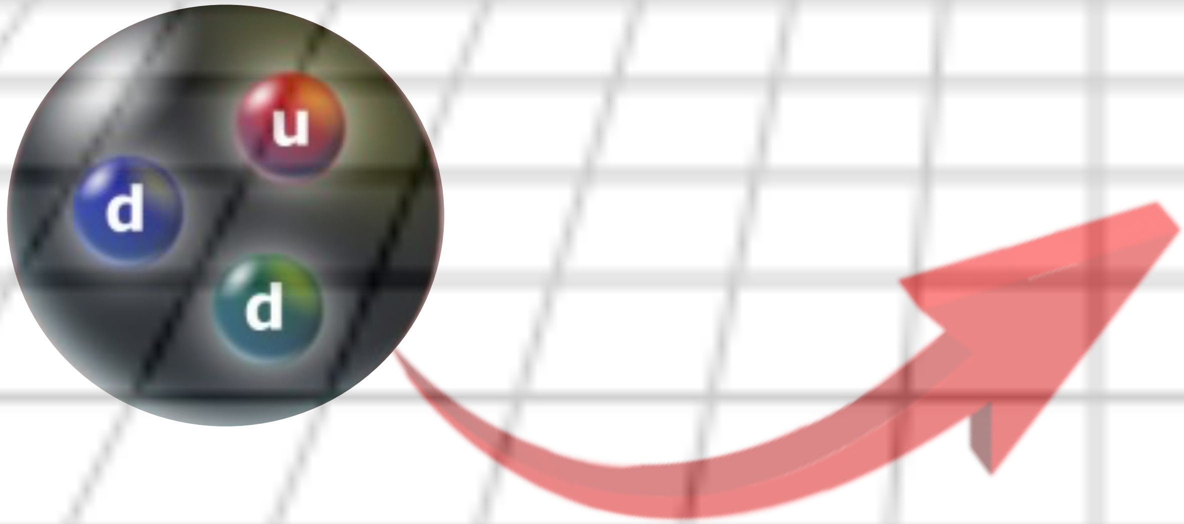
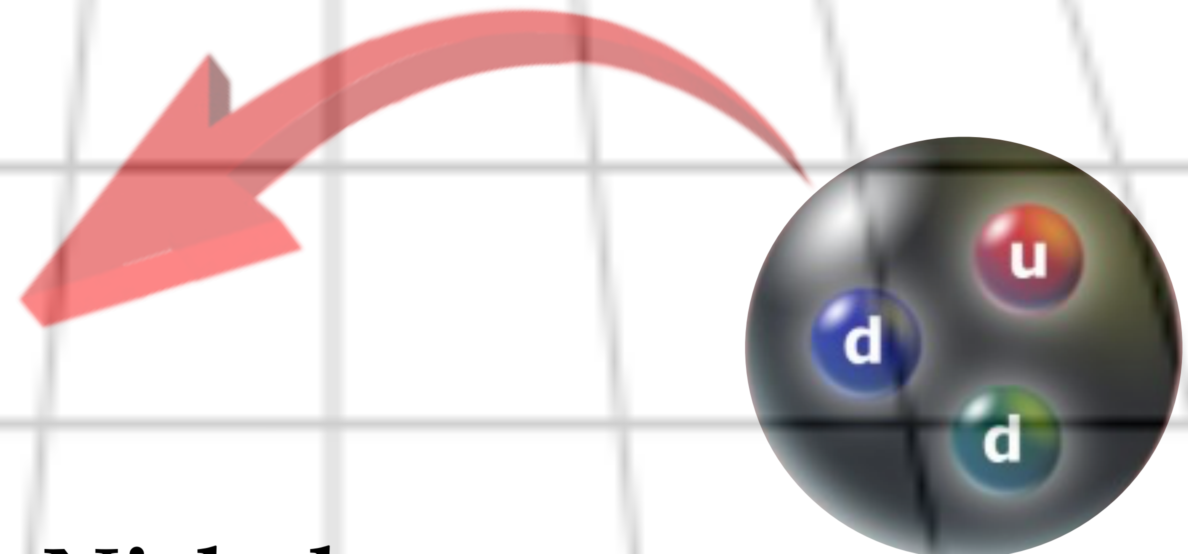


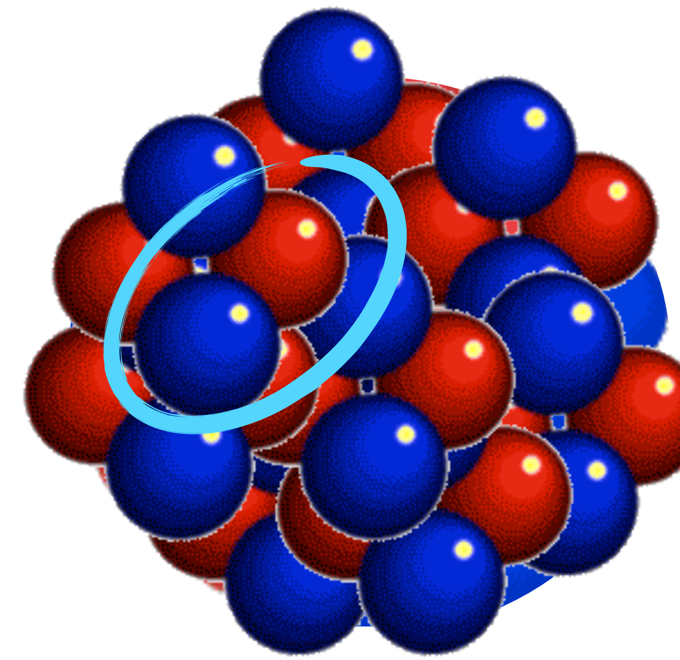
Advances in NN systems



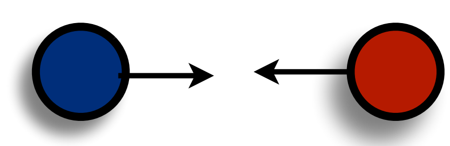
Amy Nicholson
UNC, Chapel Hill

Virtual DBD meeting, May 29, 2020

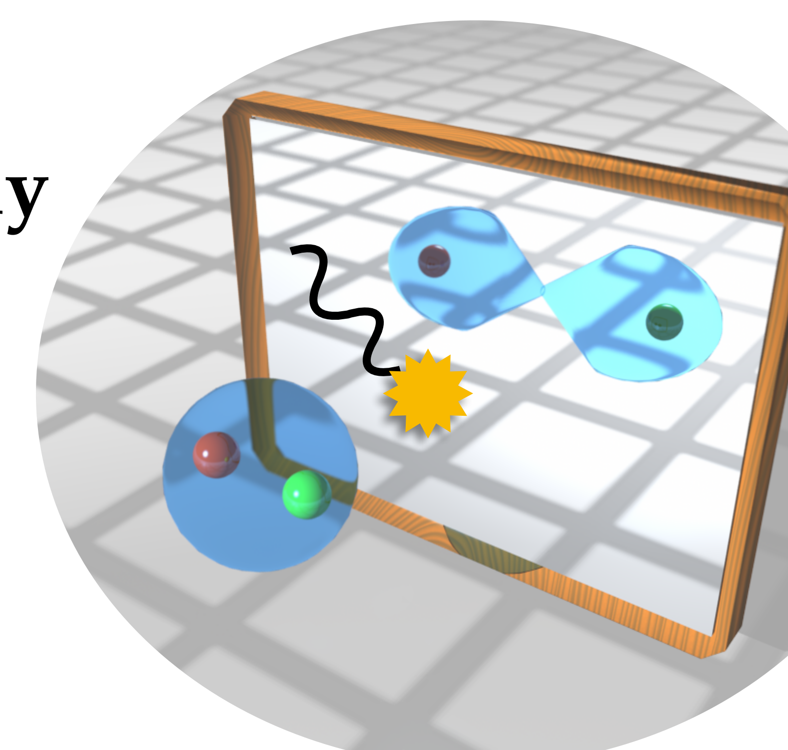
NN systems



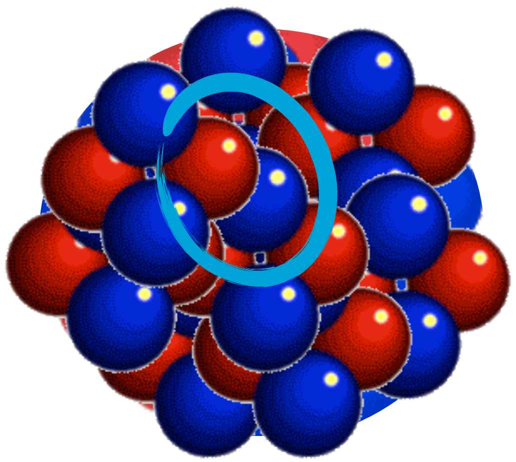
- What do we need to get nuclear physics from LQCD?
  - Phase shifts required for infinite volume matching of MEs
  - Must have full control over 2-body systems



    - How do we project onto desired states?
    - How do we disentangle signals from closely spaced energy levels?
    - How do we beat the noise?



Methods for calculating few-body interactions from LQCD:



Spectroscopy + Lüscher Method

NPLQCD

CalLat

Yamazaki, et. al.

Hanlon et. al.

Potential Method

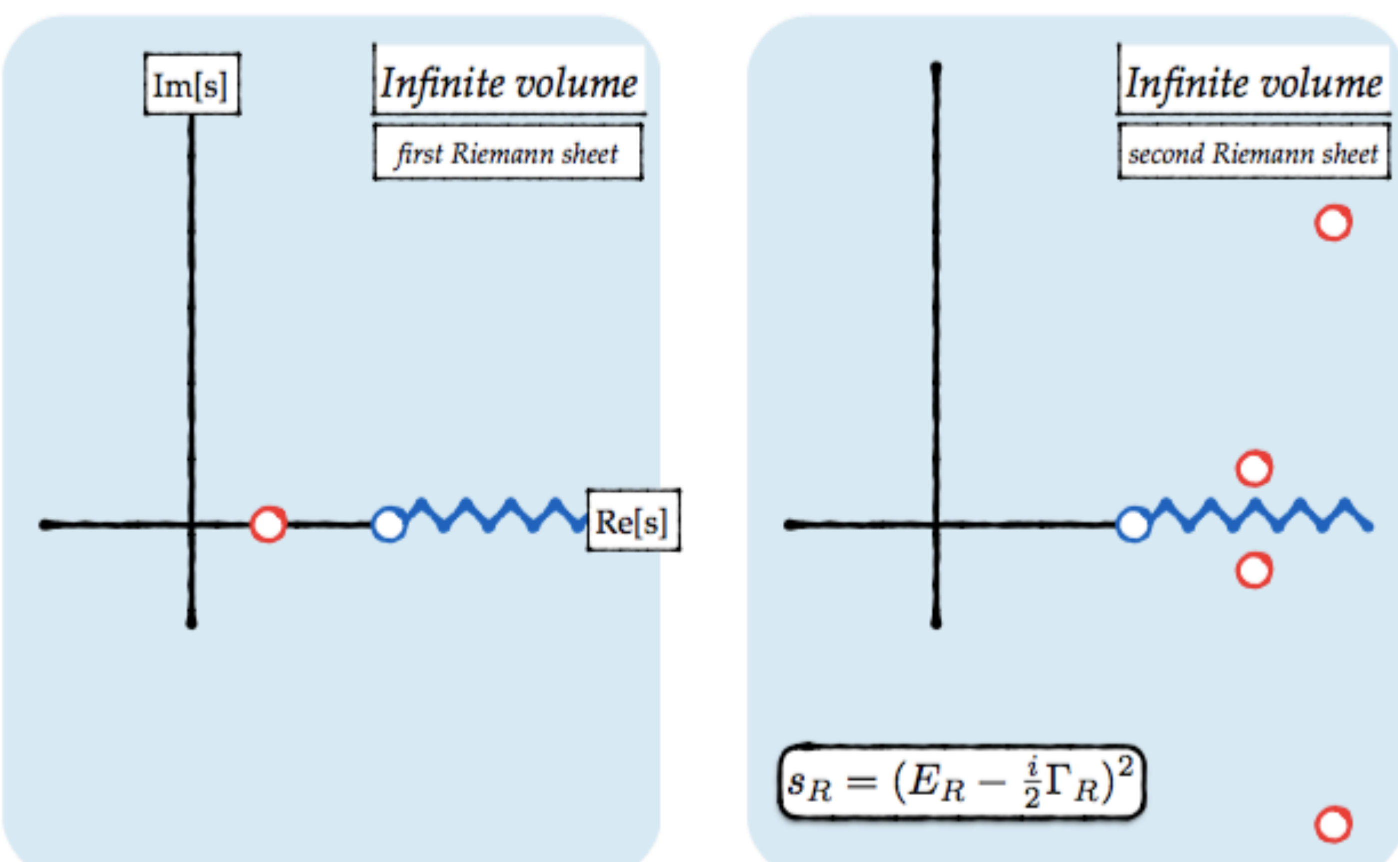
Hadrons to Atomic nuclei HAL from Lattice QCD

Spectroscopy + HOBET

THE HOBET*

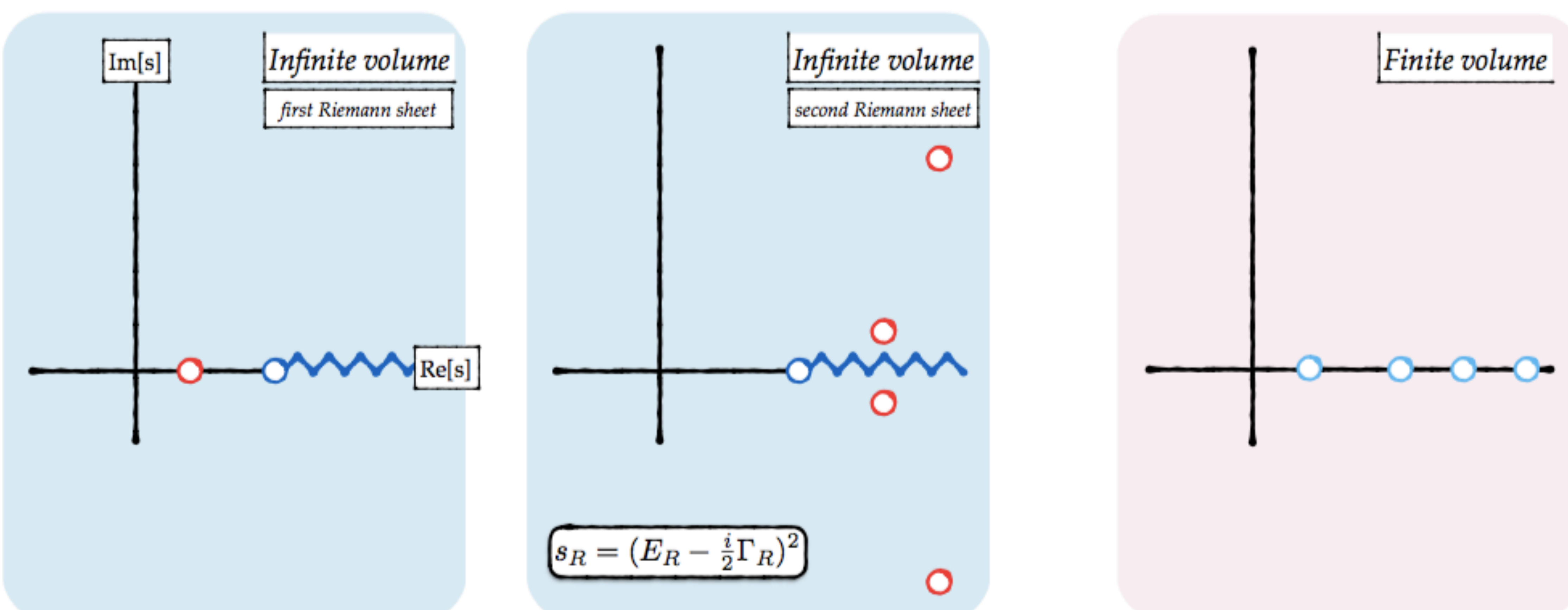
*not an official logo

Spectroscopy



Figures courtesy
R. Briceno

Spectroscopy

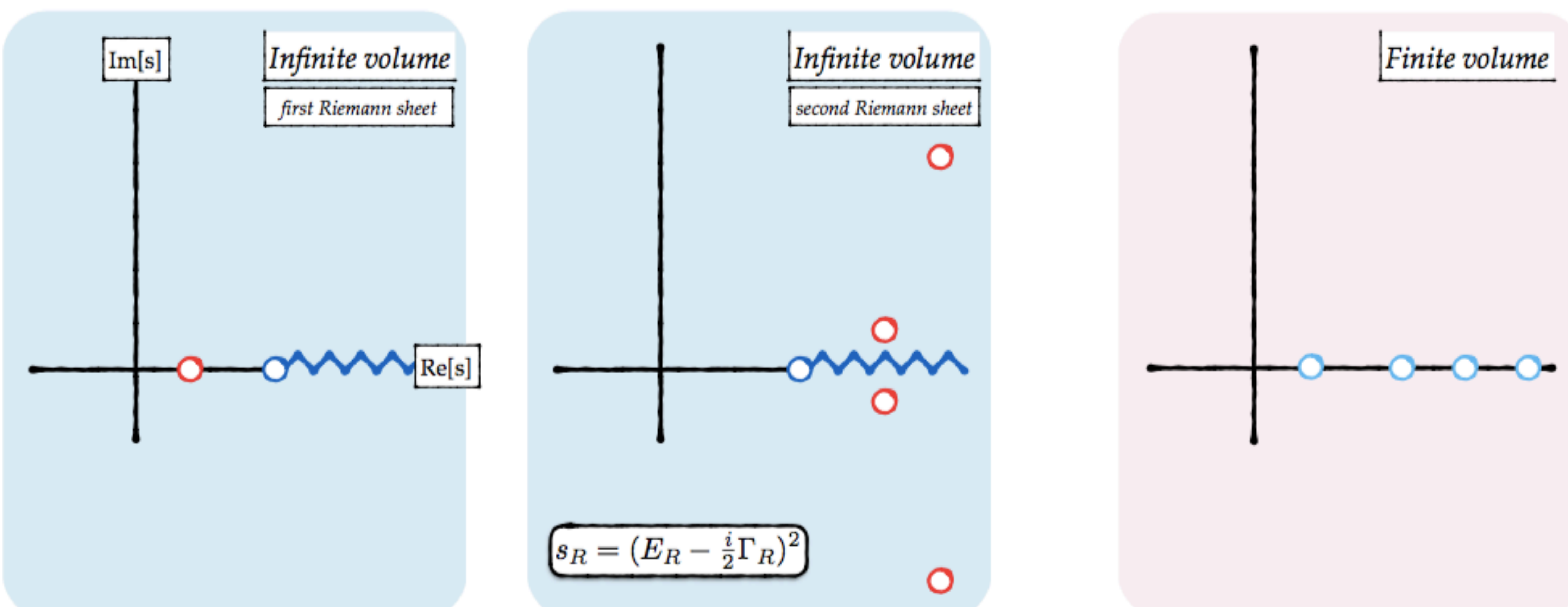


Figures courtesy
R. Briceno

Spectroscopy

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

$$\xrightarrow[t\to\infty]{} \langle 0|\mathcal{O}|E_0\rangle\langle E_0|\mathcal{O}|0\rangle e^{-E_0 t}$$



Figures courtesy
R. Briceno

Spectroscopy

- Finite volume energies simple to calculate from correlation functions at large Euclidean time:

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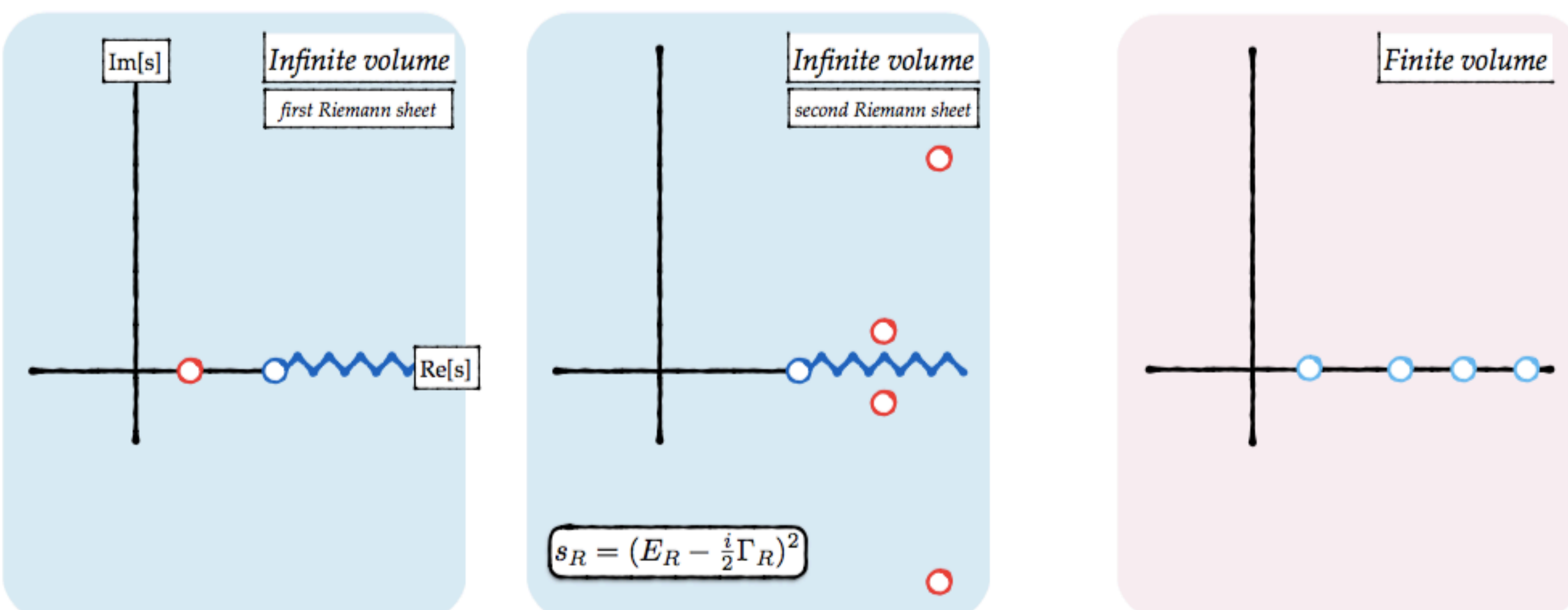

Figures courtesy R. Briceno

Spectroscopy

- Finite volume energies simple to calculate from correlation functions at large Euclidean time:
- Bound states: infinite volume extrapolation gives binding energies

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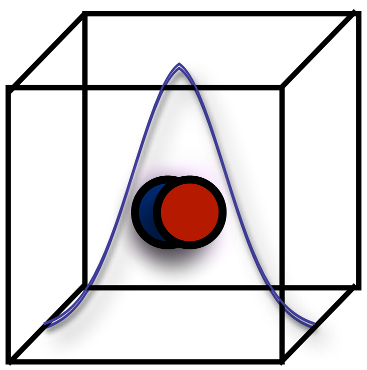

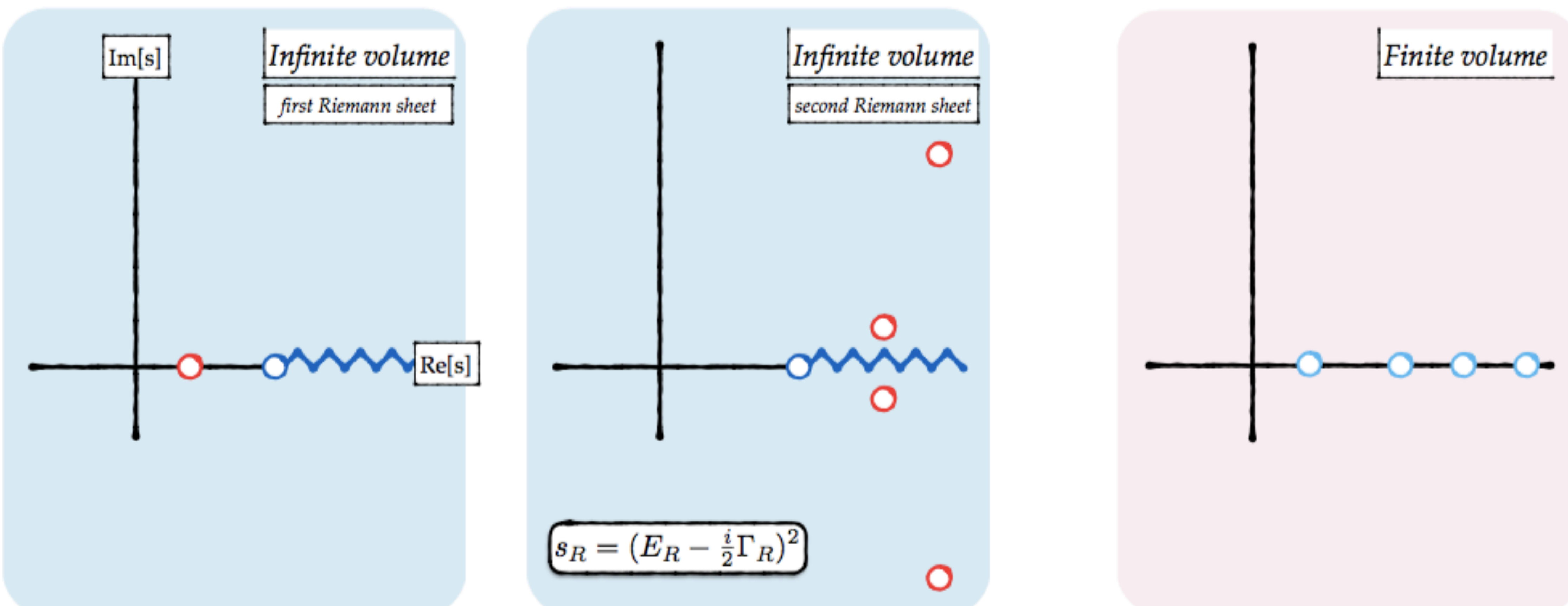

Figures courtesy R. Briceno

Spectroscopy

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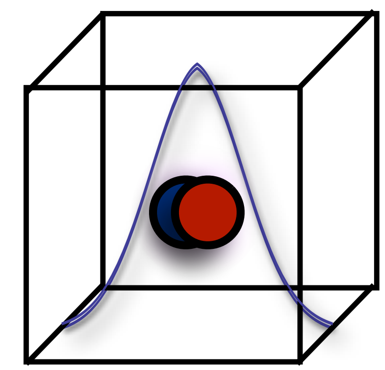
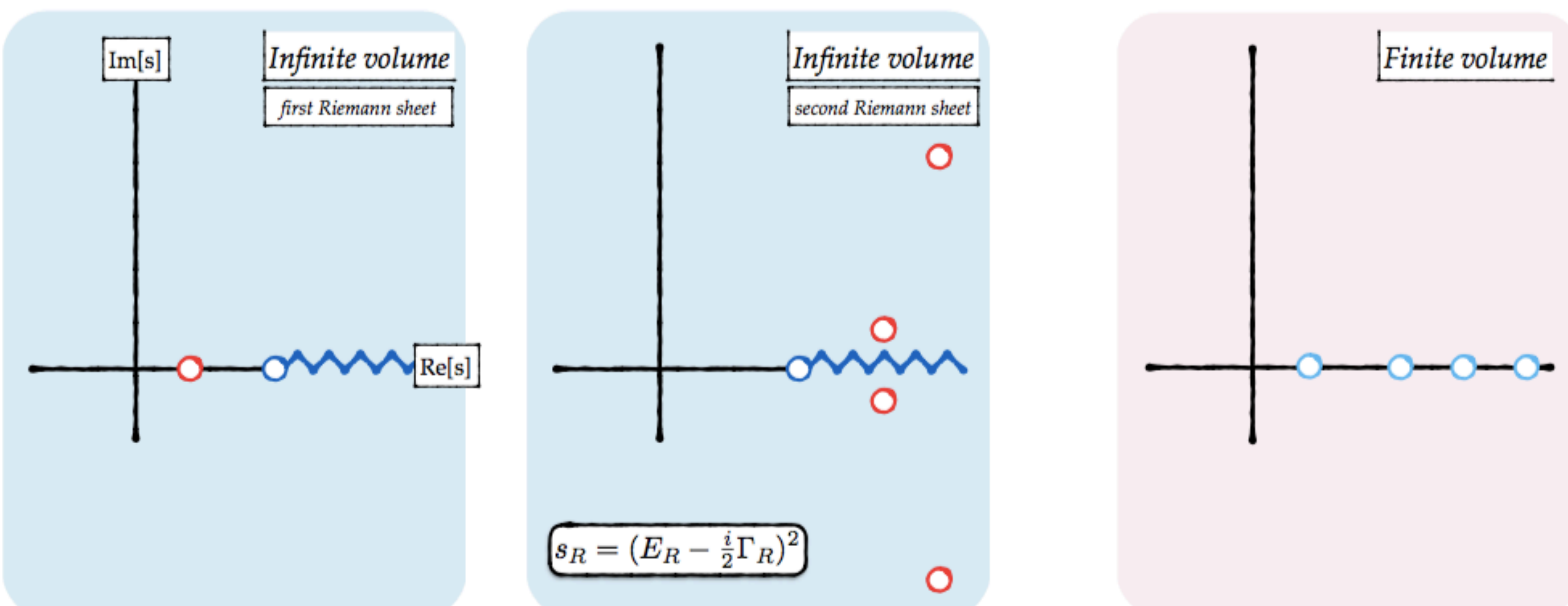


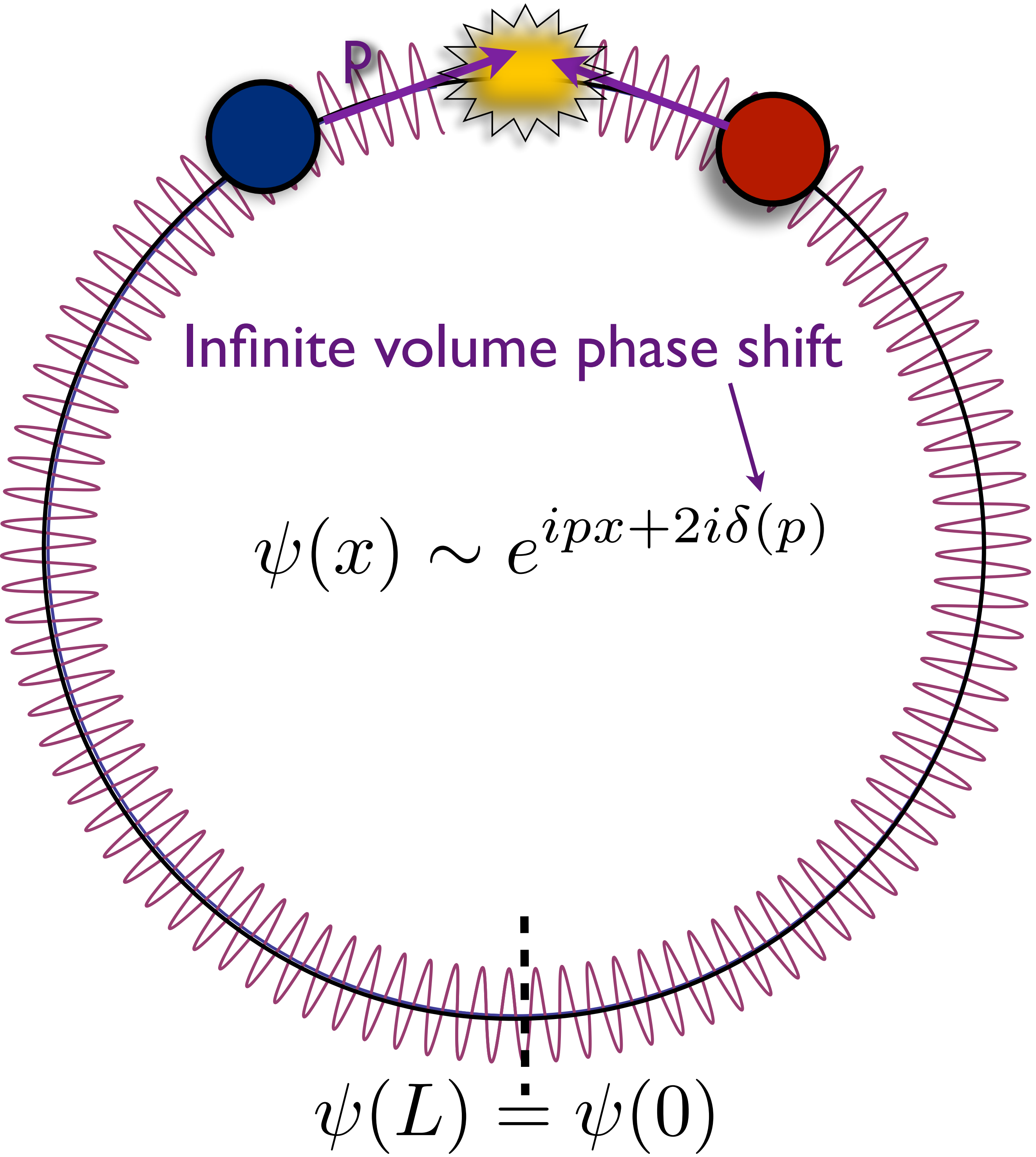
- Bound states: infinite volume extrapolation gives binding energies
- Can't directly resolve resonances or scattering states



Figures courtesy R. Briceno

“Lüscher” in 1-d

Slide stolen unabashedly from R. Briceno



"Lüscher" in 1-d

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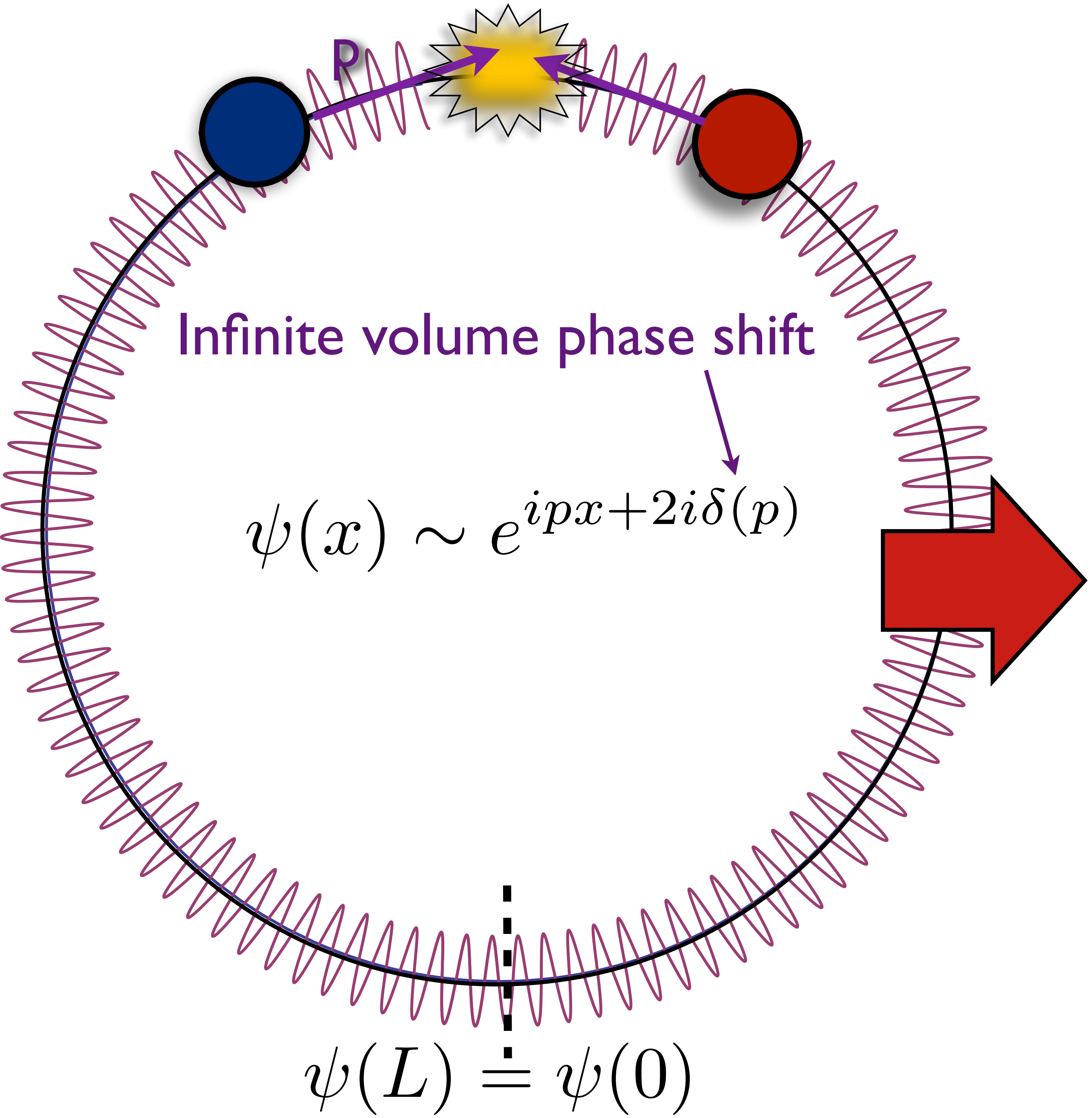
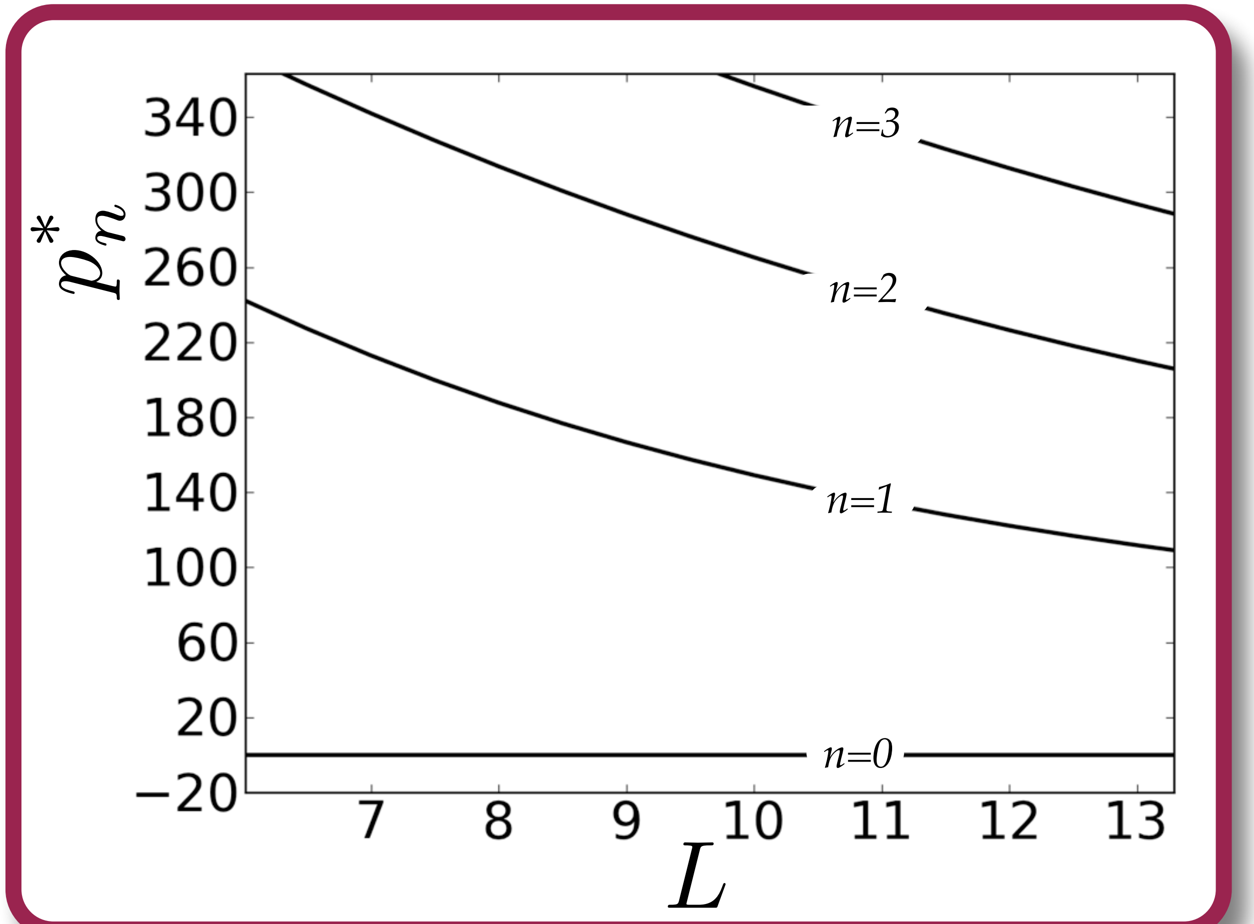


