Various Aspects of the 2HDM and Beyond

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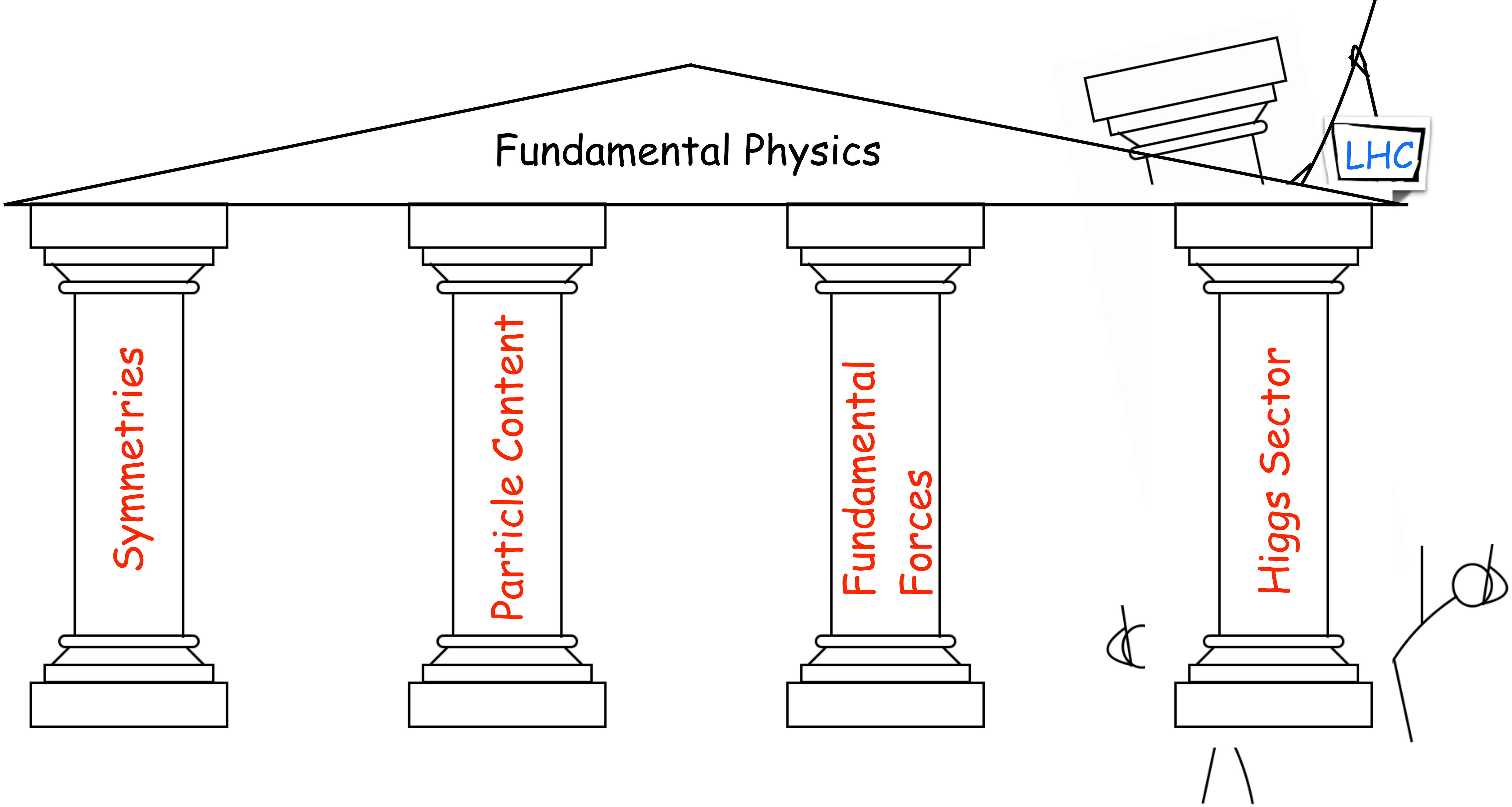
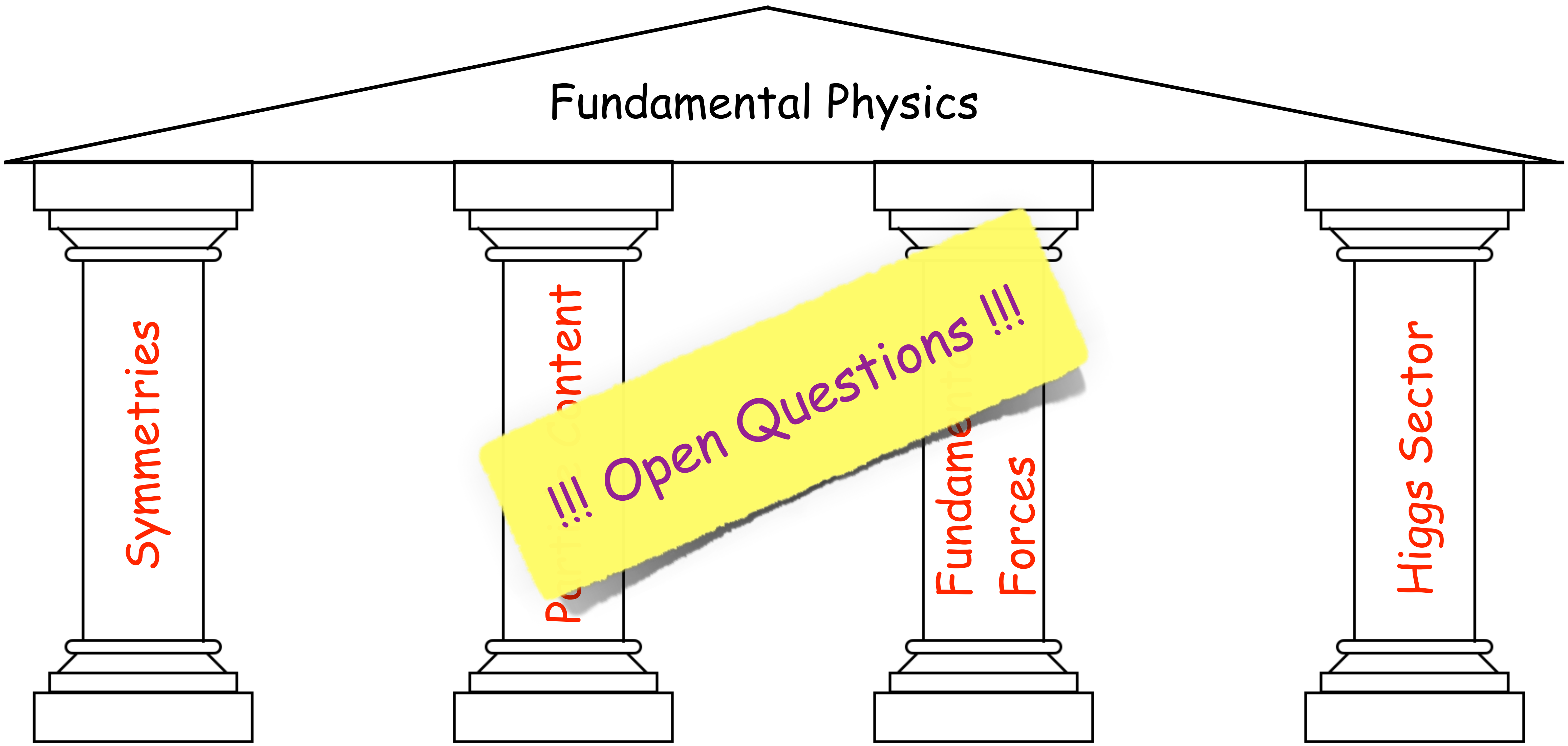
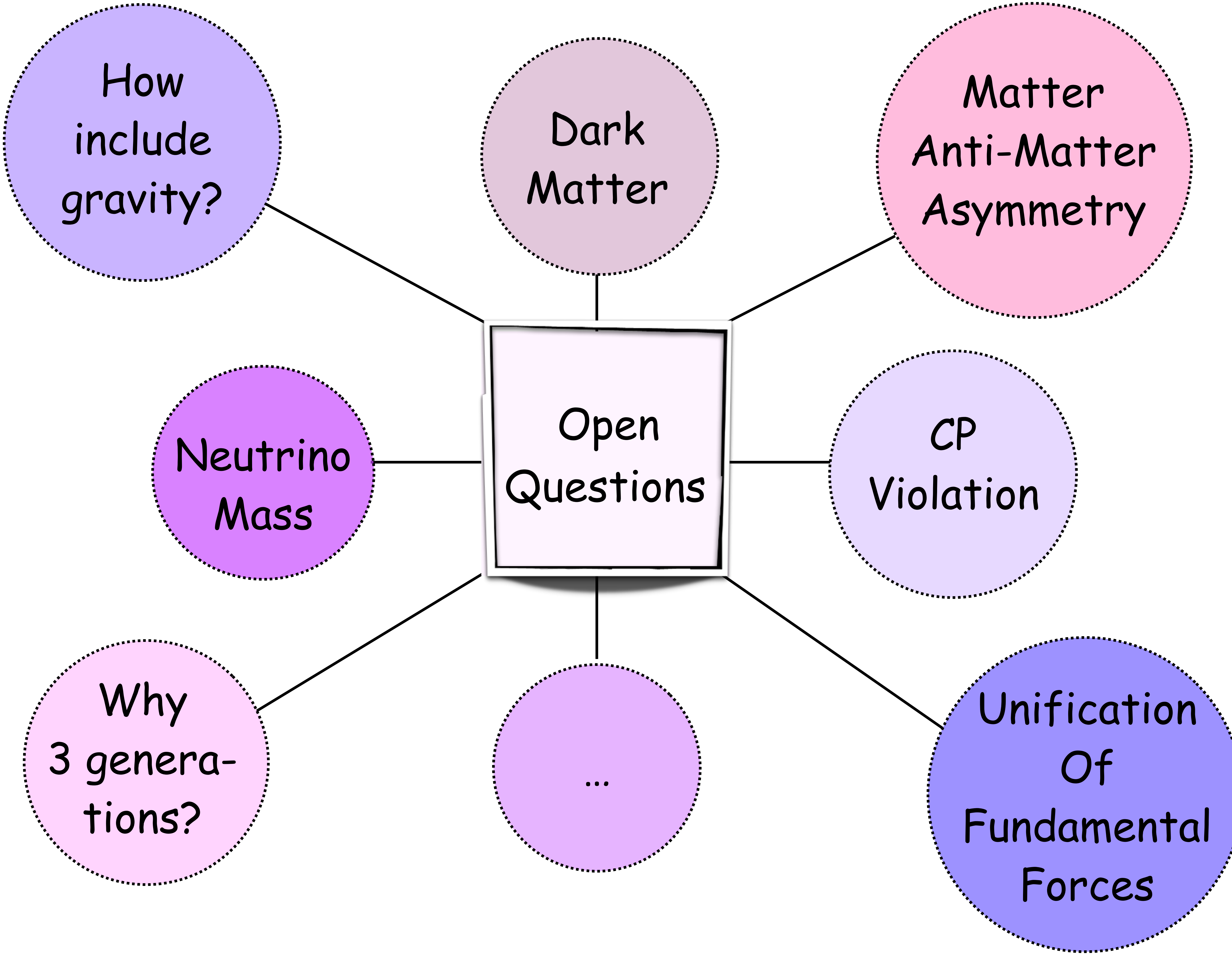
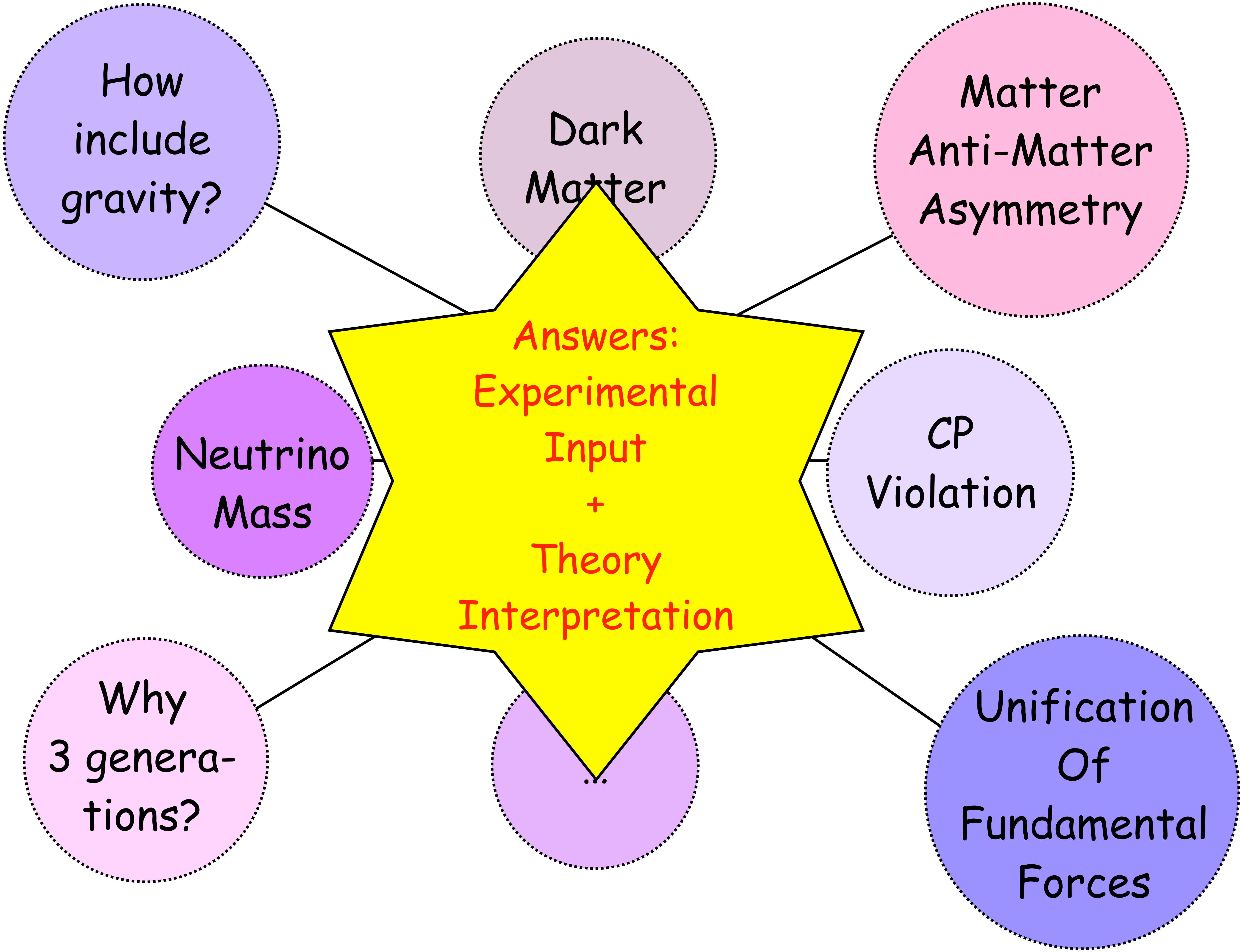
15 June 2022


Fundamental Physics
Symmetries
Particle Content
Fundamental Forces
Higgs Sector
LHC


Fundamental Physics
Symmetries
Forces
Higgs Sector
!!! Open Questions !!!


