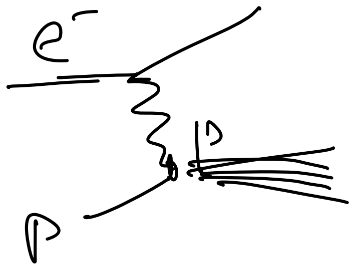


$e^- + p \longrightarrow e^- + X$ DIS

For N partons:

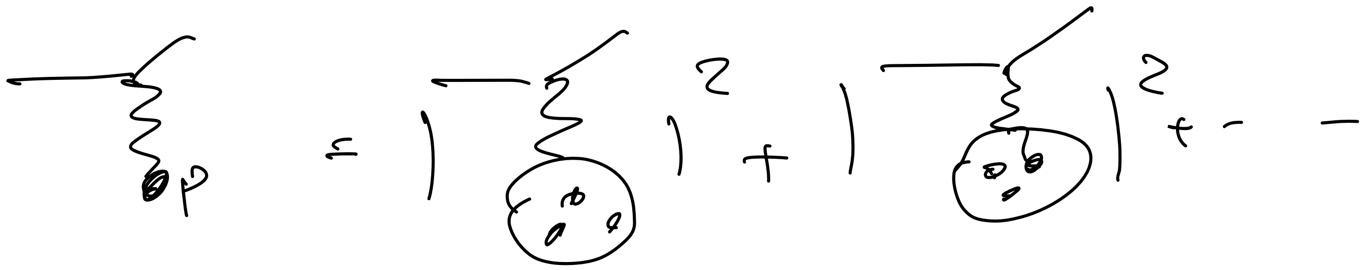
$$W_1(Q^2,\nu) = \sum_j^{\text{partons}} z_{q_j}^2 \frac{f_j(x)}{2M}$$

$$W_2(Q^2,\nu) = \sum_j z_{q_j}^2 f_j(x) \frac{x}{\nu}$$

$f(x)$ parton density function.

$$F_1(x) = M W_1(Q^2,\nu). \quad F_2(x) = \nu W_2(Q^2,\nu)$$

$$F_2(x) = 2x F_1(x)$$ Callan-Gross relation.



elastic scattering on parton.

proton: container of some constituents (parton)

parton: $s = 1/2$ $\quad m = xM$

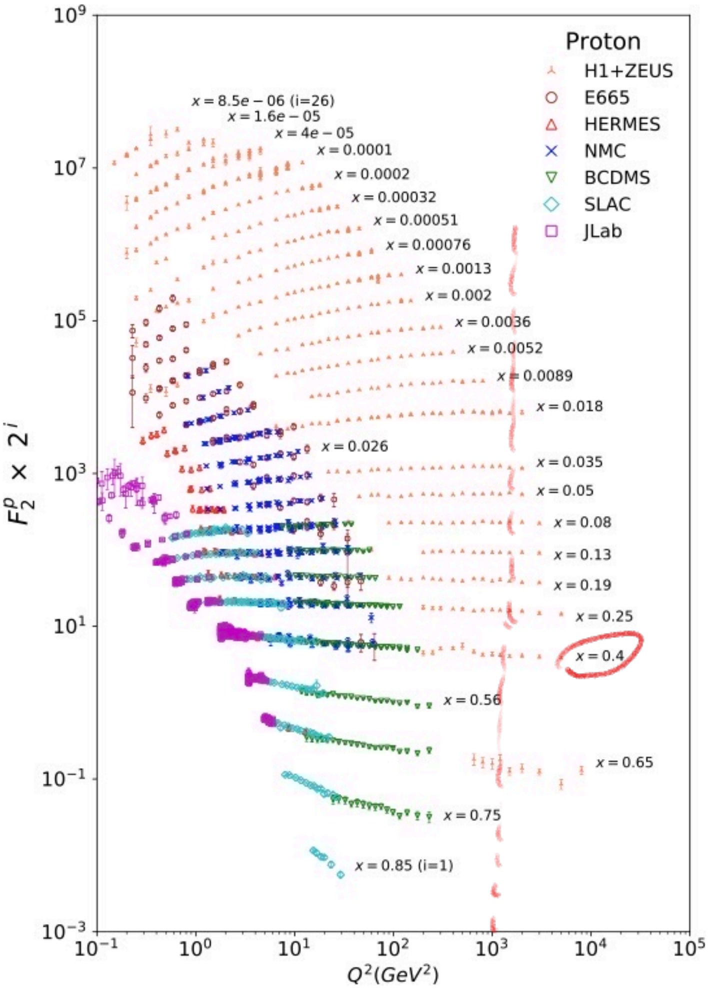
$$x = \frac{Q^2}{2M\nu} \qquad Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \nu = E - E'$$

