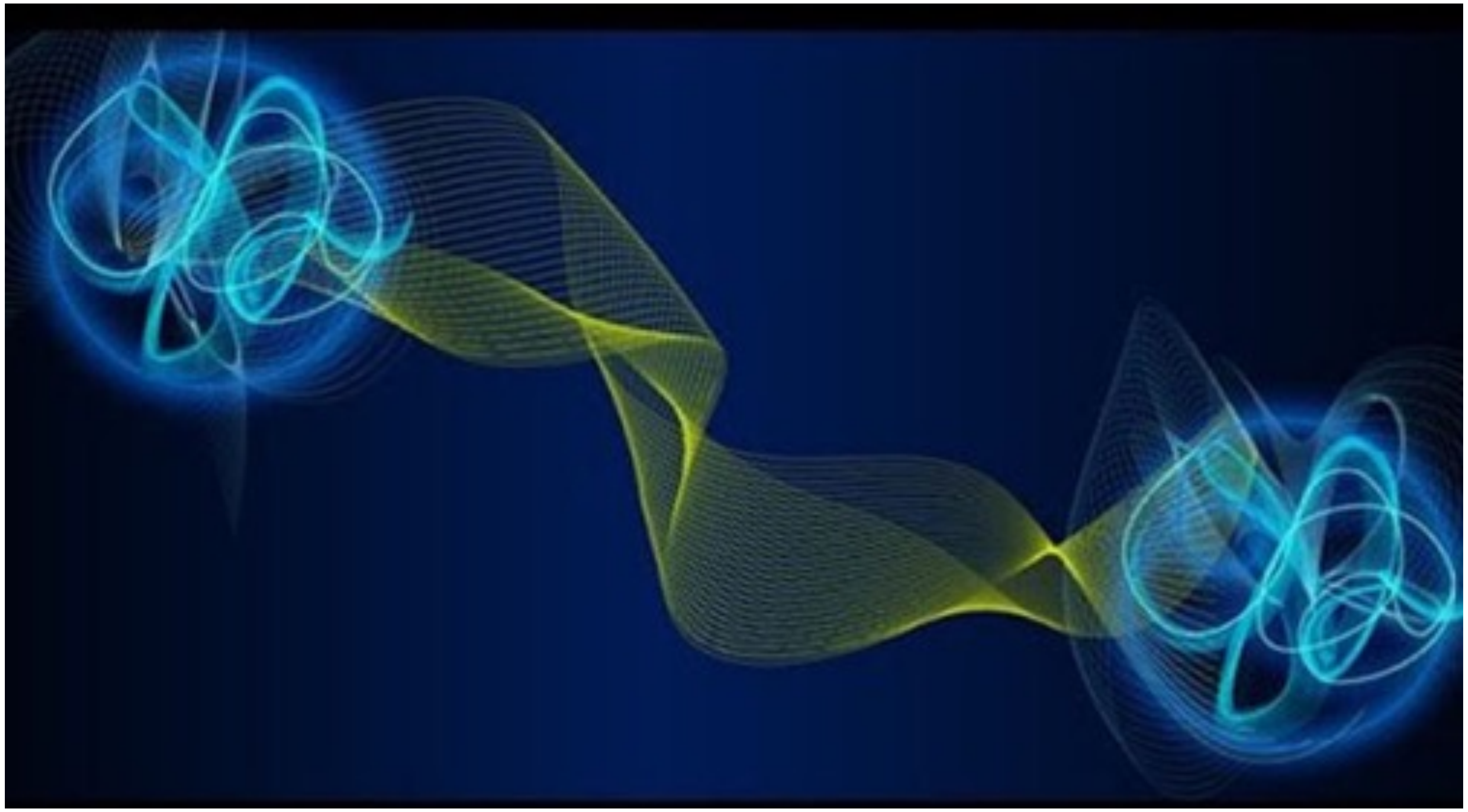
Entanglement Suppression and Emergent Symmetry



S. Beane, DBK, N. Klco, M. Savage, PRL 122, 102001 (2019), arXiv: 1812.03138

Symmetry is the theorist's friend:

- Gauge symmetries
- (Approximate) global symmetries
- Anomalous symmetries

- UV more symmetric than IR
  - ✦ Spontaneously broken symmetries
  - ✦ UV fixed point
- IR more symmetric than UV
  - ✦ IR fixed point
  - ✦ Accidental symmetries

Discovering symmetries of UV or explaining apparent symmetries of IR tells us more about the theory

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This talk:
Searching for an explanation of peculiar IR symmetries of QCD

Emergent symmetries seen in baryon-baryon interactions:

i. SU(4), SU(6) spin-flavor symmetry

ii. SU(4) Wigner symmetry

iii. Schrödinger (conformal) symmetry

iv. SU(16) (?!) in baryon octet

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Large-N_c explanation

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Large-N_c explanation

No conventional explanation

Approximate SU(4), SU(6) spin-flavor symmetry (1960s)

SU(4):

$$4 = \begin{pmatrix} u\uparrow \\ u\downarrow \\ d\uparrow \\ d\downarrow \end{pmatrix}$$

SU(6):

$$6 = \begin{pmatrix} u\uparrow \\ u\downarrow \\ d\uparrow \\ d\downarrow \\ s\uparrow \\ s\downarrow \end{pmatrix}$$

- Approximate symmetry of non-relativistic quark model
- Approximate symmetry apparent in nature:
    - masses
    - magnetic moments & transitions
    - semi-leptonic currents
    - meson-baryon couplings
    - NN scattering

SU(4), SU(6) spin-flavor symmetry

- Cannot be a symmetry of relativistic QFT (Coleman-Mandula)
- For baryon-meson couplings, does follow from QCD in large-N_c limit

Gervais, Sakita (1984); Dashen, Manohar (1993), Dashen, Jenkins, Manohar (1994)

(a) (b)

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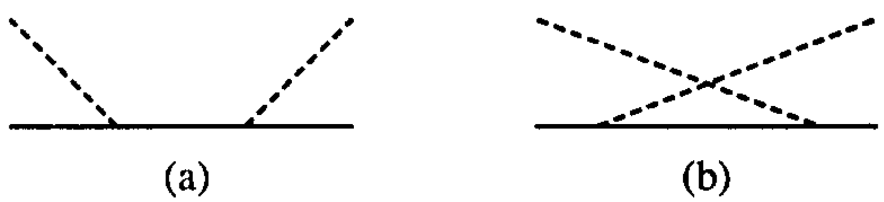
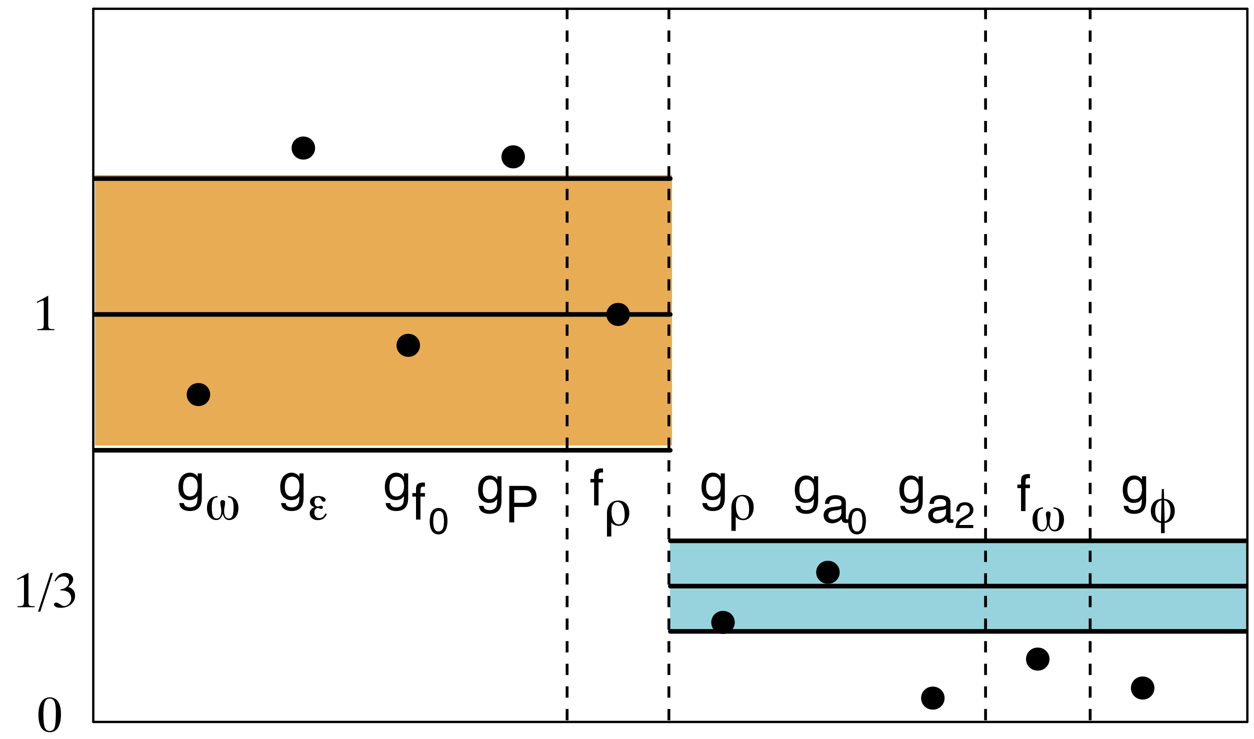


But what about baryon-baryon interactions?

Is large-N_c is evident in nuclear physics? Yes!

