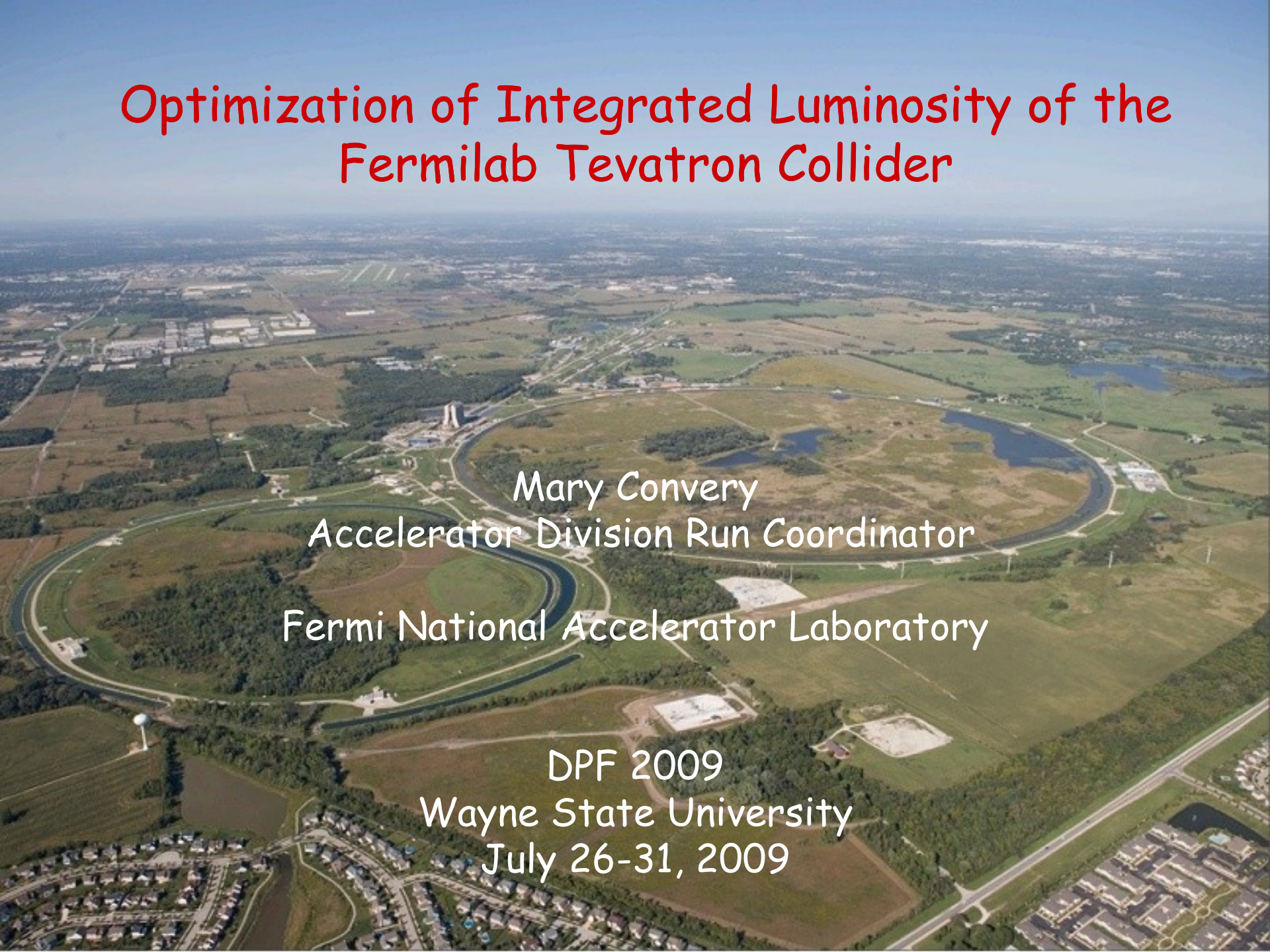
Optimization of Integrated Luminosity of the Fermilab Tevatron Collider



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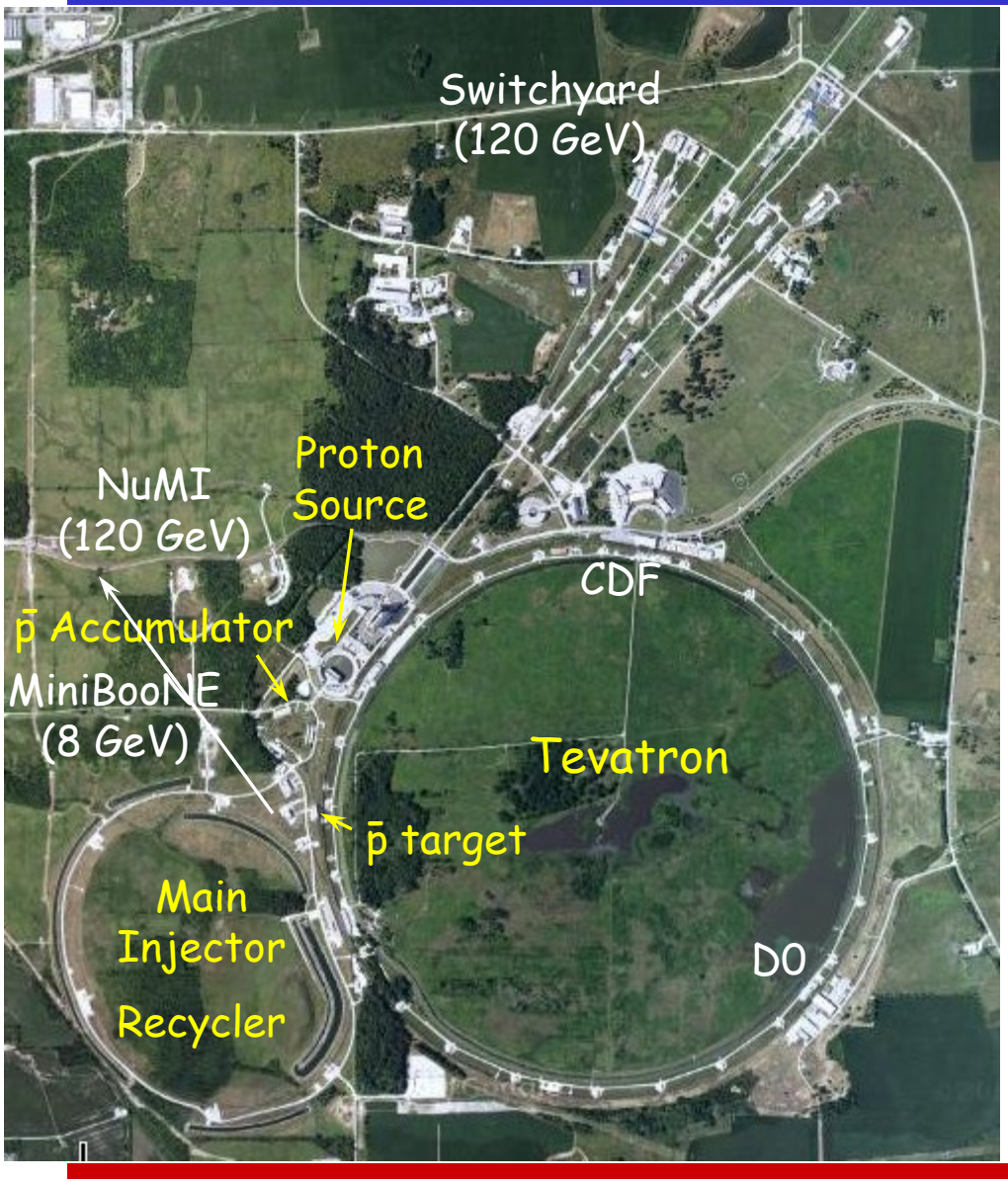
Outline

- Introduction
- Model for Optimization of Integrated Luminosity
- Optimization of antiproton production
  - Timing of transfers
  - Partial mining
- Other operational improvements
  - Reducing collider shot setup time
  - Increasing proton brightness
  - Consistency / reliability
- Results

Fermilab Accelerator Complex



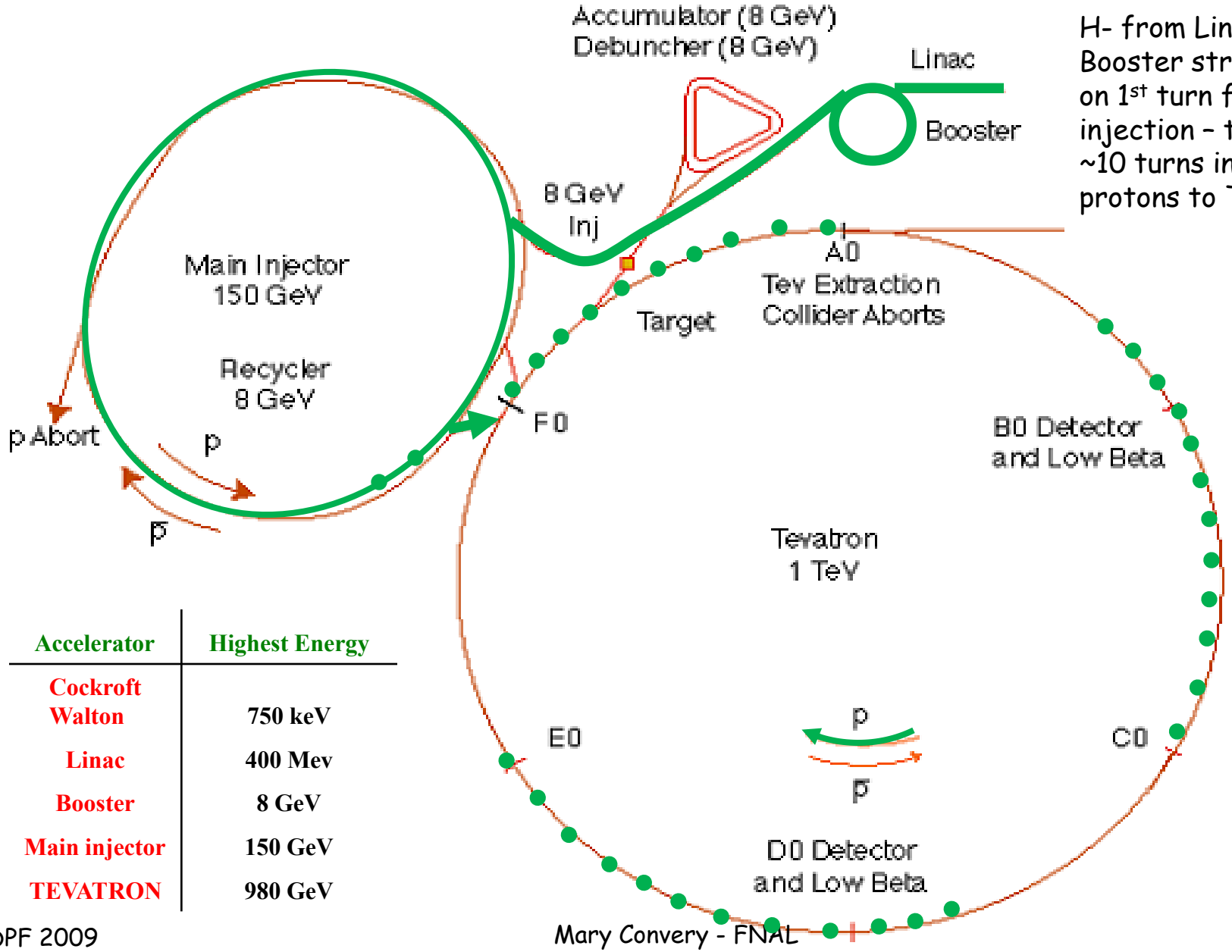
Provide beam to

Two Collider Experiments
- CDF
- DO

Two neutrino Experiments
- NuMI
- MiniBooNE

120 GeV Fixed Target Experiments

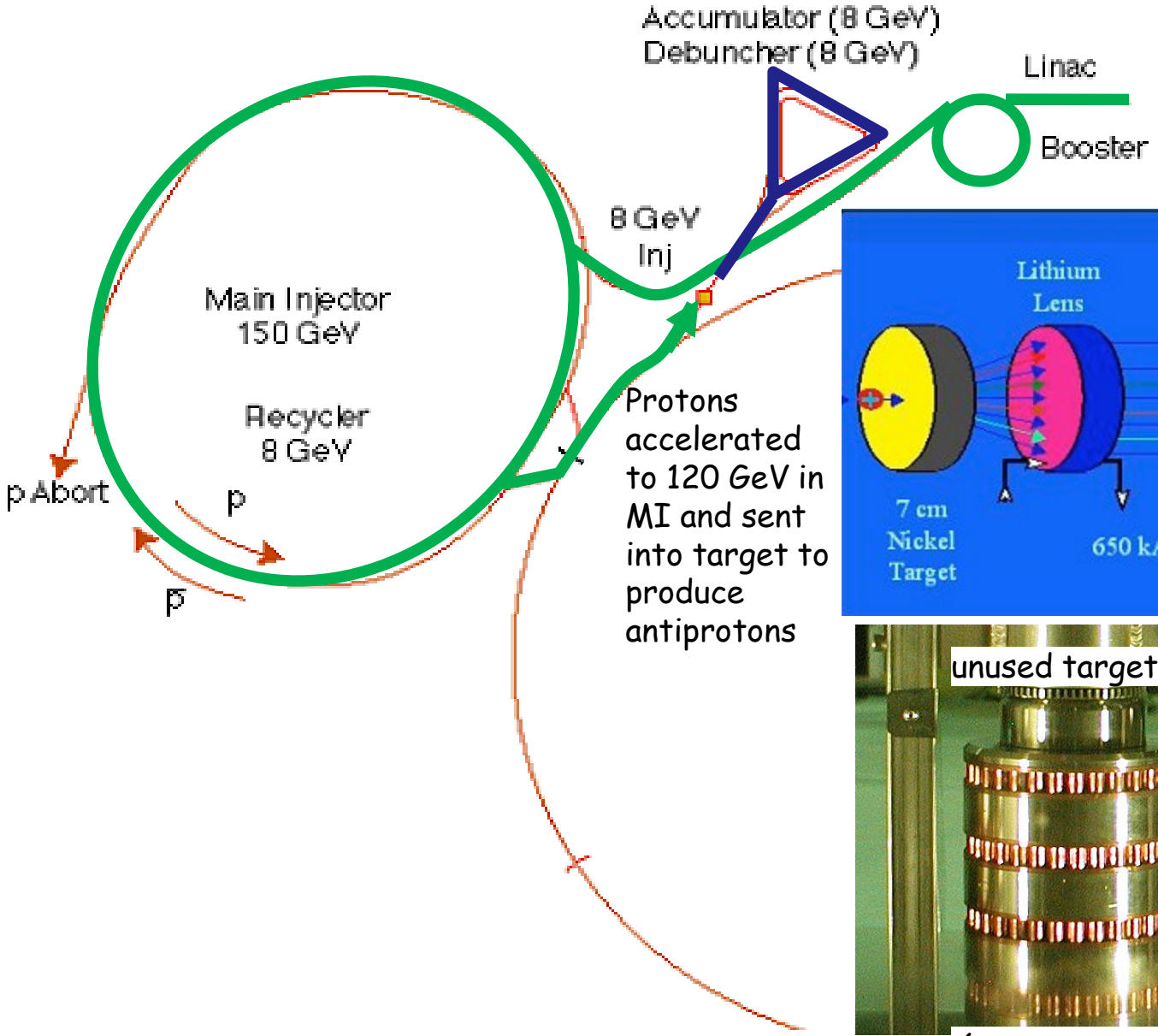
Proton injection for Tevatron store



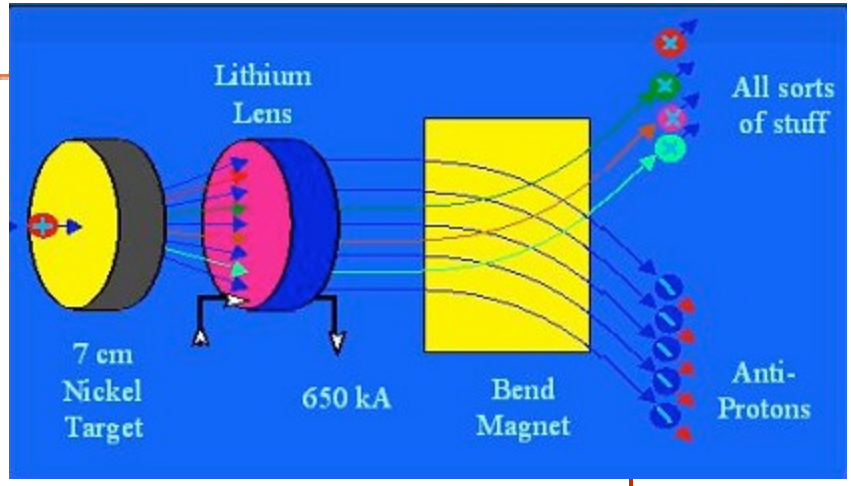
H- from Linac into Booster stripped of e's on 1st turn for multi-turn injection – typically load ~10 turns in Booster for protons to Tevatron

