Introduction to jets and jet finding

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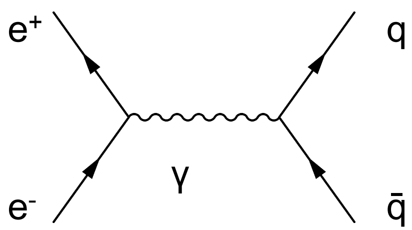
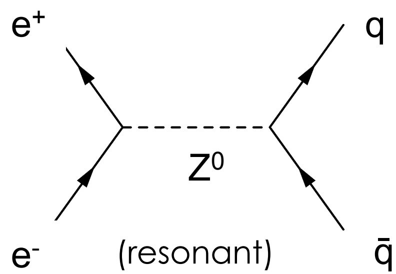
Outline

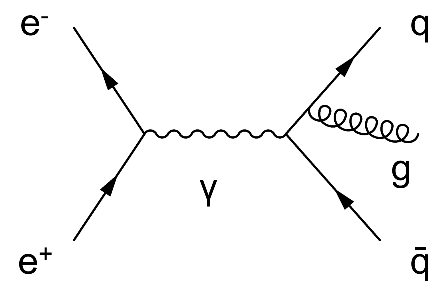
- Hard scattering processes
- Fragmentation Functions (FFs)
- Parton Distribution Functions (PDFs)
- QCD factorization
- Jets as probes of the QGP
- Jet finding
- Experimental challenges of jets in HI
- Jets in ALICE

Hard scattering processes

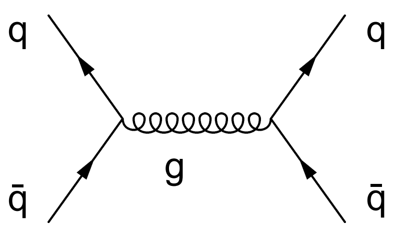
Electroweak processes (e.g. LEP)



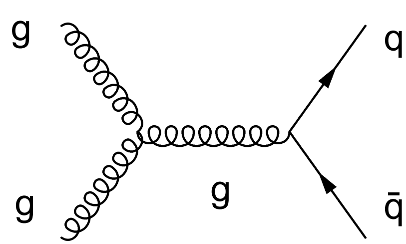




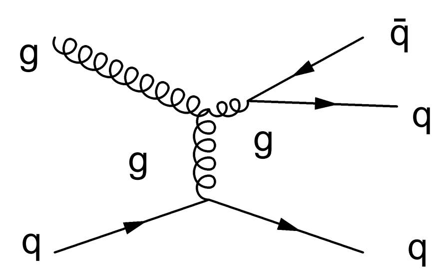
Quantum-Chromo-Dynamics processes (Tevatron, RHIC, LHC,…)



(most common at **Tevatron/RHIC** energies)



(most common at **LHC** energies)

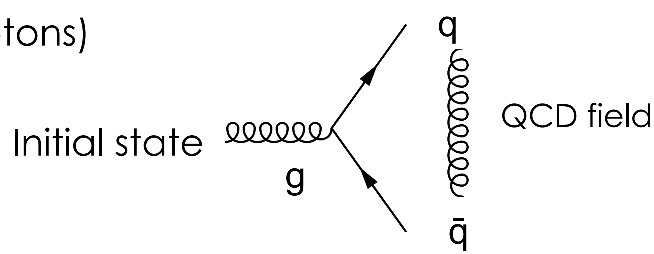


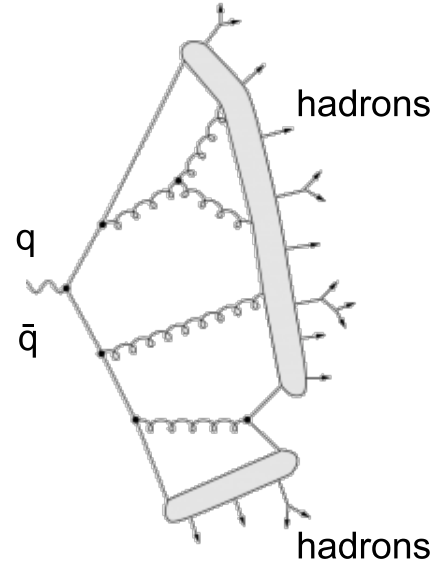
…and *t*-channels, 2^{nd} order diagrams, etc.

- ✓ **Quarks and gluons** in the final state
- ✓ **High momentum transfer**

"After" the scattering: Fragmentation Functions (FFs)

- QCD is a quantum field theory that has many non-trivial properties that derive from the SU(3) gauge symmetry
- Gluons bring **color-charge** (as opposed to the neutral photons)
  - Anti-screening effect (opposite of QED!)
  - Interaction strength grows with distance
  - Confinement and Asymptotic freedom
- As the distance between two quarks becomes larger the QCD field grows greatly (at the expenses of the kinetic energy)…
  - …till the energy of the field is high enough that a virtual $q\bar{q}$ can go on mass shell
- If the total available energy is enough the process can repeat many times, eventually leading to a "spray" – jet – of hadrons
  - **Partons fragment into jets**
  - Jets are always produced **back-to-back** (in the c.m. frame)



