Charmonium-nucleon interactions from the time-dependent HAL QCD method

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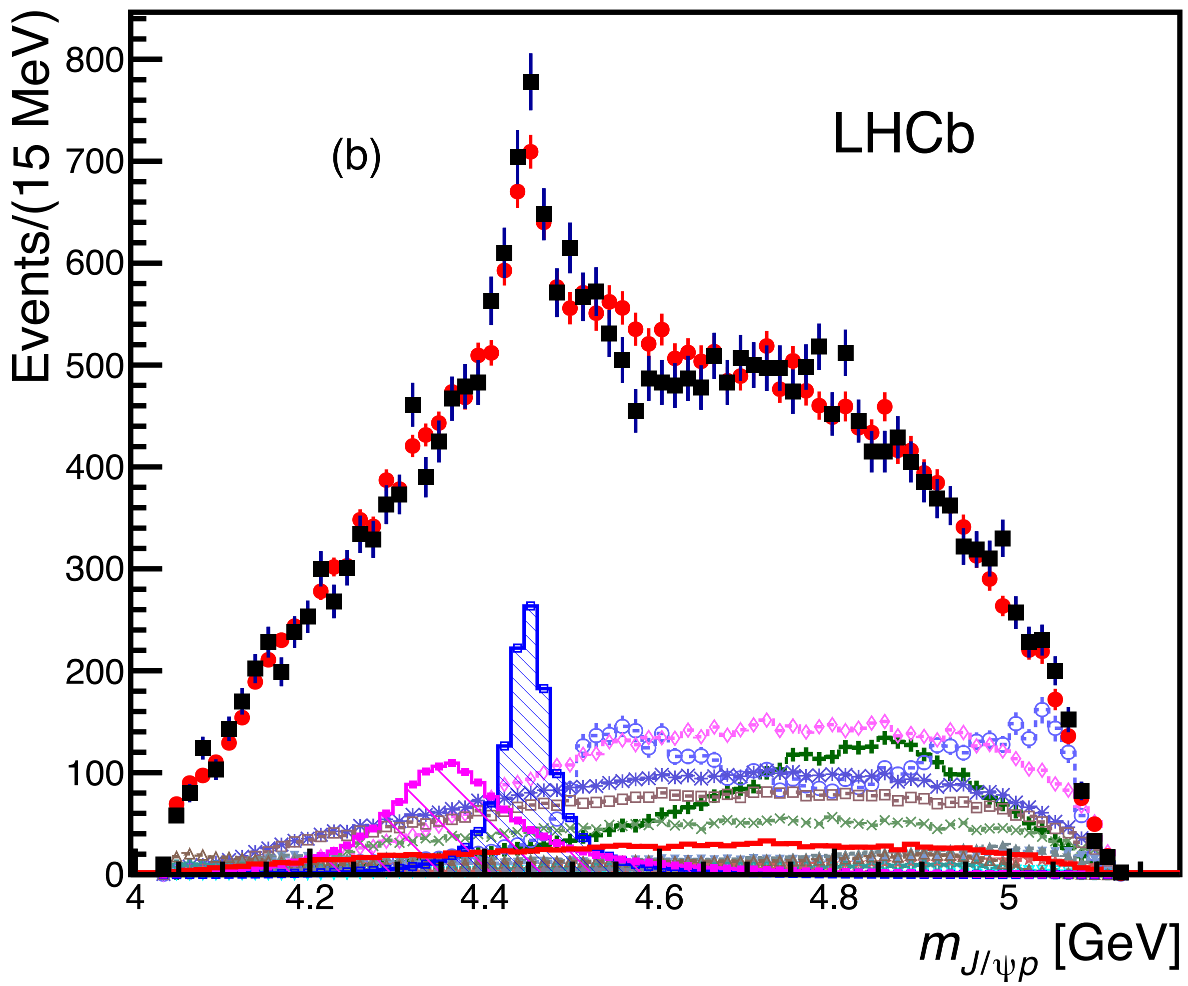
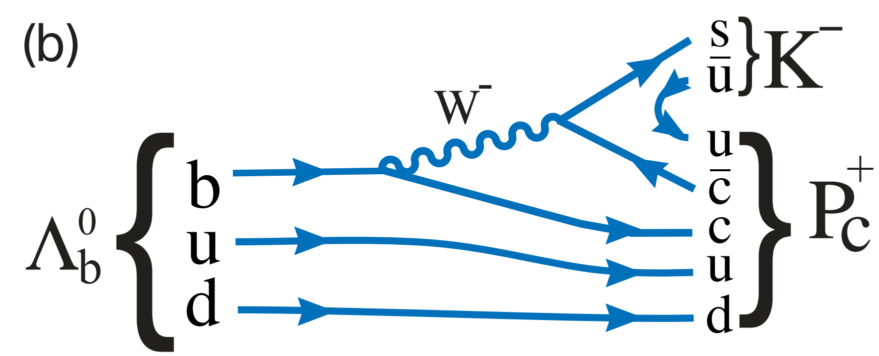
Hidden-Charm Pentaquarks



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	$5/2^+$, $5/2^-$, $3/2^-$

QCD-Based Potential

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: $\psi(\vec{r}) \xrightarrow[r\to\infty]{} \frac{\sin(kr - l\pi/2 + \delta(k))}{kr} e^{i\delta(k)}$

