Colliders and Detectors

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Hadron Collider Physics Summer School 2008/2009

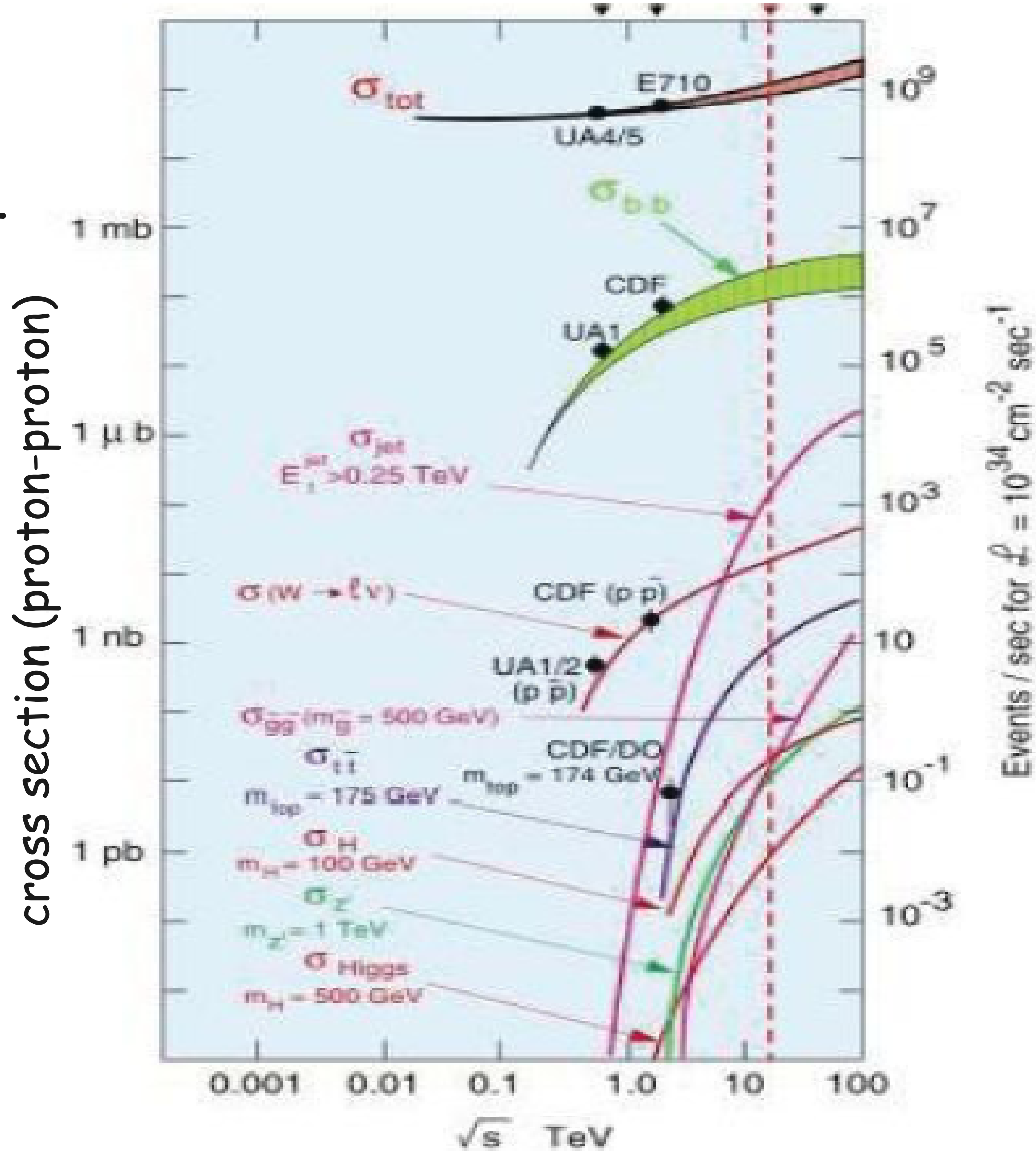
http://projects.fnal.gov/hcpss/

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

Colliders have been and are a very powerful tool.



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

$$\frac{dn_1}{ds} = \frac{n_1}{2\pi\sigma_x\sigma_y} e^{-\left(x^2/2\sigma_x^2 + y^2/2\sigma_y^2\right)}$$

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

Gaussian distribution normalized to number of particles

Number of particles n_1 in an area dxdy

$$dn_{۱}(x,y) = \frac{n_{۱}}{۲\pi\sigma_x\sigma_y} e^{-\left(x^{۲}/۲\sigma_x^{۲} + y^{۲}/۲\sigma_y^{۲}\right)} \cdot dxdy$$

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}

$$p(x, y) = \mathrm{dn}_2(x,y) = \frac{n_2}{2\pi\sigma_x\sigma_y} e^{-\left(x^2/2\sigma_x^2 + y^2/2\sigma_y^2\right)} \cdot \sigma_{\mathrm{int}}$$

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

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

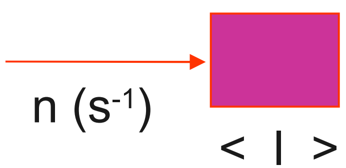
$$\Rightarrow \qquad L = \frac{n_1 n_2 f}{4\pi \sigma_x \sigma_y k}$$

Colliders vs. Fixed Target: Rate

Assumptions:

- same C.M. Energy
- same interaction cross section (e.g. $\sigma_{in} \sim 1\mu b$)

Fixed target



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

ρ= target density = $1 gr/cm^3$

l= target thickeness =1cm

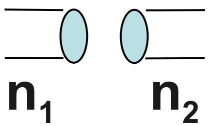
$\sigma_{int} = 1\mu b$

A= Avogadro number = 6×10^{23}

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

Colliders vs. Fixed Target: Rate cont'd

Collider



$n_1 = n_2 =$ beam particles

$i_1 = i_2 = 50$ mA ➔ $n_1 = n_2 = i_{1,2}/ef = 3.3\times10^{11}$

F= transverse section of beams= 0.1×0.01 cm^2

B= bunch number= 1

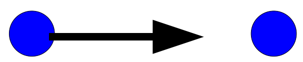
f= revolution frequency = 10^6 s^{-1}

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

Center of Mass Energy

Beam/target particles interaction:

Fixed target



E_1, P_1 E_2, P_2

$P_2 = 0$ in the lab. system

$$E^2_{CM} = m_1^2 + m_2^2 + 2\, E_1 \cdot m_1$$

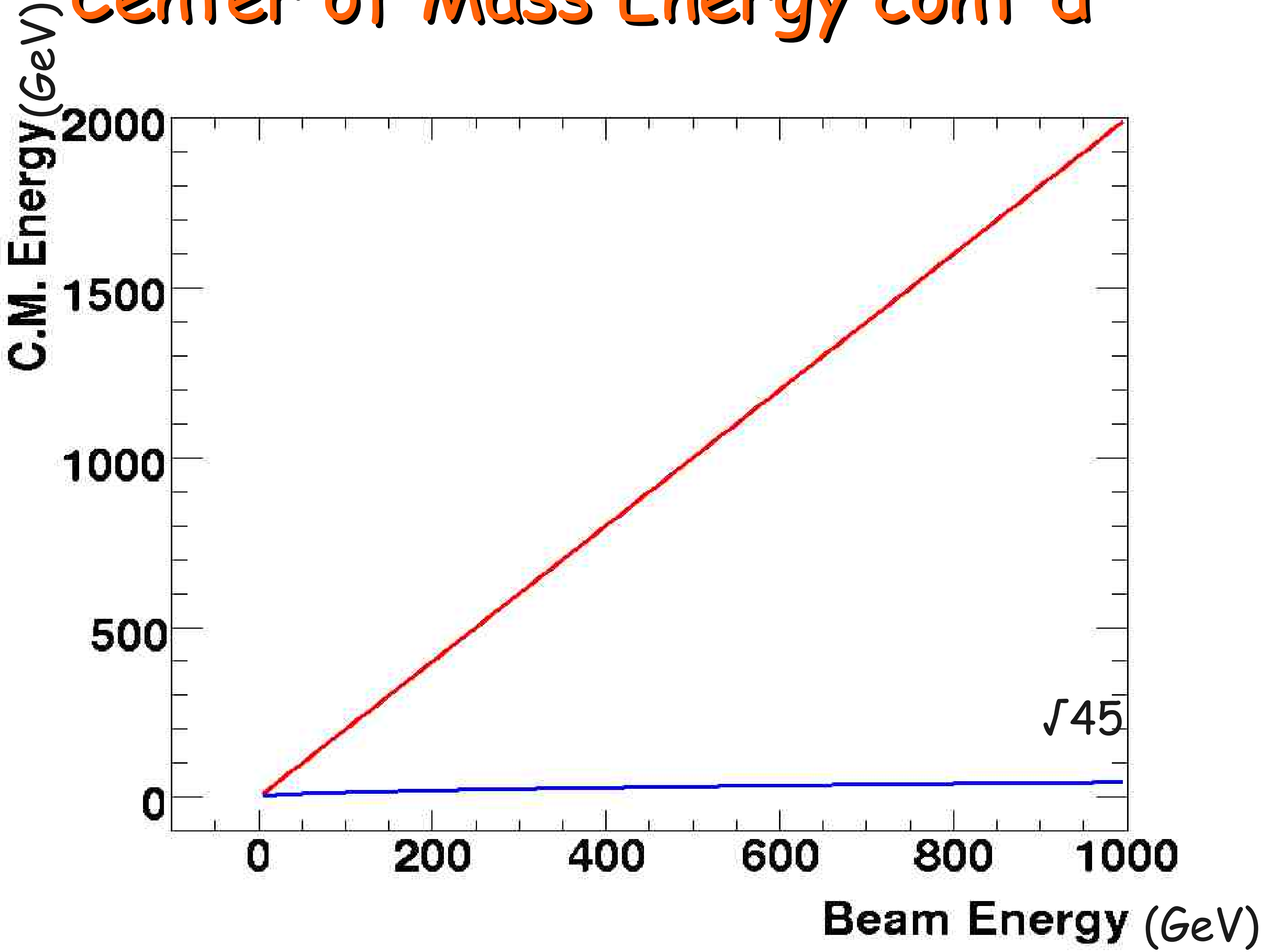
Collider

E_1, P_1 E_2, P_2

Collinear beams:

$$E^2_{CM} = m_1^2 + m_2^2 + 4\, E_1 \, E_2$$

Center of Mass Energy cont'd



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

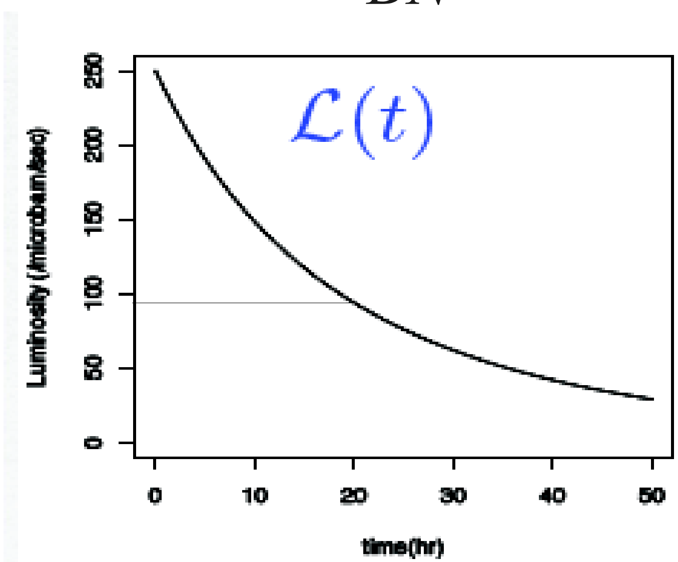
A= interaction area

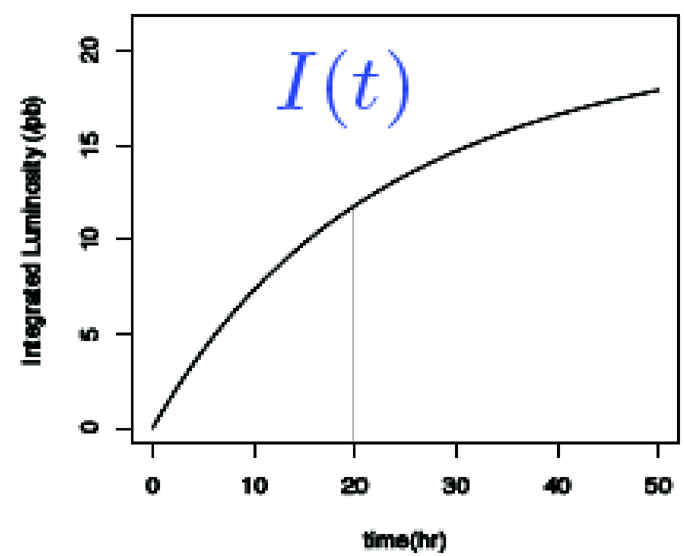
In the ideal case particles are lost only due to interactions:

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

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

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





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

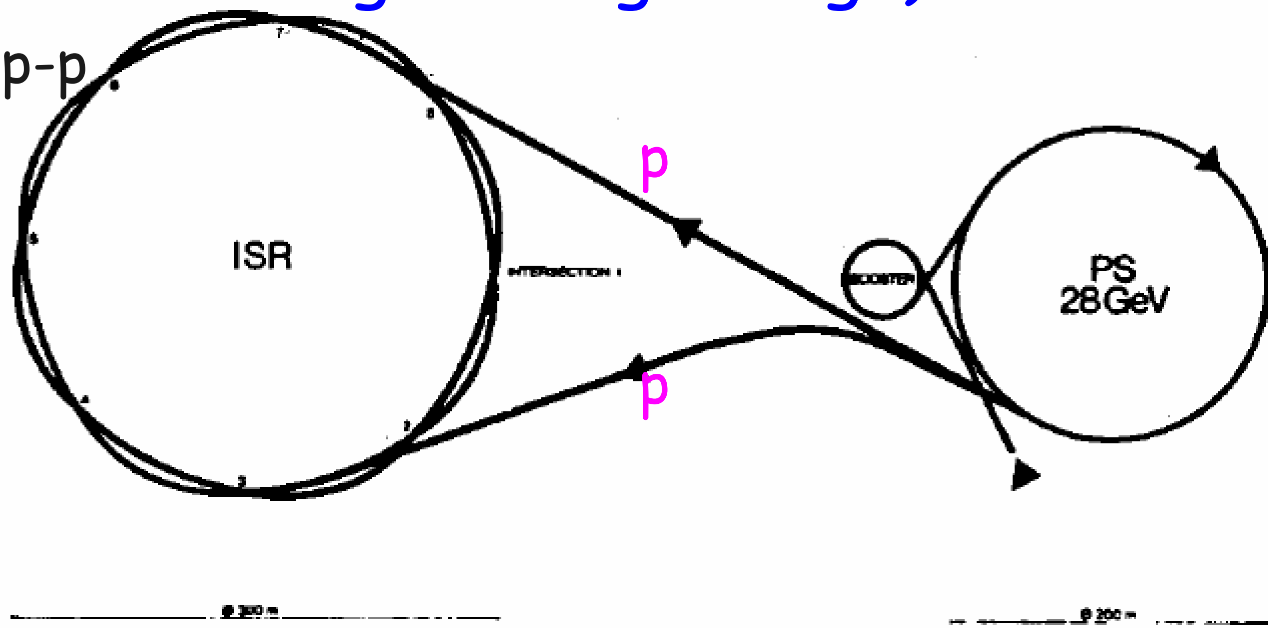
electron-positron
proton-proton
electron-pronton
proton-antiproton

Hadron Colliders

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-)

ISR(Intersecting Storage Rings)

1971: first p-p



Proton Synchrotron

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

Hadron Colliders: ISR

Standard Model just at the begin, most phenomenology

π, k, p production cross sections on protons seem constant with E

Most important results:

- measurement of σ(p$\bar{p}$), increasing with energy
- determination of dσ/dt(quadri-momentum). It follows 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

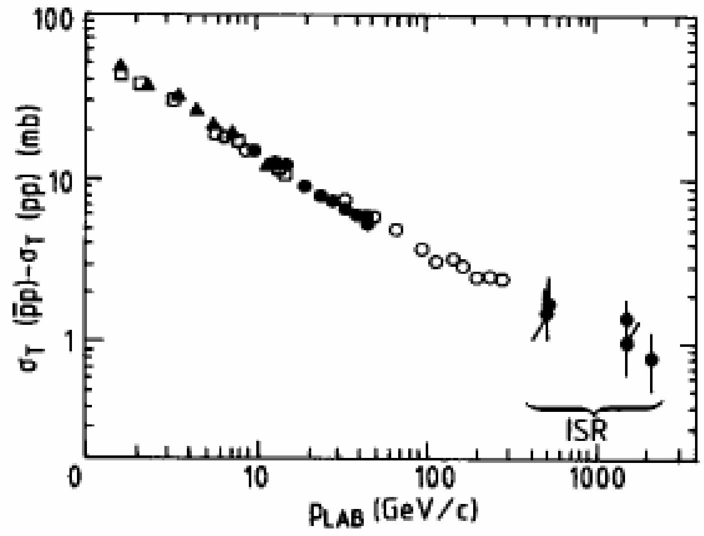


Fig. 43 Measurements of the total cross-section difference, $\sigma_T(p\bar{p})-\sigma_T(pp)$, vs. p_{lab}

Hadron Colliders: SpS (Super Proton Synchrotron)

