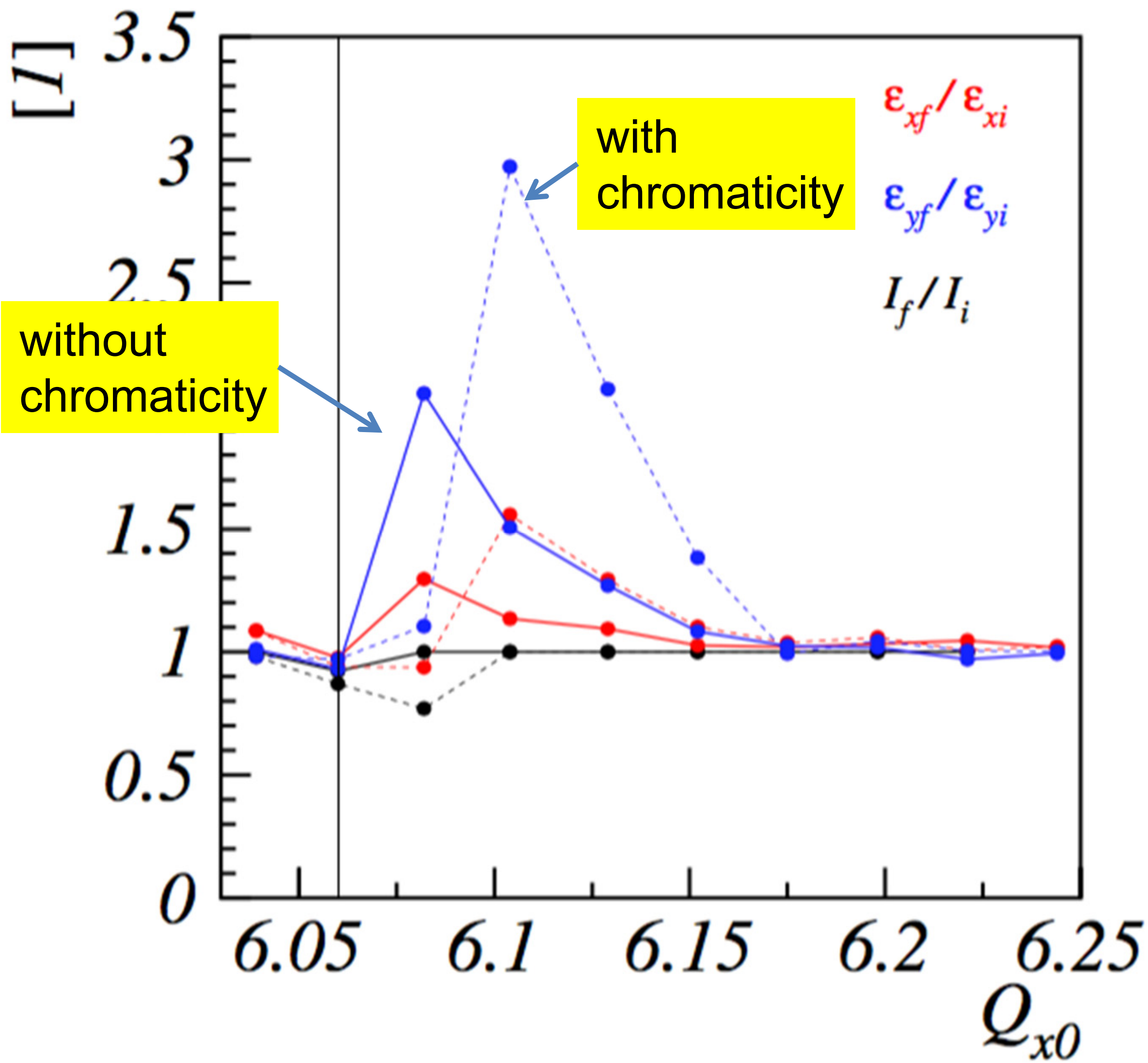
Open problems:

- Estimating the diffusion time
- Mitigation strategies:

  1) Resonance compensation
  2) E-lenses ?

