Measurements of beam halo diffusion and population density in the Tevatron and in the Large Hadron Collider

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Outline

- Introduction: halo population and halo dynamics
- Measurements with collimator scans in Tevatron and LHC
  - Tail populations
  - Diffusivity vs. betatron amplitude
- Nondestructive halo diagnostics
- Comments on halo populations and diffusivity
- Conclusions

Halo dynamics and accelerator performance

Halo dynamics influences global accelerator performance

- beam lifetime
- emittance growth
- dynamic aperture
- collimation efficiency

intrabeam scattering

lattice resonances

beam-gas scattering

coupling

It depends on a multitude of effects, some of which are stochastic in nature

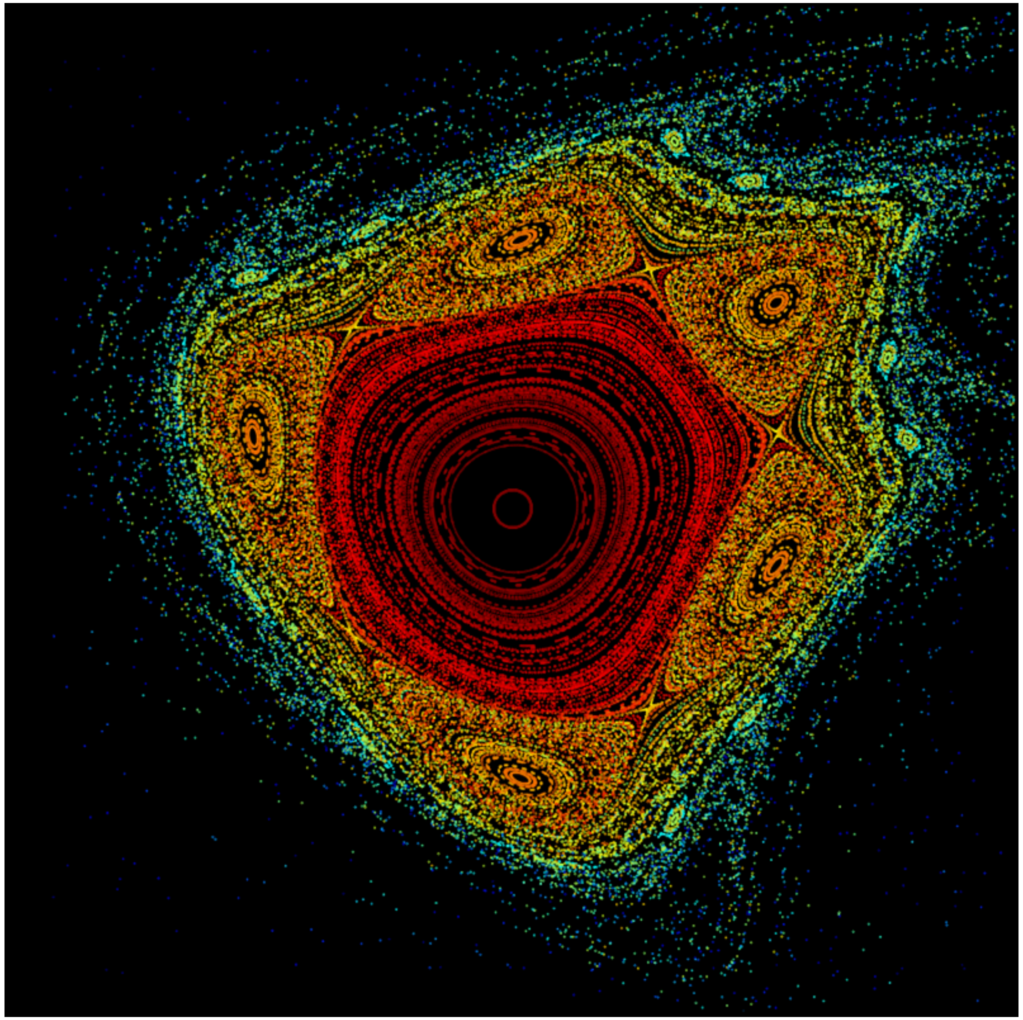
ground motion

lattice nonlinearities

power-supply ripple

beam-beam forces

Stochastic character of halo dynamics

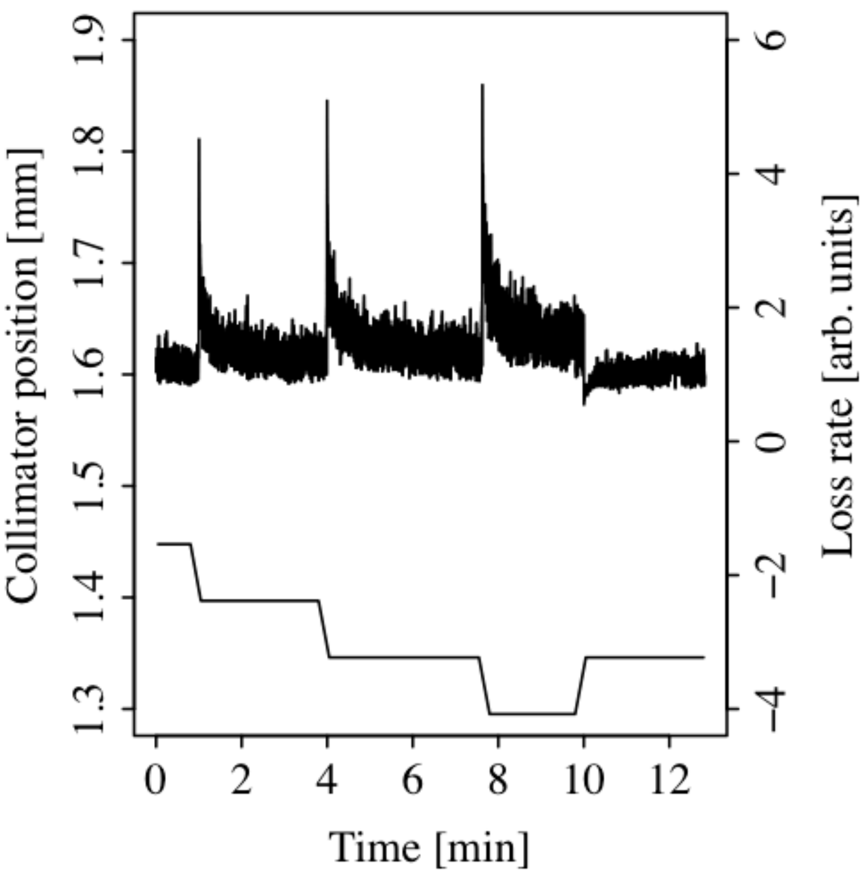


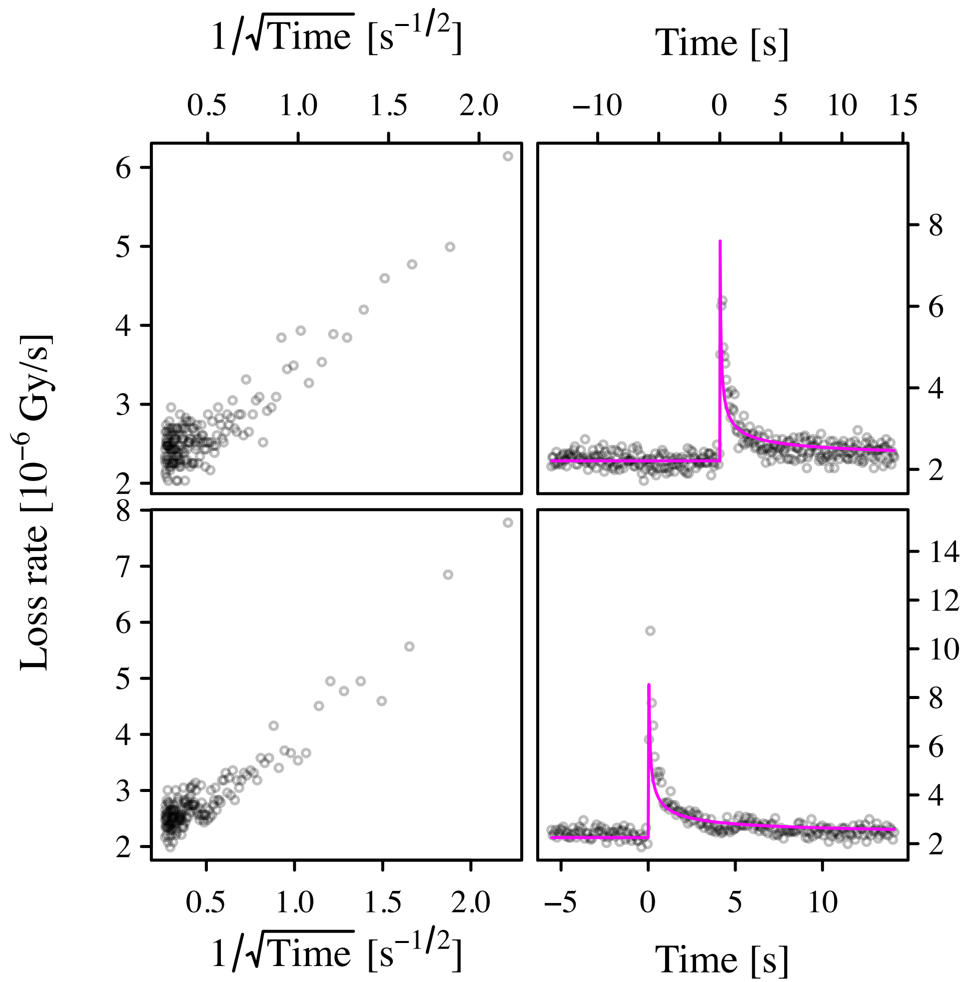
Dynamics is in general very rich: regular and chaotic regions, resonance islands, etc.

Superposition of many effects (some random) can make halo dynamics stochastic

Stochastic character of halo dynamics

Stochastic nature of halo dynamics often empirically confirmed by relaxation of losses ~ (time)$^{-1/2}$ during collimator setup (~ random walk process)

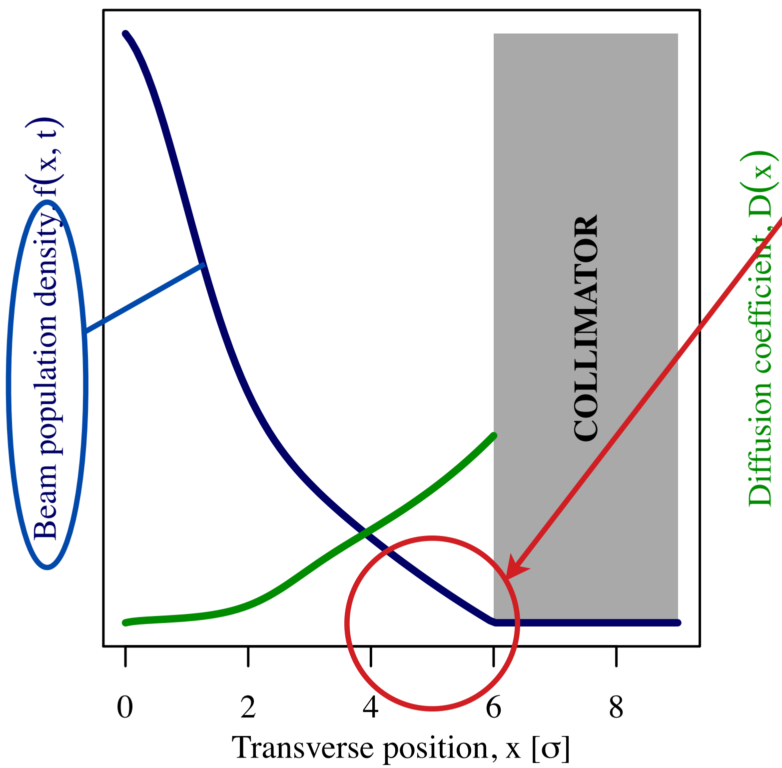




Collimation and beam halo populations are critical for LHC

- LHC and HL-LHC represent huge leaps in stored beam energy

	Tevatron	LHC (2012)	Nominal LHC (2015)	HL-LHC (2023)
Stored energy per beam	2 MJ	140 MJ	**362 MJ**	**692 MJ**



- No scrapers exist in LHC for full beam at top energy
- Halo populations (e.g., 4σ to 6σ) in LHC are not well known. Collimator scans and van-der-Meer luminosity scans indicate 0.1%-2% of total energy, which translates to 0.7 MJ to 14 MJ for HL-LHC at 7 TeV. Comparable to the whole Tevatron beam!

Yesterday's sensation
is today's calibration
and tomorrow's background.
—Anonymous physicist

Collimation and beam halo are critical for LHC

- Quench limits, magnet damage, or even collimator deformation will be reached with fast crab-cavity failures (~2σ orbit shift) or other fast losses

Schmidt et al., IPAC14; Yee-Rendon et al., IPAC14

- Hence the need to measure and monitor the halo, and to remove it at controllable rates. Beam halo monitoring and control are essential for safe operation.

