Beam-beam Effects
Analysis, Simulations and Experiments

Tanaji Sen

Tevatron Design Parameters

	Tevatron Run IIa
Luminosity [$\times 10^{31}$]	8.6
Bunch intensity [$\times 10^{11}$]	2.7/0.3
Normalized transverse emittance ($p/\bar{p}$) [95%, πmm-mrad]	20/15
RMS bunch length at top energy [cm]	37
RMS energy spread at top energy [$\times 10^{-4}$]	0.9
β^* [cm]	35
Beam-beam tune shift/IP [$p/\bar{p}$]	0.0014/0.01
Number of bunches	36
Total number of parasitics	72

Beam Losses & Emittance Growth in the Tevatron

	03/02	10/02	01/03	03/03
Protons/bunch at low-beta	140e9	170e9	180e9	205e9
Anti-protons/bunch at low-beta	7.5e9	22e9	20e9	23e9
P-loss at 150 GeV	23%	14%	16%	**10%**
Anti-proton-loss at 150 GeV	20%	9%	4%	4%
P-loss on ramp	7%	6%	9%	5%
Anti-proton-loss on ramp	14%	8%	12%	**11%**
Anti-proton-loss in squeeze	25%	5%	3%	2%
Initial $\bar{p}$ emitt. growth rate in stores ϵ_x/ϵ_y [% /hr]	-	0/0.8	1/2.4	0.4/1.2
Initial p emitt. growth rate in stores ϵ_x/ϵ_y [% /hr]	-	3.4/2.4	2.4/2.4	2/1.2

Analysis and Simulations of Beam-beam effects

Injection and Collision Energy

- Bunch by bunch orbits, tunes, coupling and chromaticities
- Tune, coupling and chromaticity footprints
- Resonance driving terms [with and w/o beam-beam effects]
- Dynamic aperture of protons and anti-protons
  DA of anti-protons vs proton intensity, beam separations
- Lifetime simulations - injection energy so far [LBNL and SLAC]

Observations and Experiments on Beam-beam effects

Injection Energy

- Anti-proton ($\bar{p}$) lifetime dependence on
  helix, $\bar{p}$ tunes and chromaticities, $\bar{p}$ emittance, p intensity
- Dynamic aperture of $\bar{p}$ bunches 1 to 4.

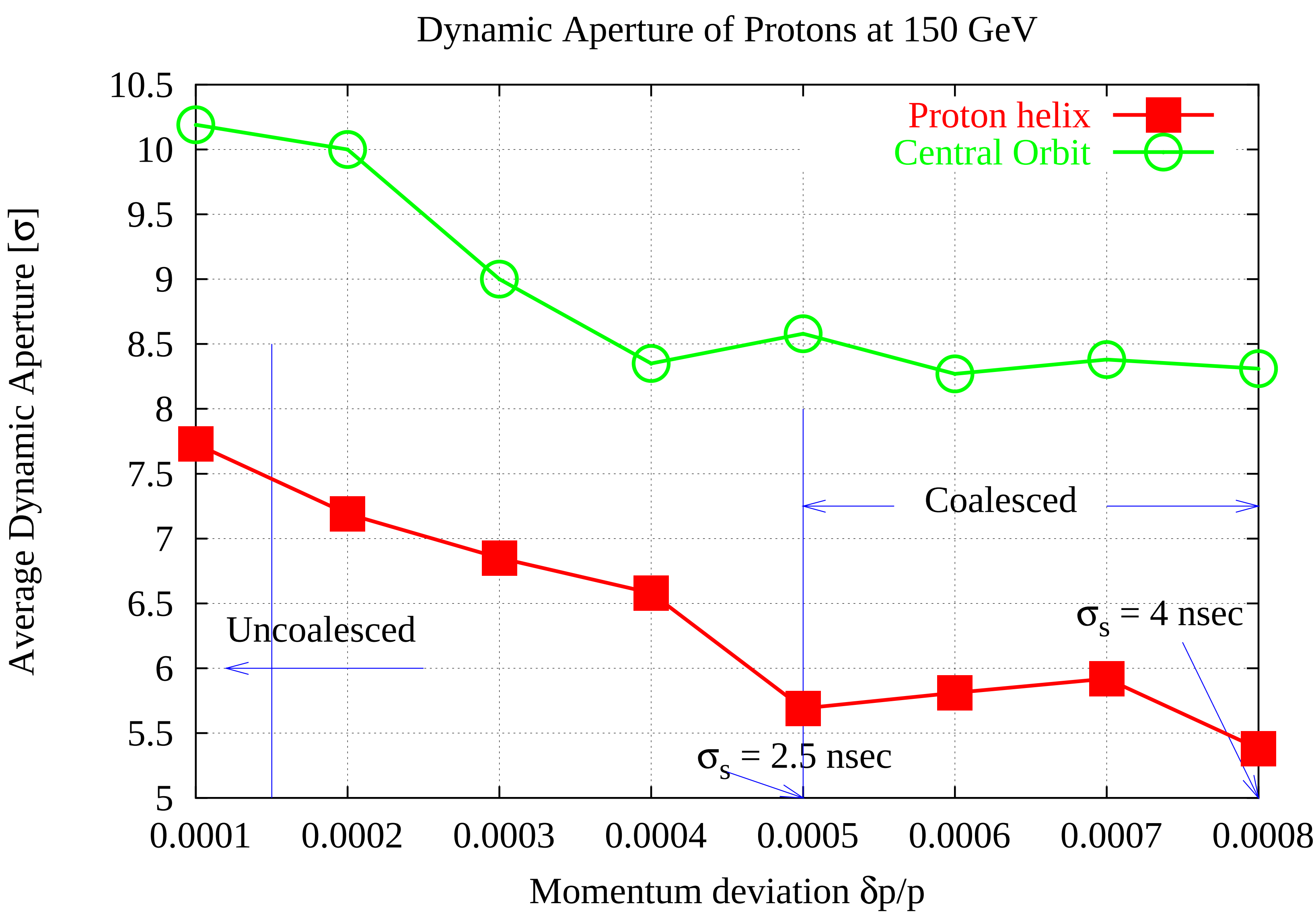
Acceleration

- $\bar{p}$ loss dependence on
  $\bar{p}$ emittance, p intensity

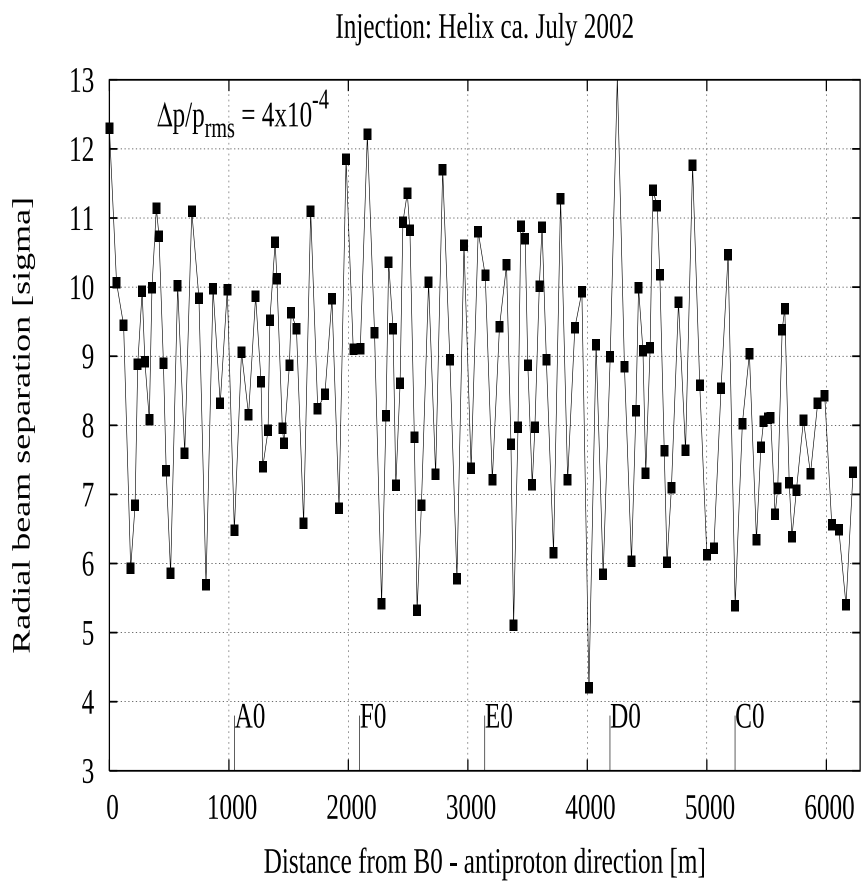
Collision Energy

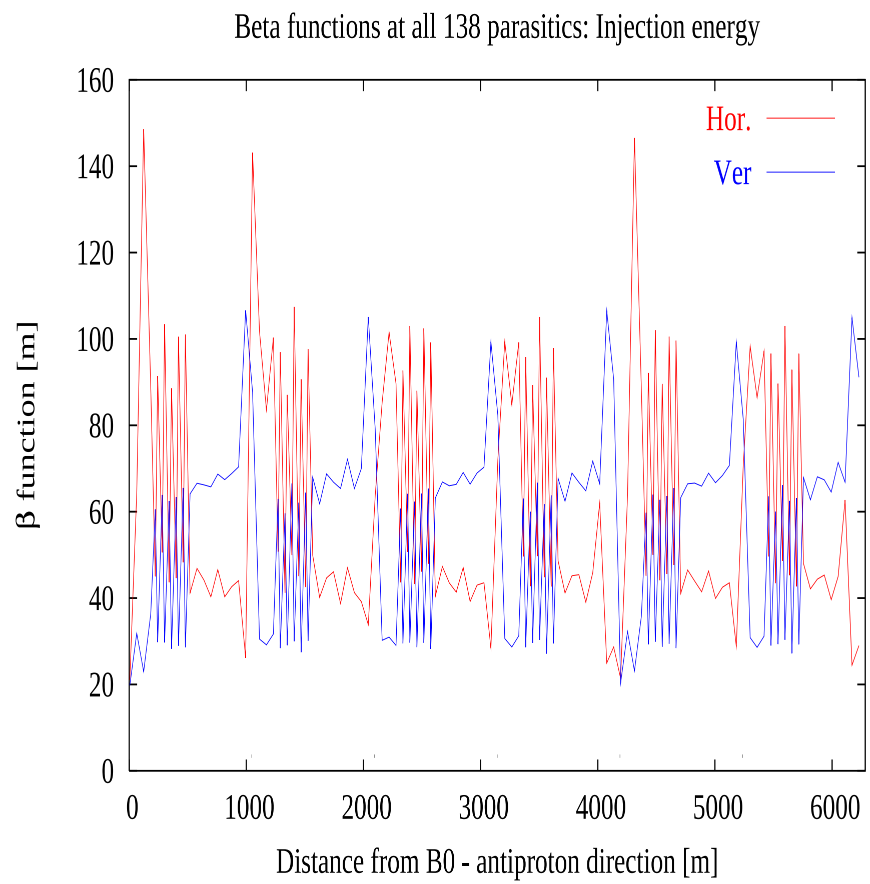
- $\bar{p}$ Bunch by bunch measurements of
  closed orbits, tunes and chromaticities
- $\bar{p}$ lifetime dependence on
  tunes, helix size, separations at parasitics nearest to the IPs, $\bar{p}$ emittances, p intensities
- Initial $\bar{p}$ emittance growth rate dependence on
  tunes, bunch number, p intensities

Dynamic aperture of protons at 150 GeV



Beam Separations at Injection





Beam-beam parameters vs Helix Angle

For round beams and large separations ($d \gg 1$), small amplitude parameters

$$\Delta\nu_x(0,0) \;\propto\; \frac{\cos 2\theta}{d^2}$$

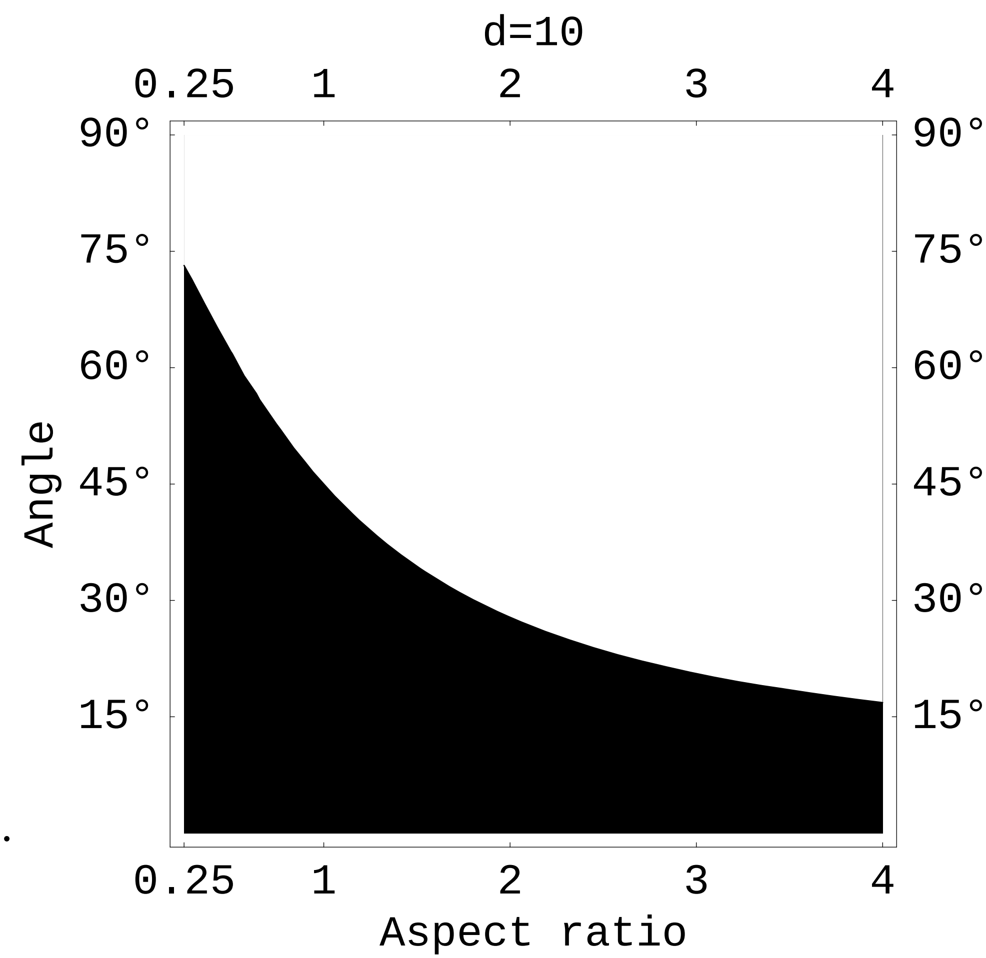
$$\Delta\nu_x'(0,0) \;\propto\; \frac{\cos\theta(2\cos 2\theta - 1)}{d^3}\eta_x$$

$$\Delta\nu_{min}(0,0) \;\propto\; \frac{\sin 2\theta}{d^2}$$

$\Rightarrow$

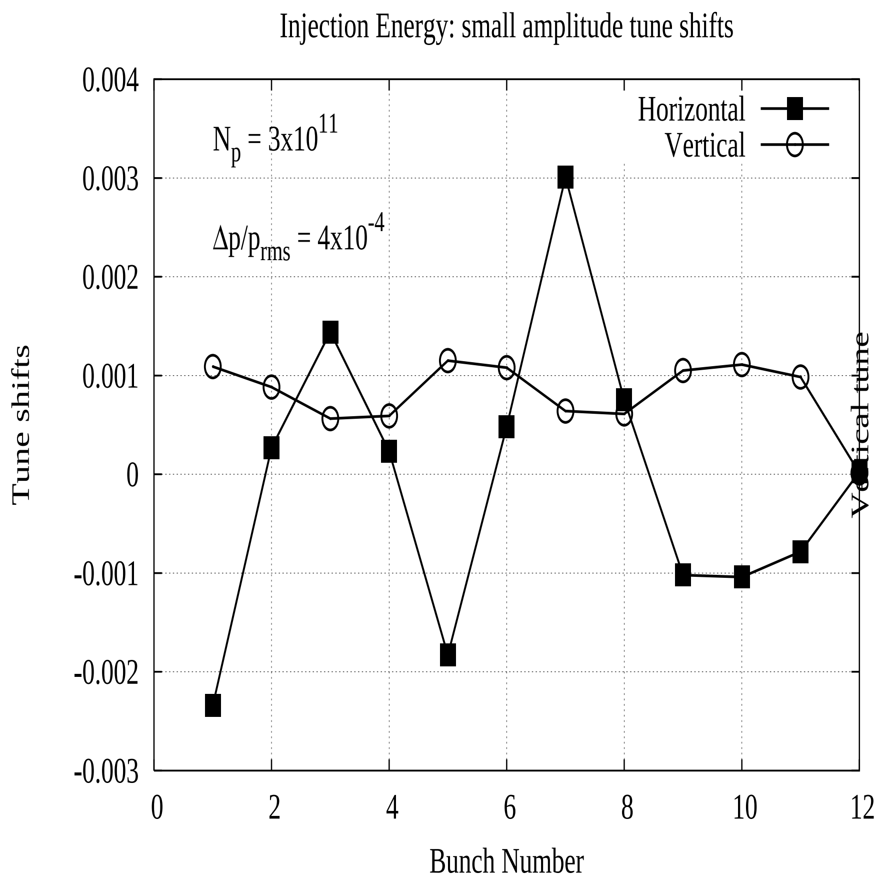
$\Delta\nu = 0$ along the diagonal
$\Delta\nu' = 0$ along 30° or the vertical axis.
$\Delta\nu_{min} = 0$ along the horizontal or vertical axis.

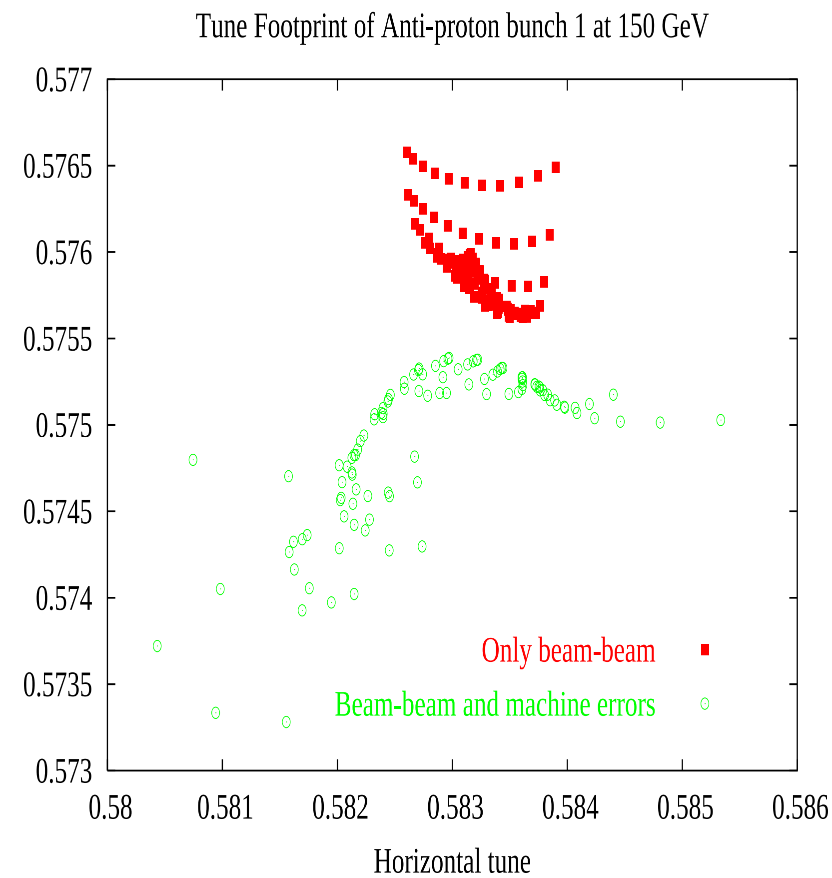
For arbitrary aspect ratio $\Rightarrow$



The tune shift is negative in the dark region and vanishes along the border.