Quantization condition:

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



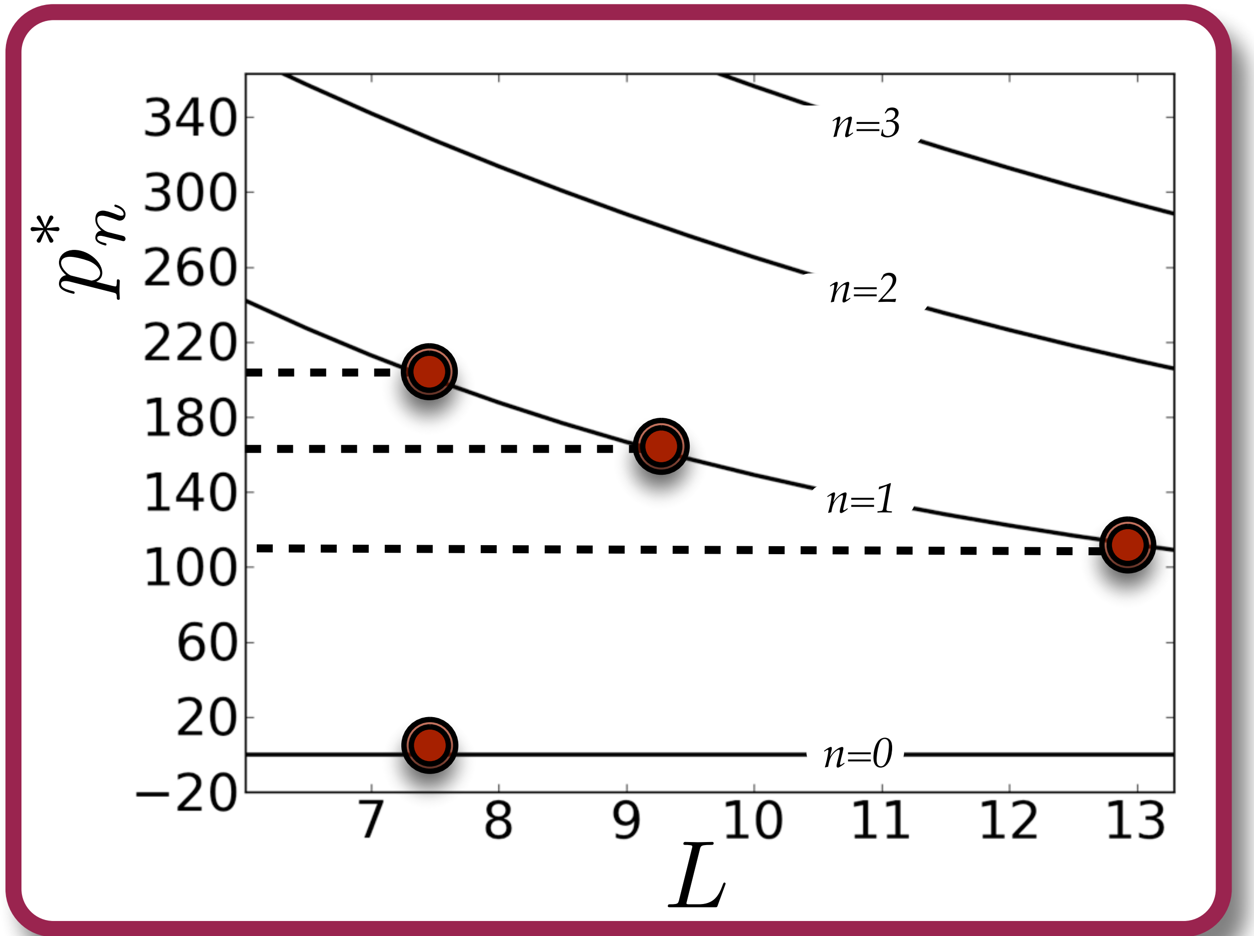
“Lüscher” in 1-d

Slide stolen unabashedly from R. Briceno

Quantization condition:

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

Lattice: measure energies at a given L



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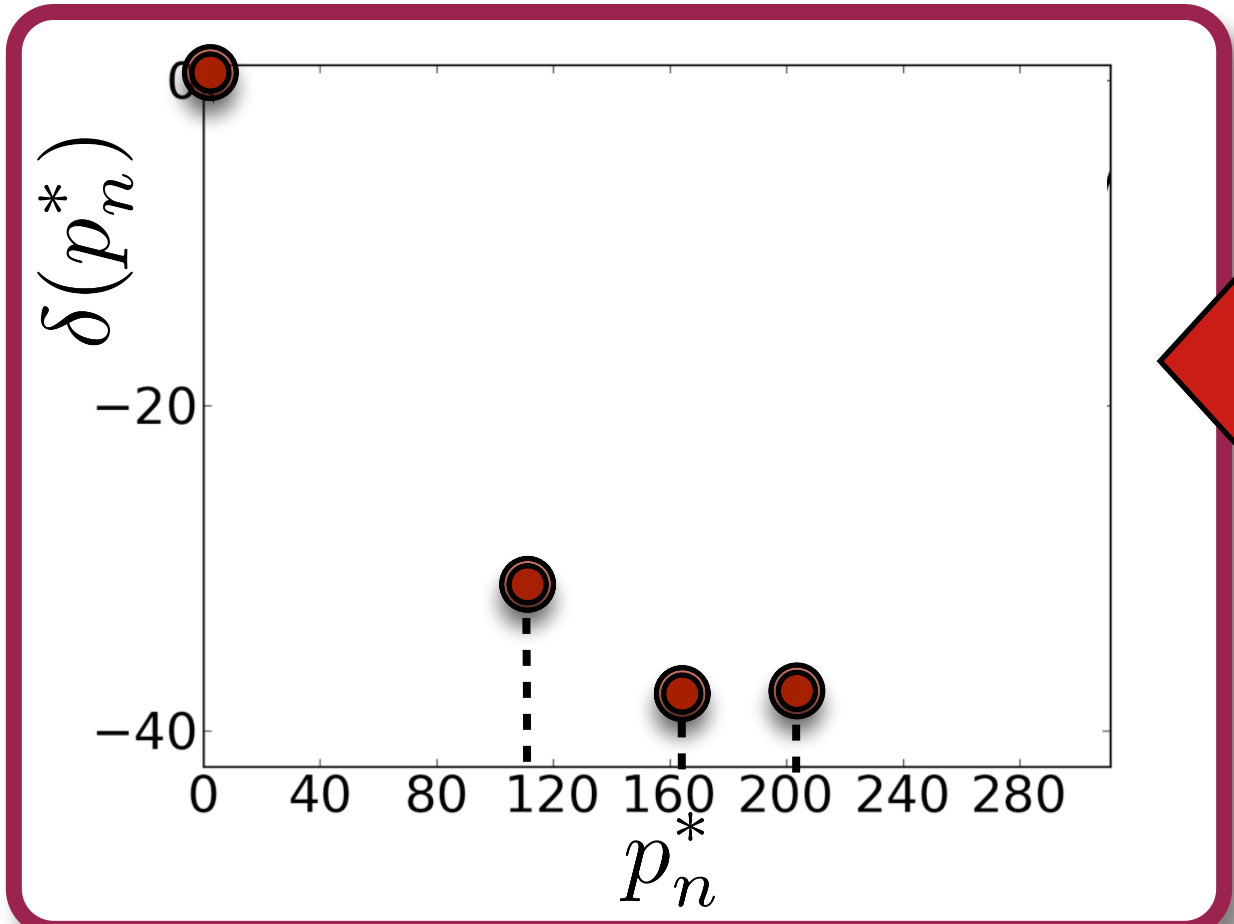

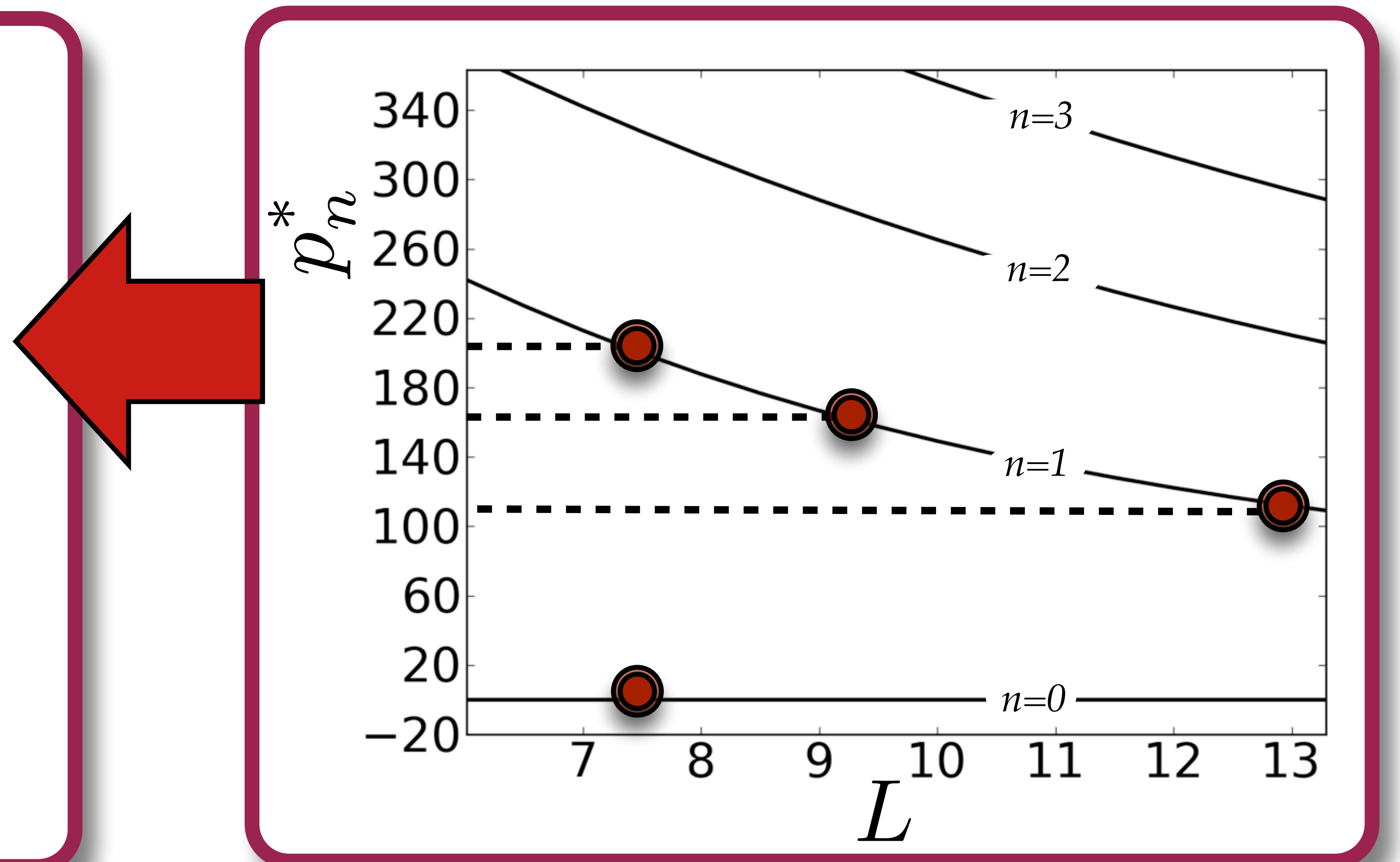

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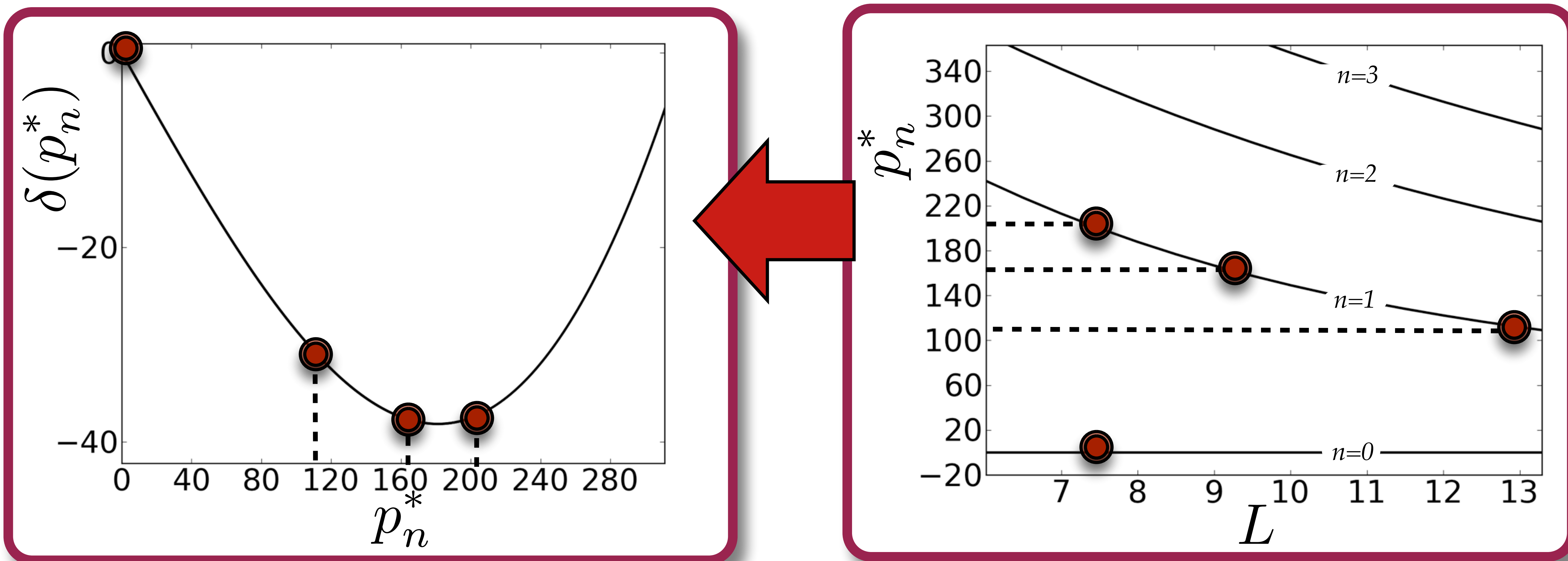
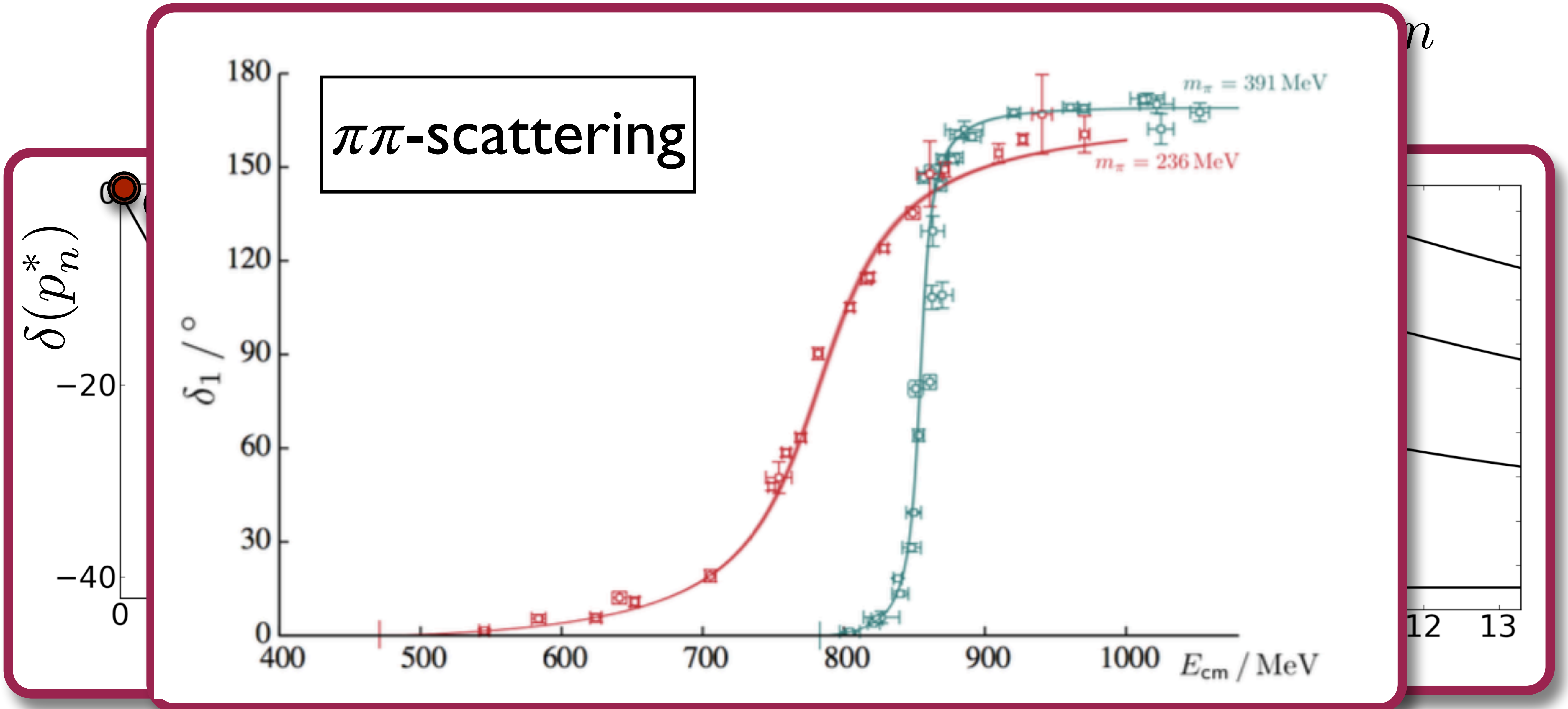


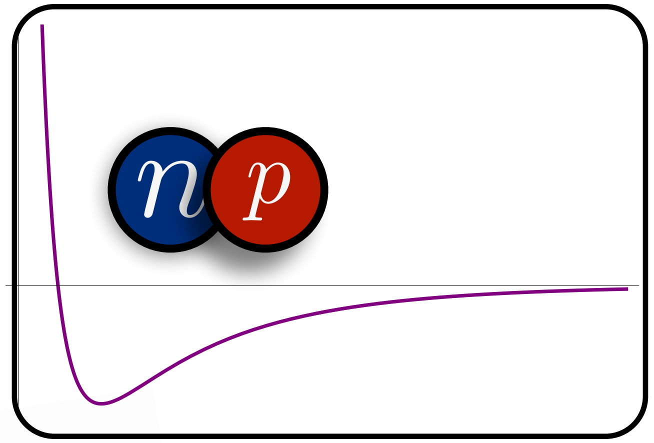
“Lüscher” in 1-d

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

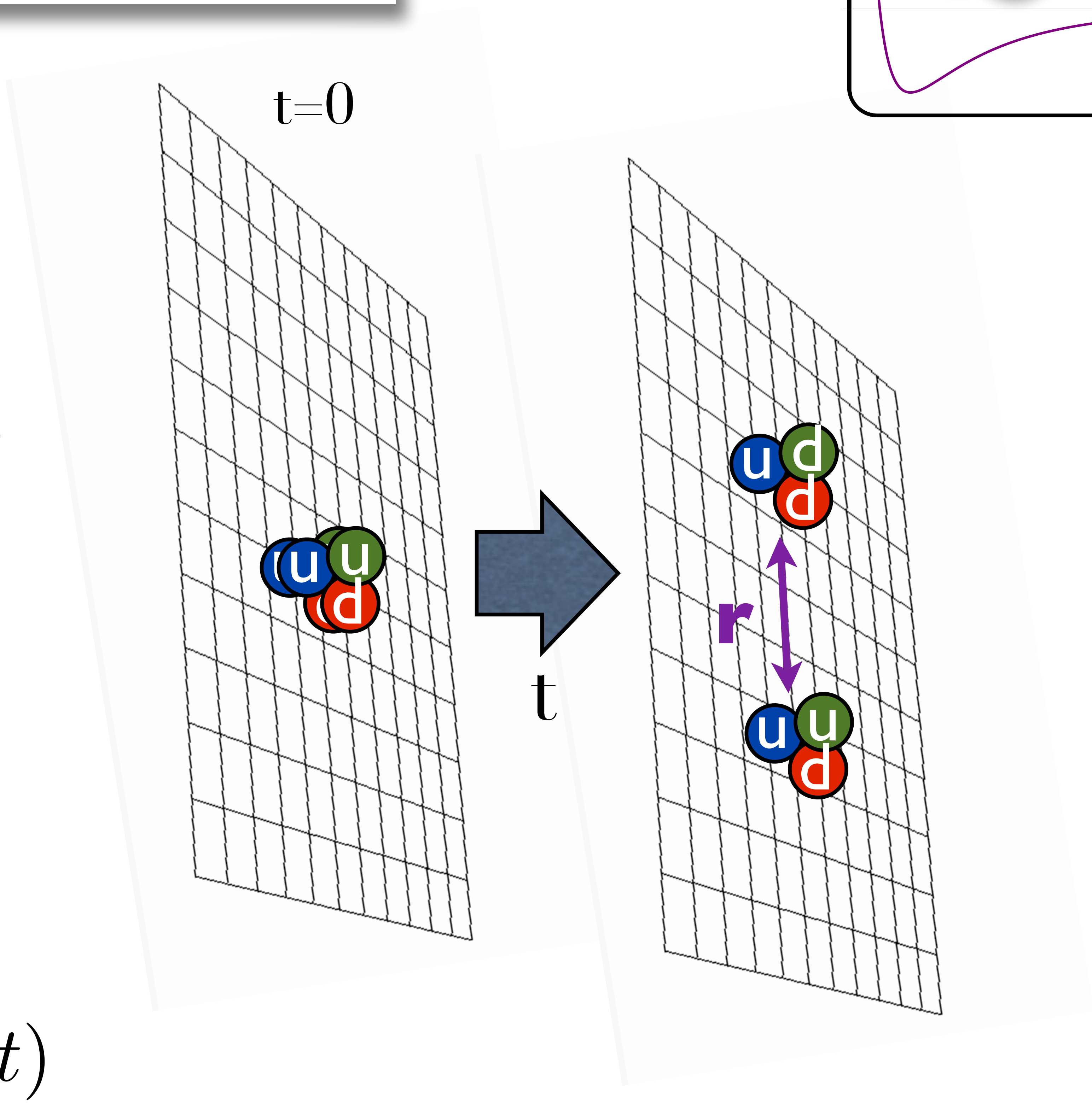
Quantization condition:



Potential method

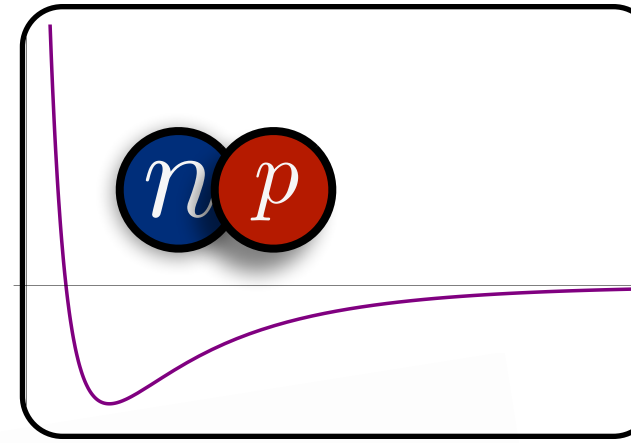


1. Create the following correlation function:



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

Potential method



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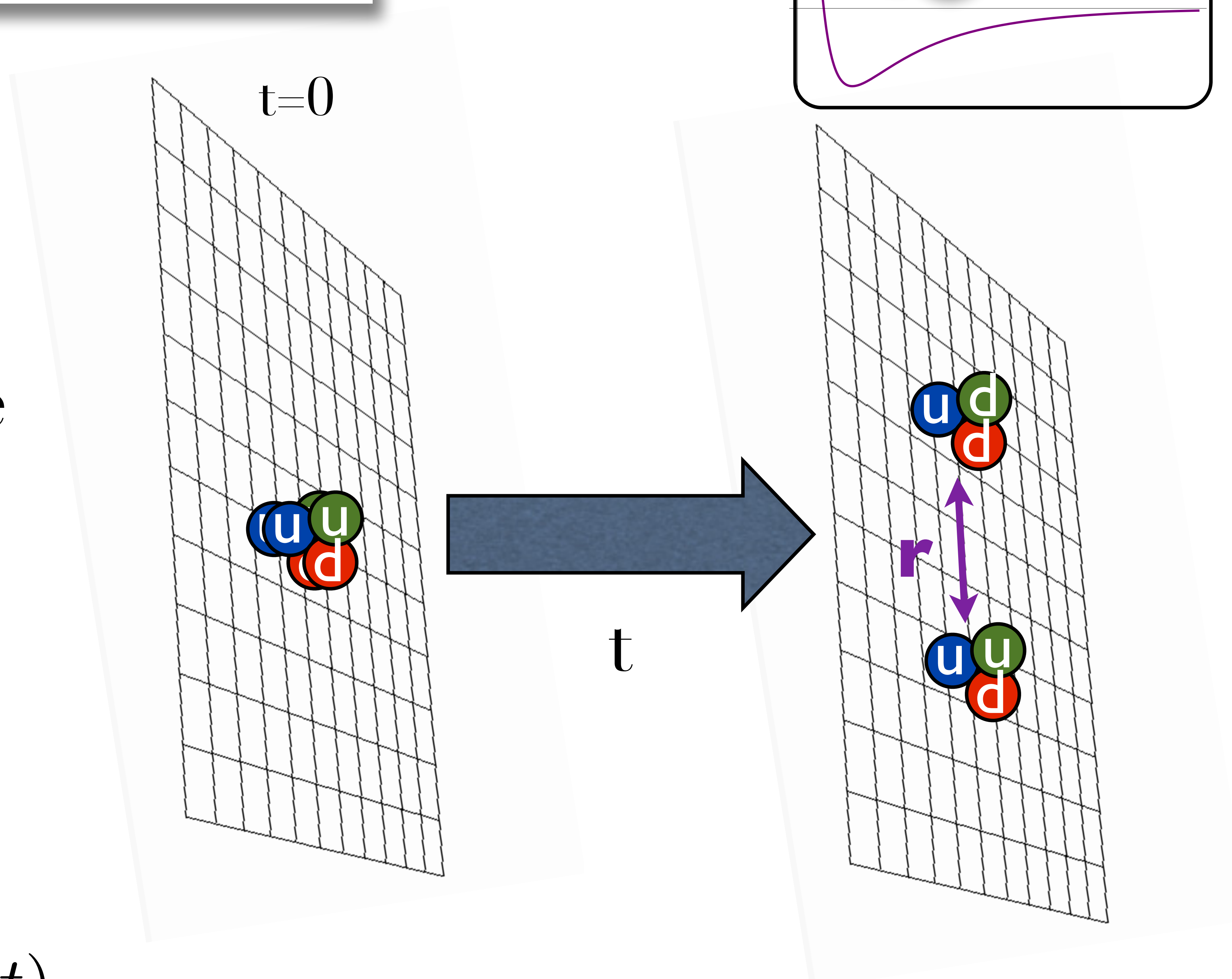
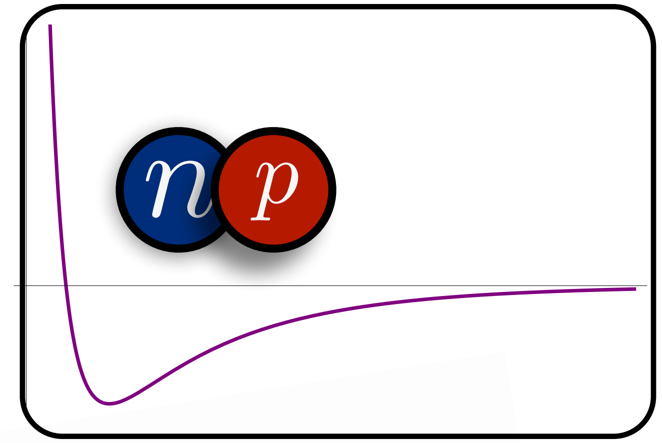
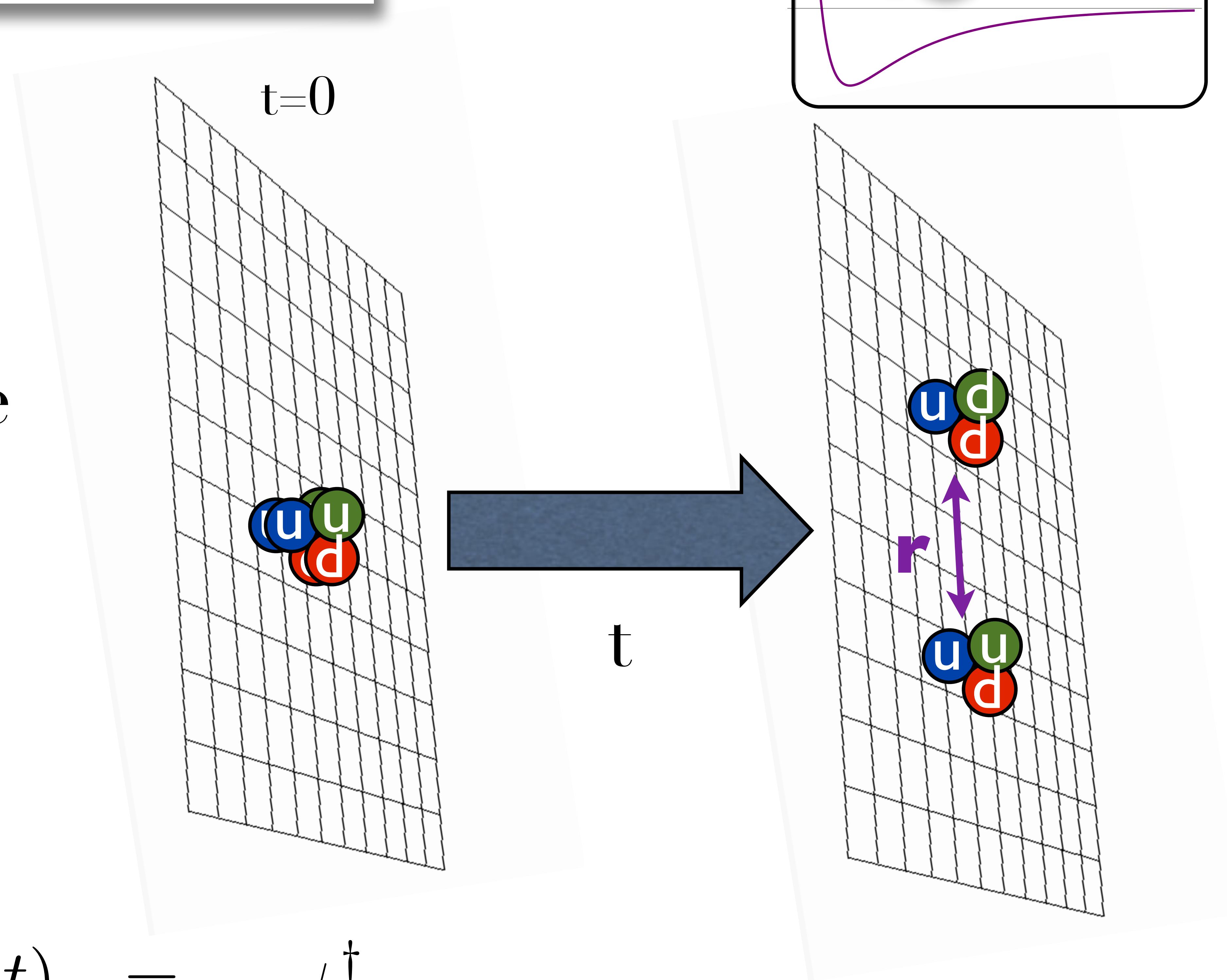


$$\lim_{t\to\infty} C_{NN}(\mathbf{r},t) \quad =$$

Potential method

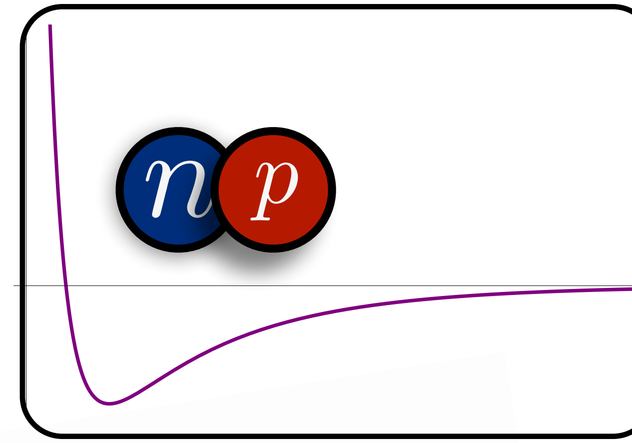




1. Create the following correlation function:

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

Potential method



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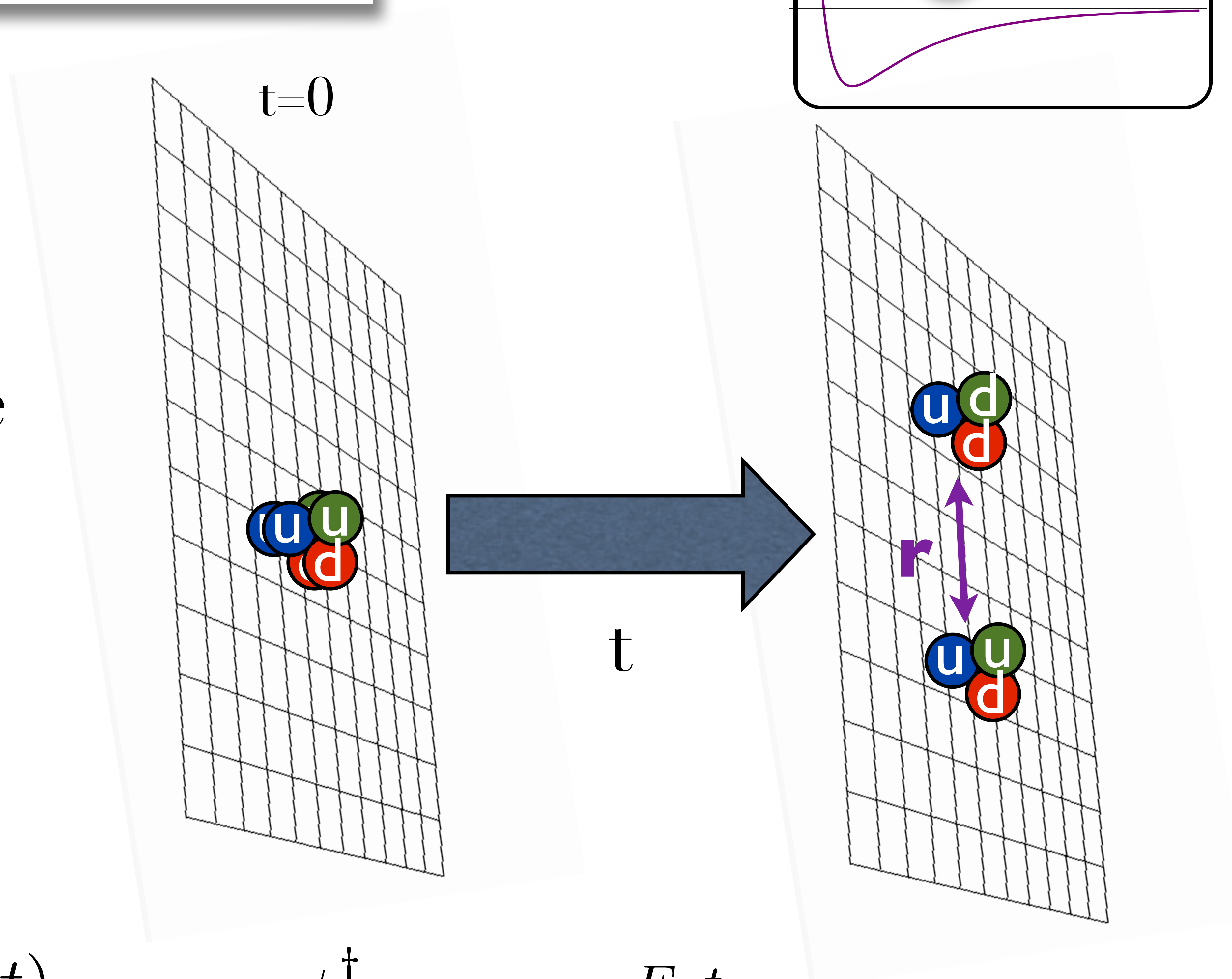
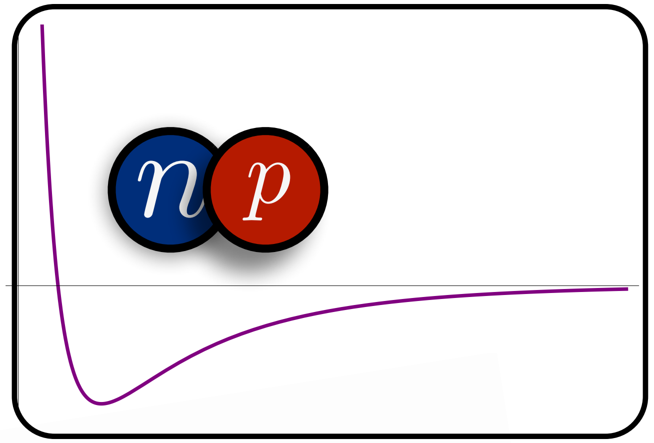


$$\lim_{t\to\infty} C_{NN}(\mathbf{r},t) = \psi_0^\dagger \times e^{-E_0 t}$$

Potential method



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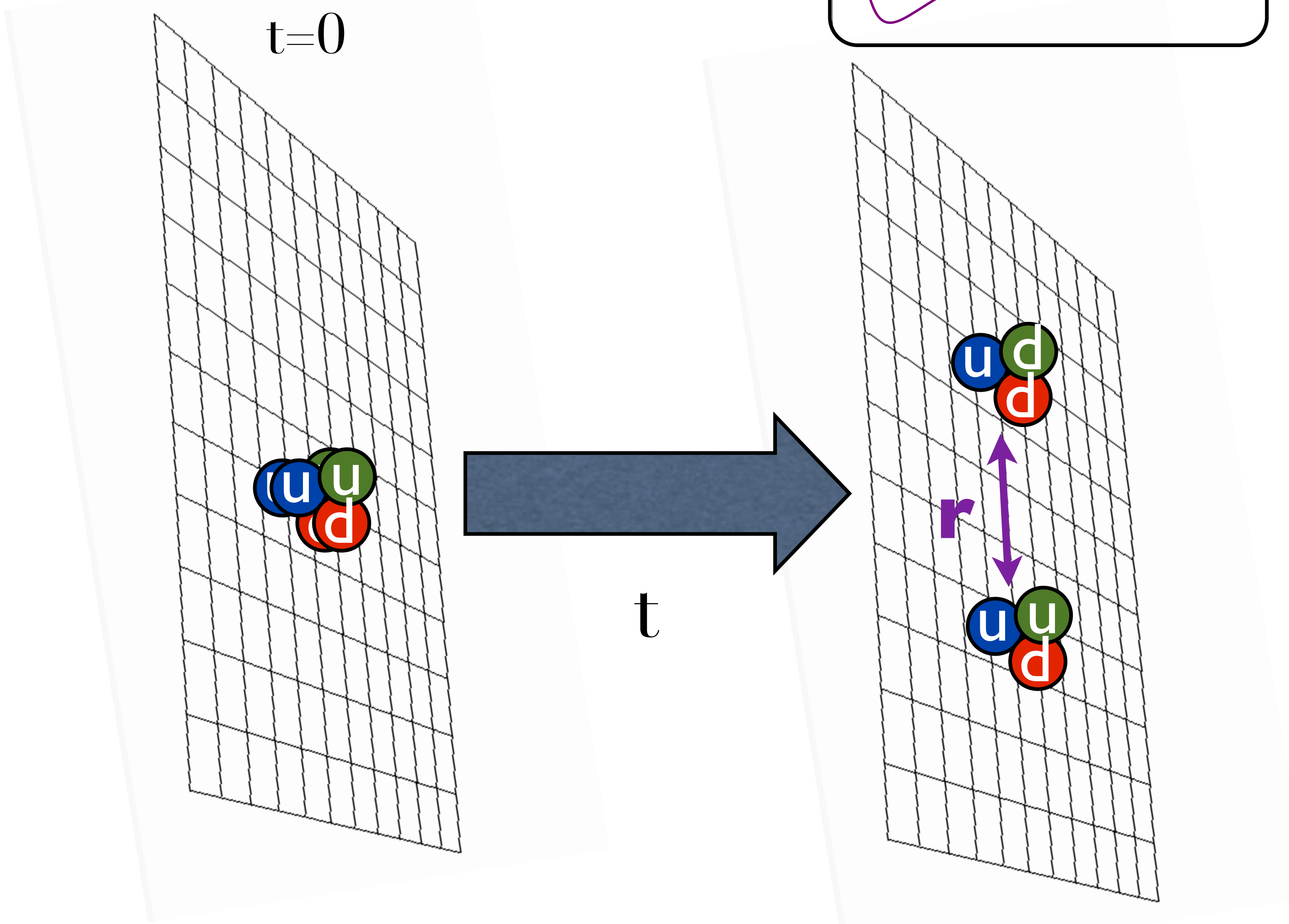
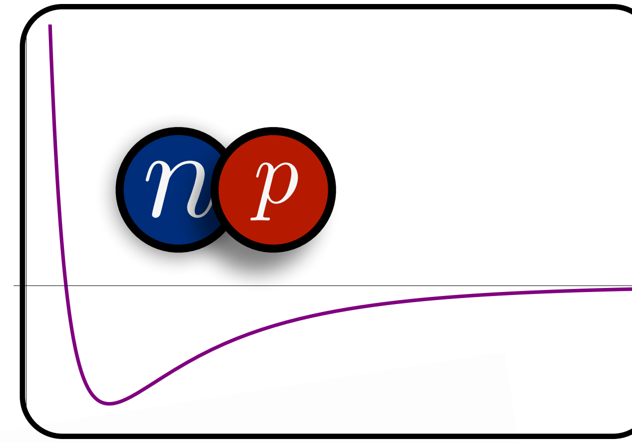


$$\lim_{t\to\infty} C_{NN}(\mathbf{r},t) = \psi_0^\dagger \times e^{-E_0 t} \times \psi_0(\mathbf{r})$$

