The partonic structure of protons and nuclei: from current facilities to the EIC

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“Frontiers in Nuclear and Hadronic Physics”

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HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Jefferson Lab

Plan of the lectures

- **PART 1: QCD factorization and global PDF fitting**
  - Lecture 1 – Hadrons, partons and Deep Inelastic Scattering
  - Lecture 2 – Parton model
  - Lecture 3 – The QCD factorization theorem
  - Lecture 4 – Global PDF fits
- **PART 2: Parton distributions from nucleons to nuclei**
  - Lecture 5 / 6
- **PART 3: The next QCD frontier – The Electron-Ion collider**
  - Lextures 7 / 8

Plan of Part 1

- **Lecture 1 – Motivation**
  - Quarks, gluons, hadrons
  - Deep Inelastic Scattering (DIS)
- **Lecture 2 – Parton model**
  - DIS revisited
  - Collinear factorization and Parton Distribution Functions (PDFs)
  - Limitations
- **Lecture 3 – The QCD factorization theorem**
  - QCD factorization, universality of PDFs
  - DIS, Drell-Yan (DY) lepton pairs, *W* and *Z* production, hadronic jets
- **Lecture 4 – Global PDF fits**
  - How to make a fit, and use its results
  - Fits as community service (*e.g.*, measure PDFs, apply to LHC)
  - Fits as a tool to study hadron and nuclear structure

Resources

- **Textbooks**
  - Povh et al., “Particles and Nuclei,” Springer, 1999
  - Halzen, Martin, “Quarks and leptons,” John Wiley and sons, 1984
  - Lenz et al. (Eds.), “Lectures on QCD. Applications,” Springer, 1997
    - esp. lectures by Levy, Rith, Jaffe
  - Devenish, Cooper-Sarkar, “Deep Inelastic Scattering,” Oxford U.P., 2004
  - Feynman, “Photon-hadron interactions,” Addison Wesley, 1972
  - Collins, “Foundations of perturbative QCD”, Oxford U.P, 2011
- **PDFs and Global QCD fitting**
  - Jimenez-Delgado, Melnitchouk, Owens, “Momentum and helicity distributions in the nucleon”, arXiv:1306.6515
  - Forte, Watt, “Progress in partonic structure of proton”, arXiv:1301.6754
  - J.Owens, “PDF and global fitting”, 2007 / 2013 CTEQ summer school
- **Lectures** (from the CTEQ pedagogical page)
  - W.K. Tung, “pQCD and parton structure of the nucleon”
  - B. Poetter, “Calculational Techniques in pQCD: The Drell-Yan Process”

Lecture 1 - Motivation

- **An illustrated introduction**
  - Hadrons are made of quarks and gluons
  - How to probe the partonic structure of hadrons

- **Deep Inelastic Scattering (DIS)**
  - A bit (!) of kinematics
  - Cross section
  - Structure function

- **A taste of the parton model**

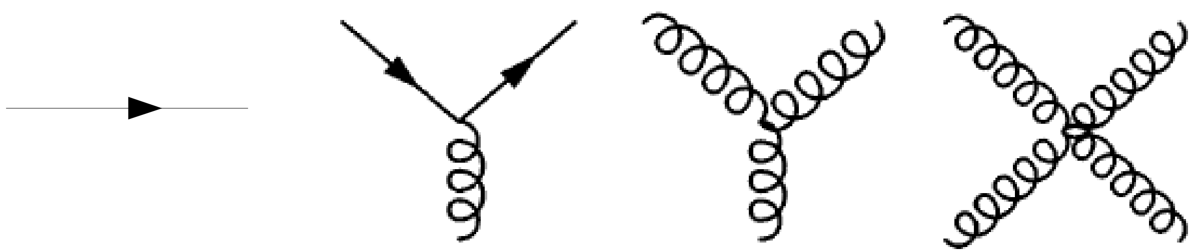
An illustrated introduction

Motivation: quarks, gluon, hadrons…

- The strong force is described in terms of colored quarks and gluons:

$$L_{QCD} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi - g\left(\bar{\psi}\gamma^{\mu}T_{a}\psi\right)A_{\mu}^{a} - \frac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu}$$

a quark   "color"   a gluon

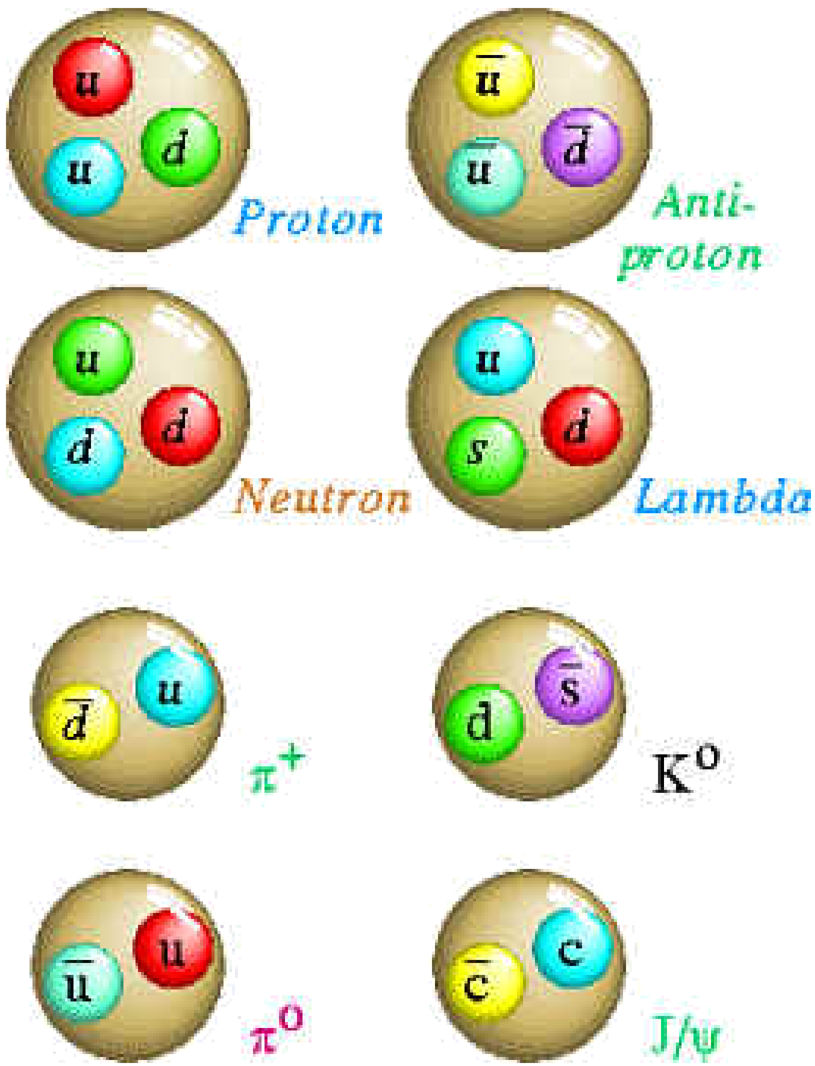


- But only color neutral hadrons can be detected – **color confinement**

  – How can one understand, say, proton and neutrons in terms of quark and gluons?

  – And, for that matter, what's the evidence for quarks and gluons?

Hadrons are made of quarks

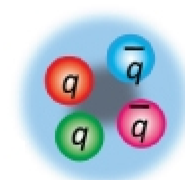


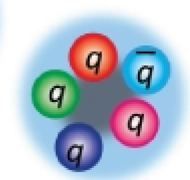
- **6 flavors (and 3 colors):**

  up, down, strange – `light`
  charm, bottom, top – `heavy`

  spin ½; charge (elm, weak)
  isospin (u = ½, d = – ½)
  strangeness (s = 1)

- **Confined in "colorless" hadrons**
  - mesons – 2 quarks
  - baryons – 3 quarks
  - Tetraquarks (?)
  - Pentaquarks (???)
  - Hybrids (quarks+gluons) …
  - Glueballs …





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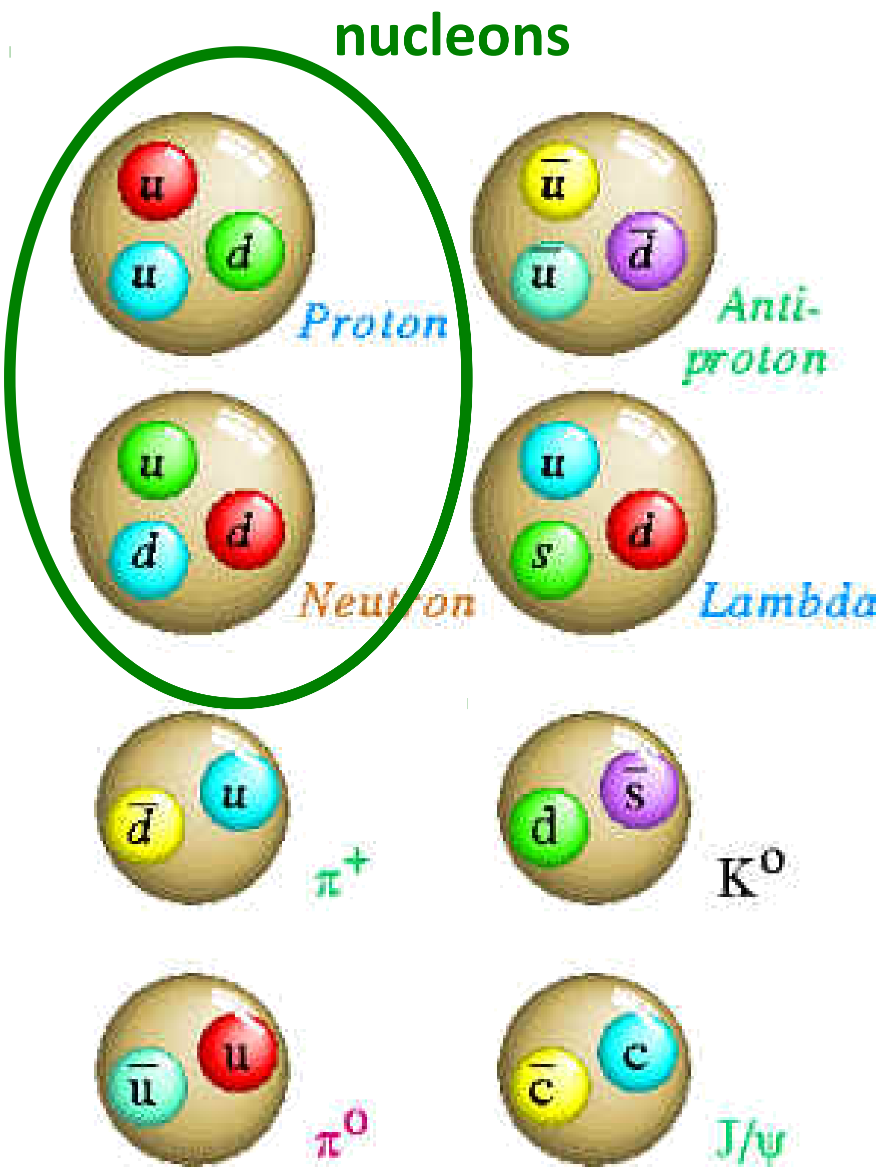

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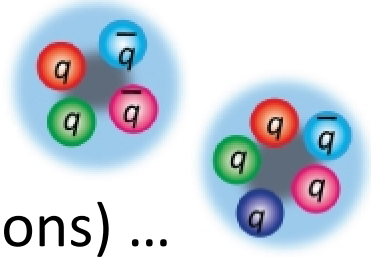
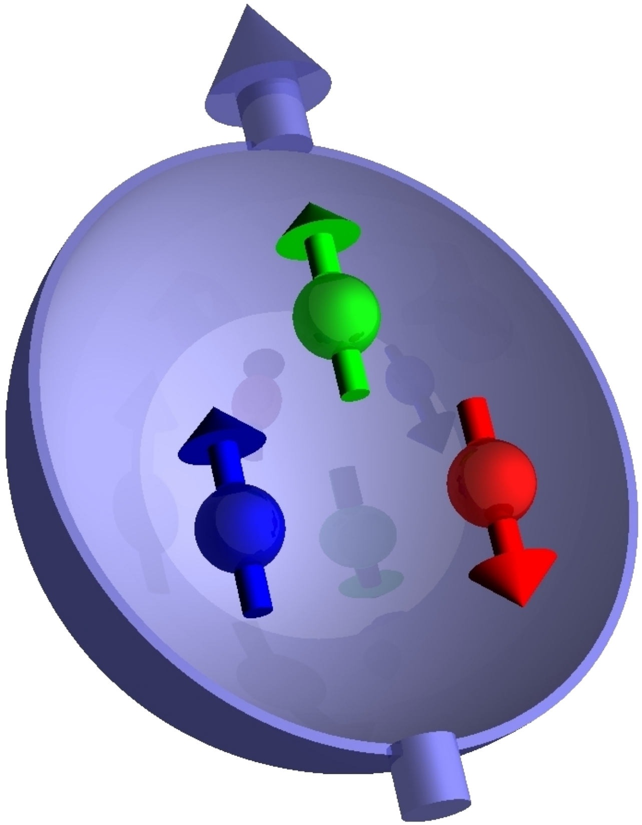
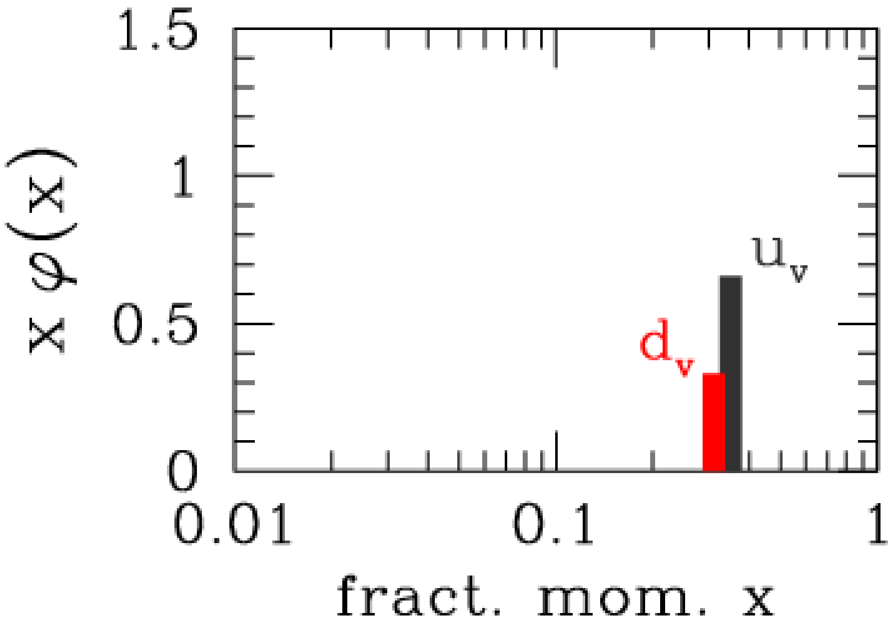
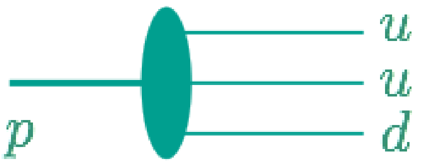


Nucleons are made of 3 quarks…



Parton Distribution Functions (PDF)





Fractional momentum: $x = \frac{p^+_{\text{parton}}}{p^+_{nucleon}}$ $p^\pm = \frac{1}{\sqrt{2}}(E \pm p_z)$

