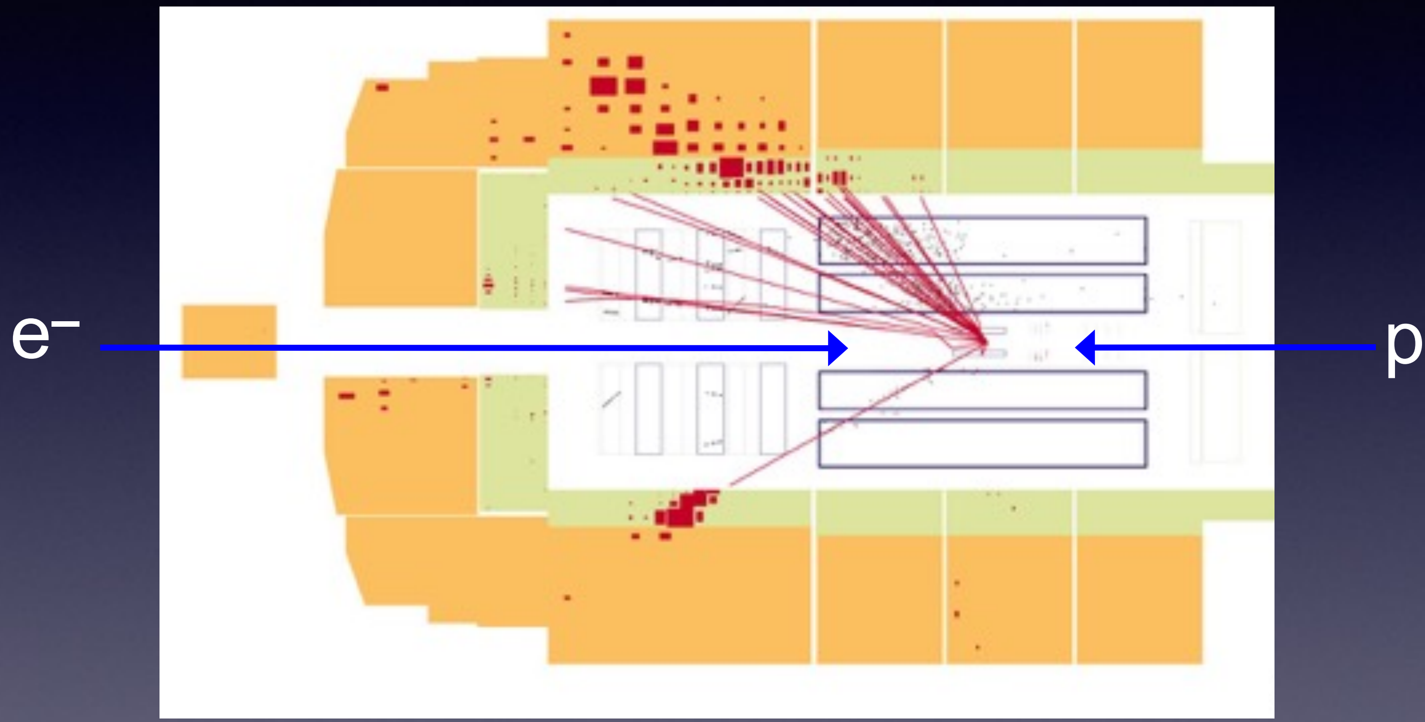
粒子物理

11. 深度非弹散射



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部分子模型

*) 强子内部结构

升级版的Rutherfold散射实验（ep散射）

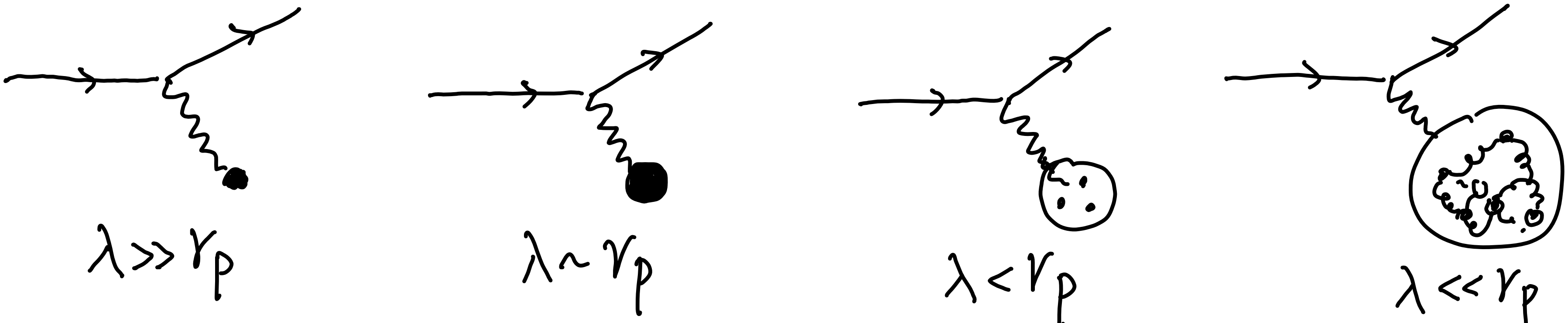
低能：弹性散射 —— 虚光子和质子整体相互作用

探测质子的整体性质（例如质子半径）

高能：深度非弹散射 —— 虚光子和质子中夸克的弹性散射

探测质子中夸克的动量分布

虚光子的探测能力取决于其波長和质子半径之比，可分为如下四种



(a) 极低能：非相对论性电子和质子(点粒子)的静电场作用

(b) $\lambda \sim r_p$ ：不再是静电作用，需要考虑质子电荷和磁矩分布

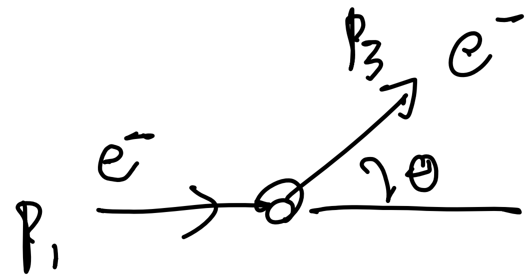
(c) $\lambda < r_p$ ：虚光子主要同质子中的价夸克发生作用（粉碎质子）

(d) 极高能 ($\lambda \ll r_p$)：虚光子可以看见质子内部更细致的动力结构

(此时质子表現为强耦合的夸克和胶子构成的海洋)

*) e^-p 弹性散射截面

1) Rutherford 散射



低能，无质子反冲 ($m_p = \infty$)，非相对论电子

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \frac{\alpha^2}{16 E_k^2 \sin^4\frac{\theta}{2}}$$，其中 $E_k = \frac{p^2}{2m_e} \ll m_e$

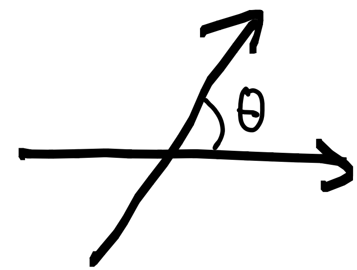
(仅有电荷相互作用)

2) Mott 散射

无质子反冲，但 e^- 是相对论性 ($m_e \ll E_k \ll m_p$)

(e^- Helicity conservation)

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \underbrace{\frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}}_{E_k\to E\ (E\gg m_e)} \ \underbrace{\cos^2\frac{\theta}{2}}_{}$$

