Space charge effect on the second order coupled resonance

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HB2016 – Malmo, Sweden

The quest of the incoherent effects of space charge

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** 3th order resonance: proof of principle	study of the space charge on **2D** 3th order resonance	resonance compensation with space charge	Experimental discovery of the fixed-lines
PS (CERN)	**SIS18** (GSI)	**PS** (CERN)	**SIS18** (GSI)	**SPS** (CERN)

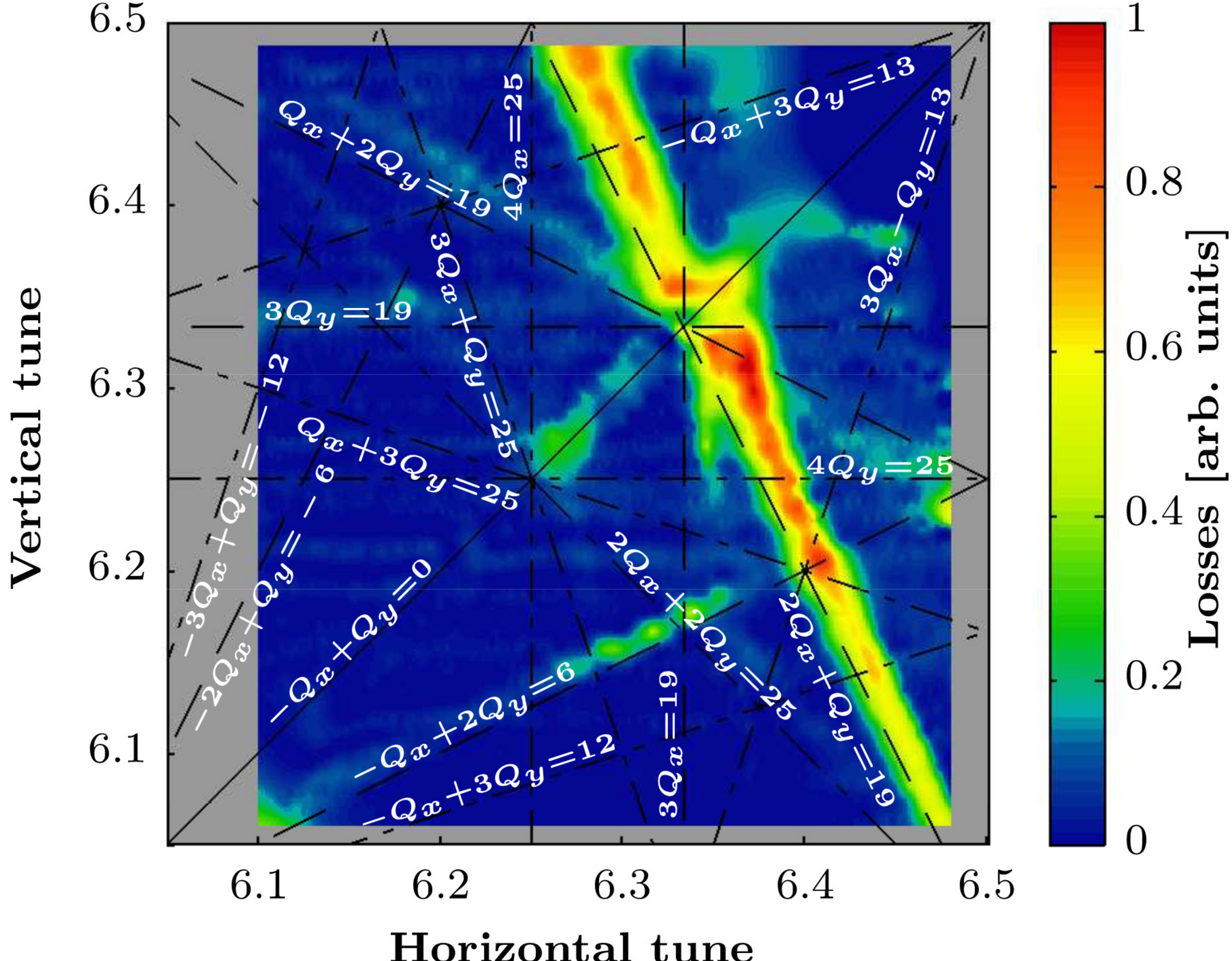
Future:

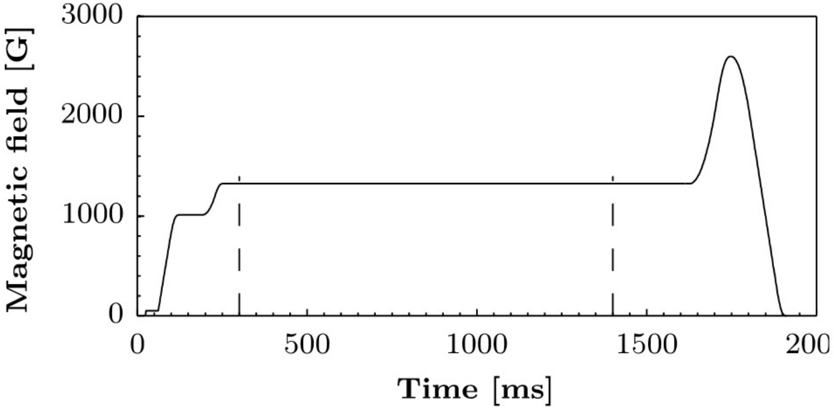
SIS18, SIS100 (GSI)

PS, SPS, .. (CERN)

Fermilab

IOTA


6.5
6.4
6.3
6.2
6.1
6.1
6.2
6.3
6.4
6.5
Vertical tune
Horizontal tune
Losses [arb. units]
1
0.8
0.6
0.4
0.2
0
Qx+2Qy=19
4Qx=25
−Qx+3Qy=13
3Qx−Qy=13
3Qx+Qy=25
3Qy=19
−3Qx+Qy=−12
−2Qx+Qy=−6
Qx+3Qy=25
4Qy=25
−Qx+Qy=0
2Qx+2Qy=25
2Qx+Qy=19
−Qx+2Qy=6
−Qx+3Qy=12
3Qx=19



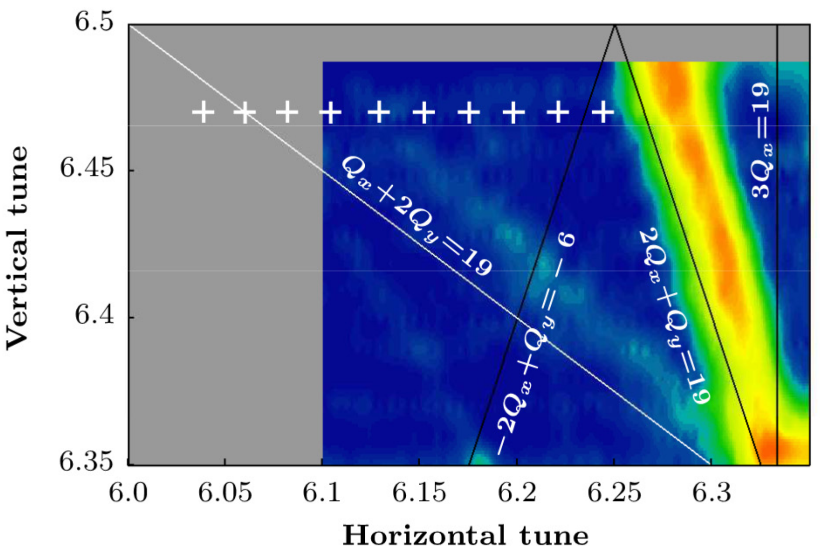


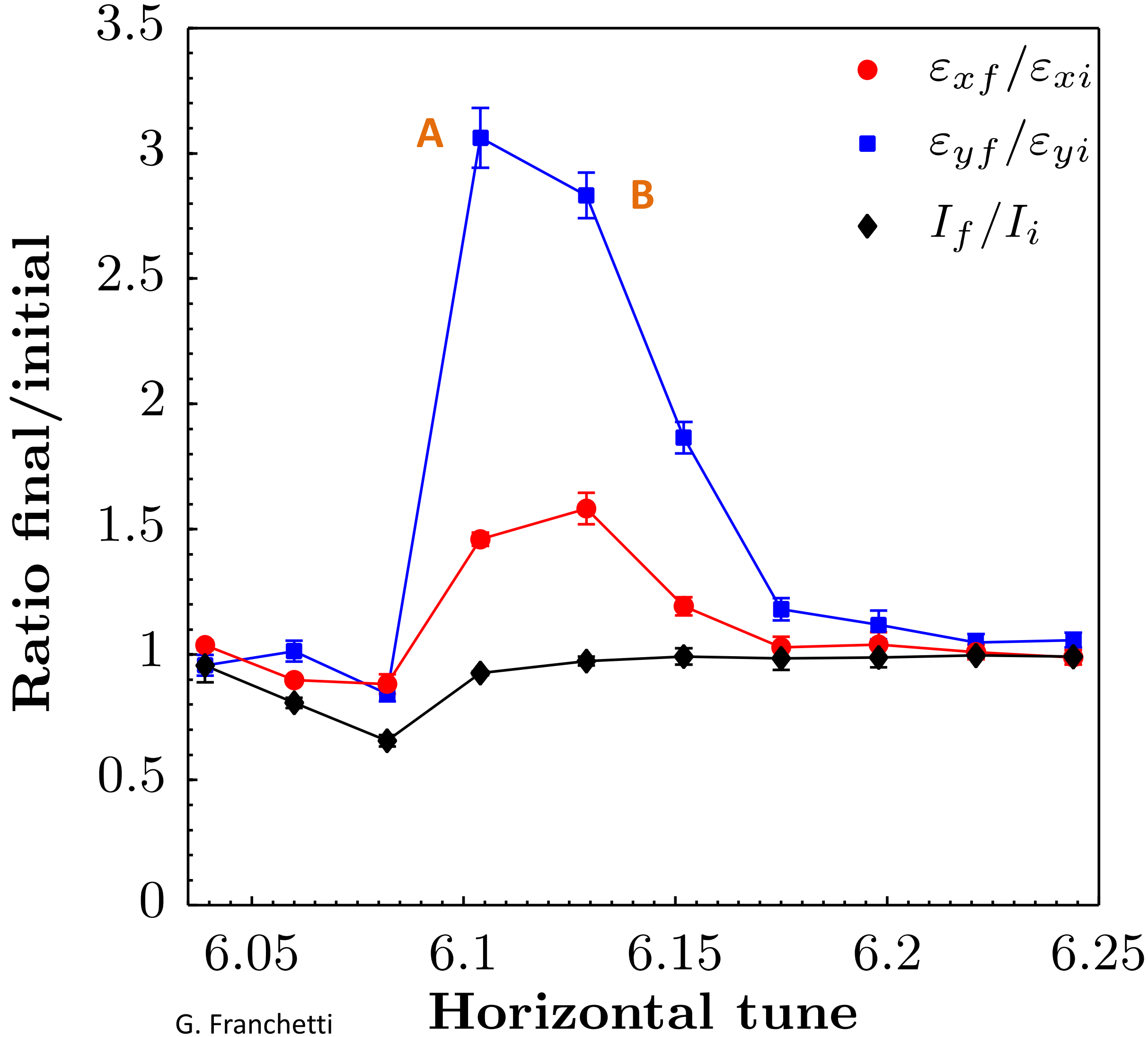
TABLE I. Beam and machine parameters.

