
Heavy New Physics and Precise Predictions of Higgs Properties: The Decoupling Renormalization Scheme in the THDM

Jonas Lang

BP2

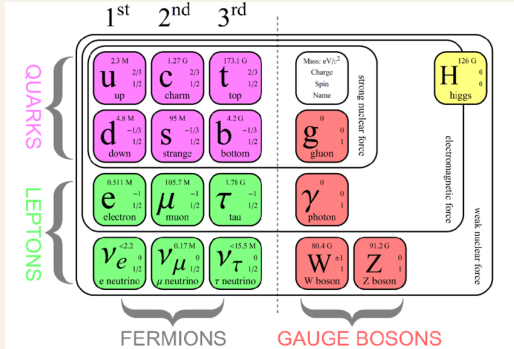
NCBJ

October 7, 2026

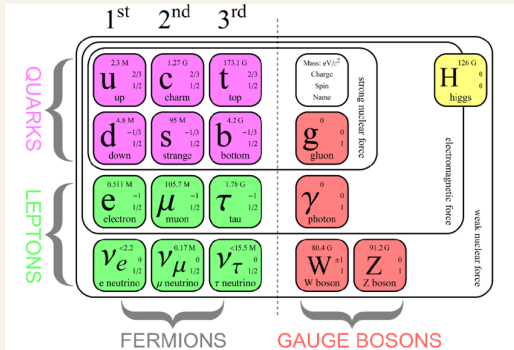
Outline

1. The Standard Model and Its Challenges
2. Renormalization Schemes for Decoupling of Heavy BSM Sectors
3. The THDM and Decoupling at One Loop
4. Results
5. Conclusion

Which short comings does the SM have?



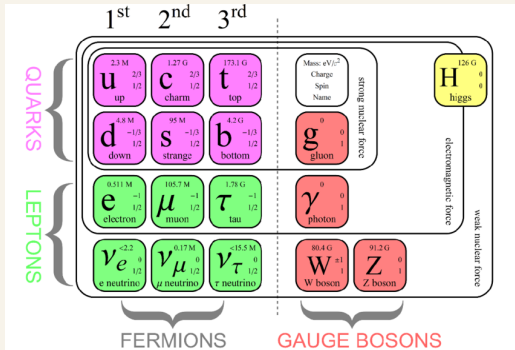
Which short comings does the SM have?



• Flavour Structure

- What determines the number of fermion generations?
- What mechanism generates the observed hierarchy of fermion masses?
- What mechanism generates the observed neutrino mass spectrum?
- ...

Which shortcomings does the SM have?

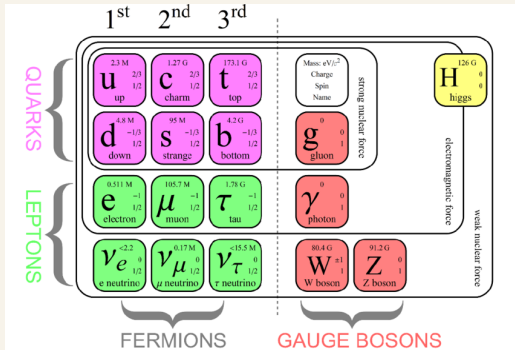


- Flavour Structure

- Baryogenesis

- Where did the matter-antimatter asymmetry come from?
- When did the asymmetry arise?
- Is the Standard Model sufficient to explain the observed asymmetry?
- ...

Which short comings does the SM have?



- Flavour Structure

- Baryogenesis

- Dark Matter

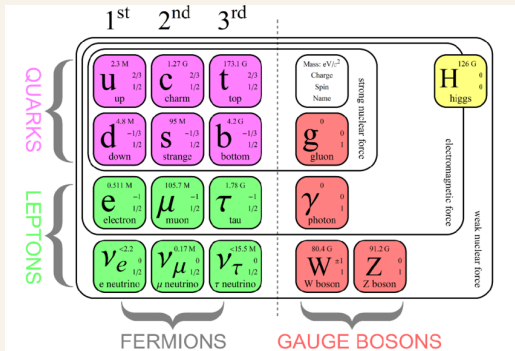
- What is dark matter actually made of?

- How does dark matter interact with ordinary matter?