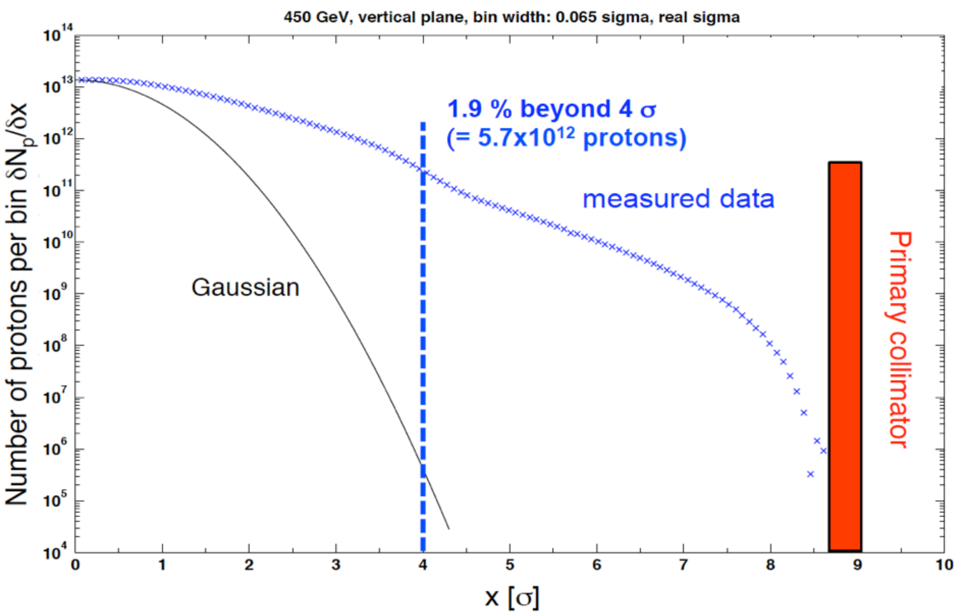
- Hollow electron lenses are the most established and flexible tool for active halo control of high-power beams

Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)
arXiv:1405.2033, CERN-ACC-2014-0248 (2014)

Some estimates of beam tails in LHC

Extinction scans at 450 GeV

Lost intensity vs. collimator position



2-4% beyond 4σ

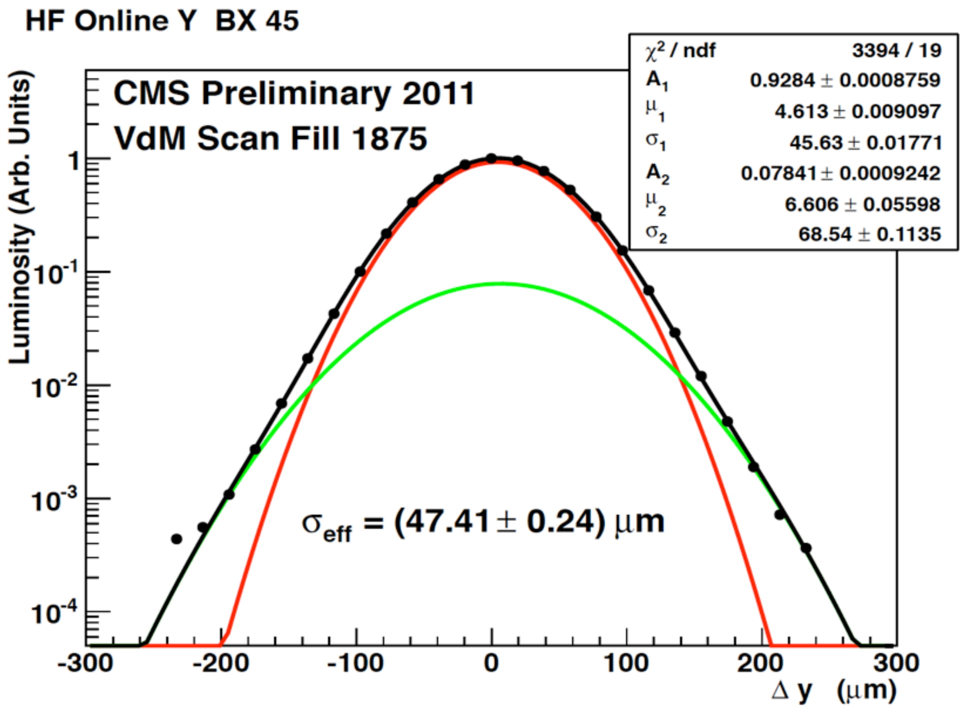
Discrepancy between slow and fast scraping

Assumption: static distribution

Burkart, PhD (2012)

Van-der-Meer luminosity scans

Luminosity vs. beam separation



0.1% above 4σ

Assumption: equal beams

CMS-PAS-EWK-11-001 (2011)

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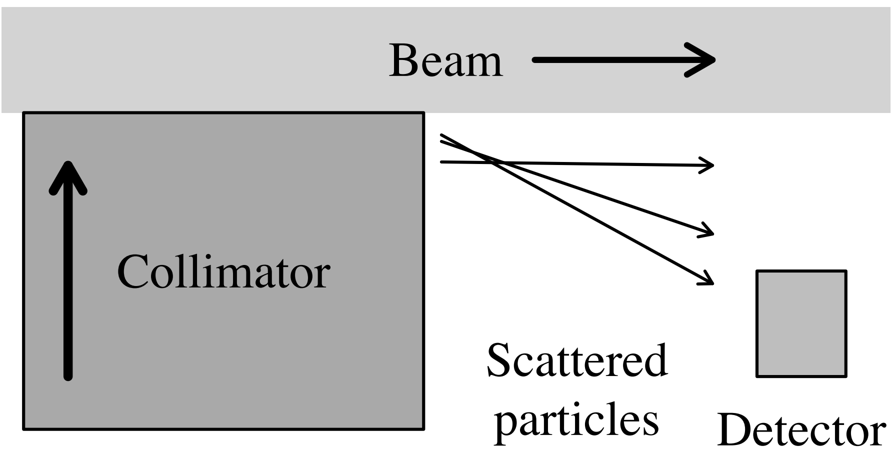
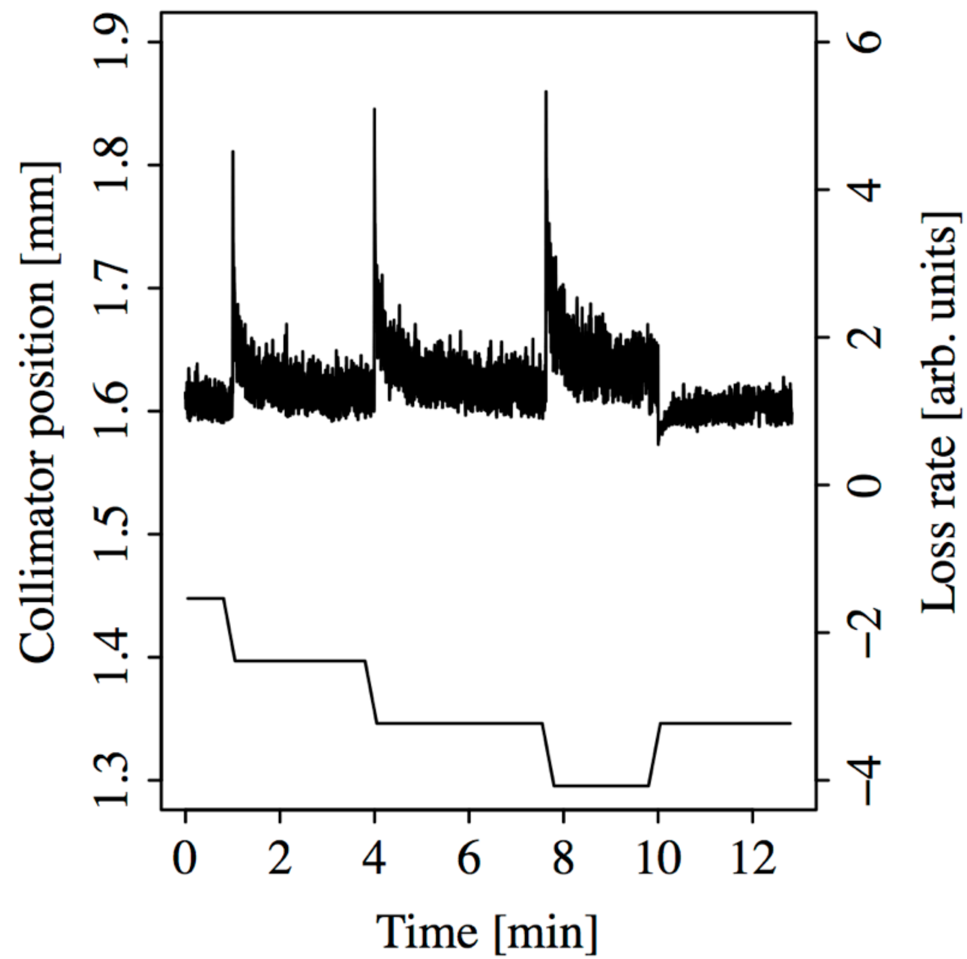
Collimator scans in Tevatron and LHC

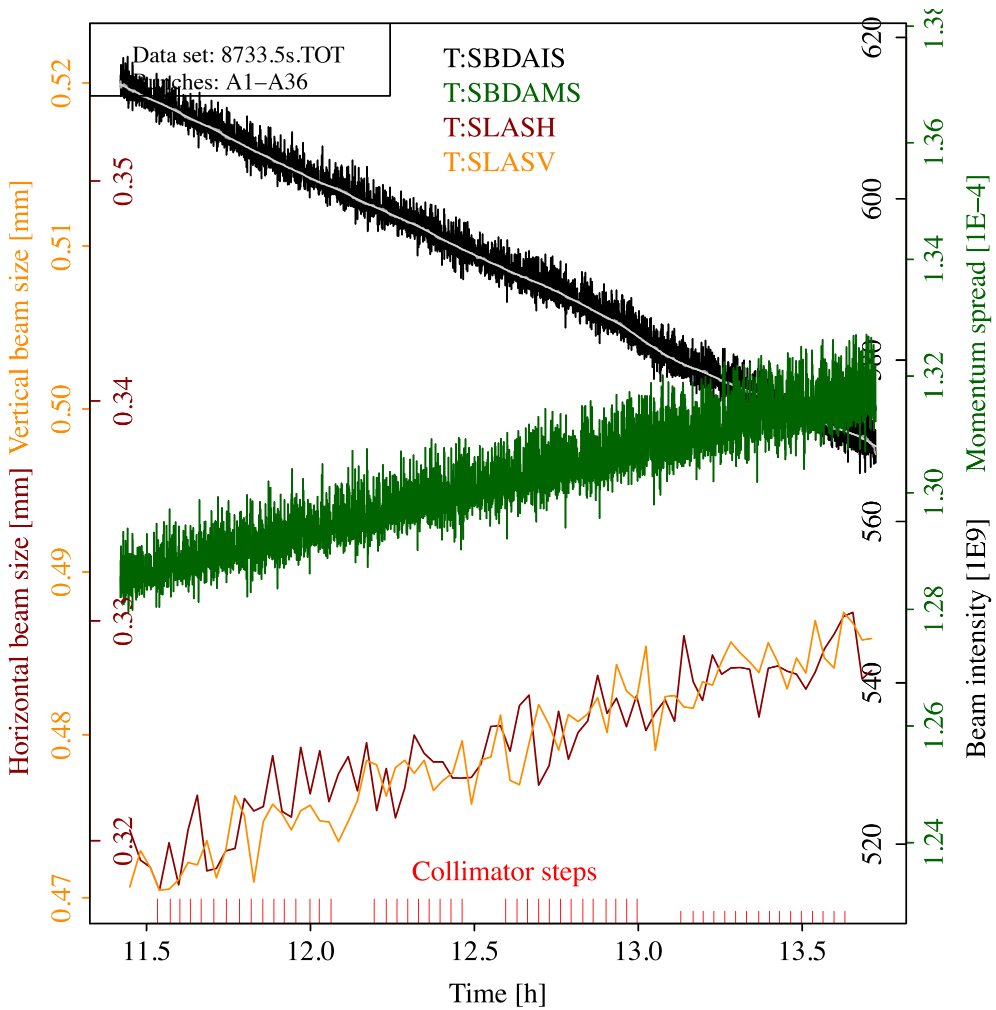
Primary collimator is moved towards or away from beam axis in small steps
Other collimators are retracted



