Long-range Beam-Beam Interactions in the Tevatron Collider

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(with input from A.Valishev)
Fermilab

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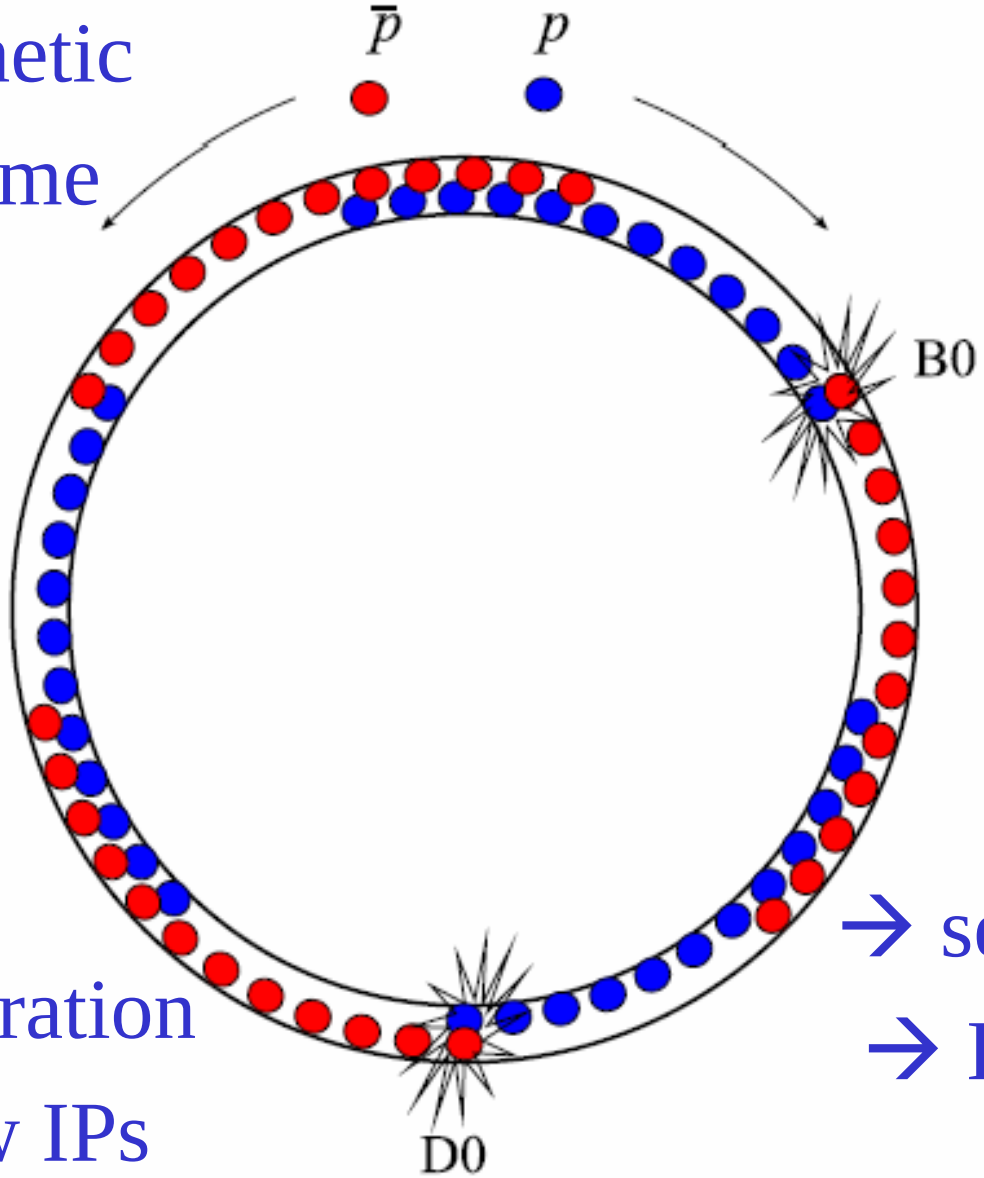
- Tevatron Helical Orbits:
  - Separators and their limitations
  - Apertures and their limitations
- Patterns of beam-beam interactions:
  - Scaling laws for separated beams
  - Orbit variations for different bunches
  - Tunes for different bunches
  - Coupling for different bunches
  - Chromaticity for different bunches
- Beam-beam effects vary from bunch to bunch:
  - Emittance growth – “scallops”
  - Beam lifetime variation along the train

Tevatron Helical Orbits

36 proton x 36 antiproton

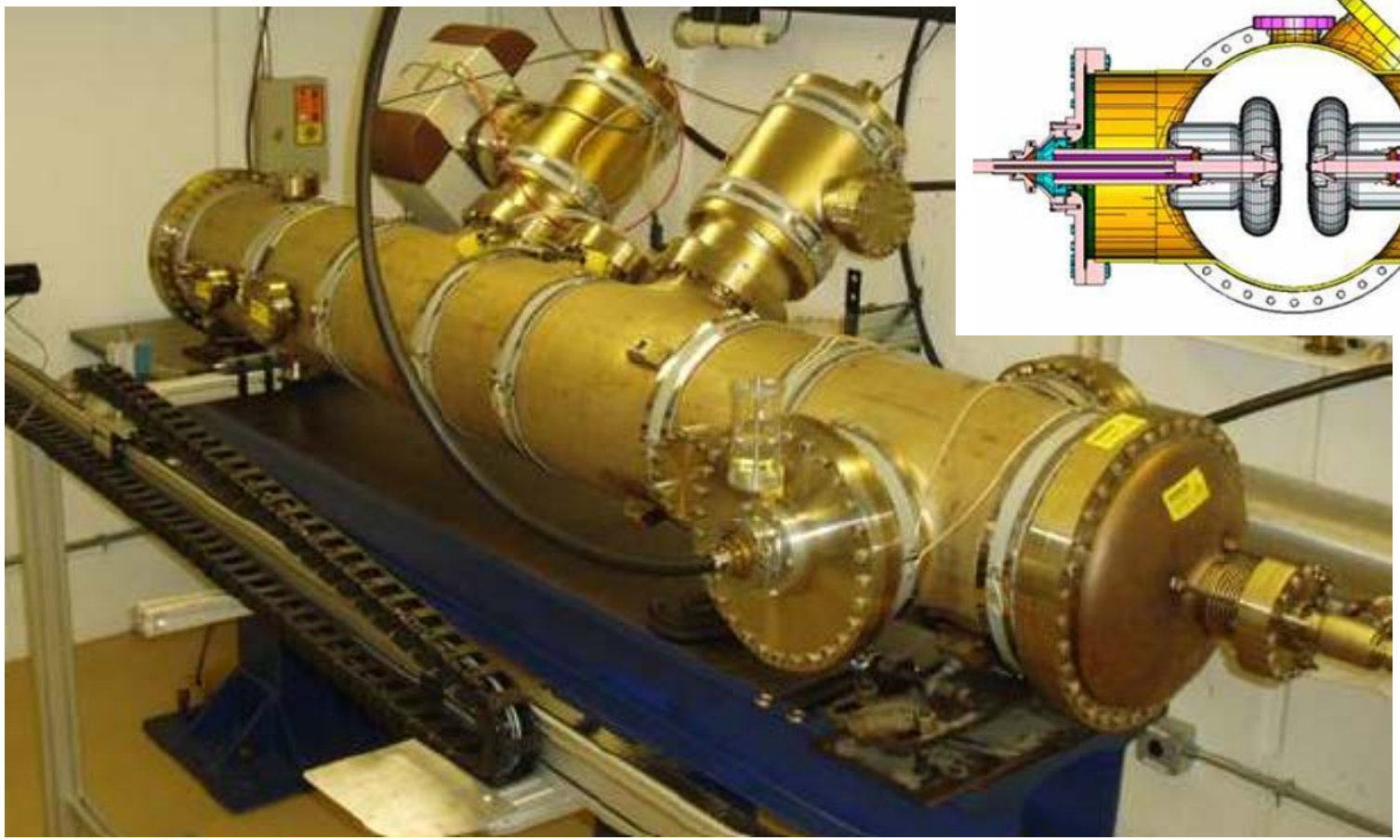
Same magnetic fields → same orbits → 72 IPs

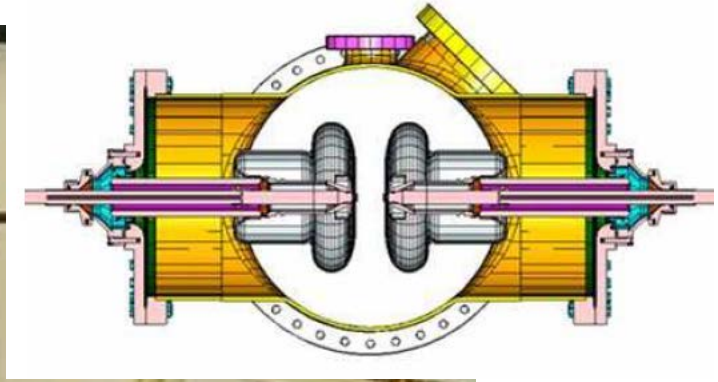


396 ns bunch separation → 59 m btw IPs

Need only 2 → separate at 70 → Electric field

Tevatron High Voltage Electrostatic Separators





300 kV over 50 mm gap; 3 m ; 24 of them (H/V)

