QCD at LHC

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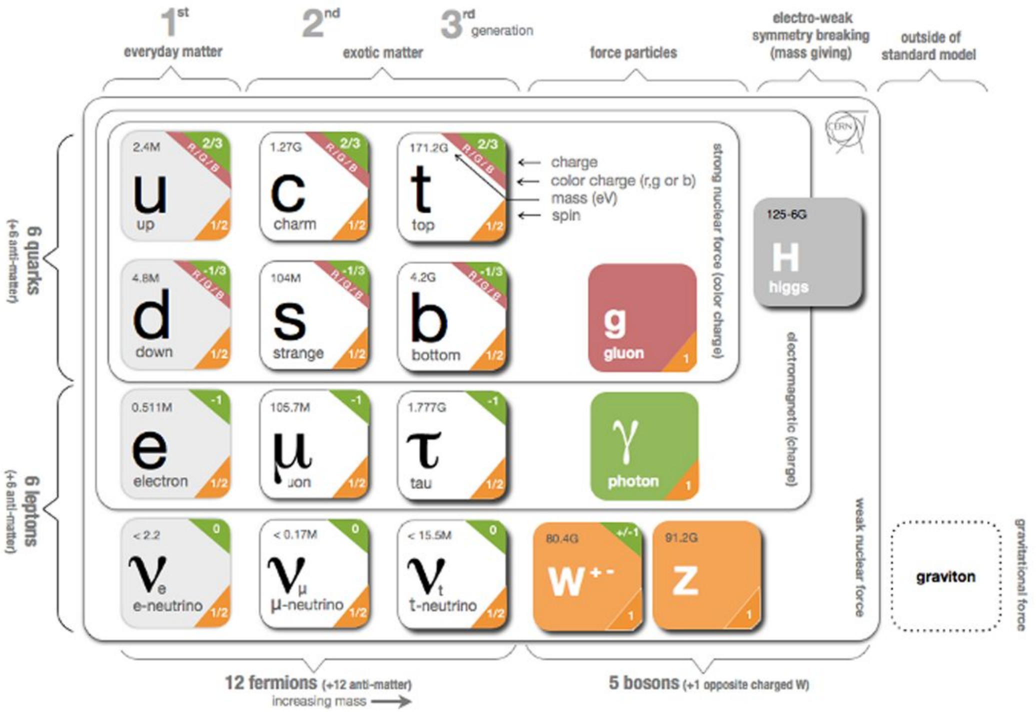
Standard Model

➢ Theory developed in the 1960s that describes the fundamental particles and the interactions between them



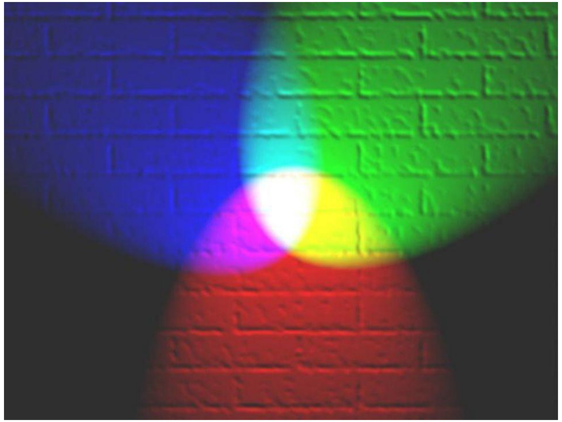
Quantum Chromodynamics (QCD)

- The **strong interaction** - described by the **Quantum Chromodynamics (QCD)** theory which is based on the gauge symmetry group SU(3)

- The particles that interact with the strong force (quarks and gluons) have an additional quantum number called **color**

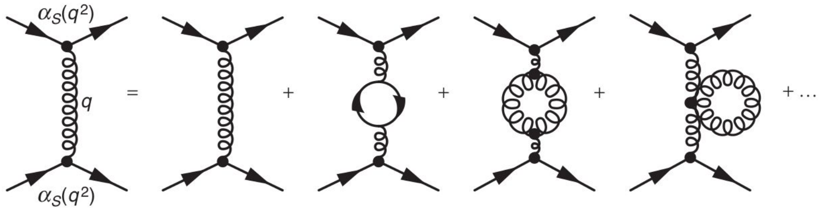
- The quarks - one of the three colors: **red**, **blue** or **green** (antiquarks - anticolors)

- The eight gluons - the combination of color and anticolor



Running of the strong coupling constant α_s

- All couplings run (QED, QCD, EW), i.e. they depend on the momentum scale (Q^2) of process

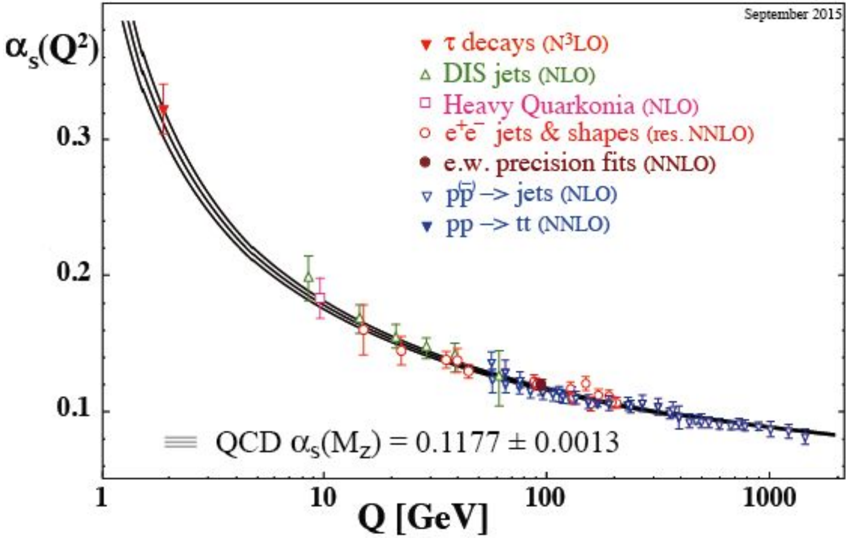


$$\alpha_S(Q^2) = \alpha_S(Q_0^2) \Big/ \left[1 + B\alpha_S(Q_0^2) \ln\left(\frac{Q^2}{Q_0^2}\right) \right]$$

$$B = \frac{11N_c - 2N_f}{12\pi}$$

N_C - number of colors

N_f - number of q flavors

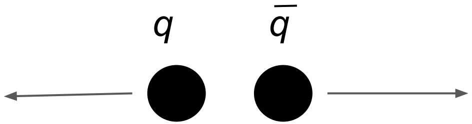


⇒ At high scales Q, coupling becomes small quarks and gluons are almost free, interactions are weak

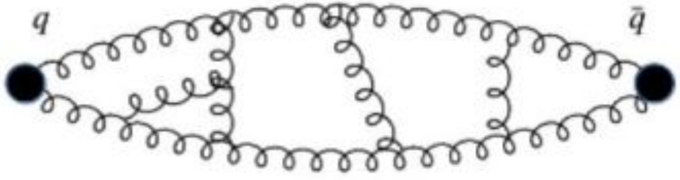
⇒ At low scales, coupling becomes strong

Color confinement

Can we detect free quarks?



