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Entanglement Maximization and Symmetry Selection in Composite Higgs Models

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Why Do We Need Protective Symmetries?

Composite Higgs: $SO(5) \to SO(4)$

Top-sector mixing breaks the Goldstone symmetry explicitly.

pNGB Higgs	→	**Top-sector mixing**	→	**Higgs potential**
Goldstone protection		Explicit breaking		UV sensitivity

Maximal Symmetry: a protection mechanism

$$\Pi_1^q(p^2) = \Pi_1^t(p^2) = 0$$

Finite fermionic Higgs potential

No additional double tuning

THE QUESTION

Can a physical criterion reveal such symmetry structures?

Entanglement Extremization as a Symmetry Probe

Low-energy QCD provides an important precedent.

2019

Entanglement suppression

Baryon S-matrix

$SU(4),\ SU(16)$

Beane et al., PRL 122, 102001

2021

Minimal entangling operators

I, SWAP

Enhanced symmetry

Low & Mehen, PRD 104, 074014

2023

Entanglement maximum

Very-low-energy np (initial-state dependent)

Wigner $SU(4)$

Miller, PRC 108, L031002

OUR QUESTION

Entanglement extremum $\longrightarrow$ amplitude constraints $\longrightarrow$ symmetry structure

Testbed: $h_3 h_4 \to t\bar{t}$ in a composite-Higgs resonance model

Helicity Entanglement from Scattering

At fixed momenta, massless top and antitop helicities form a two-qubit system.

HELICITY ENCODING

TOP / QUBIT A

$$|t_L\rangle \equiv |0\rangle_A, \qquad |t_R\rangle \equiv |1\rangle_A$$

ANTITOP / QUBIT B

$$|\bar{t}_L\rangle \equiv |0\rangle_B, \qquad |\bar{t}_R\rangle \equiv |1\rangle_B$$

SCATTERING PREPARES THE OUTGOING STATE

$$\mathcal{M}_{LL} = \mathcal{M}_{RR} = 0$$

$$|\Psi\rangle = \frac{\mathcal{M}_{LR}|01\rangle + \mathcal{M}_{RL}|10\rangle}{\sqrt{\mathcal{N}}}$$

$$\mathcal{N} = |\mathcal{M}_{LR}|^2 + |\mathcal{M}_{RL}|^2 > 0$$

CONCURRENCE

$$\Delta = \frac{2|\mathcal{M}_{LR}\mathcal{M}_{RL}|}{\mathcal{N}}$$

MAXIMAL ENTANGLEMENT

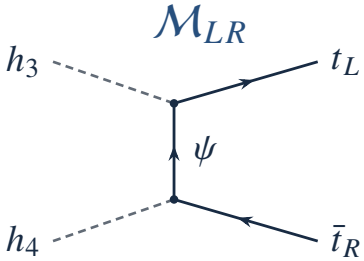
$$\Delta = 1 \iff |\mathcal{M}_{LR}| = |\mathcal{M}_{RL}|$$

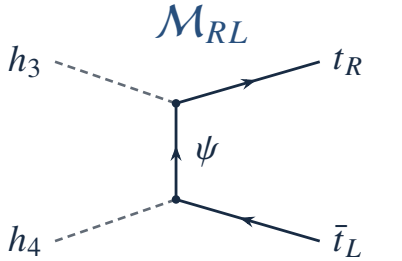
A quantum-state condition becomes a constraint on scattering amplitudes.

Higgs–Top Scattering through Top Partners

$$h_3 h_4 \longrightarrow t\bar{t}$$

One $SO(4)$ fourplet + one singlet





Exchanged fermions (couplings). t-channel shown; u-channel also included.

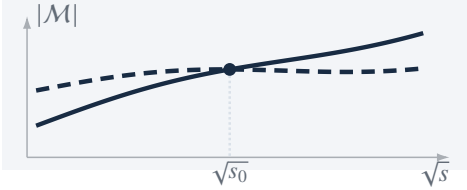
The two helicity channels probe different resonance exchanges.

