Higgs theory review

EPS-HEP 2021

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Outline

The cosmological Higgs

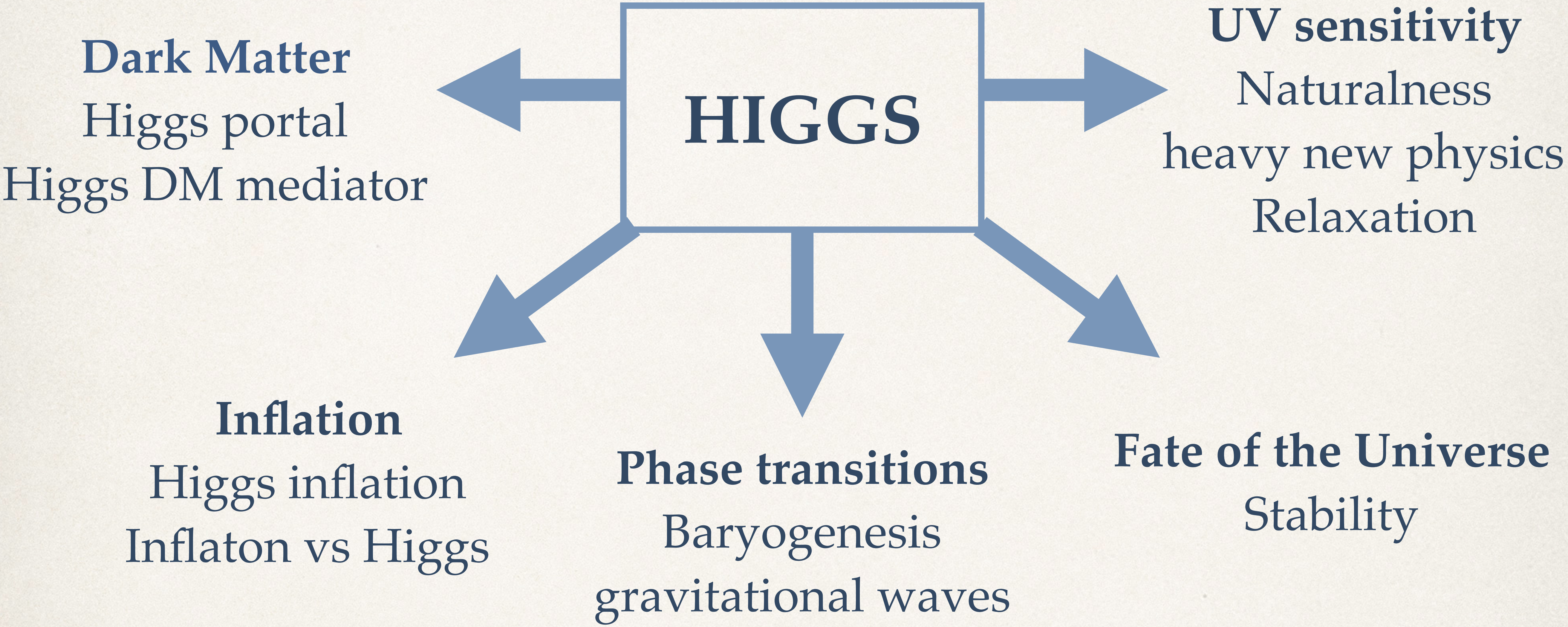
The issue with scalars

Supersymmetric and Composite Higgses

Indirect BSM searches through Higgs precision

Challenges with indirect searches

A cosmological Higgs



HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

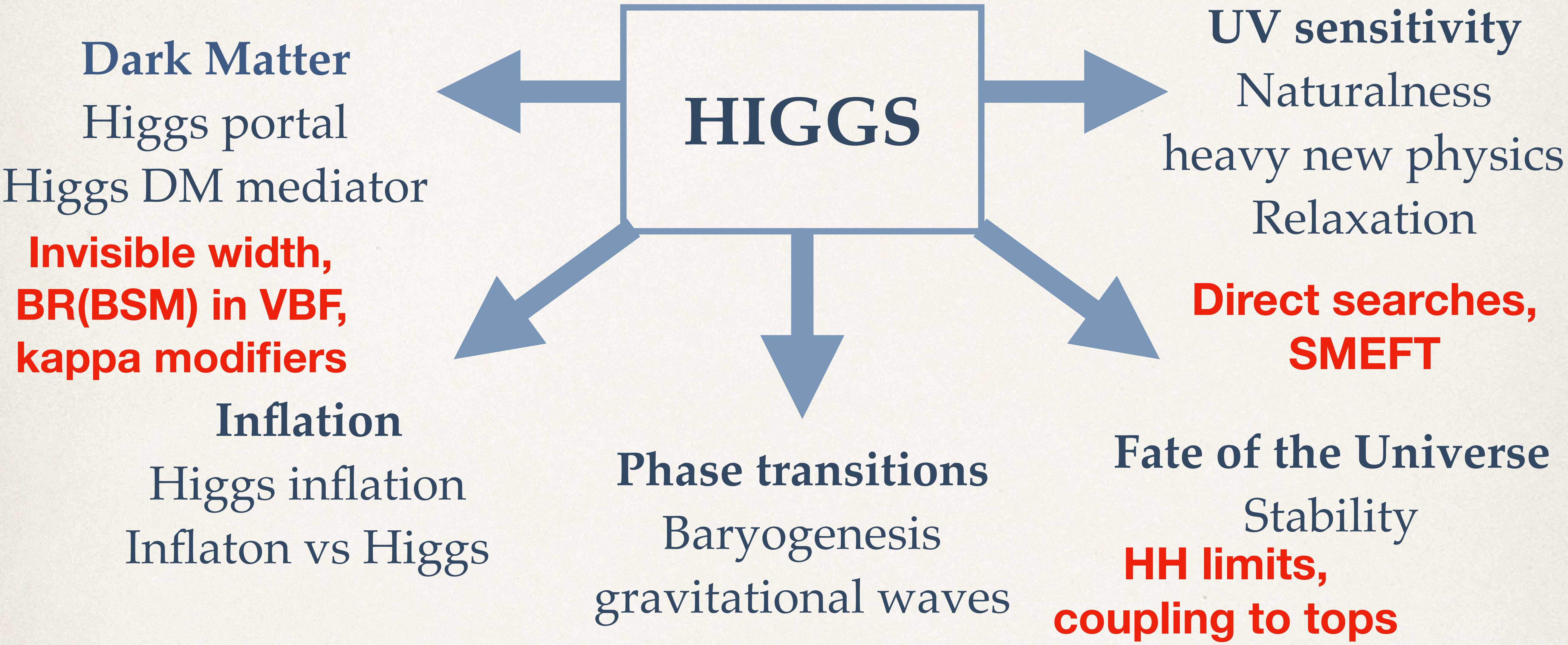
Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

The LHC provides the **most precise, controlled** way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

A cosmological Higgs



HIGGS

Dark Matter
Higgs portal
Higgs DM mediator
Invisible width, BR(BSM) in VBF, kappa modifiers

UV sensitivity
Naturalness
heavy new physics
Relaxation
Direct searches, SMEFT

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Higgs inflation
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Fate of the Universe
Stability
HH limits, coupling to tops

The LHC provides the **most precise, controlled** way of studying the Higgs and direct access to TeV scales

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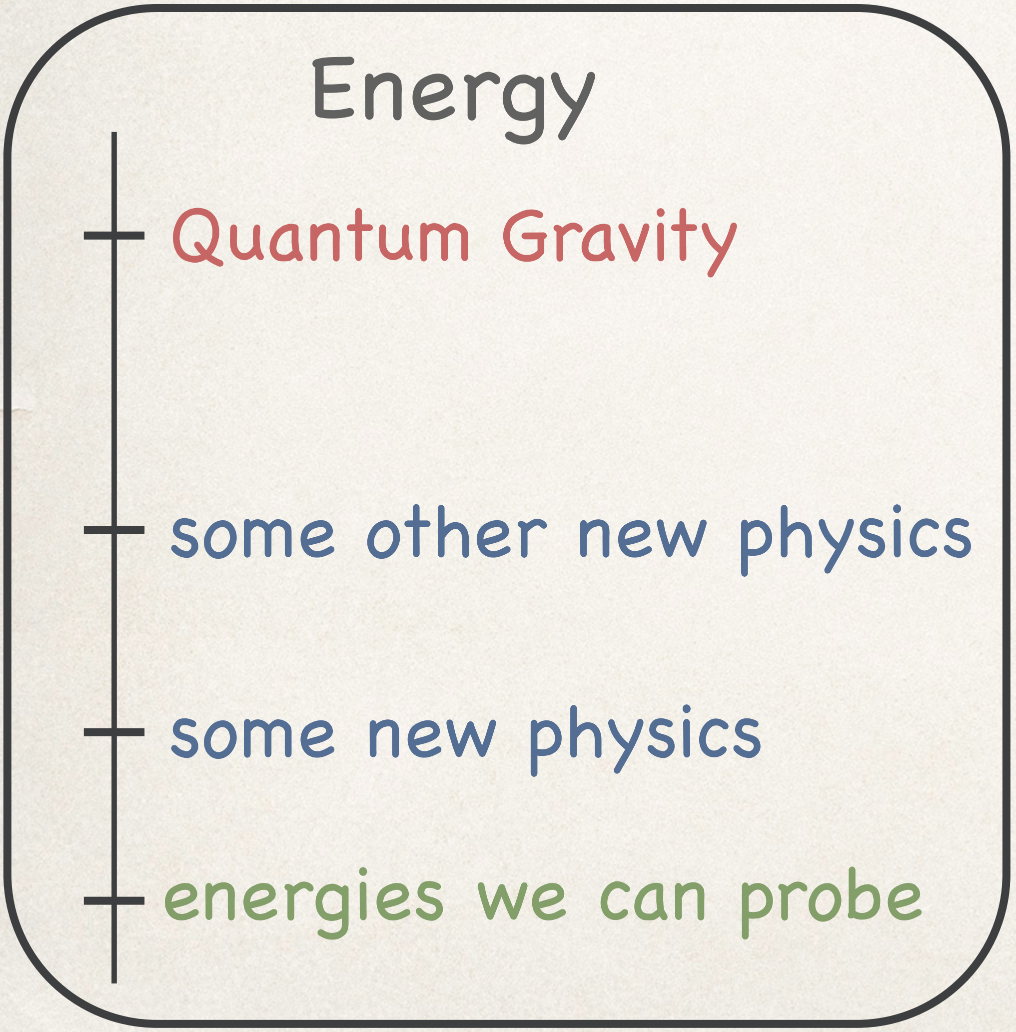
Why is the Higgs such a rare creature