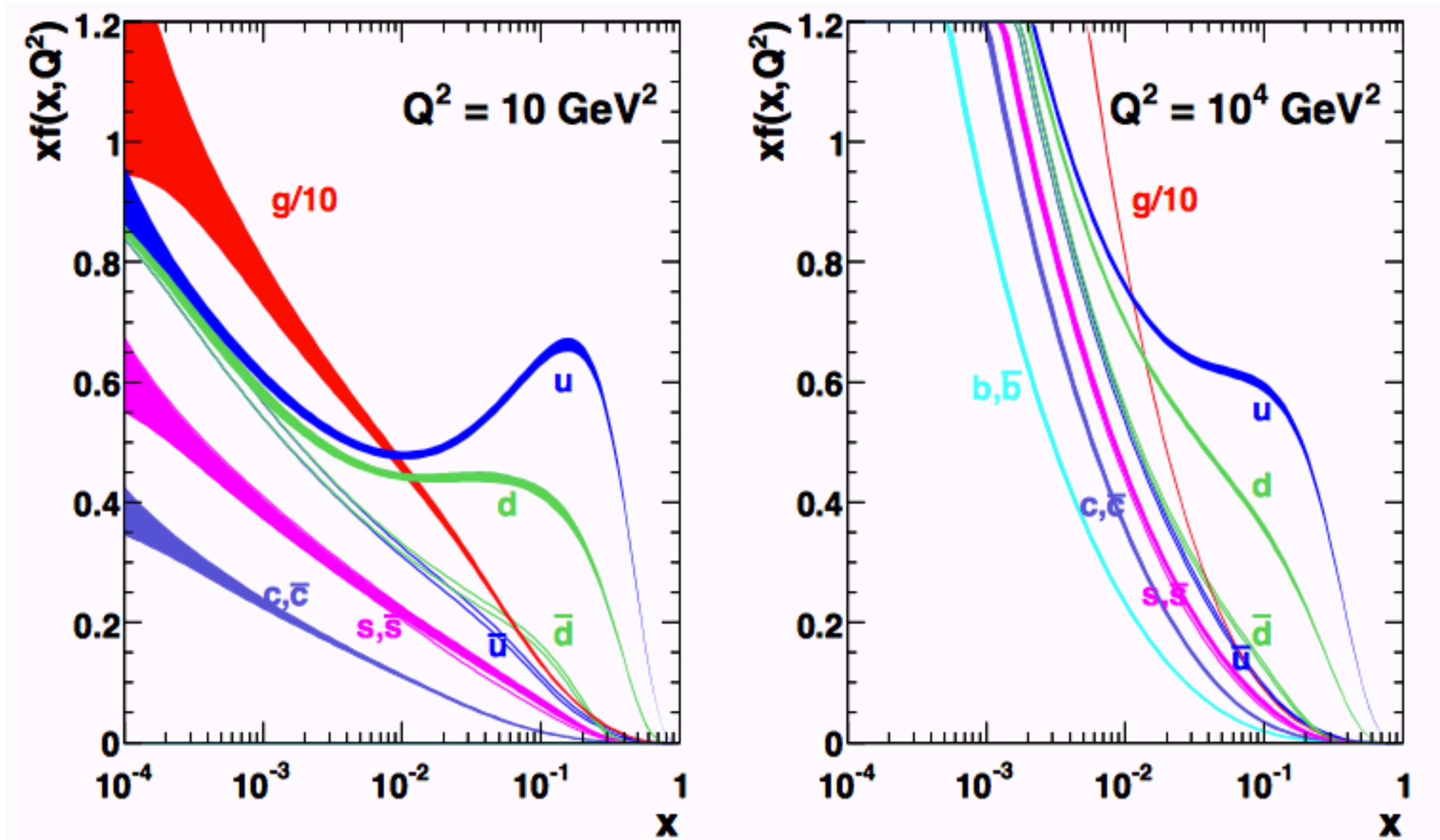


"Before" the scattering: Parton Distribution Functions (PDFs)

- In e^+e^- collisions the initial state is defined completely by the kinematics of the beams
- In pp, p$\bar{\text{p}}$ or AA collisions the initial state is determined also by the internal structure of the colliding particles
  - Parton Distribution Functions (PDFs) have been studied since the late '60s in Deep-Inelastic-Scattering (DIS) experiments

$f_{i/N}(x, Q^2)$ = probability of having a **parton** of type **i** in a **nucleus** of type **N** that carries a **fraction** x of the nucleus momentum when the **exchanged 4-momentum squared** is Q^2

Example of PDFs



QCD Next-to-Leading-Order (NLO) calculation from http://arxiv.org/pdf/0901.0002v3.pdf

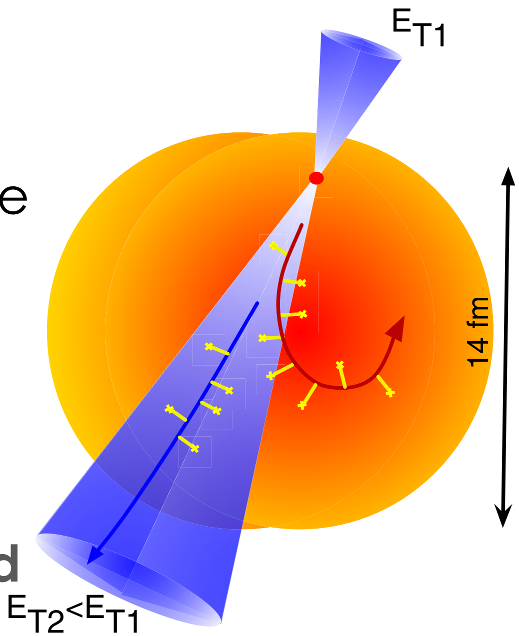
QCD factorization

- **QCD factorization theorem**: can separate the perturbative QCD processes (**hard scattering**) from the non-perturbative low-momentum ones (**parton distribution function** and **fragmentation**)
  - **Initial state (PDFs)** + **hard scattering** + **final state (FFs)**

$$d\sigma^{NN\rightarrow h+X} = \sum_{fijk} \boxed{f_{i/N}(x_1, Q^2) \otimes f_{j/N}(x_2, Q^2)} \otimes \boxed{\hat{\sigma}_{ij\rightarrow f+k}} \otimes \boxed{D^{vac}_{f\rightarrow h}(z, \mu_f^2)}$$

Jets and the QGP

- **Why are jets relevant to relativistic heavy-ion physics?**
- In a single AA collision, thousands of partons collide
  - Most of these collisions are low-momentum collisions
  - Lattice QCD predicts that a thermalized plasma, made of quark and gluons, is formed (QGP)
  - A few hard scatterings happen in this QCD-rich environment
- Which **aspects of jet production are likely modified** by the medium?
  - The **initial state (PDFs)** exists before the medium is formed
  - The **hard scatterings** involve highly virtual partons, which means that they can "survive" for a very short time (Heisenberg principle): the time scale is much shorter than the formation of the medium
  - **The fragmentation function is the major candidate to look for modification**