- Exchange of virtual gluons between quarks
- The color field between the quarks is squeezed into a tube
- The energy stored in the field is proportional the separation of the quarks



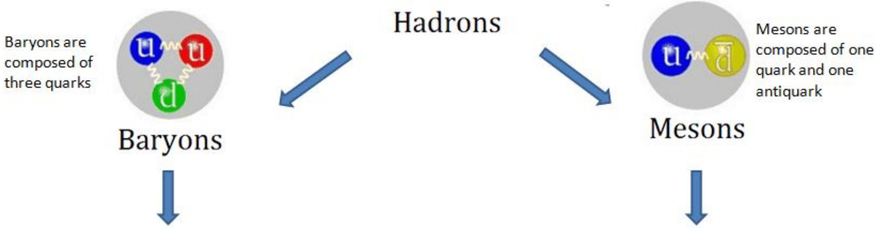
$$V(r) \sim \lambda r$$

⇒ infinite amount of energy to separate two quarks to infinity

Color confinement

- Quark arrange themselves into bound **hadronic** states that are **colourless** combinations with no colour field between them

- Hadrons can be **mesons** and **baryons**



Nucleons

Particle	Mass (MeV/c^2)	τ (sec)
p	938.2	$>10^{11}$
n	939.5	10^3

Hyperons

Particle	Mass (MeV/c^2)	τ (sec)
Λ	1115	2.6×10^{-10}
Σ^+	1189	0.8×10^{-10}
Σ^0	1192	10^{-14}
Σ^-	1197	1.6×10^{-10}
Ξ^0	1314	3×10^{-10}
Ξ^-	1321	1.8×10^{-10}
Ω^-	1675	1.3×10^{-10}

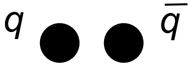
Pions

Particle	Mass (MeV/c^2)	τ (sec)
π^-, π^+	139	2.5×10^{-8}
π^0	135	1.8×10^{-16}

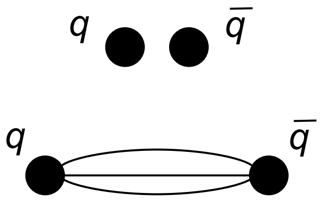
Kaons

Particle	Mass (MeV/c^2)	τ (sec)
K^-, K^+	494	1.2×10^{-8}
K^0	498	
η	550	10^{-18}

Hadronization

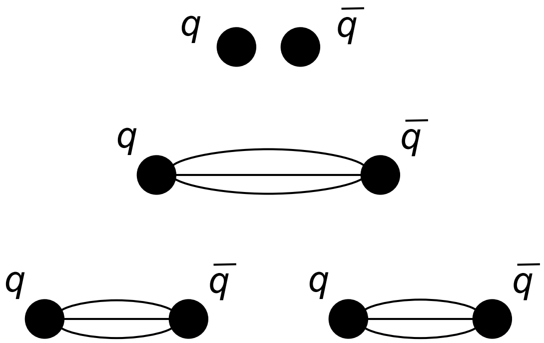


Hadronization



- Energy of the strong field between quarks increases as they are moving apart from each other

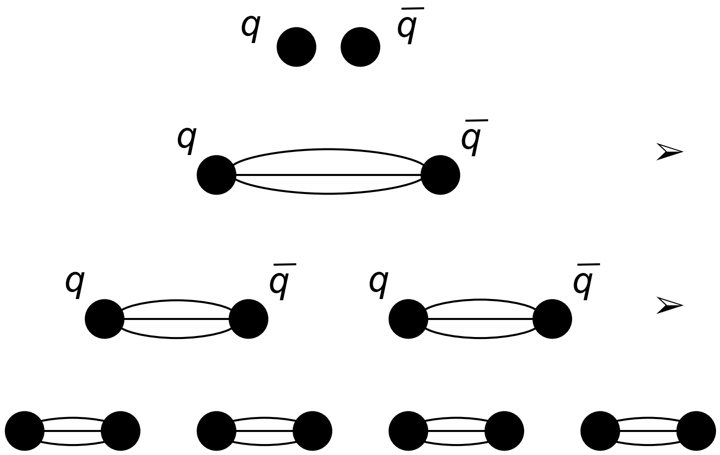
Hadronization



➢ Energy of the strong field between quarks increases as they are moving apart from each other

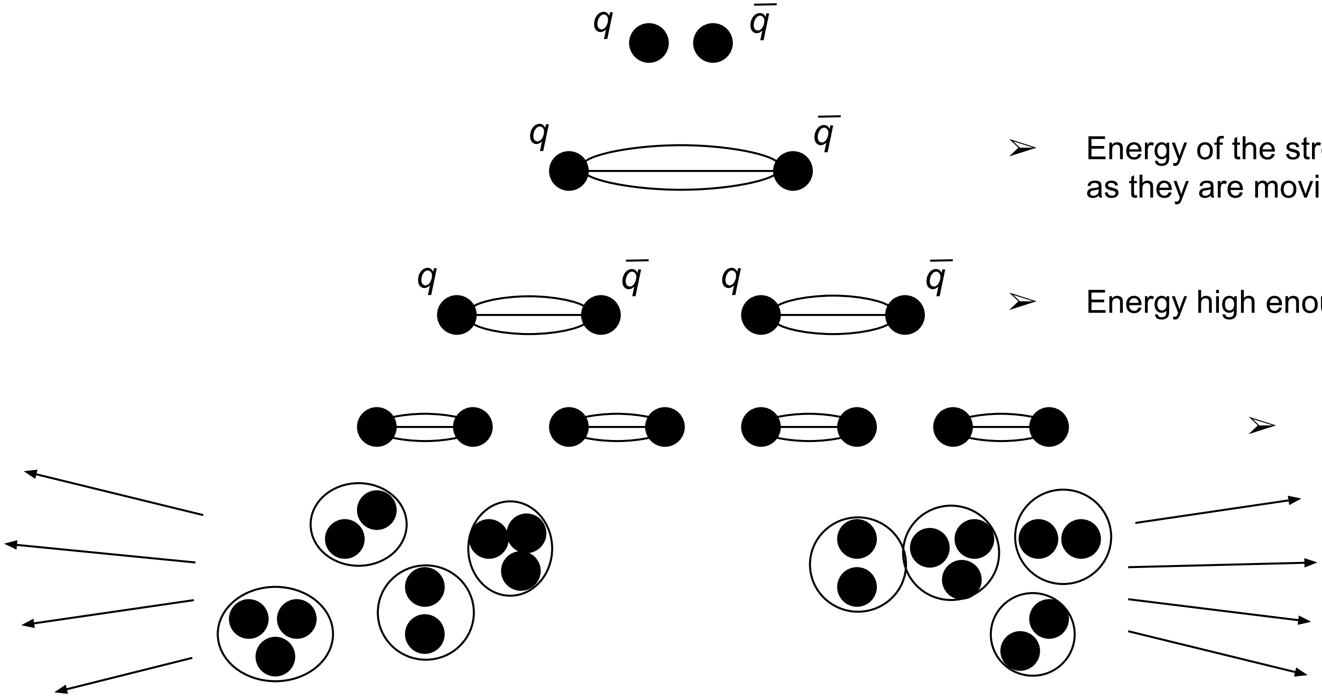
➢ Energy high enough - new pair of quarks is created