Time evolution of losses is recorded



Tevatron measurements

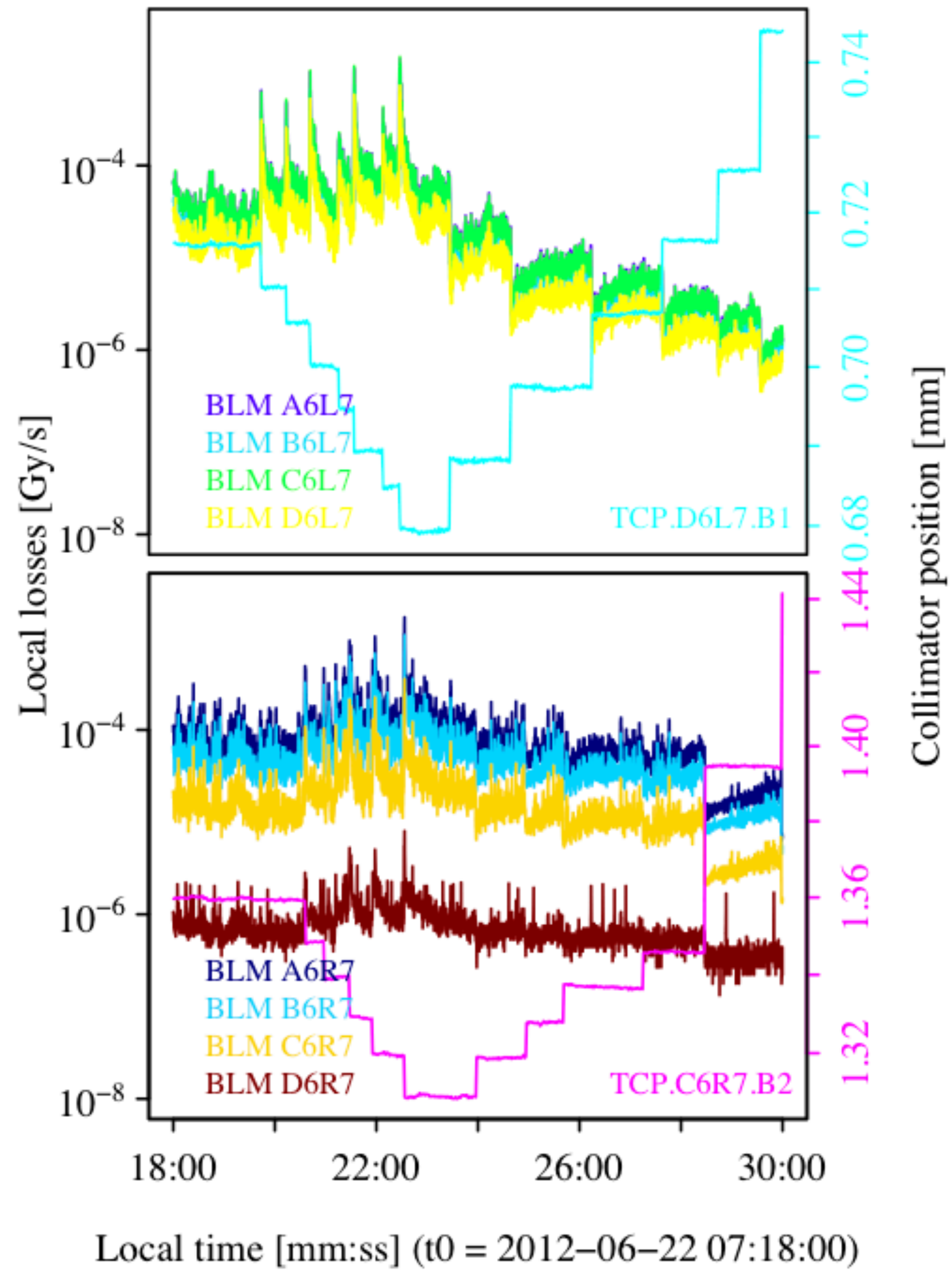


- Beam studies with antiprotons at 0.96 TeV
- Motivated by hollow electron beam collimator and beam-beam dynamics
- Many experiments at the end of regular collider stores
- One experiment with special antiproton-only store
- Scans using primary vertical collimator on antiprotons
- Minimum step: 25 μm in 20 ms

Stancari et al., IPAC11, p. 1882
Stancari et al., HB2012
Stancari et al., BB2013, arXiv:1312.5007

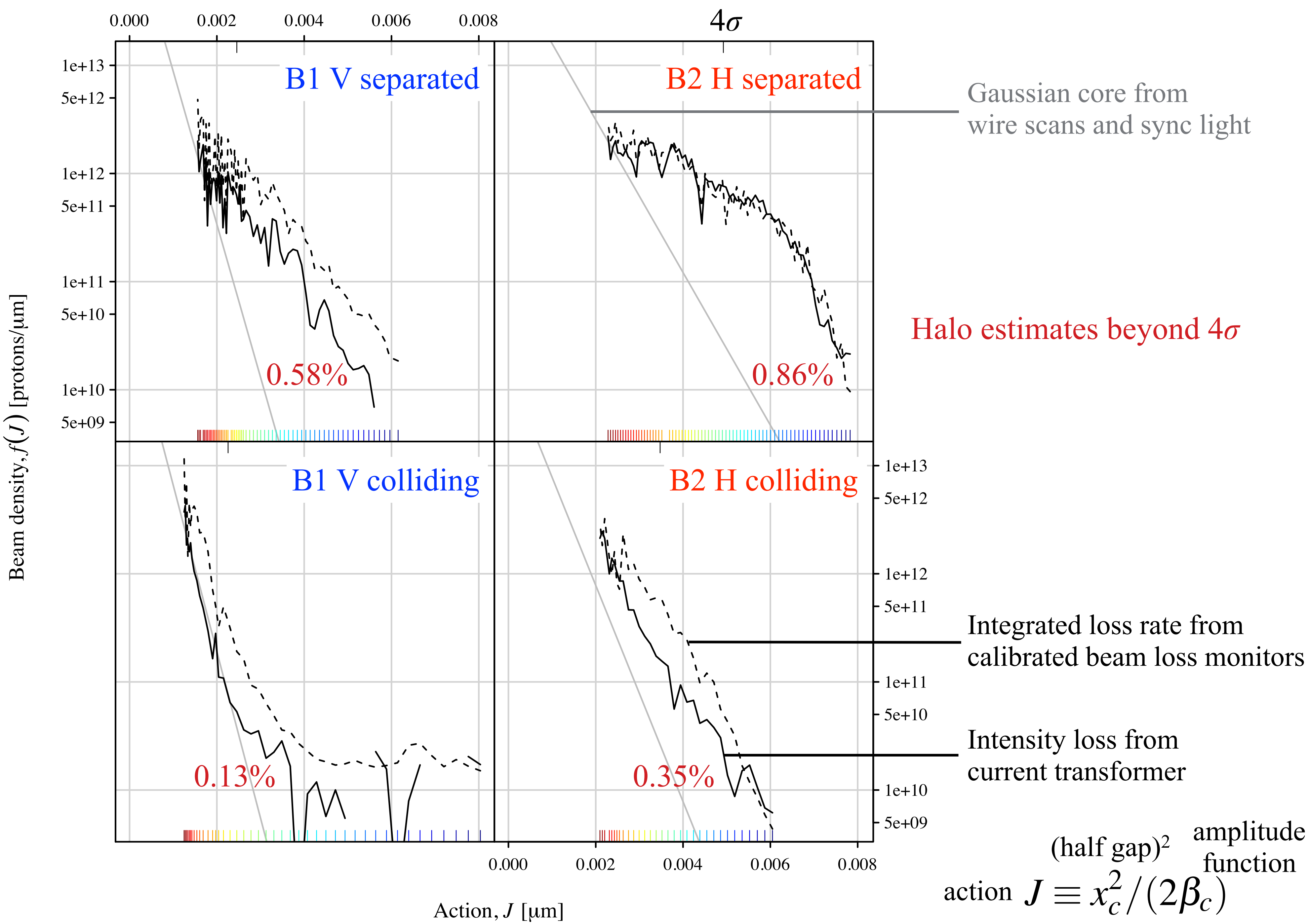
LHC measurements

- Beam studies at 4 TeV
- One nominal bunch per beam, 10^{11} *p*/bunch (no long-range)
- Scans using primary collimators: vertical on beam 1, horizontal on beam 2
- 1 scan with separated beams, 1 scan in collision
- Minimum step: 5 μm in 2.5 ms



Valentino et al., PRSTAB **16**, 021003 (2013)

Halo population density in LHC at 4 TeV with collimator scans



(half gap)^2 amplitude function

action $J \equiv x_c^2/(2\beta_c)$

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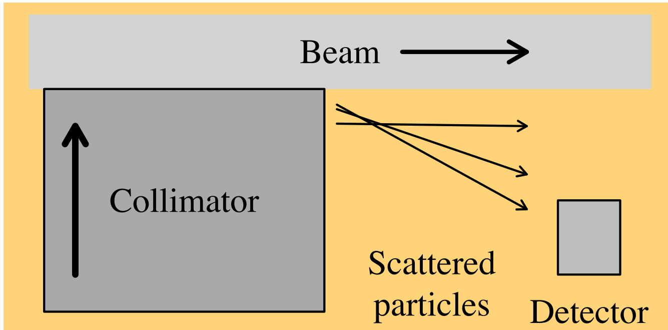
Analytical and numerical studies on collisions and halo dynamics

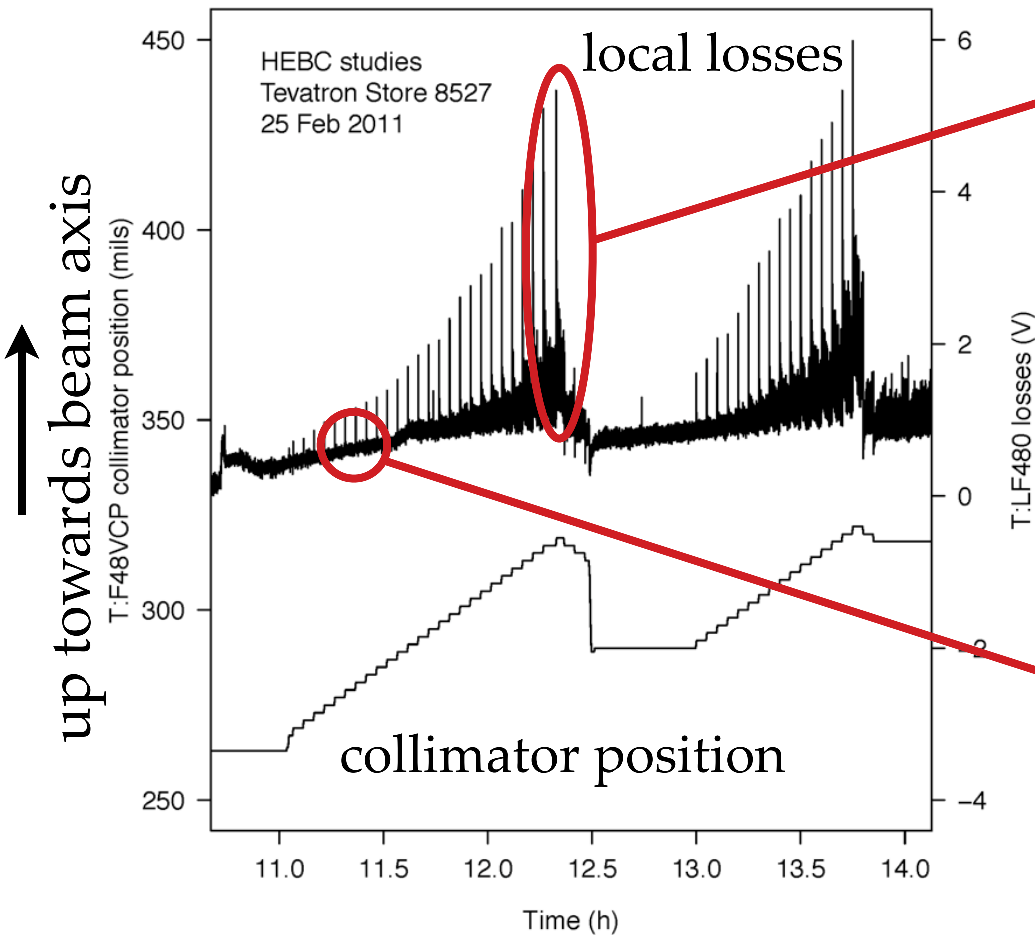
Just a few examples...

