Colliders and Detectors

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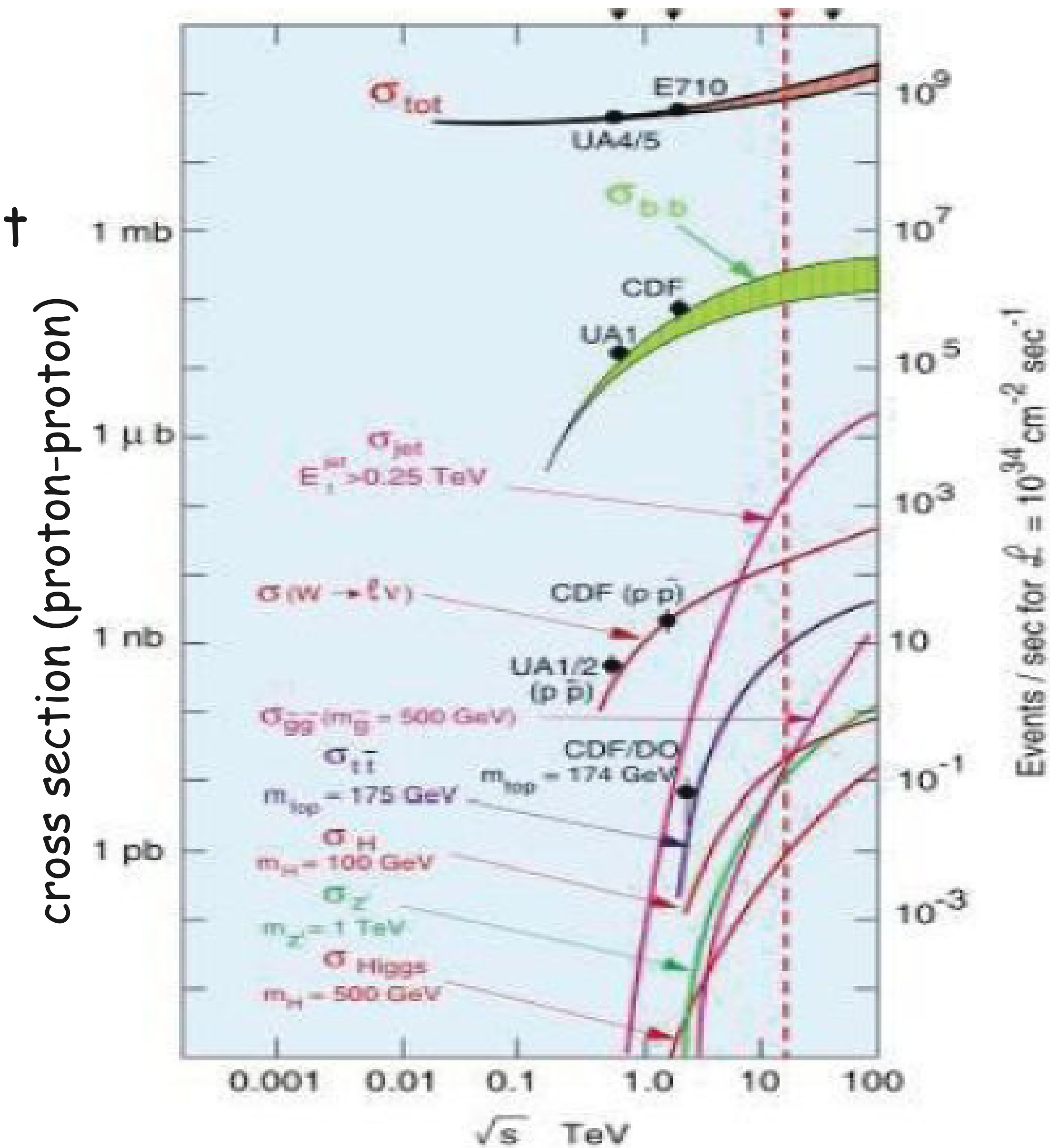
Hadron Collider Physics Summer School 2008
http://indico.fnal.gov/conferenceDisplay.py?confId=1965

V Seminario sul Software per la Fisica Nucleare, Subnucleare e Applicata
http://agenda.infn.it/conferenceTimeTable.py?confId=366

Why Colliders

Particles with high mass and low production cross section must be experimentally discovered to verify the validity of the Standard Model

A very powerful tool have been the colliders.



Colliders vs. fixed target: Rate

Fixed target:

Beam with n_1 particles per second

Target of length l with density particles n_2 per m^3

For each single particle the number of interaction in the target:

$$N = \sigma_{int} \cdot n_2 \cdot l$$

where σ_{in} is the interaction cross section.

If the target is larger than the beam, the rate R

$$R = dN/dt = \sigma_{int} \cdot n_1 \cdot n_2 \cdot l$$

$$R = \sigma_{int} \cdot L$$

$L = n_1 \cdot n_2 \cdot l$ is the luminsity $[cm^{-2} s^{-1}]$

The luminosity depends only on target and beam

Colliders vs. fixed target: Rate (2)

Colliders

Two beams with n_1 and n_2 particles per area

$$\frac{dn\,.}{ds}=\frac{n_1}{2\pi\sigma_x\sigma_y}e^{-\left(x^2 2\sigma_x^2+y^2 2\sigma_y^2\right)}$$

$$\frac{dn_2}{ds}=\frac{n_2}{2\pi\sigma_x\sigma_y}e^{-\left(x^2 2\sigma_x^2+y^2 2\sigma_y^2\right)}$$

Gaussian distribution normalized to number of particles

Number of particles n_1 in an area dxdy $dn_1(x,y)=\frac{n_1}{2\pi\sigma_x\sigma_y}e^{-\left(x^2 2\sigma_x^2+y^2 2\sigma_y^2\right)}\cdot dxdy$

The probability of interaction of a particle in beam 1 in (x,y) is the number of particles of beam 2 in the area σ_{in}

$$dn_2(x,y)=\frac{n_2}{2\pi\sigma_x\sigma_y}e^{-\left(x^2 2\sigma_x^2+y^2 2\sigma_y^2\right)}\cdot\sigma_{\text{int}}$$

Colliders vs. Fixed Target: Rate(3)

Total number of interaction per bunch per crossing N_{int}:

$$N_{\text{int}} = \int dn_1(x,y)\, p(x,y) = \sigma_{int} \frac{n_1 n_2}{4\pi^2 \sigma_x^2 \sigma_y^2} \int e^{-\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)} dxdy$$

$$= \sigma_{int} \frac{n_1 n_2}{4\pi^2 \sigma_x^2 \sigma_y^2} \int_{-\infty}^{+\infty} dx \cdot e^{-x^2 \sigma_x^2} \int_{-\infty}^{+\infty} dy \cdot e^{-y^2 \sigma_y^2} = \sigma_{int} \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$$

$$\int_{-\infty}^{+\infty} dx e^{-\frac{x^2}{\sigma_x^2}} = \sqrt{\pi}\,\sigma \frac{1}{\sqrt{2\pi}\,\sigma\sqrt{2}} \int dx e^{-\frac{x^2}{2(\sigma\sqrt{2})^2}} = \sqrt{\pi} \cdot \sigma$$

Given k packets in each bunch with a frequency f, the rate R

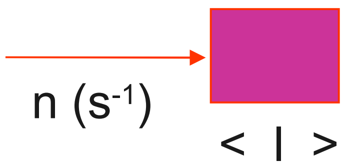
$$R = \sigma_{int} \cdot L = \frac{n_1 n_2}{4\pi \sigma_x \sigma_y k} \cdot f \sigma_{int}$$

$$\Rightarrow \quad L = \frac{n_1 n_2 f}{4\pi \sigma_x \sigma_y k}$$

Colliders vs. Fixed Target: Example

Fixed target-collider (same C.M. energy and same interaction cross section(e.g. σ_{in} ~ 1μb)

<u>Fixed target</u>



n= incident beam density =10^{12} q s^{-1}

ρ= target density = $1 gr/cm^3$

l= target thickeness =1cm

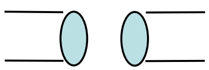
σ_{int}= 1μ b

A= Avogadro number = $6x10^{23}$

$$R = n \cdot \rho \cdot l \cdot A \cdot \sigma_{\text{int}} = 6 \times 10^5 s^{-1}$$

Colliders vs. Fixed Target: Example cont'd

Collider



n_1=n_2= beam particles

i_1= i_2=50 mA → n_1=n_2= $3.3\text{x}10^{17}$ q s^{-1}

F= transverse section of beams= 0.1x0.01 cm^2

B= bunch number= 1

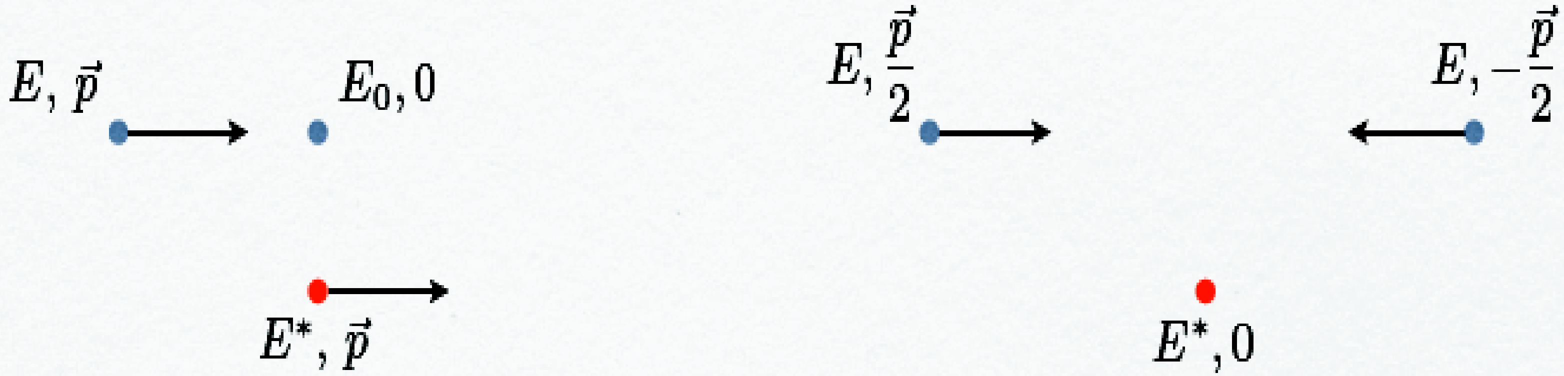
f= revolution frequency = 10^6 s^{-1}

$$R = \frac{n_1 \cdot n_2 \cdot f}{F} \cdot \sigma_{\text{int}} = \frac{i_1 \cdot i_2}{f \cdot e^2 \cdot F} \cdot \sigma_{\text{int}} \cong 100 s^{-1}$$

Center of Mass Energy

- Beam/target particles: $E_0 \equiv m_p c^2$

Fixed Target | **Collider**

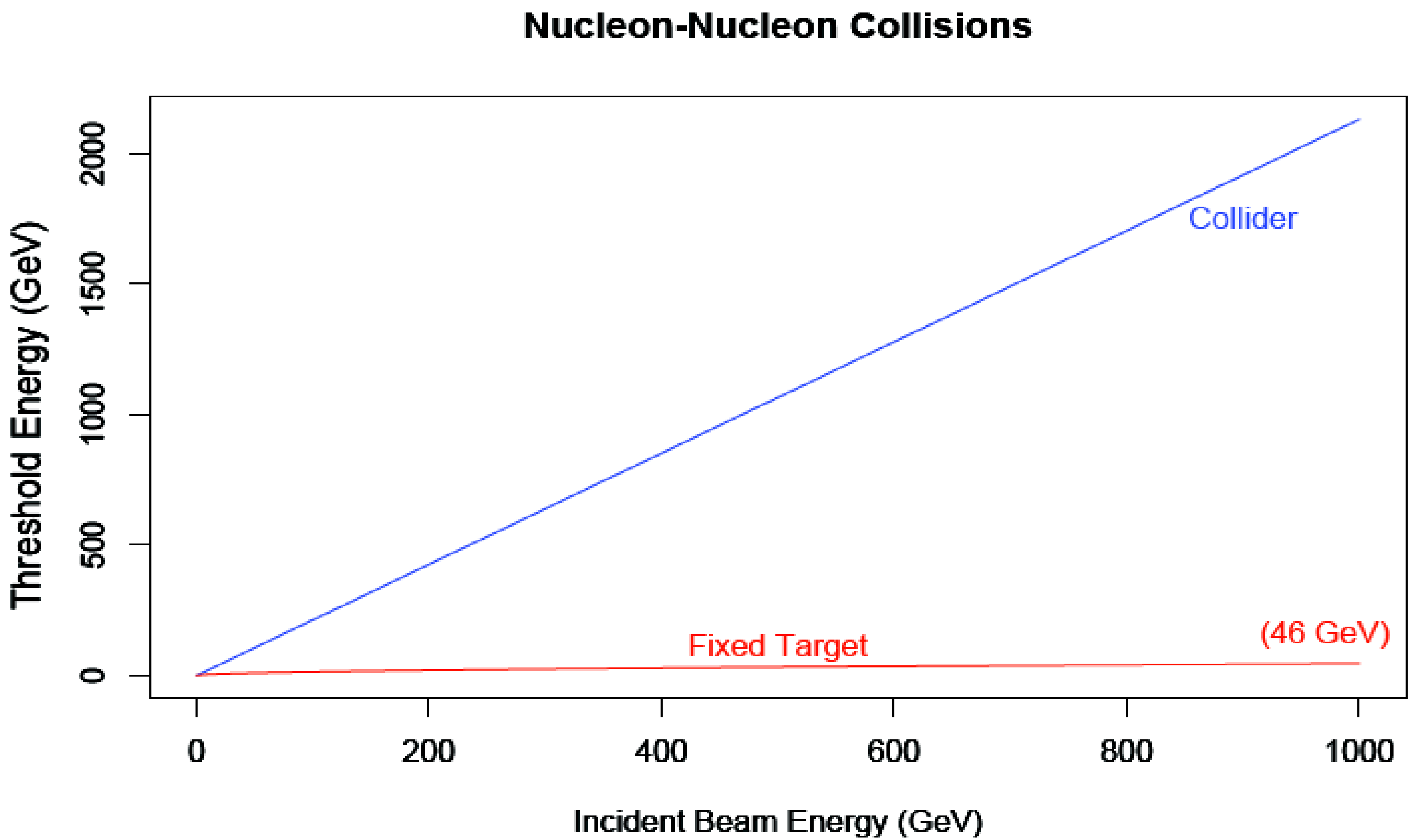


$$
\begin{aligned}
E^{*2} = (m^* c^2)^2 + (pc)^2 &= [\, E_0 + E \,]^2 \\
&= E_0^2 + 2E_0 E + (E_0^2 + (pc)^2) \\
m^* c^2 &= \sqrt{2}\, E_0 \, [1 + \gamma_{FT}]^{1/2}
\end{aligned}
$$

$$
\begin{aligned}
m^* c^2 &= 2E \\
&= 2E_0 \gamma_{coll}
\end{aligned}
$$

Mike Sypher HCPS

Center of Mass Energy cont'd



Mike Sypher HCPS

Luminosity

$$L = \frac{n_1 n_2 f B}{4\pi\sigma_x\sigma_y k} = \frac{N^2 f B}{A}$$

$n_1=n_2=N$, B=number of bunches

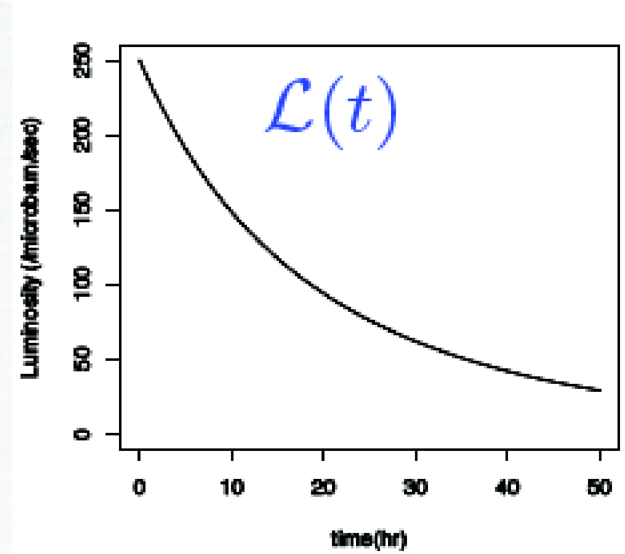
A= interaction area

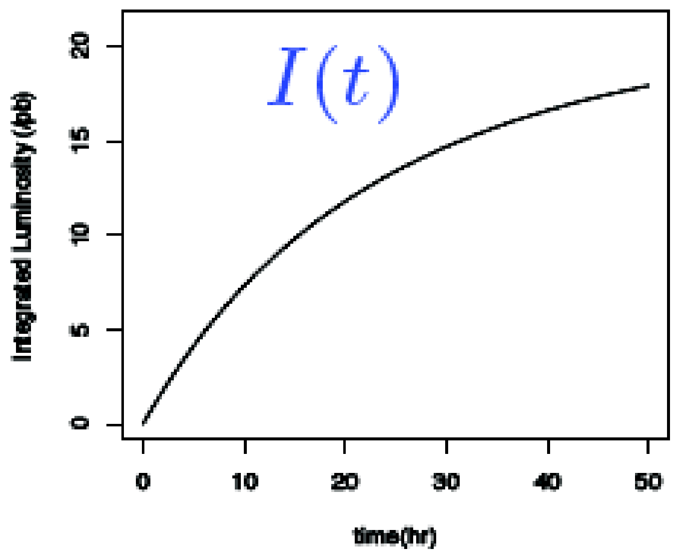
In the ideal case particles are lost only due to interactions:

$dN/dt = -L \cdot \sigma_{int} \cdot n/B$ where n=number of detectors receiving luminosity L

$$L(t) = \frac{L_0}{[1+(\frac{nL_0\sigma_i}{BN})t]}$$

$$I(T) \equiv \int_0^T \mathcal{L}(t)dt$$





A bit of History

1961 AdA, Frascati Italy
1964 VEPP 2 Novosibirsk, URSS
1965 ACO, Orsay, France
1969 ADONE, Frascati
1970 ISR, CERN Swiss
1971 CEA, Cambridge, USA
1972 SPEAR Stanford USA 8 GeV
1974 DORIS, Amburg, Germany
1975 VEPP-2M Novosibirsk, URSS
1978 PETRA Amburgo Germany 45 GeV
1979 CESR Cornell USA
1980 PEP Stanford USA
1981 Sp-parS CERN Swiss 630 GeV
1982 TEVATRON Fermilab USA 2TeV
1989 SLC, Stanford USA 90 GeV
1989 BEPC, Bejin china

1989 LEP CERN 205 GeV
1992 HERA, Amburg Germany
1994 VEPP-4M Novosibirsk Russia
1998 PEP-II Stanford USA
1999 DAΦNE, Frascati Italy
1999 KEKB Tsukuba Japan
2003 VEPP-2000 Novosibirsk Russia
2008 LHC CERN Swiss 14 TeV

electron-positron
proton-antiproton
electron-pronton
proton-proton

Hadron Colliders: ISR

ISR: p-p $\sqrt{s}$= 63 GeV (1970-1980)
SpS: p-pbar $\sqrt{s}$= 630 GeV (1980-1991)
Tevatron: p-pbar $\sqrt{s}$= 1.960 TeV (1978-2011)
LHC: p-p $\sqrt{s}$= 14 TeV (1998-)

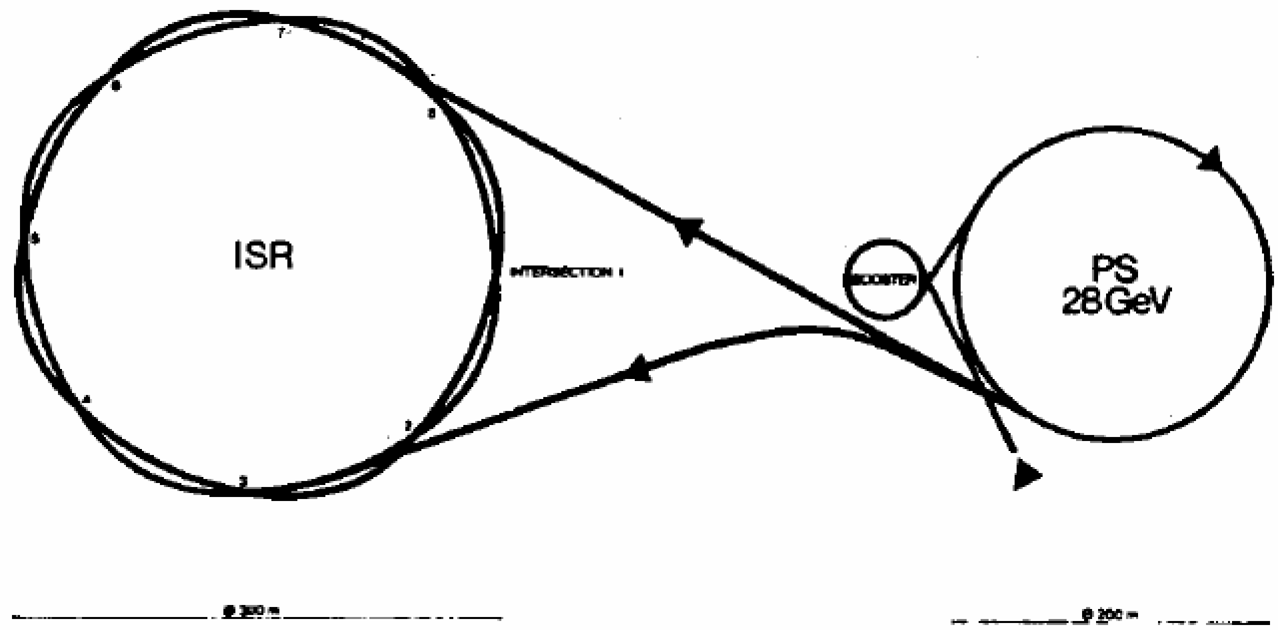


Fig. 2.1. Schematic view of the PS and ISR rings.

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Hadron Colliders: ISR

Standard Model just at the begin, most phenomenology

π, k, p cross sections constant

Most important results:

- measurement of $\sigma(p\bar{p})$, increasing with energy
- determination of $d\sigma/dt$(quadrimomentum). It follow optical-diffractive model
- first hint of jets: excess of secondary tracks at (high) transverse energy

Difference of p-p and p-$\bar{p}$ cross section, at high energies goes to zero

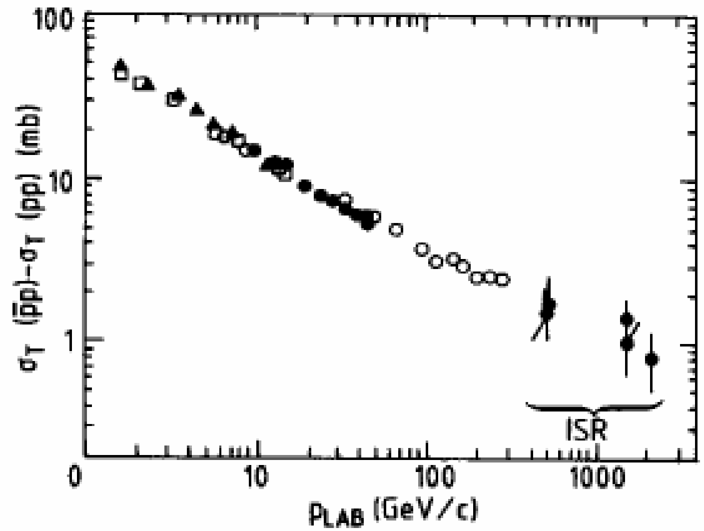


Fig. 43 Measurements of the total cross-section difference, $\sigma_T(p\bar{p})-\sigma_T(pp)$, vs. p_{lab}

Hadron Colliders: SpS

1982 CERN was able to produce, accumulate, cool and accelerate pbar

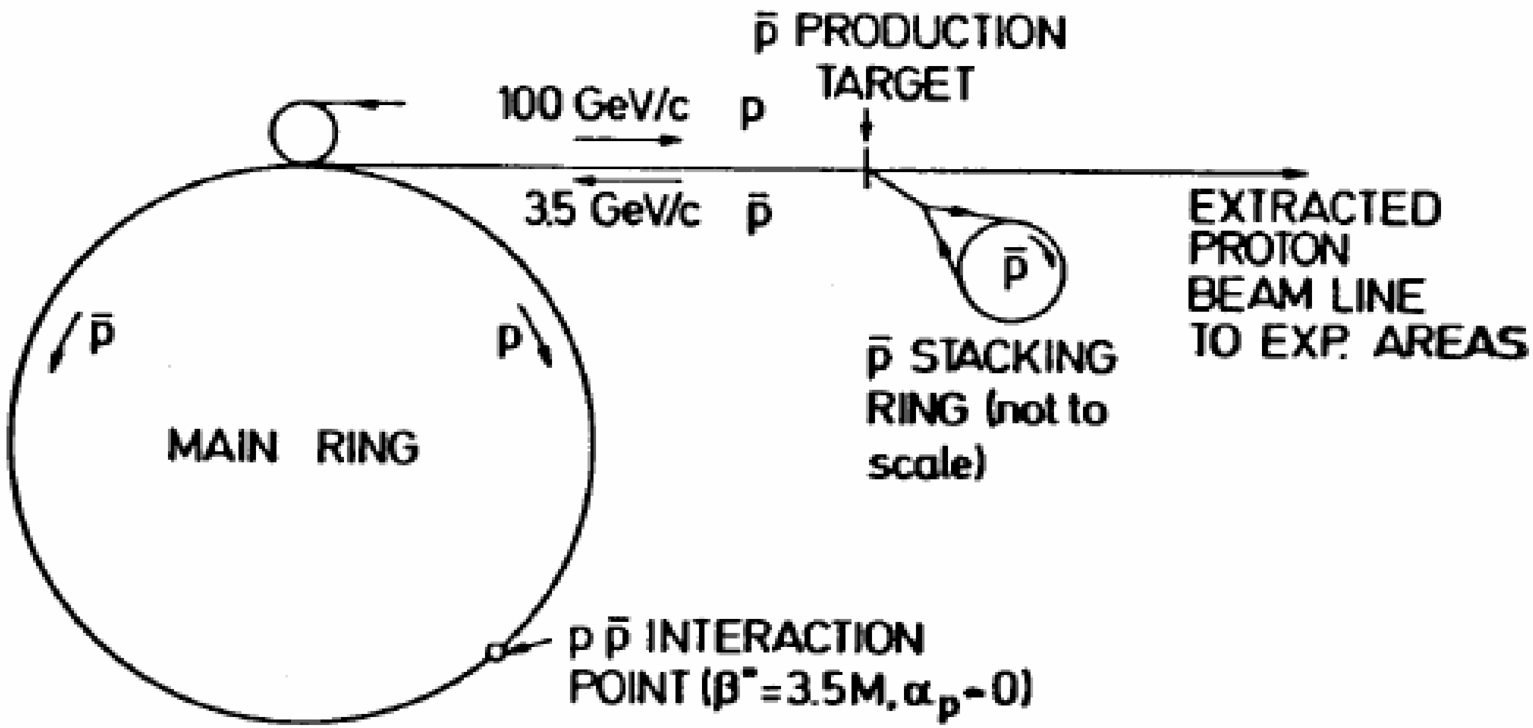


Fig. 5. General layout of the $p\bar{p}$ colliding scheme, from Ref. [9]. Protons (100 GeV/c) are periodically extracted in short bursts and produce 3.5 GeV/c antiprotons, which are accumulated and cooled in the small stacking ring. Then $\bar{p}$'s are reinjected in an RF bucket of the main ring and accelerated to top energy. They collide head on against a bunch filled with protons of equal energy and rotating in the opposite direction.

Hadron Colliders: SpS experiment

The detector UA1 (Underground Area 1) was 35 meters underground

The Standard Model is a reality:

- jets identification
- measurements of hadronic cross section
- discovery of W and Z bosons

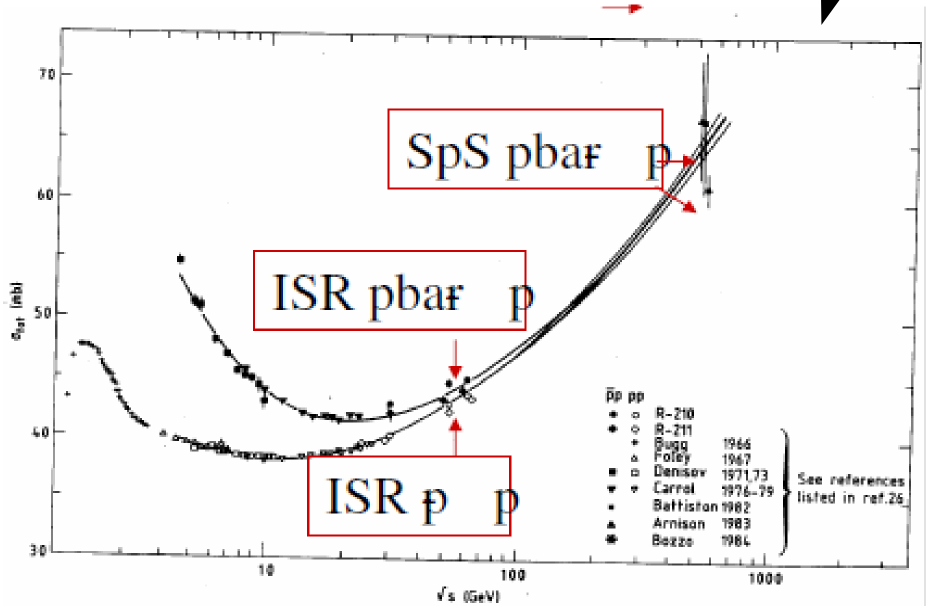
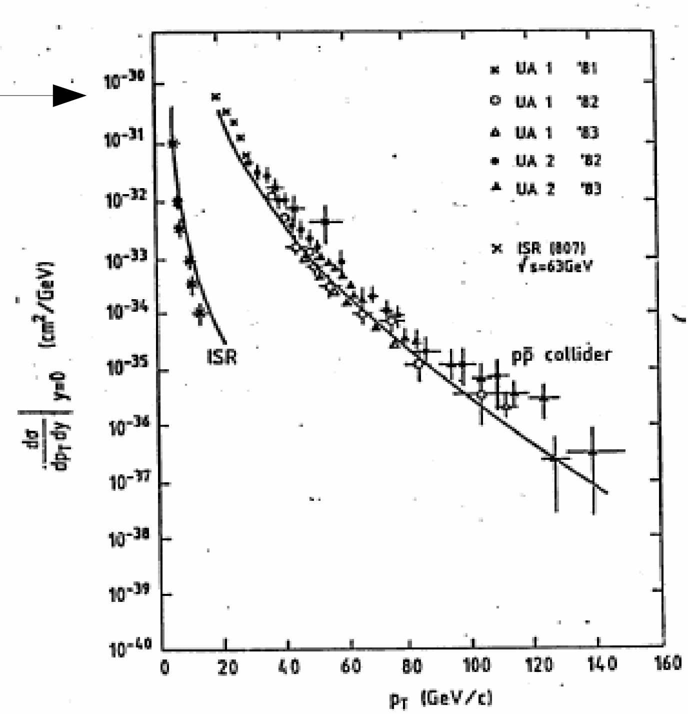


Fig. 7. The behaviour of $\sigma_{tot}(pp)$ and $\sigma_{tot}(\bar{p}p)$ as a function of $\sqrt{s}$.