observed/measured quantities with leptons/probe

$$\left.\frac{d\sigma}{d\Omega}\right|_{DIS} \sim \frac{\alpha^2}{Q^4} E'^2 \left[W_2 \sin^2\frac{\theta}{2} + 2W_1 \cos^2\frac{\theta}{2} \right]$$

$$\delta\left(\nu - \frac{Q^2}{2M}\right)$$

parton j: has charge $z_{q_j} e < e$



In principle

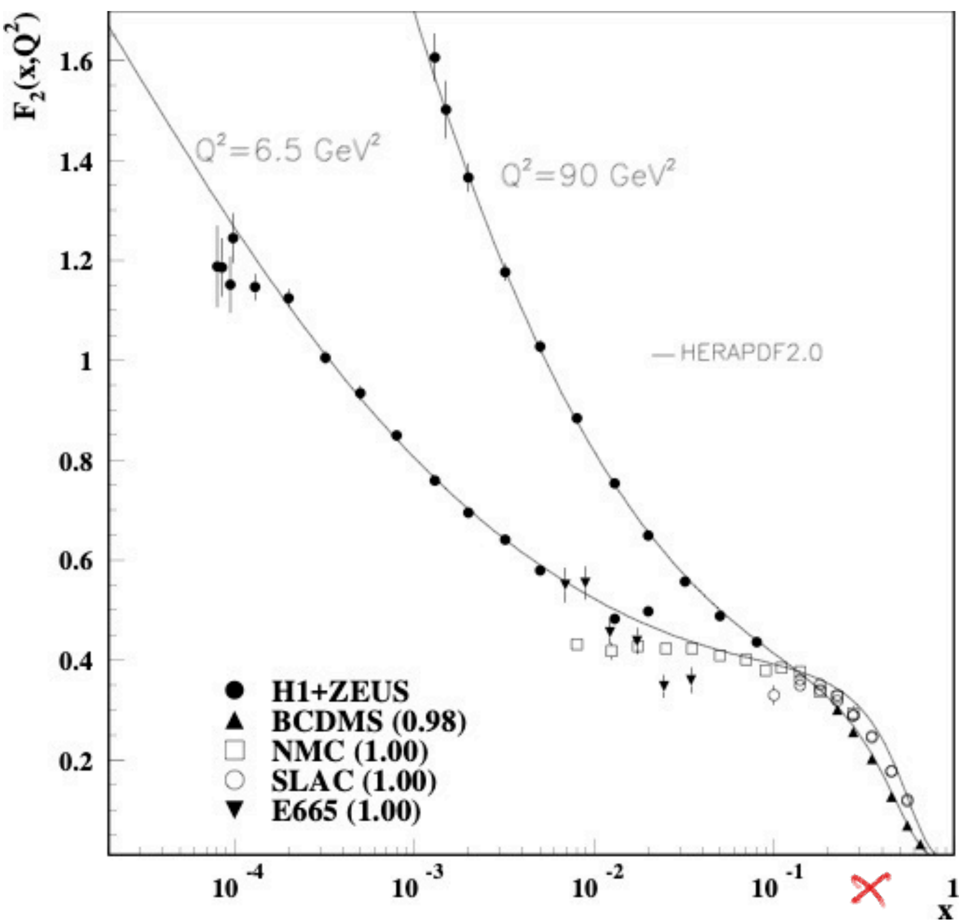
$$F_2 = F_2(Q^2, \nu)$$

$$x = \frac{Q^2}{2M\nu}$$

$\Rightarrow$ F_2 function of x
not Q^2, ν seperately.

$$f(x,y) = x^2 + y^2$$

$$f(x,y) = \frac{x}{y}$$



$$x_B = \frac{Q^2}{2M\nu}$$

Bjorken Scaling variable x

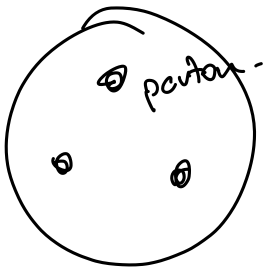
$$\int_0^1 dx\, f(x) = 1$$

$$x \in [0,1]$$

partons: evidence from D.I.S. $\equiv$ incoherent sum of elastic scattering

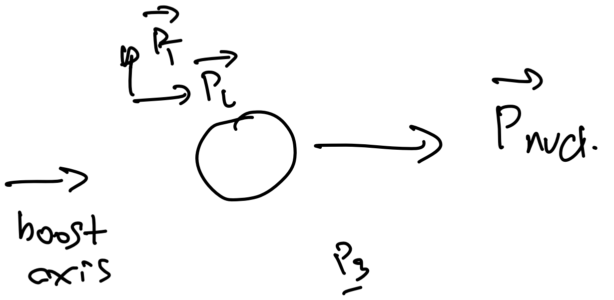
Feynman: x as property of parton.

