Composite Higgs/ Extra Dimensions

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Fundamental Question raised by the SM

How and why is the Electroweak Symmetry broken?

***Prejudice 1*: a full physical answer demands establishing the nature of the microscopic dynamics that results in such an outcome...**

... and an understanding of the EW scale vis à vis other *likely* physical scales

(flavor, neutrino masses, baryogenesis, Planck scale,...)

***Prejudice 2*: the most likely place for the relevant new physics, the EW scale itself**

QFT framework provides a sharp formulation for this intuition:

Naturalness and the Hierarchy Problem

The Higgs Boson: A Milestone

New particle associated to EWSB? All indications are positive (from observed decay rates)

To do: mapping the Higgs potential from Higgs self-interactions

⟶ a non-trivial test of the Higgs Mechanism and Spontaneous Symmetry Breaking

- SM Higgs sector may turn out to be an excellent description of this physics
- Or perhaps the Higgs sector is more complicated (multi-doublets or other)

Neither possibility would be particularly surprising...

... but could it be taken as more than a *phenomenological description* of the physics of EWSB?

The Higgs Boson: A Milestone

- Is it elementary (up to scales parametrically larger than the weak scale)?

→ would be the first *elementary scalar* we know of!

- Or rather a composite scalar state of some underlying dynamics?

→ unlike other examples (e.g. pions), here inherits dynamics that gives it a vev, also a first...

A Composite Higgs

If indeed the Higgs is a bound state of more fundamental degrees of freedom, described at low energies by

$$\mathcal{L} = (D_\mu H)^\dagger D^\mu H + m^2 H^\dagger H - \lambda (H^\dagger H)^2 + \cdots$$

(or other multi-field generalization, e.g. 2HDM)

then the virtual corrections are cutoff at the compositeness scale Λ

The scale of strong dynamics, Λ, can itself be understood from dimensional transmutation

Requirement: the new strongly interacting sector must generate

- scalar parametrically lighter than Λ
- weakly interacting
- appropriate SM quantum numbers
- correct sign for m^2

The Higgs as a pNGB

Natural to interpret the composite Higgs as a (pseudo) Nambu-Goldstone boson

The strong sector has a (large) global symmetry, spontaneously broken by its dynamics
(à la chiral symmetry breaking in QCD)

Global symmetry explicitly broken by SM gauge interactions and other terms

$$SU(3)_C \times SU(2)_L \times U(1)_Y \quad \subset \quad G \quad \longrightarrow \quad \mathcal{H}$$

Higgs in $G/\mathcal{H}$

Elementary sector: SM gauge bosons, quarks & leptons

SM gauge interactions $\longleftrightarrow$ **Mixing**

New strong sector: resonances + Higgs bound state

The Higgs as a pNGB

The dots in $\mathcal{L} = (D_\mu H)^\dagger D^\mu H + m^2 H^\dagger H - \lambda (H^\dagger H)^2 + \cdots$

should give sufficiently suppressed effects.

An important constraint from EW precision tests: new physics sector should preserve a custodial symmetry, i.e.

$$SU(2)_L \times SU(2)_R \subset \mathcal{H} \quad \longrightarrow \quad \rho = \frac{m_W^2}{m_Z^2 \cos\theta_W} \approx 1$$

Minimal model: Agashe, Contino, Pomarol '04; Contino, da Rold, Pomarol '06

$SO(5)/SO(4)$ **4 NGB's, (2,2) under** $SU(2)_L \times SU(2)_R \simeq SO(4)$

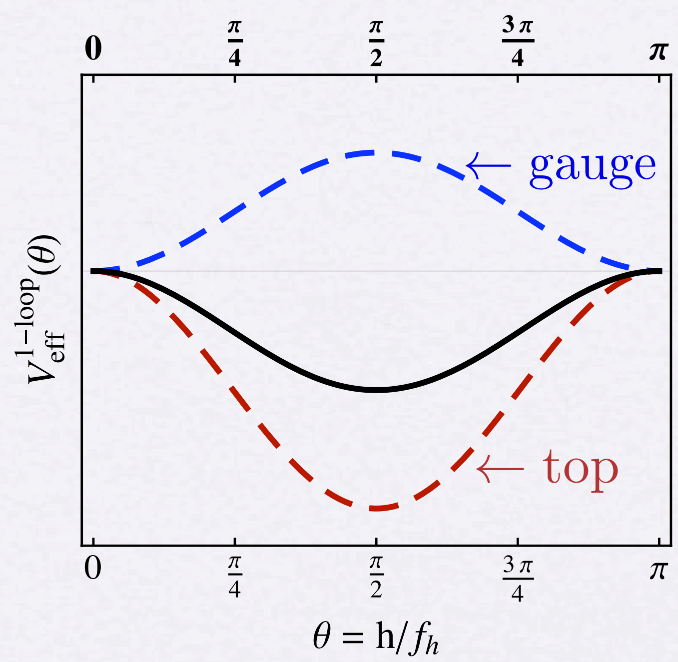
Extended Higgs sectors, e.g.:

$SO(6)/SO(5)$	$SO(6)/SO(4) \times SO(2)$	$SU(5)/SO(5)$	$\cdots$
(1 doublet + 1 singlet)	**(2HDM)**	**(3,3) + (2,2) + (1,1)**	
Gripaios, Pomarol, Riva, Serra '09	Mrazek et al. '11	Vecchi '13	

Higgs Potential

In many of these constructions, the (1-loop) induced Higgs potential is calculable

- **Gauge contributions: favor alignment (no EWSB)**
- **Fermionic contributions (e.g. top) can induce EWSB**



pNGB's parametrized by $\Sigma = e^{i\Pi/f_h}$

For SM-likeness, need to stabilize at $\epsilon \equiv \sin(h/f_h) \ll 1$

Need non-trivial dependence on ϵ **:** $V(\epsilon) \sim \epsilon^2 + \epsilon^4 + \cdots$

typically, need to arrange for some degree of cancellation, e.g. gauge vs top

Dependence on details of fermionic sector: representations under G

Partial Compositeness

Recall in `technicolor-type' constructions:

$$\frac{1}{\Lambda^2} q_i q_j Q_m Q_n \qquad \textbf{but also} \qquad \frac{1}{\Lambda^2} q_i q_j q_k q_l$$

Recent emphasis on *linear* couplings between SM and strong sector:

D.B. Kaplan, '91

Contino, Kramer, Son, Sundrum, 2011

$$y_L^f f_h \; f_L \mathcal{O}_R + y_R^f f_h \; f_R \mathcal{O}_L$$

SM do not fill G multiplets
(explicit breaking of global symm.)

in some G representation

Physical states: $f' \sim \cos\theta_f f + \sin\theta_f \Psi$ $\qquad$ $\sin\theta_f = y^f f_h / m_\Psi$

strong resonances excited by $\mathcal{O}$

Partial Compositeness

Recent emphasis on *linear* couplings between SM and strong sector:

$$y_L^f f_h \; f_L \mathcal{O}_R + y_R^f f_h \; f_R \mathcal{O}_L + Y_* H \mathcal{O}_R \mathcal{O}_L' + \cdots$$

SM do not fill G multiplets
(explicit breaking of global symm.)

in some G representation

Physical states: $f' \sim \cos\theta_f f + \sin\theta_f \Psi$

strong resonances excited by $\mathcal{O}$

SM Yukawa couplings: $y_f \sim \sin\theta_L Y_* \sin\theta_R$

SM fermion masses controlled by compositeness content in L and/or R

CKM mixing determined by ratios of L mixing angles (when hierarchical)

Warped XDim Realizations

Warped extra dimensions provide an appealing playground for these ideas

- **Compelling solution to the hierarchy problem (different from SUSY)**
- **Non-trivial understanding of SM flavor structure**
- **``A viable theory of flavor at the TeV scale" (almost)**

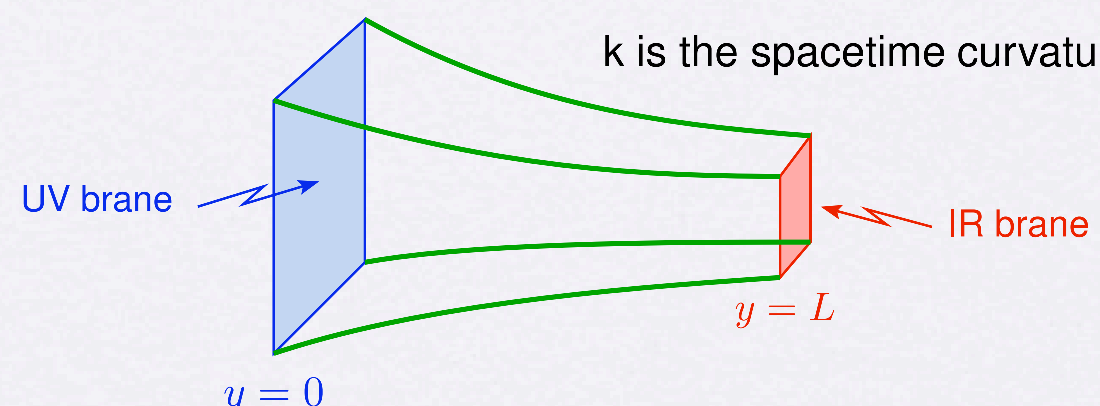
``Bulk RS Models"