ISR just under threshold for jets production

Hadron Colliders: SpS experiment

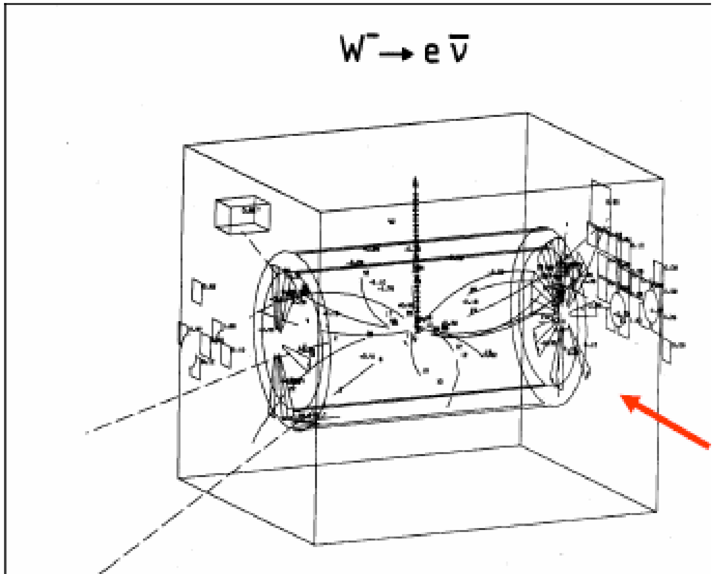


Fig. 16a. Event of the type $W^- \to e^- + \bar{\nu}_e$. All tracks and calorimeter cells are displayed.

First W candidate

Showing all tracks it is difficult to declare it is a W

UA2 demonstrated that these events were W comparing to expectations

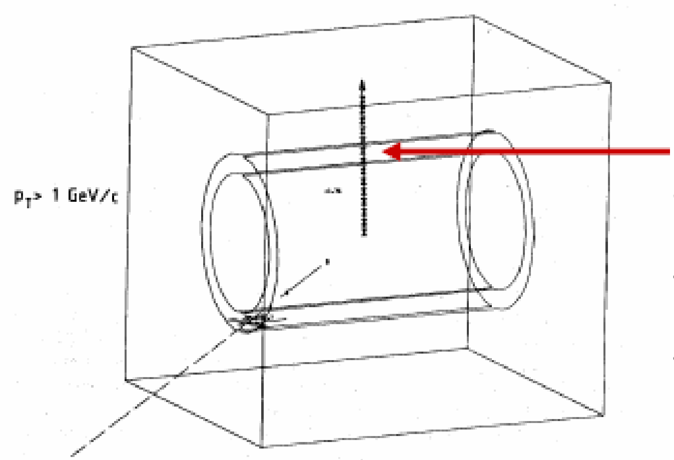
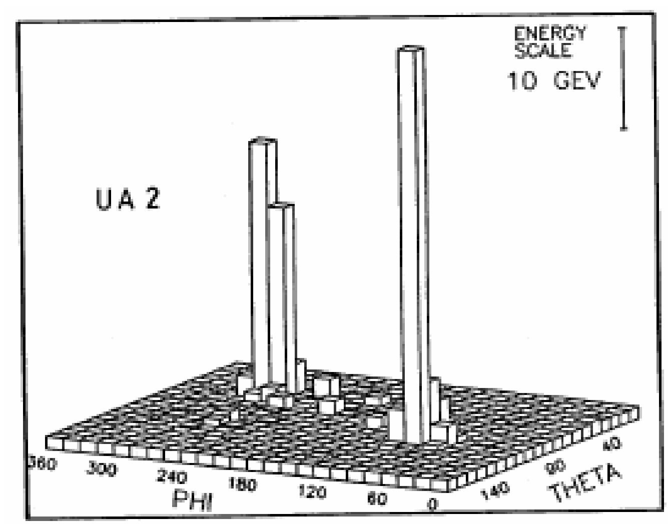


Fig. 16b. The same as picture (a), except that now only particles with $p_T > 1$ GeV/c and calorimeters with $E_T > 1$ GeV are shown.

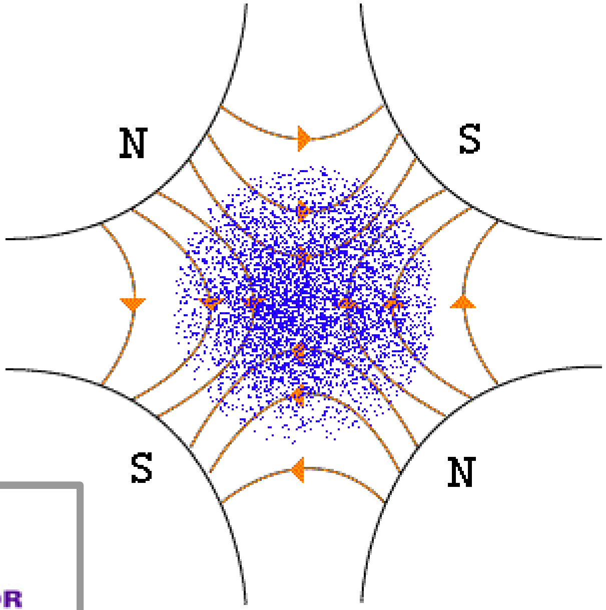
Cutting tracks with E<1GeV there is only the e



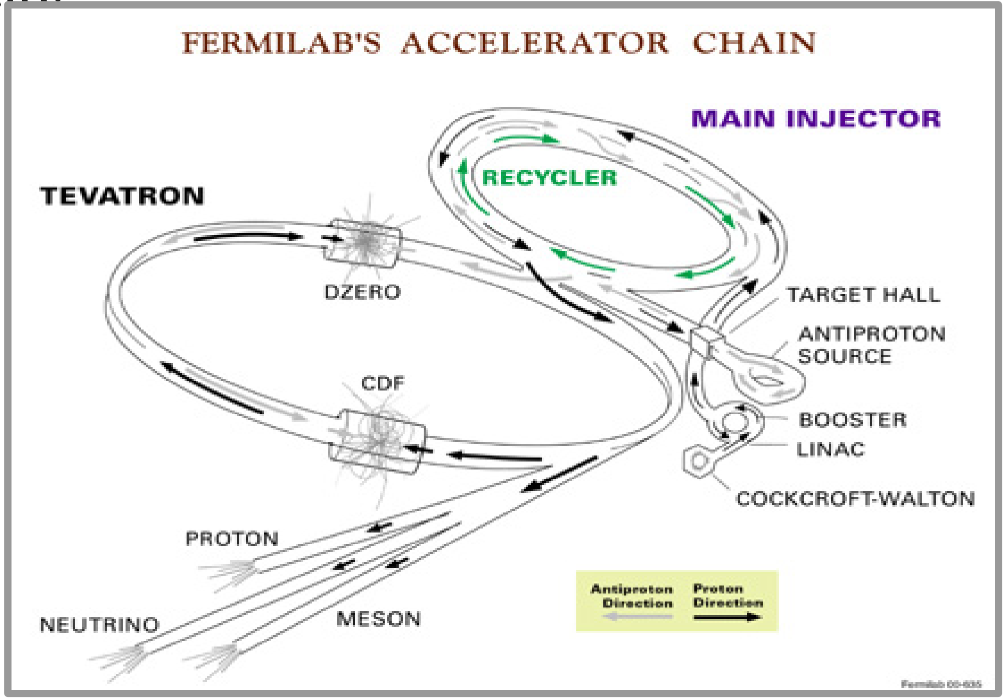
The highest E_T event of Fig. 9, showing the E_T distribution in θ and ϕ

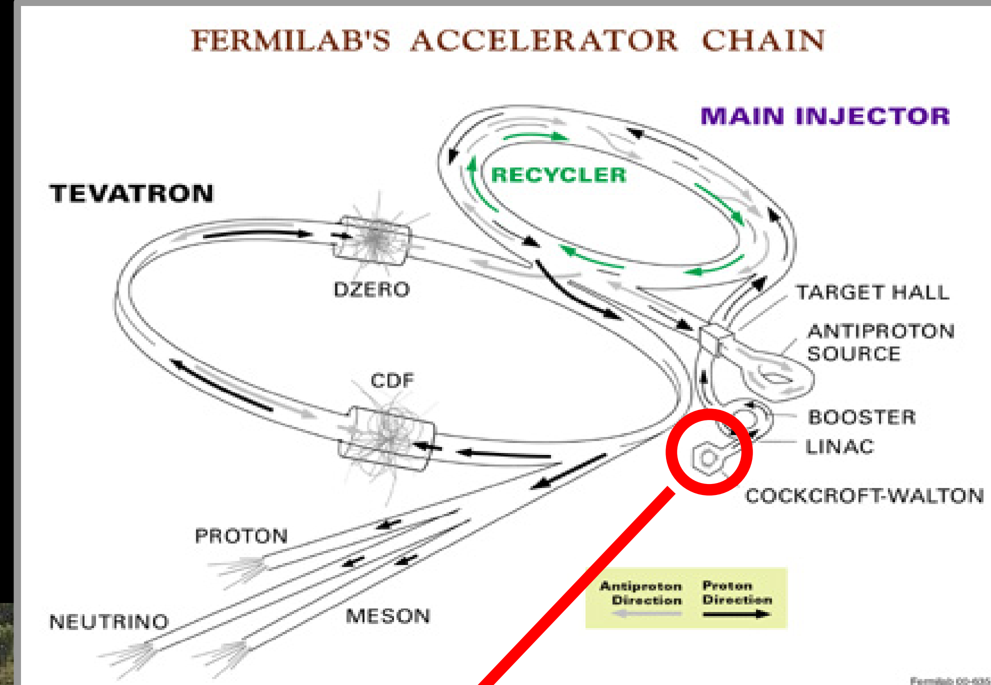
Hadron Colliders: Tevatron

The first super-conducting syncroton
Electric field to accelerate particles
Magnetic field to drive and focus particles
using dipoles and quadrupoles



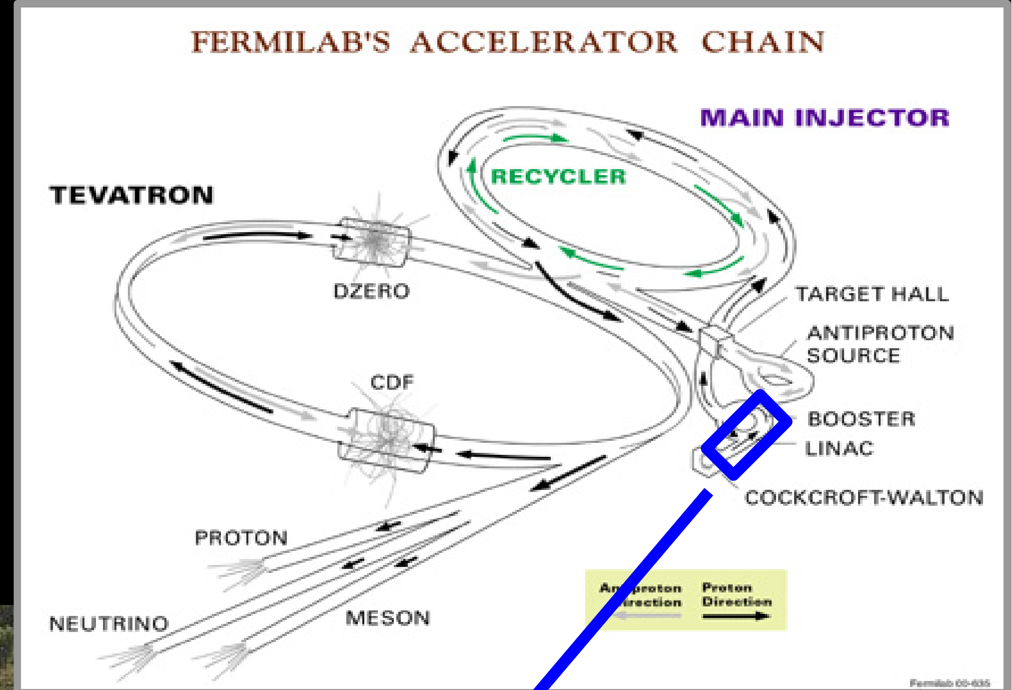
Complex chain:

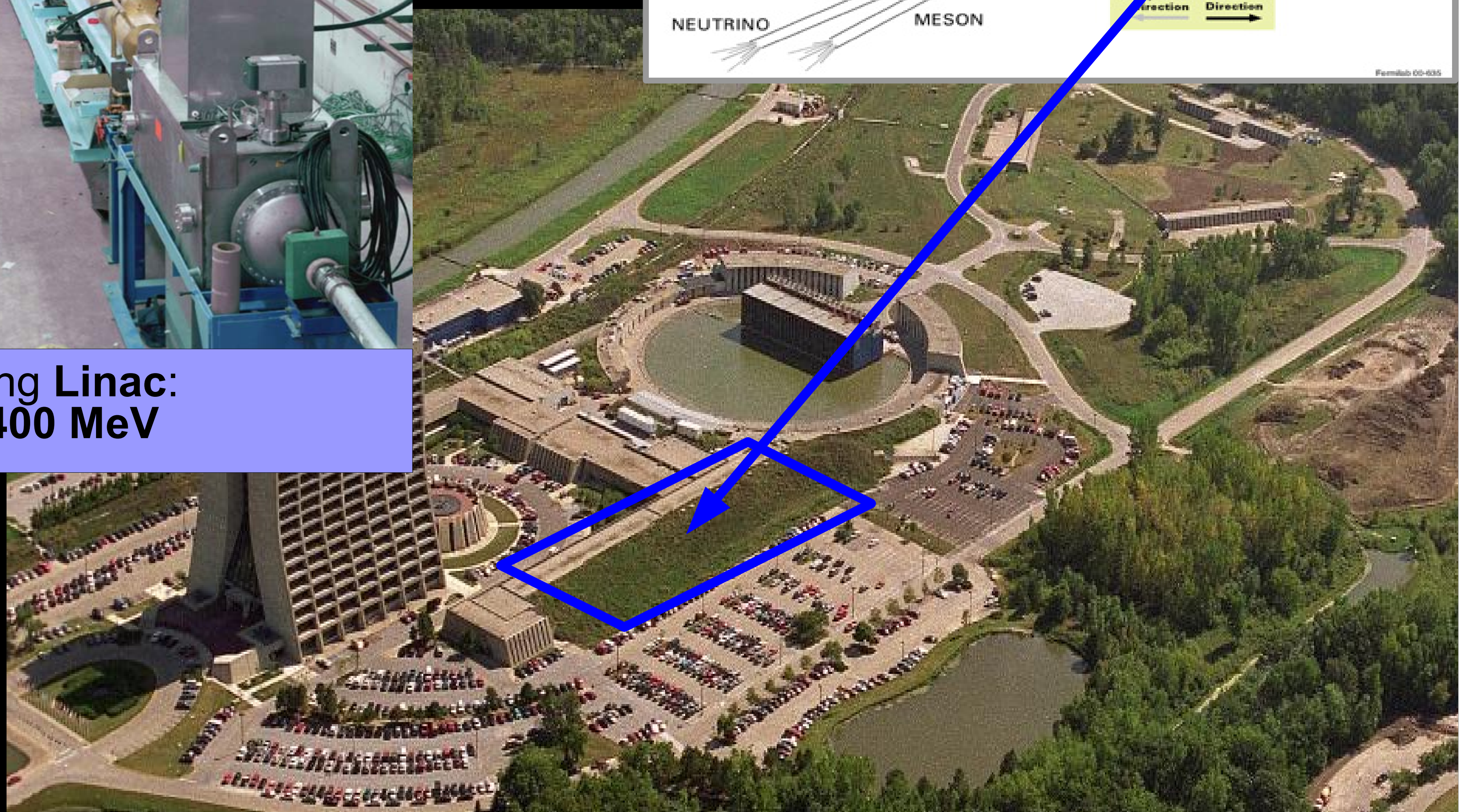




Cockroft-Walton accelerator:
H^- ions produced and accelerated up to **750 keV**

150 m long **Linac**:
H^- up to **400 MeV**





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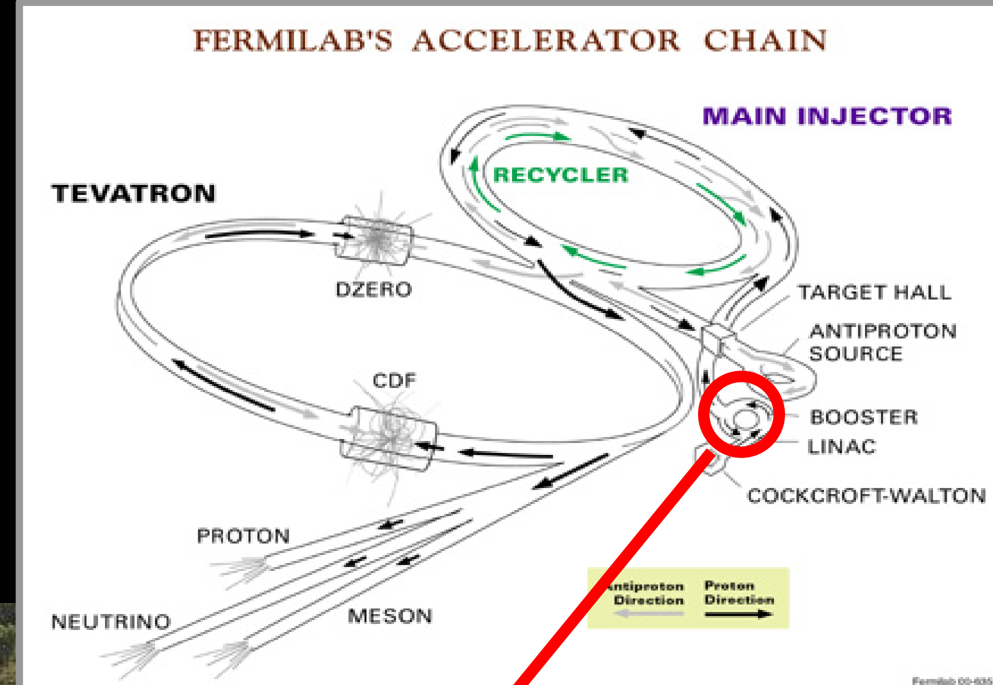

