Fermilab
Fermi National Accelerator Laboratory
Office of Science / U.S. Department of Energy
Managed by Fermi Research Alliance, LLC

LARP

Collimation Studies with Hollow Electron Beams

Giulio Stancari
Fermi National Accelerator Laboratory

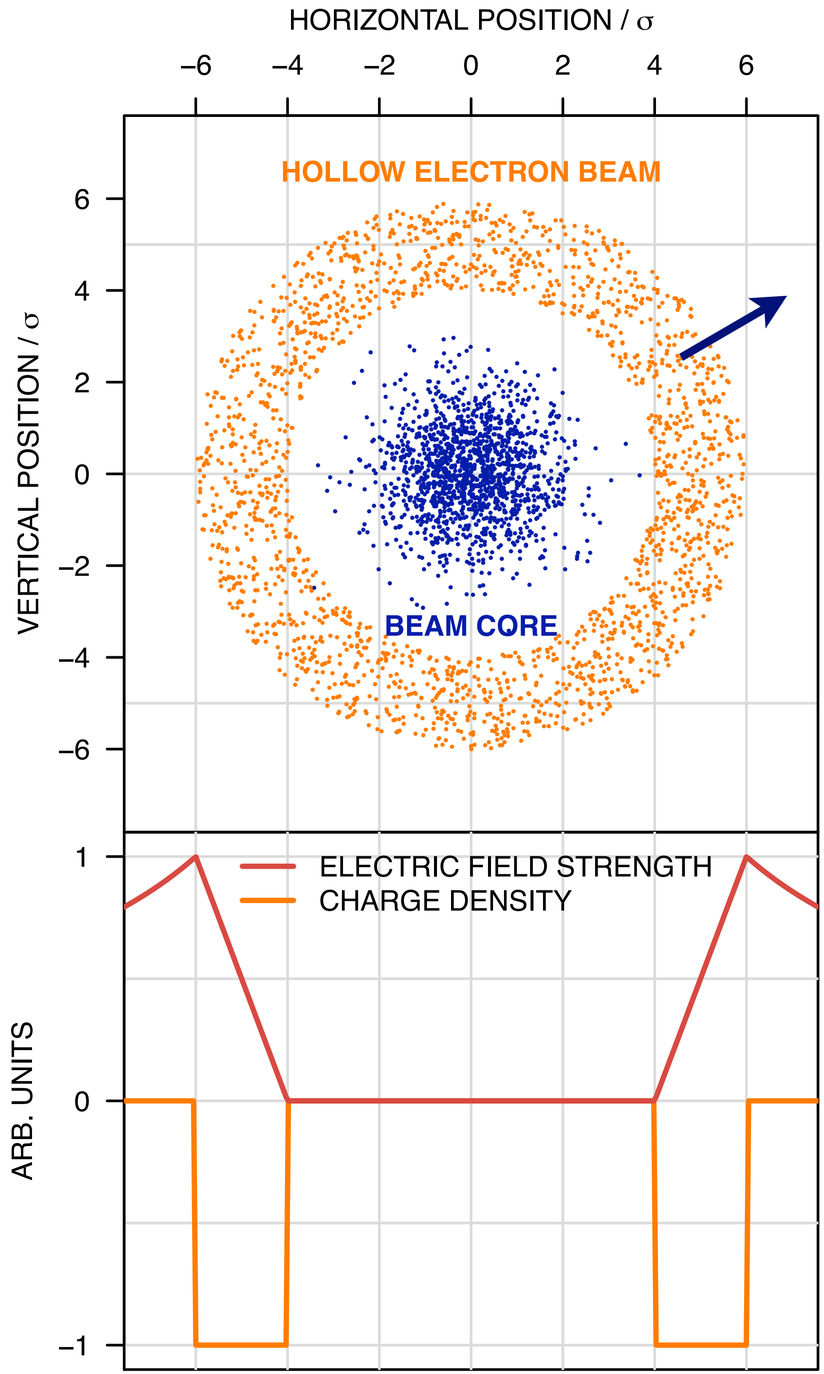
in collaboration with
A. Valishev, G. Annala, T. Johnson, G. Saewert, V. Shiltsev, D. Still

Thanks to Fermilab Accelerator Division and
CDF and DZero collaborations for support and study time

- ➡ The hollow electron beam collimator
- ➡ Tevatron experiments and results
- ➡ Conclusions and outlook

IPAC11
2nd International Particle Accelerator Conference
Donostia - San Sebastián, Spain, 4-9 September 2011

Concept of hollow electron beam collimator (HEBC)



Halo experiences nonlinear transverse kicks:

$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

About **0.2 μrad**
in TEL2 at 980 GeV

For comparison:
multiple scattering
in Tevatron collimators
$\theta_{\rm rms} = 17\ \mu{\rm rad}$

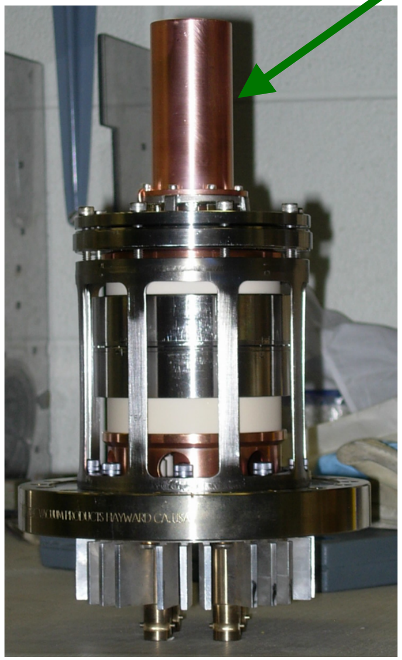
Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

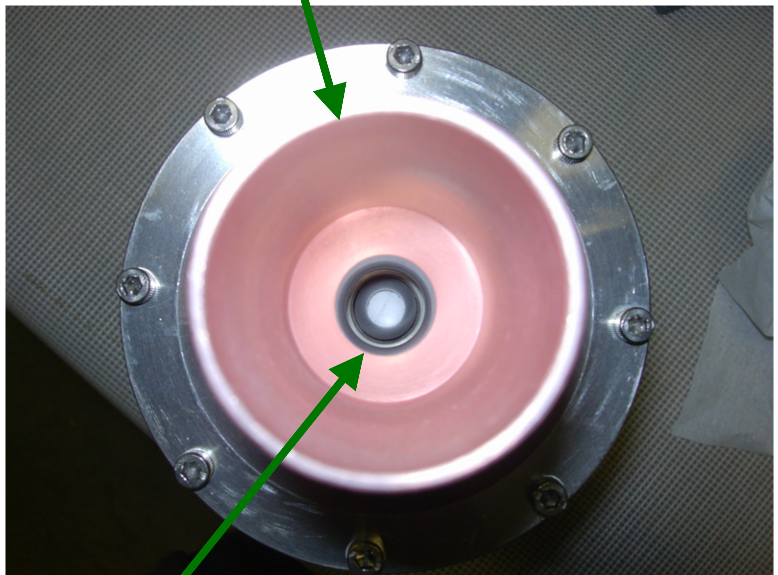
The 15-mm hollow electron gun

side view

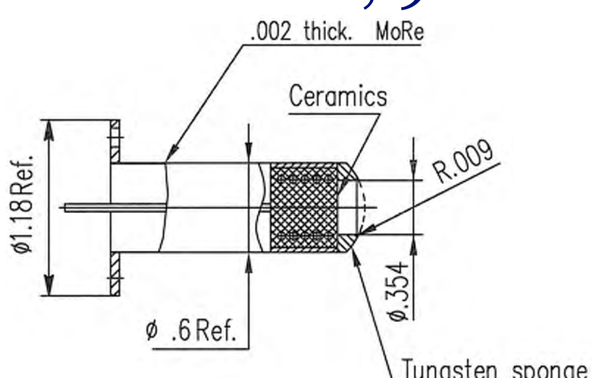
Copper anode

top view



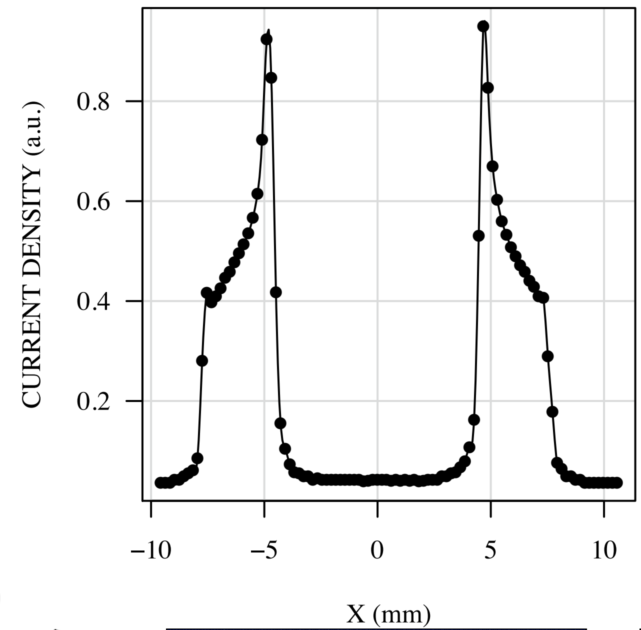


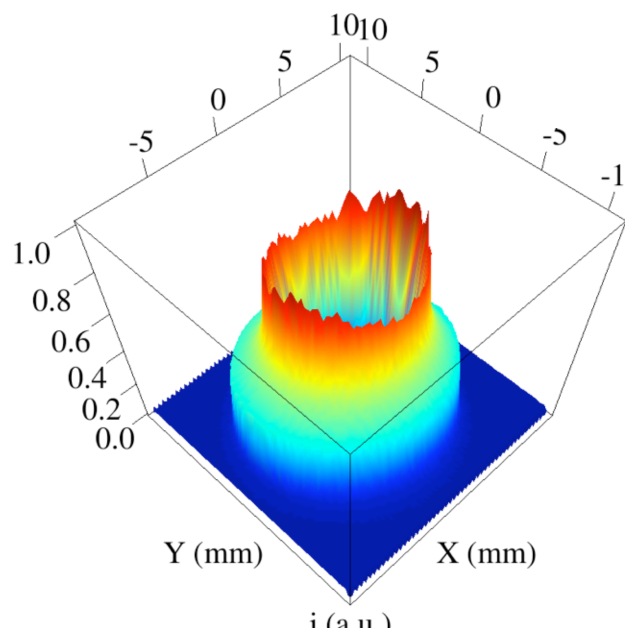
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

