The Higgs Boson
A Dissection Tool for New Physics

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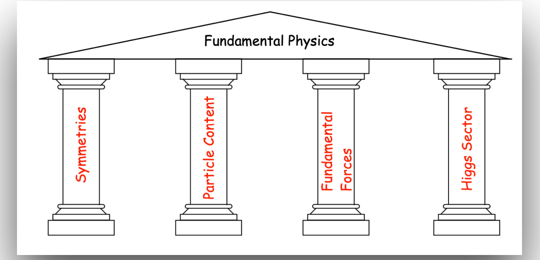
CRC
YS Meeting
25 Sep 2024

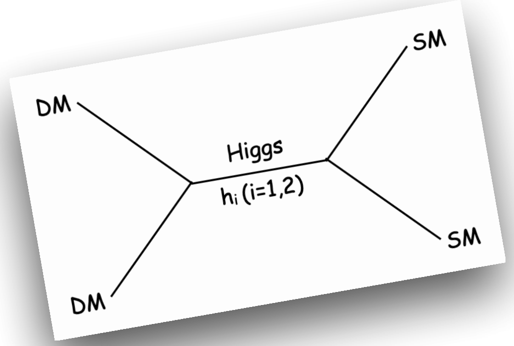
Outline

- ❑ Introduction

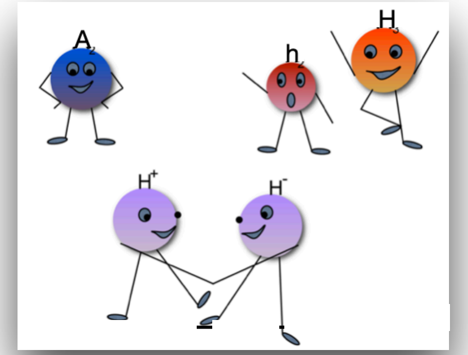


- ❑ BSM Higgs Physics - Extended Higgs Sectors

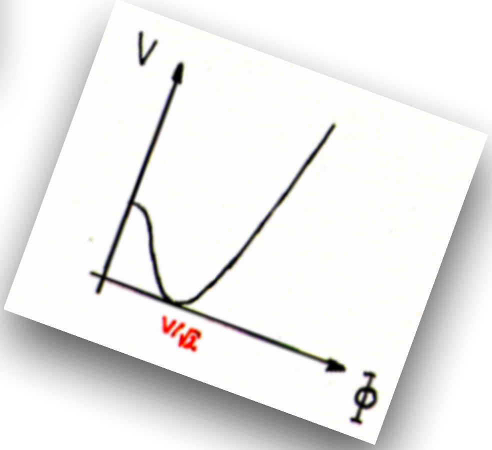
- ❑ Singlet Extensions



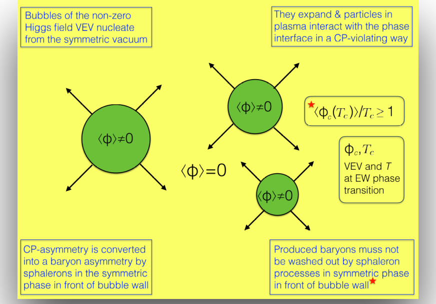
- ❑ The 2-Higgs-Doublet Model (2HDM)



- ❑ Measuring Electroweak Symmetry Breaking

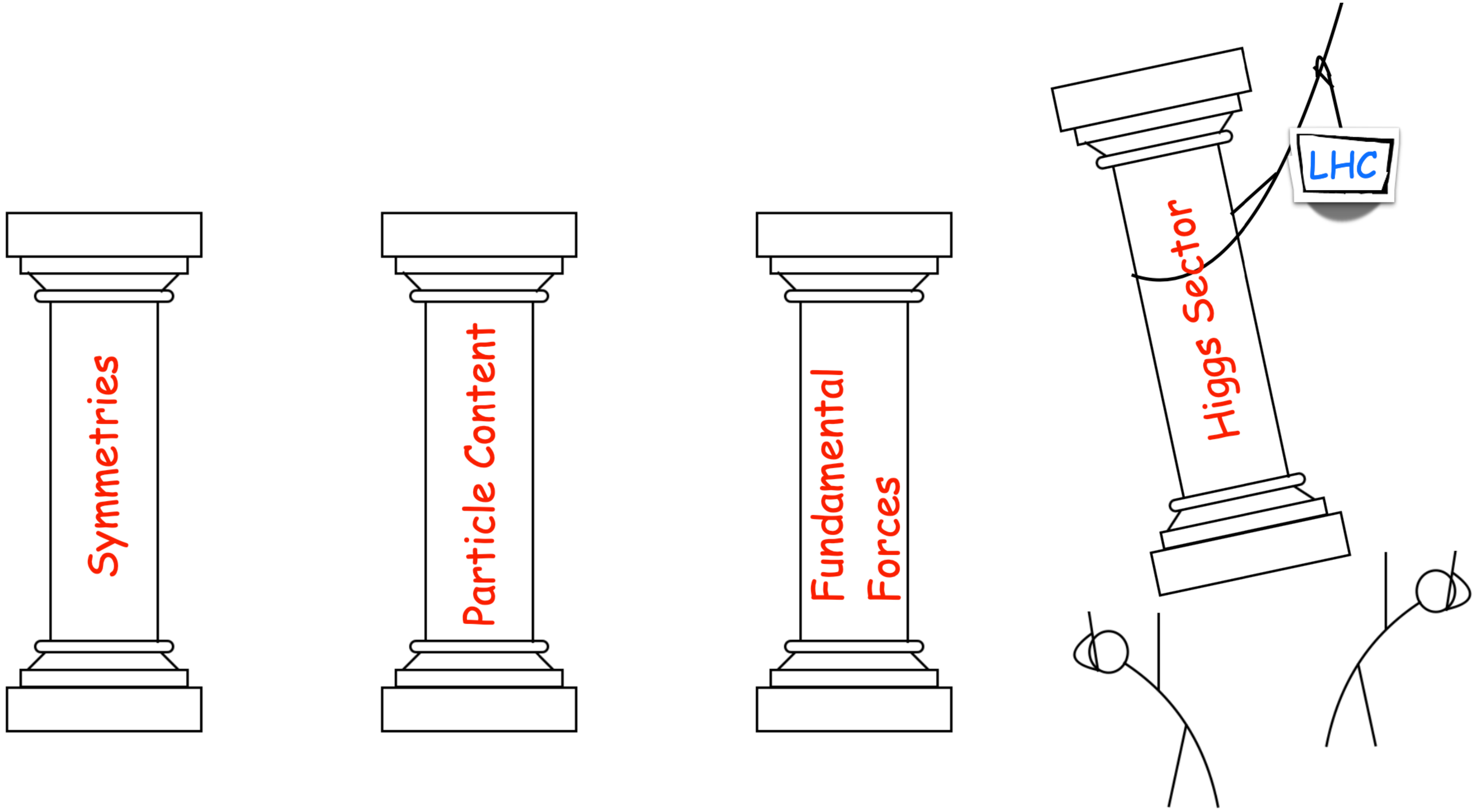


- ❑ Electroweak Baryogenesis



Introduction

The Standard Model is Structurally Complete



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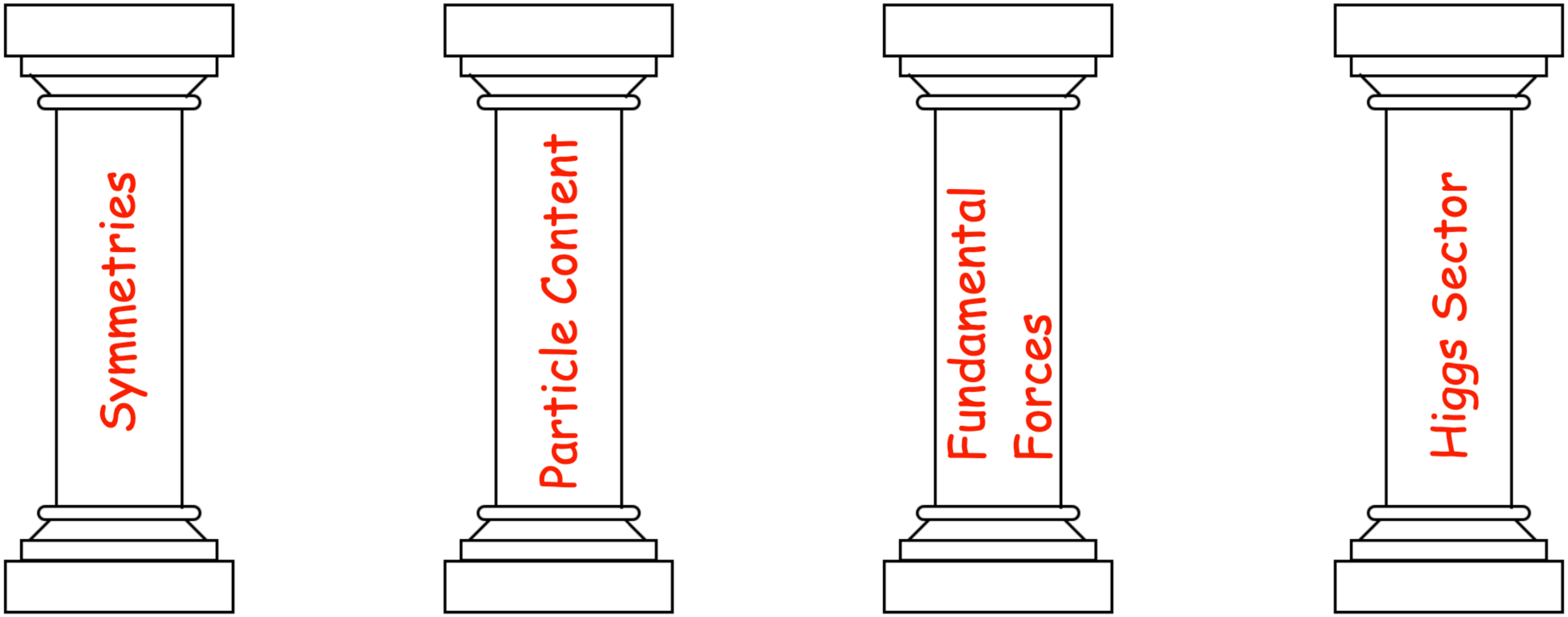

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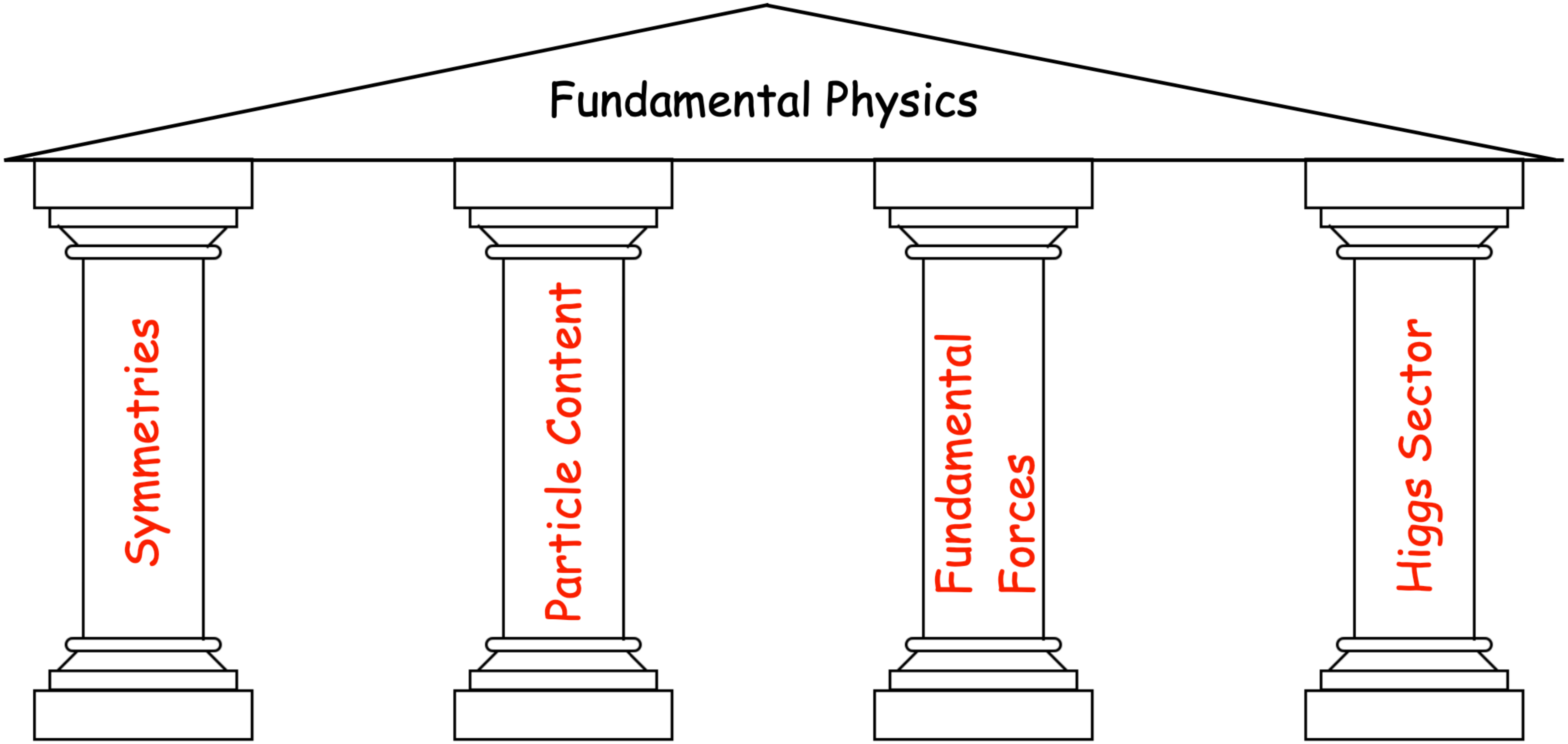
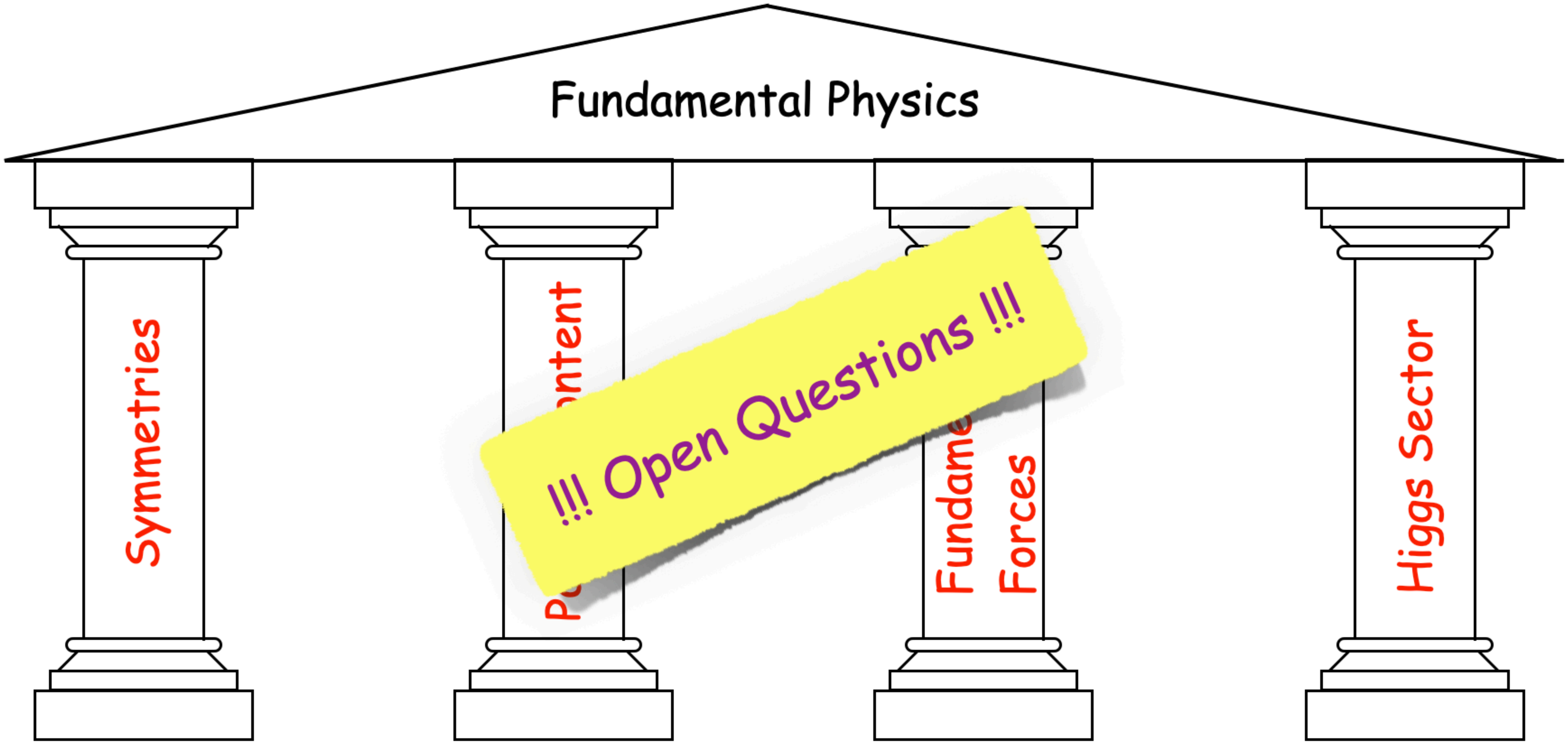
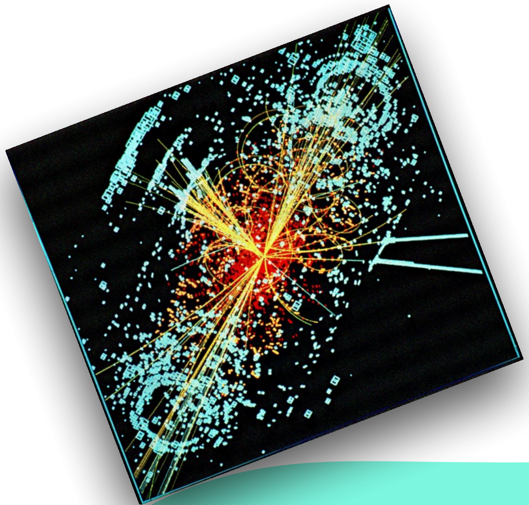


The Standard Model is Structurally Complete - But

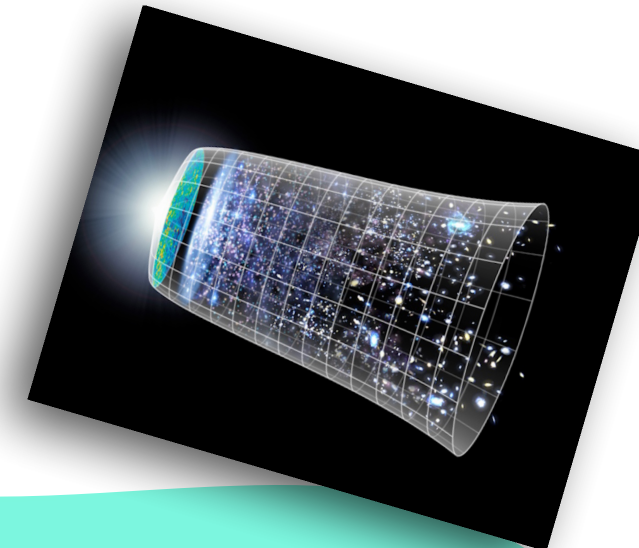


Open Questions



Particle physics

Cosmology



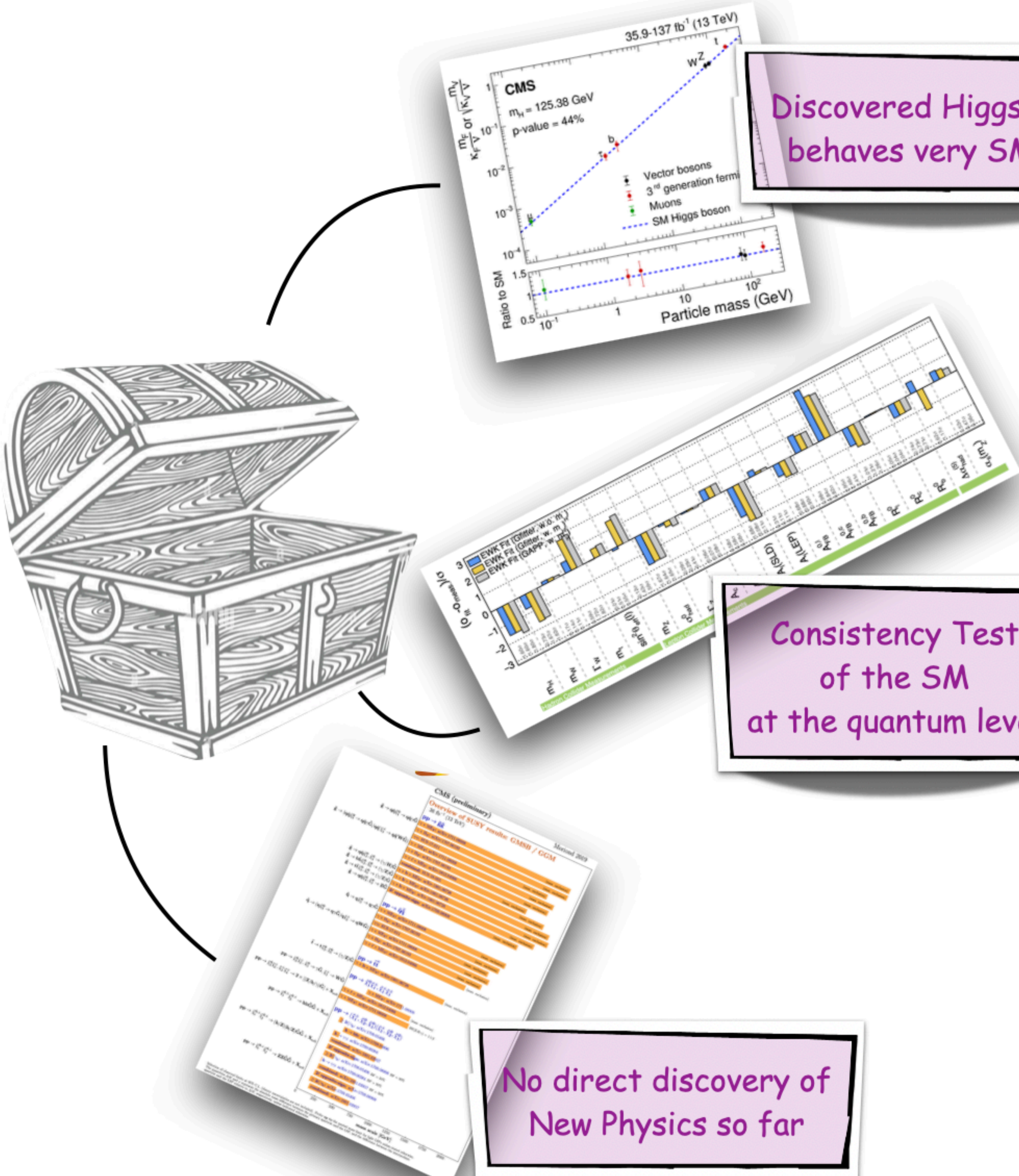
- ❖ origin of electroweak symmetry breaking
- ❖ hierarchy problem
- ❖ nature of the Higgs boson
- ❖ fermion mass and flavor puzzle
- ❖ origin of neutrino masses

- ❖ nature of Dark Matter
- ❖ matter-antimatter asymmetry
- ❖ dark energy
- ❖ inflation
- ❖ how to incorporate gravity

Decipherment of fundamental laws of nature:
judicious combination of
theoretical methods/interpretation
and experimental input/scrutiny

New physics is required, but there is no clear indication at which energy scale

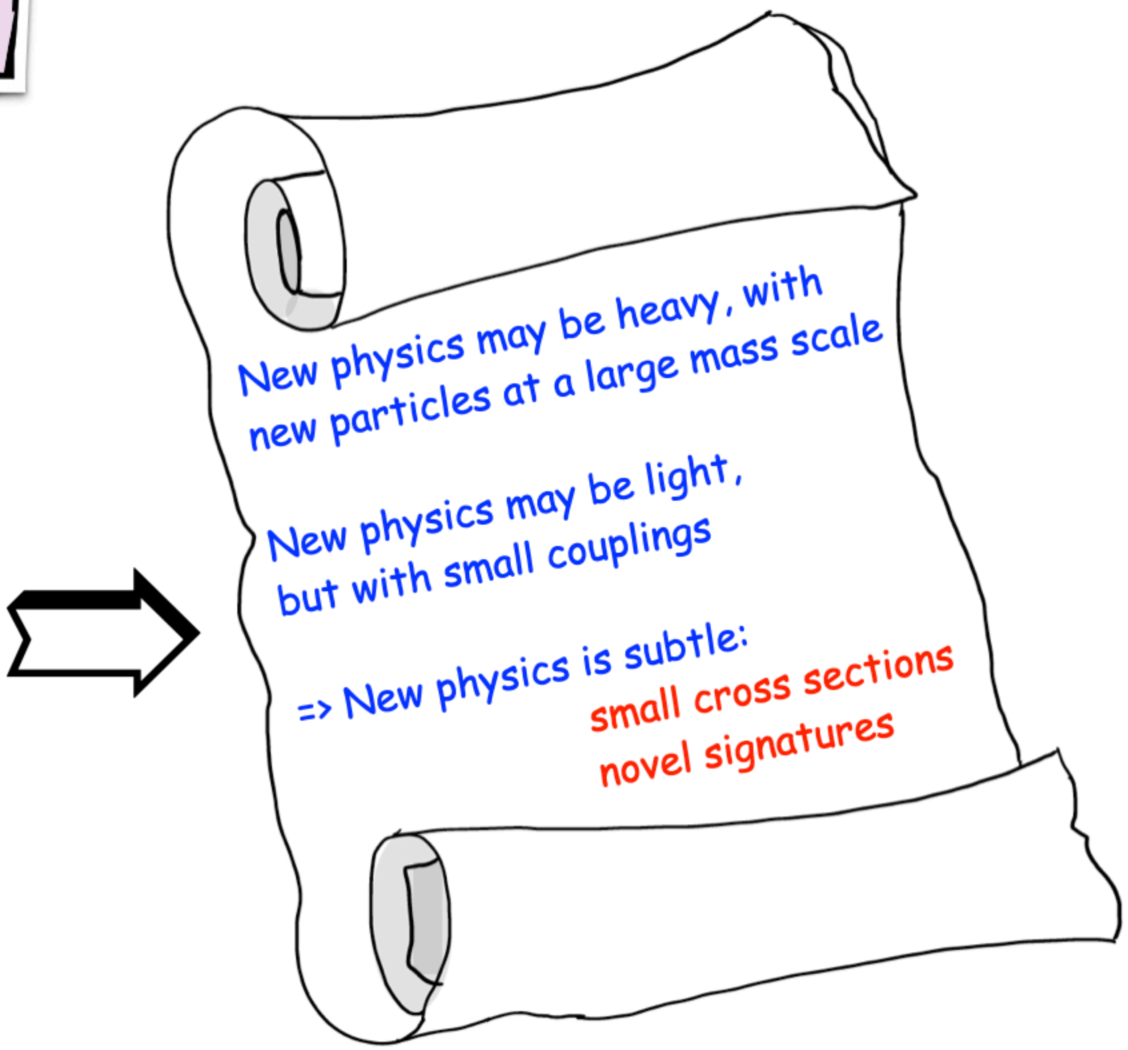
The Challenge



Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far



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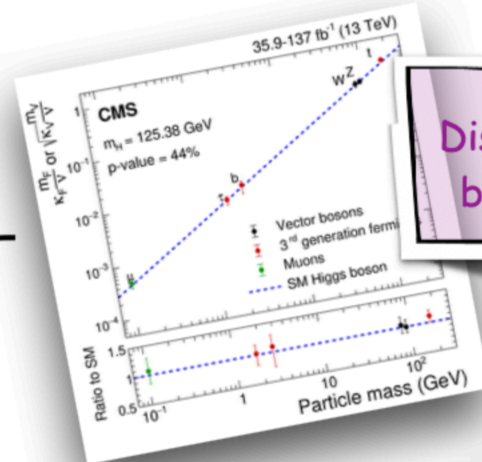

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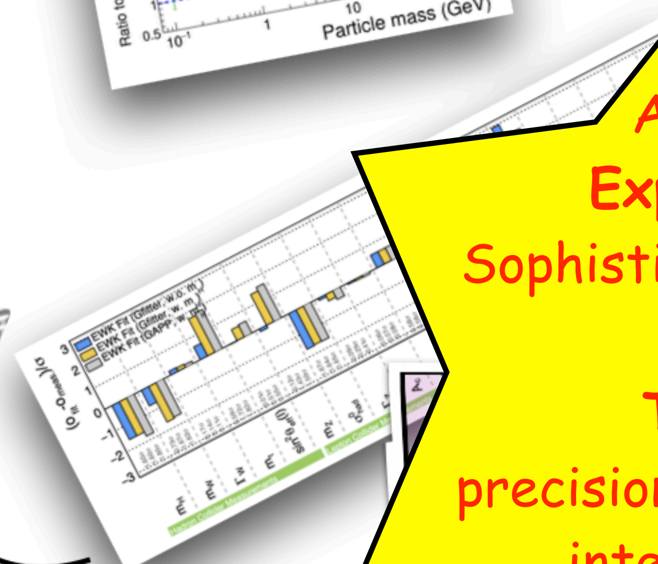


No direct discovery of New Physics so far

Answers:
Experiment:
Sophisticated analyses
+
Theory:
precision calculations &
interpretation

New physics may be heavy, with new particles at a large mass scale

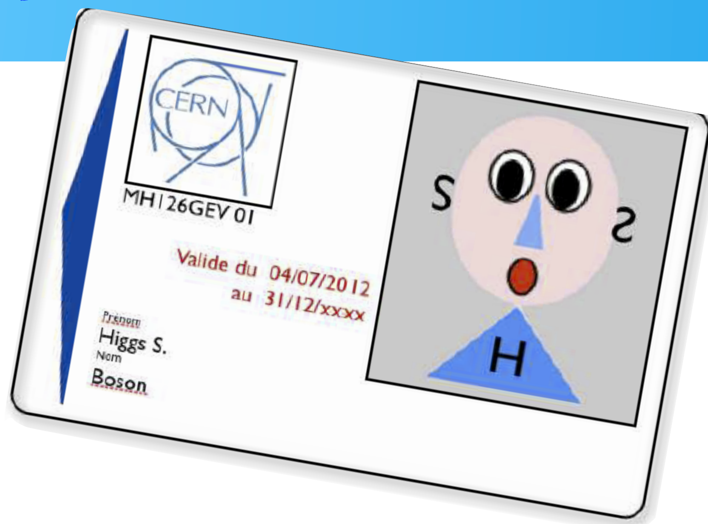
New physics may be light, but with small couplings