→ recent exciting news from the LZ-collaboration about dark matter detection

[arXiv:2609.02823](https://arxiv.org/abs/2609.02823) • LZ-Collaboration

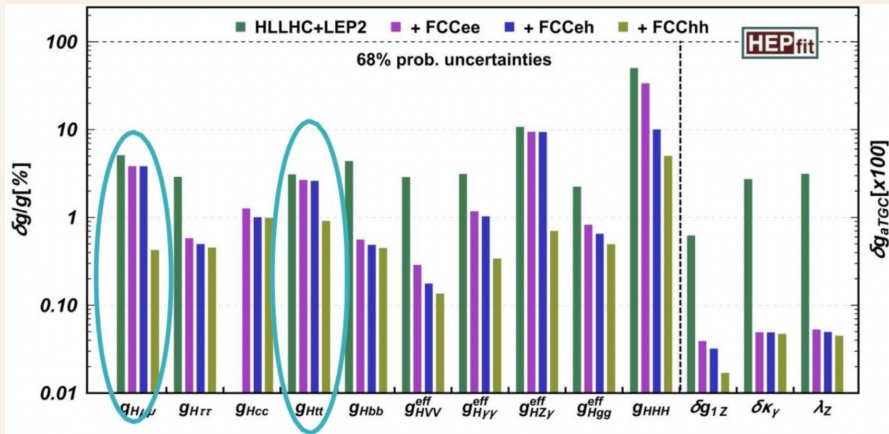
Which shortcomings does the SM have?



- Flavour Structure
- Baryogenesis
- Dark Matter

To solve the questions one ends up with an extension of the scalar sector in one way or another

What do experiments have to say?

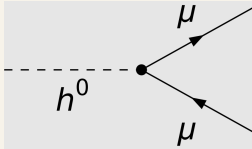


Future experiments turn the Higgs-sector in a precision playground which theoretical calculations need to match

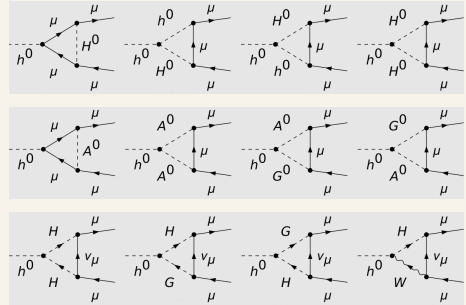
How can theorist predict what happens at (future) colliders?

Improving the approximation on which these predictions are made

$i\mathcal{A} =$



+



Feynman diagrams at one-loop order and higher are generally divergent!

How can theorist predict what happens at (future) colliders?

- Regularization

- extracting divergencies from loop integrals
- standard is dimensional regularization arXiv:2607.08847 • M. Weißwange
- analytic continuation to a dimension in which the problem is solvable and then taking the limit back to 4-spacetime dimensions

How can theorist predict what happens at (future) colliders?

- Regularization

- Renormalization

- consistent connection of theory parameters to physical observables

- $\overline{\text{MS}}$ – Scheme

+ Easy to make calculations → we have up to 5-loop SM results

– Large corrections from heavy BSM sectors
 $\mathcal{A} \propto \log \left(\frac{m_{\text{BSM}}^2}{\mu^2} \right)$

- OS-Scheme

+ Natural interpretation of parameters
+ Natural decoupling behaviour

– Not all models are OS-renormalizable
– Complex expressions for higher loop order

Can we see the importance of loop corrections?

