TOP2020

Durham (Virtually)

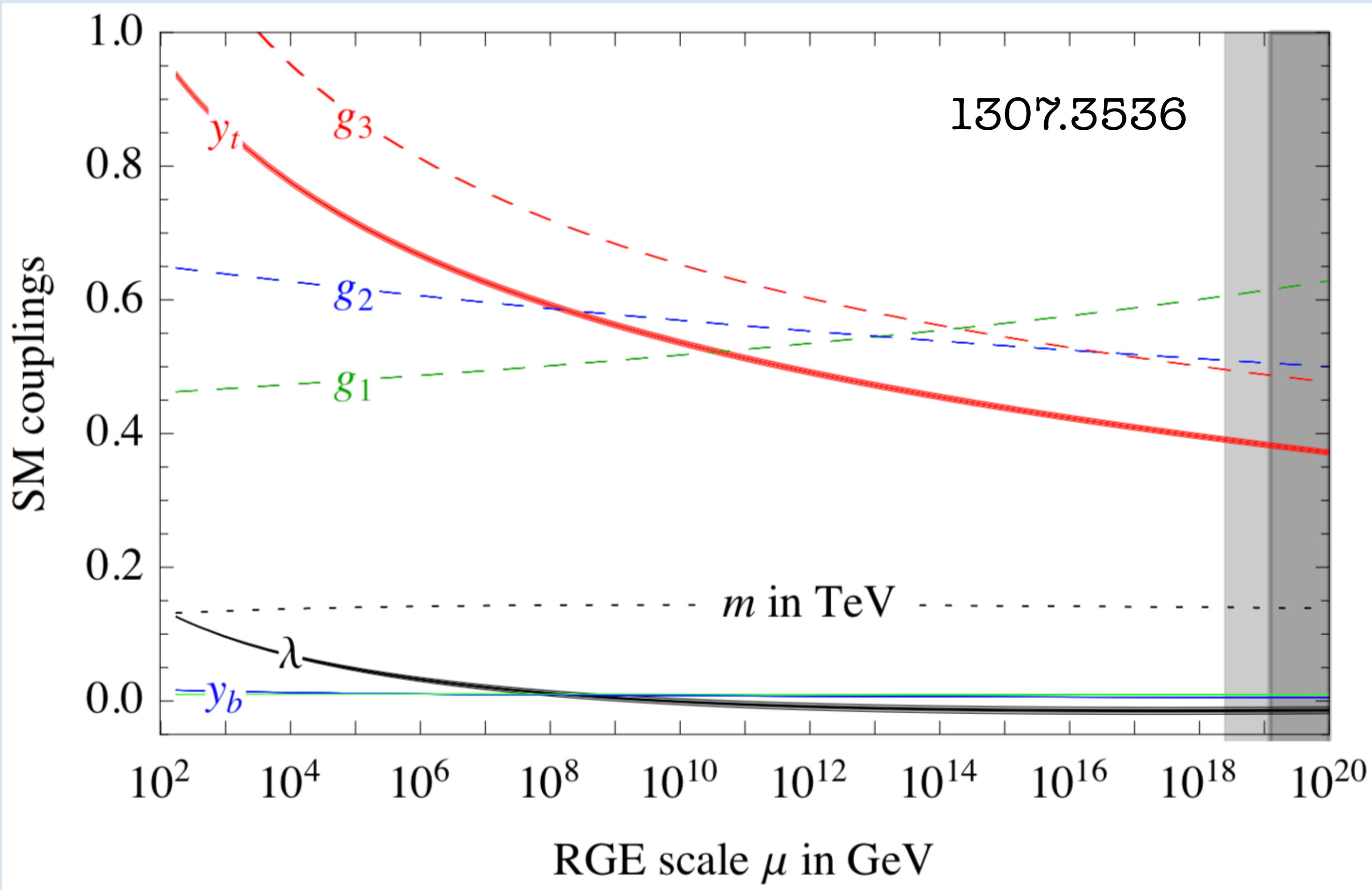
September 14th 2020

Matthew McCullough

CERN

Relevance of the Top Quark

The top quark is the only field the Standard model participating in the two most relevant interactions...



and thus provides the bridge between QCD and the Higgs.

TOP2020

Top and Higgs: A true love story.

Three courses

1. Associated tops

Observation of $t\bar{t}H$ production

The CMS Collaboration*

Why do these titles hold the key to the UV?

Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

The ATLAS Collaboration

Scientific history is littered with empirical models, with some unexplained parameters, which were later superceded by some deeper, more microscopic structure.

These models tended to look like...

This...

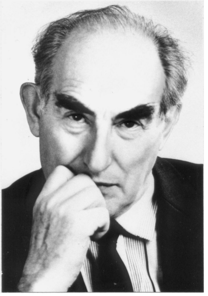
At low energies all we have of QCD is the pions

$$U = f_\pi e^{i\Pi/f_\pi}$$

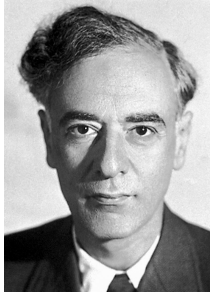
The phenomenological action

$$\mathcal{L} = \frac{1}{2}|D_\mu U|^2 - \mathrm{Tr}\,[\Sigma U + \mathrm{h.c.}] + \ldots$$

contains the parameters which fix the dynamics, but does not explain their origin.



This...



The G-L Theory of superconductivity involves a complex scalar field and the photon

$$\Phi \qquad\qquad A$$

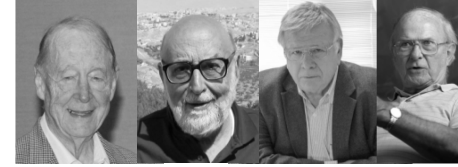
The Free energy is

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

Where the mass depends on the temperature.

and this...



The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

$$H \qquad\qquad W_\mu^a$$

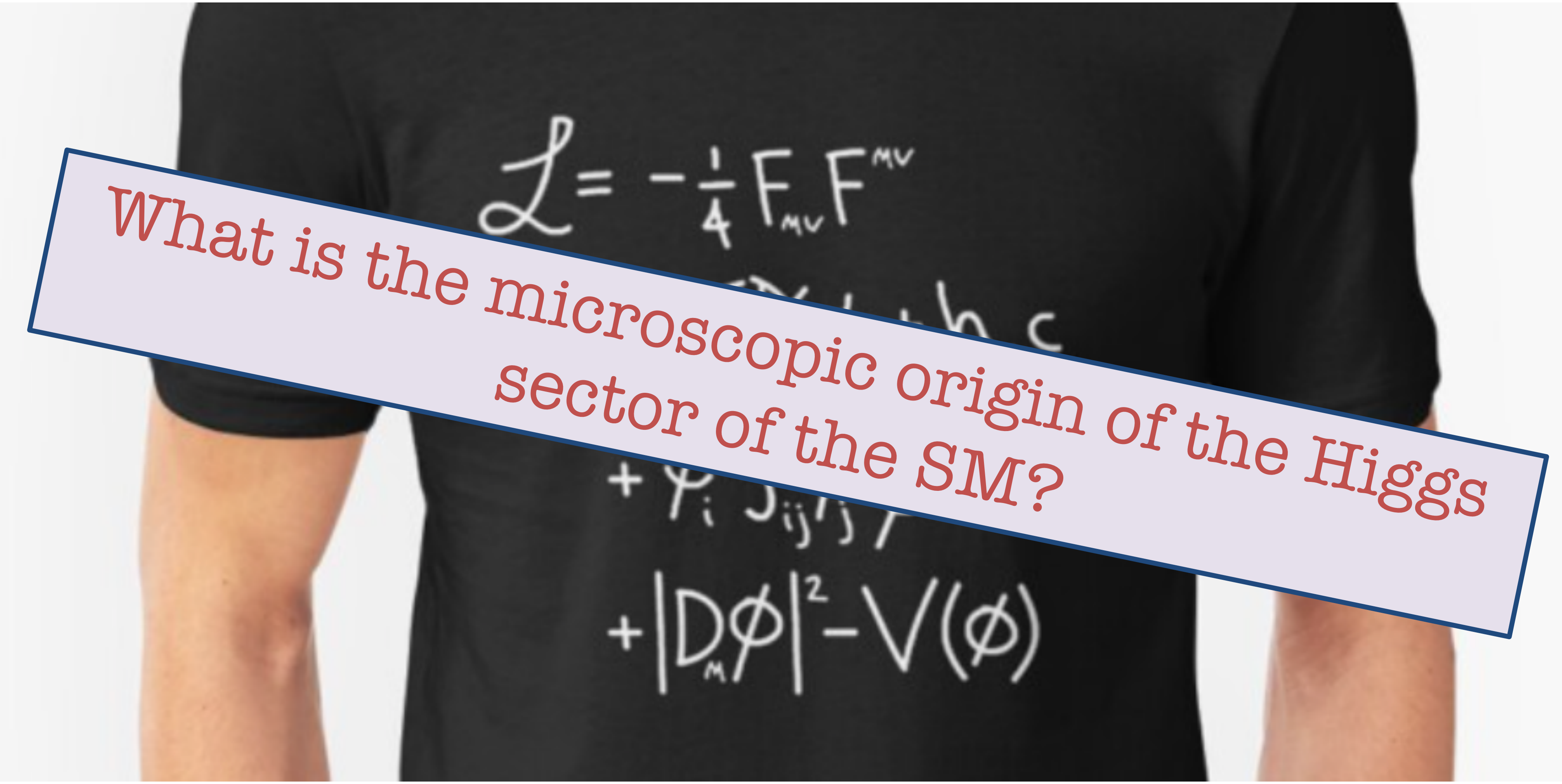
The Lagrangian for this theory is

$$\mathcal{L} = \left|(\partial_\mu + ig\sigma^a W_\mu^a)H\right|^2$$

$$+m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

This is just the relativistic non-Abelian version of Ginzburg-Landau.

