MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Aspects of Classical Scale Invariance and Electroweak Symmetry Breaking

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Strong Interactions in the LHC Era

Bad Honnef
14.11.2014

Based on hep-ph/1310.4423, JHEP 1312 (2013) 076 by M. Holthausen, J. Kubo, KSL and M. Lindner
Hep-ph/1403.4262, PRL 113 (2014) 091604 by J.Kubo, KSL and M.Lindner
Hep-ph/1405.1052, JHEP 1409 (2014) 016 by J.Kubo, KSL, M.Lindner

This talk is not about Technicolor or Composite Higgs!

We know Higgs boson exist!

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

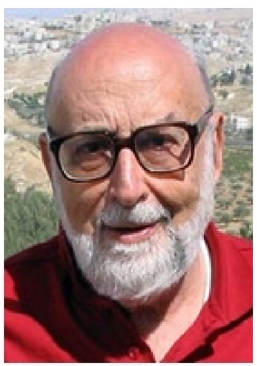


Photo: Pnicolet via Wikimedia Commons
François Englert

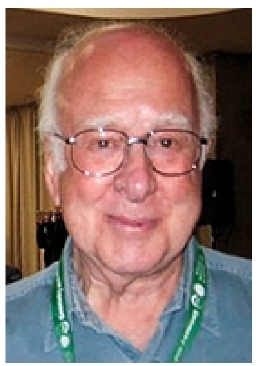
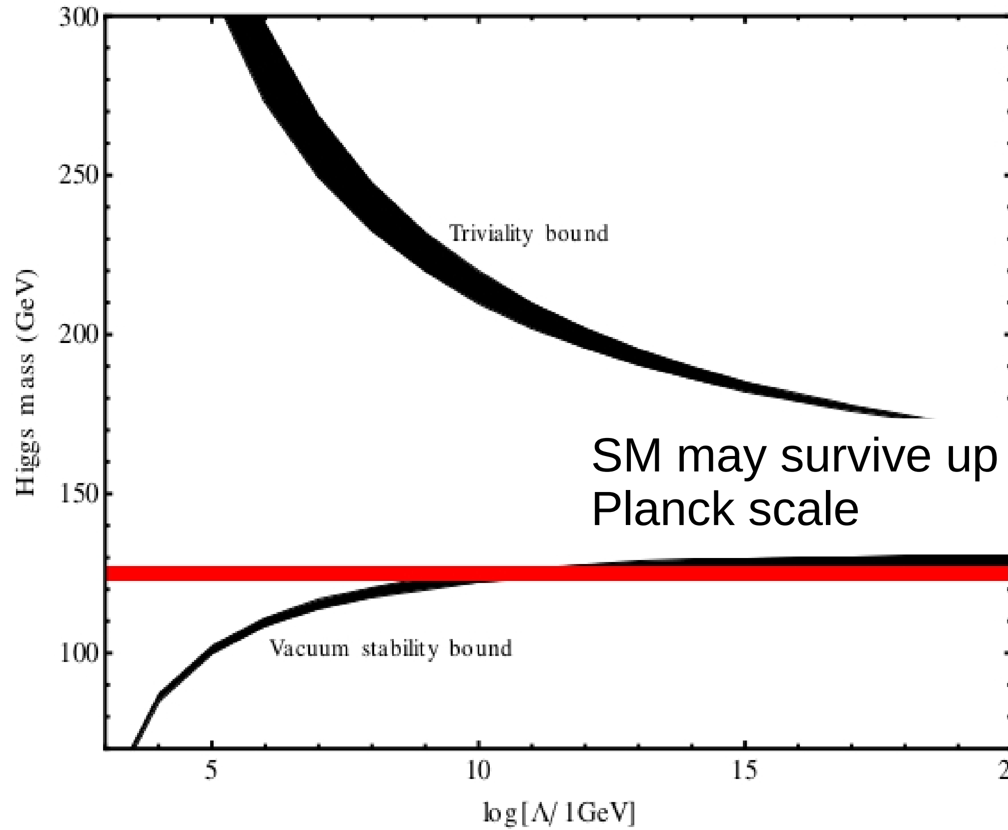


Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

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"*



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

ORIGIN OF ELECTROWEAK SCALE?

Baryogenesis Dark matter Inflation Neutrino mass

$$\boxed{\Lambda_{\mathrm{QCD}} \sim v \ll M_{\mathrm{pl}}}$$

BSM? Dark energy Strong CP problem

ORIGIN OF ELECTROWEAK SCALE?

Inflation Dark matter Neutrino mass Baryogenesis

$$\Lambda_{\rm QCD} \sim v \ll M_{\rm pl}$$

QCD scale is pure quantum phenomena

$$\Lambda_{\rm QCD} = M_{\rm pl} e^{-8\pi^2/b g_s^2(M_{\rm pl})}$$

BSM? Dark energy Strong CP problem

ORIGIN OF ELECTROWEAK SCALE?

Inflation Dark matter Neutrino mass Baryogenesis

$$\boxed{\Lambda_{\mathrm{QCD}} \sim v \ll M_{\mathrm{pl}}}$$

QCD scale is pure quantum phenomena

$$\Lambda_{\mathrm{QCD}} = M_{\mathrm{pl}} e^{-8\pi^2/bg_s^2(M_{\mathrm{pl}})}$$

Dimension Transmutation

$$g_s \to \Lambda_{\mathrm{QCD}}$$

BSM? Dark energy Strong CP problem

ORIGIN OF ELECTROWEAK SCALE?

Inflation Dark matter Neutrino mass Baryogenesis

Put in by hand?

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Dimension Transmutation

$$g_s \to \Lambda_{\text{QCD}}$$

THE HIERARCHY PROBLEM

Supersymmetry?

$$m^2(v) = m^2(M_{\rm pl}) + f(\lambda, g_i ...) M^2_{\rm heavy} \log(\frac{M_{\rm pl}}{v})$$

Extra Dimension?

Compositeness?

THE HIERARCHY PROBLEM

Supersymmetry?

$$m^2(v) = m^2(M_{\rm pl}) + f(\lambda, g_i \ldots) M^2_{\rm heavy} \log(\frac{M_{\rm pl}}{v})$$

Ad hoc cancellation?

What is the boundary condition?

Extra Dimension?

Compositeness?

THE HIERARCHY PROBLEM

But where are the new physics?

Solutions getting pushed into special corner!

$$m^2(v) = m^2(M_{\rm pl}) + f(\lambda, g_i \ldots) M_{\rm heavy}^2 \log(\frac{M_{\rm pl}}{v})$$

Ad hoc cancellation?

What is the boundary condition?

Long-held belief on naturalness must be critically reexamined!

GENERATING ELECTROWEAK SCALE

$$m^2(v) = m^2(M_{\mathrm{pl}}) + f(\lambda, g_i ...)M^2_{\mathrm{heavy}} \log(\frac{M_{\mathrm{pl}}}{v})$$

Small in the SM as

$$\frac{\mathrm{d}m^2}{\mathrm{d}\log(\mu)} \sim m^2$$

GENERATING ELECTROWEAK SCALE

$$m^2(v) = m^2(M_{\mathrm{pl}}) + f(\lambda, g_i...)M^2_{\mathrm{heavy}} \log(\frac{M_{\mathrm{pl}}}{v})$$

Small in the SM as

$$\frac{\mathrm{d}m^2}{\mathrm{d}\log(\mu)} \sim m^2$$

$$\boxed{\frac{m}{M_{\mathrm{pl}}} \ll 1}$$

Classical Scale Invariance!

Might create a large hierarchy if new physics is still in the framework of QFT with large scale seperation. But Wilsonian picture might not apply to Planck scale physics!

GENERATING ELECTROWEAK SCALE DYNAMICALLY

$$m^2(v) = \cancel{m^2(M_{\rm pl})} + f(\lambda, g_i \ldots) M^2_{\rm heavy} \log\left(\frac{M_{\rm pl}}{v}\right)$$

Impose Classical scale Invariance

Want to generate EW scale dynamically

$$m^2(v) \sim M^2_{\rm heavy} \sim M^2_{\rm pl} e^{-8\pi^2/bg^2(M_{\rm pl})}$$

Order TeV to avoid Hierarchy problem

GENERATING ELECTROWEAK SCALE DYNAMICALLY

$$m^2(v) = \cancel{m^2(M_{\rm pl})} + f(\lambda, g_i\ldots) M^2_{\rm heavy} \log(\frac{M_{\rm pl}}{v})$$

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Want to generate EW scale dynamically

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Order TeV to avoid Hierarchy problem

Minor detail: Imposing classical scale invariance also forbids the use of cutoff.
Otherwise explicit violation of scale invariance.