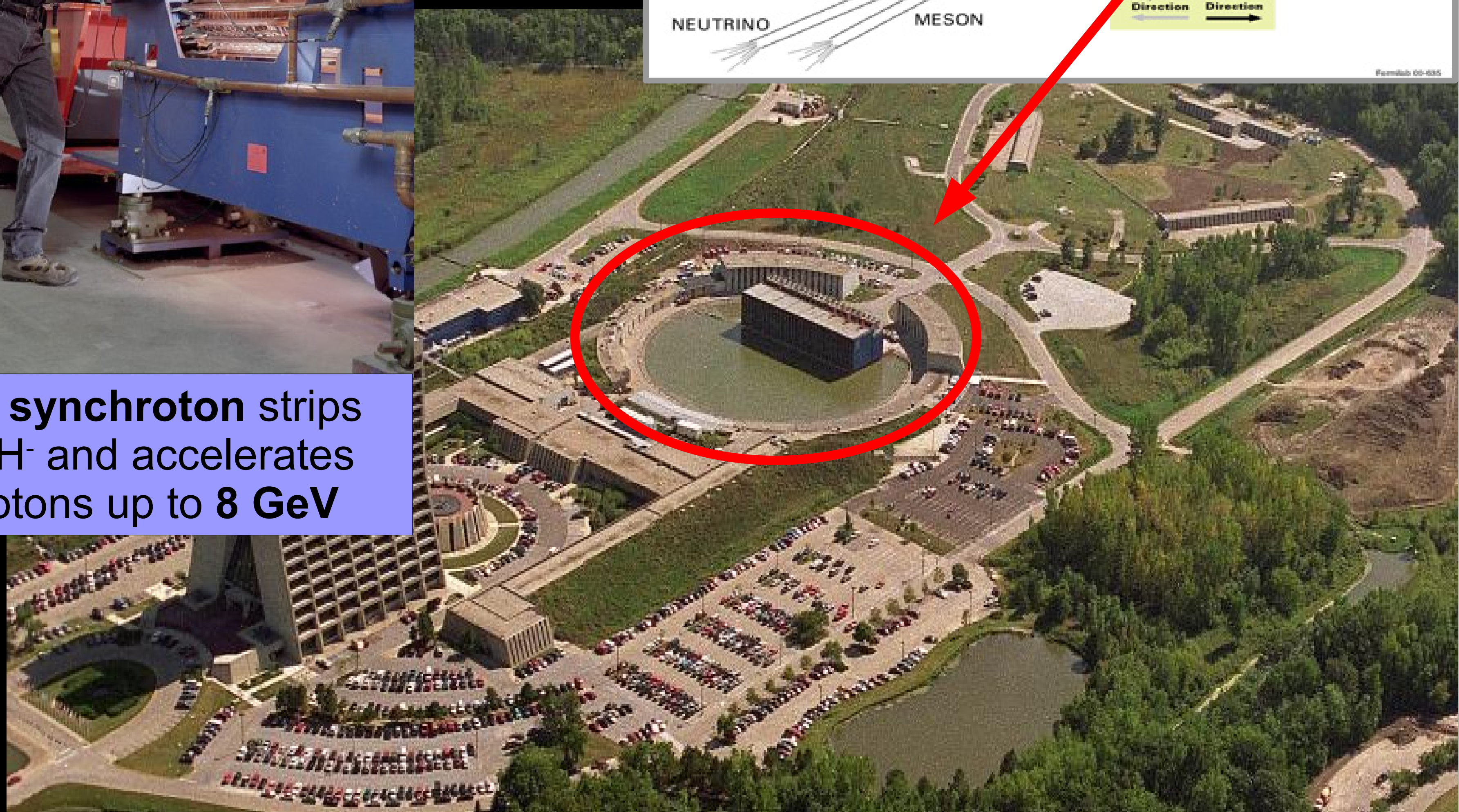

The **Booster synchroton** strips electrons off H^- and accelerates remaining protons up to **8 GeV**

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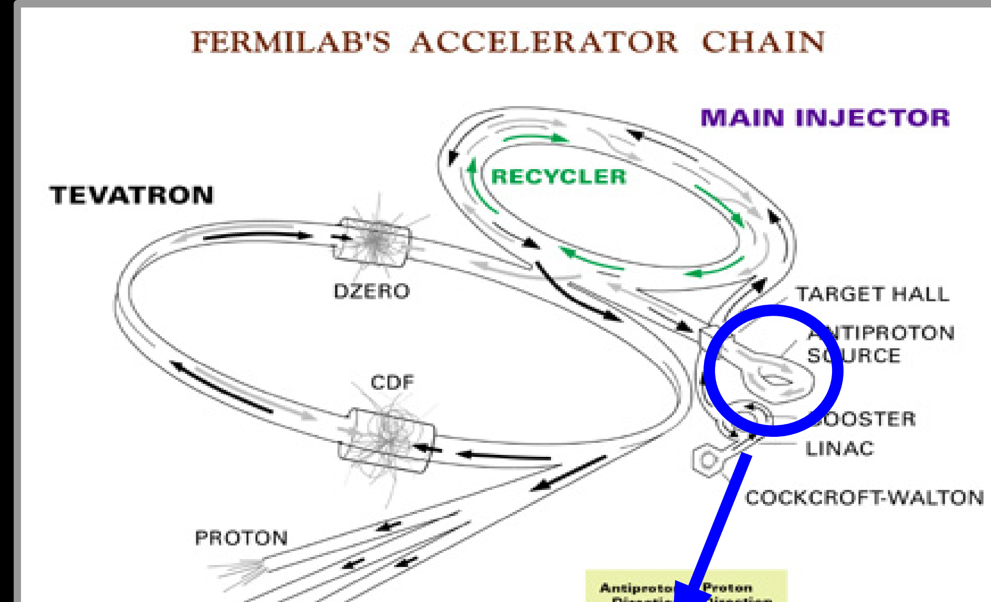
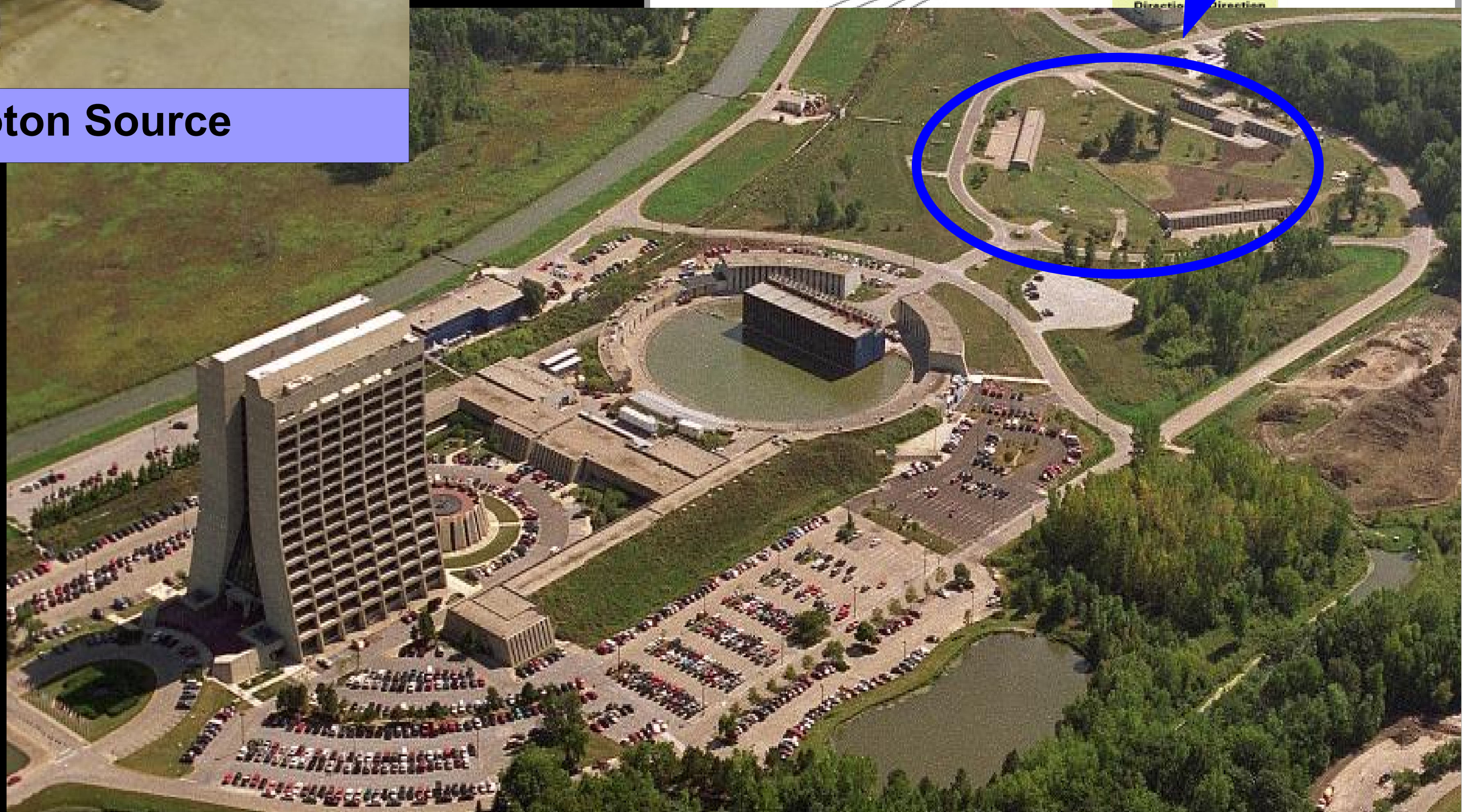
The Anti-proton Source