Perhaps you are proud of this Lagrangian? I think it's a bit of a mess. So many parameters, interactions. But most arbitrariness is linked to one, lonely, scalar field…



If this is what the ultimate fundamental theory looks like then I'm going home…

The Elephant in the Room

Ginzburg-Landau is a phenomenological model, with no explanation of parameters.

Fortunately, however, we can understand the origins of superconductivity from the detailed microscopic BCS theory (Gor'kov).

The Elephant in the Room

Ginzburg-Landau is a phenomenological model, with no explanation of parameters.

Ψ $\langle ee \rangle$

The same is true for pions and QCD...

Fortunately, however, we can understand the origins of superconductivity from the detailed microscopic BCS theory (Gor'kov).

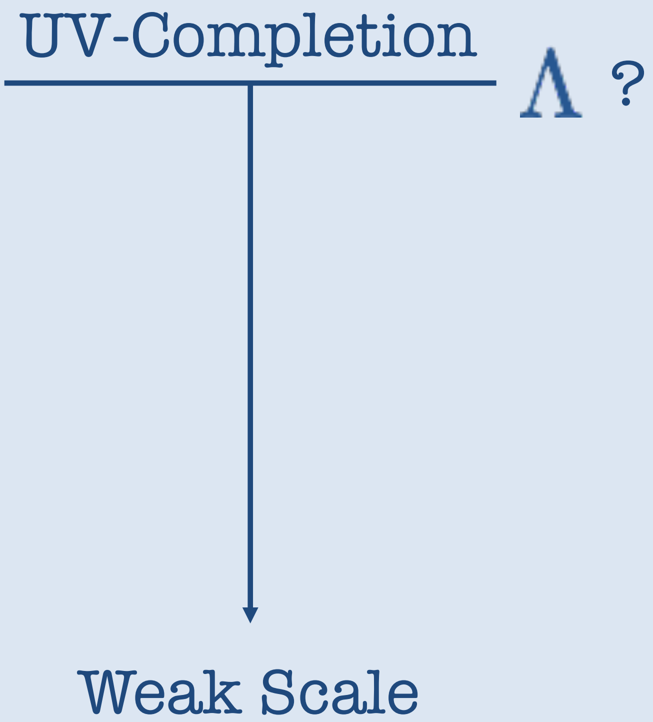
The Elephant in the Room

Like GL, the Higgs sector is a phenomenological model, with no explanation of parameters.

Unlike GL, we have no understanding of the origins of the Higgs sector (no BCS for the Higgs sector, yet...).

Look Up!

So what is the microscopic story for the SM and Higgs and what energy is it at?



Are there any hints for the energy scale?

Look Up!

There is no problem in having a scalar field with mass arbitrarily far below the microscopic scale, since the mass can be forbidden by a simple shift symmetry:

$$\phi \to \phi + \text{constant}$$

This is also consistent with having interactions

$$\mathcal{L}_{\text{Int}} = \mathcal{O}^{\mu} \partial_{\mu} \phi$$

Being a scalar does not mean being heavy and this gives no clues to the scale...

Look Up!

As with pions, if there are parameters which break the shift symmetry nothing forbids mass generation:

$$m_\pi^2 \propto m_q \Lambda$$

The Higgs also has interactions which break any potential shift symmetry. The biggest is:

$$\lambda_t H Q_3 U_3^c$$

So we expect:

$$M_H^2 \propto \hbar \lambda_t^2 \Lambda^2$$

dimensionally, where Planck's constant is usually accompanied by factors of **π**'s.

The Elephant in the Room

We expect the Higgs model is phenomenological, just like G-L, or pions. But something totally different seems to be going on.

There is a hierarchy between the model parameters and the microscopic parameters. Furthermore, this hierarchy is not protected by any symmetry: Quantum corrections do not respect such a hierarchy.

Look Up!

Since we know

$$\hbar \lambda_t^2 \sim 1$$

then we expect the microscopic physics and Higgs mass cannot be too greatly separated.

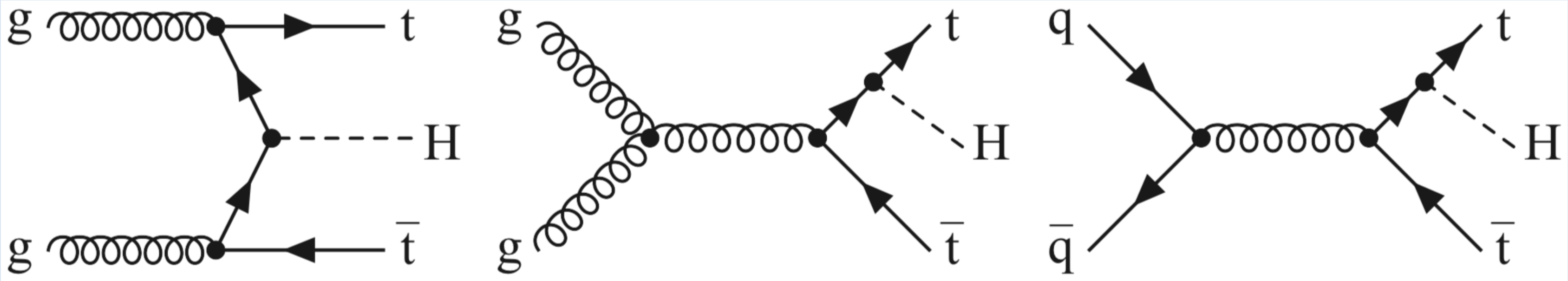
This is the hierarchy problem and the top Yukawa is right at the heart of it!

This is why theories that solve this problem have top partners, modified Yukawas, etc...

Look Up!

Model builders are tearing their hair out...

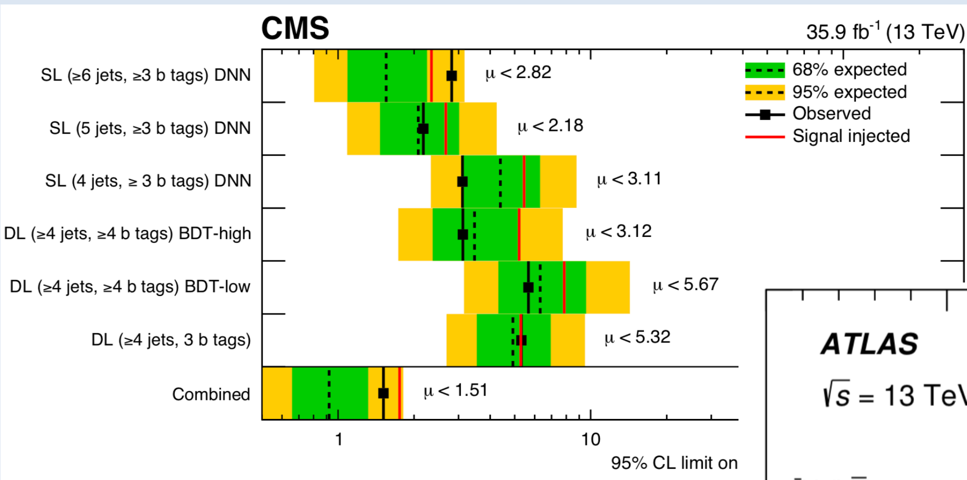
because of the top Yukawa coupling. Without it the Higgs could still be relatively natural.