Scale Current is Anomalous

$$\Delta\phi(x) = (x_\mu \partial^\mu + d)\phi(x) \Rightarrow \partial_\mu J^\mu = T^\mu_\mu \sim m^2\phi^2$$

Scale Current is Anomalous

$$\Delta\phi(x) = (x_\mu \partial^\mu + d)\phi(x) \Rightarrow \partial_\mu J^\mu = T^\mu_\mu \sim \cancel{m^2 \phi^2}$$

But dilatation current is anomalous

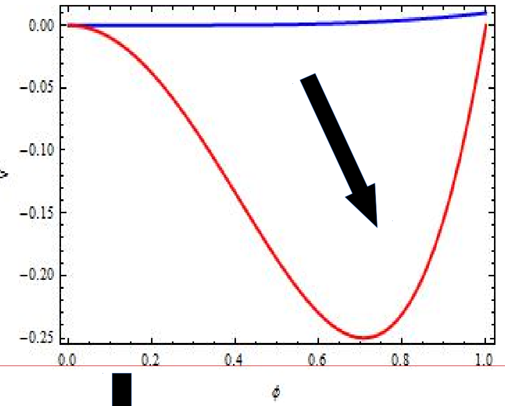
$$\partial_\mu J^\mu = T^\mu_\mu \sim \beta \mathcal{O}_4$$

Quantum origin

$$\beta \neq 0 \to T^\mu_\mu \neq 0 \to m \neq 0$$

EW scale from CSI breaking

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



Weakly

Start with classical scale invariant (CSI) lagrangian

$$\mathcal{L}_{\rm SM} \to \mathcal{L}_{{\rm SM},m^2\to 0}$$

EW scale is radiatively generated

Crucial: $\lambda_{hs} H^\dagger H S^\dagger S$

(Additional) gauge interaction grows strong and dynamically sets a condensation scale

$$\langle\bar{\phi}\phi\rangle \sim \Lambda^3 \quad \Rightarrow \quad \lambda_{hs}\Lambda^2 H^\dagger H$$

Strongly

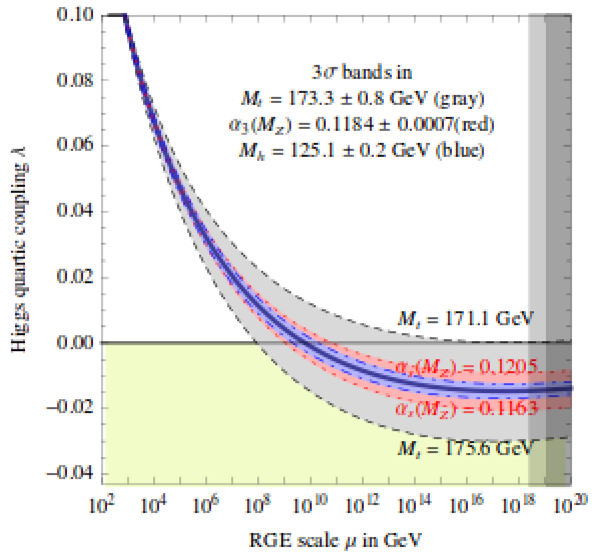
EW scale from CSI breaking

Very active field of research!

Bardeen '95
Fatelo, Gerard, Hambye, Weyers '95
Hempfling '96
Hambye '96
Meissner, Nicolai '07
Foot, Kobakhidze, Volkas '07
Foot, Kobakhidze, McDonald, Volkas '07
Chang, Ng, Wu '07
Hambye, Tytgat '08
Iso, Okada, Orikasa '09
Holthausen, Lindner, Schmidt '10
Hur, Jung, Ko, Lee '11
Hur, Ko '11
Ishiwata '12
Lee, Pilaftsis '12
Khoze '13
Kawamura '13
Gretsch, Monin '13
Carone, Ramos '13
Khoze, Ro '13
Englert, Jaekel, Khoze, Spannowsky '13
Farzinnia, He, Ren '13
Abel, Mariotti '13
Heikinheimo, Racioppi, Raidal, Spethmann, Tuominen '13
Steele, Wang, Contreras, Mann '13
Hambye, Strumia '13
Holthausen, Kubo, Lim, Lindner '13
Hashimoto, Iso, Orikasa '14
Hill '14
Guo, Kang '14
Radovcic, Benic '14
Khoze, McCabe, Ro '14
Kubo, Lim, Lindner '14
Allison, Hill, Ross '14
Farzinnia, Ren '14
Davoudiasl, Lewis '14
Altmannhofer, Bardeen, Bauer, Carena, Lykken '14
Antipin, Redi, Strumia '14

I am sorry if I left out your paper

Coleman-Weinberg Approach



Buttazzo et al.

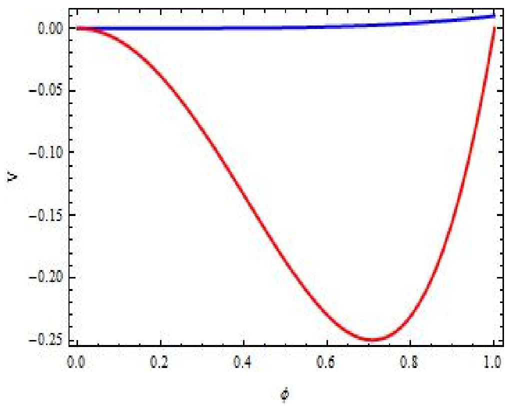
With the current measured HIggs mass, the value indicates a flat potential

$$V = -m^2 H^\dagger H + \lambda_h \cancel{(H^\dagger H)}^2$$

Classical Scale Invariance

$$V = -m^2 \cancel{H^\dagger H} + \lambda_h \cancel{(H^\dagger H)}^2$$

Coleman-Weinberg Approach



Need a flat potential

$$V = V_{\text{tree}} + V_{1-\text{loop}}$$
$$\sim \beta\phi^4 \log(v/M)$$

$$m^2 \sim \beta\langle\phi\rangle^2$$

In the SM it doesn't work due to large top loop => negative Higgs mass

Need additional bosons

For references see pervious slide

Coleman-Weinberg Approach

Adding additional scalars

$$\lambda_{hs} H^\dagger H S^\dagger S$$

- S has no VEV
- Need large coupling to pump up the Higgs mass
  $$m_h^2 \sim \beta \langle H \rangle^2$$
- Landau pole problem
- S gets mass after H obtains VEV

- S obtains VEV
- Scalar mass mixing
  $$m_h^2 \sim \lambda_{hs} \langle S \rangle$$
- SM couplings get mixing correction
- Resonance at LHC?

Coleman-Weinberg Approach

Generic model building approach: Portalia!

$$F'_{\mu\nu}F^{\mu\nu} \qquad y\bar{L}HN \qquad \lambda_{hs}H^\dagger H S^\dagger S$$

Only 3 terms in the SM which are singlets. Portals to dark side?

Coleman-Weinberg Approach

Generic model building approach:

$$\lambda_{hs} H^\dagger H S^\dagger S$$

Generate Majorana neutrino mass?

DM portal?

EW scale generated

Flat S direction, generate VEV due to quantum correction

$$y S \psi \psi$$

$$\lambda_s (S^\dagger S)^2$$

Dimensional transmutation

Scalar, Vector, Fermion DM?