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

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

Time-dependent method avoids excited-state contamination

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

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

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

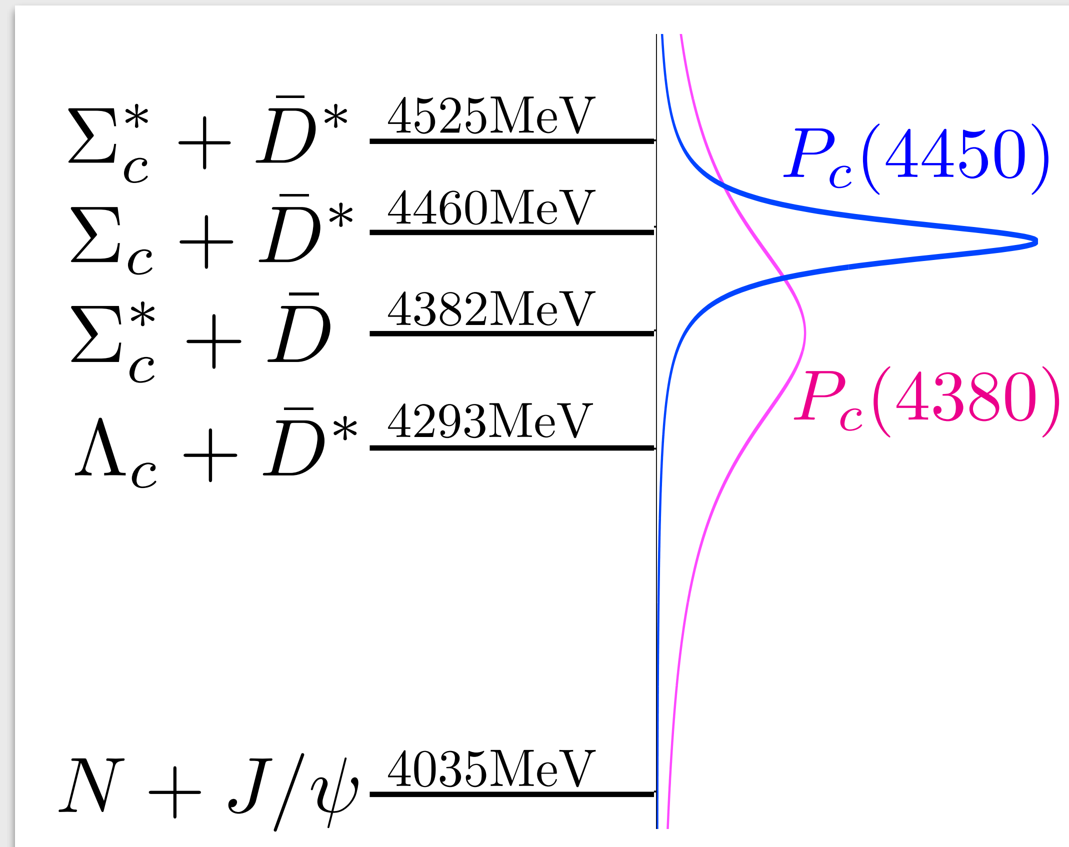
Coupled Channels

Extension to coupled-channel systems is straightforward

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

Coupled-channel potentials

Search for resonances

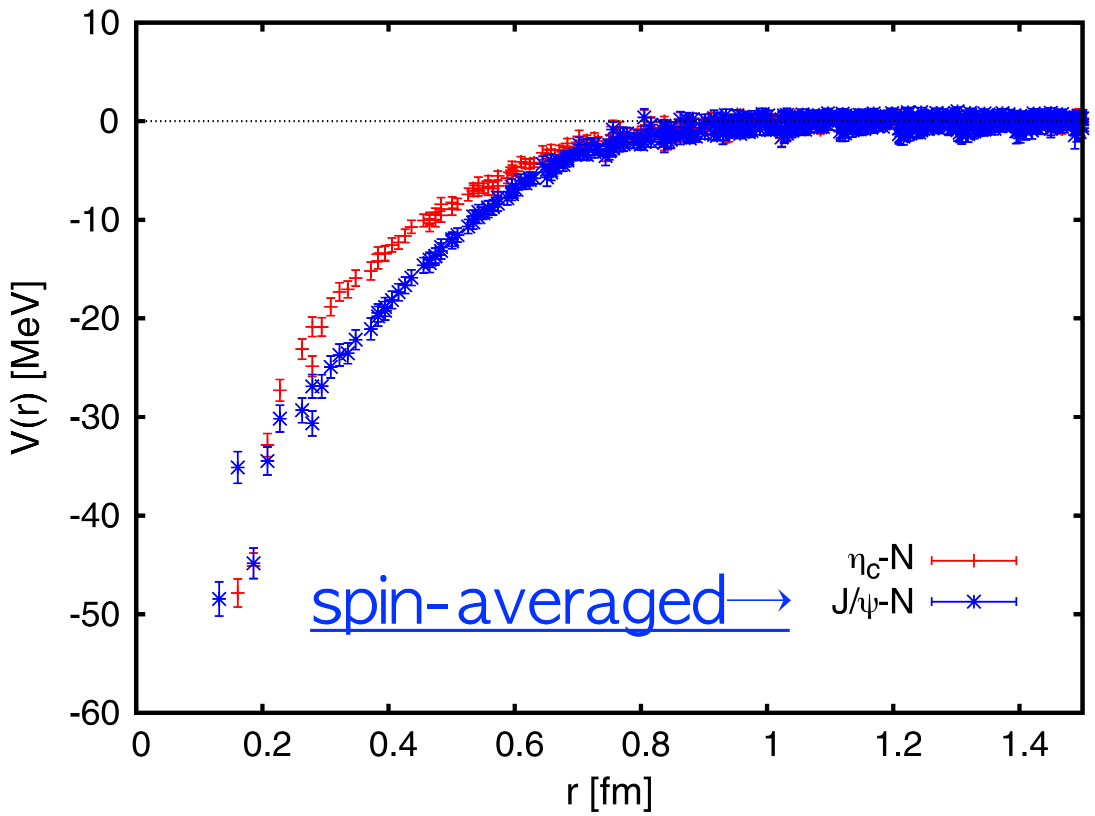


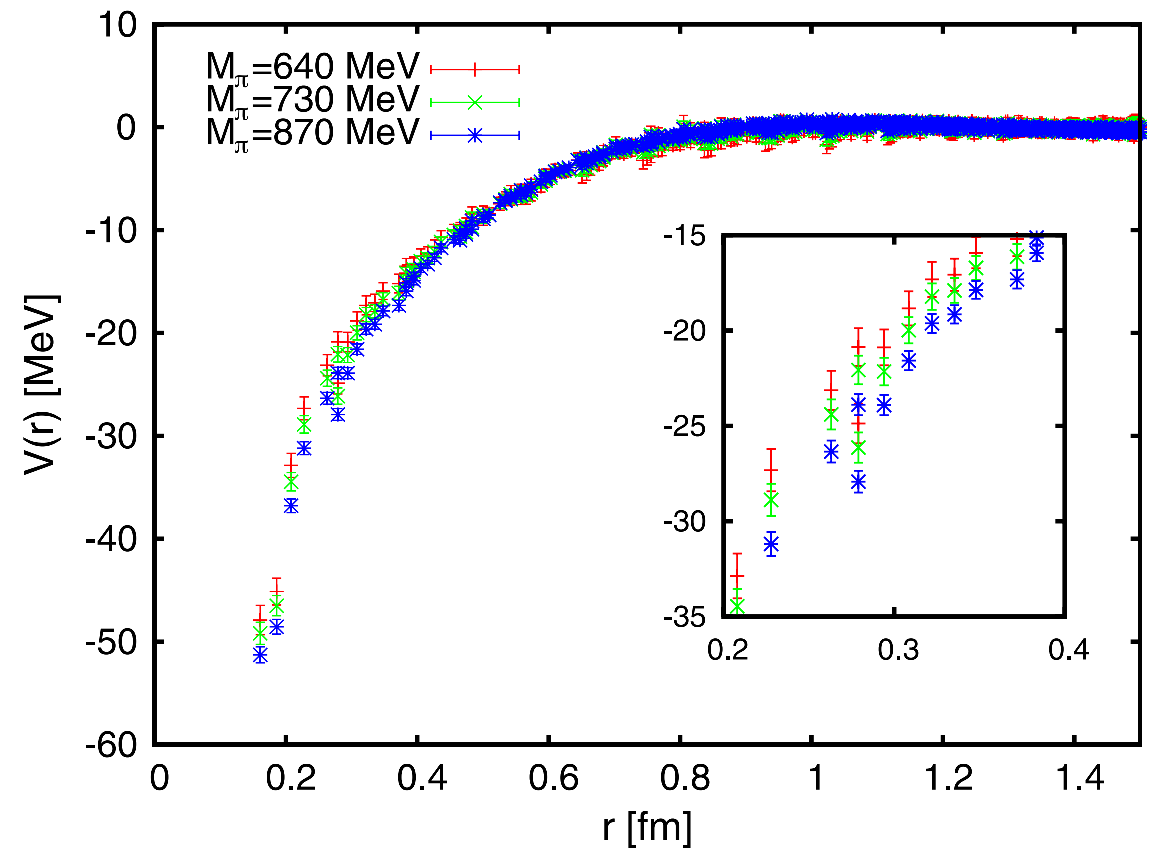
… Saved for the future
Let us discuss the charmonium-nucleon single-channel interactions

(η_c-N and J/ψ-N)

Previous Study by Kawanai and Sasaki

[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

Lattice Setup

- 2+1 flavor full QCD configuration by CP-PACS+JLQCD ($16^3 \times 32$)

  -Actions:

  RG improved gauge action (β=1.83)

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

  <u>**NOT** using the Relativistic Heavy Quark (RHQ) action for charm</u>

  <u>(statistical error may possibly exist)</u>

  -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

Effective Central Potential

$$C(t,\vec{r}) = \sum_n \langle\Omega|M(t,\vec{r}+\vec{x})B(t,\vec{x})|W;J\rangle\underline{\langle W;J|\bar{\mathcal{J}}(0)|\Omega\rangle}$$

$$\begin{cases} \eta_c + N, 1/2^- \\ J/\psi + N, 1/2^- \\ J/\psi + N, 3/2^- \end{cases}$$

- The $\eta_c N$ and $J/\psi N$ coupling and tensor force for $J^P = 1/2^-$:

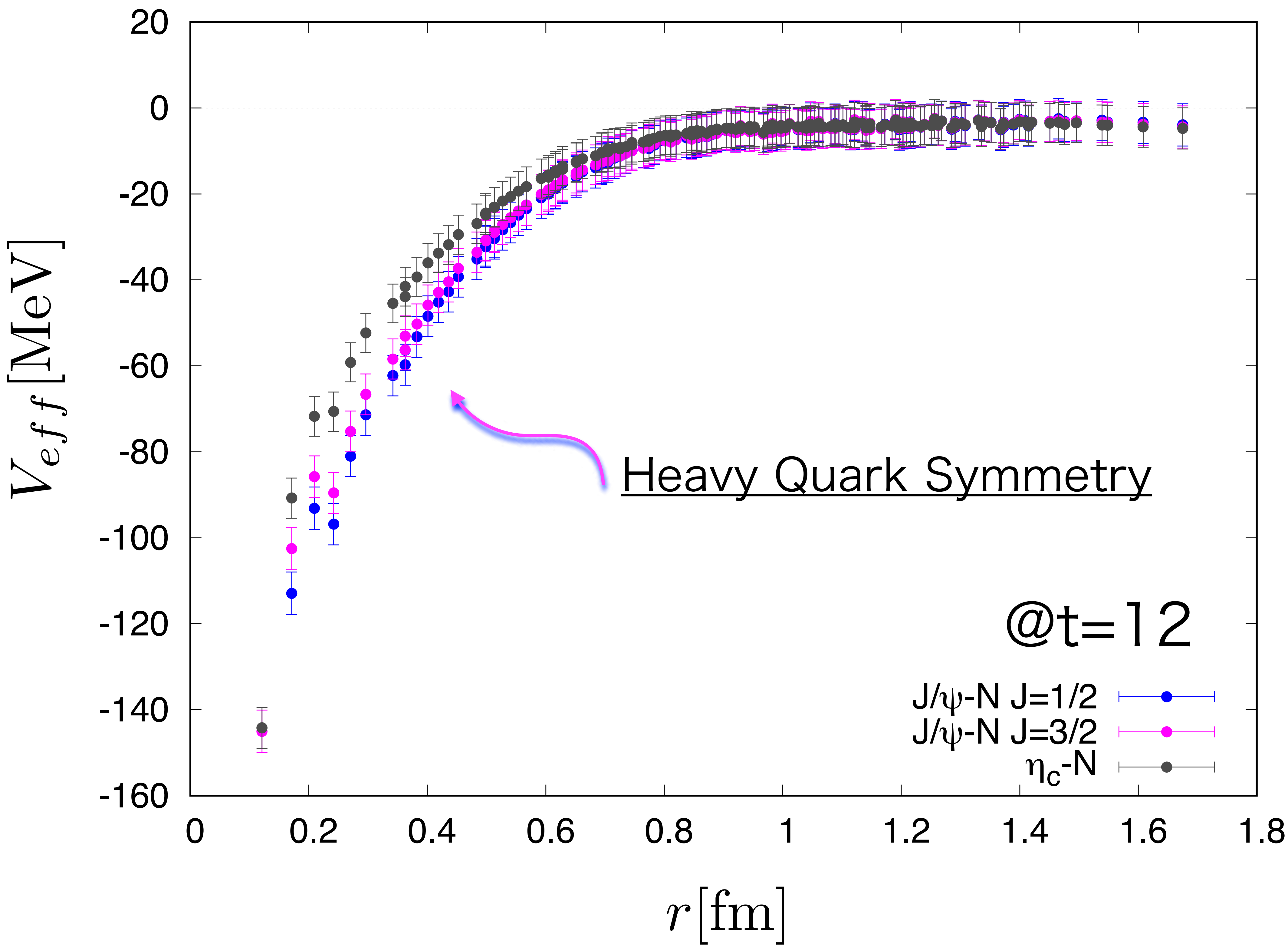
$$\begin{pmatrix} \frac{\nabla^2}{2\mu_1} + E & 0 \\ 0 & \frac{\nabla^2}{2\mu_2} + E \end{pmatrix} \begin{pmatrix} \psi_{\eta_c} \\ \psi_{J/\psi} \end{pmatrix} = \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix} \begin{pmatrix} \psi_{\eta_c} \\ \psi_{J/\psi} \end{pmatrix}$$