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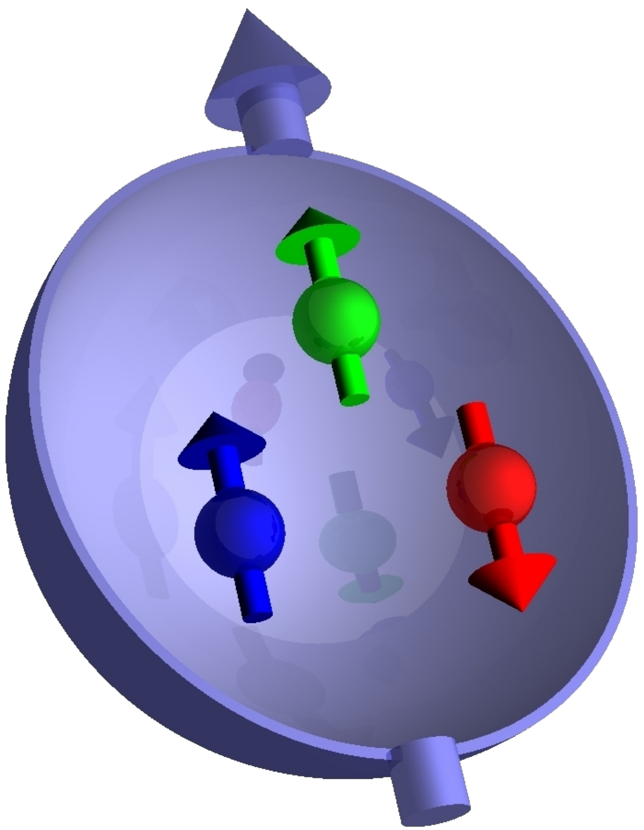

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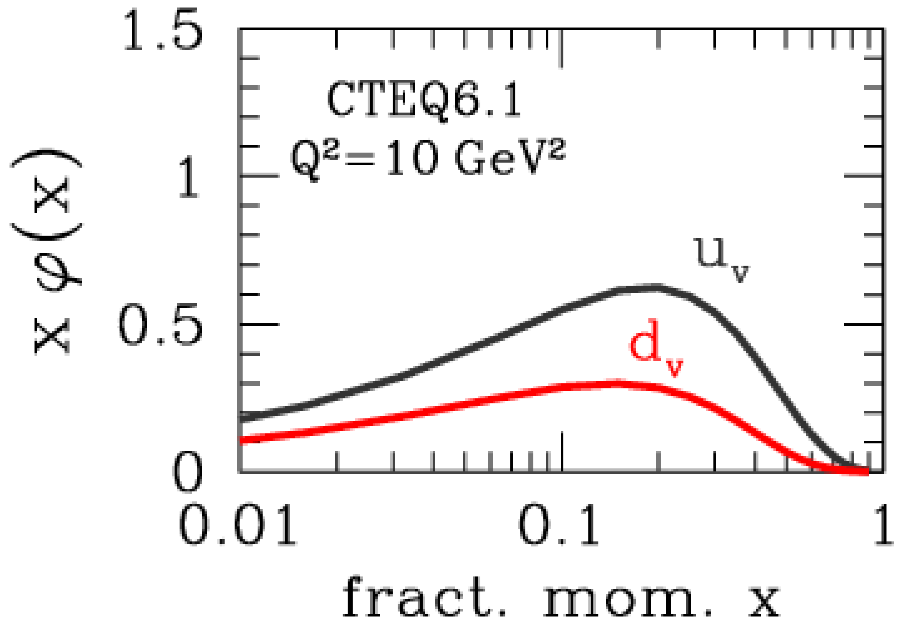

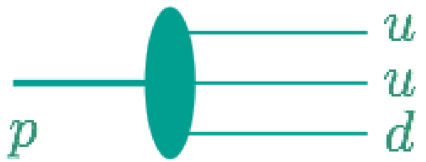

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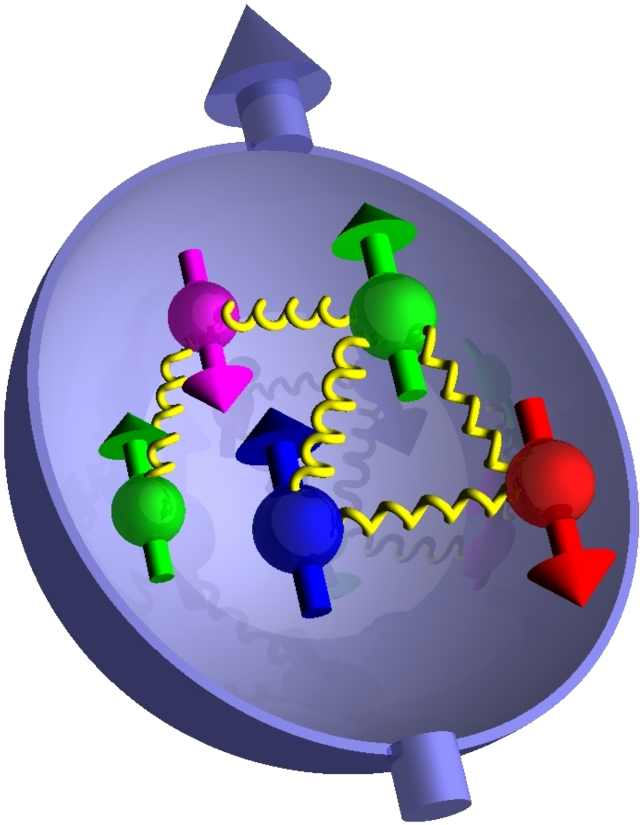
… and gluons, and sea quarks …



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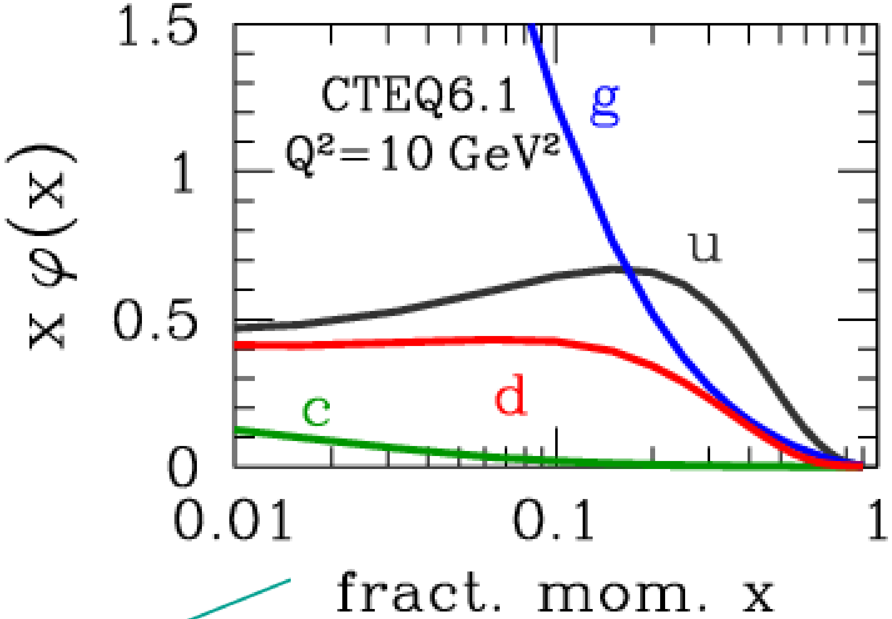

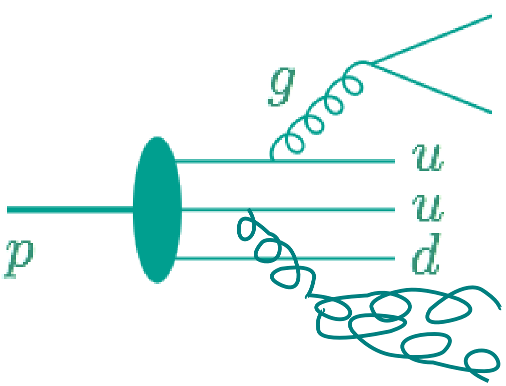

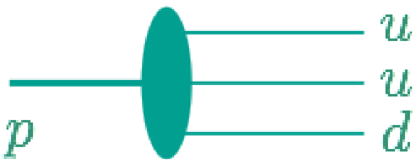

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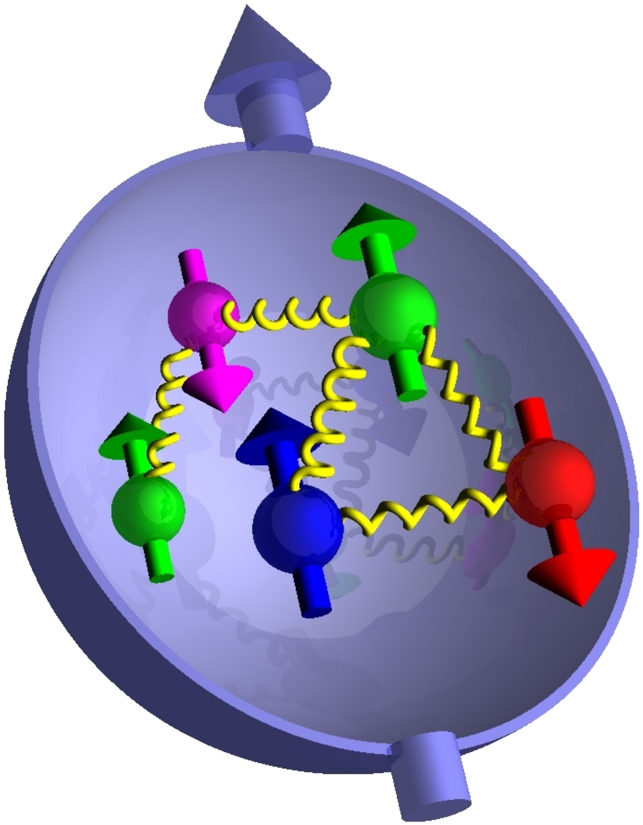

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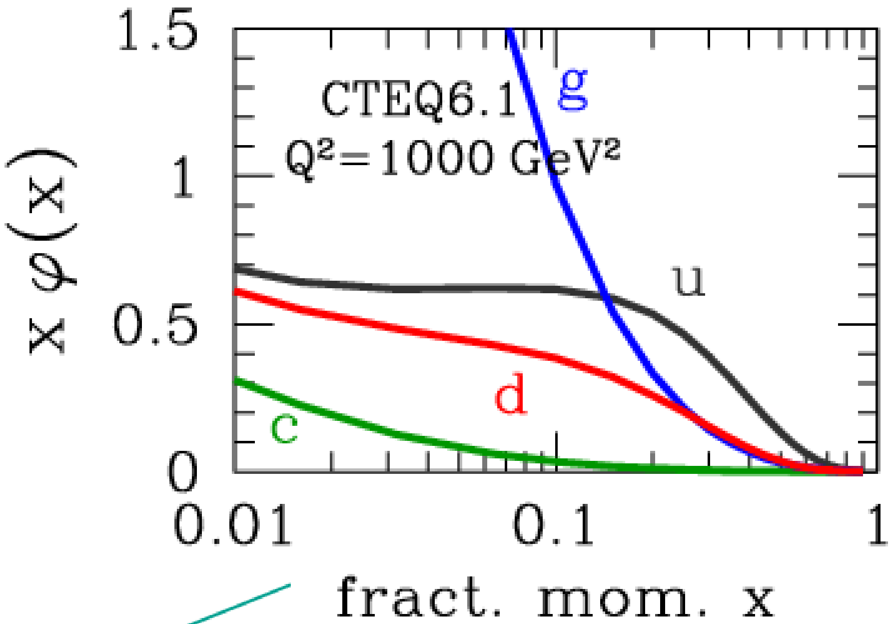
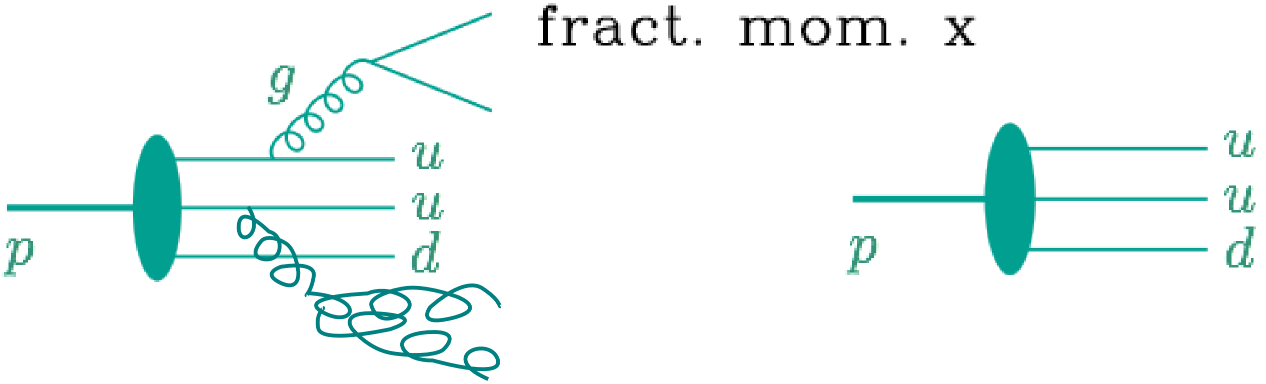
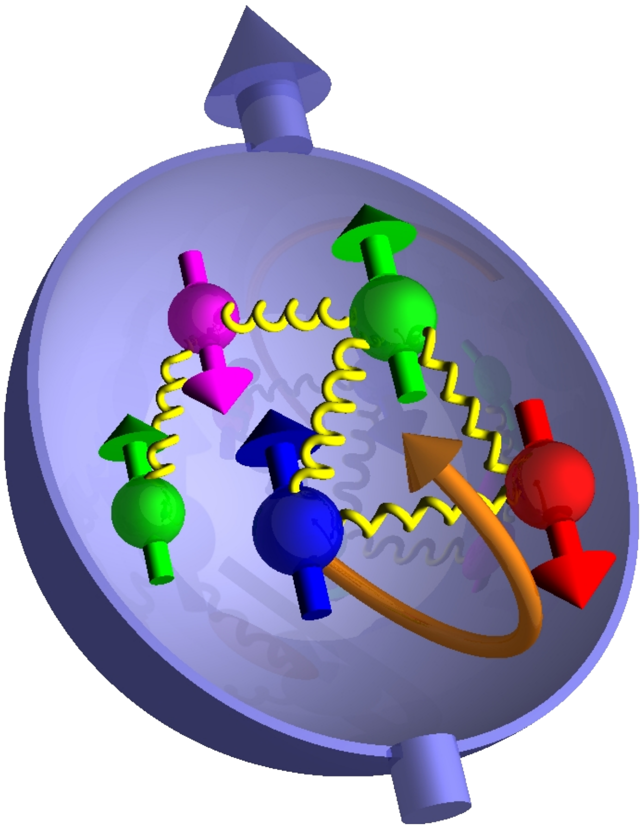




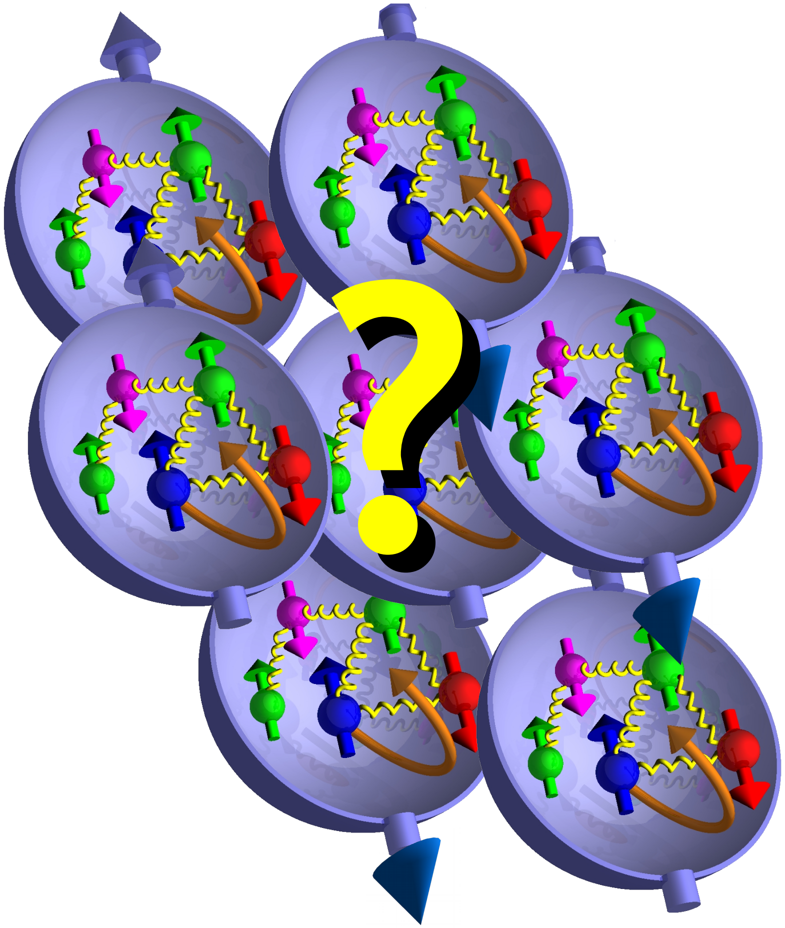
… spinning and orbiting around…



Much studied at:
JLab, HERMES, COMPASS, RHIC

Fundamental topic at:
JLab 6, Electron-Ion-Collider (EIC)

...and interacting inside nuclei



- **EMC effect**
  discovered more than 30 years ago:
  - $A \neq \Sigma$ p,n
  - quarks / hadrons modified inside a nucleus
  - still a theoretical mystery

Evidence for quarks and gluons

Evidence for quarks and gluons - a whirlwind tour

- **Baryon spectroscopy – light sector (*u*, *d*, *s*), ground state**
  - J=3/2⁺: $|q_1\uparrow, q_2\uparrow, q_3\uparrow\rangle$
  - J=1/2⁺: $|q_1\uparrow, q_2\uparrow, q_3\downarrow\rangle$

  totally symmetric w.fn.