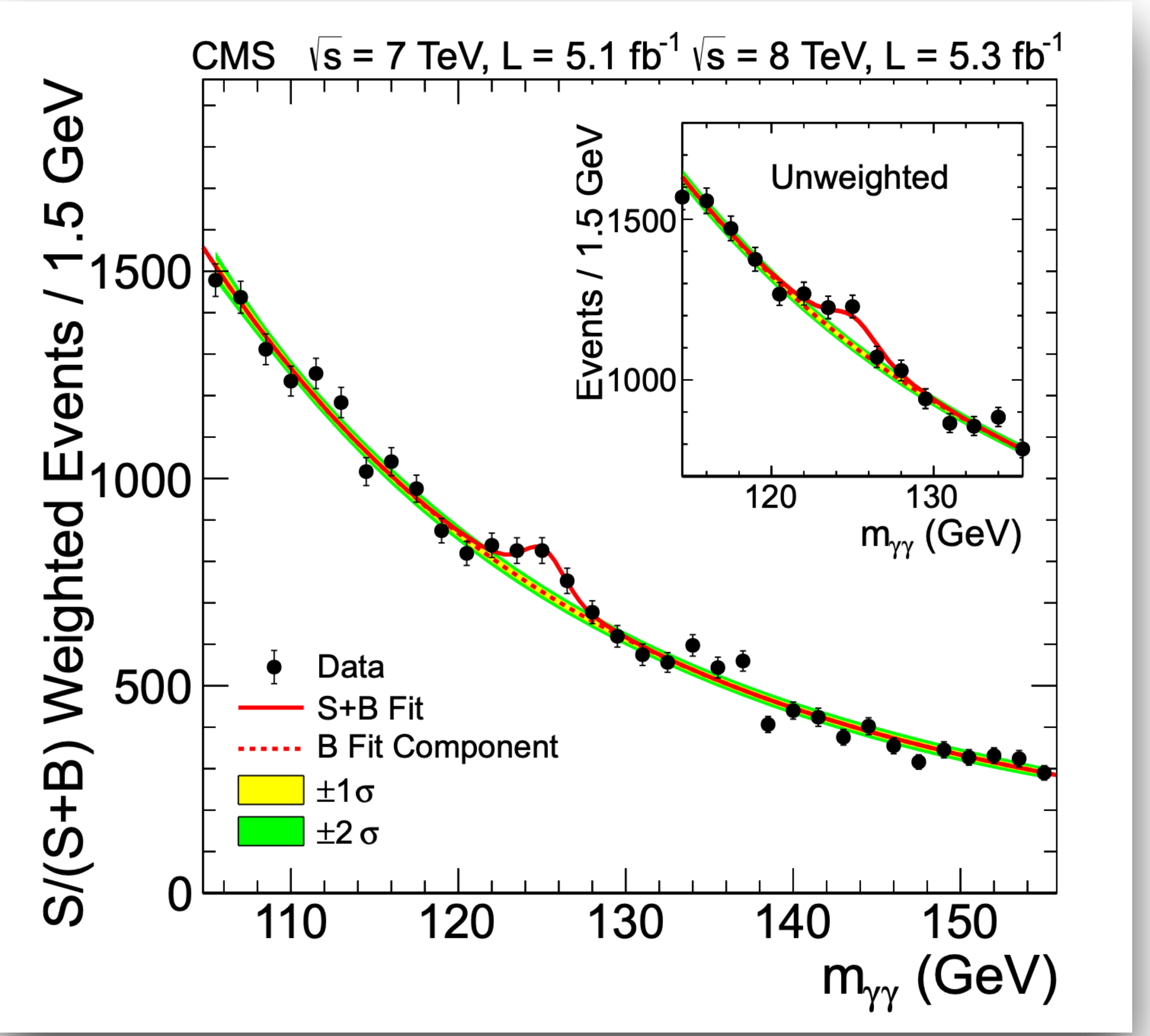
=> New physics is subtle:
small cross sections
novel signatures

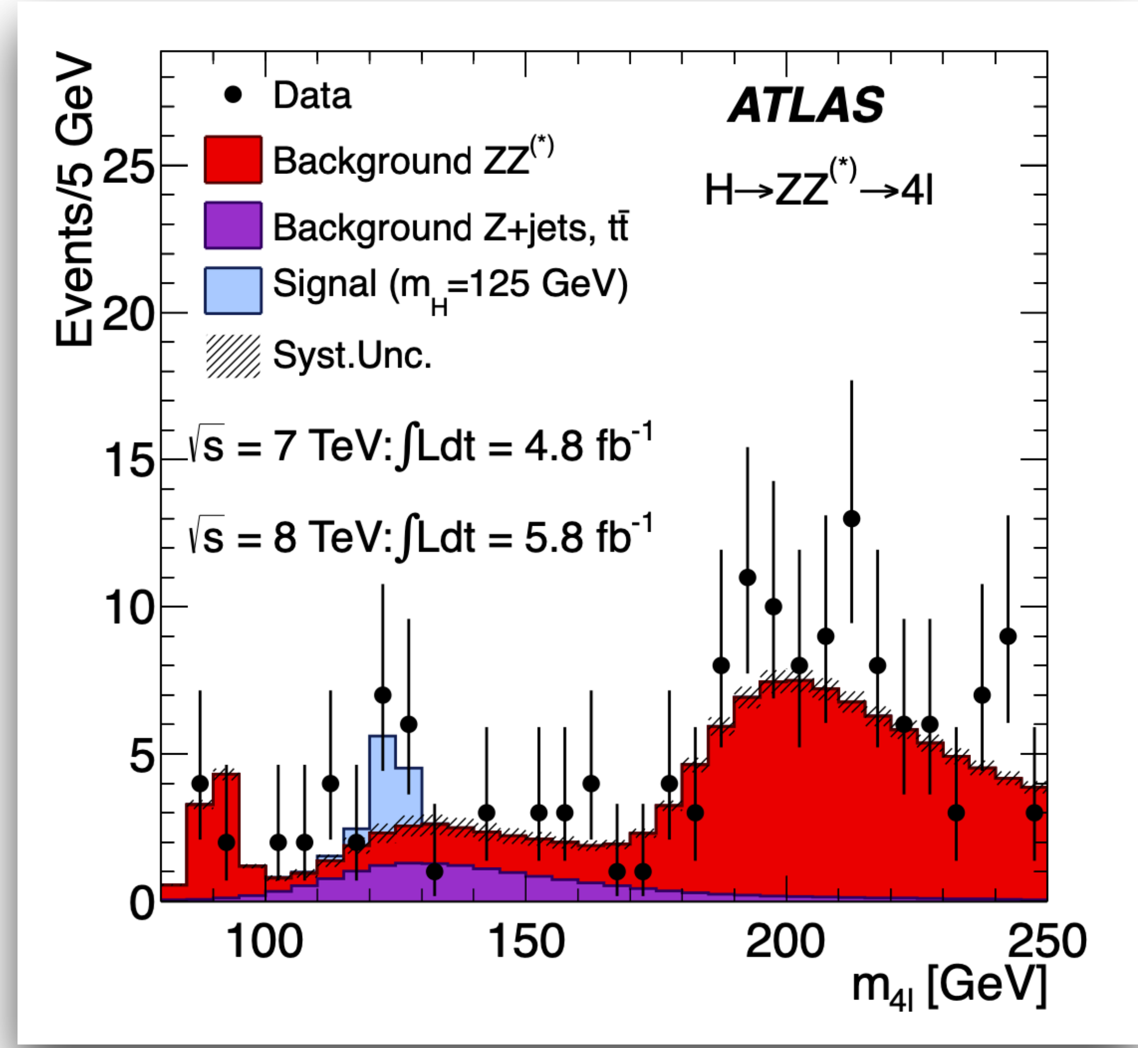
Role of the Higgs Boson

- Discovery of the Higgs boson at LHC on 4 July 2012

  Is it the Higgs boson?







Establishing the Higgs Mechanism

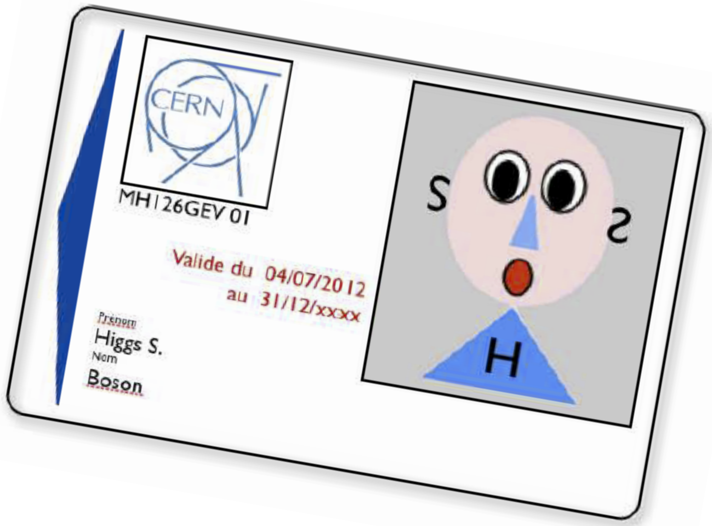
4th July 2012

Discovery of new particle announced by CERN!!

But how can we be sure that it is a Higgs? We must

- *Measure its couplings to the other SM particles*
- *We must determine its spin and CP quantum numbers*
- *We must measure the Higgs potential. I.e. its self-couplings*

My Diary



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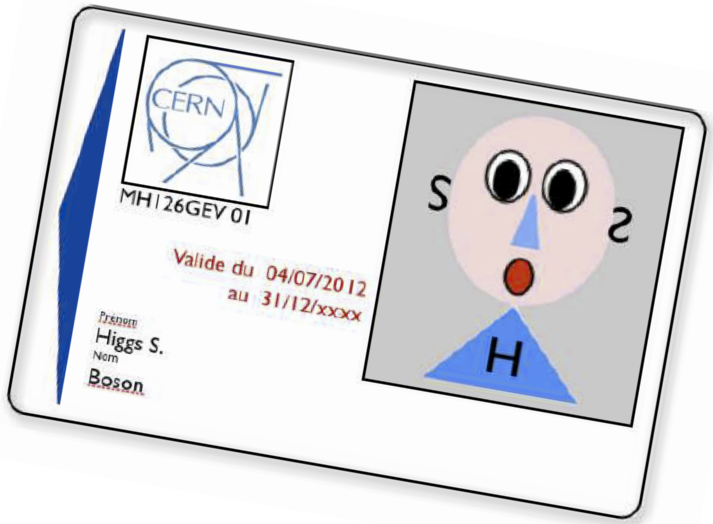

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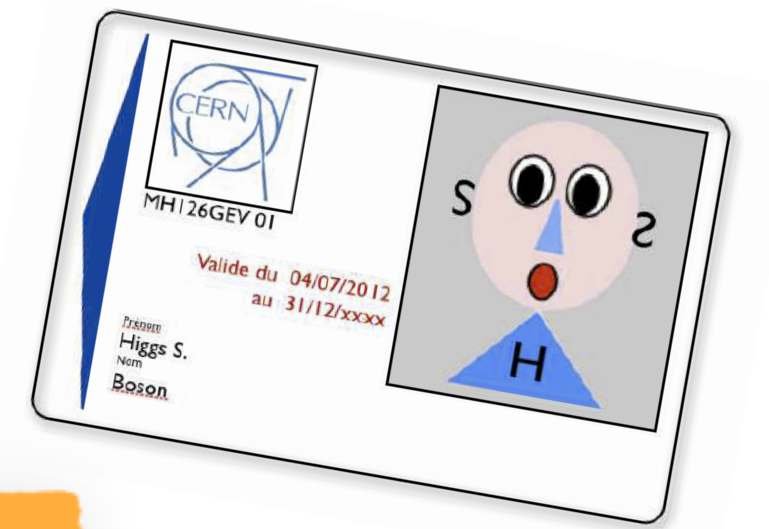
Precise measurements may give hints to beyond-SM physics (BSM)

My Diary

Role of the Higgs Boson



- We have the SM-like Higgs boson

  What can we learn from Higgs physics?

- Corner new physics with the Higgs:

$$\mathscr{L}_{\text{Higgs}} = (\mathscr{D}_\mu \Phi_i)(\mathscr{D}^\mu \Phi_i)^\dagger - V(\Phi_i) + \mathscr{L}_{\text{Yukawa}}$$

- anomalous Higgs gauge couplings
- CP violation

✏ **New Physics & DM**
✏ **Baryogenesis**

- coupling relations $g_X \sim m_X^{(2)}$

✏ **Establish Higgs mechanism**

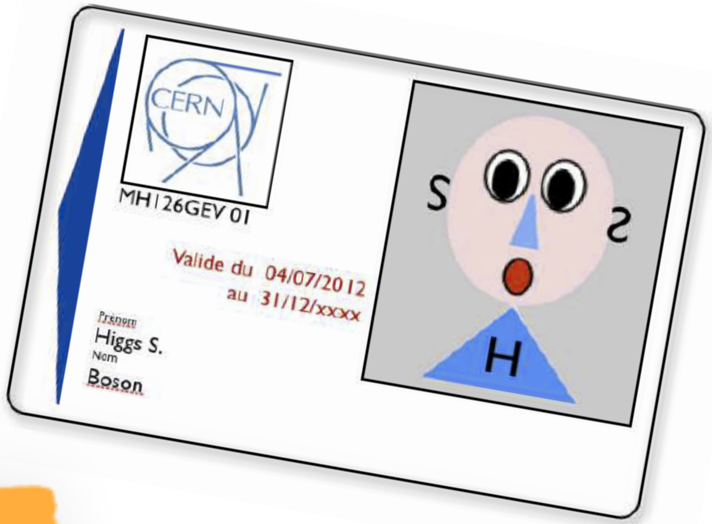
- Higgs mass
- Higgs self-interaction
- vacuum structure
- CP violation
- portal to hidden sector

✏ **Self-consistency SM**
✏ **Ultimate test Higgs mechanism**
✏ **Vacuum stability**
✏ **New Physics&DM**
✏ **Matter asymmetry**
✏ **Cosmological evolution**

- anomalous Higgs fermion couplings
- CP violation

✏ **Flavor/Matter puzzle**
✏ **New Physics**
✏ **Baryogenesis**

Role of the Higgs Boson



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✏ **New Physics & DM**
✏ **Baryogenesis**

Establish Higgs Mechanism

- coupling relations $g_X \sim m_X^{(2)}$

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New Physics

- Higgs mass
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Matter-Antimatter Asymmetry

- anomalous Higgs fermion couplings
- CP violation

✏ **Flavor/Matter puz le**
✏ **New Physics**
✏ **Baryogenes**

Flavor Matter Puzzle

Evolution of the Cosmos

BSM Higgs Physics - Extended Higgs Sectors

Vast New Physics Landscape

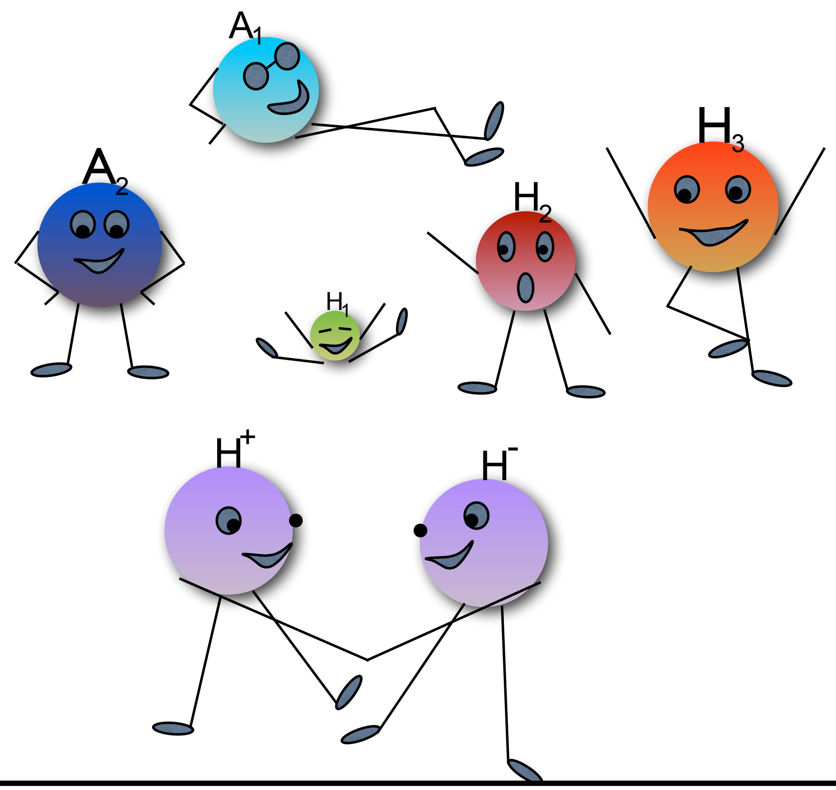
Extended Higgs Sectors

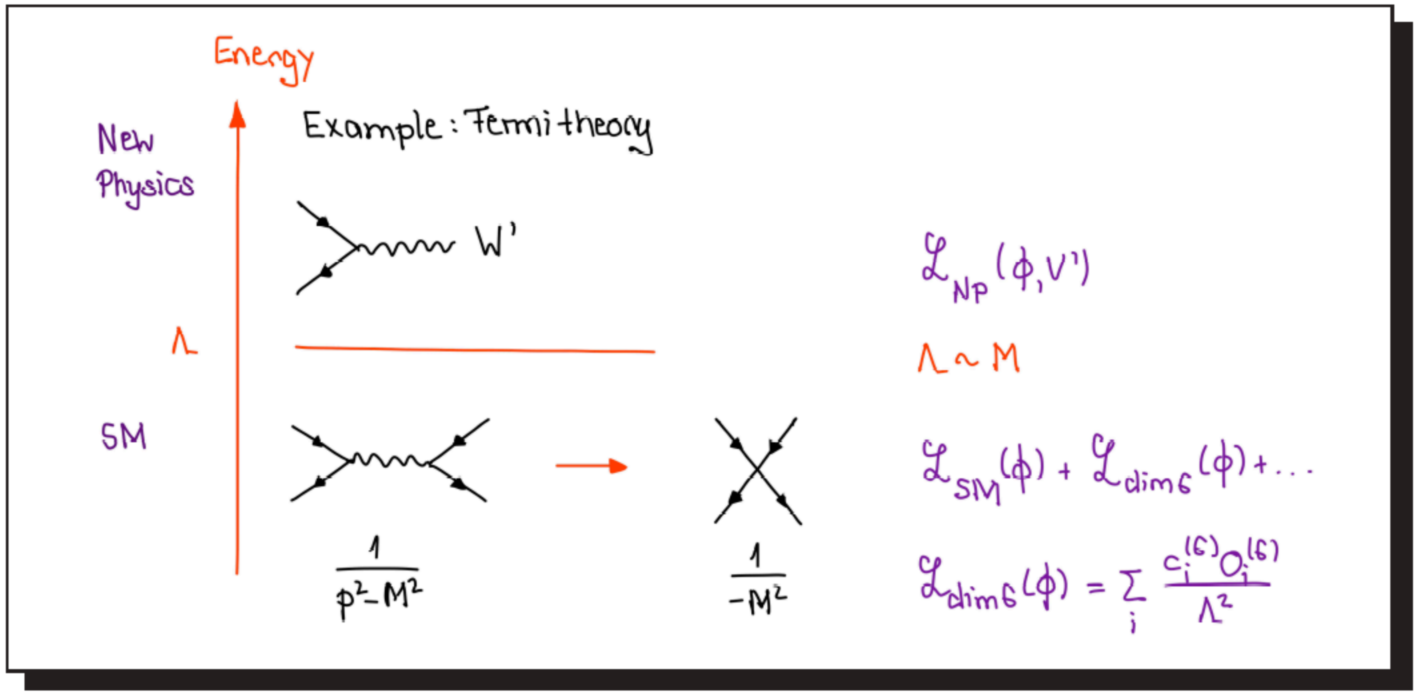
Why extended Higgs sectors?

* many new physics models require extended Higgs models ← supersymmetry!
* fermion/gauge sectors not minimal - why should the Higgs sector be minimal?
* extended Higgs sectors:
  alleviate metastability, DM candidate, additional sources of CP-violation ← baryogenesis

How systemize approach not to miss any new physics sign?

* effective theory (rather model-independent, new physics effects at high energy scales)
* specific well-motivated UV-complete models



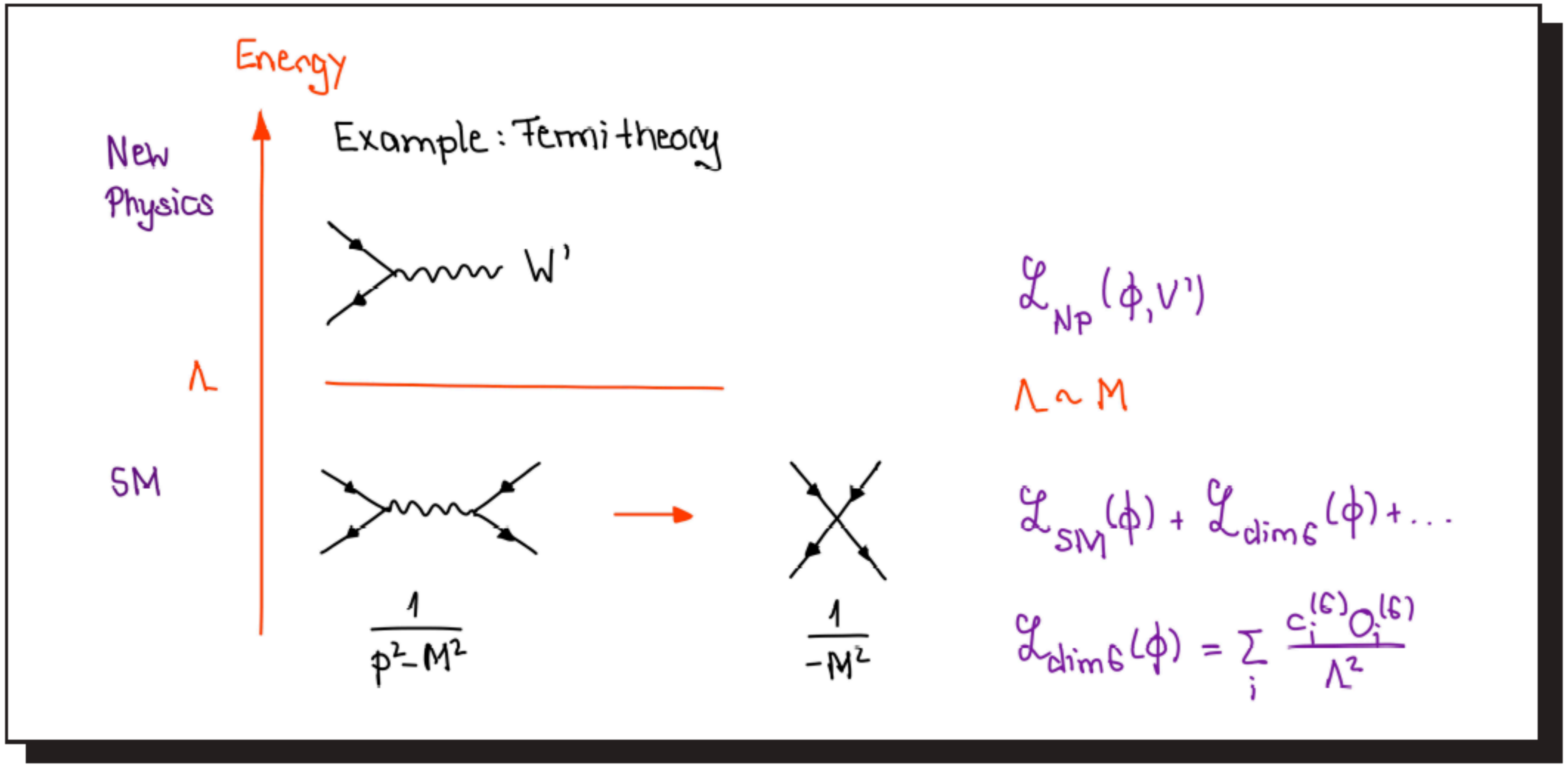


SM Effective Theory (SMEFT)

◆ SMEFT approach:

[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal; Hagiwara,Ishihara,Szalapski;Zeppenfeld;Giudice eal]

* SM field content and SM gauge symmetries, no New Physics at E < Λ
* SM deviations: higher-dimensional operators built from SM fields
* Operators = low-energy remnants of heavy new physics integrated out at Λ =>
* Operators suppressed by scale Λ



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- ✻ SM field content and SM gauge symmetries, no New Physics at $E < \Lambda$
- ✻ SM deviations: higher-dimensional operators built from SM fields
- ✻ Operators = low-energy remnants of heavy new physics integrated out at Λ =>
- ✻ Operators suppressed by scale Λ

◆ New interactions of SM particles: Higgs part of a doublet field (EWSB linearly realized) ~> leading new physics (NP) effects described by D=6 operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Electroweak Chiral Lagrangian (EWChL)

◆ SMEFT approach:

[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal; Hagiwara,Ishihara,Szalapski;Zeppenfeld;Giudice eal]

✻ EWSB linearly realized: Higgs boson part of a weak doublet[1]

✻ Additional expansion in $g_* v/\Lambda \ll 1$ (g_* typical coupling of the NP sector)

◆ EW Chiral Lagrangian (EWChL):

[Contino eal; Azatov eal; Alonso eal; Brivio eal; Elias-Miró eal; Buchada eal]

✻ EWSB non-linearly realized: Higgs treated as singlet

✻ Chiral expansion

cf. e.g. [Contino,1005.4269]

[1] Widely discussed benchmark model is **composite Higgs**: bound state from strongly interacting sector, Higgs emerges as pseudo Nambu-Goldstone boson of an enlarged global symmetry
For a composite 2HDM, cf. [deCurtis eal,'18; deCurtis,delleRose,Egle,Moretti,MM,Sakurai,'23]

◆ SMEFT analysis:

✻ Model and basis independence: **All** relevant operators need to be included

✻ Number of non-redundant dim-6 operators for 3 generations: 2499, 59 for 1 generation

[Grzadkowski eal;Alonso eal]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

Global SMEFT Fit

◆ SMEFT analysis:

✻ Model and basis independence: **All** relevant operators need to be included

✻ Number of non-redundant dim-6 operators for 3 generations: 2499, 59 for 1 generation

[Grzadkowski eal;Alonso eal]

✻ Global fit: complicated parameter space w/ many degenerate/flat directions and local minima ~>

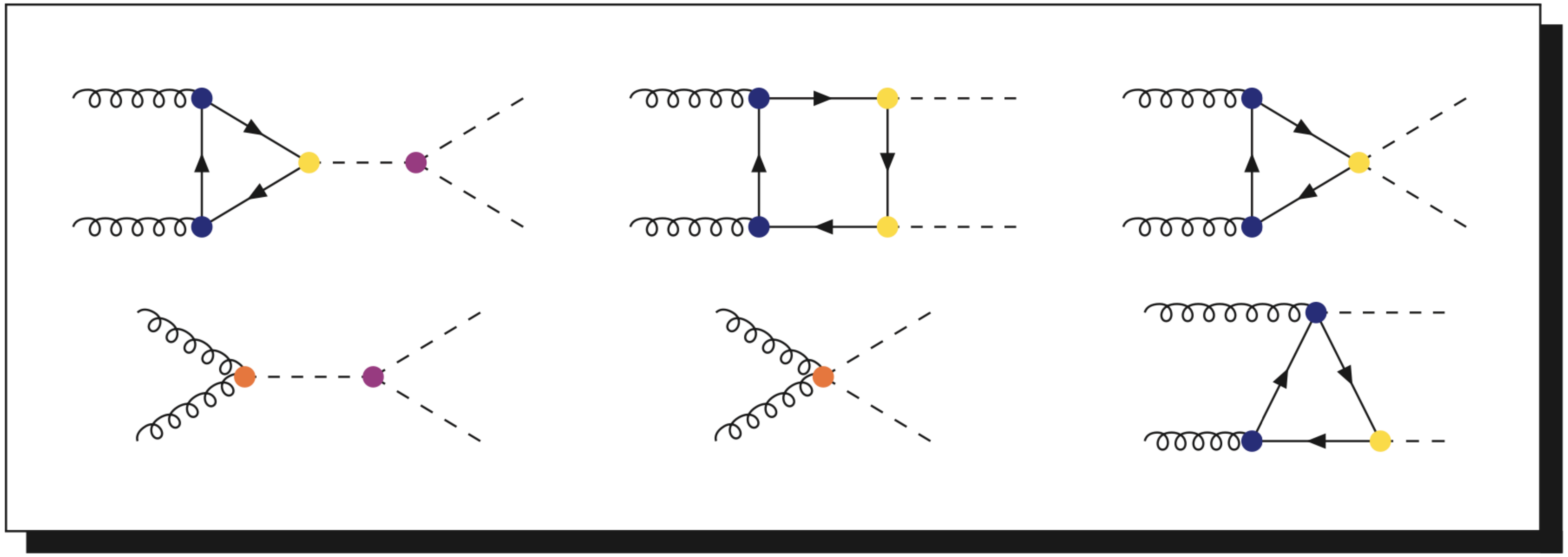
◆ Practical approach - reduce number of operators by:

✻ Symmetry assumptions, e.g. flavor, CP conservation

✻ focus on subsectors: Higgs, electroweak, top, Higgs-electroweak, top-Higgs, ...:

- ◇ include only operators relevant to the considered particle(s)/processes
- ◇ assume other operators well constrained from different processes
- ◇ note: not always justified!

Example EFT Operators Contributing to Higgs Pair Production



$$\mathcal{O}_H = \frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2 \longrightarrow$$ overall shift of couplings

$$\mathcal{O}_6 = -(\phi^\dagger\phi)^3 \longrightarrow$$ shifts Higgs self-coupling

$$\mathcal{O}_{t\phi} = (\phi^\dagger\phi)(\bar{Q}\tilde{\phi}t) + h.c. \longrightarrow$$ shifts top Yukawa coupling; $t\bar{t}HH$

$$\mathcal{O}_{\phi G} = (\phi^\dagger\phi)G^a_{\mu\nu}G^{a\mu\nu} \longrightarrow$$ pointlike Higgs to gluon couplings

$$\mathcal{O}_{tG} = (\bar{Q}\sigma^{\mu\nu}T^a t)\phi G^a_{\mu\nu} + h.c. \longrightarrow$$ chromomagnetic dipole operator

Specific UV-Complete New Physics Models

Investigations of specific UV-complete models:

* Indisponible: complement EFT approach
* EFT approach cannot capture new physics effects due to new light particles

Guidelines for model selection

* simplicity
* compatibility with relevant experimental and theoretical constraints
* solve (some of the) flaws of the SM
* testable in experiment

Validity of the models: they have comply with

* experimental constraints
* theoretical constraints

Experimental Constraints on Extended Higgs Sectors

✏ Electroweak rho parameter very close to 1: $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} \approx 1$ (in SM automatically fulfilled)

* model with n scalar multiplets ϕ_i with weak isospin I_i, weak hypercharge Y_i and VEVs v_i of the neutral components: rho parameter at tree level

$$\rho_i = \frac{\sum_{i=1}^n [I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum_{i=1}^n \frac{1}{2}Y_i^2 v_i}$$

* SU(2) singlets with $Y=0$ and SU(2) doublets with $Y=\pm 1$ satisfy

$$I(I+1) = \frac{3}{4}Y^2$$

and hence $\rho = 1$

✏ Flavor-changing neutral currents (FCNCs): very stringent constraints from experiment

solution for multi-Higgs models: apply symmetries such that all right-handed fermions of a given electric charge couple to exactly one Higgs doublet (cf. e.g.(N)2HDM type I...IV); minimal flavor violation (flavor violation only arises from CKM matrix)

Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

* Electroweak precision tests (EWPTs): Peskin-Takeuchi resp. S,T,U parameters parametrize potential NP contributions to EW radiative corrections; S,T,U are zero for SM ref. point; assumptions:

- EW gauge group is $SU(2)_L \times U(1)_Y$ ~> no additional gauge bosons beyond $Z, W^\pm, \gamma$, e.g. no Z´
- New physics couplings from light fermions are suppressed ~> only oblique corrections (= vacuum polarization), no box and vertex corrections need to be considered
- NP energy scale is large compared to the EW scale ~> expansion in q^2/M^2, M = NP scale

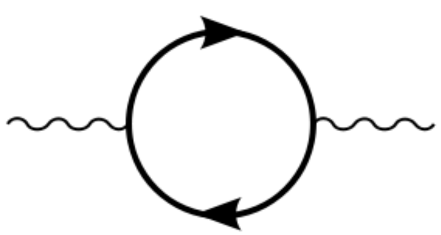
=> parametrization in terms of four vacuum polarization functions: self-energies of the $Z, W^\pm, \gamma$ and mixing between Z and γ induced by loop diagrams

$$\Pi_{\gamma\gamma}(q^2) = q^2 \Pi'_{\gamma\gamma}(0) + \ldots$$

$$\Pi_{Z\gamma}(q^2) = q^2 \Pi'_{Z\gamma}(0) + \ldots$$

$$\Pi_{ZZ}(q^2) = \Pi_{ZZ}(0) + q^2 \Pi'_{ZZ}(0) + \ldots$$

$$\Pi_{WW}(q^2) = \Pi_{WW}(0) + q^2 \Pi'_{WW}(0) + \ldots$$



$$\alpha S = 4 s_w^2 c_w^2 \left[\Pi'_{ZZ}(0) - \frac{c_w^2 - s_w^2}{s_w c_w} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right]$$

$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha U = 4 s_w^2 \left[\Pi'_{WW}(0) - c_w^2 \Pi'_{ZZ}(0) - 2 s_w c_w \Pi'_{Z\gamma}(0) - s_w^2 \Pi'_{\gamma\gamma}(0) \right]$$

Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

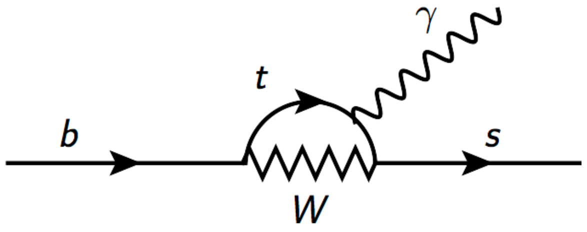
* Electroweak precision tests S,T,U parameters