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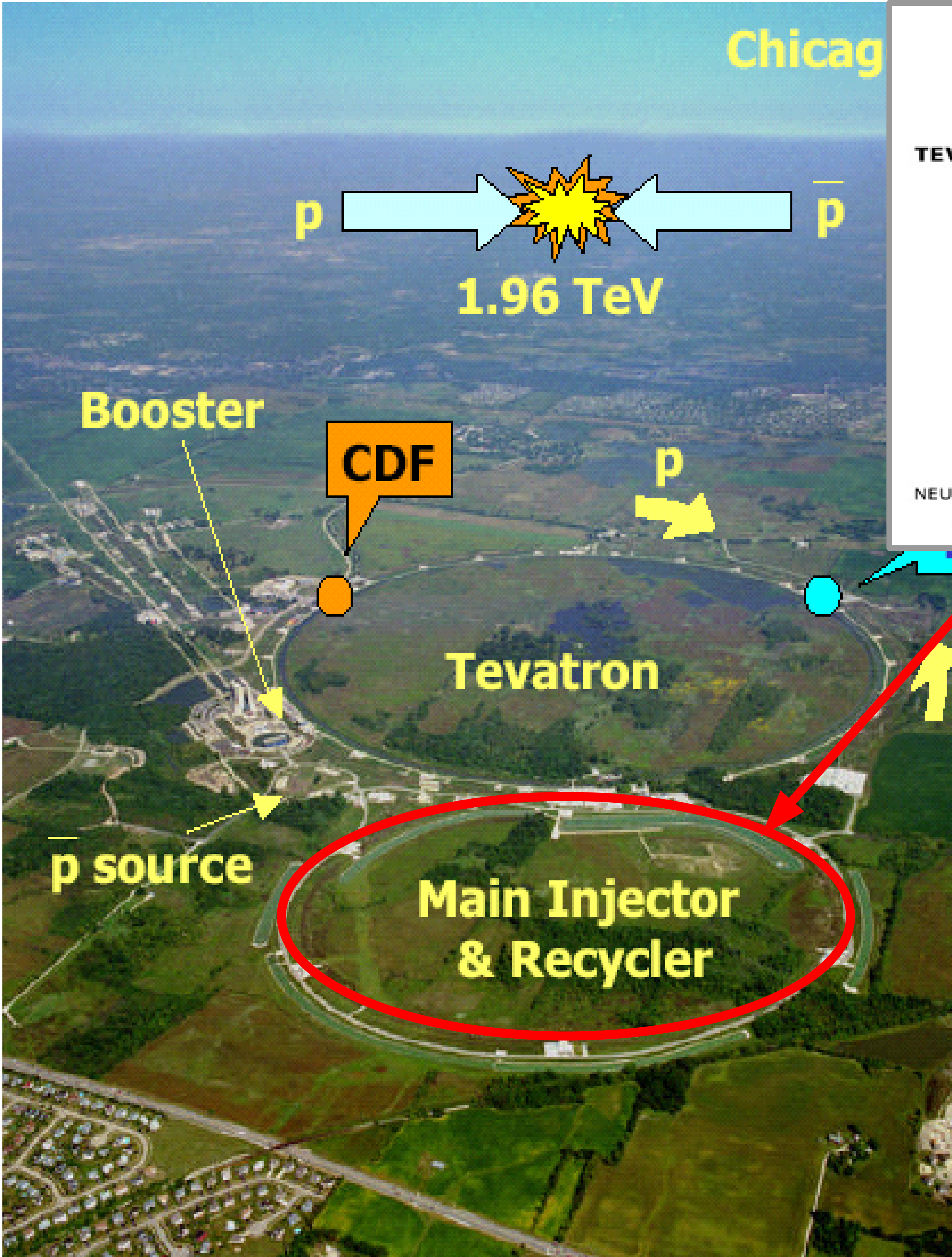
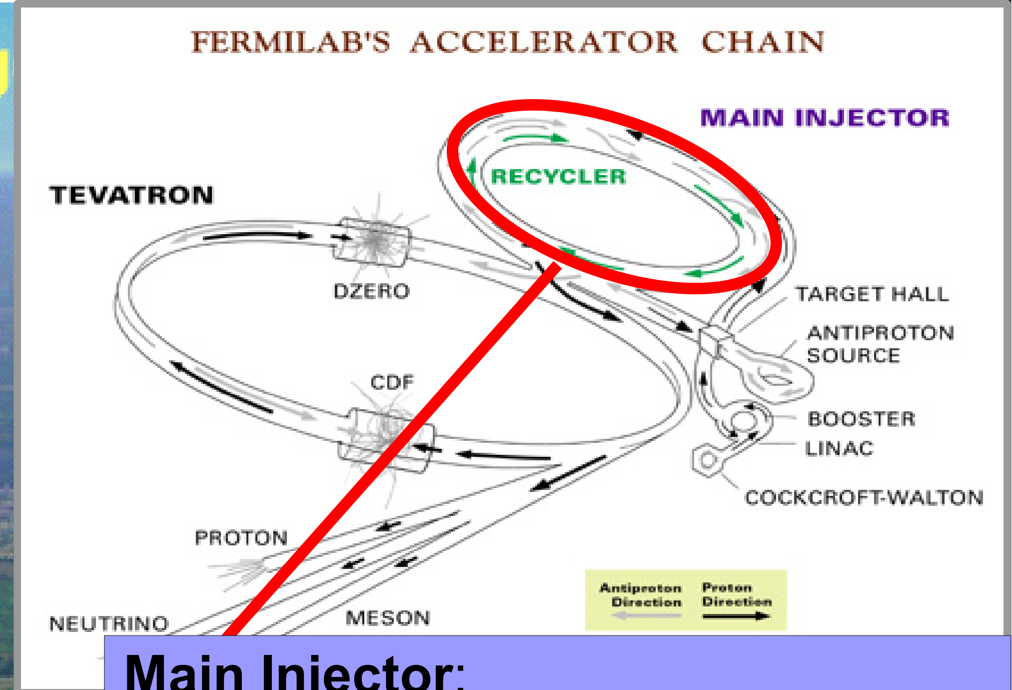
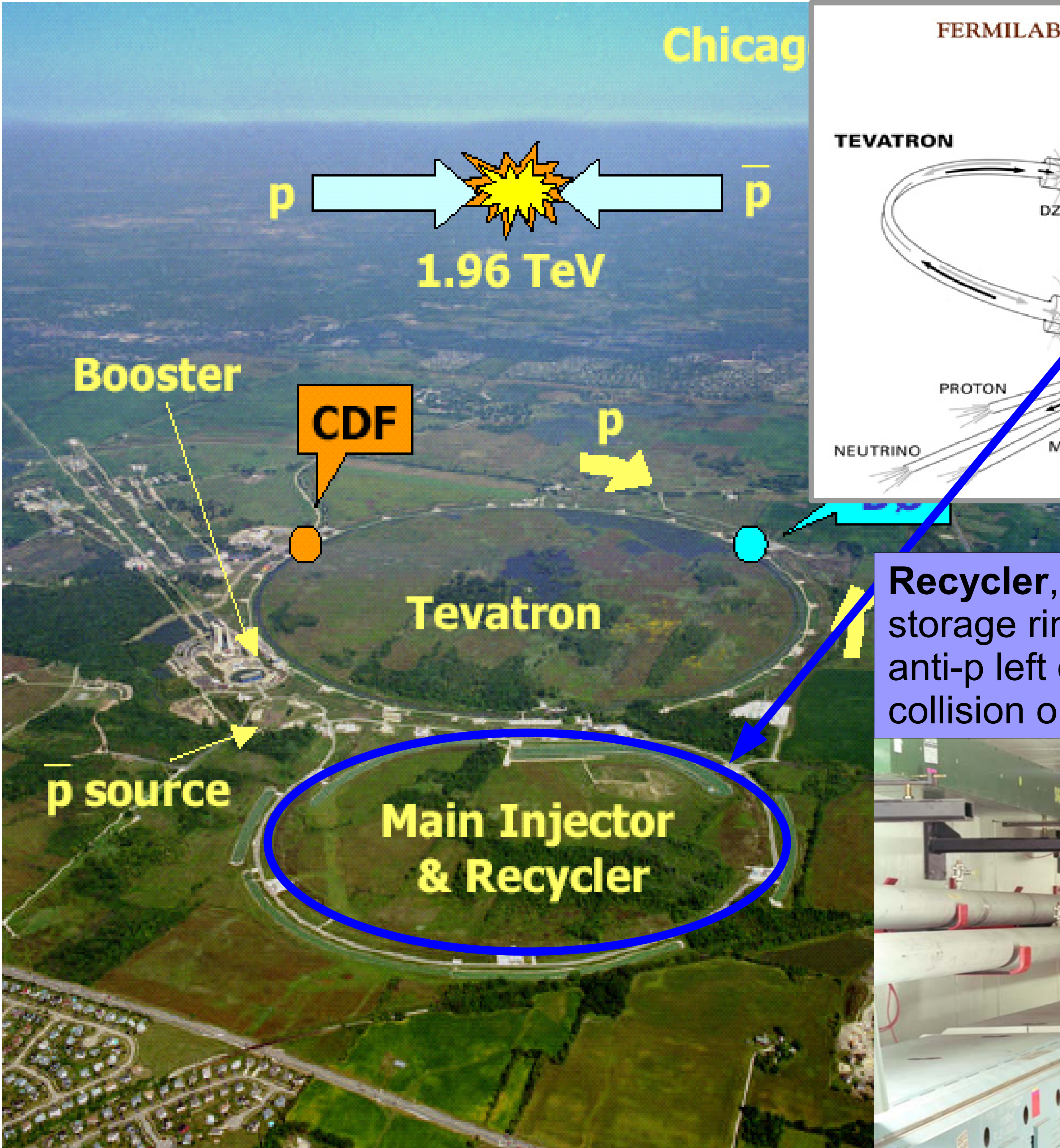
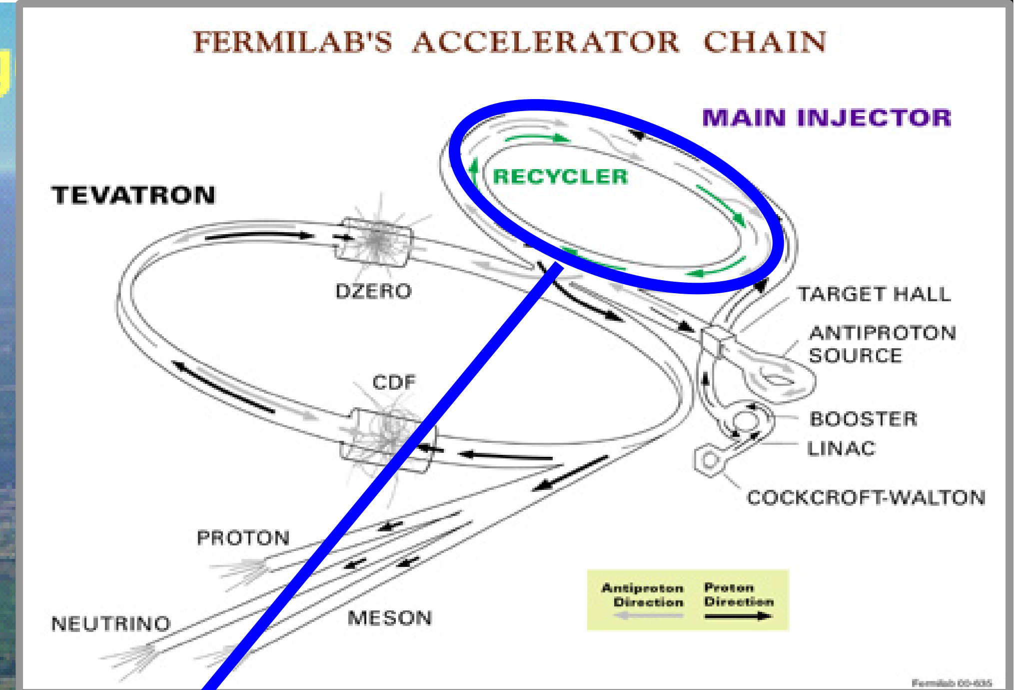




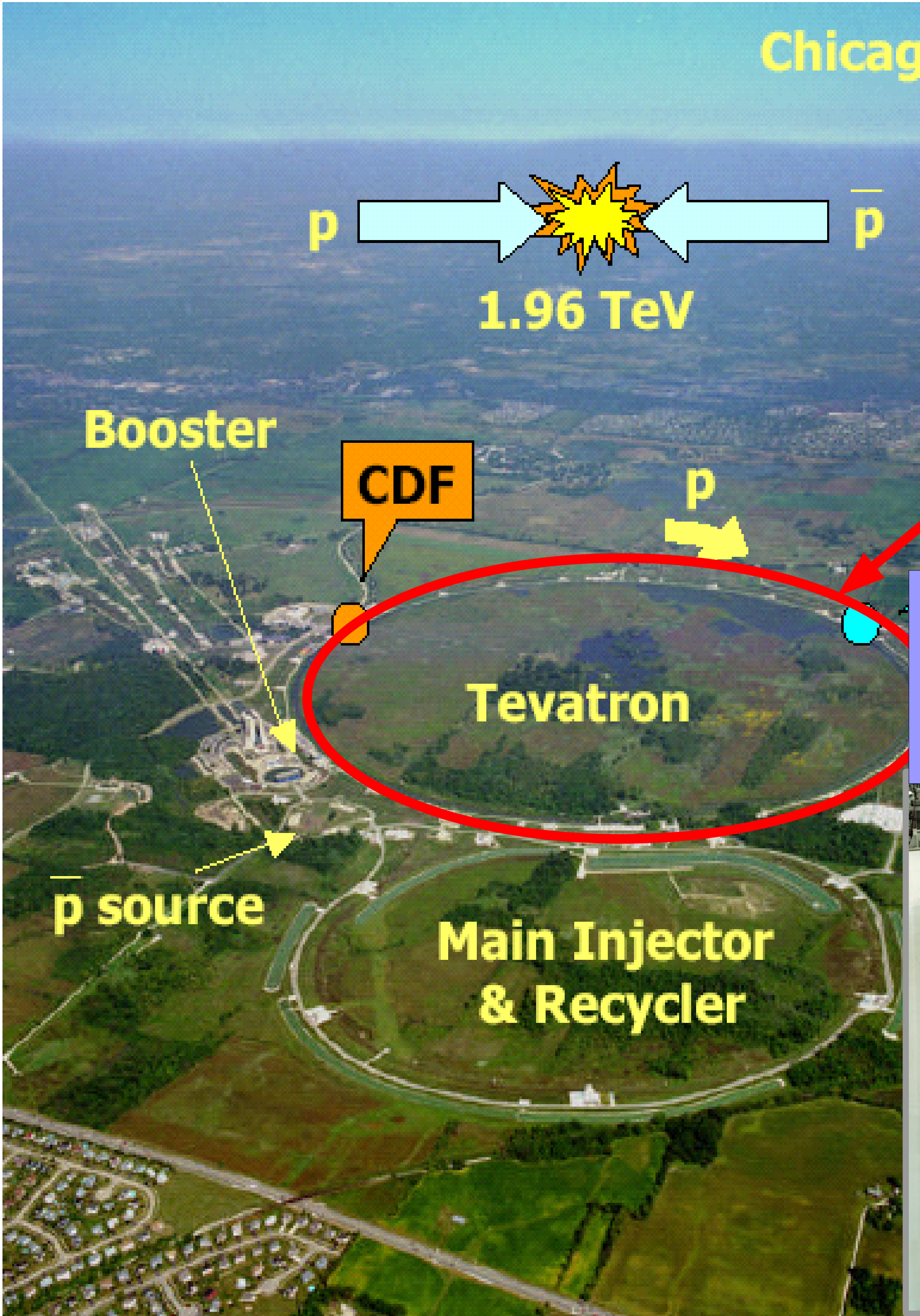
Main Injector:

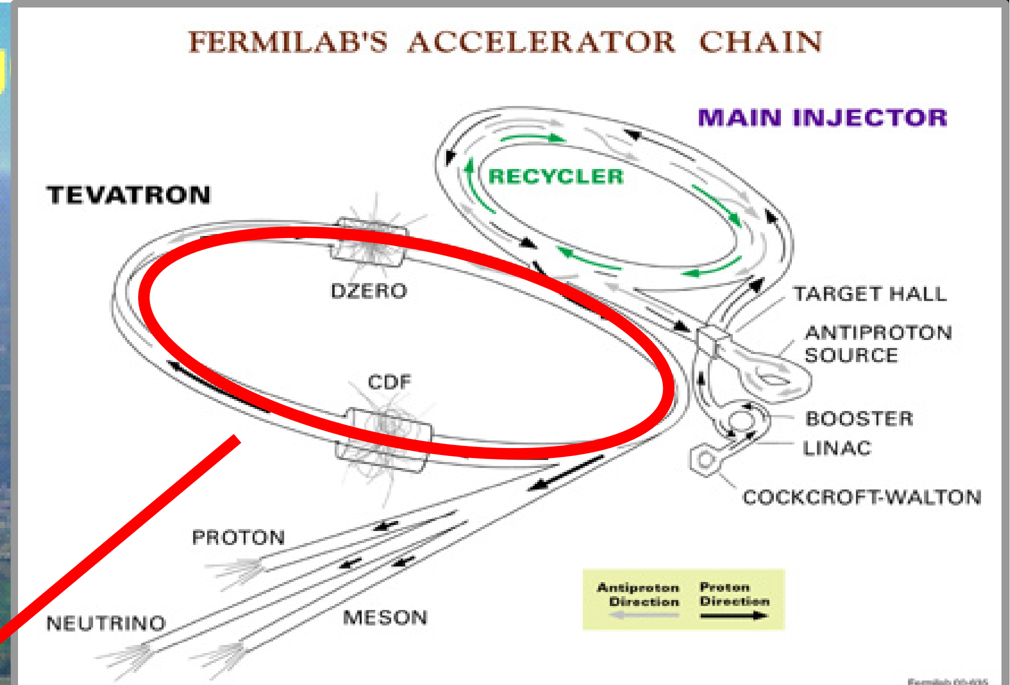
- p up to **120 GeV** for anti-p prod.
- deliver p-beams to fixed target exp
- accelerate p/anti-p up to **150 GeV** for Tevatron Injection.
- send to recycler anti-p after stores



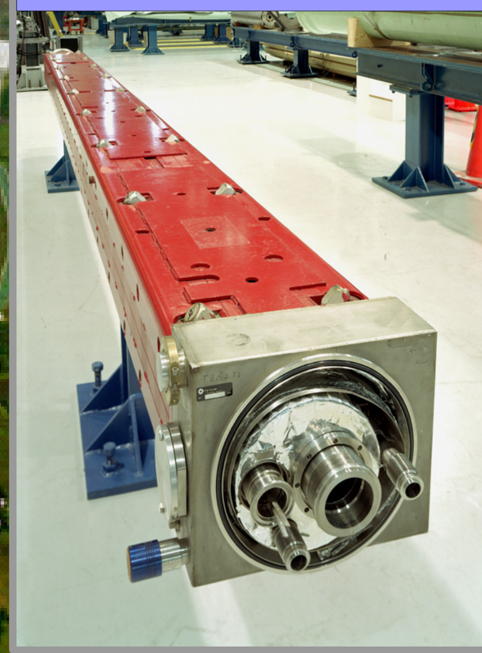


Recycler, **8 GeV** fixed energy storage ring: recover and recool anti-p left over after Tevatron collision operations





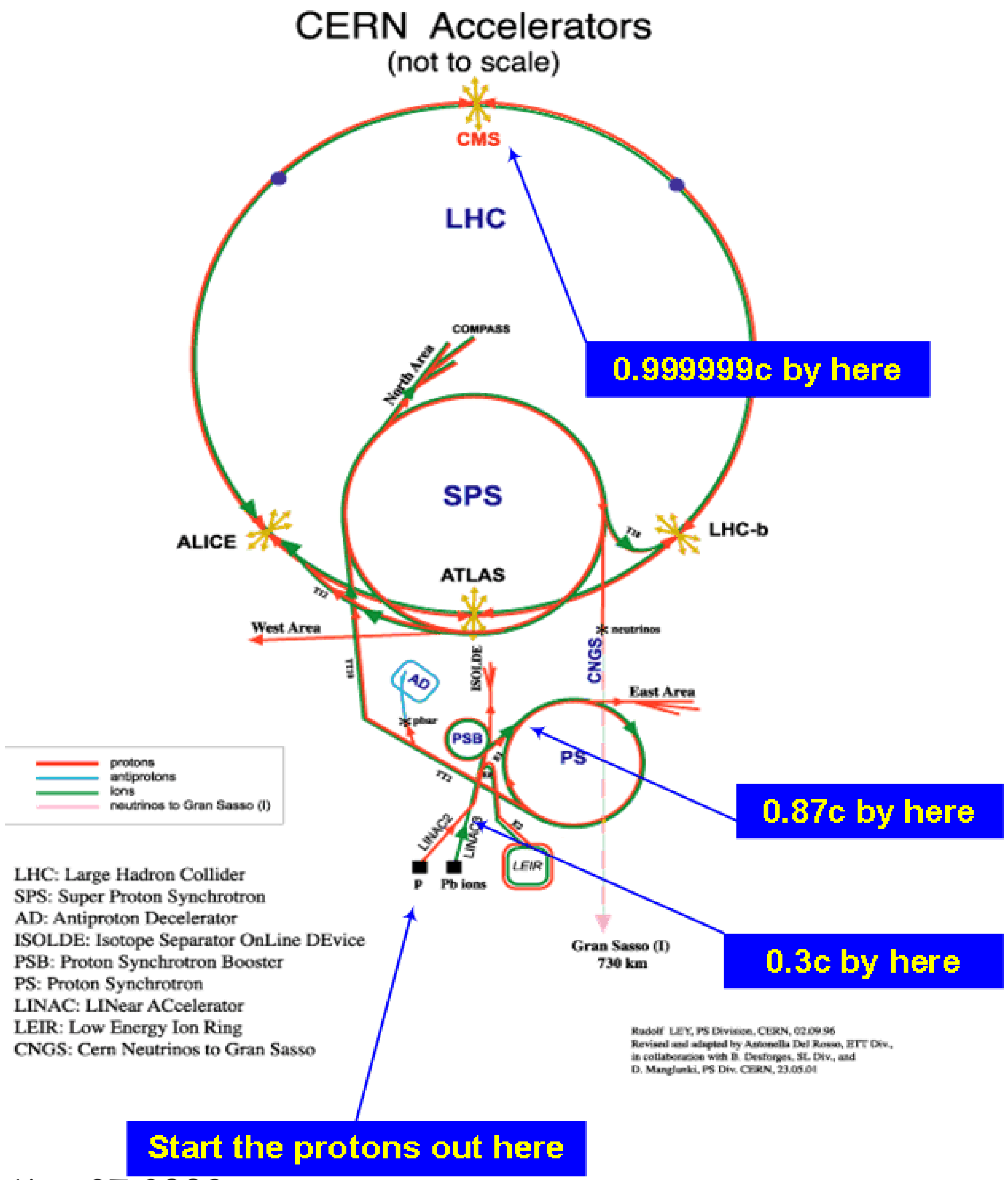
Tevatron:
p/anti-p beams up to **980 GeV,**
providing a
center of mass energy of **1.96 TeV**