- Large-N_c seems to also work in nuclear physics:



DBK, A. Manohar (1996)

Comparison of phenomenological models vs large-N predictions

- ...and large-N_c implies spin-flavor symmetries in low energy baryon-baryon interactions... DBK, M.J. Savage (1995)

SU(2N$_f$) spin-flavor symmetries in low energy baryon-baryon interactions can from large-N$_c$

- N$_f$ = 2: nucleons + Δs in 20 dim irrep of SU(4)

$$\mathcal{L}_6 = -\frac{1}{f_\pi^2}\left[a(\Psi^\dagger_{\mu\nu\rho}\Psi^{\mu\nu\rho})^2 + b\Psi^\dagger_{\mu\nu\sigma}\Psi^{\mu\nu\tau}\Psi^\dagger_{\rho\delta\tau}\Psi^{\rho\delta\sigma}\right]$$

$$\Psi^{(\alpha i)(\beta j)(\gamma k)} = \Delta^{ijk}_{\alpha\beta\gamma} + \frac{1}{\sqrt{18}}\left(N^i_\alpha\epsilon^{jk}\epsilon_{\beta\gamma} + N^j_\beta\epsilon^{ik}\epsilon_{\alpha\gamma} + N^k_\gamma\epsilon^{ij}\epsilon_{\alpha\beta}\right)$$

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- $N_f = 2$ (restricted to nucleons)

$$\mathcal{L}_6 = -\tfrac{1}{2}C_S(N^\dagger N)^2 - \tfrac{1}{2}C_T(N^\dagger\vec{\sigma}N)^2$$ ➢ general Weinberg (1990)

$$C_S = \frac{2(a - b/27)}{f_\pi^2}\,, \qquad C_T = 0$$ ➢ SU(4) prediction

Does this work?

SU(4)$_{\text{quark}}$ implies SU(4)$_{\text{Wigner}}$ in 2-nucleon sector

$$\mathcal{L}_6 = -\tfrac{1}{2}C_S(N^\dagger N)^2 - \tfrac{1}{2}C_T(\cancel{N^\dagger}\vec{\sigma}N)^2 \qquad N = \begin{pmatrix} p\uparrow \\ p\downarrow \\ n\uparrow \\ n\downarrow \end{pmatrix}$$

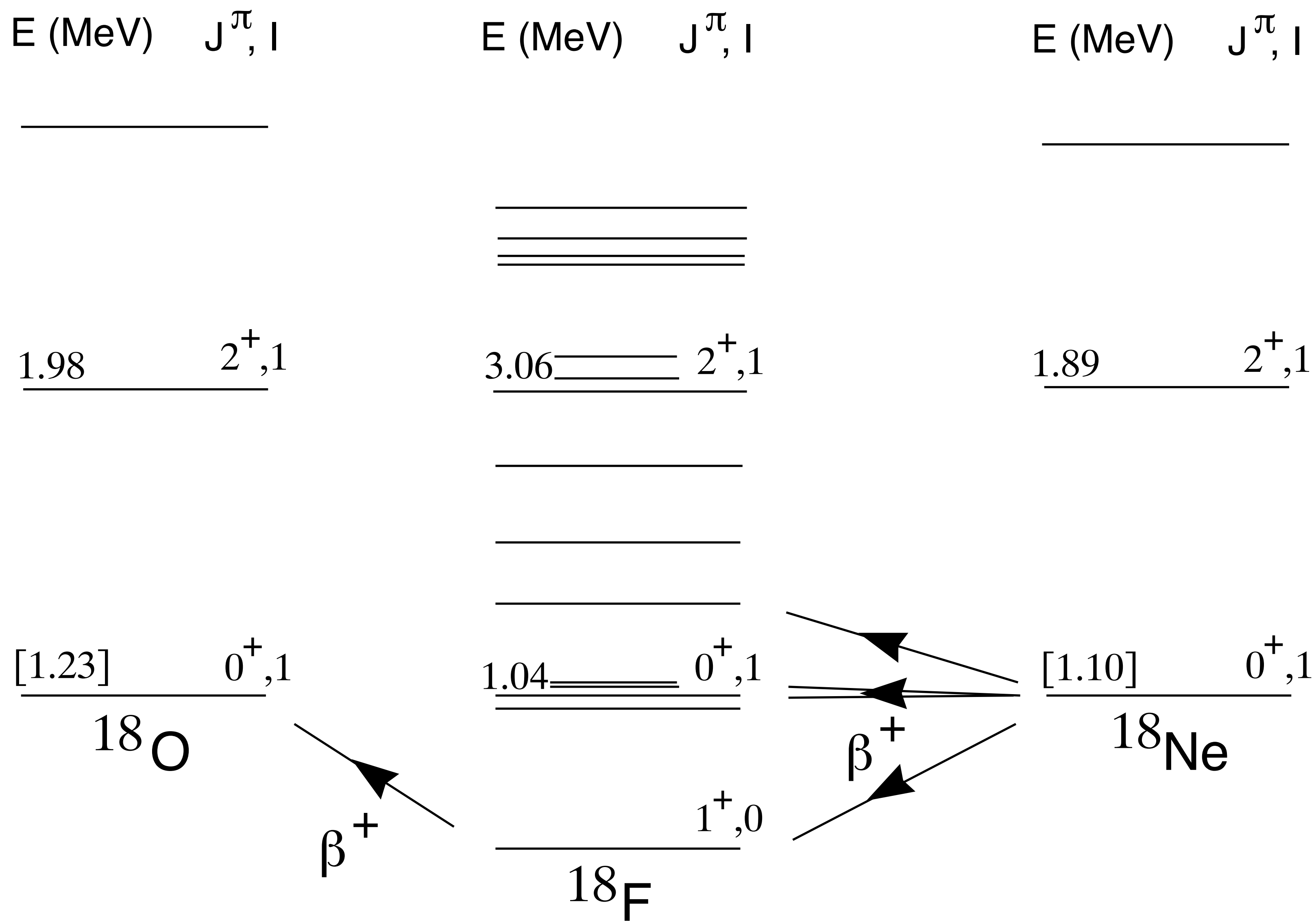
[N + Δ = 20 of SU(4)$_{\text{quark}}$; N = 4 of SU(4)$_{\text{Wigner}}$]

Diagnostic:

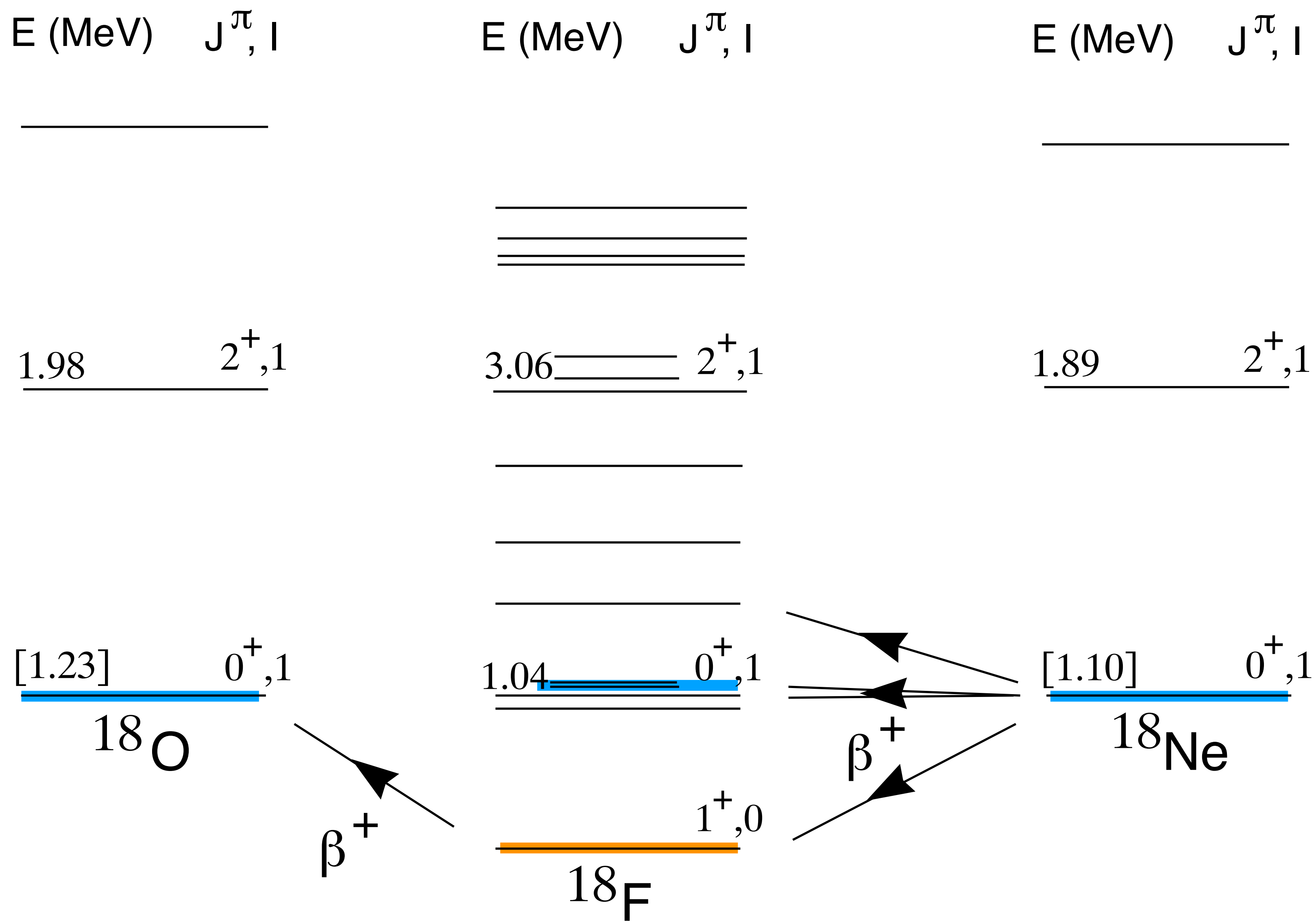
Is SU(4)$_{\text{Wigner}}$ symmetry seen in nuclear physics?

Yes!