Requires Higgs to be localized near IR brane:

- **Via AdS/CFT correspondence, interpret as *composite* in the dual 4D theory**
- **In general, requires tuning for light Higgs**
- **Implementing pNGB framework requires more structure**

(a.k.a. Gauge-Higgs Unification)

k is the spacetime curvature



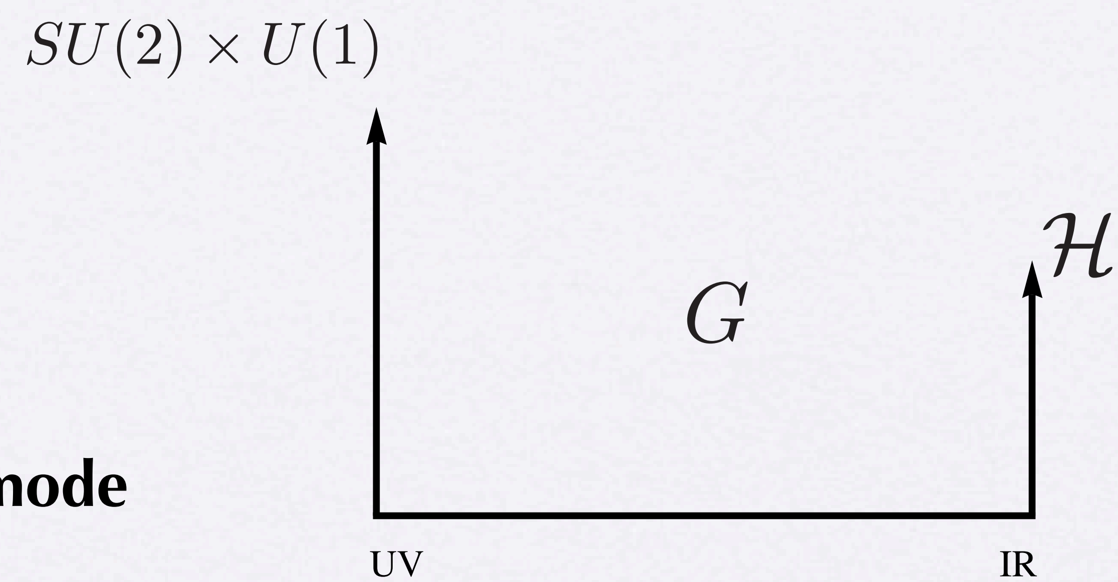
$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

Warped XDim Realizations

Bulk gauge symmetry $\longleftrightarrow$ **Global symmetry of composite sector**

Breaking by boundary conditions:

- **To SM on UV brane**
- **To $\mathcal{H}$ on IR brane**



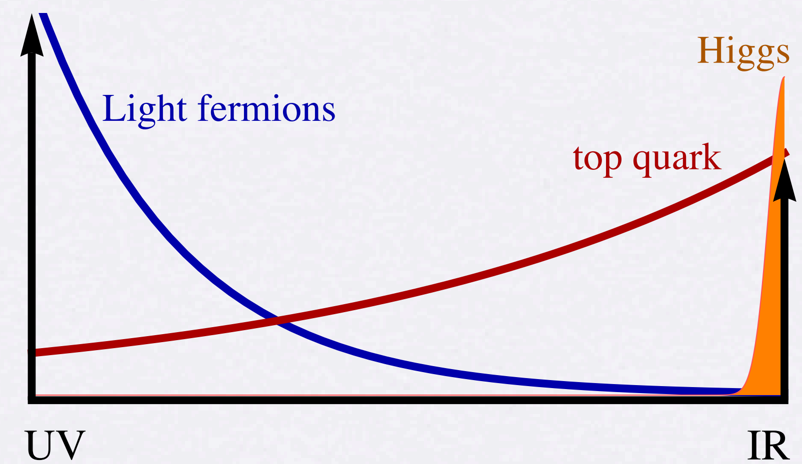
$A_5^{\hat{a}}$ **components in** $G/\mathcal{H}$ **have physical 0-mode**