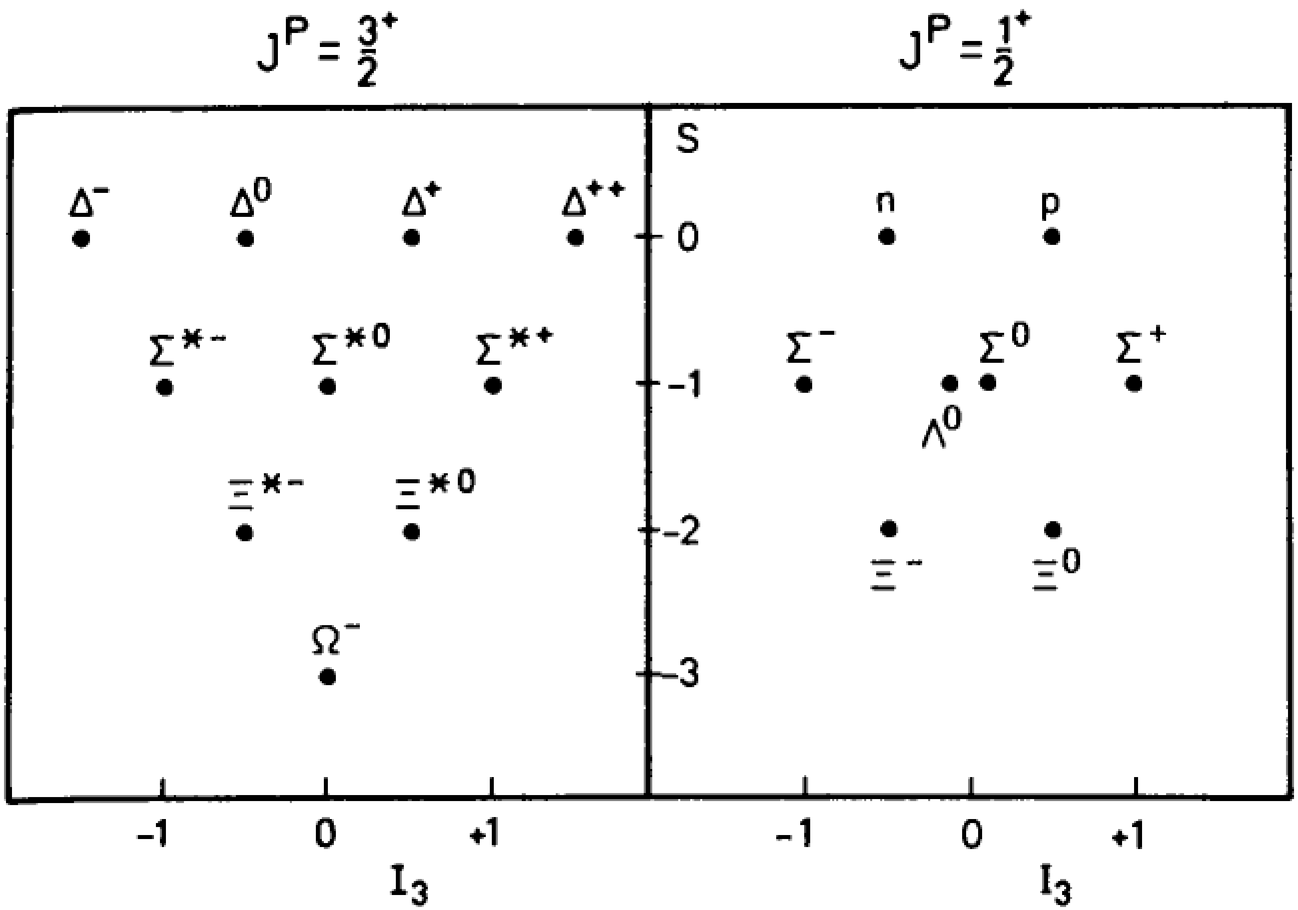


Fig:
[from Povh et al.]

Evidence for quarks and gluons - a whirlwind tour

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  - J=3/2⁺: $|q_1\uparrow, q_2\uparrow, q_3\uparrow\rangle$ spin symmetric, color antisymmetric
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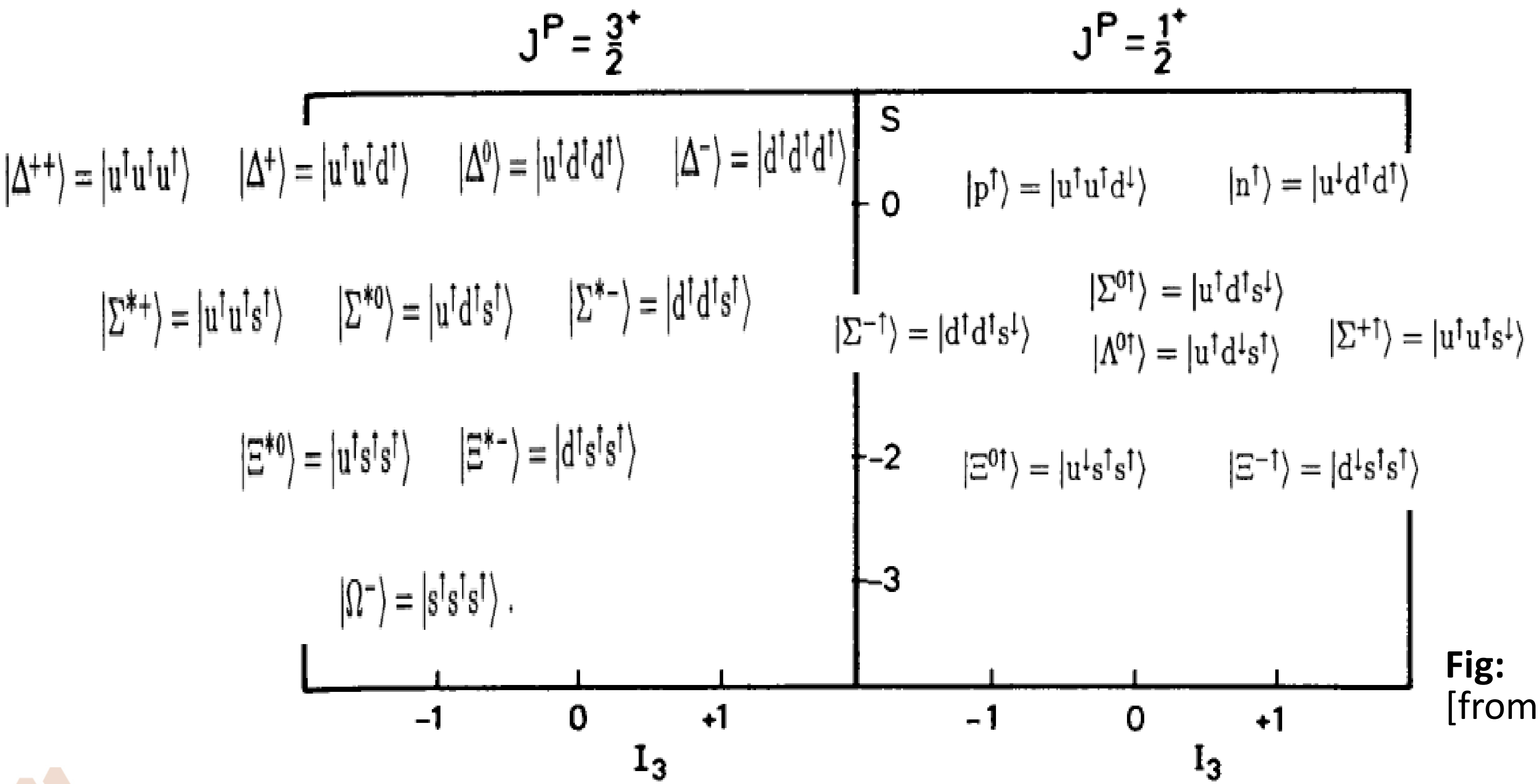
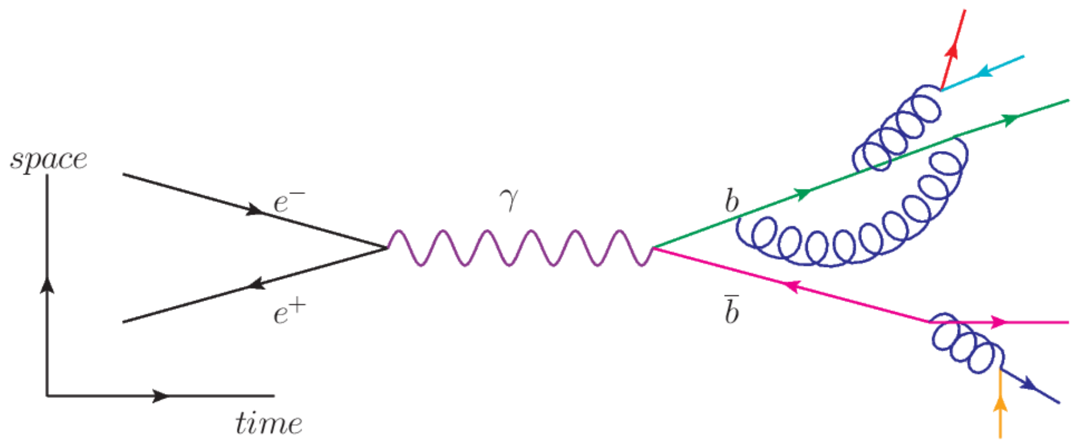


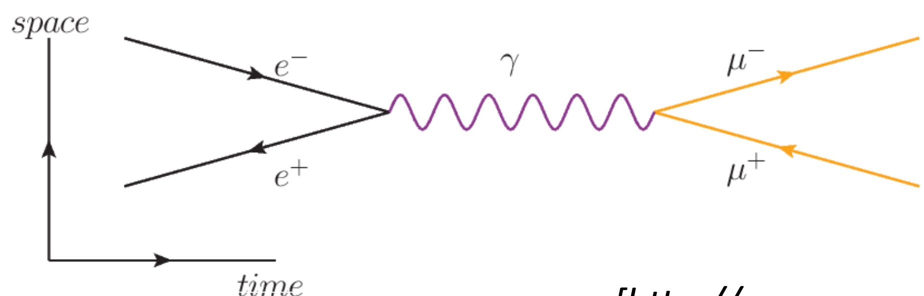
Fig:
[from Povh et al.]

Evidence for quarks and gluons - a whirlwind tour

- **$e^+ + e^-$ annihilation into hadrons**
  - quark-mediated process $e^+ + e^- \to q + \bar{q} \to hadrons$

$$R = \frac{\sigma(e^+e^- hadrons)}{\sigma(e^+e^-\mu^+\mu^-)} = N_{colors} \sum_q e_q^2$$





[http://www.quantumdiaries.org/author/richard-ruiz/]

Evidence for quarks and gluons - a whirlwind tour

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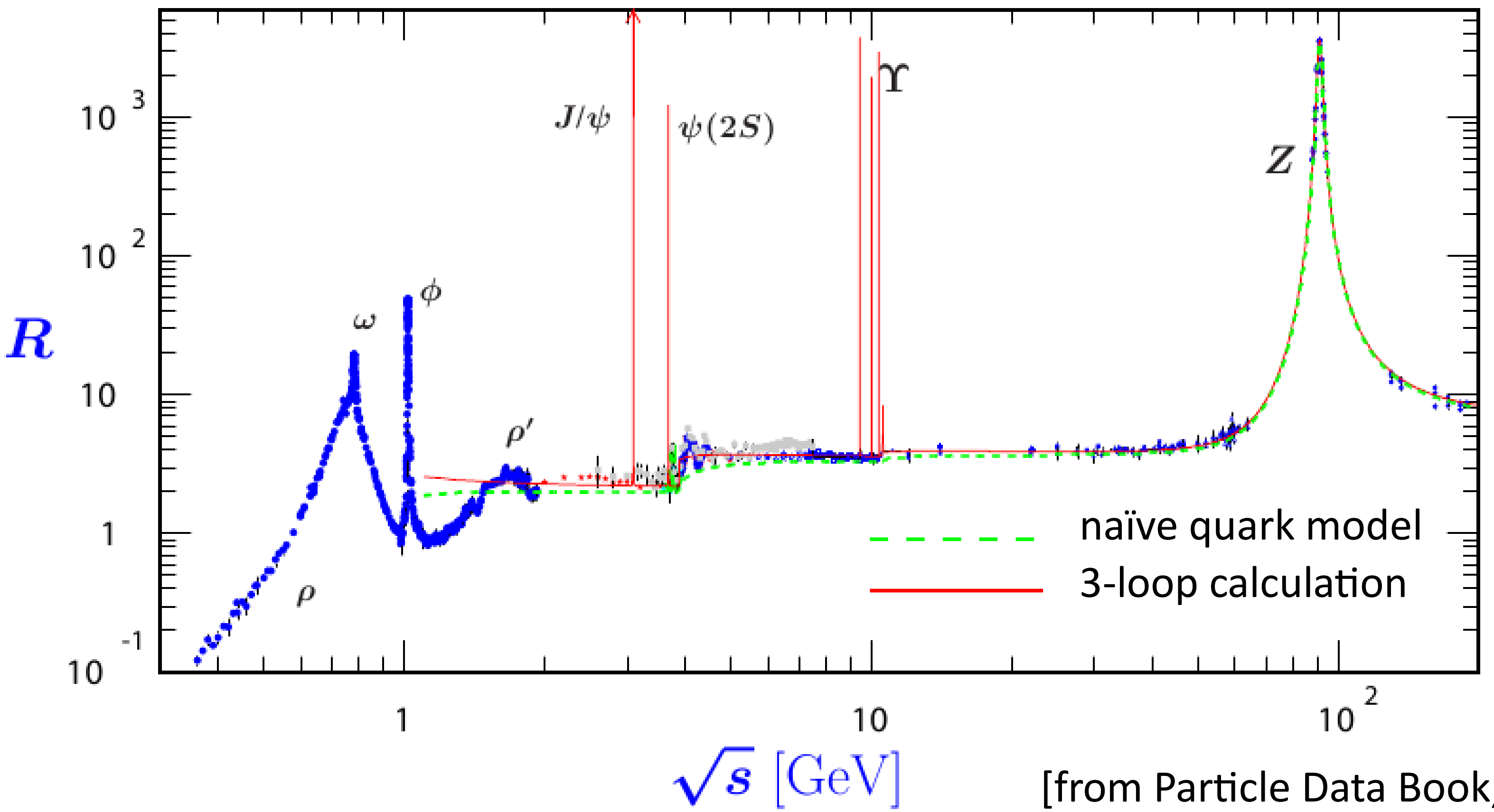


