Strong Interaction, Quarks + Gluons

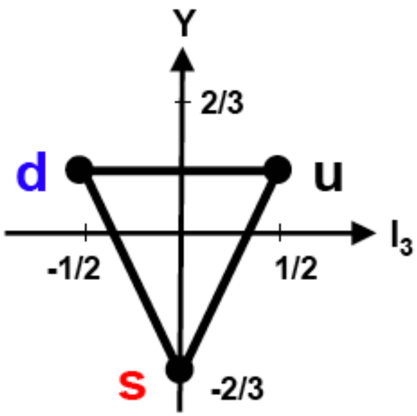
Quark Model
Partons
Gluons + QCD

Introduction to Particle Physics - Max Klein – Lecture 4 - Liverpool University 4.3.13

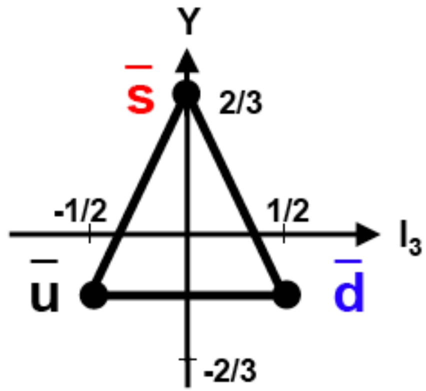
Light Quarks

Quark	Q	I_3	B	S	Y
u	+2/3	+1/2		0	+1/3
d	-1/3	- 1/2	1/3	0	+1/3
s	-1/3	0		-1	-2/3

spin
J = 1/2



Quark



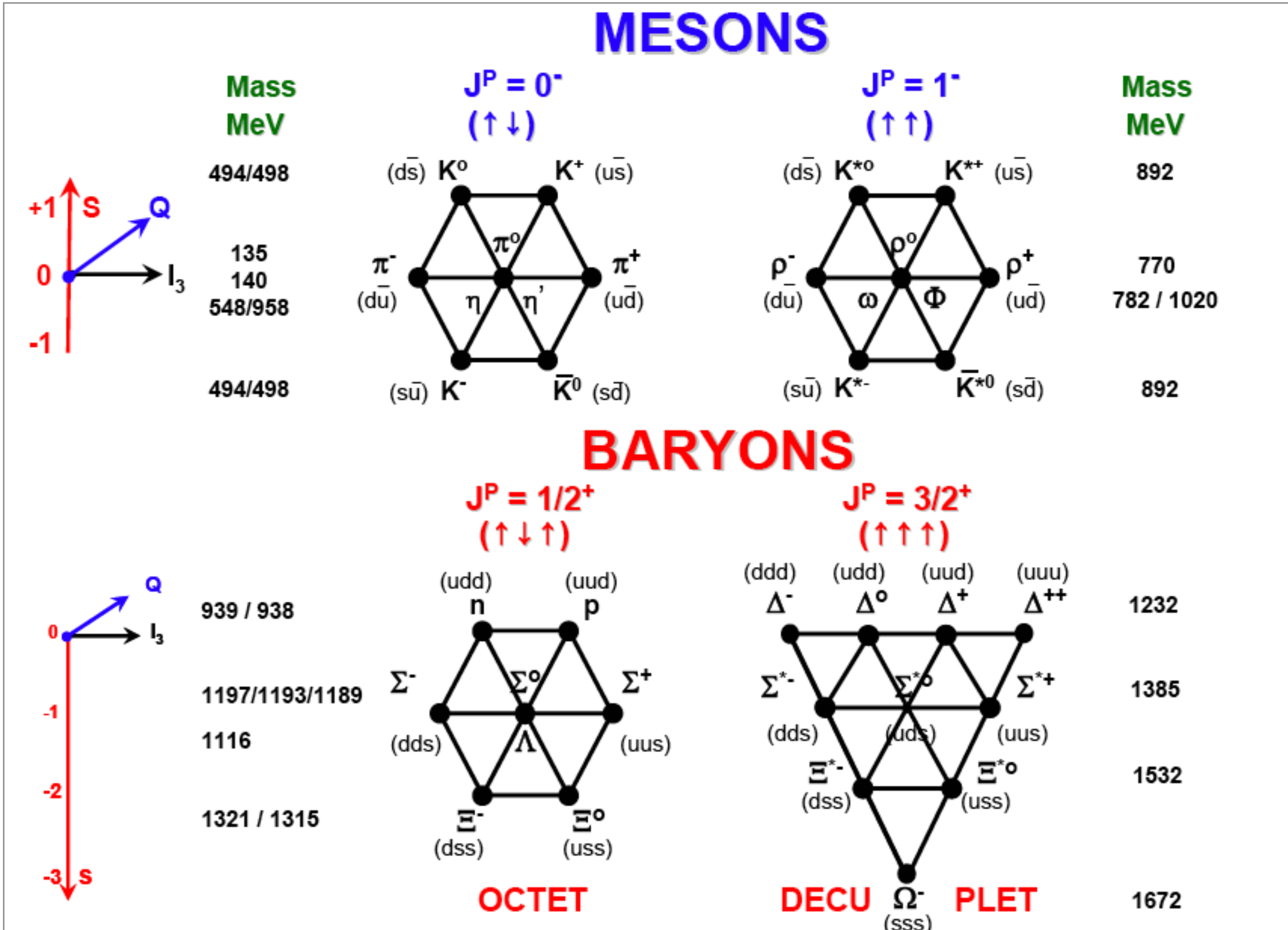
Antiquark

u	c	t
2-5 MeV	1.25 GeV	171 GeV
d	s	b
5-8 MeV	120 MeV	4.25 GeV

$Y = B + S$ hypercharge

$I_3 = Q - Y/2$ Gell-Mann - Nishijima rule

Light quarks are u,d,s, with masses much smaller than M_p


MESONS
Mass
MeV
JP = 0-
(↑↓)
JP = 1-
(↑↑)
Mass
MeV
+1
S
Q
0
I3
-1
494/498
135
140
548/958
494/498
(ds̄) K0
K+ (us̄)
π-
(dū)
π0
η
η'