$\longrightarrow$ **Identify as Higgs field**

(no tree-level potential due to 5D gauge symmetry, but induced non-locally at 1-loop)

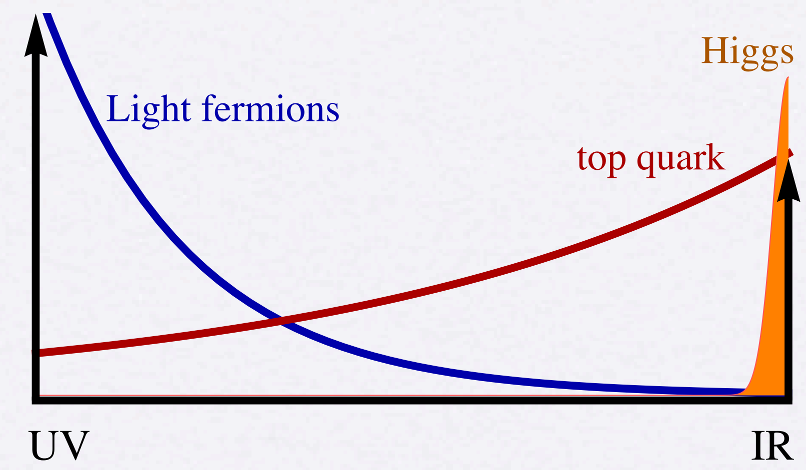
Localization of fermion 0-modes (controlled by 5D Dirac masses)

- **UV localized: mostly elementary**
- **IR localized: mostly composite**



Warped XDim Realizations

Flavor structure and ``anarchy":



- When Higgs ``fundamental" 5D scalar

  All 5D Yukawa couplings of similar, natural, size

- Gauge-Higgs Unification

  Yukawa interactions from 5D gauge interactions

  Get non-trivial flavor structure from IR localized mass terms (all of same order)

<u>Pure anarchy</u>: SM flavor only from localization of 0-modes (controlled by order one parameters)

Some consequences:

- Production of gauge resonances: controlled by gauge elementary/composite mixing angle

  ~ 1/5 of SM strength when Planck/weak hierarchy solved

- FCNC's from KK gluon exchange, effectively suppressed by >> TeV

- Important constraints remain, mostly from CP-odd observables (Kaon system)

Warped XDim Realizations

In this framework, one would expect:

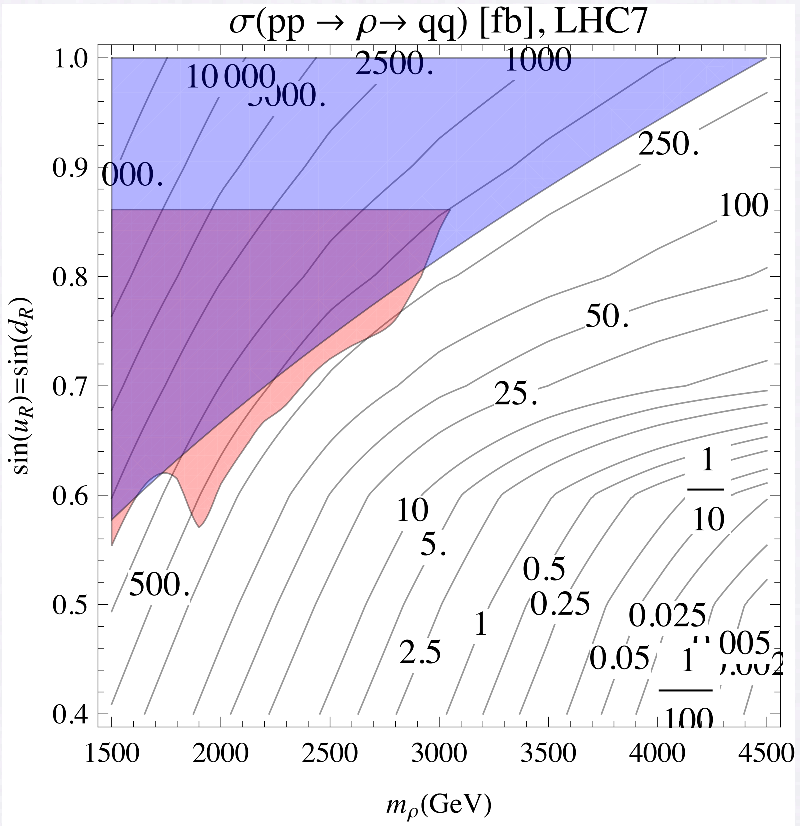
- **Challenging direct detection: heavy resonances with reduced production XS**
- **Final states with tops, W, Z, h**
- **Flavor and CP-violating observables a powerful probe**