How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Open Questions
CP Violation
Why 3 genera-tions?
...
Unification Of Fundamental Forces


How include gravity?
Dark Matter
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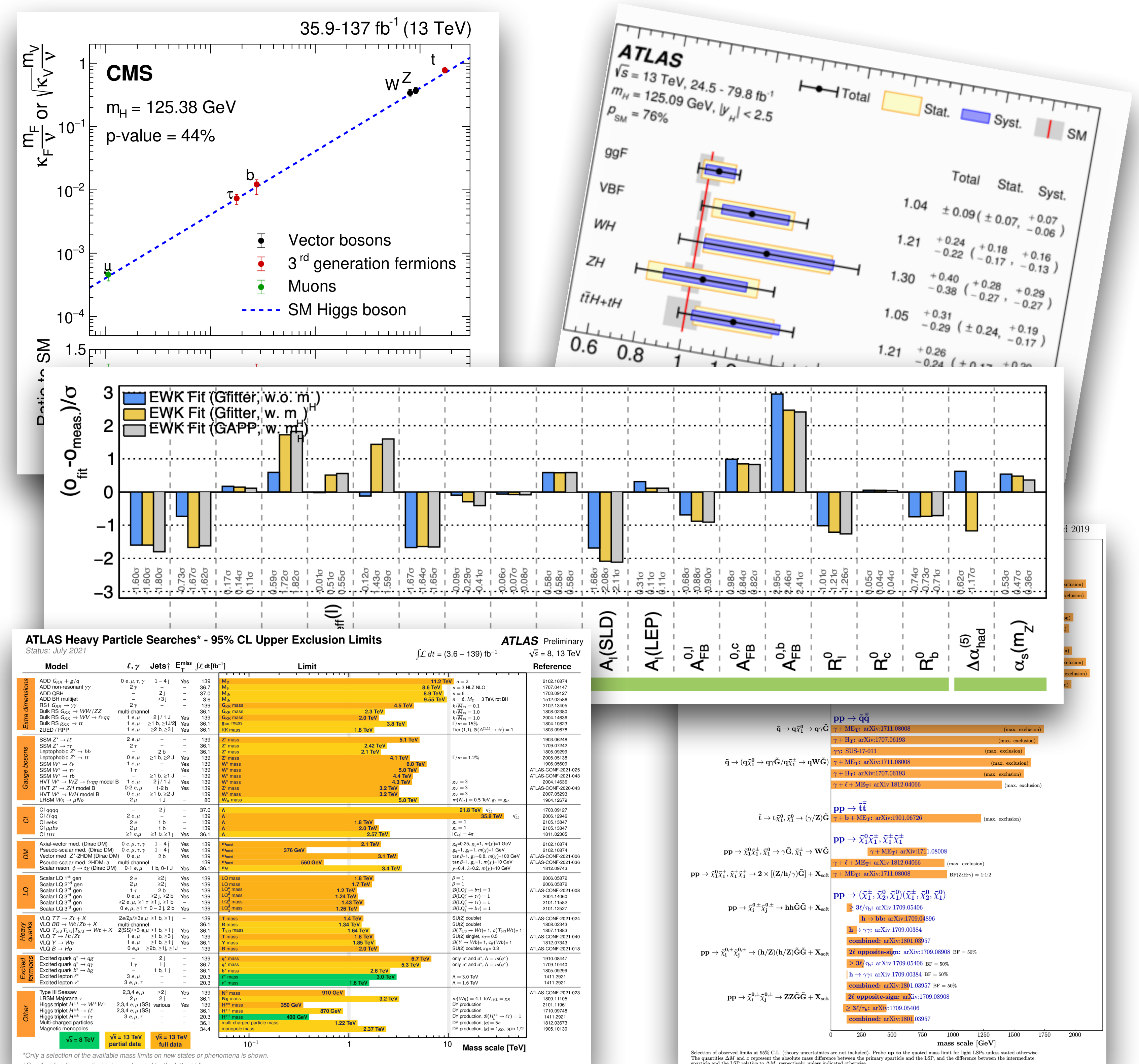
Neutrino Mass
Answers: Experimental Input + Theory Interpretation
CP Violation
Why 3 generations?
...
Unification Of Fundamental Forces

Status



Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

New physics is 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

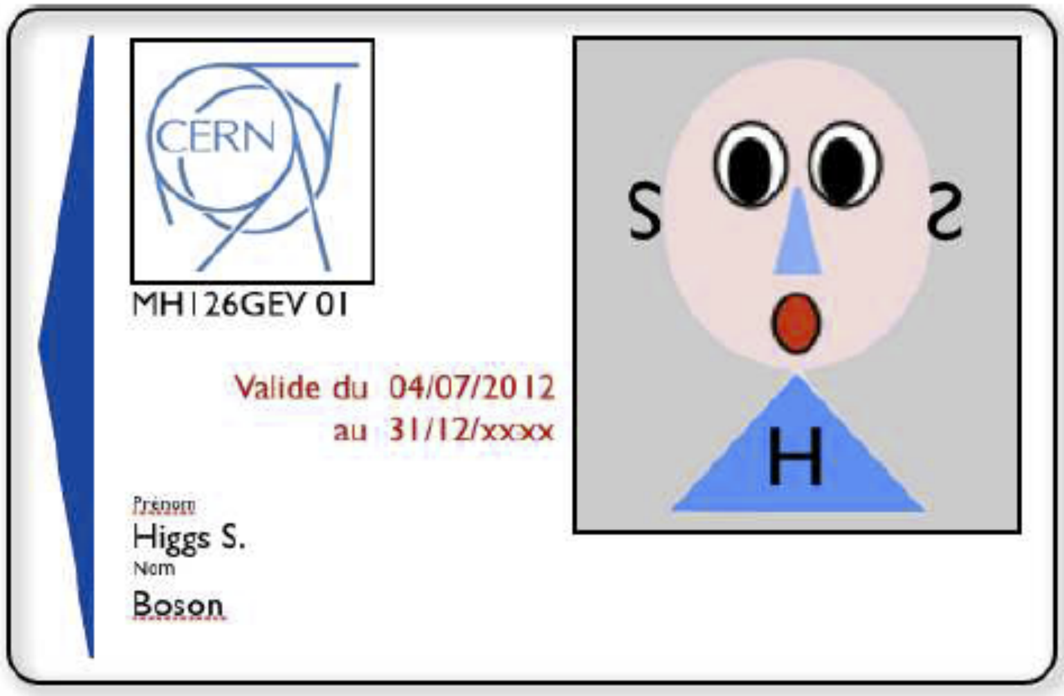
What we have

- Experimental reality: No Beyond the Standard Model Physics discovered so far!

  Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate."

- We have the SM-like Higgs boson

  What can we learn from Higgs physics?



Beyond-SM Higgs Sectors

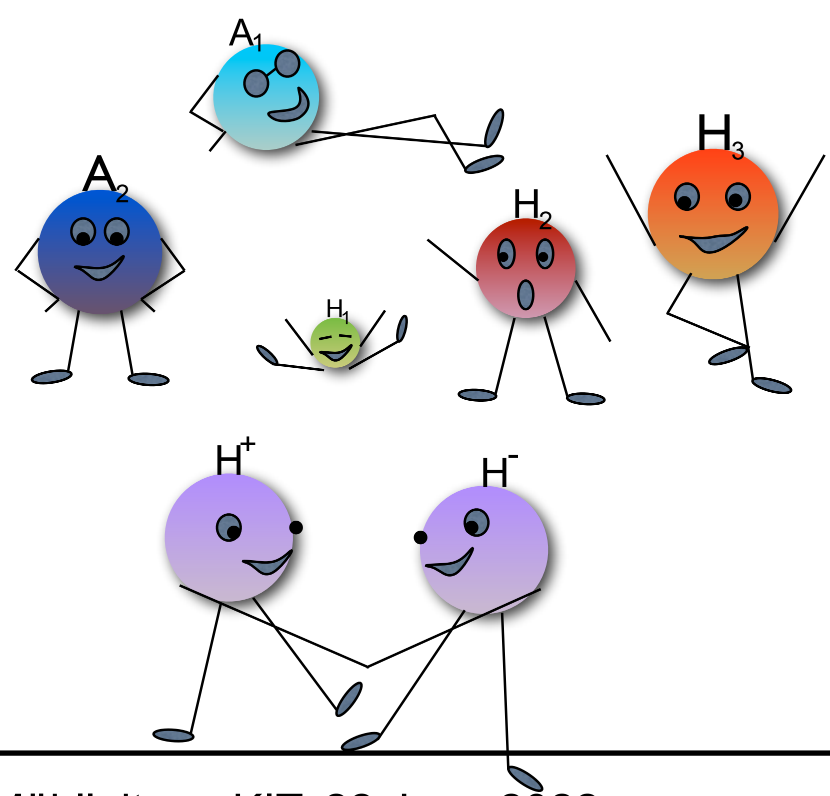
Extended Higgs Sectors

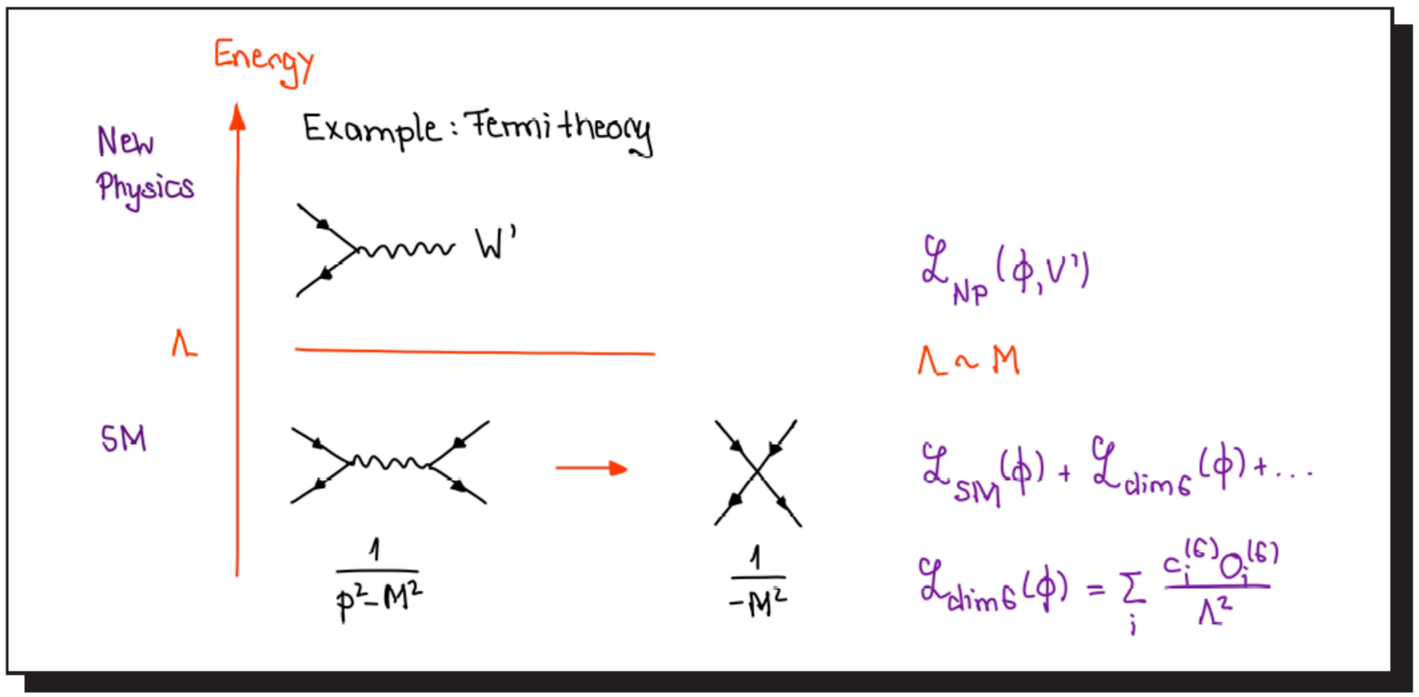
Why extended Higgs sectors?

