Hadronic Parity Violation Theory

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I am not and never have been a ~~member of the Communist Party~~ theorist,

And if you ask me I'll take the 5th Amendment

But since there is no theory for hadronic parity violation, the damage that an experimentalist can do to this subject is limited

The reason why there is no theory is because such a theory would need to understand quark-quark correlation effects in a two nucleon system. We are still trying to understand single quark effects in a one-nucleon system

From all of our previous experience with many-body systems, we know that it is very important to understand the ground state of the theory, and if the ground state is not boring it is typically highly correlated. The QCD ground state is not boring: in fact it has two condensates (gluons and quark-antiquark pairs) which are difficult to probe directly

The NN weak interaction silently probes quark-quark interactions in a way which does not excite the ground state of QCD.

What, you ask, is QCD?

U(1) Local Gauge Invariance ⇒ QED

If we demand that the electromagnetic Lagrangian be invariant under local (space-time-dependent) U(1) gauge transformations:

$$\psi(x) \to e^{i\alpha(x)}\psi(x),\ A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha(x)$$

It is possible if we add to the free Dirac L an interaction term

$-V = -j^\mu_{em} A_\mu = +e\, \bar{\psi}\gamma^\mu \psi A_\mu$ of a vector current with a new gauge field so that: $L = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi + e\bar{\psi}\gamma^\mu \psi A_\mu \to L.$

Adding new term is equivalent to defining a covariant derivative:

$$\partial_\mu \to D_\mu \equiv \partial_\mu - ieA_\mu \ \ such\ that\ D_\mu\psi \to e^{i\alpha(x)} D_\mu \psi\ under\ local\ gauge\ transformation$$

Also must add kinetic energy term quadratic in new vector (photon) field.

To maintain local gauge invariance, use:

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu \to \partial_\mu\left[A_\nu + \frac{1}{e}\partial_\nu \alpha(x)\right] - \partial_\nu\left[A_\mu + \frac{1}{e}\partial_\mu \alpha(x)\right] = F_{\mu\nu}$$

$$\Rightarrow \boxed{\mathrm{L}_{QED} = \bar{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi + e\bar{\psi}\gamma^\mu \psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}}$$

N.B. A mass term $\sim m^2 A_\mu A^\mu$ would violate local gauge invariance ⇒ massless photon!

Euler-Lagrange eq'n with respect to A_μ ⇒ Maxwell Eq'ns: $\partial_\mu F^{\mu\nu} = j^\nu$.
Hence, U(1) local gauge invariance ⇒ QED, a covariant field theory of charged fermions interacting with a massless vector field satisfying Maxwell Eq'ns and originating from a conserved vector current !

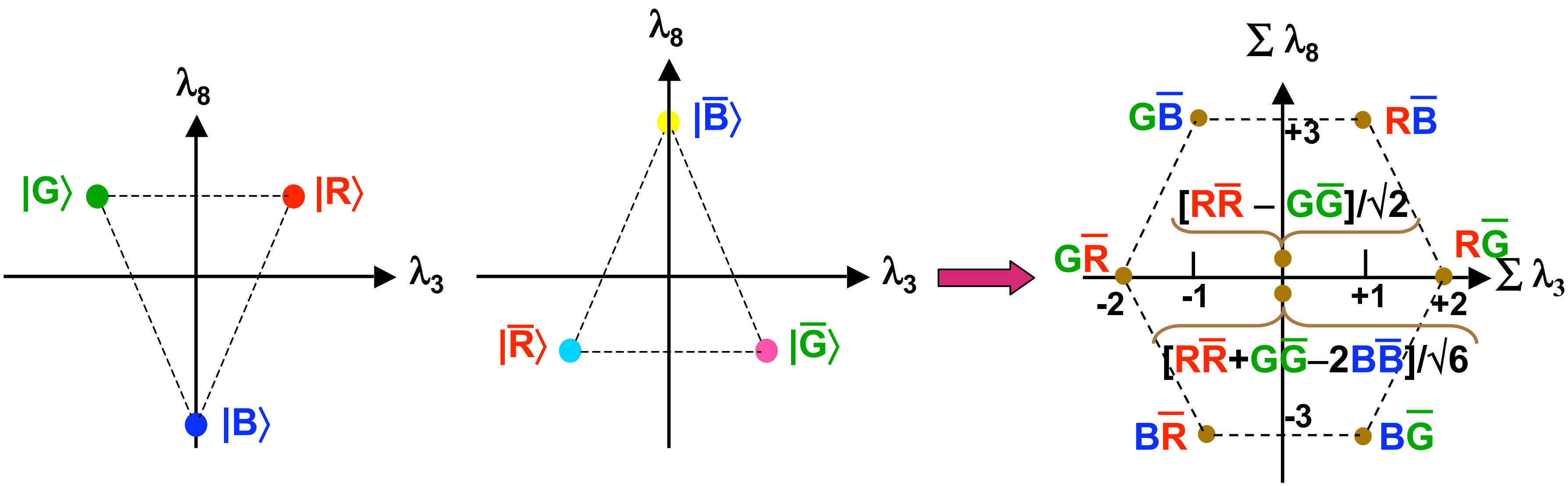
QCD Interactions Arise from Color Charge

Quarks are spin-1/2 Dirac particles that come in 3 colors: R, G, B

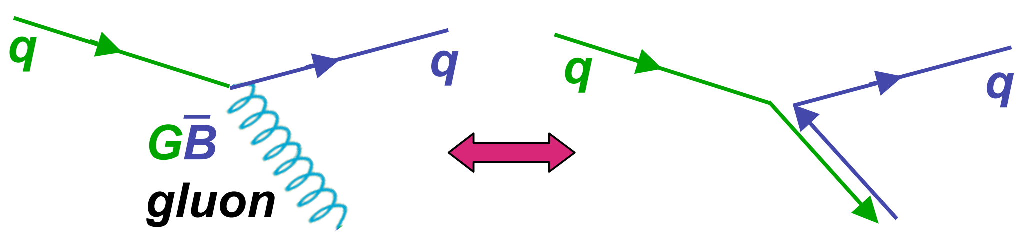
Antiquarks carry anti-color = "color propagating backwards in time":

$\bar{R}$, $\bar{G}$, $\bar{B}$

Quarks and antiquarks interact by exchanging bi-colored gluons that form an SU(3) color octet:



For example, from the point of view of color flow:



The color singlet combination: $\{R\bar{R} + G\bar{G} + B\bar{B}\}/\sqrt{3}$ is not available to gluons.

SU(3)-Color Local Gauge Invariance ⇒ QCD

For quarks of a given flavor, the general local gauge transformation allows color changes, in addition to space-time-dependent phase rotations:

$$quark\ \ field\ \ q(x) \to \hat{U} q(x) \equiv e^{i\sum \alpha_a(x)\hat{T}_a} q(x)\ \ with\ q(x)\ a\ 3-component\ color\ state$$

$$\left[\hat{T}_a , \hat{T}_b\right] = i f_{abc} \hat{T}_c\ \ with\ real\ \ f_{abc}\ antisymmetric\ under\ index\ \ pairwise\ swap$$

Non-commutivity of generators ⇒ non-Abelian group ⇒ surprising consequences of insisting on local gauge invariance. Introducing interaction with vector gauge fields (here, corresponding to 8 gluons) must be done with the transformation **which mixes gluon colors!**

$$\boxed{G_\mu^a \to G_\mu^a - \frac{1}{g}\partial_\mu \alpha_a(x) - \sum_{b,c} f_{abc}\,\alpha_b(x)\, G_\mu^c .}$$

Last term embodies coupling among gluon fields, and demands consequent term in gauge-invariant field strength tensor:

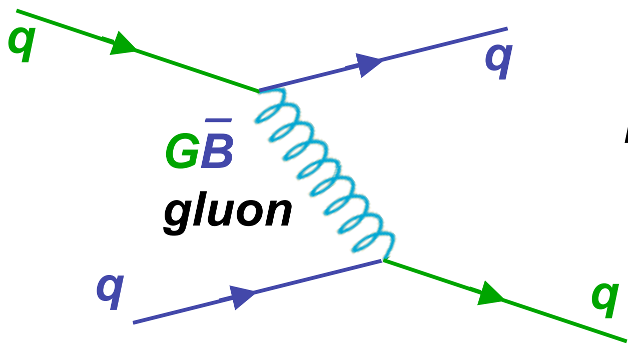
$$G_{\mu\nu}^a \equiv \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g\sum_{b,c} f_{abc}\, G_\mu^b\, G_\nu^c \ \ \Rightarrow \mathrm{SU(3)\ locally\ gauge-invariant}$$

$$L_{QCD} = \bar{q}\left(i\gamma^\mu \partial_\mu - m\right) q - g\left(\bar{q}\gamma^\mu \sum_a \hat{T}_a q\right) G_\mu^a - \frac{1}{4} G_{\mu\nu}^a\, G_a^{\mu\nu} .$$

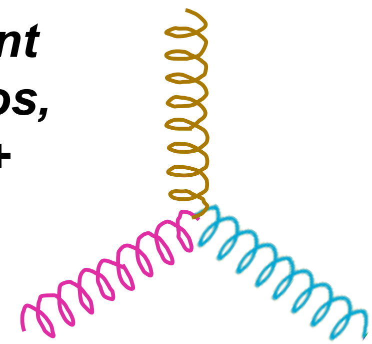
This non-Abelian (Yang-Mills) gauge field theory involves not only QED-like qqg vector coupling vertices, via 2nd term, but also ggg and gggg vertices via 3rd term ⇒ QCD !

So, If $m_\gamma = m_{gluon} = 0$, Why is the Strong Interaction Between Hadrons Short (~1 fm) Range? QCD vs. QED

In QCD, gluons carry color, while photons do not carry electric charge !

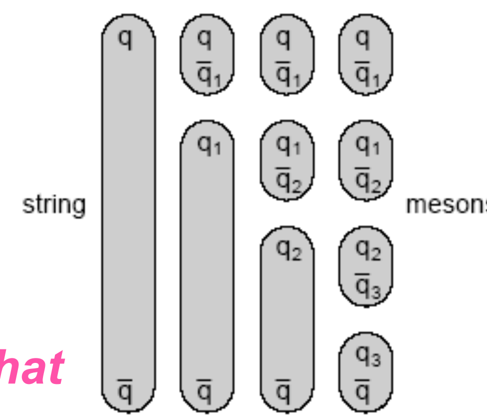


8 independent gluons represent possible color-anticolor combos, excluding singlet ($R\bar{R}$ + $G\bar{G}$ + $B\bar{B}$) ⇒ 3- and 4-gluon interactions allowed!

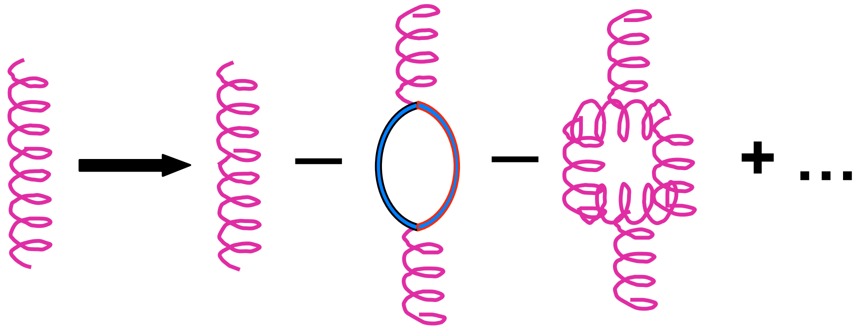


Gluon-gluon interactions:

- *strongly affect polarization of vacuum ⇒ many gluons and $q\bar{q}$ pairs excited near a color charge*
- *replace charge screening of QED (bare electron charge larger than seen from a distance) with color anti-screening*
- *make color force very strong at long distance (low momentum xfer) ⇒ **"infrared slavery"**, weak at short distance (high mom. xfer) ⇒ **"asymptotic freedom"***
- *confine color: stretch color "flux tube" btwn quarks too far and it breaks, leading to meson formation*
- *imply colorless hadrons interact via residual inter'n that can be viewed as meson exchange, of range $\lambda_\pi \approx 1.4$ fm*



QCD ⇒ QED-like Vector Currents, With Important Differences Introduced by Gluon Self-Coupling



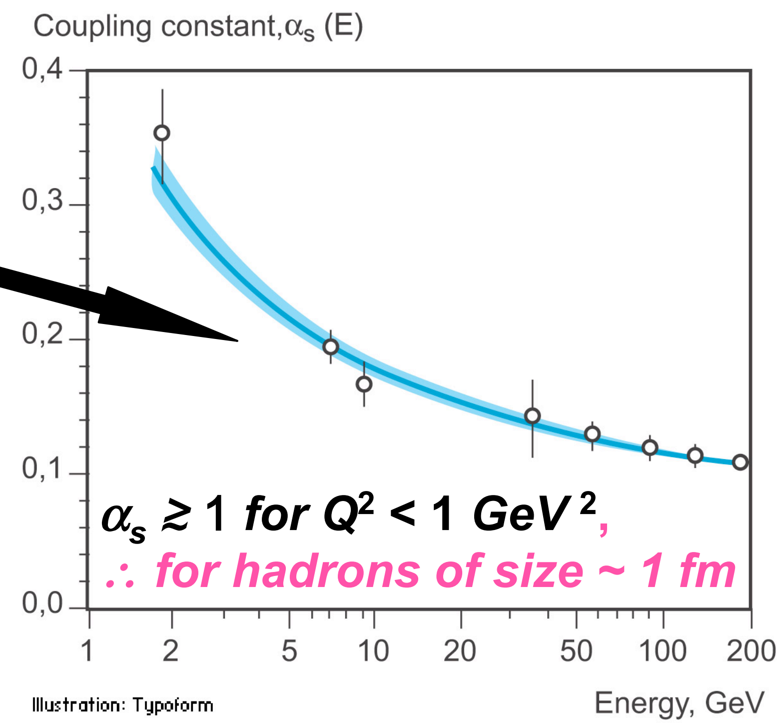
The gluon loops change the sign of the coupling constant correction from QED. For SU(3) color, Gross, Wilczek & Politzer (2004 Nobel Prize) found:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_{flavors})\ln\left(\frac{Q^2}{\mu^2}\right)}.$$

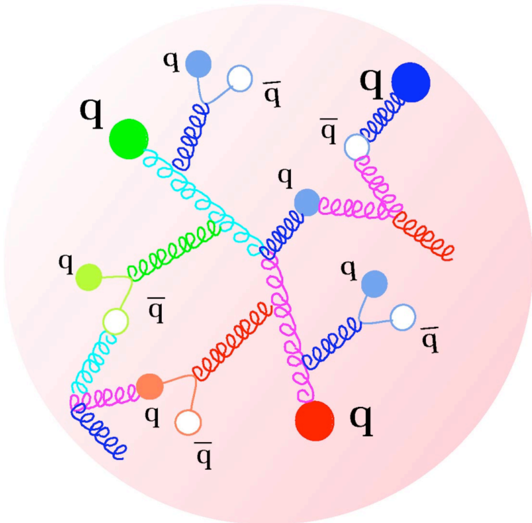
The + sign in the denominator ⇒ color force weakens with increasing Q^2 or decreasing distance ⇒ **asymptotic freedom.** Confirmed by measurements of QCD processes vs. energy.

