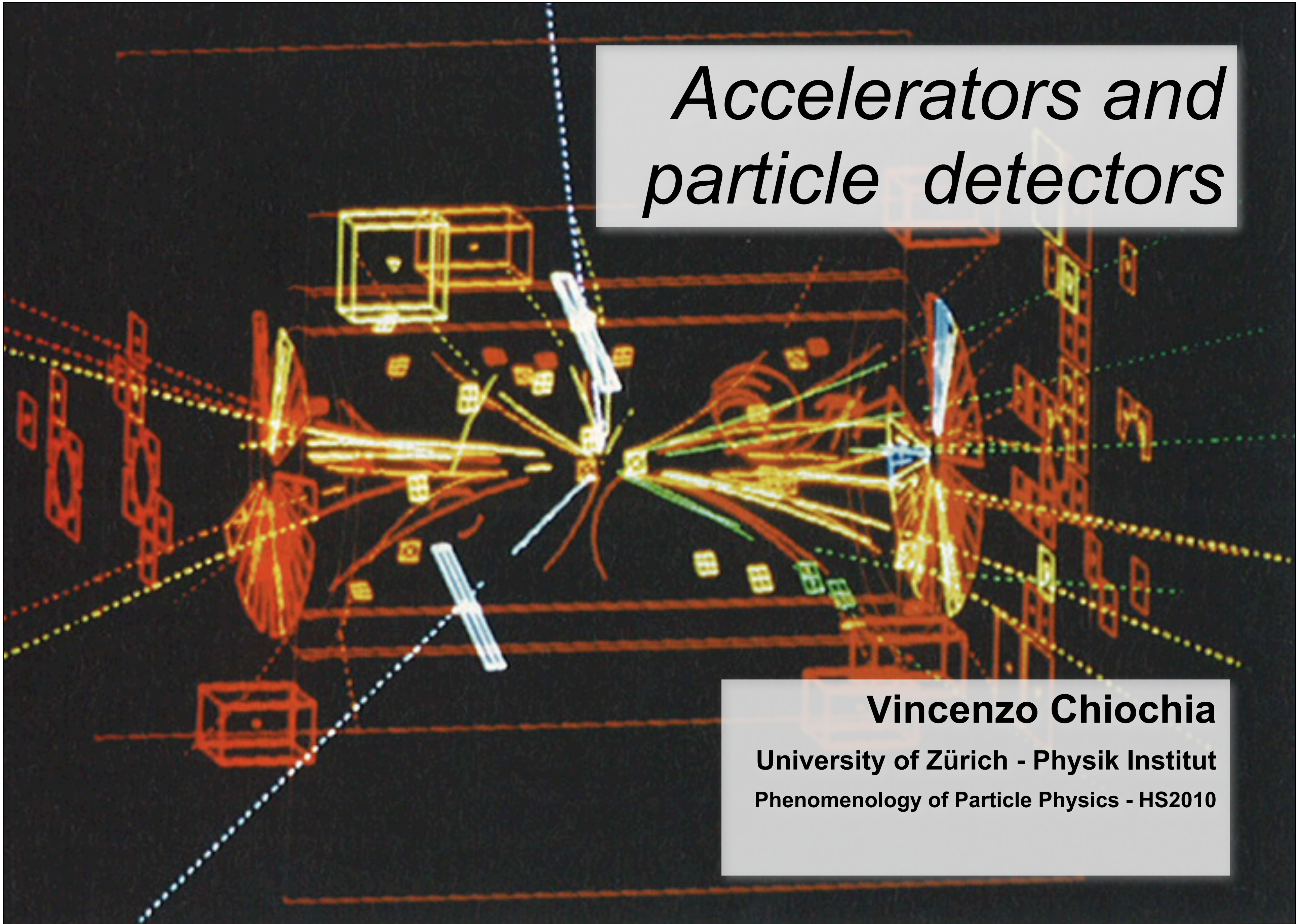


Accelerators and particle detectors

Vincenzo Chiochia

University of Zürich - Physik Institut

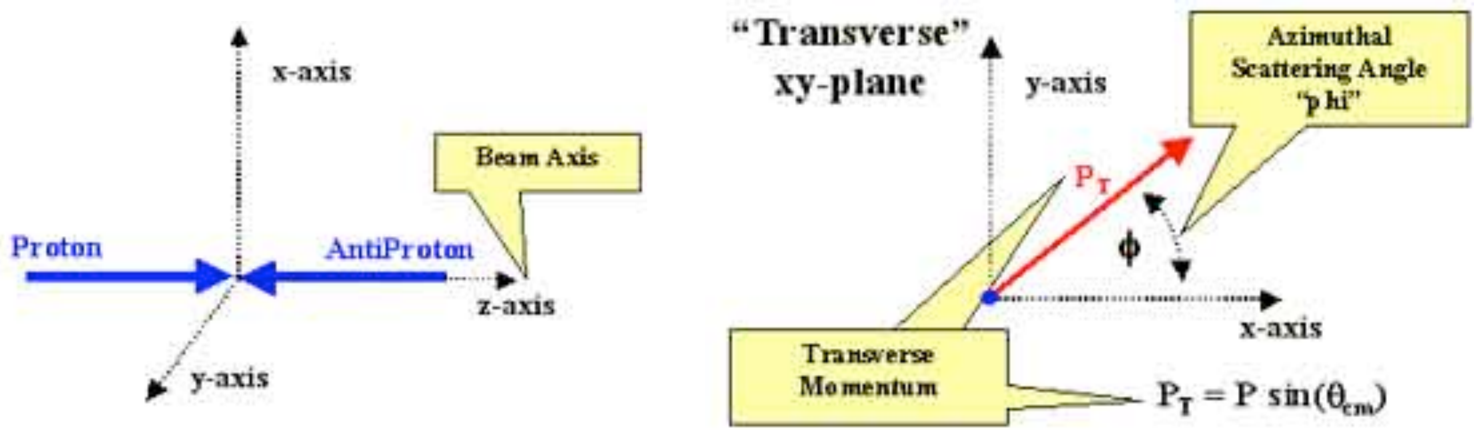
Phenomenology of Particle Physics - HS2010