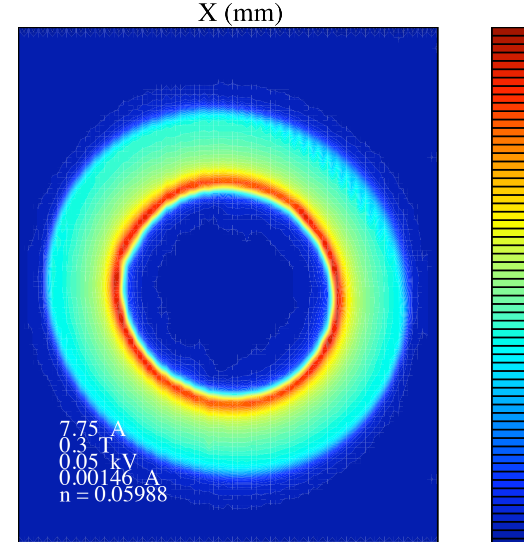


Yield: **1.1 A** at 4.8 kV

Profile measurements

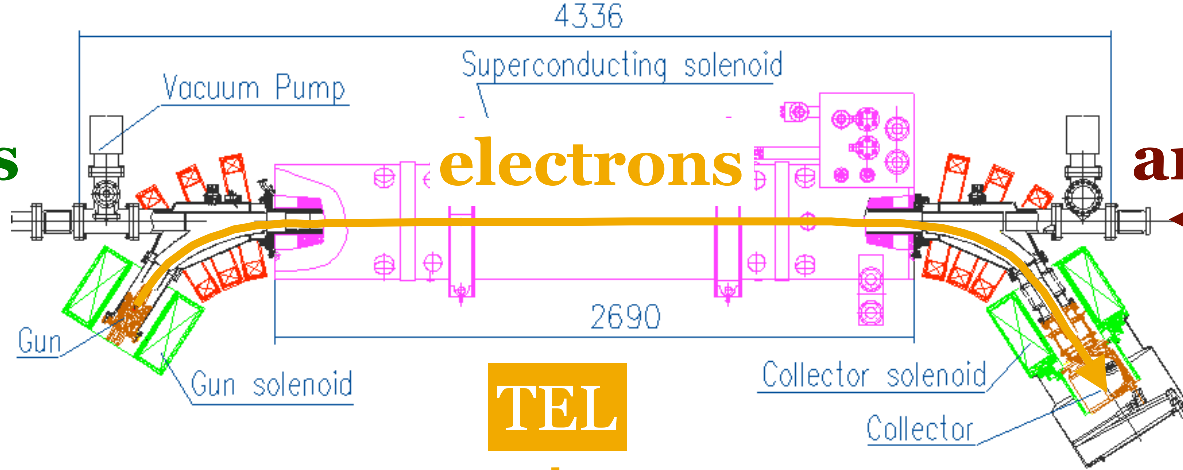






Layout of the beams in the Tevatron

protons



antiprotons

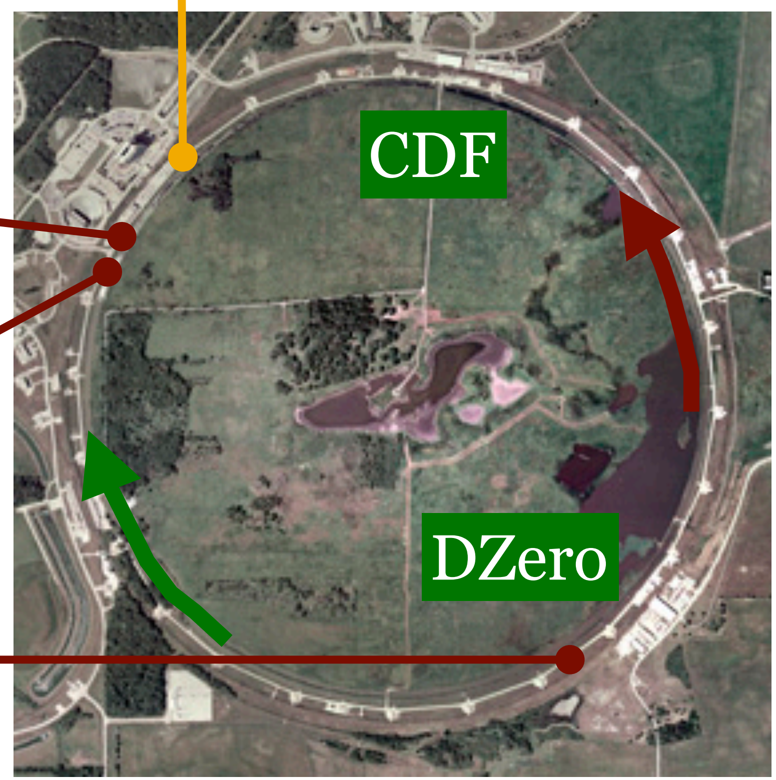
TEL

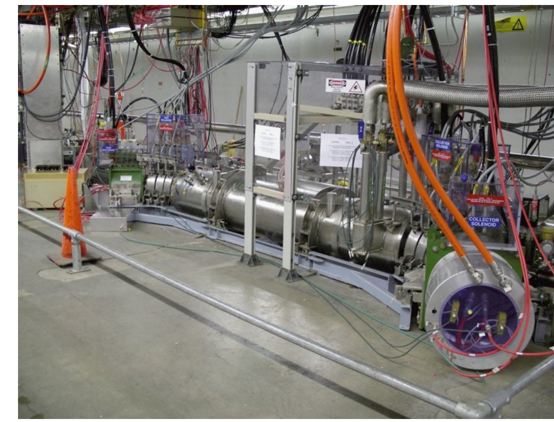
Antiproton collimators:

Primary (F49)

Secondary (F48)

Secondary (D17)