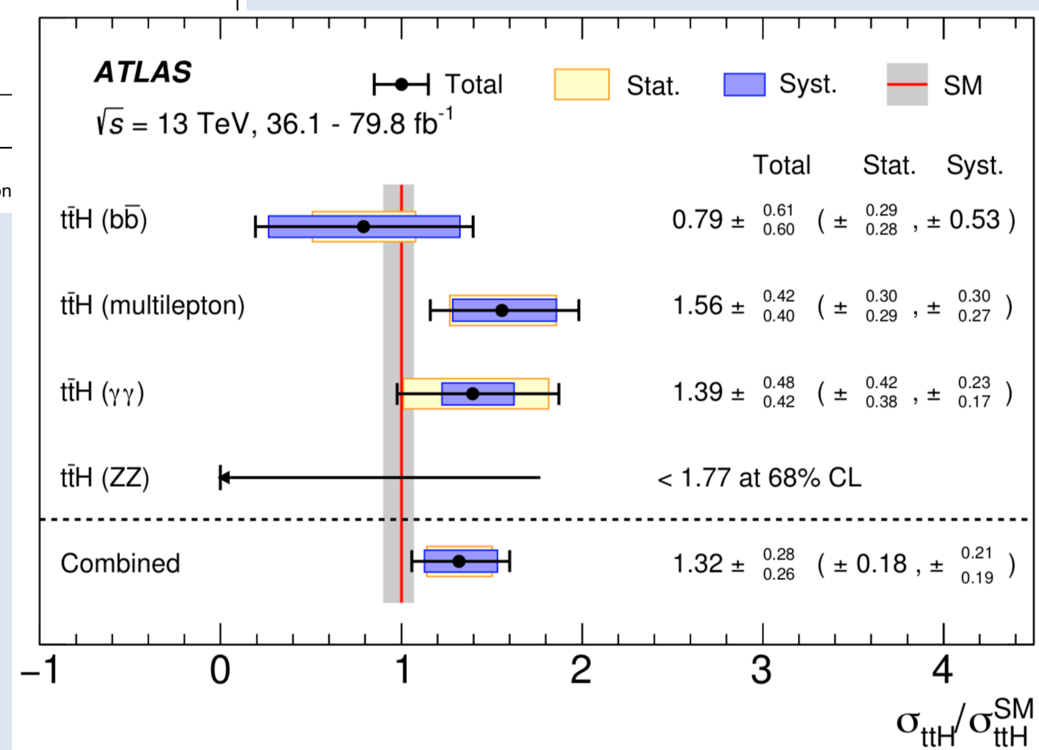


Measurements of TTH directly probe the biggest clue we have for the scale of microscopic origins of the Higgs sector...

Look Up!

We have a lot to look forward to...





Top Partners

In the Standard Model there is no symmetry protecting from corrections which scale as:

$$M_H^2 \propto \hbar \lambda_t^2 \Lambda^2$$

However, we can extend the symmetries of the Standard Model to forbid these corrections.

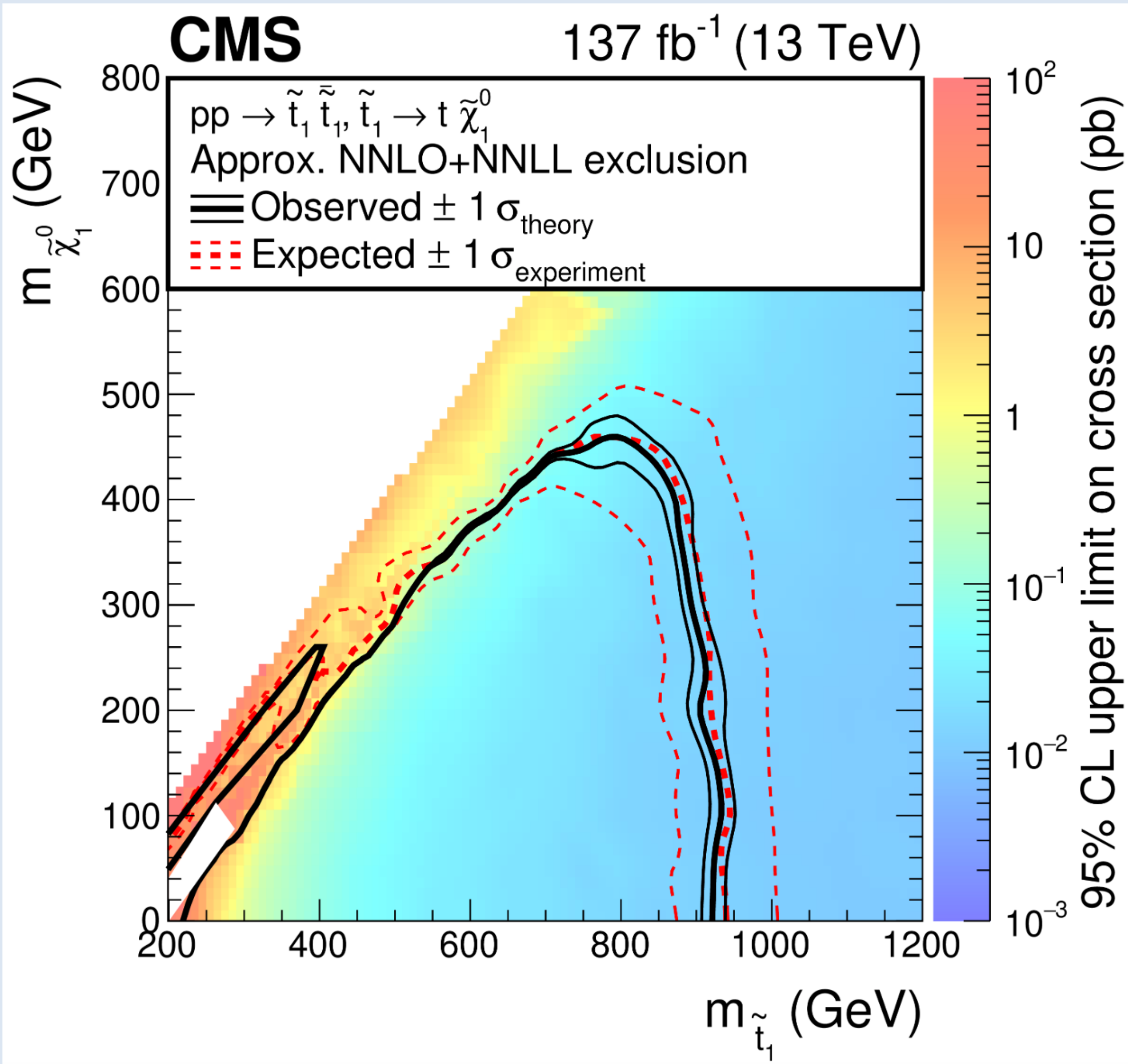
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \dots$$

Fields must fall in complete representations of symmetry, thus extending the symmetries means extending the field content:

Top Partners

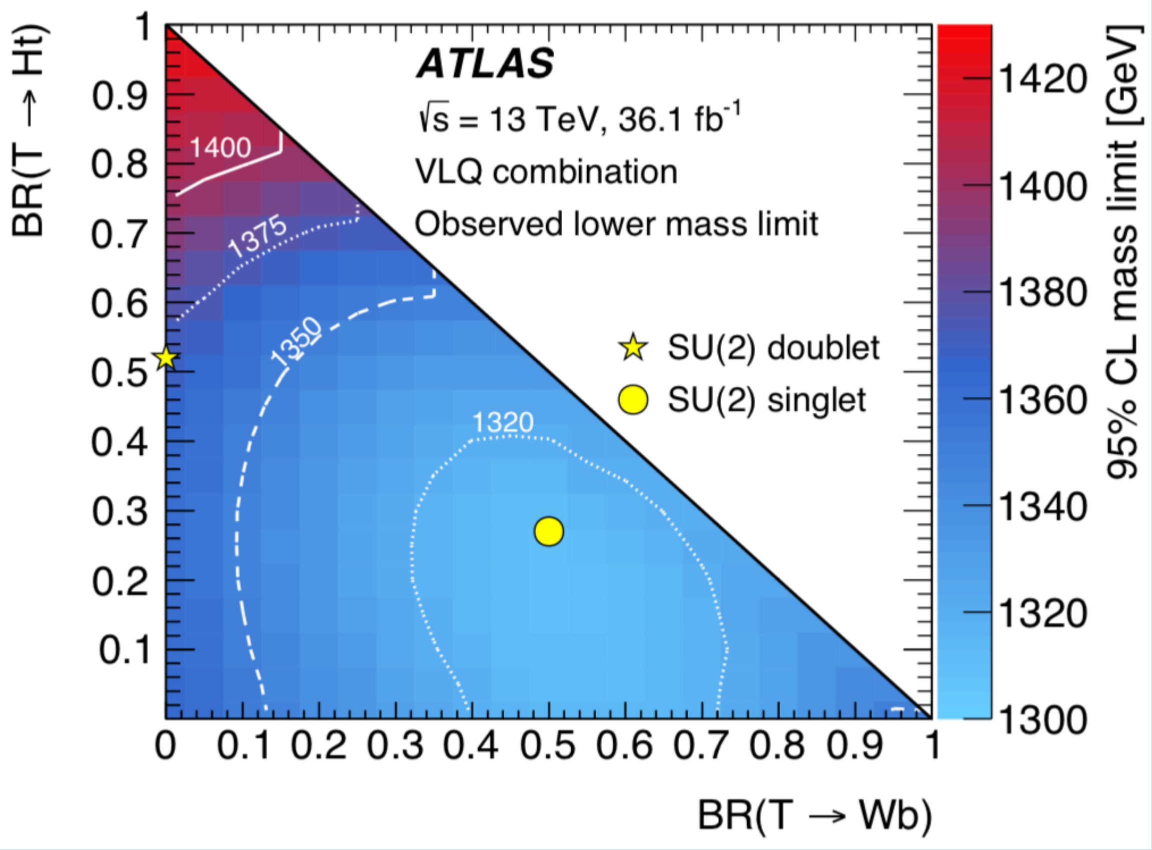
In SUSY the top coupling is compatible since large corrections are cancelled by stops.

