QCD & the Parton Model

Lecture 15 Physics 152A/252A

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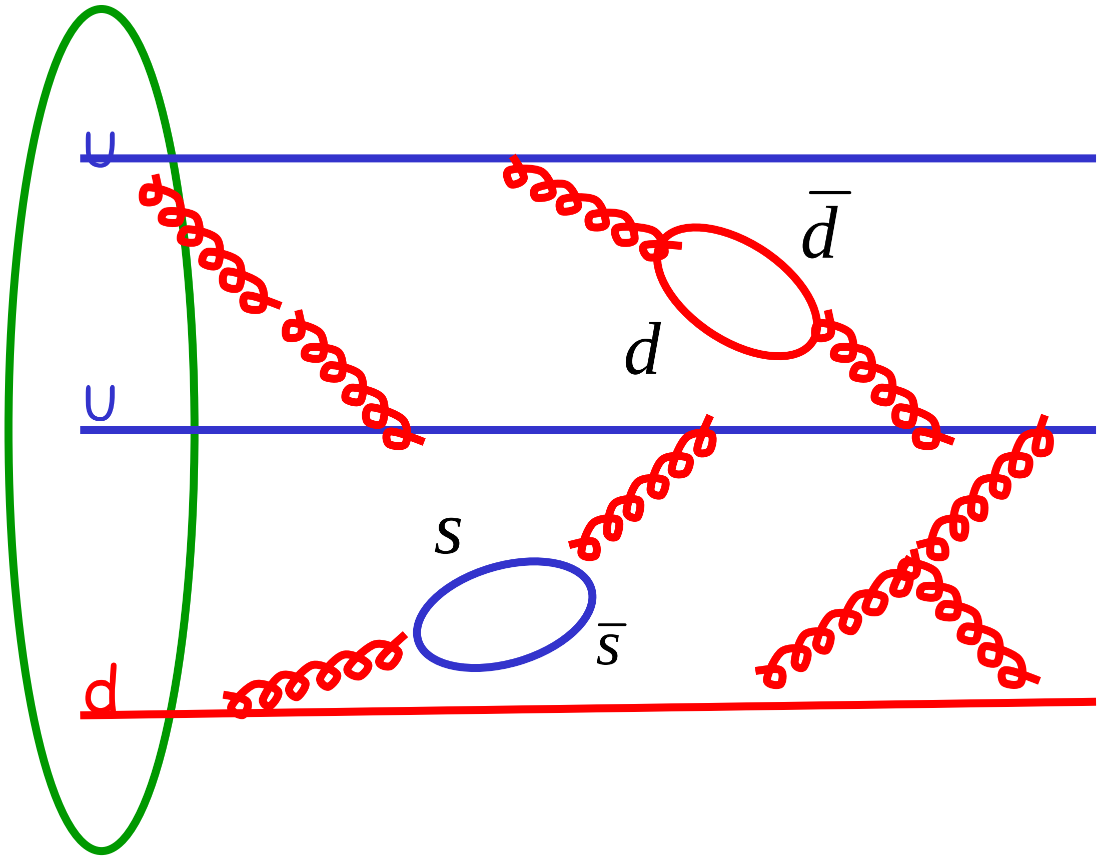
(thanks again to Colin Jessop)

Structure of the Proton



Proton is composed of u,d valence quarks which carry quantum numbers and

$$"sea"\ of\quad u,\bar{u},d,\bar{d},s,\bar{s},g\ with\_no\_net\_quantum\_number$$

Constraints on Parton Density Functions

The charm,beauty and truth compositions are negligible so proton is composed of uds quarks and anti quarks and glue . The observed quantum number constraints

No net strangeness

$$\int (s(x) - \bar{s}(x))\, dx = 0$$

Isospin I_3 =1/2

$$\int [\frac{1}{2}(u(x) - \bar{u}(x)) - \frac{1}{2}(d(x) - \bar{d}(x))]\, dx = \frac{1}{2}$$

Charge =1

$$\int \frac{2}{3}(u(x) - \bar{u}(x)) - \frac{1}{3}(d(x) - \bar{d}(x)) - \frac{1}{3}(s(x) - \bar{s}(x))\, dx = 1$$

Leads to

$$\int (u(x) - \bar{u}(x))\, dx = 2 \qquad \int (d(x) - \bar{d}(x))\, dx = 1$$

Two u quarks and 1 d quark as expected. These are called sum rules and there is one for every quantum number.

Momentum sum rule:

$$\int x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + s(x) + \bar{s}(x) + \ldots + g(x)]\, dx = 1$$

Early data on proton structure

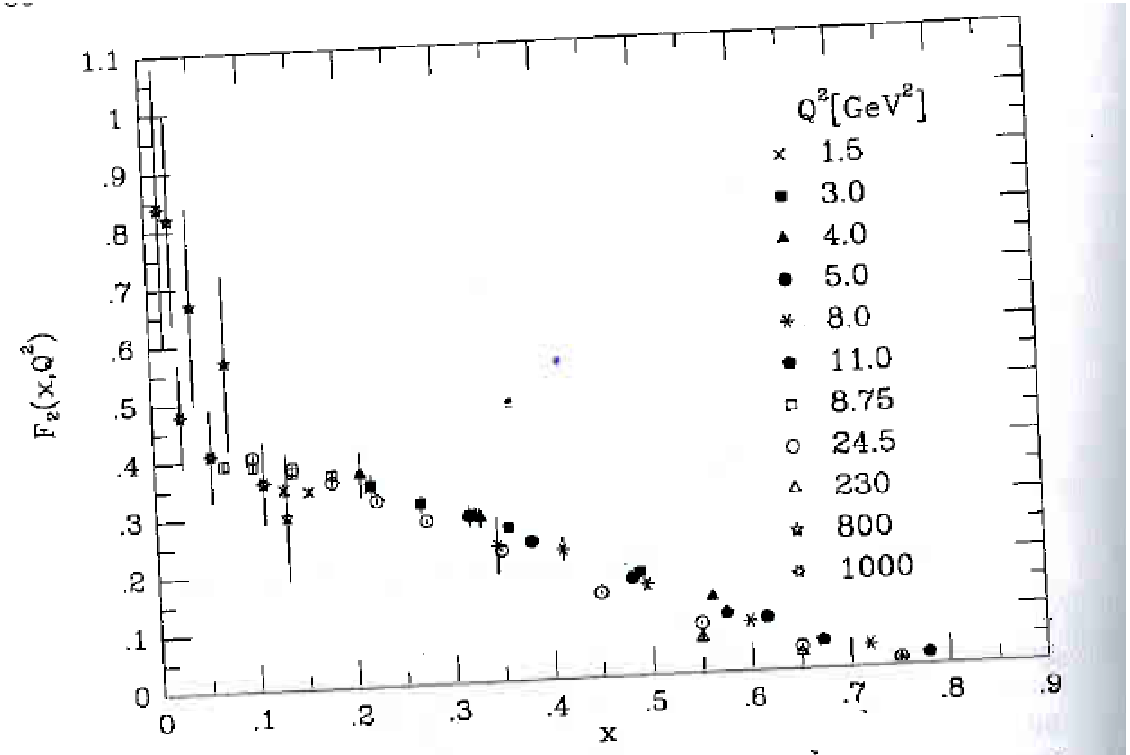


Fig. 4.2. The F_2 structure function from the SLAC-MIT, BCDMS, H1 and ZEUS collaborations.

