Lattice QCD and Nuclear physics

From Pipe Dream to Reality

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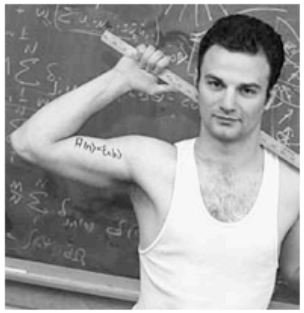

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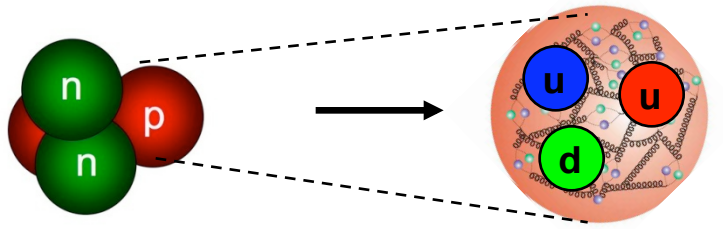
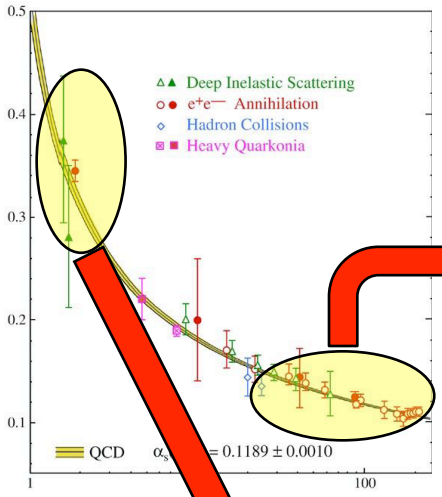
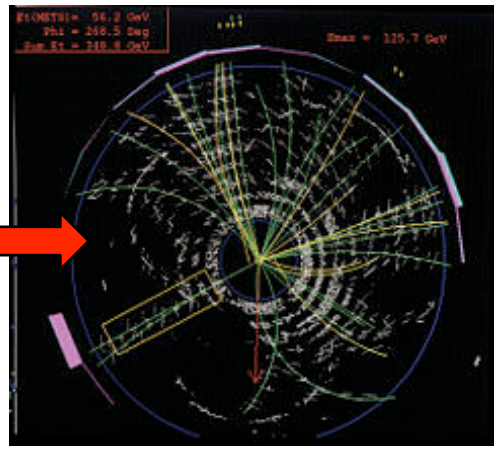
The mission of the multi-institutional NPLQCD effort is to make predictions for the structure and interactions of nuclei using lattice QCD.

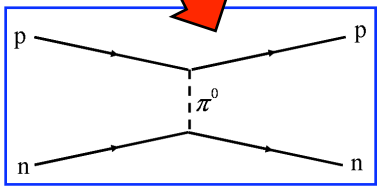
QCD 101

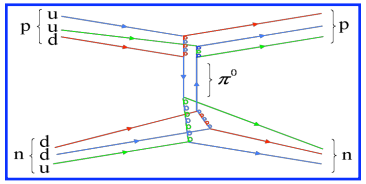
- The nuclear force is not fundamental
  - Governed by the underlying theory of quarks and gluons —QCD
- At high energies (>>1 GeV), theory exhibits ‘asymptotic freedom’
  - In this regime, QCD has been well tested perturbatively
- At low energies (< 1GeV) QCD is a strongly-interacting theory
  - We have no formal (paper & pencil) way of solving QCD in this regime











So let's put an "L" in front of "QCD". . .

- Wick rotate to imaginary time

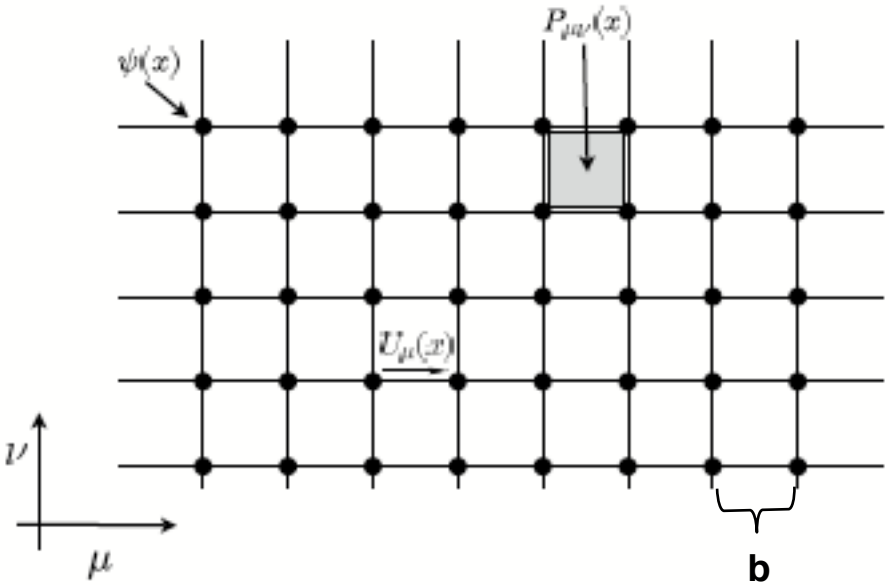
$$Z = \int \mathcal{D}A_\mu \, \mathcal{D}\psi \, \mathcal{D}\overline{\psi} \, e^{-S}$$

