$K \to \pi\pi$ and ε'

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$K \to \pi\pi$ & direct CPV

CP odd — CP even

$$|K_L\rangle = |K_2\rangle + \varepsilon |K_1\rangle$$

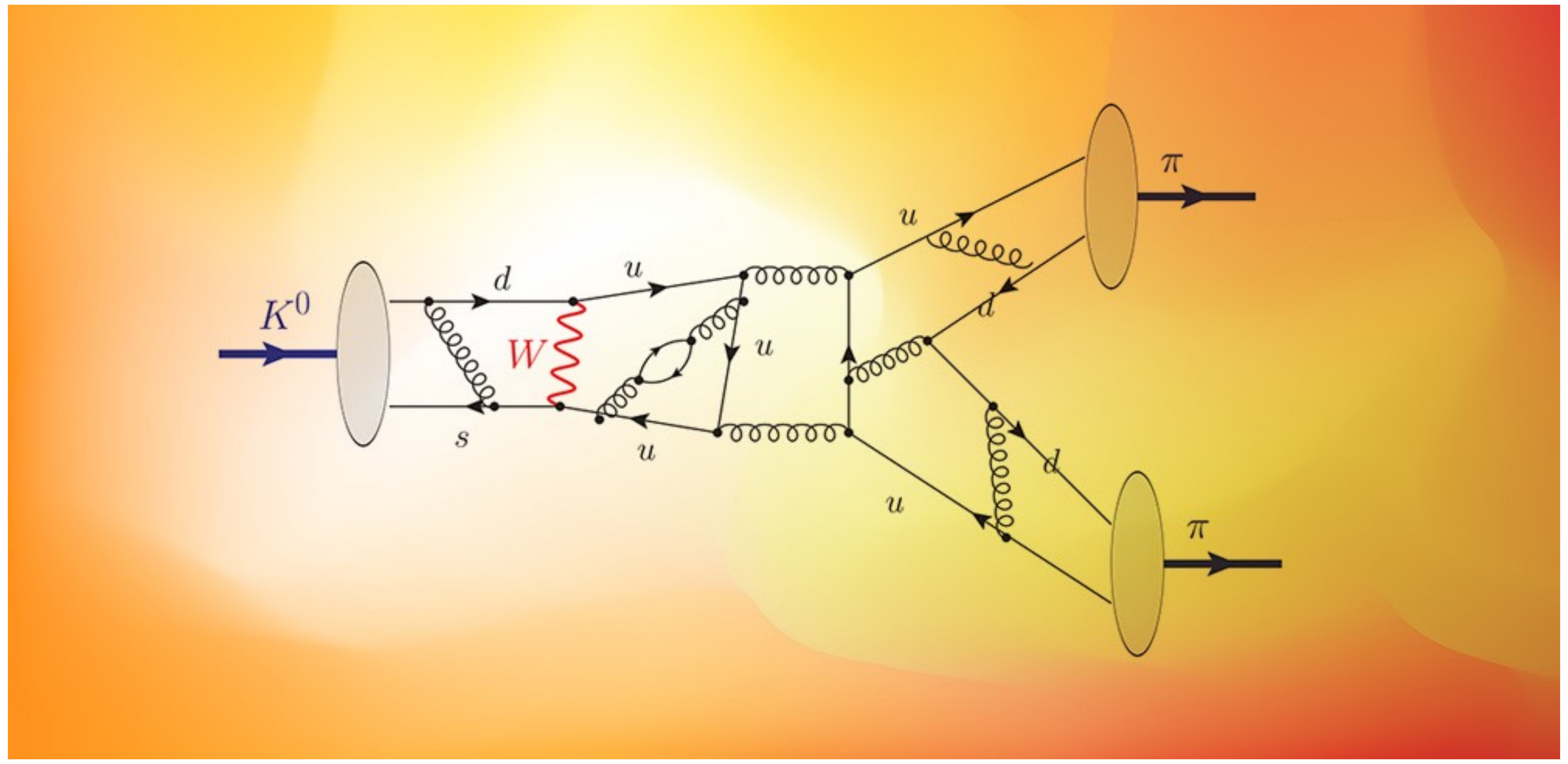
ε' direct CPV

ε indirect CPV

$|\pi\pi\rangle$

CP even

- ε' vs ε
  - Re $(\varepsilon'/\varepsilon)_{exp}$ = 16.6(2.3) x 10^{-4} (KTeV, NA48)
  - Explained by SM?



