時間依存型*HAL QCD*法による
核子-チャーモニウム間相互作用

杉浦 拓也, 大阪大学RCNP
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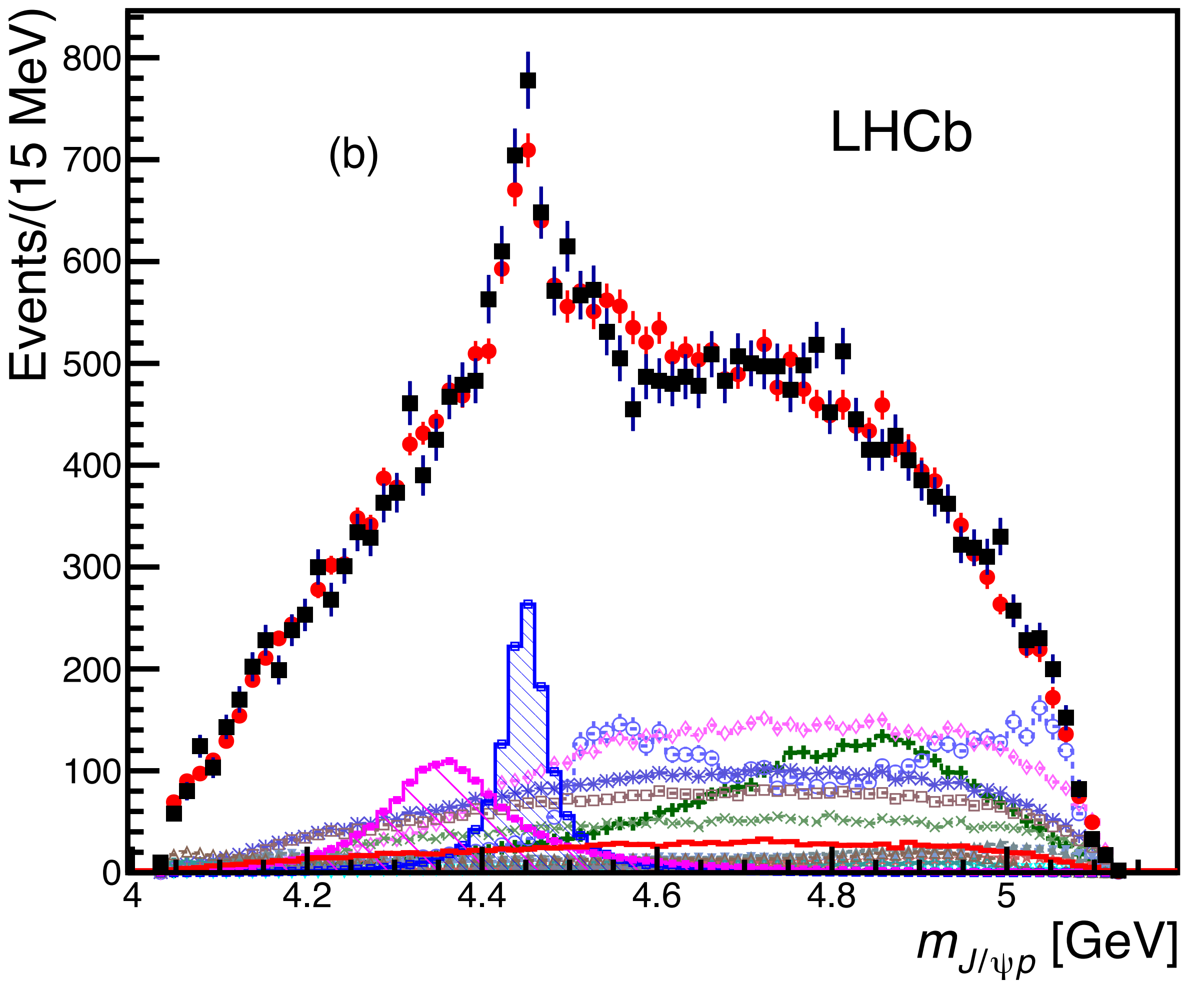
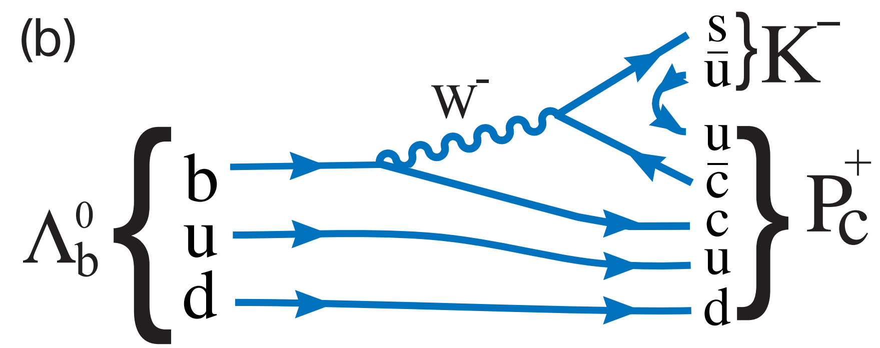
Hidden-Charm Pentaquarks



The newly-reported resonances in the weak decay $\Lambda_b \to J/\psi K p$



Expected to be hidden-charm (uudcc^{bar}) pentaquarks

[Aaji *et al.*, PRL**115** '15]

State	Mass [MeV]	Width [MeV]	J^P
$P_c^+(4380)$	4380±8±29	205±18±86	$3/2^-$, $3/2^+$, $5/2^+$
$P_c^+(4450)$	4449.8±1.7±2.5	39±5±19	$5/2^+$, $5/2^-$, $3/2^-$

Previous Studies

Molecular state

R. Chen *et al.*, Phys. Rev. Lett.**115**,132002 (2015)

L. Roca and E. Oset, Eur. Phys. J.**76**, 591 (2016)

Y. Shimizu *et al.*, Phys. Rev. D**93**, 114003 (2016)

Diquark-diquark-quark

L. Maiani *et al.*, Phys. Lett. B**749**, 289 (2015)

Quark model

S. Takeuchi and M. Takizawa, Phys. Lett. B**764**, 254 (2017)

QCD sum rule

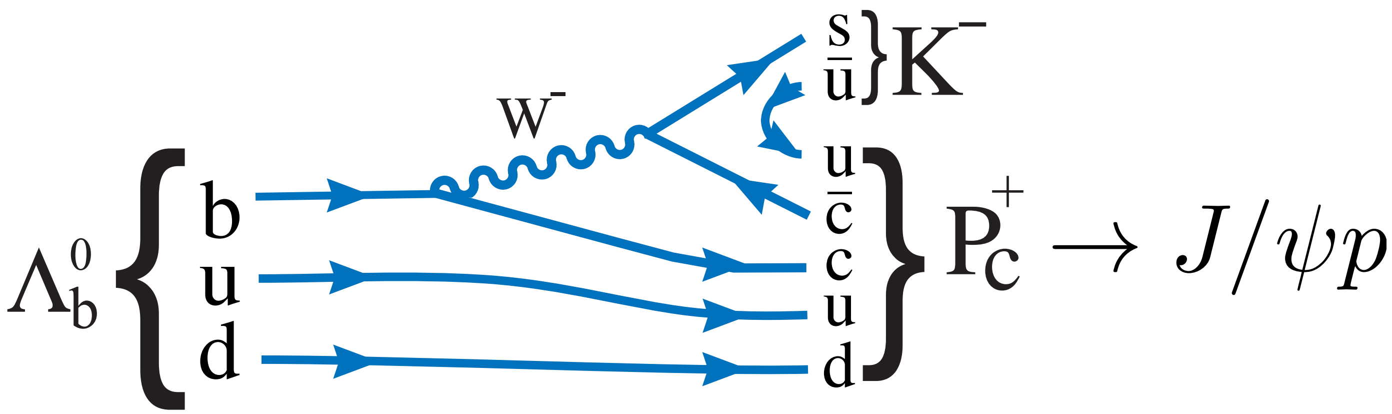
H. Chen *et al.*, Phys. Rev. Lett.**115**,172001 (2015)

Kinematical effect

F. Guo *et al.*, Phys. Rev. D**92**, 071502 (2015)

many others!

Motivation



P_c^+ must couple to J/ψ p

→best to consider the 2-body J/ψp scattering without the spectator K^-

→such an experiment unaccessible

→lattice QCD

HAL QCD method

to compute a potential faithful to the QCD S-matrix

N. Ishii *et al.*, PRL**99**, 022001 (2007)
S.Aoki *et al.*, PTP**123**,89 (2010)
N. Ishii *et al.*, PLB**712**, 437 (2012)

HAL QCD method

Method introduced by the HAL QCD collaboration

$$C(t,\vec{r}) = \langle M(t,\vec{r}+\vec{x})B(t,\vec{x})\bar{\mathcal{J}}(0)\rangle = \sum_n \psi(\vec{r};E_n)A_n e^{-E_n t}$$

faithful to QCD S-matrix: $\psi(\vec{r}) \underset{r\to\infty}{\longrightarrow} \frac{\sin(kr - l\pi/2 + \delta(k))}{kr} e^{i\delta(k)}$

$$\left[\frac{k_n^2}{2\mu} + \frac{\nabla^2}{2\mu}\right]\psi(\vec{r},E_n) = \int d\vec{r}'\, V(\vec{r},\vec{r}')\psi(\vec{r}',E_n) \simeq V(r)\psi(\vec{r},E_n)$$

[N.Ishii *et al.*, PRL**99** '07] [S.Aoki *et al.*, PTEP**123**, 89 '10]

Time-dependent method avoids excited-state contamination

$$R(t,\vec{r}) \equiv C(t,\vec{r})/e^{-(m_1+m_2)t}$$

$$\left[-\frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu}\right]R(t,\vec{r}) = \int d\vec{r}'\, V(\vec{r},\vec{r}')\, R(t,\vec{r}') \quad \text{upto } \mathcal{O}(\vec{k}^2)$$

[N.Ishii *et al.*, PLB**712** '12]

Coupled Channels

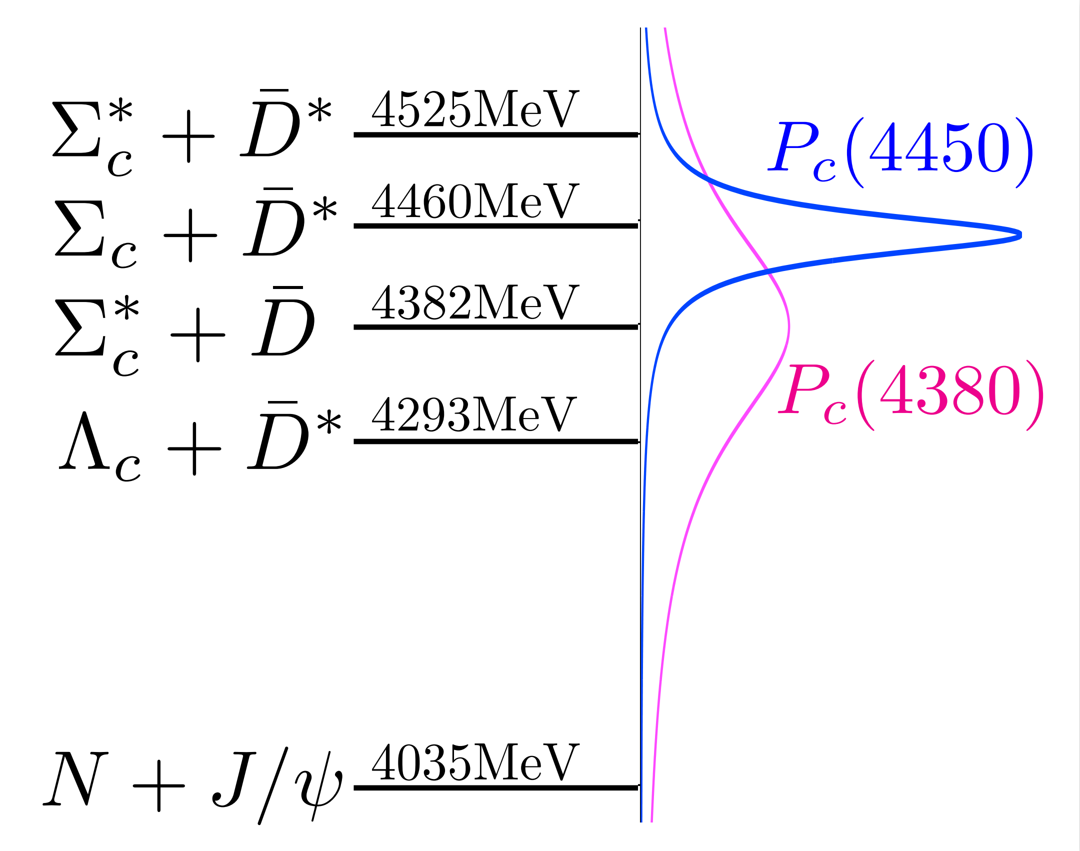
Extension to coupled-channel systems is straightforward