From Entanglement to Resonance Matching

Different resonances imply different energy profiles. — $|\mathcal{M}_{LR}|$ -- $|\mathcal{M}_{RL}|$

AT A SINGLE ENERGY

Equality may occur accidentally.



A single crossing does not fix the spectrum.

OVER AN ENERGY INTERVAL

Equality must persist as energy varies.



Persistent equality constrains the dynamics.

IN OUR RESONANCE MODEL

$$\Delta = 1 \text{ for } s \in I \implies F_L(z) \equiv \widetilde{F}_R(z)$$

$\theta = \pi/2$; real tree level; nonzero-production branch

Matching energy dependence constrains resonance masses and couplings.

Entanglement Selects a Left–Right Symmetry

Persistent helicity matching fixes the physical resonance masses and couplings.

ENTANGLEMENT-SELECTED CONDITIONS

$$M_{T_1}^2 = M_T^2, \qquad |g_L| = |g_R| \neq 0, \qquad g_X = 0$$

NEUTRAL TOP–RESONANCE INTERACTIONS

After imposing the matching condition

$$\mathcal{L}_{f\,|\,h_3,h_4} \supset -M_{T_1}\,\bar{T}_{1R}T_{1L} - M_T\,\bar{T}_R T_L$$
$$+(h_4 - ih_3)\Big(y\,\bar{t}_L t_R + g_L\,\bar{t}_L T_{1R} + g_R\,\bar{T}_L t_R\Big) + \text{h.c.}$$

GENERALIZED LEFT–RIGHT Z_2

$$t_L \leftrightarrow t_R, \quad T \leftrightarrow \pm T_1, \quad h_3 \mapsto -h_3, \quad h_4 \mapsto h_4$$

Mass terms and single-Goldstone interactions are paired under this exchange.

The symmetry is identified from entanglement, rather than imposed a priori.

A Higgs-Protected Realization: Maximal Symmetry

What physical significance can the entanglement-selected structure have?

Entanglement-selected generalized left–right Z_2

↓ One symmetry-enhanced realization

MAXIMAL SYMMETRY

Enhanced global symmetry in the composite fermion sector

ADDITIONAL ENTANGLEMENT CONDITION

$$\epsilon_t^2 = 2\epsilon_q^2 \neq 0$$

Fixes relative left–right mixings

Matches physical poles and residues

HIGGS PROTECTION

$$\Pi_1^q(p^2) = \Pi_1^t(p^2) = 0$$

Finite fermionic Higgs potential

No additional double tuning

A Higgs-protected realization of the entanglement-selected symmetry.

Gauge vs. Fermion Sectors

Same entanglement criterion, different dynamical roles.

Gauge sector

Tree-level, CP-even
covariant-derivative interactions

$$|A_{++}| = |A_{--}| \implies \Delta_V = 1$$

Projected transverse sector
$\{|++\rangle,\ |--\rangle\}$

Helicity relation already enforced

Fermion sector

Resonance spectrum and
elementary–composite mixings

$$\Delta = 1 \implies |\mathcal{M}_{LR}| = |\mathcal{M}_{RL}|$$

Imposed over an open
energy interval

Pole-and-residue matching

In the top sector, maximal entanglement constrains resonance dynamics.

Conclusions and Outlook

Quantum-information criterion	Maximal entanglement over an energy interval constrains physical scattering amplitudes.
Symmetry selection	**Pole-and-residue matching** identifies a generalized **left–right Z_2 structure**.
Physical significance	A Maximal-Symmetry realization connects the selected structure to Higgs-potential protection.
Outlook	Larger resonance sectors and additional scattering channels.

Scattering entanglement offers a criterion for symmetry selection.

Why Maximal Entanglement?

QCD motivates testing entanglement extrema as symmetry probes.

