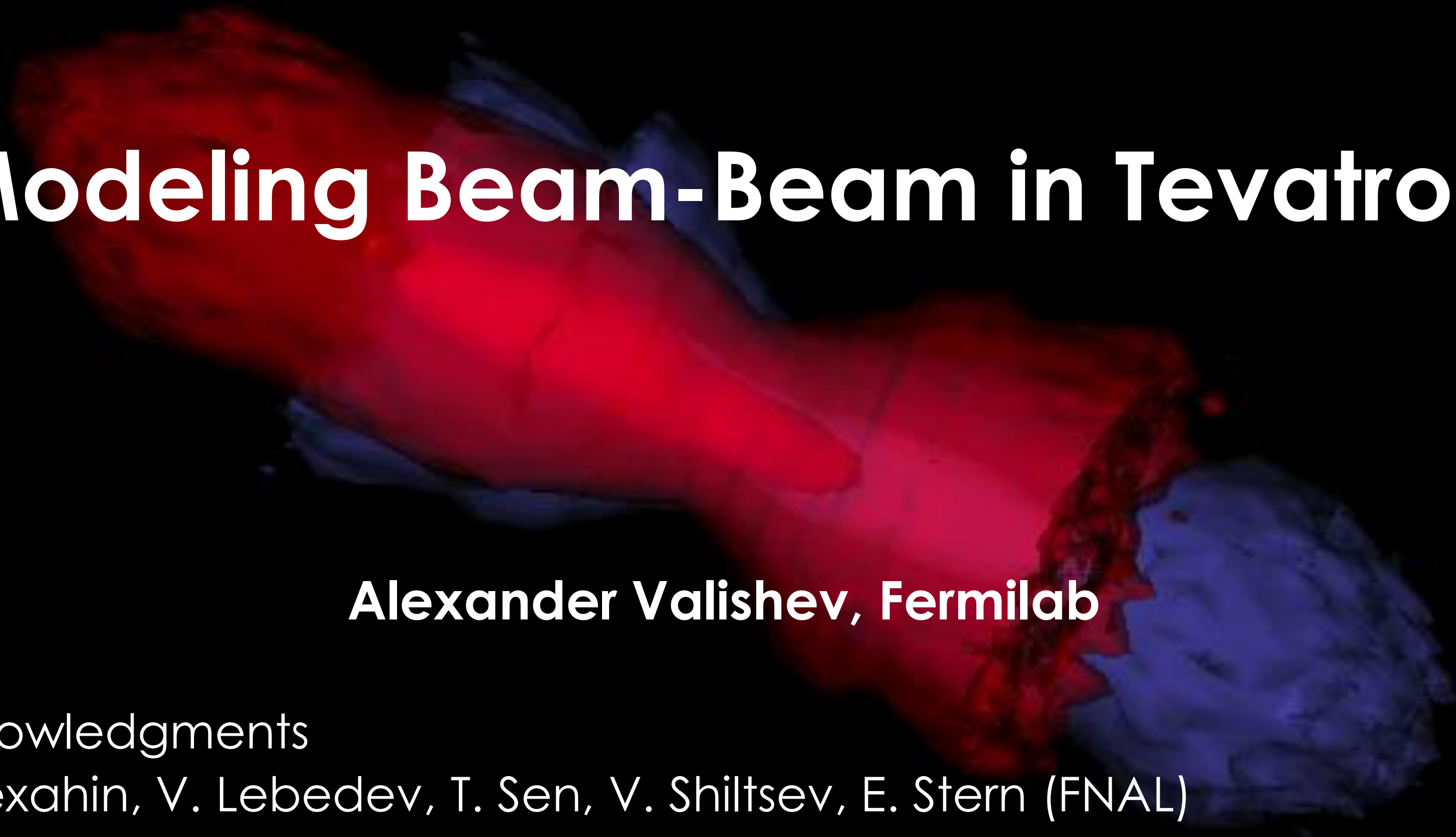

Modeling Beam-Beam in Tevatron

Alexander Valishev, Fermilab

Acknowledgments
Y. Alexahin, V. Lebedev, T. Sen, V. Shiltsev, E. Stern (FNAL)
D. Shatilov (BINP)

March 19, 2013
ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders

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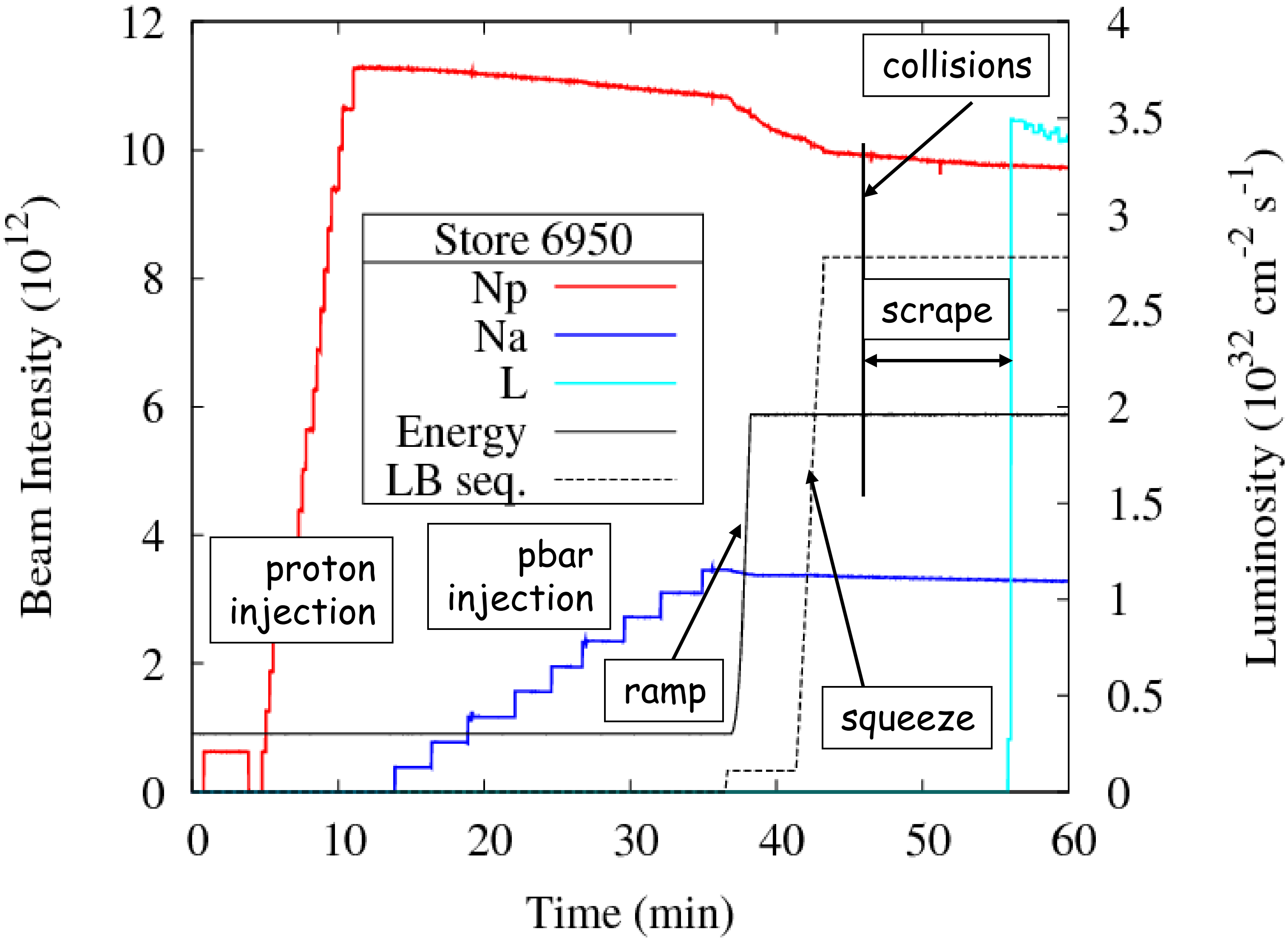
Outline

- Pre-Run II and early Run II
- Analytical models
- Luminosity modeling
- Weak-strong simulations
- Strong-strong simulations