1982 CERN was able to produce, accumulate, cool and accelerate pbar thanks to Simon Van der Meer

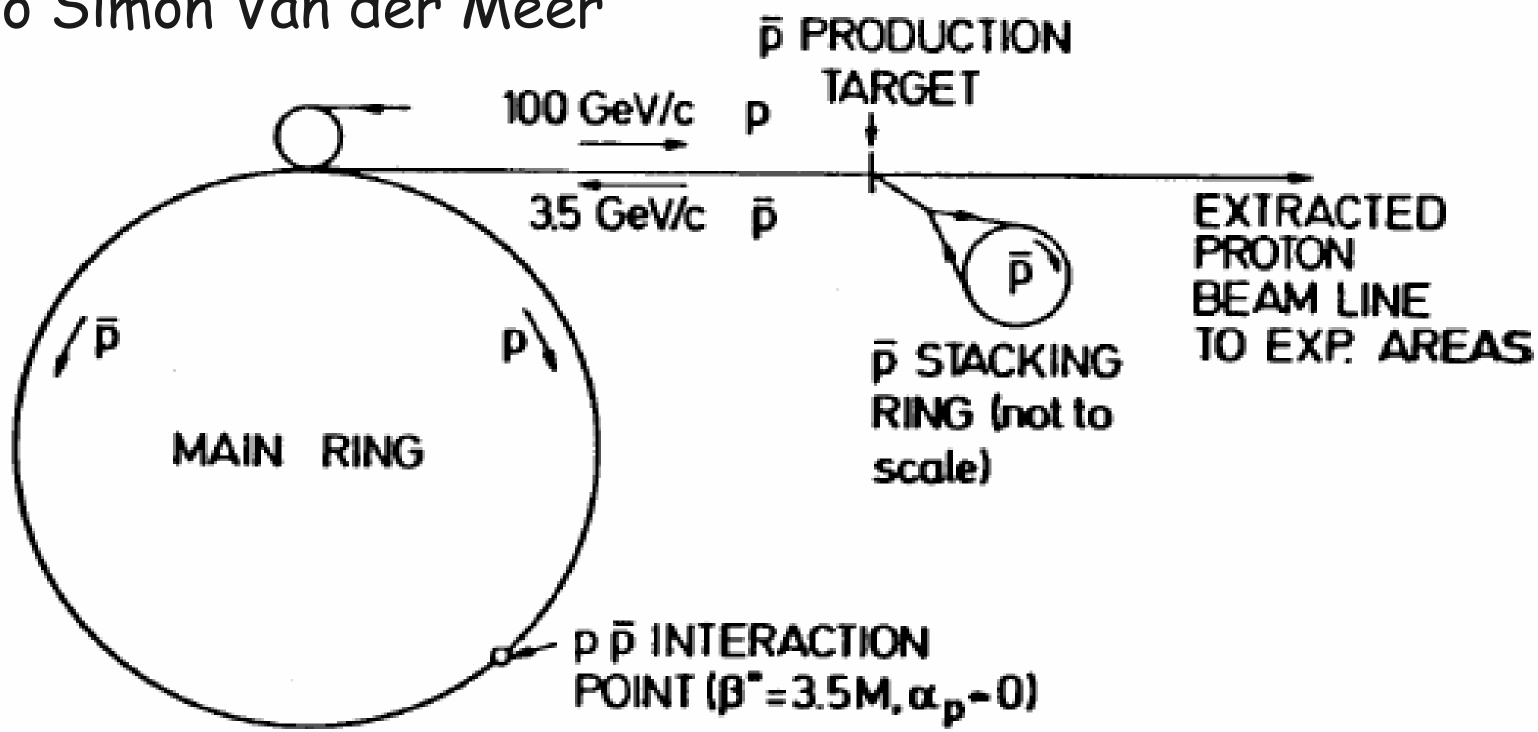


Fig. 5. General layout of the $p\bar{p}$ colliding scheme, from Ref. [9]. Protons (100 GeV/c) are periodically extracted in short bursts and produce 3.5 GeV/c antiprotons, which are accumulated and cooled in the small stacking ring. Then $\bar{p}$'s are reinjected in an RF bucket of the main ring and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

SpS Results

The detectors UA1 & UA2 (Underground Area 1,2: 35 meters underground)

The Standard Model is a reality:
- jets identification
- measurements of hadronic cross section
- discovery of W and Z bosons

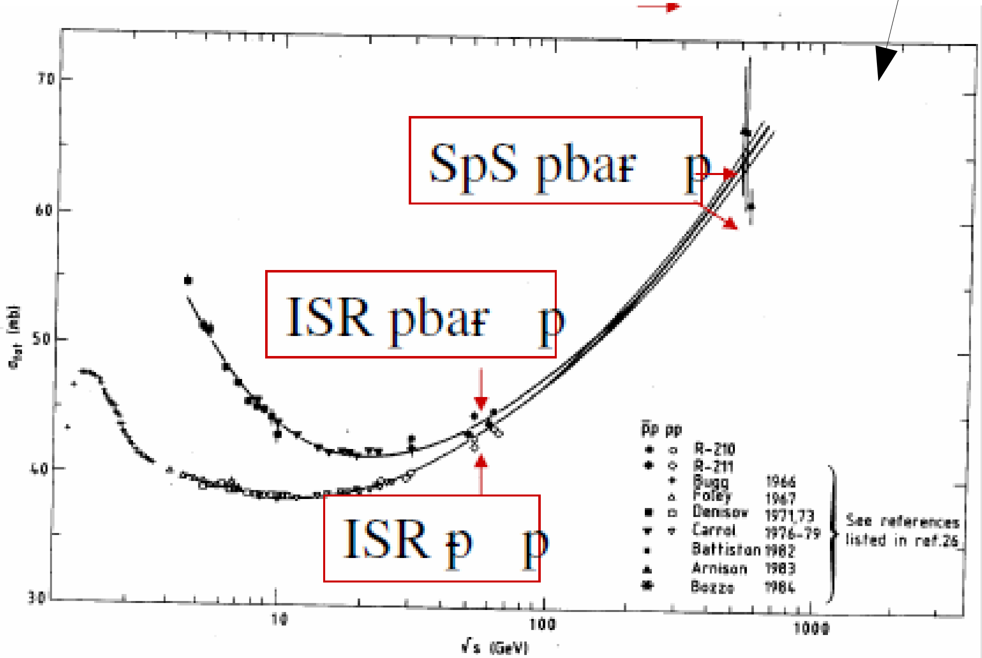
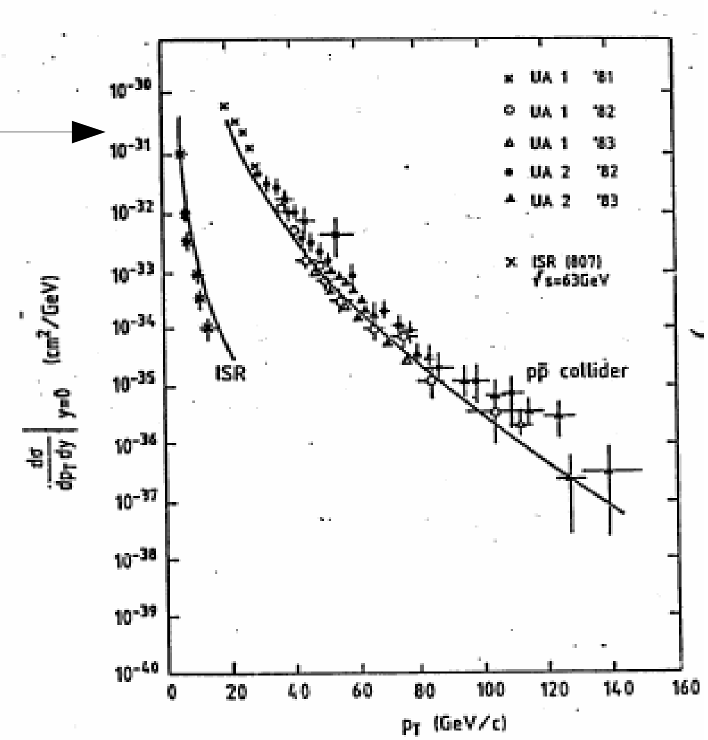


Fig. 7. The behaviour of $\sigma_{tot}(pp)$ and $\sigma_{tot}(\bar{p}p)$ as a function of $\sqrt{s}$.



ISR just
under threshold
for jets production

SpS Results: W discovery

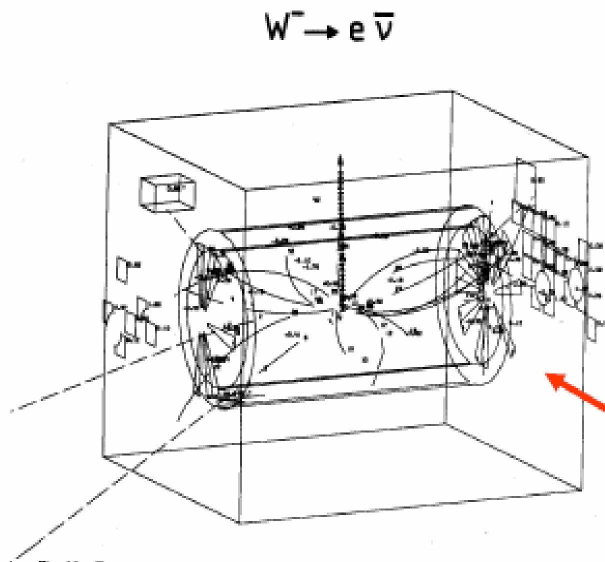


Fig. 16a. Event of the type $W^- \to e^- + \bar{\nu}_e$. All tracks and calorimeter cells are displayed.

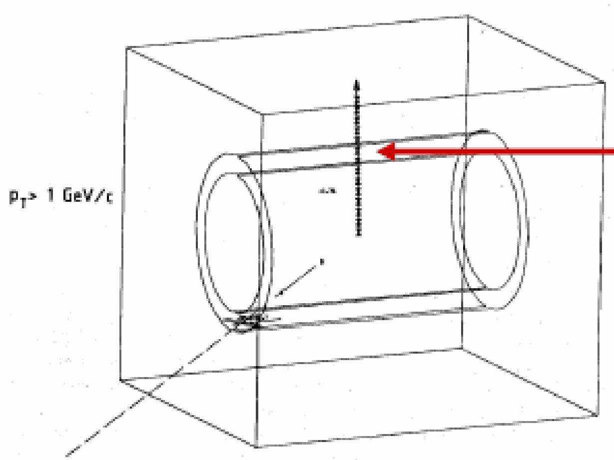


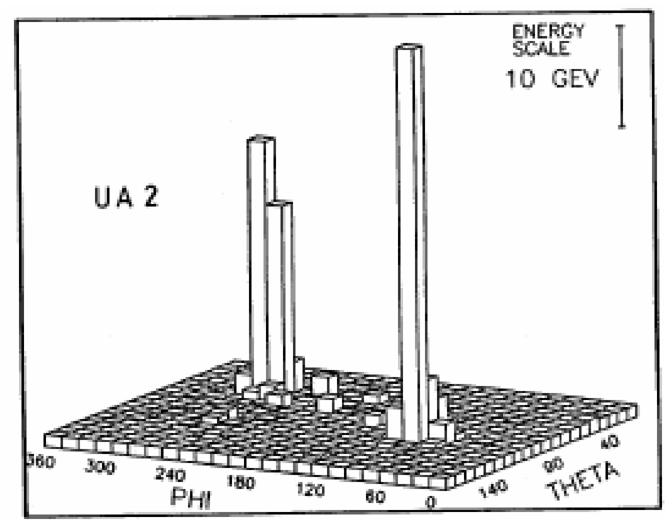
Fig. 16b. The same as picture (a), except that now only particles with $p_T > 1$ GeV/c and calorimeters with $E_T > 1$ GeV are shown.

First W candidate

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

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

UA2 demonstrated that these events were W comparing to expectations



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

SpS Results: W & Z discovery

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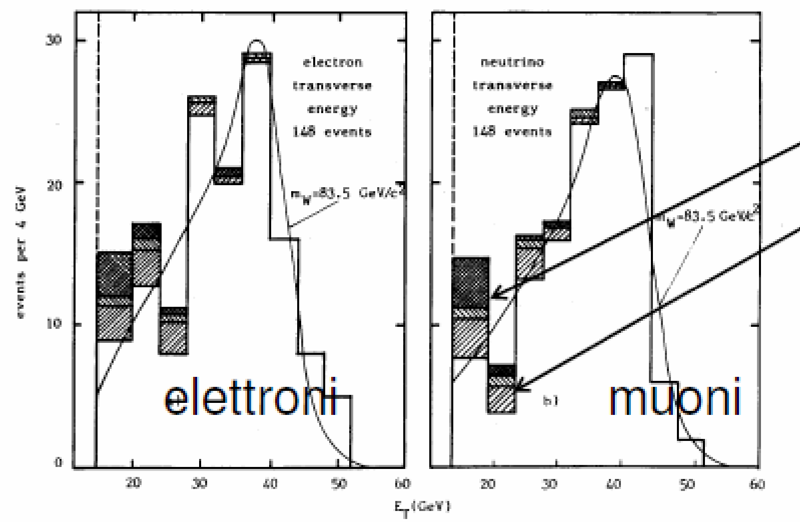

Fondo atteso da non-W e da W→τν

Fig. 3.5. The lepton transverse energy distributions for the UA1 sample of well-measured $W^{\pm} \to e^{\pm}\nu_e$ events. (a) the electron transverse energy distribution and (b) the neutrino transverse energy distribution. The shaded parts show the expected contributions from jet–jet fluctuations (cross-hatched) and $W \to \tau\nu$ decays with $\tau \to$ hadrons (top left to bottom right hatching) and $\tau \to e\nu_e\nu_\tau$ (top right to bottom left hatching). The curves show the predictions for the background subtracted distributions (normalized to the data) corresponding to W with a mass of 83.5 GeV/c^2. Transverse energy and transverse momentum are in this case equivalent expressions (UA1 [21]).

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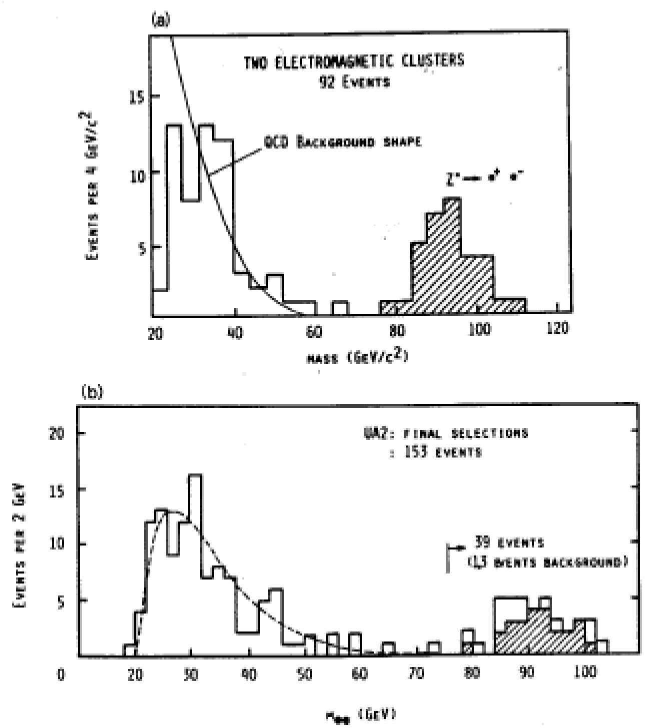
e+e- invariant: the Z^0



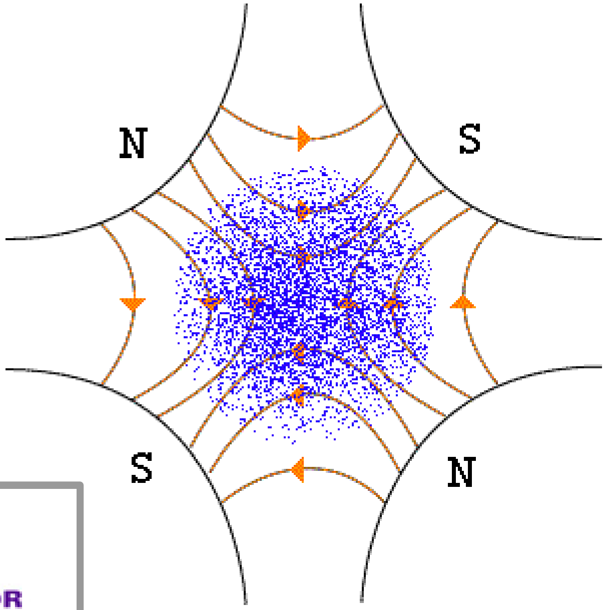
UA1

UA2

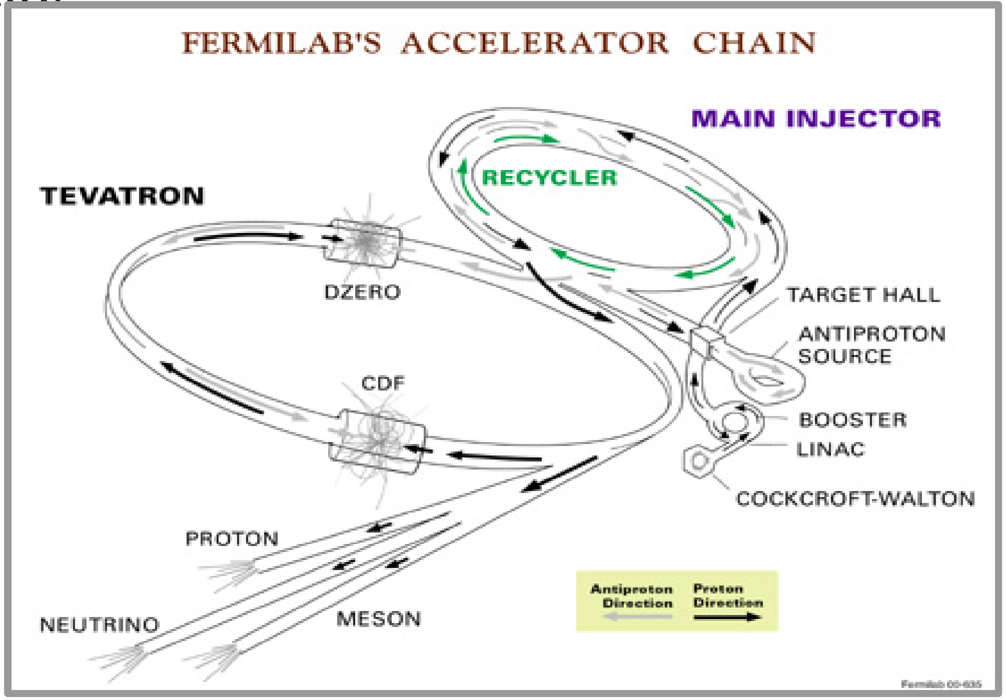
Fig. 3.9. (a) The distribution of e^+e^- pairs, recognized as $Z^0 \to e^+e^-$ processes (UA1 [21]). (b) The e^+e^- events, collected by UA2 [22].