- Coherent vs. incoherent…

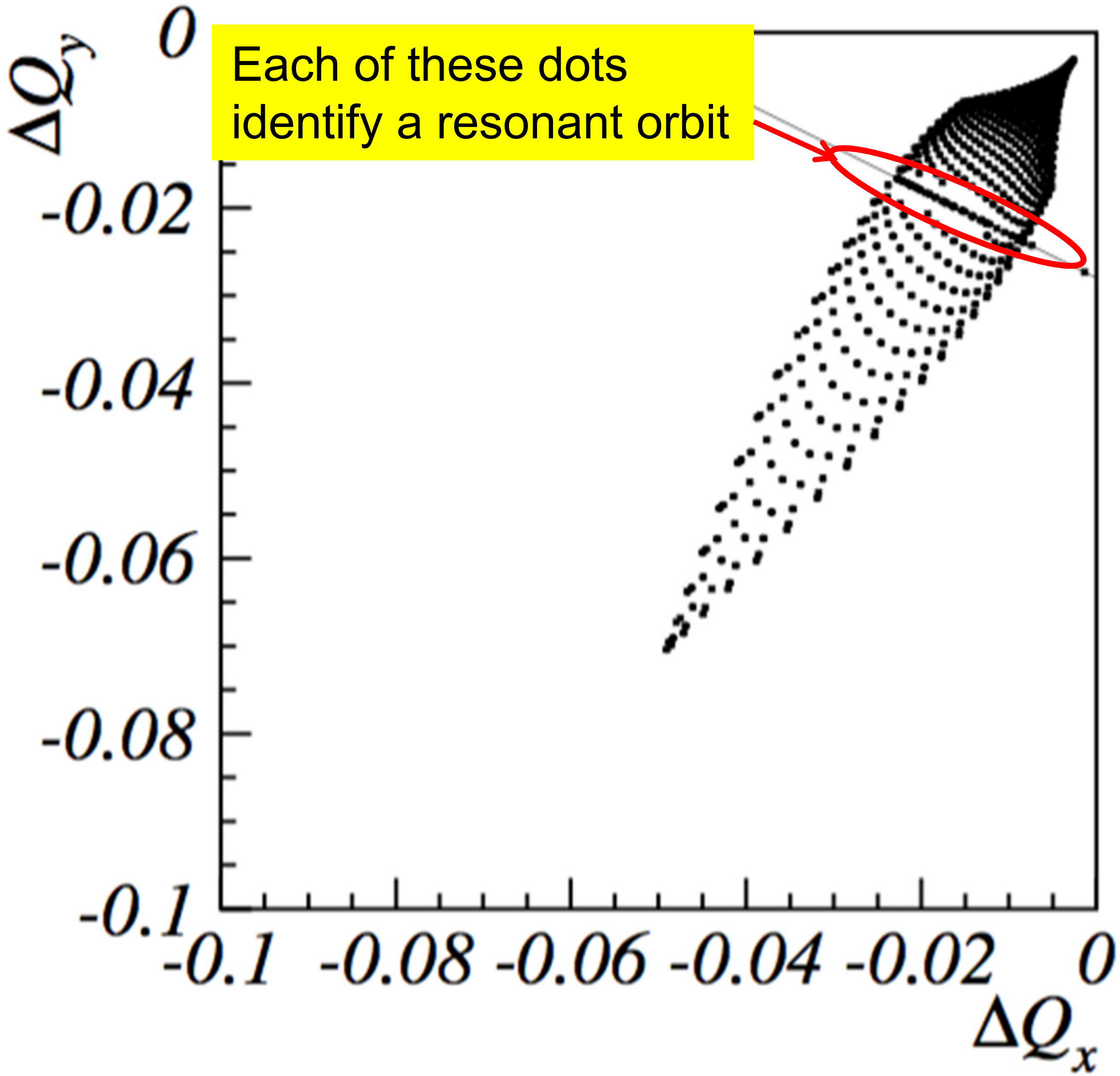
Simulations: the effect of chromaticity



How do we understand the puzzle ?

