

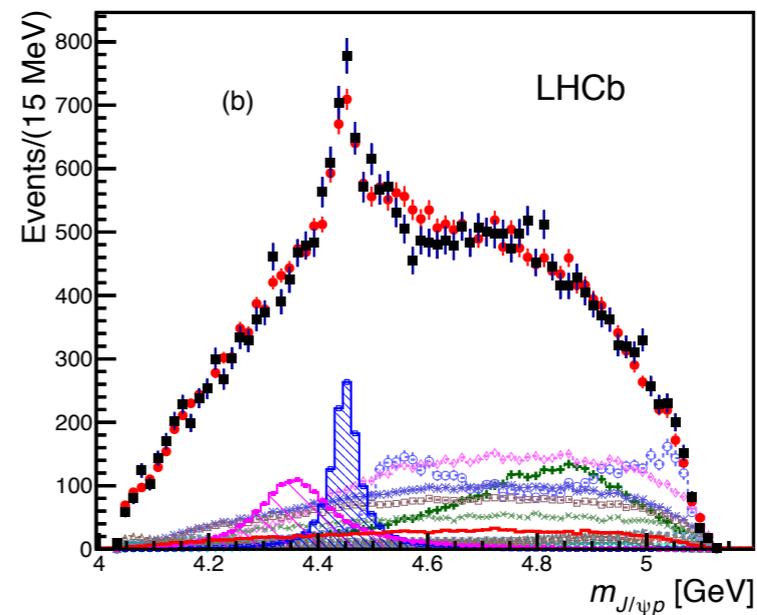
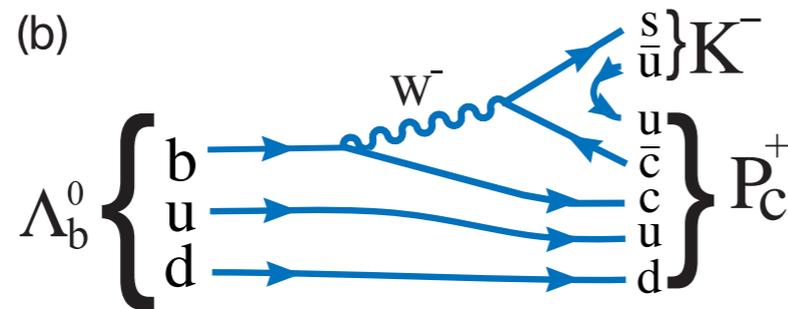
Charmonium-nucleon interactions from 2+1 flavor lattice QCD

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@Lattice2018, East Lansing, MI

Hidden-Charm Pentaquarks

- Two Pentaquark candidates have been observed by the LHCb collaboration via the decay $\Lambda_b \rightarrow J/\psi K p$ R.Aaij *et al.*, PRL115 (2015)

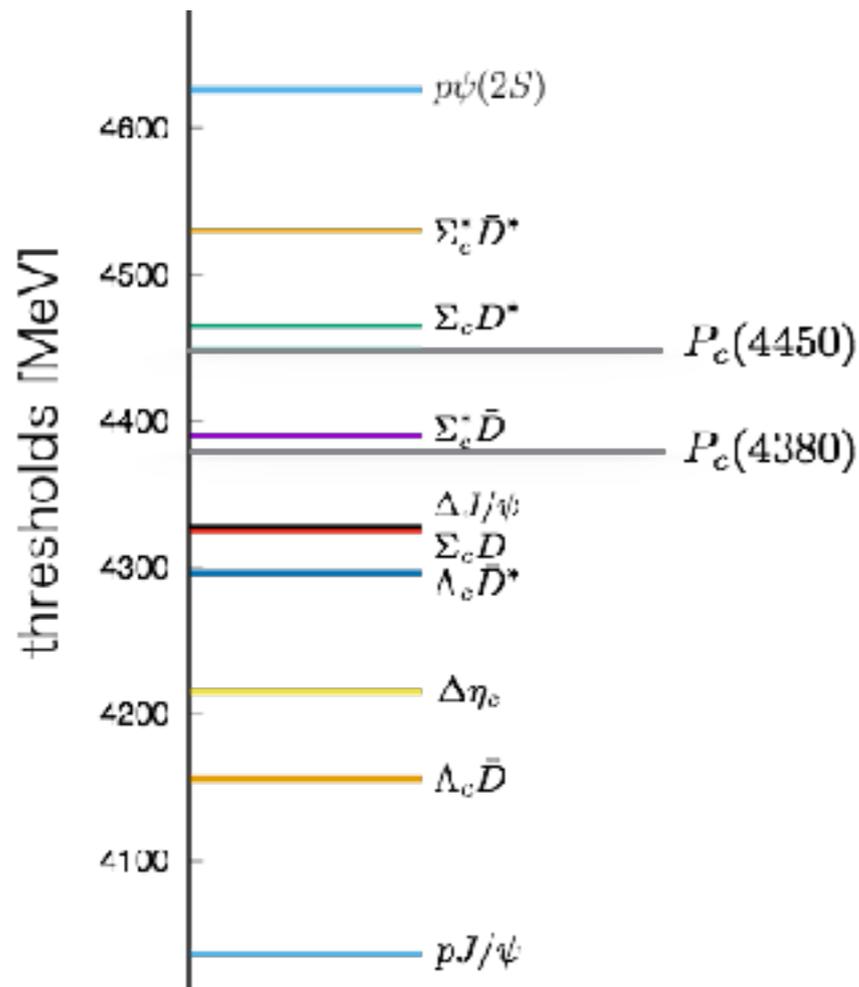


State	Mass [MeV]	Width [MeV]	J ^P
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-, 3/2^+, 5/2^+$
$P_c^+(4450)$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+, 5/2^-, 3/2^-$

- Model-independent analysis on the Λ^* contributions

R.Aaij *et al.*, PRL117,082002 (2016)

- Existence of $P_c(4380)$, $P_c(4450)$, $Z_c(4200)$ is supported by a full amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ R.Aaij *et al.*, PRL117,082003 (2016)



Hadronic Molecule?

[Roca et al., PRD92, 094003 \(2015\)](#)

- ◆ $P_c(4450) = \bar{D}^* \Sigma_c + \bar{D}^* \Sigma_c^* (J^P=3/2^-)$

[Chen et al., PRL115, 132002 \(2015\)](#)

- ◆ $P_c(4380) = \bar{D}^* \Sigma_c$
- ◆ $P_c(4450) = \bar{D}^* \Sigma_c^*$

[Eides et al., PRD93, 054039 \(2016\)](#)

- ◆ $P_c(4450) = p\psi(2S) (J^P=3/2^-)$

color-octet state ?

[Mironov et al., JETP Lett.102, 271 '15](#)

[Takeuchi et al., PLB764, 254 \(2017\)](#)

threshold cusp?