$$F_2(x,Q^2) = x\sum_q Q_q^2(q(x,Q^2)+\bar{q}(x,Q^2))$$

SLAC-MIT
~20 GeV electrons, protons at rest, Q^2 = few GeV^2

BCDMS
200-300 GeV muons, protons at rest, Q^2 = tens of GeV^2

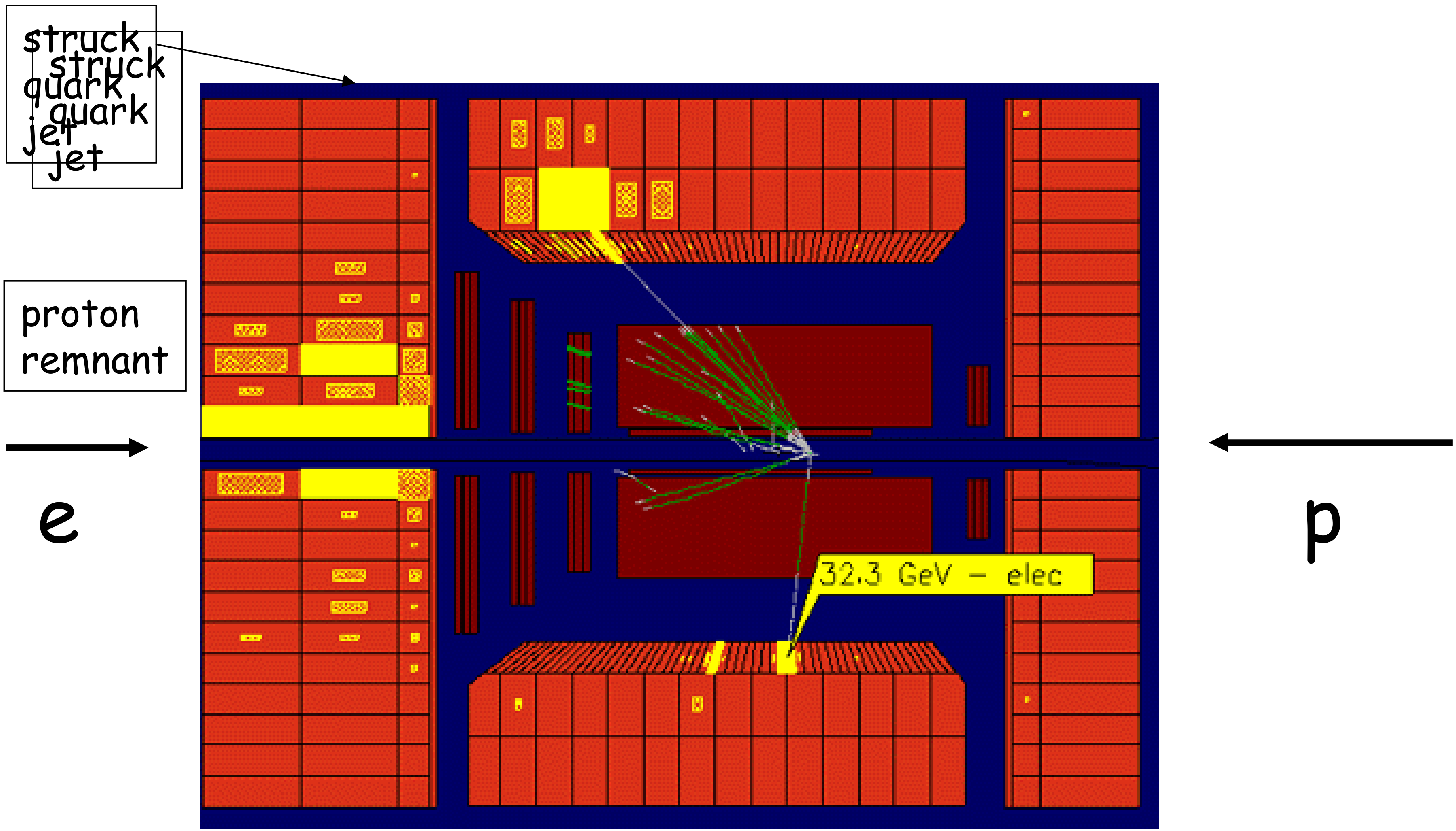
DIS at HERA collider

DESY (Hamburg)
6.3km circumference
820 GeV protons,
30 GeV electrons,
Q^2 up to ~ 10^4 GeV^2

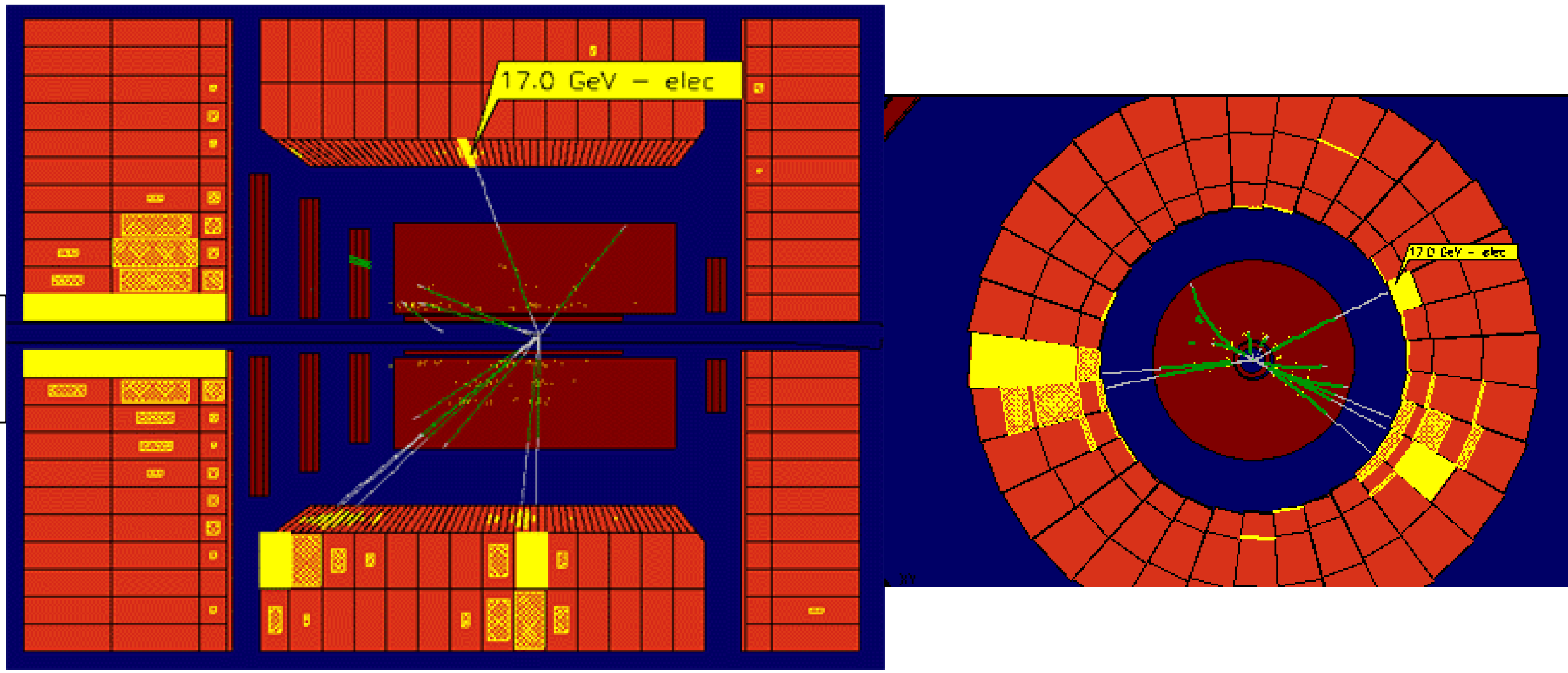
H1, ZEUS experiments

Nice event pictures, discussion at
http://www.physics.ox.ac.uk/documents/pUS/dIS/