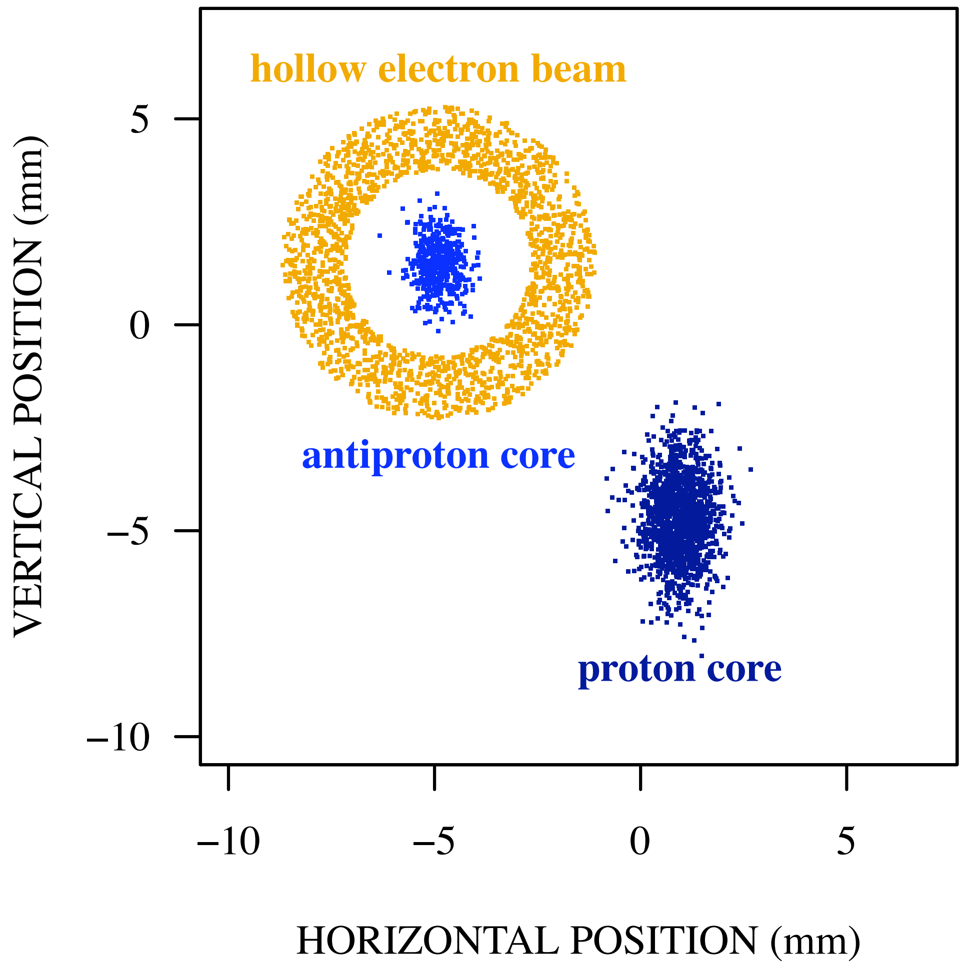


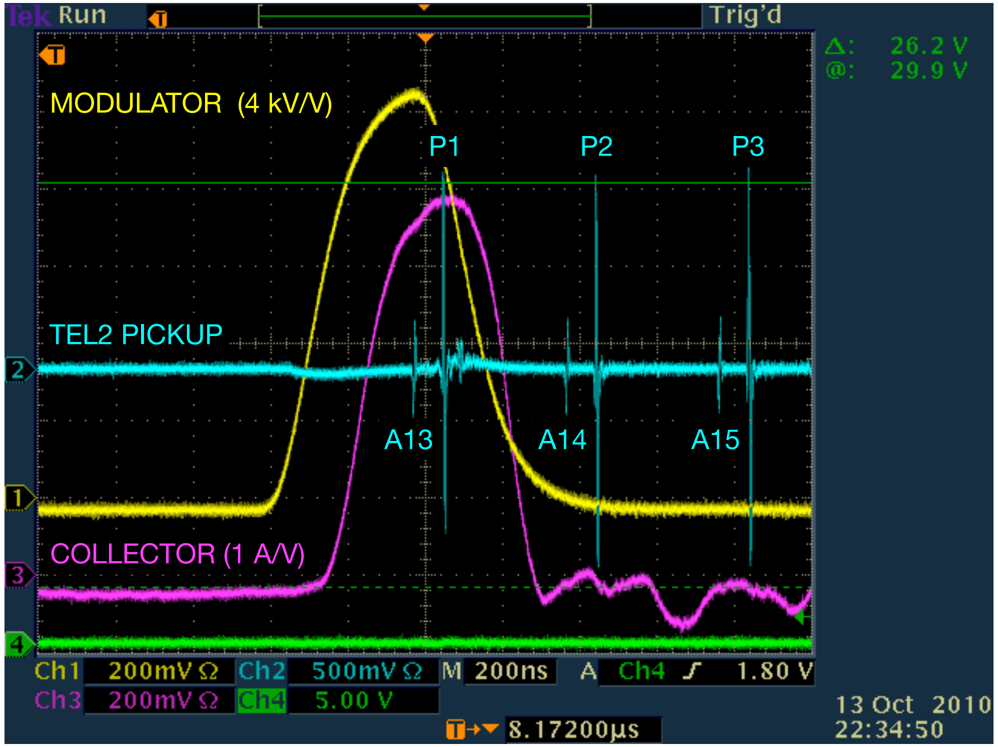


Tevatron electron lens

Layout of the beams in the Tevatron electron lens

Transverse separation is 9 mm



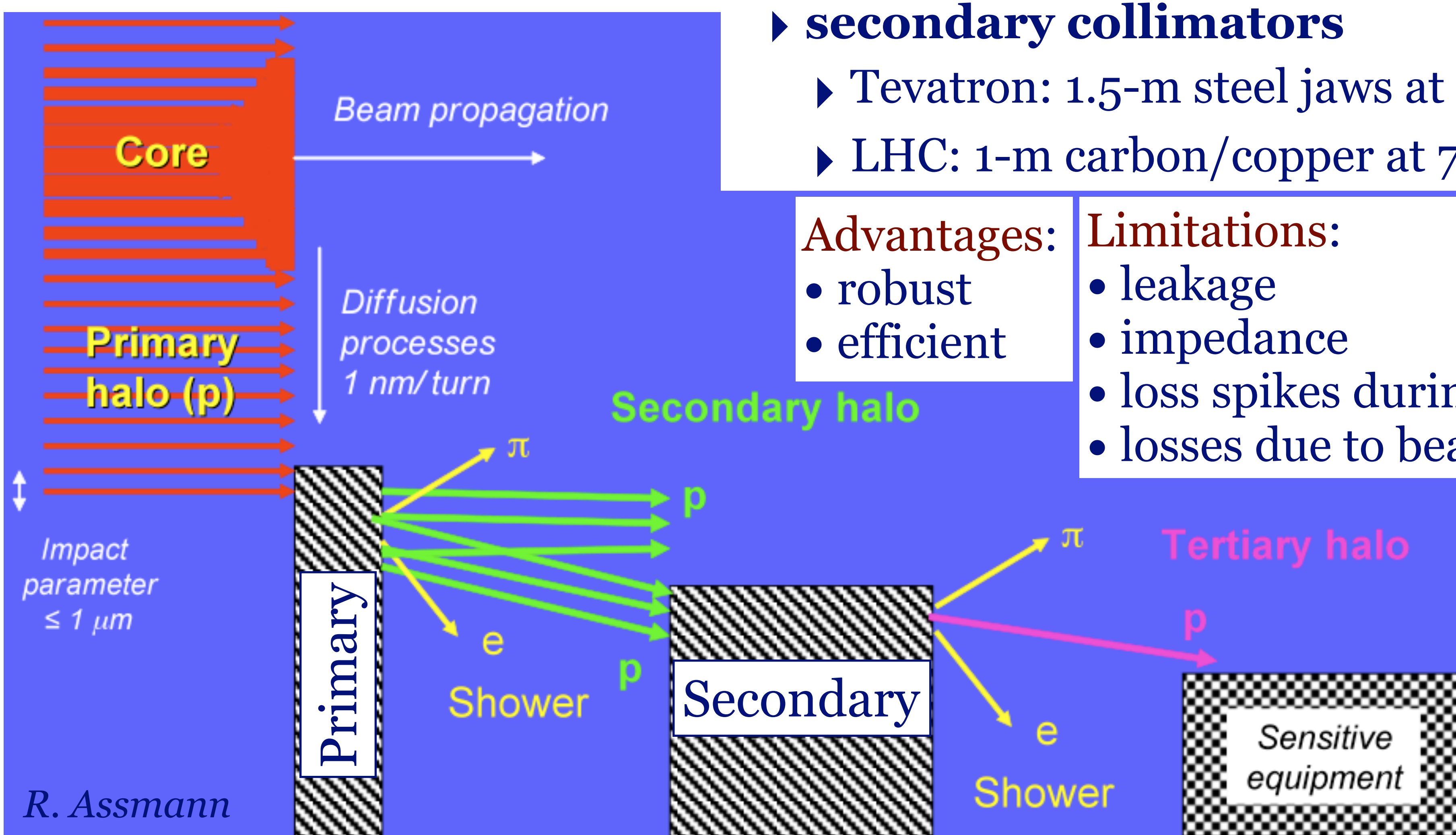


Pulsed electron beam can be synchronized with any group of bunches

The conventional multi-stage collimation system

Goals of collimation:
- reduce beam halo
- direct losses towards absorbers

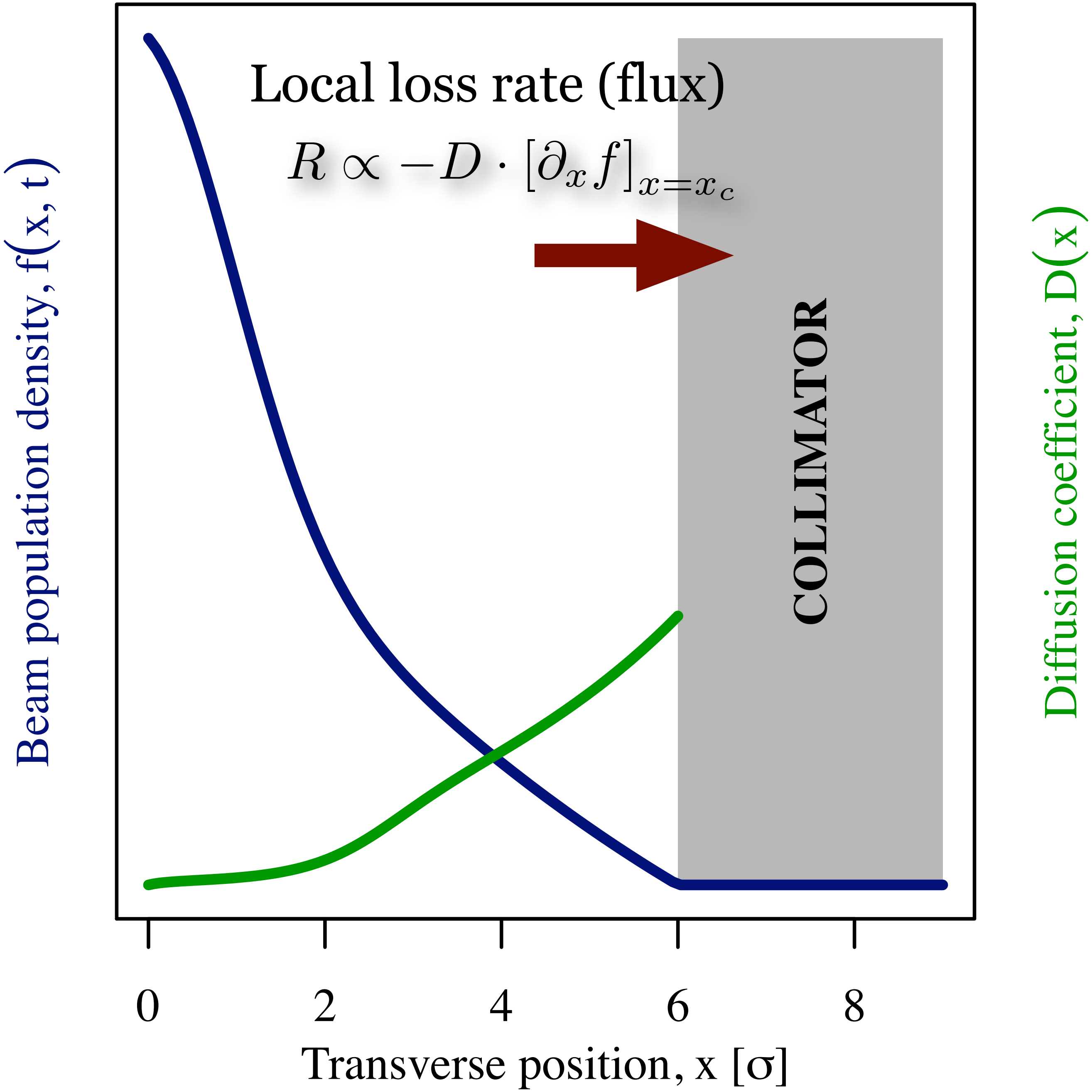
Implementations:
- **primary collimators**
  - Tevatron: 5-mm W at 5σ
  - LHC: 0.6-m carbon jaws at 6σ
- **secondary collimators**
  - Tevatron: 1.5-m steel jaws at 6σ
  - LHC: 1-m carbon/copper at 7σ



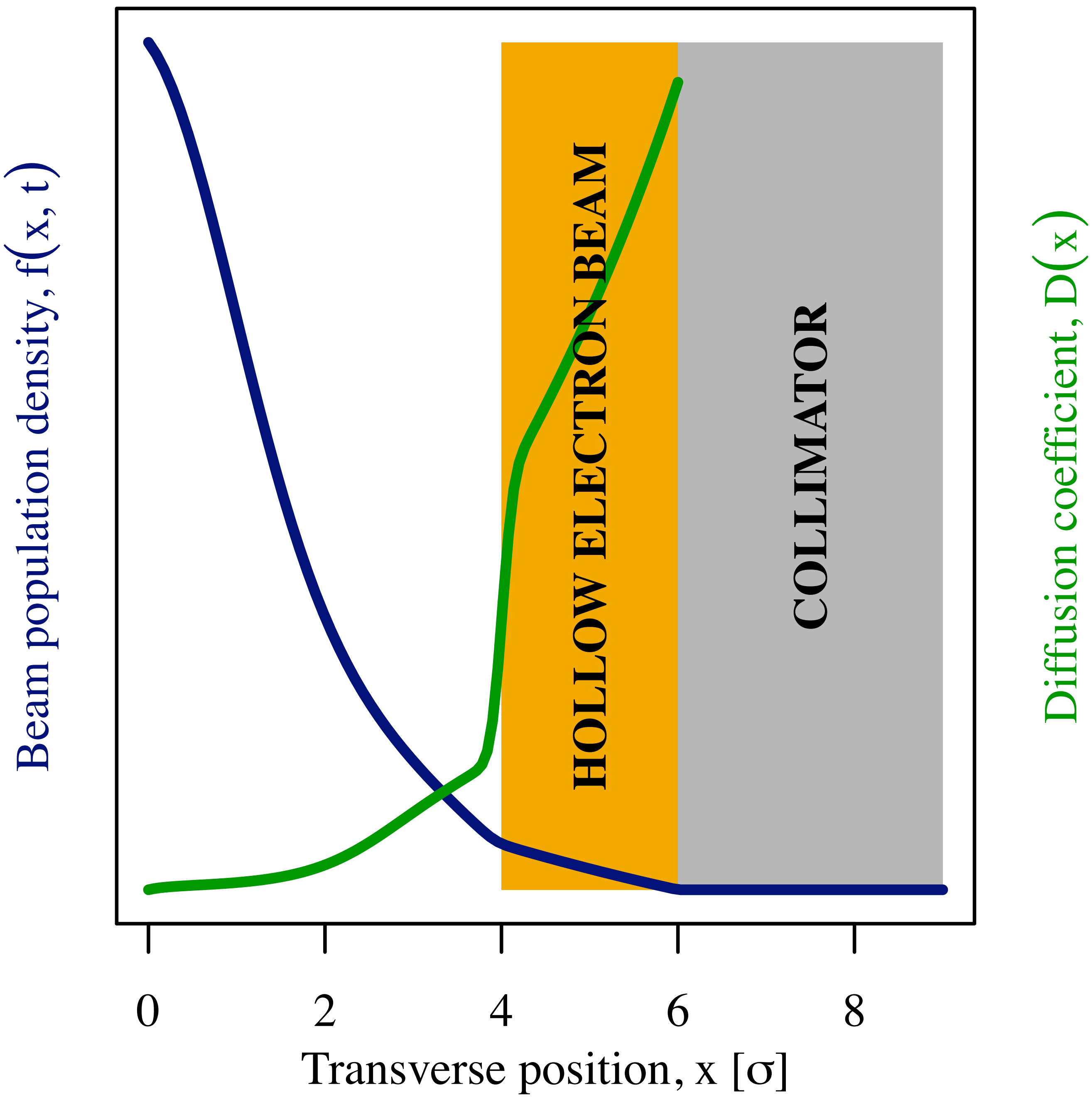
Advantages:
- robust
- efficient

Limitations:
- leakage
- impedance
- loss spikes during setup
- losses due to beam jitter