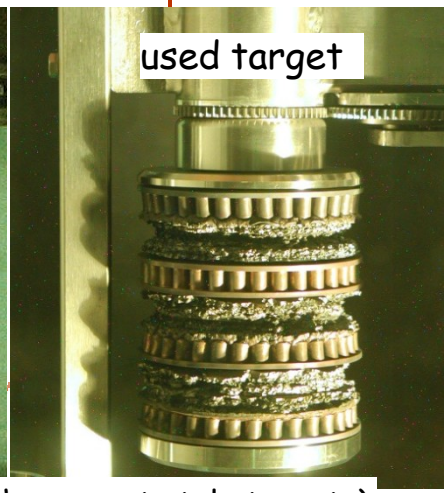
Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

Antiproton production



Protons accelerated to 120 GeV in MI and sent into target to produce antiprotons

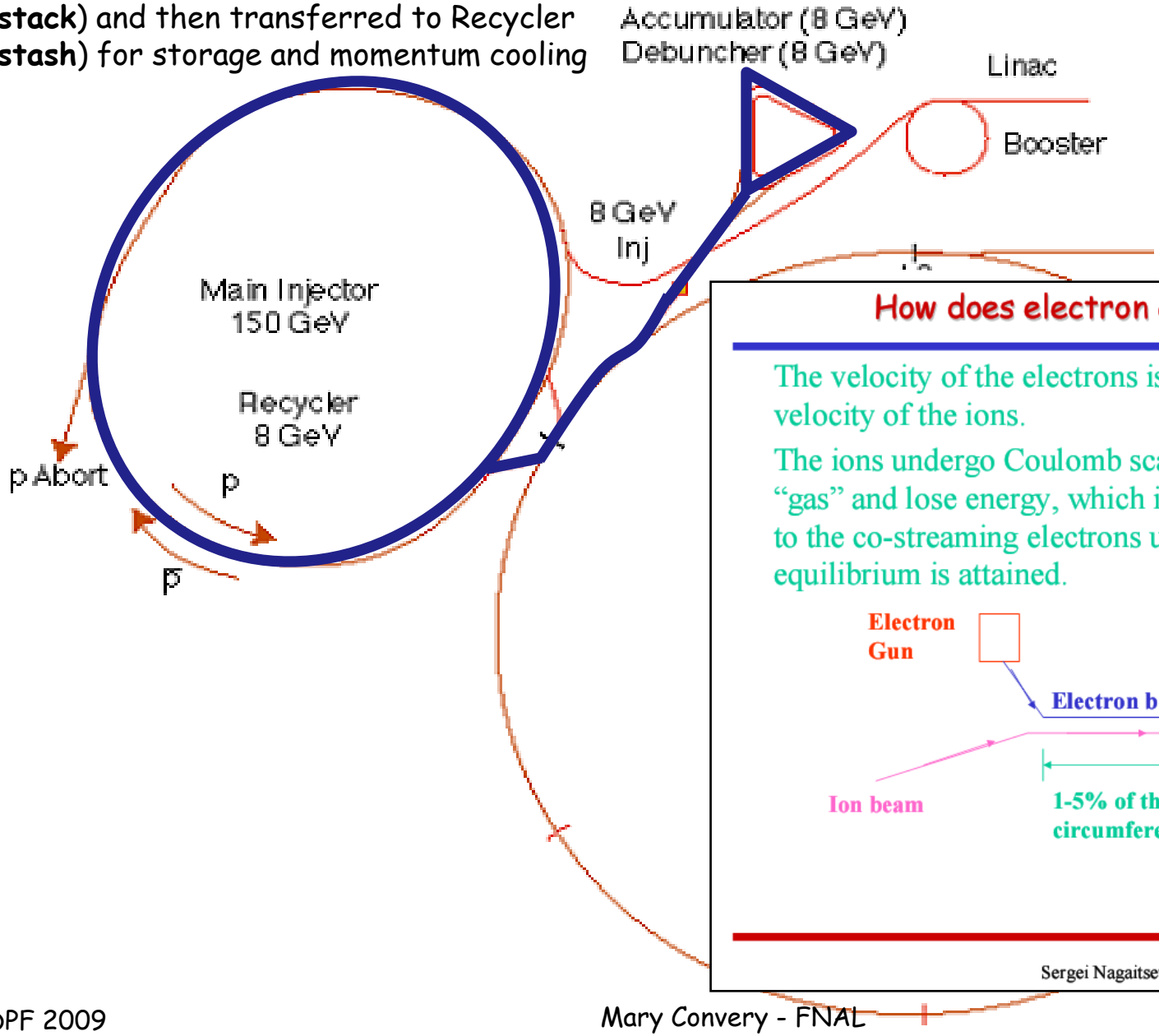




(note these are not the newest style targets)

Antiproton storage

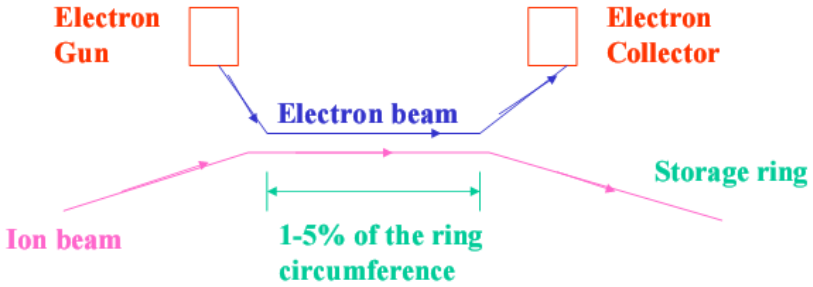
Antiprotons accumulated in Accumulator (**stack**) and then transferred to Recycler (**stash**) for storage and momentum cooling



How does electron cooling work?

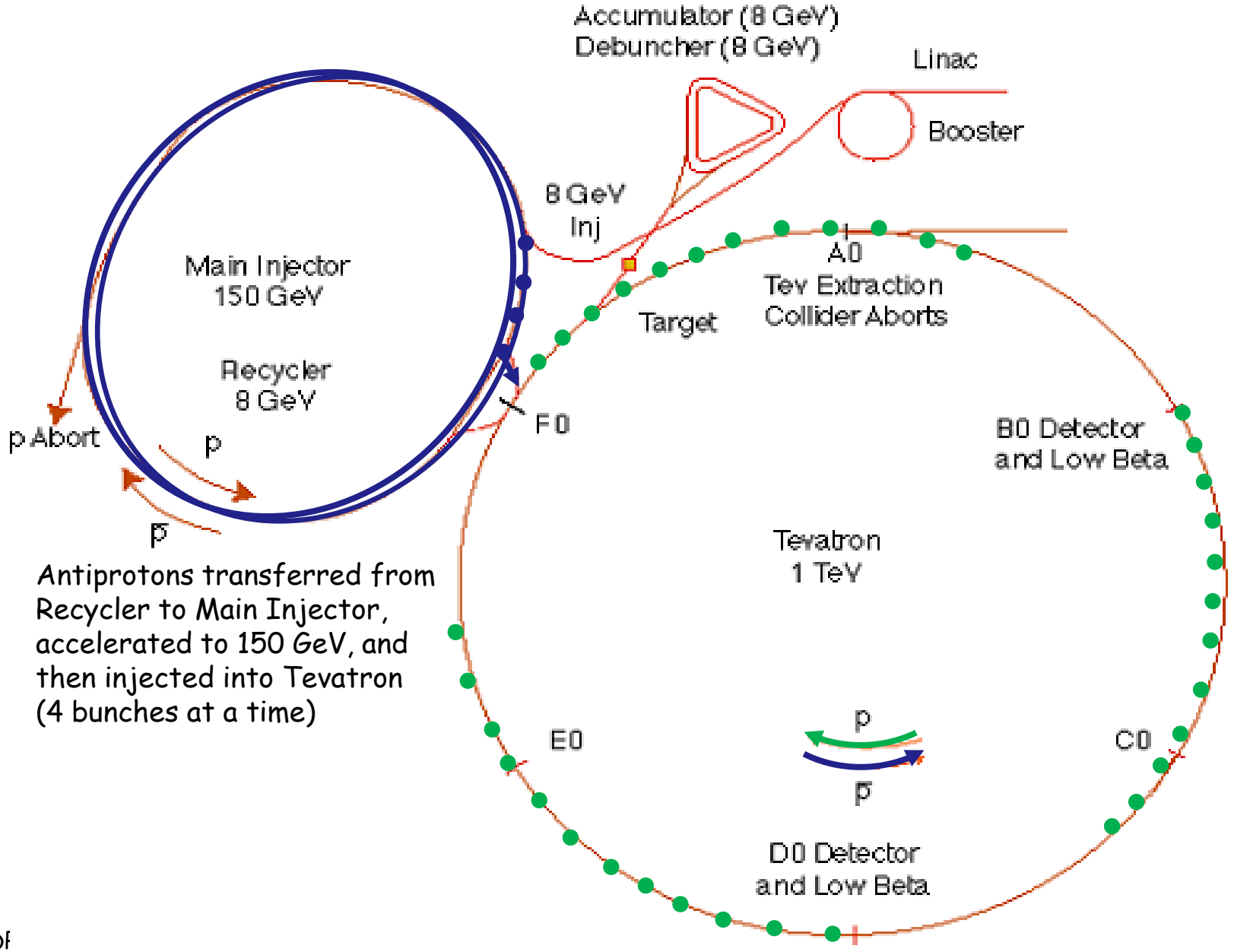
The velocity of the electrons is made equal to the average velocity of the ions.

The ions undergo Coulomb scattering in the electron "gas" and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



Sergei Nagaitsev (Fermilab/AD)

Antiproton injection for Tevatron store



Antiprotons transferred from Recycler to Main Injector, accelerated to 150 GeV, and then injected into Tevatron (4 bunches at a time)

Definitions

- Stacking/Stack:
  - Producing antiprotons and storing them in the Accumulator storage ring, where they are cooled stochastically
- Pbar ($\bar{p}$) Transfer:
  - The transfer of antiprotons from the Accumulator to the Recycler
- Stashing/Stash:
  - The process of accepting antiprotons in the Recycler and cooling them (electron cooling) to prepare for more transfers until the stash is large enough to begin collider shot setup
- Store:
  - A colliding set of protons and antiprotons in the Tevatron
- Collider Shot Setup:
  - The process of loading a store into the Tevatron

Luminosity

For an intersecting storage ring collider, the instantaneous luminosity is given by:

$$\mathcal{L} = fnN_1N_2/A$$

where

f : revolution frequency (47kHz)

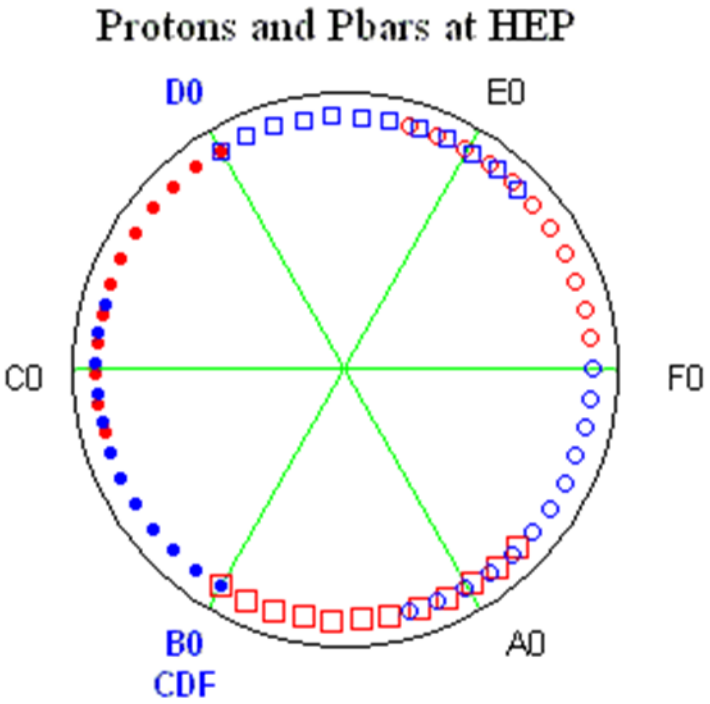
n : number of bunches in one beam in the storage ring (36)

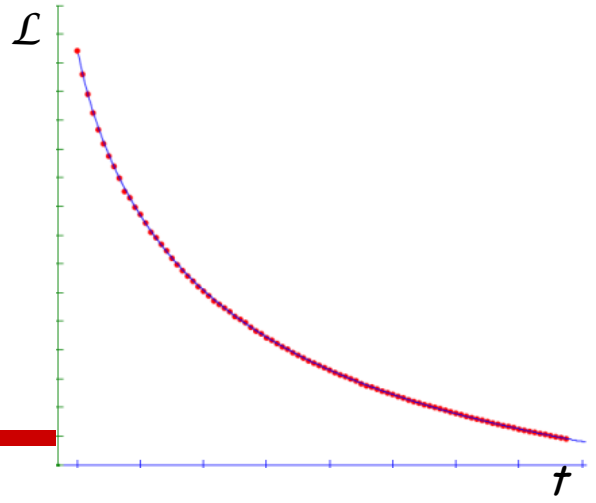
$N_i(t)$: number of particles in each bunch (~10^{11}, 10^{10})

$A(t)$: cross section of the beam (beam width ~ μm)

$\mathcal{L}$ (10^{32}cm^{-2}s^{-1} or 0.1 nb^{-1}/s)

Integrated luminosity: $\int dt\, \mathcal{L}$ (pb^{-1})