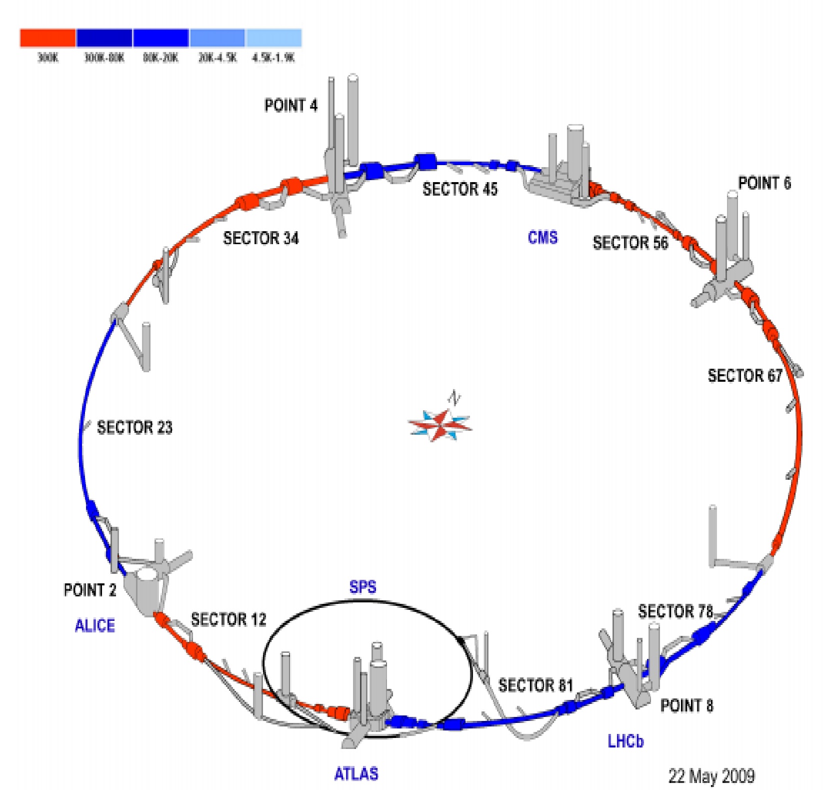


Hadron Colliders: Tevatron results
... up to now...

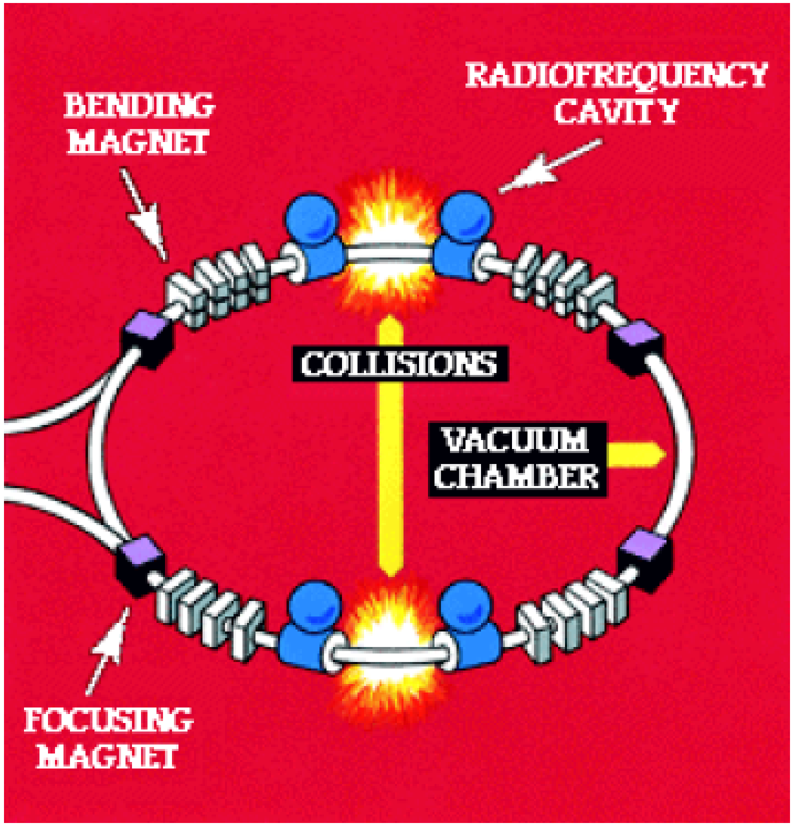
- Quark top discovery
- High precision measurements of electroweak process (W,Z)
- Higgs searches
- Beyond Standard Model
- Heavy flavor physics competitive to b-factories: Bs mixing frequency measurement, new hadrons discovery, high precision lifetimes, masses and cross section determination

Hadron Colliders: LHC





Electrons-Positrons Colliders



$\sqrt{s}$=200 MeV

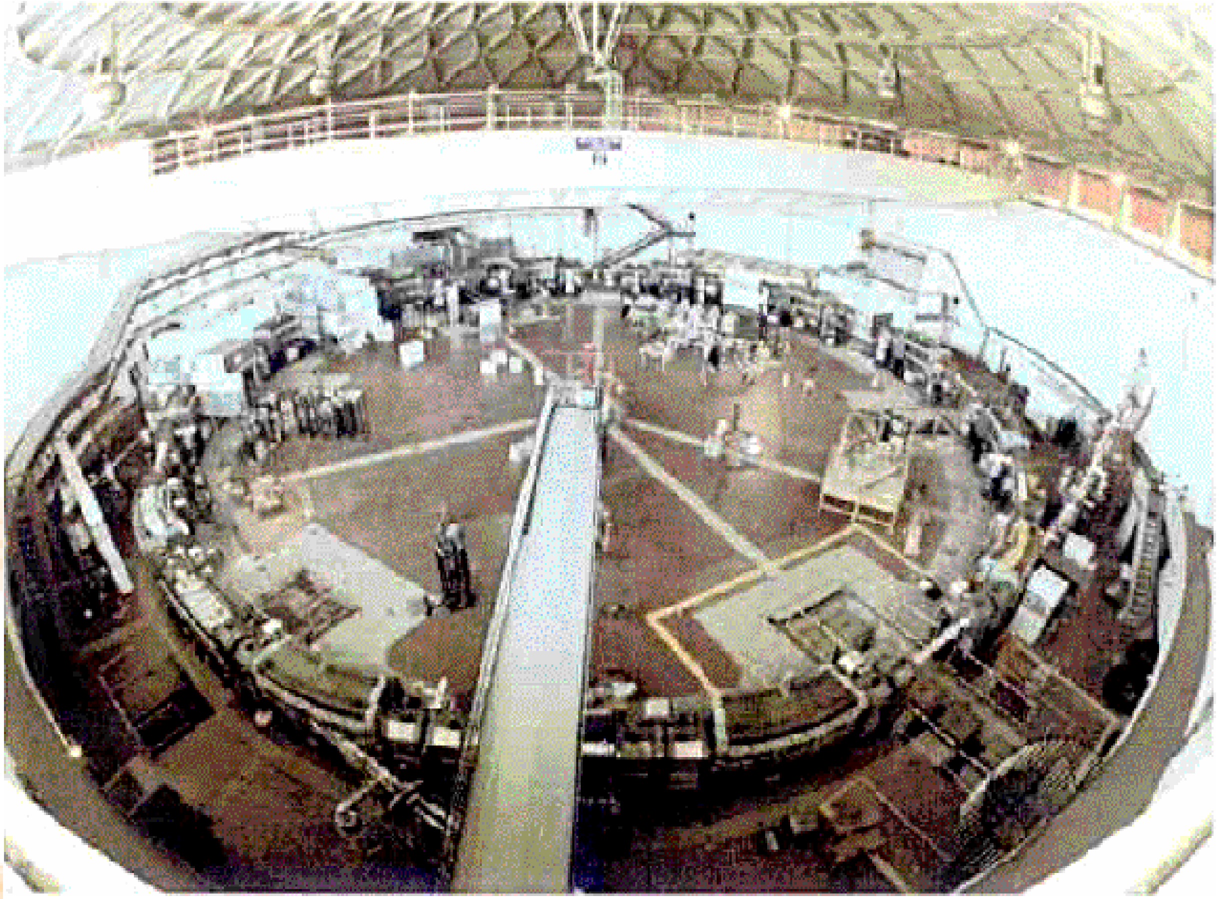
Problem: Synchrotron radiation.

The energy loss $\Delta E \sim K(E/m)^4 \beta^3 r^{-1}$

1971 AdA demonstrated that e+ e- can collide in the same tunnel

Electrons-Positrons Colliders

ADONE $\sqrt{s}$=3 GeV



To avoid problems the machine ran at $\sqrt{s}$=2.8 GeV so the J/ψ ...

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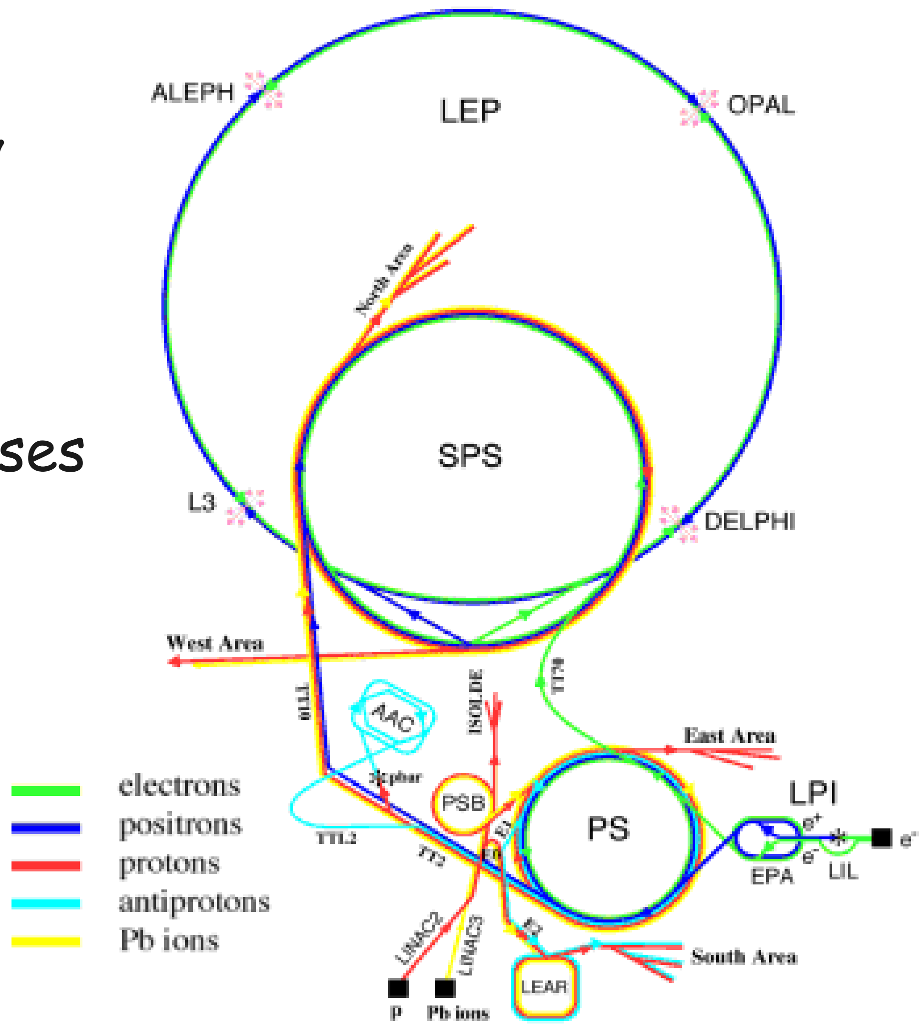
Electrons-Positrons Colliders

Petra at DESY discovered the gluon but the Standard Model was deeply verified at LEP

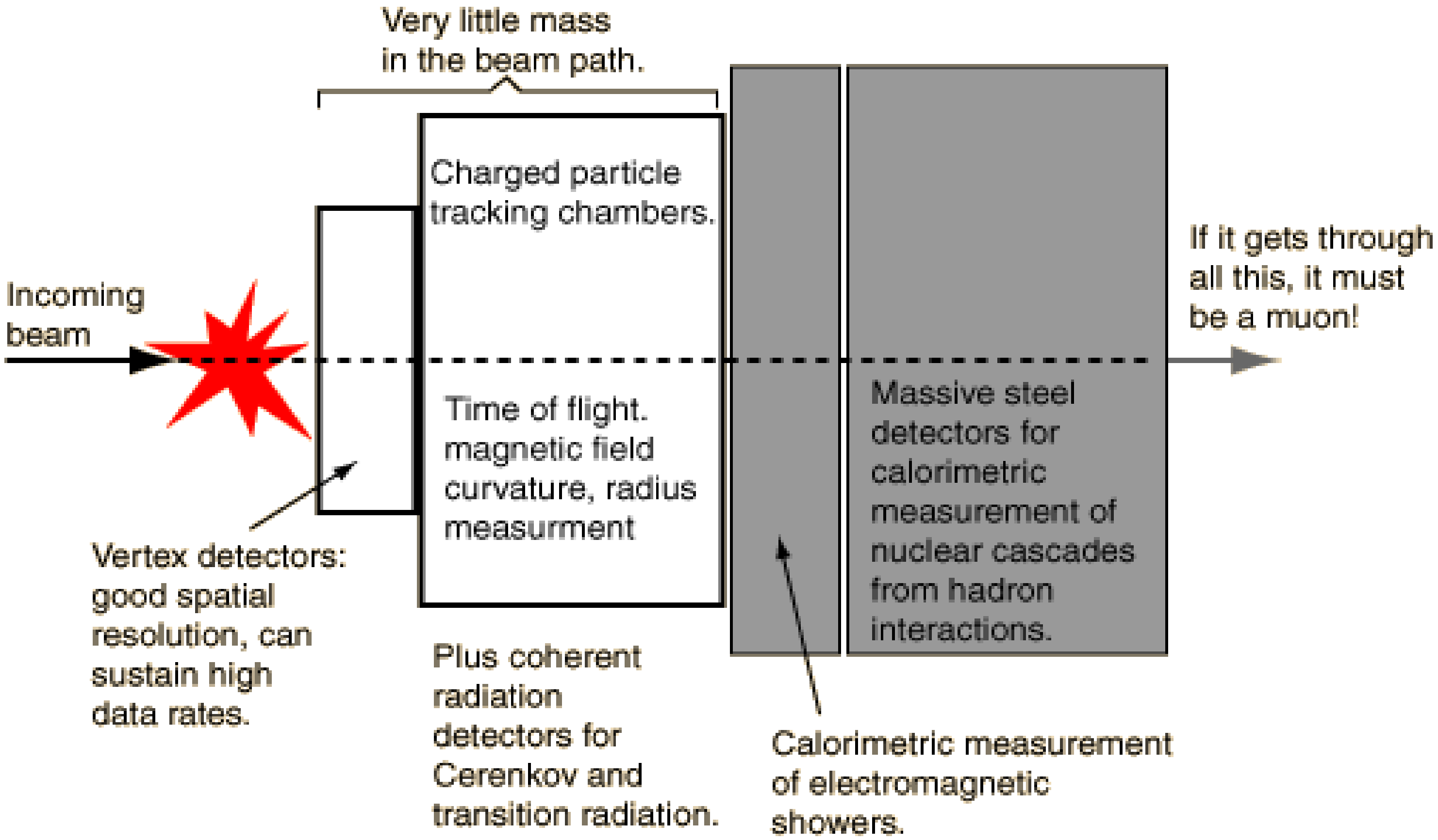
It ran at several $\sqrt{s}$ up to 205 GeV