[Guo et al., PRD92, 071502 \(2015\)](#)

- ◆ $P_c(4450) = \text{kinematical effects of } p\chi_{c1} \rightarrow pJ/\psi$

nature under debate...

- Experimental data supports resonance state(s) in the pJ/ψ scattering
- Coupled-channel analysis of this system will reveal the nature of P_c 's
... resonance? cusp?
- Lattice QCD is useful
... first-principle, limited experimental information is not a big problem

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HAL QCD method

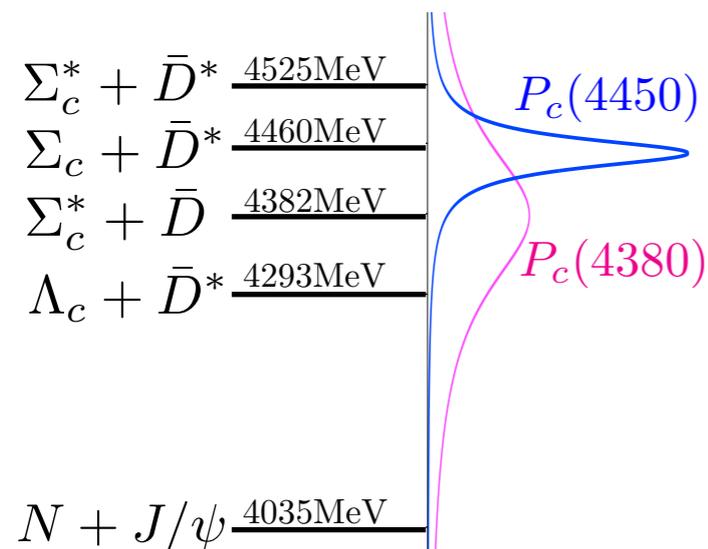
Ishii et al., PRL**99**,022001 (2007)

Aoki et al., PTP**123**,89 (2010)

Ishii et al., PLB**712**, 437 (2012)

Aoki et al., PTEP 01A105 (2012)

to compute a potential which is faithful to the QCD S-matrix

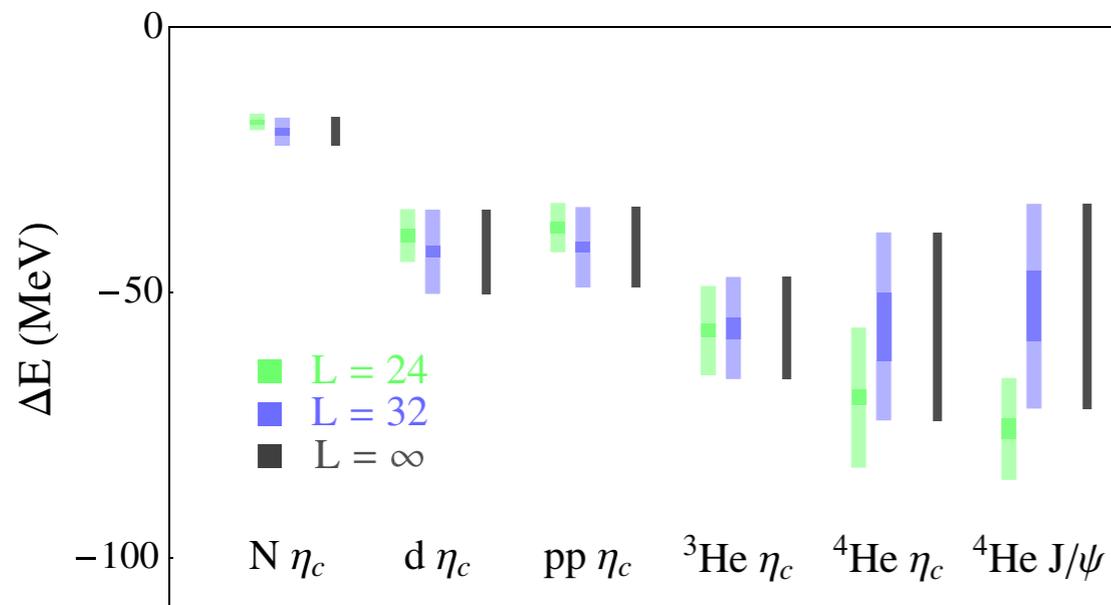


← 5 channels for $J^P=3/2^-, L=0$

We concentrate on the NJ/ψ channel this time:
... coupled-channel analysis will appear soon

[Beane et al., PRD91, 114503 '15](#)

$m_\pi = 805\text{MeV}$

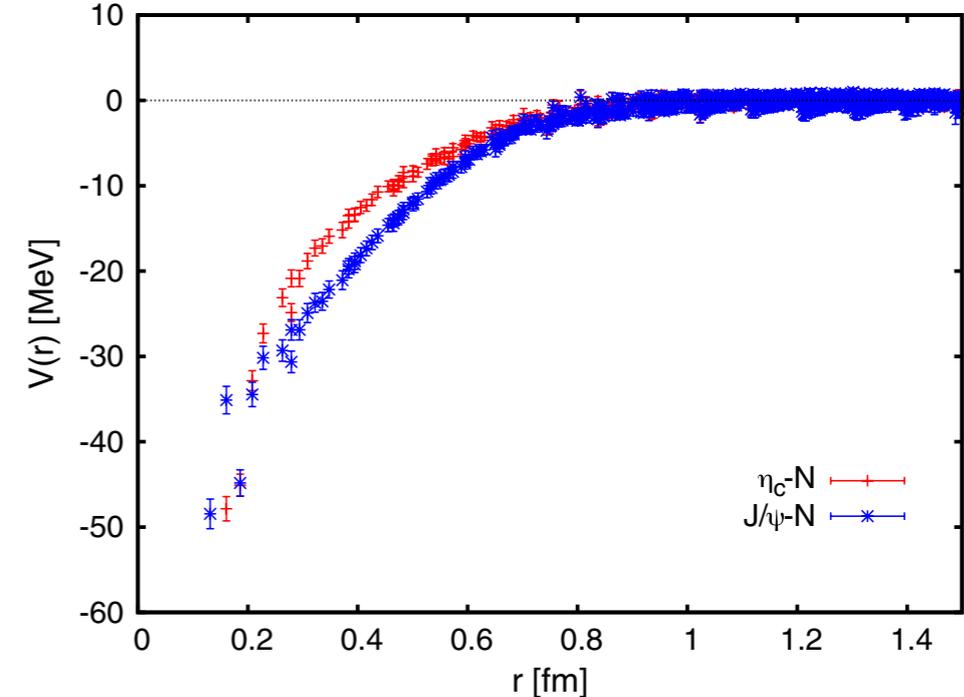


Nucleus-charmonium bound states have observed

$$B.E.(\eta_c N) = 19.8(2.6)\text{MeV}$$

[Kawanai and Sasaki, PRD82,091501 '10](#)

quenched quarks $m_\pi = 640\text{MeV}$



Potentials by the time-independent method:

attractive, but not strong enough to form a bound state

- We update KS results by using the time-dependent HAL QCD method and dynamical quarks