Perturbation approach works only for hard (high Q^2) collisions where α_s small compared to 1. Even then, can't expect QED-like precision from first order !

α_s blows up for momentum transfers ~ $\Lambda_{QCD} \approx$ 200-300 MeV ⇒ **infrared slavery.** Quarks and gluons **confined** within colorless hadrons.

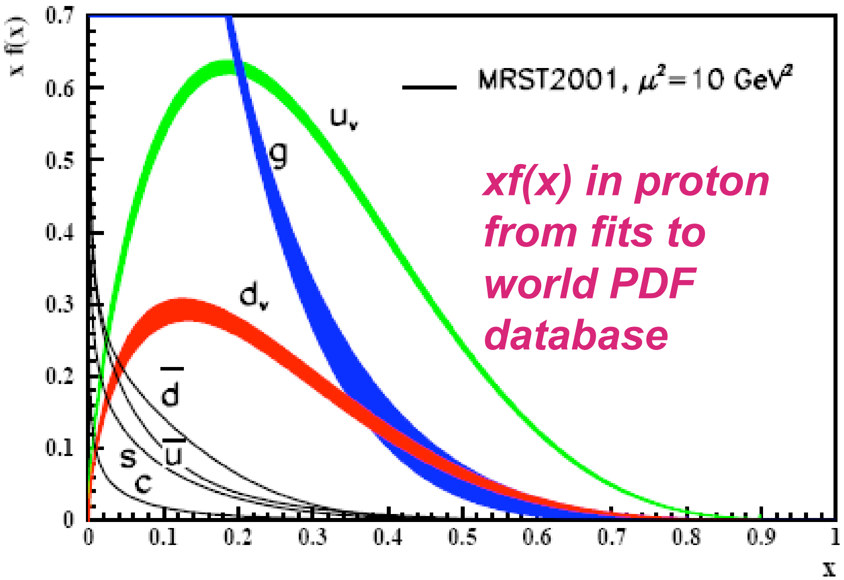


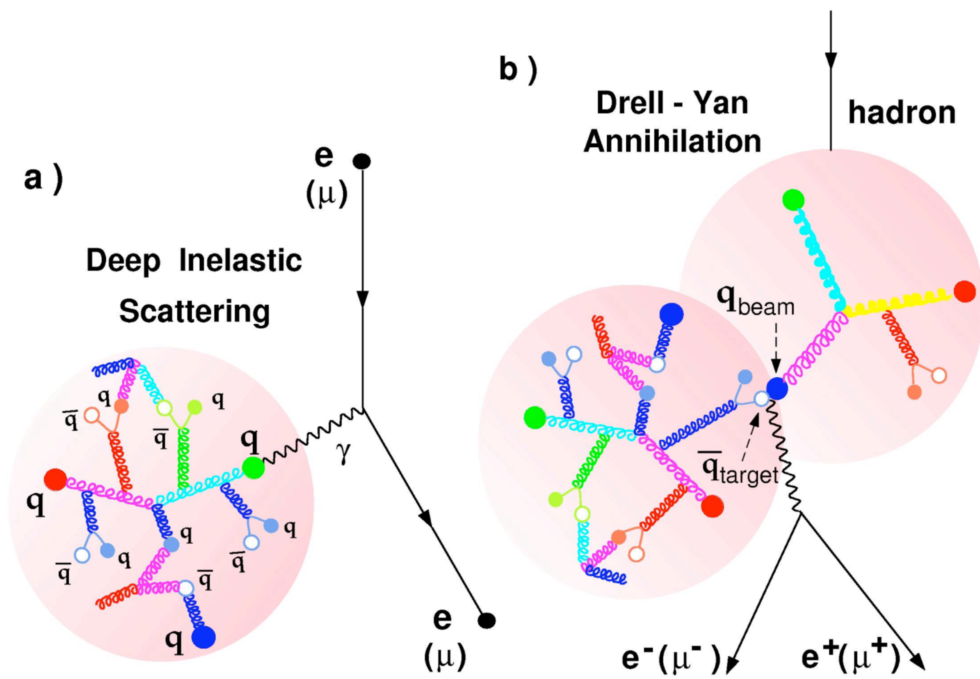
Complexity of QCD Vacuum ⇒ Rich Hadron Substructure



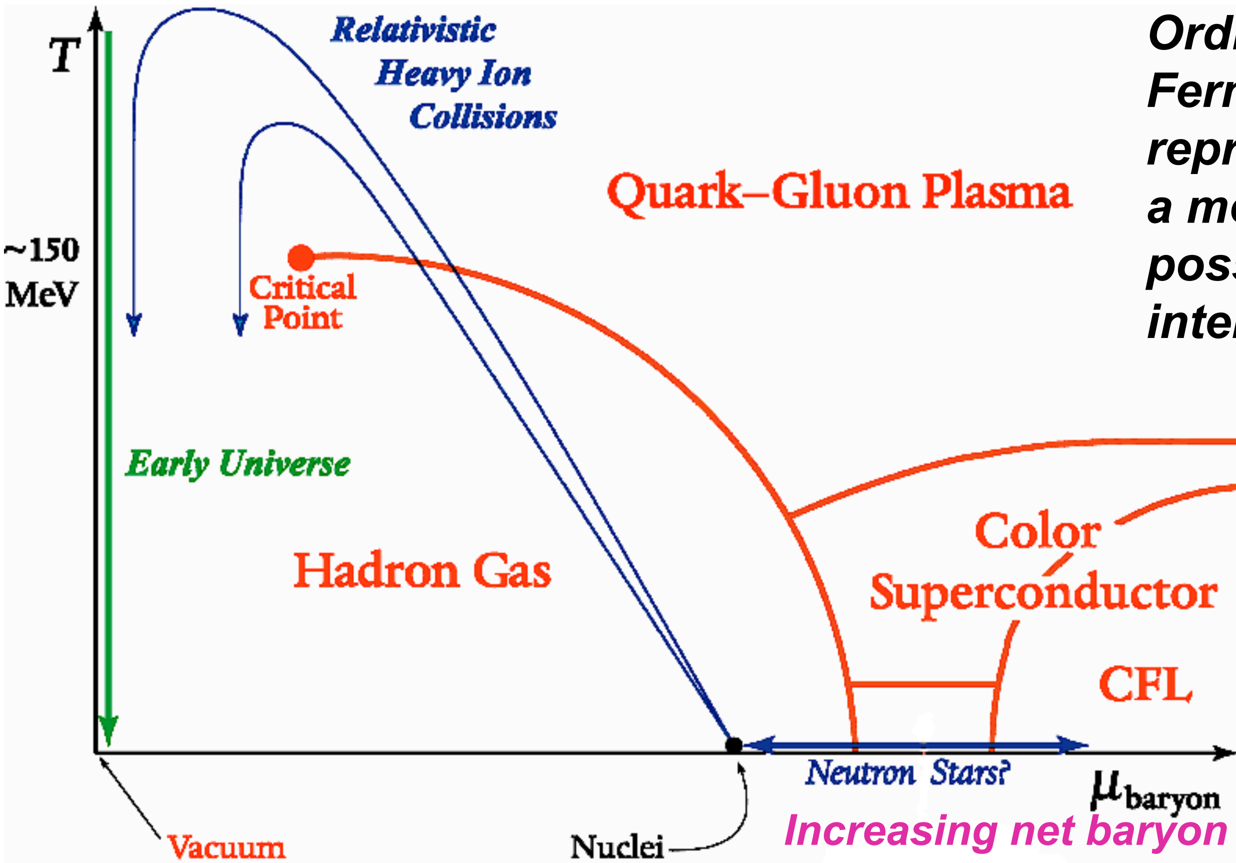
As seen by a high-energy probe, a hadron shares its momentum among many partons, not just 3 valence quarks (or a valence $q\bar{q}$ pair), but a multitude of gluons and sea $q\bar{q}$ pairs as well.

Reactions that transfer large momentum, like the EM processes pictured below, excite the nucleon with small wavelength. The larger the momentum transfer, the more gluons and sea quarks we see.





Phase Diagram for QCD Matter



Ordinary, zero-temperature, Fermi liquid nuclear matter represents just one point in a more general view of the possible states of strongly interacting matter!

As one raises T or increases baryon density, quarks & gluons should re-emerge as the fundamental degrees of freedom.

Increasing net baryon density →

At densities several times higher than normal nuclear matter saturation point, as obtainable in the cores of neutron stars, speculation focuses on "color superconducting" states: bi-colored pairs of quarks condense in the lowest-E state, giving gluons an effective mass via coupling to the pairs.

At low baryon density but high temperature, a transition to a plasma of quarks & gluons is anticipated. Collisions of heavy nuclei at RHIC attempt to form matter retracing the path of the early universe.

Constituent vs. Current Quarks and Hadron Mass

For hadrons built from light quarks:

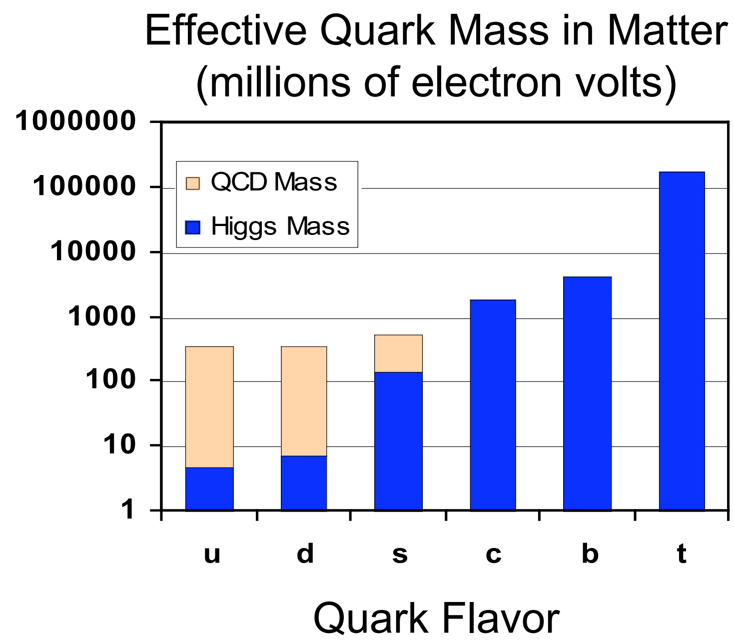
$$m_{hadron} >> \sum m_{u,d}^{"current"}$$

where $m^{current}$ are inferred from QCD Lagrangian. Hadron structure models invoke effective "dressed" (constituent) quark masses inside hadronic matter:

$$m_{u,d}^{constituent} \cong 300\ \text{MeV} \quad vs.\ m_{u,d}^{current} \approx \text{few MeV};$$

$$m_{s}^{constituent} \cong 500\ \text{MeV} \quad vs.\ m_{s}^{current} \approx 100\ \text{MeV};$$

$$m_{c}^{constituent} \cong 1.65\ \text{GeV} \quad vs.\ m_{c}^{current} \approx 1.3\ \text{GeV}.$$



Similar phenomena occur in condensed matter physics: for example the effective mass for the motion of an electron in matter is not the same as its "free" mass. Once again, we see that QCD exhibits the features of a condensed, many-body medium. Not only that, for light quarks u and d, the size of the effect is HUGE!

To understand this requires an explanation of chirality, the chiral symmetry of QCD, and its apparent "spontaneous" breakdown

Helicity and Chirality

Energy eigenstates of free Dirac equation are also states of well-defined ***helicity*** $\lambda \equiv \frac{1}{2}(\vec{\sigma}\cdot\vec{p})/|\vec{p}| = \pm\frac{1}{2}$. *Operator* $\vec{\sigma}\cdot\vec{p}$ *in* $H_{Dirac} \Rightarrow$ *no other spin component commutes with H and can be sharp in an energy eigenstate.*

Choosing $\hat{z}\|\vec{p}$, it is easy to show that:

$$\begin{pmatrix} \vec{\sigma}\cdot\hat{p} & 0 \\ 0 & \vec{\sigma}\cdot\hat{p} \end{pmatrix}\begin{pmatrix} u^{(1)}_{upper} \\ u^{(1)}_{lower} \end{pmatrix} = \begin{pmatrix} (E+m)u^{(1)}_{lower}/|\vec{p}| \\ (E-m)u^{(1)}_{upper}/|\vec{p}| \end{pmatrix} = \begin{pmatrix} p_z/|\vec{p}| \\ 0 \\ (E-m)/|\vec{p}| \\ 0 \end{pmatrix} = \begin{pmatrix} p_z/|\vec{p}| \\ 0 \\ |\vec{p}|/(E+m) \\ 0 \end{pmatrix} = \begin{cases} +u^{(1)}(\vec{p}) & for\ p_z > 0 \\ -u^{(1)}(\vec{p}) & for\ p_z < 0 \end{cases}$$

States of good helicity cannot be states of good parity in general, because parity and $\vec{\sigma}\cdot\hat{p}$ operators do not commute!