- We calculate the effective central potentials to keep things simple

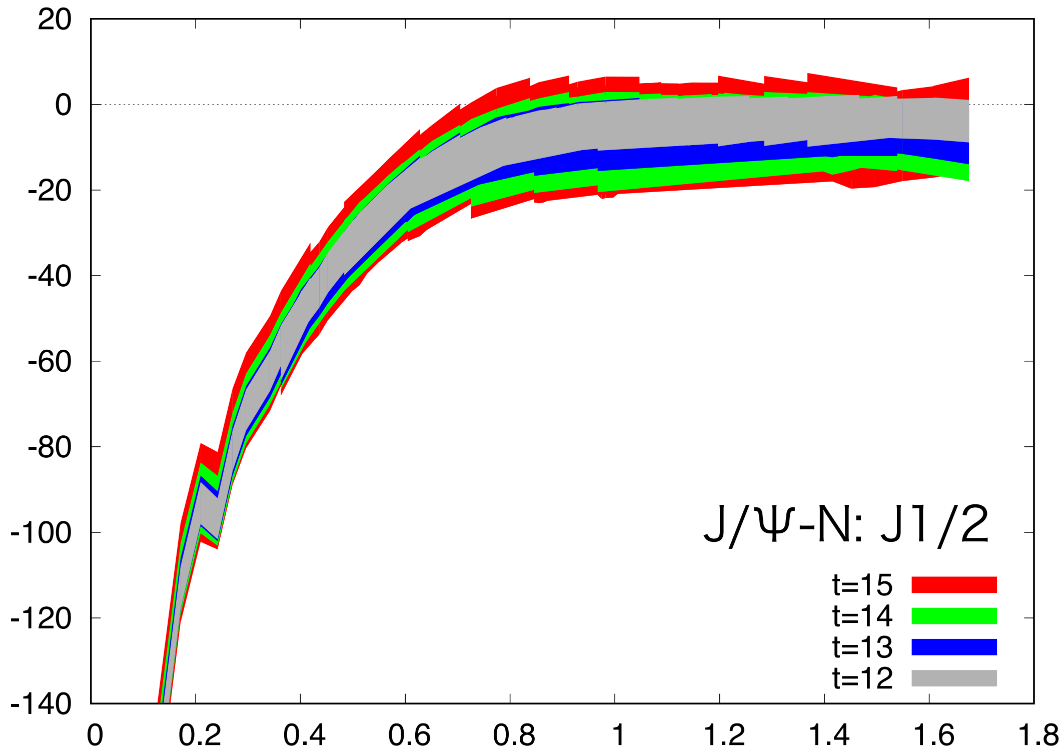
$$\left(\frac{\nabla^2}{2\mu_1} + E\right)\psi_{\eta_c} = V_{eff}^{\eta_c N}\psi_{\eta_c}$$

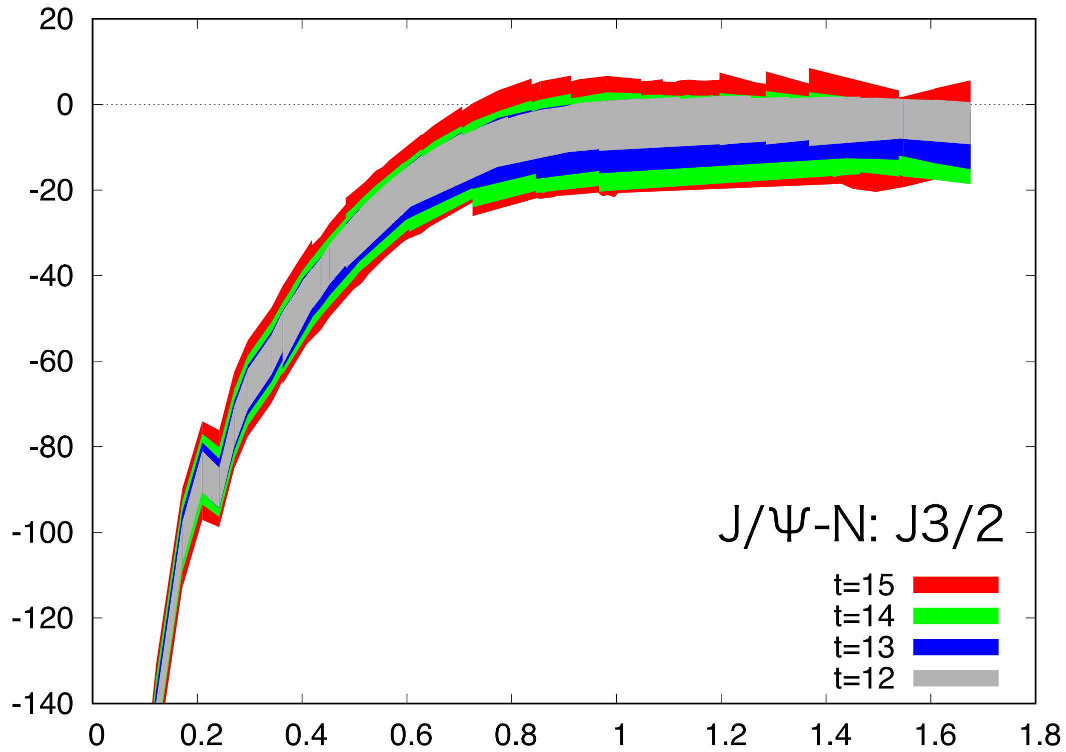
$$\left(\frac{\nabla^2}{2\mu_2} + E\right)\left[\hat{P}(l=0)\psi_{J/\psi}\right] = V_{eff}^{J/\psi N}\left[\hat{P}(l=0)\psi_{J/\psi}\right]$$

