Lecture VII. Hadronic Physics

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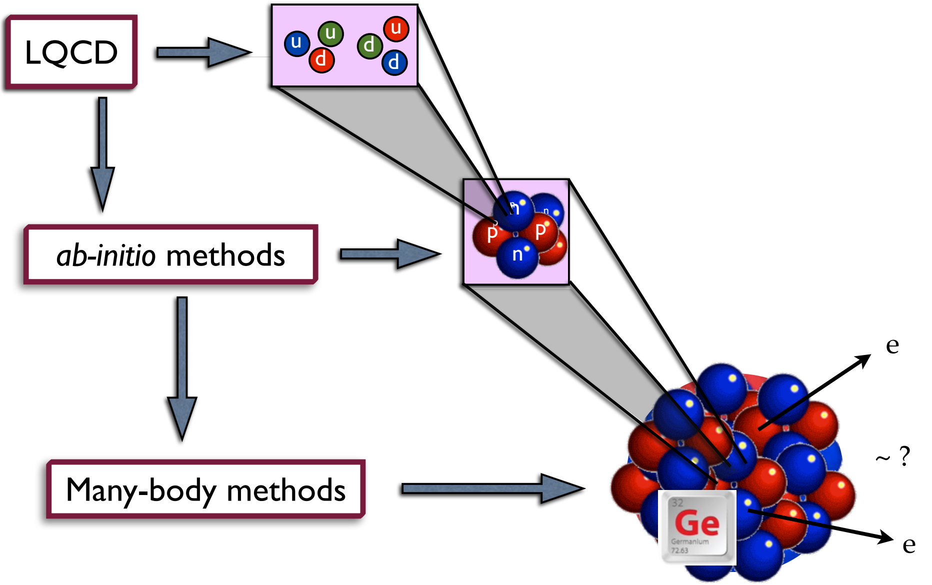
AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

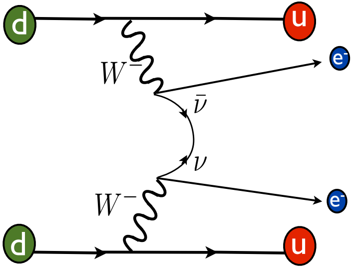
Lattice QCD

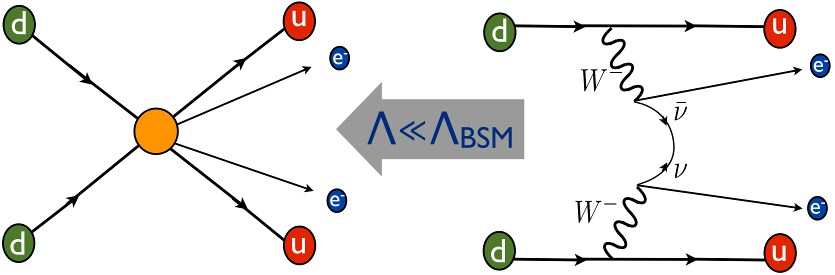
The nice slides that follow are from Amy Nicholson (UNC).

Relating Theory to Experiment



How do we get to nuclear scales?

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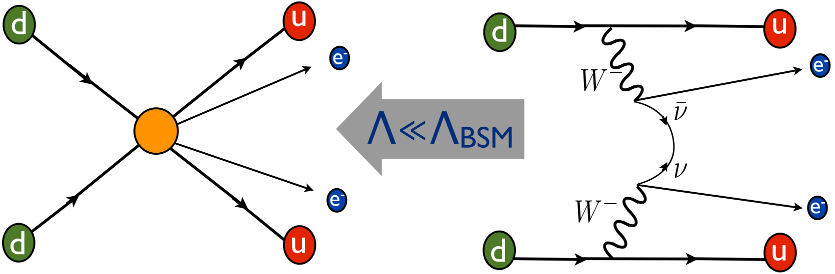
Prezeau, Ramsey-Musolf, Vogel (2003)