Calculation with G-parity BC

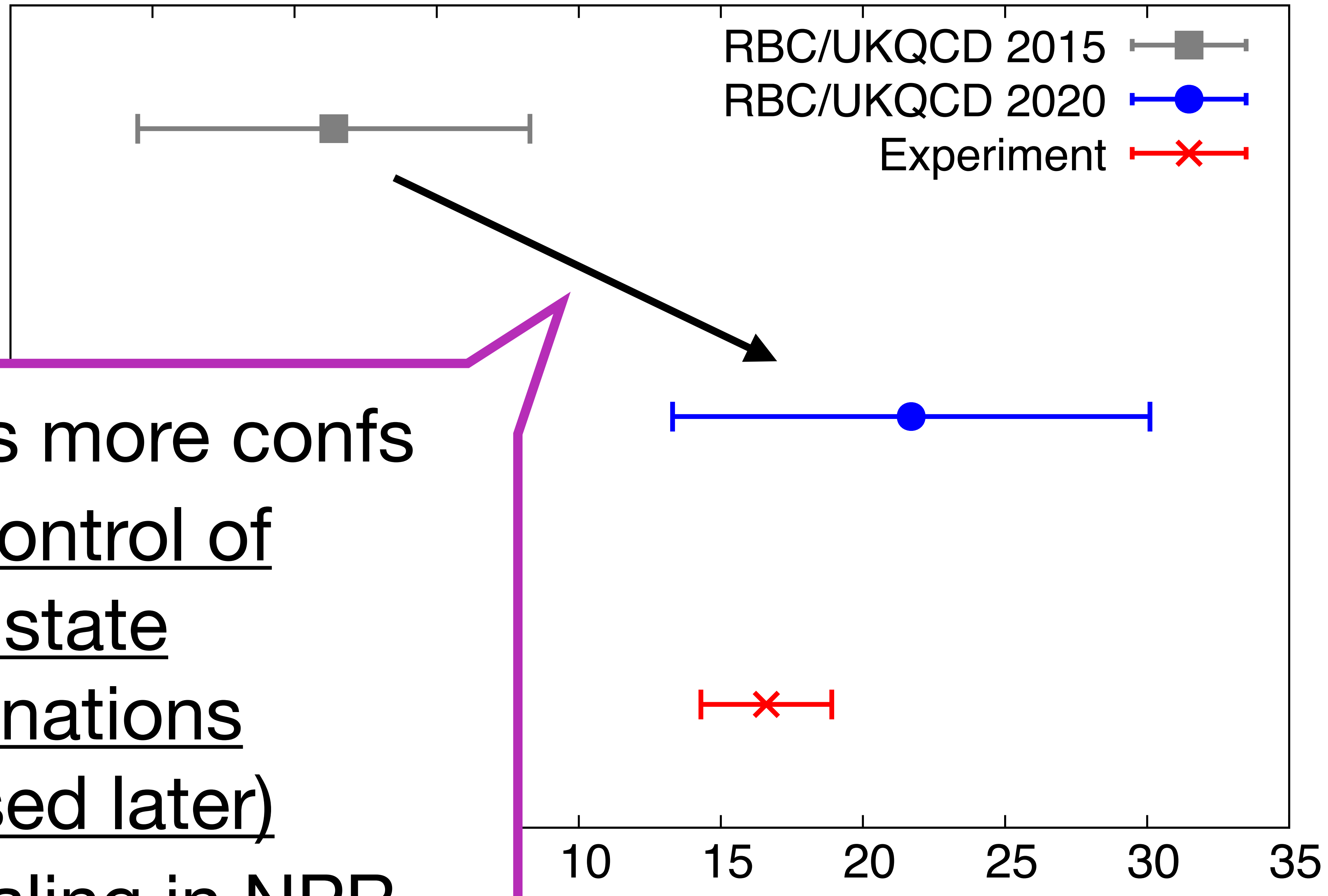
Ground ππ final state can express on-shell kinematics

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \approx \frac{\omega}{\sqrt{2}|\epsilon|}\left[\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}\right]$$

(Amplitudes: $A_I = <(\pi\pi)_I \,|\, H_W \,|\, K>$)

$(\omega = \mathrm{Re}\,A_2/\mathrm{Re}\,A_0)$

Re(ε′/ε) x10[4]



- 3+ times more confs
- Better control of excited-state contaminations (discussed later)
- Step scaling in NPR

- $\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)_{SM} = 21.7(2.6)_{stat}(6.2)_{sys}(5.0)_{EM/IB} \times 10^{-4}$
  - PRD 102,054509 (2020)

🤝

$\mathrm{Re}(\epsilon'/\epsilon)_{exp} = 16.6(2.3) \times 10^{-4}$

- Independent calculations desired
  - Phenomenological importance of ε′
  - Relatively large uncertainty compared to exp
- Major sources of systematic errors
  - QED & IB corrections
  - Finite lattice spacing effects
  - Wilson coefficients

Why periodic BC?

- Already have lattice ensembles with physical pion mass
  - a^{-1} = 1 GeV, 24^3 x 64 & a^{-1} = 1.4 GeV, 32^3 x 64 & …
  - Continuum limit without new ensemble generation
- Hope to introduce QED/IB effects near future
  - Complicated with G-parity BC (violation of charge conservation)
  - Maybe possible with periodic BC
- Presence of $E_{\pi\pi} = 2m_\pi$ state challenging
  - interesting to see feasibility of extracting signal of excited states