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

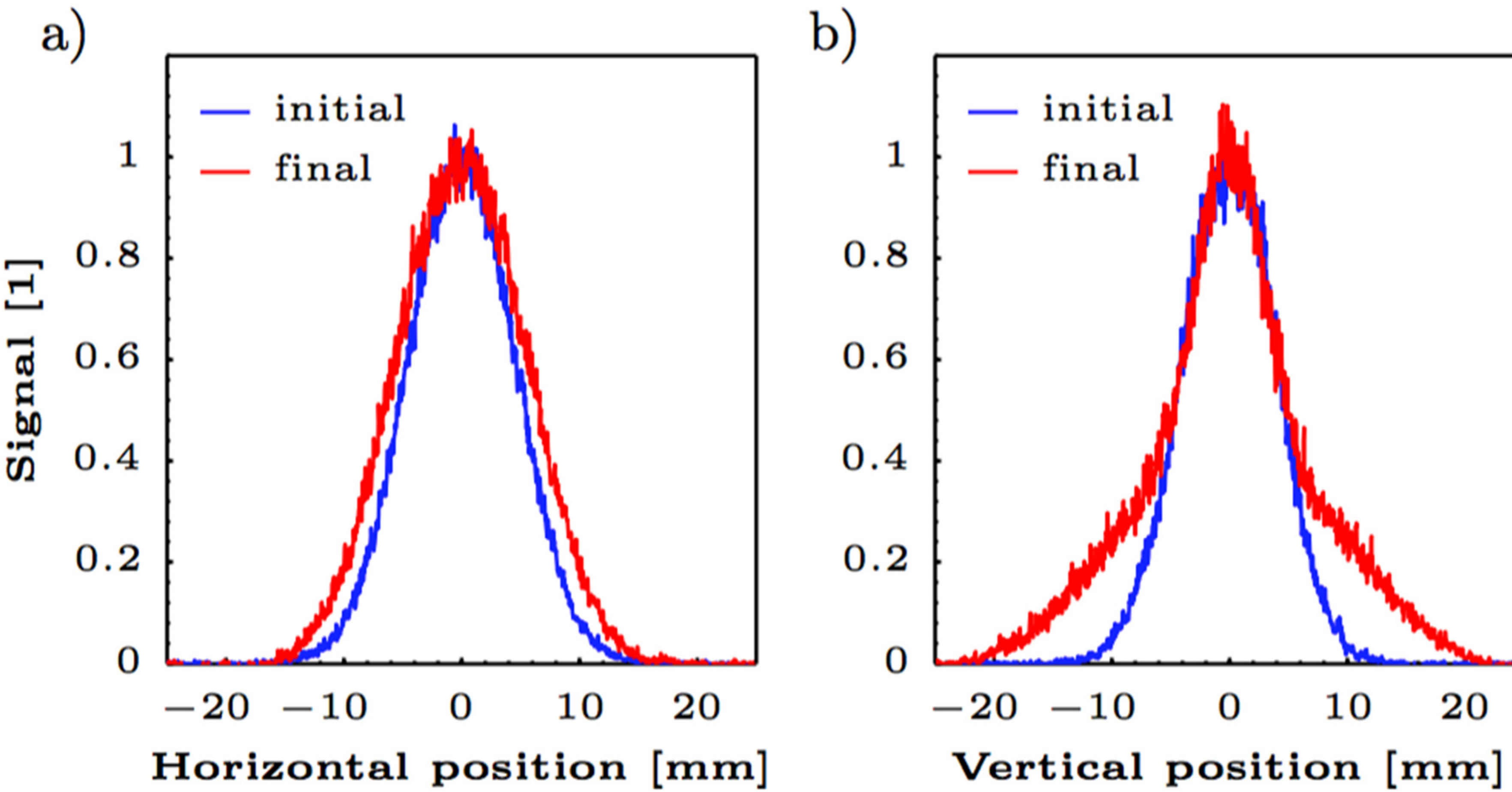
[a] The tune spread is calculated according to Ref. [18].

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

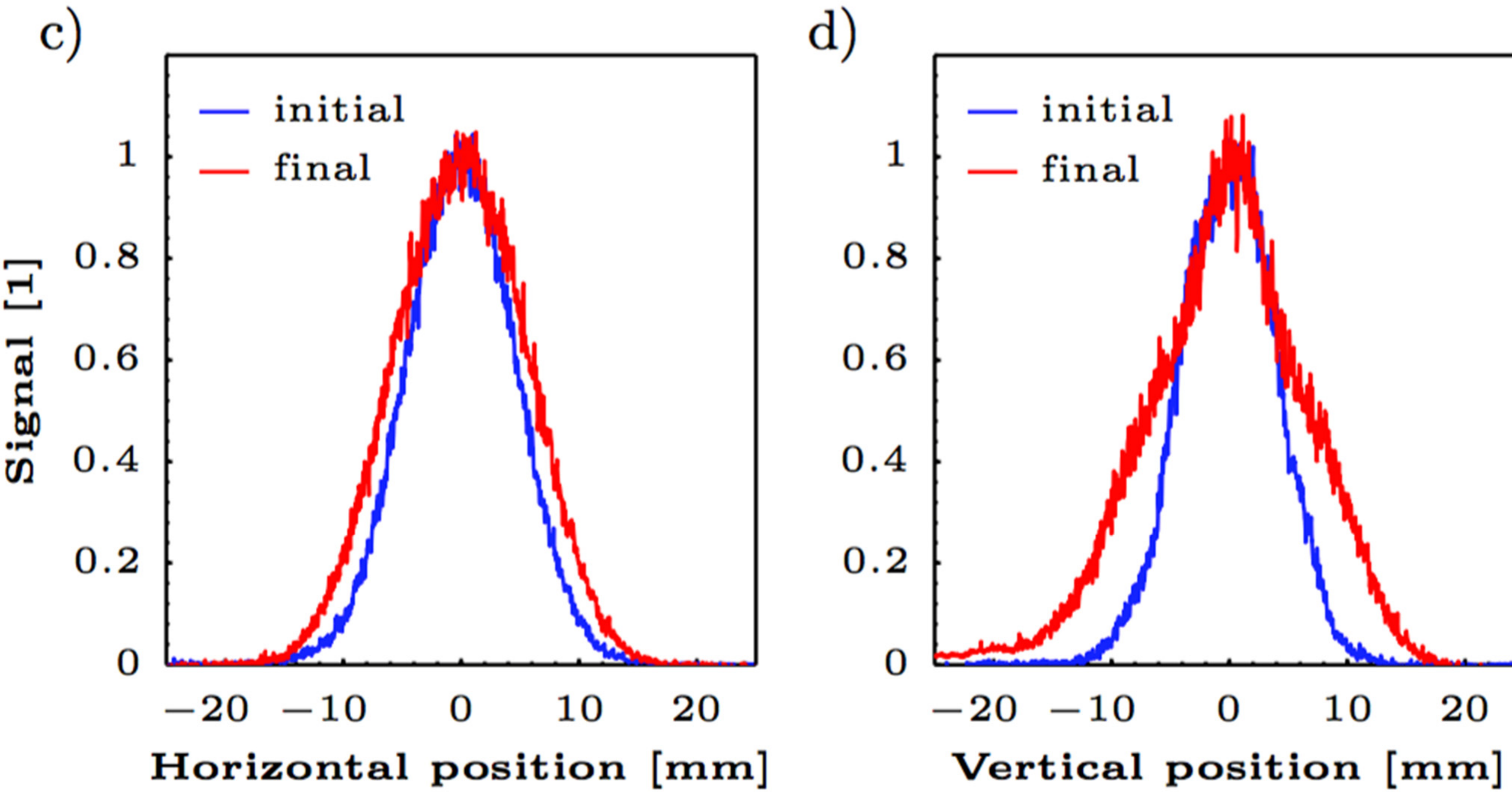
PS campaign: “towards the unknown”

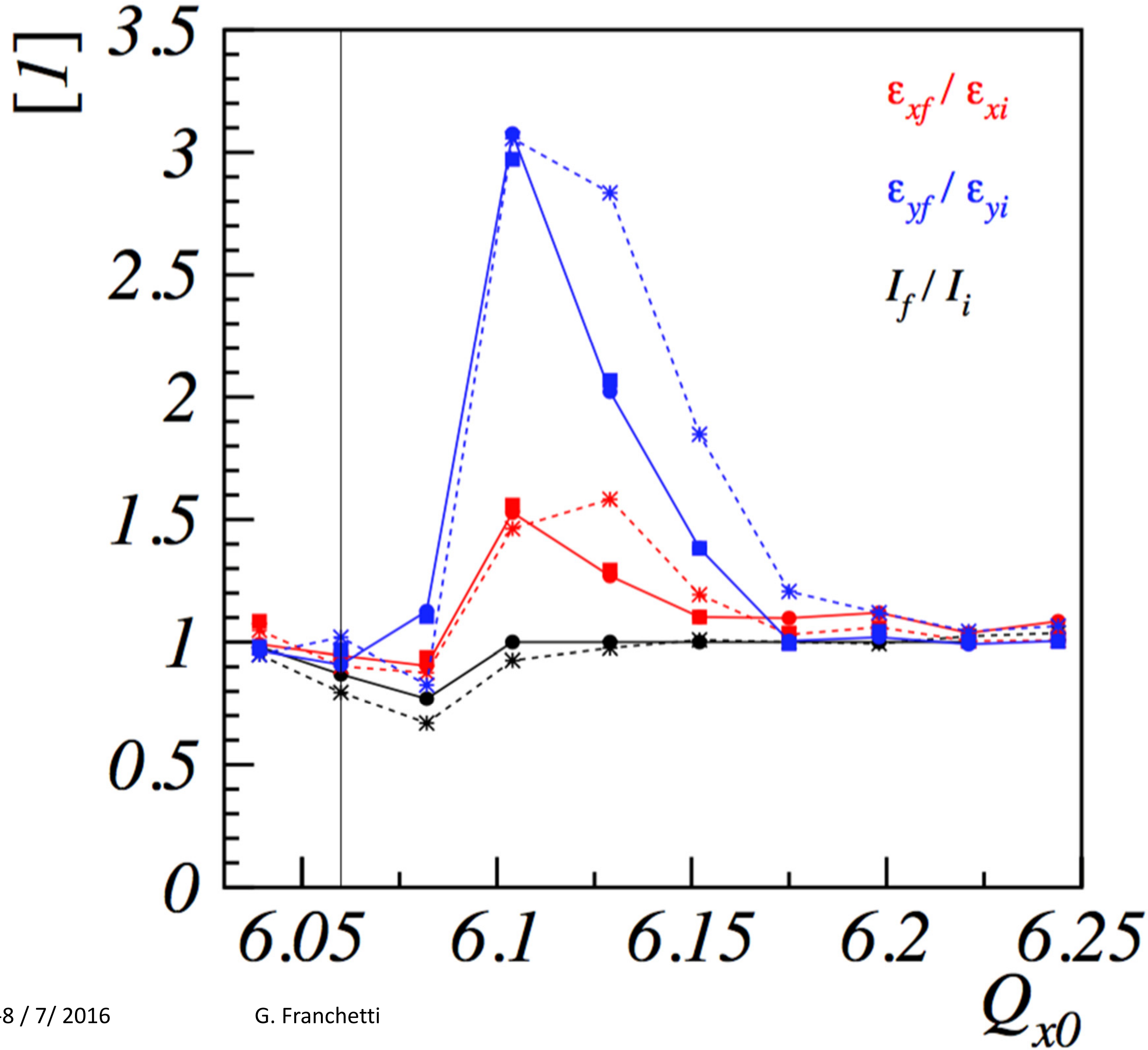


Beam Profiles @ (A)