* 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
* many new physics models require extended Higgs models ← supersymmetry!

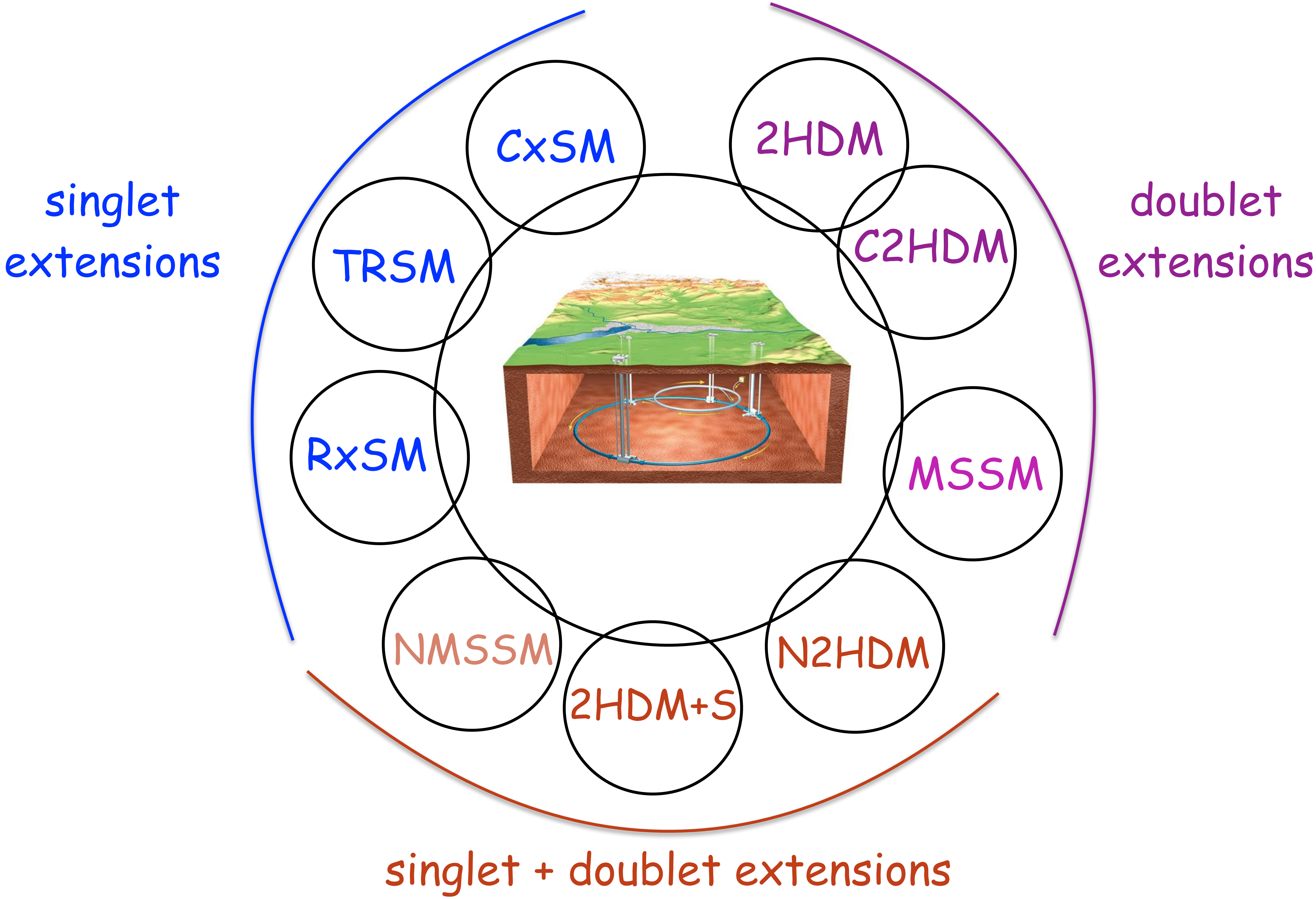
How systemize approach not to miss any new physics sign?

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





Extended Higgs Sectors



Extended Higgs Sectors

Guidelines for model selection

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

$\mathcal{E}$xperimental $\mathcal{C}$onstraints on $\mathcal{E}$xtended $\mathcal{H}$iggs $\mathcal{S}$ectors

- **Electroweak ρ parameter very close 1:** simplest solution Higgs singlets and doublets

- **Flavor-changing neutral currents (FCNCs):** symmetries so that all right-handed fermions of given electric charge couple to exactly one Higgs doublet ($e.g.$ (N)2HDM type I...IV); minimal flavour violation

- **Further Constraints**

  * EWPTs ($\leftarrow S, T, U$)
  * Flavour constraints ($B \to X_s\gamma$, R_b, ...)
  * Higgs data ($\leftarrow$ 125 GeV SM-like Higgs required, direct searches for additional Higgs bosons)
  * Direct searches for new particles predicted by the model
  * Low-energy observables
  * Relic density ($\leftarrow$ models w/ DM candidate)
  * EDM constraints ($\leftarrow$ models w/ CP violation)

Theory Constraints on Extended Higgs Sectors

- **Higgs potential bounded from below**
- **EW vacuum global minimum**
- **Perturbative unitarity**

Parameter scans with constraints:
Reduction of the parameter space
to the allowed parameter space $\rightsquigarrow$
sharpen predictions for the models!

The 2HDM

- Singlet and Doublet Extensions:

Compatible with ρ parameter; prominent example of 2HDM: supersymmetry, but SUSY relations constrain model

- 2 complex Higgs doublets: [Lee,'73], [Branco eal,'11]

motivation: baryogenesis, DM, stability of EW vacuum

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

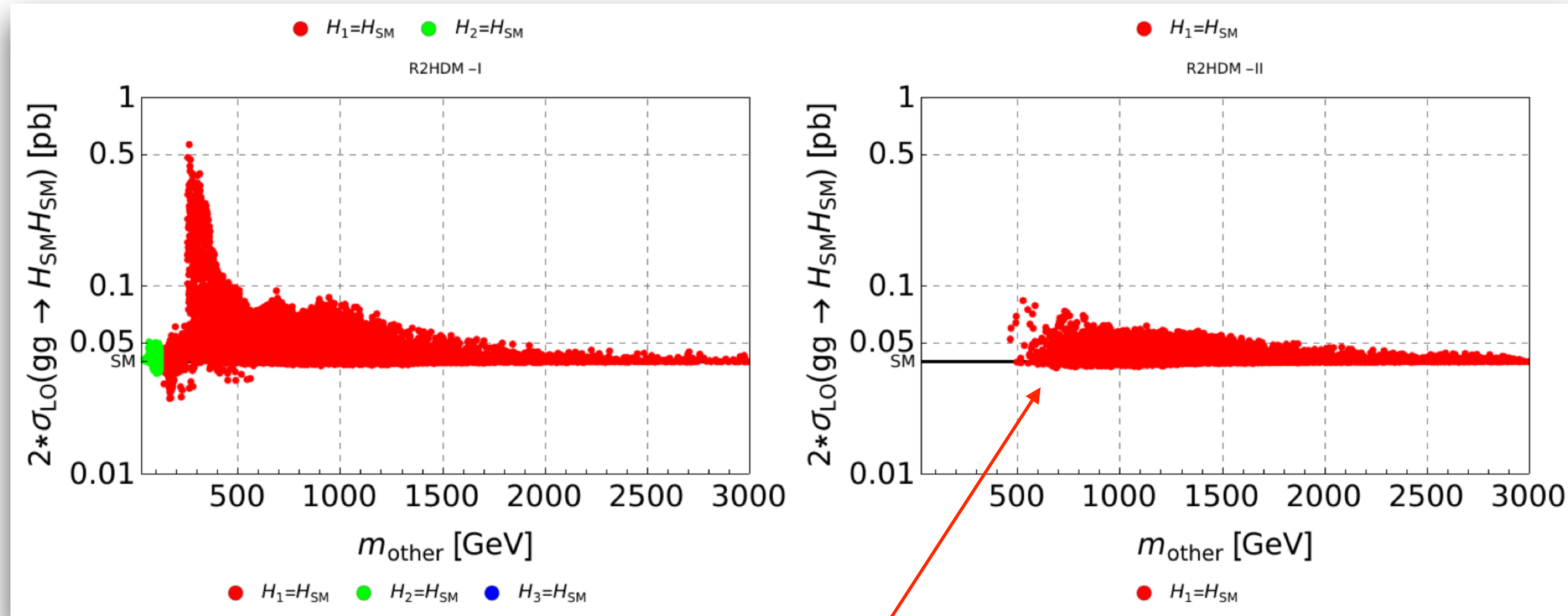
discrete symmetry $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$ softly broken

- Higgs spectrum after EWSB: 2 CP-even h,H with $m_h < m_H$,
  1 CP-odd A,
  charged Higgs pair $H^\pm$

- Possible scenarios: h SM-like or H SM-like

Mass Spectrum

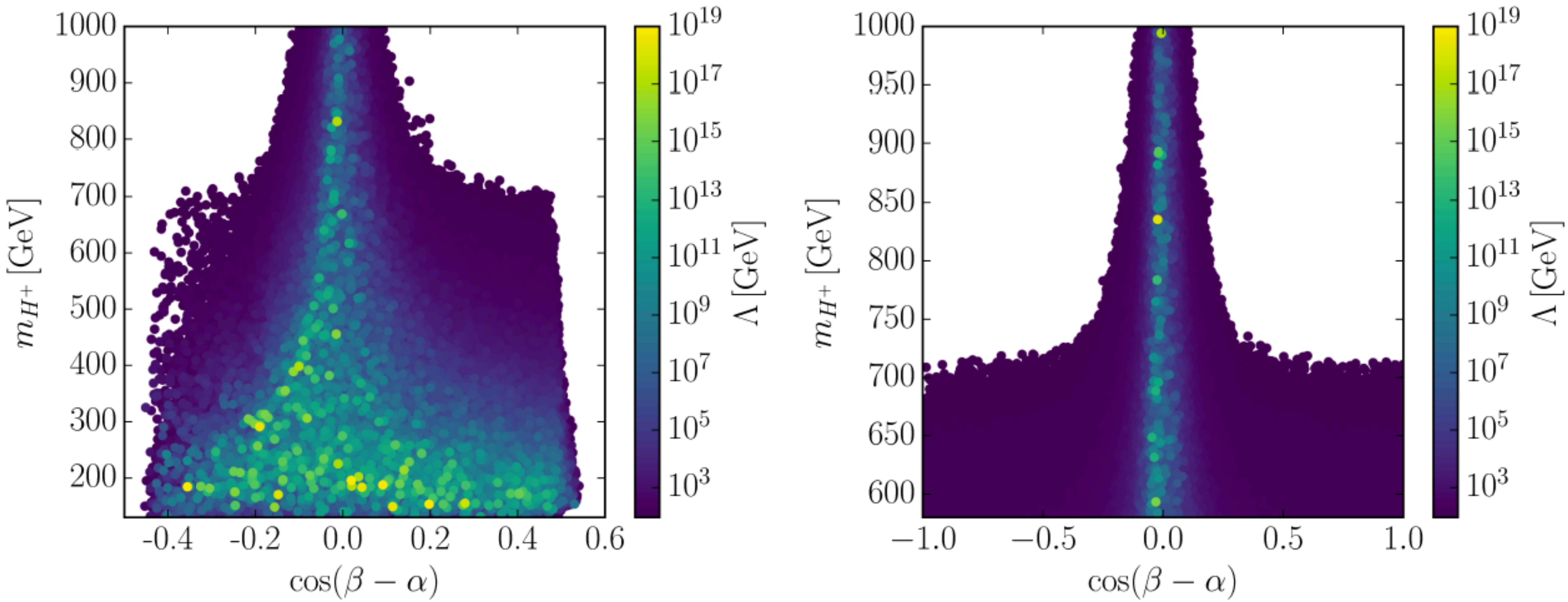
[Aboouid,Arhrib,Azevedo,Ferreira,El Falaki,MM,Santos,'21]



lower limit from B->s gamma measurements
$m_{H\pm}$ > 800 GeV [Misiak,Rehman,Steinhauser,'20]

Theory constraint and High Scale Impact

High-scale impact on alignment in 2HDMs [Basler,Ferreira,MM,Santos,'17]



Left: type I, right: type II
Alignment for $m_{H^\pm} \gtrsim 500$ GeV and validity up to the Planck scale (theor.&exp. constraints included)

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

The N2HDM

- 2 Higgs doublets and a real singlet field: [Chen eal,'13; MM eal,'17; Engeln eal,'19]

  Motivation: baryogenesis, DM, rich phenomenology

- The Higgs potential:

$$V_{\rm N2HDM} = V_{\rm 2HDM} + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2$$

discrete symmetry $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to \Phi_S$ and softly broken

