Numerical evaluation of gauge invariants in open string field theory

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arXiv:0901.nnnn[hep-th], to appear

Non-perturbative vacuum in bosonic open string field theory

- Schnabl's solution $\mathbf{\Psi_{Sch}}$

Gauge invariants

(1) Action: D-brane tension

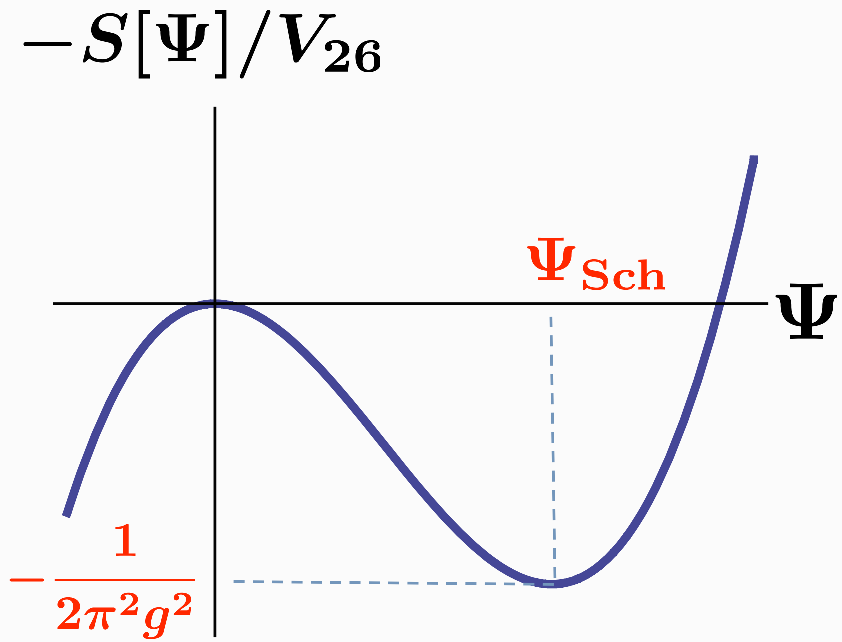
$$S[\Psi_{\rm Sch}]/V_{26} = \frac{1}{2\pi^2 g^2}$$

[Schnabl(2005),Okawa,Fuchs-Kroyter(2006)]

(2) Gauge invariant overlap:

$$\mathcal{O}_V(\Psi_{\rm Sch})/V_{26} = \frac{1}{2\pi}$$

[Ellwood, Kawano-Kishimoto-Takahashi(2008)]



Numerical solution by level truncation

- Numerical solution in the Siegel gauge : $b_0|\Psi_{\rm N}\rangle = 0$

  [...,Sen-Zwiebach(1999),...]

(1) $S[\Psi_{\rm N}]/S[\Psi_{\rm Sch}]$

(L,2L)-approx.		(L,3L)-approx.	
(2,4)	0.9485534	(2,6)	0.9593766
(4,8)	0.9864034	(4,12)	0.9878218
(6,12)	0.9947727	(6,18)	0.9951771
(8,16)	0.9977795	(8,24)	0.9979302
(10,20)	0.9991161	(10,30)	0.9991825
(12,24)	0.9997907	(12,36)	0.9998223
(14,28)	1.0001580	(14,42)	1.0001737
(16,32)	1.0003678	(16,48)	1.0003754
(18,36)	1.00049	(18,54)	1.0004937

[Gaiotto-Rastelli(2002)]

(2) $\mathcal{O}_V(\Psi_{\rm N})/\mathcal{O}_V(\Psi_{\rm Sch})$

(L,2L)-approx.		(L,3L)-approx.	
(2,4)	0.8783238	(2,6)	0.8898618
(4,8)	0.9294792	(4,12)	0.9319524
(6,12)	0.9501746	(6,18)	0.9510789
(8,16)	0.9606165	(8,24)	0.9611748
(10,20)	0.9677900	(10,30)	0.9681148
(12,24)	0.9723211	(12,36)	0.9725595
(14,28)	0.9760046	(14,42)	-

[Kawano-Kishimoto-Takahashi(2008)]
and the latest result

Evidence for gauge equivalence: $\Psi_{\rm N} \sim \Psi_{\rm Sch}$

Numerical solutions in a-gauges

- a-gauge [Asano-Kato] $(b_0 M + a\, b_0 c_0 \tilde{Q})|\Psi_a\rangle = 0$

  $Q = \tilde{Q} + c_0 L_0 + b_0 M$

$a = 0$ ⇒ Siegel gauge: $b_0|\Psi_0\rangle = 0$

$a = \infty$ ⇒ Landau gauge: $b_0 c_0 \tilde{Q}|\Psi_\infty\rangle = 0$

(1) For a-gauge solution, (6,18)-approx. $S[\Psi_a]/S[\Psi_{\rm Sch}]$

$a = \infty$	0.9609438
$a = 4.0$	0.9244886
$a = 0.5$	1.0045858
$a = -2.0$	0.9798943
⋮	⋮

[Asano-Kato(2006)]

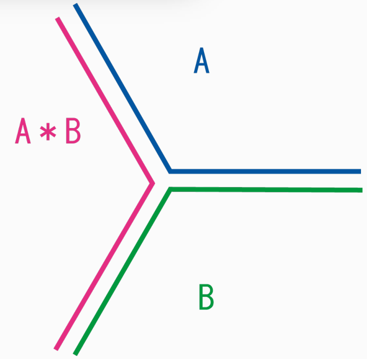
(2) $\mathcal{O}_V(\Psi_a)/\mathcal{O}_V(\Psi_{\rm Sch})$ (?) (and higher level?)

