1 Diffractive Interactions

Diffractive Interactions in a particle collider are soft, inelastic scattering processes with small momentum transfer. Theoretically, this interaction is described by the so called "Pomeron". The Pomeron has its origins in the Regge theory which studies the properties of the scattering matrix with respect to the angular momentum. This results in a scattering amplitude which is growing with rising energy of the scattering partners and has poles (Regge poles) depending on the angular momentum. The observation of logarithmically rising cross sections in near beam scattering with rising energy can be explained by the exchange of a Pomeron, a family of regge poles with rising spin quantum numbers. In hadron collisions, this corresponds to the exchange of a color neutral state fulfilling the conditions of a regge pole.

Because of the small momentum exchange in diffractive collisions, the final states propagate close to the initial beam direction. The final states can consist of the initial state particles with small momentum change, in case of proton-proton collisions, the initial state protons can be excited into higher angular momentum states and subsequently dissociate into multi particle final states. In some cases, also a third multi particle final state can be produced as shown in Figure 1. Regardless of the particular final state configuration, a common feature of diffractive interaction is the large rapidity gap between the individual final states.

Reminder: The rapidity in collider physics is a measure of the angular separation of a scattered particle and the beam direction. It is defined by

$$y = \frac{1}{2} \ln \left(\frac{E + p_z c}{E - p_z c} \right), \tag{1}$$

where E is the particles energy and $\mathrm{p_z}$ is the particles momentum component parallel to the beam direction. This quantity approaches inf if the particle is travelling close to the beam ($E \approx p_z c$) and 0 if the particle is travelling transverse to the beam. In contrast to differences in the polar angle θ, the rapidity difference of two particles is invariant under Lorentz boosts along the beam axis. In hadron collider experiments, where the momentum of the colliding partons is not known, the center of mass of the collision products is often moving along the beam axis. The rapidity provides a way of describing the angular separation of two particles independent of their movement (boost) along the beam axis. Since the rapidity is often hard to measure, because one needs the energy and the total momentum vector, the pseudorapidity is a more convenient way of describing the angular separation. It is defined by

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

where θ is the polar angle between beam axis and the particles direction.

For massless or highly relativistic particles, rapidity and pseudorapidity are equal.

Diffractive interactions can produce different final states, as shown in Figure 1

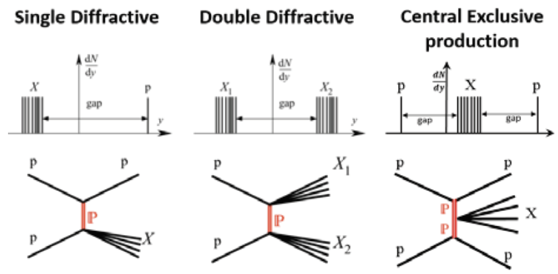

Figure 1: Different kinds of diffractive interactions. A single or double diffractive interaction (left and mid) is characterized by one or two multi particle final states separated by a large rapidity gap. A central production (right) is characterized by three final states separated by two large rapidity gaps.

In a particle collider with highly intense beams, these diffractive interactions lead to additional background processes, especially the ones producing jets in the final state.

2 Jet Reconstruction

2.1 Iterative Cone Jet Algorithms

General Principle: All reconstructed particles within a cone of radius R around a seed particle belong to a jet.
Requirements:

- Define seed particles (e.g. particles with transverse momentum above a certain energy threshold)
- Define distance between seed i and particle j (e.g. in azimuth angle ϕ and rapidity y):

$$\Delta R_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 < R_{max}^2$$

Iteration procedure:

1. Find all particles within R_{max} around a seed
2. Calculate the sum of all four momenta of the found particles
3. Take the sum as new seed particle and repeat from 1

If the sum of the four momenta is identical over two subsequent iterations, a stable cone is found. Repeat with the next seed.
Problem: Overlapping cones are not recognized and may lead to the wrong number of reconstructed jets. One way to overcome this is the removal of the particles in a stable cone from the list of reconstructed particles, before continuing with the next seed ("progressive removal"). In another approach, the overlapping region is shared between the cones, based on some predefined rule ("split-merge"). Both algorithms however, suffer from problems called *collinear* and *infrared* unsafety.
Remark: An example infrared and collinear safe cone algorithm is the SISCone algorithm.

