# Electroweak and Conformal Symmetry breaking by a Strongly Coupled Hidden Sector

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Based on hep-ph/1310.4423 by M. Holthausen, J. Kubo, KSL and M. Lindner

# We know Higgs boson exist!

**The Nobel Prize in Physics 2013**
François Englert, Peter Higgs

## The Nobel Prize in Physics 2013

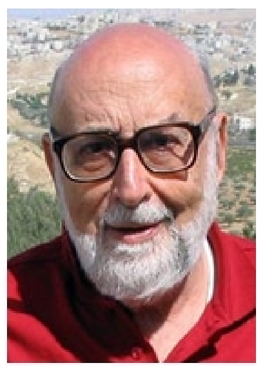


Photo: Pnicolet via Wikimedia Commons
François Englert

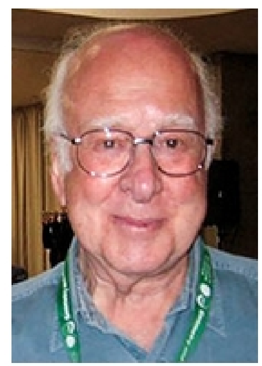
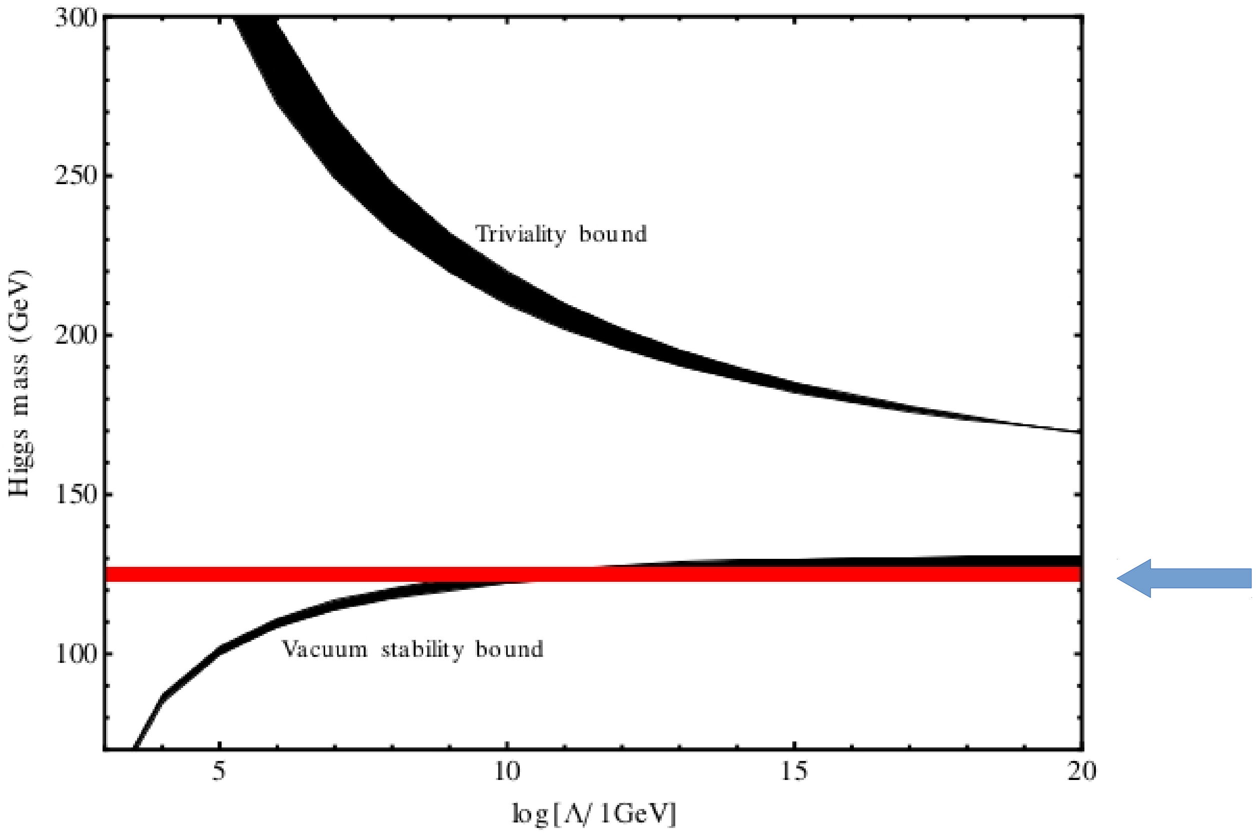


Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

There!

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

# The Higgs coupling




SM may survive up to Planck scale

Holthausen, Lim, Lindner '12
Degrassi et al. '12
Buttazzo et al. '13
Bezrukov et al. '12

BSM?