⇒ our computation

Bosonic cubic open string field theory

Action: $$S[\Psi] = -\frac{1}{g^2}\left(\frac{1}{2}\langle\Psi, Q\Psi\rangle + \frac{1}{3}\langle\Psi, \Psi*\Psi\rangle\right)$$

$$Q = \oint \frac{dz}{2\pi i}\left(cT^{\mathrm{m}} + bc\partial c + \frac{3}{2}\partial^2 c\right)$$



Equation of motion: $$Q\Psi + \Psi*\Psi = 0$$

Gauge transformation: $$\delta_\Lambda\Psi = Q\Lambda + \Psi*\Lambda - \Lambda*\Psi$$

$$\rightarrow \quad \delta_\Lambda S[\Psi] = 0$$

Restrict string field to twist even sector in the universal space:

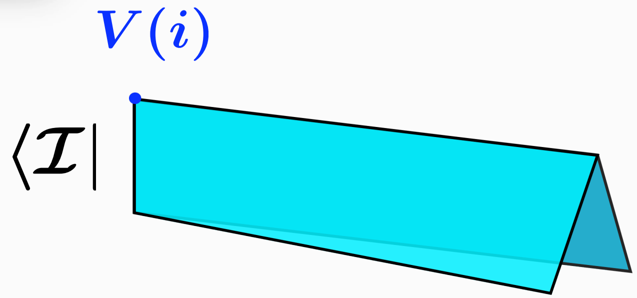
$$\Psi = (t_1 + t_2 b_{-1}c_{-1} + t_3 L^{(\mathrm{m})}_{-2} + \cdots)c_1|0\rangle + (u_1 b_{-2} + \cdots)c_0 c_1|0\rangle$$

Gauge invariant overlap

Gauge invariant for on-shell closed string state

$$\mathcal{O}_V(\Psi) = \langle \mathcal{I}|V(i)|\Psi\rangle = \langle \hat{\gamma}(1_c, 2)|\Phi_V\rangle_{1_c}|\Psi\rangle_2$$

$$|\Phi_V\rangle = c_1\bar{c}_1|V_m\rangle$$



V_m :matter primary with (1,1)-dim.

$$\rightarrow \quad \delta_\Lambda \mathcal{O}_V(\Psi) = 0$$

Ellwood's proposal (2008): $\mathcal{O}_V(\Psi) = \mathcal{A}_\Psi^{\rm disk}(V) - \mathcal{A}_0^{\rm disk}(V)$

↑

Disk amplitude for a closed string vertex V specified by a solution Ψ

In particular, $\mathcal{O}_V(\Psi_{\rm Sch}) = 0 - \mathcal{A}_0^{\rm disk}(V)$

$|\Phi_V\rangle = -\frac{1}{26}\eta_{\mu\nu}\alpha^\mu_{-1}\bar{\alpha}^\nu_{-1}c_1\bar{c}_1|0\rangle$ for explicit numerical computation

Construction of numerical solutions

$\Psi_0 = \frac{64}{81\sqrt{3}} c_1|0\rangle$: nontrivial solution for (0,0)-approx.

$(b_0 M + a\, b_0 c_0 \tilde{Q})\Psi_{n+1} = 0$: a-gauge condition

$\mathcal{P}(Q_{\Psi_n}\Psi_{n+1} - \Psi_n * \Psi_n) = 0$: linear equations!

$\mathcal{P} = c_0 b_0$:a projection to solve equations

$Q_{\Psi_n}\Phi \equiv Q\Phi + \Psi_n * \Phi - (-1)^{|\Phi|}\Phi * \Psi_n$:"BRST op." around Ψ_n