Quark-parton model



high energy limit. $E \gg m_e, m_p, m_{parton}$.

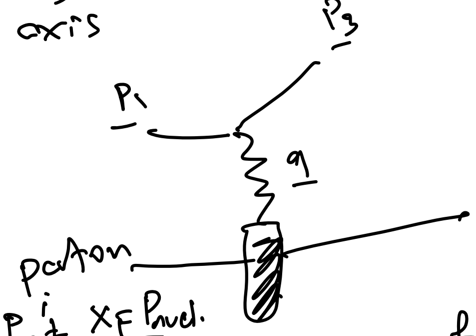
$$x_F = \frac{|\vec{P}_L|}{|\vec{P}_{nucl}|}$$



SLAC experiment: $E_e = 25$ GeV

$$\underline{P}_{part} = x_F \underline{P}_{nucl}$$

x_F: fraction of momentum carried by parton.



$$\underline{P}^f_{part} = \underline{P}^{in}_{part} + \underline{q}$$

$$\underbrace{|\underline{P}^f_{part}|^2}_{m_p^2 \simeq 0} = |\underline{P}^{in}_{part}|^2 + \underline{q}^2 + 2\,\underline{P}^{in}_{part}\cdot\underline{q}$$

high energy limit.

$$q^2 \equiv -Q^2 \quad \Rightarrow \quad Q^2 = 2\,\underline{P}^{in}_{part}\cdot\underline{q} =$$

$$\underline{P}^{LAB}_{nucl} = (M, 0) \qquad \underline{q} = (E-E', \vec{P}_1 - \vec{P}_3) = (\nu, \vec{P}_1 - \vec{P}_3)$$

$$Q^2 = 2x_F M\nu \Rightarrow \underbrace{x_F = \frac{Q^2}{2M\nu}}\simeq x_B \text{ at high energy}$$

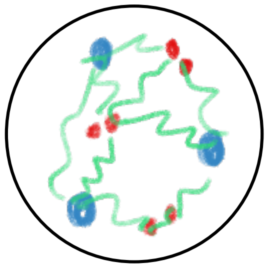
N partons $\sum_i x_i = 1$ $\qquad \sum_i \underline{P}^i_{part} = \underline{P}_{nucl}$

proton: uud $\qquad$ u, d quarks. $\begin{matrix}+\frac{2}{3} \\ -\frac{1}{3}\end{matrix}\begin{pmatrix}u \\ d\end{pmatrix}$

$$Q_p = +1 = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$$

proton $u\ u\ d\ d\ \bar{d}\ s\ \bar{s}$

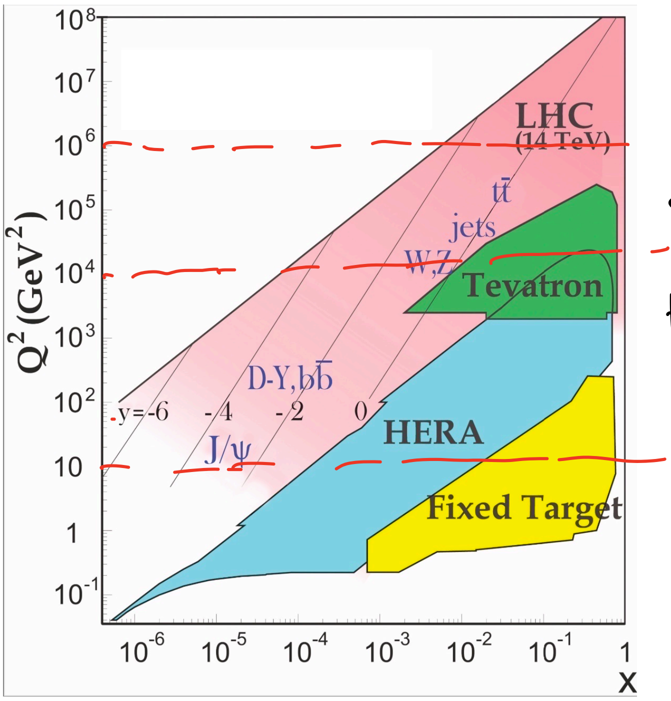
$\sum\ x_u\ x_u\ x_d\ x_d\ x_{\bar{d}}\ x_s\ x_{\bar{s}} = 1.$