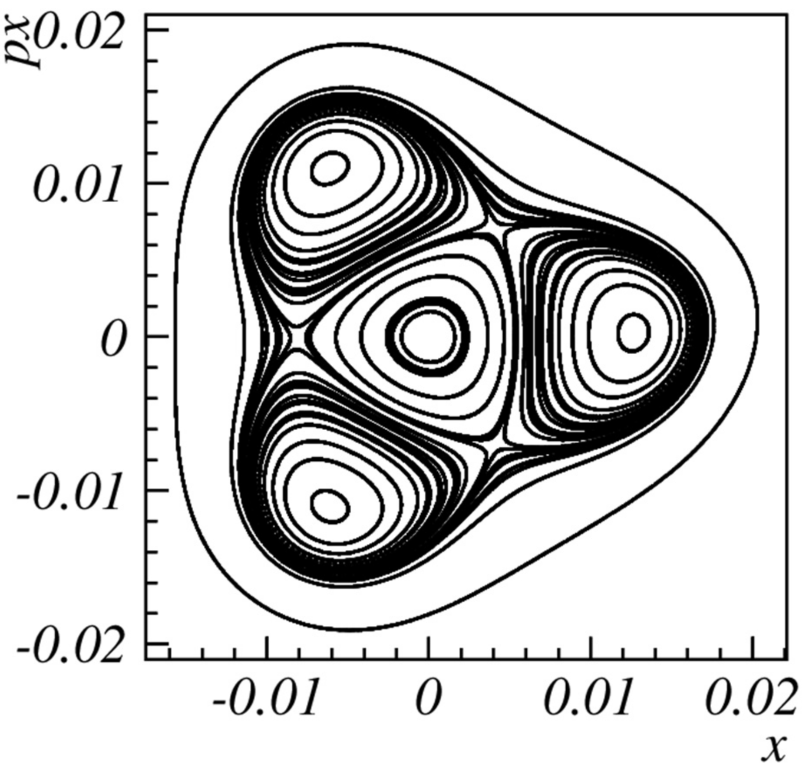
Something is missing!