But...



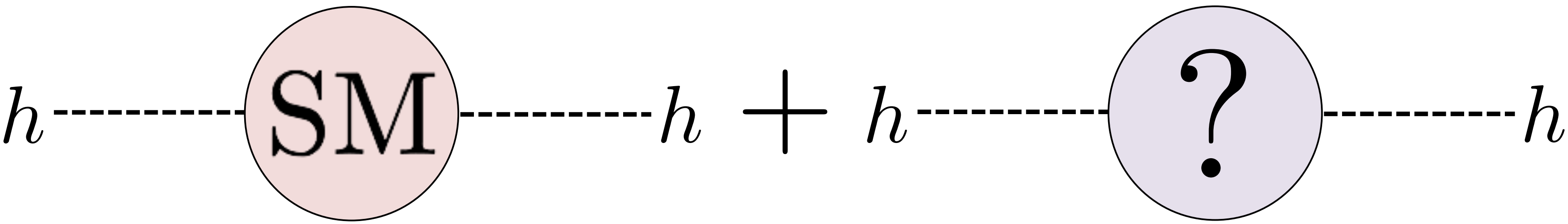
Top Partners

In pNGB Higgs models the coupling can be consistent with a shift symmetry, at the cost of extra fermions…



Neutral Naturalness

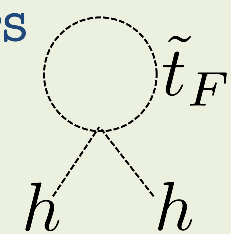
Could there be totally hidden states which tame sensitivity to physics at the cutoff?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners



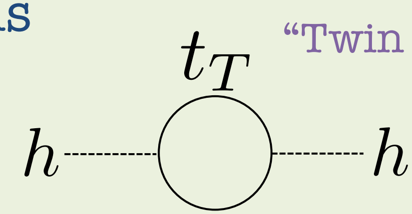
"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions

"Twin Tops"

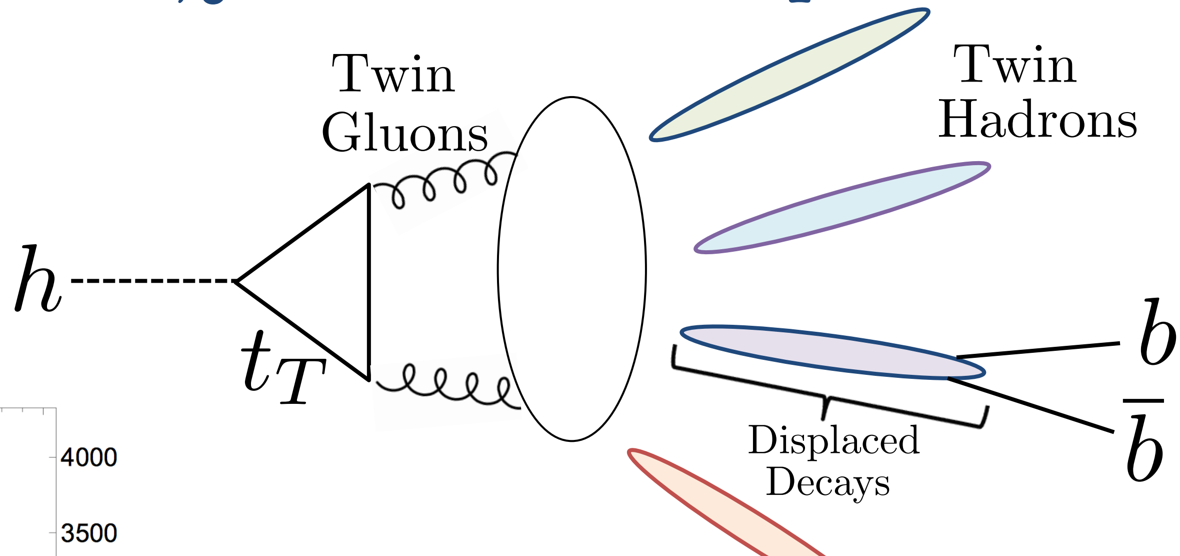


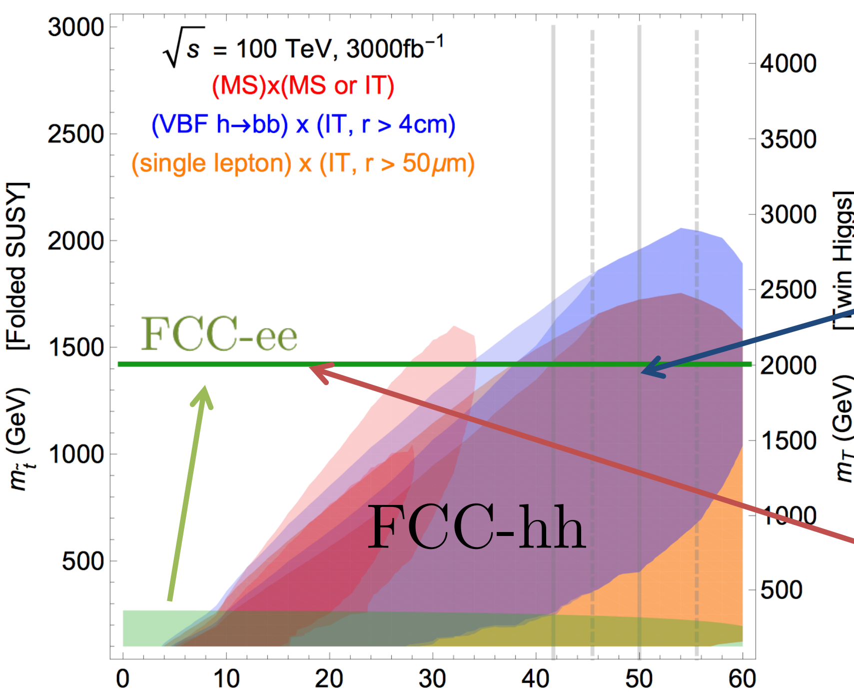
...but they must be charged under new hidden QCD'.

Neutral Naturalness

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:





Curtin, CV 1506.06141

FCC-hh can thoroughly probe larger Twin scales through displaced searches.

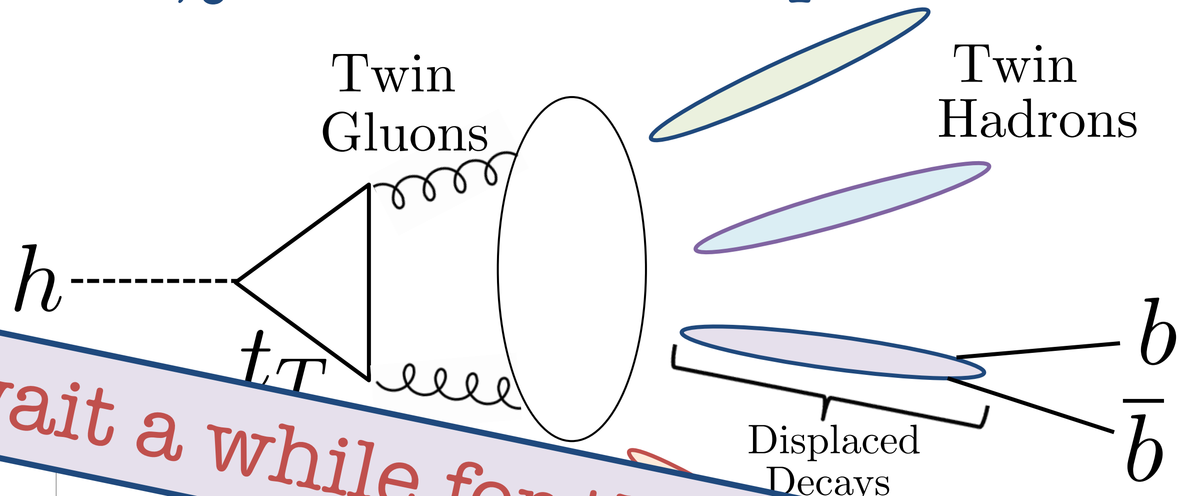
FCC-ee/CEPC has indirect access for top partners, including for low confinement scales.