Small amplitude tune shifts & Tune footprints: Injection

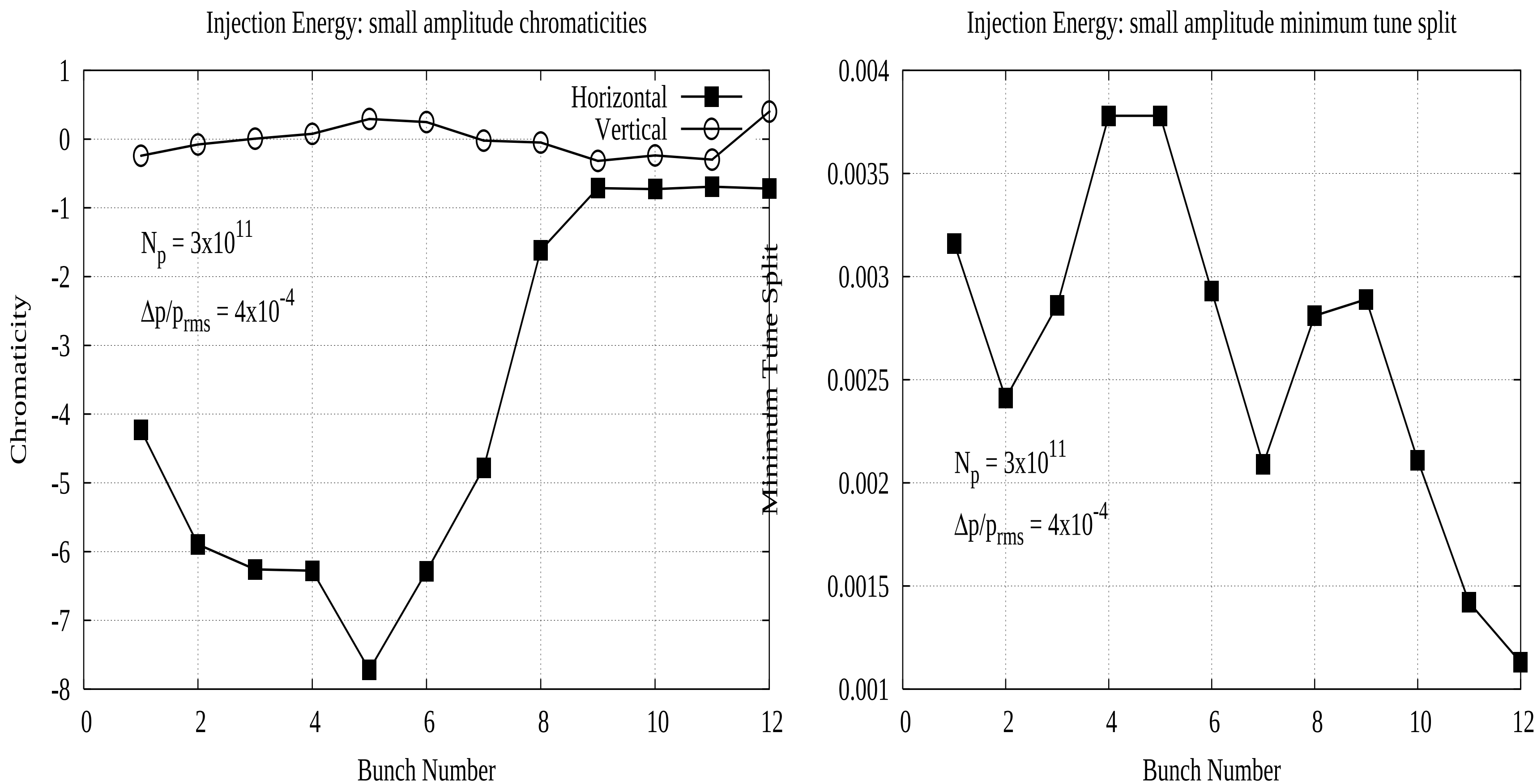




Bunch to bunch tune spread $\Delta\nu_x \sim 0.005$.

Changes are small at the end of a train: A9-A12

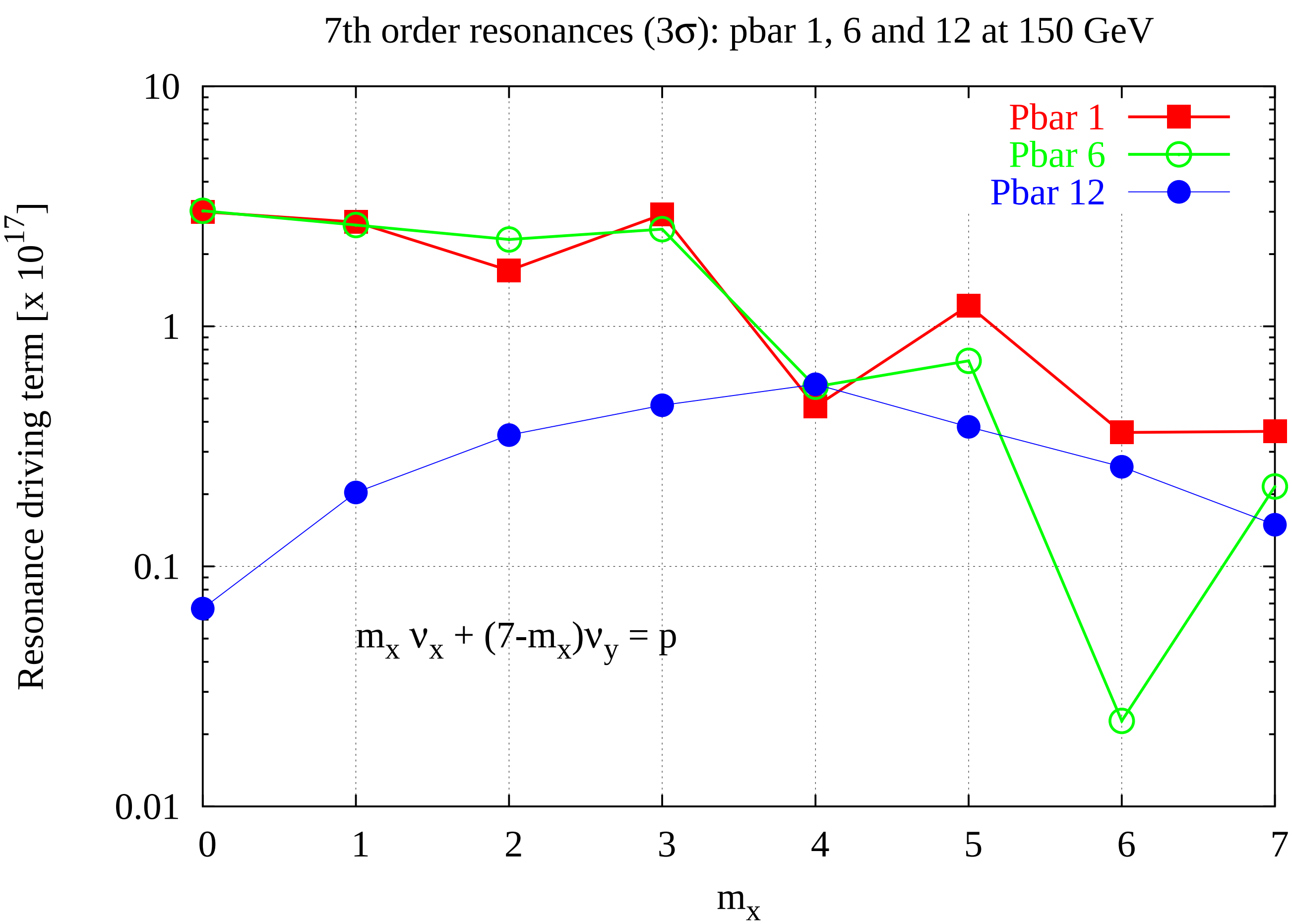
Small amplitude chromaticities and coupling: Injection



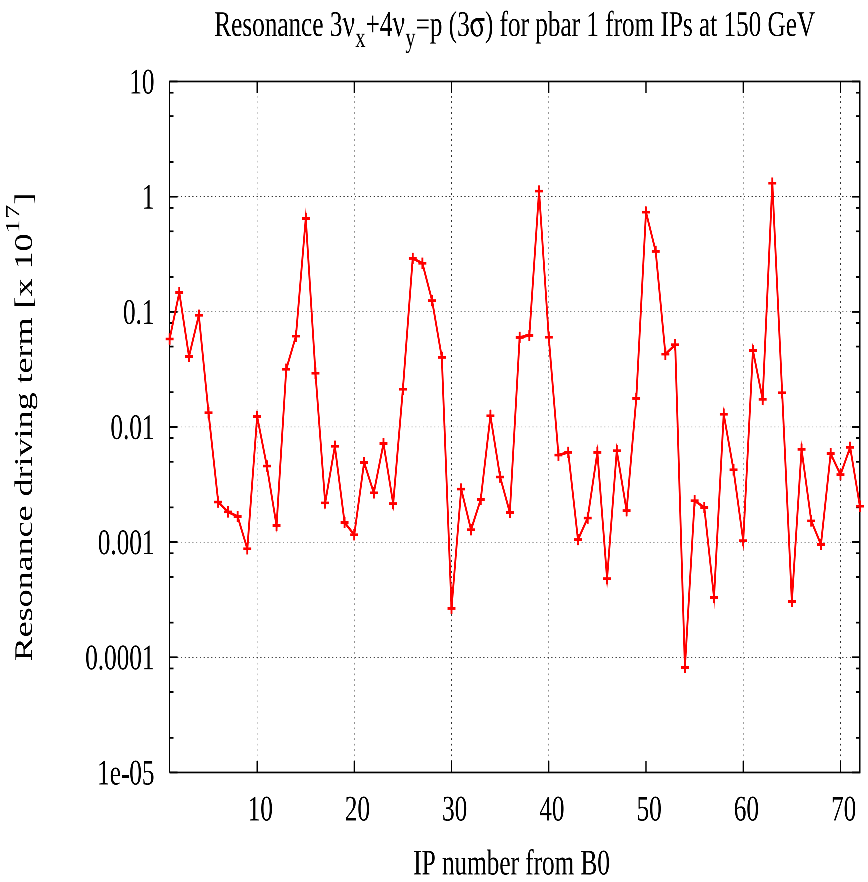
Beam-beam chromaticity → some bunches more susceptible to synchro-betatron resonances, instabilities.

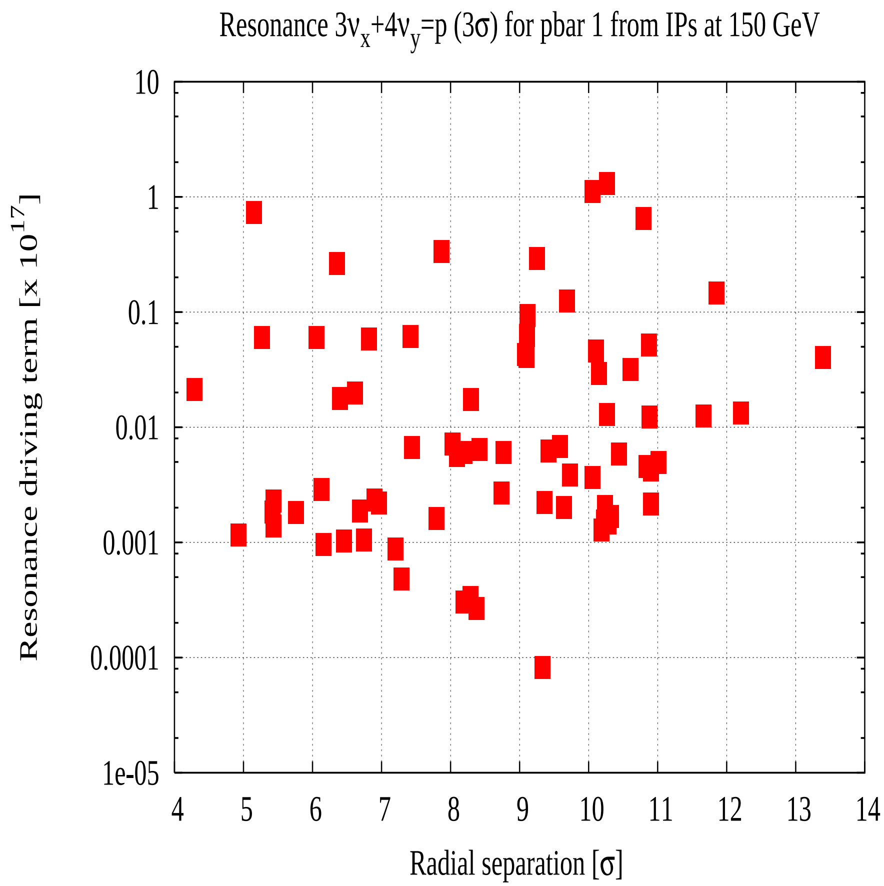
Changes are small towards the end of a train.

