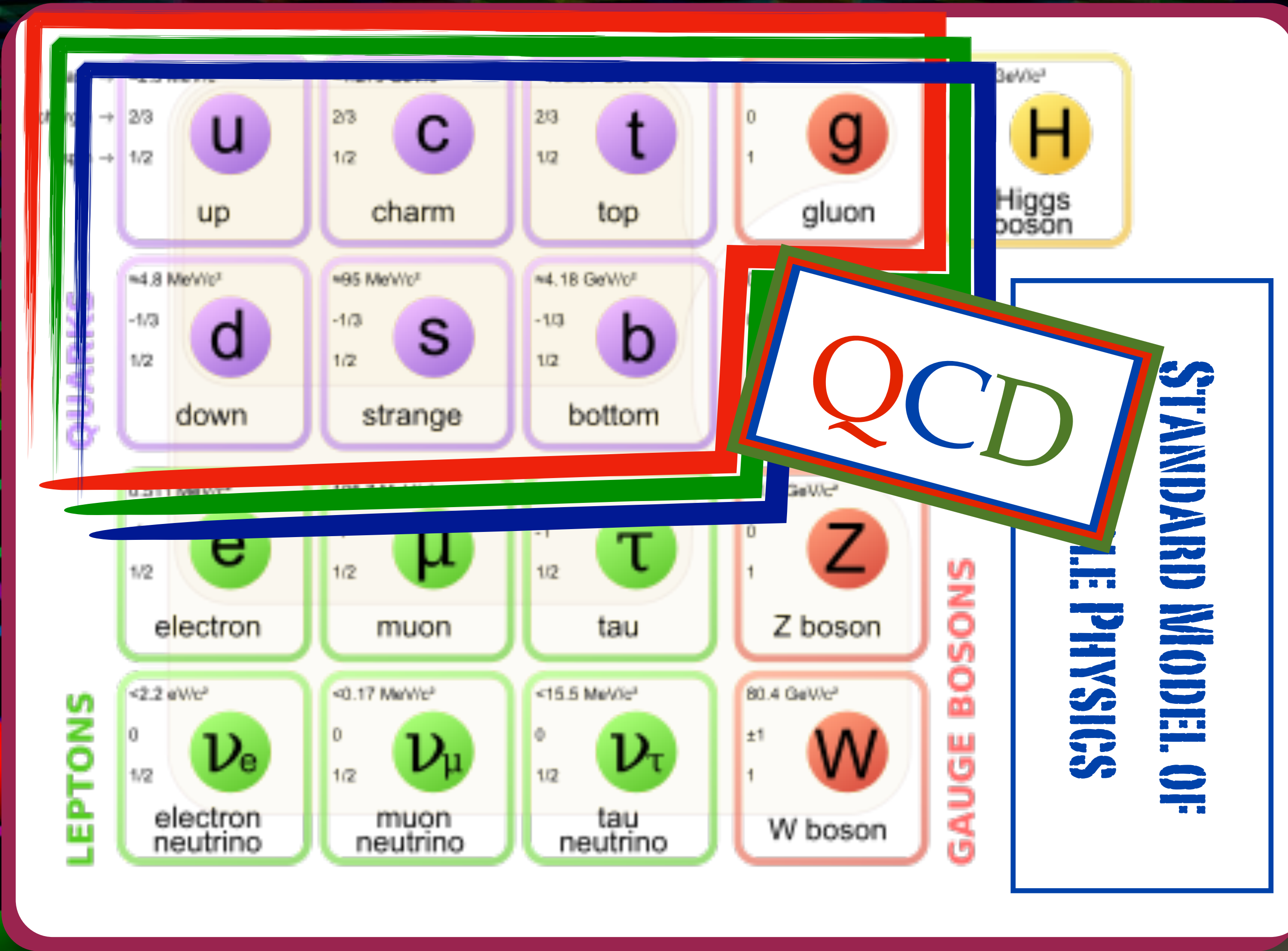
Nuclear Physics from Lattice QCD

Amy Nicholson
UNC, Chapel Hill

EINN 2019 Paphos, Cyprus
October 30, 2019

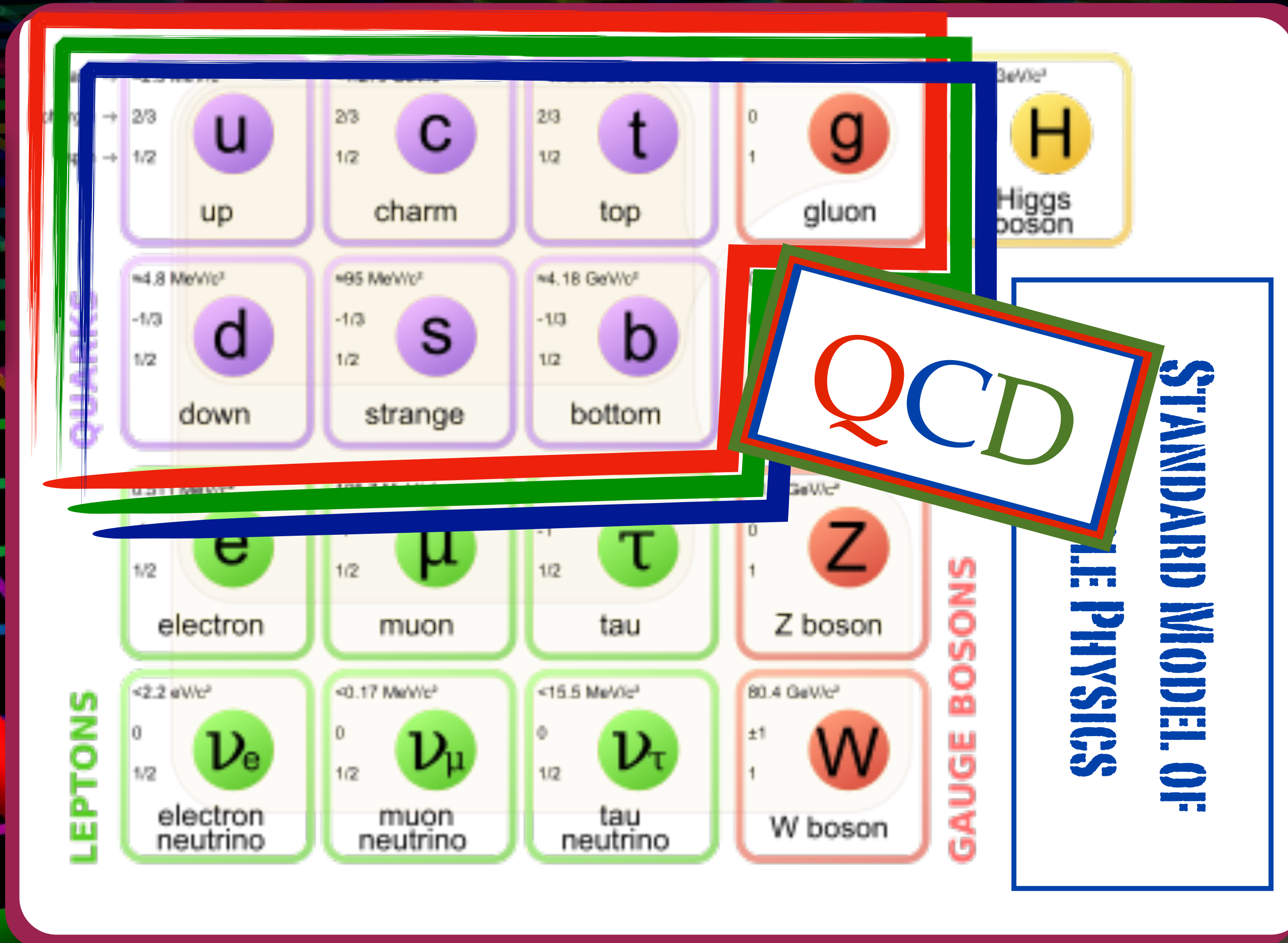
Lattice QCD

- Numerical solution to QCD:
    - Non-perturbative formulation of QCD in discretized, finite spacetime
    - Currently our only reliable technique for solving QCD at low energies
- All uncertainties are quantifiable and may be systematically removed
    - Extrapolations to continuum, infinite volume, physical pion mass

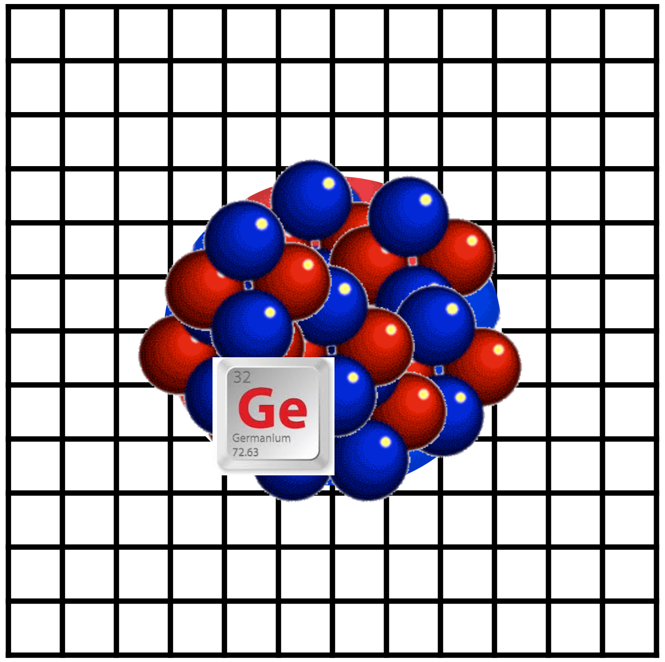


Lattice QCD

- Why LQCD for nuclear physics?
  - Test the SM
  - Match experimental signals to new physics models
  - Extract experimentally difficult quantities
    - Hadron interactions with non-zero strangeness
    - Three-neutron interactions
    - Understand quark mass dependence (fine-tuning?)
    - ….



LQCD won't be used to directly calculate heavy nuclei



Why?

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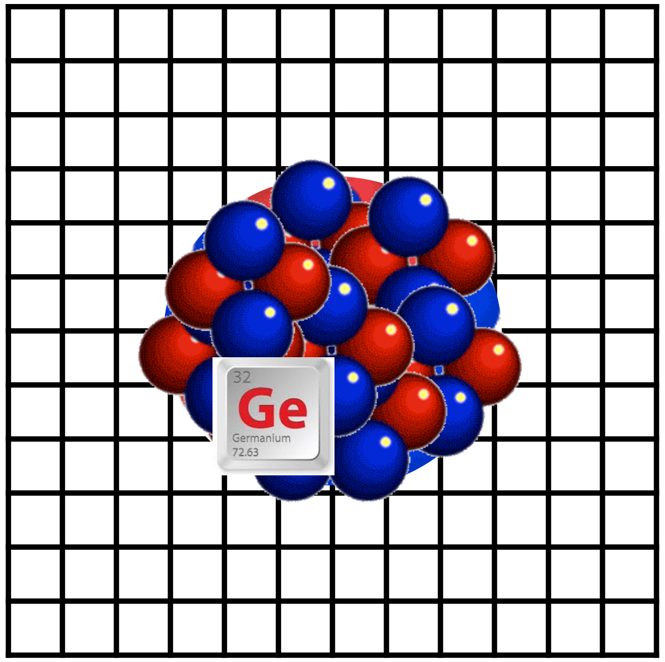

- Need extremely large lattices
  - Large range of scales
  - Tiny energy splittings

Why?

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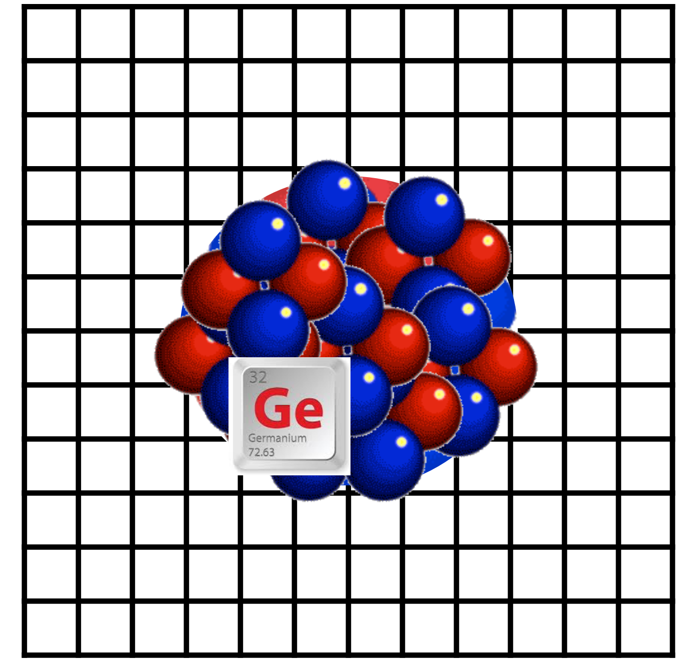
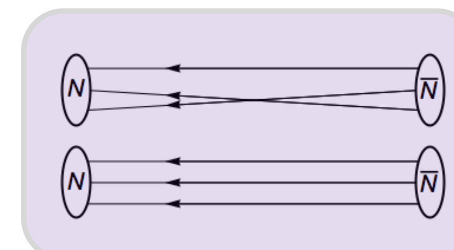


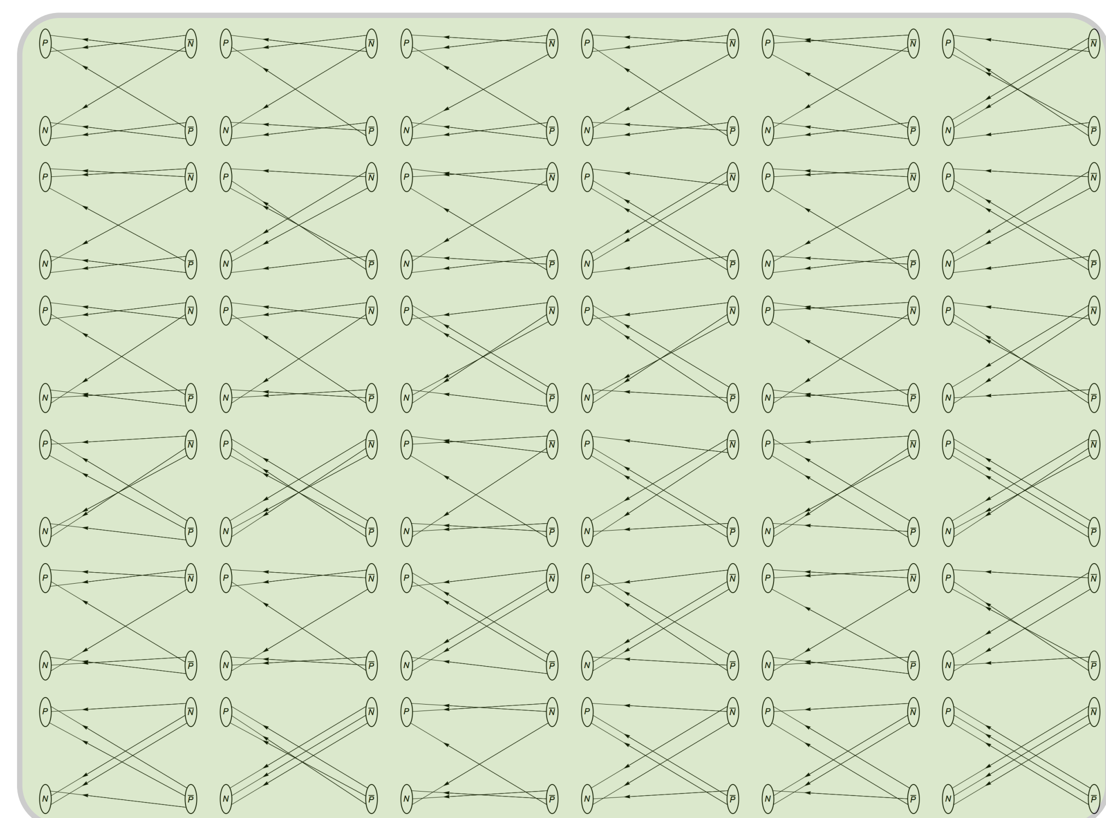
- Need extremely large lattices
  - Large range of scales
  - Tiny energy splittings
- Wick contractions: (A+Z)!x(2A-Z)!

$He^4 : 518400$

Nucleon:



Deuteron:



*Doi & Endres, Originos et. al., Günther et. al., Detmold, et. al.

Why?

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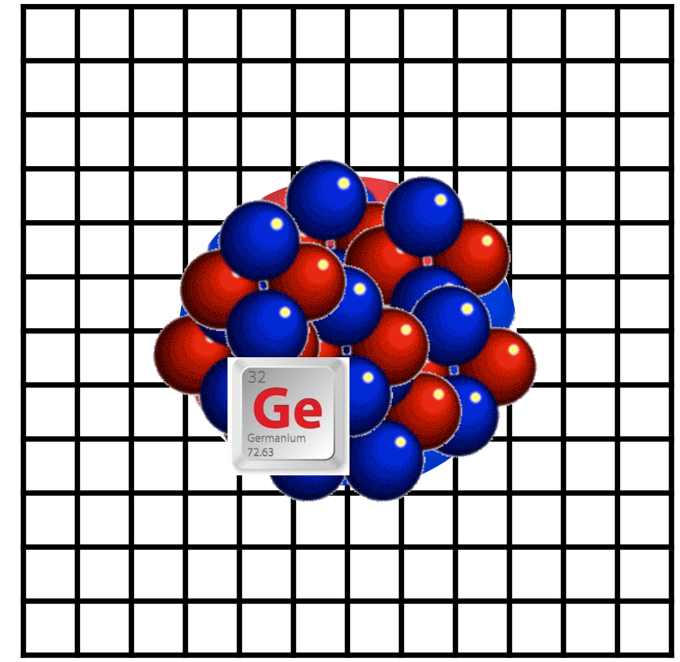


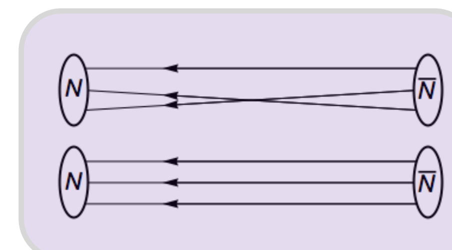
- Need extremely large lattices
  - Large range of scales
  - Tiny energy splittings
- Wick contractions: (A+Z)!x(2A-Z)!

$He^4 : 518400$

- Nucleon noise/sign problem

  signal/noise $\sim e^{-A(M_n - 3/2 m_\pi)t}$

Nucleon:



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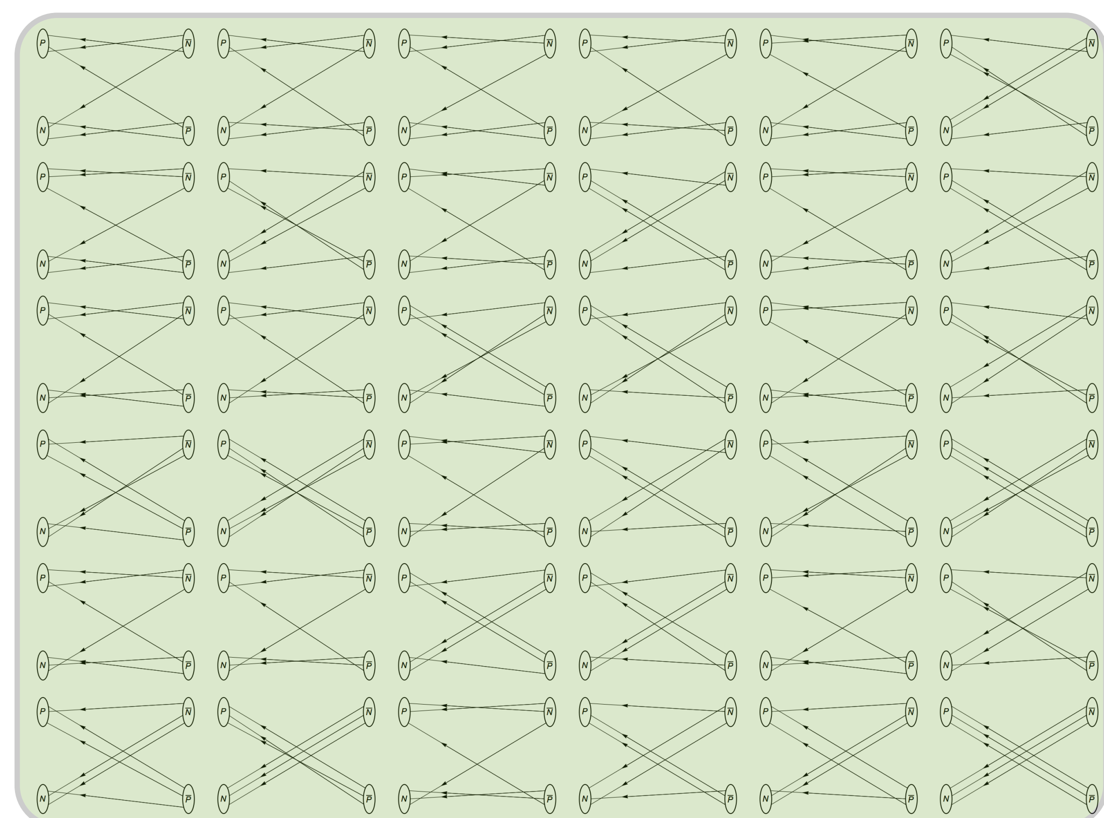

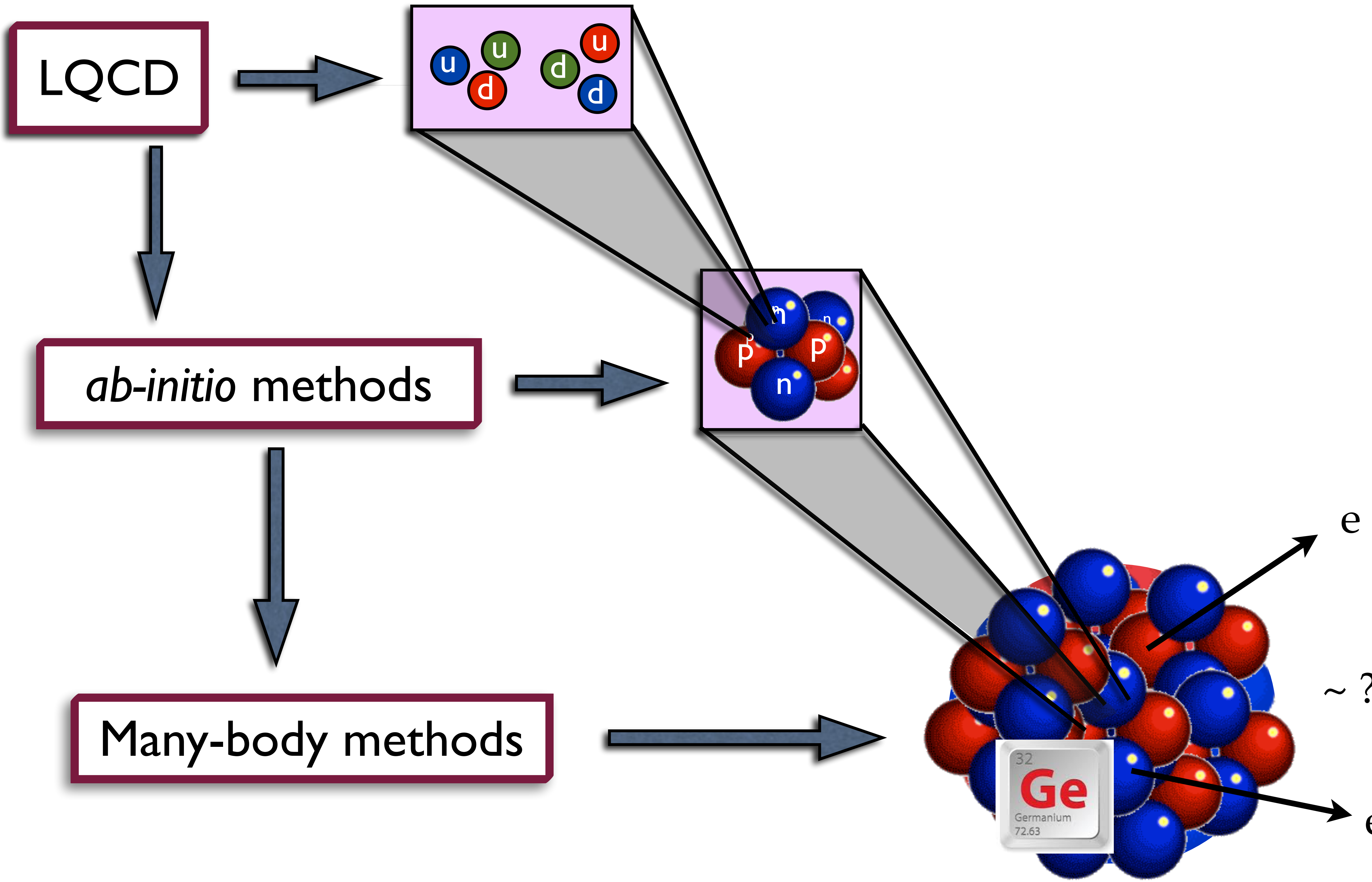
LQCD
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Precision era for (single nucleon) LQCD

Neutron-proton mass difference: accurate to 300 KeV (BMW 2015)

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REPORT

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Sz. Borsanyi[1], S. Durr[1,2], Z. Fodor[1,2,3,*], C. Hoelbling[1], S. D. Katz[3,4], S. Krieg[1,2], L. Lellouch[5], T. Lippert[1,2], A. Portelli[5,6], K. K. Szabo[1,2], B. C. Toth[1]

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[2]Jülich Supercomputing Centre, Forschungszentrum Jülich, D-52428 Jülich, Germany.
[3]Institute for Theoretical Physics, Eötvös University, H-1117 Budapest, Hungary.
[4]Lendület Lattice Gauge Theory Research Group, Magyar Tudományos Akadémia–Eötvös Loránd University, H-1117 Budapest, Hungary.
[5]CNRS, Aix-Marseille Université, Université de Toulon, CPT UMR 7332, F-13288, Marseille, France.
[6]School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK.
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Science 27 Mar 2015:
Vol. 347, Issue 6229, pp. 1452-1455

Axial charge of the nucleon: g_A = 1.271(13) (CalLat 2018)

nature
International journal of science

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Letter | Published: 30 May 2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

Nature **558**, 91–94 (2018) | Download Citation

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Citation

FLAG Review 2019

March 5, 2019

Flavour Lattice Averaging Group (FLAG)

S. Aoki,[1] Y. Aoki,[2,3] * D. Bečirević,[4] T. Blum,[5,3] G. Colangelo,[6] S. Collins,[7] M. Della Morte,[8] P. Dimopoulos,[9] S. Dürr,[10] H. Fukaya,[11] M. Golterman,[12] Steven Gottlieb,[13] R. Gupta,[14] S. Hashimoto,[2,15] U. M. Heller,[16] G. Herdoiza,[17] R. Horsley,[18] A. Jüttner,[19] T. Kaneko,[2,15] C.-J. D. Lin,[20,21] E. Lunghi,[13] R. Mawhinney,[22] A. Nicholson,[23] T. Onogi,[11] C. Pena,[17] A. Portelli,[18] A. Ramos,[24] S. R. Sharpe,[25] J. N. Simone,[26] S. Simula,[27] R. Sommer,[28,29] R. Van De Water,[26] A. Vladikas,[30] U. Wenger,[6] H. Wittig[31]

10 Nucleon matrix elements

Authors: S. Collins, R. Gupta, A. Nicholson, H. Wittig

A large number of experiments testing the Standard Model (SM) and searching for physics Beyond the Standard Model (BSM) involve either free nucleons (proton and neutron beams) or the scattering of electrons, protons, neutrinos and dark matter off nuclear targets. Necessary

Nucleon axial charge

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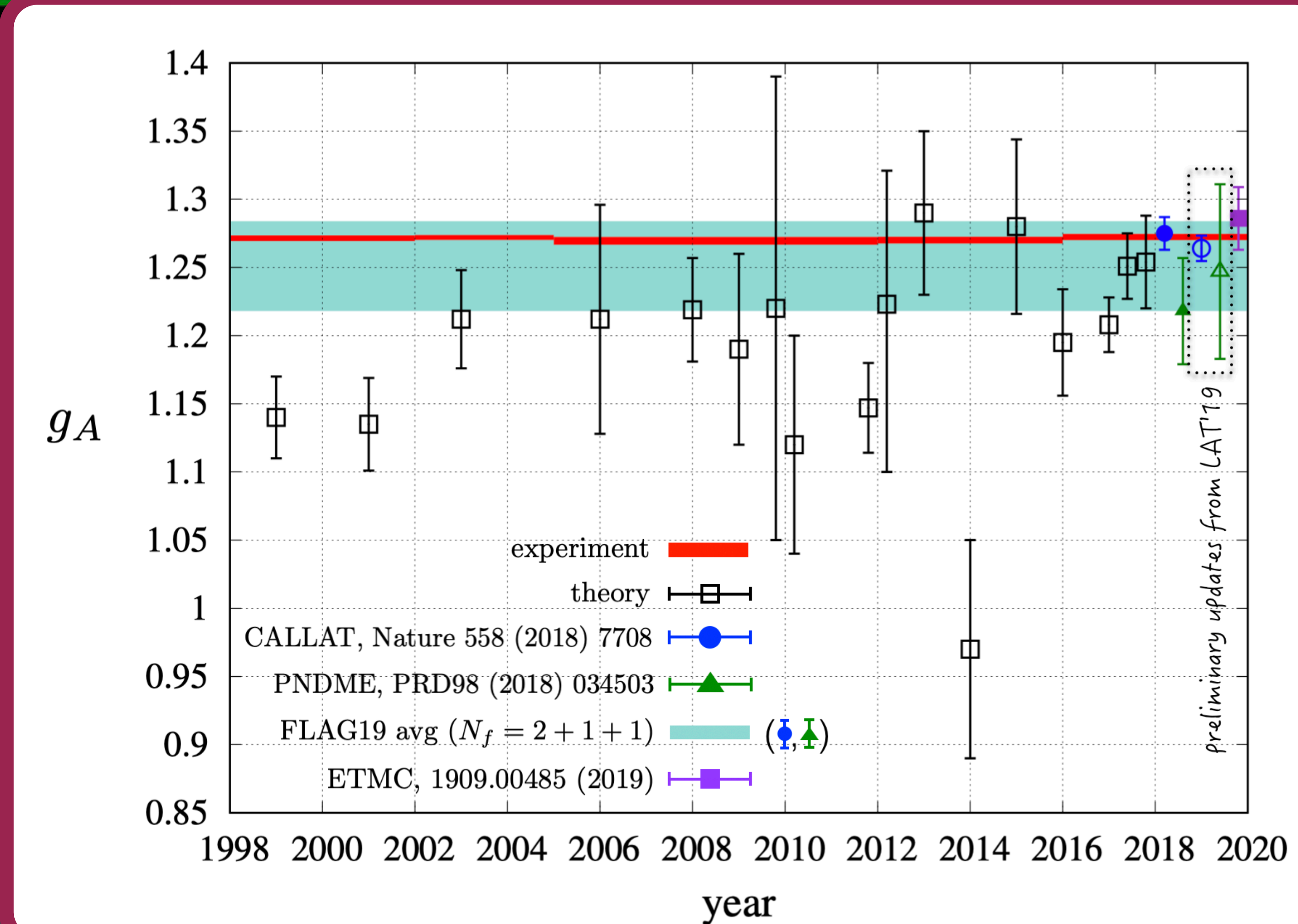
Nucleon Axial Charge in Full Lattice QCD

R. G. Edwards, G. T. Fleming, Ph. Hägler, J. W. Negele, K. Orginos, A. V. Pochinsky, D. B. Renner, D. G. Richards, and W. Schroers (LHPC Collaboration)

Phys. Rev. Lett. **96**, 052001 – Published 7 February 2006

The axial charge is the ideal starting point in the quest for precision lattice calculation of hadron structure for several reasons. It is accurately measured experimentally and the isovector combination $\langle 1\rangle_{\Delta u} - \langle 1\rangle_{\Delta d}$ has no contributions from disconnected diagrams, which are much more computationally demanding than the connected diagrams considered in this work. The functional dependence on both m_π^2 and volume is known at small masses from chiral perturbation theory (χPT) [5,6] and renormalization of the lattice axial vector current can be performed accurately nonperturbatively using the five-dimensional conserved current for domain wall fermions. Thus, conceptually, it is a "gold plated" test of our ability to calculate hadron observables from first principles on the lattice. In addition, since it is known to be particularly sensitive to finite lattice volume effects that reduce the contributions of the pion cloud [7,8], it is also a stringent test of our control of finite volume artifacts.



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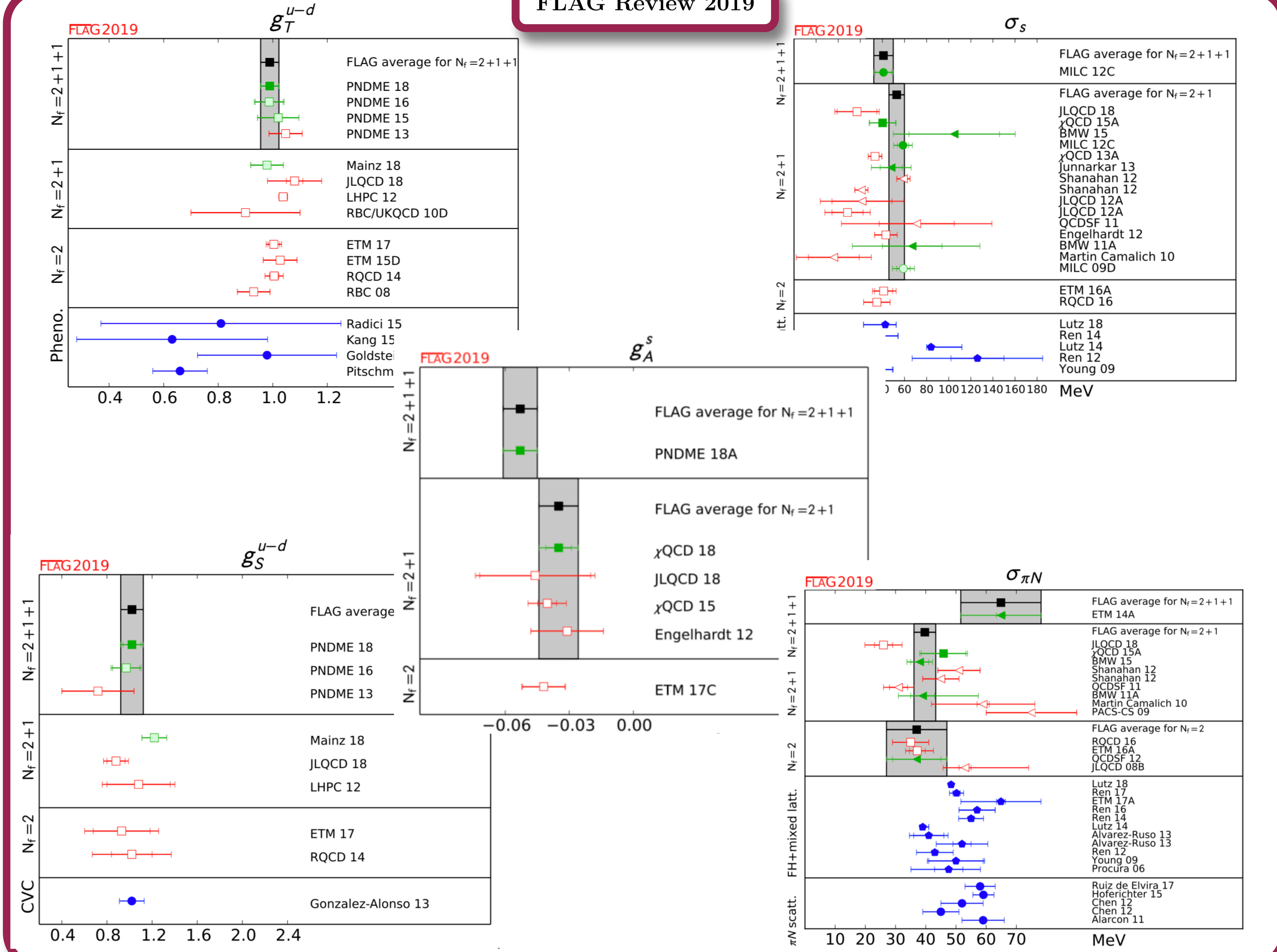
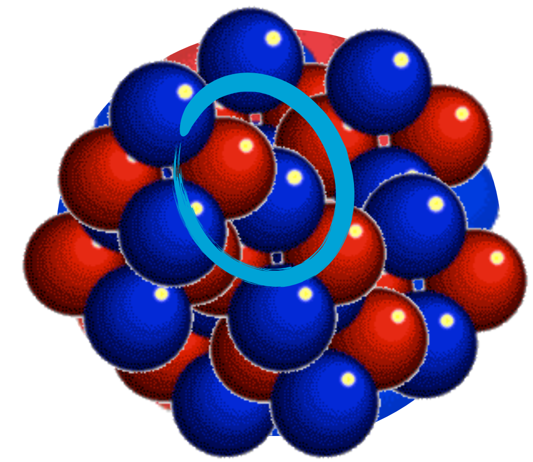
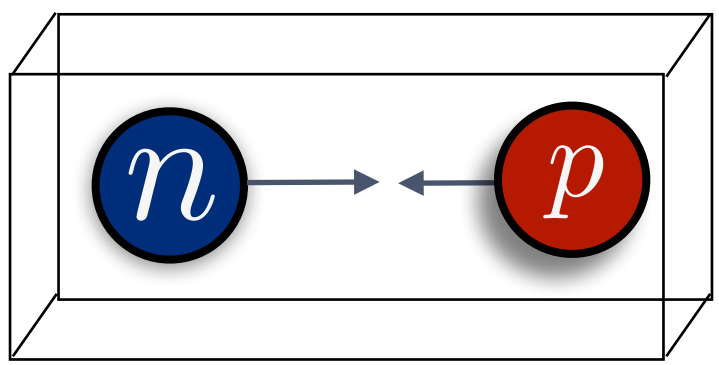


Two methods for calculating few-nucleon interactions from LQCD:



Spectroscopy + Lüscher Method

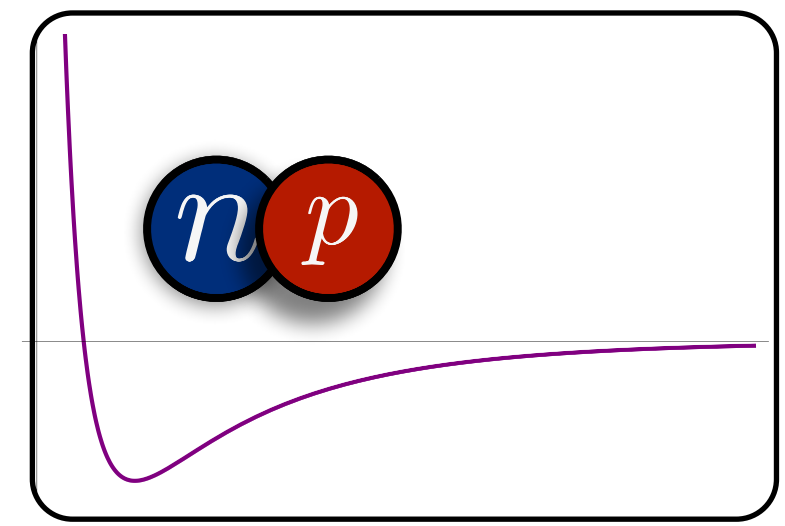


NPLQCD

CalLat

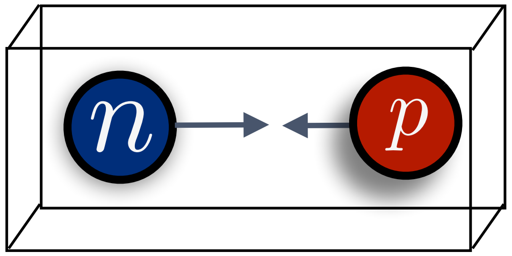
Yamazaki, et. al.