  - S parameter: measures difference between left-handed & right-handed fermions w/ weak isospin ~> tightly constrains number of new fourth-generation chiral fermions
  - T parameter: measures isospin violation (<- sensitive to loop corrections to Z and W vacuum polarization)
  - S and T parameter: affected by varying the Higgs boson mass
    Before discovery: mass of Higgs boson constrained by EWPTs to lie within close to LEP lower bound (114 GeV) and 200 GeV.
  - U parameter: not very useful in practice, parametrizes dim-8 effects

* Flavour constraints: NP effects to flavor observables from loop corrections
  - Example: $B \to X_s \gamma$ receives NP contributions from $H^\pm$ exchange;
    sets lower bound of about 800 GeV on $m_{H^\pm}$ in the 2HDM type II

[Deschamps eal,'09;Mahmoudi,Stal,'09;Hermann eal,'12;Misiak eal,'15; Misiak,Steinhauser,'17;Misiak,Rehman,Steinhauser,'20]

SM diagram:



Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

* Higgs data:
  - one of the Higgs bosons must have a mass of 125 GeV and behave very SM-like, i.e. comply with LHC Higgs data
  - remaining Higgs bosons have to comply with LHC exclusion limits from searches for additional Higgs bosons

* Direct searches for new particles predicted by the model:
  - model has to respect exclusion limits on these particles (e.g. lower bounds on stop or gluino masses in supersymmetric models)

* Low-energy observables like the anomalous magnetic moment

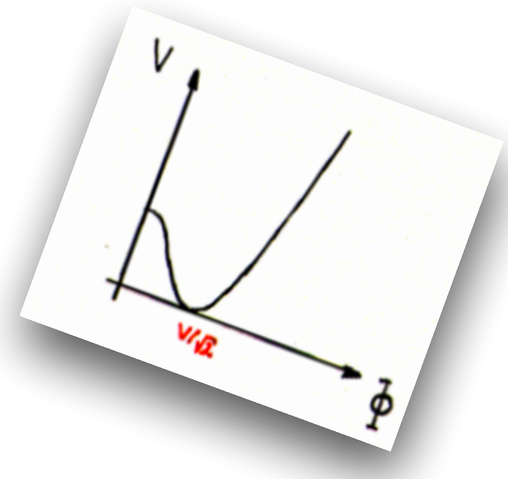
* Electric Dipole Moment (EDM) constraints: stringent constraints on CP violation in CP-violating models

* Dark Matter (DM) observables (relic density, direct and indirect detection limits): constrains models w/ DM candidate

Theory Constraints on Extended Higgs Sectors

✏ Theory constraints: (will be discussed in detail below)

* Higgs potential bounded from below
* EW vacuum with v=246 GeV is the global minimum
* Perturbative unitarity



Parameter Scans of the Models

Parameter scans w/ constraints:
Reduction of the parameter space
to the still allowed parameter space
~> sharpens predictions of the models

✏ Parameter scans performed with ScannerS: [Coimbra,Sampaio,Santos;MM,Sampaio,Santos,Wittbrodt]

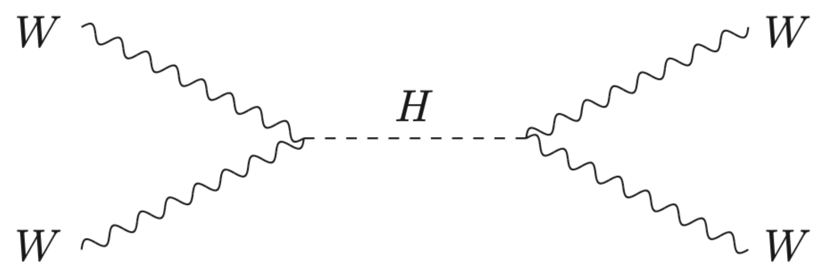
ScannerS: Tool for performing scans in models with extended Higgs sectors checking for the theoretical and experimental constraints

- link to HiggsTools to check for Higgs constraints [Bahl,Biekötter,Bechtle,Heinemeyer,Li,Paasch,Weiglein,Wittbrodt]

- link to MicrOMEGAs to check for Dark Matter constraints [Bélanger,Boudjema,Pukhov eal]

Higgs Realization

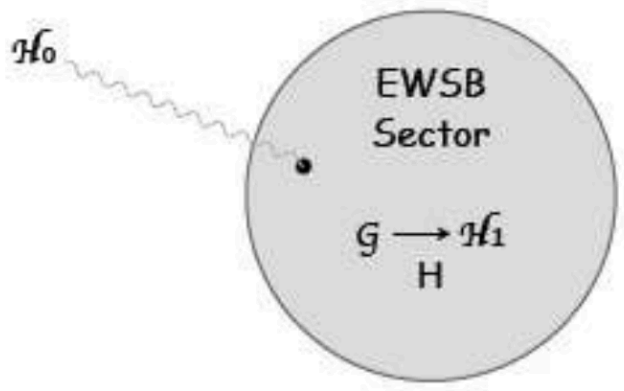
Weakly coupled models



SM and its singlet, doublet, triplet extensions, SUSY

New particles necessary
to stabilize the Higgs mass

Strongly-interacting dynamics

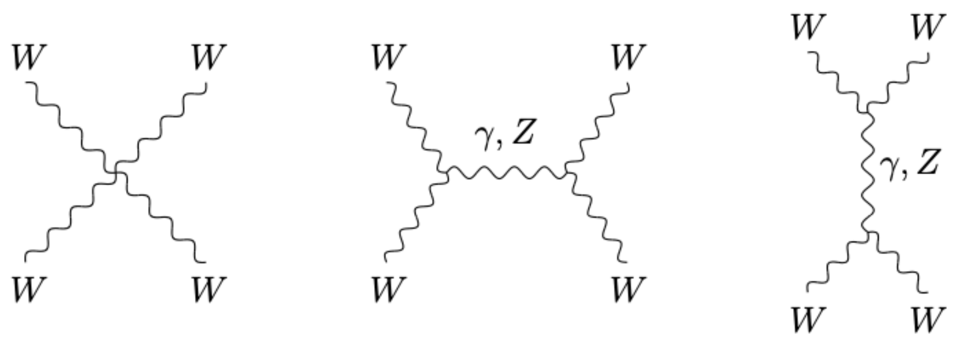


Composite Higgs Models

Resonances for unitarity
Higgs boson composite object

Weakly or Strongly Interacting Higgs?

Scattering of longitudinally polarized W bosons



$$\mathcal{A} = \frac{G_F s}{8\pi\sqrt{2}}$$

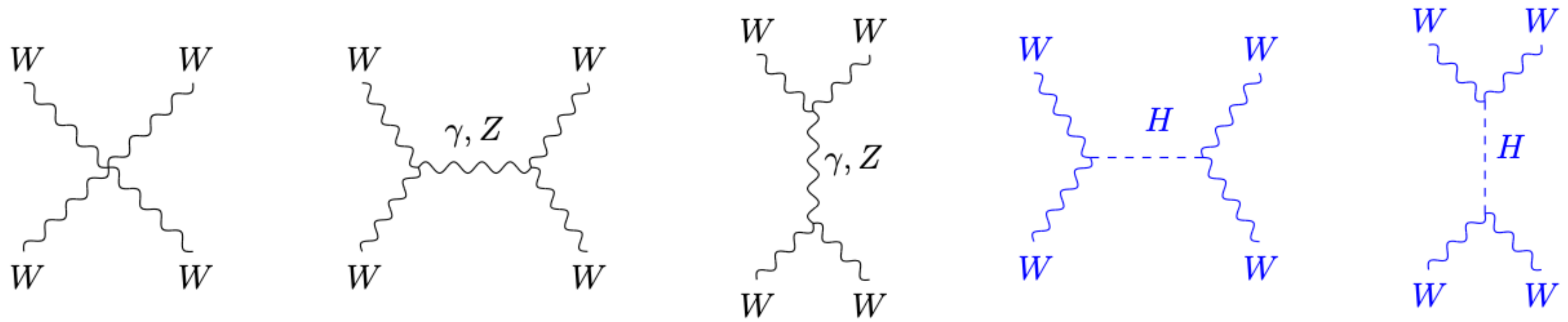
Higgs boson ensures unitarity of the W scattering (If its mass is $\lesssim 1$ TeV.)

SM fails at the Planck scale.

Is there a reason to assume that there is
New Physics between the weak and the Planck scale?

Weakly or Strongly Interacting Higgs?

Scattering of longitudinally polarized W bosons



$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs boson ensures unitarity of the W scattering (If its mass is $\lesssim 1$ TeV.)

SM fails at the Planck scale.

Is there a reason to assume that there is
New Physics between the weak and the Planck scale?

Types of Higgs Sector Extensions

- ✏ Strongly interacting light Higgs
- ✏ Weakly interacting
- ✏ SUSY/non-SUSY (w/ or w/o discrete symmetries)
- ✏ singlet/doublet/triplet extensions
- ✏ w/ or w/o CP violation
- ✏ ...

Singlet Extensions

Complex Singlet Extended SM (CxSM)

- Add complex singlet field w/ hypercharge 0 to the SM Higgs sector:

$$\mathbb{S} = S + iA$$

- CxSM Higgs potential (renormalizable, w/ global softly broken U(1) symmetry):

$$V_{\rm CxSM} = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \boxed{\left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right)}$$

- Doublet and singlet fields:

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} \quad \text{and} \quad \mathbb{S} = \frac{1}{\sqrt{2}}\left[v_S + S + i(v_A + A)\right]$$

v=246 GeV electroweak VEV; v_S, v_A singlet VEVs of real and imaginary field component

- Applying discrete symmetries: possibility to have DM candidate, e.g.
  impose two separate discrete symmetries: S -> -S and A -> -A ($b_1 \in \mathbb{R}$, $a_1 = 0$)
  - v_A=v_S=0 => h is SM Higgs boson, 2 Dark Matter particles (S,A)
  - v_A=0 => A is the Dark Matter candidate, h mixes with S => 2 visible Higgs bosons h_i (i=1,2), one must behave SM-like

  Spectrum: h_1, h_2, A; one of the $h_{1,2}$ is the h_{125}

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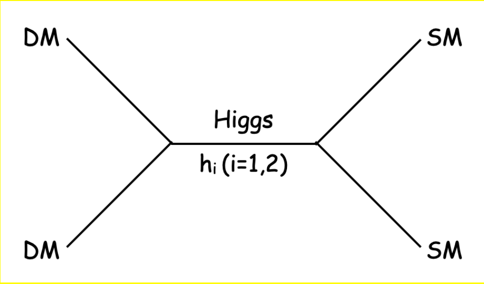
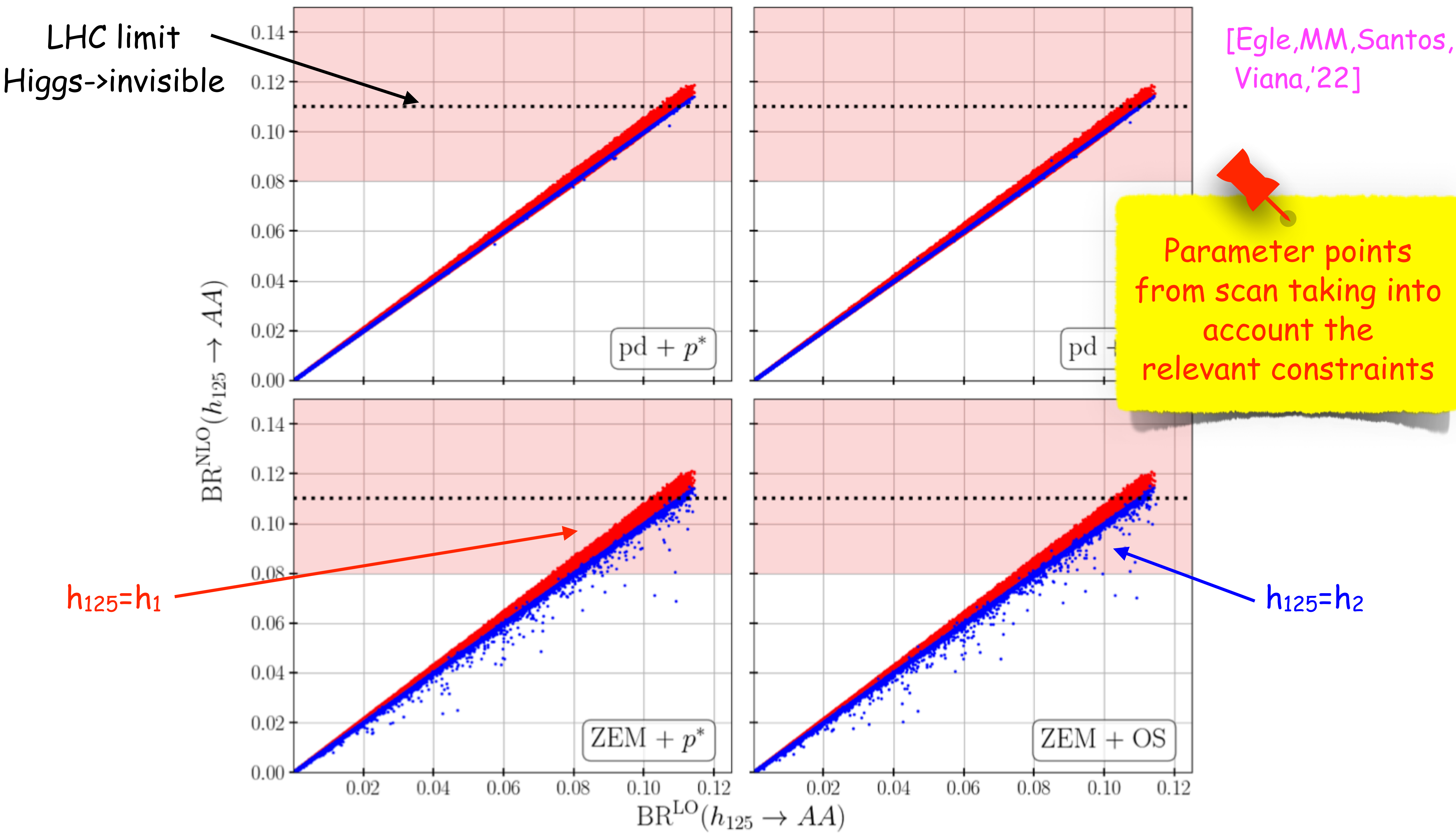
Spectrum: h_1, h_2, A; one of the $h_{1,2}$ is the h_{125}

Higgs as portal to DM

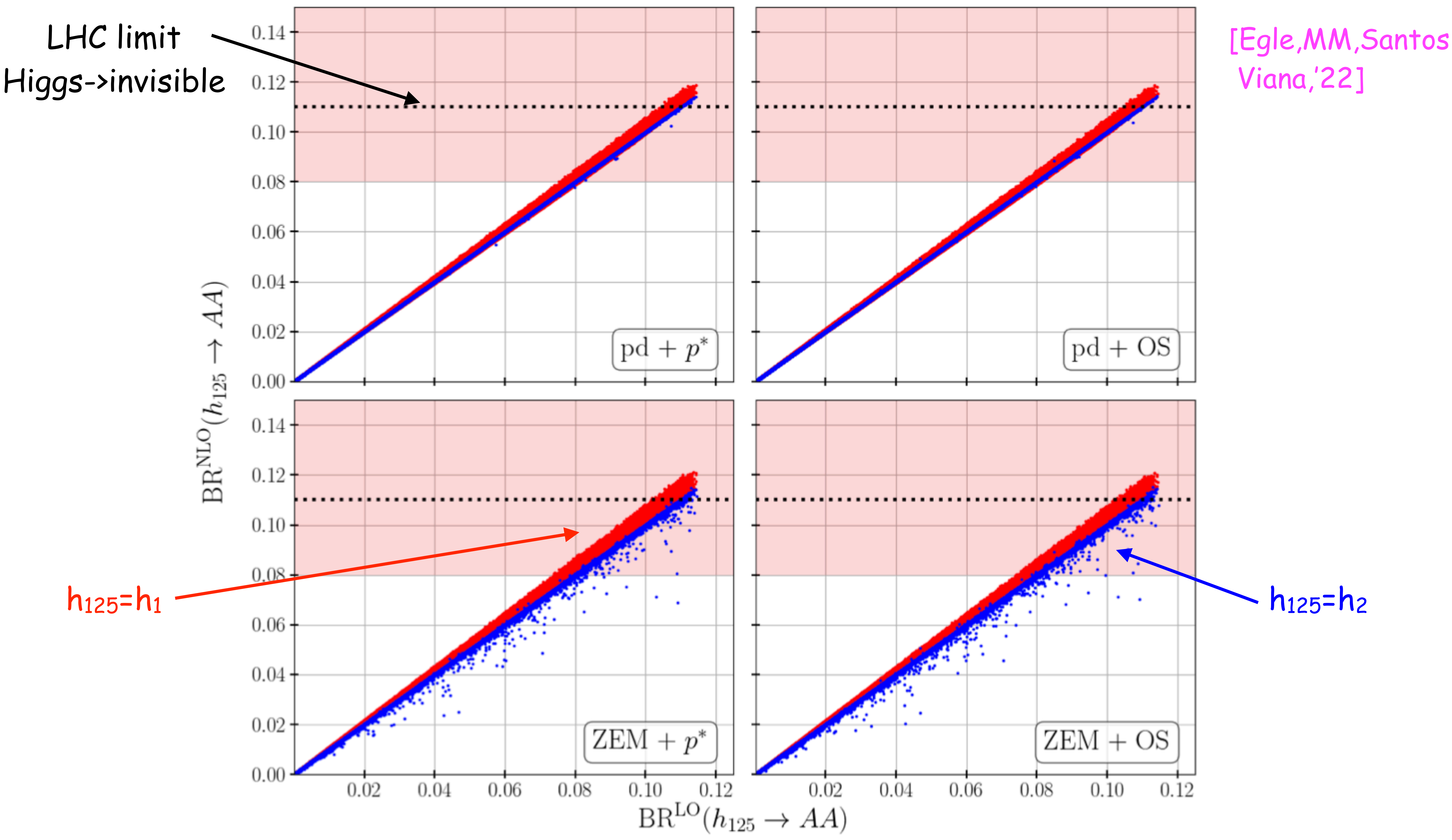


LHC Test: Higgs Decay into 2 DM Particles $h_{125} \to AA$



Parameter point allowed at leading order may be excluded at next-to-leading order and vice versa

LHC Test: Higgs Decay into 2 DM Particles $h_{125} \to AA$



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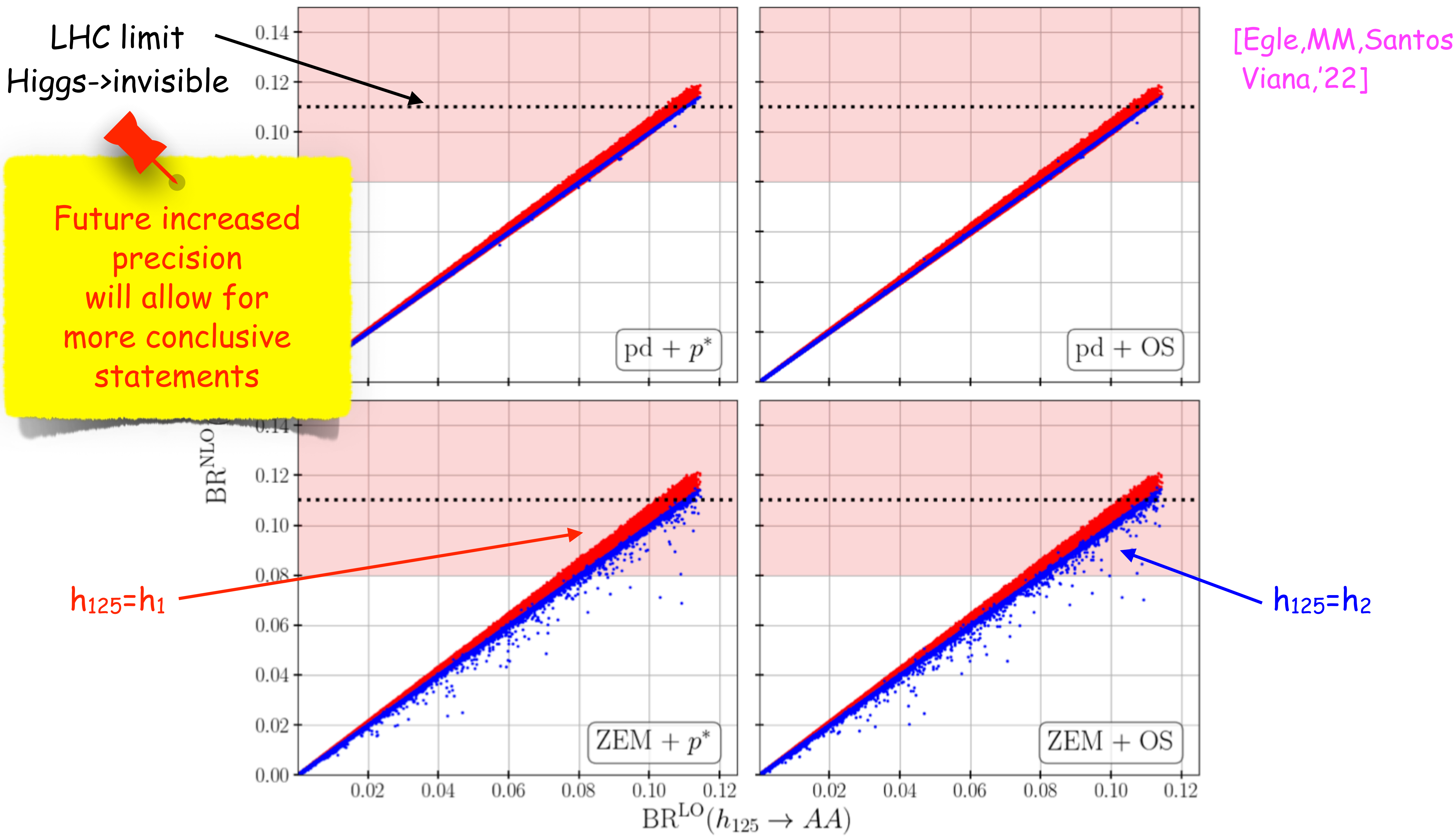
LHC Test: Higgs Decay into 2 DM Particles $h_{125} \to AA$

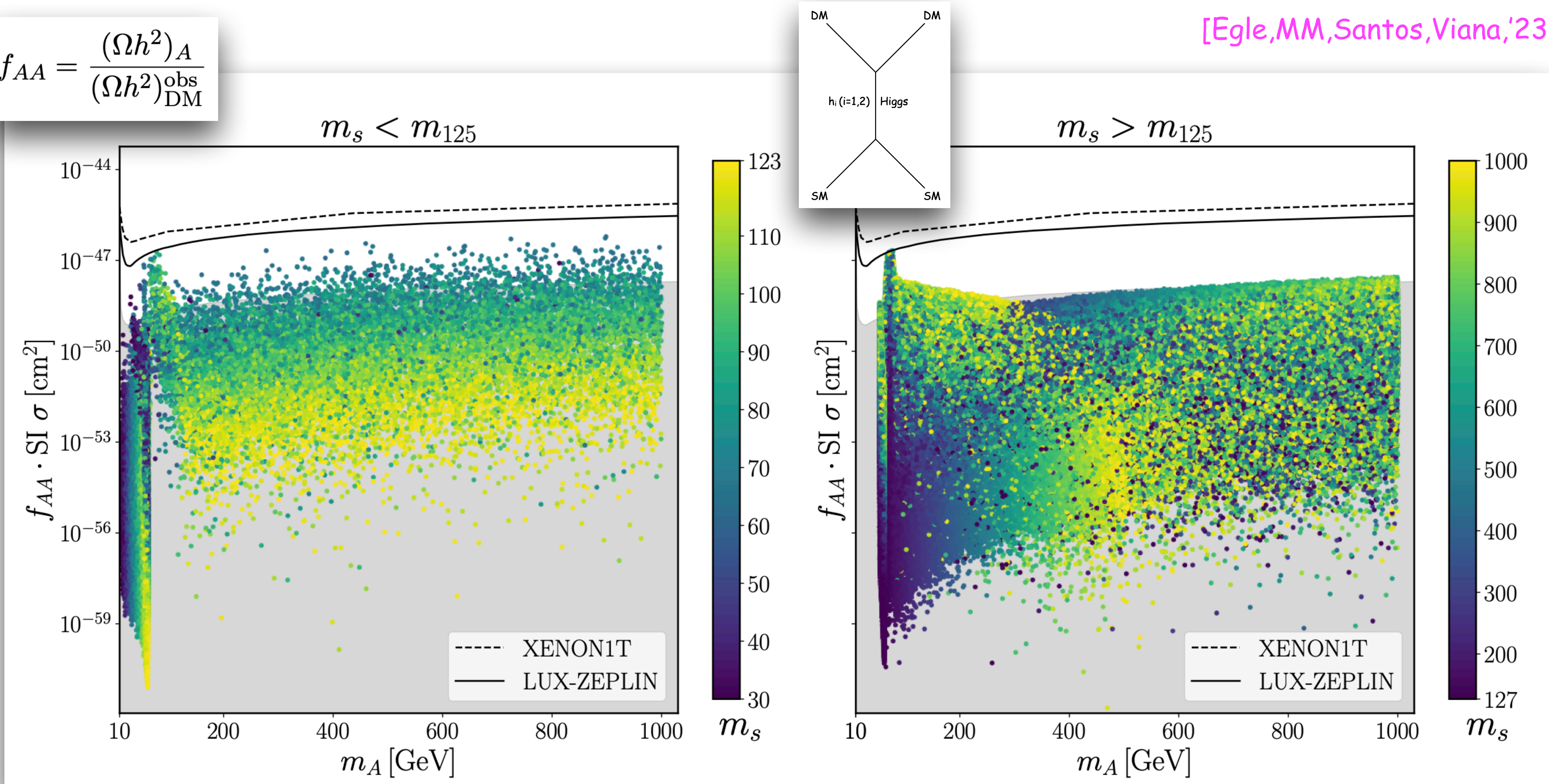


Parameter point allowed at leading order may be excluded at next-to-leading order and vice versa

Compatibility w/ Direct Detection Constraints

$$f_{AA} = \frac{(\Omega h^2)_A}{(\Omega h^2)^{\text{obs}}_{\text{DM}}}$$

[Egle,MM,Santos,Viana,'23]

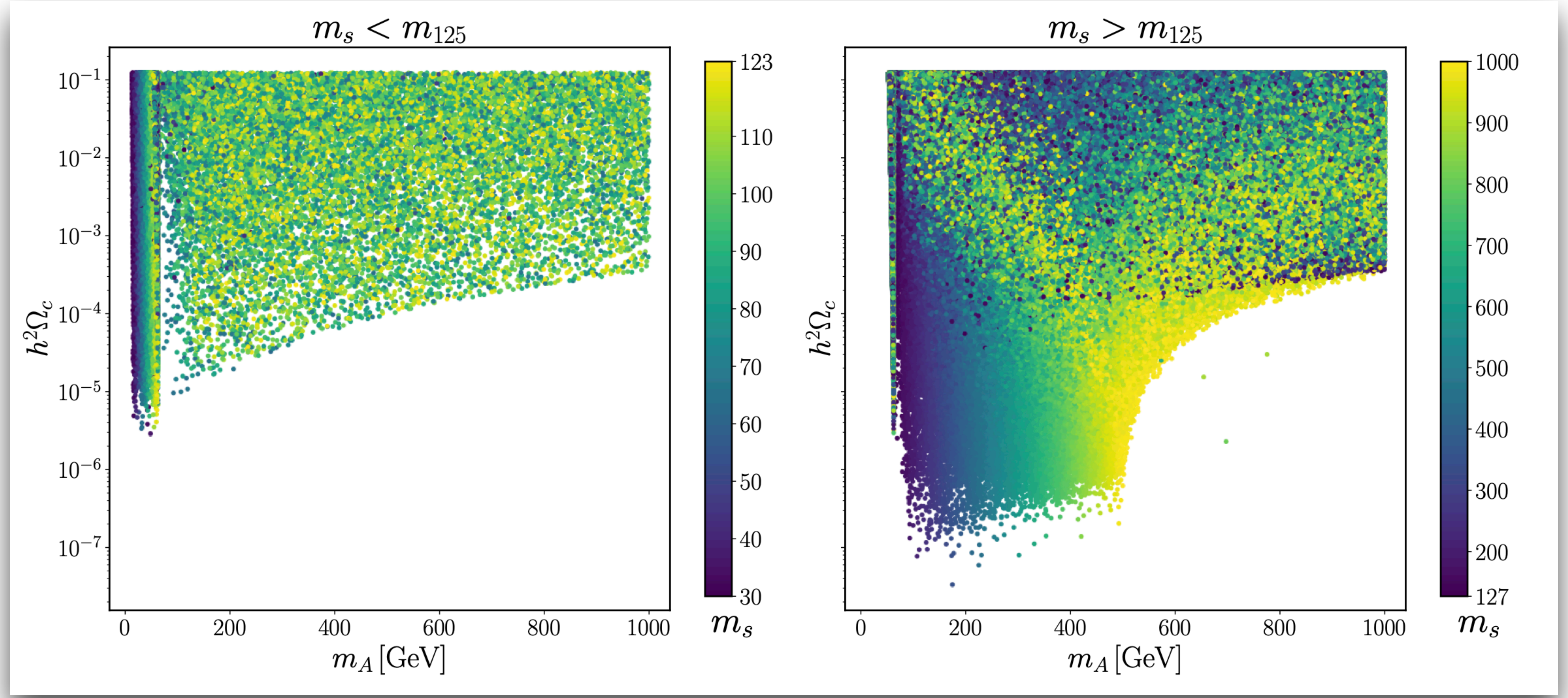


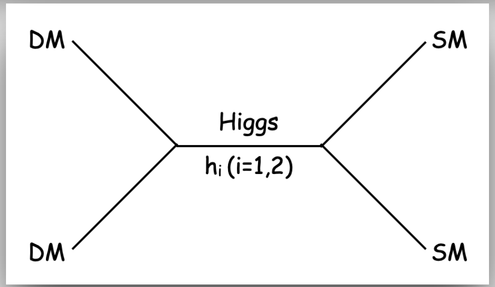
m_{125} mass of SM-like Higgs, m_s mass of non-SM-like Higgs

SI σ : spin-independent DM-nucleon scattering cross section

Compatibility w/ Relic Density

[Egle,MM,Santos,Viana,'23]





Real Singlet Extended SM (RxSM)

✏ Add real singlet field S w/ discrete $\mathbb{Z}_2$ symmetry ($S \to -S$) to the SM Higgs sector

✏ Most general renormalizable RxSM Higgs potential:

$$V_{\rm RxSM} = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4$$

✏ Higgs doublet and singlet field:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} \quad \text{and} \quad S = v_S + s$$

v=246 GeV electroweak SM VEV; v_S singlet VEV

✏ 2 possible phases:

Symmetric phase w/ $v_S = 0$: h is SM Higgs, S is DM candidate

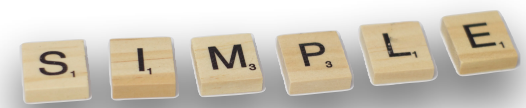
Broken phase w/ $v_S \neq 0$: h mixes with S ⇝ 2 visible Higgs bosons h_i ($i = 1,2$)

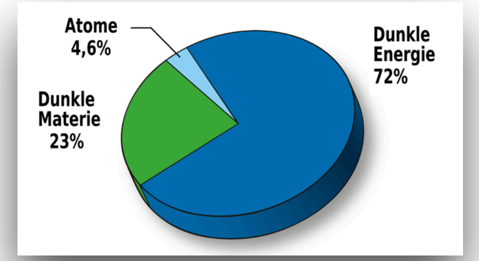
The 2-Higgs-Doublet Model (2HDM)

The 2-Higgs-Doublet Model (2HDM)

✏ The 2-Higgs-Doublet Model (2HDM) - Motivation:

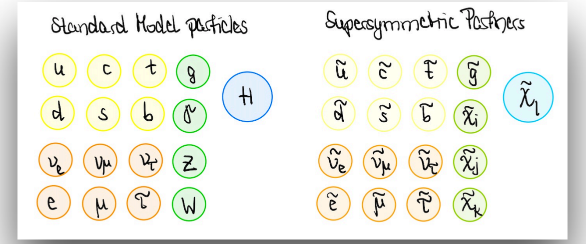
- one of the simplest SM extensions



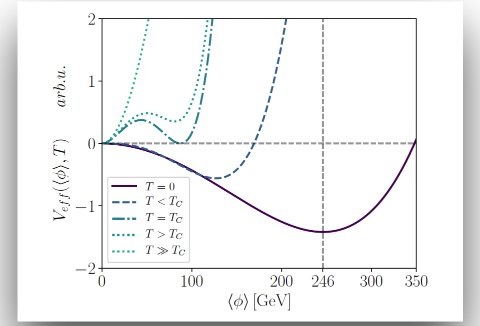


- provides DM candidate in its inert version

- supersymmetry requires introduction
  of two Higgs doublets



- provides strong-first-order phase transition
  (one of the three Sakharov conditions for the generation of
  the baryon asymmetry through EW baryogenesis)



The 2-Higgs-Doublet Model (2HDM)

✏ Compatibility with constraints?