Potential method



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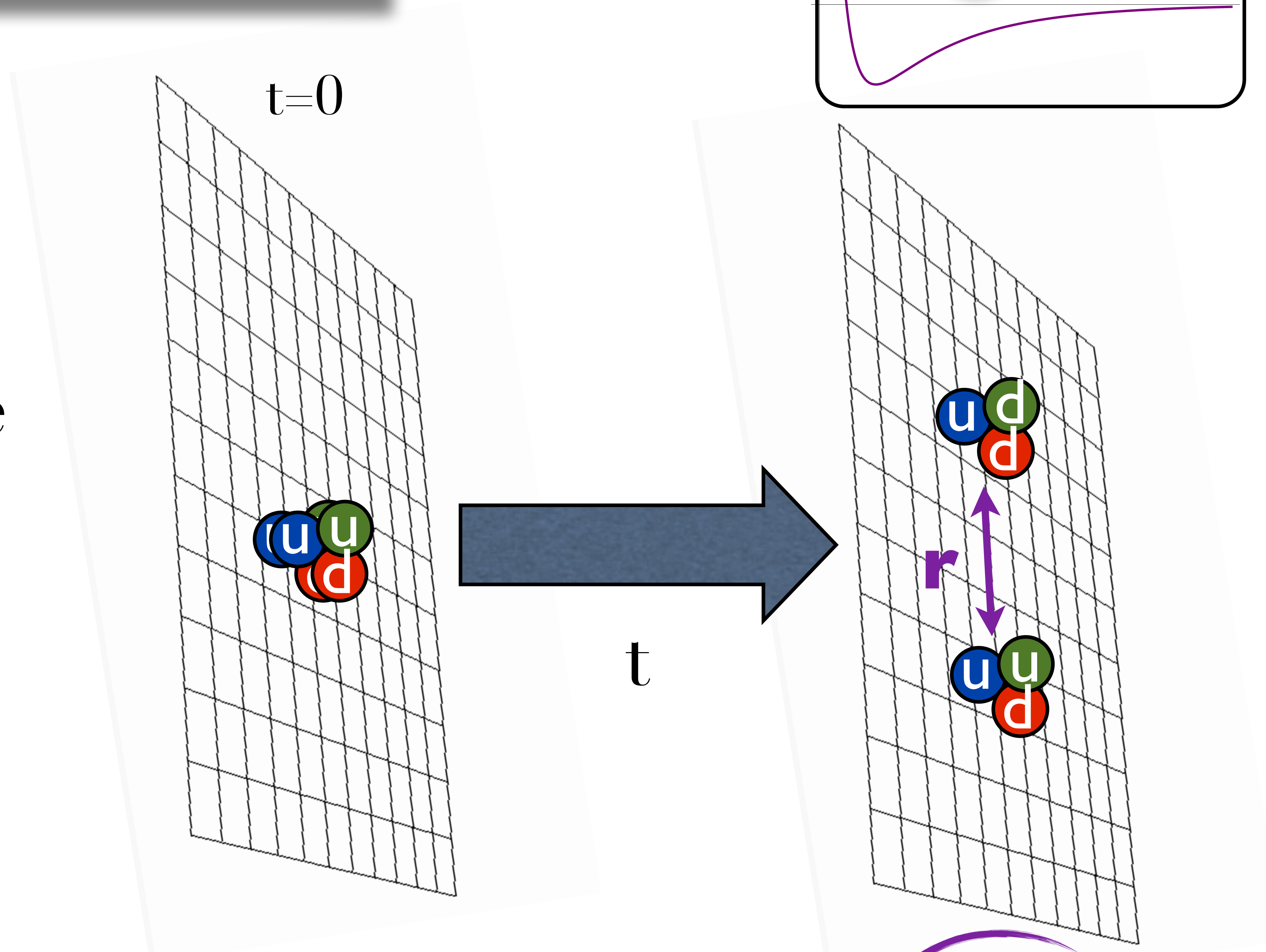

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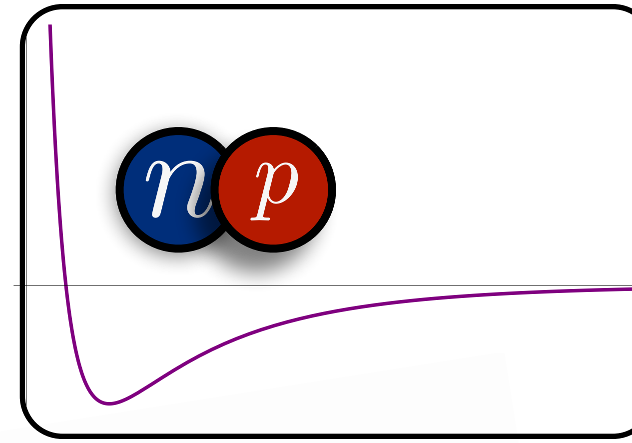
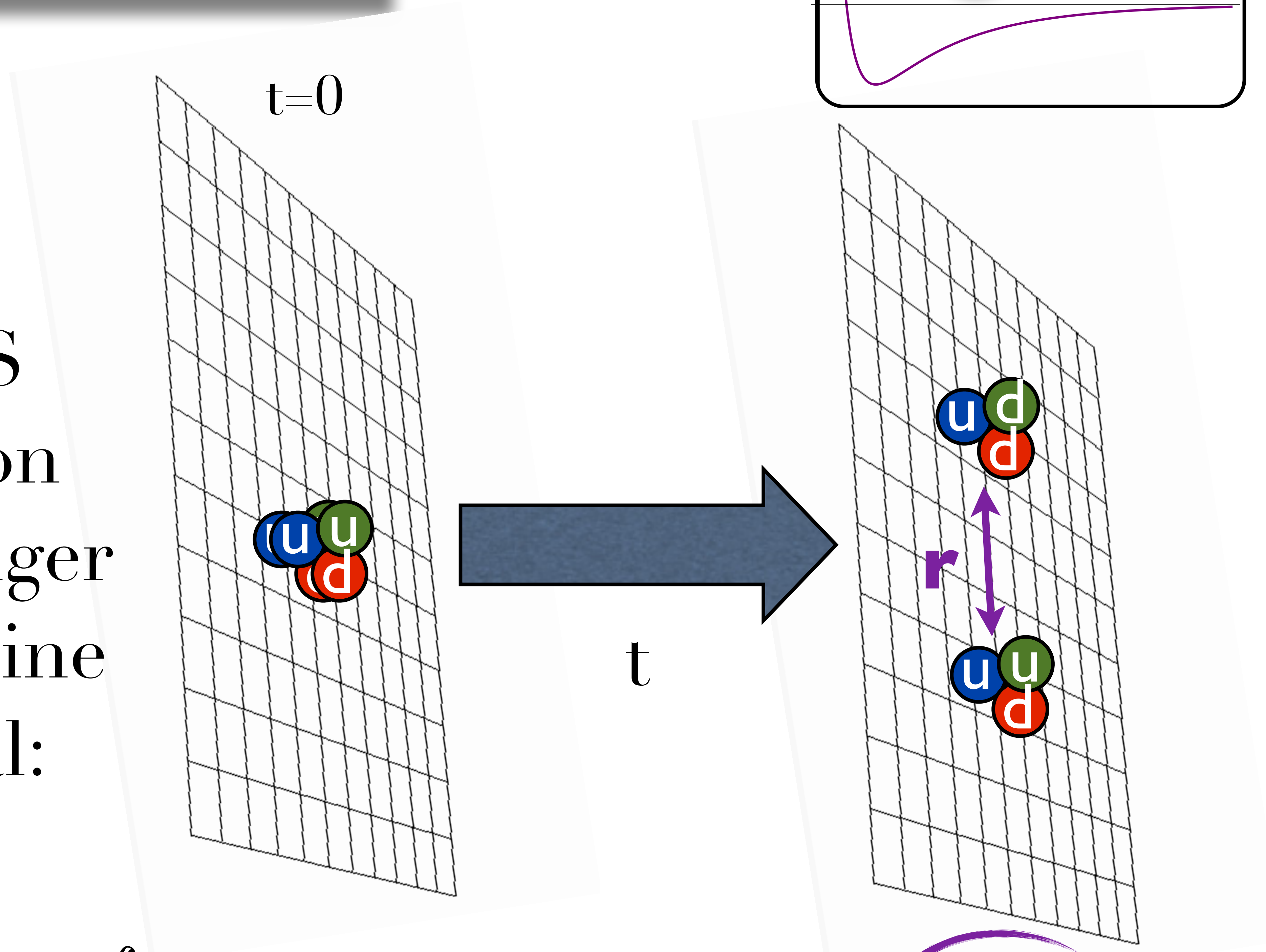
Potential method

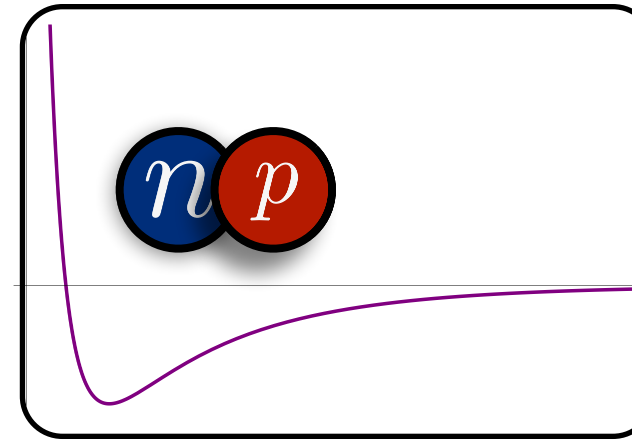


2. Plug NBS wave-function into Schrödinger Eq. to determine the potential:



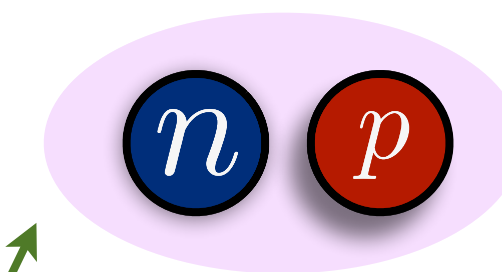
$$\left[\frac{\mathbf{p}^2}{2\mu} - H_0\right] \psi_{\mathbf{p}}(\mathbf{r}) = \int d^3r' U(\mathbf{r},\mathbf{r}') \psi_{\mathbf{p}}(\mathbf{r}') \longleftarrow \psi_0(\mathbf{r})$$

Potential method

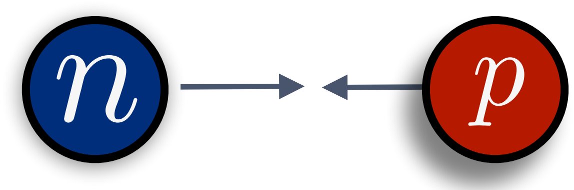


2. Plug NBS wave-function into Schrödinger Eq. to determine the potential:

Binding energies

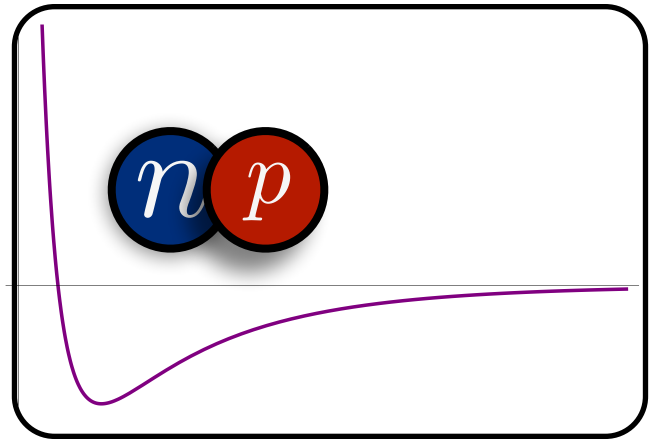


Phase shifts



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

Potential method



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

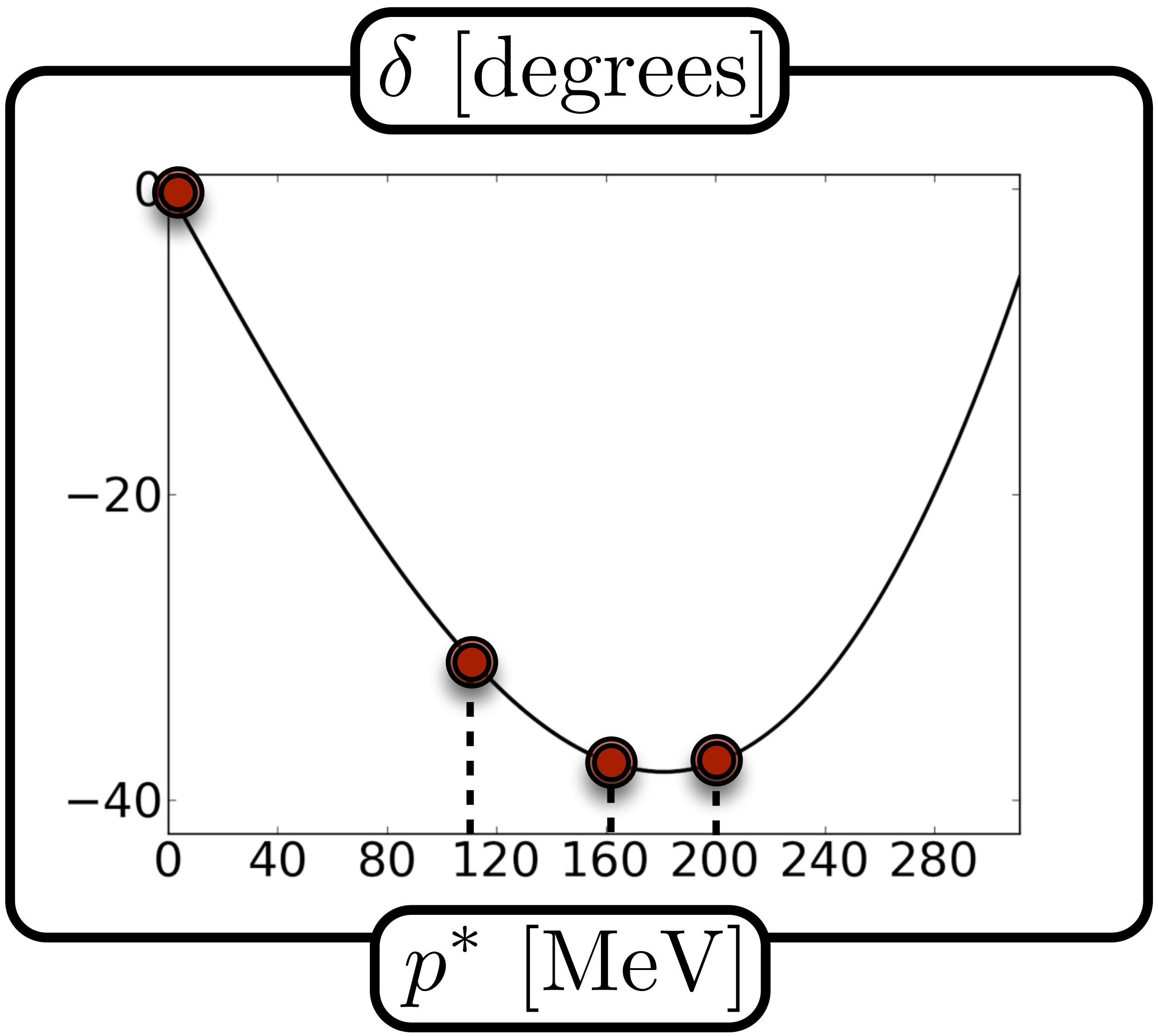
$$U(\mathbf{r},\mathbf{r}') = V_C(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}') + \mathcal{O}(\nabla_{\mathbf{r}}^2/\Lambda^2)$$

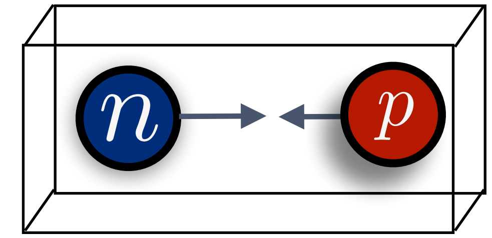
$$V_C(\mathbf{r}) \simeq \frac{\mathbf{p}^2}{2\mu} + \lim_{t\to\infty} \frac{1}{2\mu}\frac{\nabla_{\mathbf{r}}^2 C_{NN}(\mathbf{r},t)}{C_{NN}(\mathbf{r},t)}$$

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

Some comparisons

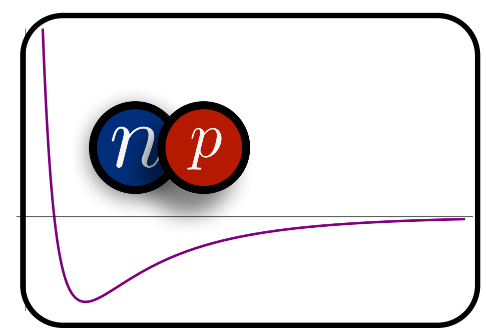
see Drischler, et al, 1910.07961





Luscher

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



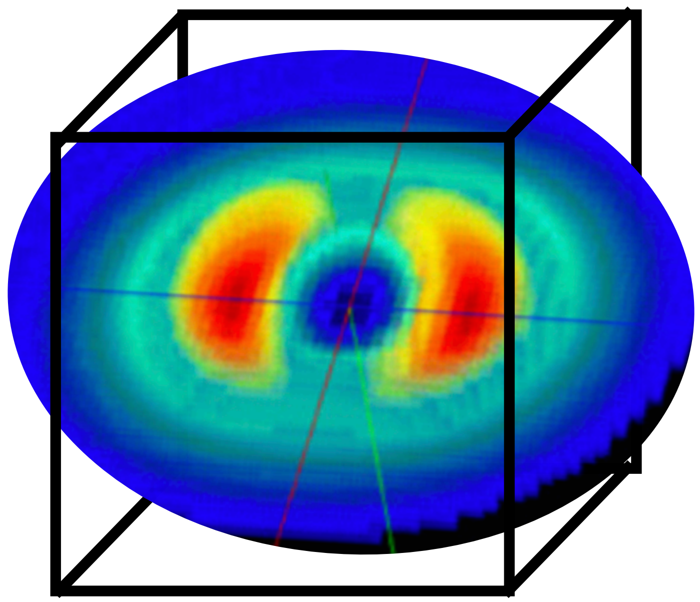
Potential

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

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

LQCD connection to HOBET

(K. McElvain and W. Haxton)



Formulate HOBET with the same (IR) BC as LQCD, fix (UV) couplings to reproduce LQCD energy levels, then remove the BC and make predictions

LQCD connection to HOBET

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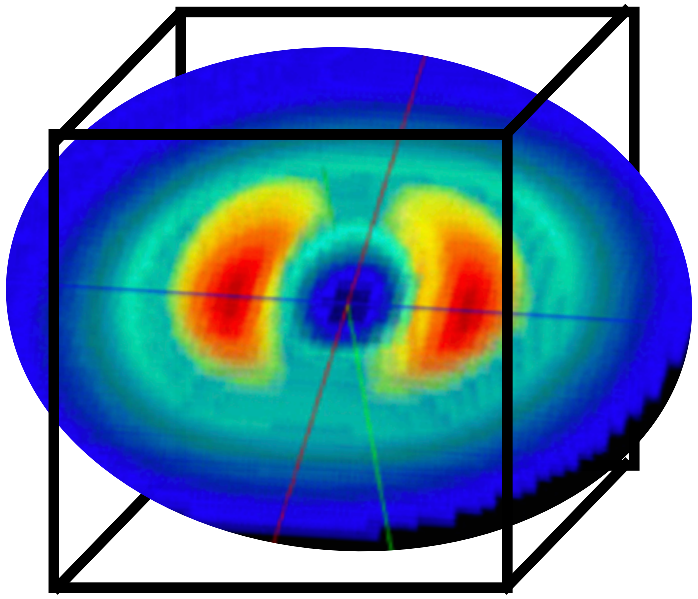
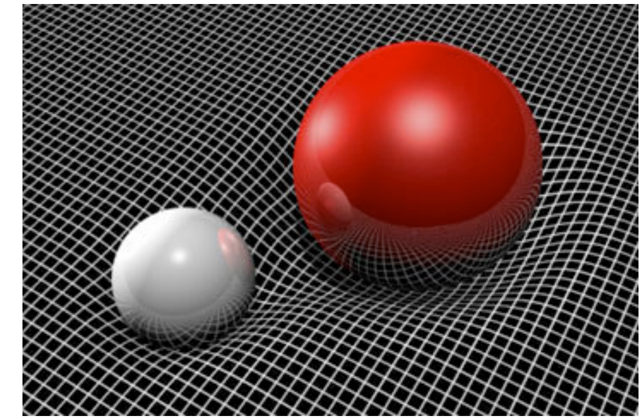


Formulate HOBET with the same (IR) BC as LQCD, fix (UV) couplings to reproduce LQCD energy levels, then remove the BC and make predictions

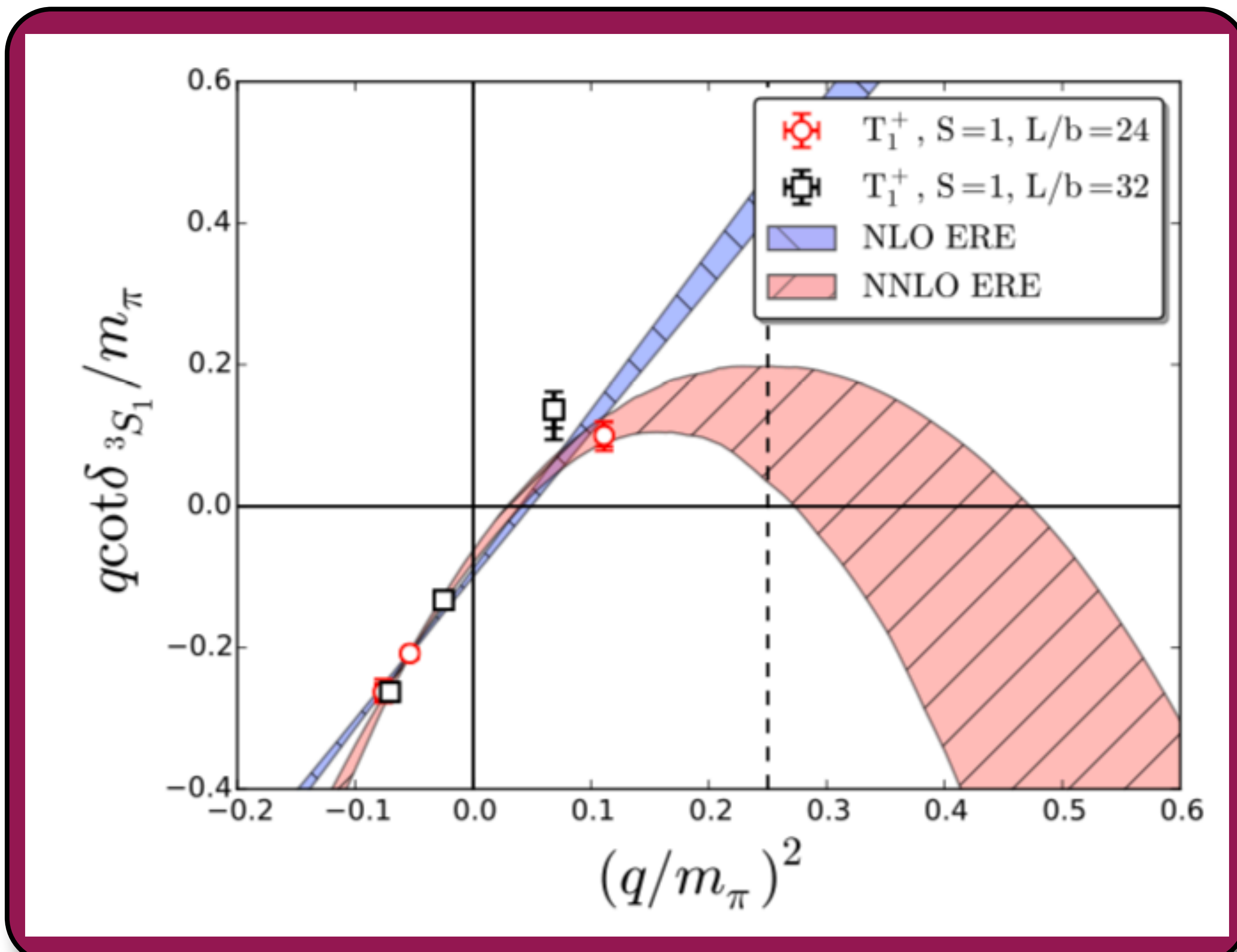
- No need to truncate partial wave expansion
- Can deal with volumes smaller than Compton wavelength of the pion
- Luscher formalism for N>2 is messy
- Alternate method for determining binding energies

Composite states at $m_\pi \sim 800$ MeV

- L=32
- L=24



$p\cot\delta = ip$



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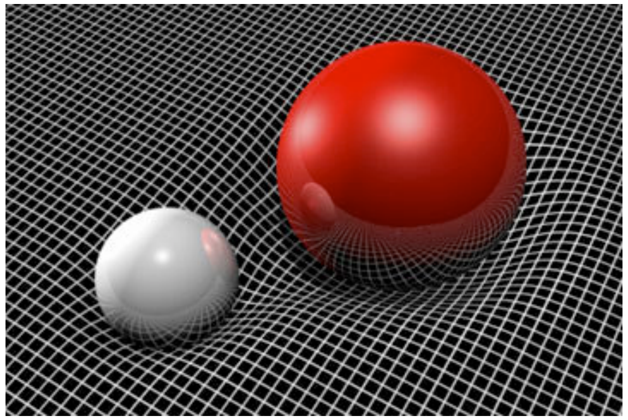

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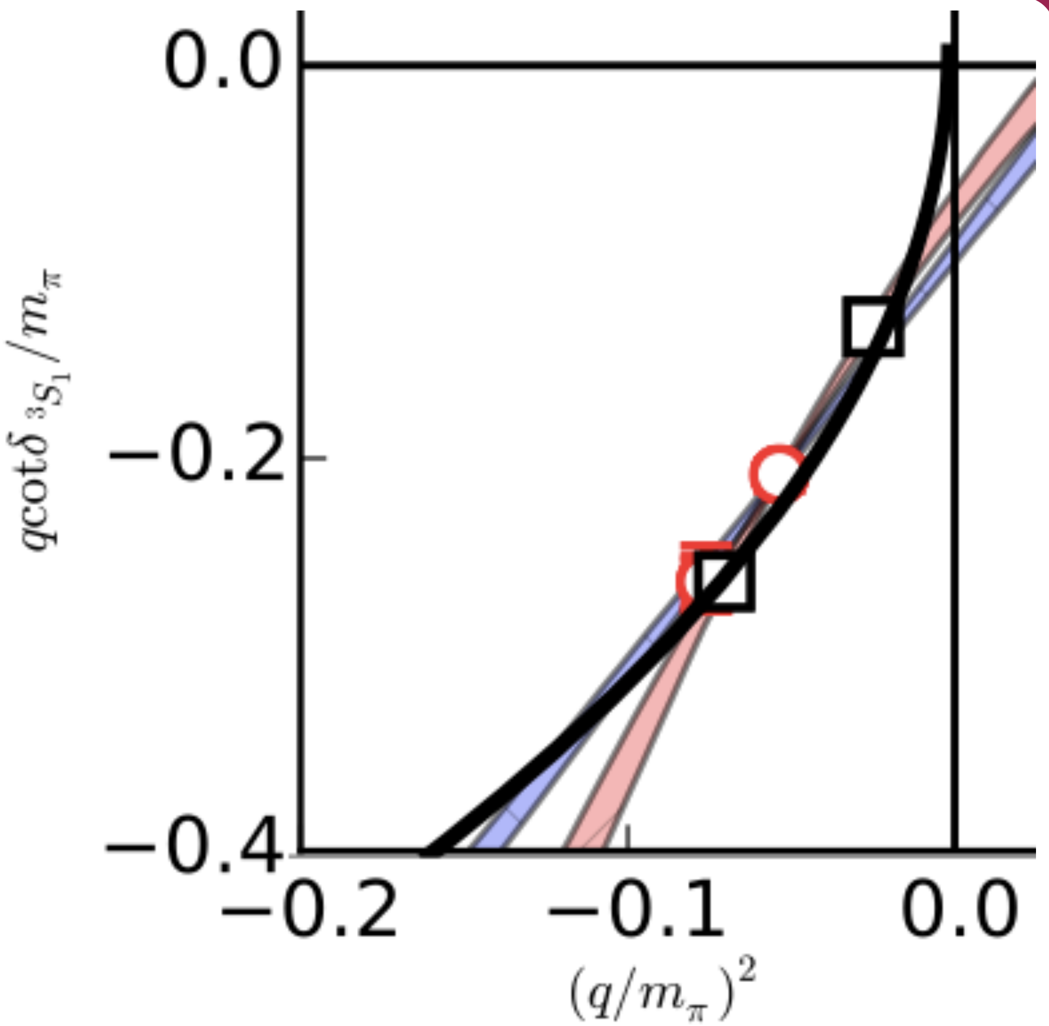

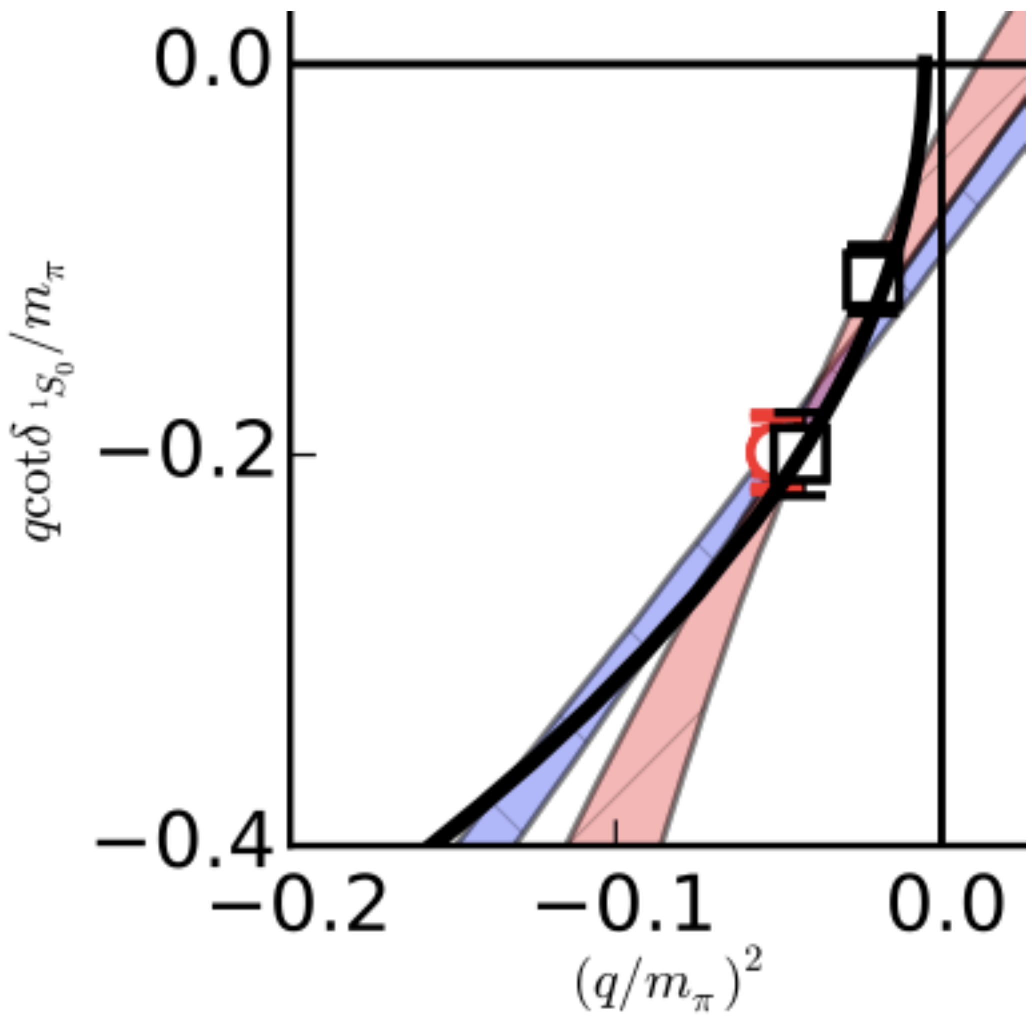

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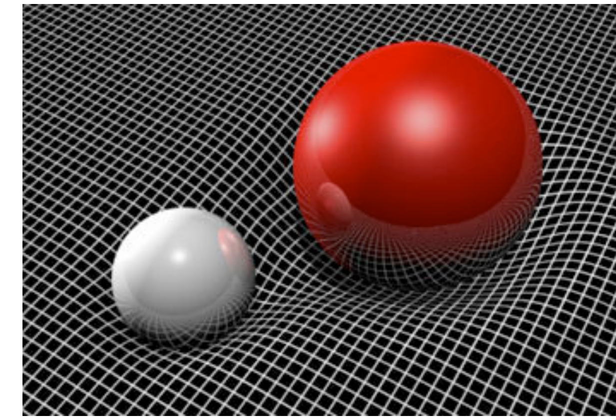