Potential Method



Hadrons to Atomic nuclei
HAL
from Lattice QCD

Lüscher



- Direct scattering "experiments" not possible in finite volume/Euclidean time
- Lüscher: measure discrete spectra of interacting particles in a box, and infer the interaction (scattering phase shift)

“Lüscher” in 1-d

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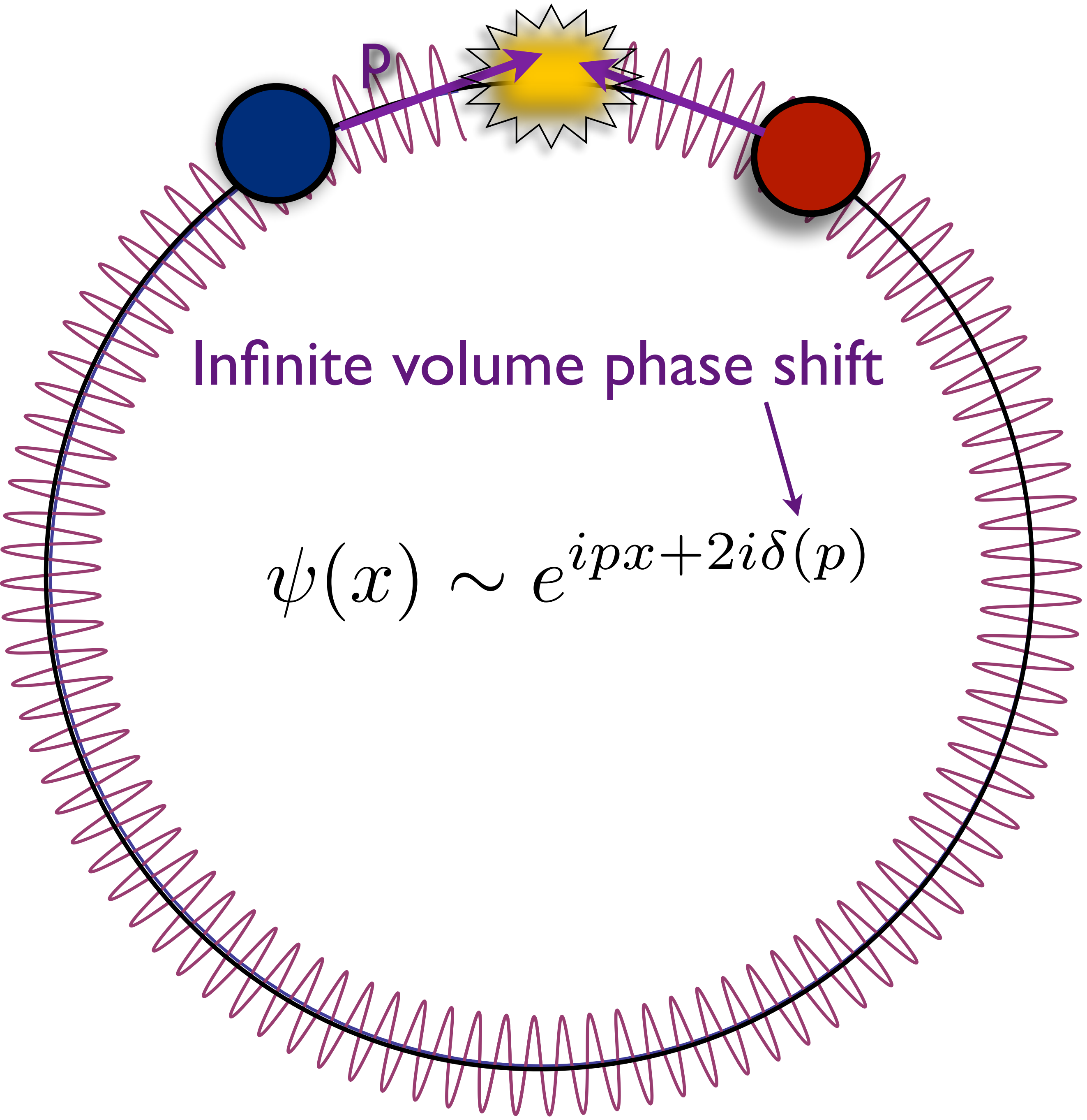

$$\psi(x) \sim e^{ipx+2i\delta(p)}$$

“Lüscher” in 1-d

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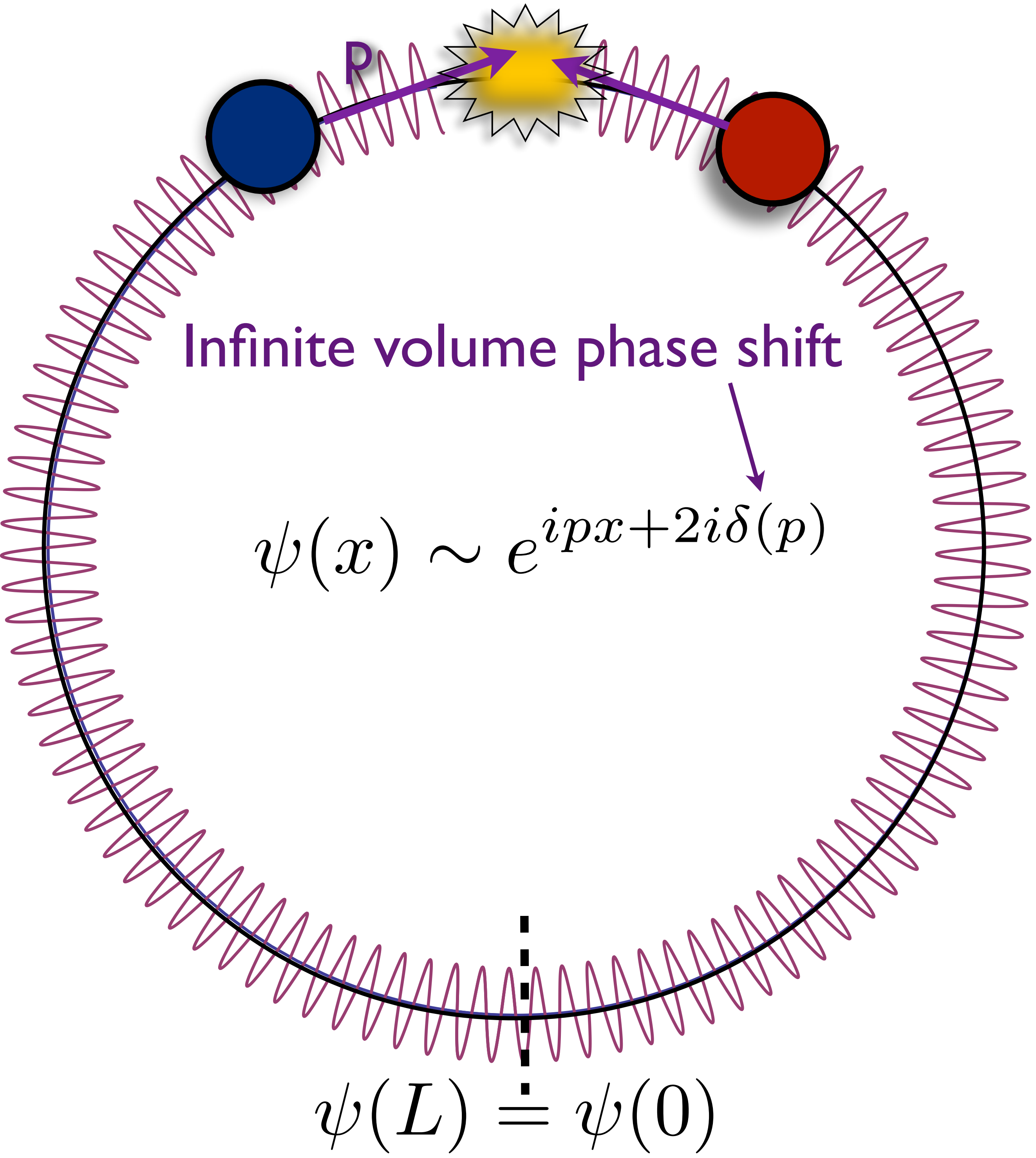

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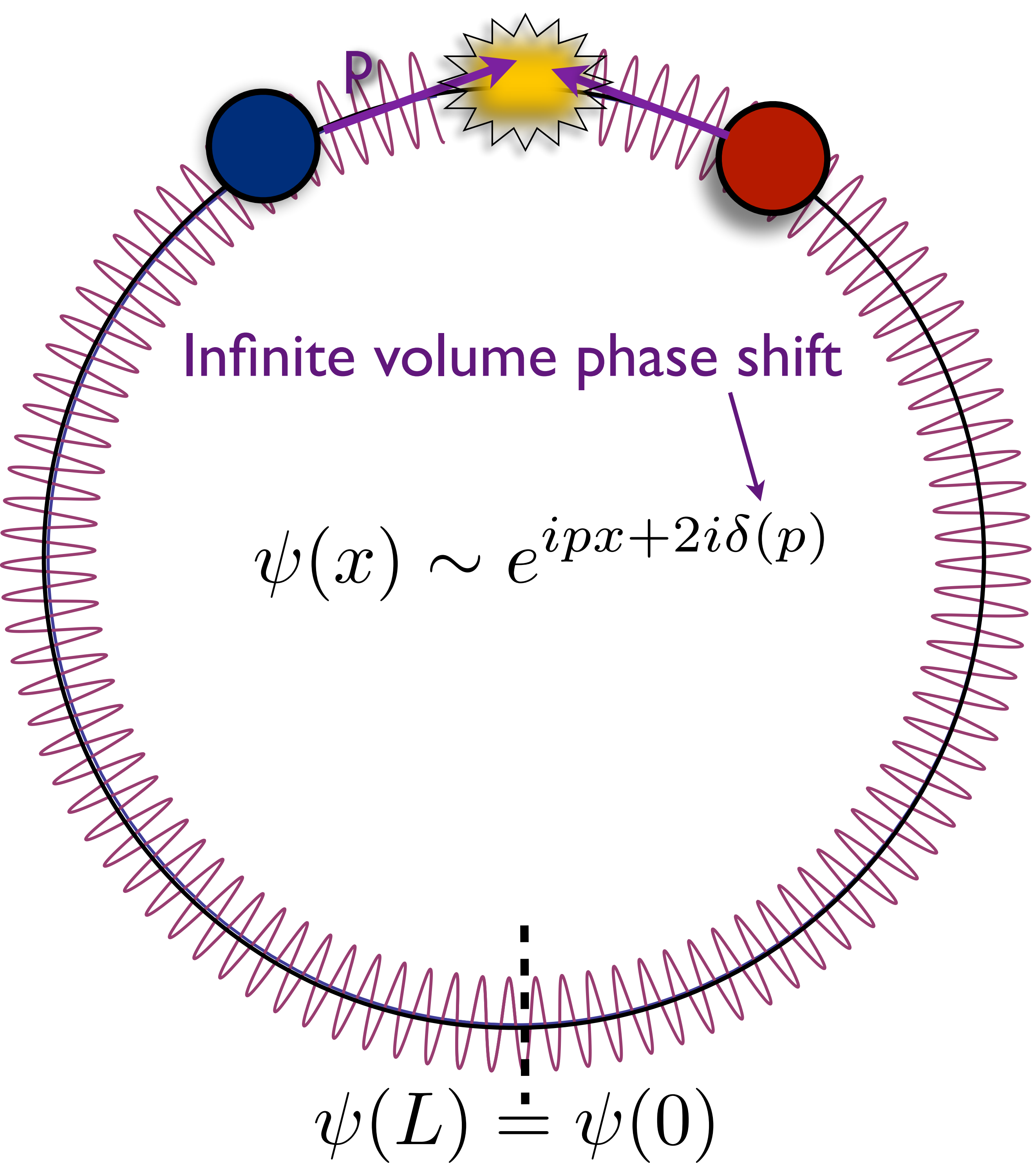

Quantization condition:

$$Lp_n^* + 2\delta(p_n^*) = 2\pi n$$

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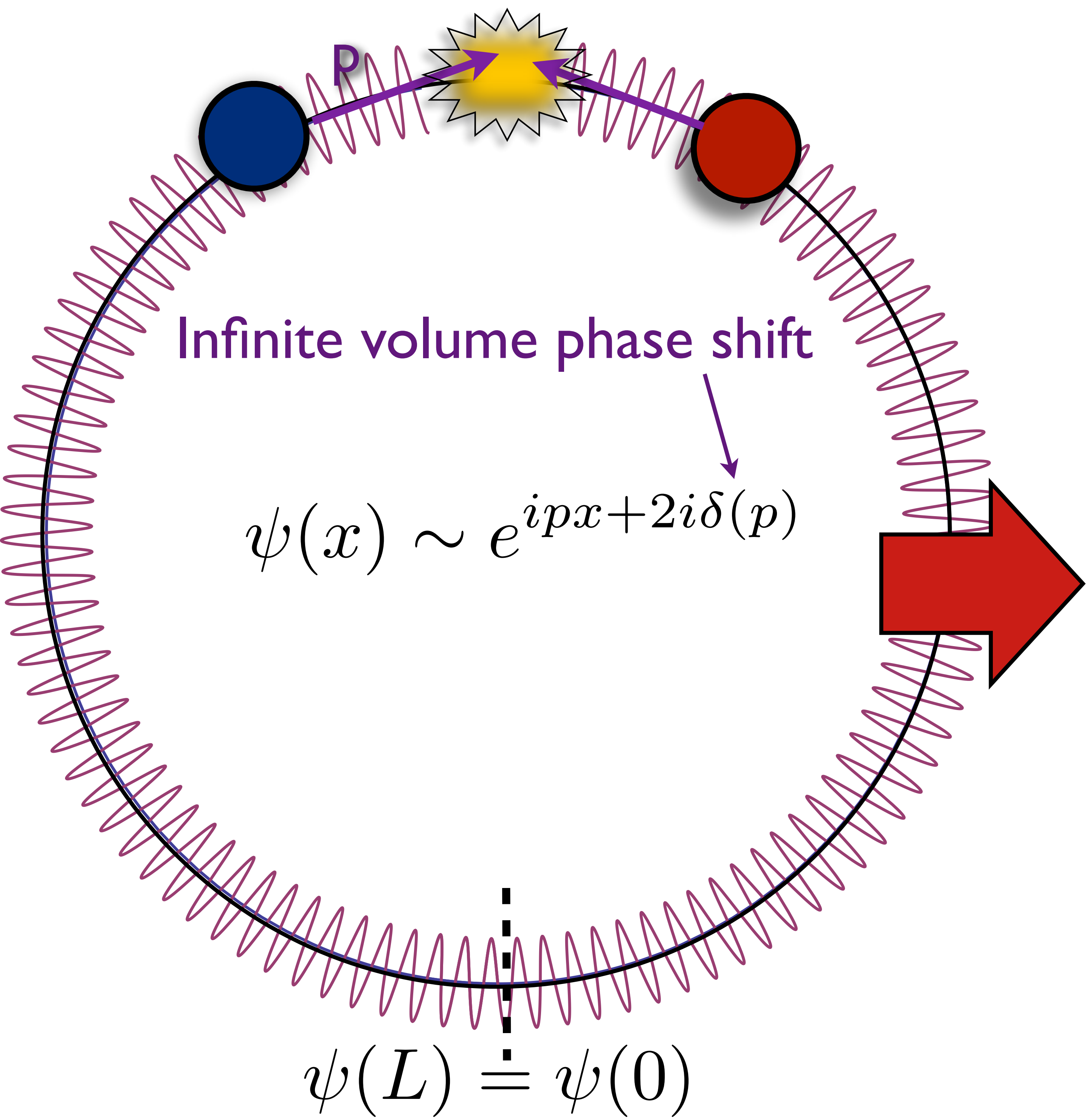
"Lüscher" in 1-d



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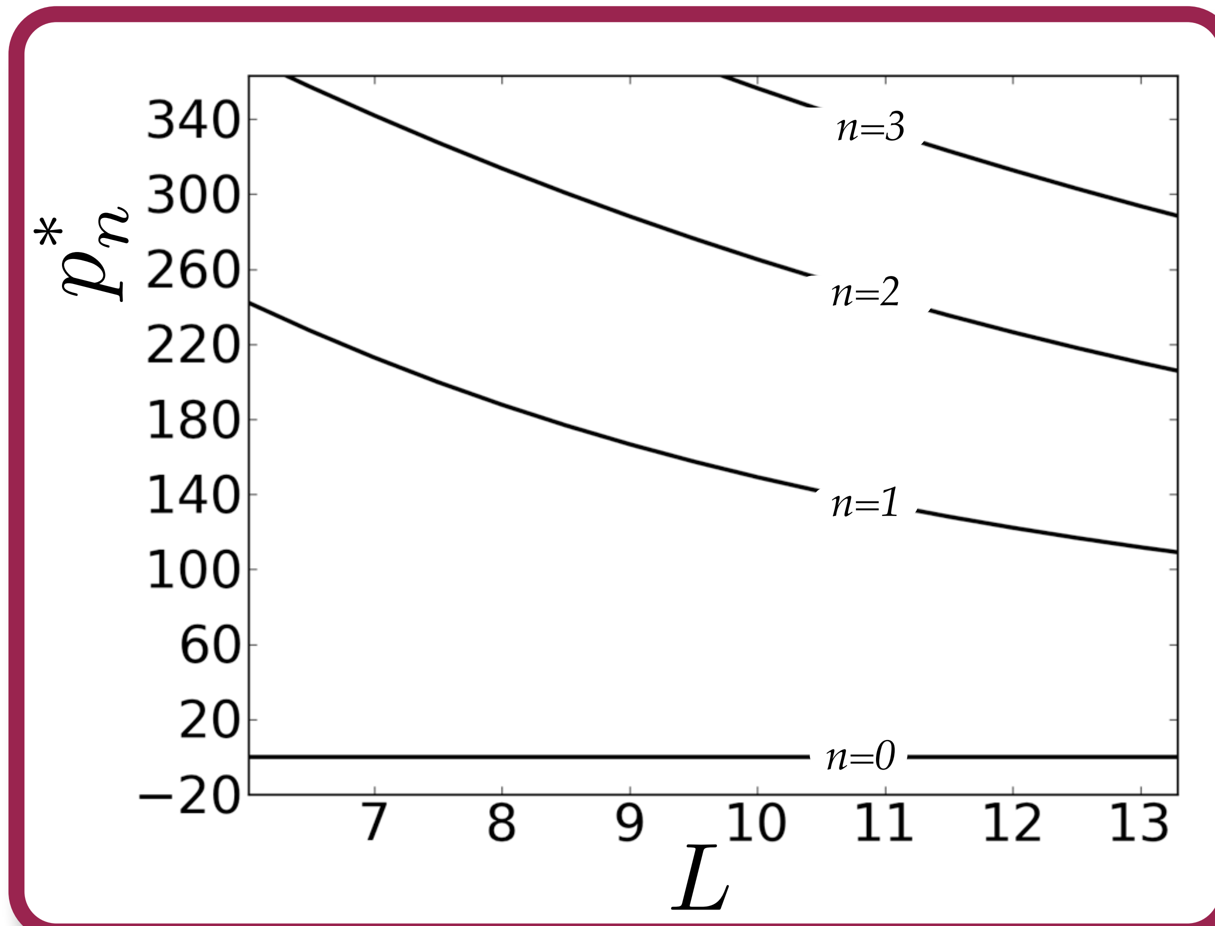

"Lüscher" in 1-d

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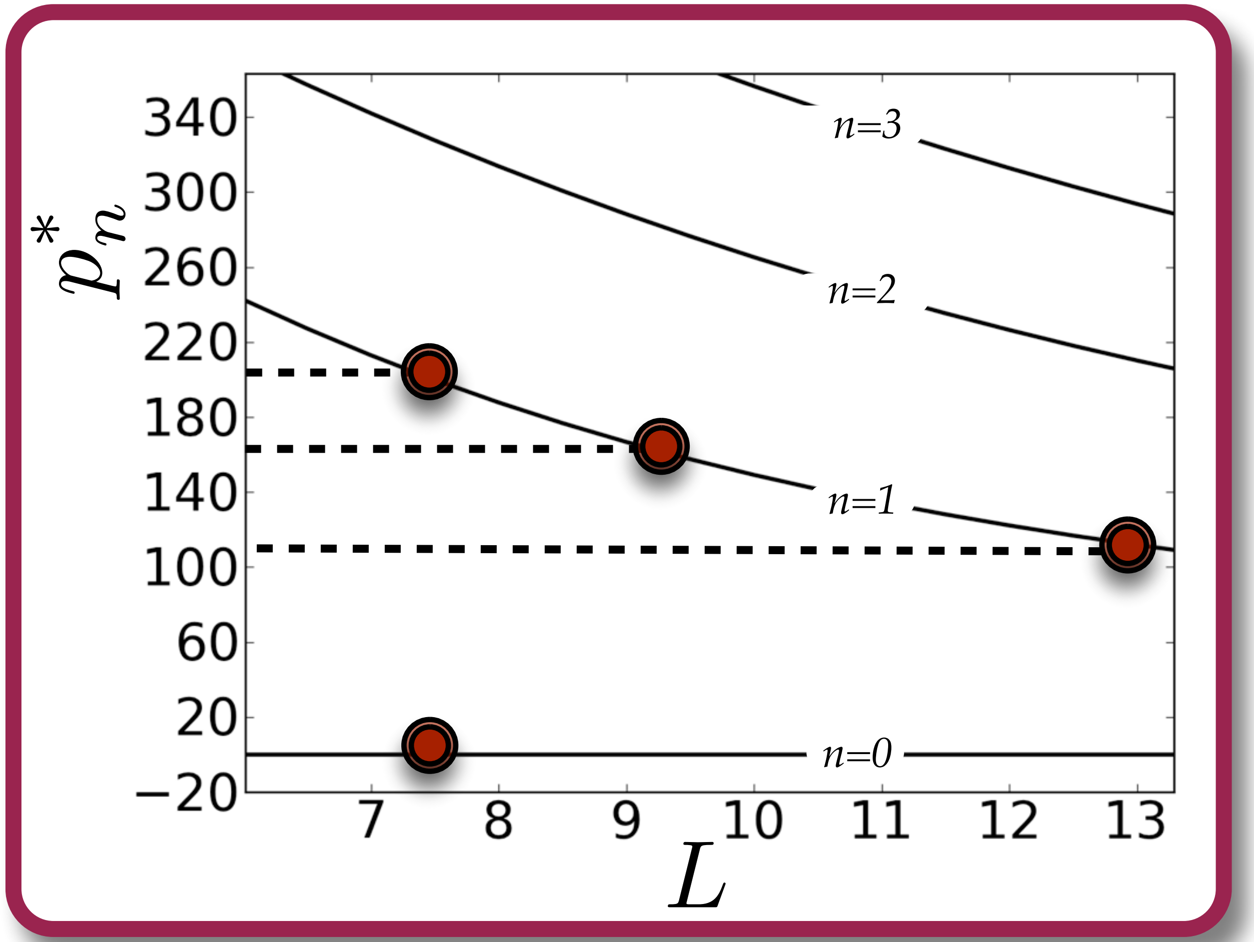
Lattice: measure energies at a given L



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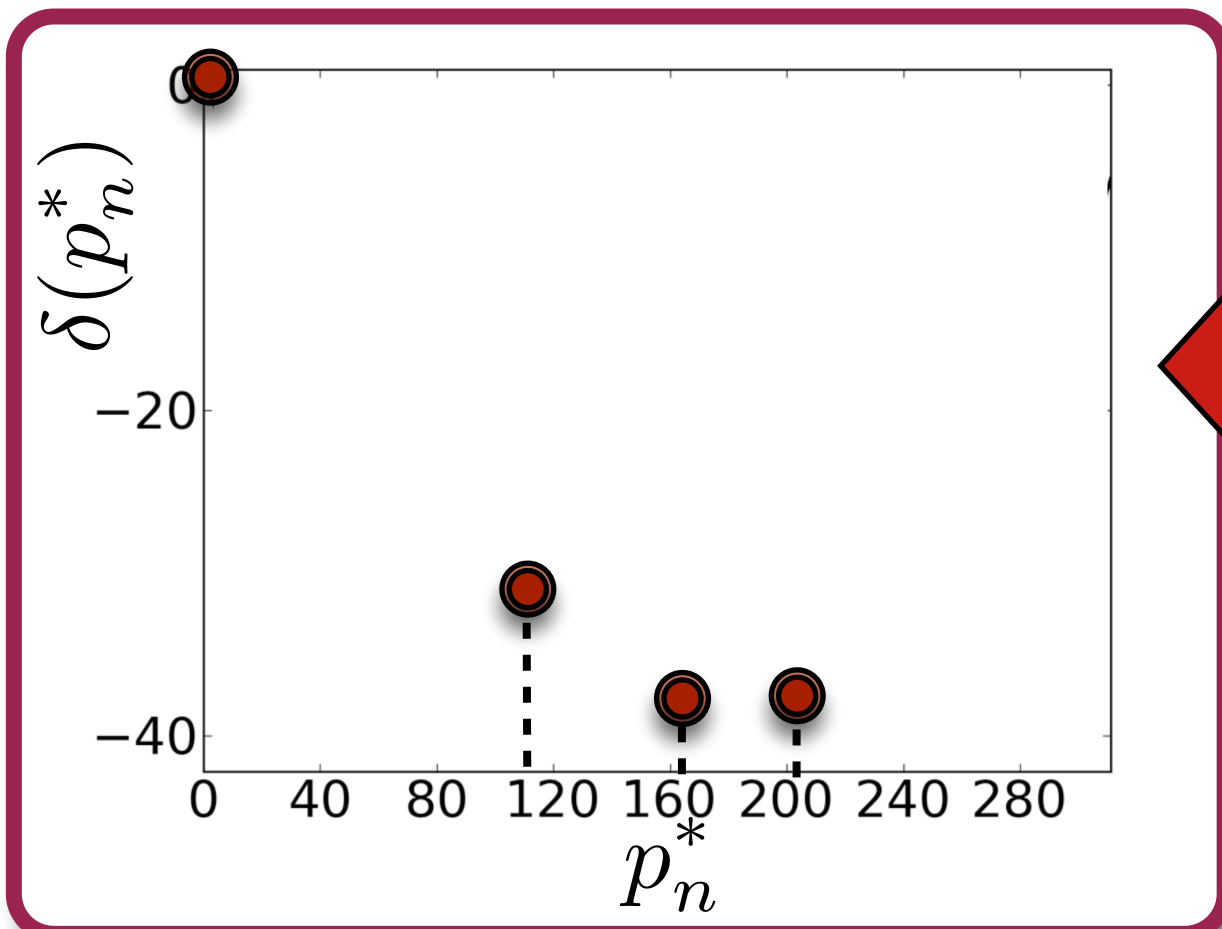

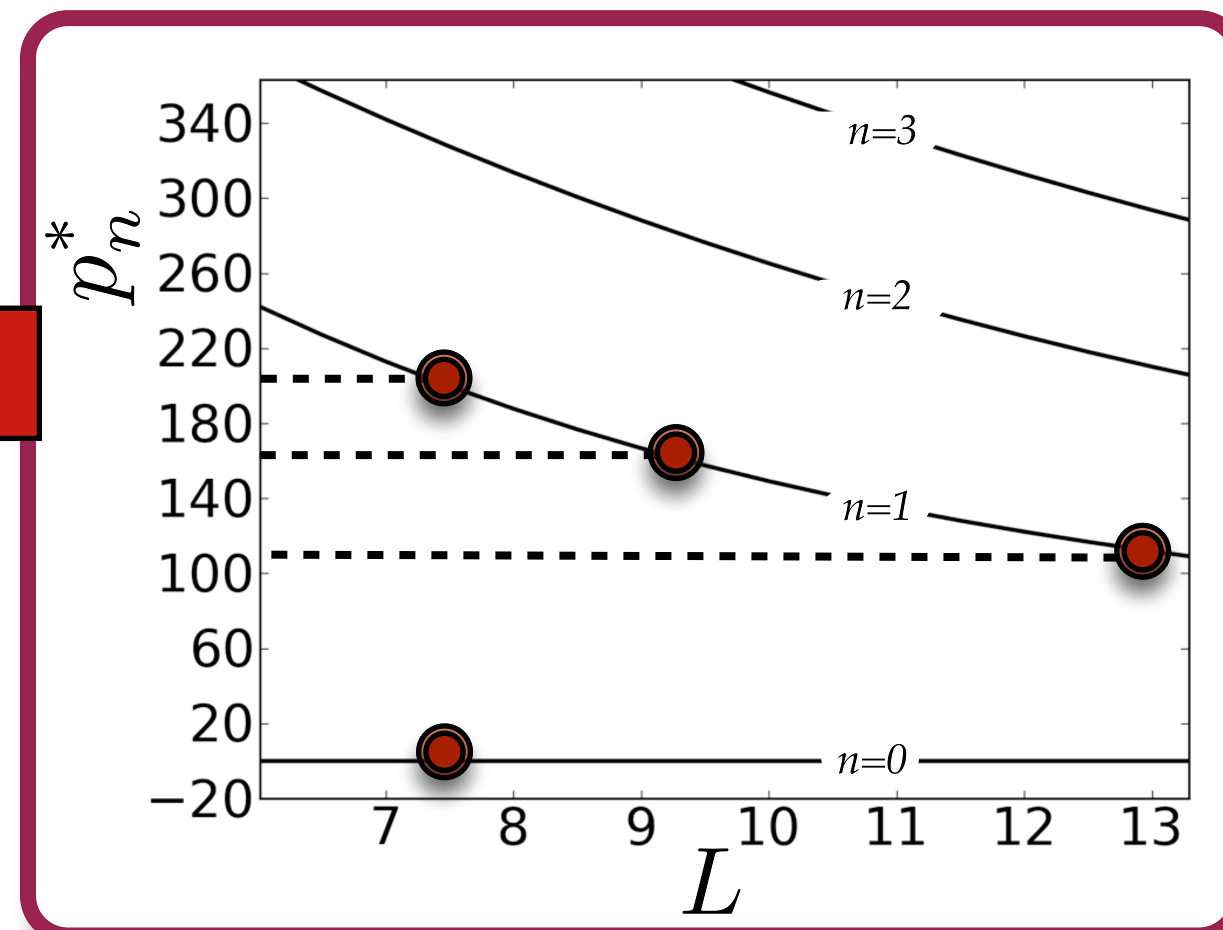

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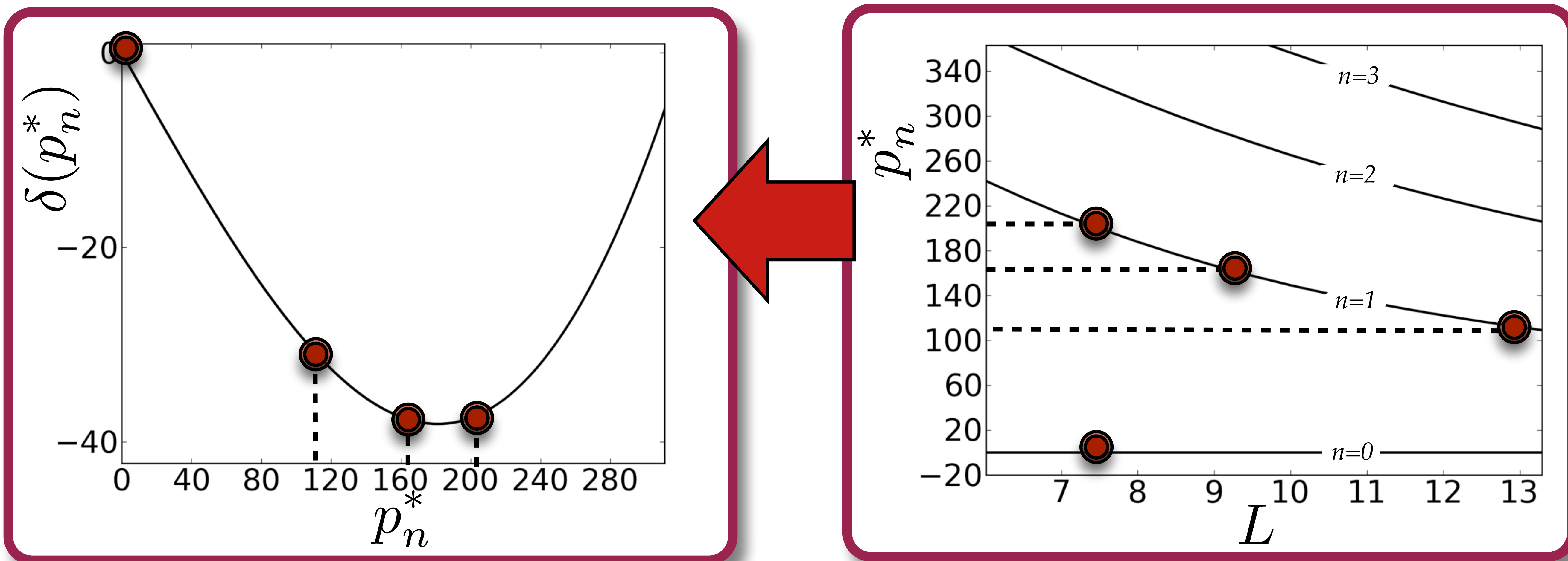