Seventh Order Beam-beam resonances - 150 GeV

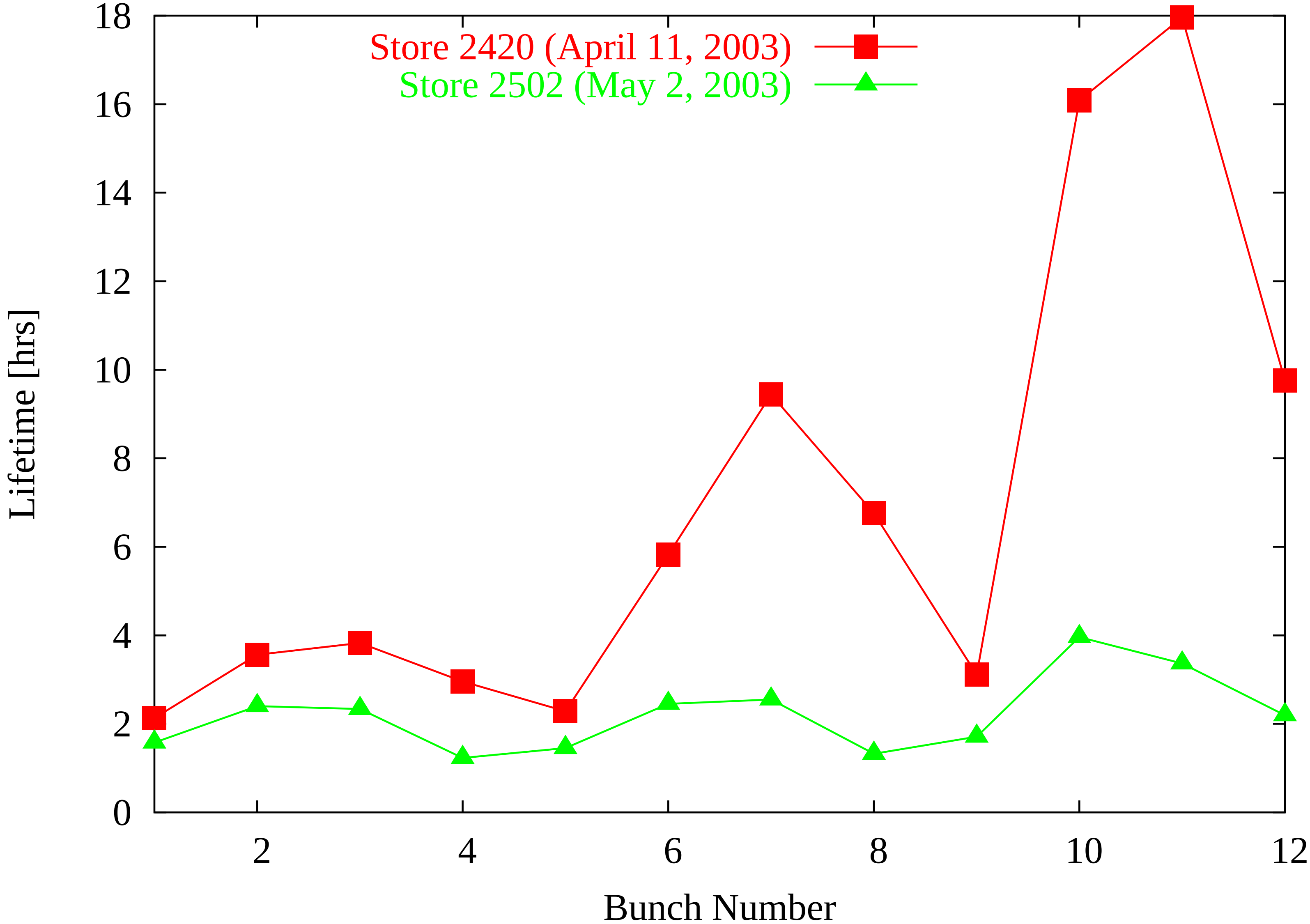


$3\nu_x$ + 4 ν_y = 4 resonance from parasitics - pbar bunch 1 at 150 GeV

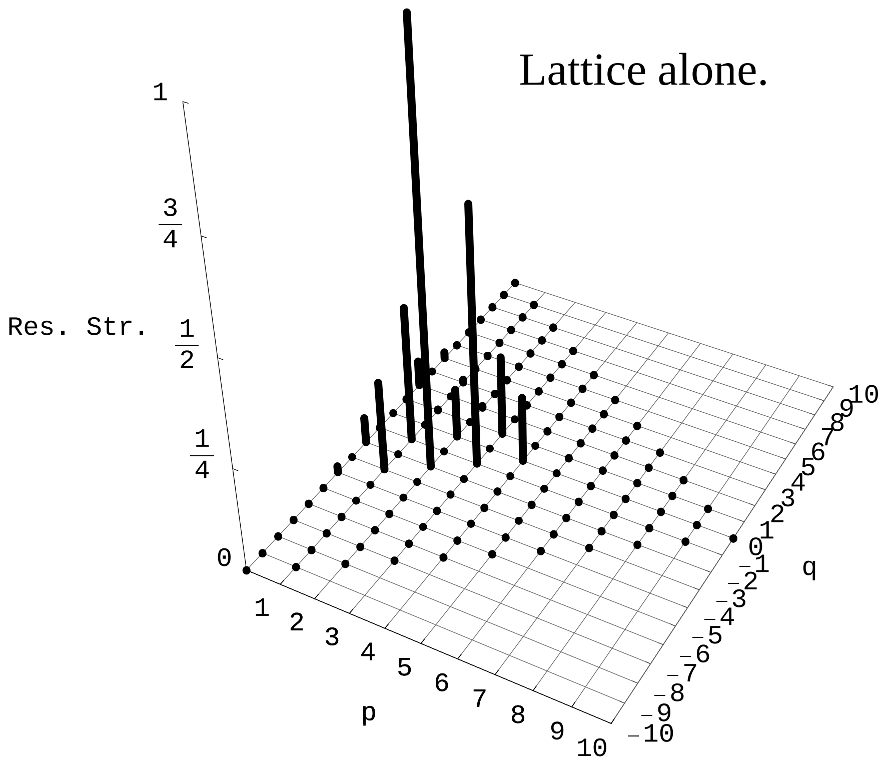


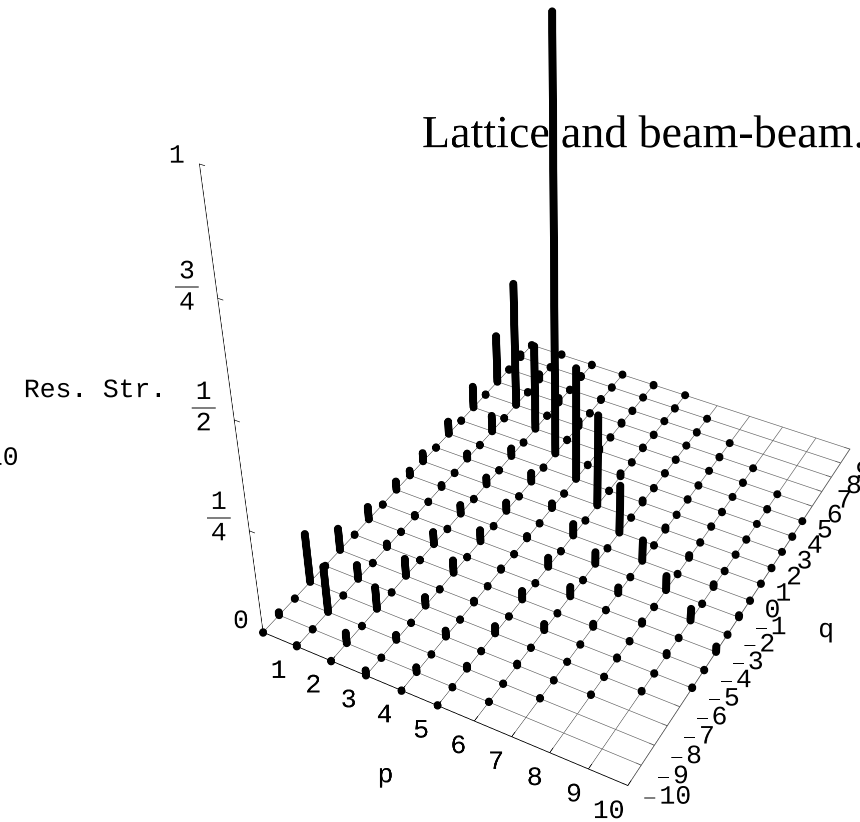


Anti-proton lifetimes at Injection: Stores 2420, 2502



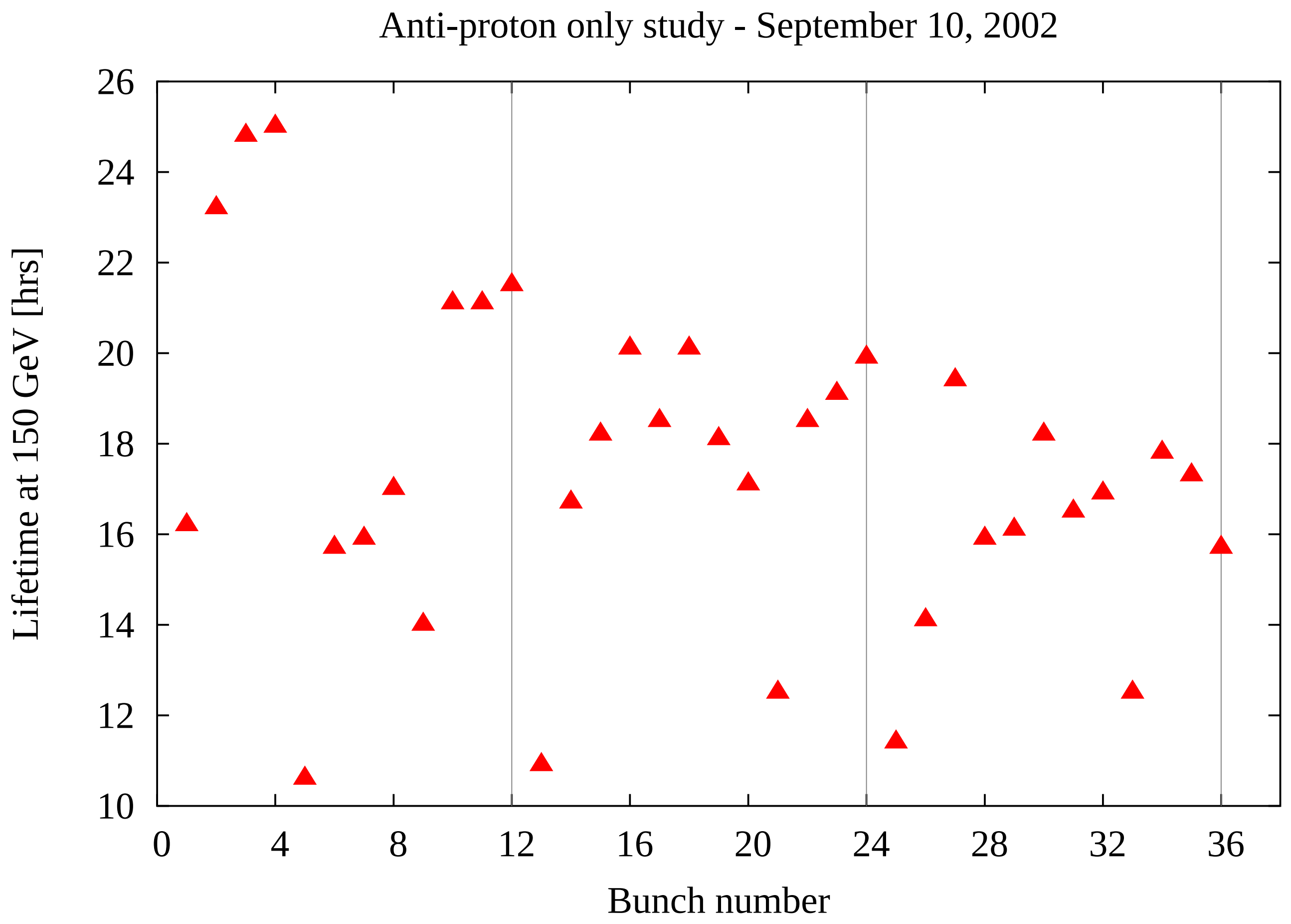
Resonances at Injection





	Resonances (p, q) at 2σ	
	Largest	Others
Lattice driven	(2, -2)	(3,-1), (1,-1), (1,-3), (3,1), (4, 0)
Lattice and beam-beam driven	(3, 4)	(1, 6), (4, 3), (5, 2), (2, 5), (0, 7)

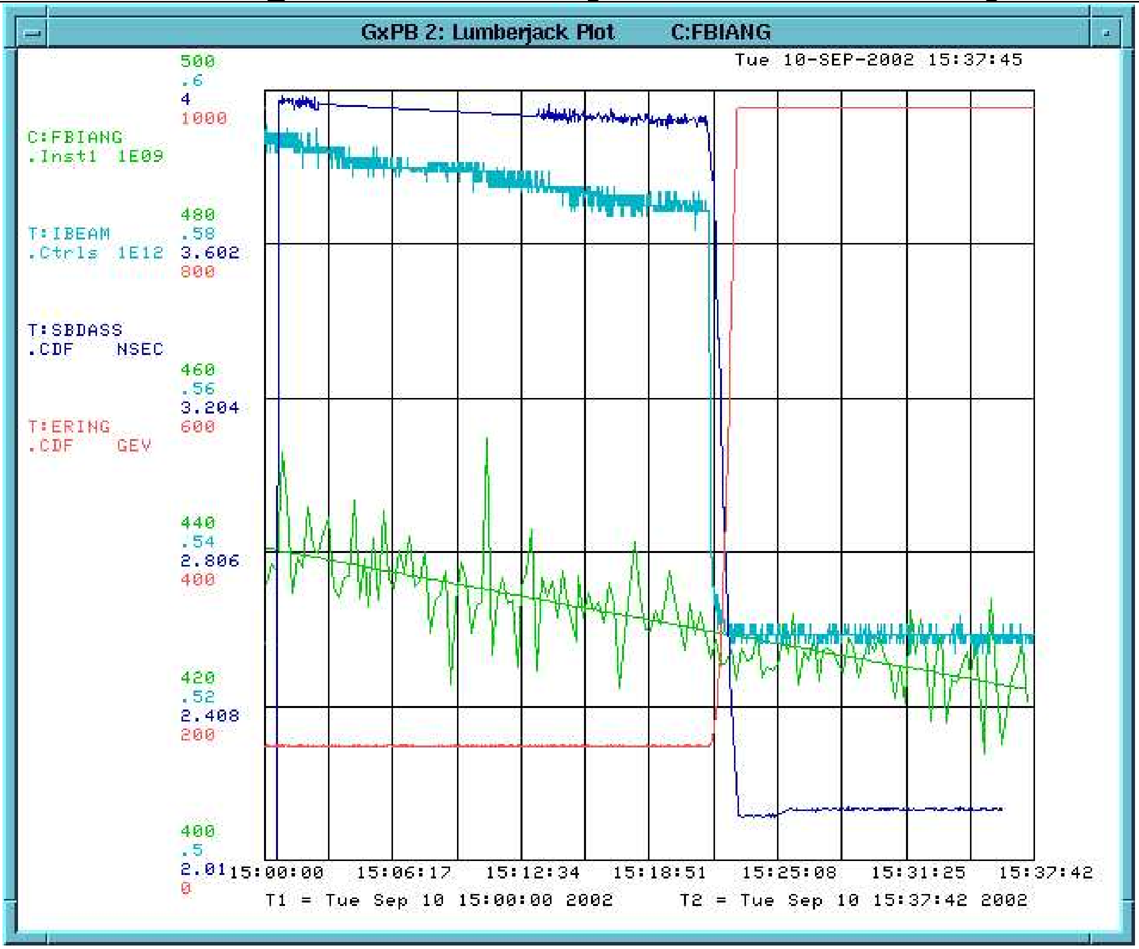
Anti-protons only - Beam Study



In this study, τ was well anti-correlated with the vertical emittance.

In typical stores, $1 \leq \tau(\bar{p}) \leq 10$ hours.

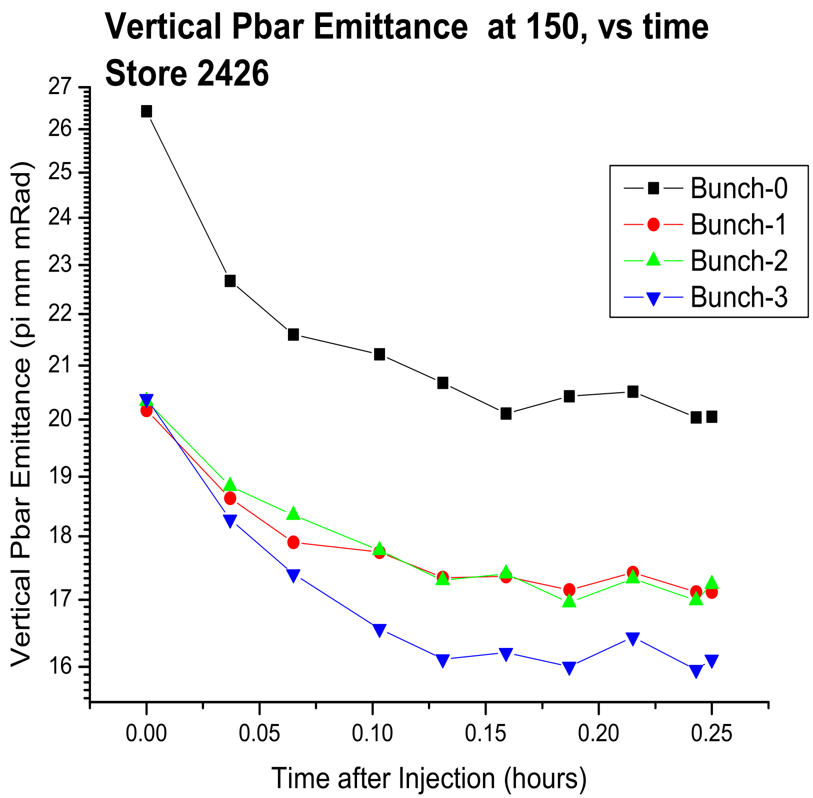
Anti-protons only - Beam Study

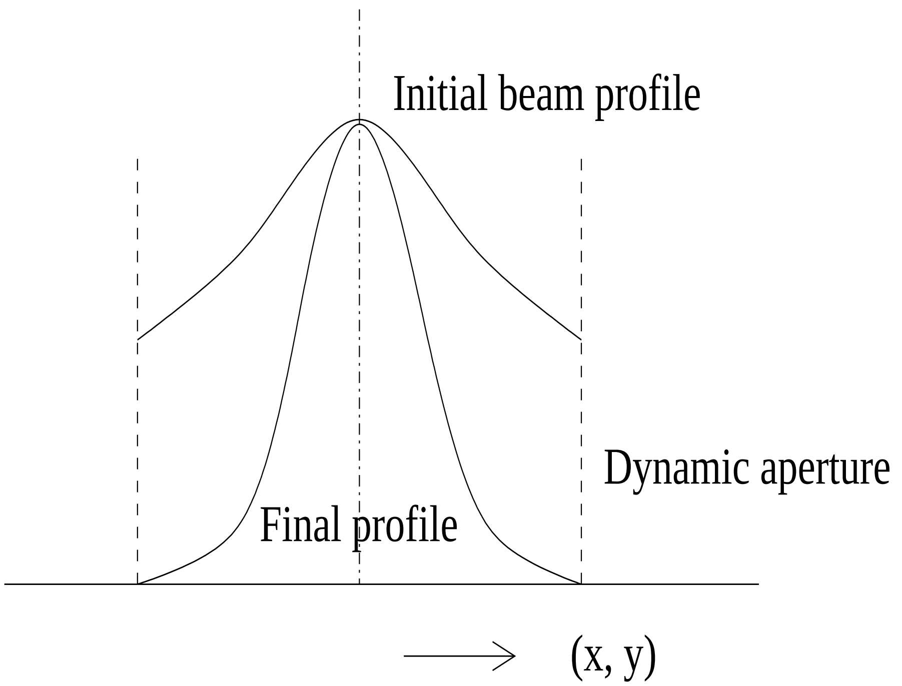


Loss of anti-protons during the ramp was very small ~ 2%.

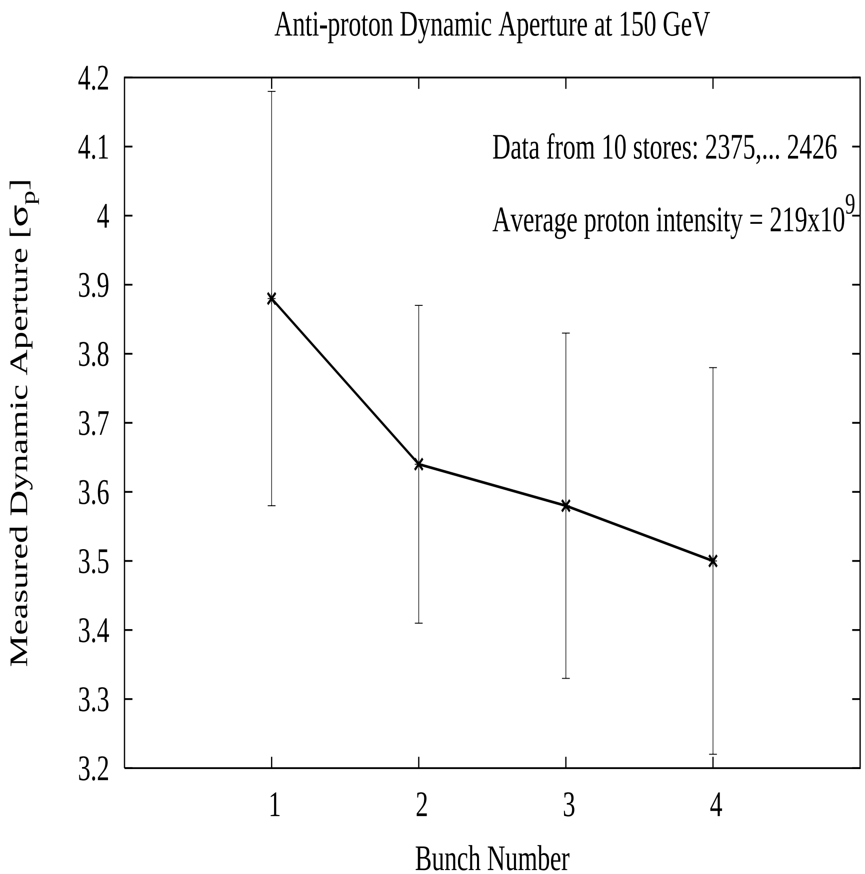
In typical stores, anti-proton losses during the ramp are $\sim 10\%$.