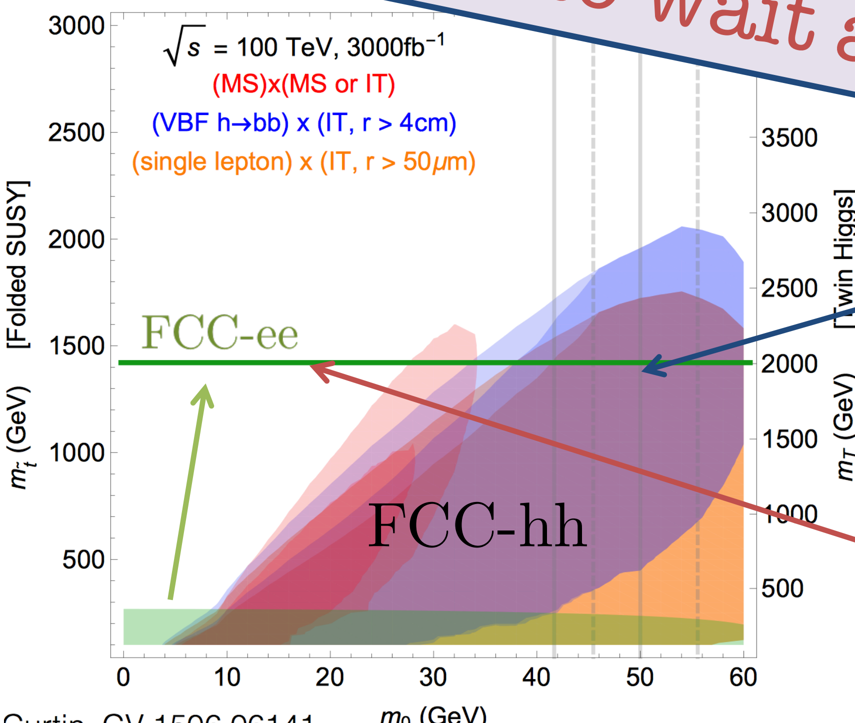
Neutral Naturalness

Naturalness not hidden, just look in new places…

New hidden sector introduces exotic Higgs decays:

May have to wait a while for these ones…





Curtin, CV 1506.06141

FCC-hh can thoroughly probe larger Twin scales through displaced searches.

FCC-ee/CEPC has indirect access for top partners, including for low confinement scales.

Measurements of the top Yukawa and searches for exotic top-quark final states are crucial for address the question:

What is the microscopic origin of the Standard Model Higgs sector?

2. Four tops

Evidence for $t\bar{t}t\bar{t}$ production in the multilepton final state in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Why are these recent results crucial steps forward for our understanding of the Higgs boson?

Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Organizing the Unknown

To understand the origin and nature of the Higgs boson, we need to study how it behaves.

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2 \qquad \mathcal{O}_W = \frac{ig\, c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu} \qquad \mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2 \qquad \mathcal{O}_{WW} = \frac{g^2\, c_{WW}}{M^2}|H|^2 W^{a\,\mu\nu} W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'\, c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu} \qquad \mathcal{O}_{GG} = \frac{g_s^2\, c_{GG}}{M^2}|H|^2 G^{a,\mu\nu} G^a_{\mu\nu}$$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2 \qquad \mathcal{O}_R = \frac{c_R}{M^2}|H|^2 |D^\mu H|^2$$

$$\mathcal{O}_{BB} = \frac{g'^2\, c_{BB}}{M^2}|H|^2 B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2 \qquad \mathcal{O}_{WB} = \frac{gg'\, c_{WB}}{M^2} H^\dagger \sigma^a H B^{\mu\nu} W^a_{\mu\nu}$$

Effective field theory...

Operators like those above capture leading effects of heavy physics beyond the standard model. Probing them could reveal origins.

Organizing the Unknown

To understand the origin and nature of the Higgs boson, we need to study how it behaves.

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2 \qquad \mathcal{O}_W = \frac{ig\, c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu} \qquad \mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

$$\mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2 \qquad \mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2 \qquad \mathcal{O}_{WW} = \frac{g^2\, c_{WW}}{M^2}|H|^2 W^{a\,\mu\nu} W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'\, c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu} \qquad \mathcal{O}_6 = \frac{c_6}{M^2}|H|^6 \qquad \mathcal{O}_{GG} = \frac{g_s^2\, c_{GG}}{M^2}|H|^2 G^{a,\mu\nu} G^a_{\mu\nu}$$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2 \qquad \mathcal{O}_R = \frac{c_R}{M^2}|H|^2 |D^\mu H|^2$$

$$\mathcal{O}_{BB} = \frac{g'^2\, c_{BB}}{M^2}|H|^2 B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2 \qquad \mathcal{O}_{WB} = \frac{gg'\, c_{WB}}{M^2} H^\dagger \sigma^a H B^{\mu\nu} W^a_{\mu\nu}$$

Operators like those above capture leading effects of heavy physics beyond the standard model. Probing them could reveal origins.

Organizing the Unknown

Naïve dimensional analysis:

$$[H] = [A_\mu] = \frac{1}{LC} \quad , \quad [\psi] = \frac{1}{L^{3/2}C}$$

Fields carry not only dimension of inverse length, but also inverse coupling.

Fermi Scale

Interaction: $\mathcal{L} \sim \frac{\psi^4}{\Lambda^2}$

UV-completion

Dimension: $[\Lambda] = [G_F^{-1/2}] = \frac{[M_W]}{[g]}$

Coupling

Organizing the Unknown

Higgs Only

$[g_*^0]$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$

$[g_*^2]$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2$$

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2$$

$$\frac{c_R}{\ldots}|H|^2|D^\mu H|^2$$

$[g_*^4]$

$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$

Any new physics interacting primarily with Higgs and gauge sectors matches, at leading order, to these operators.

$$\mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2$$

Mixed

$$\mathcal{O}_B = \frac{ig'\,c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_W = \frac{ig\,c_W}{2M^2}(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H)D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_{GG} = \frac{g_s^2\,c_{GG}}{M^2}|H|^2 G^{a,\mu\nu}G^a_{\mu\nu}$$

$$\mathcal{O}_{WB} = \frac{gg'\,c_{WB}}{M^2}H^\dagger\sigma^a H B^{\mu\nu}W^a_{\mu\nu}$$

$$\mathcal{O}_{WW} = \frac{g^2\,c_{WW}}{M^2}|H|^2 W^{a\,\mu\nu}W^a_{\mu\nu}$$

$$\mathcal{O}_{BB} = \frac{g'^2\,c_{BB}}{M^2}|H|^2 B^{\mu\nu}B_{\mu\nu}$$

Organizing the Unknown

Higgs Only

$[g_*^0]$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$

$[g_*^2]$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2$$

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2$$

$$\mathcal{O}_R = \frac{c_R}{M^2}|H|^2|D^\mu H|^2$$

$[g_*^4]$

$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$

Gauge Only

$$\mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2$$

$$\mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2$$

$$\mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

Mixed

$$\mathcal{O}_B = \frac{ig'\,c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_W = \frac{ig\,c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H)D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_{GG} = \frac{g_s^2\,c_{GG}}{M^2}|H|^2 G^{a,\mu\nu}G^a_{\mu\nu}$$

$$\mathcal{O}_{WB} = \frac{gg'\,c_{WB}}{M^2}H^\dagger \sigma^a H B^{\mu\nu}W^a_{\mu\nu}$$

$$\mathcal{O}_{WW} = \frac{g^2\,c_{WW}}{M^2}|H|^2 W^{a\,\mu\nu}W^a_{\mu\nu}$$

$$\mathcal{O}_{BB} = \frac{g'^2\,c_{BB}}{M^2}|H|^2 B^{\mu\nu}B_{\mu\nu}$$

$$\mathcal{O}_{\Box} = \frac{c_{\Box}}{M^2} |\Box H|^2$$

The lowest
coupling-dimension
Higgs-only operator.

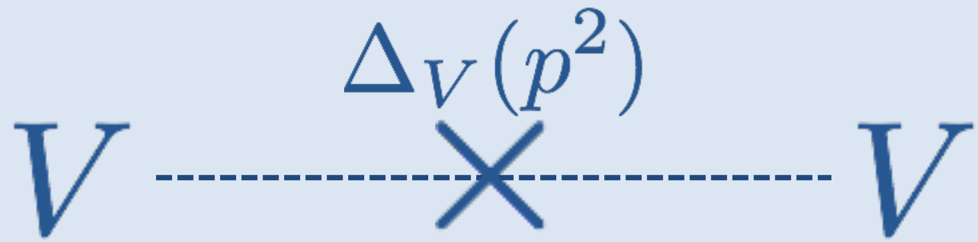
$$\mathcal{O}_{\Box} = \frac{c_{\Box}}{M^2} |\Box H|^2$$

Parameterises
BSM deviations in how
the Higgs moves.

Oblique Corrections

Oblique corrections have been a formidable toolkit in the effort to explore the electroweak sector.

- S-parameter
- T-parameter
- W-parameter
- Y-parameter



The latter two contribute to amplitudes in an "energy-growing" manner:

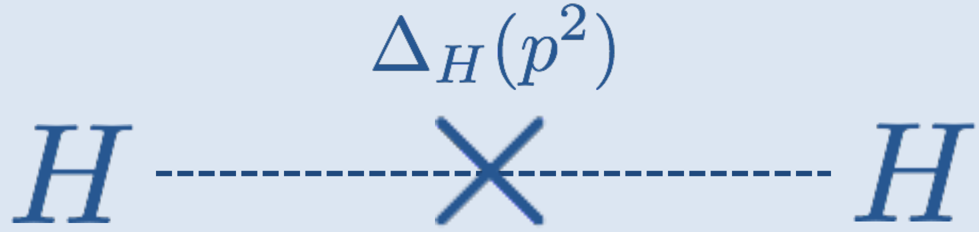
$$\Delta_W(p^2) \approx \frac{1}{p^2 - M_W^2} - \frac{\hat{W}}{M_W^2}$$

Making these oblique parameters an excellent target for hadron colliders…

Oblique Corrections

Makes sense to extend to the Higgs sector. Especially since the Higgs can easily interact with new states...