π+
(ud̄)
(sū) K-
K̄0 (sd̄)
(ds̄) K*0
K*+ (us̄)
ρ-
(dū)
ρ0
ω
Φ
ρ+
(ud̄)
(sū) K*-
K̄*0 (sd̄)
892
770
782 / 1020
892
BARYONS
JP = 1/2+
(↑↓↑)
JP = 3/2+
(↑↑↑)
Q
0
I3
-1
-2
-3
S
939 / 938
1197/1193/1189
1116
1321 / 1315
(udd)
n
(uud)
p
Σ-
Σ0
Σ+
(dds)
Λ
(uus)
Ξ-
(dss)
Ξ0
(uss)
OCTET
(ddd)
Δ-
(udd)
Δ0
(uud)
Δ+
(uuu)
Δ++
Σ*-
Σ*0
Σ*+
(dds)
(uds)
(uus)
Ξ*-
(dss)
Ξ*0
(uss)
DECU
Ω-
(sss)
PLET
1232
1385
1532
1672

Light Quark Masses

1. $M_{\Sigma^-} + M_{\Sigma^\circ} - 2\ M_{\Sigma^+} = 3m_d - 3m_u = 11$ MeV

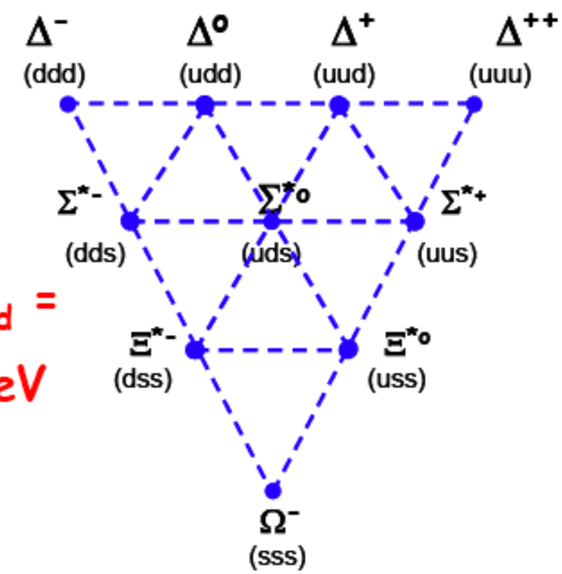
   (dds) + (uds) - 2 (uus) = 3 d - 3 u

   $m_d - m_u \sim$ MeV

2. decuplet equal spacing rule:

   $M_{\Omega} - M_{\Xi^*} = M_{\Xi^*} - M_{\Sigma^*} = M_{\Sigma^*} - M_{\Delta} = m_s - m_d =$