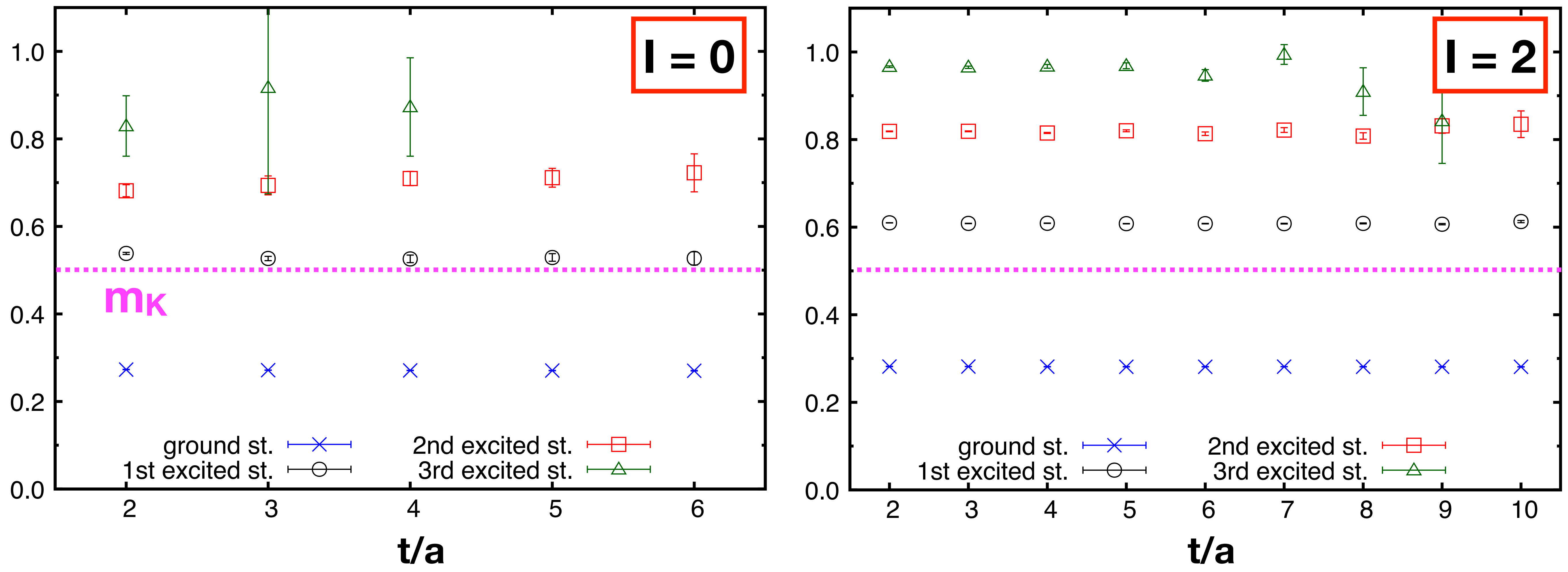
Setup

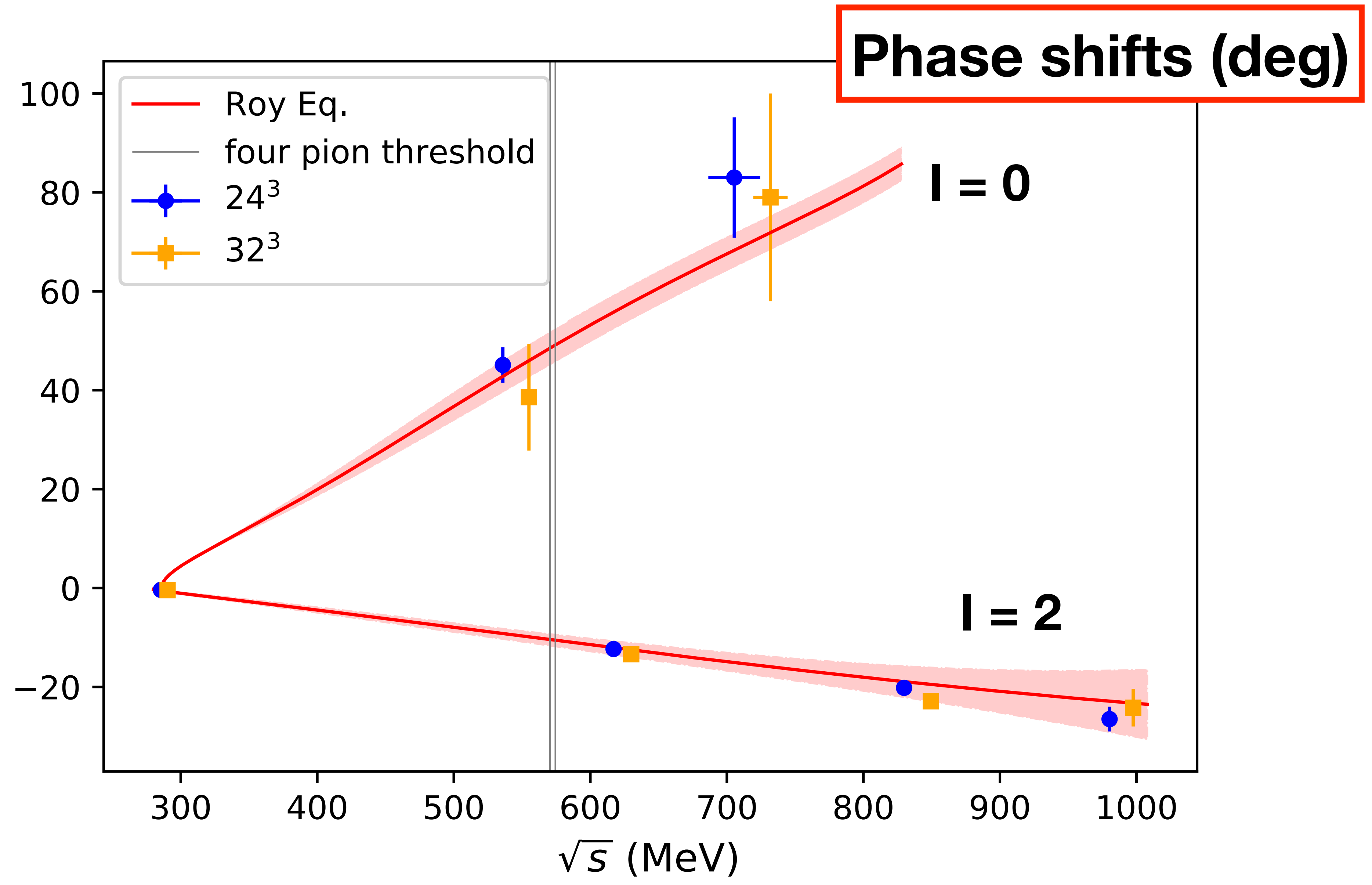
- 2+1 MDWF ensembles with physical m_π (RBC/UKQCD)
  - a^{-1} = 1.02 GeV, 24^3 x 64
  - a^{-1} = 1.38 GeV, 32^3 x 64
- GEVP to extract ME with excited ππ states
  - $O_\pi(\vec{p})O_\pi(-\vec{p})$ w various $\vec{p}$
  - O_σ: iso-singlet scalar operator for I = 0
  - also control higher-state contamination
- All-to-all propagator method
- AMA correction (exact calculation w fewer confs)