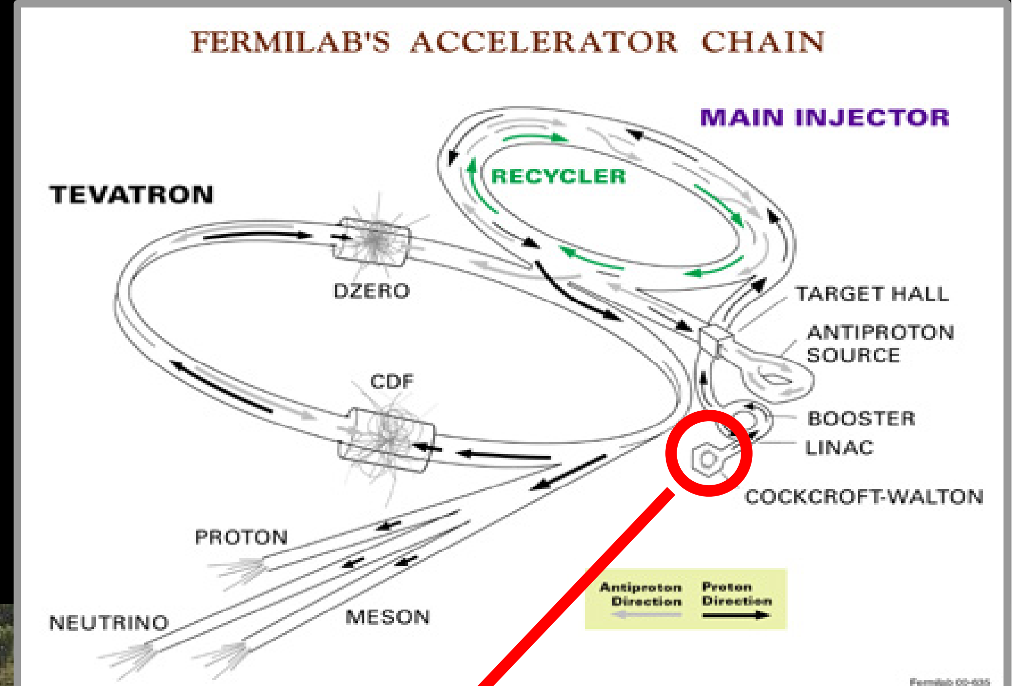
Hadron Colliders: Tevatron

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

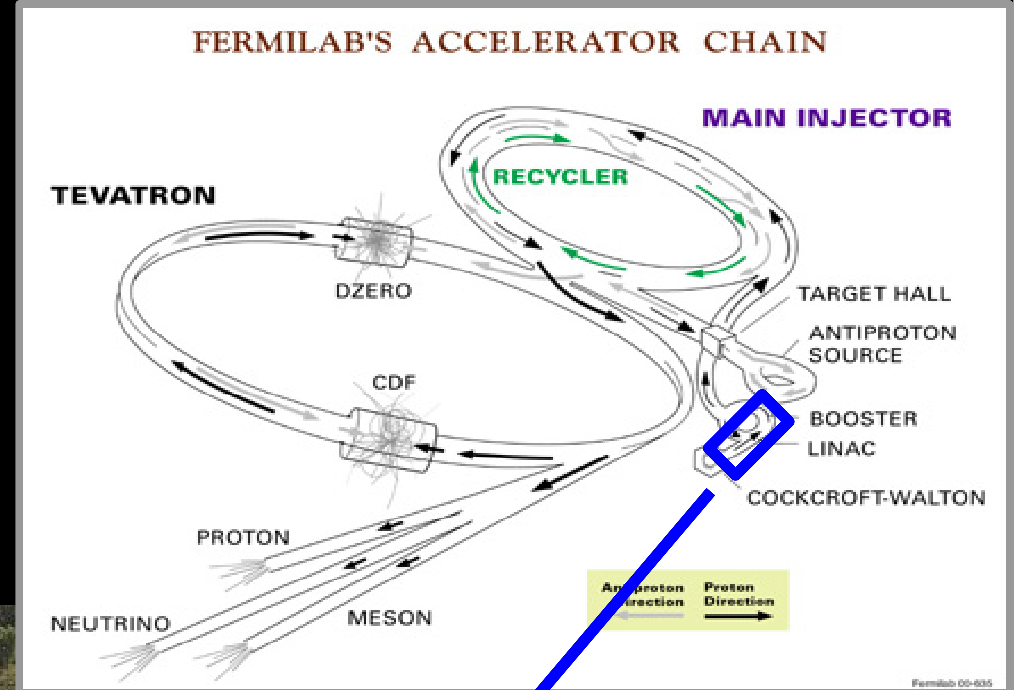


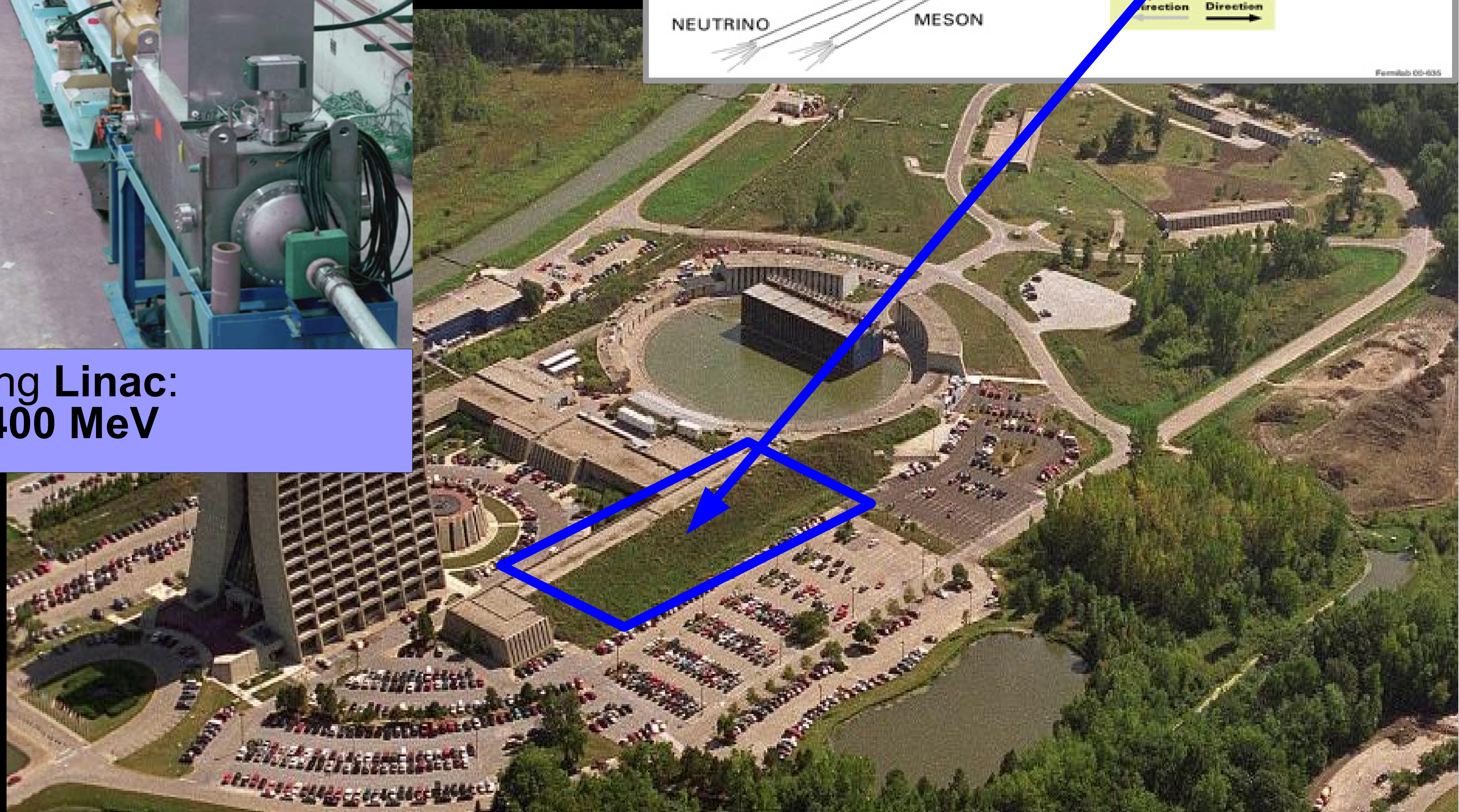
Complex chain:





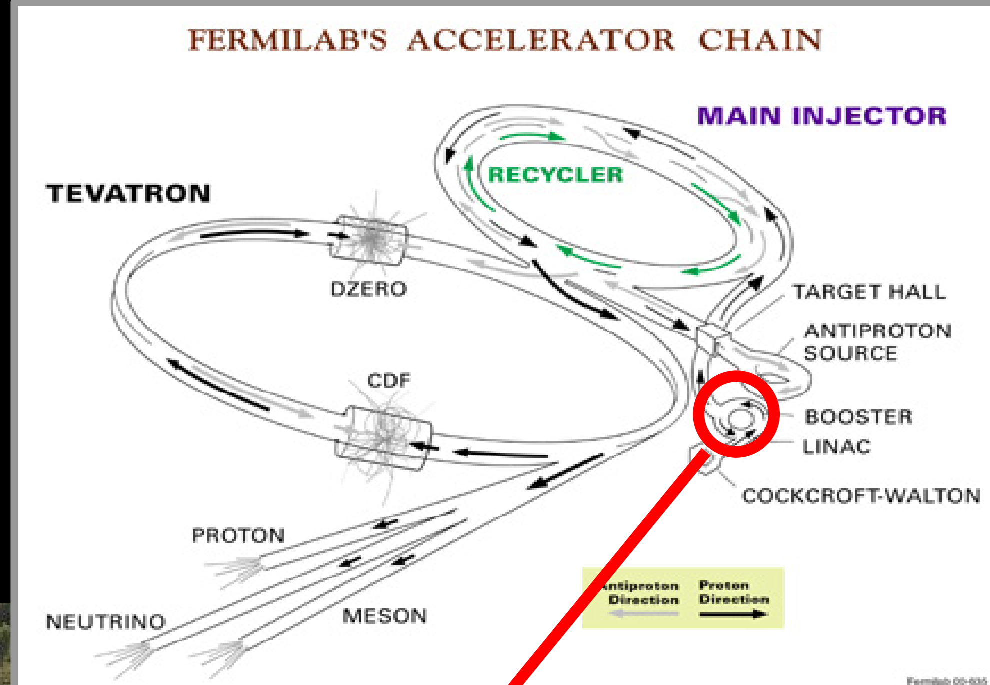
Cockroft-Walton accelerator:
H^- ions produced and accelerated up to **750 keV**