where S is the QCD action

$$\mathcal{S} = \int d^4x \, \left(\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \overline{\psi} M \psi\right) .$$

- Discretize space and time and formulate theory within a box

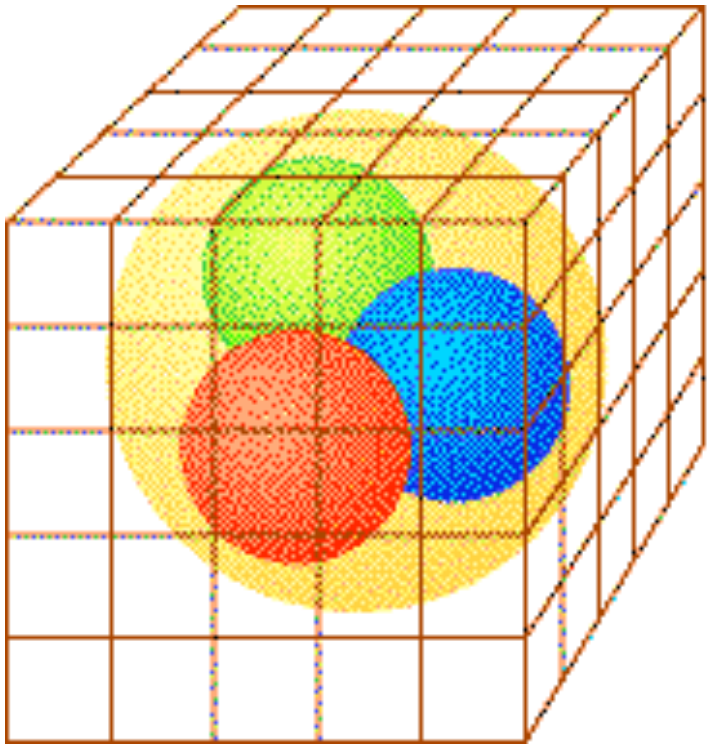
$$\int [d\phi] \rightarrow \prod_n \int_{-\infty}^{\infty} d\phi_n$$



Lattice configuration

So let's put an "L" in front of "QCD"

Euclidean Lattice



b

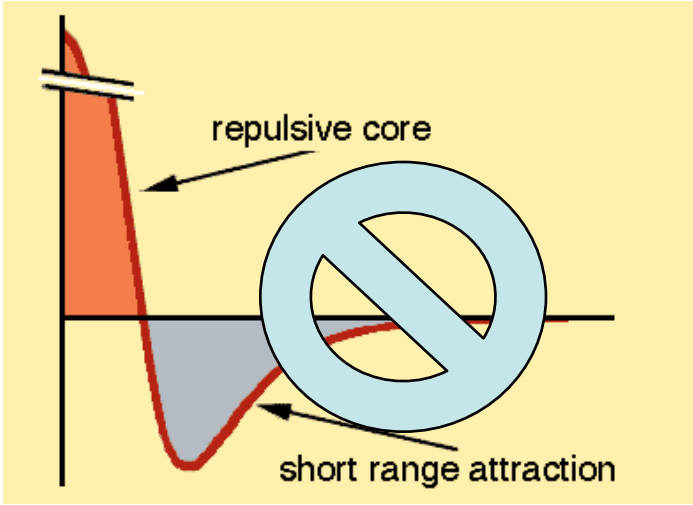
L

Theory is now amenable to numerical studies

To date, LQCD (+ HPC) is the only method for calculating QCD at energy regimes relevant for Nuclear Forces

What Lattice QCD *can* and *cannot* do!