Lecture outlook

- Introduction to particle accelerators and detectors
  - Basic principles of particle accelerators
  - Fixed target and collider experiments
  - Luminosity
  - Basic building blocks of a particle physics experiments
- Data analysis tools:
  - Variables in the laboratory frame
  - Momentum conservation:
    - Transverse momentum and missing mass
    - Examples: two jets events, three jet events, W discovery
  - Method of invariant mass

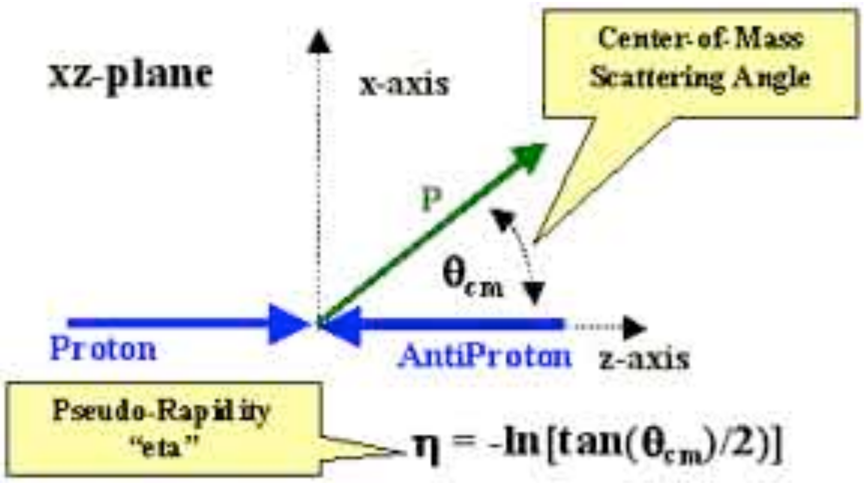
Laboratory frame

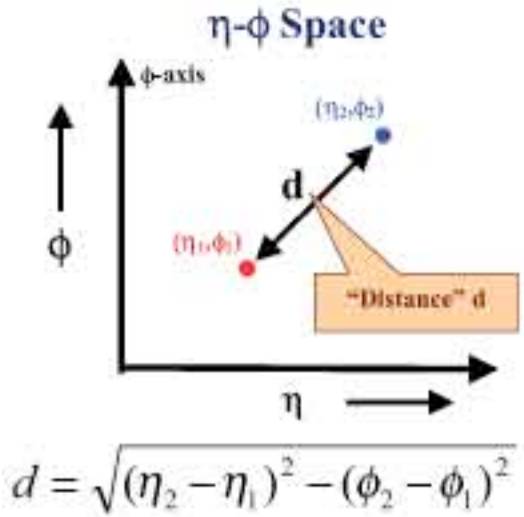
- The momentum of each particle produced in a collision can be decomposed in:
  - Component parallel to the beams (longitudinal, parallel to z)
  - Component perpendicular to the beams (transverse, in x-y plane)
  - The transverse component is: $P_T = P \sin(\theta_{CM})$
- Example:
  - Longitudinal and transverse momentum in proton-antiproton scattering



Pseudorapidity

- To measure the longitudinal angle of the emerging particle jet one usually uses a variable called **pseudo-rapidity**



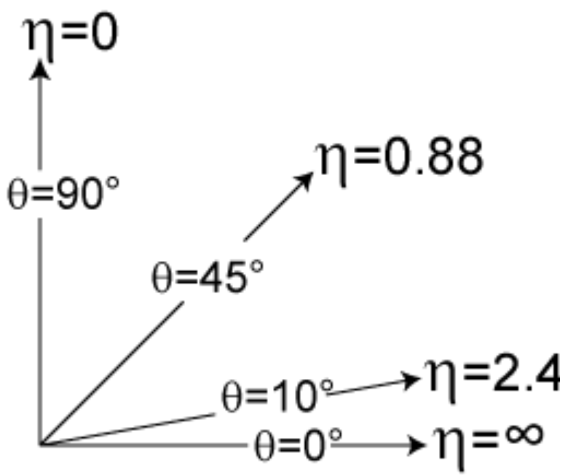


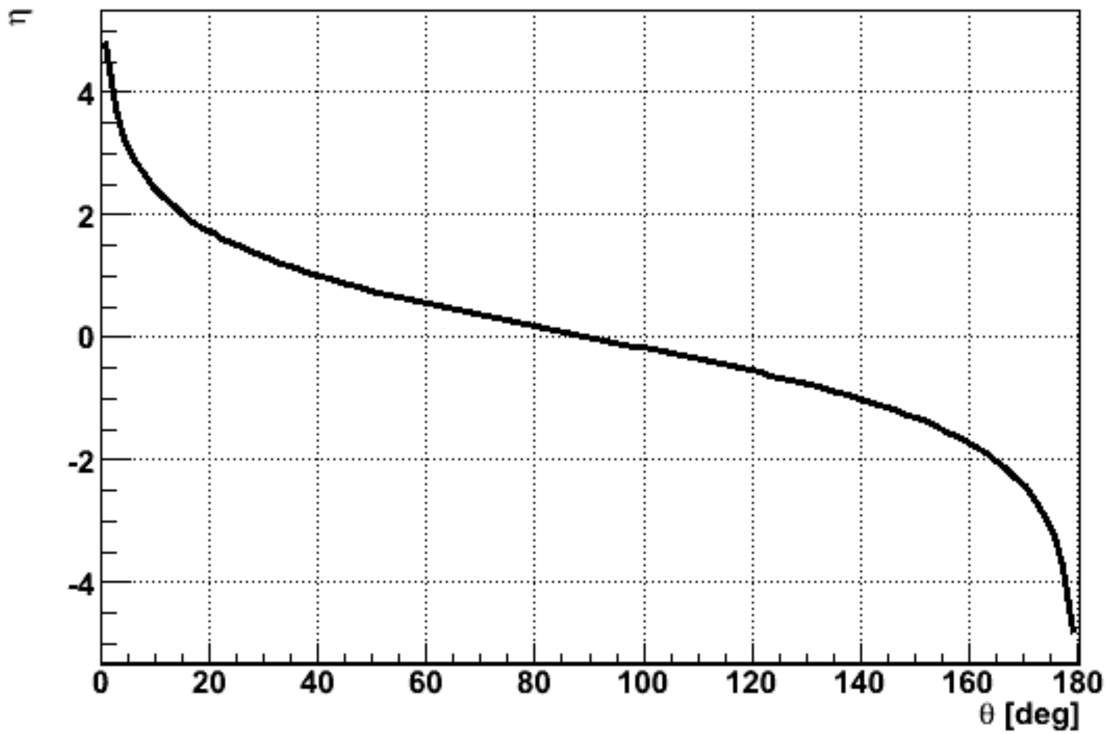
- The pseudorapidity (η) is **Lorentz invariant under longitudinal boosts**
- Momenta in the transverse plane are also invariant under longitudinal relativistic transformations
- Distance between particles or jets is usually measured in the **(η,ϕ) plane**

