Entanglement Suppression, Emergent Symmetry, and a SM-like Higgs Boson

The Galileo Galilei Institute For Theoretical Physics
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- Argonne/Northwestern

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Entanglement is quantum world's most prominent feature:

- It refers to the situation where a measurement on a subsystem will improve our knowledge on the rest of the system.

- A quantum state of a system is entangled if it cannot be written as a tensor-product state of its subsystems.

- Consider a bipartite system $\mathcal{H}_{12} = \mathcal{H}_1 \otimes \mathcal{H}_2$, a state vector $|\psi\rangle \in \mathcal{H}_{12}$ is *entangled* if there is NO $|\psi_1\rangle \in \mathcal{H}_1$ and $|\psi_2\rangle \in \mathcal{H}_2$ such that

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$$

On the other hand, symmetry is among the most fundamental principles in physics:

- Powerful characterization of nature based on invariance under a specified group of transformations.
- Symmetries give rise to conserved quantities: energy, momentum, angular momentum, etc.
- Combining with quantum mechanics, there is a subtle realization of symmetry – spontaneous symmetry breaking.
- All known fundamental interactions are based on symmetry principles.

But what is the origin of symmetry?

There are two historical perspectives:

Beauty In, Garbage Out –
As we explore higher and higher energy regimes, we discover more and more symmetries. The symmetry is usually hidden or broken in low energies.

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But neither explain whether symmetry can be the natural outgrowth of more fundamental principles.

John Wheeler famously coined the phrase:

It from bit : "All things physical are information-theoretic in origin"

INFORMATION, PHYSICS, QUANTUM: THE SEARCH FOR LINKS

John Archibald Wheeler * †

Abstract

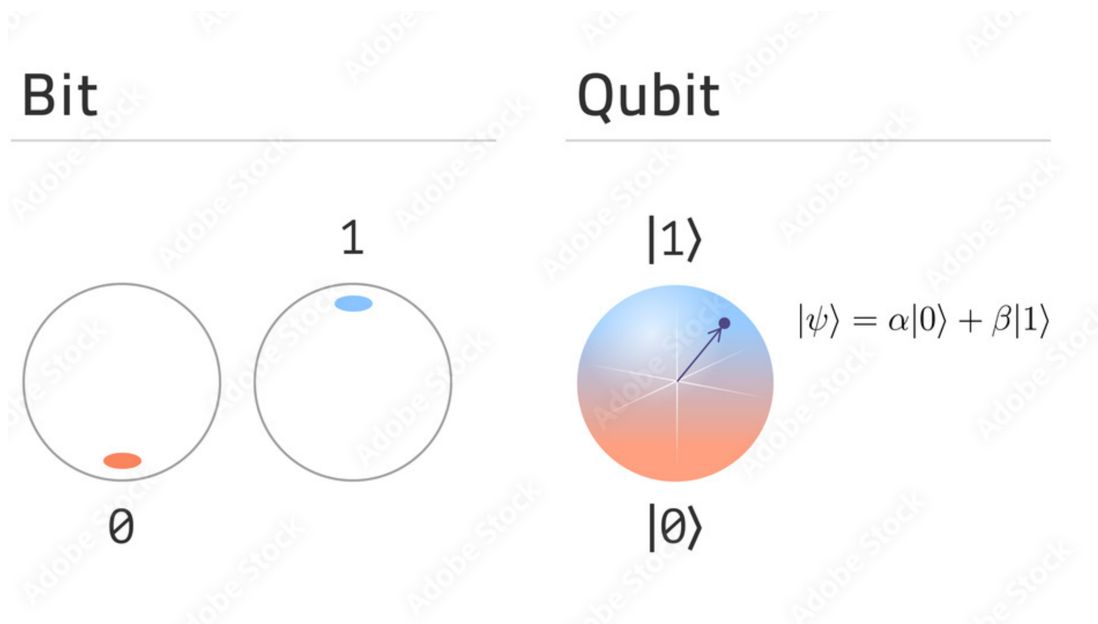
This report reviews what quantum physics and information theory have to tell us about the age-old question, How come existence? No escape is evident from four

winnowing: **It from bit**. Otherwise put, every **it** — every particle, every field of force, even the spacetime continuum itself — derives its function, its meaning, its very existence entirely — even if in some contexts indirectly — from the apparatus-elicited answers to yes or no questions, binary choices [52], **bits**.

Indeed, we have seen remarkable connections between fundamental physics and information science in the past decade.

It is natural to ask:

Can symmetry come from qubit?



In 2018 a group from Seattle made a fascinating observation regarding emergent symmetries and entanglement suppression in low-energy QCD:

PHYSICAL REVIEW LETTERS **122,** 102001 (2019)

Entanglement Suppression and Emergent Symmetries of Strong Interactions

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(Received 20 December 2018; published 14 March 2019)

Entanglement suppression in the strong-interaction S matrix is shown to be correlated with approximate spin-flavor symmetries that are observed in low-energy baryon interactions, the Wigner $SU(4)$ symmetry for two flavors and an $SU(16)$ symmetry for three flavors. We conjecture that

This raises the intriguing possibility of understanding symmetry from quantum entanglement!

In this talk, we will study:

- Emergent (approximate) global symmetries in two very different physical systems: low-energy QCD and 2HDMs.
- Connection between symmetry and entanglement suppression in 2-to-2 scattering.
- Elucidate the connection from an information-theoretic viewpoint.

In this talk, we will study:

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- Connection between symmetry and entanglement suppression in 2-to-2 scattering.

- Elucidate the connection from an information-theoretic viewpoint.

In the case of 2HDM, a SM-like Higgs boson emerges as an outcome of entanglement suppression!

Emergent symmetries in low-energy QCD:

- Schrodinger symmetry (non-relativistic conformal invariance)

The largest symmetry group preserved by the Schrodinger equation, which includes Galilean boosts, scale and special conformal transformations.

- Spin-flavor symmetries

Symmetries mixing flavor (internal) with spin (spacetime).
Possible only in non-relativistic systems.
Examples: $SU(2N_f)$ quark spin-flavor symmetries; Wigner's "supermultiplet" SU(4) spin-flavor symmetry.

$SU(2N_f)$ spin-flavor symmetries are symmetries of non-relativistic quark model and date back to 1960s:

SU(4): $$\mathbf{4} = \begin{pmatrix} u\uparrow \\ u\downarrow \\ d\uparrow \\ d\downarrow \end{pmatrix}$$

SU(6): $$\mathbf{6} = \begin{pmatrix} u\uparrow \\ u\downarrow \\ d\uparrow \\ d\downarrow \\ s\uparrow \\ s\downarrow \end{pmatrix}$$

They can be derived from QCD in the large N_c (=3) limit!