Naturalness

Predictive theory: quantum mechanical. In QFT, physical quantities *run*
mass term in a Lagrangian, quantum corrections

$$\mathcal{L}_m = -m_\Psi \bar{\Psi}\Psi - m_\phi^2 \phi^2$$



Energy

Quantum Gravity

some other new physics

some new physics

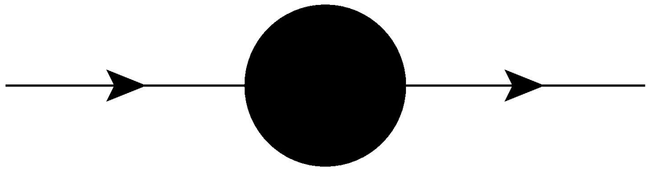
energies we can probe

Fermions

Massless fermion, additional symmetry

$$\Psi \to e^{-i\gamma_5\theta}\Psi$$

if this chiral symmetry is preserved QM



$$\delta m_\Psi \propto m_\Psi \, \log(\mu_1/\mu_2)$$

chiral symmetry protects fermions
masses from large UV corrections
Light fermions are technically natural

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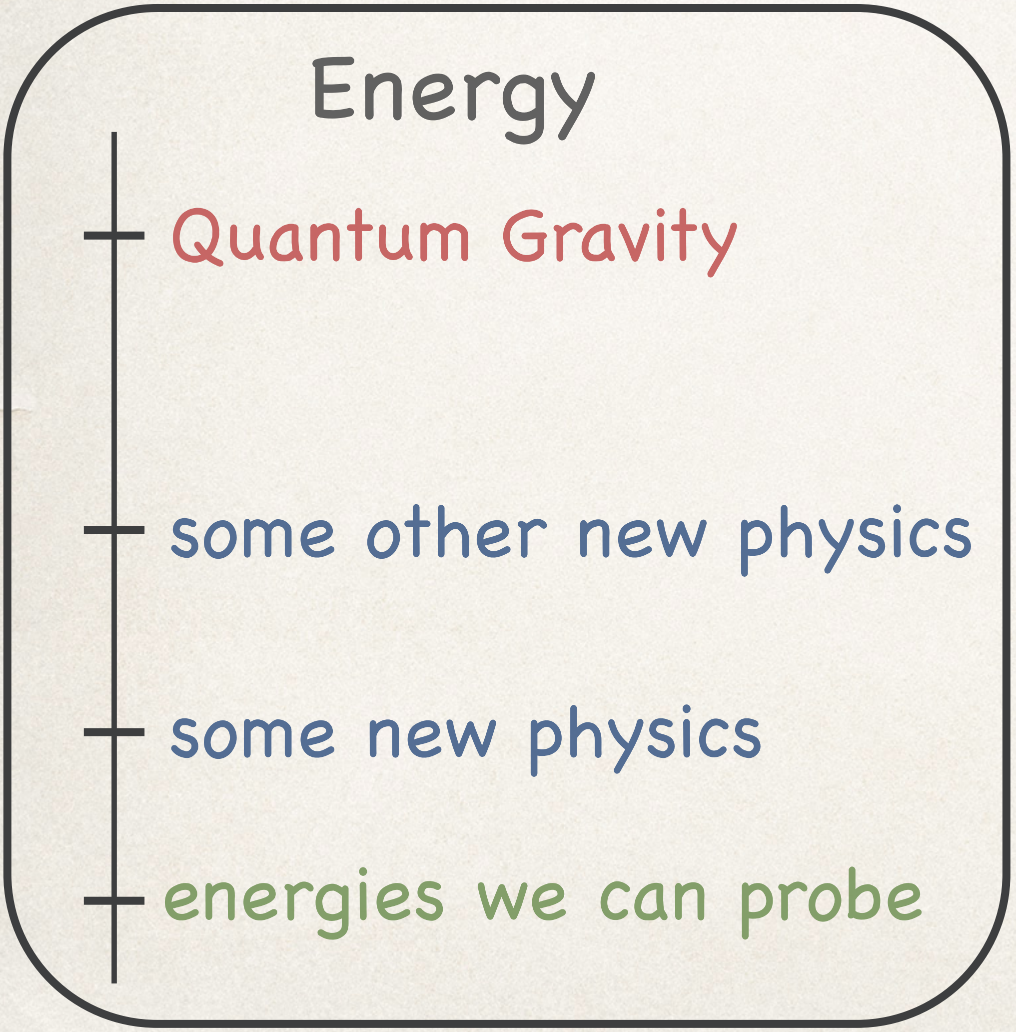
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Scalars

Massless scalar, scale invariance

This classical symmetry is not preserved
QM (is anomalous)

scalars are not protected by a symmetry, are UV sensitive, natural value for the mass is the highest scale it couples to

Light scalars are **unnatural**

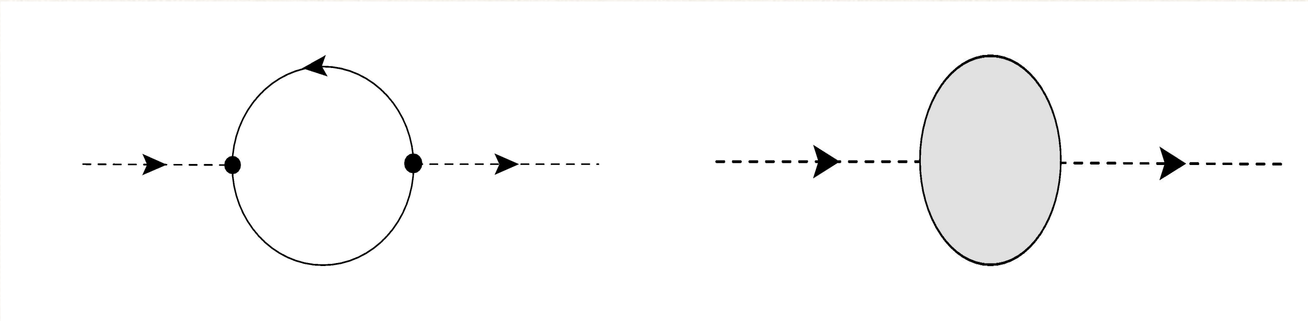
Rationale for New Physics

Example: Naturalness

Energy

- Quantum Gravity
- some other new physics
- some new physics
- energies we can probe

Quantum corrections to scalars



threshold corrections

QGrav

$$\delta m_\phi^2 \propto c_1\, \Lambda_{NP}^2 + c_2\, M_{Pl}^2$$

(Physical mass)^2 = (bare mass)^2 + (unsuppressed Qcorrections)^2

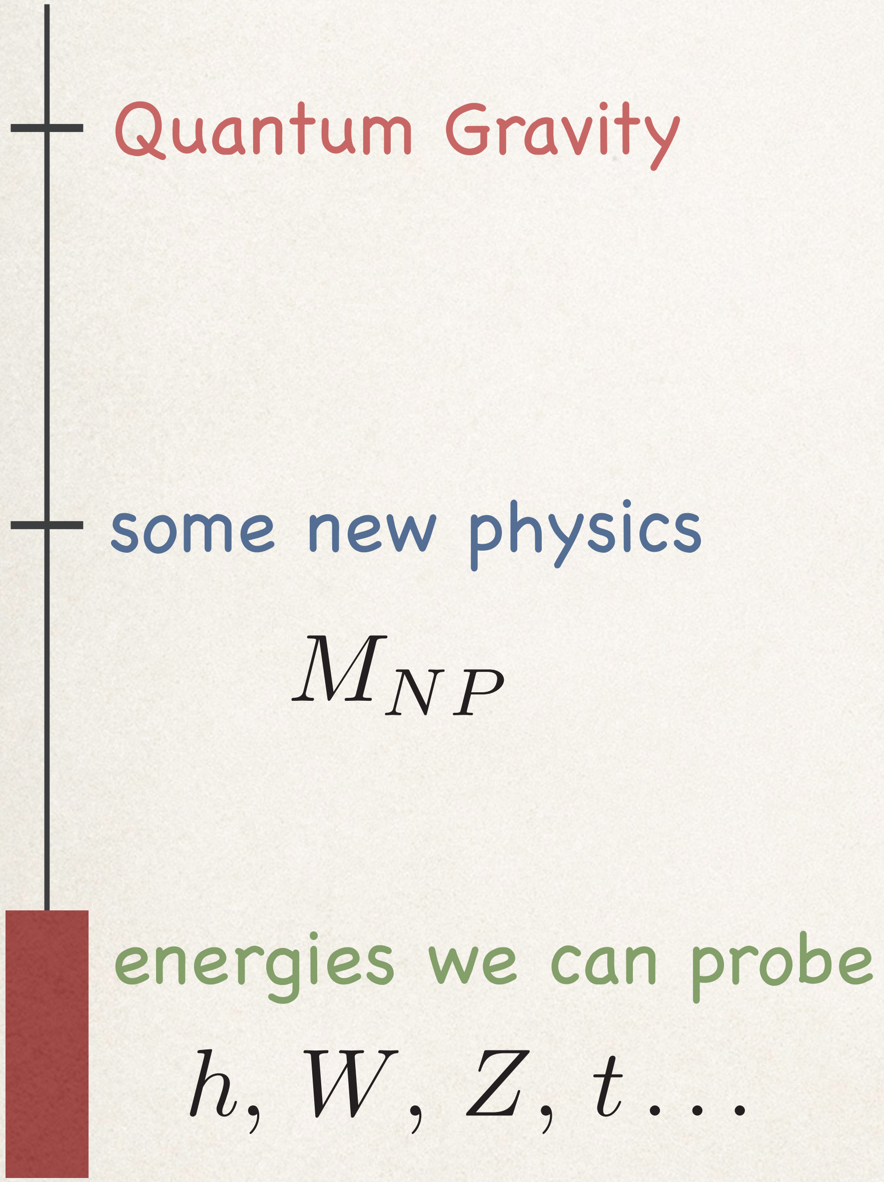
light scalar = enormous fine-tuning

The Higgs is a scalar, and there is no sight of new physics so far

Should we just live with it?

