A brief history of accelerators, detectors and experiments: (See Chapter 14 and Appendix H in Rolnick.)

First came the study of the debris from cosmic rays (the God-given particle beam) –

1930’s –

1933 - discovered the positron, confirming the existence of anti-particles

1937 - discovered muon, created confusion because Yukawa had “explained” the nuclear interaction in terms of a strongly interaction particle with mass ~ 100 MeV – right mass, wrong interactions

1940’s –

1943 - discovered the kaon but its role was not understood at the time (we will come back to this)

1947 – discovered the pion finally proving that Yukawa was right

The next step came from understanding how to employ magnetic fields to keep charged particles in a circular orbit while you accelerate them with electric fields. This led to the first accelerators, which used magnetic fields \( (B) \) of fixed magnitude and accelerated charged particles traveling in varying orbits (or radius \( (R) \)) as the energy increased – cyclotrons

\[
p(\text{GeV}/c) = 0.3B(T)R(\text{m}). \tag{7.1}
\]

1950’s -

1952 – the cyclotron at the University of Chicago found the \( \Delta \) (an excited proton) as a direct channel resonance

1955 – the Bevatron at Berkeley (LBL) produced and identified the anti-proton
1960’s – saw the advent of the synchrotron – an accelerator with varying B-field and fixed radius (much easier to build and maintain the vacuum system – now a beam pipe rather than a large chamber the size of the magnet). These machines provided the first real proton beams at ~ 30 GeV that were applied to fixed targets:

1959 - PS (Proton Synchrotron) at CERN with $E_{\text{beam}} \sim 28$ GeV

1961 - AGS (Alternating Gradient Synchrotron) at the Brookhaven National Laboratory (BNL) p’s with $E_{\text{beam}} \sim 33$ GeV

1964 – DESY (in Germany) e’s with $E_{\text{beam}} \sim 7$ GeV

1966 – SLAC (linear accelerator) e’s with $E_{\text{beam}} \sim 22$ GeV

1967 – Cornell e’s with $E_{\text{beam}} \sim 12$ GeV

1967 – Serpukhov (in Russia) p’s with $E_{\text{beam}} \sim 76$ GeV

1970’s – increasing energy on fixed targets (instantaneous luminosity ~ $10^{37}$/cm$^2$/s)

1972 – Tevatron at Fermilab (R ~ 1 km, B ~ 1.3 T) at E ~ 100 GeV (1972) to 500 GeV (1980)

1976 - SPS (Super Proton Synchrotron) at CERN p’s with $E_{\text{beam}} \sim 500$ GeV

1977 - KEK (in Japan) p’s with $E_{\text{beam}} \sim 12$ GeV

1980’s

Fermilab – TeV I with $E_{\text{beam}} \sim 900$ GeV (B ~ 3 T) on fixed targets and secondary beams

Plus the parallel program with colliding beams

1970’s – $e^+e^-$ colliders (luminosity ~ $10^{31} – 10^{32}$ /cm$^2$/s)

SPEAR at SLAC with 4.2 GeV on 4.2 GeV found J/$\psi$ (also seen at BNL)
PEP at SLAC (Stanford) with 15 GeV on 15 GeV
DORIS at DESY with 5.6 GeV on 5.6 GeV
PETRA at DESY with 23 GeV on 23 GeV
  - pp colliders
ISR at CERN with 30 GeV on 30 GeV

1980’s - $e^+e^-$ colliders

CESR at Cornell with 6.5 GeV on 6.5 GeV
TRISTAN at KEK with 30 GeV on 30 GeV
SLC at SLAC with 50 GeV on 50 GeV to produce the $Z$ as s-channel resonance ($\sim 10^{30}/\text{cm}^2/\text{s}$), linear collider
LEP I at CERN with 60 GeV on 60 GeV to produce the $Z$
BEPC in China with 2.8 GeV on 2.8 GeV
  - $p\bar{p}$ colliders
S $p\bar{p}$ S at CERN with 270 GeV on 270 GeV up to 450 GeV on 450 GeV – confirmed the $W$ and $Z$ particles (before the electron machines)
Tevatron I at Fermilab with 900 GeV on 900 GeV