The large circumference, 27 Km, made it a “linear-like” collider to minimize synchrotron radiation losses

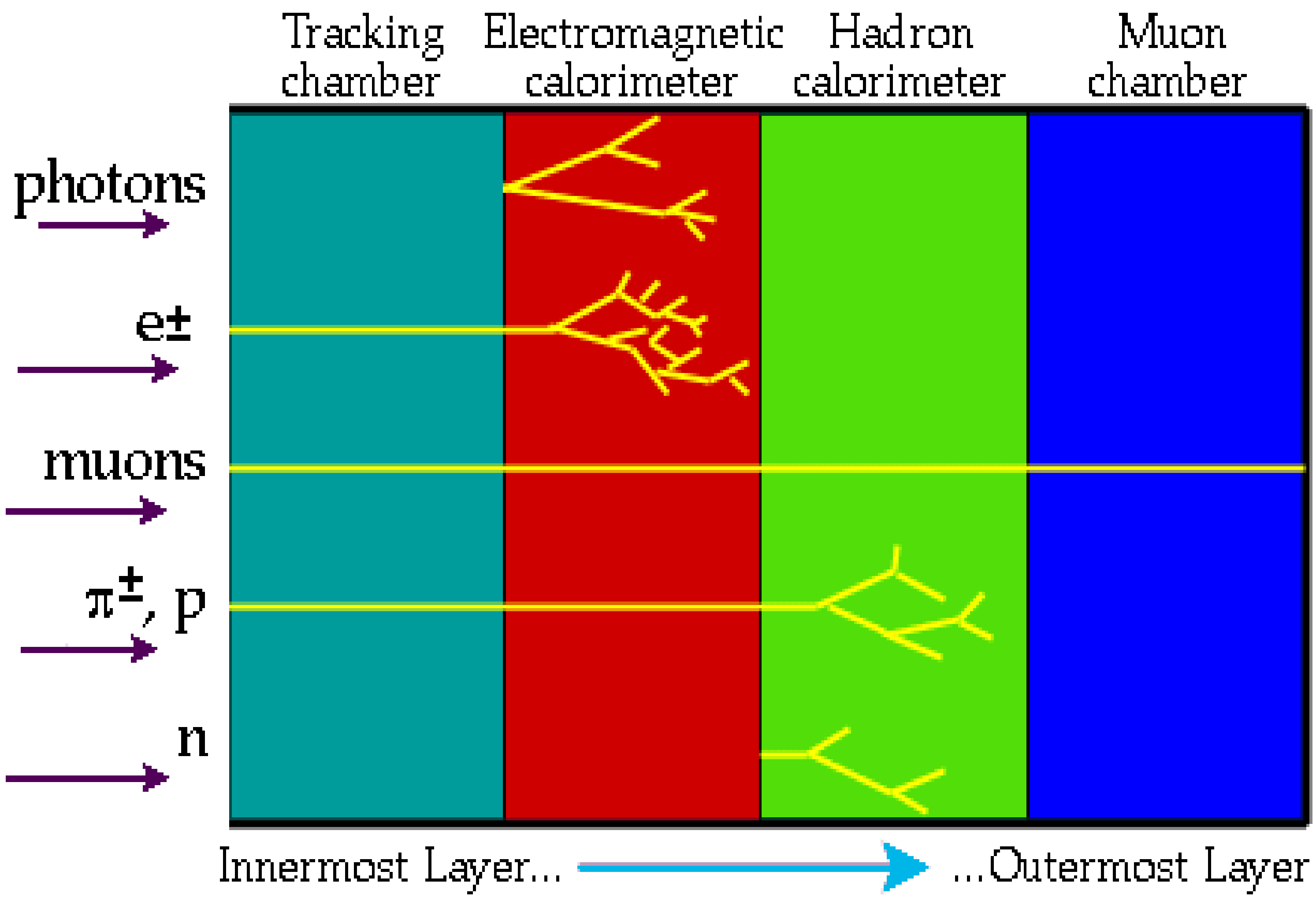


Detectors: Fundamental Principles

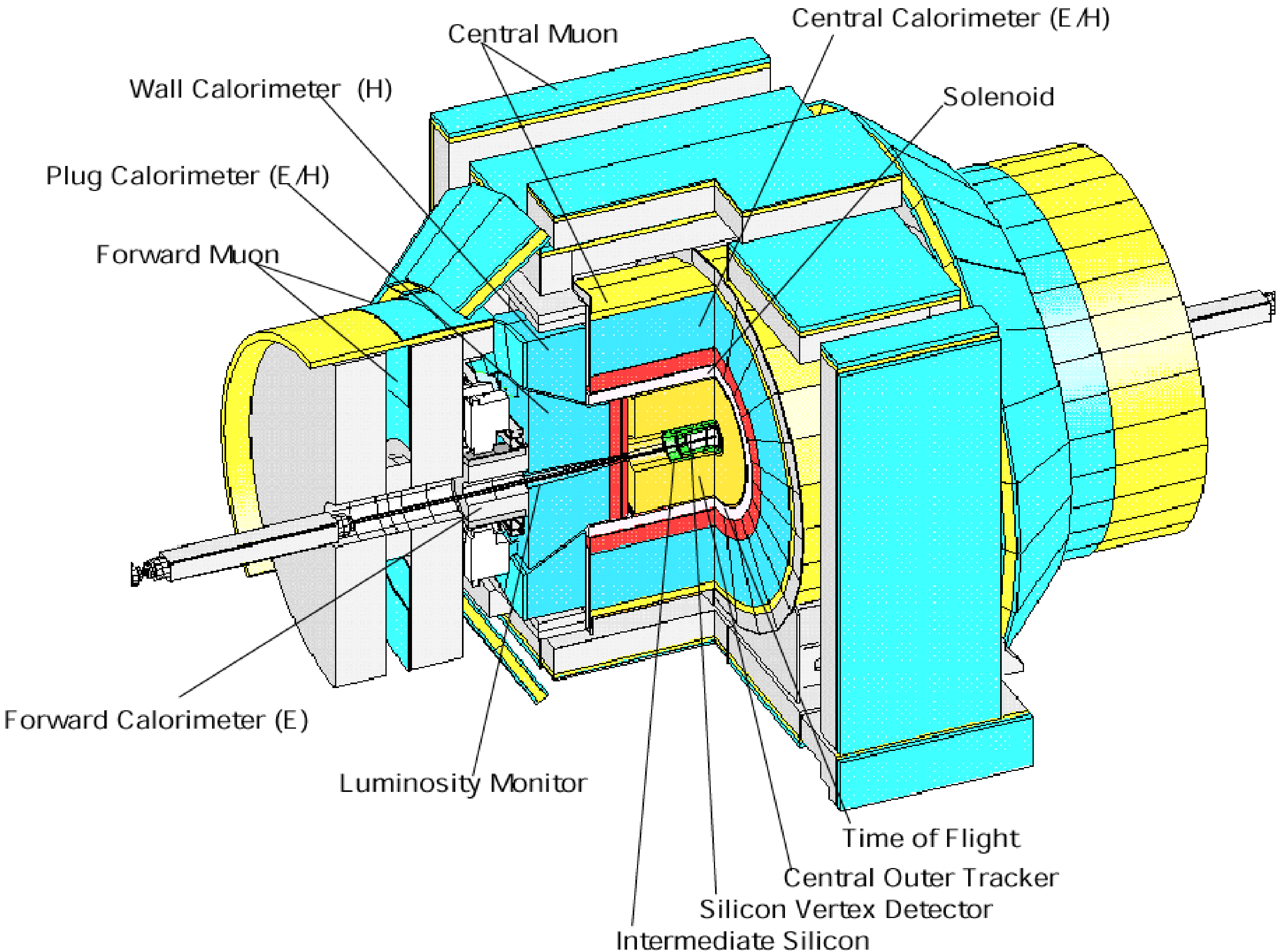
Detectors used at accelerator are complex devices.



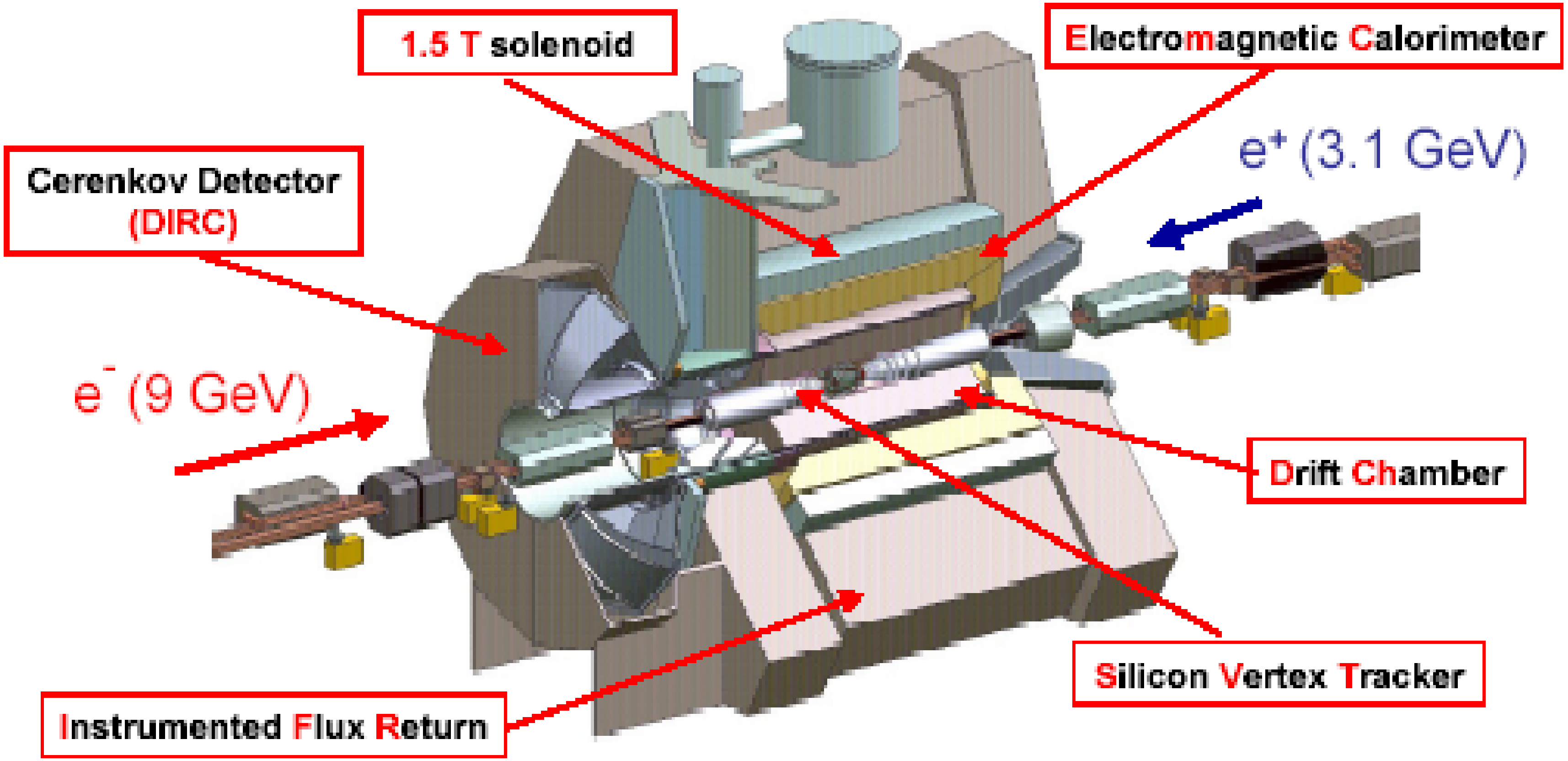
Detector for each particles



An example: CDF detector



An example: Babar



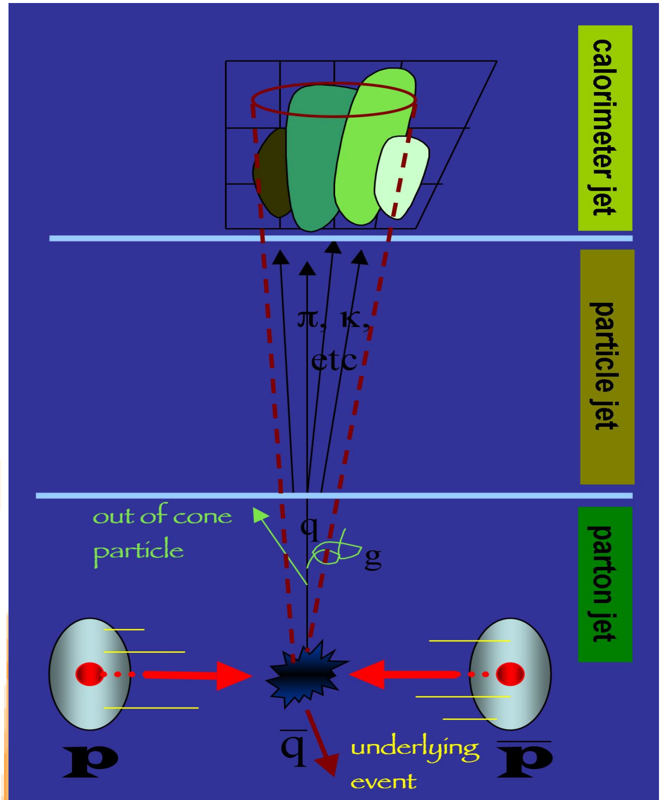
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T + 0.45\ \%$

DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

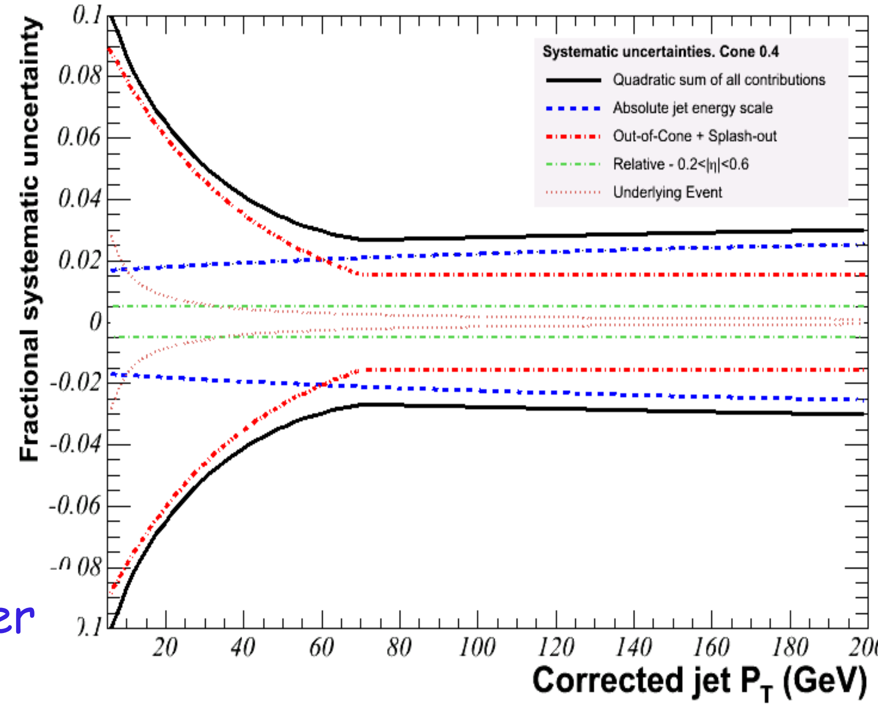
EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