We can define $\Psi_n \longmapsto \Psi_{n+1}$

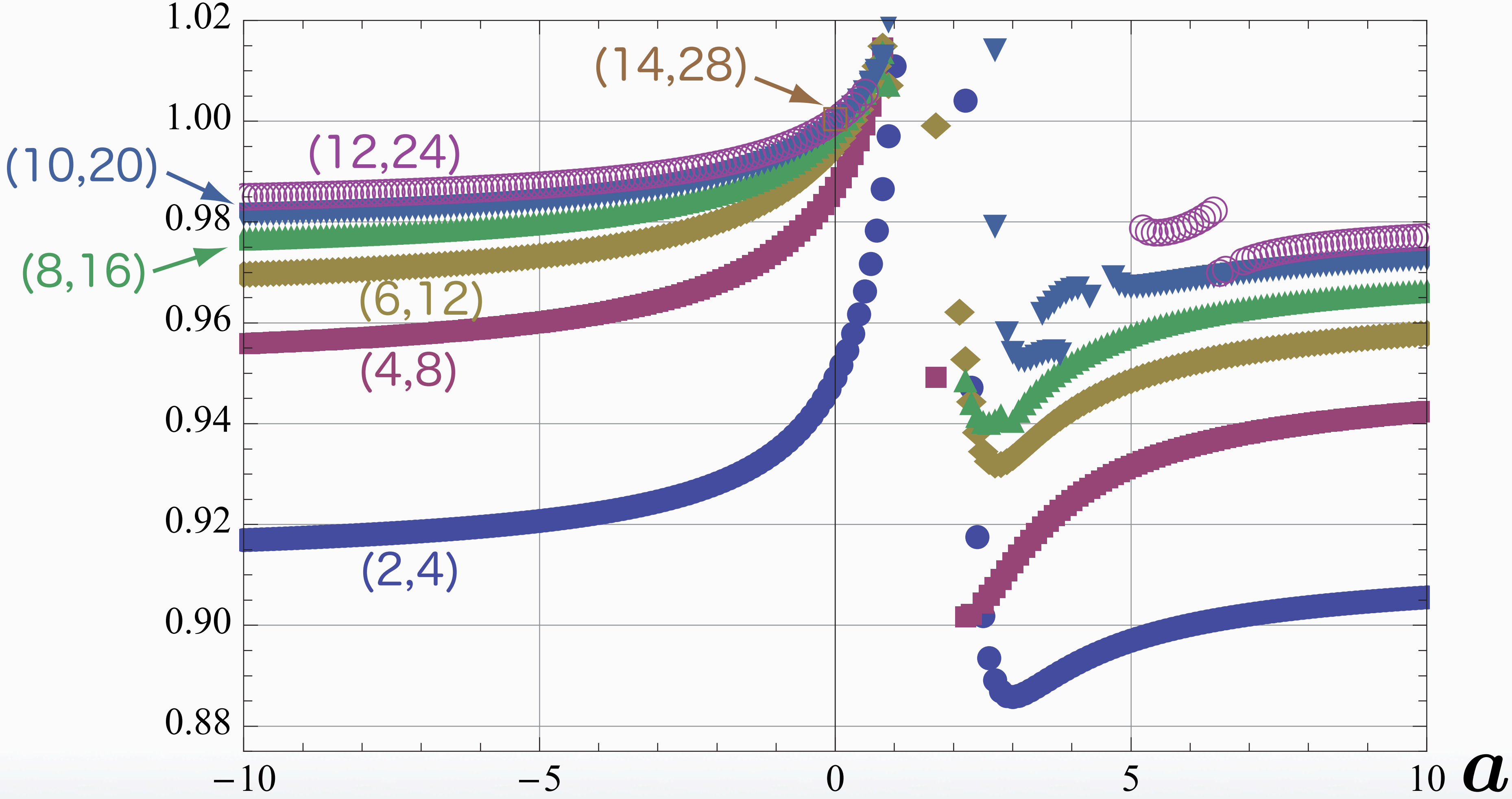
$\Psi_{n+1} \simeq (Q_{\Psi_n})^{-1}(\Psi_n * \Psi_n)$ [Gaiotto-Rastelli(2002)]

If it converges for $n \longrightarrow \infty$,

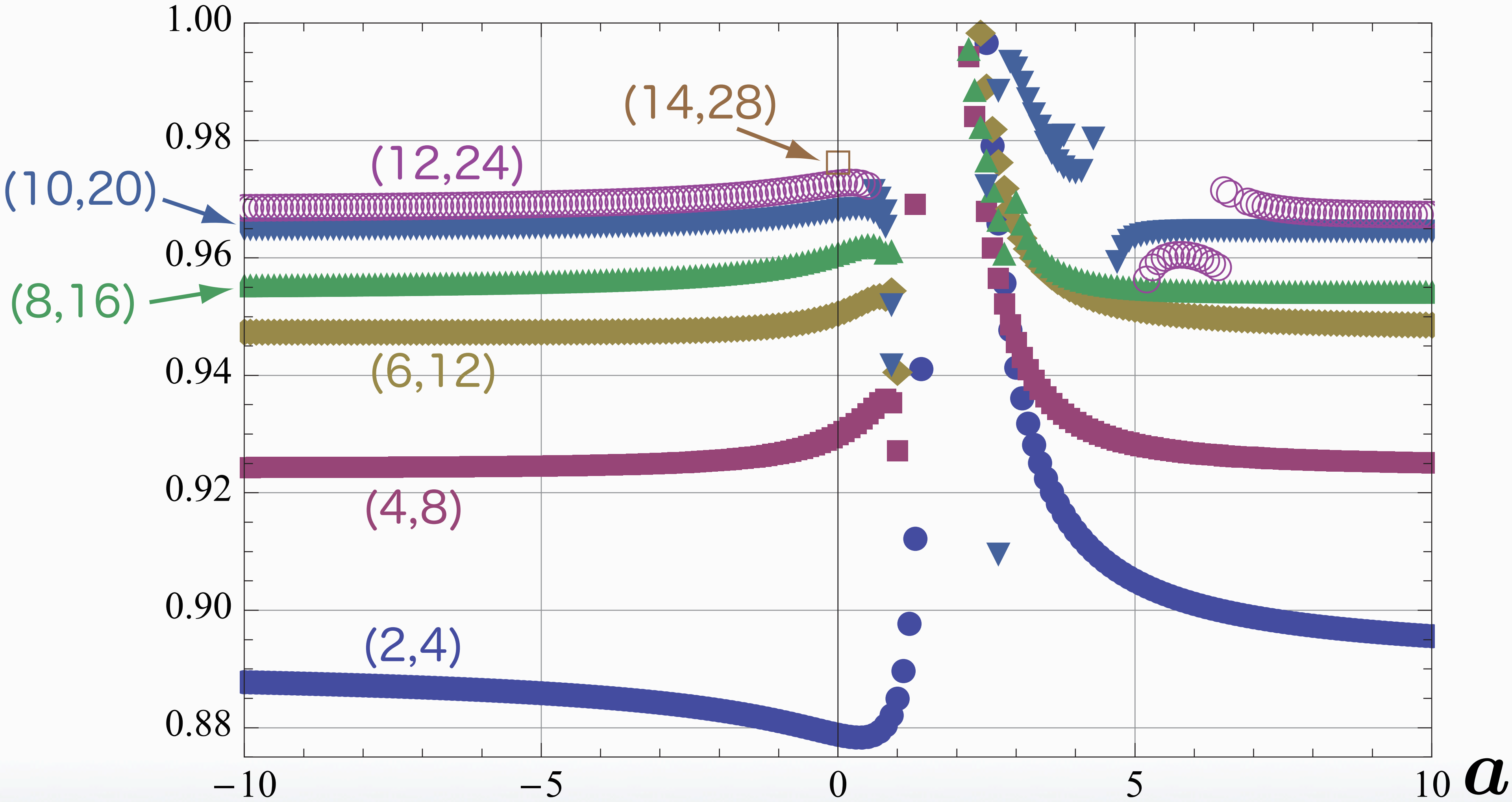
$(b_0 M + a\, b_0 c_0 \tilde{Q})\Psi_\infty = 0$: a-gauge condition