Dark energy

Strong CP problem

# THE HIERARCHY PROBLEM

Baryogenesis

Inflation

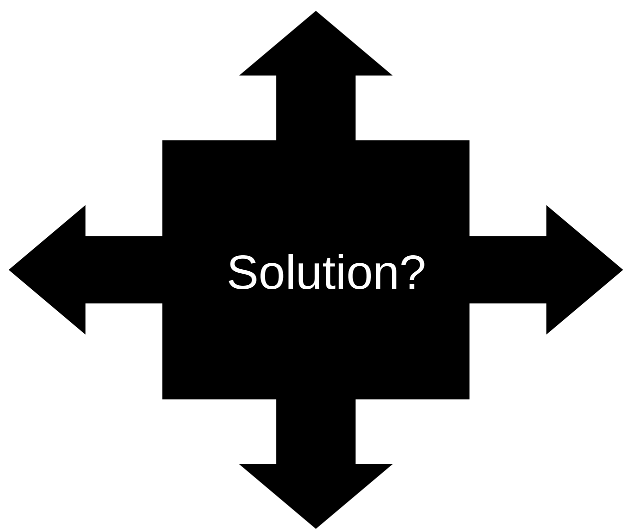
Dark matter

Neutrino mass

$$\delta m_h^2 \propto f(\lambda, g_i \ldots)\Lambda^2$$

Compositeness

Conformal symmetry?




Supersymmetry

Extra Dimension

BSM?

Dark energy

Strong CP problem

# THE HIERARCHY PROBLEM

Baryogenesis

Dark matter

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Neutrino mass

$$\delta m_h^2 \propto f(\lambda, g_i \ldots)\Lambda^2$$

Cor

**But where are the new physics?**

Conformal symmetry?

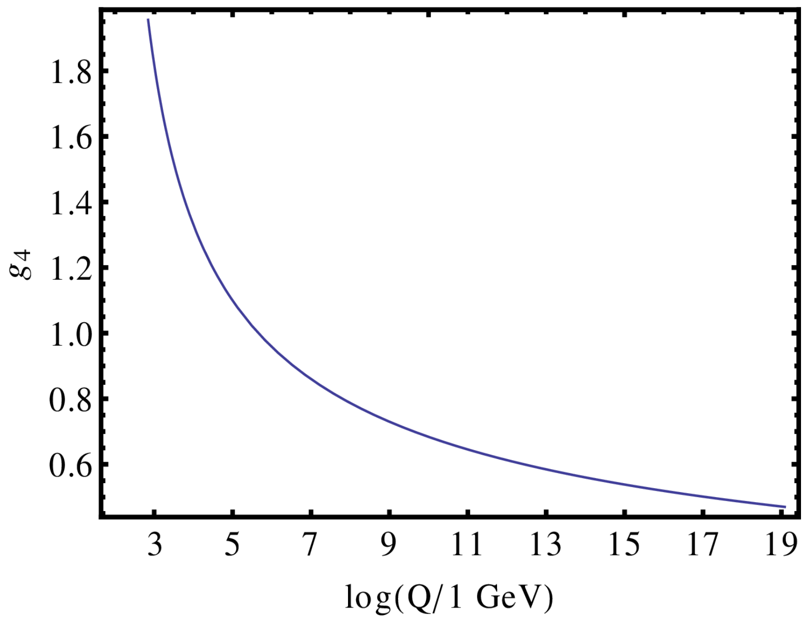

y

**Long-held belief on naturalness must be critically reexamined!**

Extra D

# Electroweak Scale

- Strong hierarchy between EW and Planck scale.
- QCD scale can be explained by running couplings and dimensional transmutation.
- Would be nice if EW sector can mimic such mechanism.



# Conformal Symmetry

$$\text{Stays small if } m_H(M_{pl}) \approx 0$$

$$\frac{d\,m_H^2}{d\,\ln\mu} = \frac{3m_H^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{3g_1^2}{20}\right)$$

- Assume that this condition is set by physics of quantum gravity (does not have to be a QFT).
- Wilsonian way of integrating out UV physics may not applied to Planck scale.
- No intermediate scale of physics between EW and Planck scale exist.
- Quantum correction breaks conformal symmetry. Logarithmic terms related to conformal anomaly survive.

Bardeen '95
Meissner, Nicolai '07,'08
Holthausen et al. '10,'13
Foot et al. '07,'08,'11,'13
Iso et al. '09,'13
Hur et al. '11
Heikinheimo et al. '13
Shaposhnikov et al. '08
Kawamura '13

# Ways to obtain the scale from conformal theory

Start with *classical* scale invariant lagrangian

Through RG evolution, the scalar potential develop flat direction, quantum correction shift the vev to non-vanishing value: Coleman-Weinberg

Additional gauge interaction grows strong and dynamically sets a condensation scale