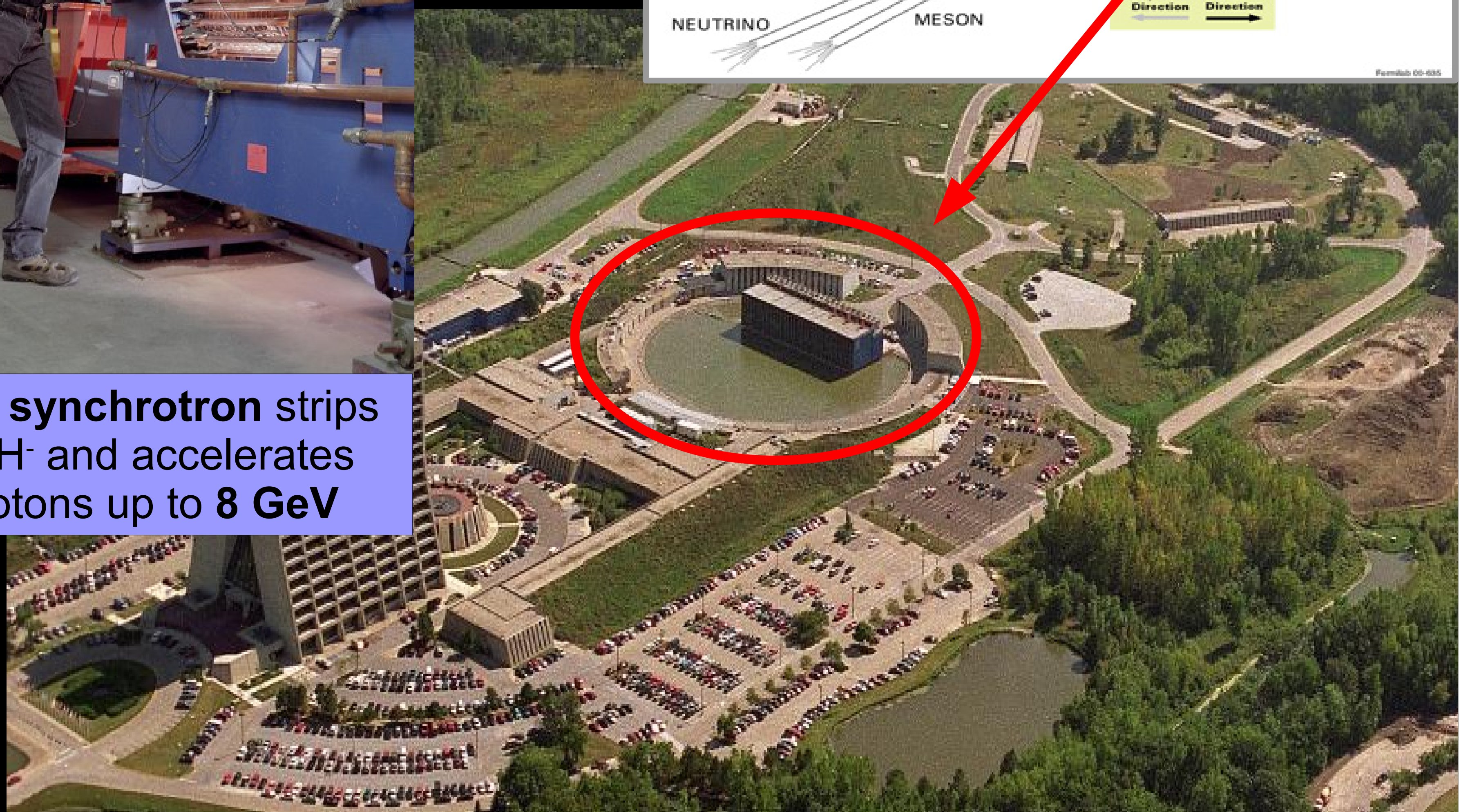




150 m long **Linac**:
H$^-$ up to **400 MeV**

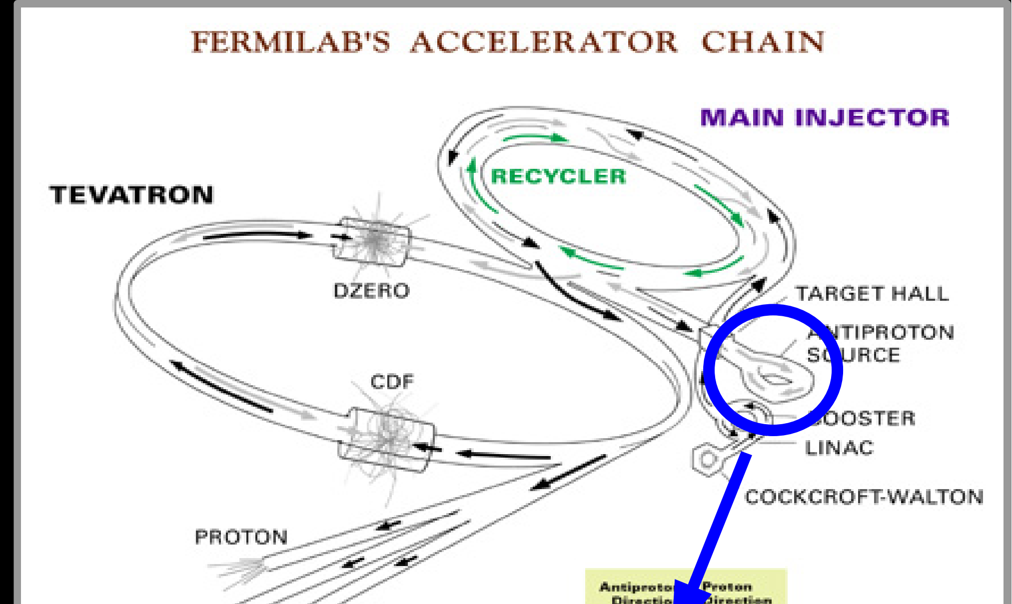
April, 15 2010



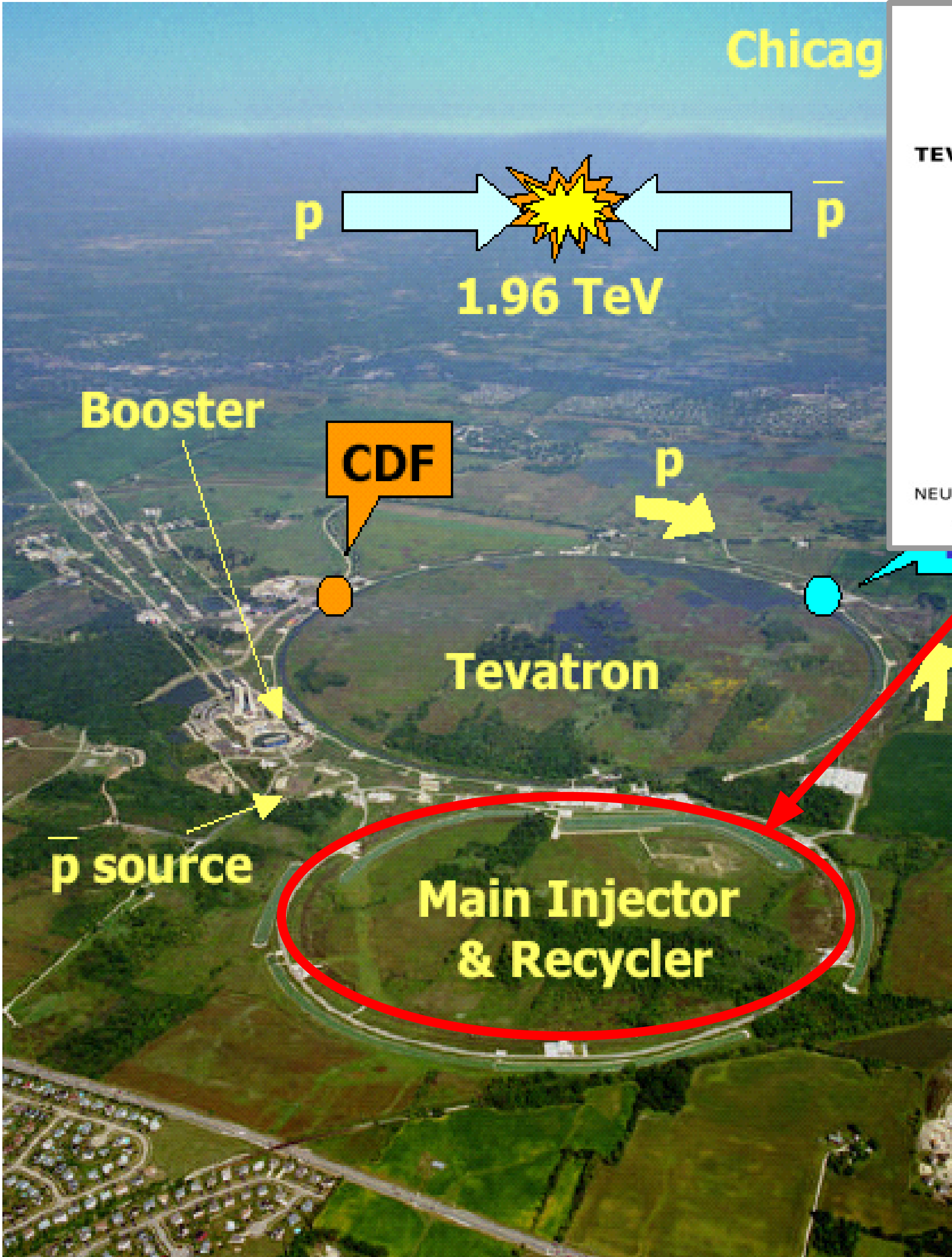


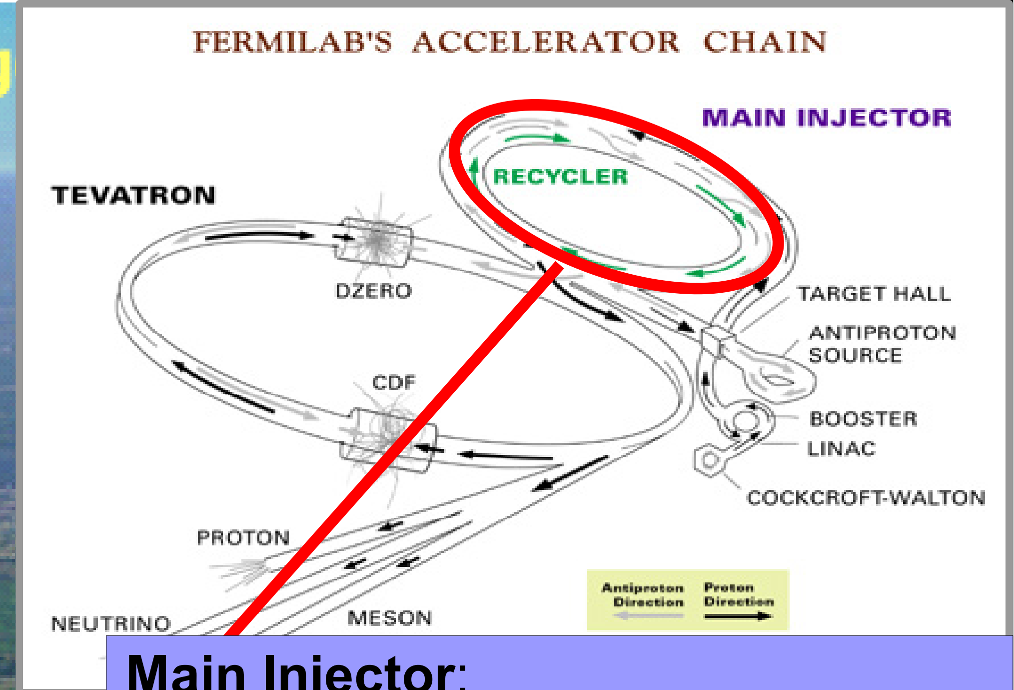
The **Booster synchrotron** strips electrons off H^- and accelerates remaining protons up to **8 GeV**

April, 15 2010



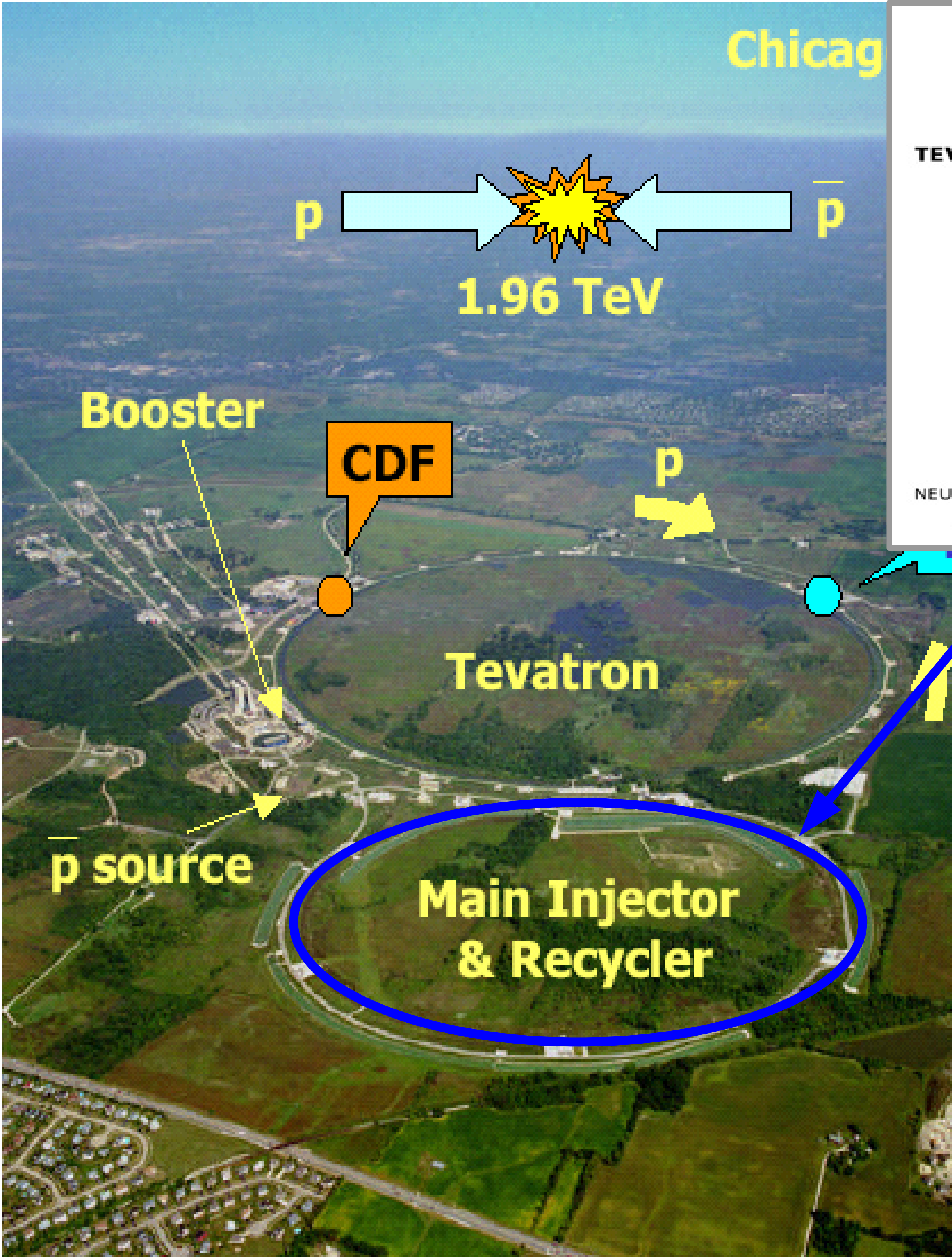
The Anti-proton Source

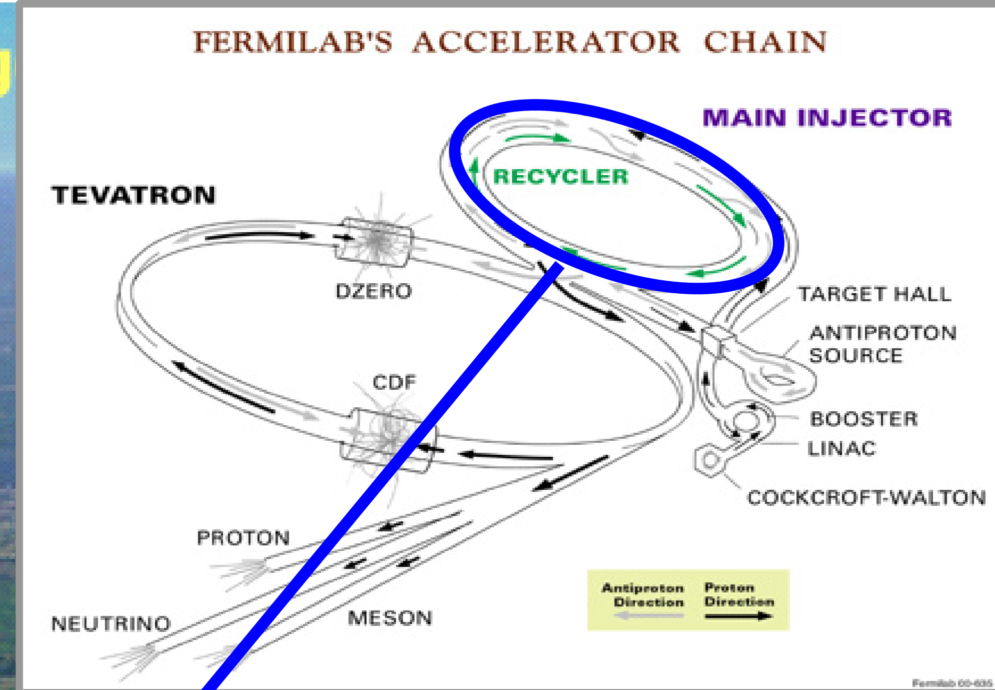




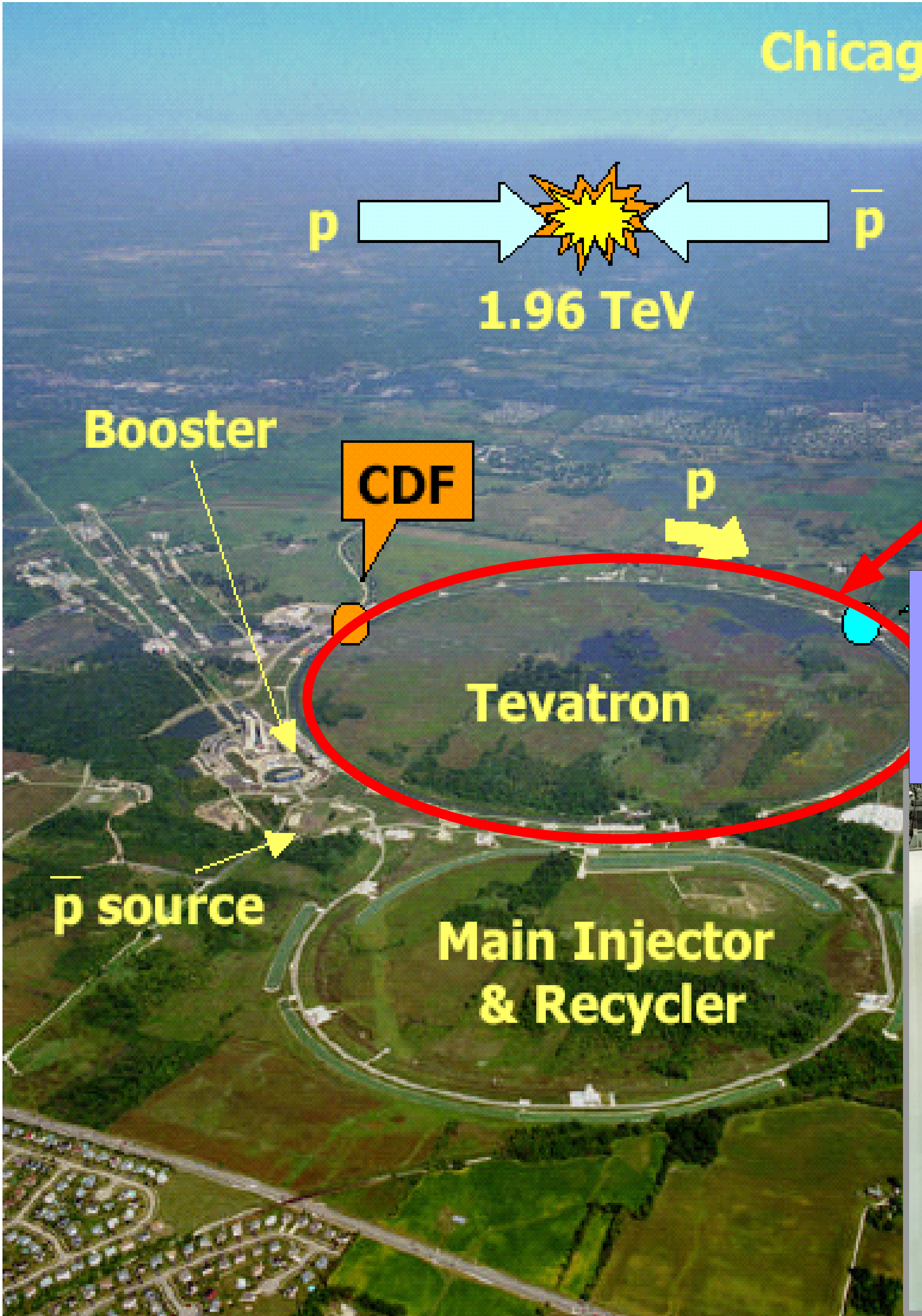
Main Injector:

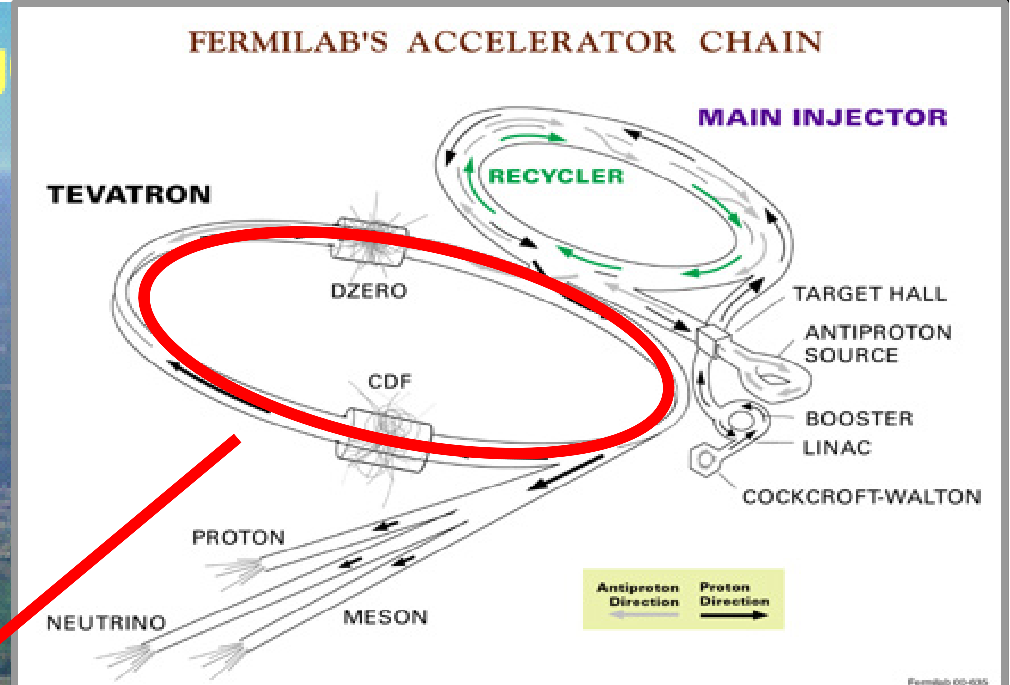
- p up to **120 GeV** for anti-p prod.
- deliver p-beams to fixed target exp
- accelerate p/anti-p up to **150 GeV** for Tevatron Injection.
- send to recycler anti-p after stores