Relate quartic coupling with gauge coupling?

$$(D_\mu S)^\dagger D^\mu S$$

Coleman-Weinberg Approach

$$\lambda_{hs} H^\dagger H S^2 + \lambda_s S^4$$

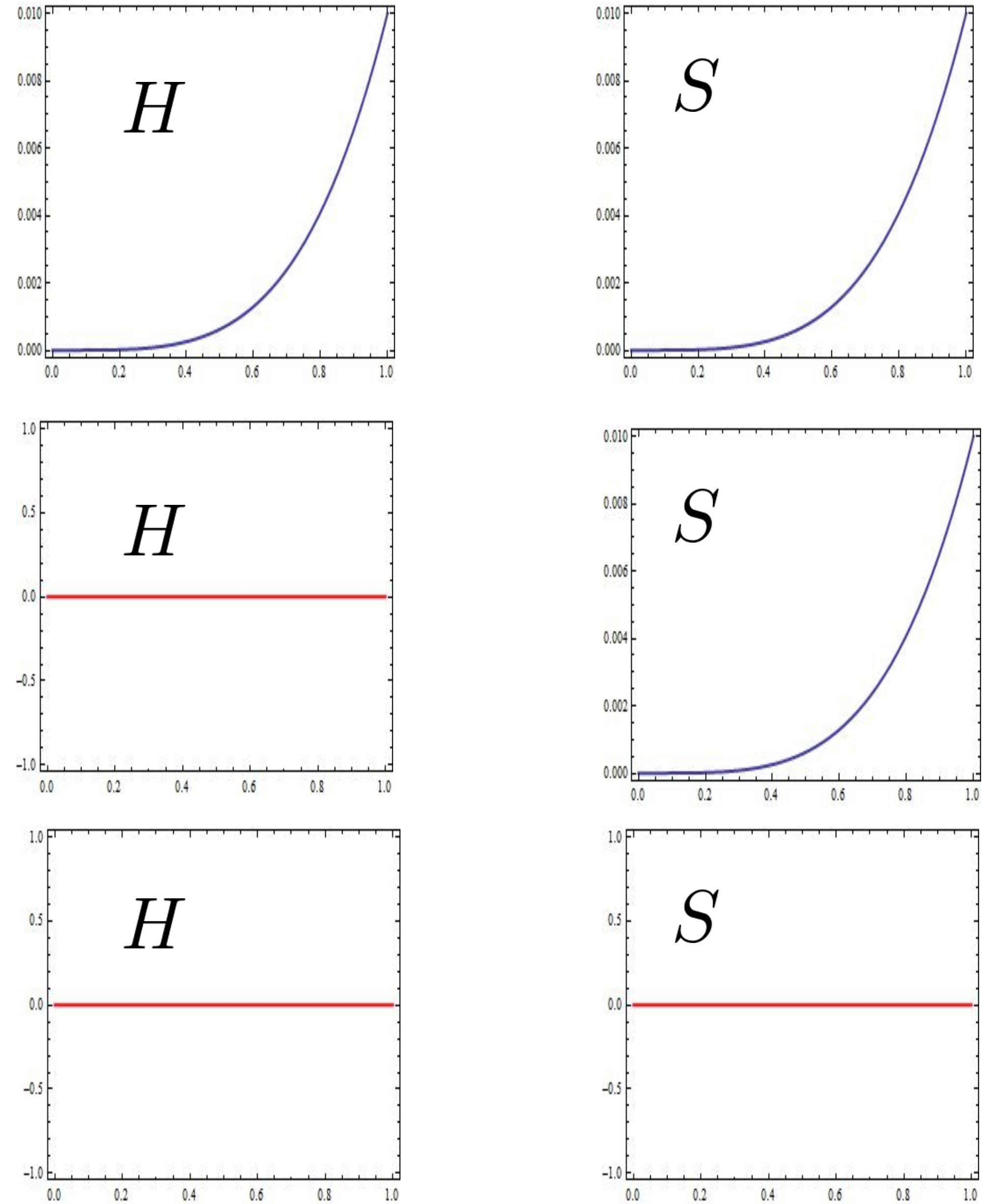
Couplings assumed

$$\cancel{\lambda_{hs} H^\dagger H S^2} + \lambda_s S^4$$

radiatively generated

True Flatlandia, every scalar couplings generated radiatively

See Iso et al.



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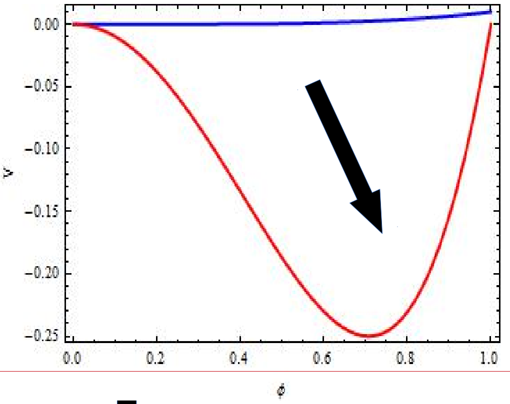

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Focus today

(Additional) gauge interaction grows strong and dynamically sets a condensation scale

$$\langle\bar{\phi}\phi\rangle \sim \Lambda^3 \;\rightarrow\; \lambda_{hs}\Lambda^2 H^\dagger H$$

Strongly

Generating EW Scale from Strongly Interacting Sector

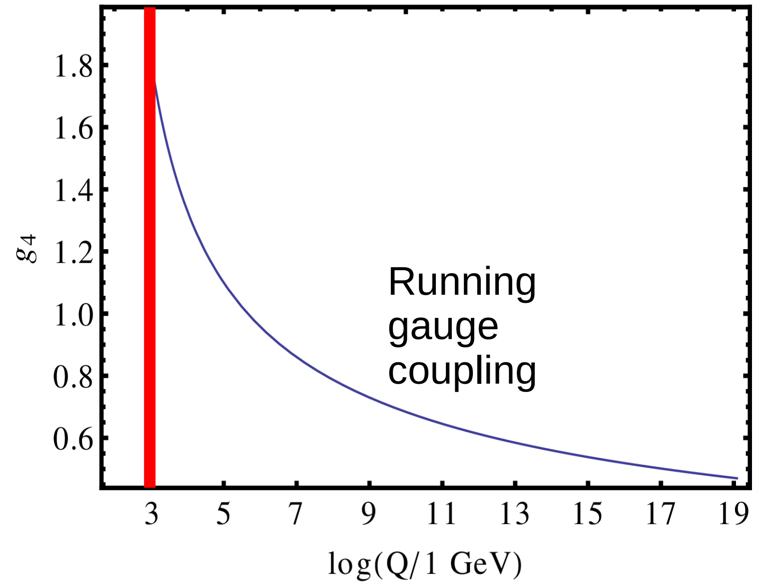
- Strong hierarchy between EW and Planck scale.
- QCD scale can be explained by running couplings and dimensional transmutation.
- Would be nice if EW sector can mimic such mechanism.

Direct Transmission

$$\lambda_{hs} H^\dagger H \langle S^\dagger S \rangle$$

$$\downarrow$$

$$\lambda_{hs} \Lambda^2 H^\dagger H$$



$$\leftarrow \quad \lambda_{hs} H^\dagger H S^\dagger S \quad \rightarrow$$

Indirect Transmission

$$\langle \bar{\psi}\psi \rangle \sim \Lambda^3$$

$$\downarrow$$

$y S \langle \bar{\psi}\psi \rangle$ shift the S field, S obtains a vev

$$\downarrow$$

$$\lambda_{hs} v_s^2 H^\dagger H$$

Generating EW Scale from Strongly Interacting Sector

Handwaving classification

	New gauge group?	Just SM gauge group
New particle?	Technicolor Hidden QCD	Exotic QCD representation
SM particle	Top condensate Top color	Just SM :(

Generating EW Scale from Strongly Interacting Sector

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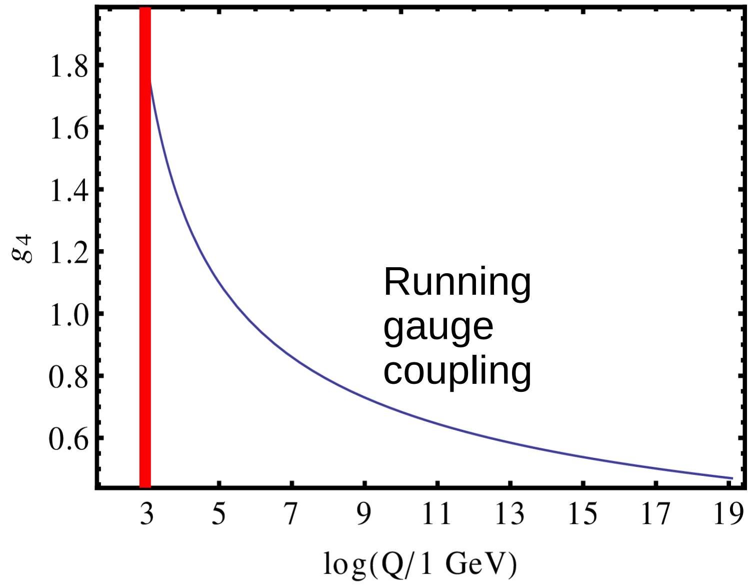
Part 1