HERA – ep → e + jet + X



HERA – ep → e + 2 jets + X

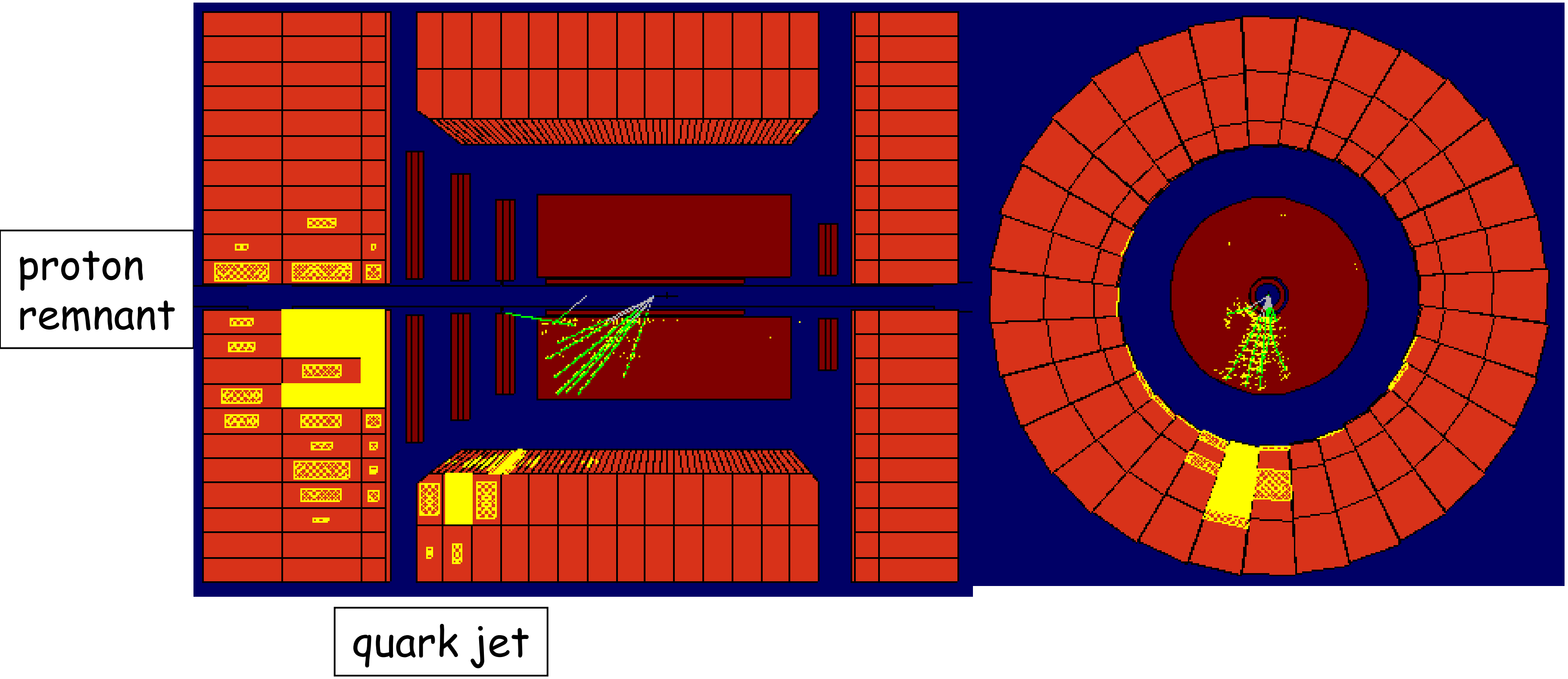


proton
remnant

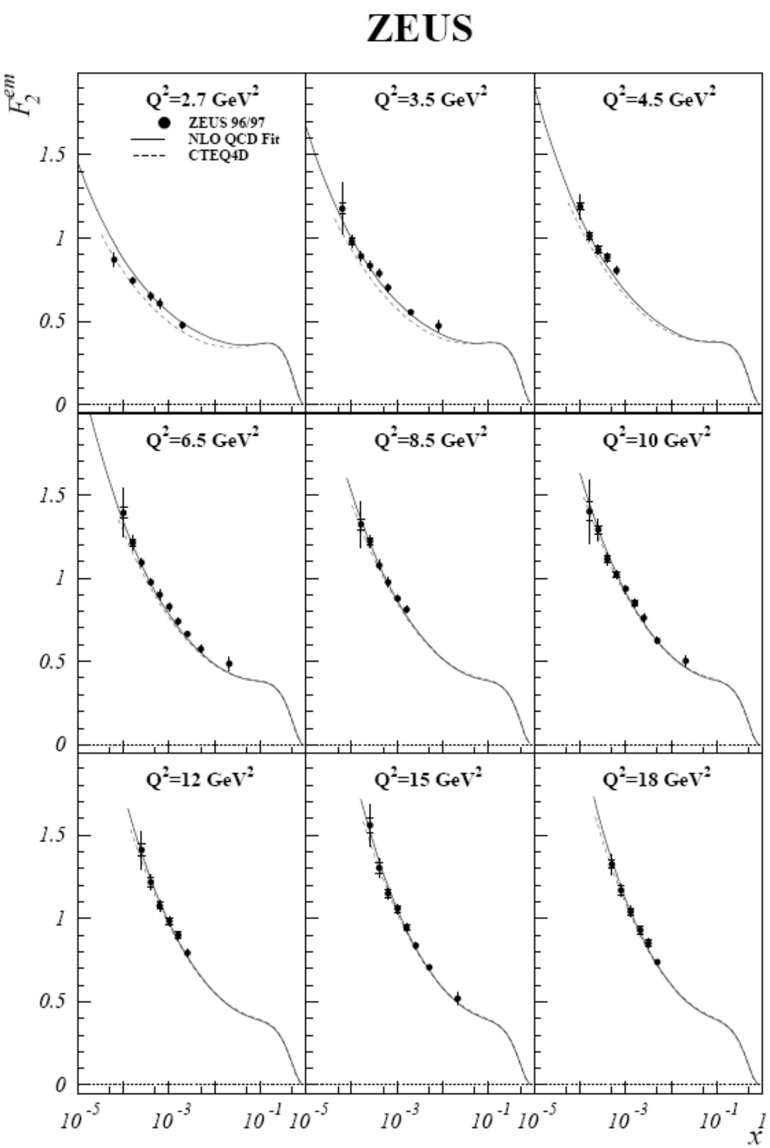
quark + gluon jets

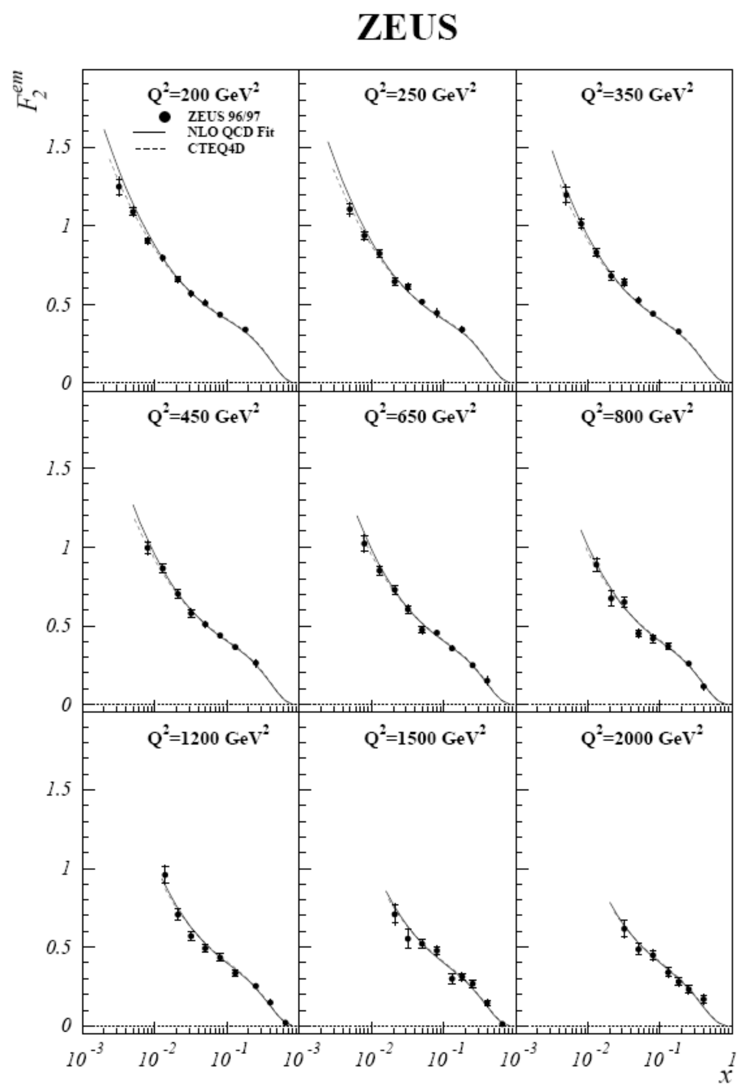
HERA – ep → ν + jet + X

Charged current (W exchange) event – no electron visible

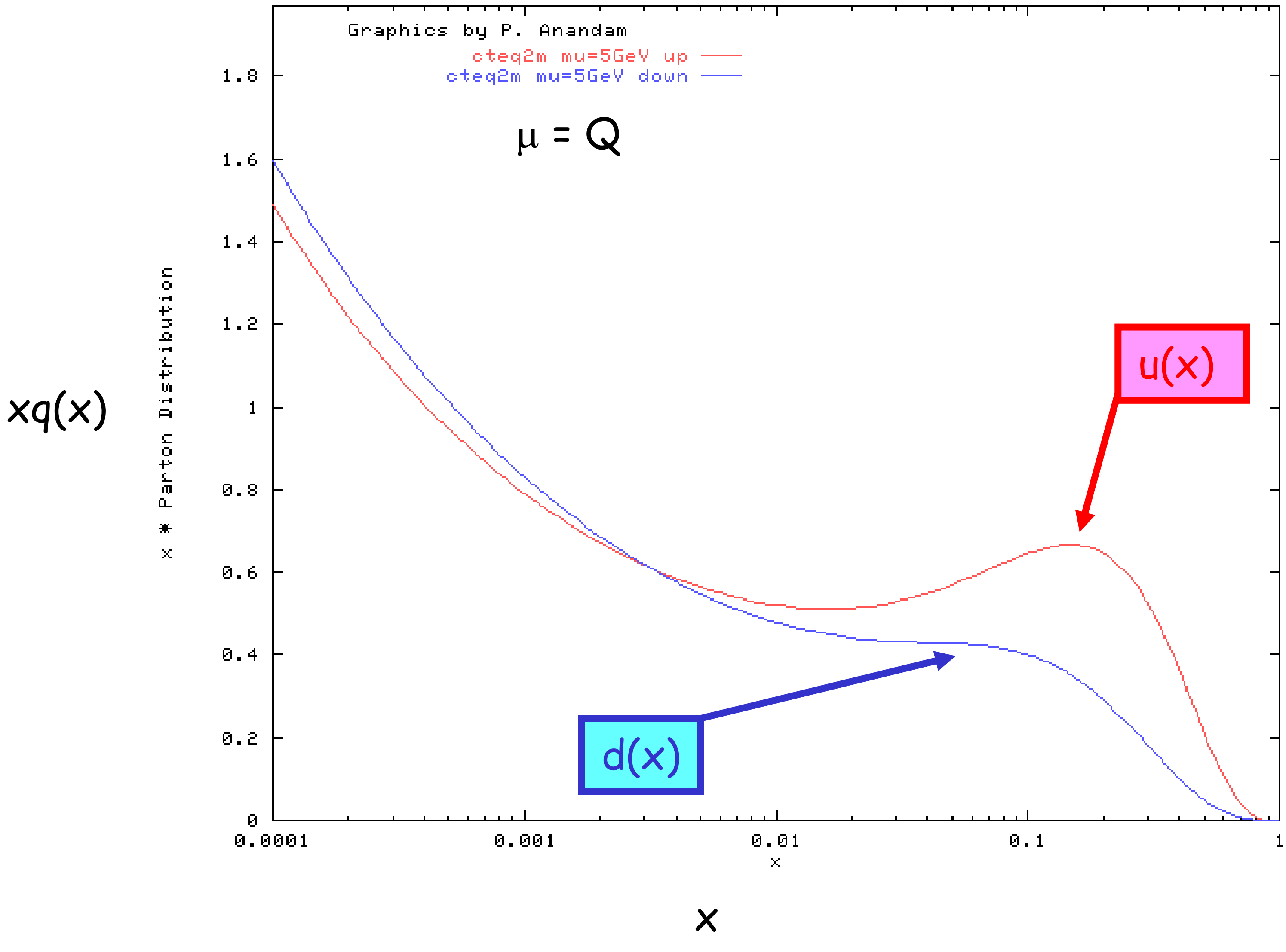


HERA data on F_2