Hadronization



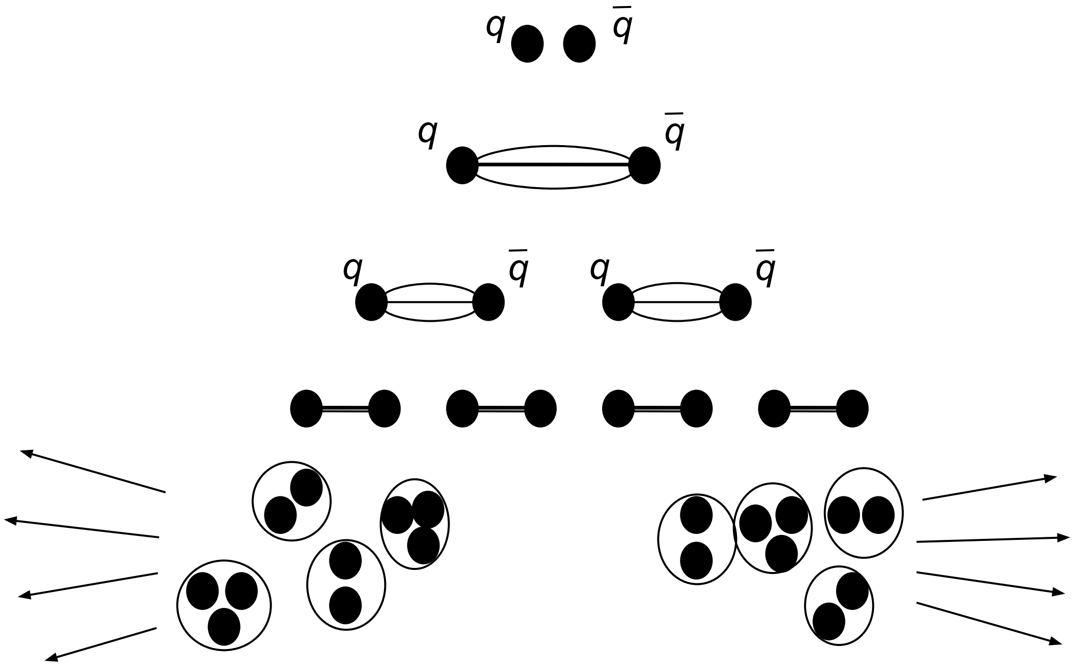
- ➢ Energy of the strong field between quarks increases as they are moving apart from each other
- ➢ Energy high enough - new pair of quarks is created
- ➢ This process is repeated until…

Hadronization



- ➢ Energy of the strong field between quarks increases as they are moving apart from each other
- ➢ Energy high enough - new pair of quarks is created
- ➢ This process is repeated until the energy is low enough to create hadrons

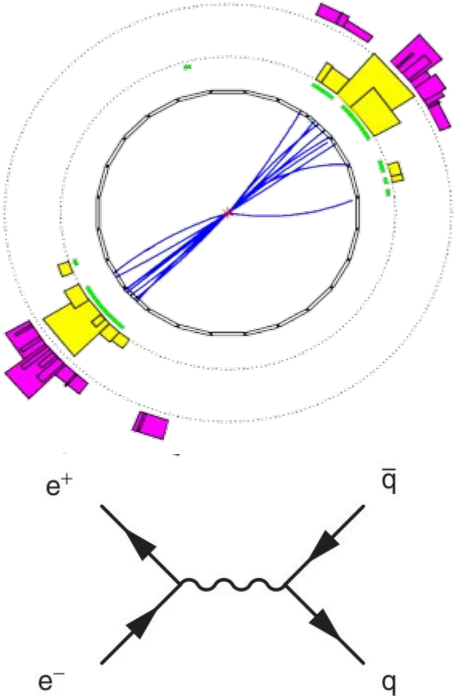
Hadronization

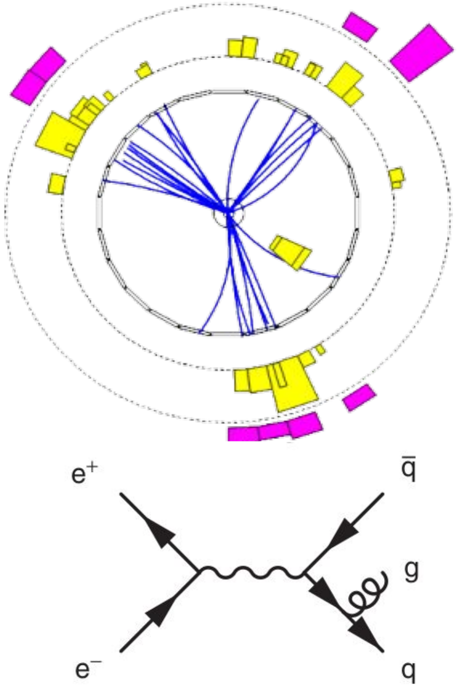


- This process is called **hadronization**
- The produced hadrons are often the results of boosted interactions, which makes the particles to be collinear and form what is called a **jet**

Jet production in e$^+$e$^-$ collisions

- Jet production in high-energy electron–positron collisions also provides direct evidence for the existence of gluons



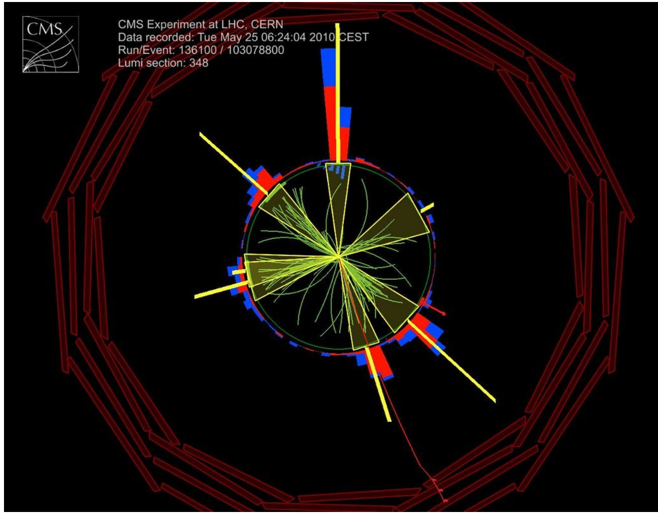


Jets at LHC

- **Jets** - less well defined than leptons or muons, but important for understanding LHC physics