Experiments are challenging and data is scarce

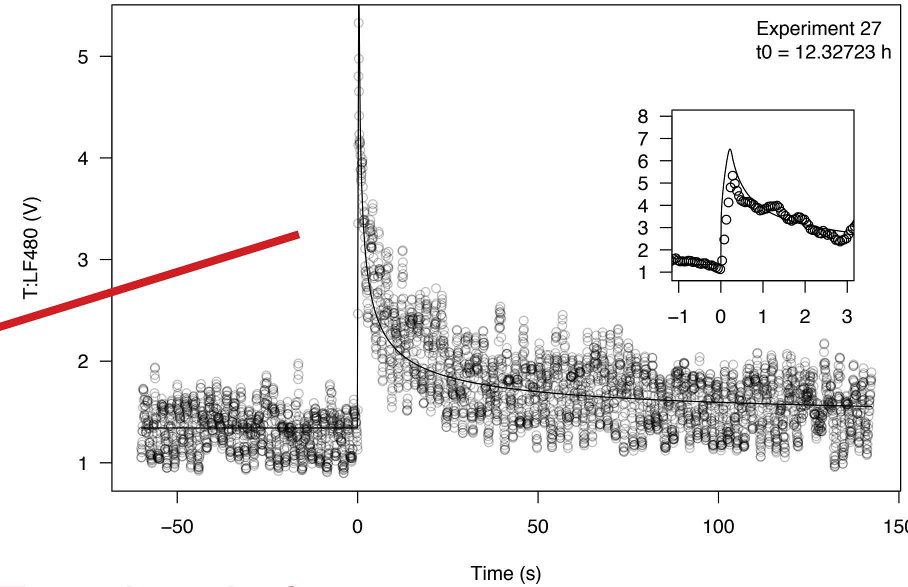
- **SSC**: *long-range, diffusive dynamic aperture*
  - Irwin, SSC-233 (1989)
- **HERA at DESY**: *nonlinearities, tune modulation, fluctuations in orbit offset and beam size*
  - Zimmermann, PhD Thesis (1993)
  - Brüning, PhD Thesis (1994)
  - Seidel, PhD Thesis (1994)
  - Zimmermann, Part. Accel. 49, 67 (1995)
  - Sen and Ellison, PRL 77, 1051 (1996)
- **LHC at CERN**: *head-on, long-range, triplet nonlinearities*
  - Papaphilippou and Zimmermann, PRSTAB 2, 104001 (1999)
  - Papaphilippou and Zimmermann, PRSTAB 5, 074001 (2002)
  - Assmann et al., EPAC (2002)
- **Tevatron at Fermilab**: *beam-beam, nonlinearities, electron lenses*
  - Sen et al., PRSTAB 7, 041001 (2004)
  - Stern et al., PRSTAB 13, 024401 (2010)
  - Previtali et al., IPAC (2012)
- **RHIC at BNL**: *beam-beam, nonlinearities, electron lenses*
  - Abreu et al., BNL-81974-2009-IR, BNL-81975-2009-IR (2009)
- **Beam / electron cloud**:
  - Ohmi and Oide, PRSTAB 10, 014401 (2007)

Measurement of diffusion rate vs. amplitude with collimator scans

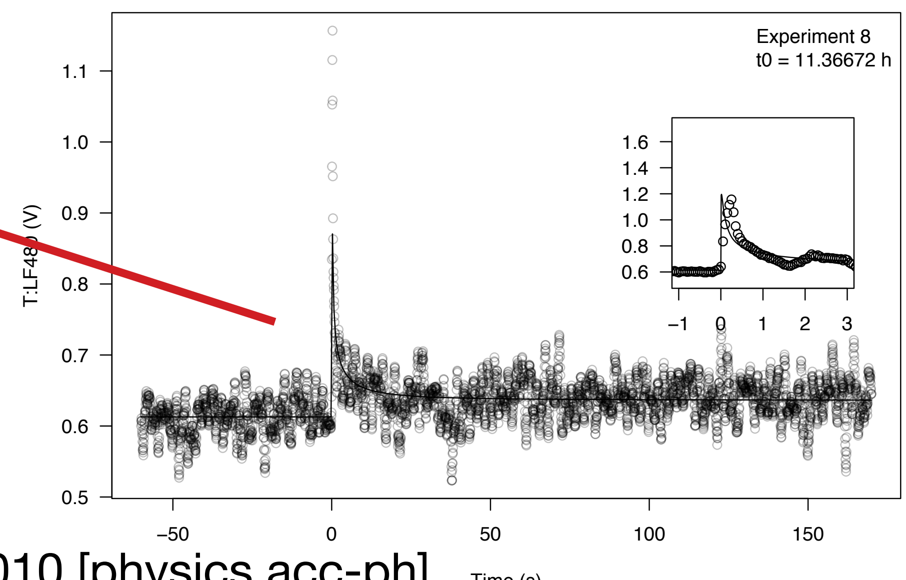




Mess and Seidel, NIMA **351**, 279 (1994)

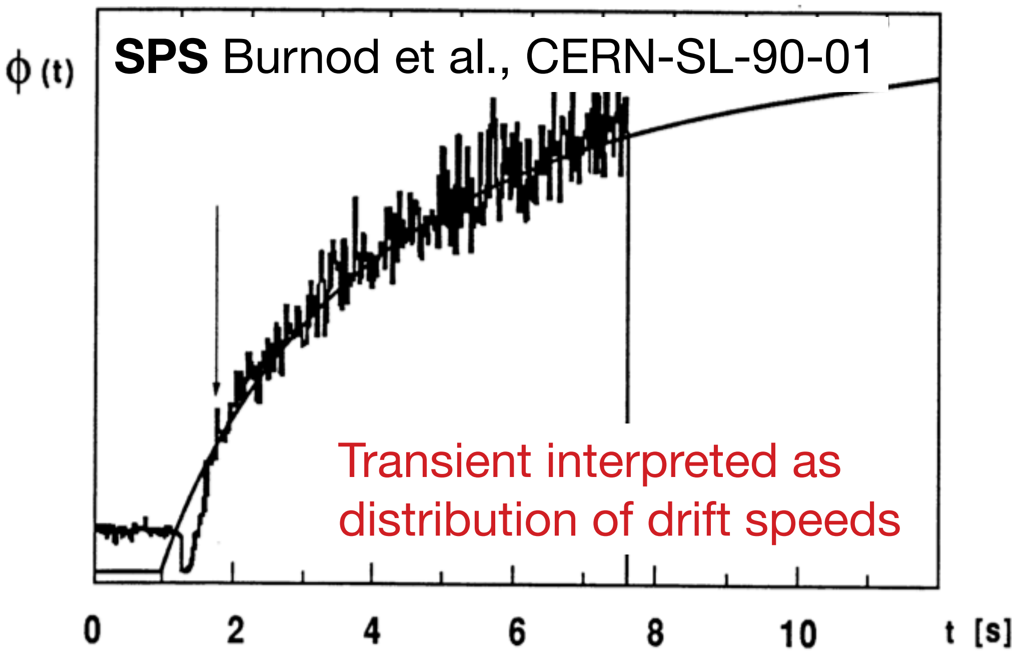


Transient is faster at
large amplitudes (higher diffusion rate)

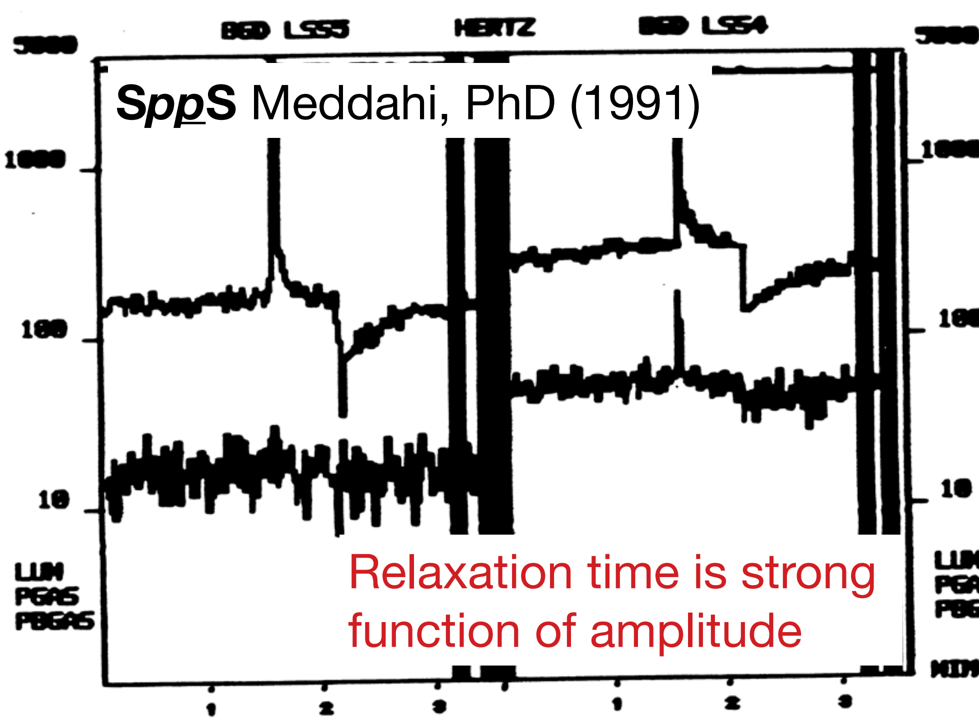


Stancari, FERMILAB-FN-0926-APC, arXiv:1108.5010 [physics.acc-ph]

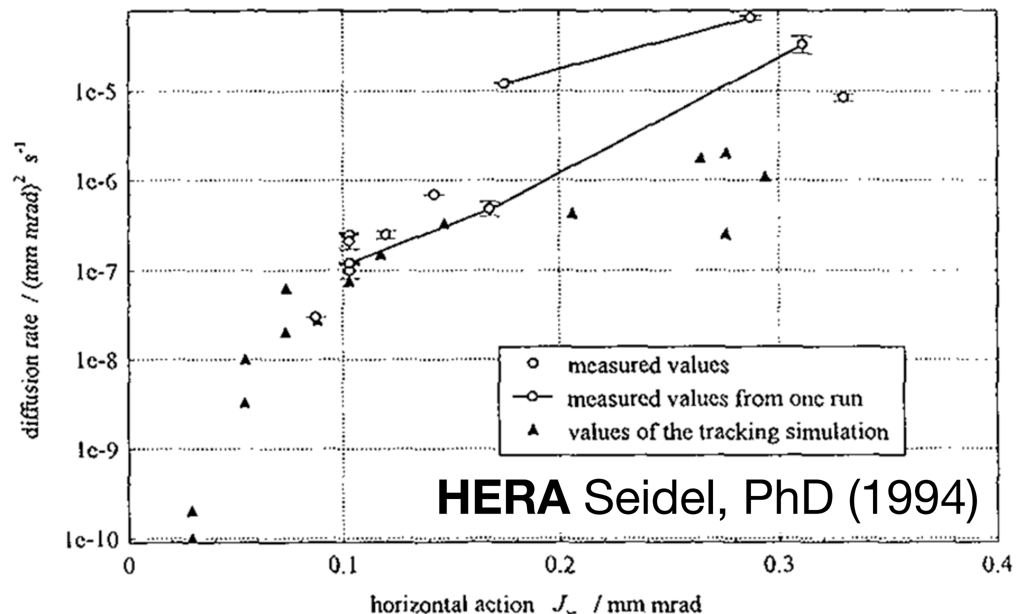
Previous observations



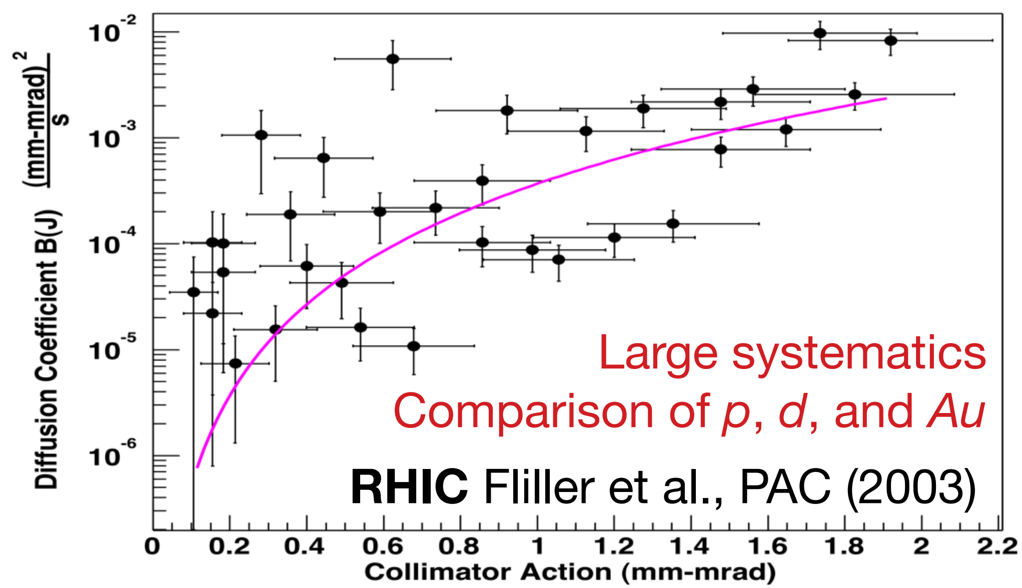
Transient interpreted as distribution of drift speeds