Pseudorapidity

- Particles produced at θ=90° have zero pseudorapidity
- High |η| values are equivalent to very shallow scattering angles
- Typical coverage of central detectors extends to |η|~3.
  - Coverage of high rapidities (θ<5°) achieved with detectors at large z positions

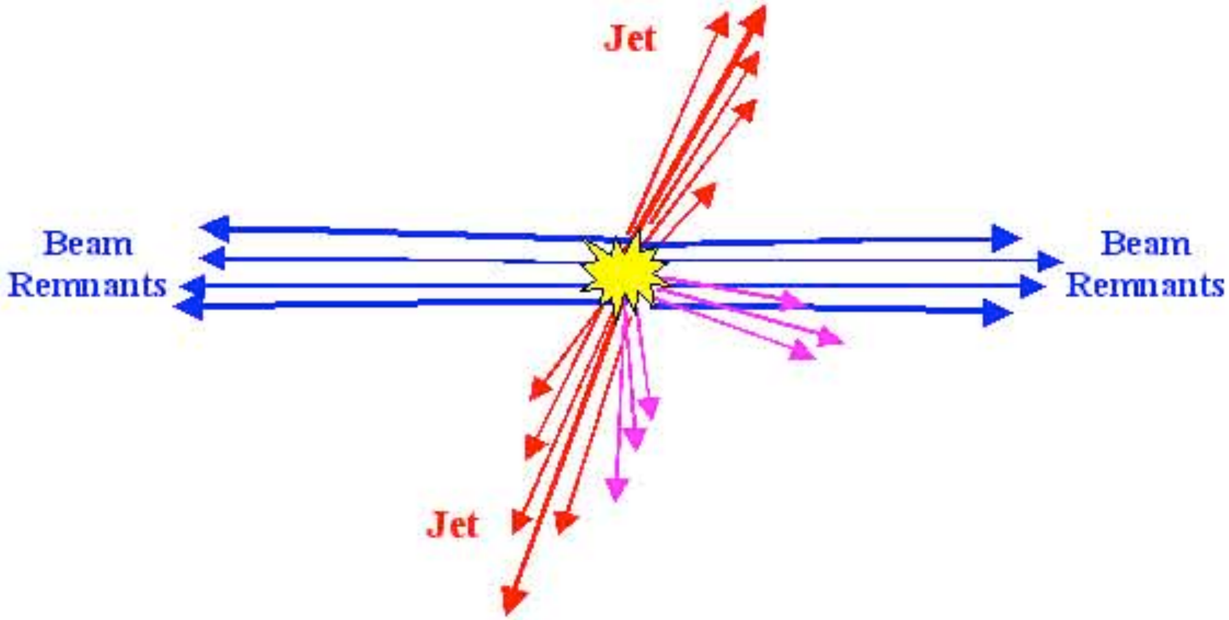
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$