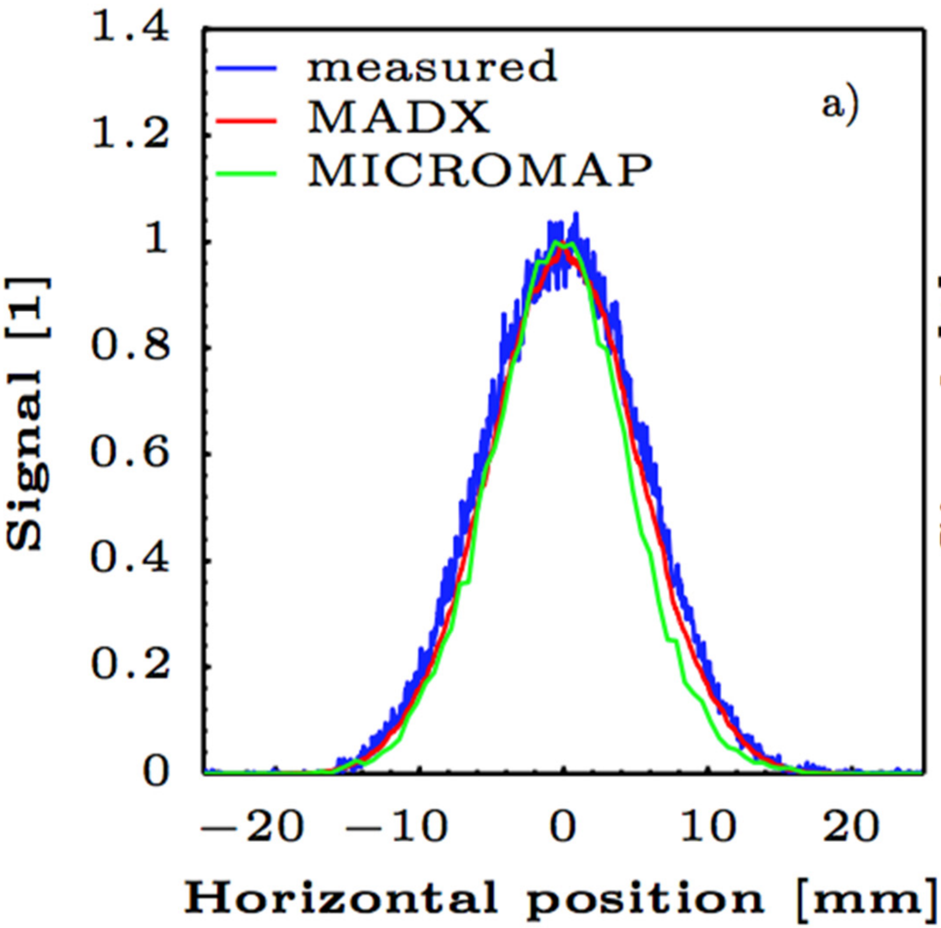


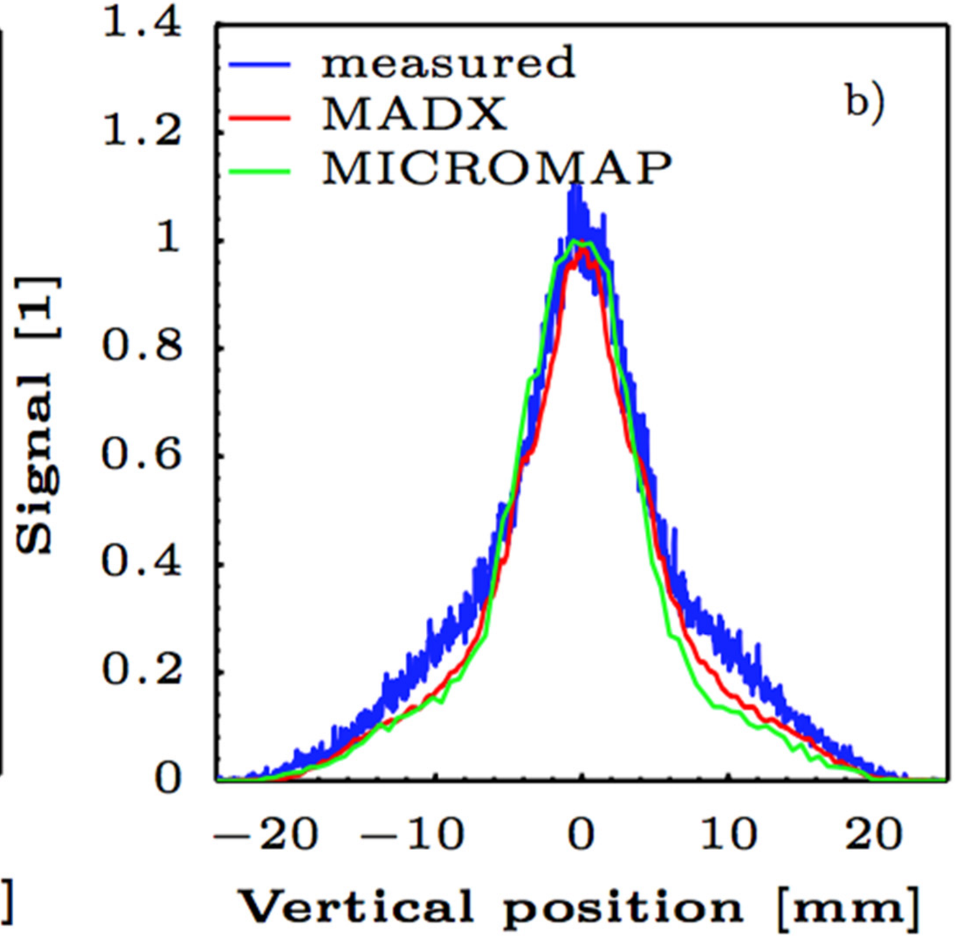
Beam Profiles @ (B)




[I]
3.5
3
2.5
2
1.5
1
0.5
0
6.05
6.1
6.15
6.2
6.25
Q_{x0}
$\varepsilon_{xf} / \varepsilon_{xi}$
$\varepsilon_{yf} / \varepsilon_{yi}$
I_f / I_i