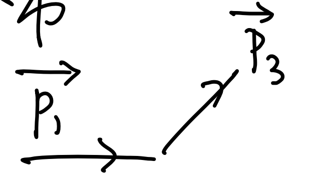


初态电子自旋和末态电子自旋波函数重叠

$d^{1/2}_{1/2,1/2}(\theta)$

(仅有电荷相互作用)

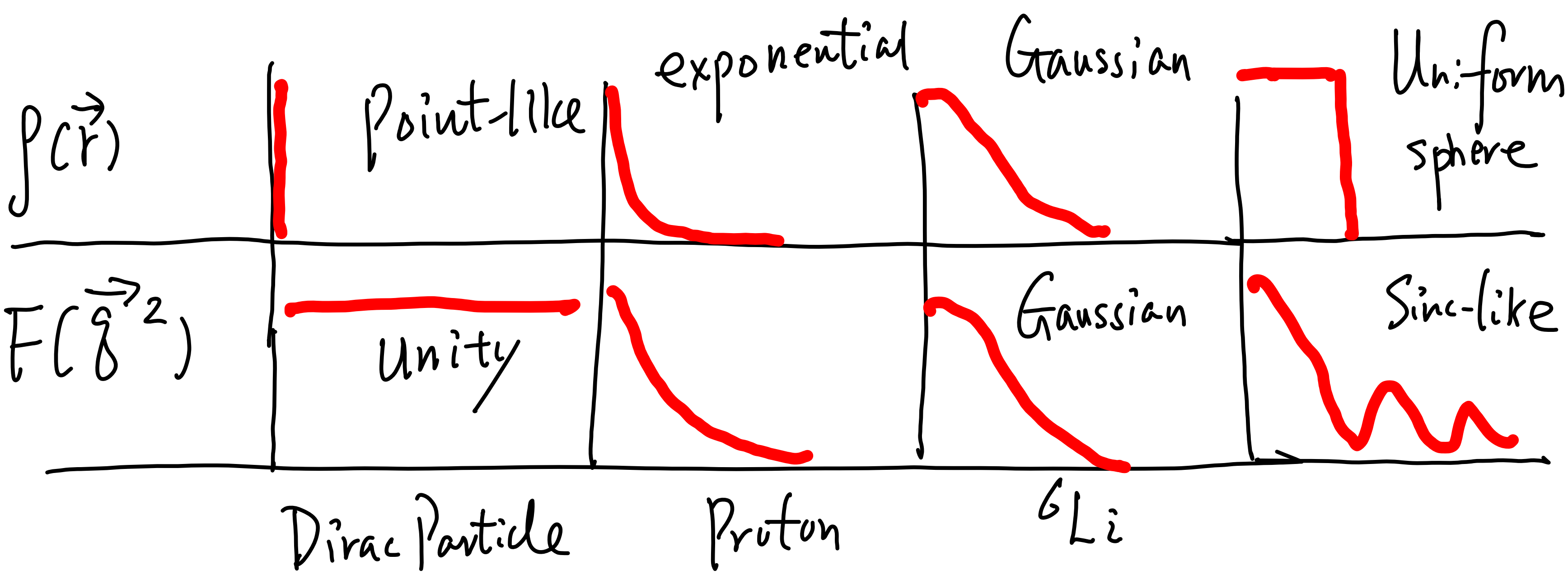
3) 质子是复合的，可能具有非平庸的电荷分布



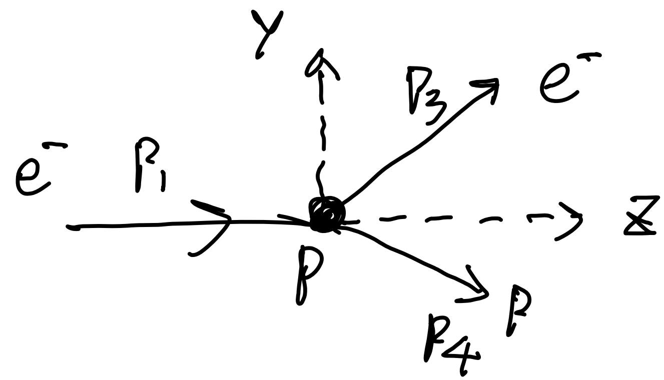
$$\text{形状因子} \longrightarrow F(\vec{q}^{\,2}) = \int \rho(\vec{r})\, e^{-i\vec{q}\cdot\vec{r}}\, d^3\vec{r}$$

$$\vec{q} = \vec{p}_1 - \vec{p}_3$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\, |F(\vec{q}^{\,2})|^2$$



4) 相对论性电子+质子反冲



$$p_1 = (E_1, 0, 0, E_1)$$

$$p_2 = (M, 0, 0, 0)$$

$$p_3 = (E_3, 0, E_3 \sin\theta, E_3 \sin\theta)$$

$$p_4 = (E_4, \vec{p_4})$$

$$|M|^2 \propto \frac{s^2+u^2}{t^2}$$

$$= \frac{8e^4}{(p_1-p_3)^4}\left[(p_1\cdot p_2)(p_3\cdot p_4)+(p_1\cdot p_4)(p_2\cdot p_3)-M^2(p_1\cdot p_3)\right]$$

⊗ $q^2 = (p_1-p_3)^2 = -4E_1E_3\sin^2\frac{\theta}{2} < 0$

$E_1 - E_3 = -\frac{q^2}{2M} > 0$

$(E_1 > E_3)$

代入得：

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{recoil}} = \frac{\alpha^2}{4E_1^2\sin^4\frac{\theta}{2}} \underbrace{\frac{E_3}{E_1}}_{\text{proton recoil}} \left(\cos^2\frac{\theta}{2} - \underbrace{\frac{q^2}{2M^2}\sin^2\frac{\theta}{2}}_{\text{磁矩相互作用 (spin-spin)}}\right)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E_1^2\sin^4\frac{\theta}{2}}\cos^2\frac{\theta}{2}$$

注意：弹性散射截面仅依赖于单一变量 θ

$$\frac{E_3}{E_1} = \frac{M}{M+E_1(1-\cos\theta)}, \quad q^2 = -\frac{2ME_1^2(1-\cos\theta)}{M+E_1(1-\cos\theta)}$$

5) 形状因子

一般而言，我们需要两个结构函数来描述有限大小质子电荷分布 (G_E) 和磁矩分布 (G_M)

量子场论：

$e^- - e^- - \gamma$ ： $A_\mu j^\mu = A_\mu (-e)\, \bar{u}(k')\, \gamma^\mu u(k)$

$p - p - \gamma$ ： $A_\mu J^\mu = A_\mu (+e)\, \bar{u}(p') \{\cdots\} u(p)$

因为 J^μ 是 Lorentz 矢量，所以 J^μ 中仅有两项

$$\{\cdots\} = \left\{ F_1(q^2)\gamma^\mu + \frac{\kappa}{2m} F_2(q^2)\, i\sigma^{\mu\nu} q_\nu \right\}$$

$$q = p - p'$$

其中 $F_1(q^2)$ 和 $F_2(q^2)$ 是形状因子，κ — 反常磁矩

注意：(1) 流守恒禁戒掉 $\gamma^\mu\gamma^5$ 项

(2) 流守恒禁戒 $p\!\!\!/\,\gamma^\mu$

(3) 如果 proton 是点粒子，那么 $K=0$，$F_1(q^2)=1$

(4) $q^2\to 0$ 时，我们仅能看到一个电荷为 e，
磁矩为 $\dfrac{(1+K)e}{2M}$

将上述 p-p-γ 有效相互作用代入到散射振幅中得

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\right)\frac{E'}{E}\left\{\left(F_1^2 - \frac{k^2 q^2}{4M^2}F_2^2\right)\cos^2\frac{\theta}{2} - \frac{q^2}{2M^2}(F_1 + kF_2)^2\sin^2\frac{\theta}{2}\right\}$$