* Rho parameter: fulfilled as it is a doublet extension

* Flavour-changing neutral currents: will be discussed below

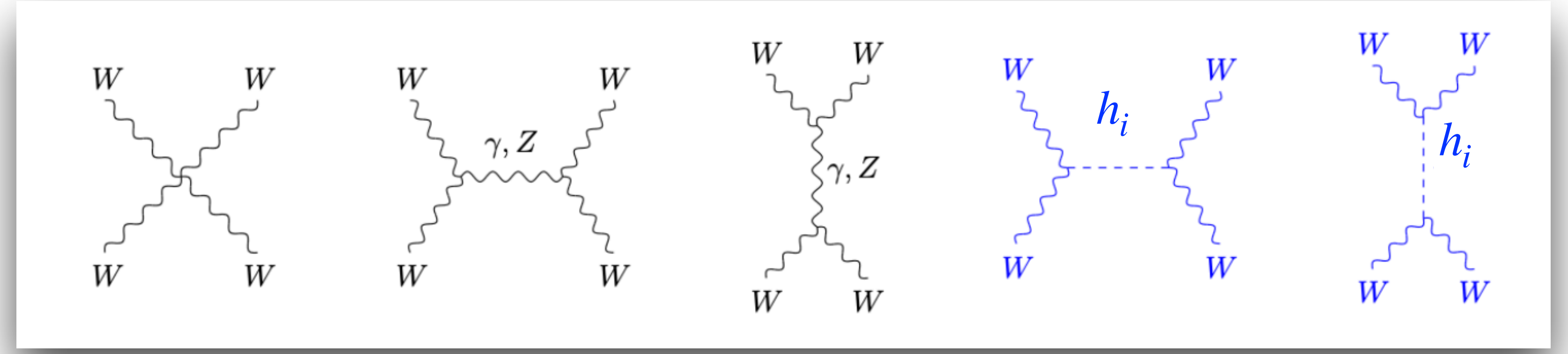
* Unitarity constraints:

$V_L V_L \to V_L V_L,\ f_+ \bar{f}_+ \to V_L V_L$ (f_+=fermion w/ positive helicity) must not violate unitarity bounds

SM: ∃ Higgs w/ couplings $g_{HWW} = \frac{g m_W}{2}$ and $g_{Hff} = \frac{g m_f}{\sqrt{2} m_W}$

2HDM:, ∃ two scalar Higgs bosons: $h_i = h, H$ with sum rules for the couplings:

$$\sum_i g^2_{h_i VV} = g^2_{hVV} + g^2_{HVV} = (g^{\rm SM}_{HVV})^2 \quad \text{and} \quad \sum_i g_{h_i VV} g_{h_i ff} = g_{hVV} g_{hff} + g_{HVV} g_{Hff} = g^{\rm SM}_{HVV} g^{\rm SM}_{Hff}$$



The 2HDM Higgs Potential

[T.D.Lee,Phys.Rev.D8(1973)1226; Branco eal.,1106.0034]

✏ 2 Higgs doublets Φ_i $(i = 1{,}2)$ w/ potential having the following properties:
SU(2)$_L$xU(1)$_Y$ gauge-invariant, renormalizable, CP conservation,
discrete $\mathbb{Z}_2$ symmetry under which $\Phi_1 \to -\Phi_1$, $\Phi_2 \to \Phi_2$ => potential w/ softly broken $\mathbb{Z}_2$

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2$$
$$+ \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]$$

CP conservation: all parameters are real

✏ Electroweak minimum of the potential: $\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$ and $\langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$

✏ Expansion of Higgs doublets around VEVs: $\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \qquad a = 1, 2$

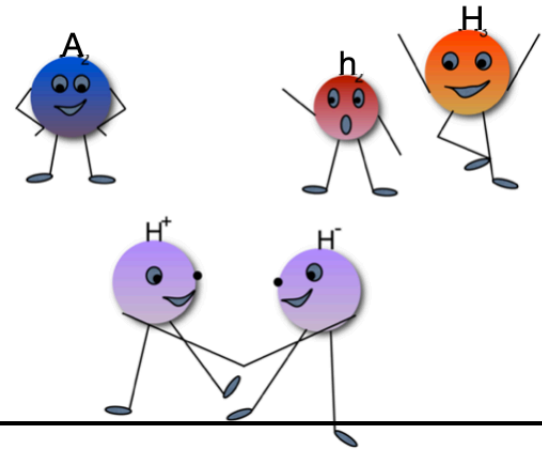
The 2HDM Higgs Spectrum

✏ Higgs spectrum and masses:

- Plug in expansion around EW minimum in the potential V
- collect all terms bilinear in the fields ~> mass matrices
- diagonalize mass matrices w/ orthogonal matrices that are functions of the
  mixing angle α (neutral CP-even matrix) and
  mixing angle β (neutral CP-odd and charged matrices) ~>

  physical states

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} , \quad \begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} , \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$



The 2HDM Higgs Masses

✏ Higgs spectrum and masses:

2 neutral CP-even Higgs bosons: h and H, with $m_h \leq m_H$
1 neutral CP-odd Higgs boson: A
2 charged Higgs bosons: H^+, H^-

Mixing angle β : $\tan\beta = \frac{v_2}{v_1}$; to reproduce the W and Z masses, we must have $v_1^2 + v_2^2 = v^2$

Masses:

$$m_{H^\pm}^2 = \left(\frac{m_{12}^2}{v_1 v_2} - \frac{\lambda_4 + \lambda_5}{2}\right)(v_1^2 + v_2^2) = M^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

$$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

$$m_A^2 = \left(\frac{m_{12}^2}{v_1 v_2} - \lambda_5\right)(v_1^2 + v_2^2) = M^2 - \lambda_5 v^2$$

$$m_{H,h}^2 = \frac{1}{2}\left[\mathcal{M}_{11} + \mathcal{M}_{22} \pm \sqrt{(\mathcal{M}_{11} - \mathcal{M}_{22})^2 + 4\mathcal{M}_{12}^2}\right]$$

$\mathcal{M}_{ij}$ matrix elements of the mass matrix in the neutral CP-even sector

✏ 2HDM input parameters: $m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \cos(\beta - \alpha), v, \tan\beta$

Flavour-Changing Neutral Currents (FCNC)

✏ Problem w/ 2 Higgs doublets:
Mass and coupling matrices cannot be diagonalized simultaneously ~> FCNC at tree level!

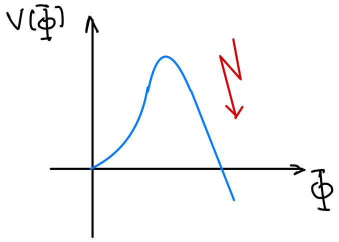
✏ Solution: Extend discrete $\mathbb{Z}_2$ symmetry of Higgs sector to Yukawa sector such that only one Higgs doublet couples to a given right-handed fermion field

✏ Four 2HDM types:

- type I 2HDM: All quarks couple to just one of the Higgs doublets (conventionally chosen to be Φ_2).
- type II 2HDM: The $Q = 2/3$ right-handed (RH) quarks couple to one Higgs doublet (conventionally chosen to be Φ_2) and the $Q = -1/3$ RH quarks couple to the other (Φ_1).
- Lepton-specific model: The RH quarks all couple to Φ_2 and the RH leptons couple to Φ_1.
- Flipped model: The RH up-type quarks couple to Φ_2, the RH down-type quarks couple to Φ_1, as in type II, but now the RH leptons couple to Φ_2.

Theory Constraints

✏ Potential Bounded-From-Below: quartic part of the potential positive for arbitrarily large field values ~> (tree-level analysis)



[Deshpande,Ma,'78;Klimenko,'85]

$$\lambda_1 \geq 0\,, \qquad \lambda_2 \geq 0$$
$$\lambda_3 \geq -\sqrt{\lambda_1\lambda_2}\,, \qquad \lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1\lambda_2}$$

Inclusion of higher-order effects: check the tree-level conditions for running λ_i at any scale Q up to which model is considered to be valid

$$\frac{d\lambda_i}{d\ln Q} = \beta_i(g_j)$$

Theory Constraints

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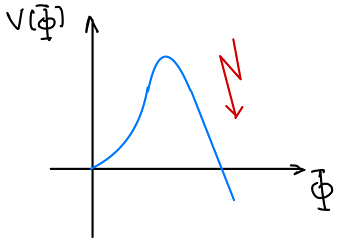

[Deshpande,Ma,'78;Klimenko,'85]

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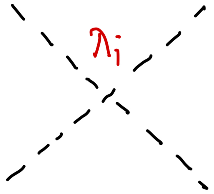
Inclusion of higher-order effects: check the tree-level conditions for running λ_i at any scale Q up to which model is considered to be valid

$$\frac{d\lambda_i}{d\ln Q} = \beta_i(g_j)$$

✏ Perturbative Unitarity:

make sure that the potential couplings do not become non-perturbatively large: analyze eigenvalues of the S matrix for scalar-scalar scattering amplitudes:



=> Require (tree-level perturbative unitarity:

$$\begin{aligned}
|\lambda_3 - \lambda_4| &< 8\pi \\
|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| &< 8\pi \\
\left|\frac{1}{2}\left(\lambda_1 + \lambda_2 + \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\right)\right| &< 8\pi \\
\left|\frac{1}{2}\left(\lambda_1 + \lambda_2 + \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\right)\right| &< 8\pi.
\end{aligned}$$

Theory Constraints - The Vacuum

✏ Electroweak vacuum w/ v=246 GeV is the global minimum:

possible 2HDM vacuum directions ω_i

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\,\eta_1 \\ \zeta_1 + \omega_1 + i\,\psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \omega_{CB} + i\,\eta_2 \\ \zeta_2 + \omega_2 + i\,(\psi_2 + \omega_{CP}) \end{pmatrix}$$

neutral CP-conserving minima: ω_1, ω_2

neutral CP-violating minimum: ω_{CP}

charge-breaking minimum: ω_{CB}

[Ferreira eal,'04;Barroso eal,'05;Ivanov,'07;Ivanov'08]

- If the potential has a CP-conserving minimum ω_1, ω_2 , then any other stationary point (either ω_{CP} or ω_{CB}) is a saddle point w/ a higher value of the potential

[Ivanov'08;Barroso,'12,'13]

- Two CP-conserving minima could coexist, however! Panic Vacuum!

Vacuum w/ the symmetry breaking pattern (v=246 GeV) is the global minimum if and only if

$$D = m_{12}^2 (m_{11}^2 - \sqrt{\lambda_1/\lambda_2}\, m_{22}^2)(v_2/v_1 - (\lambda_1\lambda_2)^{1/4}) > 0$$

Theory Constraints - The Vacuum

✏ Electroweak vacuum w/ v=246 GeV is the global minimum:

possible 2HDM vacuum directions ω_i

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\,\eta_1 \\ \zeta_1 + \omega_1 + i\,\psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \omega_{\rm CB} + i\,\eta_2 \\ \zeta_2 + \omega_2 + i\,(\psi_2 + \omega_{\rm CP}) \end{pmatrix}$$

Note: These rules are No longer valid when vacuum is investigated including higher-order corrections

neutral CP-conserving minima: ω_1, ω_2

neutral CP-violating minimum: $\omega_{\rm CP}$

charge-breaking minimum: $\omega_{\rm CB}$

[Ferreira eal,'04;Barroso eal,'05;Ivanov,'07;Ivanov'08]

- If the potential has a CP-conserving minimum ω_1, ω_2 , then any other stationary point (either $\omega_{\rm CP}$ or $\omega_{\rm CB}$) is a saddle point w/ a higher value of the potential

[Ivanov'08;Barroso,'12,'13]

- Two CP-conserving minima could coexist, however! Panic Vacuum!

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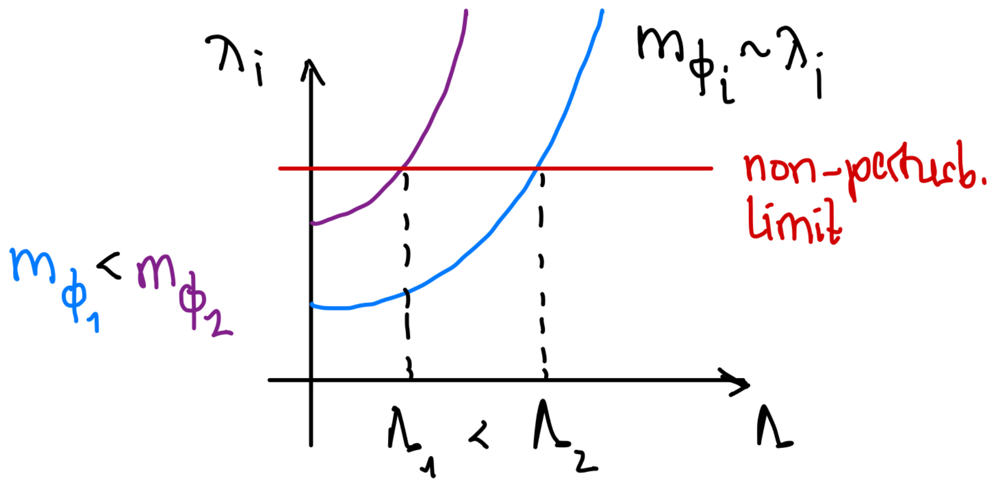
Theory Constraints

- Inclusion of renormalization group running of the parameters:
  (capture - „hopefully" - bulk of higher-order corrections)

[Basler,Ferreira,MM,Santos,'17]

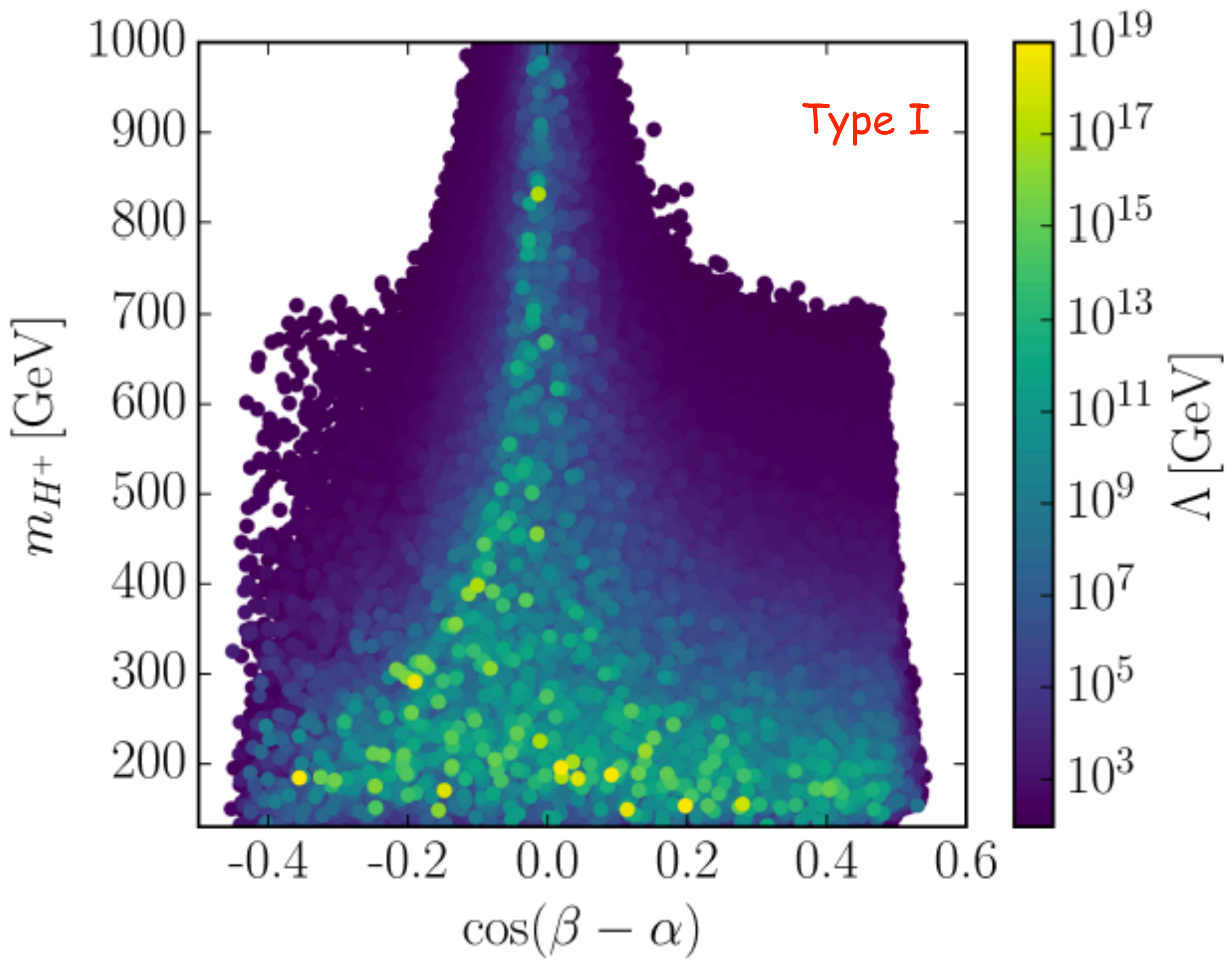
- Perform RGE running of all potential parameters and VEVs starting at m_Z
- At each scale between m_Z and the Planck scale verify whether the theoretical constraints are still verified
- If yes, proceed to a higher scale and repeat

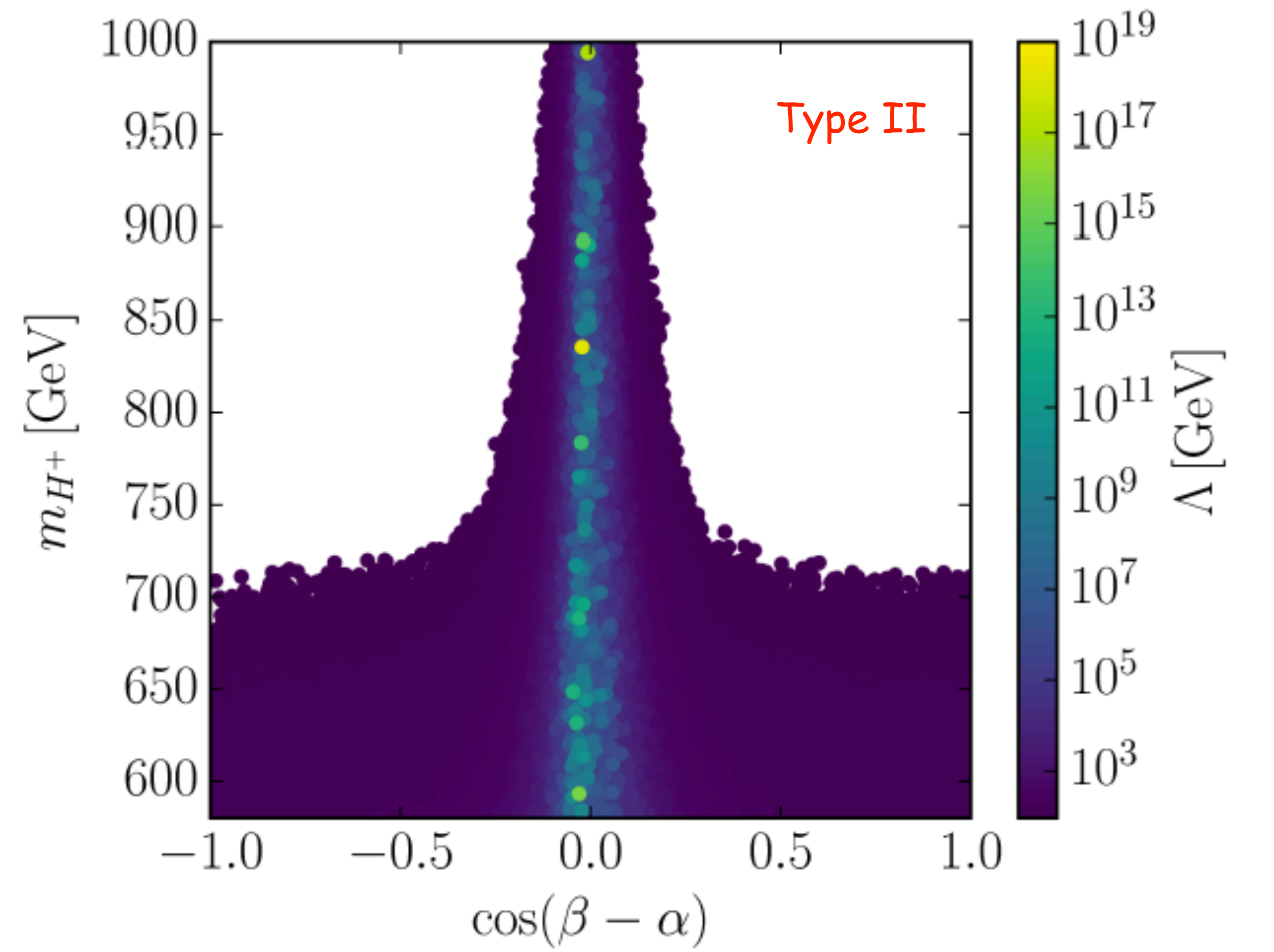
Note: Higgs mass values and quartic couplings are closely related ~> if at scale m_Z we start with a heavy Higgs spectrum ~> start values of quartic couplings λ_i are large ~> scale up to which model remains perturbative, is lowered



Theory Constraints and High Scale Impact

Flavor constraints set stringent lower bound on $m_{H^\pm}$ in 2HDM Type II! [Basler,Ferreira,MM,Santos,'17]





$m_{H^\pm} \geq 500 GeV$ and requirement of validity up to the Planck scale ~> alignment (exp. & theor. constraints included) $\cos(\beta-\alpha) \approx 0$, i.e. h behaves very SM-like

See also [Chakrabarty eal; Bhupal Dev eal; Das,Saha; Chowdhury,Eberhardt; Ferreira eal; Cacchio eal; Cherchiglia,Nishi; Krauss eal; Goodsell,Staub; Braathen eal; ...]

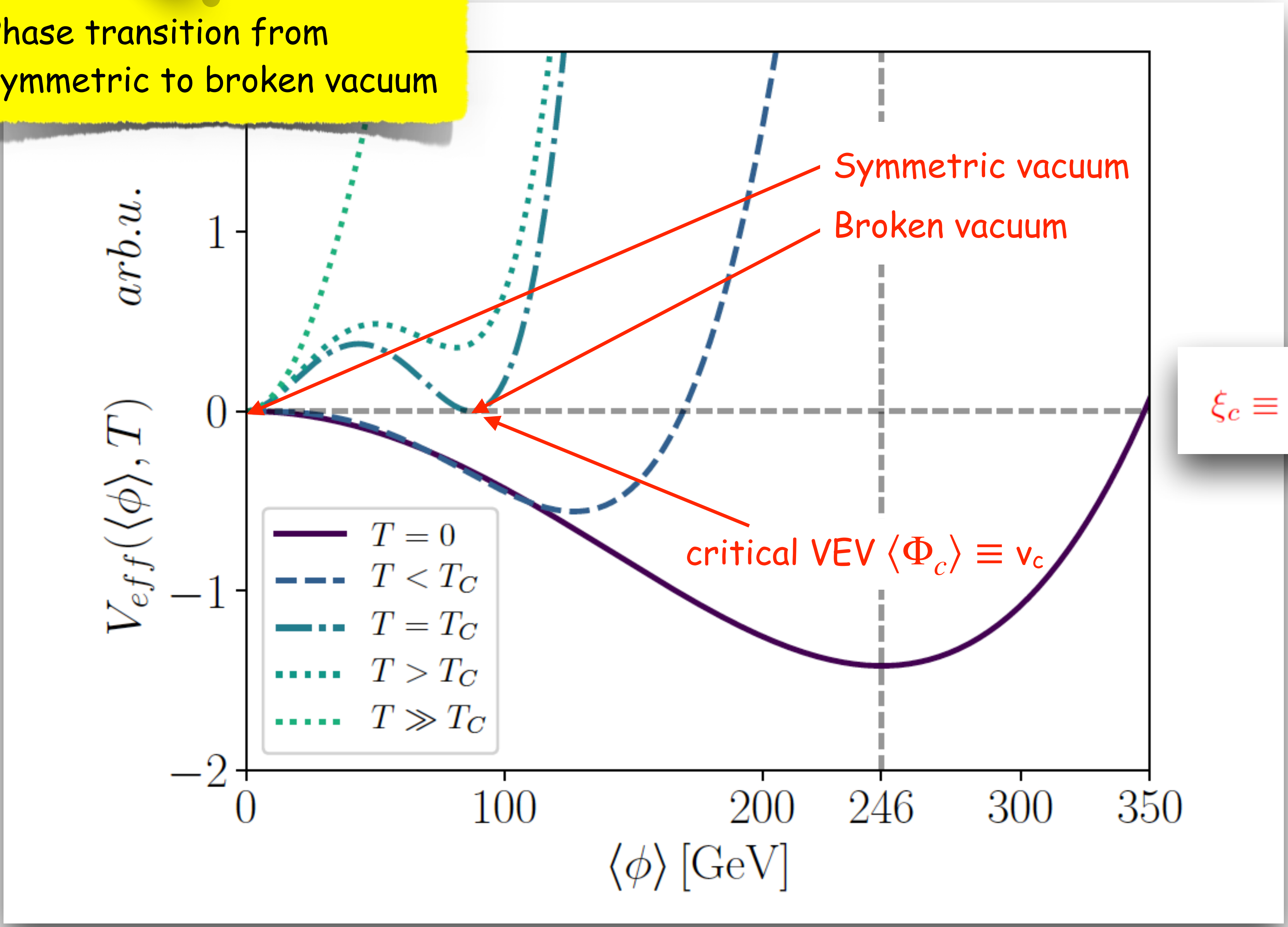
What happens during evolution of the Universe?

✏ What about the Higgs potential during the evolution of the Universe?
investigation of effective Higgs potential at non-zero temperature

Strong First-Order Electroweak Phase Transition (SFOEWPT)

Phase transition from symmetric to broken vacuum

[From Ph. Basler, PhD Thesis]



$$\xi_c \equiv \frac{\langle\Phi_c\rangle}{T_c} \geq 1$$

What happens during evolution of the Universe?

✏ What about the Higgs potential during the evolution of the Universe?
investigation of effective Higgs potential at non-zero temperature

✏ Vacuum of the 2-Higgs-Doublet-Model: four minimum directions possible

$$V_{\rm tree} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + {\rm h.c.} \right] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + {\rm h.c.} \right] .$$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\,\eta_1 \\ \zeta_1 + \omega_1 + i\,\psi_1 \end{pmatrix} , \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \omega_{\rm CB} + i\,\eta_2 \\ \zeta_2 + \omega_2 + i\,(\psi_2 + \omega_{\rm CP}) \end{pmatrix}$$

$$\{\omega_{\rm CB}, \omega_1, \omega_2, \omega_{\rm CP}\}|_{T=0} = \{0, v_1, v_2, 0\} , \text{ with}$$

$$\omega_{\rm EW}|_{T=0} \equiv \left. \sqrt{\omega_1^2 + \omega_2^2 + \omega_{\rm CB}^2 + \omega_{\rm CP}^2} \right|_{T=0} = \sqrt{v_1^2 + v_2^2} \equiv v = 246 \text{ GeV}$$

Sample Benchmark Point BP1

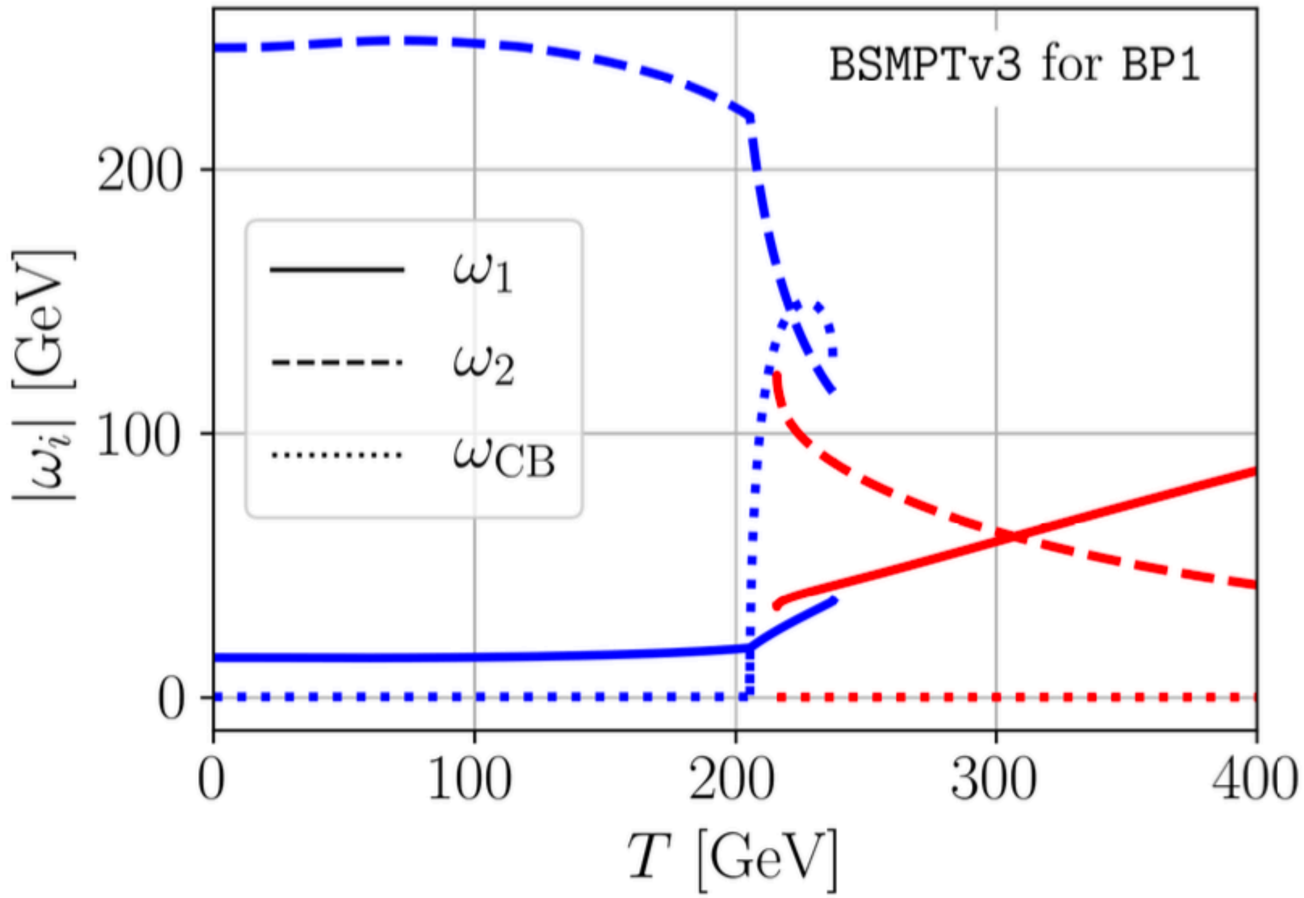
- BP1 input parameters:

From [Aoki,Biermann,Borschensky,Ivanov,MM,Sakurai,'23]

$$\texttt{BP1:} \quad \text{type} = 1\,,\ \lambda_1 = 6.931\,,\ \lambda_2 = 0.2631\,,\ \lambda_3 = 1.287\,,\ \lambda_4 = 4.772\,,\ \lambda_5 = 4.728\,,$$
$$m_{12}^2 = 1.893 \times 10^4\,\text{GeV}^2\,,\ \tan\beta = 16.578\,.$$

Transition History

high-T phase, low-T phase [Basler,Biermann,MM,Müller,Santos,Viana,´24]



	BP1
phases$_{\texttt{BSMPT}}$	0: {216, 400}
	1: {0, 237}
pairs$_{\texttt{BSMPT}}$	0: [0 → 1] {216, 237}
$t_{\texttt{MinimaTracer}}$	41.47 s
T_c	{226.3}
T_n	{222.9, 222.9}
T_p	{222.6}
T_f	{222.6}
$t_{\texttt{CalcTemps}}$	6.87 min
history	0 − (0) → 1