   142 ~ 145 ~ 153 ~ 145 MeV

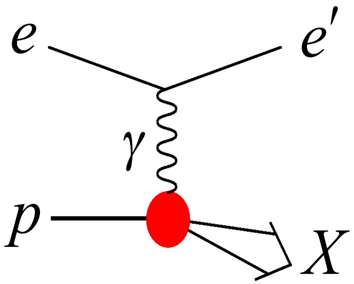


3. Gell-Mann-Okubo mass relation:

   $3\ M_{\Lambda} + M_{\Sigma} = 2\ (M_N + M_{\Xi})$

   3 (uds) + (uds) = 2 [(uud) + (dss)]

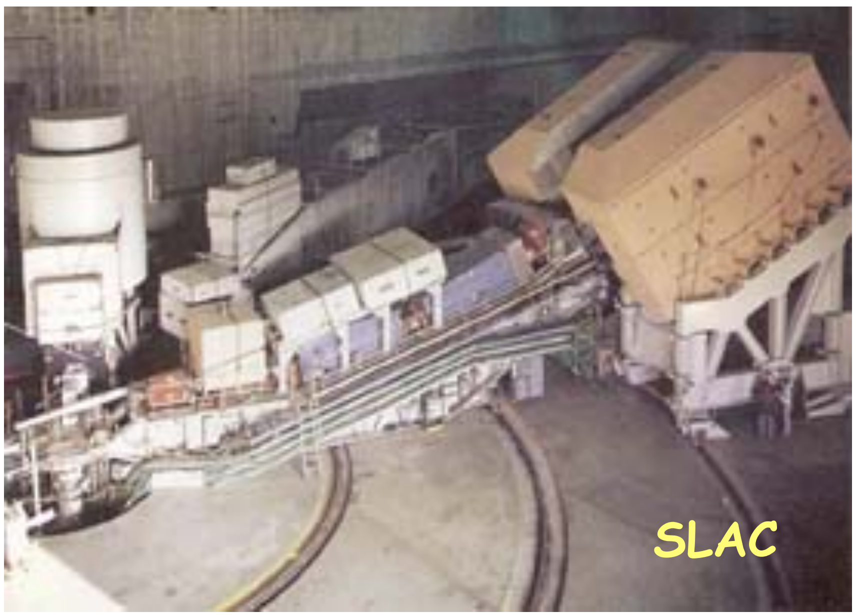
The discovery of partons in deep inelastic ep scattering in1969