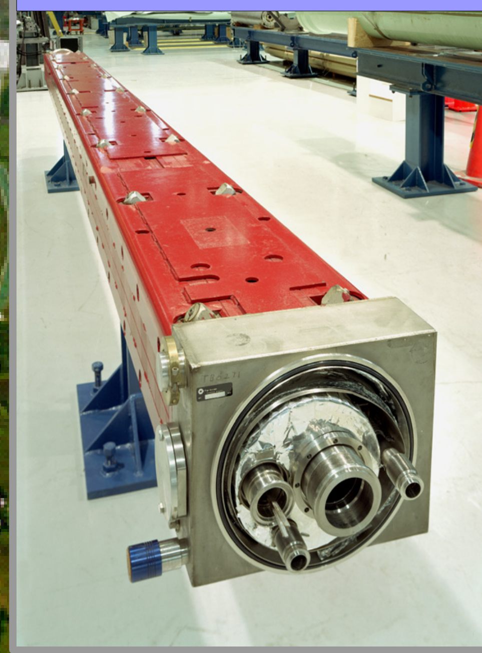


Recycler, **8 GeV** fixed energy storage ring: recover and recool anti-p left over after Tevatron collision operations

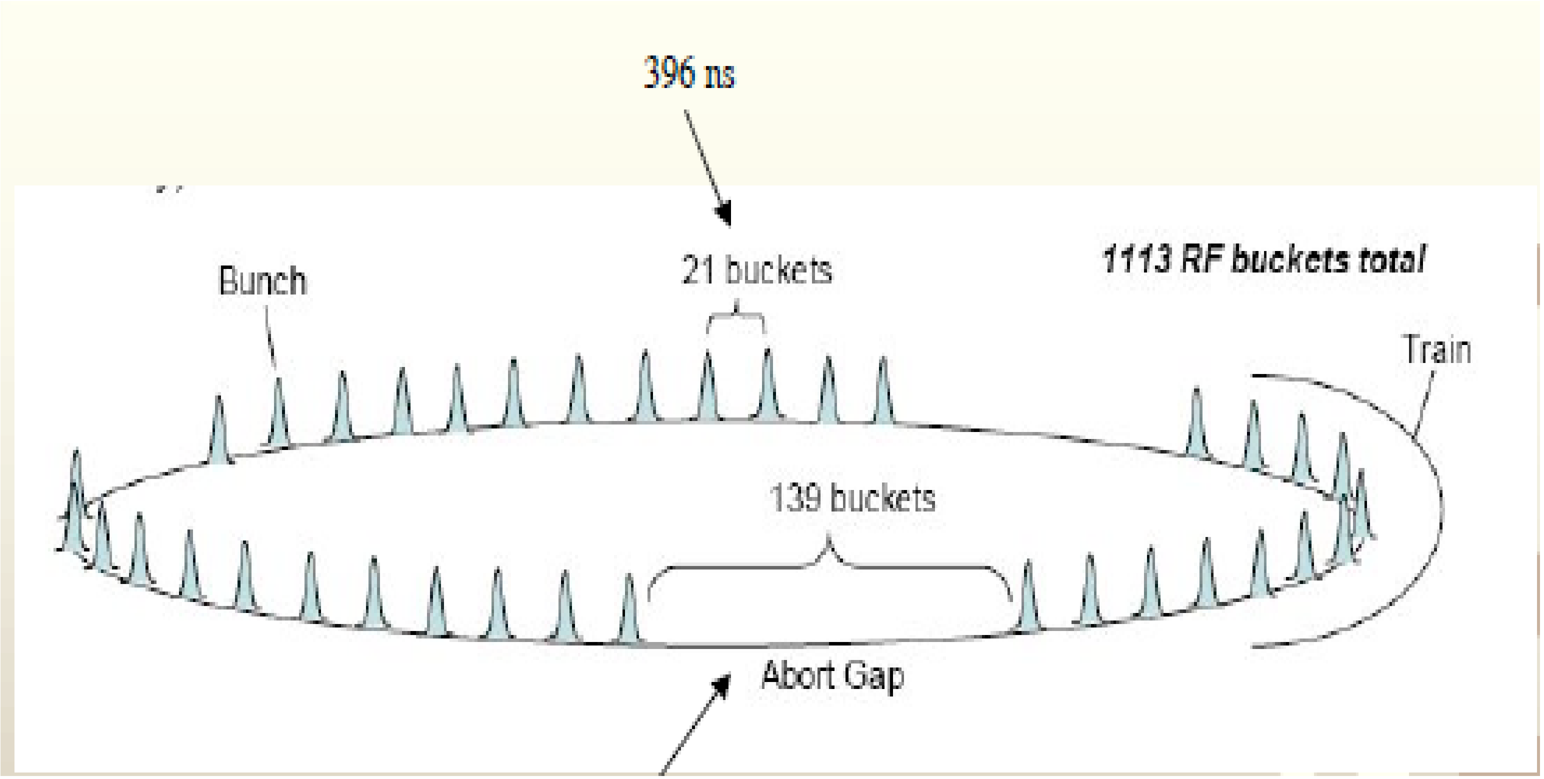




Tevatron:
p/anti-p beams up to **980 GeV,**
providing a
center of mass energy of **1.96 TeV**



Tevatron bunch structure



2.6μs

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

The new hadron Colliders: LHC

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider (SppbarS)

1989 : Start of LEP operation (Z/W boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of LHC installation

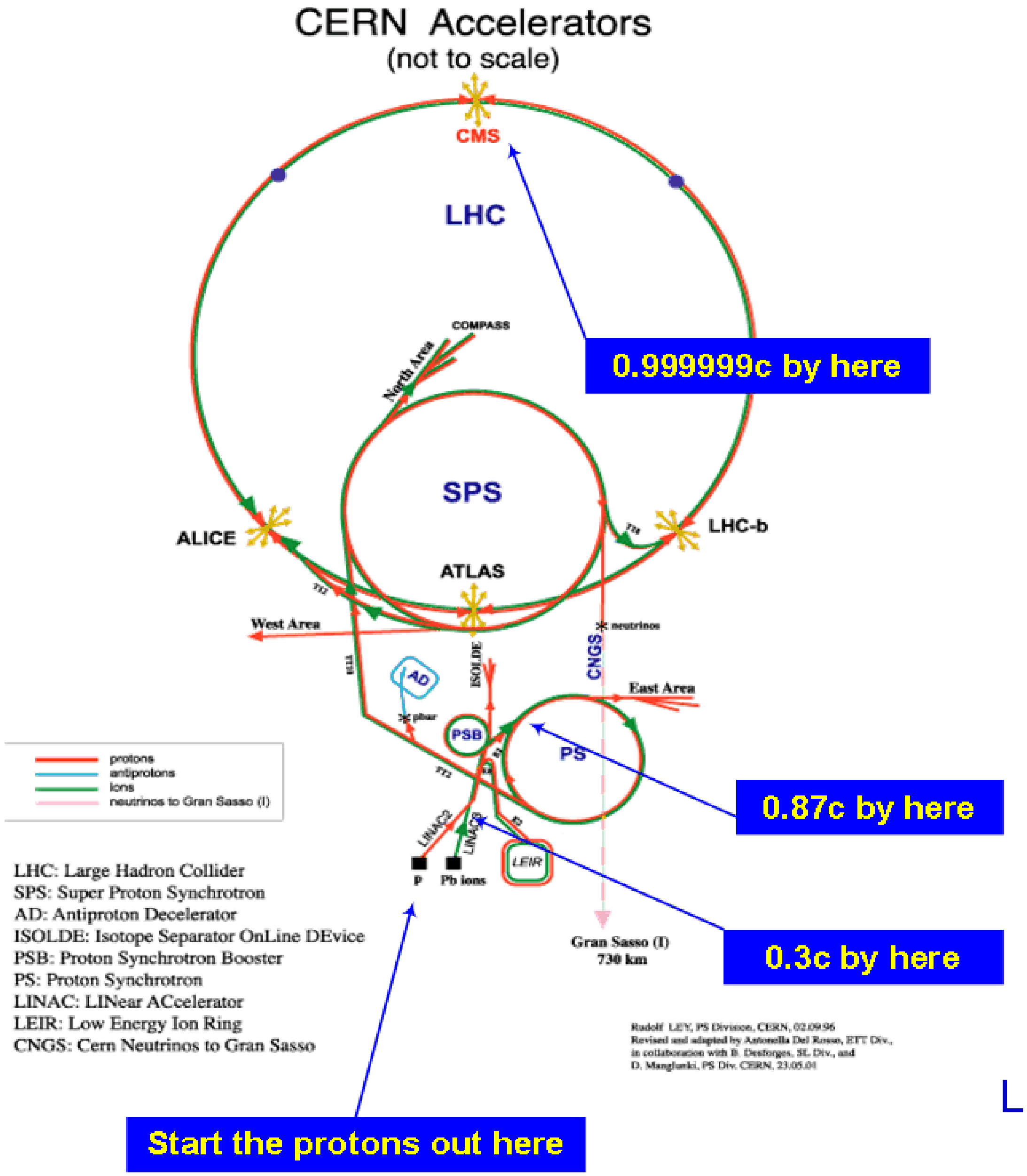
2005 : Start of LHC hardware commissioning

2008 : Start of (short) beam commissioning
Powering incident on 19th Sept.

2009 : Repair, re-commissioning and beam commissioning

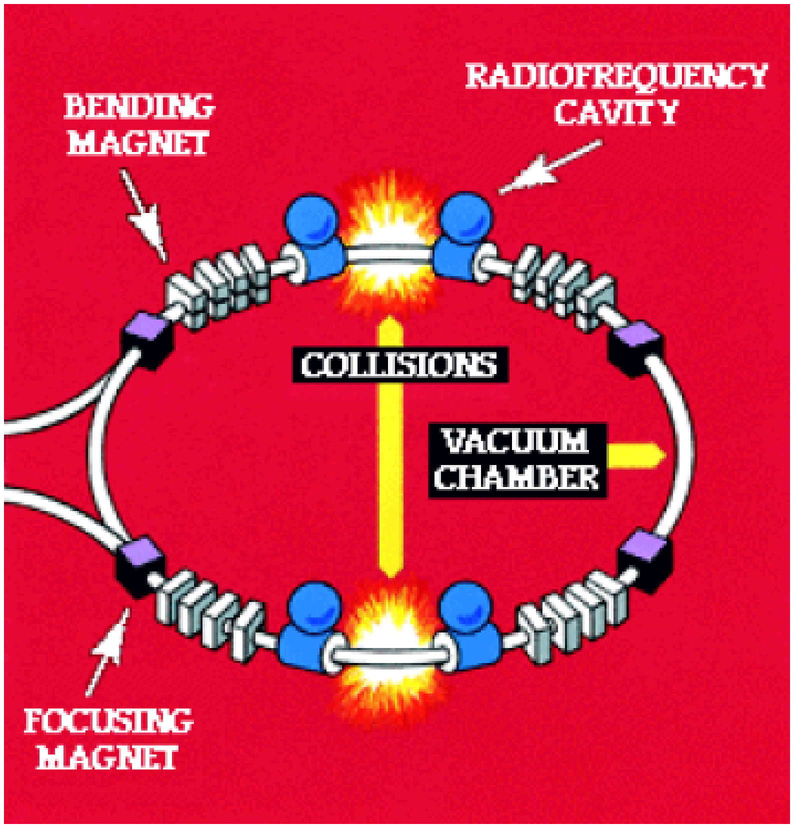
J. Wenninger

The new hadron Colliders: LHC



LHC animation

Electrons-Positrons Colliders



$\sqrt{s}$=200 MeV

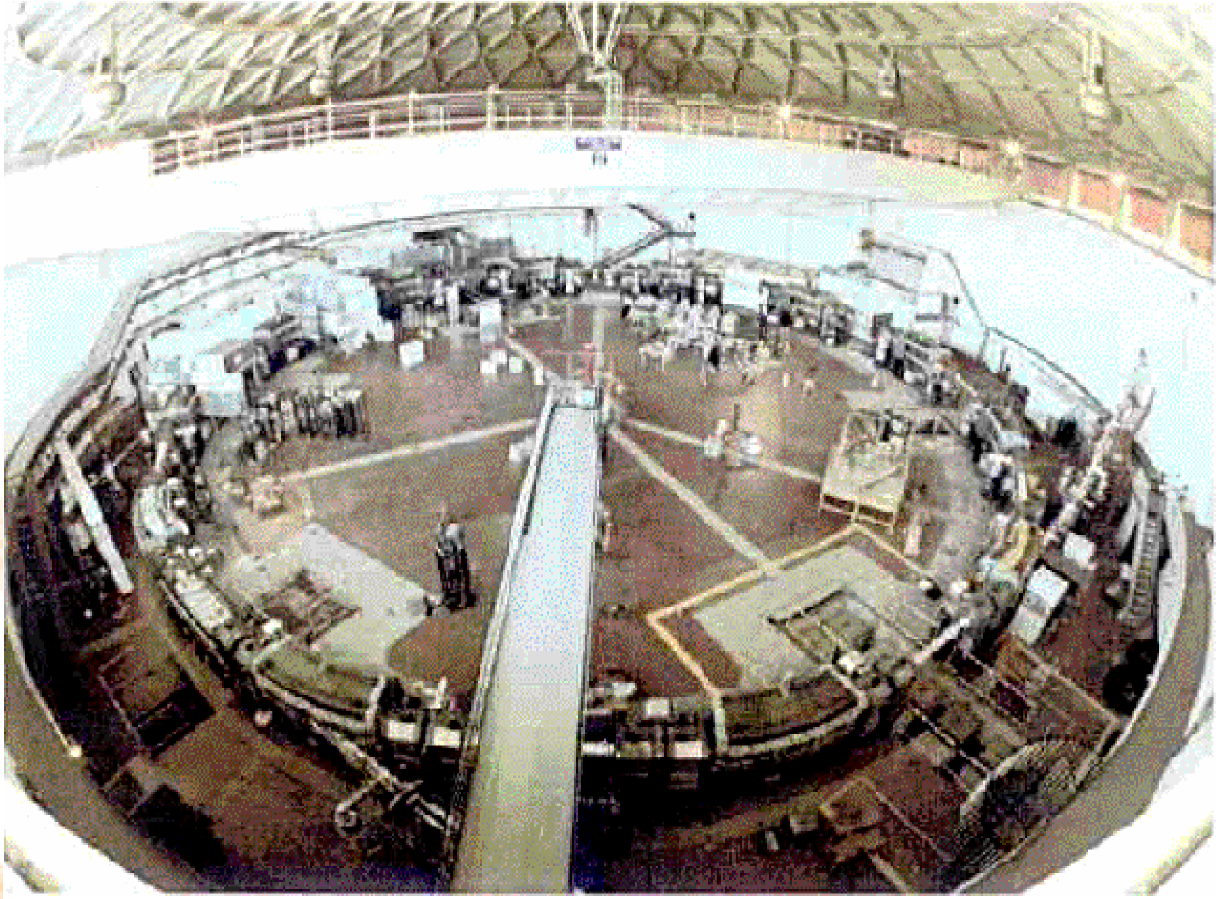
Problem: Synchrotron radiation.