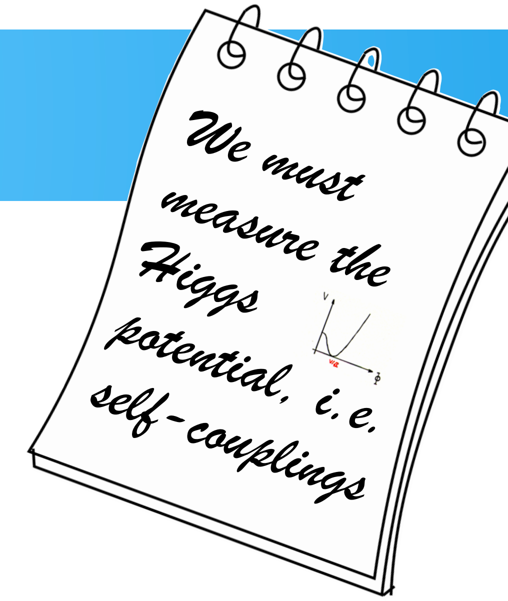
History:

BSMPTv3

- first-order PT from neutral (red) to charge-breaking CB phase (blue)
- second-order PT into a neutral minimum

Measuring EWSB

Trilinear Higgs Self-Coupling



❖ SM Higgs potential: in physical gauge

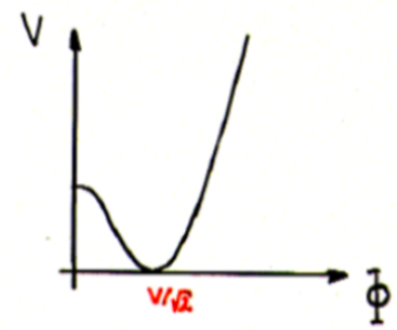
$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higgs self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$

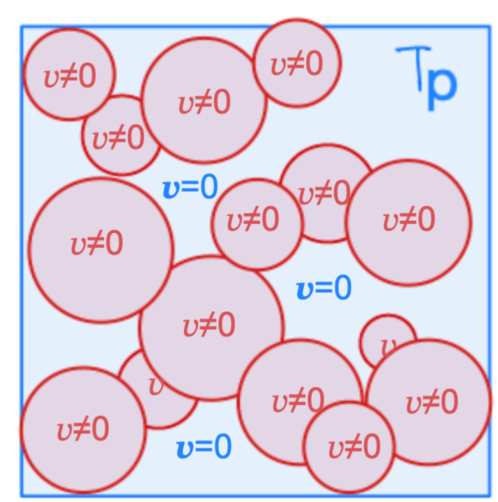
(units $\lambda_0 = 33.8\,\mathrm{GeV}/\lambda_0^2$)



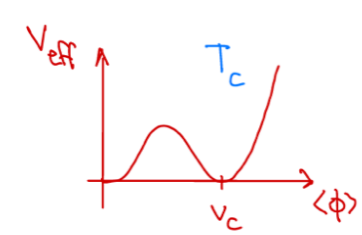
Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential	}	Experimental verification Of the scalar sector of the EWSB mechanism

❖ Importance of the trilinear Higgs self-coupling:

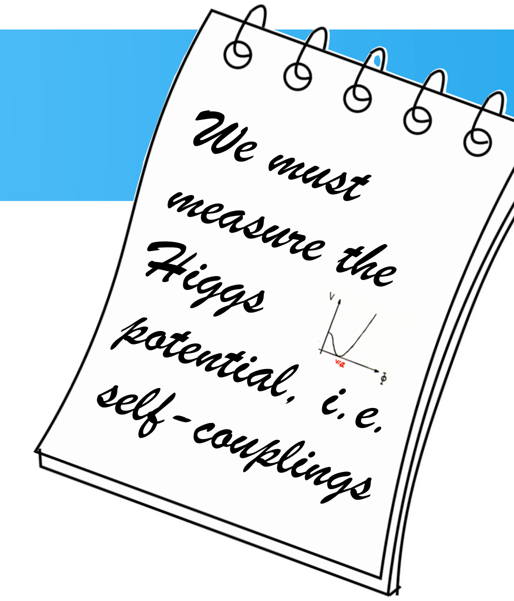
- Determines shape of the Higgs potential
- Sensitive to beyond-SM physics
- Important input for electroweak phase transition*



*matter-asymmetry through electroweak baryogenesis



Trilinear Higgs Self-Coupling



❖ SM Higgs potential: in physical gauge

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

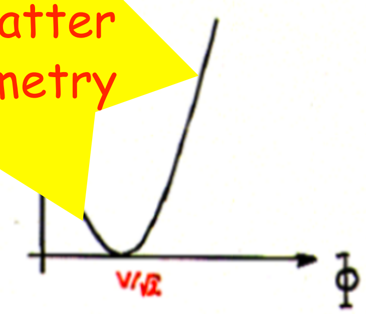
trilinear coupling : $\lambda_{HHH} = 3M_H^2/M_Z^2$

quartic coupling : $\lambda_{HHHH} = 3M_H^2/M_Z^4$

(units $\lambda_0 = 33.8\,\text{GeV}/\lambda_0^2$)

Ultimate test Higgs Mechanism

Matter-Antimatter Asymmetry



New Physics

Evolution of Cosmos

Measurement of scalar boson self-couplings and Reconstruction of the EWSB potential	}	Experimental verification Of the scalar sector of the EWSB mechanism

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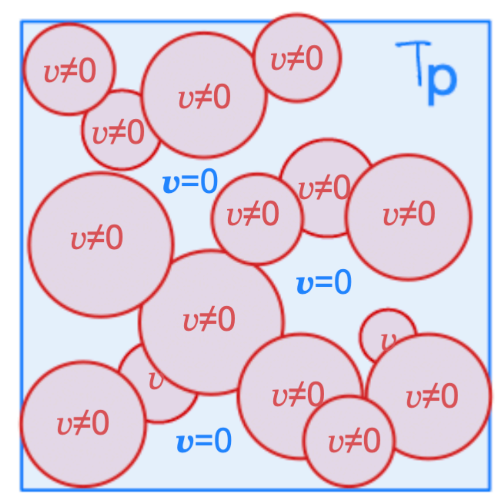

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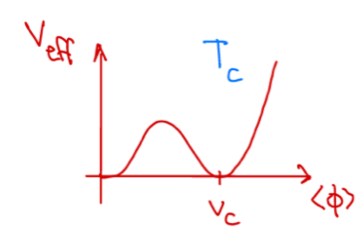
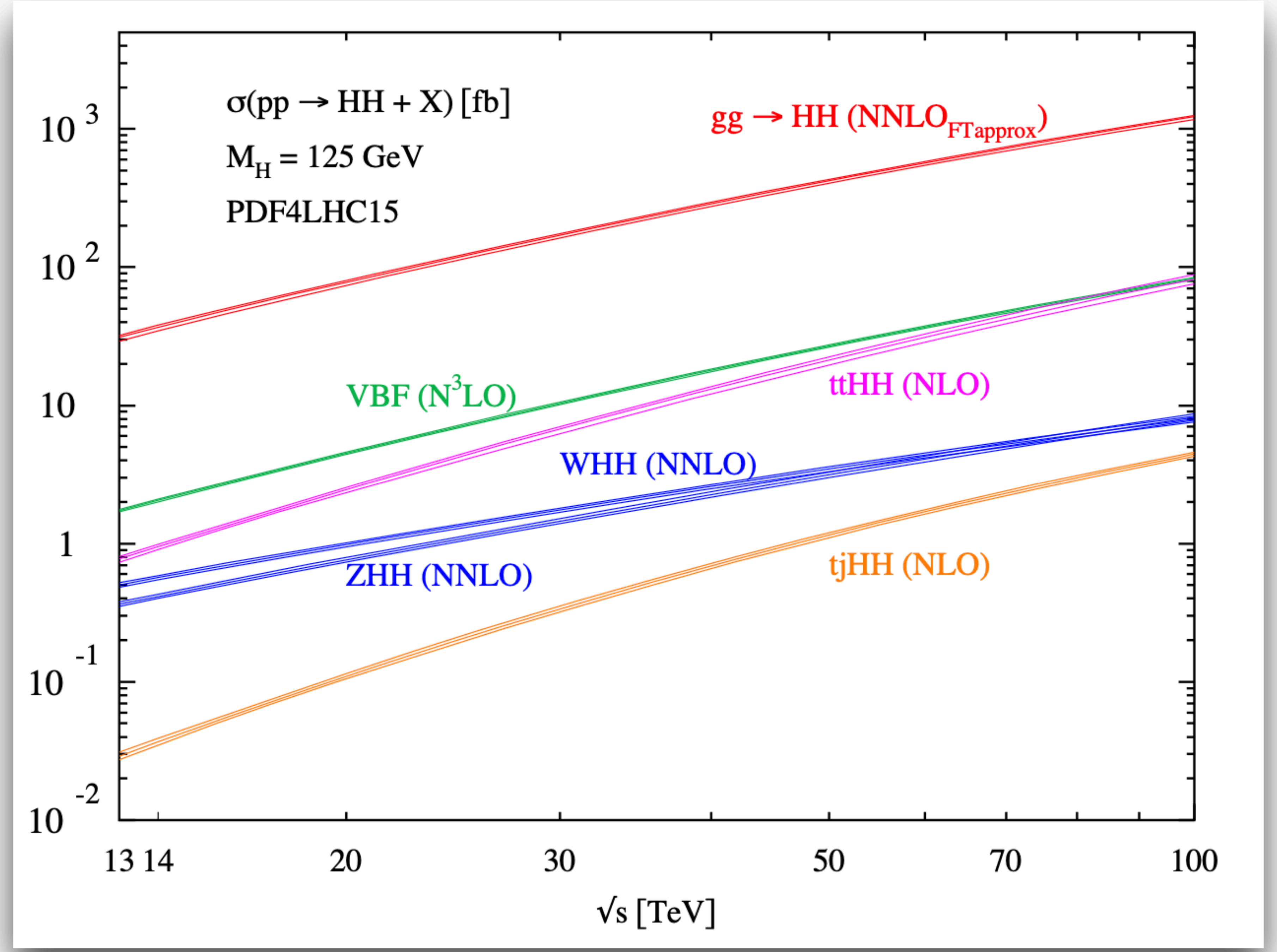


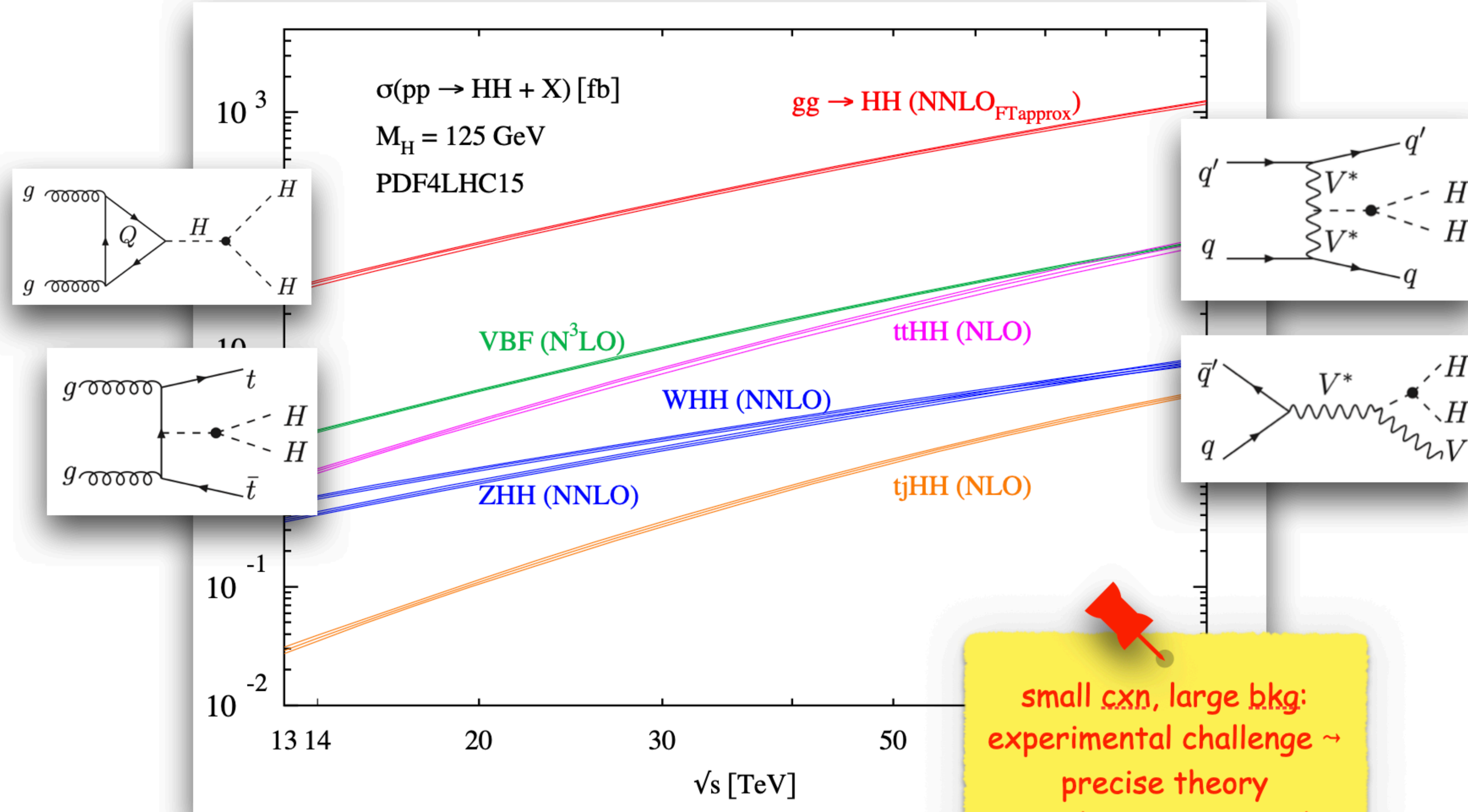
Measurement of λ_{HHH} - Higgs Pair Production

[HH, White paper]



Measurement of λ_{HHH} - Higgs Pair Production

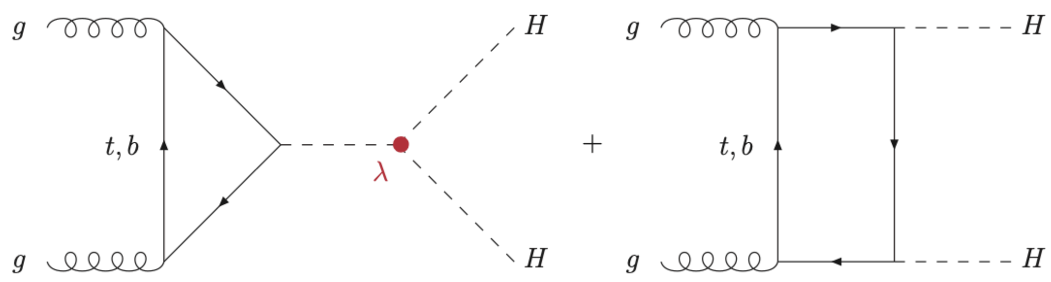
[HH, White paper]



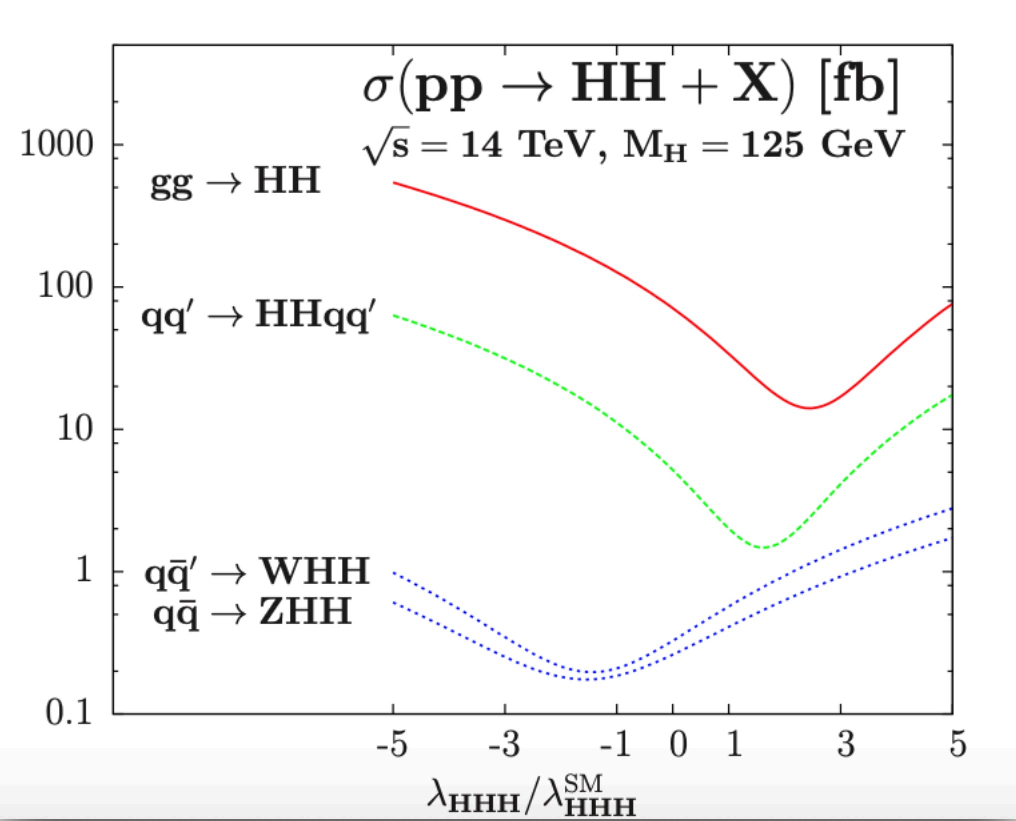
small cxn, large bkg: experimental challenge ⇝ precise theory predictions required

Higgs Pair Production through Gluon Fusion

- Loop mediated at leading order - SM: third generation dominant



- Threshold region sensitive to λ; large M_{HH}: sensitive to c_{tt}/c_{bb} [e.g. boosted Higgs pairs]



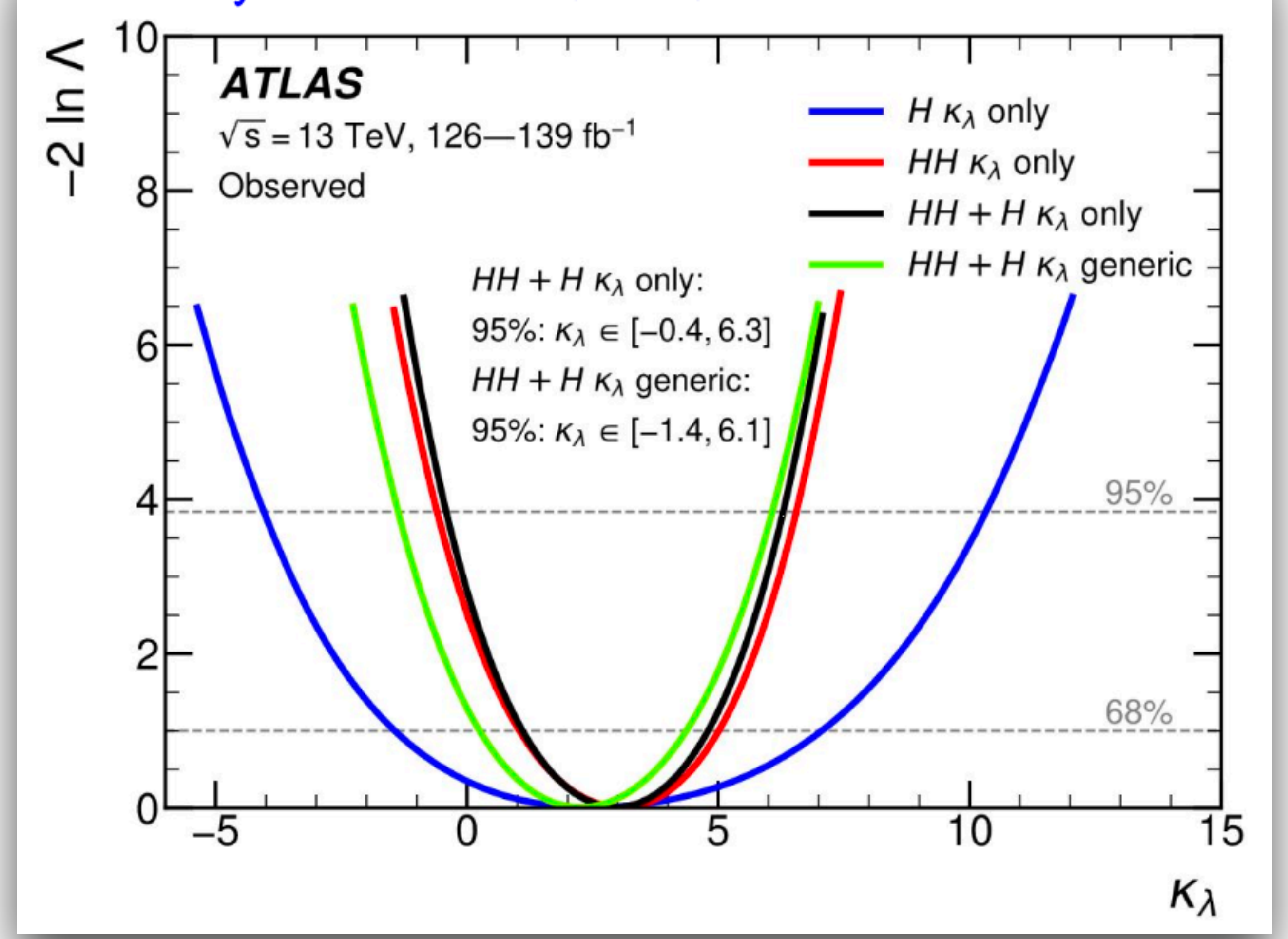
[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

decreasing with M_{HH}

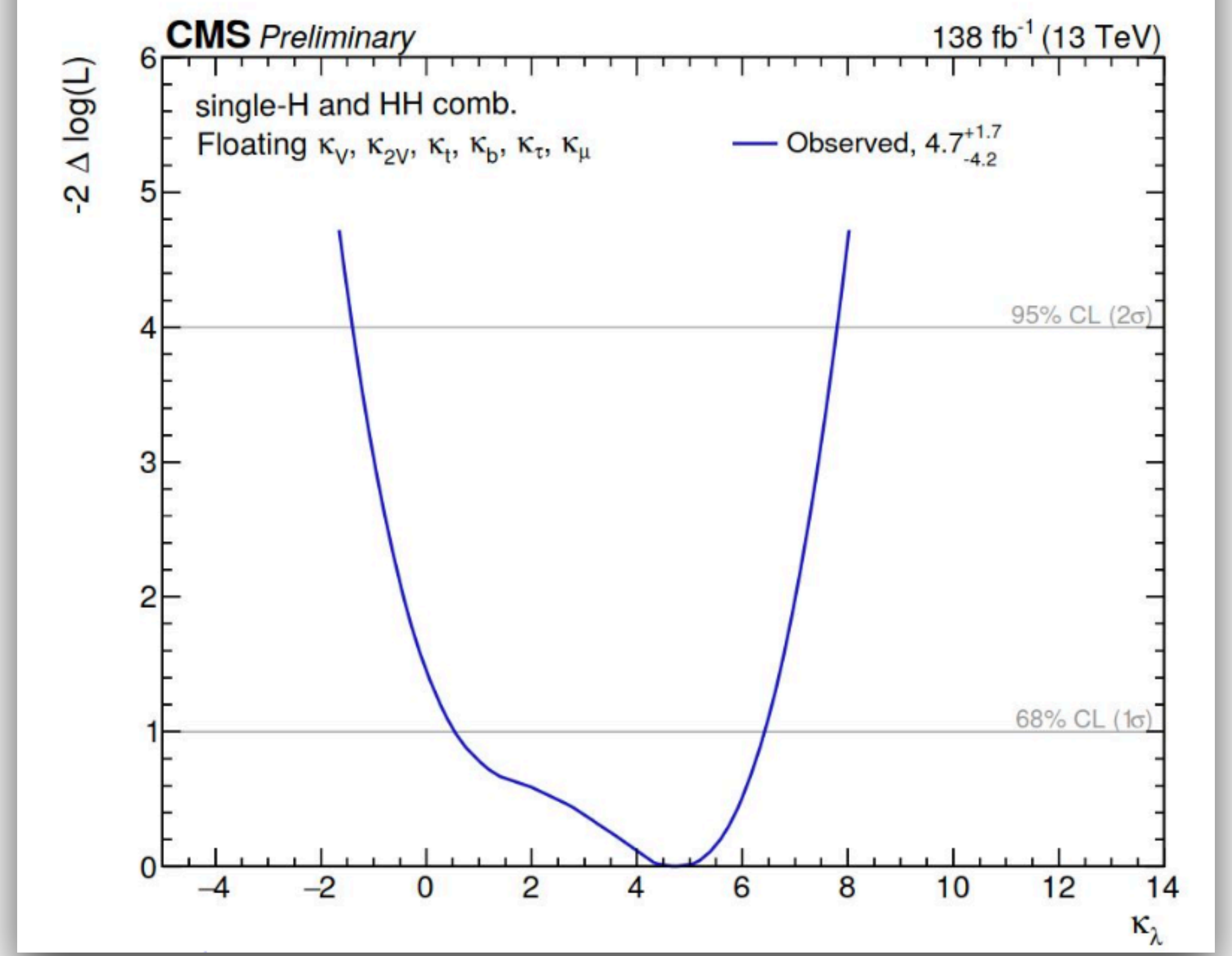
Experimental Results - Limits on λ_{HHH}

Phys. Lett. B 843 (2023) 137745



ATLAS: $-1.4 < \kappa_\lambda < 6.1$ at 95 % CL

CMS-HIG-23-006



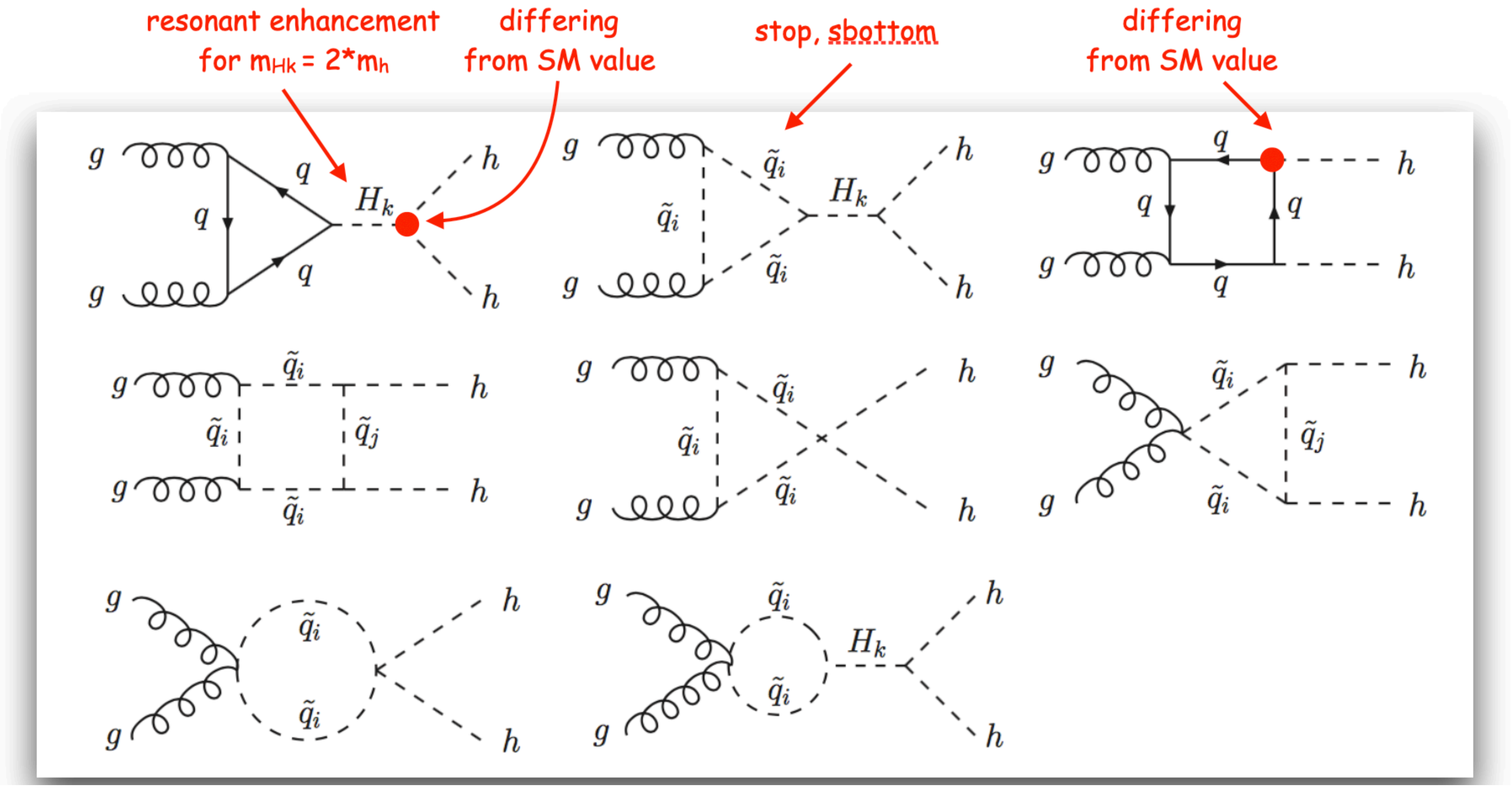
CMS: $-1.2 < \kappa_\lambda < 7.5$ at 95 % CL

New Physics Effects in Higgs Pair Production

- Cross section: - different trilinear couplings - different Yukawa couplings - novel particles in the loops - resonant enhancement - novel couplings

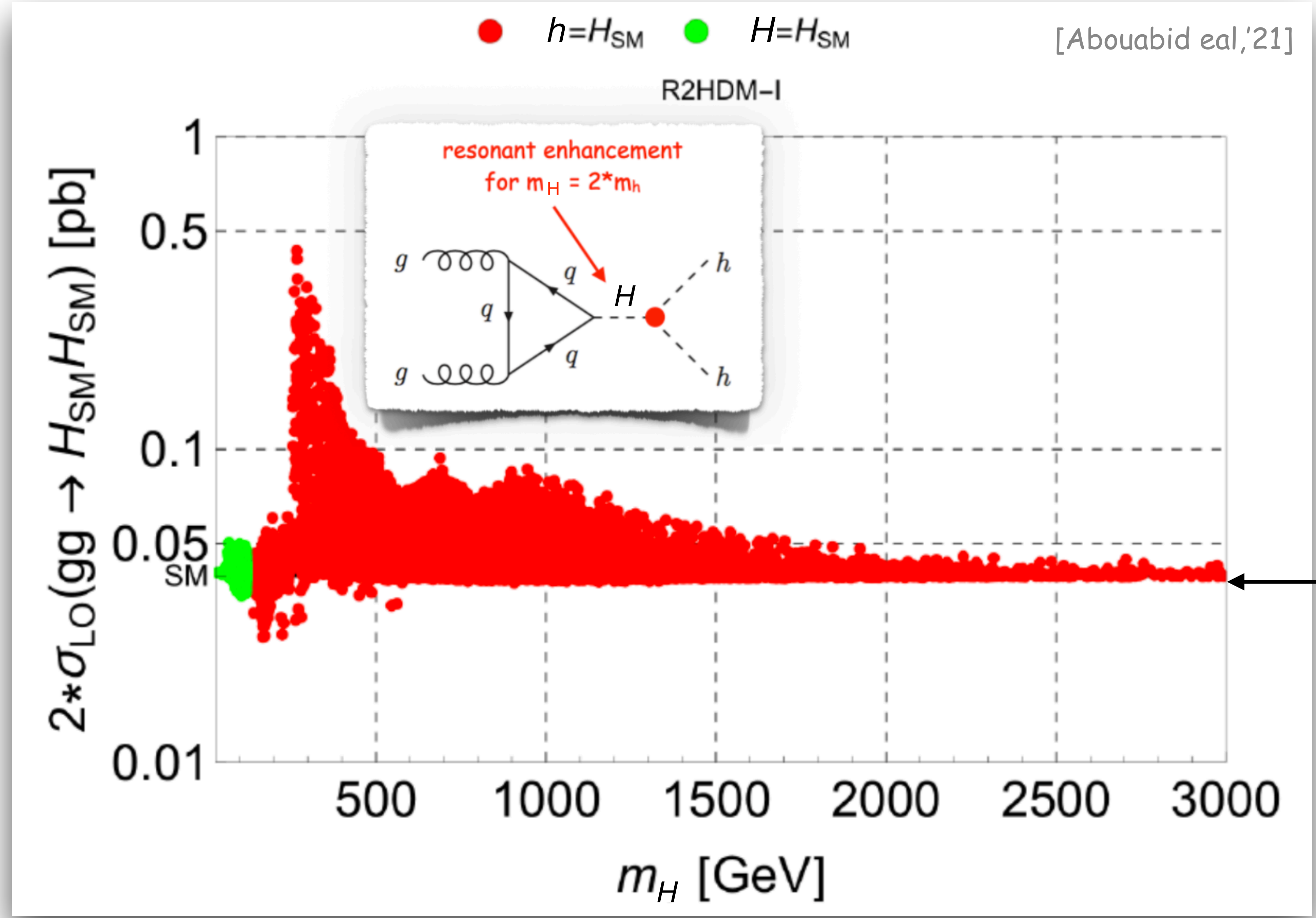
- Example NMSSM:

[taken from Dao,MM,Streicher,Walz,´13]



Example 2-Higgs-Doublet Model (2HDM)

✏ 2HDM Higgs sector: 2 Higgs doublets $\overset{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-



Parameter scan points compatible w/ all relevant theoretical & experimental constraints

SM HH cxn value (LO)

Allowed Ranges of Trilinear Higgs Couplings

[Abouabid eal,'21]

Large values of $\lambda_{3H_{SM}}$ required for SFOEWPT!