- H-parameter:



1903.07725

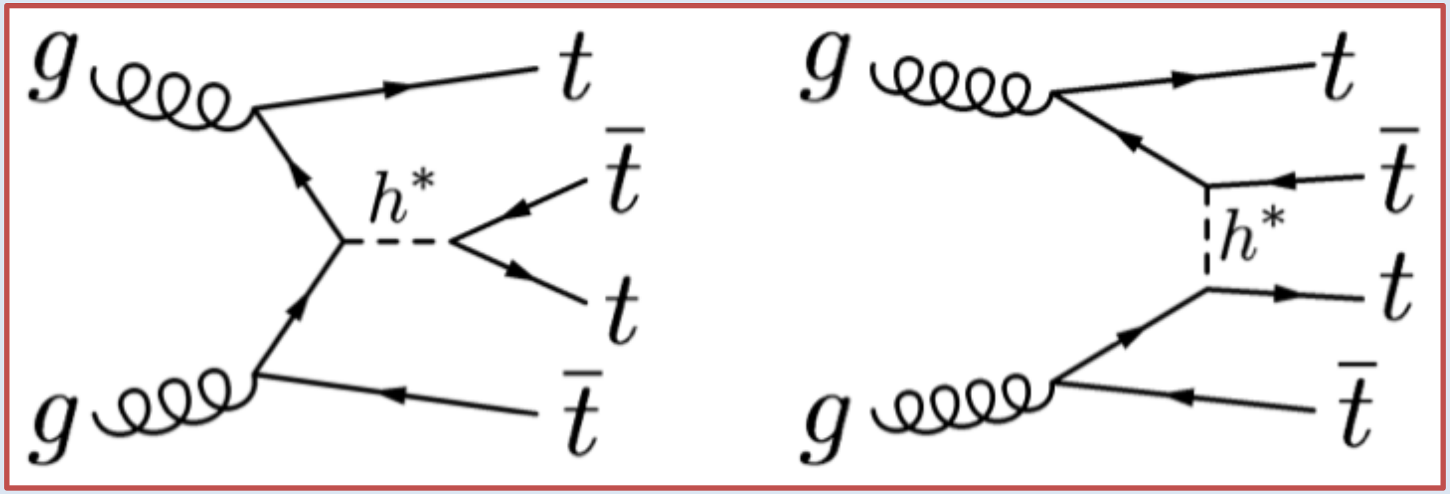
This also contributes to amplitudes in an "energy-growing" manner:

$$\Delta_H(p^2) \approx \frac{1}{p^2 - m_h^2} - \frac{\hat{H}}{m_h^2} + \dots$$

However, one needs to take the Higgs off-shell, which isn't easy...

Oblique Corrections

Most promising avenue to take this Higgs off-shell is through four-top production:

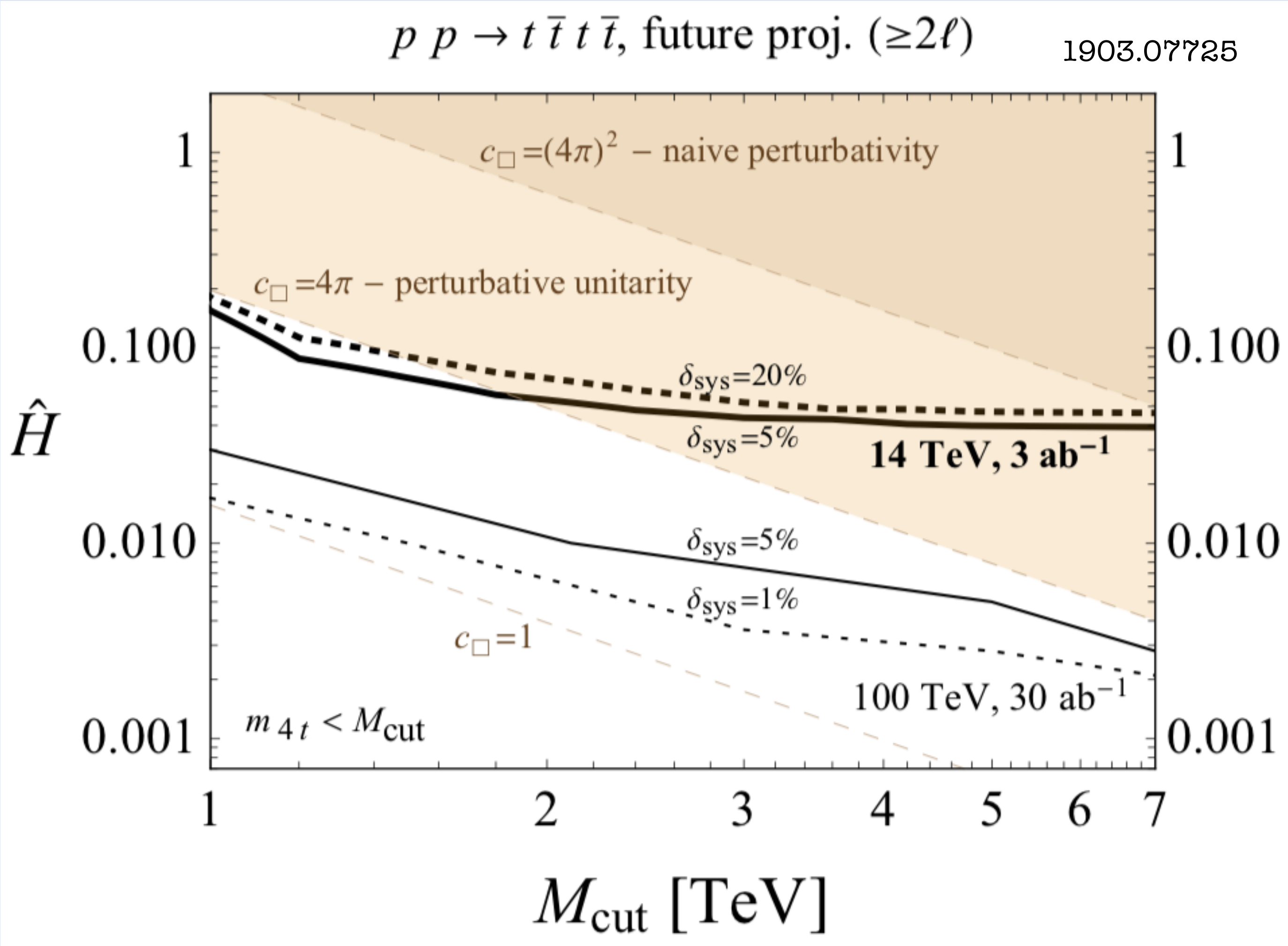


We may relate this Wilson coefficient to the scale of new physics as:

$$\frac{\hat{H}}{m_h^2} = \frac{c_\Box}{M^2}$$

Oblique Corrections

Suggests the practical way to probe this special operator is with four tops at future colliders:



A Unique Operator

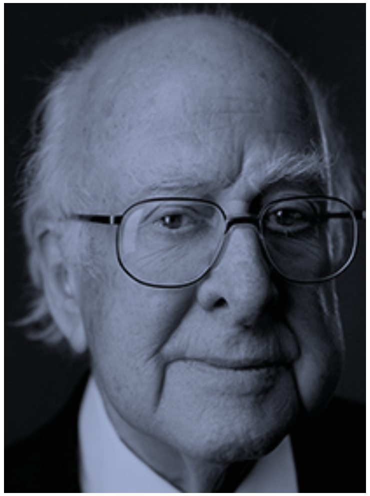
CMS did better than our estimates:

Abstract

1908.06463

The standard model (SM) production of four top quarks ($t\bar{t}t\bar{t}$) in proton-proton collision is studied by the CMS Collaboration. The data sample, collected during the 2016–2018 data taking of the LHC, corresponds to an integrated luminosity of 137 fb^{-1} at a center-of-mass energy of 13 TeV. The events are required to contain two same-sign charged leptons (electrons or muons) or at least three leptons, and jets. The observed and expected significances for the $t\bar{t}t\bar{t}$ signal are respectively 2.6 and 2.7 standard deviations, and the $t\bar{t}t\bar{t}$ cross section is measured to be $12.6^{+5.8}_{-5.2}$ fb. The results are used to constrain the Yukawa coupling of the top quark to the Higgs boson, y_t, yielding a limit of $|y_t/y_t^{SM}| < 1.7$ at 95% confidence level, where y_t^{SM} is the SM value of y_t. They are also used to constrain the oblique parameter of the Higgs boson in an effective field theory framework, $\hat{H} < 0.12$. Limits are set on the production of a heavy scalar or pseudoscalar boson in Type-II two-Higgs-doublet and simplified dark matter models, with exclusion limits reaching 350–470 GeV and 350–550 GeV for scalar and pseudoscalar bosons, respectively. Upper bounds are also set on couplings of the top quark to new light particles.