5 channels to consider
for S-wave $J^P=3/2^-$

Coupled-channel potentials

↓

Search for resonances



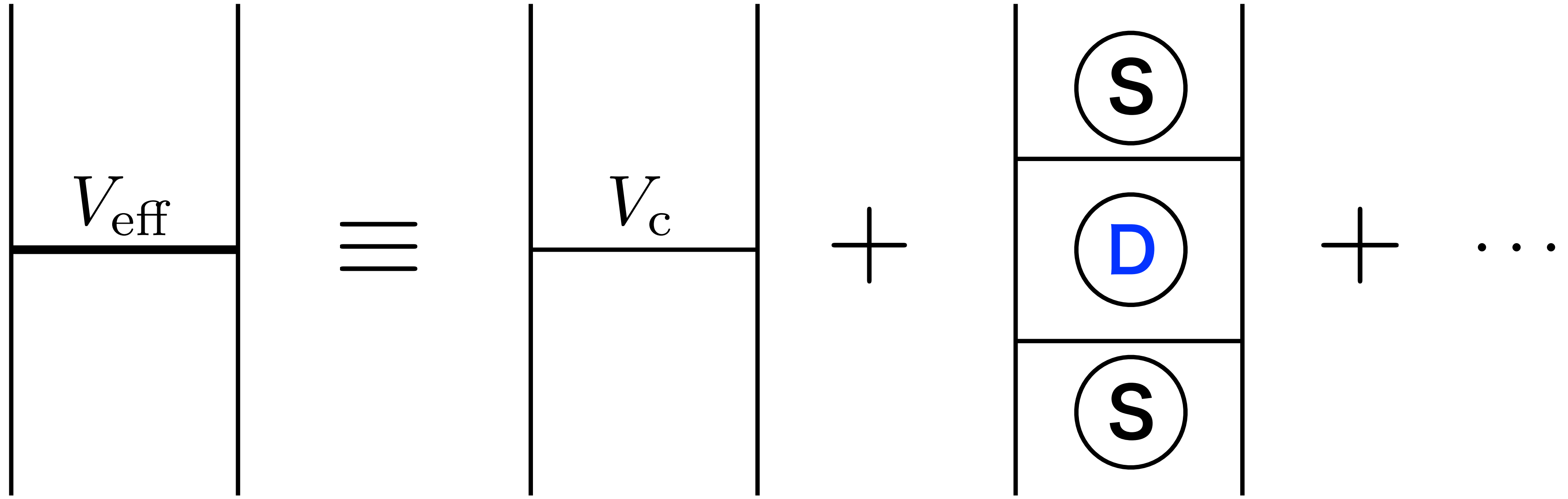
… Saved for the future
Let us discuss the charmonium-nucleon single-channel interactions

(η_c-N and J/ψ-N)

Effective Central Potentials

The η_c-N and J/ψ-N couples via the S-D mixing

⇨ We calculate the S-wave **effective central potential**

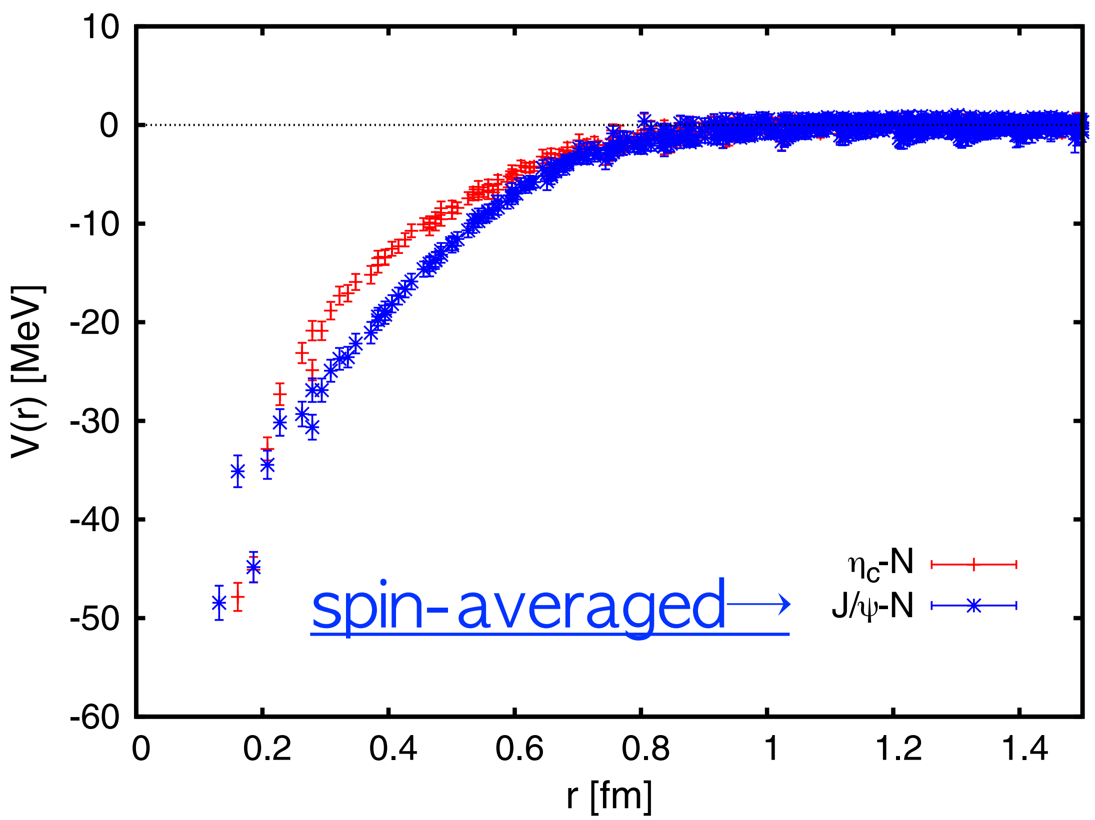


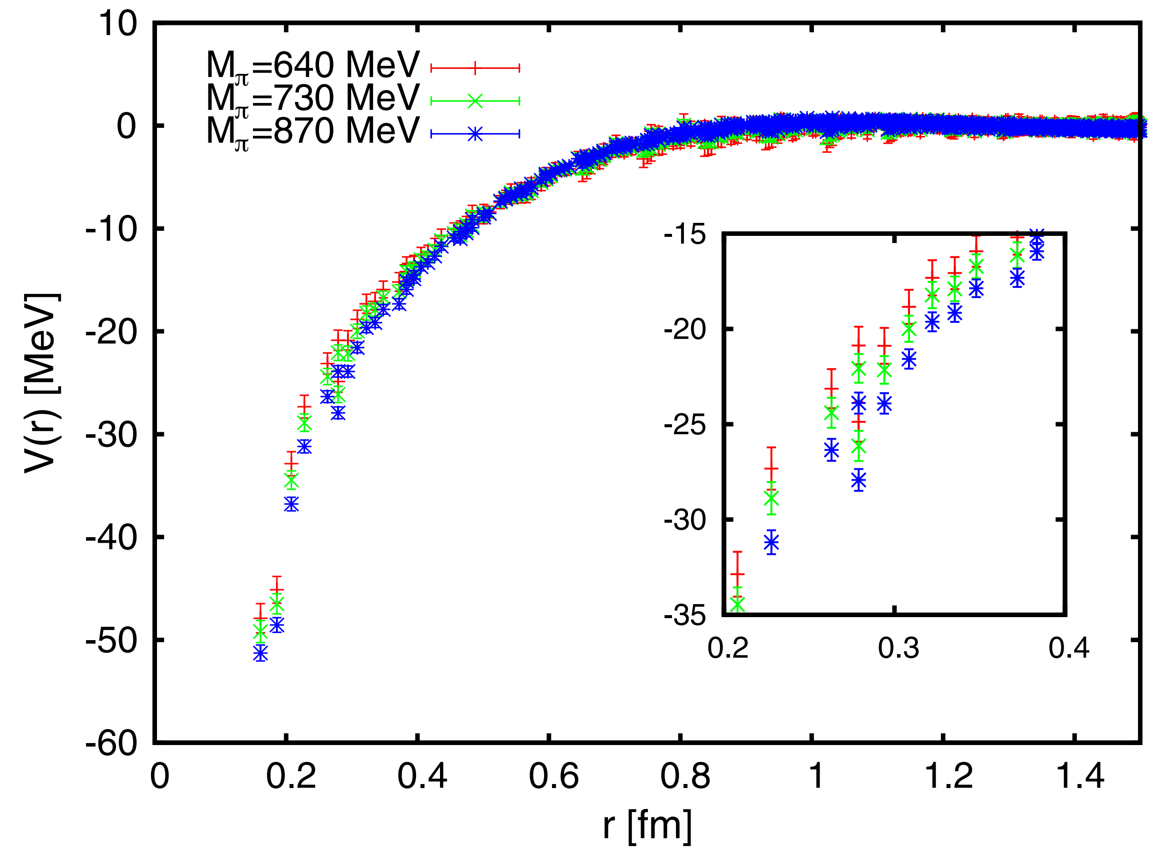
e.g.

$$\left(\frac{\nabla^2}{2\mu_2}+E\right)\left[\hat{P}(l=0)\psi_{J/\psi}\right]=V_{eff}^{J/\psi N}\left[\hat{P}(l=0)\psi_{J/\psi}\right]$$

Previous Lattice Result

[T.Kawanai and S.Sasaki, PRD**82** '10]





1. Both attractive; J/Ψ-N is slightly stronger than η_c-N
2. Not strong enough to have bound states
3. Moderate quark mass dependence

To be improved:
- Dynamical fermions
- Use of the time-dependent method

Numerical Setup

- 2+1 flavor full QCD configuration by CP-PACS+JLQCD ($16^3\times32$)

  -Actions:

  RG improved gauge action (β=1.83)

  Non-perturbatively O(a) improved clover quark action (c_{sw}=1.7610)

  NOT using the Relativistic Heavy Quark (RHQ) action for charm (statistical error may possibly exist)

  -Lattice size:

  a=0.1209 fm, a^{-1}=1.632 GeV ⇒ La=1.93 fm

  -Hopping parameters:

  κ_{ud}=0.13760 ⇒ m_π=874 MeV, m_N=1816 MeV

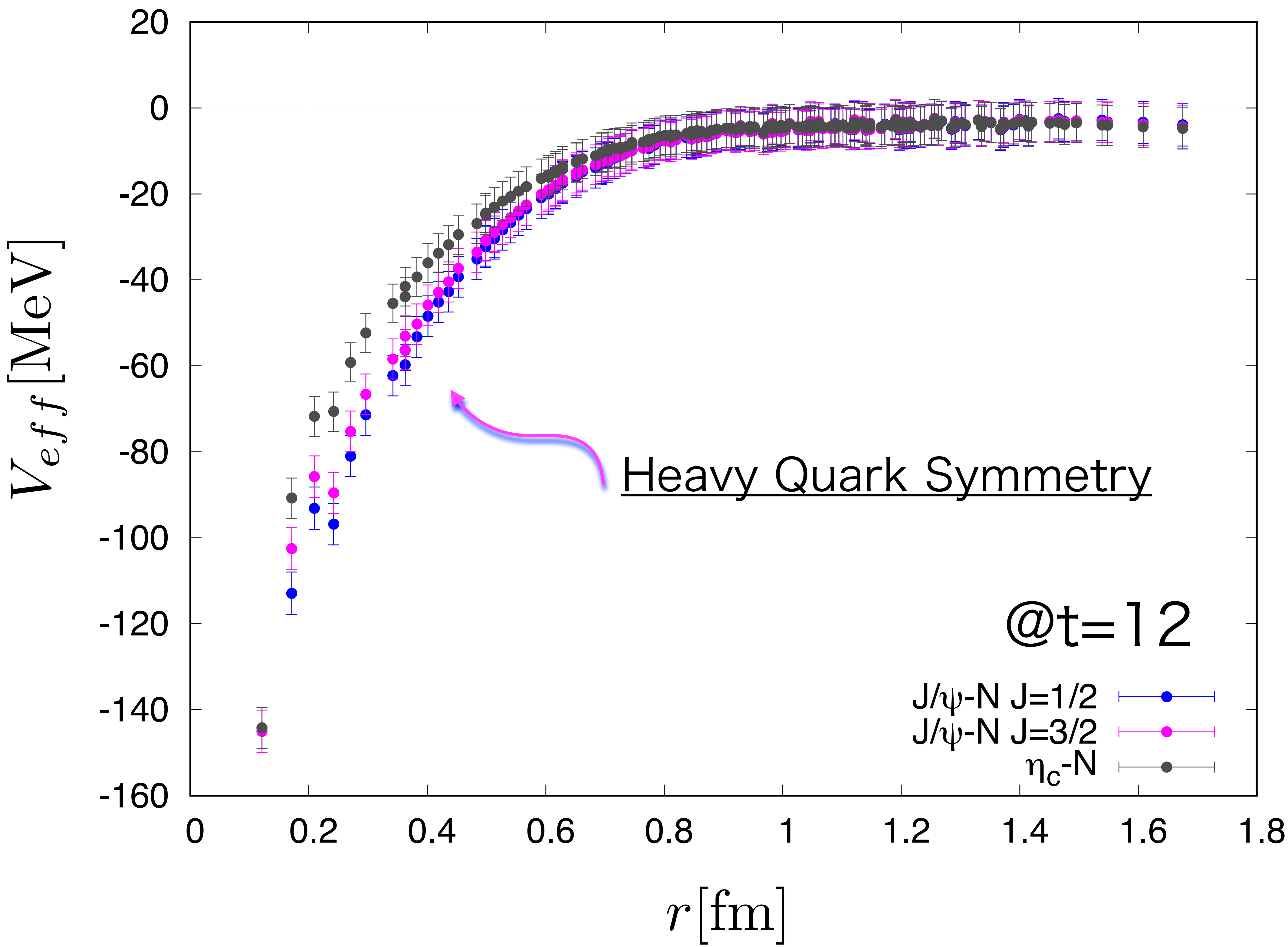
  κ_c =0.11660 ⇒ $m_{\eta c}$=2995 MeV, $m_{J/\psi}$=3088 MeV

  (c.f. $m_{\eta c}^{(phys)}$=2983 MeV, $m_{J/\psi}^{(phys)}$=3096 MeV)

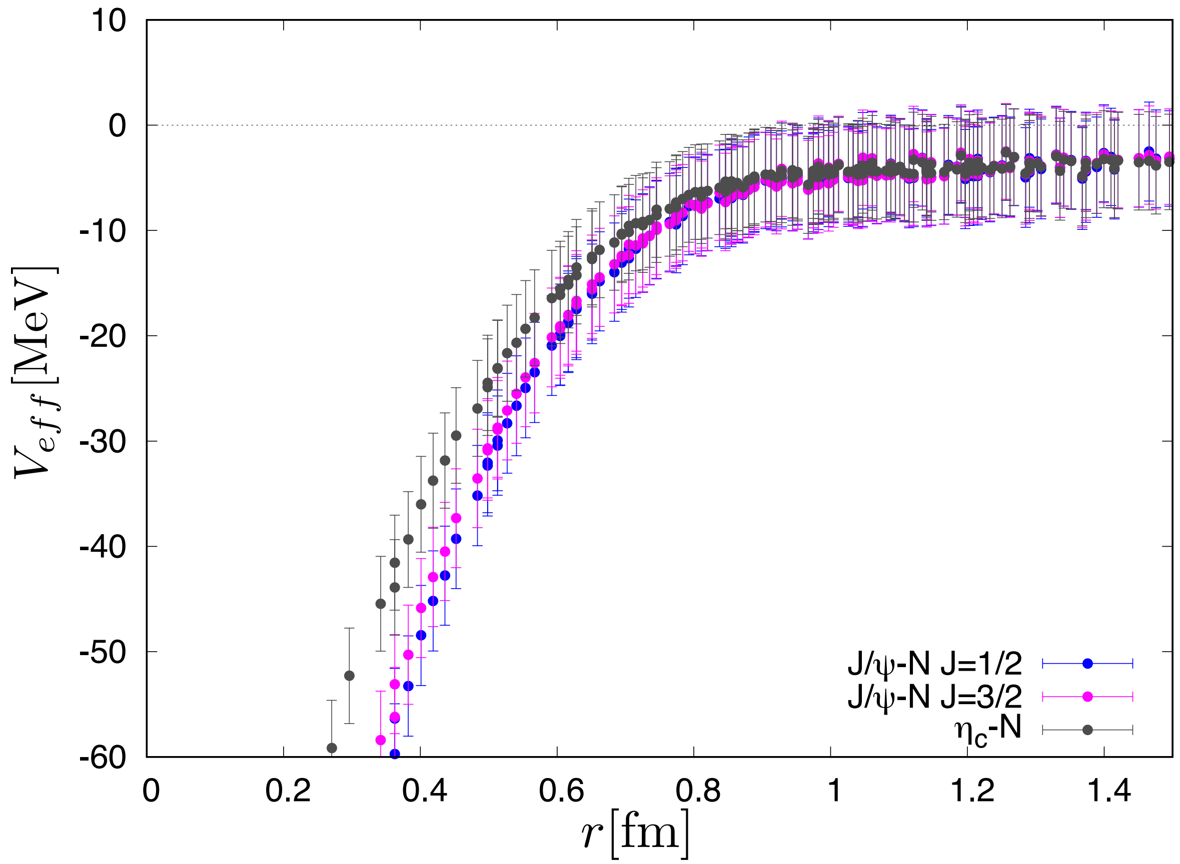
  -Statistics:

  700 configurations × 16 source points

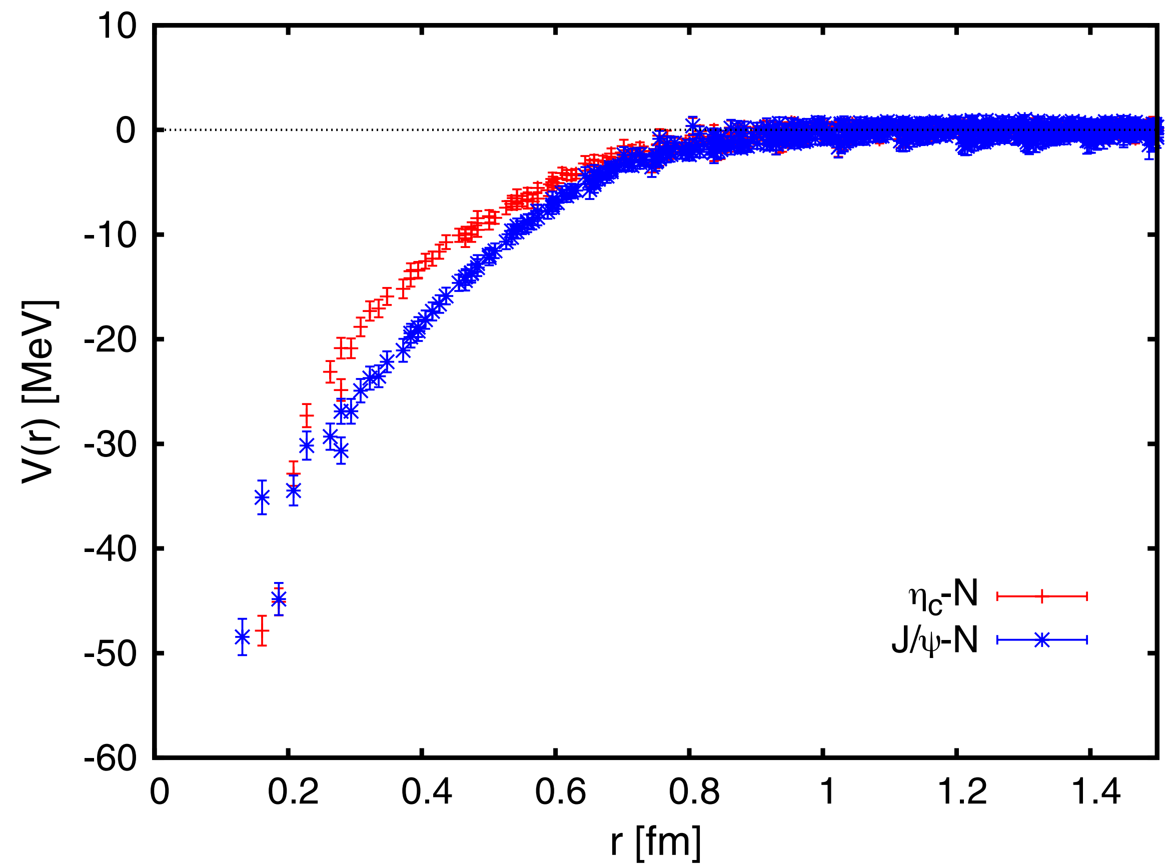
Result: The Potentials



Ours

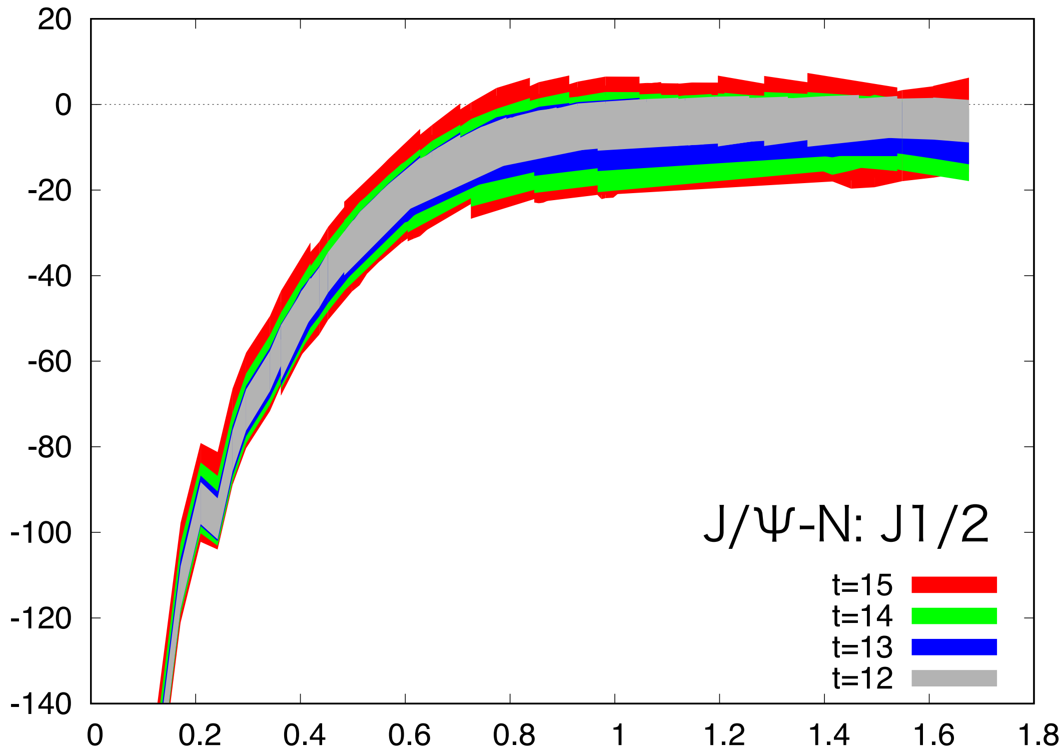


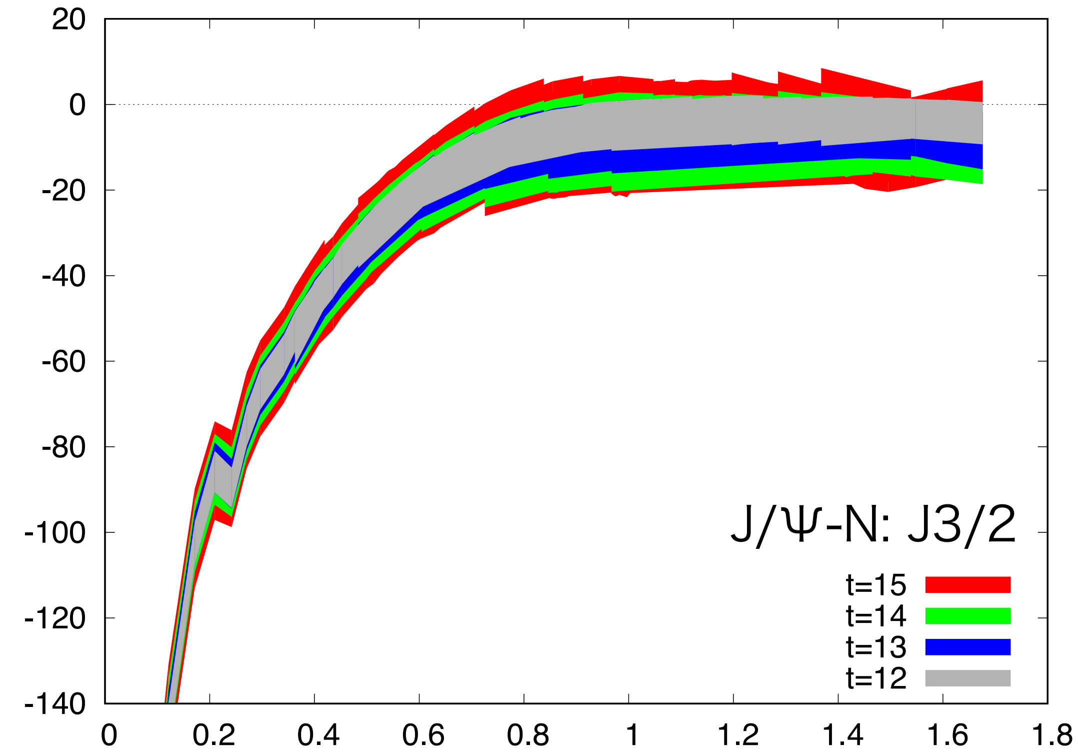
Kawanai-Sasaki

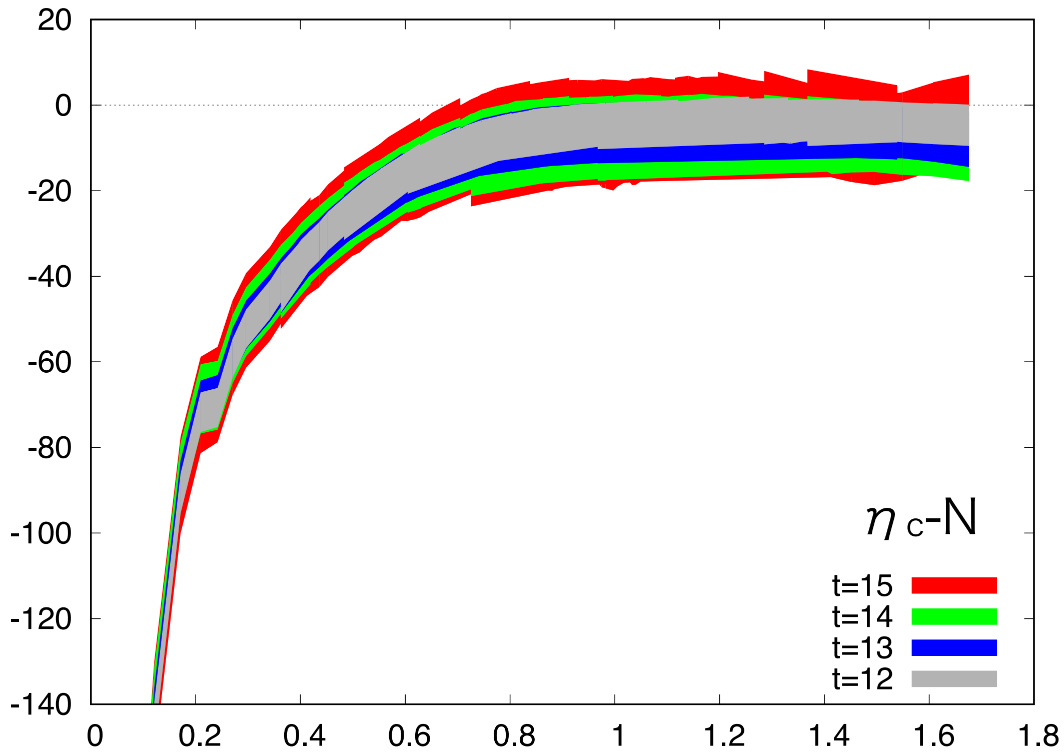


Qualitatively same behavior as the previous results

Elastic-State Saturation







$$\left[-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu}\right]R(t,\vec{r}) = \underline{V(r)}R(t,\vec{r})$$

- The potentials are t-stable

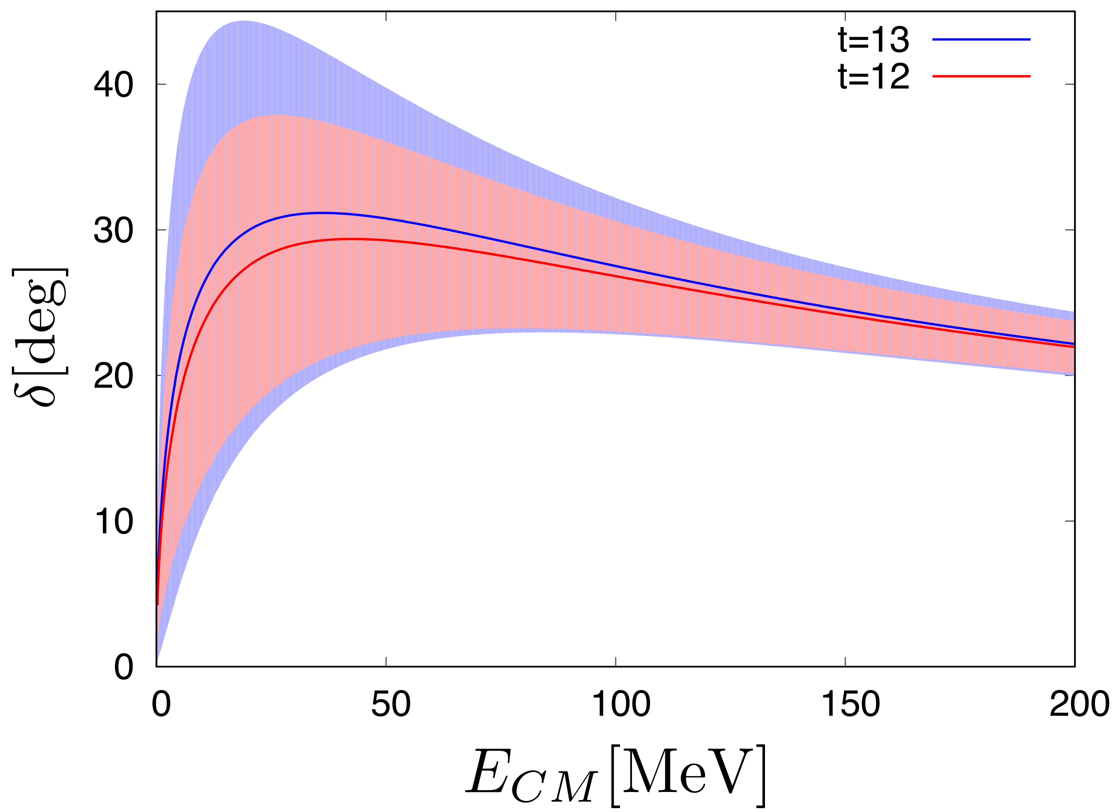
  … saturation achieved @t=12

Phase Shift

Schrodinger eq. (S-wave)

$$\left(\frac{1}{2\mu}\frac{d^2}{dr^2}+E\right)\phi(r;E)=V_{eff}(r)\phi(r;E)$$

$$\phi(r;E)\longrightarrow\frac{i}{2}\left(\hat{h}_0^{(-)}(kr)-s_0(k)\hat{h}^{(+)}(kr)\right)$$



@t=12

J/ψ-N (J=1/2)

$$a=0.68\pm0.44\,\mathrm{fm}$$

$$r=1.04\pm0.03\,\mathrm{fm}$$

J/ψ-N (J=3/2)

$$a=0.63\pm0.42\,\mathrm{fm}$$

$$r=1.11\pm0.03\,\mathrm{fm}$$

η_c-N

$$a=0.44\pm0.34\,\mathrm{fm}$$

$$r=1.33\pm0.06\,\mathrm{fm}$$

Summary

- We have calculated the effective charmonium-nucleon interactions by the time-dependent HAL QCD method
- The difference between the J/Ψ-N(J=1/2) and J/Ψ-N(J=3/2) potentials is very small, which is compatible with the heavy quark symmetry
- The results are consistent with the previous study within statistical errors.