Dashen, Monohar (1993); Dashen, Jenkins, Manohar (1994); Kaplan, Savage (1995)

In low-energy nuclear physics, there is a different SU(4) symmetry first observed by Wigner:

JANUARY 15, 1937 PHYSICAL REVIEW VOLUME 51

On the Consequences of the Symmetry of the Nuclear Hamiltonian on the Spectroscopy of Nuclei

E. WIGNER*
Princeton University, Princeton, New Jersey
(Received October 23, 1936)

The structure of the multiplets of nuclear terms is investigated, using as first approximation a Hamiltonian which does not involve the ordinary spin and corresponds to equal forces between all nuclear constituents, protons and neutrons. The multiplets turn out to have a

In this case the neutron and proton fill out a "supermultiplet":

$$N = \begin{pmatrix} p \uparrow \\ p \downarrow \\ n \uparrow \\ n \downarrow \end{pmatrix}$$

In the EFT language, Wigner's SU(4) is accidental in that, after imposing the SU(4) quark spin-flavor symmetry, the only remaining operator has this symmetry.

So far these spin-flavor symmetries can be argued from the large N_c limit.

There are emergent symmetries beyond the large N_c :

- Unnaturally large scattering lengths in low-energy NN scattering in the s-wave, which include $^1S_0$ and $^3S_1$ channels.

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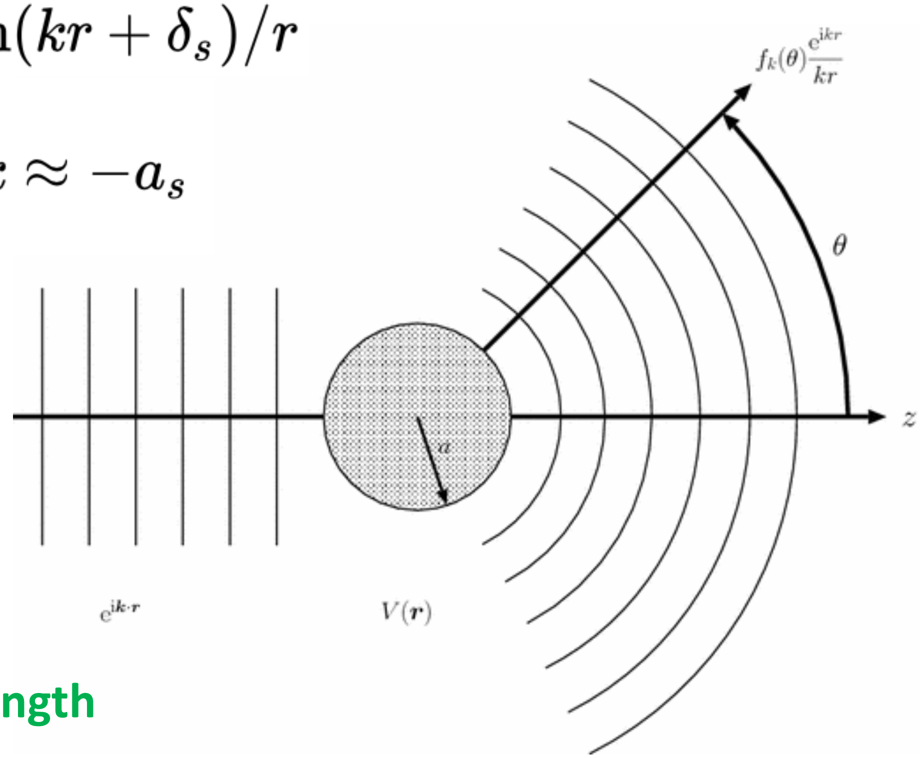
$$\psi(r,\theta) = e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

the s-wave solution $\psi(r) = A\sin(kr + \delta_s)/r$

$$f = \frac{1}{2ik}(e^{2i\delta_s} - 1) \approx \delta_s/k \approx -a_s$$

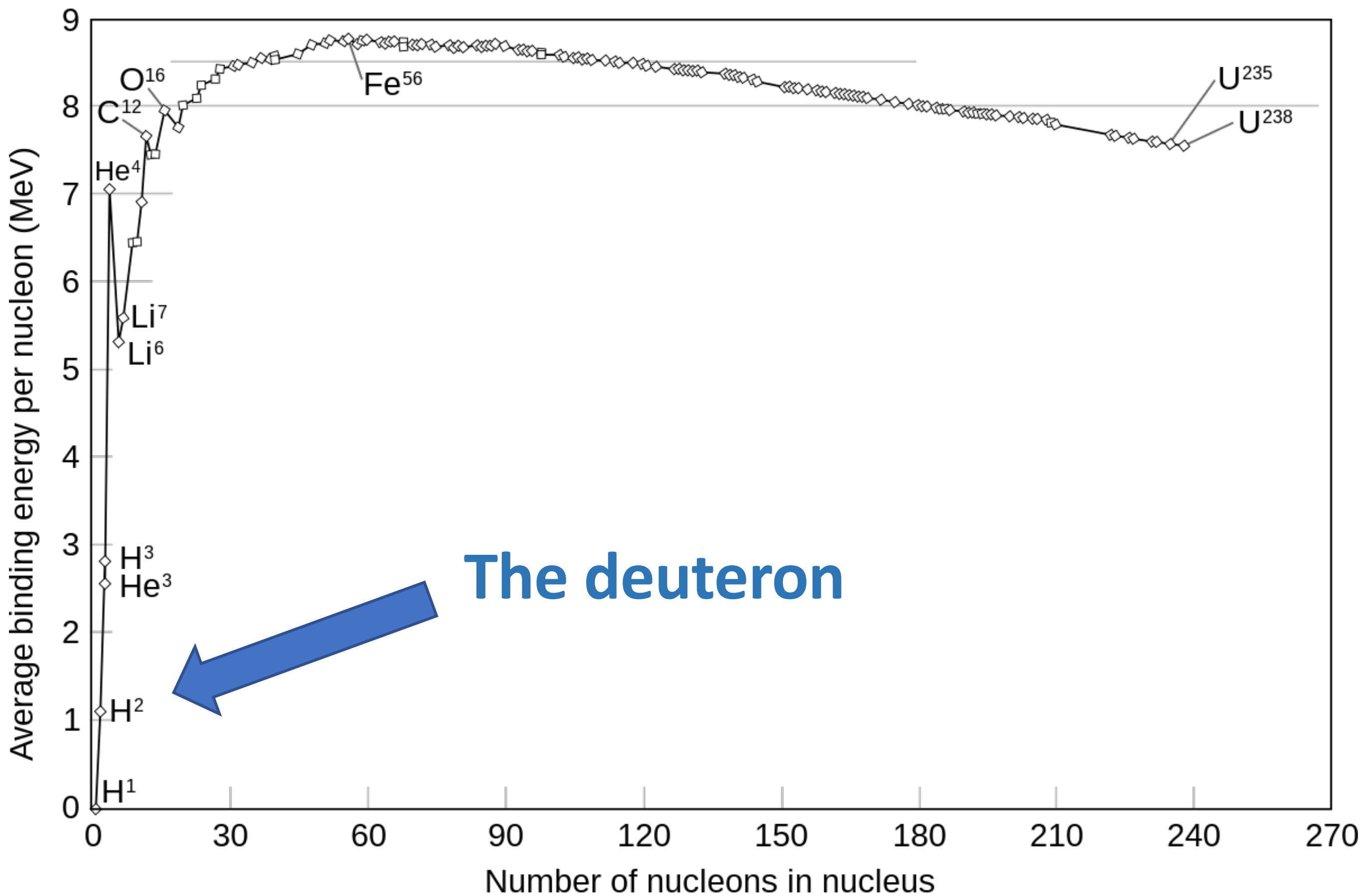
$$\sigma = \frac{4\pi}{k^2}\sin^2\delta_s = 4\pi a_s^2$$