“Lüscher” in 1-d

D. J. Wilson, R. A. Briceno, J. J. Dudek, R. G. Edwards and C. E. Thomas, Phys. Rev. D 92, 094502 (2015)

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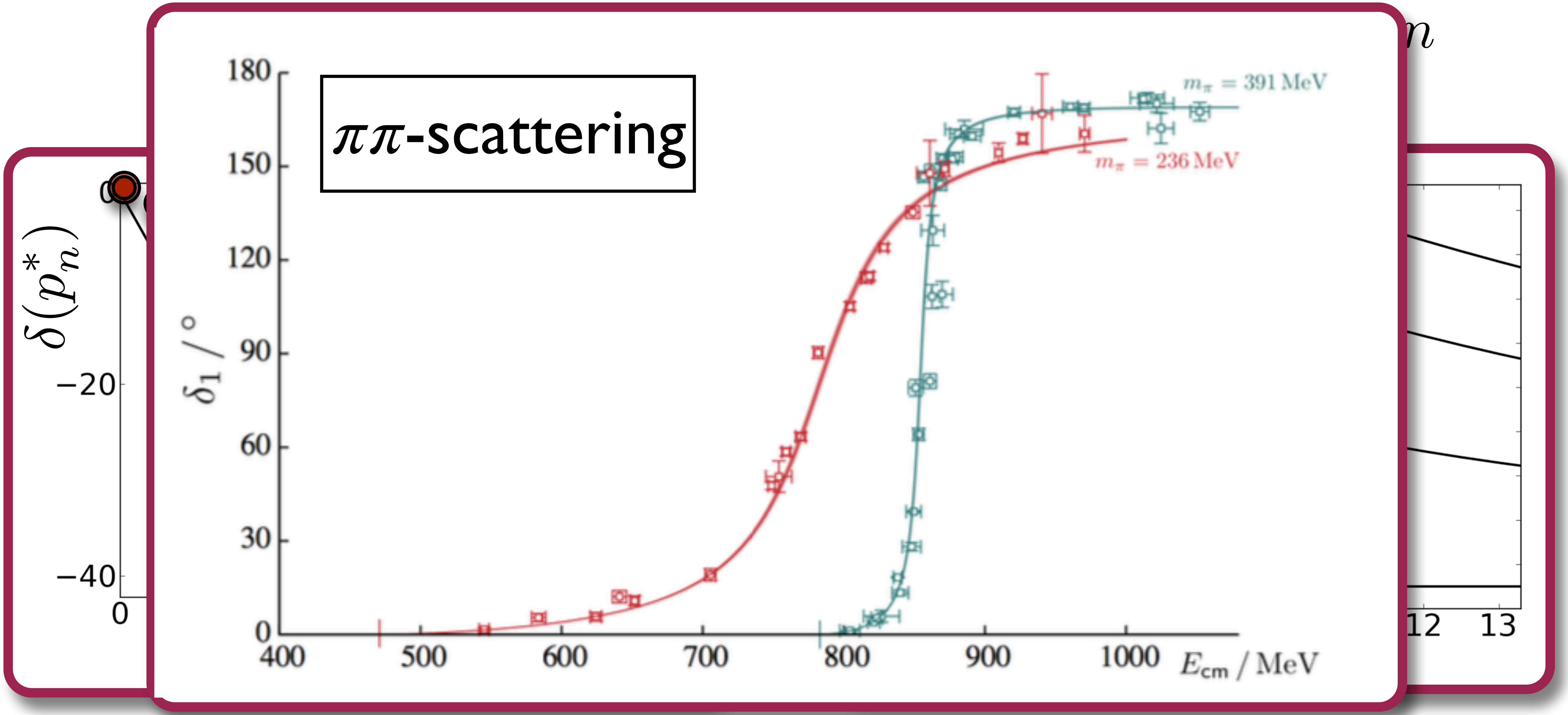
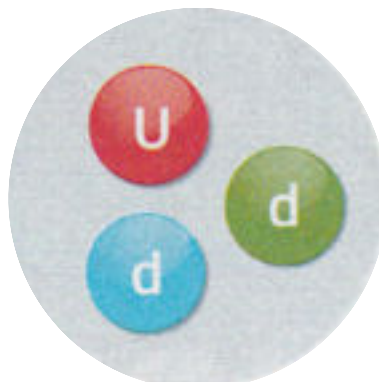
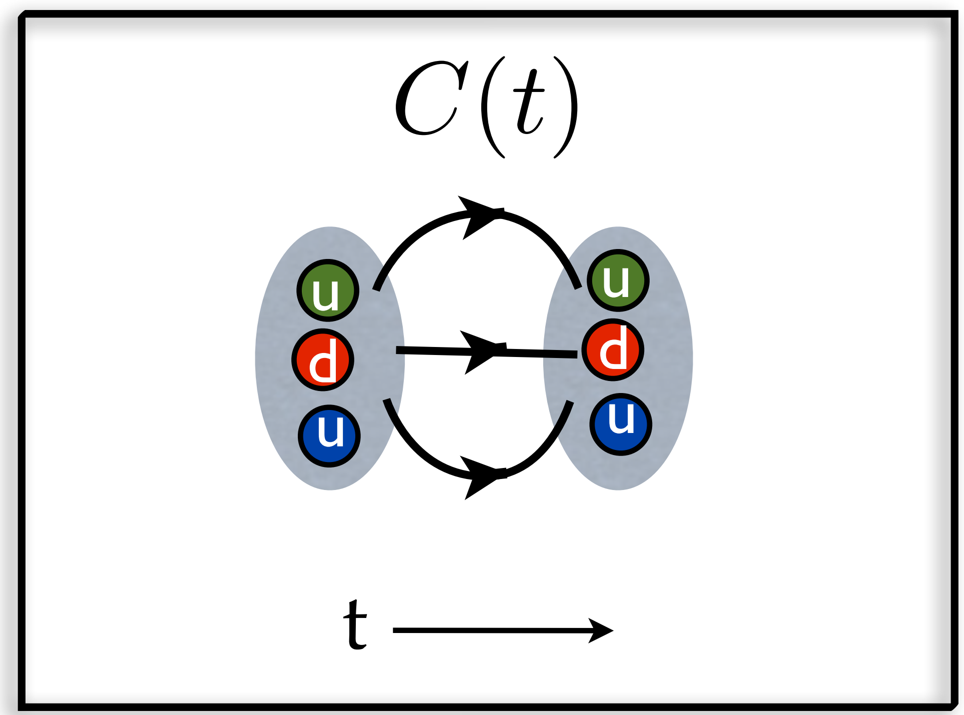


Calculating Observables

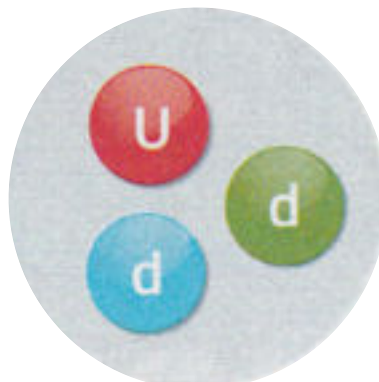
$\mathcal{O}$:



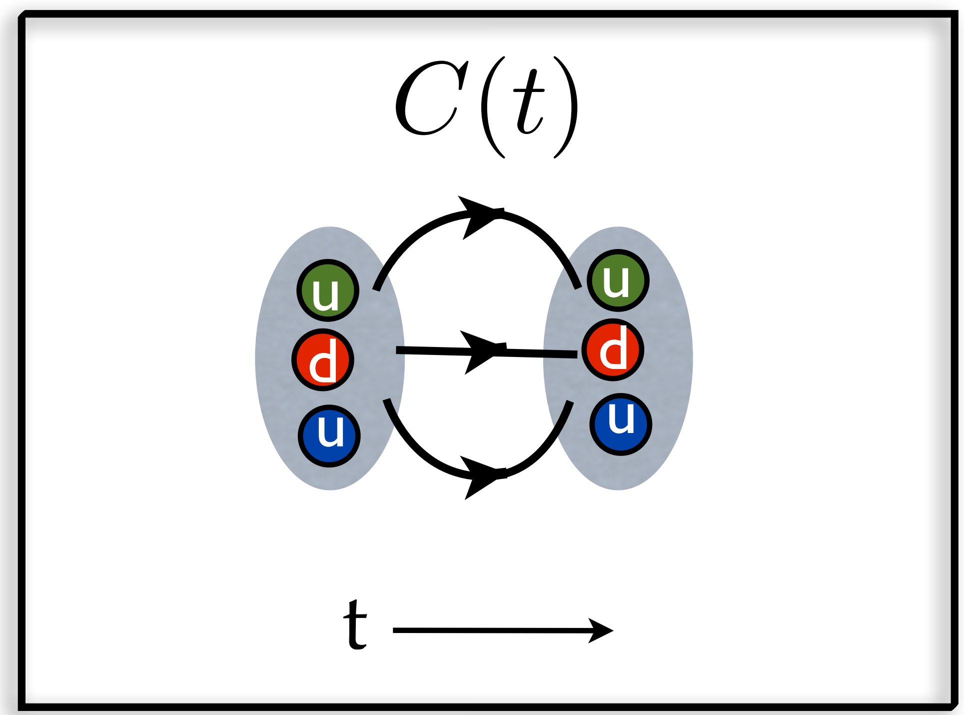


Calculating Observables

$\mathcal{O}:$



$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle$



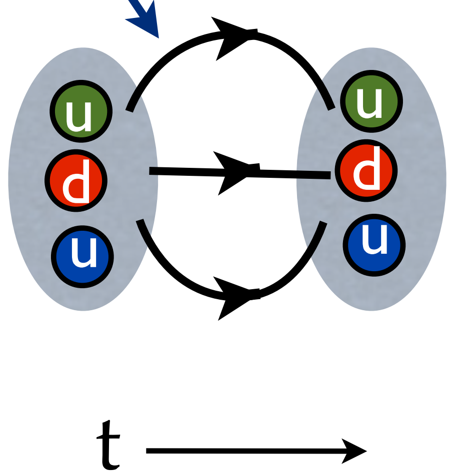
Calculating Observables

$\mathcal{O}$:

$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle$$

(Euclidean) Time evolution

$C(t)$



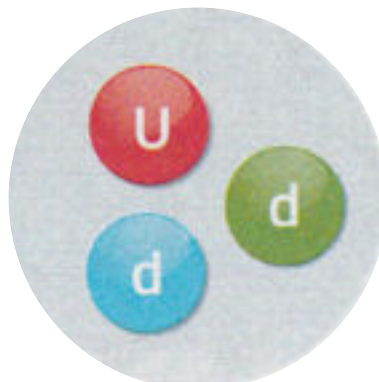
Calculating Observables

$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t}$$

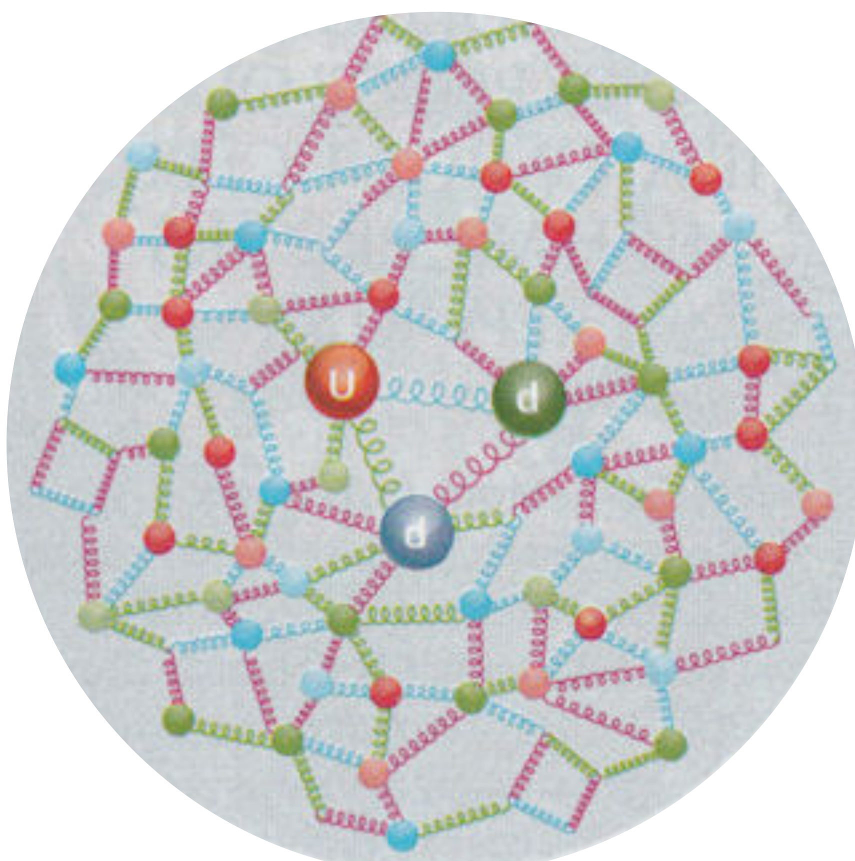
(Euclidean) Time evolution

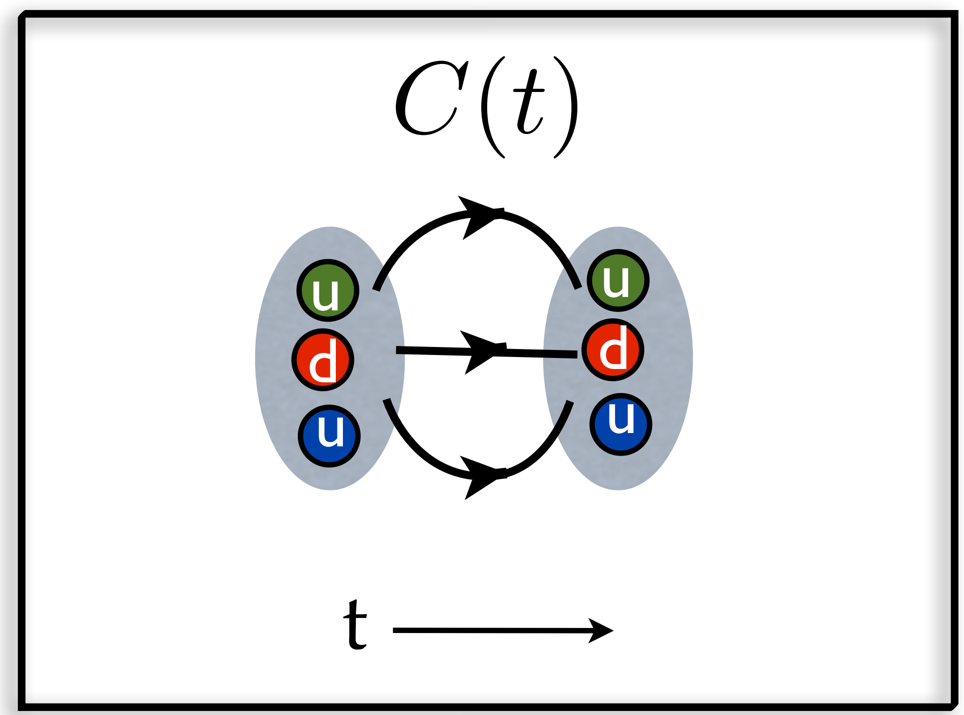
Complete set of states

$\mathcal{O}$:



ψ_n :





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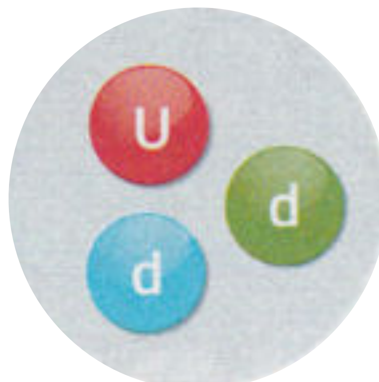
Like a Boltzmann factor

$\mathcal{O}$:



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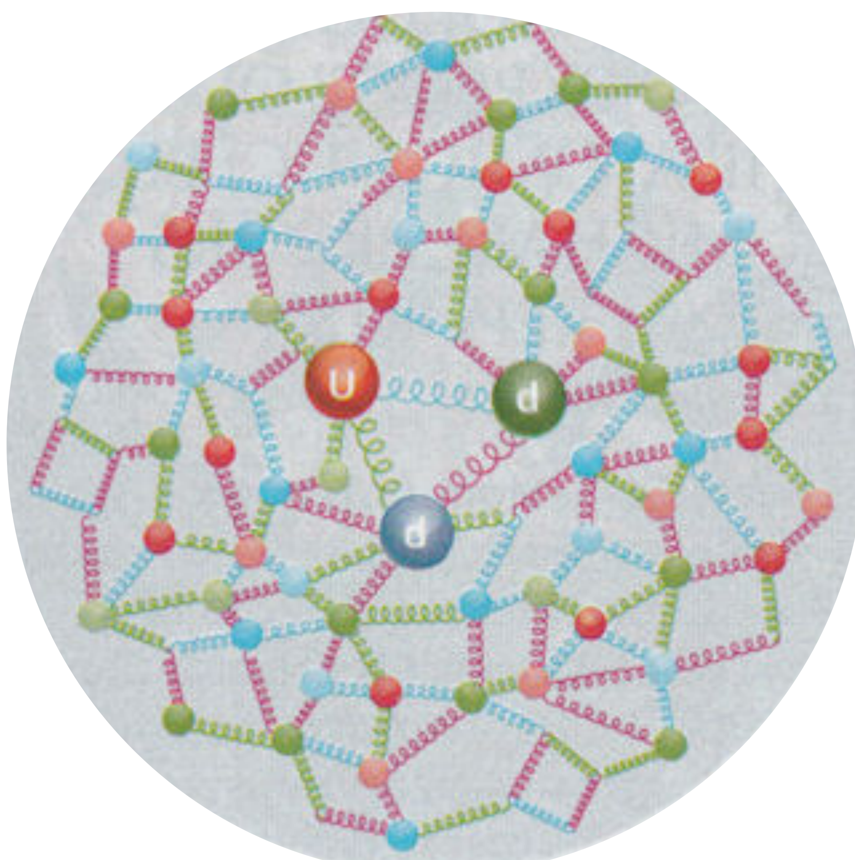

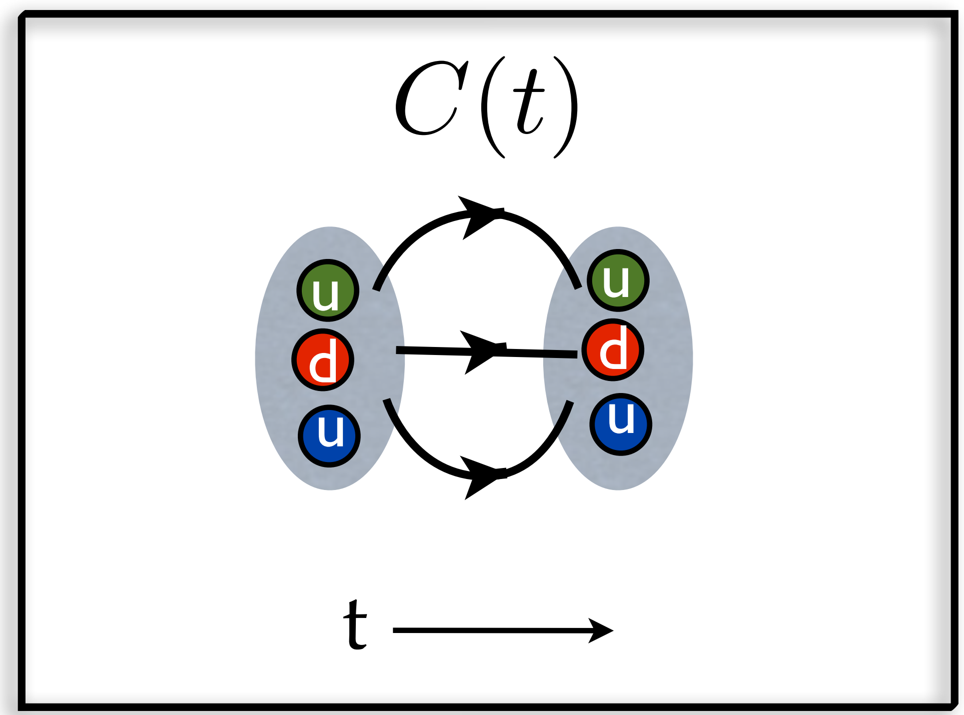

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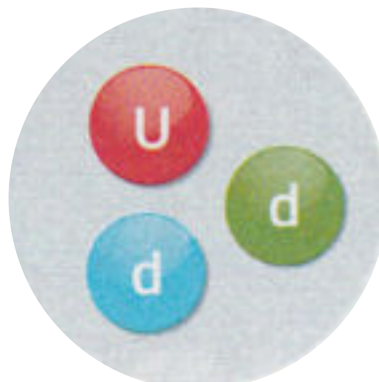
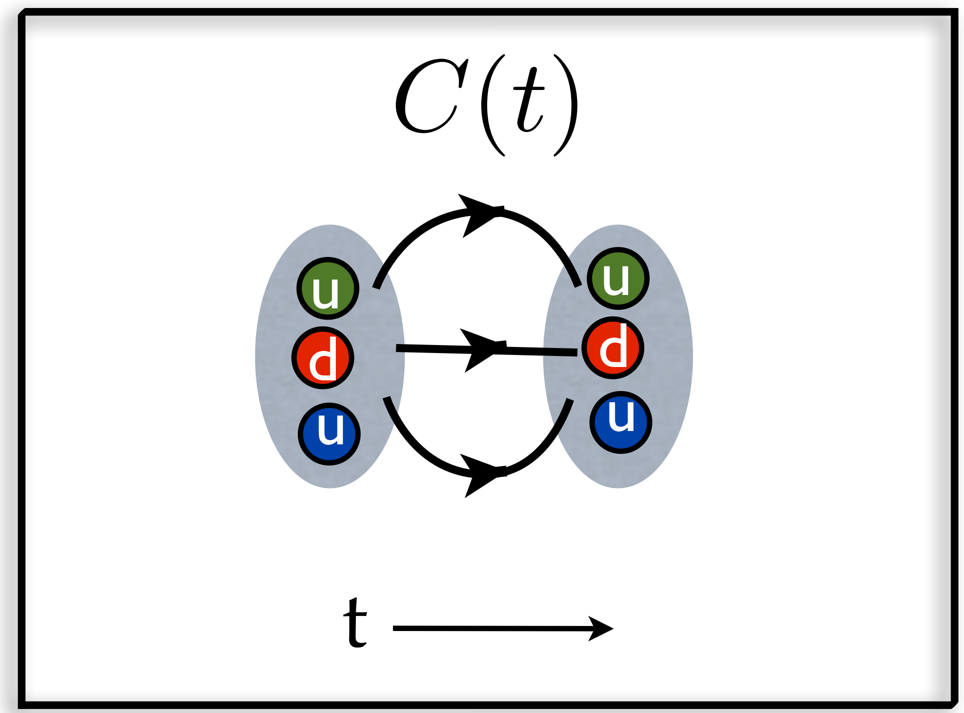
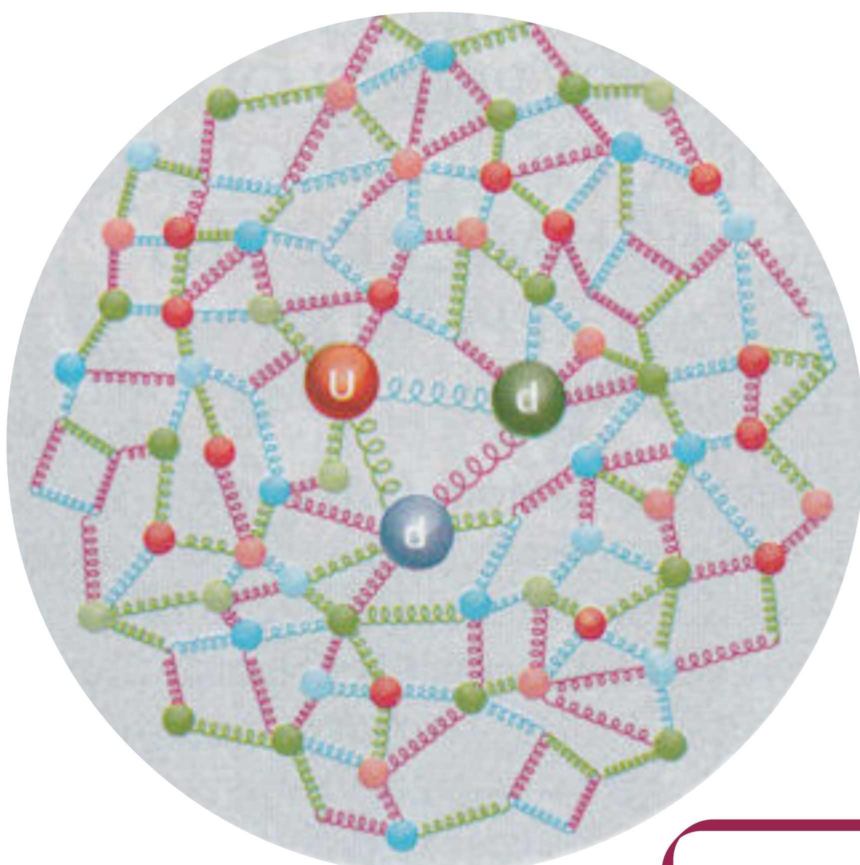
Like a Boltzmann factor

$\mathcal{O}$:





ψ_n :



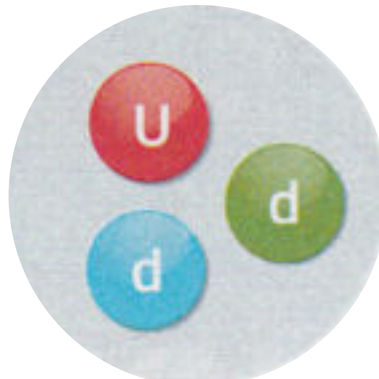
$$C(t) = A_0 e^{-E_0 t} + A_1 e^{-E_1 t} + A_2 e^{-E_2 t} + A_3 e^{-E_3 t} + \cdots$$

Calculating Observables

$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t}$$

Like a Boltzmann factor

$\mathcal{O}$:



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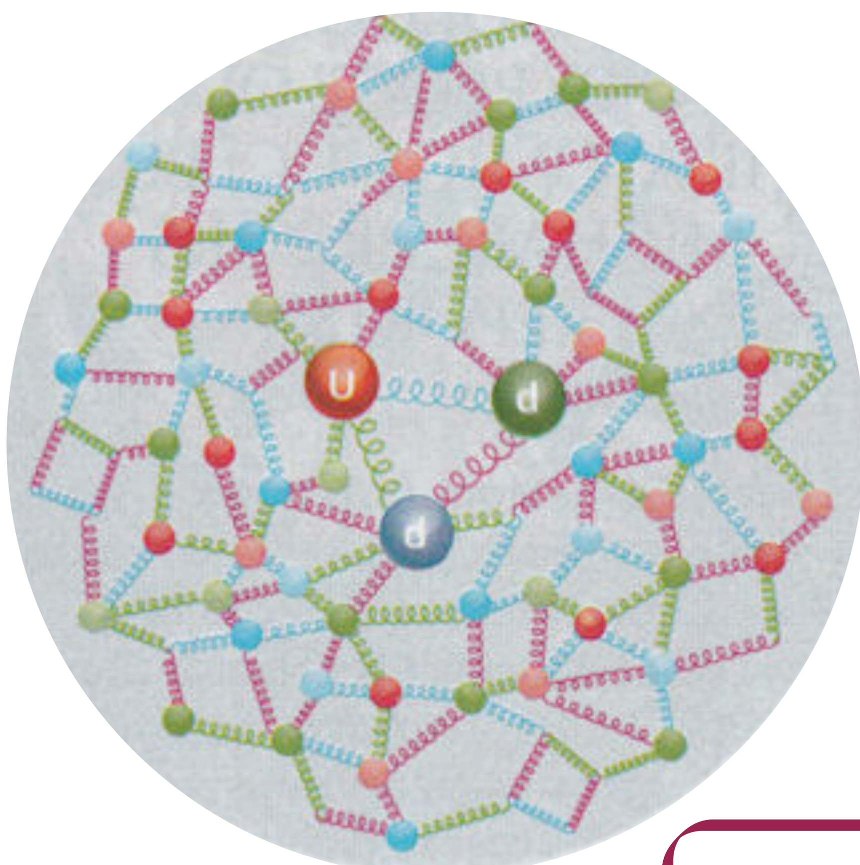
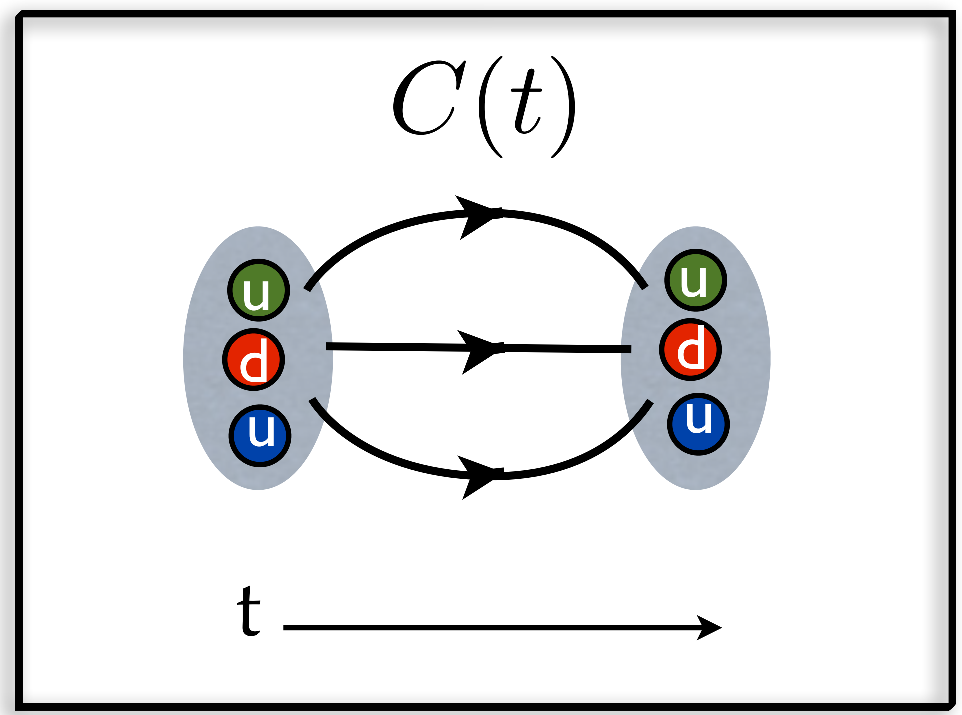




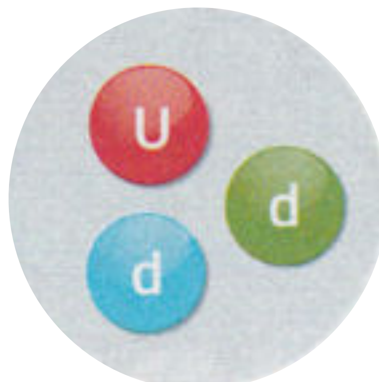
$$C(t) = A_0 e^{-E_0 t} + A_1 e^{-E_1 t} + A_2 e^{-E_2 t} + A_3 e^{-E_3 t} + \cdots$$

Calculating Observables

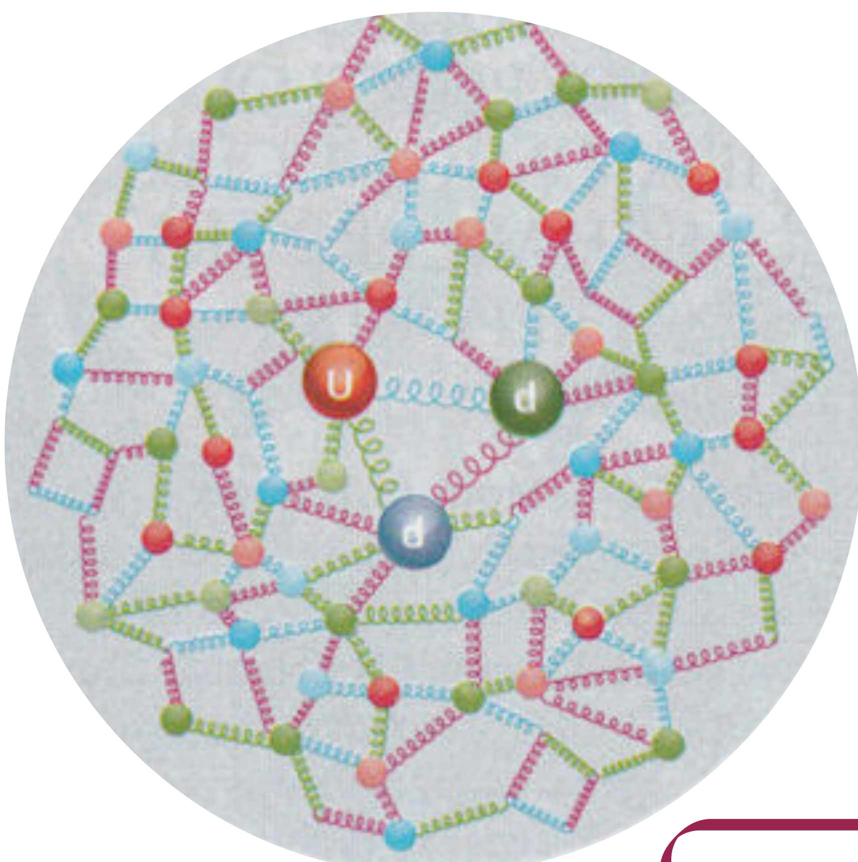
$$\langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = \langle \mathcal{O}(0)e^{-Ht}\mathcal{O}(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n t}$$

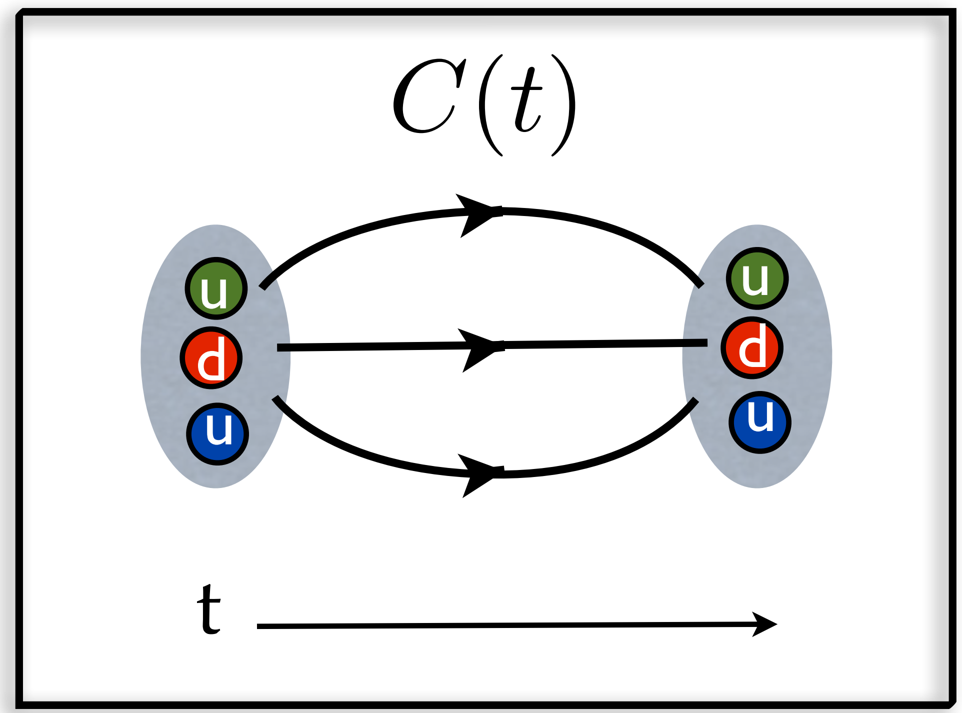
Like a Boltzmann factor

$\mathcal{O}$:



ψ_n :





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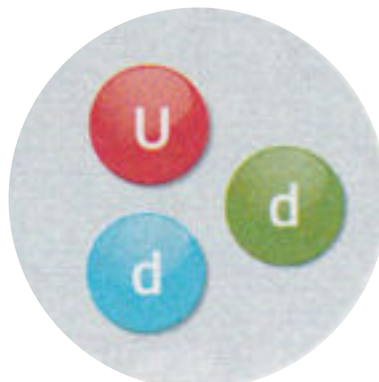

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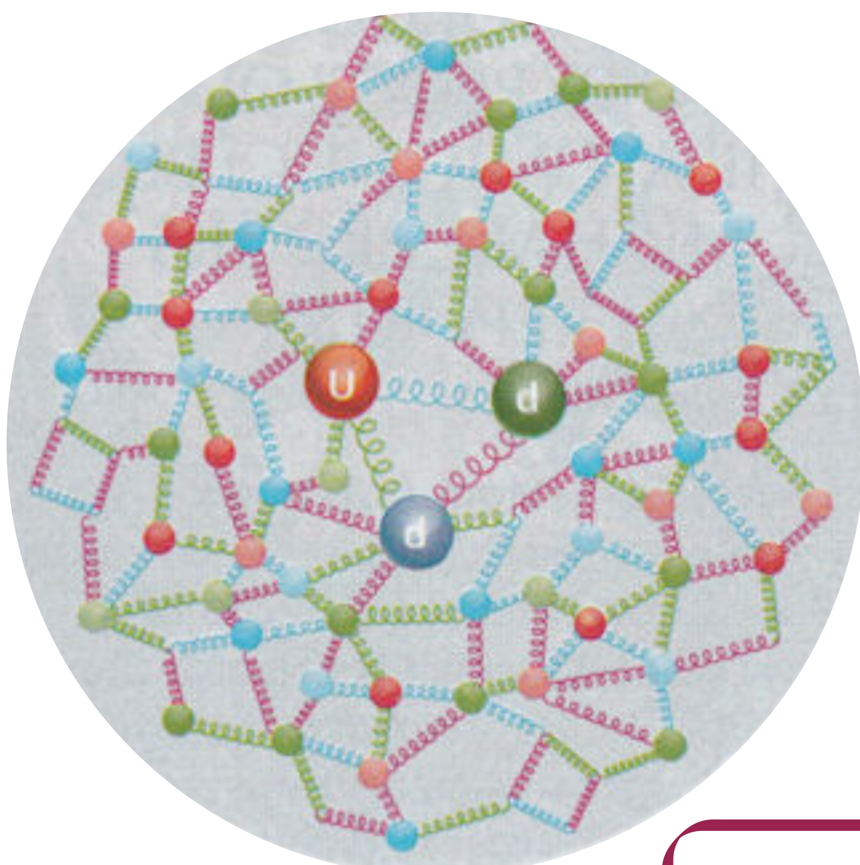