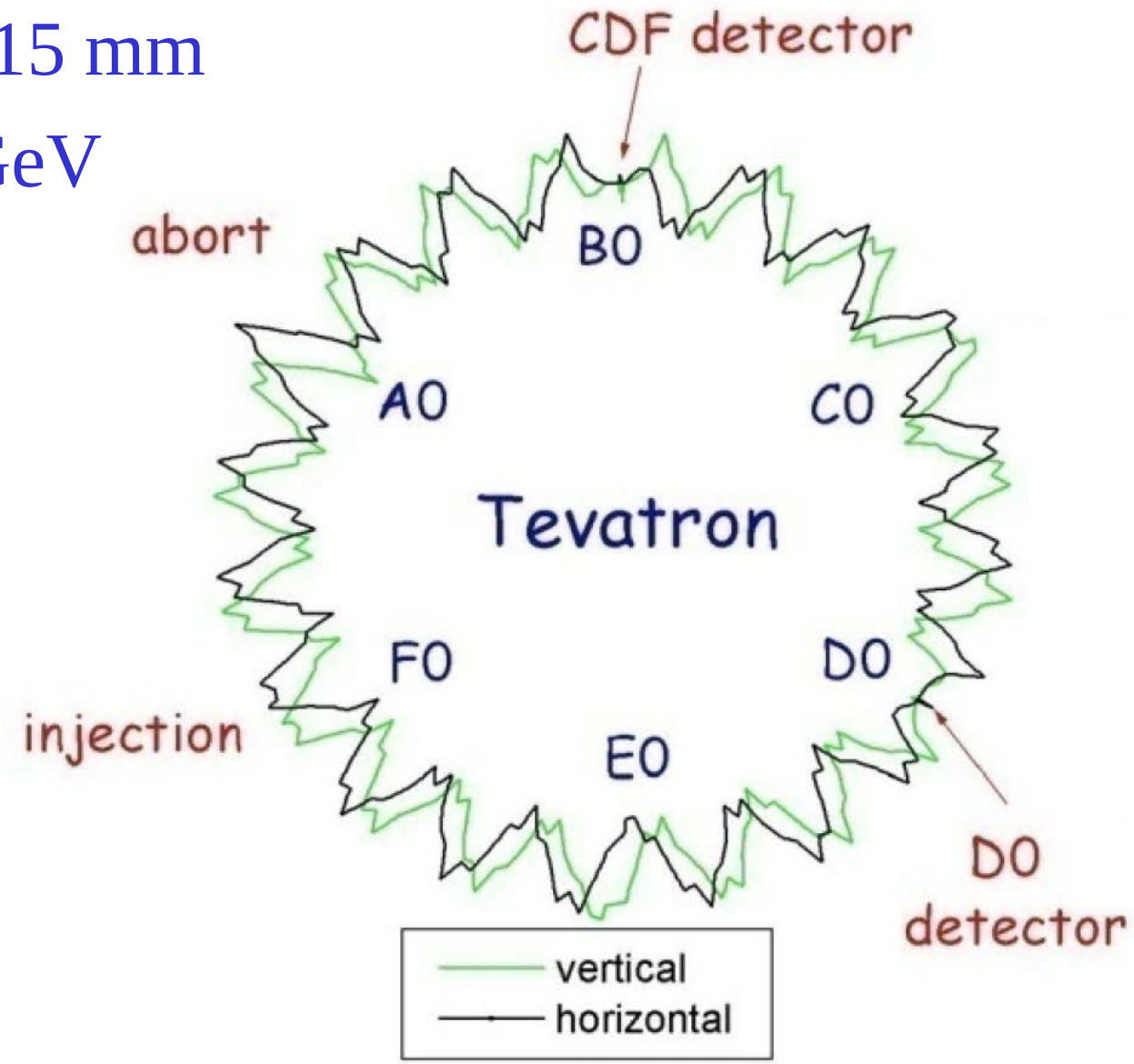
Tevatron Helix

size 12-15 mm

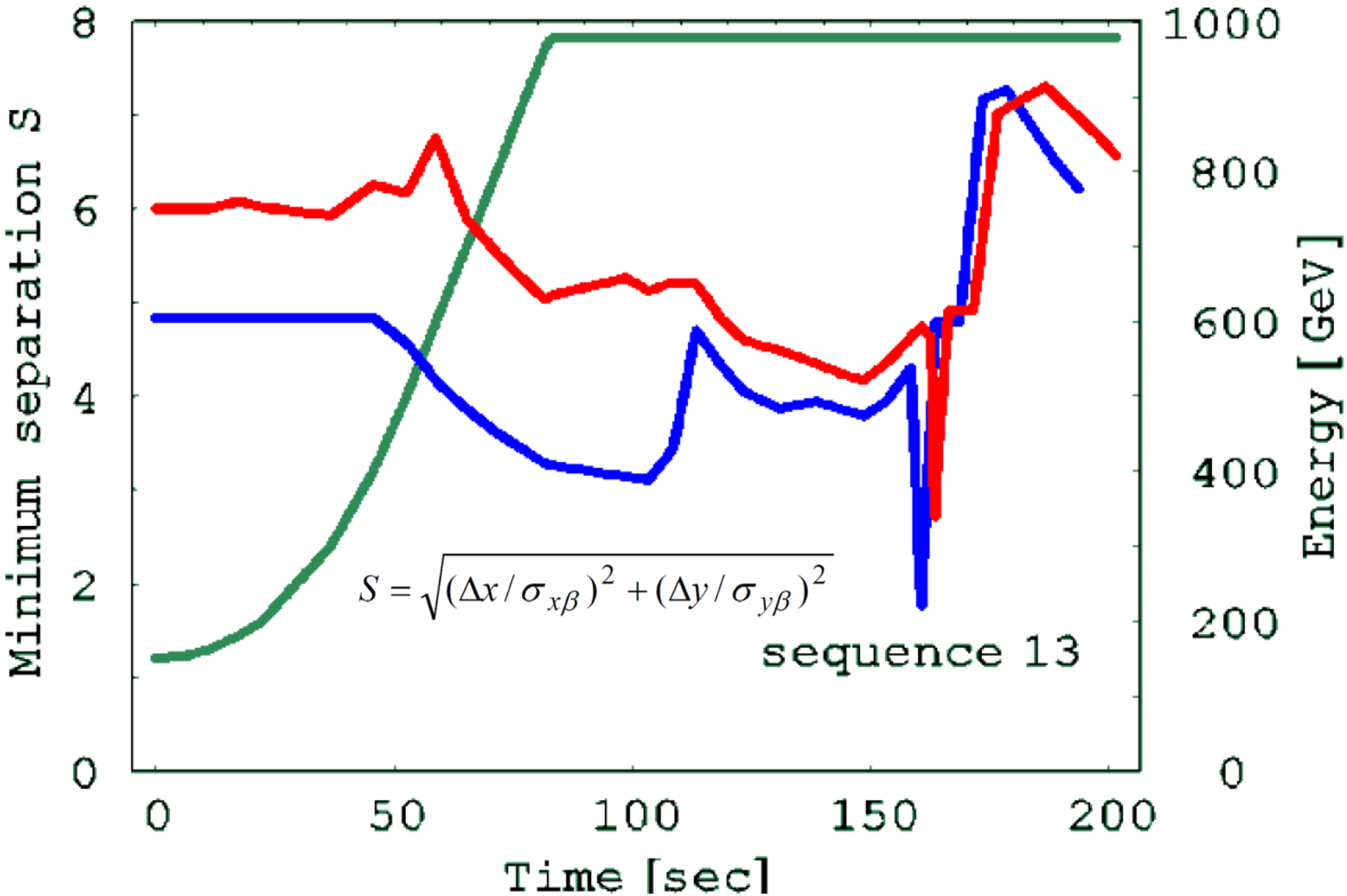
at 150 GeV

6-8 mm

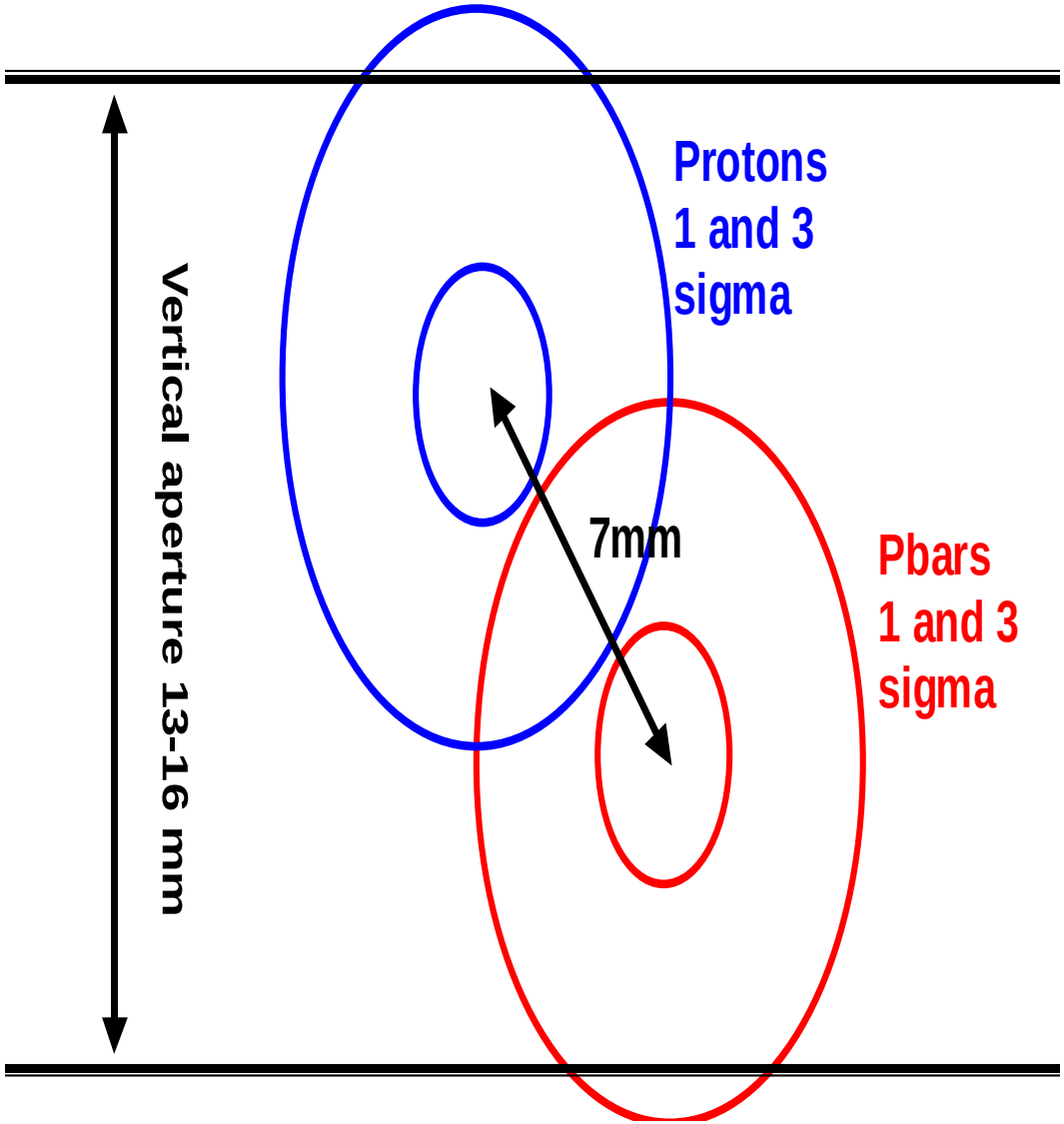
at LB



Many Optimizations of Helix



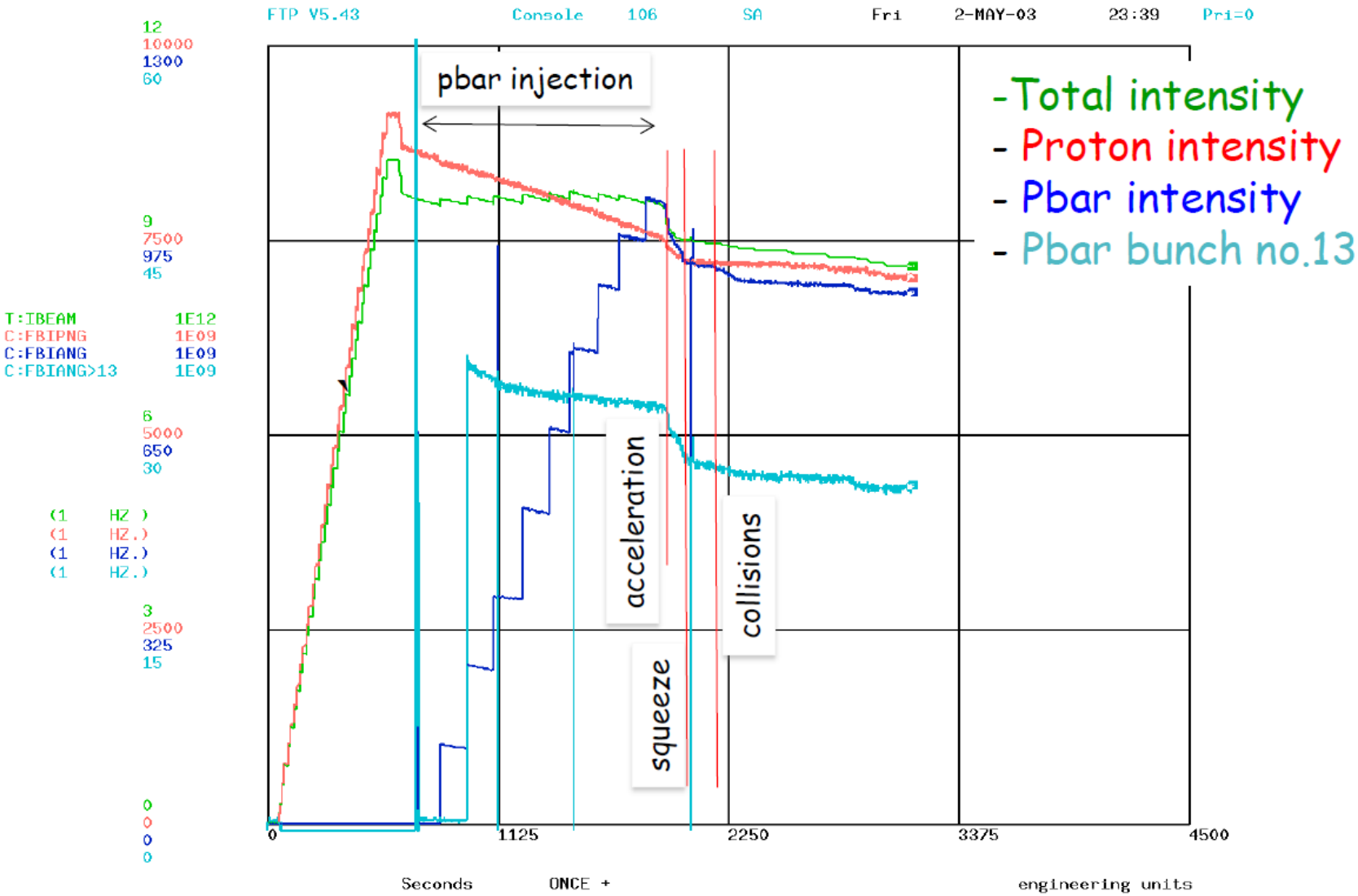
Sometimes - Drastic



16 mm aperture magnets at C0 were taken out and replaced with 40 mm aperture dipoles in 2003