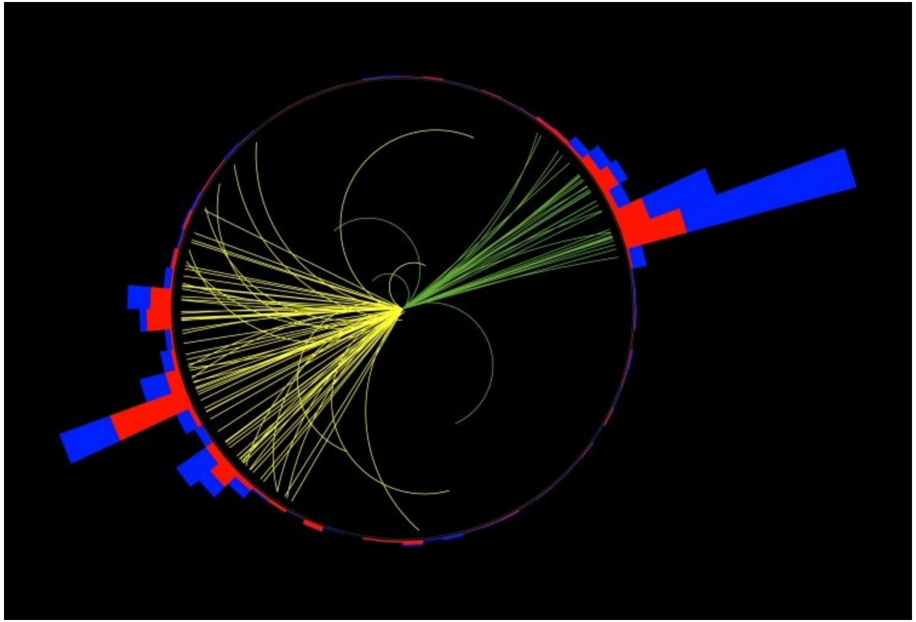
- <u>Standard Model physics</u>:
  - Many standard model processes produce jets, are sensitive to α_s
  - Multijet cross section measurements test QCD
  - Hadronic decays of heavy particles

- <u>New physics searches:</u>
  - Many searches looking for final states with jets, or in regions of phase space with high jet multiplicities



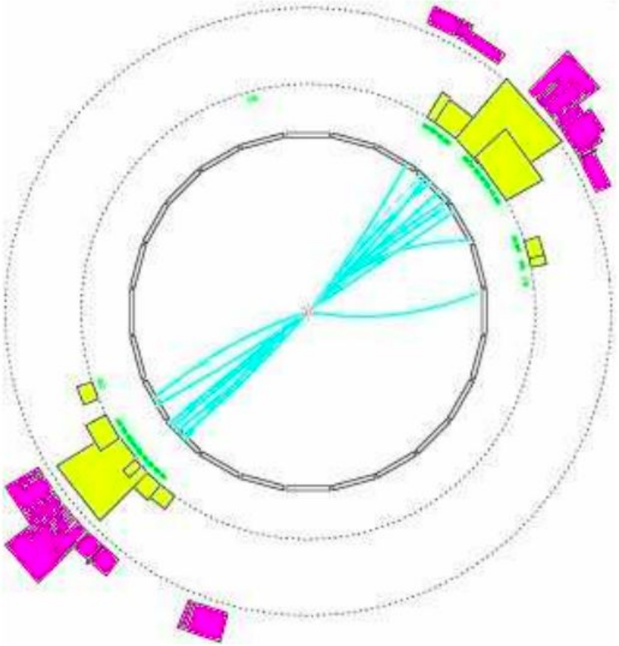
Jets at LHC

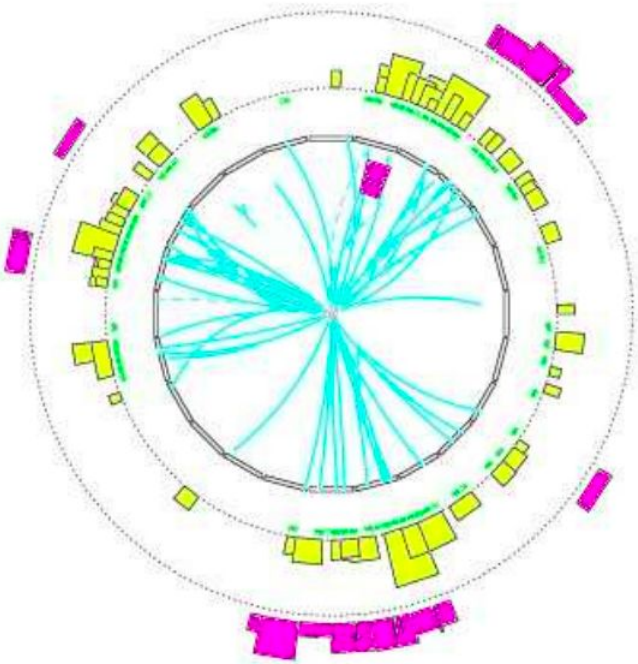
- Jets of particles leave signals in components such as the **tracker** and the **electromagnetic and hadronic calorimeters**



Jet finding

How many jets do you see?





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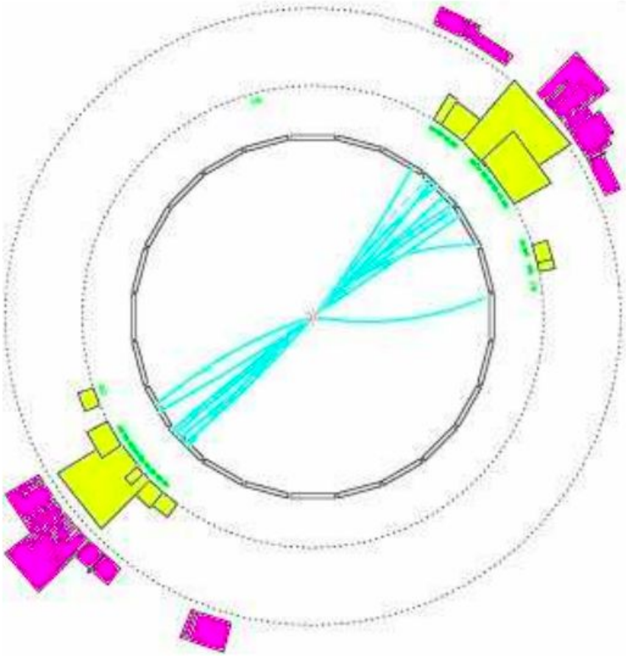