Valence quarks: u u d (electric charge)

Sea quarks/anti-quarks: $s\bar{s} + q_j\bar{q}_j$

gluons: g mediators of strong interaction



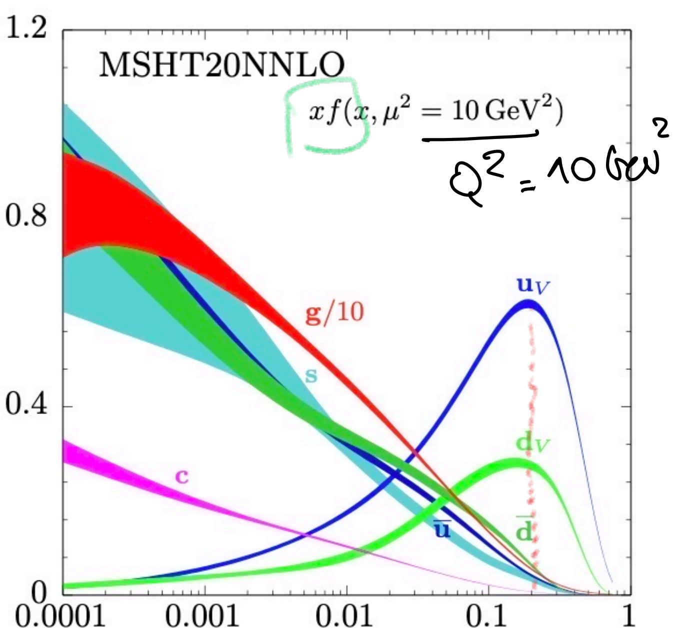
Tevatron: $\sqrt{s} = 1.96$ TeV

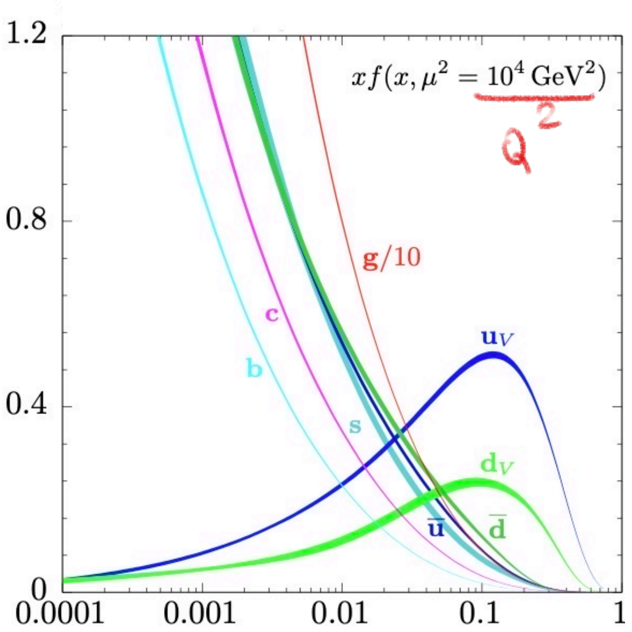
$p \rightarrow\ \leftarrow p$

Hera $e^- + p$(beam).

$e^- \rightarrow\ \leftarrow p$

f(x): parton density function.





d_V: f(x) for valence d quark.

u_V: f(x) for valence u quark.

$\bar{u}$: f(x) for sea antiquark $\bar{u}$

Experimentally: $\sum_i^{\text{valence}} x_i = 0.5 \Rightarrow$ existence of sea $q\bar{q}$ and gluons.