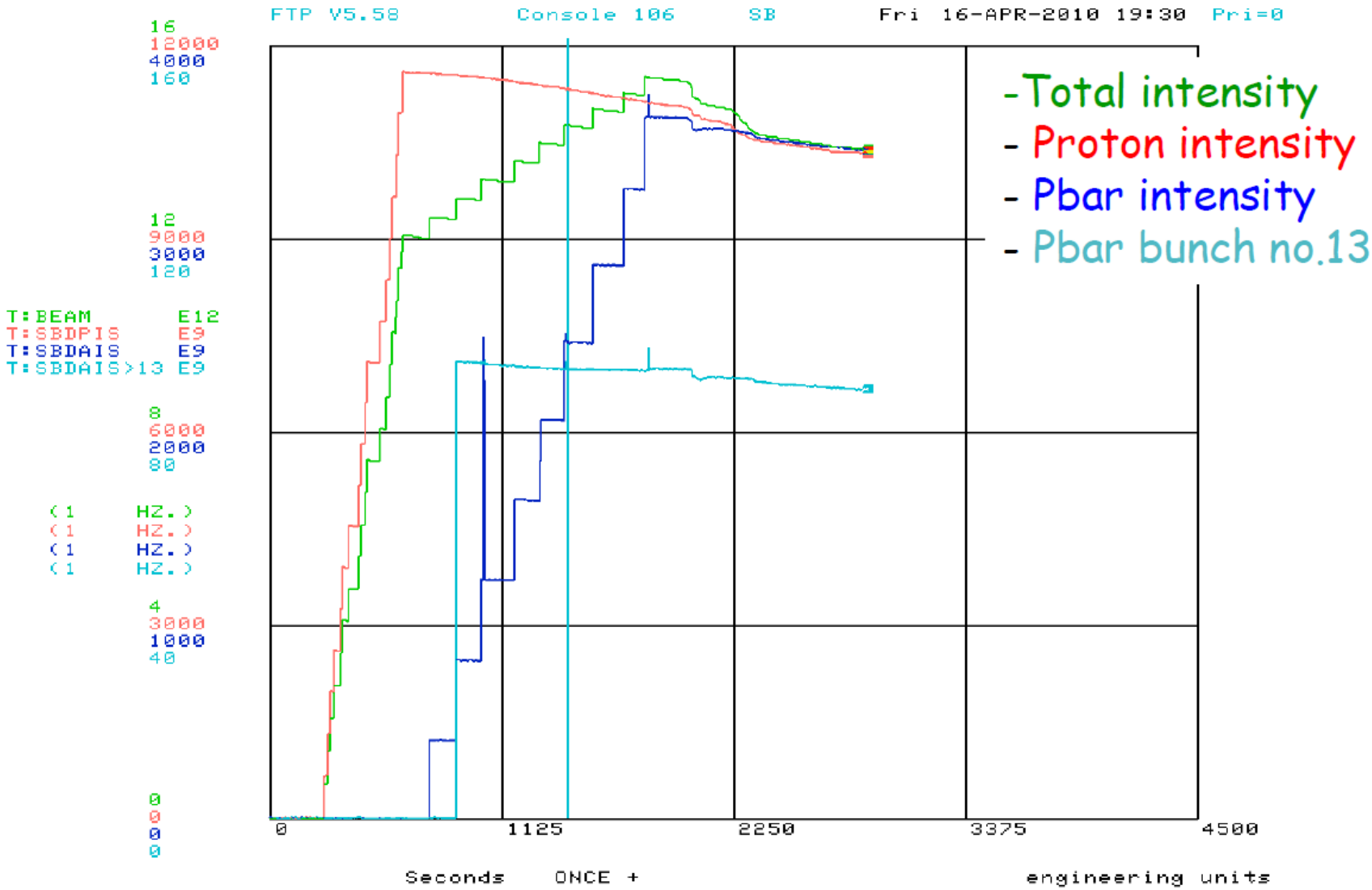
Patterns of Beam-beam Interactions

Collider Fill Cycle for Store 2511 in 2003



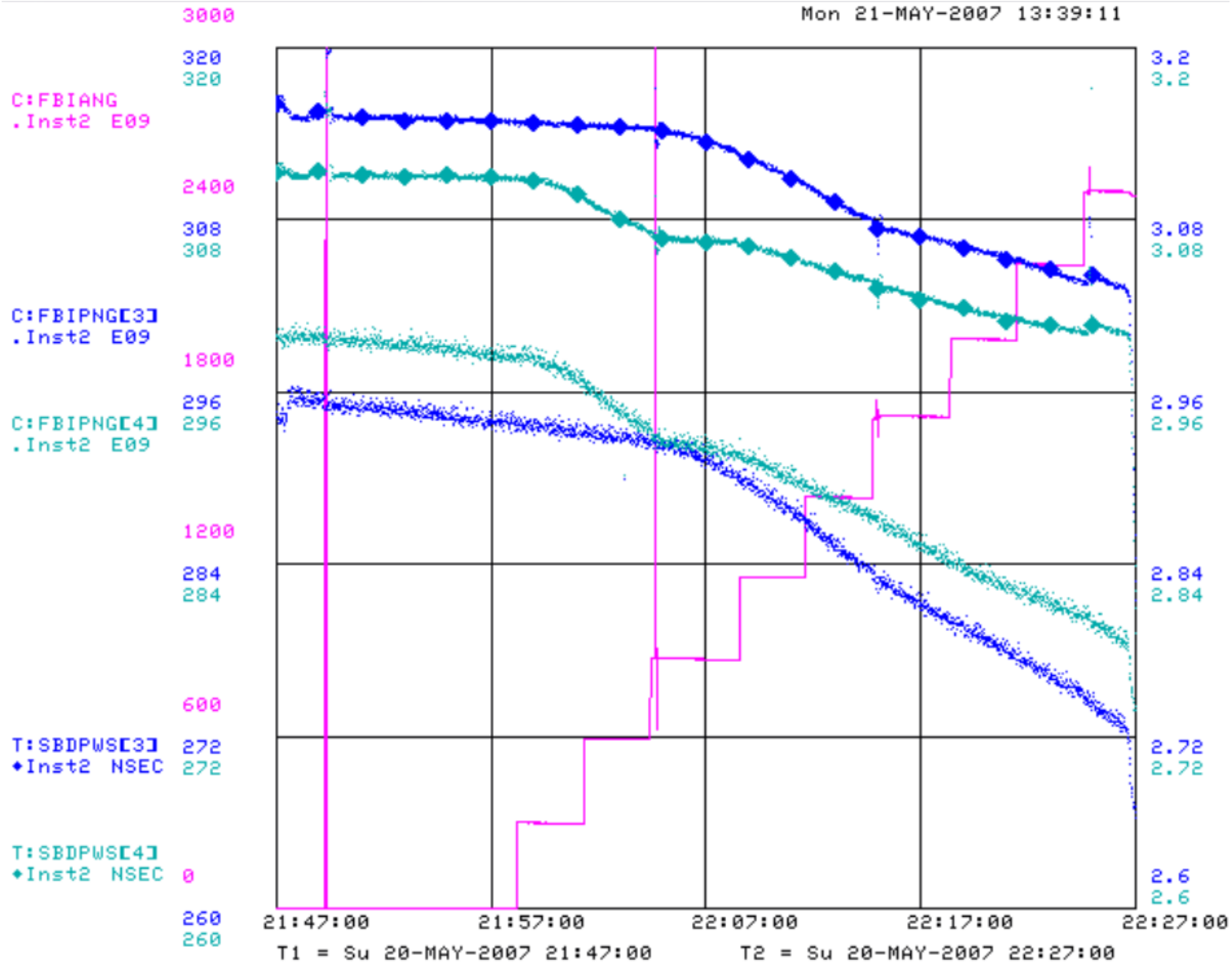
Store 2511 L_0=0.4x10^{32}

Collider Fill Cycle for Store 7747 (2011)