γ^5 is called the "chirality" operator. The operators $\frac{1}{2}(1+\gamma^5)$ and $\frac{1}{2}(1-\gamma^5)$ are **QM projection operators which** *project out right- and left-handed chiral components, respectively, of u(p). The Dirac energy and helicity eigenspinors are* **not** *γ^5 eigenstates unless m=0.*

$$\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & \hat{1}_2 \\ \hat{1}_2 & 0 \end{pmatrix} = \gamma^{5\dagger} \Rightarrow (\gamma^5)^2 = \hat{1}_4;\ \{\gamma^5,\gamma^\mu\} = 0.$$

$$u(p) = \tfrac{1}{2}(1+\gamma^5)u(p) + \tfrac{1}{2}(1-\gamma^5)u(p)$$

$$= \quad u_R(p) \quad + \quad u_L(p)$$

$$But:\quad \tfrac{1}{2}(1+\gamma^5)v(p) = v_L(p),\ \tfrac{1}{2}(1-\gamma^5)v(p) = v_R(p)$$

Helicity and chirality are therefore **not** *identical concepts if m>0. Helicity is conserved, but is frame-dependent: γ^5* **commutes with Lorentz trans.**

QED and QCD Vector Currents: Parity Conservation, Chiral Symmetry, and (Approximate) Helicity Conservation

Under parity: $\overline{\psi}\psi$ (scalar) is unchanged, $\overline{\psi}\gamma^5\psi$ (pseudoscalar) changes sign, and

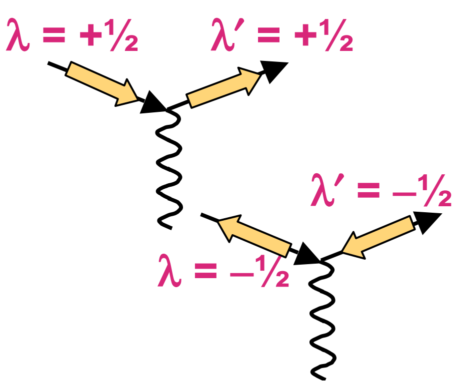
$$J'^{\mu}_{vector} \equiv \overline{\psi}'\gamma^{\mu}\psi' = \overline{\psi}\gamma^0\gamma^{\mu}\gamma^0\psi = +J^{vector}_{\mu} = \begin{cases} \overline{\psi}\gamma^0\psi \\ -\overline{\psi}\gamma^{\mu\neq 0}\psi \end{cases};$$

$$J'^{\mu}_{axial} \equiv \overline{\psi}'\gamma^5\gamma^{\mu}\psi' = \overline{\psi}\gamma^0\gamma^5\gamma^{\mu}\gamma^0\psi = -J^{axial}_{\mu} = \begin{cases} -\overline{\psi}\gamma^5\gamma^0\psi \\ \overline{\psi}\gamma^5\gamma^{\mu\neq 0}\psi \end{cases}$$

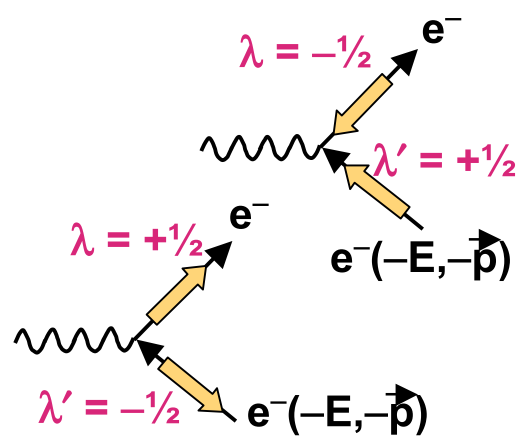
Both QED and QCD interactions involve the conserved Dirac (4-vector) current $\overline{\psi}\gamma^{\mu}\psi$. The product of vector currents is even under parity, so both QED and QCD conserve parity. Furthermore, there is no vector coupling between L- and R spinors, leading to a property known as chiral symmetry:

$$\overline{u}_L\gamma^{\mu}u_R = u_L^{\dagger}\gamma^0\gamma^{\mu}u_R = u^{\dagger}\tfrac{1}{2}(1-\gamma^{5\dagger})\gamma^0\gamma^{\mu}\tfrac{1}{2}(1+\gamma^5)u$$

$$= \tfrac{1}{4}u^{\dagger}\gamma^0(1+\gamma^5)\gamma^{\mu}(1+\gamma^5)u = \tfrac{1}{4}\overline{u}\gamma^{\mu}(1-\gamma^5)(1+\gamma^5)u = 0.$$



For m=0 or E >>m, this means that helicity is conserved at the vertex



Chiral Symmetry of QCD in Massless Quark Limit

QCD symmetries important for light quarks can be seen by rewriting L in terms of chiral [(1±γ⁵)/2] projections of the quark spinors:

$$L_{QCD} = \bar{q}\left(i\gamma^\mu\partial_\mu - m\right)q - g\left(\bar{q}\gamma^\mu\sum_a \hat{T}_a q\right)G^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a;$$

$$L^{flavor\ j}_{QCD} = \bar{q}^L_j\gamma^\mu\left(i\partial_\mu - g\sum_a \hat{T}_a G^a_\mu\right)q^L_j + \bar{q}^R_j\gamma^\mu\left(i\partial_\mu - g\sum_a \hat{T}_a G^a_\mu\right)q^R_j$$

$$-\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a - m_j\left(\bar{q}^L_j q^R_j + \bar{q}^R_j q^L_j\right)$$

For flavors where $m_j << \Lambda_{QCD}$ (certainly u and d, perhaps s) we can neglect the mass terms, and also $m_u \sim m_d$. Then two simplifications occur:

1) L is flavor-independent, ∴ invariant under flavor transformations ⇒ SU(2) isospin (good) or SU(3) flavor symmetry (not so good).

2) L-handed and R-handed quarks interact separately, without mutual coupling ⇒ L is invariant under independent flavor transformations for L- and R-handed quark sectors. This is $SU(2)_L \times SU(2)_R$ [or $SU(3)_L \times SU(3)_R$] chiral symmetry.

Chiral symmetry ⇒ separately conserved L & R flavor-changing currents:

$$J^{\mu,L}_\alpha = \bar{q}^L\gamma^\mu\hat{t}_\alpha q^L,\quad J^{\mu,R}_\alpha = \bar{q}^R\gamma^\mu\hat{t}_\alpha q^R \quad with\ \hat{t}_\alpha = 3\ SU(2)\ or\ 8\ SU(3)\ \underline{flavor}\ generators;$$

$$\partial_\mu J^{\mu,L}_\alpha = \partial_\mu J^{\mu,R}_\alpha = 0 \ \Rightarrow\ \partial_\mu J^{\mu,V}_\alpha = \partial_\mu J^{\mu,A}_\alpha = 0\ \ where\ J^{\mu,V}_\alpha \equiv \bar{q}\gamma^\mu\hat{t}_\alpha q;\ \ J^{\mu,A}_\alpha \equiv \bar{q}\gamma^\mu\gamma^5\hat{t}_\alpha q.$$

Isospin Symmetry in QCD

Isospin: *Introduced (1930's) by Heisenberg, Wigner to distinguish n and p as two "substates" of the same particle ("nucleon", N), distinguished by their isospin projection, in analogy to a spin-1/2 particle.*

Thus: $|p\rangle = |I=1/2, I_3=+1/2\rangle; \; |n\rangle = |I=1/2, I_3=-1/2\rangle$

Where subscript "3" denotes analog of z-projection in abstract 3-dimensional "isospin space", where isospin operators generate rotations, just as normal angular momentum operators generate rotations in ordinary 3-dimensional physical space.

In NN system, in analogy to two coupled spin-1/2 particles, we have:

$$|I=1, I_3=+1\rangle = |I_3(1)=+1/2\rangle |I_3(2)=+1/2\rangle = |p(1)p(2)\rangle;$$

$$|I=1, I_3=0\rangle = \frac{1}{\sqrt{2}}\{|I_3(1)=+1/2\rangle |I_3(2)=-1/2\rangle + |I_3(1)=-1/2\rangle |I_3(2)=+1/2\rangle\}$$

$$\frac{1}{\sqrt{2}}\{|p(1)n(2)\rangle + |n(1)p(2)\rangle\};$$

$$|I=1, I_3=-1\rangle = |I_3(1)=-1/2\rangle |I_3(2)=-1/2\rangle = |n(1)n(2)\rangle;$$

Triplet of $I=1$ states, *Symm.* under particle interchange

$$|I=0, I_3=0\rangle = \frac{1}{\sqrt{2}}\{|I_3(1)=+1/2\rangle |I_3(2)=-1/2\rangle - |I_3(1)=-1/2\rangle |I_3(2)=+1/2\rangle\}$$

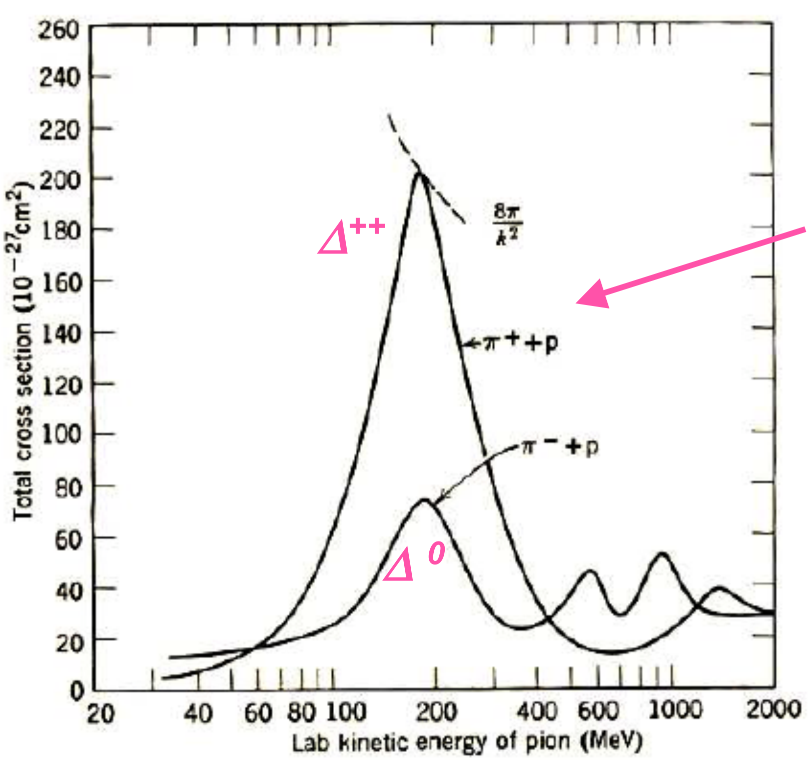
$$\frac{1}{\sqrt{2}}\{|p(1)n(2)\rangle - |n(1)p(2)\rangle\}$$

Singlet *Antisym.* $I=0$ state

Other Examples of Isospin Multiplets:

Pions: π^+, π^0, π^-, ***all with $m_\pi \approx$ 140 MeV, spin-0*** $\Rightarrow$

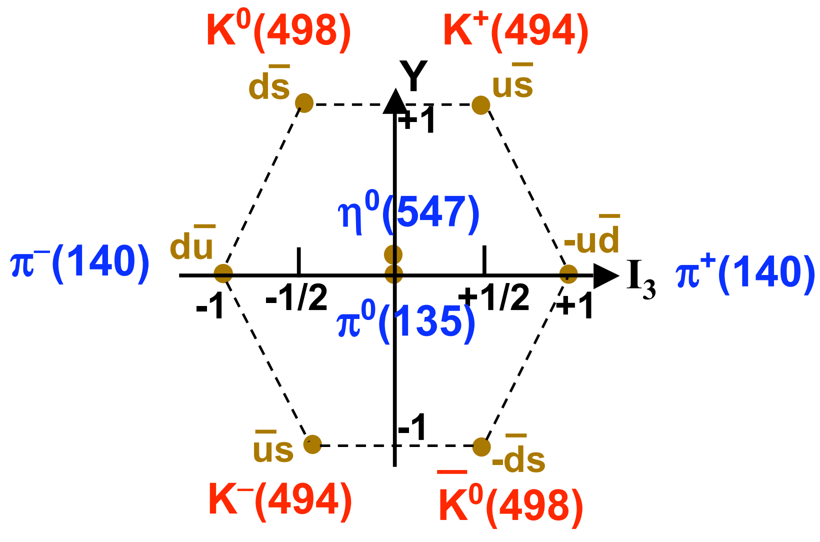
$$|\pi^+\rangle = |I=1, I_3=+1\rangle;\ |\pi^0\rangle = |I=1, I_3=0\rangle;\ |\pi^-\rangle = |I=1, I_3=-1\rangle$$



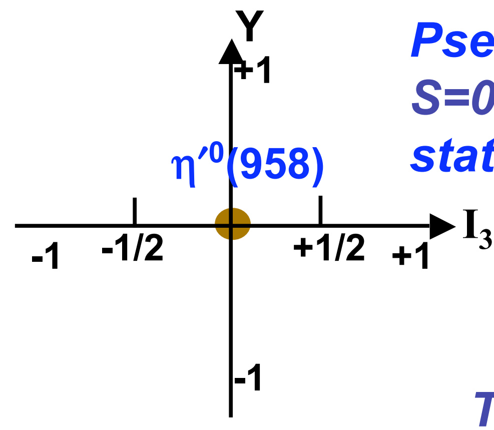
Deltas: $\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$, ***all with $m_\Delta \approx$ 1233 MeV, spin-3/2, excited states of the nucleon first observed as resonances in pion-nucleon scattering*** $\Rightarrow$ $I_\Delta = 3/2$

Quark level: ***u and d are the fundamental isospin doublet – isospin is a subset of "flavor" – the small bare mass difference $m_u \neq m_d$ is (mainly) responsible for small violations of isospin conservation in strong interaction processes.***

Isospin Symmetry in Pseudoscalar and Vector Mesons

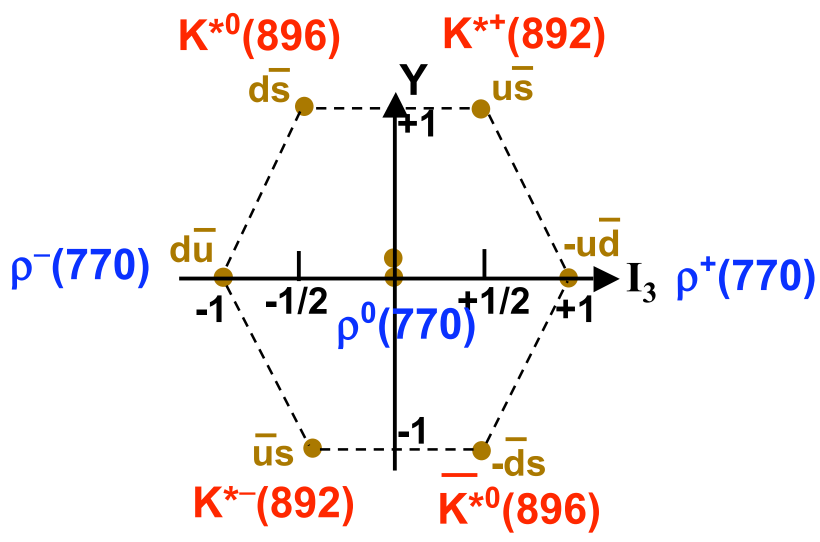


Flavor octet

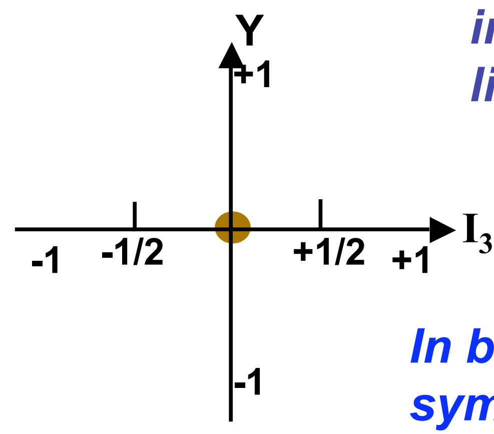


Flavor singlet

Pseudoscalars have S=0 and q and q in L=0 state ⇒ negative parity



Flavor octet

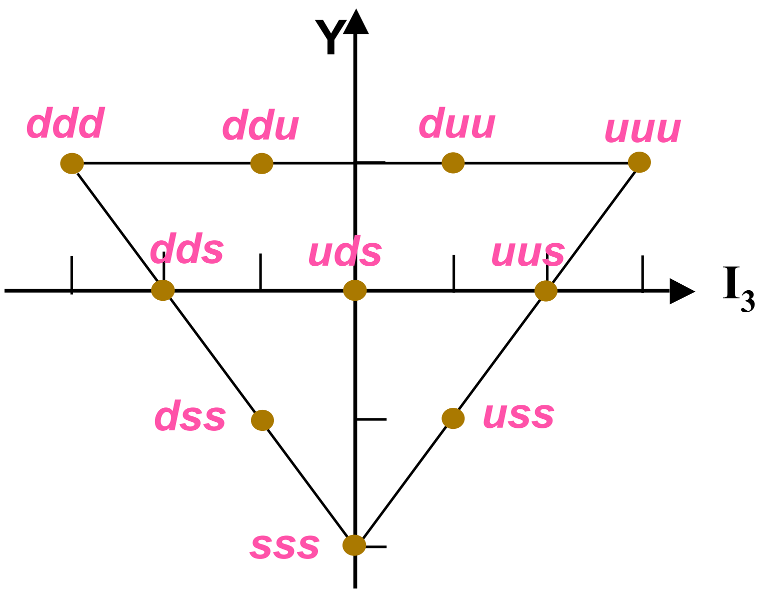


Flavor singlet

The vector mesons have L=0, S=1 ⇒ $J^P=1^-$. They are typically several hundred MeV higher in mass than the light pseudoscalars.