# Ways to obtain the scale from conformal theory

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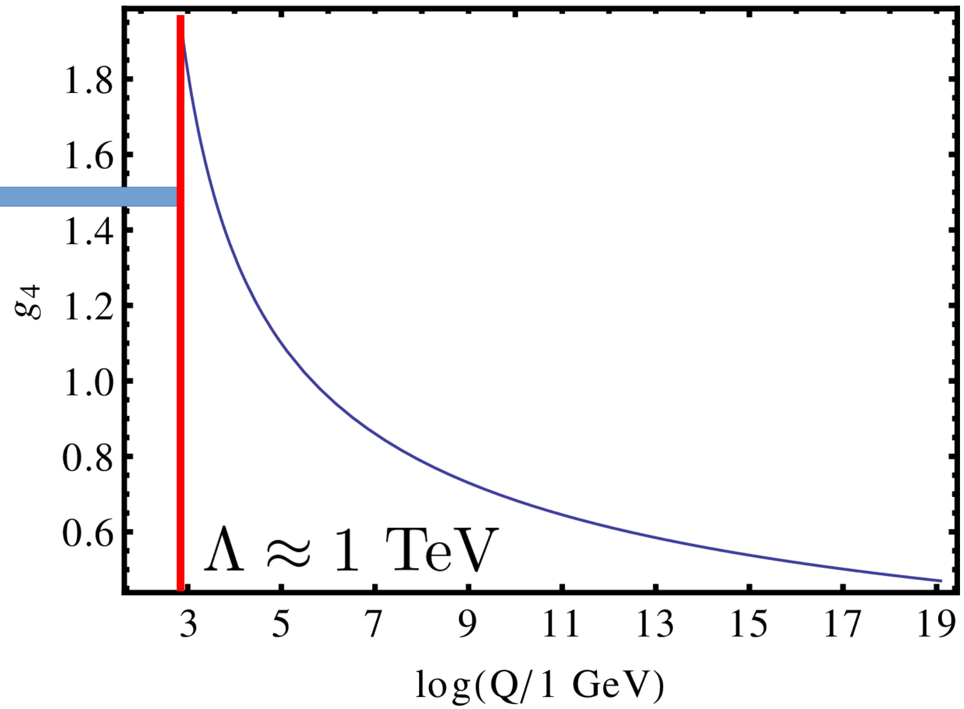
Focus today

# New Idea = Conformal + Strong hidden sector

Dynamical chiral symmetry breaking of hidden fermions

Bonus: Dark pions as dark matter candidate

The condensation scale is transferred to SM by Higgs portal.




Strongly coupled hidden sector runs ala QCD

Holthausen, Kubo, Lim, Lindner '13
Hur, Jung, Ko, Lee '11
Hur, Ko '11
Heikinheimo, Racioppi, Raidal, Spethmann, Tuominen '13

# Concrete Model

$\mathrm{SU}(3)_H$

$\text{fundamental}, \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}+S} - \frac{1}{2}\mathrm{Tr}\ F^2 + \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

Singlet mediator

$$V_{\mathrm{SM}+S} = \lambda_H (H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H)$$

NJL approach

$\Phi_{ij} = \bar{\psi}_i(1-\gamma_5)\psi_j$

$$\mathcal{L}_{\mathrm{NJL}} = \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu \partial_\mu - yS)\psi + 2G\ \mathrm{Tr}\ \Phi^\dagger \Phi + G_D\ (\det \Phi + h.c.)$$

- Advantage of having 3 dark color and 3 flavors = Can use QCD data to scale up spectrum
- Nambu-Jona-Lasinio approach allows us to determine a lot of paramaters dynamically.
- Less free parameters if we mimic QCD, but in general can be of any gauge group and flavor.

# After all the tedious algebras...

$\langle \bar{\psi}\psi \rangle$ CP even scalar, mixes with *h* and *S*

$$\mathcal{L}_{\rm NJL} \supset i\ {\rm Tr}\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - \left(\sigma + yS - \frac{G_D}{8G^2}\sigma^2\right){\rm Tr}\bar{\psi}\psi - i{\rm Tr}\bar{\psi}\gamma_5\phi\psi - \frac{1}{8G}\left(3\sigma^2 + 2\sum_{a=1}^{8}\phi_a\phi_a\right)$$
$$+\frac{G_D}{8G^2}\left(-{\rm Tr}\bar{\psi}\phi^2\psi + \sum_{a=1}^{8}\phi_a\phi_a{\rm Tr}\bar{\psi}\psi + i\sigma{\rm Tr}\bar{\psi}\gamma_5\phi\psi + \frac{\sigma^3}{2G} + \frac{\sigma}{2G}\sum_{a=1}^{8}(\phi_a)^2\right)$$