1-dimensional diffusion cartoon of collimation



1-dimensional diffusion cartoon with hollow electron beam



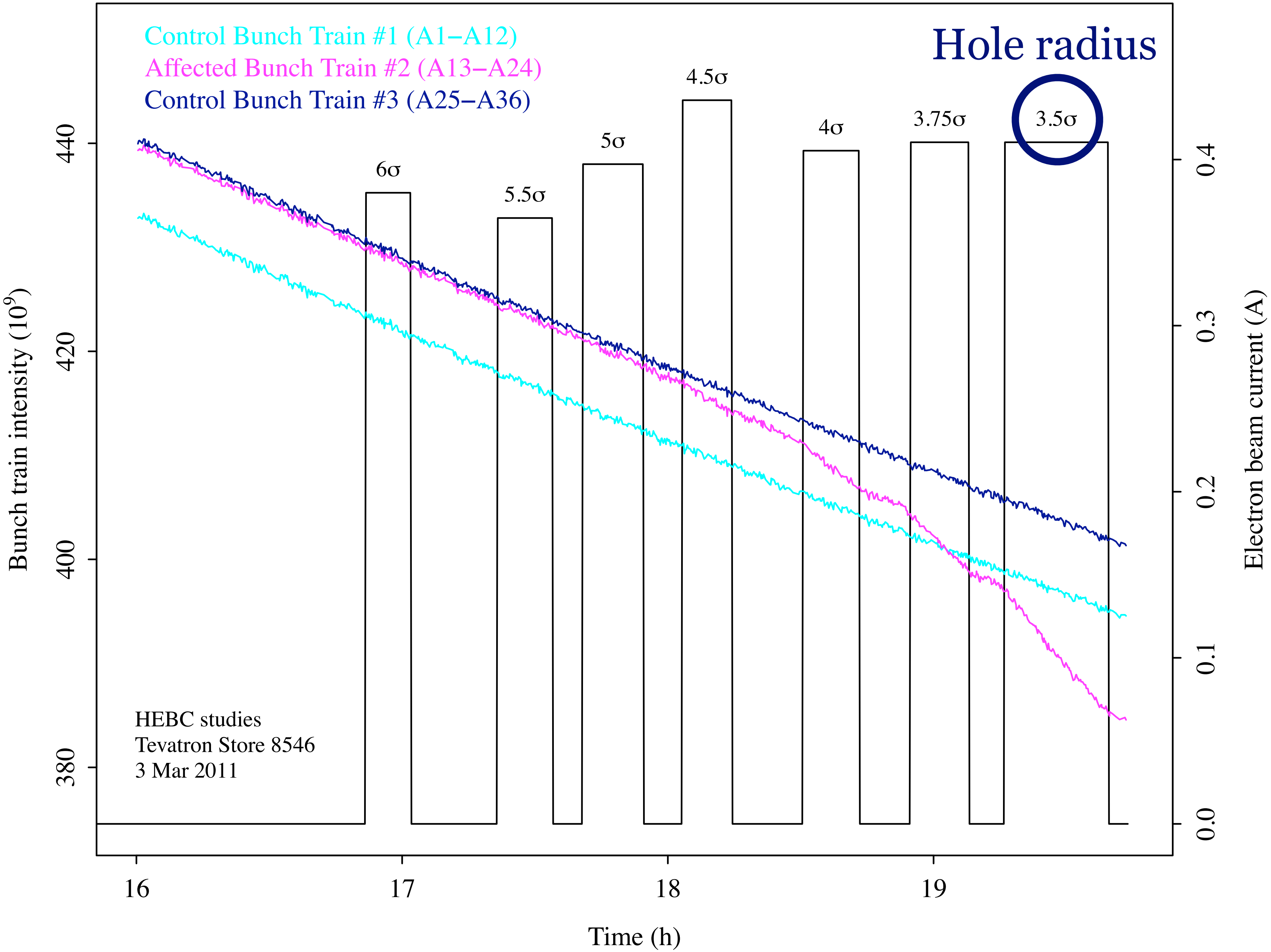
A good complement to a two-stage system for high intensities?

- Can be close to or even overlap with the main beam
  - no material damage
  - tunable strength (“variable thickness”)
- Works as “soft scraper” by enhancing diffusion
- Low impedance
- Resonant excitation is possible (pulsed e-beam)
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology
- Critical beam alignment
- Control of hollow beam profile
- Beam stability at high intensity
- Cost

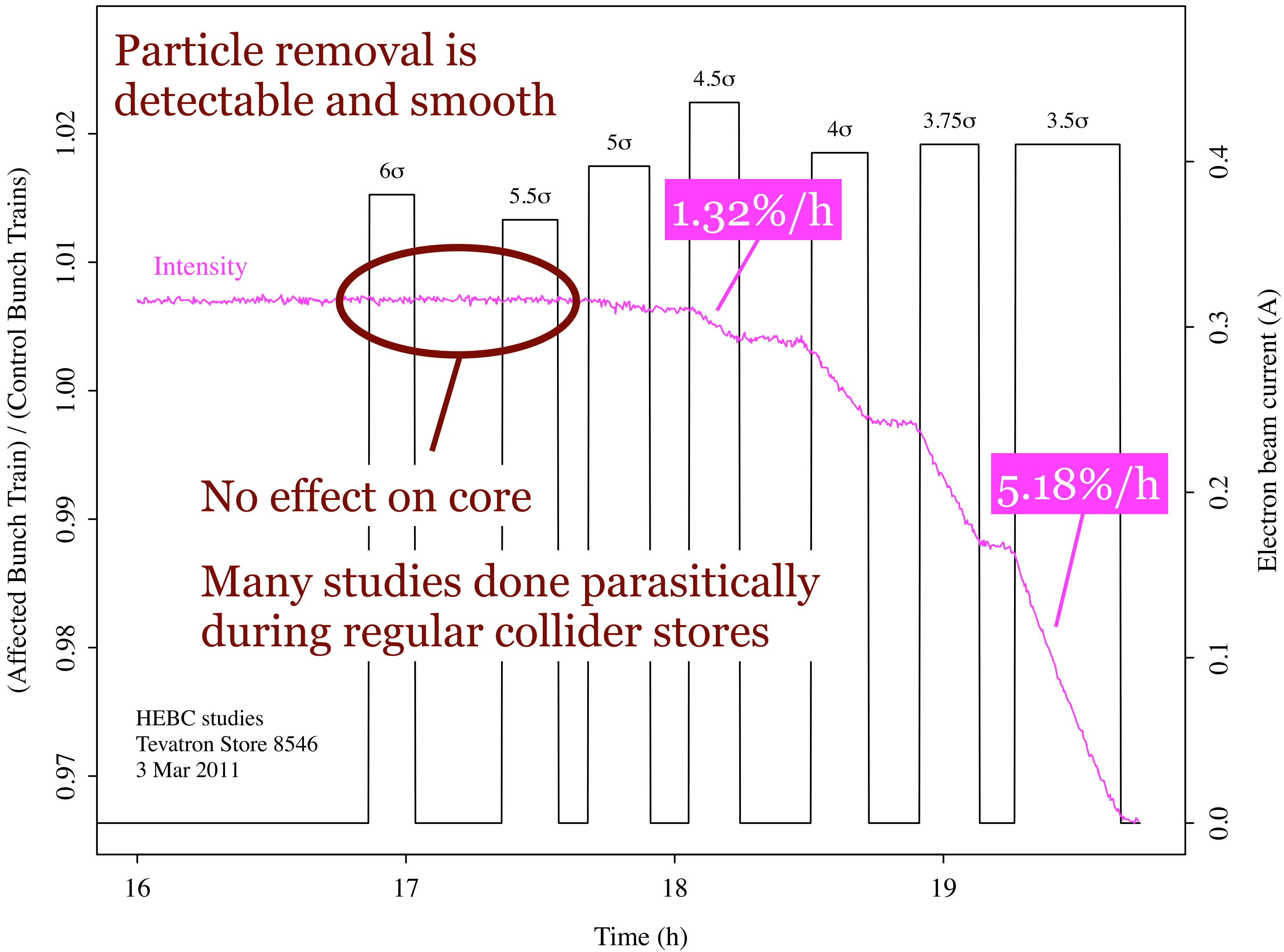
Tevatron beam studies

- Started in October 2010
- 19 experiments so far: parasitic and dedicated
- Measured many **observables** vs. main factors: beam current, relative alignment, hole size, pulsing pattern, collimator configuration:
  - overall particle **removal rate**
  - **effects on the core** and on unaffected bunches
  - **removal rate vs. particle amplitude**
  - enhancement of transverse beam **diffusion**
  - **collimation efficiency**
  - **fluctuations** in loss rates
- A few examples shown here

Electrons acting on 1 antiproton bunch train (#2, A13-A24)



Removal rate: affected bunch train relative to other 2 trains



Is the core affected? Are particles removed from the halo?

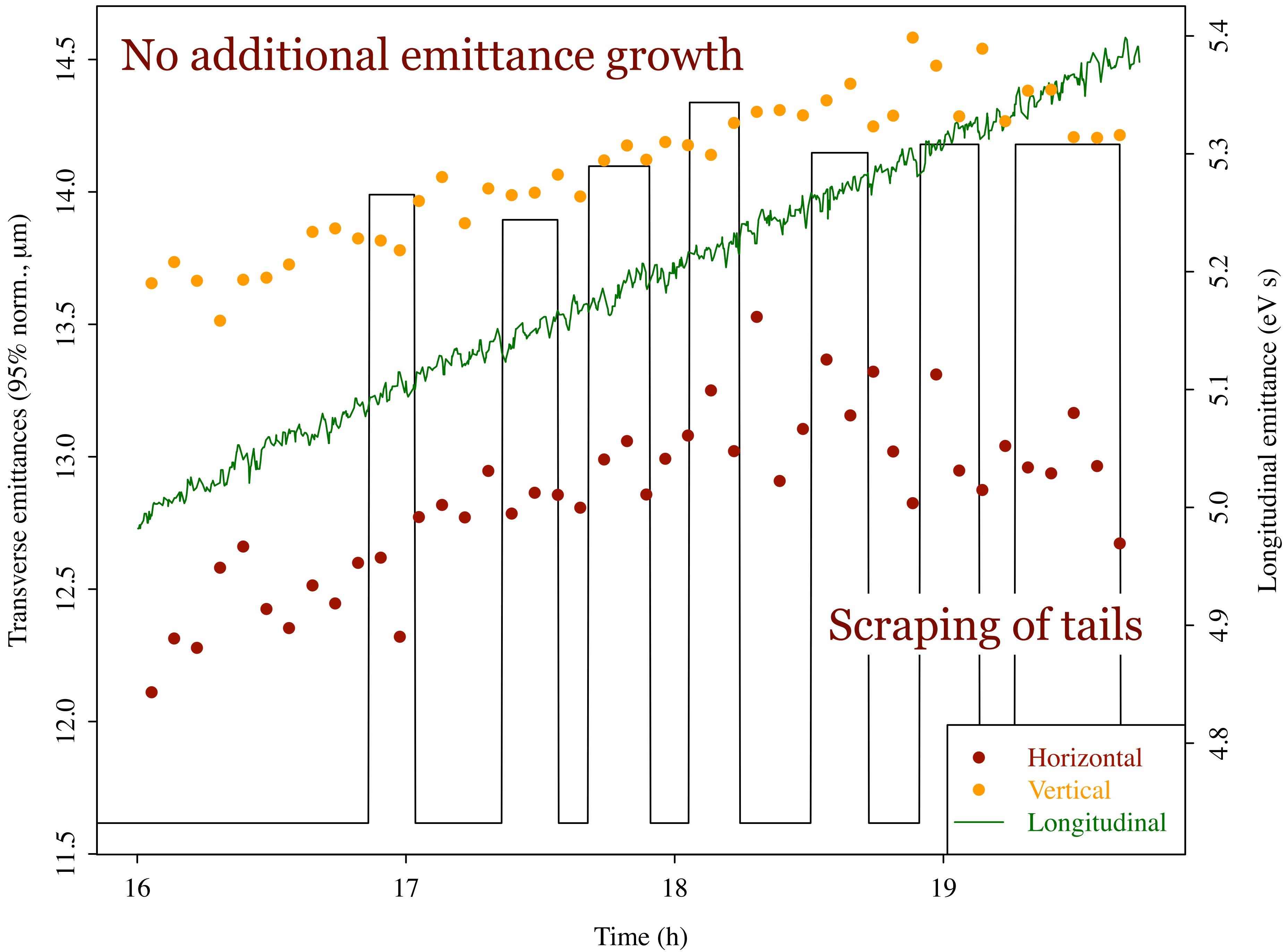
Several strategies:

- **No removal** when e-beam is shadowed by collimators (previous slide)
- Check **emittance** evolution
- Compare **intensity** and **luminosity** change when scraping antiprotons:

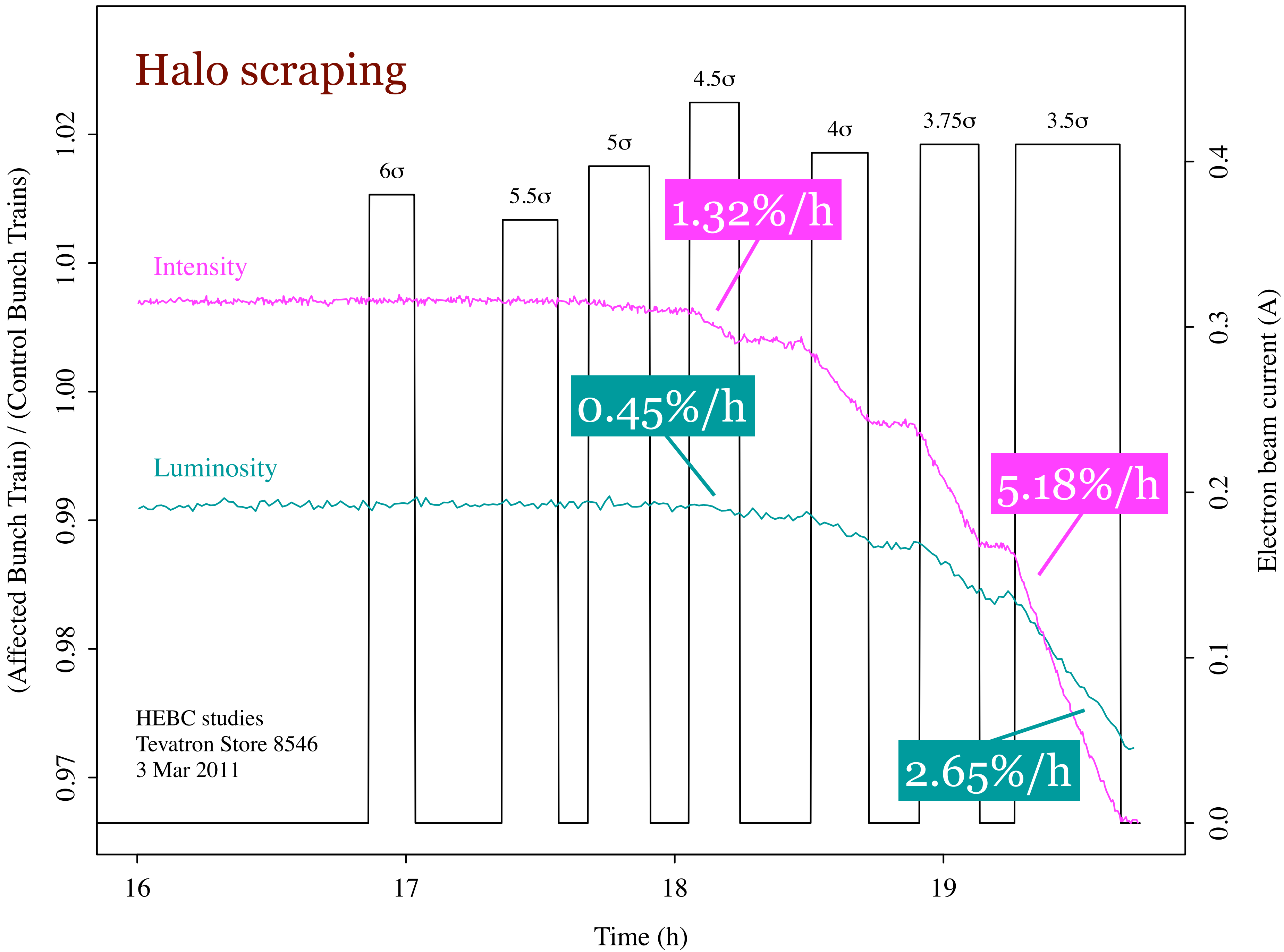
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2 \frac{\Delta \sigma}{\sigma}$$

  - same fractional variation if other factors are constant
  - luminosity decreases more if there is emittance growth or proton loss
  - luminosity decreases less if removing halo particles (smaller relative contribution to luminosity)
- **Removal rate** vs. amplitude (collimator scan, steady state)
- **Diffusion rate** vs. amplitude (collimator scan, time evolution of losses)

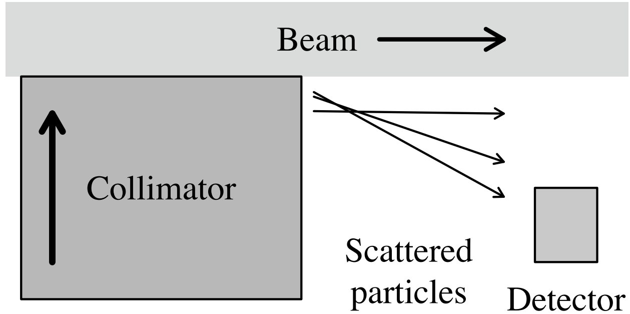
Emittances of affected bunch train

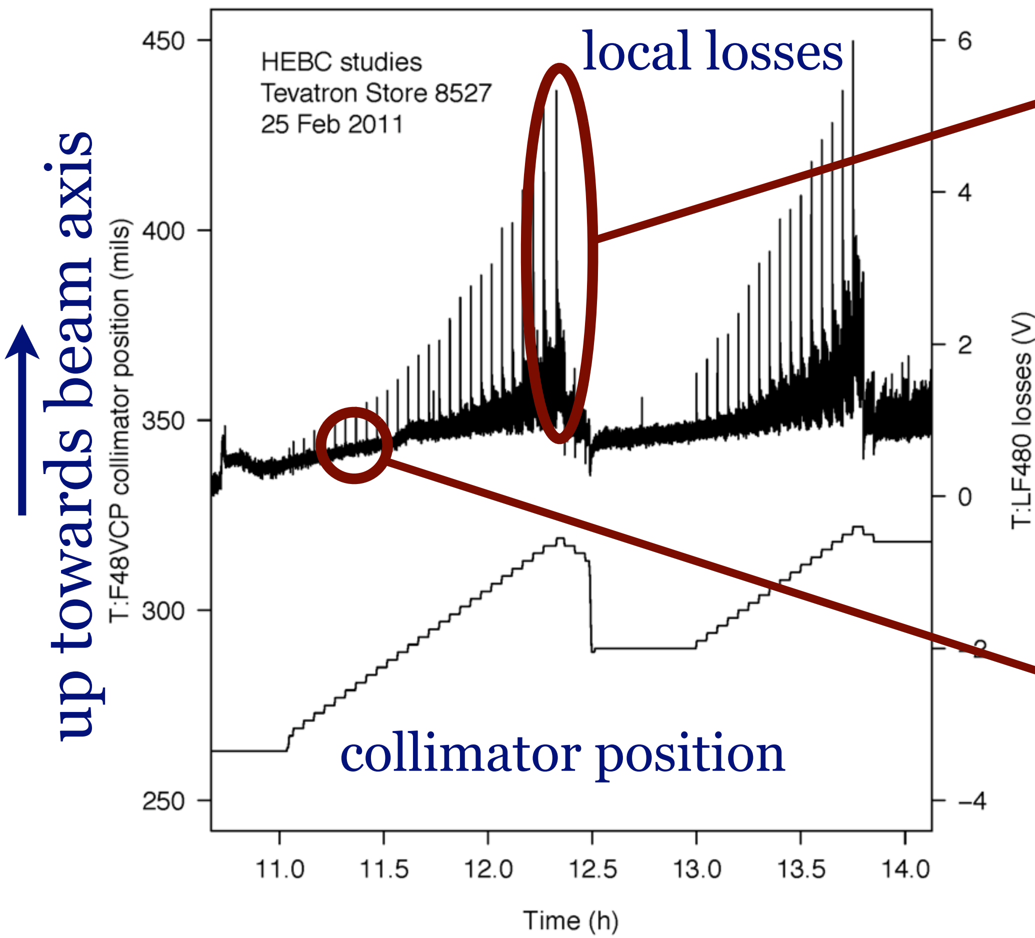


Luminosity of affected bunch train relative to other 2 trains

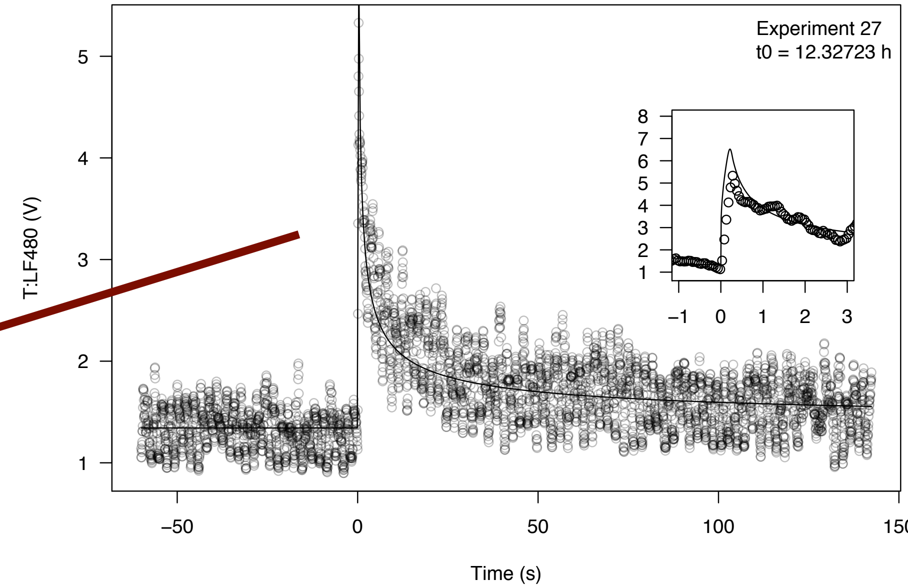


Diffusion rate vs. amplitude from collimator scans

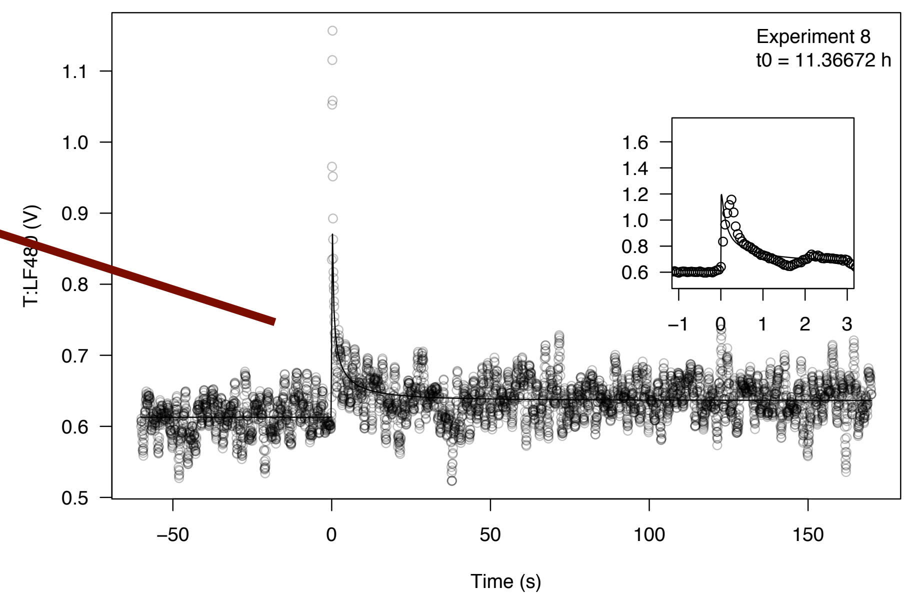




Mess and Seidel, NIMA **351**, 279 (1994)