Direct Transmission

$$\lambda_{hs} H^\dagger H \langle S^\dagger S \rangle$$

$$\lambda_{hs} \Lambda^2 H^\dagger H$$



$$\lambda_{hs} H^\dagger H S^\dagger S$$

Indirect Transmission

$$\langle \bar{\psi}\psi \rangle \sim \Lambda^3$$

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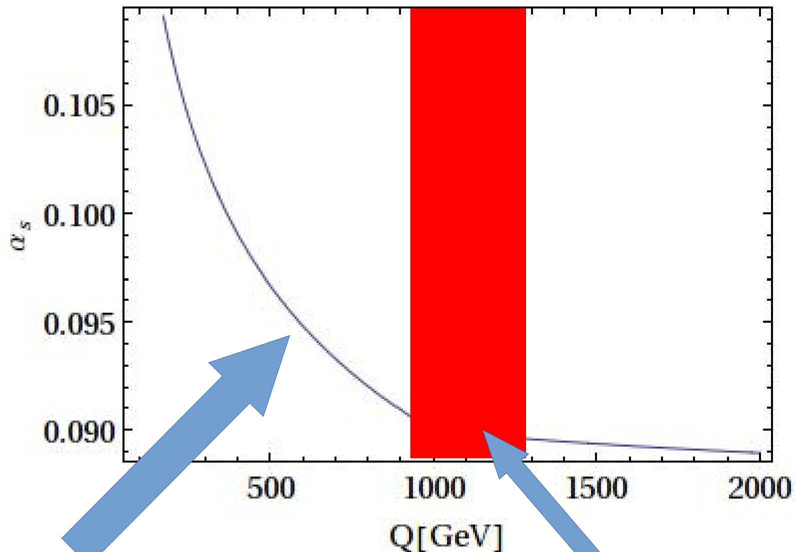
$$\lambda_{hs} v_s^2 H^\dagger H$$

Direct Transmission = Scalar Bound State

For instance: QCD



Low energy
QCD unaltered

Extra condensate at TeV?

- But strong coupling is weak at TeV?
- Possible if the representation of this new field is large

$$\boxed{C_2(S)\alpha_s(\Lambda) \gtrsim 1}$$

$\Uparrow \quad \Downarrow$

(compensate)

$$\lambda_{hs} H^\dagger H S^\dagger S \to \lambda_{hs} H^\dagger H \langle S^\dagger S\rangle = \lambda_{hs}\Lambda^2 H^\dagger H$$

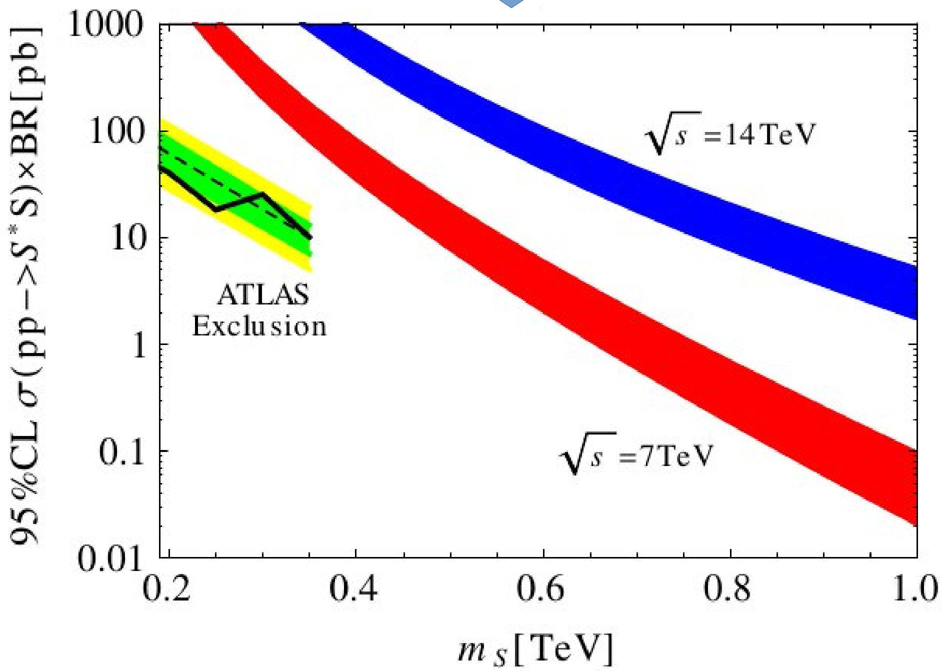
Rep ($\boldsymbol{R}$)	$C_2(\boldsymbol{R})$	$C(\boldsymbol{R})$	Λ (GeV)
8	3	3	1
10	6	15/2	20
15	16/3	10	10
15′	28/3	35/2	1000
21	40/3	35	10^5

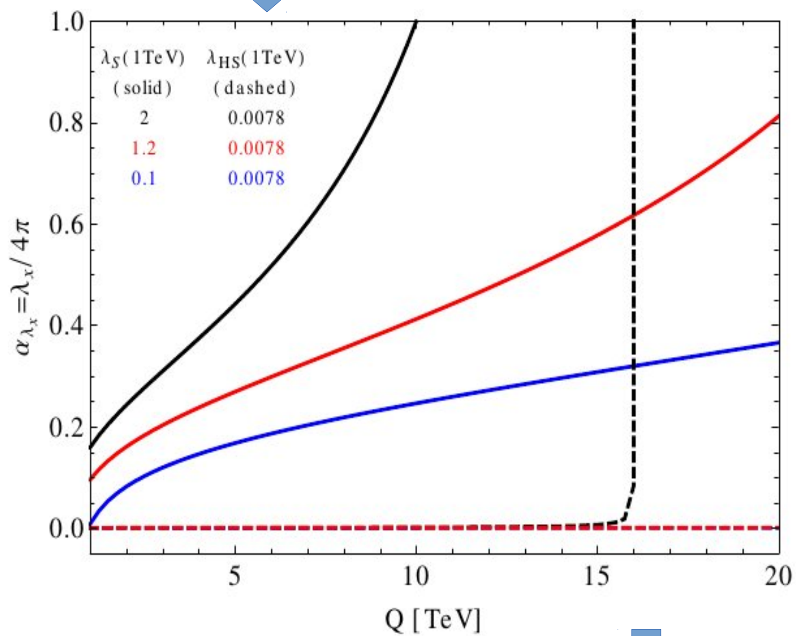
$\boxed{\text{Idea: } v \sim \Lambda_{\rm QCD}}$

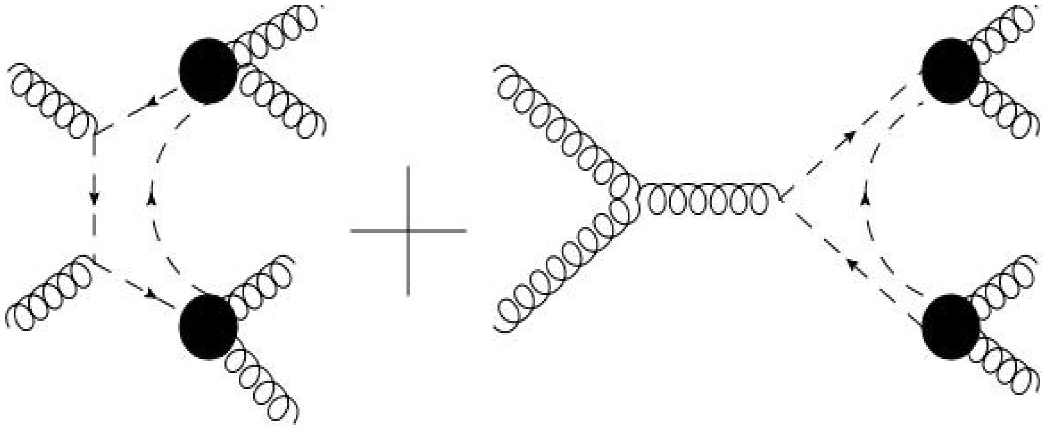
Kubo, Lim, Lindner

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger(D^\mu_{ik}S_k) + \lambda_{HS}H^\dagger H S^\dagger S - \lambda_{\mathbf{1}_i}\left[\bar{\boldsymbol{S}} \times \boldsymbol{S} \times \bar{\boldsymbol{S}} \times \boldsymbol{S}\right]_{\mathbf{1}_i}$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + \boxed{(D_{\mu,ij}S_j)^\dagger(D^\mu_{ik}S_k)} + \lambda_{HS}H^\dagger H S^\dagger S \boxed{- \lambda_{\mathbf{1}_i}\left[\bar{\boldsymbol{S}}\times\boldsymbol{S}\times\bar{\boldsymbol{S}}\times\boldsymbol{S}\right]_{\mathbf{1}_i}}$$