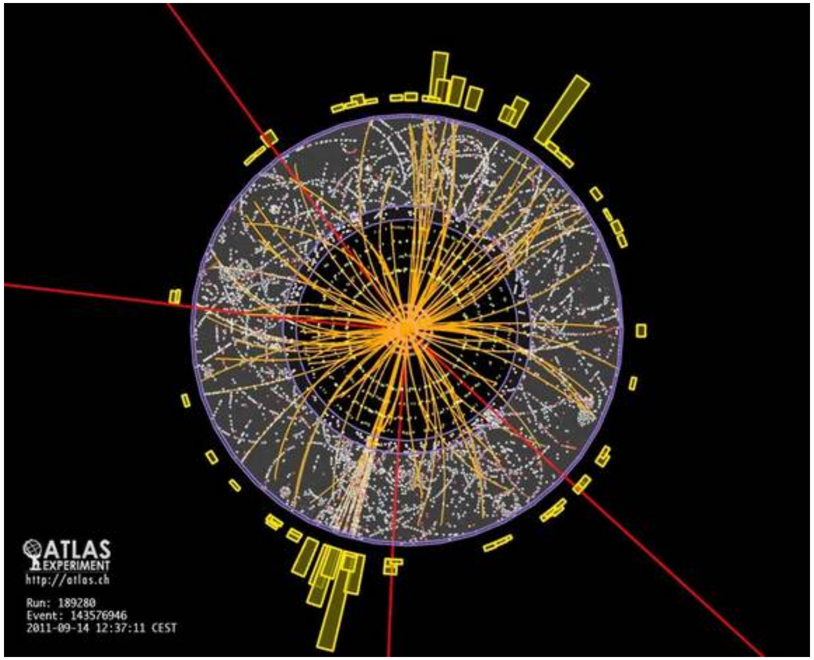


Note: the hadronization part of the **FF** happens at a time scale $1/m_h$: for most hadrons (low mass) this happens **outside** the medium!

Jets as probe of the QGP

- What can we expect from jet measurements in AA collisions?
- Jet quenching
  - Suppression of jet yield
  - Broadening of jet shape
  - Disappearance of away side jets
  - Di-jet or γ-jet energy imbalance
  - …

Jet finding



- Ok, this is nice… but how do we actually measure jets?
- Basic idea: look for regions in the η, ϕ phase space with many high momentum particles
  - Need an algorithm to do this efficiently and quantitatively
  - Attempt to recover the kinematics of the original hard scattered parton
- Cone algorithms
  - Draw a cone of radius R around the most energetic particle in the event and sum all the momenta within that cone
  - Remove this cone from the event and repeat until no more particles above threshold are found
  - Can be improved in several (some very complicated) ways

IRC-safety

- Jet finding algorithms are good, but not perfect
- Very hard to reconstruct the kinematics of the original parton
- Need to use the same algorithm in phenomenological model to compare with data
- Some constrains on the algorithms from theorists
  - **Infra-Red safety**: the outcome of the algorithm should not change because a low momentum particle is added to the event
  - **Collinear safety**: if a particle splits into two collinear particles the outcome should not change
- Important to avoid singularities in the calculations!

Sequential recombination algorithms

- Most **cone algorithms are not IRC-safe** (exception: SISCone)
- **Sequential recombination algorithm** are a nice alternative
  - Used to be very slow
  - Modern, fast implementation: **FastJet**
  - Widely used at LHC
- Based on the definition of a measure

$$d_{\mathrm{ij}} = \min(k_{\mathrm{Ti}}^{\mathrm{p}}, k_{\mathrm{Tj}}^{\mathrm{p}}) \frac{\Delta_{\mathrm{ij}}^2}{R^2}$$

$$d_{\mathrm{iB}} = k_{\mathrm{Ti}}^{\mathrm{p}}$$

k_{Ti} = transverse momentum of particle i

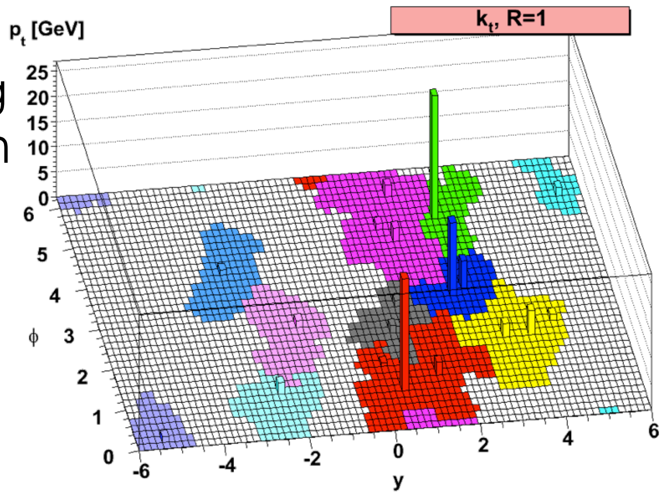
The choice of the **exponent p** distinguish one algorithm from the other:

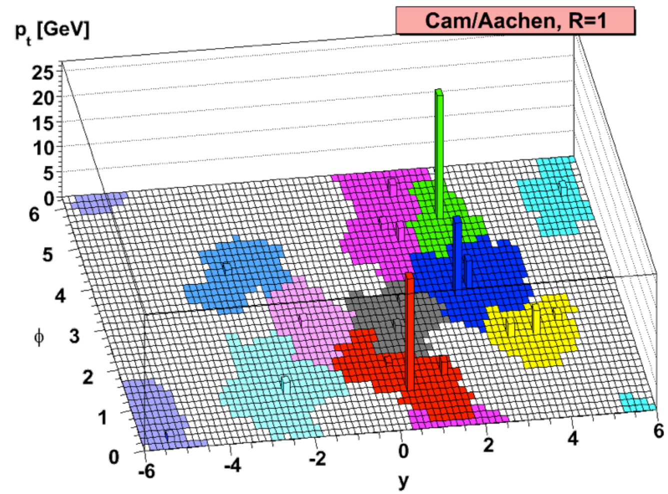
- p = 0: **Cambridge/Aachen**
- p = 2: $\boldsymbol{k_{\mathrm{T}}}$
- p = -2: **anti-$\boldsymbol{k_{\mathrm{T}}}$**

