HIGH LUMINOSITY 100 TeV PROTON - ANTIPROTON COLLIDER

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Introduction

★ With the discovery of the Higgs boson exploration will continue to search for beyond the standard model (BSM) physics.

★ The energy scale for new physics is known to be in the multi-TeV range.

★ A 100 TeV proton-antiproton collider is proposed with luminosity of 10^{34} $cm^{-2}s^{-1}$, and 200 km circumference ring using 8 Tesla NbTi magnets.

★ Advantages in $p\bar{p}$ collision are presented, such as higher cross sections for high mass production and synchrotron radiation reduction.

★ Key aspects to achieve high luminosity include increasing $\bar{p}$ momentum acceptance, in a Fermilab-like antiproton source, and more antiproton cooling.

Why a Proton-Antiproton Collider?

- ★ **Proton antiproton colliders have shown to be competitive:** CERN (W & Z bosons), Fermilab (Top quark).
- ★ **The cross section for $p\bar{p}$ collisions is greater than in pp collisions for high masses.** Antiquarks for production can come directly from an antiproton, so detector pileup is reduced.
- ★ **Scaling to a 200 km $p\bar{p}$ ring, the SR is reduced from 35 to 1.75 W/m compared with a 100 km ring.**
- ★ **Higher cross section reduces the synchrotron radiation:** lower beam current can produce the same rare events rates.
- ★ **A $p\bar{p}$ collider only requires one ring instead of the two needed for a pp collider.**

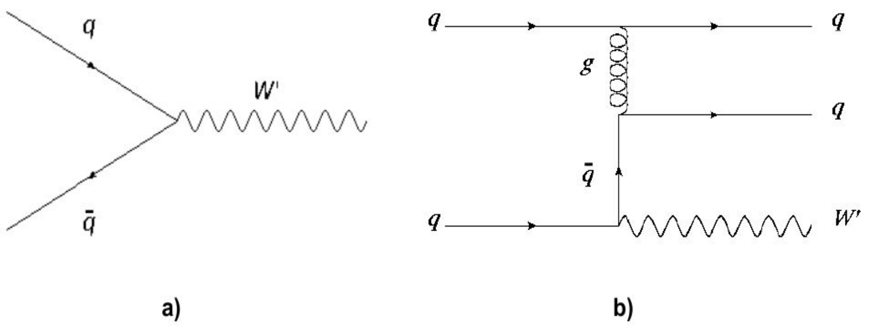


Figure 1. *Feynman diagrams for W' production in (a) $q\bar{q}$ collision, and (b) qq collision (t channel).*