$$350\,\mathrm{GeV} \lesssim m_S \lesssim 3\,\mathrm{TeV}$$

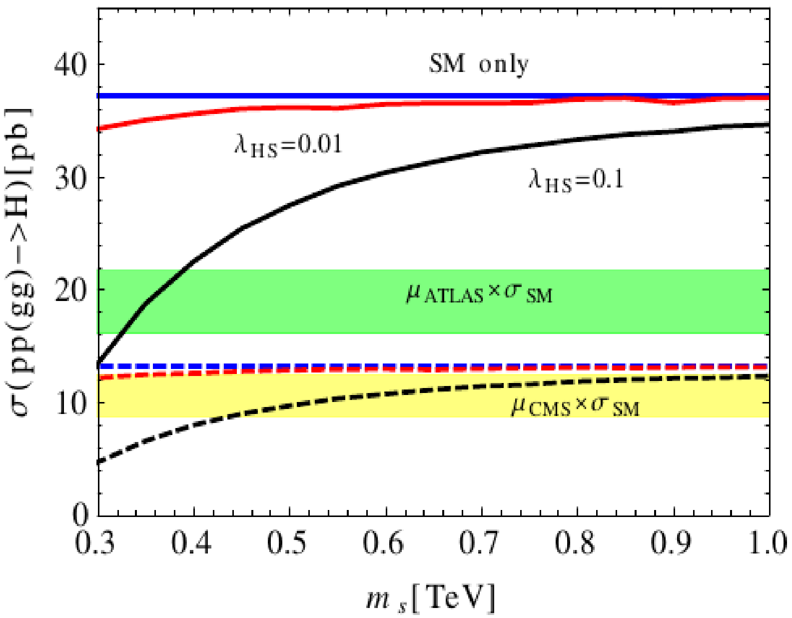
Can be detected or ruled out by the LHC!

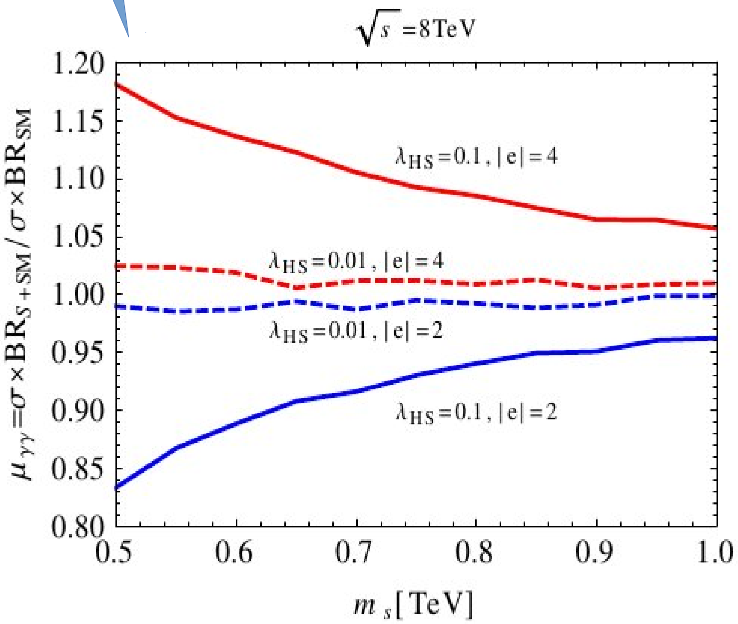
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik}S_k) \boxed{+ \lambda_{HS} H^\dagger H S^\dagger S} - \lambda_{\mathbf{1}_i} \left[\bar{\boldsymbol{S}} \times \boldsymbol{S} \times \bar{\boldsymbol{S}} \times \boldsymbol{S}\right]_{\mathbf{1}_i}$$

Suppression due to minus sign

Accidental U(1) symmetry in Lagrangian

$H \to \gamma\gamma$ enhanced for large electric charge





Higgs production rate in gluon fusion channel is reduced.

Challenges

-  determining $C_2(S)\alpha_s(\Lambda) \gtrsim 1$
- Pinning down the collider signature
- Measurement of strong coupling at high energy

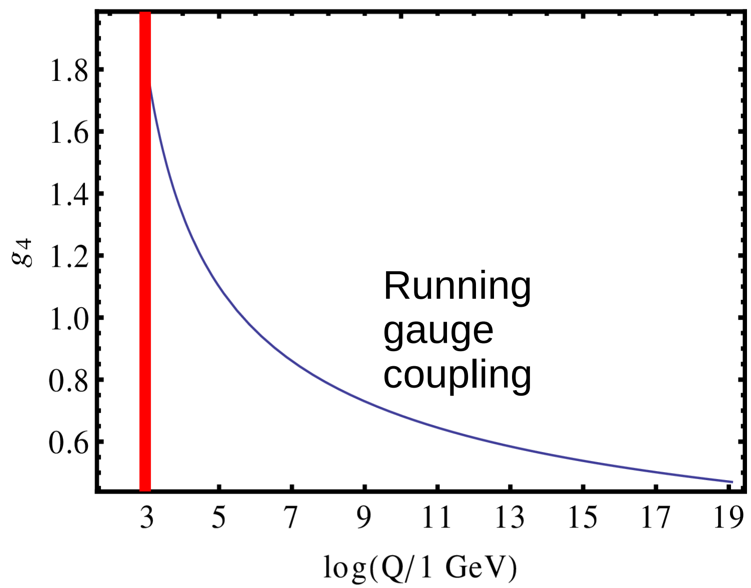
Generating EW Scale from Strongly Interacting Sector

- 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.

Direct Transmission

$$\lambda_{hs} H^\dagger H \langle S^\dagger S \rangle$$

$$\lambda_{hs} \Lambda^2 H^\dagger H$$



$$\lambda_{hs} H^\dagger H S^\dagger S$$

Part 2

Indirect Transmission

$$\langle \bar{\psi} \psi \rangle \sim \Lambda^3$$

$y S \langle \bar{\psi} \psi \rangle$ shift the S field, S obtains a vev

$$\lambda_{hs} v_s^2 H^\dagger H$$

Indirect Transmission = CSI + Strong hidden sector

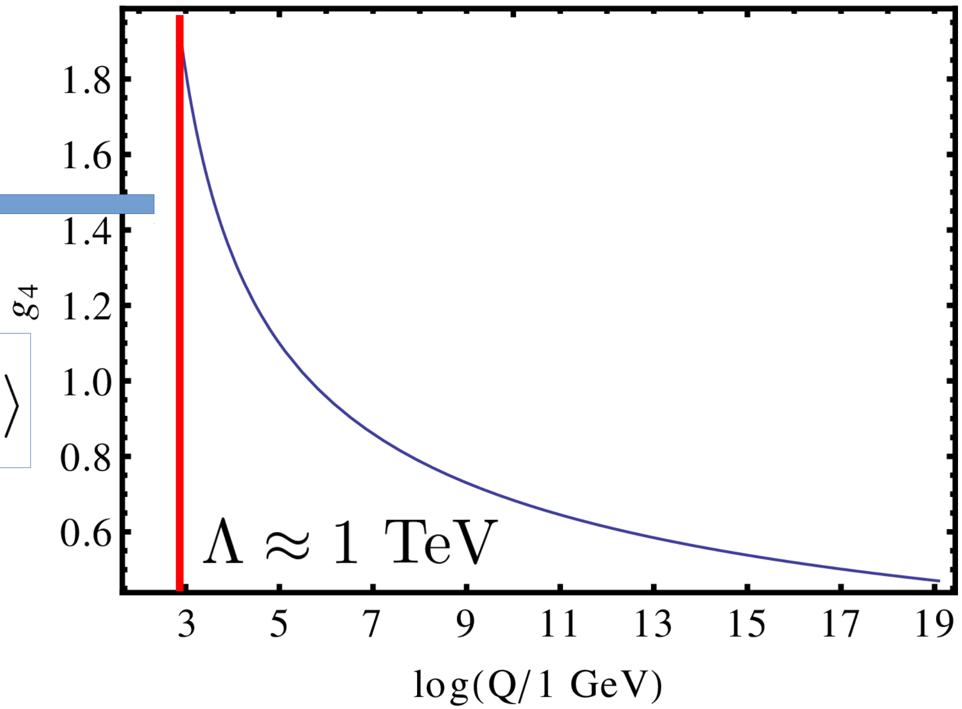
$\langle \bar{\psi}\psi \rangle$

Dynamical chiral symmetry breaking of hidden fermions

Bonus: Dark pions as dark matter candidate $\langle \bar{\psi}\gamma_5\psi \rangle$