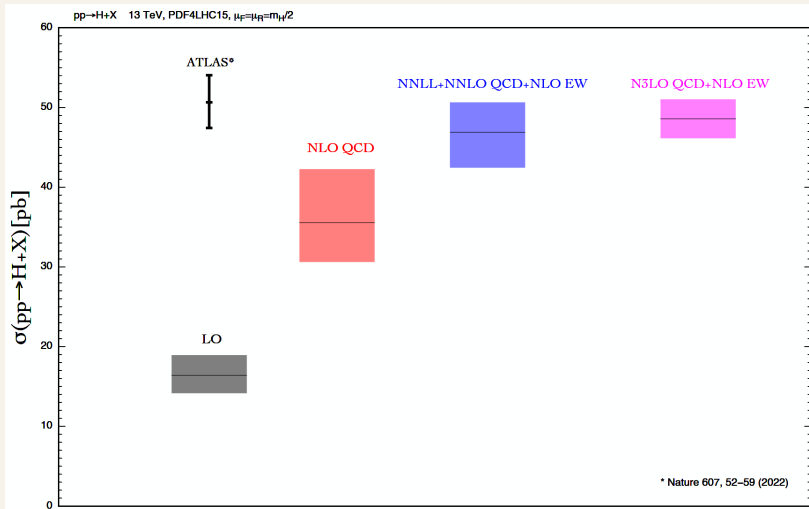


Image • M. Grazzini

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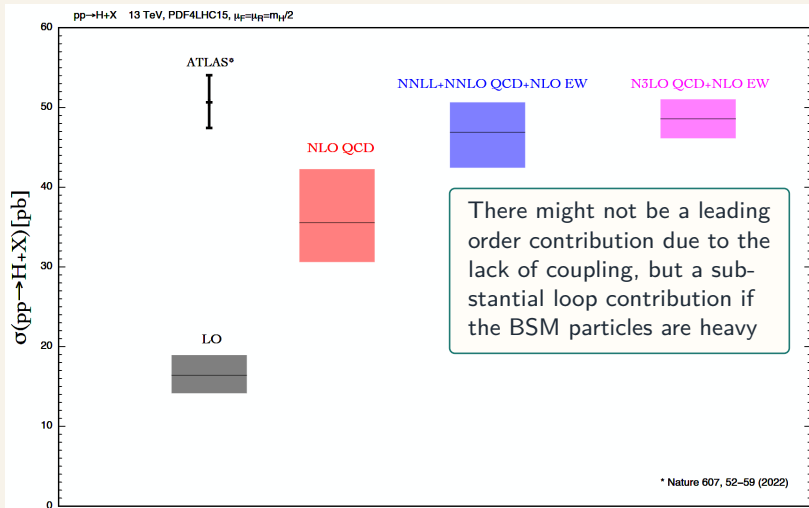
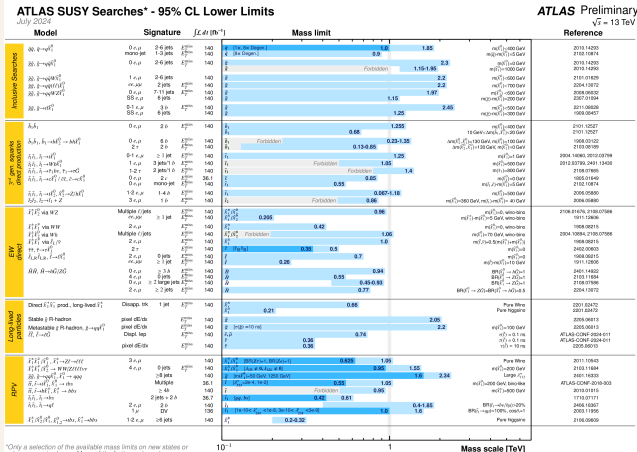


Image • M. Grazzini

What are viable extensions to the SM?



Image © H. Murayama



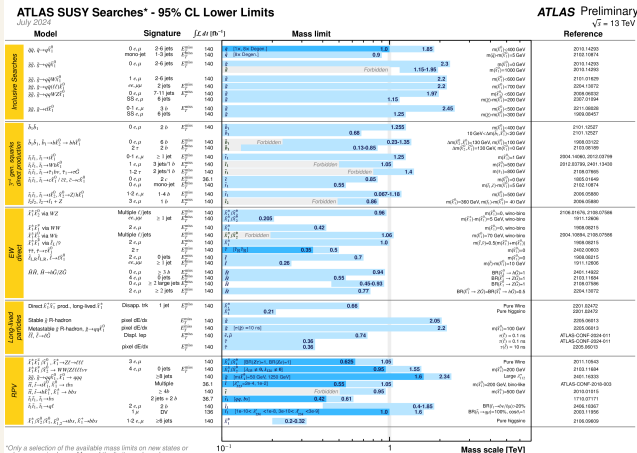
*Only a selection of the available mass limits on new states of phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

What are viable extensions to the SM?