Model for Optimization of Integrated Luminosity

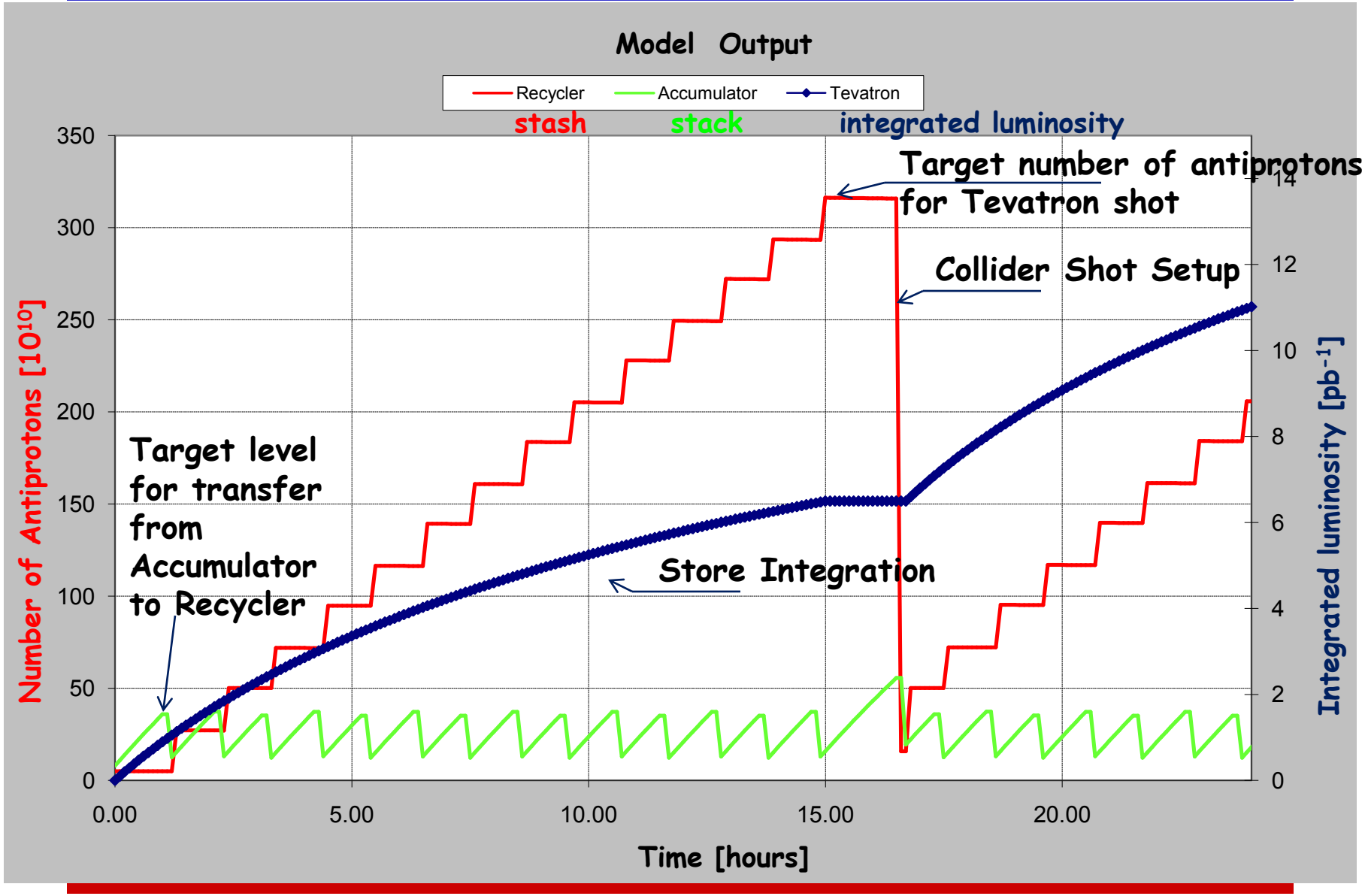
Model Introduction

- From the beginning of Run II to nearly a year ago
  - Emphasis was placed on increasing initial luminosity
    - Incorporation of upgrades
    - Increasing antiproton production rate
- Present day
  - Complex is more stable, conditions more reproducible
  - Allows us to use this model to optimize integrated luminosity
- How are we optimizing integrated luminosity?
  - Presuming stable beam conditions, the limiting factor becomes antiproton production rate
  - By using recent historical data to model the accelerator complex performance, we find the optimal use of antiprotons for maximizing integrated luminosity

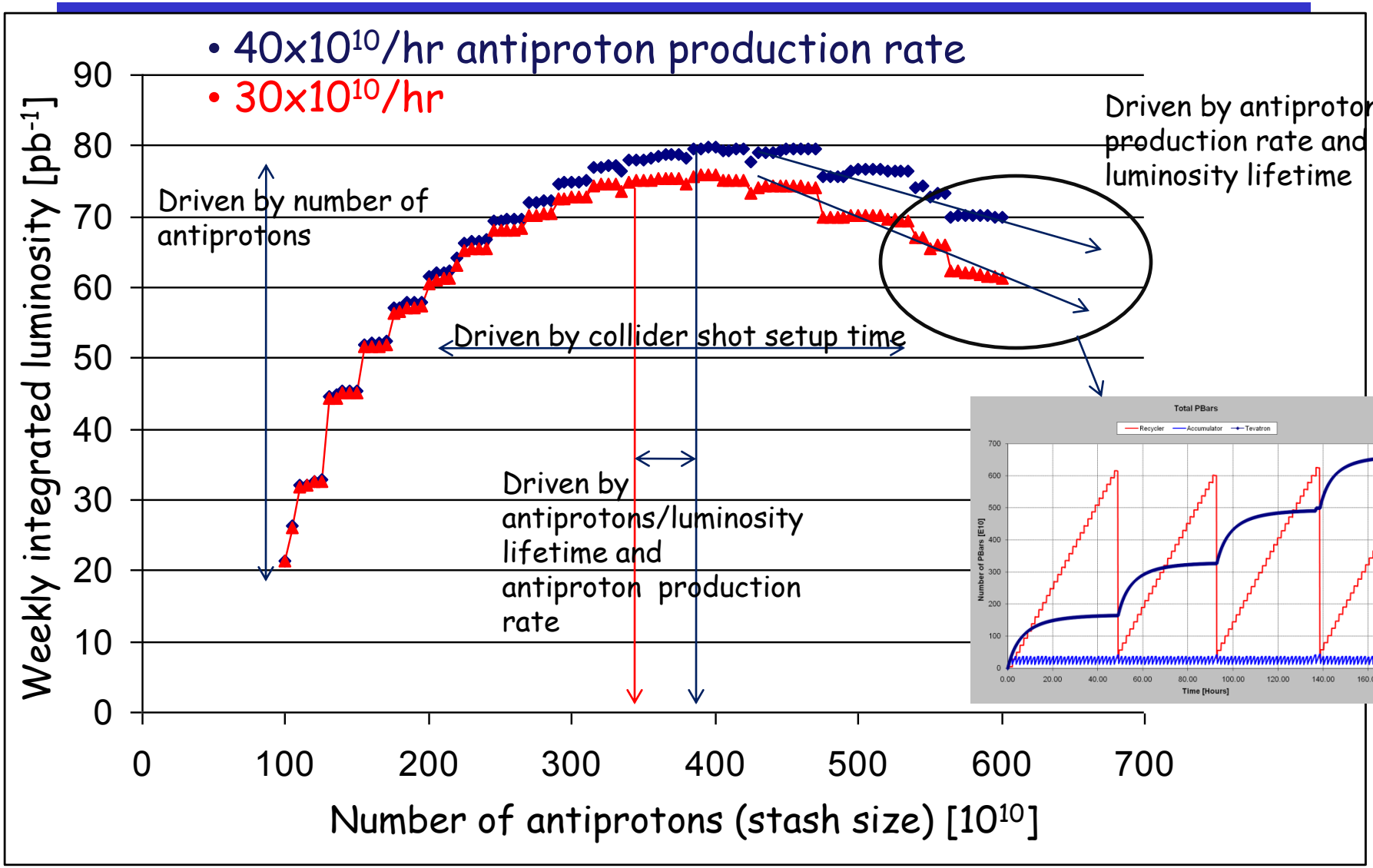
Model Assumptions /Parameters

- Proton Parameters are kept fixed
  - Proton beam conditions have little variation
    - Intensity ~320 x10^9 per bunch
    - Emittances ~16-17 π mm-mrad at 8 GeV
- Luminosity Parameters
  - Using historic data to obtain
    - Initial luminosity dependence on number of antiprotons in stash
    - Typical luminosity lifetime behavior (~independent of initial lum)
- Antiproton Parameters
  - Effective production rate
    - Stacking rate
    - Pbar transfer efficiency
    - Lifetimes in both Accumulator and Recycler
    - Interruption to stacking during pbar transfers
  - Efficiency of antiproton transfers to Tevatron

Modeled Production and Integration

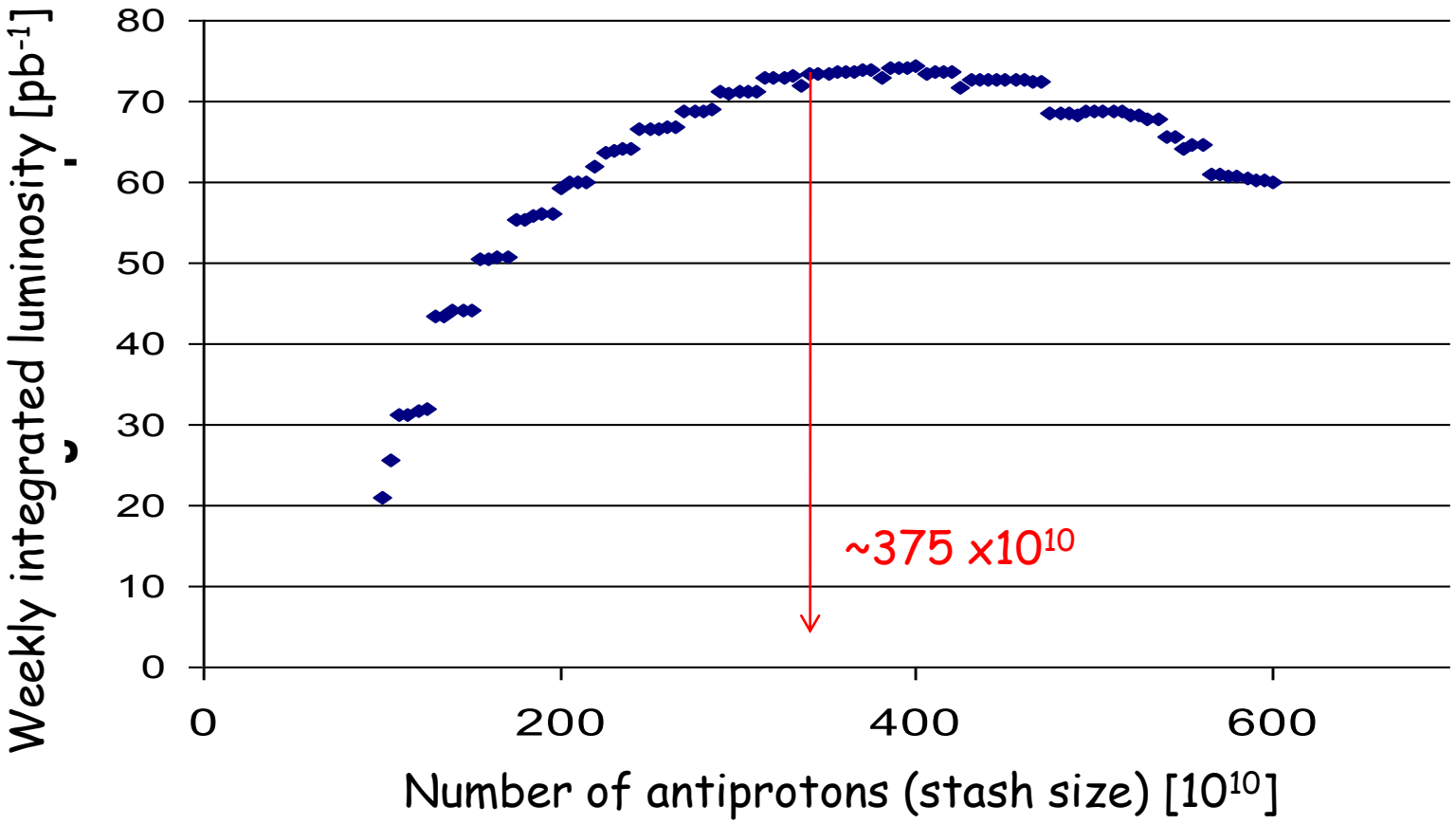


Response of the model



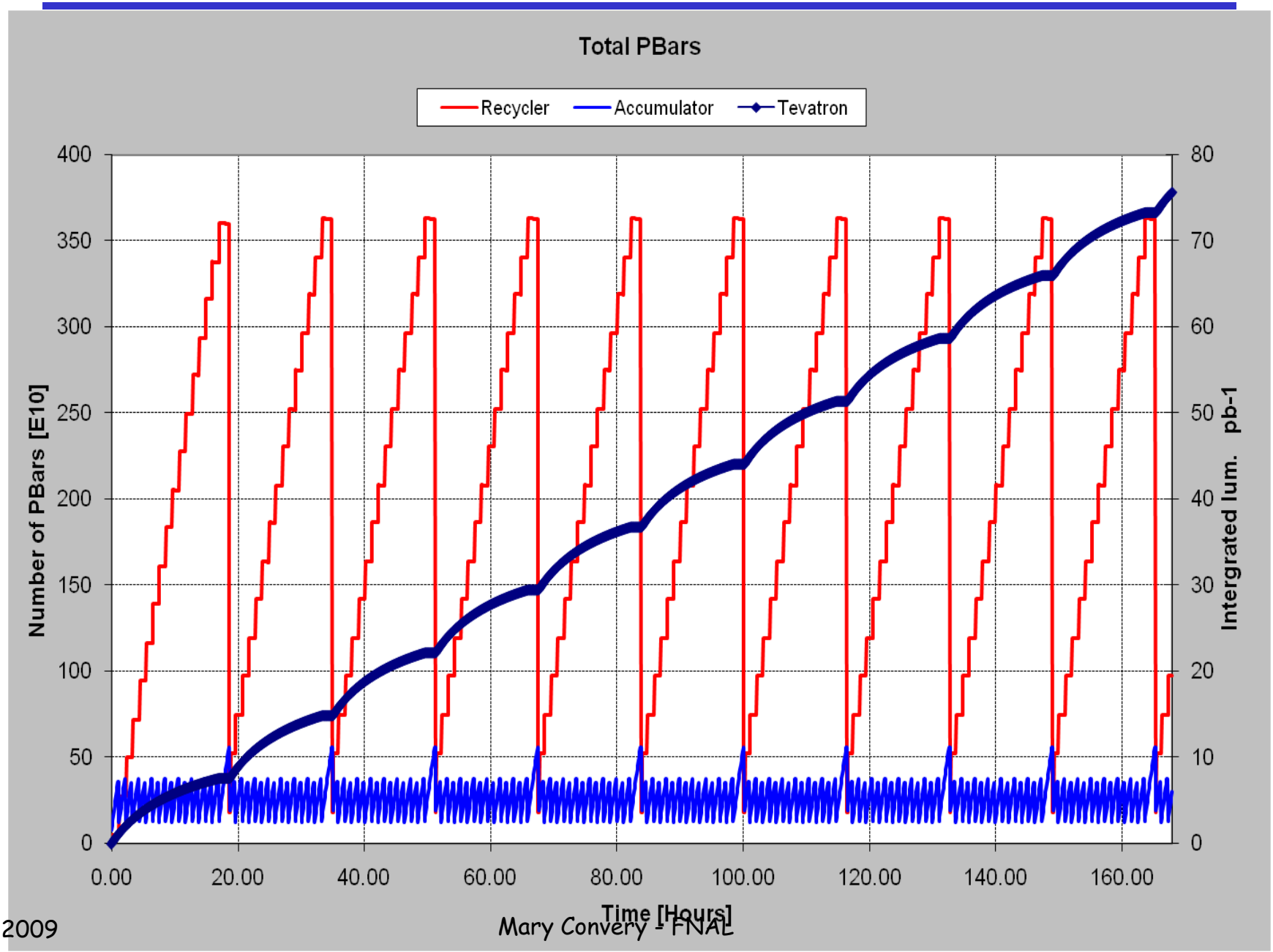
Output of model using actual conditions

- Antiproton production rate of 30×10^{10}/hr
- Collider shot setup time of 1.5 hours