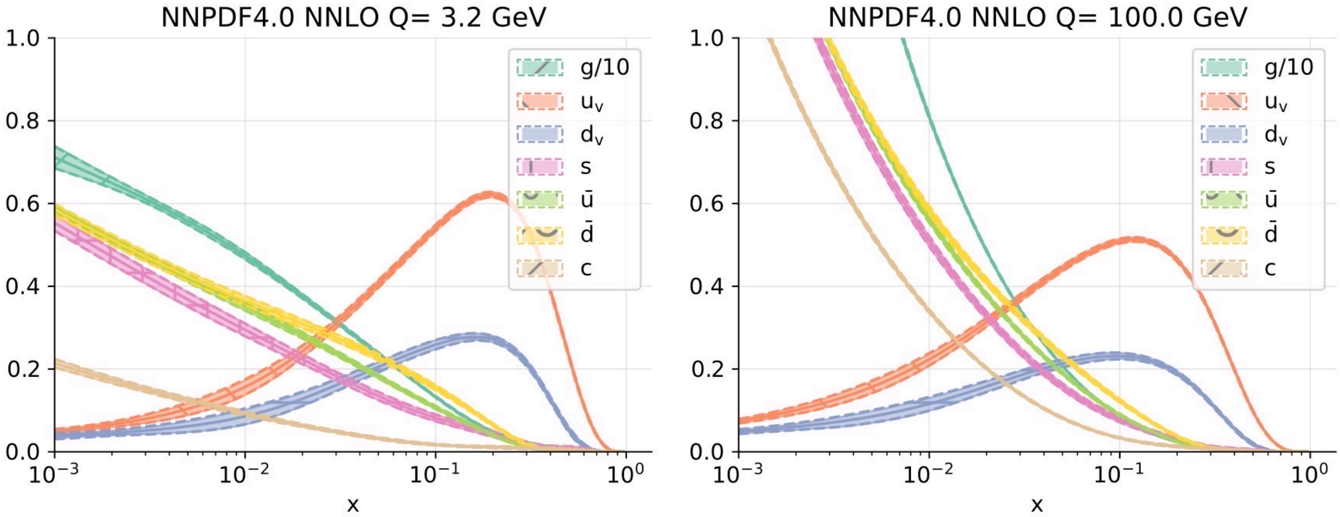
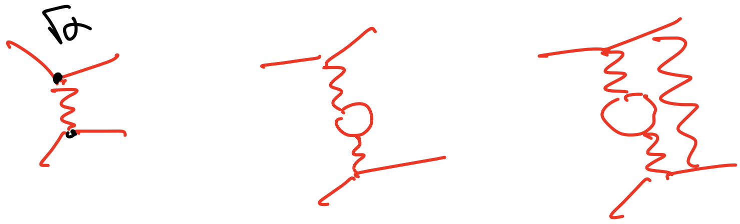


Figure 1.1. The NNPDF4.0 NNLO PDFs at $Q = 3.2$ GeV (left) and $Q = 10^2$ GeV (right).

NNLO: Next-to-Next-to-Leading-order.

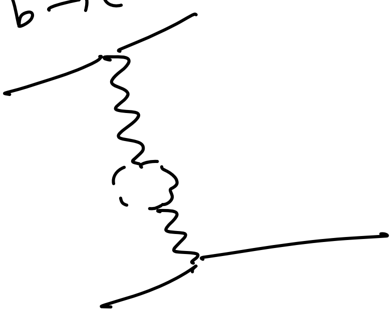
LO:



LO: α. NLO: α^2 NNLO: α^3

N^3LO: Next-Next-Next LO.

a+b → c+d



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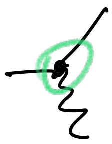
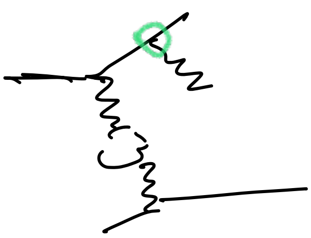
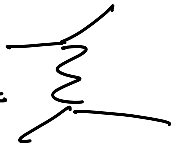
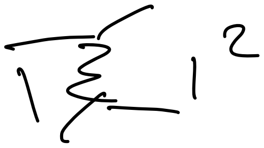
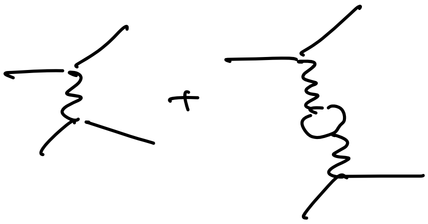
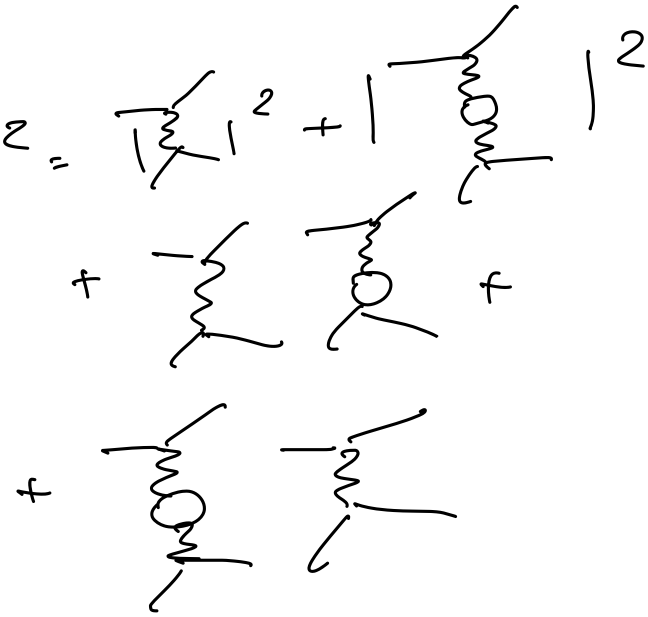