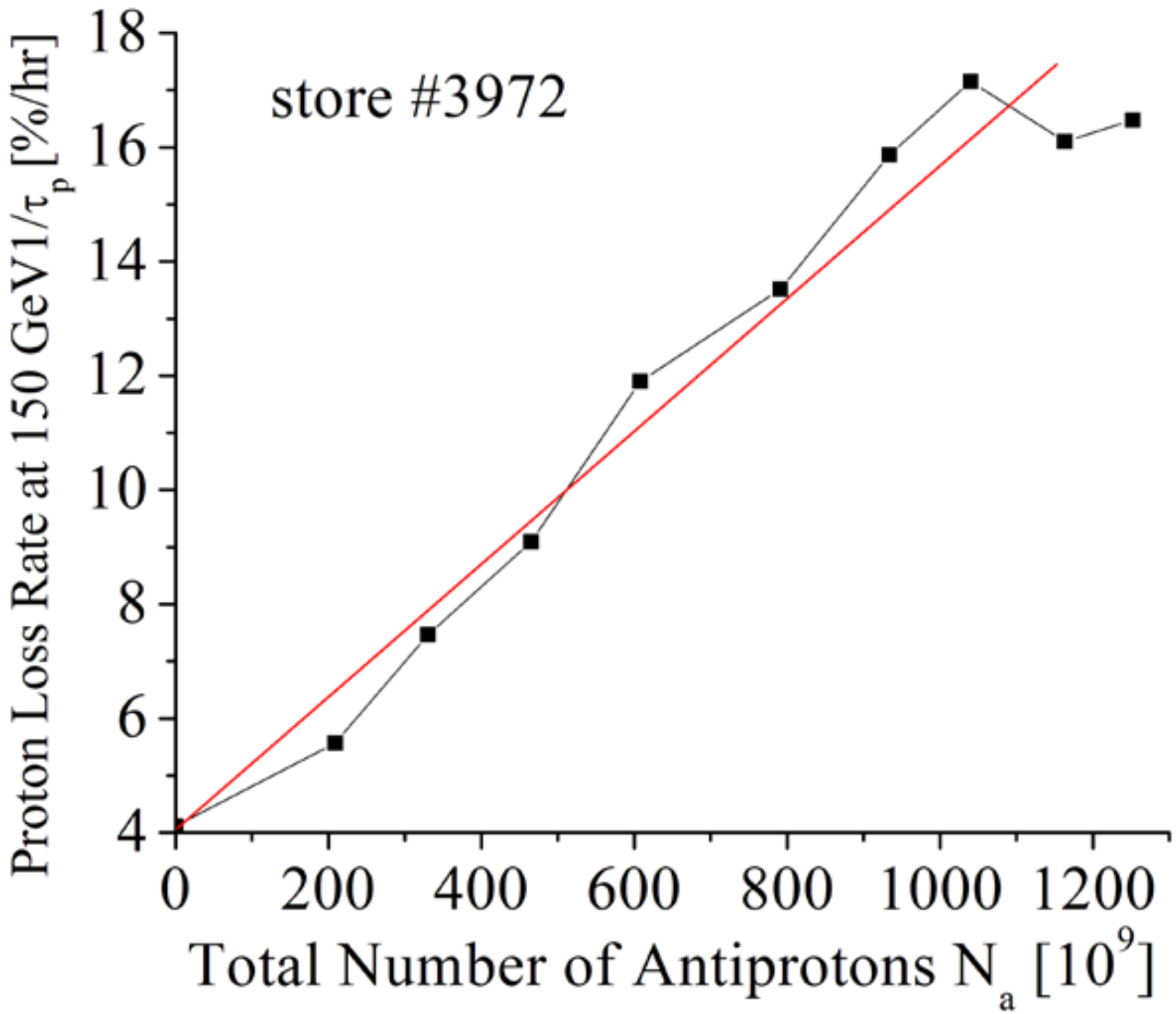


Record Store 7747 $L_0=4\times10^{32}$

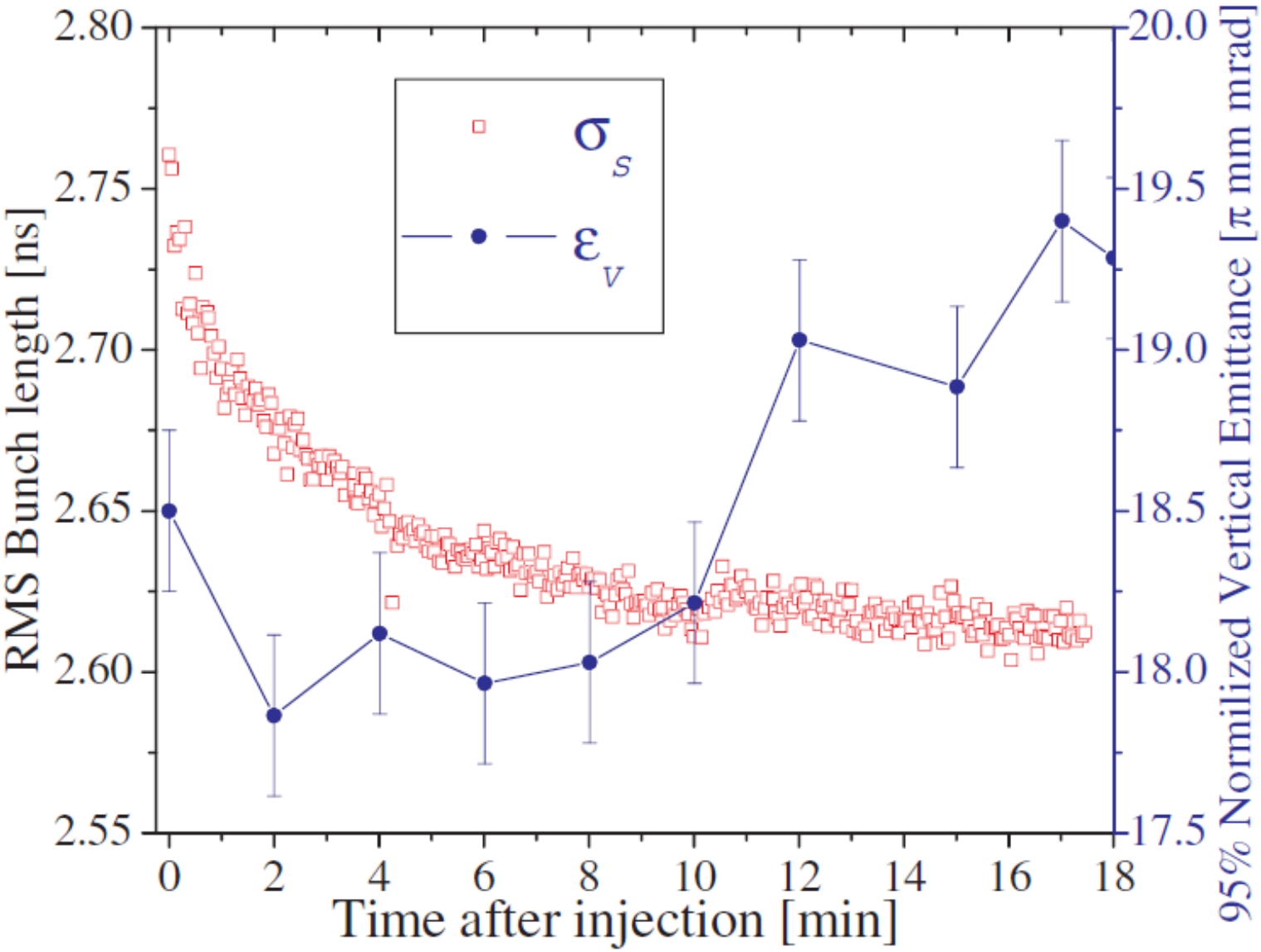
LR Effects during Injection Process



Losses Driven by Opposite Beam

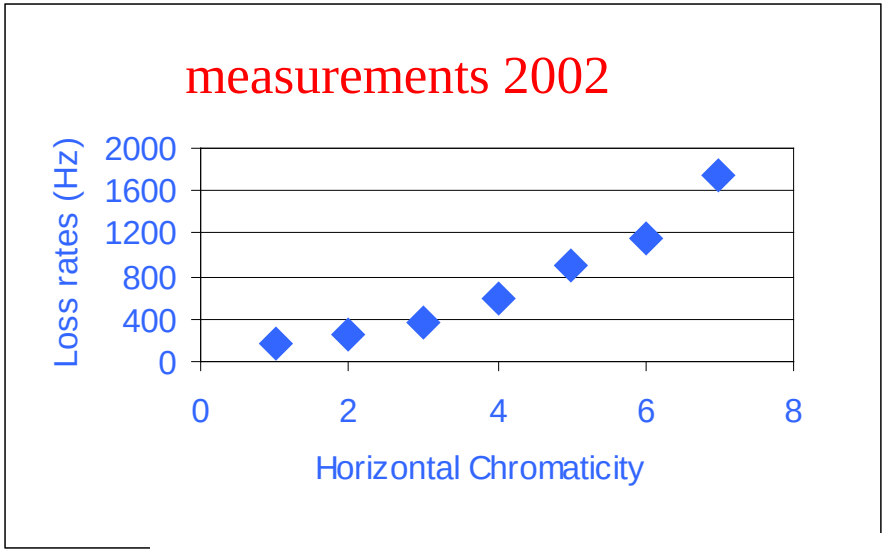


Longitudinal Shaving of Antiprotons

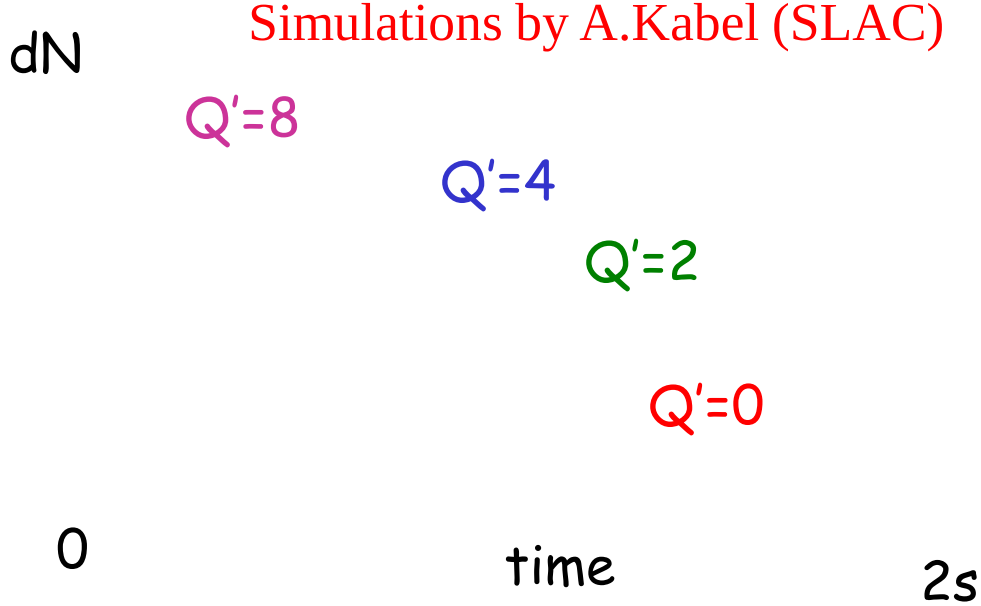


Poor Pbar Lifetime on 150 GeV Helix

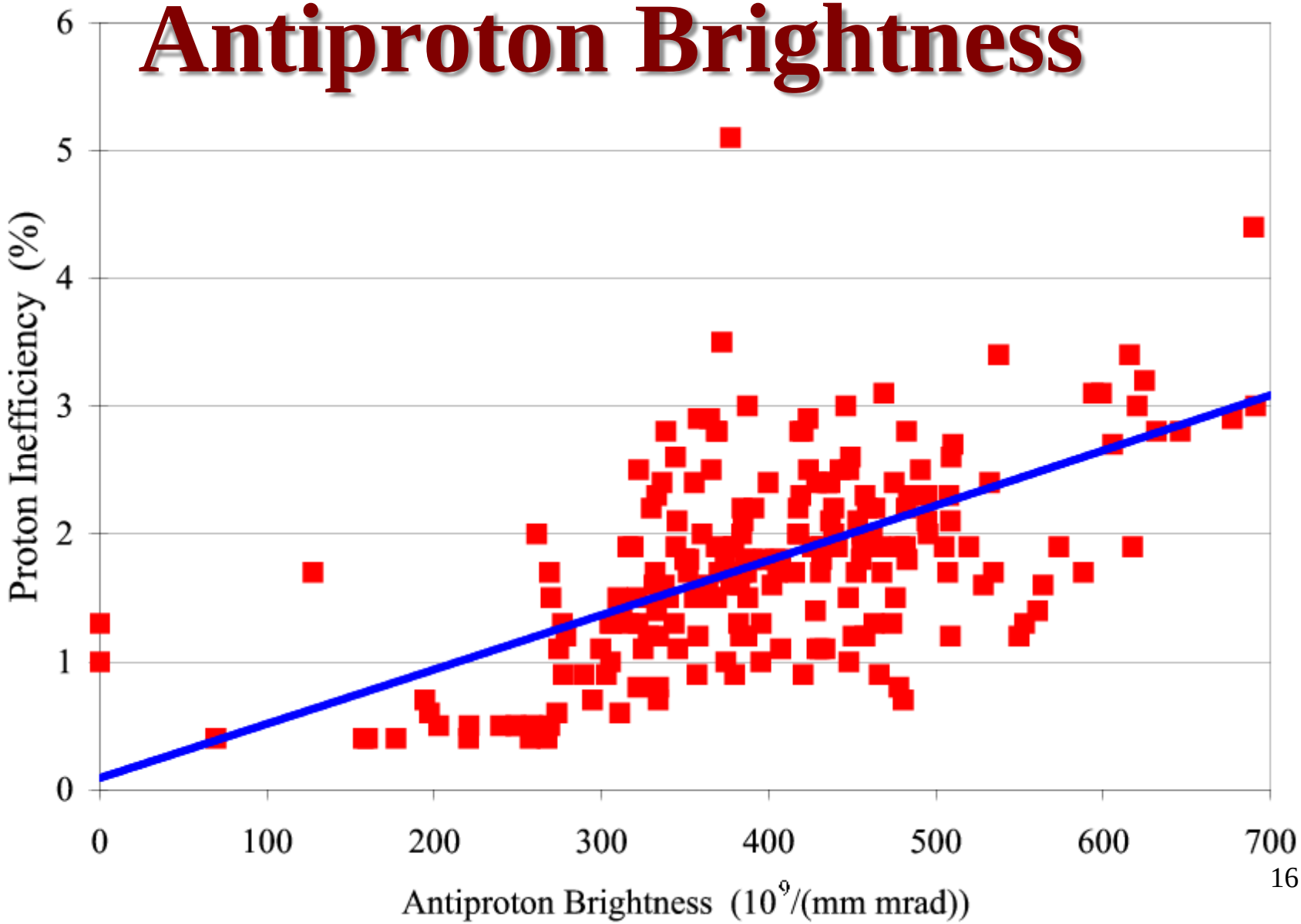
- Poor P/Pbar lifetime at 150
  - 1-4 hours, 15-20% loss
  - **Sqrt(time)** dependence
  - Worse with larger Np, Q'
  - Longitudinal shaving
- Possibilities to fix it:
  - Open aperture (C0, align)
  - Reduce emittances (reshimming)
  - Reduce impedance (F0 liner)
  - Reduce chromaticities
    - Found experimentally (plot)
    - Confirmed in simulations →
    - Weak HT Instability → liner, dampers, octupoles
    - **dN=15-20% → 2-4% !**



Simulations by A.Kabel (SLAC)



