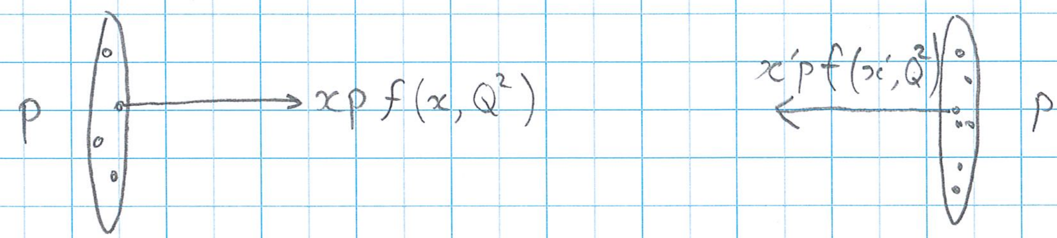
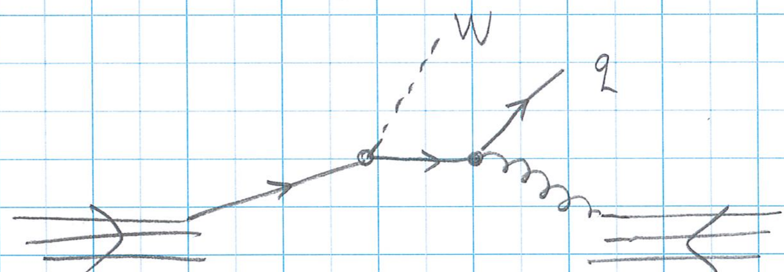
The Structure of a high energy event

1. Incoming beams



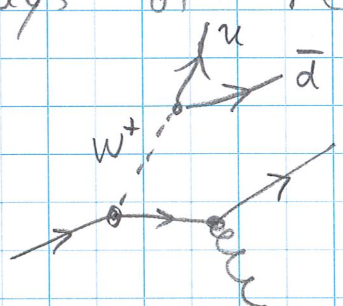
Initial state momentum distribution described by parton distribution functions.

2. Hard scattering



Matrix element calculated via Feynman diagrams.

3. Decays of resonances $(W^\pm, Z^0, t, H)$

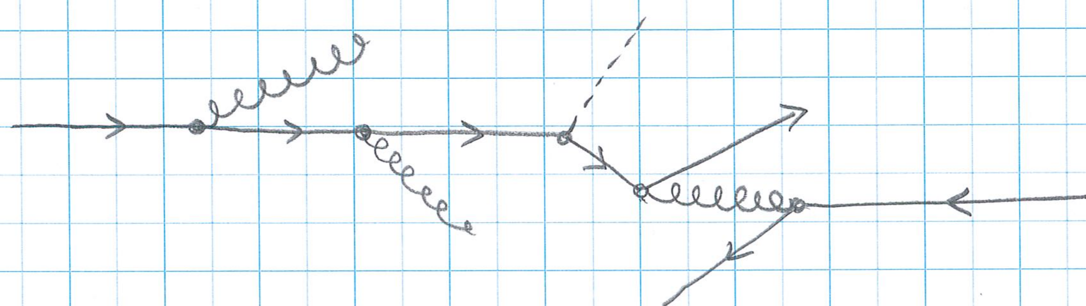


Sums over intermediate kinematic variables, helicities, etc.

Correlated with hard process.

4. Initial state radiation.

Accelerated charges radiate field quanta.
Electric charges radiate photons
Color charges radiate gluons.



This is called a "space-like" parton shower.