Resonant orbits

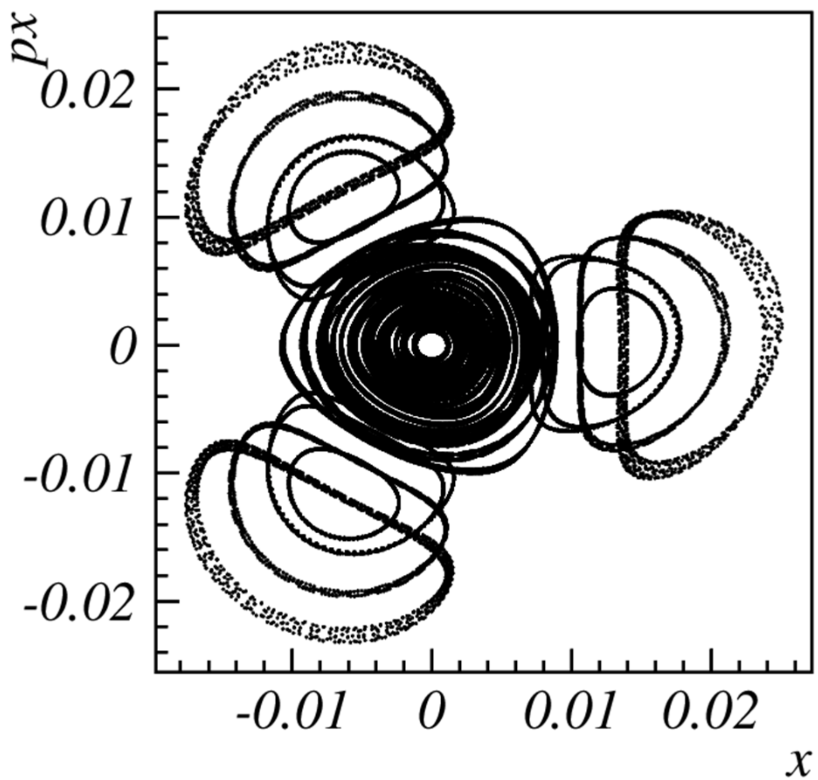


The difficulty of the coupled dynamics

Near the resonance 3 Q_x = 13 Q_x = 4.335, Q_y = 3.27



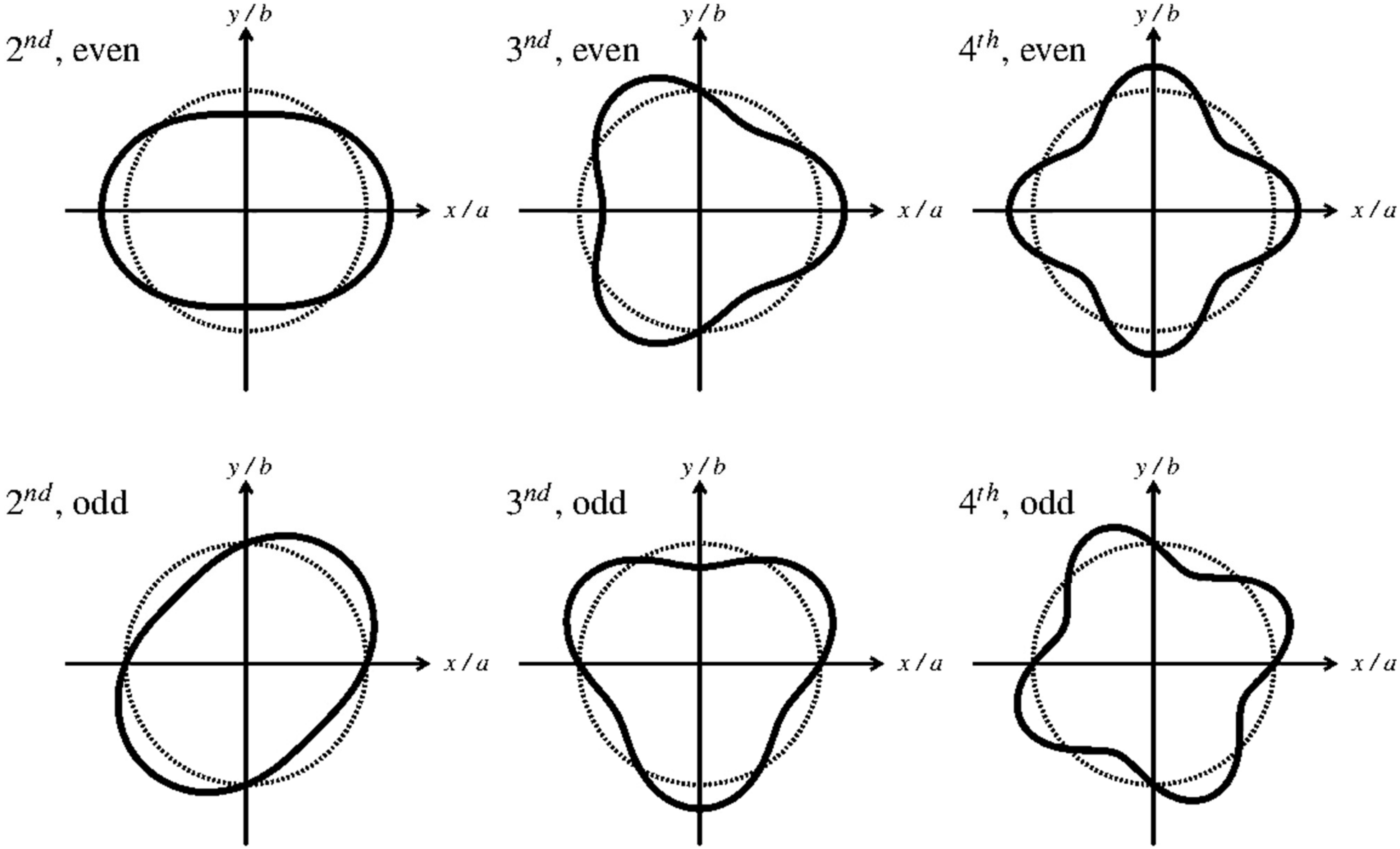
$$y = y' = 0$$



$$y \neq y' \neq 0$$

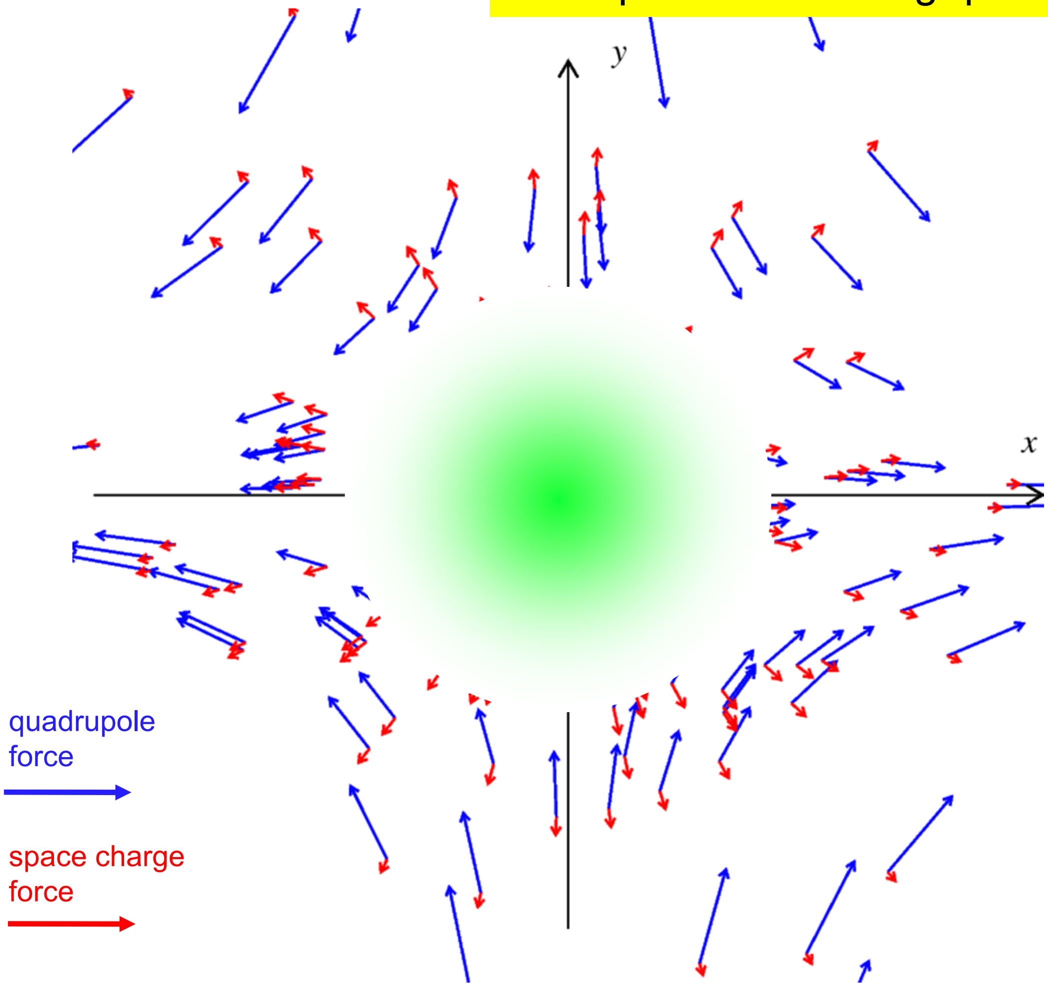
X – Y coupling