Relaxation time is strong function of amplitude



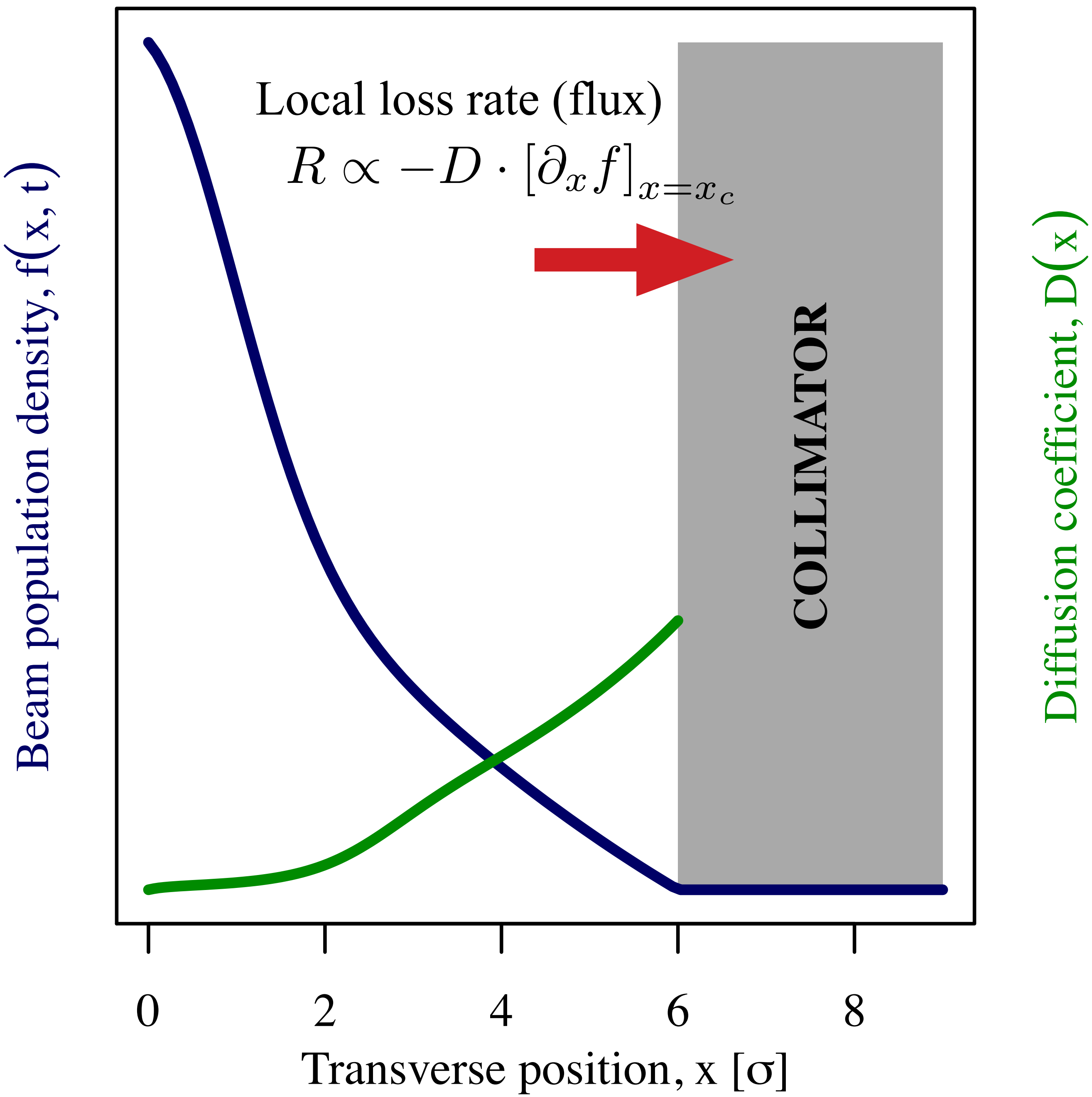
Calculated beam-beam and tune modulation close to measured diffusion rate



Large systematics

Comparison of *p*, *d*, and *Au*

1-dimensional diffusion cartoon of collimation



Diffusion model of loss rate evolution in collimator scans

Distribution function of tails evolves under diffusion with boundary condition at collimator

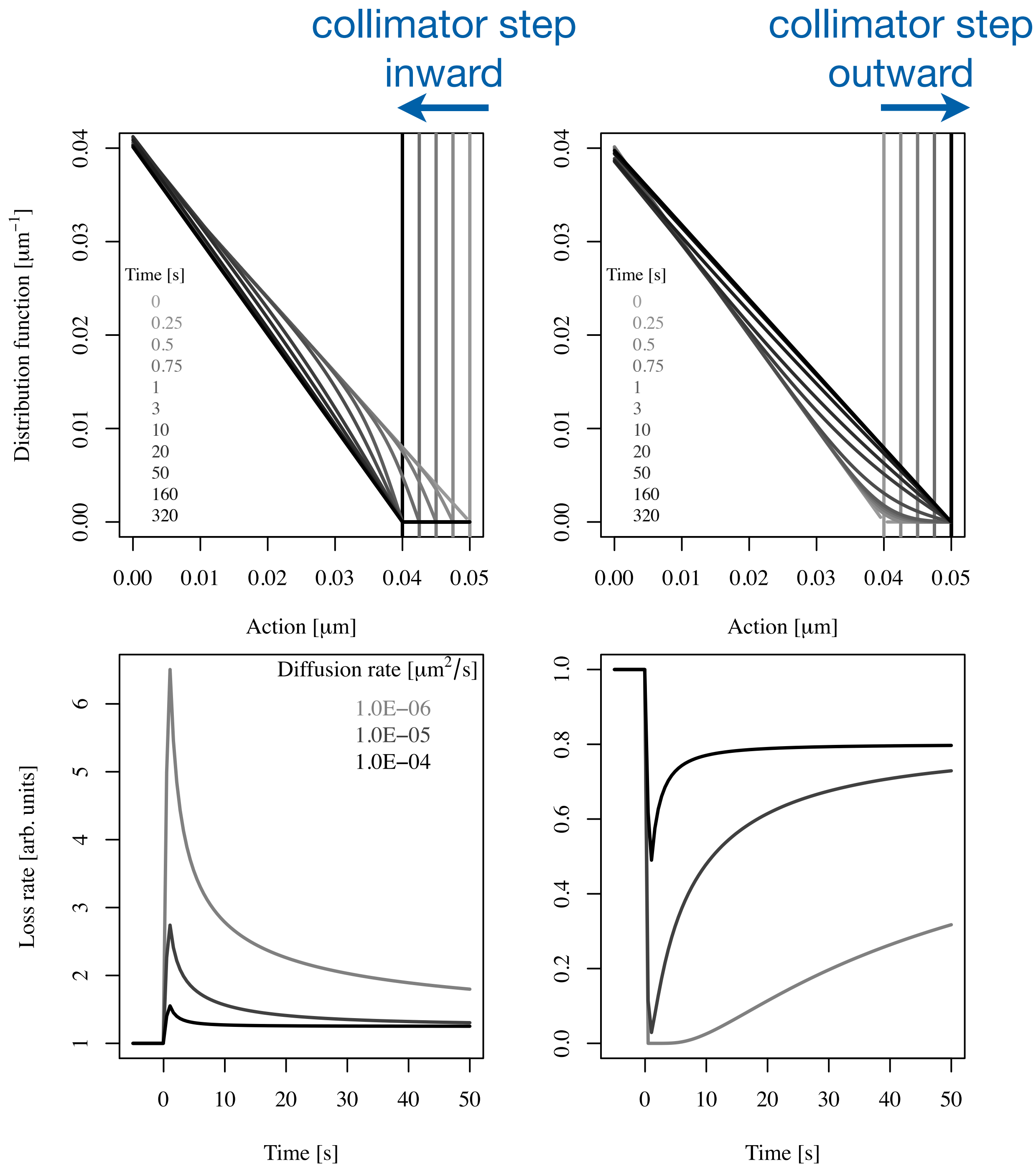
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

Instantaneous loss rate is proportional to slope of distribution function

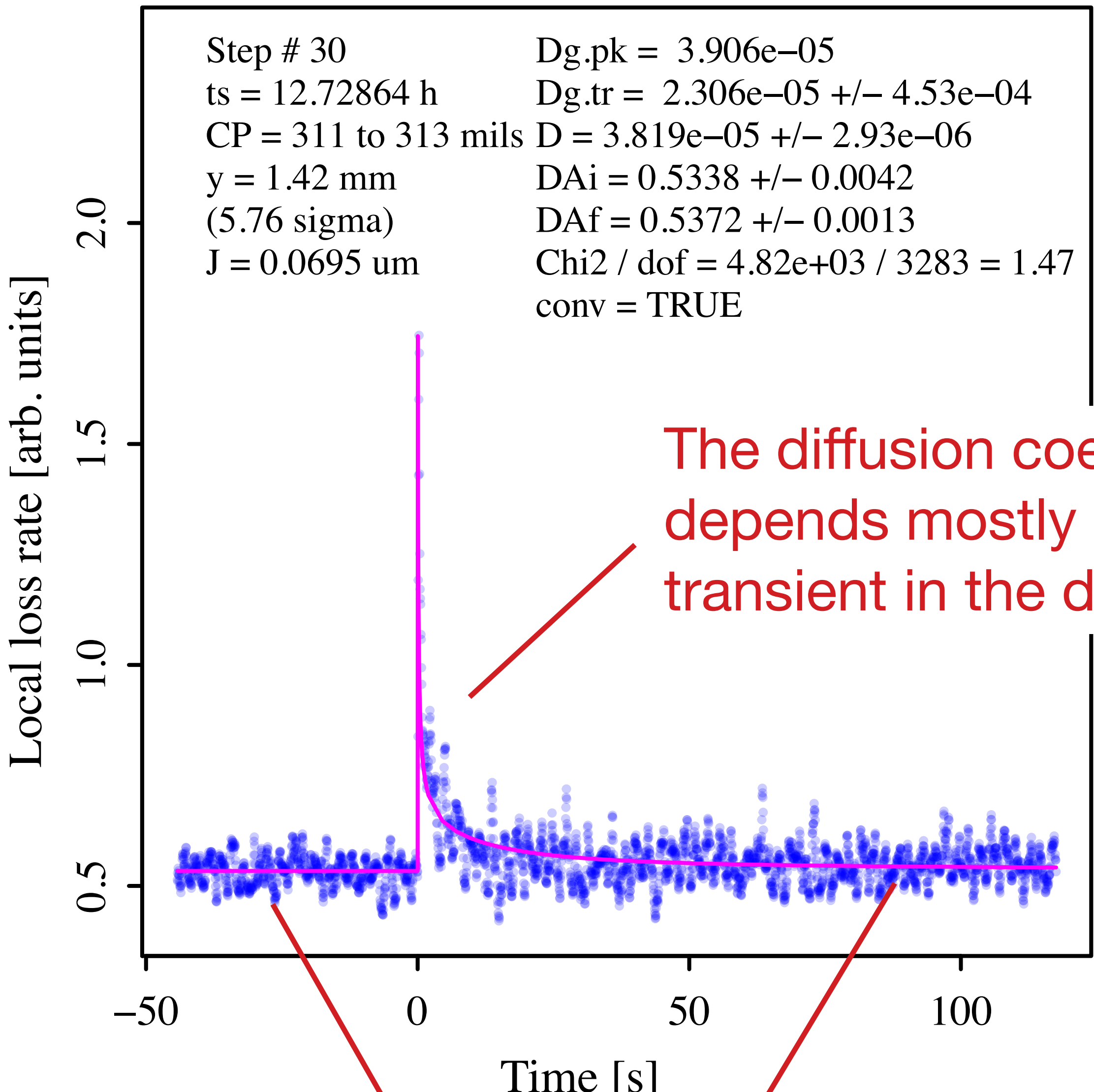
$$R = -k \cdot D \cdot \left[\partial_J f \right]_{J=J_c} + B$$