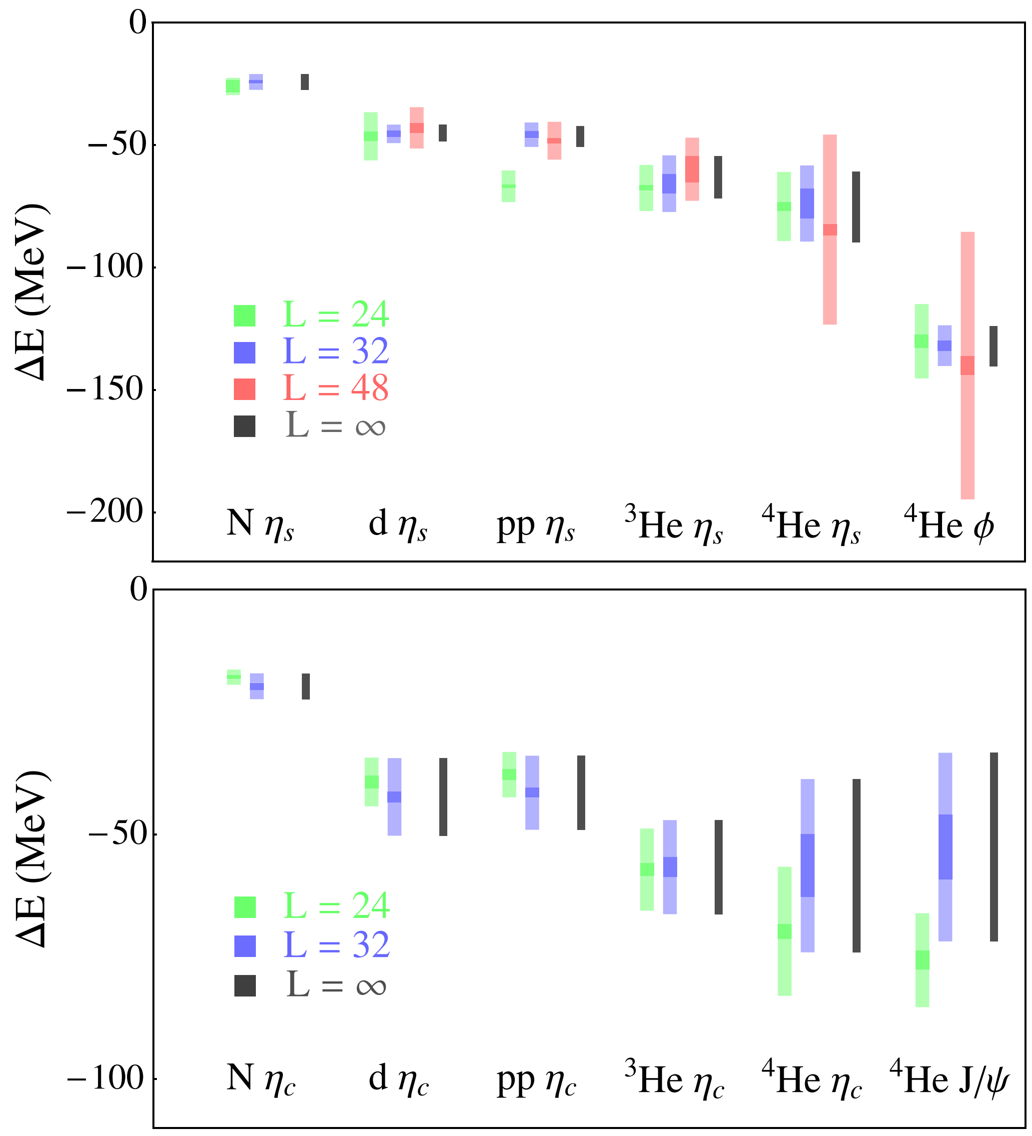
Future plans

on-going!

- Improve statistics
- RHQ action for charm / m_π dependence
- Tensor forces of the J/Ψ-N
- Coupling to the other channels

.backup/

Another Lattice Result



[S. Beane *et al.*, PRD**91** 114503 '15]

Both ss^{bar} and cc^{bar} are deeply bound to N with BE~20MeV

There's a conflict between the HAL QCD method and the Luscher's method (NPL collaboration)

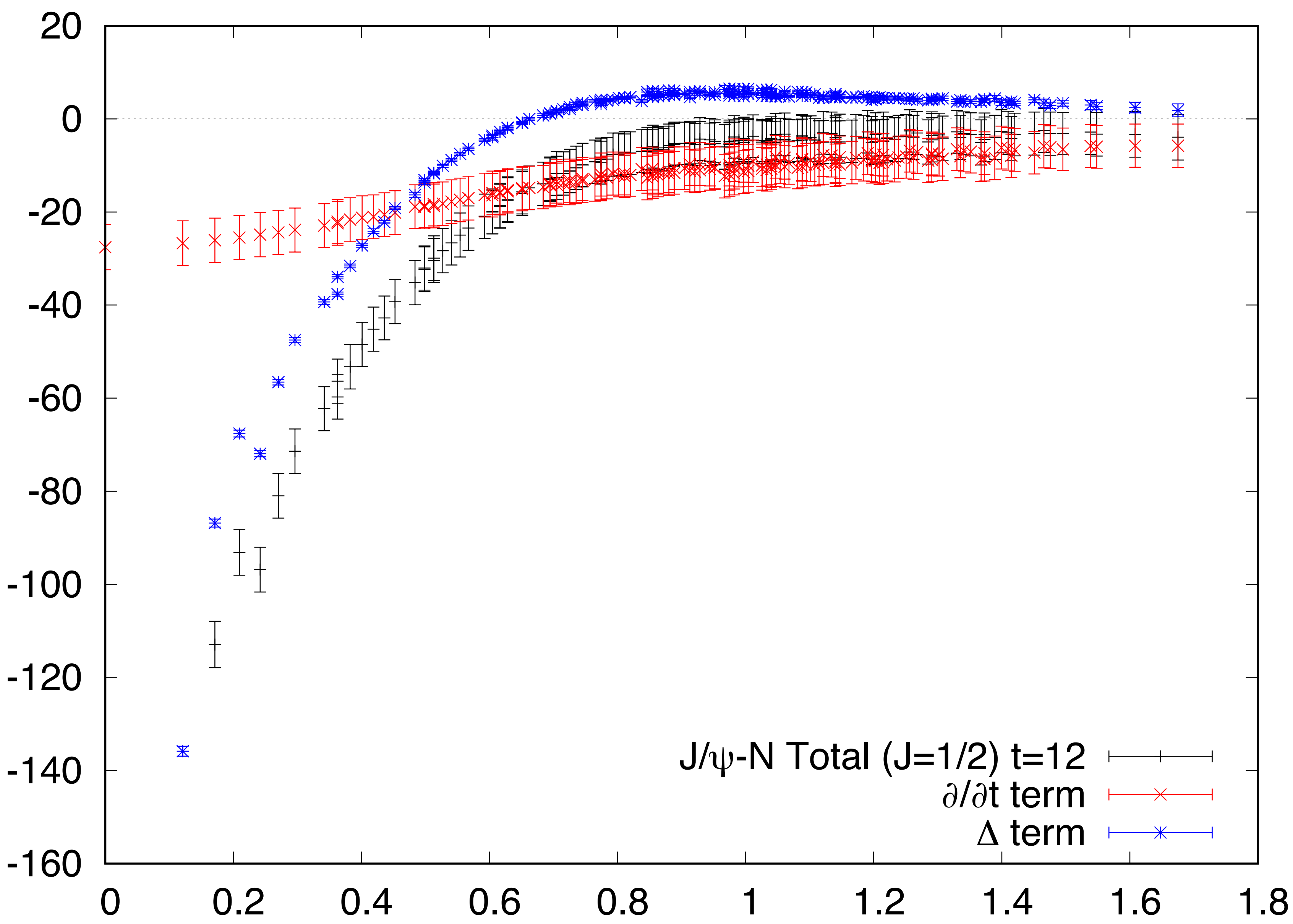
see [T. Iritani *et al.*, PRD**96**, 034521 '17]

Time-Dependent Method

$$\left[-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu}\right]R(t,\vec{r})=V(r)R(t,\vec{r}) \;\Rightarrow\; V(r)=\frac{1}{R(t,\vec{r})}\frac{\nabla^2 R(t,\vec{r})}{2\mu}-\frac{1}{R(t,\vec{r})}\frac{\partial R(t,\vec{r})}{\partial t}$$

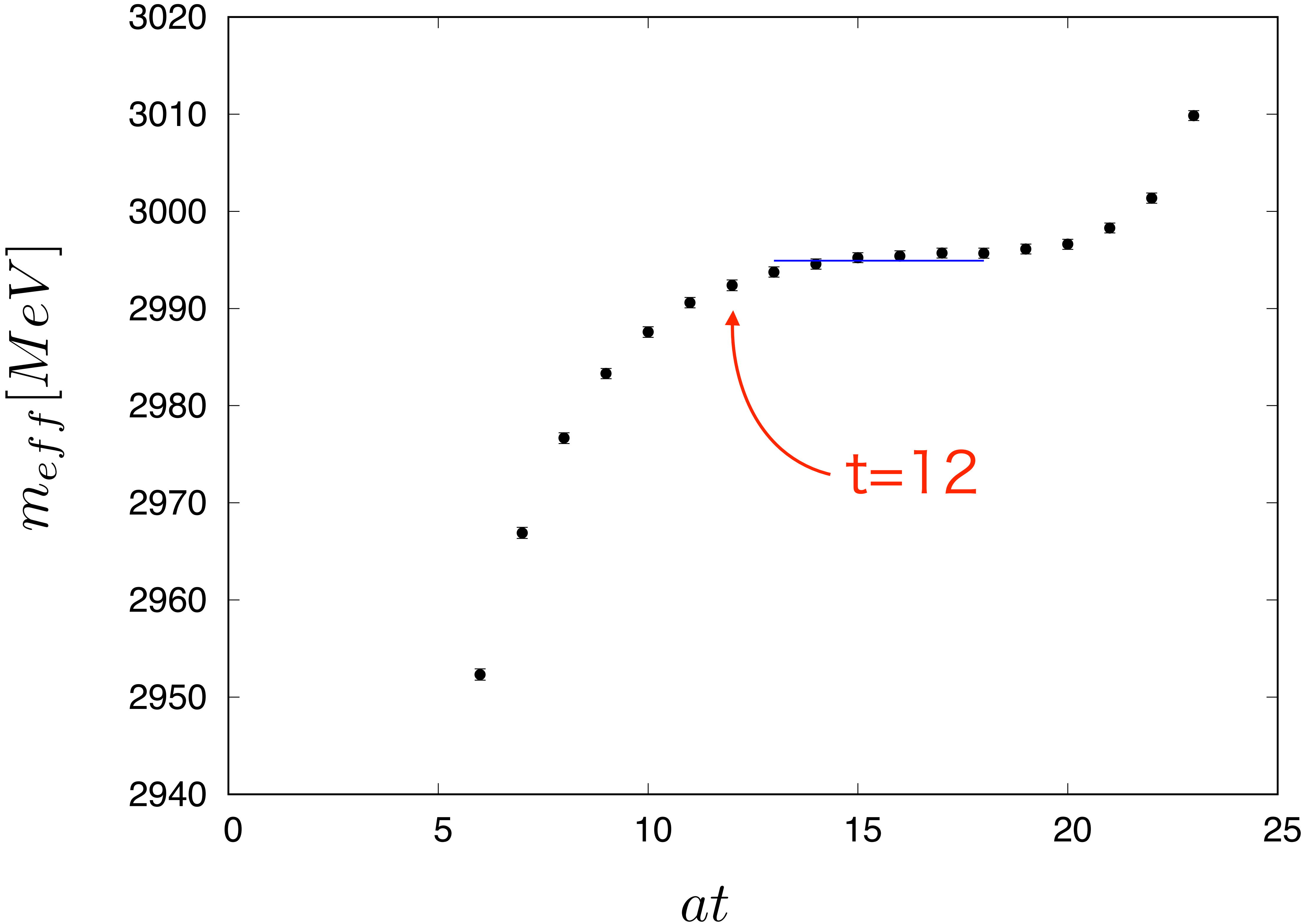
$$=\frac{k^2}{2\mu}\quad(\text{Const.})$$