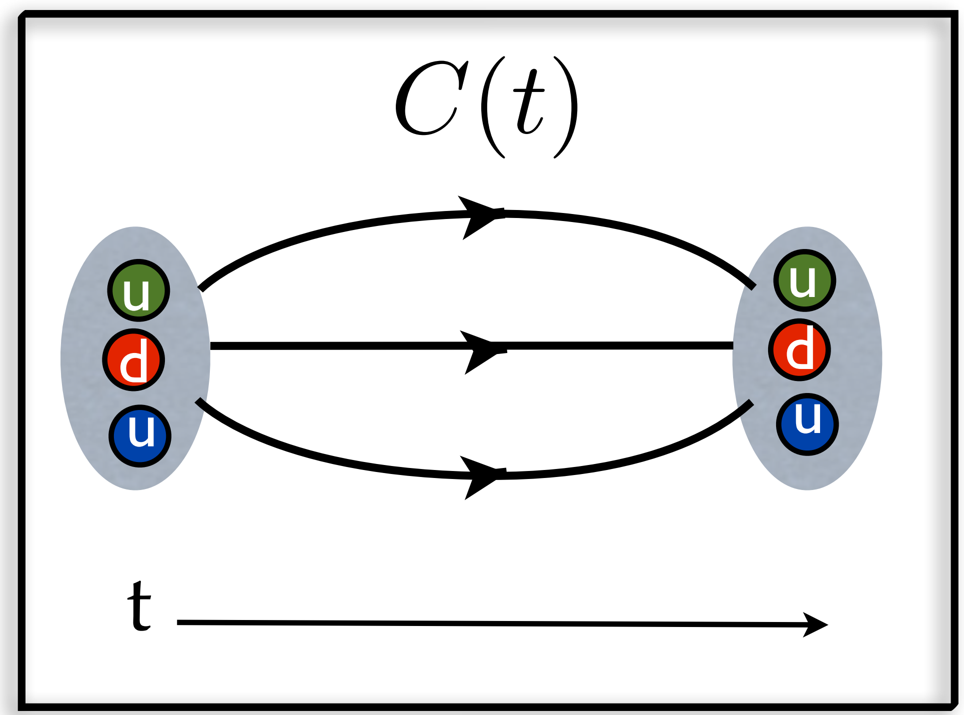

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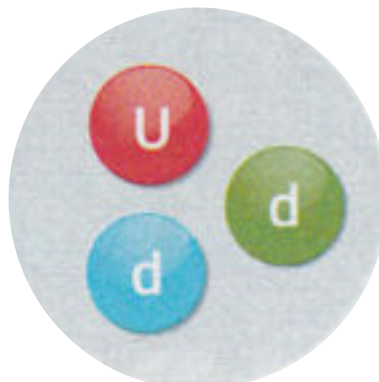

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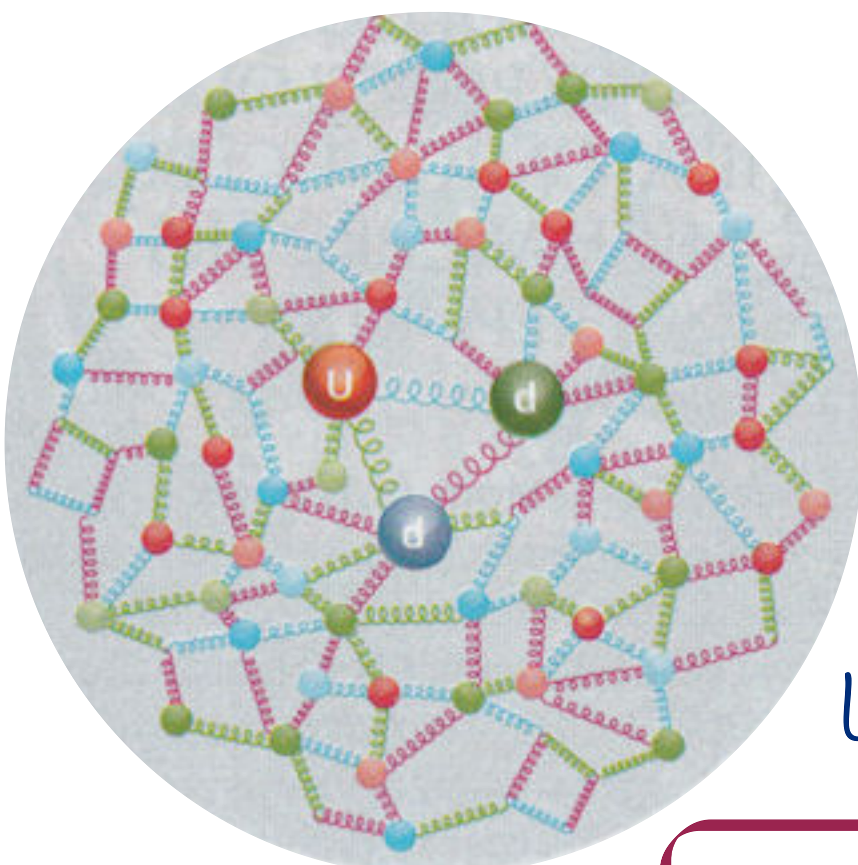

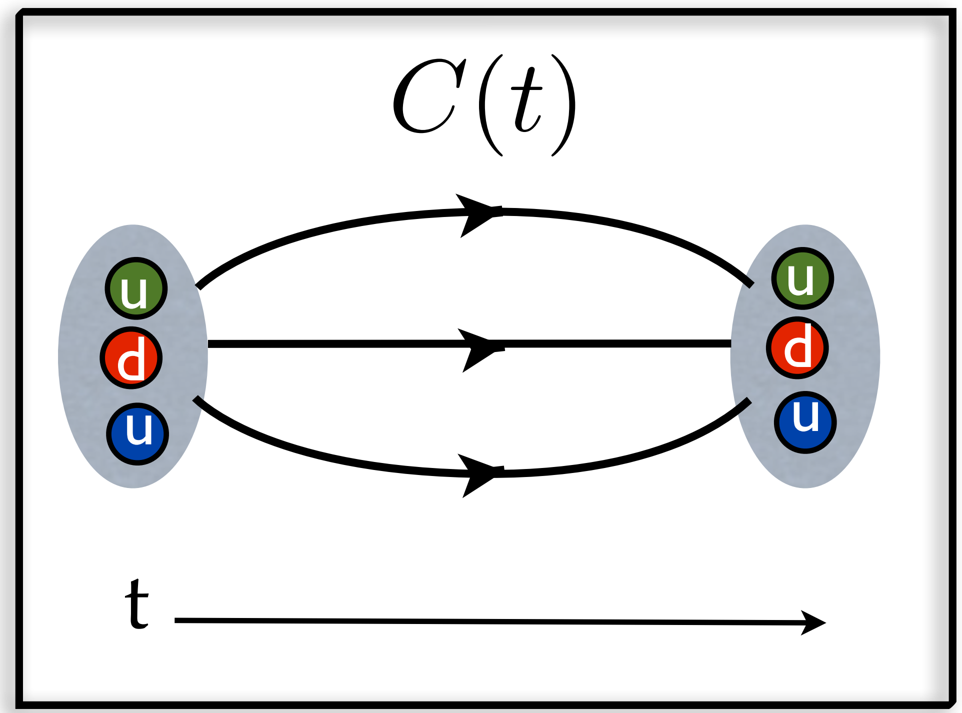

Long time limit = zero temperature

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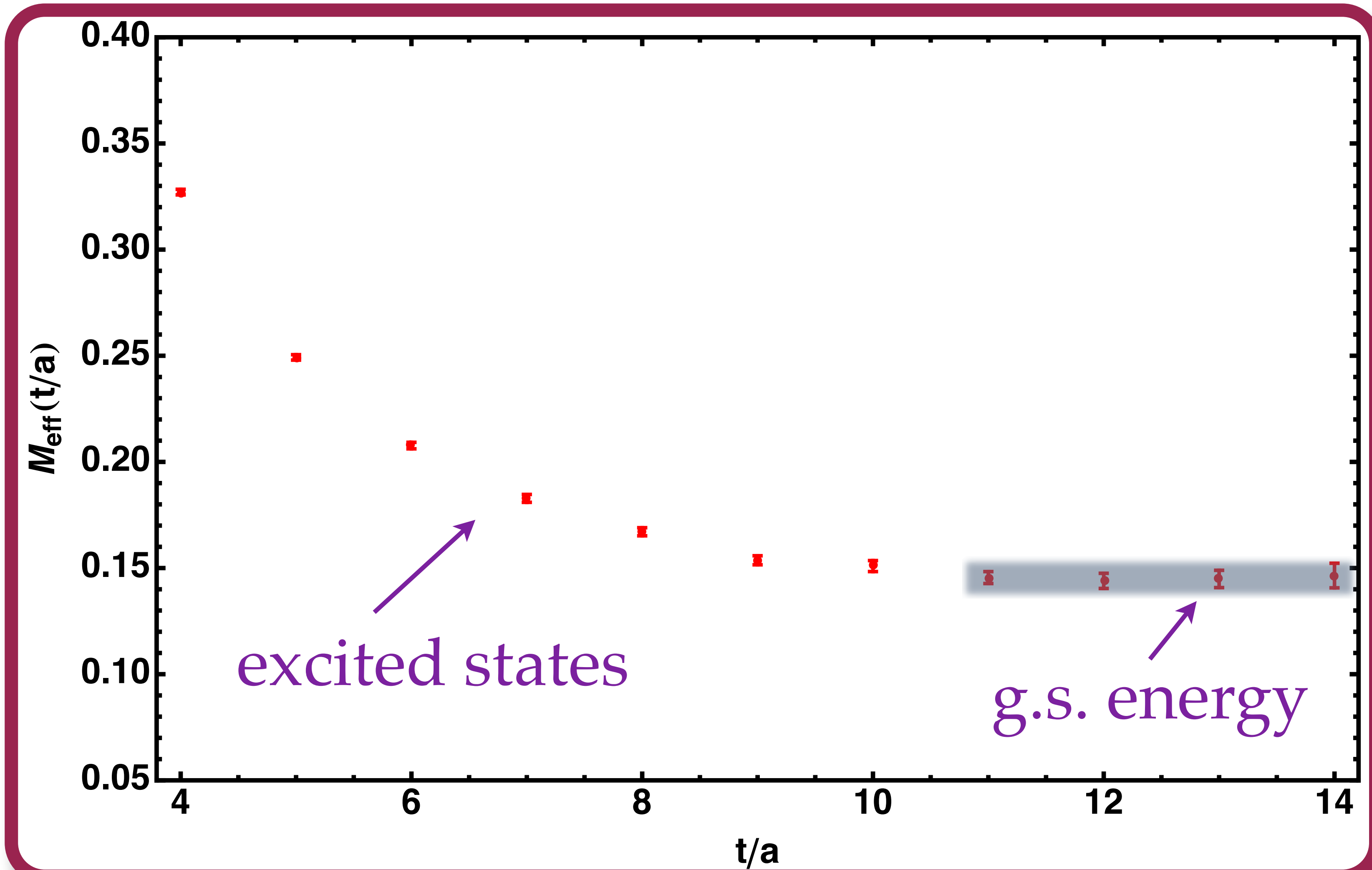
Calculating Observables



Effective mass plot:

$$M_{\rm eff} \equiv \ln \frac{C(t)}{C(t+1)}$$

$$\xrightarrow[t\to\infty]{} E_0$$

Long time limit = zero temperature

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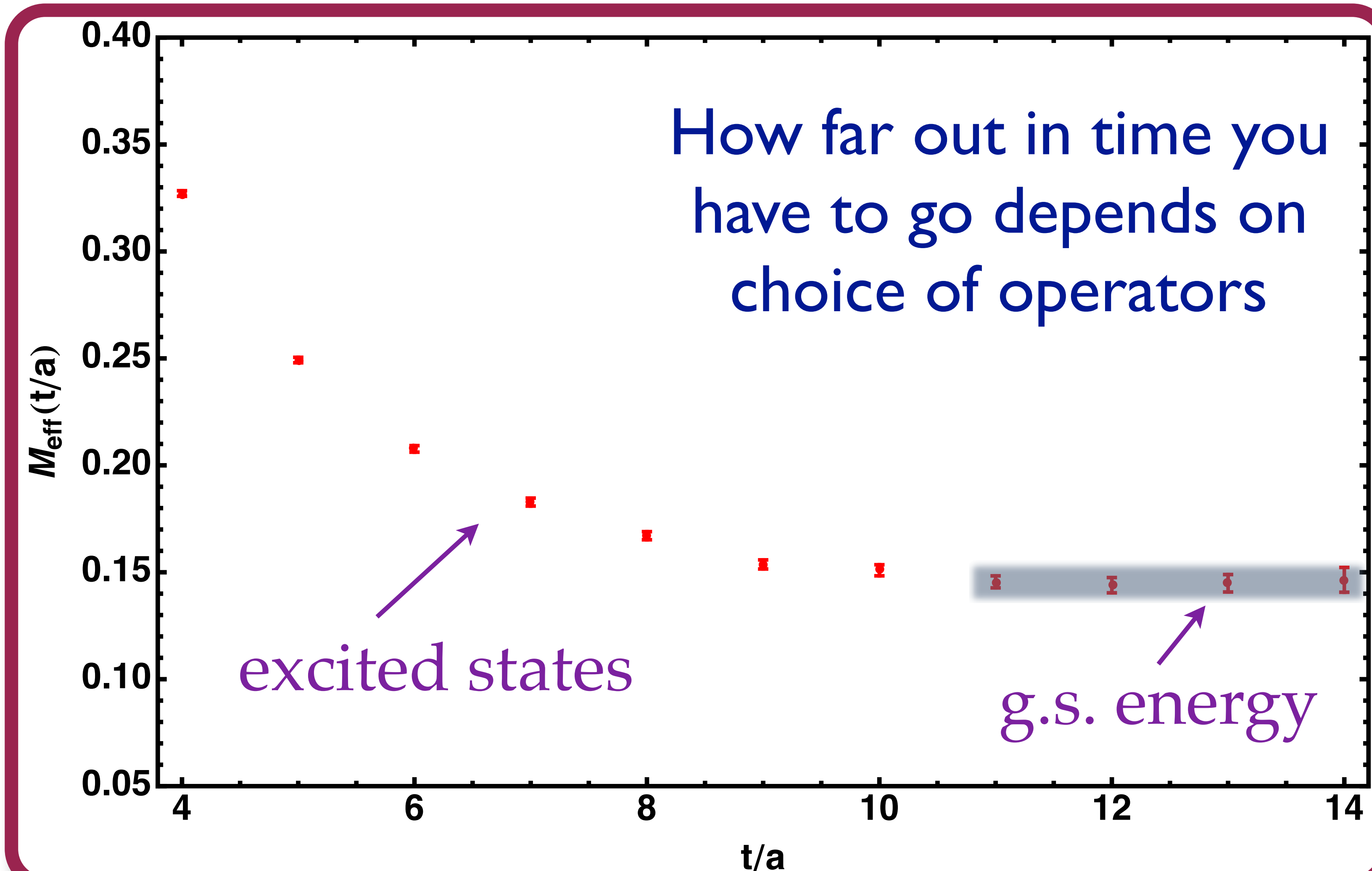

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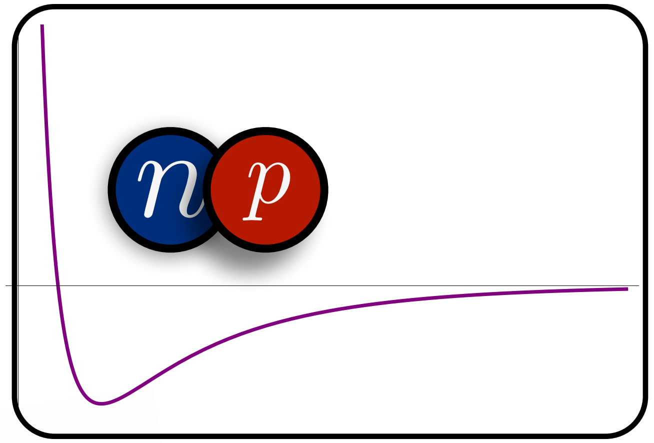
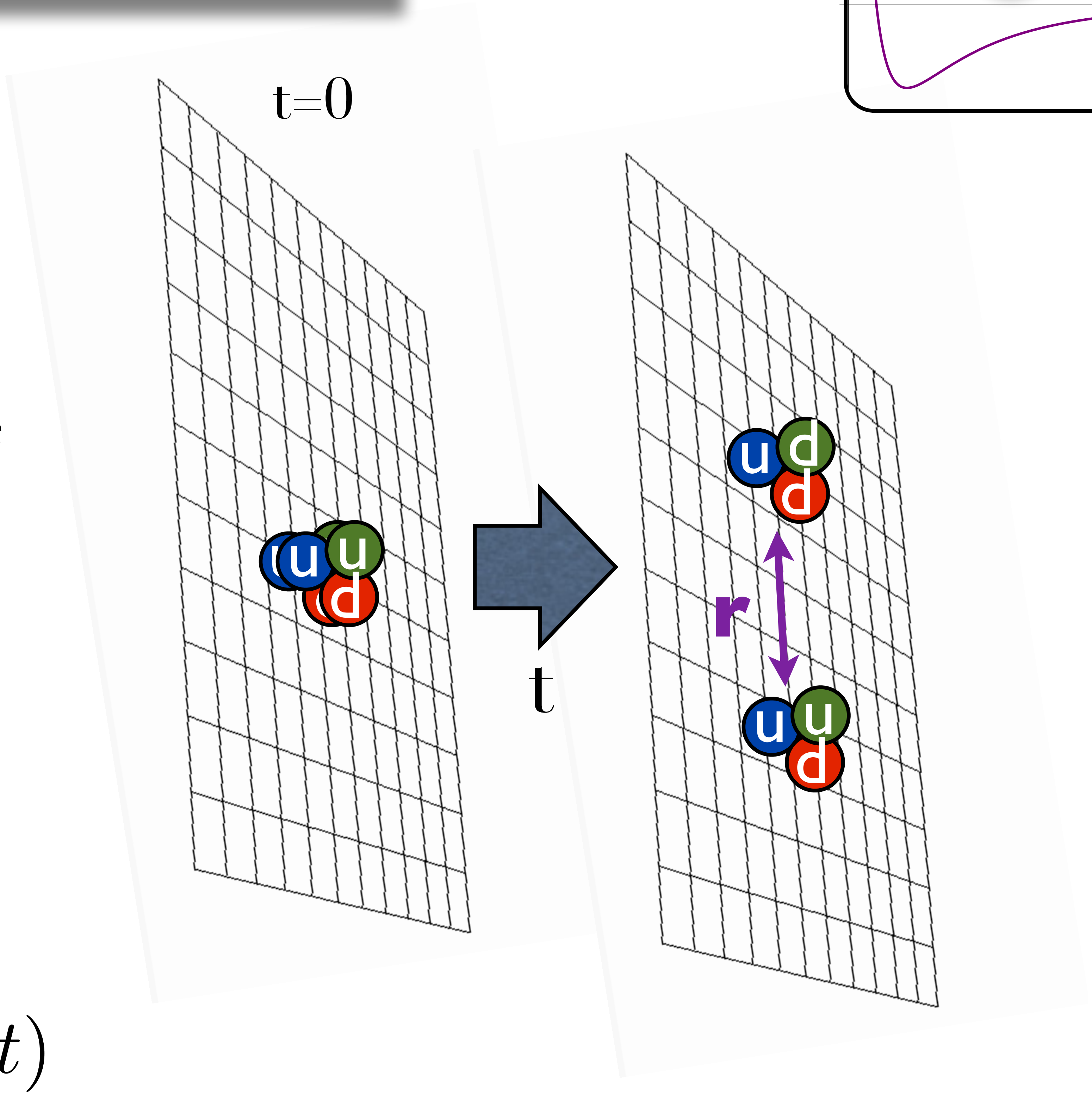
Potential method

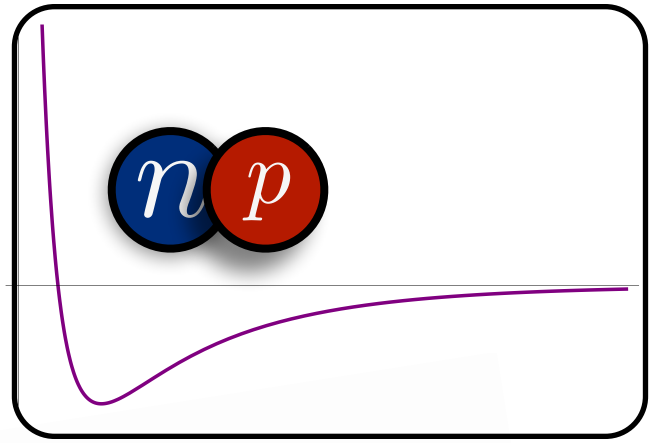


1. Create the following correlation function:



$$C_{NN}(\mathbf{r}, t)$$

Potential method



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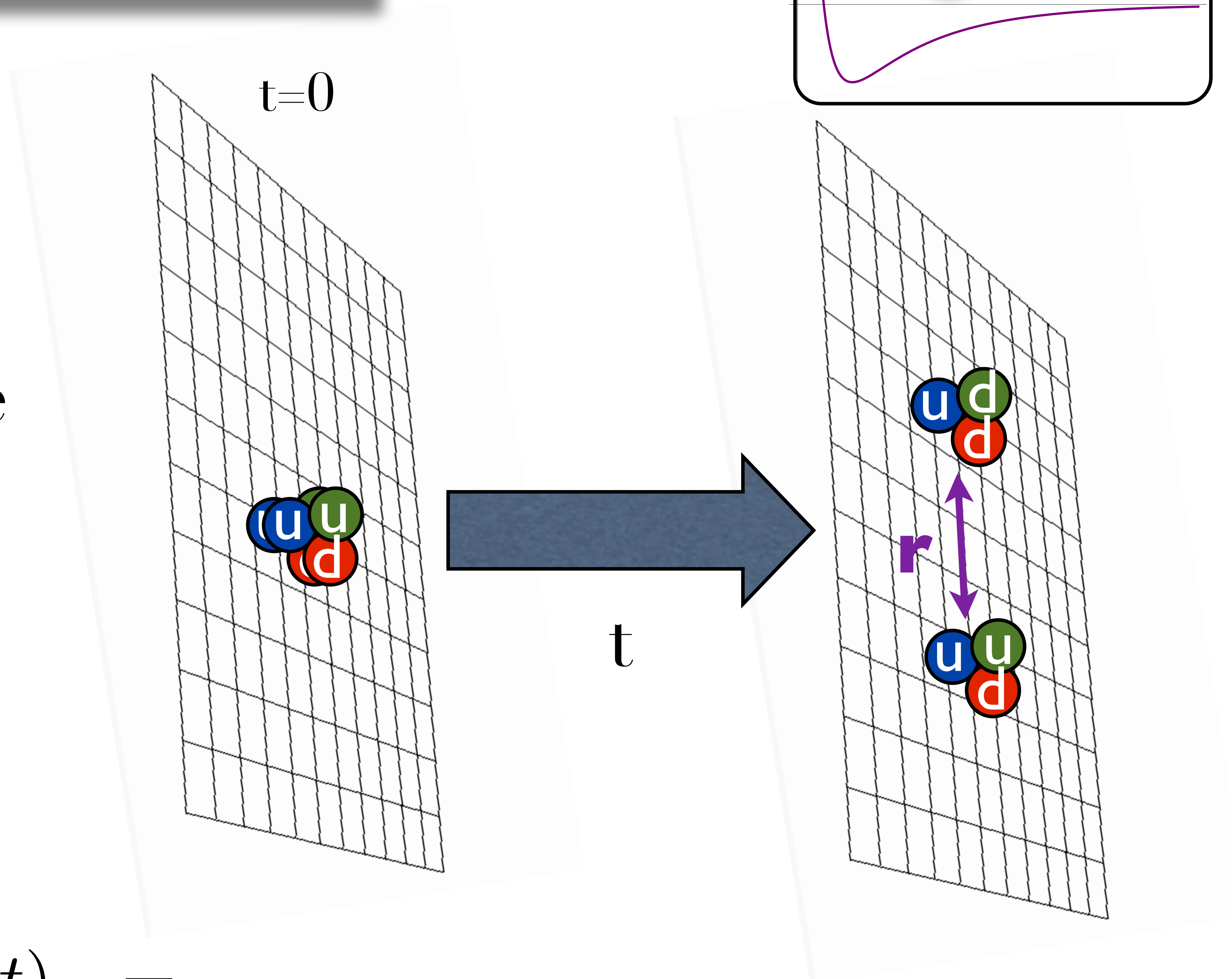
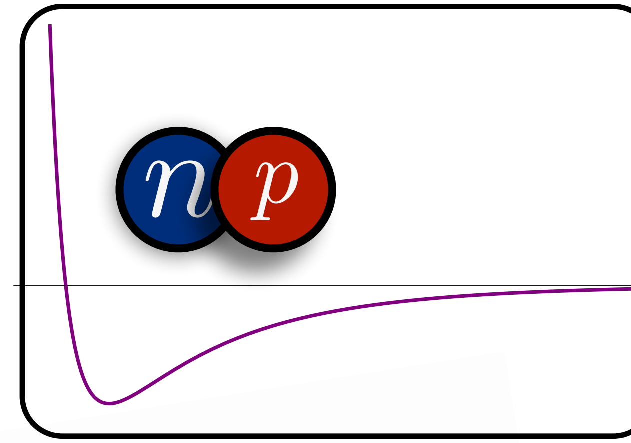
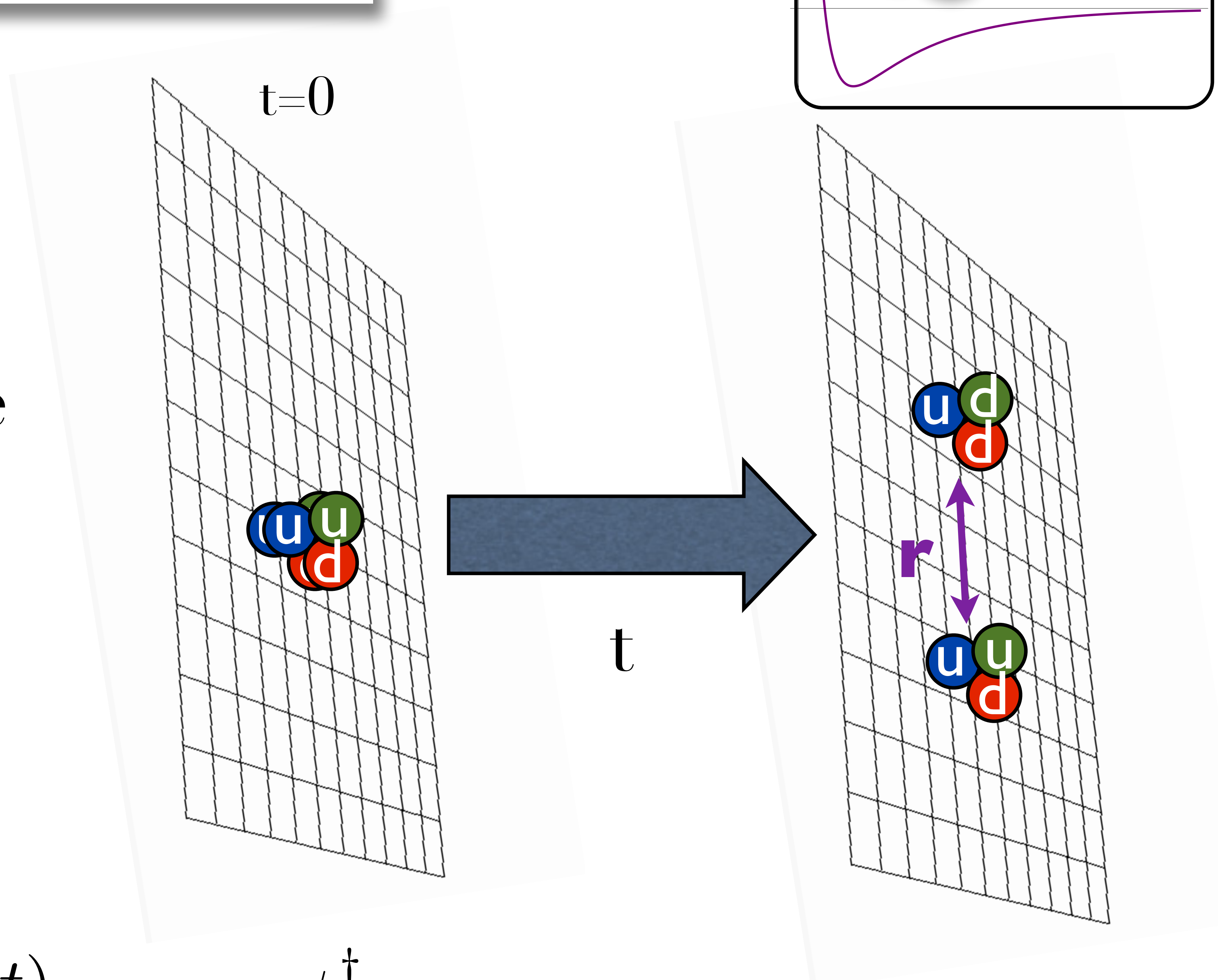


$$\lim_{t\to\infty} C_{NN}(\mathbf{r}, t) \quad =$$

Potential method

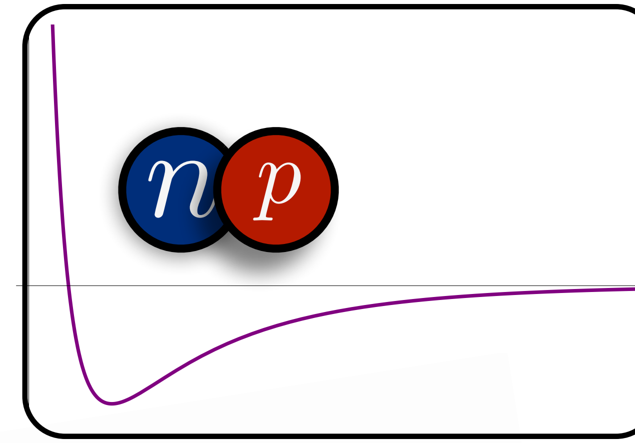


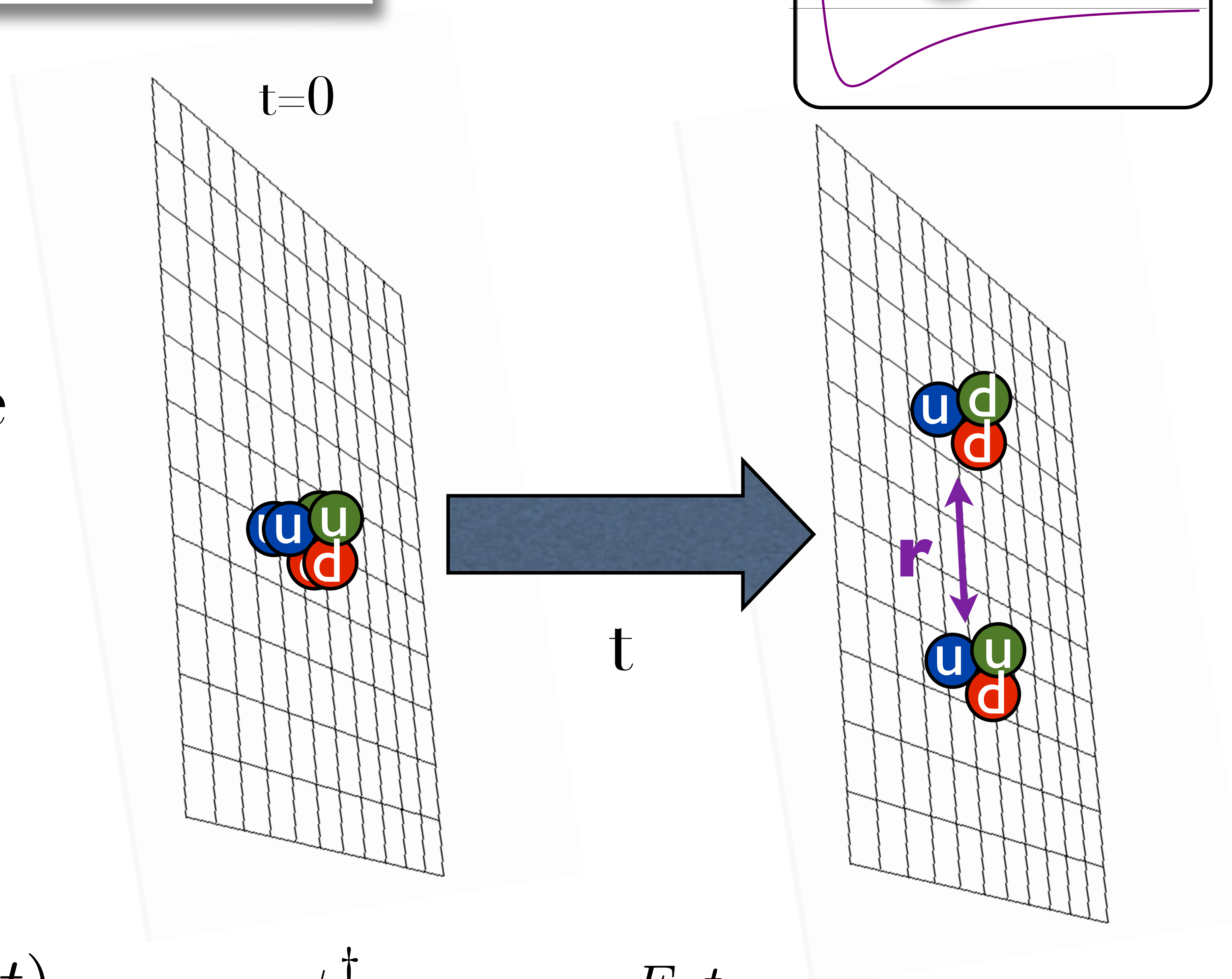


1. Create the following correlation function:

$$\lim_{t\to\infty} C_{NN}(\mathbf{r},t) \quad = \quad \psi_0^\dagger$$

Potential method





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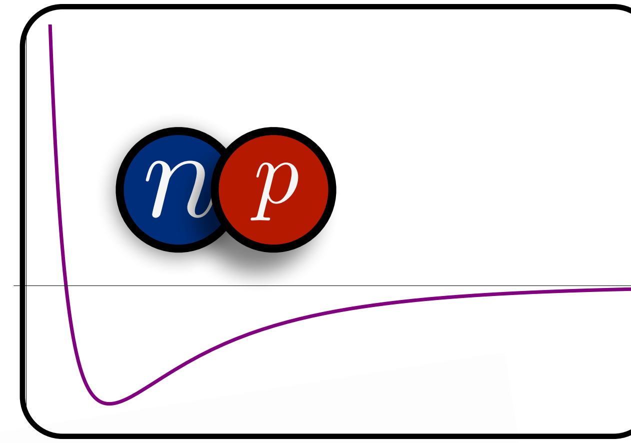
$$\lim_{t\to\infty} C_{NN}(\mathbf{r},t) = \psi_0^\dagger \times e^{-E_0 t}$$

Potential method



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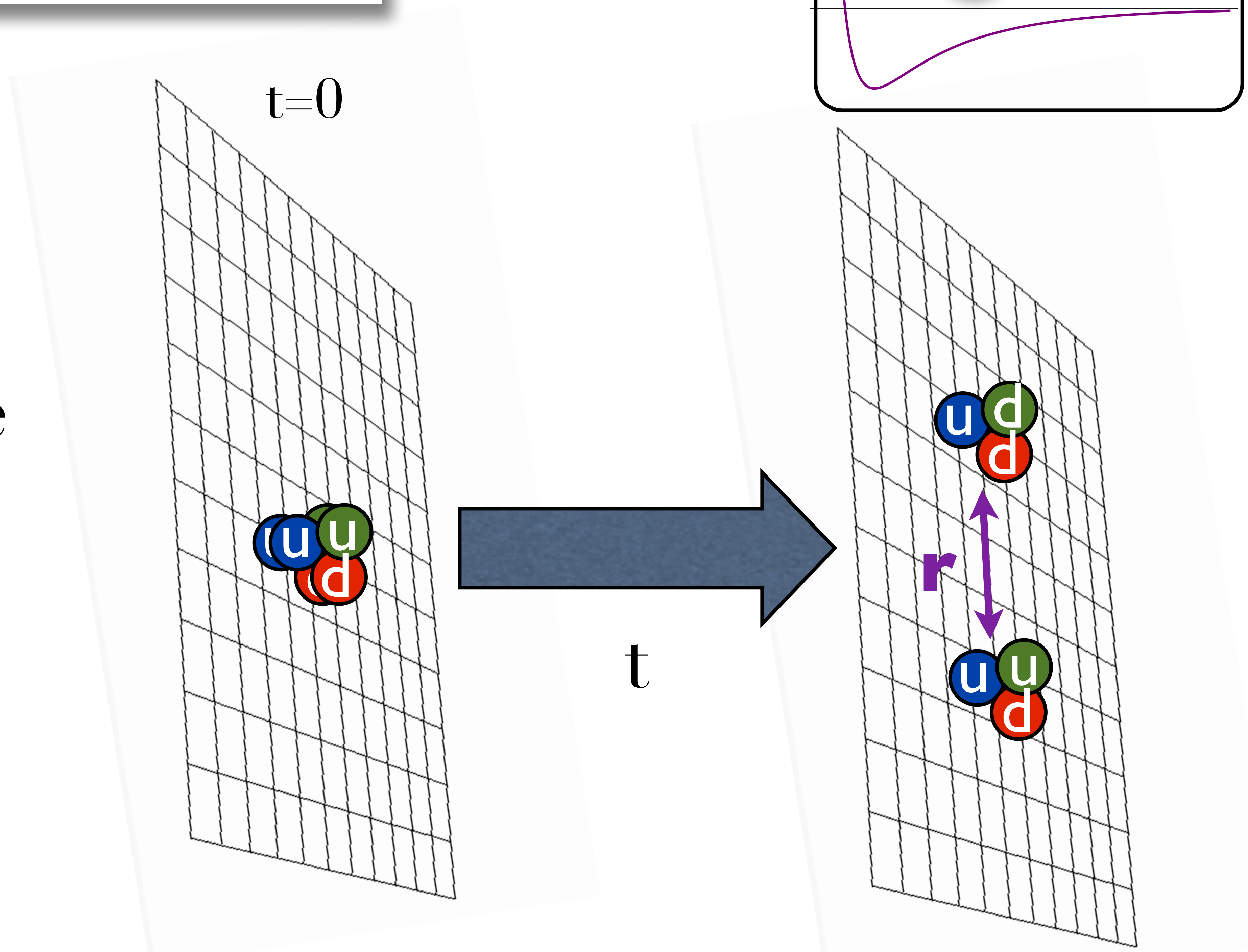
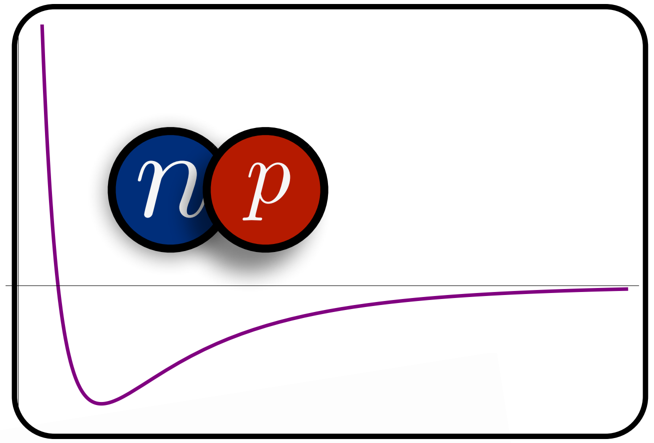


$$\lim_{t\to\infty} C_{NN}(\mathbf{r},t) = \psi_0^\dagger \times e^{-E_0 t} \times \psi_0(\mathbf{r})$$