Rosenbluth Formula $\Rightarrow$

$$= \left(\frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\right)\frac{E'}{E}\left\{\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\frac{\theta}{2} + 2\tau G_M^2\sin^2\frac{\theta}{2}\right\}$$

其中 $G_E = F_1 + \frac{kq^2}{4M^2}F_2$, $\tau = \frac{-q^2}{4M^2} > 0$

$G_M = F_1 + kF_2$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rosenbluth} = \left(\frac{\alpha^2}{4E^2\sin^4\theta/2}\right)\frac{E'}{E}\cos^2\frac{\theta}{2}\left(\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\frac{\theta}{2}\right)$$

$$= \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left(\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\frac{\theta}{2}\right)$$

At low q^2: $\tau = -\frac{q^2}{4M^2} \approx 0$

$$\frac{\frac{d\sigma}{d\Omega}}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} \approx G_E^2(q^2)$$

At high q^2: $\tau \gg 1$

$$\frac{\frac{d\sigma}{d\Omega}}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} \approx \tau\left(1+2\tan^2\frac{\theta}{2}\right)G_M^2(q^2)$$

e^- p Elastic Scattering at Very High q^2

★At high q^2 the Rosenbluth expression for elastic scattering becomes

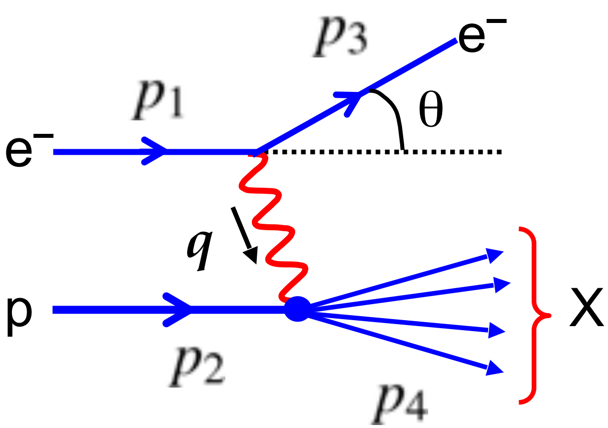
$$\left(\frac{d\sigma}{d\Omega}\right)_{elastic} = \frac{\alpha^2}{4E_1^2 \sin^4\theta/2}\frac{E_3}{E_1}\left(\frac{q^2}{2M^2}G_M^2 \sin^2\frac{\theta}{2}\right) \qquad \tau = -\frac{q^2}{4M^2} \gg 1$$

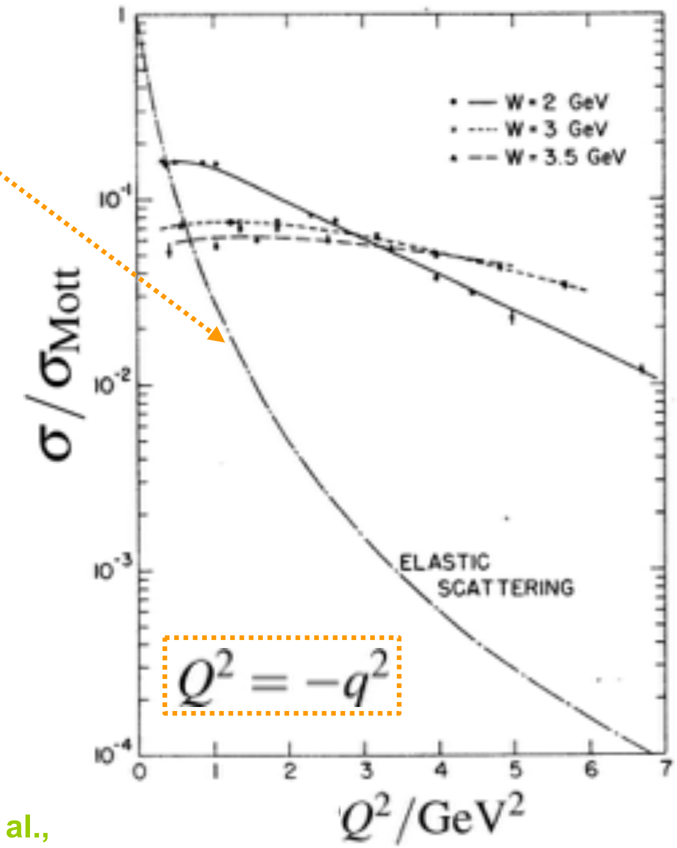
•From e⁻ p elastic scattering, the proton magnetic form factor is

$$G_M(q^2) \approx \frac{1}{(1+q^2/0.71\mathrm{GeV}^2)^2} \quad \Rightarrow \quad G_M(q^2) \propto q^{-4} \quad \text{at high } q^2$$

$$\Rightarrow \left(\frac{d\sigma}{d\Omega}\right)_{elastic} \propto q^{-6}$$

•Due to the finite proton size, elastic scattering at high q^2 is unlikely and inelastic reactions where the proton breaks up dominate.