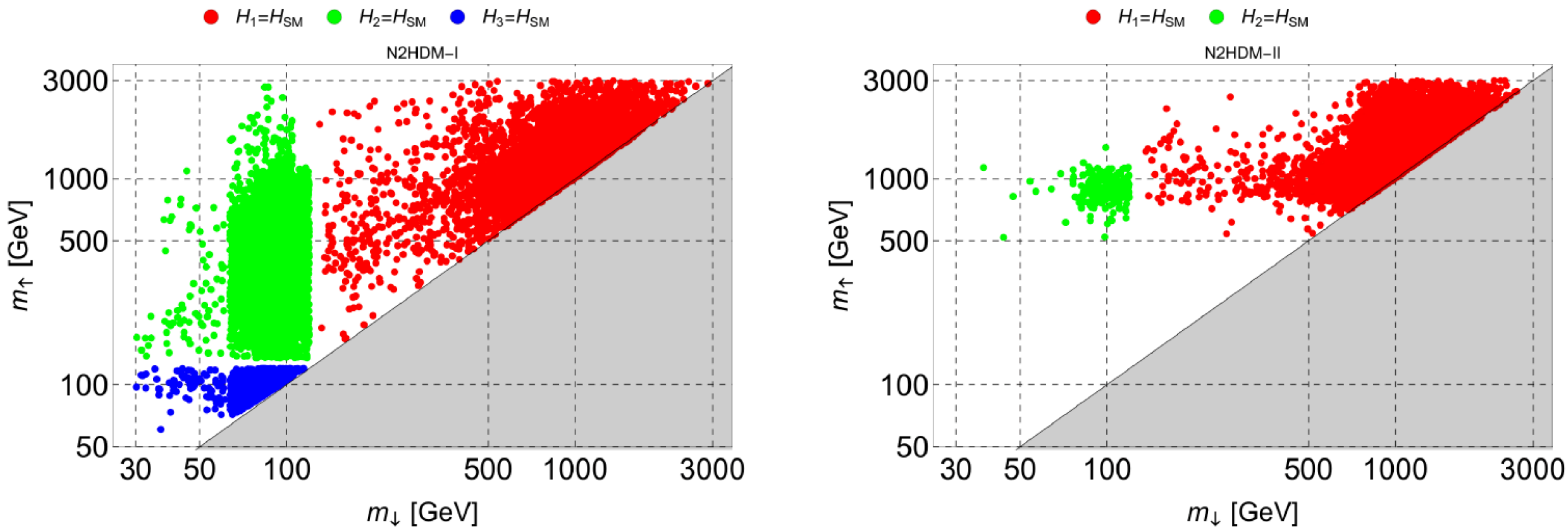
$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to \Phi_2\,, \quad \Phi_S \to -\Phi_S\,.$$

- Higgs spectrum after EWSB: 3 CP-even $H_{1,2,3}$ with $m_{H1} < m_{H2} < m_{H3}$,
  1 CP-odd A,
  charged Higgs pair $H^\pm$

- Possible scenarios: $H_{1,2,3}$

Mass Spectrum

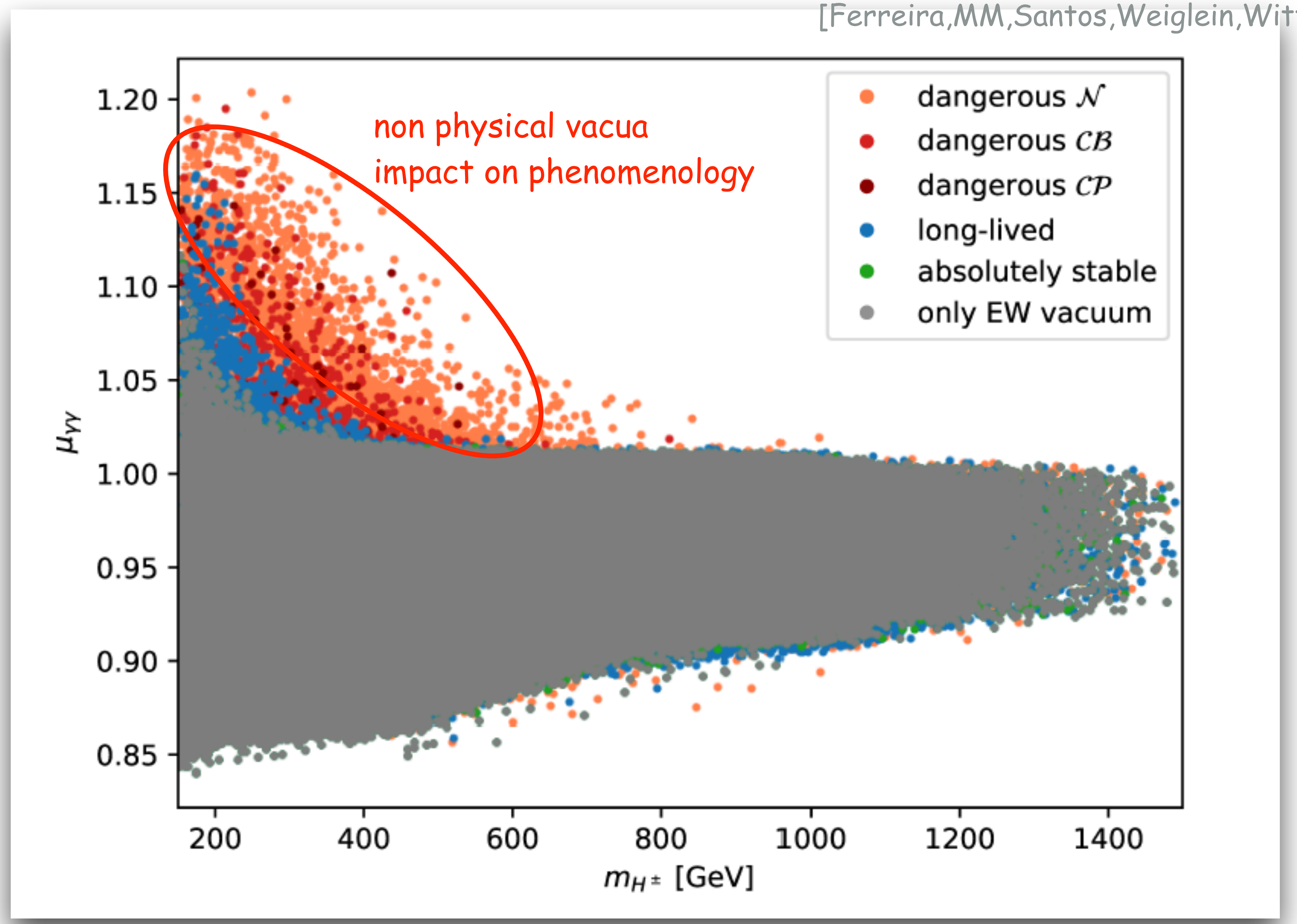
[Aboouid,Arhrib,Azevedo,Ferreira,El Falaki,MM,Santos,'21]



Theory constraint: vacuum stability

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

[Ferreira,MM,Santos,Weiglein,Wittbrodt,'19]



The C2HDM

✦ The CP-Violating 2HDM: [Ginzburg,Krawczyk,Osland,'02]

Motivation
- can provide a strong first order electroweak phase transition (like 2HDM)
- has additional sources of CP violation (required by electroweak baryogenesis)
- has rich phenomenology, in particular interesting di-Higgs signatures

✦ The Model: 2 complex Higgs doublets $\mathbf{\Phi}_1$, $\mathbf{\Phi}_2$,

CP-violating scalar potential w/ softly broken $\mathbb{Z}_2$ symmetry $\mathbf{\Phi}_1 \to \mathbf{\Phi}_1$, $\mathbf{\Phi}_2 \to -\mathbf{\Phi}_2$

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

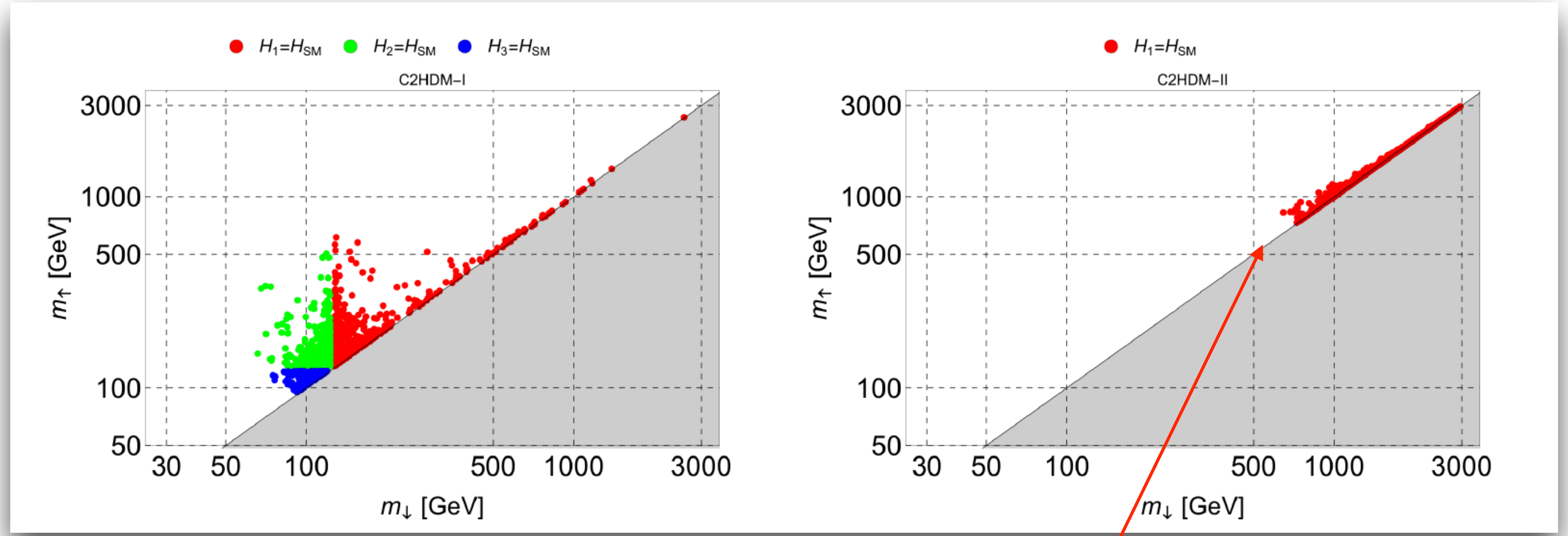
complex

✦ After EWSB: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}$ and $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$

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

Mass Spectrum

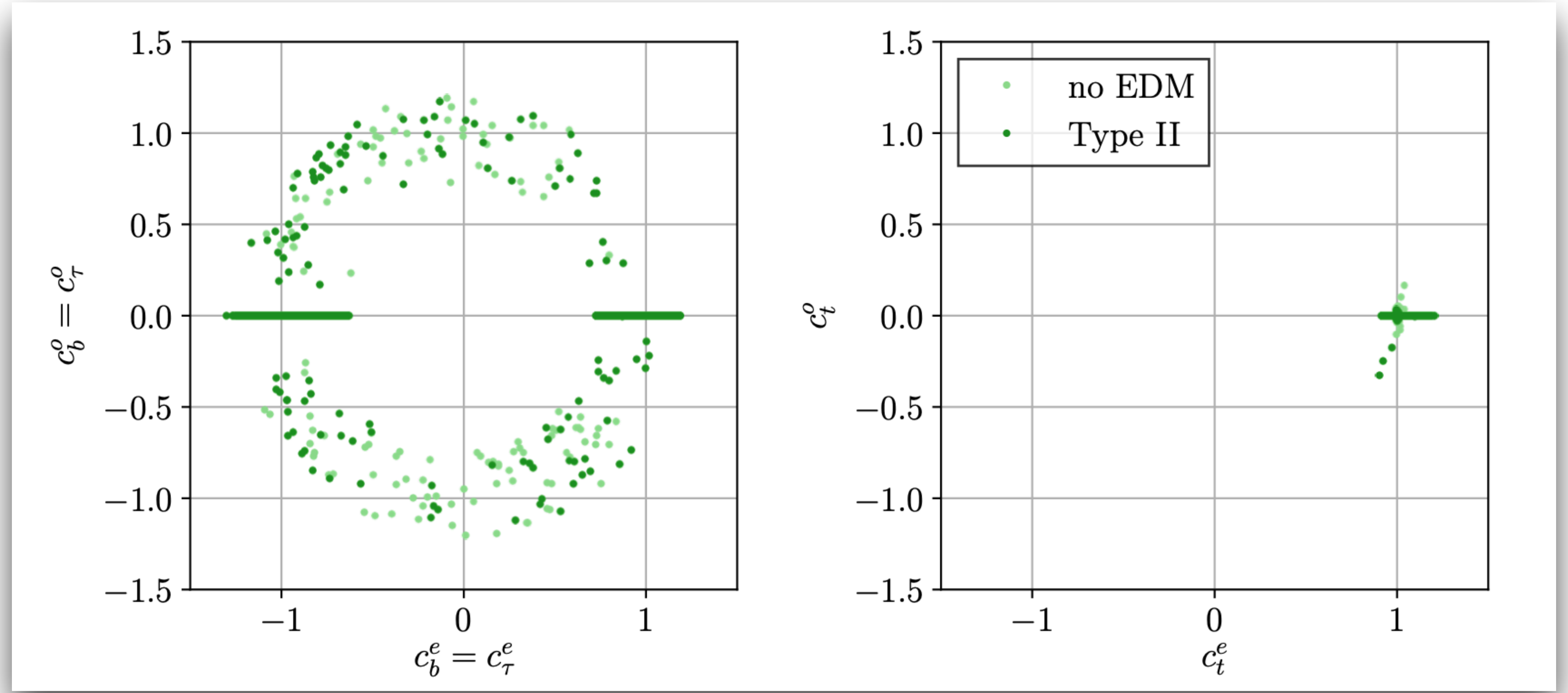
[Aboouid,Arhrib,Azevedo,Ferreira,El Falaki,MM,Santos,'21



lower limit from B->s gamma measurements
$m_{H\pm}$ > 800 GeV [Misiak,Rehman,Steinhauser,'20]