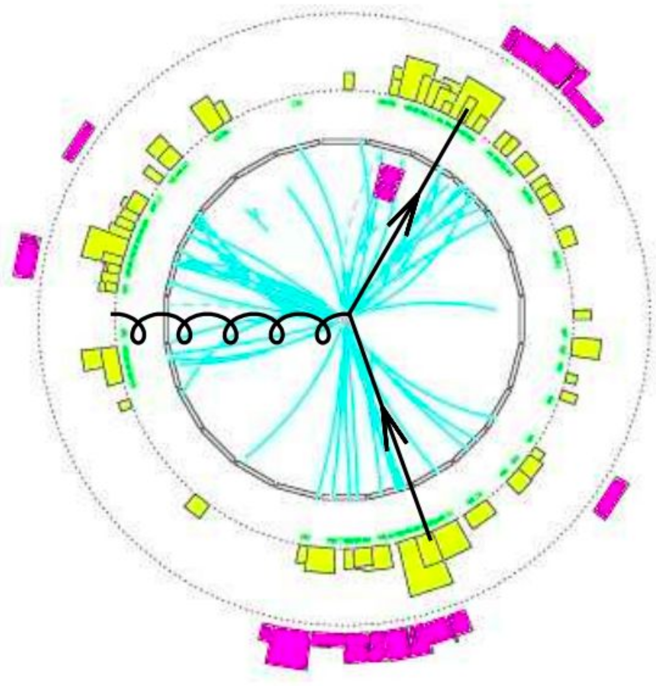

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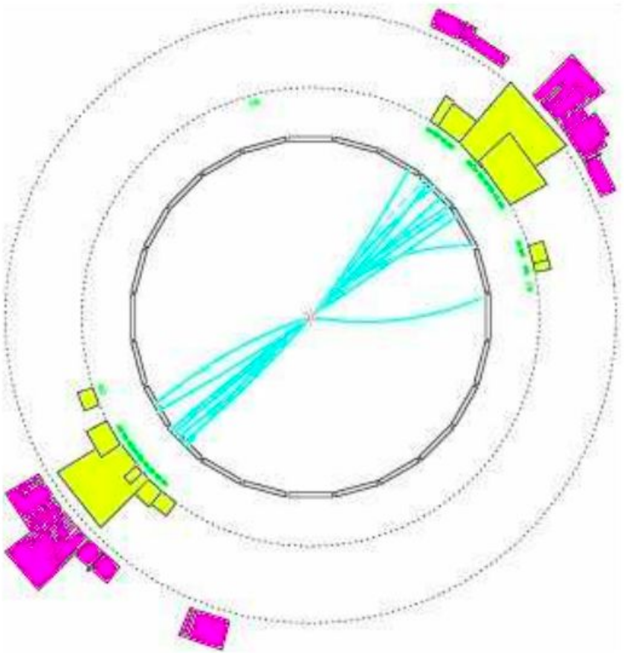
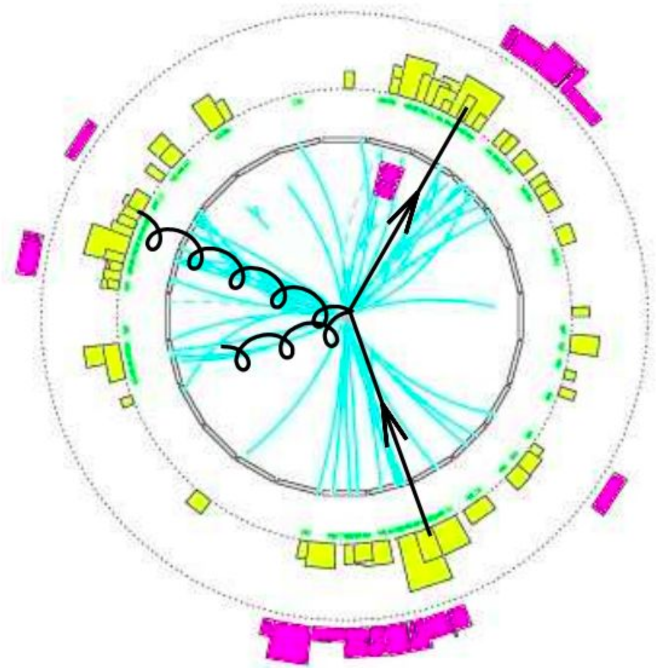




Jets algorithms

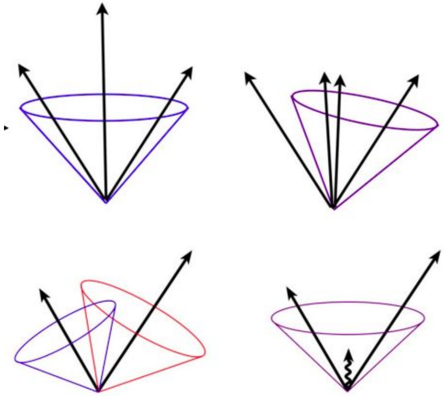
- To decide unambiguously whether a measured object belongs to a jet or not, a mathematical prescription is required - **jet algorithm**
- Algorithm has to be applicable to theoretical calculations as well as to measurements from different experiments

Jets should be invariant with respect to certain modifications of the event:

➢ **<u>collinear splitting</u> :**
  - Collinear splittings should not bias jet finding

➢ **<u>infrared emission :</u>**
  - soft radiation should not affect jet configuration
  - Only observables that are IR safe can be calculated in pQCD

➢ Jet should be independent of detector technology



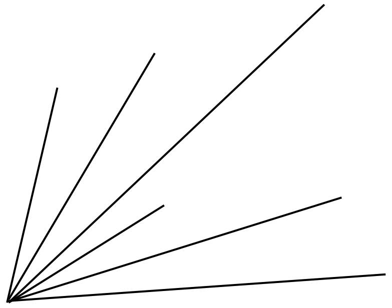
Jets algorithms

- Cone algorithms
  - particles in jets will show up in conical regions and thus they cluster based on (η-φ) space, resulting in jets with rigid circular boundaries
  - select the most energetic particle as a seed with the
  - constituents within cone of radius R are considered part of the jet

- Sequential Clustering Algorithms
  - particles within jets will have small differences in transverse momenta and thus groups particles based on momentum space, resulting in jets that have fluctuating areas in (η-φ) space.

Sequential Clustering Algorithm

- Work their way backwards through this branching by combining pairs of particles into a single one
- A distance measure based on angular separation and energy/pT of constituent has to be determined
- The particles that are closest are combined



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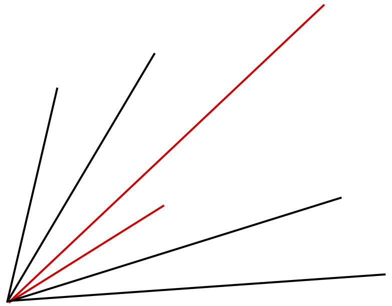

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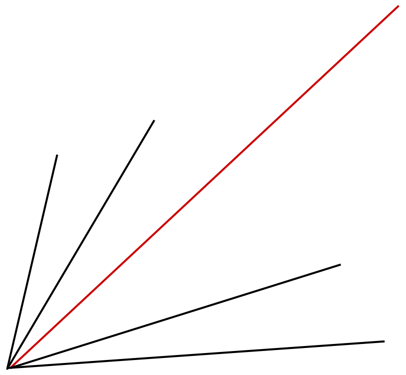

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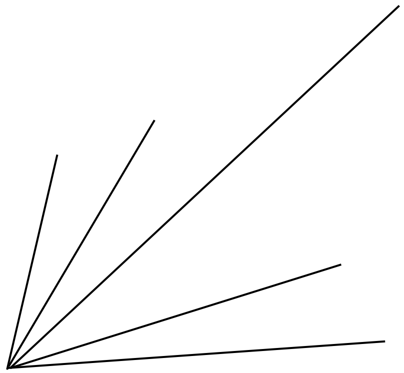