Achievements

- ππ scattering
  - GEVP successfully worked
  - m_K close to 1st excited state
  - Phase shifts from Lüscher's method consistent with Roy equation
- arXiv: 2301.09286 [hep-lat]

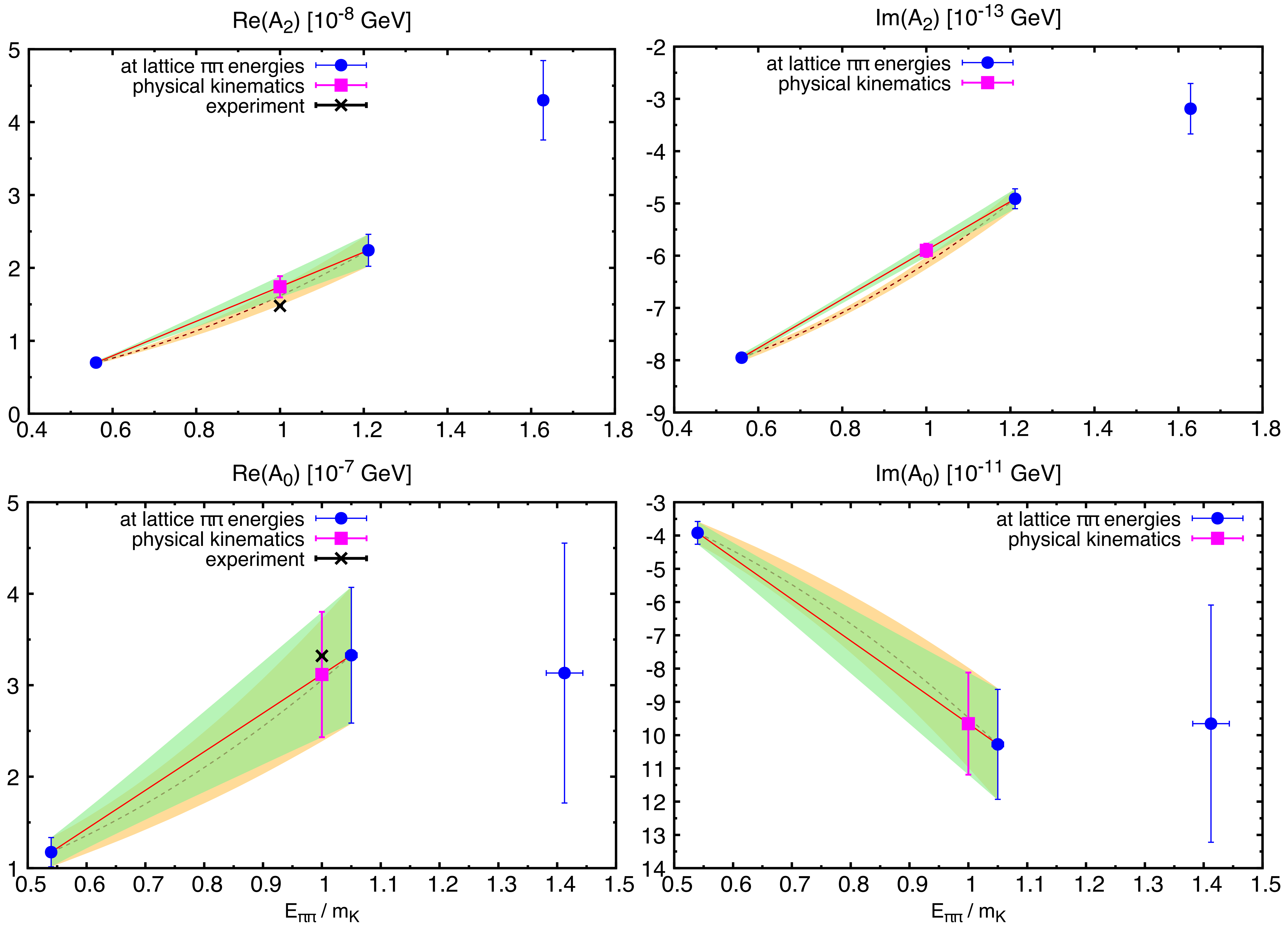
Effective energies (lattice units)





Achievements

- $K \to \pi\pi$ amplitudes
- Interpolation to physical kinematics
- Paper to be on arXiv soon