The Decoupling Principle

For $m_{\text{BSM}} \gg \mathcal{O}(v)$, the BSM sector should gradually decoupling from the light SM sector

Image • T. Applequist, J. Carrazzone



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Image • Atlas Collaboration

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Image • T. Applequist, J. Carrazzone

- EFTs

- SM is treated as effective theory
- Valid for $m_{\text{BSM}} \gg \mathcal{O}(v)$
- No BSM fields directly present
- BSM influence appears through higher order operators

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

	Model	Signature	$\mathcal{L}(\text{fb}^{-1}\text{th}^{-1})$	Mass Limit	Reference
Indirect Searches	$00, \bar{0} - \psi_1^0$	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
	$10, \bar{1} - \psi_1^0$	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
	$00, \bar{0} - \psi_1^0 \psi_1^0$	$1.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0 \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
	$10, \bar{1} - \psi_1^0 \psi_1^0$	$1.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0 \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
	$00, \bar{0} - \psi_1^0 \psi_1^0 \psi_1^0$	$0.0, \mu$ 7.11 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0 \psi_1^0 \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
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	$00, \bar{0} - \psi_1^0 \psi_1^0 \psi_1^0 \psi_1^0$	$0.0, \mu$ 14.22 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0 \psi_1^0 \psi_1^0 \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
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	$00, \bar{0} - \psi_1^0 \psi_1^0 \psi_1^0 \psi_1^0 \psi_1^0$	$0.0, \mu$ 21.33 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0 \psi_1^0 \psi_1^0 \psi_1^0 \psi_1^0$ (4.8 GeV) (Begin)	2011-14230 2102-10474
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3-jet + visible emission	h_1, h_2	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0$ (4.8 GeV) (Begin)	2101-13227 2102-10474
	$h_1, h_2, h_1 - h_2^0 \rightarrow h h^0$	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0$ (4.8 GeV) (Begin)	2101-13227 2102-10474
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EW direct	$F_1^{\pm} \psi_1^0$ via WZ	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\bar{0} - \psi_1^0$ (4.8 GeV) (Begin)	2101-13227 2102-10474
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Long lived particles	Direct $\tilde{L} \rightarrow \ell, \text{prod.}, \text{long-lived } \tilde{L}_1^{\pm}$	Chieppio, 10K 1 jet $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\tilde{L}_1^{\pm}$ 0.21, 0.86	2201-02472 2201-02472
	Stable $\tilde{R}$ -hadron	gluon cE/ds gluon cE/ds	140	$\tilde{R}$ 0.21, 0.86	2008-06113
	Metastable $\tilde{R}$ -hadron, $\tilde{R} \rightarrow \psi_1^0 \psi_1^0$	gluon cE/ds Dieta, 1 jet $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\tilde{R}$ 0.21, 0.86	2008-06113
	$\tilde{R} \rightarrow \psi_1^0 \psi_1^0$	gluon cE/ds Dieta, 1 jet $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\tilde{R}$ 0.21, 0.86	2008-06113
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RPV	$F_1^{\pm} \psi_1^0 \psi_1^0, \tilde{F}_1^{\pm} \psi_1^0 \psi_1^0 \rightarrow 2\ell + 2\ell + 2\ell + 2\ell$	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\tilde{F}_1^{\pm} \psi_1^0 \psi_1^0, \tilde{F}_1^{\pm} \psi_1^0 \psi_1^0 \rightarrow 2\ell + 2\ell + 2\ell + 2\ell$	2011-10463
	$F_1^{\pm} \psi_1^0 \psi_1^0, \tilde{F}_1^{\pm} \psi_1^0 \psi_1^0 \rightarrow 2\ell + 2\ell + 2\ell + 2\ell$	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\tilde{F}_1^{\pm} \psi_1^0 \psi_1^0, \tilde{F}_1^{\pm} \psi_1^0 \psi_1^0 \rightarrow 2\ell + 2\ell + 2\ell + 2\ell$	2101-11644
	$F_1^{\pm} \psi_1^0 \psi_1^0, \tilde{F}_1^{\pm} \psi_1^0 \psi_1^0 \rightarrow 2\ell + 2\ell + 2\ell + 2\ell$	$0.0, \mu$ 2.6 jets $\mathcal{E}_{\text{miss}}^{\text{max}}$	140	$\tilde{F}_1^{\pm} \psi_1^0 \psi_1^0, \tilde{F}_1^{\pm} \psi_1^0 \psi_1^0 \rightarrow 2\ell + 2\ell + 2\ell + 2\ell$	2101-11644
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*Only a selection of the available mass limits on new states or

10⁻¹

1

Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Preliminary

 $\sqrt{s} = 13 \text{ TeV}$

Image • Atlas Collaboration

What are viable extensions to the SM?