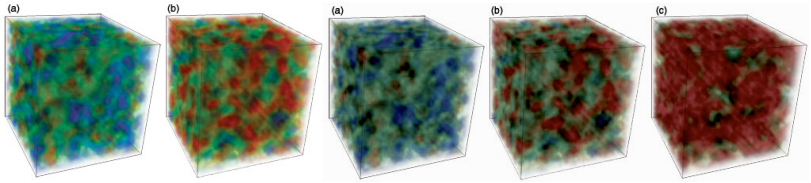
- Cannot measure potentials relevant for nuclear physics!



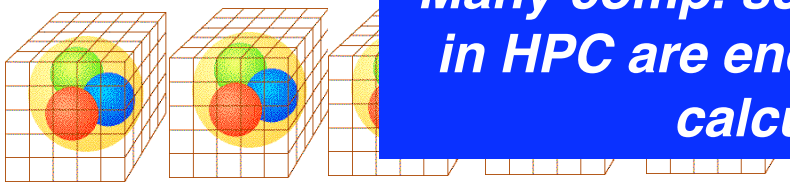
- We measure physical observables, i.e. phase shifts, energy levels within a box, etc.

The anatomy of LQCD calculation

- Generation of gluon fields

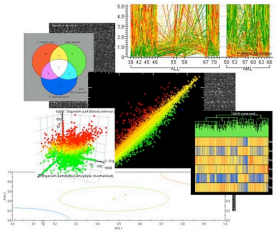


- Measurements



- Contractions

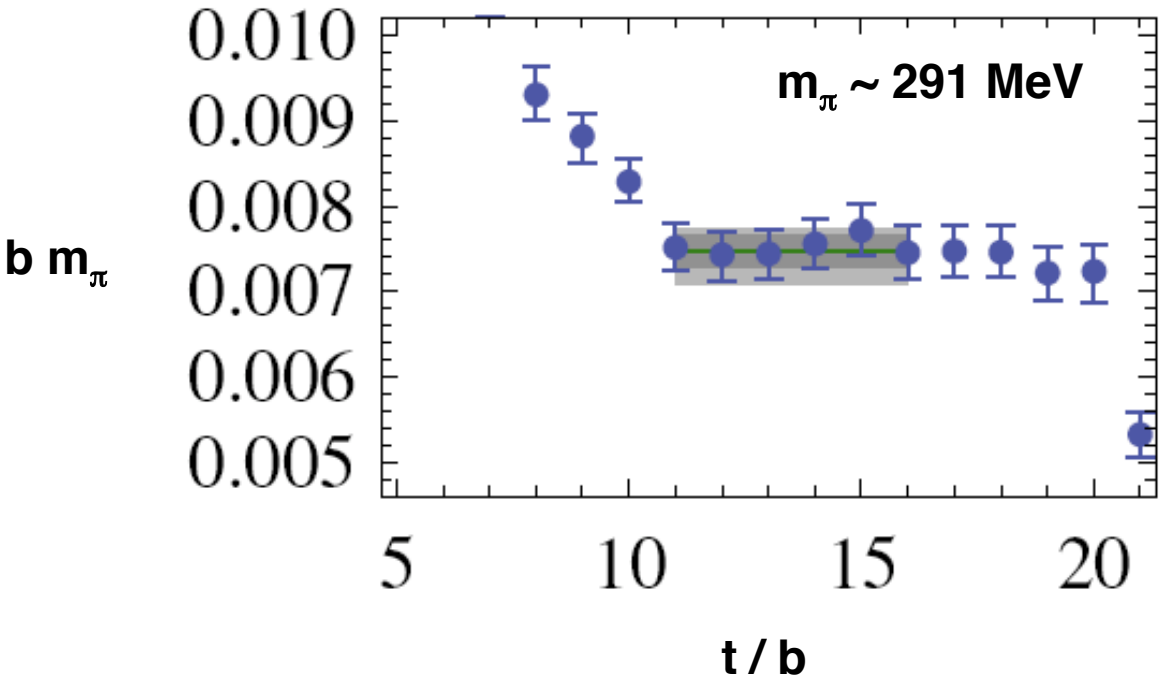
- Extraction of Observable



Many comp. sci. and applied math. issues in HPC are encapsulated in nuclear force calculations via LQCD

- Hybrid Monte Carlo
  - Molecular dynamics integrator (e.g. Omelyan)
  - Sparse matrix inversion (e.g. CG, CG+deflation, BCGStab)
    - Condition number ~$10^{7\text{-}8}$
  - Problem scales as $b^{-6}\, L^{5} m_{\pi}^{-3}$
- ors
- (e.g. CG,
- nble generation
- Forming physically relevant objects
  - Combinatoric—essentially serially so far
- Data Analysis
  - Large ‘noisy’ data sets
  - Dispersed on different machines

Example of extracting the pion mass. . .