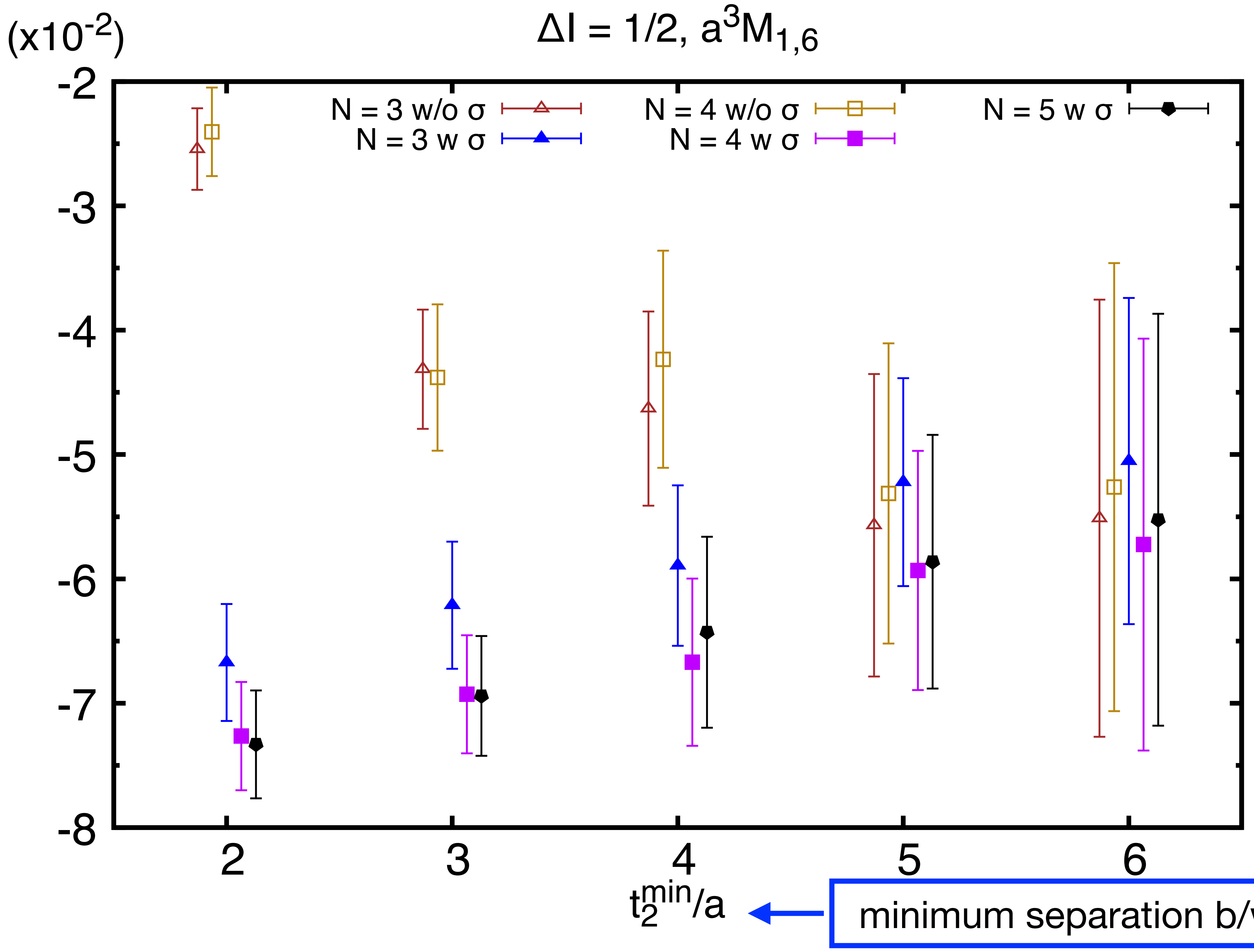
Goal vs where we are

- Goal (for next allocation year): continuum limit of A_0 with < 10% stat error
  - then only a few sources of systematic errors to be taken into account
- Measurements so far
  - 450 configs on 24^3 done
  - 250 configs on 32^3 almost done → 500 in the 23–24 allocation year
- Precision performance and expect

	24^3 x 64	32^3 x 64		24^3 x 64 (expectation)	32^3 x 64 (expectation)
N_{conf}	258	107	→	450	500
Stat error on $\mathrm{Re}A_0$	22%	16%	→	17%	7.4%
Stat error on $\mathrm{Im}A_0$	15%	16%	→	11%	7.4%

- might need some improvement to achieve 10% after continuum limit

Dominant source of stat error on $\mathrm{Im}A_0$



- $\Delta I = 1/2$ matrix element of Q_6
  - most significant for $\mathrm{Im}A_0$
- Various GEVP bases w N operators
- 258 confs on $24^3 \times 64$

minimum separation b/w ππ operator and Q_6

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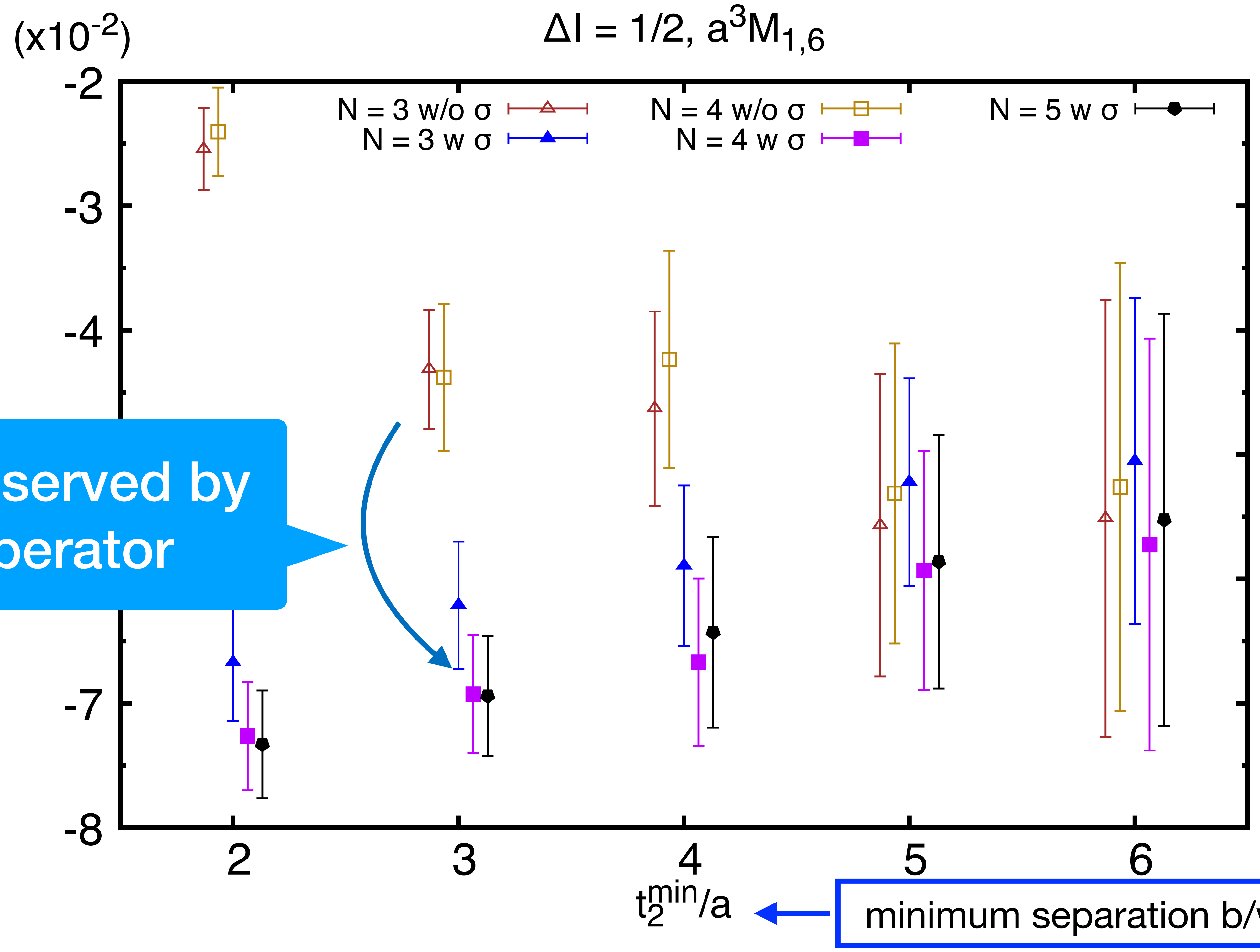