In both cases, isospin symmetry leads to near-degenerate masses in a multiplet

Isospin Symmetry in the $J^P=3/2^+$ and $1/2^+$ (L=0) Baryons

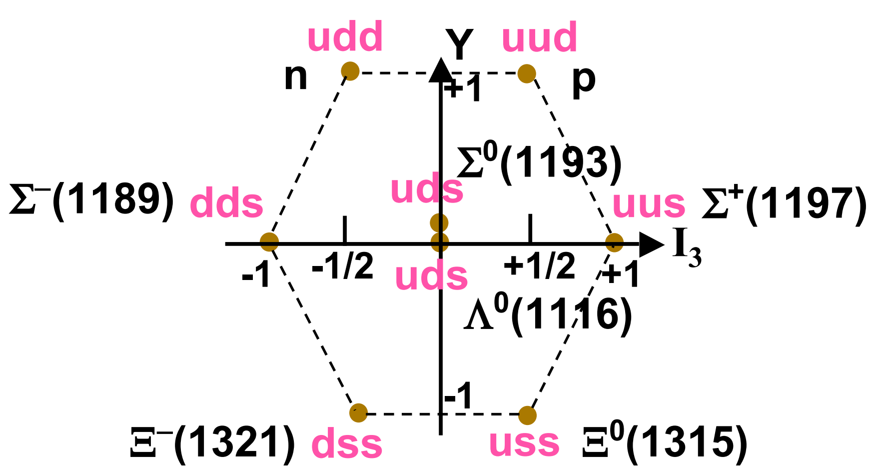


$\Delta(1232)$ I=3/2

$\Sigma^*(1385)$ I=1

$\Xi^*(1530)$ I=1/2

$\Omega^-(1672)$ I=0



Both sets of L=0 baryons exhibit isospin symmetry

QCD Ground State Breaks Chiral Symmetry, Gives Large "Effective Mass" To Light Quarks

Light hadrons form SU(2), but <u>not</u> $SU(2)_L \times SU(2)_R$ flavor multiplets. Why?

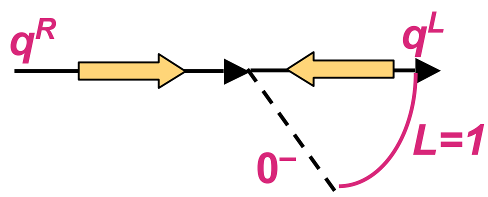
L_{QCD} invariant under parity ($L \leftrightarrow R$) and, for m_q=0, under chiral transformations. But parity and chiral (L vs. R) operators do not mutually commute! Could accommodate by mass degeneracy of opposite parity hadrons, but this is not observed, e.g., no 0^+ to match 0^- pions.

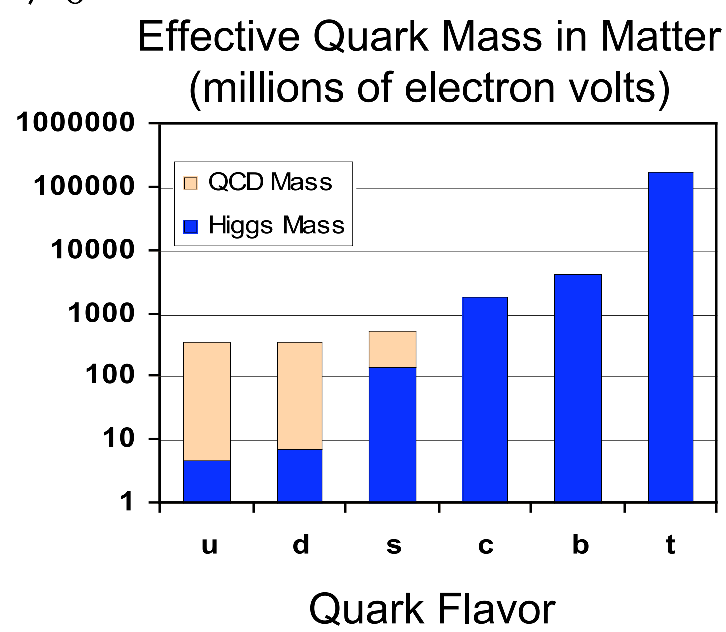
Chiral symmetry is explicitly broken by the quark masses, but these effects are very small for u,d. Most of the breaking is attributed to spontaneous breaking of chiral symmetry in the QCD vacuum:

$$\langle 0|\bar{\psi}_q \psi_q|0\rangle \neq 0 \;\Rightarrow \langle 0|\bar{\psi}_q^L \psi_q^R|0\rangle = \langle 0|\bar{\psi}_q^R \psi_q^L|0\rangle^\dagger \neq 0$$

$$\textit{while}\; \langle 0|\bar{\psi}_q^L \psi_q^L|0\rangle = \langle 0|\bar{\psi}_q^R \psi_q^R|0\rangle = 0\,.$$

SSB of a continuous symmetry $\Rightarrow$ massless scalar Goldstone bosons. Here need pseudoscalar (0^-) bosons (triplet for SU(2) χSB $\Rightarrow \pi^\pm, \pi^0$; octet for SU(3) $\Rightarrow \pi$, K, η) to enable quark helicity-flip:





QCD Summary: Confinement and Chiral Symmetry Breaking

Renormalizable gauge field theory, a generalization of QED to an interaction with 3 types of elementary charge (R,G,B).

Vector interaction of quarks with gluons ->L_{QCD} conserves parity (like EM)

In m_q=0 limit and for u and d quarks, a $SU(2)_L \times SU(2)_R$ symmetry in L.
This full symmetry does not appear in the QCD spectrum: ***spontaneous breaking of chiral symmetry in the QCD vacuum occurs. The dynamical mechanism for how this happens is not understood.***

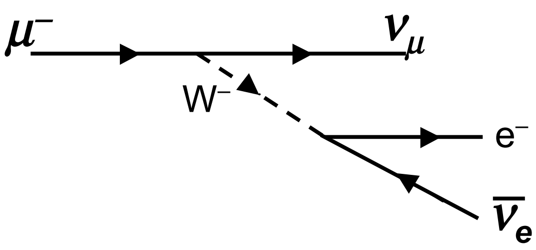
χSB reduces the remaining symmetry to SU(2) transformations among the u and d flavors (isospin). Due to small current quark masses, this symmetry is approximate (good to ~1%) but still very useful

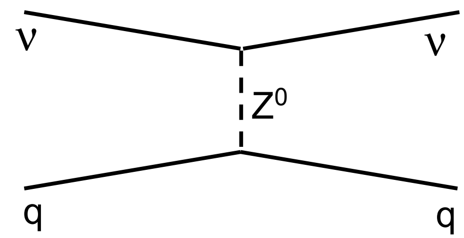
QCD gauge coupling becomes large at large distance according to perturbation theory. Quarks "must" be permanently confined since we have never isolated one.The mechanism by which quarks are permanently confined is not completely understood.

$m_q \langle 0 | \bar{\psi}_q \psi_q | 0 \rangle \sim 50\, MeV$ ***only, so where does the proton mass come from? Gluon field energy from the QCD "gluon condensate"!*** $< 0 | \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a | 0 >$

Reminder: Basic Features of the Weak Interactions

Charge-changing weak currents are mediated by $W^{\pm}$ exchange; neutral weak currents mediated by Z^0 exchange.

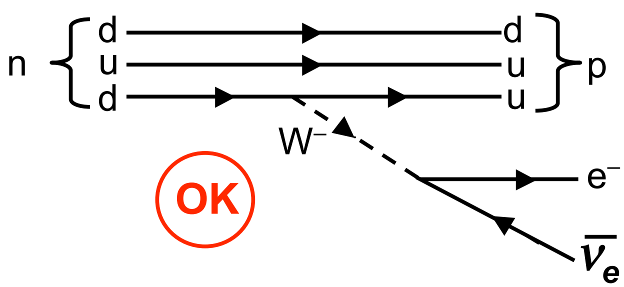


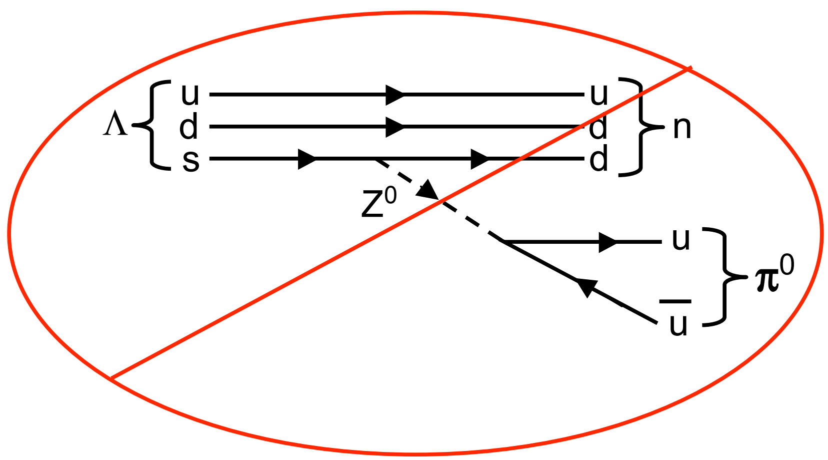


Heavy boson exchange ⇒ very short range, often approximated by contact interaction at low and moderate momentum transfers.

$$\lambda_W = \frac{\hbar c}{M_W c^2} = \frac{0.197\ GeV \cdot fm}{80.4\ GeV} = 0.0025\ fm = 2.5 \times 10^{-18}\ m$$

Charged weak currents change quark flavor, but neutral currents don't:

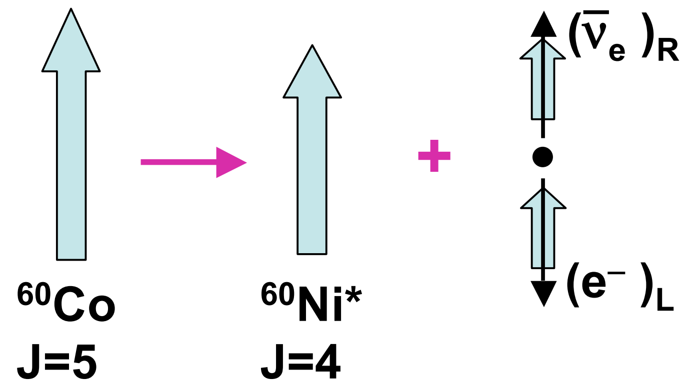




$\Lambda \rightarrow n\pi^0$ does proceed via W exchange

Parity Violation and the Structure of the Weak Current

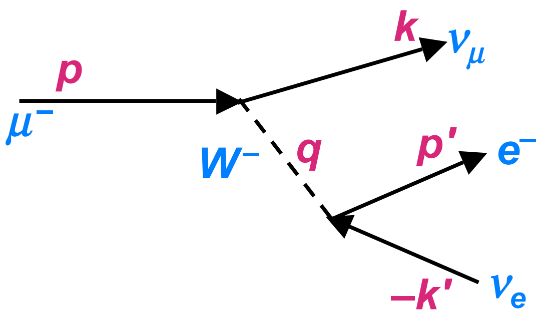
Parity violation in weak interactions was first predicted by Lee & Yang (1956) to account for observed K^+ decay to both even ($\pi\pi$) and odd ($\pi\pi\pi$) parity final states. ***Subsequently confirmed in nuclear β-decay by C.S. Wu at NBS via $\langle \vec{s}_{Co} \cdot \vec{p}_e \rangle \neq 0$ pseudoscalar correlation, consistent with emission of left-handed (negative helicity) e^- and right-handed $\bar{\nu}_e$.***



Weak currents can therefore not be pure vector $\bar{u}\gamma^\mu u$ or pure axial vector $\bar{u}\gamma^\mu\gamma^5 u$ in form. Observation of only L-handed neutrinos suggests equal mixture of the two: $e.g.,\ J^\mu = \bar{u}_\nu \gamma^\mu \tfrac{1}{2}(1-\gamma^5)u_e$.

In the Standard Model, parity violation is included by allowing the (charged current) weak interaction to act only on L chiral component of u(p) particle spinors ("maximal" parity violation). Why Nature chooses to do this is not yet fully understood, but it is pretty enough to be interesting.