Example of evidence for $SU(4)_{Wigner}$: β-decay in A=18 isobars



Example of evidence for $SU(4)_{Wigner}$: β-decay in A=18 isobars



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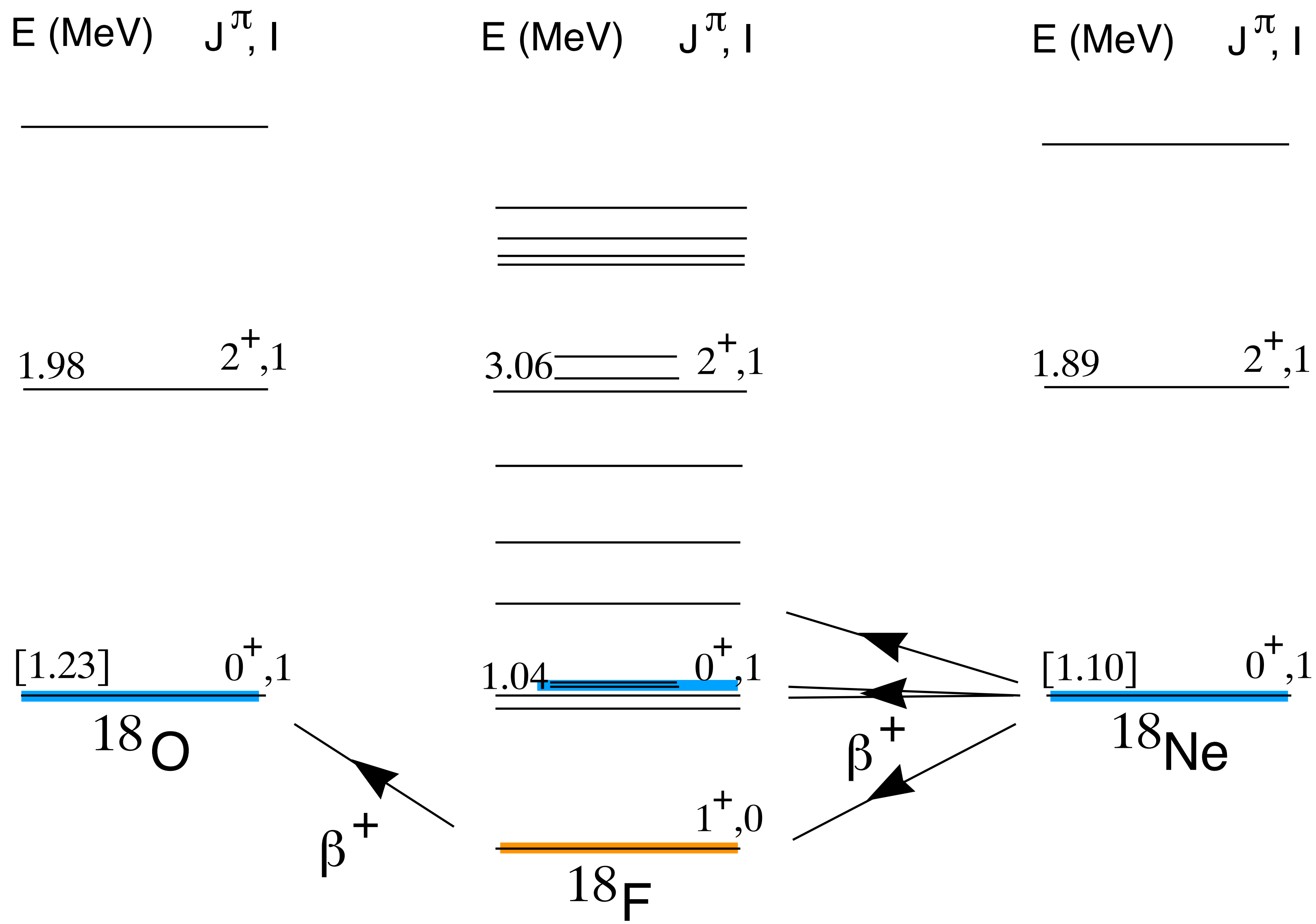

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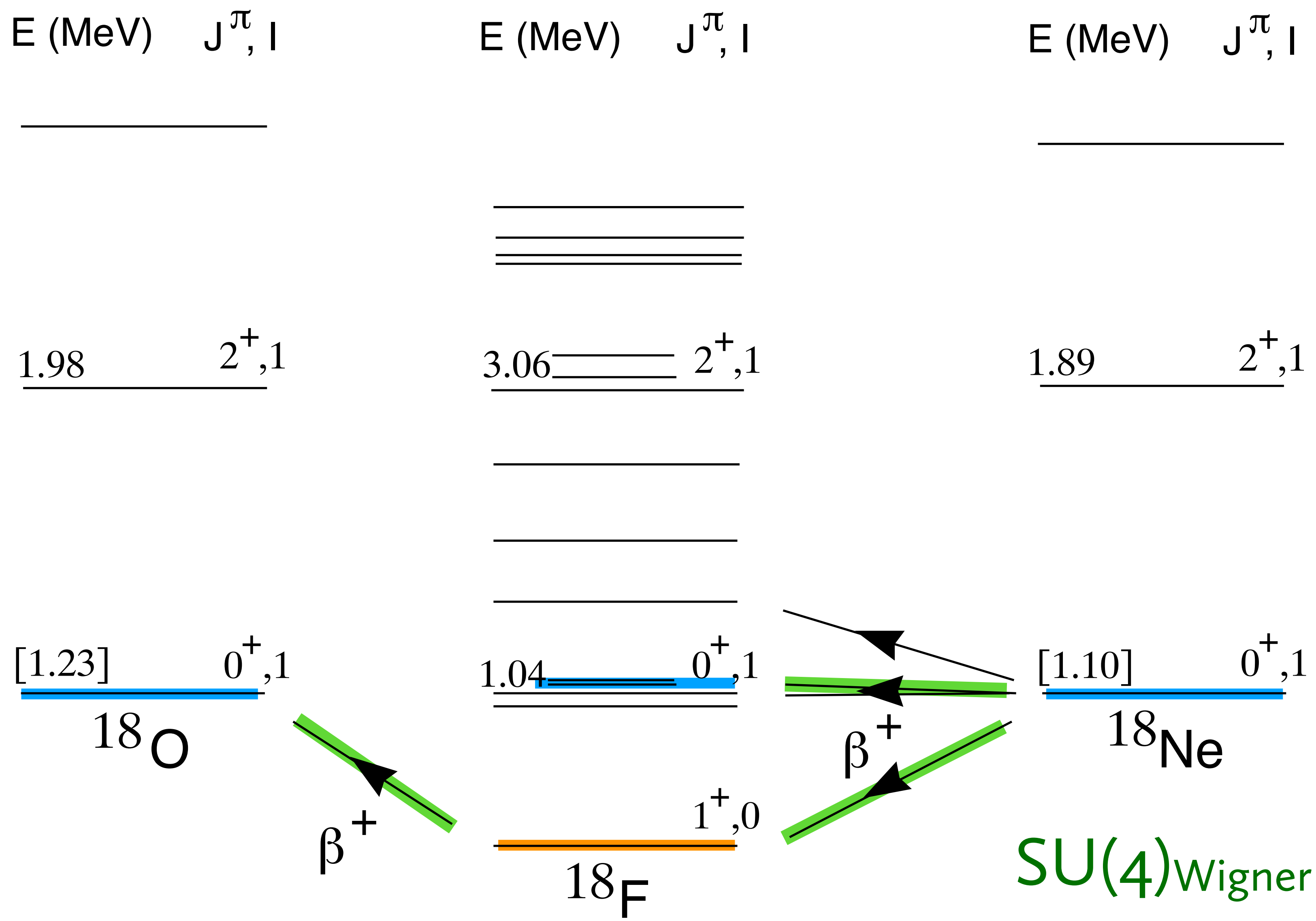

SU(4)$_{\text{Wigner}}$ allowed transitions

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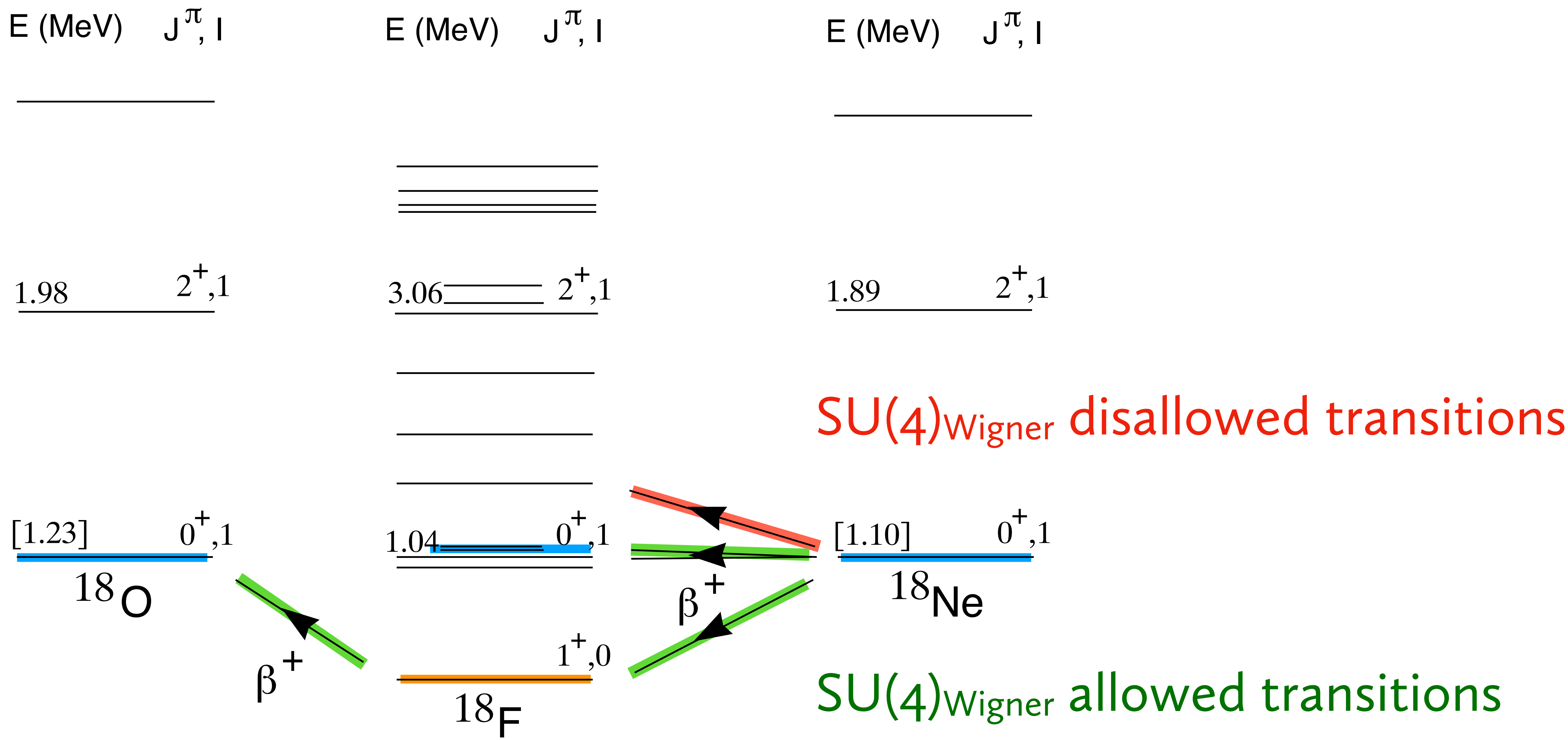