The scattering length



In NN scattering:

- $^1S_0$: a_0 = -23.7 fm
- $^3S_1$: a_1 = 5.4 fm → Deuteron, which is a shallow, near-threshold bound state!
- $1/m_\pi$ = 1.4 fm



In the limit the scattering length *a* diverges, the system has no scale and exhibits Schrodinger symmetry, also known as the non-relativistic conformal invariance. Mehen, Stewart, Wise (1999)

At the infinitesimal level,

$$\text{boosts:} \qquad \vec{x}\,' = \vec{x} + \vec{v}\,t \;, \quad t' = t \;,$$

$$\text{scale:} \qquad \vec{x}\,' = \vec{x} + s\vec{x} \;, \quad t' = t + 2st \;,$$

$$\text{conformal:} \qquad \vec{x}\,' = \vec{x} - ct\vec{x} \;, \; t' = t - ct^2 \;,$$

So NN scattering has approximate Schrodinger symmetry.

WHO ORDERED THAT??!

- Nucleons are part of spin-1/2 octet baryons:

In the SU(3) flavor-symmetric limit :

$$B = \begin{pmatrix} \Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

A low-energy effective field theory:

$$\langle \cdot \rangle \equiv \mathrm{Tr}(\cdot)$$

$$\begin{aligned} \mathcal{L}_{\mathrm{LO}}^{n_f=3} = & -\frac{c_1}{f^2}\langle B_i^\dagger B_i B_j^\dagger B_j \rangle - \frac{c_2}{f^2}\langle B_i^\dagger B_j B_j^\dagger B_i \rangle - \frac{c_3}{f^2}\langle B_i^\dagger B_j^\dagger B_i B_j \rangle - \frac{c_4}{f^2}\langle B_i^\dagger B_j^\dagger B_j B_i \rangle \\ & - \frac{c_5}{f^2}\langle B_i^\dagger B_i \rangle \langle B_j^\dagger B_j \rangle - \frac{c_6}{f^2}\langle B_i^\dagger B_j \rangle \langle B_j^\dagger B_i \rangle, \quad i, j = \uparrow, \downarrow \end{aligned}$$

Savage, Wise (1995)

Lattice QCD could compute the six Wilson coefficients under some special circumstances:

INT-PUB-17-017, MIT-CTP-4912, NSF-ITP-17-076

Baryon-Baryon Interactions and Spin-Flavor Symmetry from Lattice Quantum Chromodynamics

Michael L. Wagman,[1,2] Frank Winter,[3] Emmanuel Chang, Zohreh Davoudi,[4]
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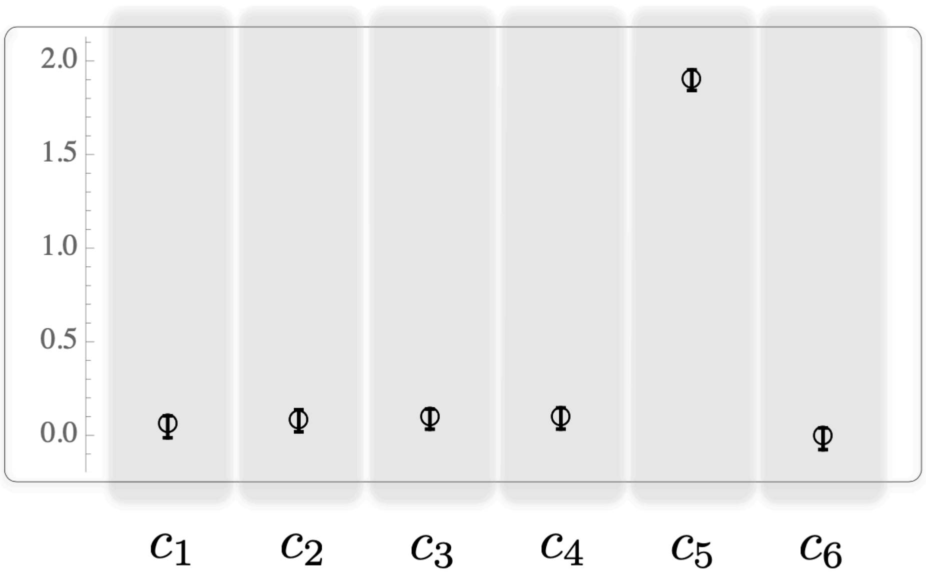

m_π = 804 MeV

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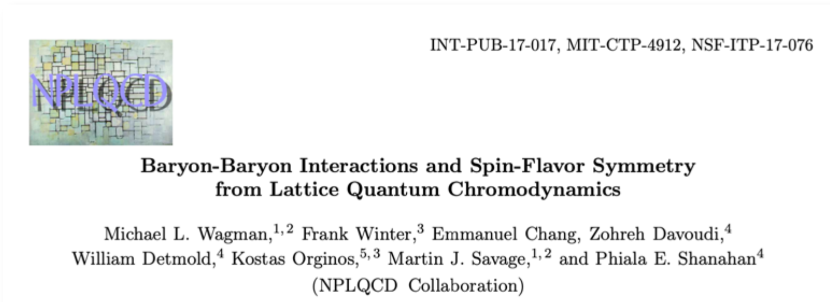
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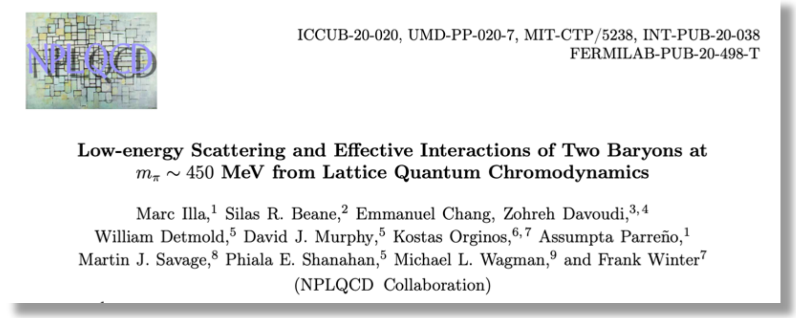
ICCUB-20-020, UMD-PP-020-7, MIT-CTP/5238, INT-PUB-20-038
FERMILAB-PUB-20-498-T