M.Breidenbach et al.,
Phys. Rev. Lett. 23 (1969) 935

1967年 SLAC-MIT-CALTECH合作进行 $e^- - e^-$ 弹性散射

之后，CALTECH小组退出

1967年 SLAC-MIT进行 $e^- - p$ DIS碰撞，测量inclusive X-sectio

即 $e^- + p \to e^- + X$

Inclusive测量提供的物理信息不如Exclusive测量

因为不要求测量X的属性，

但好处是测量简单，不需测X而探测口

⇒ SLAC-MIT实验被视作为快速而粗糙的

测量，能在探索新的能量范围，为以后的

Exclusive测量做准备

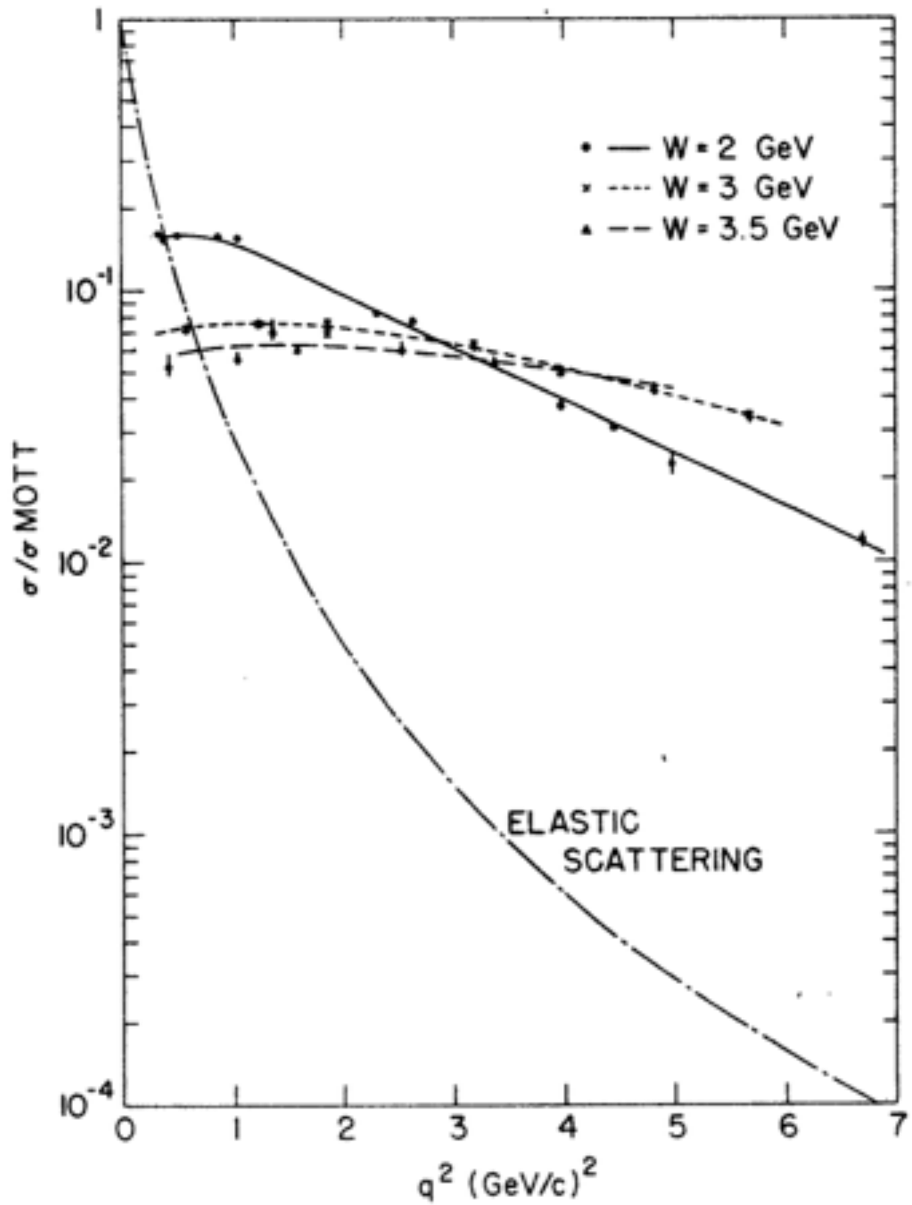
然而，SLAC-MIT组发现大动量转移时截面超出!!!

*）标度不变性（“伸缩”不变性）

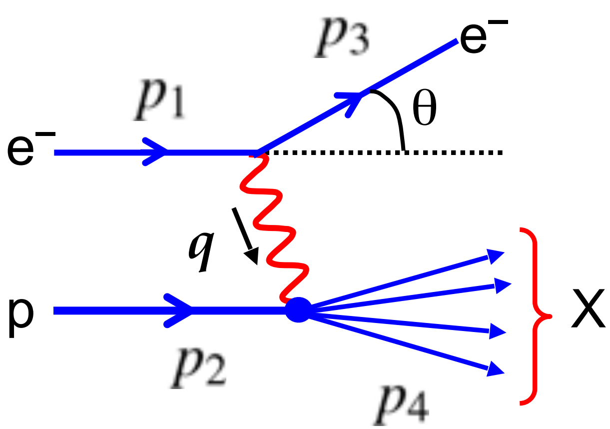
基于量纲分析，我们只能比较具有相同量纲的物理量。

深度非弹散射过程(DIS)的结构函数具有标度无关性，意味着结构函数都是无量纲的物理量的函数。

这些无量纲物理量要依赖于具有量纲的物理量，因此无量纲物理量是有量纲物理量的比值或组合。



Kinematics of Inelastic Scattering



- For inelastic scattering the mass of the final state hadronic system is no longer the proton mass, M
- The final state hadronic system must contain at least one baryon which implies the final state invariant mass $M_X > M$

$$M_X^2 = p_4^2 = (E_4^2 - |\vec{p}_4|^2)$$

★ For inelastic scattering introduce four new kinematic variables: $\boxed{x, y, \nu, Q^2}$

★ **Define:** $\boxed{x \equiv \frac{Q^2}{2p_2.q}}$ Bjorken x (Lorentz Invariant)

where $\boxed{Q^2 \equiv -q^2}$ $Q^2 > 0$

- Here $M_X^2 = p_4^2 = (q + p_2)^2 = -Q^2 + 2p_2.q + M^2$

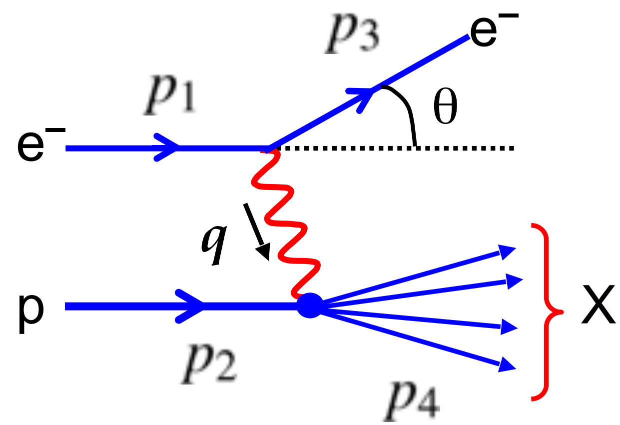
⇨ $Q^2 = 2p_2.q + M^2 - M_X^2$ ➡ $Q^2 \leq 2p_2.q$

Note: in many text books W is often used in place of M_X

hence $\boxed{0 < x < 1}$ **inelastic** $\boxed{x = 1}$ **elastic**

Proton intact $M_X = M$

★**Define:** $\boxed{y \equiv \frac{p_2 \cdot q}{p_2 \cdot p_1}}$ (Lorentz Invariant)



- In the Lab. Frame:

$$p_1 = (E_1, 0, 0, E_1) \quad p_2 = (M, 0, 0, 0)$$
$$q = (E_1 - E_3, \vec{p}_1 - \vec{p}_3)$$

$$\rightarrow \quad y = \frac{M(E_1 - E_3)}{ME_1} = 1 - \frac{E_3}{E_1}$$

So y is the fractional energy loss of the incoming particle

$$\boxed{0 < y < 1}$$

- In the C.o.M. Frame (neglecting the electron **and** proton masses):

$$p_1 = (E, 0, 0, E); \quad p_2 = (E, 0, 0, -E); \quad p_3 = (E, E\sin\theta^*, 0, E\cos\theta^*)$$

$$\rightarrow \quad y = \tfrac{1}{2}(1 - \cos\theta^*) \qquad \text{for} \quad E \gg M$$

★**Finally Define:** $\boxed{\nu \equiv \frac{p_2 \cdot q}{M}}$ (Lorentz Invariant)

- In the Lab. Frame: $\nu = E_1 - E_3$

ν is the energy lost by the incoming particle

Relationships between Kinematic Variables

- Can rewrite the new kinematic variables in terms of the squared centre-of-mass energy, s, for the electron-proton collision

$$e^- \xrightarrow{p_1} \quad \xleftarrow{p_2} p$$

$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2p_1.p_2 = 2p_1.p_2 + M^2 + \cancel{m_e^2}$$

Neglect mass of electron

$$2p_1.p_2 = s - M^2$$

- For a fixed centre-of-mass energy, it can then be shown that the four kinematic variables

$$Q^2 \equiv -q^2 \qquad x \equiv \frac{Q^2}{2p_2.q} \qquad y \equiv \frac{p_2.q}{p_2.p_1} \qquad \nu \equiv \frac{p_2.q}{M}$$

are not independent.