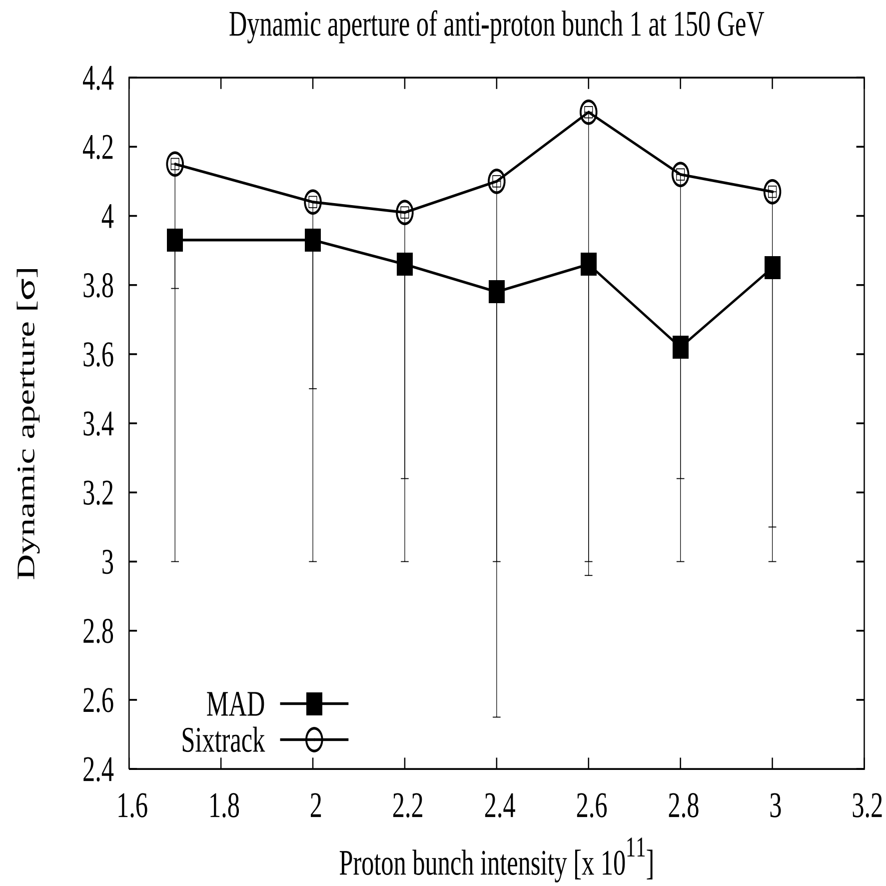
Anti-proton dynamic aperture at 150 GeV



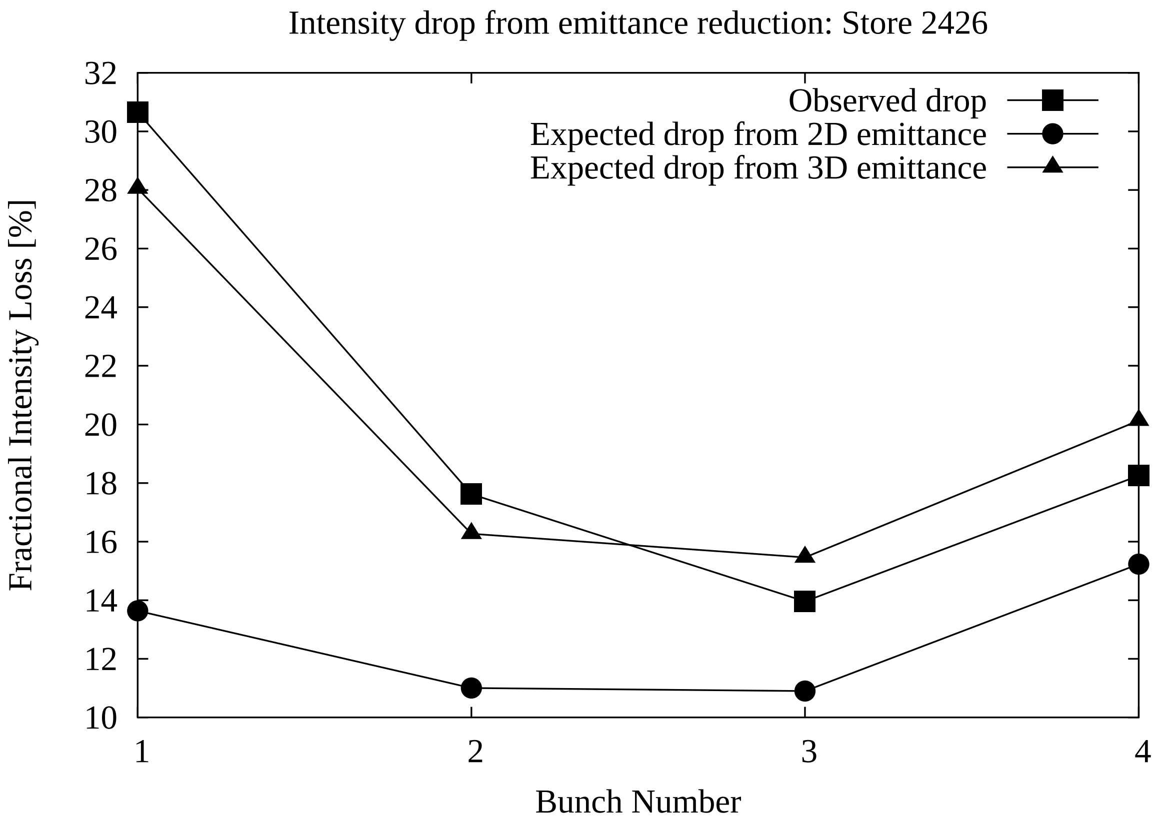


Anti-proton dynamic aperture at 150 GeV



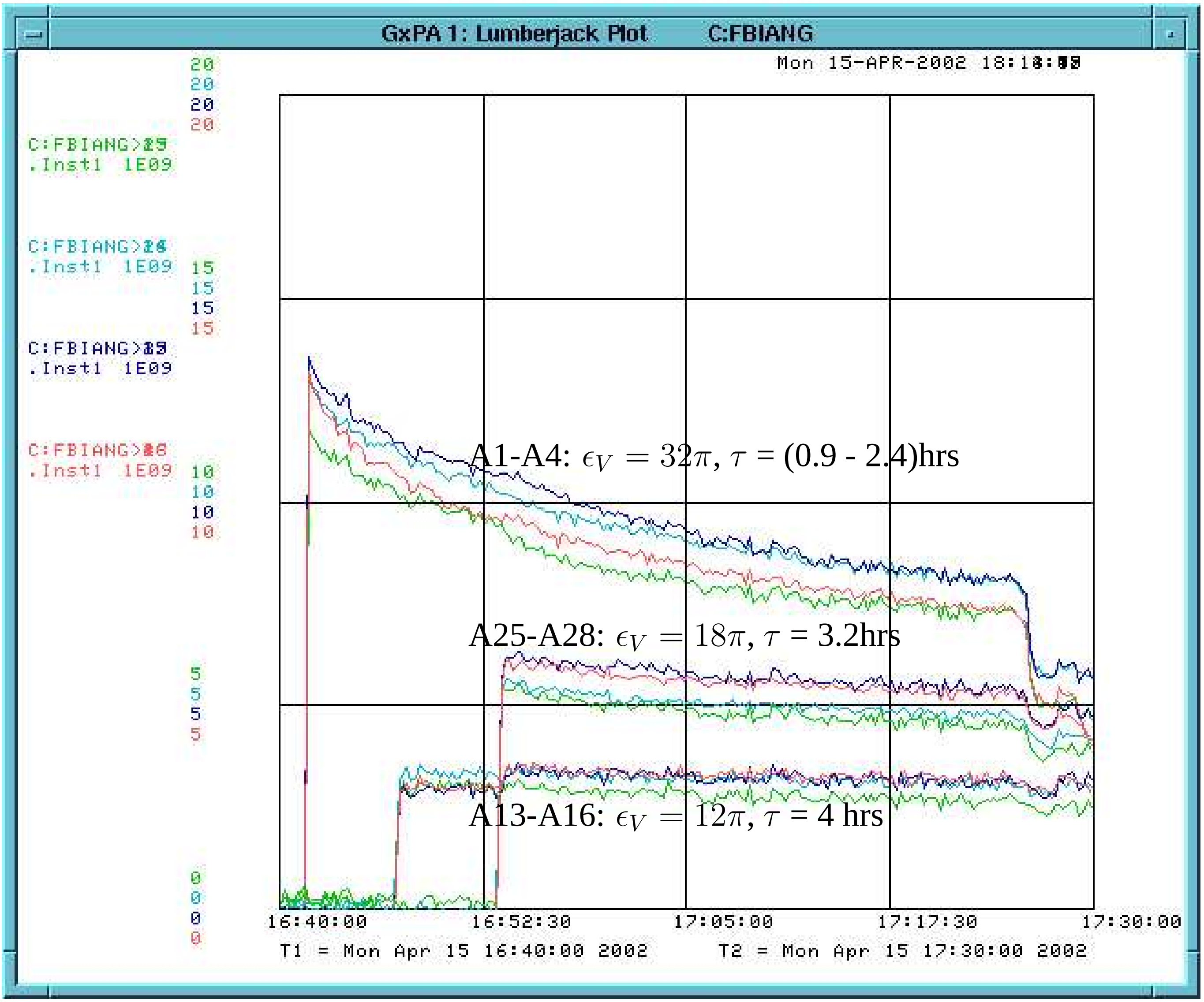


Expected and Measured Intensity Drop: Store 2426

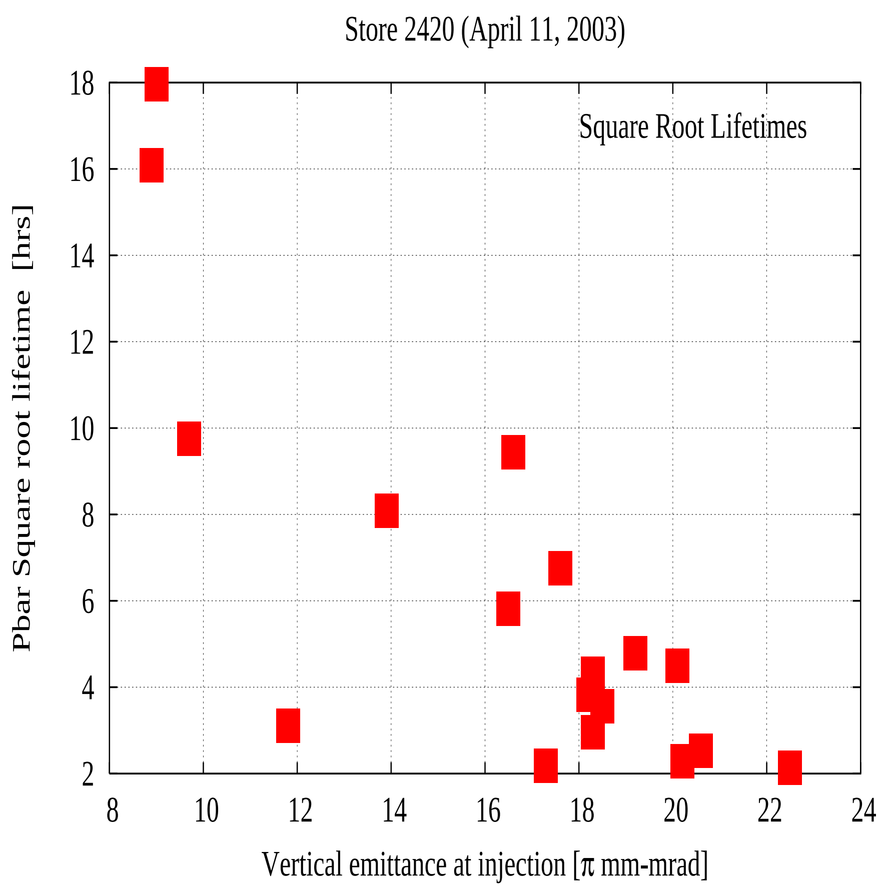


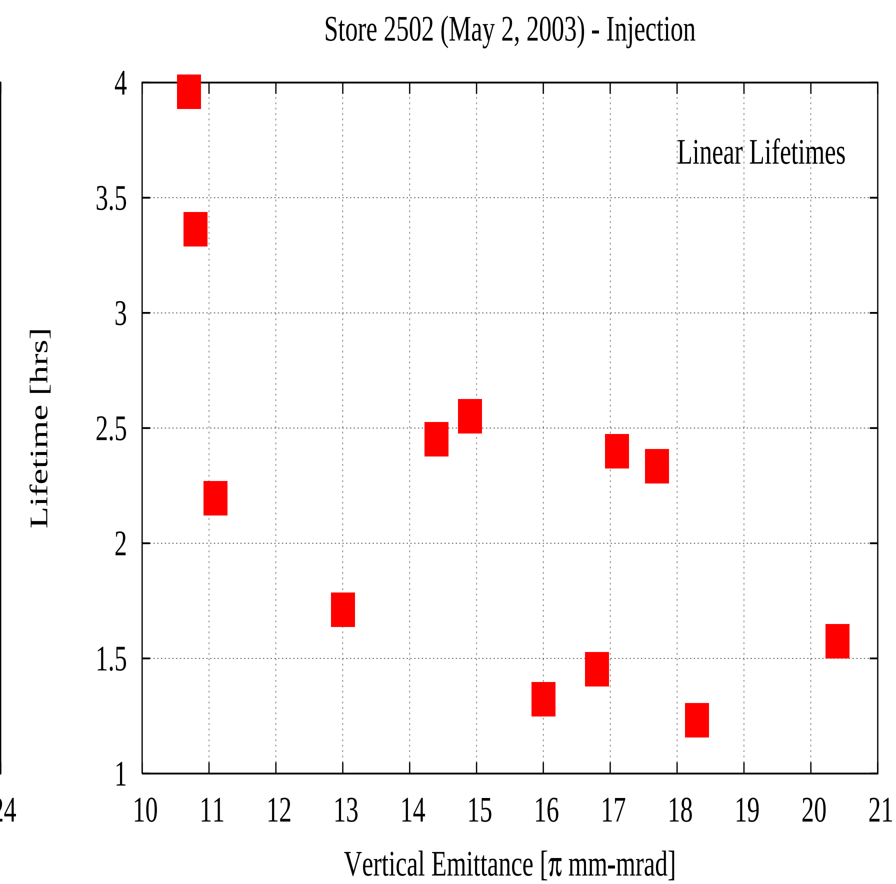
- The expected drop in intensity was calculated from the final bunch area (2D and 3D). The bunches are assumed to completely fill their dynamic aperture. The expected 3D loss and measured loss agree to within 2%.
- The largest difference in 2D and 3D areas was for bunch 1. This bunch had the greatest reduction in longitudinal emittance.
- This store occurred before the vertical dampers were restored. Since then, we have not seen this significant emittance shaving at injection.

Anti-proton lifetime at 150 GeV vs Vert. Emittance



Anti-proton lifetime vs Vert. Emittance at 150 GeV





Lifetime Simulations at 150 GeV

Parallel codes have been developed that run at NERSC

- A. Kabel(SLAC): Code `PlibB`

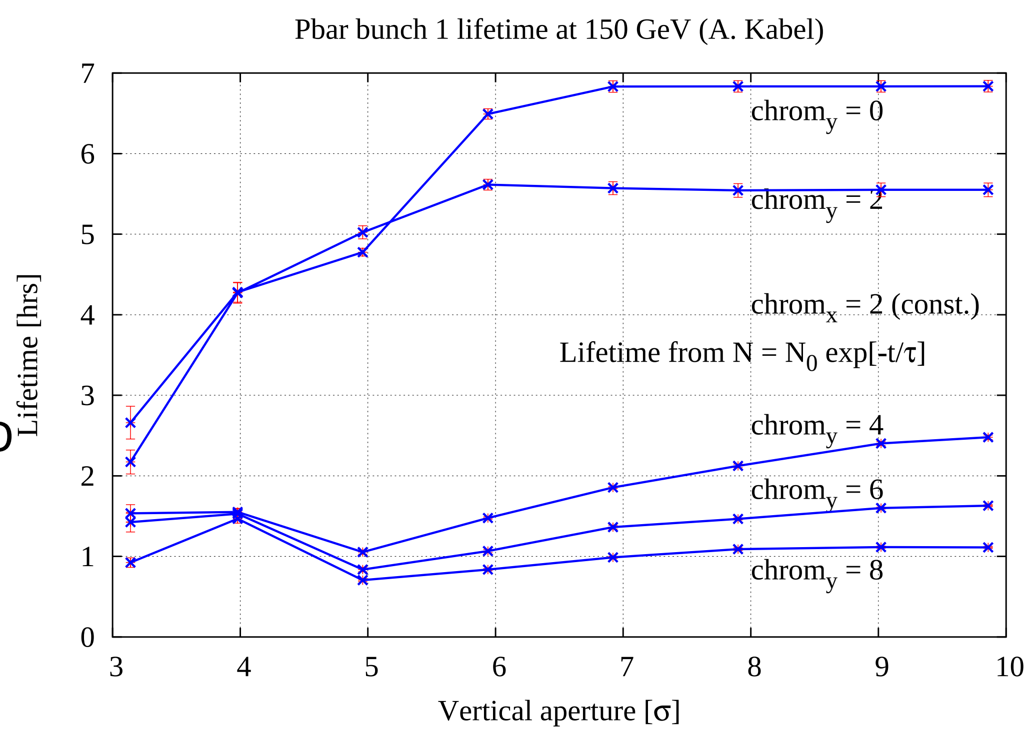
  Fast evaluation of complex error function

- J.Qiang(LBNL): Code `Beambeam3D`

  Uses a shifted Green's function approach

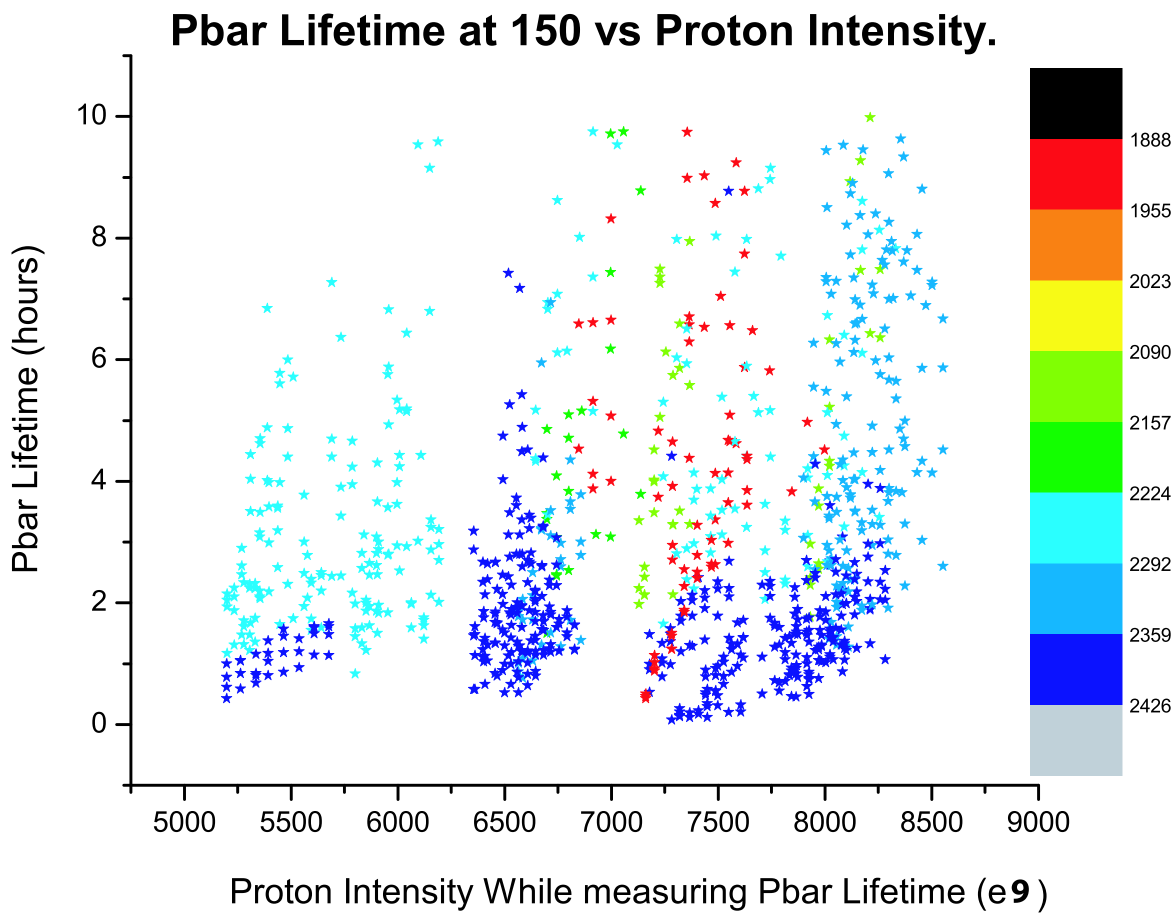
Both codes include the long-range interactions and transverse noise.

At small apertures, both predict lifetimes close to the observed lifetimes.



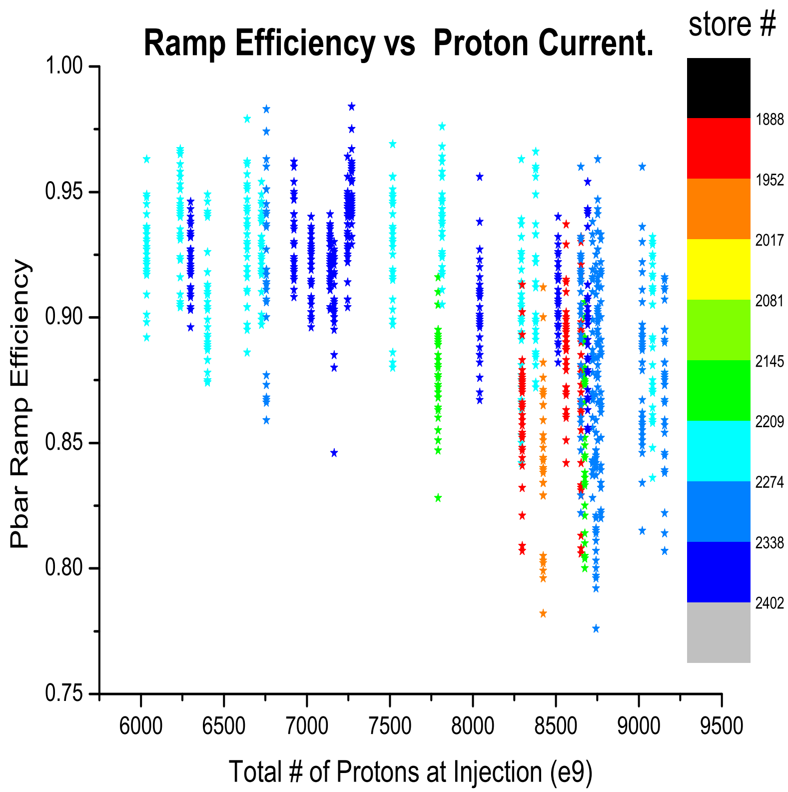
This predicts a qualitative increase in lifetime when the vertical chromaticity is dropped below 4 units.

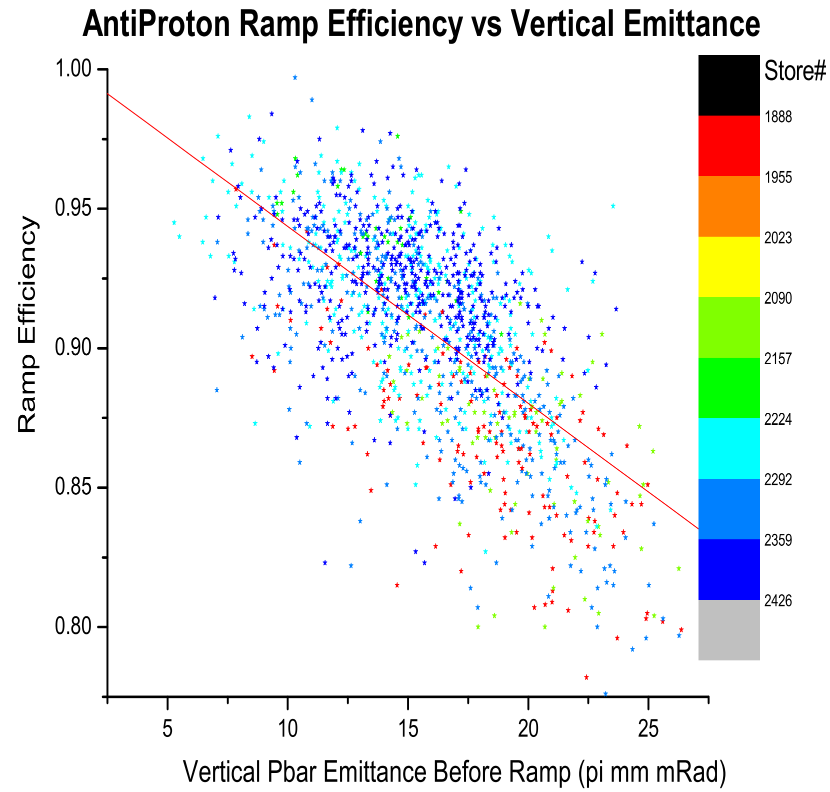
Anti-proton lifetime at Injection - Several Stores



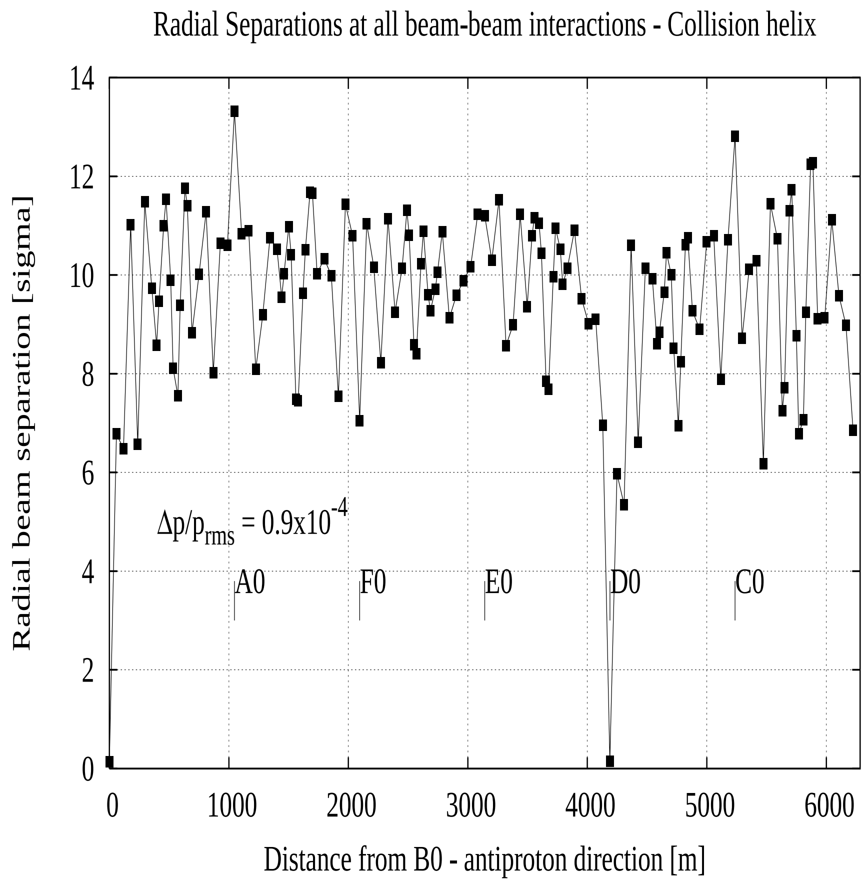
Dependence of anti-proton lifetime on proton intensities is low so far.