1990’s - $e^+e^-$ colliders

LEP II at CERN with 80 GeV on 80 GeV to see $W^+W^-$ production up to 104 GeV on 104 GeV, perhaps to seeing the Higgs boson
B factories at SLAC (BaBar) and KeK
DAΦNE in Italy with 0.5 GeV on 0.5 GeV (strangeness factory)
- e^+(e^-)p collider

HERA at DESY with 30 GeV e on 920 GeV p

- p\bar{p} collider

TeV I at Fermilab (1, 2) continued with luminosity \( \sim 10^{32} \text{ /cm}^2\text{/s} \)

2000’s - p\bar{p} collider

TeV II at Fermilab (spring 2001) with 0.98 TeV on 0.98 TeV and luminosity \( \sim 10^{33} \text{ /cm}^2\text{/s} \), B \sim 4 \text{T}

- pp collider

LHC at CERN (~ 2010) with 3.5 TeV on 3.5 TeV and luminosity \( \sim 10^{34} \text{ /cm}^2\text{/s} \) (with \( \sigma_{\text{TOT}} \sim 100 \text{ mb} \sim 10^{-25} \text{ cm}^2 \) this means \( 10^9 \) interactions/s and many overlapping events)

During the 1970’s through today both CERN and Fermilab (and to a lesser extent SLAC and KEK) had various programs using the primary proton beams on targets to make secondary beams to perform fixed target physics with anti-proton, \( \mu \), \( \nu \), \( \pi \), K, \( \gamma \) and \( \Lambda \) beams.

The first detectors were the photographic emulsions used in the cosmic ray experiments. This technology, coupled with other tracking techniques is still in use today, e.g., in the confirmation of the tau-neutrino in the DONUT experiment. As charged particles move through the material they interact and deposit energy, i.e., ionize or “expose” the film. After developing the film information can be obtained on

- E from the track length
- \( v \) from the density of developed grains
- p from the amount of multiple scattering.

The velocity measure stems from the specific form of the dE/dx losses due to EM interactions in the emulsion (see Jackson’s book and the PDG review). Generically we have
\[
\frac{dE}{dx} \propto \frac{\ln(\gamma v)}{v^2}
\]  
(7.2)

for the energy loss by a charged particle in matter. This expression exhibits a minimum near \(\ln(\gamma v) \sim 3\) where, in a material with density \(\rho\), the value of the energy loss at the minimum is about (g = gram)

\[
\left. \frac{dE}{dx} \right|_{\text{min}} \sim 1.5 \text{ MeV cm}^2 / \text{g} \times \rho.
\]  
(7.3)

The first real detectors used magnetic fields to bend the path of charged particles allowing the measurement the momentum, and some way to render the track of the particle visible. These included

- cloud chambers
- bubble chambers
- streamer chambers
- drift chambers
- scintillation chambers

and all depended on the interaction of electrically charged particles with matter. The information on the momentum was supplemented with information on the velocity and/or the mass by

- time of flight measurements
- \(\frac{dE}{dx}\) measurements
- Čerenkov light (different index of refraction giving \(\beta > 1\) for chosen range of \(v\)).

Little information was available for neutral particles unless they decay into charged particles.

Modern detectors at the colliders are very elaborate (and large) and cover nearly \(4\pi\) with just tiny openings at the ends to admit the two colliding beams. Two well know examples are CDF and DØ at Fermilab and ATLAS and CMS at CERN. These detectors have a component to detect nearly everything except neutrinos and those they “detect” neutrinos via energy/momentum conservation (the detectors are nearly “hermetic”).
Very close to the beam (~ cm’s) they have tracking, typically with (radiation hard) silicon strips to identify particles that decay on that distance scale (1 cm/c ~ 10^{-10} s, typical weak decays).

Further from the collision region (~ m) there is more tracking with a magnetic field to measure momenta of charged particles.