- i.e. the scaling variables x and y can be expressed as

$$x = \frac{Q^2}{2M\nu} \qquad y = \frac{2M}{s - M^2}\nu$$

Note the simple relationship between y and ν

and $$xy = \frac{Q^2}{s - M^2} \quad \Rightarrow \quad Q^2 = (s - M^2)xy$$

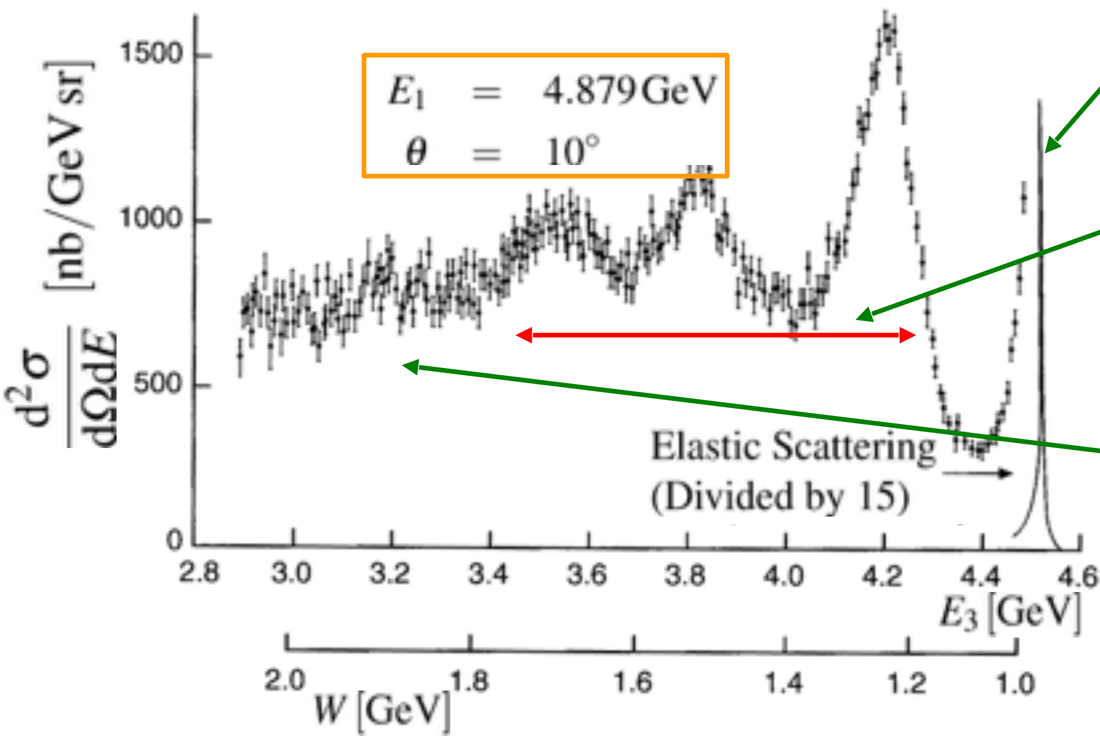
- For a fixed centre of mass energy, the interaction kinematics are completely defined by any **two** of the above kinematic variables (except y and ν)
- For elastic scattering $(x = 1)$ there is only one independent variable. As we saw previously if you measure electron scattering angle know everything else.

Inelastic Scattering

Example: Scattering of 4.879 GeV electrons from protons at rest

- Place detector at 10° to beam and measure the energies of scattered e⁻
- Kinematics fully determined from the electron energy and angle !
- e.g. for this energy and angle : the invariant mass of the final state hadronic system

$$W^2 = M_X^2 = 10.06 - 2.03E_3$$



Elastic Scattering

proton remains intact

$$W = M$$

Inelastic Scattering

produce "excited states" of proton e.g. $\Delta^+(1232)$

$$W = M_\Delta$$

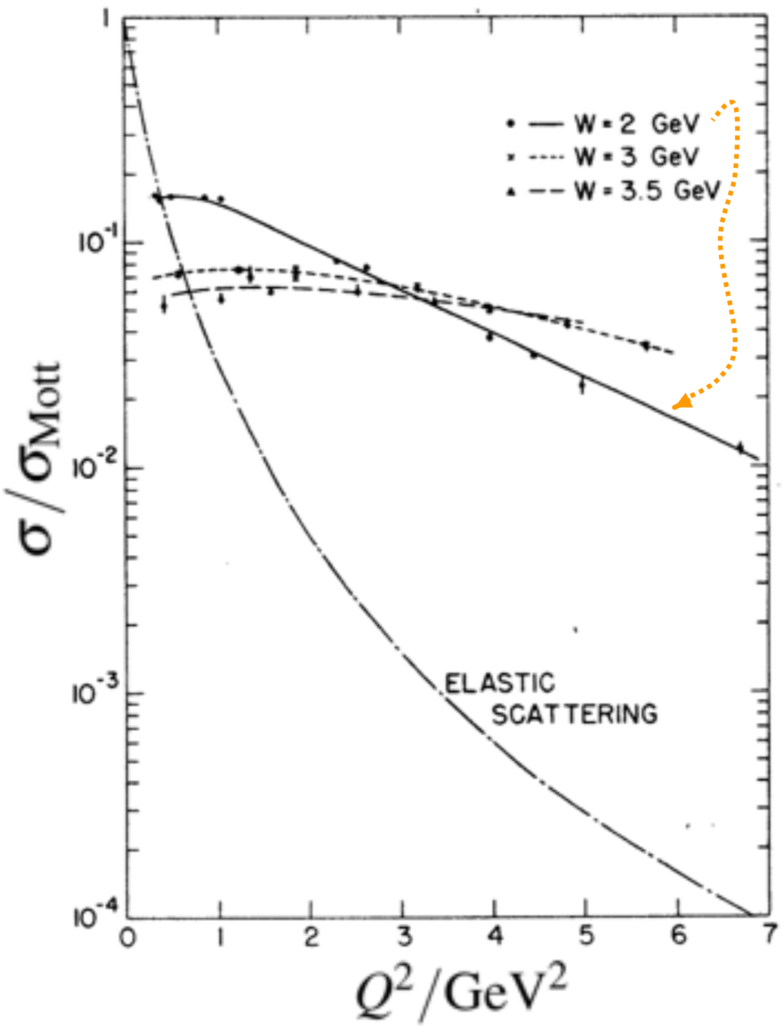
Deep Inelastic Scattering

proton breaks up resulting in a many particle final state

$\boxed{\text{DIS = large } W}$

Inelastic Cross Sections

- Repeat experiments at different angles/beam energies and determine q^2 dependence of elastic and inelastic cross-sections



- Elastic scattering falls of rapidly with q^2 due to the proton not being point-like (i.e. form factors)