Back to the Higgs

The Higgs is a very special creature in the SM:
a fundamental and light scalar



Quantum Gravity

some new physics

M_{NP}

energies we can probe

$h, W, Z, t\ldots$

$$\boxed{\delta m_h^2 \sim M_{NP}^2 \Rightarrow m_h^{phys} \sim M_{NP}}$$

unless

1. There's *nothing* (DESERT)

2. Something *special* happens

2i.) fine-tuning (small=huge-huge)

$$m^2_{h,phys} \simeq m^2_{h,bare} + \delta m_h^2$$

2ii.) new symmetries

$$\delta m_h^2 \propto \text{ parameter breaks the symm}$$

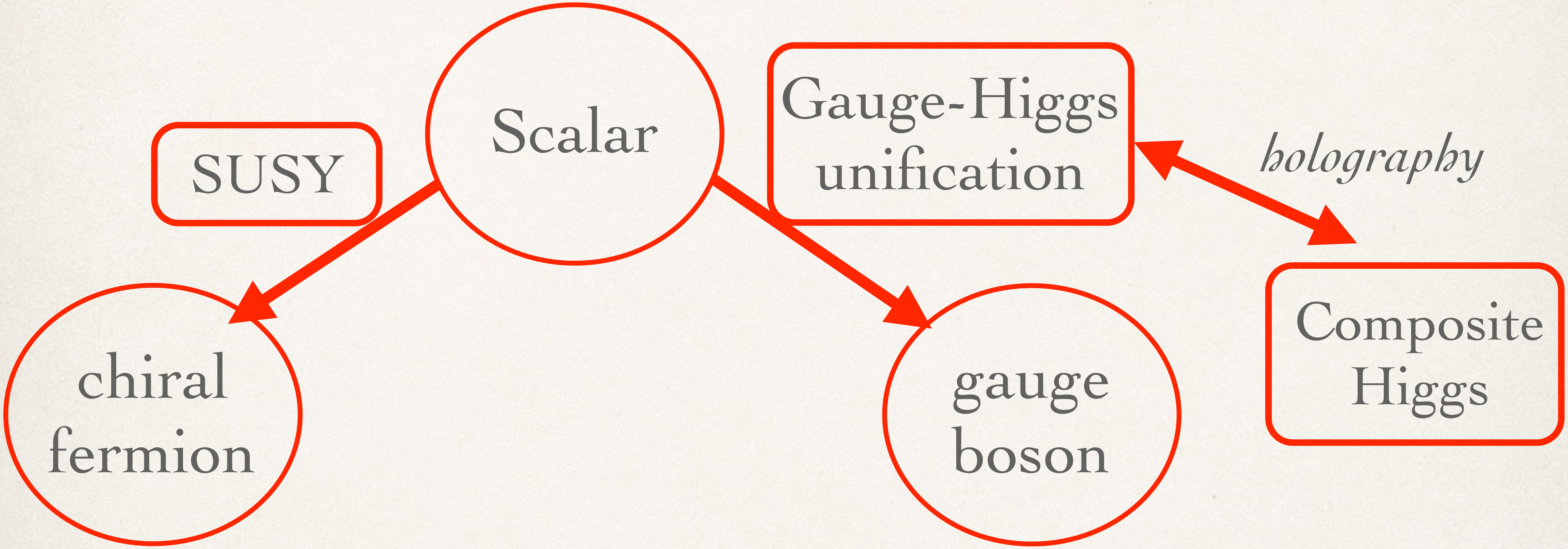
2iii.) dynamics

scalar=bound state of fermions or gauge fields

Light scalars

The light Higgs is a reality since 2012

symmetry/duality arguments to explain its nature



Scalar

SUSY

chiral fermion

Gauge-Higgs unification

gauge boson

holography

Composite Higgs

Many, many possible realizations (phenomenology)

Predict new states, to be discovered

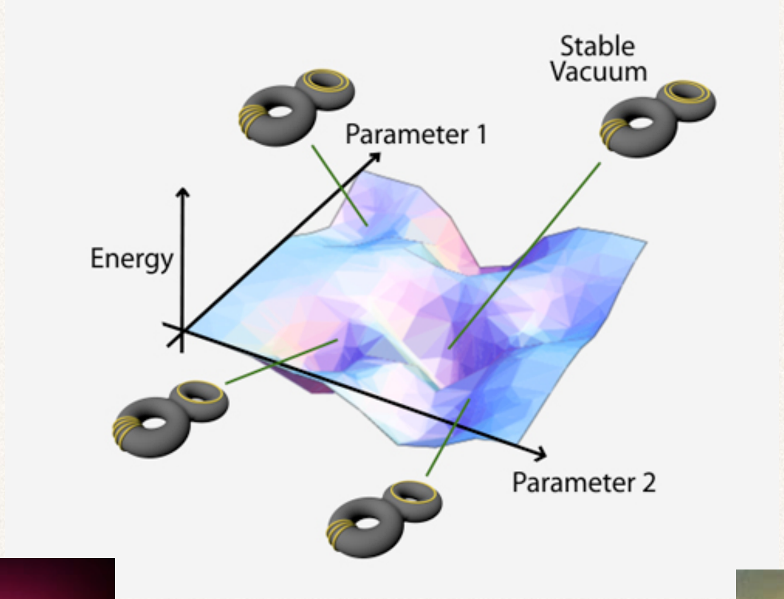
(SUSY partners, techni-baryons and mesons, spin-two…)

AND induce deviations in the Higgs behaviour

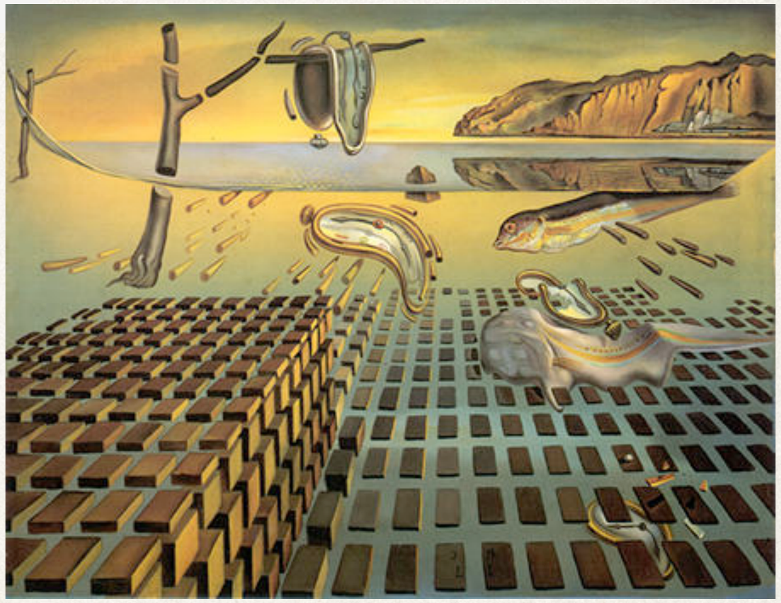
The nature of the Higgs is still a mystery

What fundamental principle could be behind this behaviour?

Landscape of String Theory?



Something like Superconductivity?



New dimensions? Supersymmetry?

Supersymmetry

Symmetries

We build field theories imposing symmetries on the action

Example s=0, 1/2, 1, 2

Klein-Gordon, Dirac, Yang-Mills, Fierz-Pauli

great ref: Landau-Lifshitz ClassFT

What is possible or not depends on whether a symmetry can be written for it

Coleman-Mandula **no-go theorem** [1962]:

Lie Algebra $=$ Poincare $\otimes$ Internal

symmetries of S-matrix

(space-time, internal)

=> internal and external (s-t) symmetries do not talk to each other

Supersymmetry (SUSY)

Supersymmetry is a way around that
abandons the Lie group framework
internal generators = > fermionic **Q**
super-Poincare algebra

SUSY has important consequences

Q | B > = | F >
Q | F > = | B > *

Fermions and bosons are no longer two separate worlds

Normal field B or F -> SUSY field is both

e.g. Higgs -> SUSY Higgs $(H, \tilde{H})$ Higgs (s=0)+Higgssino (s=1/2)

BUT all fields in superfield are *degenerate*

=> Higgs should come with a 125 GeV fermion

**being sloppy with daggers*

SUSY breaking

=> Higgs should come with a 125 GeV fermion

=> electron should come with a 0.511 GeV charged scalar

=> there should be a massless fermion (photino) force mediator

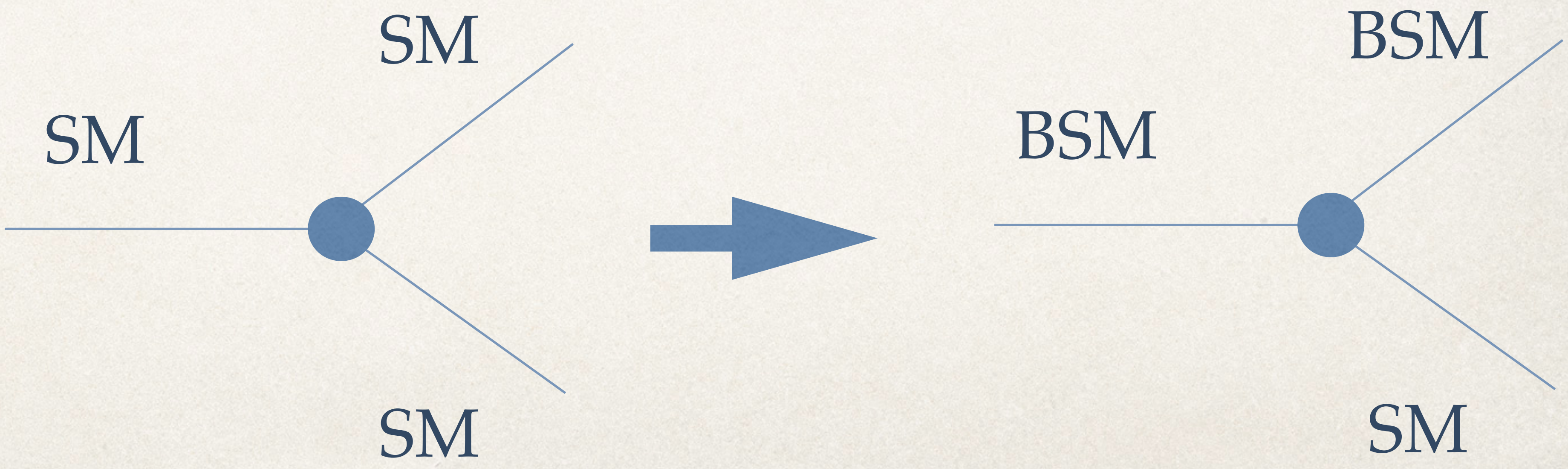
etc, etc

All that is wrong!

Then SUSY must be *broken*=> splitting between partners in the superfield of order the SUSY breaking scale

if SUSY is broken, does any symmetry survive?