Code experiment benchmarking





Distance from the resonance

Bare optics

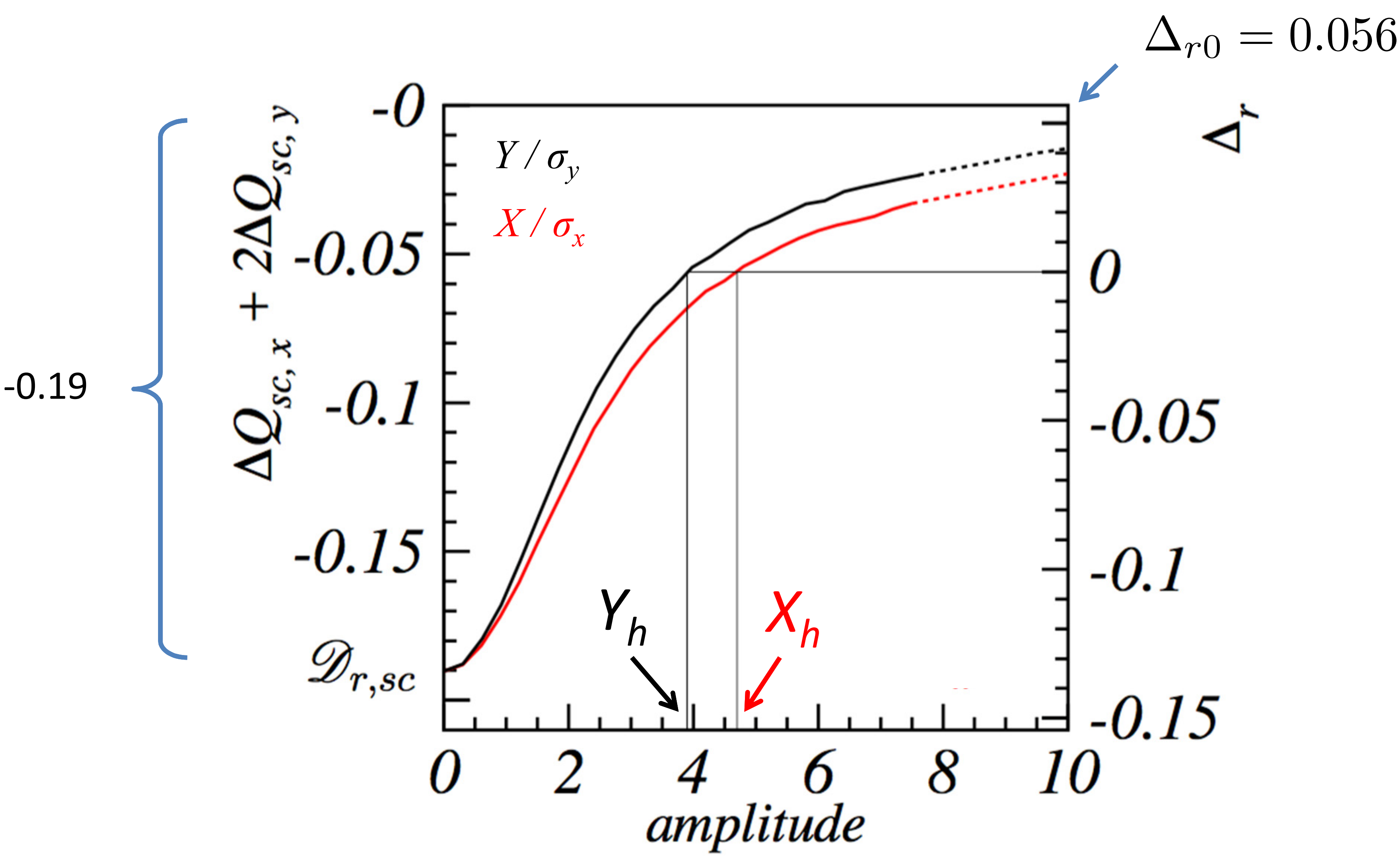
$$\Delta_{r0} = Q_{x0} + 2Q_{y0} - 19$$

Bare optics + space charge of
one particle at amplitudes X,Y

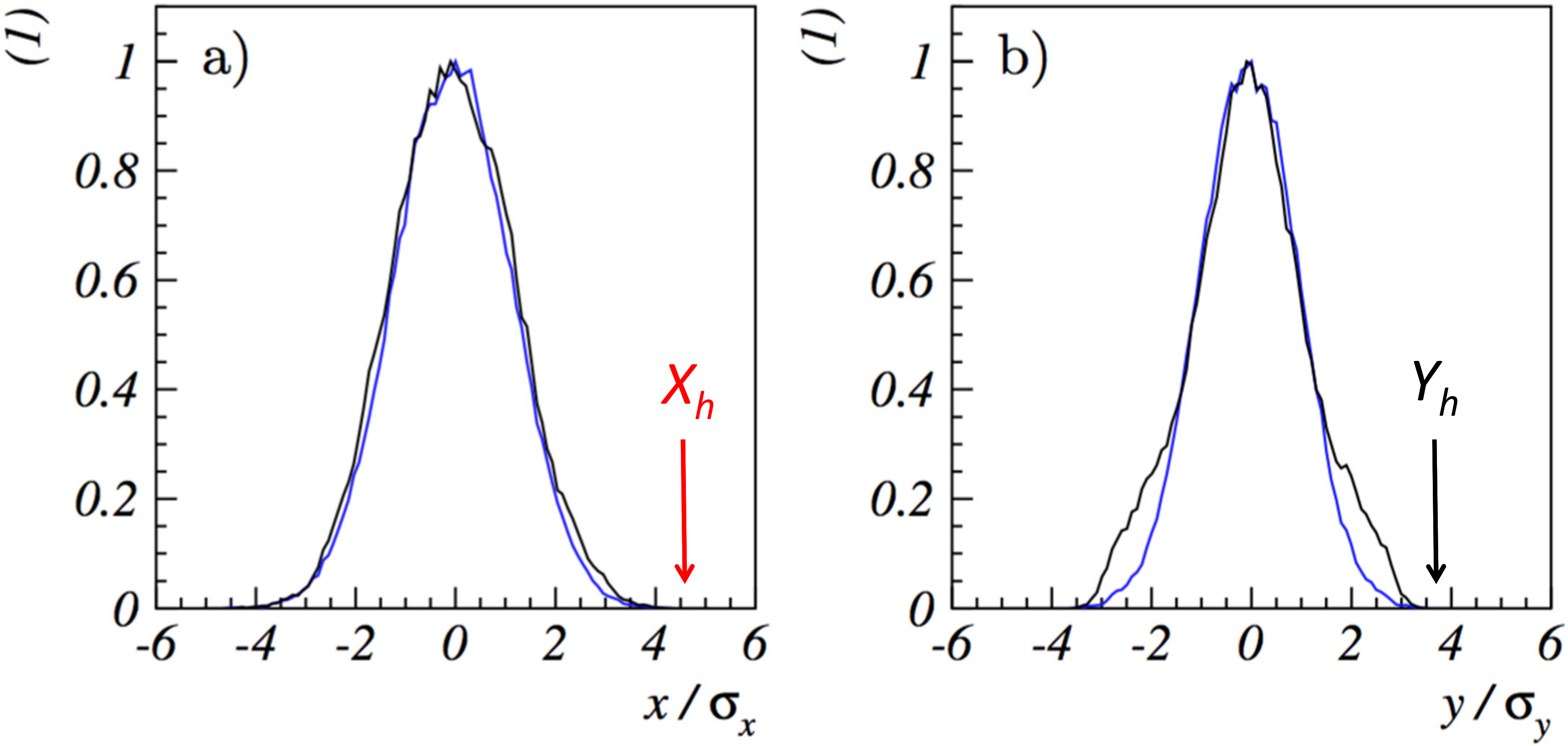
$$\Delta_r = \Delta_{r0} + \Delta Q_{sc,x}(X,Y) + 2\Delta Q_{sc,y}(X,Y)$$

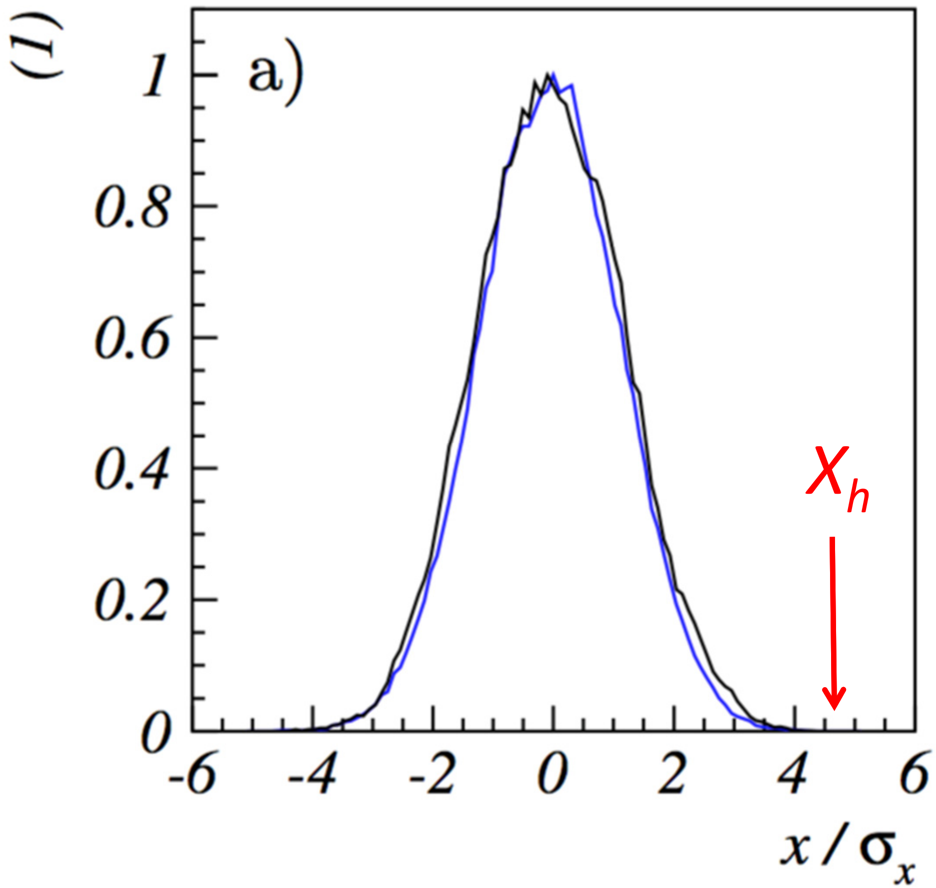
Resonance condition → $\Delta_r = 0$

Resonant particles



Comparison with simulations





Something seems wrong !
The -x- profile does not exhibit
an halo that ends at X_h

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

effect of space charge
AMPLITUDE DEPENDENT

incoherent tune-shift

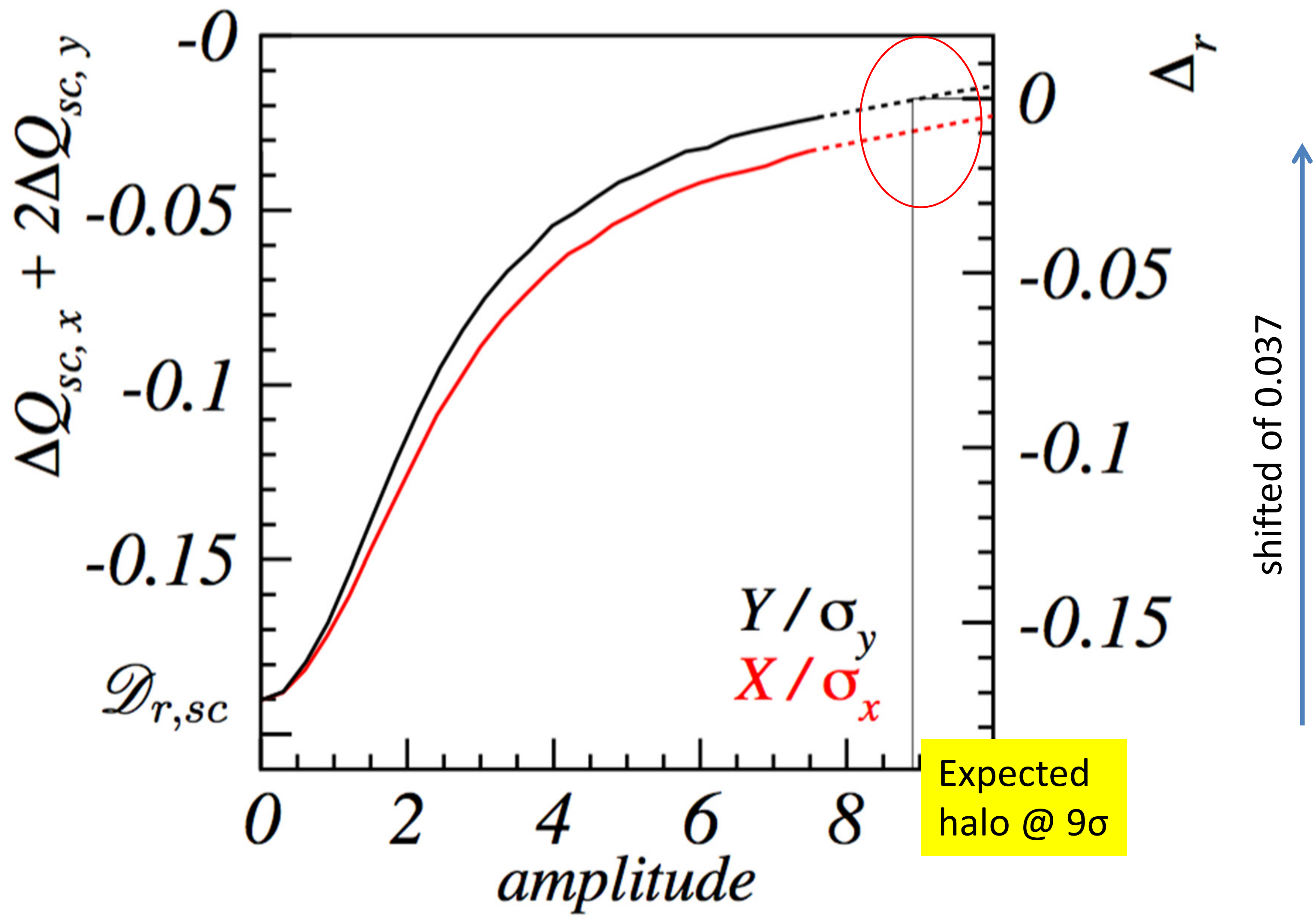
$$\Delta Q_{x,max} \simeq -0.05,$$
$$\Delta Q_{y,max} \simeq -0.071$$