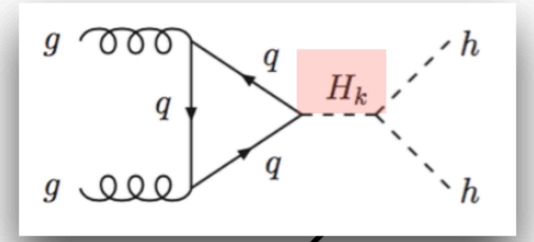
	R2HDM		C2HDM	
	$y^{\text{R2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{R2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{C2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{C2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

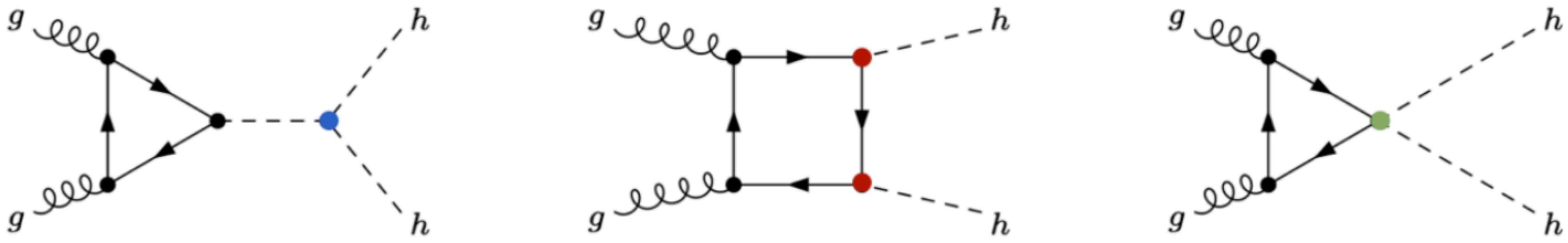
	N2HDM		NMSSM	
	$y^{\text{N2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{N2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{NMSSM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{NMSSM}}_{3H_{\text{SM}}}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

Comparison with EFT

- **Effective Lagrangian:** $$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t t\bar{t}\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3$$

c_3: trilinear coupling modification; c_t: top-Yukawa coupling modification;
c_{tt}: effective two-Higgs-two-fermion coupling
no c_g, c_{gg}: no new heavy colored BSM particles assumed





- **Matching relations of our specific BSM models:**

Higgs-top Yukawa coupling	:	$g_t^{H_{SM}}(\alpha_i,\beta)$	$\rightarrow$	c_t
trilinear Higgs coupling	:	$\frac{g_3^{H_{SM}H_{SM}H_{SM}}(p_i)}{3M^2_{H_{SM}}/v}$	$\rightarrow$	c_3
two-Higgs-two-top quark coupling	:	$\sum_{k=1}^{k_{max}}\left(\frac{-v}{m^2_{H_k}}\right) g_3^{H_k H_{SM} H_{SM}}(p_i)\, g_t^{H_k}(\alpha_i,\beta)$	$\rightarrow$	c_{tt}

2HDM versus EFT

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- **R2HDM T2 sample parameter point:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	1131	1082	1067	-0.924	0.820	552749

- **corresponding EFT values:**

$$g_t^{H_2} = -1.126$$

$$c_3 = 0.782\,,\ c_t = 0.951\,,\ c_{tt} = -0.122$$

- **goodness of approximation?:**

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2H_1H_1}$ [GeV]	$\sigma_{\text{R2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
1131	78.80	-0.1222	-504.52	30.5	26.1	86%
1200	89.74	-0.1031	-479.29	27.7	24.8	90%
1500	470.2	-4.853 10^{-2}	-352.42	21.8	21.4	98%

- **Remark:**

$$\sigma_{\text{R2HDM}}^{\text{w/o res}} = 18.6 \text{ fb} \quad \text{and} \quad \sigma_{\text{SMEFT}}^{c_{tt}=0} = 18.6 \text{ fb}$$

N2HDM versus EFT

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- **N2HDM T1 sample parameter point:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	269	582	390	380	4.190
α_1	α_2	α_3	v_s [GeV]	$\mathrm{Re}(m_{12}^2)$ [GeV^2]	
1.432	-0.109	0.535	1250	28112	

$g_t^{H_2} = 0.179$ and $g_t^{H_3} = 2.337 \times 10^{-2}$

- **corresponding EFT values:**

$$c_3 = 0.877\,,\ c_t = 1.012\,,\ c_{tt} = 4.127 \times 10^{-2}$$

- **goodness of approximation?: (m_{H3} kept fixed)**

m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2H_1H_1}$	$\sigma_{\rm N2HDM}^{\rm w/\ res}$ [fb]	$\sigma_{\rm SMEFT}^{c_{tt}\neq 0}$ [fb]	ratio
269	0.075	4.410×10^{-2}	4.127×10^{-2}	-72.42	183.70	20.56	11%
300	0.083	3.170×10^{-2}	2.877×10^{-2}	-64.80	162.80	21.28	13%
400	0.177	9.544×10^{-3}	6.721×10^{-3}	-34.68	43.33	22.60	52%
420	0.229	6.895×10^{-3}	4.063×10^{-3}	-27.62	31.70	22.76	72%
440	0.284	4.600×10^{-3}	1.767×10^{-3}	-20.22	26.26	22.90	87%
450	0.315	3.564×10^{-3}	7.323×10^{-4}	-16.39	24.84	22.96	92%
500	2.567	-7.132×10^{-4}	-3.545×10^{-3}	4.05	23.56	23.22	99%

Electroweak Baryogenesis

Electroweak Baryogenesis

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  - * (i) B number violaton (sphaleron processes)
  - * (ii) C and CP violation
  - * (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

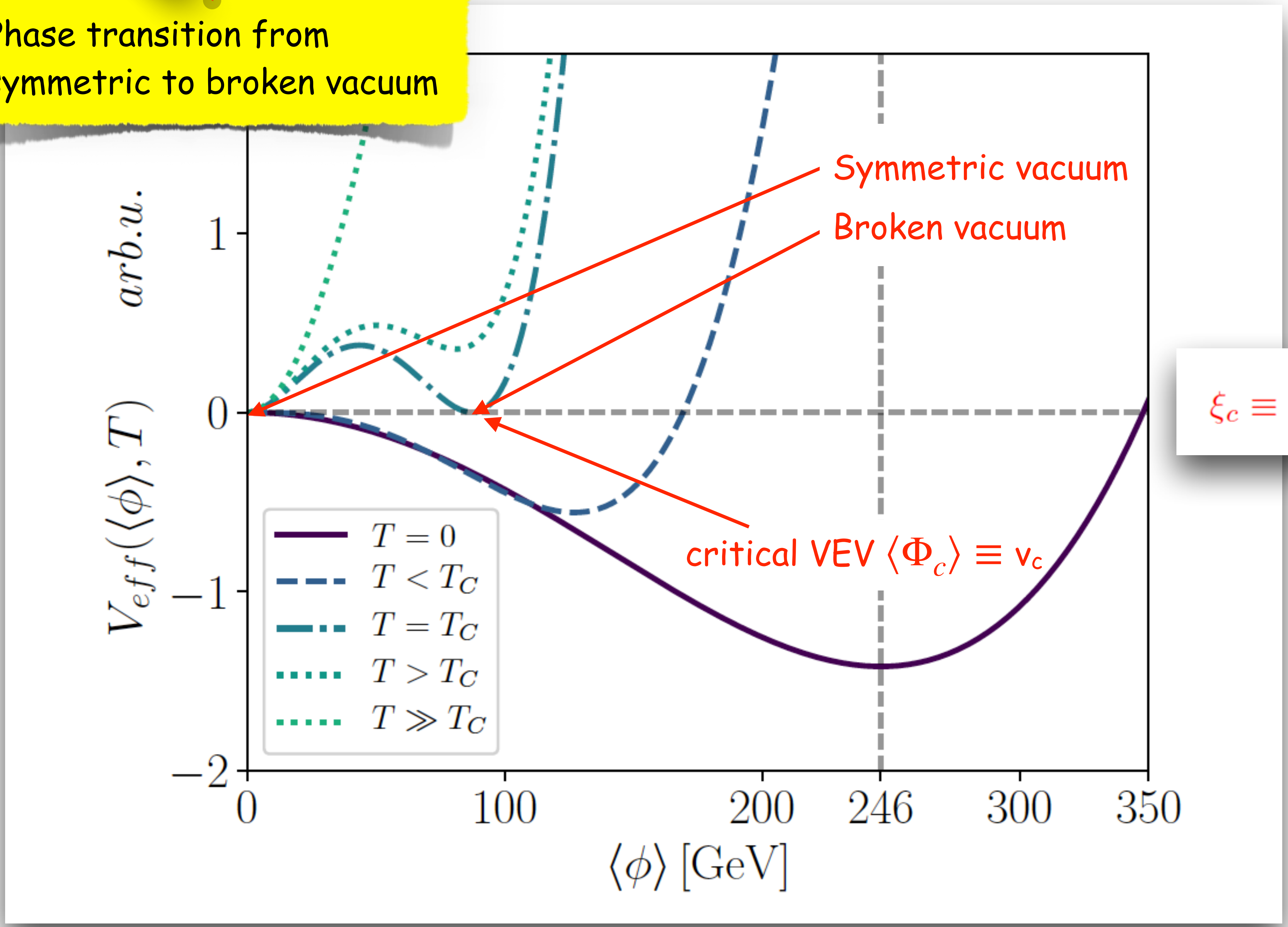
$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

Strong First-Order Electroweak Phase Transition (SFOEWPT)

Phase transition from symmetric to broken vacuum

[From Ph. Basler, PhD Thesis]



$$\xi_c \equiv \frac{\langle\Phi_c\rangle}{T_c} \geq 1$$

Electroweak Baryogenesis (EWBG)

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- **Sakharov Conditions:** [Sakharov '67]
  - ∗ (i) B number violaton (sphaleron processes)
  - ∗ (ii) C and CP violation
  - ∗ (iii) Departure from thermal equilibrium

- SM: smooth cross-over
- not enough CP violation
- large trilinear Higgs coupling required

=> physics beyond the SM needed
Extended Higgs sectors!

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

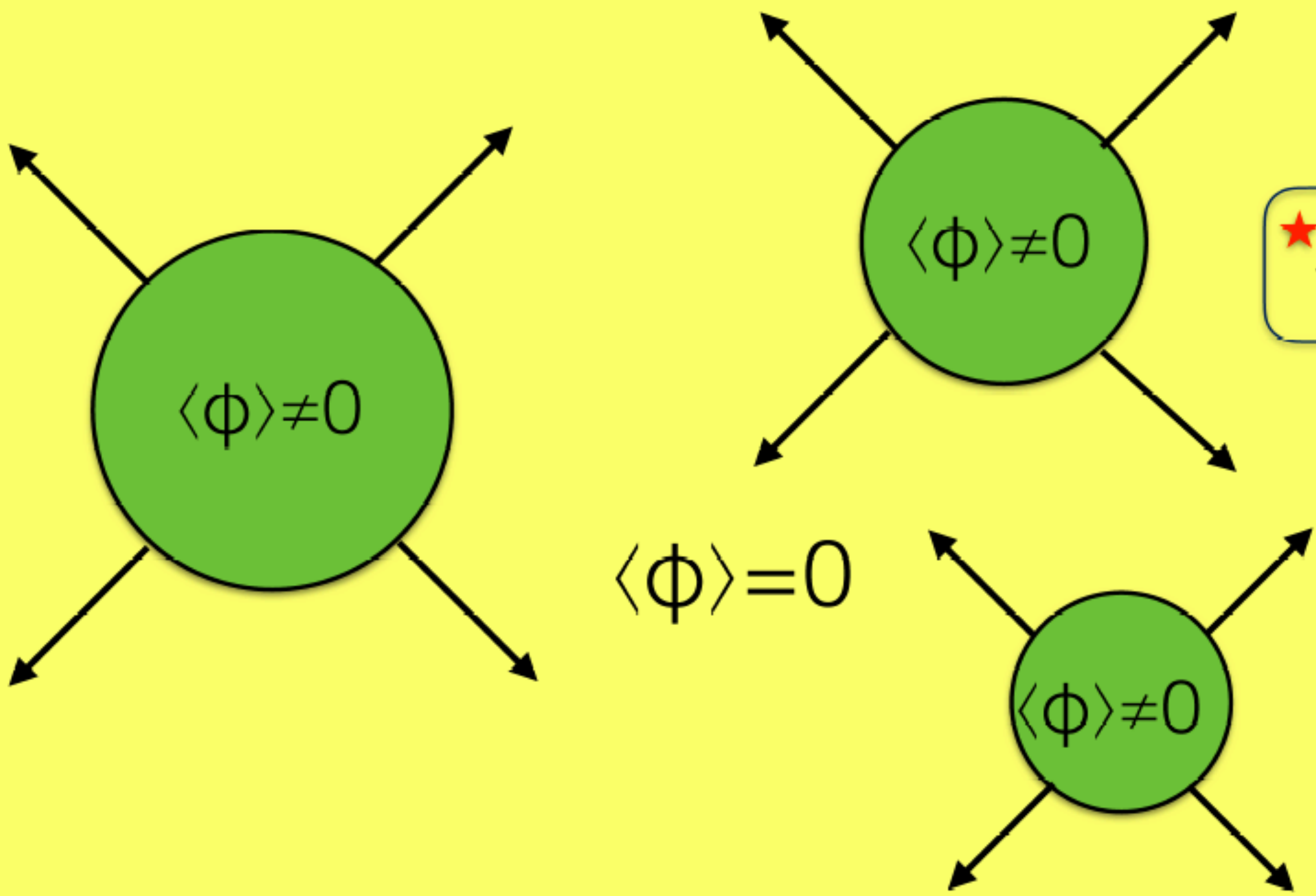
$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

EWBG in a Nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle \phi_c(T_c)\rangle / T_c \geq 1$

ϕ_c, T_c
VEV and T at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall★

Strong-First-Order Phase Transitions (SFOPT) and Gravitational Waves

SFOEWPT (for EWBG)

↓ can source

Gravitational Waves (GW)

↑ sensitive to

Pulsar timing arrays, LISA (space bound interferometer)

Strong-First-Order Phase Transitions (SFOPT) and Gravitational Waves

Directly probe echo of Cosmological FOPT

Discovery of Physics Beyond the SM

SFOEWPT (for EWBG)

↓ can source

Gravitational Waves (GW)

↑ sensitive to

Pulsar timing arrays, LISA (space bound interferometer)

The Model „CP in the Dark"

✦ Next-to-Minimal 2-Higgs Doublet Model: [Azevedo,Ferreira,MM,Patel,Santos,Wittbrodt,'18]

$$
\begin{aligned}
V^{(0)} = & \; m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + \text{ h.c.}\right) \\
& + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] \\
& + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 \,.
\end{aligned}
$$

✦ with one discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$

one SM-like Higgs plus dark sector: h_1,h_2,h_3,$H^\pm$

✦ trilinear coupling A is complex: dark sector with explicit CP violation <- not constrained by electric dipole moment

Vacuum Structure of „CP in the Dark“

- General vacuum structure at T≠0:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \omega_1 + i\Psi_1 \end{pmatrix}, \; \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \omega_{CB} + i\eta_2 \\ \zeta_2 + \omega_2 + i(\Psi_2 + \omega_{CP}) \end{pmatrix}, \; \Phi_S = \zeta_S + \omega_S$$

electroweak VEVs: ω_1, ω_2 , CP-violating VEV: ω_{CP}

charge-breaking VEV: ω_{CB} (unphysical; found to be zero for all of our scan points)

Z_2-symmetry breaking VEV: ω_S

- General vacuum structure at T=0:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\Psi_1 \end{pmatrix}, \; \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + i\eta_2 \\ \zeta_2 + i\Psi_2 \end{pmatrix}, \; \Phi_S = \zeta_S$$

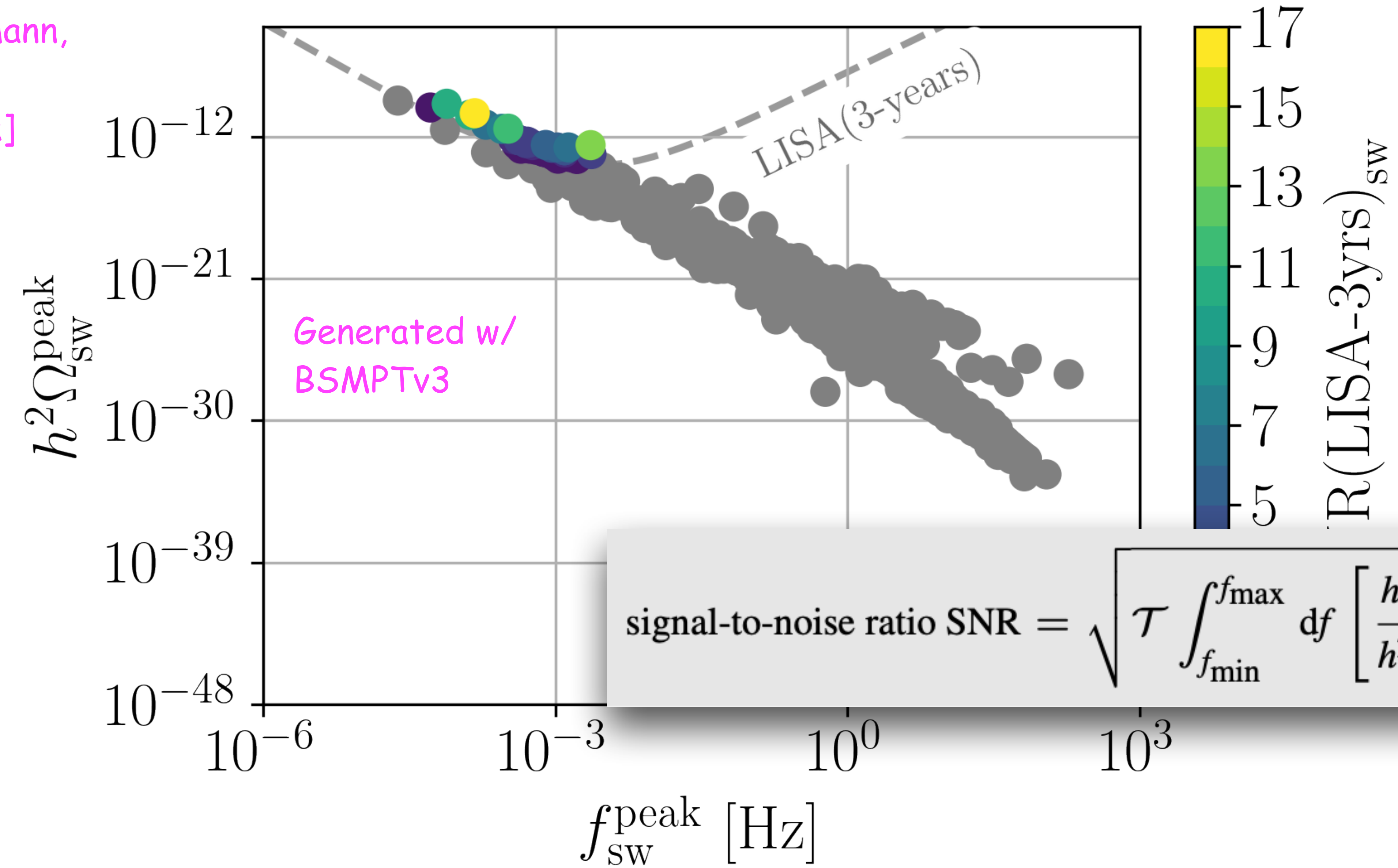
$$\langle \Phi_1 \rangle|_{T=0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \; \langle \Phi_2 \rangle|_{T=0} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \; \langle \Phi_S \rangle|_{T=0} = 0$$

$\omega_1|_{T=0\,GeV} = v1 \equiv v = 246.22$ GeV

GW from (S)FOEWPT in „CP in the Dark"*

[Basler,Biermann, MM,Müller, Santos,Viana]

*[Azevedo,Ferreira, MM,Patel,Santos, Wittbrodt]



$$\text{signal-to-noise ratio SNR} = \sqrt{\mathcal{T}\int_{f_{\rm min}}^{f_{\rm max}} df \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm Sens}(f)}\right]^2}$$

- ∃ points w/ SNR(LISA-3yrs)>10, compatible w/ all relevant theor. and exp. constraints
- all points lead to EW minimum at T=0 (no vacuum trapping)
- all of the LISA-sensitive points (colored points) have SFOEWPT: ξ_c>1

GW from (S)FOEWPT in „CP in the Dark"*

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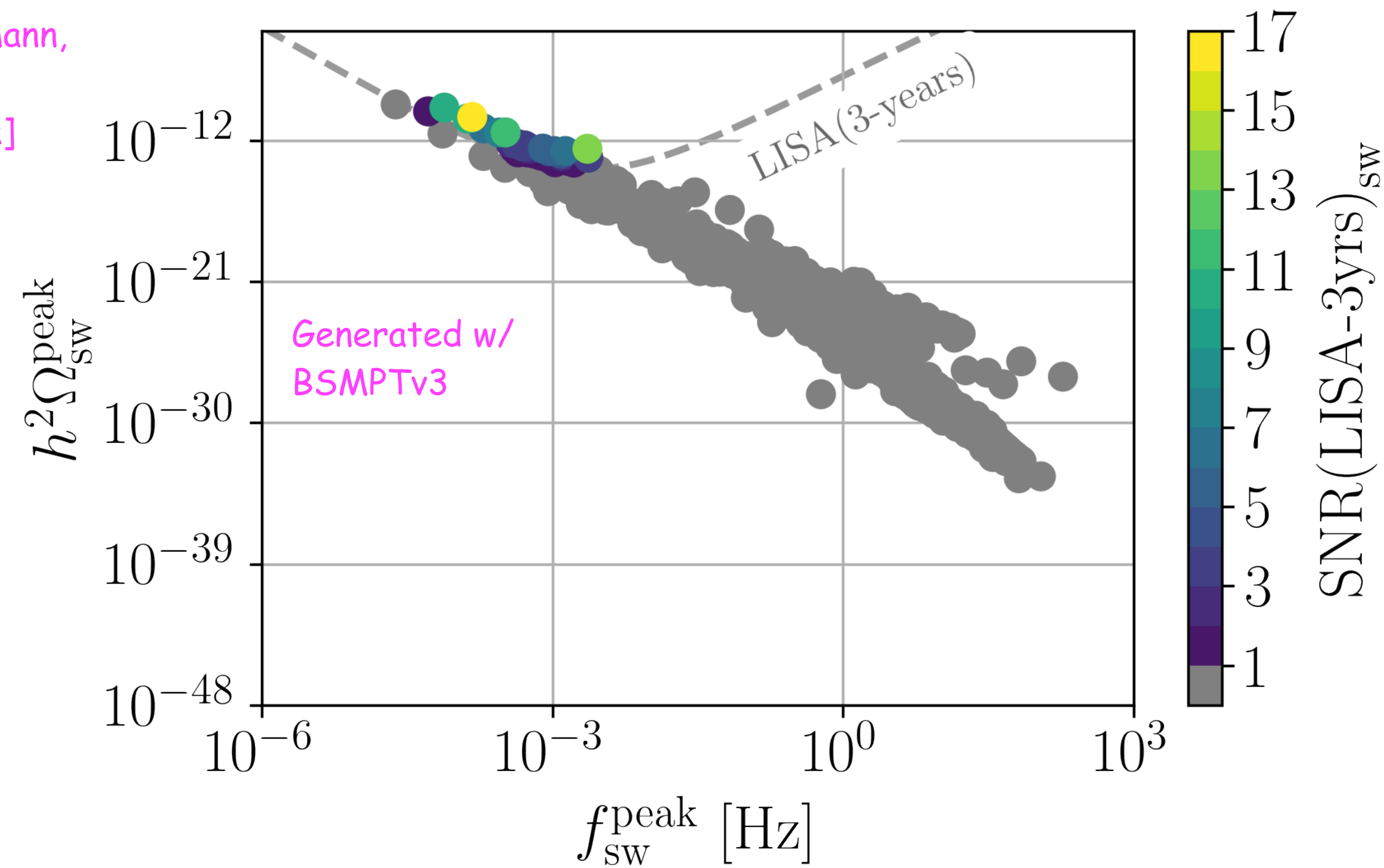

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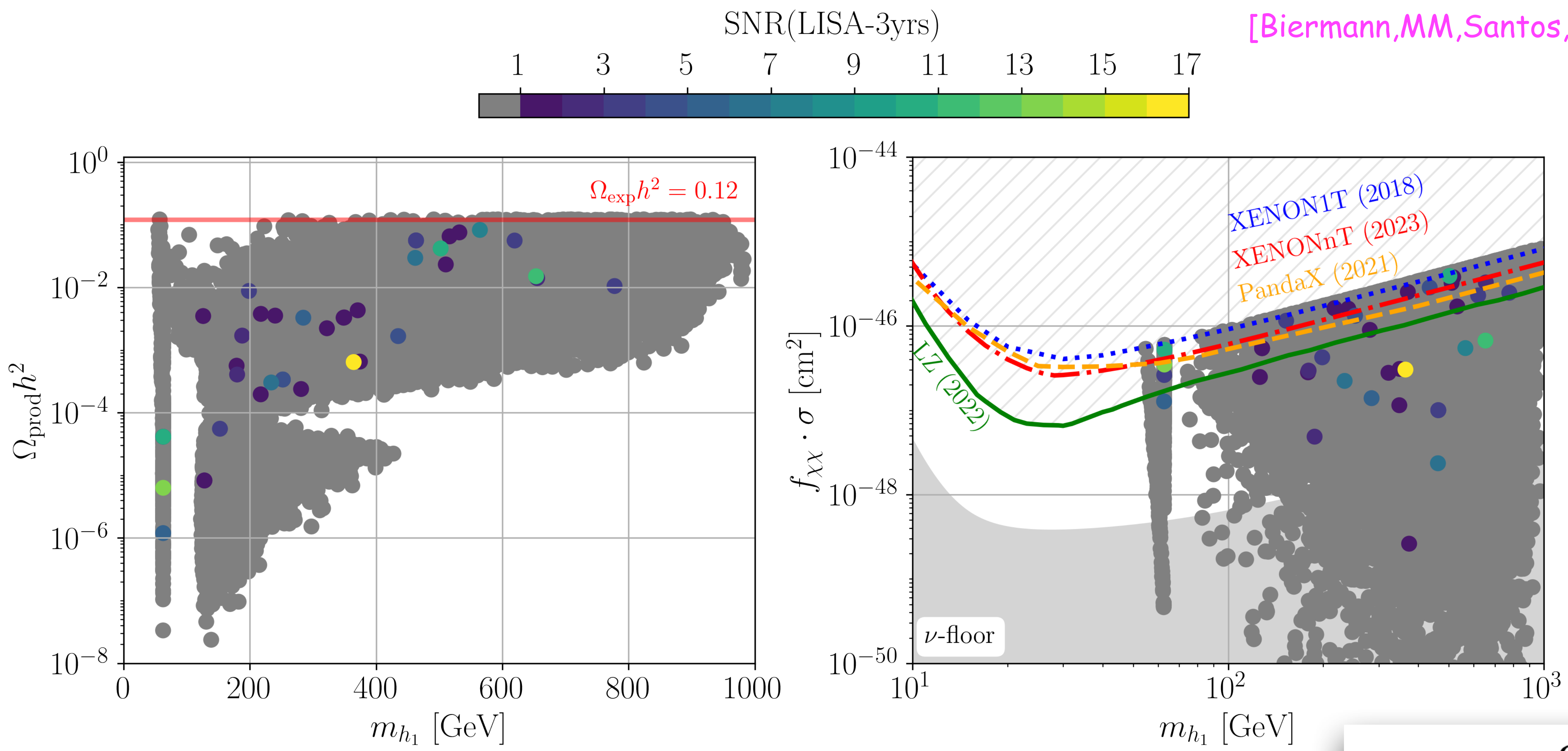
- all of the LISA-sensitive points (colored points) have SFOEWPT: ξ_c>1

DM Observables and GW

[Biermann,MM,Santos,Viana]

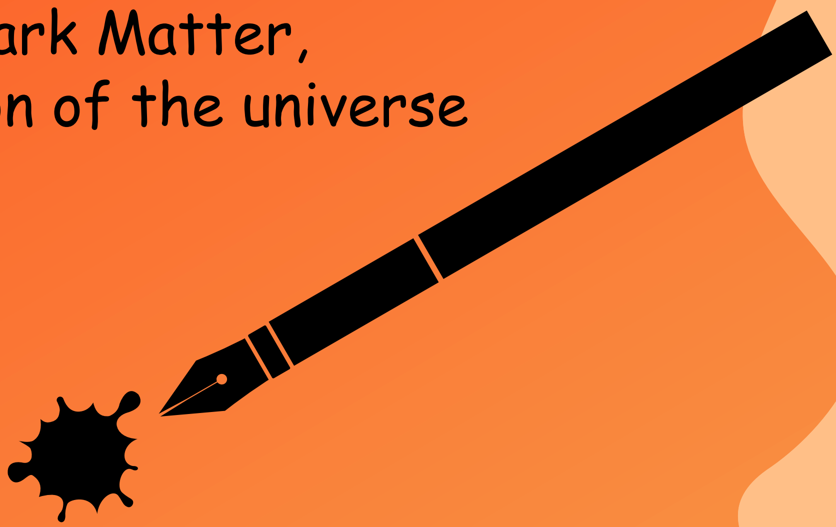


$$\sigma \cdot f_{\chi\chi} \equiv \sigma \cdot \frac{\Omega_{\rm prod}h^2}{\Omega_{\rm obs}h^2}$$

- Viable GW points (SNR(LISA-3yrs)>1 - colored points):
  compatible w/ relic density (<Ωh^2)
  above neutrino floor
  testable at future direct detection experiments

Conclusions

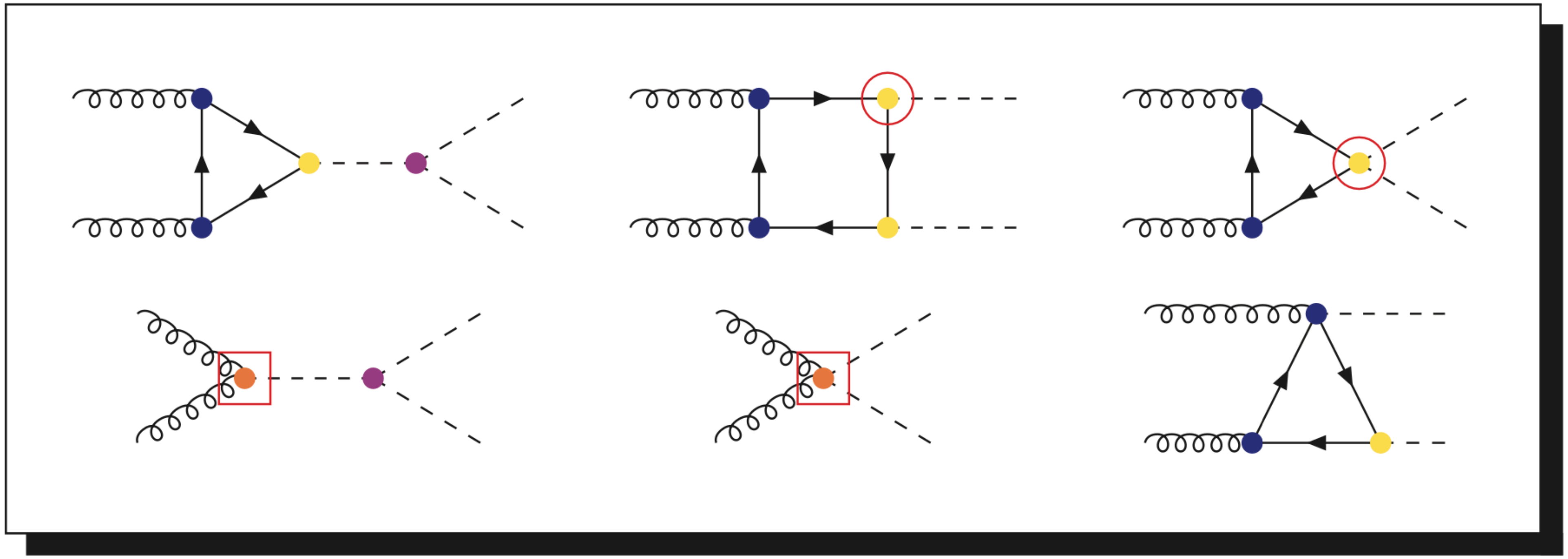
- ✦ Open Problems of the SM ⇝ BSM w/ (mostly extended) Higgs sectors
- ✦ Higgs tool: new physics model, flavour/matter puzzle, Dark Matter, baryon asymmetry, vacuum stability, evolution of the universe
- ✦ Precision investigation of the Higgs boson:
  - -> establish electroweak symmetry breaking
  - -> indirect constraints on BSM physics



- ✦ Not miss any new physics hint:
  - -> sophisticated expermental investigations, precise theory predictions
  - -> multi-pronged approach (collider physics - astroparticle physics - cosmology)
- ✦ Exciting times ahead!