Collider physics

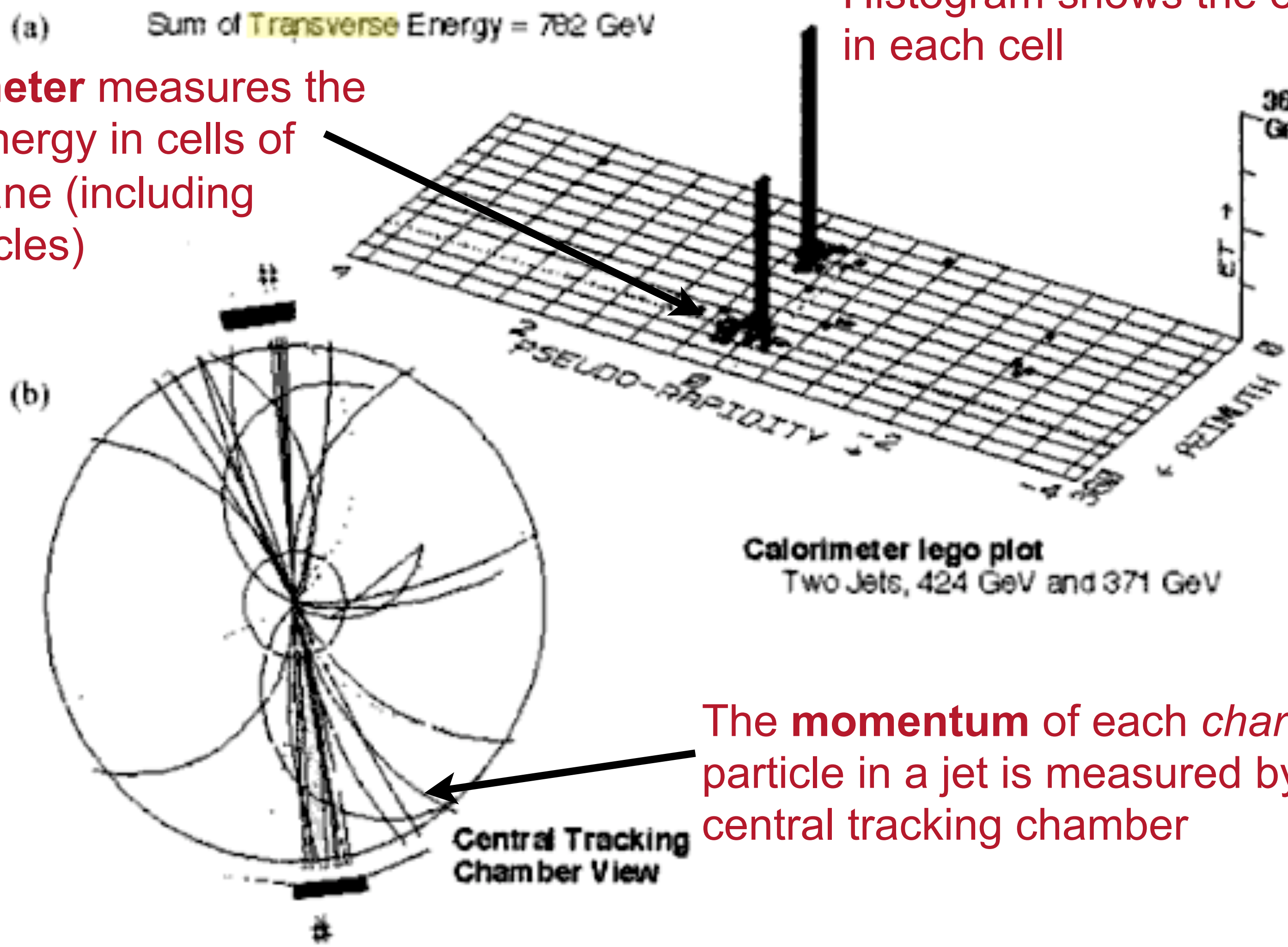
- Experiments in hadron colliders usually deal with particles at high **transverse momentum**
- Reasons:
  - Incoming particles collide head-on (no transverse momentum)
  - Final state particles must have zero total transverse momentum
  - Hard processes (large momentum transfer) produce particles in the center of the detector
- Example: proton + antiproton → jet + jet



Two jets events in eta,phi plane

Histogram shows the energy in each cell

The **calorimeter** measures the deposited energy in cells of the (η,ϕ) plane (including *neutral* particles)



The **momentum** of each *charged* particle in a jet is measured by the central tracking chamber