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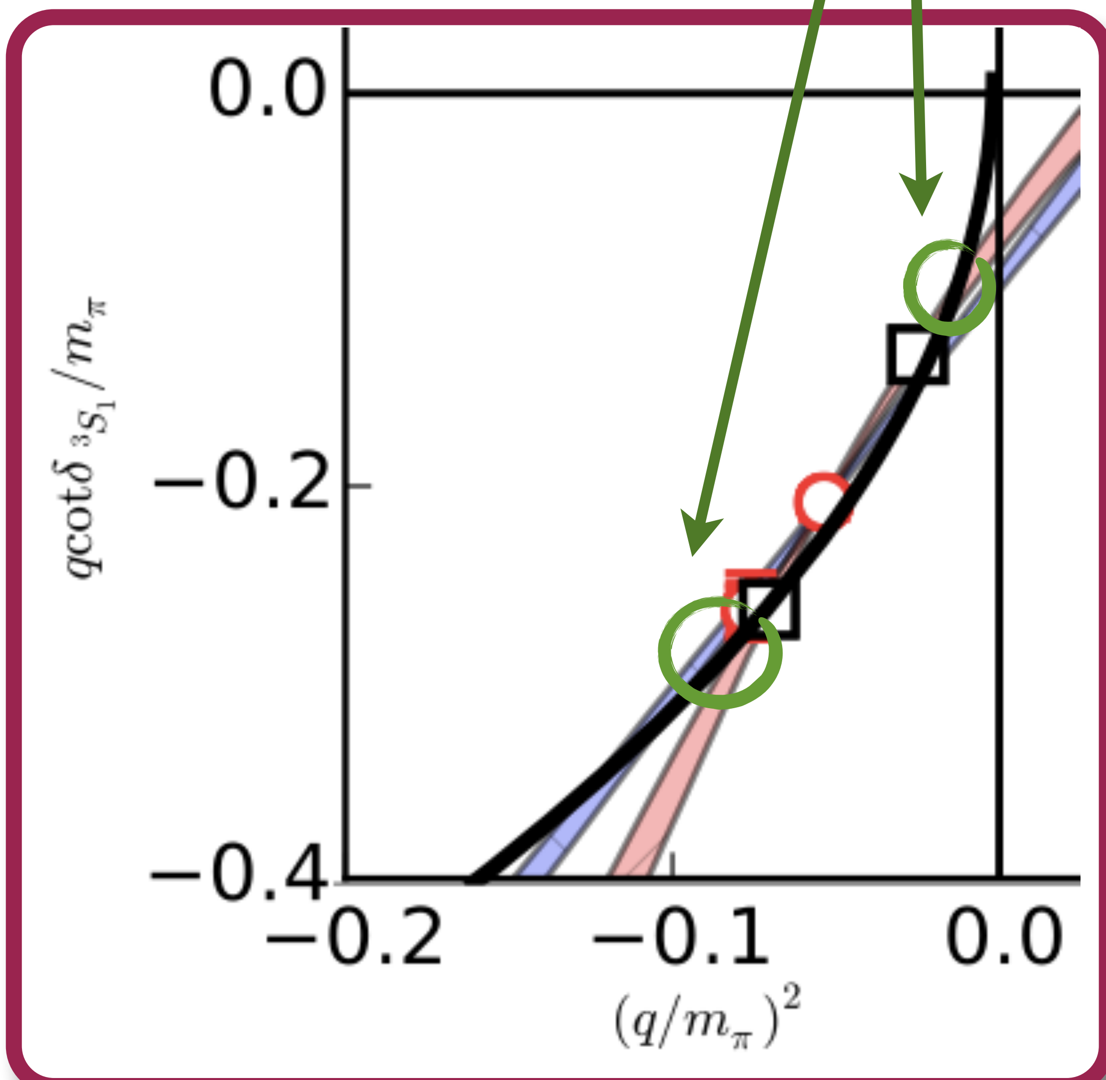
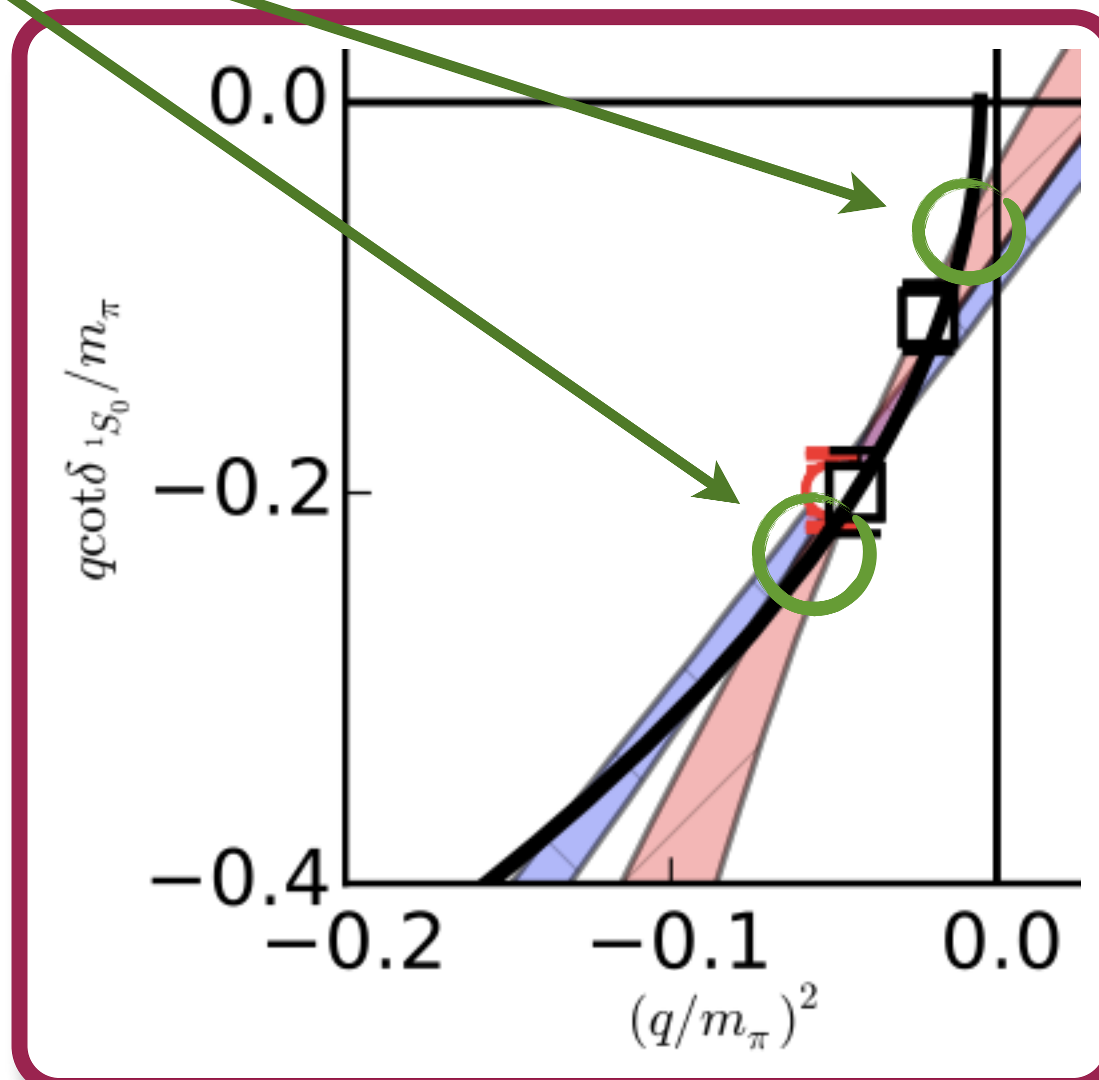
NNLO crossings





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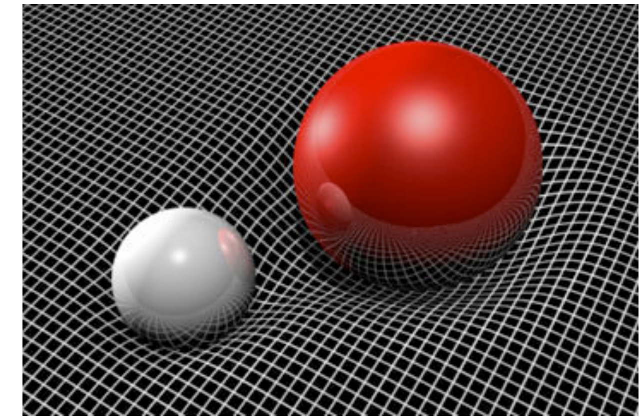

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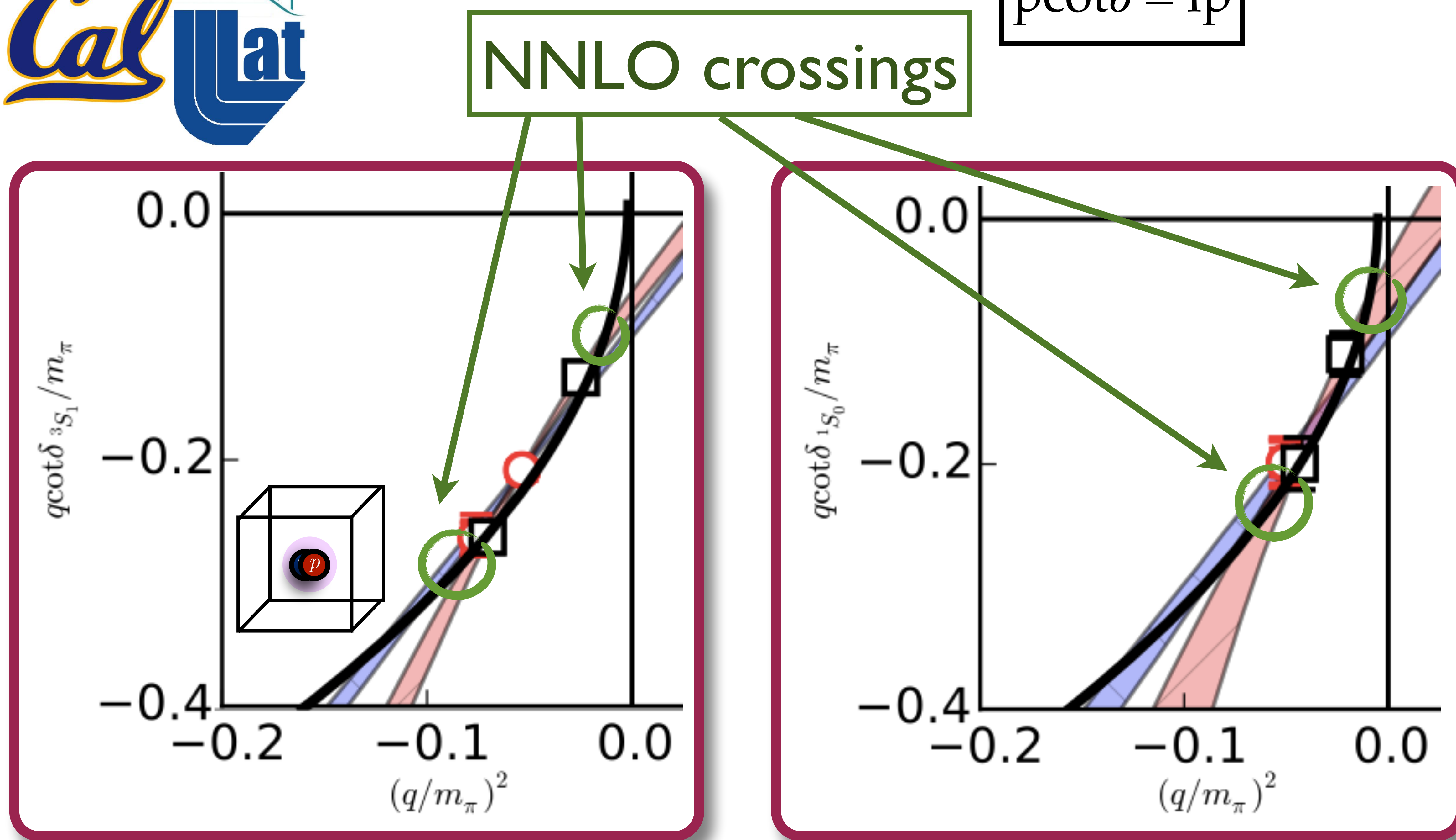

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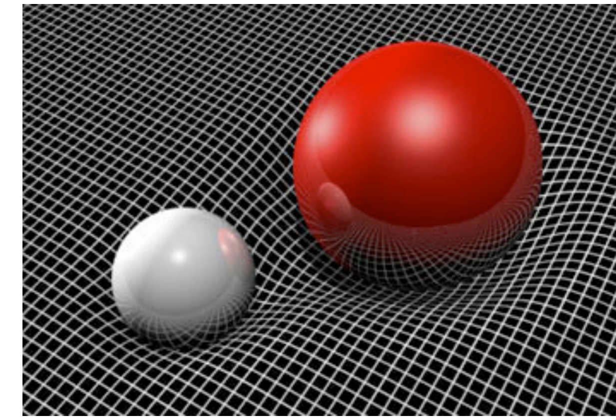
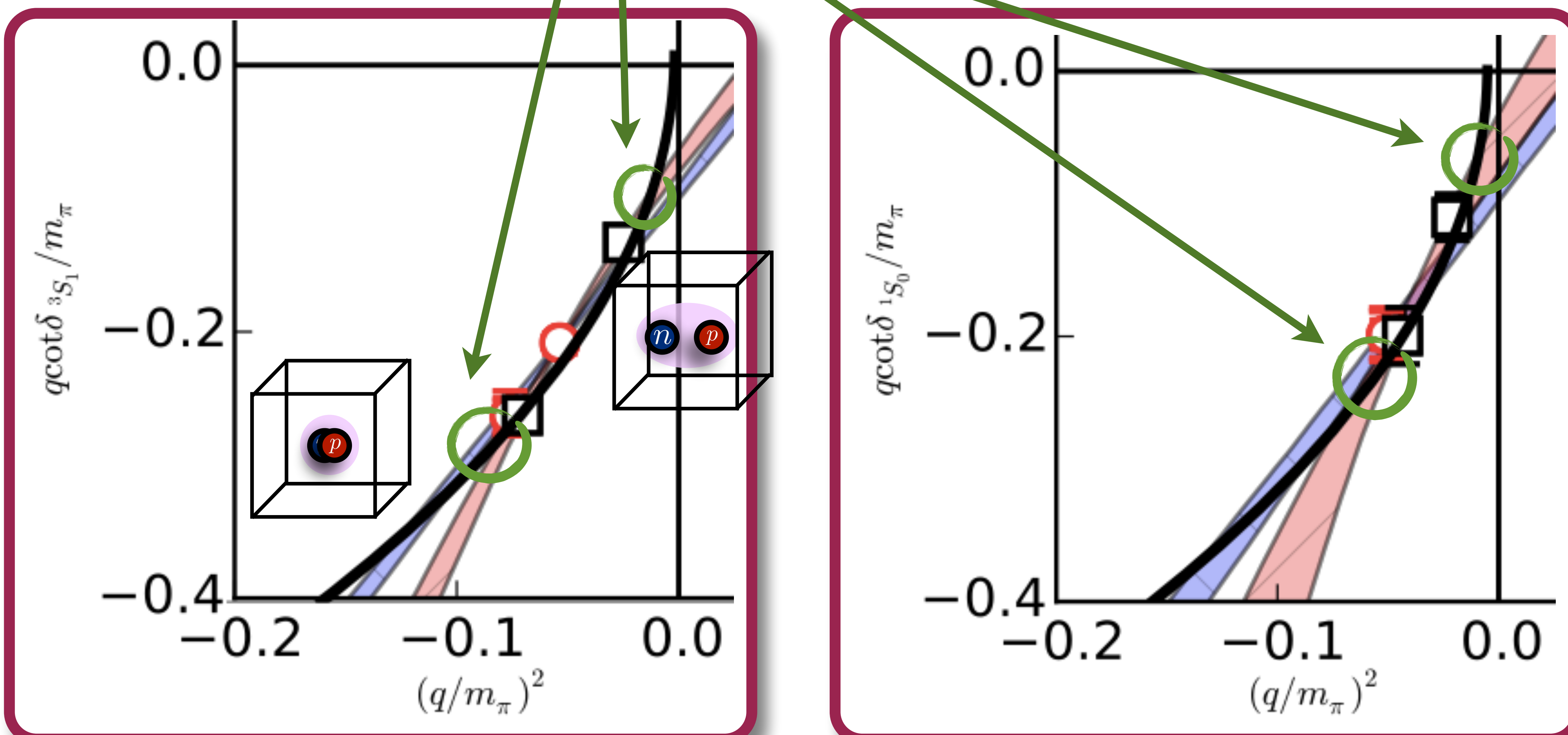
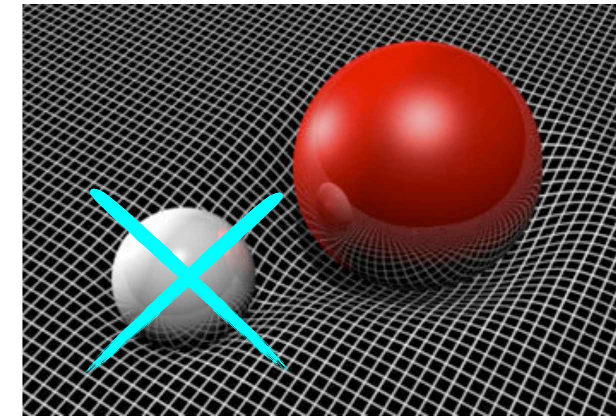


$p\cot\delta = ip$

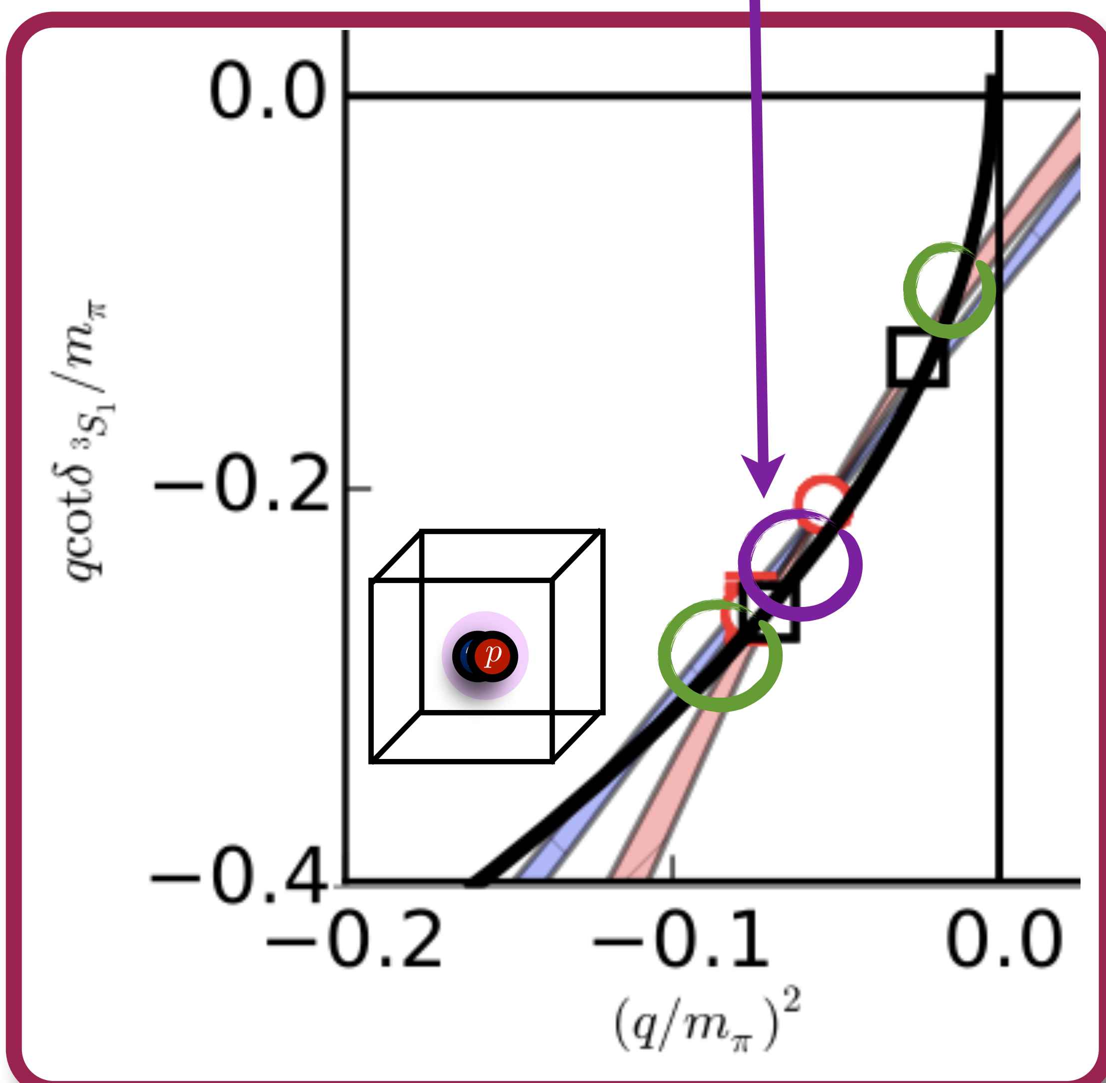
NNLO crossings

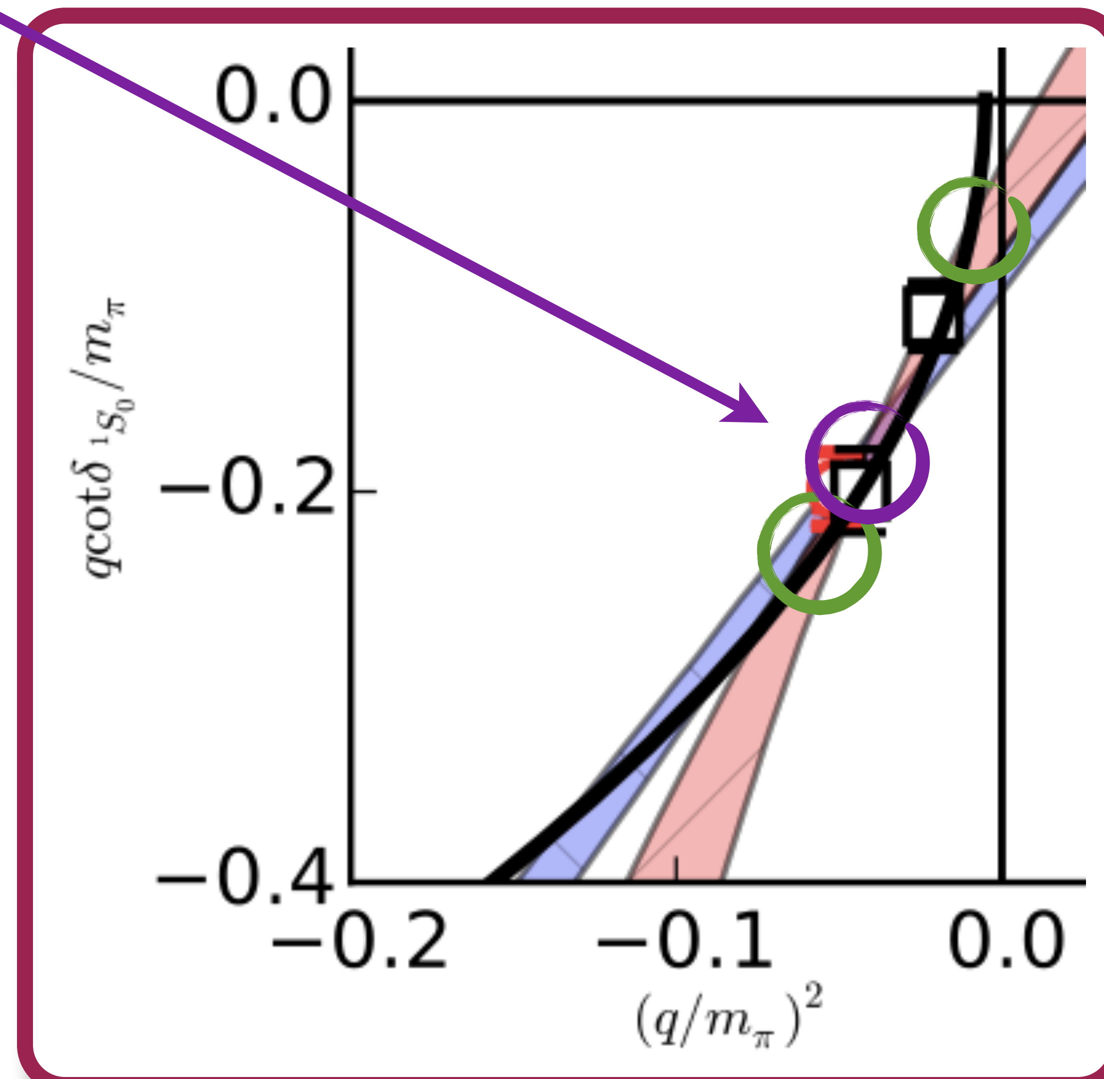




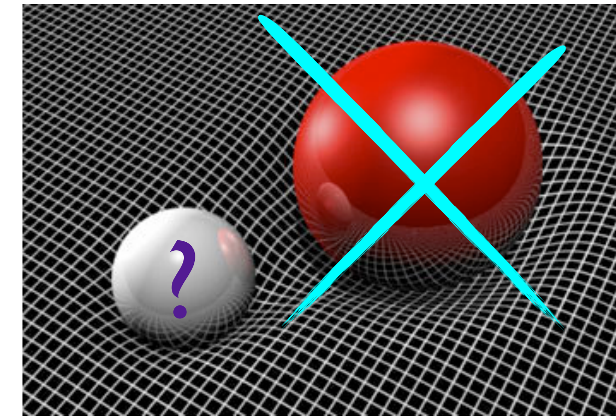
Yamazaki, et. al.

$p\cot\delta = ip$

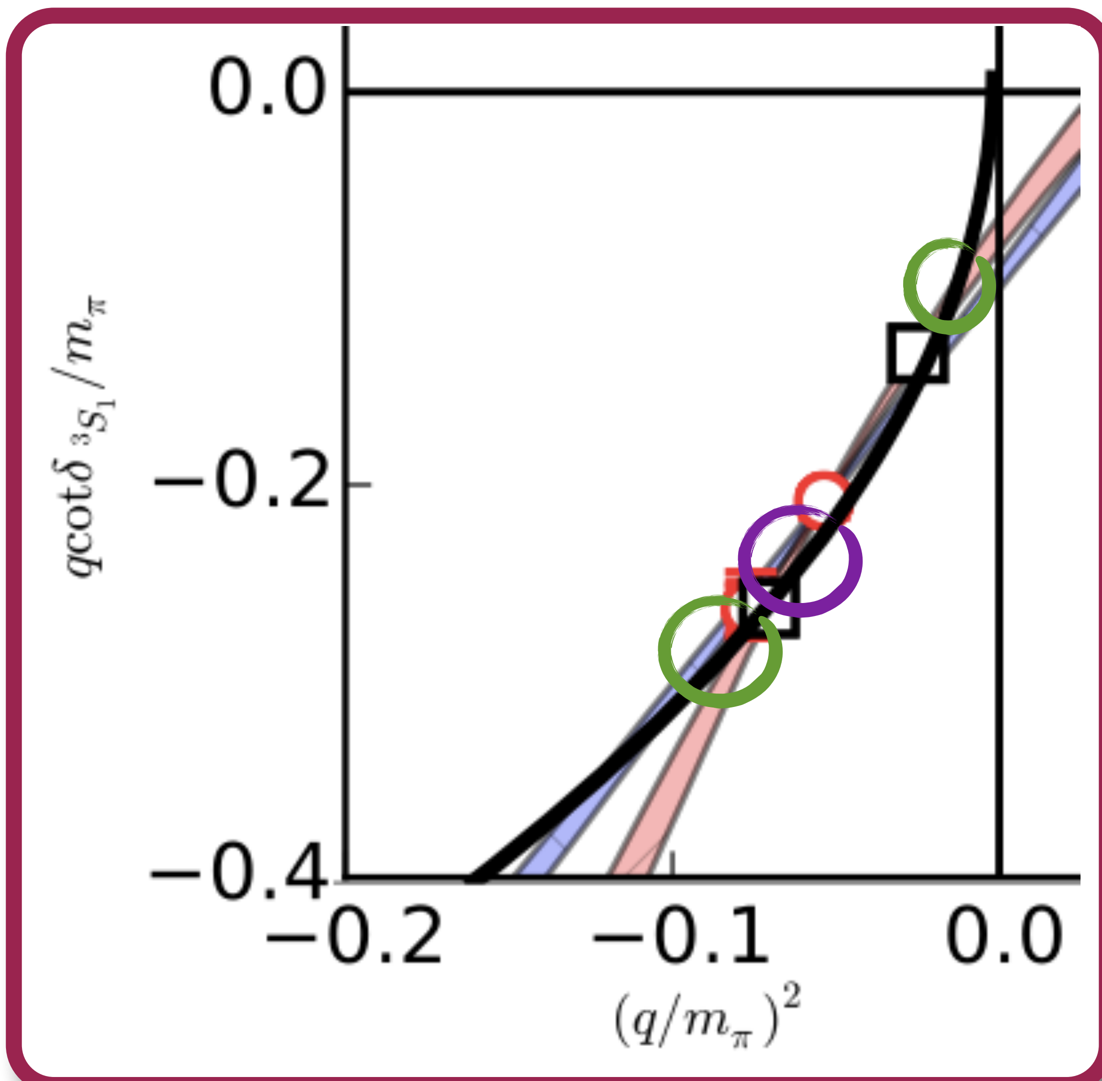


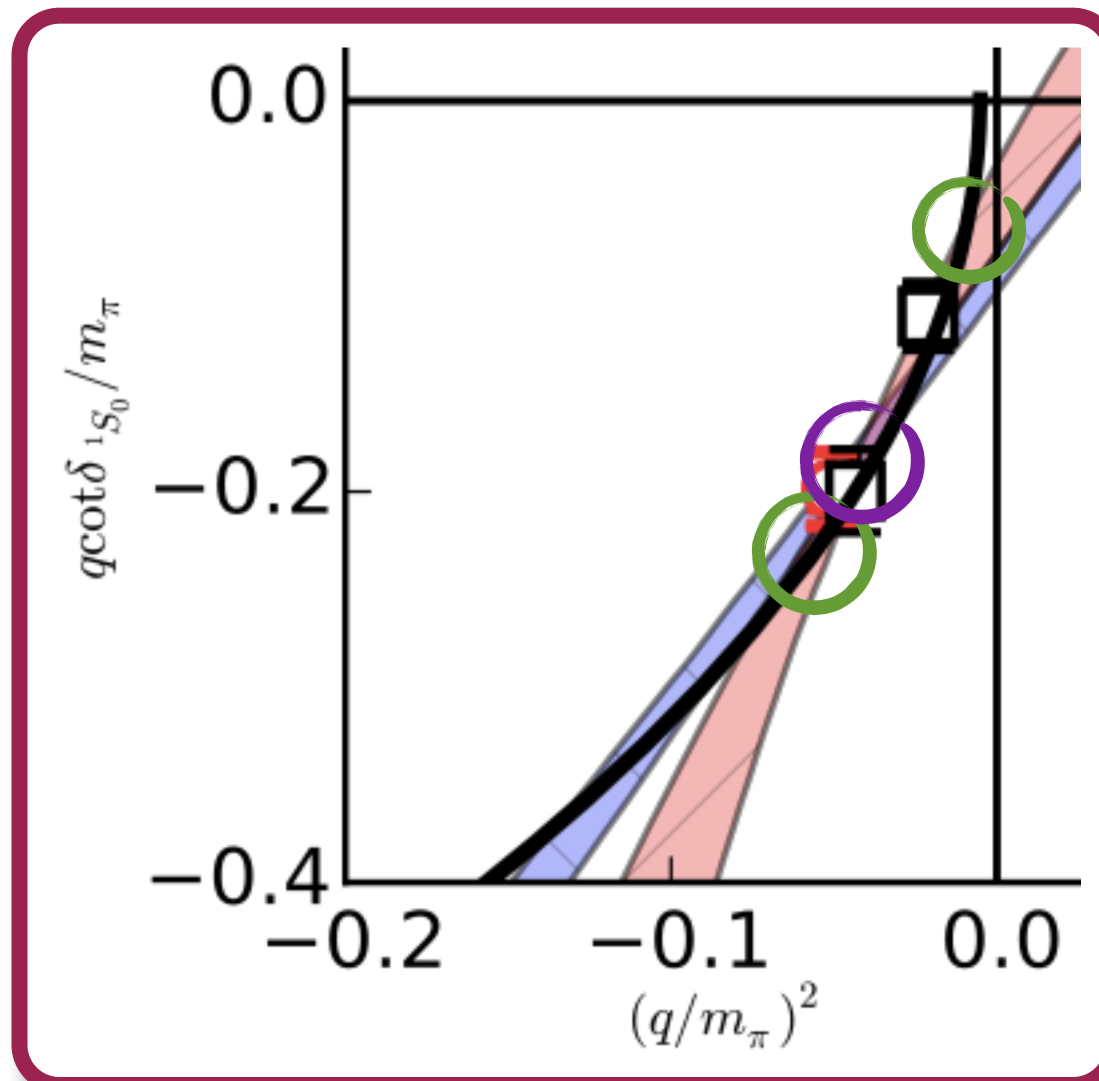


Hadrons to Atomic nuclei HAL from Lattice QCD

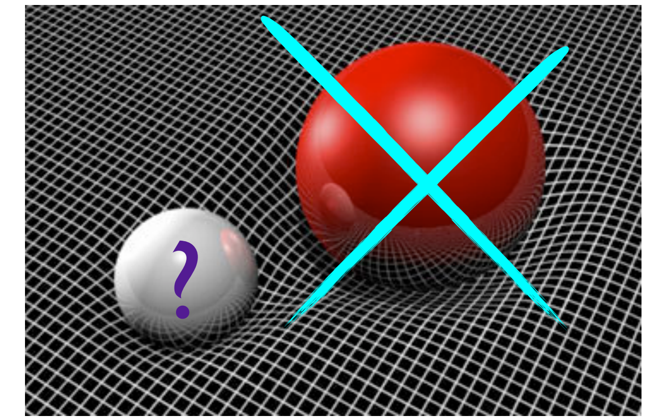


$$p\cot\delta = ip$$

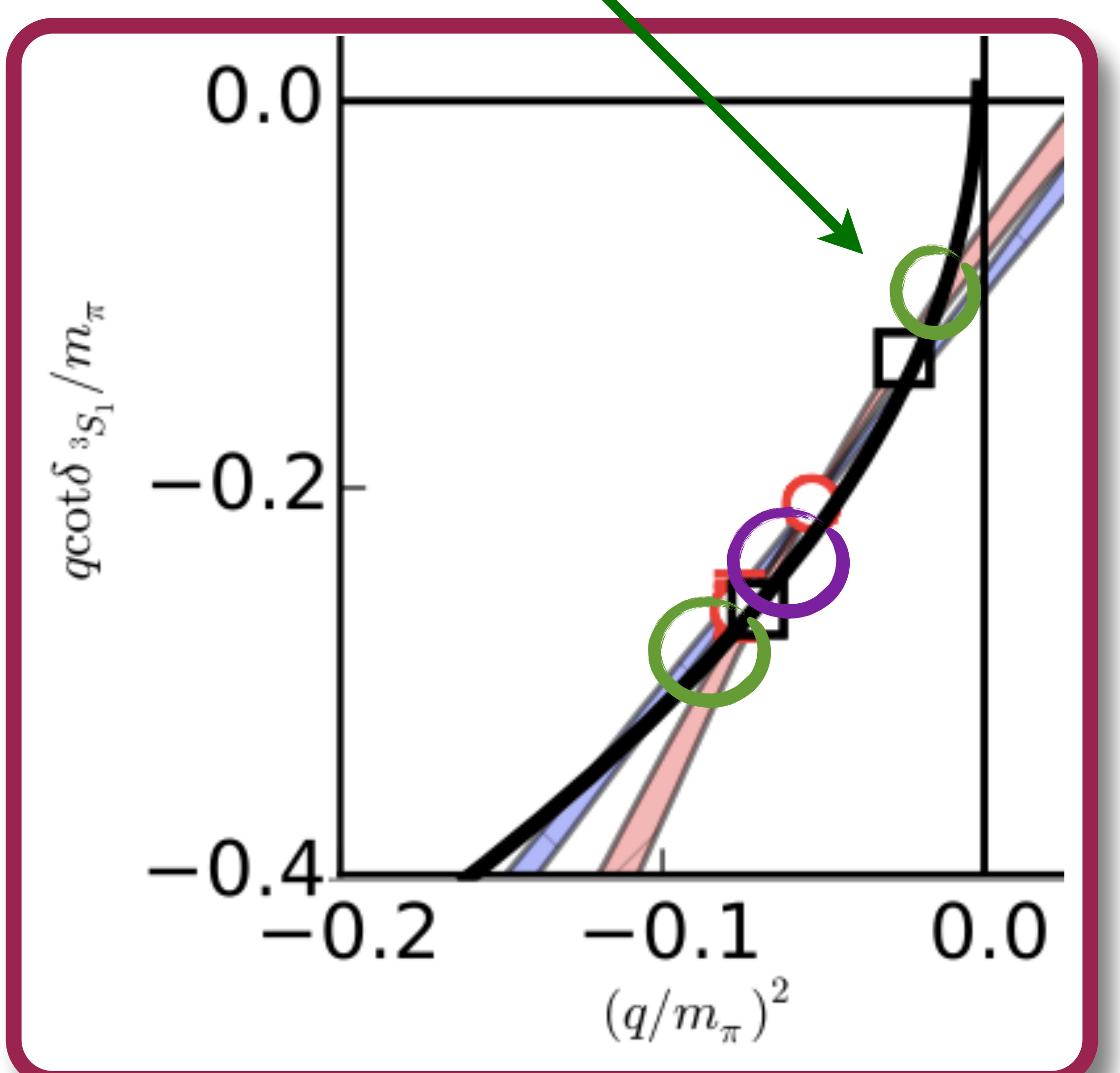


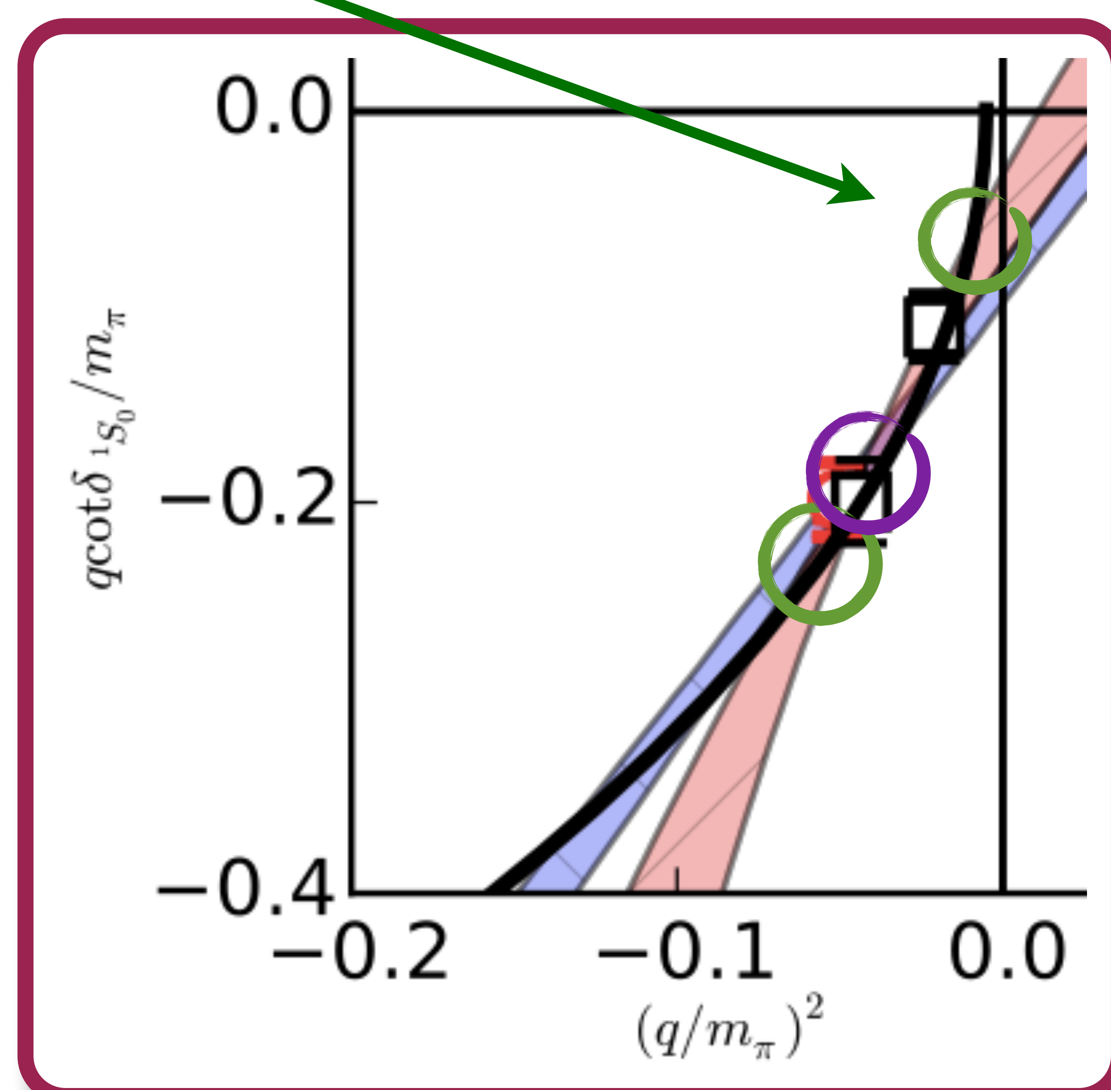


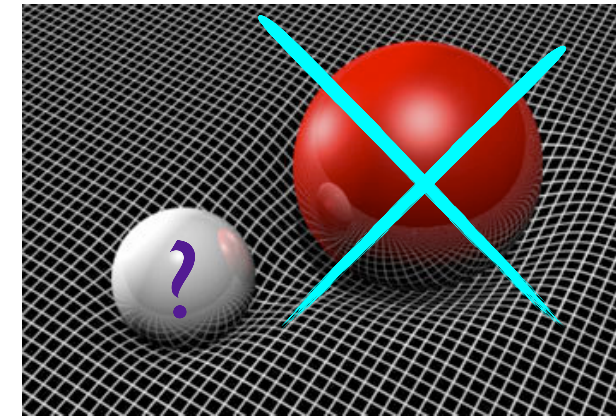
?