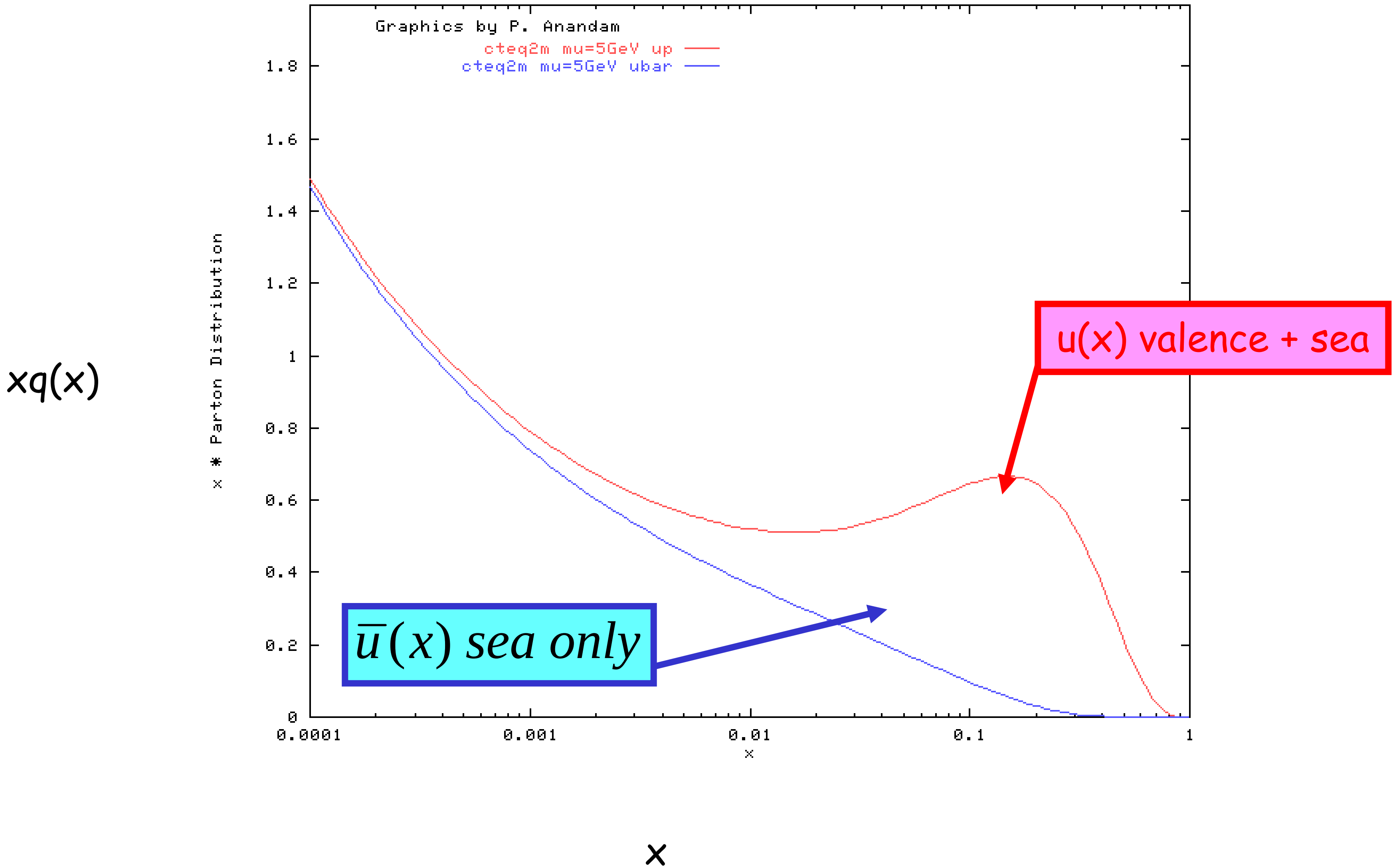




u(x) and d(x) parton distributions for proton



u(x) and $\bar{u}(x)$ parton distributions for proton



Gluon distribution

Quark distributions can be measured by e or μ scattering
--- but not the gluon distribution as gluons are not electrically charged.
A nonzero gluon distribution can be inferred from the momentum sum rule:

$$\int x(u(x)+\overline{u}(x)+d(x)+\overline{d}(x)+s(x)+\overline{s}(x)+g(x)\,)\,dx=1.0$$

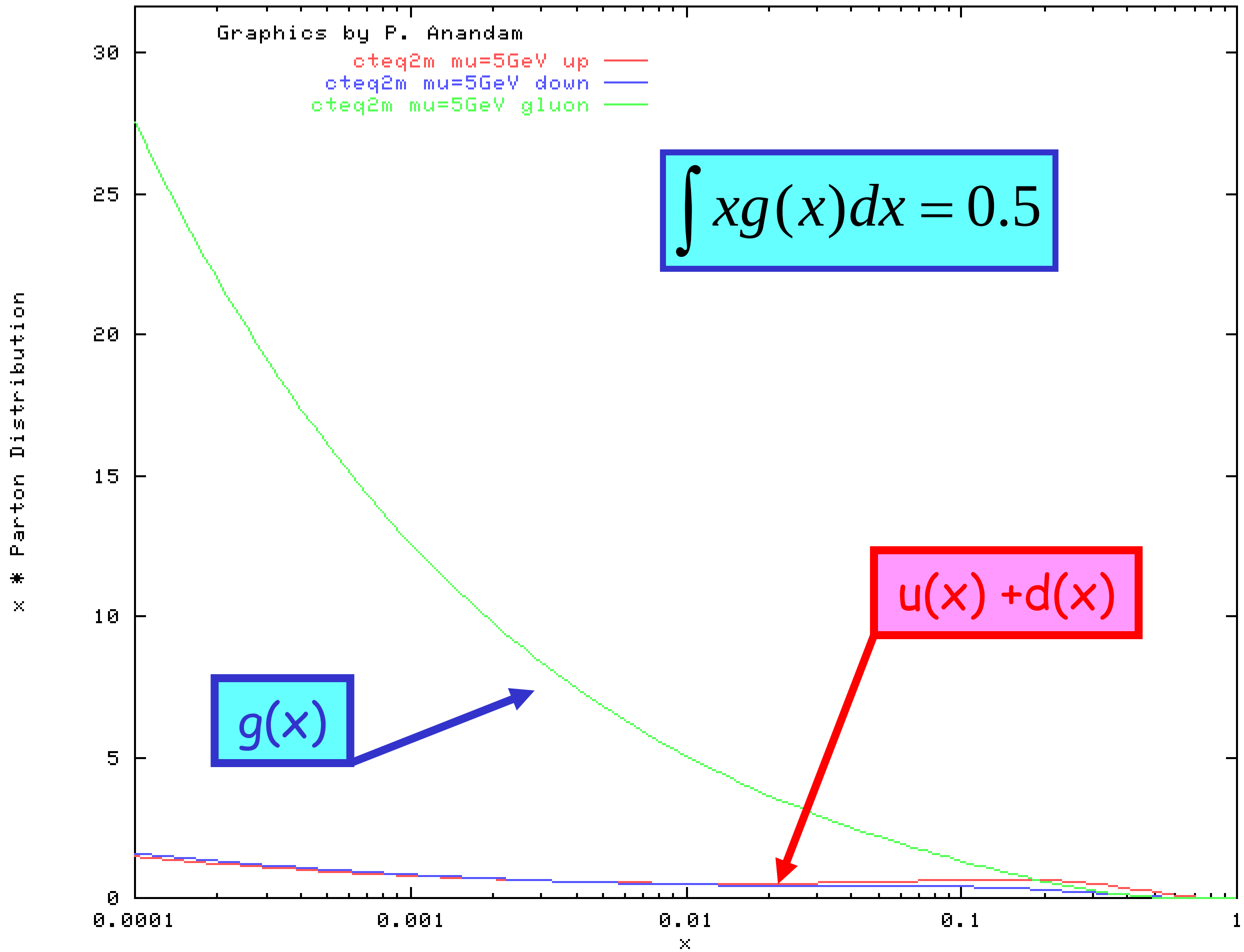
so:

$$\int xg(x)dx=\int 1.0-(u(x)+\overline{u}(x)+d(x)+\overline{d}(x)+s(x)+\overline{s}(x))\,dx$$

More generally, Q^2 evolution of q(x,Q^2), and hence F_i(x,Q^2), involves g(x,Q^2), so gluon distribution can be extracted that way. Nevertheless, it is not as well known as the quark distributions.

Gluons carry 50% of proton momentum

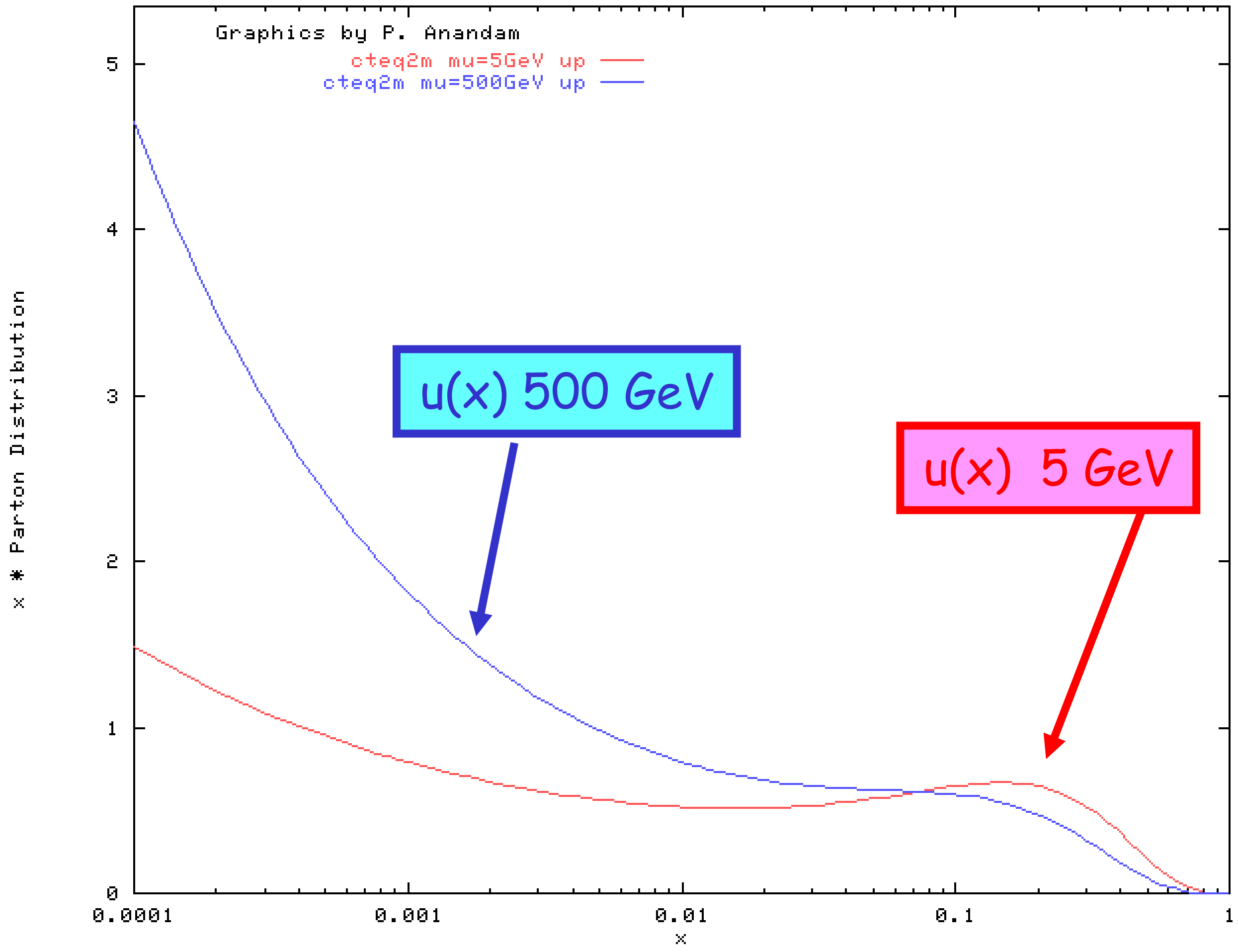
xq(x)