A robust understanding of four-top physics, both theoretically and experimentally, will be necessary to answer a simple, fundamental, question:



How does the Higgs move?

3. Top mass

Measurement of the jet mass distribution and top quark mass in hadronic decays of boosted top quarks in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

The fate of the Universe written in these papers.

Measurement of the top-quark mass in $t\bar{t}$ + 1-jet events collected with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

Destiny

It was pointed out a long time ago that the Universe could have a lower-energy vacuum state:

Krive and Linde

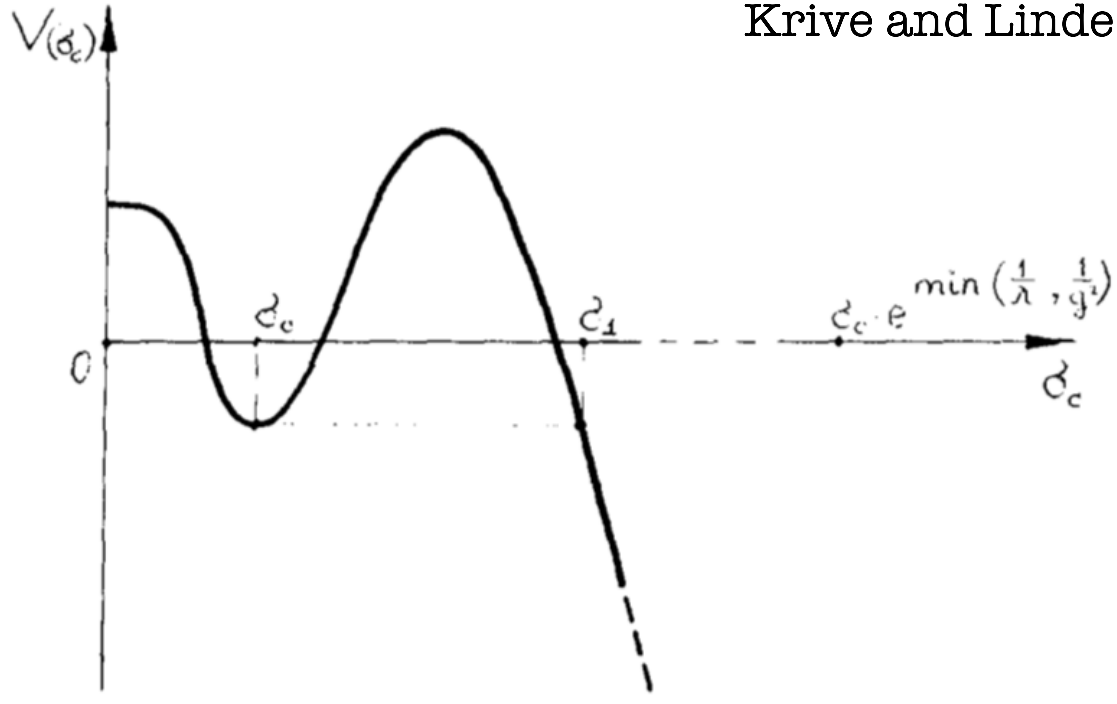


Fig. 1. Effective potential of the σ model at $m_\sigma << m_\psi$.

Destiny

It was pointed out a long time ago that the Universe could have a lower-energy vacuum state:

META

Limitation of the fermion mass in gauge theories of weak and electromagnetic interactions

Krasnikov, N.V. (AN SSSR, Moscow. Inst. Yadernykh Issledovanij)

Citation | Export | ···

Abstract

[en] It is shown that in gauge models of weak and electromagnetic interactions the fermion (quark, lepton) mass is no more than the most heavy boson mass in the order of magnitude. In the SU(2)XU(1) gauge model of weak and electromagnetic interactions with one isodoublet of scalar fields the fermion mass may not be more than 750 GeV

Original Title	Ogranichenie na massu fermionov v kalibrovochnykh teoriyakh slabogo i ehlektromagnitnogo vzaimodejstvij
Primary Subject	PHYSICS OF ELEMENTARY PARTICLES AND FIELDS (A2100)
Source	For English translation see the journal Sov. J. Nucl. Phys.
Record Type	Journal Article
Journal	Yadernaya Fizika; v. 28(2); p. 549-551
Country of publication	USSR

Destiny

It was pointed out a long time ago that the Universe could have a lower-energy vacuum state:

Papers followed which considered the Standard Model explicitly.

...s in gauge theories of weak and electromagnetic interactions

...h Issledovanij)

Citation Export ···

[en] It is show... ...ton) mass is no more than the most ... weak and electromagnetic interactions with one ... than 750 GeV

Original Title	Ogranichenie na massu fermionov v kalibrovochnykh teoriyakh slabogo i ele... vzaimodejstvij
Primary Subject	PHYSICS OF ELEMENTARY PARTICLES AND FIELDS (A2100)
Source	For English translation see the journal Sov. J. Nucl. Phys.
Record Type	Journal Article
Journal	Yadernaya Fizika; v. 28(2); p. 549-551
Country of publication	USSR

Destiny

It was pointed out a long time ago that the Universe could have a lower-energy vacuum state:

META

Limitation of the fermion mass in gauge theories of weak and electromagnetic interactions

Krasnikov, N.V. (AN SSSR, Moscow. Inst. Yadernykh Issledovanij)

Citation Export ···

Abstract

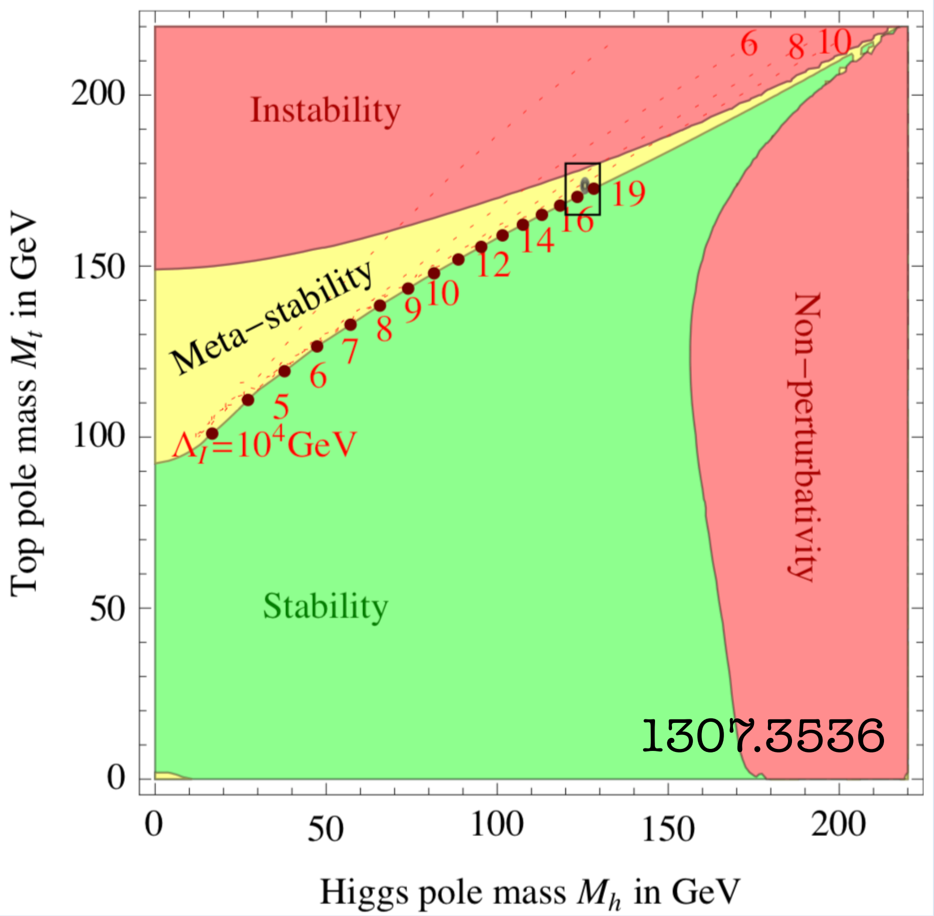
[en] It is shown that in gauge models of weak and electromagnetic interactions the fermion (quark, lepton) mass is no more than the most heavy boson mass in the order of magnitude. In the SU(2)XU(1) gauge model of weak and electromagnetic interactions with one isodoublet of scalar fields the fermion mass may not be more than 750 GeV

What???