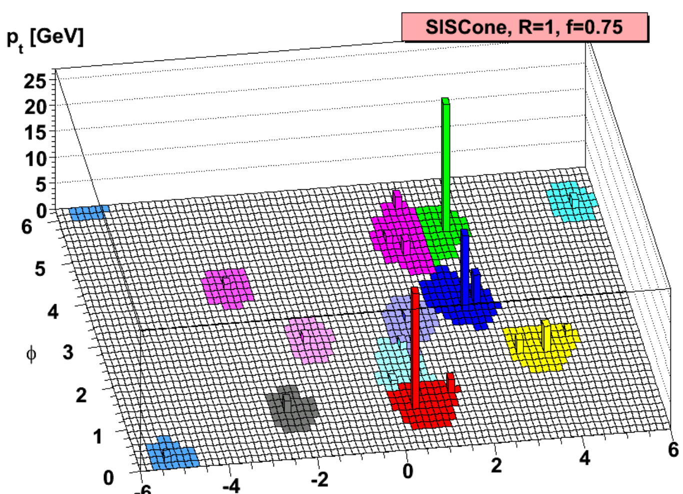
All these algorithms are IRC-safe!

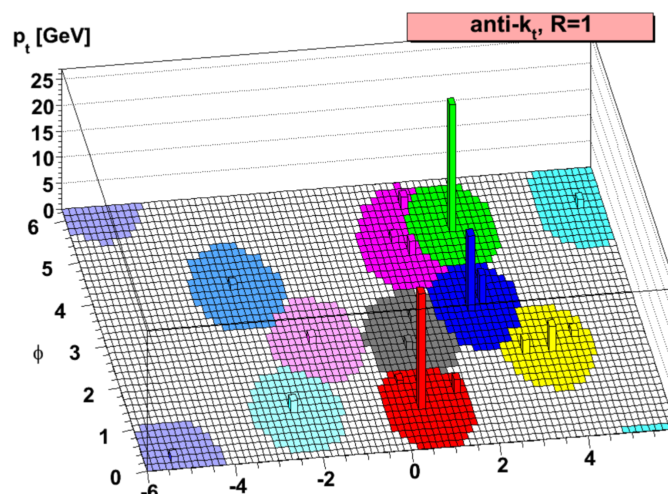
A parton-level example

Clustering starts from low-p_T particles



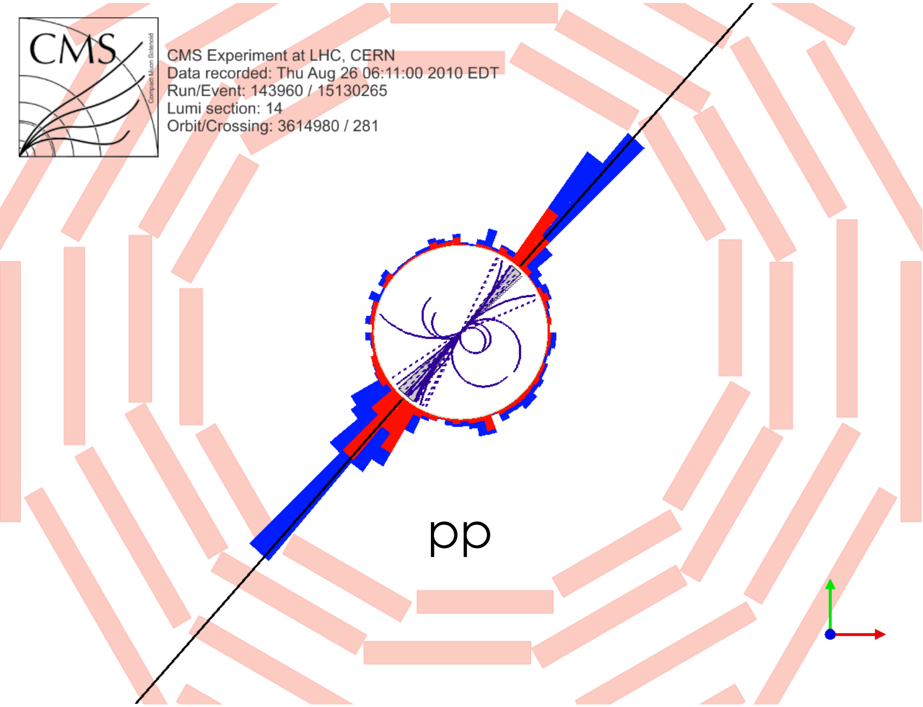


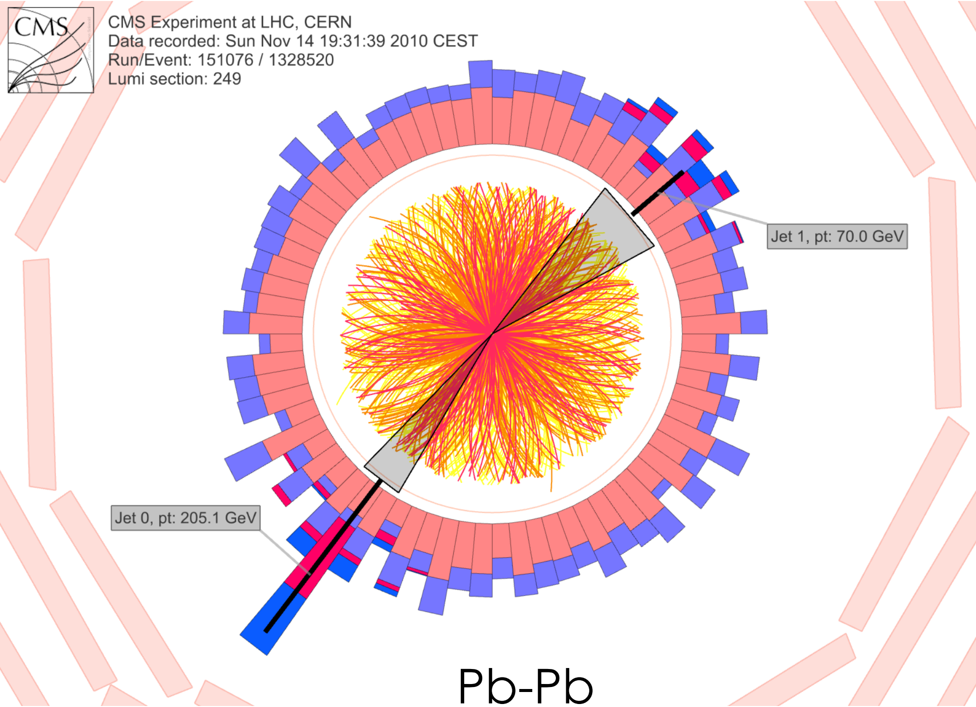




Clustering starts from high-p_T particles, “soft-resilent” algorithm

Experimental challenges



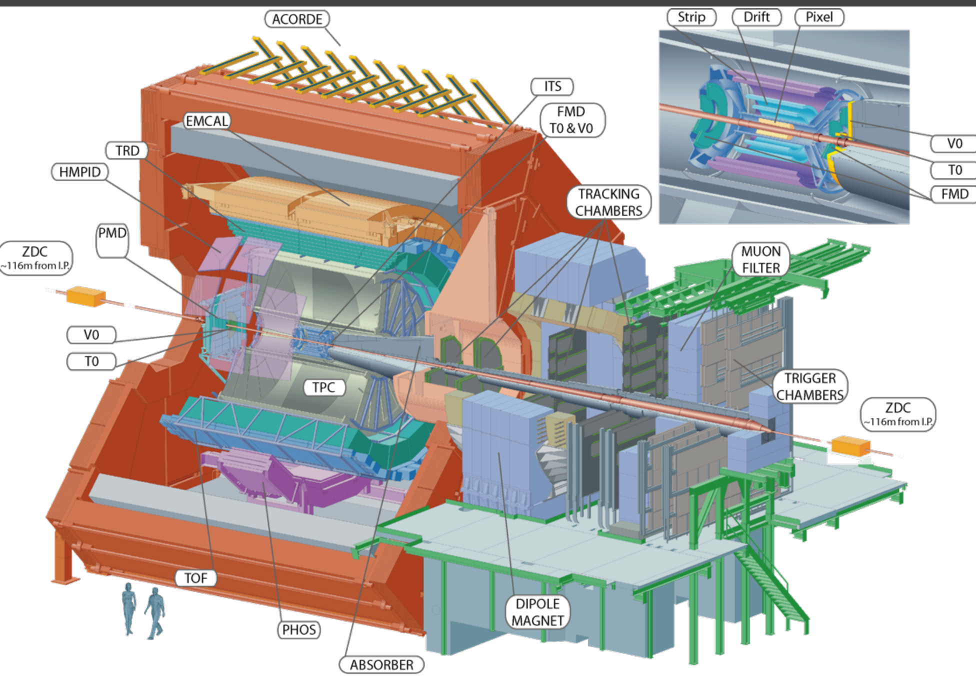


Huge background in Pb-Pb: looking for a jet is like looking for a (big) needle in a haystack!

Background in AA collisions

- Huge background, **difficult to disentangle from the hard scattering**
  - theoretically – the scattered parton interacts with the medium
  - experimentally – we don't know the history of each particle, only their final state
- Jet finders cluster ALL particles in the event: only a very small fraction are "real" jets, the rest are low-momentum particles randomly clustered together
- Reduce **combinatorial (fake) jets** by using only high momentum particles and/or requiring a high momentum leading hadron
  - Bias the fragmentation!
- Several strategies to **subtract the background**, two main differences
  - CMS/ATLAS: subtract background BEFORE jet finding
  - ALICE/STAR: subtract background AFTER jet finding
- **Region-to-region fluctuations** in the background are important
  - Affect jet momentum resolution