= ?



a+b → c+d+γ

$\mathcal{M} =$  $\mathcal{M}^2 =$ 

$\mathcal{M} =$  $\mathcal{M}^2 =$ 

$$\mathcal{M} = \mathcal{M}(\alpha) + \mathcal{M}(\alpha^2) + \mathcal{M}(\alpha^3)$$

$f(x)$: parton density function.

$$x = \frac{|\underline{P}_{part}|}{|\underline{P}_{nucl}|}$$

$$\sum P^i_{part} = \underline{P}_{nucl}.$$

$$\int_0^1 dx \Big[\underbrace{\sum f_i(x)}_{\text{partons}} \Big]\, x = 1.$$

$$\int_0^1 dx \Big[\sum_{\text{flavors}} q_f(x) + \bar{q}_f(x) + g(x) \Big]\, \underset{\sim}{x} = 1.$$

Momentum sum rule.

$$\int_0^1 dx \left[u^p(x) - \bar{u}^p(x) \right] = 2$$ 2 valence up quarks. in total

$$\int_0^1 dx \left[d^p(x) - \bar{d}^p(x) \right] = 1$$ 1 valence downquark. in total

$u^p(x)$ = or $\neq$ $u^n(x)$ $\qquad$ $p = (uud)$, $n = (udd)$

proton density function of u quark in proton. $\qquad$ in neutron.

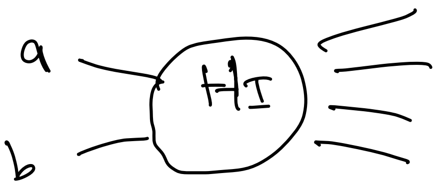
DGLAP equations. $\Rightarrow$ evolution of pdf
↳ Altarelli - Parisi

DIS $\Longrightarrow$ partons (relations) quarks?

1950-1960: $\quad p, n, \pi^{\pm}, K^{\pm}, \pi^0, K^0, \Delta$

Baryons: $q_1 q_2 q_3$

mesons: $q_1 \bar{q}_2$



#events. made of hadrons. leptons.

$$\#\text{events} \propto \sigma \propto |M|^2 \rho(E_f)$$

$$M = \langle f | H_I | i \rangle$$

To study H_I $\Rightarrow$ look for symmetries / selection rules.

symmetry: transformation acts on a state leaves the state unchanged

T: transformation. $\qquad$ $\psi_i = \psi(q, \vec{x}, t)$
↳ charge, quantum #

$|\psi'\rangle = T|\psi\rangle.$

$\langle T\rangle = \langle\psi|T|\psi\rangle$

$\langle\psi'| = \langle\psi|T^{+}$

$\langle\psi|T^{+}T|\psi\rangle = \langle\psi|\psi\rangle$

$\frac{d}{dt}\langle T\rangle = \emptyset$ $\quad [T, H] = 0$

$[T, H] = 0. \Rightarrow \quad TH|\psi\rangle$
$\quad HT|\psi\rangle$

$\psi(q, \vec{x}, t)$

symmetries: 1/ External symm: time reversal, parity, translation, rotation.

Continuous
- translation $\vec{x}$
- translation t
- rotation $\vec{x}$

Discrete.
- Time reversal. $T\psi(\vec{x},t) = \psi(\vec{x},-t)$
- Parity $\vec{x} \to -\vec{x}$ $\quad P\psi(\vec{x},t) = \psi(\vec{x},t)$

2/ Internal symmetries: act on internal quantum #.
NOT on $\vec{x}$ or t

Continuous
- Isospin

Discrete
- charge conjugation.
- C: proton $\longrightarrow \bar{p}$
- no change of momentum
- no change of spin