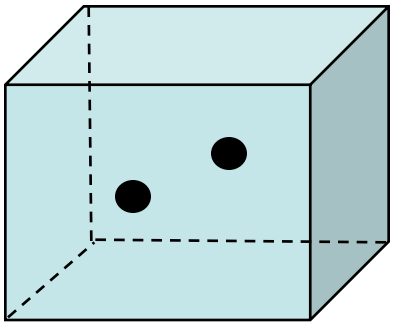
LQCD is an outlet for theorists with experimental-envy

LQCD has come quite far, but it still has much to offer. . .

- No longer doing quenched LQCD, but fully-dynamical
- Have much better control of symmetries (or lack of) within LQCD calculations
  - Domain-wall fermions
  - Overlap fermions
- However, quark masses (or pion masses) are still large compared to physical masses
- Box sizes are still somewhat small L~ 2.5-3,5 fm on a side
- Lattice spacings are still somewhat course b~.1fm
- “LQCD can’t do it now, but in ten years. . . “

. . . exascale computing will make calculations in large volumes at physical pion masses routine

Lüscher showed that energies of two particles in a box can be calculated in terms of their elastic scattering amplitudes and masses



Comm. Math. & Phys., 105, 153 (1986)

Measured from LQCD

$$E \sim \frac{p^2}{2\mu}$$

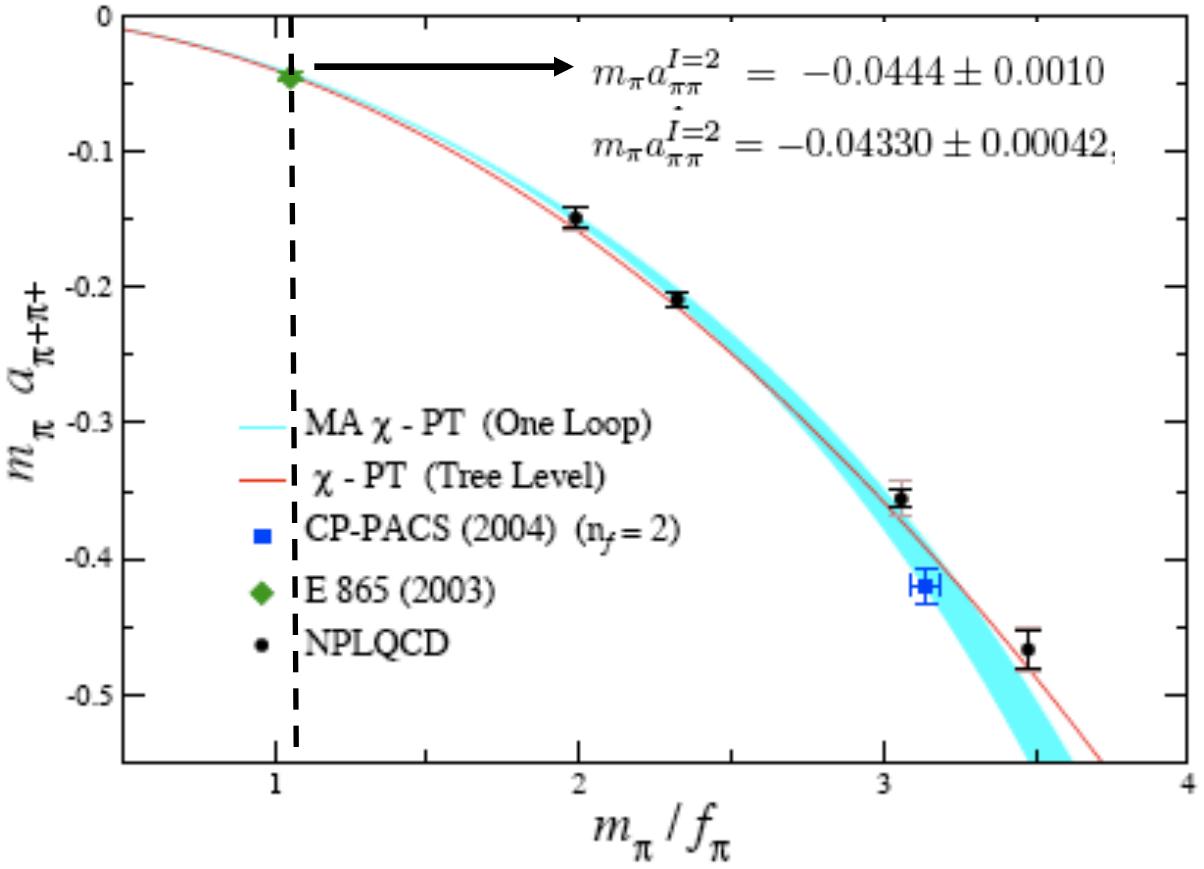
$$p \cot \delta(p) = \frac{1}{\pi L} S\left(\left(\frac{pL}{2\pi} \right)^2 \right) = -\frac{1}{a} + \frac{1}{2} r p^2 + \ldots$$