Leptonic Weak Process (Muon Decay)



$$\mathsf{M}_{\mu^- \to e^- \nu_\mu \bar{\nu}_e} = \left[\frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu}(k) \gamma^\sigma \frac{1}{2}(1-\gamma^5) u_\mu(p) \right] \times \frac{\left[-g_{\sigma\rho} + q_\sigma q_\rho / M_W^2 \right]}{q^2 - M_W^2} \left[\frac{g}{\sqrt{2}} \bar{u}_e(p') \gamma^\rho \frac{1}{2}(1-\gamma^5) u_{\nu_e}(-k') \right]$$

using the Feynmann rules for the tree-level amplitude. In $\mu^- \to e^- \nu_\mu \nu_e$, momentum transfer $q^2 << M_W^2$, so to excellent approximation:

$$\mathsf{M}_{\mu^- \to e^- \nu_\mu \bar{\nu}_e} \to \left[\frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu}(k) \gamma^\sigma \frac{1}{2}(1-\gamma^5) u_\mu(p) \right] \frac{1}{M_W^2} \left[\frac{g}{\sqrt{2}} \bar{u}_e(p') \gamma_\sigma \frac{1}{2}(1-\gamma^5) u_{\nu_e}(-k') \right]$$

$$\equiv \frac{G_F}{\sqrt{2}} \left[\bar{u}_{\nu_\mu}(k) \gamma^\sigma (1-\gamma^5) u_\mu(p) \right] \left[\bar{u}_e(p') \gamma_\sigma (1-\gamma^5) v_{\bar{\nu}_e}(k') \right] \text{ with the weak coupling}$$

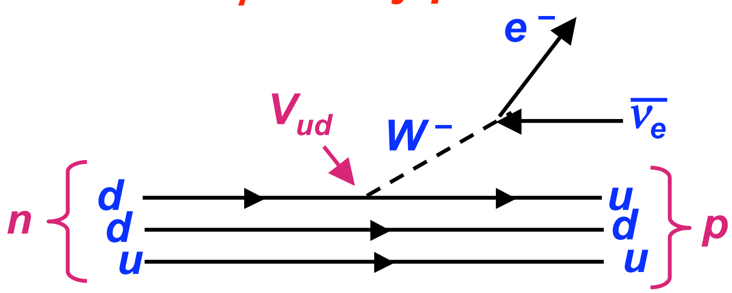
$$\text{constant first introduced by Fermi: } G_F \equiv \frac{g^2 \sqrt{2}}{8 M_W^2}.$$

Semileptonic Weak Process: Neutron and Nuclear β-Decay

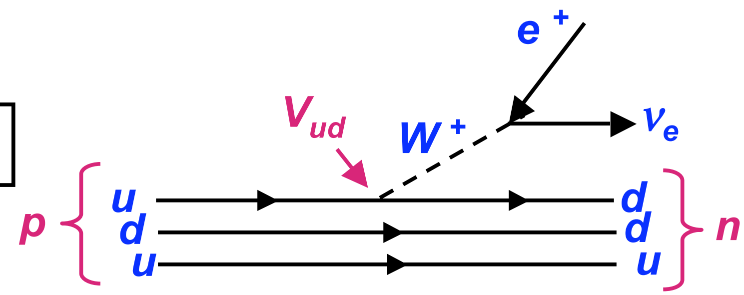
In weak interactions of quarks bound within baryons (spin ≠ 0), the charged current need not take the simple V – A form found for leptons. In general, allow for various bilinear coupling forms:

$$J^{\mu}_{baryon}(x) = \overline{\psi}_f \left[\underbrace{f_1(q^2)\gamma^{\mu}}_{vector} + \underbrace{if_2(q^2)\sigma^{\mu\nu}q_{\nu}}_{tensor} + \underbrace{g_1(q^2)\gamma^{\mu}\gamma^5}_{axial\ vector} + \underbrace{g_3(q^2)\gamma^5 q^{\mu}}_{pseudoscalar} \right] \psi_i$$

Nuclear β-decay proceeds via:



or



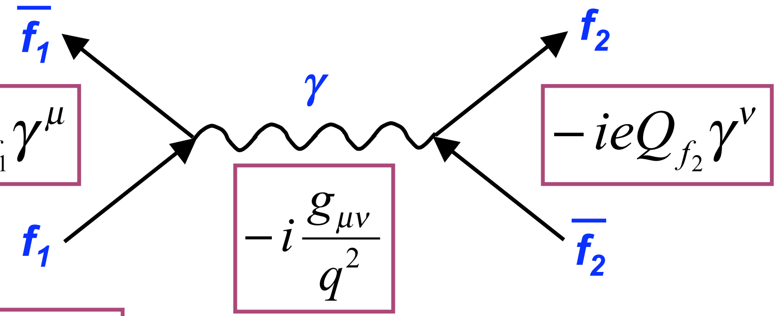
For free nucleons, only ***$n \rightarrow pe^-\overline{\nu}_e$ (τ = ? s)*** *energetically allowed. Inside nucleus, energy release depends on binding energy of initial and final-state nucleons. In any case,* ***$q^2 \rightarrow 0$*** *and no evidence seen of need for tensor or pseudoscalar terms in nucleon decay:*

$$q^2 \rightarrow 0,\ \ f_1(q^2) \rightarrow g_V\,,\ \ g_1(q^2) \rightarrow g_A \Rightarrow$$

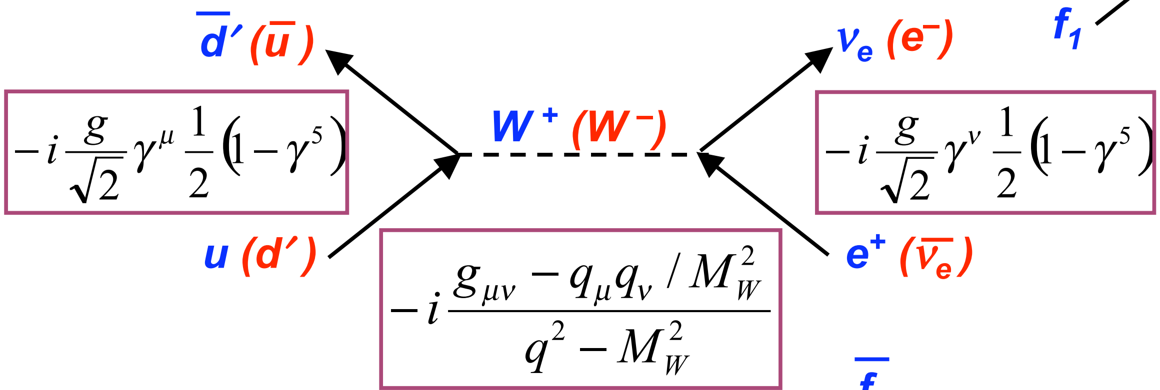
$$J^{\mu}_{n\rightarrow p}(x) = \overline{\psi}_p(x)\gamma^{\mu}(g_V + g_A\gamma^5)\hat{\tau}^+\psi_n(x),\ \ \text{with } \hat{\tau}^+ \text{ an isospin raising operator}$$

(Selected) Feynman Rules in Electroweak Theory

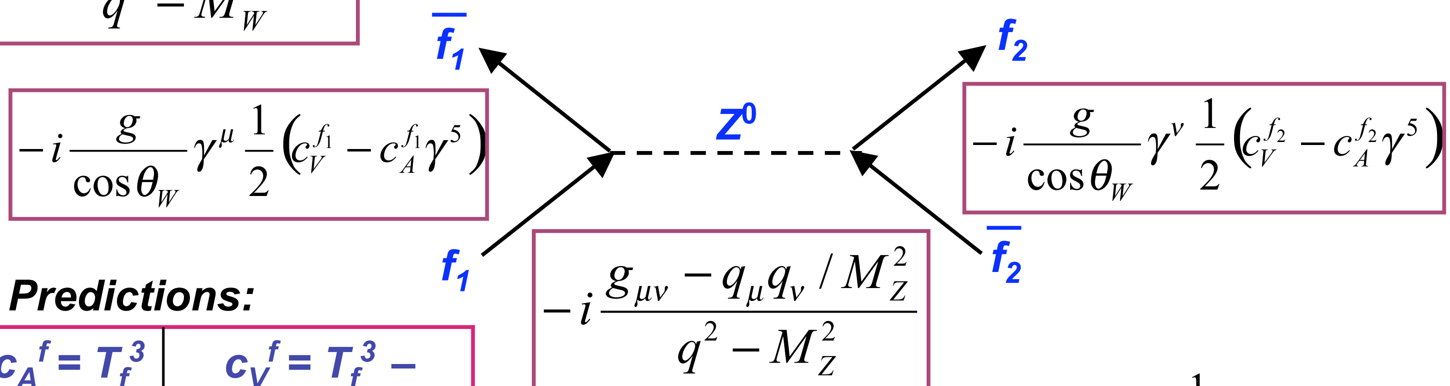
$$-i\mathcal{M}^{EW} \rightarrow$$



$$-ieQ_{f_1}\gamma^{\mu} \qquad -i\frac{g_{\mu\nu}}{q^2} \qquad -ieQ_{f_2}\gamma^{\nu}$$



$$-i\frac{g}{\sqrt{2}}\gamma^{\mu}\frac{1}{2}\left(1-\gamma^5\right) \qquad -i\frac{g_{\mu\nu}-q_{\mu}q_{\nu}/M_W^2}{q^2-M_W^2} \qquad -i\frac{g}{\sqrt{2}}\gamma^{\nu}\frac{1}{2}\left(1-\gamma^5\right)$$



$$-i\frac{g}{\cos\theta_W}\gamma^{\mu}\frac{1}{2}\left(c_V^{f_1}-c_A^{f_1}\gamma^5\right) \qquad -i\frac{g_{\mu\nu}-q_{\mu}q_{\nu}/M_Z^2}{q^2-M_Z^2} \qquad -i\frac{g}{\cos\theta_W}\gamma^{\nu}\frac{1}{2}\left(c_V^{f_2}-c_A^{f_2}\gamma^5\right)$$

Standard Model Predictions:

fermion	Q_f	$c_A^f = T_f^3$	$c_V^f = T_f^3 - 2Q_f\sin^2\theta_W$
ν_e, ν_μ, ν_τ	0	1/2	$\frac{1}{2}$
e^-, μ^-, τ^-	–1	–1/2	$-\frac{1}{2}\left(1-4\sin^2\theta_W\right)$
u,c,t	2/3	1/2	$\frac{1}{2}\left(1-\frac{8}{3}\sin^2\theta_W\right)$
d,s,b	-1/3	–1/2	$-\frac{1}{2}\left(1-\frac{4}{3}\sin^2\theta_W\right)$

$$e.g.,\ Z_{\mu} = \varepsilon_{\mu}e^{-ip\cdot x}, \quad \text{with } \varepsilon_{\mu}^{\lambda=\pm 1} = \mp\frac{1}{\sqrt{2}}\{0;1,\pm i,0\};$$

On-shell W or Z: propagator → free particle state

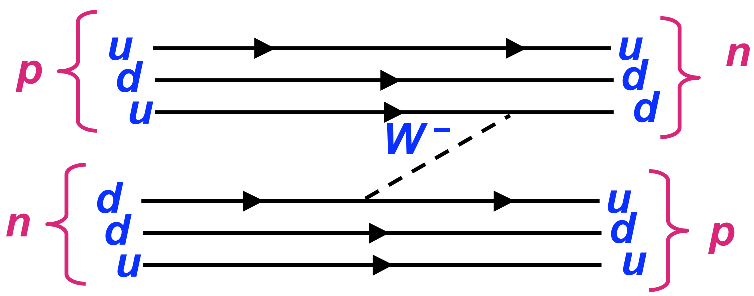
$$\varepsilon_{\mu}^{\lambda=0} = \frac{1}{M}\{|\vec{p}|;0,0,E\} \ for\ \hat{z}\|\vec{p}$$

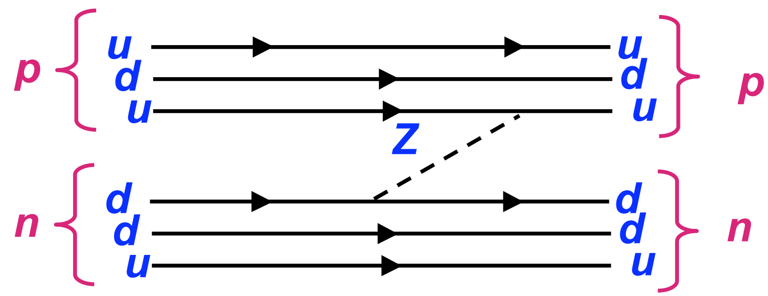
$$\Rightarrow p^{\mu}\varepsilon_{\mu} = 0, \quad \sum_{\lambda}\varepsilon_{\mu}^{(\lambda)}{}^{*}\varepsilon_{\nu}^{(\lambda)} = -g_{\mu\nu} + \frac{p_{\mu}p_{\nu}}{M^2}.$$

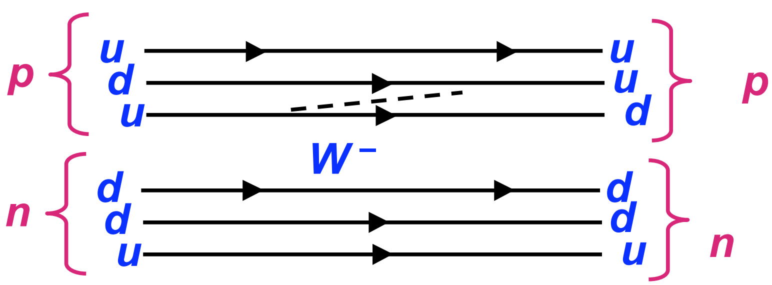
Nonleptonic Weak Processes: NN Weak Interaction

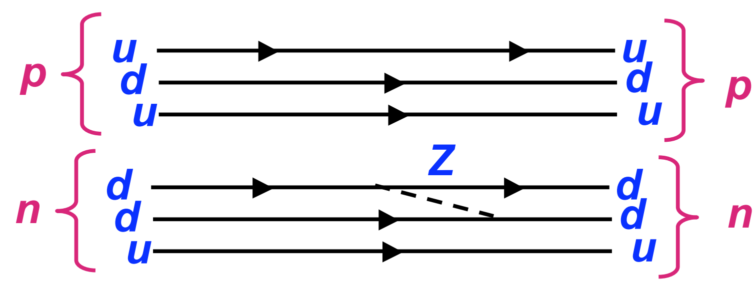
Although the quark-quark weak interactions at tree level can be written down in the same way as for leptonic and semileptonic processes, now BOTH the quarks in the initial AND final states are bound within hadrons by QCD.

For the weak interaction between nucleons, some (of the many) possible processes are (not showing the gluons!):









Many possible amplitudes can contribute, but nonperturbative QCD makes direct calculation of the amplitudes difficult. Is there anything simple we can say?

qq Weak Interaction: Isospin Dependence

The quark-quark weak interaction at energies below the W and Z mass can also be written in a "current-current" form, with contributions from charged currents and neutral currents

$$M_{CC} = \frac{g^2}{2M_W^2} J^{\dagger}_{\mu,CC} J^{\mu}_{CC}; M_{NC} = \frac{g^2}{\cos^2\theta_W M_Z^2} J^{\dagger}_{\mu,NC} J^{\mu}_{NC}$$

$$J^{\mu}_{CC} = \bar{u}\frac{-1}{2}\gamma^{\mu}(1-\gamma^5)\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}; J^{\mu}_{NC} = \sum_{q=u,d} \bar{q}\frac{-1}{2}\gamma^{\mu}(c_V^q - c_A^q\gamma^5)q$$

The weak interaction does NOT conserve isospin, but QCD conserves isospin to a good approximation. Therefore we can classify what are the possible isospin changes from qq weak interactions as follows:

Charged current: $\Delta I=0,2$ ($\sim V^2_{ud}$), $\Delta I=1$ ($\sim V^2_{us}$)

Neutral current: $\Delta I=0,1,2$.