$\sim \langle \bar{\psi}\gamma_5\psi \rangle$

Dark pions

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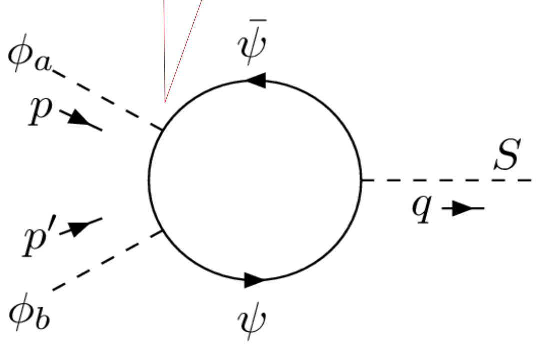
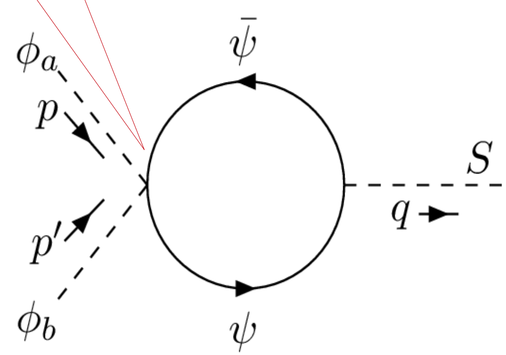
$$\mathcal{L}_{\rm NJL} \supset i\,\mathrm{Tr}\bar\psi\gamma^\mu\partial_\mu\psi - \left(\sigma + yS - \frac{G_D}{8G^2}\sigma^2\right)\mathrm{Tr}\bar\psi\psi - i\mathrm{Tr}\bar\psi\gamma_5\phi\psi - \frac{1}{8G}\left(3\sigma^2 + 2\sum_{a=1}^{8}\phi_a\phi_a\right)$$
$$+\frac{G_D}{8G^2}\left(-\mathrm{Tr}\bar\psi\phi^2\psi + \sum_{a=1}^{8}\phi_a\phi_a\mathrm{Tr}\bar\psi\psi + i\sigma\mathrm{Tr}\bar\psi\gamma_5\phi\psi + \frac{\sigma^3}{2G} + \frac{\sigma}{2G}\sum_{a=1}^{8}(\phi_a)^2\right)$$

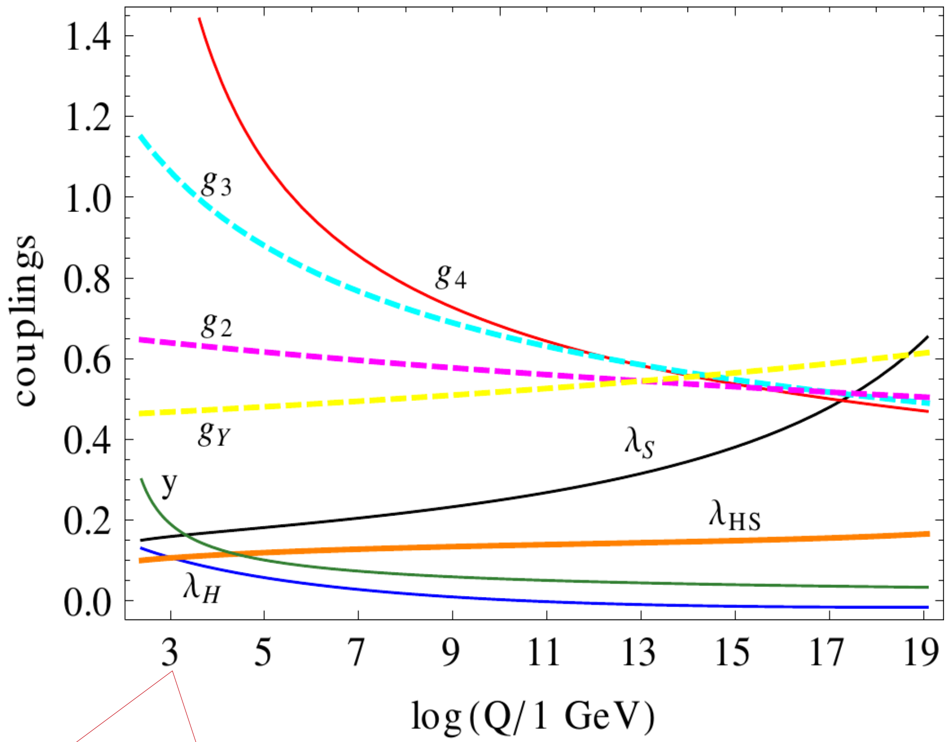



$\sim \langle\bar\psi\gamma_5\psi\rangle$

Dark pions

# Constraining the Parameter Space




- Possible reason why $\Omega_B \sim \Omega_{DM}$
- Possible reason that QCD scale is lower than EW due to different number of flavor

$$\lambda_H(1\ \text{TeV}) \approx 0.13$$

$$y(1\ \text{TeV}) \in (0, 0.7)$$

$$\lambda_s(1\ \text{TeV}) \in (0, 0.2)$$

$$\lambda_{HS}(1\ \text{TeV}) \in (0, 0.2)$$

- To ensure that the theory survives up to Planck scale
- Mass of DM has to be smaller than hidden fermion's constituent mass