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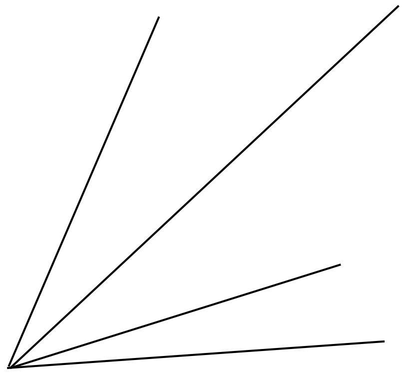

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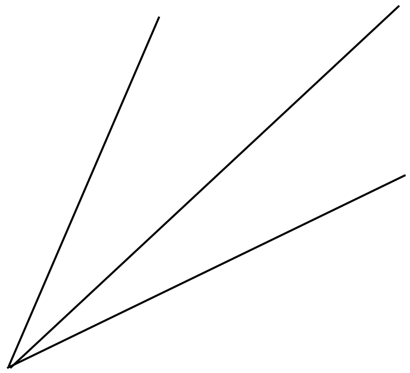

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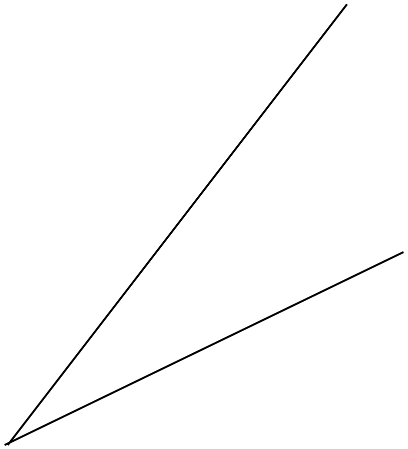


How do we decide which particles should we combine?

When do we stop combining particles?

Sequential Clustering Algorithm

- Distance between two particles:

$$d_{ij} = min(p_{ti}^a, p_{tj}^a) \times \frac{R_{ij}^2}{R}$$

space distance between the two particles

radius parameter which determines the final size of the jet

exponent corresponding to a particular clustering algorithm

- Distance between the beam axis and the detected particle:

$$d_{iB} = p_{ti}^a$$

Sequential Clustering Algorithm

- Distance between two particles:

$$d_{ij} = min(p^a_{ti}, p^a_{tj}) \times \frac{R^2_{ij}}{R}$$

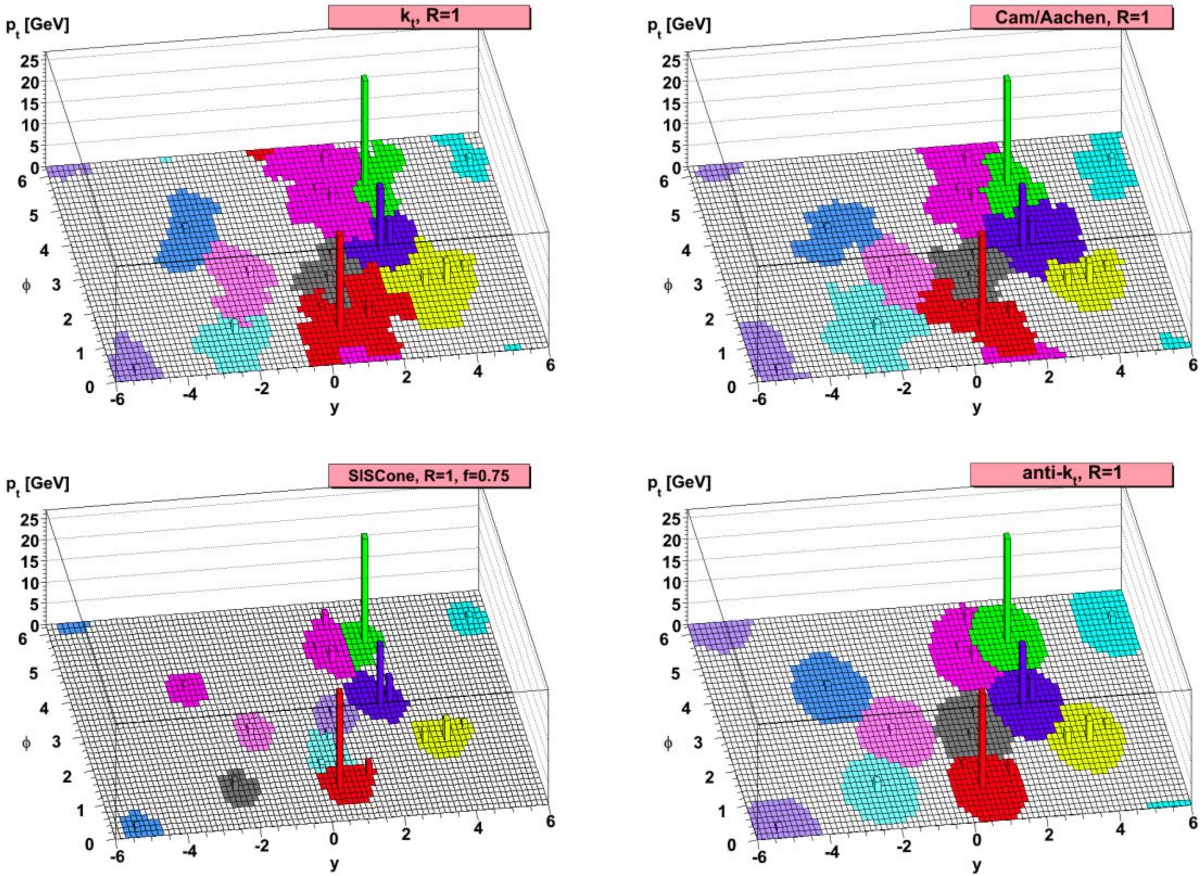
- Distance between the beam axis and the detected particle:

$$d_{iB} = p^a_{ti}$$

Algorithm flow:

- Find the minimum distance
- If d_{ij} is the minimum : particles *i* and *j* are combined into one particle *(ij), i* and *j* are removed from the list of particles
- If d_{iB} is the minimum: *i* is labelled a final jet and removed from the list of particles
- This process is repeated until:
  - all particles are part of a jet with the distance between the jet axes R_{ij} greater than R - **inclusive clustering**
  - desired amount of jets have been found - **exclusive clustering**

Sequential Clustering Algorithm



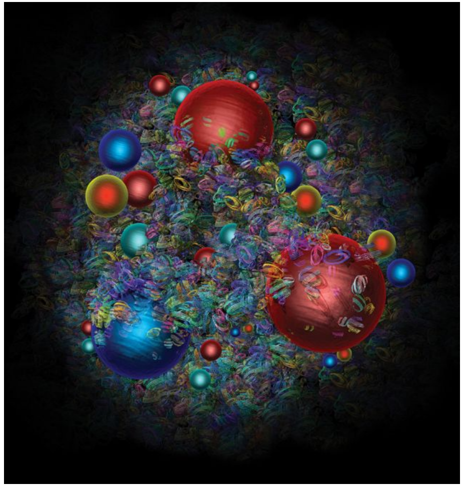
Proton-proton collisions

- Protons are baryons composed of two ***u*** quarks and one ***d*** quark ("valence" quarks) and "sea" quarks