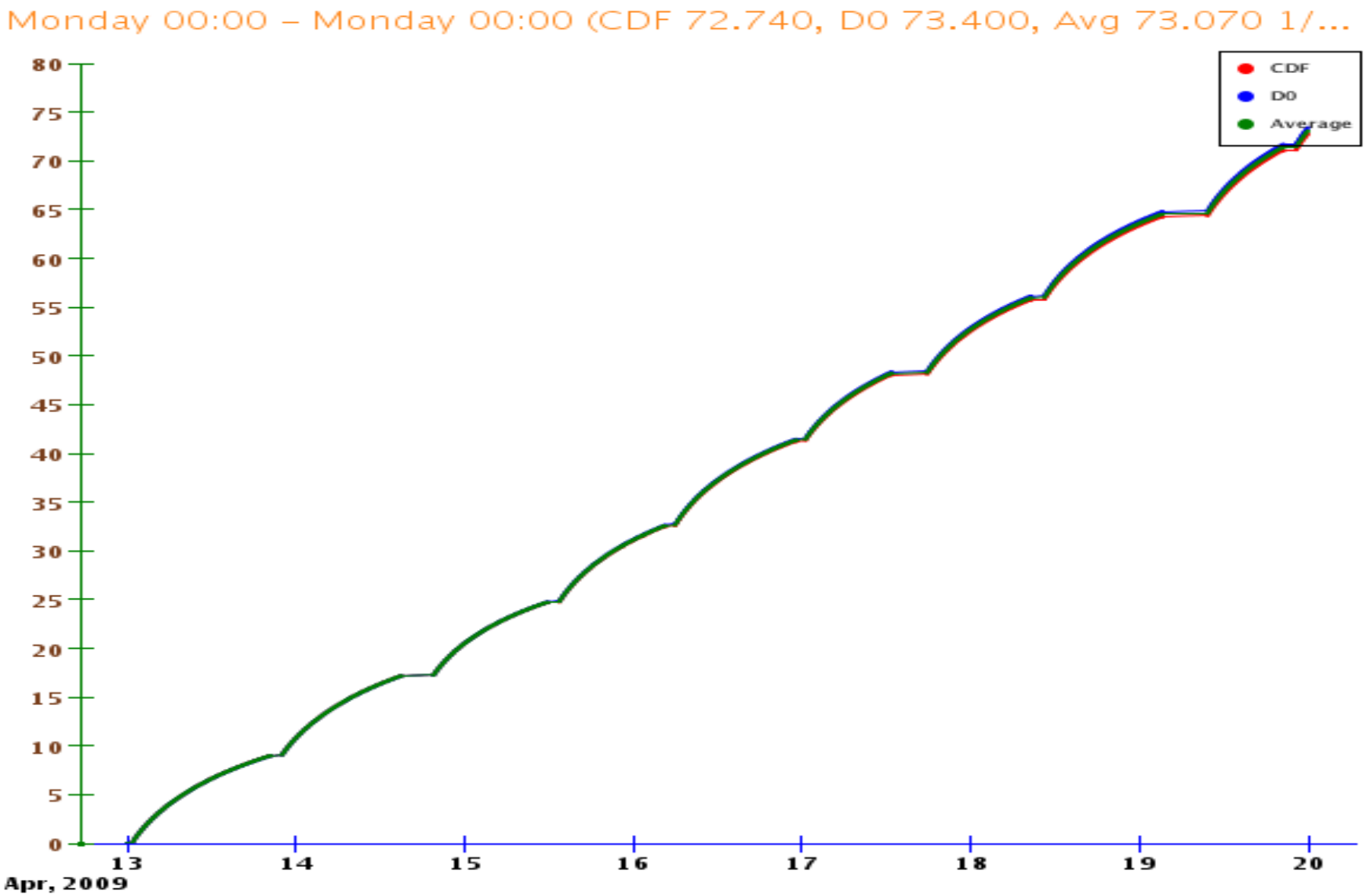


- Predicts optimal target stash of 375×10^{10} antiprotons

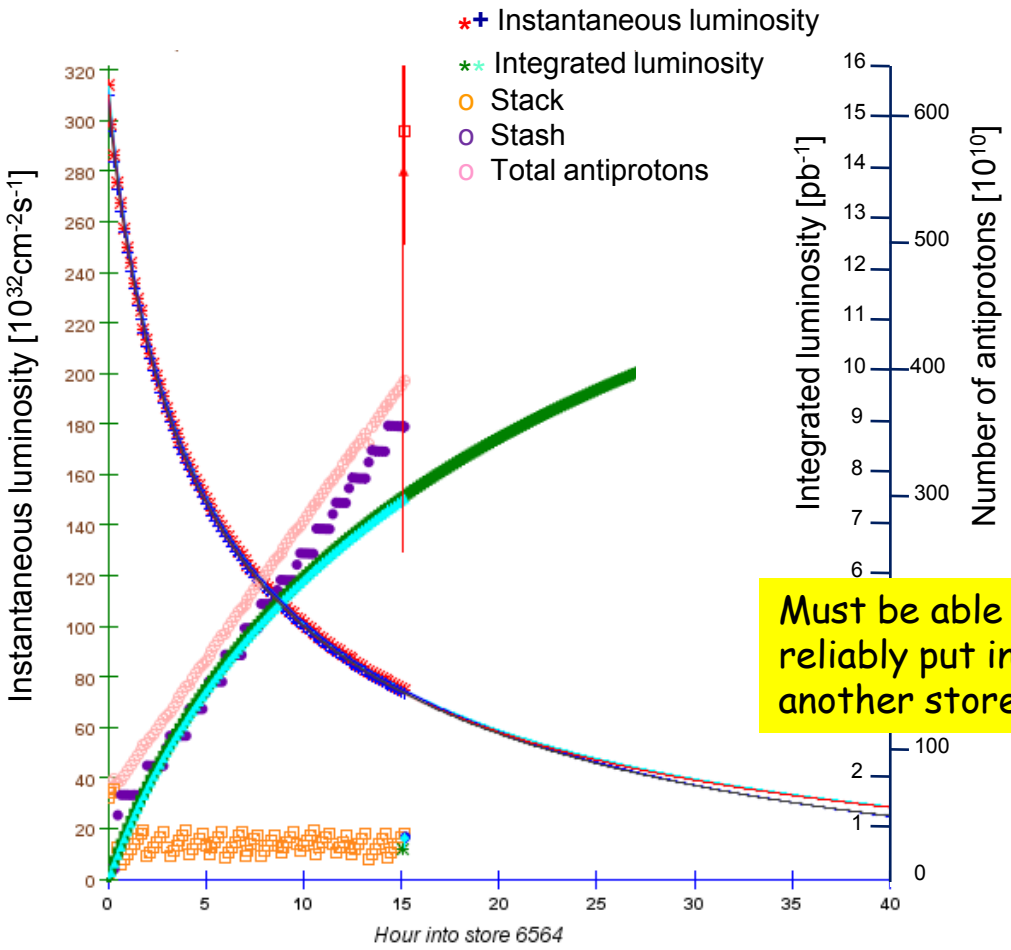
Model week (predicts integrated lum ~76pb^{-1})



Actual "perfect" week (73pb^{-1})



Tool used for Daily Decision Making



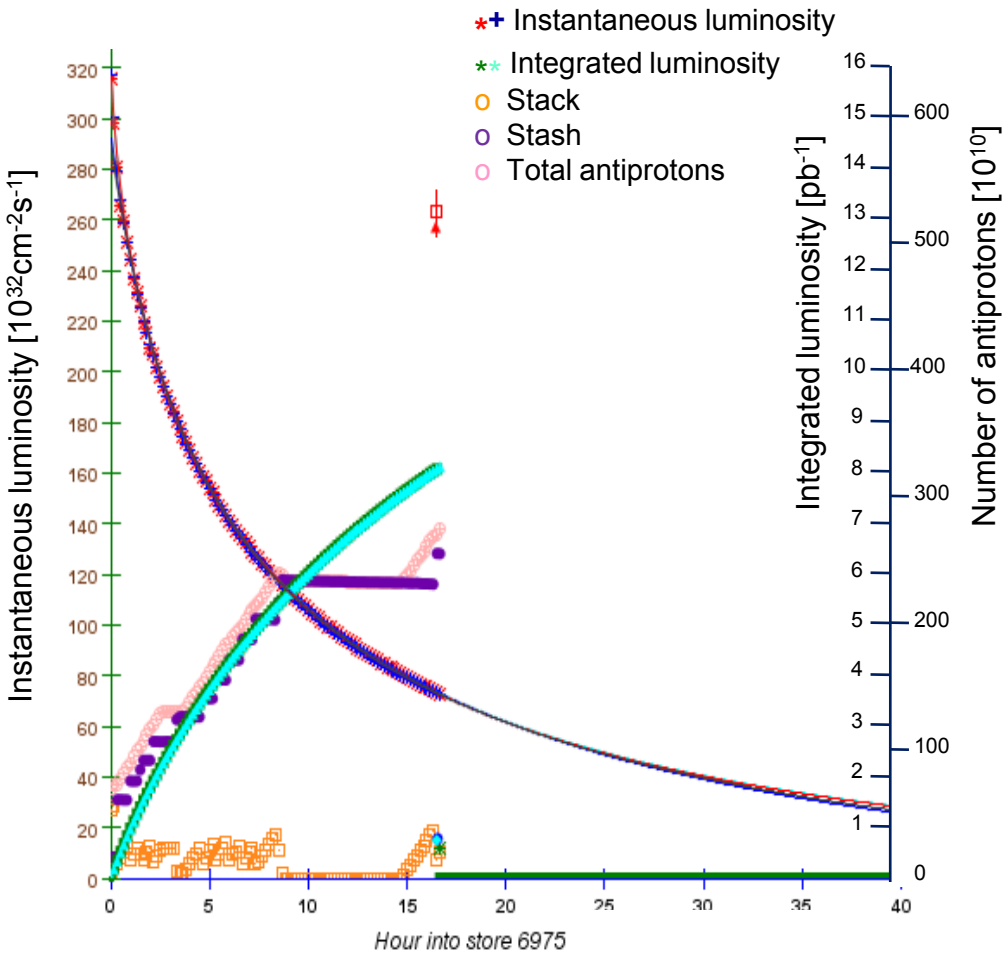
Must be able to reliably put in another store

- Fit luminosity decay of current store
- Predict integrated luminosity of next 2.5 hours of current store
- Predict initial luminosity of new store from current stash based on historical data
- Predict integrated luminosity in first hour of new store (1.5 hrs shot setup) based on historical data
- Compare (current) vs (ss+new)

~600 nb^{-1} ~800 nb^{-1}

- When we reach the optimal target stash size based on the model, this tool confirms that we will be integrating more by terminating the existing store and putting in a new one

Tool used for Daily Decision Making



- Fit luminosity decay of current store
- Predict integrated luminosity of next 2.5 hours of current store
- Predict initial luminosity of new store from current stash based on historical data
- Predict integrated luminosity in first hour of new store (1.5 hrs shot setup) based on historical data
- Compare (current) vs (ss+new)

  ~750 nb^{-1} ~790 nb^{-1}

- Also use this tool when significant stacking downtime

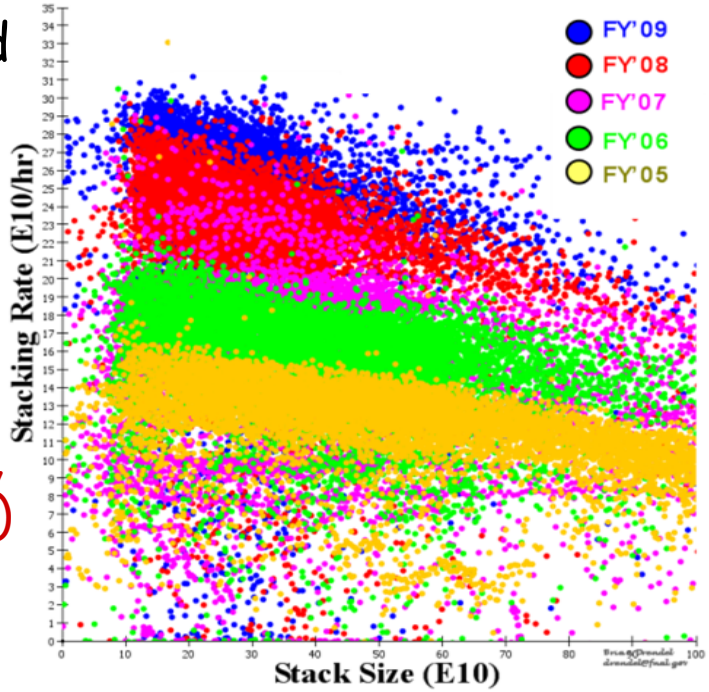
Model summary

- Tools are in place for
  - Weekly optimization of integrated luminosity
  - Store-by-store operational decisions
- Gives us insight as to what areas to attack to improve integrated luminosity
- Directs our response to interruptions of our standard operating conditions
- As improvements are made to the complex, the model parameters are revisited to ensure that we are optimized

Optimization of antiproton production

Optimizing pbar transfers

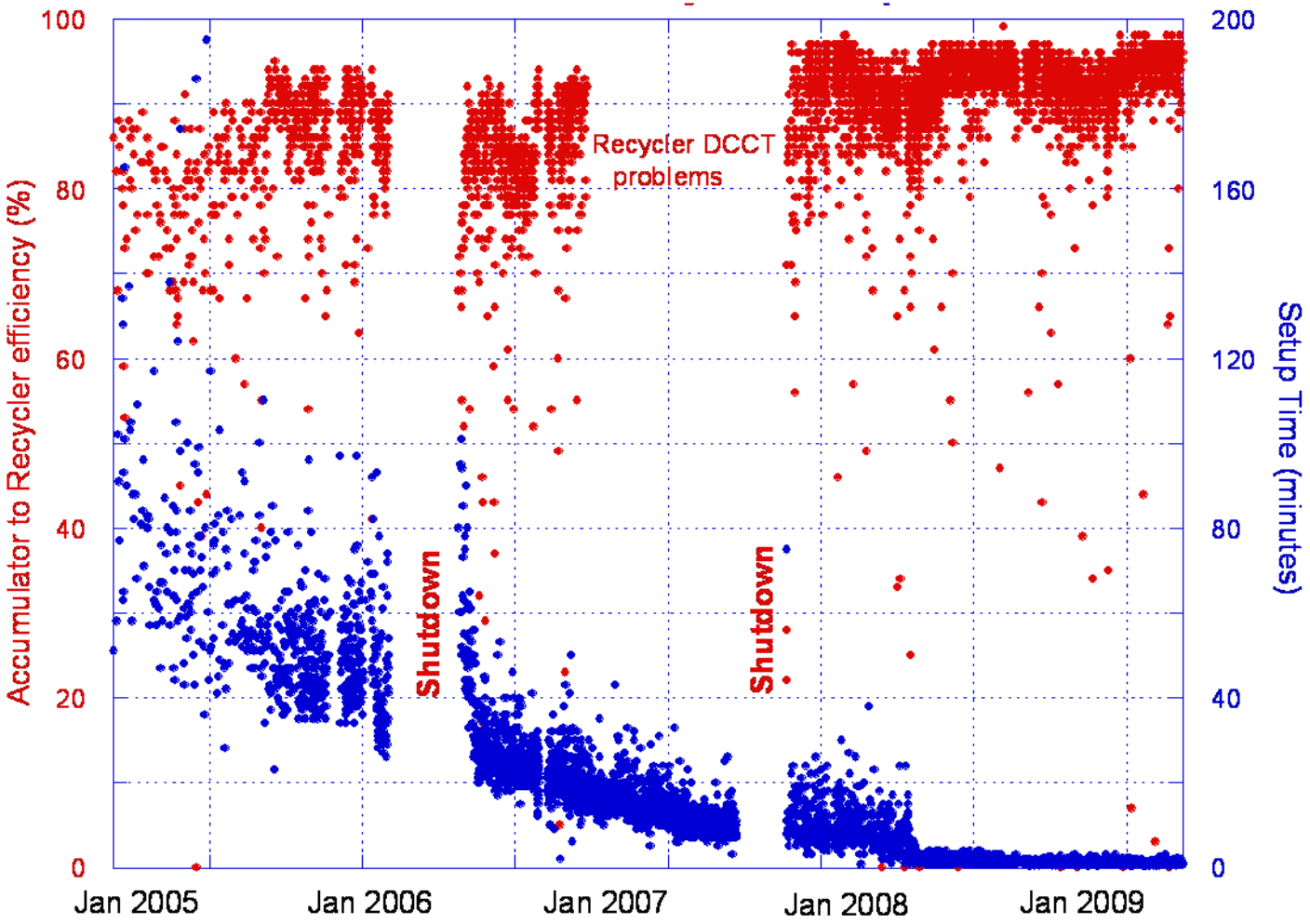
- Stack size at which a transfer is initiated
  - Stacking rate declines as stack size increases
  - Transfer from Accumulator to Recycler
    - Percentage of antiprotons removed from the stack (depends on stack size, number of individual transfers in a set)
    - Transfer efficiency to the Recycler
    - Impact on overall stacking rate (non-stacking time during the transfer process)
  - Lifetime in Recycler
  - Cooling between last transfer and collider shot