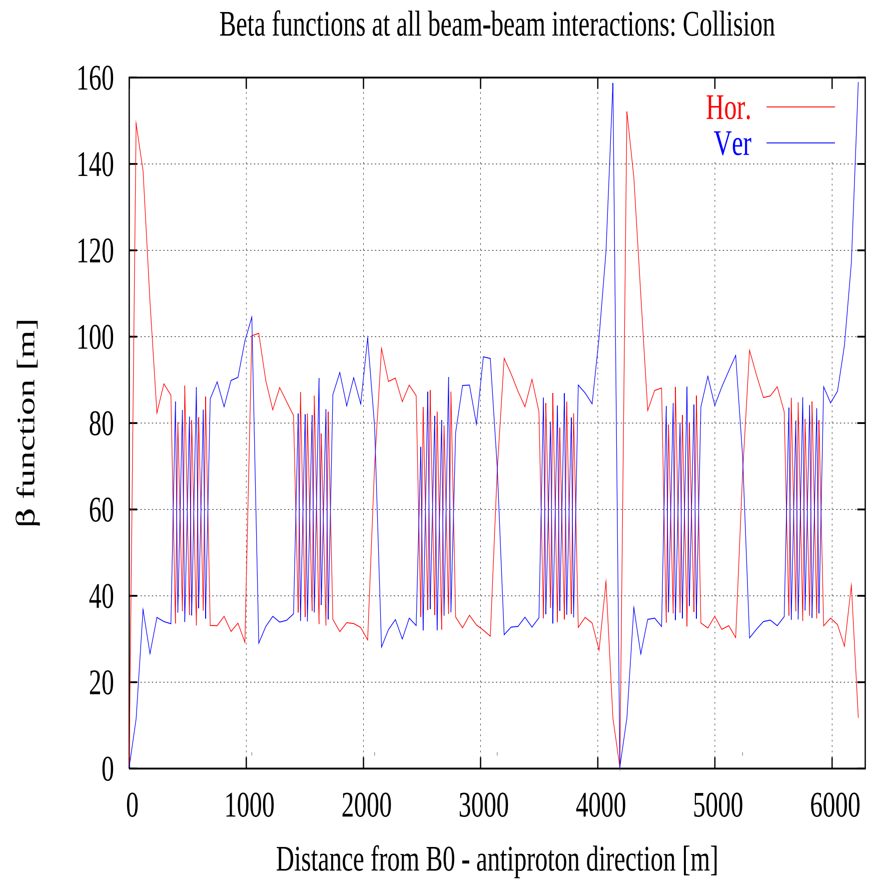
Anti-proton ramp efficiency in stores



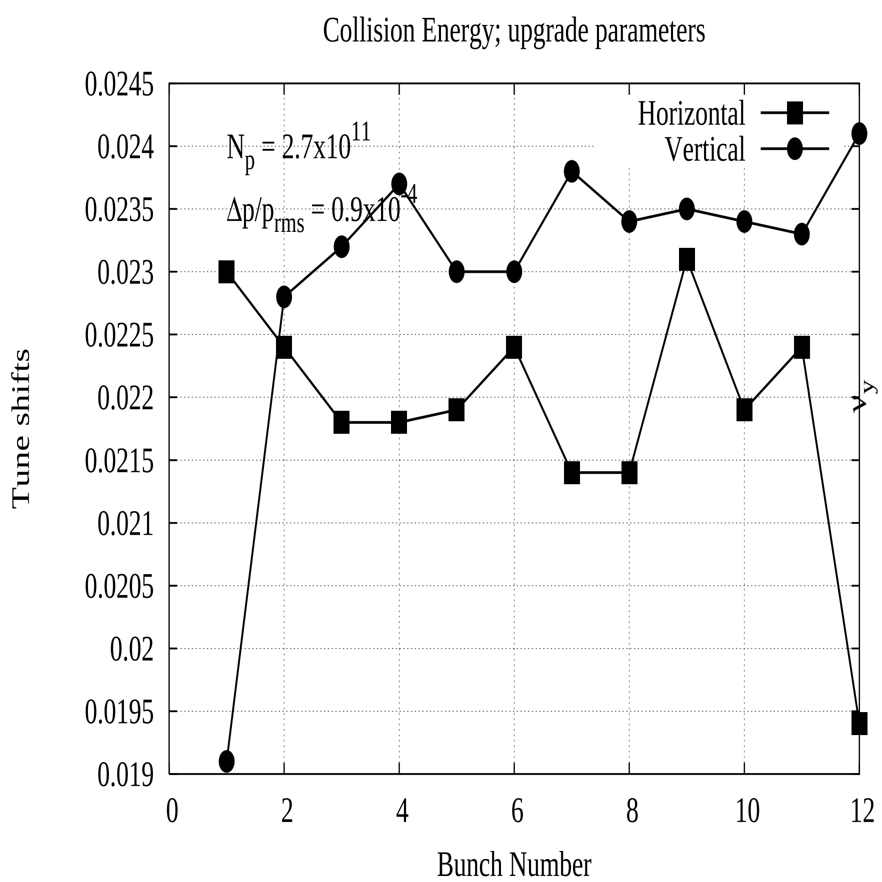


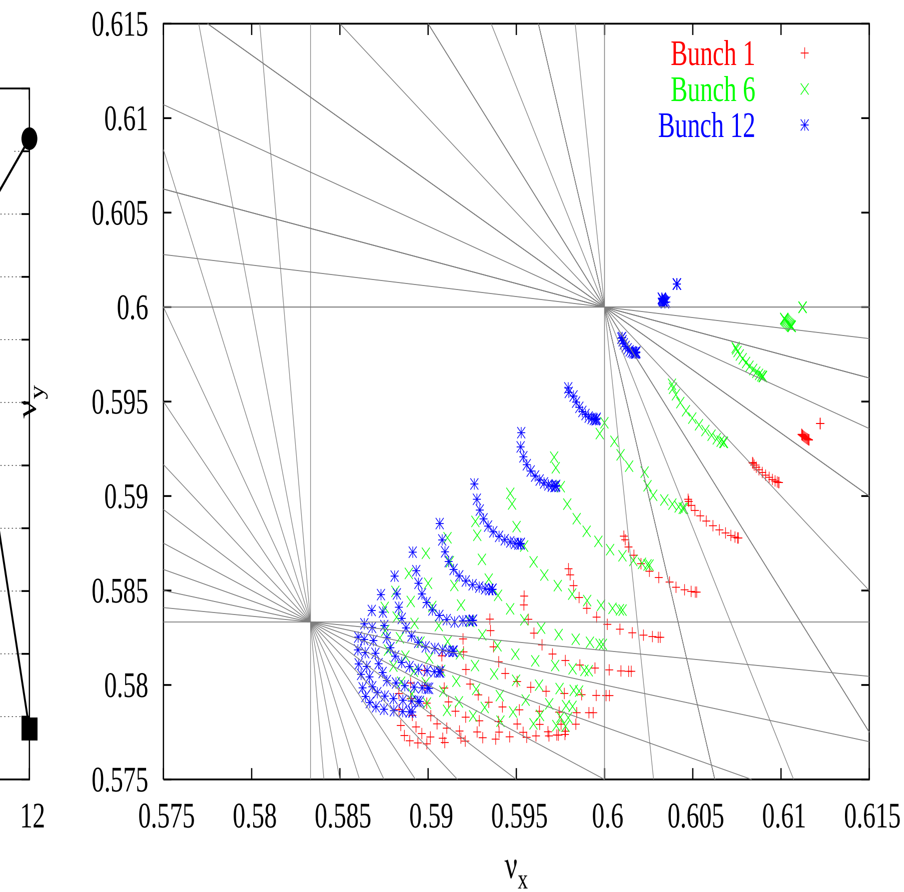
Beam Separations at 980 GeV





Small amplitude tune shifts & Tune footprints: Collision

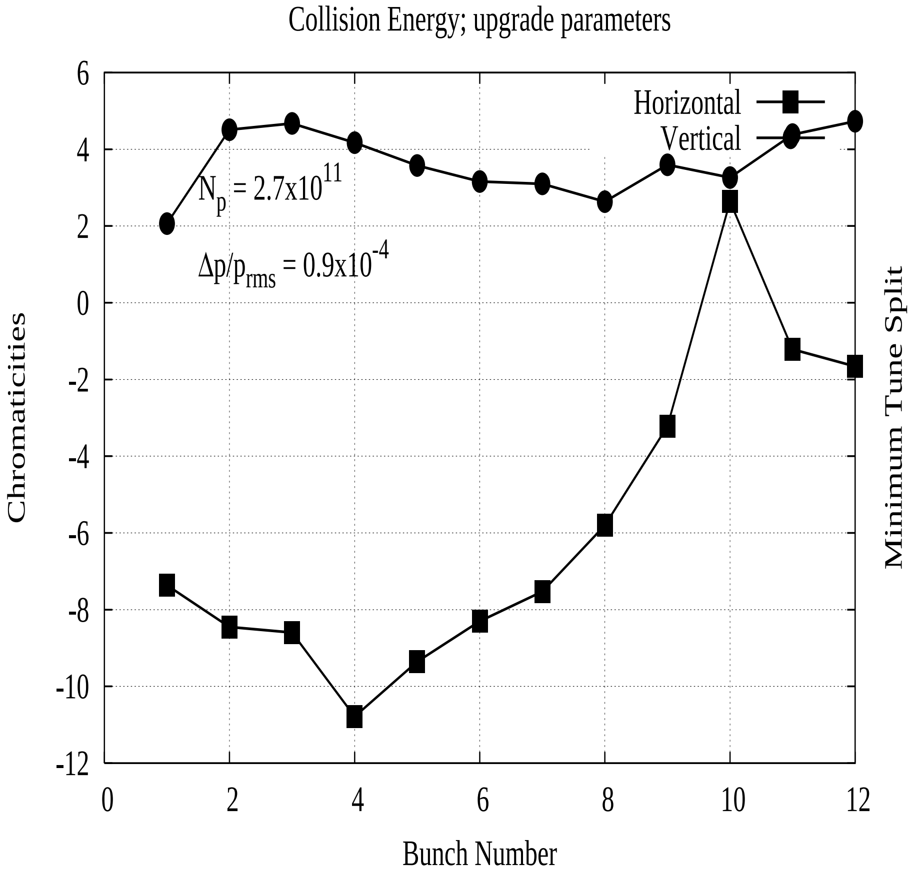


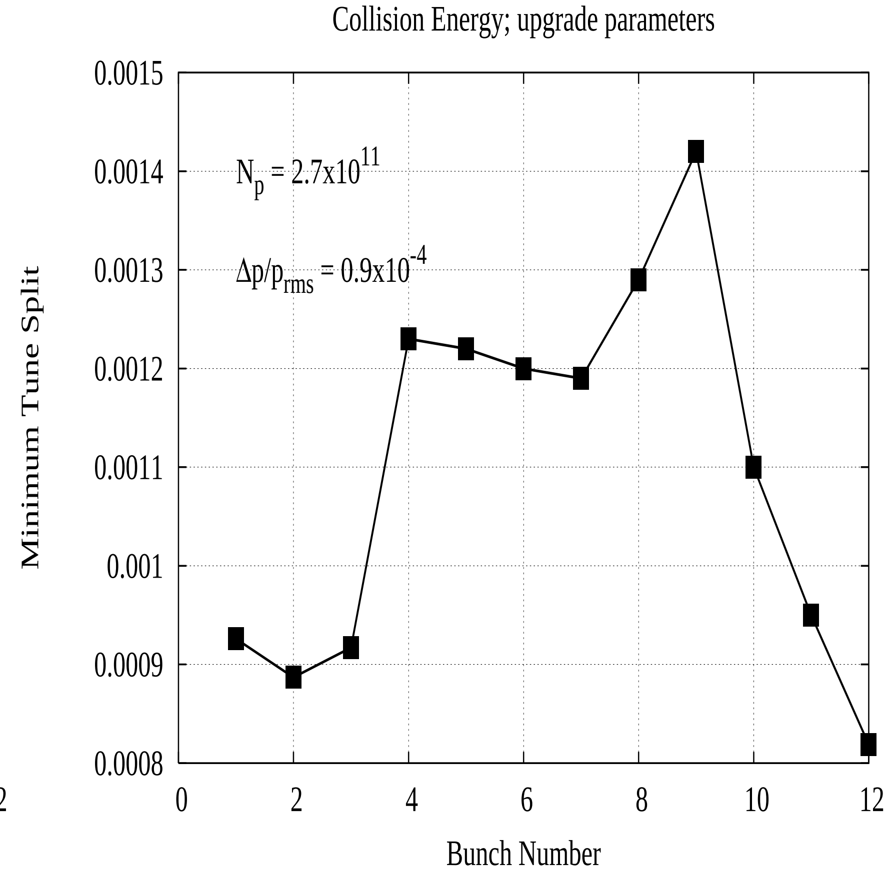


Bunch 1 has lower ν_x, bunch 12 has lower ν_y.

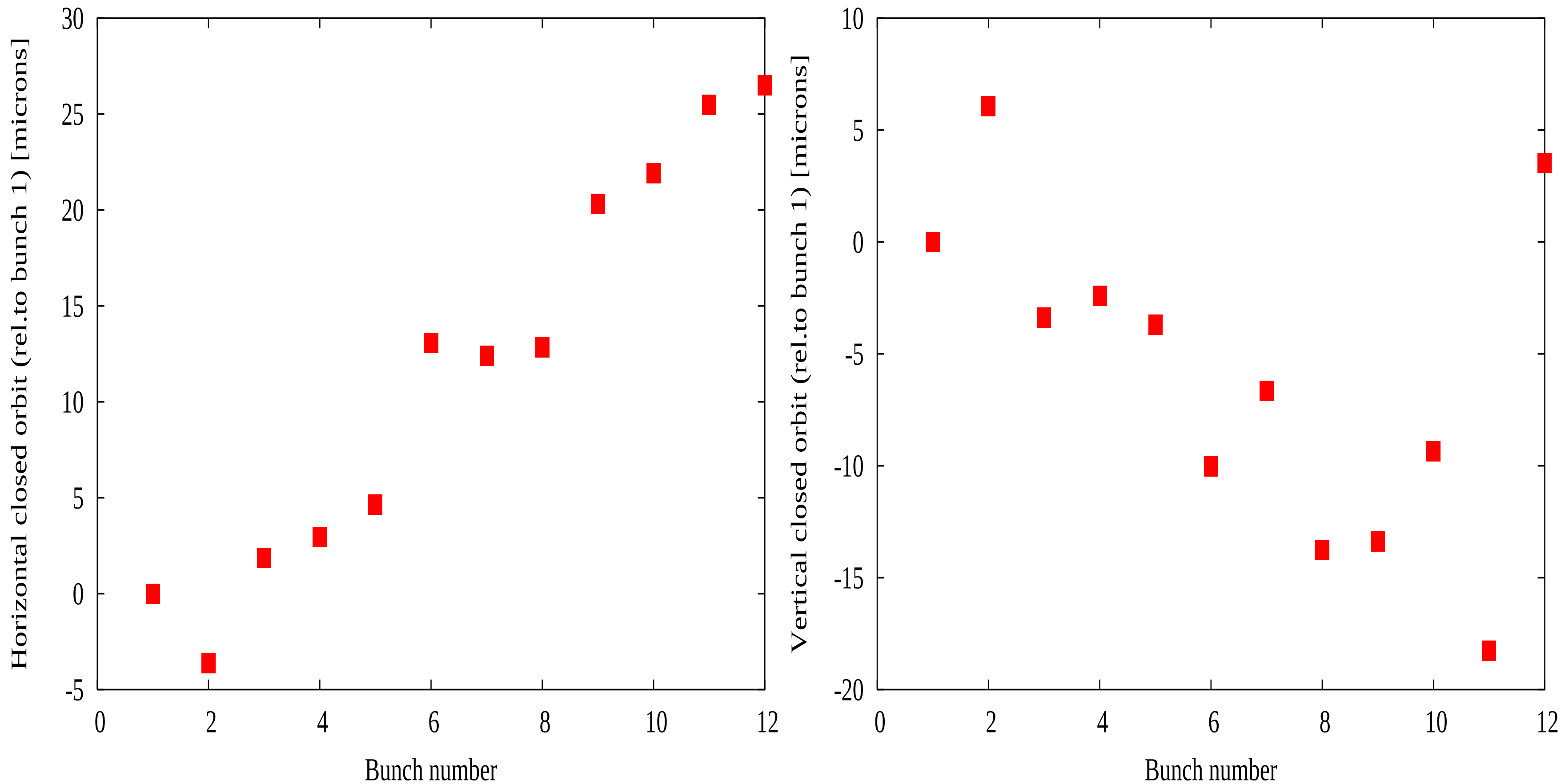
Spread between bunches 2-11: $\Delta\nu_x \sim 0.0015$, $\Delta\nu_y \sim 0.001$.

Small amplitude chromaticities and coupling: Collision



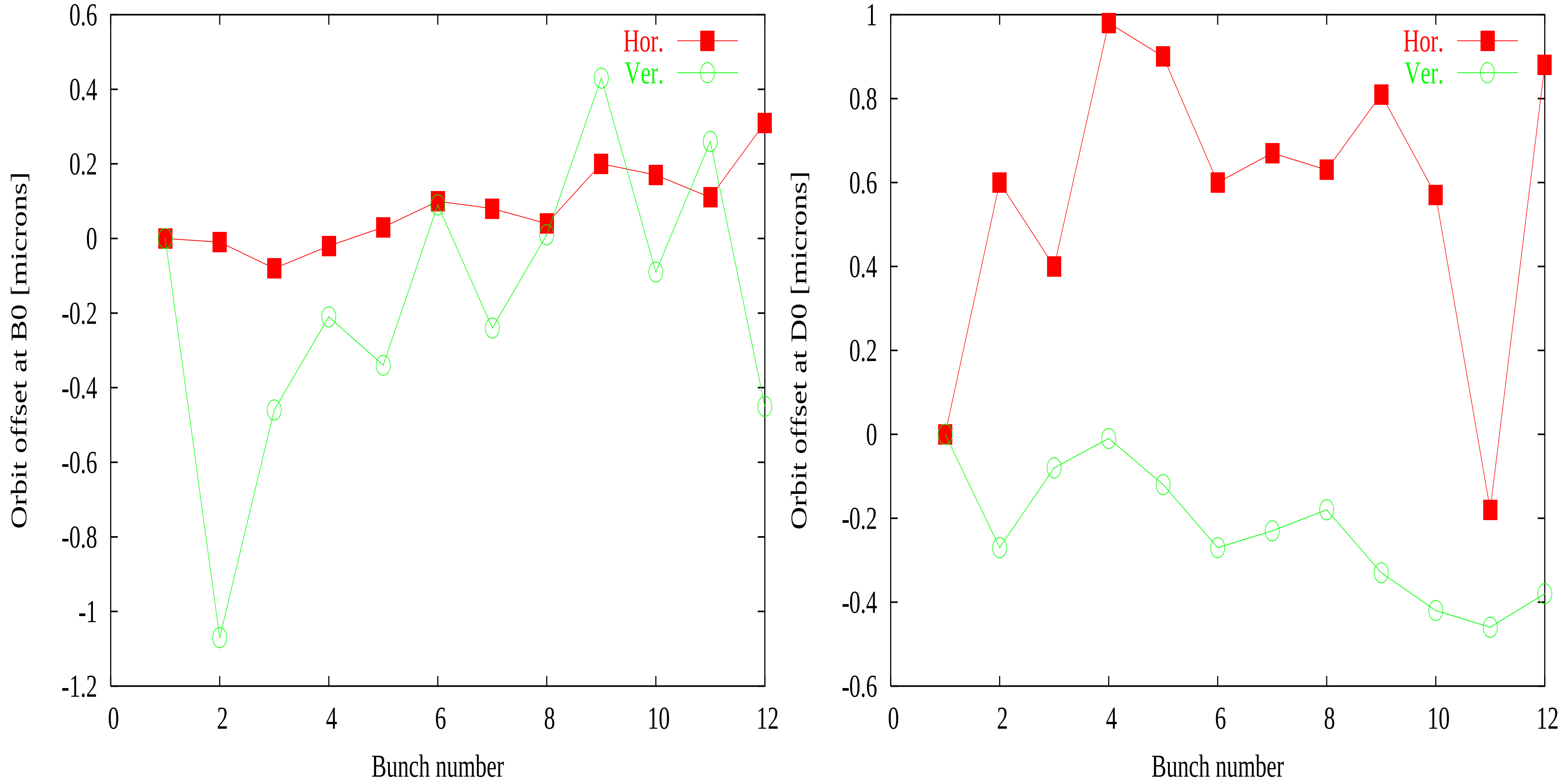


Pbar Closed Orbit Shifts at Sync Light Monitor (980 GeV)