Jets in ALICE

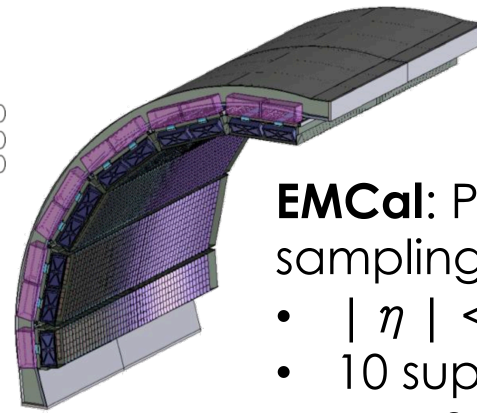


Tracking: $|\eta| < 0.9$, $0 < \Phi < 2\pi$

TPC: gas detector

ITS: silicon detector

Charged constituents



EMCal: Pb-scintillator sampling calorimeter

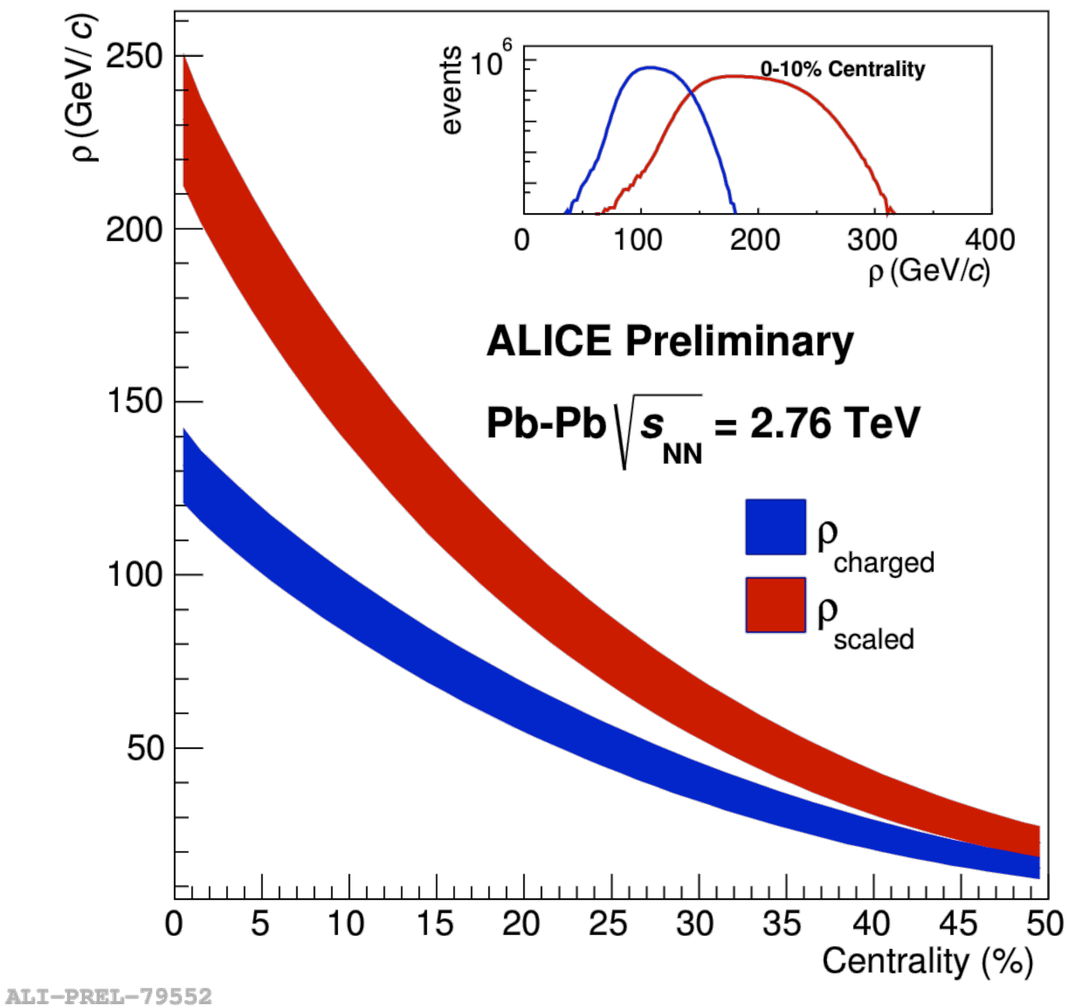
- $|\eta| < 0.7$, $1.4 < \phi < \pi$
- 10 supermodules, 11152 individual towers

Charged particle correction prevents double counting

Neutral constituents

JET

ALICE: average background



- Event-by-event **charged background density**:

$$\rho_{\text{charged}} = \text{median}\left(\frac{p_{\text{T}}^{k_{\text{T}}\,\text{jet}}}{A^{k_{\text{T}}\,\text{jet}}}\right)$$

- Median approach reduces bias from signal jets
- **Scaled** to account for neutral energy:

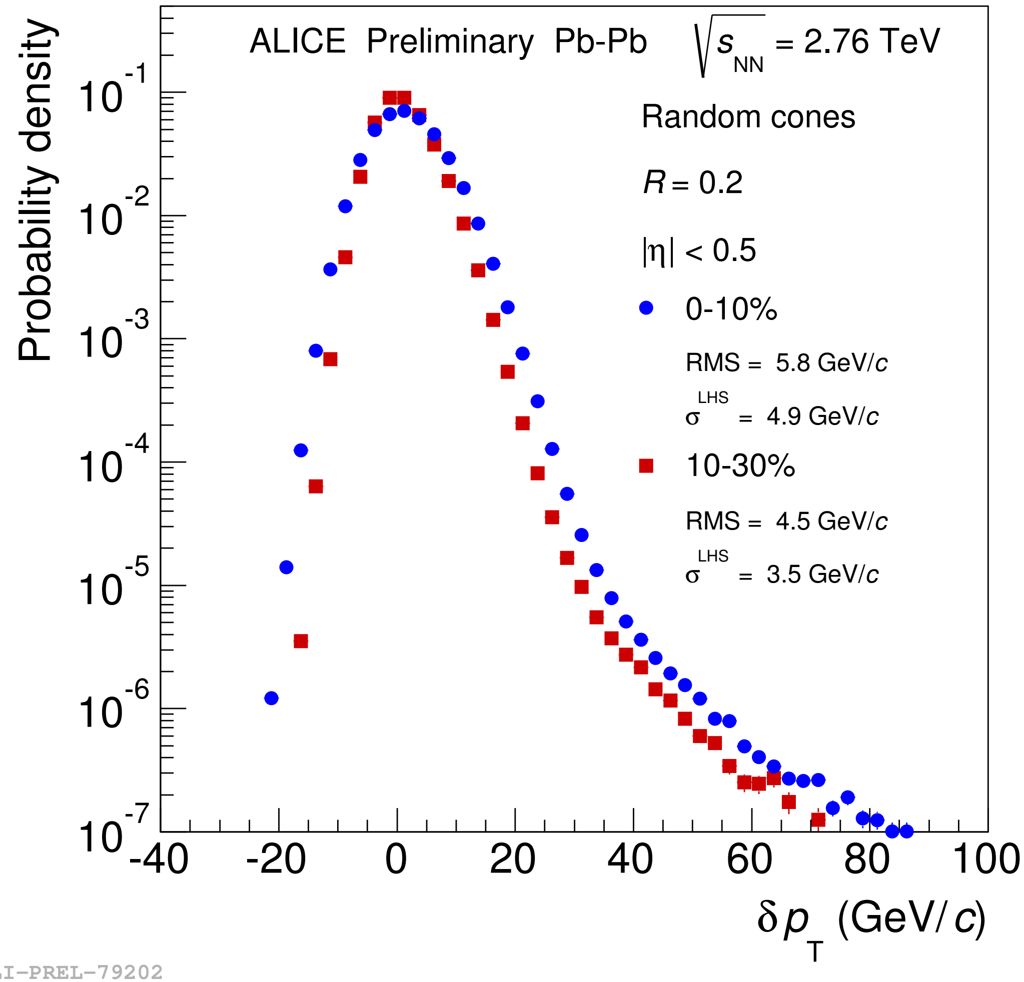
$$\rho_{\text{scaled}} = s_{\text{EMC}} \cdot \rho_{\text{charged}}$$

- Background density in most central events:

~ 200 GeV/c per unit area

~ 25 GeV/c for an R = 0.2 jet!