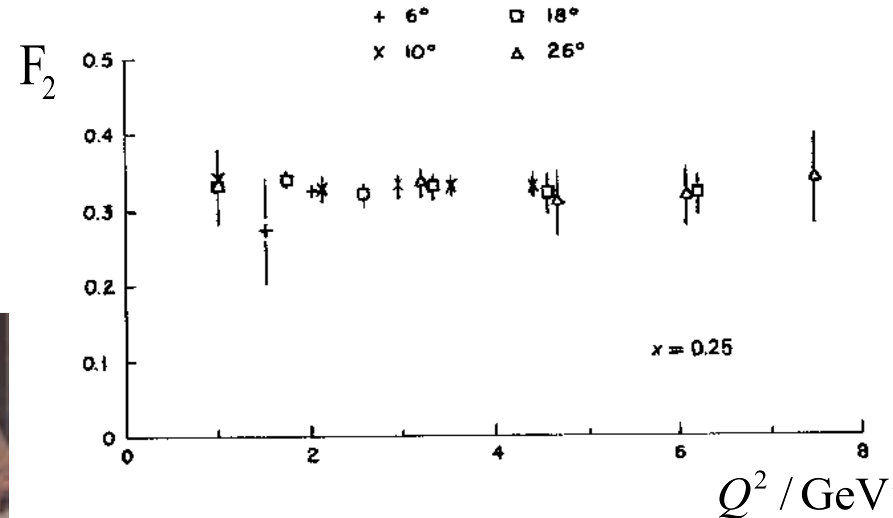
$E_e = 1.5 \ldots 20\ \mathrm{GeV}$

$\theta = 6° \ldots 26°$

$Q^2 = 1 \ldots 7\ \mathrm{GeV}^2$



Friedman, Kendall, Taylor



$$F_2(Q^2, \nu) \rightarrow F_2(x)$$

pointlike scattering centers inside proton

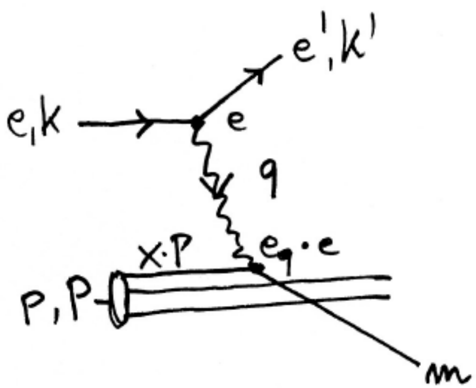
x = momentum fraction carried by quarks

Q^2 negative 4 momentum transfer squared

ν=E-E': energy transfer = energy of the photon

spatial resolution: $d = 1/\sqrt{Q^2} = 10^{-16}$m

Deep Inelastic Scattering - F_2



$$q = (k - k')$$

$$(xP + q)^2 = m^2, P^2 = M_p^2$$

$$Q^2 = -q^2 > 0$$

$$if: Q^2 >> x^2 M_p^2, m^2:$$

$$q^2 + 2xPq = 0:$$

$$x = \frac{Q^2}{2Pq}$$

"fixed target":

$$P = (M_p, 0,0,0)$$

$$2Pq = 2M_p(E - E')$$

$$= 2M_p E \cdot \frac{\nu}{E} \equiv s \cdot y$$

$$Q^2 = sxy \le s$$

$$s = 2M_p E$$

$$s = 4E_e E_p$$

- ep collider

$$\sigma(ep \to eX) = \frac{d^2\sigma}{dxdQ^2} \approx \frac{2\pi\alpha^2}{Q^4}(1 + (1 - y)^2) \cdot F_2$$

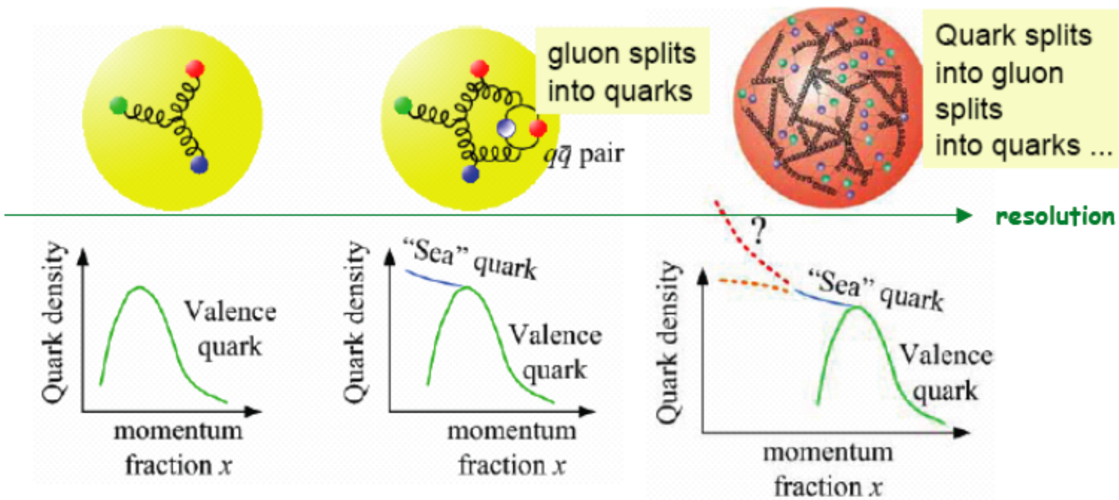
$$F_2(x, Q^2) = x \sum_q e_q^2 (q + \bar{q}), q = u,d,s,c,b,t$$

$$q = q(x, Q^2)$$

In DIS the inclusive cross section depends on two variables, the negative 4-momentum transfer squared (Q^2), which determines the resolving power of the exchanged particle in terms of p substructure, and the variable Bjorken x, which Feynman could relate to the fraction of momentum of the proton carried by a parton [in what he called the 'infinite momentum frame' in which the transverse momenta are neglected].

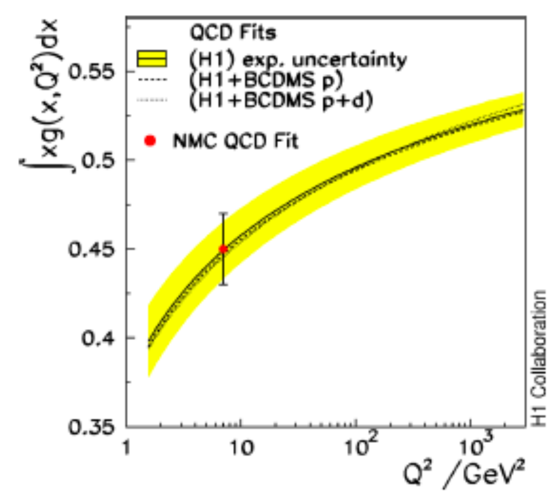
Feynman's partons were readily linked to Gell-Mann and Zweig's quarks.