Significant shift observed by introducing σ operator

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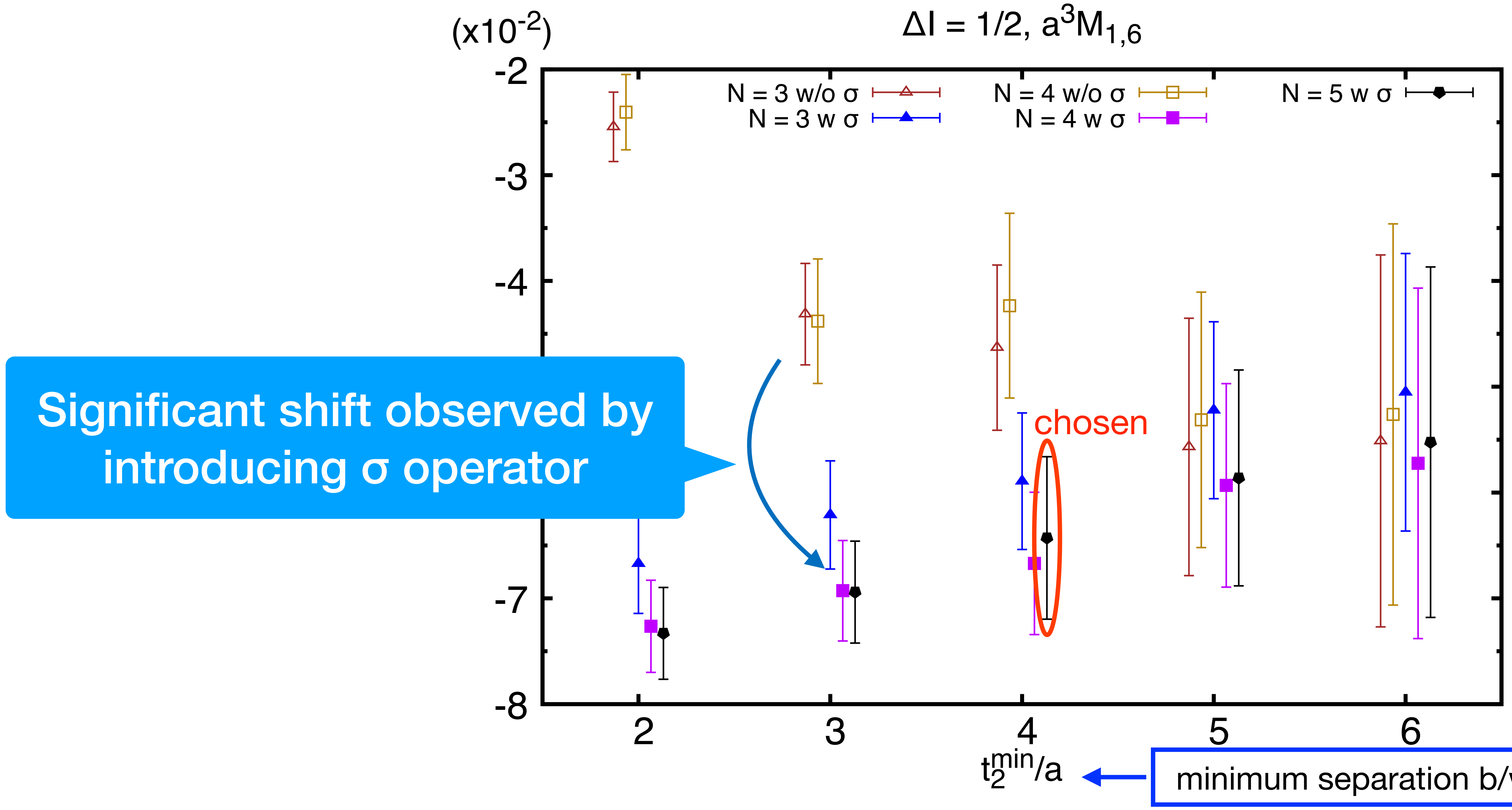