- Inelastic scattering cross sections only weakly dependent on q^2

- Deep Inelastic scattering cross sections almost independent of q^2 !

i.e. "Form factor" → 1

⇒ **Scattering from point-like objects within the proton !**

M.Breidenbach et al., Phys. Rev. Lett. 23 (1969) 935

*) 标度不变性(伸缩不变性)

基于"量纲分析"：我们仅能在相同量纲的物理量之间做比较

深度非弹散射过程(DIS)的结构函数是无量纲量(它们只是无量纲数值。但也们依赖于有量纲的变量，因此结构函数仅能依赖于这些有量纲变量的无量纲比值或组合。

通常选取 q^2 和 ν 来刻画 DIS 过程，另外一个量纲物理量 M

$[\text{GeV}]^2$ $[\text{GeV}]$ $[\text{GeV}]$

$$\Rightarrow \frac{M\nu}{q^2} \quad \text{无量纲}$$

如果 $\frac{M\nu}{q^2}$ 是唯一的无量纲组合，那么也也是结构函数唯一可依赖的量 ⟶ 严格的标度无关性

问题：如何证明 $\frac{M\nu}{q^2}$ 是描述 DIS 过程的唯一相关的无量纲量？

由 q^2、ν 和 M 还可以构造其他无量纲量 $\frac{q^2}{M^2}$，$\frac{\nu}{M}$

显然，如果结构函数依赖于 $\frac{q^2}{M^2}$ 或 $\frac{\nu}{M}$，那么它们就不是标度无关的（$\frac{q^2}{M^2}$ 和 $\frac{\nu}{M}$ 随 q^2 和 ν 变化）

$\Longrightarrow$ 标度无关性假设：

当 q^2 和 $M\nu$ 都逐渐变大时，它们的比值 $\frac{M\nu}{q^2}$ 保持有限（比约肯极限）

Elastic → Inelastic Scattering

★**Recall:** Elastic scattering

- Only **one independent variable**. In Lab. frame express differential cross section in terms of the electron scattering angle (Rosenbluth formula)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\theta/2} \frac{E_3}{E_1} \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2} \right) \qquad \tau = \frac{Q^2}{4M^2}$$

Note: here the energy of the scattered electron is determined by the angle.

- In terms of the Lorentz invariant kinematic variables can express this differential cross section in terms of Q^2

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \left(1 - y - \frac{M^2 y^2}{Q^2}\right) + \frac{1}{2} y^2 G_M^2 \right]$$

which can be written as:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[f_2(Q^2) \left(1 - y - \frac{M^2 y^2}{Q^2}\right) + \frac{1}{2} y^2 f_1(Q^2) \right]$$

★ Inelastic scattering

- For Deep Inelastic Scattering have **two independent variables**. Therefore need a double differential cross section

Deep Inelastic Scattering

★ It can be shown that **the most general Lorentz Invariant expression** for $e^-p \to e^-X$ inelastic scattering (via a single exchanged photon is):

$$\boxed{\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1-y-\frac{M^2y^2}{Q^2}\right)\frac{F_2(x,Q^2)}{x} + y^2F_1(x,Q^2)\right]} \quad (1)$$

INELASTIC SCATTERING

c.f.

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1-y-\frac{M^2y^2}{Q^2}\right)f_2(Q^2) + \frac{1}{2}y^2f_1(Q^2)\right]$$

ELASTIC SCATTERING

We will soon see how this connects to the quark model of the proton

• **NOTE:** The form factors have been replaced by the **STRUCTURE FUNCTIONS**

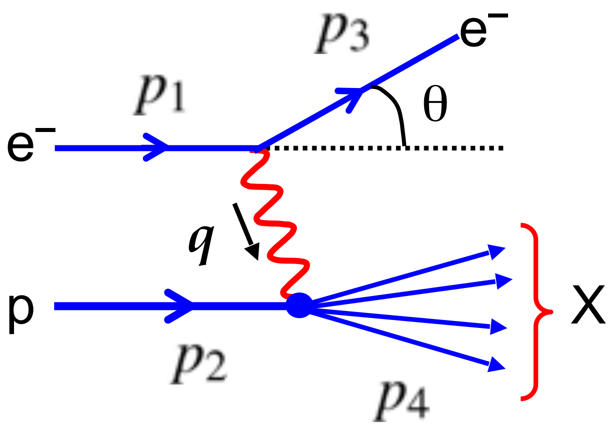
$F_1(x,Q^2)$ and $F_2(x,Q^2)$ 结构函数

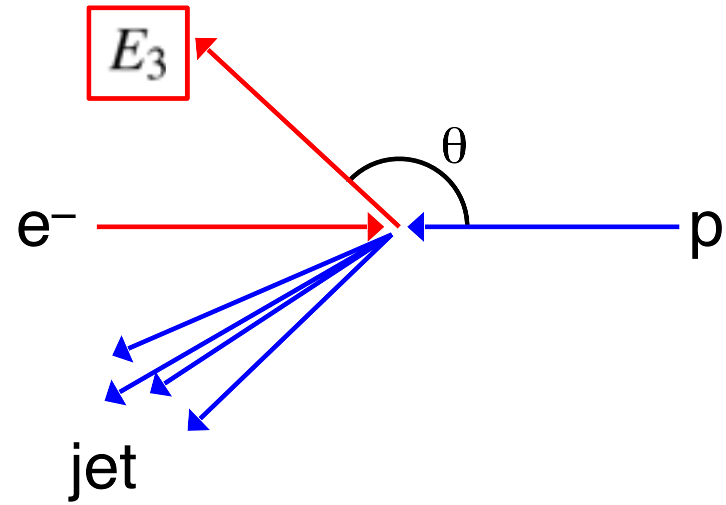
which are a function of x and Q^2: can not be interpreted as the Fourier transforms of the charge and magnetic moment distributions. We shall soon see that they describe the **momentum distribution** of the quarks within the proton

★ In the limit of high energy (or more correctly $Q^2 \gg M^2y^2$) eqn. (1) becomes:

$$\boxed{\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2F_1(x,Q^2)\right]} \quad (2)$$

- In the Lab. frame it is convenient to express the cross section in terms of the angle, θ, and energy, E_3, of the scattered electron – **experimentally well measured.**





$$Q^2 = 4E_1E_3\sin^2\theta/2; \quad x = \frac{Q^2}{2M(E_1-E_3)}; \quad y = 1-\frac{E_3}{E_1}; \quad \nu = E_1 - E_3$$

- In the Lab. frame, Equation (2) becomes:

$$\boxed{\frac{d^2\sigma}{dE_3 d\Omega} = \frac{\alpha^2}{4E_1^2\sin^4\theta/2}\left[\frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M}F_1(x,Q^2)\sin^2\frac{\theta}{2}\right]} \quad (3)$$