Original Title	Ogranichenie na massu fermionov v kalibrovochnykh teoriyakh slabogo i ehlektromagnitnogo vzaimodejstvij
Primary Subject	PHYSICS OF ELEMENTARY PARTICLES AND FIELDS (A2100)
Source	For English translation see the journal Sov. J. Nucl. Phys.
Record Type	Journal Article
Journal	Yadernaya Fizika; v. 28(2); p. 549-551
Country of publication	USSR

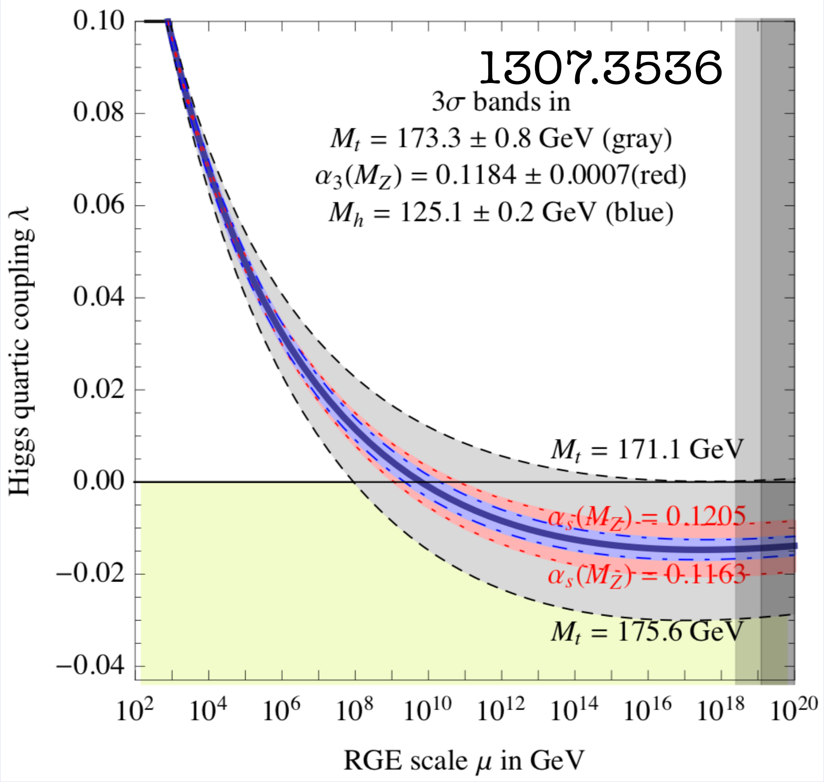
Destiny

The modern incarnation of our Understanding of the vacuum structure of the Universe is:



Destiny

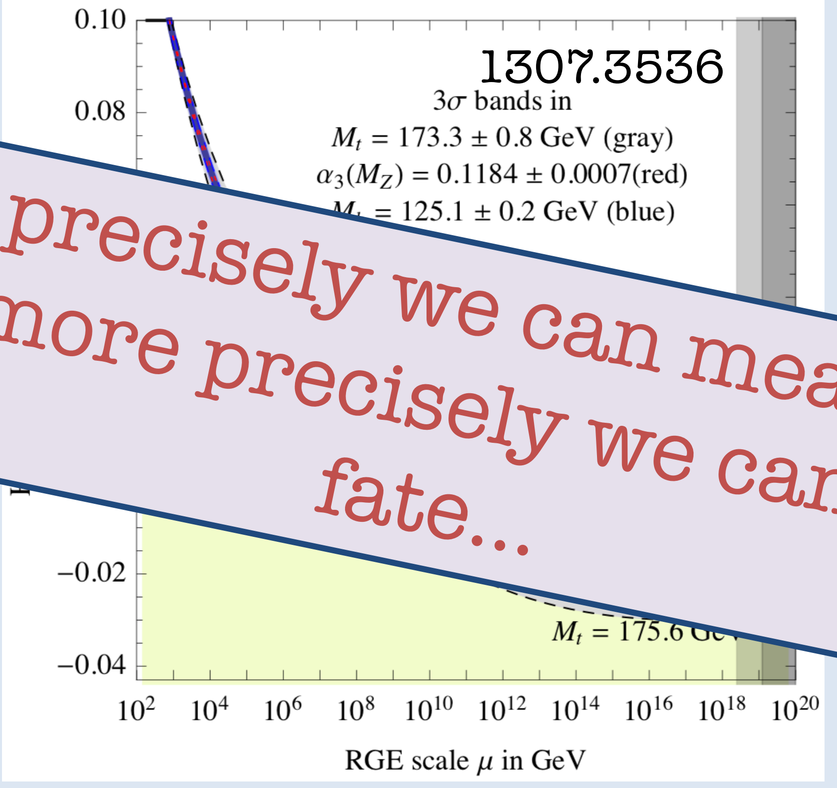
Which follows from:



The dominant uncertainty for predicting our long-term future isn't the US elections, it's the top quark mass…

Destiny

Which follows from:



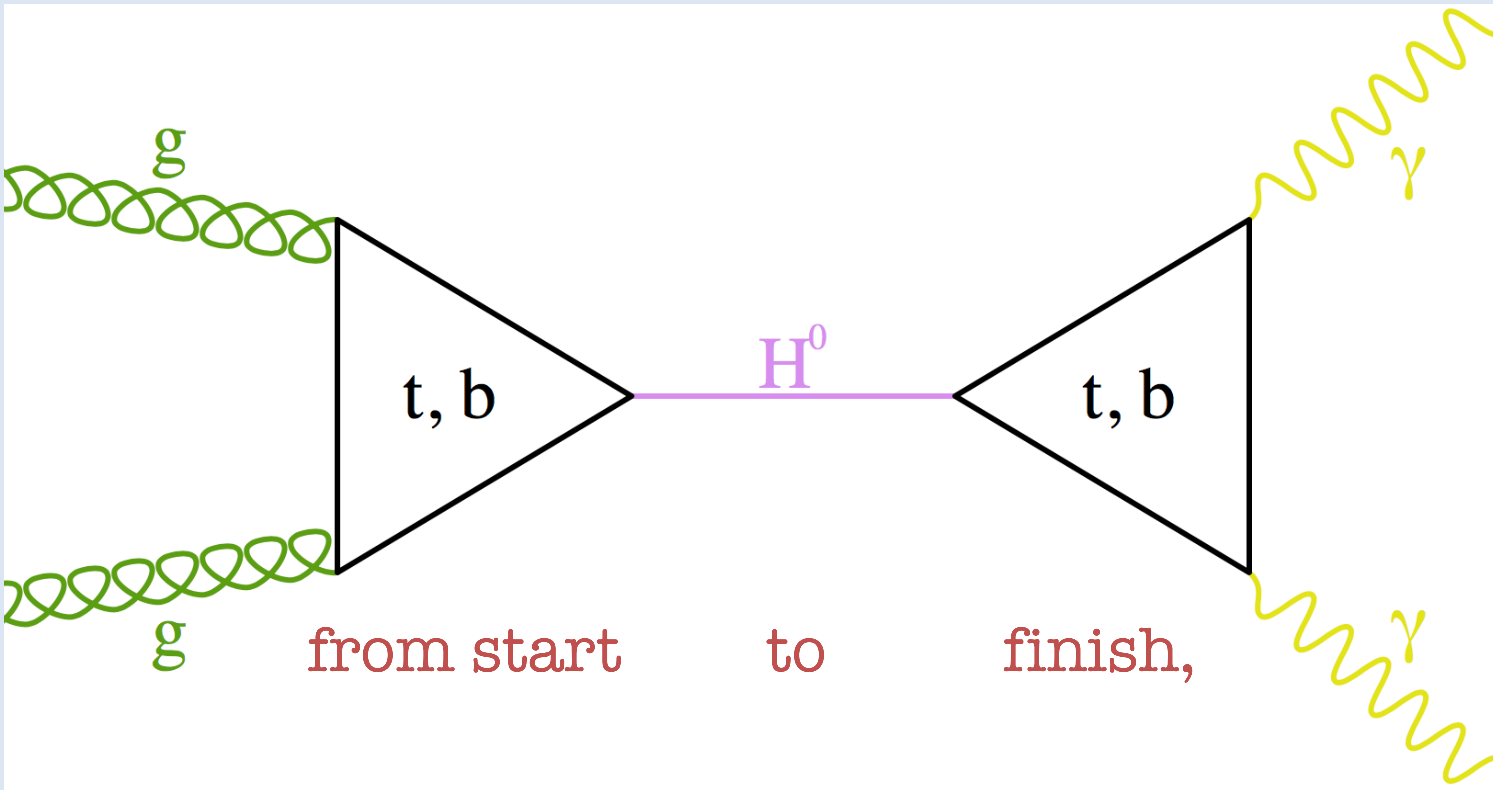
The more precisely we can measure the top mass, the more precisely we can predict our fate...

The dominant uncertainty for predicting our long-term future isn't the US elections, it's the top quark mass...

Conclusions

The Top-Higgs Relationship

The top quark played a crucial role in Higgs physics right from the start, dominating the Higgs discovery...



from start to finish,

and this relationship will continue for as long as we strive to understand the Higgs.

What are the microscopic origins of the Standard Model?

How does the Higgs behave at short distances?

What is the destiny of the Universe?

Ask the Top Quark.