[from Particle Data Book, pdg.lbl.gov]

Evidence for quarks and gluons - a whirlwind tour

- **Jets in high-energy $e^+ + e^-$ collisions**
  - Hadron produced in 2, 3, … N, high-energy collimated "jets"
  - Evidence of common origin from a parton

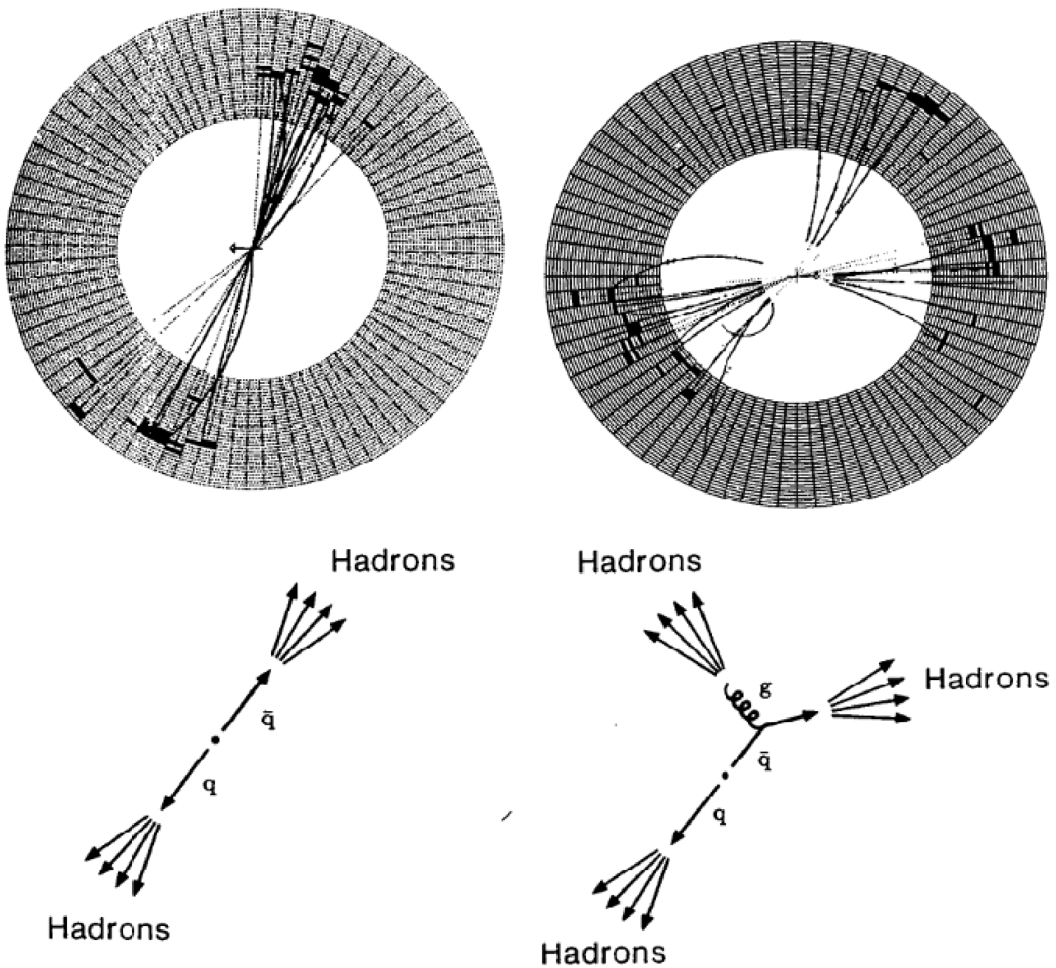


Fig.: 2- and 3-jet events observed by the JADE detector at PETRA [from Povh et al.]

Probing the quark and gluon structure of a hadron

Probing the nucleon parton structure

- Need large momentum transfer $Q^2 = q_\mu q^\mu$ to "resolve" partons

- Example 1: **Deep Inelastic Scattering (DIS)** $e^\pm + p \to e^\pm + X$
  - Photon wave-length in rest frame, neglect proton mass $M/Q \ll 1$:

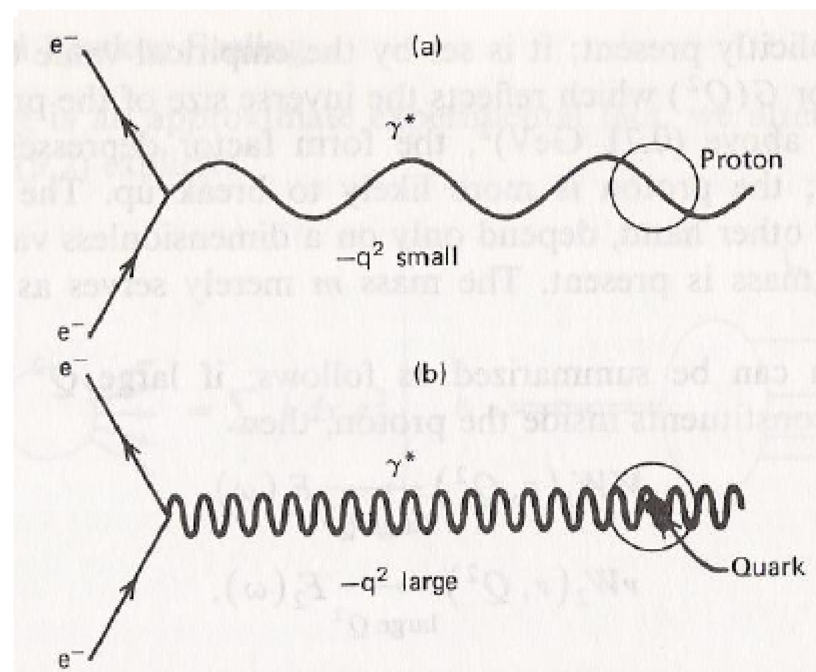
$$\lambda = \frac{1}{|\vec{q}\,|} = \frac{1}{\sqrt{\nu^2 + Q^2}} \approx \frac{1}{\nu} = \frac{2Mx}{Q^2}$$

  - *E.g.*, for x=0.1, Q^2=4 GeV^2 (and putting back *c* and *hbar*),

    $\lambda = 10^{-17}$ m $= 10^{-2}$ fm

    to be compared with

    $R_p \approx 1$ fm



Probing the nucleon parton structure

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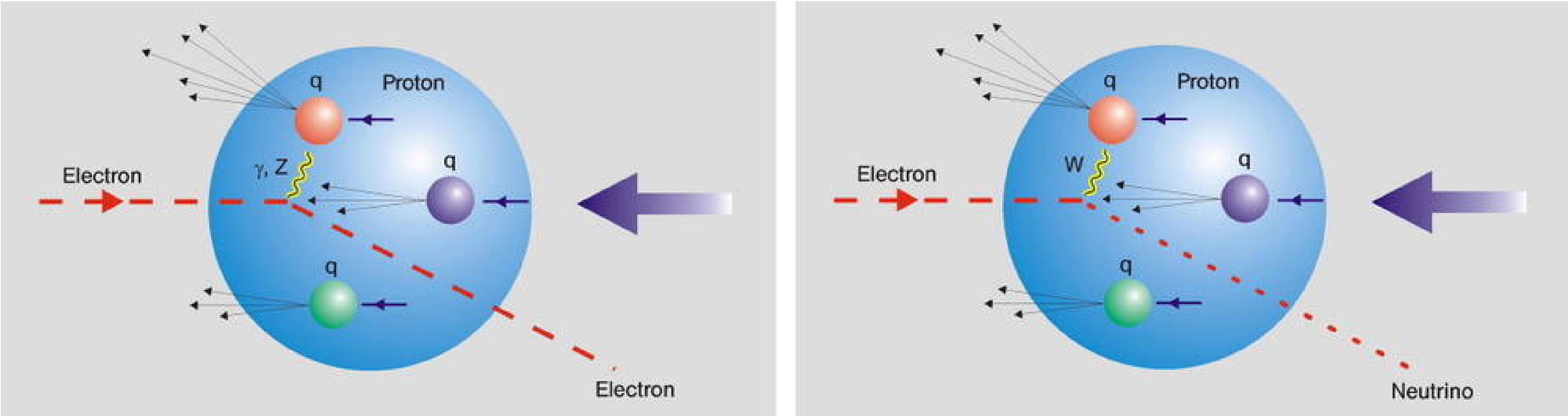
- Example 1: **Deep Inelastic Scattering (DIS)**

$$e^\pm + p \to e^\pm + X$$
$$e^+(e^-) + p \to \bar{\nu}(\nu) + X$$

$$Q^2 = -p^2_{\gamma,Z}$$



Probing the nucleon parton structure

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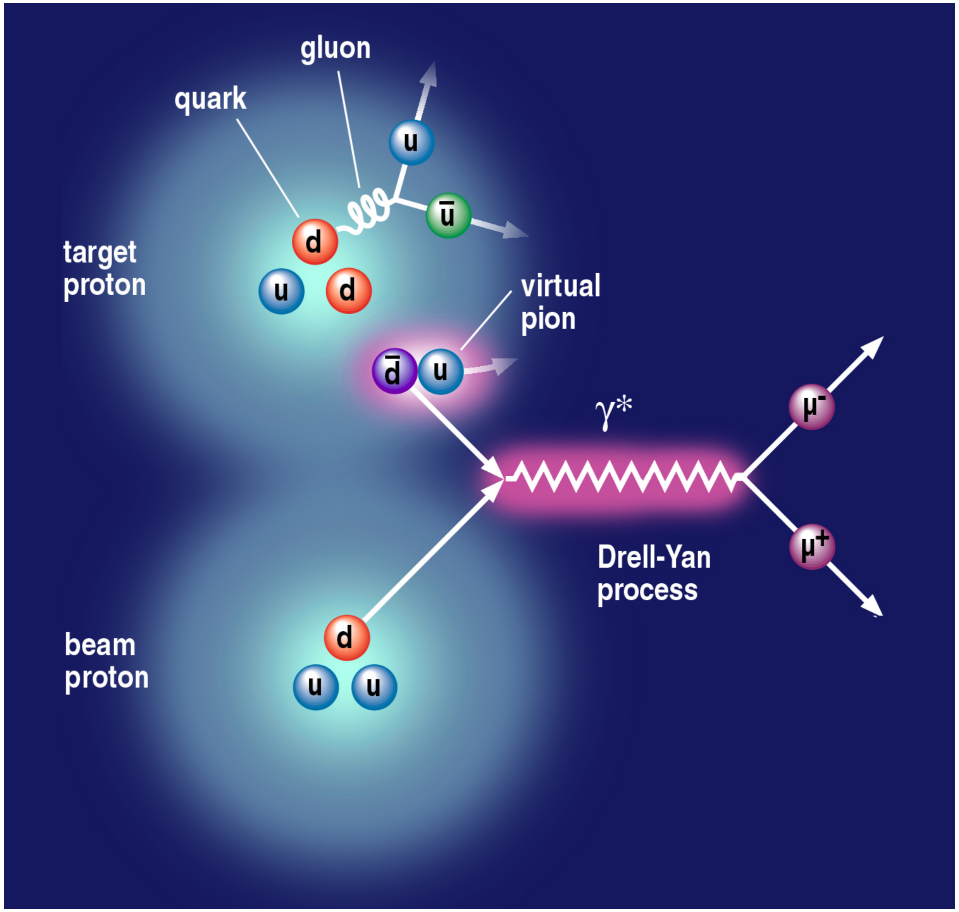
- Example 2: **Lepton-pair production ("Drell-Yan" process)**



$$p + p\,(\bar{p}) \to \ell + \bar{\ell} + X$$

$$Q^2 = (p_\ell + p_{\bar{\ell}})^2$$

Probing the nucleon parton structure

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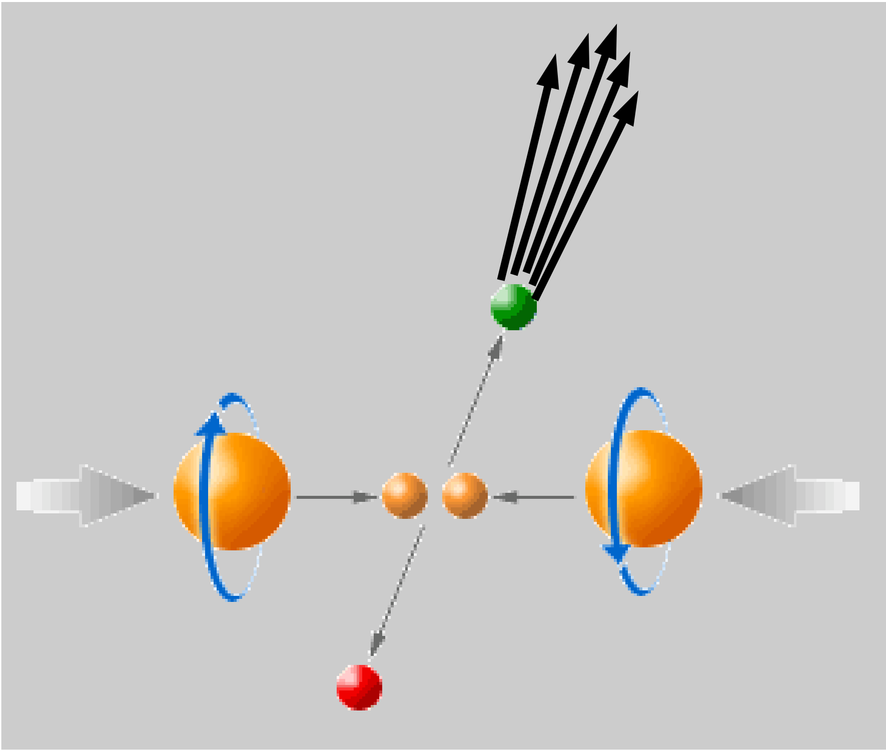
- Example 3: **jet production in p+p collisions**