$\mathcal{P}(Q\Psi_\infty + \Psi_\infty * \Psi_\infty) = 0$: projected part of eq. of motion

$S[\Psi_a]/S[\Psi_{\mathbf{Sch}}]$ (L,2L)-approx.

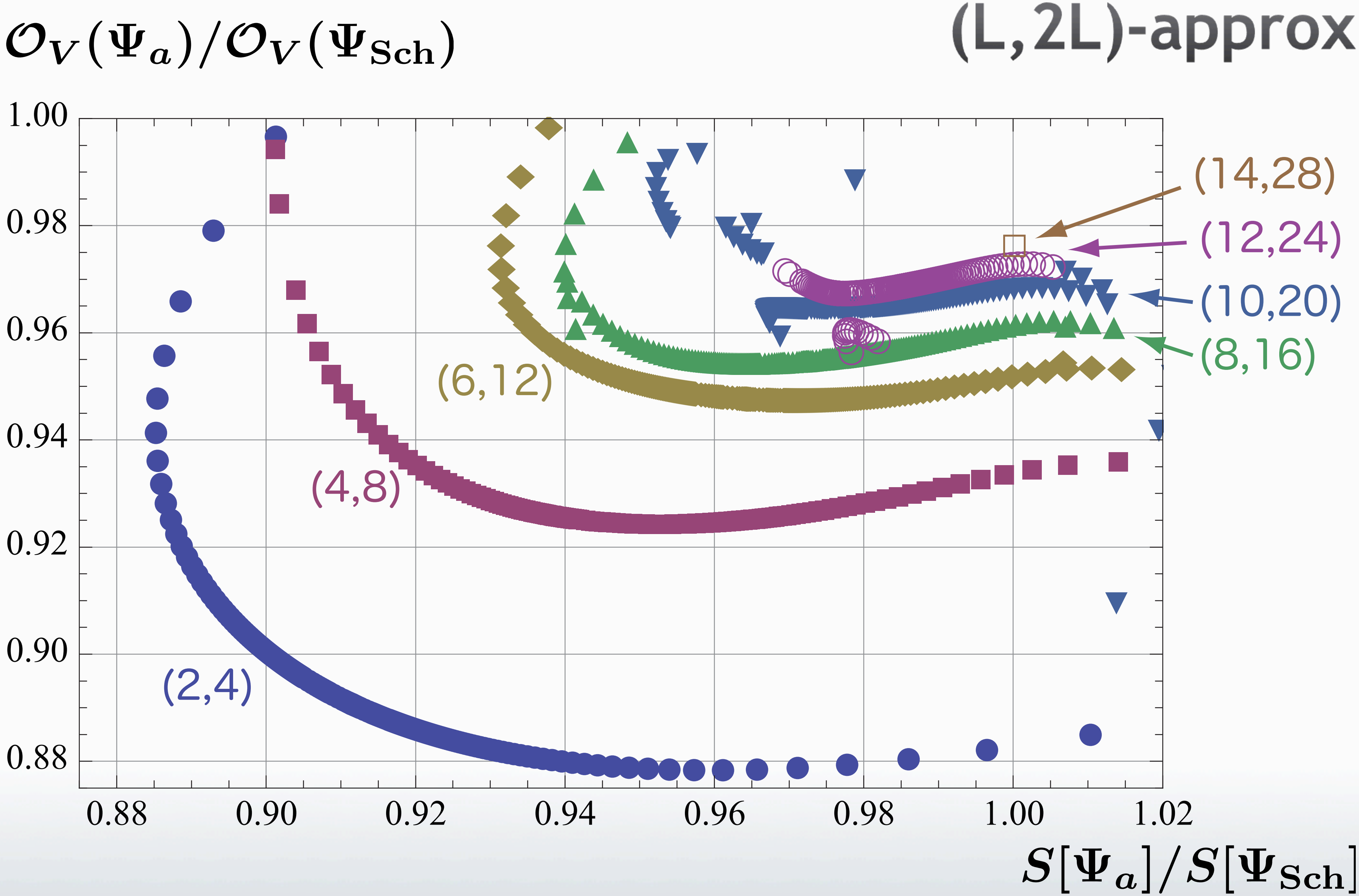


$\mathcal{O}_V(\Psi_a)/\mathcal{O}_V(\Psi_{\mathrm{Sch}})$ (L,2L)-approx.