yes, R-parity



SUSY breaking

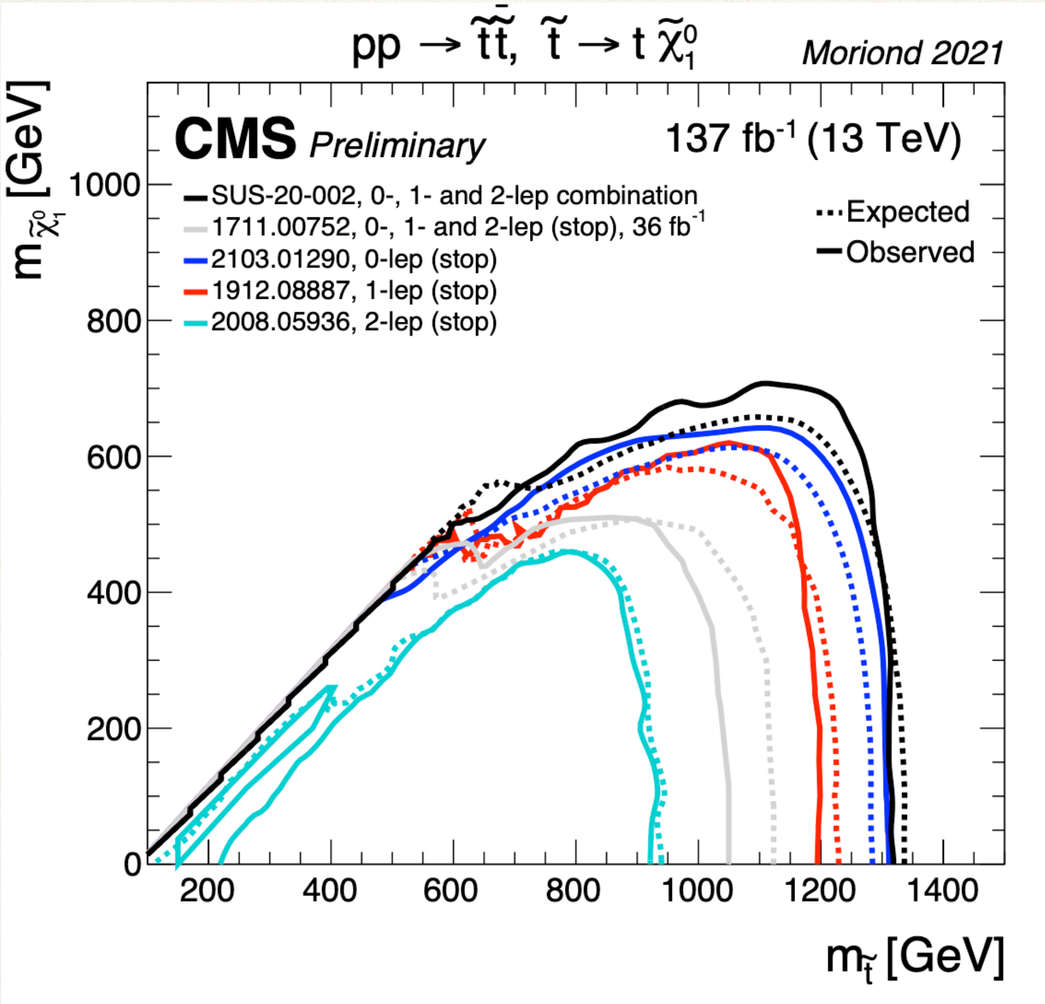
if SUSY is broken, does any symmetry survive?

yes, SUSY is still a good symmetry above SUSY breaking scale

Higgsino : chiral fermion -> protected by chiral symmetry

Higgs -> protected by chiral symmetry at high-energies

$$\delta m_h^2 \propto \text{ parameter breaks the symm } \sim m_{soft}^2 \sim (TeV)^2$$



Higgs is *naturally light* in SUSY as long as the SUSY particles are not too far from the EW scale

Naturalness in SUSY => light SUSY particles

Compositeness

Composite Higgs in a nutshell

As pions in QCD:
light Higgs as a pseudo-GB from spontaneous breaking of a global symmetry

Contrary to pions in QCD:
the Higgs has

1. CP-even properties
2. its potential needs to trigger EWSB
3. it should couple as mass

Contrary to the SM Higgs:
EWSB can be non-linearly realized,
Higgs could be a singlet (not doublet)

Composite Higgs: Quantum numbers

$\mathcal{G} \to \mathcal{H}$

pGBs from SSB

$$\Sigma(x) = \exp(i\sqrt{2}h^a(x)X^a/f)\Sigma_0$$

The CP properties of the resulting pGBs depend on the CP properties of the strong sector

A. **Coupling to gauge**

part of the global sym H is weakly gauged

depends on the embedding

$$\Pi_1(p^2)\Sigma^T A_\mu A_\nu \Sigma$$

B. **Coupling to fermions**

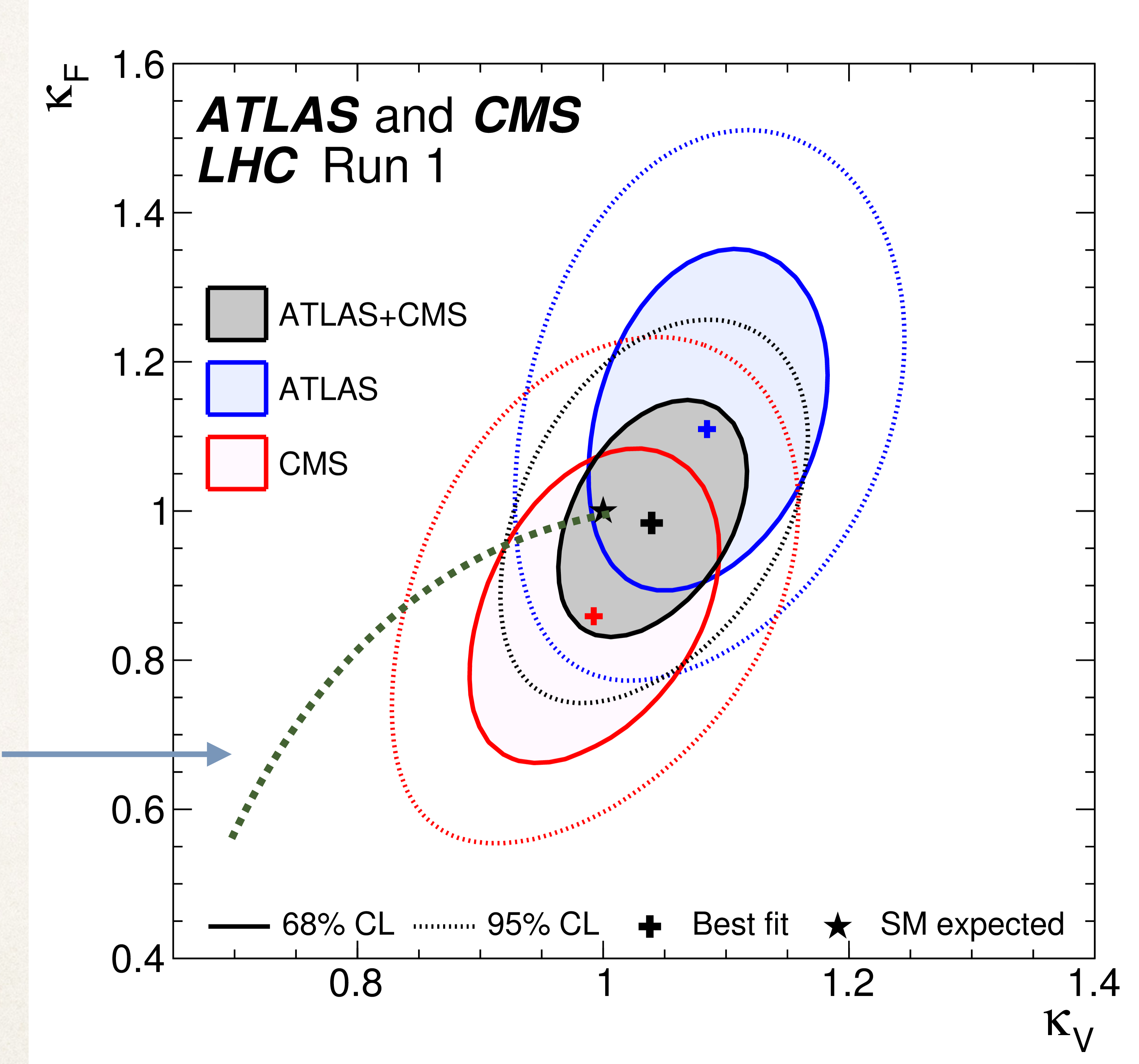
many options for fermion rep

$$\overline{\Psi}\Gamma^i\Sigma_i\Psi$$

choice of global breaking and embedding: **CP-even scalar doublet**

pheno: Non-linear realization, Higgs couplings deviations

Composite Higgs: Quantum numbers



coupling to fermions

coupling to vectors

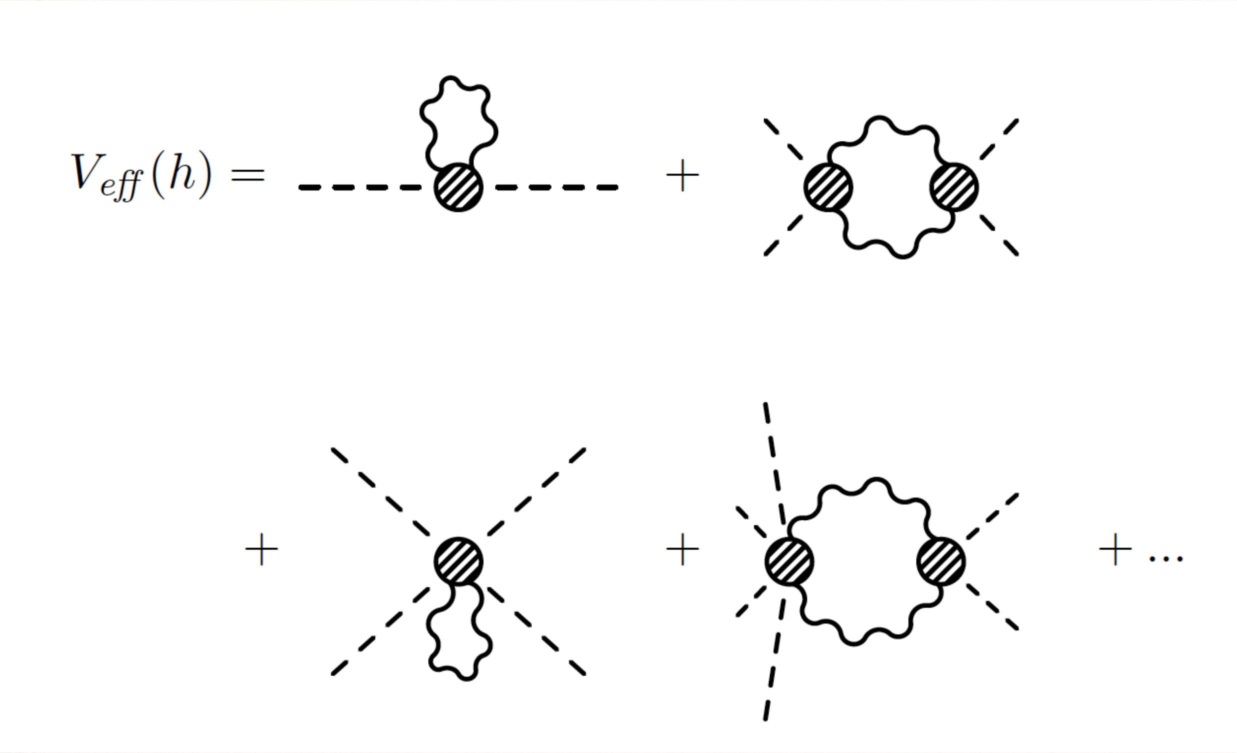
different CHMs
correspond to different lines
the effect decreases as