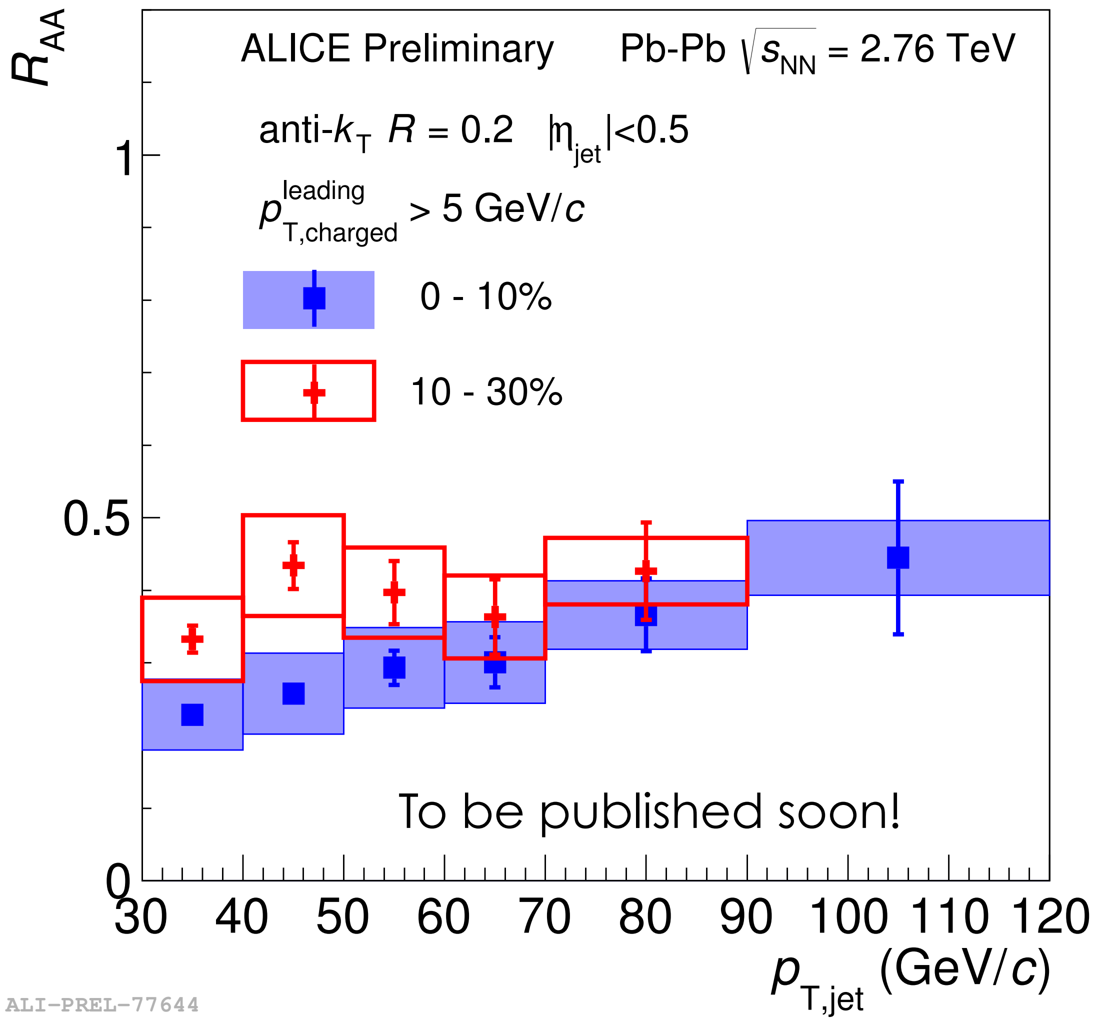
ALICE: background fluctuations



- Background density fluctuates within event
  - Smears jet momentum
- Fluctuation size characterized by δp_{T}

$$\delta p_{\mathrm{T}} = \sum p_{\mathrm{T,\,part}} - \rho_{\mathrm{scaled}} \pi R^2$$

ALICE: jet suppression



- Compare with jet yield in pp collisions
  - Need to factorize out the difference in the initial state (i.e. the PDFs)
  - Done using a Monte Carlo "Glauber" model that assumes independent binary collisions
- R_{AA} = nuclear modification factor

$$R_{AA} = \frac{1/N_{evt}\, d^2N_{jets}/dp_T d\eta}{T_{AA}\, d^2\sigma_{pp}/dp_T d\eta}$$

Conclusions

- QCD processes happen at very different time scales, which makes it possible to factorize them
- Hard scatterings happen prior to the formation of the QCD medium
- The FFs can be modified by the medium (hadronization outside of the medium for most hadrons)
  - Jet quenching effects are predicted
- Various jet finding algorithms
  - Cone (used in the past), sequential recombination (LHC)
- Experimentally challenging because of the huge fluctuating background

Backups

Nucleus and nucleon structures

- 1909: Rutherford discover the **nucleus** using scattering of α-particles through a gold foil (E ~ 5 MeV)
- 1950s: first measurements of **nuclear form factors** using scattering of electrons off a nucleus (E ~ 500 MeV)
- 1960s: **nucleon form factors** obtained using electron scattering with energies of (E ~ 1 GeV)
- Late 1960s: first electron Deep-Inelastic-Scattering (DIS) experiments are performed at SLAC (E ~ 25 GeV) – **parton structure** is first observed
- 1980: DIS experiments at CERN using muons (E ~ 300 GeV) – **“sea” quarks** are observed
- 2000s: DIS experiments at DESY (30 GeV electrons against 900 GeV protons)

Need higher energy to resolve smaller objects!