$$p\cot\delta = ip$$

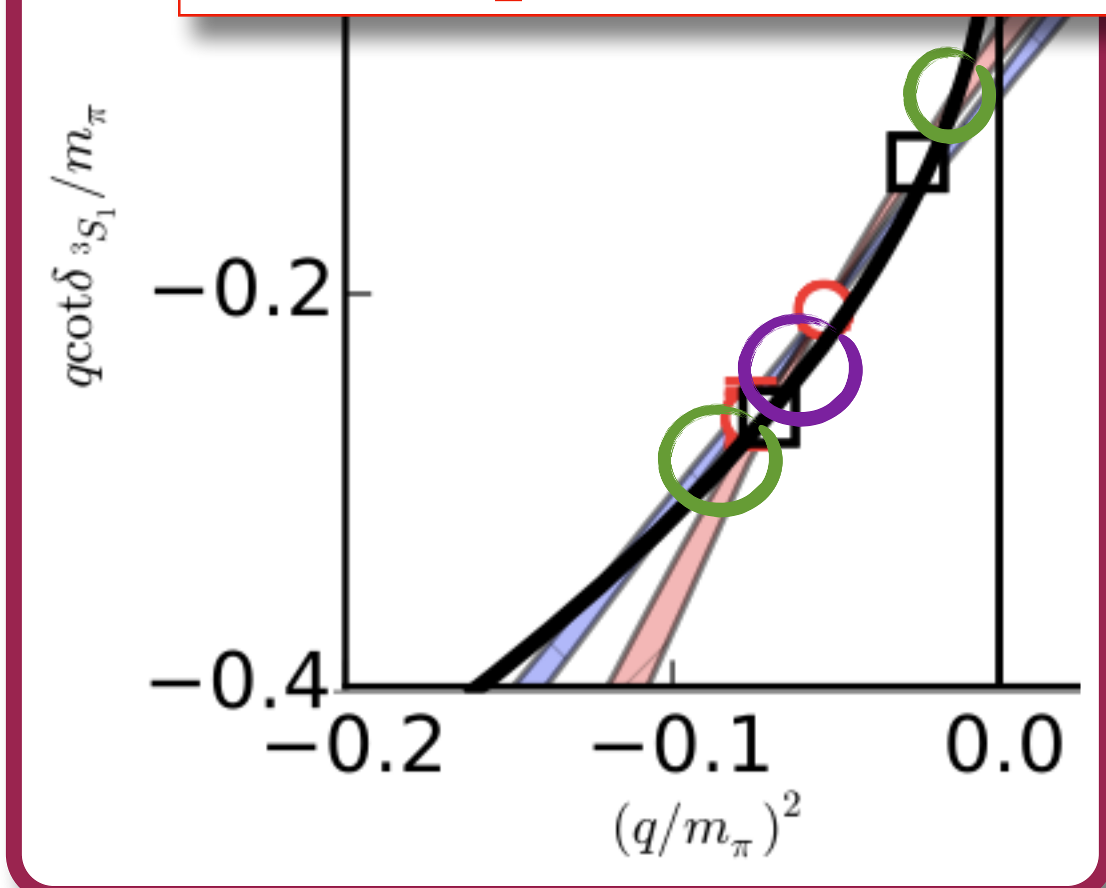


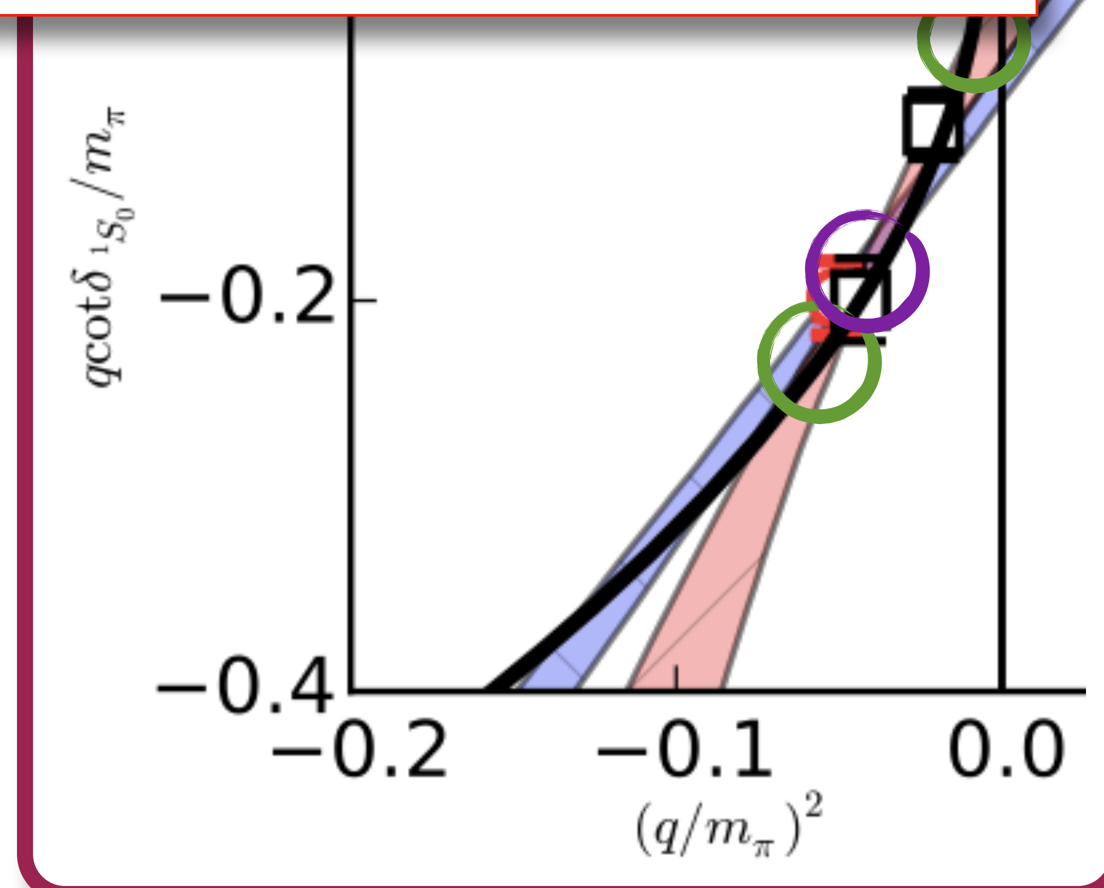




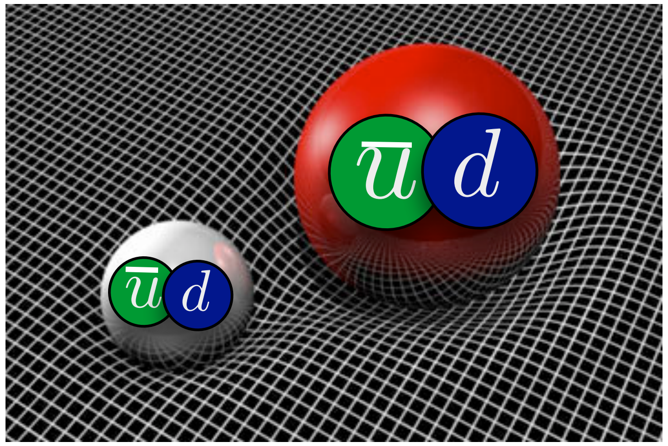
$$\mathrm{p}\cot\delta = \mathrm{ip}$$

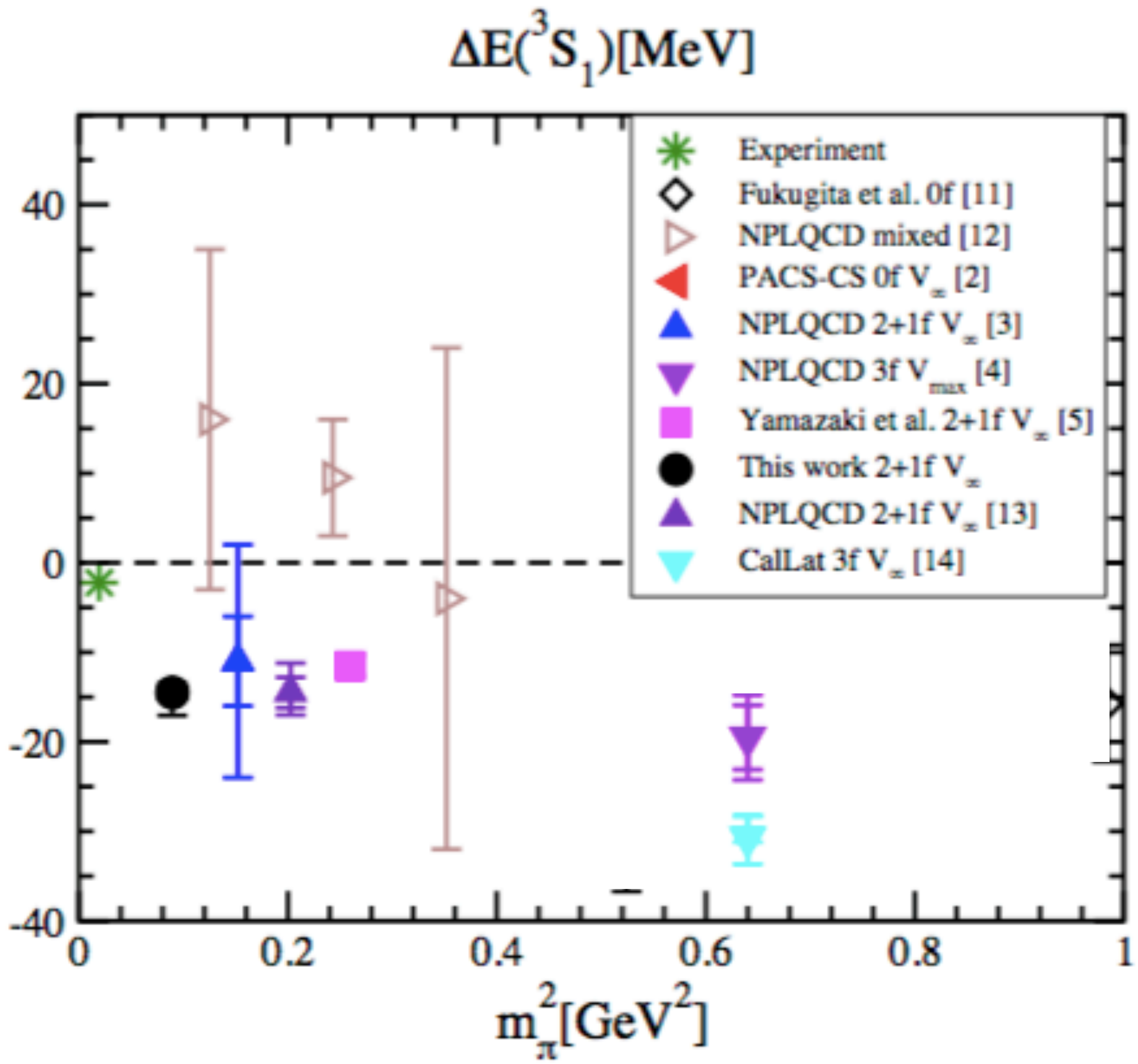
HAL has pointed to issues with an ERE interpretation of some of these results

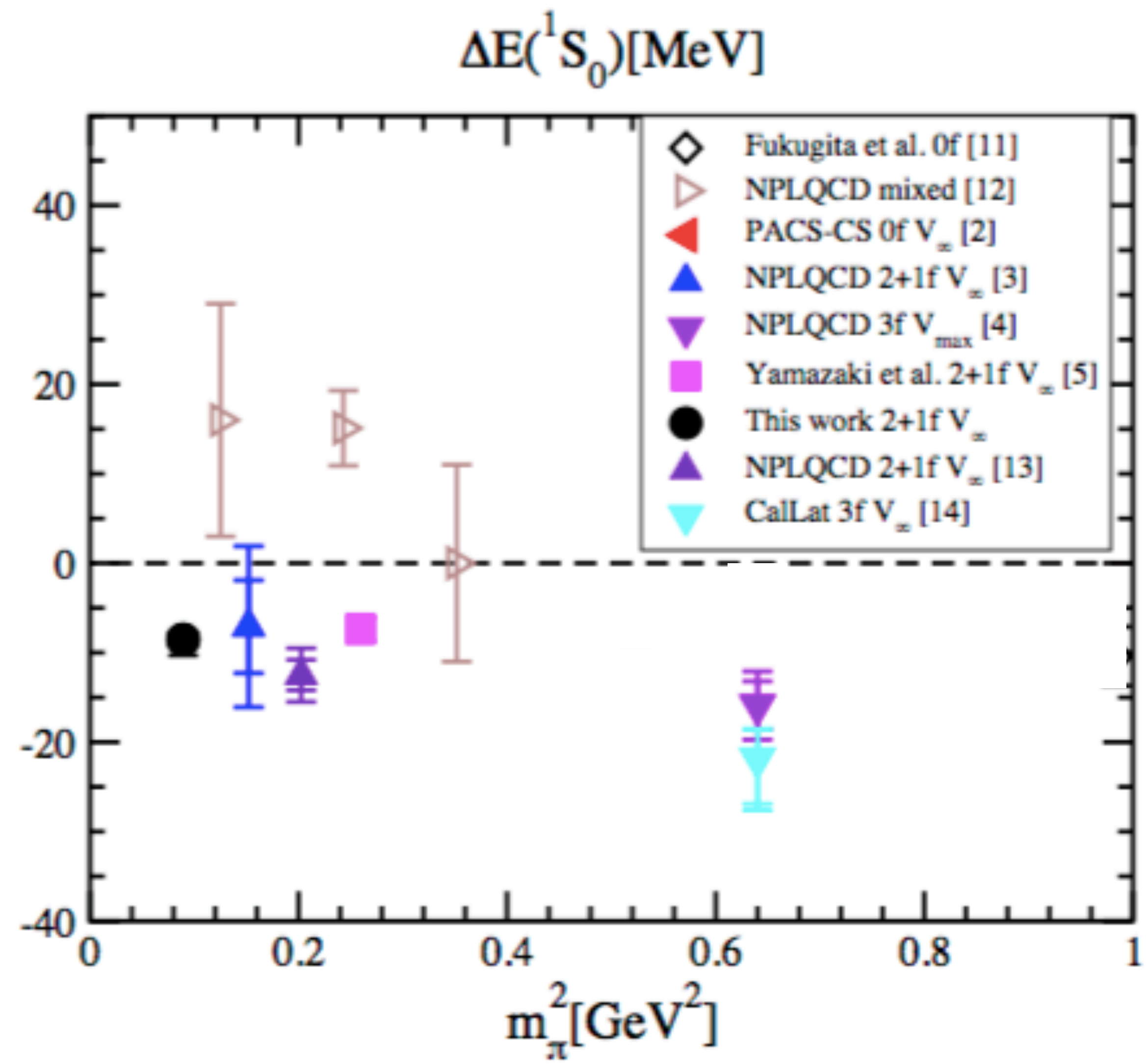




NN Binding energies

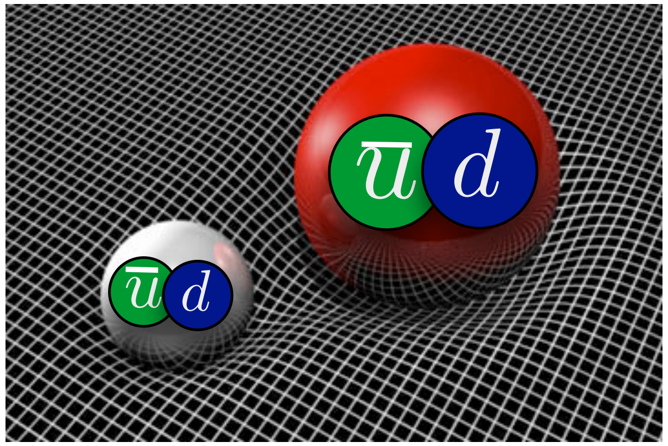


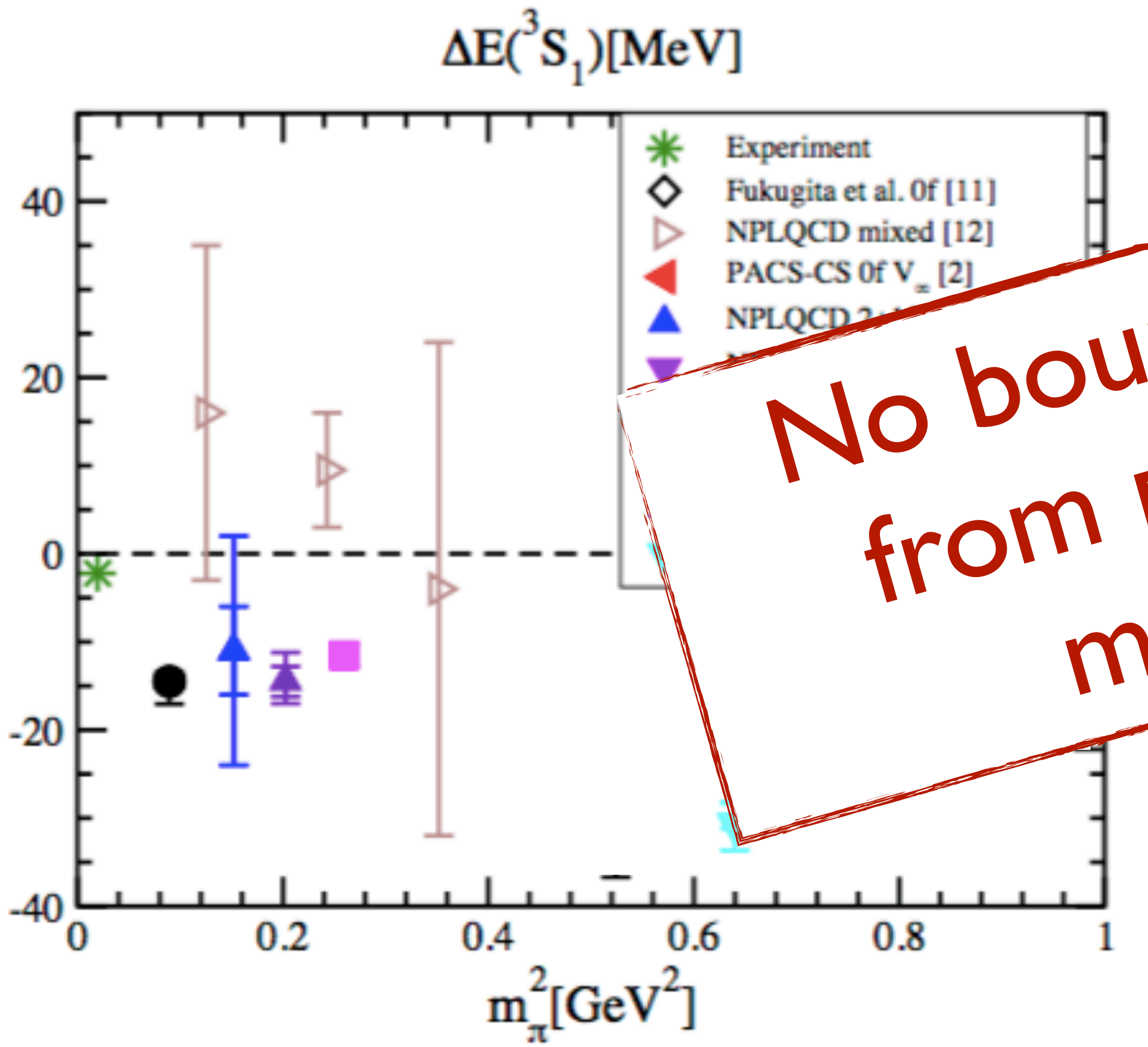


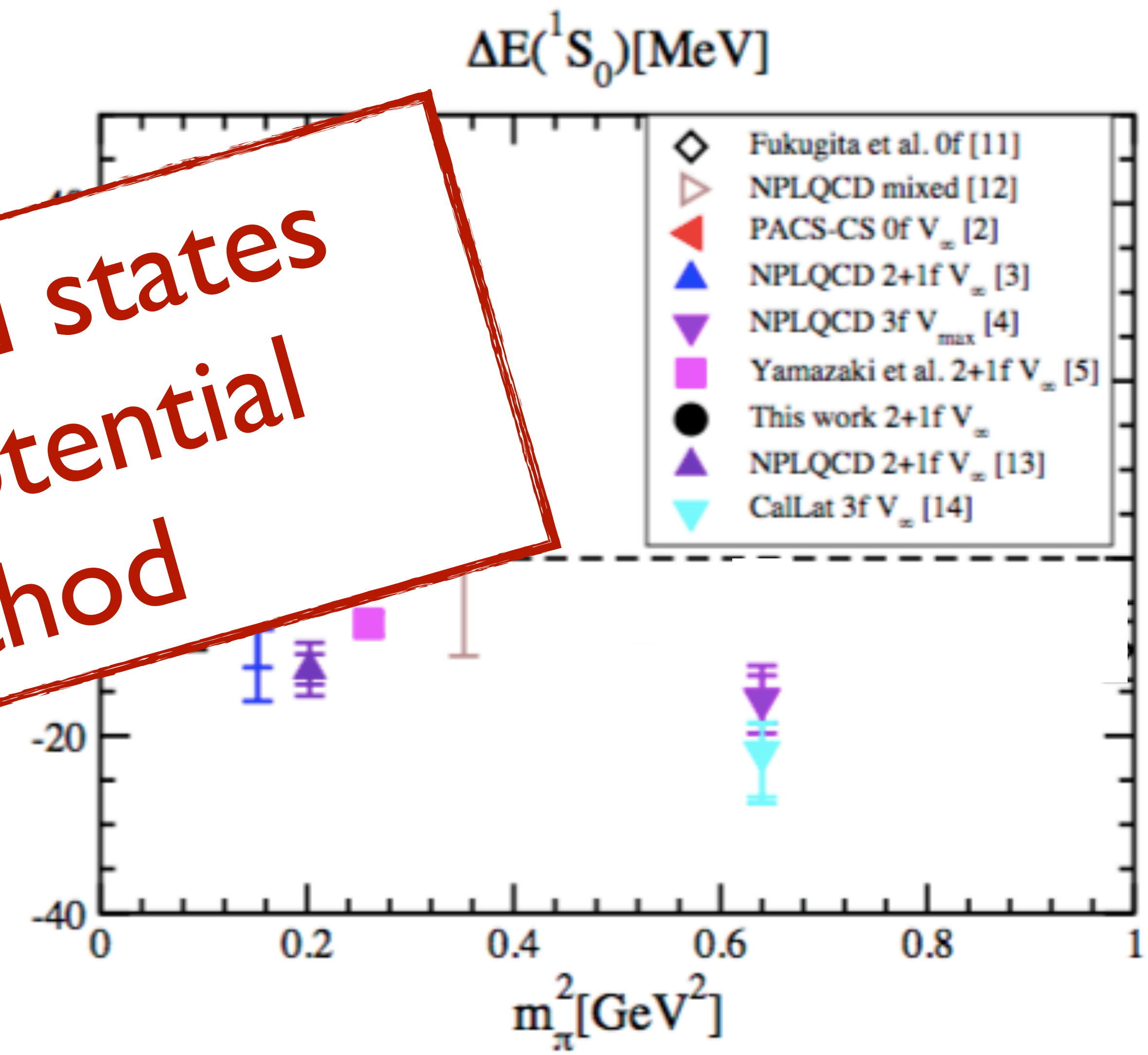


T. Yamazaki, arXiv:1511.09179

NN Binding energies



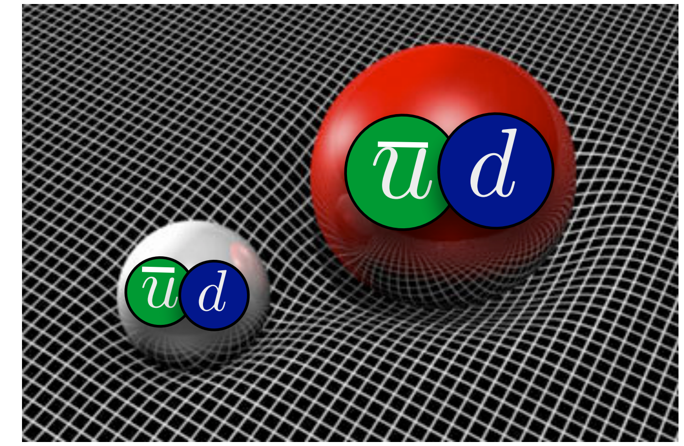


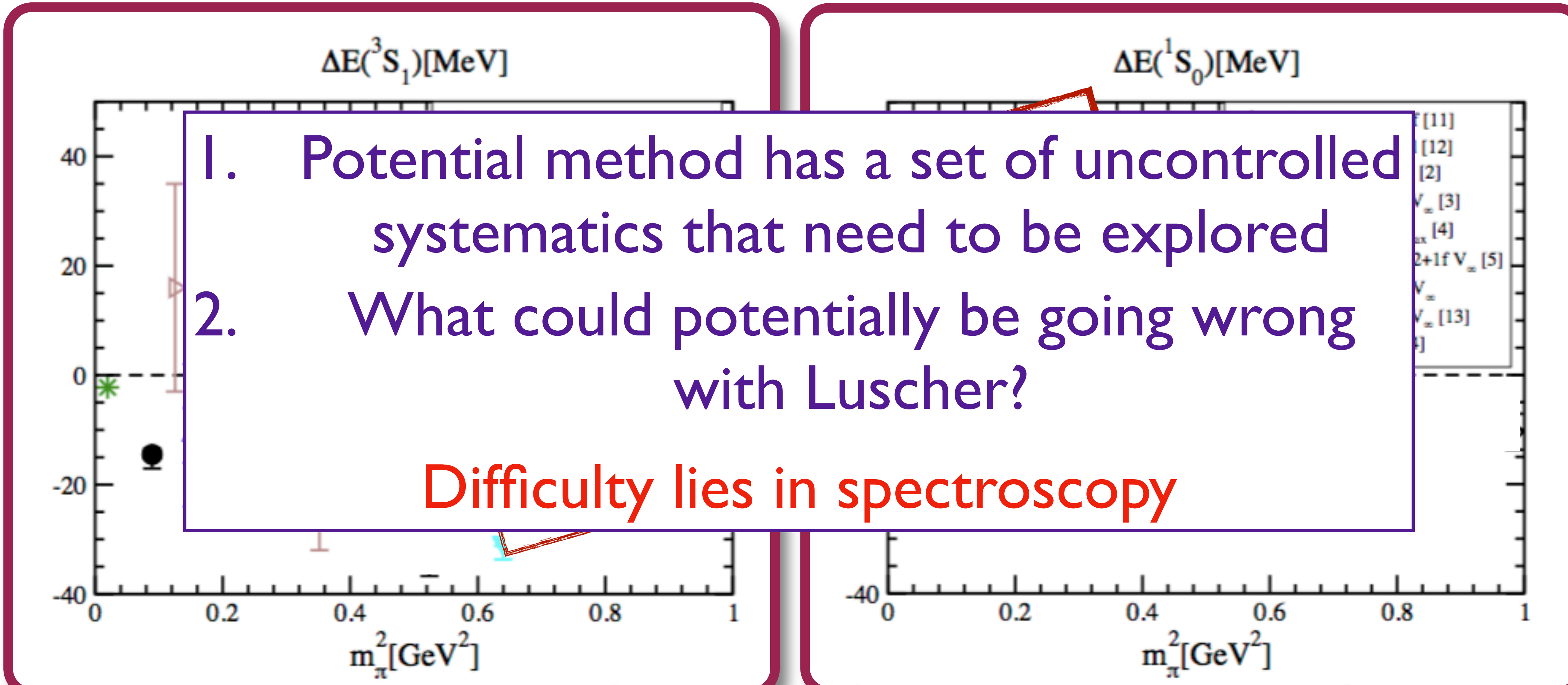


No bound states from potential method

T. Yamazaki, arXiv:1511.09179

NN Binding energies





1. Potential method has a set of uncontrolled systematics that need to be explored
2. What could potentially be going wrong with Luscher?

Difficulty lies in spectroscopy

T. Yamazaki, arXiv:1511.09179

Calculating the energies

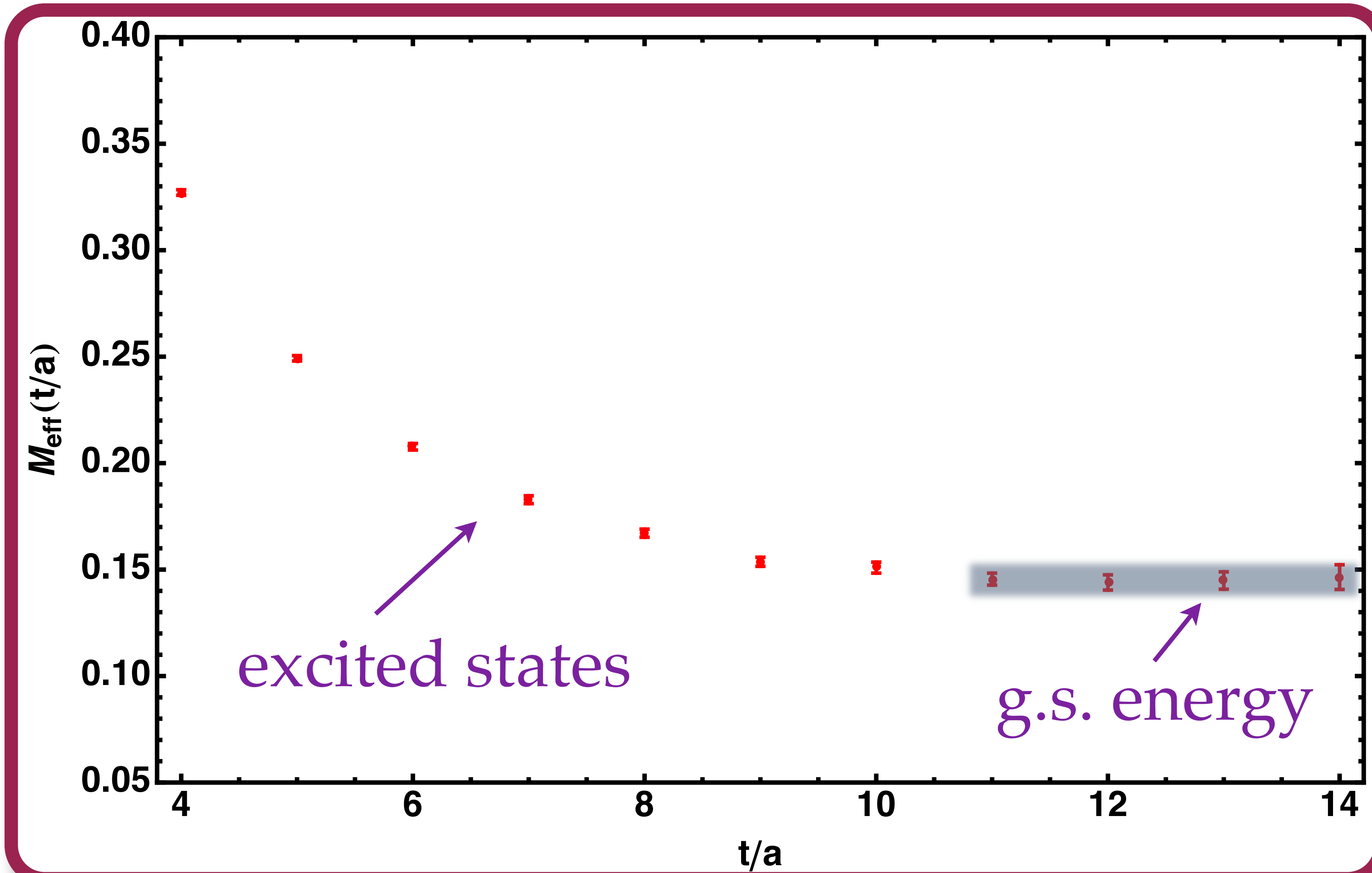
Imaginary time projection:

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

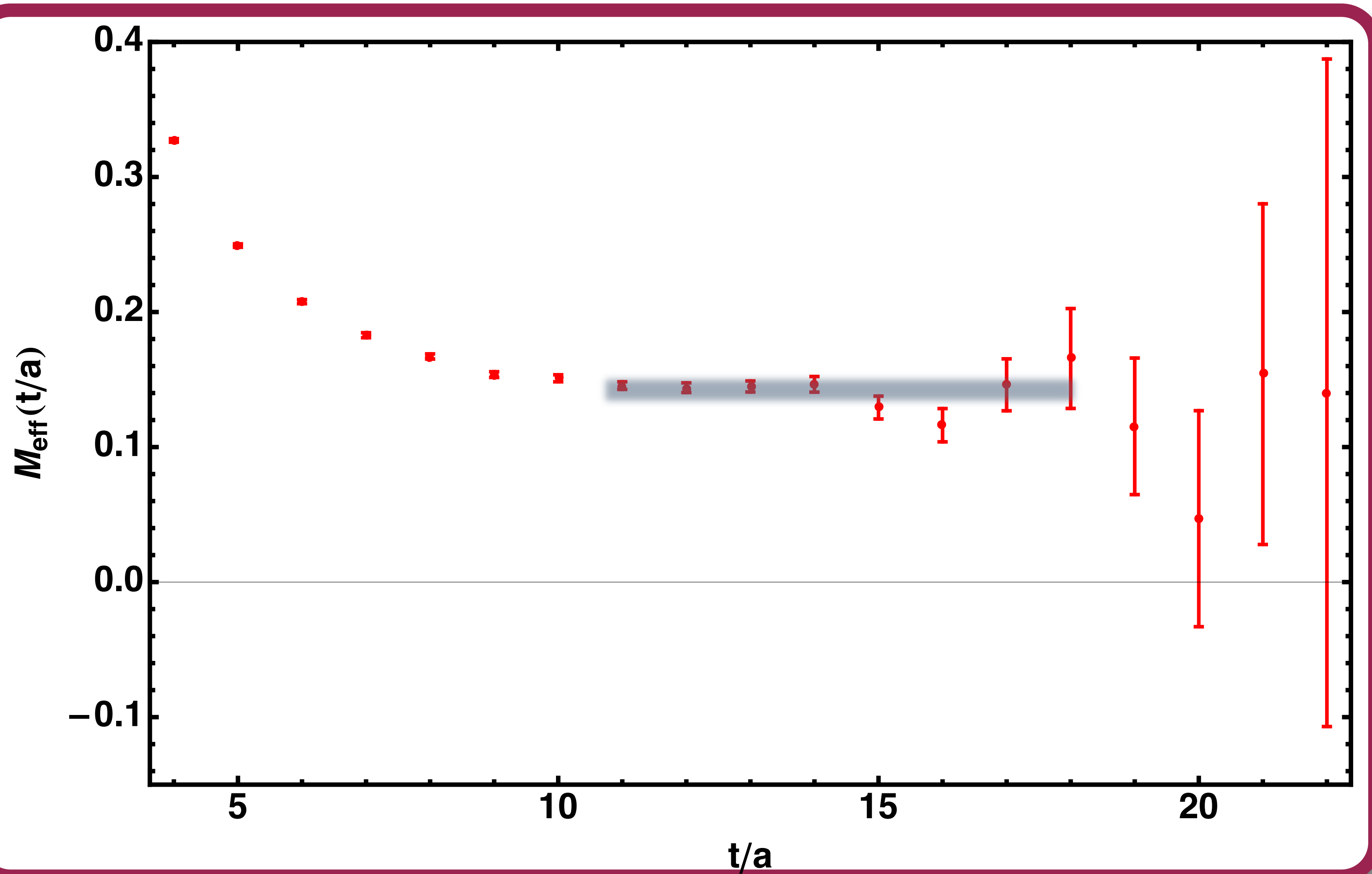
$$\xrightarrow[t\to\infty]{} Z_0 e^{-E_0 t}$$

Effective mass plot:

$$M_{\text{eff}} \equiv \ln \frac{C(t)}{C(t+1)} \xrightarrow[t\to\infty]{} E_0$$

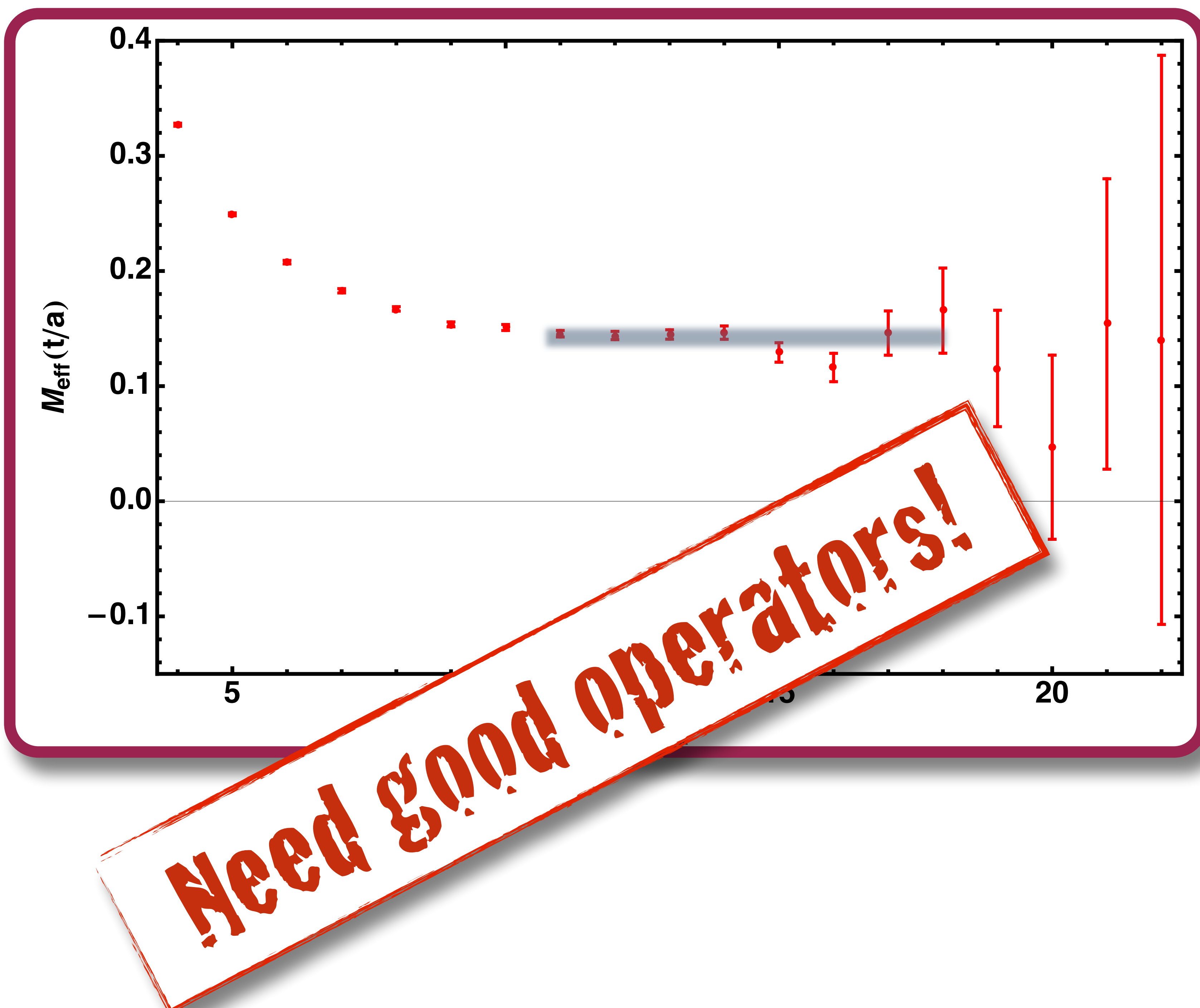


Nucleons: Signal-to-noise



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

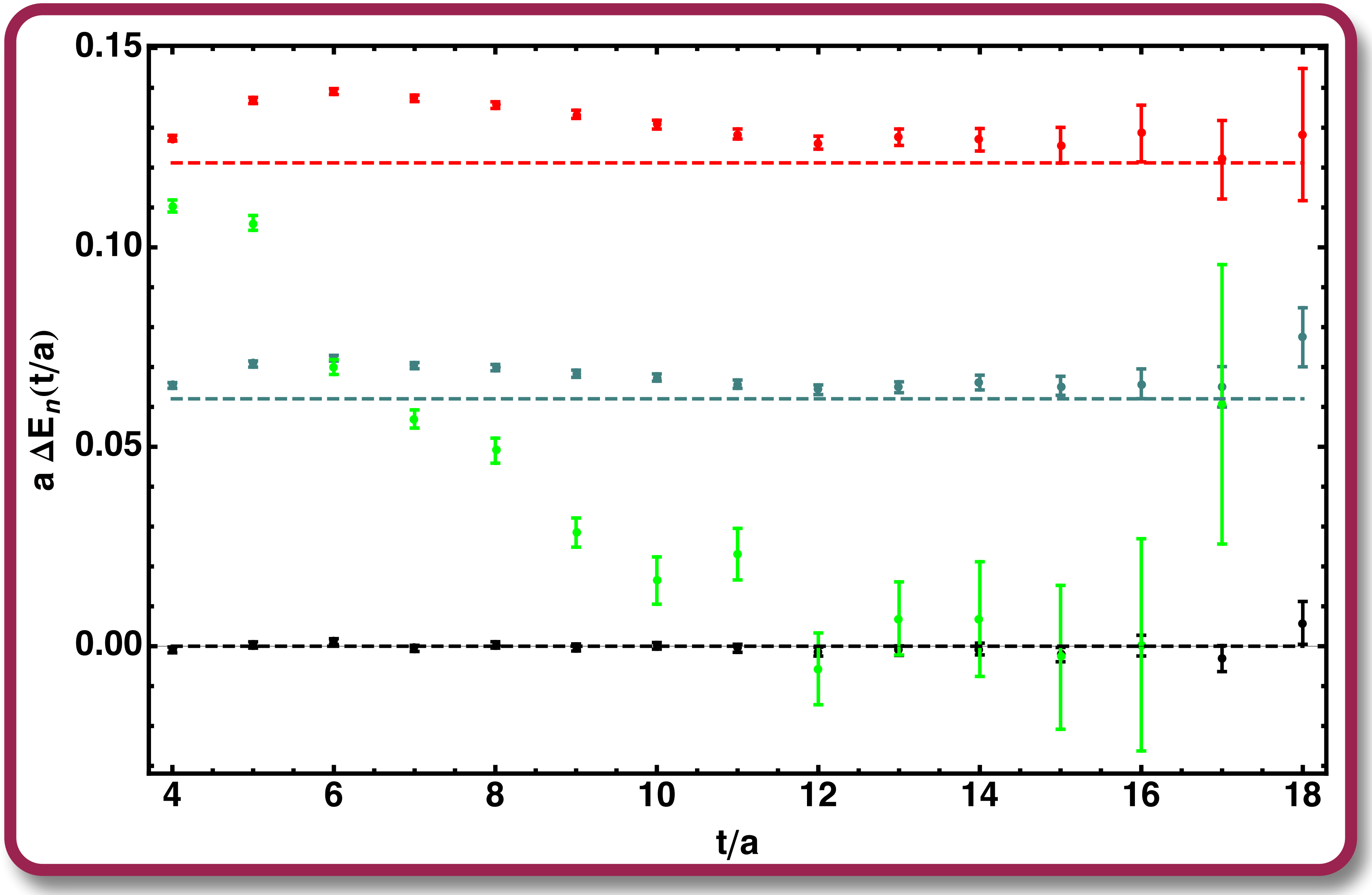
Nucleons: Signal-to-noise



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

Trying to pull off tiny correction compared to large nucleon mass:

$\Delta E = E_{NN} - 2E_N$



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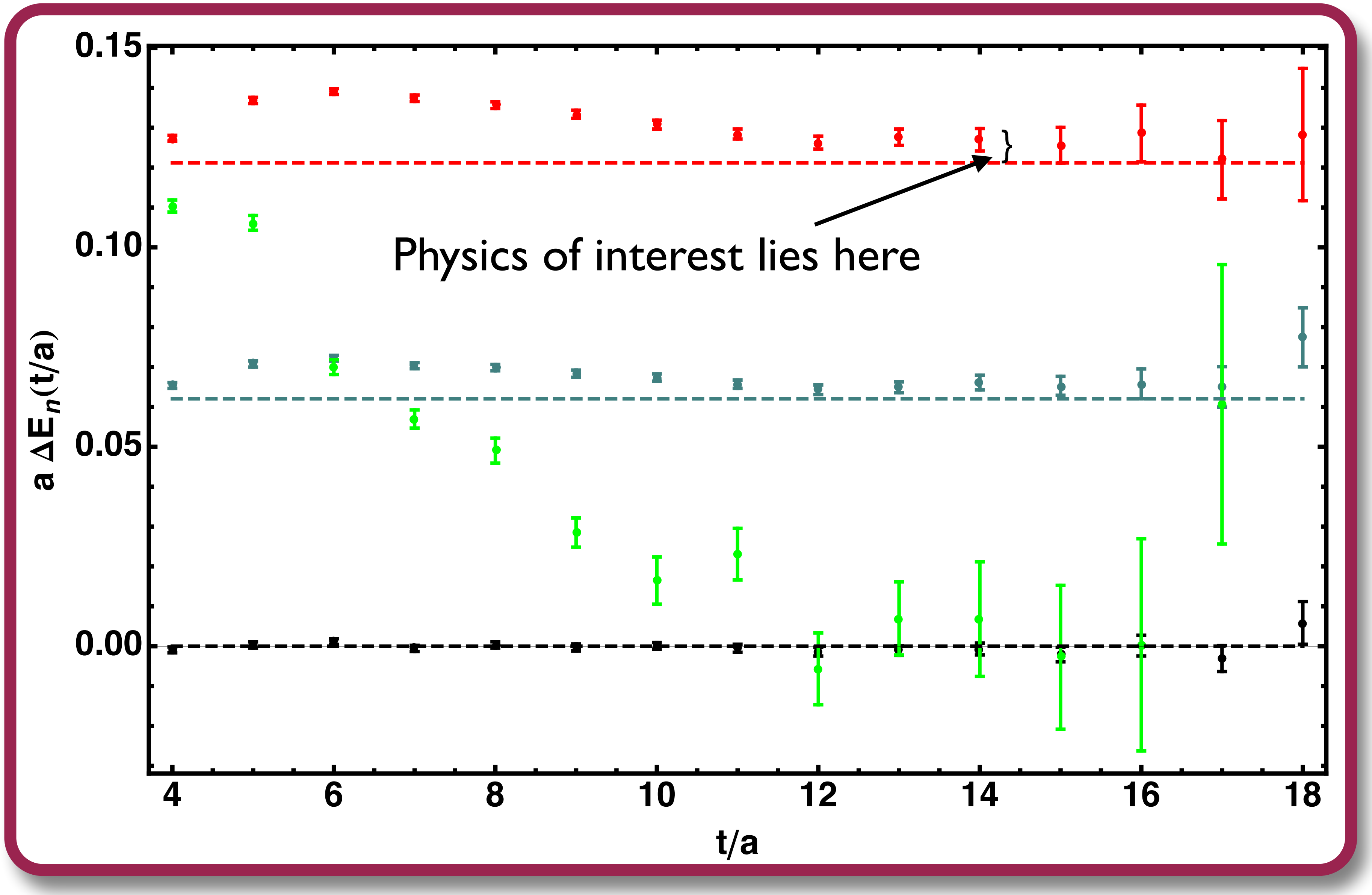

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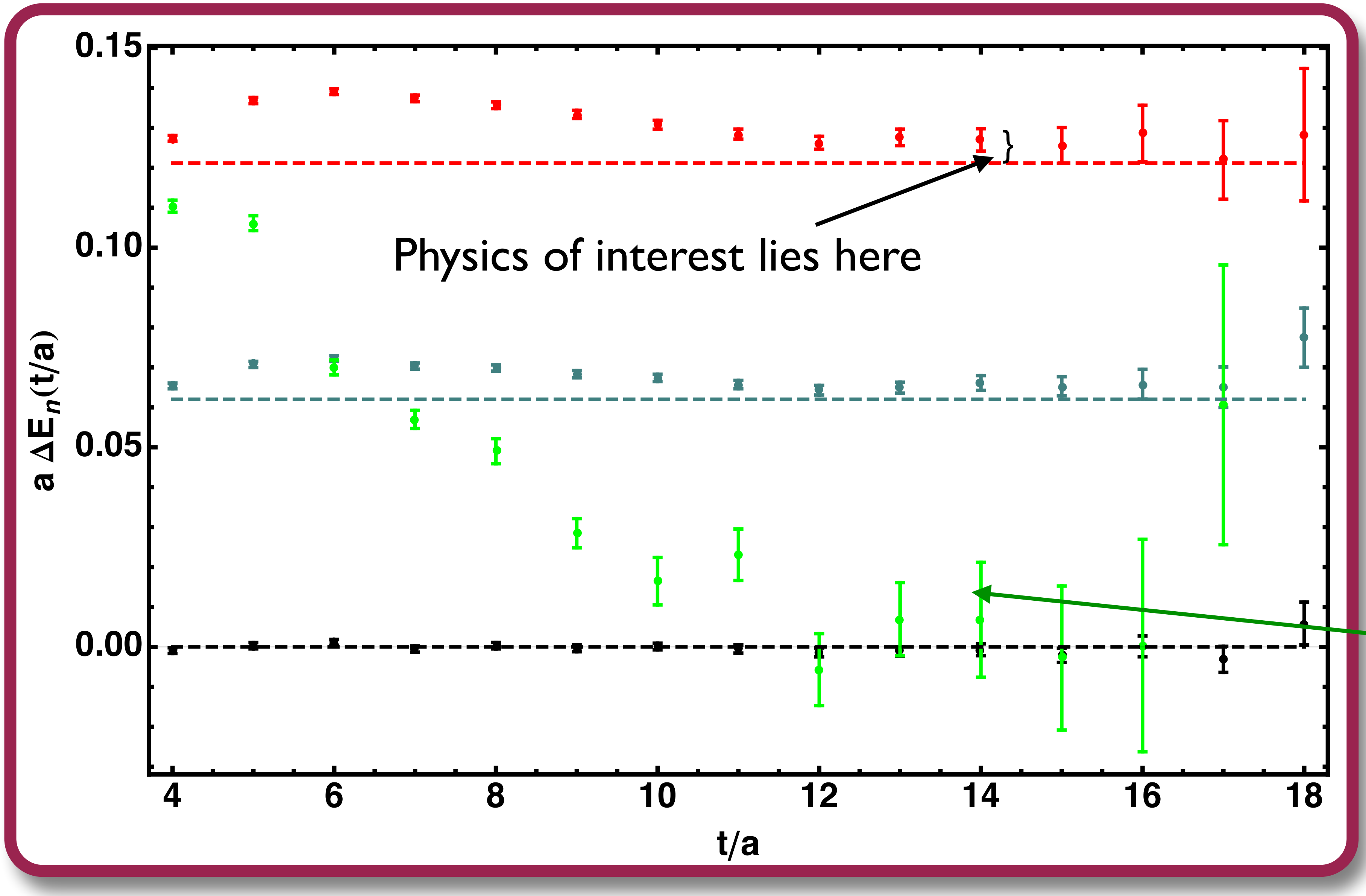
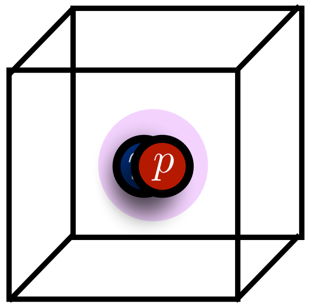
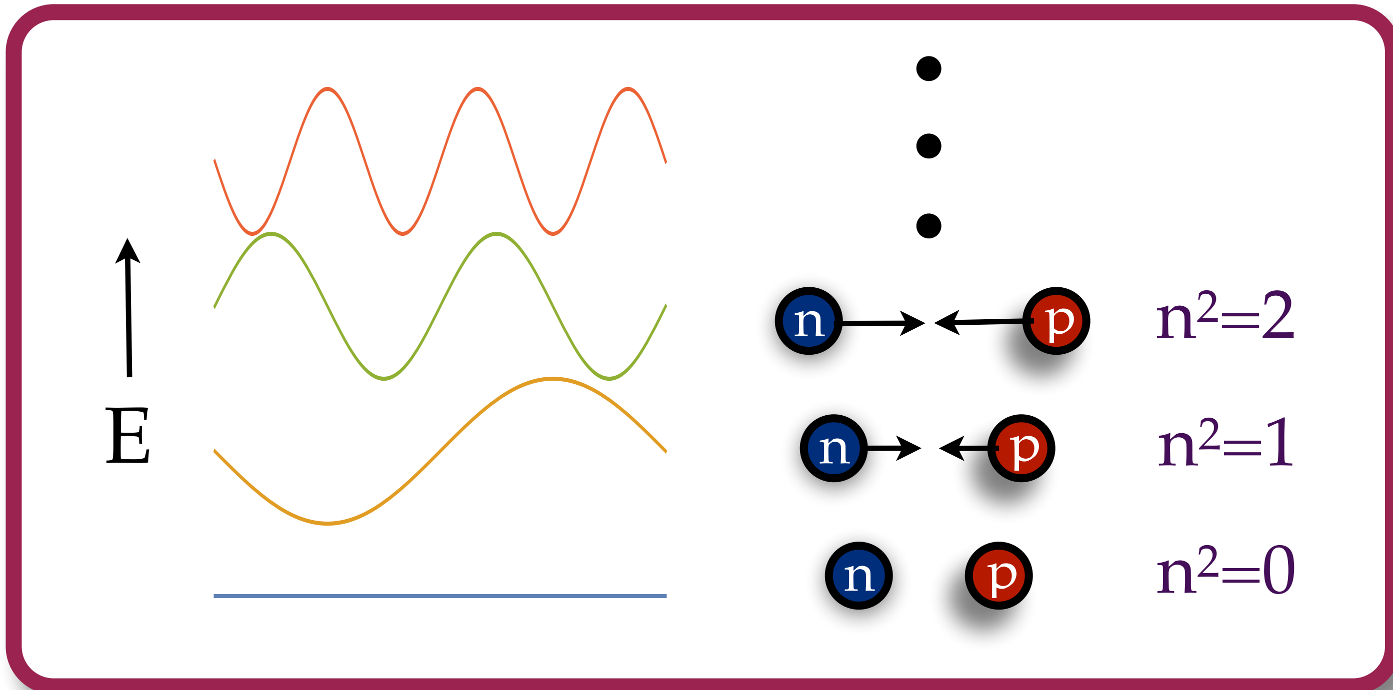


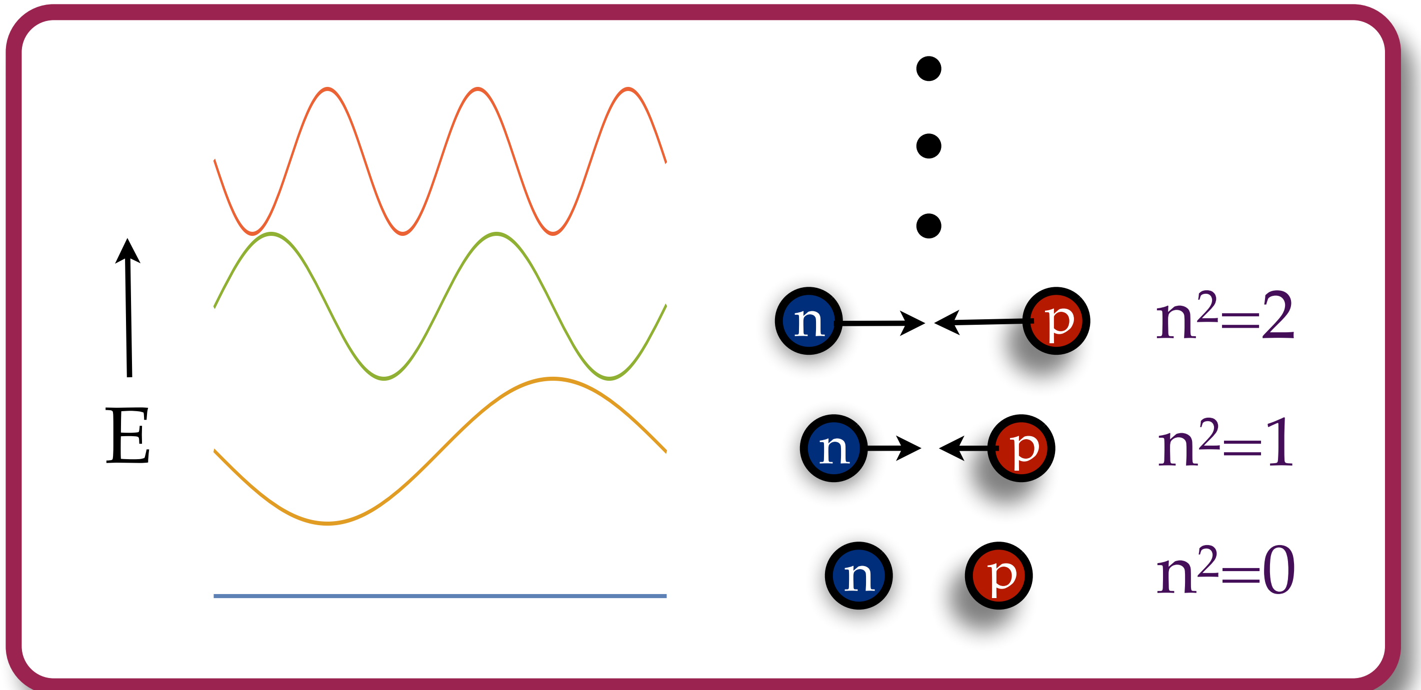


Excited state contamination



Elastic scattering
(2-body)
$\Delta E \sim 50$ MeV
(Luscher)

Excited state contamination



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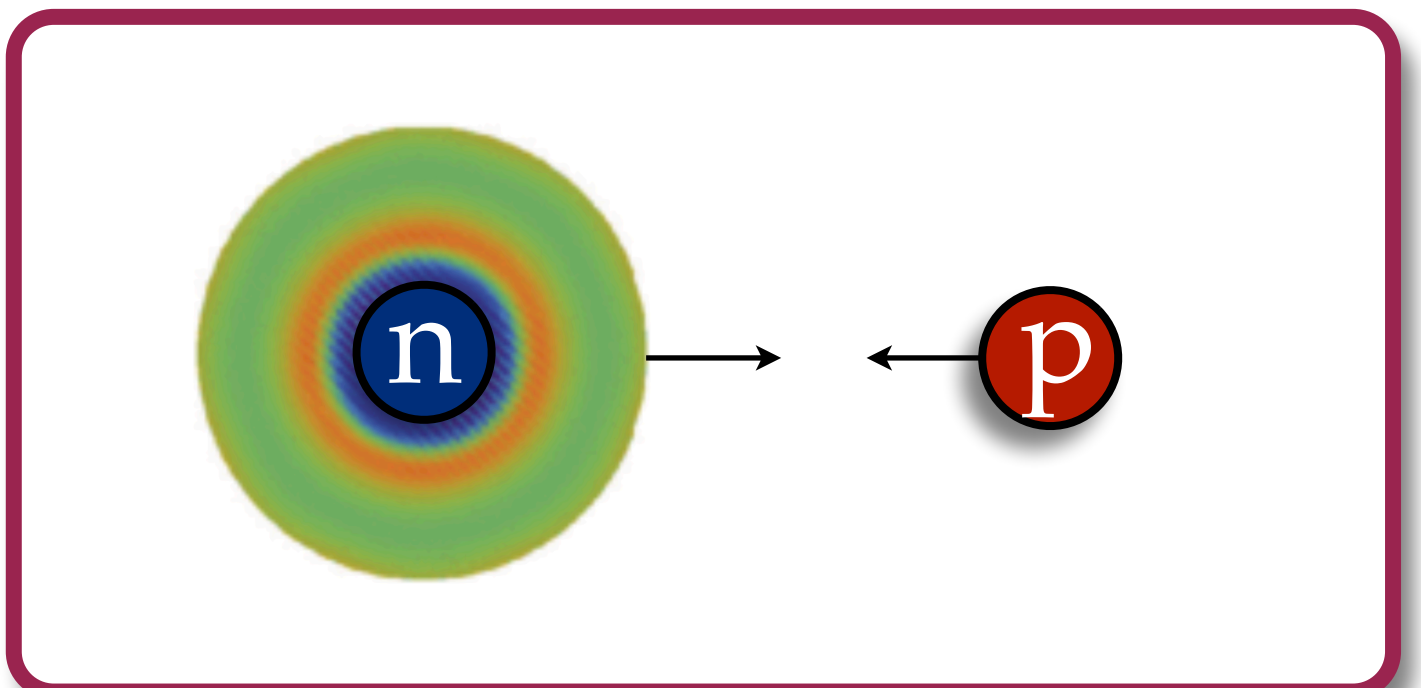


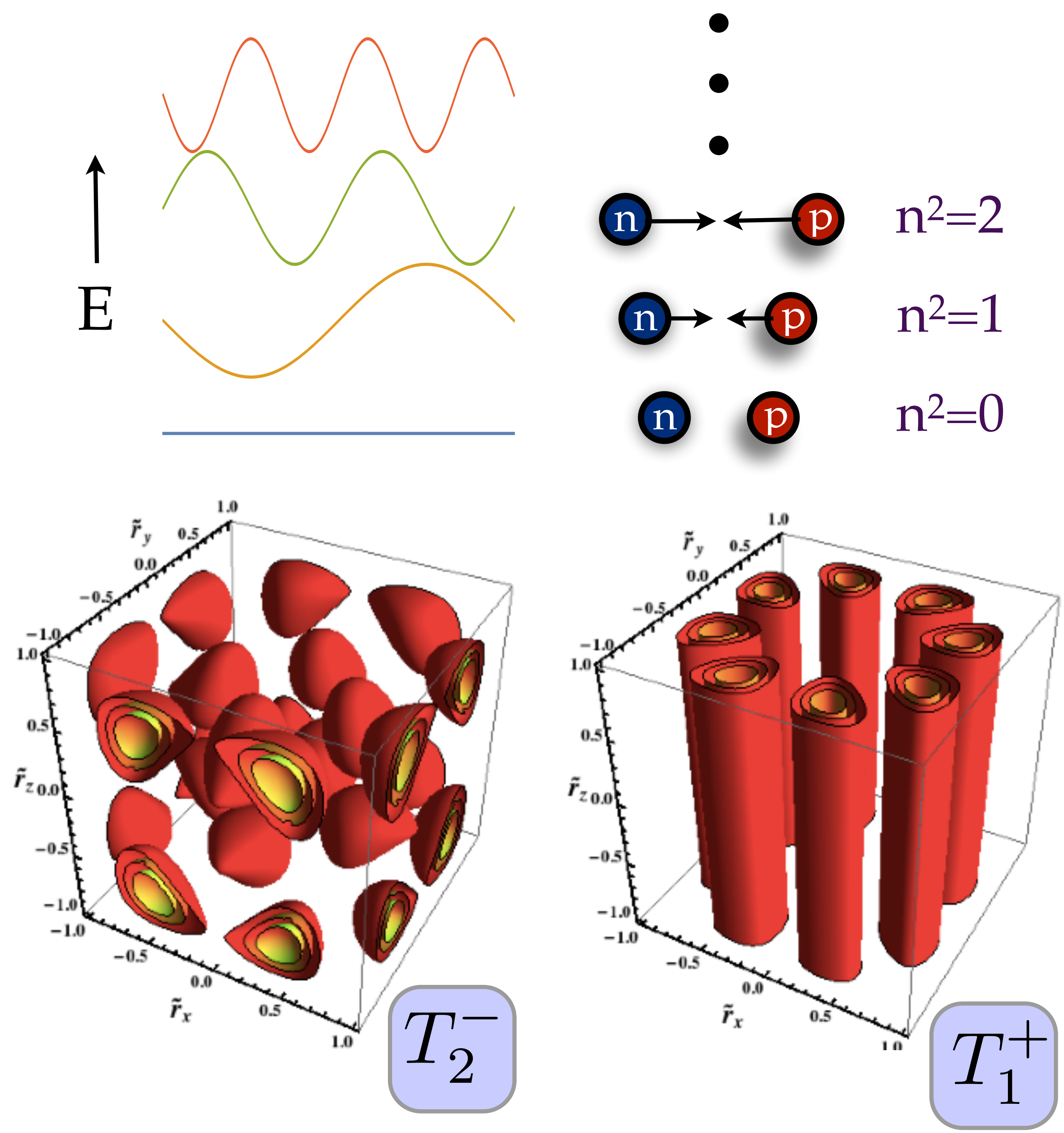
Inelastic single body
$\Delta E \sim m_\pi$
(HAL, Luscher)

Reducing elastic 2-body excited states

- Project onto non-interacting eigenstates of the box

- Very costly to perform exact momentum/angular momentum projection at both source & sink (~V)

- Perform exact projection only at the sink



Figures from Luu & Savage (2011)

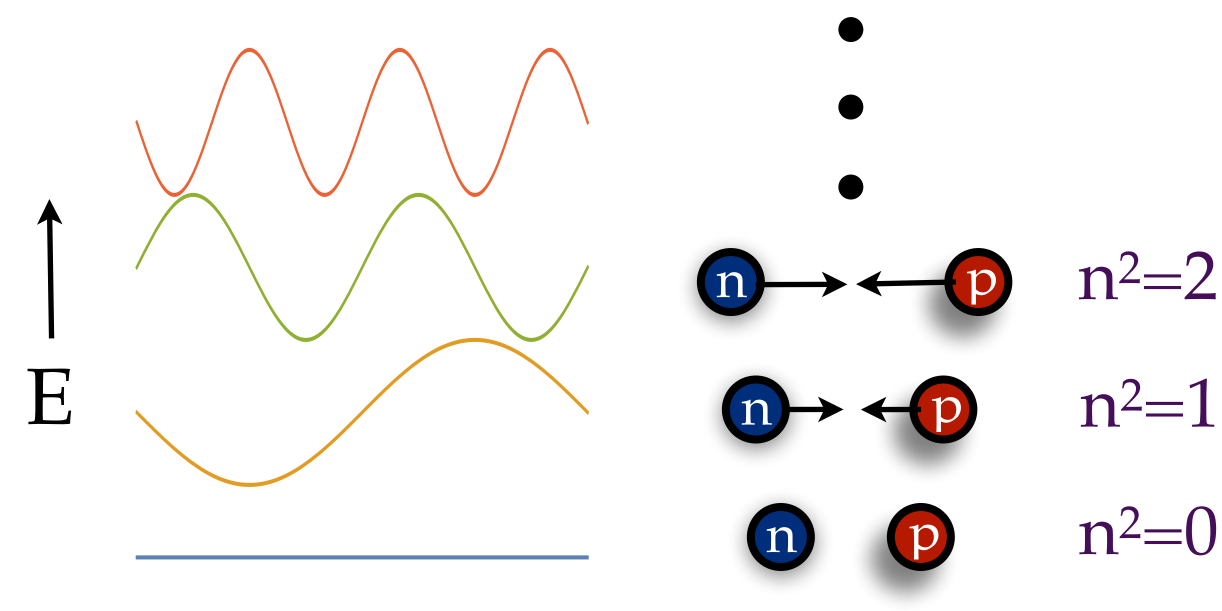
Reducing elastic 2-body excited states

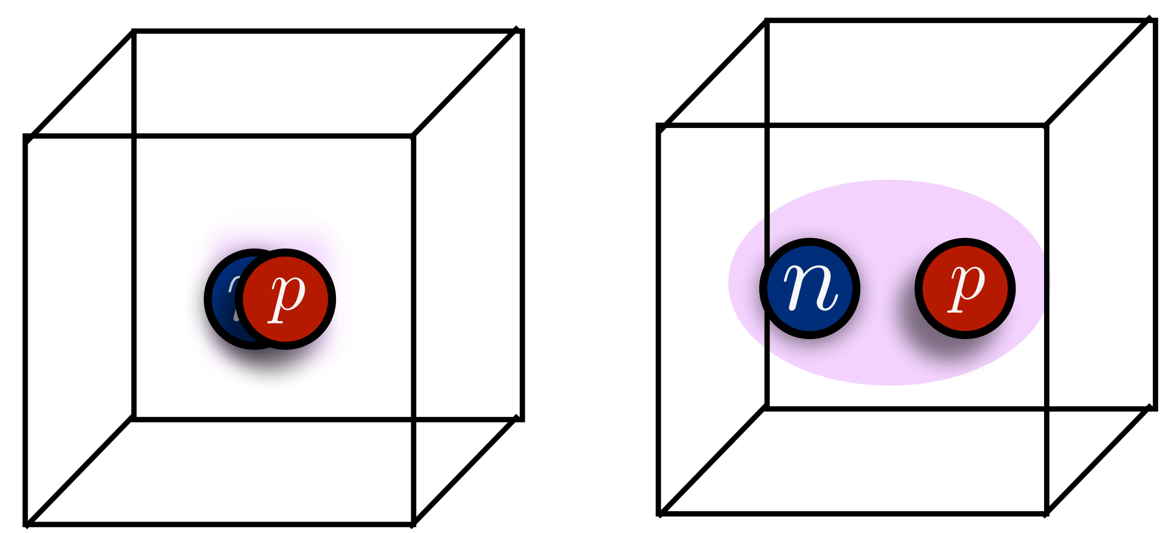
- Project onto non-interacting eigenstates of the box

- Very costly to perform exact momentum/angular momentum projection at both source & sink (~V)

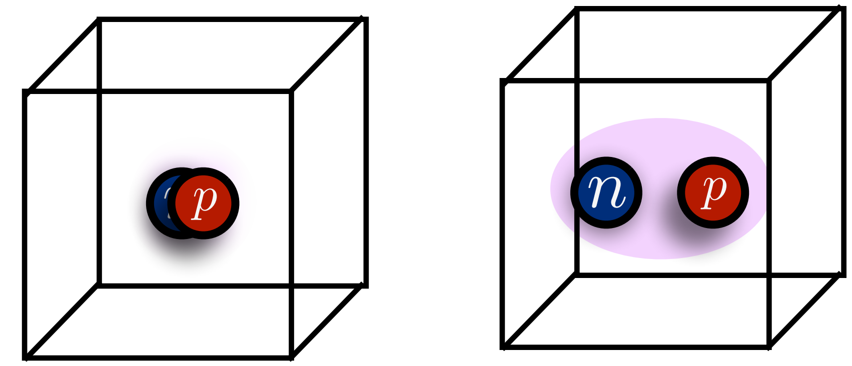
- Source: need spatially displaced source operators to have overlap with $\ell > 0$