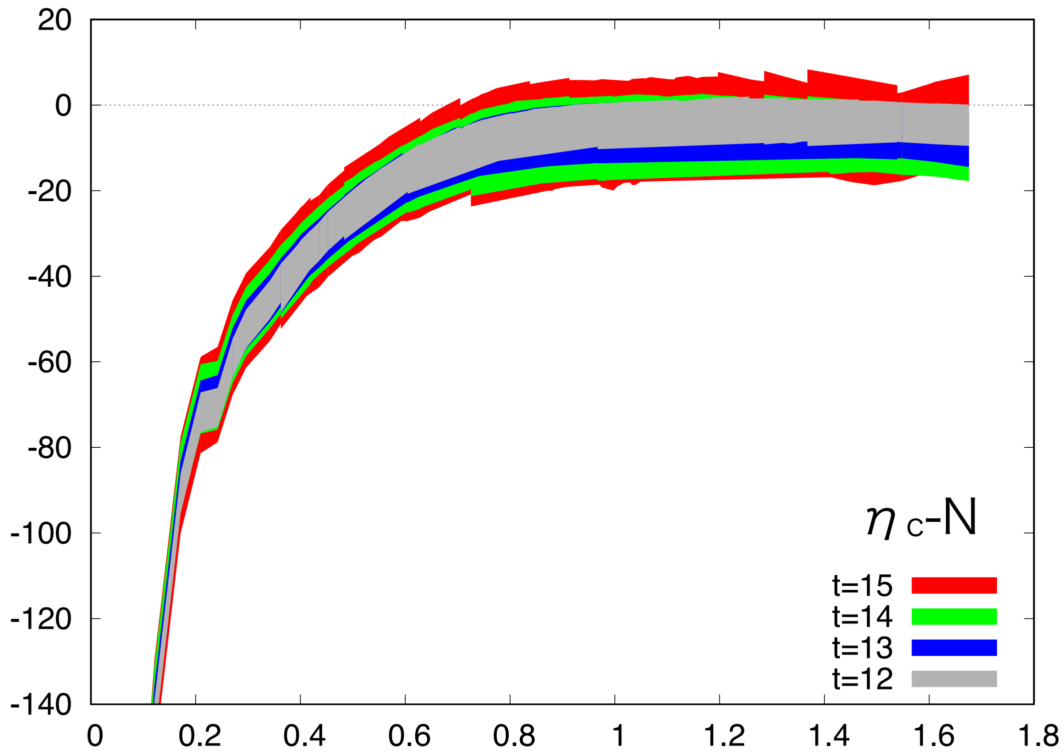
Result: Potentials



Saturation of the Potentials







- The potentials are t-stable

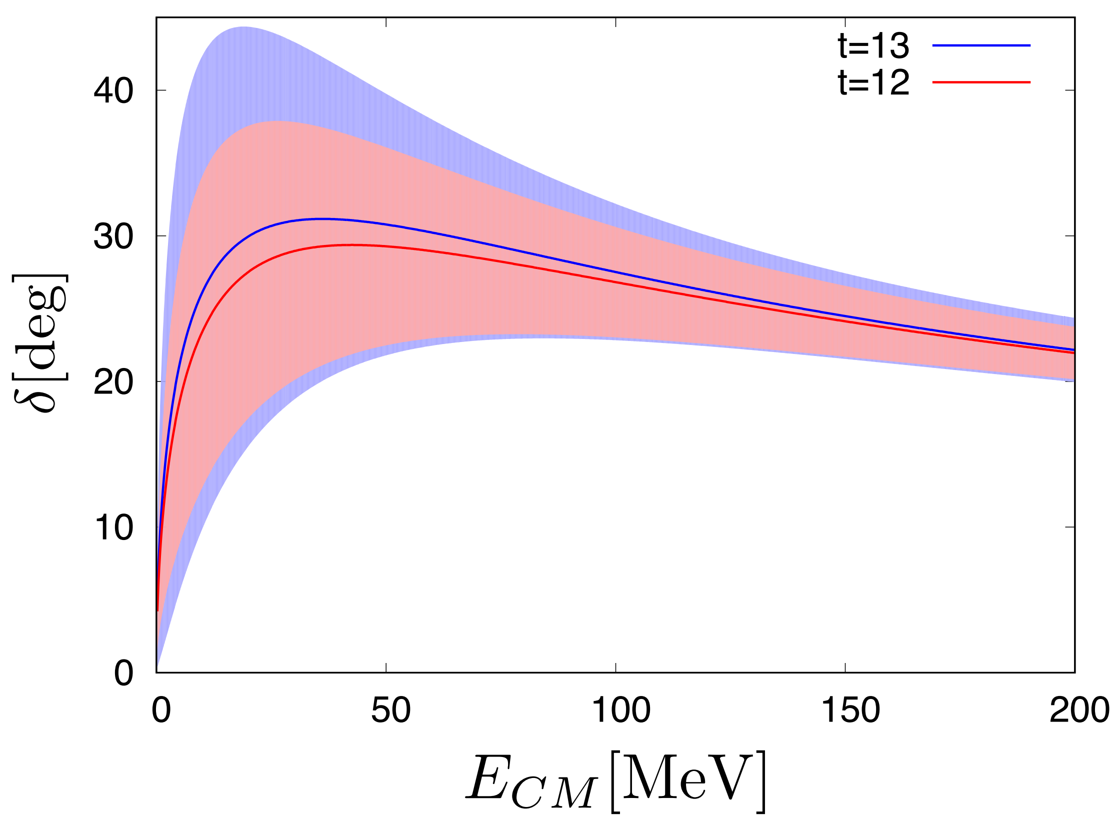
  … saturation achieved @t=12

Scattering 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

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

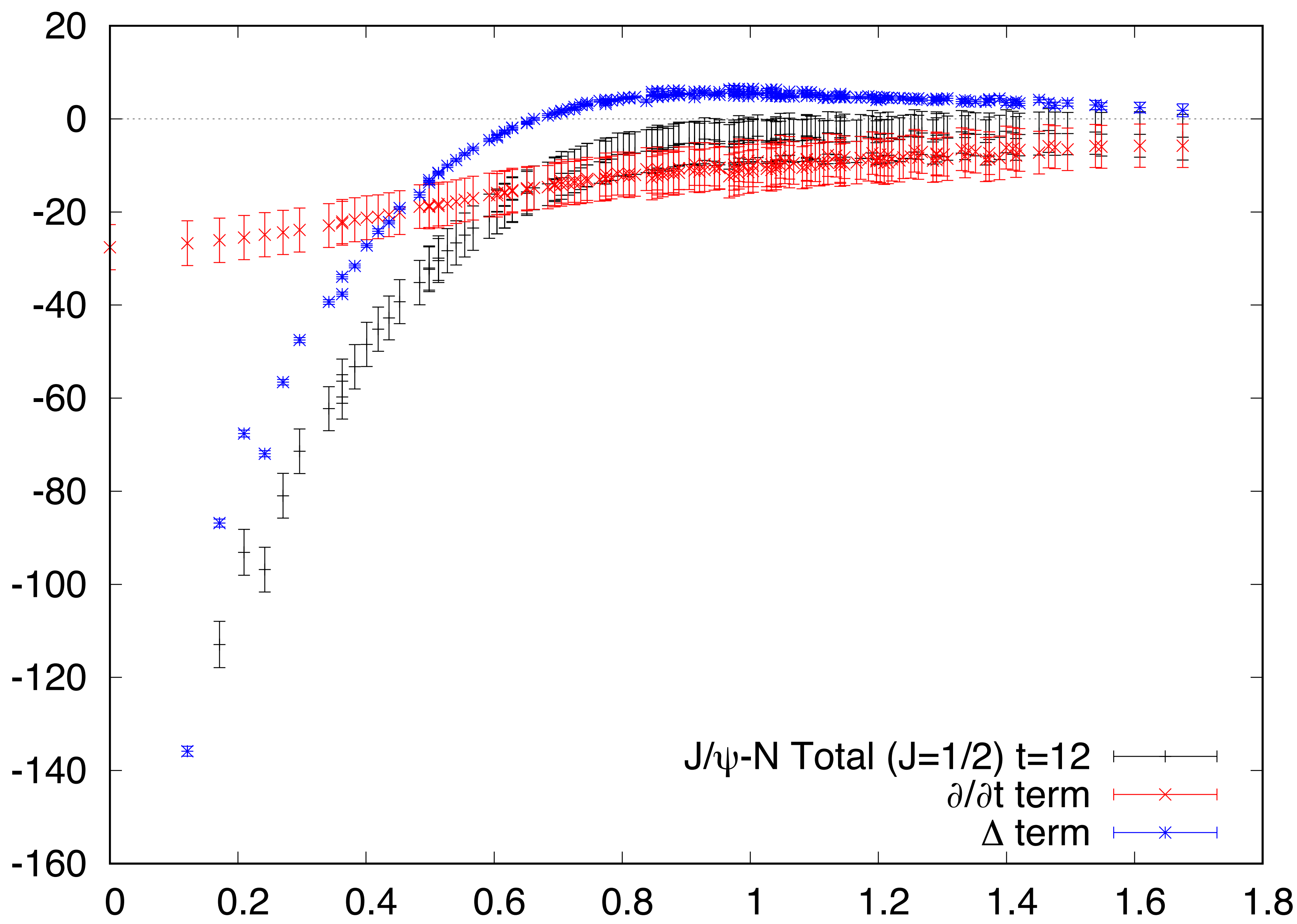
.backup/

Time-Dependent Method