Typical Collider Cycle $L_0 = 3.5 \times 10^{32}$



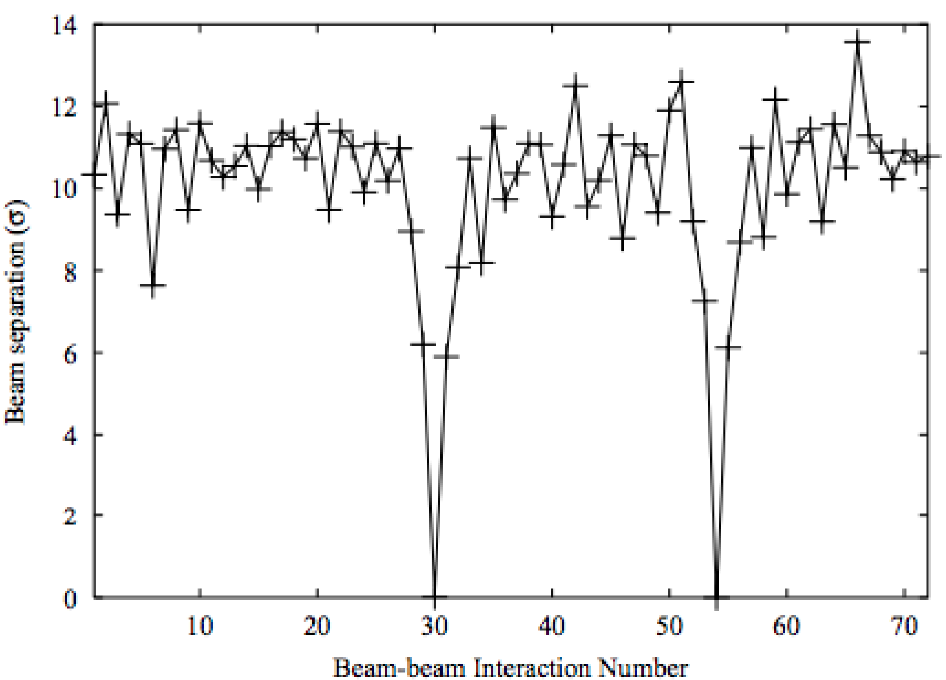
Run Ib to Run II – 6 bunches to 36

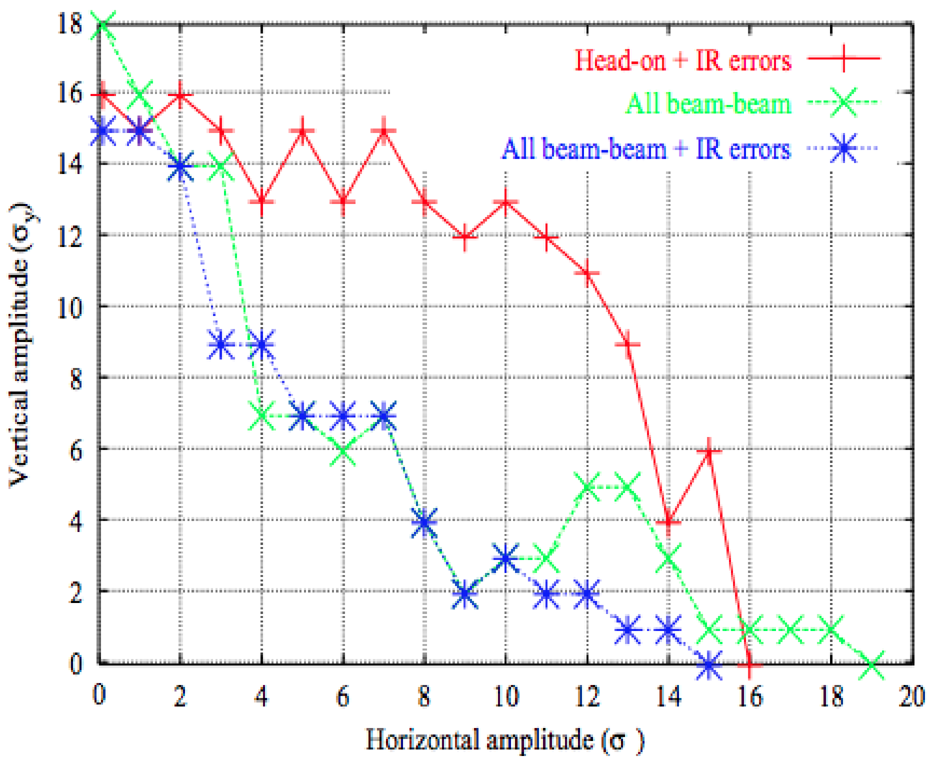
	Run Ib $p/\bar{p}$	Run IIa $p/\bar{p}$
Luminosity [$cm^{-2}sec^{-1}$]	1.6×10^{31}	8.6×10^{31}
Bunch Intensities $\times10^{11}$	(2.3/0.55)	(2.7/0.3)
Emittances 95% [mm-mrad]	23/13	20/15
Number of bunches	6	36
Bunch separation [m]	1049.3	118.8
Beam size at IP [μm]	37/28	33/29
Beam-beam parameter/IP $\times10^{-3}$	3.4/7.4	1.5/9.9

- In Run IIb the number of bunches was to increase >100 because it was expected the experiments would be unable to sustain pileup above 0.85×10^{32}
- Planned weak-strong operation, ξa=0.02, ξp=0.003

Run Ib to Run II – 6 bunches to 36

- The significance of 70 long-range interactions for antiproton lifetime was recognized (T. Sen et al, PAC'01)
- Simulated weak-strong DA~8σ at $\Delta p/p=0$, expected DA<6σ for realistic conditions





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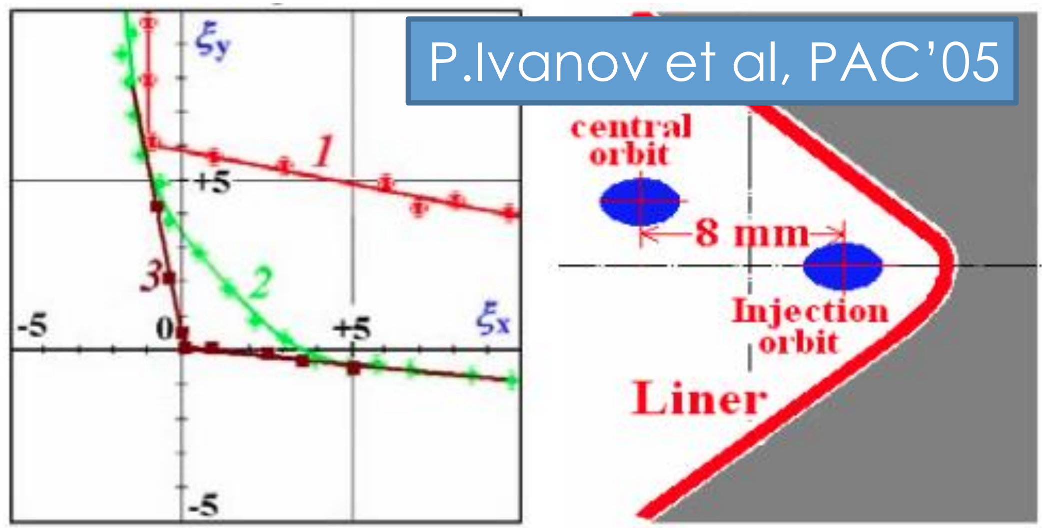
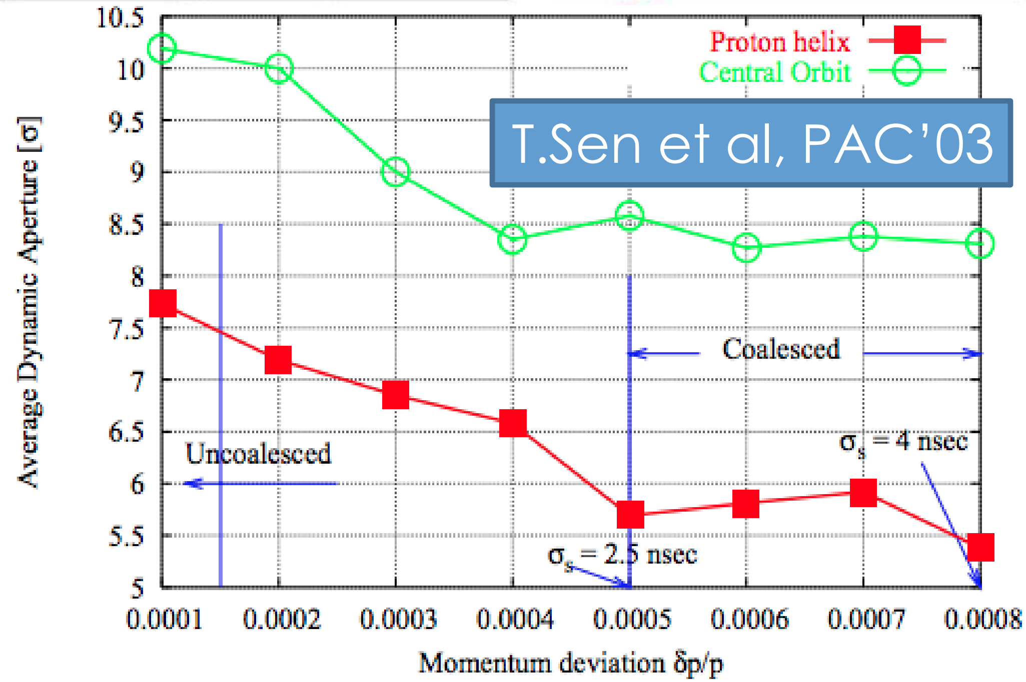
Proton Lifetime at Injection Energy

- Proton losses during pbar injections were a significant limiting factor early in Run II
- Simulations identified that a combination of strong sextupoles and long-range interactions reduced DA
- How one relates DA to lifetime or emittance growth? Nevertheless:
  - Sextupole strength was lowered owing to reduction of impedance
  - Helical orbits were rearranged to improve long-range