loss monitor calibration

background rate



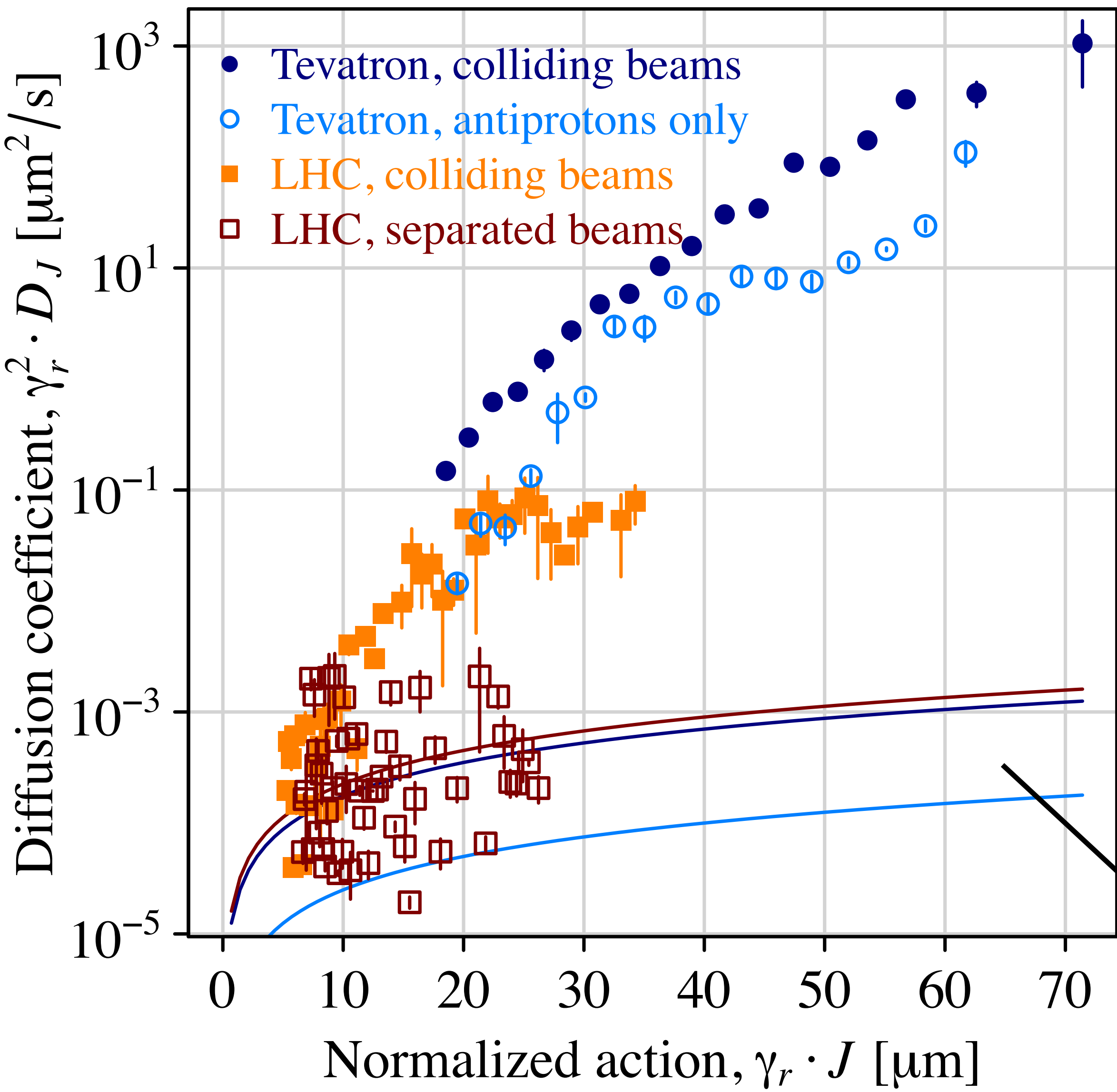
Diffusion model fit to loss rate data



The diffusion coefficient depends mostly on the transient in the data

Particle fluxes before and after the step are determined by the steady-state loss levels

Beam halo diffusion rates in the Tevatron and in the LHC



Effect of beam-beam is 1-2 orders of magnitude

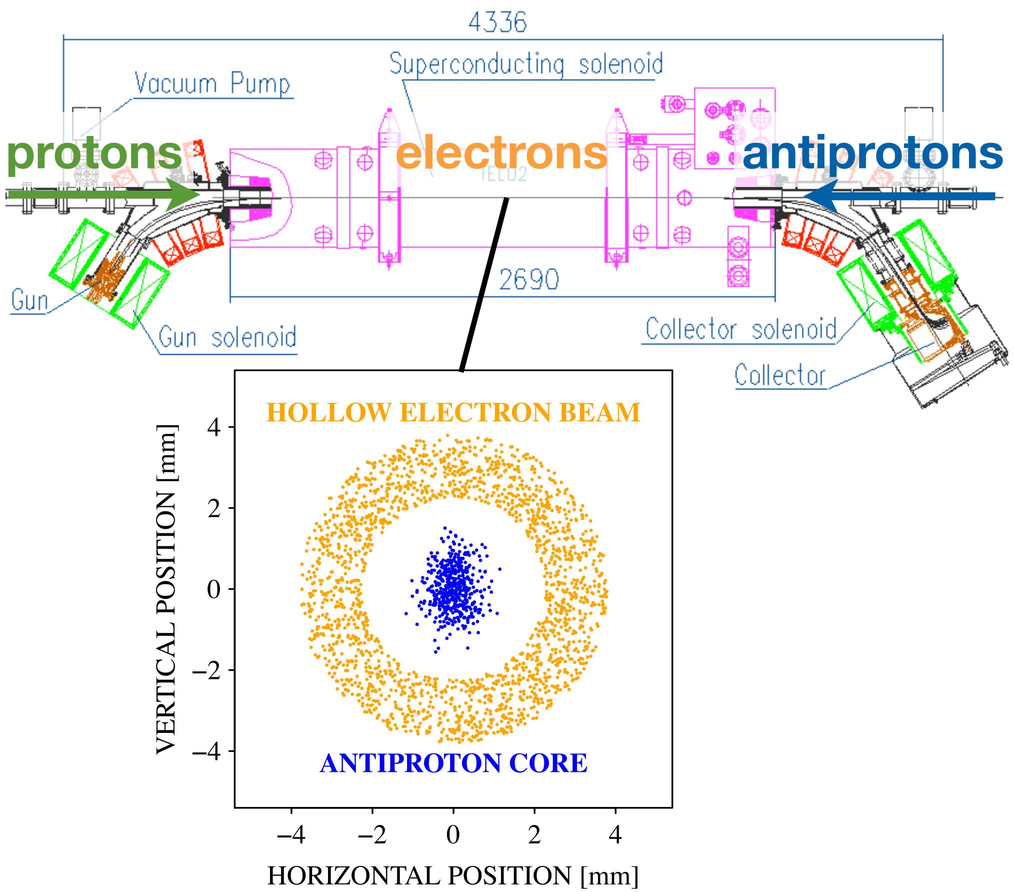
Near core, diffusivity consistent with emittance growth

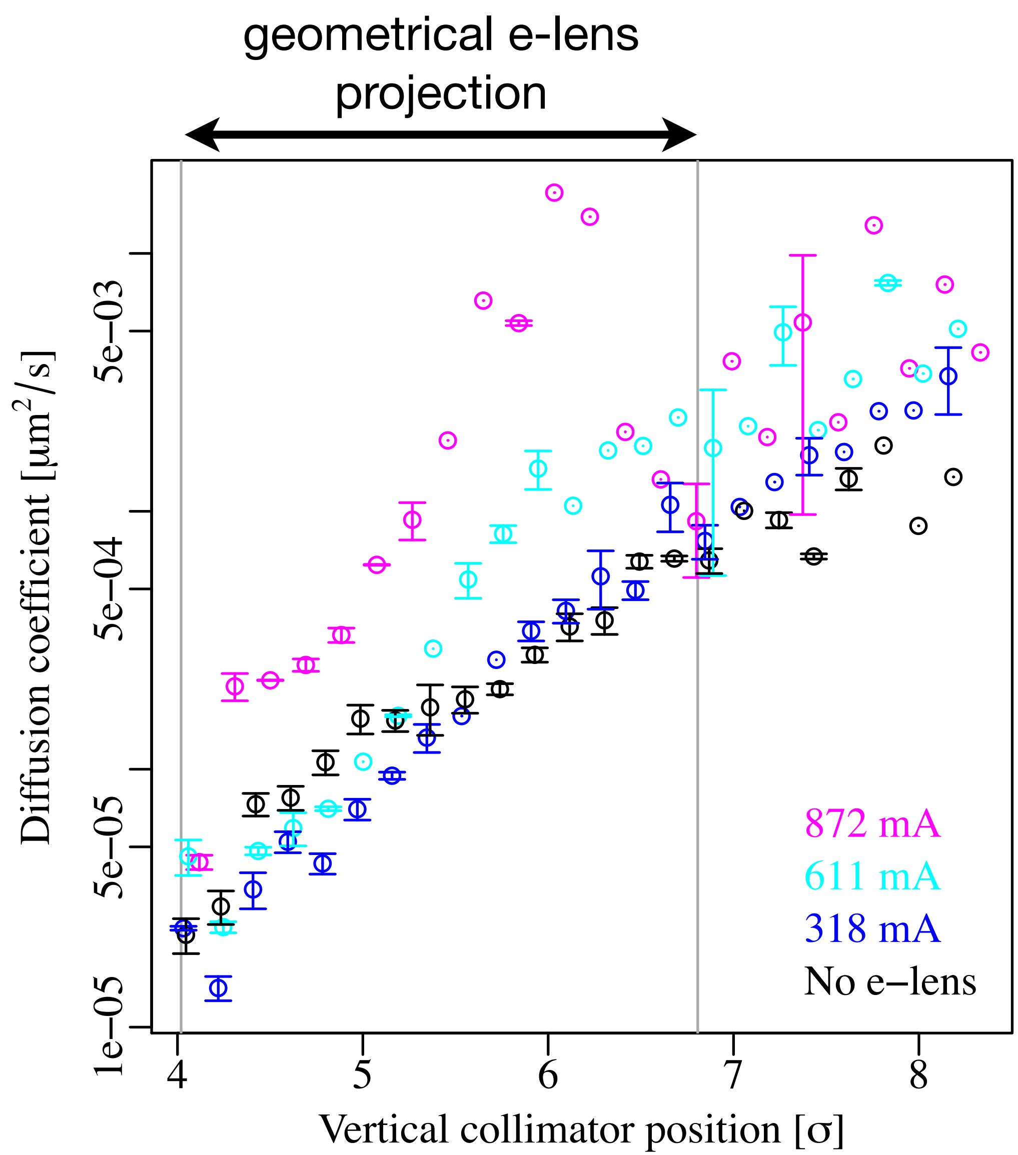
Very low noise and nonlinearities in LHC

curves from measured core emittance growth

$$D_J = \dot{\varepsilon} \cdot J$$

Effect of hollow electron lens on diffusion in the Tevatron





To our knowledge, first direct observation of controlled diffusion enhancement in specific amplitude range!

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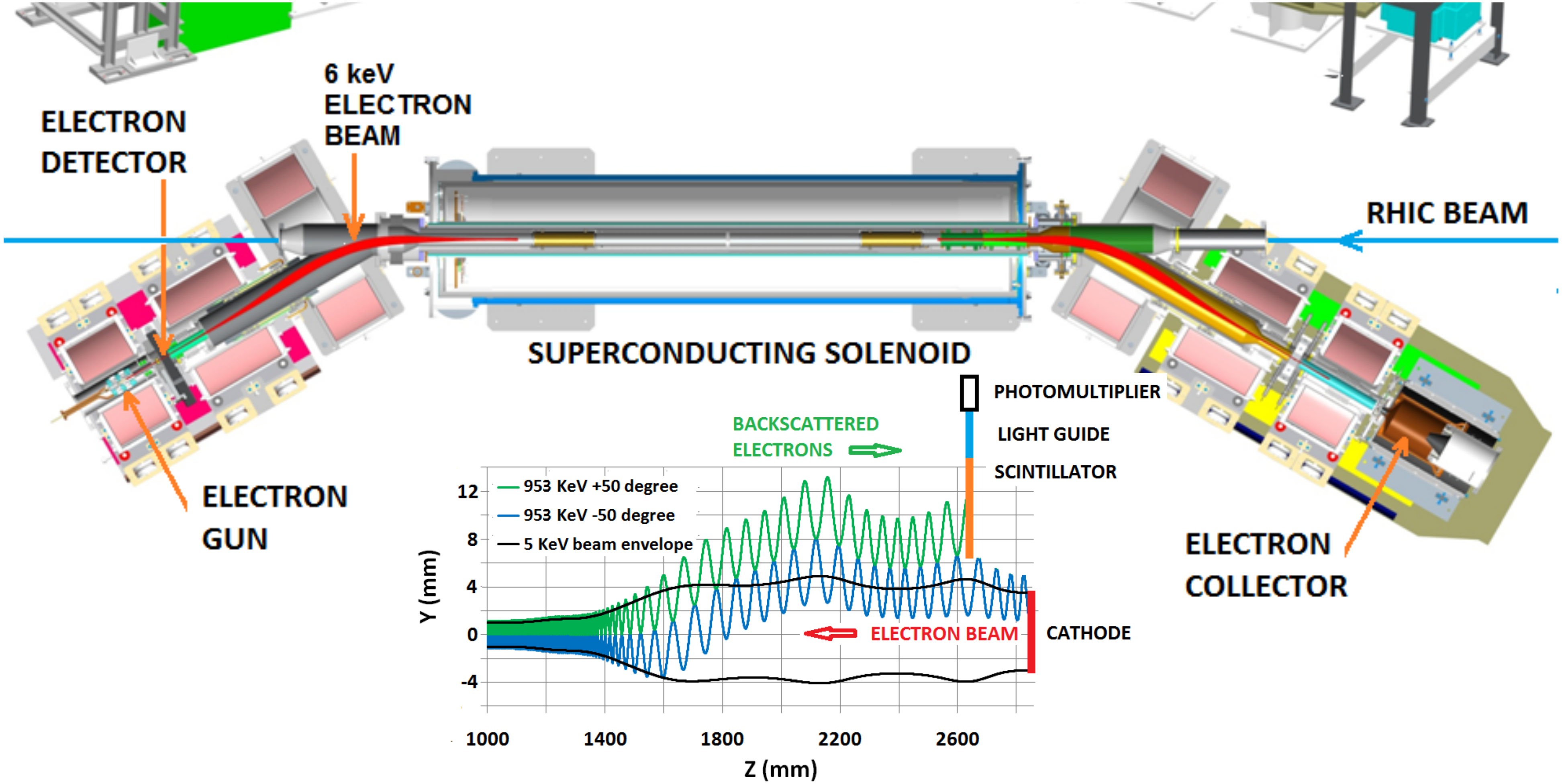
Backscattered electron detector in RHIC electron lenses