Consider the parton branching process $a \to bc$

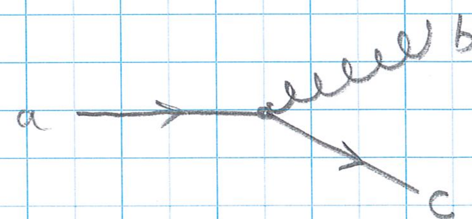
$p_{\perp a} = 0 \qquad p_{\perp c} = -p_{\perp b}$

$$E^2 - p_L^2 - p_\perp^2 = m^2$$

$$(E + p_L)(E - p_L) = m^2 + p_\perp^2$$

$$E_b = zE_a = p_{Lb}$$
$$E_c = (1-z)E_a = p_{Lc}$$

$$p_+ \, p_- = m^2 + p_\perp^2$$



$$p_- = \frac{m^2 + p_\perp^2}{p_+}$$

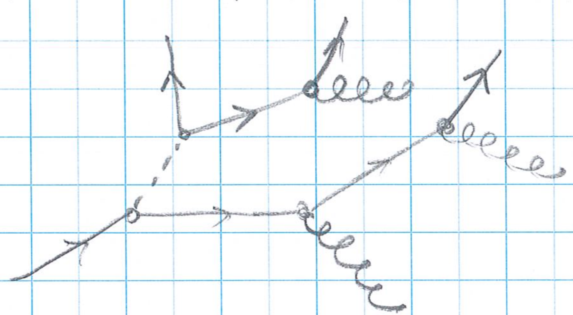
$$\frac{m_a^2 + \cancel{p_{\perp a}^2}^{\,0}}{p_{+a}} = \frac{m_b^2 + p_{\perp b}^2}{z\, p_{+a}} + \frac{m_c^2 + p_{\perp c}^2}{(1-z)\, p_{+a}}$$

$$m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z} = \frac{m_b^2}{z} + \frac{m_c^2}{1-z} + \frac{p_\perp^2}{z(1-z)}$$

In the initial state shower, we assume that $m_a = 0$ and $m_c = 0$. The radiated parton has mass

$$m_b^2 = -\frac{p_\perp^2}{1-z} < 0 \quad \text{(space like 4-vector)}$$

5. Final state radiation



This time $m_b = m_c = 0$

$$m_a^2 = \frac{p_\perp^2}{z(1-z)} > 0 \quad \text{(timelike 4-vector)}$$

Final state splittings are described by DGLAP evolution:

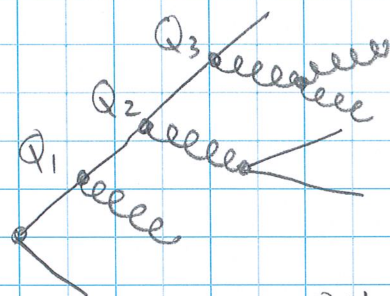
$$P_{q\to qg} = \frac{4}{3}\,\frac{1+z^2}{1-z}$$

$$P_{g\to gg} = \frac{3\left(1-z(1-z)\right)^2}{z(1-z)}$$

$$P_{g\to q\bar{q}} = \frac{n_f}{2}\left(z^2+(1-z)^2\right)$$

n_f = # of quark flavors.

Emission is approximately time-ordered



$$Q_1^2 > Q_2^2 > Q_3^2$$

Other variables can be used to order the shower:

$$Q'^2 = E_a^2 \, \theta_{a\to bc}^2 \approx \frac{m^2}{z(1-z)} \quad \text{angular ordering}$$

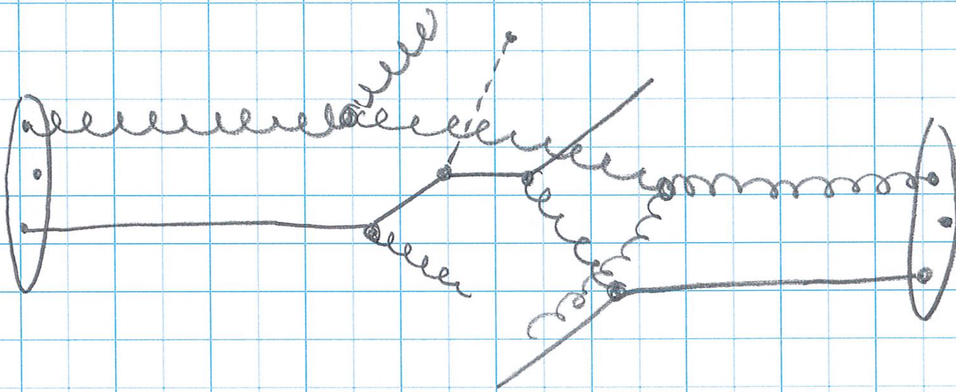
$$Q'^2 = p_\perp^2 \approx m^2 z(1-z) \quad p_T\text{-ordered.}$$

The shower evolves until Q^2 falls below some cutoff ($\sim 1\ \mathrm{GeV}^2$) at which point non-perturbative effects set in.