Thank you for your attention!

Example EFT Operators Contributing to Higgs Pair Production



Non-linear EFT:

couplings of one/two Higgs bosons to gluons become linear independent

couplings of one/two Higgs bosons to fermions become linear independent

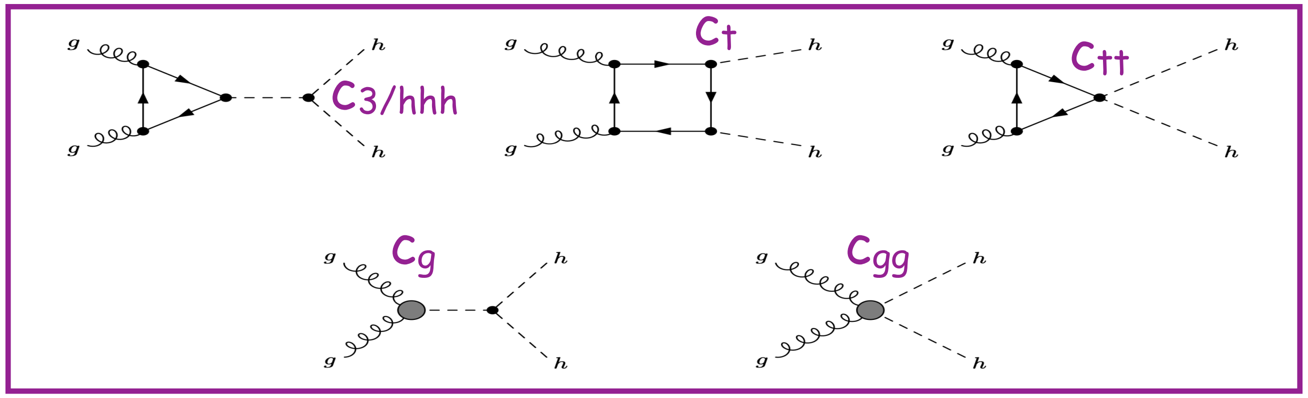
can be probed directly in di-Higgs productions

Processes w/ 0,1,2 Higgs boson need to be connected to disentangle linear/non-linear dynamics

Note: EFT operators destroy SM cancellation between triangle and box diagrams

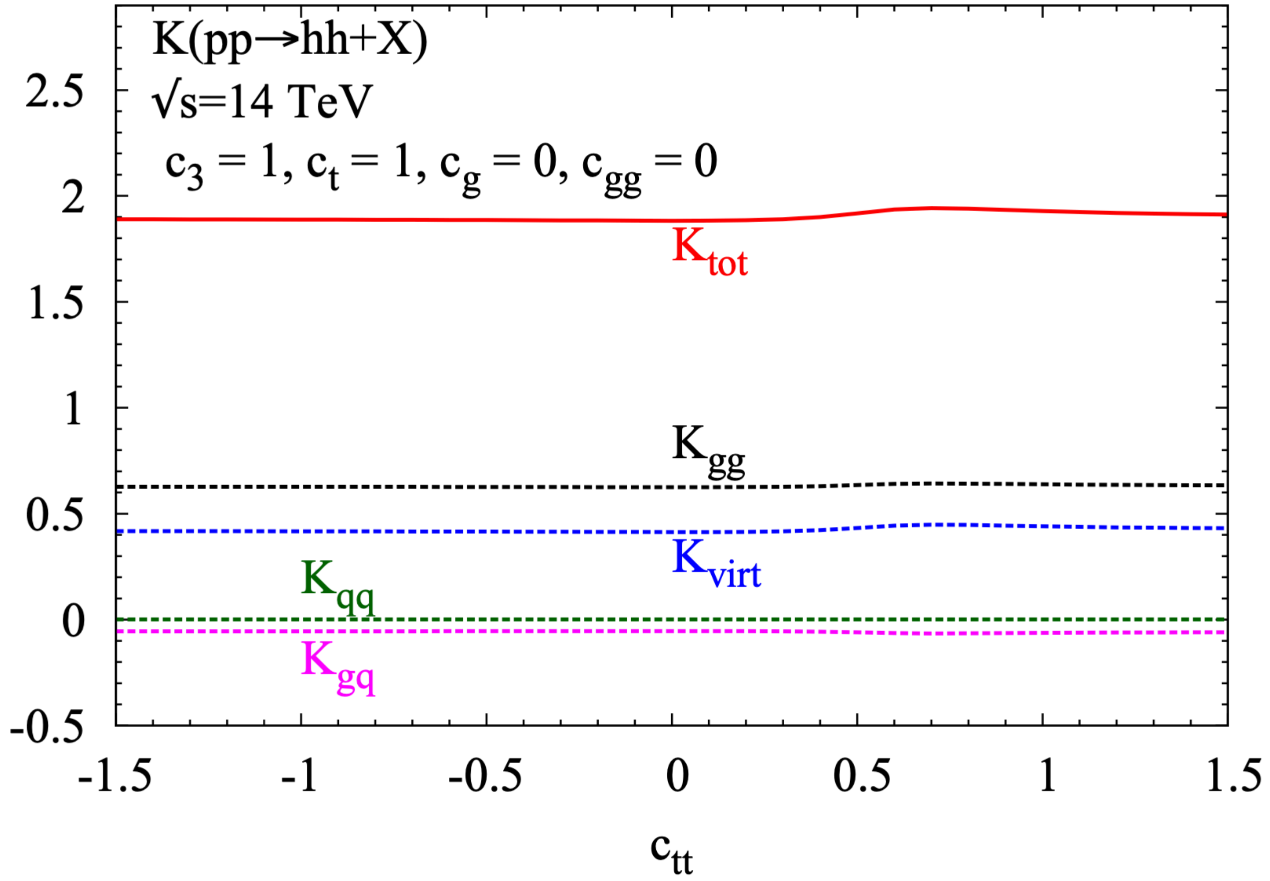
$\rightsquigarrow$ limits derived on λ_{HHH} depend on EFT description

EFT Effect at NLO QCD in HH

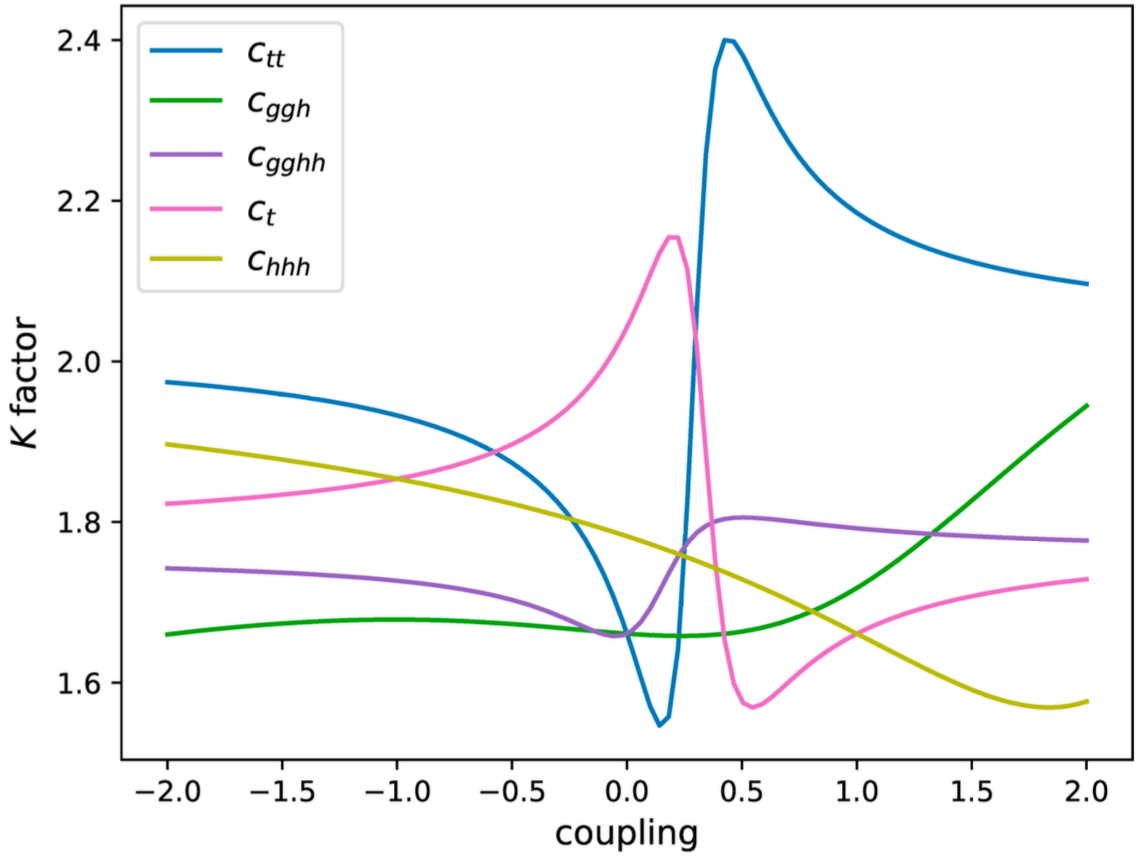


K-factor:
ratio of NLO
to LO observable

[Gröber,MM,Spira,Streicher,'15]



[Buchalla,Capozi,Celis,Heinrich,Scyboz,'18]



Tops integrated out at NLO:
- flat dependence of K-factors

[see also de Florian,Fabre,Mazzitelli,´17]

Inclusion of full top dependence at NLO:
- non-uniform K-factors

Decoupling

- Alignment limit: one of the neutral Higgs bosons has to be approximately aligned with the direction of the Higgs VEV in field space ~> limit of a SM Higgs

- Alignment with decoupling: Alignment limit in extended Higgs sector realized if all additional Higgs states are very heavy: decoupling limit

- Alignment without decoupling: occurs generically in 2HDMs

✏ Masses of the heavy 2HDM Higgs bosons take the form: $\Phi \equiv H, H^\pm, A$

$$m_\Phi^2 = M^2 + \lambda_i v^2 (+\mathcal{O}(v^4/M^2))$$

λ_i linear combination of $\lambda_1, \ldots, \lambda_5$

✏ In case $M^2 \gg \lambda_i v^2$: heavy Higgs bosons decouple, h behaves SM-like ($\sin(\beta - \alpha) \to 1$) alignment/decoupling limit

✏ alignment without decoupling: H can become SM-like particle ($\cos(\beta - \alpha) \to 1$) ~> light Higgs h with mass below 125 GeV in the spectrum

✏ Strong coupling regime: $M^2 \leq \lambda_i v^2$: large value of m_Φ for λ_i large (limited by perturbativity)

Flavour-Changing Neutral Currents

✏ Yukawa Lagrangian:

$$\mathcal{L}_Y = -\Big\{\bar{Q}'_L(\Gamma_1\Phi_1+\Gamma_2\Phi_2)D'_R - \bar{Q}'_L(\Delta_1\tilde{\Phi}_1+\Delta_2\tilde{\Phi}_2)U'_R + \bar{L}'(\Pi_1\Phi_1+\Pi_2\Phi_2)E'_R + h.c.\Big\} ,$$

where Q'_L, L'_L denote the left-handed quark and lepton doublets and $Q \equiv (U,D)^T$, $L \equiv (\nu,E)^T$, with $U \equiv (u,c,t)^T$, $D \equiv (d,s,b)^T$, $\nu \equiv (\nu_e,\nu_\mu,\nu_\tau)^T$ and $E \equiv (e,\mu,\tau)^T$. The indices L,R denote left- and right-handed fermions f given by

$$f_{L,R} = P_{L,R} f \equiv \frac{1}{2}(1 \mp \gamma_5) f \ .$$

We have defined $\tilde{\Phi}_a = (\Phi_a^T \epsilon)^\dagger$, with

$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} .$$

The couplings Γ_a, Δ_a and Π_a $(a=1,2)$ are 3×3 complex matrices in flavour space.

Problem w/ 2 Higgs doublets: Mass and coupling matrices cannot be diagonalized simultaneously
~> FCNC at tree-level!

- Solution: Extend discrete $\mathbb{Z}_2$ symmetry of Higgs sector to Yukawa sector such that only one Higgs doublet couples to a given right-handed fermions

Flavour-Changing Neutral Currents

- Four 2HDM types:

  - type I 2HDM: All quarks couple to just one of the Higgs doublets (conventionally chosen to be Φ_2).
  - type II 2HDM: The $Q = 2/3$ right-handed (RH) quarks couple to one Higgs doublet (conventionally chosen to be Φ_2) and the $Q = -1/3$ RH quarks couple to the other (Φ_1).
  - Lepton-specific model: The RH quarks all couple to Φ_2 and the RH leptons couple to Φ_1.
  - Flipped model: The RH up-type quarks couple to Φ_2, the RH down-type quarks couple to Φ_1, as in type II, but now the RH leptons couple to Φ_2.

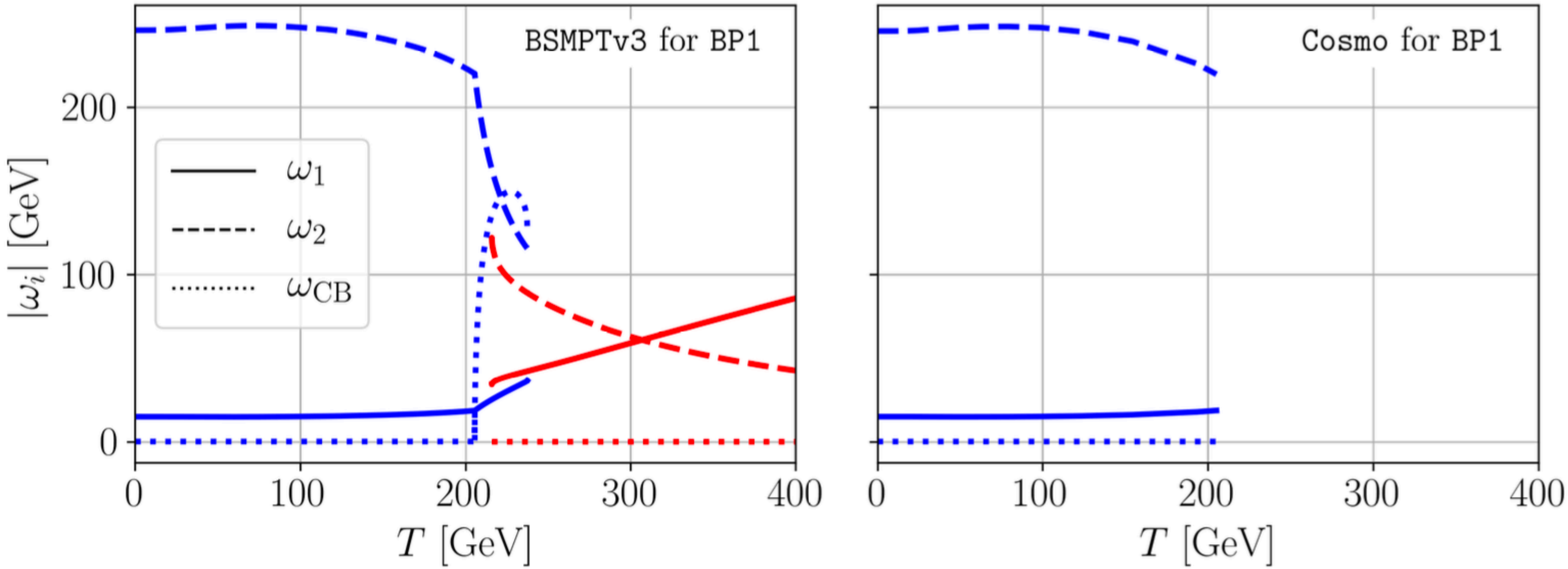
- Alternative solution: alignment in flavor space of the Yukawa couplings

$$\Gamma_2 = \xi_d e^{-i\theta}\Gamma_1 \,, \quad \Delta_2 = \xi_u^* e^{i\theta}\Delta_1 \,, \quad \Pi_2 = \xi_l e^{-i\theta}\Pi_1$$

masses and couplings are proportional to each other ~> can be diagonalized simultaneously
four Yukawa types appear as special cases of the aligned 2HDM (A2HDM)

Transition History - Comparison w/ CosmoTransitions

high-T phase, low-T phase [Basler,Biermann,MM,Müller,Santos,Viana,´24]



History:

BSMPTv3

- first-order PT from neutral (red) to charge-breaking CB phase (blue)
- second-order PT into a neutral minimum

CosmoTransitioins

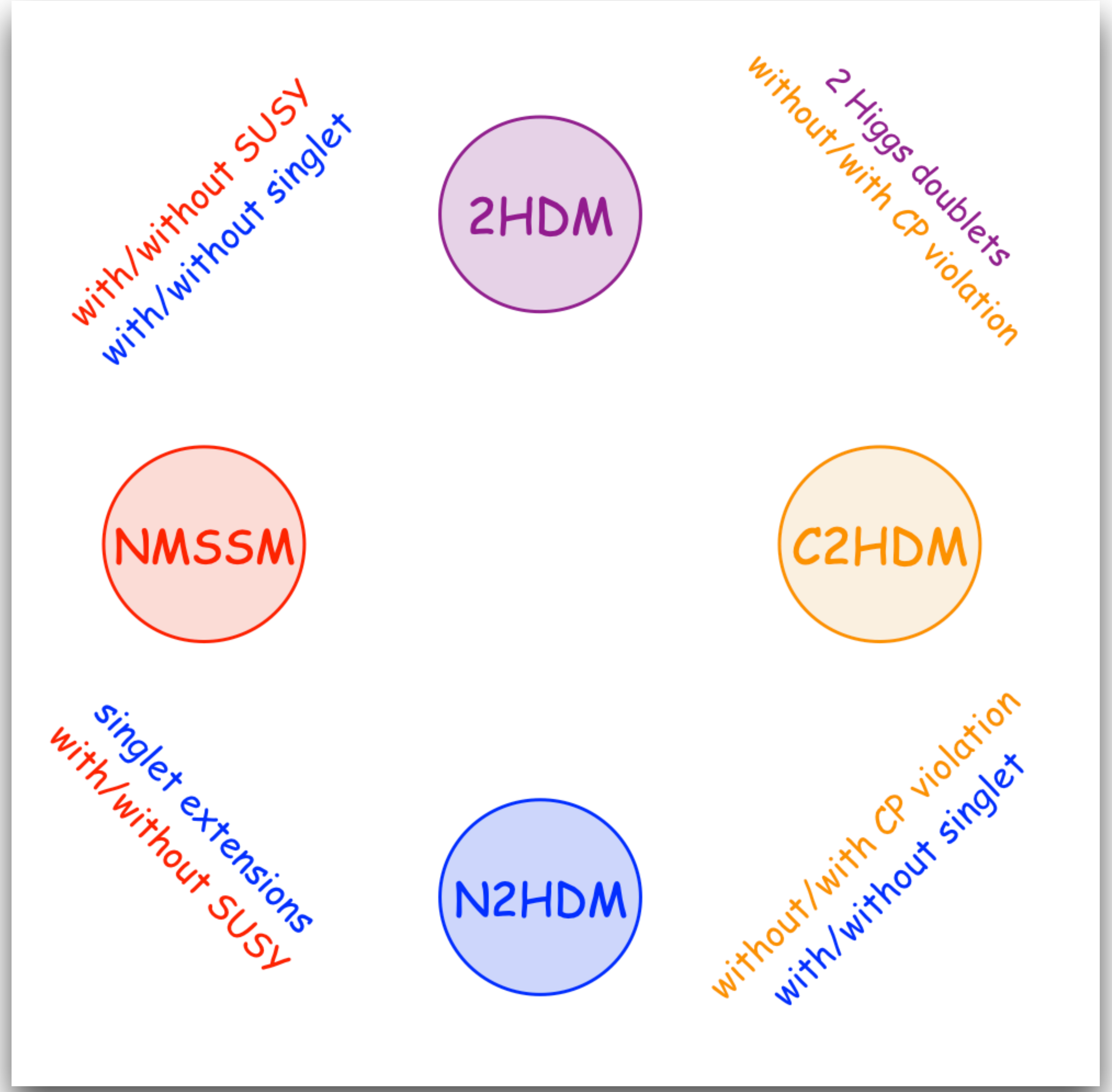
- agrees w/ low-T phase until T~200 GeV
- fails to trace any minima for higher temperatures

Overview on BSM Higgs Pair Production

Overview of Higgs Pair production possibilities
including theoretical and experimental constraints
in archetypical BSM Higgs sectors
including different symmetries

provide benchmark points / lines / planes
for experiment

Investigated Models



Investigated Models

2HDM	C2HDM	N2HDM	NMSSM
2 Higgs doublets	CP-violating	Singlet extension	Supersymmetry
h,H,A,H^+,H^-	H1,H2,H3,H^+,H^-	H1,H2,H3,H^+,H^-	H1,H2,H3,A,H^+,H^-
SFOEWPT, DM, plus charged Higgs	plus CP violation baryogenesis	rich pheno, DM SFOEWPT	a lot (DM, CPviol, Hierarychy, ...)

Resonant Enhancement

Higgs-to-Higgs Cascade decays

- Following results based on:
  Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, MMM, Santos, „Benchmarking Di-Higgs Production in Extended Higgs Sectors“, JHEP 09 (2022) 011

How Define Resonant Di-Higgs Production?

Additional Higgs bosons H_k: possible resonant enhancement of the di-Higgs cross section

* If $m_{Hk} < m_{Hi} + m_{Hj}$ then clear case of „non-resonant" production

* If $m_{Hk} > m_{Hi} + m_{Hj}$: resonance contribution may be suppressed due to small couplings, large masses, large widths or destructive interference effects

* Distinction resonant/non-resonant: if cross section** more than 10% of total di-Higgs result ~> resonant limits

From an experimental point of view the cross section would not be distinguishable from „non-resonant" production then. => Our recipe:

* HiggsBounds turned off for di-Higgs

* Use SusHi to calculate $\sigma(H_k)$ for all possible intermediate resonances H_k at NNLO QCD

* Calculate $\sigma(H_k) \times BR(H_k \to H_{SM} H_{SM})$** and compare it with experiment

* Exception: exp. limits assume narrow resonance -> we keep points if $(\Gamma_{tot}(H_k)/m_{Hk})_{limit} > 5\%$

Provided final states on request: 4b, (2b)(2tau), (2b)(2gamma), (2b)(2W), (2b)(2Z), (2W)(2gamma), 4W

Suppress interfering Higgs signals by excluding scenarios with neighboring Higgs masses below 5 GeV.

The CP-Violating 2HDM (C2HDM)

The CP-Violating 2HDM (C2HDM)

- CP violation: one of the three Sakharov conditions for the generation of the baryon-anti baryon asymmetry through electroweak baryogenesis

- C2HDM Higgs potential: w/ softly broken $\mathbb{Z}_2$ symmetry [Ginzburg,Krawczyk,Osland,'02]

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right]$$

All parameters are real except for m_{12}^2 and λ_5: $m_{12}^2 = |m_{12}^2|\, e^{i\phi(m_{12}^2)}, \quad \lambda_5 = |\lambda_5|\, e^{i\phi(\lambda_5)}$

The two complex phases are not independent of each other

$$2\mathrm{Re}(m_{12}^2)\,\tan\phi(m_{12}^2) = v_1 v_2\,\mathrm{Re}(\lambda_5)\,\tan\phi(\lambda_5)$$

Ensure CP violation (both phases cannot be removed simultaneously) by choosing:

$$\phi(\lambda_5) \neq 2\,\phi(m_{12}^2)$$

The CP-Violating 2HDM (C2HDM)

- Mass spectrum and mixing: CP violation ~> neutral formerly CP-even (h,H) and CP-odd (A) states mix to mass eigenstates H_i $(i = 1,2,3)$ with indefinite CP quantum number

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

with
$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$
and
$$m_{H_1} \le m_{H_2} \le m_{H_3}$$

$$-\pi/2 < \alpha_1 \le \pi/2, \qquad -\pi/2 < \alpha_2 \le \pi/2, \qquad -\pi/2 < \alpha_3 \le \pi/2$$

only two masses are independent:

$$m_{H_3}^2 = \frac{m_{H_1}^2 R_{13}(R_{12}\tan\beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

Charged Higgs sector is unchanged.

- C2HDM input parameters: $m_{H_i}, m_{H_j}, m_{H^\pm}, \mathrm{Re}(m_{12}^2), v, \tan\beta, R_{23}, c^2_{H_iVV}, c^2_{H_itt}$, with $m_{H_i} \le m_{H_j}$ and sign of R_{13} to lift degeneracy from squared couplings

- Allowed amount of CP violation: stringently constrained by EDM measurements

The CP-Violating 2HDM (C2HDM)

- Mass spectrum and mixing: CP violation ~> neutral formerly CP-even (h,H) and CP-odd (A) states mix to mass eigenstates H_i $(i = 1,2,3)$ with indefinite CP quantum number

$$\Phi_1 = \begin{pmatrix} \phi \\ \frac{v_1+\rho \ldots}{\sqrt{\ldots}} \end{pmatrix} \qquad \begin{pmatrix} H_1 \\ \ldots \end{pmatrix} \ldots \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

3 neutral CP-mixed Higgs bosons: H_1, H_2, H_3, with $m_{H_1} \le m_{H_2} \le m_{H_3}$

2 charged Higgs bosons: H^+, H^-

with $$R = \begin{pmatrix} \ldots \\ -(c_1 \ldots & \ldots \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \quad \ldots \le m_{H_2} \le m_{H_3}$$

$$-\pi/2 < \alpha_1 \le \pi/2, \qquad -\pi/2 < \alpha_2 \le \pi/2, \qquad -\pi/2 < \alpha_3 \le \pi/2$$

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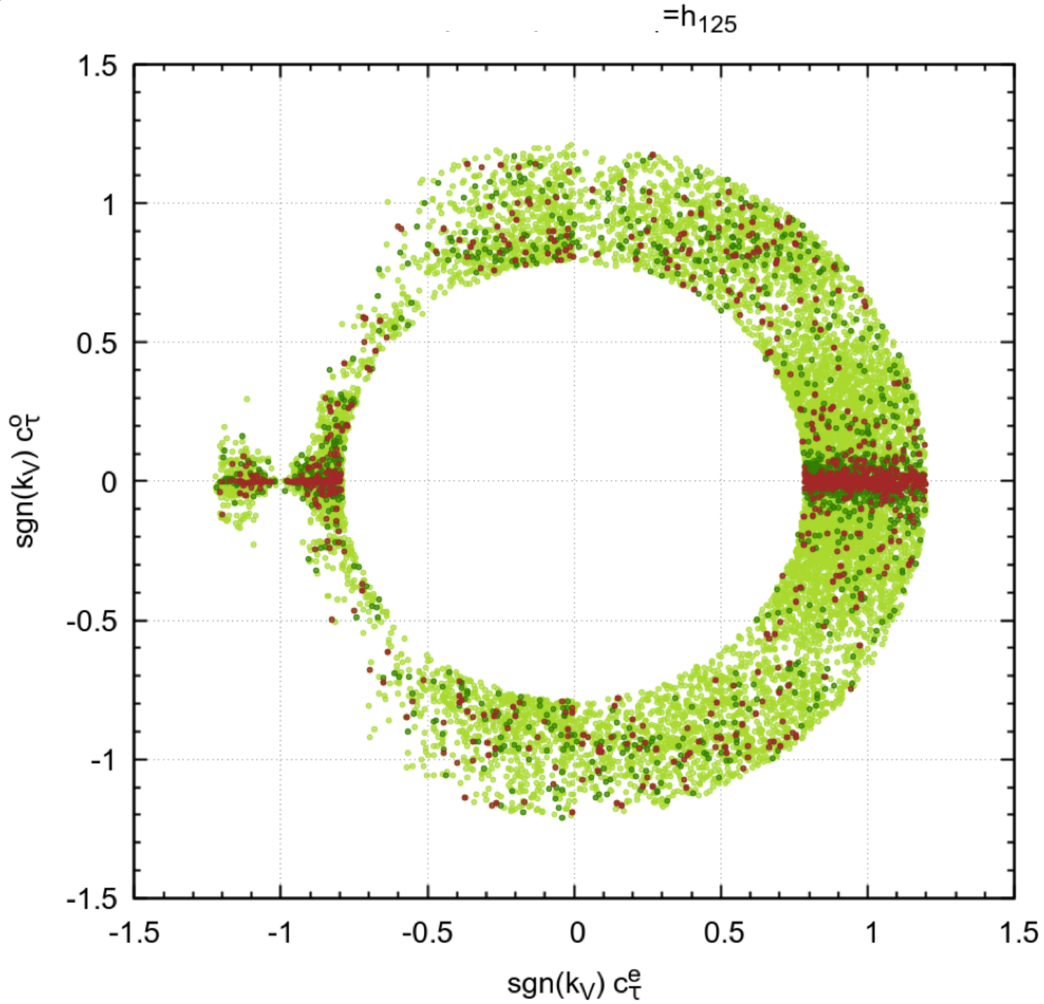
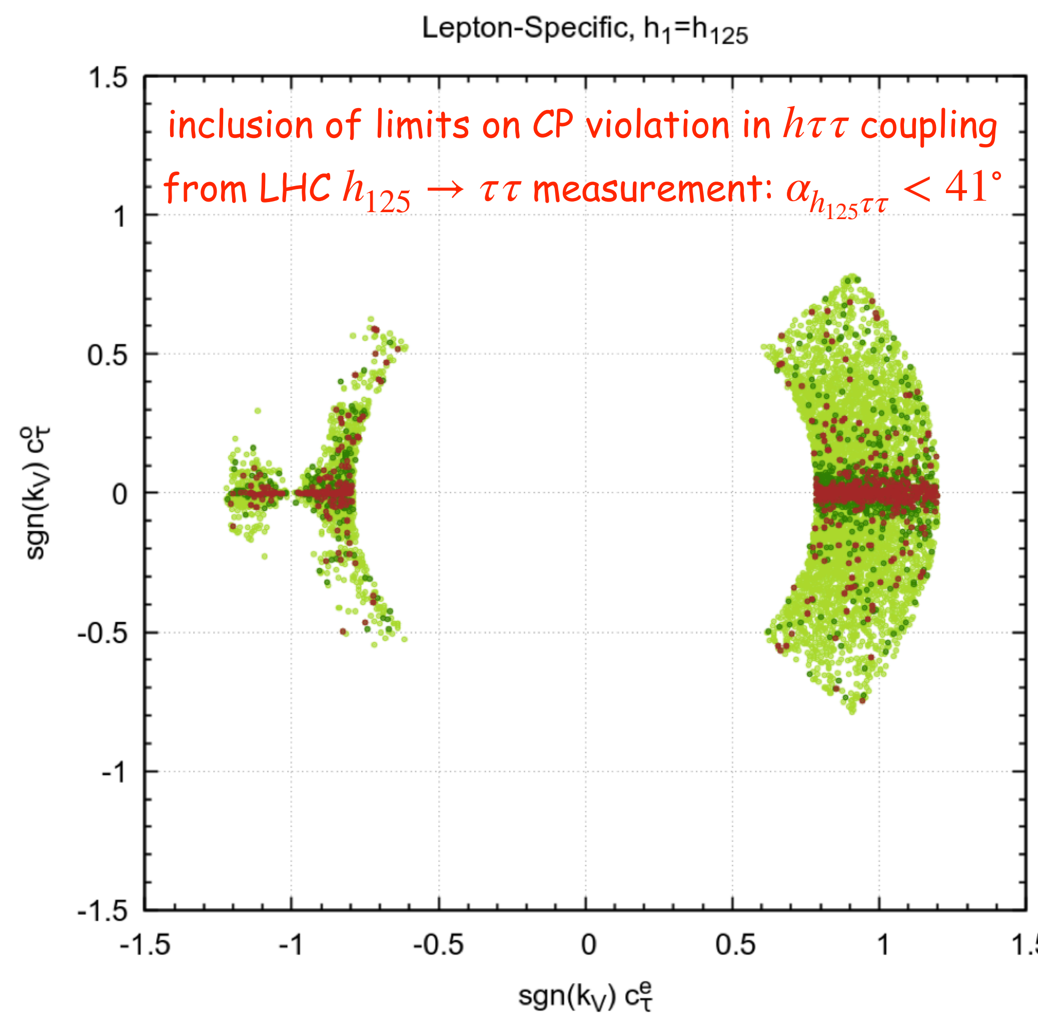
- Allowed amount of CP violation: stringently constrained by EDM measurements

Interdependence between LHC Higgs Data and the Electron EDM

$$\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{f} \left[c^e(h_i f \bar{f}) + i c^o(h_i f \bar{f}) \gamma_5 \right] \, f \, h_i$$

[Biekötter,Fontes,MM,Romão,Santos,Silva,'24]





Combined fits from LHC run2&3 on Higgs data&searches, new EDM results, data from direct CP-violation searches in angular correlations of the τ's in $h_{125} \to \tau\tau$, the bound on $m_{H^\pm}$ from $b \to s\gamma$ constrain possible amount of CP-violation: only in the LS case a sizable amount of CP-odd components, $|c^o| \approx |c^e|$, is still allowed, where CP violation occurs in the $h_{125}\tau\tau$ coupling. The amount is ultimately limited by the LHC measurements of $\alpha_{h_{125}\tau\tau}$

The dark red points obey the currently strongest limit on the eEDM 4.1 × 10–30 e.cm reported by JILA [60].