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

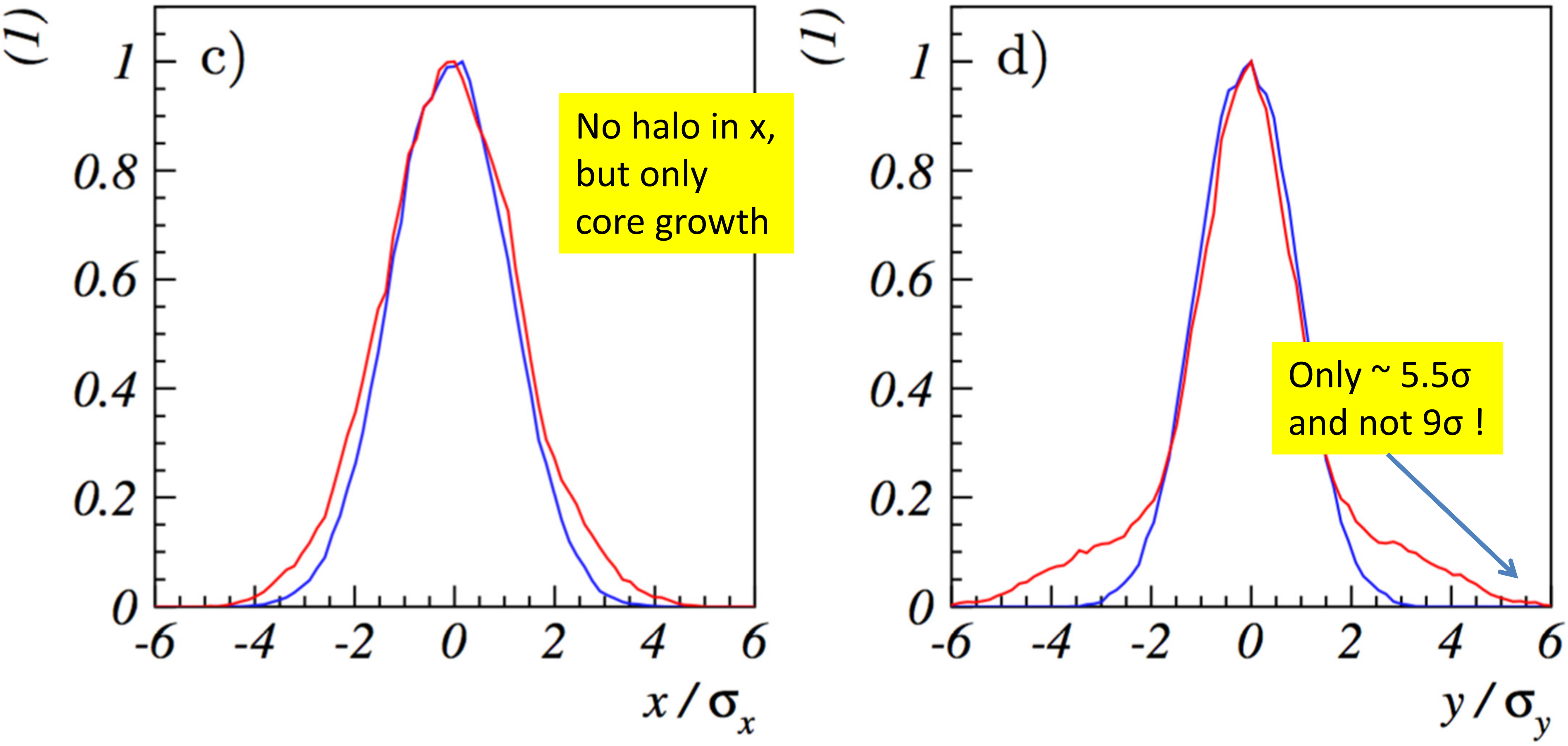
effect of chromaticity
AMPLITUDE INDEPENDENT

consider a test particle
with maximum dp/p

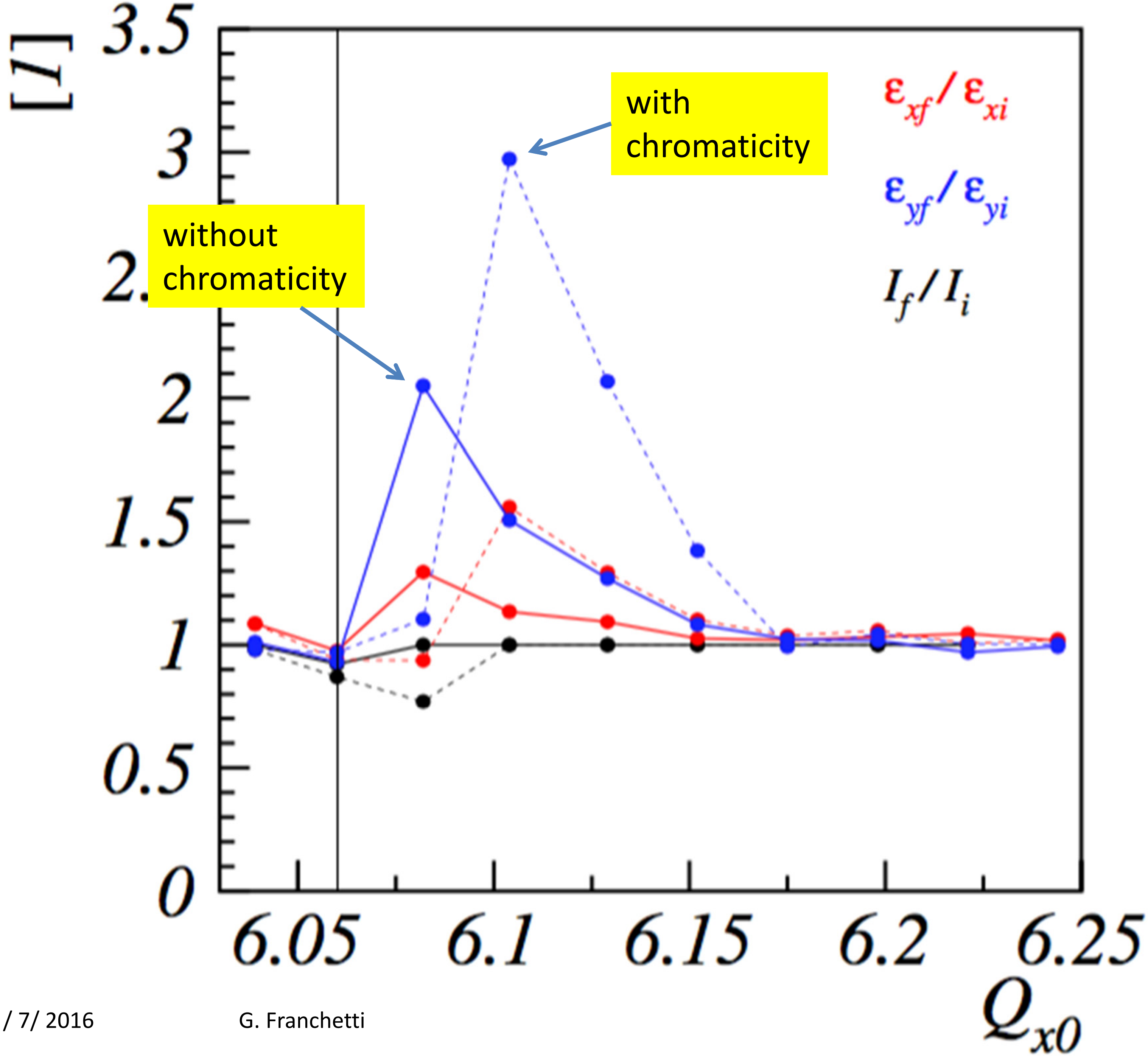
0.037


$\Delta Q_{sc,x} + 2\Delta Q_{sc,y}$
-0
-0.05
-0.1
-0.15
$\mathscr{D}_{r,sc}$
Δ_r
0
-0.05
-0.1
-0.15
Y/σ_y
X/σ_x
0
2
4
6
8
amplitude
Expected
halo @ 9σ
shifted of 0.037

Including chromaticity



Something seems very wrong!
The -x- profile does not exhibit
a halo, and the -y- profile have
a smaller halo than expected


[I]
3.5
3
2.
2
1.5
1
0.5
0
6.05
6.1
6.15
6.2
6.25
Q_{x0}
with chromaticity
without chromaticity
$\varepsilon_{xf}/\varepsilon_{xi}$
$\varepsilon_{yf}/\varepsilon_{yi}$
I_f/I_i