- Optimized with set of 2 transfers initiated when stack reaches ~25×10^{10}
  - Previously had varying number of transfers from ~40×10^{10}

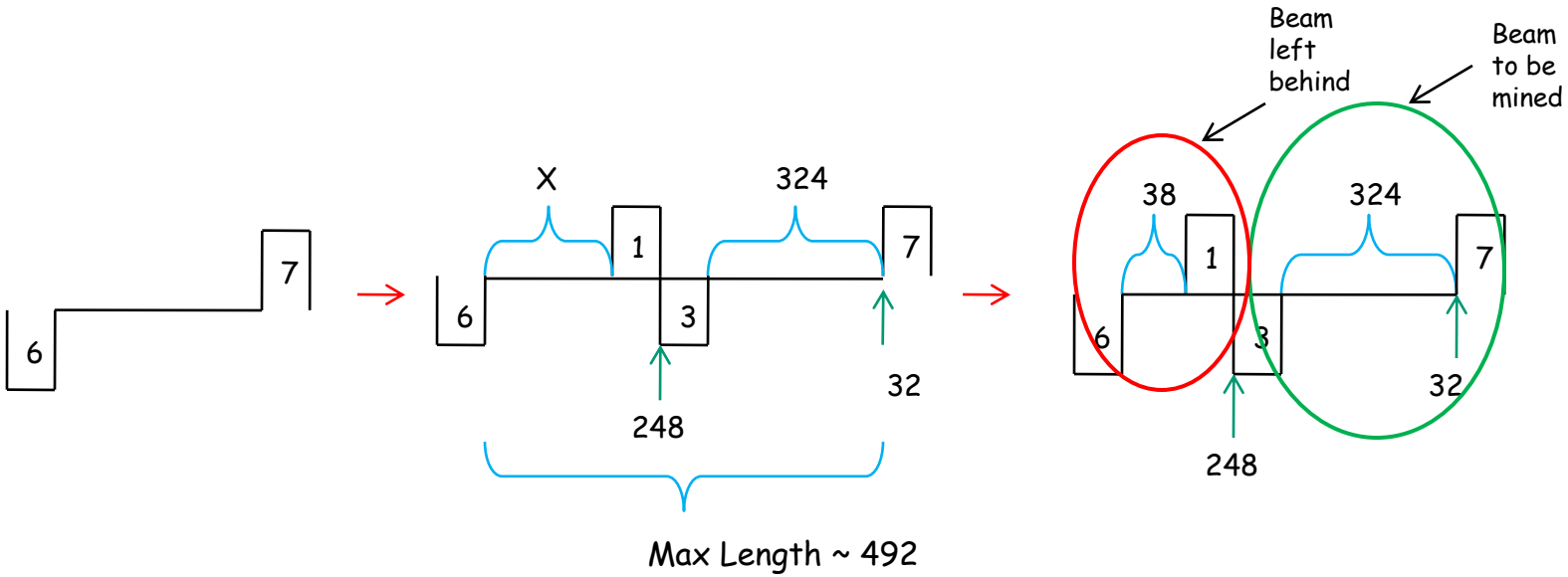
Rapid pbar transfers

- Reduced time needed for transfer, especially non-stacking time, while maintaining good efficiency



"Partial mining"

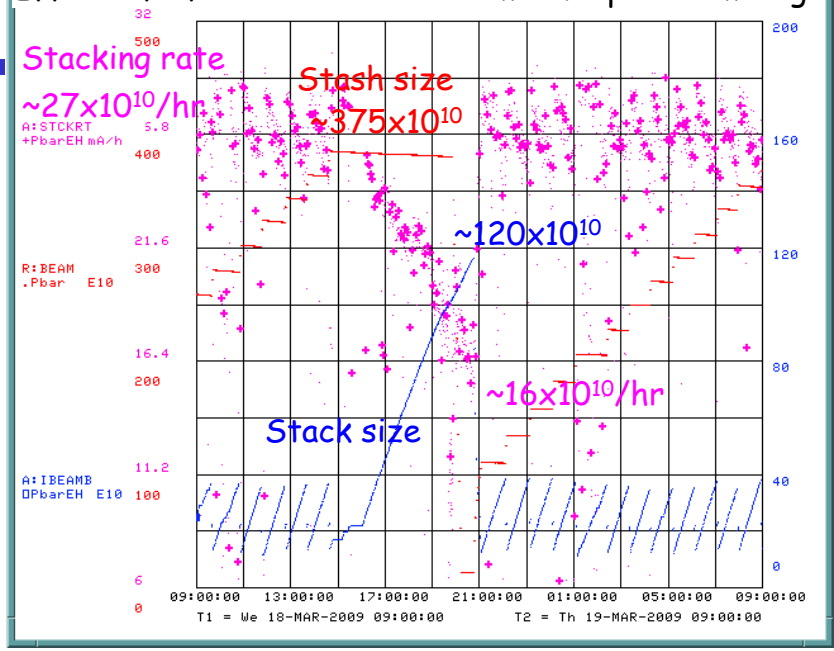
- Ability to extract ("mine") only a percentage of the Recycler stash without compromise of cooling or lifetime
  - RF manipulations separate beam to be extracted from beam to be left behind
  - Are limitations on amount can extract / leave behind (20%-80%)



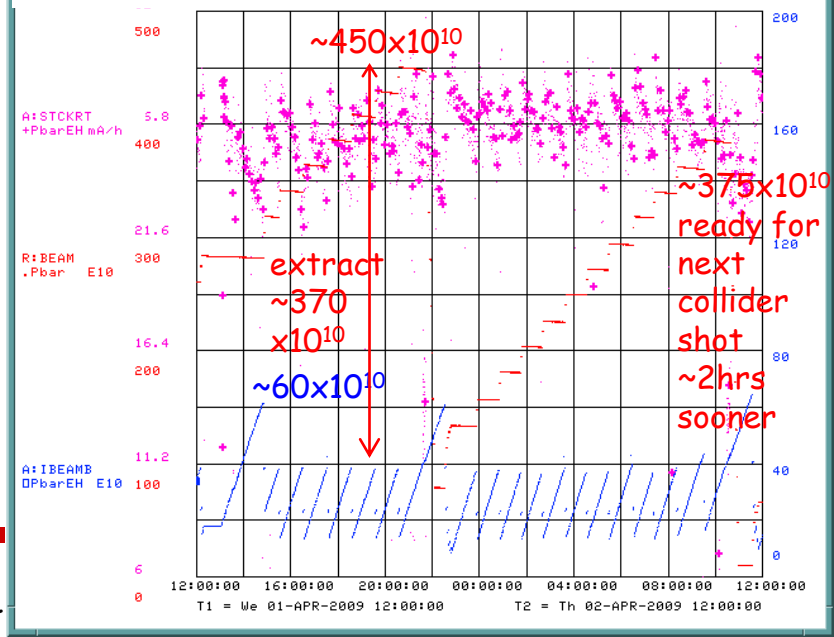
Partial mining

- Motivation:
  - Improve antiproton production rate
    - Small stack = higher stacking rate
    - More efficient transfer to the RR from smaller stack sizes
  - Improve the flexibility of the Collider program
    - Allows to tailor shots to the Tevatron if problems develop
    - Faster store turn-around
      - Reach the target stash sooner after a failure

Effect of ~few hour Tev downtime w/o partial mining

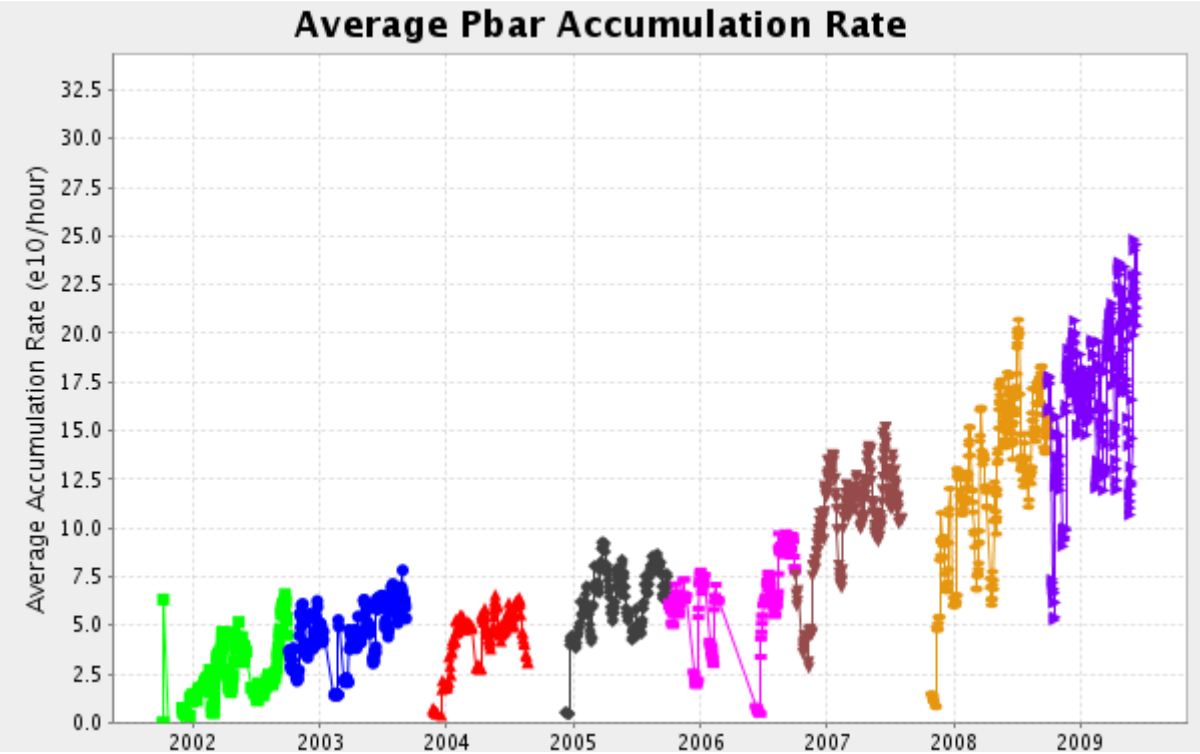


Effect of ~few hour Tev downtime with partial mining



Summary of Maximizing Antiproton Production

- Items addressed:
  - Optimized number of stacking cycles (when to initiate transfer)
  - Reduced time needed for transfer
  - Partial mining
- along with increased protons on target and a long list of machine improvements…



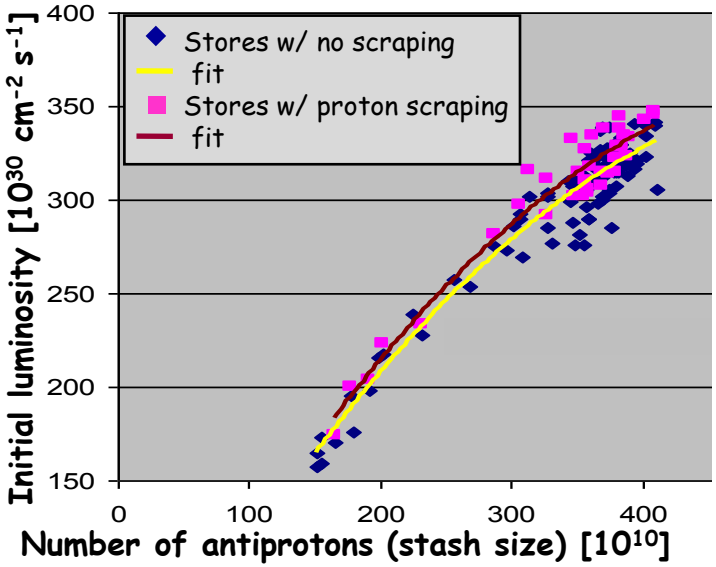
Other operational improvements

Optimizing Proton Brightness

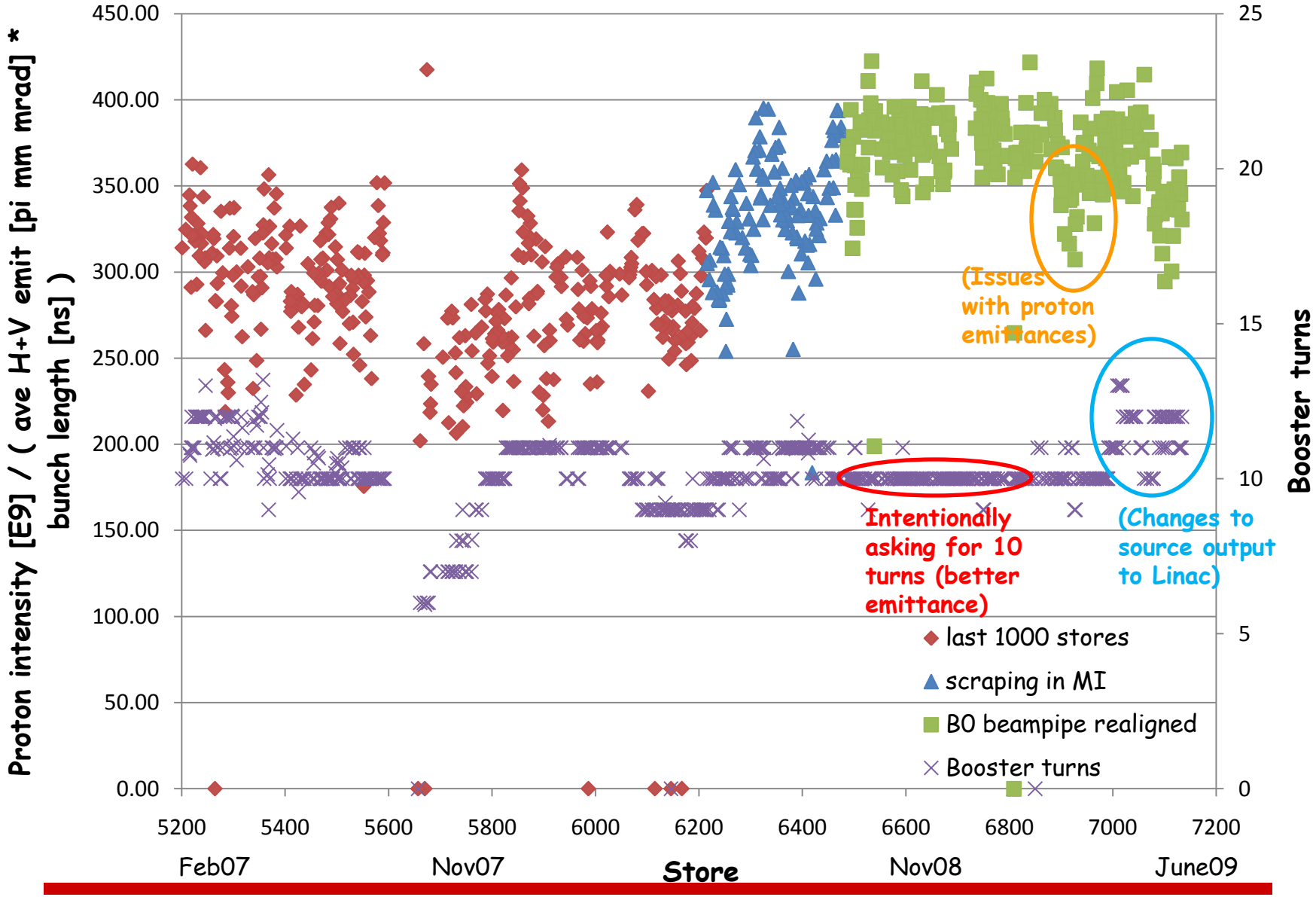
$$L \propto \frac{N_p N_a}{(\varepsilon_p + \varepsilon_a)}$$

intensity/emittance = brightness
(more beam in smaller area)