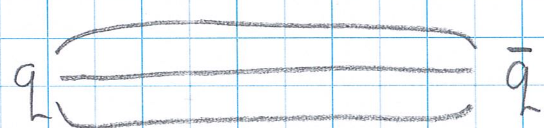
Matrix elements describe well-separated parton emission ; parton showers describe colinear emission , with angular or p_T ordering.

Important to match ME + PS in a consistent way.

6. Multiple parton interactions + ISR + FSR



7. Connect the color charges.



Color charges are connected by flux tubes or strings of gluon fields!

- Hard partons
- ISR + FSR + MPI
- proton remnants.

Fragmentation : non-perturbative process that turns strings into hadrons.

Potential models and lattice QCD suggest that

$$F(r) \sim \text{const.} = \kappa \approx 1 \ \text{GeV}/\text{fm} .$$

$$V(r) = \kappa r$$

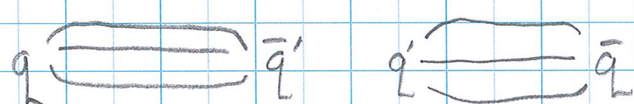
Model for string breaking:

$$P \propto e^{-\pi p_\perp^2/\kappa}\, e^{-\pi m_q^2/\kappa}$$

$$\langle p_\perp \rangle \sim 0.4 \text{ GeV}/c$$

Heavy quarks are suppressed

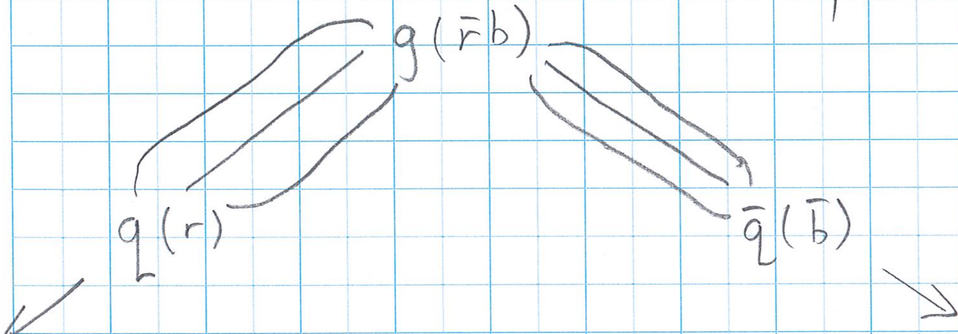
$$u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$$



PYTHIA

Gluons have two colors:

predicts $\langle n_{ch} \rangle \sim \log E_{jet}$



Cluster Fragmentation: Evolve the parton shower down to a nonperturbative scale, form high mass clusters of the remaining $q, \bar{q}, g$ and decay to bound states via phase space.

HERWIG

7. Particle Decays.

Described adequately by quantum mechanics (angular momentum conservation) and low energy measurements.

Decay tables catalog branching fractions to exclusive final states.

Unmeasured exclusive final states decay according to various models.

No interference between decay products, even for strong decays.

Weakly decaying particles with short lifetimes decay in vacuum:

τ, $B^\pm$, B^0, B_s, Λ_b, D, Λ_c, etc

Longer lived particles could decay outside the beam pipe and/or interact with detector material before decay

γ, $\pi^\pm$, K^0_L, K^0_S, $K^\pm$, Λ, Ξ, p, n, etc.

Specialized generators for some decays:

TAUOLA for τ decays
EvtGen for B decays

Phenomenological addition of final state radiation:

PHOTOS.