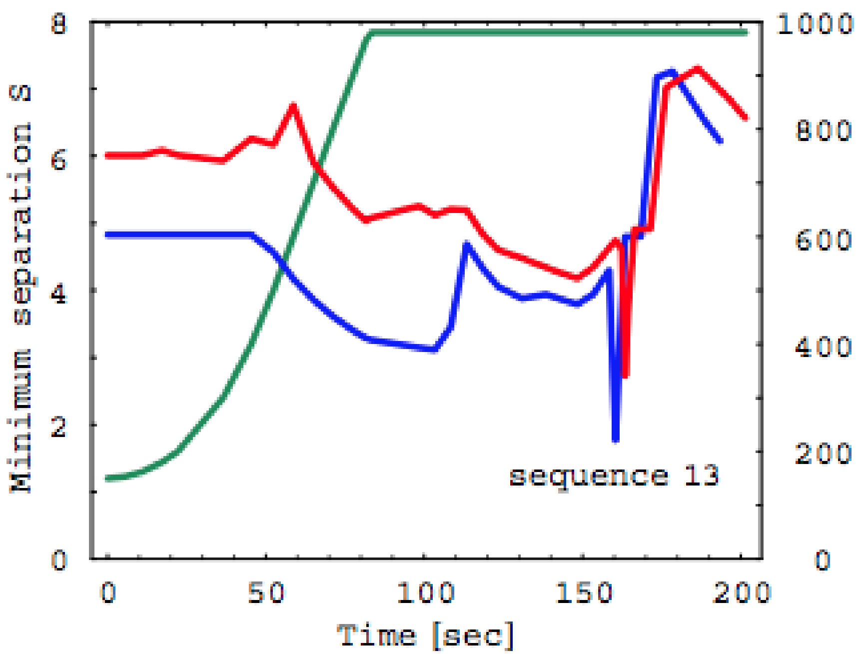
Analytical Models

- Bunch-by-bunch orbit, tune, coupling, chromaticity due to beam-beam

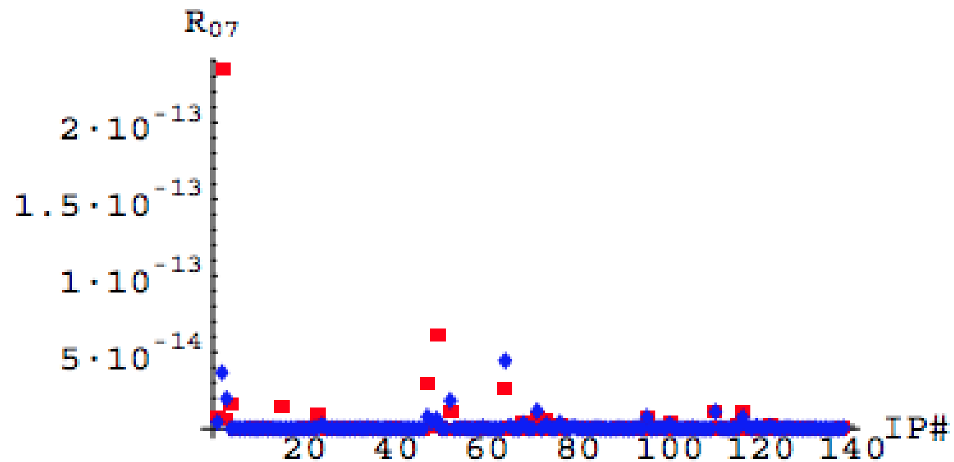
- Resonance Driving Terms. 7th order and 12th order RDTs were used as criteria for optimization of
  - Helical orbits
  - Proton working point

$$|R_{bb}^{(m,n)}| \approx \frac{r_p N}{\pi\gamma}\frac{(m-1)!}{2^{m/2}m_x!m_y!}\frac{\sigma_{x\beta}^{m_x}\sigma_{y\beta}^{m_y}}{(d_y^2+d_x^2)^{m/2}}\times$$

$$I_x^{\frac{m_x}{2}} I_y^{\frac{m_y}{2}} \left| \begin{Bmatrix} \sin \\ \cos \end{Bmatrix} (m \arctan\frac{d_y}{d_x}) \right|$$



Y.Alexahin, PAC'07



Beam-Beam in Overall Picture

- Beam-beam is not the single effect determining the evolution of luminosity. Tevatron luminosity lifetime was significantly affected by
  - Luminous particle losses
  - Intrabeam scattering
  - Beam-gas scattering
  - Noise
- Tevatron strived to extract every % of potential integrated luminosity from beams delivered by injectors
- A comprehensive model of luminosity evolution was necessary to understand the quantitative significance of beam-beam effects

Luminosity Evolution Model

- The model of luminosity evolution makes use of finite-step numerical integration of a system of equations for bunch intensities and emittances of the two beams
- No fitting of luminosity to predefined function – the 'ultimate' luminosity integral is predicted based on initial values of beam intensities and emittances
  - model parameters e.g. noise strength were measured in beam studies
- Deviation from this 'ultimate' luminosity quantifies the strength of beam-beam effects

$$\frac{d\varepsilon_x}{dt} = -\frac{2\varepsilon_x}{\tau_{SRx}} + \frac{d\varepsilon_{xSR}}{dt} + \frac{d\varepsilon_{xIBS}}{dt} + \frac{d\varepsilon_{xBB}}{dt} + \frac{d\varepsilon_{xExt}}{dt}$$

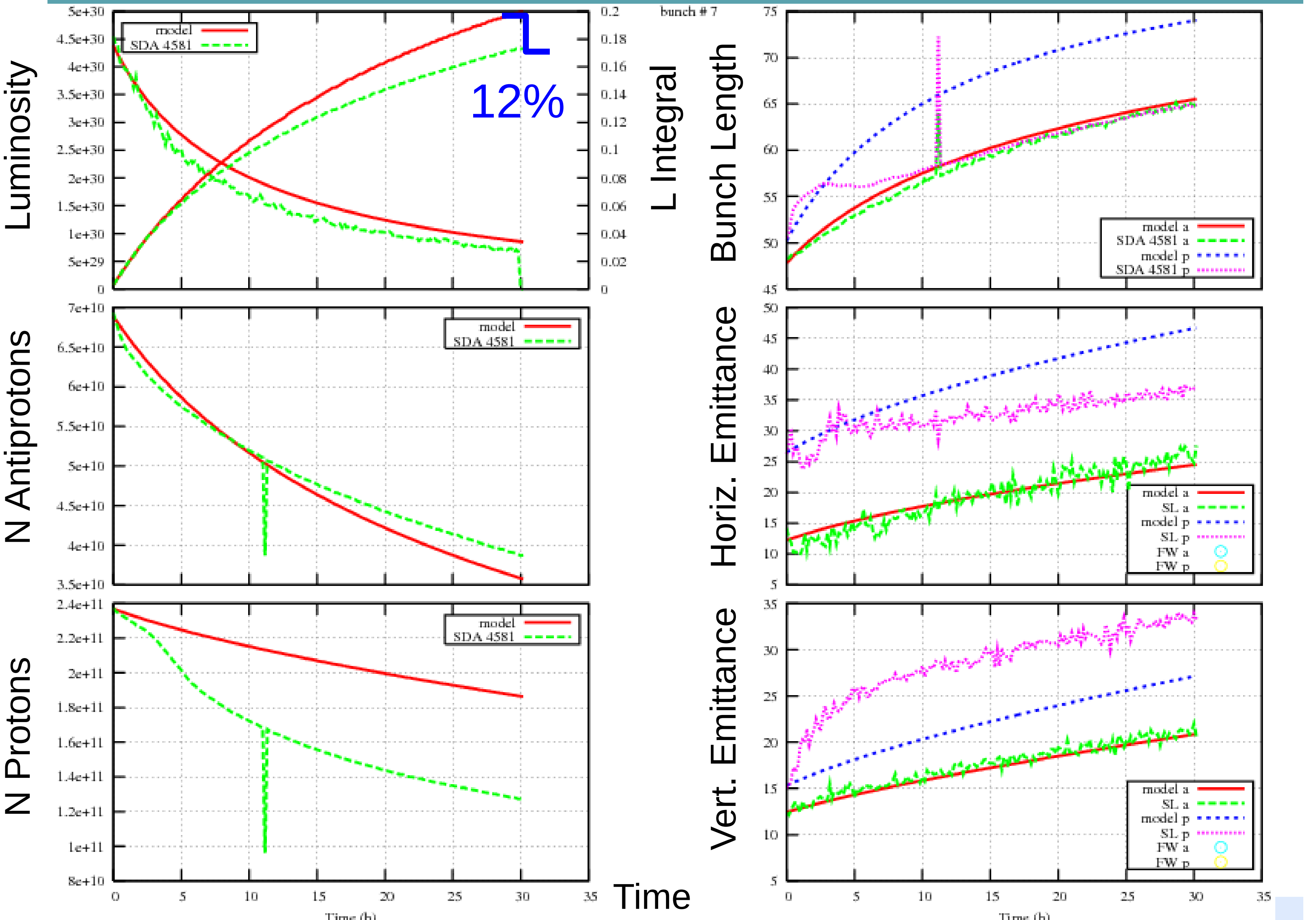
$$\frac{d\varepsilon_y}{dt} = -\frac{2\varepsilon_y}{\tau_{SRy}} + \frac{d\varepsilon_{ySR}}{dt} + \frac{d\varepsilon_{yIBS}}{dt} + \frac{d\varepsilon_{yBB}}{dt} + \frac{d\varepsilon_{yExt}}{dt}$$

$$\frac{d\sigma_E^2}{dt} = -\frac{2\sigma_E^2}{\tau_{SRE}} + \frac{d\sigma_{SR}^2}{dt} + \frac{d\sigma_{IBS}^2}{dt} + \frac{d\sigma_{BB}^2}{dt}$$