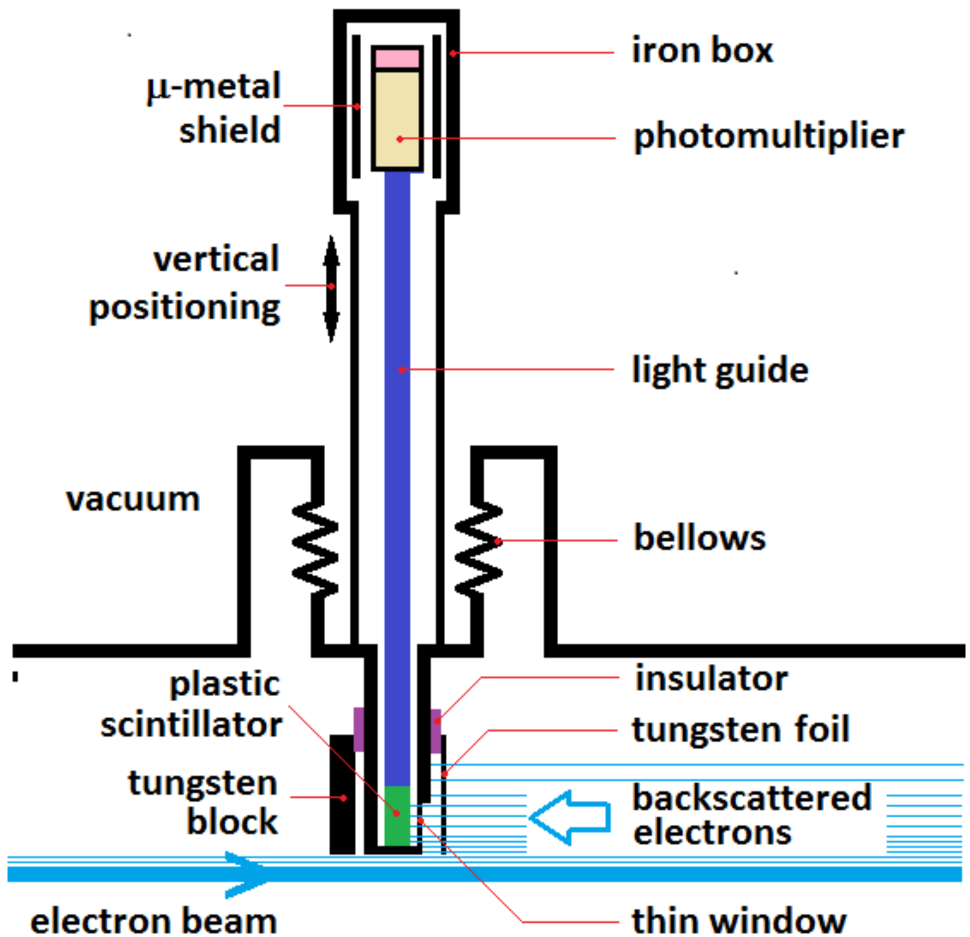
- The rate of electrons backscattered towards the gun by Coulomb collisions is a **sensitive probe of the overlap** between electron and circulating beam

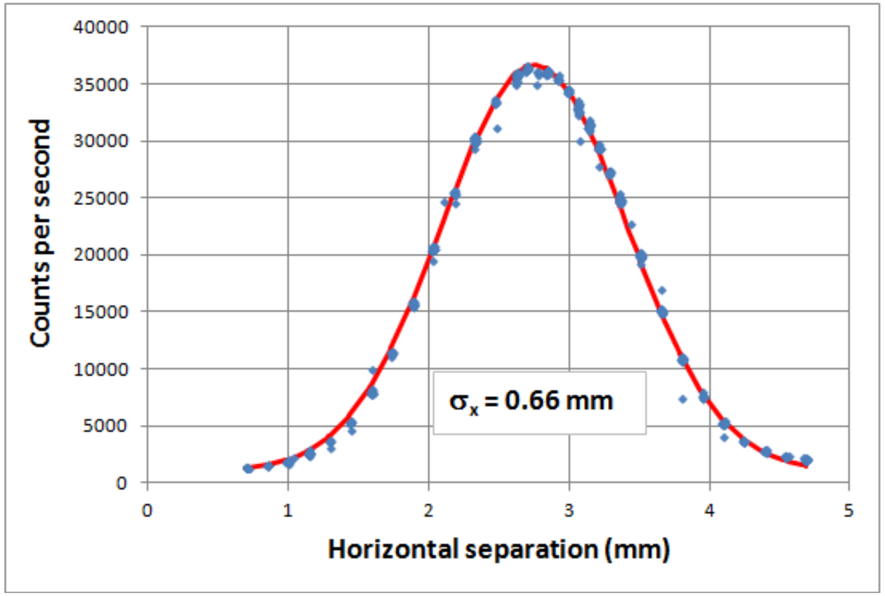
- High dynamic range, promising for **continuous nondestructive halo monitoring**

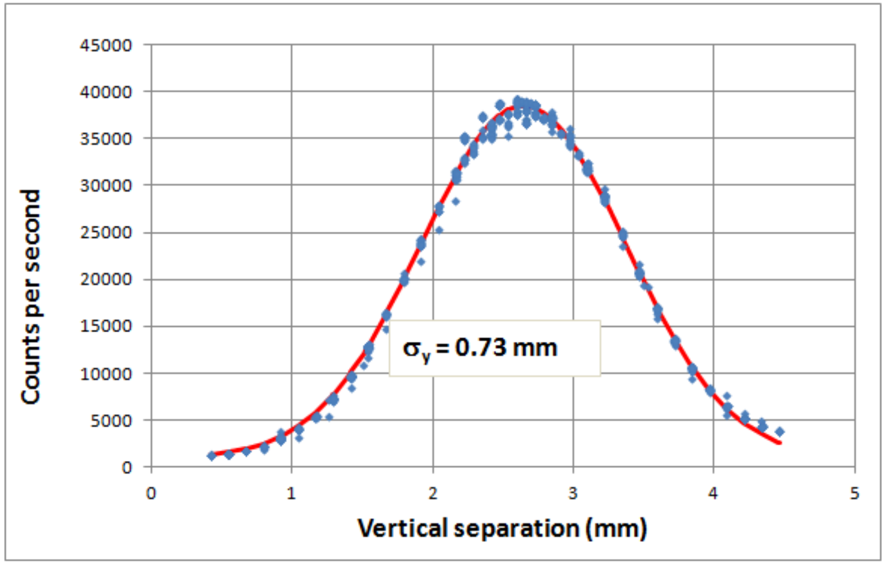
Thieberger et al., IBIC 2014

Backscattered electron detector tested with ions in RHIC

Counting rate vs. electron beam position in overlap region







Thieberger et al., IBIC 2014

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Relationship between diffusion and halo population

The diffusion equation relates density and diffusivity $\partial_t f = \partial_J (D \partial_J f)$

Simple example of given distribution (assumed known): Gaussian with long lifetime and slow emittance growth

$$f_G(J,t) = (N/\varepsilon) \cdot \exp[-J/\varepsilon]$$
$$N(t) = N_0 \exp(-\lambda t)$$
$$\varepsilon = \varepsilon_0 \exp(\gamma t)$$

The diffusion equation gives relations between diffusivity, decay rate, and emittance growth

$$\gamma = 2 \left\langle \left(D/\varepsilon - D'\right) \cdot J \right\rangle / \varepsilon^2 \qquad D(J) = \gamma \varepsilon J + \lambda \varepsilon^2 [\exp(J/\varepsilon) - 1]$$

Diffusivity grows exponentially with action
In realistic case ($D \sim J^n$), tails are inevitable

In general, analysis of collimator scans must take drift and diffusion into account: integrated loss rates (“fluxes”) are not necessarily proportional to local population densities (“tails”)!

Discussion and conclusions

-Understanding **halo populations and dynamics** is essential for machine protection, accelerator performance, and experimental backgrounds

-**Collimator scans** in small steps allow one to measure populations and diffusivities simultaneously, reducing systematics

-**Population densities** were measured over two orders of magnitude over a wide range of amplitudes

-**Diffusivities vs. amplitude**

- -were consistent with emittance growth near core
- -showed the effects of collisions and of the hollow electron lens
- -will be calibrated against known transverse damper excitations

-**Nondestructive, continuous halo monitoring** in LHC

- -synchrotron light with coronagraph or wide-range camera
- -backscattered electrons? (needs electron lens and scanning)

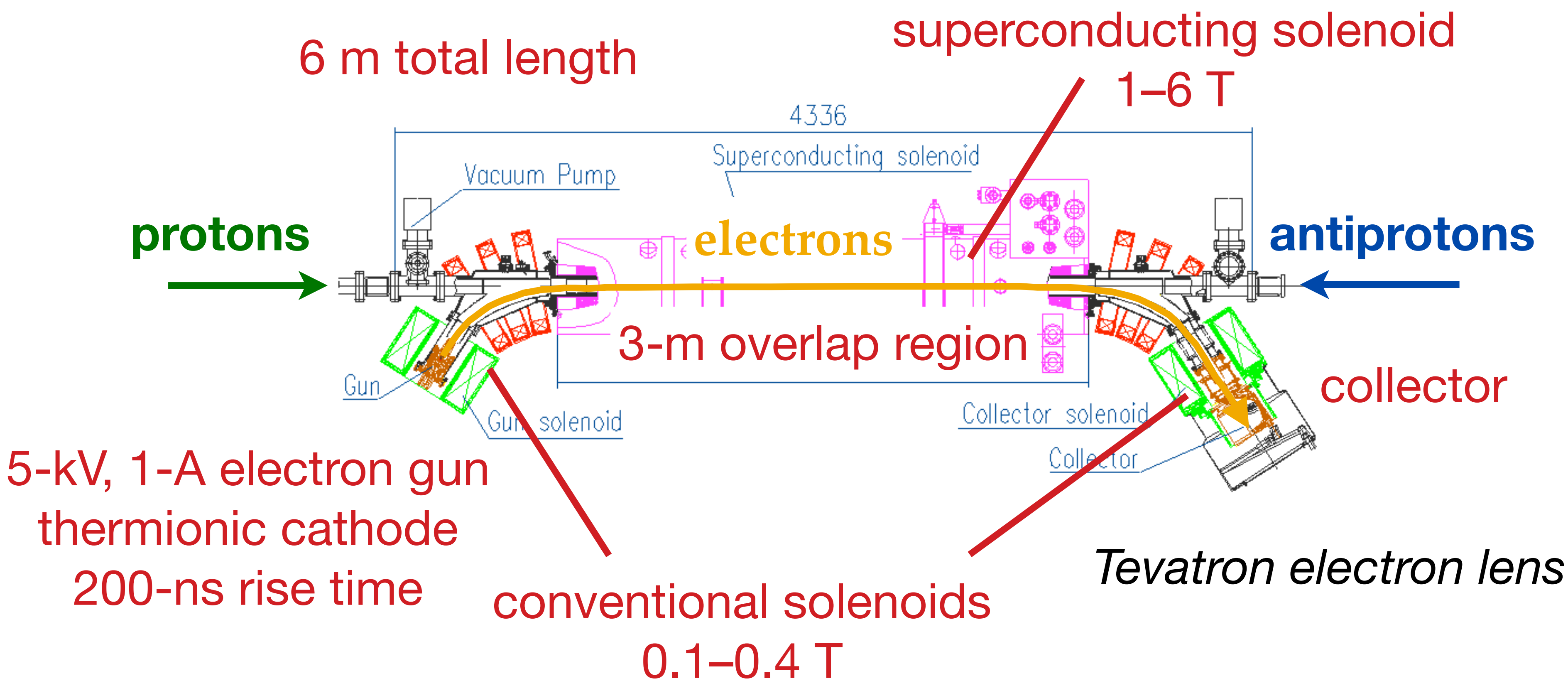
-Option for **active halo control**: hollow electron lenses

Thank you for your attention!