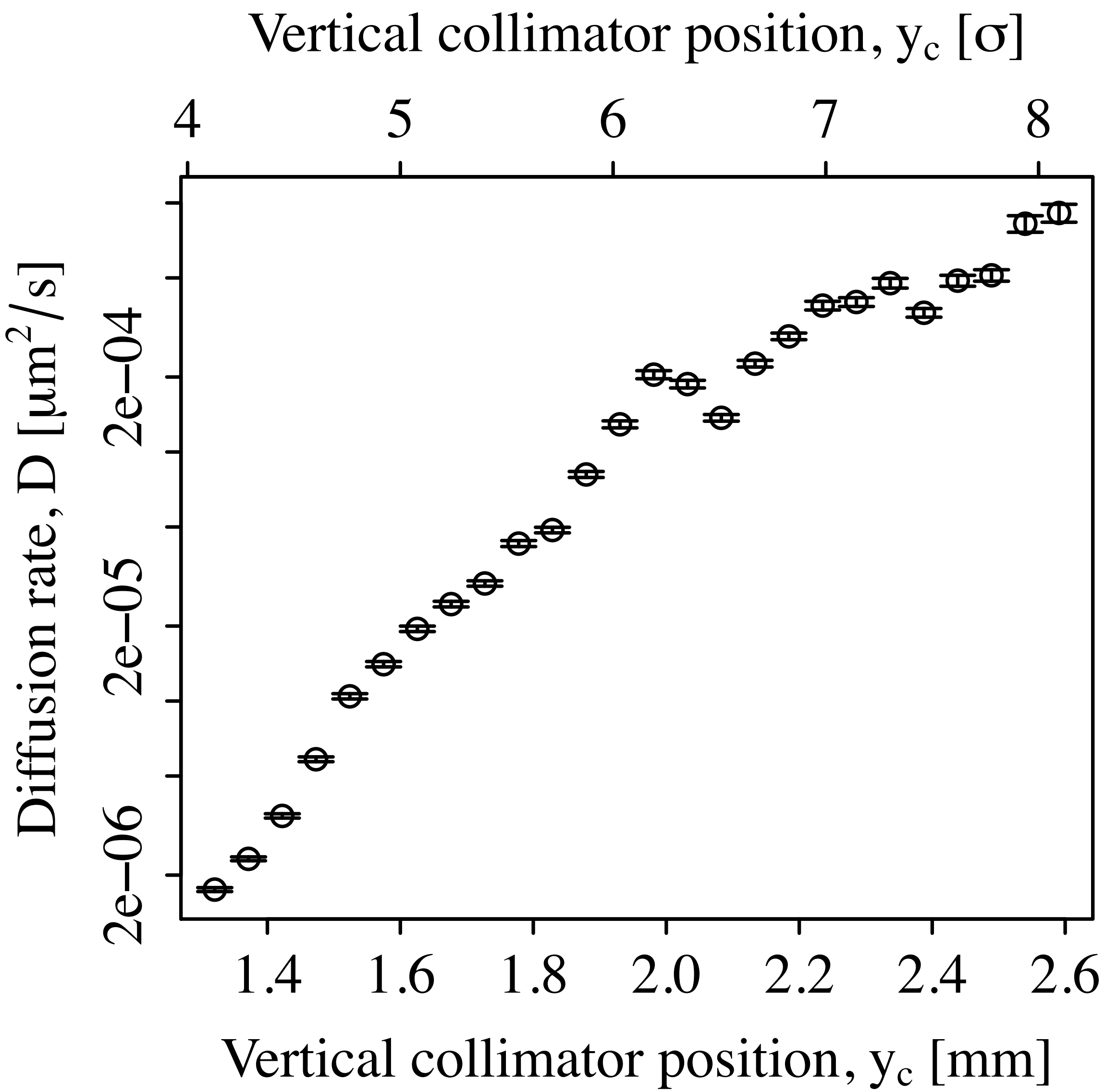


Tails repopulate faster at large amplitudes (higher diffusion rate)



Keeping loss spikes below quench limit constrains collimator settings

Diffusion rate vs. amplitude - preliminary



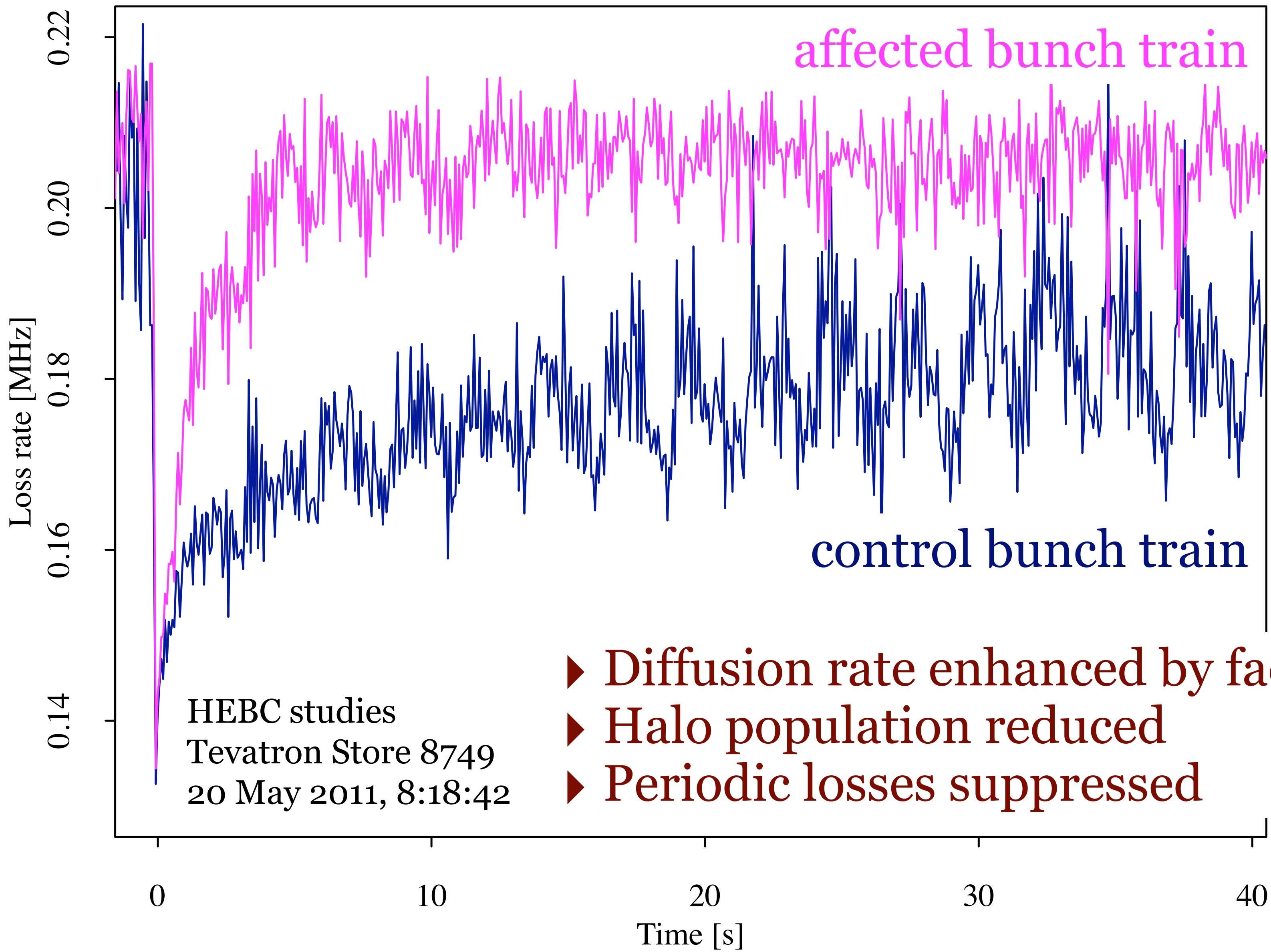
- First measurement of diffusion rates in Tevatron
- $D \sim J^{4.5}$

➡ see Stancari et al., TUPZ033 (this conference)
➡ arXiv:1108:5010

New gated loss monitors during collimator scan

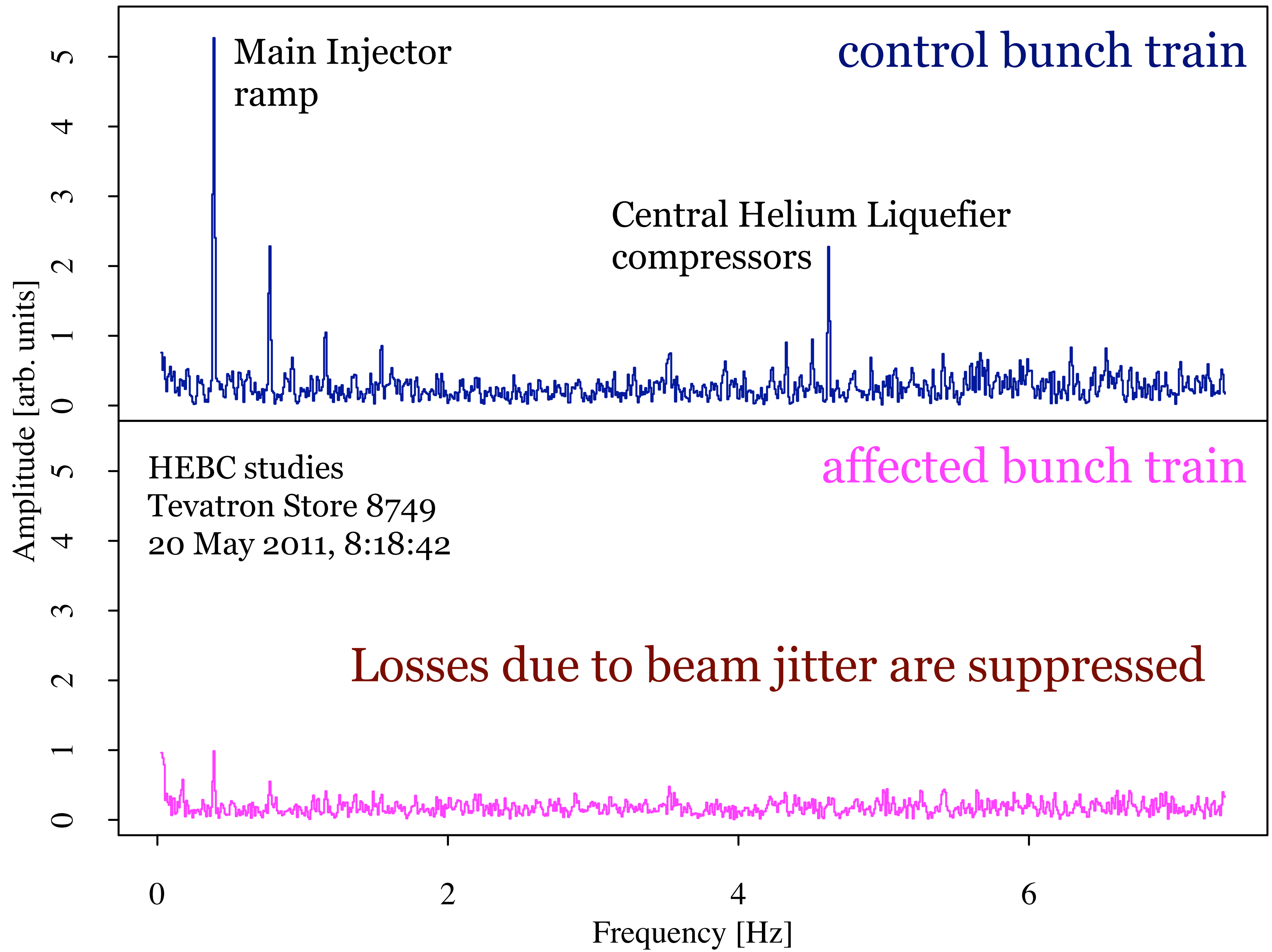
Electrons (0.9 A) on pbar train #2, 4.25σ hole