Modes of oscillation



Space charge vs. magnet force

Example in a focusing quadrupole



Quadrupole forces

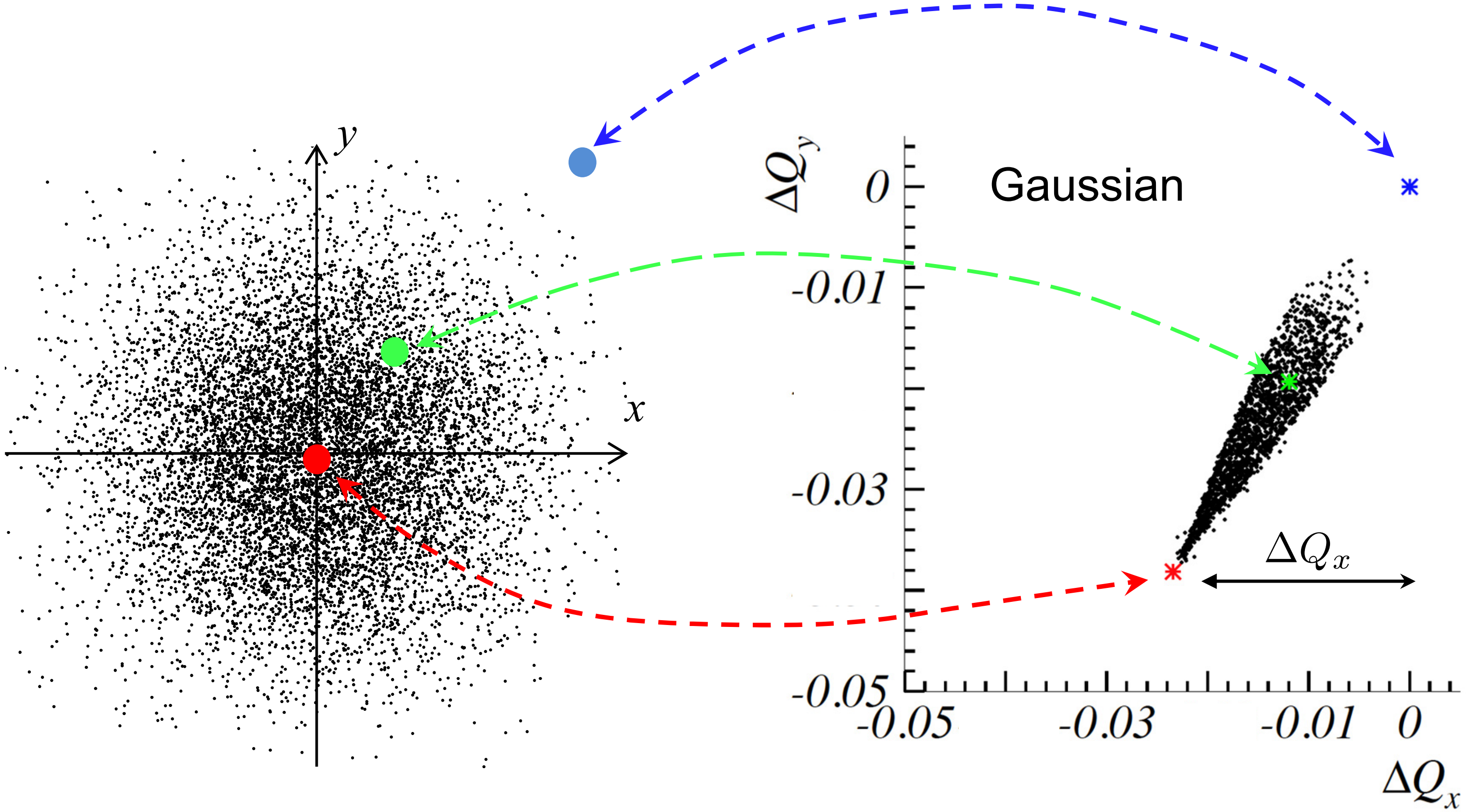
$$F_x = kx$$
$$F_y = -ky$$

Space charge forces

$$F_x = K\frac{x}{r^2}\left(1 - e^{-\frac{1}{2}\frac{x^2+y^2}{\sigma^2}}\right)$$

$$F_y = K\frac{y}{r^2}\left(1 - e^{-\frac{1}{2}\frac{x^2+y^2}{\sigma^2}}\right)$$

Space charge detuning



For a Gaussian distribution

$$\Delta Q_x = -\frac{R^2}{Q_x}\frac{K}{2}\frac{1}{\sqrt{\tilde{\epsilon}_x\langle\beta_x\rangle_s}(\sqrt{\tilde{\epsilon}_x\langle\beta_x\rangle_s}+\sqrt{\tilde{\epsilon}_y\langle\beta_y\rangle_s})}$$