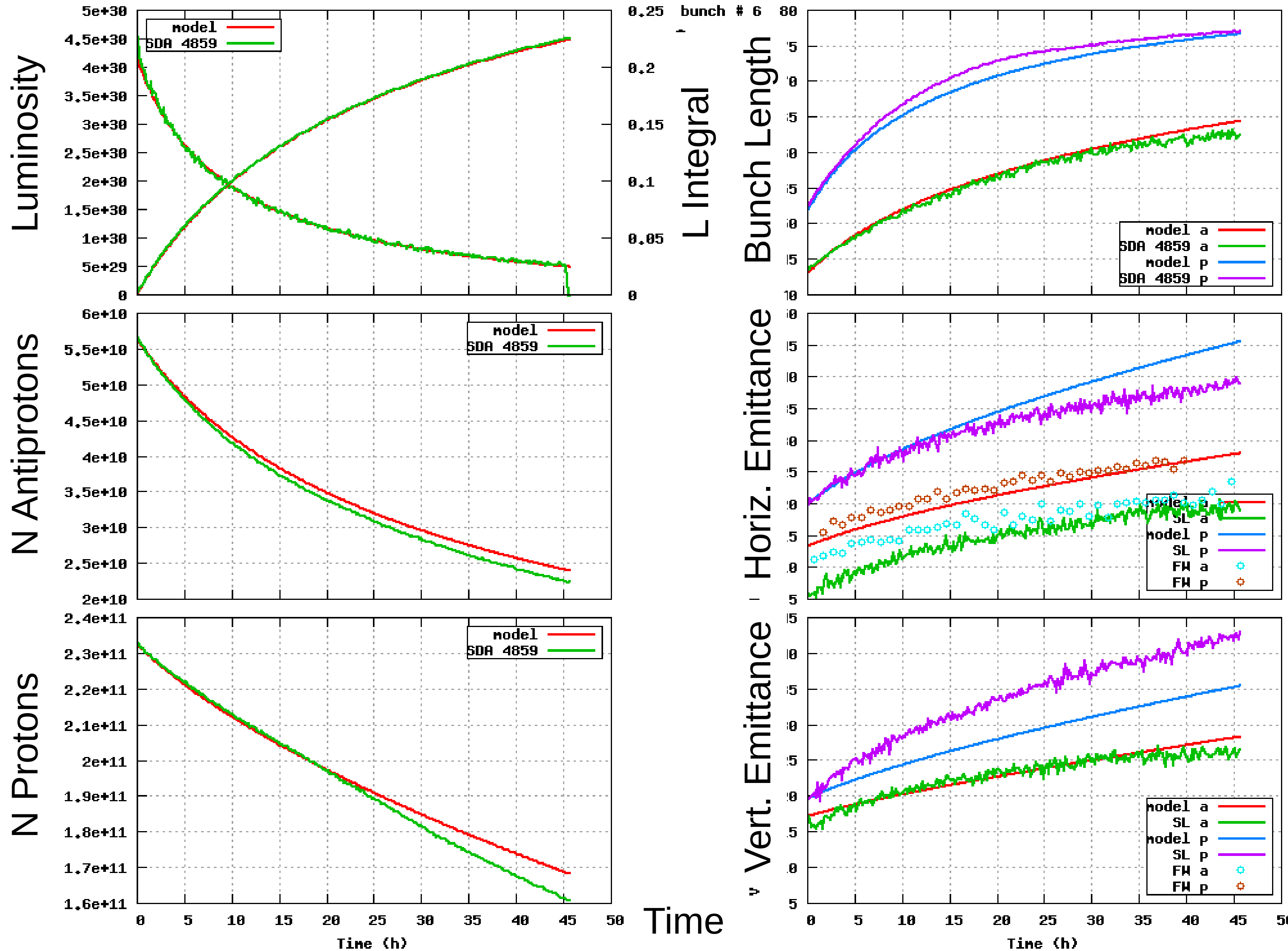
$$\frac{dN}{dt} = -N_{IP}\frac{L}{N_b}\sigma_{tot} - \frac{N}{\tau_{Ext}}$$

V.Lebedev, PAC'03

Store 4581, L_0=1.72x10^{32} Old Helix



Store 4859, L_0=1.70x10^{32} New Helix



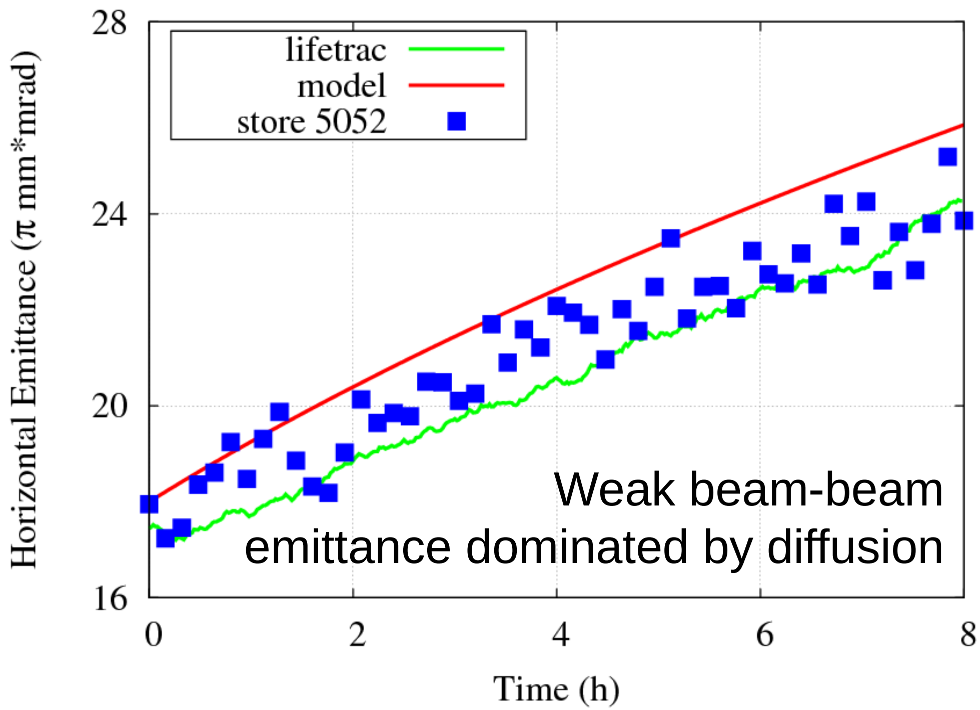
Lifetrac Weak-Strong Simulations

- Weak-strong, Gaussian strong bunch
- Macro-particle weak bunch, typically 10000 particles
  - Average over large number of turns to improve statistics
- Full details of the measured machine optics, beam separation, and collision pattern with all 72 IPs
- Effect of noise/diffusion
- Parallel, capable to simulate up to 10^8 turns
- ‘Measurable’ quantities – emittances and beam life time

D. Shatilov et al, PAC’05

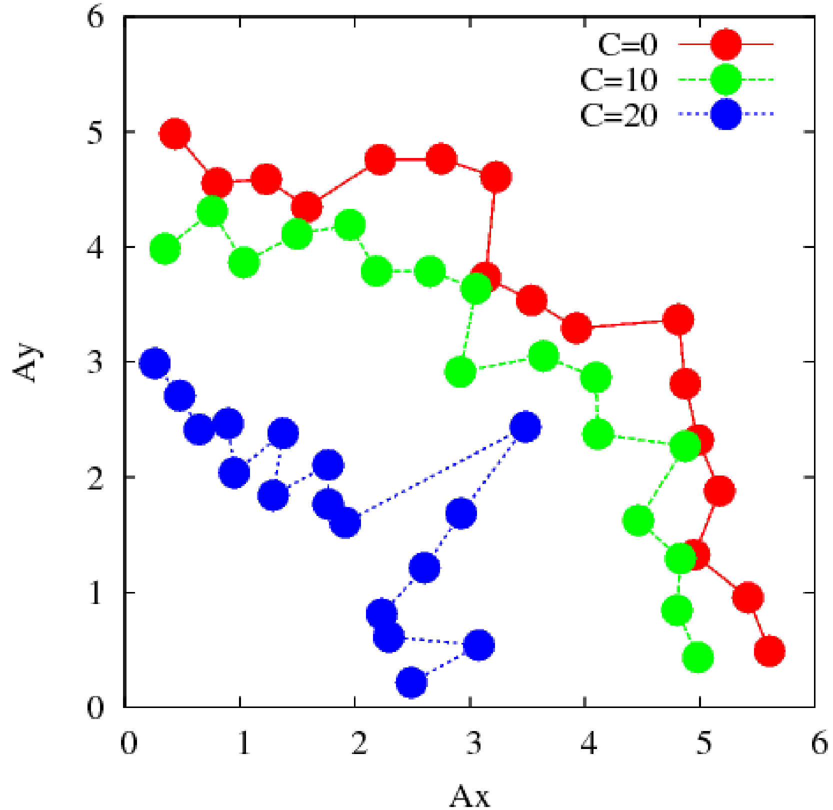
Model Cross Check

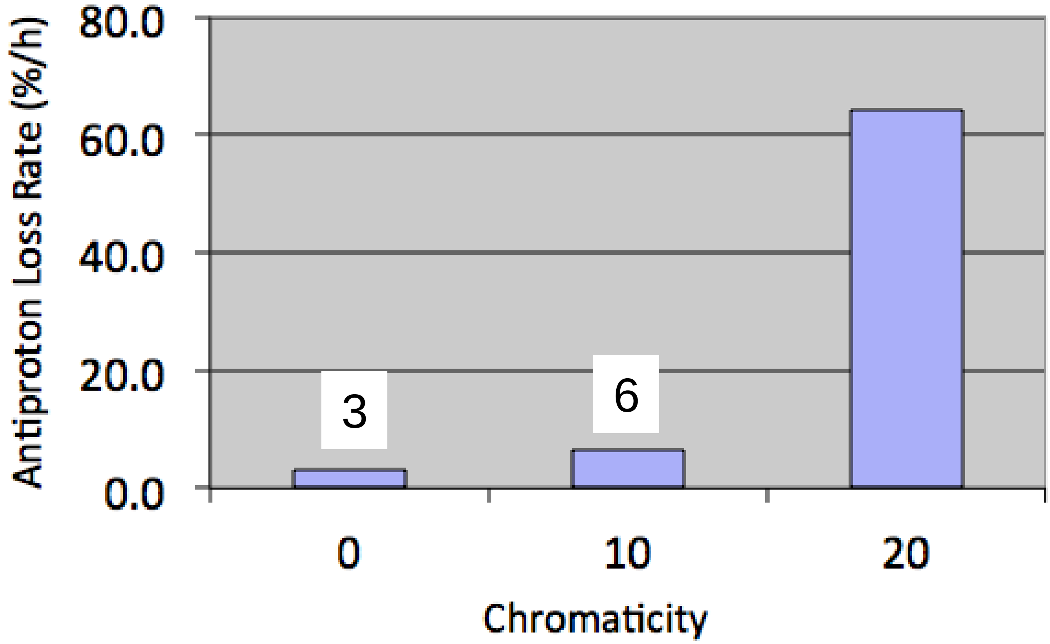
- Interaction of beam-beam with extrinsic diffusion is non-trivial.
- External noise provides particle transport in the regions of the phase space which are free from resonance islands