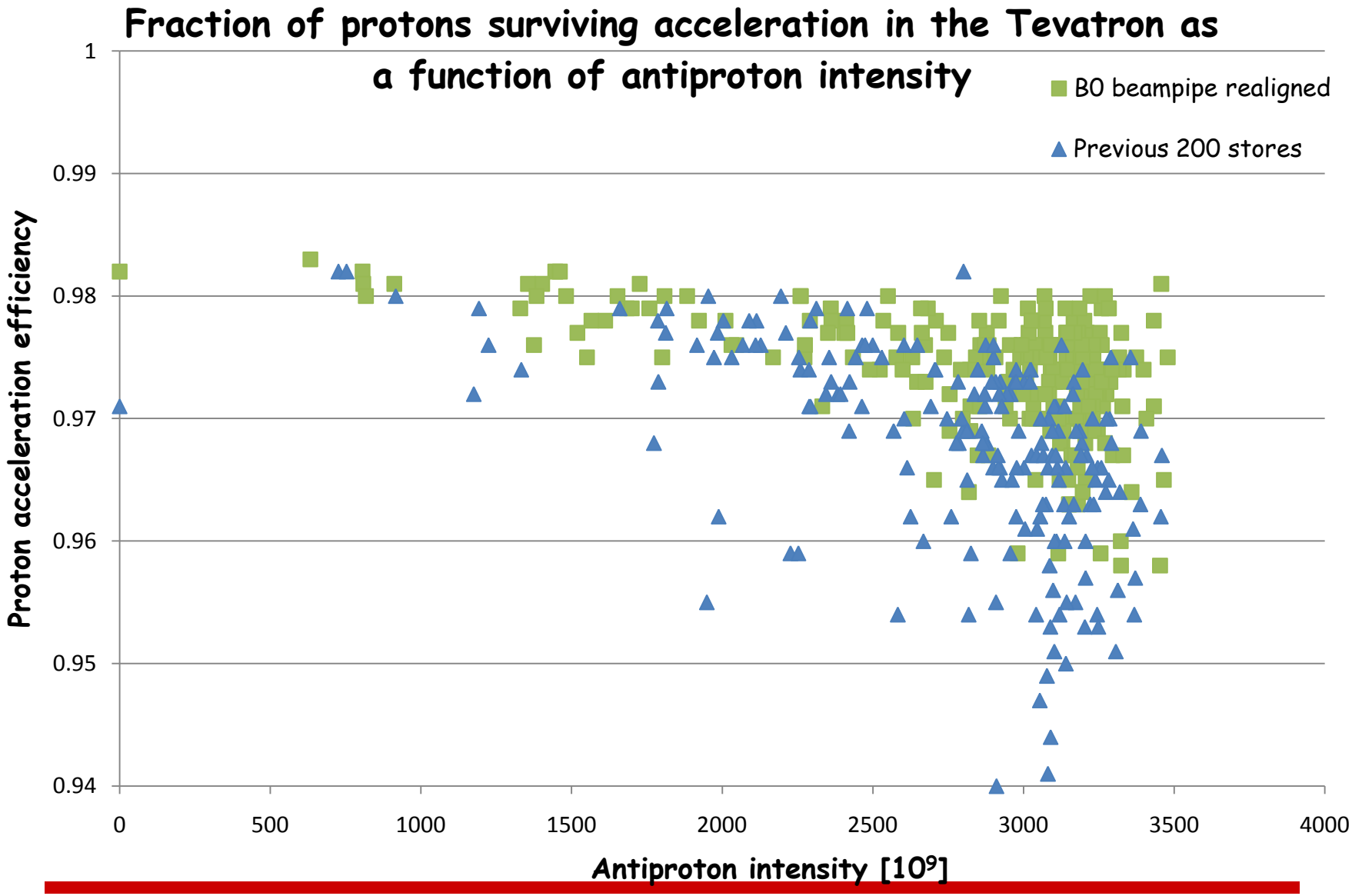
- Increase brightness by increasing intensity and/or decreasing emittance
- Pbar brightness >> proton brightness leads to stronger beam-beam effects
  - brighter protons for reduced beam-beam effects, also allowed removal of intentional pbar blow-up at injection for brighter pbars
- Achieved by scraping the proton halo in the Main Injector before accelerating and injecting into Tevatron (start with higher intensity beam, scrape to nominal intensity)
- Improved initial luminosity ~3-4%
- Improved transfer and acceleration efficiencies
- Improved dynamic aperture of the machine, reduced quenching (beam falling out of machine catastrophically)



Proton brightness in the Tevatron

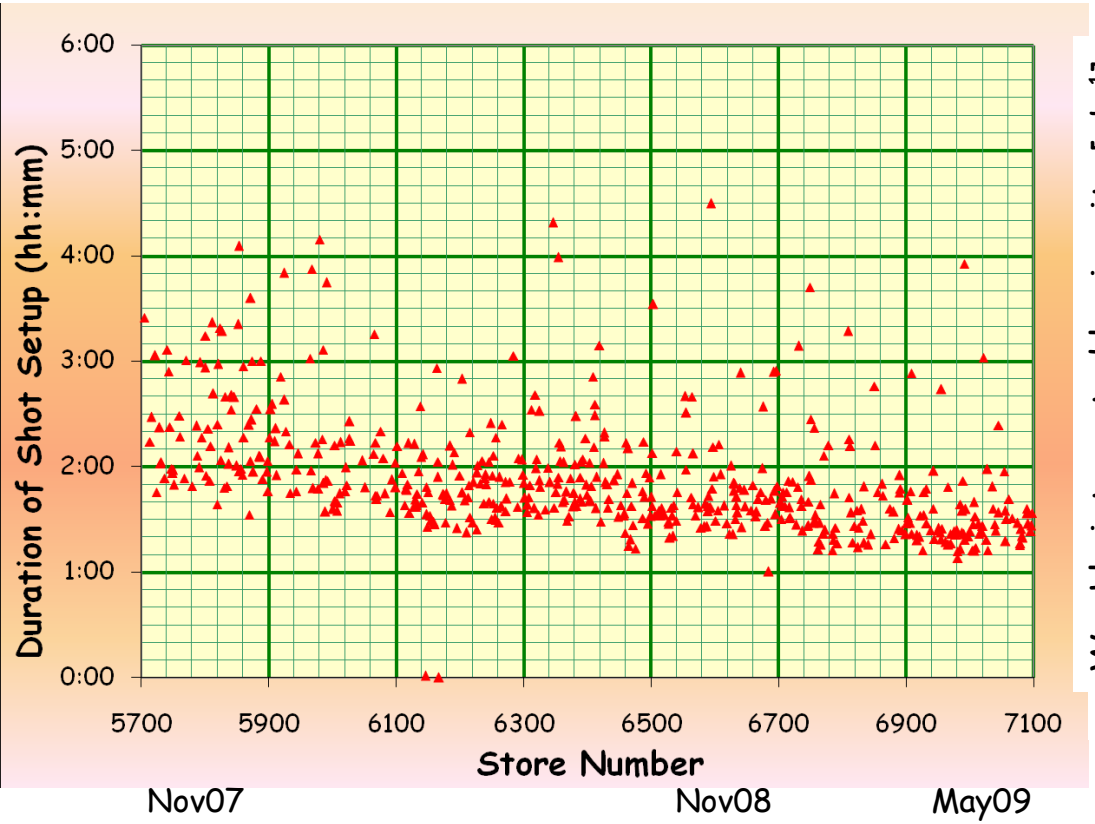


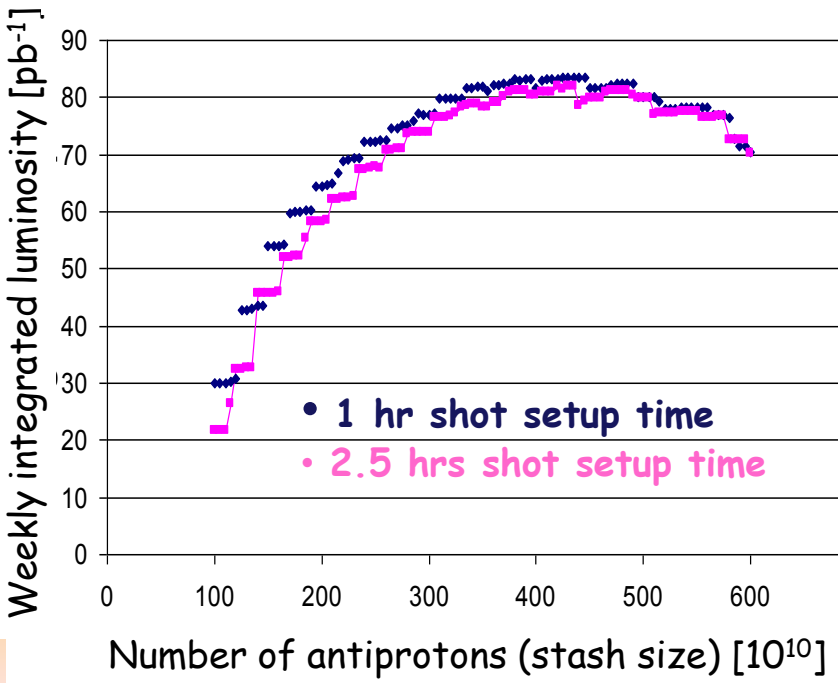
Removal of aperture restriction



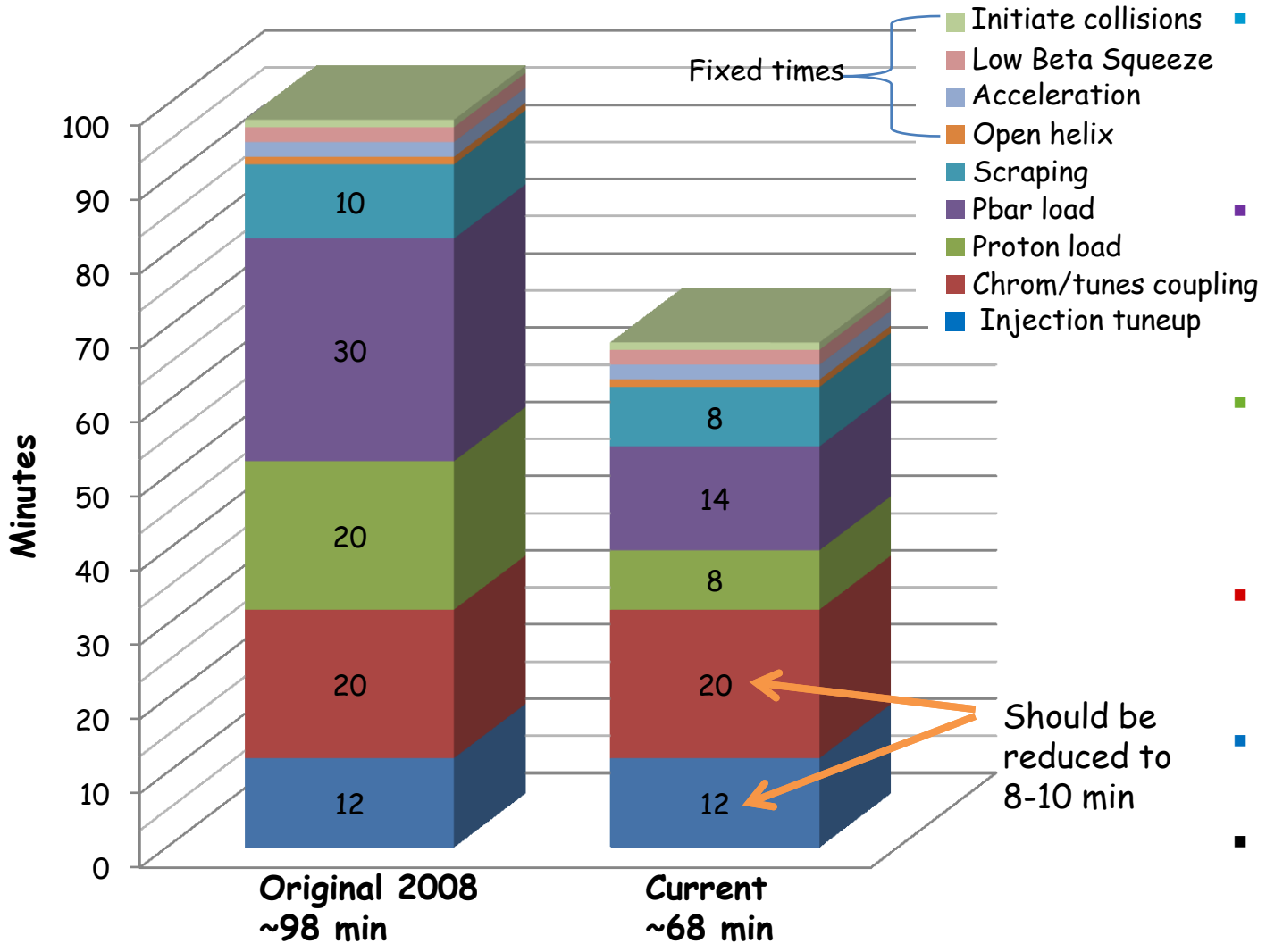
Optimizing Tevatron Shot Setup Length

- Collider shot setup time reduced from 2.5 to 1.25 hour
- Greatest effect on integrated luminosity when keeping stores for shorter duration (shooting from smaller antiproton stash)