Key quantity:

NBS wave function

$$G(\vec{r}, t) = \langle 0 | N(\vec{r}, t) N(\vec{0}, t) \bar{J}(t_0 = 0) | 0 \rangle$$

$$= \sum_n c_n \psi(\vec{r}; W_n) e^{-W_n t}$$

faithful to QCD S-matrix:

$$\psi(\vec{r}) \longrightarrow \frac{\sin(kr - l\pi/2 + \delta(k))}{kr} e^{i\delta(k)}$$

- E-indep. / non-local potential

Ishii et al., PRL**99**,022001 (2007)

Aoki et al., PTP**123**,89 (2010)

$$\left(\frac{k_n^2}{2\mu} + \frac{\nabla^2}{2\mu} \right) \psi(\vec{r}; W_n) = \int d^3 r' U(\vec{r}, \vec{r}') \psi(\vec{r}'; W_n) \quad W_n = 2\sqrt{k_n^2 + m_N^2}$$

U is common for n ; $W_n < W_{th}$

Ground-state saturation is required to extract NBS w.f.

$$G(\vec{r}, t) \sim c_0 \psi(\vec{r}; W_0) e^{-W_0 t} \quad t \rightarrow \infty$$

: **hard to achieve** because of bad S/N ratio for large t

- Time-dependent method

Ishii et al., PLB712, 437 (2012)

$$\left(-\frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu}\right) R(\vec{r}, t) = \int d^3r' U(\vec{r}, \vec{r}') R(\vec{r}', t) \quad \text{upto } \mathcal{O}(k^4)$$

$$R(\vec{r}, t) = G(\vec{r}, t) e^{(m_1+m_2)t}$$

Requirements:

Elastic-state saturation

$$G(\vec{r}, t) \sim \sum_{W_n < W_{th}} c_n \psi(\vec{r}; W_n) e^{-W_n t}$$

: much easier to achieve than the GS saturation

Convergence of the derivative expansion

$$U(\vec{r}, \vec{r}') \sim V(\vec{r}) \delta^3(\vec{r} - \vec{r}')$$

Necessary condition: $V(r) = \frac{1}{R(\vec{r}, t)} \left(-\frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu}\right) R(\vec{r}, t)$ is independent of t

General form of the J/ψ -N interaction at the lowest order of the derivative expansion:

$$V(r) = V_0(r) + V_\sigma(r) \boldsymbol{\sigma} \cdot \boldsymbol{\Sigma} + V_T(r) [3(\hat{\mathbf{r}} \cdot \boldsymbol{\sigma})(\hat{\mathbf{r}} \cdot \boldsymbol{\Sigma}) - (\boldsymbol{\sigma} \cdot \boldsymbol{\Sigma})] + V_{T'}(r) [3(\hat{\mathbf{r}} \cdot \boldsymbol{\Sigma})^2 - \boldsymbol{\Sigma}^2]$$

$\boldsymbol{\sigma}$: nucleon spin

$\boldsymbol{\Sigma}$: J/ψ spin

- For now we calculate the effective central potentials

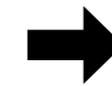
$$\left(\frac{\nabla^2}{2\mu_1} + E \right) \psi_{\eta_c} = V_{eff}^{\eta_c N} \psi_{\eta_c}$$

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

2+1_f full QCD confs by PACS-CS

S.Aoki *et al.*, PRD79,034503 (2009)

- Iwasaki gauge
- O(a) improved Clover Wilson quarks
- $a=0.0907$ fm ($\beta=1.90$)
- Volume: $32^3 \times 64$
- $L a \sim 3$ fm



$$\begin{aligned} m_\pi &= 700 \text{ MeV} \\ m_N &= 1585 \text{ MeV} \end{aligned}$$

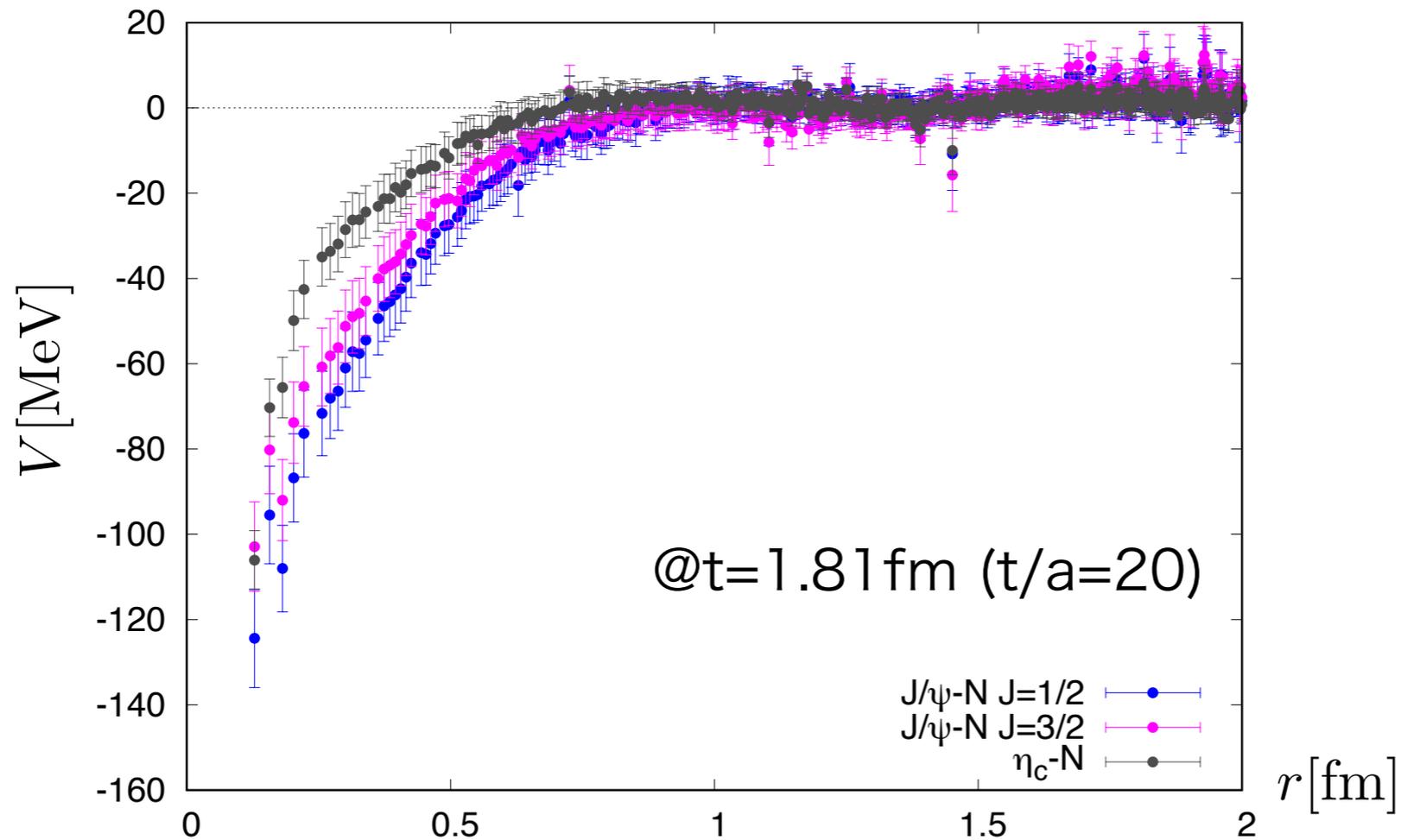
Tsukuba-type Relativistic Heavy Quark (RHQ) action