Two jets events

Total jet momentum

$P(1,2) = \Sigma_i P_i(1,2)$

$P_z(1) = -P_z(2)$

$P_T(1) = -P_T(2)$

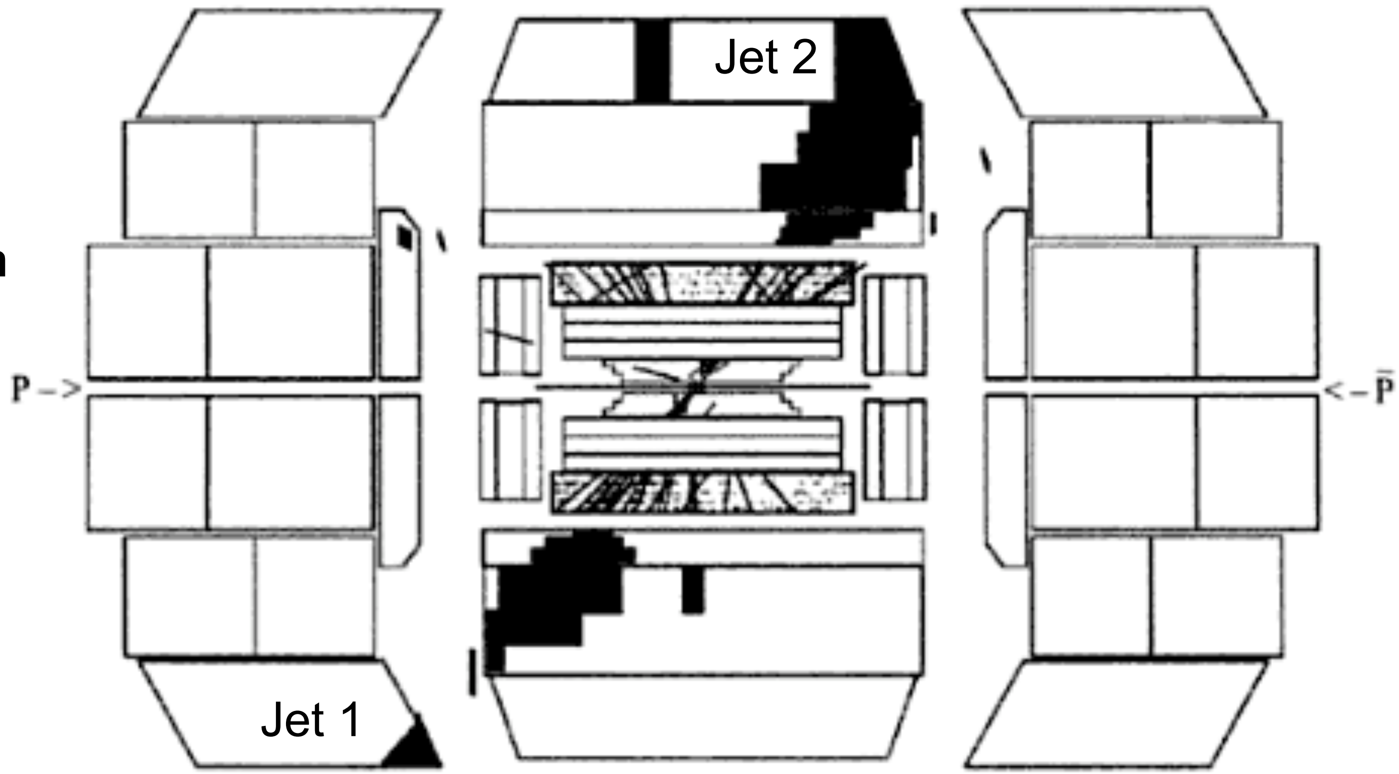
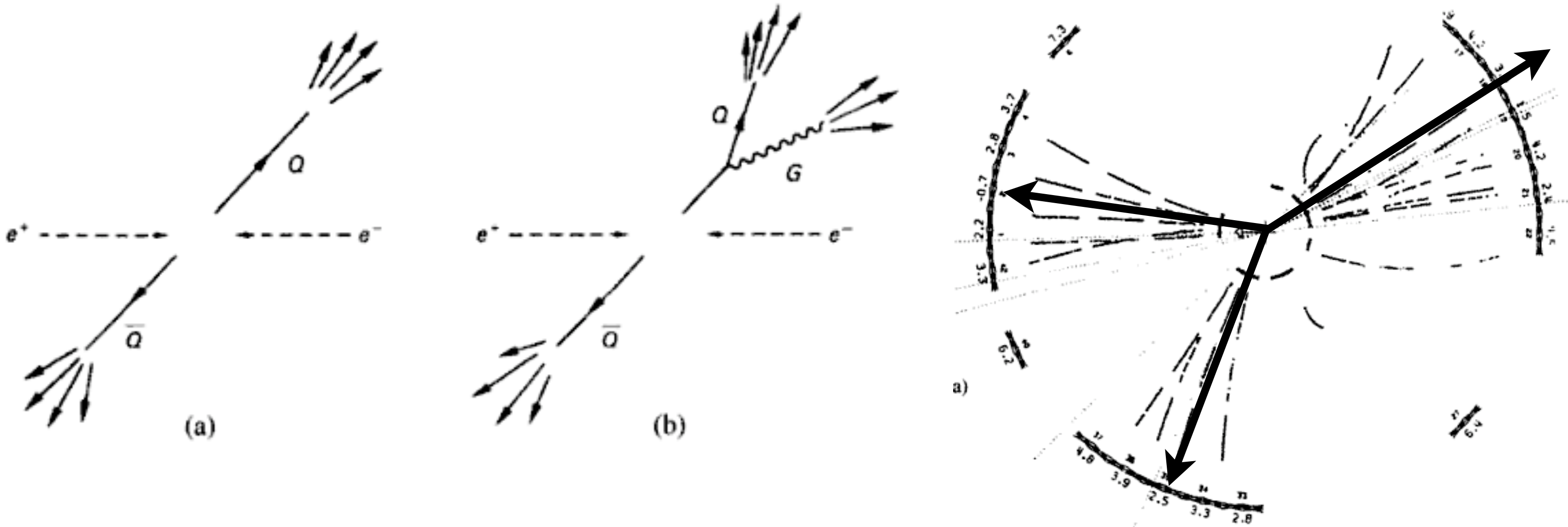


Figure 2.19 Schematic representation of a two jet event at D0. The shading represents the scale of energy deposited in the calorimeters. The first compartment is the electromagnetic calorimeter followed by two hadronic compartments. This is a projection in polar angle ([8] – D0 – with permission).

Three jets in e+e- annihilation

- Electron-proton pairs can annihilate producing quark pairs (e.g. at LEP)
- In some cases, a gluon can be radiated from the out-coming quark



- In the latter case one observes three particle jets in the final state:
  - Two quark jets and one gluon jet
- If no particle escapes the detector the three jets must have total transverse energy equal to zero

Missing mass

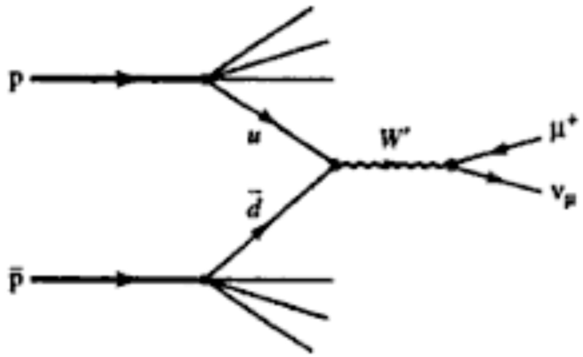
- A collision is characterized by an initial total energy and momentum (E_{in}, $\mathbf{p}_{in}$)
- In the final state we have n particles:
  - $E=\Sigma_i E_i$, $\mathbf{p}=\Sigma_i \mathbf{p}_i$
  - Sometime we measure $E<E_{in}$ and $\mathbf{p}\neq\mathbf{p}_{in}$
- In this case one of more particles have not been detected
  - Typically: **neutral particles**
  - Most often neutrinos, but also neutrons, π^0, K^0_L (the latter for long decay time)
- We define the concept of **missing mass**:

$$\text{Missing mass} = [(E_{in}-E)^2-(\mathbf{p}_{in}-\mathbf{p})^2]^{1/2}$$

- If the spectrum of the missing mass has a well-defined peak one particle has escaped our detector

W boson decays

- The W boson is produced in proton collisions mainly via the following process:



- A u-quark collides with a anti-d quark producing a W+ boson
- The W+ decays into lepton (muon) and neutrino pairs
- The muon is detected and its momentum can be measured
- The neutrino escapes the detector undetected:
- The total sum of the transverse momenta is not zero!
  - In other words, the experimental signature of the neutrino in the experiment is the **missing transverse momentum**