$$\xi = v^2/f^2$$

Composite Higgs: Potential and EWSB

Usual paradigm:
potential generated via **Coleman-Weinberg** contributions

e.g. GAUGE



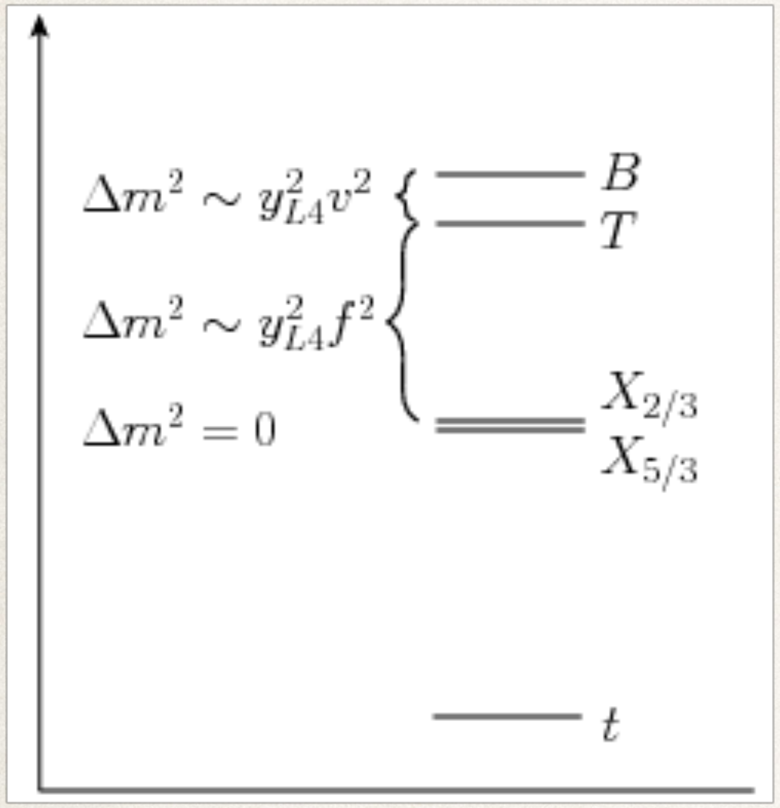
Georgi-Kaplan (80's)
gauge-top *does not* trigger EWSB
need new fermionic resonances
TOP-PARTNERS

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

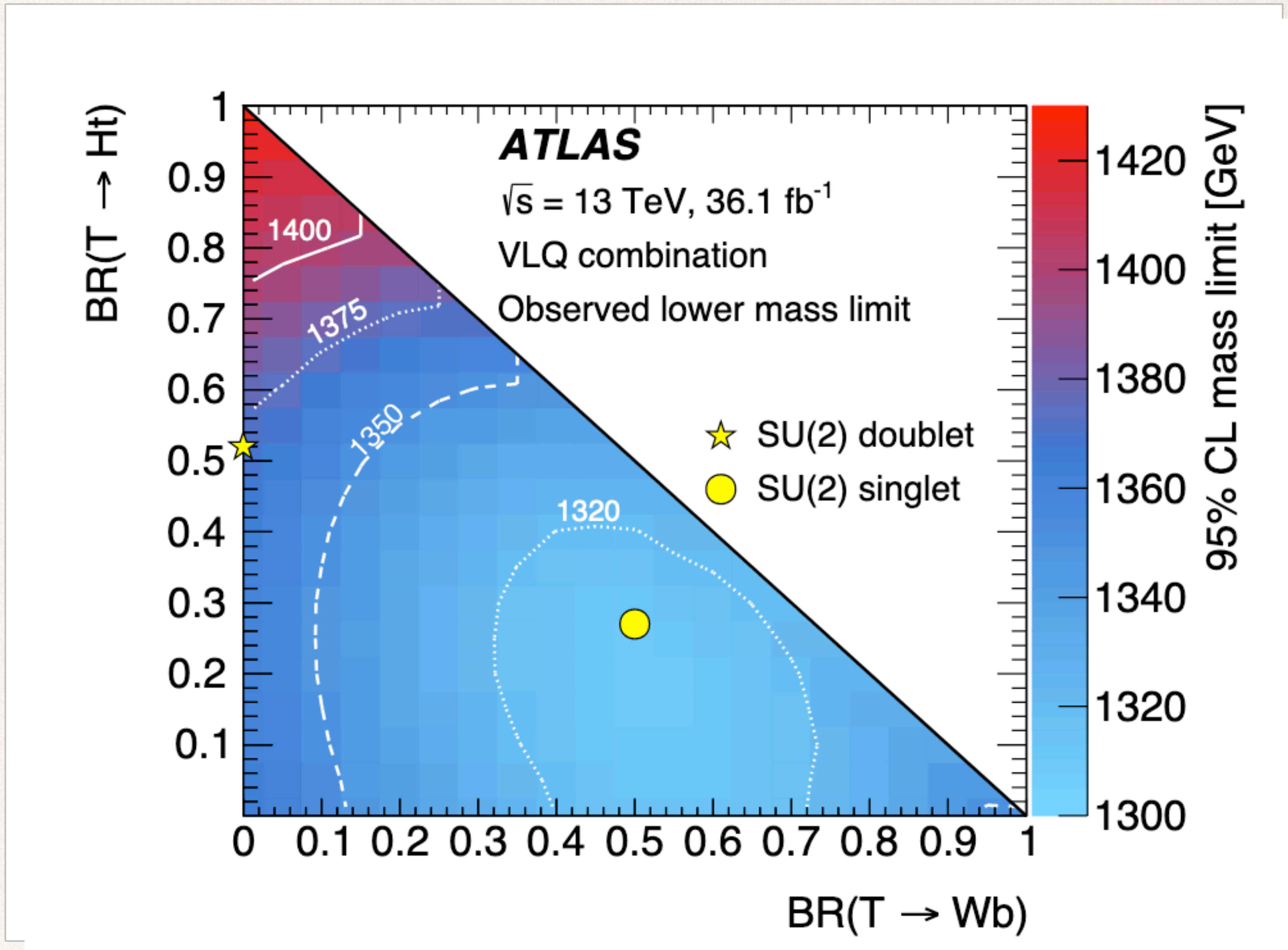
pheno: New, light (below TeV) techni-baryons
should couple to the Higgs, W, Z

Composite Higgs: Potential and EWSB

typical distribution of top-partners



Panico et al. 2016

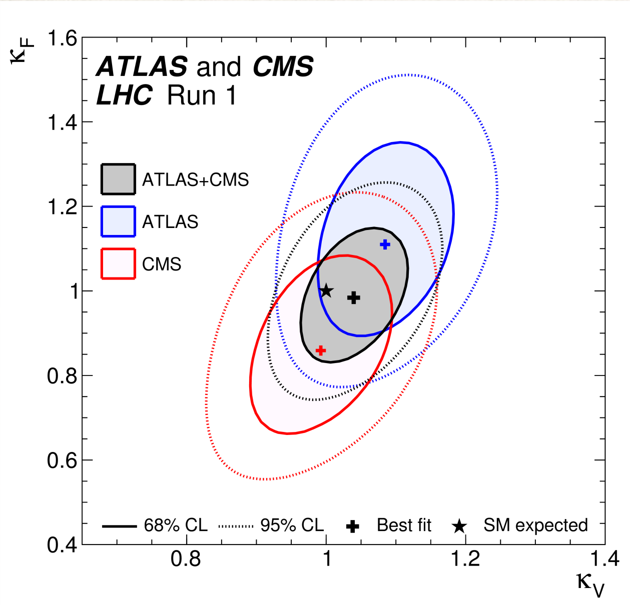


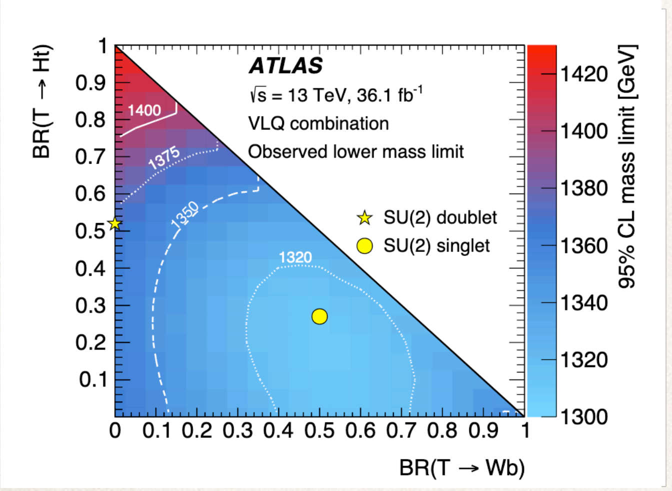
resonances below ~ 1.3 TeV are excluded

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

tuning in the Higgs potential severe

Status in model-building





Given the experimental constraints,
lack of deviations in the Higgs behaviour and
absence for new composite fermions
interest in more natural (non-minimal) models

e.g. new ways to trigger EWSB and fermion mass generation, measure of tuning of the theory, un-coloured fermion resonances…

examples:

EWSB triggered by other scalars: see-saw CH

VS, SETFORD. 1508.06133

new symmetries in the global sector: Maximally symmetric CH

CSAKI, MA, SHU. 1702.00405

Casting a wide net: the *new* SM

EFT approach

Well-defined theoretical approach

Assumes New Physics states are heavy

Write Effective Lagrangian with only light (SM) particles

BSM effects can be incorporated as a momentum expansion

dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

BSM is a **perturbation** around the SM

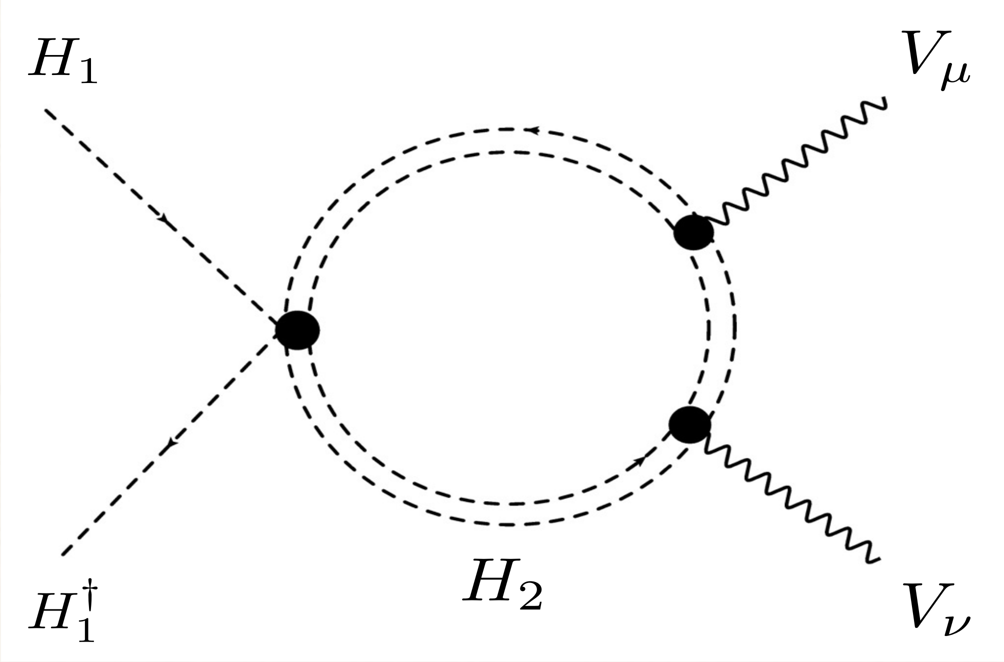
Each operator can be improved at higher orders in QCD and EW corrections

EFT from UV models

As long as the new states are heavy, one can **integrate them out**

example:

2HDM



compute the integral
expand of external momenta
below the mass

GORBAHN, NO, VS. 1502.07352

first terms on the expansion are a number of dimension-six operators e.g.