when the ground-state saturation is achieved

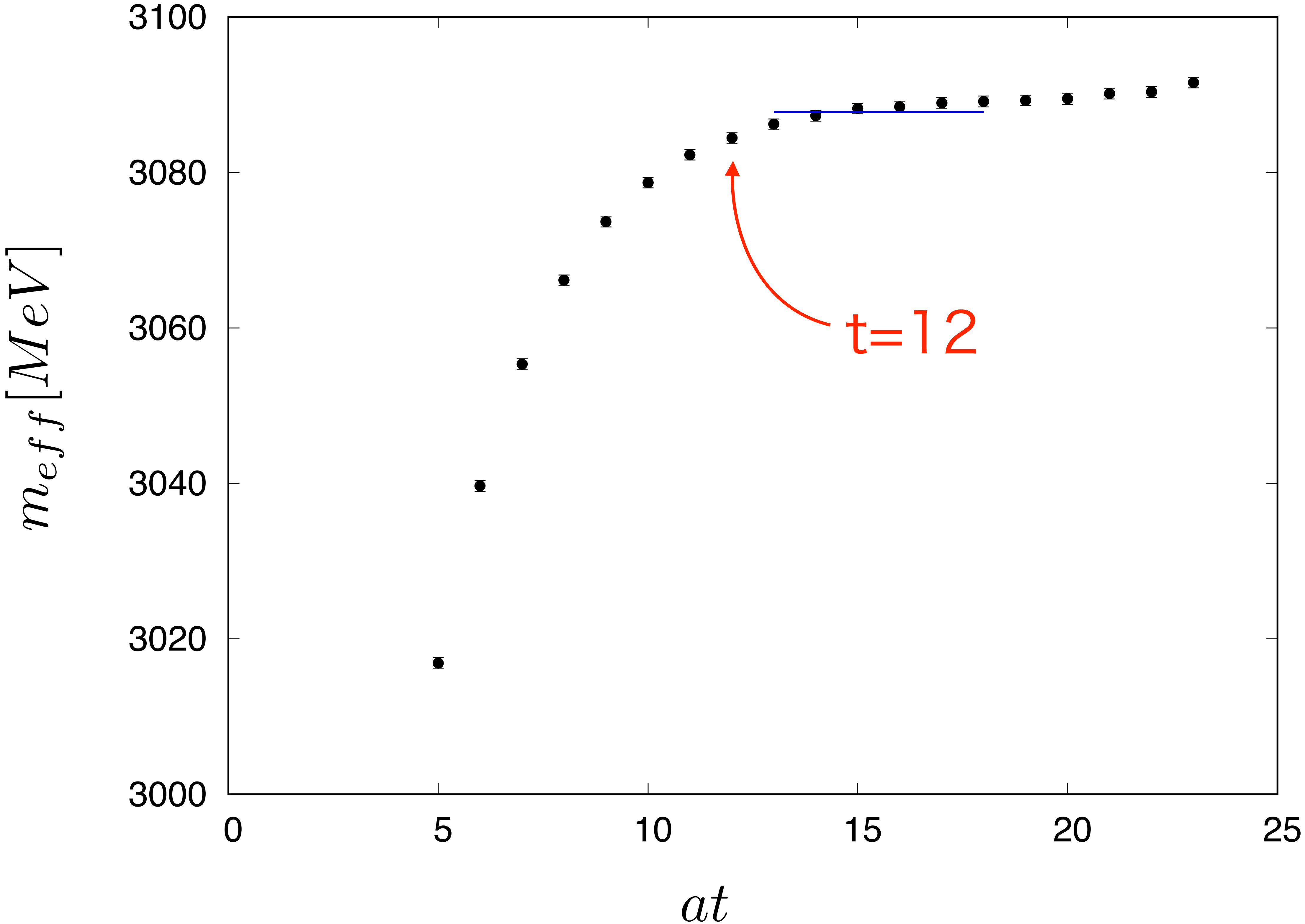


Ground-state saturation is not necessary in the time-dependent method.

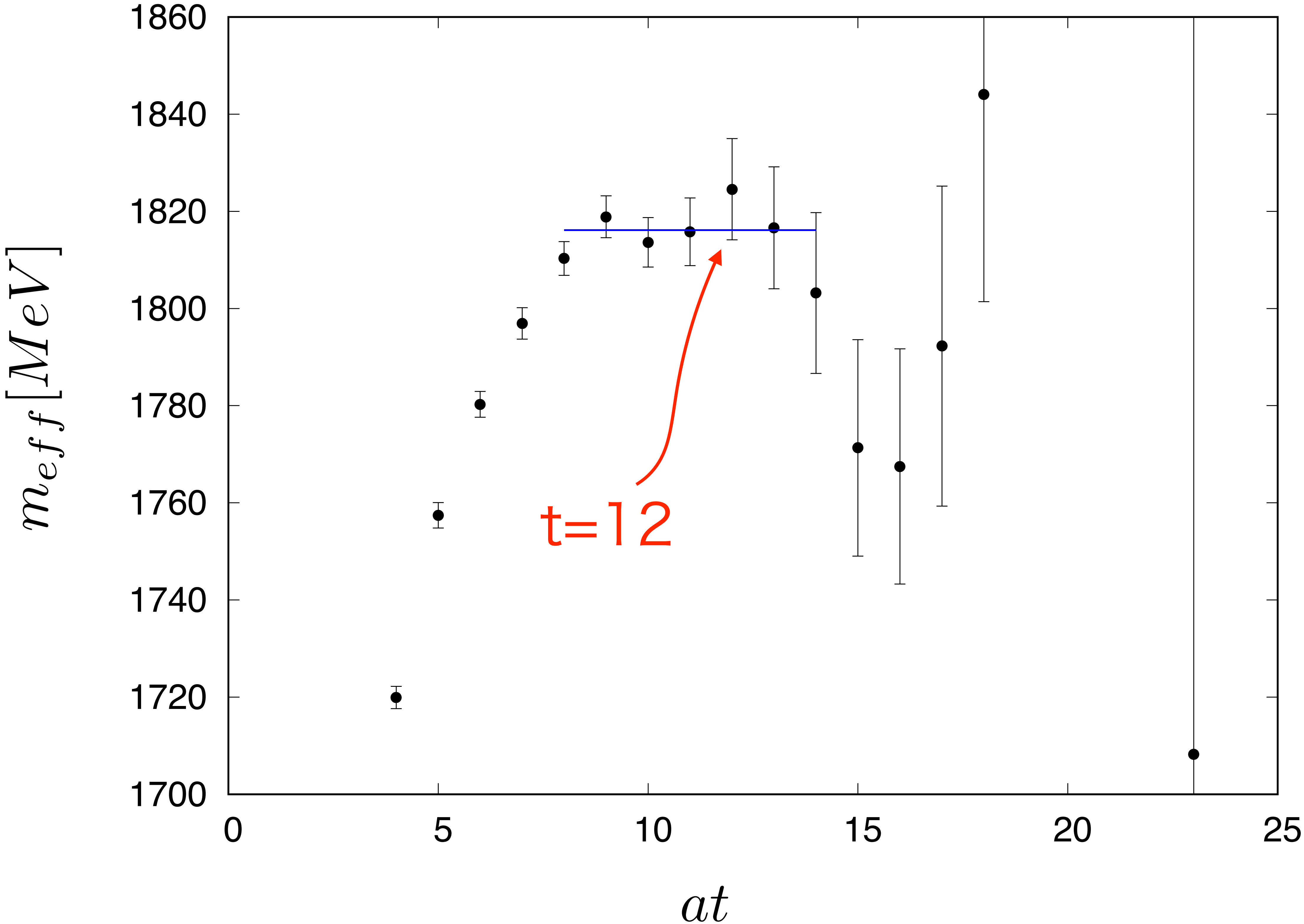
Ground-State Saturation: effective mass of η_c



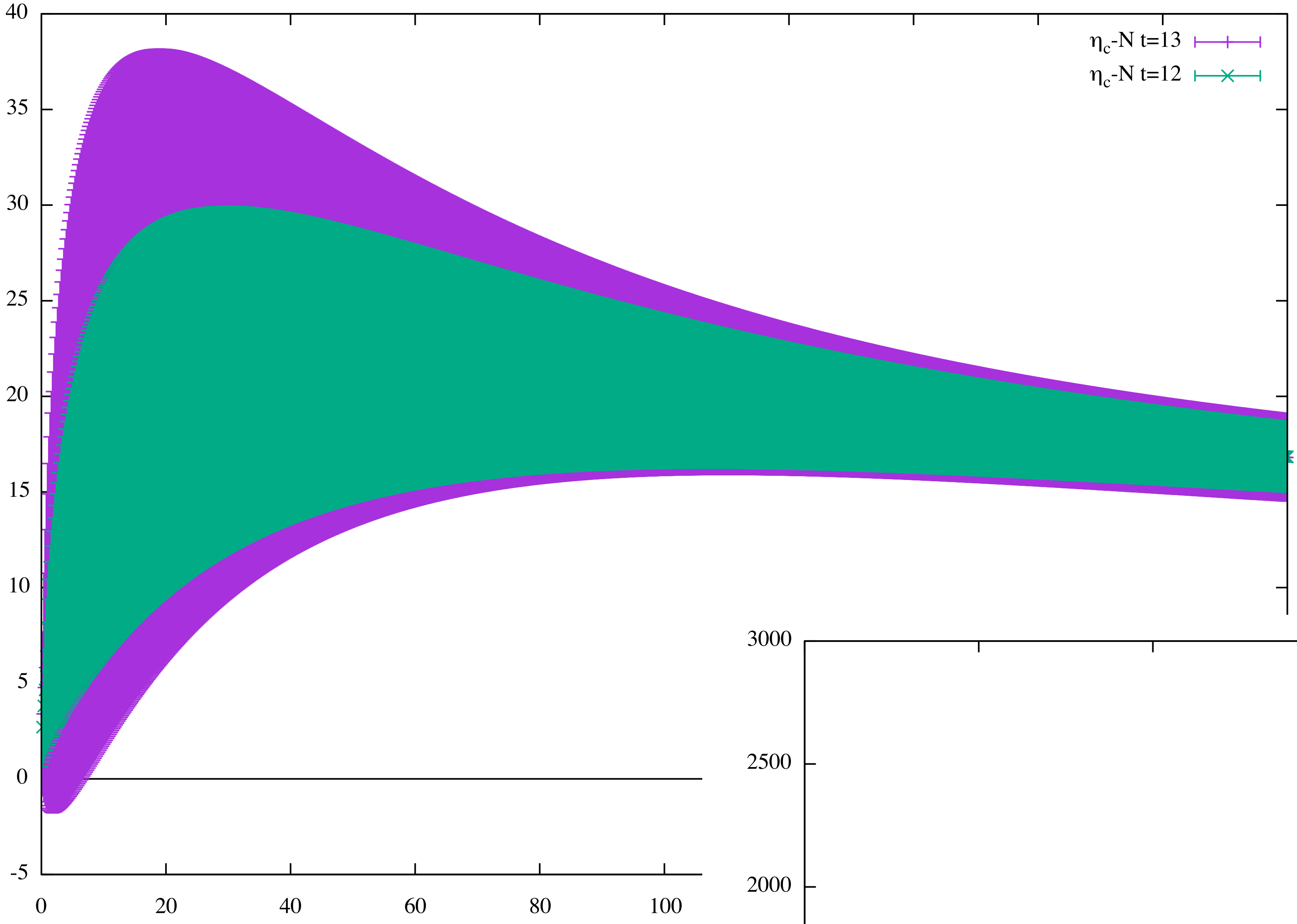
Ground-State Saturation: effective mass of J/ψ