The "dynamic" structure of the proton

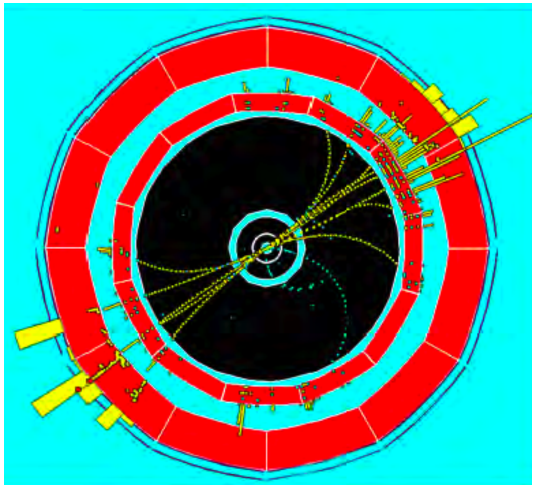


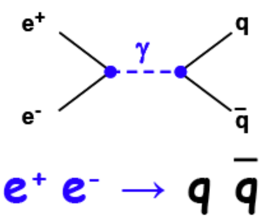
Early on the measured integrated density of quarks was observed to not add up to 1. This implied that half of proton's momentum is carried by gluons. A strong support for the existence of gluons.

The view on proton's structure is dynamic. It is determined by the resolving power of the process, as in ordinary microscopes. However, with a lepton beam emitting a photon or Z,W boson for resolving the proton structure, one reaches MUCH smaller dimensions. The best limit for the point-like structure of quarks is now $r_q < 10^{-20}$ m (LHC)



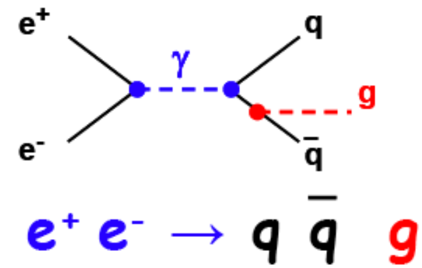
The Gluon and its ‘Bremsstrahlung’

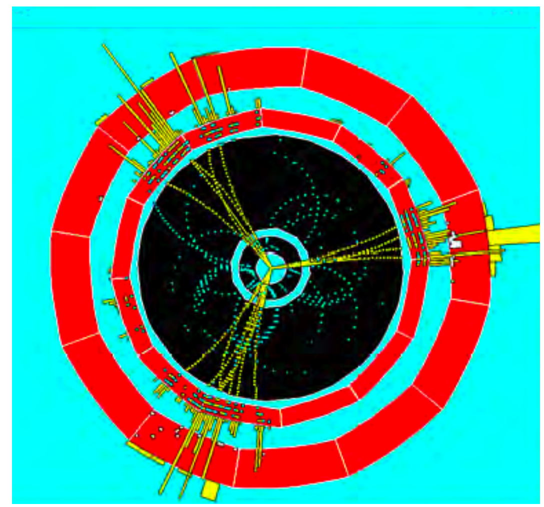




The lowest order reaction leads to two bundles (“jets”) of particles which are back-to-back in azimuth, “balanced” in transverse momentum. The observation of jet production was a major success of the Quark Parton Model approach.