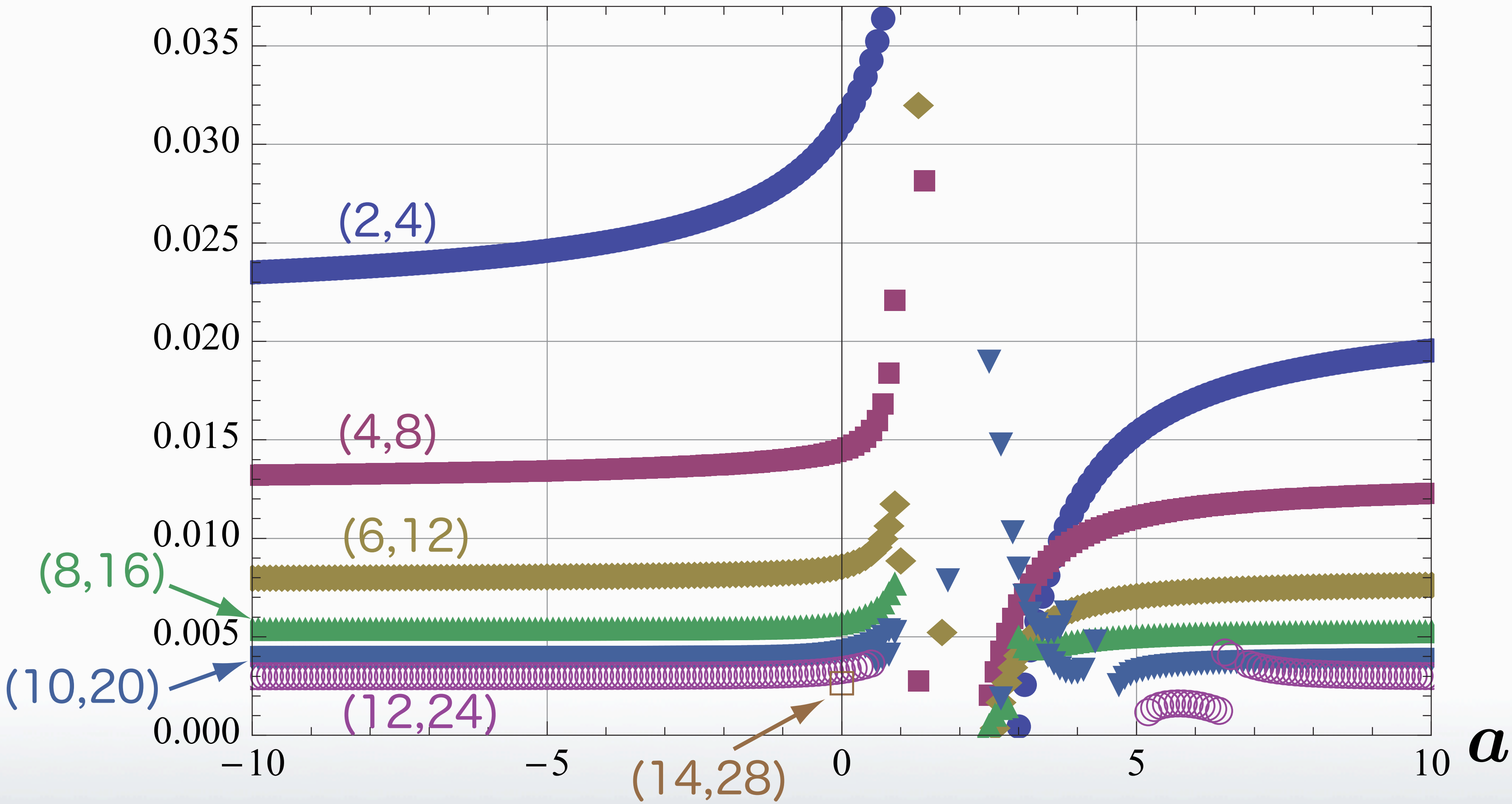
Gauge invariants for various a-gauge solutions

(L,2L)-approx.