Lattice induced resonances

Lattice induced nonlinear resonances

$$n_x Q_{x0} + n_y Q_{y0} = m$$

G. Guignard, CERN 78-11, (1978);
A. Bazzani et al., CERN94-02 (1994).

Resonant dynamics

Resonance driving terms

A combination of optics, and Magnets strength

$$\kappa = \frac{1}{2\pi(2R)^{(N/2)}|n_x|!|n_z|!}\int_0^{2\pi} d\theta\ \beta_x^{|n_x|/2}\ \beta_z^{|n_z|/2}\ \times$$

$$\times \exp\left\{i\left[n_x\mu_x + n_z\mu_z - (n_xQ_x + n_zQ_z - p)\theta\right]\right\}\begin{cases}(-1)^{(|n_z|+2)/2}\ K_z^{(N-1)} & \text{for } n_z \text{ even}\\ (-1)^{(|n_z|-1)/2}\ K_x^{(N-1)} & \text{for } n_z \text{ odd}\end{cases}$$

Magnets nonlinearities drives resonances

Including the chromaticity

$$\Delta_r = \Delta_{r0} + \Delta Q_{sc,x}(X,Y) + 2\Delta Q_{sc,y}(X,Y) + Q'_x \delta p/p + 2Q'_y \delta p/p$$