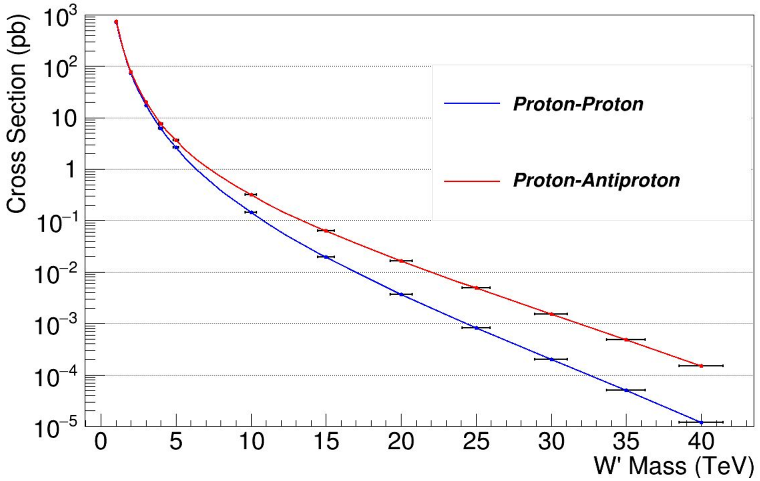
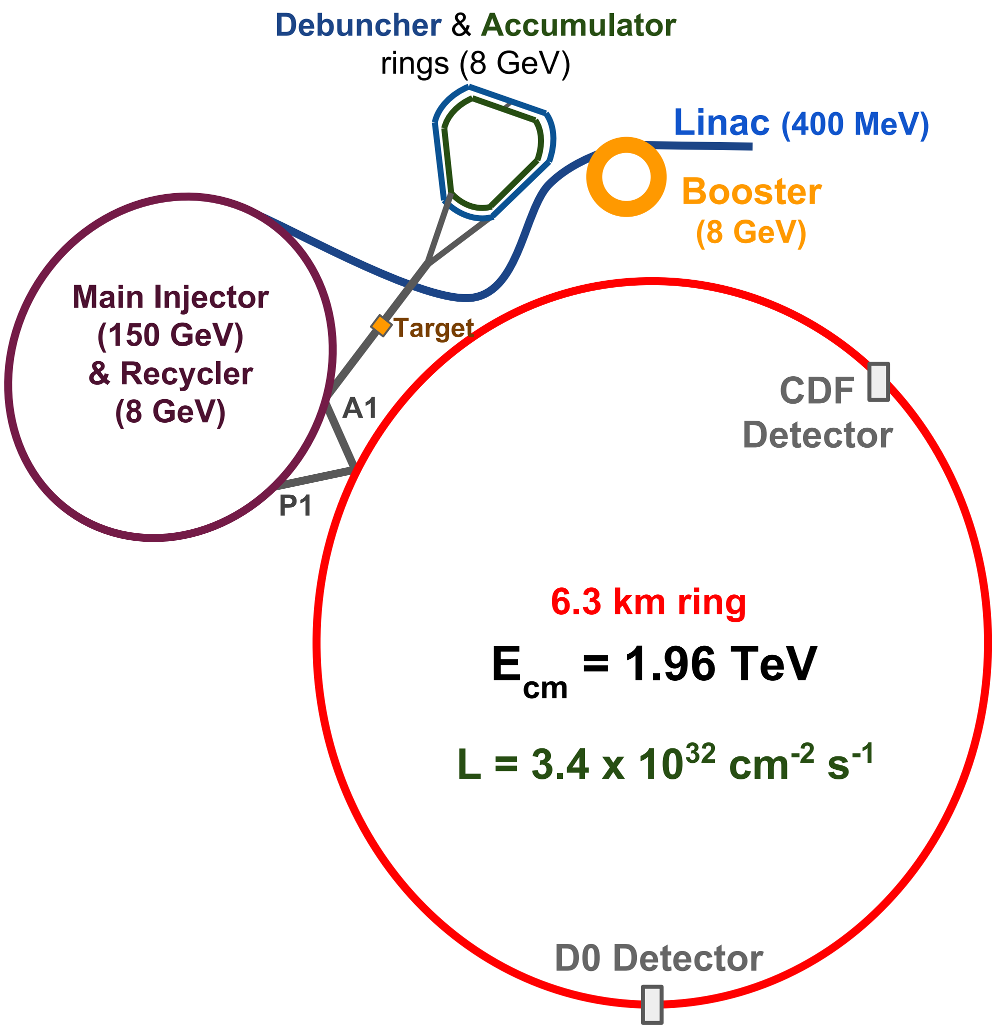


Figure 2. *W' cross section as a function of the mass using pp and $p\bar{p}$ collisions with E_{cm} = 100 TeV.*

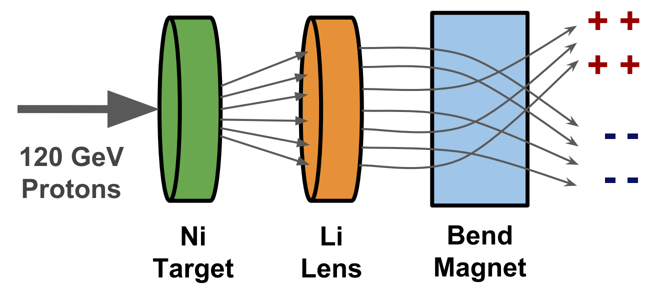
Tevatron (1987-2011)



Fermilab Antiproton Source

a) Target Station:

- ~38 x 10^{10} $\bar{p}/hr$ antiprotons (8.9 GeV) are created.



b) Debuncher Ring:

- Antiprotons are stochastically precooled during 2.2 s.
- Emittance reduction of 300 to 30 μm.

c) Accumulator Ring:

- Store the cooled $\bar{p}$'s (Stacking rate of 25 × 10^{10} $\bar{p}$ /hr).
- Additional stochastic cooling is done.
- Emittance reduction of 30 to 3 μm.

d) Recycler Ring:

- Additional $\bar{p}$'s storage (up to 600 x 10^{10})
- Stochastic and electron cooling.