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

1971 AdA (Anello Di Accumulazione) demonstrated that e+ e- can collide in the same tunnel

Electrons-Positrons Colliders

ADONE $\sqrt{s}$=3 GeV

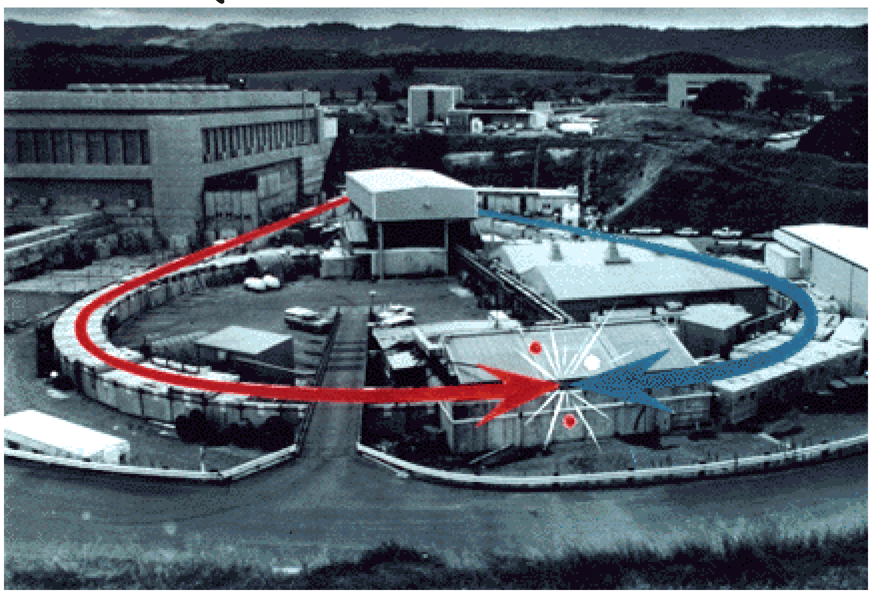


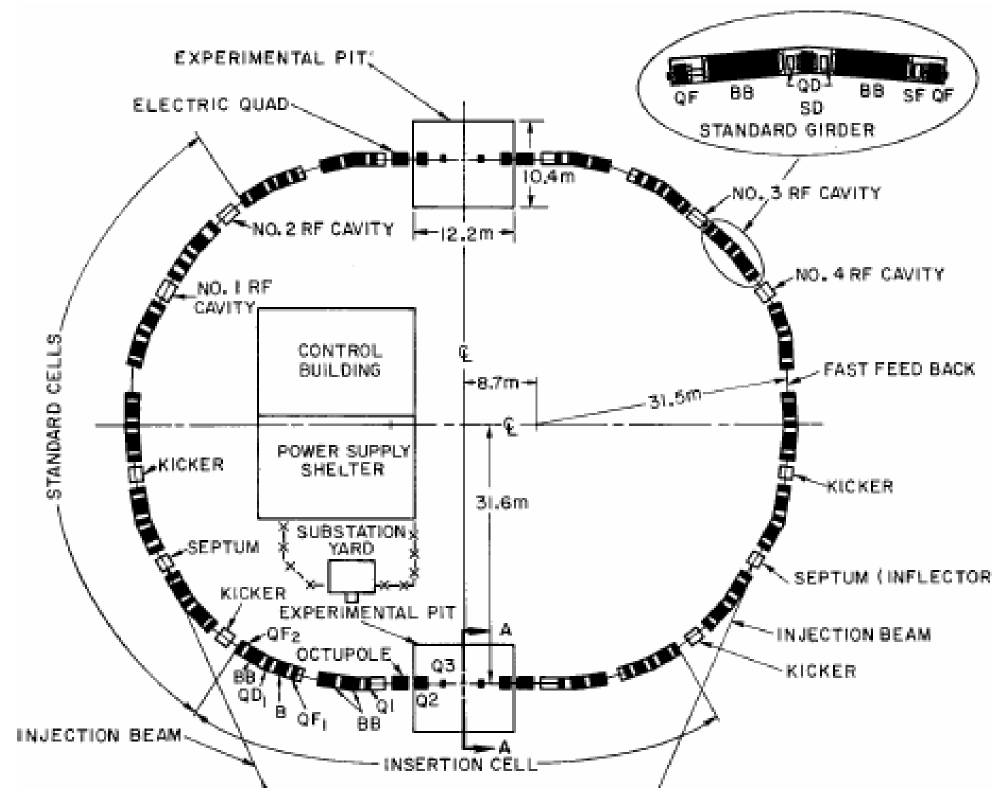
To avoid problems the machine ran at $\sqrt{s}$=2.8 GeV so the J/ψ ...

G. Bellettini

Electrons-Positrons Colliders

SPEAR (Stanford Positron Electron Accelerating Ring)





SPEAR radius 40 meters

Maximum $\sqrt{s}$=8 GeV

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SPEAR Results: Charm discovery(1974)

Only one experiment MARK1

BNL Muon production had an “anomaly”

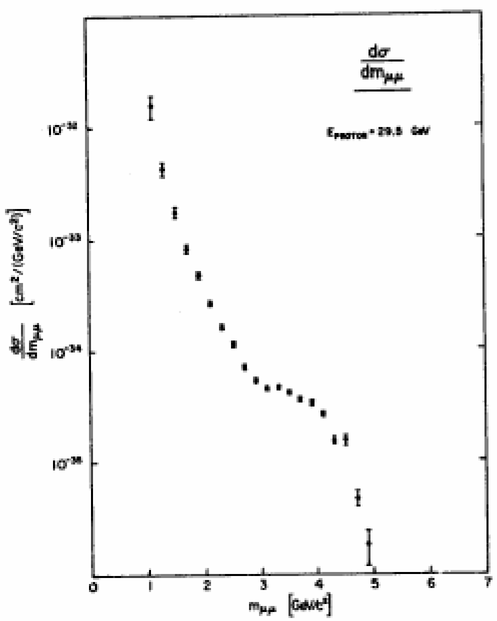


FIG. 6. $d\sigma/dm$. Proton energy = 29.5 GeV.

MARK1 Cross section scan as function of Ecm showed a huge peak: the J/ψ

EW LETTERS 2 DECEMBER 1974

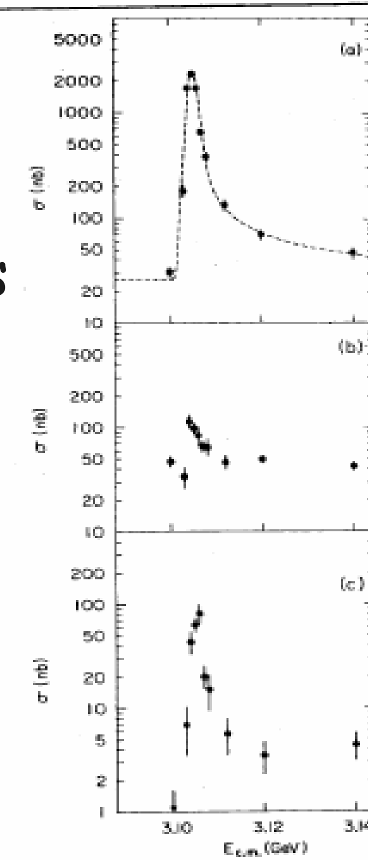
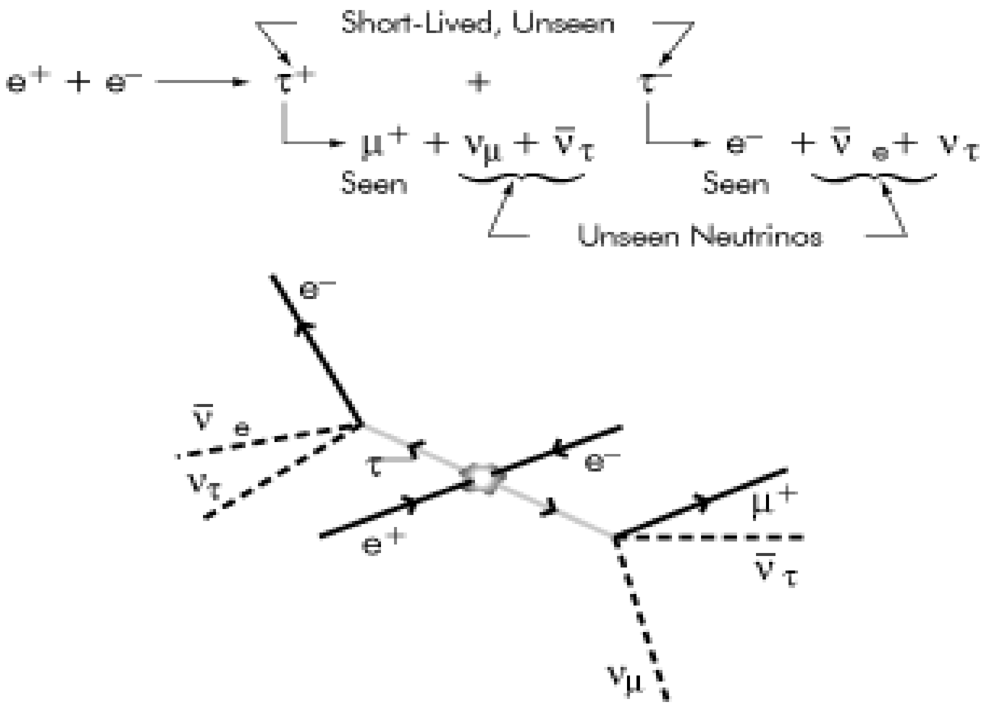


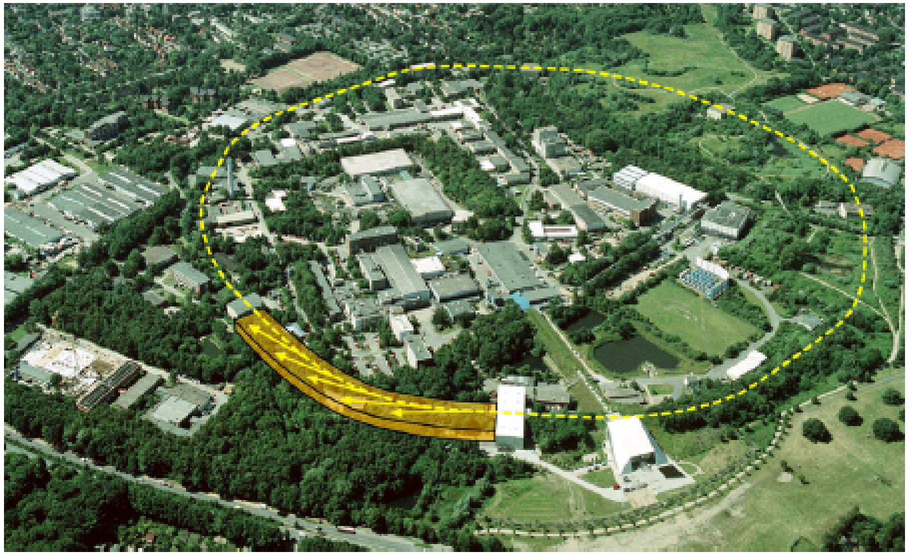
FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

G. Bellettini

SPEAR Results: Tau discovery(1975)

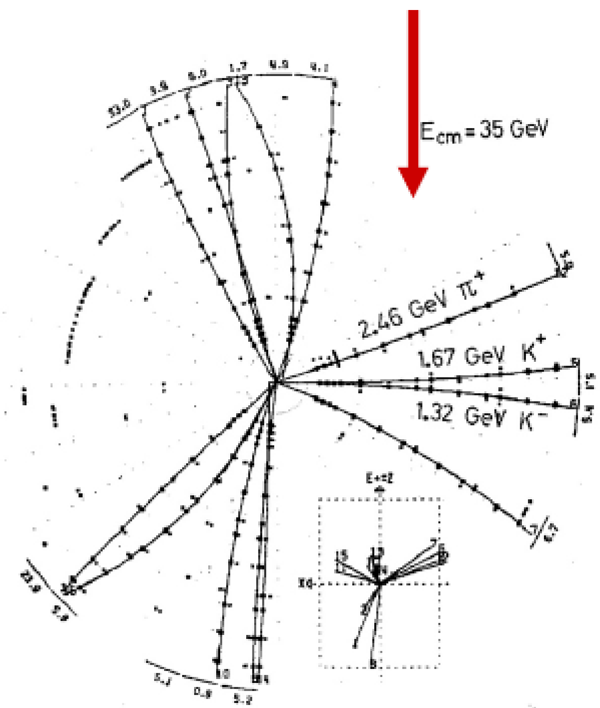


Petra (DESY)



$\sqrt{s}$=45 GeV
circumference 2.3km

PETRA Results: Gluon discovery



First observation of events $e^+e^- \to q\bar{q}g$. Events with three jets in the final state.

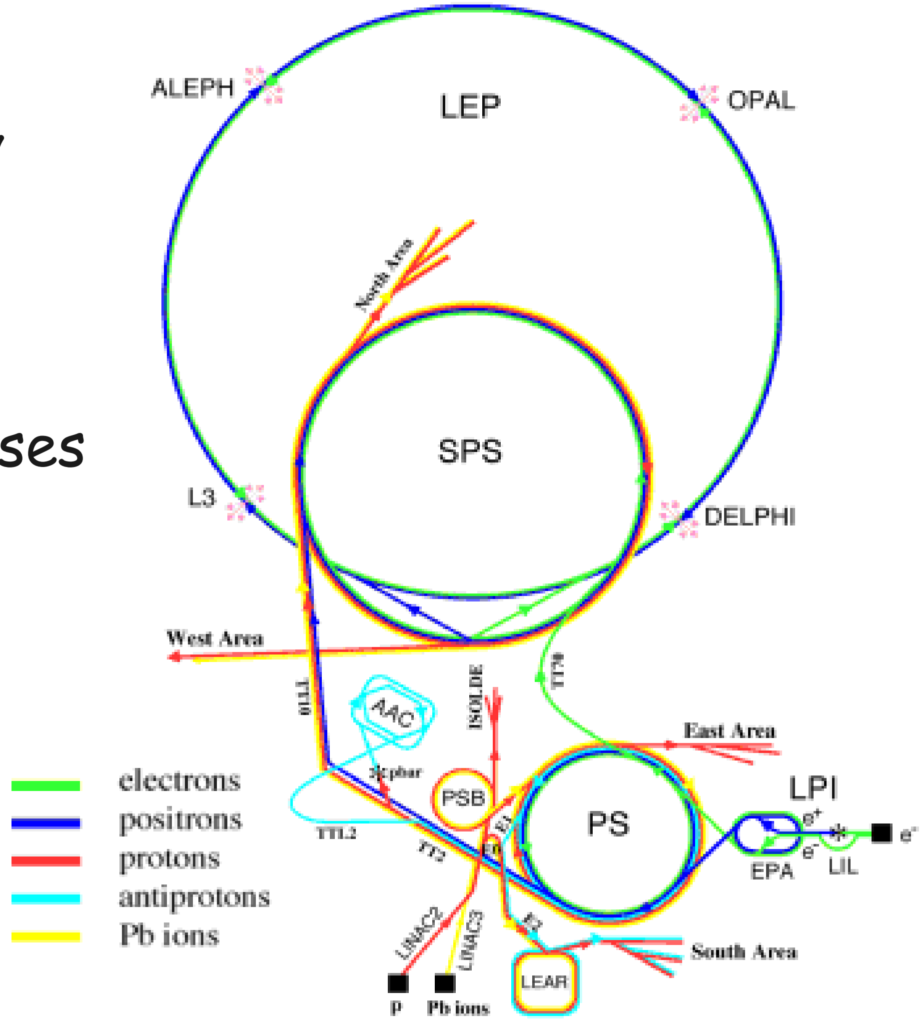
G. Bellettini

Electrons-Positrons Colliders

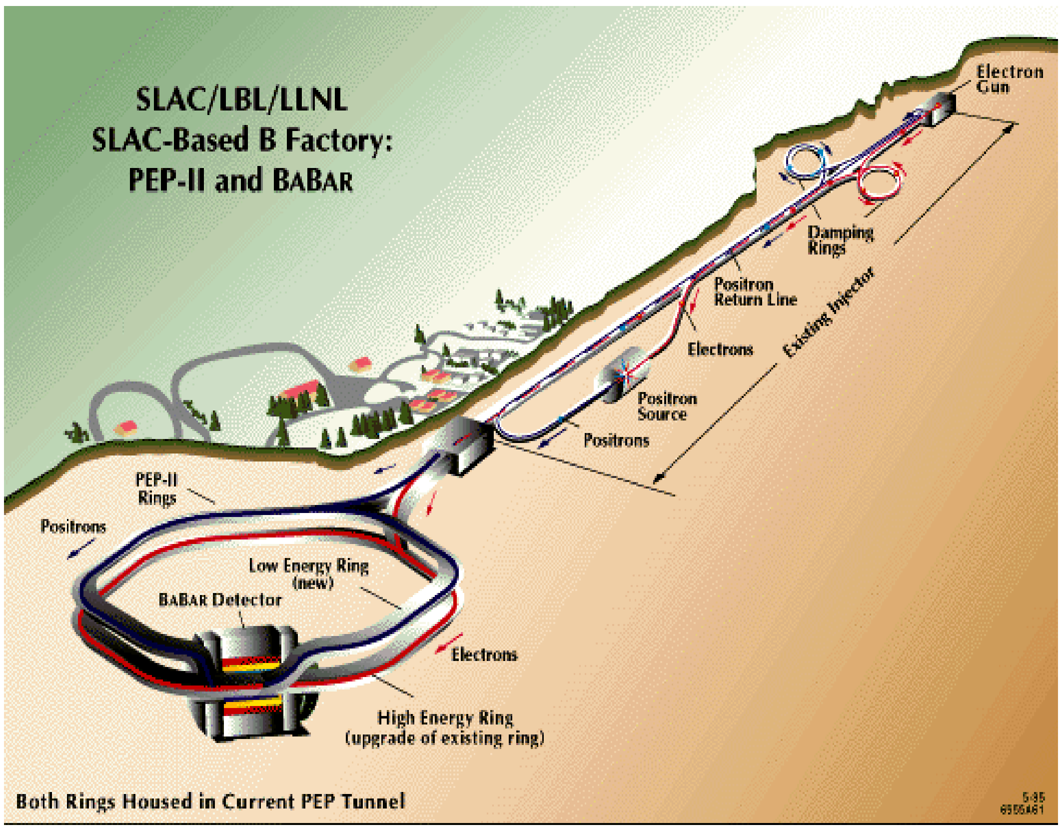
LEP: where the Standard Model was deeply verified.