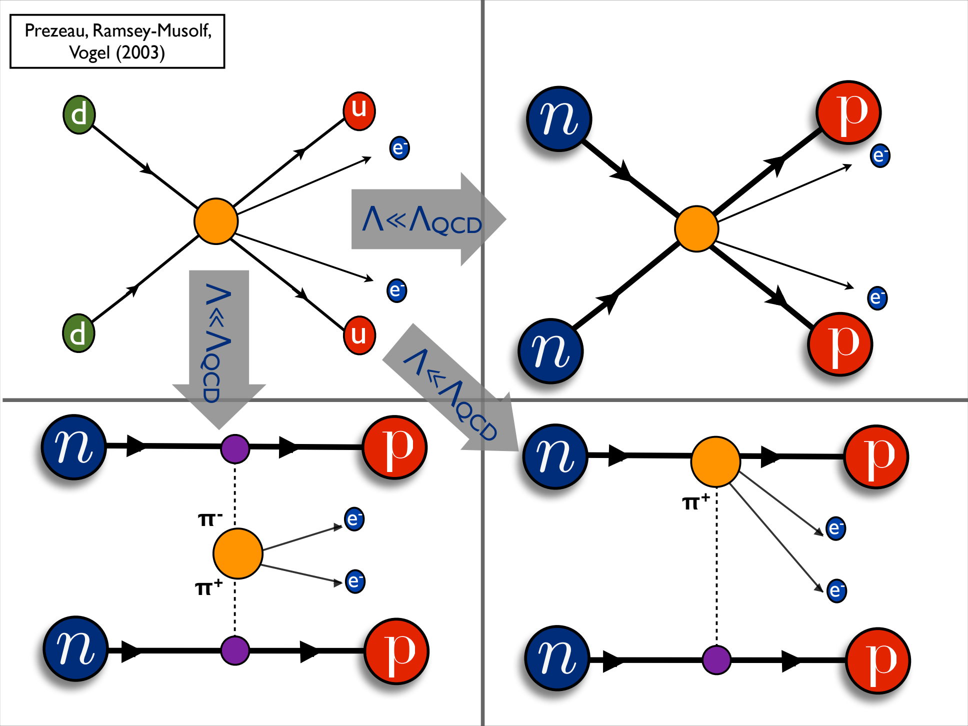
$$\mathcal{O}^{ab}_{1+} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_R \tau^b \gamma_\mu q_R),$$

$$\mathcal{O}^{ab}_{2\pm} = (\bar{q}_R \tau^a q_L)(\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R)(\bar{q}_L \tau^b q_R),$$

$$\mathcal{O}^{ab}_{3\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L \tau^b \gamma_\mu q_L) \pm (\bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_R \tau^b \gamma_\mu q_R),$$

$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L \mp \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R - \bar{q}_R \tau^b q_L),$$

$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L \pm \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R + \bar{q}_R \tau^b q_L).$$


Prezeau, Ramsey-Musolf, Vogel (2003)
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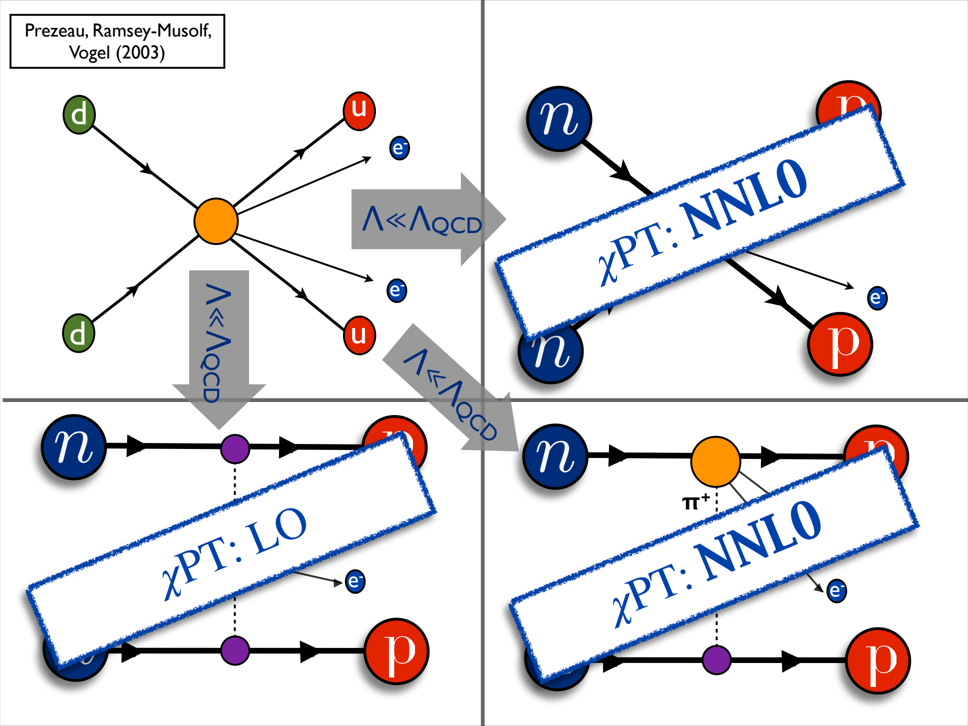