Y.Namekawa *et al.*, PRD84,074505 (2011)

- Remove cutoff errors of $\mathcal{O}((m_Q a)^n)$ and $\mathcal{O}(\Lambda_{QCD} a)$

Statistics

- 399 confs x 4 sources

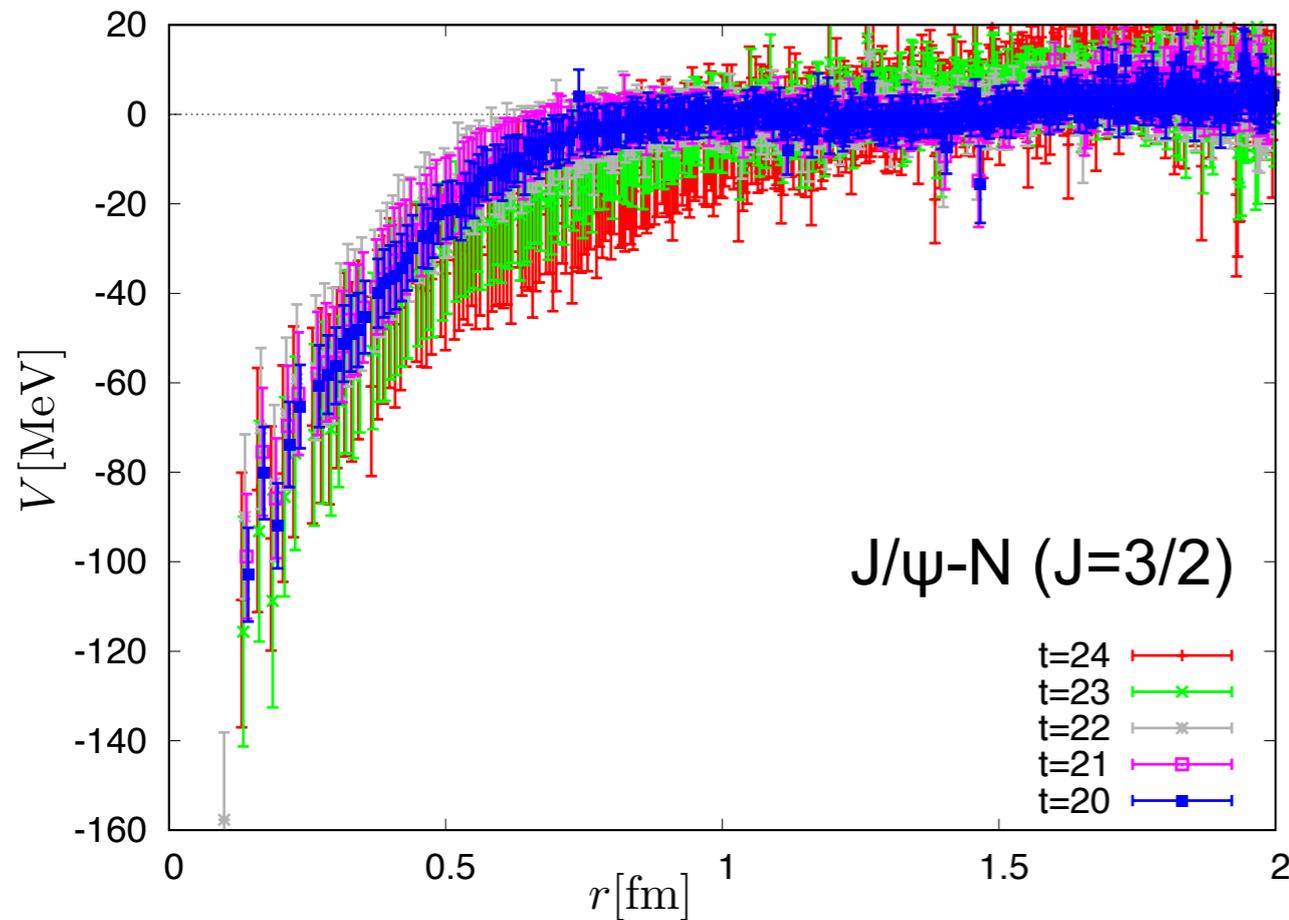


- The necessary condition is satisfied at $t/a=20$ (see next slide)
- All components are attractive, but not very strong
- They look similar : Heavy Quark Symmetry
- Breaking of HQS: $\eta_c N < J/\psi N (J = \frac{3}{2}) < J/\psi N (J = \frac{1}{2})$

Check of Necessary Condition

The necessary condition

$$V(r) = \frac{1}{R(\vec{r}, t)} \left(-\frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu} \right) R(\vec{r}, t) \text{ is t-indep.}$$