Potential method



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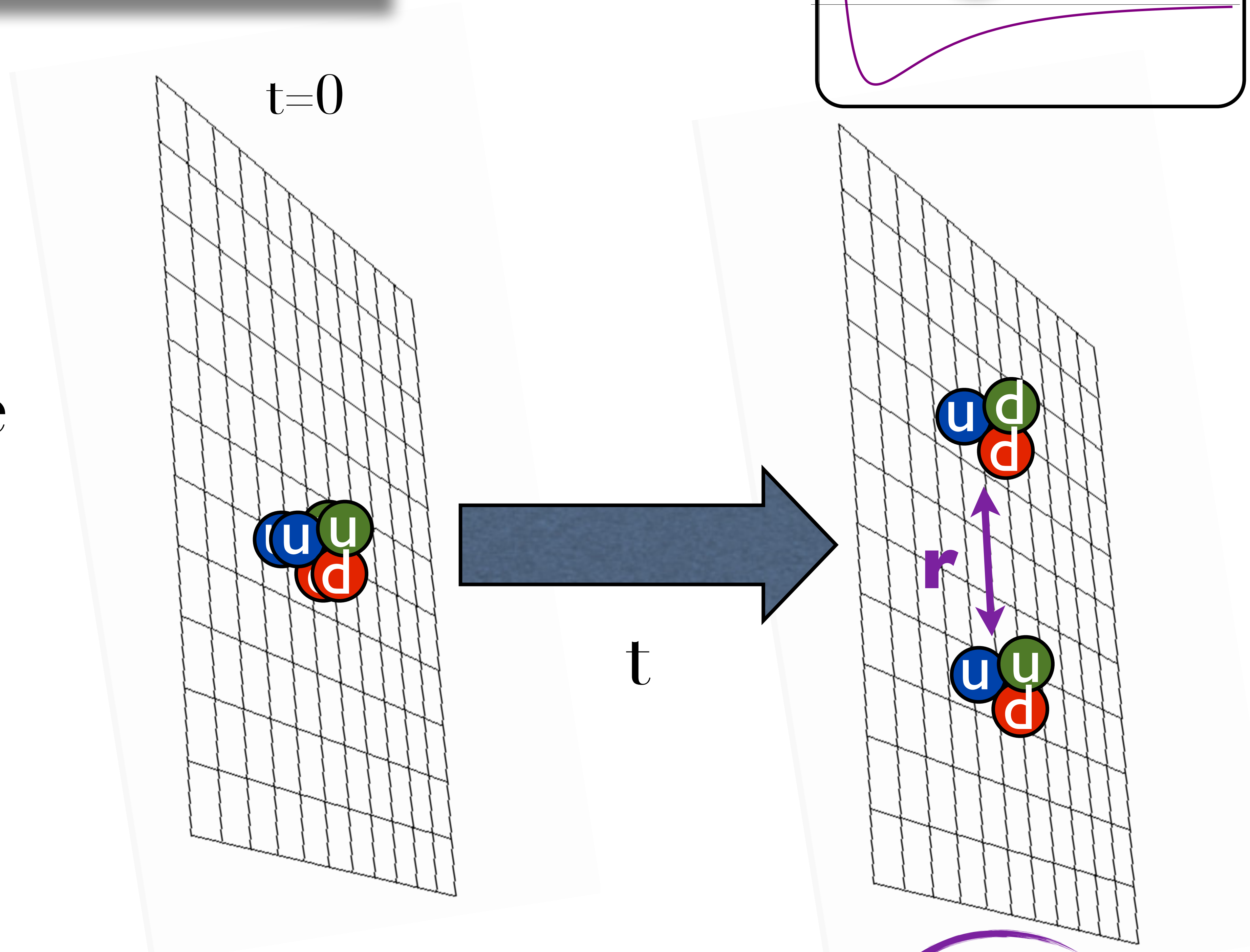

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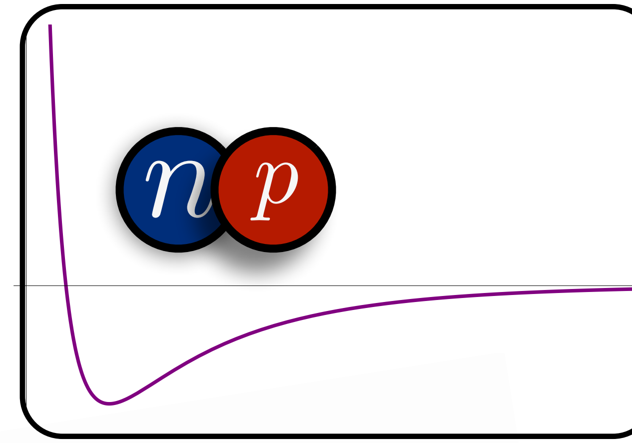
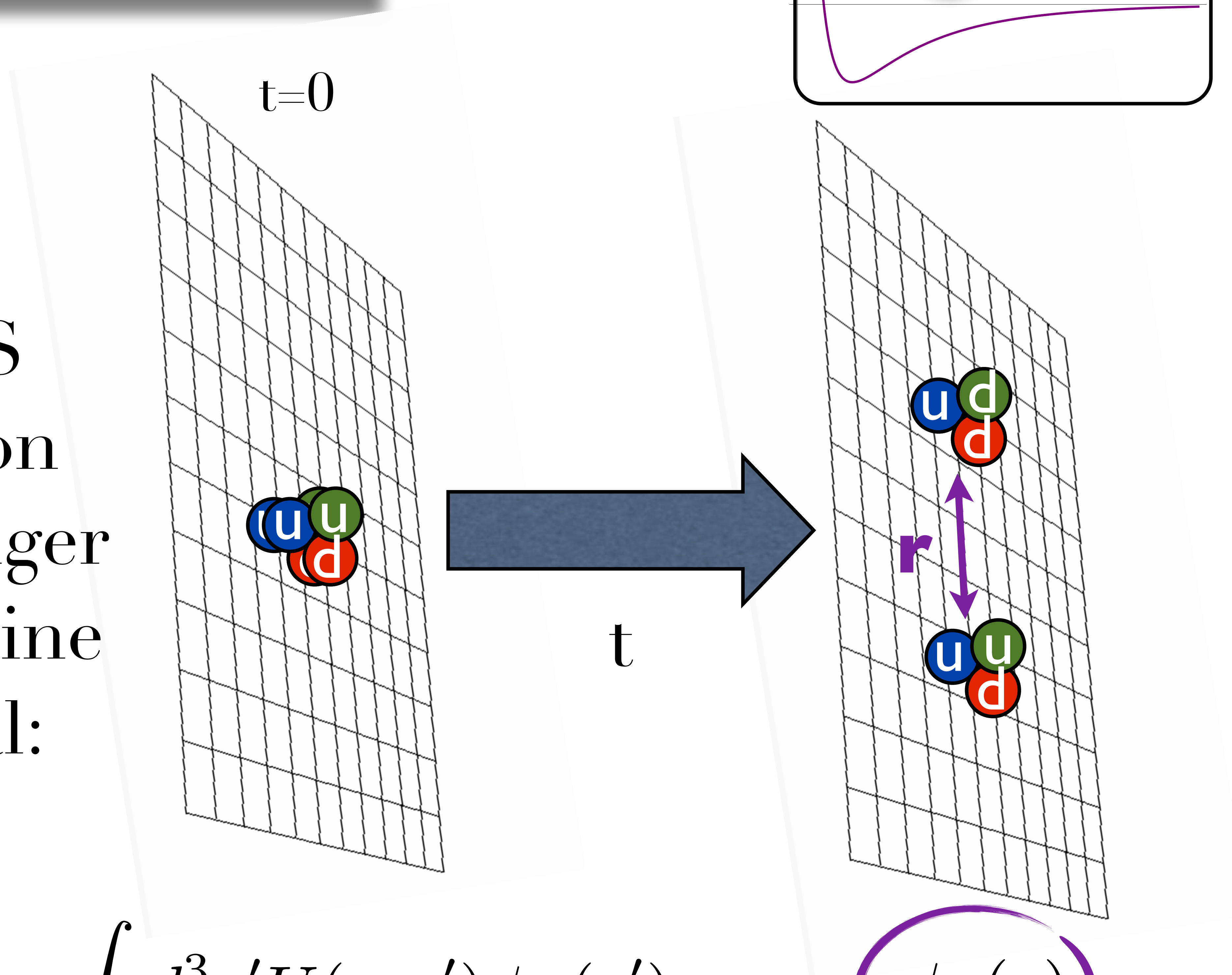
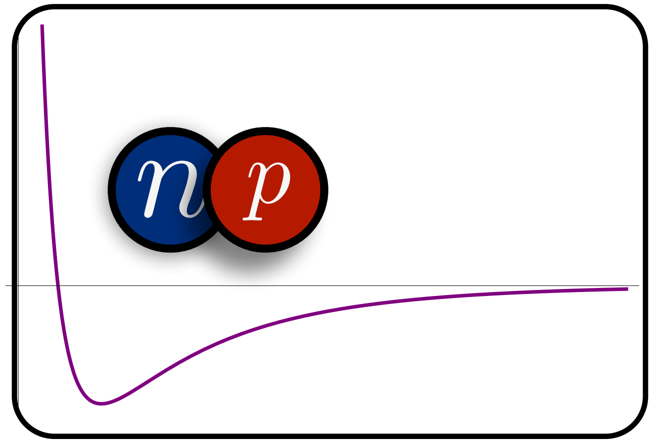




2. Plug NBS wave-function into Schrödinger Eq. to determine the potential:

$$\left[\frac{\mathbf{p}^2}{2\mu} - H_0\right]\psi_{\mathbf{p}}(\mathbf{r}) = \int d^3r' U(\mathbf{r},\mathbf{r}')\psi_{\mathbf{p}}(\mathbf{r}') \longleftarrow \psi_0(\mathbf{r})$$

Potential method



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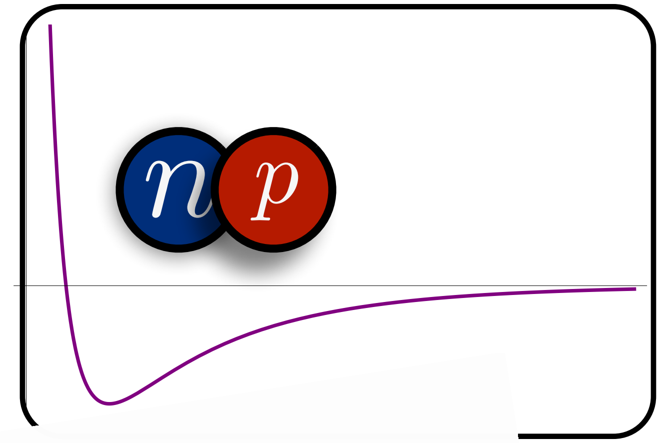
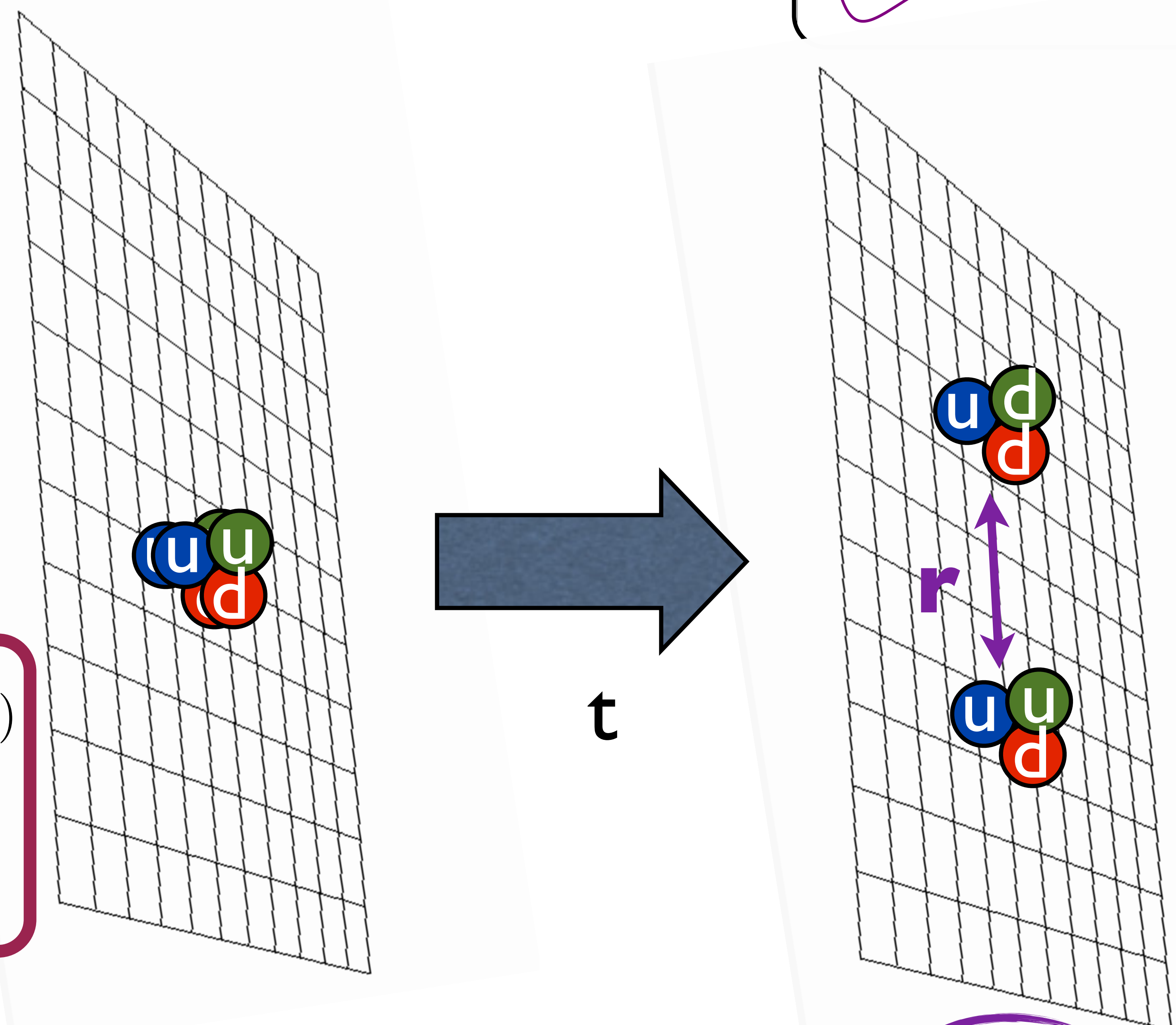


3. Use derivative expansion to determine the leading order potential:

$$U(\mathbf{r},\mathbf{r}') = V_C(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}') + \mathcal{O}(\nabla_{\mathbf{r}}^2/\Lambda^2)$$

$$V_C(\mathbf{r}) \simeq \frac{\mathbf{p}^2}{2\mu} + \lim_{t\to\infty}\frac{1}{2\mu}\frac{\nabla_{\mathbf{r}}^2 C_{NN}(\mathbf{r},t)}{C_{NN}(\mathbf{r},t)}$$



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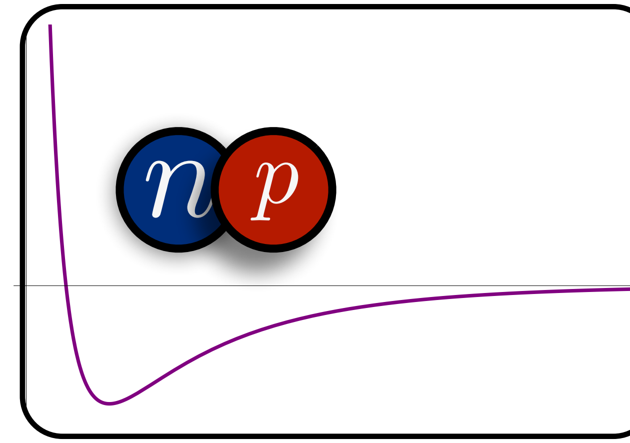

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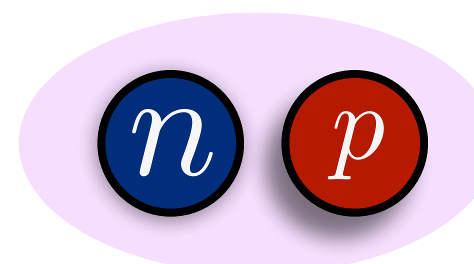
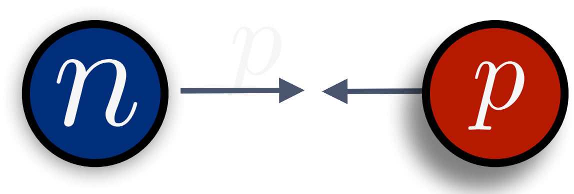
Binding energies



Phase shifts



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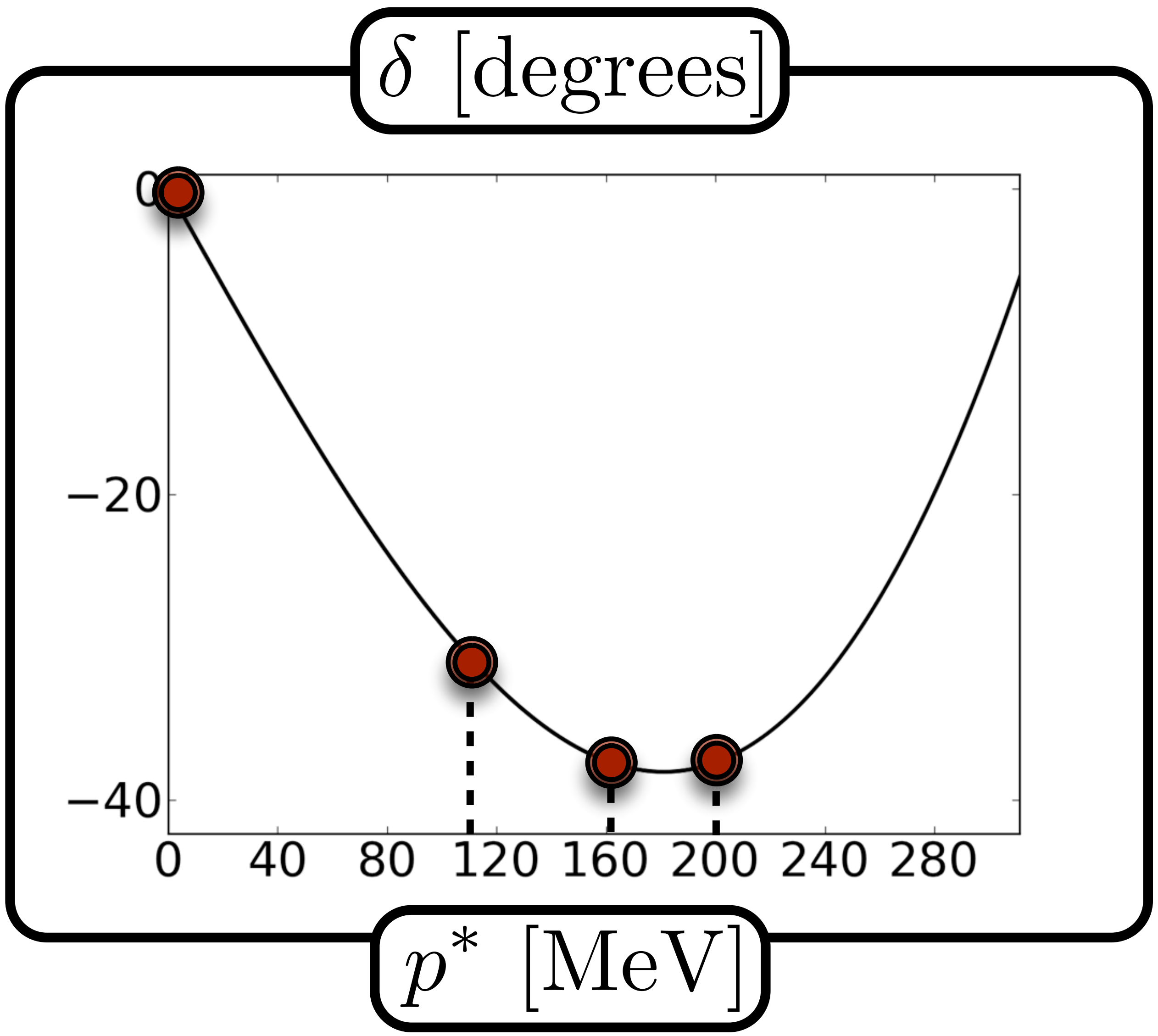
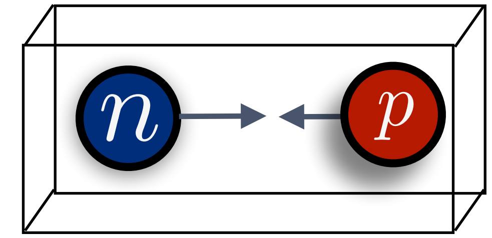
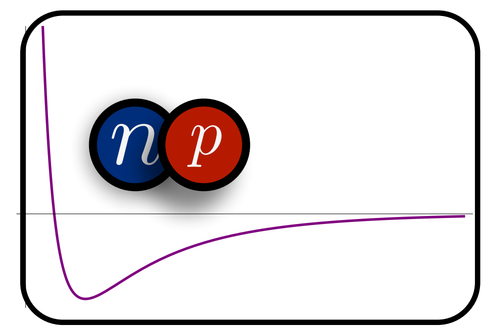
Some comparisons between methods





Luscher

- discrete phase shifts
- need single state saturation
- no volume extrapolation
- no uncontrolled approximations

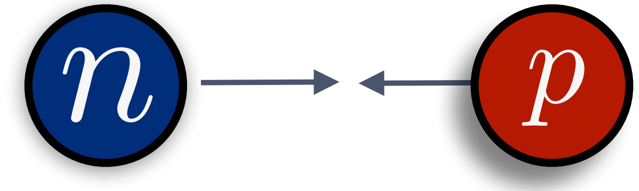


Potential

- nearly continuous phase shifts
- only need elastic state saturation
- need volume extrapolation
- cutoff in gradient expansion

$$U(\mathbf{r},\mathbf{r}') = V_C(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}') + \mathcal{O}(\nabla^2_{\mathbf{r}}/\Lambda^2)$$

NN scattering: Lüscher



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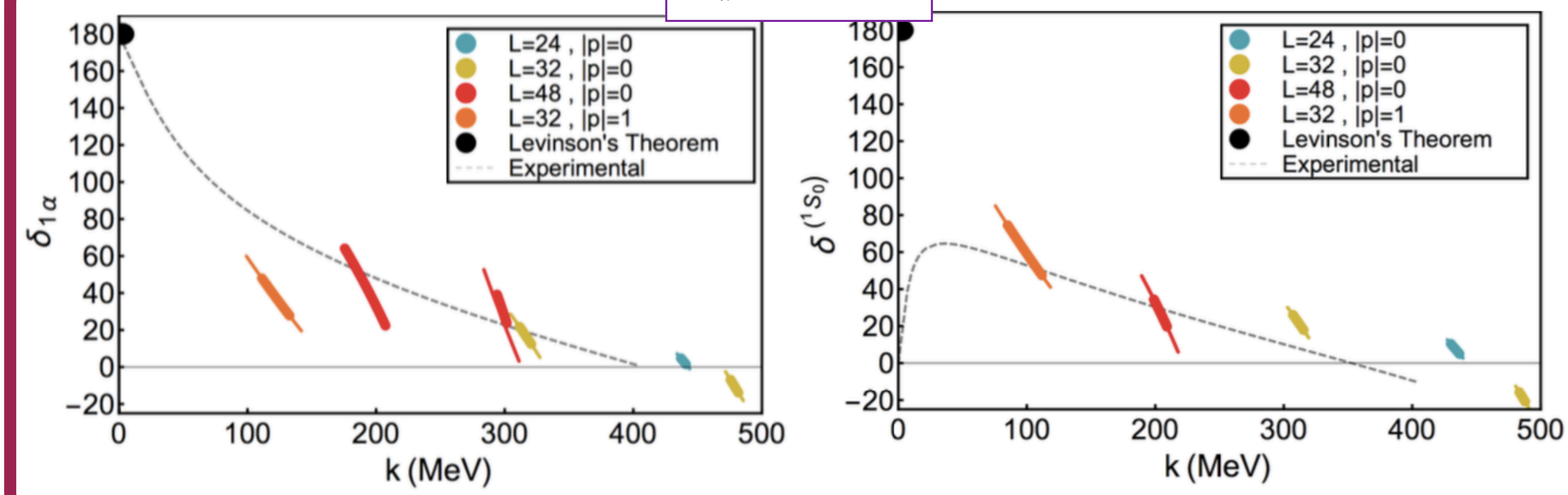
m_π ~ 450 MeV



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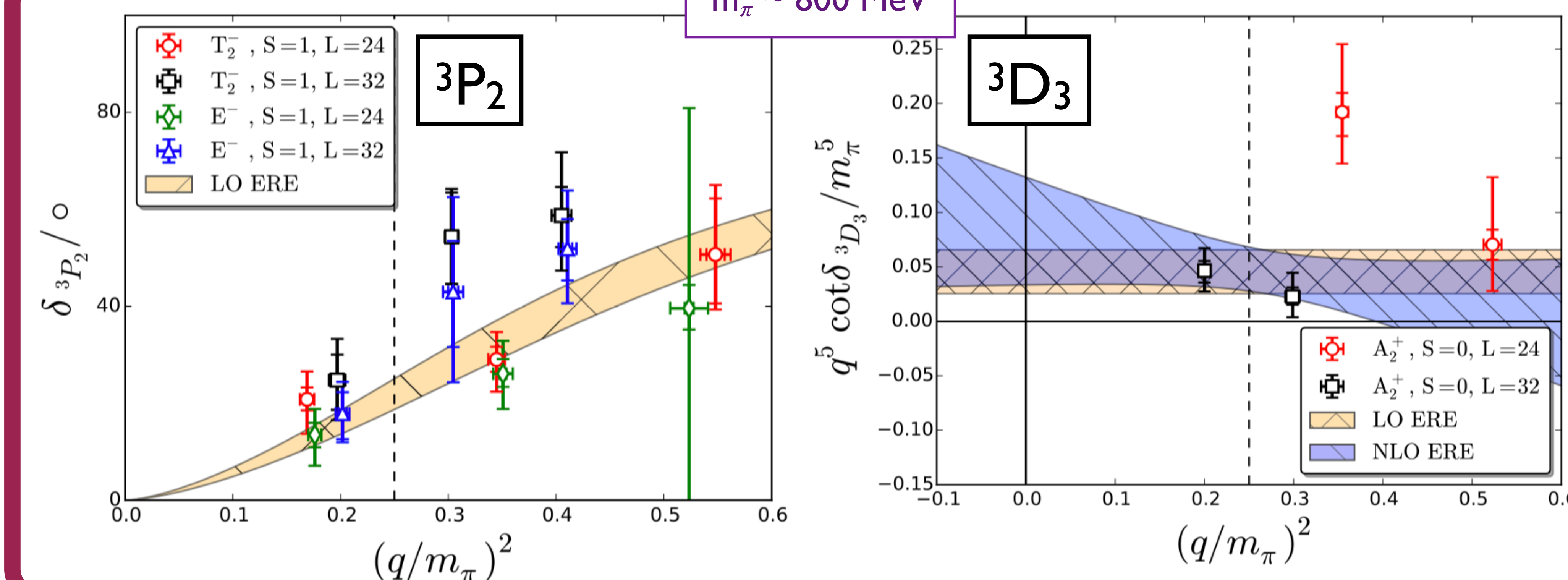
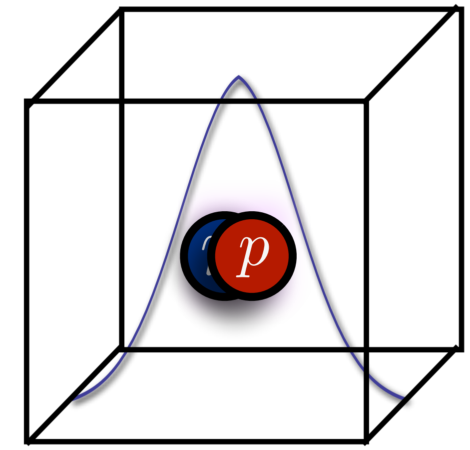
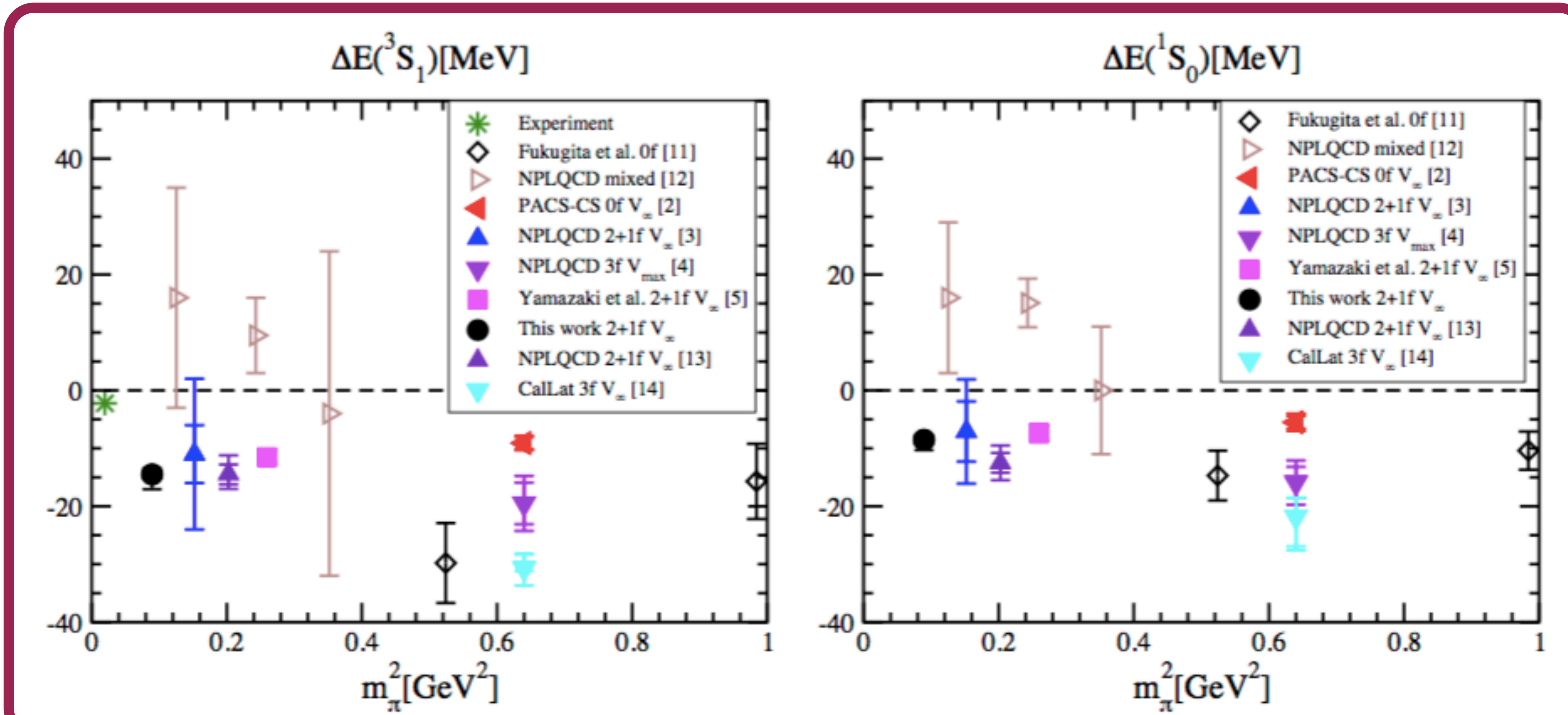