The Decoupling Principle

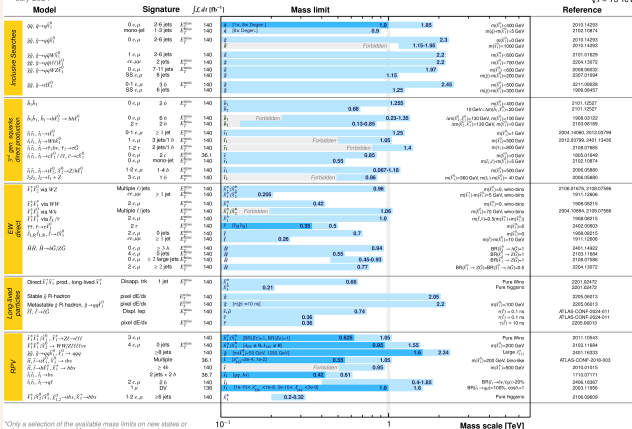
For $m_{\text{BSM}} \gg \mathcal{O}(\nu)$, the BSM sector should gradually decoupling from the light SM sector

Image • T. Appellequist, J. Carrazzone

- EFTs
 - Exact Calculations
 - Generally applicable to all scales
 - Especially in the regime where EFTs are not applicable
- $m_{\text{BSM}} \gtrsim \mathcal{O}(\nu)$

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024



Is there a renormalization scheme with nice properties?

We split the theory parameters in

- SM-like parameters
 - Parameters that can be directly linked to a parameter in the pure SM
 - can include modifications
 - e.g. W/Z-mass, lepton-or quark masses, gauge coupling

Is there a renormalization scheme with nice properties?

We split the theory parameters in

- SM-like parameters
- BSM parameters with influence
 - Parameters that are new from the SM
 - and **directly influence the decoupling**
 - e.g. heavy masses of new particles, couplings

Is there a renormalization scheme with nice properties?

We split the theory parameters in

- SM-like parameters
- BSM parameters with influence
- BSM parameters without influence
 - these parameters can take any value and the decoupling behaviour is still present
 - e.g. couplings

Is there a renormalization scheme with nice properties?

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BSM parameters that influence the decoupling need to follow certain trajectories to reach the decoupling limit

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BSM parameters that influence the decoupling need to follow certain trajectories to reach the decoupling limit

- Renormalization condition for SM-like parameters

$$P_{\text{BSM}}^{\text{dec}}(\mu) = P_{\text{SM}}^{\overline{\text{MS}}}(\mu)$$

$$\delta P_{\text{BSM}}^{\text{dec}} = \delta P_{\text{SM}}^{\overline{\text{MS}}} + \delta P_{\text{BSM}}^{\text{OS}} - \delta P_{\text{SM}}^{\text{OS}}$$

- each SM-like parameter is matched to the actual SM-value at a certain scale

- Renormalization condition for BSM parameters

$\overline{\text{MS}}$ -prescription

- we cant measure BSM parameters directly so this scheme is good enough

How does the THDM work?

We extend the SM with a second doublet Φ_2 with the same quantum numbers

$$\begin{aligned} V_{\text{THDM}} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\ & + \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ & + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\ & + \left(\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right) \\ & + \left(\left(\lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \right) \left(\Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right) \end{aligned}$$

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If the mass matrix has a negative Eigenvalue both scalars develop a vacuum expectation value

$$\langle \Phi_1 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad \langle \Phi_2 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

The parametrization of the field is therefore:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\varphi_i) \end{pmatrix}$$

How does the THDM work?