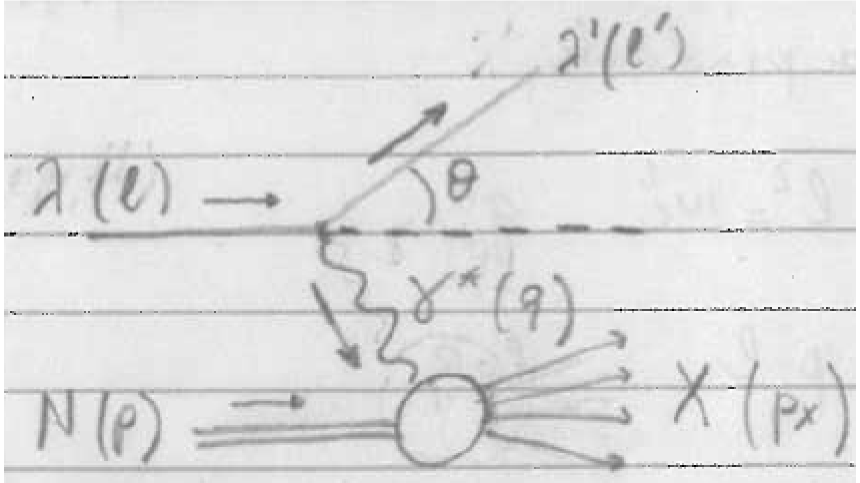
$$p + p\,(\bar{p}) \to jet + X$$

$$Q^2 = E^2_{jet}$$

Deep Inelastic Scattering

Kinematics

- **Inclusive lepton-hadron scattering:**



$$\lambda = e, \mu, \nu, \ldots$$

$$N = p, n, \ldots$$

$$q^\mu = \ell^\mu - \ell'^\mu$$ Virtual photon momentum

$$p_X^\mu = \sum_{i \in X} p_i^\mu$$ Hadronic final state momentum

  – Notation: $p^2 = p_\mu p^\mu \quad p \cdot q = p_\mu q^\mu$
  – Masses: $p^2 = M^2 \quad \ell^2 = m_\lambda^2$

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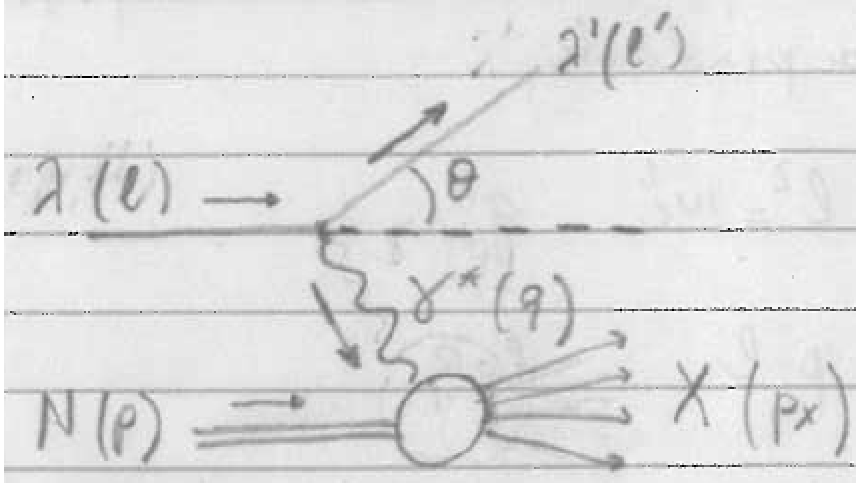

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- The photon is virtual: $q^2 < 0$

Neglect compared to q^2 (MeV vs. GeV)

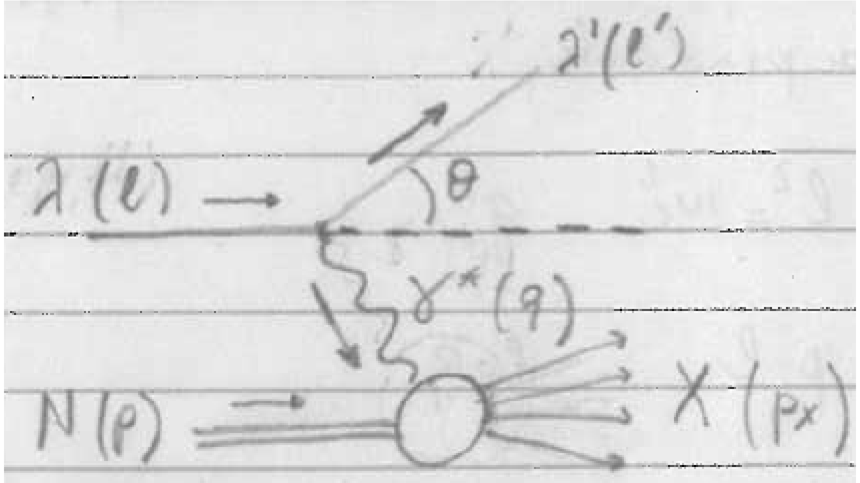
$$q^2 = (l - l')^2 = m_\lambda^2 + m_\lambda^2 - 2\ell \cdot \ell'$$

$$= -2EE' + |\vec{\ell}|\,|\vec{\ell}'|\cos\theta = -2EE'(1 - \cos\theta) \le 0$$

$$m_\lambda^2 = 0 \Rightarrow |\vec{\ell}| = E$$

Kinematics

- **Inclusive lepton-hadron scattering:**



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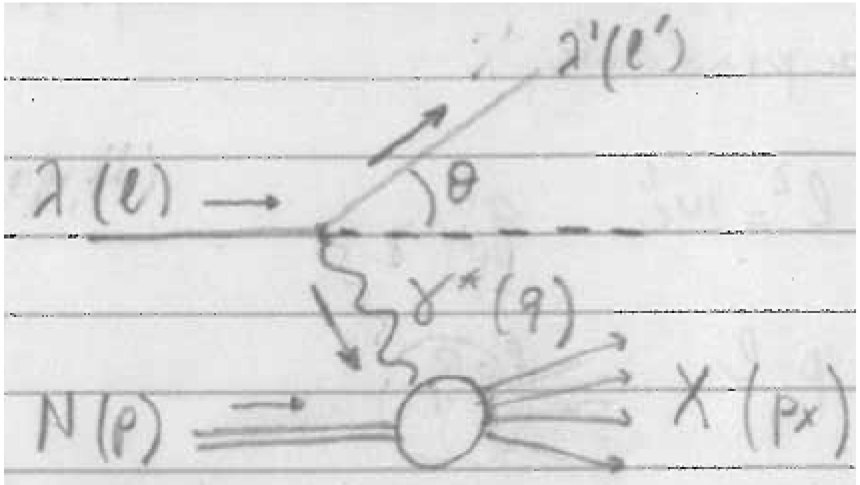

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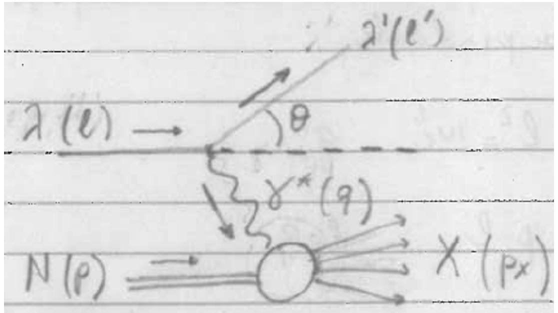
- **Measuring *q*²** (see [Levy]):
  – Scattered lepton
  – Hadronic final state
  – Mixed methods

$$q = \ell - \ell' = p_X - p$$

Kinematics

- **Lorentz invariants**



$$Q^2 = -q^2$$
virtuality

$$x_B = \frac{-q^2}{2p \cdot q}$$
Bjorken x

$$\nu = \frac{p \cdot q}{\sqrt{p^2}}$$
beam energy loss *

$$y = \frac{p \cdot q}{p \cdot \ell}$$
inelasticity *

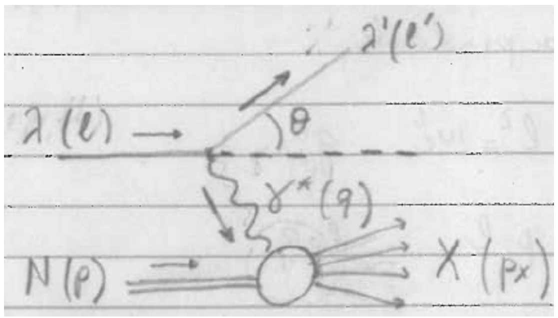
$$W^2 = (p+q)^2$$
(final state) invariant mass

$$s = (p+\ell)^2$$
center-of-mass energy

* interpretation valid in hadron rest frame, see later

Kinematics

- **Lorentz invariants**



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– **Ex.1** (easy) – Do these 6 invariants exhaust all possibilities?

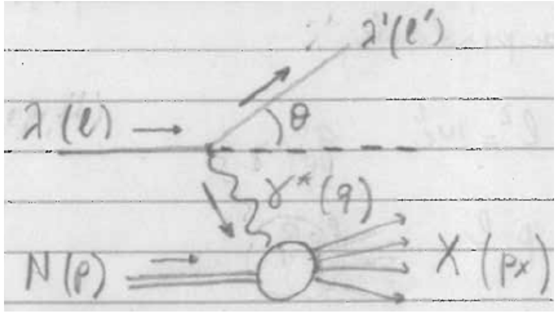
– **Ex.2** (easy) – Are all 6 independent of each other? Prove that:

$$\nu = \frac{Q^2}{2Mx_B} \qquad s - M^2 = \frac{Q^2}{2x_B y} \qquad W^2 = M^2 + Q^2\left(\frac{1}{x_B} - 1\right)$$

* interpretation valid in hadron rest frame, see later

Kinematics

❑ Kinematic limits on invariants



– $Q^2 > 0$

– $0 < x_B < 1$

- By baryon number conservation the final state must contain at least 1 proton, if the target is a proton: $p_X = p_{proton} + \sum_i p_i$

  Then, $p_X^2 = M^2 + \sum_i p_{proton} \cdot p_i + \sum_{i,j} p_i \cdot p_j$

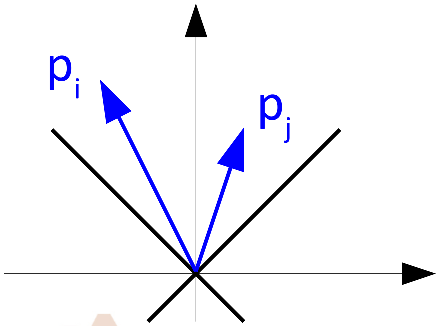
- All final state hadrons are on-shell: $p_i^2 = M_i^2 \;\Rightarrow\; E_i \geq |\vec{p}_i\,|$

  Then,

  $$p_j \cdot p_j = E_i E_j - |\vec{p}_i|\,|\vec{p}_i| \cos\theta_{ij} \geq E_i E_j - |\vec{p}_i|\,|\vec{p}_i| \geq 0$$

  so that

  $$W^2 = p_X^2 \geq M^2 \;\Rightarrow\; Q^2 \frac{1 - x_B}{x_B} \geq 0 \;\Rightarrow\; 0 \leq x_B \leq 1$$



Kinematics

Kinematic limits on invariants, cont'd

- $\nu \geq 0$
  - **Ex.3** (easy) Hint: use definition and $W^2 - M^2 \geq 0$
- $0 \leq y \leq 1$

  Consider the "target rest frame" such that $\vec{p} = 0$

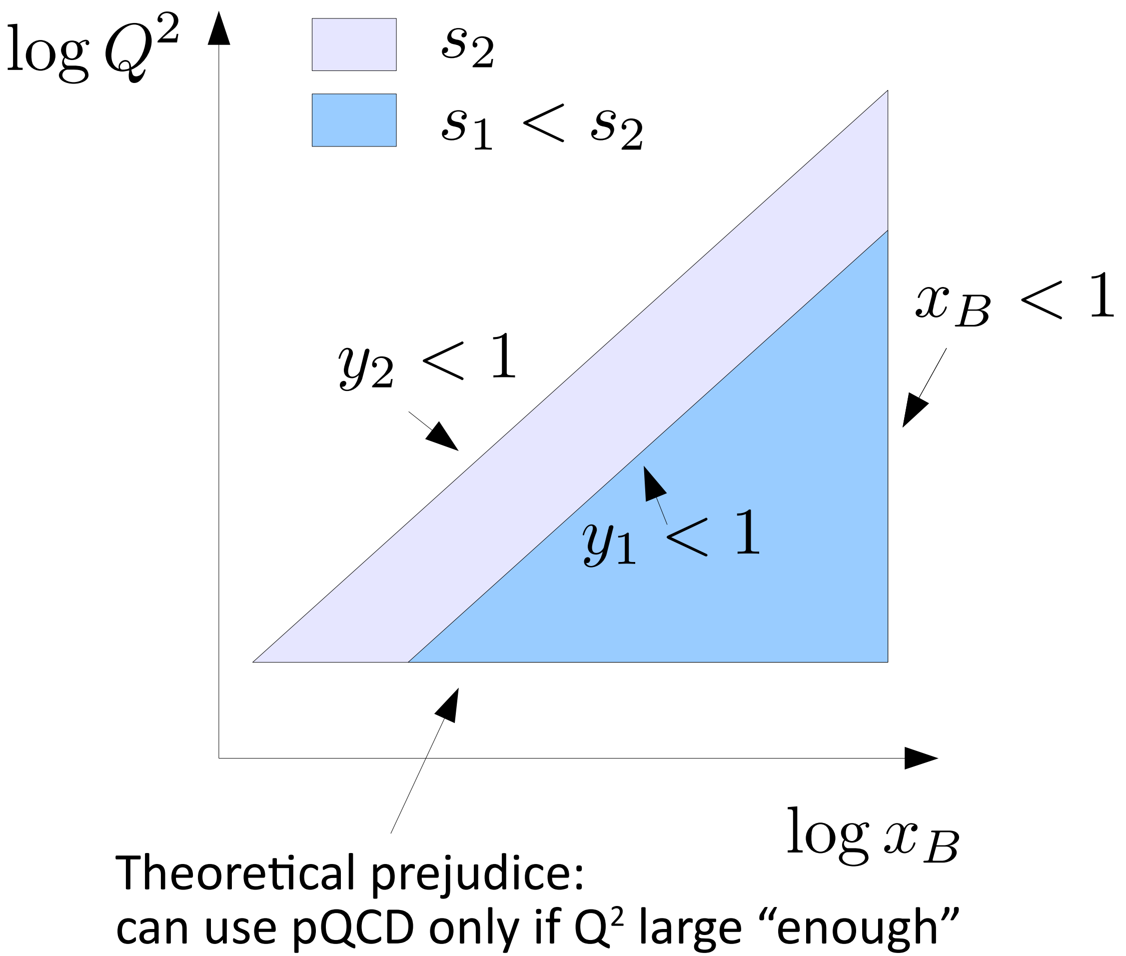
  $$p = (M, \vec{0}_T, 0) \quad \ell = (E_\ell, \vec{0}_T, \ell_z) \quad \ell' = (E'_\ell, \vec{\ell}'_T, \ell'_z)$$

  Then, $y = \dfrac{M(E_\ell - E'_\ell)}{M E_\ell} = 1 - \dfrac{E'_\ell}{E_\ell}$

  - **Ex.4** (hard): find a Lorentz invariant proof

Kinematics

- **Kinematic plane – theoretical**
  - Pick x_B , Q^2, y as independent variables