Example of **vertical collimator step out**, 50 μm

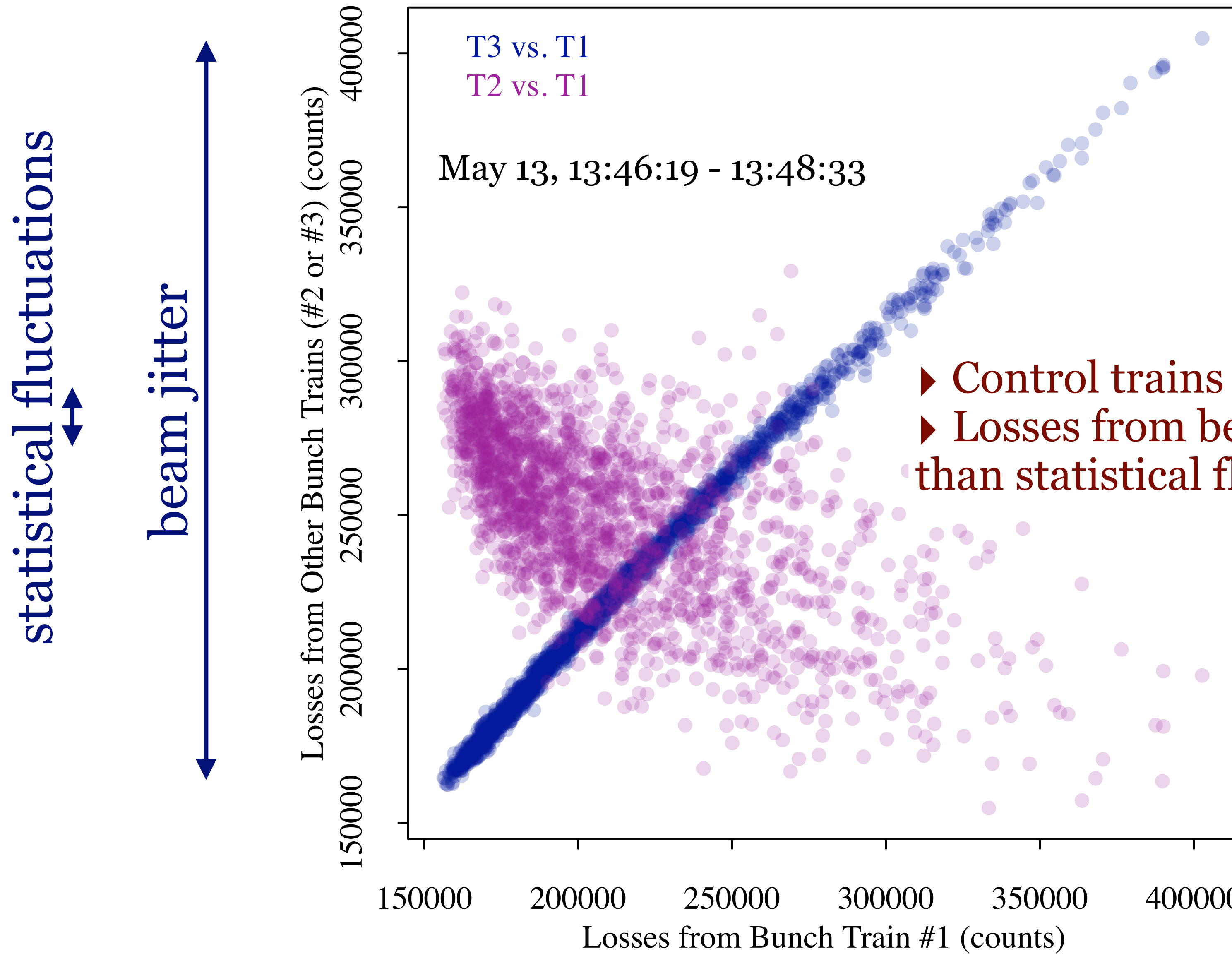


- Diffusion rate enhanced by factor ~10
- Halo population reduced
- Periodic losses suppressed

Fourier analysis of losses



Correlation of steady-state losses



- Control trains strongly correlated
- Losses from beam jitter much larger than statistical fluctuations

- Hollow beam eliminates correlations among trains
- Interpretation: larger diffusion rate, lower tail population, less sensitive to jitter

Summary and outlook

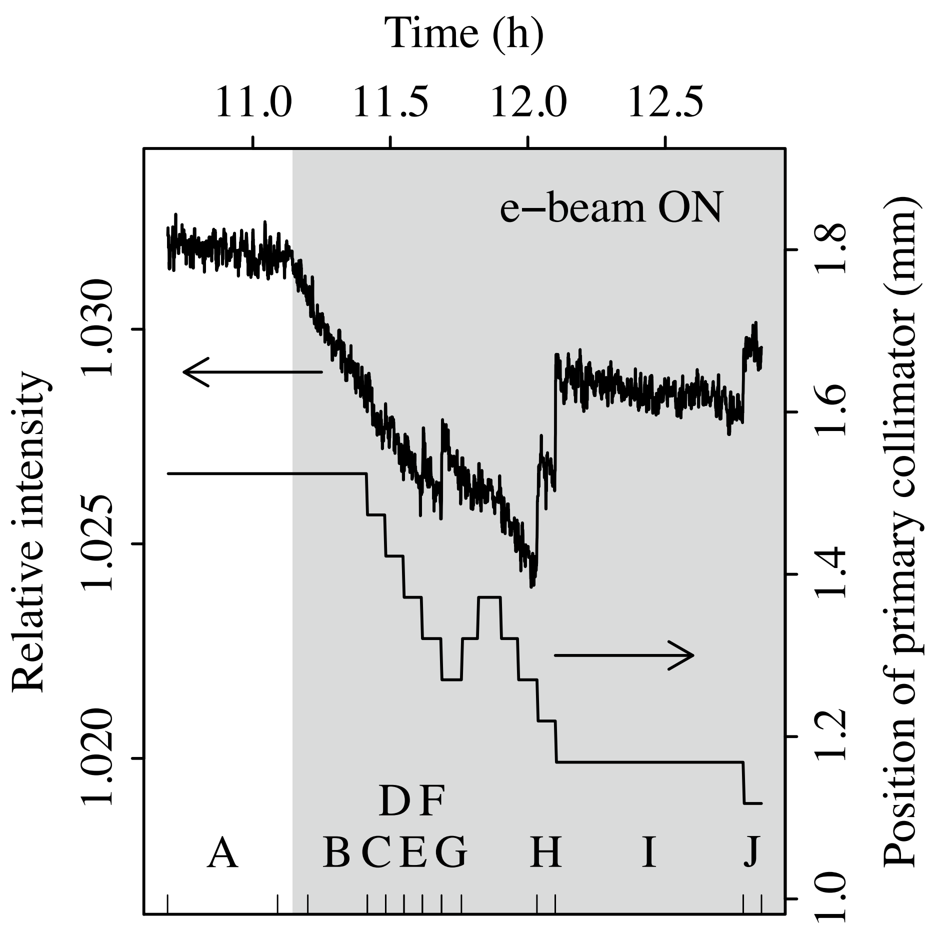
- Hollow electron beams open up new options for beam scraping in high-intensity storage rings and colliders
- Many observations at the Tevatron: compatibility with collider operations, halo removal rates, effects on core, diffusion, fluctuations in losses, collimation efficiencies, ...
- First results in *Phys. Rev. Lett.* **107**, 084802 (2011); arXiv:1105.3256
- A few more studies planned
- New 1-inch, 3-A gun assembly and test
- Validate Tevatron simulations against collected data
- TEL2 hardware will become available after Tevatron shutdown
- Transfer experimental program to CERN? Support from DOE LARP Review and LHC Collimation Review (June 2011).
- Study applicability to LHC in collaboration with CERN: needed? feasible? Possible improvements: scraping before collisions and collimator setup, efficiency for ions.

Thank you for your attention

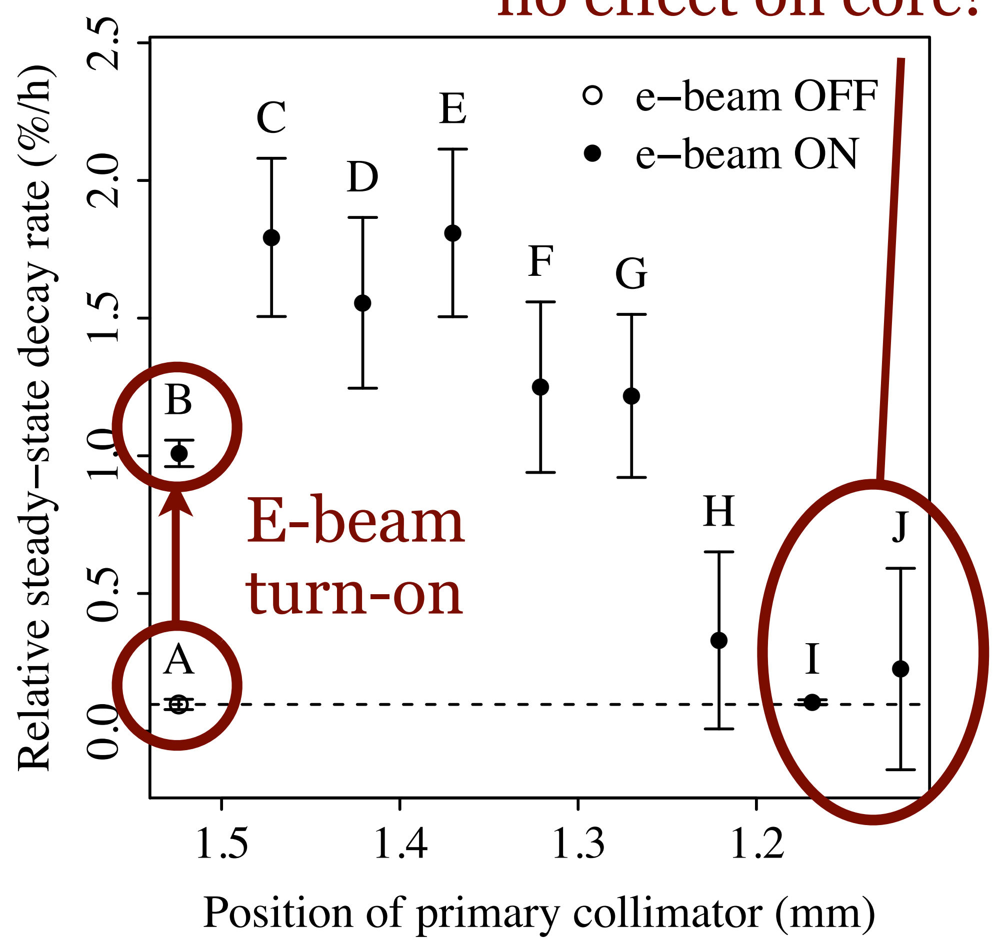
Backup

Removal rate vs. amplitude from collimator scan

Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)
Vertical scan of primary collimator (others retracted)