- **EDM measurements:** place stringent constraints on size of CP-violating phase
  After taking into account all relevant theoretical and experimental constraints still possible

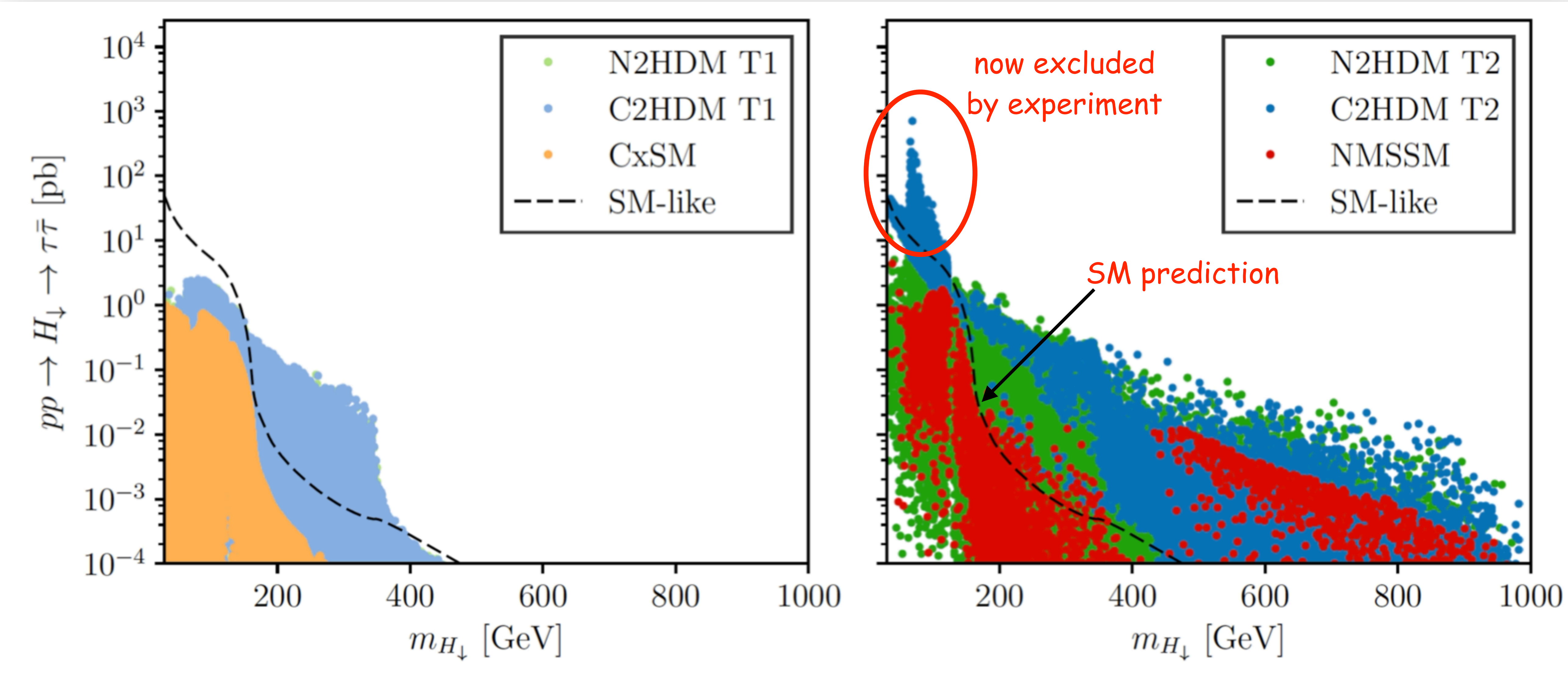
$H_2 = h_{125}$ [Fontes,MM,Romao,Santos,Silva,Wittbrodt,'17]



h_{125} couples like pseudoscalar to down-type fermions, like scalar to up-type fermions

Example: Higgs search in tau final states

Parameter scan results in various new physics models [MM,Sampaio,Santos,Wittbrodt,'17]

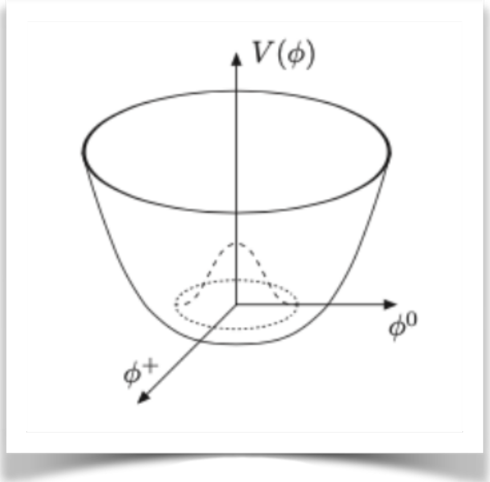



Di-Higgs Production

Higgs Pair Production

- Ultimate test of the Higgs mechanism:

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

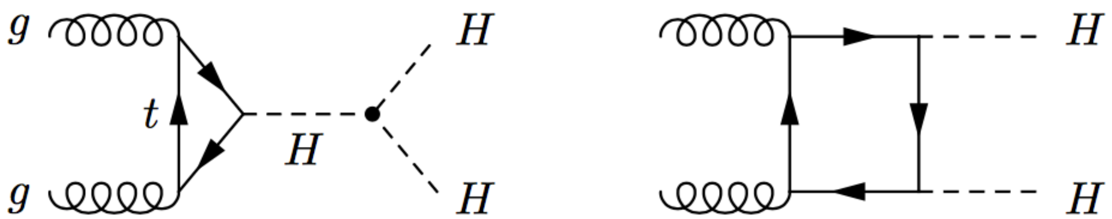


- Test of Higgs self-couplings at colliders :

λ_{HHH} via Higgs pair production

λ_{HHHH} via triple Higgs production

- SM Higgs pair production at the LHC - dominant process: gluon fusion



SM: destructive interference triangle and box diagrams

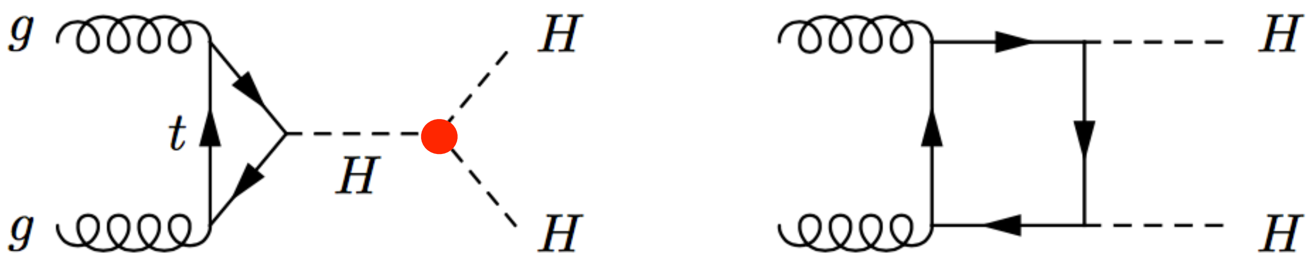
$$\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb}$$

Challenge: small cxn and large QCD bkg

at FT_{approx}: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects
and full mass dependence in the one-loop double real corrections at NNLO

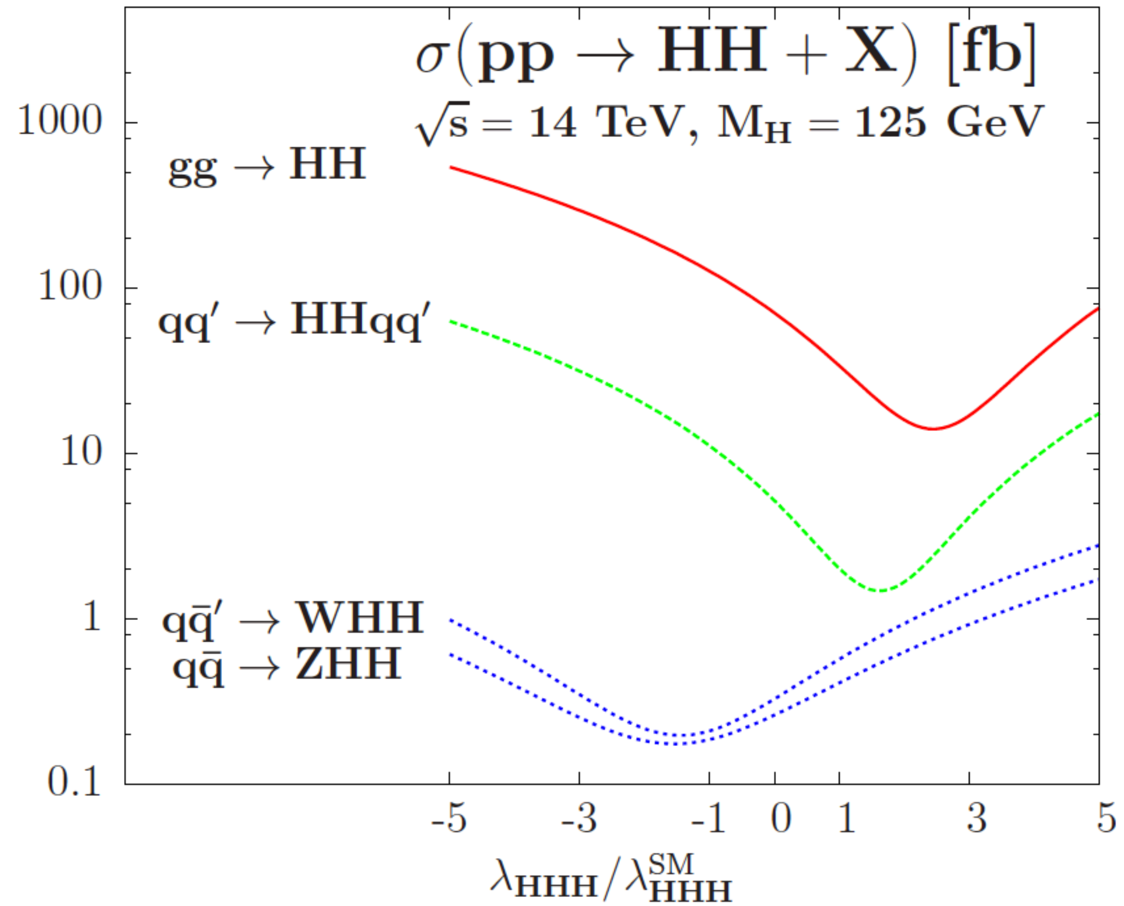
SM Higgs Pair Production

✦ SM Higgs pair production at the LHC - dominant process: gluon fusion



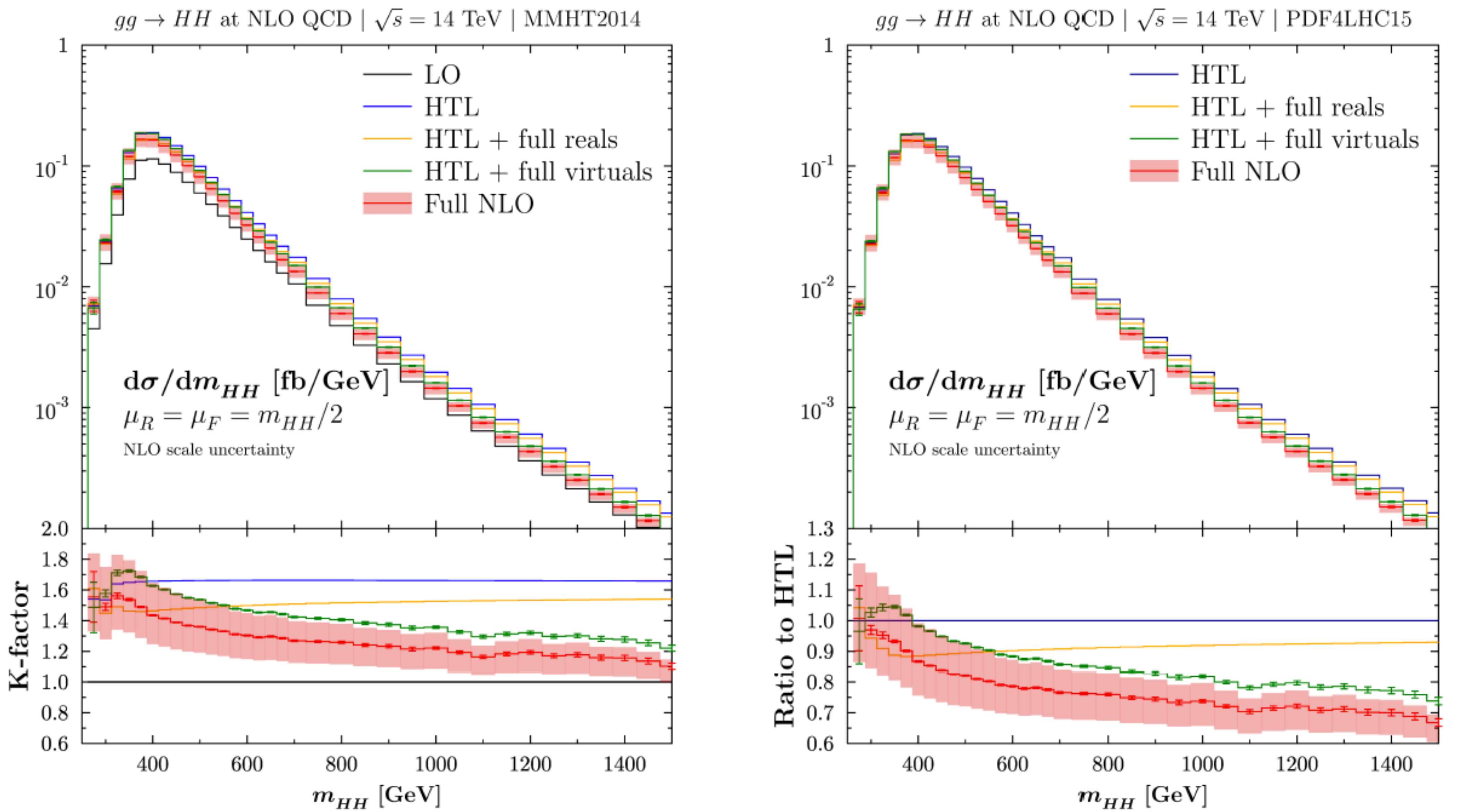
✳ SM: destructive interference triangle and box diagrams