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

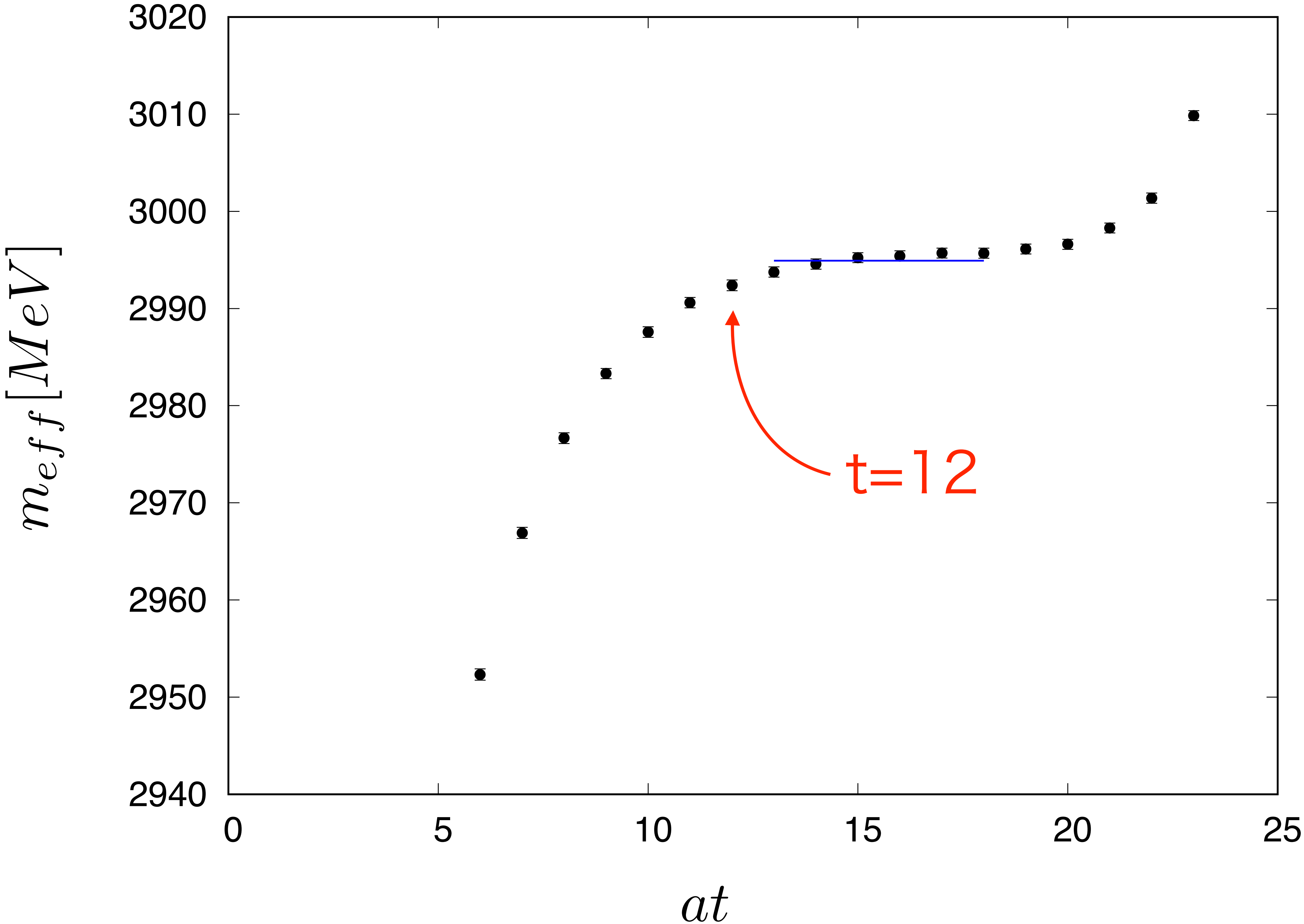
$$= \frac{k^2}{2\mu} \quad (\mathrm{Const.})$$

when the ground-state saturation is achieved

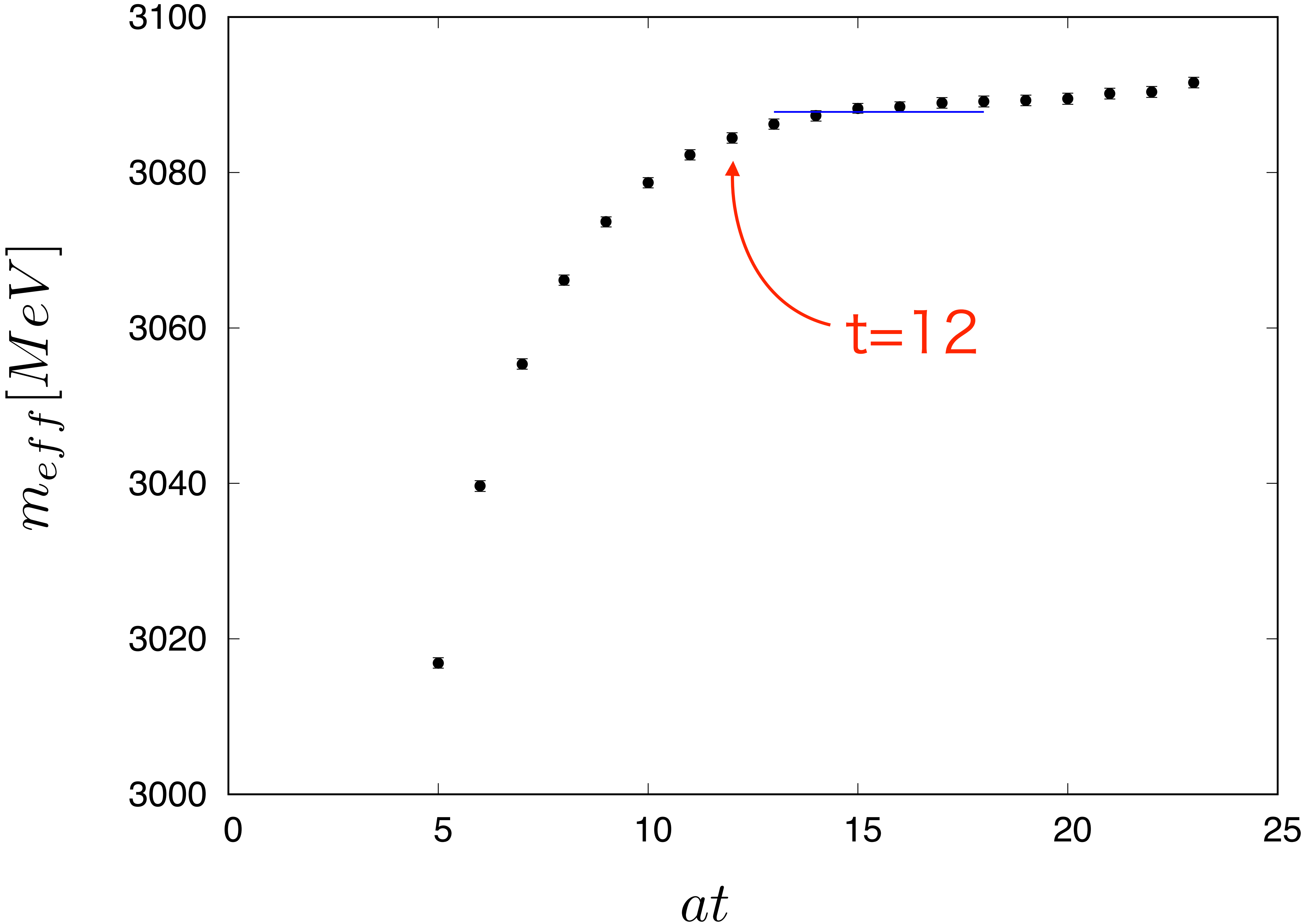


Ground-state saturation is not necessary in the time-dependent method.

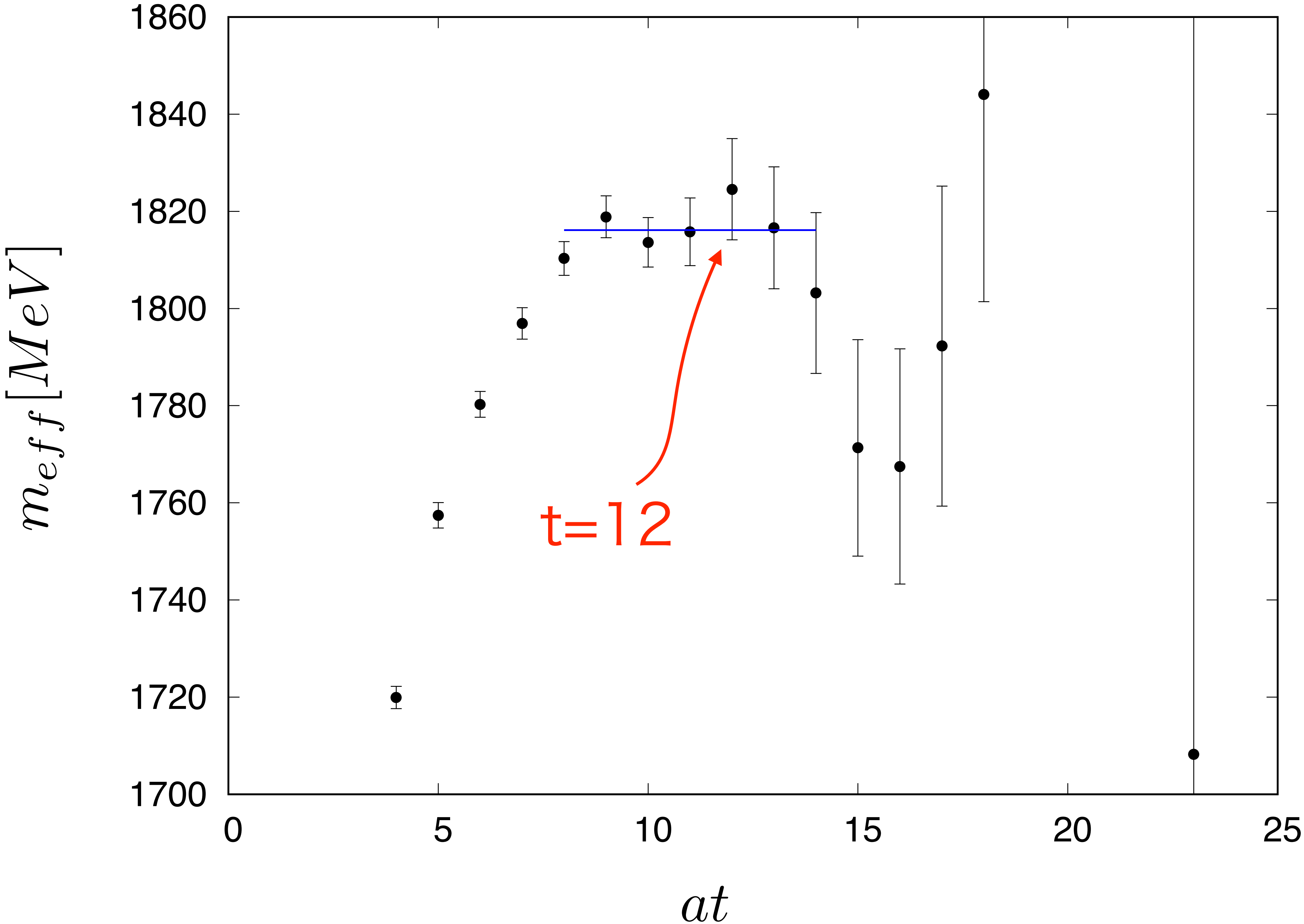
Ground-State Saturation: effective mass of η_c