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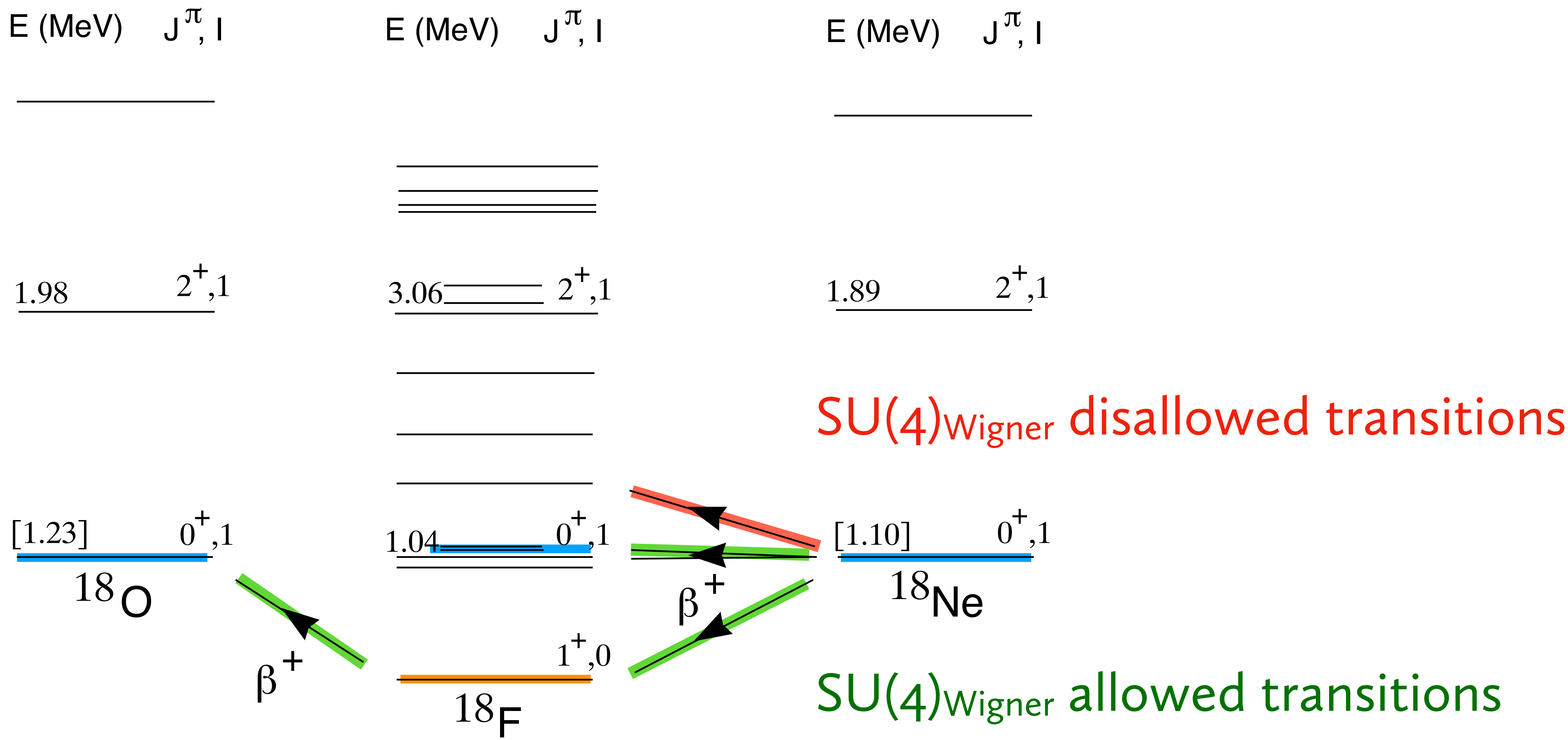

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SU(4)$_{\text{Wigner}}$ allowed matrix elements ~**10 x greater** than SU(4)$_{\text{Wigner}}$ disallowed

So far: no surprises? — emergent spin-flavor symmetries can be explained by large-N_c

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First surprise: unnaturally large scattering lengths in NN scattering give approximate Schrödinger symmetry (nonrelativistic conformal symmetry)

$^1S_0$ scattering length = -23.7 fm ~ 1/8 MeV

$^3S_1$ scattering length = + 5.4 fm ~ 1/35 MeV

Very low scales for QCD

$$\mathcal{A} \simeq \frac{4\pi}{M} \frac{1}{\left(-\frac{1}{a} + i\sqrt{ME}\right)}$$

1/a is very small for both

Who ordered that??

Second surprise arises for N_f=3:

Baryon-baryon interactions N_f=3;

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baryon decuplet

baryon octet

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baryon decuplet baryon octet

General low-energy EFT for just the octet: M.J. Savage, M.B. Wise (1995)

$$\begin{aligned}\mathcal{L} \quad = \quad & -c_1 \mathrm{Tr}\, B_i^\dagger B_i B_j^\dagger B_j - c_2 \mathrm{Tr}\, B_i^\dagger B_j B_j^\dagger B_i - c_3 \mathrm{Tr}\, B_i^\dagger B_j^\dagger B_i B_j \\ & -c_4 \mathrm{Tr}\, B_i^\dagger B_j^\dagger B_j B_i - c_5 \mathrm{Tr}\, B_i^\dagger B_i \mathrm{Tr}\, B_j^\dagger B_j - c_6 \mathrm{Tr}\, B_i^\dagger B_j \mathrm{Tr}\, B_j^\dagger B_i\end{aligned}$$

$$B_i = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}_i$$

i = ⬆, ⬇

Low energy octet-octet interactions:

$$
\begin{aligned}
\mathcal{L} \quad = \quad & -c_1 \mathrm{Tr}\, B_i^\dagger B_i B_j^\dagger B_j - c_2 \mathrm{Tr}\, B_i^\dagger B_j B_j^\dagger B_i - c_3 \mathrm{Tr}\, B_i^\dagger B_j^\dagger B_i B_j \\
& -c_4 \mathrm{Tr}\, B_i^\dagger B_j^\dagger B_j B_i - c_5 \mathrm{Tr}\, B_i^\dagger B_i \mathrm{Tr}\, B_j^\dagger B_j - c_6 \mathrm{Tr}\, B_i^\dagger B_j \mathrm{Tr}\, B_j^\dagger B_i
\end{aligned}
$$

SU(6) prediction:

$$
\begin{aligned}
c_1 &= -\frac{7}{27} b\,, & c_2 &= \frac{1}{9} b\,, & c_3 &= \frac{10}{81} b\,, \\
c_4 &= -\frac{14}{81} b\,, & c_5 &= a + \frac{2}{9} b\,, & c_6 &= -\frac{1}{9} b\,.
\end{aligned}
$$

Does this work? Look at lattice data

- NPLQCD collaboration, 2015
- equal quark masses
- m_π = 806 MeV

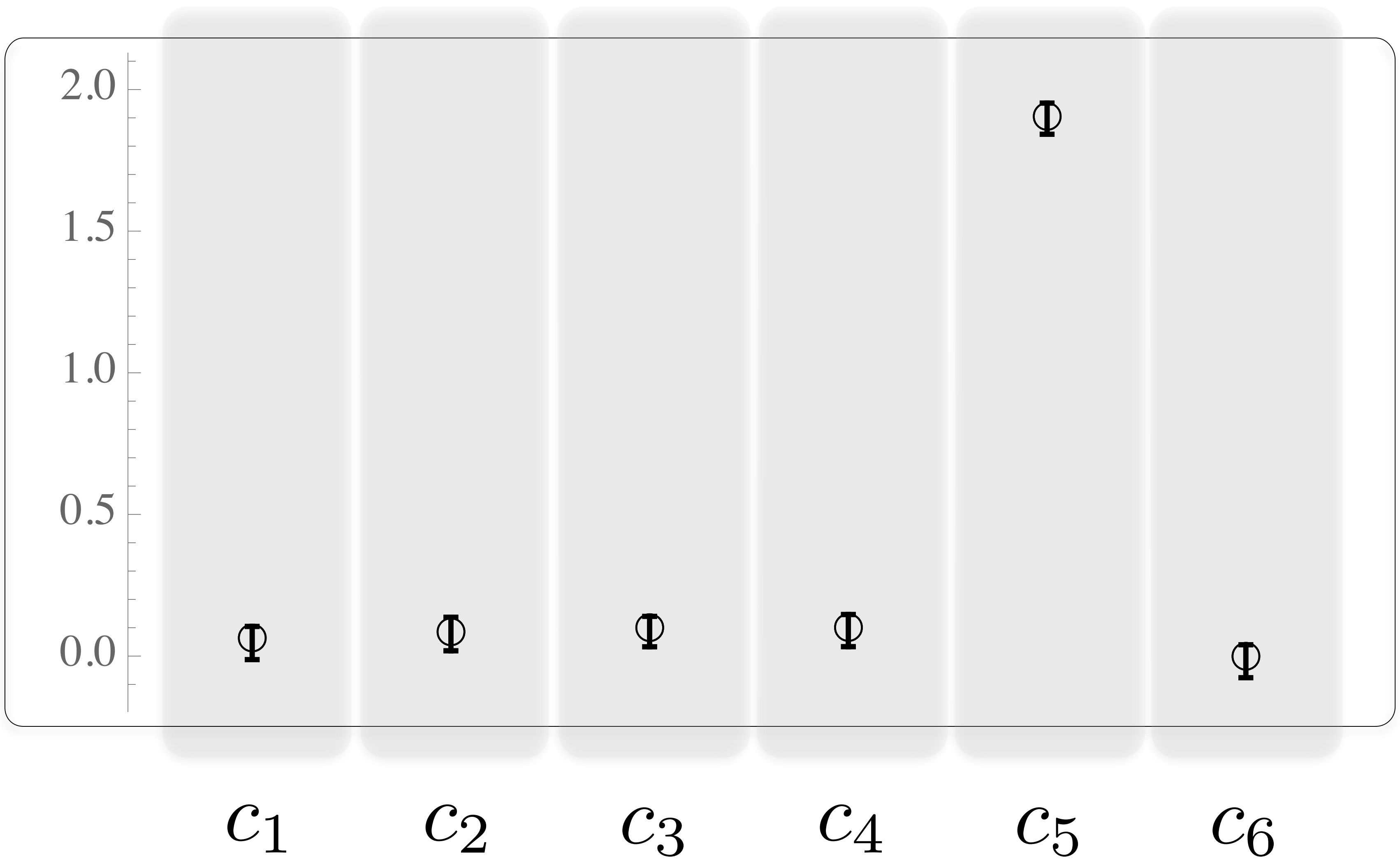
PHYSICAL REVIEW D **96,** 114510 (2017)