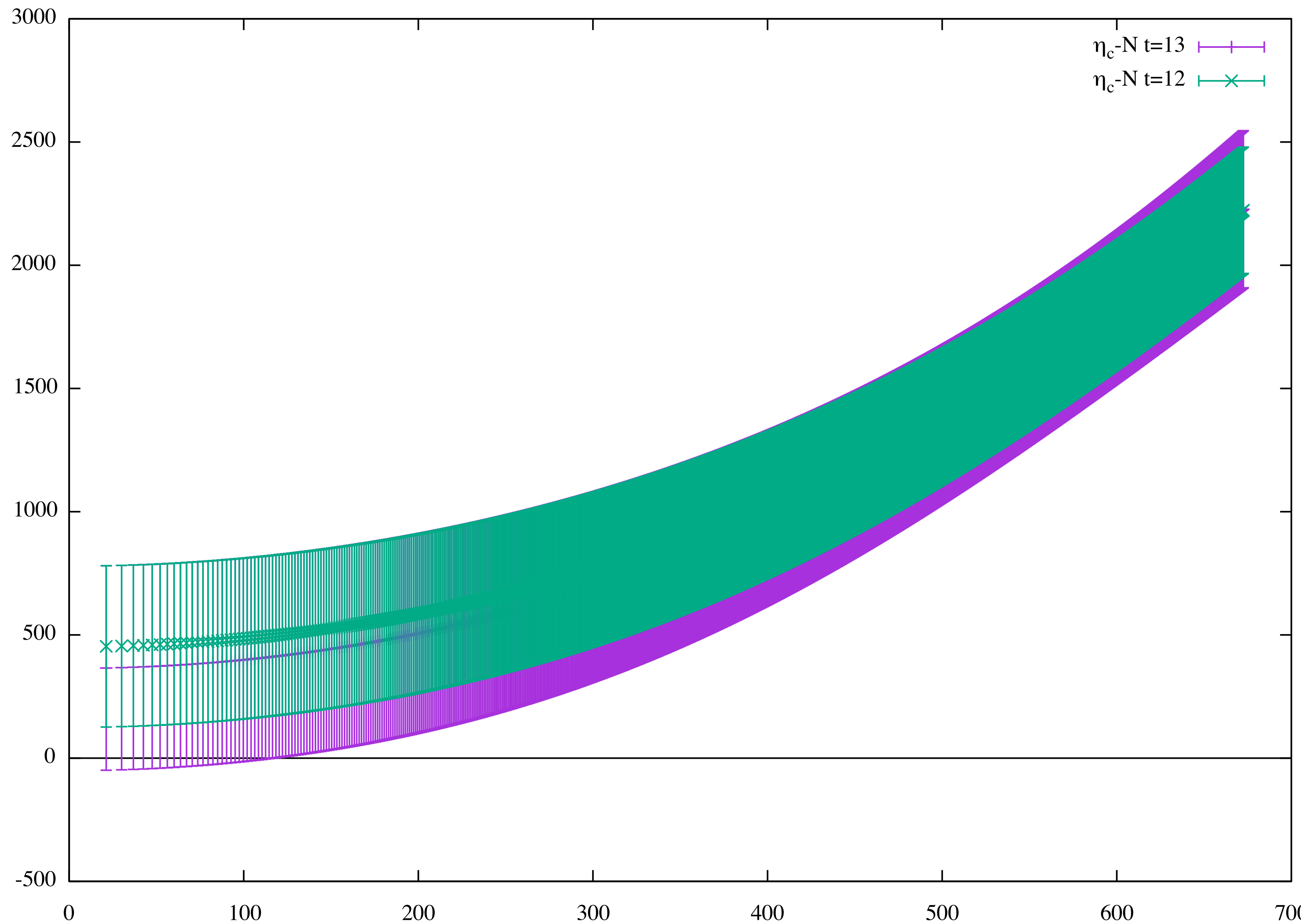
Ground-State Saturation: effective mass of N



$\eta_c - N$

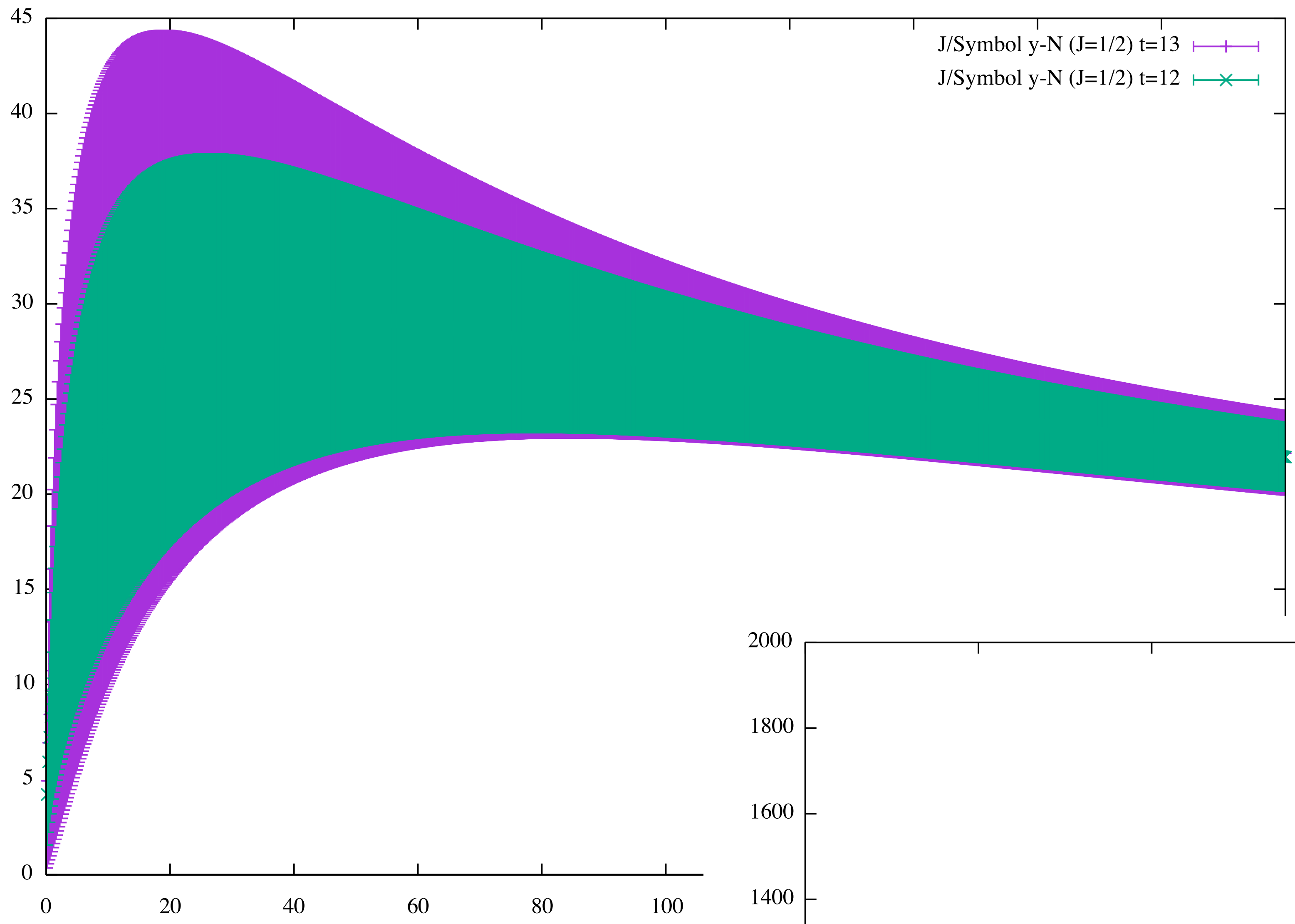


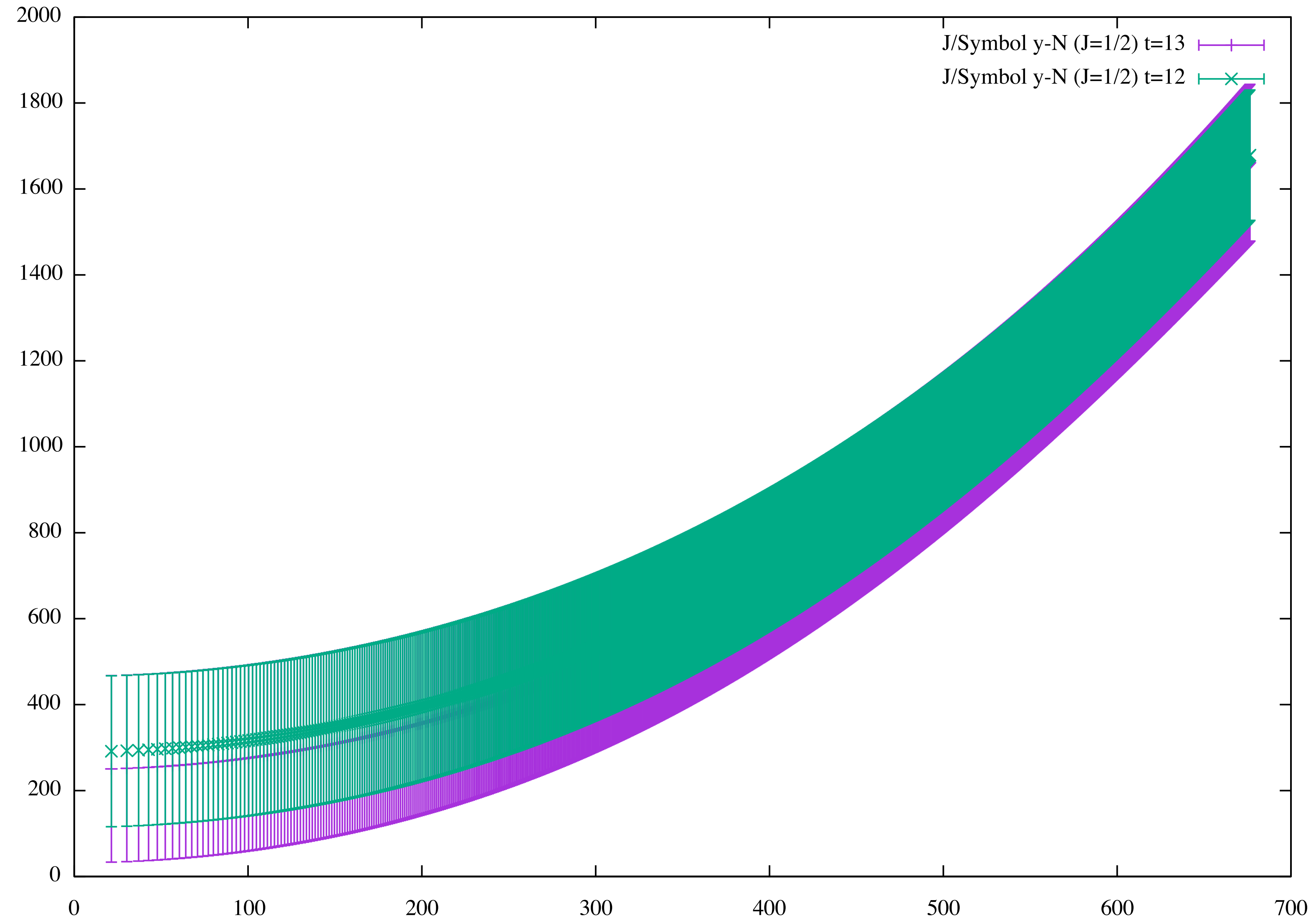
η_c-N t=13
η_c-N t=12
40
35
30
25
20
15
10
5
0
-5
0
20
40
60
80
100