x

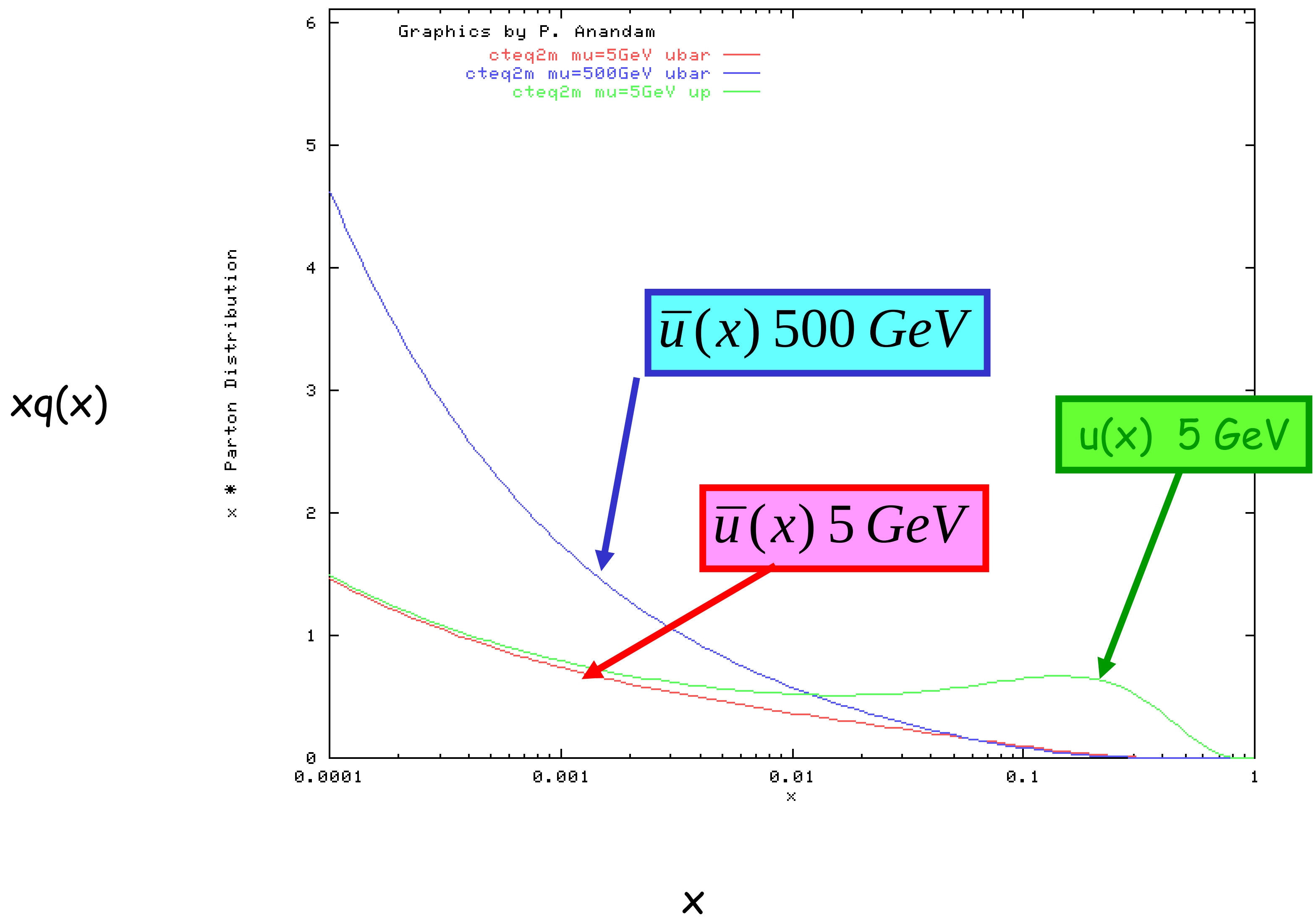
At high $Q^2 = \mu^2$ see more of sea

xq(x)