Prezeau, Ramsey-Musolf, Vogel (2003)
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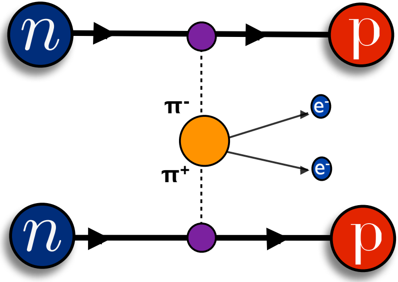

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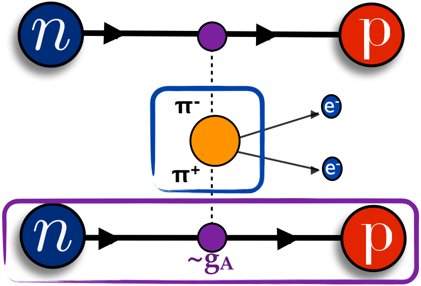

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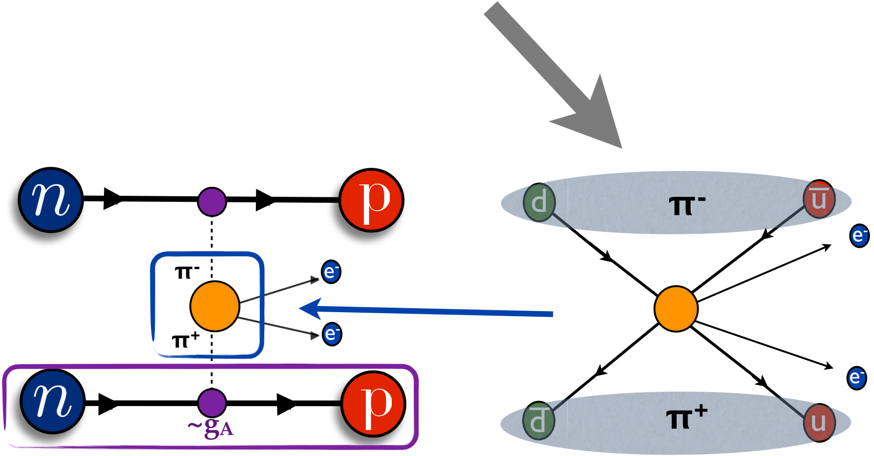
This is the matrix element we need to calculate using LQCD



What Do You Do With These Amplitudes?

Chiral effective field theory!

In QCD vacuum

$$\sum_{q=u,d} \langle m_q \bar{q} q \rangle \neq 0$$

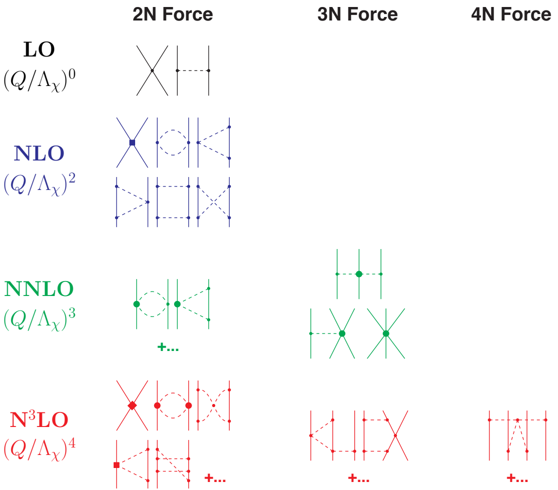
which spontaneously breaks a chiral (left-right) symmetry.