Low-energy Scattering and Effective Interactions of Two Baryons at $m_\pi \sim 450$ MeV from Lattice Quantum Chromodynamics

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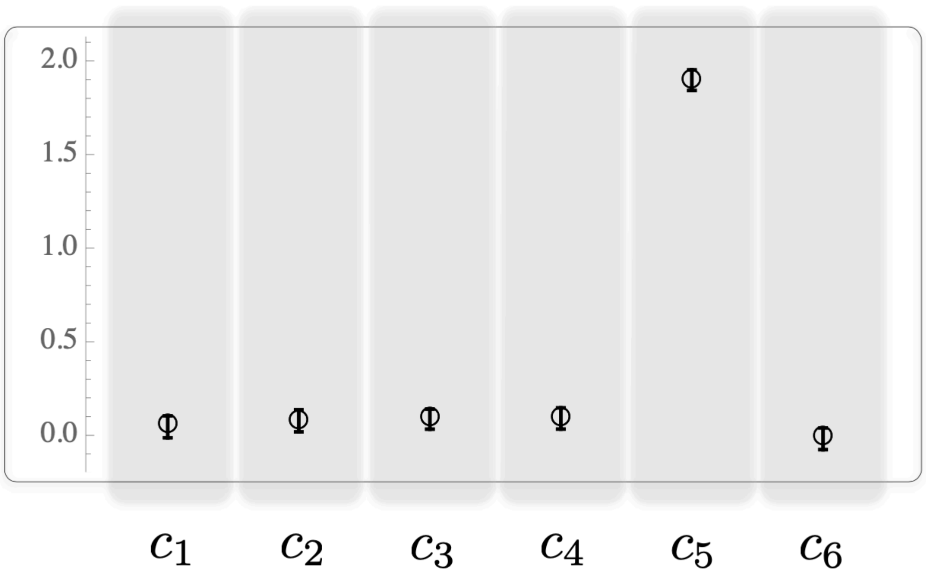

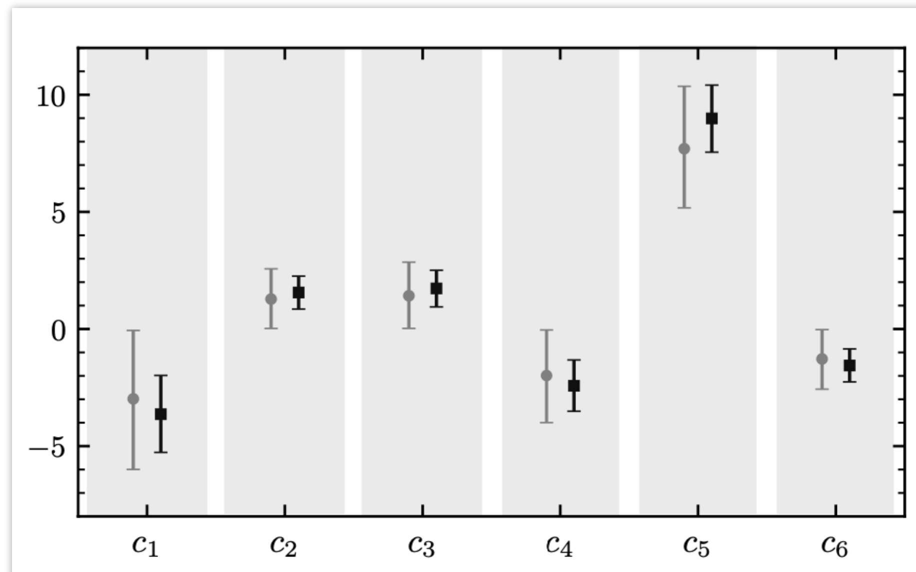

m_π = 804 MeV

m_π = 450 MeV

m_π = 150 MeV in reality

In the limit where all coefficients but c_5 are vanishing:

$$\mathcal{L}_{\text{LO}}^{n_f=3} = -\frac{c_1}{f^2}\langle B_i^\dagger B_i B_j^\dagger B_j\rangle - \frac{c_2}{f^2}\langle B_i^\dagger B_j B_j^\dagger B_i\rangle - \frac{c_3}{f^2}\langle B_i^\dagger B_j^\dagger B_i B_j\rangle - \frac{c_4}{f^2}\langle B_i^\dagger B_j^\dagger B_j B_i\rangle$$
$$-\frac{c_5}{f^2}\langle B_i^\dagger B_i\rangle\langle B_j^\dagger B_j\rangle - \frac{c_6}{f^2}\langle B_i^\dagger B_j\rangle\langle B_j^\dagger B_i\rangle, \qquad i,j = \uparrow,\downarrow$$

The remaining operator can be re-written,

$$\mathcal{B} = (n_\uparrow, n_\downarrow, p_\uparrow, p_\downarrow, \ldots)\ , \qquad \mathcal{L} = -c_5\left(\mathcal{B}^\dagger\mathcal{B}\right)^2$$

which is invariant under an SU(16) spin-flavor symmetry

$$\mathcal{B} \to U\mathcal{B}\ , \qquad U^\dagger U = 1$$

U = 16x16
unitary matrix!

There is no large N_c explanation!

To summarize, in low-energy QCD there exist several emergent global symmetries that are not symmetries of the fundamental QCD Lagrangian:

1. Approximate SU(4), SU(6) quark spin-flavor symmetries. → from large N_c !

2. Approximate Wigner's SU(4) spin-flavor symmetry. → from large N_c !

3. Approximate Schrodinger symmetry in NN scattering → ???

4. Approximate SU(16) symmetry as indicated by lattice simulations. → ???

Our goal is to understand 3 and 4 from a quantum information-theoretic perspective.

To discuss entanglement suppression, we need to quantify the amount of entanglement → Entanglement Measure!

Many possibilities for Entanglement Measure. For bipartite systems:

von Neumann entropy: $E(\rho) = -\mathrm{Tr}(\rho_1 \ln \rho_1) = -\mathrm{Tr}(\rho_2 \ln \rho_2)$

Linear entropy: $E(\rho) = -\mathrm{Tr}(\rho_1(\rho_1 - 1)) = 1 - \mathrm{Tr}\rho_1^2$

$$\rho = |\psi\rangle\langle\psi| \qquad \rho_{1/2} = \mathrm{Tr}_{2/1}(\rho)$$

The common property is that the entanglement measure vanishes for a product state $|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$, but attains the maximum for maximally entangled states (such as the Bell states.)

Entanglement is a property of the quantum state.

But we are more interested in the ability of a *quantum-mechanical operator* (i.e. the S-matrix) to entangle.

However, there is a subtlety here, as the amount of entanglement generated by an operator could depend on the initial state.