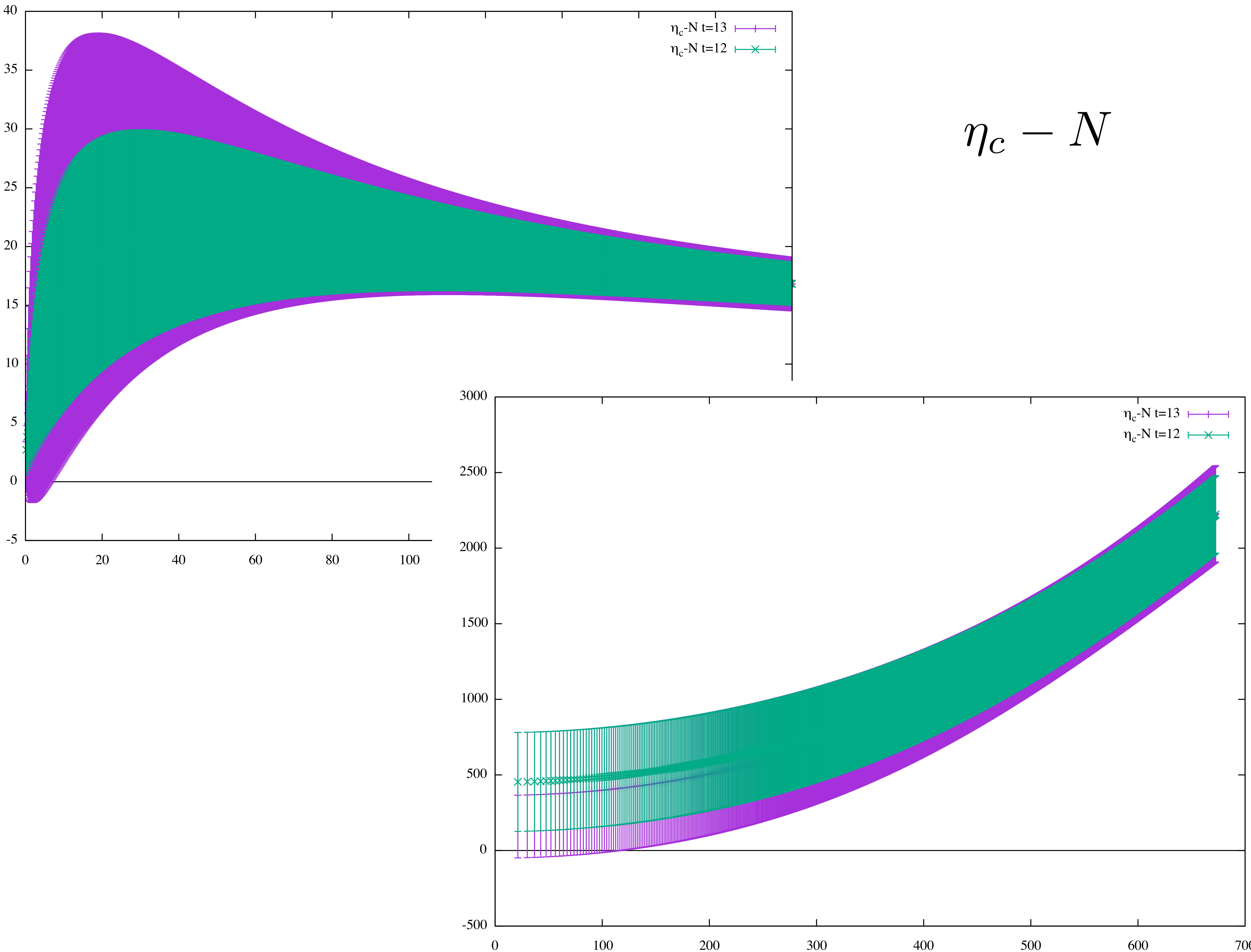
Ground-State Saturation: effective mass of J/ψ



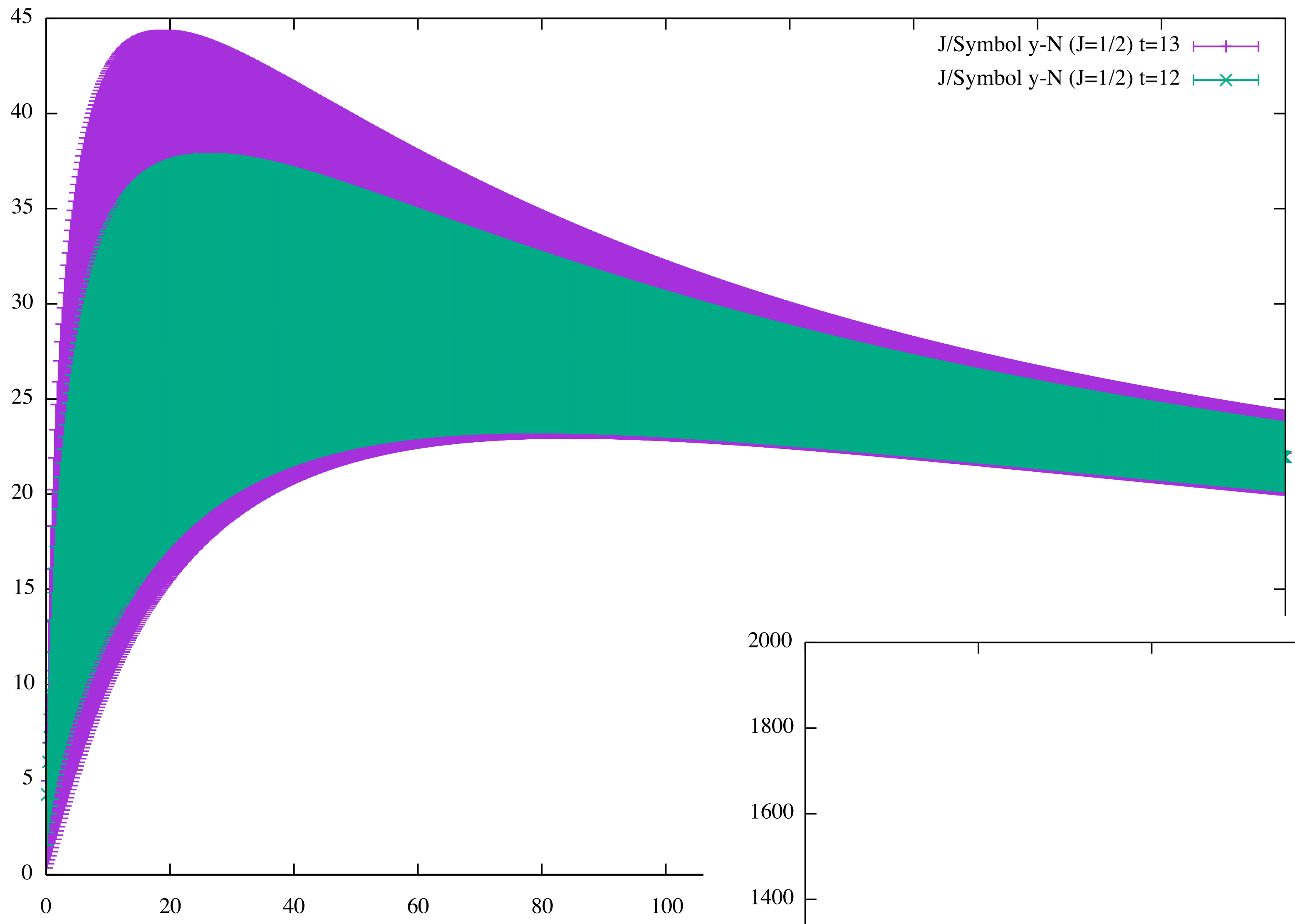
Ground-State Saturation: effective mass of N