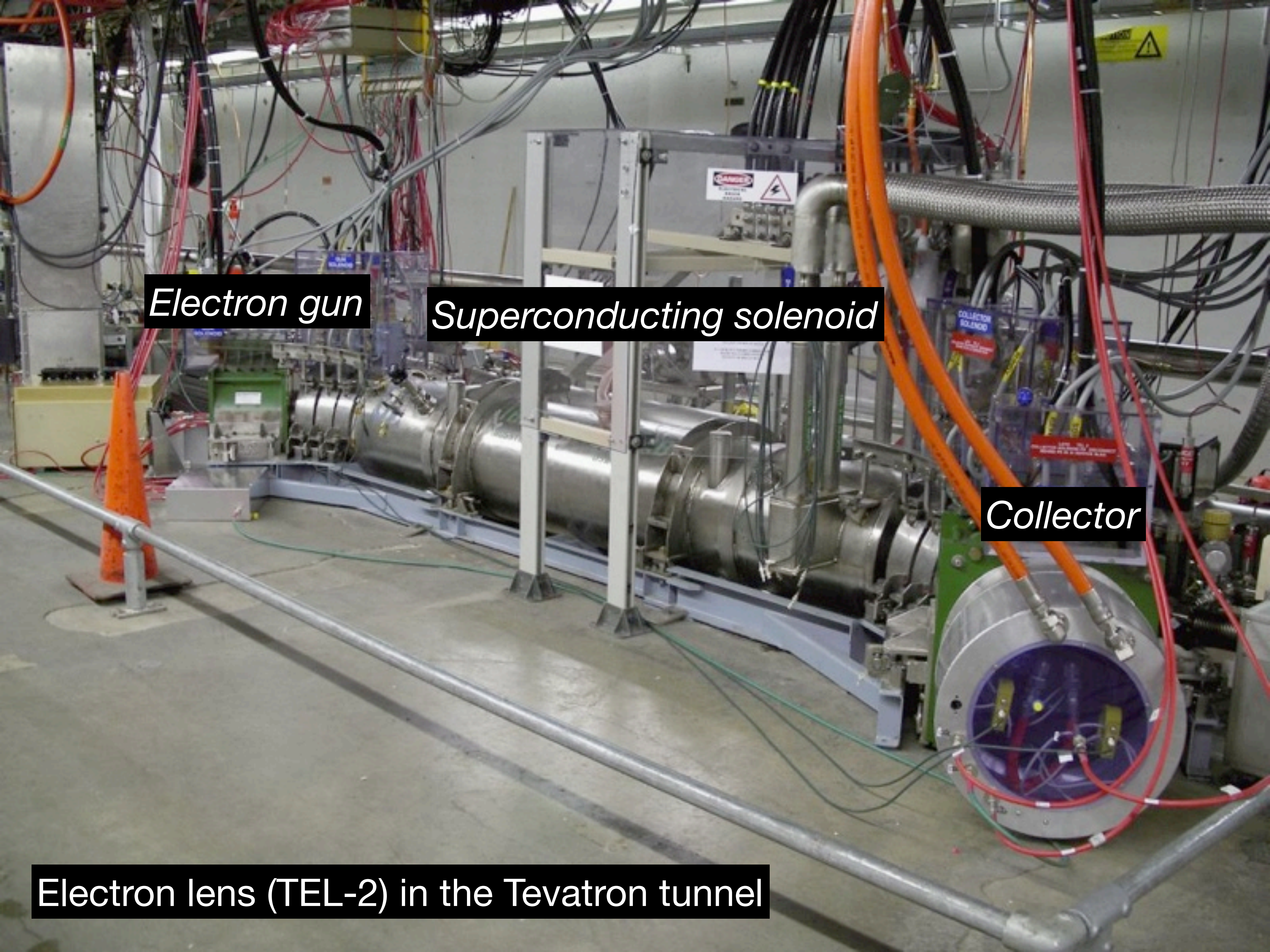
Backup slides

What's an electron lens?

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Stability provided by strong axial magnetic fields



Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)

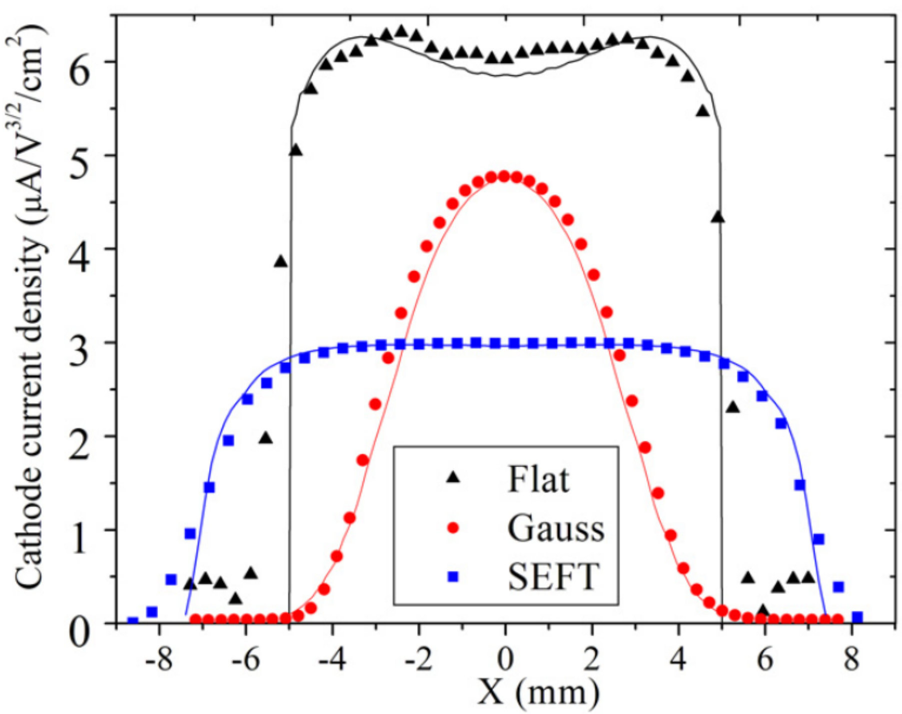


Electron lens (TEL-2) in the Tevatron tunnel

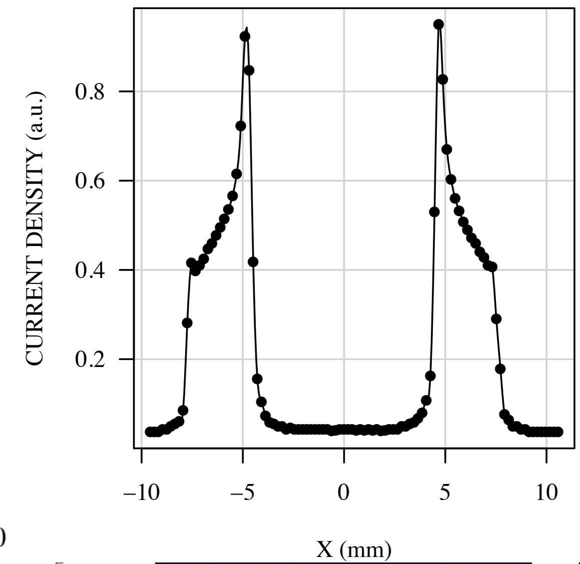
First main feature: control of electron beam profile

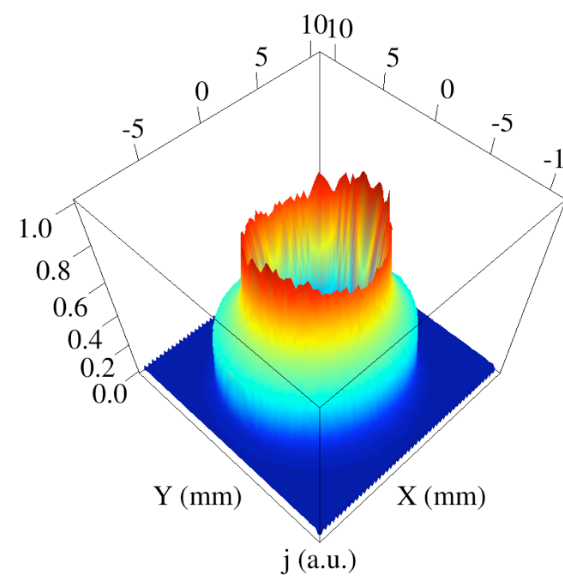
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

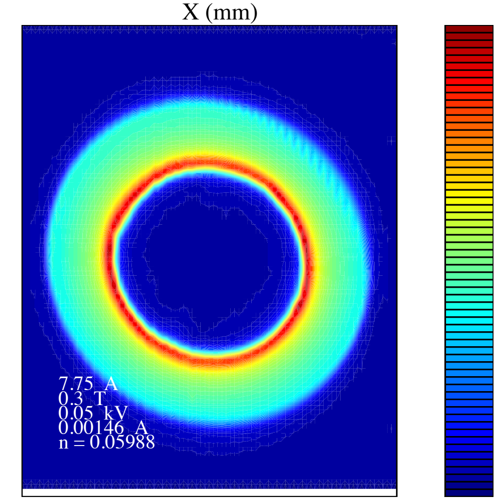
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping



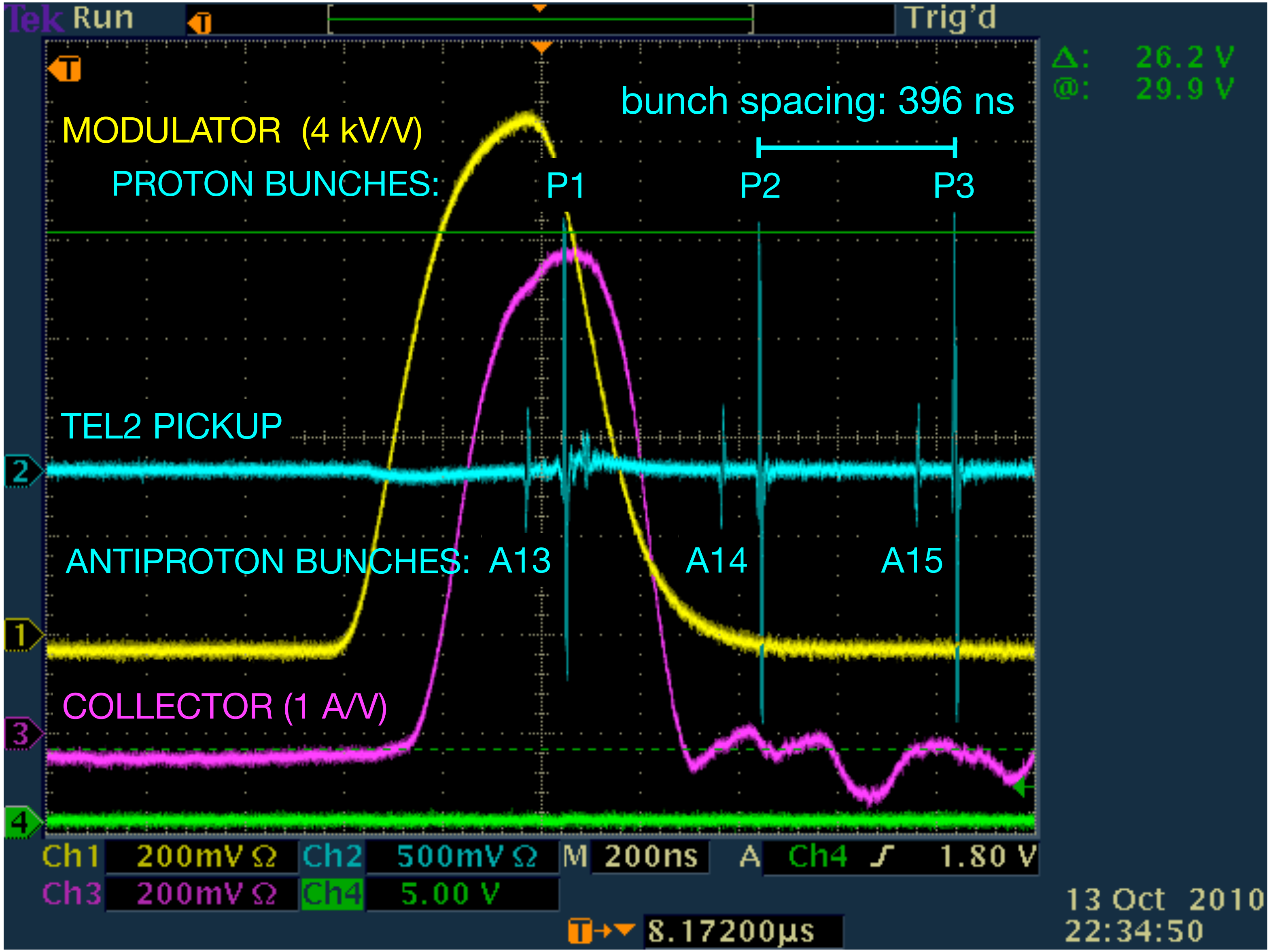




Gaussian profile for compensation of nonlinear beam-beam forces

Second main feature: pulsed electron beam operation

Beam synchronization in the Tevatron



Pulsed electron beam could be **synchronized with any group of bunches**, with a different intensity for each bunch

Example of loss-rate analysis after collimator step