# Effective Potential

$$V_{\text{eff}} = V_{\text{SM}+S} + V_{\text{NJL}}$$

$$V_{\text{NJL}}(\sigma, S) = \frac{3}{8G}\sigma^2 - \frac{G_D}{16G^3}\sigma^3 - 3n_c I_0(M,0)$$

From here we can calculate mass spectrum of $h, S$ and $\sigma$

Constituent mass for hidden fermions $M = \sigma + yS - \frac{G_D}{8G^2}\sigma^2$

Step 1

$G, G_D, \Lambda$ from QCD is used to calibrate the potential

→

Step 2

Obtain the minimum for the effective potential

→

Step 3

Fix the vev of *h* and scale up the rest of parameters

→

Step 4

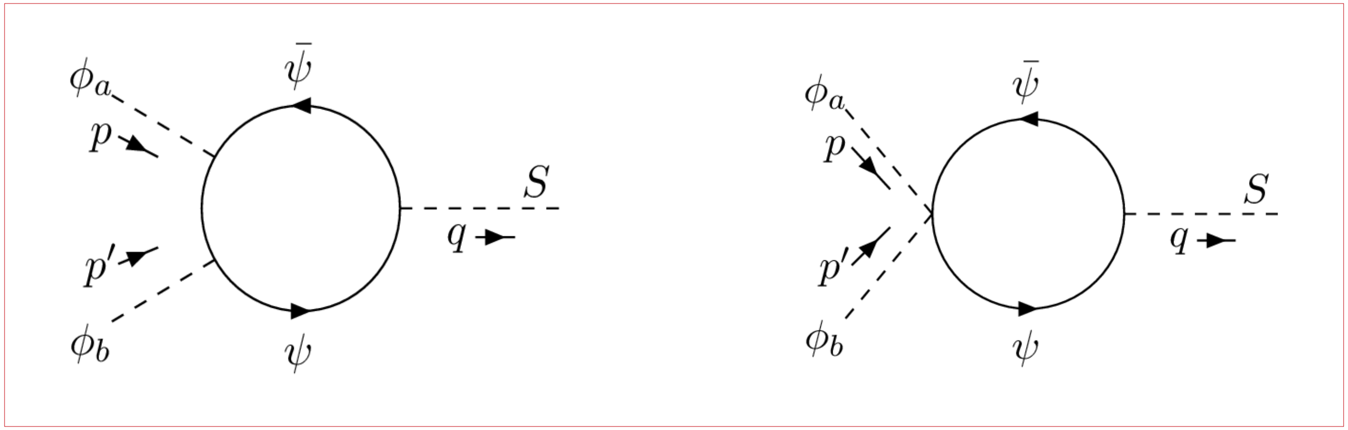
Calculate the masses of scalar by first obtaining the inverse propagator $\Gamma_{ij}$

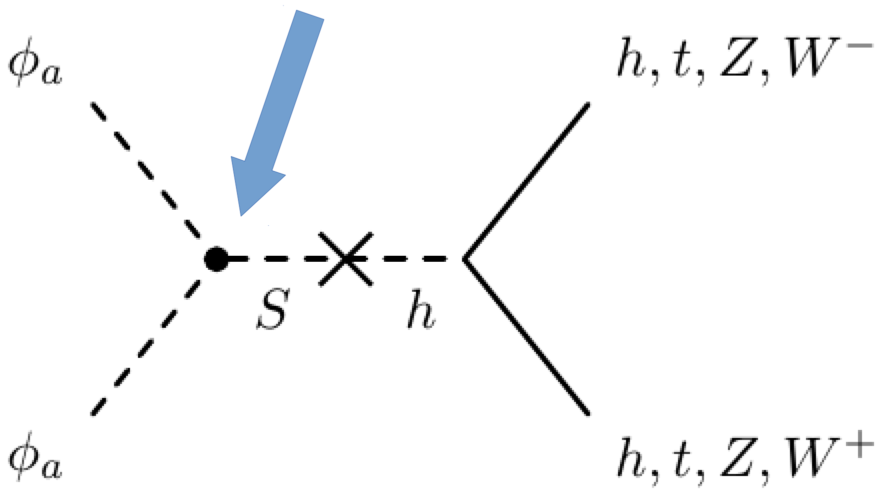
$$\Gamma_{ij}(\tilde{m}_k^2)\ \xi_j^{(k)} = 0$$

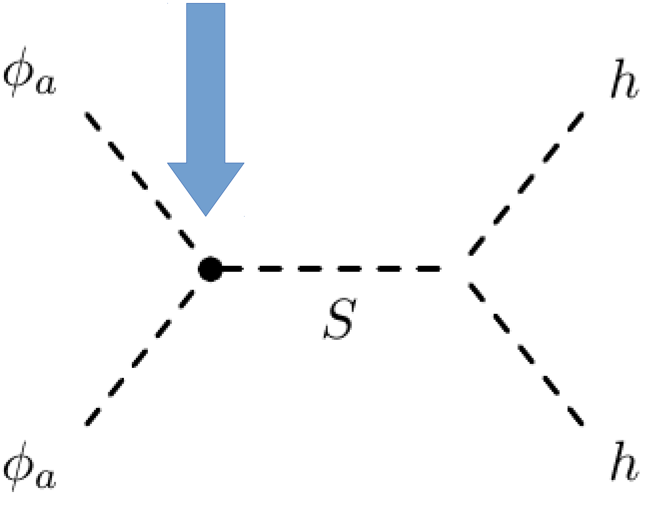
$\xi$ rotates flavor eigenstate to mass eigenstate