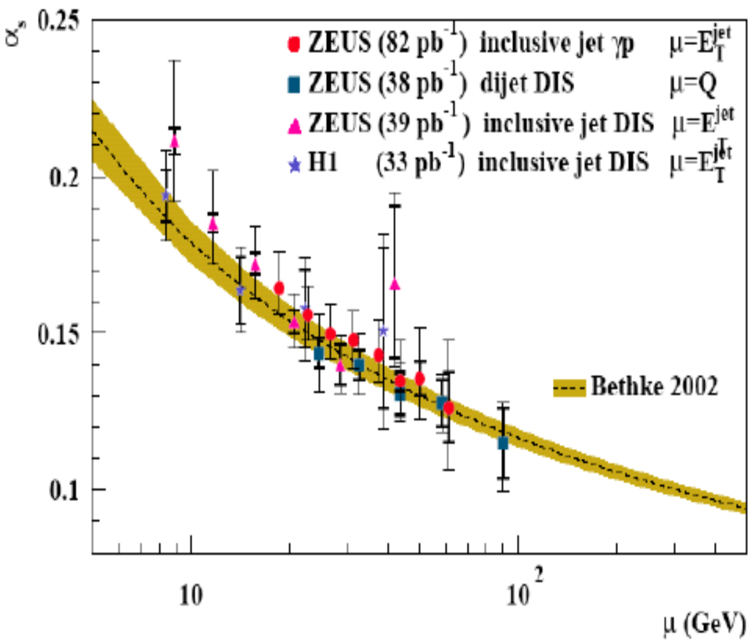
3 jets discovered at DESY in 1979





At the LHC observe a significant number of multi jet events. Jet production is an important means to understand the dynamics of quark-gluon interactions in the underlying field theory: Quantum Chromo-Dynamics [QCD]

Quantum Chromodynamics



$$\mu\frac{\partial\alpha_s}{\partial\mu} = 2\beta(\alpha_s) = -\frac{\beta_0}{2\pi}\alpha_s^2$$

The story of asymptotic freedom is around a minus sign and who got it first, back in 1974...

QED: one photon, QCD: 8 gluons

At high energies the effective charge is small; the coupling approaches an asymptotic value. In this regime the coupling constant is so small that the quarks can be considered free. The strong interaction gets weakened and perturbative calculations become meaningful in the theory of strong interactions, a major surprise!

QCD is asymptotically free



F.Wilzcek D.Gross H.Politzer

Adapting to new, hypothetical theories?

"… when I reported these things here in Göttingen, they laughed at me that I should take such fantasies seriously"

R.Courant to N.Bohr, 1922, December, 8

Fermi's "A Tentative Theory of ß Decay" refused to publish in Nature

cited by Pontecorvo

1962: Gell Mann predicts the Omega minus (sss state)

" The paper looks crazy, but if I accept it and it is nonsense, everyone will blame Gell-Mann and not Physics Letters. If I reject it and it turns out to be right, I will be ridiculed."

cited by Lipkin

" …we know that … mesons and baryons are mostly, if not entirely, made up out of one another. The probability that a meson consists of a real quark pair rather than two mesons… must be quite small" Gell-Mann XIII ICHEP Berkeley, 1967

Zweig, who invented the Quark Model with Gell Mann in 1964, could not get a paper published describing his quark theory until the mid 70ies.

cited by H.Kendall

"The correct theory will not be found within the next 100 years"

F.Dyson 1960

The Lagrangian of QCD

gluon

q propagation and q-g interaction

quark mass

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j \left(i\gamma^\mu D_\mu + m_j \right) q_j$$

where $$G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$$

and $$D_\mu \equiv \partial_\mu + i t^a A^a_\mu$$

That's it!

selfinteraction of gluon field

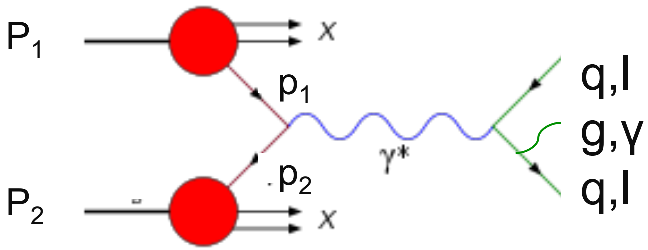
j ... quark flavors

a,b,c ... 3 colors

μ,ν ... space-time

F.Wilczek, Physics Today, August 2000.