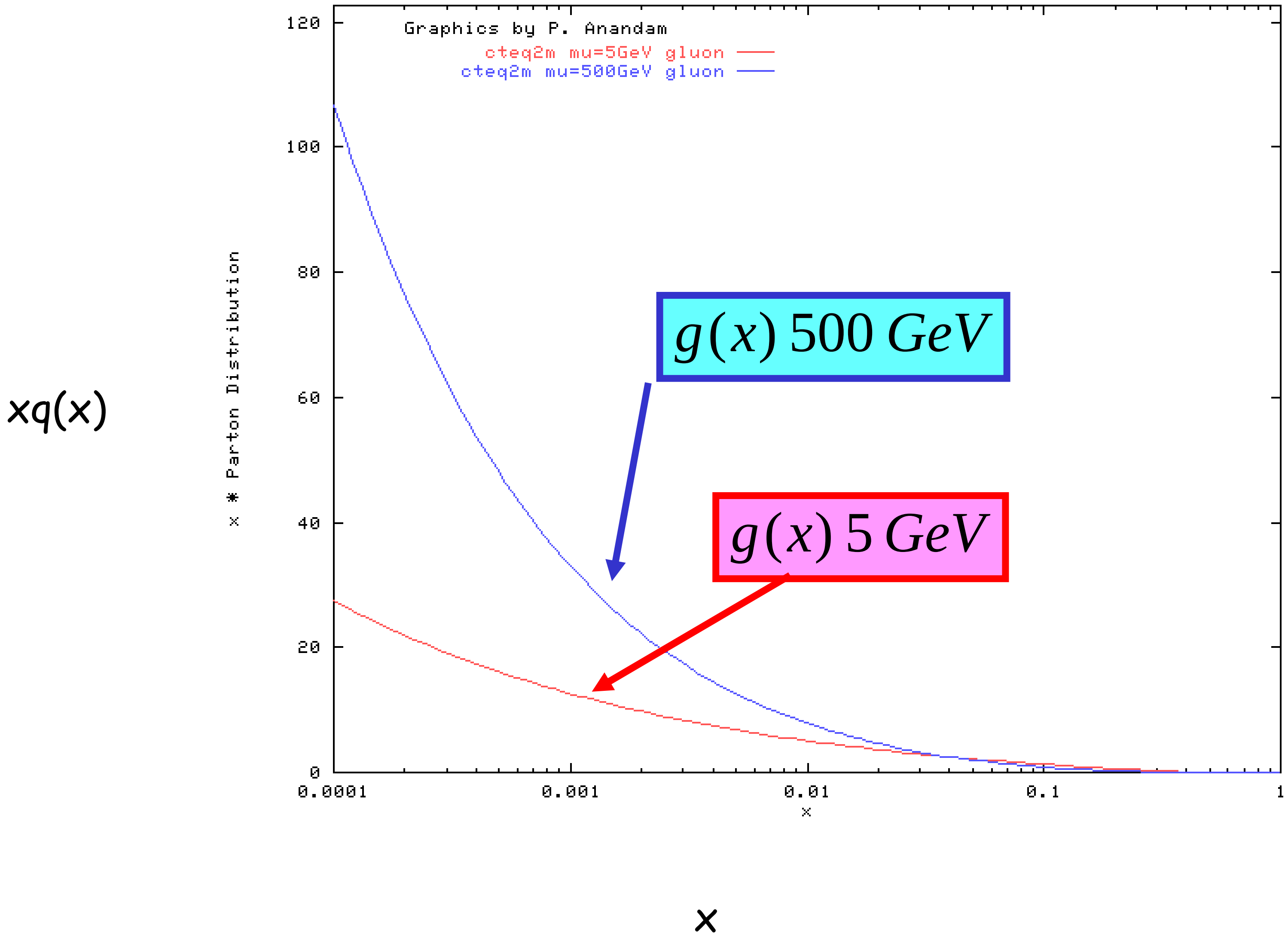


x

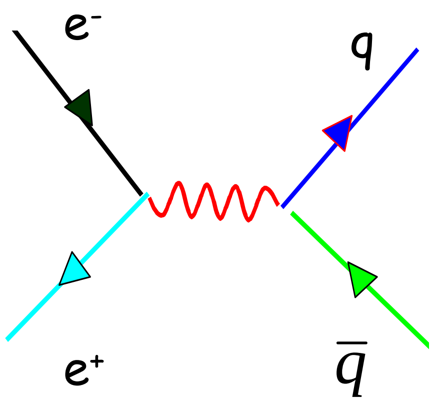
At high Q^2 see less valence quarks more sea antiquarks



More low x gluons less high x valence quarks at high Q^2



QCD in e^+e^- Annihilation



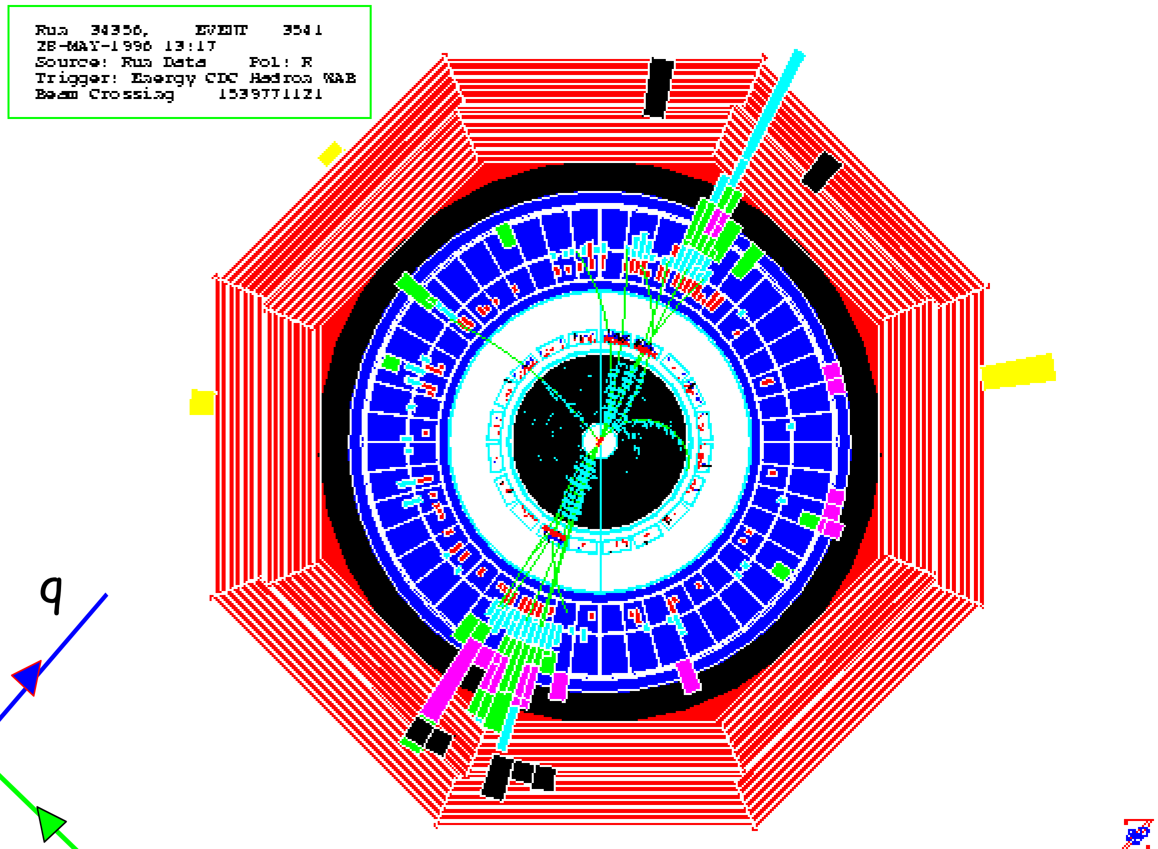
Cleanest laboratory for studying perturbative QCD:

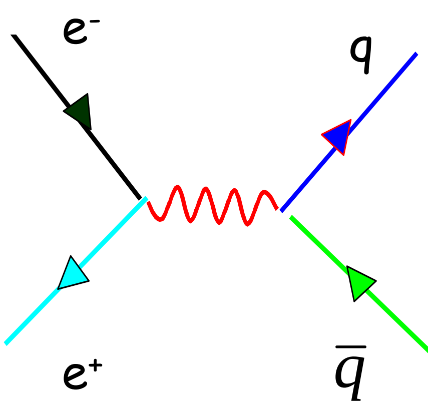
- No hadrons in initial state

→no need to use parton distribution functions

- No “remnants” of initial proton(s)
- Quarks and gluons produced at short distances and emerge as jets

Two Jet Event





Distribution follows

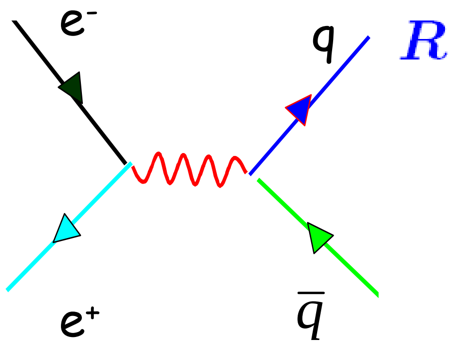
$$\frac{d\sigma}{d(\cos\vartheta)_{cm}} \propto (1+\cos^2\vartheta)$$