# Dark matter: Dark Pions

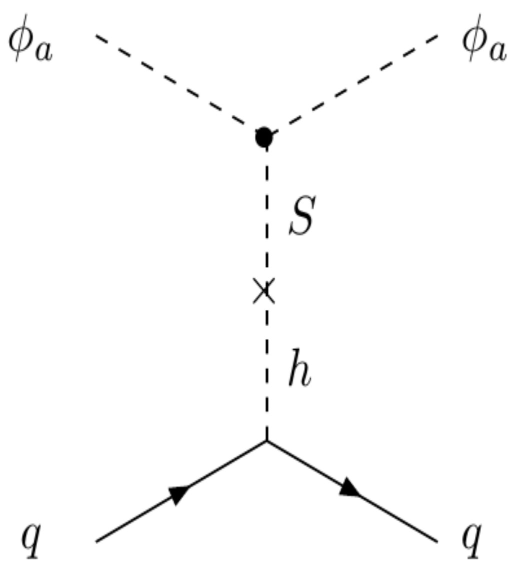
- Dark pions exist as PNGB due to chiral symmetry breaking.
- Stable due to flavor symmetry, no ad hoc discrete symmetry needed.
- Dark pions talk to SM particles (h mixing through S) via loop suppressed interaction.

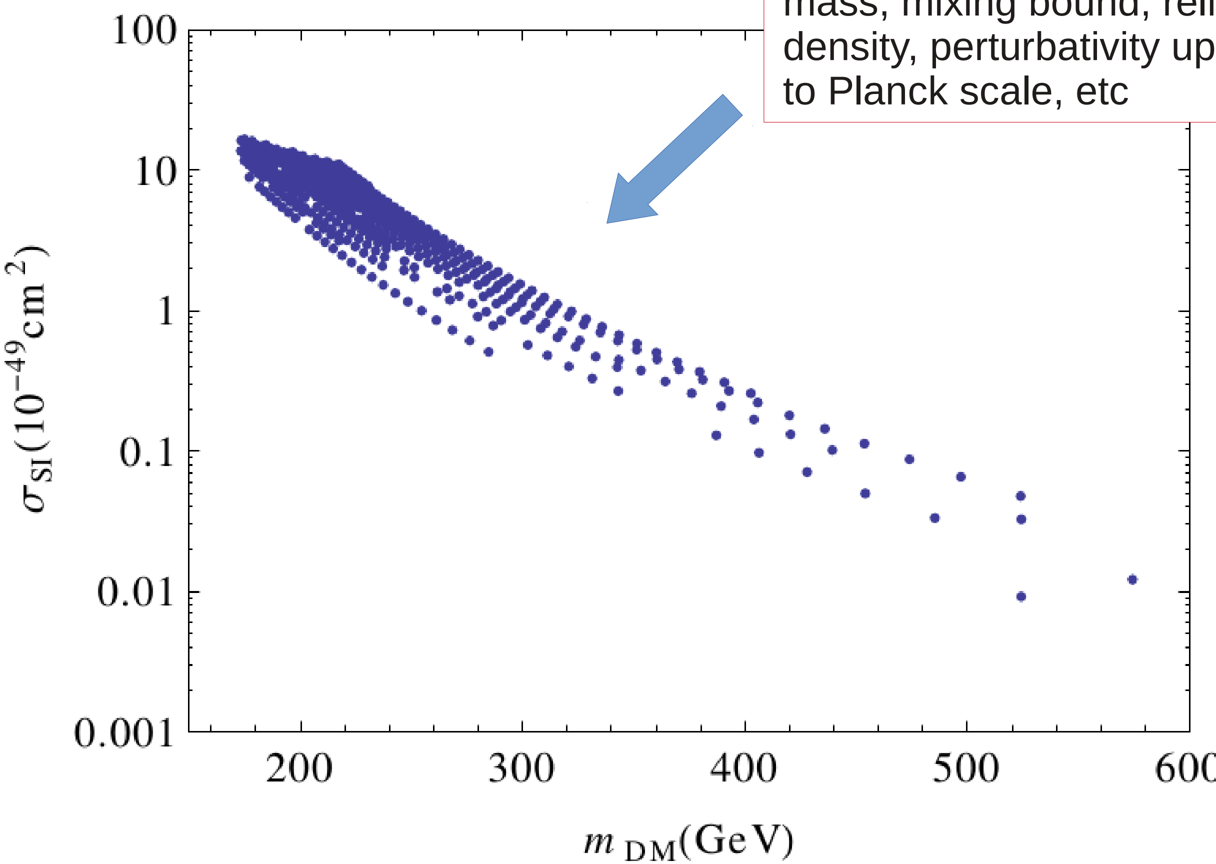


# Direct Detection Prospect




Caused by restrictive parameter space and the need to satisfy the Higgs mass, mixing bound, relic density, perturbativity up to Planck scale, etc

The model predicts no signal in LUX and XENON1T. But the small range of parameter space can be confirmed or excluded by next generation DM direct detection.