How to get a Luminosity of 10^{34} cm^{-2} s^{-1}

$\gamma = E_{beam}/m_p$

Number of Bunches

Number of particles per bunch

$$L = \frac{\gamma f N_B N_1 N_2}{4\pi\varepsilon\beta^*}$$

Revolution frequency

Emittance

Betatron value in the IP

Taking as reference the Tevatron Luminosity:

$$L_{scaled} = E_{increased} \times f_{decreased} \times \beta^*_{factor} \times L_{current}$$
$$= \frac{50\,TeV}{0.98\,TeV} \times \frac{6.28\,km}{200\,km} \times 2 \times (3.4 \times 10^{32}\,cm^{-2}s^{-1})$$
$$= 1.1 \times 10^{33}\,cm^{-2}s^{-1}$$

10x bunches (10 x 36) to achieve a luminosity of $10^{34}cm^{-2}s^{-1}$

$\bar{P}_{\text{Burn rate}} = \sigma L = 540 \times 10^{10}$/hr

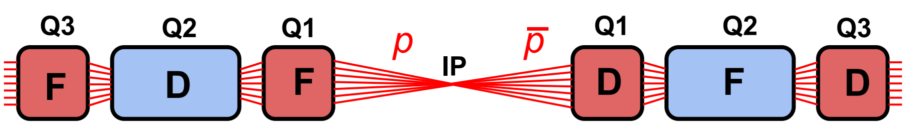
(σ = 153 mbarn, total proton/antiproton cross section for E_{cm} = 100 TeV)

The Fermilab Debuncher cooled ~40 x 10^{10} $\bar{p}$/hr,

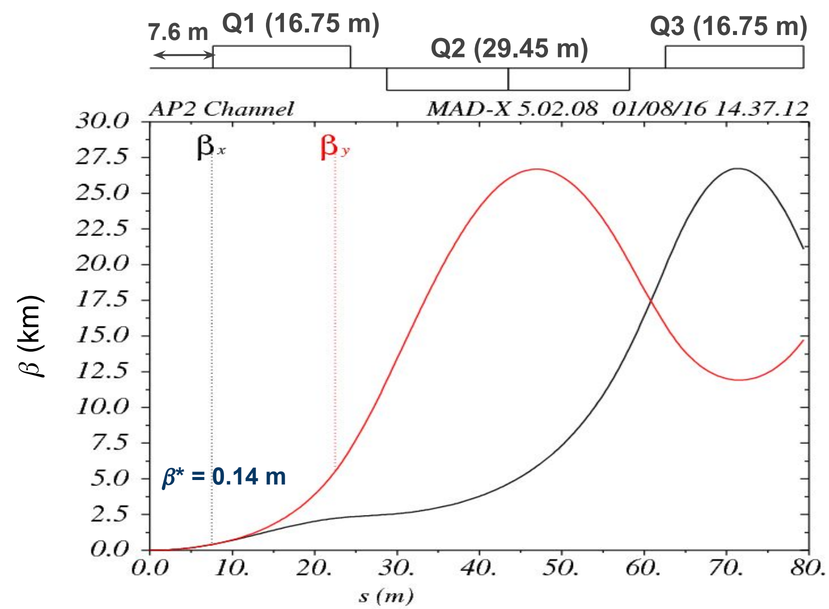
12x more antiprotons are needed to keep up the burn rate

β^* in the Interaction Region

- Magnetic quadrupoles provide the final focusing of the beam for the collision.



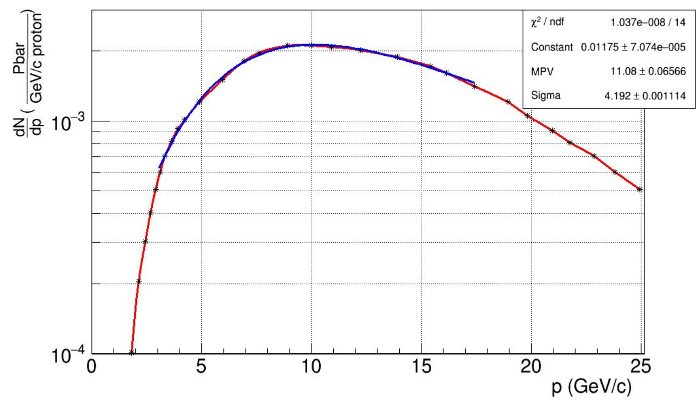
- Using Mad-X the β^* is fixed and the the Tevatron Inner Quadrupole System is scaled in order to get $\beta_{x,max} = \beta_{y,max}$
- Nb_3Sn quadrupoles are required (~13 T)
- Quadrupoles Aperture = 40 mm
- More central $p\bar{p}$ events allow shorter detector and low β^*.