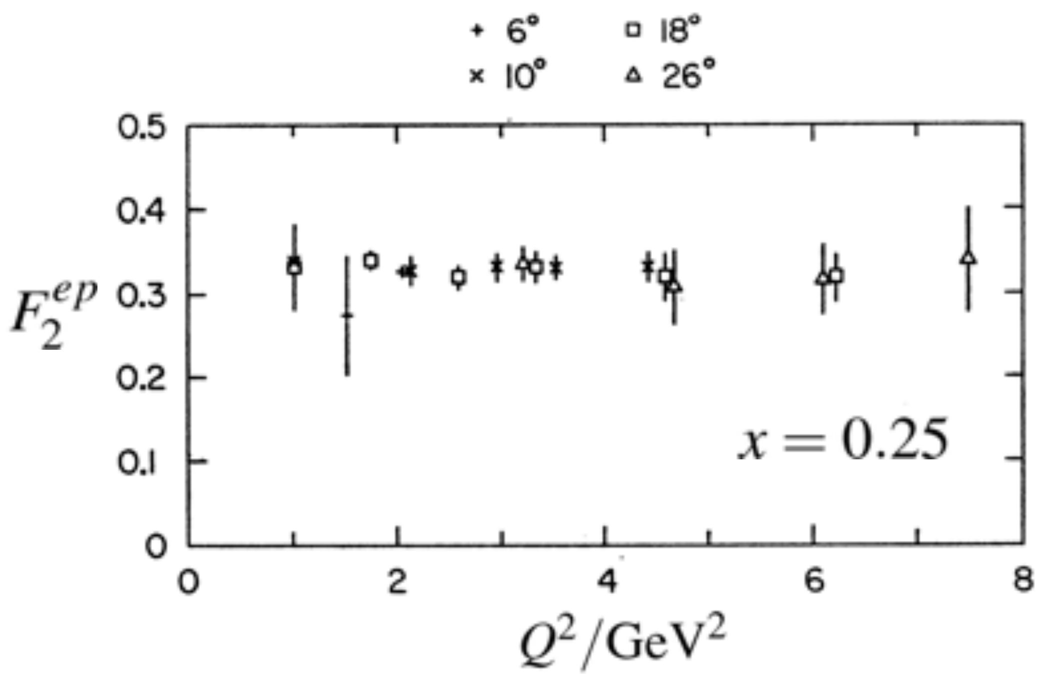
Electromagnetic Structure Function

Pure Magnetic Structure Function

Measuring the Structure Functions

★To determine $F_1(x,Q^2)$ and $F_2(x,Q^2)$ for a given x and Q^2 need measurements of the differential cross section at several different scattering angles and incoming electron beam energies

Example: electron-proton scattering F_2 vs. Q^2 at fixed x



J.T.Friedman + H.W.Kendall,

Ann. Rev. Nucl. Sci. 22 (1972) 203

♦ Experimentally it is observed that both F_1 and F_2 are (almost) independent of Q^2

Bjorken Scaling and the Callan-Gross Relation

★The near (see later) independence of the structure functions on Q^2 is known as **Bjorken Scaling**, i.e.

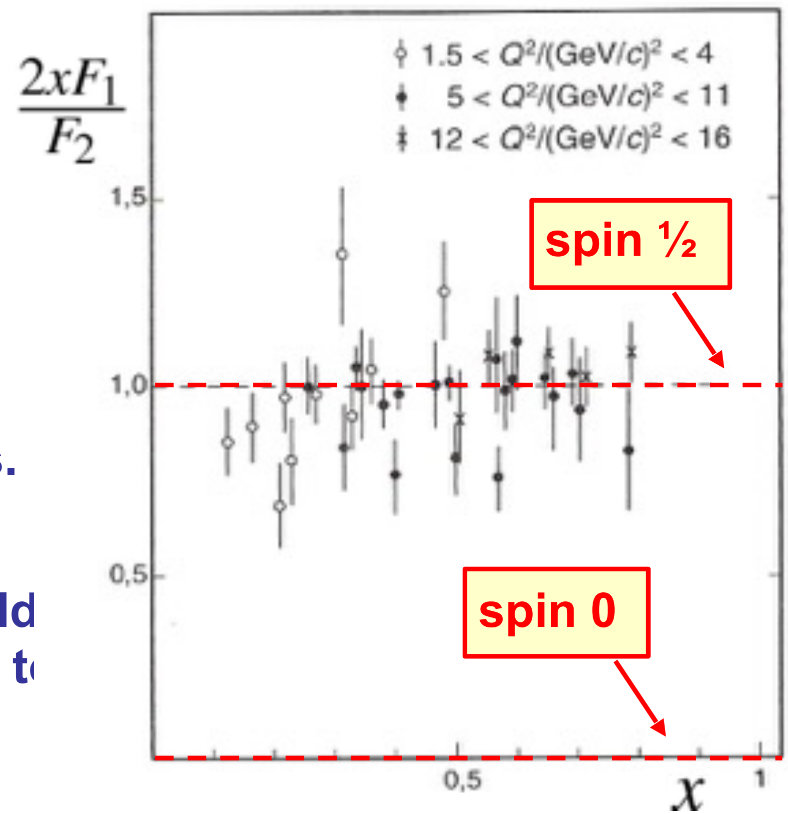
$$\boxed{F_1(x,Q^2) \rightarrow F_1(x) \qquad\qquad F_2(x,Q^2) \rightarrow F_2(x)}$$

- It is strongly suggestive of scattering from **point-like** constituents within the proton

★It is also observed that $F_1(x)$ and $F_2(x)$ are not independent but satisfy the **Callan-Gross relation**

$$\boxed{F_2(x) = 2xF_1(x)}$$

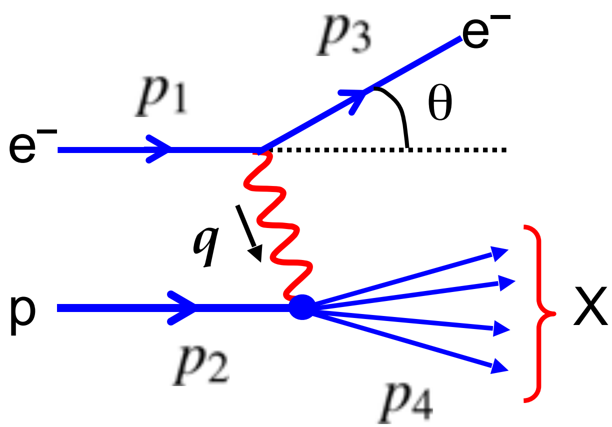
- As we shall soon see this is exactly what is expected for scattering from **spin-half** quarks.

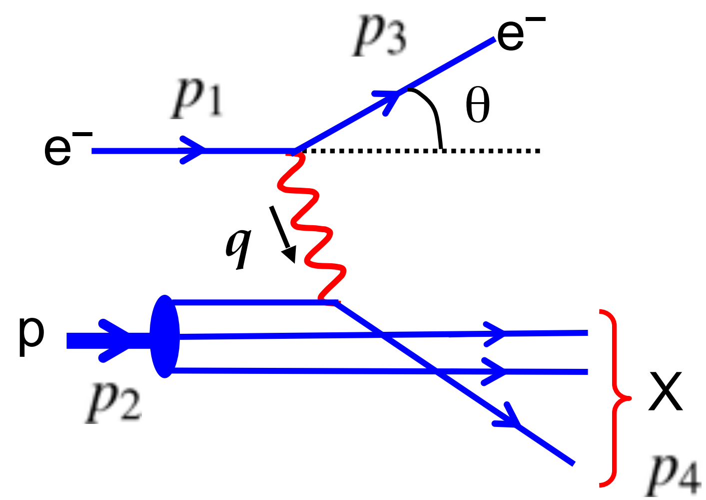


Note: if quarks were spin zero particles we would expect the purely magnetic structure function to be zero, i.e. $F_1(x) = 0$

The Quark-Parton Model

- Before quarks and gluons were generally accepted Feynman proposed that the proton was made up of point-like constituents "**partons**"
- Both Bjorken Scaling and the Callan-Gross relationship can be explained by assuming that Deep Inelastic Scattering is dominated by the scattering of a single virtual photon from point-like spin-half constituents of the proton.