Like spontaneous magnetization, which gives rise to massless "magnons" (spin waves). Pions are the analog of magnons for chiral symmetry. If the *u* and *d* quarks had the same mass, pions would be massless. In the real world they have mass, but much less than other hadronic objects.

Chiral perturbation theory is the "effective theory" for interacting pions. It has infinitely many parameters but only a finite number at each order of $\lambda_\chi = q/\Lambda$ or m_π/Λ, the expansion parameter (q is a typical momentum and Λ is the scale at which other hadrons can exist, about 1 GeV.) The theory breaks down if λ_χ gets close to Λ.

Chiral Effective Field Theory with Nucleons

Here you try to add nucleons to the mix. There is no problem with adding a single nucleon, but with two or more, things get a little tricky. Proceeding naively, the terms in the nucler interaction have effect only at increasingly large powers of λ_χ.



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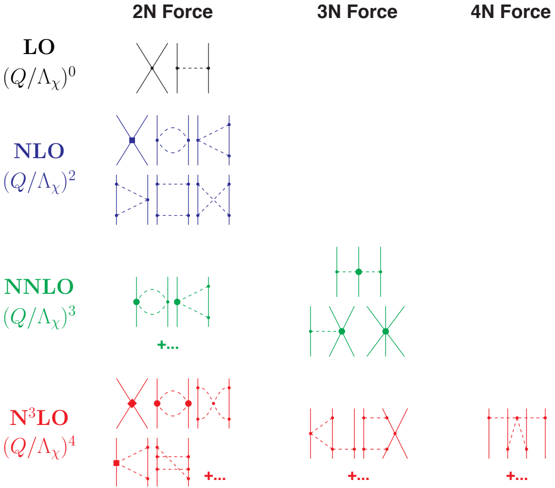
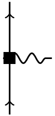
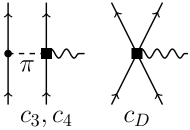


Comes with Consistent Weak Current

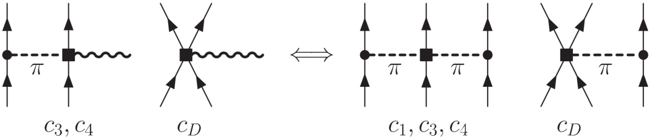
Pions are axial, just like the part of the weak current important for $\beta\beta$ decay. The leading piece of the axial current is



just the usual one-body current, more or less. At next order, you get

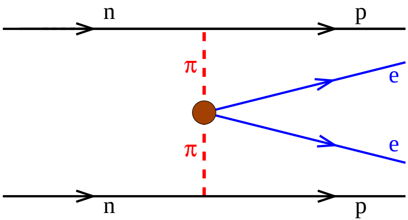


with the constants fixed by the three-body interaction:

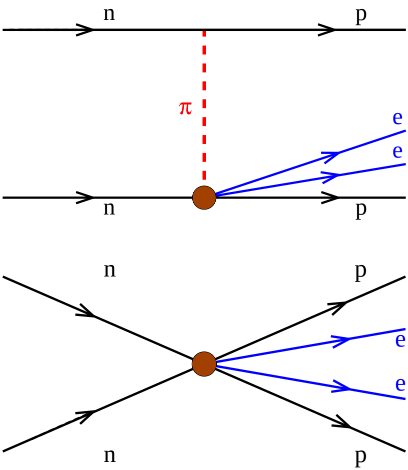


Operators for Heavy Particle Exchange

Leading diagrams for heavy particle exchange



Subleading diagrams



How Useful?

In principle, this is exactly what you'd need for a controlled calculation of weak processes with controlled error bars. In practice…

1. Extension of "power counting" to nonperturbative nuclear-structure calculations not fully rigorous.
2. Arguments about how best to determine parameters
3. You also need a many-body calculation with quantifiable errors (we'll get to that next).