- Even for s-wave, displaced sources are cleaner

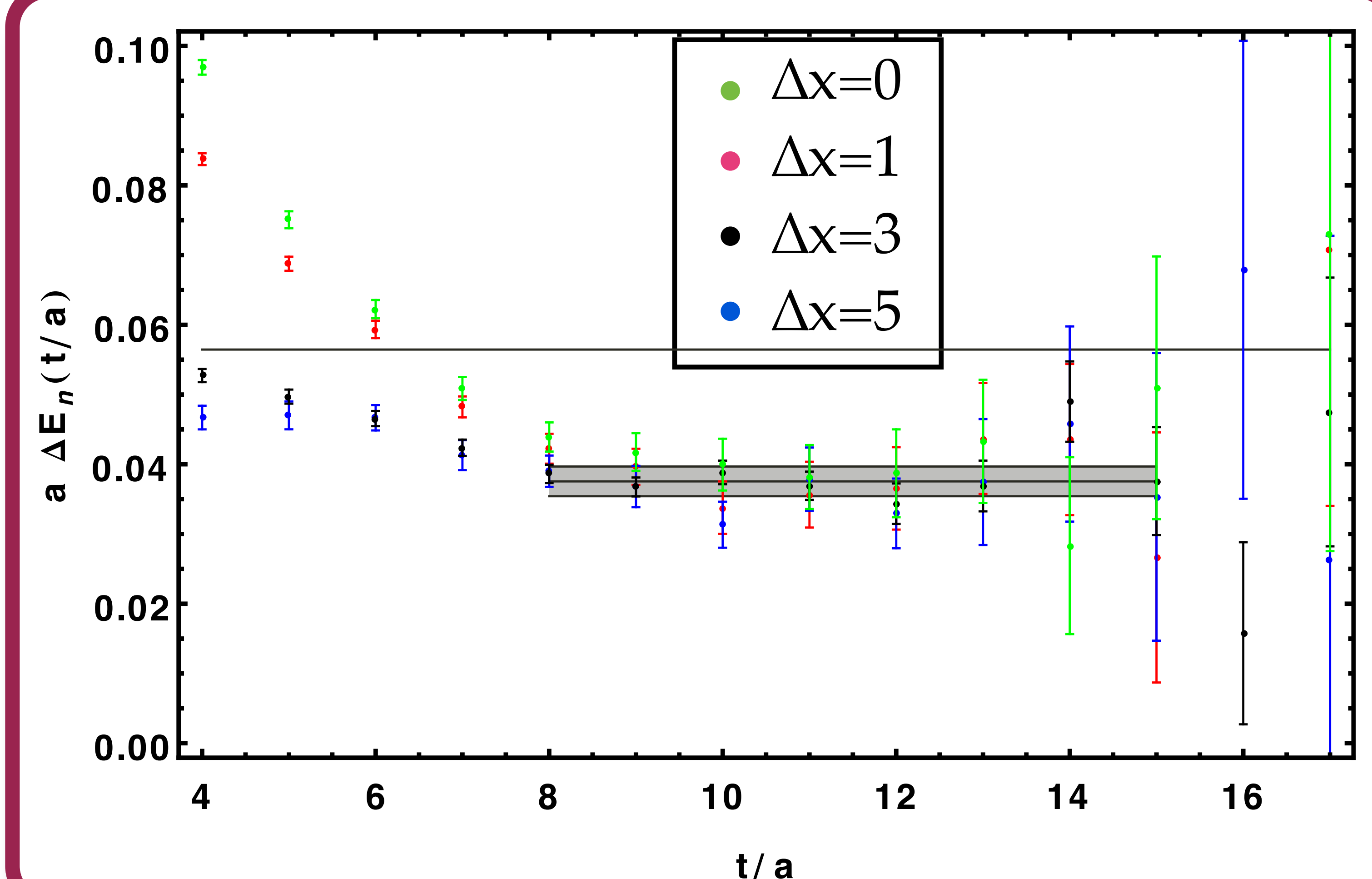




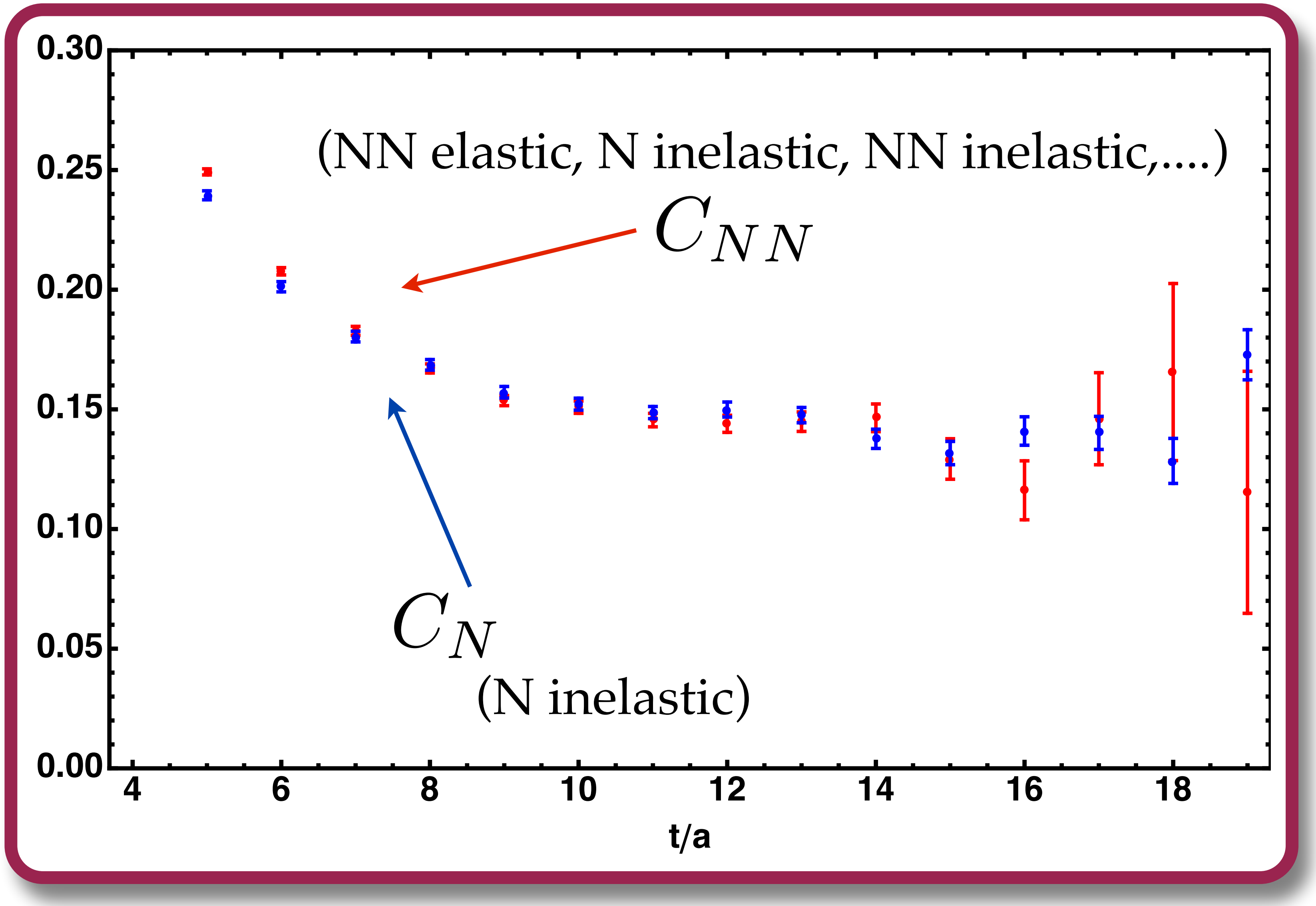
Source: position space



Large displacements are necessary for maximal overlap with low-energy states



Excited state contributions to NN



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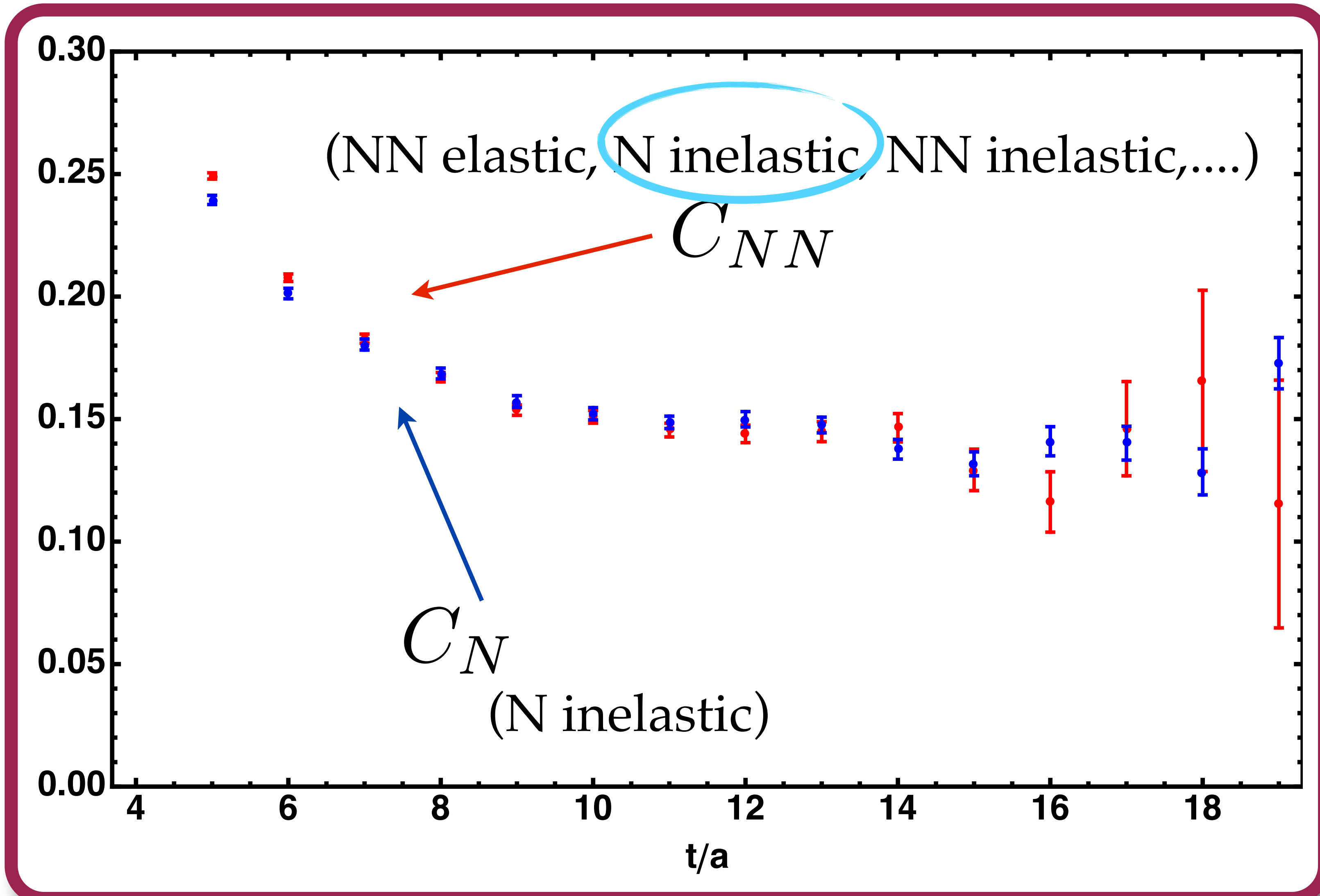
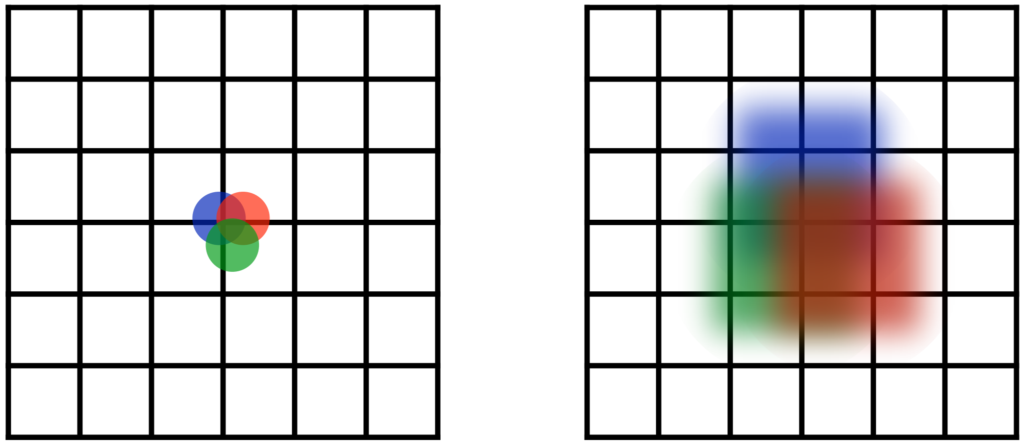
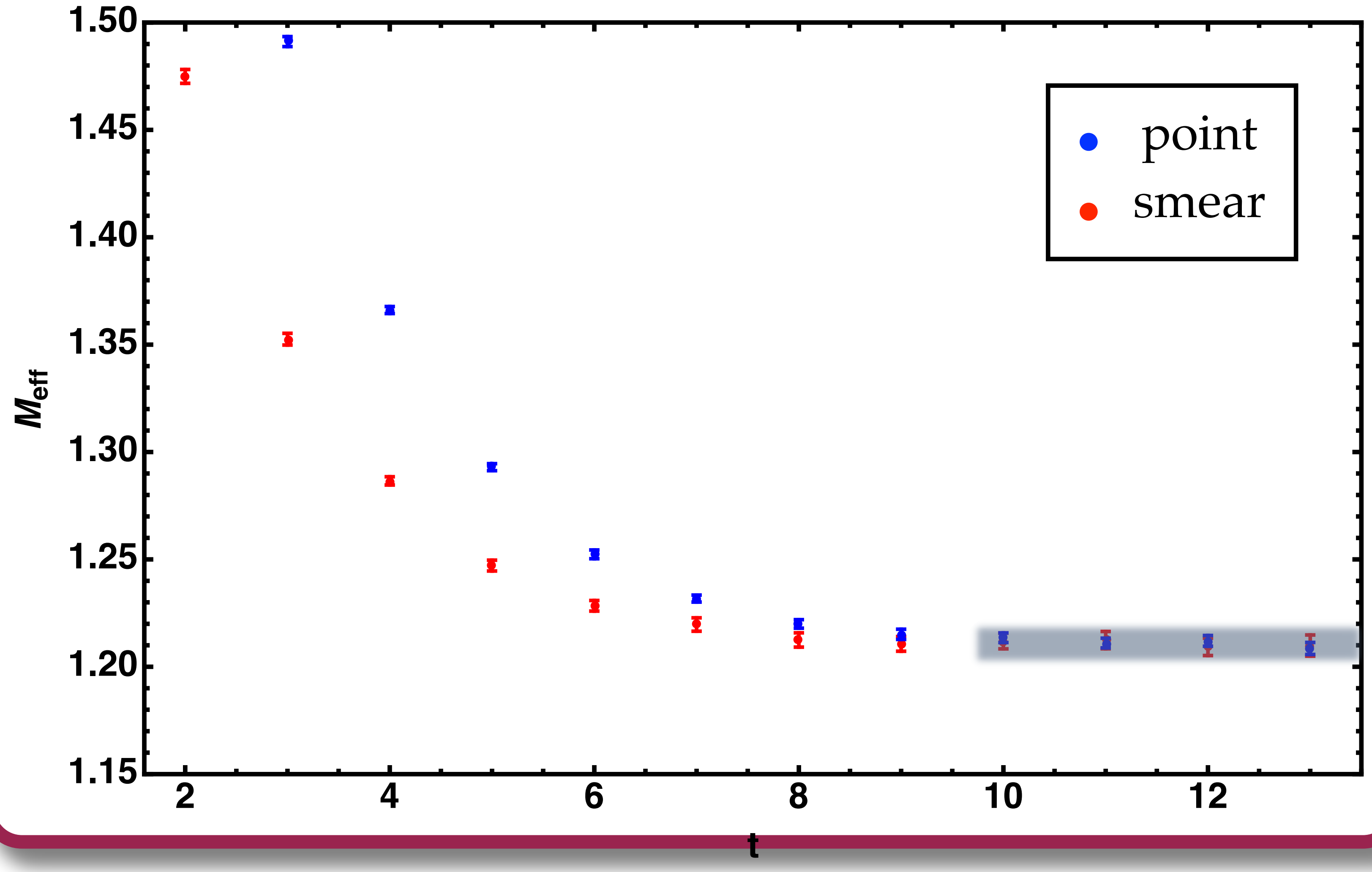


Long time behavior of NN correlator dominated by inelastic single nucleon excited state (problem for HAL method!)

Reducing single nucleon inelastic states: Matrix Prony (poor man's GEVP)

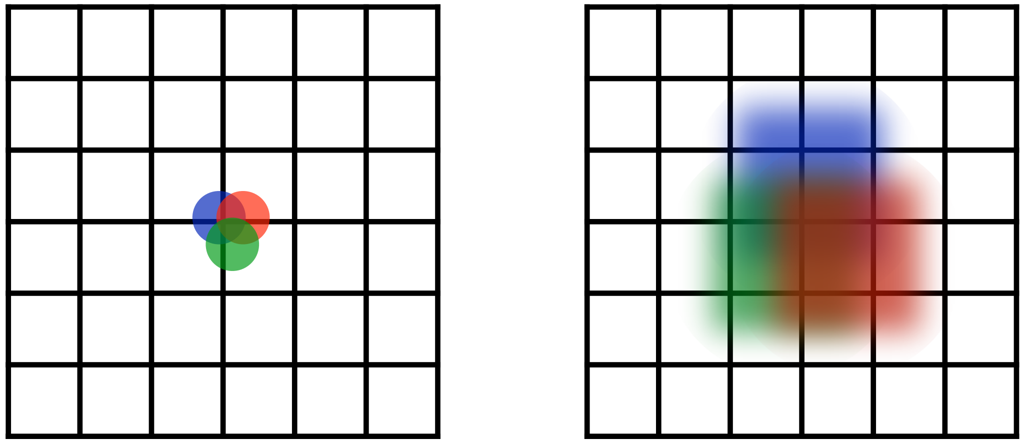


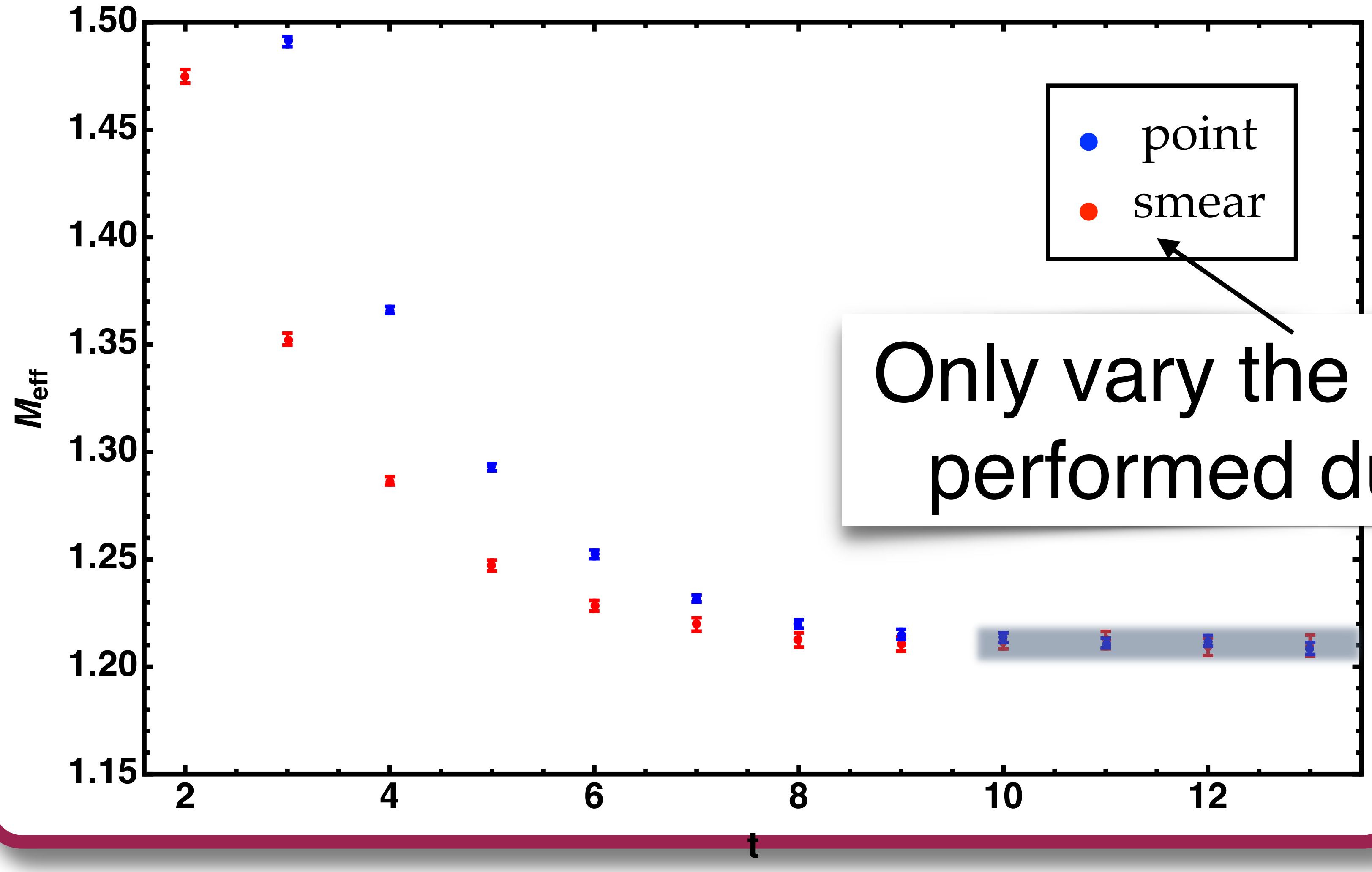


Single nucleon correlator

NPLQCD (2009)

Reducing single nucleon inelastic states: Matrix Prony (poor man's GEVP)





Only vary the sink: easily performed during FFT

Single nucleon correlator

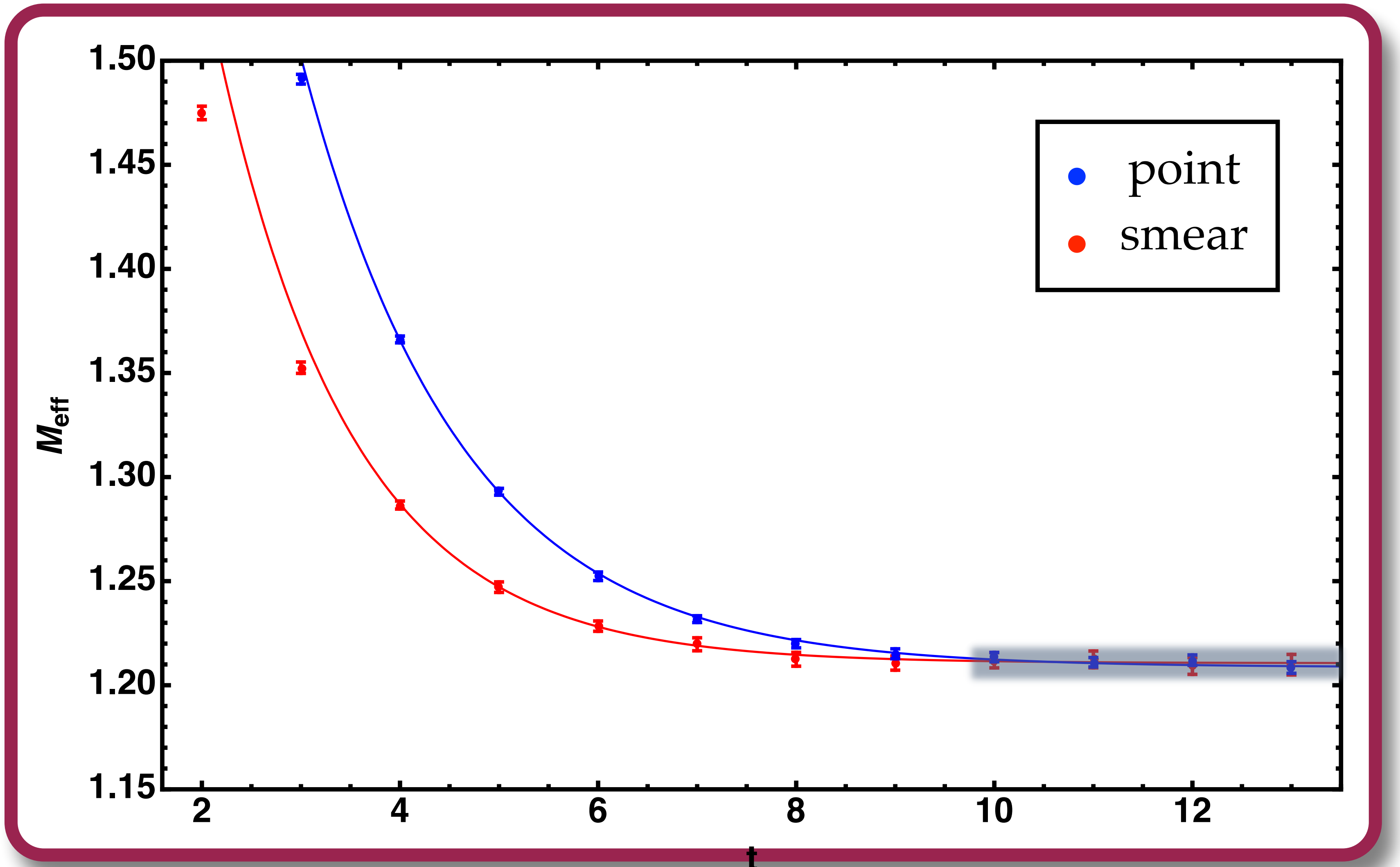
NPLQCD (2009)

Reducing single nucleon inelastic states: Matrix Prony (poor man's GEVP)

$$C_0(t+t_0) + \alpha C(t) = 0$$

$$\alpha = -e^{-E_0 t_0}$$

$$E_0 = -\frac{1}{t_0} \ln \frac{C(t+t_0)}{C(t)}$$



Single nucleon correlator

NPLQCD (2009)

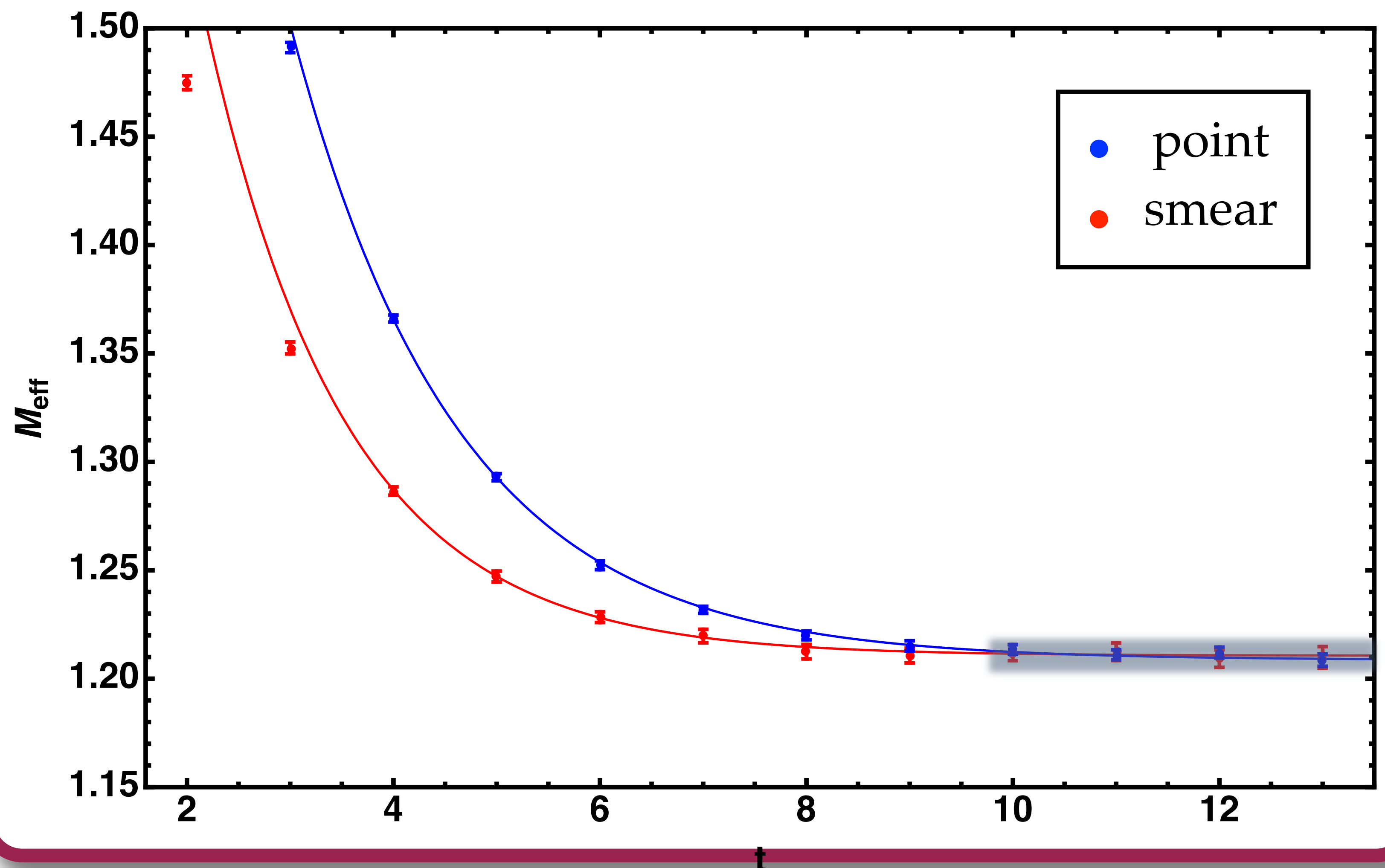
Reducing single nucleon inelastic states: Matrix Prony (poor man's GEVP)

$$MC(t+t_0) - VC(t) = 0$$

$$C(t) = \sum_{n=1}^{N} \alpha_n u_n \lambda_n^{-t} \qquad \lambda = e^{E_n}$$

$$Mu = \lambda^{t_0} V u$$

$$M = \left[\sum_{\tau=t}^{t+t_W} C(\tau+t_0)C(\tau)^T\right]^{-1} \quad V = \left[\sum_{\tau=t}^{t+t_W} C(\tau)C(\tau)^T\right]^{-1}$$



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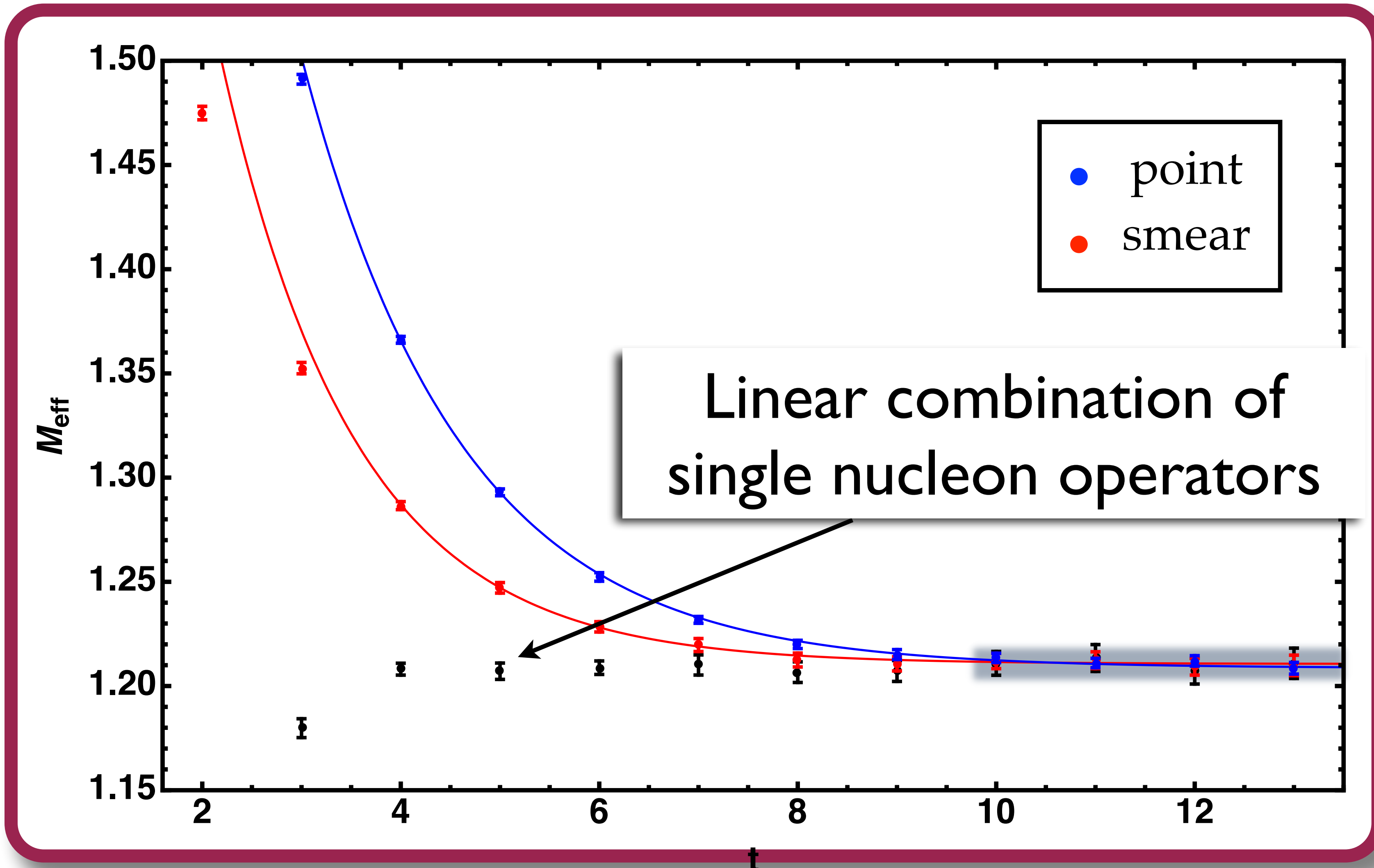

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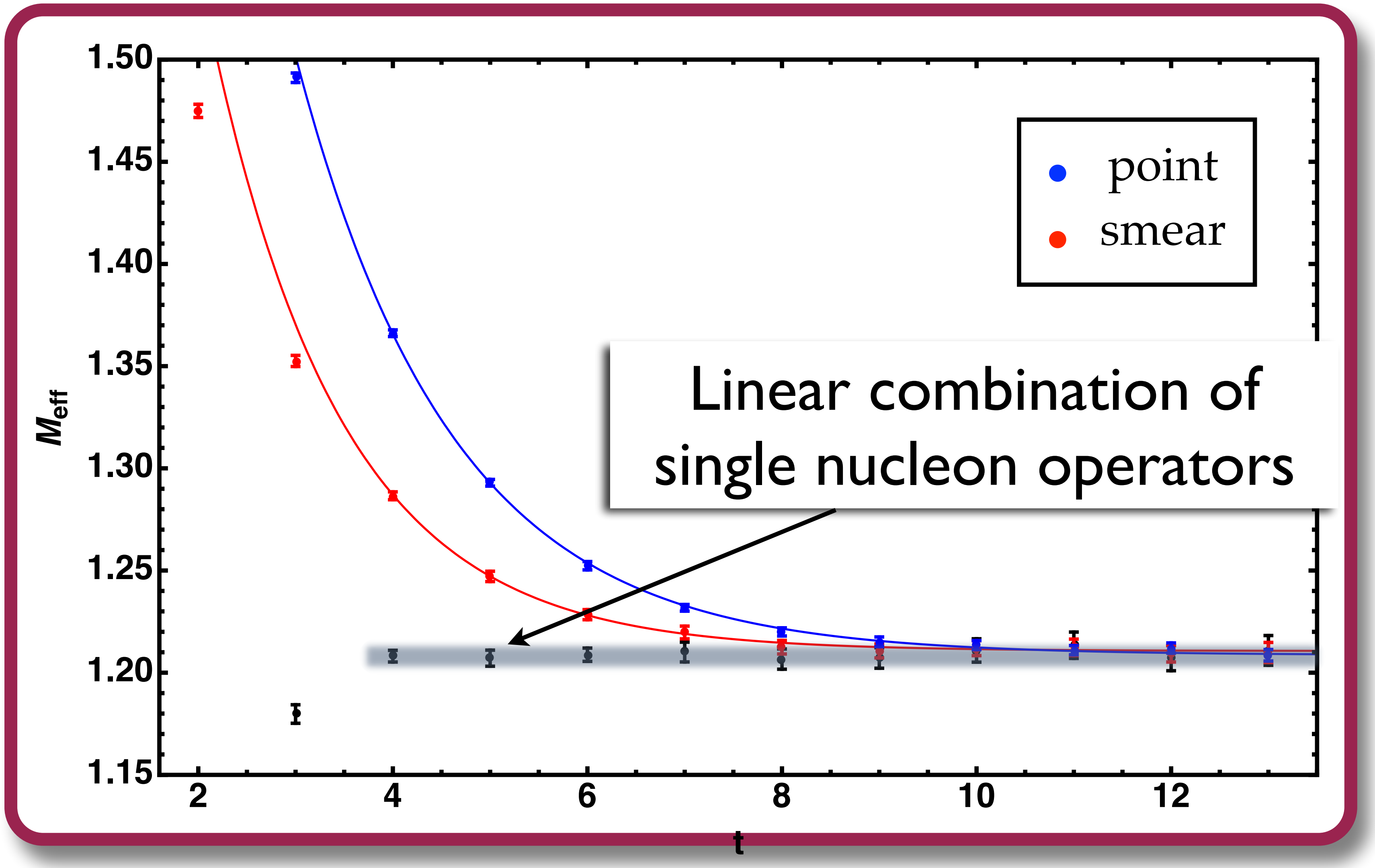
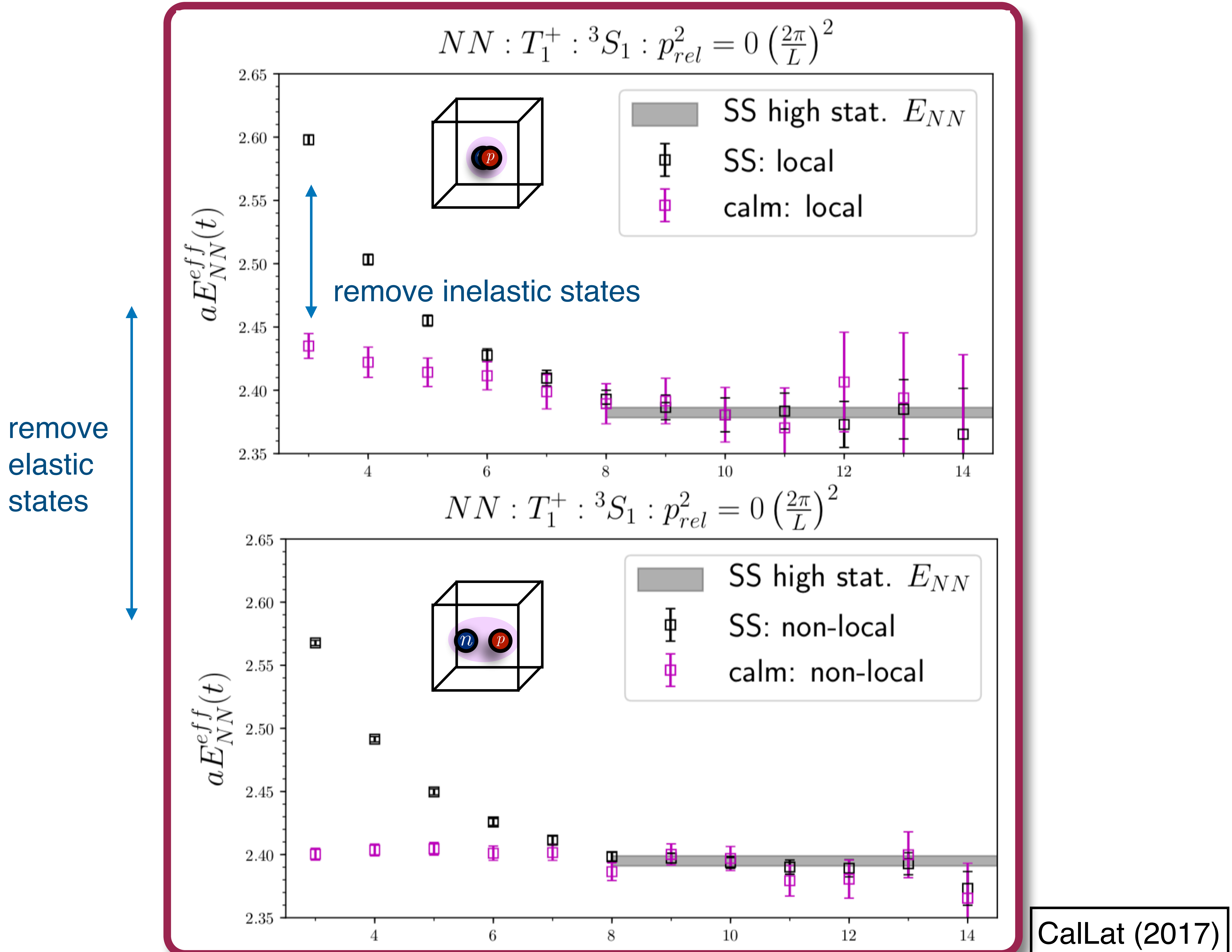


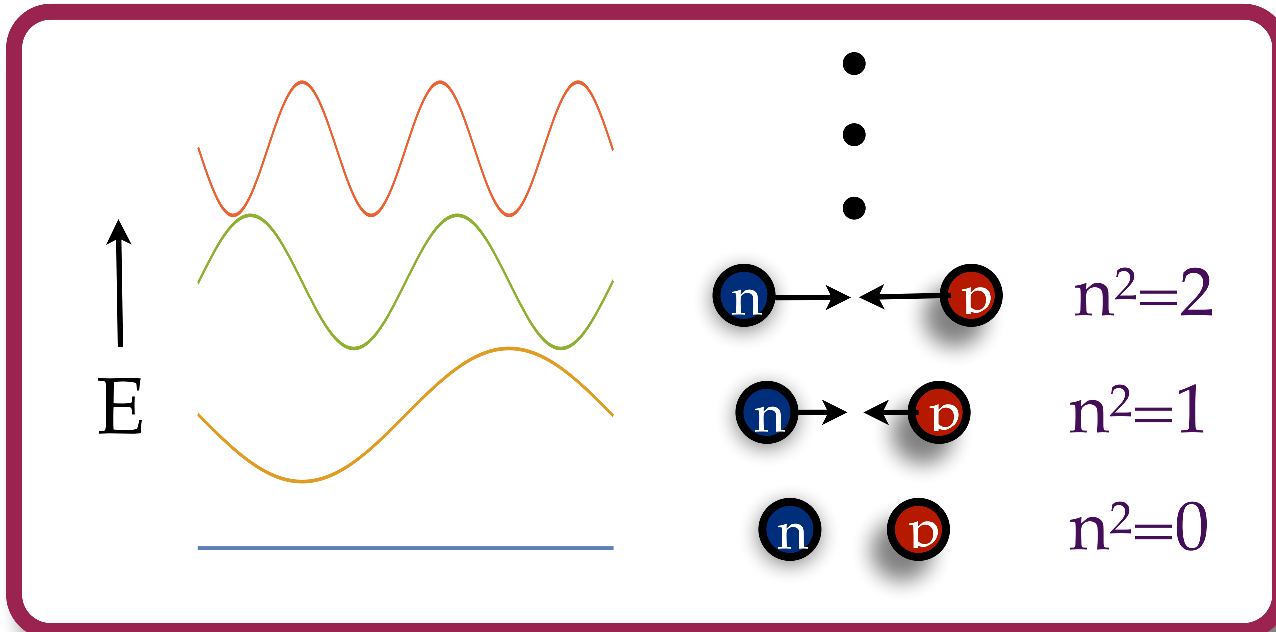
Single nucleon correlator

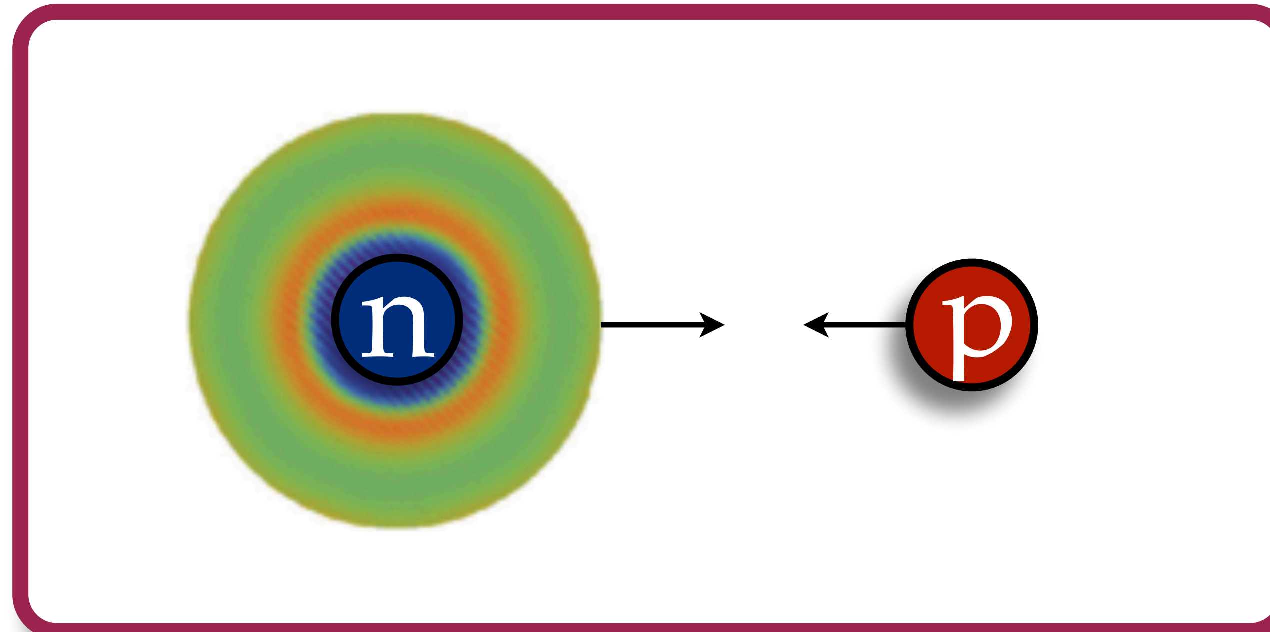
NPLQCD (2009)



$NN : T_1^+ : {}^3S_1 : p_{rel}^2 = 0\left(\frac{2\pi}{L}\right)^2$
SS high stat. E_{NN}
SS: local
calm: local
remove inelastic states
$aE_{NN}^{eff}(t)$
remove elastic states
$NN : T_1^+ : {}^3S_1 : p_{rel}^2 = 0\left(\frac{2\pi}{L}\right)^2$
SS high stat. E_{NN}
SS: non-local
calm: non-local
$aE_{NN}^{eff}(t)$
CalLat (2017)

MP method for NN





- NPLQCD first used MP directly on NN correlators
- Works best as a two-step process: determine single-nucleon op, then minimize two-body elastic excited states
- Prony often doesn't work well for more than 2 ops:
  - excited states extracted are unreliable
  - may be able to do two stages of Prony to further reduce elastic excited states

The future? GEVP approaches

Variational basis of interpolating operators: $O_i(x_0)$

Define the states: $|\tilde{\phi}_i\rangle = \hat{O}_i|0\rangle \quad \text{and} \quad |\phi_i\rangle = \mathrm{e}^{-t_0\,\hat{H}/2}|\tilde{\phi}_i\rangle$

The future? GEVP approaches

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Variational principle (t > t_0):

$$\lambda_1(t,t_0) = \underset{\{\alpha_i\}}{\mathrm{Max}} \frac{\langle\phi|\mathrm{e}^{-(t-t_0)\hat{H}}|\phi\rangle}{\langle\phi|\phi\rangle}\,, \quad |\phi\rangle = \sum_{i=1}^{N} \alpha_i|\phi_i\rangle$$

Eigenvalue: $\lambda_1(t,t_0) \;\approx\; \mathrm{e}^{-E_1(t-t_0)}$

The future? GEVP approaches

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Eigenvalue: $\lambda_1(t,t_0) \approx \mathrm{e}^{-E_1(t-t_0)}$