Baryon-baryon interactions and spin-flavor symmetry from lattice quantum chromodynamics

Michael L. Wagman,[1,2] Frank Winter,[3] Emmanuel Chang,[2] Zohreh Davoudi,[4] William Detmold,[4] Kostas Orginos,[5,3] Martin J. Savage,[1,2] and Phiala E. Shanahan[4]

(NPLQCD Collaboration)

$$m_\pi \approx 806 \text{ MeV}$$
$$\mu = m_\pi$$



$$
\begin{aligned}
\mathcal{L} \;=\;& -c_1 \mathrm{Tr}\, \cancel{B_i^\dagger} B_i B_j^\dagger B_j - c_2 \mathrm{Tr}\, \cancel{B_i^\dagger B_j} B_j^\dagger B_i - c_3 \mathrm{Tr}\, \cancel{B_i^\dagger} B_j^\dagger B_i B_j \\
& -c_4 \mathrm{Tr}\, B_i^\dagger \cancel{B_j^\dagger} B_j B_i - c_5\, \mathrm{Tr}\, B_i^\dagger B_i \;\mathrm{Tr}\, B_j^\dagger B_j - c_6\, \mathrm{Tr}\, B_i^\dagger \cancel{B_j}\, \mathrm{Tr}\, B_j^\dagger
\end{aligned}
$$

NPLQCD results:

- Only $c_5 \neq 0$
- c_5 near critical value for large scattering lengths

Similar to N_f=2 large-N_c result: $$\mathcal{L}_6 = -\frac{1}{2}C_S(N^\dagger N)^2 - \frac{1}{2}C_T\cancel{(N^\dagger}\vec{\sigma}N)^2$$

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& -c_4\,\cancel{\mathrm{Tr}\, B_i^\dagger B_j^\dagger B_j B_i} - c_5\,\mathrm{Tr}\, B_i^\dagger B_i\;\mathrm{Tr}\, B_j^\dagger B_j - c_6\,\cancel{\mathrm{Tr}\, B_i^\dagger B_j\,\mathrm{Tr}\, B_j^\dagger B}
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But:

- EFT possesses **SU(16)** analog of SU(4)$_{\text{Wigner}}$
- \+ near critical value for large scattering lengths — *conformal symmetry*

NOT large-N_c predictions

low energy symmetries of spin 1/2 baryons

$N_f=2$	$N_f=3$
$SU(4)_{\text{Wigner}}$ ✔ large-N_c	$SU(16)_{\text{NPLQCD}}$?
~conformal ?	~conformal ?

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...but: these symmetries correlated with low entanglement

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

BY E. SCHRÖDINGER

[Communicated by Mr M. BORN]

[*Received* 14 August, *read* 28 October 1935]

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When two systems, of which we kn ve
representatives, enter into tempora
known forces between them, and w
influence the systems separate agai
described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or wave-functions) have become entangled.

How to quantify entanglement?

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Quantum entropy:

$S = -\,\mathrm{Tr}\,\rho \log_2 \rho$, ρ = density matrix

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E.g. pure state: $$|\,\psi\,\rangle = |\uparrow_x\ \downarrow_y\,\rangle$$

$$\hat{\rho} = |\,\psi\,\rangle\langle\,\psi\,|$$

$$\rho = \begin{pmatrix} 1 & 0 & \dots \\ 0 & 0 & \dots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

➤ rank 1

S = 0

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➤ rank 1

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E.g. mixed state: $$\rho = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & \dots \\ 0 & 1 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

➤ rank 2

S = 1

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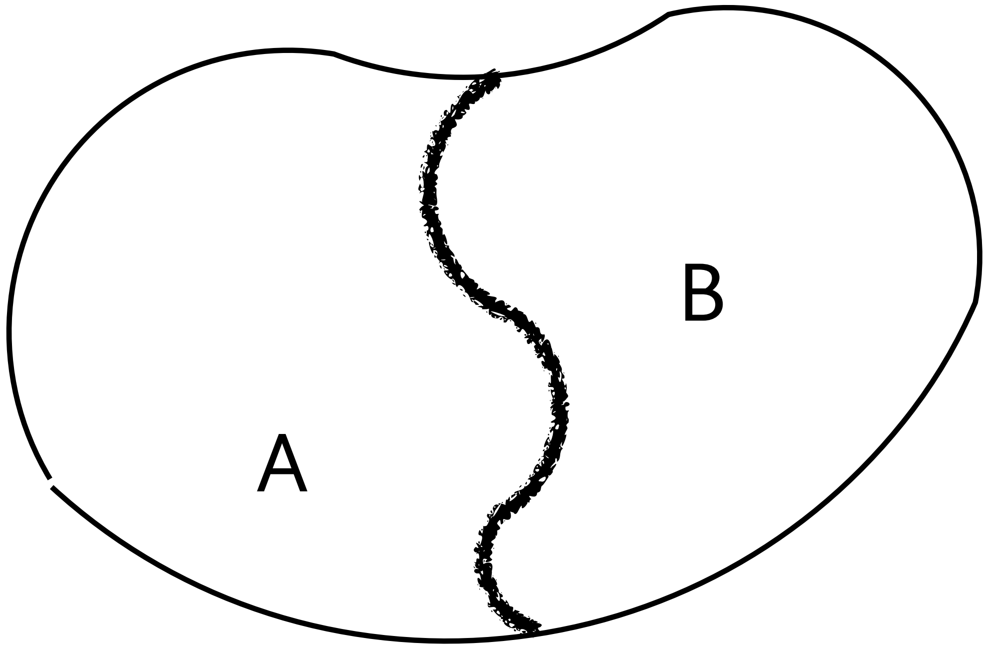
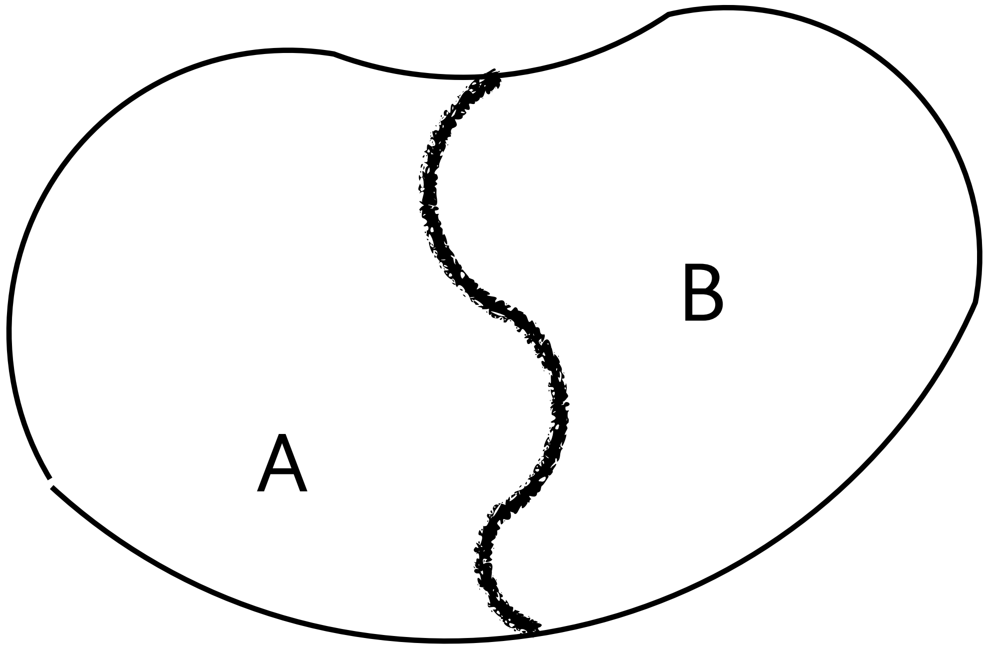


Factorizable Hilbert space: $\mathcal{H} = \mathcal{H}_A \times \mathcal{H}_B$

Reduced density matrix:

$$\rho_A = \mathrm{Tr}_B\, \rho$$
$$\rho_B = \mathrm{Tr}_A\, \rho$$



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$$\rho_B = \mathrm{Tr}_A\, \rho$$

Pure state on $\mathcal{H}$ — typically ρ_A, ρ_B will represent mixed states, reflected in entropy:

$$S = 0\ , \qquad S_A = S_B \neq 0$$

Shows that systems A and B are entangled

How to quantify entanglement of a N-N scattering process?