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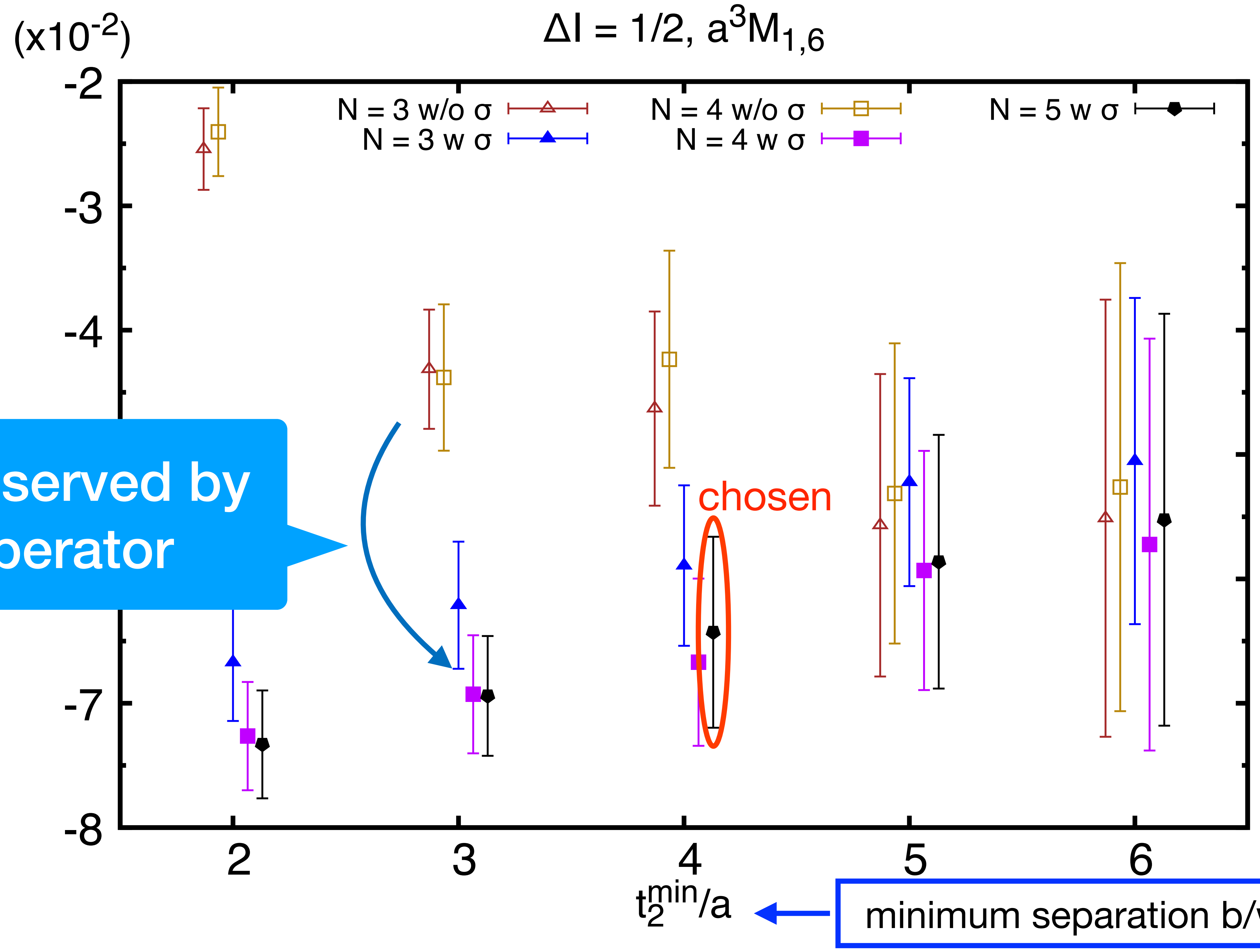

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No evidence of significant excited-state contamination w σ but any room for further improvement?