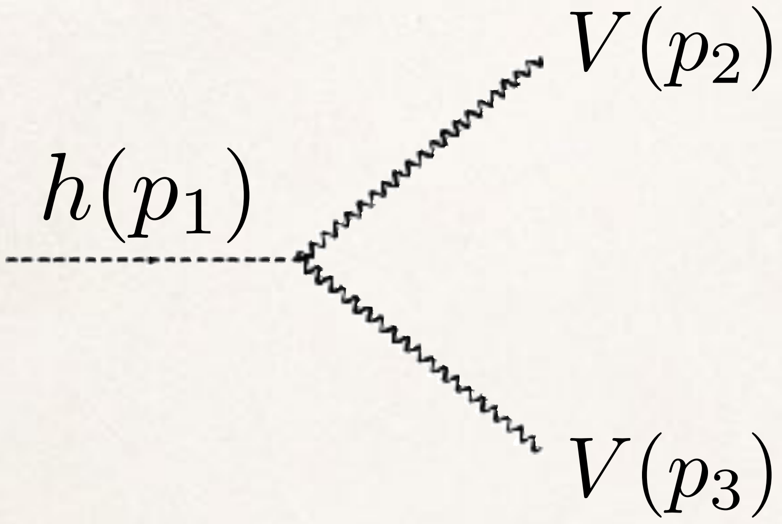
$$\boxed{\frac{ig}{2m_W^2}\bar{c}_W}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} \qquad \text{where } \bar{c}_W = \frac{m_W^2\,(2\,\tilde{\lambda}_3+\tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$$

next term in the expansion: dimension-eight

Differential information is key

Models offer richer kinematics than the kappa-formalism and the EFT approach captures them

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

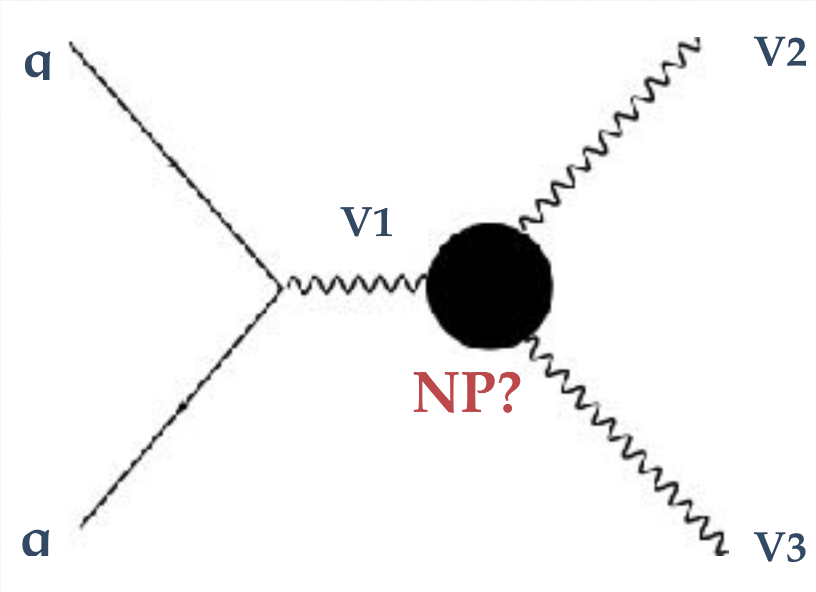


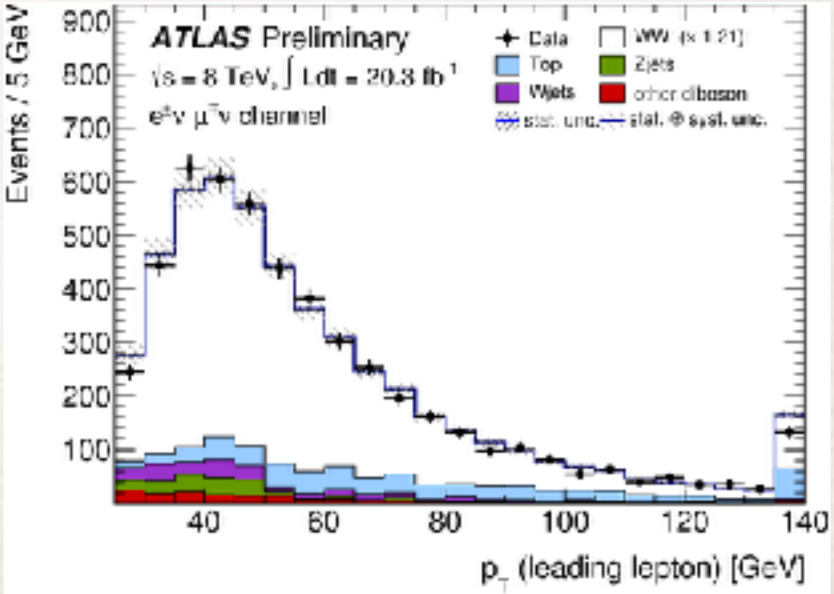
$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

$$-i g^{(1)}_{hVV} p_3^{\mu} p_2^{\nu} \quad -i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

+ *off-shell pieces*

exploited in searches for anomalous **TGCs**





Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

$$\bar{c}_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right]\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right)\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2)\,\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$c_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

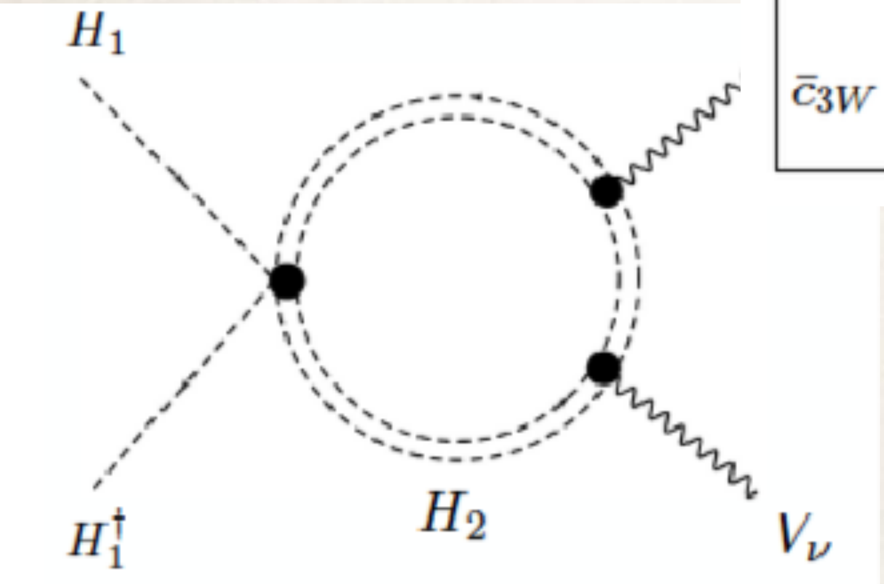
$$\bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = \frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + m_W^2\,\tilde{\lambda}_4$$

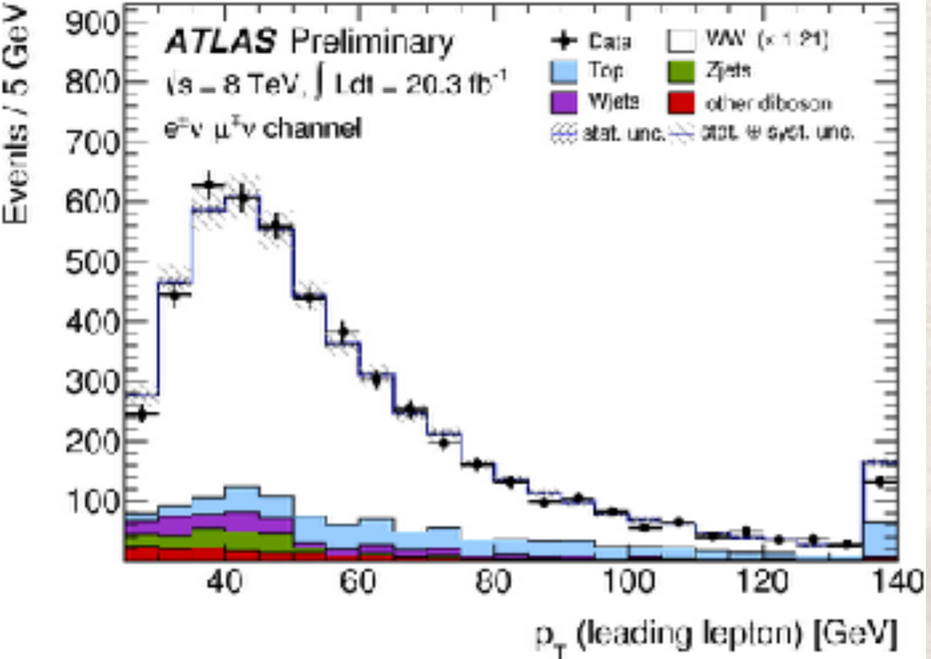
$$\bar{c}_{3W} = \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde{\mu}_2^2}$$