Drell-Yan Scattering and Jets



$$P^2 = M_p^2 = E_p^2 - \vec{p}^{\,2}$$

$$s = (P_1 + P_2)^2 = 4E_p^2$$

$$E_p = \left|\overrightarrow{p_{1,2}}\right| = \frac{\sqrt{s}}{2}$$

$$p_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1)$$

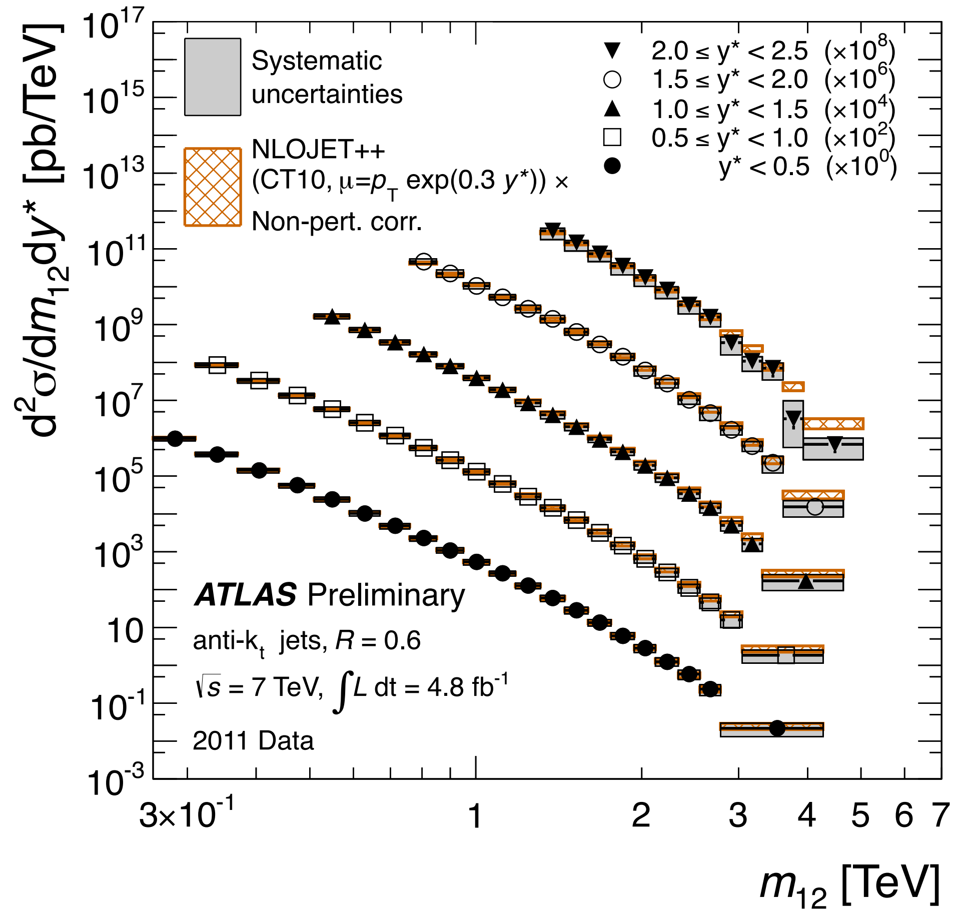
$$p_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)$$