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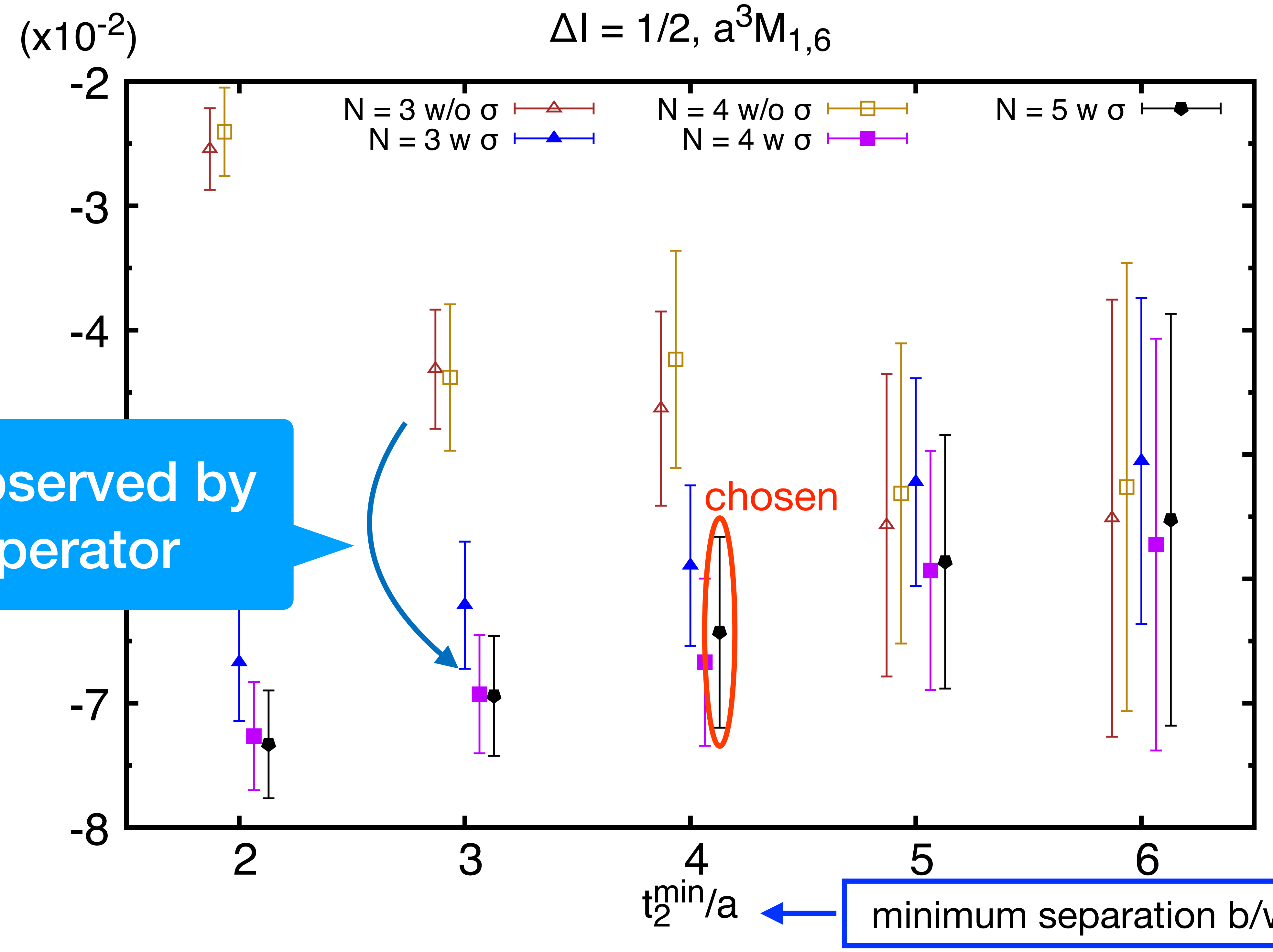

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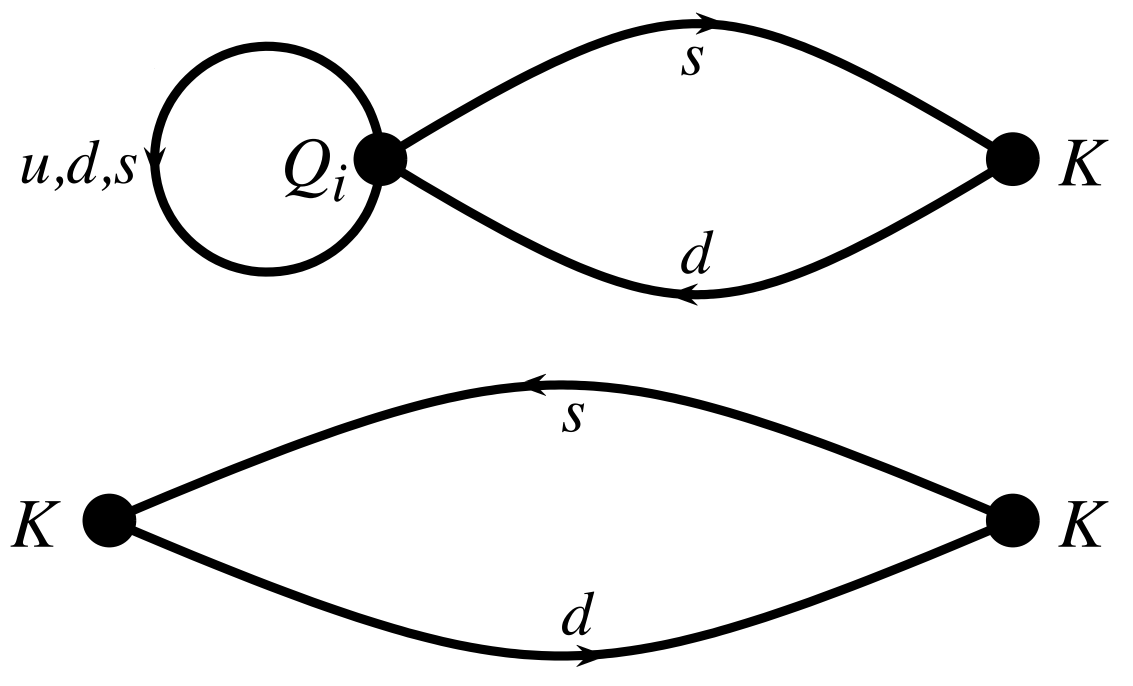
minimum separation b/w ππ operator and Q_6

Introducing a KK sink operator in 23–24 alloc year

- very cheap to implement (we have saved needed meson fields)
- can take care of potential contamination from $\langle KK \mid Q_i \mid K\rangle$
- give a few new types of diagrams



NPR

- Significant dependence on intermediate renormalization scheme & scale found
  - RI-SMOM($\not{q},\not{q}$) vs RI-SMOM(γ_μ,γ_μ) schemes
  - $\mu \approx 1.48a^{-1}$ → big difference up to 15%
  - $\mu \approx 1.28a^{-1}$ → 3–4%, ok but
  - $(1.48/1.28)^2 \neq 15\% / 4\%$ is concerning
- Plan to calculate with a few more intermediate scales to better understand in 23–24 alloc year
- Code is ready

Summary

- Goal: continuum limit with ≤10% stat error on A_0
  - More statistics: additional measurements on 32^3 lattice to 500 confs
  - Better control of systematic errors – NPR
  - Improvement ideas (KK sink operator, …)
- Request at JLab
  - 37 M KNL core hours
  - Carry forward current 200 TB disk
  - Additional 530 TB on short-term tape