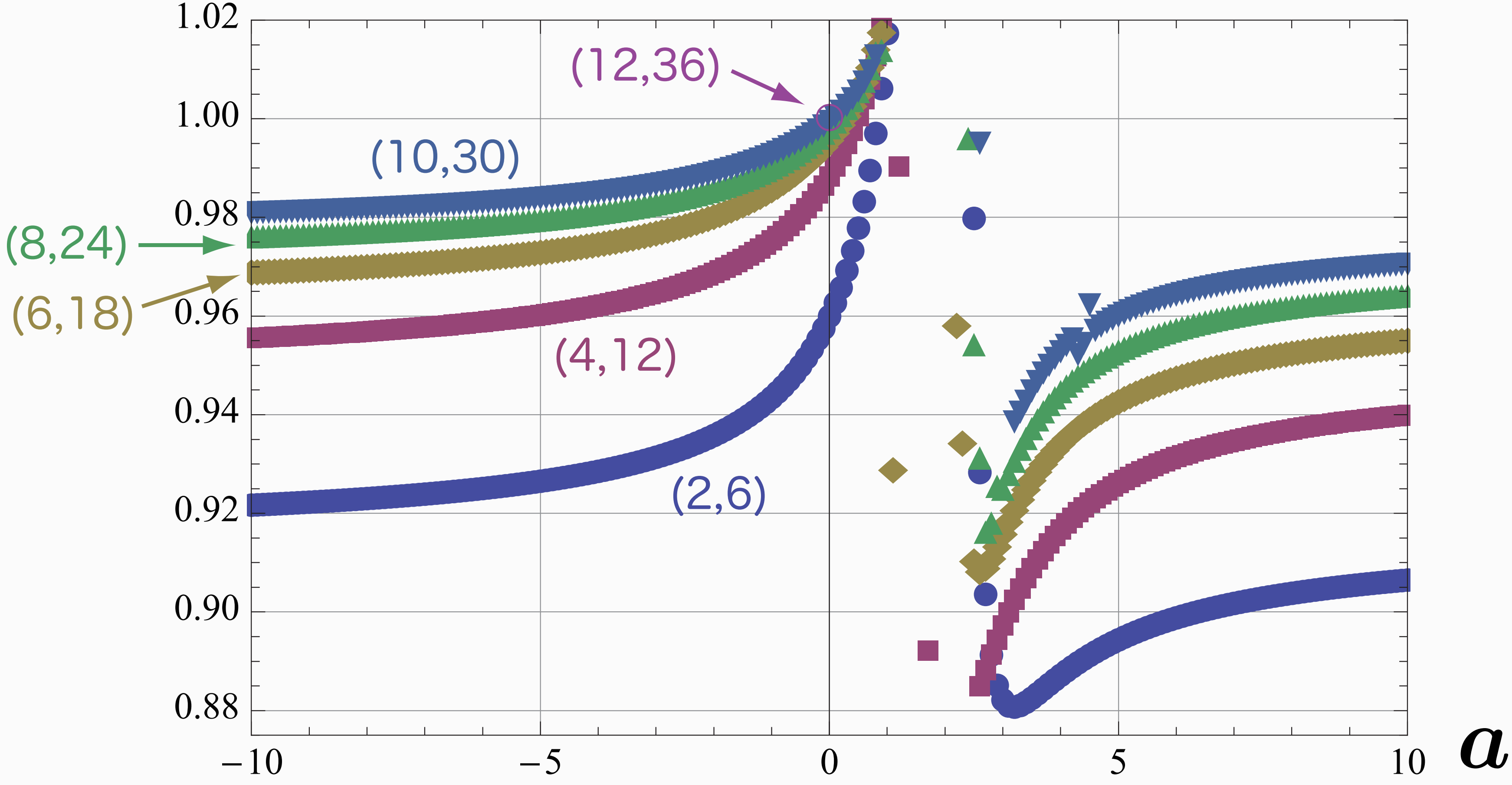


Coefficient of $c_{-2}c_1|0\rangle \in (1-\mathcal{P})(Q\Psi_a+\Psi_a*\Psi_a)$

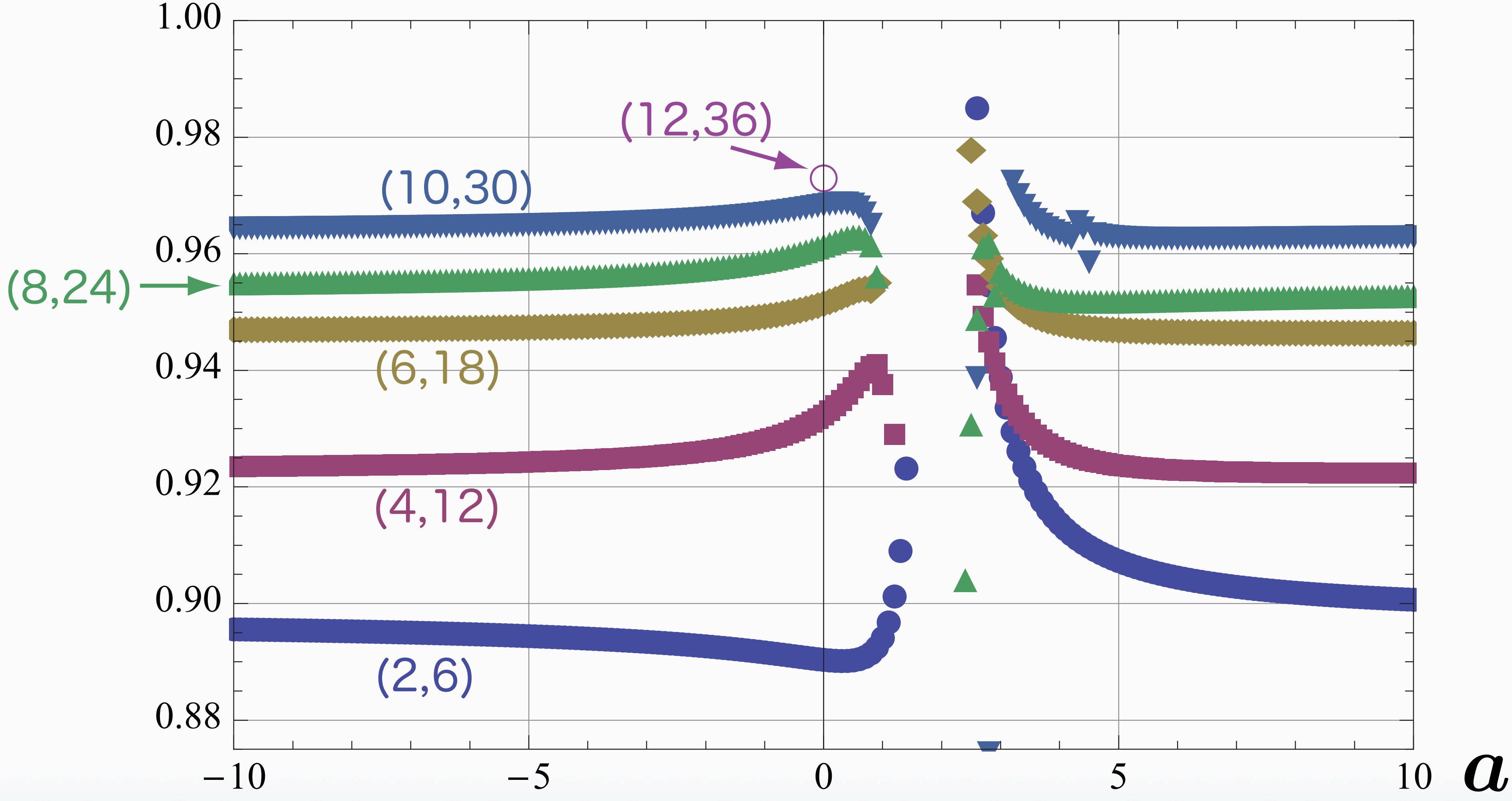
(L,2L)-approx.