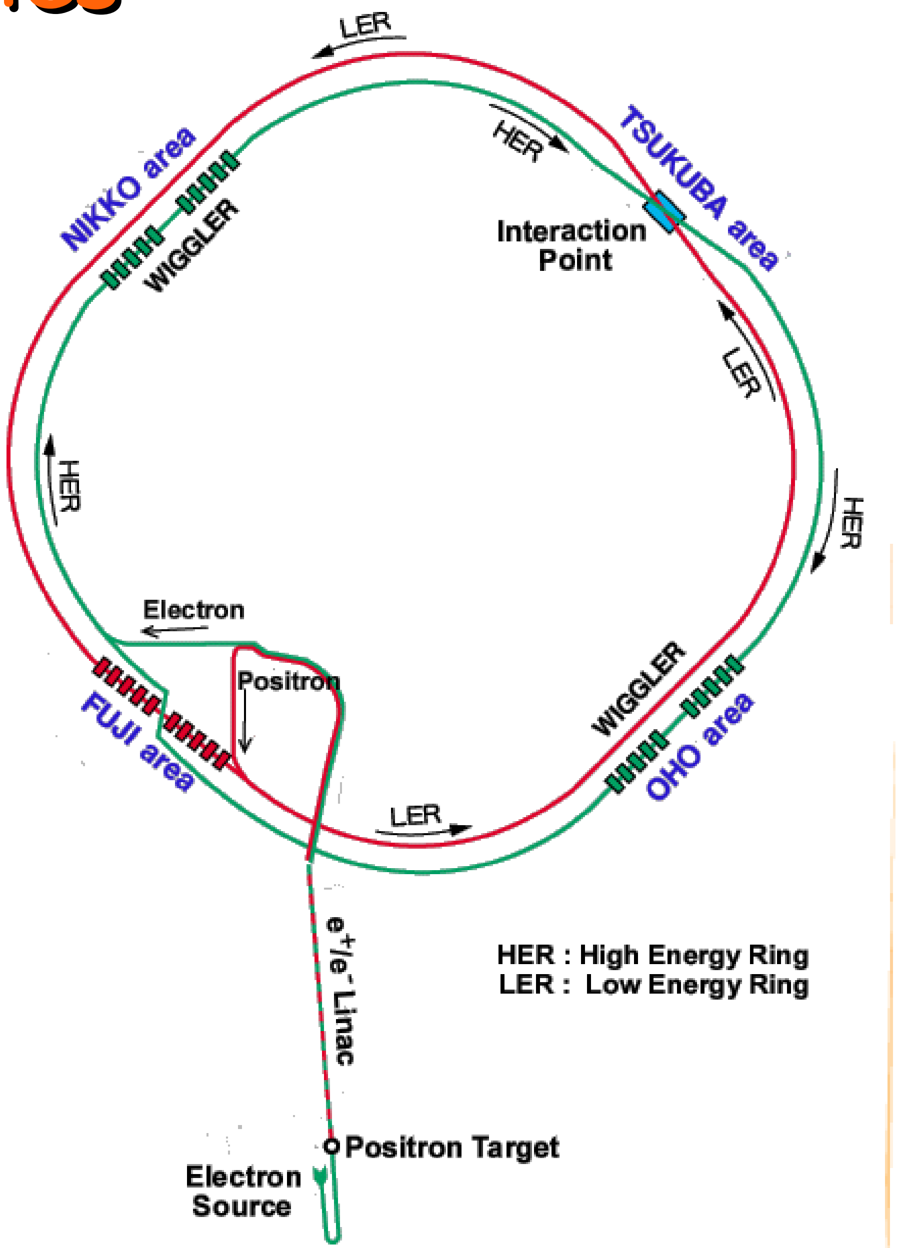
It ran at several $\sqrt{s}$ up to 205 GeV

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



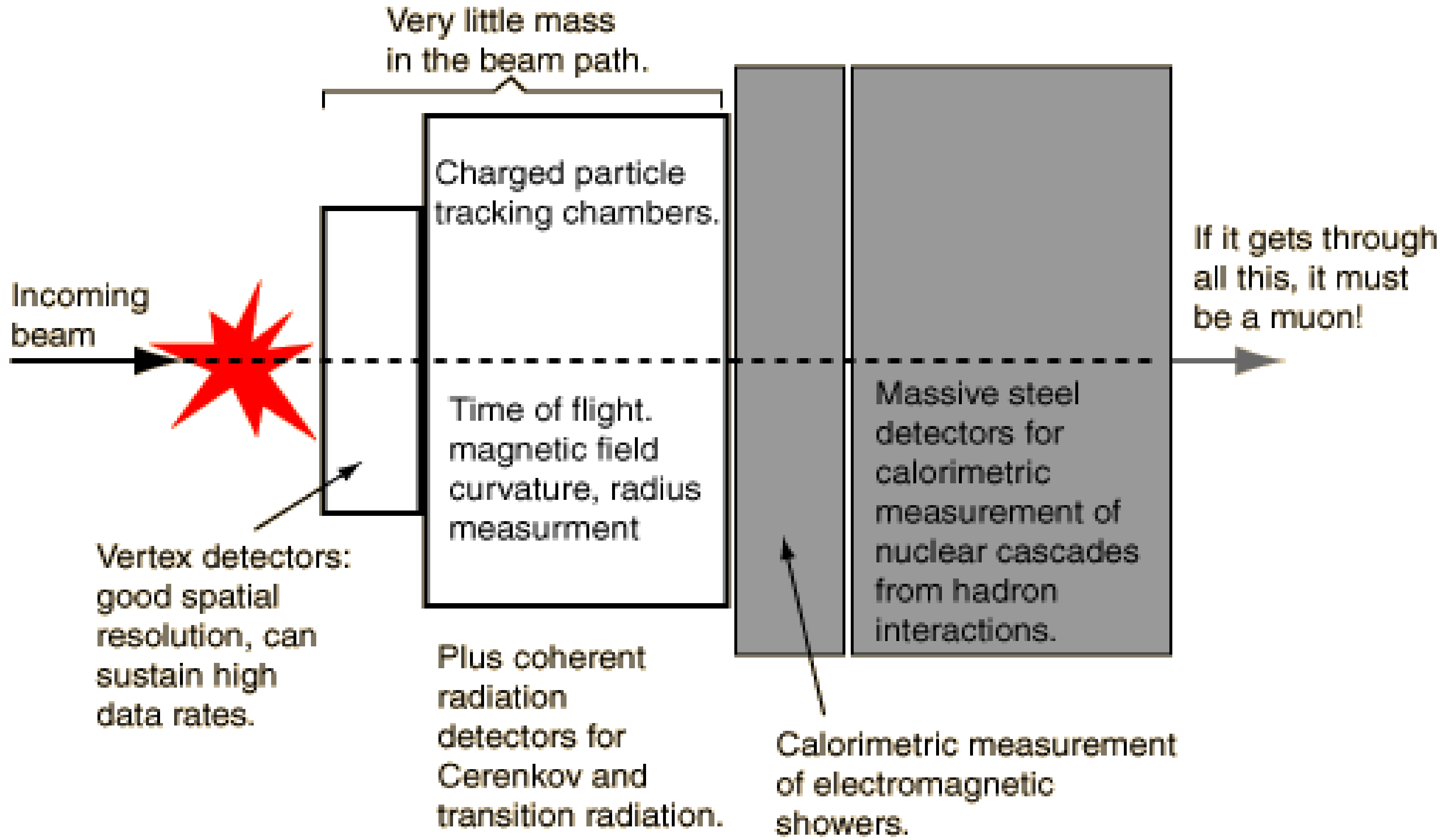
B-Factories


SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BABAR
Electron Gun
Damping Rings
Positron Return Line
Existing Injector
Electrons
Positron Source
Positrons
PEP-II Rings
Positrons
Low Energy Ring (new)
BABAR Detector
Electrons
High Energy Ring (upgrade of existing ring)
Both Rings Housed in Current PEP Tunnel

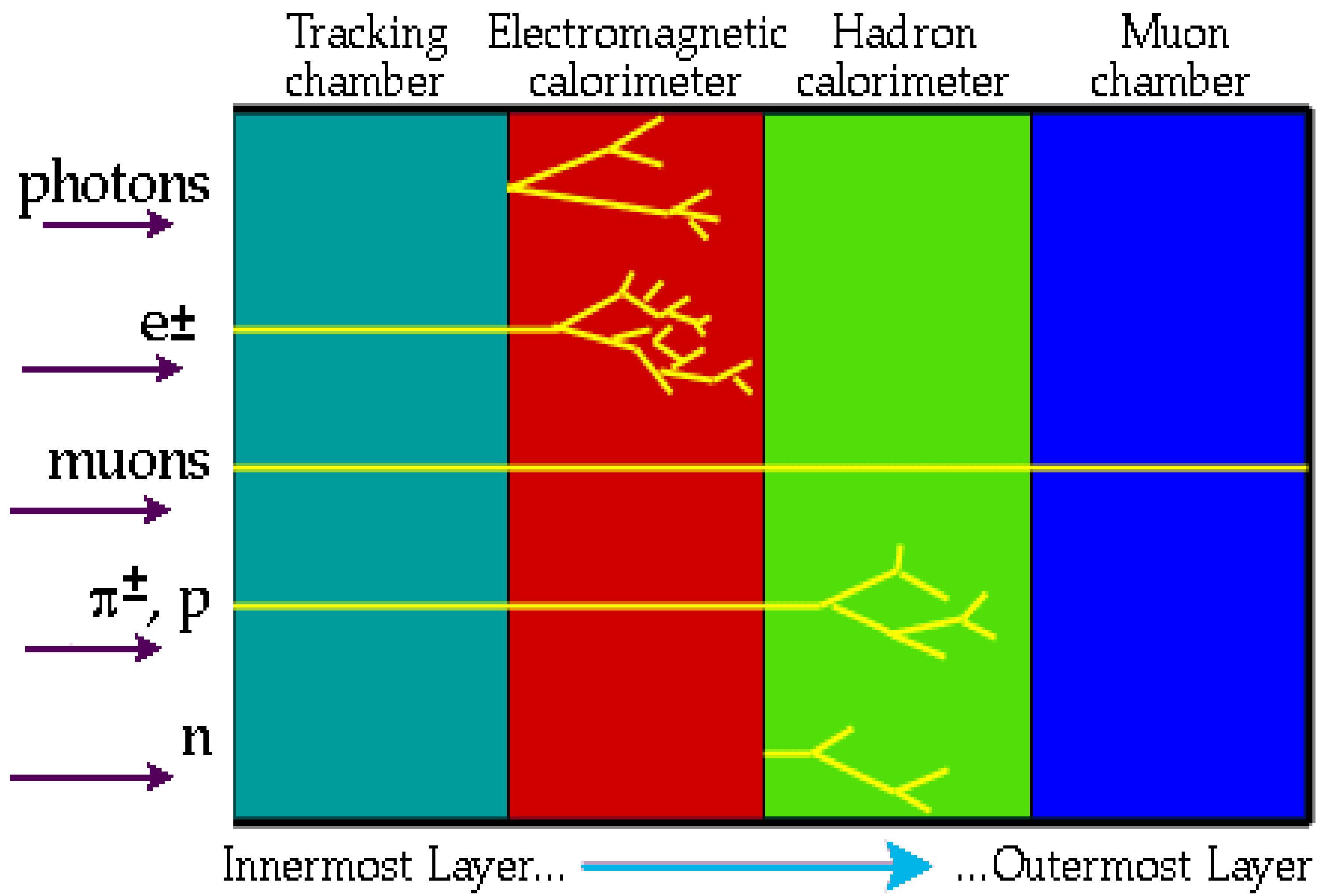

LER
HER
TSUKUBA area
Interaction Point
NIKKO area
WIGGLER
LER
HER
HER
Electron
Positron
FUJI area
LER
WIGGLER
OHO area
e+/e- Linac
Positron Target
Electron Source
HER : High Energy Ring
LER : Low Energy Ring

Detectors: Fundamental Principles

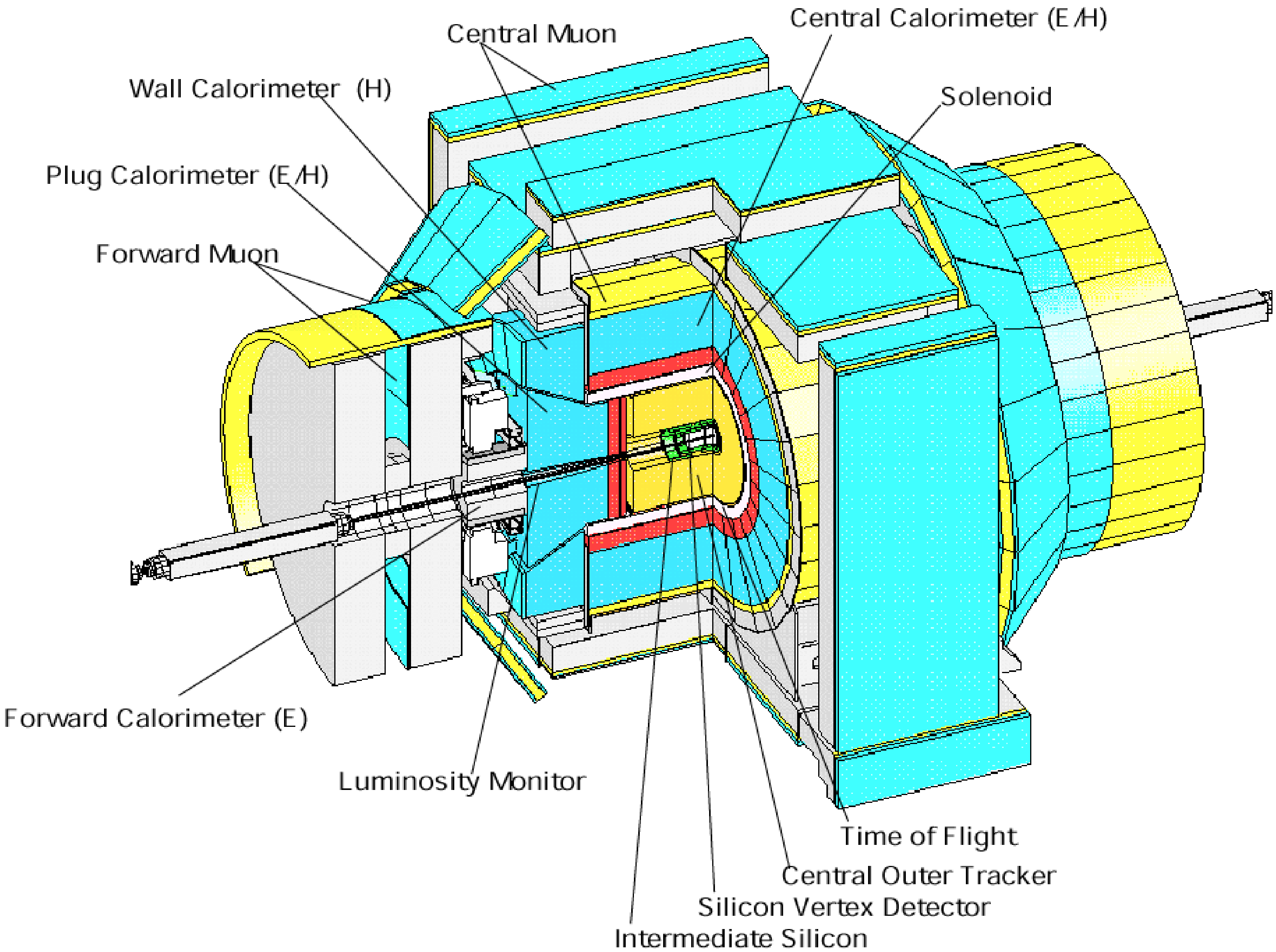
Detectors used at accelerator are complex devices.