Example: W boson discovery

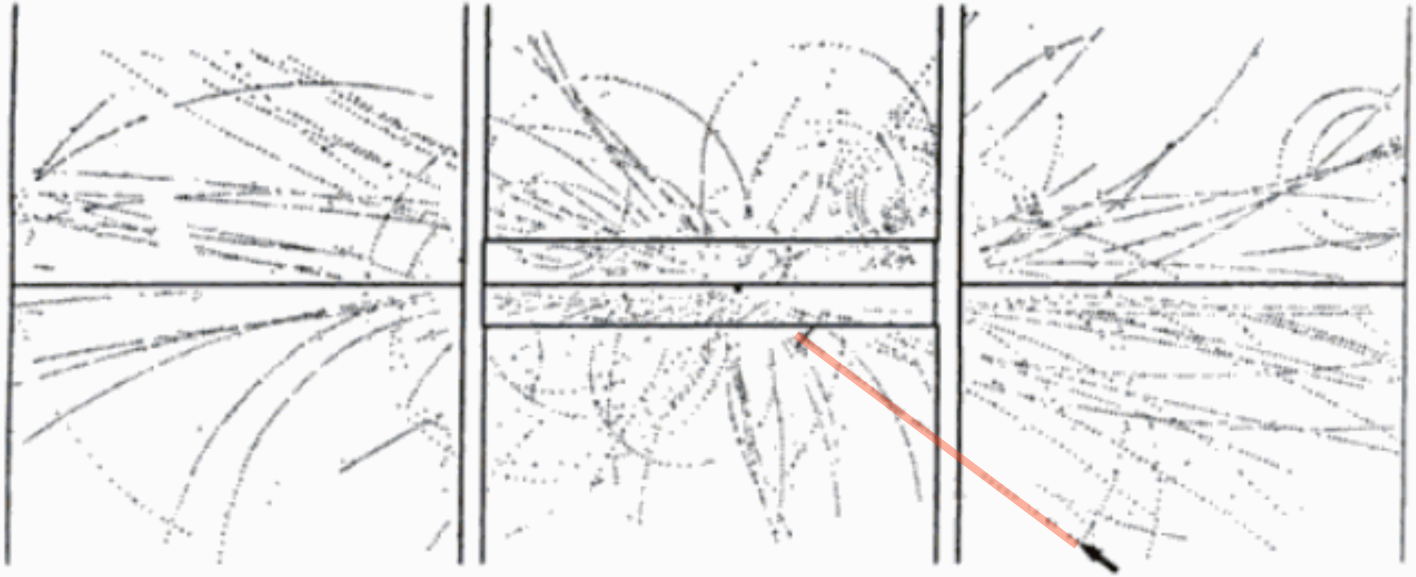


Fig. 2.8. One of the first events attributed to production and decay of a W boson, $W^+ \to e^+ + \nu_e$. The picture shows a reconstruction of the drift chamber signals in a large detector, UA1, surrounding the beam pipe of the CERN proton–antiproton collider. These signals originated in the collision of a 270 GeV proton (from the right) with a 270 GeV antiproton (from the left). Among the 66 tracks observed, one, shown by the arrow, is a very energetic (42 GeV) positron identified in a surrounding electromagnetic calorimeter. The transverse momentum of the positron is 26 GeV/c, while the missing transverse momentum in the whole event is 24 GeV/c, consistent with that of the neutrino (from Arnison *et al.* 1983).

Invariant mass

- The **invariant mass** is a characteristic of the total energy and momentum of an object or a system of objects that is the same in all frames of reference.
- When the system as a whole is at rest, the invariant mass is equal to the total energy of the system divided by c^2. If the system is one particle, the invariant mass may also be called the **rest mass**.

$$(mc^2)^2 = E^2 - \|\mathbf{p}c\|^2$$ natural units (c=1): $$m^2 = E^2 - \|\mathbf{p}\|^2.$$

- For a system of N particles:

$$(W c^2)^2 = \left(\sum E\right)^2 - \left\|\sum \mathbf{p}c\right\|^2$$

  - where W is the invariant mass of the decaying particle

- In a two body decay $M \to 1+2$:

$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 = m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right).$$

Invariant mass: applications

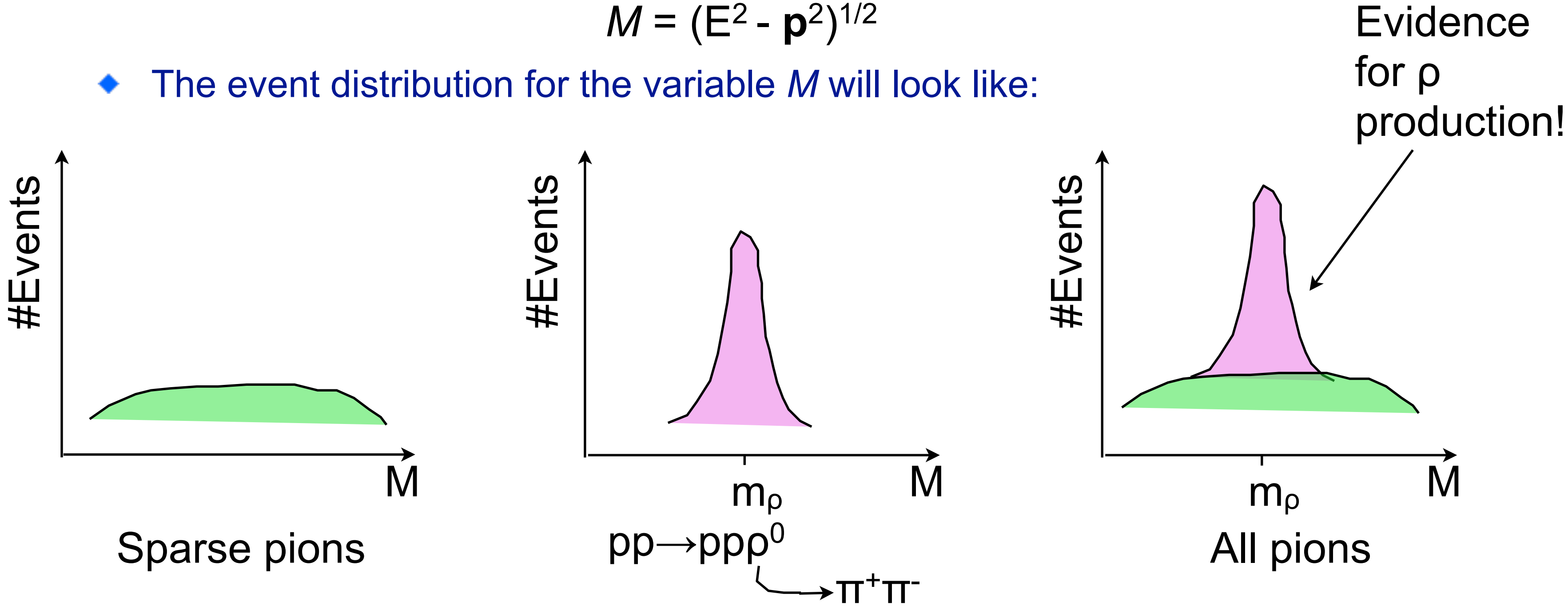
- Particles like ρ, ω, ϕ have average lifetime of 10^{-22}-10^{-23} s
  - How do we know of their existence if they live so shortly?
- Example: reaction $pp \rightarrow pp\pi^+\pi^-$
  - We identify all four particles in the final state and measure their momentum
  - Let's focus on the pion pair, the total energy & momentum are:

$$E = E_+ + E_- \qquad \mathbf{p} = \mathbf{p_+} + \mathbf{p_-}$$

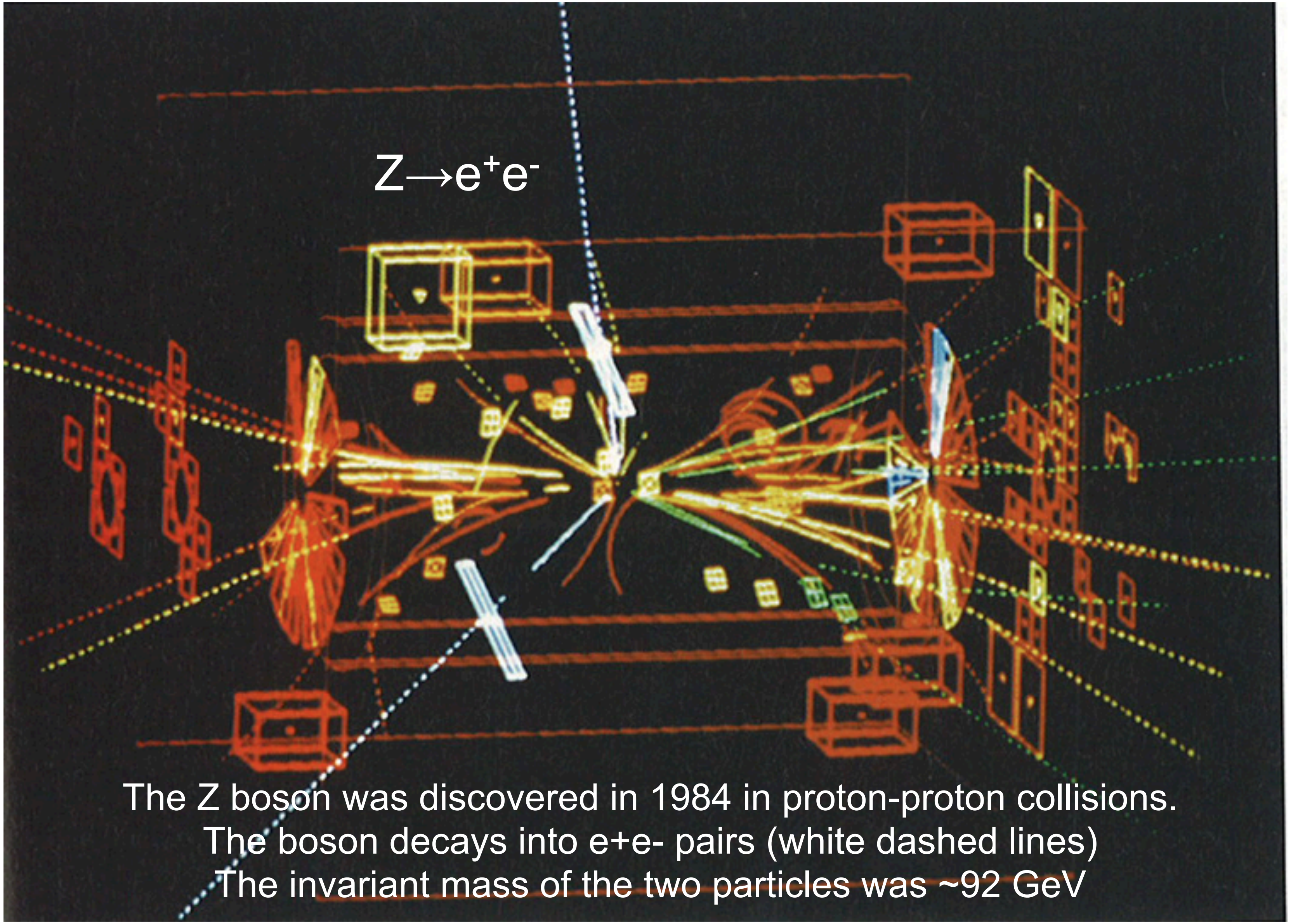
  - The invariant mass is:

$$M = (E^2 - \mathbf{p}^2)^{1/2}$$

  - The event distribution for the variable M will look like:

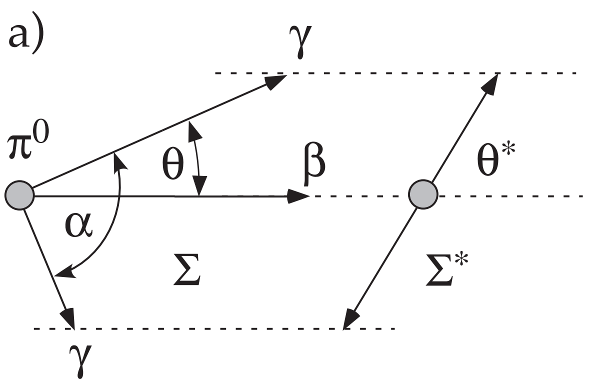


Example: Z discovery

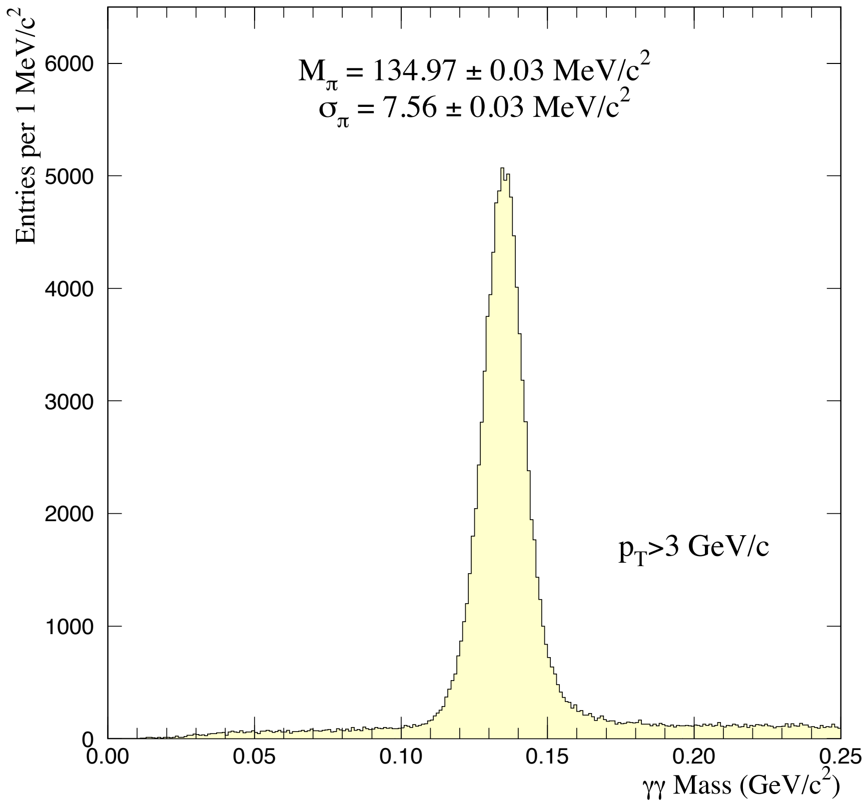


Example: π^0 reconstruction

- Neutral pions decay in photon pairs
  - Measuring the angle and energy of the emitted photons one can reconstruct the mass of the decaying pion



Exercise: calculate invariant mass formula for massless decay products (e.g. photons)



Invariant mass: 3 body decay

- In case of a 3-body decay:

$$R \Rightarrow 1 + 2 + 3.$$

- We can construct three invariant masses:

$$\begin{aligned} m_{12}^2 &\equiv (\mathcal{P}_1 + \mathcal{P}_2)^2, \\ m_{13}^2 &\equiv (\mathcal{P}_1 + \mathcal{P}_3)^2, \\ m_{23}^2 &\equiv (\mathcal{P}_2 + \mathcal{P}_3)^2 \end{aligned}$$

- For the three body case one finds:

$$\begin{aligned} m_{12}^2 + m_{13}^2 + m_{23}^2 &= m_1^2 + m_2^2 + m_3^2 + (\mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3)^2 \\ &= m_1^2 + m_2^2 + m_3^2 + M^2. \end{aligned}$$

- Only two independent invariant masses

Example: Dalitz plot

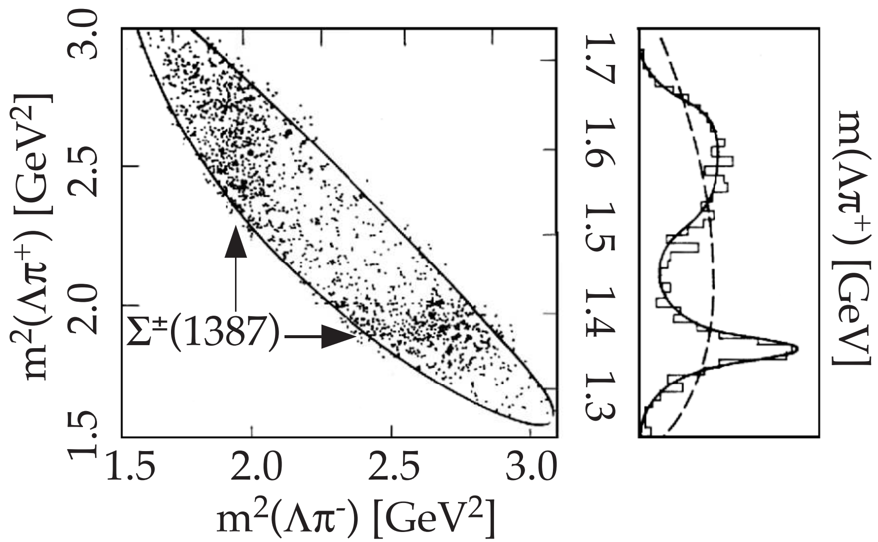
- As an example, let's study the reaction:

$$K^- p \to \Lambda\, \pi^+ \pi^- \; (\Lambda \to \pi^- p),$$

- We can measure two invariant masses

$$m_{12} \equiv m(\Lambda\pi^-) \qquad m_{13} \equiv m(\Lambda\pi^+)$$

- The so-called "Dalitz plot" shows the relation between $(m_{13})^2$ and $(m_{12})^2$



- The $\Sigma^\pm$ resonance appears as two bands in the Dalitz plot around 1.4 GeV

$$\Sigma^\pm(1387) \to \Lambda\pi^\pm.$$