Beta values (β_x, β_y) are plotted as a function of the coordinate s.

How to get 12x more Antiprotons

- **In Fermilab only antiprotons with momentum acceptance of 8.9 GeV/c ± 2% were selected.**
- **The goal is to collect more antiprotons: 11 GeV/c ± 24%.**
- **Disperse the beam into 12 different momentum channels.**

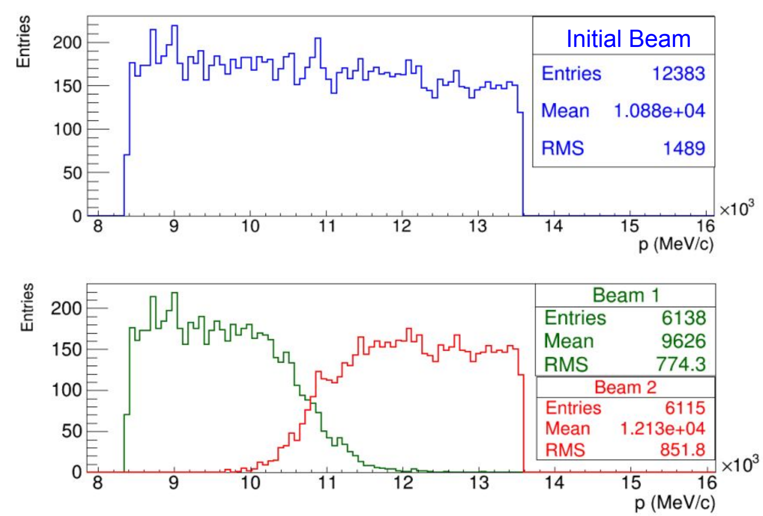


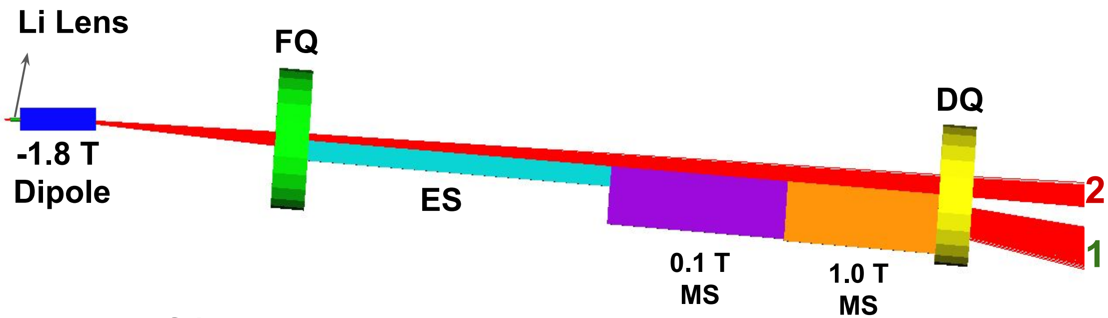
Momentum distribution of the antiprotons produced by a 120 GeV proton beam hitting a tungsten target. *(C. Hojvat and A. Van Ginneken, Nucl. Instrum. Meth. 206, 67(1983))*

Beam Separation and transportation:

- The initial beam (11 GeV/c ± 24%) enters the 18.6 cm Li Lens, and then is spread by a magnetic dipole.
- To divide the beam: an electrostatic septa ES and two magnetic septa MS to increase the separation.
- FQ and DQ quadrupoles to transport the beam.