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



Next-to-Leading Order gg->HH with Full Mass Dependence

[Baglio,Campanario,Glaus,MM,Streicher,Spira,'18]
(see also [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke,'16])



inclusive: -15% mass effects on top of LO
exclusive: even more

Challenge Measurement

[Grazzini eal'19]
for extensive list of refs.
see |di Micco eal'19]

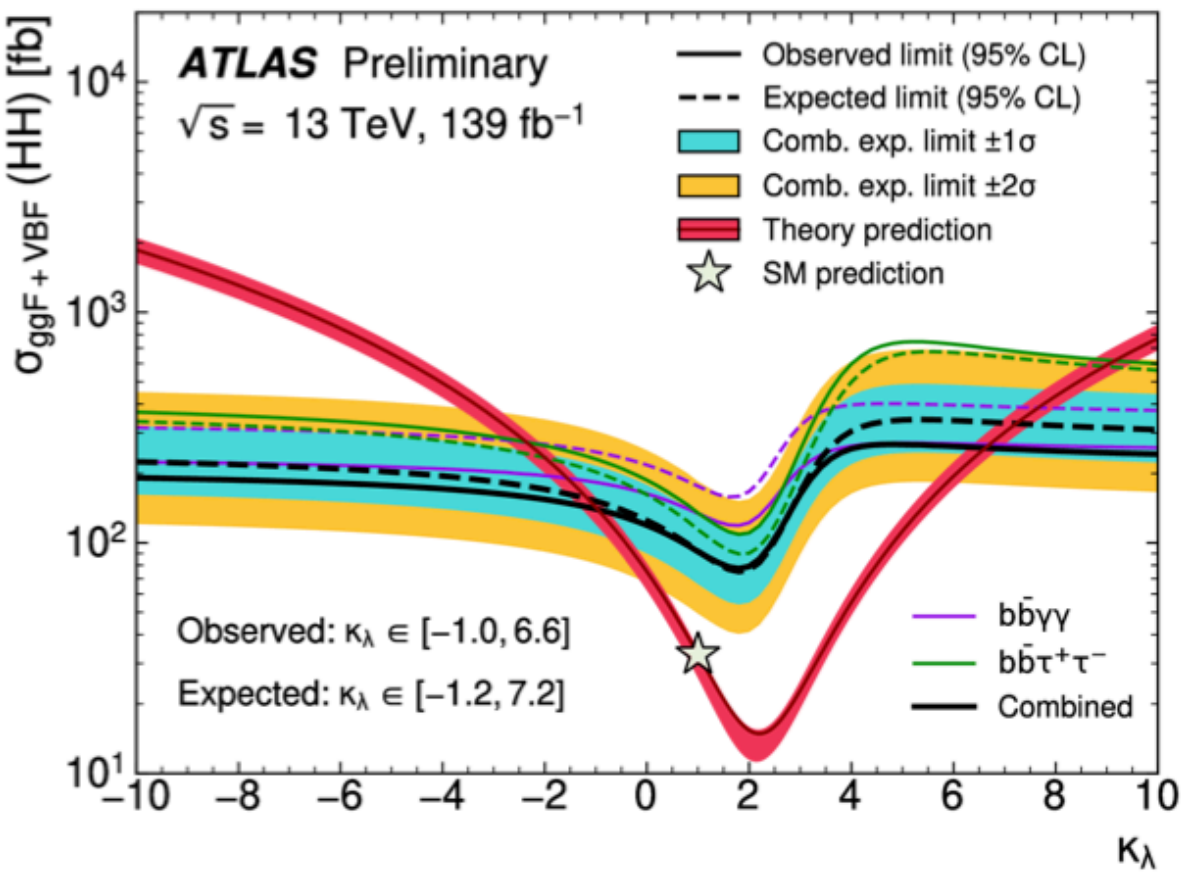
✦Cross section:

$$\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} \quad = \quad 31.05^{+6\%}_{-23\%}\ \text{fb}$$

at FT_{approx}: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO

✦Challenge: small cross sections and large QCD backgrounds

Experimental Results - Limits on Trilinear Higgs Self-Coupling



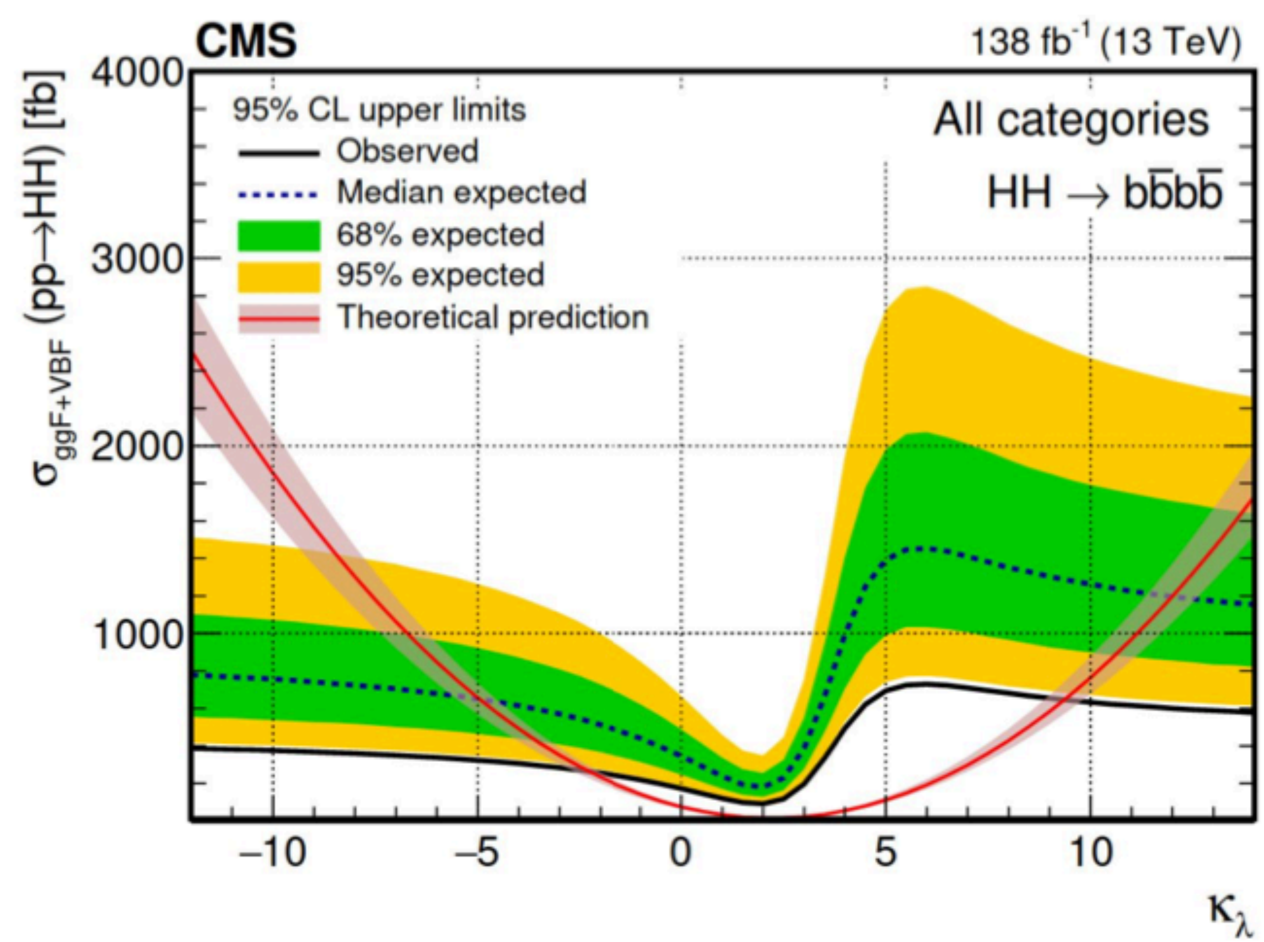
[Rui Zhang, ATLAS, HH Workshop´22]

Observed: $\kappa_\lambda \in [-1.0, 6.6]$

Expected: $\kappa_\lambda \in [-1.2, 7.2]$

[Fabio Monti, CMS, HH Workshop´22]

Obs. $k_\lambda \in [-2.3, 9.4]$
Exp. $k_\lambda \in [-5.0, 12.0]$

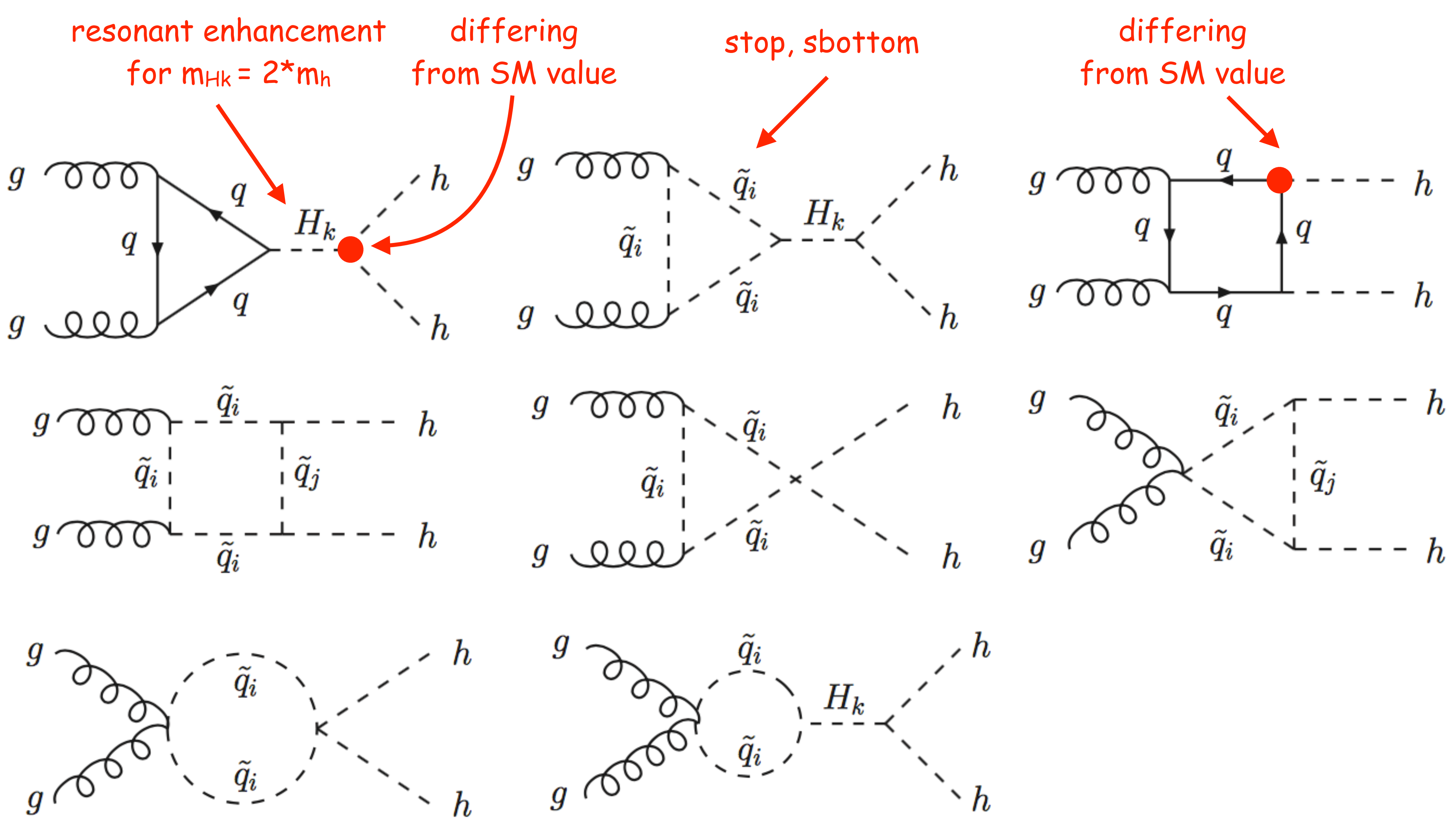


New Physics Effects in Higgs Pair Production

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

✦Example NMSSM:

[taken from Dao,MM eal'13]



Aim

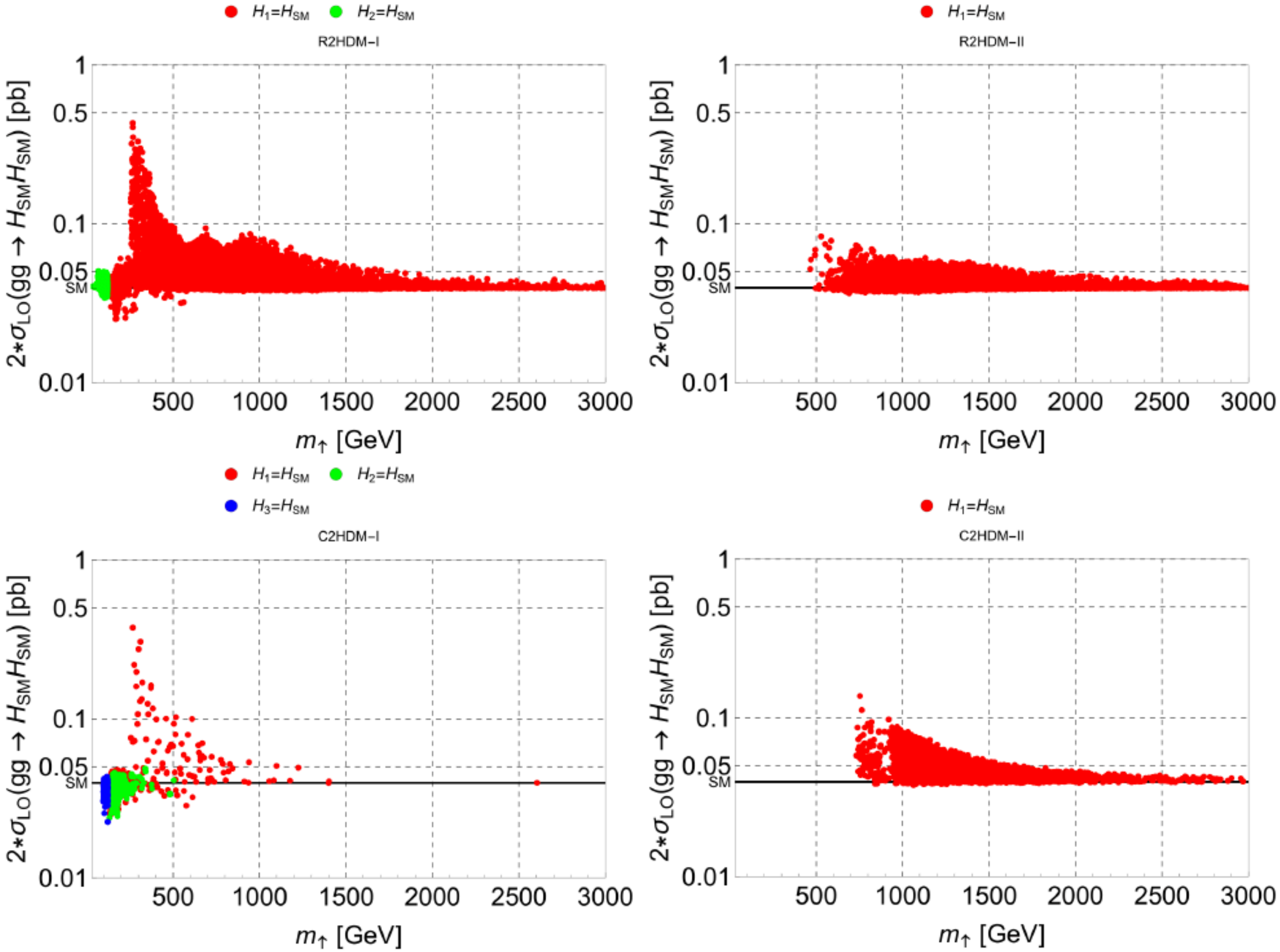
Overview of Higgs Pair production possibilities
including theoretical and experimental constraints
in archetypical BSM Higgs sectors
including different symmetries

provide benchmark points / lines / planes
for experiment

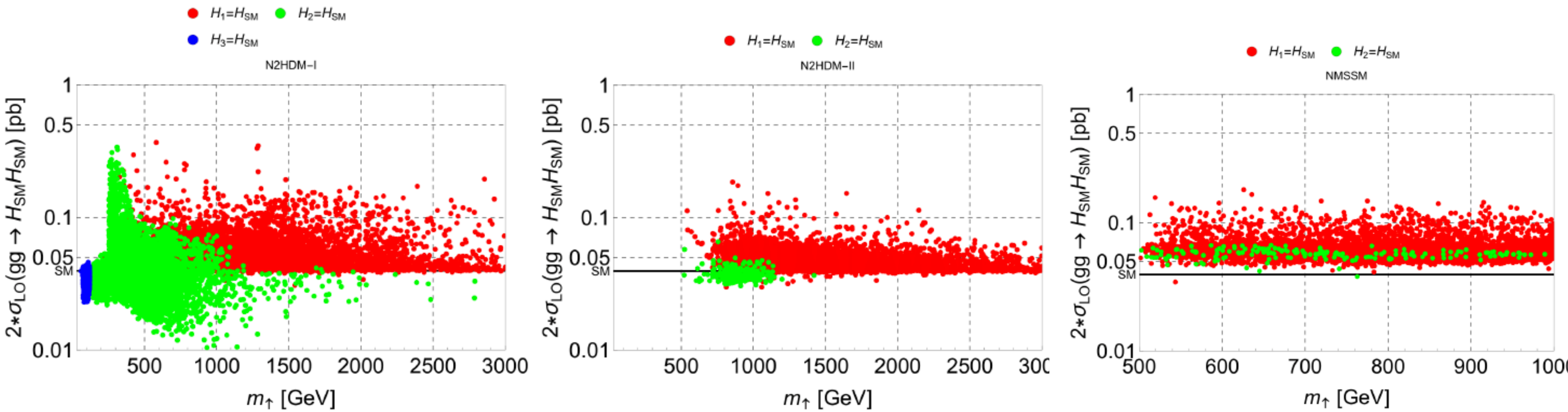
Allowed Coupling Deviations

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

	R2HDM		C2HDM	
	$y_{t,H_{\rm SM}}^{\rm R2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm R2HDM}/\lambda_{3H}$	$y_{t,H_{\rm SM}}^{\rm C2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm C2HDM}/\lambda_{3H}$
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**	
	$y_{t,H_{\rm SM}}^{\rm N2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm N2HDM}/\lambda_{3H}$	$y_{t,H_{\rm SM}}^{\rm NMSSM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm NMSSM}/\lambda_{3H}$
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	–	–	–	–



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



Maximum Cross Section Values - Resonant Production

Model \ SM-like	H1	H2
R2HDM T1	444 fb	
R2HDM T2	81 fb	
C2HDM T1	387 fb	47 fb
C2HDM T2	130 fb	no point
N2HDM T1	376 fb	344 fb
N2HDM T2	188 fb	63 fb
NMSSM	183 fb	65 fb

NLO SM HH production (in the heavy top limit): 38 fb

Implications of Baryogenesis

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

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

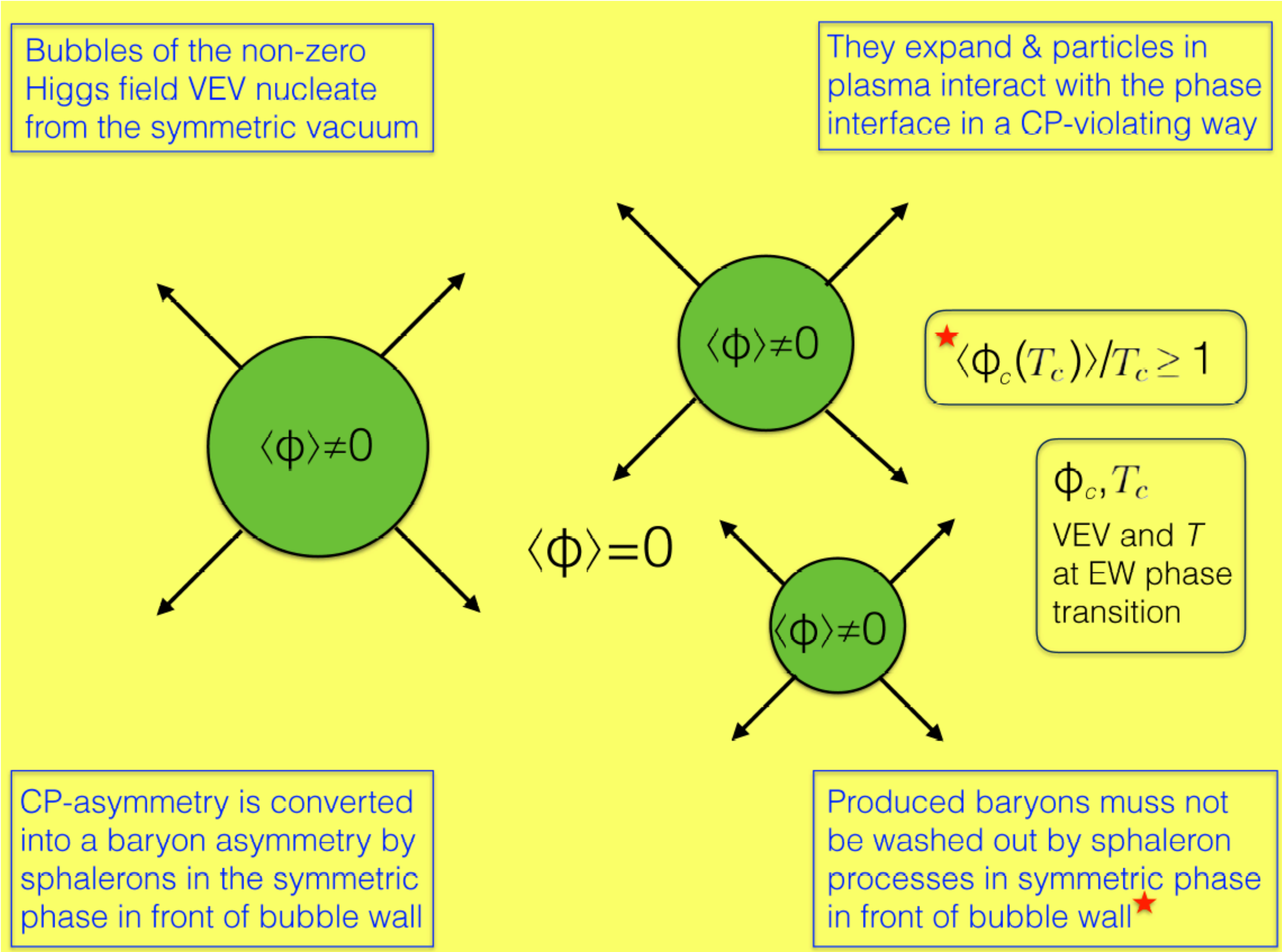
- **Sakharov Conditions:** [Sakharov '67]
  - (i) B number violaton (sphaleron processes)
  - (ii) C and CP violation
  - (iii) Departure from thermal equilibrium

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

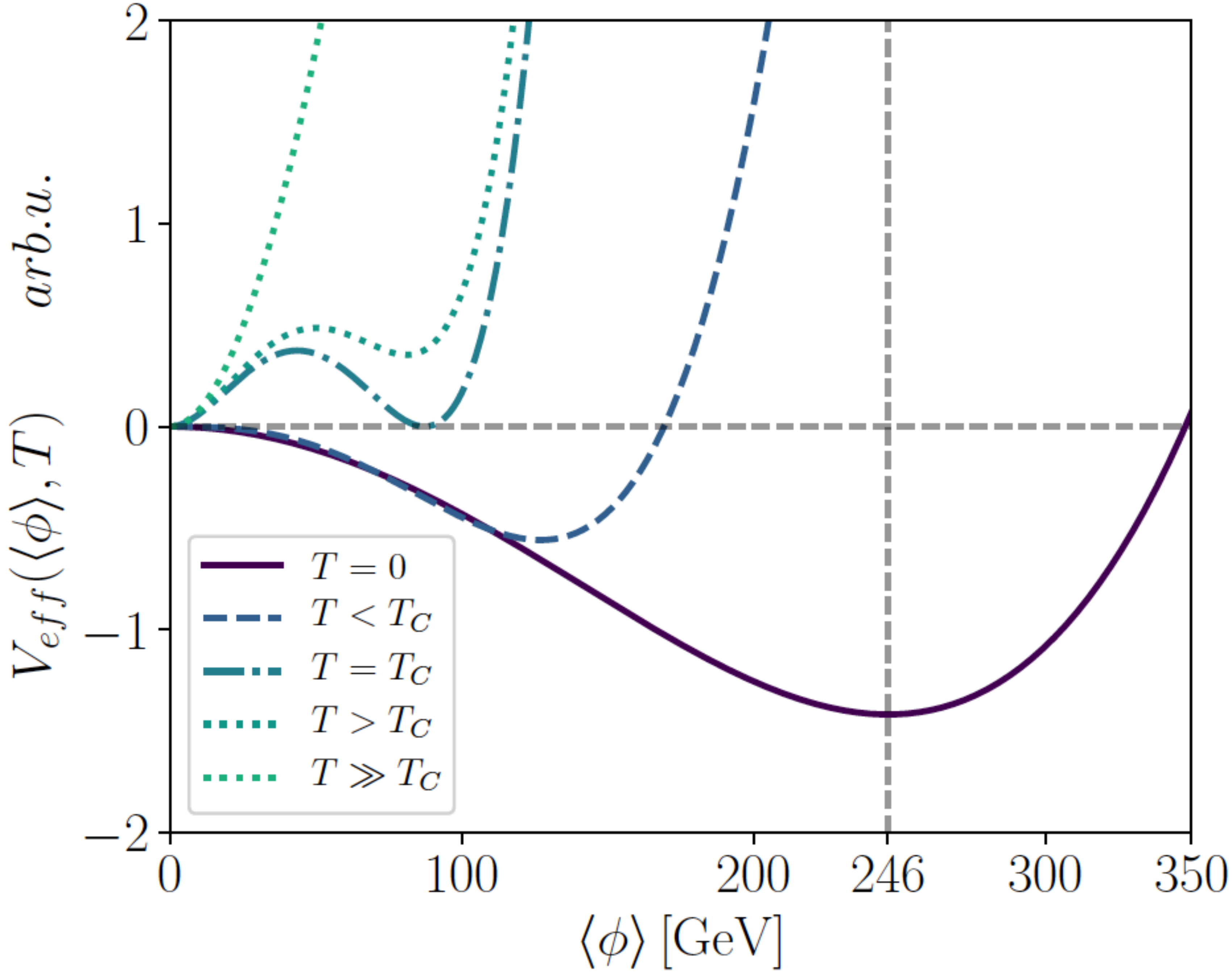
$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