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Consider the CNOT (controlled NOT) gate in the computational basis:

$$\{|\uparrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, |\downarrow\downarrow\rangle\}$$

$$\text{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

CNOT does not entangle any of the basis state. However,

$$\frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \otimes |\uparrow\rangle \xrightarrow{\text{CNOT}} \frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$

The "entanglement power" deals with this issue is by averaging over the initial states:

$$E(U) = \overline{E(U\,|\psi_1\rangle \otimes |\psi_2\rangle)},$$

For quibts, the average is over the Bloch sphere.

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A minimally entangling operator has *E*(*U*) = 0, i.e.,

$$|\quad\rangle \otimes |\quad\rangle \xrightarrow{U} |\quad\rangle \otimes |\quad\rangle$$

There is, however, a notion of equivalent classes in this definition:

$$U \sim U' \qquad \text{if} \qquad U = (U_1 \otimes U_2)U'(V_1 \otimes V_2)$$

Modulo the equivalent class, there are two and only two minimally entangling operators, which in the computational basis,

$$\mathbf{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} , \qquad \mathrm{SWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} .$$

Identity gate: do nothing.
SWAP gate: interchange the qubits.

$$\mathrm{SWAP} \sim -1 \quad \text{as} \quad [\mathrm{SWAP}]^2 = 1$$

In terms of Pauli matrices,

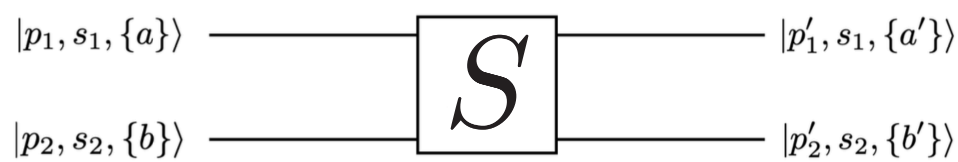
$$\mathrm{SWAP} = (1 + \boldsymbol{\sigma} \cdot \boldsymbol{\sigma})/2 \ , \qquad \boldsymbol{\sigma} \cdot \boldsymbol{\sigma} \equiv \sum_a \boldsymbol{\sigma}^a \otimes \boldsymbol{\sigma}^a \ .$$

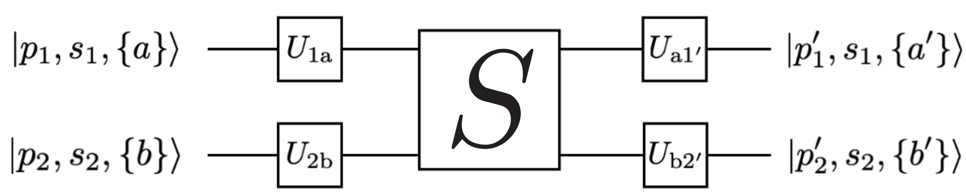
Low, Mehen: 2104.10835

In the scattering process the S-matrix acts on the IN-state:

$$|\text{out}\rangle = S\;|\text{in}\rangle$$

For 2-to-2 scattering of spin-1/2 fermions, the S-matrix can be viewed as a quantum logic gate acting on the spin-space:





Consider the scattering of two qubits, Alice and Bob, in the low-energy:

- Only the s-wave channel dominates.

- The S-matrix can be decomposed into ${}^1S_0$ and ${}^3S_1$ channels → there are two phase shifts: δ_0 and δ_1 , respectively.

- Rotational invariance and Unitarity then uniquely fix the S-matrix:

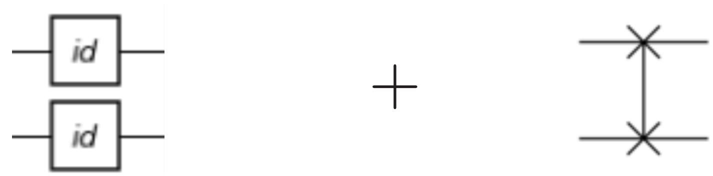
$$S = e^{2i\delta_0}\frac{(1-\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})}{4} + e^{2i\delta_1}\frac{(3+\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})}{4}$$

Spin-projector into ${}^1S_0$ channel

Spin-projector into ${}^3S_1$ channel

In terms of quantum logic gates,

$$S = \frac{1}{2}\left(e^{2i\delta_1} + e^{2i\delta_0}\right)\mathbf{1} + \frac{1}{2}\left(e^{2i\delta_1} - e^{2i\delta_0}\right)\ \mathrm{SWAP},$$



Conditions for the S-matrix to minimize entanglement:

1. $S = 1$ if $\delta_0 = \delta_1$ ➡ SU(4) or SU(16) spin-flavor sym.
2. S = SWAP if $|\delta_0 - \delta_1| = \pi/2$ ➡ Schrodinger sym.

Low, Mehen: 2104.10835

Let’s extend the analysis to other spin-1/2 baryons, which have a rich theoretical structure and phenomenology:

-- A total 8x8 = 64 scattering channels!

-- Strong interaction preserves charge (Q) and strangeness (S)

→ Classify the scattering channel into sectors with definitive (Q, S).

We are able to obtain the associated emergent symmetries when each (Q, S) sector is minimally entangled:

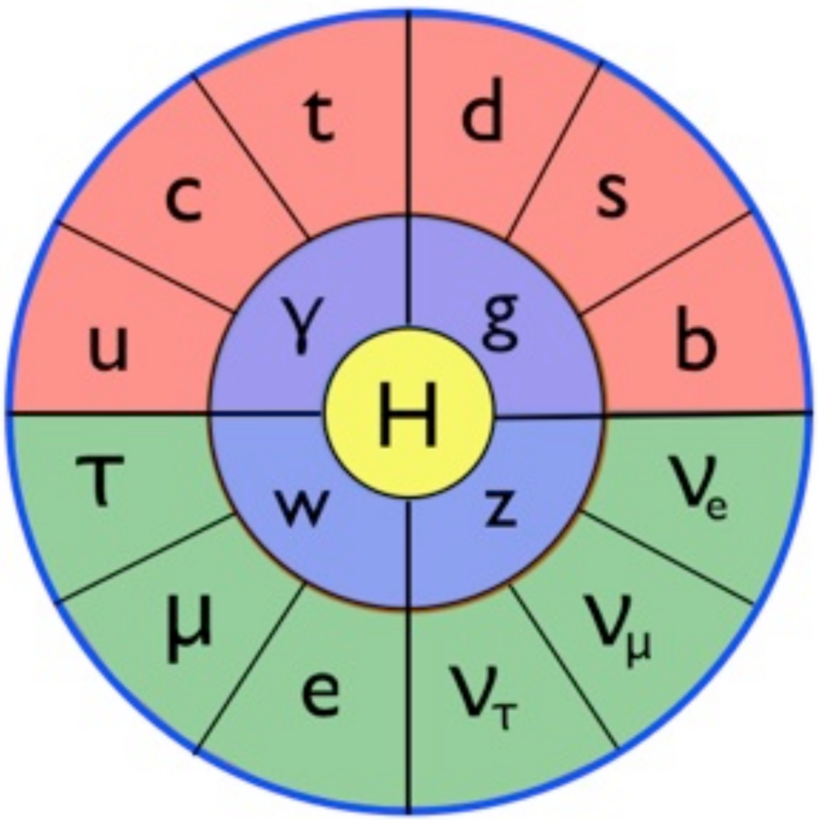
Flavor Subspace	Symmetry of Lagrangian
np $\Sigma^-\Xi^-$ $\Sigma^+\Xi^0$	$SU(6)$ spin-flavor symmetry or conformal symmetry in $\mathbf{27}$ and $\overline{\mathbf{10}}$ irrep channels
$n\Sigma^-$ $p\Sigma^+$ $\Xi^-\Xi^0$	conjugate of $SU(6)$ spin-flavor symmetry or conformal symmetry in $\mathbf{27}$ and $\mathbf{10}$ irrep channels
$(p\Lambda,\ p\Sigma^0,\ n\Sigma^+)$ $(n\Lambda,\ n\Sigma^0,\ p\Sigma^-)$ $(\Sigma^-\Lambda,\ \Sigma^-\Sigma^0,\ n\Xi^-)$ $(\Sigma^+\Lambda,\ \Sigma^+\Sigma^0,\ p\Xi^0)$ $(\Sigma^-\Xi^0, \Xi^-\Sigma^0, \Xi^-\Sigma^0)$ $(\Xi^-\Sigma^+, \Xi^0\Lambda, \Xi^0\Sigma^0)$	$SO(8)$ flavor symmetry or conformal symmetry in $\mathbf{27}$, $\mathbf{8}_{\boldsymbol{S}}$, $\mathbf{8}_{\boldsymbol{A}}$, $\mathbf{10}$ and $\overline{\mathbf{10}}$ irrep channels
$(\Sigma^+\Sigma^-,\ \Sigma^0\Sigma^0,\ \Lambda\Sigma^0,\ \Xi^-p,\ \Xi^0n,\ \Lambda\Lambda)$	$SU(16)$ symmetry or $SU(8)$ and conformal symmetry