Momentum Distribution



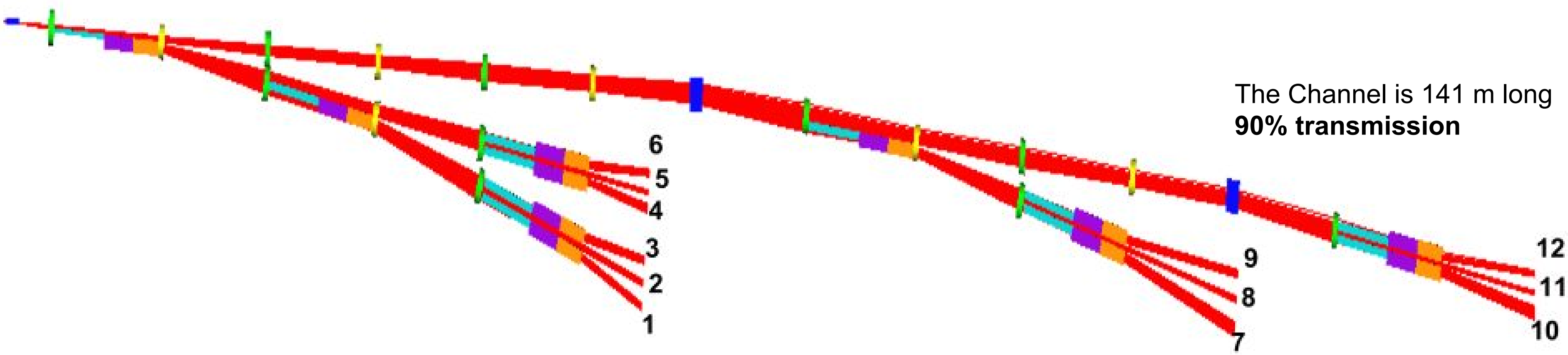


G4beamline simulation

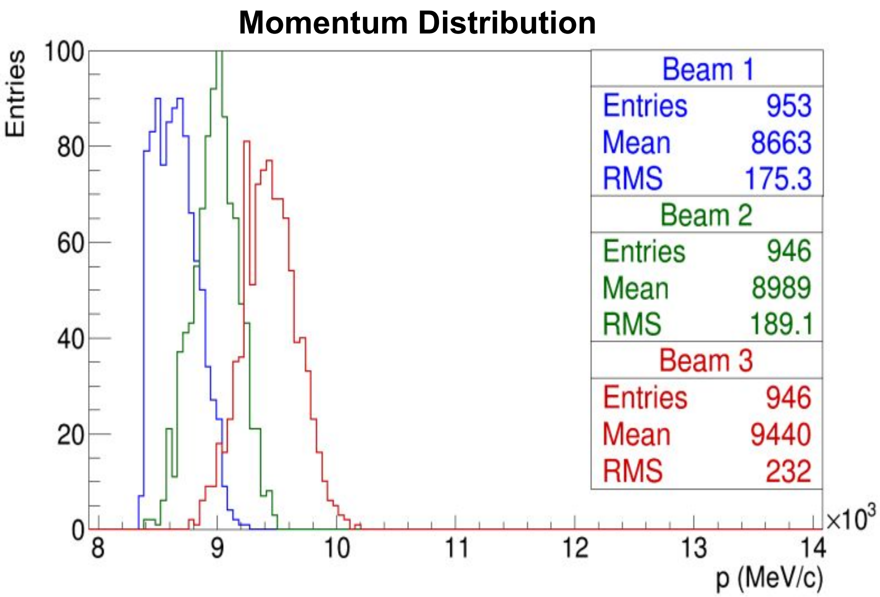
Li Lens: r = 1 cm, L = 18.6 cm, I = 500 kA
ES: L = 6m, E = 1 MV/m, gap = 0.30 m, septum = 0.2 mm
0.1 T MS: L = 3.5 m, height = 1 m, septum = 4 mm
1.0 T MS: L = 3.0 m, height = 1 m, septum = 20 mm
FQ & DQ: L = 0.66 m, R = 1.0 m, Gradient = ±2.0 T/m

