Worked example of an interaction from LEP

Accelerators operate at a specified CM energy typically for weeks at a time.
If CM energy of collider ≥ mass of pair of particles, collider can produce those particles provided conservation laws hold. Can also “tune” into a resonance to create a specific particle - see the spikes in the cross section in electron-positron collisions (below).

Plot of cross section for electron-positron collisions – data from LEP and other sources

Example interaction: event display

One specific interaction event measured at the Z⁰ CM energy by the ALEPH detector at the LEP (now LHC).
Shows the production of a Bs meson in the decay of the short lived Z⁰.
How do we tell?
First the Z⁰ must decay into two particles - a particle and antiparticle pairing.


Example interaction: putting it together

The purpose of this specific example is to put all the acquired knowledge together - review the following:

- Kinematics of collisions - CM energy of electron and positron
  - A specific CM energy is needed to resonantly create $Z^0$

- Kinematics of decays - invariant CM energy of systems of particles - (2-body decays are easy!)
  - $Z^0$ decay is mostly a 2-body decay with 2 "jets" except when further photons or gluons are radiated.
  - In this specific event one of the two jets is only comprised of 6 particles, each the product of a 2-body decay, allowing a by-hand reconstruction of the events in this jet. Taking these pair-wise can determine what the invariant CM energy of the possible parent particles as well as their laboratory energy and momentum. Projecting tracks back can confirm the choice of pairs.

- Look at quantum numbers of decay products for further clues as to parents
  - e.g. what are the flavour quantum numbers; are there limitations on the possible spin; remember baryon number and lepton number must be conserved - what does this say about the quantum numbers of the decaying particle?

- Identify decay processes -
  - e.g. two charged leptons originating from the same point are a good indicator of an electromagnetic decay; would also indicate a specific angular momentum or spin of decaying particle e.g. a meson of spin 1 (unit angular momentum); does the composition of the parent particle allow for an annihilation event?

- $Z^0$ resonance
  - The $Z^0$ itself couples/decays to any pair of particle and anti-particles in a 3pt vertex that is energetically allowable. This entails 6 leptons, and 5 quarks but not the top quark nor two W's due to their masses. Can we identify the particle-antiparticle pair at the base of the two "jets"?

- Jets and hadronisation
  - When the $Z^0$ decays then typically 2 "jets" are seen. This only occurs if the $Z^0$ decays into a quark-antiquark pairing. (Ask yourself why?) Can we identify from reconstructing the event what quarks were at the origin of these jets?

Example interaction: detector

The ALEPH detector at the LEP (1989-1996)

The event display above shows in wireframe the parts of the detector that observes "hits".

- Trajectories of particles are obtained by tracking chamber, typically only charged particles
- Energy deposited in the calorimeters are indicated in pink for hadronic and blue for electromagnetic calorimeter
- Muon chambers - upper right in event display
- Charged particles curve due to motion in magnetic field. Degree of curvature is a measure of momentum
- This allows us to begin identifying the particles and classifying the event

Read M & S Chapter 4 for a summary of each detector system or view the ATLAS videos on webpage or at http://atlas.ch for a broadly similar detector system (details differ)
Example interaction: identification

Analysis:
- Sum of energies and momenta of all tracks in left hand "jet" (shown in green) are equal and opposite to the sum of the two light blue, two red tracks and two orange tracks on the right hand side. None of these six tracks point back to the interaction vertex, so they must be decay products of shorter lived particles.
- The two red tracks, pierce the hadron calorimeter and can be identified as muons. Their tracks have a common point of origin. The invariant mass of their system is 3.69 GeV and this invariant mass corresponds to a $\psi$ meson.
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- Two light blue tracks, penetrate the hadron calorimeter, and are charged kaons: $K^+$ and $K^-$. These also have a common point of origin. The invariant mass of their system is 1.02 GeV corresponding to a $\phi$ meson.
- Two orange tracks, pions, can be identified as having a common origin. Their invariant mass make up a $K_{s}$ meson.
- The neutral particles are not observed by the inner tracking chamber.
- A complete quark line diagram, of this half of the Z⁰ decay event, can then be drawn.