TABLE V. Symmetries predicted by entanglement minimization in each flavor sector.

Liu, Low, Mehen: 2210.12085

Next we will consider a fully relativistic quantum system.

The great Success of the Higgs Boson!



H^0 $J = 0$

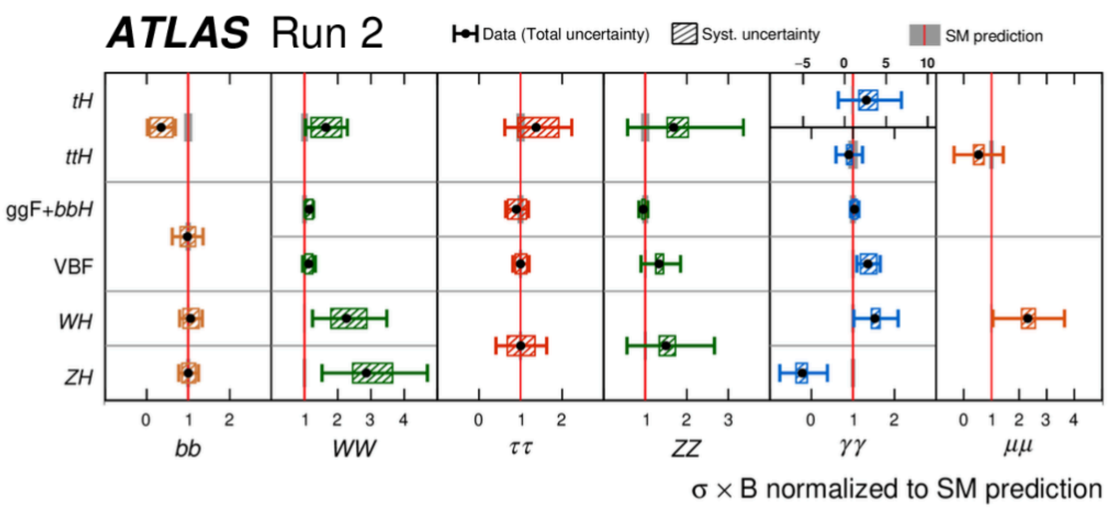
Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 1.7$ GeV, CL = 95%

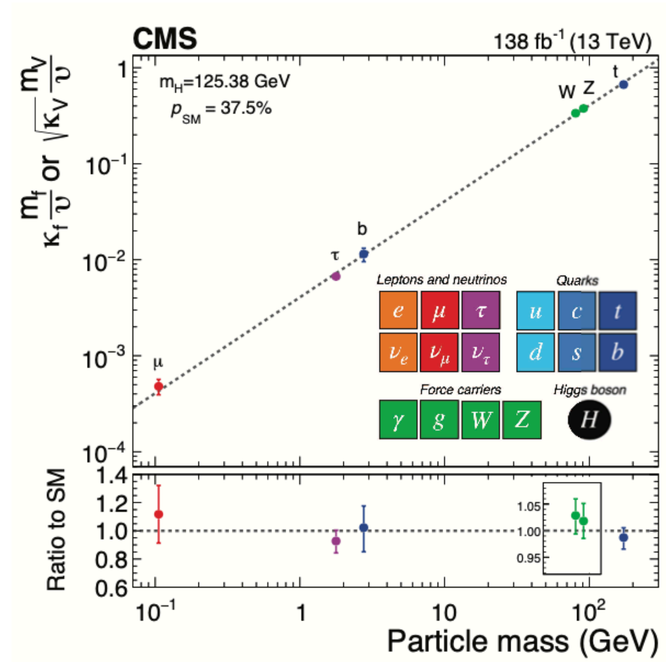
H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^- < 7.0$, CL = 95%
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

Measurements at the LHC point to a Standard Model-like Higgs boson:





In most BSM models, a SM-like Higgs is by no means generic!

We need special choices of parameters!!

- Consider 2HDM, the prototypical model for BSM theories:

$$\begin{aligned}\mathcal{V} \;=\; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] \\ & +\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \,,\end{aligned}$$

- There exists a "basis" where all parameters are real. The VEV's are

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \,, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \,,$$

$$v^2 \equiv v_1^2 + v_2^2 = \frac{4m_W^2}{g^2} = (246 \text{ GeV})^2 \qquad \tan\beta = \frac{v_2}{v_1}$$

- There are 8 real degrees of freedom:

  3 eaten Goldstones and 5 physical scalars -- 2 charged Higgs, 1 CP-odd neutral Higgs and 2 CP-even neutral Higgs.