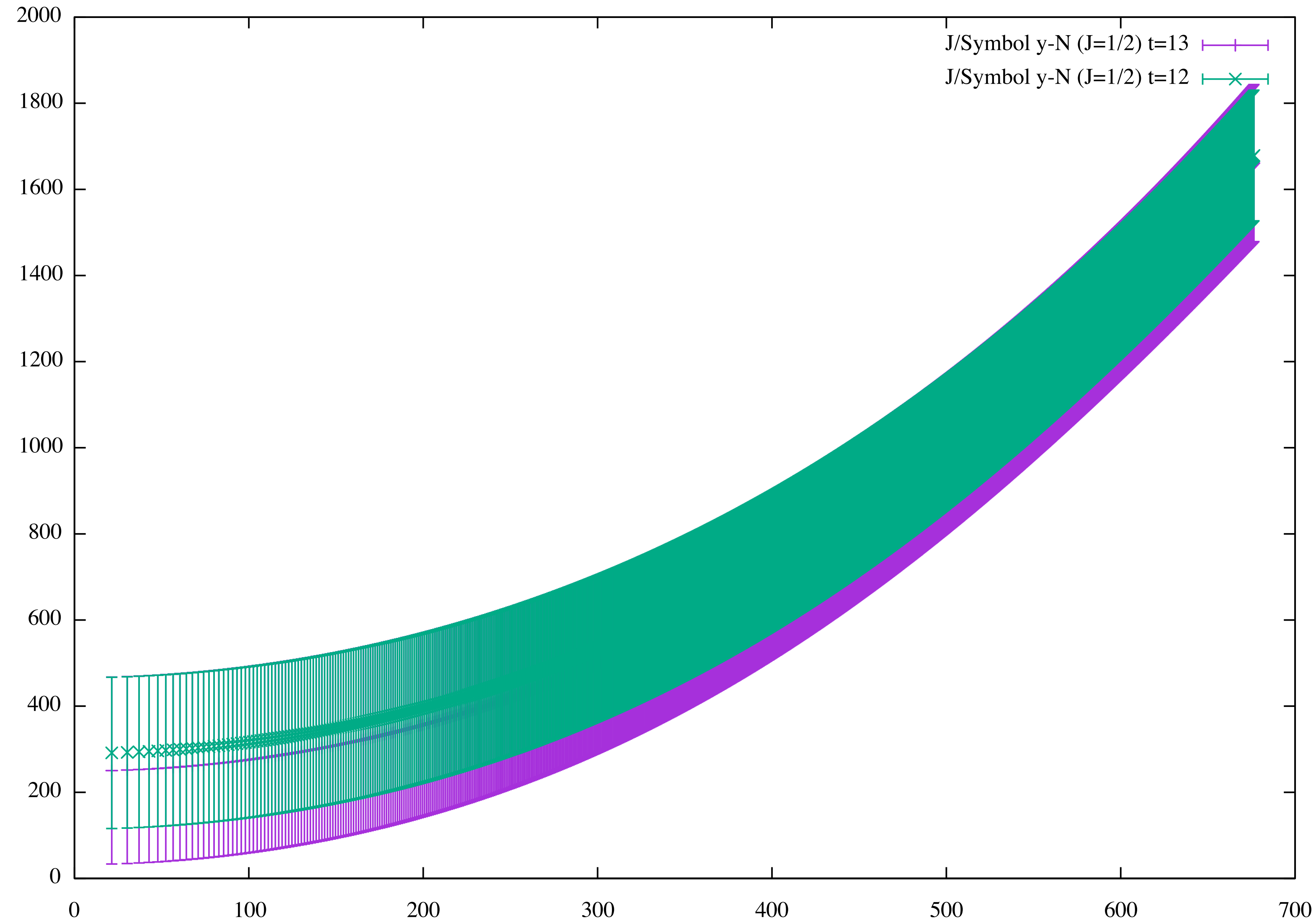


$\eta_c - N$

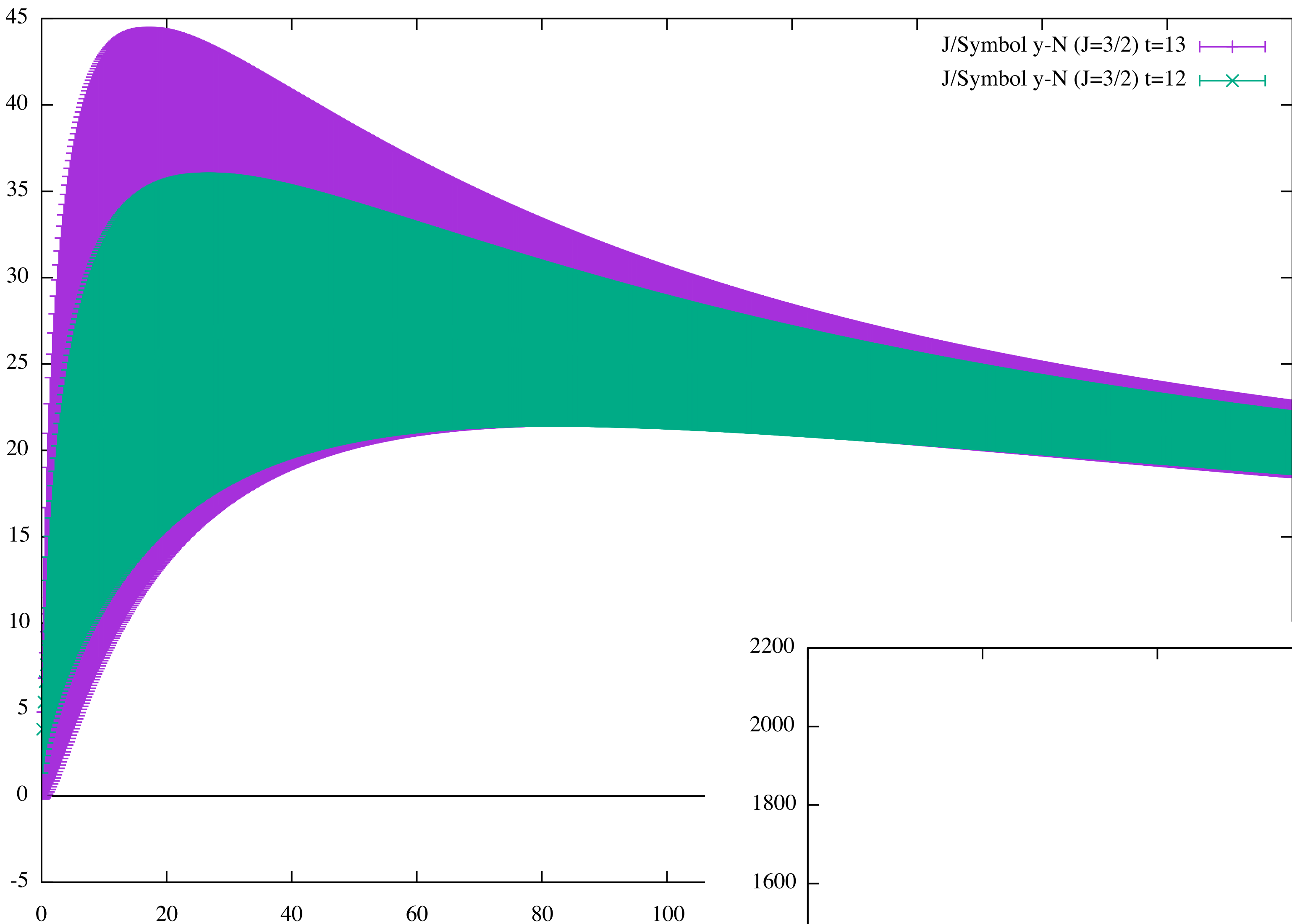

ηc-N t=13
ηc-N t=12
40
35
30
25
20
15
10
5
0
-5
0
20
40
60
80
100
ηc-N t=13
ηc-N t=12
3000
2500
2000
1500
1000
500
0
-500
0
100
200
300
400
500
600
700