C2HDM Higgs Decay Widths

[Fontes,MM,Romão,Santos,Silva,Wittbrodt,'17]

- Fortran code C2HDM_HDECAY: partial decay widths and branching ratios in the CP-violating 2HDM including off-shell decays, loop-induced decays and state-of-the-art higher-order QCD correction

The Next-to-2HDM (N2HDM)

The Next-to-2HDM (N2HDM)

[Chen,Freid,Sher,'14] [MM,Sampaio,Santos,Wittbrodt,'16]

- The N2HDM: based on the CP-conserving 2HDM w/ a softly broken $\mathbb{Z}_2$ symmetry, extended by a real singlet field Φ_S

- Motivation:
  - enlarged Higgs sector ~> rich phenomenology
  - study effect of singlet admixture
  - rich vacuum structure (possibility of strong first order phase transition)
  - possible Dark Matter candidate

The Next-to-2HDM (N2HDM)

[Chen,Freid,Sher,'14] [MM,Sampaio,Santos,Wittbrodt,'16]

- The N2HDM: based on the CP-conserving 2HDM w/ a softly broken $\mathbb{Z}_2$ symmetry, extended by a real singlet field Φ_S

- The tree-level potential:

$$\left.\begin{aligned} V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ &+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \end{aligned}\right\} \text{2HDM structure}$$

$$+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \,.$$

invariant under two discrete symmetries:

$$\mathbb{Z}_2\text{:} \quad \Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to \Phi_S \quad \text{(softly broken)}$$

$$\mathbb{Z}_2'\text{:} \quad \Phi_1 \to \Phi_1\,, \quad \Phi_2 \to \Phi_2\,, \quad \Phi_S \to -\Phi_S$$

- After EWSB:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S$$

The Next-to-2HDM (N2HDM)

- Higgs spectrum and mixing angles: charged ($H^\pm$) and pseudoscalar (A) sector unchanged, three neutral scalar field ρ_1, ρ_2, ρ_S mix to Higgs mass eigenstates $H_i\,(i = 1{,}2{,}3)$

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix} \quad \text{with} \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

and $\quad m_{H_1} < m_{H_2} < m_{H_3}$ $\qquad -\frac{\pi}{2} \le \alpha_{1,2,3} < \frac{\pi}{2}$

- N2HDM input parameters: $m_{H_{1,2,3}}, m_A, m_{H^\pm}, m_{12}^2, \alpha_1, \alpha_2, \alpha_3, v, \tan\beta$

- FCNCs at tree-level: avoided by extending $\mathbb{Z}_2$ symmetry to Yukawa sector ~> 4 N2HDM types analogously to the 2HDM

[MM,Sampaio,Santos,Wittbrodt,1612.01309]

e.g. Yukawa coupling modification factors of the N2HDM H_i Higgs bosons w.r.t. the corresponding SM coupling

	u-type	d-type	leptons
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
lepton-specific	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
flipped	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

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$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

$$\ldots s_{\alpha_1} c_{\alpha_2} \quad s_{\alpha_2}$$
$$\ldots - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} \quad c_{\alpha_2} s_{\alpha_3}$$
$$\ldots + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) \quad c_{\alpha_2} c_{\alpha_3}$$

3 neutral CP-mixed Higgs bosons: H_1, H_2, H_3, with $m_{H_1} \le m_{H_2} \le m_{H_3}$
1 neutral CP-odd Higgs boson A
2 charged Higgs bosons: H^+, H^-

and $m_{H_1} < m_{H_2} < m_{H_3}$ $\qquad -\frac{\pi}{2} \le \alpha_{1,2,3} < \frac{\pi}{2}$

- N2HDM input parameters: $m_{H_{1,2,3}}, m_A, m_{H^{\pm}}, m_{12}^2, \alpha_1, \alpha_2, \alpha_3, v, \tan\beta$

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flipped	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

Theory Constraints

- Theoretical constraints: tree-level perturbative unitarity, boundedness from below, global minimum; for details, cf. [MM,Sampaio,Santos,Wittbrodt,1612.01309]

- More on the N2HDM potential minimum structure: [Ferreira,MM,Santos,Weiglein,Wittbrodt,1905.1023]

  - First normal stationary point $\mathcal{N}$: both doublet w/ non-zero real VEV, singlet VEV=0 => $\mathbb{Z}_2'$ preserved; singlet does not mix w/ remaining scalars ~> DM phase

$$\langle\Phi_1\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}} = 0$$

  - Second normal stationary point $\mathcal{N}s$: both doublet and singlet w/ non-zero real VEV => $\mathbb{Z}_2'$ broken; singlet mixes w/ the remaining scalars

$$\langle\Phi_1\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2' \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}s} = v_S'$$

  - Analogously first and second charge-breaking, resp. CP-breaking stationary points

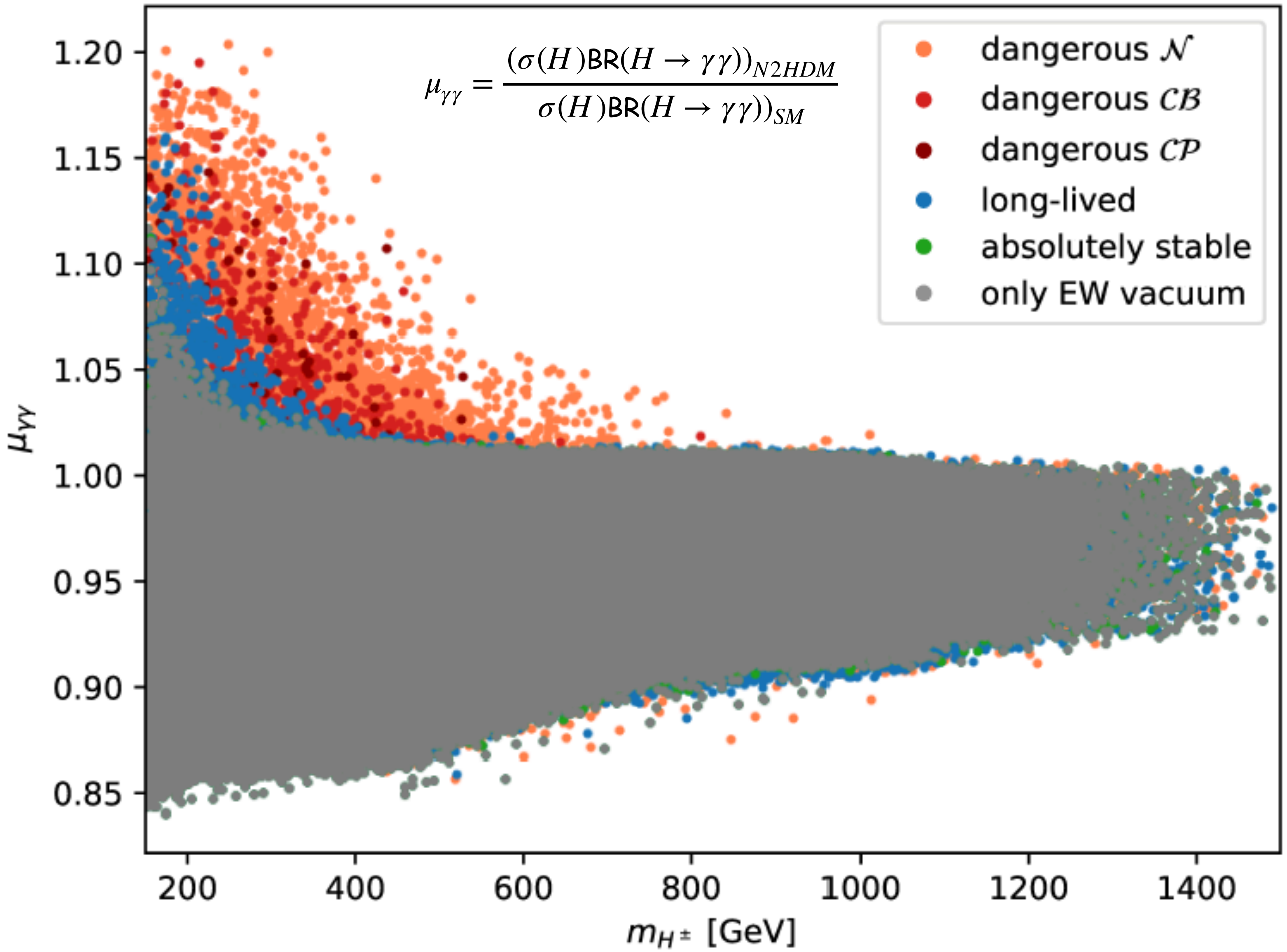
  - Stationary point S: doublets do not acquire VEV, only singlet has non-zero VEV ~> EW gauge bosons and fermions massless ~> unphysical

  - Further possibilities: existence of multiple minima of types $\mathcal{N}$, $\mathcal{N}$s or S, also panic vacuum!

Interplay Vacuum Stability and Collider Observables

Possible vacua in the Next-to-Minimal 2-Higgs-Doublet Model (N2HDM)

[Ferreira,MM,Santos,Weiglein,Wittbrodt,1905.1023]



Note: Vacuum structure will be changed through higher-order correction!

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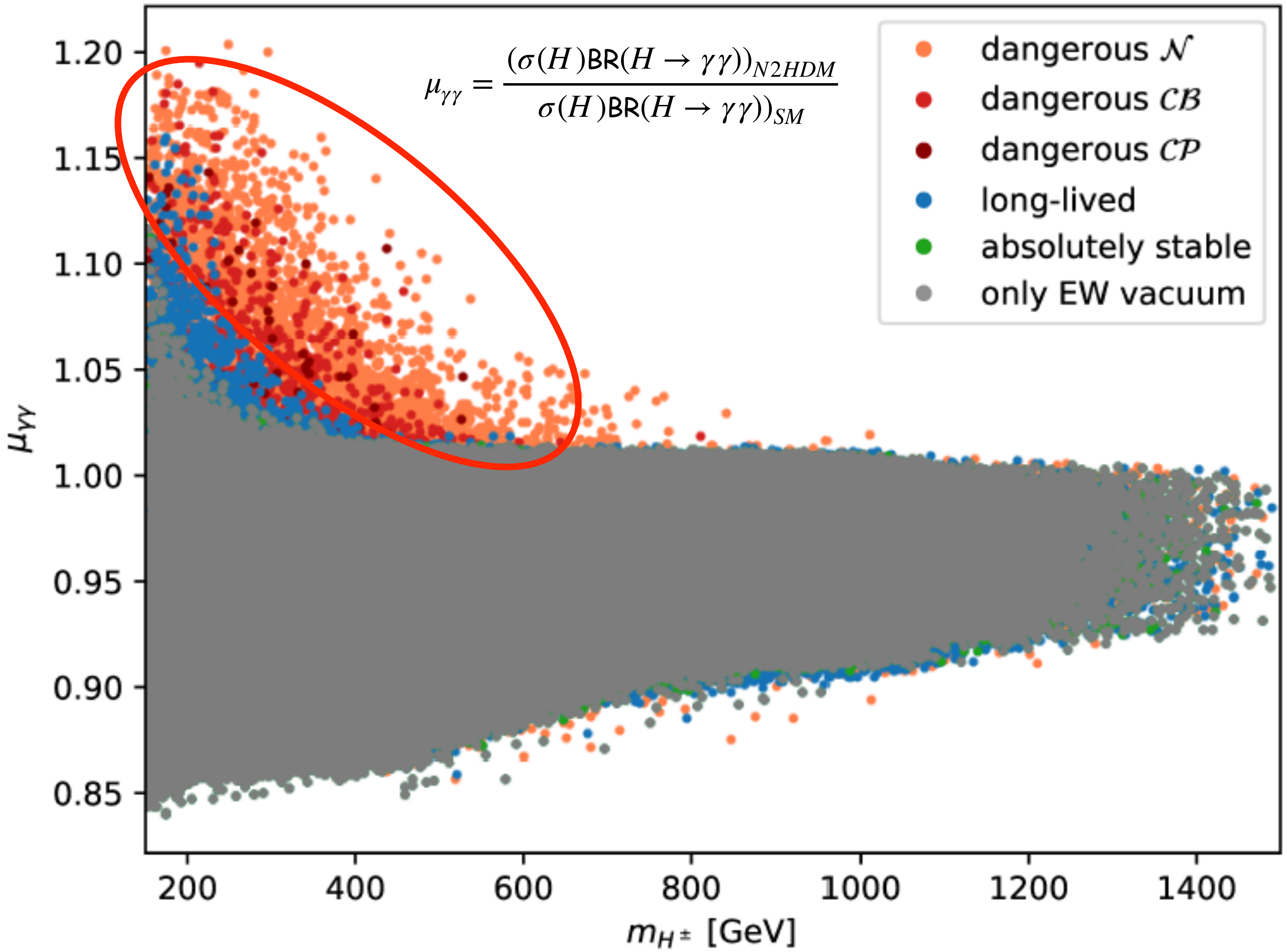


Note: Vacuum structure will be changed through higher-order correction!

The Dark Phases of the N2HDM

- Discrete symmetries: If both symmetries

$$\mathbb{Z}_2\colon\ \Phi_1 \to \Phi_1\ , \quad \Phi_2 \to -\Phi_2\ , \quad \Phi_S \to \Phi_S \qquad \mathbb{Z}_2'\colon\ \Phi_1 \to \Phi_1\ , \quad \Phi_2 \to \Phi_2\ , \quad \Phi_S \to -\Phi_S$$

are exact ~> DM candidates; tree-level potential (no m_{12}^2):

$$\begin{aligned} V_{\text{Scalar}} = &\ m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\ + &\ \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right] \\ + &\ \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\Phi_1^\dagger \Phi_1 \Phi_S^2 + \frac{\lambda_8}{2}\Phi_2^\dagger \Phi_2 \Phi_S^2\,, \end{aligned}$$

Broken Phase (BP): doublets+singlet non-zero VeVs; $\mathbb{Z}_2$,$\mathbb{Z}_2'$ spont. broken ~> no DM candidates

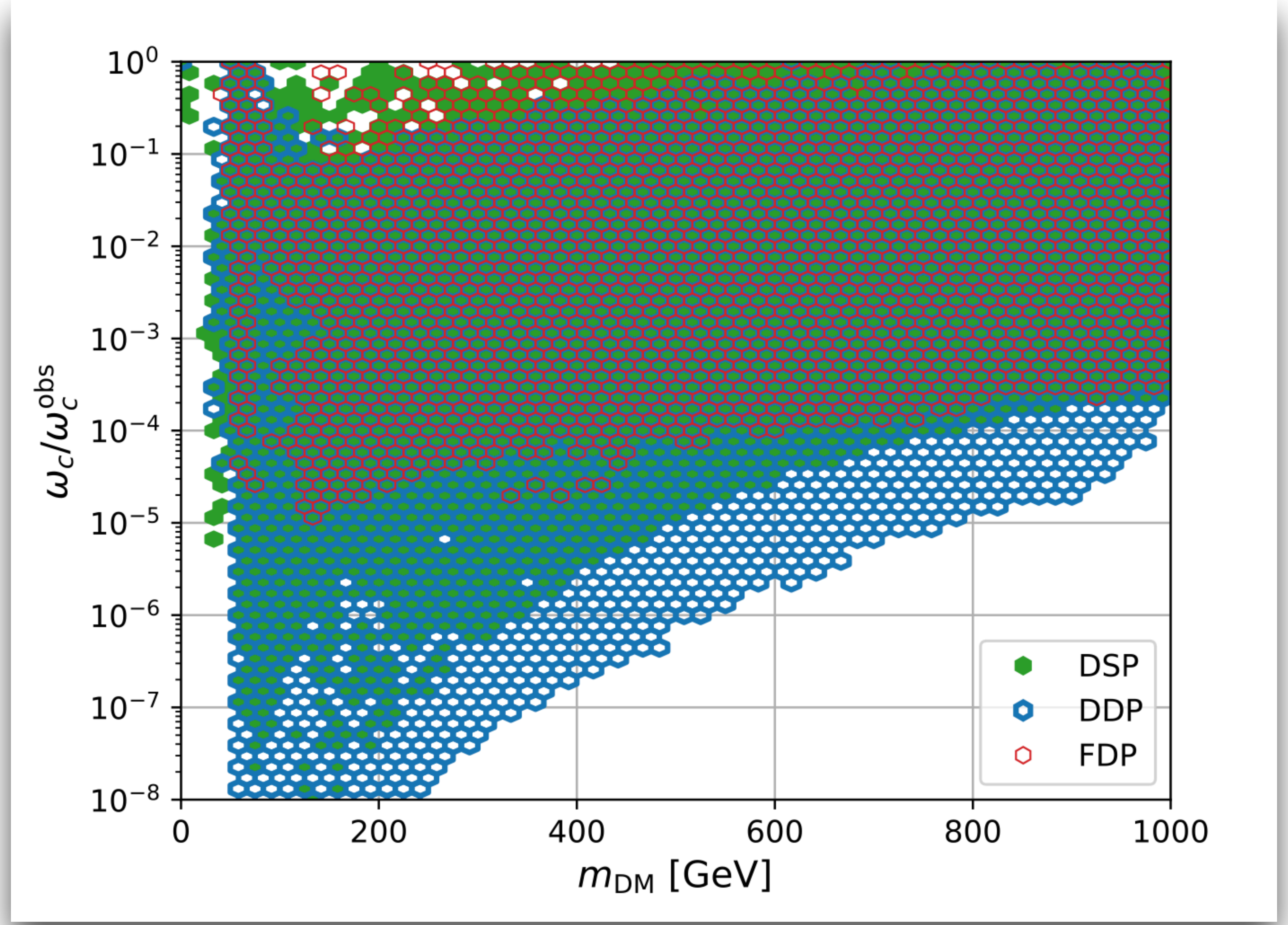
Dark Doublet Phase (DDP): one doublet+singlet non-zero VeVs; $\mathbb{Z}_2$ exact,$\mathbb{Z}_2'$ spont. broken ~> 4 dark sector particles ($A_D, H_D, H_D^\pm$), 2 visible particles (H_1, H_2)

Dark Singlet Phase (DSP): both doublets non-zero VeVs, singlet zero VEWV; $\mathbb{Z}_2'$ unbroken ~> 1 DM sector particle (H_D), 5 visible particles ($H_1, H_2, A, H^\pm$)

Fully Dark Phase (FDP): only one doublet non-zero VeV; $\mathbb{Z}_2$ and $\mathbb{Z}_2'$ exact ~> visible SM Higgs (H_{SM}), dark particles ($H_D^D, H_D^S, A_D, H_D^\pm$)

Impact on DM Observables - Relic Density

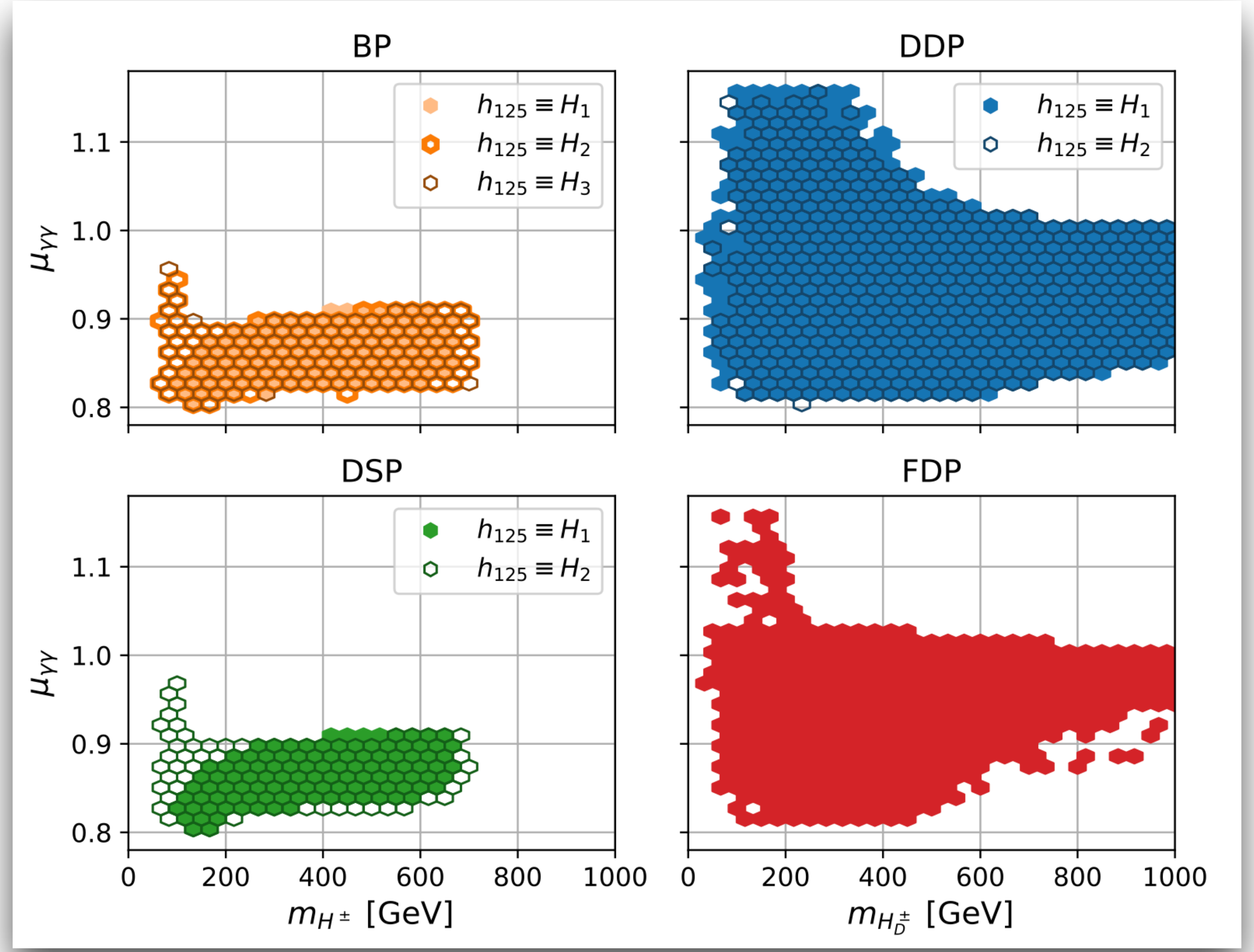
[Engeln,Ferreira,MM,Santos,Wittbrodt,2004.05382]



Interplay with Collider Observables

$$\mu_{\gamma\gamma} = \frac{(\sigma(H)\text{BR}(H \to \gamma\gamma))_{N2HDM}}{\sigma(H)\text{BR}(H \to \gamma\gamma))_{SM}}$$

[Engeln,Ferreira,MM,Santos,Wittbrodt,2004.05382]



Visible $H^\pm$ always suppress $\mu_{\gamma\gamma}$ compared to the SM; $H_D^\pm$ have more freedom in their couplings ~> enhance or suppress rate

=> $\mu_{\gamma\gamma}$ measurement could exclude BP, DSP

Di-Higgs Beats Single Higgs

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Possible for models w/ singlet-dominated and/or h_d-like (small gluon fusion production cxn!) non-SM-like Higgs boson => **NMSSM benchmark:**

λ	κ	A_λ [GeV]	A_κ [GeV]	$\mu_{\rm eff}$ [GeV]	$\tan\beta$
0.545	0.598	168	-739	258	2.255
$m_{H^\pm}$ [GeV]	M_1 [GeV]	M_2 [GeV]	M_3 [TeV]	A_t [GeV]	A_b [GeV]
548	437.872	498.548	2	-1028	1083
$m_{\tilde{Q}_3}$ [GeV]	$m_{\tilde{t}_R}$ [GeV]	$m_{\tilde{b}_R}$ [GeV]	A_τ [GeV]	$m_{\tilde{L}_3}$ [GeV]	$m_{\tilde{\tau}_R}$ [GeV]
1729	1886	3000	-1679.21	3000	3000

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_{A_1} [GeV]	m_{A_2} [GeV]
123.20	319	560	545	783
$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{A_1}$ [GeV]	$\Gamma^{\rm tot}_{A_2}$ [GeV]
3.985×10^{-3}	0.010	4.207	6.399	6.913
h_{11}	h_{12}	h_{13}	h_{21}	h_{22}
0.419	0.909	0.015	0.187	-0.102
h_{23}	h_{31}	h_{32}	h_{33}	a_{11}
0.977	0.889	-0.407	-0.212	0.908
a_{21}	a_{13}	a_{23}		
-0.104	0.114	0.994		

singlet-like H_2

Di-Higgs Beats Single Higgs

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Possible for models w/ singlet-dominated (suppressed couplings to SM particles) and/or h_d-like (suppressed direct production) non-SM-like Higgs boson => **NMSSM benchmark:**

H_2 is singlet-like: dominant decay channel into A_1 A_1

Single Higgs Production (4b final state)

$$\sigma^{\rm NNLO}(H_2)_{4b} = \sigma^{\rm NNLO}(H_2) \times {\rm BR}(H_2 \to A_1 A_1) \times {\rm BR}(A_1 \to b\bar{b})^2$$
$$= 13.54 \times 0.887 \times 0.704^2 \text{ fb} = 5.95 \text{ fb} .$$

Di-Higgs Production (6b final state)

$$\sigma^{\rm NLO}(H_1 H_2) = 111 \text{ fb} \qquad {\rm BR}(H_1 \to b\bar{b}) = 0.539$$

$$\sigma^{\rm NLO}(H_1 H_2) \times {\rm BR}(H_1 \to b\bar{b}) \times {\rm BR}(H_2 \to A_1 A_1) = 53 \text{ fb}$$

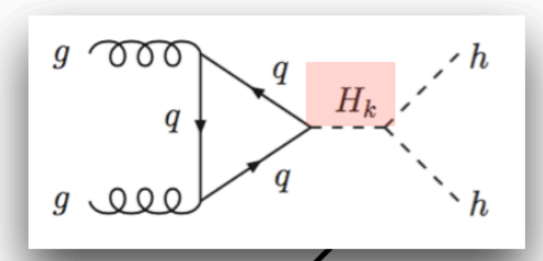
$$\sigma^{\rm NLO}(H_1 H_2)_{6b} = 53 \times 0.704^2 \text{ fb} = 26 \text{ fb}$$

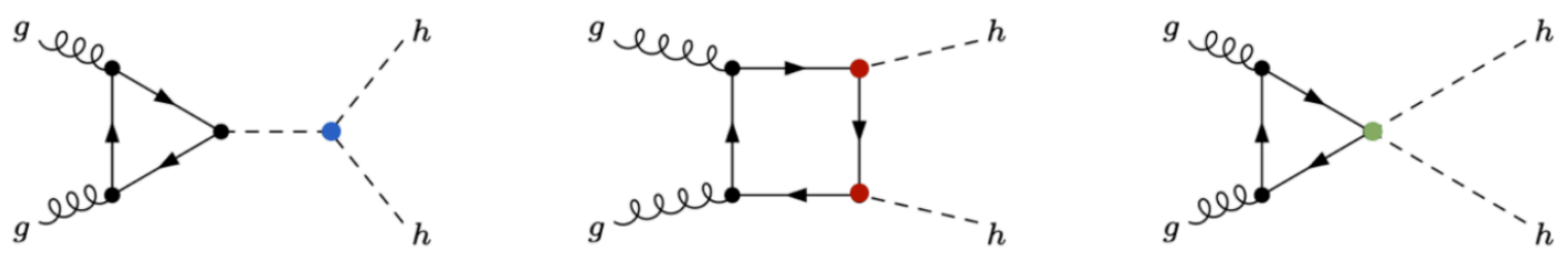
Comparison with EFT

- **Effective Lagrangian:**

$$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t t\bar{t}\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3$$

c_3: trilinear coupling modification; c_t: top-Yukawa coupling modification;
c_{tt}: effective two-Higgs-two-fermion coupling
no c_g, c_{gg}: no new heavy colored BSM particles assumed





- **Matching relations of our specific BSM models:**

Higgs-top Yukawa coupling	:	$g_t^{H_{\text{SM}}}(\alpha_i,\beta)$	$\rightarrow$	c_t
trilinear Higgs coupling	:	$\dfrac{g_3^{H_{\text{SM}}H_{\text{SM}}H_{\text{SM}}}(p_i)}{3M_{H_{\text{SM}}}^2/v}$	$\rightarrow$	c_3
two-Higgs-two-top quark coupling	:	$\sum_{k=1}^{k_{\max}}\left(\frac{-v}{m_{H_k}^2}\right) g_3^{H_k H_{\text{SM}} H_{\text{SM}}}(p_i)\, g_t^{H_k}(\alpha_i,\beta)$	$\rightarrow$	c_{tt}

2HDM versus EFT

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

✦ R2HDM T2 sample parameter point:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	1131	1082	1067	-0.924	0.820	552749

✦ corresponding EFT values:

$$g_t^{H_2} = -1.126$$

$$c_3 = 0.782\,,\ c_t = 0.951\,,\ c_{tt} = -0.122$$

✦ goodness of approximation?:

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2H_1H_1}$ [GeV]	$\sigma_{\rm R2HDM}^{\rm w/\ res}$ [fb]	$\sigma_{\rm SMEFT}^{c_{tt}\neq 0}$ [fb]	ratio
1131	78.80	-0.1222	-504.52	30.5	26.1	86%
1200	89.74	-0.1031	-479.29	27.7	24.8	90%
1500	470.2	-4.853 10^{-2}	-352.42	21.8	21.4	98%

✦ Remark:

$$\sigma_{\rm R2HDM}^{\rm w/o\ res} = 18.6\ {\rm fb} \quad {\rm and} \quad \sigma_{\rm SMEFT}^{c_{tt}=0} = 18.6\ {\rm fb}$$

N2HDM versus EFT

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- **N2HDM T1 sample parameter point:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	269	582	390	380	4.190
α_1	α_2	α_3	v_s [GeV]	$\mathrm{Re}(m_{12}^2)$ [GeV^2]	
1.432	-0.109	0.535	1250	28112	

$$g_t^{H_2} = 0.179 \quad \text{and} \quad g_t^{H_3} = 2.337 \times 10^{-2}$$

- **corresponding EFT values:**

$$c_3 = 0.877\,,\ c_t = 1.012\,,\ c_{tt} = 4.127 \times 10^{-2}$$

- **goodness of approximation?: (m_{H3} kept fixed)**

m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2H_1H_1}$	$\sigma_{\text{N2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
269	0.075	4.410×10^{-2}	4.127×10^{-2}	-72.42	183.70	20.56	11%
300	0.083	3.170×10^{-2}	2.877×10^{-2}	-64.80	162.80	21.28	13%
400	0.177	9.544×10^{-3}	6.721×10^{-3}	-34.68	43.33	22.60	52%
420	0.229	6.895×10^{-3}	4.063×10^{-3}	-27.62	31.70	22.76	72%
440	0.284	4.600×10^{-3}	1.767×10^{-3}	-20.22	26.26	22.90	87%
450	0.315	3.564×10^{-3}	7.323×10^{-4}	-16.39	24.84	22.96	92%
500	2.567	-7.132×10^{-4}	-3.545×10^{-3}	4.05	23.56	23.22	99%