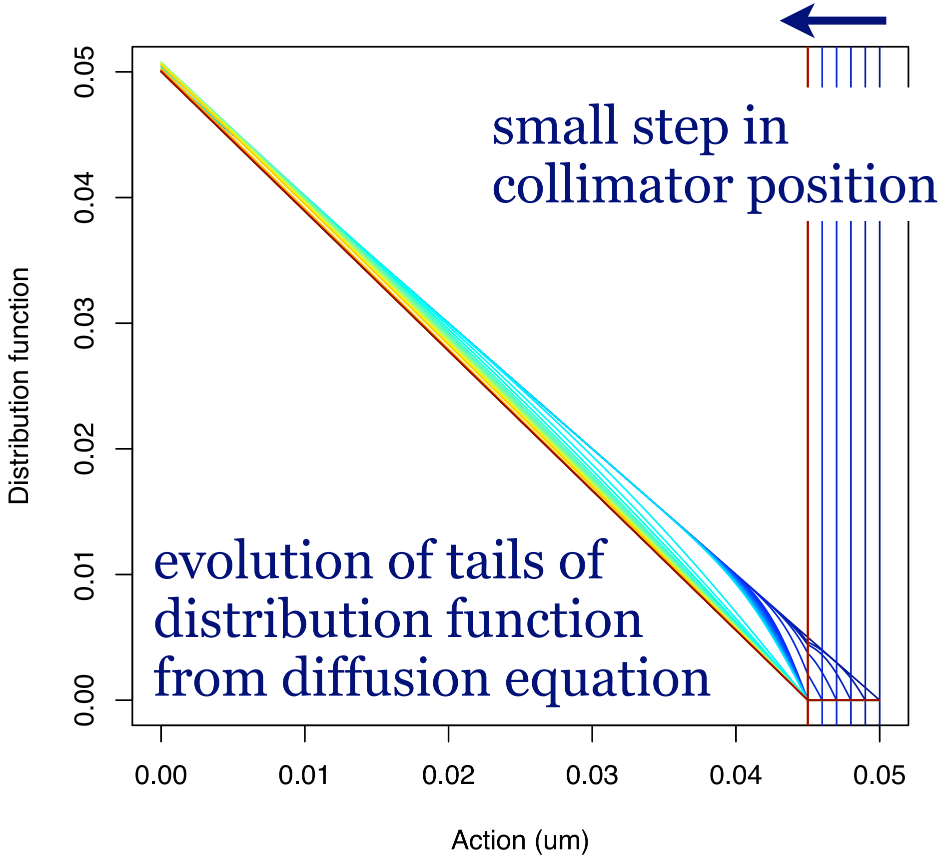
E-beam shadowed, no effect on core!

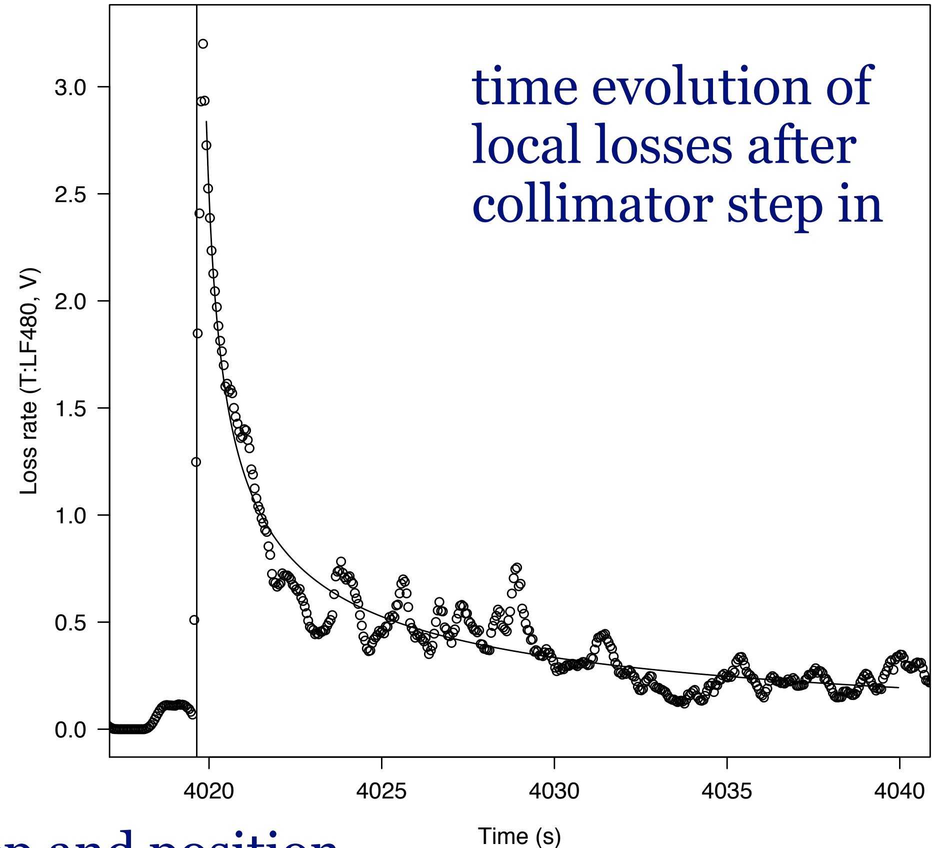


down towards beam axis

Diffusion rate vs. amplitude from collimator scans

Mess and Seidel, NIM A **351**, 279 (1994)





collimator step and position

observed loss rate

$$L(t) = a_1 \left\{ 1 + \frac{|\Delta x_c| / x_c}{\sqrt{\pi R (t - t_0)}} \right\} + a_0$$

background

normalization (intensity, efficiency, ...)

parameter related to diffusion rate

$$D = R \cdot x_c^4 / \beta_c^2$$

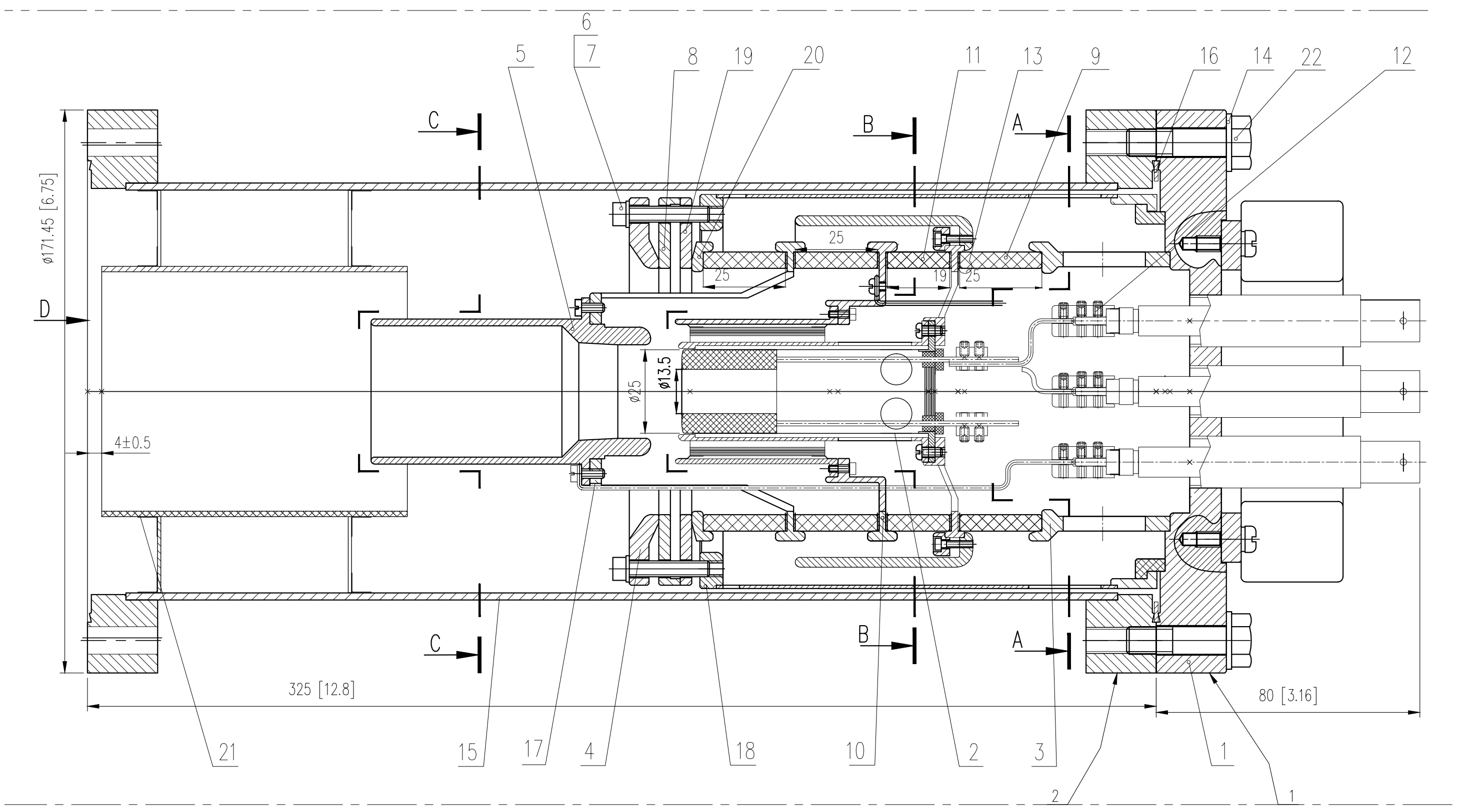
New gated antiproton loss monitors

- Scintillator paddles installed near F49 antiproton absorber
- Gated to individual bunch trains
- Logged at 15 Hz

For simultaneous measurements of **diffusion rates**, **collimation efficiency**, and **loss spikes** on affected and control bunch trains at maximum electron currents

Design of larger (1-inch) hollow gun

- 25 mm outer diameter, 13.5 mm inner diameter
- Up to 3 A at 5 kV



- Goal: To test technical feasibility
- Characterization in Fermilab electron-lens test stand