NPLQCD hep/lat 0312004

$$S(x) \equiv \sum_{j}^{|j|<\Lambda} \frac{1}{|j|^2 - x} - 4\pi\Lambda$$

Note that scattering length can be of any size -- only constraint is that range of interaction is smaller than length of box r < L

Weinberg's prediction for the interaction between pions works surprisingly well



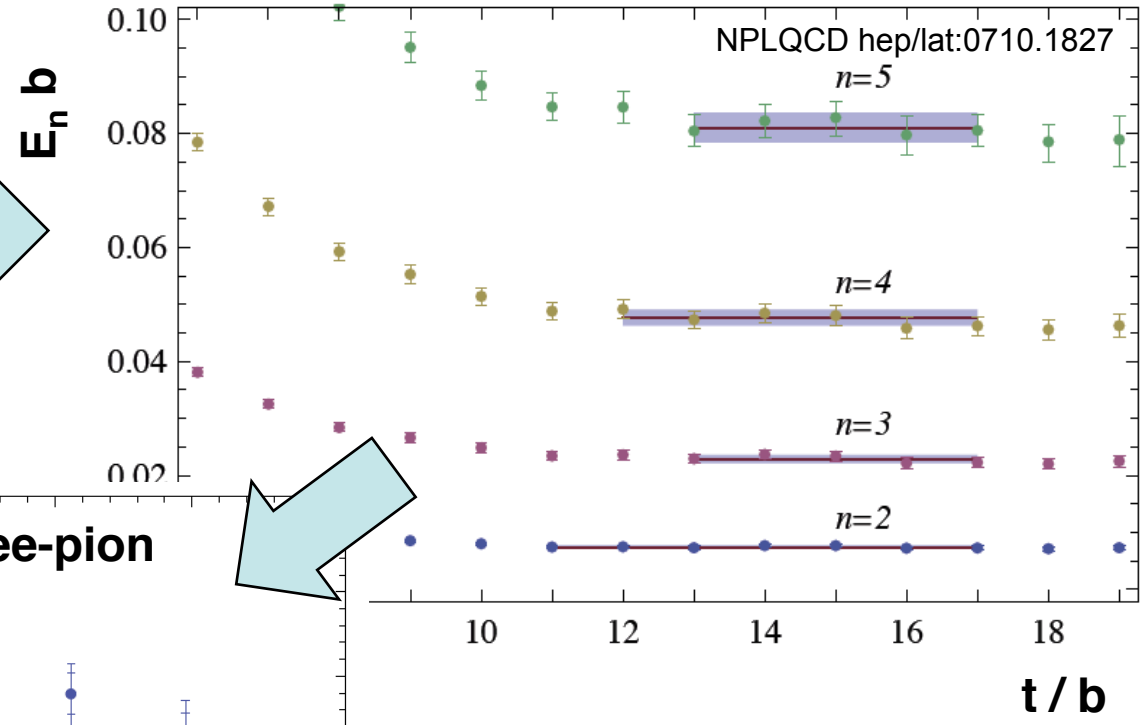