Scattering from a proton with structure functions

Scattering from a point-like quark within the proton

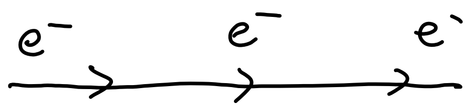
★ How do these two pictures of the interaction relate to each other?

费曼的部分子模型

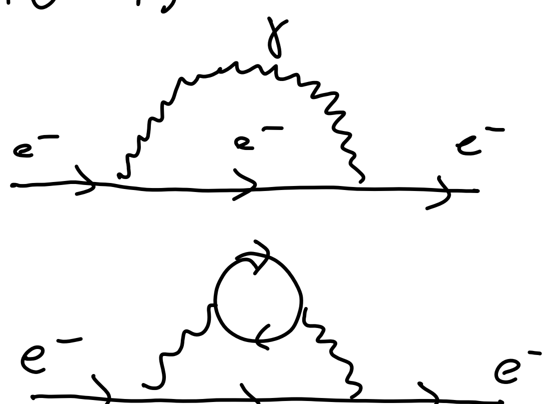
电子可视作为无结构的点粒子，而质子有结构

→ 场论语言来讲，它们具有完全不同的意义

自由电子



+QED修正

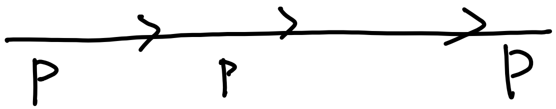


量子效应 ⇒ 电子云 （电子必须被视作为包含电子、正电子和光子的云，它们共同携带电子的量子数、能动量）

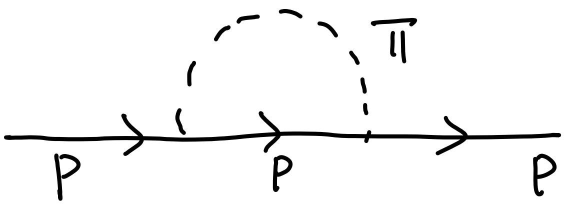
↘ 微扰小量（小扰动）

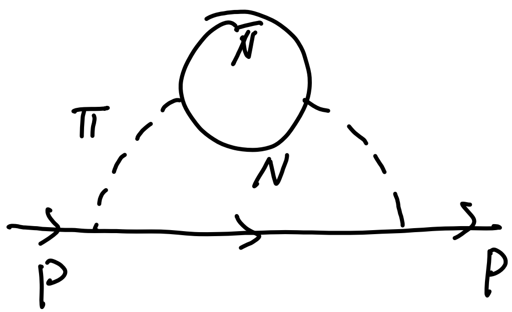
⇒ 从实用角度，我们仍可将电子视作为点粒子（场论中无结构实体）

质子



+强相互作用修正





强耦合常数很大，所有阶扰动都要考虑

(无穷多的复杂项)

⇒ 场论中的质子具有内在的复杂结构

所有短寿命粒子云都对质子构成有贡献

⇒ 质子必须看作为粒子云

完全无法计算

费曼认为：质子（和所有强子）都是由无数粒子构成的云

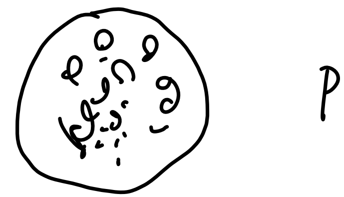
① 介子-核子场论中，云由介子，核子和反核子组成

② 夸克理论中，云里包含夸克和反夸克

费曼简单地假定粒子群含有量子数不详的实体 —— 部分子

这听起来太平庸了！但费曼的天才构思是：

高能的两个质子碰撞



因为强相互作用是短程的，

两个盘子之间只有很短时间的相互作用

并且，在此期间它们实际看到的是一张冻结的"部分子"快照

费曼设想：

高能强子碰撞看成是发生在两个盘子的个别部分子之间。由于相互作用时间非常短，所以每个盘子内部的部分子之间的相互作用可以忽略不计。

⟹ 发生高能散射的瞬间，每个质子内的部分子都是独立的准自由的实体。

（注意：相对论性质子视作为冻结的圆盘是指“无穷大动量坐标系”
部分子视作为自由粒子是指“冲激近似”）

原子模型：处于中心的原子核及弥漫其周围的电子云

部分子模型：质子是由单一的无定形的部分子云组成的

费曼的部分子模型 避开了最困难的强相互作用

→所有强相互作用的影响都包含在部分子的动量分布之内

→如果能够知道部分子动量分布，那么就可以将部分子视作点粒子，从而电子-质子散射就可以按电子-部分子之间的QE

相互作用。

⇒上个世纪60年代，猜测部分子的性质及其量子数是热门话题

流行的猜测：部分子具有与夸克相同的量子数

夸克—部分子模型：将部分子认同为夸克

困难：标度无关性要求夸克在和电子相互作用时为自由粒子

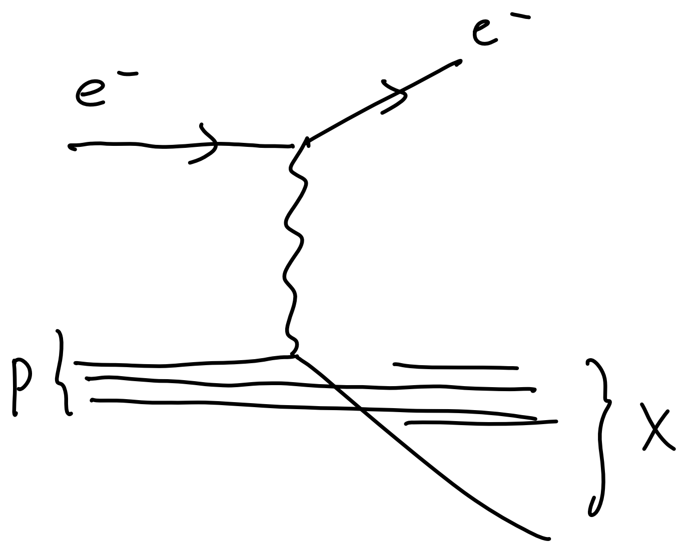
自由粒子就可以从质子中打出来，出现在末态产物中

但从未观测到自由夸克，这意味着我们需要假设

自由夸克必须持续经历软的，低动量转移的与伴随部分子

之间的強相互作用，并且要求这些软性作用不破坏标度不变性。

部分子模型中的DIS:



深度非弹散射可视作为:
一个入射电子发射一个光子,而后这个光子与单个自由部分子发生相互作用
⇒ 电子与核粒子的部分子之间的弹性散射

⇒ 结构函数除标度无关性之外,其大小和形状均可以在各种测量过程中被测得。每个部分子对总结构函数的贡献都可按QED计算,并且其贡献仅与自旋和电荷相关

⟹ 测量不同的函数可得到部分子量子数的信息