Bare tunes

$\Delta_{r0} = 0.056$

effect of space charge
AMPLITUDE DEPENDENT

incoherent tune-shift

$\Delta Q_{x,max} \simeq -0.05,$

$\Delta Q_{y,max} \simeq -0.071$

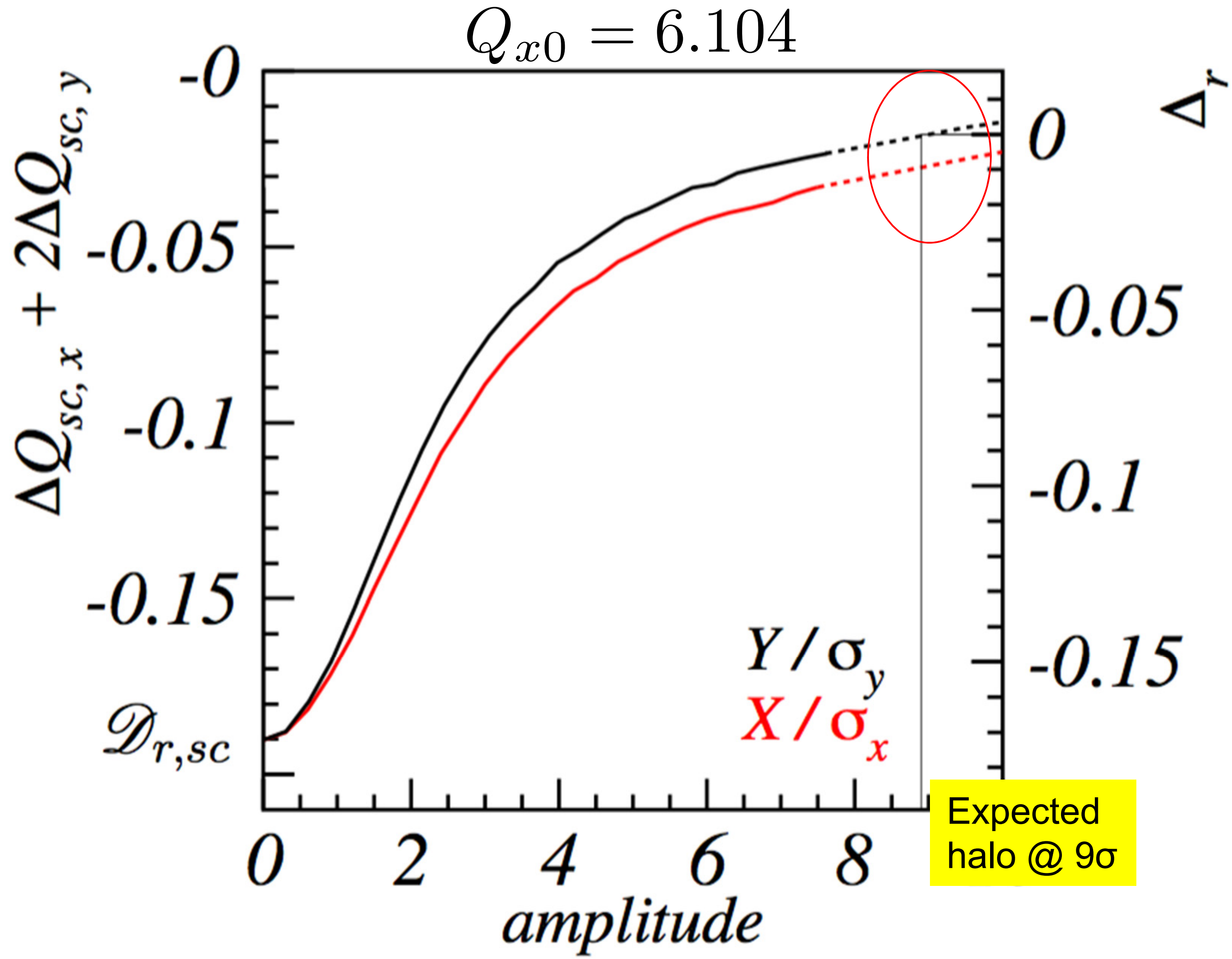
$\mathscr{D}_{r,sc} \simeq -0.19$

effect of chromaticity
AMPLITUDE INDEPENDENT

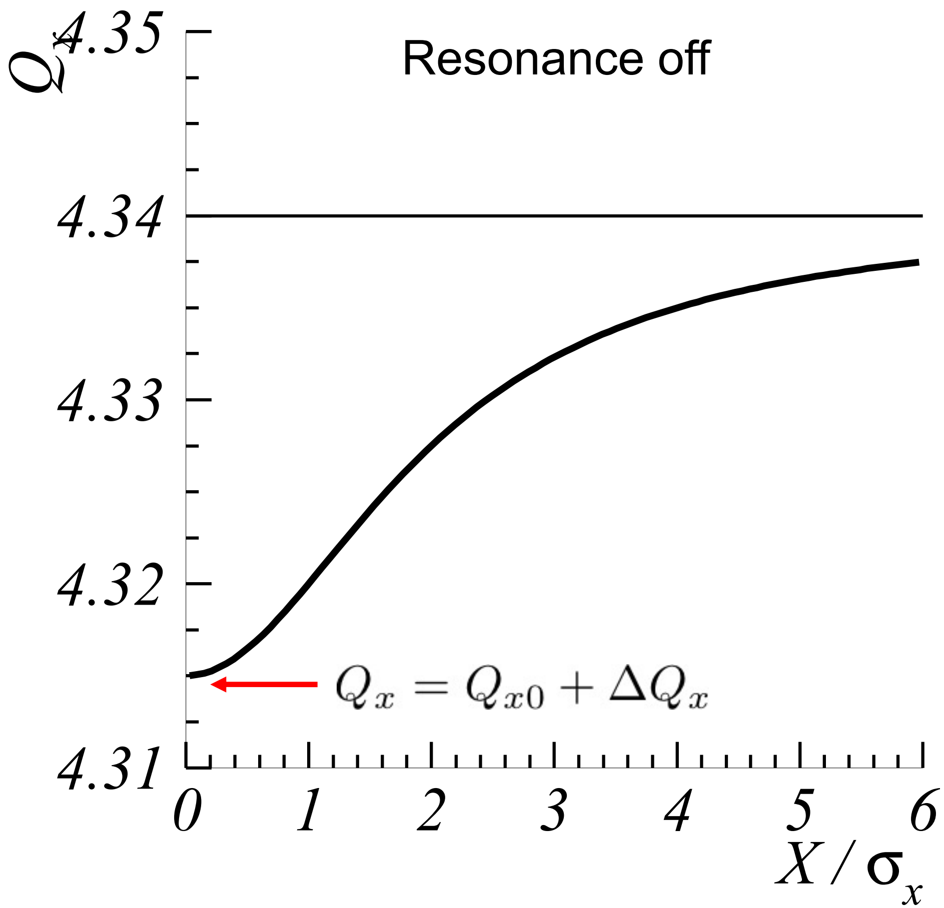
consider a test particle
with maximum dp/p

+/- 0.037

Resonant Particle including chromaticity



Position of the islands (1D resonances)



Position of the islands (1D resonances)