- Proper simulation of emittance growth requires both beam-beam and diffusion

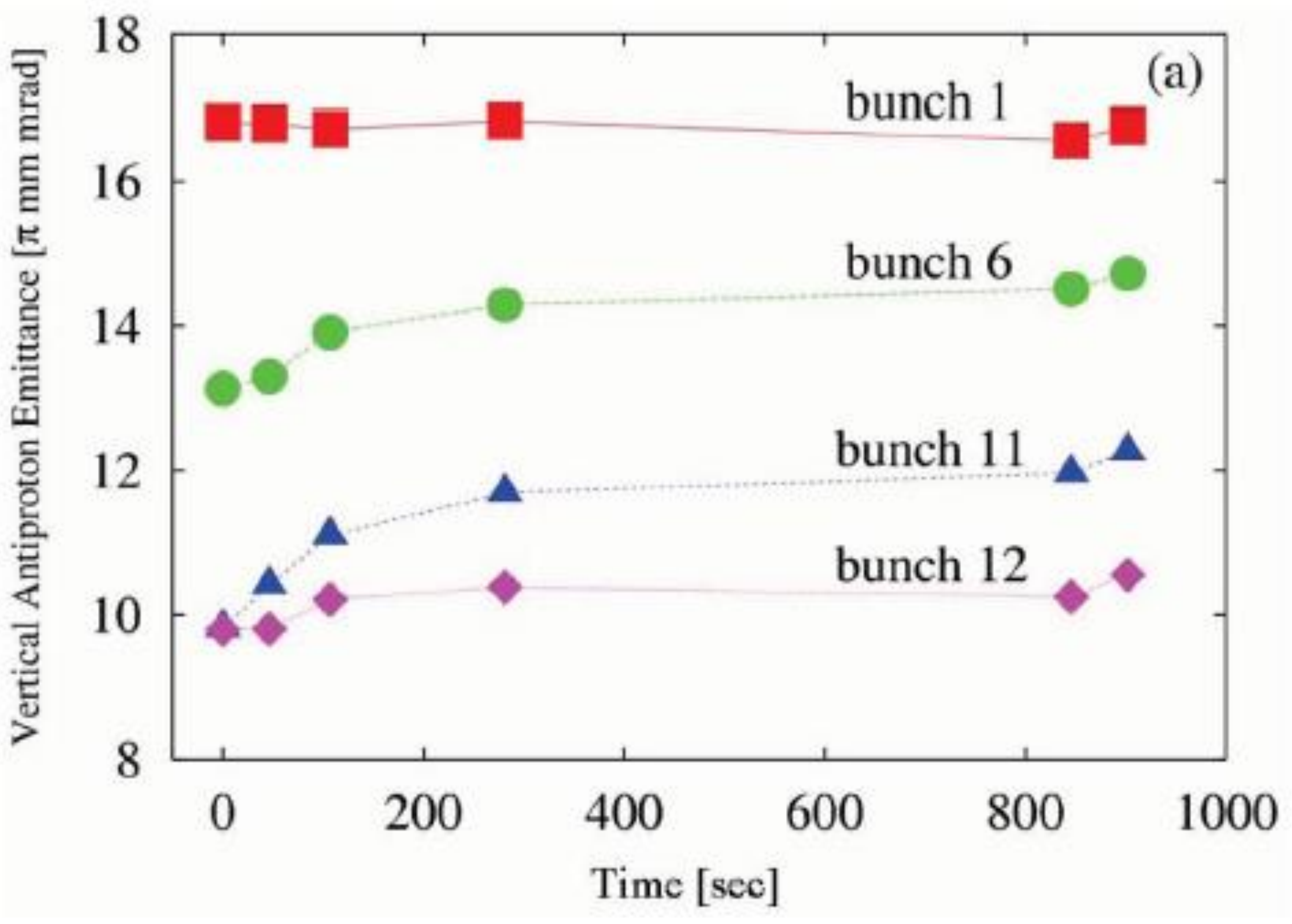
DA vs. Multiparticle: Lifetime Effect of Tune Chromaticity





Lifetrac simulation for antiproton bunch #6, ξ=0.02

Fast Antiptoron Blow-up in Collision



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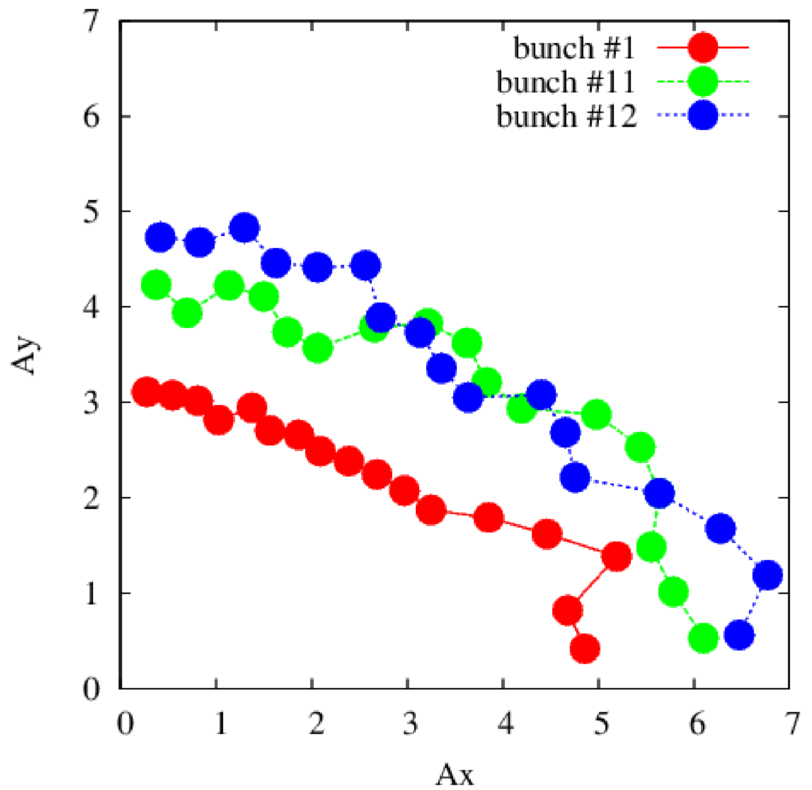
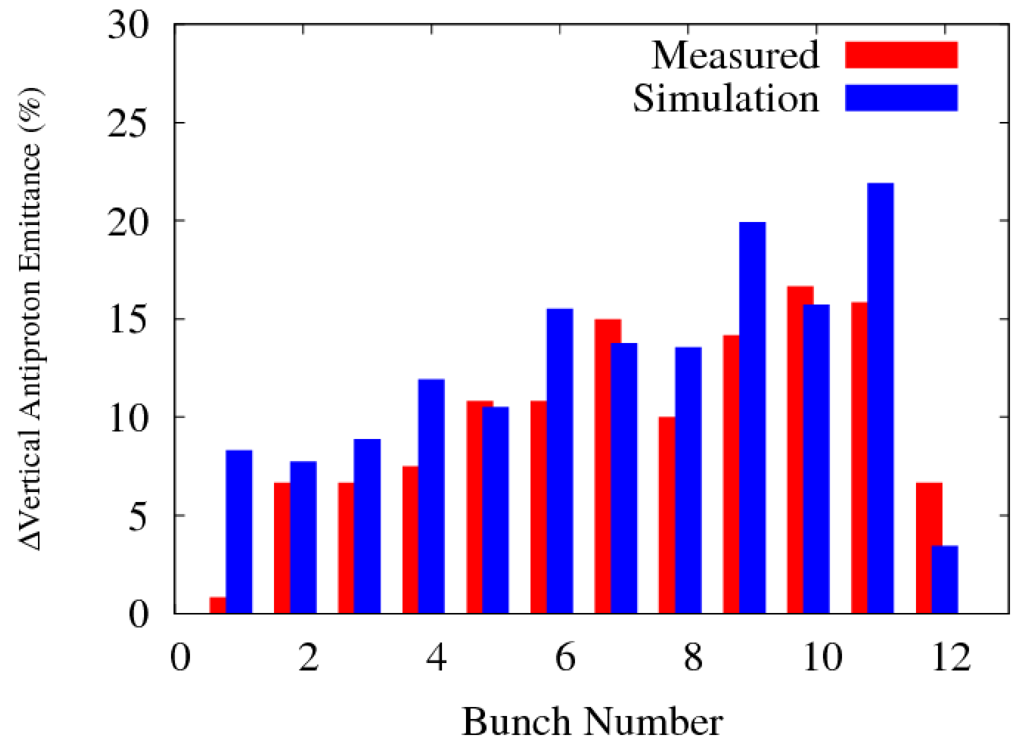
DA vs Multiparticle: Emittance