But should remember that ``flavor anarchy" not a must:

⟶ **May implement versions of MFV**

⟶ **``Right-handed compositeness"**

⟶ **Sensitivity in dijet resonance searches**



Redi, Weiler, '11

Potentially large deviations in Higgs processes

See talks in previous session...

Strongly Interacting Light Higgs

Giudice, Grojean, Pomarol, Rattazzi '07

Resonances in multi-TeV range, from EW (and flavor) constraints

Simplification: heavy sector characterized by two parameters $g_{SM} \lesssim g_\rho \lesssim 4\pi$

(may have to treat ``top partners" separately) $m_\rho = g_\rho f_h$

EFT below scale of strong resonances:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

with e.g.

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,
\end{aligned}$$

Strongly Interacting Light Higgs

Contino, Ghezzi, Grojean, Mühleitner, Spira '13

Telling weakly coupled ... from strongly coupled ...from pNGB apart?

- **Familiar weakly coupled example: MSSM with R-parity** $g_\rho \sim 1 \quad \longrightarrow \quad m_\rho \sim f_h$

  Corrections induced at loop-level, or suppressed in decoupling limit, potential large $\tan\beta$ enhancement in down-type couplings

  $\longrightarrow$ Small $\bar{c}_H, \bar{c}_W, \bar{c}_B, \bar{c}_u$ but enhancement due to $\bar{c}_d$

- **Strongly interacting case:** $m_\rho \gg f_h$

  Dominant $\bar{c}_H, \bar{c}_u, \bar{c}_d, \bar{c}_6$ while $\bar{c}_W, \bar{c}_B$ suppressed by $(g/g_*)^2$

- **pNGB:**

  In addition, $\bar{c}_g, \bar{c}_\gamma$ suppressed by $(g_{\not{G}}/g_*)^2$

Strongly Interacting Light Higgs

In unitary gauge and after canonical normalization:

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + \ldots$$

$$+\, m_W^2\, W_\mu^+ W^{-\,\mu}\left(1 + 2c_W\,\frac{h}{v} + \ldots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu\left(1 + 2c_Z\,\frac{h}{v} + \ldots\right)$$

$$-\sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \ldots\right) + \ldots$$

Operators generated at loop level: (recently challenged by Jenkins, Manohar & Trott)

$$W_{\mu\nu}^+ W^{-\,\mu\nu} h\,, \quad Z_{\mu\nu} Z^{\mu\nu} h\,, \quad \gamma_{\mu\nu}\gamma^{\mu\nu} h\,, \quad Z_{\mu\nu}\gamma^{\mu\nu} h$$

Strongly Interacting Light Higgs

Including only the effects from pNGB non-linearities: $\xi \equiv \frac{v^2}{f^2}$

(G symmetry allows resummation to all orders)

from Contino, Ghezzi, Grojean, Mühleitner, Spira '13

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1-\bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1-\bar{c}_H/2-2\bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi \ \ (\psi=u,d,l)$	$1-(\bar{c}_H/2+\bar{c}_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1+\bar{c}_6-3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

Effects of resonances (e.g. top partners) should also be included!

Elucidation across Frontiers

- **Energy Frontier:**

  Resonances starting at few TeV (+ tower) at the edge of LHC reach

- **Intensity Frontier:**

  Flavor and CP-violation can play a crucial role in elucidating the structure of the composite sector

- **Cosmic Frontier:**

  EW baryogenesis in the context of pNGB scenarios?

  Dark Matter and connection to Higgs sector?

Questions

- **Program of Higgs precision measurements, interpreted within EFT approach:**

  What will it take to establish underlying strong dynamics?

  Compared to growth with energy in $V_L V_L \to V_L V_L / hh$ scattering?

  pNGB versus ``tuned composite scalar"?

  What about distinguishing different models (fermion representations)?

- **If (indirect) evidence for strong interactions: can we point to the scale of resonances?**

- **If (eventually) new resonances are discovered directly, what would it take to establish an ``extra-dimensional" origin, as opposed to a more general 4D description?**