We extend the
quantum num

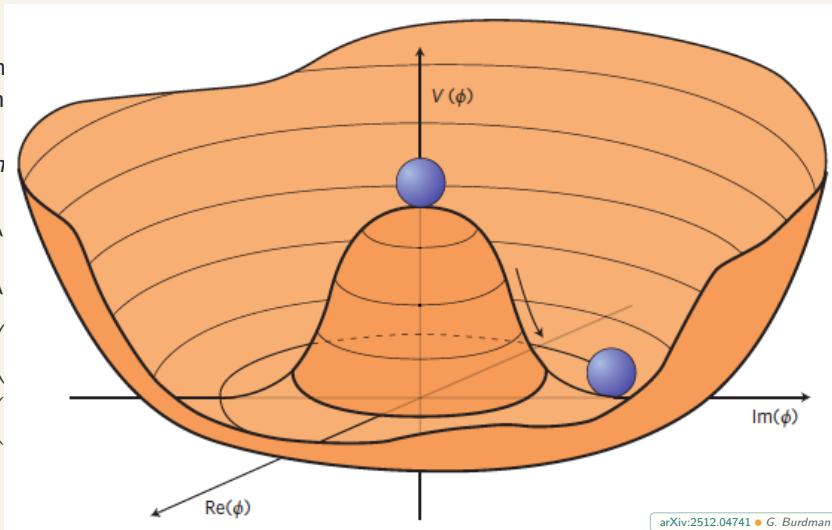
$$V_{\text{THDM}} = n$$

$$+ \lambda$$

$$+ \lambda$$

$$+ \left(\right.$$

$$+ \left(\right.$$



negative
develop a

$$\rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

the field is

$$+ i\varphi_i)$$

arXiv:2512.04741 • G. Burdman

Which new particles appear in the scalar sector?

We plug in the parametrization and extract the quadratic terms of the potential:

$$V_{2\text{HDM}}^2 = \frac{1}{2}(\rho_1 \quad \rho_2) M_{\rho}^2 \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} + \frac{1}{2}(\varphi_1 \quad \varphi_2) M_{\varphi}^2 \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix} + (\phi_1^+ \quad \phi_2^+) M_{\phi^{\pm}}^2 \begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix}$$

Two CP-even fields with masses M_h and M_H

A Nambu-Goldstone field and a CP-odd field with mass M_{A_0}

A Nambu-Goldstone field and a charged field with mass $M_{H^{\pm}}$

$$\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H^0 \\ h^0 \end{pmatrix}$$

$$\begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

$$\begin{pmatrix} \phi_1^{\pm} \\ \phi_2^{\pm} \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} G^{\pm} \\ H^{\pm} \end{pmatrix}$$

Is there a decoupling Limit?

What to expect?

- one Higgs like scalar $M_h \sim \mathcal{O}(v)$
- heavy other scalars $M_H, M_{A_0}, M_{H^\pm} \gg \mathcal{O}(v)$

To see that we first realize there is only one dimensionful parameter we can change! We define

$$m_D, m_L \approx \mathcal{O}(v) \quad \text{and} \quad M_{A_0}^2, M_{H^\pm}^2, m_S^2 \approx m_{12}^2$$

[arXiv:hep-ph/9501320](https://arxiv.org/abs/hep-ph/9501320) • H. E. Haber

The masses of the CP-even scalars become

$$M_{H,h}^2 = \frac{1}{2} \left[m_S^2 \pm \sqrt{m_S^4 - 4M_{A_0}^2 m_L^2 - 4m_D^4} \right] \quad \cos^2(\beta - \alpha) = \frac{m_L^2 - M_h^2}{M_H^2 - M_h^2}$$

The trajectory towards decoupling is very much convoluted

How do we finally parametrize the THDM?

Originally we describe the THDM with the 8 scalar, 9 fermion (and 2 gauge) parameters

$$\begin{aligned} m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \\ Y_U, Y_D, Y_L \\ g_1, g_2 \end{aligned}$$

In principle we can choose any convenient set of parameters.

$$\underbrace{M_h, m_U, m_D, m_L, e, m_W, m_Z}_{\text{SM-like}}, \underbrace{m_{12}^2, M_H, \lambda_3}_{\text{BSM-influence}}, \underbrace{\lambda_4, \lambda_5, \tan(\beta)}_{\text{BSM-no influence}}$$

$$\underbrace{M_h, m_U, m_D, m_L, e, m_W, m_Z}_{\text{SM-like}}, \underbrace{M_H, M_A, M_{H^\pm}, \alpha}_{\text{BSM-influence}}, \underbrace{\lambda_5, \tan(\beta)}_{\text{BSM-no influence}}$$