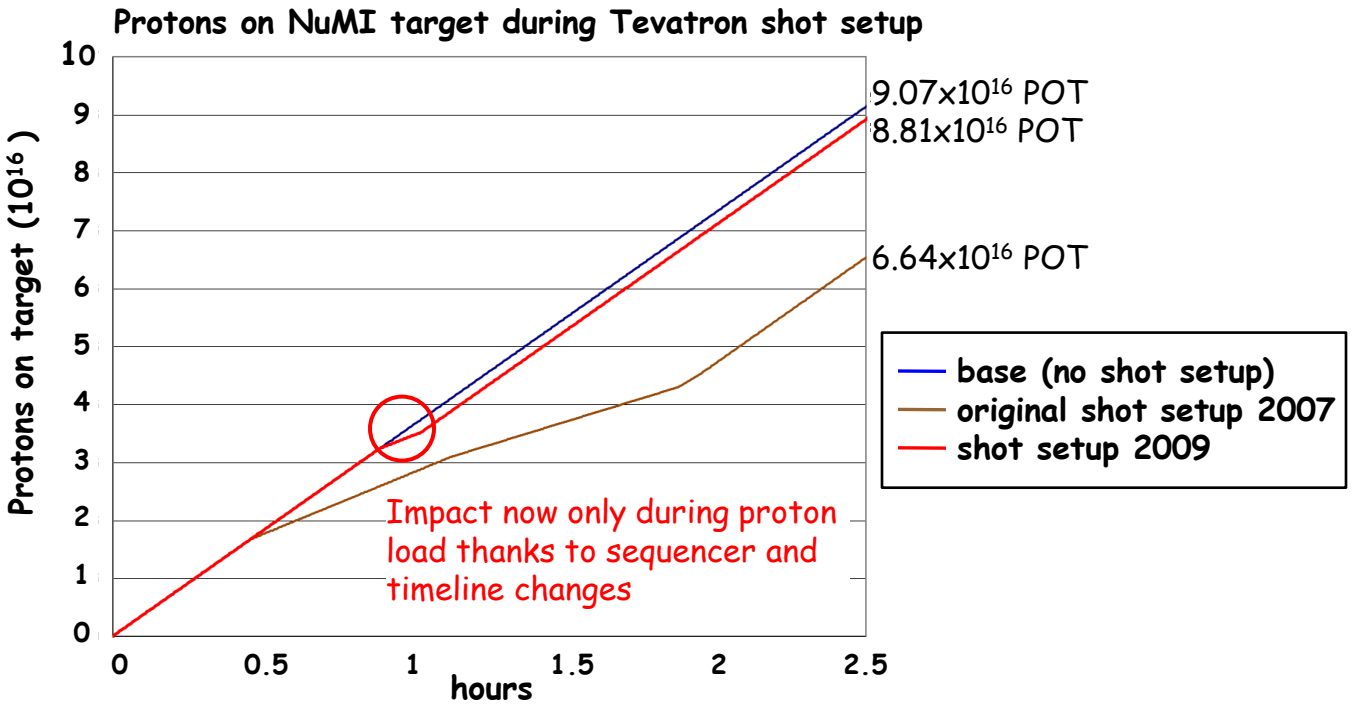
Shot Setup Time Distributions



- Insert collimators faster when far from beam
- Time line changes, Recycler RF manipulations
- Inject 2 bunches at a time (multi-batch coalescing in Main Injector)
- Software for automated measurements
- Use of historical settings
- Tevatron Sequencer optimization

Other consequences of faster shot setup

- More time for stacking, beam to fixed target experiments

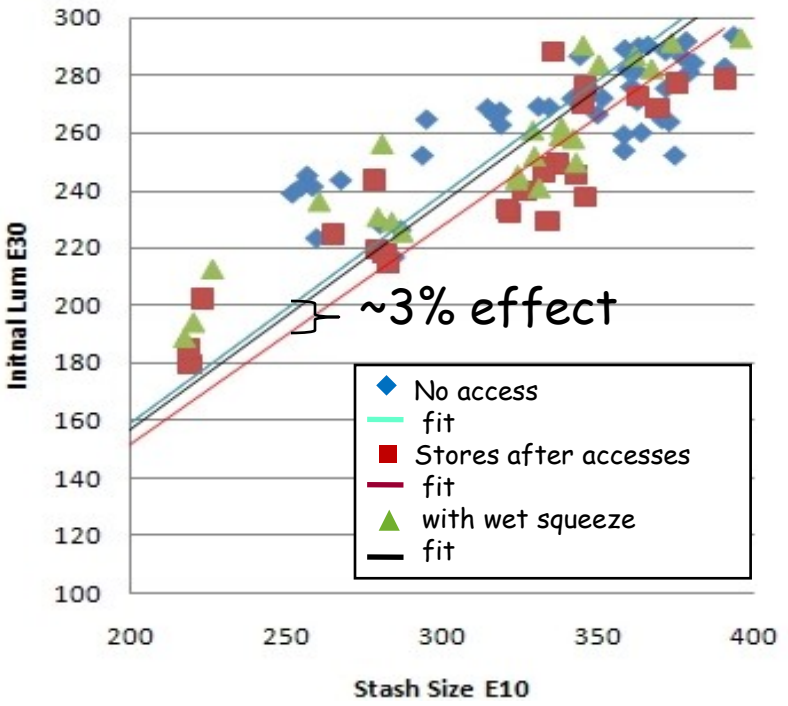


Consistency, reliability

- Shoot from consistent stash size
  - Recycler cooling
  - Tevatron tunes
- Tevatron stability
  - Controlled proton tune (based on antiproton intensity)
  - Orbit stabilization
  - Controlled antiproton/proton emittance ratio
    - Blow-up antiprotons
    - Scrape protons
  - Removal of aperture restriction near CDF interaction region
  - Monitoring lattice stability
- With stable machine and beam parameters, beam-beam effects are no problem up to 3.5×10^{32} $cm^{-2}s^{-1}$

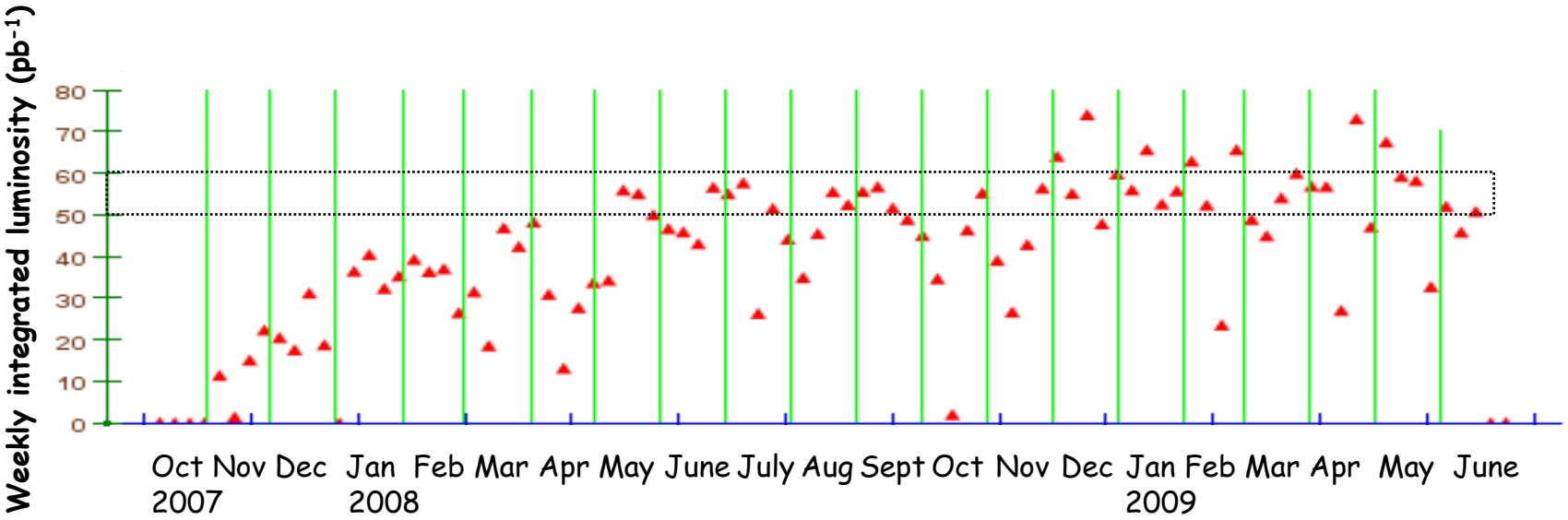
Improved Reliability After Access

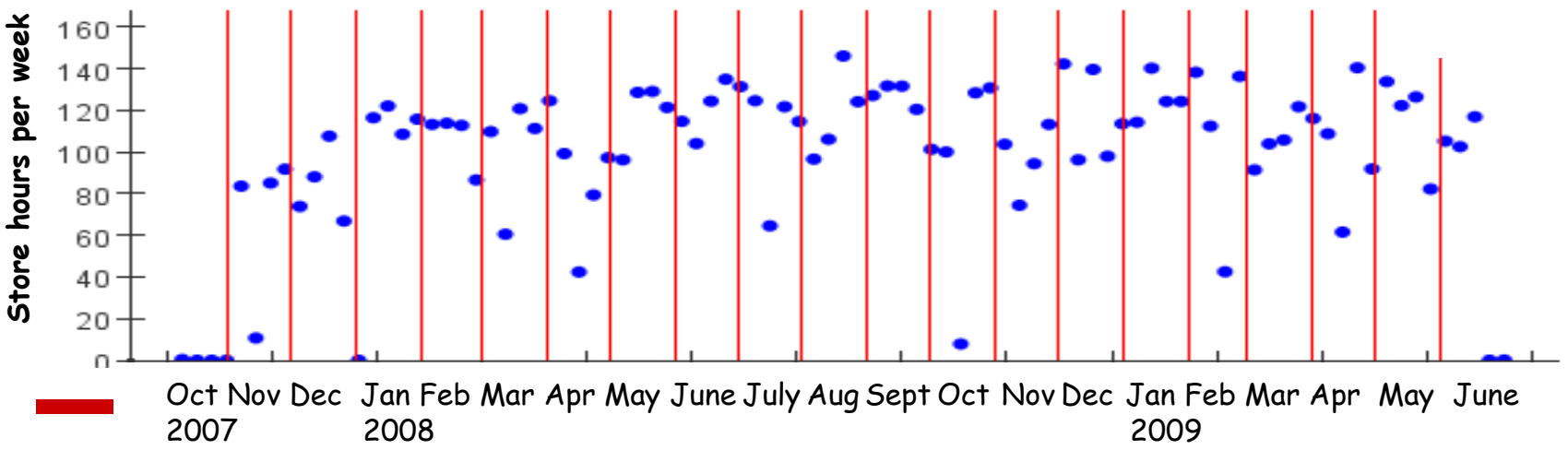
- Recovery after access (~2hr overhead)
  - Turn on / check out power supplies
  - Dry squeeze (no beam)
    - Check out low-β quads which are turned off for collision hall access
  - Wet squeeze(s) (beam)
    - Check/correct orbits
      - affect setting of Tunes/Chromaticity /Coupling
    - Less likely to develop problems during shot setup