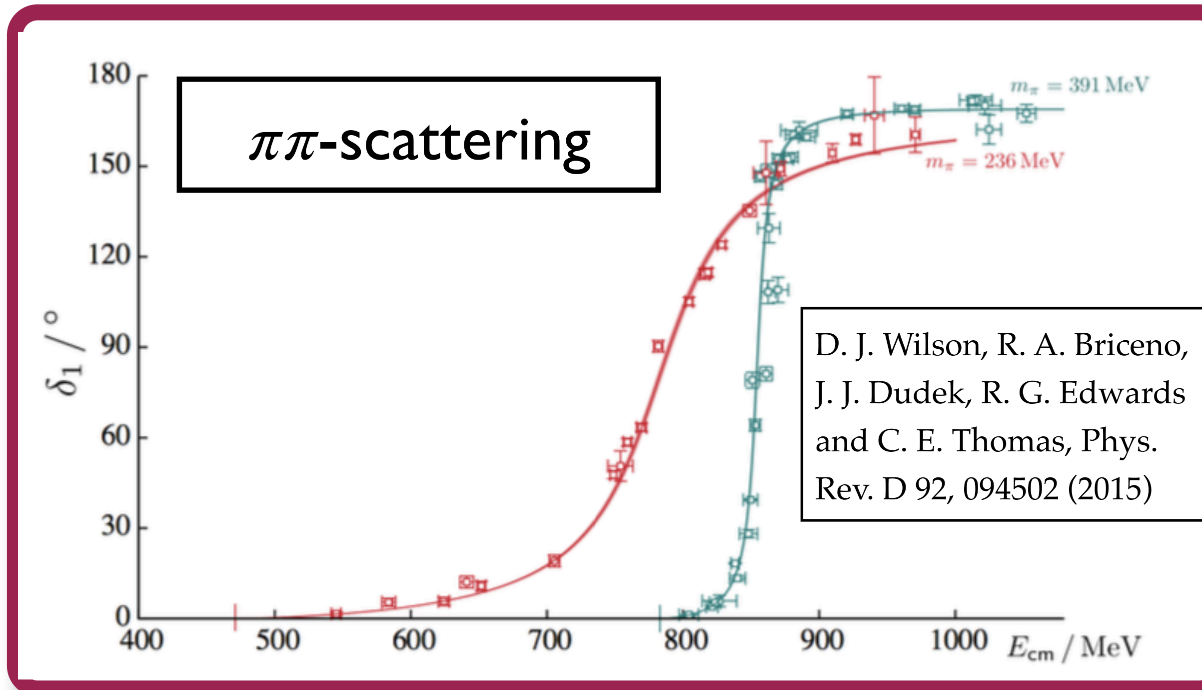
Largest eigenvalue of a GEVP, which can be used to determine multiple states:

$$C_{ij}(t) = \left\langle \hat{O}_i(t)\hat{O}_j^\dagger(0) \right\rangle$$

$$C(t)\,v_n(t,t_0) = \lambda_n(t,t_0)\,C(t_0)\,v_n(t,t_0)$$

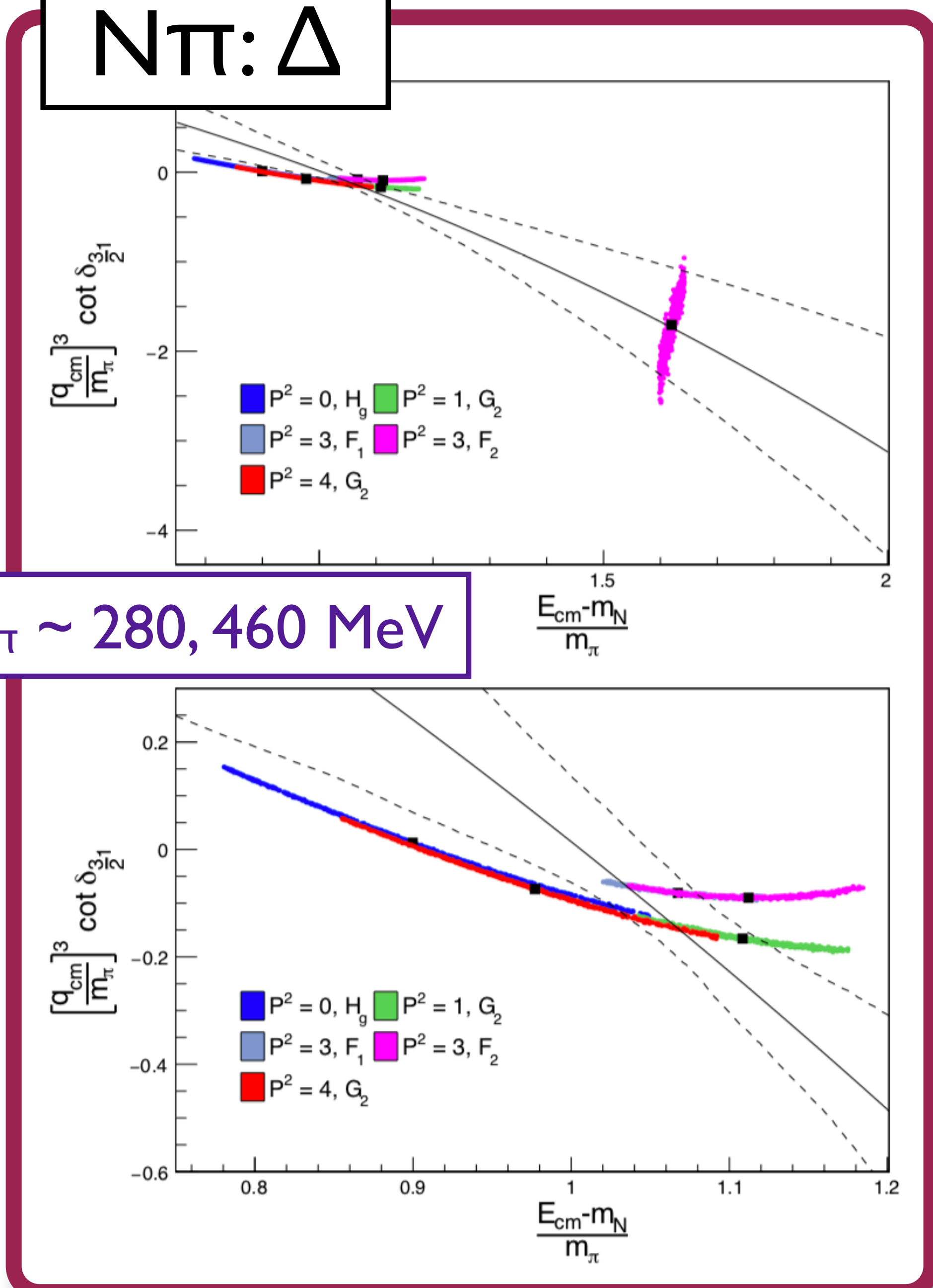
$$n = 1,\ldots,N$$

The future?
GEVP approaches



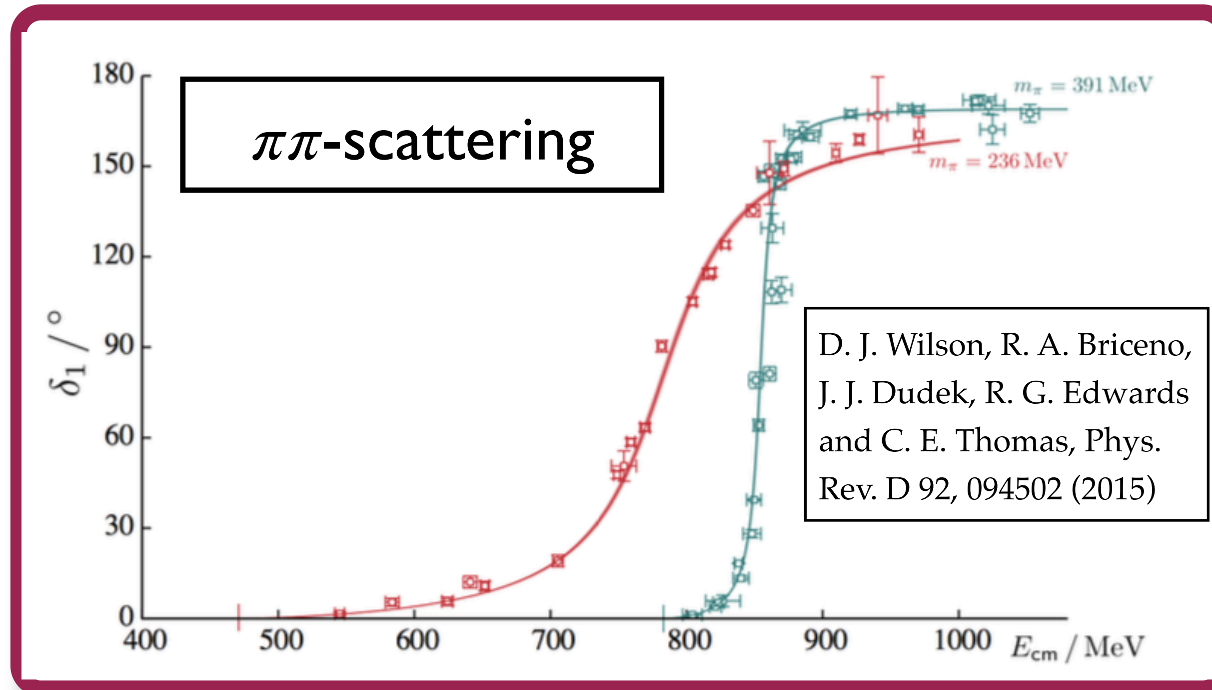
The future? GEVP approaches

Nπ: Δ



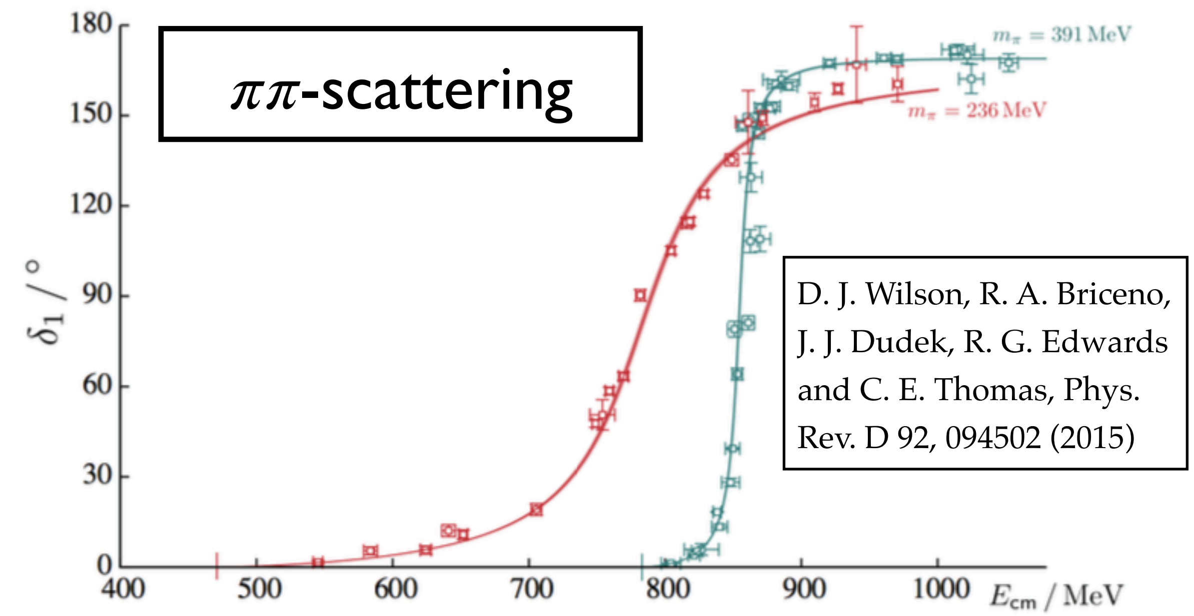
m_π ~ 280, 460 MeV

Andersen, Bulava, Horz, Morningstar (2018)



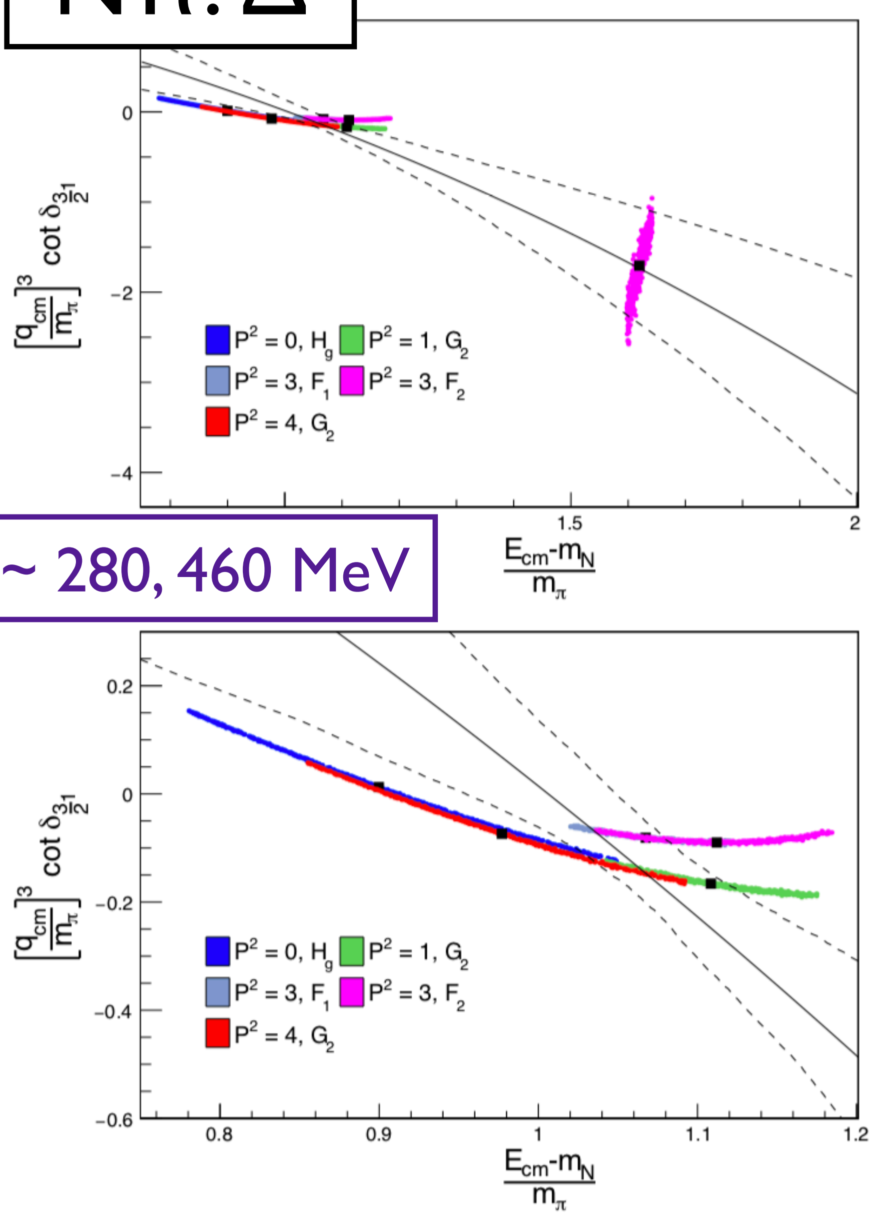
The future? GEVP approaches

ππ-scattering



Nπ: Δ

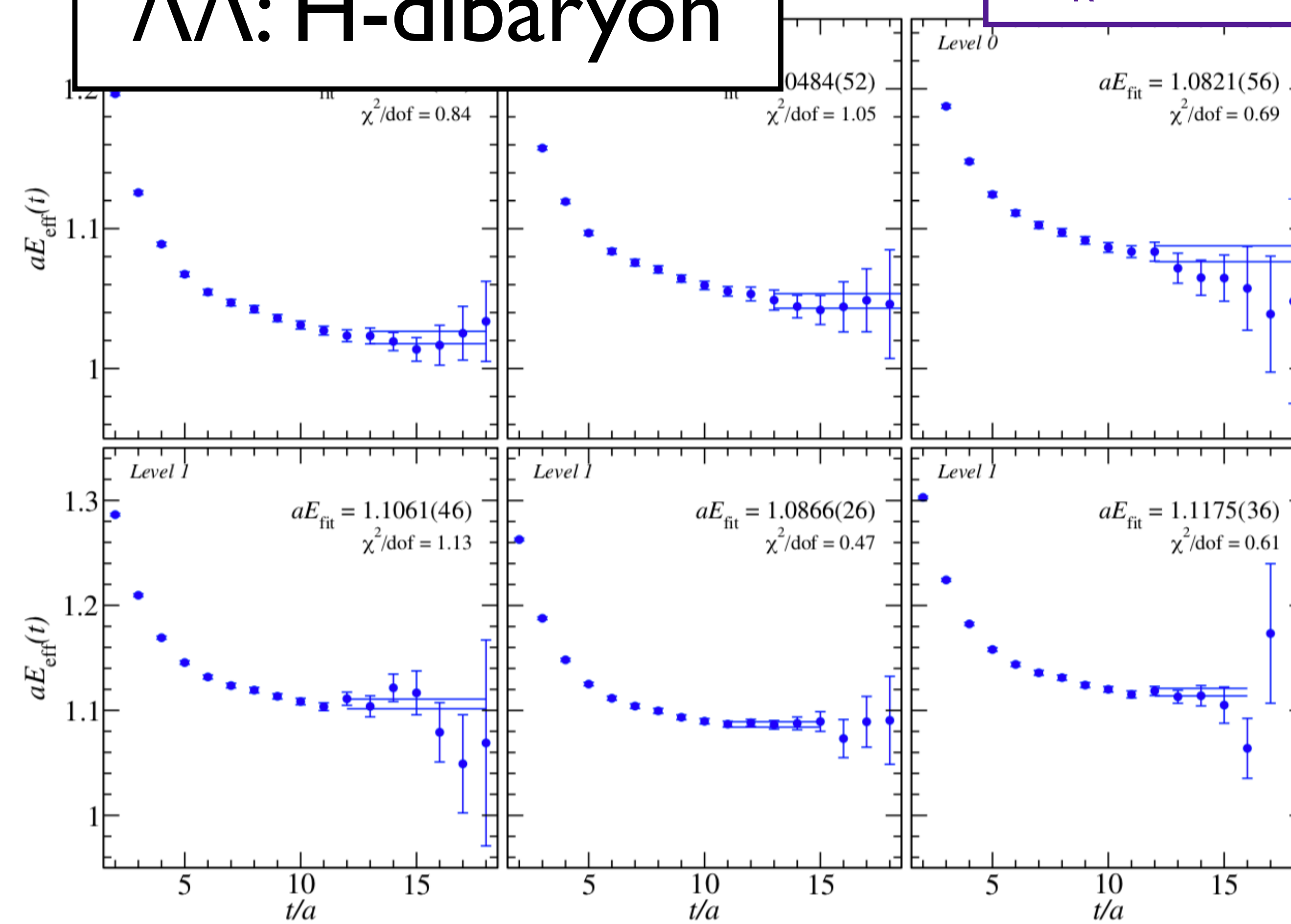
$m_\pi \sim 280, 460$ MeV



Andersen, Bulava, Horz, Morningstar (2018)

ΛΛ: H-dibaryon

$m_\pi \sim 800$ MeV



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

The future? GEVP approaches NN?

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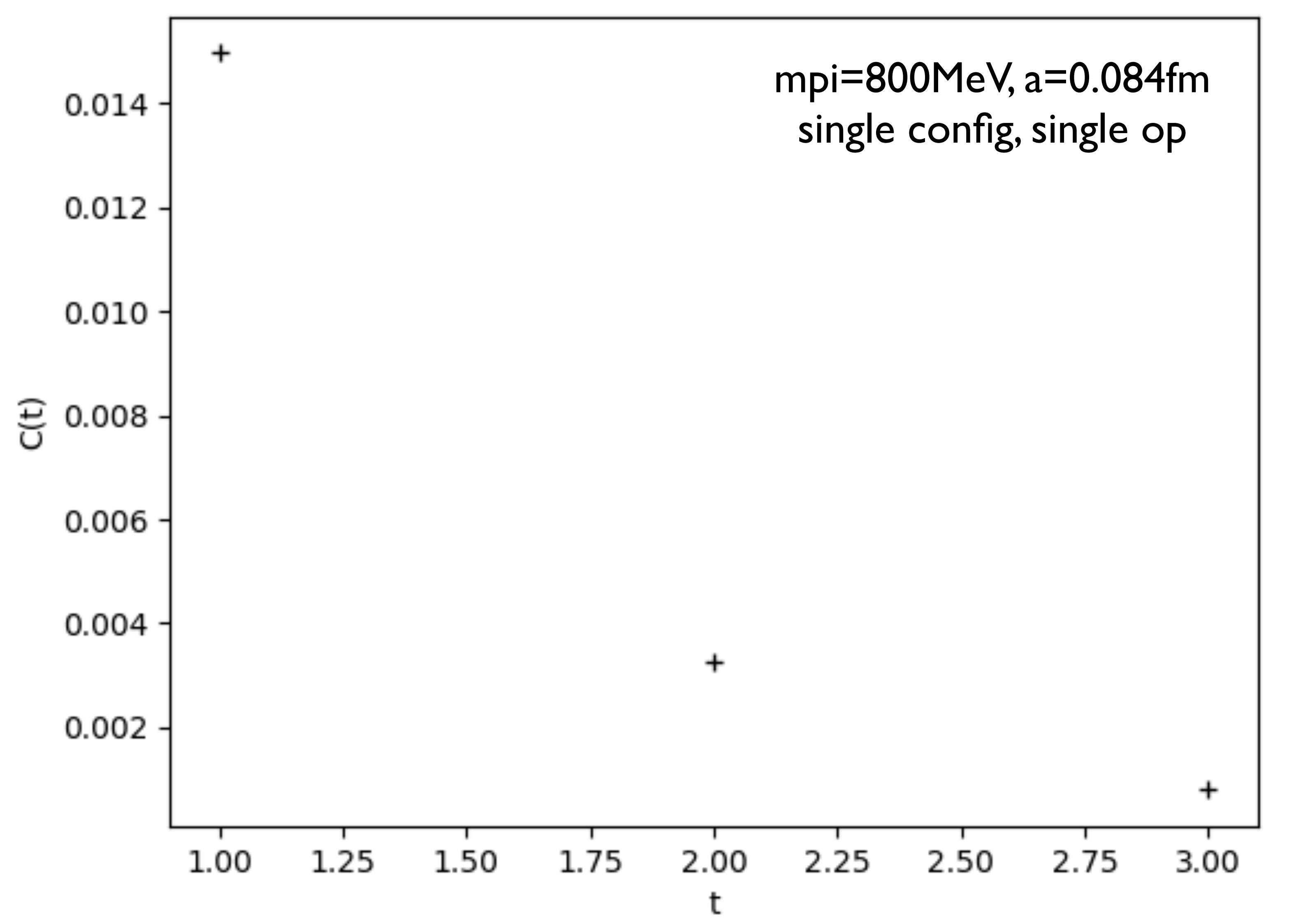
    - sLapH stochastically projects onto low momentum states, easing this scaling with V

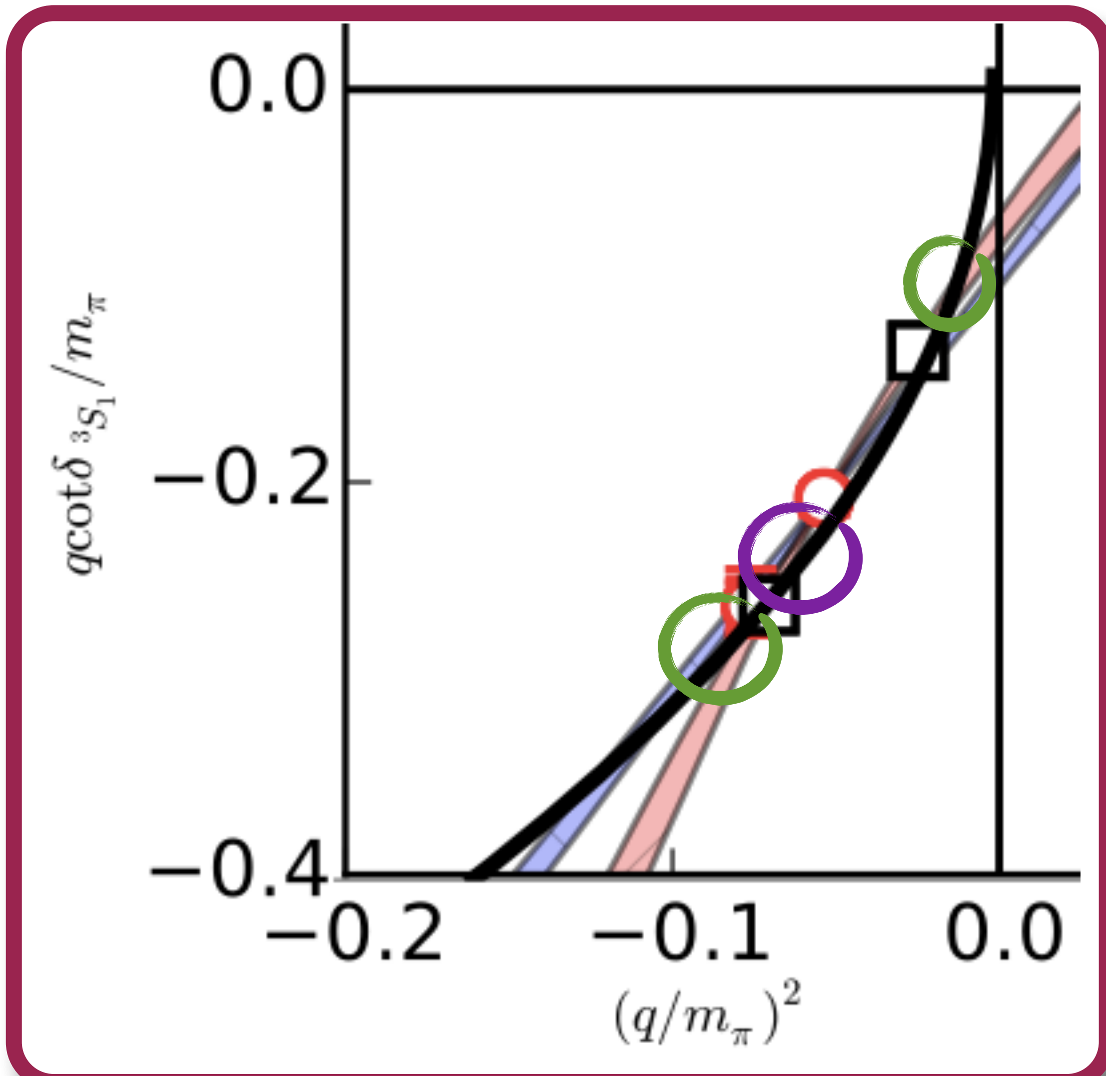
NN scattering with sLapH

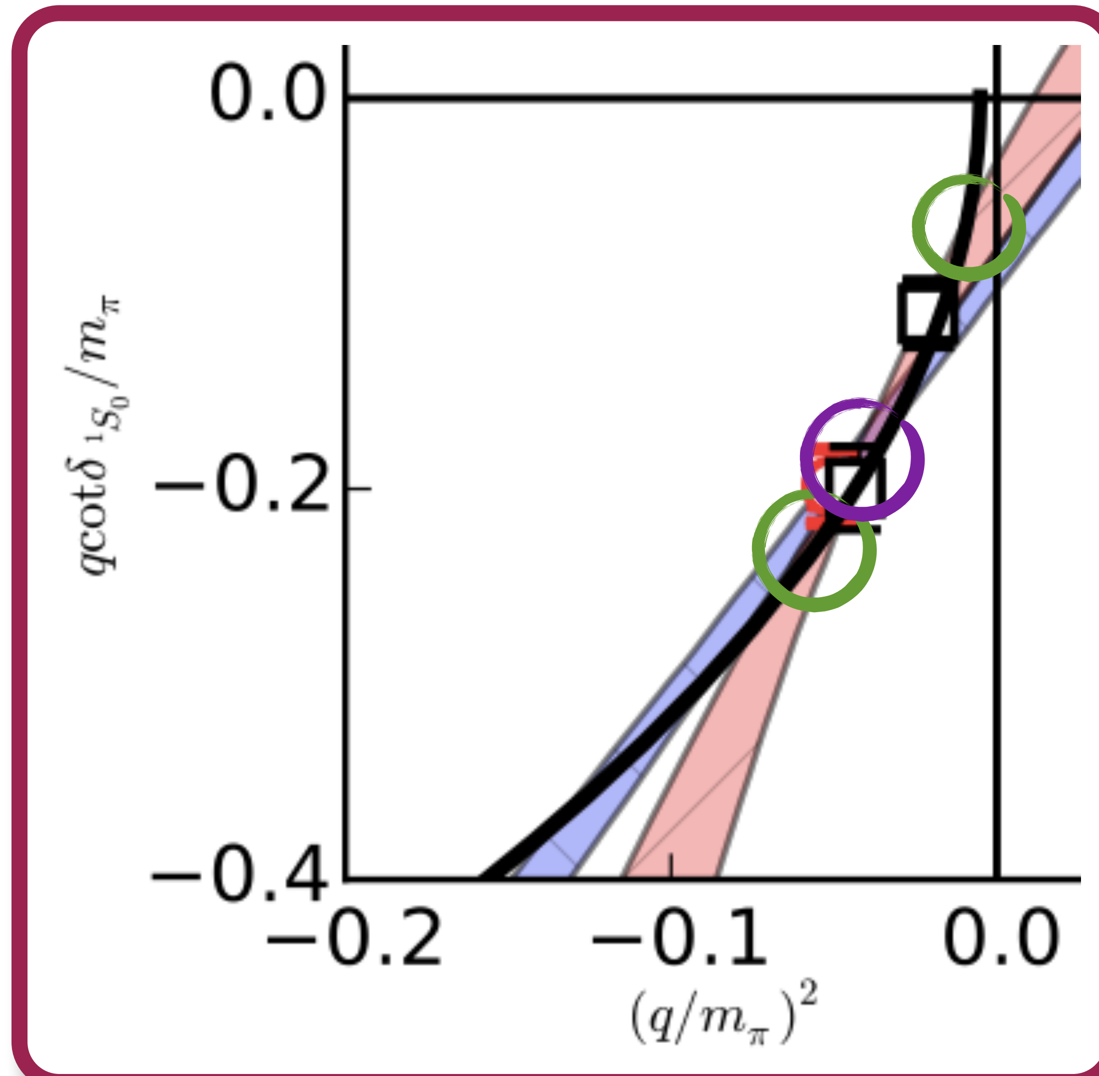


+ C. Andersen, J. Bulava, A. Hanlon, D. Howarth, B. Hörz, C. Morningstar

Fully resolving this puzzle likely requires GEVP including both momentum space and local ops

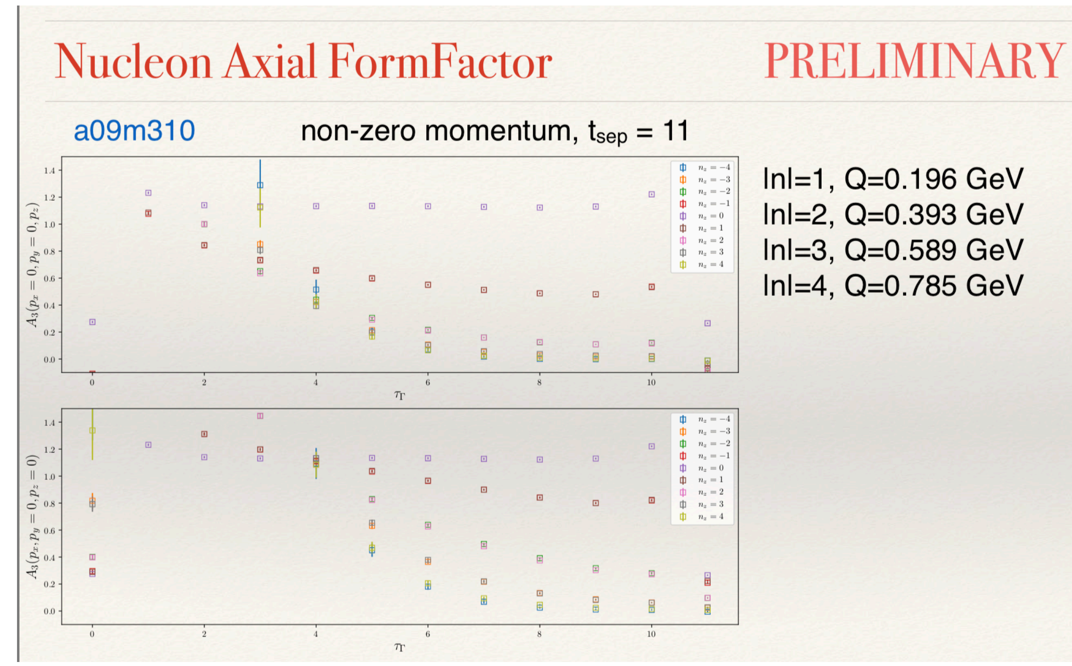
We are currently performing a comparison of methods (HAL potential, Luscher using both MP and sLapH) on same ensembles at 800 MeV



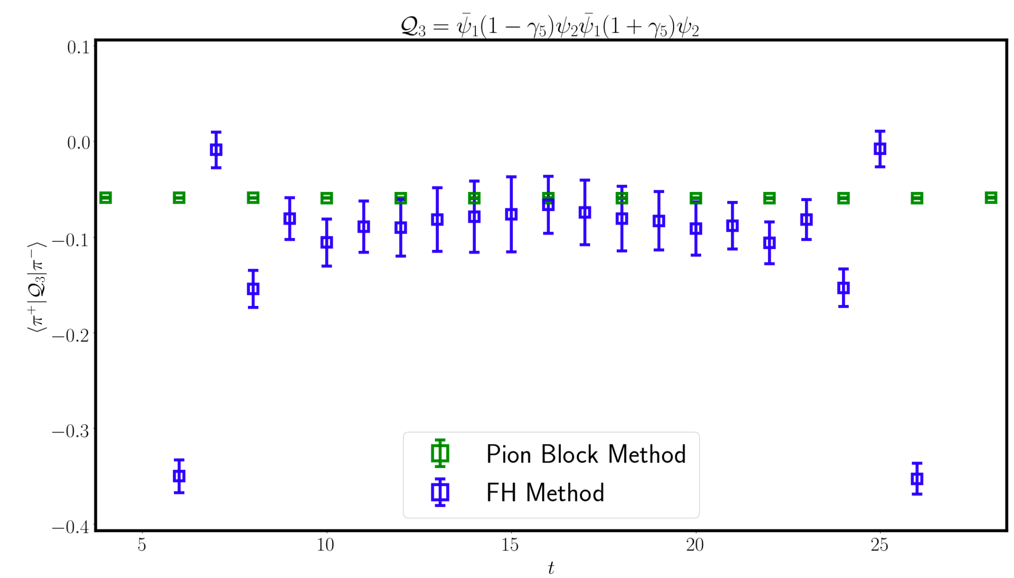


Other progress

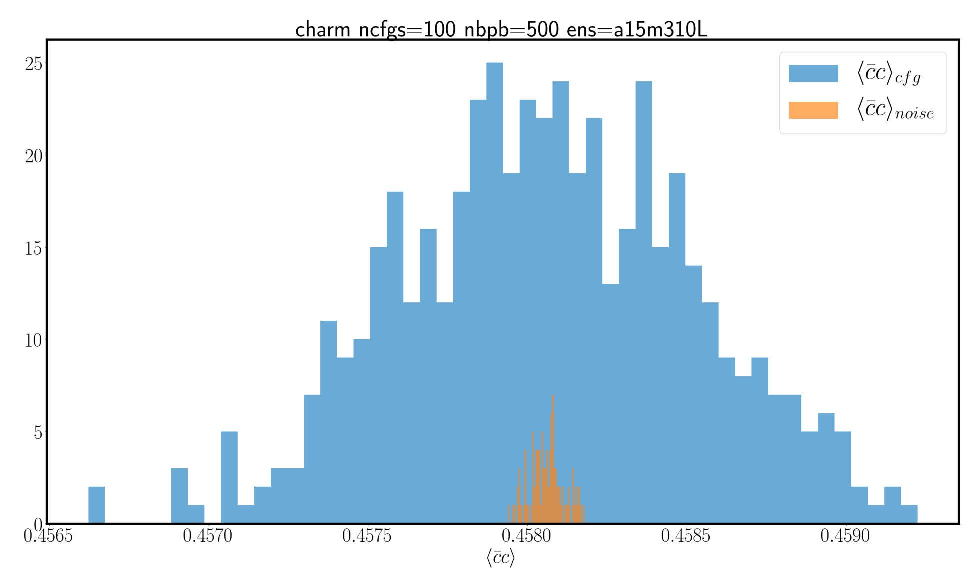
- Nucleon axial form factors



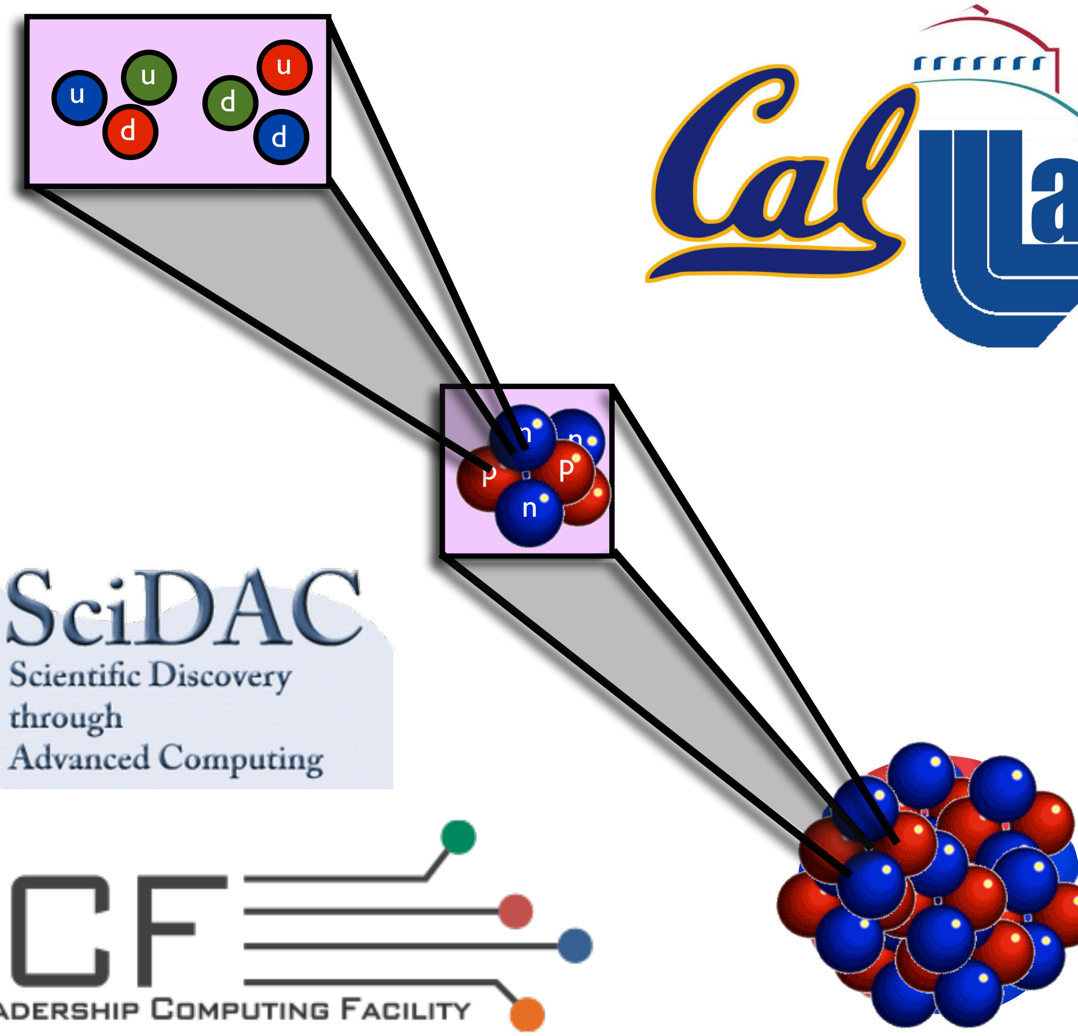
- Feynman-Hellmann method for computing 4-quark MEs



- Charm content of the nucleon (DM MEs) $\langle N|\bar{c}c|N\rangle$



- RIKEN/LBL: C.C. Chang
- RIKEN: E. Rinaldi
- NERSC: T. Kurth
- nVidia: M.A. Clark
- LBL/UCB: A. Walker-Loud, B. Hörz
- Glasgow: C. Bouchard
- LLNL: P. Vranas, D. Howarth
- Carnegie Mellon: C. Morningstar
- SDSU: J. Bulava, C. Andersen
- UMD: E. Berkowitz
- Mainz: A. Hanlon
- UNC: H. Monge-Camacho, AN



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