- The mixing angle in the CP-even neutral sector is defined as

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \equiv R(\alpha) \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

- The 2x2 mass matrix can be diagonalized:

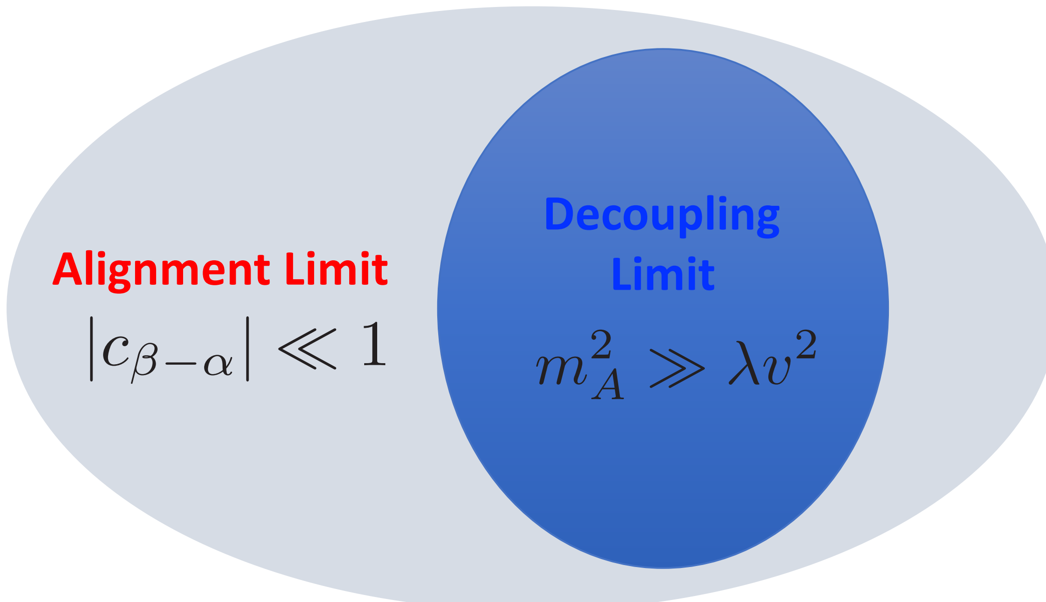
$$R^T(\alpha) \begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} R(\alpha) = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

- A SM-like Higgs emerges when

$$g_{hVV} = g_{hVV}^{\text{SM}} \; s_{\beta-\alpha} \qquad\qquad |c_{\beta-\alpha}| \ll 1$$

- This is the "alignment limit", which is more general than the "decoupling limit":

$$m_A^2 \gg \lambda v^2$$



- A SM-like Higgs emerges when

$$g_{hVV} = g_{hVV}^{\mathrm{SM}}\ s_{\beta-\alpha} \qquad\qquad |c_{\beta-\alpha}| \ll 1$$

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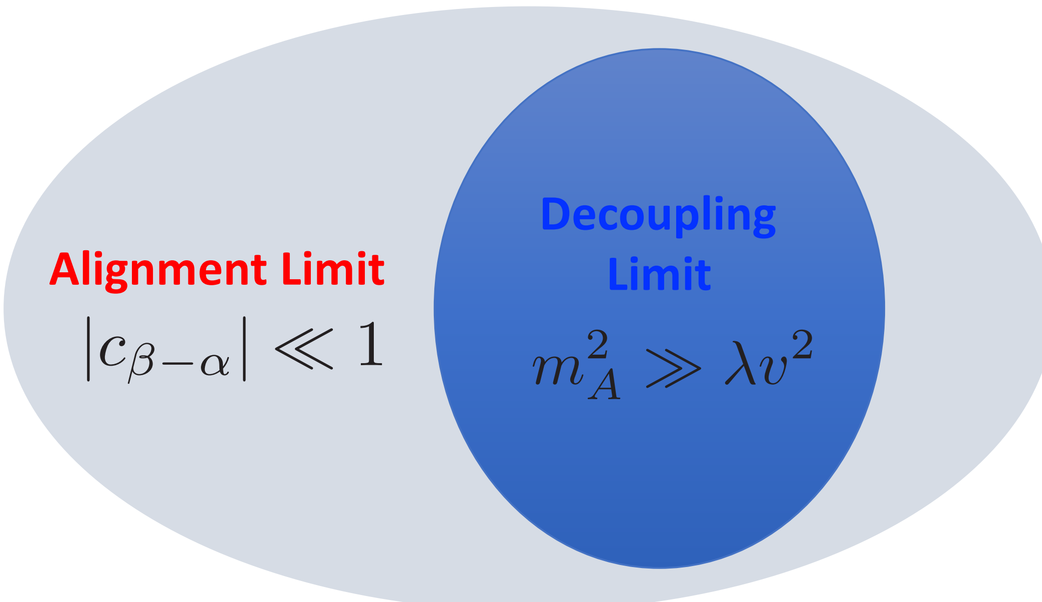
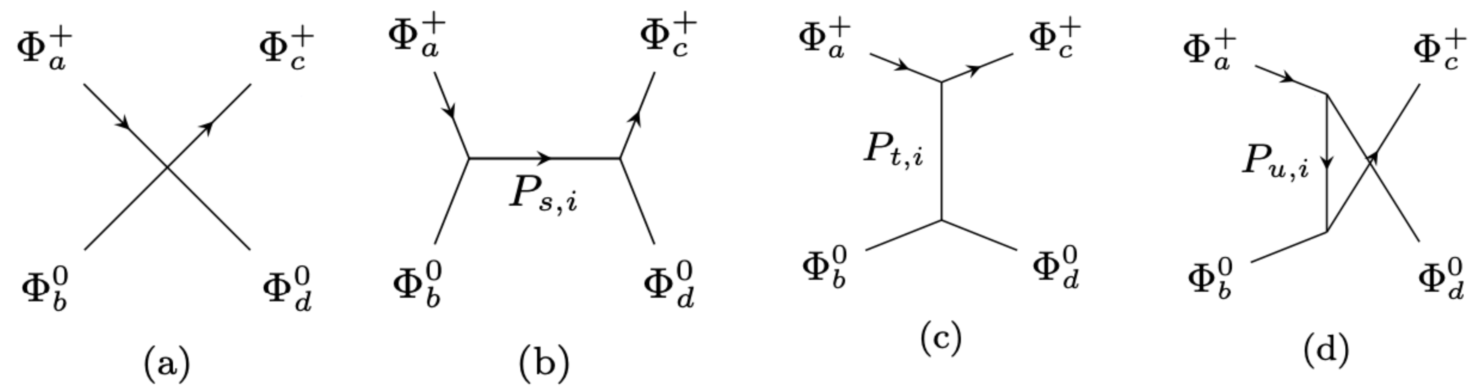


Experimental data point to an "approximate" alignment limit!

We studied the tree-level S-matrix, in the limit the gauge and Yukawa couplings are turned off, of the 2-to-2 scattering of Higgs bosons:

$$\Phi_a^+ \Phi_b^0 \to \Phi_c^+ \bar{\Phi}_d^0$$



$$S = 1 + iT$$

$$\langle \Phi_c \Phi_d | \, iT \, | \Phi_a \Phi_b \rangle = i(2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_c) M_{ab,cd}$$

- Demanding that the S-matrix is in the equivalent class of Identity gate in the flavor subspace:

$$S = [\mathbf{1}]$$

lead to the following conditions on the tree amplitudes:

$$\begin{aligned}
&M_{11,11} + M_{22,22} = M_{12,12} + M_{21,21} \ , \\
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What scalar potential could give rise to such an entanglement-suppressing S-matrix??