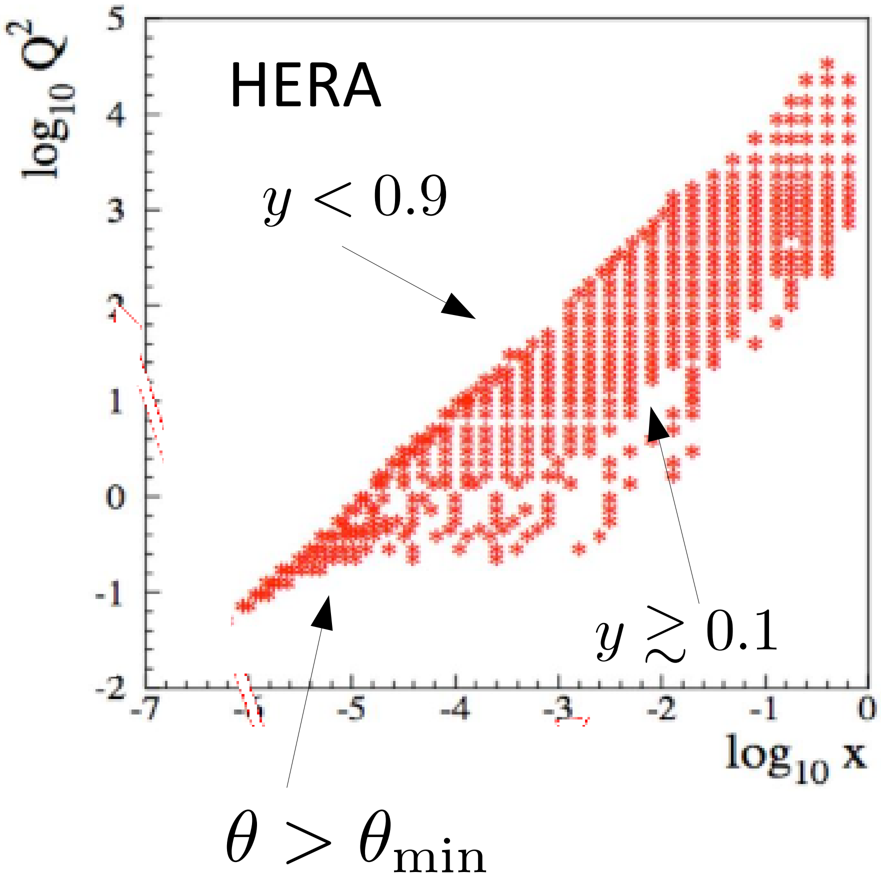
$$y_i \approx \frac{Q^2}{x s_i}$$

$$s_2 > s_1$$

Kinematics

- **Kinematic plane – in practice**

e+p collider

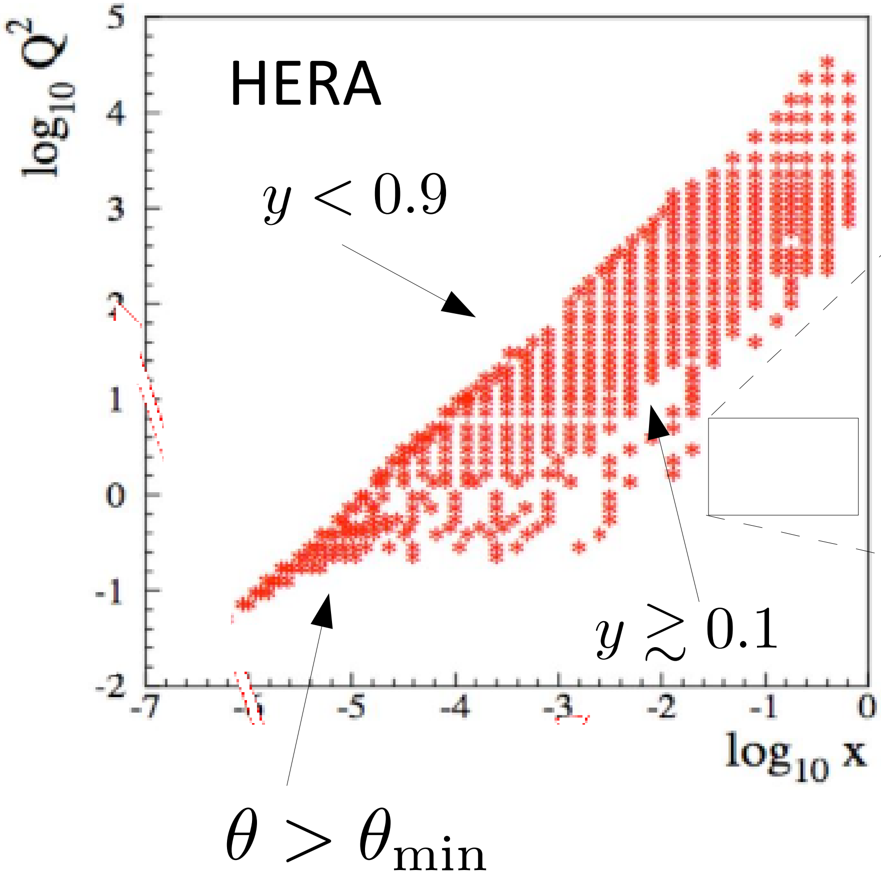


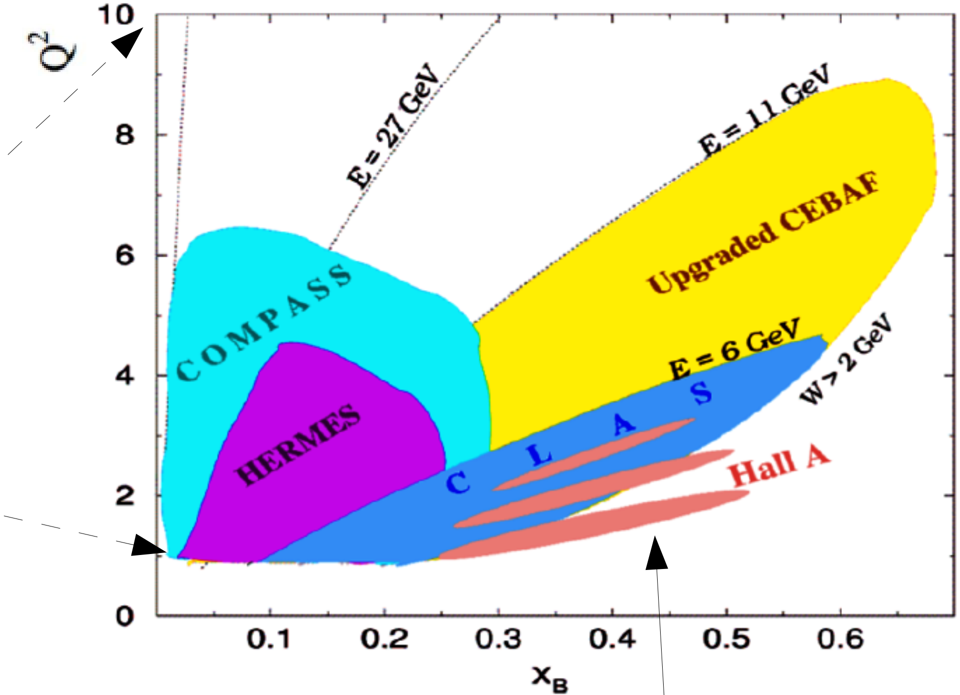
Kinematics

❑ Kinematic plane – in practice

e+p collider

fixed target experiments





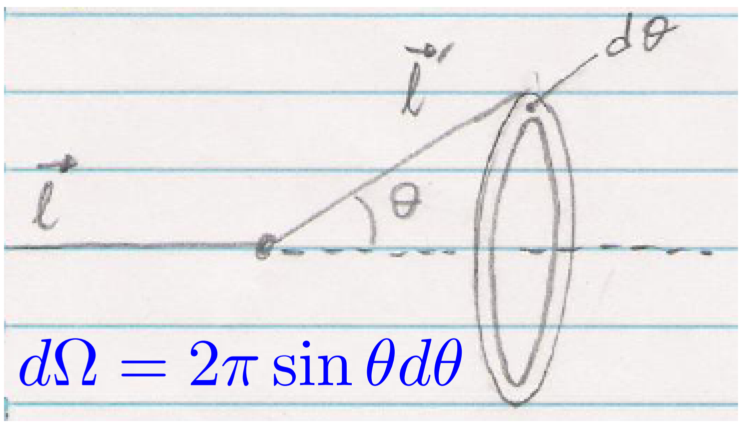
Fixed-angle spectrometers

Cross section

- DIS in the target rest frame (for collider, Breit frames see [Levy])

$$p = (M, \vec{0}_T, 0) \qquad \ell = (E_\ell, \vec{0}_T, \ell_z)$$

$$q = (q_0, \vec{q}_T, q_z) \qquad \ell' = (E'_\ell, \vec{\ell}'_T, \ell'_z)$$



  – invariants

$$\nu = p \cdot q / M = q_0 = E_\ell - E'_\ell$$

$$y = p \cdot q / p \cdot \ell = \nu / E_\ell$$

$$Q^2 = 2 E_\ell E'_\ell (1 - \cos\theta) = 4 E_\ell E'_\ell \sin^2(\theta/2)$$

- Cross section

$$\frac{d\sigma}{dx_B dQ^2} = \frac{y}{x_B} \frac{\pi}{E'_\ell} \frac{d\sigma}{dE'_\ell d\Omega}$$

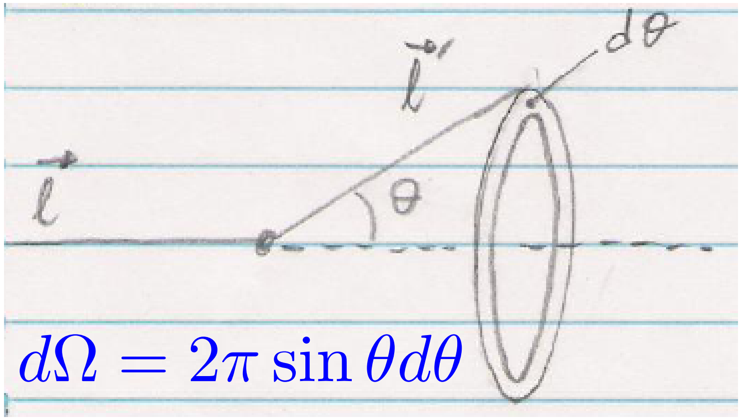
  – **Ex.5** (med) : prove this (hint: work out $dQ^2/d\theta$)
  – **Ex.6** (hard) : directly show that r.h.s. Is Lorentz invariant

Cross section

- DIS in the target rest frame (for collider, Breit frames see [Levy])

$$p = (M, \vec{0}_T, 0) \qquad \ell = (E_\ell, \vec{0}_T, \ell_z)$$

$$q = (q_0, \vec{q}_T, q_z) \qquad \ell' = (E'_\ell, \vec{\ell}'_T, \ell'_z)$$



– invariants

$$\nu = p \cdot q / M = q_0 = E_\ell - E'_\ell$$

$$y = p \cdot q / p \cdot \ell = \nu / E_\ell$$

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- Cross section

$$\frac{d\sigma}{dx_B dQ^2} = \frac{y}{x_B} \frac{\pi}{E'_\ell} \frac{d\sigma}{dE'_\ell d\Omega}$$

$$\frac{d\sigma}{dx_B dQ^2} = \frac{\nu}{x_B} \frac{d\sigma}{d\nu dQ^2}$$

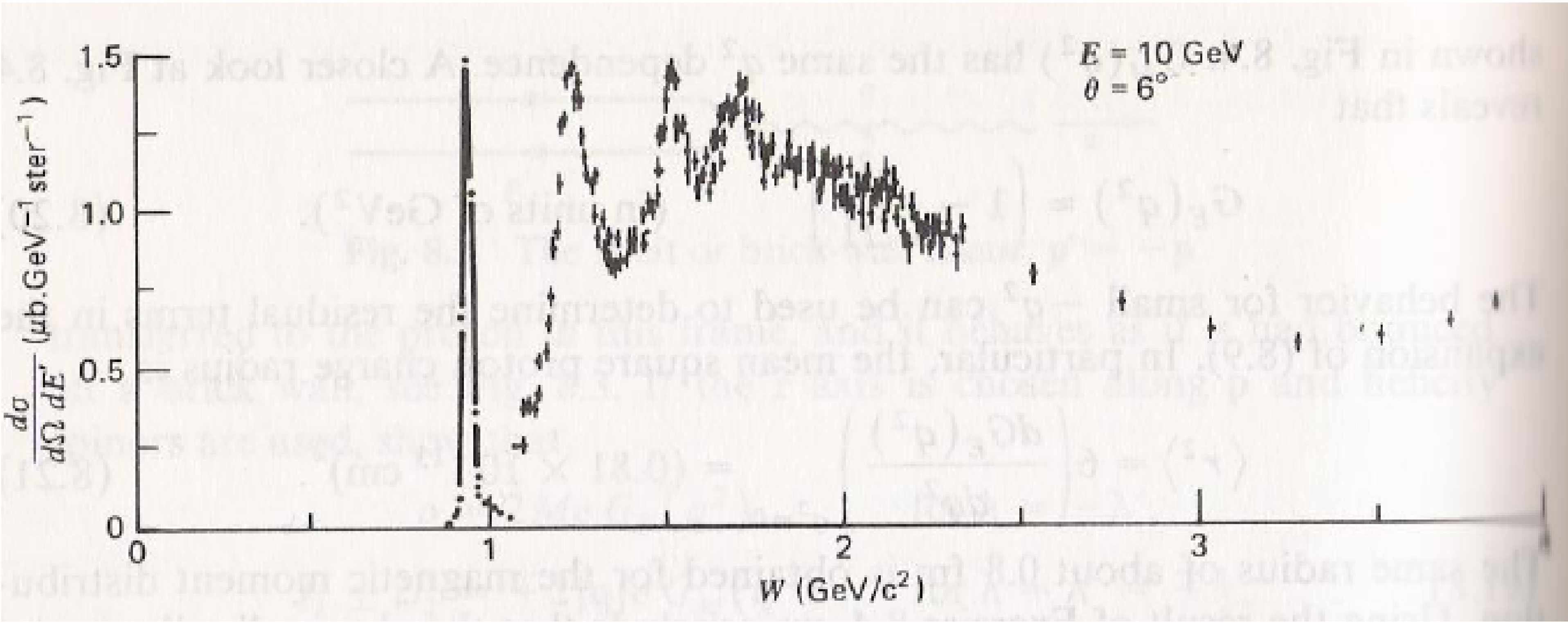
$$= \frac{y}{Q^2} \frac{d\sigma}{dx_B dy} = \frac{y}{x_B} \frac{d\sigma}{dy dQ^2}$$

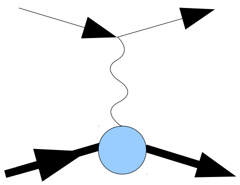
– and also

– **Ex.5** (med) : prove this (hint: work out $dQ^2/d\theta$)

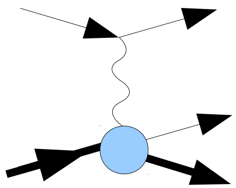
– **Ex.6** (hard) : directly show that r.h.s. Is Lorentz invariant

Cross section

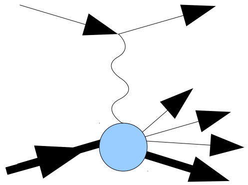




Elastic: W=M
(no energy to produce
any other particle)