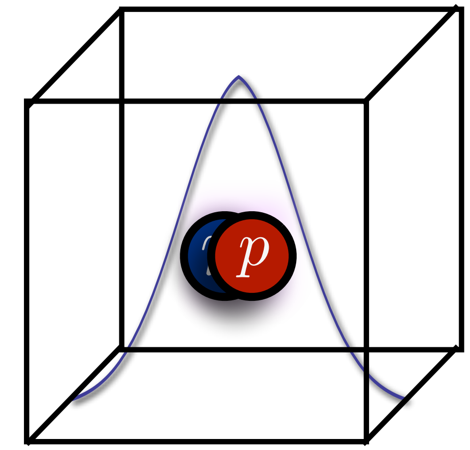
NN Binding energies

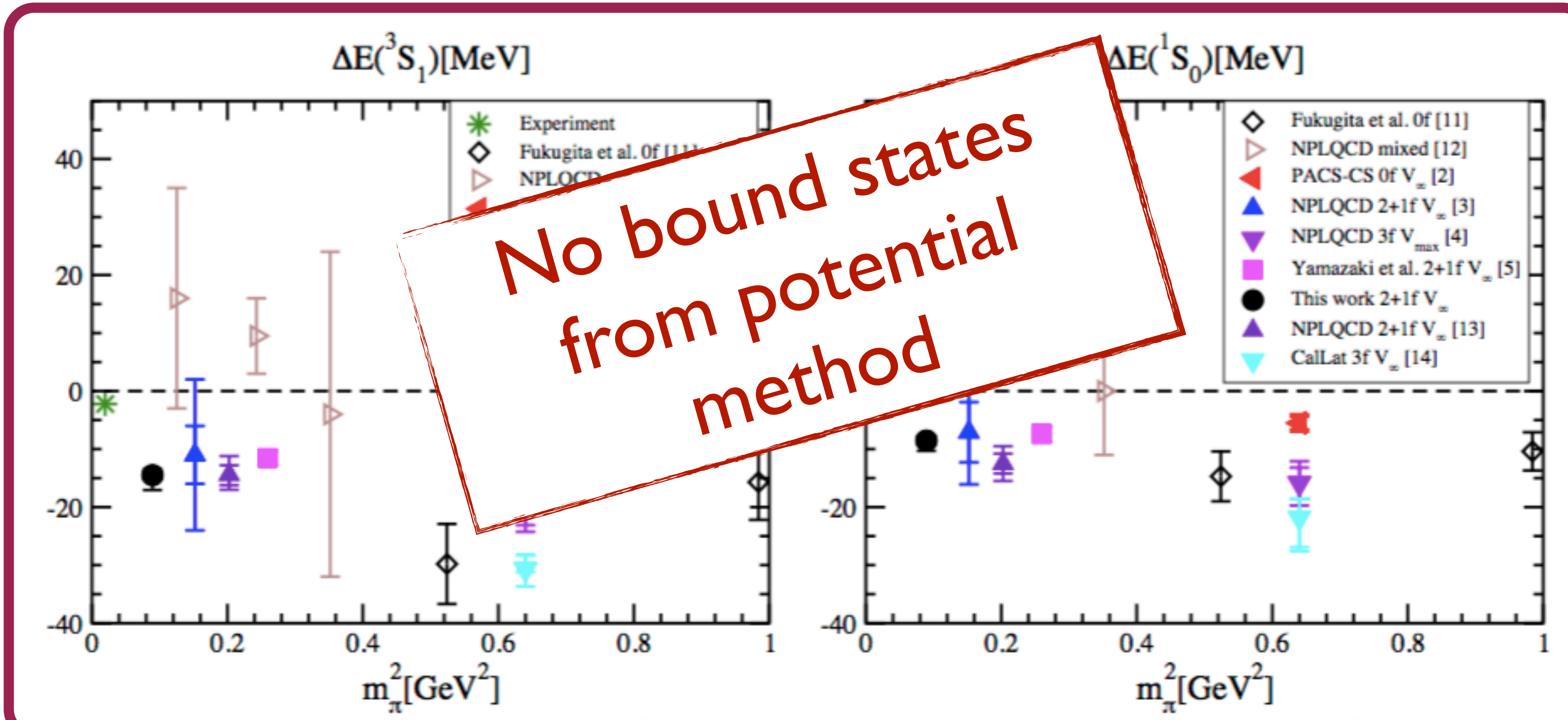




T. Yamazaki, arXiv:1511.09179

NN Binding energies





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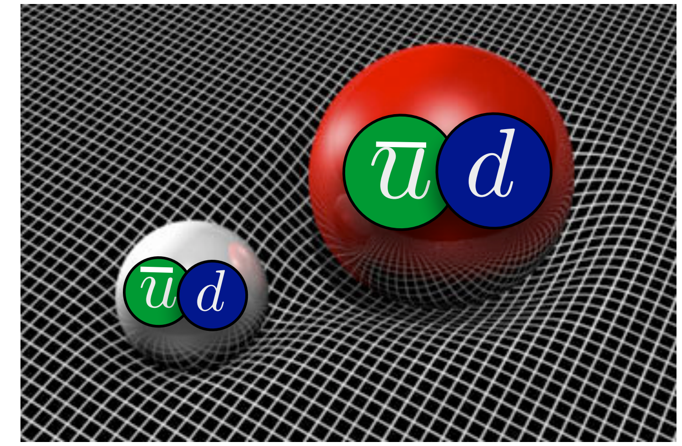
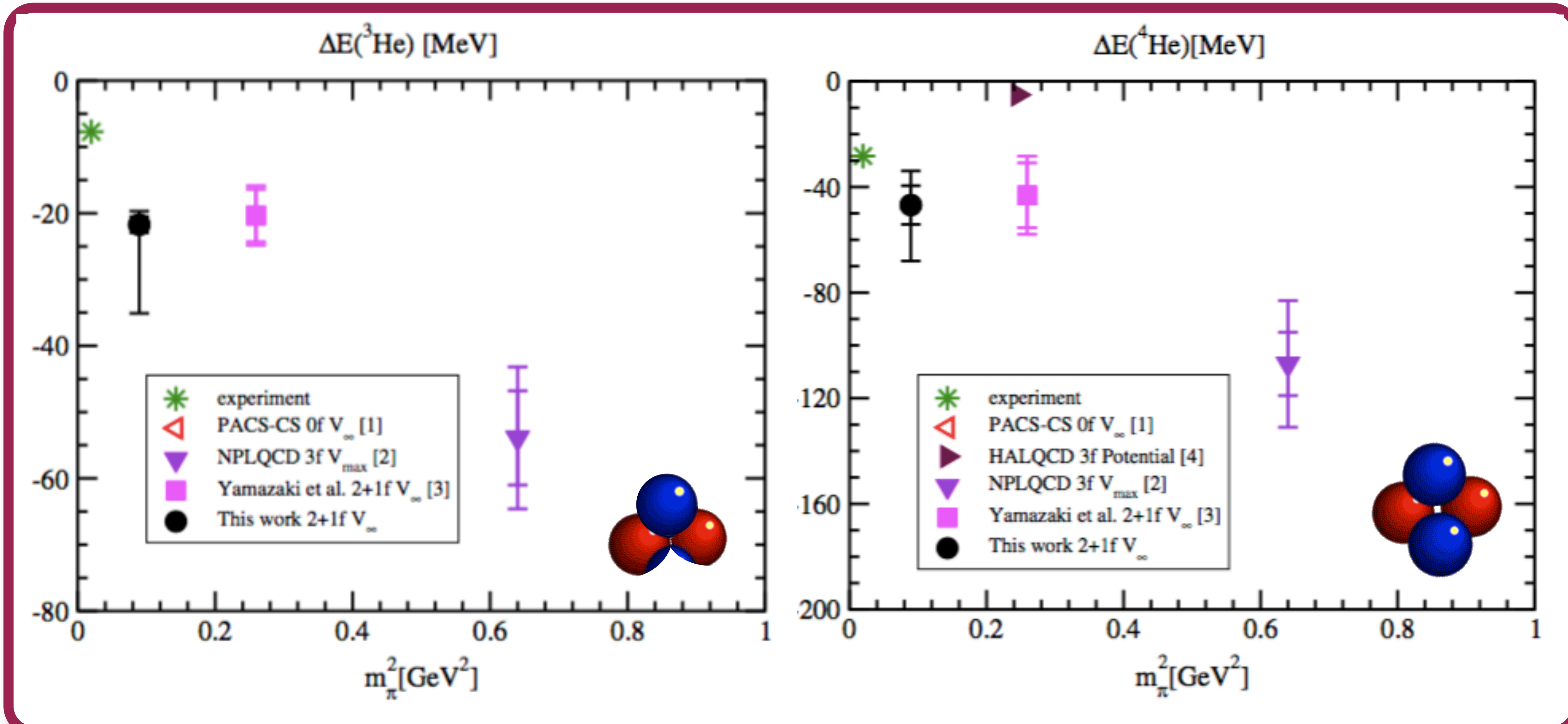
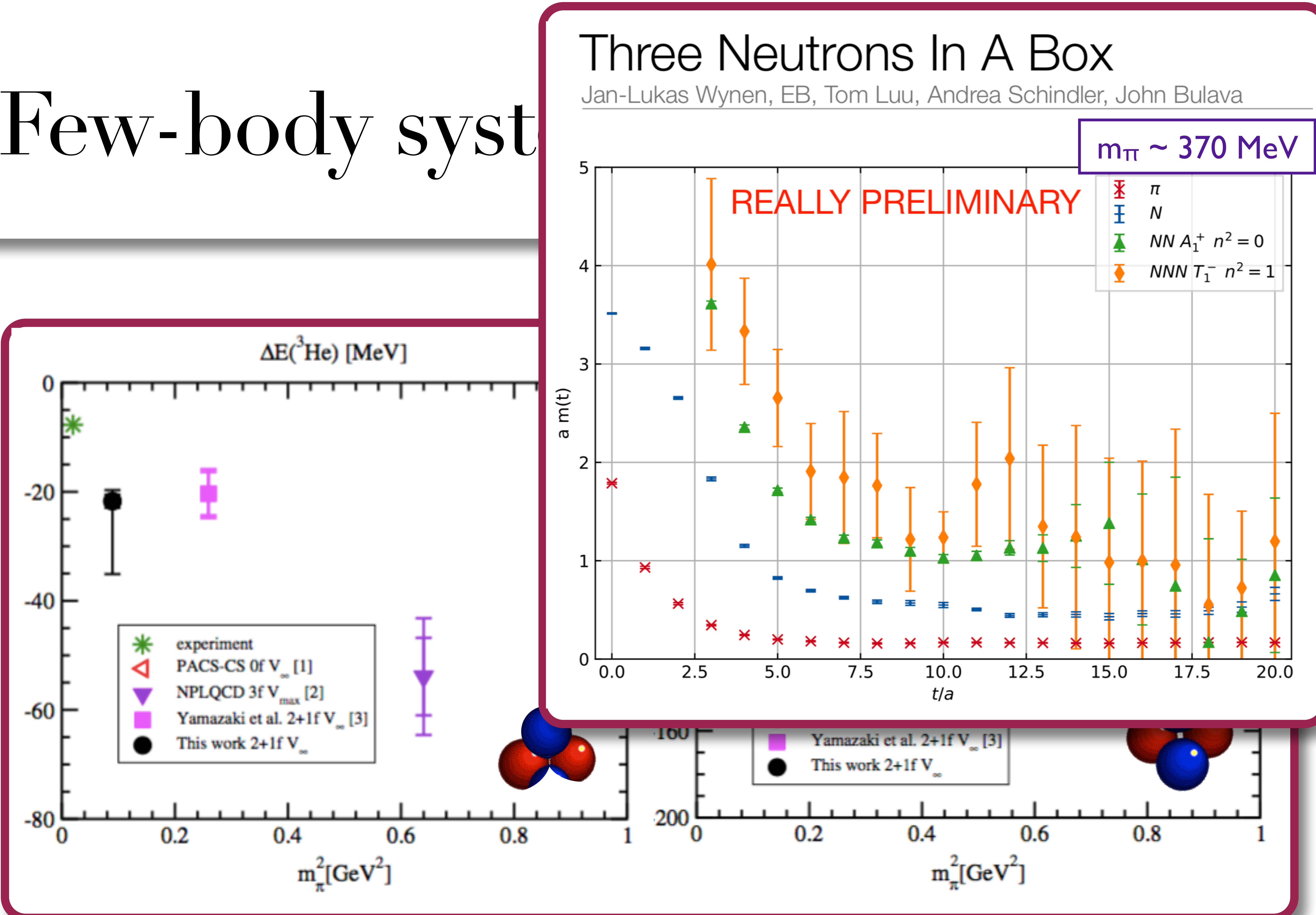
Few-body systems





T. Yamazaki, arXiv:1511.09179

Few-body syst



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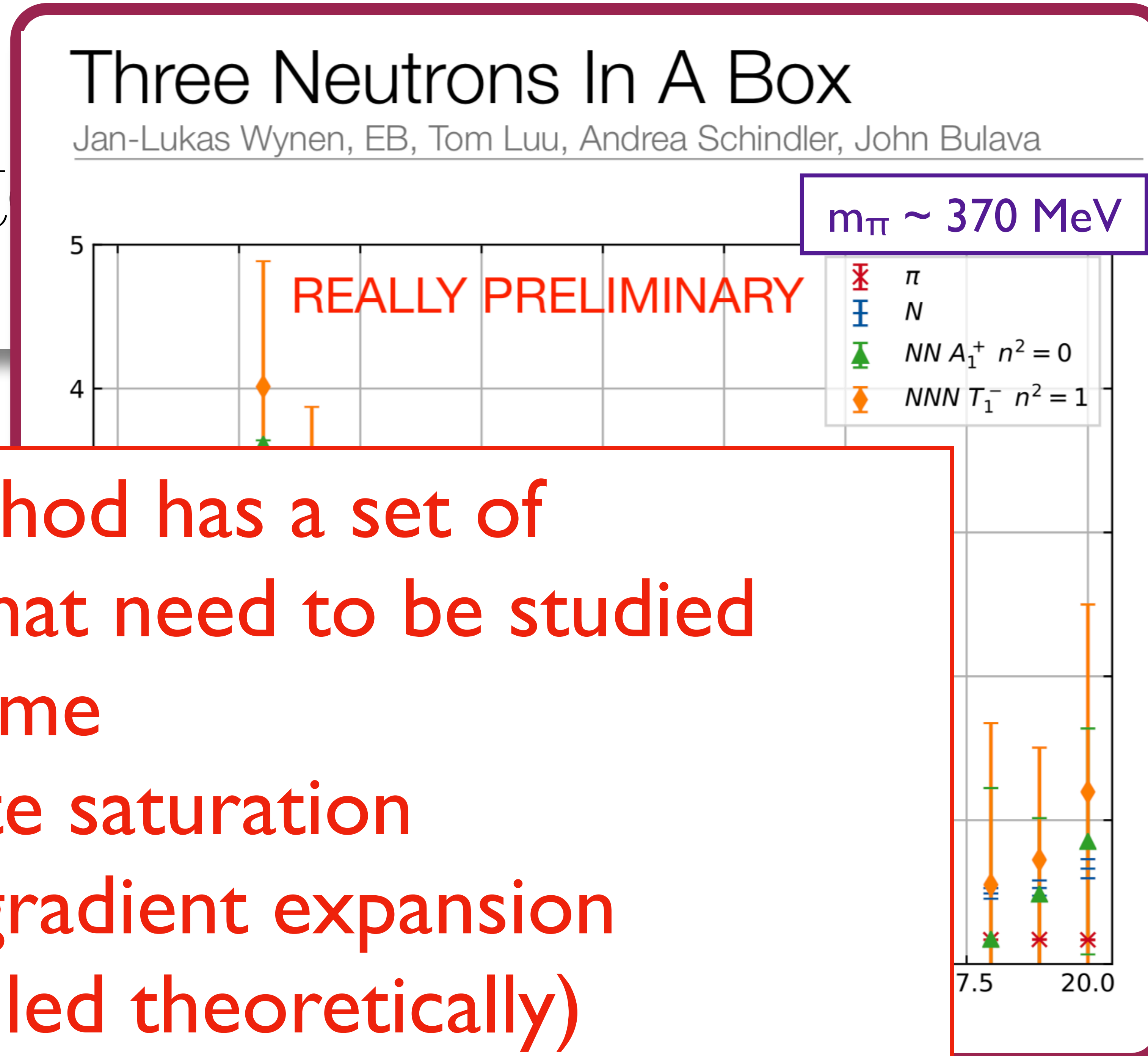
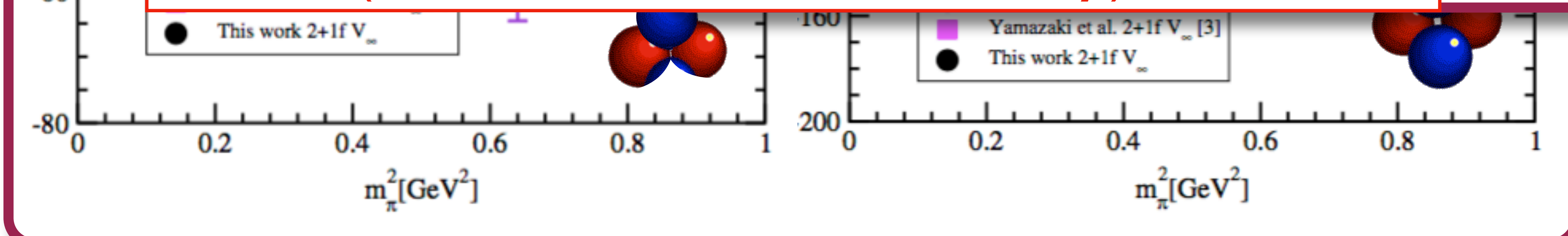
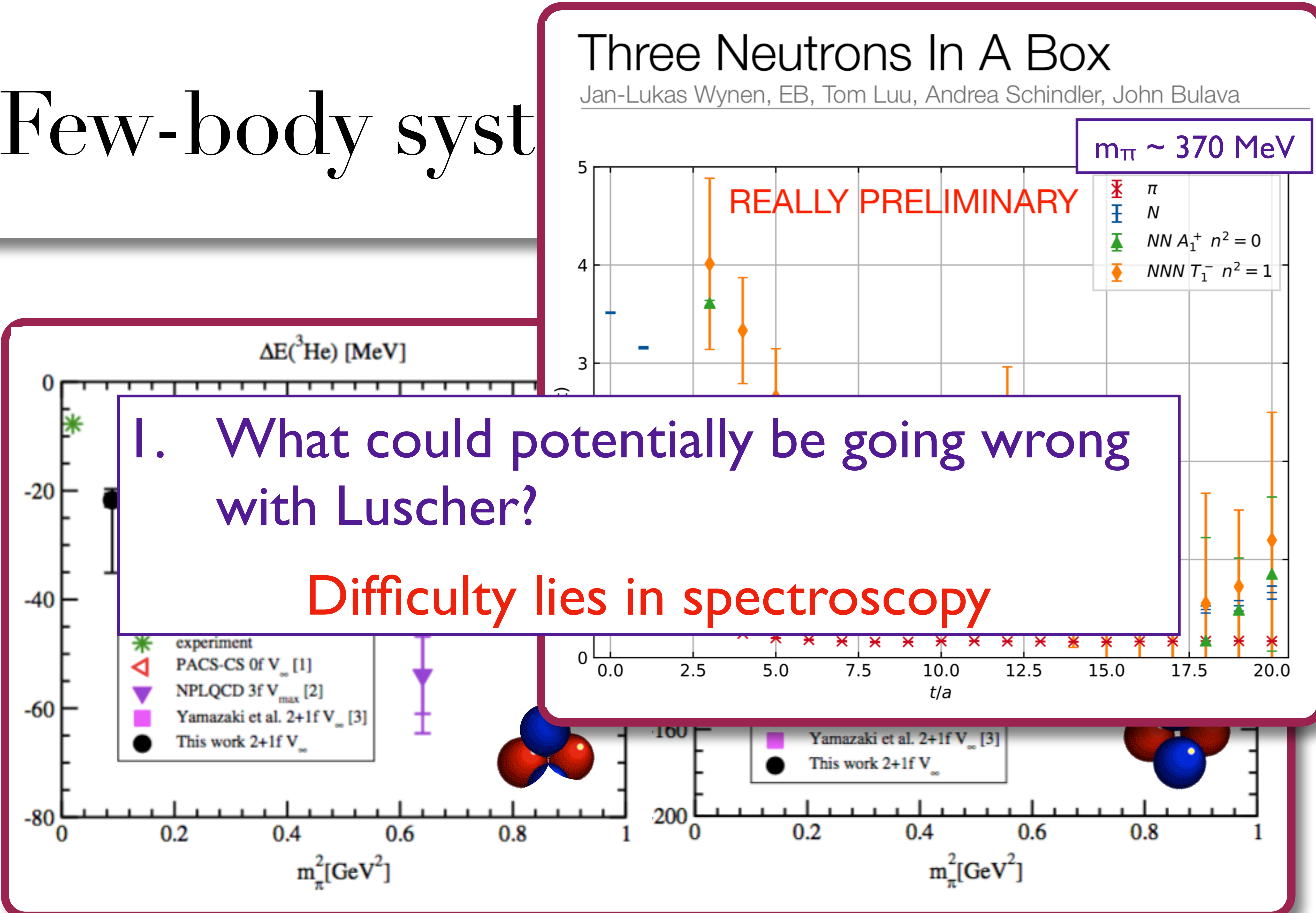




1. Potential method has a set of systematics that need to be studied
   1. Finite volume
   2. Elastic state saturation
   3. Cutoff in gradient expansion (uncontrolled theoretically)

T. Yamazaki, arXiv:1511.09179

Few-body syst



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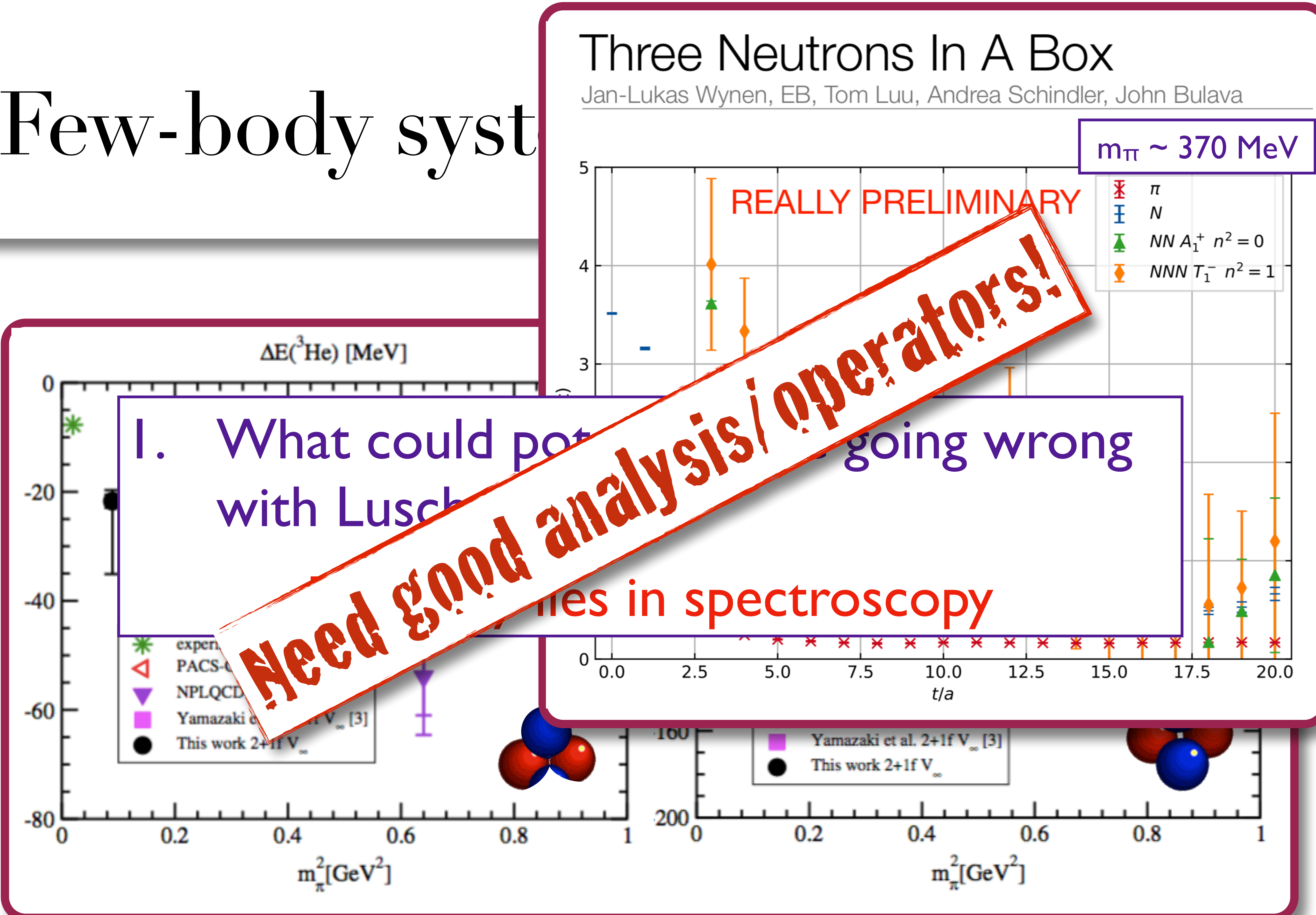


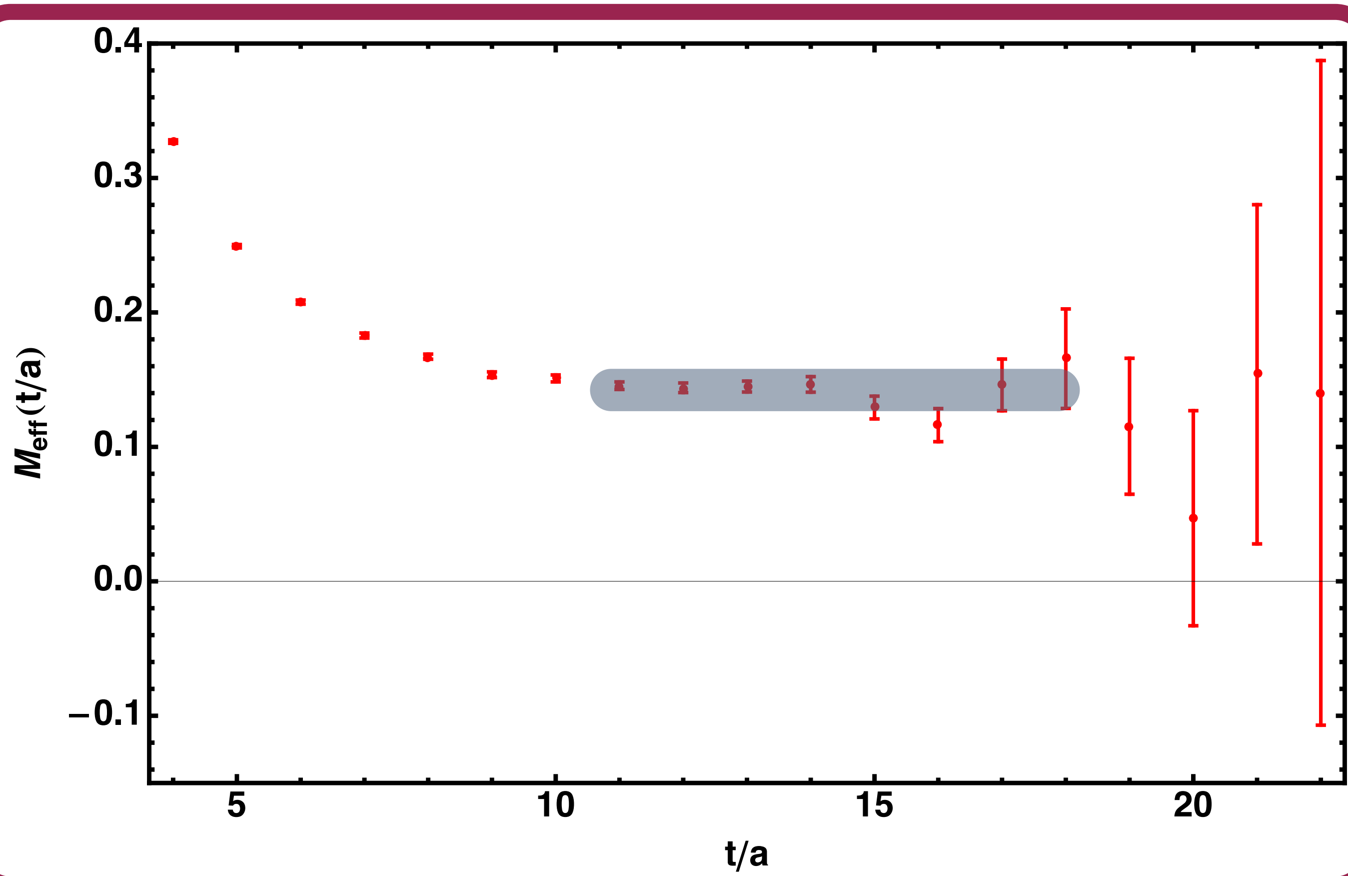
1. What could pot... going wrong with Lusch...

...les in spectroscopy

Need good analysis/operators!

T. Yamazaki, arXiv:1511.09179

Nucleons: Spectroscopy



$$\sim e^{A(M_n - 3/2 m_\pi)t}$$

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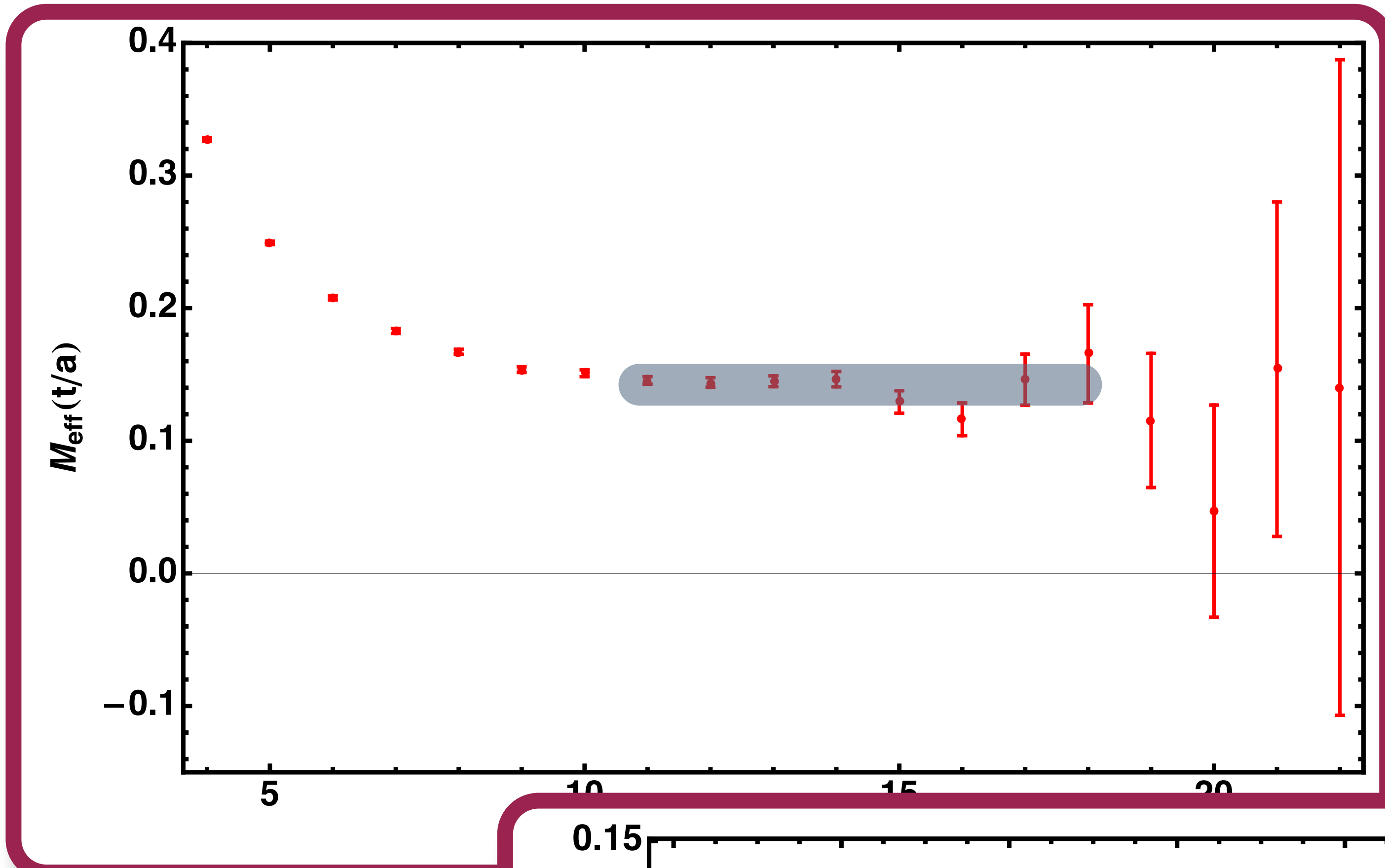

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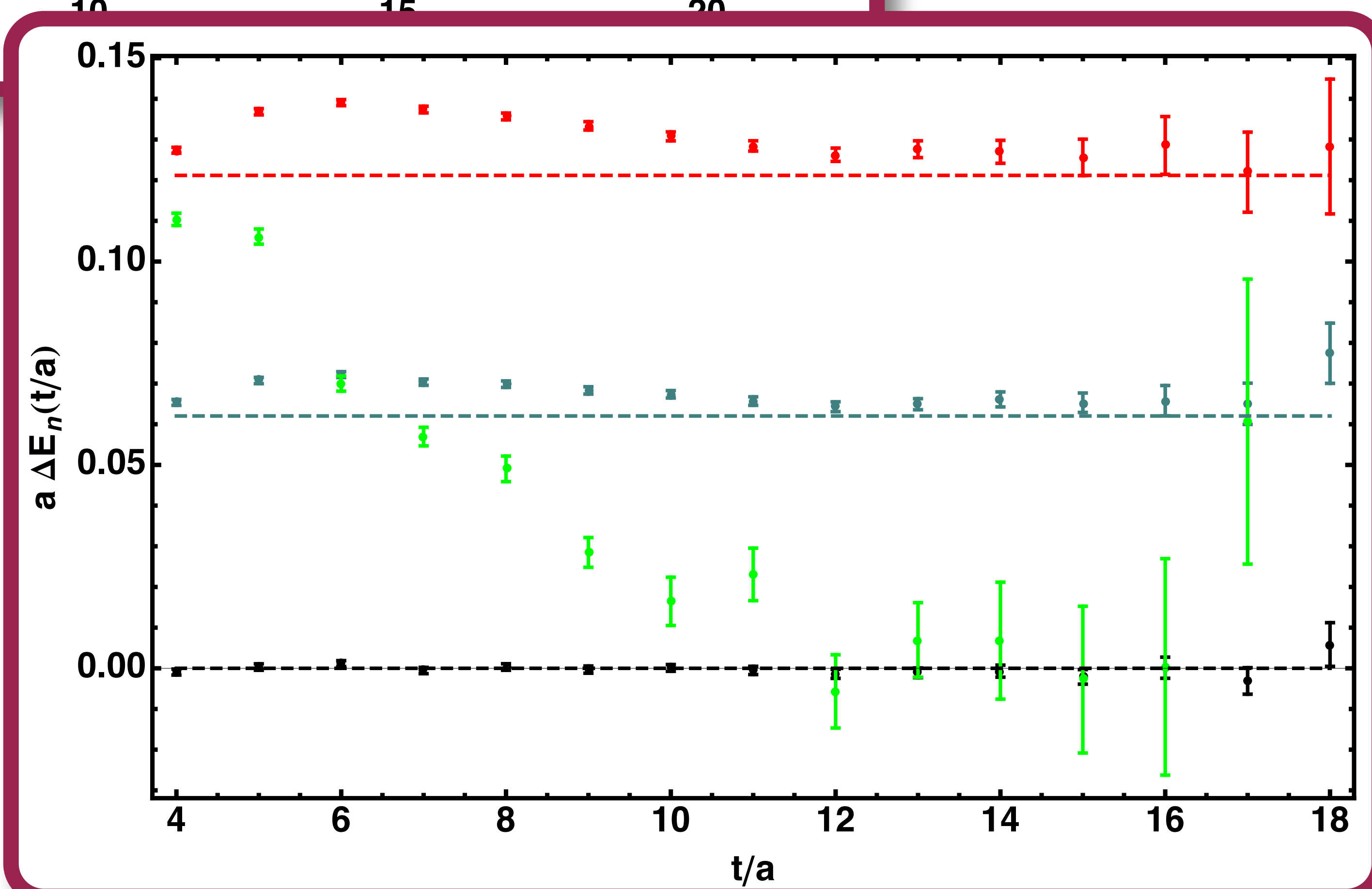

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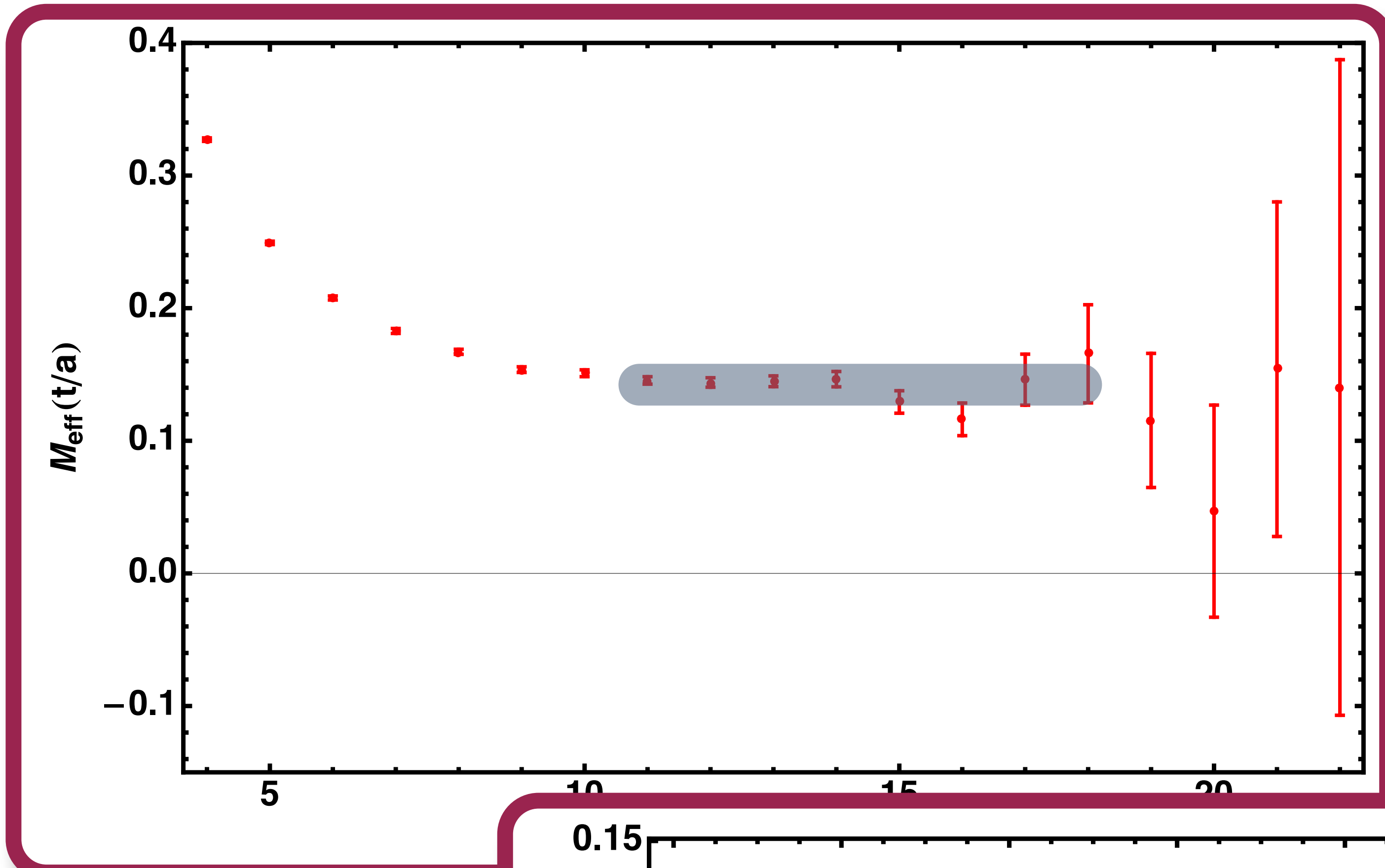