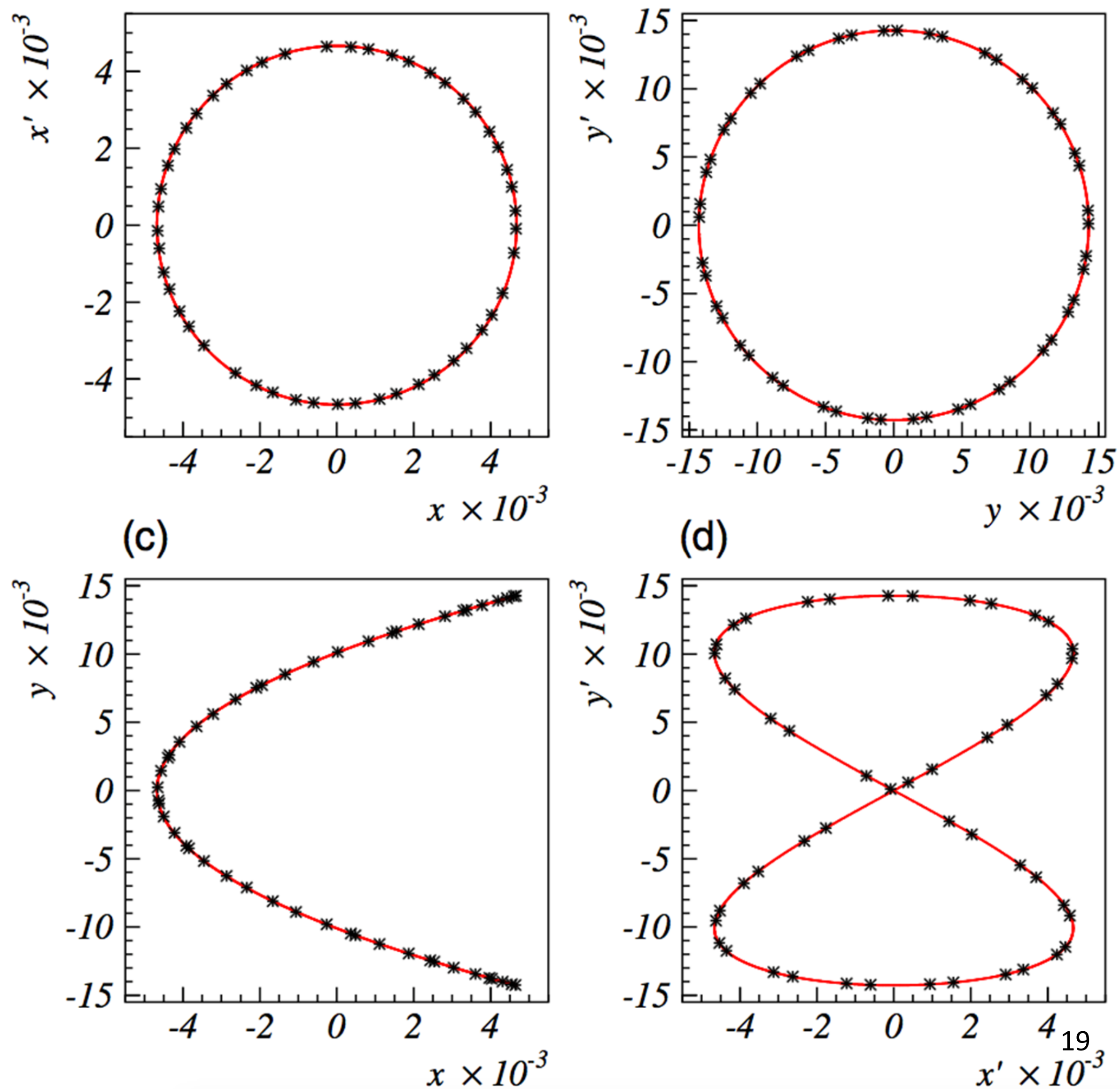
Coupled dynamics on the resonance

fixed lines

F. Schmidt PhD thesis, *and others*

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

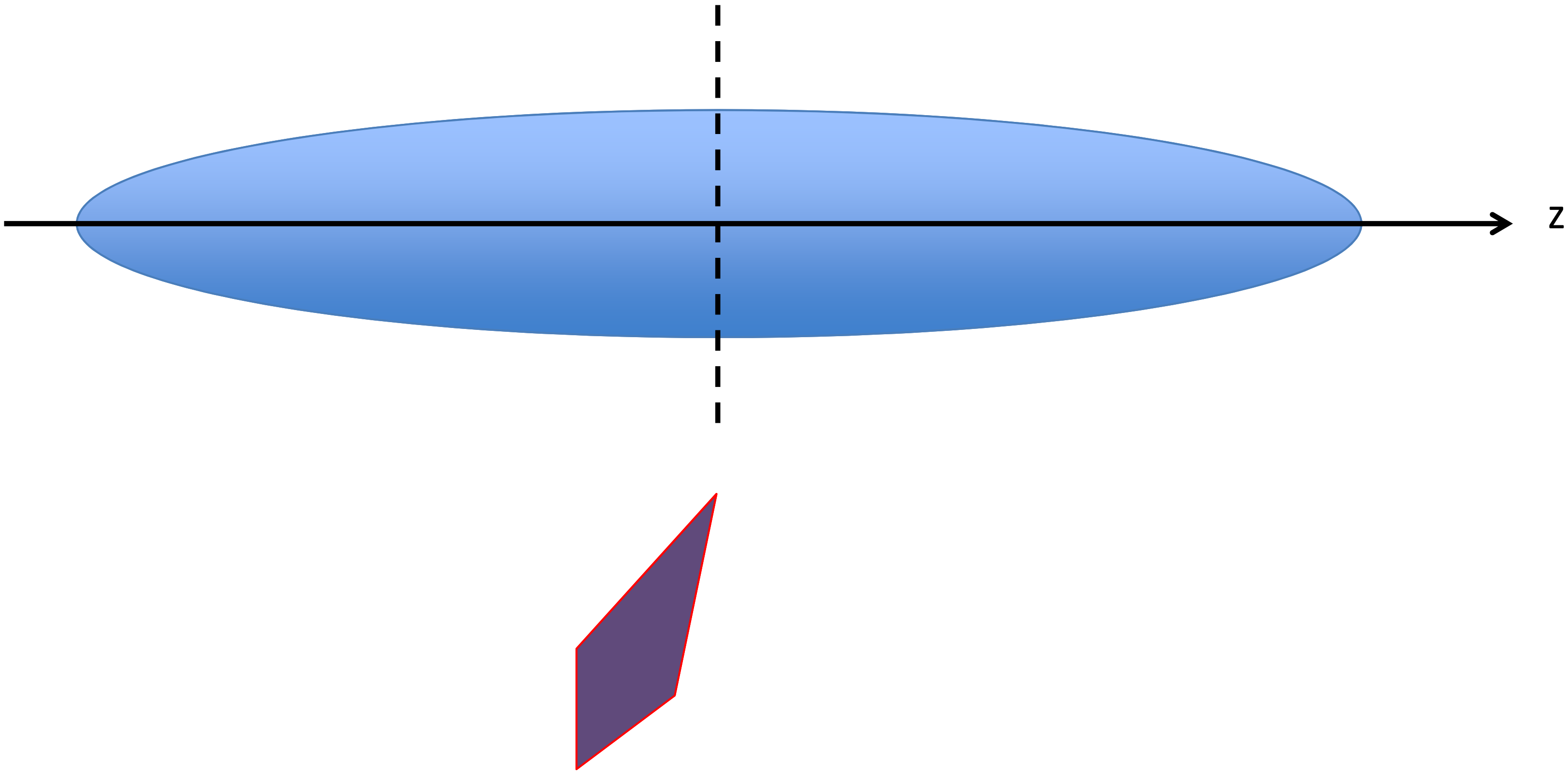
G. Franchetti and F. Schmidt
http://arxiv.org/abs/1504.04389