- Quarks and gluons within protons are referred to as **partons**

- Structure of proton described by the **Parton model**

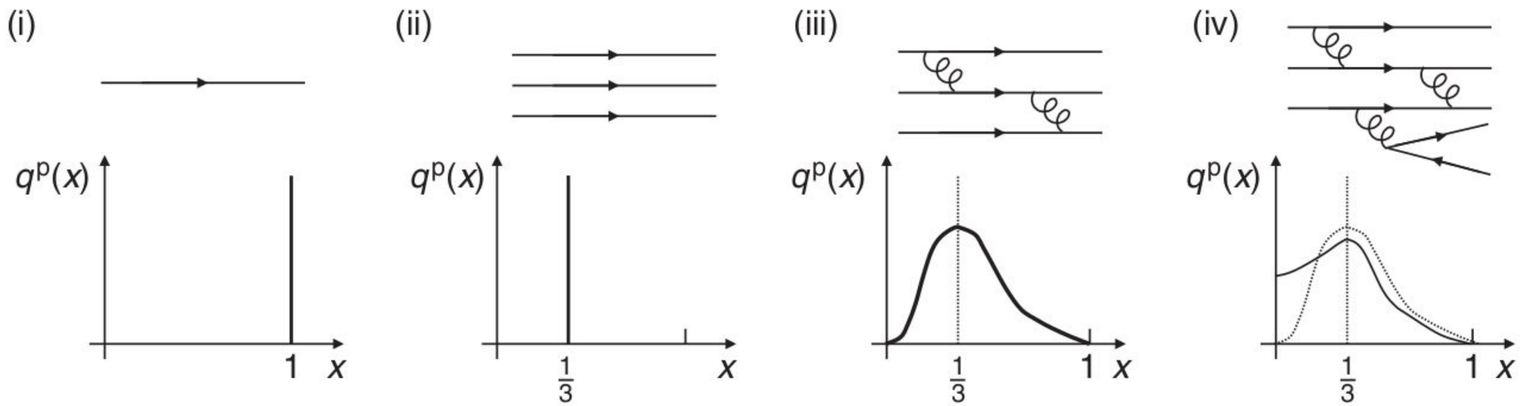
  ⇒ partons carry a fraction of the total proton momentum, which gives the probability that parton has a fraction *x* of the total proton momentum *P* ($p_i = xP$)



Parton distribution function

- The quarks inside the proton will interact with each other through the exchange of gluons
- The dynamics of this interacting system will result in a distribution of quark momenta within the proton
- These distributions are expressed in terms of **Parton Distribution Functions (PDFs)**

Forms of the quark PDFs :



single point-like particle

3 static quarks

3 interacting quarks which can exchange momentum

interacting quarks including higher-order diagrams

Parton distribution function

- Functional forms of the PDFs - not a priori known and **have to be obtained from experiment**
  - deep inelastic scattering (DIS) experiments such as lepton-hadron collider HERA
  - hadron colliders such as LHC
  - the fixed-target experiments

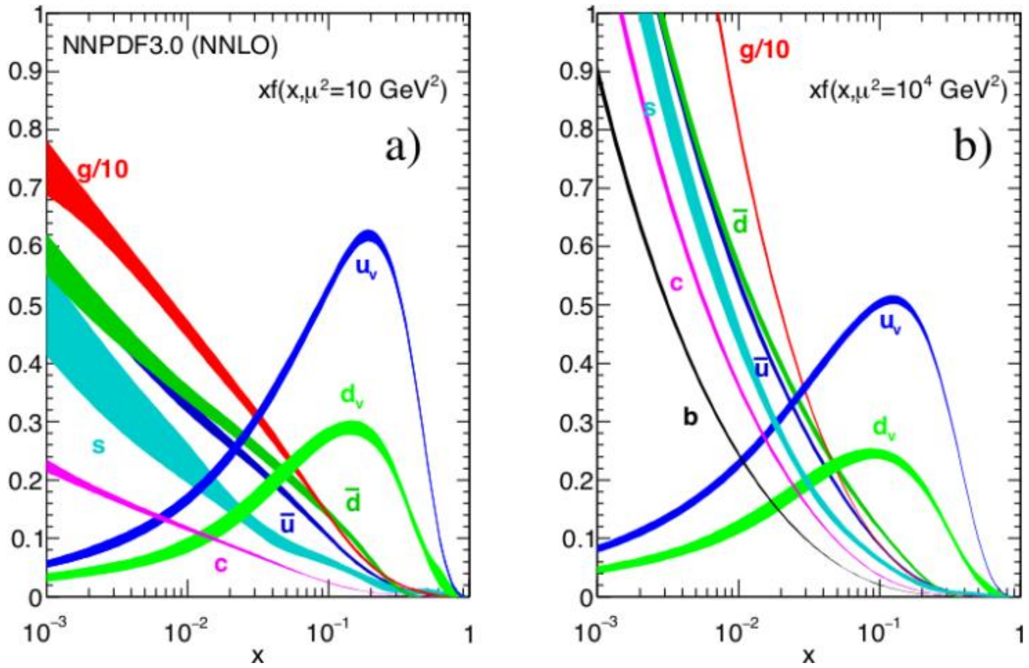
- The PDFs depend on the scale at which the hadron is probed
- Evolution of PDFs with the scale μ_F described by the **Dokshitzer-Gribov-Lipatov- Altarelli-Parisi (DGLAP) equations**:

$$\mu_F \frac{\delta f_a(x,\mu_F)}{\delta \mu_F^2} = \sum \frac{\alpha_s(\mu_F^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} P_{a\to bc}(\frac{x}{\xi},\mu_F) f_a(\xi,\mu_F)$$

- $P_{a\to bc}$ - Altarelli-Parisi splitting function, that gives the probability for a parton *a* to split into two partons *bc*.
- ξ - resulting particle momentum fraction of the quark with momentum p_a

Parton distribution function

- Because of the universality of the PDFs, it is possible to use PDFs extracted from well-known processes to obtain predictions corresponding to different scales or different final states



Cross section

- The **cross section** is a measure of quantum mechanical probability for the interaction
- It depends on the fundamental physics involved in the Feynman diagrams that contribute to the process