Pislak et al. hep/ex 0301040

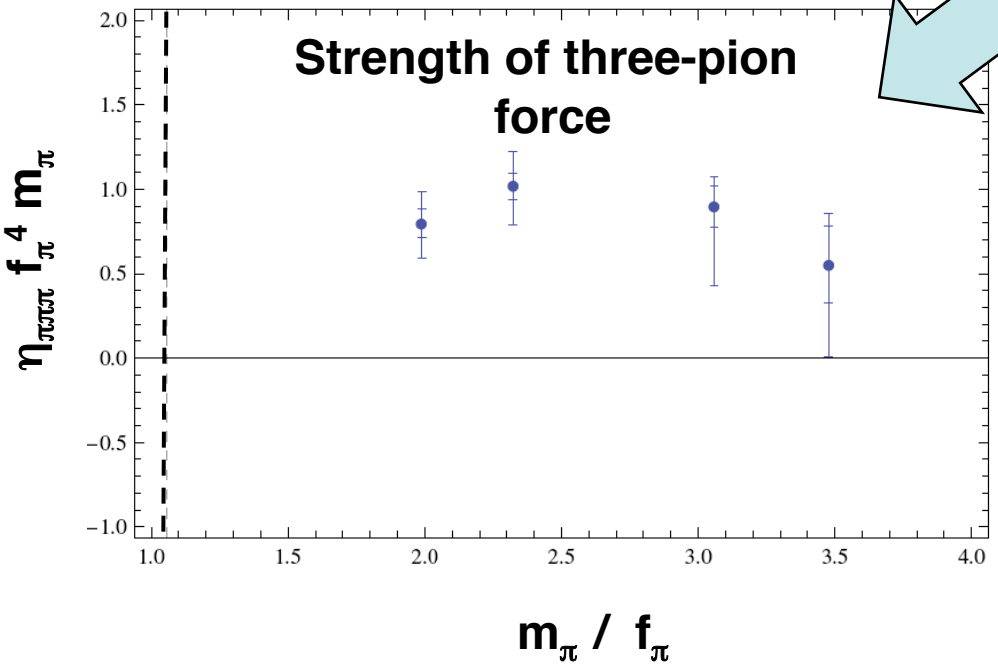
NPLQCD hep/lat 0706.3026

In certain cases, HPC (+ LQCD) is allowing precision calculation of nuclear forces at the sub-percent level

We now know pions have a repulsive three-body force

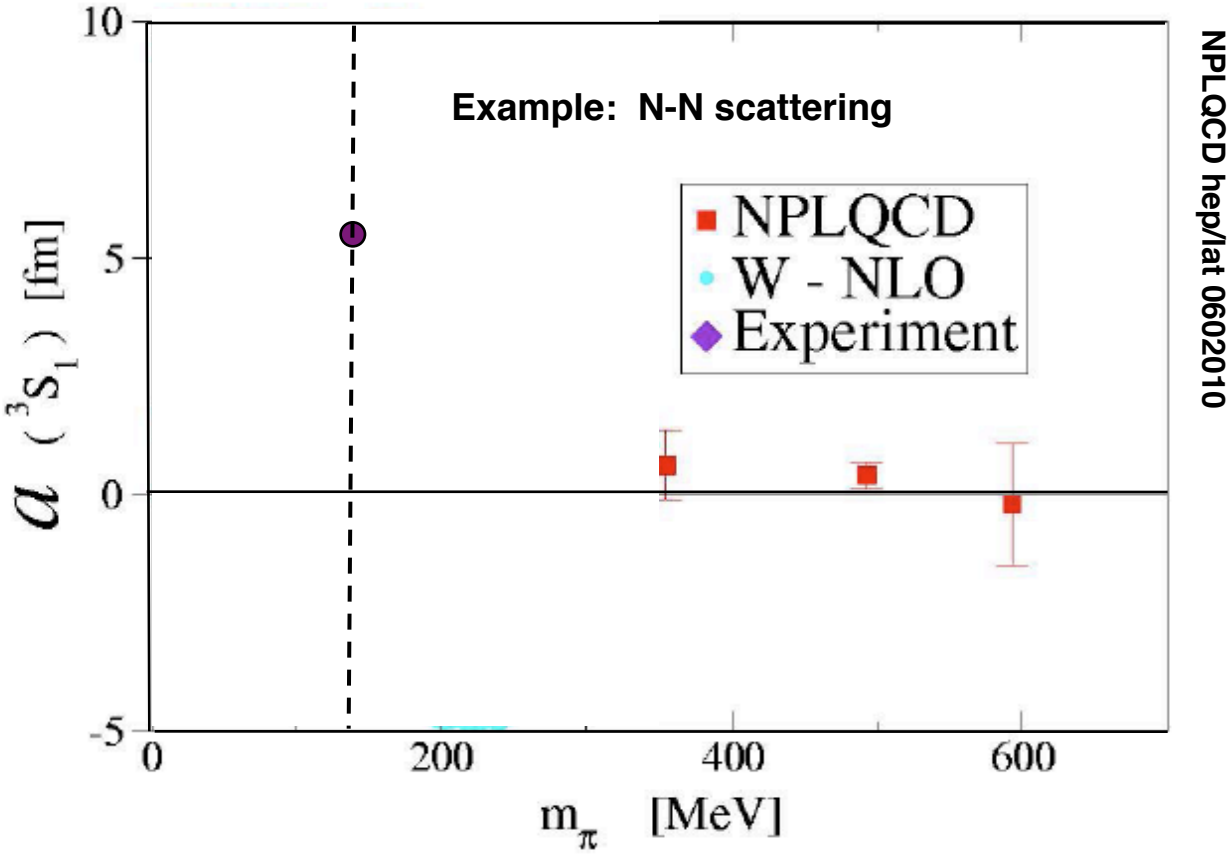
The interaction energies of multiple pions in a box