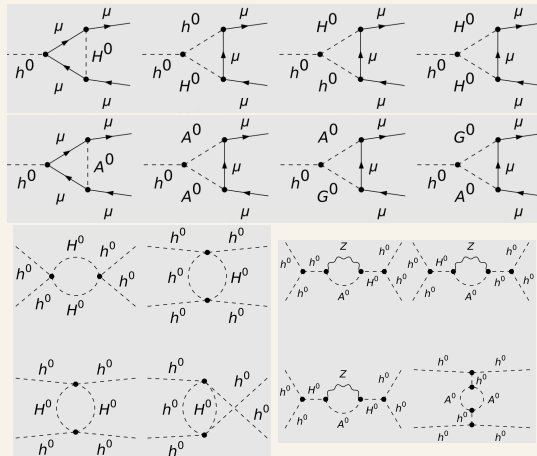
What destroys the decoupling

- At Tree-Level

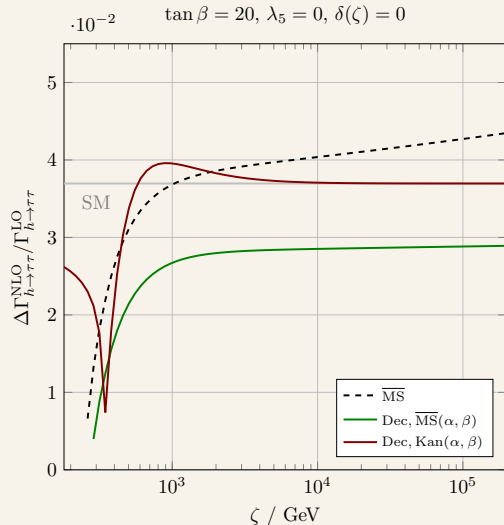
- clear relation between individual parameters
- straight forward decoupling trajectory

- At higher Loop-level

- loop correction introduce new influences for parameters from other parameters
- need new rules for other parameters that had no influence on decoupling at tree-level



How do the different schemes compare?

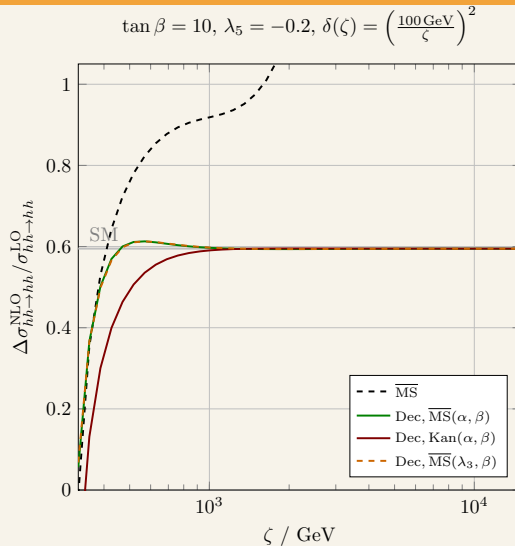


The plot utilizes the definitions:

$$\zeta = M_H = M_{A_0} = M_{H^\pm}$$

$$\delta = \beta - \alpha$$

How good are the schemes?



Summary and Outlook

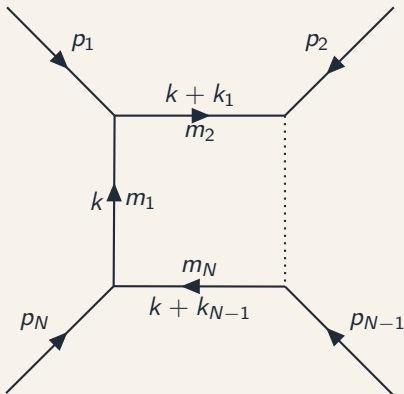
Takeaway Points:

- The scalar sector will be an essential sector to check BSM physics
- Not all renormalization schemes are well suited to make predictions in the presence of a heavy BSM sector
- The decoupling renormalization scheme provides a good middleground of keeping the decoupling behaviour at one-loop order and utilizing higher loop order standard model $\overline{\text{MS}}$ results

Future Plans:

- automatize this calculation, especially to be able to apply the decoupling renormalization scheme in other models
- certain part of the calculation can be used to limit the cubic Higgs coupling and certain production cross-sections

Diverging loop integrals



$$\sim \int \frac{d^4 k}{(2\pi)^4} \frac{A(k, k_i, m_i)}{(k^2 - m_1^2)((k + k_1)^2 - m_2^2) \cdots ((k + k_{N-1})^2 - m_N^2)}$$

$$\sim \int \frac{d^4 k}{(2\pi)^4} \frac{A(k, k_i, m_i)}{k^{2N}}$$

There are two observations

- if $A = 1$, the tadpole and bubble diagrams diverge but triangle, box and diagrams with more external legs converge, and
- if $A = A(k, k_i, m_i)$, the last condition worsens!