The condensation scale is transferred to SM by Higgs portal.

$$\langle \bar{\psi}\psi \rangle \to \langle S \rangle \to \langle H \rangle$$



Idea: $v \sim \Lambda_{\rm dark}$

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

$\mathrm{SU}(3)_H$

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

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

Singlet mediator

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

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

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

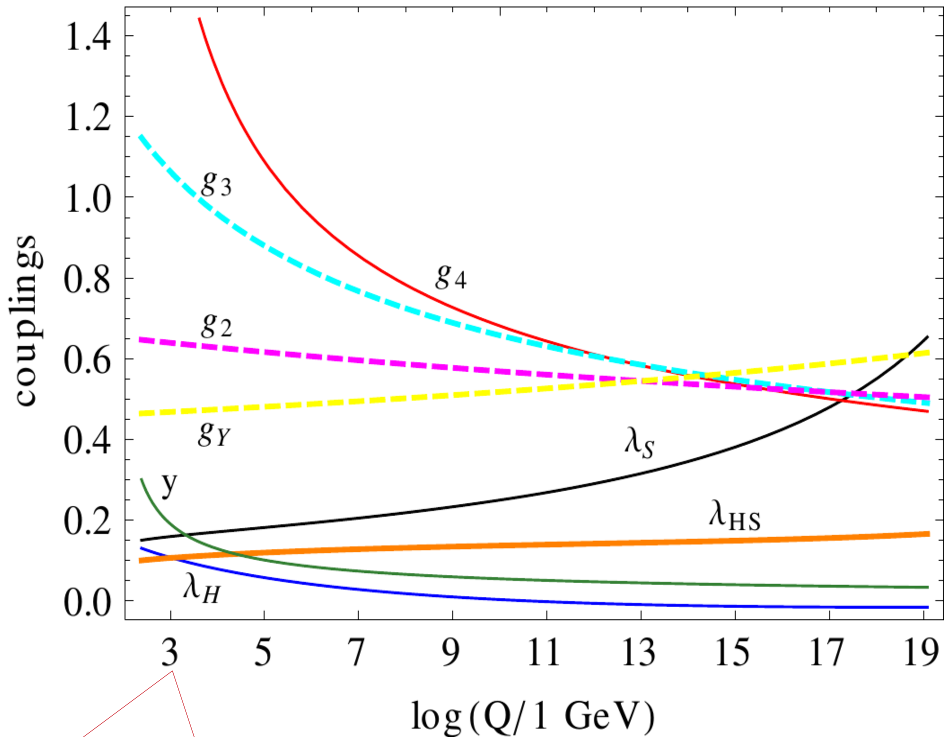
NJL approach

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

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

- 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.

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

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

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

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

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

- 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

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

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

From here we can calculate mass spectrum of h, S and σ

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

Step 1

G, G_D, Λ 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 Γ_{ij}

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

ξ rotates flavor eigenstate to mass eigenstate

After all the tedious algebras...

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

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

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

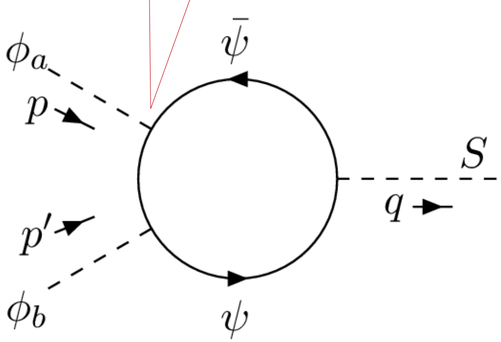
Dark pions

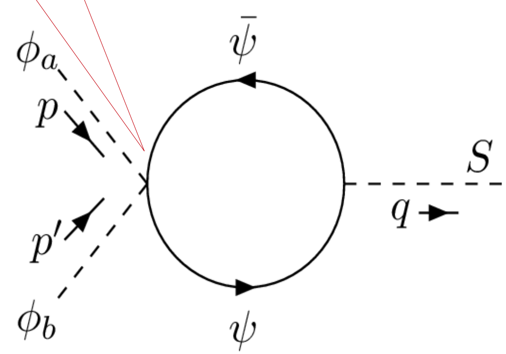
After all the tedious algebras...

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

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

$$+\frac{G_D}{8G^2}\left(-\mathrm{Tr}\bar{\psi}\phi^2\psi + \sum_{a=1}^{8}\phi_a\phi_a\mathrm{Tr}\bar{\psi}\psi + i\sigma\mathrm{Tr}\bar{\psi}\gamma_5\phi\psi + \frac{\sigma^3}{2G} + \frac{\sigma}{2G}\sum_{a=1}^{8}(\phi_a)^2\right)$$





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

Dark pions

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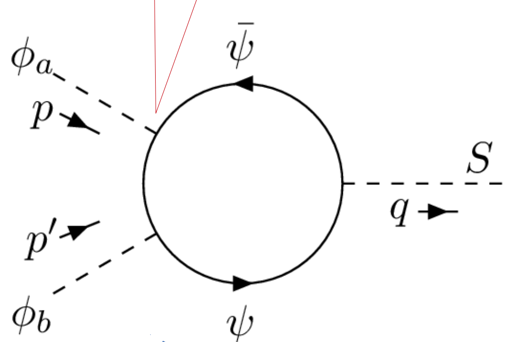