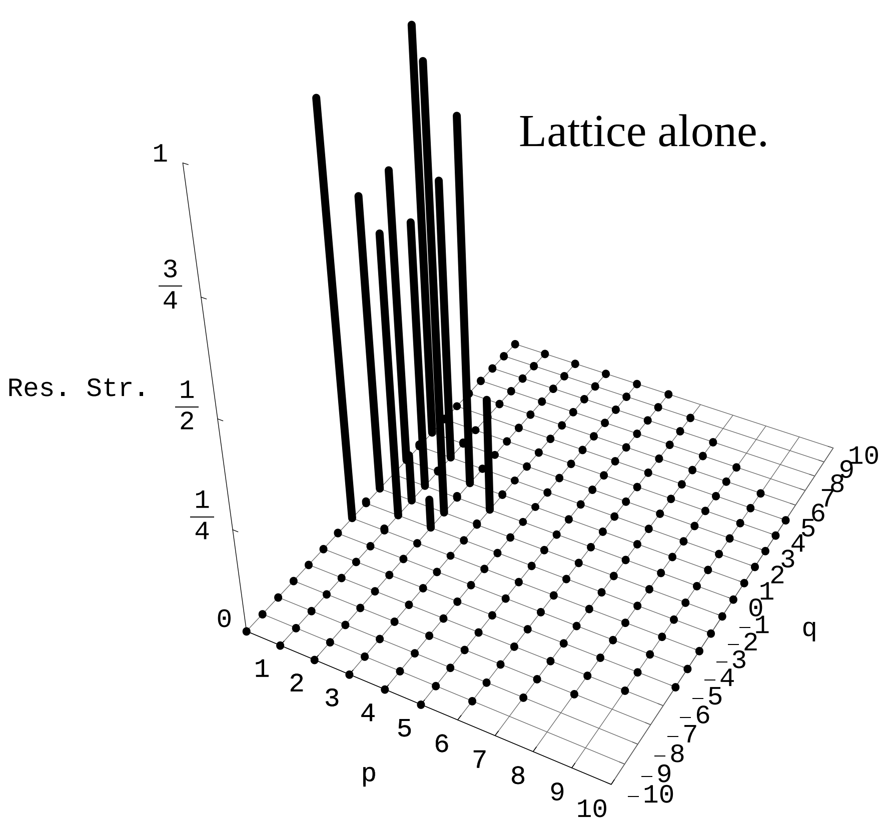


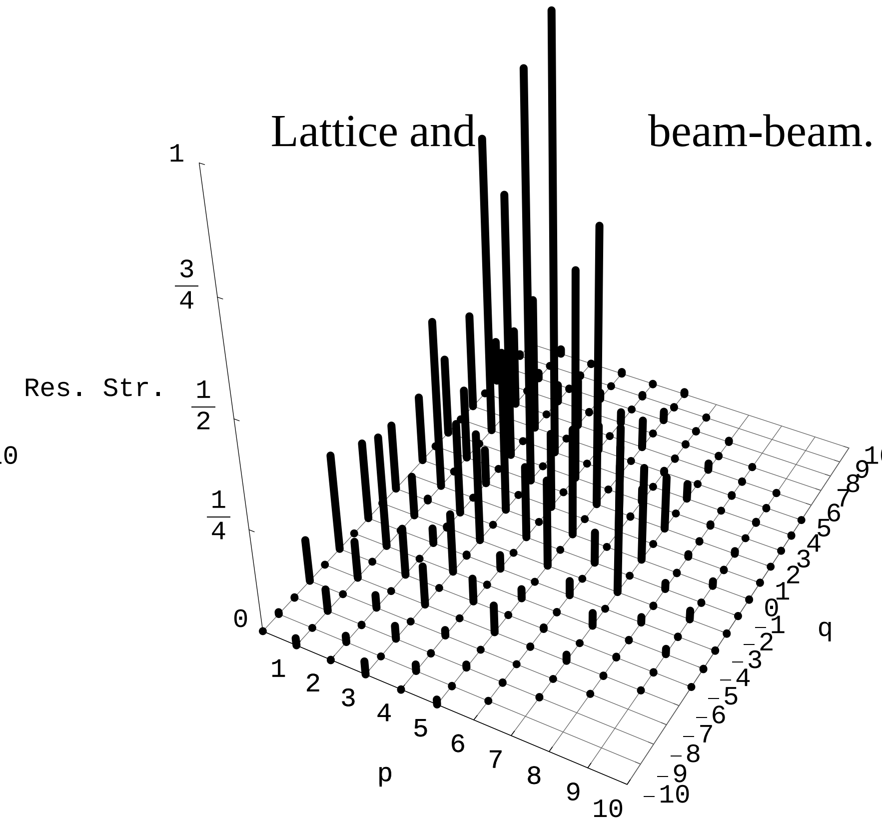
Parameters: $N_p = 210 \times 10^9$, $\epsilon_p = 20\pi$, $\sigma_p(p) = 1.4 \times 10^{-4}$
Lattice functions with all known multipole errors and a_1 error in dipoles.

Pbar Closed Orbit Shifts at B0 and D0 (980 GeV)

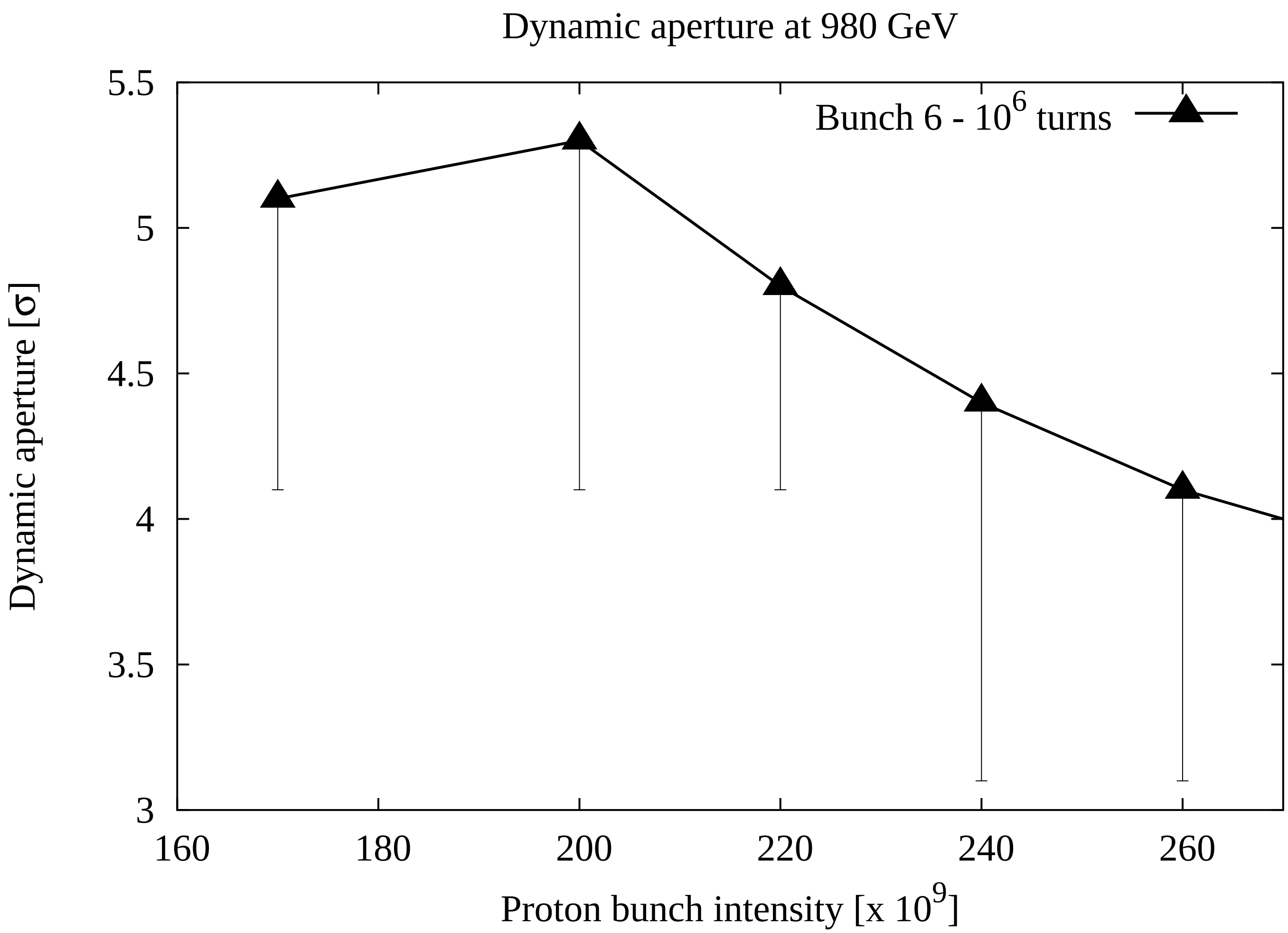


Resonances at Collision

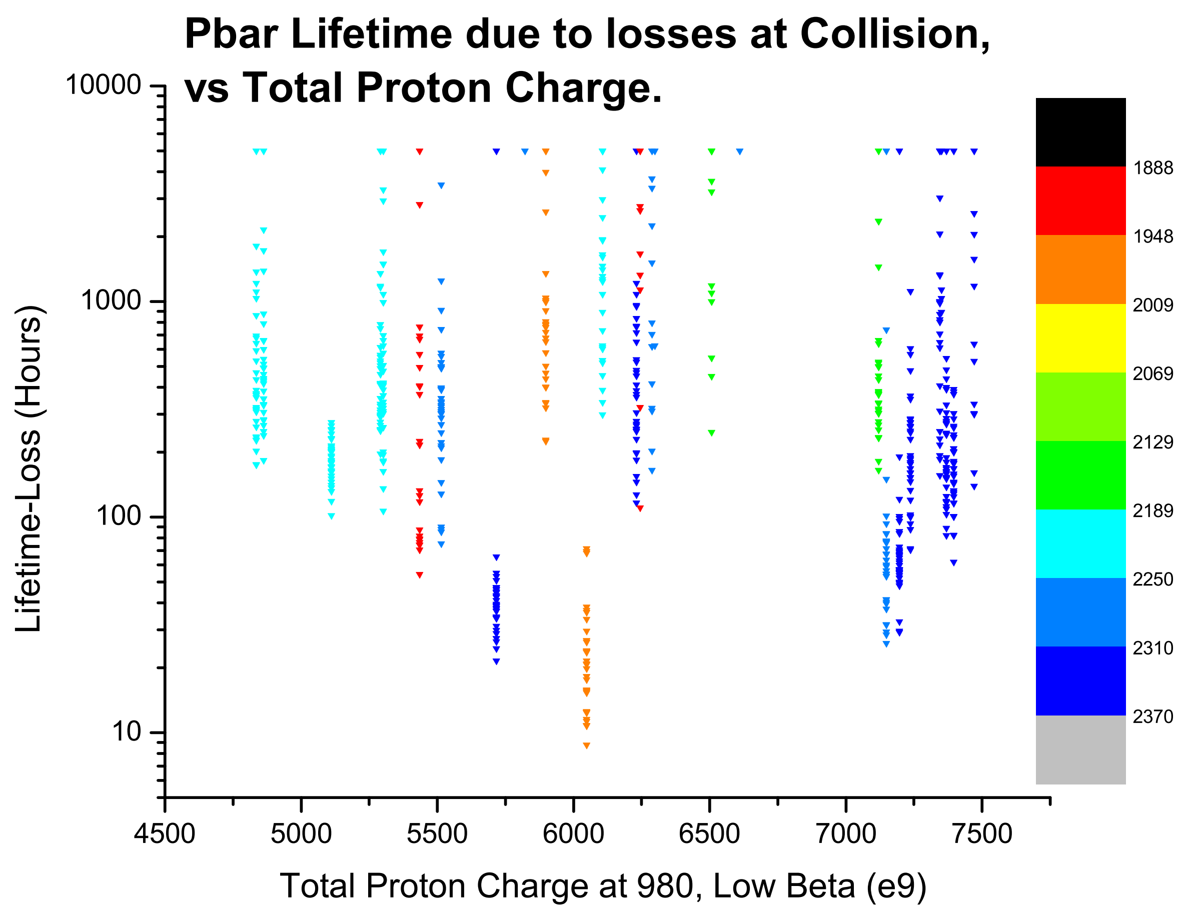




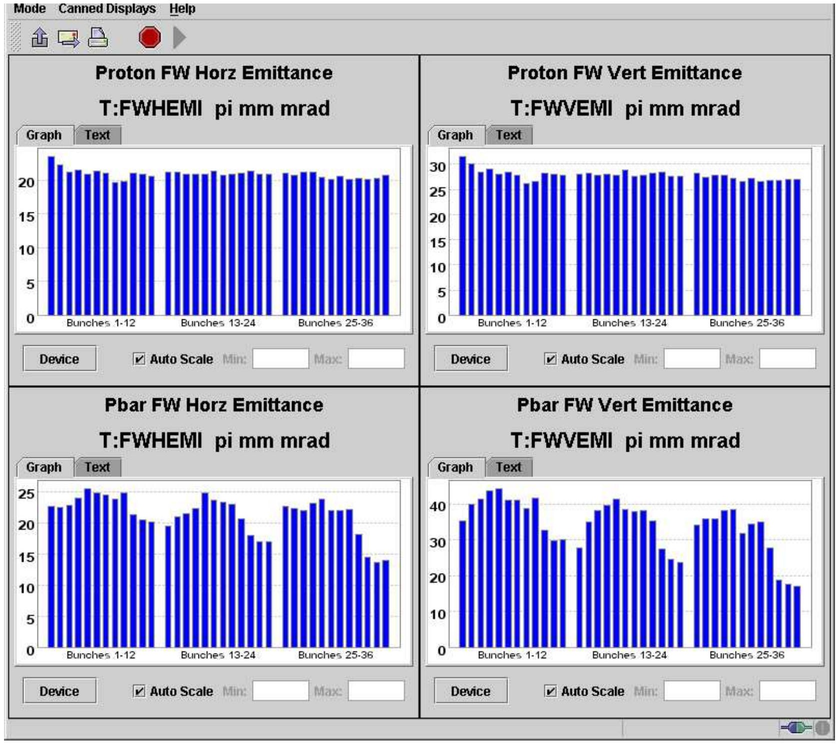
	Resonances (p, q) at 2σ	
	Largest	Others
Lattice driven	(2, -1)	(0, 3), (2, 1), (1, -3), (1,-2), (1, 2)
Lattice and beam-beam driven	(3, 4)	(3, 2), (1, 4), (2, 3), (5, 2), (2, 3)



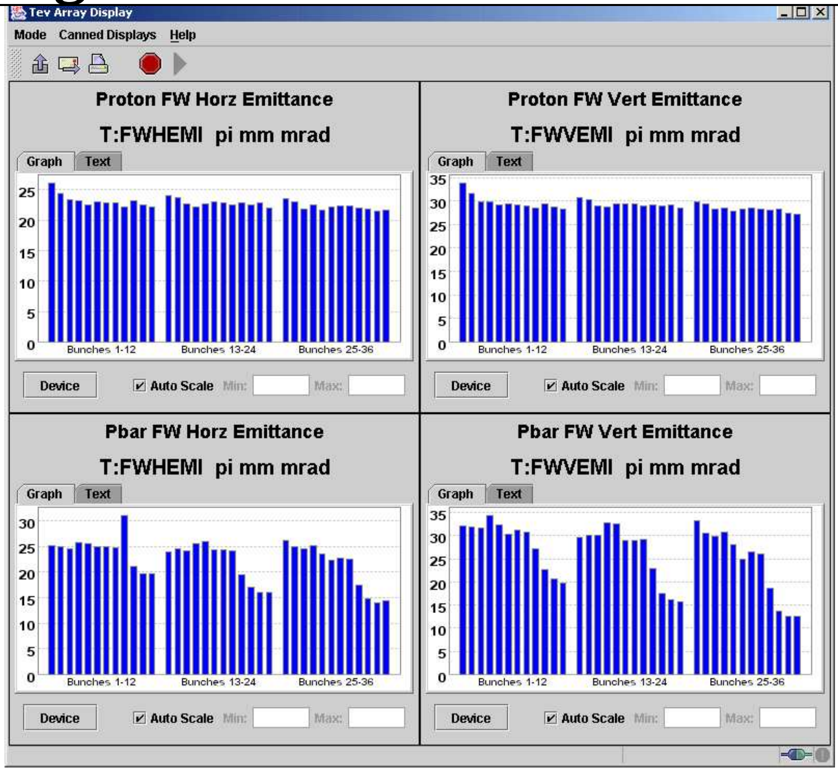
Dynamic aperture at 980 GeV
Bunch 6 - 10^6 turns
Dynamic aperture [σ]
5.5
5
4.5
4
3.5
3
160
180
200
220
240
260
Proton bunch intensity [x 10^9]


Pbar Lifetime due to losses at Collision,
vs Total Proton Charge.
10000
1000
100
10
Lifetime-Loss (Hours)
4500
5000
5500
6000
6500
7000
7500
Total Proton Charge at 980, Low Beta (e9)
1888
1948
2009
2069
2129
2189
2250
2310
2370

Anti-proton emittance growth at Collision

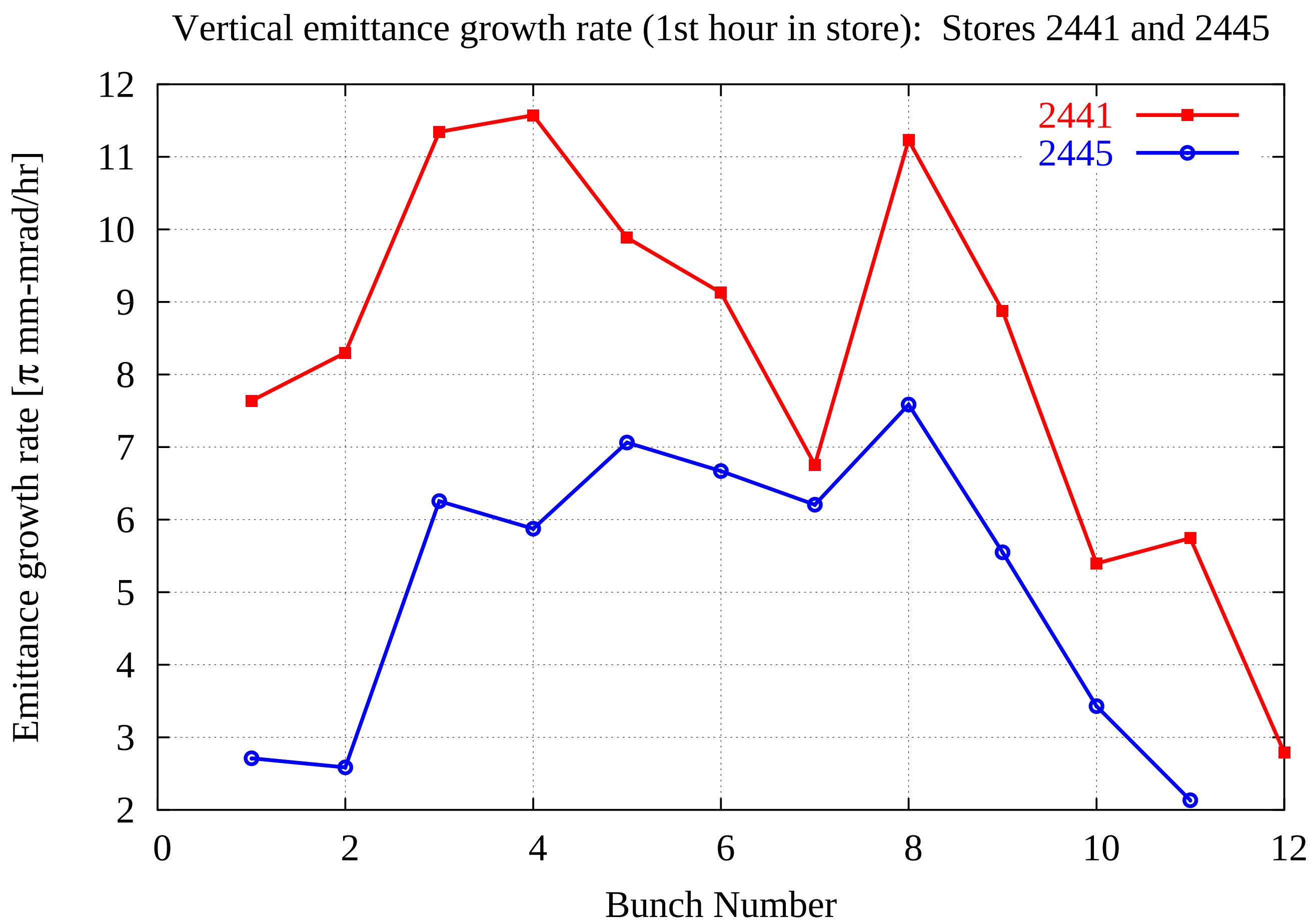


Start of Store 2441.