One way: PRL 122, 102001 (2019), arXiv: 1812.03138;

A simpler way: in preparation;

Rough description:

- Compute reduced density matrix ρ_1 for 2-particle state
- Define entanglement for pure 2-particle state as $[1 - \mathrm{Tr}\,(\rho_1)^2]$
- Compute entanglement power of the S-matrix as difference in entanglement between $|\psi_{in}\rangle$ and $|\psi_{out}\rangle$
- average over initial spin-flavor orientations

Entanglement power in s-wave nucleon-nucleon scattering
Function of two phase shifts for $^3S_1$ and $^1S_0$ channels

$$\hat{\mathbf{S}} = \frac{1}{4}\left(3e^{i2\delta_1} + e^{i2\delta_0}\right)\hat{\mathbf{1}} \; + \; \frac{1}{4}\left(e^{i2\delta_1} - e^{i2\delta_0}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}}$$

$$\mathcal{E}(\hat{\mathbf{S}}) = \frac{1}{6}\,\sin^2\left(2(\delta_1 - \delta_0)\right)$$

Entanglement power of S

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Entanglement power of S

Vanishes when: 1. $\delta_0 = \delta_1$ $\Leftarrow$ $SU(4)_{Wigner}$ symmetry

or: 2. $\delta_{0,1} = 0$ or $\pi/2$ $\Leftarrow$ conformal symmetry

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or: 2. $\delta_{0,1} = 0$ or $\pi/2$ $\Leftarrow$ conformal symmetry

Look at the low energy EFTs for $p_{cm} < m_\pi/2$:

$$\mathcal{L}_6 = -\tfrac{1}{2}C_S(N^\dagger N)^2 - \tfrac{1}{2}C_T(N^\dagger\vec{\sigma}N)^2$$

$$^1S_0: \quad \bar{C}_0 = (C_S - 3C_T)$$

$$^3S_1: \quad \bar{C}_1 = (C_S + C_T)$$

Fit C_0, C_1 to scattering lengths

$$\mathcal{L}_6 = -\tfrac{1}{2}C_S(N^\dagger N)^2 - \tfrac{1}{2}C_T(N^\dagger\vec{\sigma}N)^2$$

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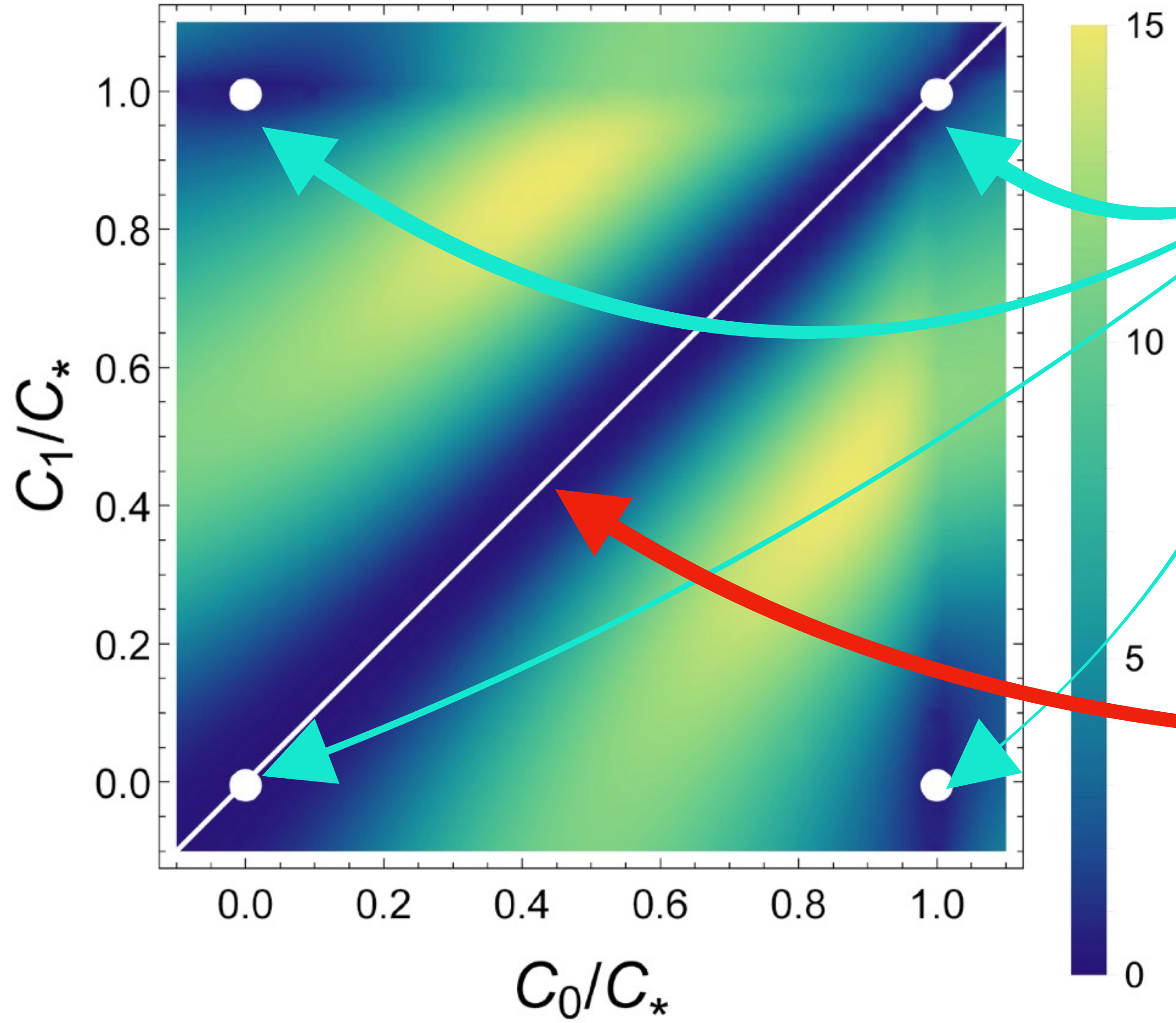
$$\mathcal{E}(\hat{\mathbf{S}}) = \frac{1}{6}\,\sin^2\left(2(\delta_1 - \delta_0)\right)$$



Conformal fixed points (zero or infinite scattering lengths, $\delta_i = 0, \pi/2$)

$SU(4)_{\mathrm{Wigner}}$ symmetry line ($\delta_0 = \delta_1$)

Minimal entanglement in scattering occurs at points of enhanced symmetry

Real world: Fit C_0, C_1 to scattering lengths

⇨ $C_T/C_S = 0.08 \ldots \sim$ SU4 symmetric

⇨ $C_0 = .94\, C_\star$,
⇨ $C_1 = 1.35\, C_\star \ldots$ $\sim$ pretty close to conformal

OK, what about N_f=3?

Find entanglement power of S-matrix is minimized for

- SU(16) symmetry
- Conformal symmetry

...exactly the results found by LQCD, with no known QCD explanation

OK, what about N_f=3?

Find entanglement power of S-matrix is minimized for

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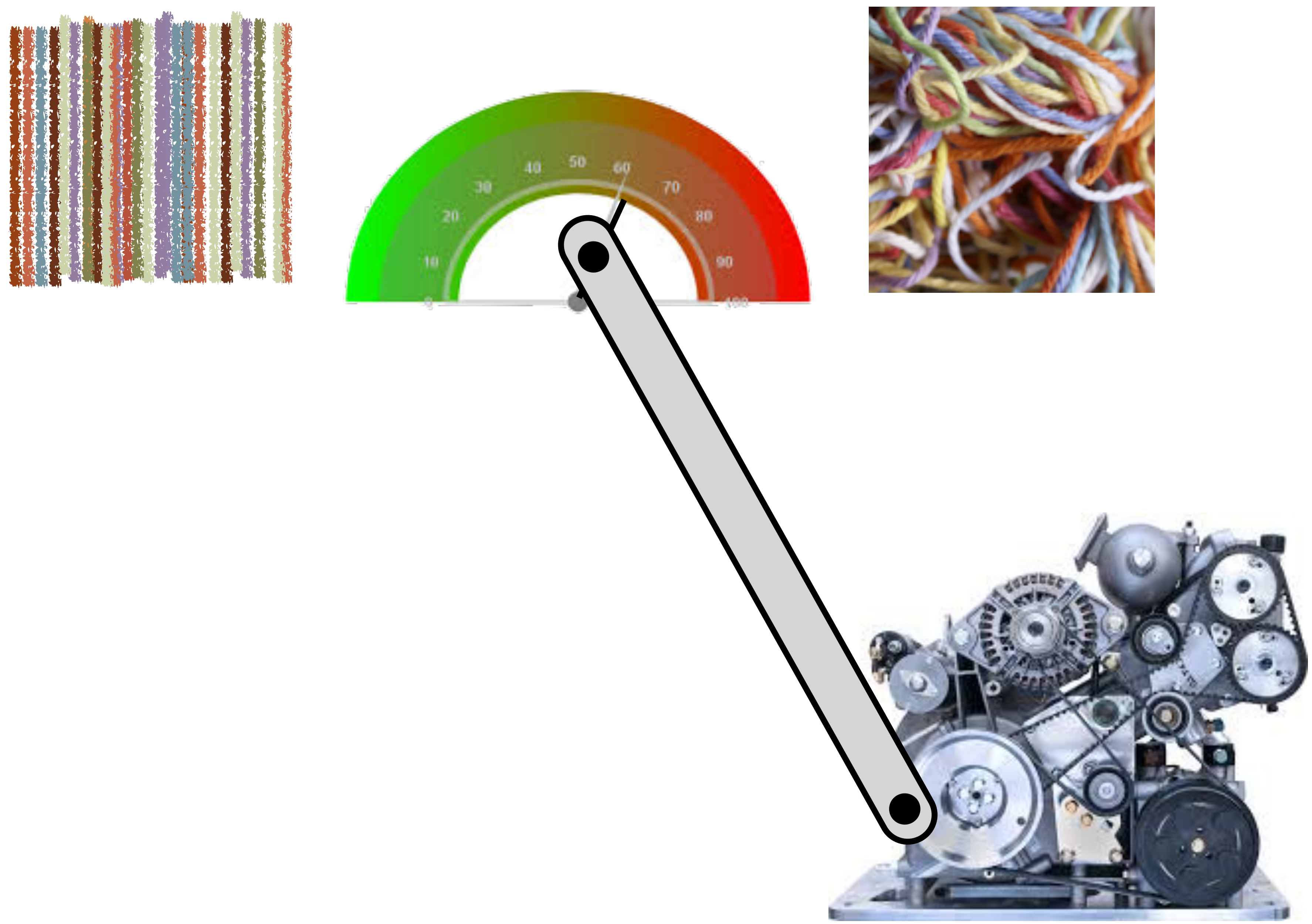
...exactly the results found by LQCD, with no known QCD explanation

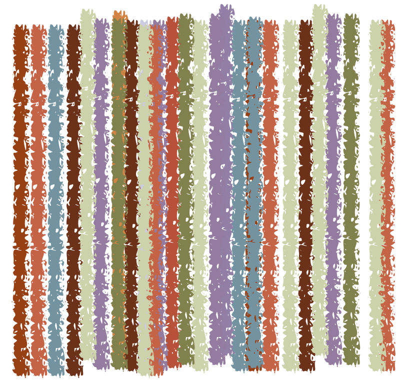
Could enhanced symmetries be evidence for entangle-phobia as a property of strong interactions?