MAXIMAL CONCURRENCE

$\Delta = 1$



equal magnitudes

$$|\mathcal{M}_{LR}| = |\mathcal{M}_{RL}| \neq 0$$

Over an open energy interval

$$F_L(z) \equiv \widetilde{F}_R(z)$$

Matched heavy poles and residues

$\Longrightarrow$ **generalized left–right Z_2**

$\theta = \pi/2$, nonzero-production branch

MINIMAL CONCURRENCE

$\Delta = 0$



one vanishes

$$\mathcal{M}_{LR} = 0 \text{ or } \mathcal{M}_{RL} = 0$$

At an isolated kinematic point

$$\widetilde{F}_R(z_\star) = 0$$

Does not enforce pole matching

No persistent branch with $y \neq 0$ in our resonance completion

TAKEAWAY

A persistent maximum selects left–right matching; a pointwise zero does not.

General-Angle Helicity Amplitudes

The 90° slice simplifies the calculation, but does not create the symmetry.

$$t = -\frac{s}{2}(1 - \cos\theta), \qquad u = -\frac{s}{2}(1 + \cos\theta)$$

Massless external states

$$K_L = \langle 3|\not{k}_2|4], \qquad K_R = [3|\not{k}_2|4\rangle, \qquad |K_L| = |K_R|$$

IDENTICAL SCALAR CHANNELS

$h_a h_a \to t\bar{t}, \quad a = 3, 4$

$$\mathcal{M}^{aa}_{LR} = -K_L\,[F_L(t) - F_L(u)]$$
$$\mathcal{M}^{aa}_{RL} = -K_R\,[F_R(t) - F_R(u)]$$

Antisymmetric in $t \leftrightarrow u$

At $\theta = \pi/2$: $t = u = z$

$$\mathcal{M}^{aa}_{LR} = \mathcal{M}^{aa}_{RL} = 0$$

Zero production: no normalized helicity state

MIXED SCALAR CHANNEL

$h_3 h_4 \to t\bar{t}$

$$\mathcal{M}^{34}_{LR} = -iK_L\,[F_L(t) + F_L(u)]$$
$$\mathcal{M}^{34}_{RL} = +iK_R\,[\widetilde{F}_R(t) + \widetilde{F}_R(u)]$$

Symmetric in $t \leftrightarrow u$

At $\theta = \pi/2$: $t = u = z$

$$\mathcal{M}^{34}_{LR} \propto F_L(z), \quad \mathcal{M}^{34}_{RL} \propto \widetilde{F}_R(z)$$

Nonzero probe of resonance dynamics

$\widetilde{F}_R(z) = F_R(z) - 2g_X^2/(z - M_Q^2)$

FULL-ANGLE RESULT

$$M^2_{T_1} = M^2_T, \qquad g_X = 0, \qquad g_L^2 = g_R^2 \neq 0$$

Same left–right Z_2 for all neutral product channels, wherever production is nonzero

Why Are the Other Branches Excluded?

Real tree-level kernels on an open spacelike interval; require nonzero production.

$$|F_L(z)| = |\widetilde{F}_R(z)| \implies F_L(z) = \eta\, \widetilde{F}_R(z), \quad \eta = \pm 1$$

NEGATIVE-SIGN BRANCH

$F_L(z) = -\widetilde{F}_R(z)$

Match the common massless top pole:

$y^2 = -y^2 \quad \Rightarrow \quad y = 0$

Vertex identity and $M_T^2 \geq M_Q^2$ give:

$g_L^2 + (1 - M_Q^2/M_T^2) g_R^2 = 0$

Couplings vanish, or coincident terms cancel.

$\implies \mathcal{N} = 0$

No normalized outgoing helicity state

COINCIDENT-POLE BRANCH ($\eta = +1$)

$g_X \neq 0 \quad \Rightarrow \quad M_T^2 = M_Q^2$

Mass relation then forces:

$\epsilon_{qQ} = 0$

Residue and vertex identities give:

$g_R^2 = g_X^2, \qquad g_L = 0$

Explicit vertices also imply $y = 0$.

$\implies \mathcal{N} = 0$

Coincident exchanges cancel identically

NONZERO-PRODUCTION BRANCH

$$M_{T_1}^2 = M_T^2, \qquad g_X = 0, \qquad g_L^2 = g_R^2 \neq 0$$

Physical pole-and-residue matching $\implies$ generalized left–right Z_2