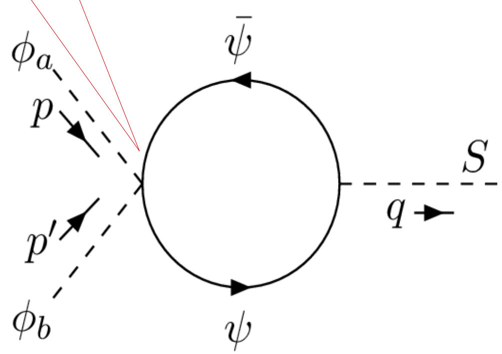

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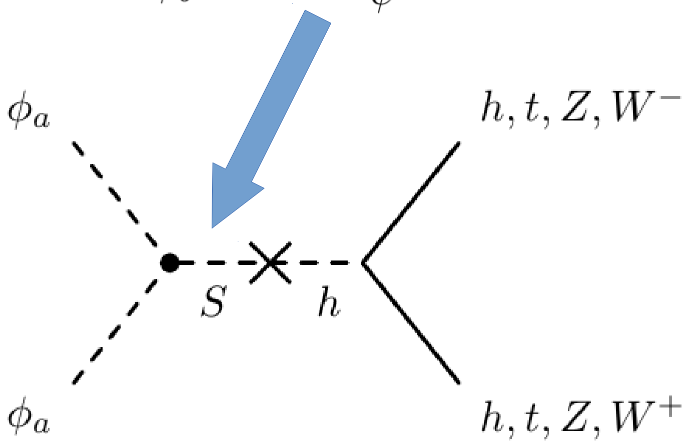
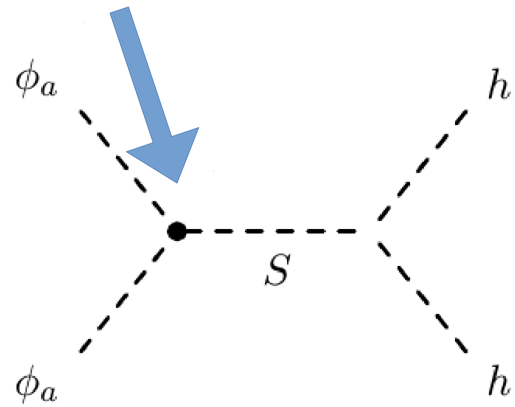
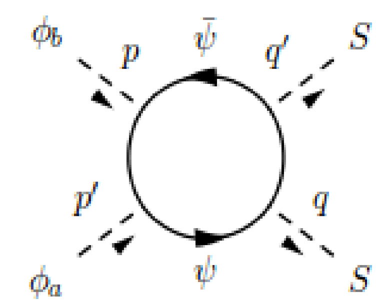
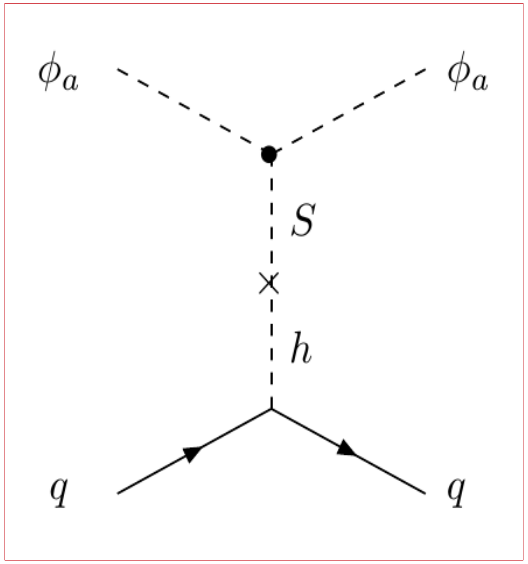
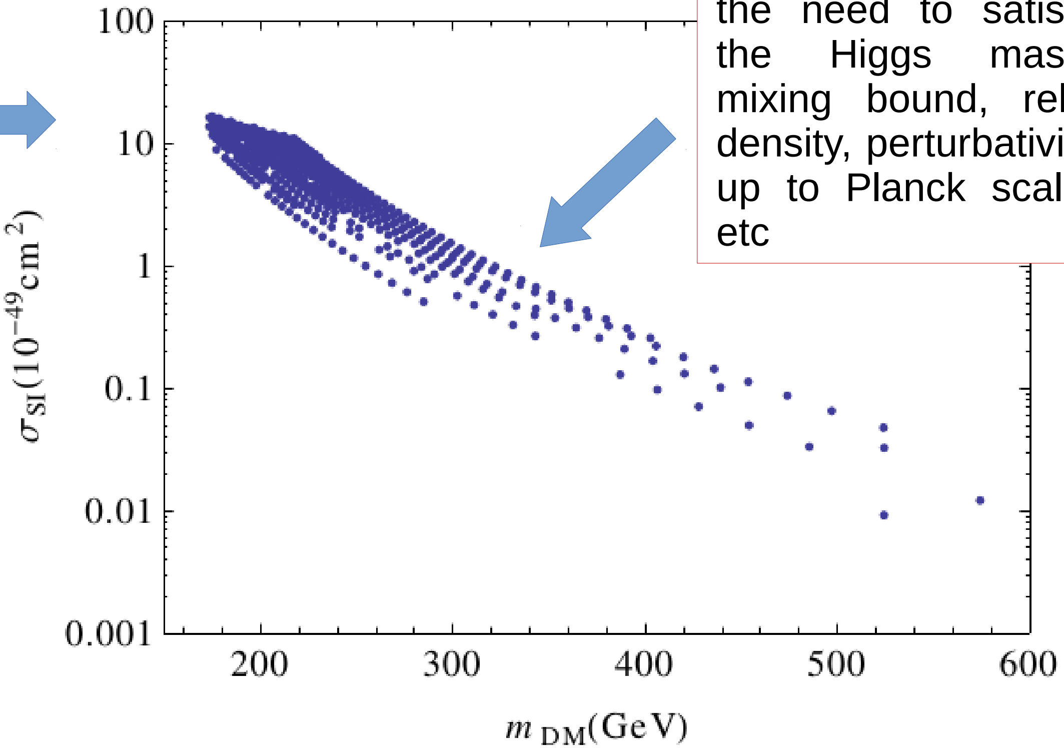






Direct Detection Prospect



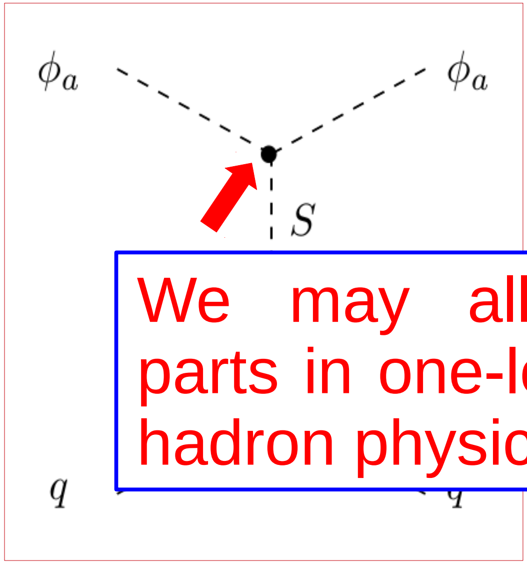


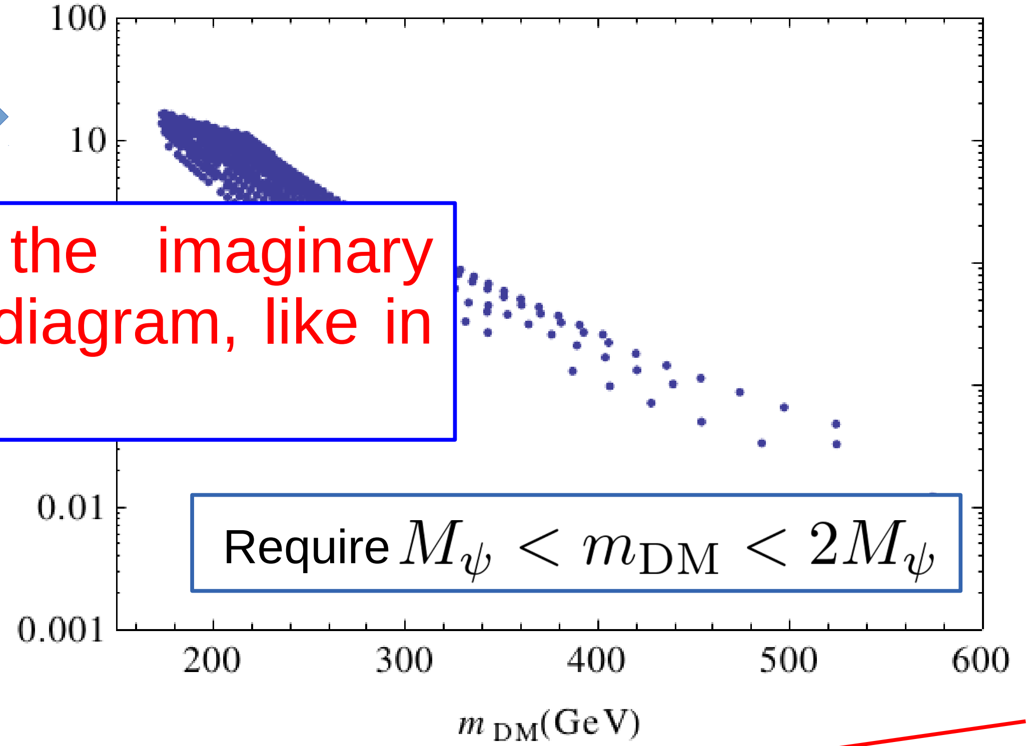
Caused by restrictive parameter space and the need to satisfy the Higgs mass, mixing bound, relic density, perturbativity up to Planck scale, etc

Naively

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.