2.2 Infrared and Collinear Unsafety

General: Dependence of the outcome of the jet finding algorithm on random emission of soft particles or collinear splitting of high energetic particles in the jet. This reduces the efficiency in identifying a desired process in a set of collision events and increases the risk of passing false positives through the event selection.
Infrared Unsafety:
For example caused by a final state parton emitting a soft gluon as shown in **??**.

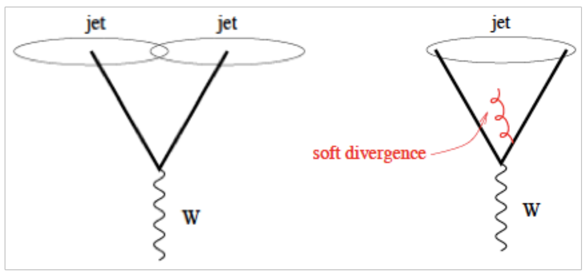

Figure 2: Left: Decay of a W boson into two quarks. Two hadronic jets are found by the clustering algorithm. Right: Decay of a W boson into two quarks with an additional emission of a soft gluon forming another soft jet. In the presence of this new seed, the clustering algorithm merges the two hard jets into one. Present in split-merge algorithms.

Collinear Unsafety For example, caused by the decay of a hadronic state in the jet before entering the detector.

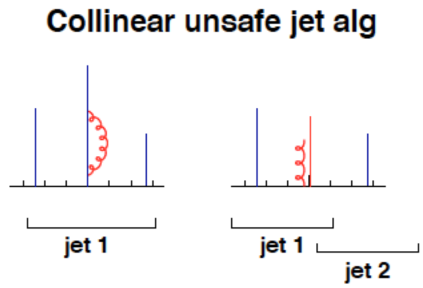

Figure 3: Collinear unsafe jet algorithm. In the left picture, the algorithm clusters all the particles to one jet around the central seed particle. In the right picture, the hardest particles undergoes collinear splitting so the algorithm picks the left particle as seed and obtains two jets, the right particle being a jet on its own now. Present in progressive removal algorithms.

2.3 Sequential Recombination Jet Algorithms

General Principle: Group the reconstructed particles based on a predefined distance measure (first example: Jade algorithm). This distance measure can not only depend on angles or spatial distances, but also an the energy or momentum of the particles.
Requirements:

- Define distance measure:

  $y_{ij} = \frac{2E_iE_j(1-\cos(\theta_{ij}))}{Q^2}$

- Define *resolution threshold* y_{cut}

Iteration:

1. Calculate distance y_{ij} between every pair of particles in the list of reconstructed particles
2. Find the minimum y_{min} and compare it to y_{cut}
3. If y_{min} is smaller than y_{cut}, merge the two particles into one by summing their four momenta. Repeat from 1.

The number of jets is defined by the choice of y_{cut}. This algorithm is collinear safe, because collinear particles are combined because of their small opening angle ($(1-\cos(\theta)) \rightarrow 0$). It is also infrared save, because low energy particles also lead to small distances.
Problem: Soft back-to-back particles are also combined, which contradicts the picture of a jet as collimated stream of particles. Algorithms like the kt algorithms try to overcome this problem by modifying the distance measure to assign large distances to soft back-to-back particles.

2.4 Difference between kt and Anti kt Algorithm

In contrast to the Jade algorithm, the kt and anti-kt algorithms introduce distance measures depending on the minimum or maximum momentum of the particle pair. In addition, the maximum separation of a particle pair is limited by a maximum cone radiusR_{max} similar to a cone algorithm. The distance measures are defined as:

kt:
$d_{ij} = min\left(p_{ti}^2, p_{tj}^2\right) \frac{\Delta R_{ij}^2}{R_{max}^2}$
$\Delta R_{ij} = (y_i - y_j) + (\phi_i - \phi_j)$

anti-kt:
$d_{ij} = min\left(p_{ti}^{-2}, p_{tj}^{-2}\right) \frac{\Delta R_{ij}^2}{R_{max}^2}$
$\Delta R_{ij} = (y_i - y_j) + (\phi_i - \phi_j)$

The kt algorithm tends to cluster the the soft particles of the event first, leading to to somewhat irregular jet shapes, because of the random nature of fragmentation in the development of the hadronic jet. This is helpful in identify the substructure of jets to distinguish e.g. quark and gluon jets. The anti-kt algorithm favours clustering around hard particles, leading to rather circular jets with a radius up to R_{max}. Both algorithms are collinear and infrared safe.