The $\Delta I=1$ terms comes only from the quark-quark neutral currents in the absence of strange quarks (due to small size of V_{us}, we expect this term to be suppressed anyway by a factor of $V^2_{us}\sim 0.05$

These terms are about the same size, so any large differences in different channels can only come from the ground state dynamics of QCD. This is one of the few ways to probe the nonperturbative ground state of QCD

NN Weak Interaction: Independent Amplitudes

Consider elastic NN scattering at low enough energies that the nucleons are nonrelativistic. In this case, we can describe the scattering using phase shifts in a partial wave expansion. For spinless particles, you remember the usual form of the partial wave expansion

$$\psi \xrightarrow[r\to\infty]{} \sum_{\ell=0}^{\infty} b_\ell P_\ell(\cos\theta)\frac{\sin\left(kr-\ell\frac{\pi}{2}+\delta_\ell\right)}{kr} = e^{ikz} + f\left(k^2,\theta\right)\frac{e^{ikr}}{r} \Rightarrow$$

$$f(k^2,\theta)=\sum_{\ell=0}^{\infty}\frac{1}{2ik}(2\ell+1)\left(e^{2i\delta_\ell}-1\right)P_\ell(\cos\theta)\ \ with\ real\ \ phase\ shifts\ \delta_\ell$$

In our case, since the nucleons are spin 1/2, we need the spin-dependent generalization of the partial wave expansion:

$$\psi \xrightarrow[r\to\infty]{} e^{ikz}\left|S_i,m_{S_i}\right\rangle + \frac{e^{ikr}}{r}\sum_{S_f,m_{S_f}}\left|S_f,m_{S_f}\right\rangle\left\langle S_f,m_{S_f}\right|M(k^2,\theta)\left|S_i,m_{S_i}\right\rangle$$

And we can measure the matrix elements of M. Recall that the parity operator inverts space:

$$\hat{P}f(\vec{r}) = f(-\vec{r});\ under\ \hat{P},\ (x,y,z)\to(-x,-y,-z),\ (r,\theta,\varphi)\to(r,\pi-\theta,\pi+\varphi)$$

$\hat{P}^2 = \hat{1} \Rightarrow$ parity eigenfcns are either even (eigenvalue P = +1) or odd (P = -1)

$$\hat{P}Y_{LM}(\theta,\phi) = Y_{LM}(\pi-\theta,\pi+\phi) = (-1)^L Y_{LM}(\theta,\phi)\ \ for\ spherical\ harmonics$$

So, states of good orbital angular momentum quantum # L have well-defined spatial parity $(-1)^L$.

NN Weak Interaction: Independent Amplitudes

If we consider low energy NN scattering, the parity violating amplitudes are those that connect L=0 and L=1 two-nucleon states. We can classify them.

Total NN (two identical fermion) wave function

$$\Psi_{tot}^{NN}(1,2) = \psi_{space}(\vec{r}_1, \vec{r}_2) \,|\, S_{tot}, S_z \rangle \,|\, I_{tot}, I_3 \rangle$$

must be $\mathcal{A}$ under interchange, restricting Pauli-allowed L,S,I combinations:

$I_{tot} = 1$ (isospin-$\mathcal{S}$):

Space-$\mathcal{S}$ (even L) $\otimes$ spin-$\mathcal{A}$ ($S_{tot} = 0$) $\Rightarrow$ $^1S_0$, $^1D_2$, $^1G_4$, …
or Space-$\mathcal{A}$ (odd L) $\otimes$ spin-$\mathcal{S}$ ($S_{tot} = 1$) $\Rightarrow$ $^3P_{0,1,2}$, $^3F_{2,3,4}$, …

$I_{tot} = 0$ (isospin-$\mathcal{A}$):

Space-$\mathcal{A}$ (odd L) $\otimes$ spin-$\mathcal{A}$ ($S_{tot} = 0$) $\Rightarrow$ $^1P_1$, $^1F_3$, …
Space-$\mathcal{S}$ (even L) $\otimes$ spin-$\mathcal{S}$ ($S_{tot} = 1$) $\Rightarrow$ $^3S_1$, $^3D_{1,2,3}$, $^3G_{3,4,5}$, …

$\left.\right\}$ ***$^{(2S+1)}L_J$ notation, with L=0,1,2,3,4,… denoted as S,P,D, F,G,…***

Only upper 2 rows available for pp or nn. For np system, all combinations available. We therefore have 5 independent NN parity-violating amplitudes:

$^3S_1 \Leftrightarrow {}^1P_1$ ($\Delta I=0$, np); $^3S_1 \Leftrightarrow {}^3P_1$ ($\Delta I=1$, np); $^1S_0 \Leftrightarrow {}^3P_0$ ($\Delta I=0,1,2$; nn,pp,np)

Some Approaches to Non-Perturbative QCD

Lattice QCD: *solve QCD numerically for quarks and gluons confined to finite space-time lattice; extrapolate to continuum limit (lattice spacing $\rightarrow$ 0) and to light quark masses (so-called chiral limit) to predict properties of hadrons and of quark-gluon matter.*

Great recent progress & success! Concerns: provides limited insight; CPU limitations $\Rightarrow$ limits to applications, extrapolation uncertainties.

Effective field theory: *impose QCD symmetry constraints on L written in terms of effective degrees of freedom (not quarks and gluons) most relevant at low energies; adjust numerous coupling strength parameters to reproduce experiment (à la Standard Model).*

Used for low-E πN and NN interactions, and to extrapolate lattice QCD results to $m_q \rightarrow 0$. Rigor at given expansion order, but applicability range limited to low momentum transfer processes.

QCD-inspired models: *e.g., constituent-quark potential models of hadrons; one-boson-exchange models of NN interaction, chiral models, instanton models, etc.*

Wide applicability and predictive power, once parameters set for simple systems, but (except for chiral EFT!) lose guarantee of controlled expansion.

Fortunately for us, strong NN interaction is well-measured and understood. Weak NN can be added as a perturbation

Symmetry Constraints on the Strong NN Potential

At low E, the NN system can be treated by solving the Schrödinger eq'n with a Hermitian potential that may depend on the vector separation and on the nucleon spins, isospins and momenta.

Okubo and Marshak (1958) wrote down the most general potential form that maintains invariance under: space & time translations and rotations; parity and time reversal; isospin rotations and particle interchange.

$$V_{NN} = V_0(r) + V_\sigma(r)\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_\tau(r)\vec{\tau}_1\cdot\vec{\tau}_2 + V_{\sigma\tau}(\vec{\sigma}_1\cdot\vec{\sigma}_2)(\vec{\tau}_1\cdot\vec{\tau}_2) \quad \textbf{central}$$

$$+ V_{LS}(r)\vec{L}\cdot\vec{S} + V_{LS\tau}(r)(\vec{L}\cdot\vec{S})(\vec{\tau}_1\cdot\vec{\tau}_2) \quad \textbf{Spin-orbit, with } \vec{S}\equiv\tfrac{1}{2}(\vec{\sigma}_1+\vec{\sigma}_2)$$

$$+ V_T(r)S_{12} + V_{T\tau}(r)S_{12}\vec{\tau}_1\cdot\vec{\tau}_2 \quad \textbf{Tensor, with } S_{12}\equiv 3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r}) - \vec{\sigma}_1\cdot\vec{\sigma}_2$$

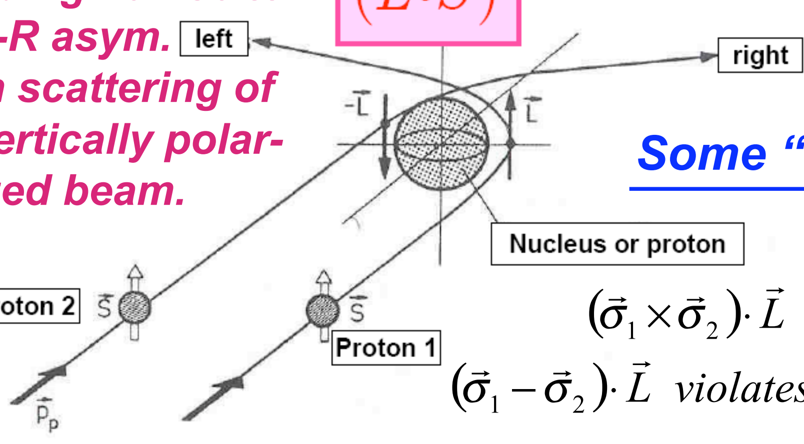
$$+ V_Q(r)Q_{12} + V_{Q\tau}(r)Q_{12}\vec{\tau}_1\cdot\vec{\tau}_2 \quad \textbf{Quadratic spin-orbit, with } Q_{12}\equiv\frac{1}{2}\left\{(\vec{\sigma}_1\cdot\vec{L})(\vec{\sigma}_2\cdot\vec{L}) + (\vec{\sigma}_2\cdot\vec{L})(\vec{\sigma}_1\cdot\vec{L})\right\}$$

$$+ V_{PP}(r)(\vec{\sigma}_1\cdot\vec{p})(\vec{\sigma}_2\cdot\vec{p}) + V_{PP\tau}(r)(\vec{\sigma}_1\cdot\vec{p})(\vec{\sigma}_2\cdot\vec{p})(\vec{\tau}_1\cdot\vec{\tau}_2)$$

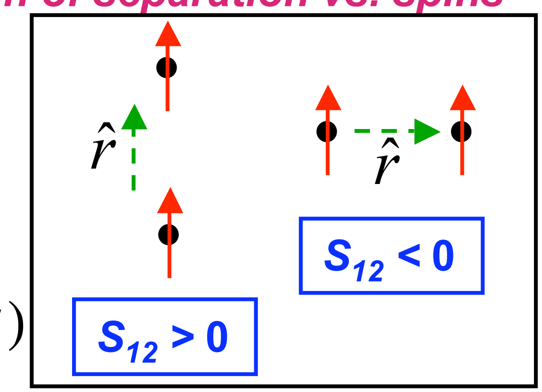
Momentum-dependent tensor

Can give rise to L-R asym. in scattering of vertically polar-ized beam.

$(\vec{L}\bullet\vec{S})$



Can give rise to preferential orientation of separation vs. spins



Some "forbidden" terms:

$\vec{S}\cdot\vec{p}$ violates parity

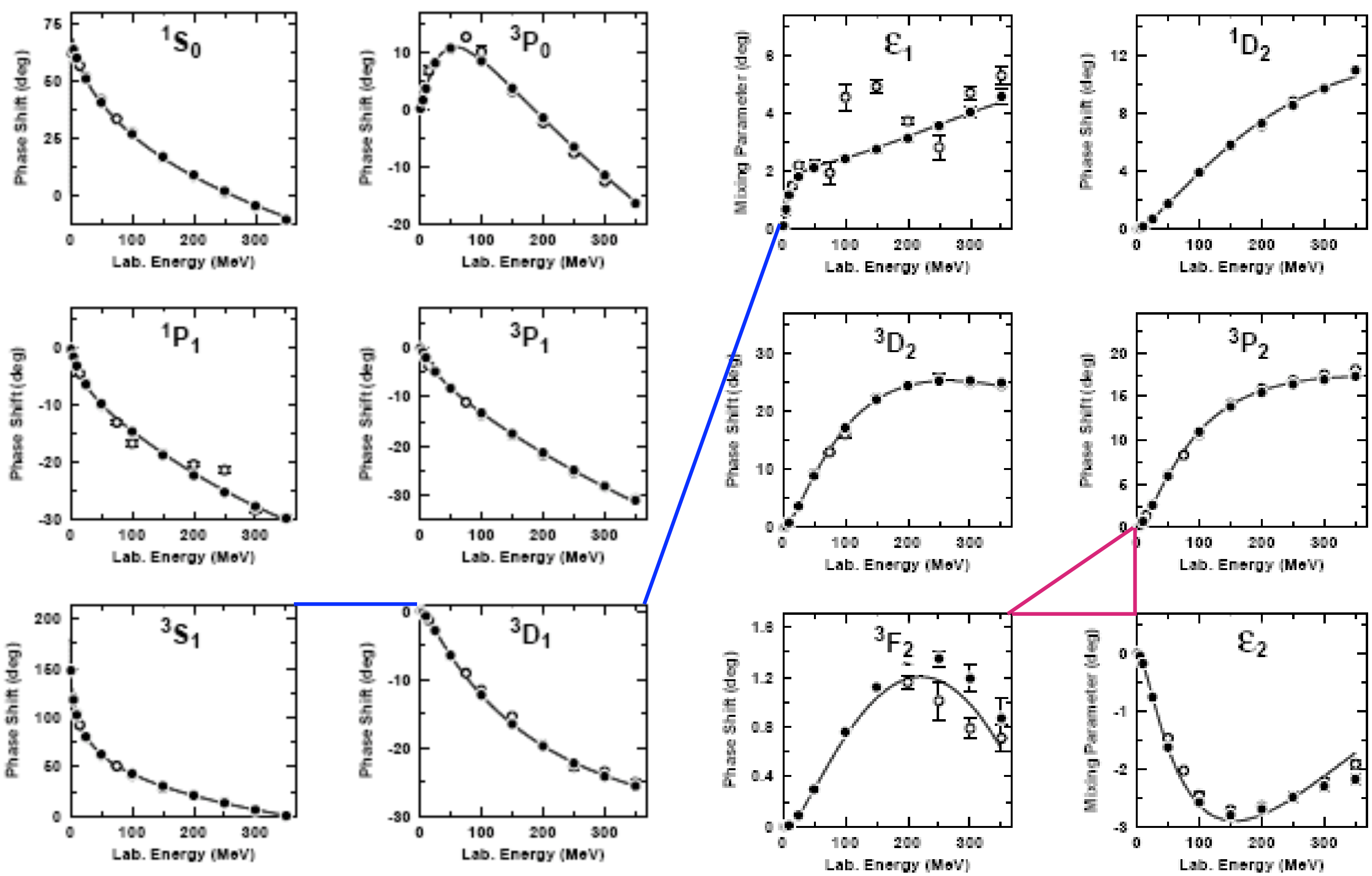
$(\vec{\sigma}_1\times\vec{\sigma}_2)\cdot\vec{L}$ violates time reversal

$(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\vec{L}$ violates isospin (S not conserved)

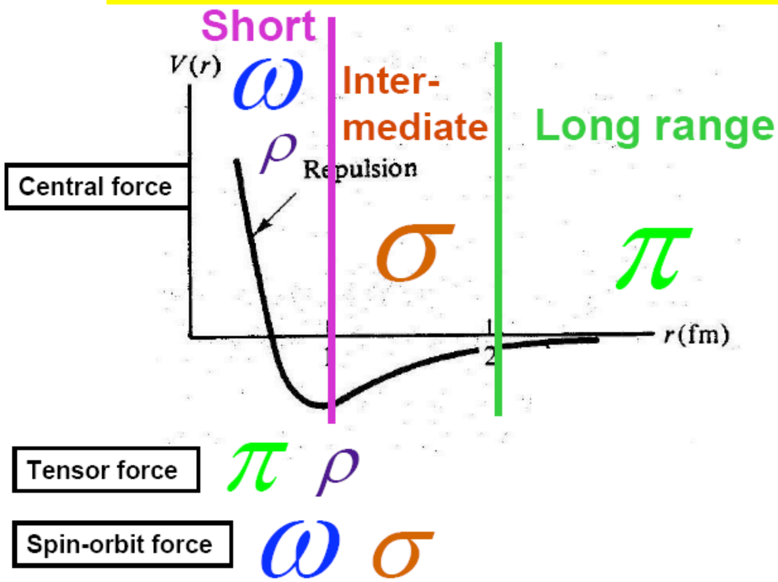
Experiment ⇒ Phase Shifts ⇐ Potential Model

Real $\delta_l \Rightarrow$ angular redistribution, but no loss of incident beam flux from elastic channel. Phase shifts for each contributing space-spin state and tensor mixing parameters ε_J (e.g., ${}^3S_1$-${}^3D_1$, ${}^3P_2$-${}^3F_2$) are adjusted to fit elastic data. Potential models are tuned to fit phase shifts as a fcn. of E.