Jet Energy determination



Jet energy corrections are needed to scale the measured energy of the jet back to the energy of the final state particle level jet:

- non-linearity effects and energy loss in the un-instrumented regions
- multiple interactions
- underlying event
- out of cone



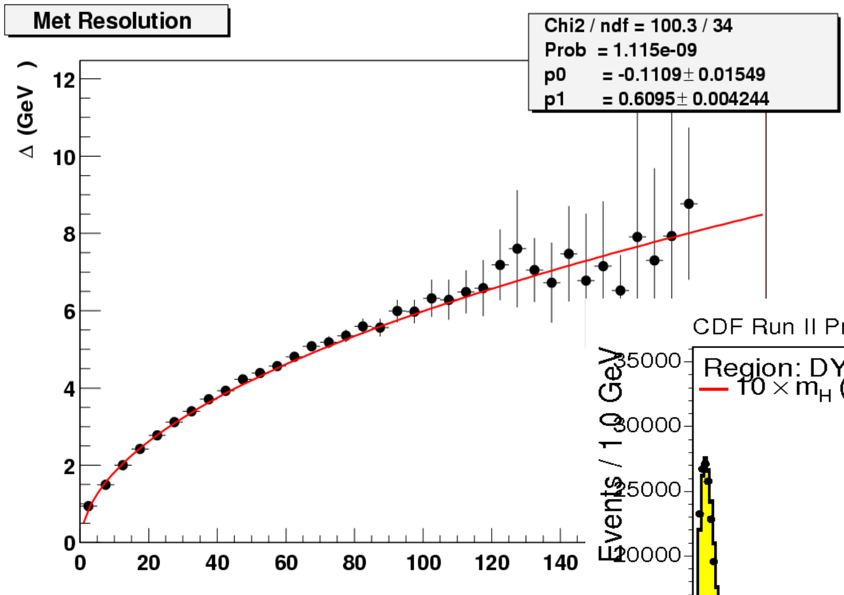
Low Pt: Dominated by MC/data uncertainties

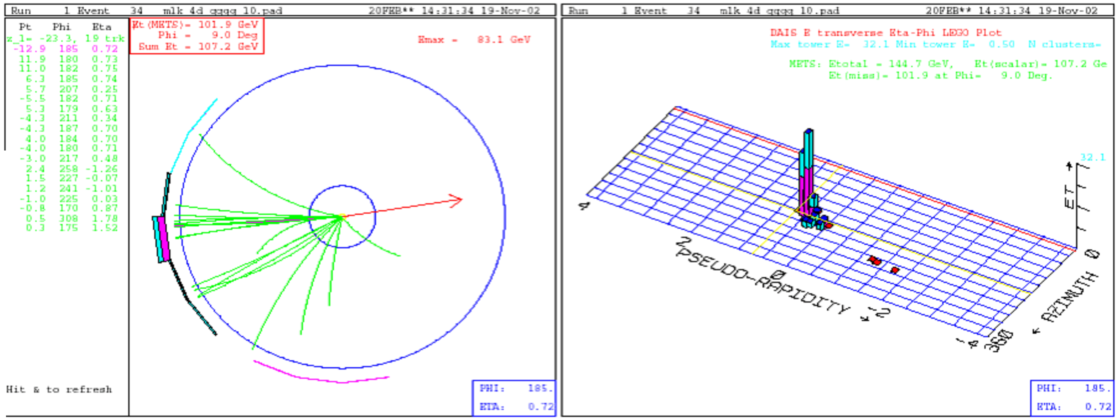
High Pt: Dominated by calorimeter simulation uncertainties

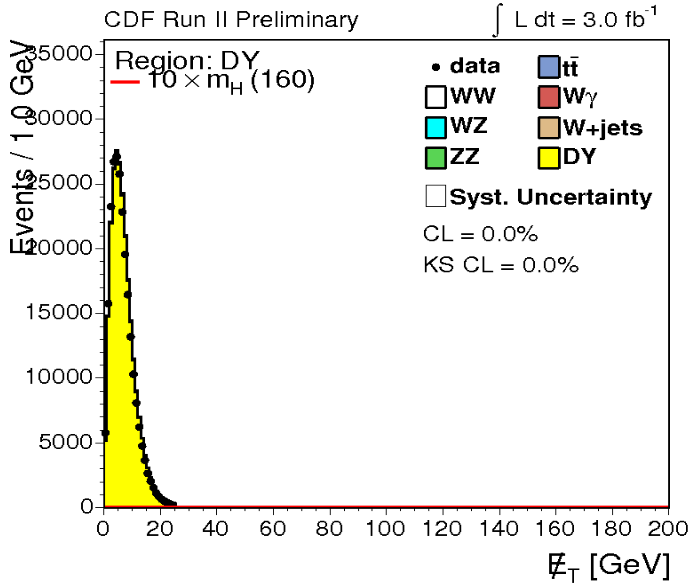
Neutrino Identification

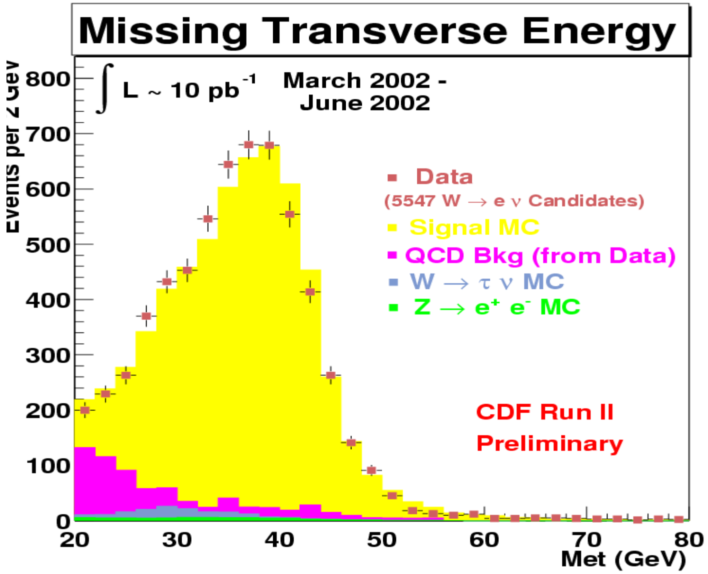
Not enough material in collider detectors to have neutrino interactions.
Neutrinos are identified via the transverse missing energy:

$$\vec{\not{E}}_t = \sum_{towers} E_i \sin(\theta_i)\hat{n}_i$$



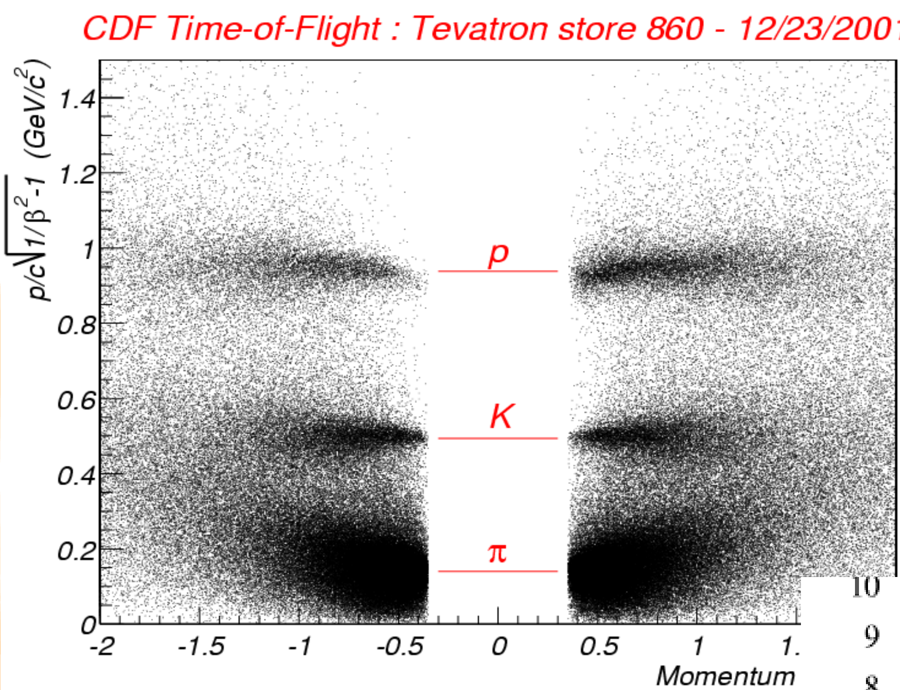




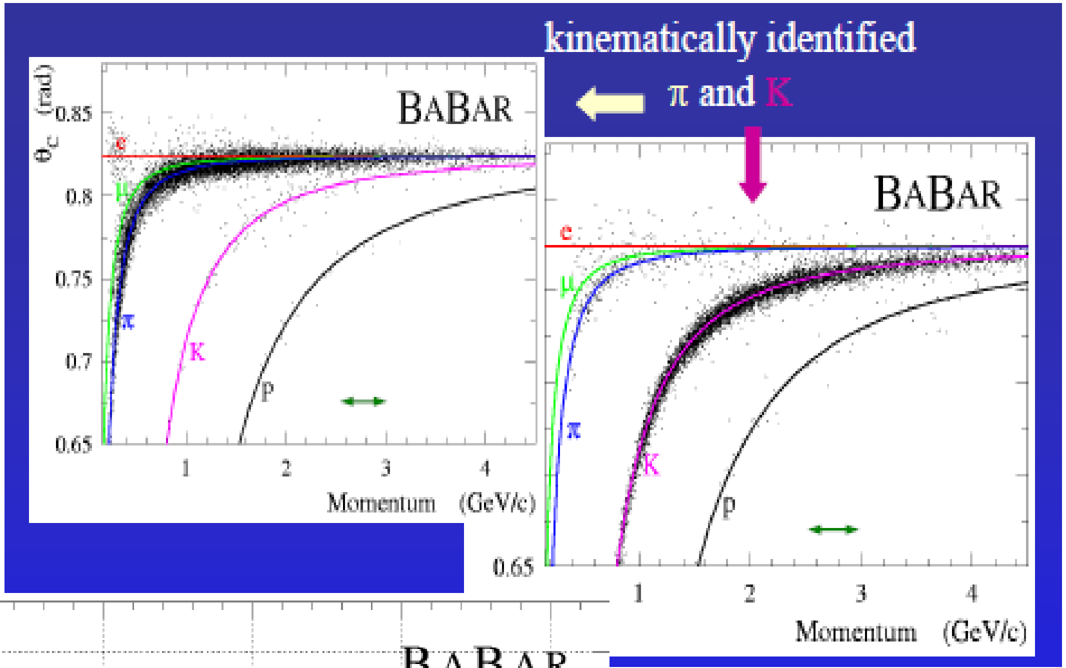


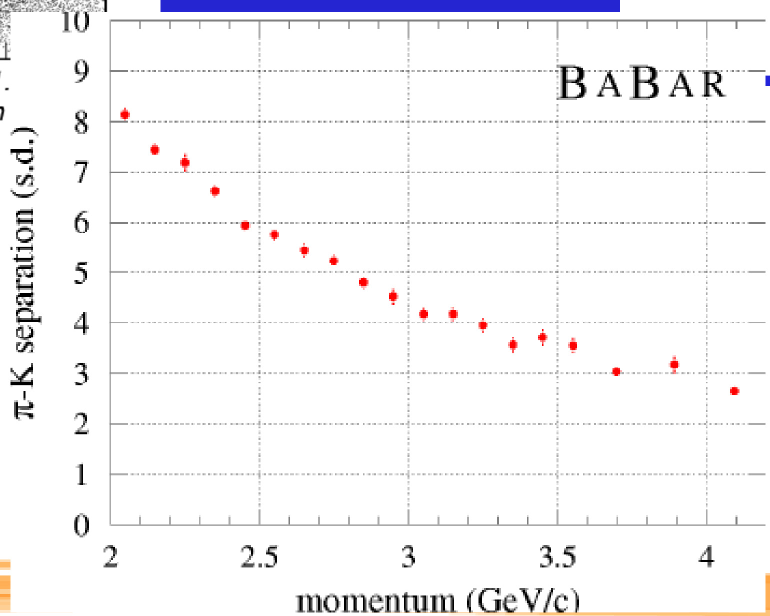
Particle Identification

TOF at CDF



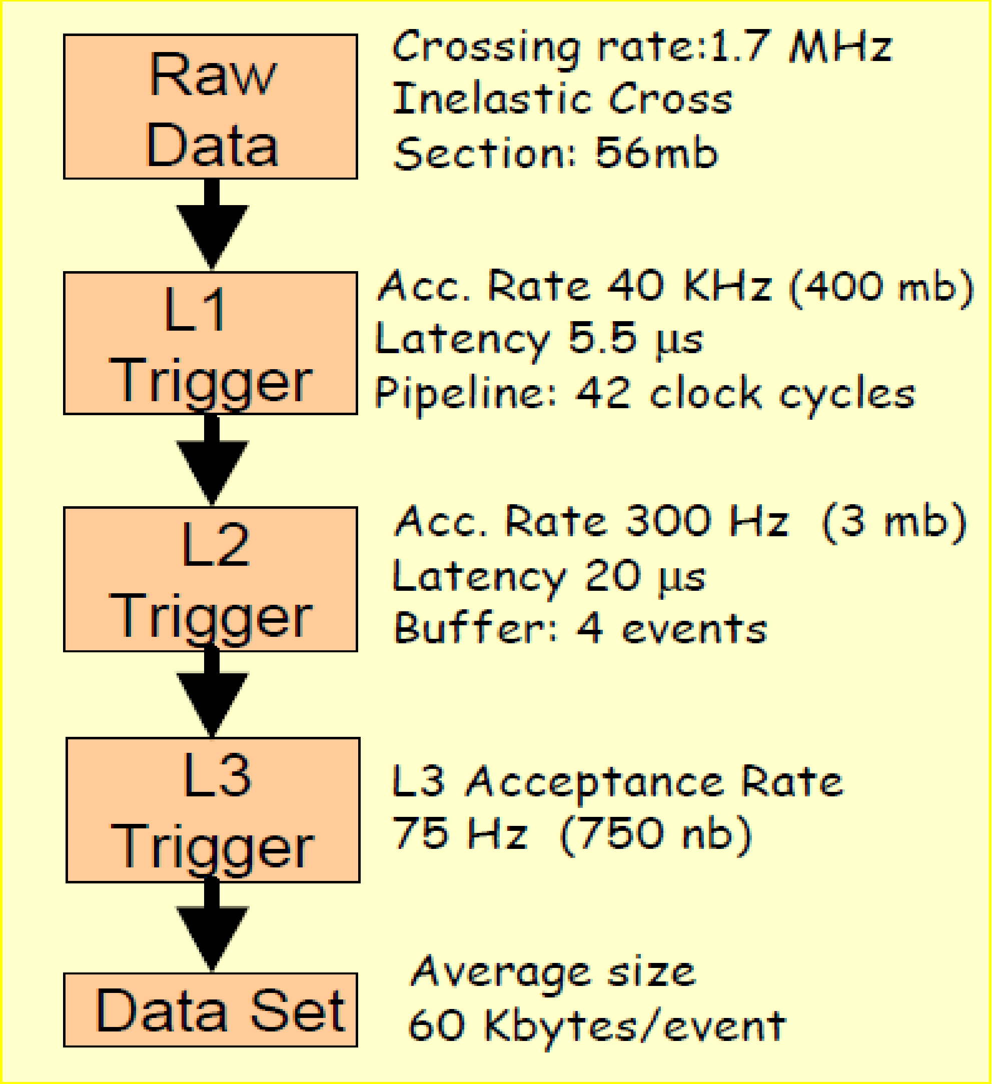
DIRC at Babar





Hadron Collider: Trigger!

Trigger Overview



Level 1 synchronous streams:
- Calorimeter
- eXtremely Fast Tracker
- Muons

Level 2 asynchronous systems:
- Calorimeter Clustering
- Silicon Vertex Tracker
- Shower Maximum

Level 3:
- Offline-like

Ready for the Physics!