Nuclear form factors

Quantum scattering cross section can be obtained using Born approximation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{\text{Mott}} \cdot \left|F(\boldsymbol{q}^2)\right|^2$$

← nuclear form factor

where

$$\left(\frac{d\sigma}{d\Omega}\right)^{*}_{\text{Mott}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} \cdot \left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right)$$

← electron spin effects

Under Born approximation and for small $\boldsymbol{q}^2$, the nuclear form factor $F(\boldsymbol{q}^2)$ is the Fourier transform of the nuclear charge distribution:

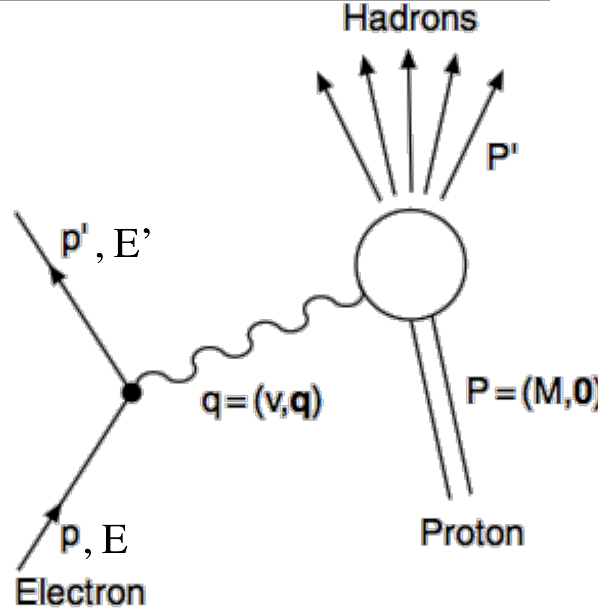
$$F(\boldsymbol{q}) = \int e^{i\boldsymbol{q}\boldsymbol{x}/\hbar} f(\boldsymbol{x}) d^3x$$

Nuclear shapes were determined to be spherical or ellipsoidal, with a charge density falling off exponentially.

Particles and Nuclei 6th ed., Povh et al., Springer

Deep-Inelastic-Scattering

- Electron scattering off a nucleus, E >> 1 GeV
- For elastic scattering with fixed beam energy, energy and momentum conservation implies that only one free kinematic parameter
- For inelastic scattering, there is an additional degree of freedom, the excitation energy of the proton; the invariant mass of the excited state is:



$$W^2c^2 = P'^2 = (P+q)^2 = M^2c^2 + 2Pq + q^2 = M^2c^2 + 2M\nu - Q^2$$

where $\nu = E - E'$

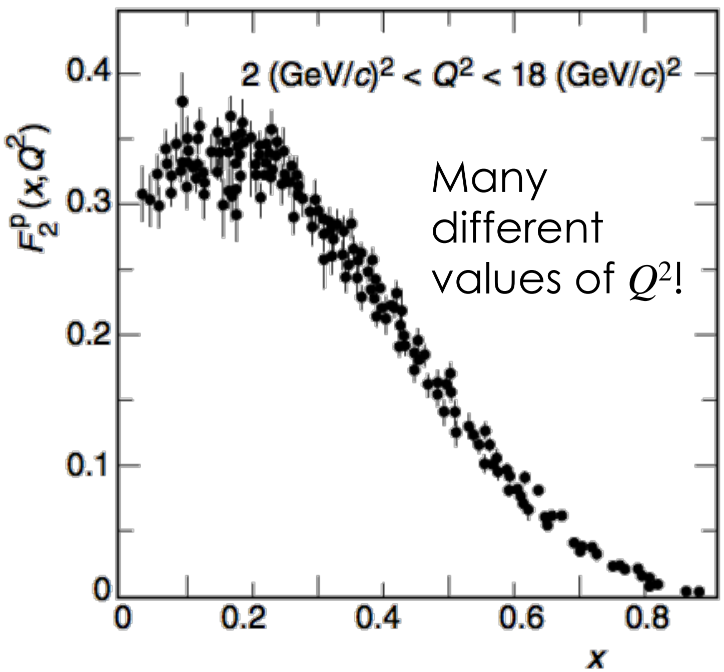
- If $W = M$ (elastic scattering), then

$$2M\nu - Q^2 = 0$$

- If $W > M$ (inelastic scattering), then $2M\nu - Q^2 > 0$

Bjorken scaling

- Define $x := \frac{Q^2}{2Pq} = \frac{Q^2}{2M\nu}$
- Elastic $2M\nu - Q^2 = 0$ → $x = 1$
- Inelastic $2M\nu - Q^2 > 0$ → $0 < x < 1$

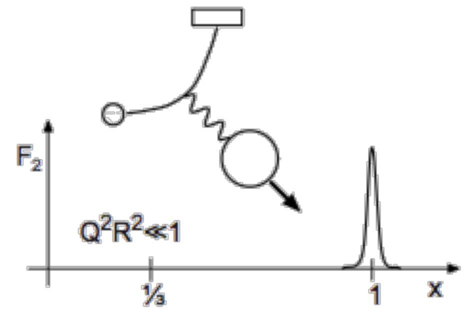


Structure function F_2 – proportional to cross section
The peak is slightly shifted to the left due to higher order effects that become important at higher Q^2, but it's interestingly close to **1/3**…

Can be interpreted as elastic scattering off a charged "parton" with mass

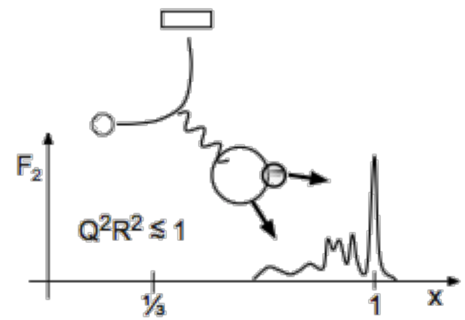
$$m_p \approx M/3$$

Parton distribution functions



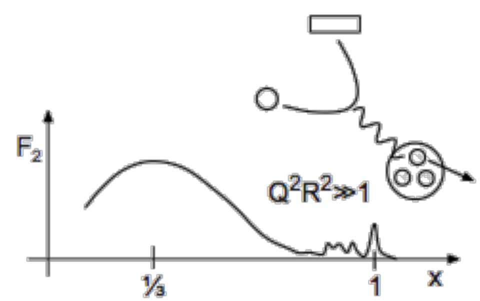
$Q^2 << 1\ \text{GeV}^2$

Elastic x = 1



$Q^2 \approx 1\ \text{GeV}^2$

Quasi-elastic (excited states of the proton)



$Q^2 >> 1\ \text{GeV}^2$

Deep-Inelastic (parton structure)

At even higher Q^2, smaller x values become available (not shown), large peak near $x \approx 0$

"Sea" quarks
=
quark-antiquark pairs

Also neutral partons: **gluons**!