Direct Detection Prospect





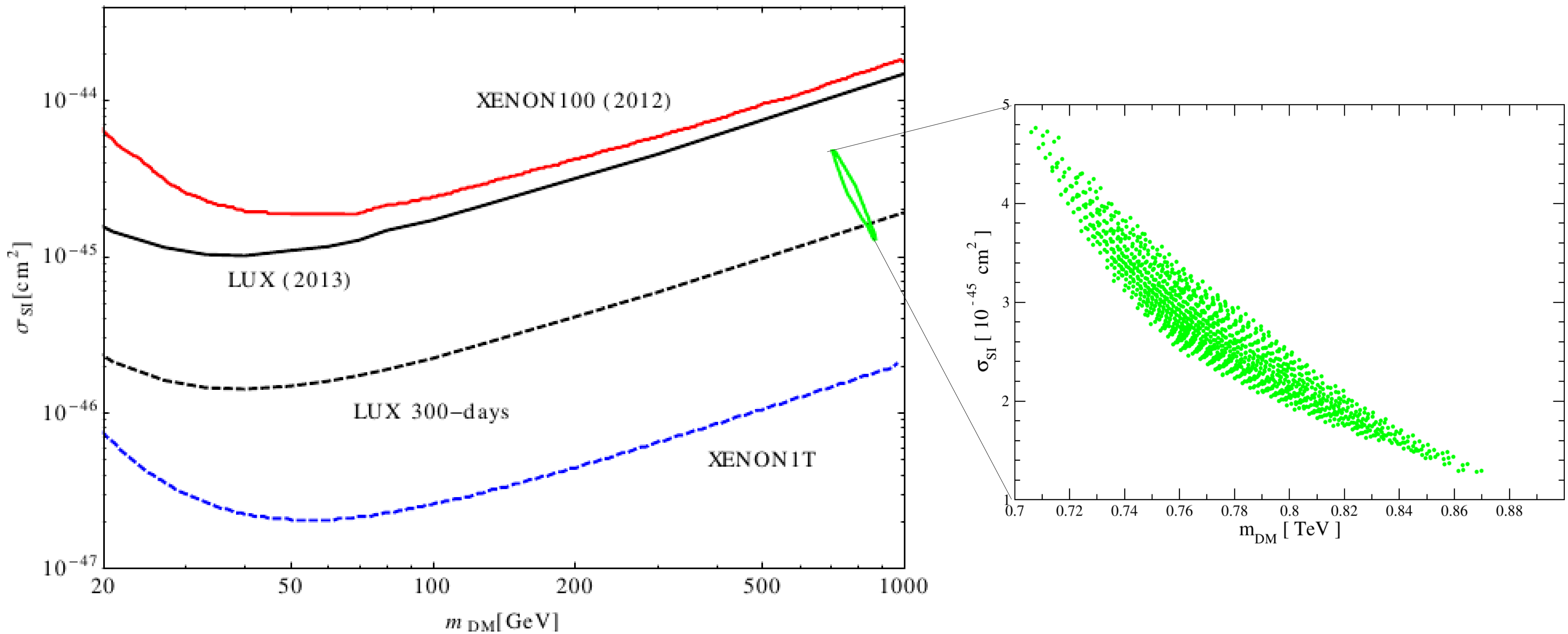
We may allow the imaginary parts in one-loop diagram, like in hadron physics.

Require $M_\psi < m_{\rm DM} < 2M_\psi$

~~Naively~~

~~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.~~

Direct Detection Prospect



Limited Parameter Space can be probed by XENON1T!

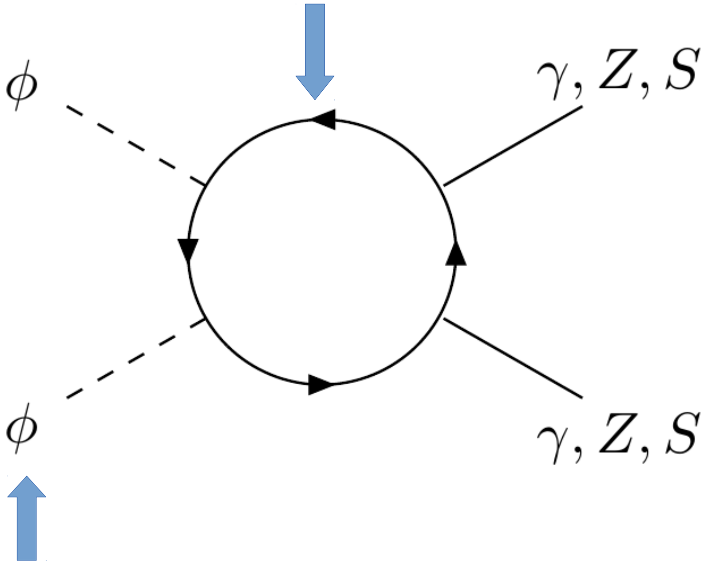
CSI and Accidental U(1)

Still has U(1) symmetry in $\bar{\psi}\psi$

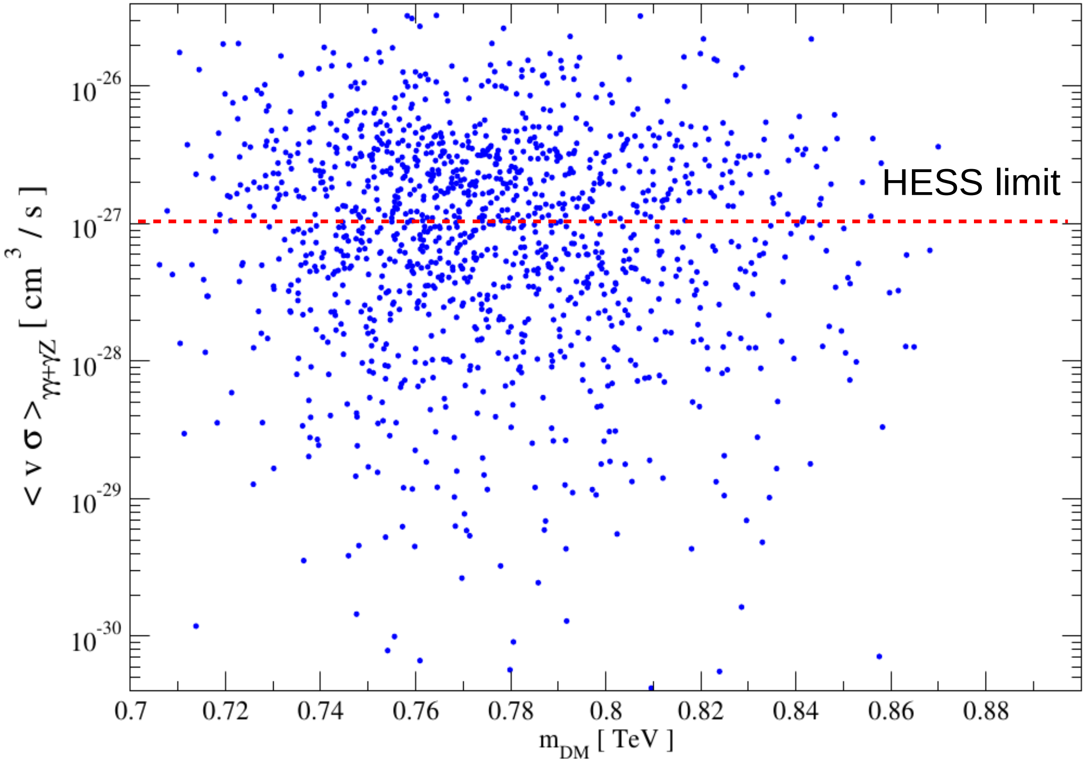
We can exploit this free lunch by identifying it with electromagnetism

e.g. Q = 1/3

Charged dark fermion



DM remains neutral



Highly non-trivial to use NJL approach while maintaining gauge invariance. Needs “least subtraction method” (More fun stuffs in our paper).

What about gravity?

$\mathcal{L} \sim R^2 + R^{\mu\nu} R_{\mu\nu} + \xi S^2 R$ Conformal gravity

$$\mathcal{L} \sim \xi S^2 R \to \xi \langle S \rangle^2 R = M_{pl} R$$

But this is order TeV, fine-tuning

$R^2 + R^{\mu\nu} R_{\mu\nu}$ contains nasty ghost!

Summary

- With no sign of new physics from LHC, long-held belief on naturalness should be scrutnized.
- Classical scale invariance might act as protective symmetry as alternative solution to hierarchy problem, and generates EW scale radiatively.
- We propose 2 models that generate EW scale dynamically.

- 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.

- A QCD extension with scalar of larger irreducible representation that condenses at TeV scale, generating EW scale via dimensional transmutation.
- The mass of the extra scalar is very restrictive, and can be confirmed or ruled out by LHC.
- Higgs production rate in gluon fusion is suppressed. Accidental U(1) symmetry may enhance $H \to \gamma\gamma$

A new way of model building?

Thank you :-)