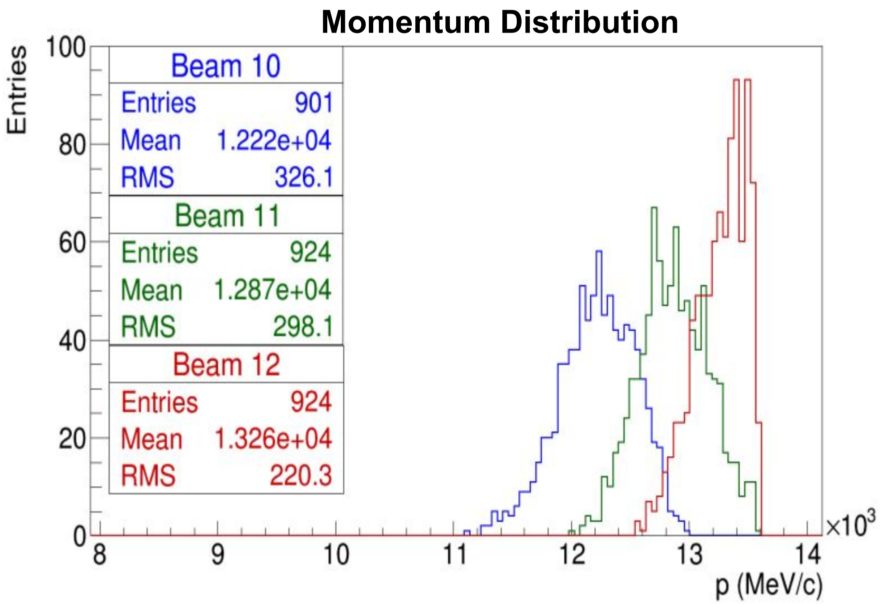
12 Different Momentum Channels

An initial beam with momentum acceptance p = 11.0 GeV/c ± 24% is divided to get finally 12 beams with momentum acceptance of about ± 2%.



The Channel is 141 m long
90% transmission





Antiproton Cooling

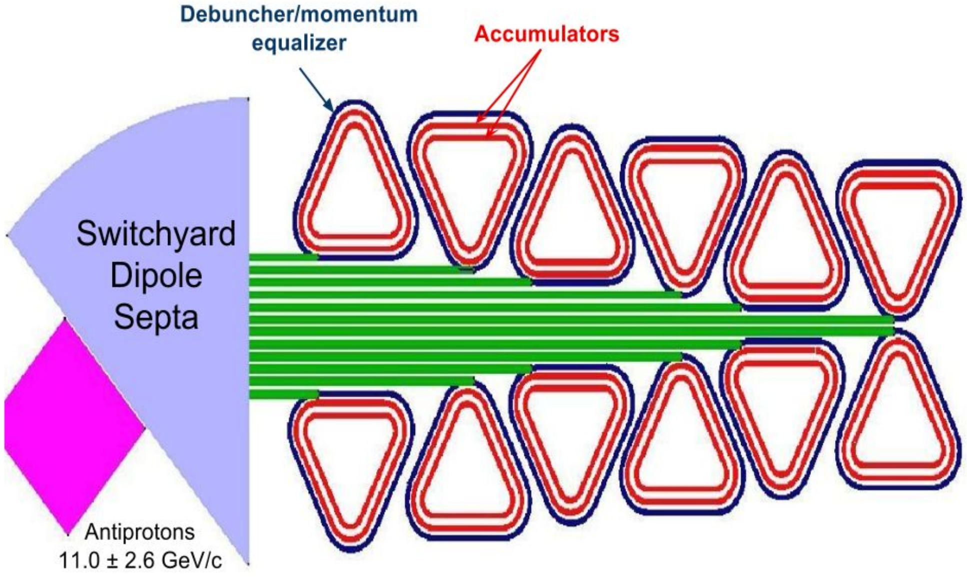
Beam Cooling: Reduce the energy spread and angular divergence of the beam.

Debuncher/momentum equalizer ring

- Each Debuncher phase rotates the beam to lower the momentum spread and also ramp the beam central momenta up or down to 8.9 GeV/c.
- The central momenta of all 12 channels would be equalized.

Accumulator Ring

- Two 25 x 10^{10} p̄/hr accumulator rings can keep up with one 40 x 10^{10} p̄/hr debuncher output rate.
- Antiprotons are cooled 2x faster.