E.g., some low-L phase shifts from np scattering exp'ts + a potential model fit to them (solid curves), up to pion production threshold:



Major Inferred Features of the Strong NN Potential



1) V_{NN} has finite range R, because δ_{lsj} remains small for l > kR. S-waves dominate for $E_{lab} \lesssim 10$ MeV.
2) Longest-range part of central potential is attractive, with range characteristic of one-π exchange
3) Short-range (~0.5 fm) repulsive core needed to account for $\delta\,(^1S_0)$ sign change near $E_{lab} \cong 250$ MeV.
4) Polarization measurements indicate $\vec{L}\cdot\vec{S}$ term, including short-range part affecting P-waves at $E_{lab} \gtrsim 100$ MeV.
5) Phase-shift differences among $^3P_{0,1,2}$ indicate need for tensor force.
6) Backward cross section peak for np at E_{lab} ~ few hundred MeV $\Rightarrow$ important charge-exchange ($\vec{\tau}_1\cdot\vec{\tau}_2$) contribution.
7) Low-energy behavior of $\delta\,(^1S_0) \Rightarrow$ appreciable isospin violations:

$$\psi_{\ell=0}(r>R) \xrightarrow[k\to 0]{} \frac{C(r-a)}{r} = e^{i\delta_0}\left(\cos\delta_0 + \frac{\sin\delta_0}{kr}\right)$$

$$\Rightarrow \delta_0 \xrightarrow[k\to 0]{} -ka\,,\quad a \equiv scattering\ length;$$

$a << 0 \Rightarrow$ nearly bound $^1S_0$ state

$$\text{exp't} \Rightarrow a_{np} = -23.74 \pm 0.02\ \text{fm} \neq a_{pp}^{nuclear} = -17.3 \pm 0.4\ \text{fm} \neq a_{nn}^{nuclear} = -18.9 \pm 0.4\ \text{fm}$$

Do NN Potentials Have Predictive Power for Light Nuclei?

Other models employing more ad hoc short-range potentials do comparably well for NN with similar # parameters. How do these all do for A=3 systems?

Two bound states: ^{3}***H (triton)*** $\cong \underbrace{\uparrow_n \downarrow_n \uparrow_p}_{L=0}$ ^{3}***He*** $\cong \underbrace{\uparrow_p \downarrow_p \uparrow_n}_{L=0}$ ***with tighter binding, smaller size than deuteron:***

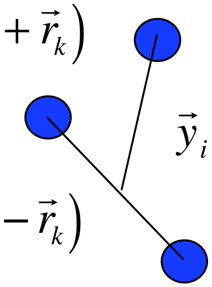
	^{3}H	^{3}He
magnetic moment: μ/μ_N	$=2.979 \approx \mu_p/\mu_N$	$=-2.127 \approx \mu_n/\mu_N$
binding energy:	**= – 8.482 MeV**	**= – 7.718 MeV**
Last N separation energy:	S_n **= 6.26 MeV**	S_p **= 5.49 MeV**
$\left\langle r_{ch}^2 \right\rangle^{1/2}$	$= 1.70$ fm	$= 1.87$ fm

N.B. $M_n > M_p \Rightarrow M(^3H) - M(^3He) =$ **530 keV** $\Rightarrow$ ^{3}***H*** β ***-decays to*** ^{3}***He with*** E_e^{max} **= 18.6 keV.** ***Endpoint used to test*** m_ν ***.***

Faddeev eq'ns ⇒ exact Schrödinger sol'n for 3 bodies subject to mutual 2-body finite-range inter'ns in terms of:

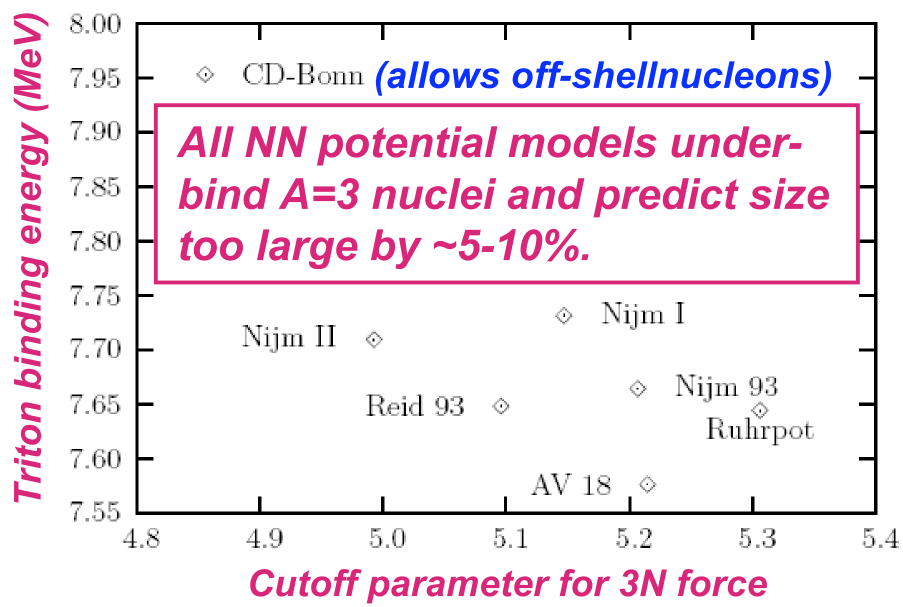
Jacobi coordinates

$$\vec{R} = \tfrac{1}{3}\left(\vec{r}_i + \vec{r}_j + \vec{r}_k\right)$$



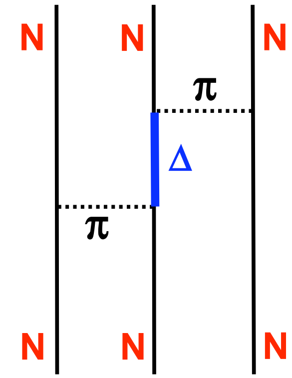
$$\vec{y}_i = \sqrt{\frac{2}{3}}\left(\vec{r}_i - \tfrac{1}{2}\left(\vec{r}_j + \vec{r}_k\right)\right)$$

$$\vec{r}_i = \tfrac{1}{\sqrt{2}}\left(\vec{r}_j - \vec{r}_k\right)$$

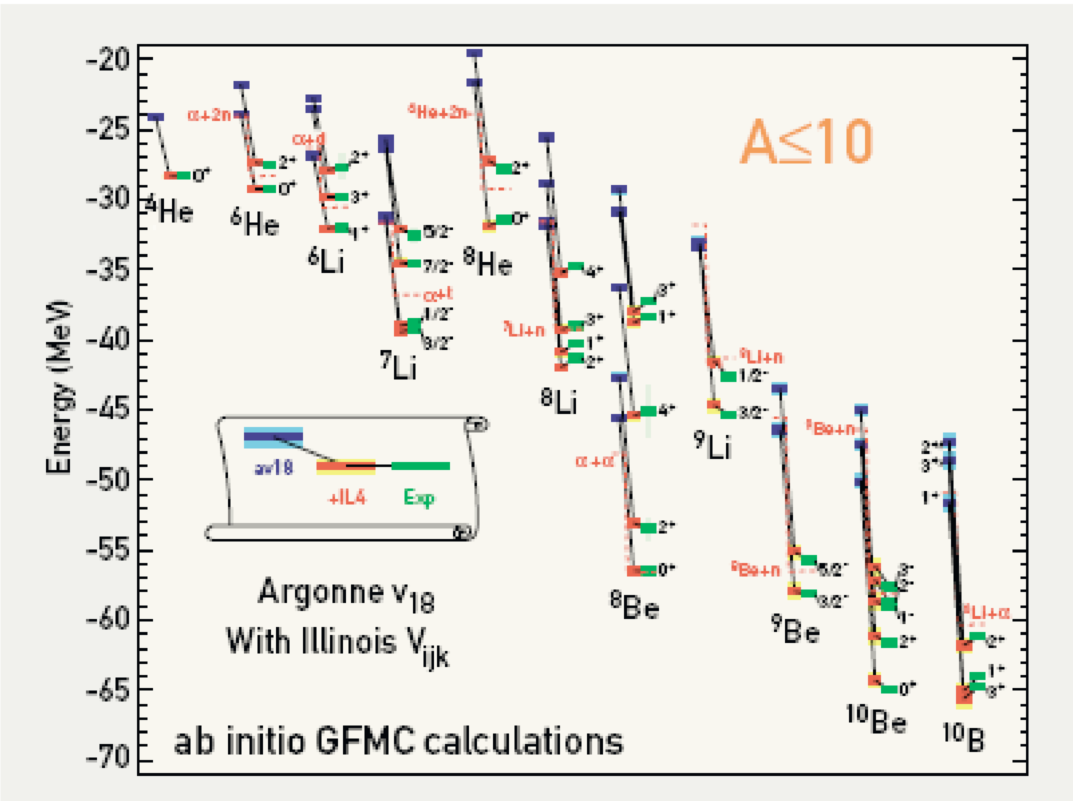


Three-Nucleon Forces Needed to Understand Light Nuclei

Understanding A=3 and 4 binding requires introduction of NNN interactions that cannot be treated as sequential NN interactions. There are many possible diagrams -- ones treated most often are of following type:



Inclusion of a couple of selected diagrams of this type, with parameters adjusted to fit A=3 and A=4 (28.3 MeV) binding energies, yields excellent predictions for energy levels of all other light nuclei up to A~12.



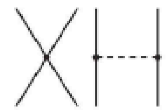
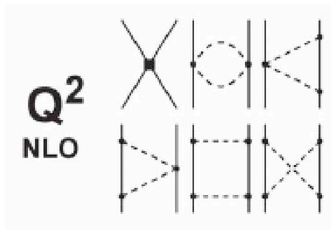
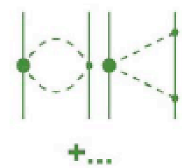
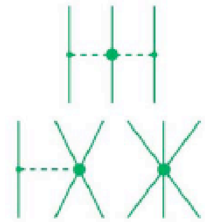
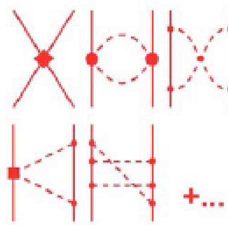
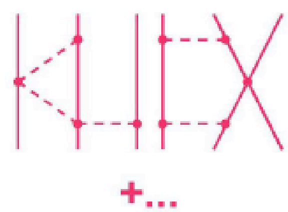
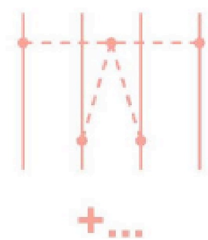
These are computer-intensive variational calculations, exploiting Monte-Carlo sampling of many complex multi-parameter trial wave functions, e.g., evaluating:

$$\langle \Psi_{exact} | \hat{O} | \Psi_{exact} \rangle = \lim_{\beta \to \infty} \frac{\langle \psi_{trial} | \hat{O} e^{-\beta \hat{H}} | \psi_{trial} \rangle}{\langle \psi_{trial} | e^{-\beta \hat{H}} | \psi_{trial} \rangle}$$

NNN inter'ns should have at least as complex a spin & iso-spin structure as NN, but are far less constrained by scattering data. How to proceed?

Chiral Effective Field Theory ⇒ Common Framework for NN, NNN and NNNN Interactions

One can include NN terms in L_{chiral} and order terms (as in χPT) in powers of pion mass/ momentum over $\Lambda_{\chi SB} \cong 1$ GeV. Consistent treatment through given order then automatically includes 3N, 4N inter'ns:

		2N forces	3N forces	4N forces
Leading Order	Q^0 LO			
Next-to Leading Order	Q^2 NLO			
Next-to-Next-to Leading Order	Q^3 N²LO			
Next-to-Next-to-Next-to Leading Order	Q^4 N³LO			

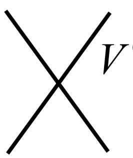
$$L = L_{\pi\pi} + L_{\pi N} + L_{NN} \quad with$$

$$L_{\pi\pi} = L_{\pi\pi}^{(2)} + L_{\pi\pi}^{(4)} + \ldots;$$

$$L_{\pi N} = L_{\pi N}^{(1)} + L_{\pi N}^{(2)} + L_{\pi N}^{(3)} + \ldots;$$

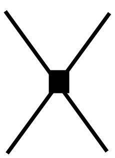
$$L_{NN} = L_{NN}^{(0)} + L_{NN}^{(2)} + L_{NN}^{(4)} + \ldots$$

Parameterize NN contact terms at each order in terms of spin-momentum operators that preserve desired symmetries, e.g.:



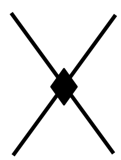
$$V^{(0)}(\vec{p}',\vec{p}) = C_S + C_T\,\vec{\sigma}_1\cdot\vec{\sigma}_2$$

adds 2 parameters.



$$V^{(2)}(\vec{p}',\vec{p}) = C_1 q^2 + C_2 k^2 + \left(C_3 q^2 + C_4 k^2\right)\vec{\sigma}_1\cdot\vec{\sigma}_2 + C_5\left[-i\vec{S}\cdot\left(\vec{q}\times\vec{k}\right)\right] + C_6\left(\vec{\sigma}_1\cdot\vec{q}\right)\left(\vec{\sigma}_2\cdot\vec{q}\right) + C_7\left(\vec{\sigma}_1\cdot\vec{k}\right)\left(\vec{\sigma}_2\cdot\vec{k}\right)$$

adds 7 params.