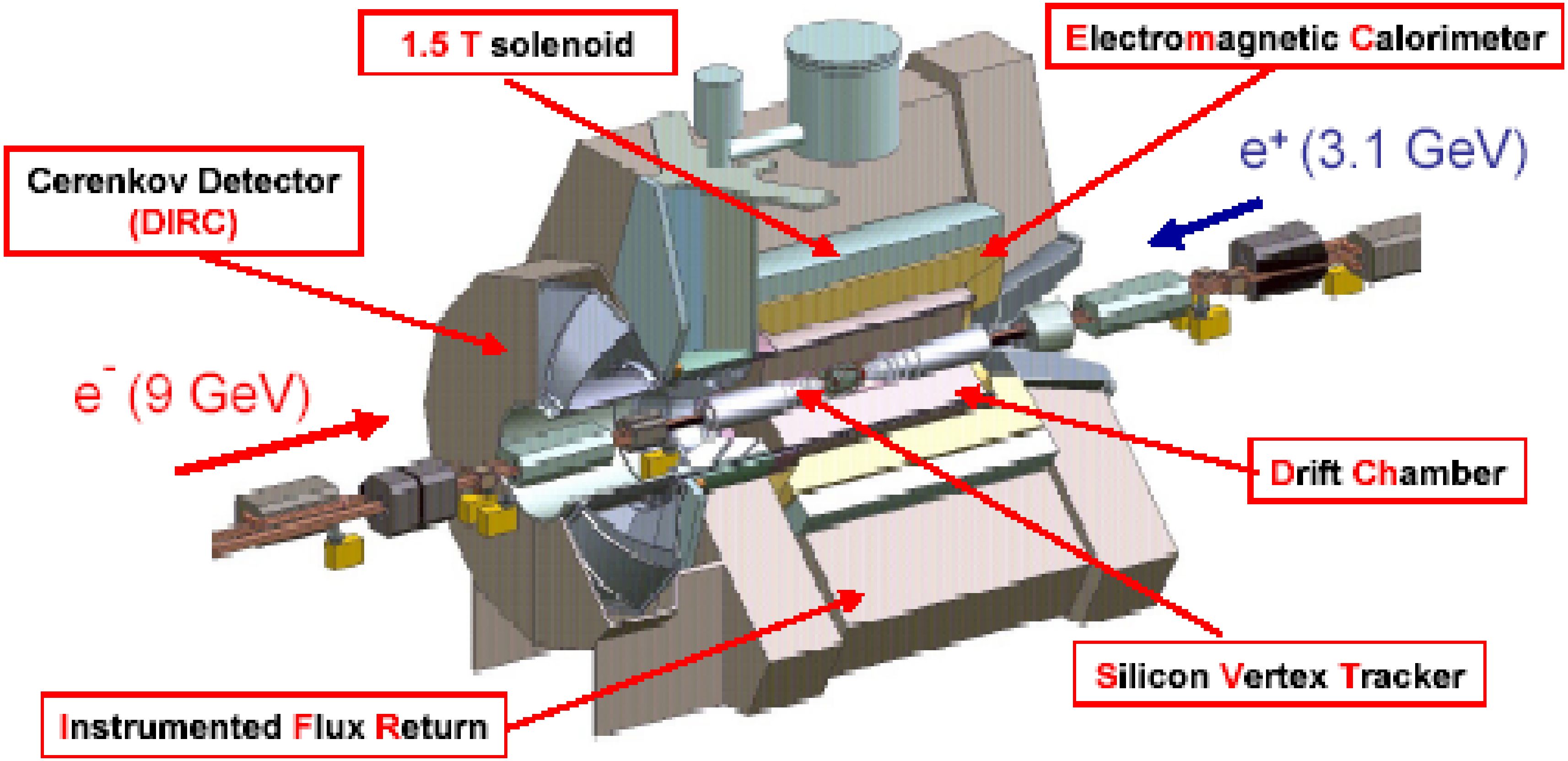
Detector for each particles



An example: CDF detector



An example: Babar



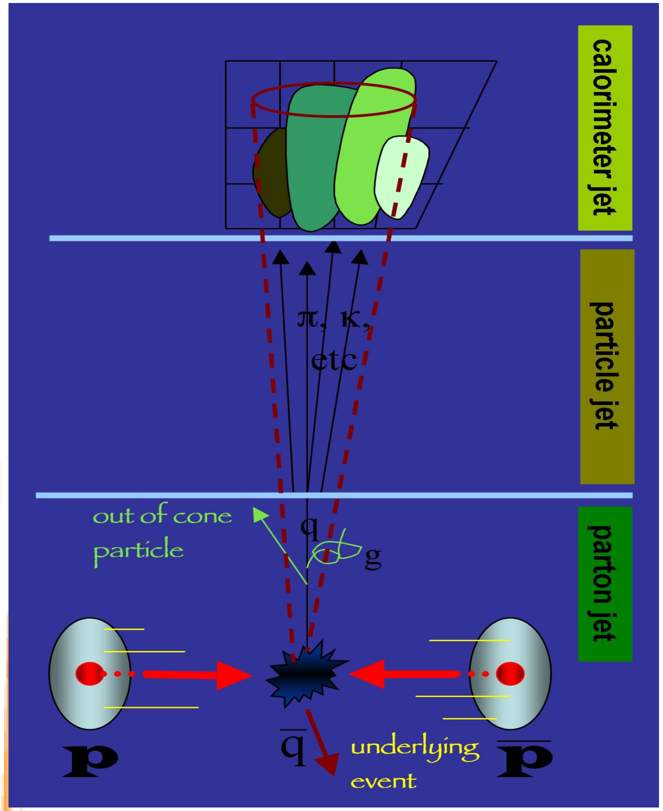
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

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

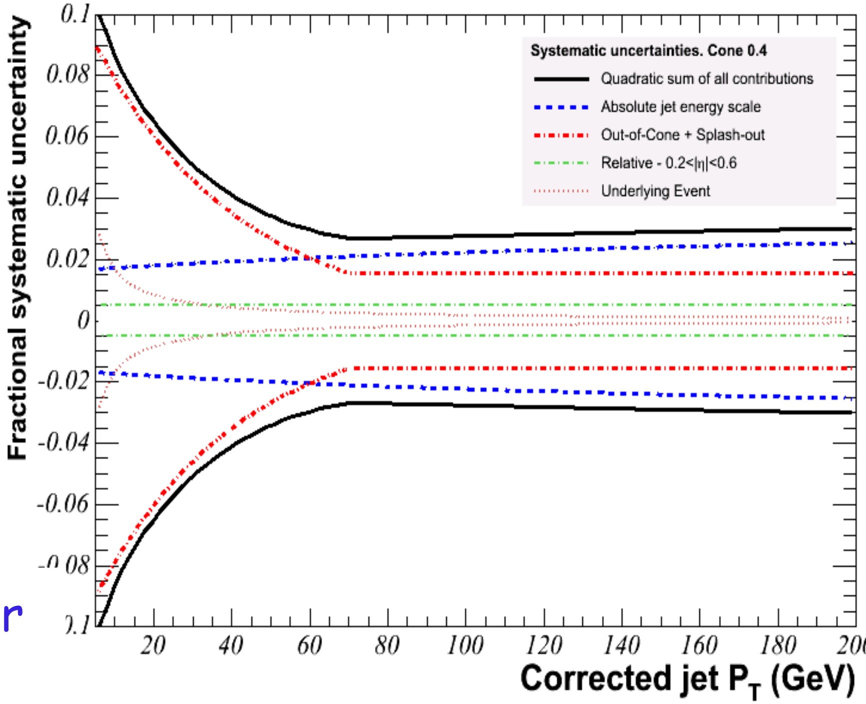
EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

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



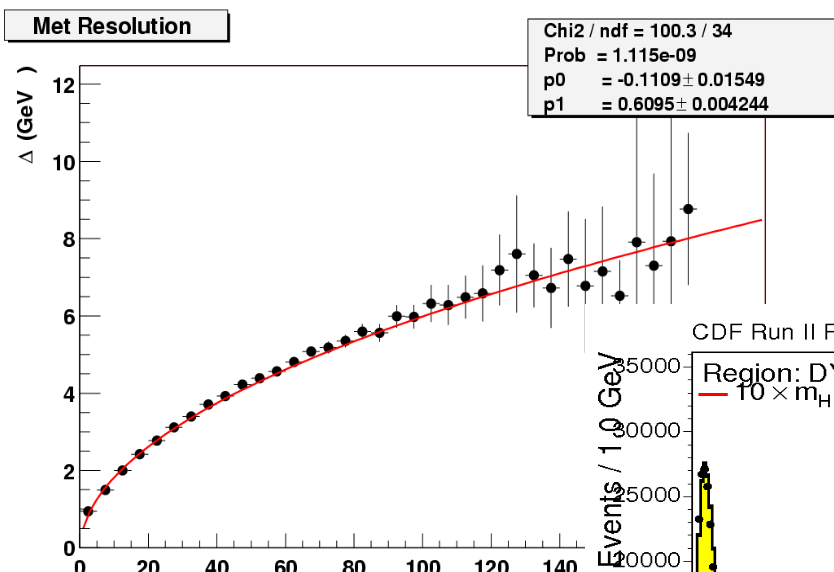
Low Pt: Dominated by MC/data uncertainties

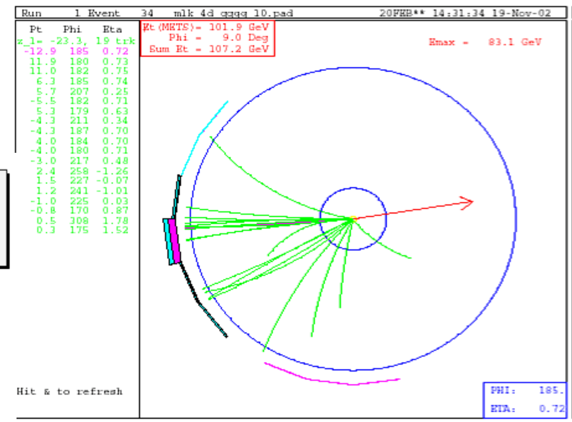
High Pt: Dominated by calorimeter simulation uncertainties

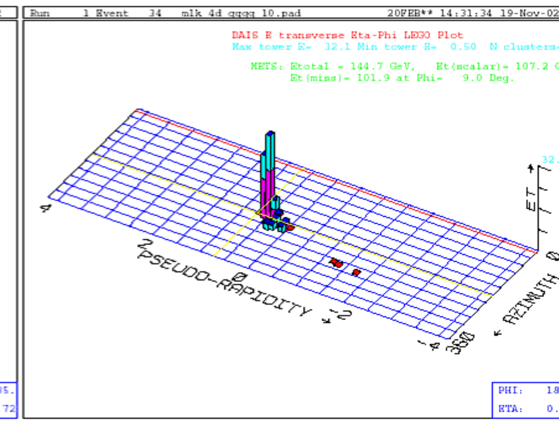
Neutrino Identification

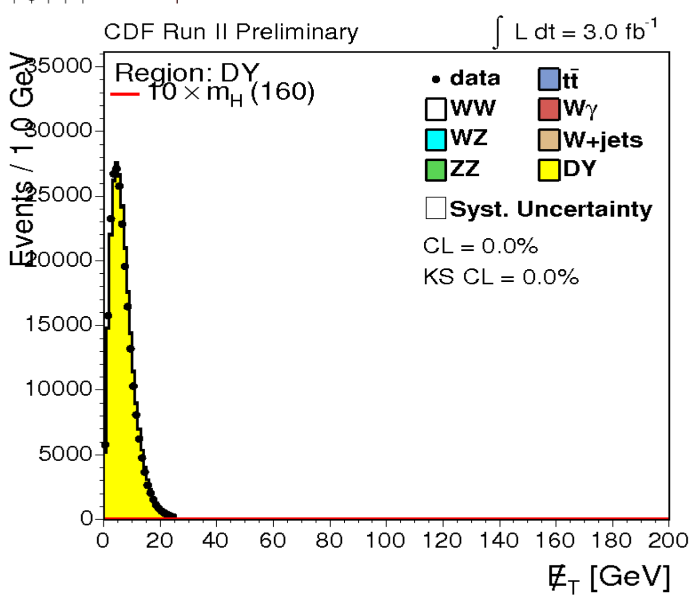
Not enough material in collider detectors to have neutrino interactions.
Neutrinos are identified via the transverse missing energy:

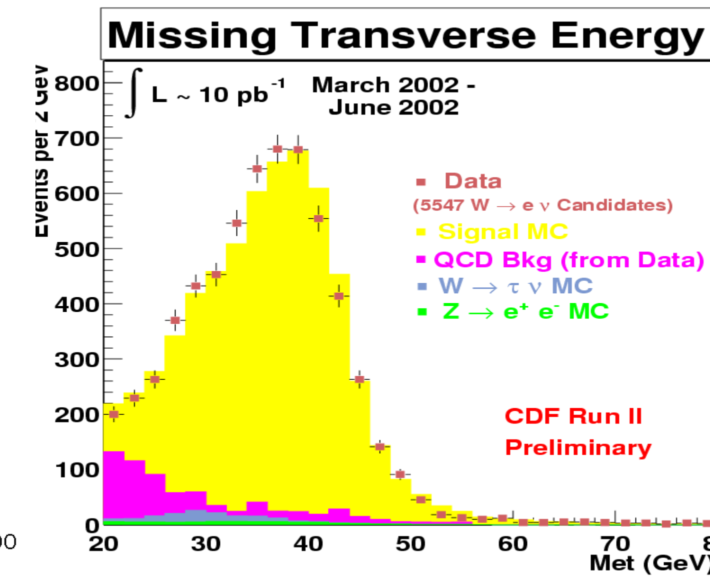
$$\vec{\not E}_t = \sum_{towers} E_i \sin(\theta_i)\,\hat{n}_i$$





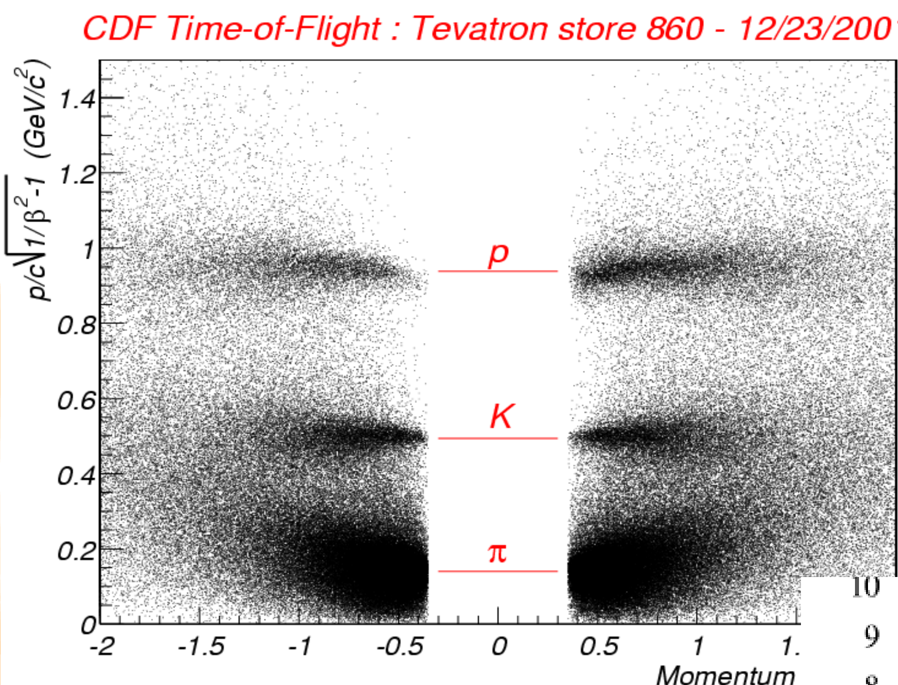




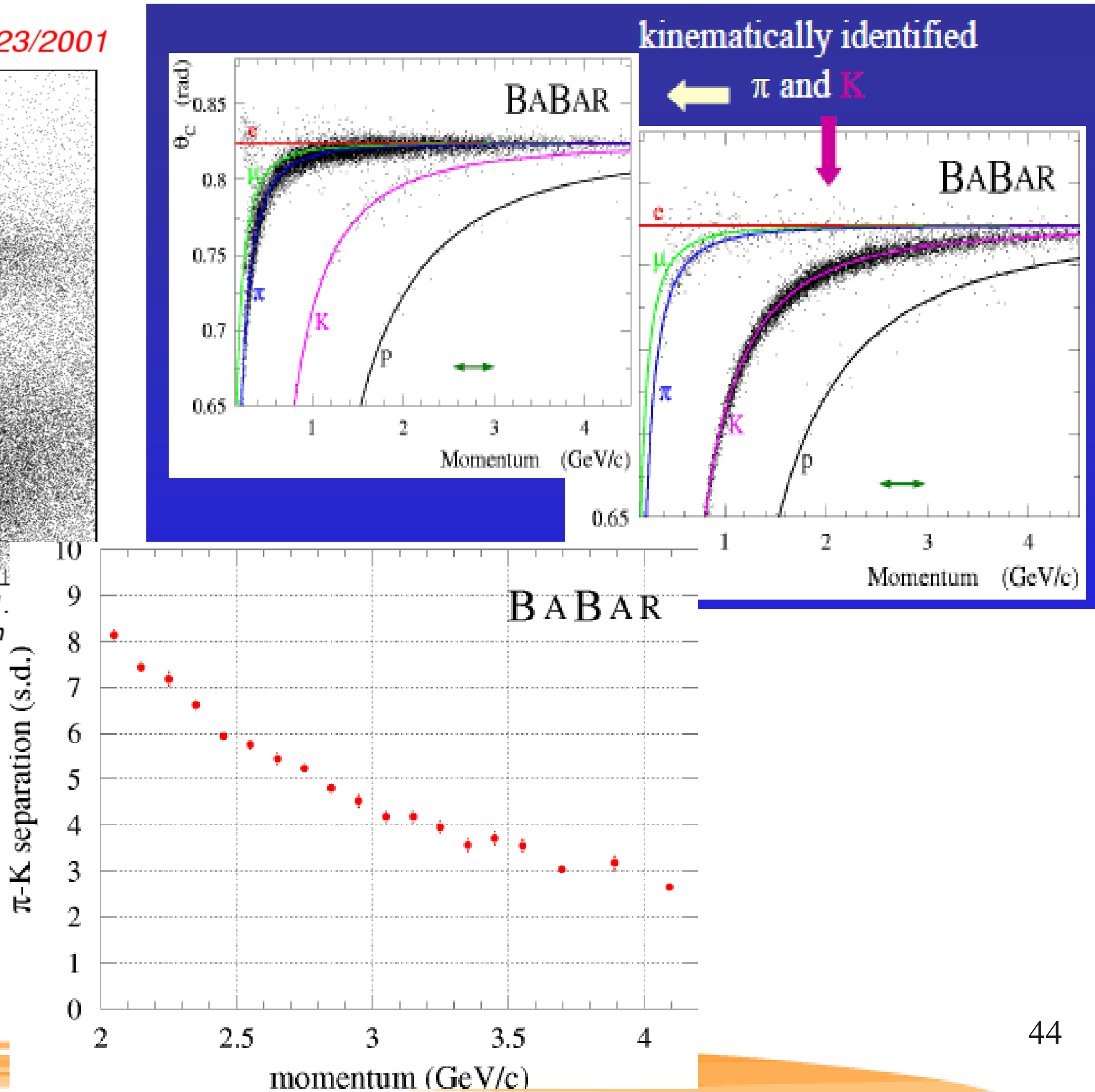


Particle Identification

TOF at CDF



DIRC at Babar



Hadron Collider: Trigger!

Trigger Overview

Raw Data — Crossing rate:1.7 MHz, Inelastic Cross Section: 56mb

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L1 Trigger — Acc. Rate 40 KHz (400 mb), Latency 5.5 μs, Pipeline: 42 clock cycles

↓

L2 Trigger — Acc. Rate 300 Hz (3 mb), Latency 20 μs, Buffer: 4 events

↓

L3 Trigger — L3 Acceptance Rate 75 Hz (750 nb)

↓

Data Set — Average size 60 Kbytes/event

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!