Example interaction: kinematics

Analysis:
- The observed laboratory 3-momenta of the muons and the kaons are as follows:

<table>
<thead>
<tr>
<th>particle</th>
<th>$p_x$ (GeV/c)</th>
<th>$p_y$ (GeV/c)</th>
<th>$p_z$ (GeV/c)</th>
<th>$m$ (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
<td>9.409</td>
<td>1.500</td>
<td>9.485</td>
<td>0.106</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>13.044</td>
<td>4.368</td>
<td>8.817</td>
<td>0.494</td>
</tr>
<tr>
<td>$K^+$</td>
<td>5.095</td>
<td>2.350</td>
<td>4.459</td>
<td>0.106</td>
</tr>
<tr>
<td>$K^-$</td>
<td>3.577</td>
<td>1.523</td>
<td>3.229</td>
<td>0.106</td>
</tr>
</tbody>
</table>

Step 1: For each and every particle calculate its energy in this frame

$$E^2 = m^2 c^4 + p^2 c^2$$

$$E^2 = m^2 c^4 + (\vec{p} \cdot \vec{p}) c^2$$

$$E^2 = m^2 c^4 + (p_x^2 + p_y^2 + p_z^2) c^2$$

Step 2: For each pair of particles calculate their invariant mass:

$$M^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2$$

$$= E_1^2 + E_2^2 + 2E_1E_2 - (p_{1x} + p_{2x})^2 - (p_{1y} + p_{2y})^2 - (p_{1z} + p_{2z})^2$$

$$M^2 = E_1^2 + E_2^2 + 2E_1E_2 - p_{1x}^2 - p_{2x}^2 - 2\vec{p}_1 \cdot \vec{p}_2$$

$$M^2 = m_1^2 c^4 + m_2^4 c^4 + 2E_1E_2 - 2(p_{1x} + p_{2x})(p_{1y} + p_{2y})$$

Step 3: Identify parent particle by invariant mass and by flavour quantum numbers (if conserved) to get quark composition.
Example interaction: explanatory notes

Quark line diagram:
- A complete quark line diagram of one side of the event can be drawn. The dotted line separates the 6 particle tracks under discussion from the much greater number of tracks that from the "jet" on the other side of the dotted line.
- The $Z^0$ decays into a $b$ quark and antiquark pair $Z^0 \rightarrow b \bar{b}$.
- As they separate hadronisation occurs producing in the first instance a $d \bar{s}$ pair, with the $b$ quark on the right hand side of the dotted line. Shortly after an $s \bar{q}$ quark pair appear due to further hadronisation. The necessary gluons are not shown.
- On the right hand side a $b\chi_c(2S)$ is formed together with a $K_{s0}^0$ whose trajectories can be tracked back to the vertex of the interaction point where the $e^+e^-$ collision has occurred and thus where the resonant $Z^0$ was formed.
- The "boost" of the $b\chi_c(2S)$ meson means that although it has a very short proper lifetime, time dilation means that the observed laboratory lifetime is longer. It decays at some distance away from the interaction vertex.
- The left hand side of the event is not shown in any detail. The large number of particles and tracks observed indicate that the hadronisation continues. Further the subsequent decay of the $b$ quark may not result in the relatively stable and long lived $\psi(2S)$ and $\phi$ mesons on the right hand side, in addition to the long lived $K_{s0}^0$ meson. Instead quicker decays into further hadrons contribute to the shower of hadronic particles.

Example interaction: quarks

Quark line diagram: Examples of the most prominent classes of decay mechanisms can be seen in this one event:
- The $\chi_c(1S)$ decays strongly into a $K^+\pi^-$ and $K^-\pi^+$ pair with a long lifetime. The necessary gluon (or photon) which must link to the vertex of the $e^+e^-$ pair is not shown. Note that both strangeness and isospin is conserved in this interaction as is baryon number.
- The $\psi(1S)$ decays electromagnetically via a virtual (massive) photon producing a muon anti-muon pair. The strong decay of this lower mass charmonium resonance is suppressed giving rise to its relatively long lifetime. All the flavour quantum numbers must be zero as the decay products are leptons. The decay must be electromagnetic for that reason as well, as there are neither quarks nor neutrinos in the decay products. A single virtual photon from such $\psi(1S)$ annihilation does not conserve momentum and can be described as "off-shell" or massive in that the rest mass of this virtual photon is non-zero.
- The neutral $K_{s0}^0$ meson decays via a weak decay, in this instance into two other neutral mesons $\phi(1S)$ and $\psi(1S)$. The quark decay mechanism is $b\rightarrow cW^-$ with a subsequent $W^-\rightarrow \mu\bar{\nu}_\mu$. The virtual $W^-$ is shown coupling to the two quark lines involved with flavour changing occurring at each point of interaction.
- The $\chi_c(2S)$ also decays weakly, but into two charged mesons (pions) with the quark flavour change $s\rightarrow uW^-$ with the $W^-$ into the $\mu\bar{\nu}_\mu$ pair which form $\phi(1S)$.

Here ends the anatomy of this specific (example) event.