# Phase Transition

To know whether EW baryogenesis can take place, we need to know whether there exist strong first order phase transition.

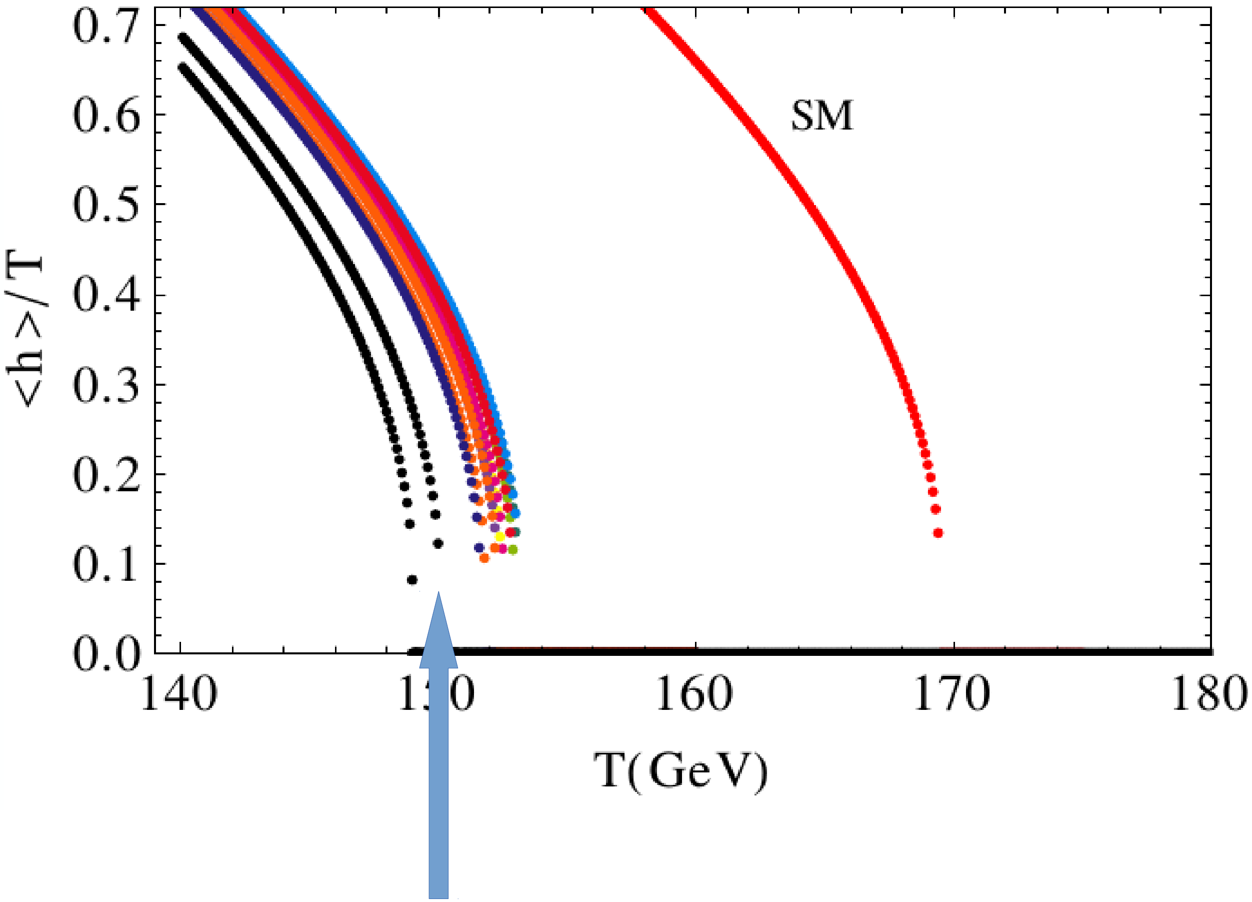
$$V_{\mathrm{EFF}}(\phi_c, T) = V_{\mathrm{SM}+S}(\phi_c) + V_{\mathrm{NJL}}(\phi_c) + V_{\mathrm{CW}}(\phi_c) + V_{\mathrm{FT}}(\phi_c, T) + V_{\mathrm{RING}}(\phi_c, T)$$