Proton Loss in Squeeze vs. Antiproton Brightness

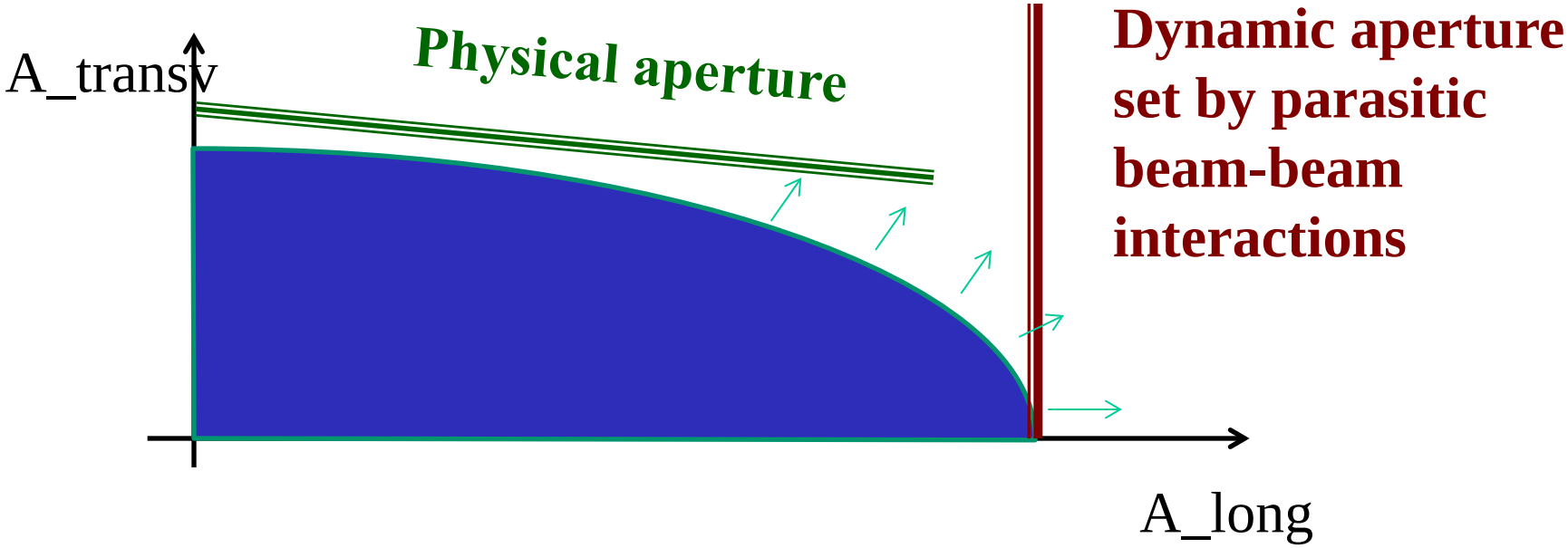


What we found empirically

- Losses were dependent on :

$$\frac{\Delta N_{a,p}}{N_{a,p}} = 1 - \frac{N(t)}{N(t=0)} \propto \sqrt{t} \cdot \varepsilon_{a,p}^{2} \frac{N_{p,a}}{\varepsilon_{p,a}} Q'^{2}{}_{a,p} \cdot F(\varepsilon_L, Q_{x,y}, S_{a-p})$$

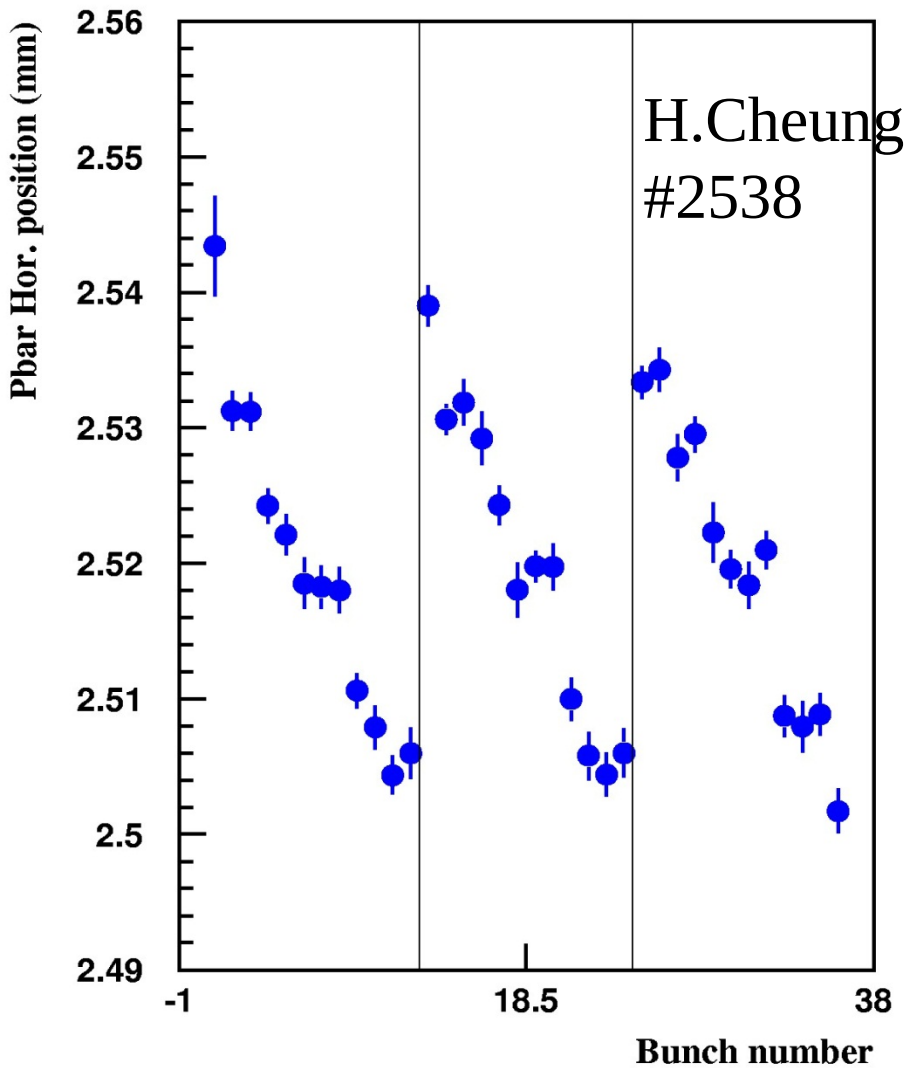
- The can be described by the model of "Diffusion + DA set by Beam-Beam"



All beam indicators become bunch dependent due to long-range beam-beam effects

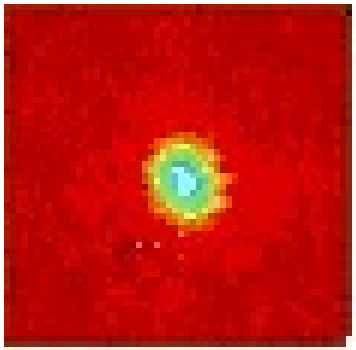
- Orbits
- Tunes and couplings
- Chromaticities
- In both – protons and pbars
- Have 3-fold symmetry (trains of 12)

Long-range B-B Seen at Low-Beta (980 GeV)

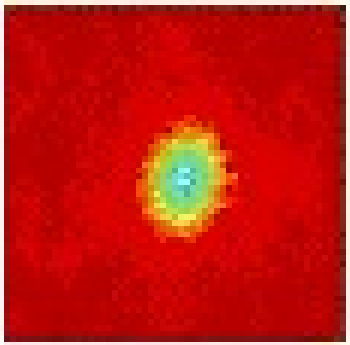


- SL reports ♦, mean, N, tilt bunch-by-bunch for both protons and pbars
- SL reports scallops (when they appear) in good agreement with FWs
- It also shows 40 micron b-by-bunch hor pbar orbit variation along the bunch train with 3-train symmetry (4 microns for protons)