- For $t/a \geq 20$, all $V(r)$ are consistent within statistical error

elastic-state saturation achieved

derivative expansion converged

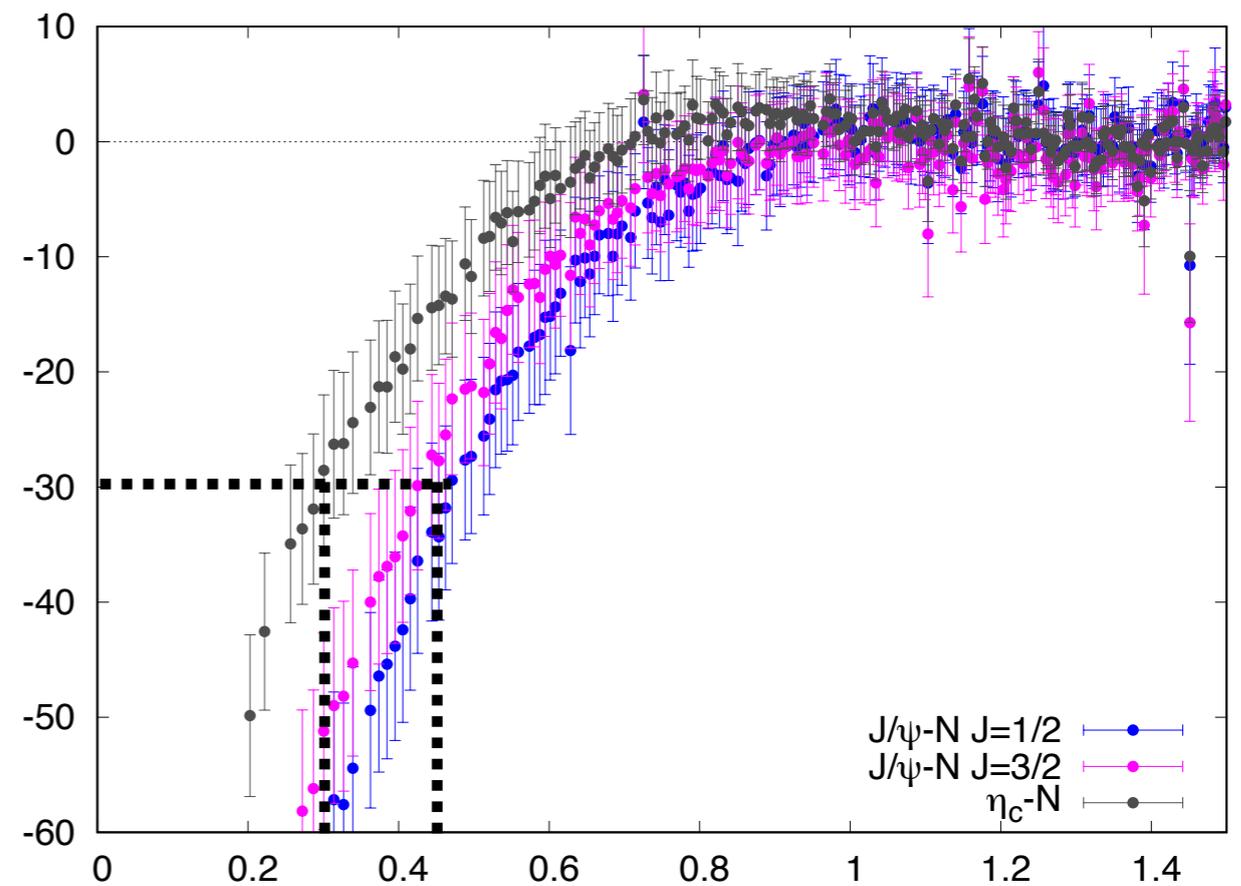
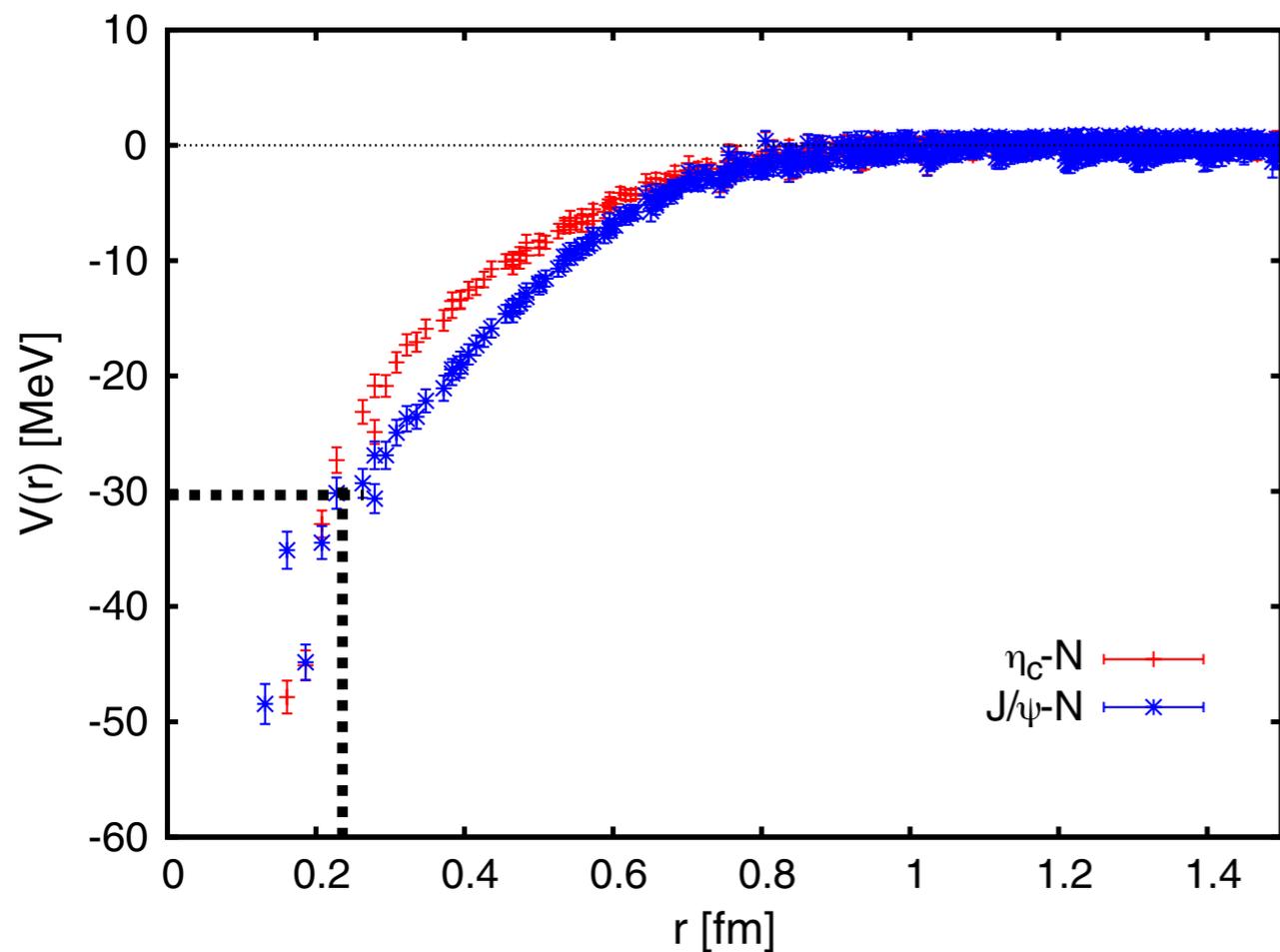
- Similarly for the other two

vs KS Results

T.Kawanai and S.Sasaki, PRD82 (2010)

- Quenched fermions
- Old version of HAL QCD method (assume GS saturation)

- ↔ Dynamical fermions
- ↔ Time-dependent method



Our potentials look deeper / shorter-ranged?