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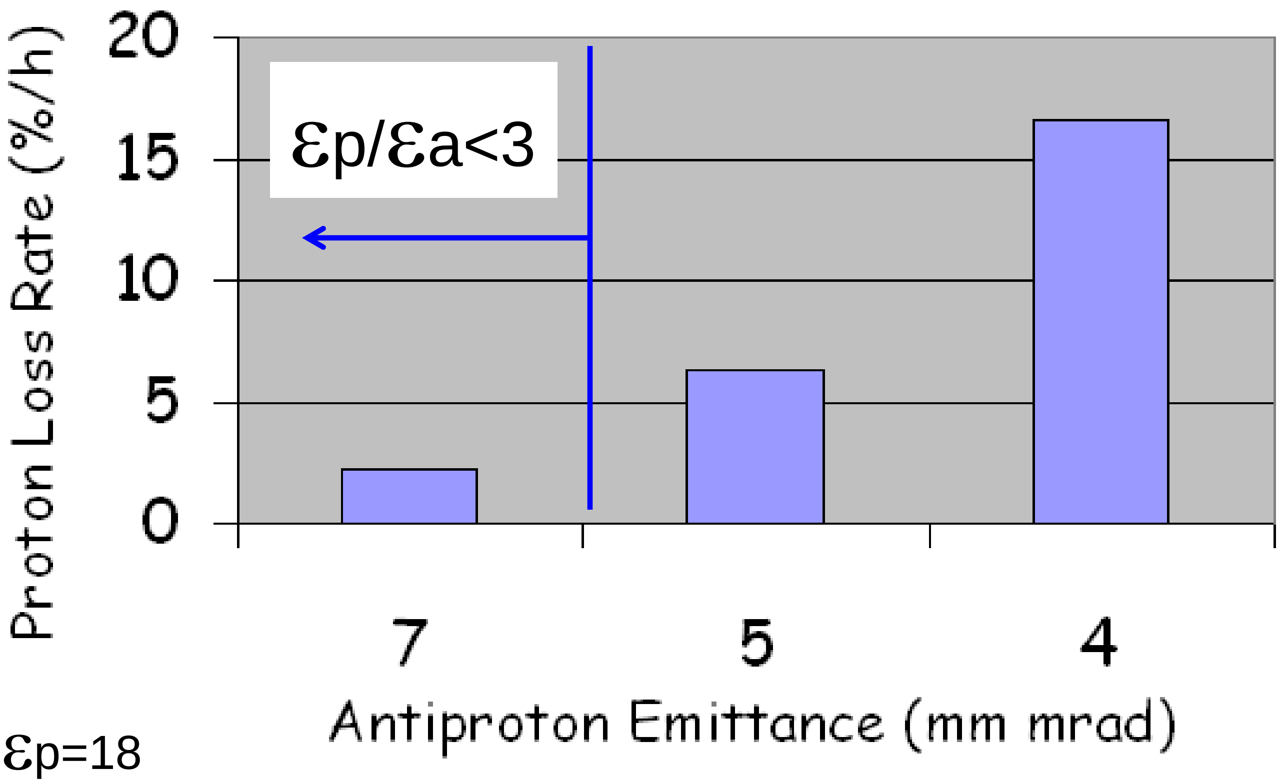
Tevatron Ultimate Parameters

Number of bunches	36
Protons per bunch	2.9×10^{11}
Antiproton per bunch	0.9×10^{11}
Initial proton emittance (95% norm)	18 *mm*
Initial antiproton emittance (95% norm)	8 *mm*
Initial proton bunch length	0.55 m
Initial antiproton bunch length	0.45 m
β-function at IP	0.28 m
Proton working point (Q_x,Q_y)	20.583, 20.585
Proton chromaticities (Cx, Cv)	4, 5
Initial luminosity	4.0×10^{32} cm^{-2}s^{-1}
Luminosity lifetime	5 h

Effect of P/A Emittance Ratio

After

- Correction of β^* chromaticity
- Careful choice of working point



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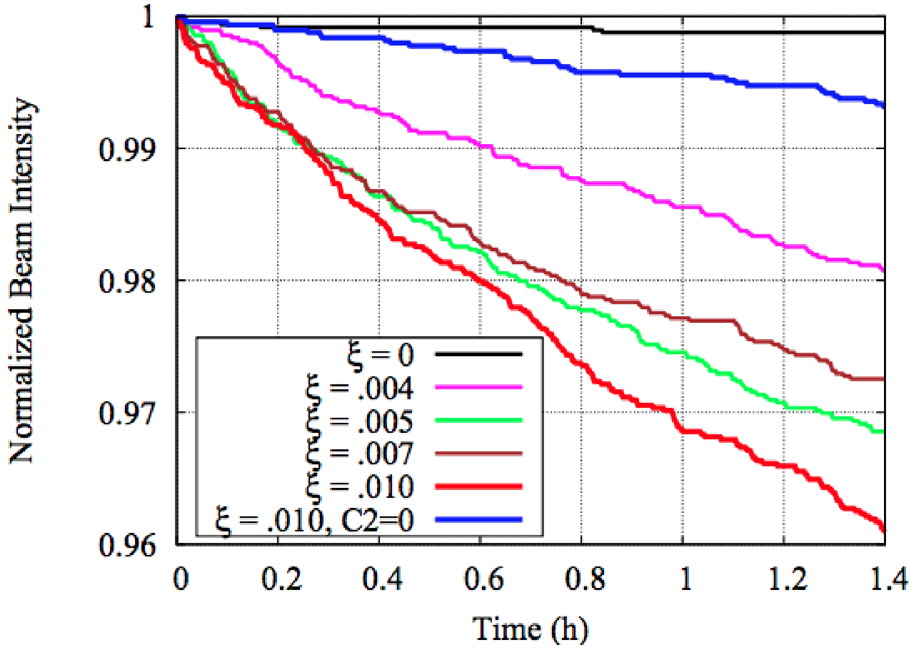
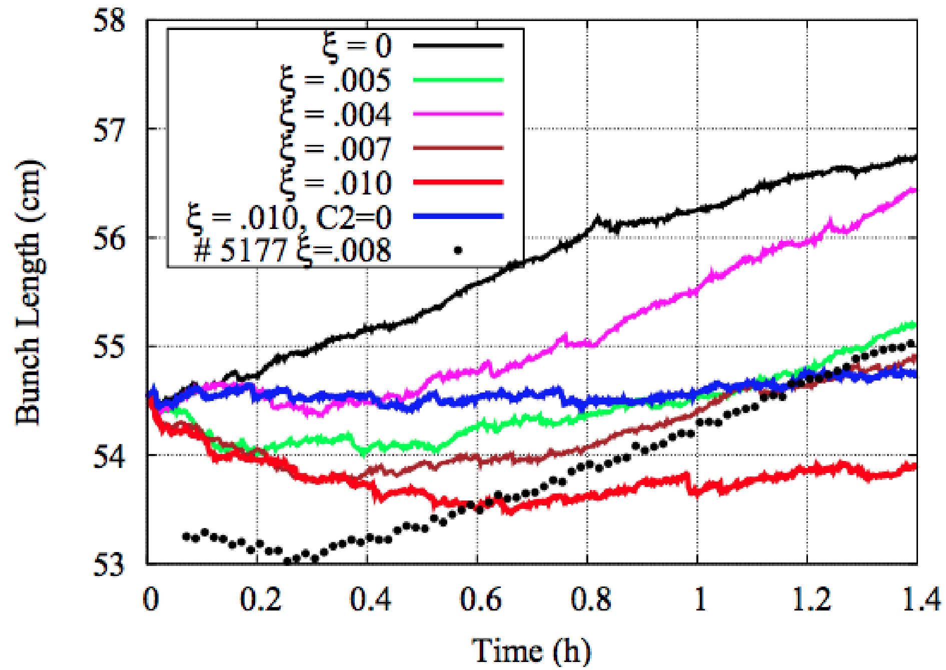
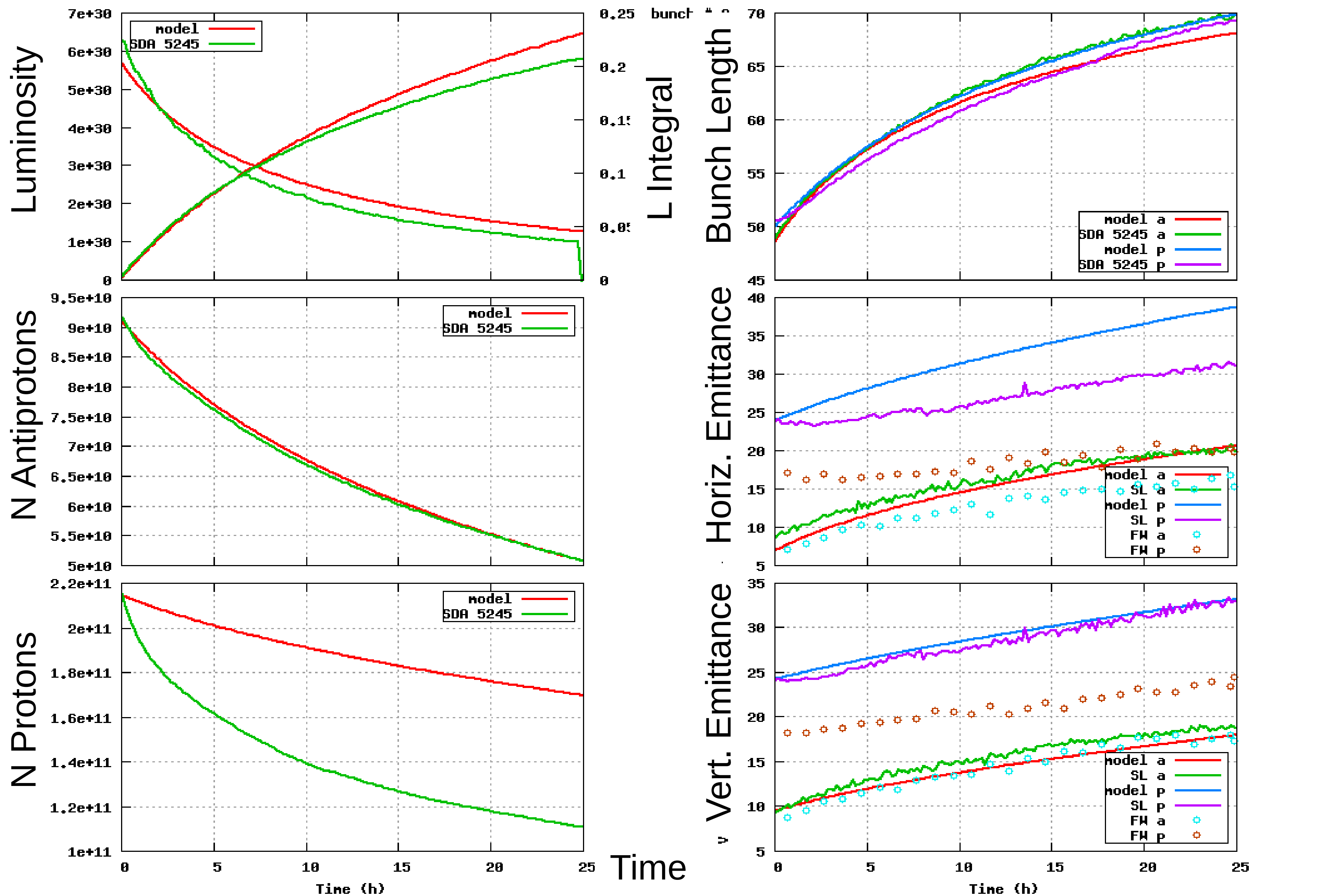
Effect of β* Chromaticity