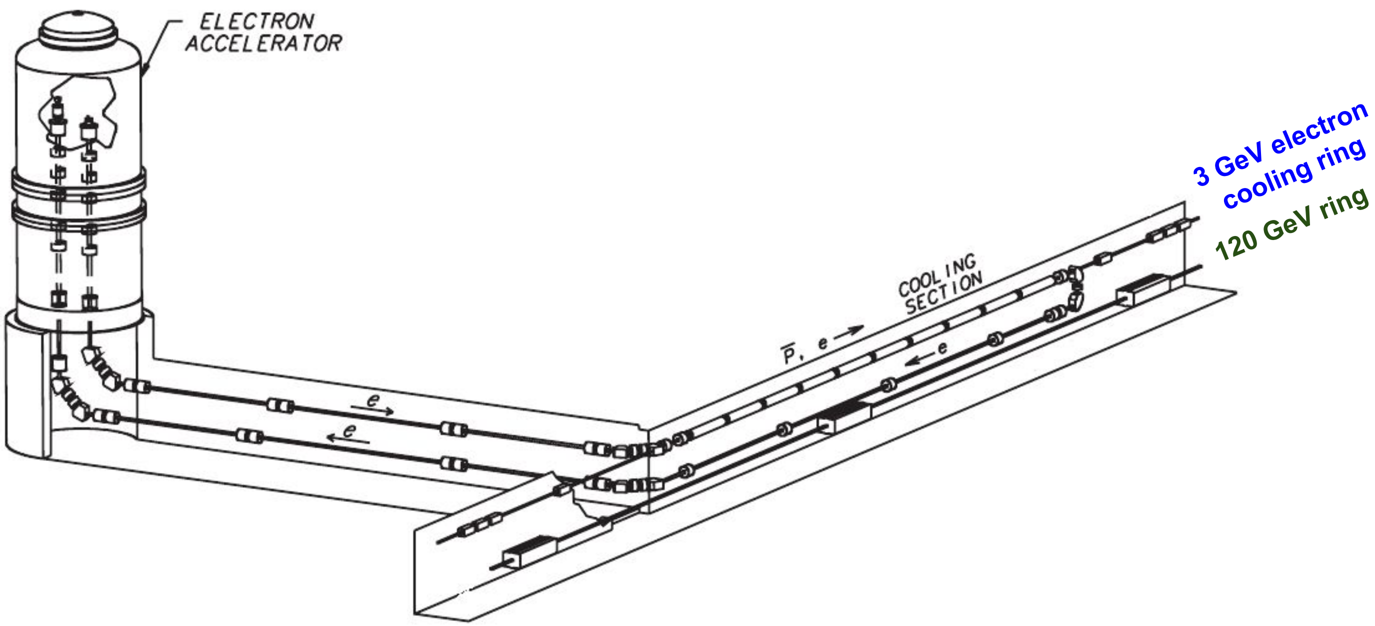


To cool 12x more antiprotons, 12 independent cooling systems would be implemented.

Antiproton Cooling

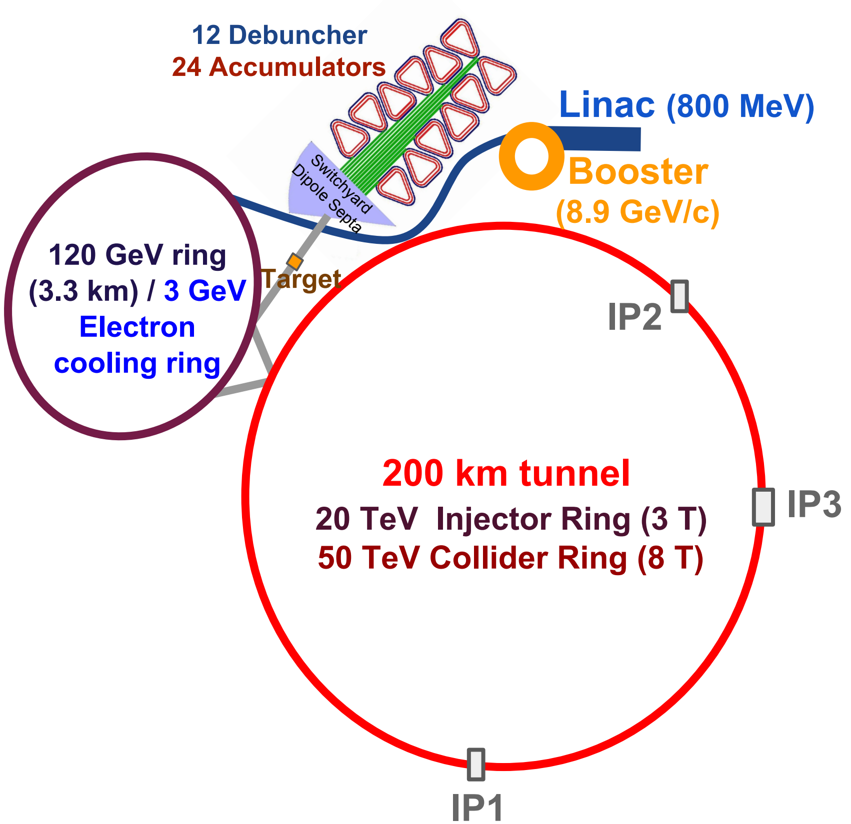
Electron Cooling Ring

- Electrons can cool large numbers of low emittance antiprotons in one ring.
- Electron cooling rate increases as $\gamma^{-2}\eta$, where η is the ring fraction occupied by electrons.
- Lowering γ by a factor of **3** and increasing ring fraction by **10**, cooling rate would increase by **90** versus what was achieved at FNAL.