$S[\Psi_a]/S[\Psi_{\mathbf{Sch}}]$ (L,3L)-approx.



$\mathcal{O}_V(\Psi_a)/\mathcal{O}_V(\Psi_{\mathrm{Sch}})$ (L,3L)-approx.



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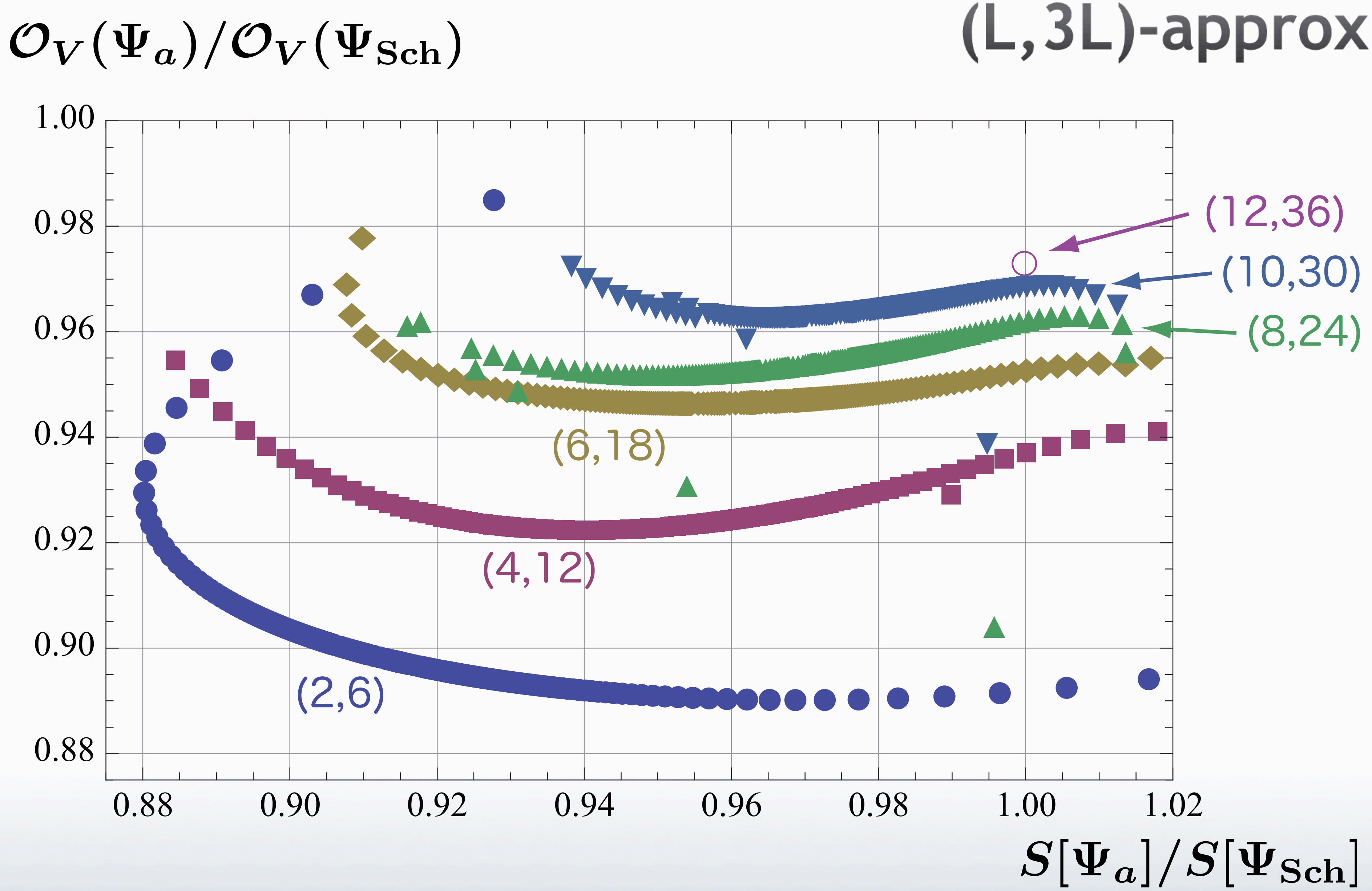