Start of Store 2445: $\Delta\nu_y$ =- 0.001.

Anti-proton emittance growth at Collision



Vertical emittance growth rates in the two stores.

Status of Beam-beam effects

- **Injection**
  - Limit anti-proton lifetimes to under 10 hrs
  - No significant influence on protons
- **Ramp**
  - Cause about 10% anti-proton losses

    Anti-proton emittance growth during the ramp may be beam-beam related.
  - Not much influence on protons
- **Squeeze**
  - Anti-proton losses are low
  - Proton losses are occasionally vey high - causing quenches.
- **Collision**
  - Anti-proton and proton lifetimes not much affected by beam-beam at present intensities in good stores.
  - Occasionally have large emittance growth of anti-protons at start of store.
  - Proton losses (thought to beam-beam related) can sometimes be higher than acceptable

Improvements

- Increasing the beam separations at all stages.
- Improving the alignment in the Tevatron.
- Smaller beam emittances.
- Operating with lower chromaticities (together with octupoles).
- Improved IR optics, e.g. local decoupling.
- Different bunch patterns.
- Active compensation of beam-beam effects

Backup Slides

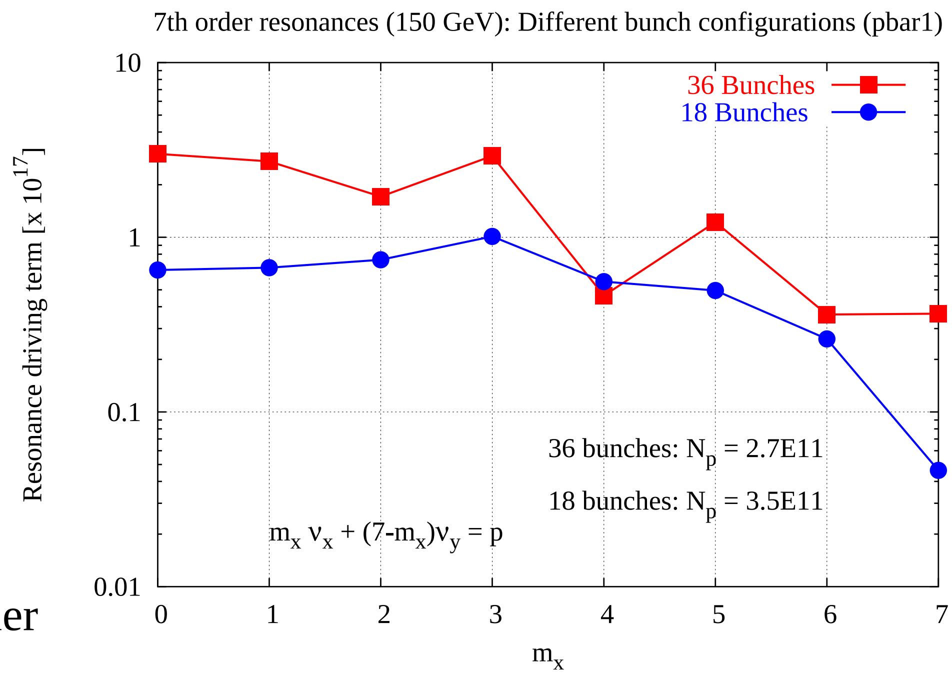
7th Order Resonances with 36 or 18 bunches

- Resonance strengths with 18 bunches were calculated assuming a reasonable maximum proton bunch intensity 3.5×10^{11} that could be injected into the Tevatron.
- Beam-beam driven 7th order resonances are the dominant ones at 150 GeV.
- *The four largest 7th order resonance driving terms with 18 bunches are 2-4 times smaller* than with the 36 bunch configuration for pbar bunch 1.

  The resonance strengths are also similarly smaller for the other pbar bunches.
- Resonance strengths scale linearly with proton intensity.

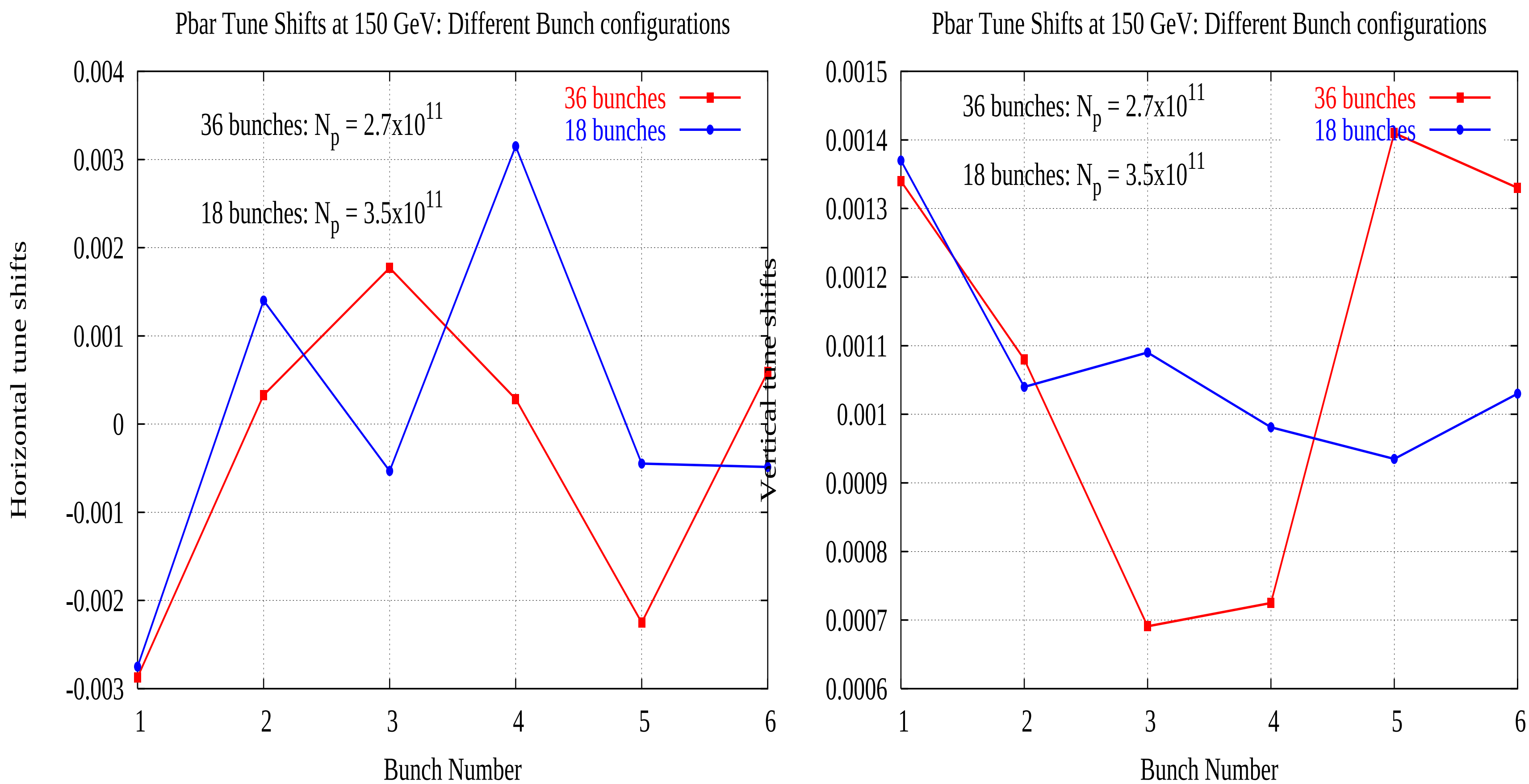
  $\Rightarrow$ Resonance strength ($N_p = 2.7 \times 10^{11}$) = $0.77\times$ Resonance strength ($N_p = 3.5 \times 10^{11}$).

  if all other parameters stay constant.



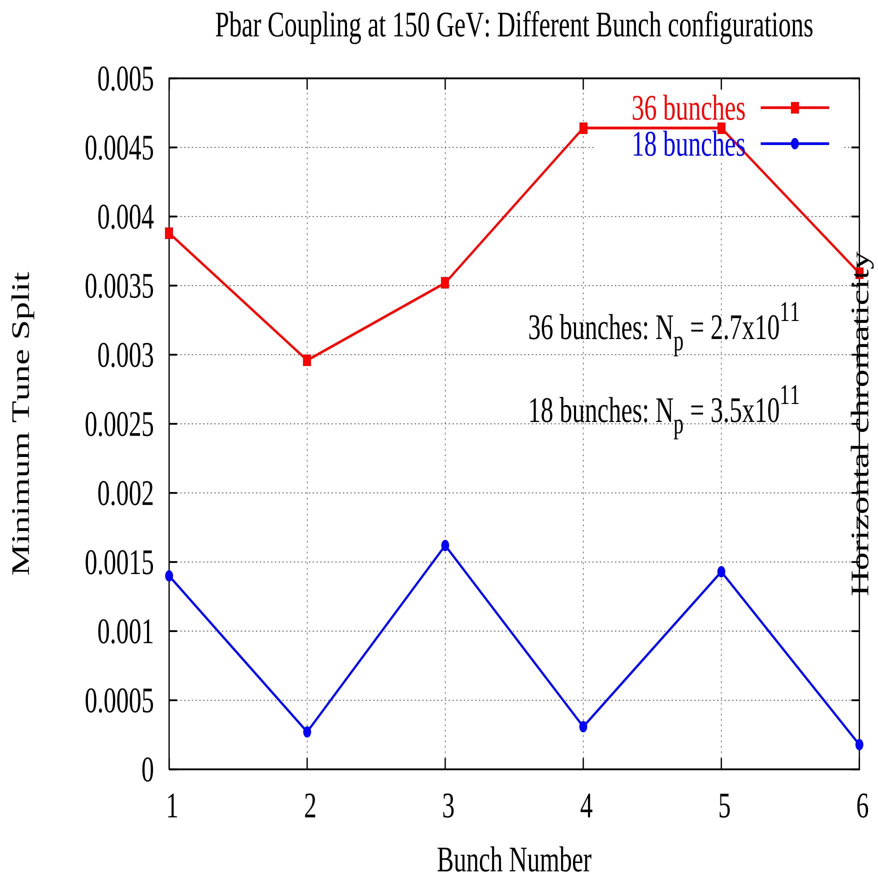
7th order resonance driving terms for pbar bunch 1 with 18 proton bunches compared with 36 proton bunches.

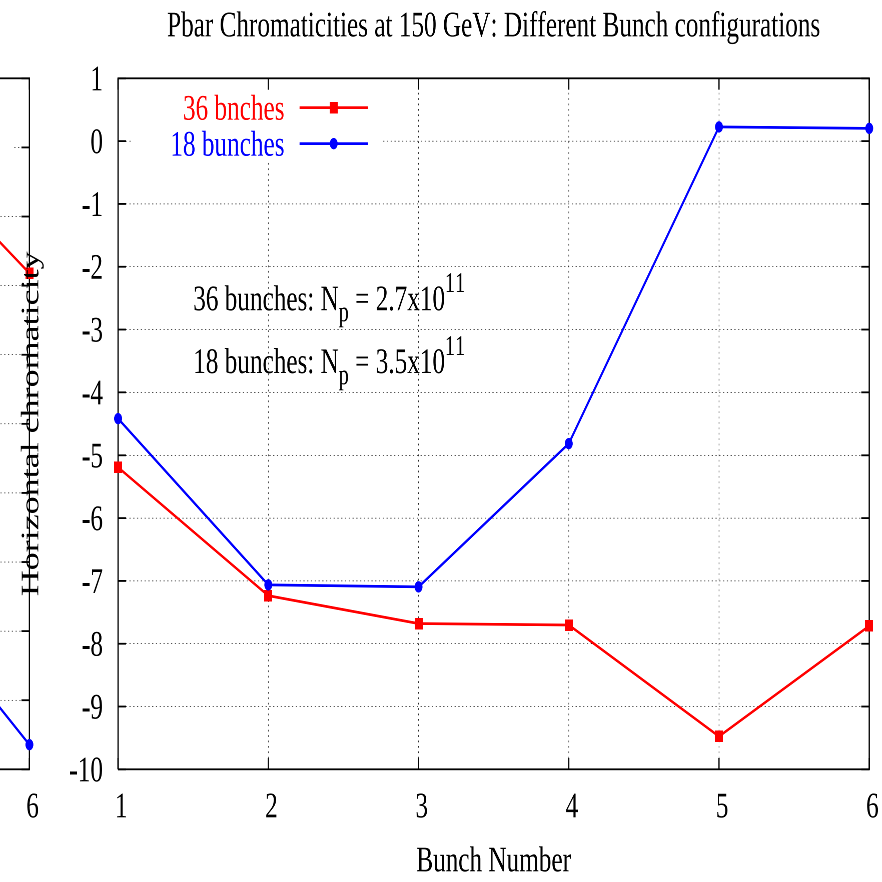
Small amplitude pbar tune shifts: 18 vs 36 bunches (150 GeV)



Bunch by bunch horizontal (left) and vertical (right) tune shifts for the two configurations.

Small amplitude pbar coupling and chromaticity: 18 vs 36 bunches (150 GeV)

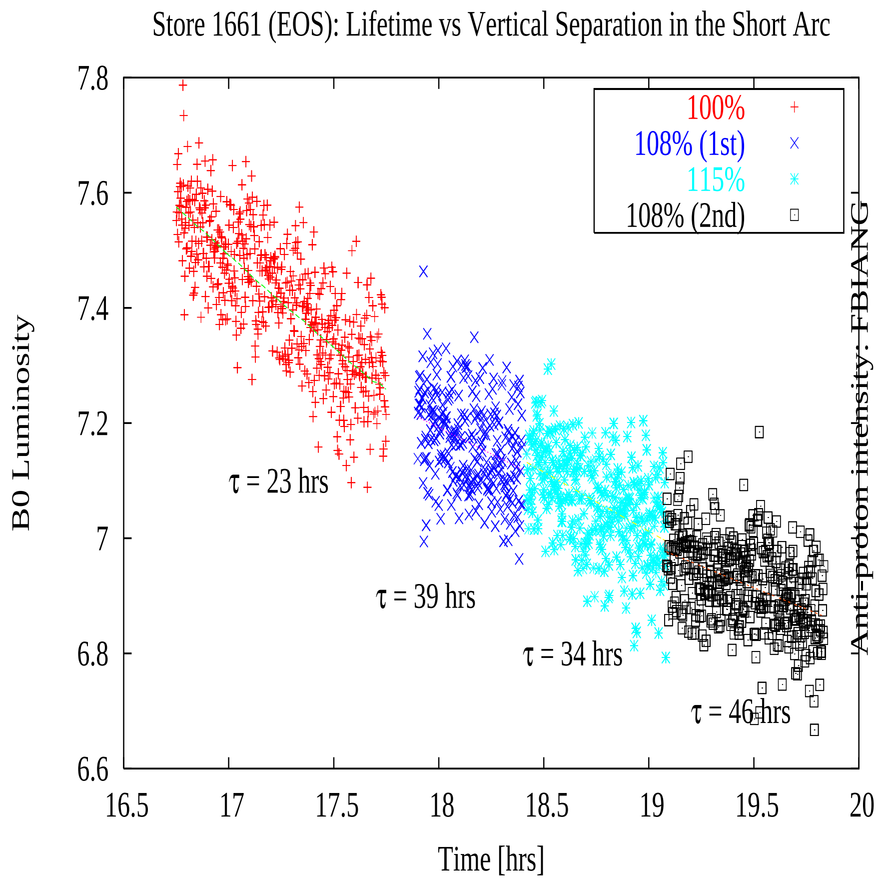


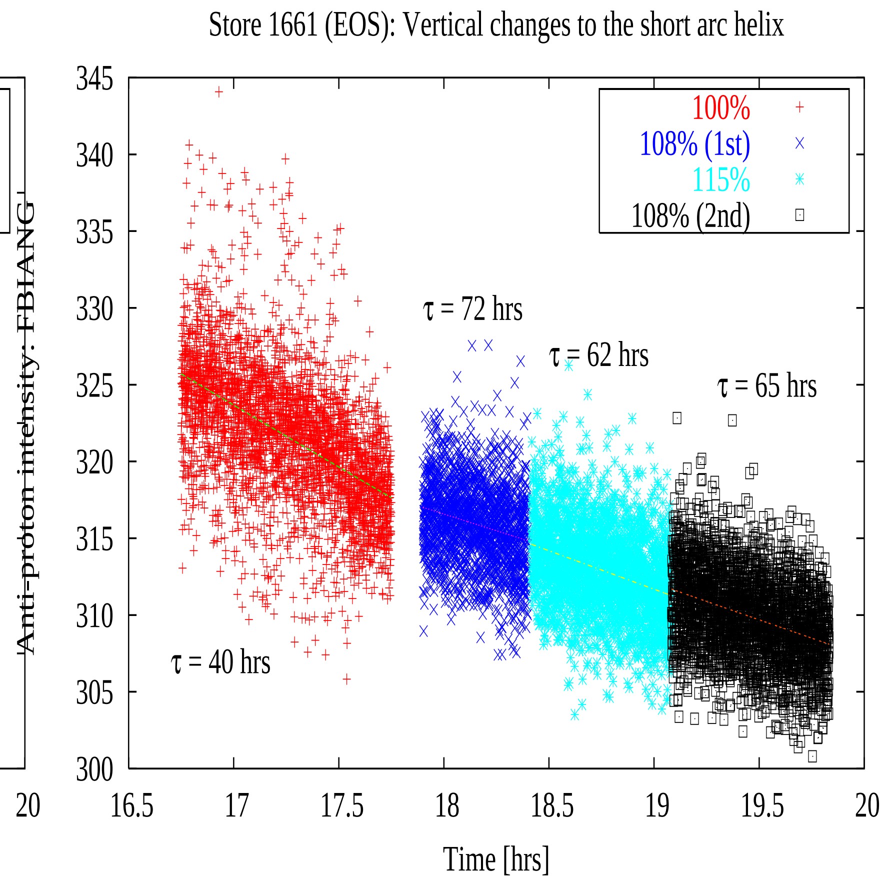


Helix Size at Collision

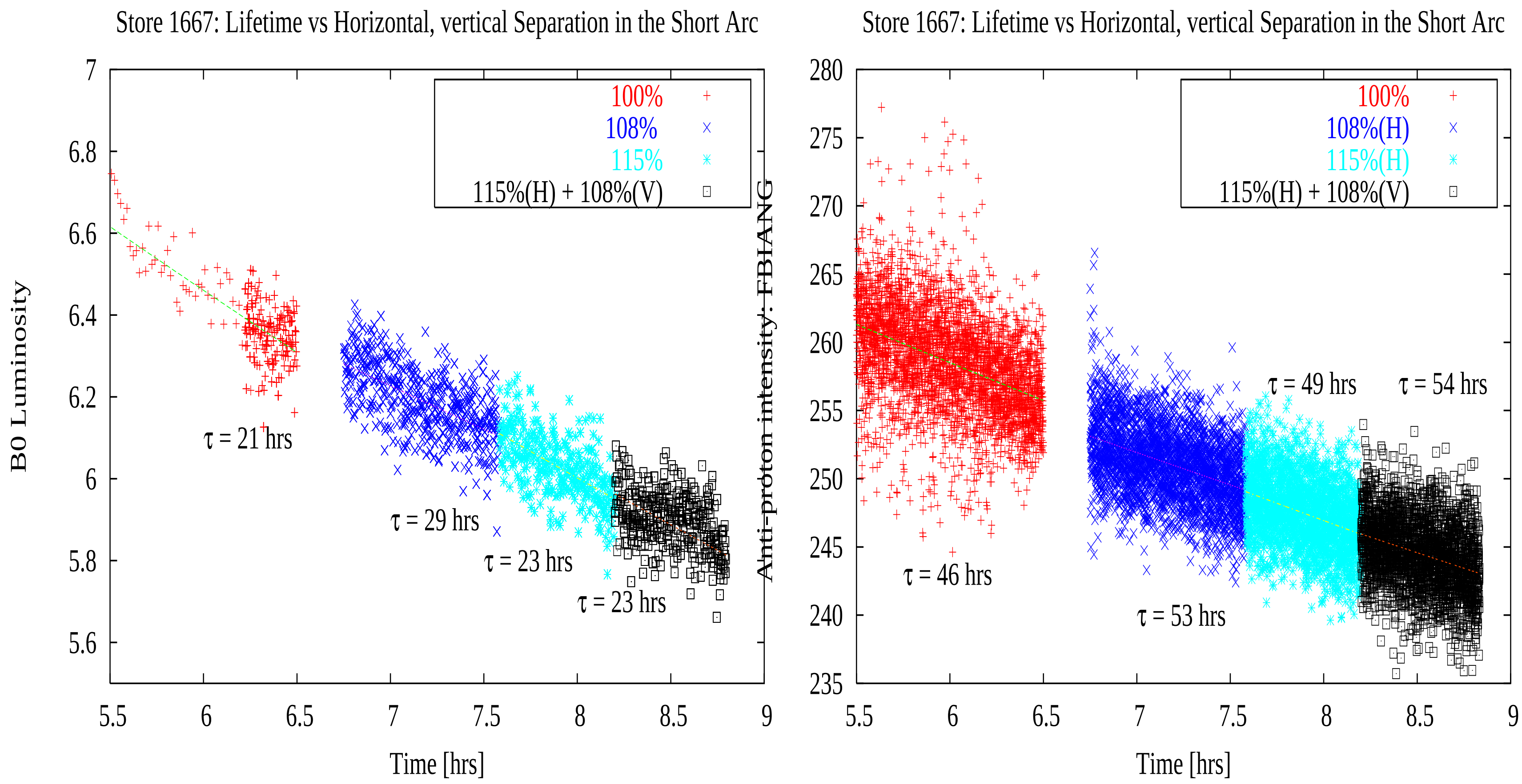
- August 14, 2002: Vertical separations in the short arc increased from 8-15% at the end of Store 1661.
- August 17, 2002: Repeat of August 14th settings and horizontal separations in the short arc increased by 15% at the end of Store 1667.
- September 18, 2002: Increased horizontal separations in the short arc by 8% at the end of Store 1764.
- September 23, 2002: Increased horizontal separations in the short arc by 8% at the *start* of Store 1781.
- March 21, 2003: Varied horizontal and vertical separations in the entire arc at the end of Store 2328.