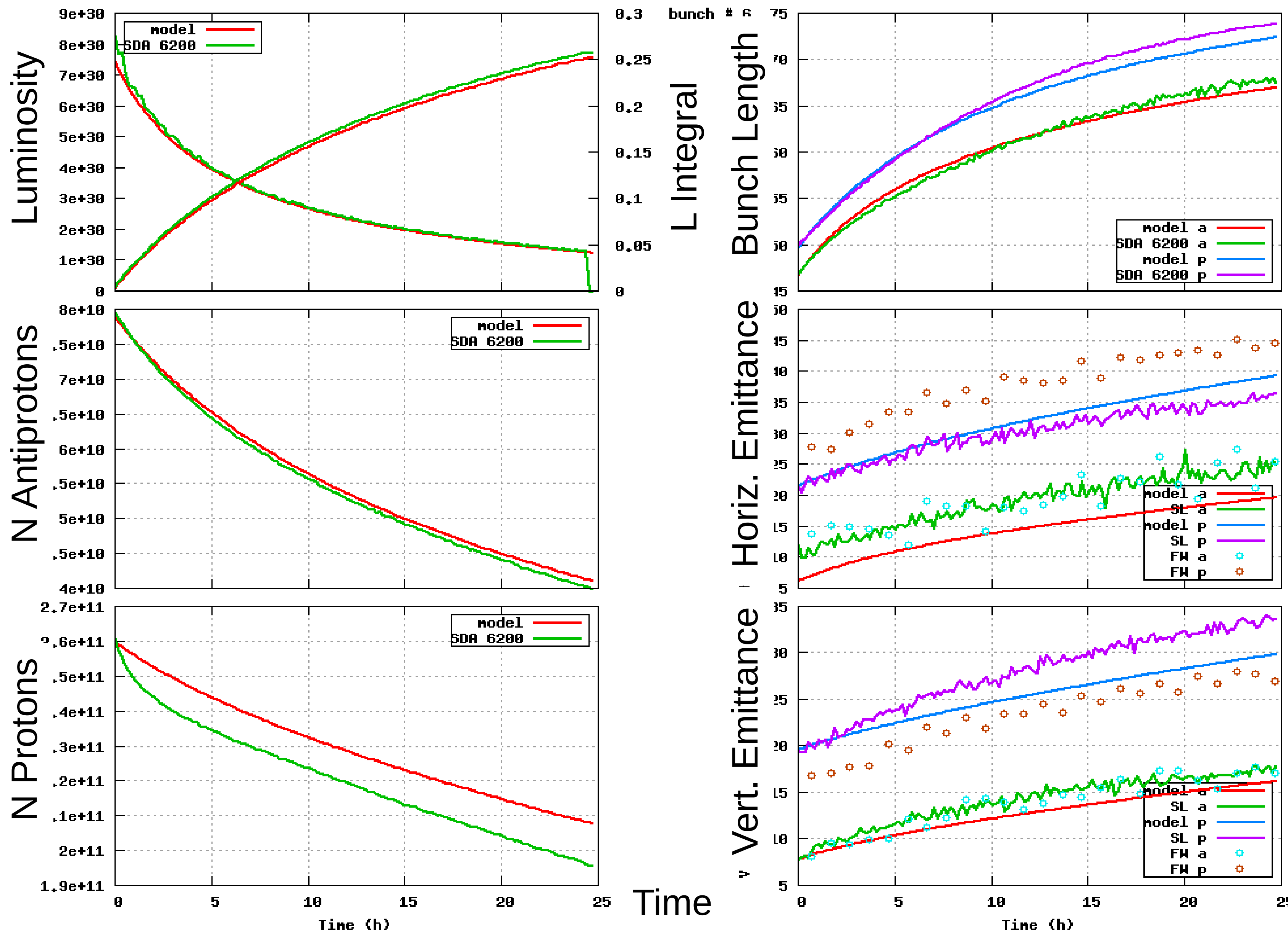


- Modulation of transverse beam size by synchrotron oscillations
- Not exactly $d^2Q/d\delta^2$

Store 5245, L_0=2.92x10^{32}



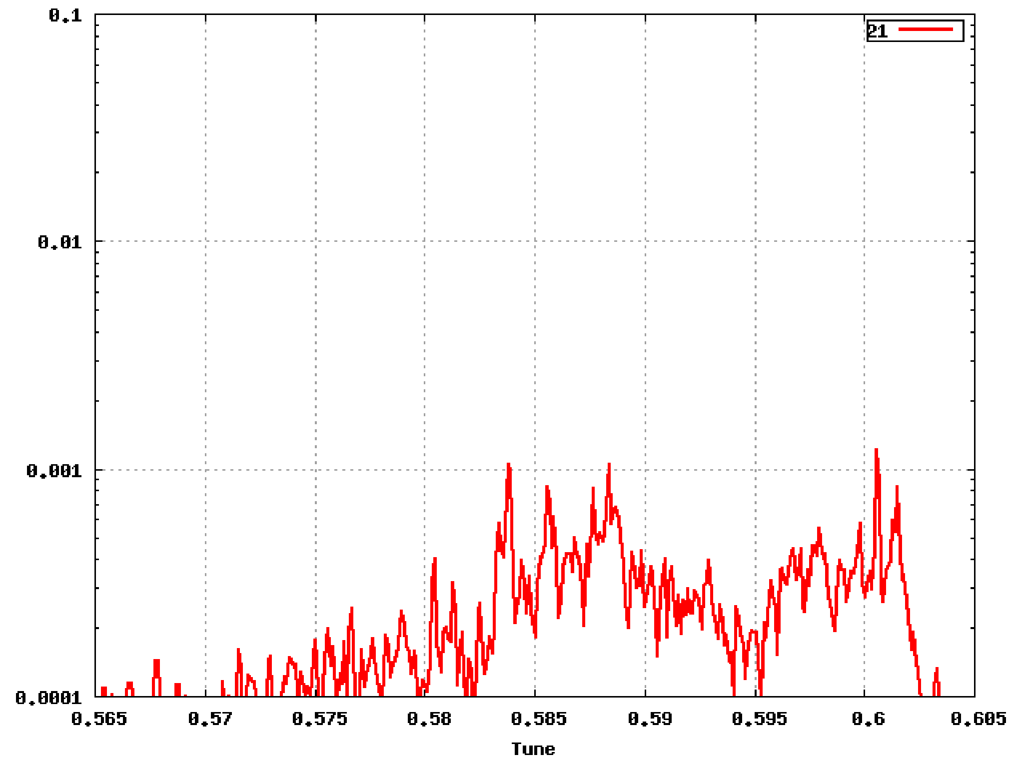
Store 6200, L_0=2.95x10^{32}



Strong-Strong Simulations

Motivation

- Weak-strong simulations clearly demonstrated the benefit of running at lower chromaticity
- In HEP mode, the head-on tune spread stabilizes coherent instabilities
- What is the chromaticity threshold during low-beta squeeze when beams experience only long-range interactions?
- In special study beams were separated at end of a store headtail developed