Gorbahn, No and VS
1502.07352, JHEP

MODELS



DATA

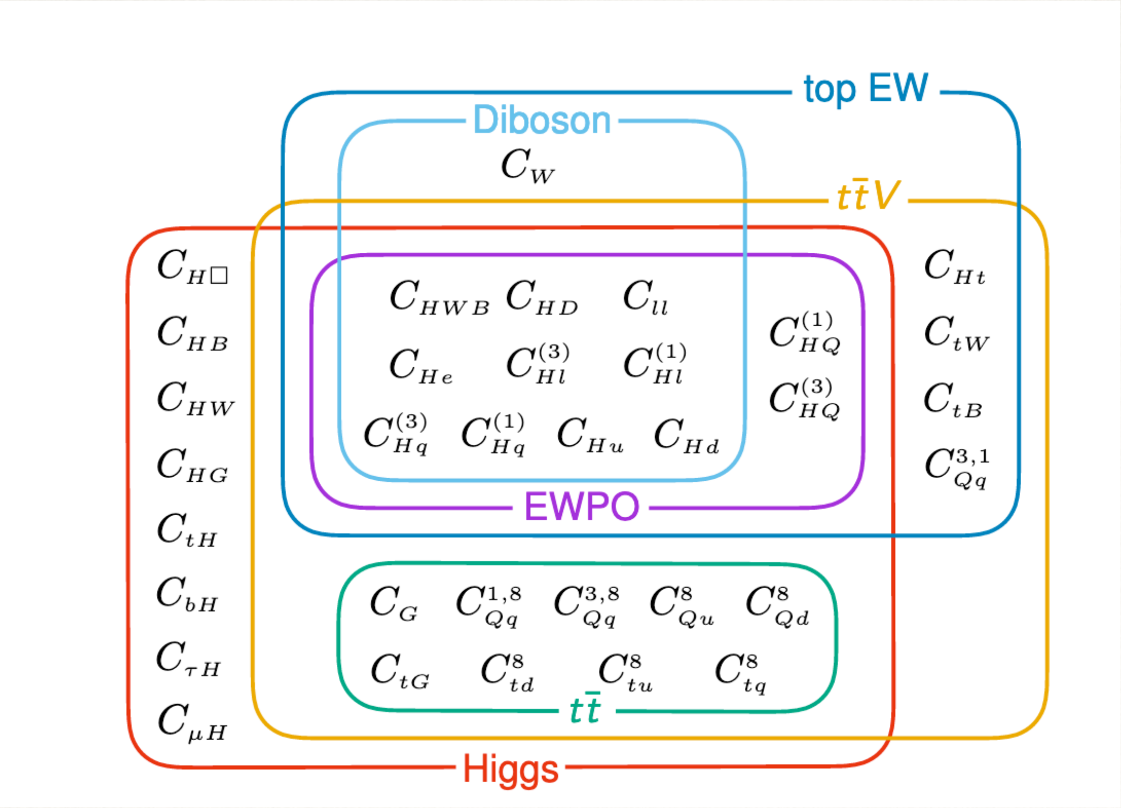


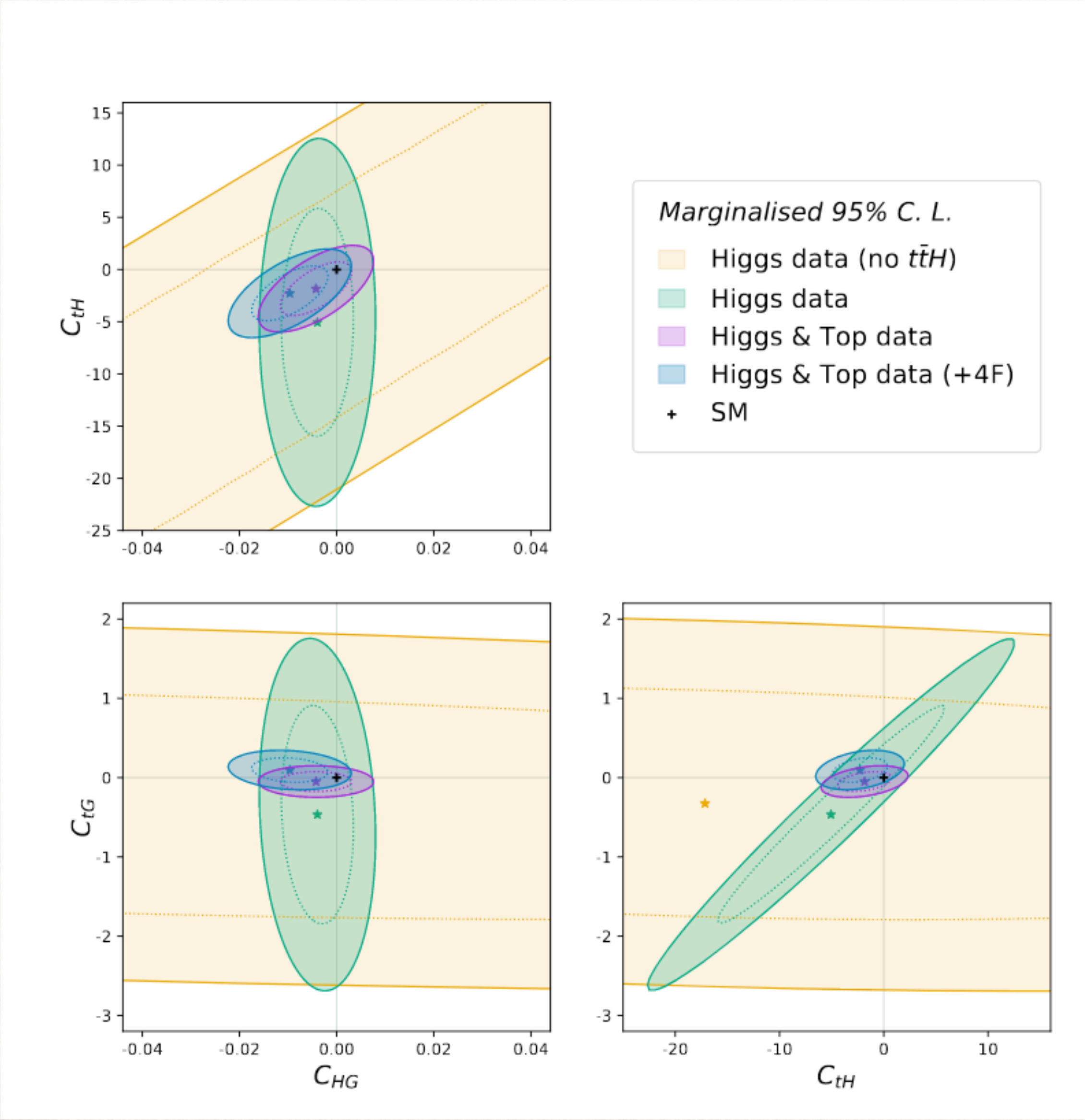
Advantages

- **Combination**: LHC Higgs and EW production, low energy, EWPTs
- **Precision:** higher-order EW and QCD, dimension-eight, chiral logs
- **Consistency:** Backgrounds and signal
- **Reduces model biases:** explore theories beyond known paradigms
- **Matching:** Direct connection to models

Disadvantages

- **Assumptions**: Only SM light states
- **Complexity:** Large number of parameters
- **Validity:** EFT cannot be used in regions of energies ~ scale of new resonances





Ellis, Madigan, Mimasu, VS, You
2012.02779, JHEP

A truly global EFT analysis is possible with Run2 data (+LEP)

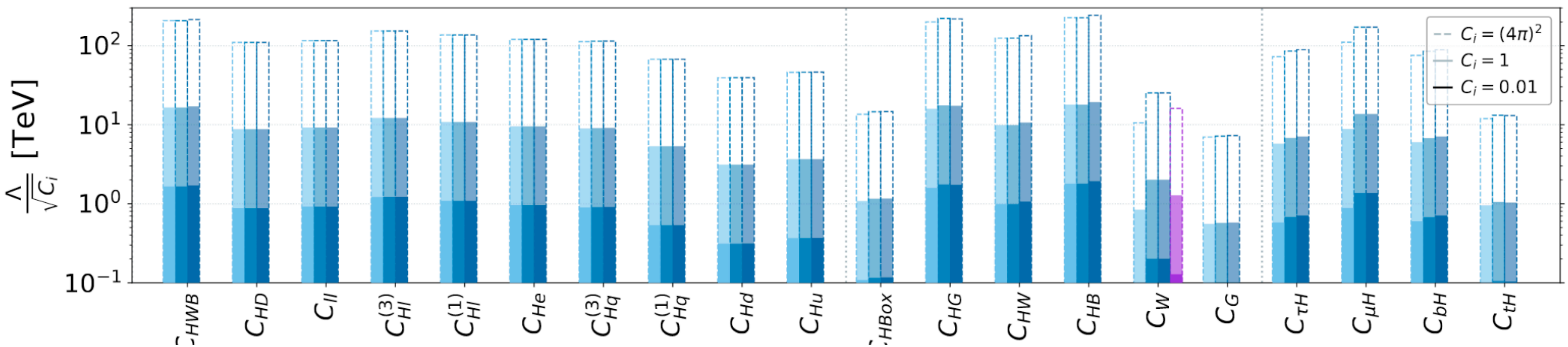
We performed the most complete global fit with Higgs+Diboson+Top+4F data (341 observables) against 20 (MFV)/34 (top-specific) operators

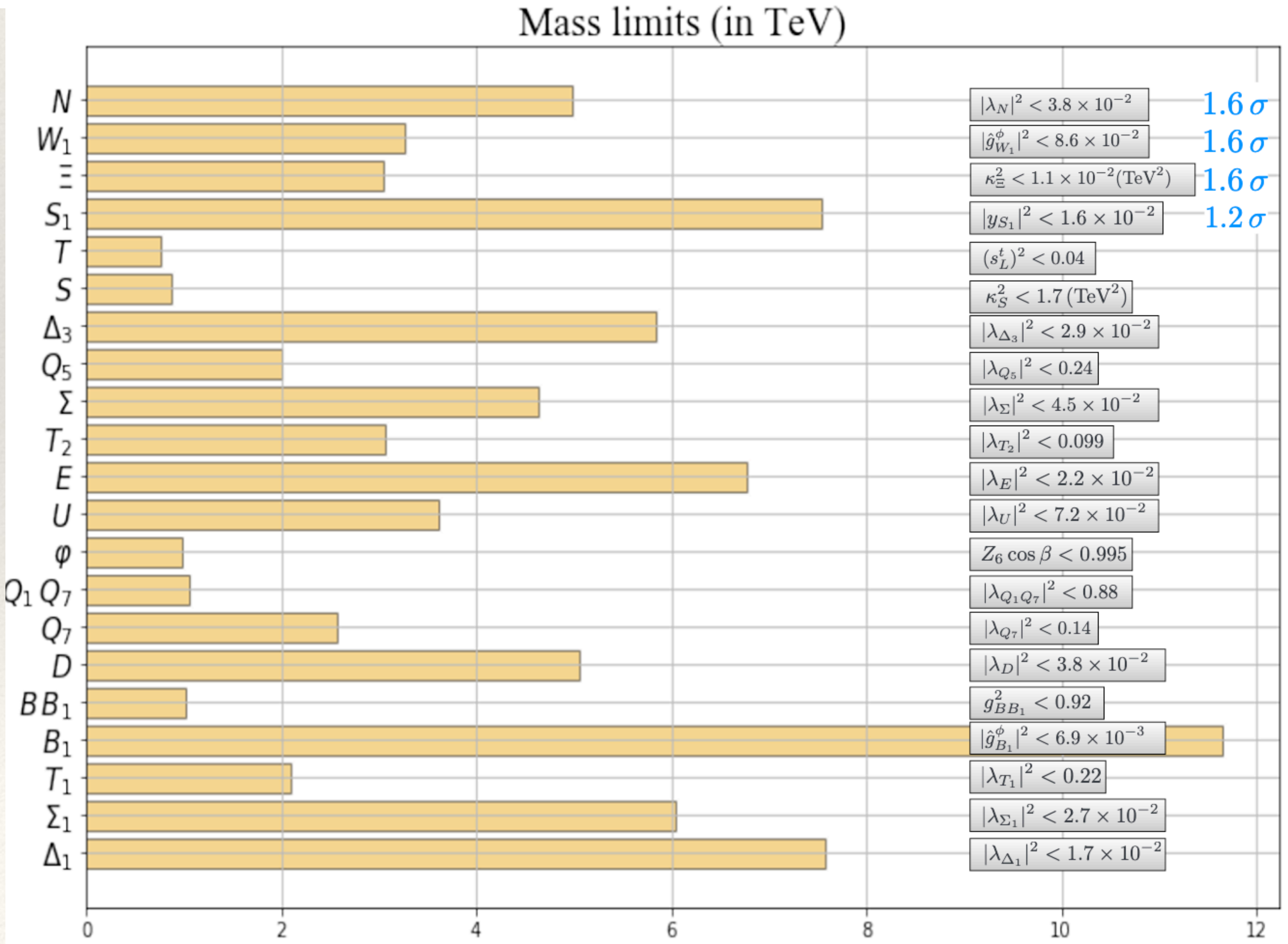
This is an example of the interplay between Higgs (green) and Higgs+Top (pink) information