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- The resulting scalar potential is

$$V = Y\left(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2\right) + \frac{\lambda}{2}\left(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2\right)^2$$
$$= Y\,\vec{\Phi}\cdot\vec{\Phi} + \frac{\lambda}{2}\left(\vec{\Phi}\cdot\vec{\Phi}\right)^2$$

$$\vec{\Phi} = \left(\mathrm{Re}\,\phi_1^+, \mathrm{Im}\,\phi_1^+, \mathrm{Re}\,\phi_1^0, \mathrm{Im}\,\phi_1^0, \mathrm{Re}\,\phi_2^+, \mathrm{Im}\,\phi_2^+, \mathrm{Re}\,\phi_2^0, \mathrm{Im}\,\phi_2^0\right)^T$$

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- This potential has a maximal SO(8) symmetry, which rotates the eight real components in the two complex doublets.

- The SO(8) broken down to SO(7) by the Higgs VEV.

  All non-SM Higgs are Goldstone bosons, which become massive after turning on gauge and Yukawa couplings.

- More importantly, a SM-like Higgs boson follows from this scalar potential.

A SM-like Higgs is a consequence of entanglement suppression!

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In pursuit of a new paradigm:

Can symmetry be the outgrowth of more fundamental principles?

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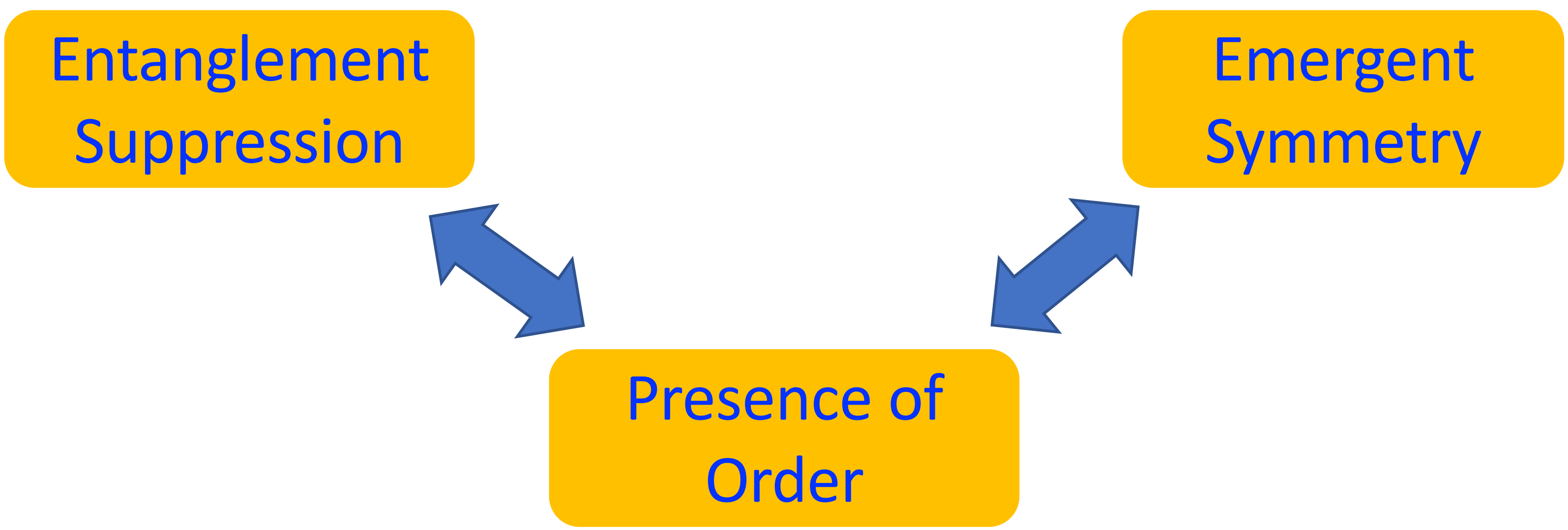

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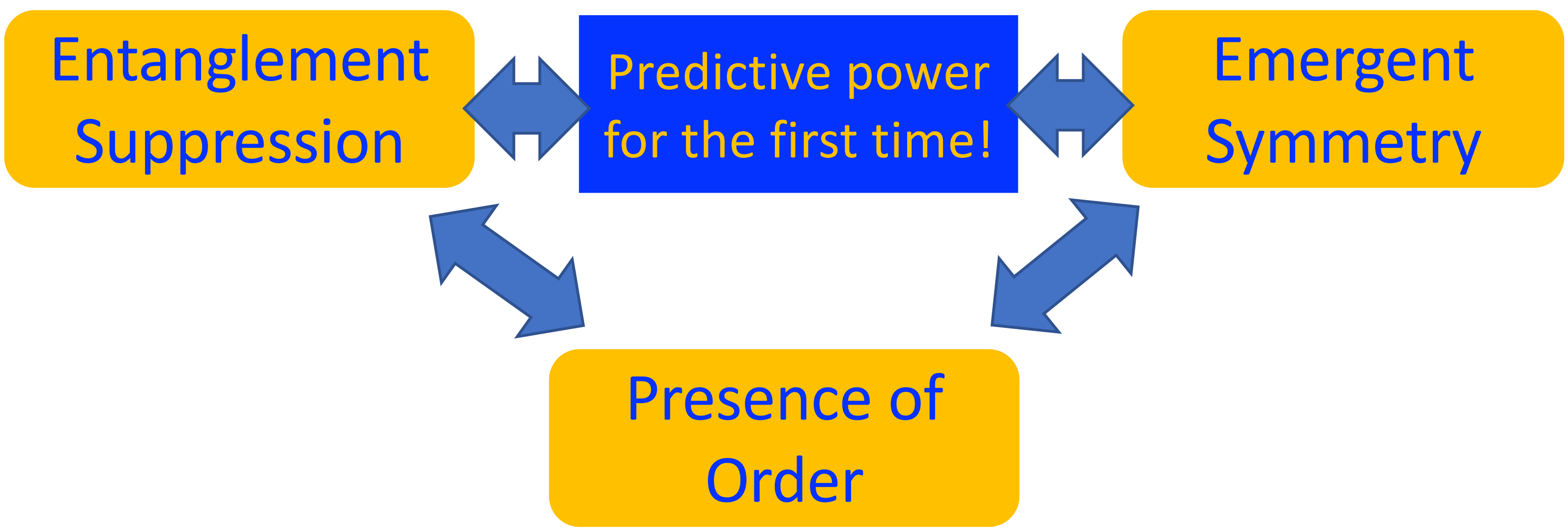

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Understanding these issues might help us devise more efficient quantum algorithms for simulating systems exhibiting a particular type of symmetry.