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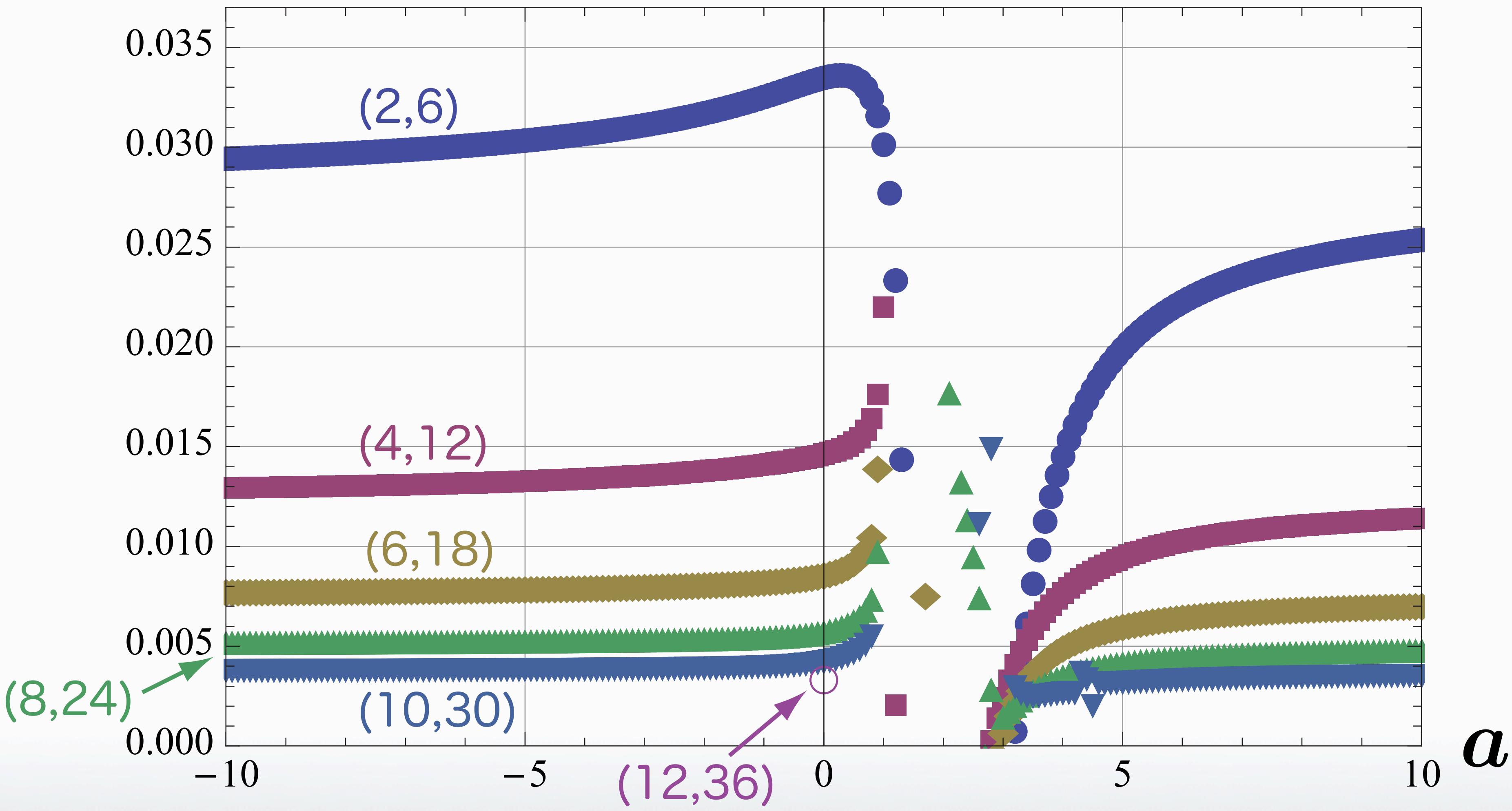

Summary

- We have evaluated gauge invariants (action and gauge invariant overlap) for numerical solutions in a-gauges by level truncation approximation.

- We have checked "BRST invariance" of solutions.

- For $-\infty \leqq a \lesssim 0,\ 1 \ll a \leqq \infty$, they reproduce analytic values of Schnabl's solution.

- The results are consistent with the expectation that these solutions in a-gauges are gauge equivalent to Schnabl's solution and represent unique non-perturbative vacuum.

※Perturbatively, $a = 1$ -gauge is ill-defined.