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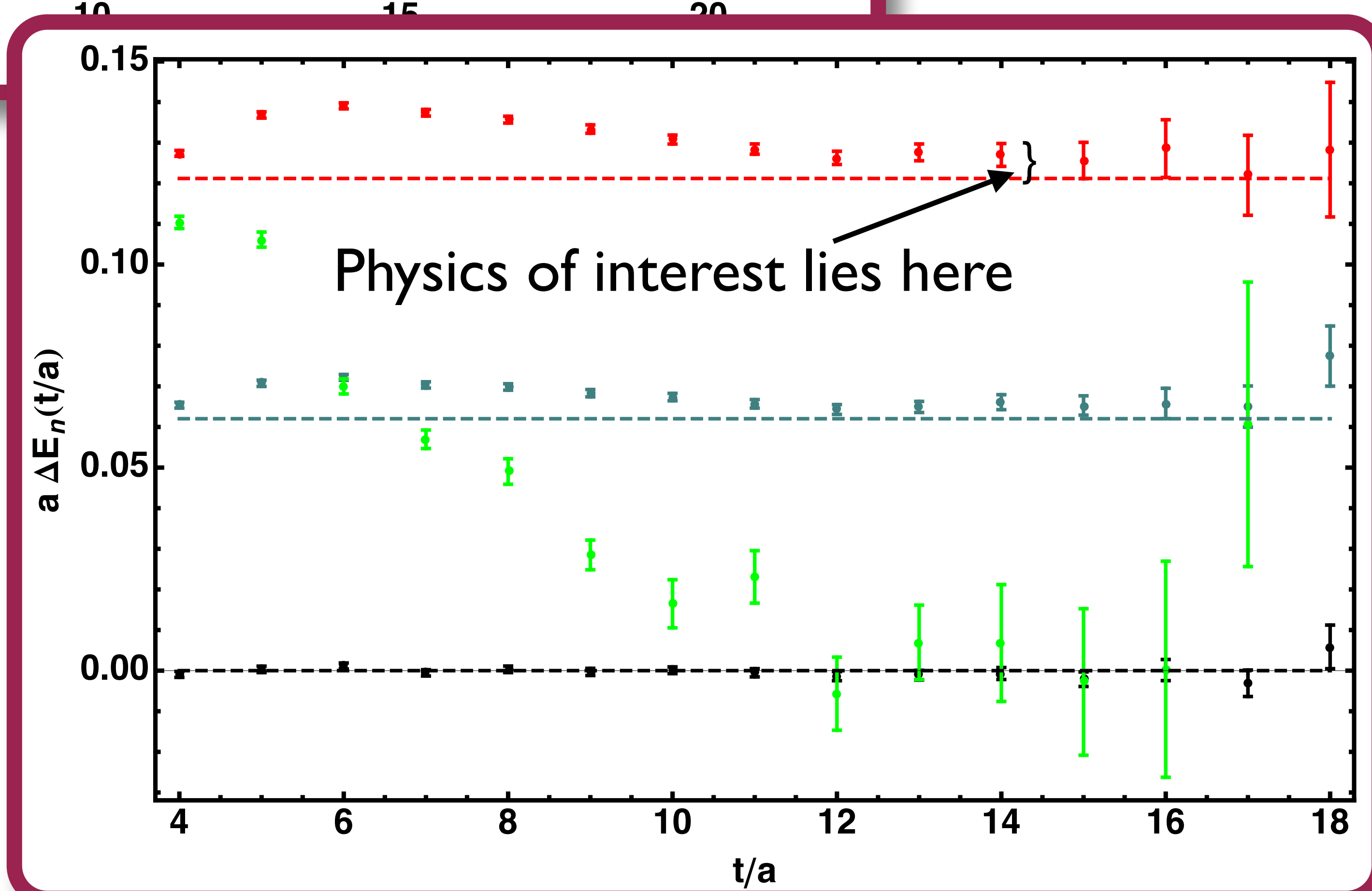

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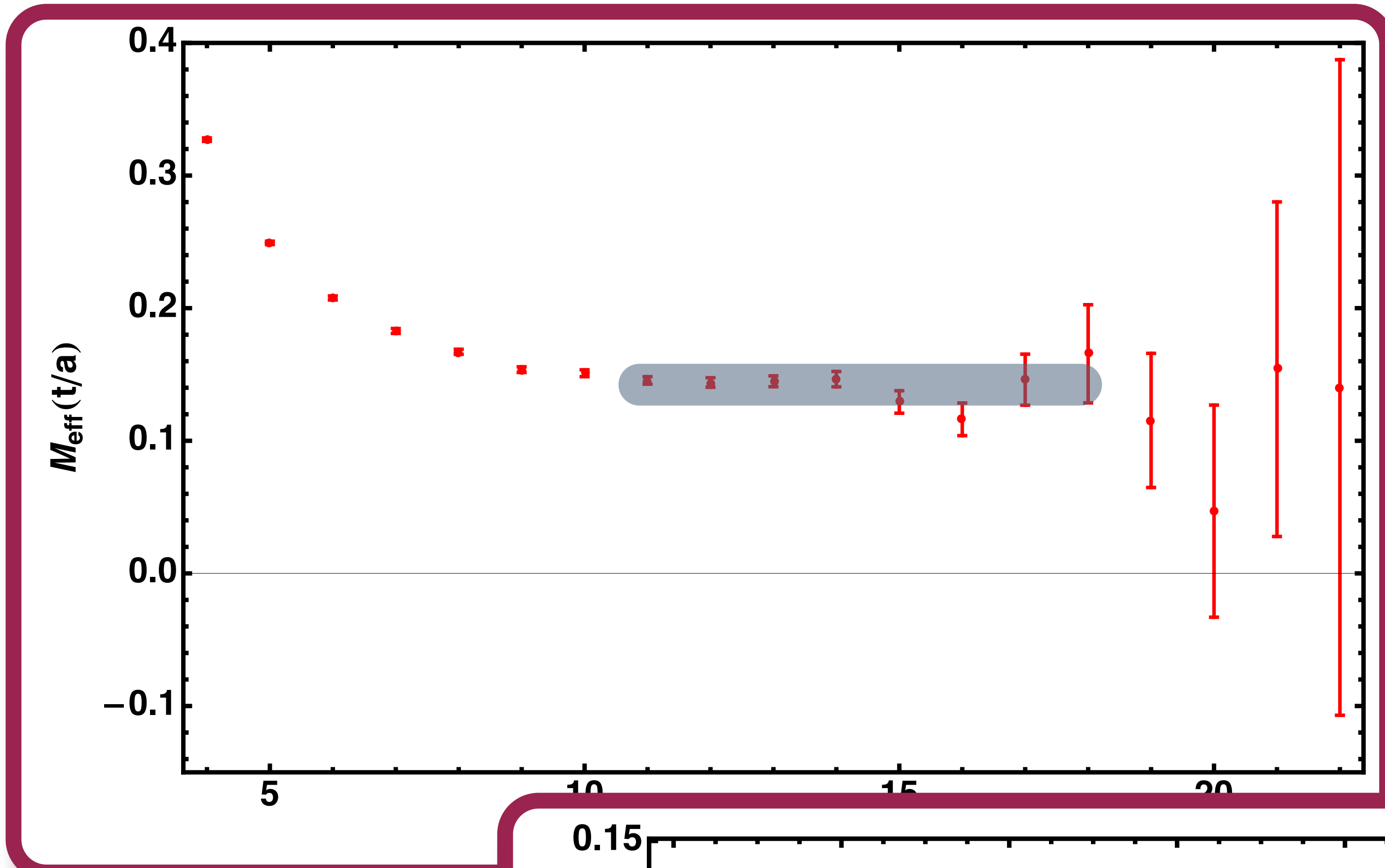

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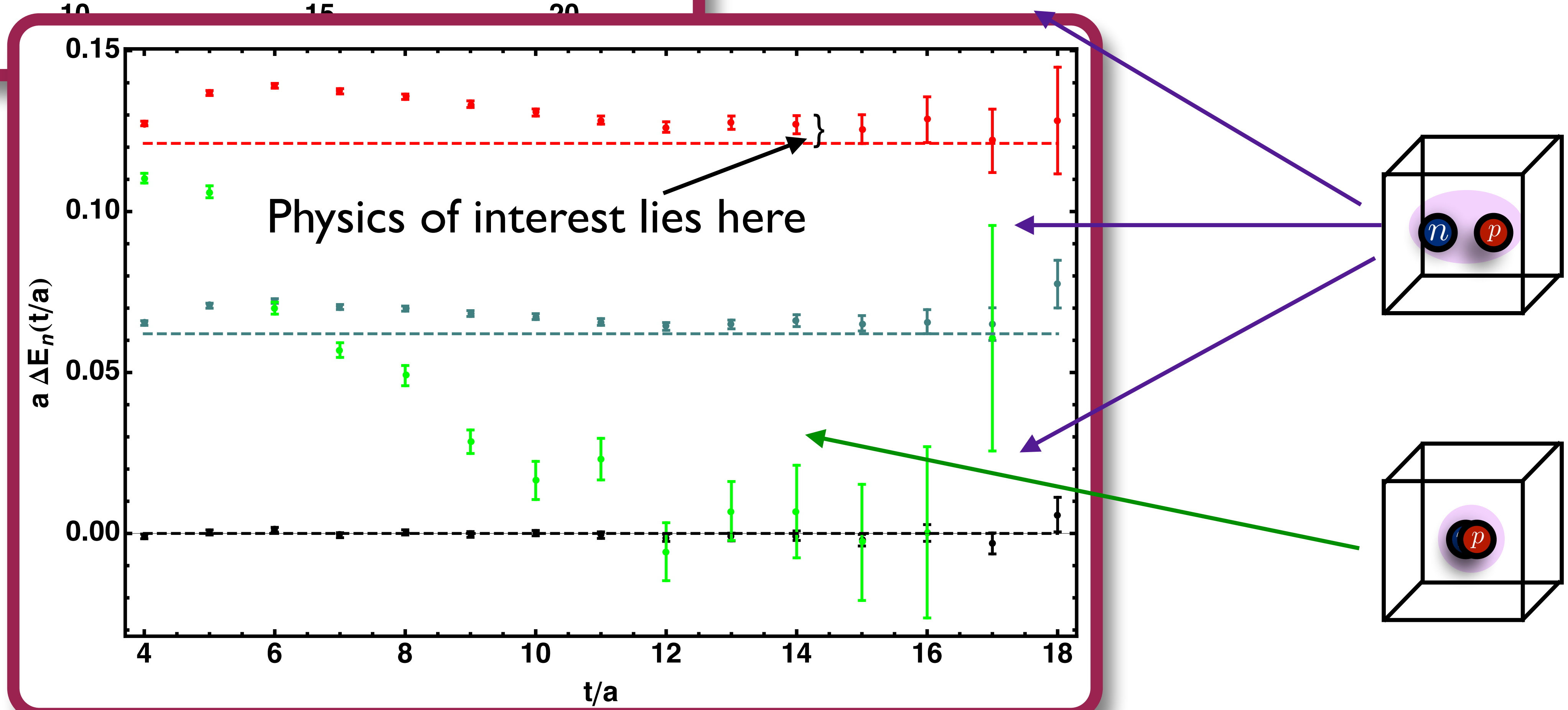
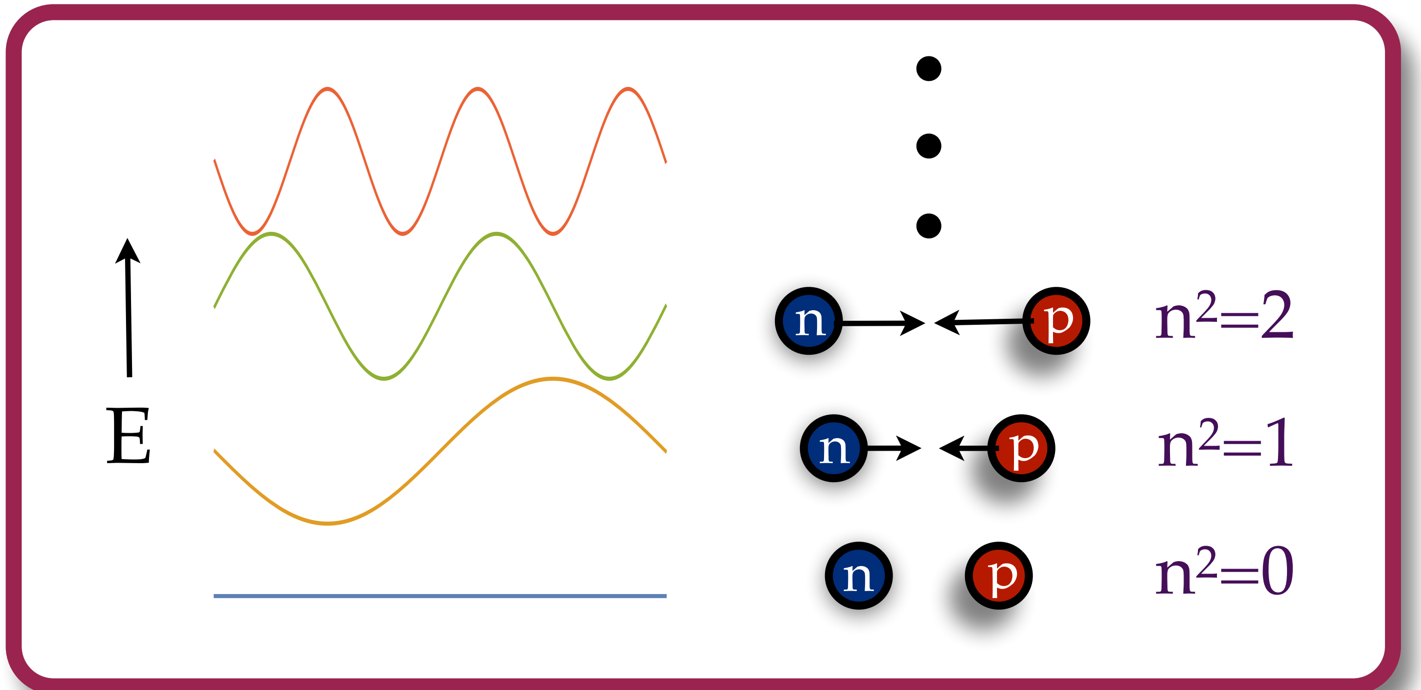
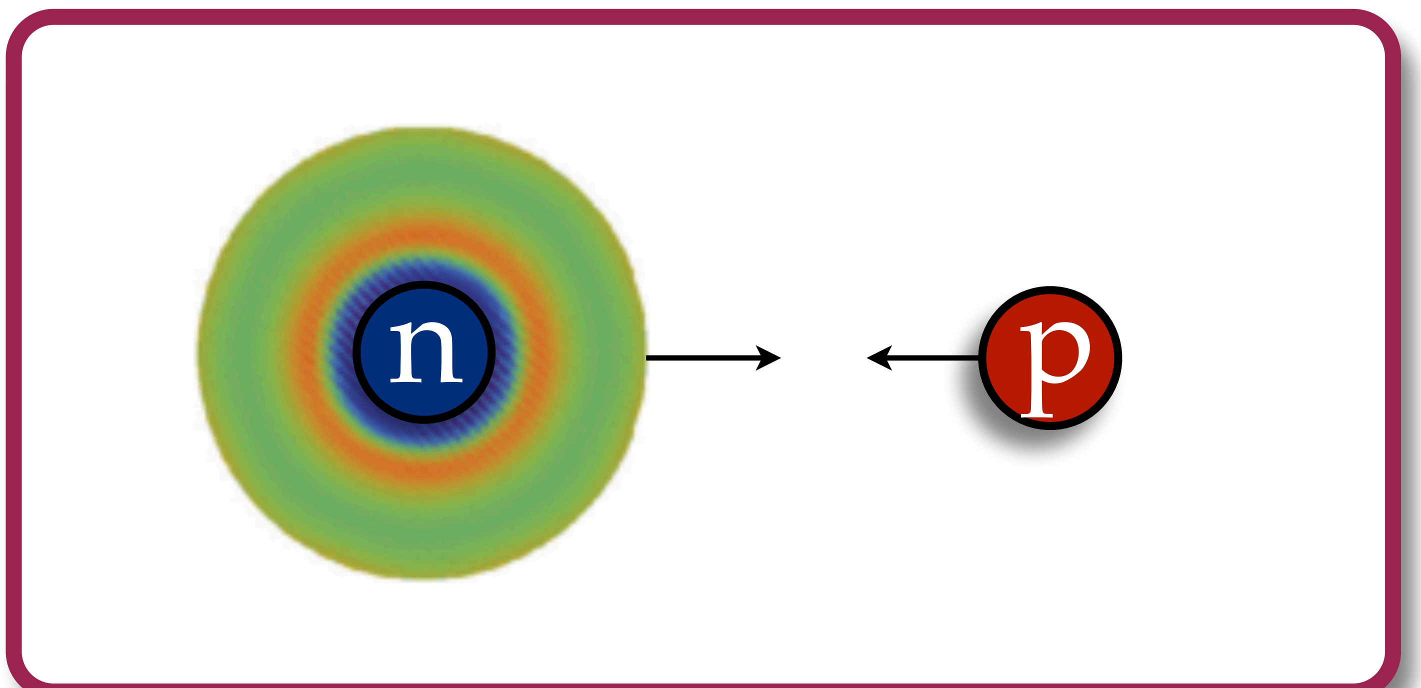


Excited state contamination



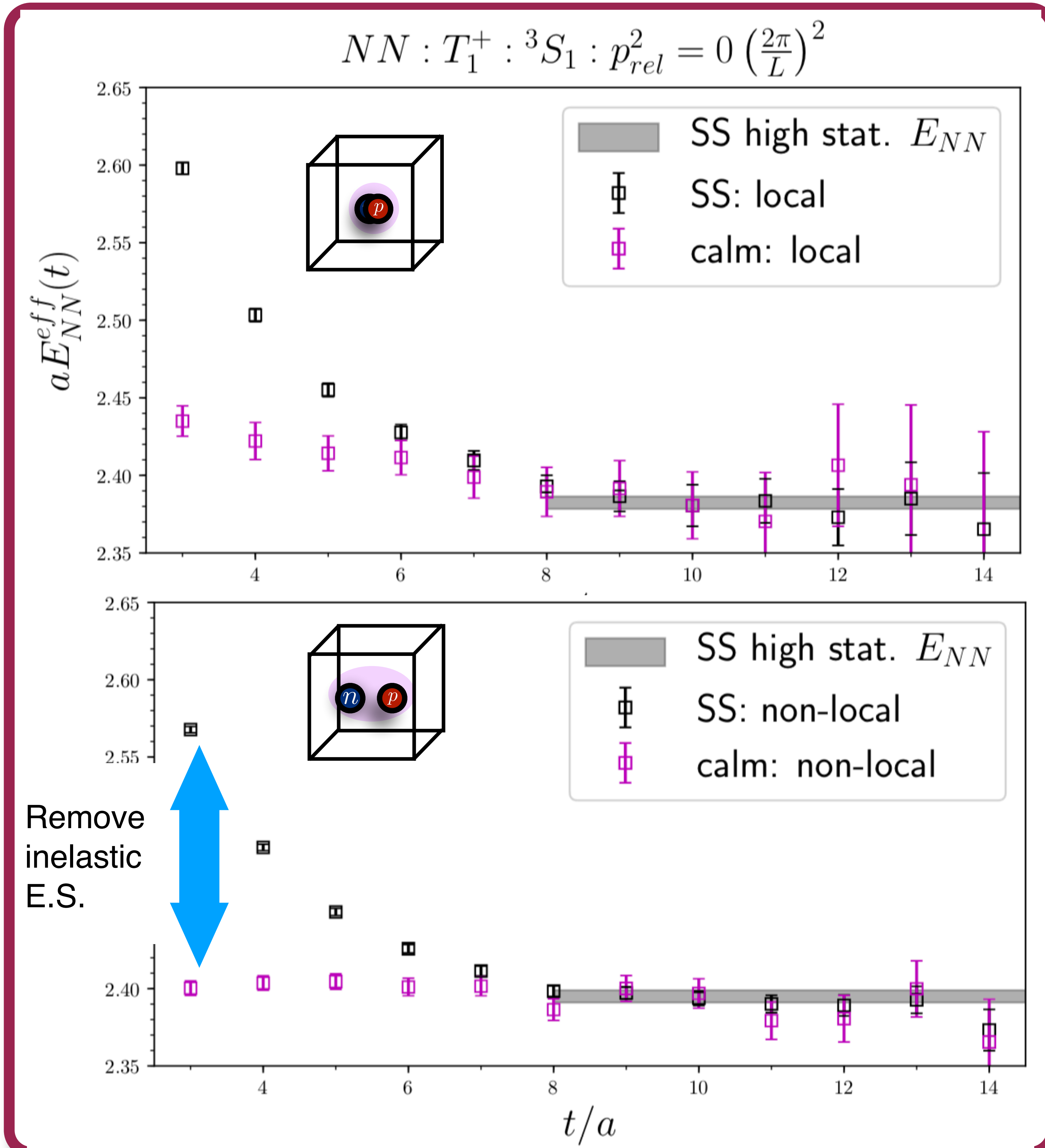
Elastic scattering
(2-body)

$\Delta E \sim 50$ MeV



Inelastic single body

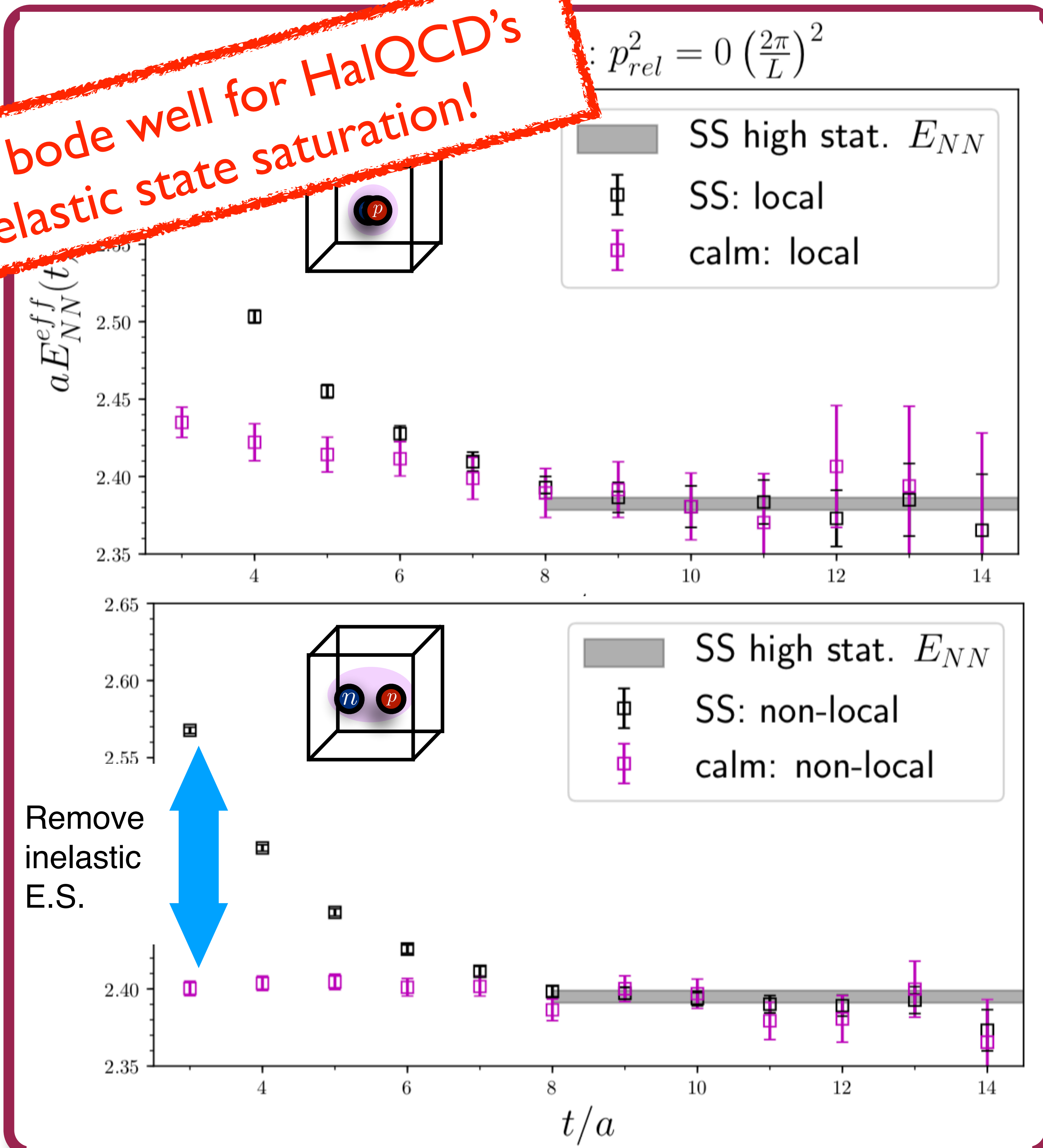
$\Delta E \sim m_\pi$



Remove elastic E.S.

CalLat (2017)
Matrix Prony: NPLQCD (2009)

This doesn't bode well for HalQCD's claim of elastic state saturation!

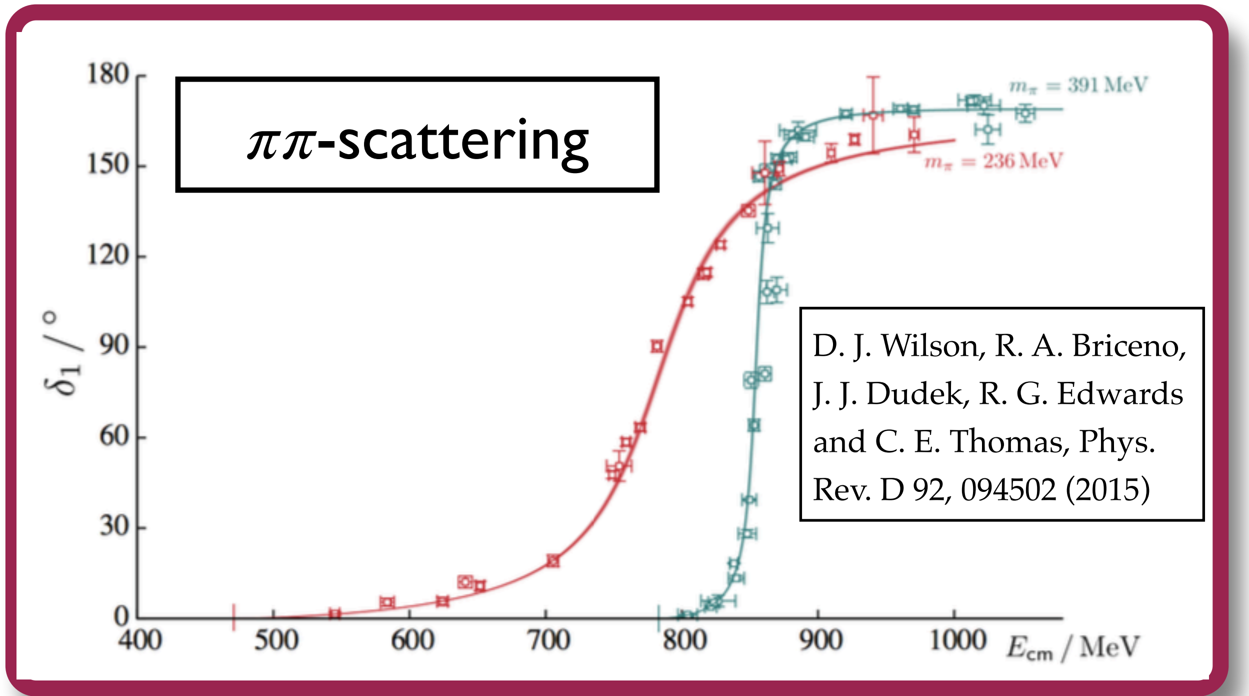


Remove elastic E.S.

Remove inelastic E.S.

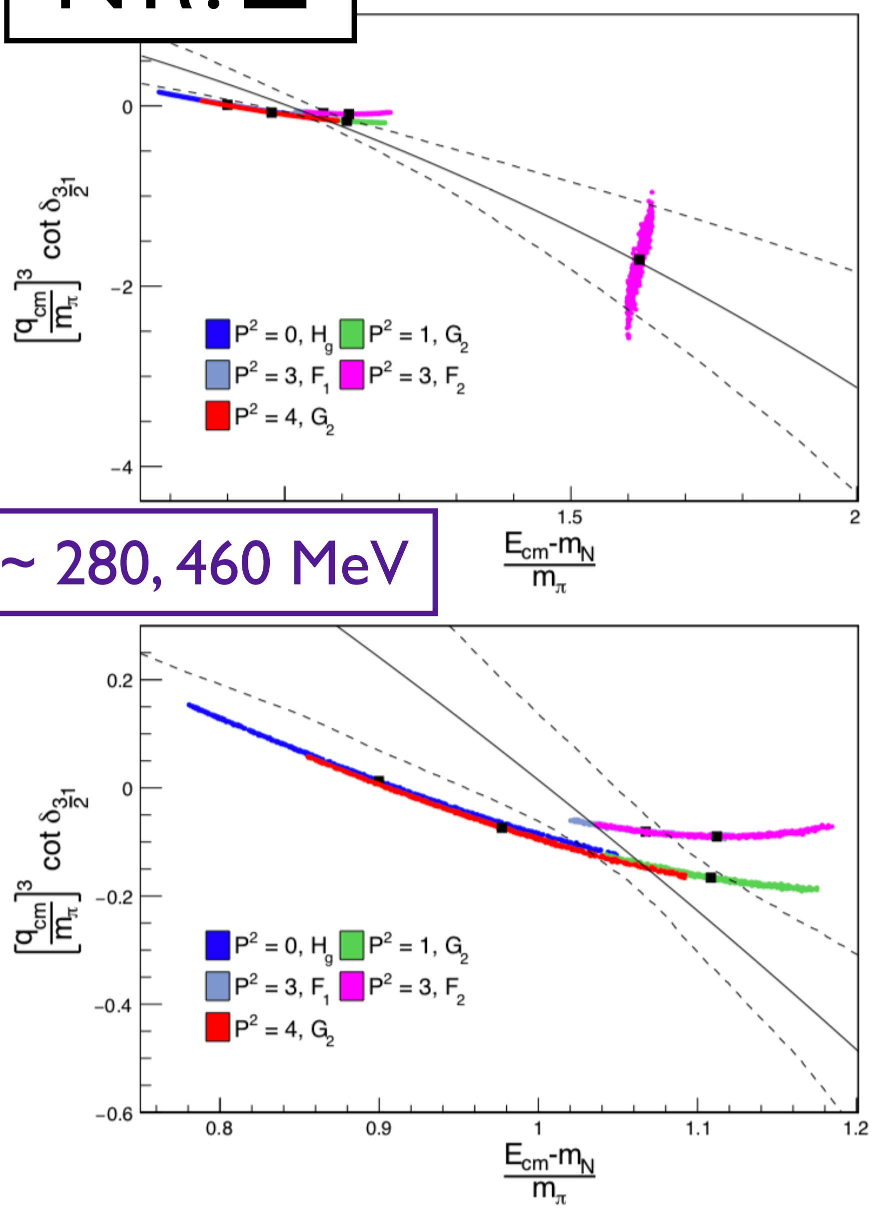
CalLat (2017)
Matrix Prony: NPLQCD (2009)

The future: GEVP approaches



The future: GEVP approaches

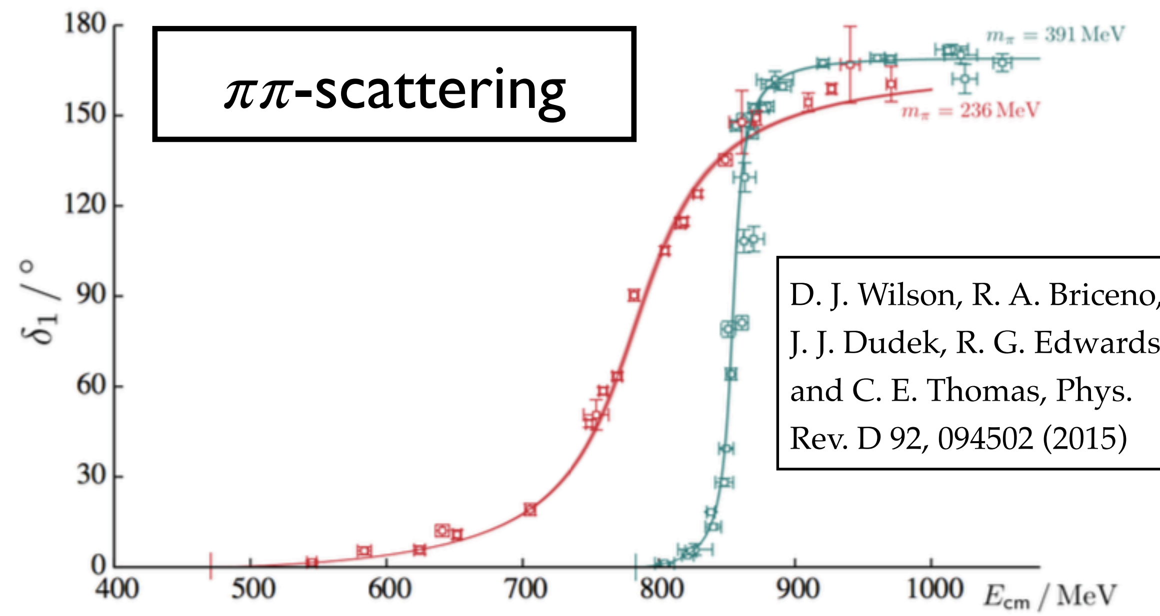
Nπ: Δ



m_π ~ 280, 460 MeV

Andersen, Bulava, Horz, Morningstar (2018)

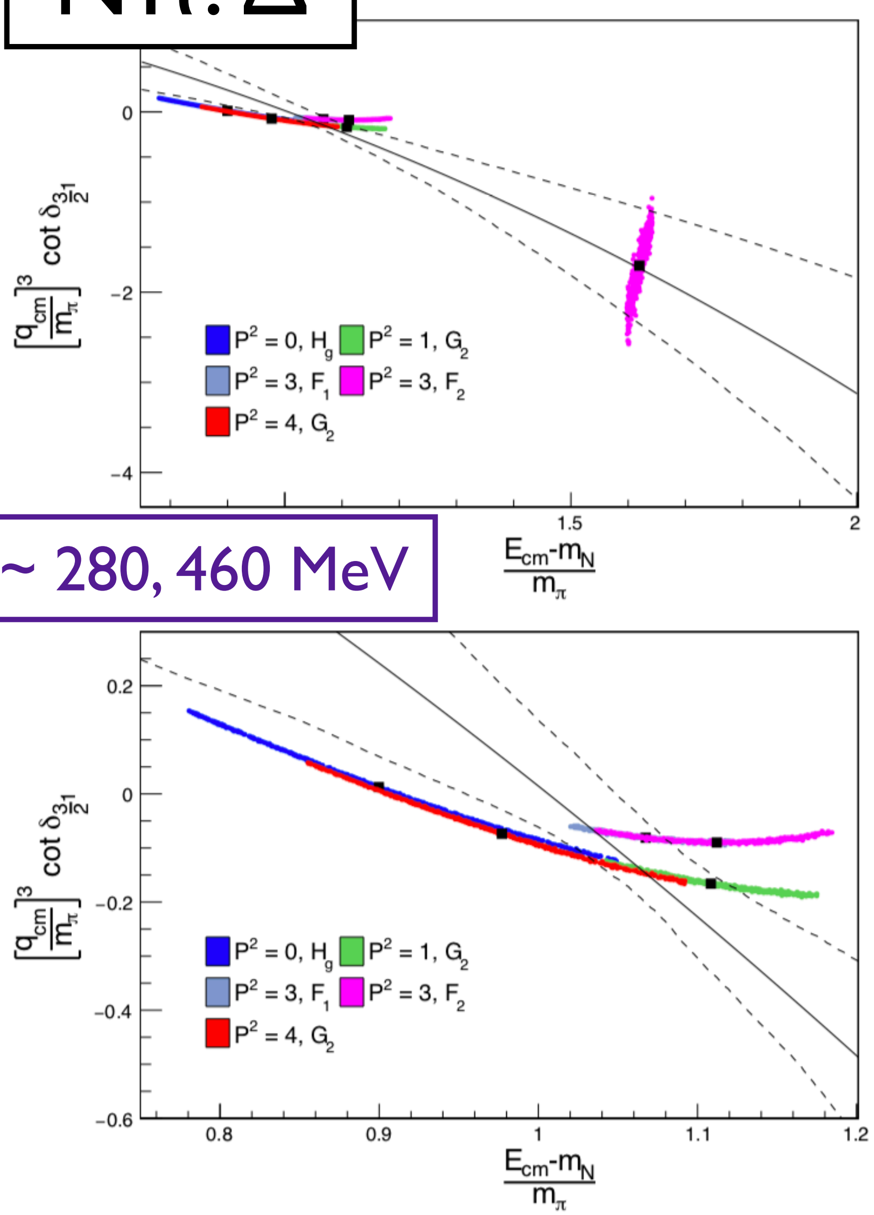
ππ-scattering



D. J. Wilson, R. A. Briceno, J. J. Dudek, R. G. Edwards and C. E. Thomas, Phys. Rev. D 92, 094502 (2015)

The future: GEVP approaches

Nπ: Δ



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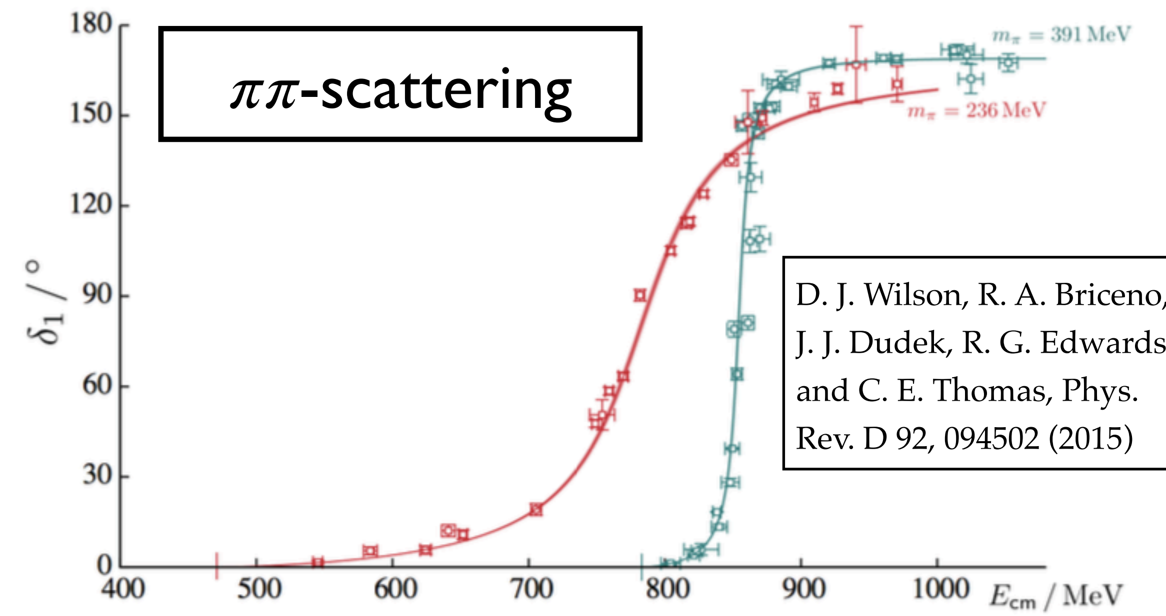
Andersen, Bulava, Horz, Morningstar (2018)