Next (~ few m) come the calorimeters (both hadronic and EM) that measure energy (via energy deposition) of particles like neutrons and photons.

On the outer boundary (~ 10 m) are muon detectors (in first approximation a muon is a charged particle that penetrates all the matter inside of the detector, i.e., a muon is relatively heavy and has no strong interactions).

These 4π detectors are the natural result of the corresponding evolution of the way we look at particle interactions. In first approximation we can think of this as evolving from low to high energies (the original cosmic ray studies are the exception). First came elastic and quasi-elastic, 2 → 2 and 2 → 3, processes with baryon resonances and maybe 1 pion produced. The theoretical focus was on exclusive channels where everything was detected. Detector components were designed to detect 1 particle in a specific direction and there were typically 2 or 3 such components. With the advent of higher energies in the 1970’s final states started to include as many as 10 produced particles. Given the limited detectors it was natural to study (semi-) inclusive processes,

\[ p + \bar{p} \rightarrow \pi + X. \]  

(7.4)

The idea is that a single pion is detected and no constraint is placed on the rest of the final state, i.e., all possibilities for X are summed over. This can be thought as an analog of the totally inclusive cross section in the form

\[ p + \bar{p} \rightarrow X, \] 

(7.5)

where again we sum over all states X. (Perhaps, not surprisingly, there is an analog of the optical theorem that applies to the semi-inclusive cross section.) Clearly more detailed knowledge of the final state is important. Over the last 50 years the detectors have evolved as noted so that now they measure nearly all of the particles in the final state. However, the data still tend to be analyzed by constructing various semi-inclusive cross sections. Examples, are inclusive W, Z, μ⁺μ⁻ and jet production
\[ p + \bar{p} \rightarrow \begin{cases} W^\pm \\ Z^0 \\ \mu^+ \mu^- \\ \text{jet} \end{cases} + X. \]  \hspace{1cm} (7.6)

The lepton pair process is called the Drell-Yan process. A jet is a collimated spray of hadrons (plus leptons and photons) that arises from the “showering” of energetic quarks or gluons that were initially produced essentially by themselves in momentum space by some short distance (large momentum transfer) process. Superimposed on the “hard” production processes listed above, which are well described in terms of quarks and gluons, is an underlying event created by the “soft” interactions of the remaining components of the colliding hadrons (the “spectators”). The underlying event is observed to be very similar (but not identical) to what is called a “minimum bias” event, a hadron collision where nothing very exciting happens and the produced hadrons (largely pions) are fairly uniformly distributed in the angular space \((\eta, \phi)\) and sharply cutoff in transverse momentum \((P_T < 500 \text{ MeV})\). As noted earlier, the processes listed above, which can be successfully calculated in the perturbative regime of the Standard Model, constitute only a small fraction of the total \(p\bar{p}\) cross section. Here is a representation of a very high ET (“transverse energy”) event seen at DØ and here is a “physics” view. Note the middle region of the detector within the blue representing the calorimeter and then all the “boxes” outside of the detector representing the amount of energy deposition in the calorimeters. Here is a DØ top quark event with 4 jets and 2 muons, one of which is coincident with a jet. The particle identification is indicated in this view. Finally consider a DØ event with 2 jets and a Z boson that decays into electron-positron pair – detector view, “lego” view.

At \(e^+e^-\) colliders the initial state, and thus the final state, is much simpler. As a result the total cross section is well understood in terms of the EM couplings of the \(e^+e^-\) initial state to a photon and that photon to all charged matter fields (the quarks and the leptons). Even though the hadronic final states at \(e^+e^-\) colliders do contain low energy pions, the analysis still tends to be performed in terms of exclusive process, e.g.,

\[ e^+e^- \rightarrow \text{4 jets}. \]  \hspace{1cm} (7.7)

Here is information from ALEPH at CERN about events that might have contained Higgs bosons (but apparently did not). Note the drawing of the detector. Detectors at \(e^+e^-\) colliders are very similar to those at proton machines.