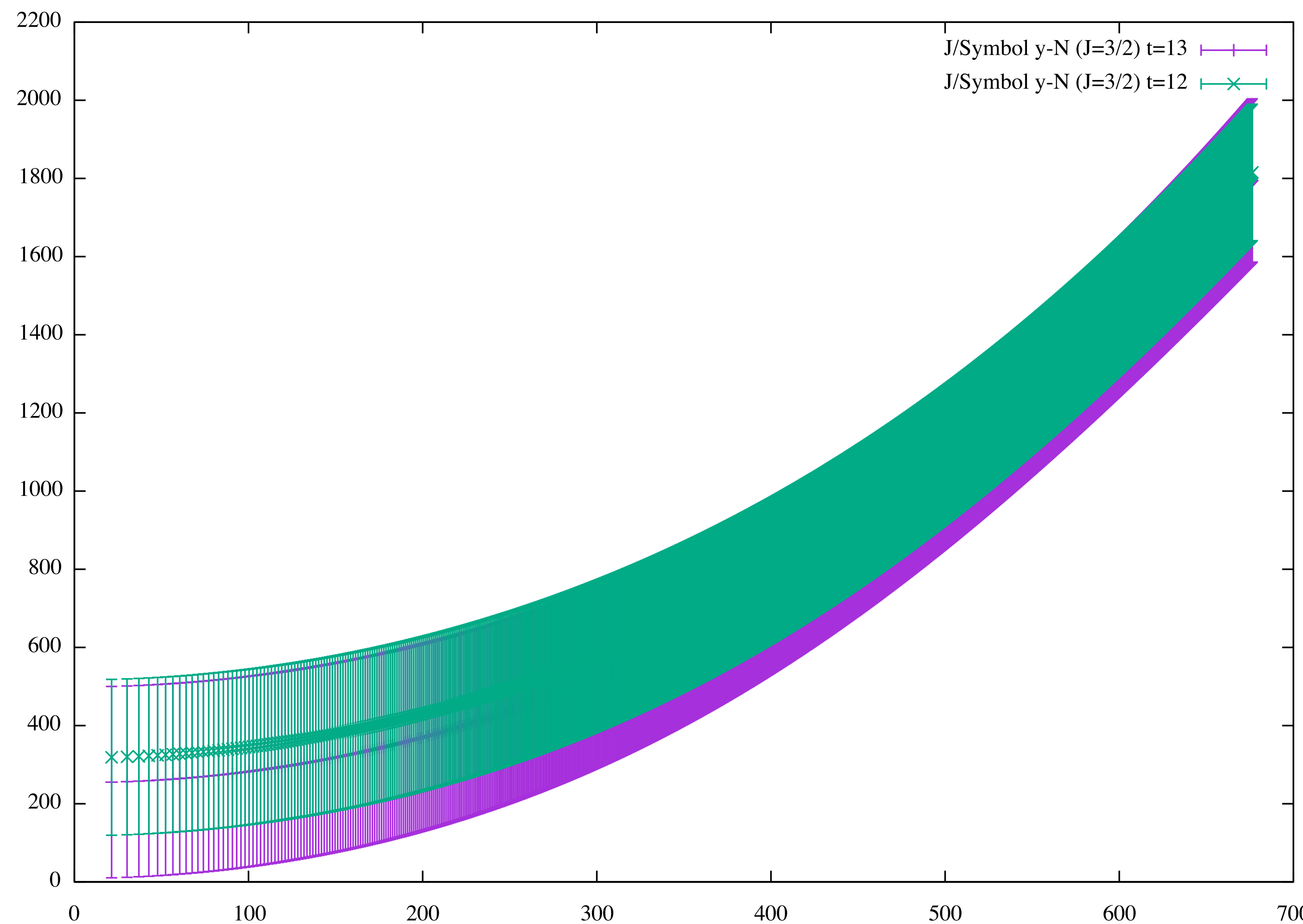
$$J/\psi - N(J = \frac{1}{2})$$



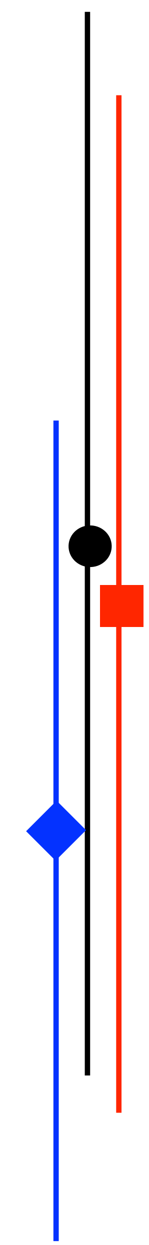


$$J/\psi - N(J = \frac{3}{2})$$



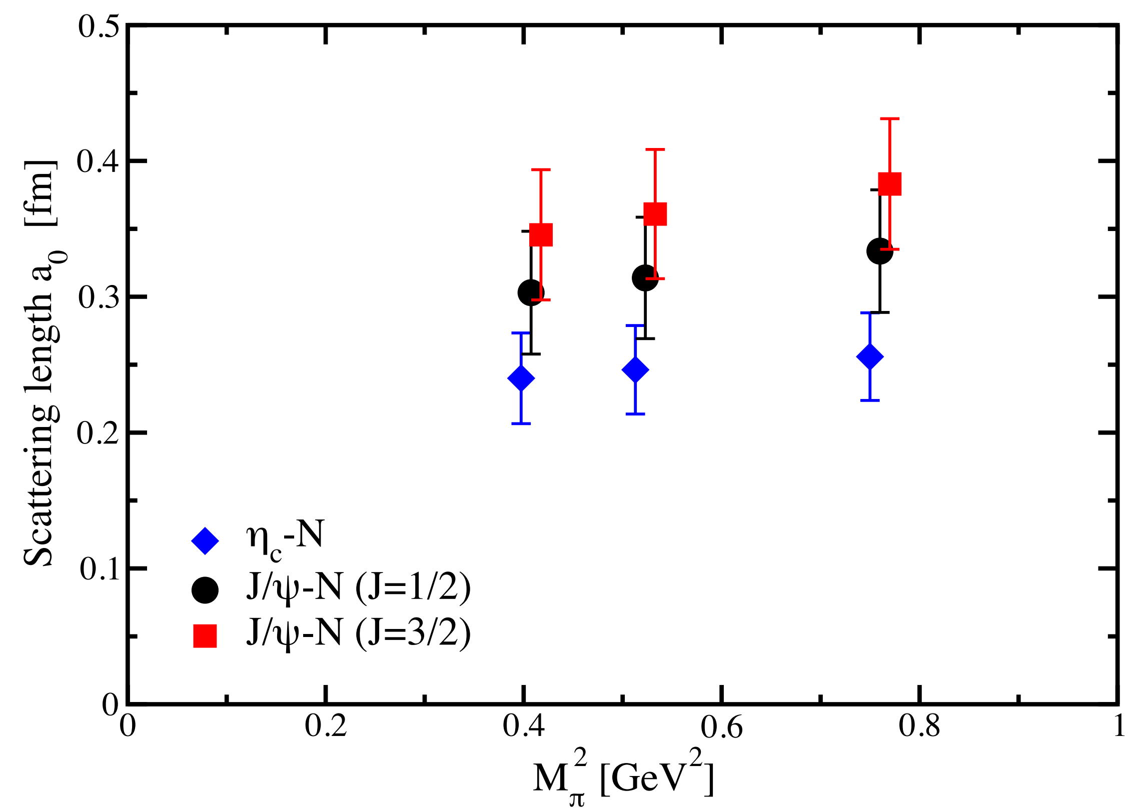


our result



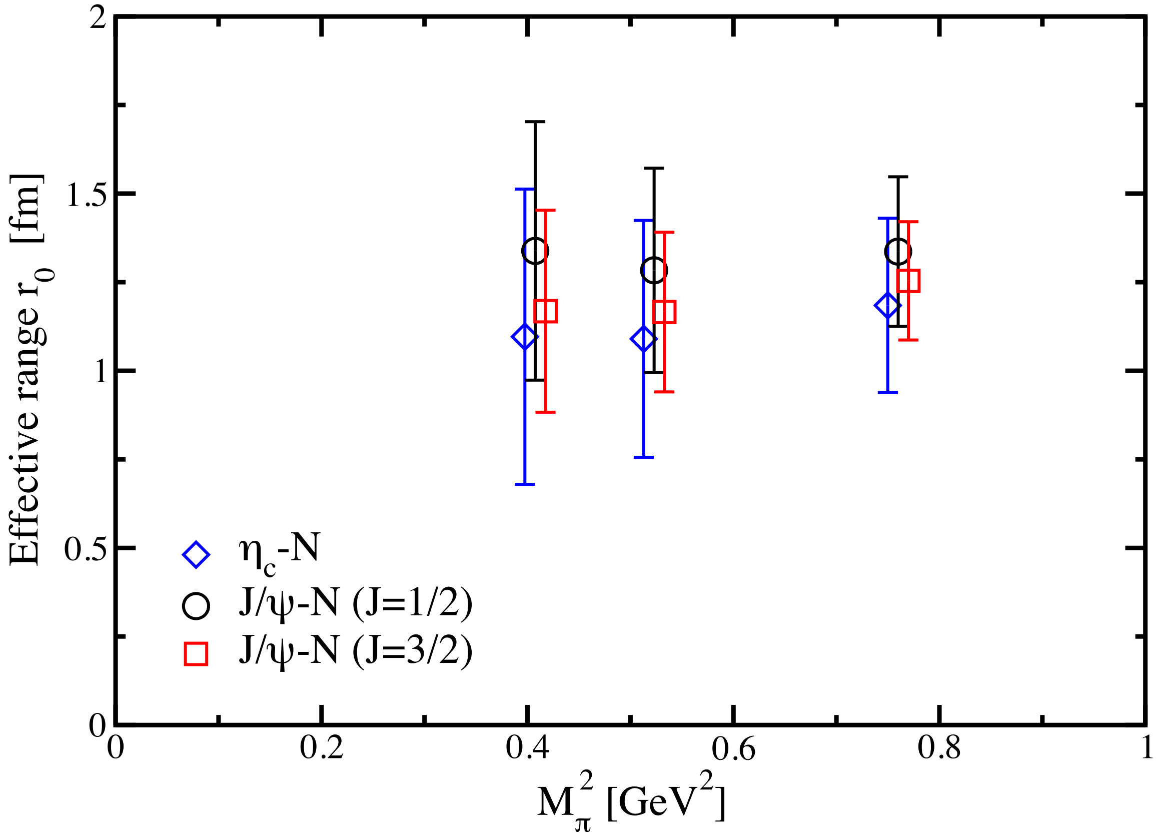
Lüscher's formula

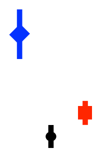
[T.Kawanai and S.Sasaki, PoS LATTICE2010 156]



Lüscher's formula

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





our result