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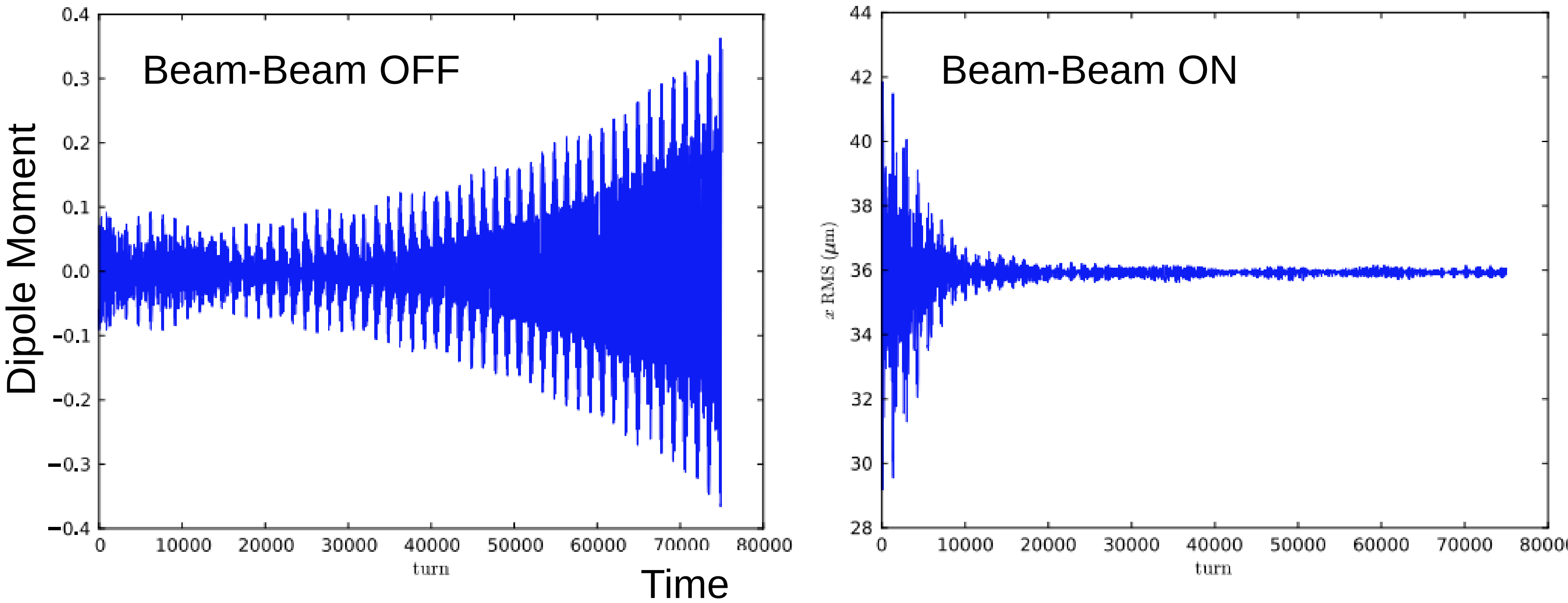
BeamBeam3D Simulation

- PIC solver for beam-beam interactions (J.Qiang, LBNL)
- Multi-bunch, Tevatron optics and collision pattern
- Resistive wall impedance

E. Stern et al, PRSTAB (2010)



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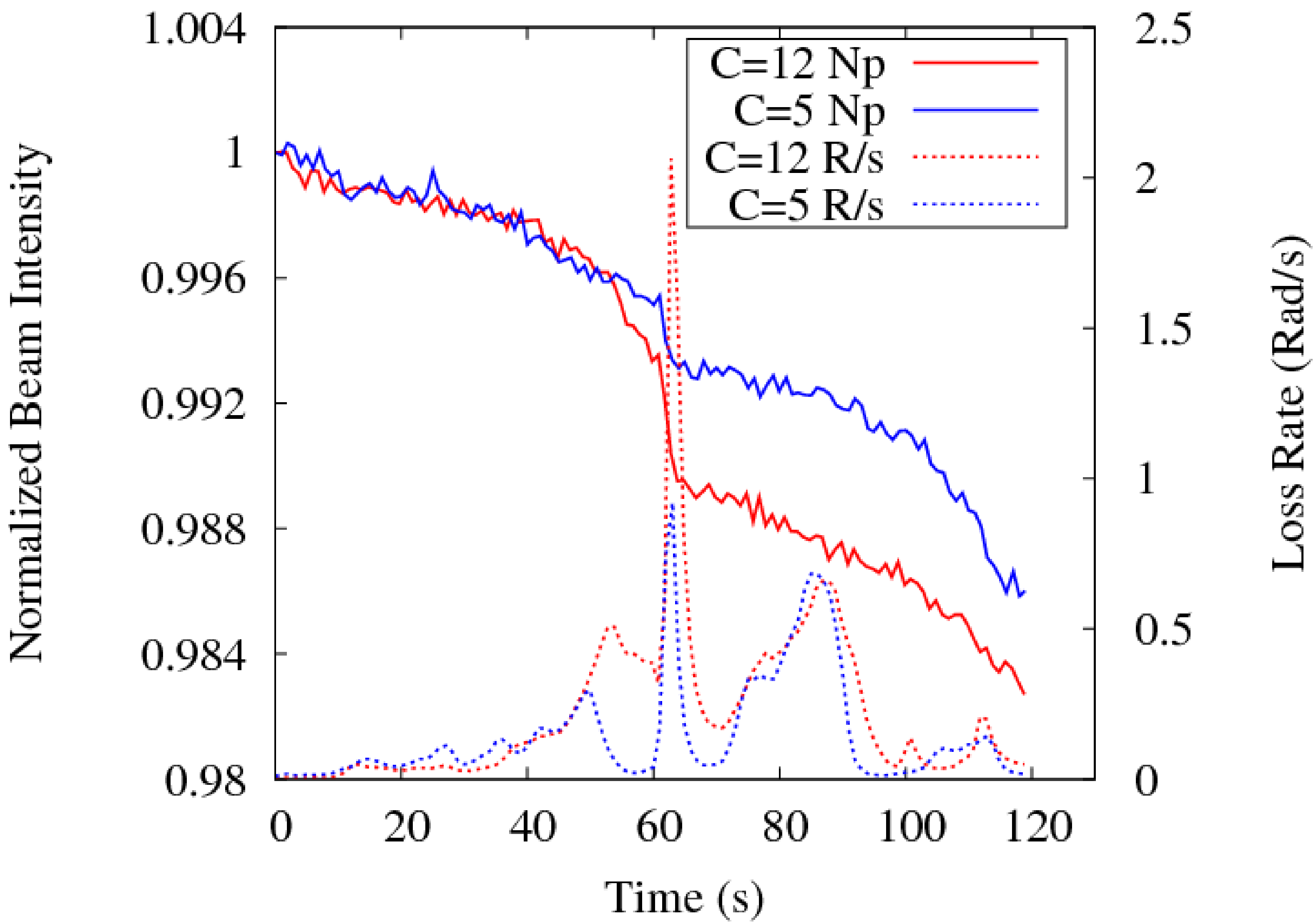
Measured Effect of Chromaticity



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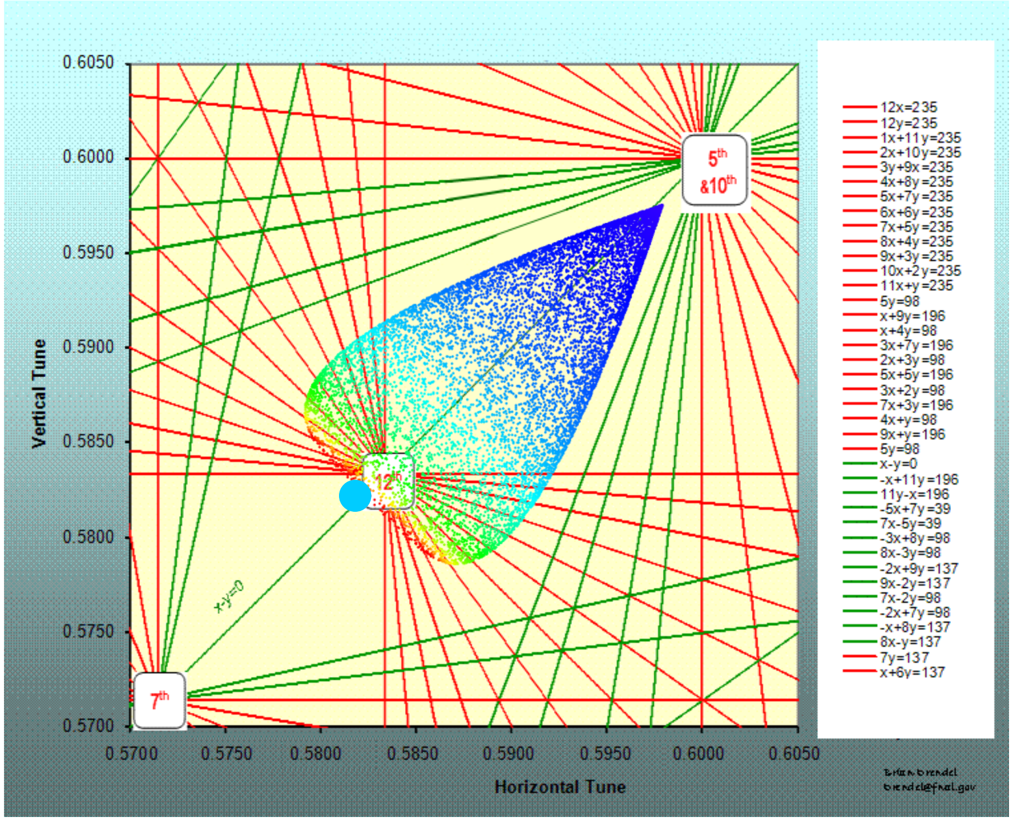
Summary

Beam-beam modeling was evolving in the course of Tevatron collider Run II

- To address immediate questions/challenges
- Plan improvements
- Steer the development of collider program

- There is nothing fundamentally complex in modeling beam-beam in hadron machines. Rather, complexity stems from significance of details and analysis of large amount of experimental data
  - However, see following talks

Thank you for your attention!



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