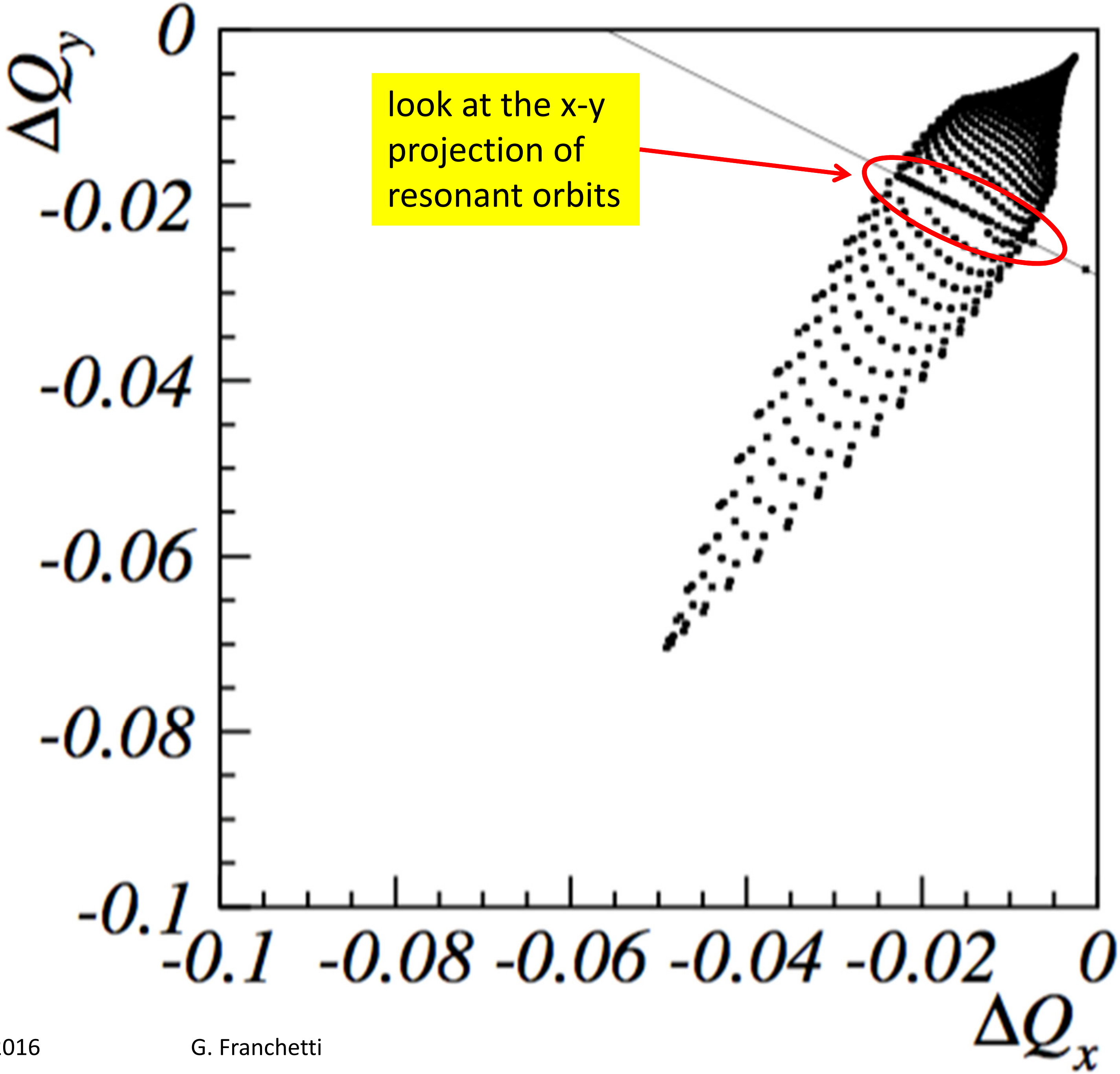


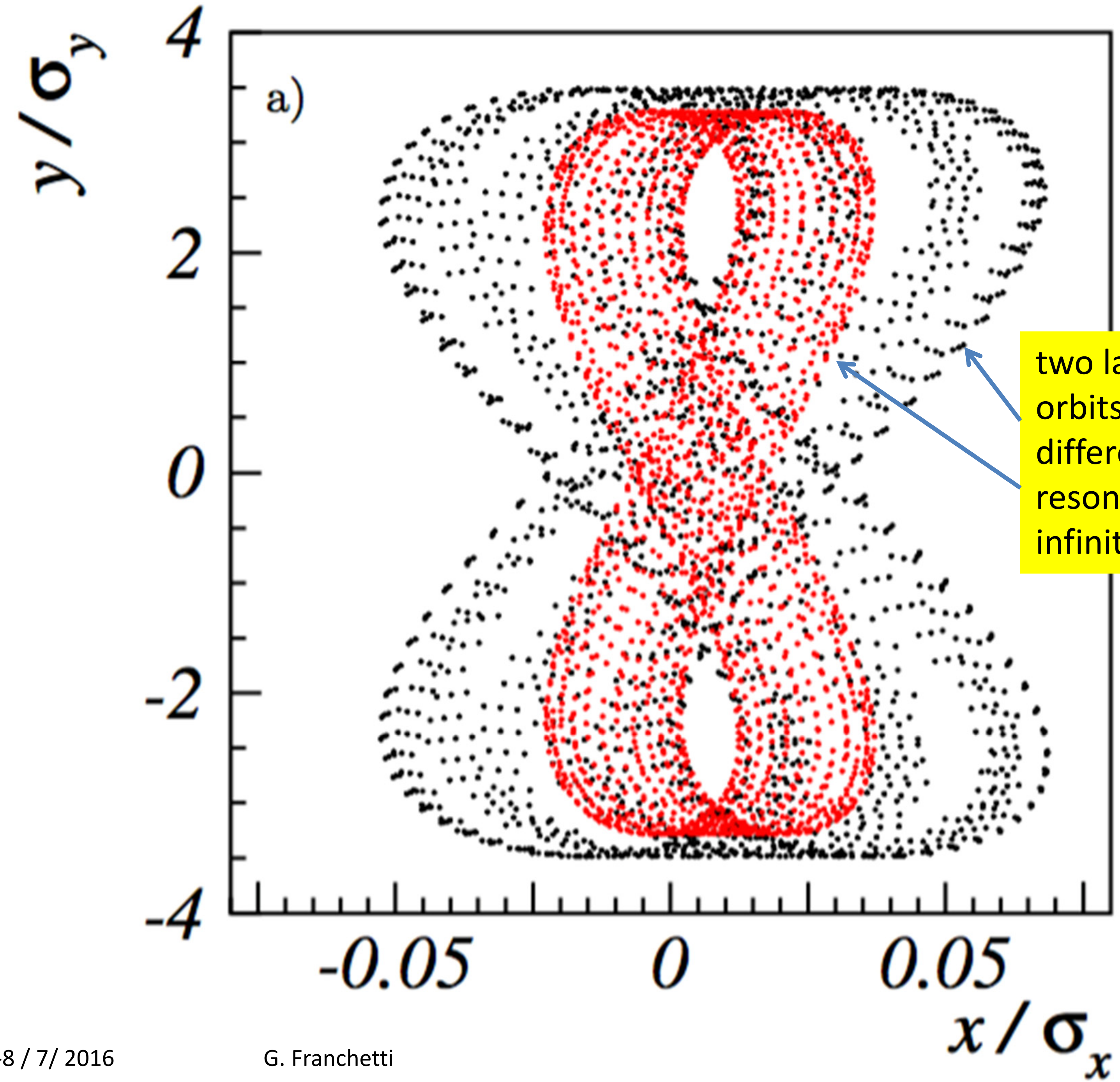
SPS campaign on May 2015:"Dream of glory"

Space charge induced coupled dynamics in a bunch

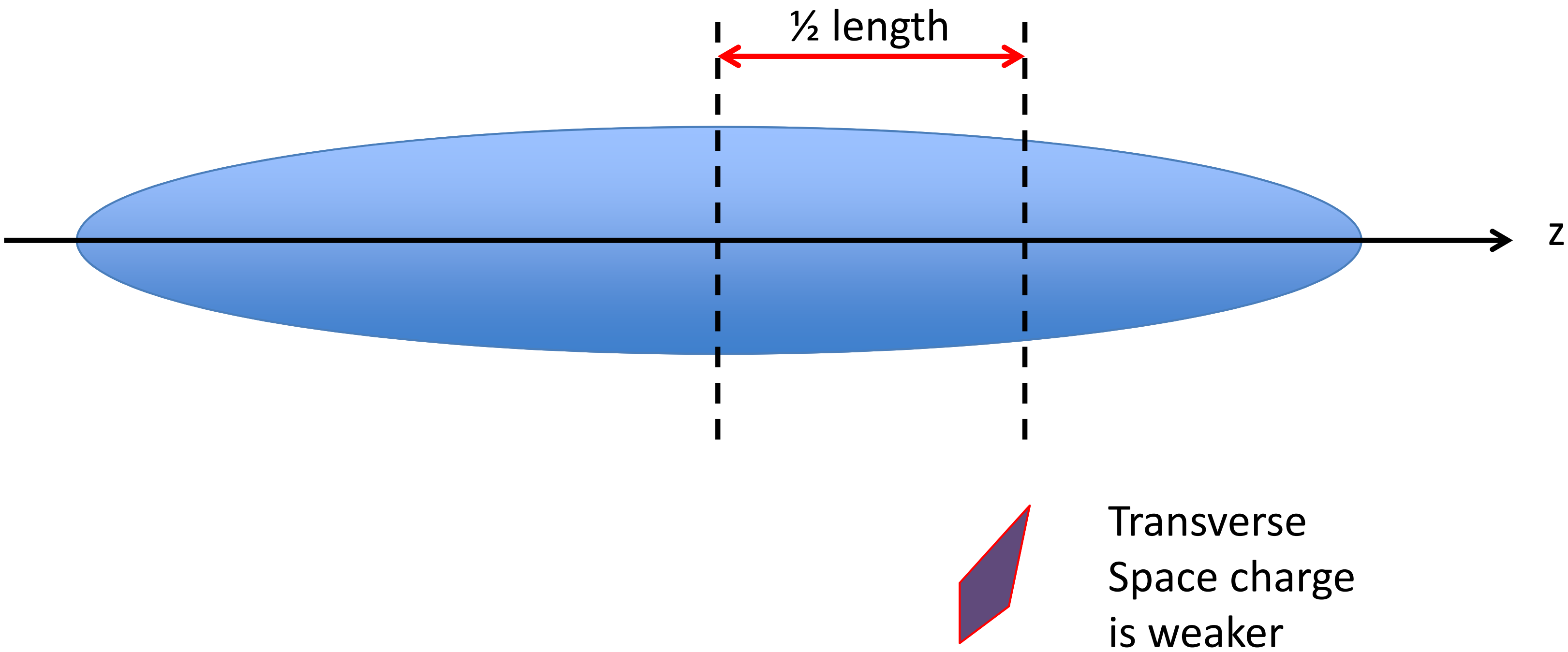
longitudinal motion keep frozen, to make retrieve orbits

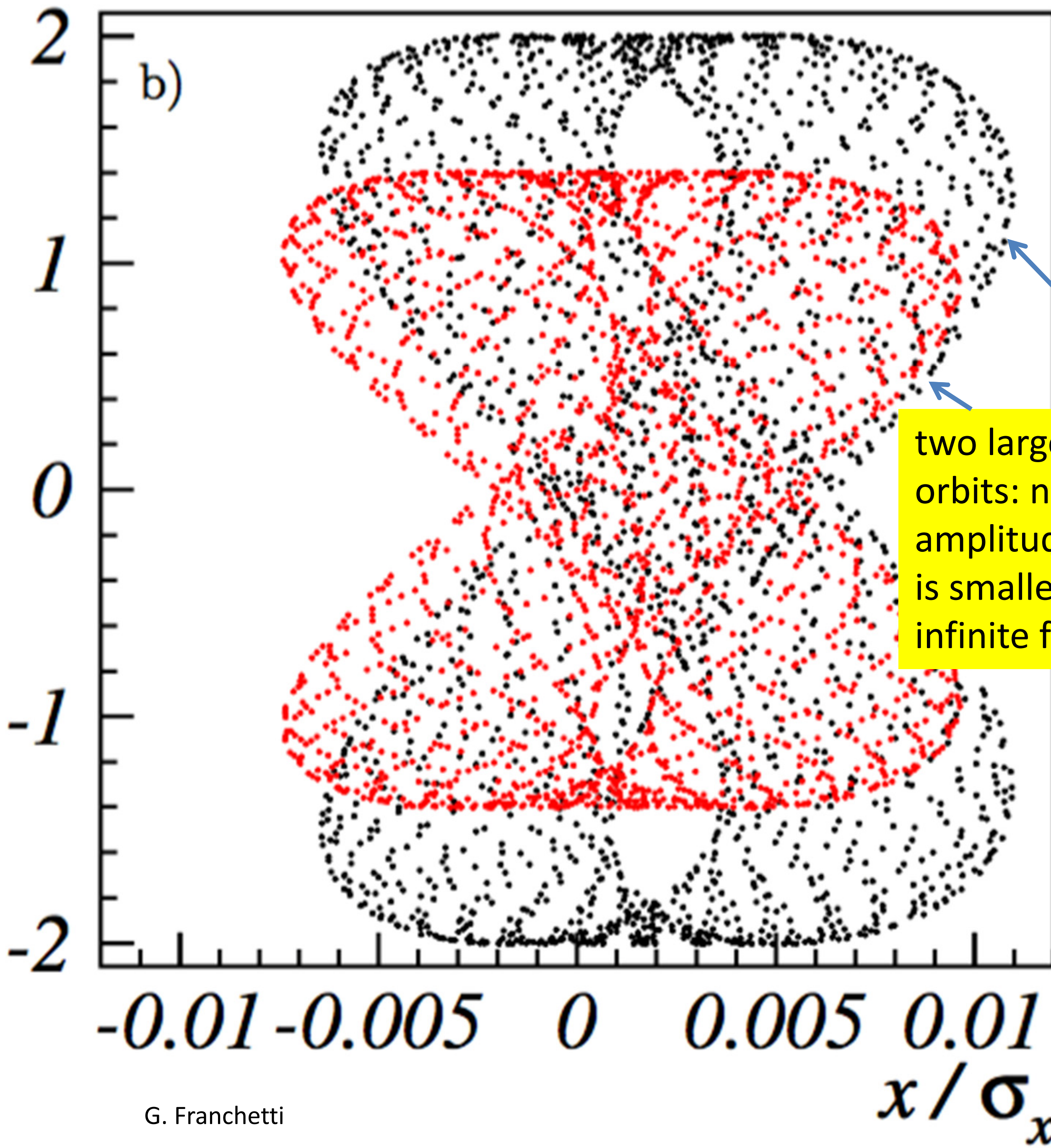



look at the x-y projection of resonant orbits
ΔQ_y
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.1
-0.08
-0.06
-0.04
-0.02
0
ΔQ_x



two larger resonant orbits: situation very different than 1D resonances. There are infinite fixed lines !!