$$V_{\mathrm{CW}}(\phi_c) = \frac{1}{64\pi^2} \sum_i n_i \left\{ m_i^4(\phi_c) \left( \ln \left[ \frac{m_i^2(\phi_c)}{m_i^2(\langle\phi_c\rangle)} \right] - \frac{3}{2} \right) + 2 m_i^2(\langle\phi_c\rangle) m_i^2(\phi_c) \right\}$$

$$V_{\mathrm{FT}}(\phi_c, T) = \frac{T^4}{2\pi^2} \left( \sum_i n_i^B J_B(m_i^2(\phi_c)/T^2) + \sum_i n_i^F J_F(m_i^2(\phi_c)/T^2) \right)$$

$$V_{\mathrm{RING}}(\phi_c, T) = -\frac{T}{12\pi} \sum_i n_i^B \left[ (M_i^2(\phi_c, T))^{3/2} - (m_i^2(\phi_c))^{3/2} \right]$$

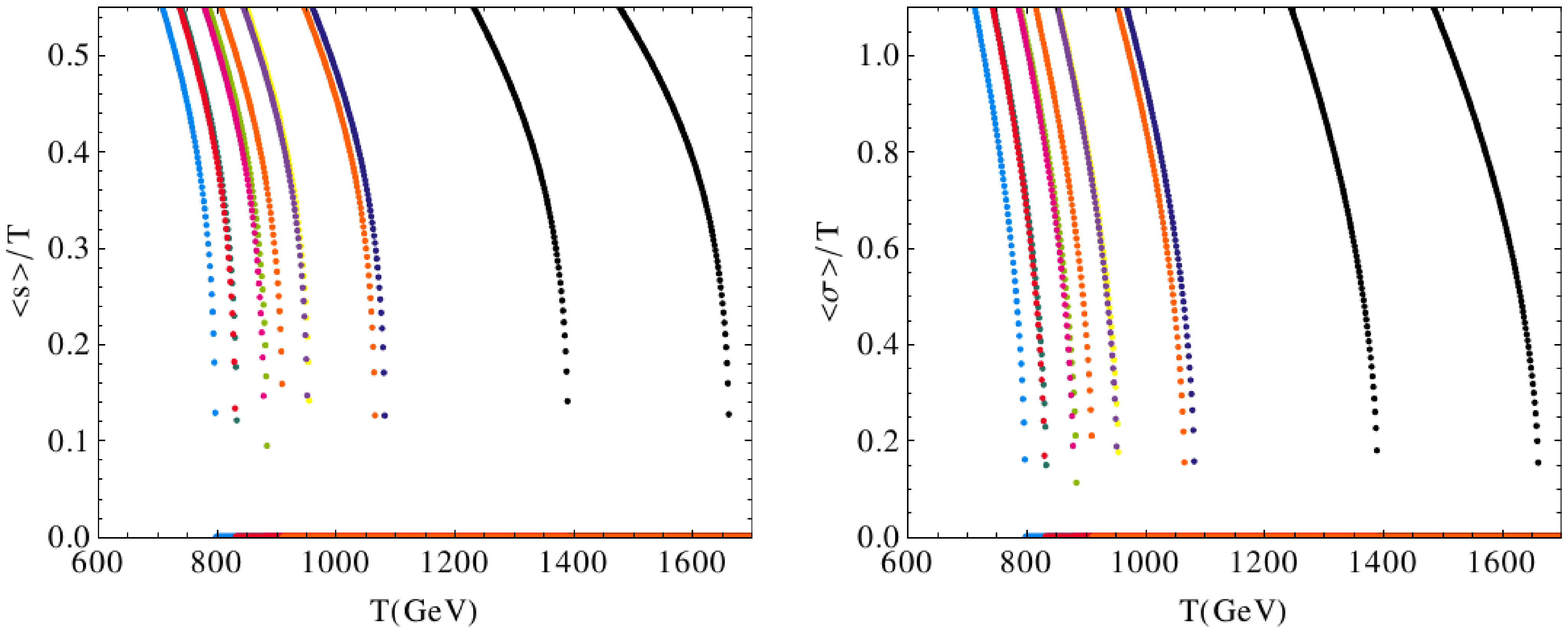
# Phase Transition




Weakly first order*, cannot account for EW Baryogenesis

*Need lattice simulation to confirm

# Phase Transition




Also weakly first order

# Summary

- With no sign of new physics from LHC, long-held belief on naturalness should be scrutnized.
- Conformal symmetry might act as protective symmetry as alternative solution to hierarchy problem.
- We study a strongly coupled hidden sector model based on NJL where the spontaneous chiral symmetry breaking induces EWSB via singlet mediator.
- The strongly coupled hidden sector is a scaled up QCD → Less free parameter.
- The model provides natural DM candidates, i.e. the dark pions, which are stable under flavor symmetry.
- Restrictive parameter space to be excluded or confirmed by next-gen experiments.
- Weakly first order phase transition is obtained, but lattice simulation is needed for confirmation.
- Rich possibilities with further extension.