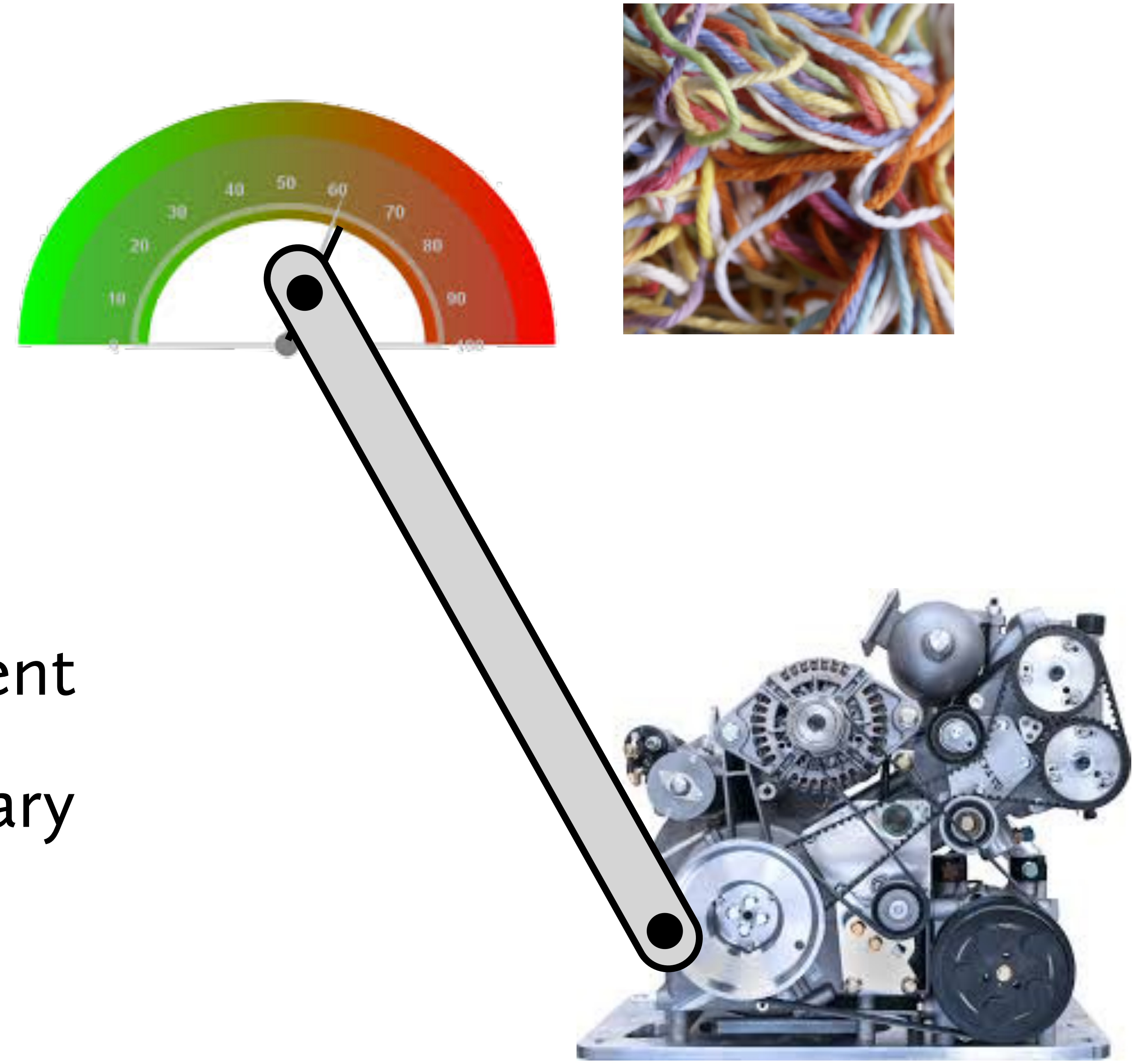
Is there a connection between entanglement and dynamics?



DYNAMICS

Is there a connection between entanglement and dynamics?

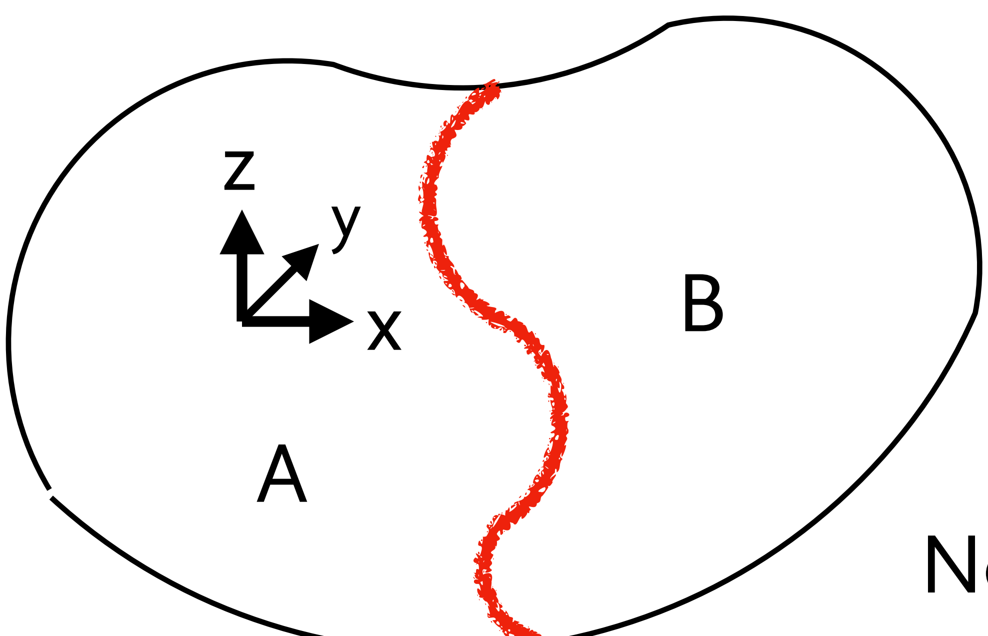




DYNAMICS

Observed that ground states
seem to obey area-law entanglement

$S_A = S_B \propto$ area of shared boundary



Not a general feature of wave functions

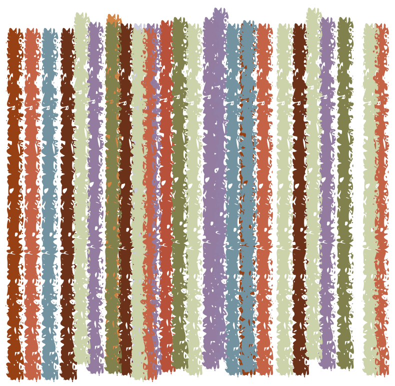
Entanglement seems to know about dynamics - e.g. correlation length

In a strongly coupled system with composite particles (eg, QCD) can might their wave functions and interactions (and hence their symmetries) adjust to minimize entanglement?

?