Probably because KS underestimated the short-range part

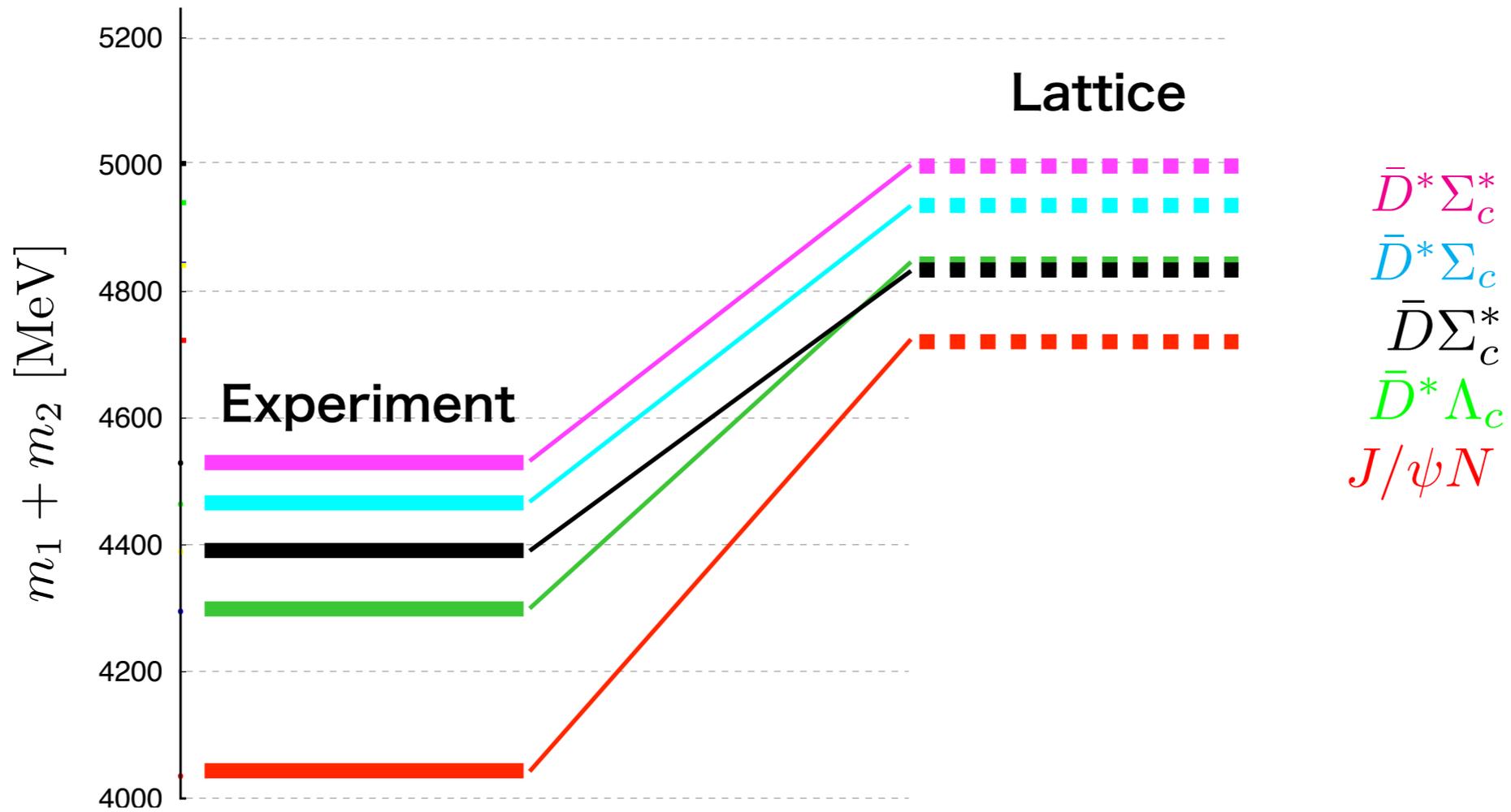
- Updated results of the charmonium-nucleon potentials by the time-dependent HAL QCD method
- Consistent with the previous studies within statistical errors at the moment

What to do

- **Increase statistics**
- **Include other channels**
- m_π dependence
- J/ψ nuclei
- Tensor forces of the J/Ψ -N