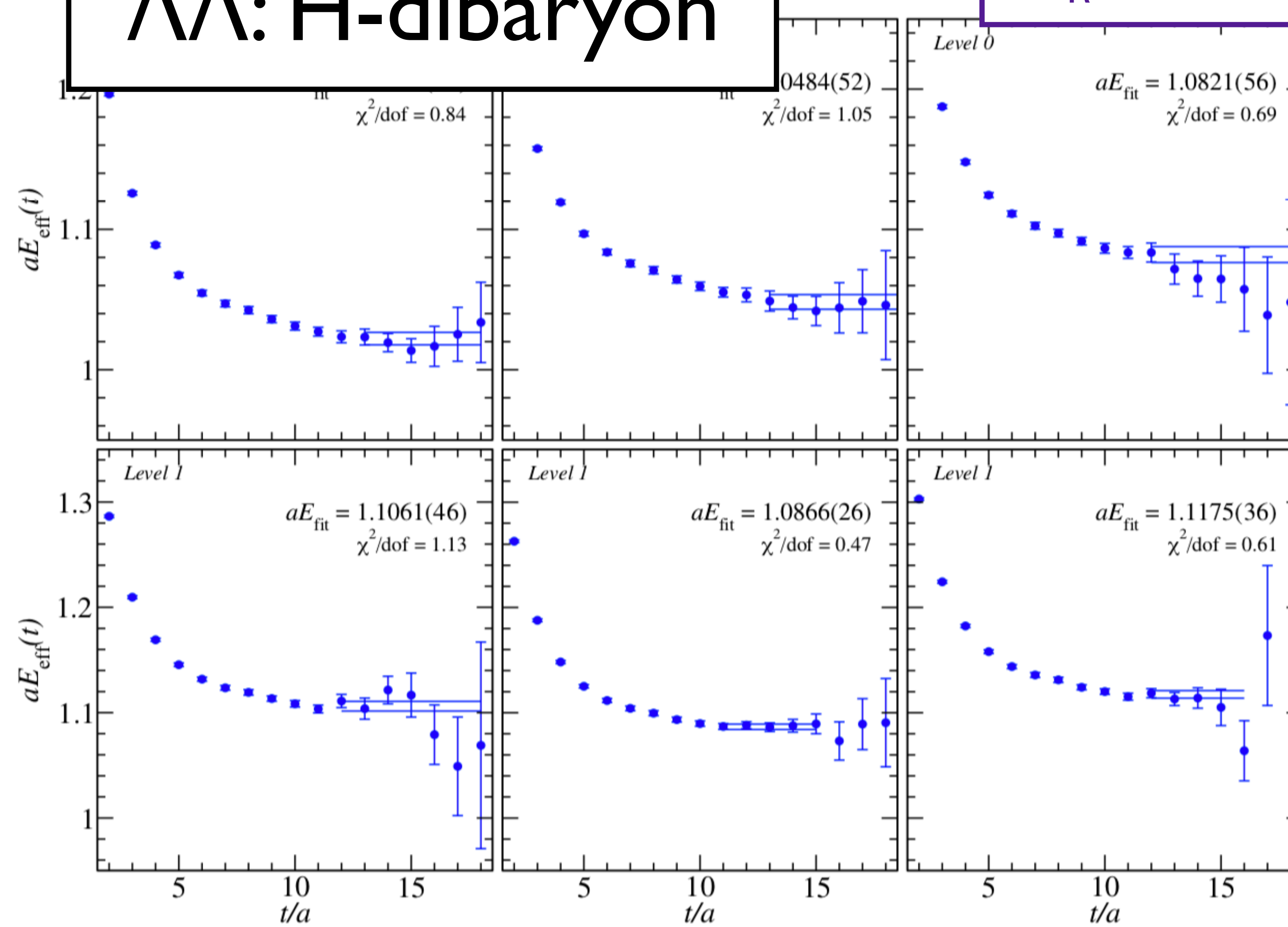
$\pi\pi$-scattering



D. J. Wilson, R. A. Briceno, J. J. Dudek, R. G. Edwards and C. E. Thomas, Phys. Rev. D 92, 094502 (2015)

ΛΛ: H-dibaryon

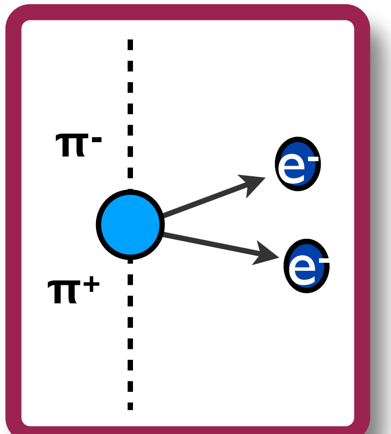
m_π ~ 800 MeV

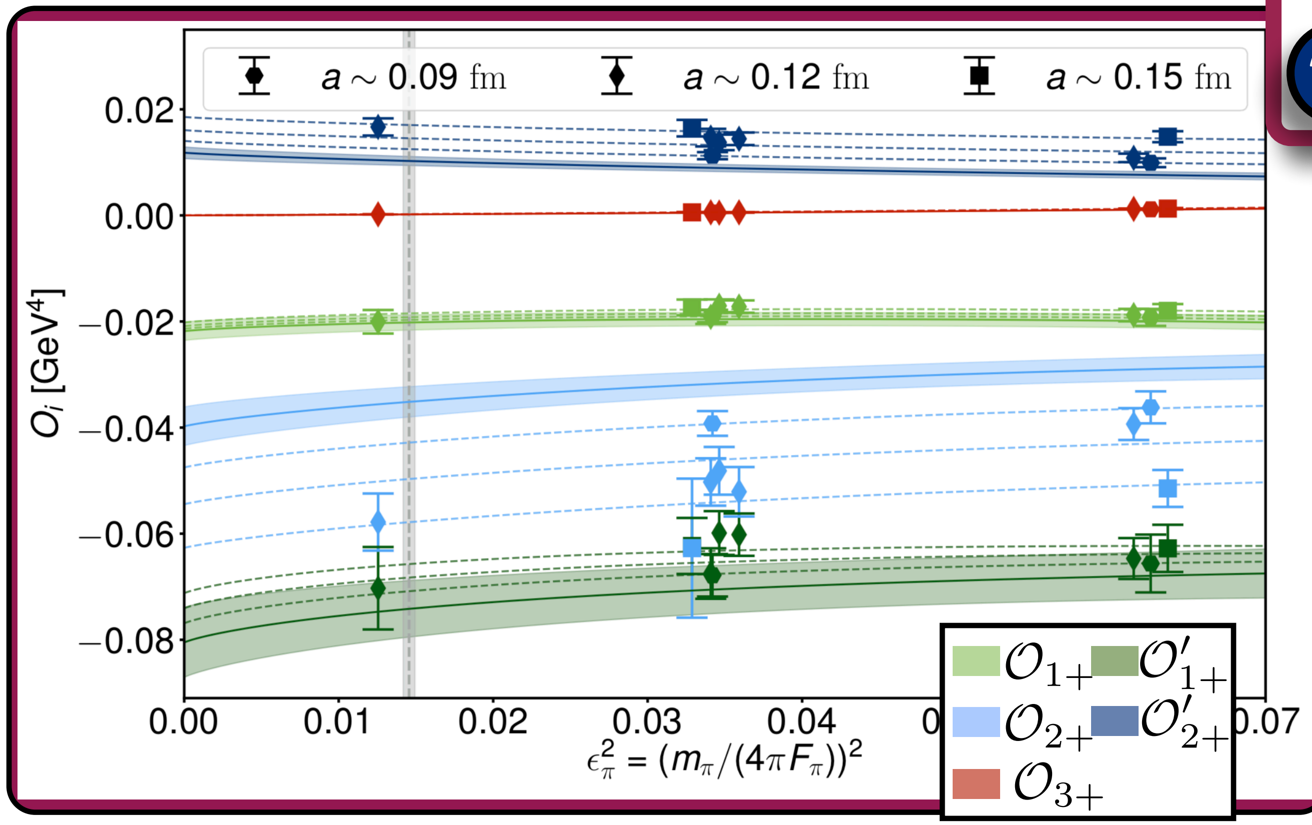


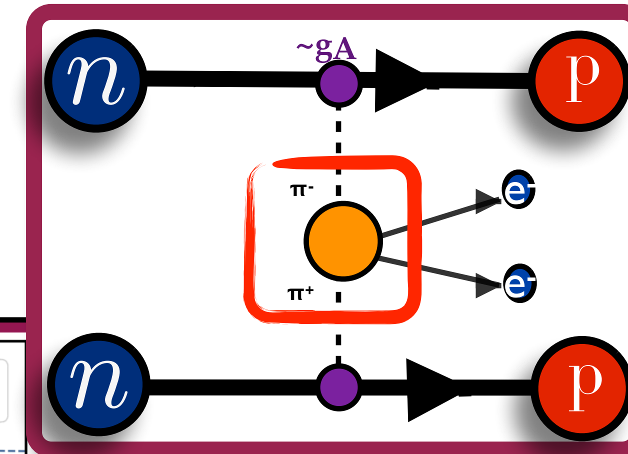
Hanlon, Francis, Green, Junnarkar, Wittig (2018)

Matrix elements: Neutrinoless Double Beta Decay

- Short-ranged contributions unconstrained from experiment







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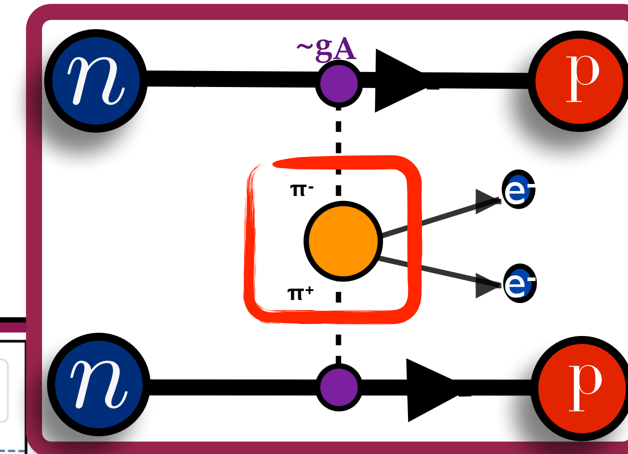

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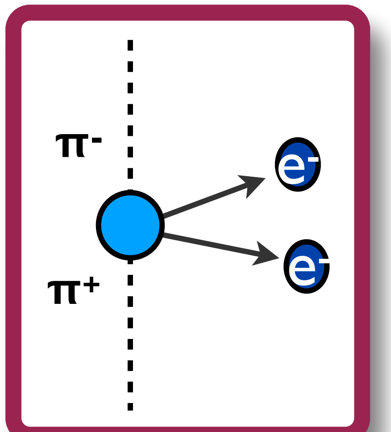
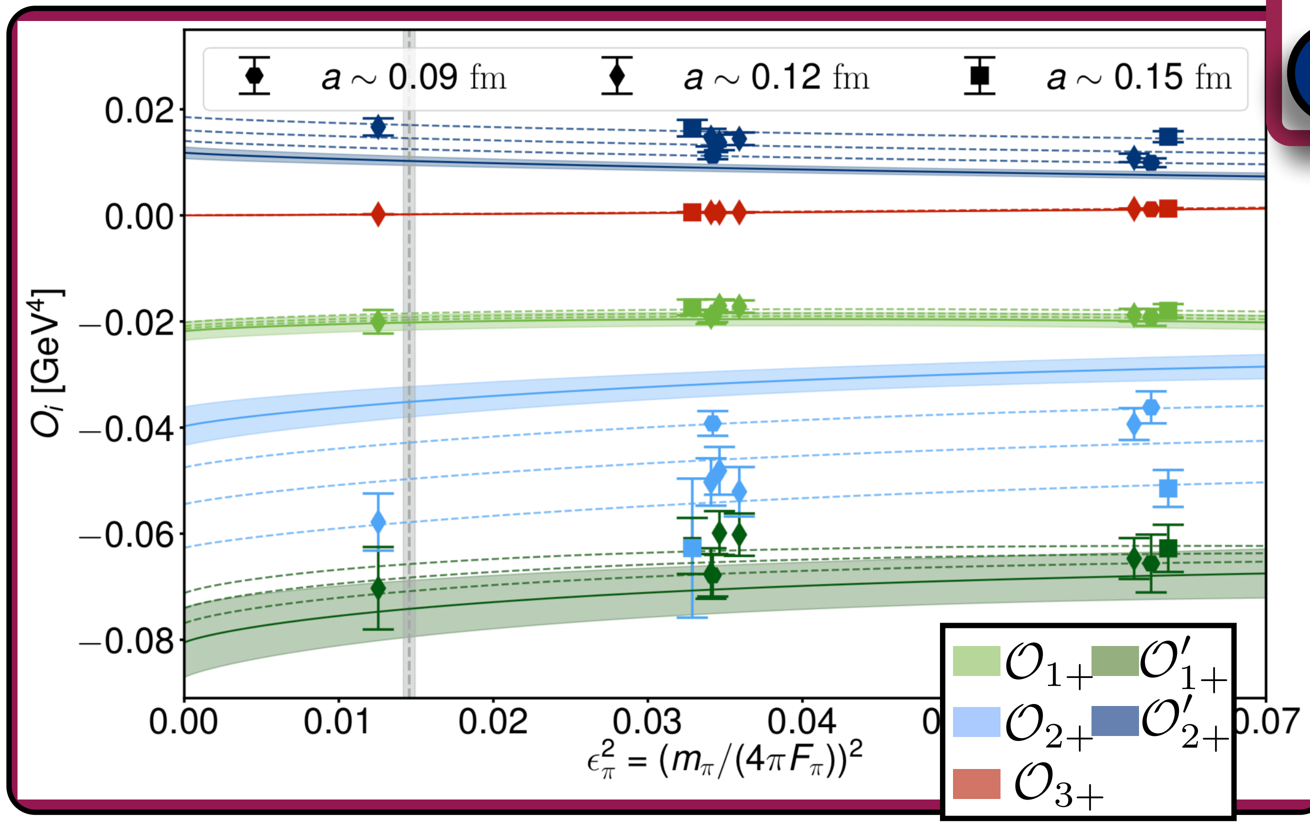
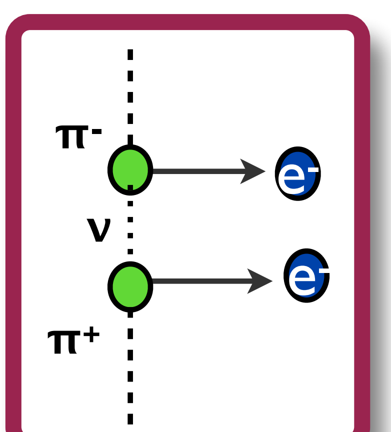
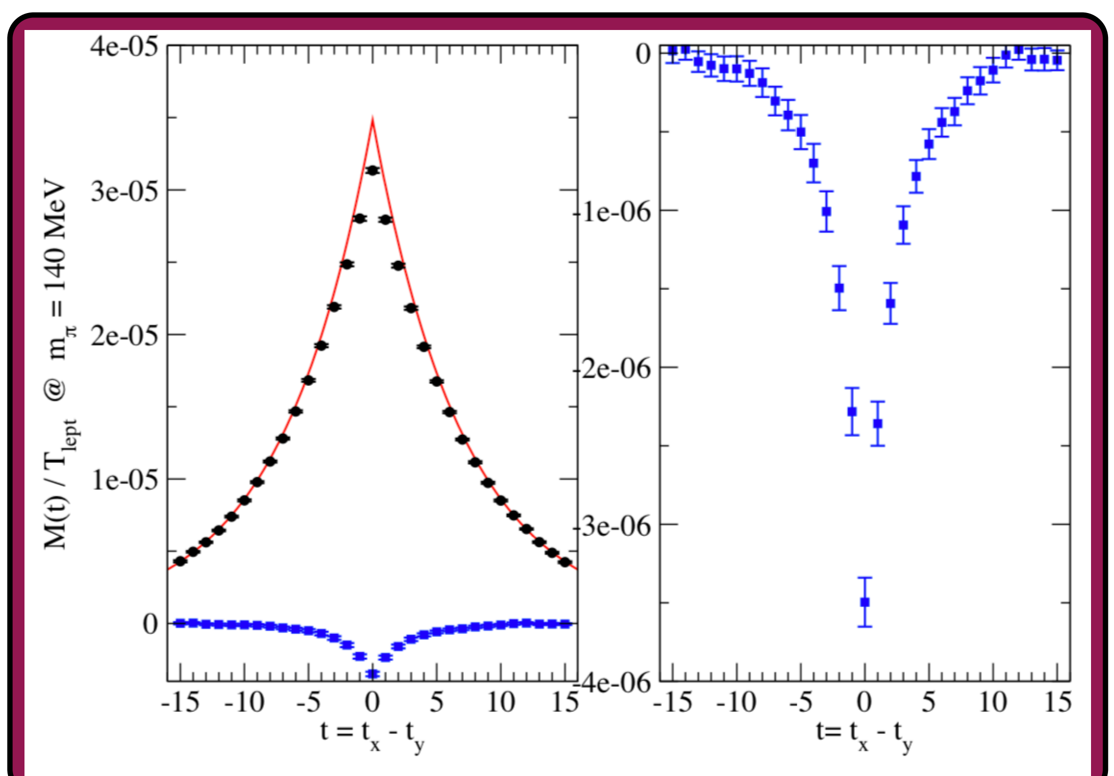




- Long-range contributions may require non-perturbative treatment even for two nucleons



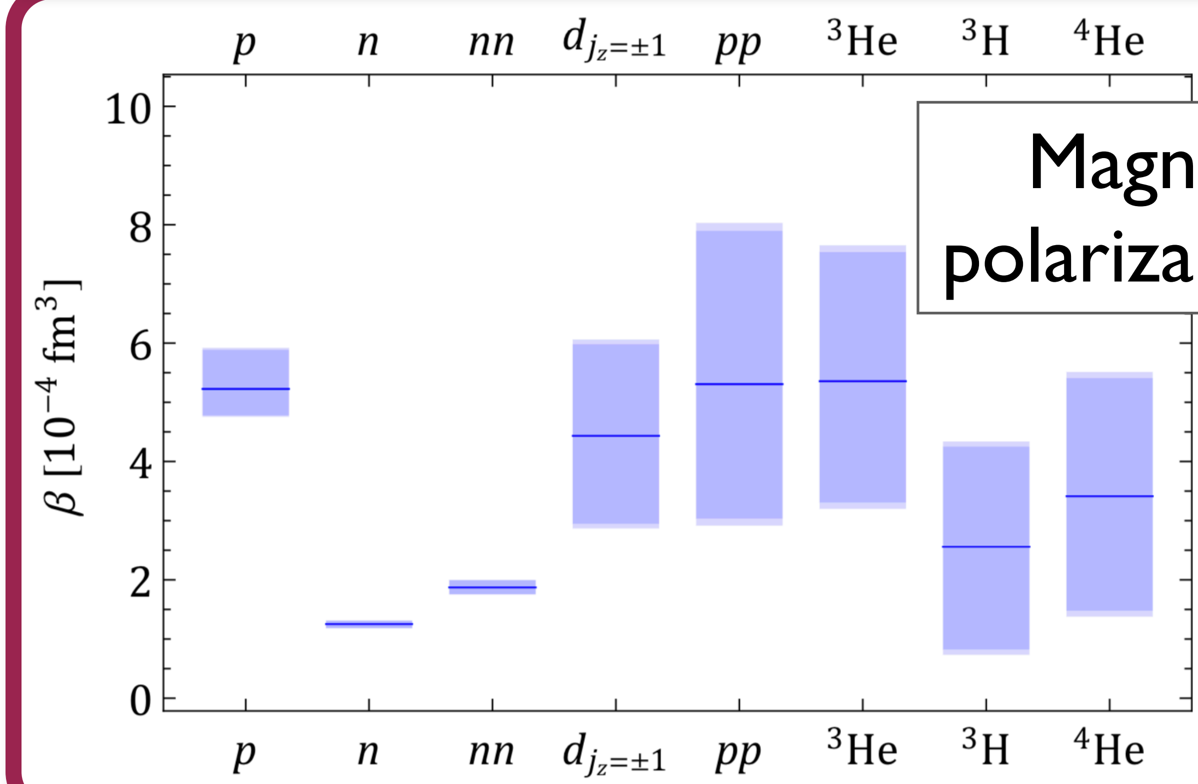


Xu Feng, Lu-Chang Jin, Xin-Yu Tuo, Shi-Cheng Xia, Phys. Rev. Lett. 122, 022001 (2019)

see also D. Murphy, W. Detmold Lattice 2018

Matrix elements: Background Field

Magnetic polarizabilities



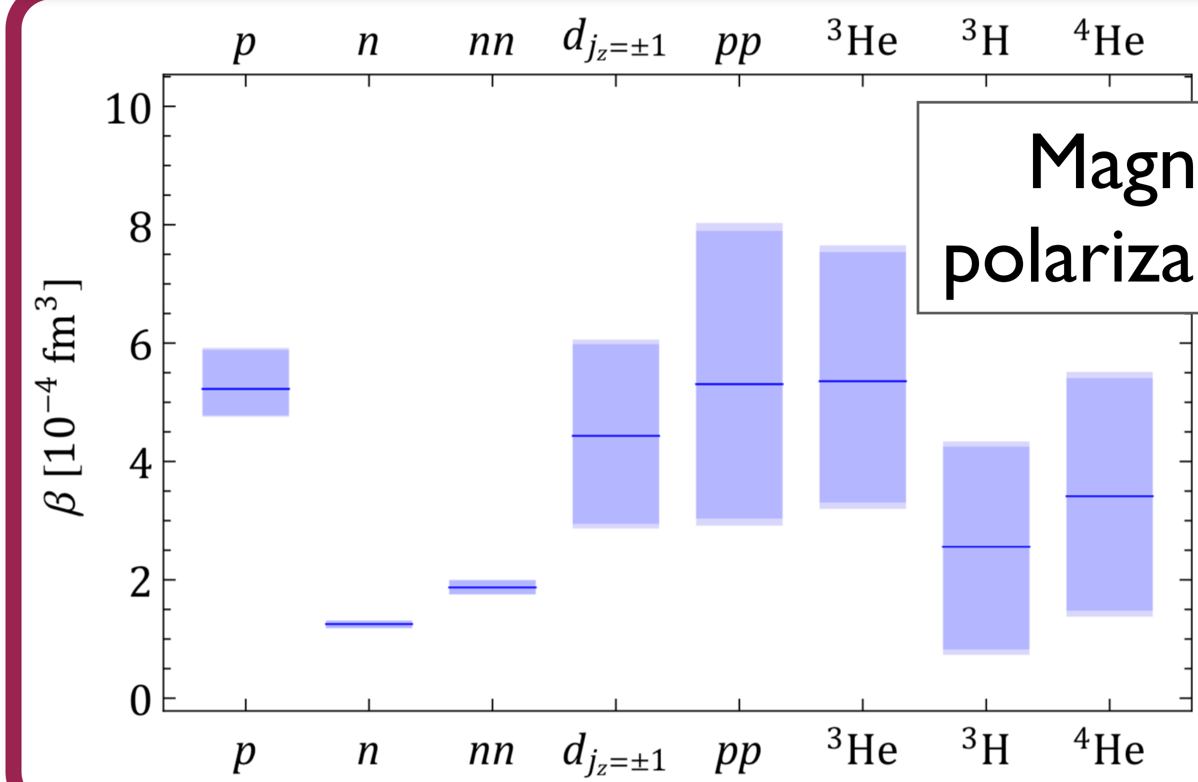
Scalar, Axial, Tensor charges

	p	d	pp	^{3}He
$g_S^{(0)}$	3.65(7)	7.20(15)	7.22(15)	10.4(2)
$g_S^{(3)}$	0.78(2)	-	1.55(4)	0.77(2)
$g_S^{(8)}$	2.94(6)	5.84(12)	5.86(12)	8.55(18)
$g_S^{(s)}$	0.234(8)	0.45(2)	0.45(2)	0.63(3)
$g_A^{(0)}$	0.634(9)	1.26(2)	-	0.63(1)
$g_A^{(3)}$	1.14(2)	-	-	1.13(2)
$g_A^{(8)}$	0.633(9)	1.25(2)	-	0.625(9)
$g_A^{(s)}$	0.0002(6)	0.001(1)	-	0.003(2)
$g_T^{(0)}$	0.684(12)	1.36(2)	-	0.678(12)
$g_T^{(3)}$	1.12(2)	-	-	1.12(3)
$g_T^{(8)}$	0.684(12)	1.36(2)	-	0.676(12)
$g_T^{(s)}$	0.00007(13)	0.0002(2)	-	0.0004(4)

$m_\pi \sim 800$ MeV

Matrix elements: Background Field

Magnetic polarizabilities



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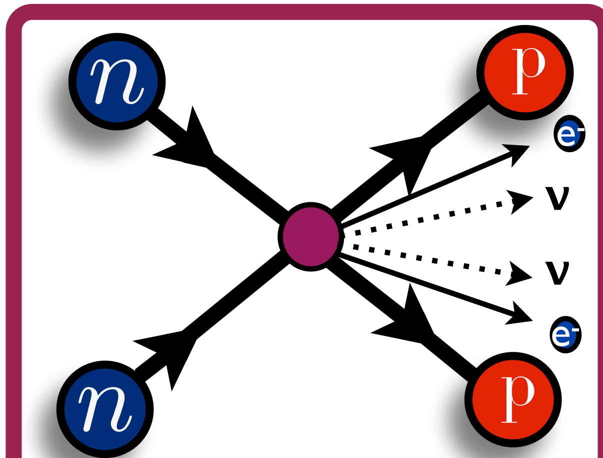
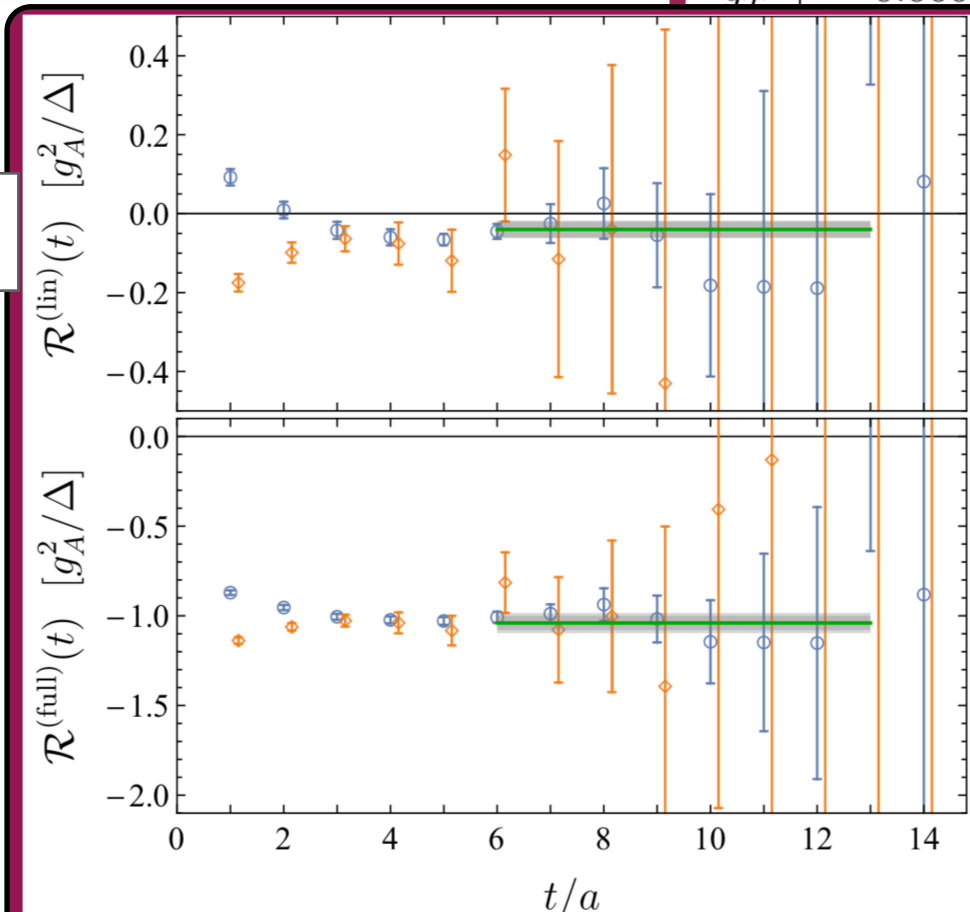
Isotensor polarizability



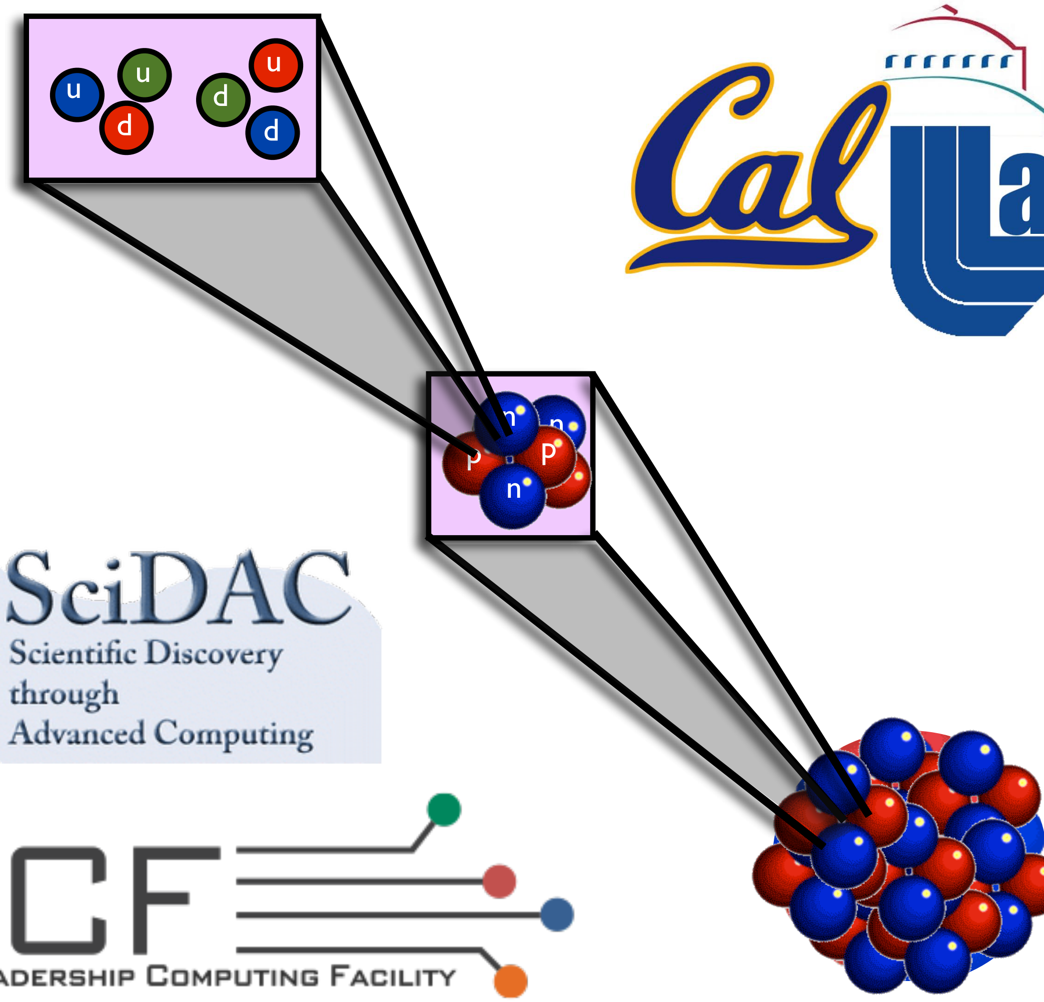


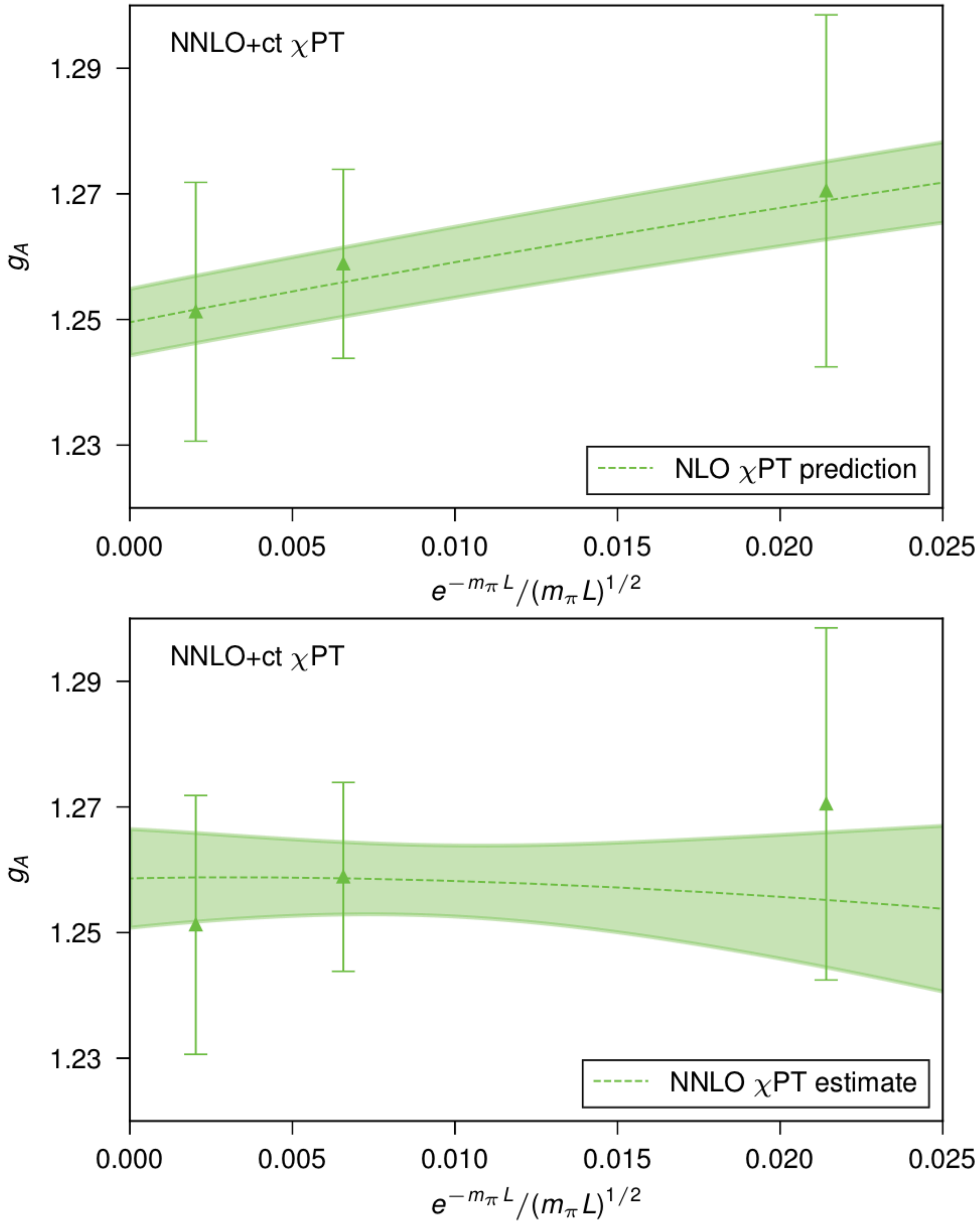
m_π ~ 800 MeV

Summary

- LQCD has entered a precision era for single nucleon observables
  - Systematics are important and must be carefully controlled
  - Convergence for single baryon HBChiPT (without Deltas) may be poor
- Multi-nucleon calculations
  - Results from several groups at heavier than physical pion mass
  - Physical pion mass will require excellent operators
    - Variational methods?
      - Francis et al. 1805.03966 (H-dibaryon)
      - Andersen, Bulava, Hörz, Morningstar, CalLat
  - Several relevant ME's now being calculated, but physical pion mass still currently only available for single hadron

- RIKEN/LBL: C.C. Chang
- RIKEN/BNL: E. Rinaldi
- NERSC: T. Kurth
- Liverpool: N. Garron
- UW/INT C. Monahan
- nVidia: M.A. Clark
- JLab: B. Joo
- WM/JLab: K. Orginos
- CCNY: B. Tiburzi
- LBL/UCB: A. Walker-Loud
- Glasgow: C. Bouchard
- LLNL: A. Gambhir, P. Vranas
- Jülich: E. Berkowitz
- WM/LBL: D. Brantley, H. Monge-Camacho




NNLO+ct χPT
1.29
1.27
1.25
1.23
g_A
NLO χPT prediction
0.000
0.005
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0.015
0.020
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$e^{-m_\pi L}/(m_\pi L)^{1/2}$
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