LOW ENTANGLEMENT

HIGH ENTANGLEMENT



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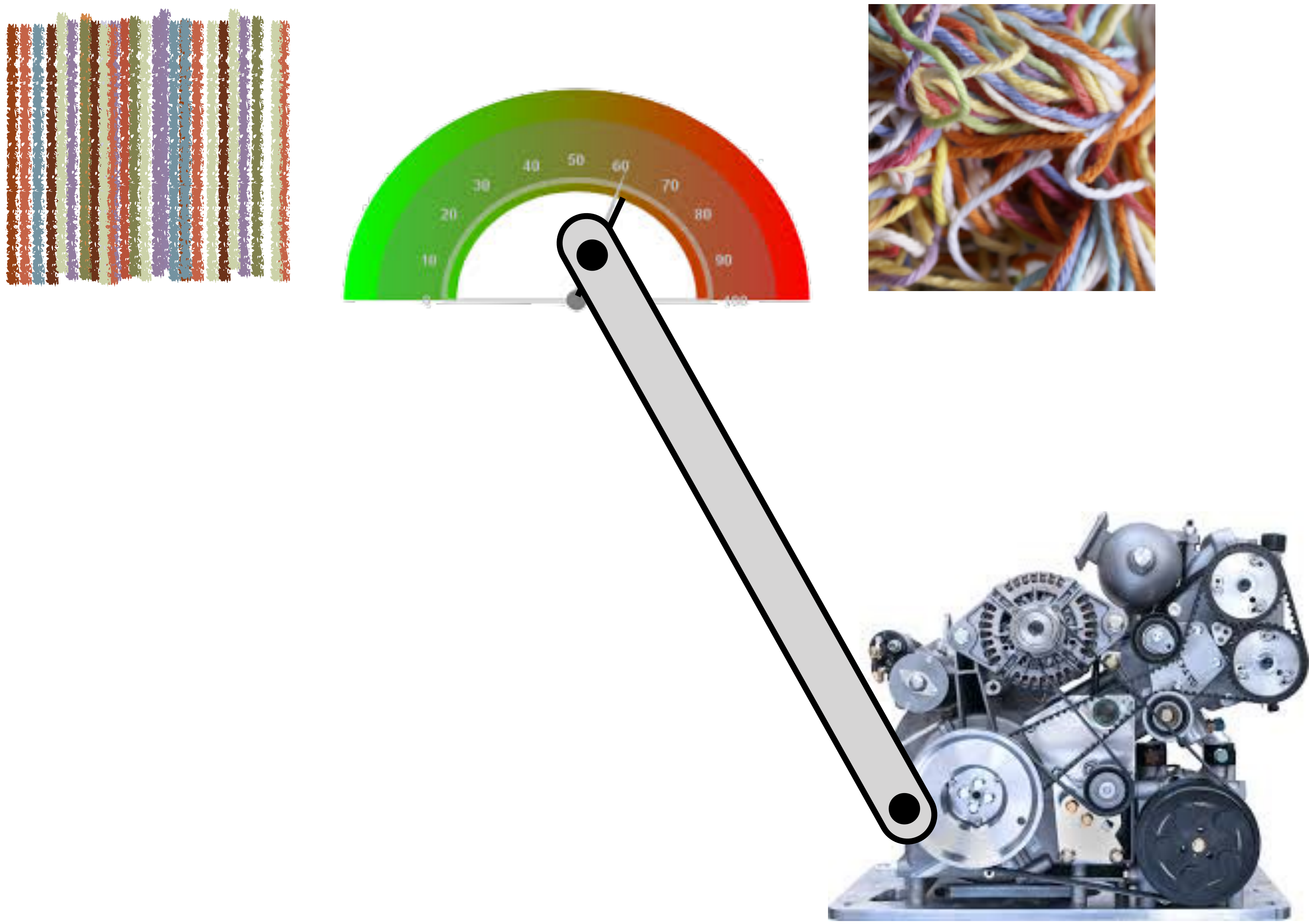
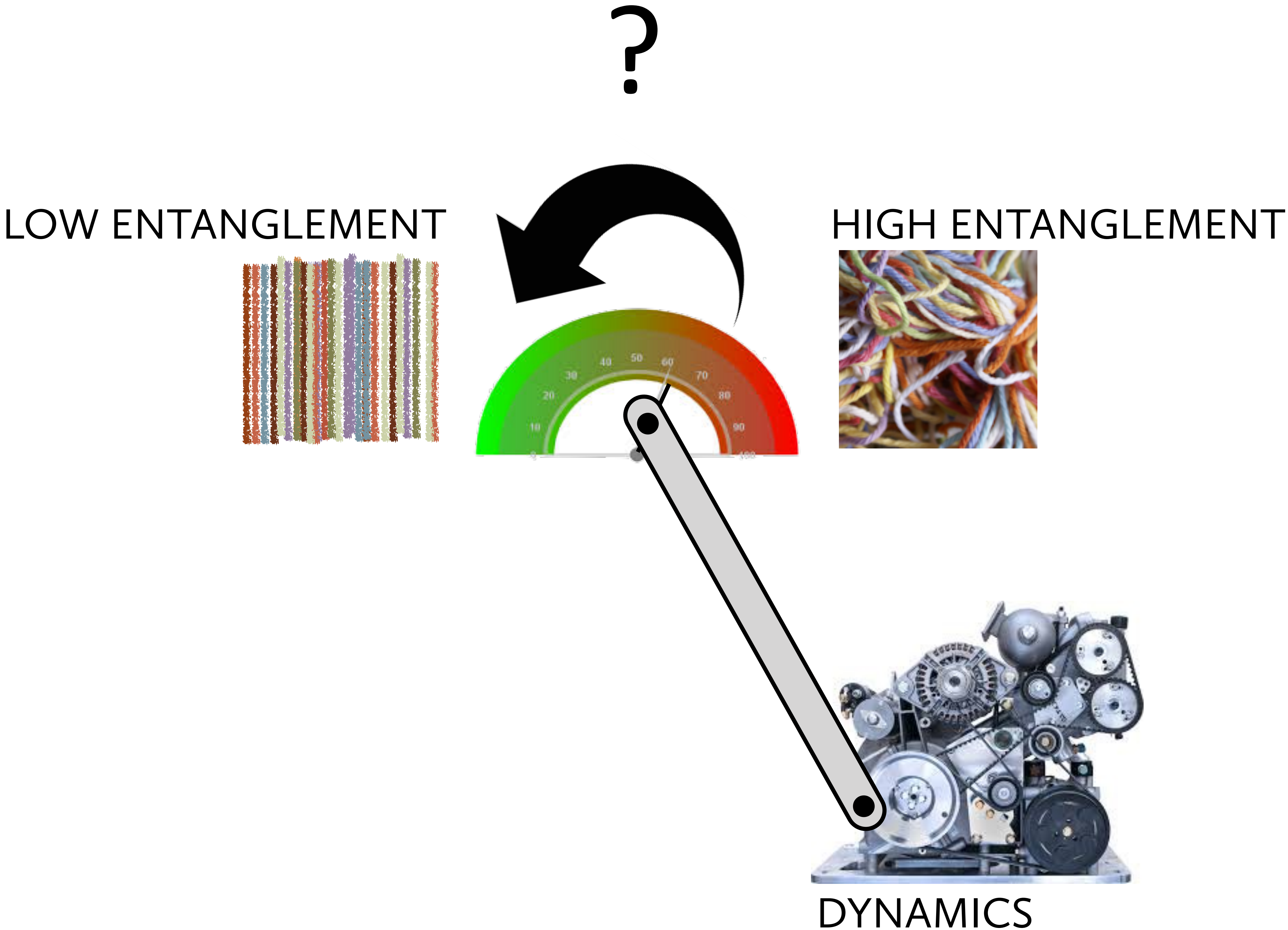
LOW ENTANGLEMENT

HIGH ENTANGLEMENT



DYNAMICS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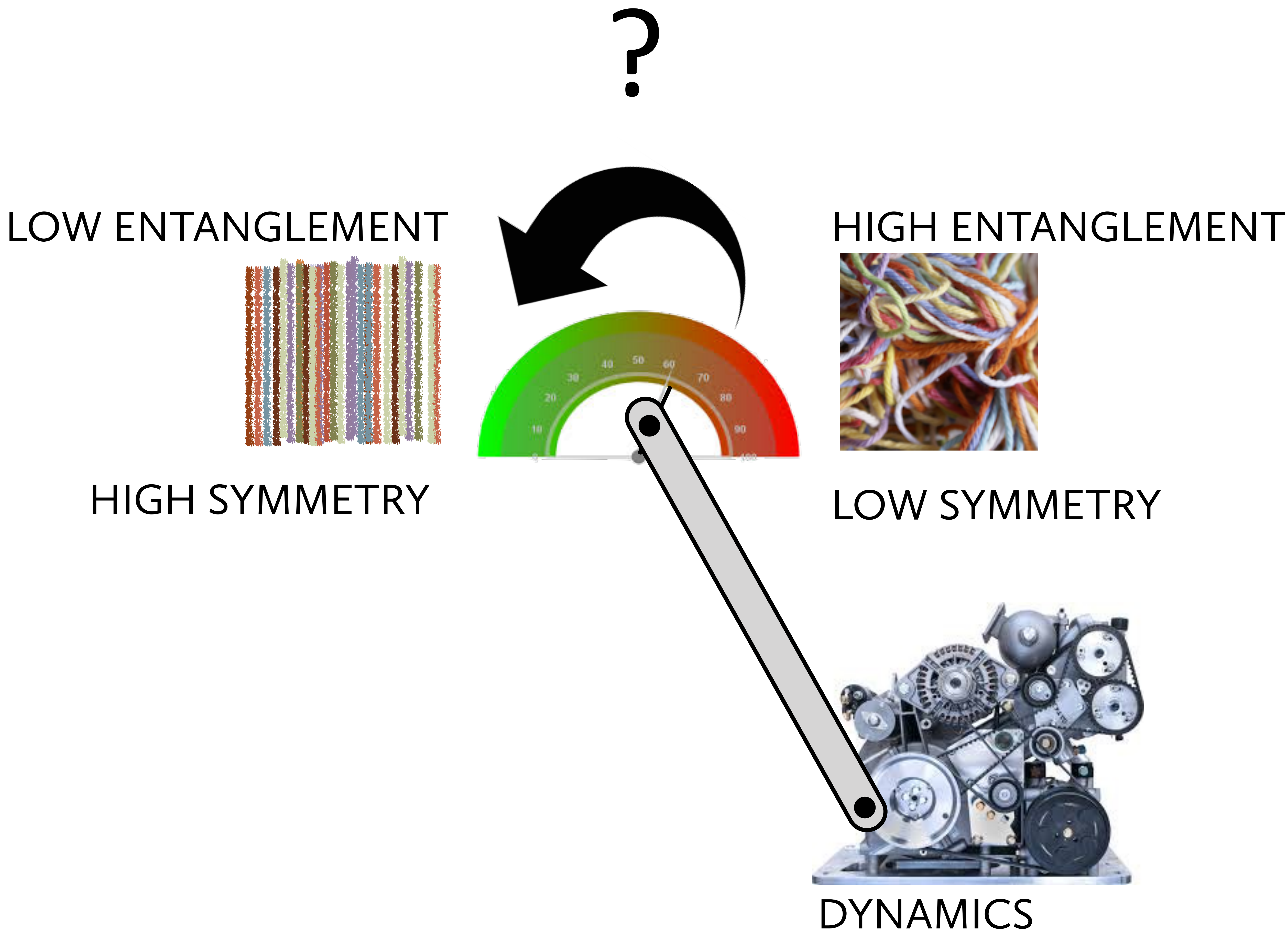
LOW ENTANGLEMENT
HIGH ENTANGLEMENT
DYNAMICS


?
LOW ENTANGLEMENT
HIGH SYMMETRY
HIGH ENTANGLEMENT
LOW SYMMETRY
DYNAMICS

Conclusions:

In pursuit of a new paradigm…

Empirical approximate symmetries w/o explanation in the strong interactions:

- non-quark spin-flavor symmetries
- NR conformal (Schrödinger) symmetries

Entanglement is minimized for flavor & spin diagonal interactions, as well as for conformal fixed points

Can some symmetries be explained by dynamical systems "wanting" to minimize entanglement?

Need to look at multi-nucleon interactions, e.g. 3-body terms

Need to find other examples, models; perhaps gravity duals?