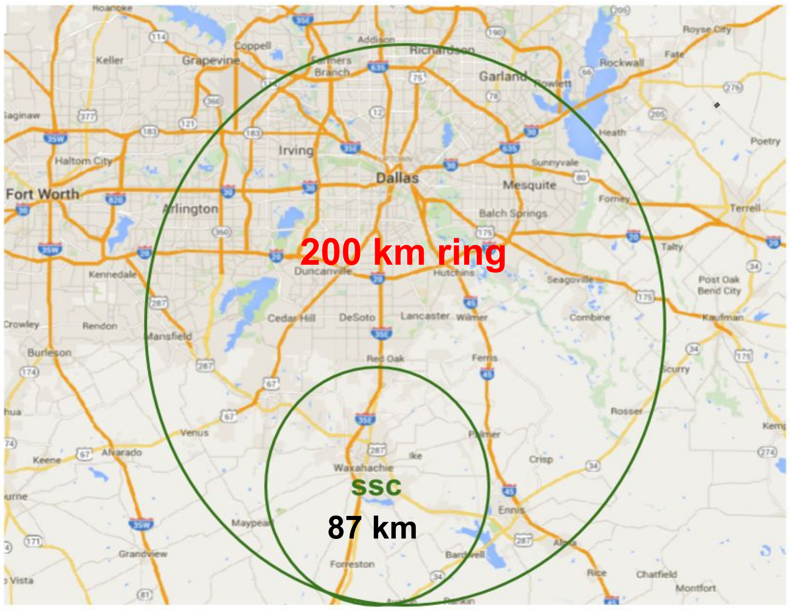
100 TeV p$\bar{p}$ collider Layout

In Fermilab



- Fermilab has the advantage of existing infrastructure.
- Injector ring could be built first and used as a collider. The 50 TeV ring would be an upgrade.

In Texas (USA)



- 200 km collider ring connected to the SSC (Superconducting Super Collider) existing tunnel (~45% complete).
- Texas has a homogeneous soft rock composition allowing rapid and cheaper tunnel boring.

Tunneling and Magnets Costs

Tunneling costs for 4 m diameter tunnel*

	Cost/m	200 km tunnel
CERN (Molasse/limestone)	$39,000	100 km limit
FERMILAB (Dolomite)	$15,000	$3 billion
Texas (Chalk/marl)	$6,000	$1.2 billion

* M. Breidenbach and W. Barletta, ESS-DOC-371

Tunneling-time estimate

	Length (km)	Volume of rock (million m^3)	Time (years)	Tunneling Machines
LEP	27	0.3	4	3
Channel Tunnel	3 x 50	5.6	6	11
200 km Tunnel (Texas)	200	2.5	3 †	4

† *Rock in Texas is faster to boring ~45 m/day based on SSC tunneling rates (P. McIntyre - Texas A&M University)*

Main Dipole Magnets Cost

- 3 or 4.5 T superferric magnets use about half as much NbTi per T/m as 8 T cosθ magnets.
- A 100 Km collider (100 TeV) requires expensive Nb_3Sn 16 T magnets

	Energy (TeV)	Dipole Field (T)	Dipole Cost (T-m)	Total Cost estimate
Injector	20	3	$1000 (Superferric magnet)	$0.42 Billion
Collider Ring	50	8	$2000 (LHC single aperture magnet)	$2.2 Billion

* $0.5M / magnet x 1232 magnets = $0.6 billion (LHC)

Summary

- ★ A high luminosity 100 TeV proton-antiproton collider is a competitive option as a future collider.
- ★ This collider reduces synchrotron radiation and pile up as compared to a 100 TeV pp collider, due to higher rare event cross sections.
- ★ To get high luminosity, 12x more antiprotons would be collected and cooled with 12 independent cooling systems.
- ★ New Quadrupole Inner System to obtain low β^* (14 cm).
- ★ Tunneling time would be faster and cheaper in Texas.
- ★ Low cost 3 T and 8 T magnets (NbTi).
- ★ Antiprotons would be recycled during runs without leaving the collider ring, by joining them to new bunches with synchrotron damping. The longitudinal damping time is two hours.

Thank you for your attention