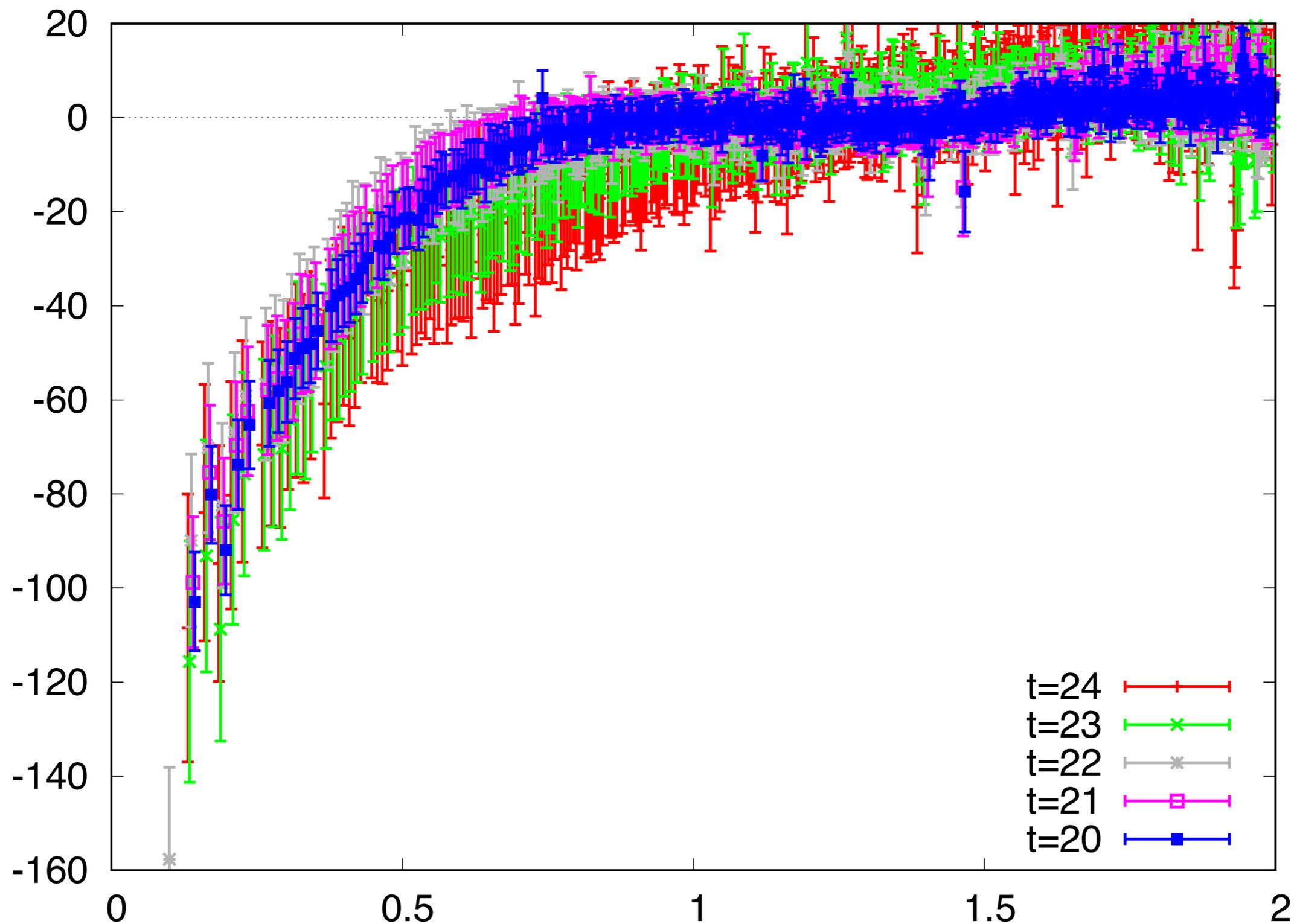
backup slides

Thresholds on Lattice

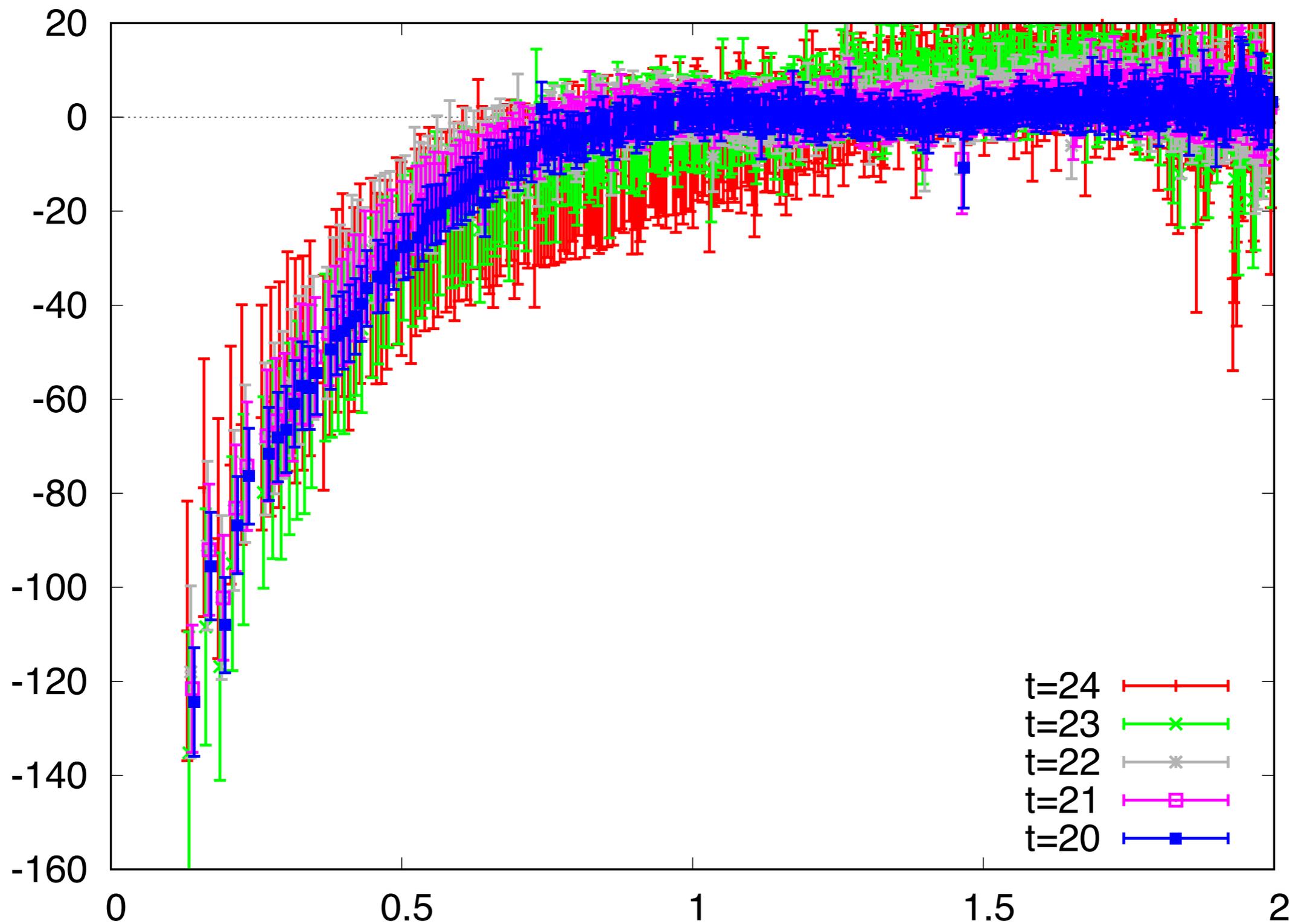


π	ρ	D	D*	η_c	J/ ψ
700 (140)	1110 (770)	1999 (1870)	2160 (2010)	3021 (2983)	3138 (3096)
N	Σ_c	Σ_c^*	Λ_c	lattice experiment [MeV]	
1585 (940)	2780 (2455)	2842 (2520)	2683 (2286)		