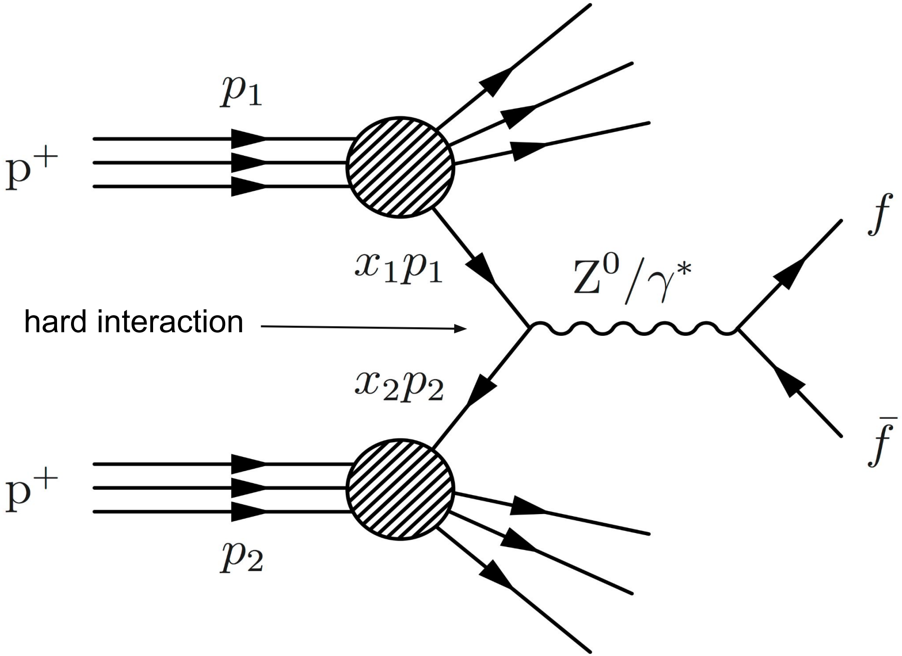
- The cross section of a proton-proton interaction cannot be computed easily, due to the complex structure of protons

$$\sigma_{pp\to X} = \sum_{a,b} \int \int dx_a dx_b f_a(x_a, \mu_F) f_b(x_b, \mu_F) \underline{\sigma_{ab\to X}(x_a x_b, \mu_R, \mu_F)}$$

cross section at the partonic level.

Drell-Yan process

➢ Annihilation of **quark-antiquark** pairs from hadrons with the **creation of a Z boson or a virtual photon**, which decays into a **lepton-antilepton pair**



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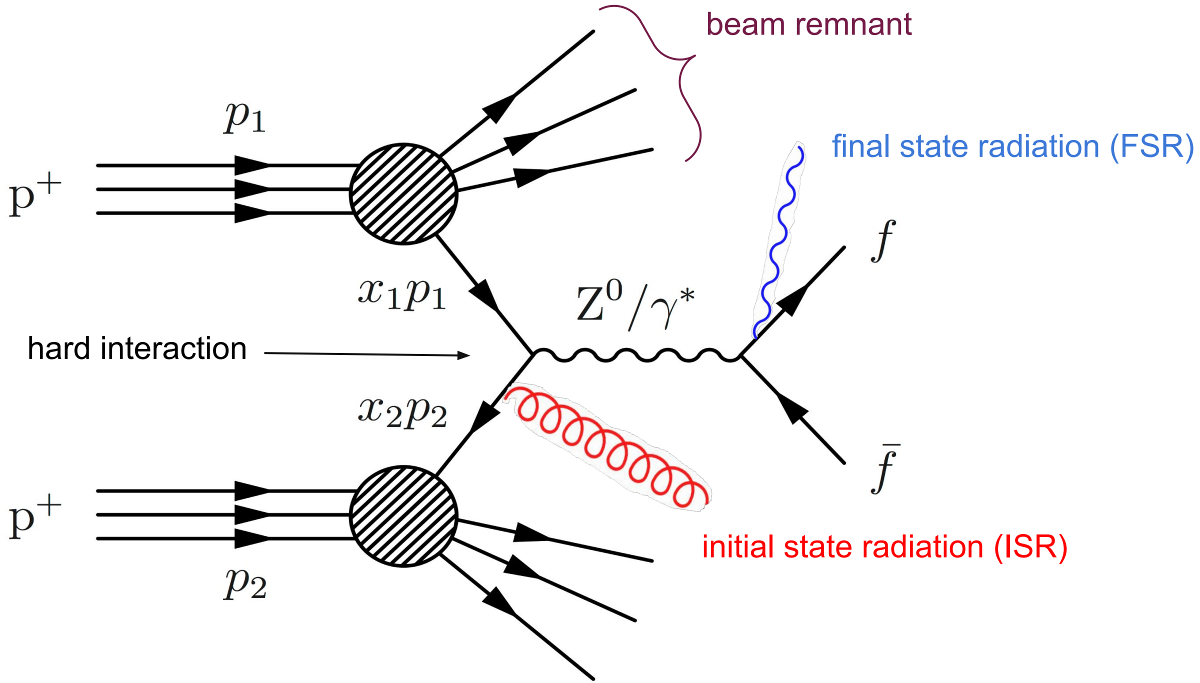
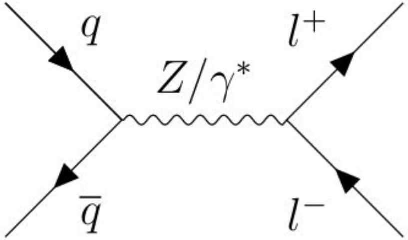
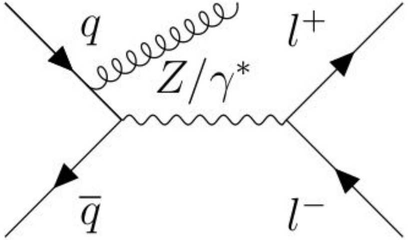
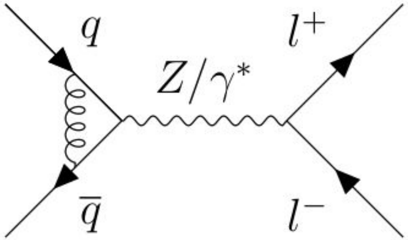
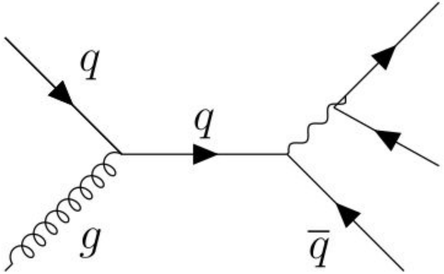


Drell-Yan process higher orders









Drell-Yan process cross section

- The cross section of the Drell-Yan process:

$$\sigma(pp \to l^+l^-) = \sum_q \int\int dx_q dx_{\bar{q}} f_q(x_q, \mu_F^2) f_{\bar{q}}(x_{\bar{q}}, \mu_F^2) \sigma(q\bar{q} \to l^+l^-)$$

- Following the perturbative QCD, the partonic cross section can be expanded in series with respect to the coupling constant α_s :

$$\sigma(q\bar{q} \to l^+l^-) = \sigma_{LO} + \alpha_s \sigma_{NLO} + \ldots$$

- The partonic cross section can be calculated using the Matrix Element of the Feynman diagram

Theoretical predictions

- To establish connection between theory and experiment it is necessary to simulate the proton-proton interactions

- The evolution of an event in simulation starts with the **two beam particles that are colliding**
- The partons from beams start irradiating - **initial state shower** is simulated
- The incoming partons enter the **hard interaction** and the outgoing particles are produced
- In the hard process, **short-lived resonances** can be created and their decay is considered in this step
- The outgoing particles undergo radiation - **final state radiation** is simulated.
- The simulation of **underlying events**.
- The process of **hadronization** is simulated.
- The **decay of long-life particles**, such as τ leptons or B-hadrons.