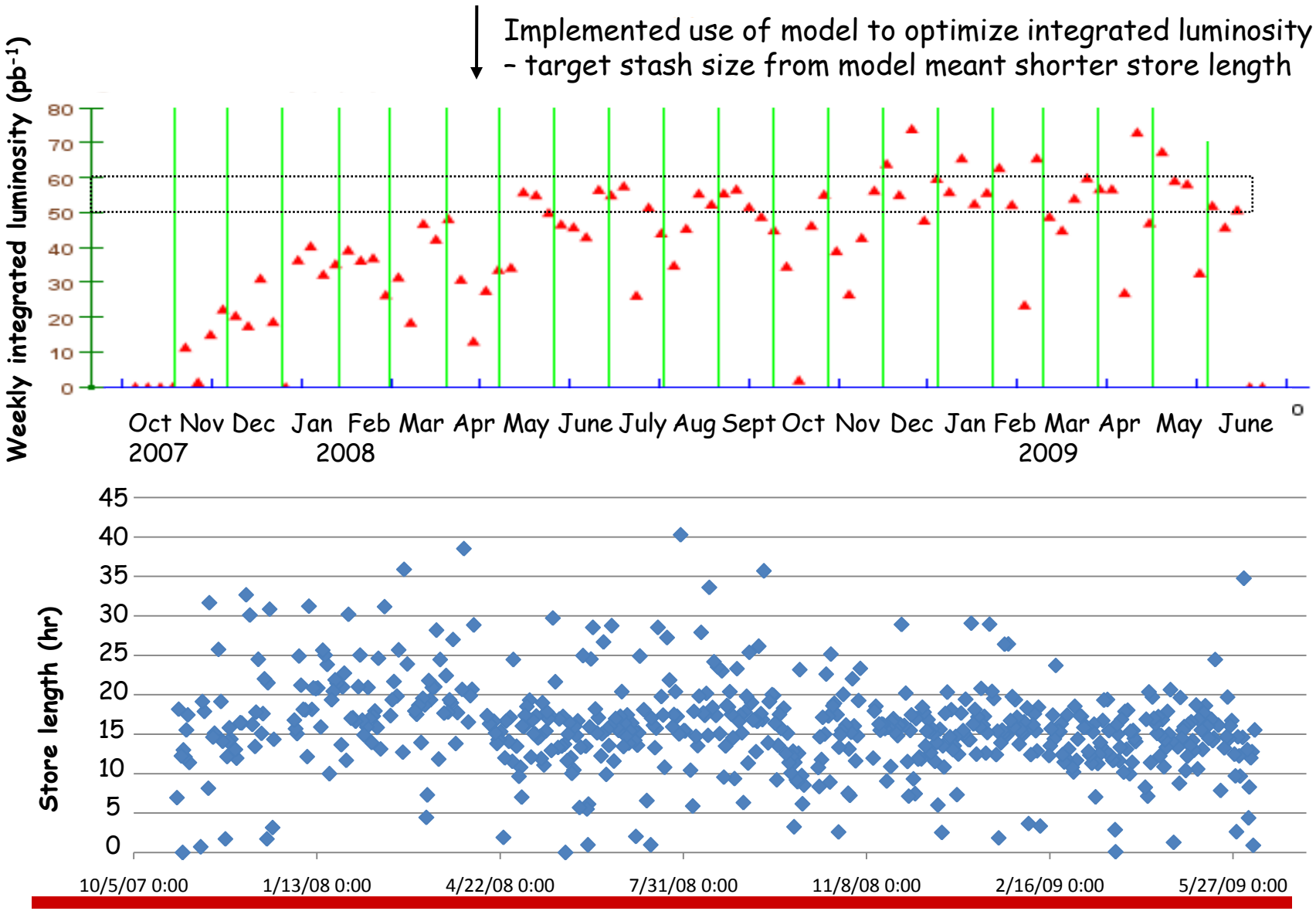
Results

Integrated luminosity and store hours per week

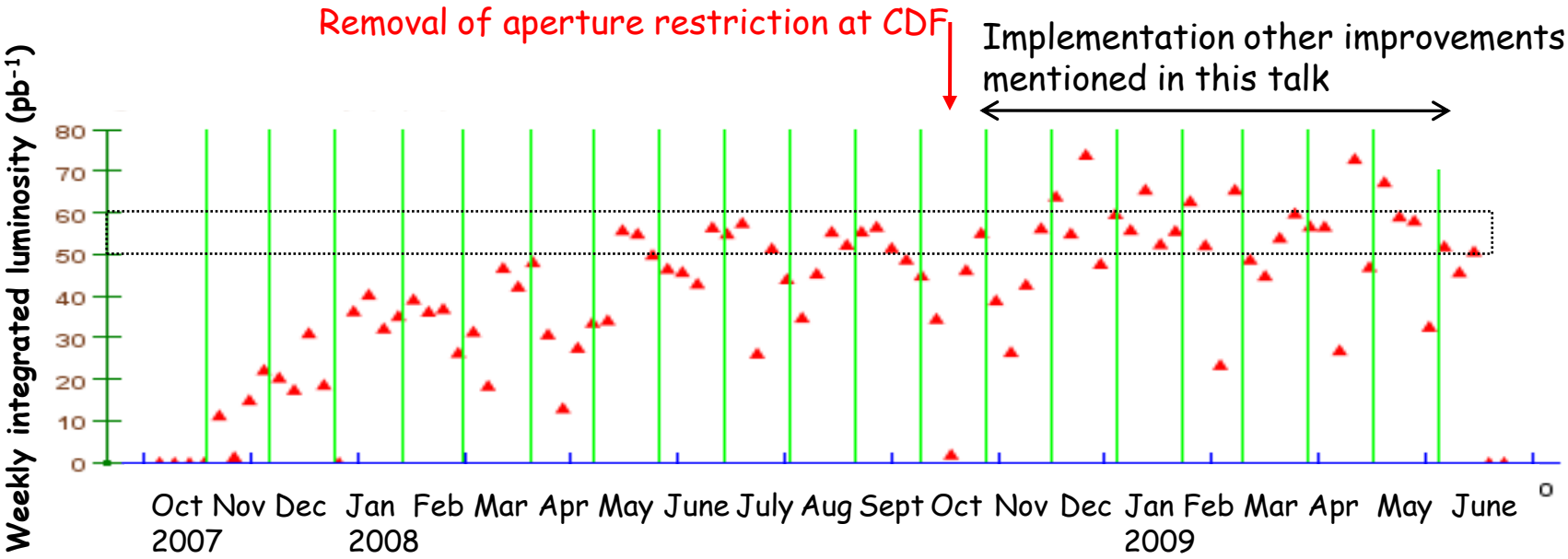


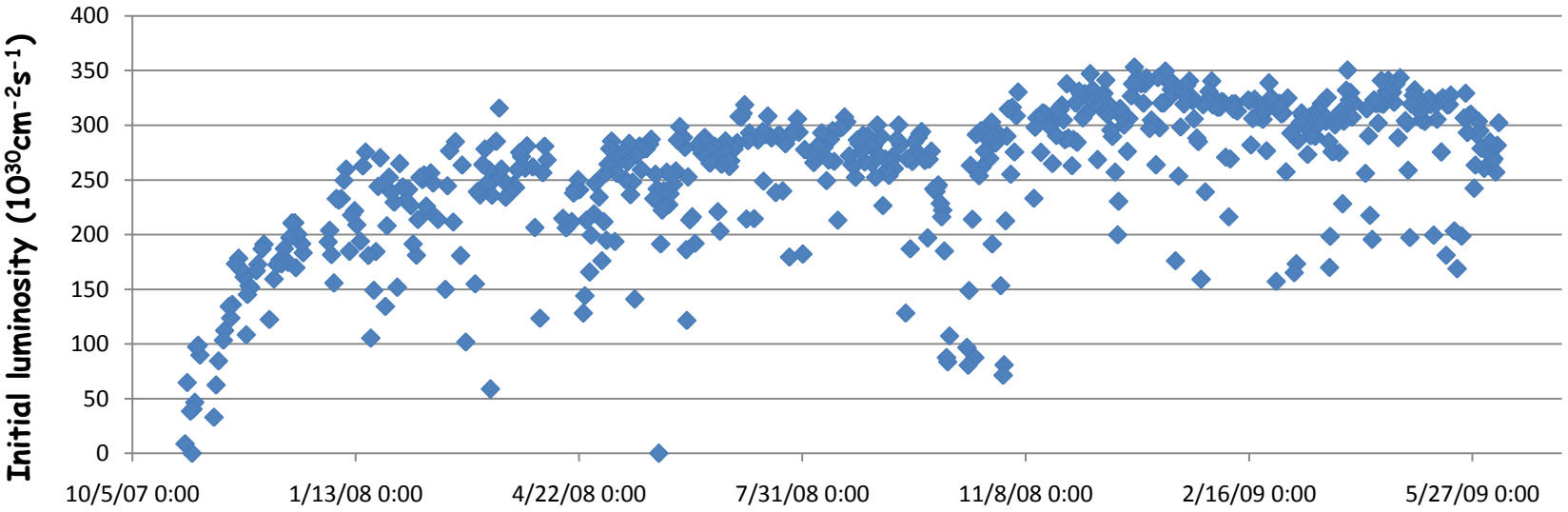


Weekly integrated luminosity and store length

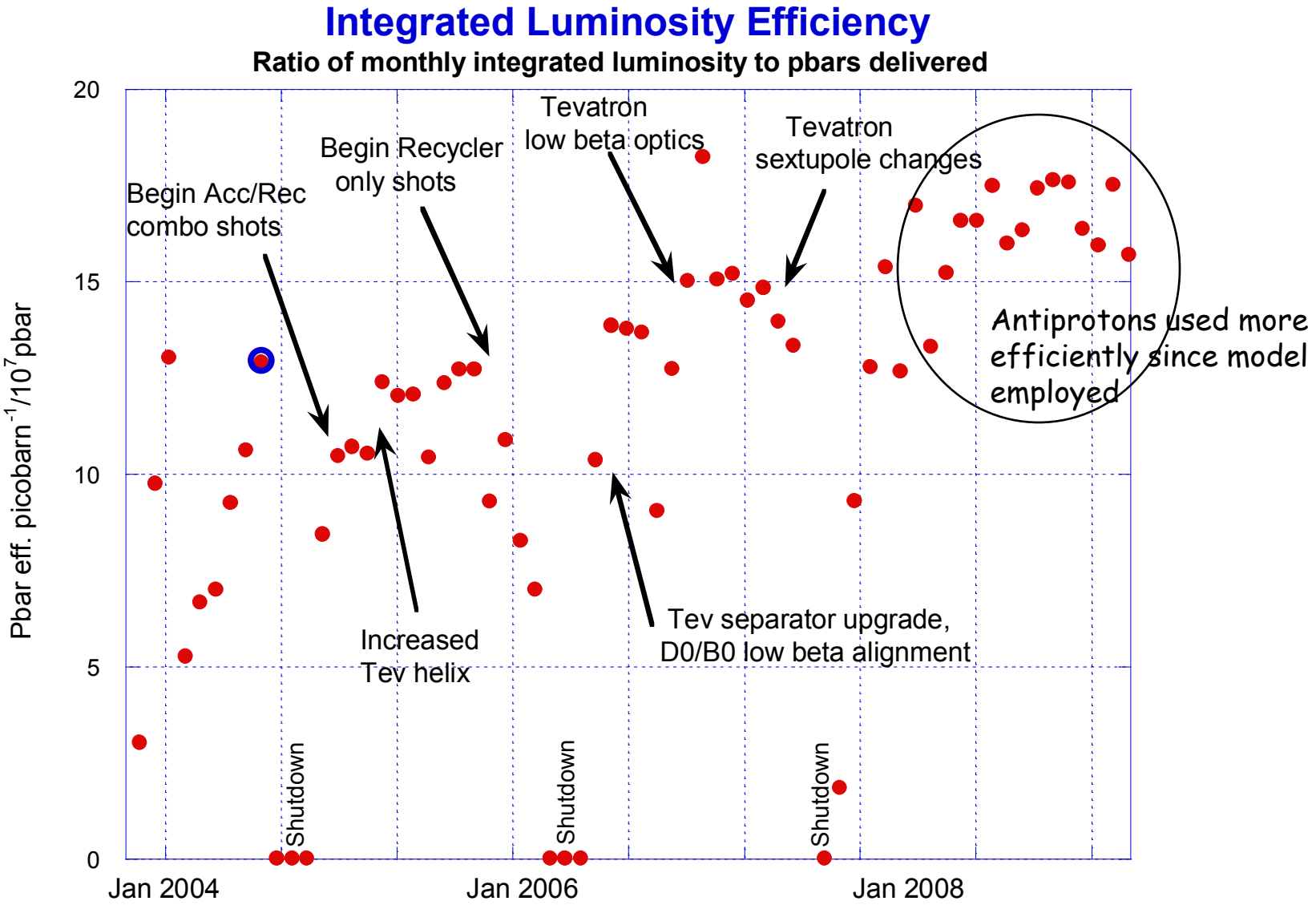


Weekly integrated and initial luminosities

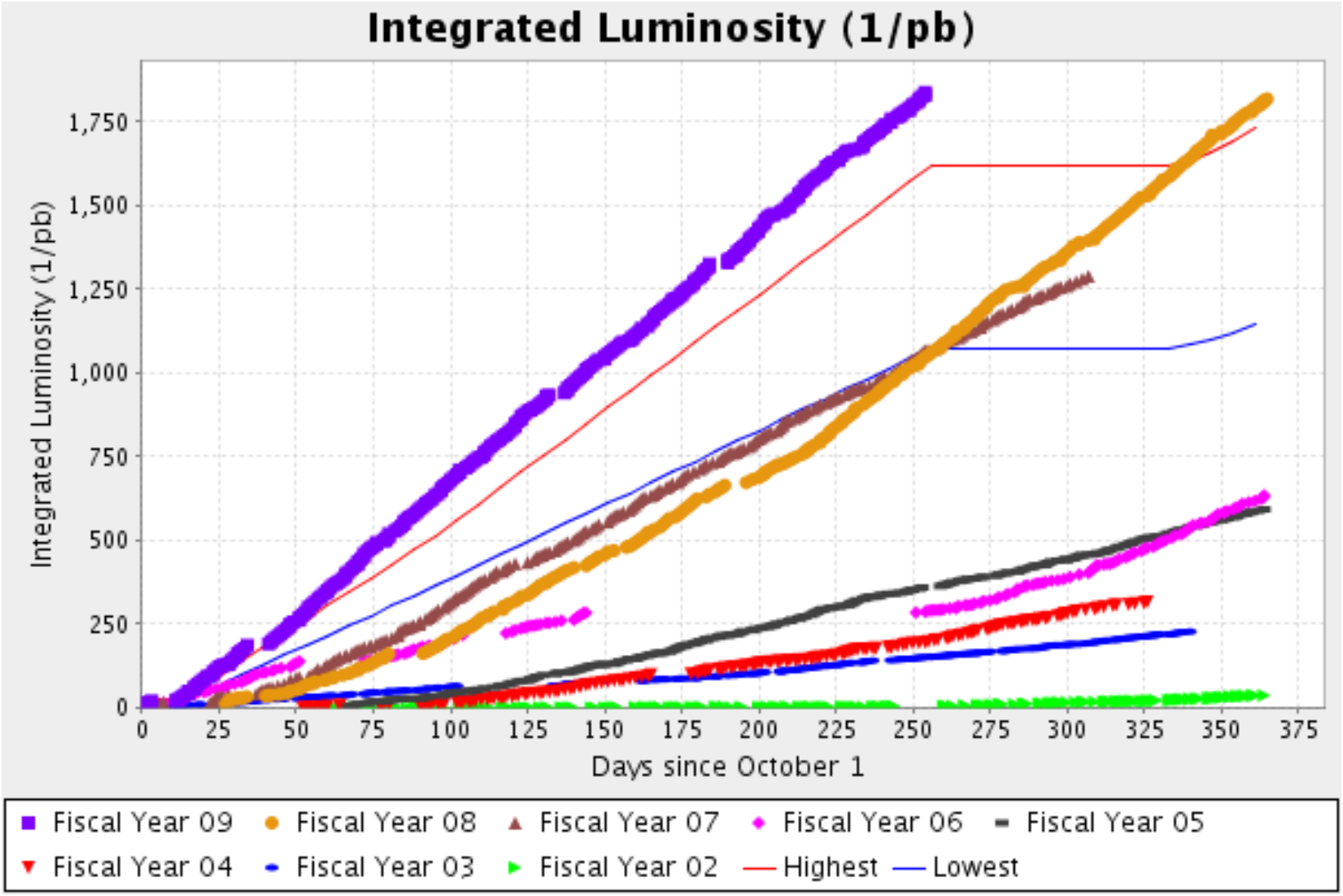




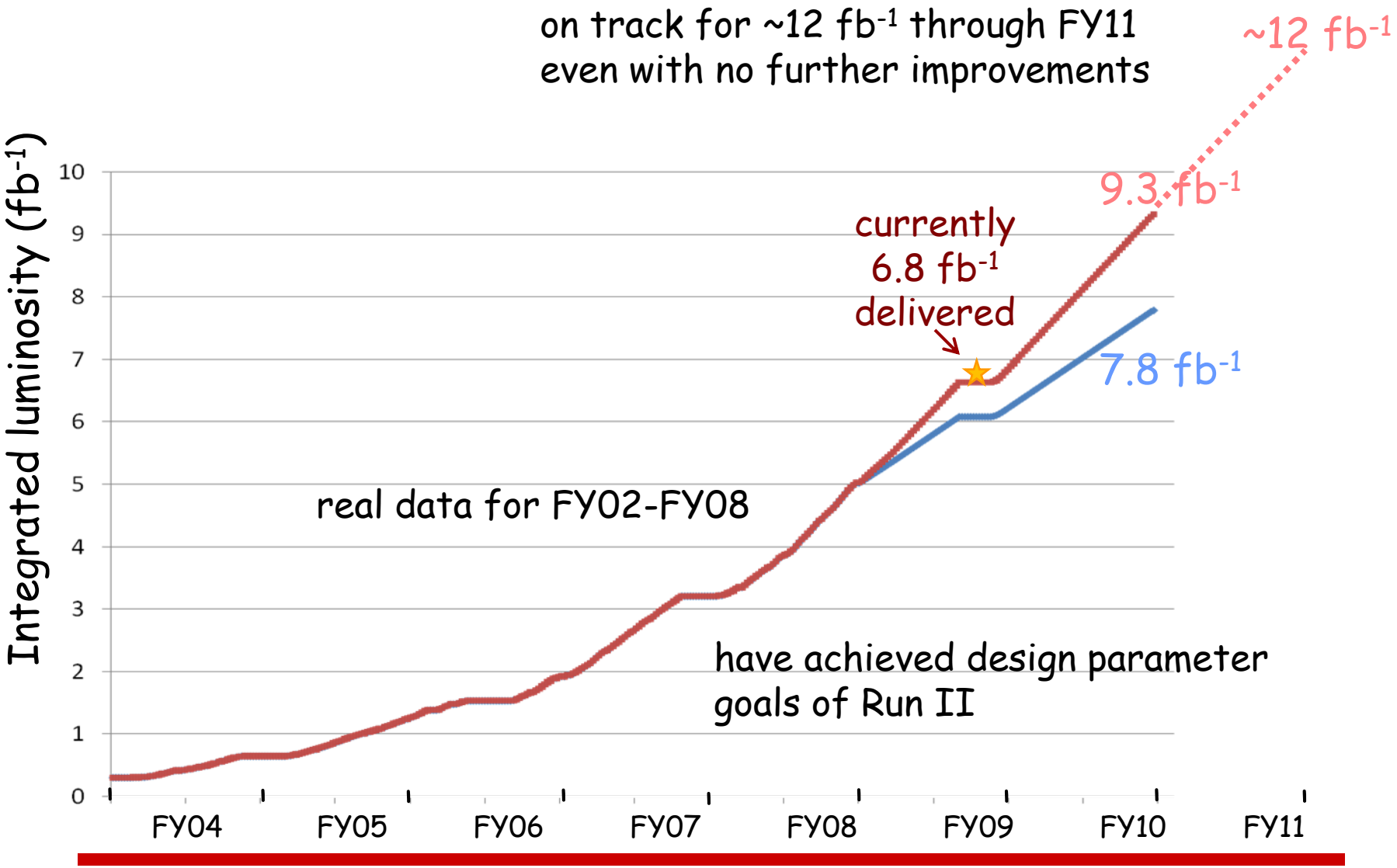
Effective use of available antiprotons



Integrated luminosity by year



Luminosity performance and projections



Conclusions

- Model for optimizing integrated luminosity in the Fermilab Tevatron determines target number of antiprotons for terminating store and putting in a new one
  - Has led to improvement of approximately 35% in integrated luminosity
- Operational changes have increased overall antiproton production
  - Optimized pbar transfers
  - New method for leaving behind a fraction of the antiprotons in Recycler when extracting for a Tevatron store
- Other recent operational improvements
  - Decreasing collider shot-setup time
  - Reducing beam-beam effects by making the proton and antiproton brightnesses more compatible, e.g. scraping proton beam to smaller emittance
  - Efforts towards consistency, reliability
- Still pushing to get as much luminosity as we can!