$$m_{12}^2 = (p_1 + p_2)^2 = s x_1 x_2 = s\tau$$

$$y = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

$$x_1 = \sqrt{\tau}e^{y}, x_2 = \sqrt{\tau}e^{-y}$$

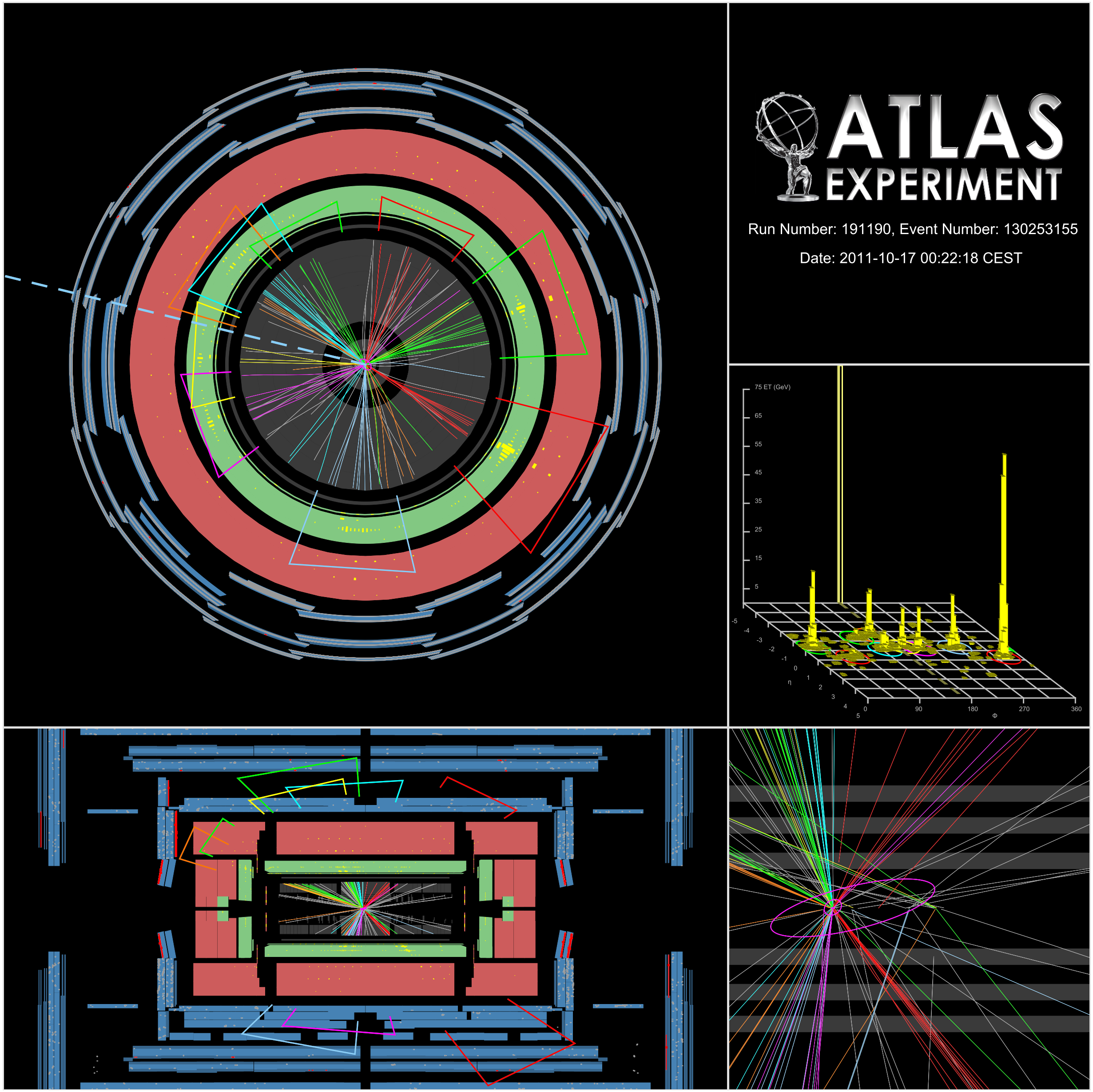
$$x_F = \frac{2p_L}{\sqrt{s}} = x_1 - x_2$$



Drell-Yan process is THE tool for studying the partonic structure of the proton and for searching for new physics at the LHC. Few TeV mass range being explored.

Transverse view of a multi-jet event from SUSY searches on ATLAS

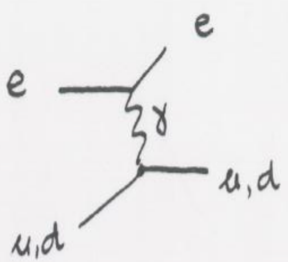
r,z view



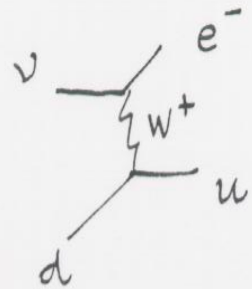
Multiple, large (missing) energy depositions in angular space.

The event has multiple vertices "pile-up" because of the large pp cross section, high luminosity and acceptance N=σLA

Fractional Charges in Deep Inelastic Scattering



neutral current (elm: γ)



charged current (weak!)

HERA: 

inverse charged current.

$F_2 = x \sum e_q^2 (q + \bar{q})$

proton: uud

neutron: ddu

$e_u = 2/3 \quad e_d = -1/3$

$F_2^p = x\left[e_u^2 (u+\bar{u}) + e_d^2 (d+\bar{d})\right]$

$F_2^n = x\left[e_d^2 (u+\bar{u}) + e_u^2 (d+\bar{d})\right]$

$\frac{1}{2}\left(F_2^{ep} + F_2^{en}\right) = F_2^{eN}$

$= x\, \frac{e_u^2 + e_d^2}{2}\left[u + \bar{u} + d + \bar{d}\right]$

$F_2^{\nu p} = 2x\left[d + \bar{u}\right]$

$F_2^{\nu n} = 2x\left[u + \bar{d}\right] \qquad F_2^{\nu N} = x\left[u + \bar{u} + d + \bar{d}\right]$

$\rightarrow \frac{F_2^{eN}}{F_2^{\nu N}} = \frac{1}{2}\left(e_u^2 + e_d^2\right) = \frac{5}{18} \simeq 0.28$

$\frac{\text{GGM } \nu N}{\text{SLAC } eN} : 0.29 \pm 0.05$