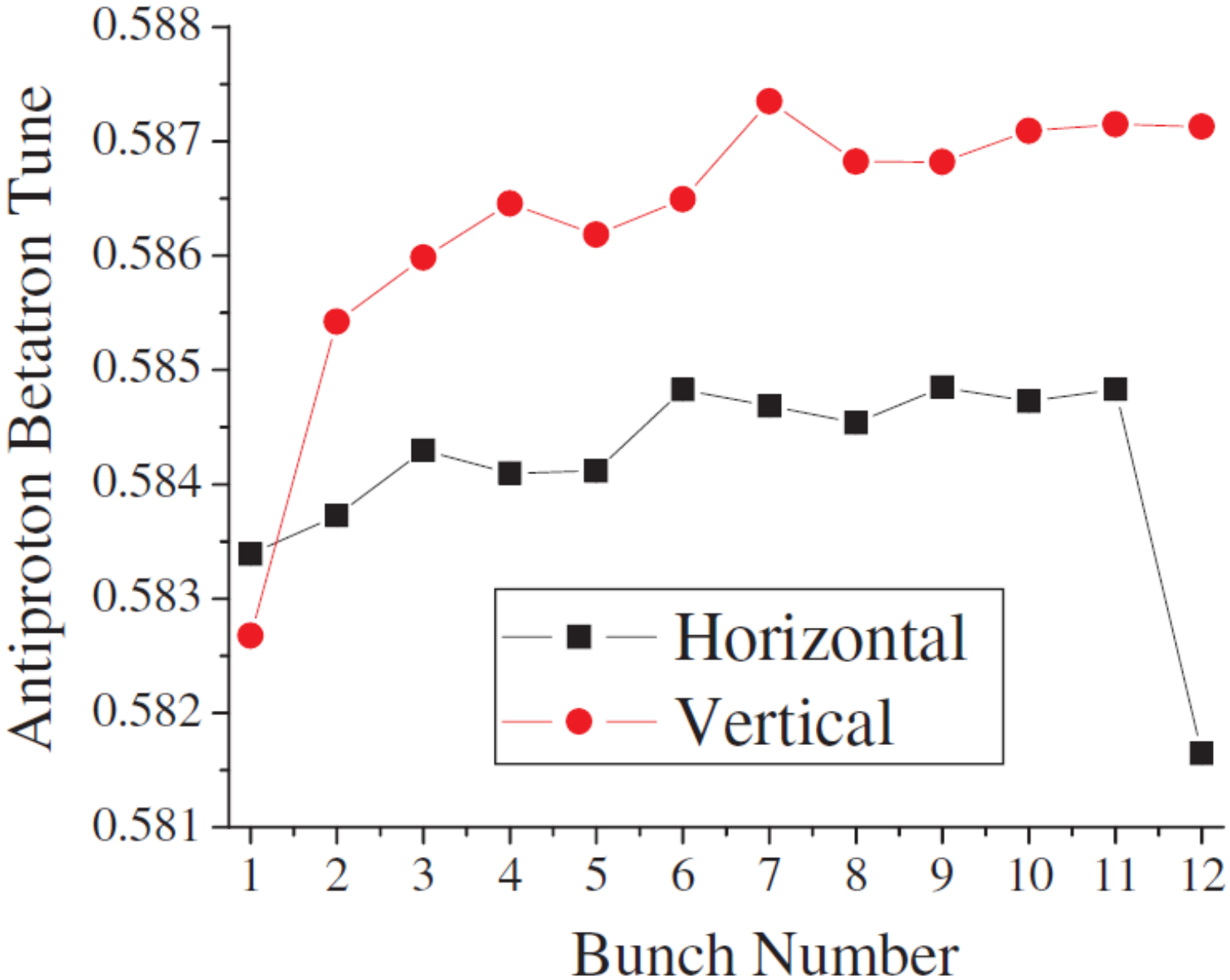
Bunch #1



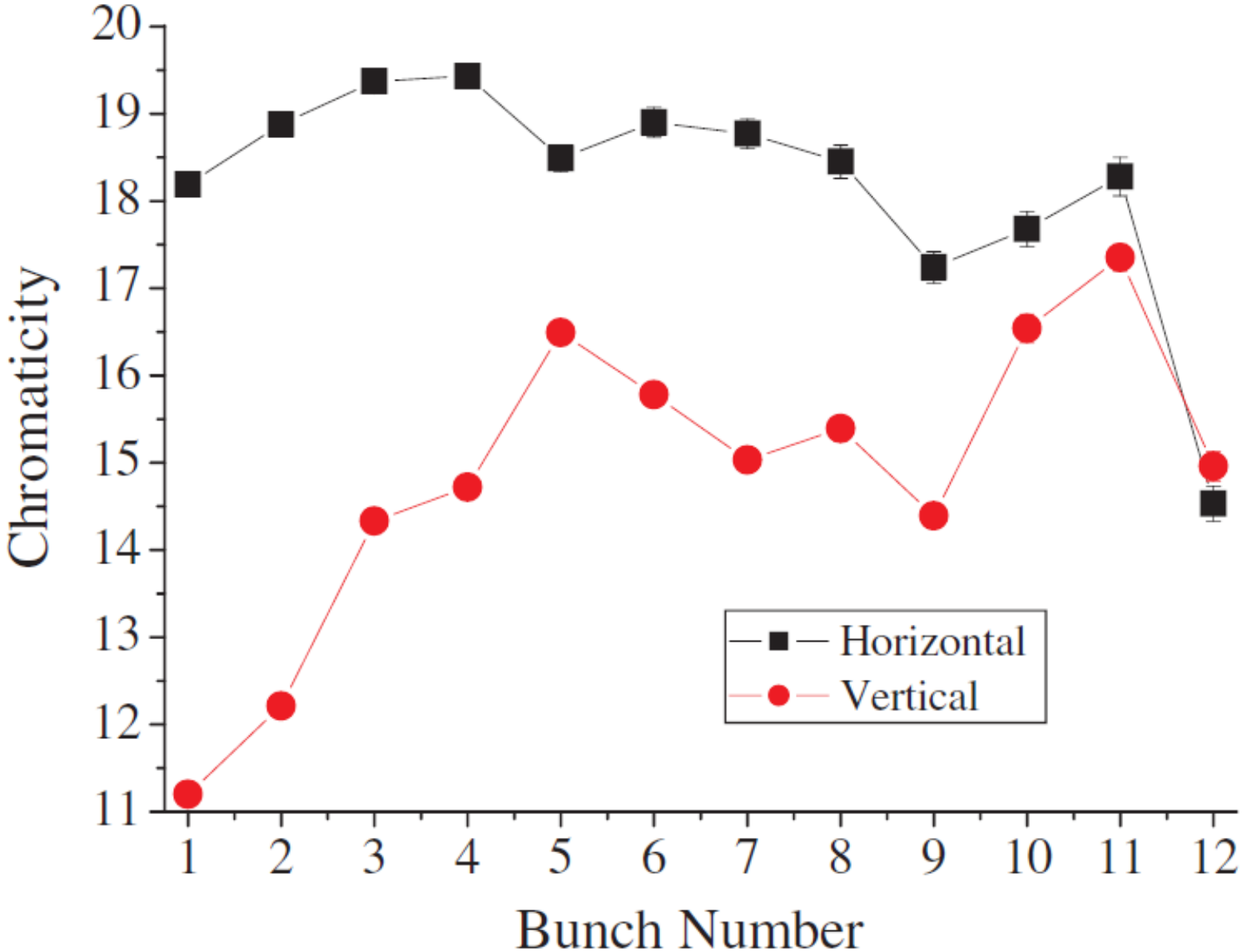
Bunch #8



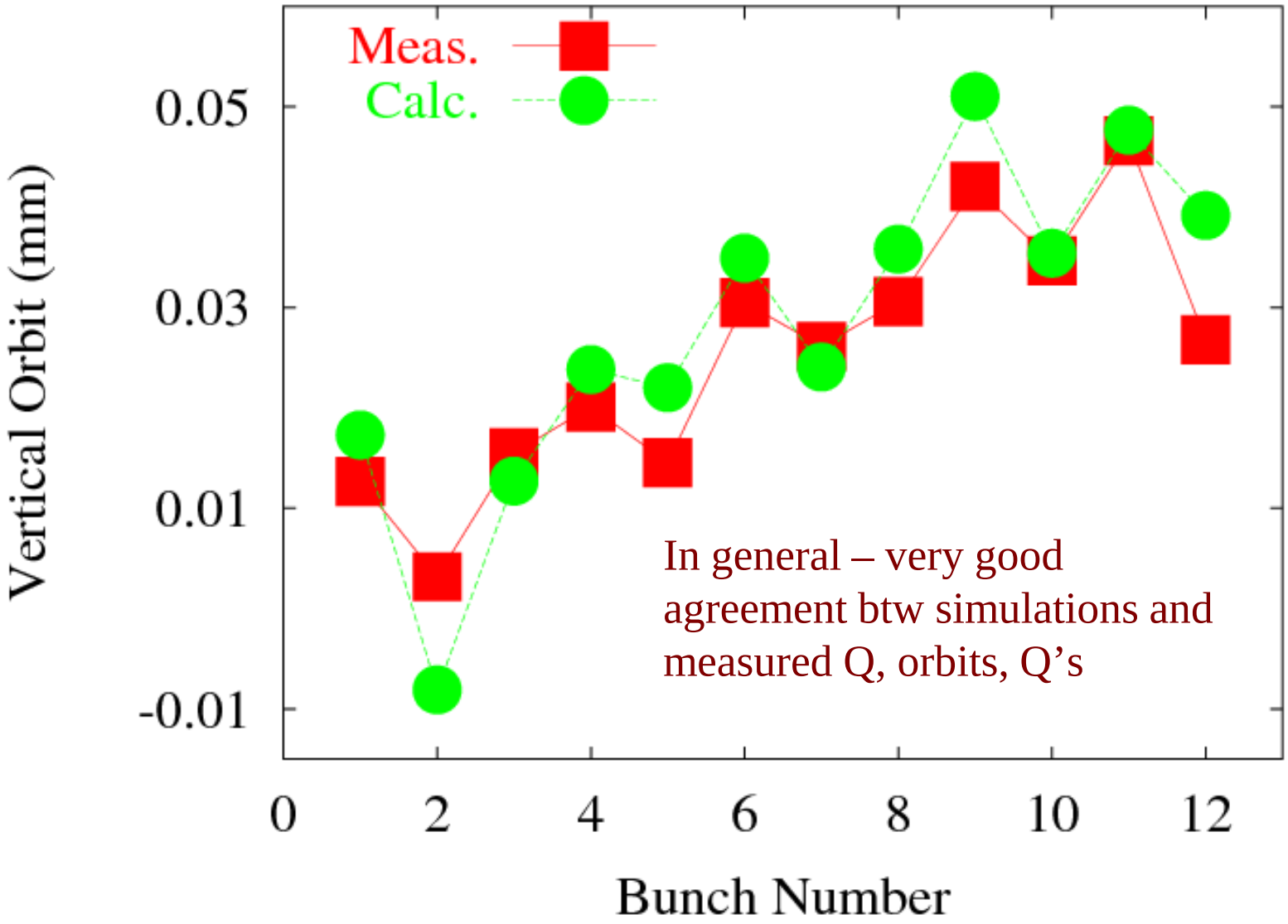
Pbar Bunch Tunes @ LB



Pbar Bunch Chromaticity@ LB



Antiproton Bunch-to-bunch Orbit



In general – very good agreement btw simulations and measured Q, orbits, Q's

Beam-beam interactions affecting performance:

Beam-Beam Tune Shifts

$$\xi = 2\frac{N_p r_p}{4\pi\varepsilon_p}$$

head-on tune shift, two IPs, now with

at the end of te Run II

total max head-on tuneshift was about

0.025 for pbars, 0.02-0.025 for protons

tune shift for separated beams is smaller:

$$\Delta\nu = \sum_i \frac{\beta_i N_p r_p}{2\pi\gamma d_i^2} = \sum_i \frac{2\xi}{(d_i/\sigma_i)^2}$$

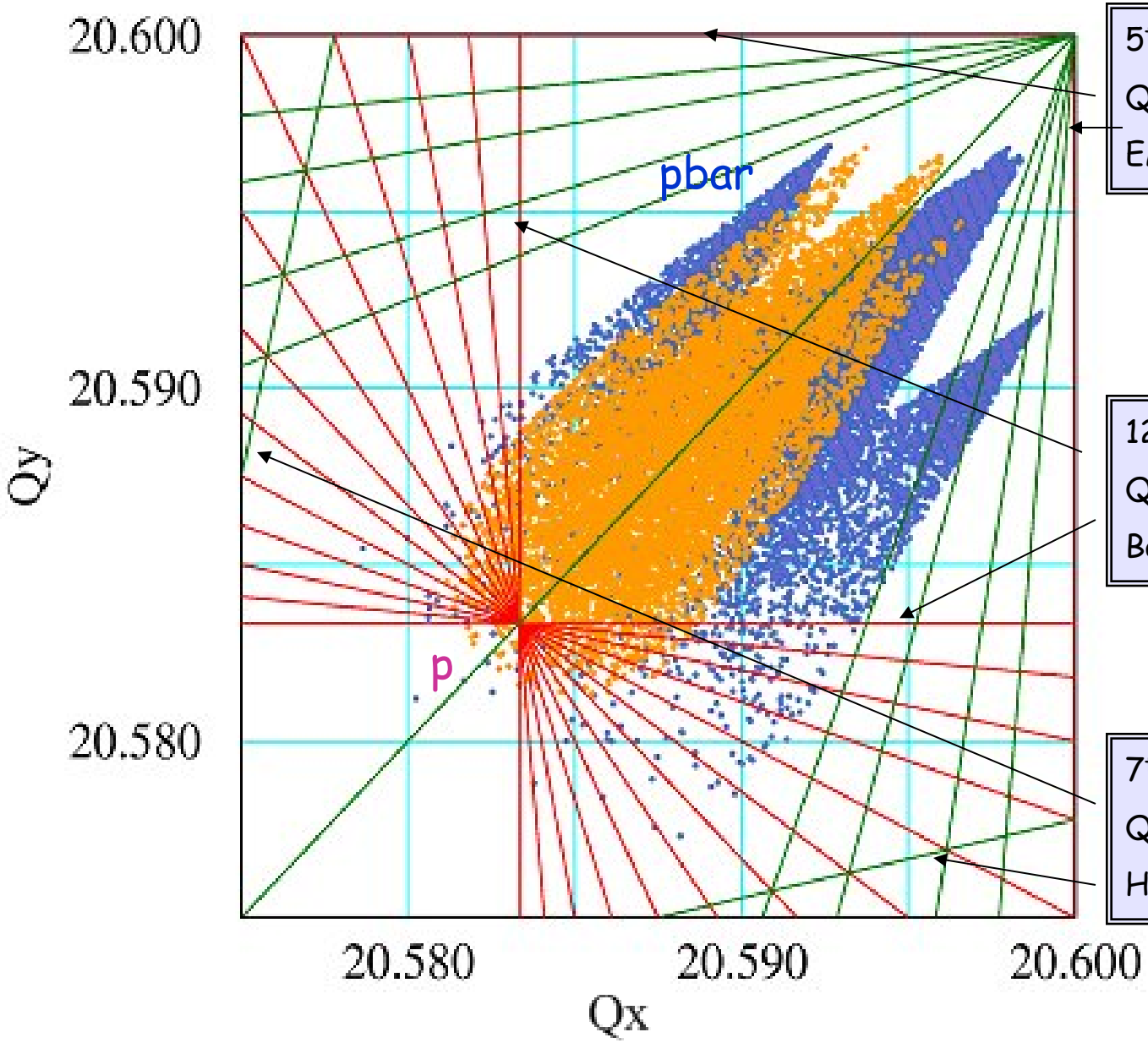
but: a) always present, $\Delta\nu$=0.002-0.005

b) MANY near-misses i = 70

c) different bunch-by-bunch

d) HV separator limited: γd^2 scales as V^2/γ

Situation at Low-beta: Confinement



5th order resonances:

Q=3/5=0.600 –

EMITTANCE BLOWUP

protons
antiprotons

12th order resonances:

Q=7/12=0.583 -

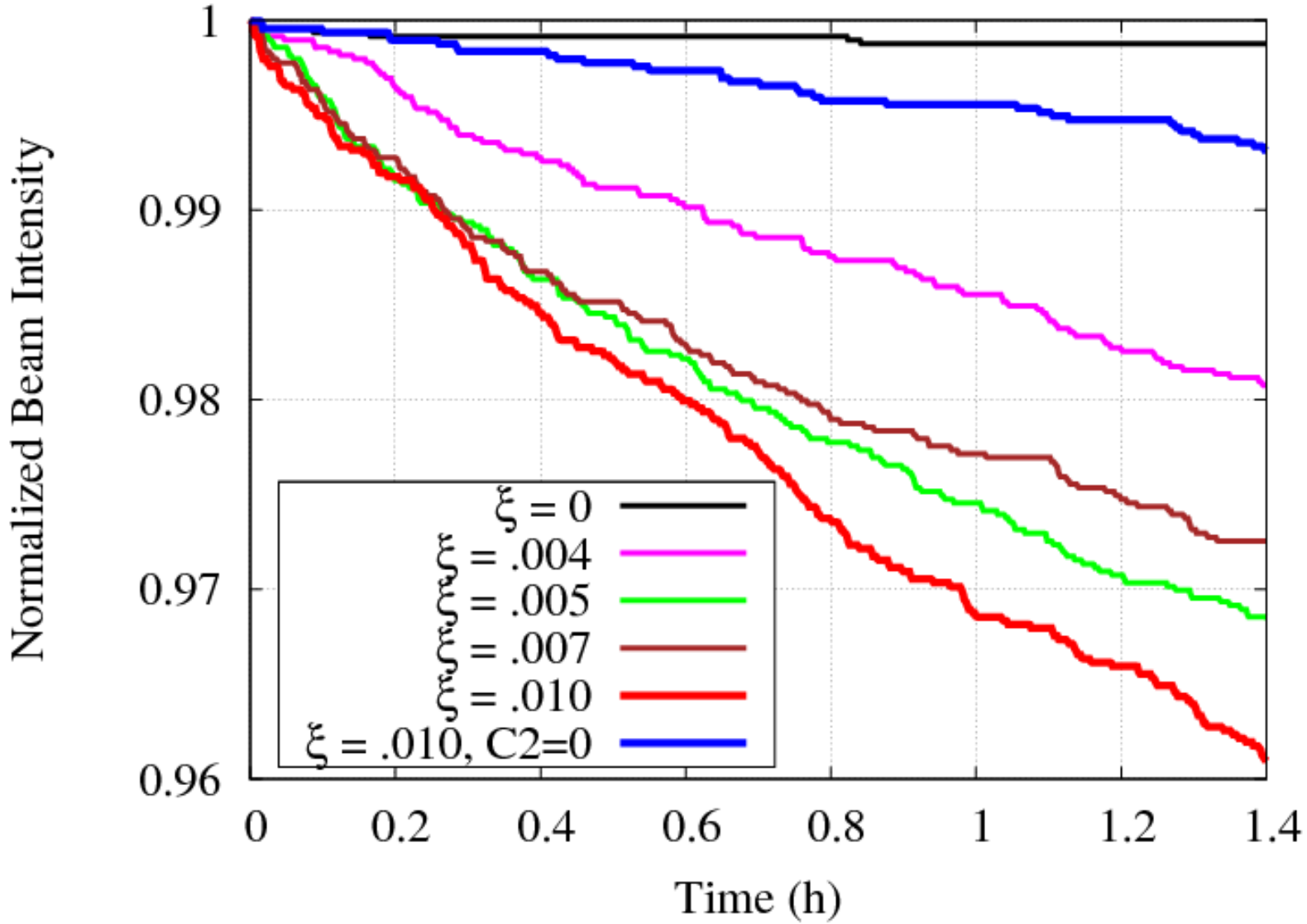
Bad lifetime

7th order resonances:

Q=4/7=0.571 -

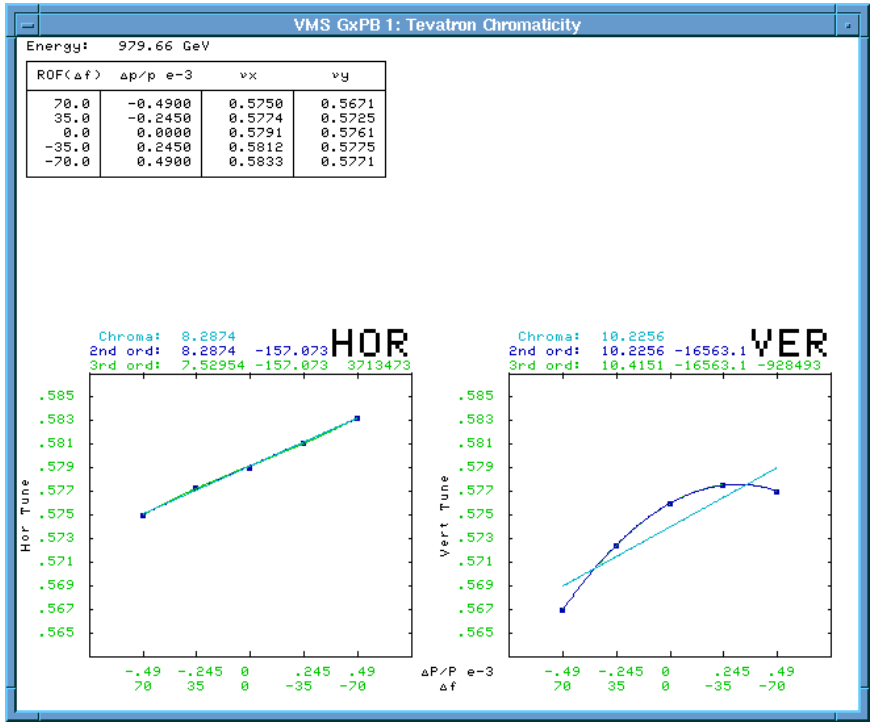
HIGH LOSSES

WP (Tunes) is not he Only Story - Effect of β* Chromaticity. Simulation

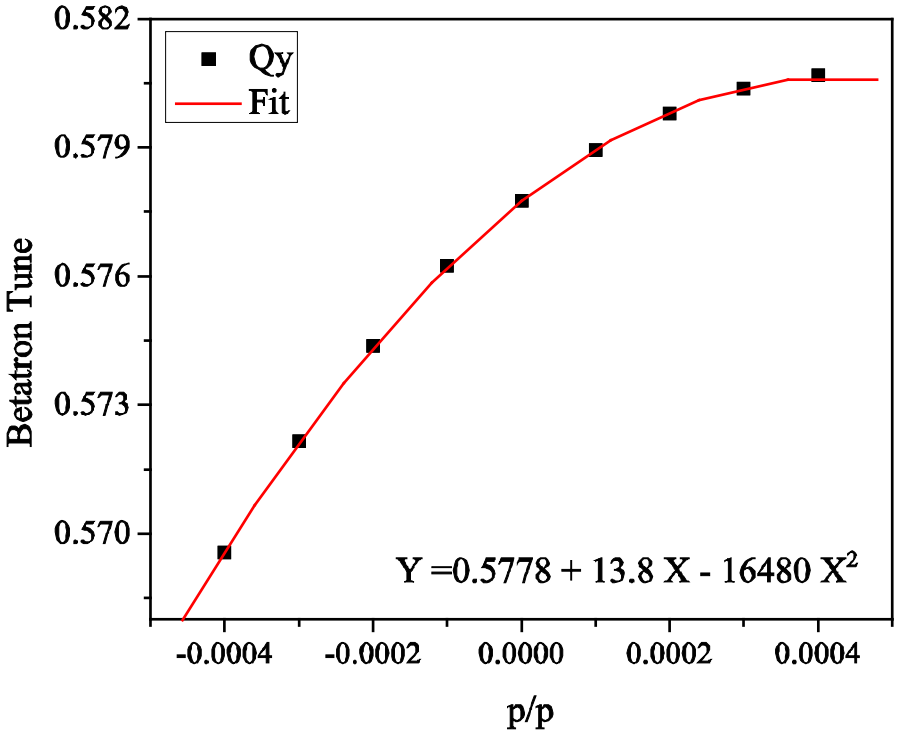


2nd Order Tune Chromaticity

Measured C2 = -16560

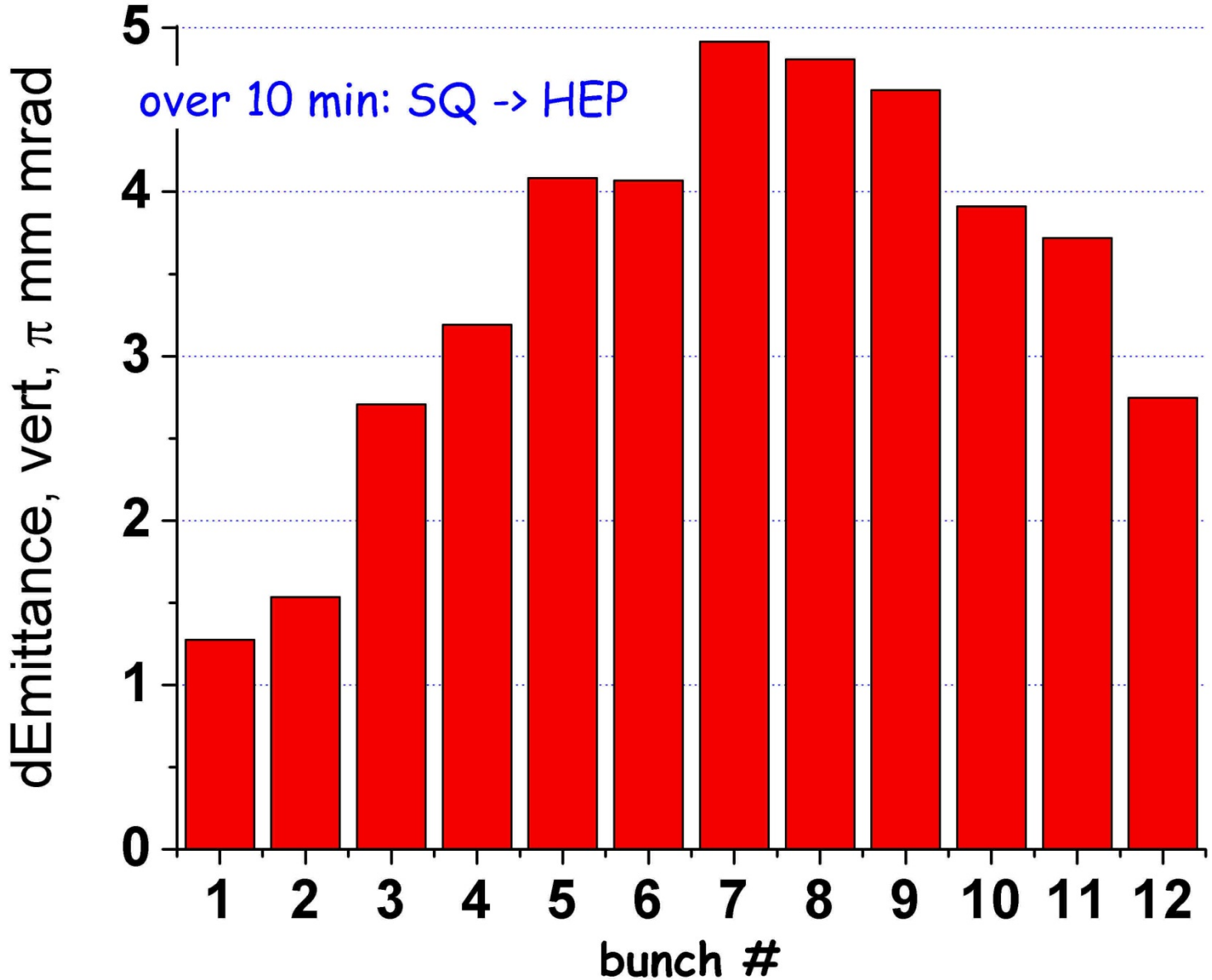


Model C2 = -16480

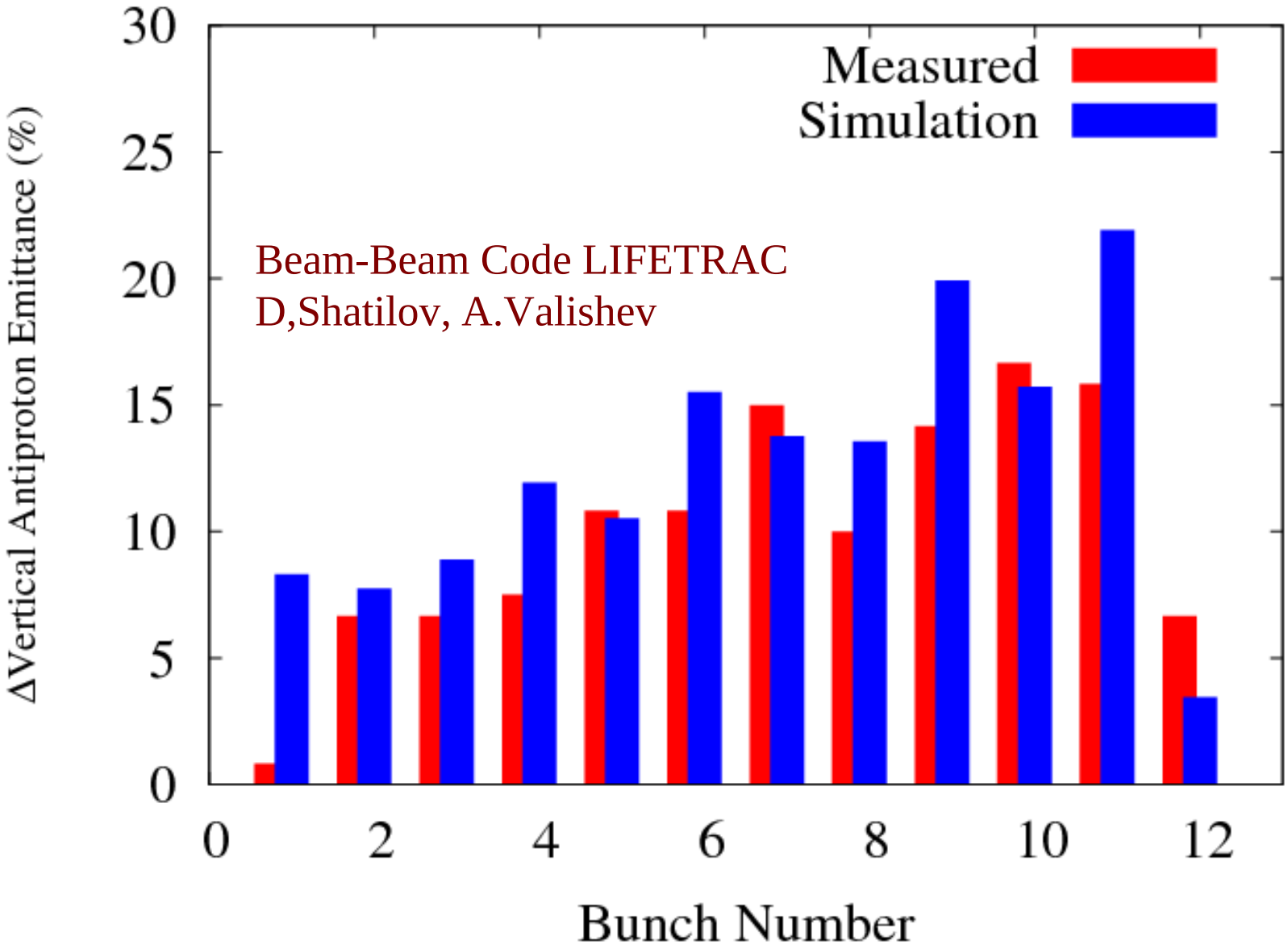


- Reduced to ~500 by reconnection of sextupoles into new families

Pbar Emittance Growth Near Qy=0.6



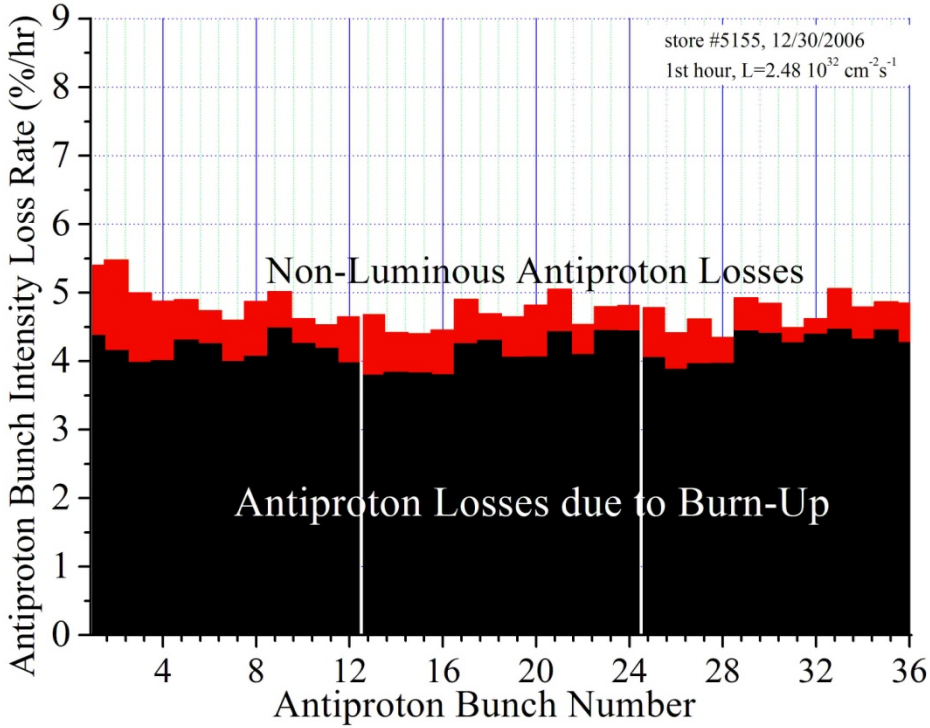
“Scallops”: Simulation and Measurement



Losses due to beam-beam interactions

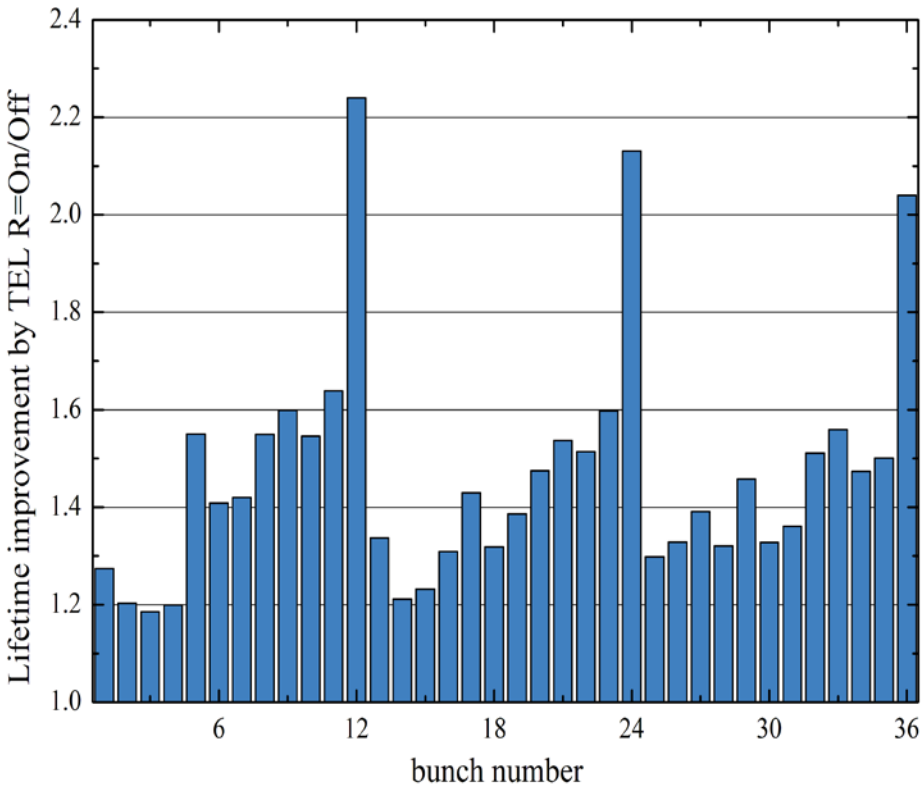
Antiprotons 980 GeV :

ξ_{max}=+(0.020-0.024)



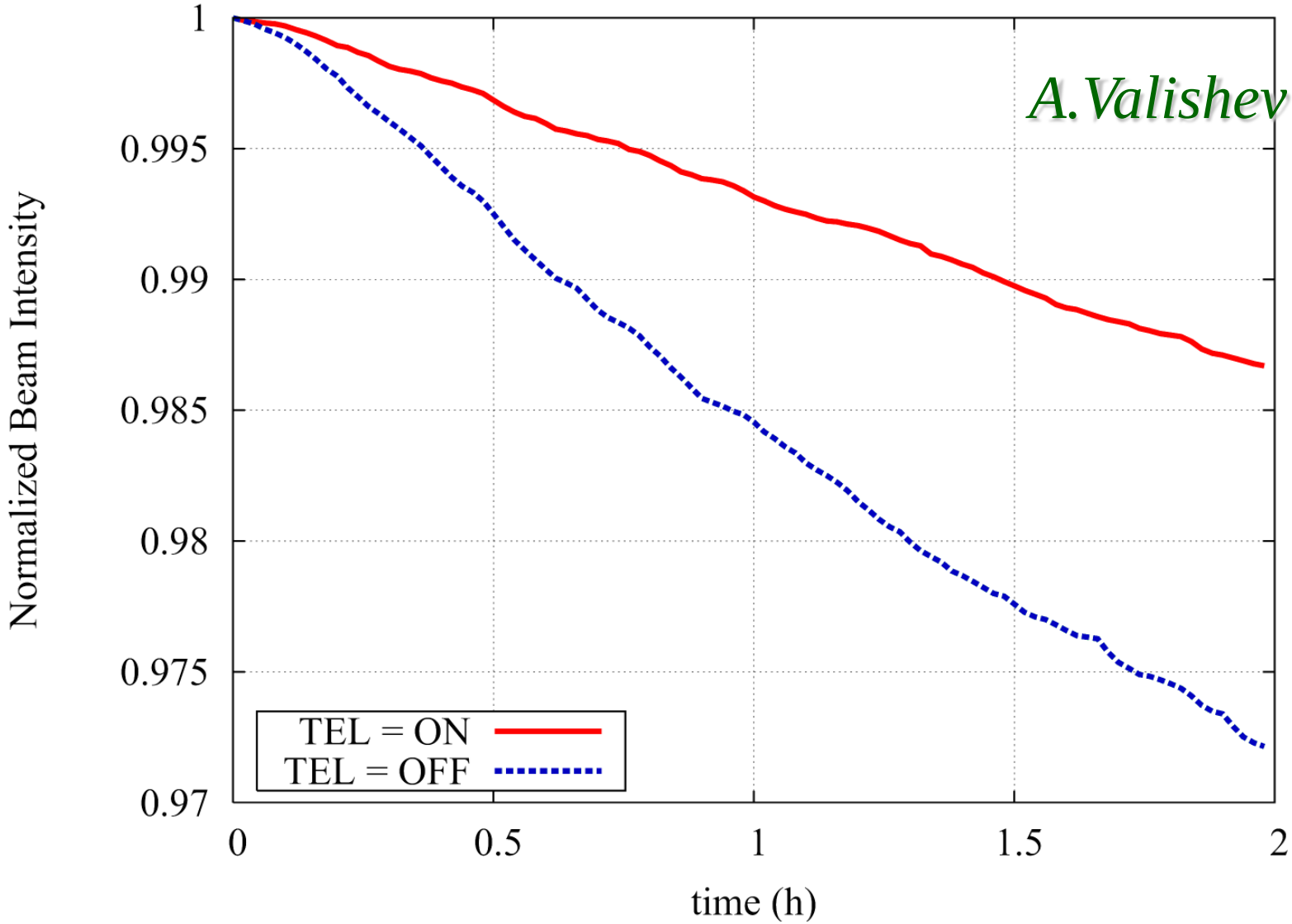
TEL2 acts on all bunches (DC)

Bunches are not equal !



Bunch P12 has systematically the lowest vertical tune that reduces its lifetime (too close to 7/12 resonance). TEL2 raises the tune up by dQ=+1.5e-3 at 0.6 A

LIFETRAC Simulation of TEL



Summary

- Long-range beam-beam effects occurred in the Tevatron at all stages (injection, ramp, squeeze, collisions) and in both beams
- They resulted in beam losses, and emittance blow-ups – with **bunch-to-bunch** dependent patterns
- Careful optimization of helical orbit separation and many operational tune-ups and upgrades have led to essentially putting the effects on the luminosity under control by the mid/end of Run II
- Trustable LIFETRAC simulations helped us a lot, beam-beam compensation by TELs demonstrated

Complexity of Beams in *log*-Scale:

Complexity 0 — APS, LCLS

Complexity 0.5 — FNAL/MI

Complexity 1 — B-factories

Complexity 1.5 — eCool, HERA

Complexity 2 — DCI/Orsay,80

Complexity 2 — Tevatron,LHC

Complexity 2.5 — BBComp/3BI