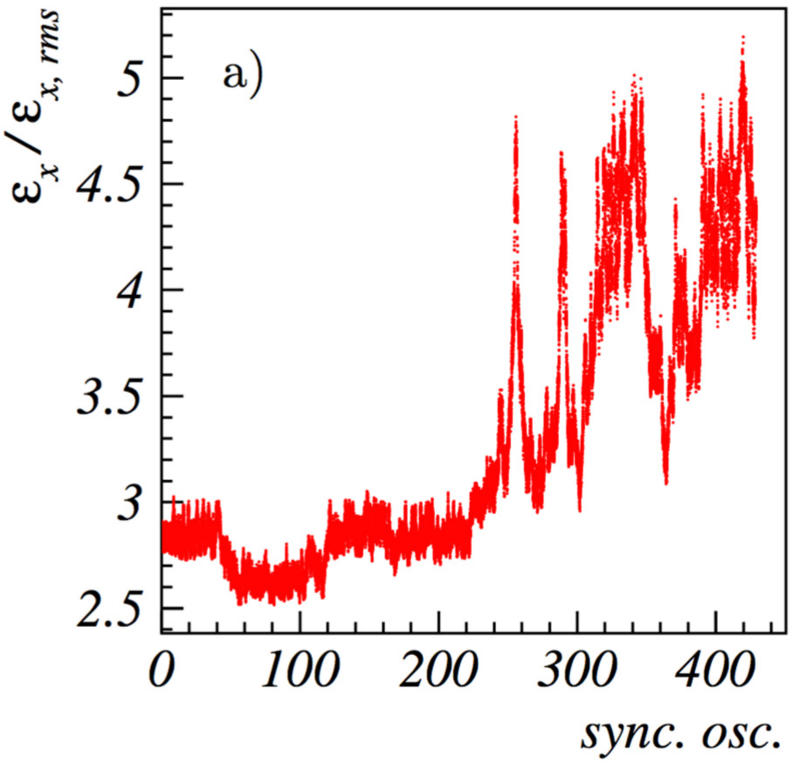

½ length
z
Transverse
Space charge
is weaker

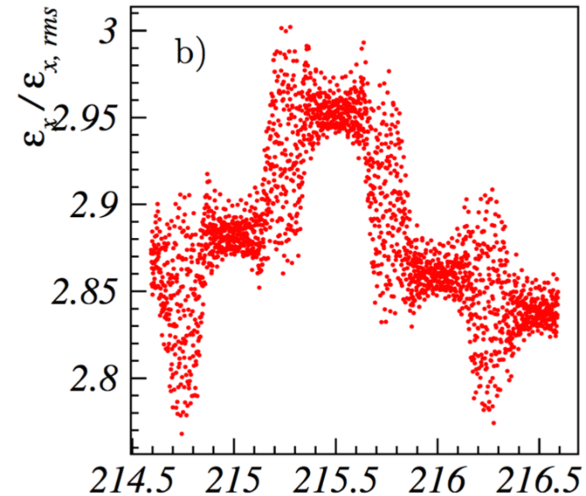


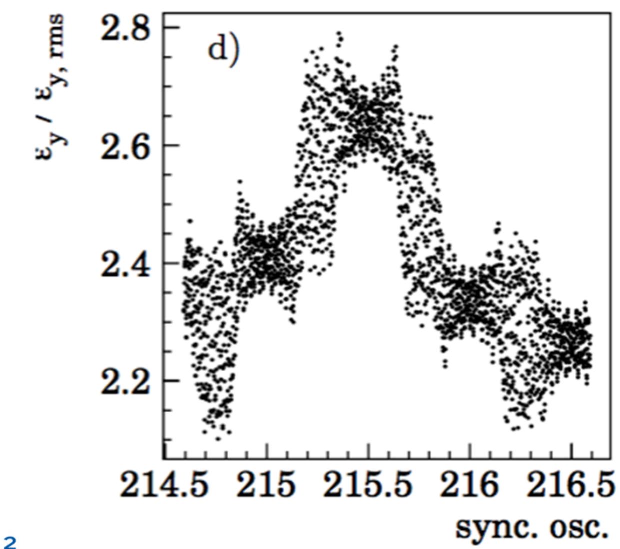
two larger resonant orbits: now the amplitude of the orbits is smaller. We still have infinite fixed lines.

Periodic crossing of fixed lines induced by space charge and synchrotron motion

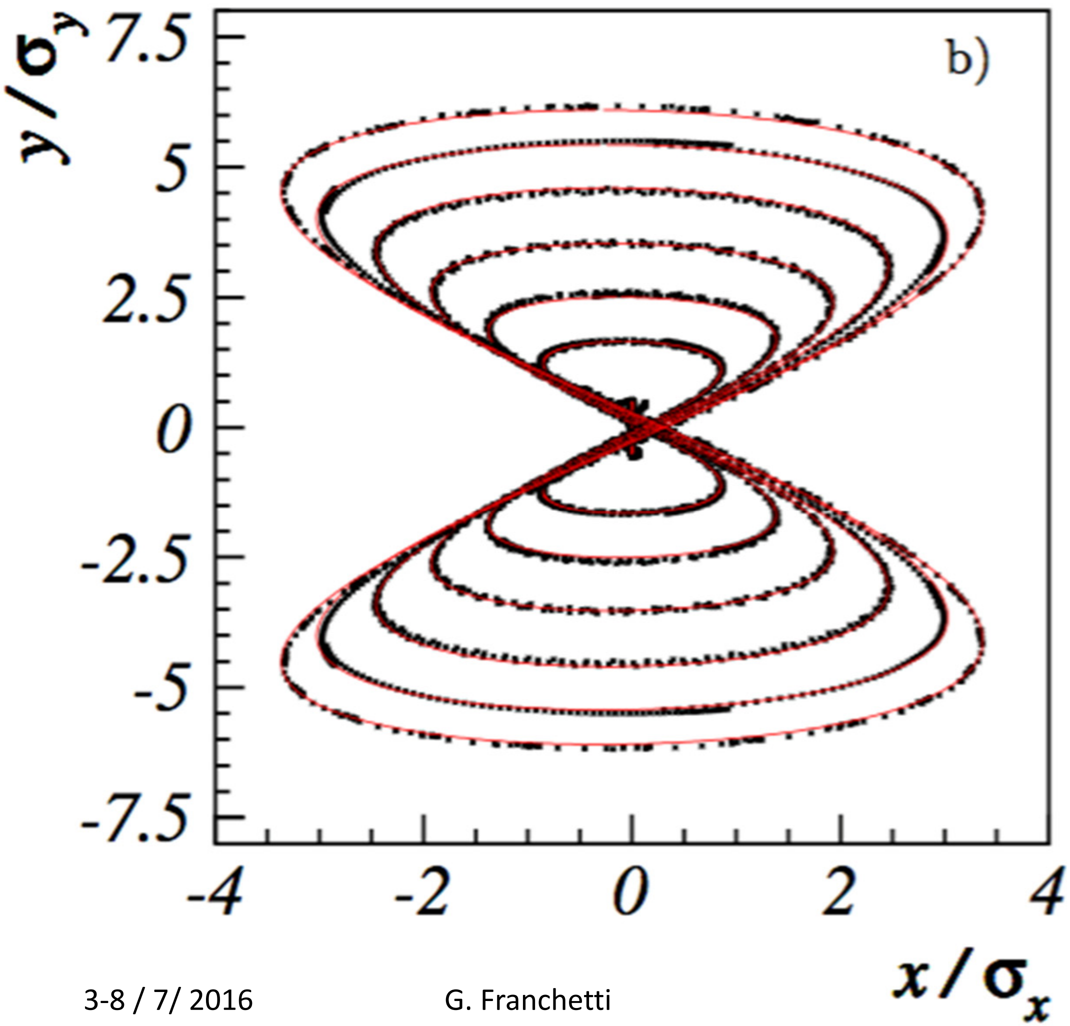
Scattering (of the invariants)







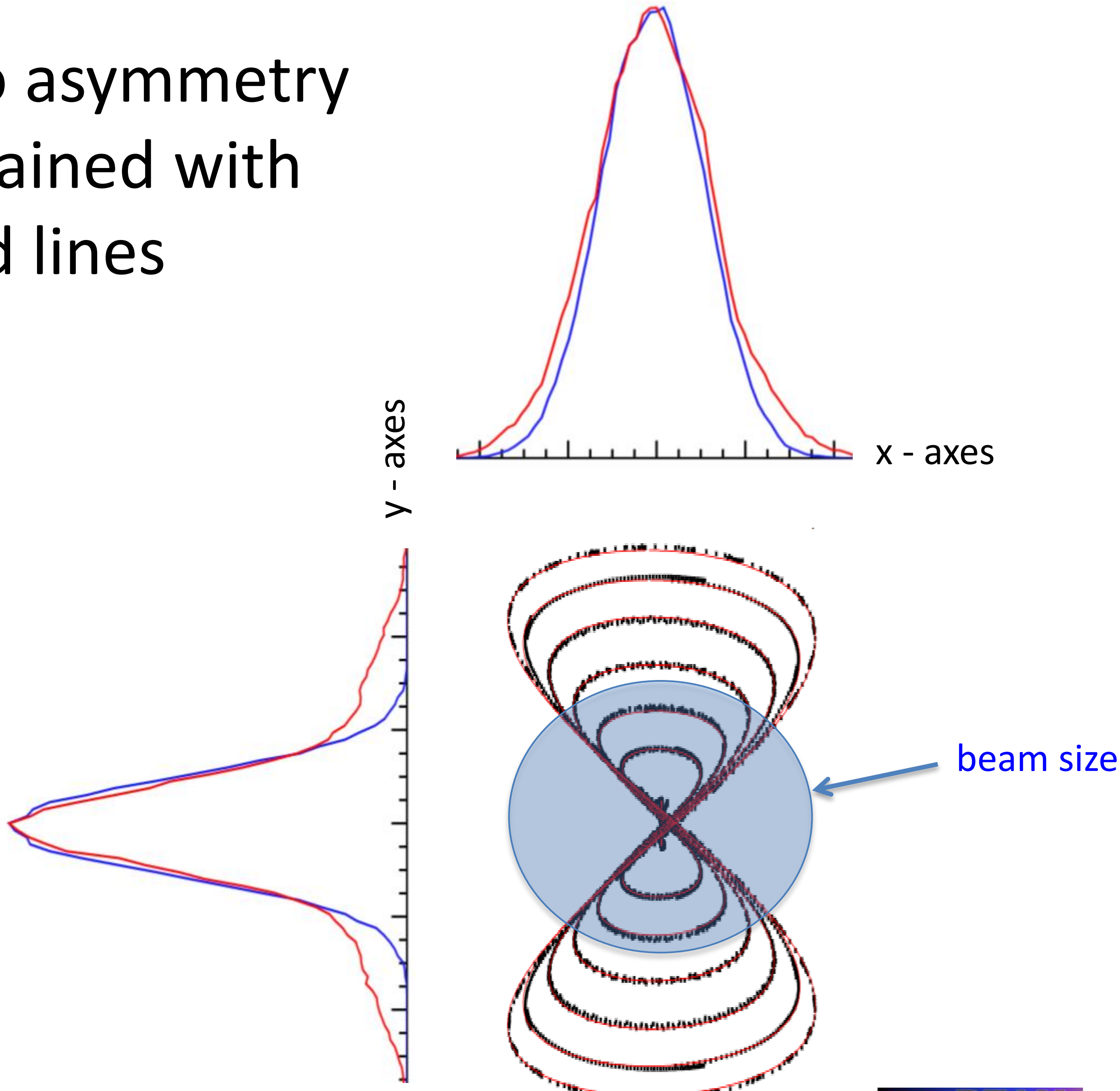
Adiabatic limit



Artificially very slow synchrotron motion

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

Halo asymmetry explained with fixed lines



Conclusion / Outlook

- A benchmarking on the 3rd order coupled resonance is achieved for the full PS structure.
- Outstanding asymmetric halo are formed and decently well retrieved by the simulations
- Thinking in terms of resonance detuning arises paradoxes
- The “fixed-lines” are the new objects that explain the dynamics of the resonance
- **“Fixed lines” are measured in the SPS**
- Simulations shows that the periodic crossing of the fixed-lines causes the asymmetric halo as result of fixed lines geometry.
- *Although there are infinite fixed lines, halo diffuses to **“one”** value → adiabatic limit*
- **The doors are open for massive studies of all coupled resonances and space charge**