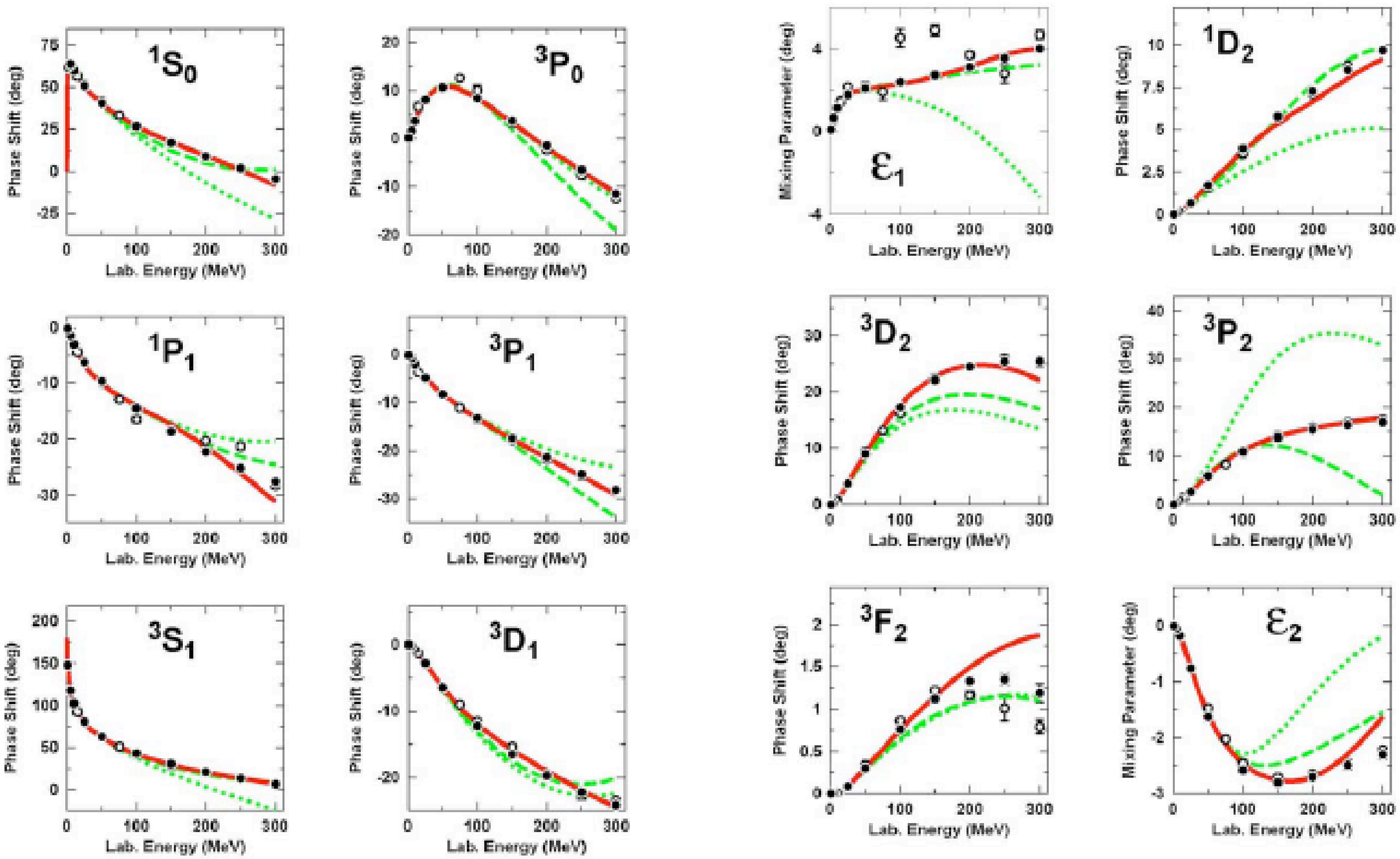
$V^{(4)}(\vec{p}',\vec{p})$ *adds 15 params.*

N²LO 3N force adds 2 params., etc.

Potentials from Chiral EFT Account Well for NN Data

Phase shifts up to 300 MeV

Red Line: N3LO Potential by Entem & Machleidt, PRC 68, 041001 (2003).
Green dashed line: N2LO Potential, and
green dotted line: NLO Potential
by Epelbaum et al., Eur. Phys. J. A15, 543 (2002).

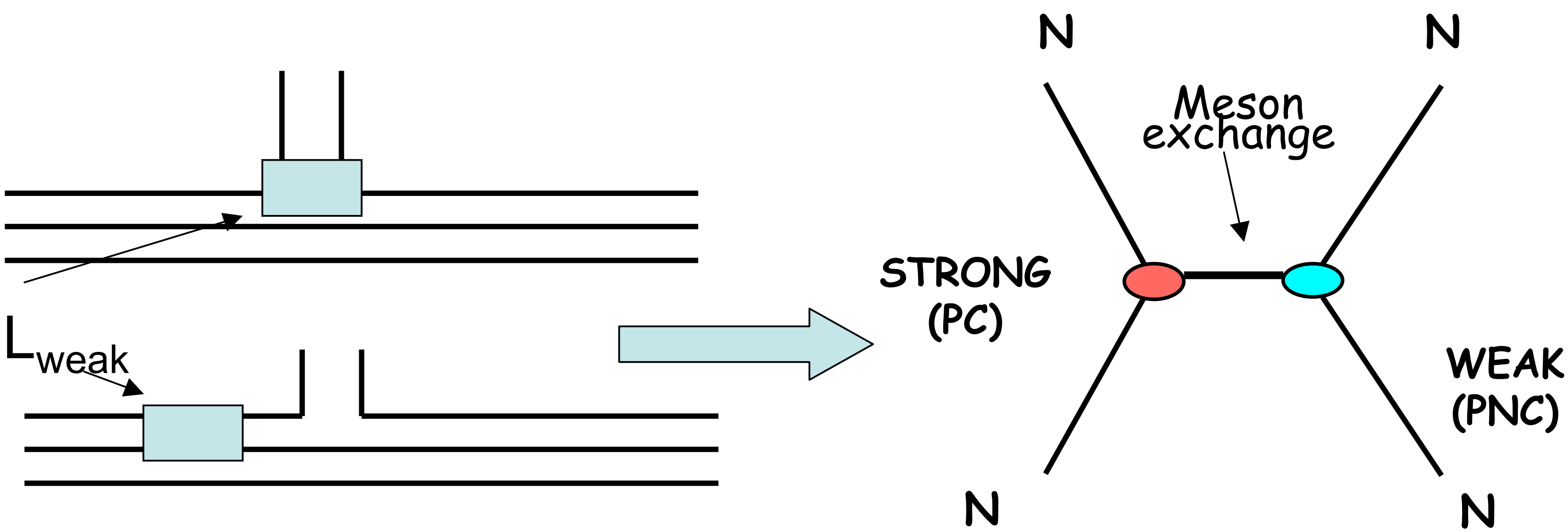


~ same quality of fit as OBE models, with similar # or fewer params.

If EFT gives consistent basis for under-standing 3N, 4N inter'ns, it will represent considerable advance.

Theory still under construction

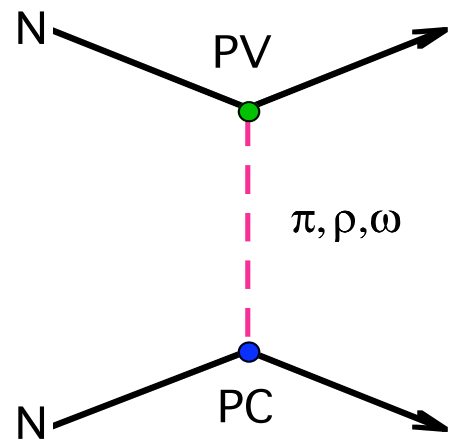
Different Theoretical Approaches to weak NN interaction



- Kinematic: 5 S->P transition amplitudes in elastic NN scattering [Danilov]
- QCD effective field theory: χ perturbation theory [Liu, Holstein, Musolf, et al, incorporates chiral symmetry of QCD]
- Dynamical model: meson exchange model for weak NN [effect of qq weak interactions parametrized by ~6 couplings, Desplanques, Donoghue, Holstein,…]+ QCD model calculations
- Standard Model [need QCD in strong interaction regime, lattice+EFT extrapolation (Beane&Savage)]

Meson Exchange Model (DDH) and other QCD Models

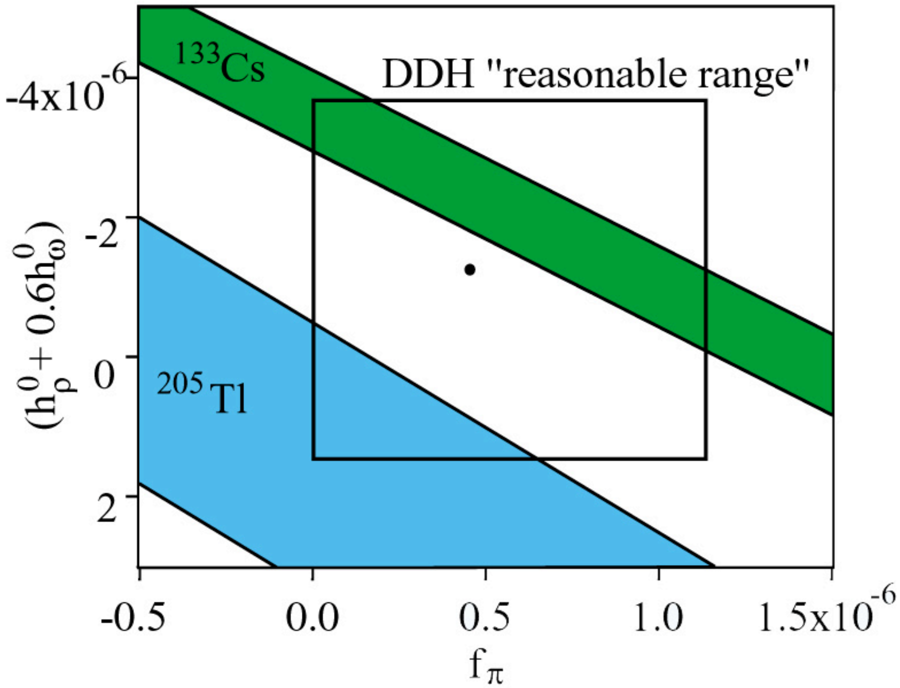
assumes π, ρ, and ω exchange dominate the low energy PNC NN potential as they do for strong NN

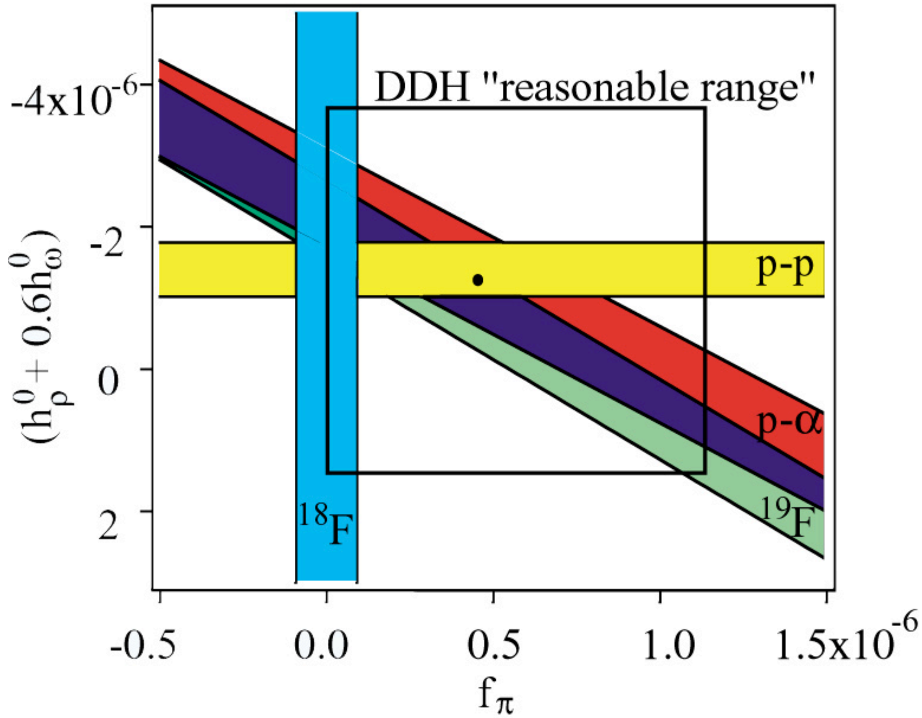


Weak meson-nucleon couplings $f_\pi, h_\rho^0, h_\rho^1, h_\rho^2, h_\omega^0, h_\omega^1$ to be determined by experiment

f_π now calculated to be ~3E-7 with QCD sum rules (Hwang+Henley, Lobov) and SU(3) soliton model (Meissner+Weigel), calculation in chiral quark model in progress (Lee et al).

ΔI = 0, 1 Weak NN Constraints in DDH Model





Present goal: perform measurements in few body systems interpretable in terms of weak NN, at low E to apply χPT

Nonzero P-odd effects seen experimentally in p-p and p-α

Next step: see P-odd effects in low energy neutron reactions

NN χPT coefficients and quantum numbers (Liu07)

Partial wave transition	$I \leftrightarrow I'$	ΔI	n-n	n-p	p-p	EFT coupling
$^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		√		$m\rho_t$
$^3S_1 \leftrightarrow {}^1P_1$	$0 \leftrightarrow 0$	0		√		$m\lambda_t$
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	0	√	√	√	$m\lambda_s^{nn}$
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	1	√		√	$m\lambda_s^{np}$
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	2	√	√	√	$m\lambda_s^{pp}$
$^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		√		$C^\pi\,[\sim f_\pi]$

First 5 couplings are allowed s->p transition amplitudes in NN elastic scattering in “pionless” EFT limit (same as Danilov parameters)

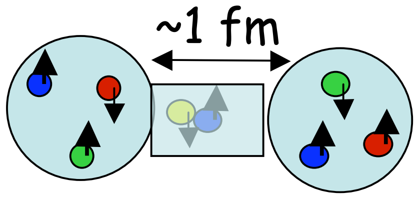
Last coupling is long-range part of weak pion exchange $[\text{in DDH} \sim f_\pi]$

NN χPT coefficients and observables (Liu07)

EFT coupling (partial wave mixing)	np A_γ	np P_γ	nD A_γ	nα ϕ	np ϕ	pp A_z	pα A_z
$m\rho_t\,(^3S_1\text{-}\,^3P_1)$	-0.09	0	1.4	-2.7	1.4	0	-1.07
$m\lambda_t\,(^3S_1\text{-}\,^1P_1)$	0	0.7	1.2	1.3	-0.6	0	-0.54
$m\lambda_s^{nn}\,(^1S_0\text{-}\,^3P_0)$	0	0	0.6	1.2	0	0	-0.48
$m\lambda_s^{np}\,(^1S_0\text{-}\,^3P_0)$	0	-0.16	0.5	0.6	2.5	0	-0.24
$m\lambda_s^{pp}\,(^1S_0\text{-}\,^3P_0)$	0	0	0	0	0	-0.45, -0.78	0
$C^\pi\,(^3S_1\text{-}\,^3P_1)[\sim f_\pi]$	-0.3	0	0	0	0.3	0	0
experiment (10^{-7})	0.6 ±2.1	1.8 ±1.8	42 ±38	8 ±14		-0.93, -1.57 ±0.2	-3.3 ±0.9

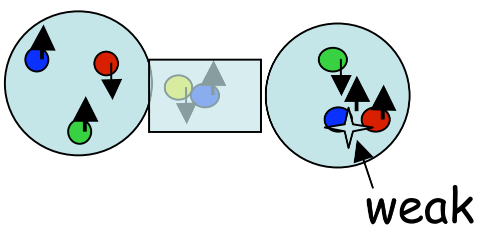
Column gives relation between PV observable and weak couplings in EFT with pion
Needs calculations of PV in few body systems (NN done, others in progress)

"Conclusion": the Weak NN Interaction on one slide



NN repulsive core (from Pauli principle applied to quarks)->1 fm range for strong NN

|N>=|qqq>+|qqq$\bar{q}$q>+…=valence+sea quarks+gluons+…
interacts through strong NN force, mediated by mesons |m>=|q$\bar{q}$>+…
Interactions have long (~1 fm) range, <u>QCD conserves parity</u>



Both W and Z exchange possess much smaller range [~1/100 fm]

If the quarks are close, the weak interaction can act, which violates parity at a length scale small compared to that set by Λ_{QCD}
Relative weak/strong amplitudes: $\sim[e^2/m^2_W]/[g^2/m^2_\pi]\sim 10^{-6}$
Quark-quark weak interaction induces NN weak interaction
<u>Visible using parity violation</u>

<u>q-q weak interaction: an "inside-out" probe of strong QCD</u>