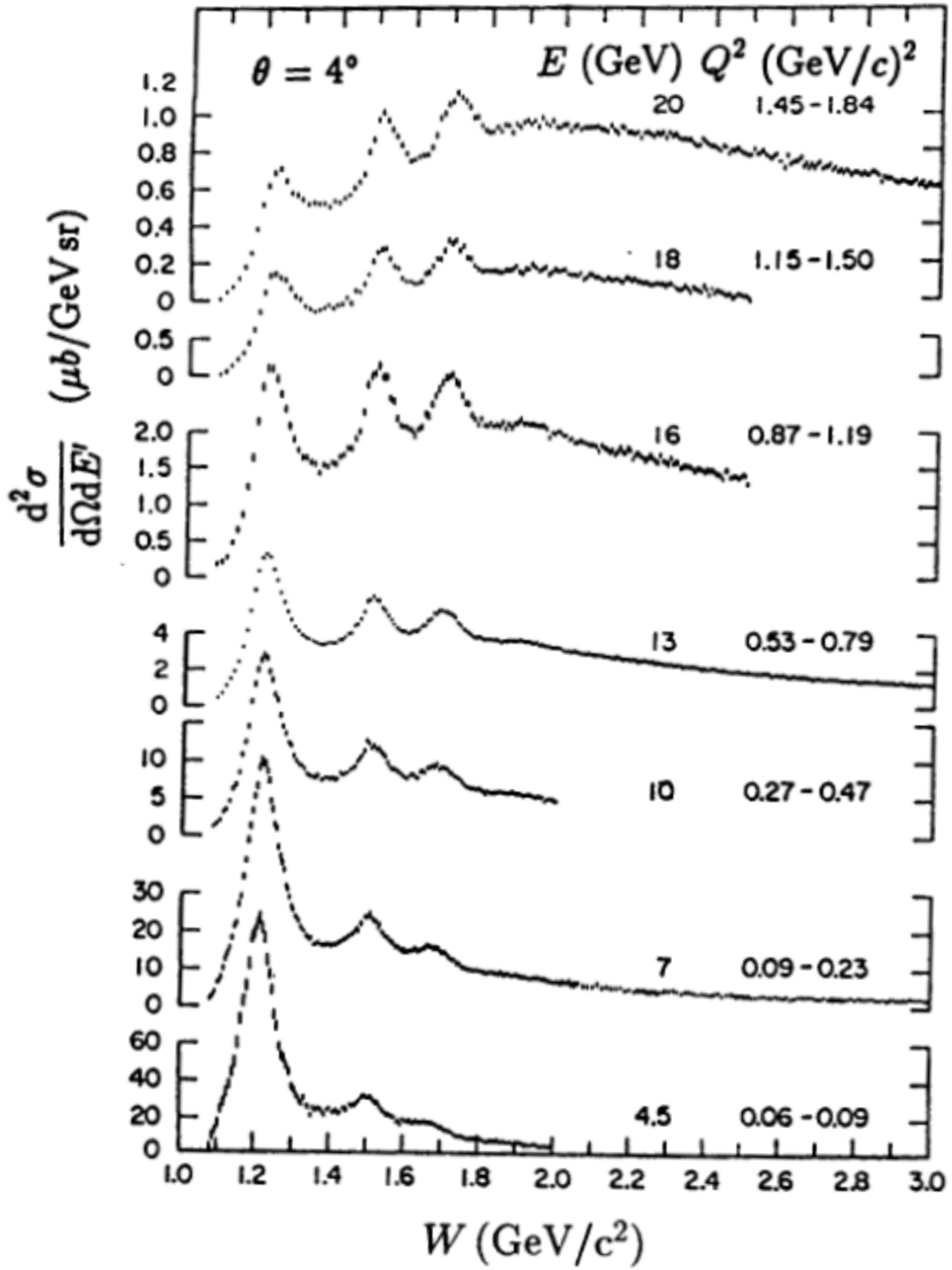
Inelastic
(resonance region)
(W for only a few particles)



Deep inelastic
(large W, more particles)

$Q^2, W^2 \to \infty \quad x_B$ fixed

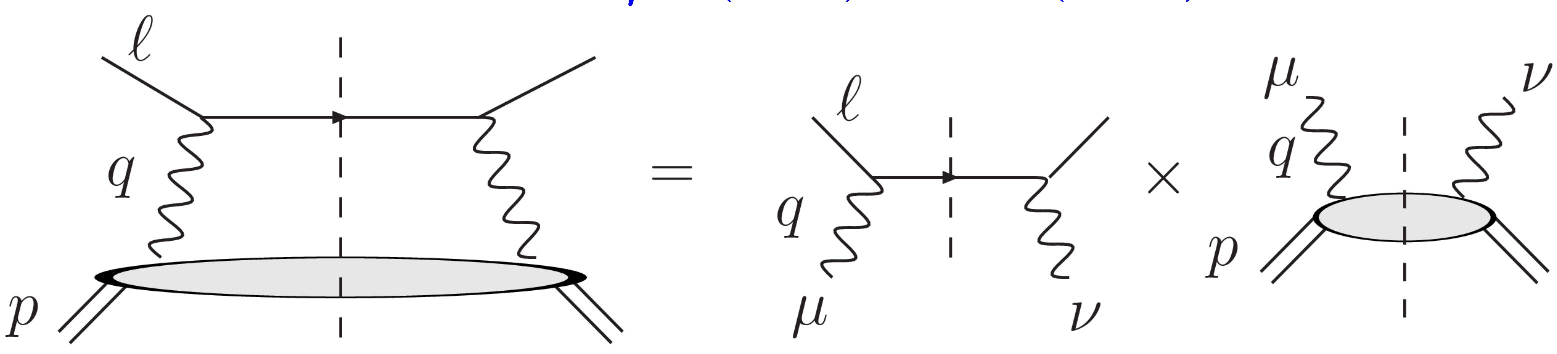
Cross section



Structure functions

- Leptonic and hadronic tensors – 1 photon exchange

$$d\sigma \propto L_{\mu\nu}(\ell, q) W^{\mu\nu}(p, q)$$



  – Electron is elementary: $L_{\mu\nu}$ can be calculated perturbatively

- Lorentz decomposition + gauge invariance = structure functions

$$W^{\mu\nu}(p,q) = \Big(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\Big) F_1(x_B, Q^2)$$
$$+ \Big(p^\mu - \frac{p\cdot q}{q^2} q^\mu\Big)\Big(p^\nu - \frac{p\cdot q}{q^2} q^\nu\Big) F_2(x_B, Q^2)$$
$$+ i\varepsilon_{\mu\nu\alpha\beta} \frac{p^\alpha q^\beta}{2p\cdot q} F_3(x_B, Q^2)$$

$\neq 0$ only for $W^\pm$, Z^0 boson exchanges

Structure functions

- Lorentz decomposition + gauge invariance = structure functions

$$W^{\mu\nu}(p,q) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_1(x_B, Q^2)$$
$$+ \left(p^\mu - \frac{p\cdot q}{q^2} q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2} q^\nu\right) F_2(x_B, Q^2)$$
$$+ i\varepsilon_{\mu\nu\alpha\beta} \frac{p^\alpha q^\beta}{2p\cdot q} F_3(x_B, Q^2)$$

- Note:
  - F_1, F_2, F_3 are Lorentz invariants

    (the tensor structure is explcitly factorized out)
  - Most general structure compatible with Lorentz and gauge invariance, no missing functions
  - **Ex.7** (med) : convince yourself of these 2 statements

    (gauge invariance implies $q_\mu W^{\mu\nu} = 0$)

Structure functions and cross section

- The cross section (for a γ exchange) reads

$$\frac{d\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^4} L_{\mu\nu}(\ell, q) W^{\mu\nu}(p, q)$$

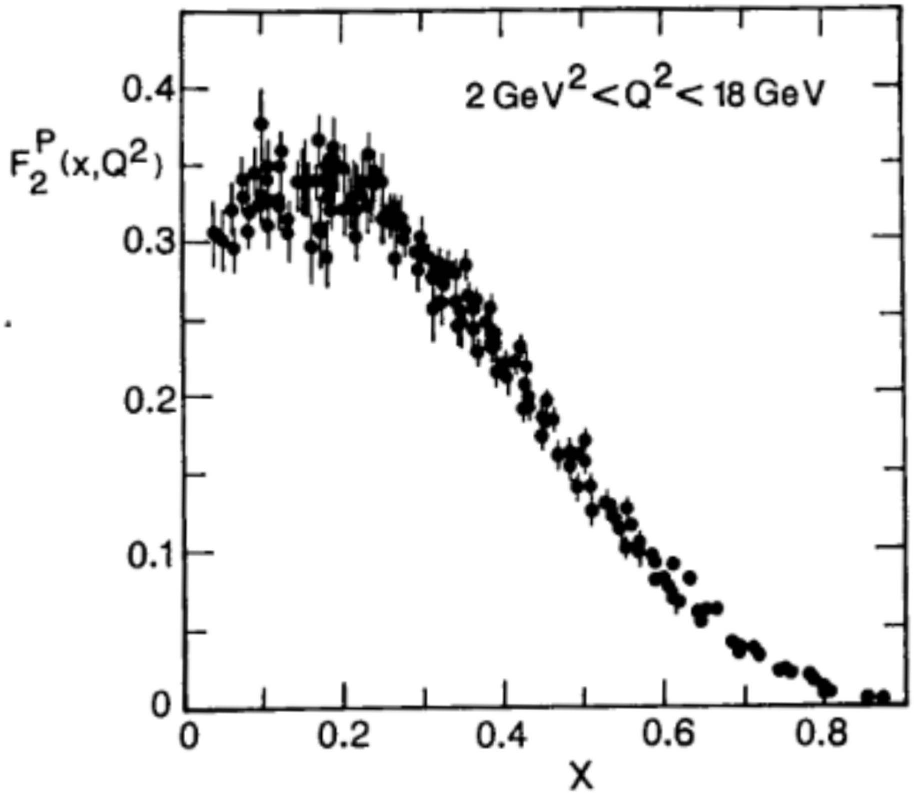
- Using

$$L_{\mu\nu} = 2\big(\ell_\mu \ell'_\nu + \ell'_\mu \ell'_\nu - \ell \cdot \ell' g_{\mu\nu}\big)$$

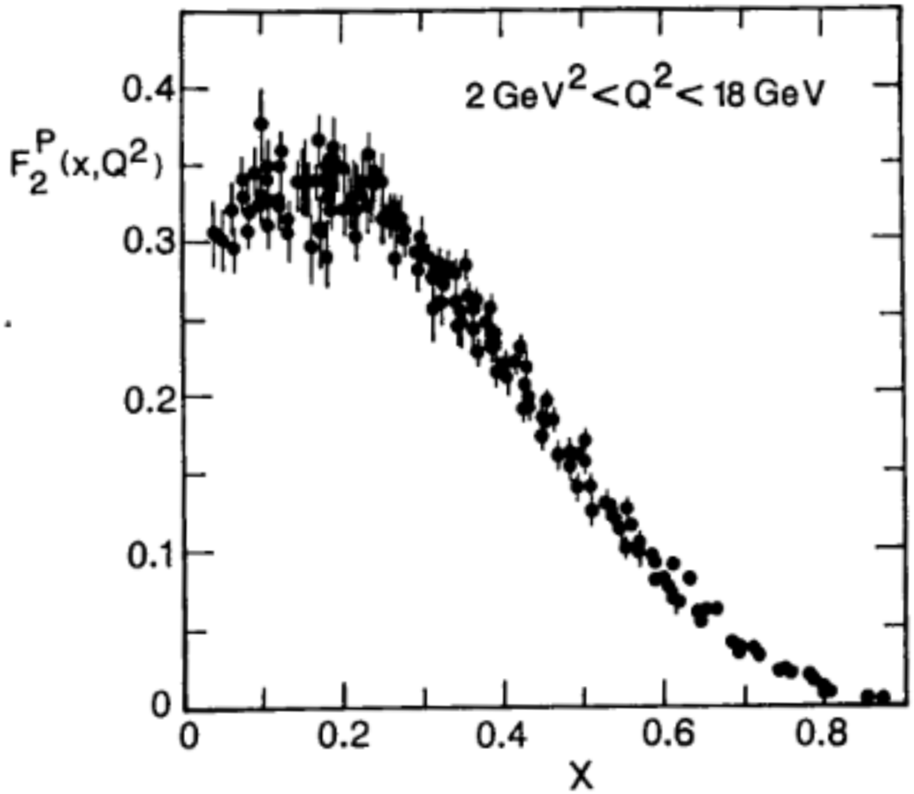
one obtains

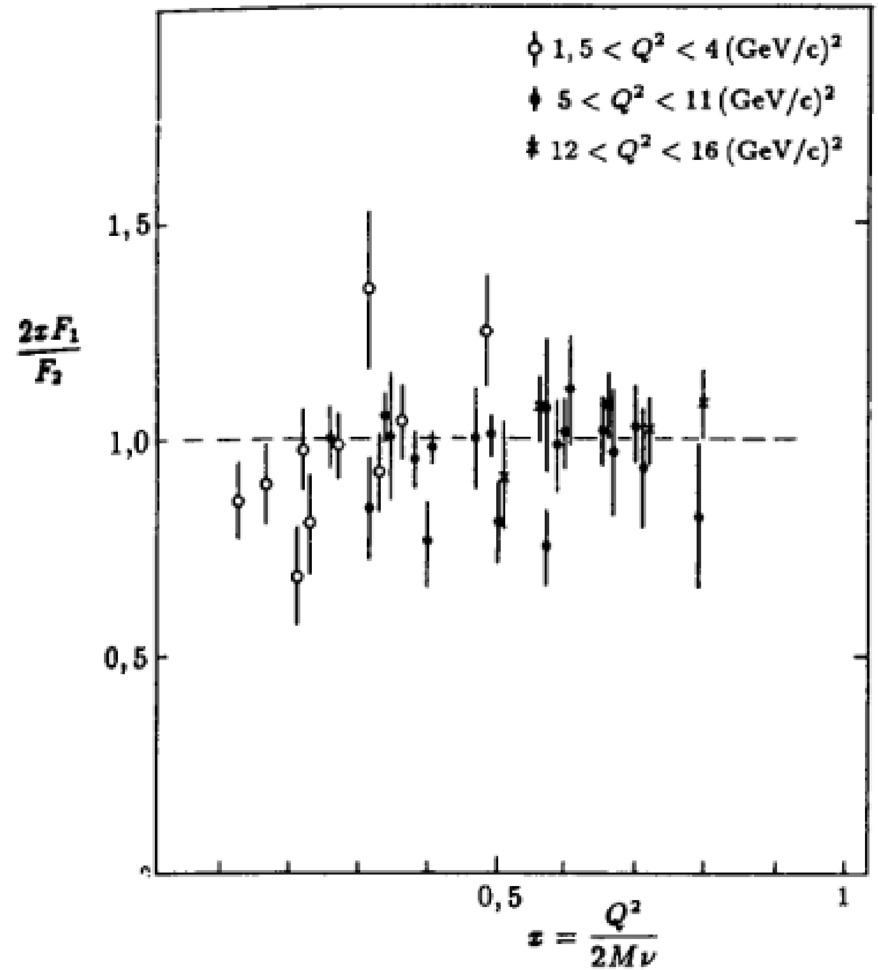
$$\frac{d\sigma}{dx_B\,dQ^2} = \frac{4\pi\alpha^2}{x_B Q^4}\left\{\left(1 - y - x_B^2 y^2 \frac{M^2}{Q^2}\right) F_2(x_B, Q^2) + y^2 x_B F_1(x_B, Q^2) \mp \left(y - \frac{y^2}{2}\right) x_B F_3(x_B, Q^2)\right\}$$