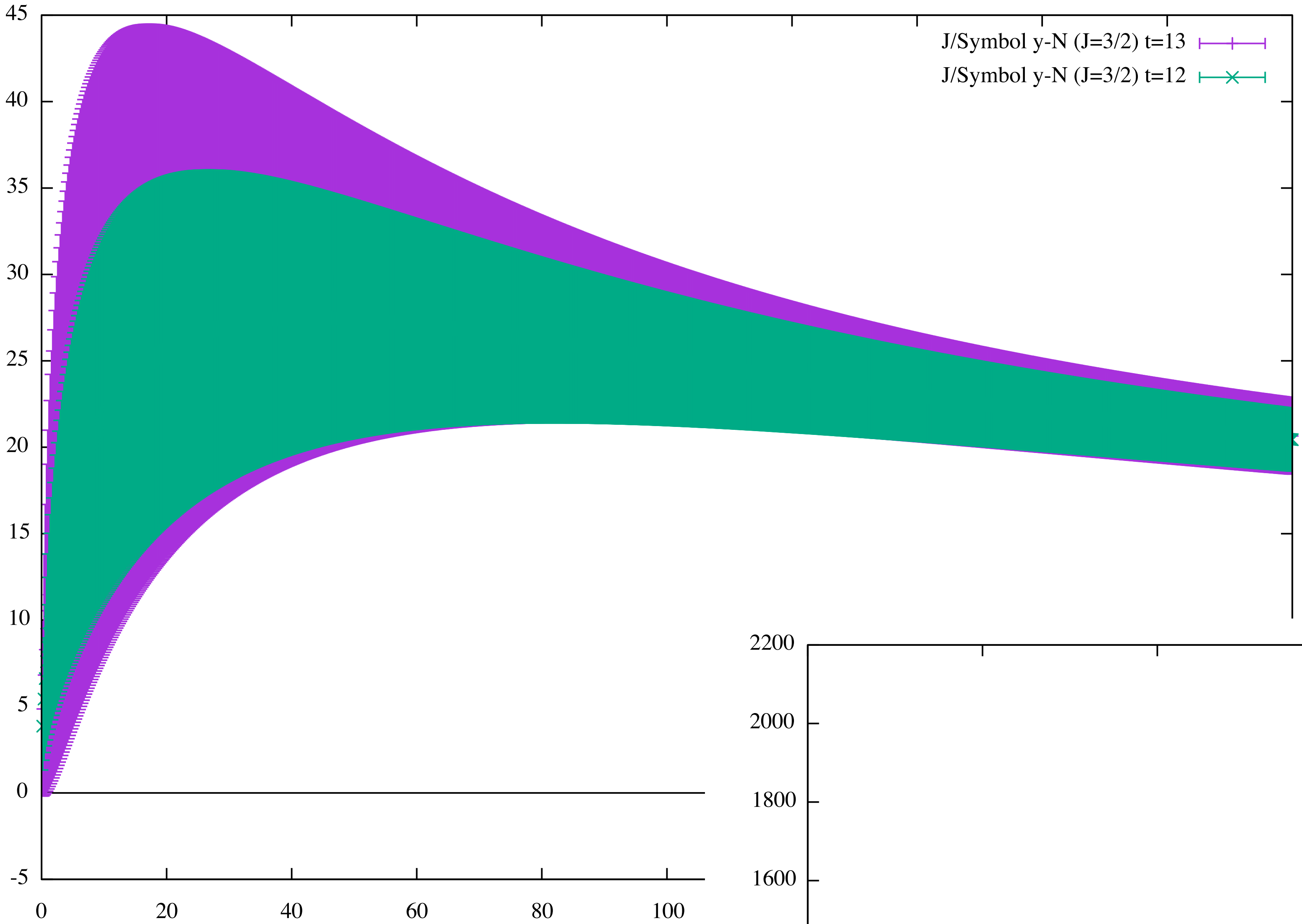
η_c-N t=13
η_c-N t=12
3000
2500
2000
1500
1000
500
0
-500
0
100
200
300
400
500
600
700

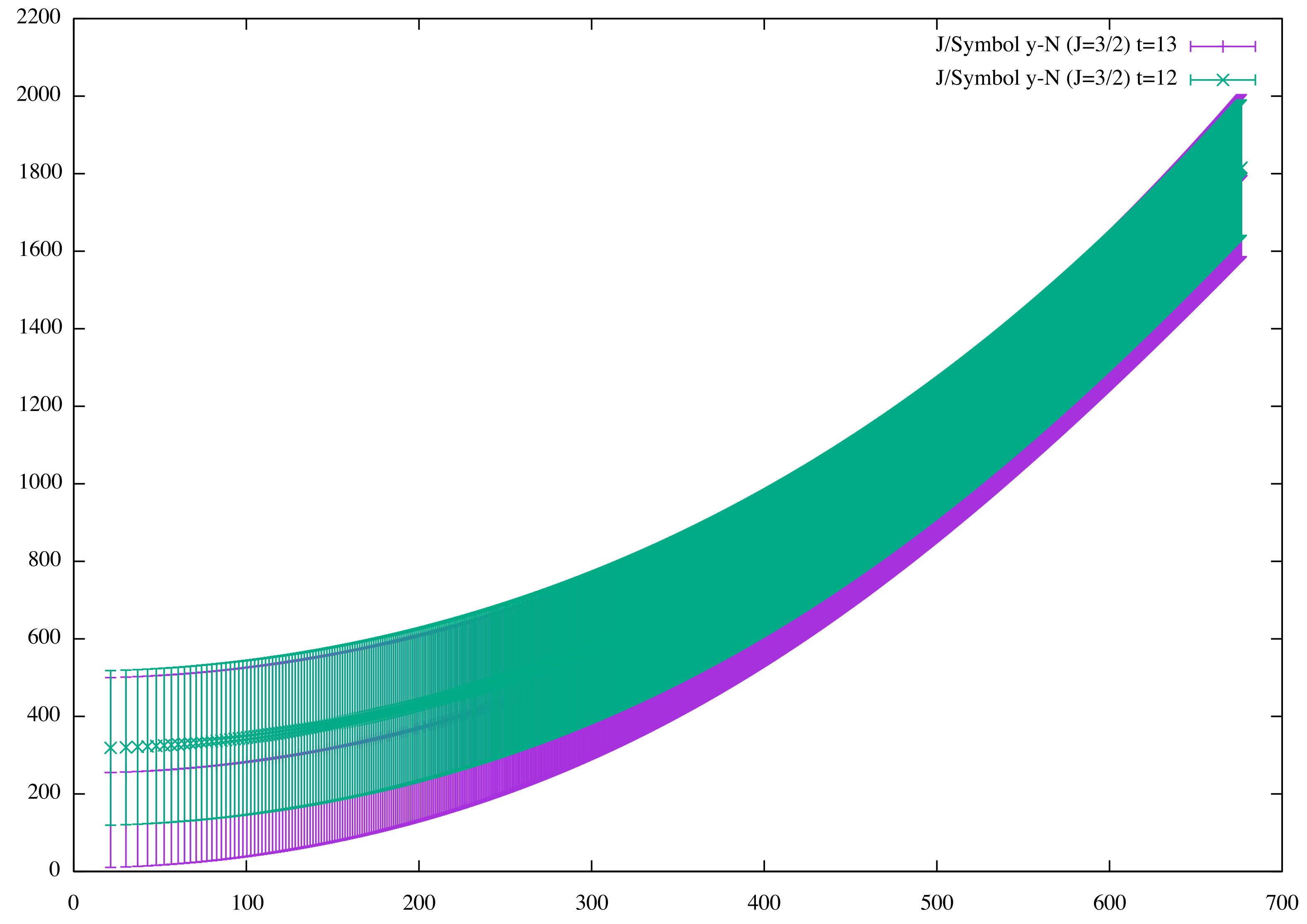
$$J/\psi - N(J = \frac{1}{2})$$



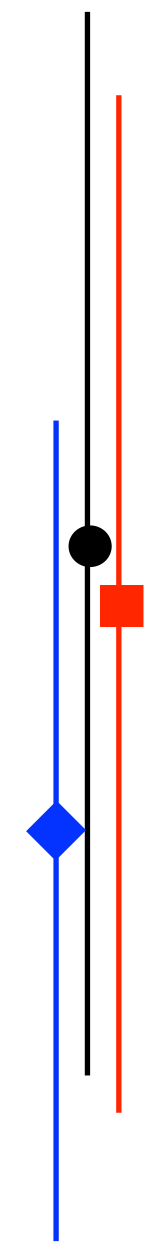


$$J/\psi - N(J = \frac{3}{2})$$



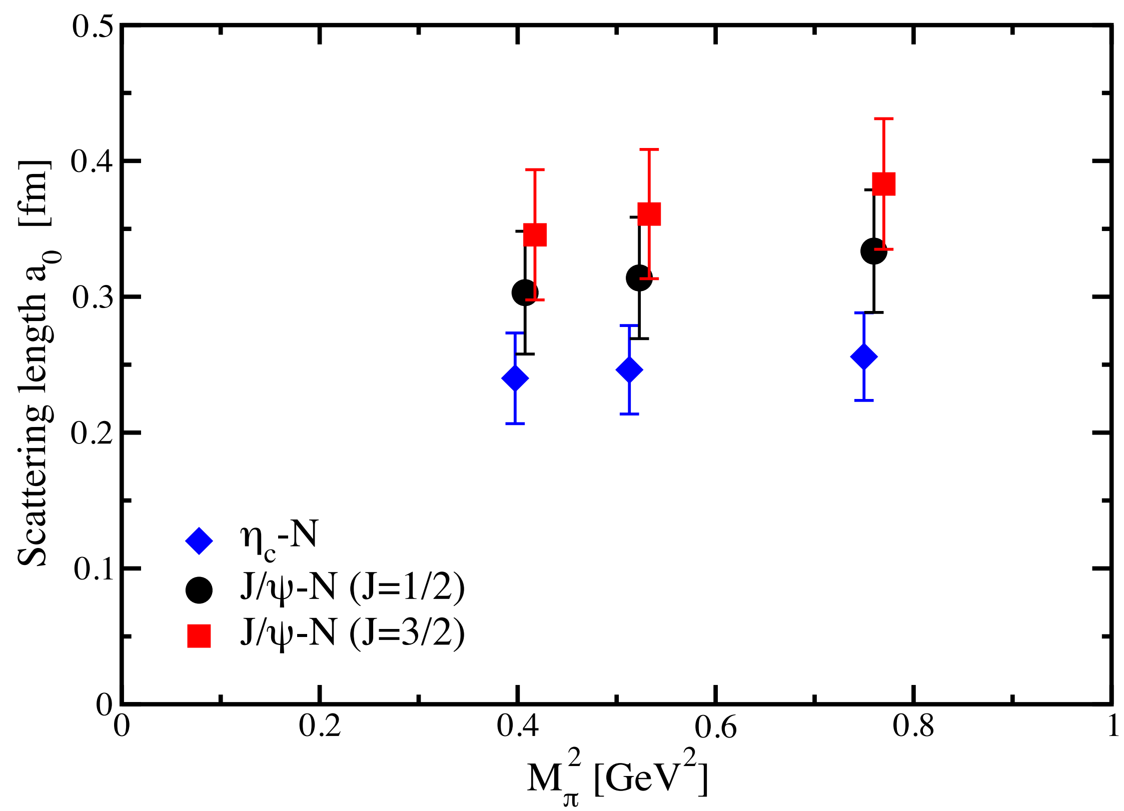


our result



Lüscher's formula

[T.Kawanai and S.Sasaki, PoS LATTICE2010 156]



Lüscher's formula

[T.Kawanai and S.Sasaki, PoS LATTICE2010 156]