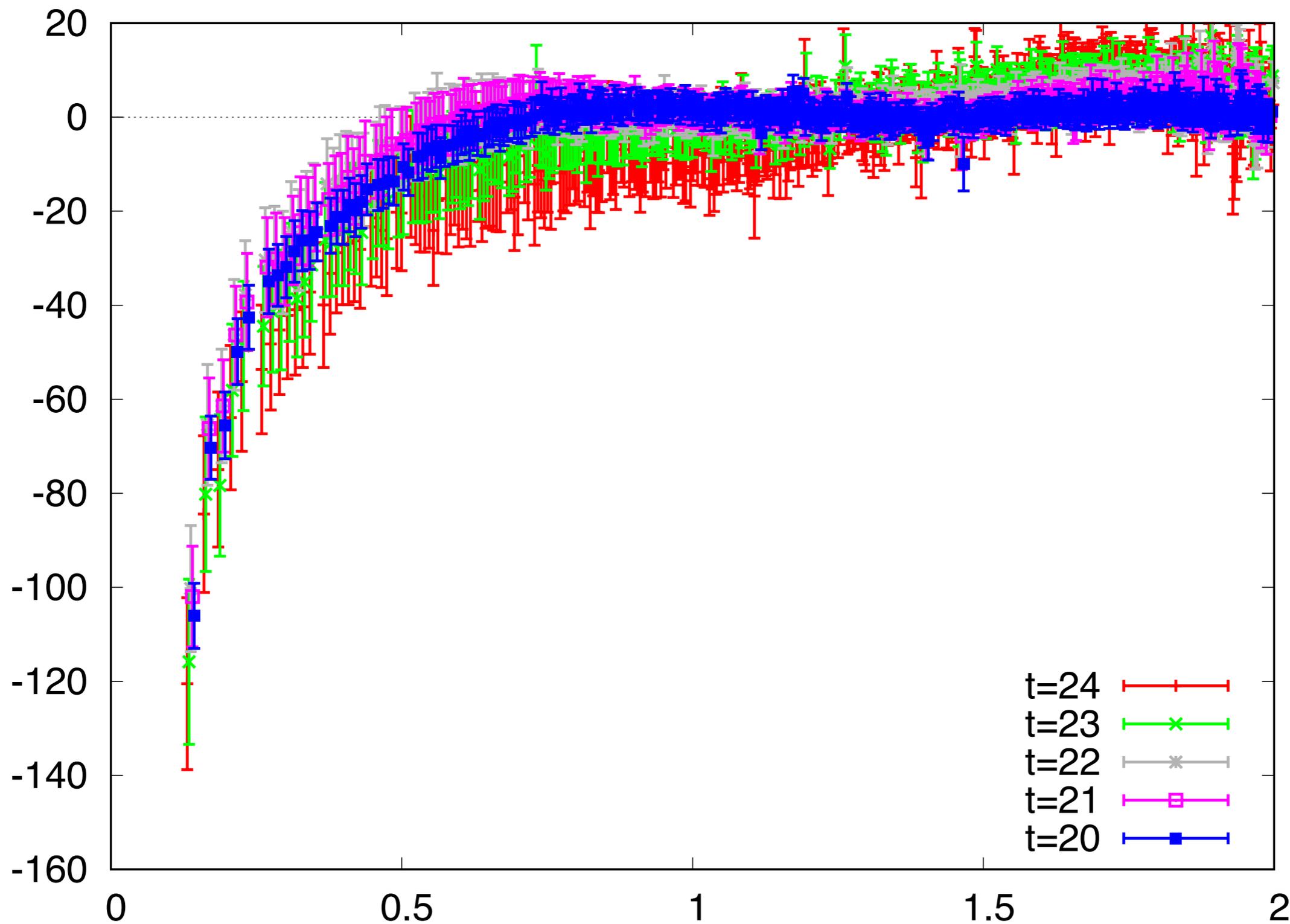
Consistency check of J/psi-N J=3/2



Consistency check of J/psi-N J=1/2

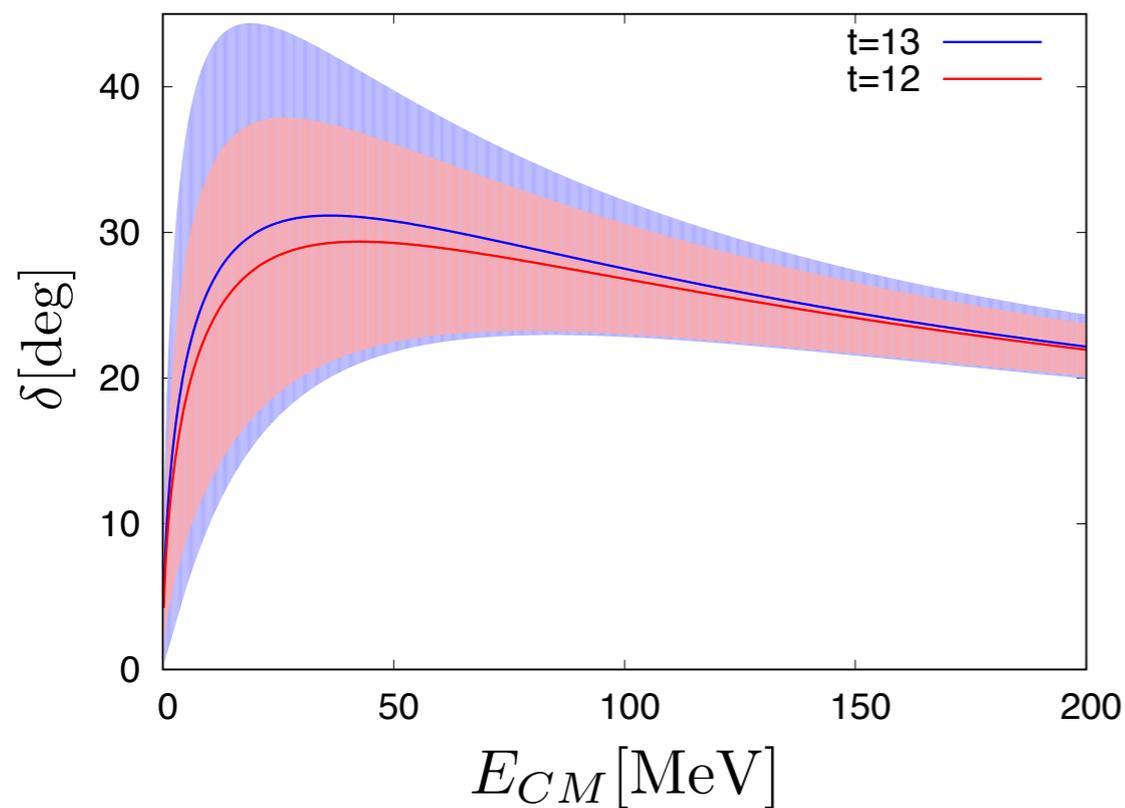


Consistency check of eta_c-N J=1/2



Phase shift

[arXiv:1711.11219]

**J/ψ-N (J=1/2)**

@t=12

$$a = 0.68 \pm 0.44 \text{ fm}$$

$$r = 1.04 \pm 0.03 \text{ fm}$$

J/ψ-N (J=3/2)

$$a = 0.63 \pm 0.42 \text{ fm}$$

$$r = 1.11 \pm 0.03 \text{ fm}$$

η_c-N

$$a = 0.44 \pm 0.34 \text{ fm}$$

$$r = 1.33 \pm 0.06 \text{ fm}$$