Structure functions

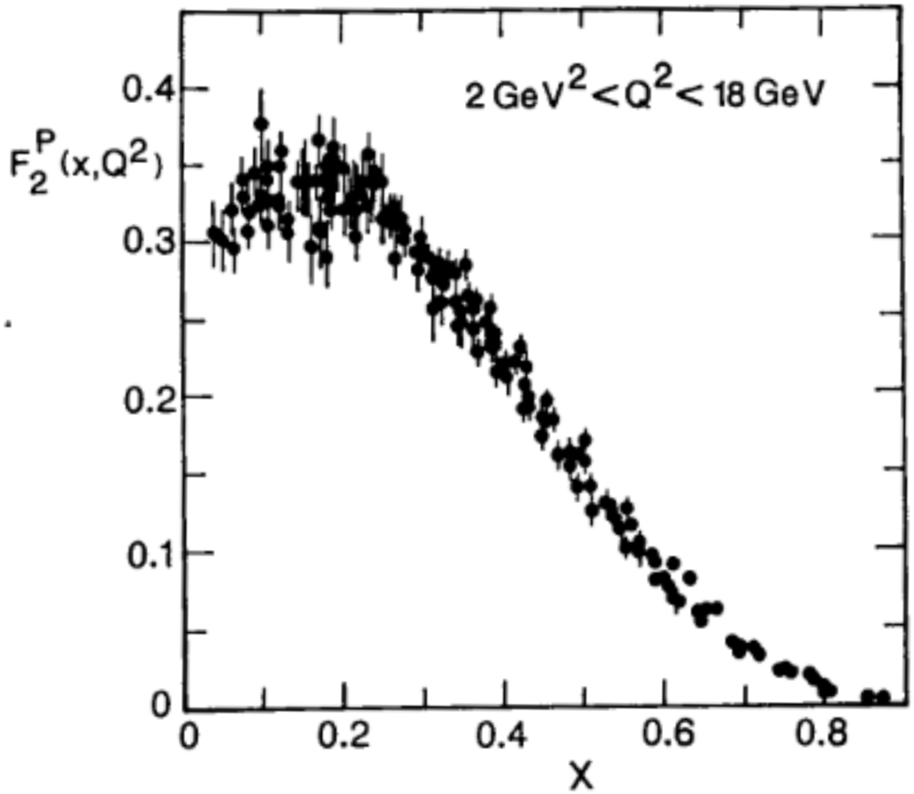


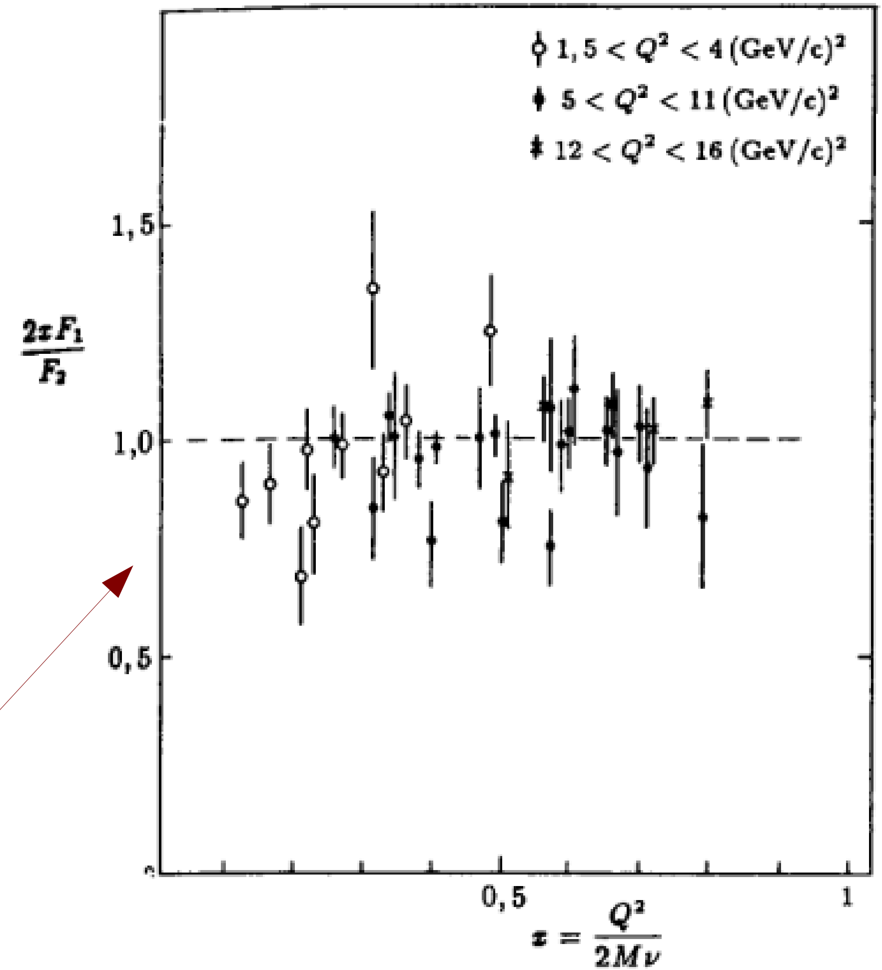
Structure functions





Structure functions

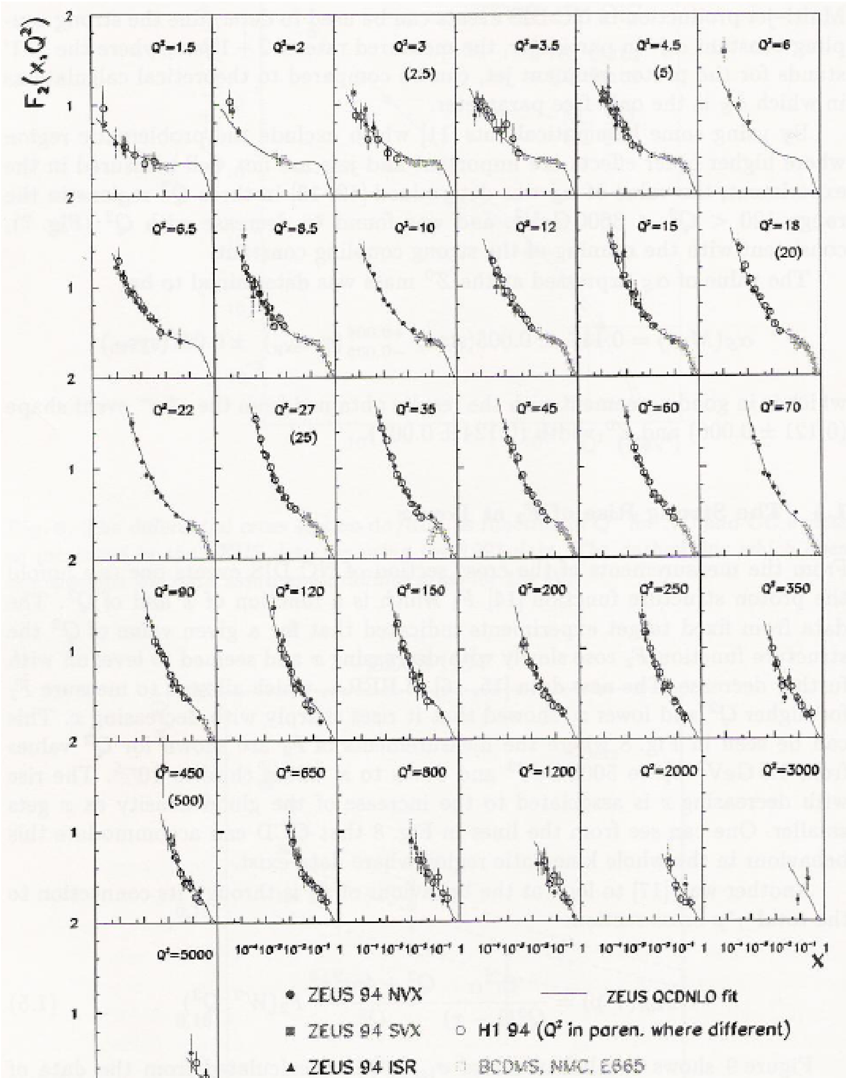




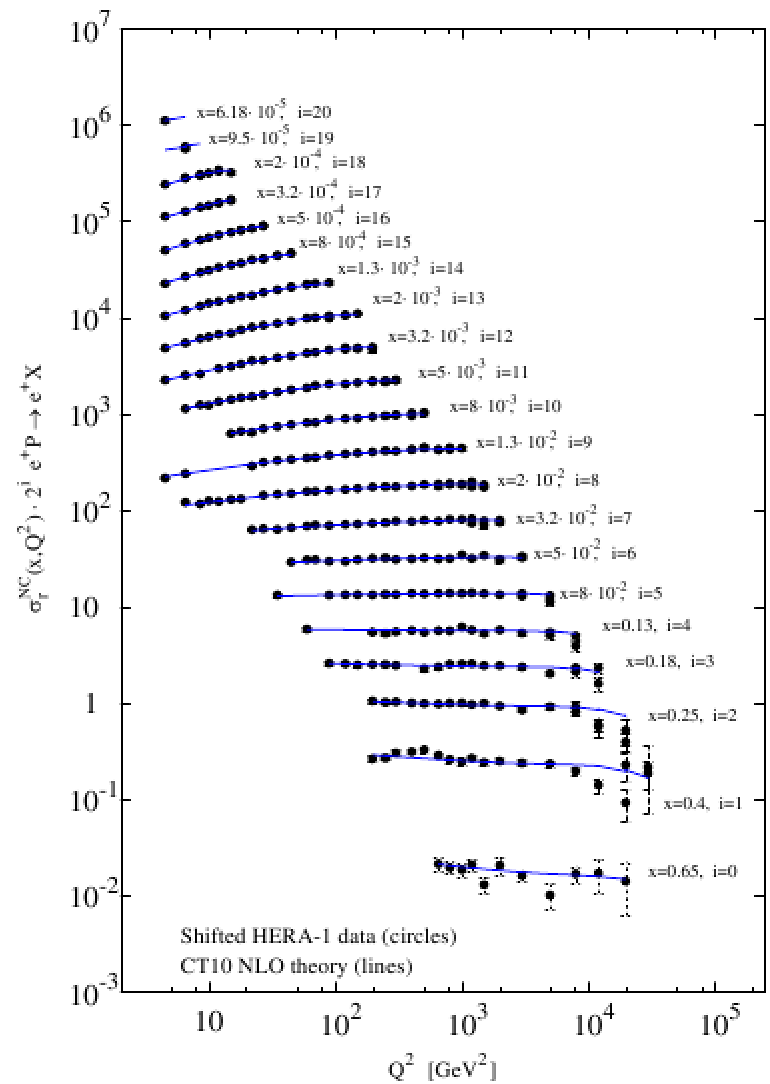
Same as if target was a free spin ½ particle:

The photon is scattering on quasi-free quarks

Structure functions



$10^{-5} < x < 0.6$



- Note: evolution with Q^2 and rise at low-x (here come the gluons!)

A taste of the parton model

A taste of the parton model

- The photon scatters on quasi-free quarks
  - Empirical evidence: $F_2 = 2x_B F_1$
  - Photon wave-length in rest frame, neglect proton mass $M/Q \ll 1$:

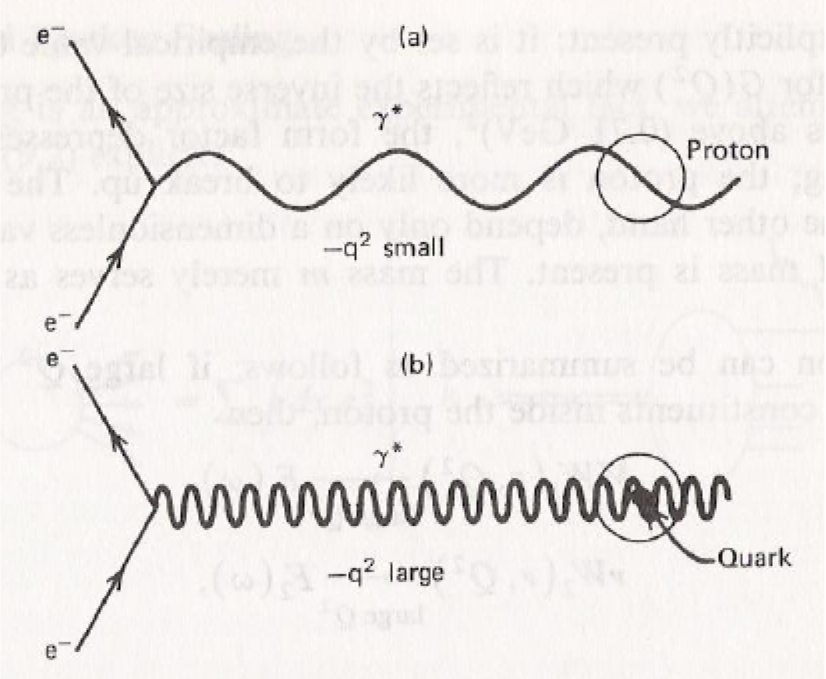
$$\lambda = \frac{1}{|\vec{q}|} = \frac{1}{\sqrt{\nu^2 + Q^2}} \approx \frac{1}{\nu} = \frac{2Mx}{Q^2}$$

  - *E.g.*, for x=0.1, Q^2=4 GeV^2 (and putting back *c* and *hbar*),

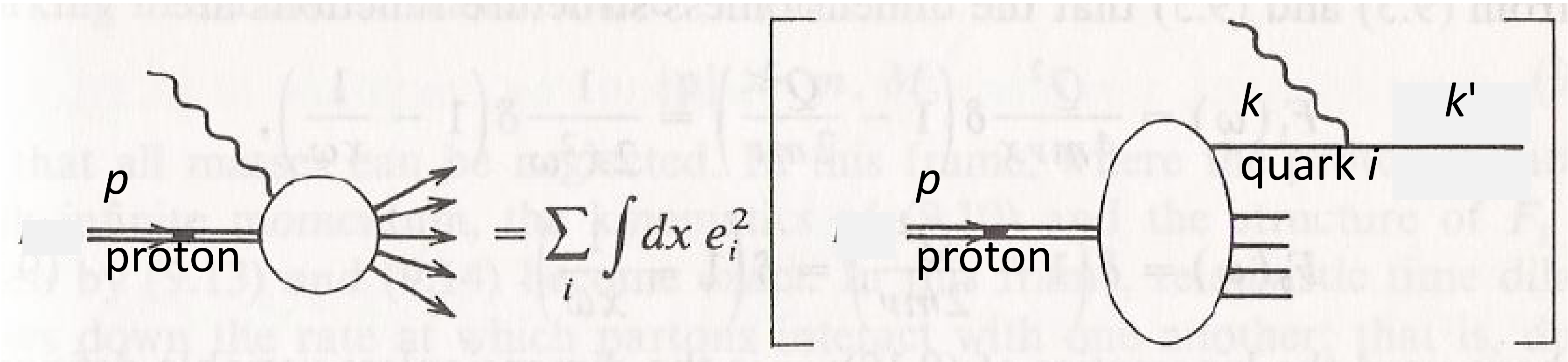
    $\lambda = 10^{-17}$ m = 10^{-2} fm

    to be compared with

    $R_p \approx 1$ fm



A taste of the parton model



- DIS ≈ photon-quark *elastic* scattering
- Interpretation of x_B
  - Parton carries fraction x of proton's momentum: $k^\mu = x\, p^\mu$
  - 4-momentum conservation: $k' = k+q$
  - Partons have zero mass: $k^2 = k'^2 = 0$

$$x = \frac{Q^2}{2p \cdot q} = x_B$$

- **The virtual photon probes quarks with $x = x_B$**

A taste of the parton model

- **Beware:** There is an inconsistency in the derivation:
  - From $k = xp$ follows that quarks are massive, $M_q = xM$!!

- A heuristic way out is to work in the "infinite momentum frame", where $|\vec{p}| \to \infty$ so that one can neglect the proton's mass:

$$E_p = \sqrt{\vec{p}^{\,2} + M^2} \to |\vec{p}|$$

  - This frame is also important to better justify the parton model
  - But quarks should be massless in any frame
    - The problem lies in the definition of x
    - We'll see a better solution in tomorrow's lecture
  - Similarly, the vector 3-momentum is not a Lorentz-invariant scale
    - In fact, M can be neglected compared to Q, not $|\vec{p}|$, as we shall see

Lecture 1 - recap

- **Hadrons are made of quarks and gluons**
  - Partonic structure probed in DIS, DY, jets, ... (we'll see more)
- **Deep Inelastic Scattering (DIS)**
  - The master method to measure quarks and gluons
  - Invariant kinematics, target rest frame
  - Cross section, parametrized in terms of structure functions
- **A taste of the parton model**
  - Phenomenological evidence for quasi-free quarks, gluons
  - Some trouble in heuristic, textbook arguments
- **Next lecture: Parton model, parton distributions (PDF)**
  - (QCD improved) parton model
  - More kinematics
  - Factorization, universality: Drell-Yan, W and Z, jets