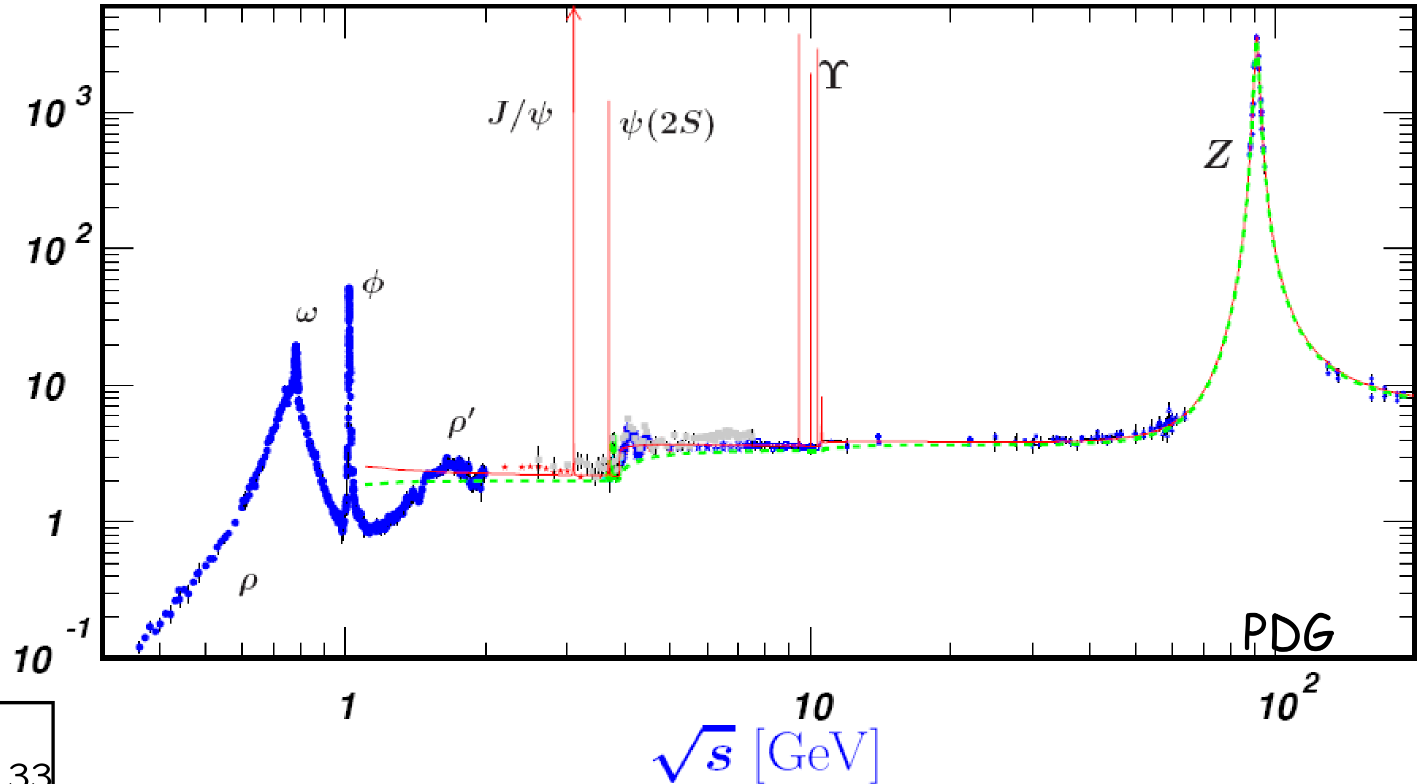
Just like $e^+ e^- \to \mu^+ \mu^-$

-> quarks have spin 1/2

The R ratio:

$$R(s) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

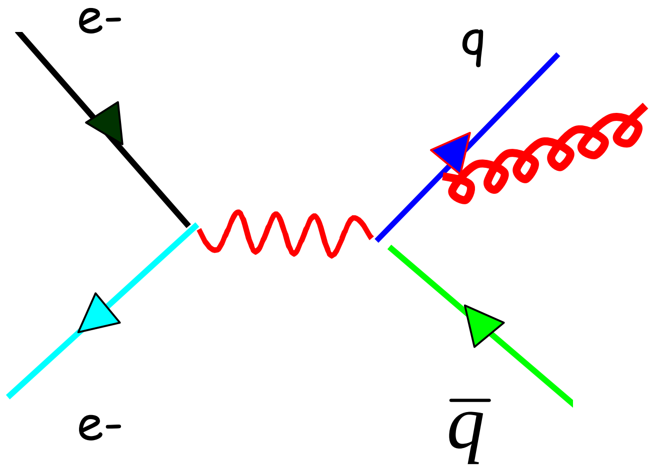


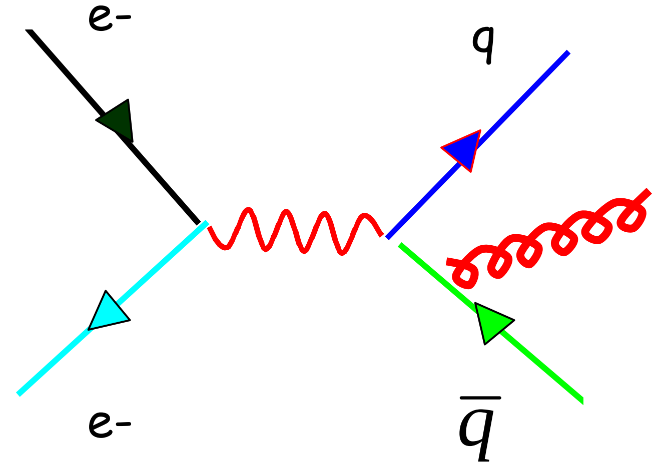


u,d,s	$\to$	2
u,d,s,c	$\to$	$10/3 = 3.33$
u,d,s,c,b	$\to$	$11/3 = 3.67$

$$R(s) = 3\sum_q Q_q^2\left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

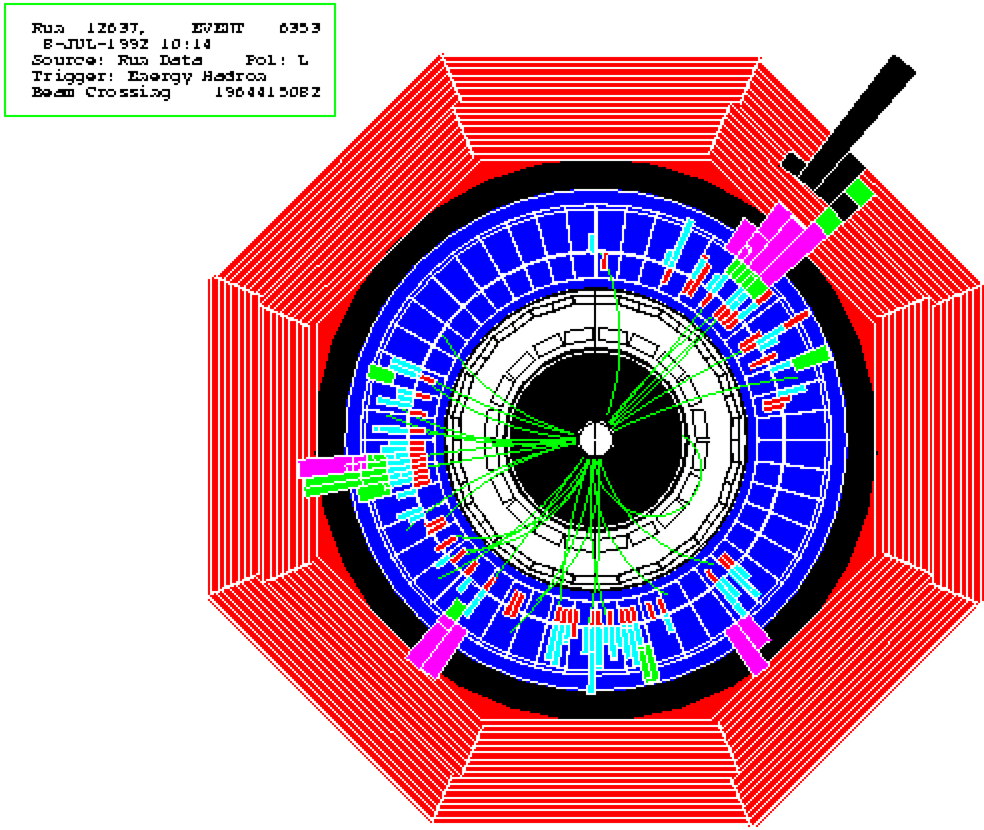
Proof that Gluons Exist





Gluons fragment into jets similarly to quarks so expect 3 jet events

Proof that Gluons Exist



3 jet events observed at rate consistent with expectations