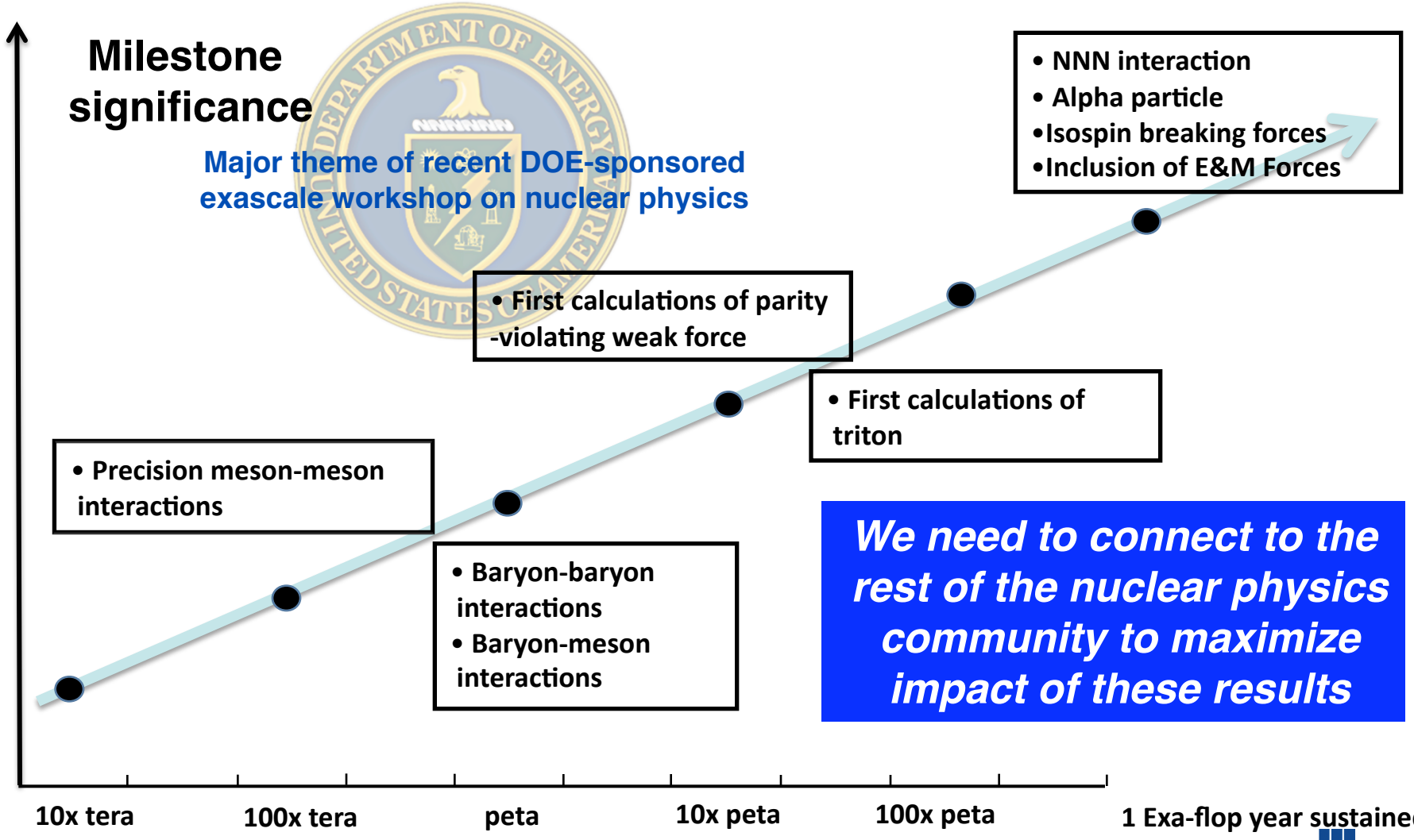
High-performance computing is allowing us to probe systems that are experimentally inaccessible

Nature's fine tuning in the NN sector disappears at larger-than-physical pion mass



High-performance computing is allowing us to understand how nature depends on fundamental constants of nature

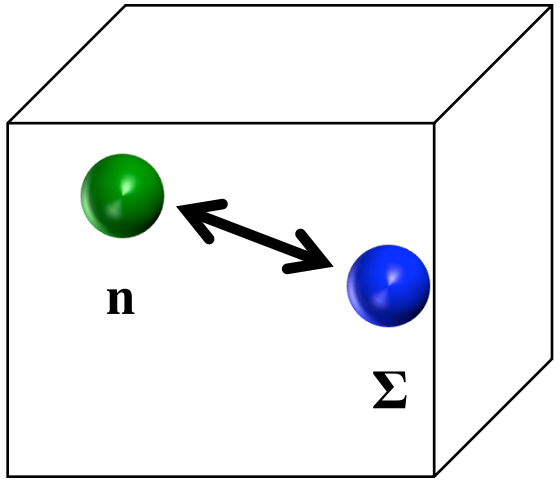
Milestones in calculating Nuclear Forces from QCD . . .