These *combinations*
and *public* frameworks to do fits
(like our ***Fitmaker***)
are going to become state-of-the-art

Current SMEFT constraints reach the TeV for most of t he param space

Ellis, Madigan, Mimasu, VS, You
2012.02779, JHEP





And when translated into vanilla extensions of the SM, the mass limits are also probing the TeV scale

Lots of work needed to advance this area: higher-order calculations, optimisation of strategies, better exp understanding of correlations…

Challenges

1. Theory biases

Is the EFT framework really *model-independent?*
Not completely
e.g. In non-linear realisations of EWSB
the Higgs could be a **SINGLET**
as opposed to the doublet case

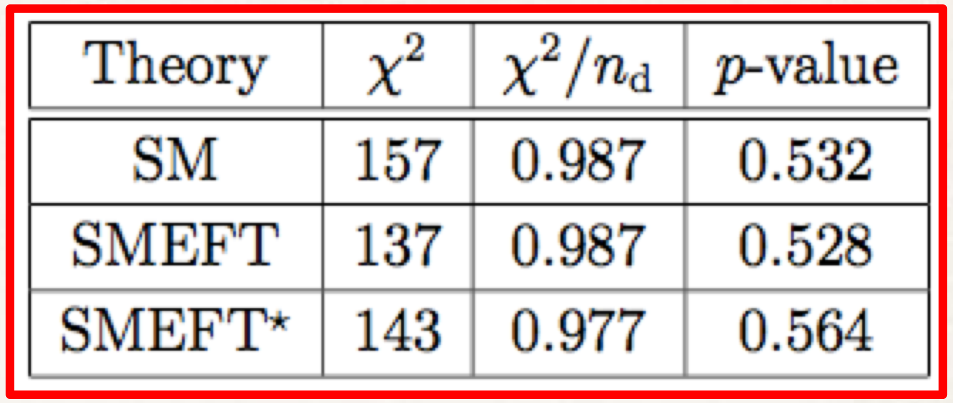
Higgs = (vev + higgs particle + W/Z dofs)

CONSEQUENCES
*de-correlation of Higgs and VV
*EFT expansion changes

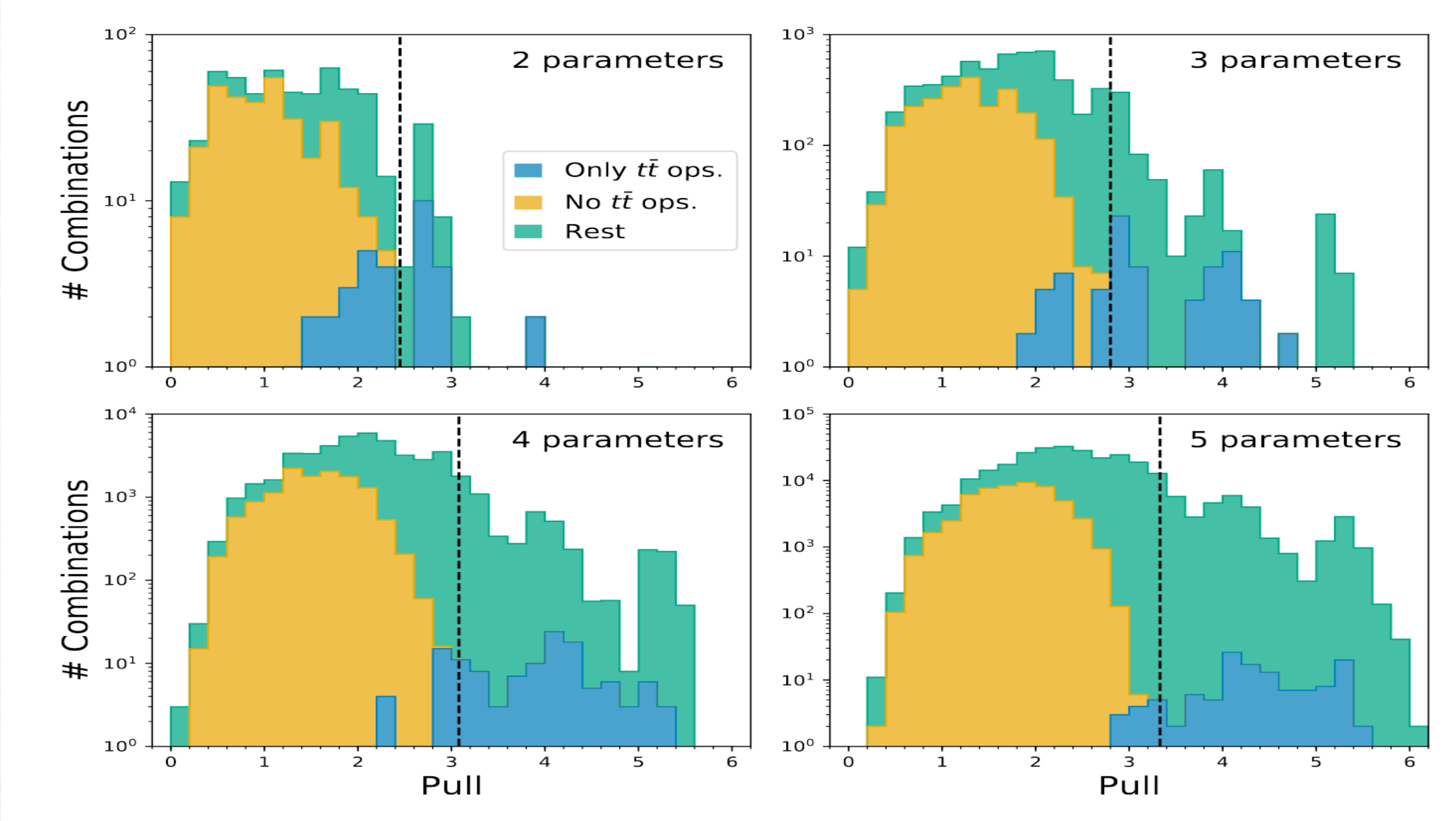
EFT provides a *large enough* set of deformations from the SM serves the purpose of guiding searches and interpretation in terms of UV models

2. Parameter complexity

BUT EFT's extra parameters
constrained by current measurements
Data can't favour SM yet

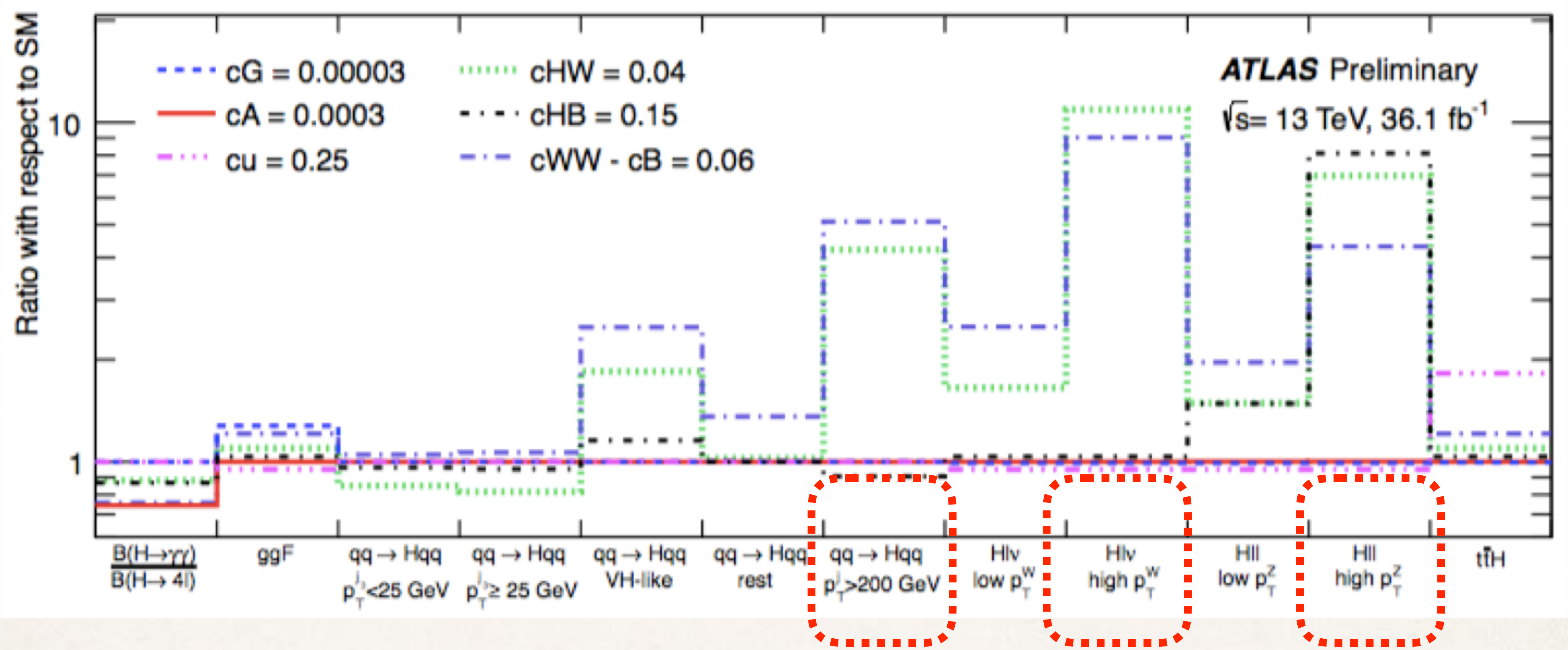


Theory	χ^2	χ^2/n_d	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564



Combination of many channels is key—> GLOBAL FITS

3. *Extreme* kinematics



In these regions our theoretical/experimental understanding is weaker

e.g. WW at high-pT (large EW corrections)

e.g. Higgs+jet at high-pTH

and the **EFT validity** needs to be taken into account

This problem can be addressed by working harder

Many of us developing MC tools EFT@NLO and dim-8 effects

Summary

The true nature of the Higgs particle is still unknown
a scalar is a theoretical puzzle
and a natural connection to Early Universe
The LHC is *the* place where we produce this particle

Direct searches will continue testing broader sets of models
Indirect searches for NP have gained a lot of traction at the LHC
but advancement requires more intense thy/exp communication

Are there any blind spots in experimental searches?
model-building exploration could inspire them
New opportunities in the precision era for the LHC
SMEFT is a way to exploit it