Store 1661 (EOS): Vertical changes to the short arc helix

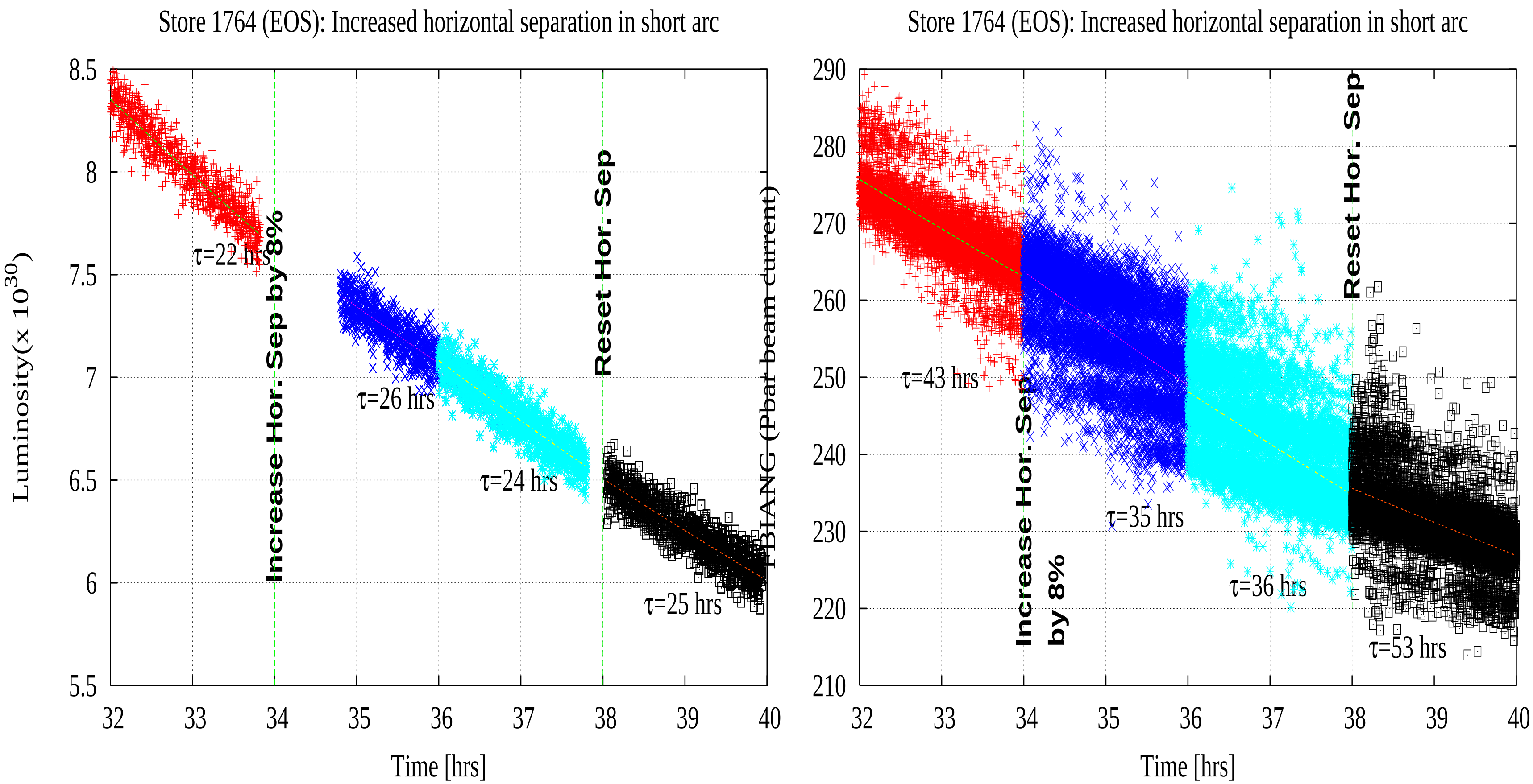




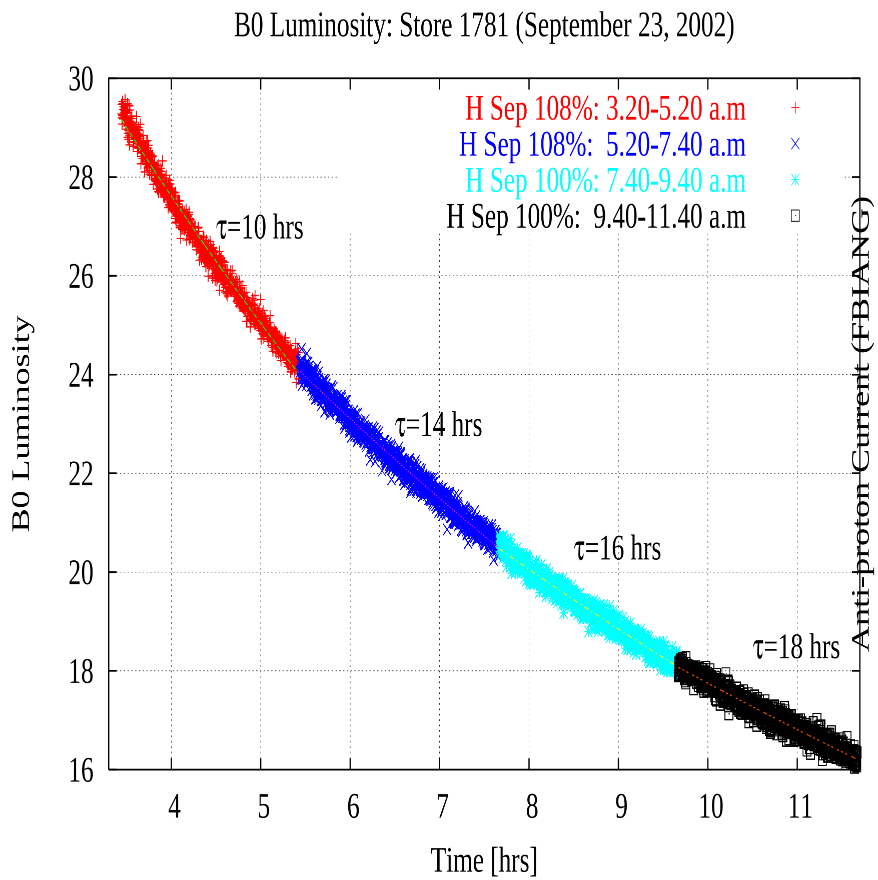
Store 1667 (EOS): Vertical & horizontal changes to the short arc helix

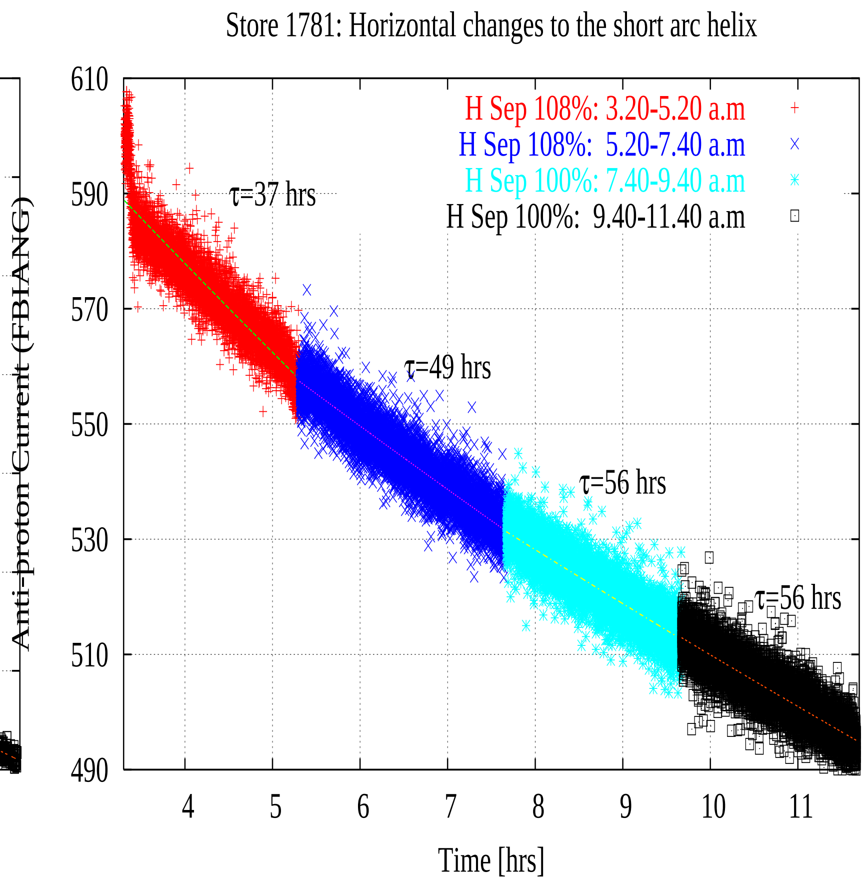


Store 1764 (EOS): Horizontal changes to the short arc helix



Store 1781 (Start of Store): Horizontal changes to the short arc helix





Losses vs Helix Size

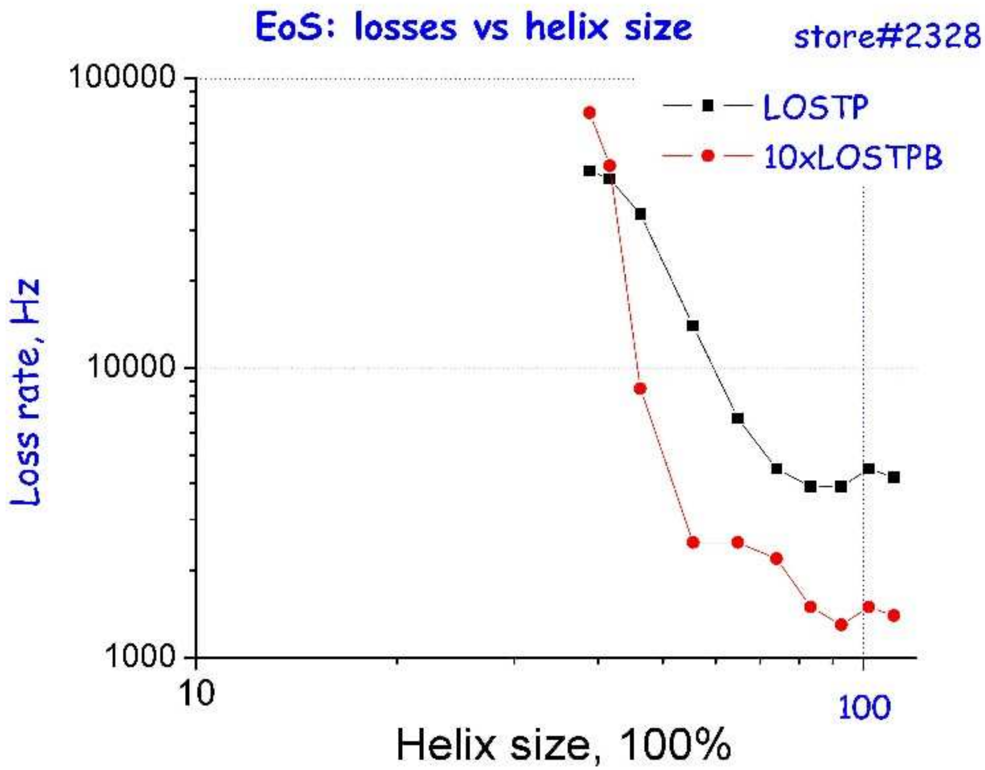


Figure 1: Losses (at end of store) vs helix size.

Losses were observed at the end of a store by changing the helix size in both planes. Increasing the helix size to 10%

$$\tau(p) = 86\text{hrs} \rightarrow 68\text{hrs}$$
$$\tau(\bar{p}) = 43\text{hrs} \rightarrow 33\text{hrs}$$

Decreasing the helix size to 80% of original

$$\tau(p) \rightarrow 141\text{hrs}$$
$$\tau(\bar{p}) \rightarrow 67\text{hrs}$$

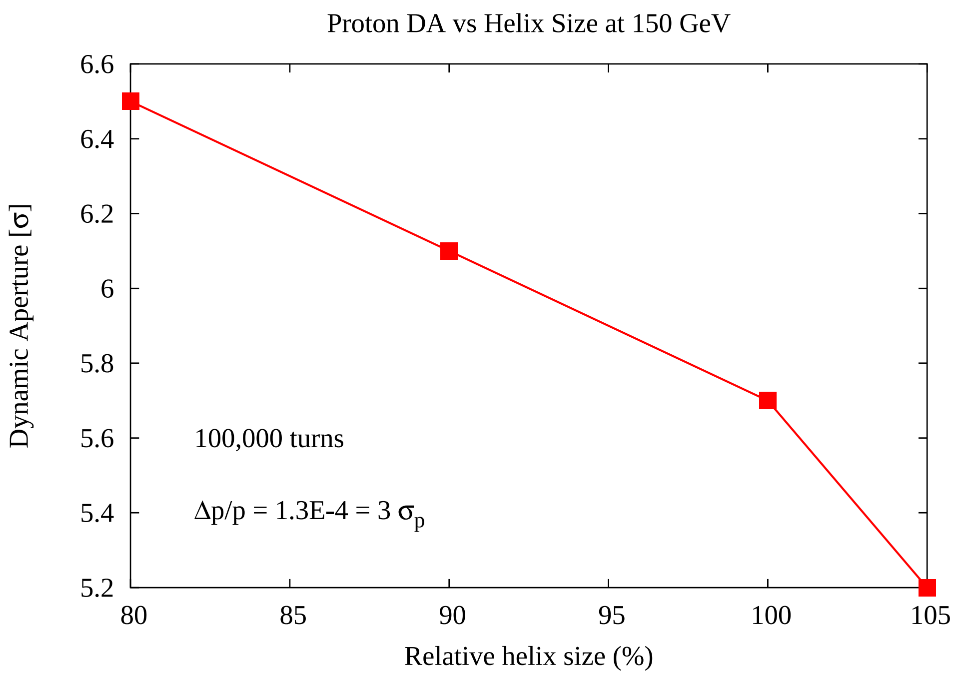
- Emittances did not change much at the end ⇒ tails were lost
- Tunes decreased < 0.002 down to 65% of original helix.

  Sharp losses at the end were likely due to (7th, 12th) order resonances.

Helix Size At Injection

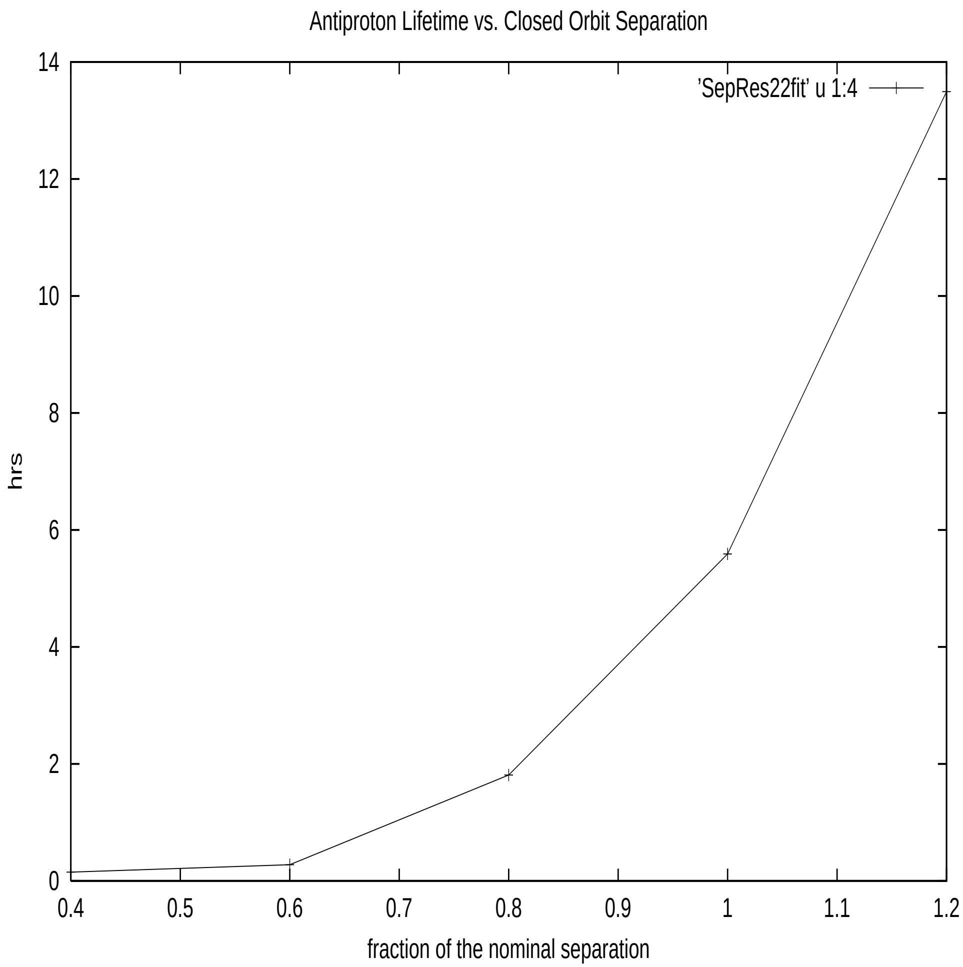
- Proton DA vs helix size
- Anti-proton lifetime vs helix size

Proton Dynamic Aperture vs Helix Size (150 GeV)



- Parameters: $\epsilon = 20\pi$, $\Delta p/p = 1.3 \times 10^{-3} \simeq 3\sigma_p$.
- Dynamic aperture calculated after 100,000 turns. The dynamic aperture of protons increases by nearly 1σ when the helix is reduced from 100% to 80%.
- The chaotic border (estimator of long-term stability) is estimated to be 4.7σ for the 80% helix and 3.9σ for the 100% helix.
- This calculation suggests that reducing the helix to 80% would have an observable beneficial impact on the *proton* lifetime at injection.

Anti-proton lifetime simulation vs Helix Size (150 GeV)



- Simulation by J. Qiang (LBNL) using his code BeamBeam3D with 10^6 particles followed for 10^5 turns (2 seconds in the Tevatron).
- Random noise is included to simulate beam-gas scattering.
- The only nonlinearities are the long-range beam-beam interactions. No machine nonlinearities.
- Proton parameters: $N_p = 2.2{\times}10^{11}$, $\epsilon = 25\pi$, $\Delta p/p = 7 \times 10^{-4}$. Machine chromaticities: $Q'_x = 2$, $Q'_y = 8$.
- The physical aperture is fixed at 3.25σ.
- This simulation shows that decreasing the aperture from 100% to 80% of its present value would reduce the anti-proton lifetime by more than a factor of two.