http://extremecomputing.labworks.org/nuclearphysics/index.stm

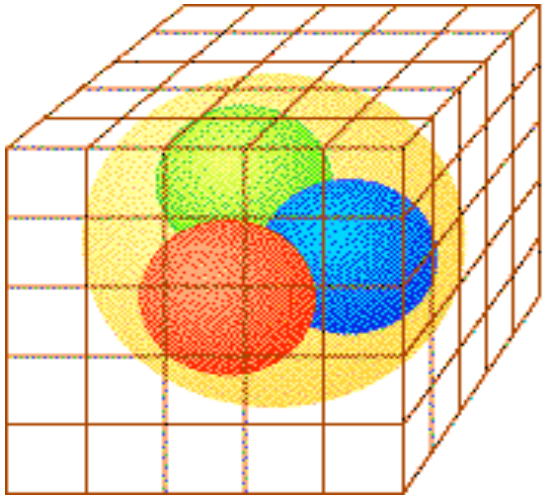
We need many-body techniques for multi-particles in a box

- Box boundary conditions are defined in single-particle coordinates
  - Interesting implications for working in jacobi basis
- Cubic group has finite number of irreps
- Excited states within a box give useful information
- Calculations with asymmetric spatial volumes, or non-zero CM motion are interesting in this case
- These results are *very useful* for the LQCD community

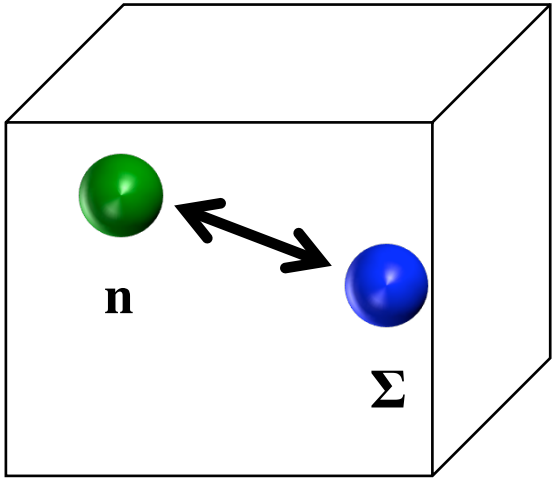


How do we connect LQCD with the rest of the nuclear physics community?

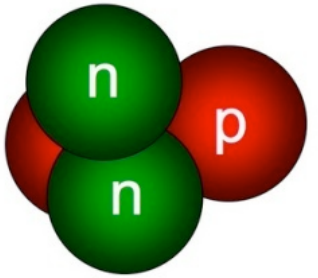
LQCD

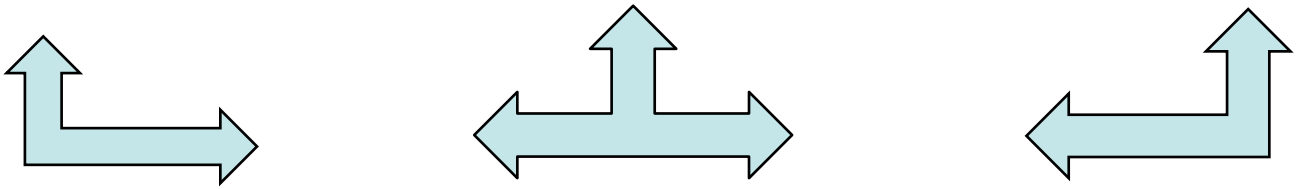


Many-body investigations within a box



Ab-initio nuclear structure





Match LECs of EFTs or fit "phenomenological" potentials to LQCD results

Year 3. . .

- Develop many-body techniques for two- and three-body systems in a box
- Develop EFTs constrained by LQCD for various hadronic systems

Year 4&5

- Continue development of many-body techniques for 3- and 4-body techniques in a box
- Incorporate results from lower pion mass LQCD calculations (mass pion ~ 230 MeV and 180 MeV)
- Investigate hyperon systems
  - E.g. Lambda-Lambda
- Continue development of many-body techniques and EFTs
  - Extrapolate to physical pion mass?
  - Pion-less, LO three-nucleon force?

The Unification of Nuclear Physics due to High-Performance Computing