How to deal with integrals?

We first need to get a grip on the divergent integrals, this process is called **Regularization**.

$$A(a, \Delta) = \int \frac{d^4 k}{(2\pi)^4} \frac{1}{(k^2 - \Delta + i\epsilon)^a} = i(-1)^a \int \frac{d^4 k}{(2\pi)^4} \frac{1}{(k^2 + \Delta)^a}$$

- Cut-off Regularization:

We impose an upper limit to the Momentum Integral

$$A(a, \Delta) = \frac{i(-1)^a}{16\pi^2} \int_0^{\Lambda^2} dk^2 \frac{k^2}{(k^2 + \Delta)^a}$$

- cut-off breaks momentum translation invariance
- there could be problems with gauge invariance of the final result

- Dimensional Regularization:

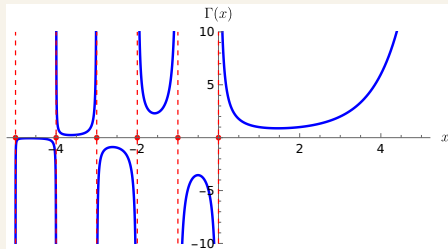
We assume that the space-time dimension is d . We solve the integral in for $d < 2a$ and then analytically continue the result to $d = 4$

$$\int \frac{d^4 k}{(2\pi)^2} \longrightarrow \tilde{\mu}^{4-d} \int \frac{d^d k}{(2\pi)^d}$$

- a non-integer space-time dimension seems artificial, and
- its non-trivial to extend the γ -matrices (γ_5 -Problem)

Limit back to 4 dimensions

$$A(a, \Delta) = \frac{i}{16\pi^2} \frac{\Gamma(a - \frac{d}{2})}{\Gamma(a)} \left(\frac{\Delta}{4\pi\tilde{\mu}^2} \right)^{\frac{d}{2}-2} (-\Delta)^{2-a}$$



The Gamma function is an analytic function with simple poles at negative integers. In the case $a - \frac{d}{2} \leq 0$ we expand $\Gamma(a - \frac{d}{2})$

$$A(1, \Delta) = \frac{i}{16\pi^2} \Delta \left(\frac{1}{\epsilon} - \log\left(\frac{\Delta}{\mu^2}\right) + 1 \right)$$

$$A(2, \Delta) = \frac{i}{16\pi^2} \left(\frac{1}{\epsilon} - \log\left(\frac{\Delta}{\mu^2}\right) \right)$$

We encapsulated the divergence in the term $\frac{1}{\epsilon}$

The renormalization procedure

Experimentally: Fundamental processes are local and relativistic invariant up to some energy $E_{\max}$ and relations between parameters and observables cannot depend on physics at much higher scales!

Theoretically this means that relations between physical quantities as well as observables in a theory described by $\mathcal{L}(\phi_0; m_0, \lambda_0)$, CAN NOT depend on the regularization

The following procedure should result in a unambiguous and testable predictions of the theory:

1. replace auxiliary parameters m_0, λ_0 by renormalized quantities m, λ
2. observables f expressed through physical quantities m, λ are independent of regularization
 $f = f(m, \lambda) = f(m_0(m, \lambda), \lambda_0(m, \lambda)) \Rightarrow \text{Regularization independent}$

Yukawa interactions in the THDM

$$\mathcal{L}_{\text{Yukawa}} = -\overline{Q}(Y_{U,1}(i\sigma^2\Phi_1) + Y_{U,2}(i\sigma^2\Phi_2))u - \overline{Q}(Y_{D,1}\Phi_1 + Y_{D,2}\Phi_2)d - \overline{L}(Y_{L,1}\Phi_1 + Y_{L,2}\Phi_2)l + \text{h.c.}$$

Classification of the THDM in terms of is lepton interactions:

	u_i	d_i	l_i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
lepton-specific	Φ_2	Φ_2	Φ_1
flipped	Φ_2	Φ_1	Φ_2