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

Baryogenesis in a Nutshell



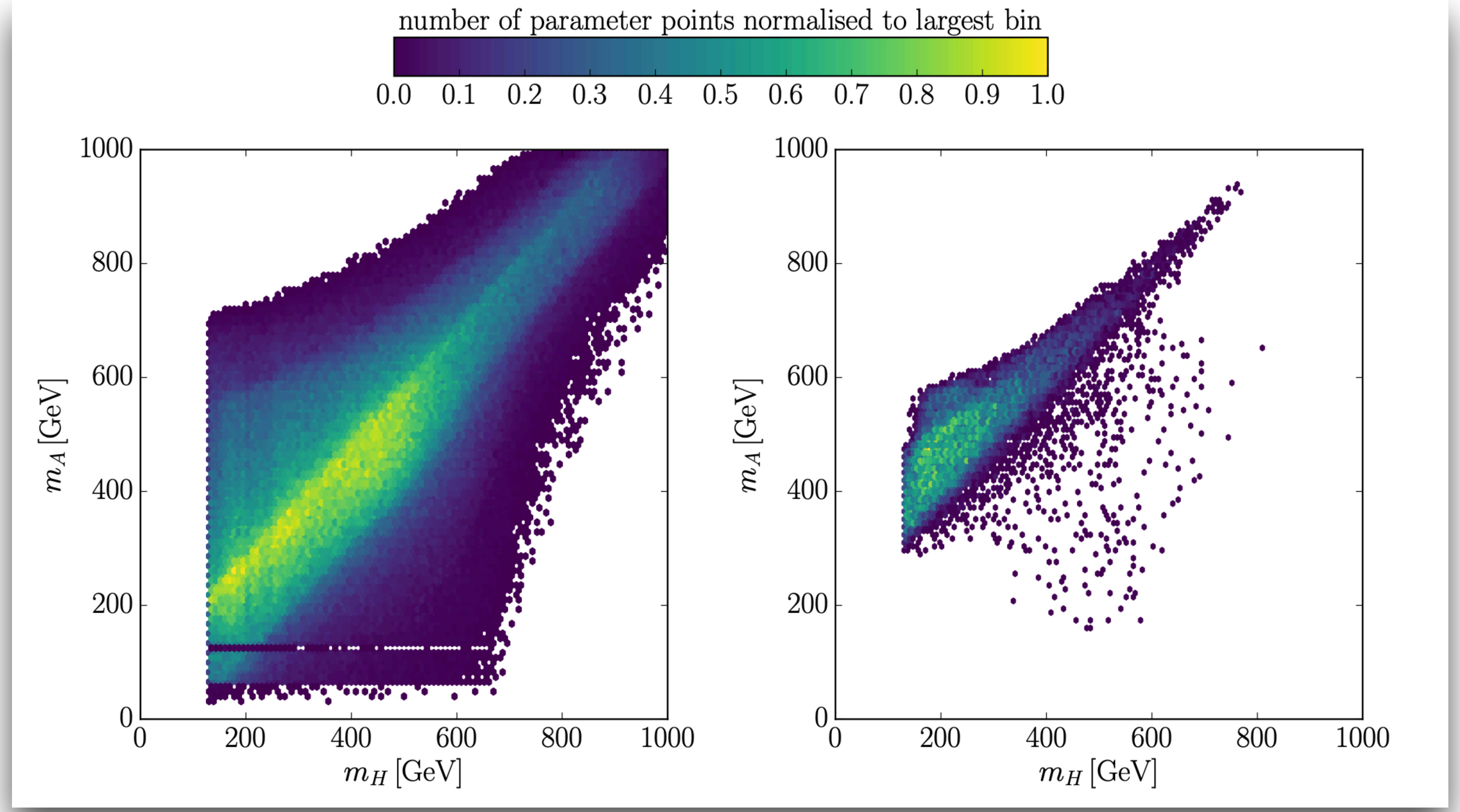
Strong First Order Electroweak Phase Transition



2HDM: SFOEWPT and Mass Spectrum

2HDM Type I w/ h SM-like Higgs

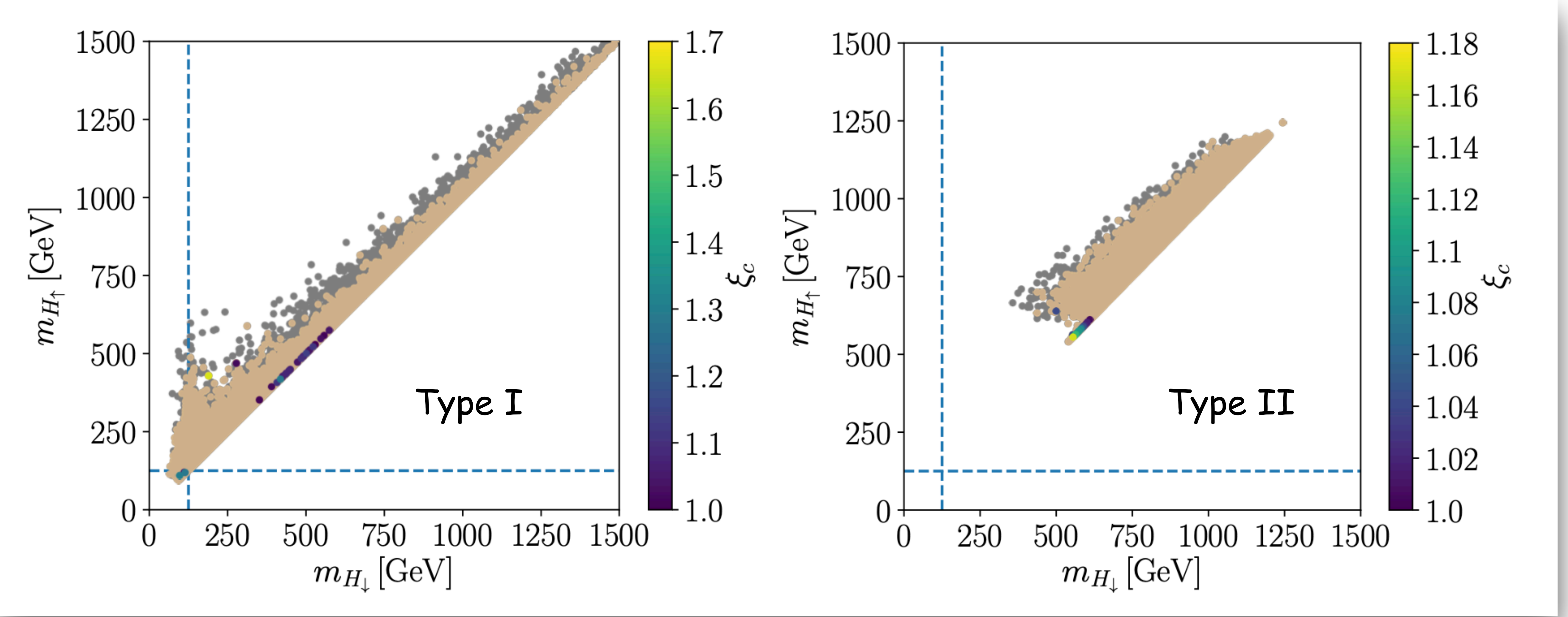
[Basler,Krause,MM,Wittbrodt,Wlotzka,'17]



SFOEWPT favor large mass splittings between A and H, but also other scenarios are found; ξ_c up to 4.5

C2HDM: SFOEWPT and Mass Spectrum

[Basler,MM,Müller,'19]



SFOEWPT tightens mass gap: $\Delta_{m_{H_i},m_{H_j}} = \min_{m_{H_i} \neq m_{H_j}} \left| m_{H_i} - m_{H_j} \right|$ with $H_{i,j} \in \{h, H_\downarrow, H_\uparrow, H^\pm\}$

$$\text{Type I}: \max_{\text{sample}} \Delta_{m_{H_i},m_{H_j}} \approx 61 \text{ GeV} \xrightarrow{\text{EWPT}} \approx 21 \text{ GeV}$$

$$\text{Type II}: \max_{\text{sample}} \Delta_{m_{H_i},m_{H_j}} \approx 62 \text{ GeV} \xrightarrow{\text{EWPT}} \approx 33 \text{ GeV}$$

Conclusions

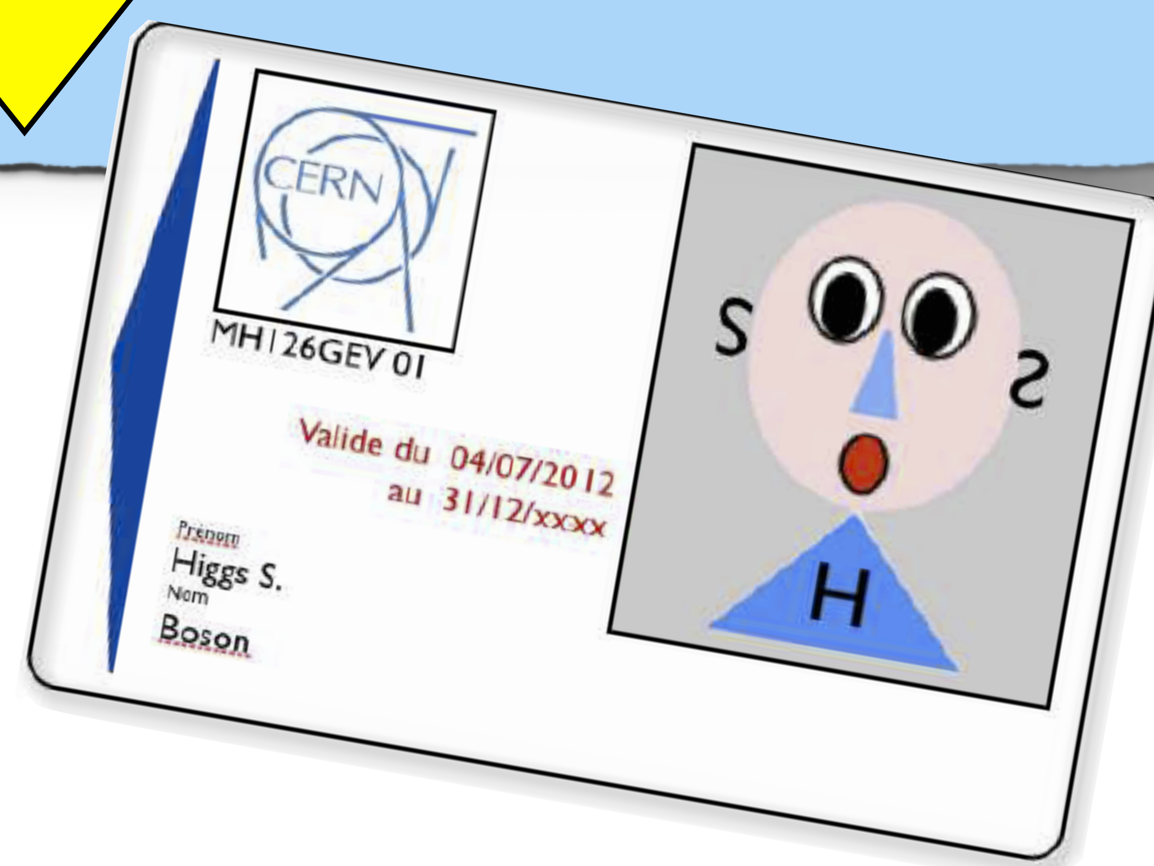
✦ **Flaws of SM call for new physics; no direct signs of new physics => Higgs boson**

✦ Insights
- in allowed parameter ranges of the BSM models, in scale of new physics
- in mechanism of mass generation, structure & dynamics of electroweak symmetry breaking
- in nature of Dark Matter
- in baryogenesis
- in flavor/CP puzzle

✦ Interesting times ahead!

The answer to life, the universe and everything!

Not quite, but



Thank you for your attention!

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

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

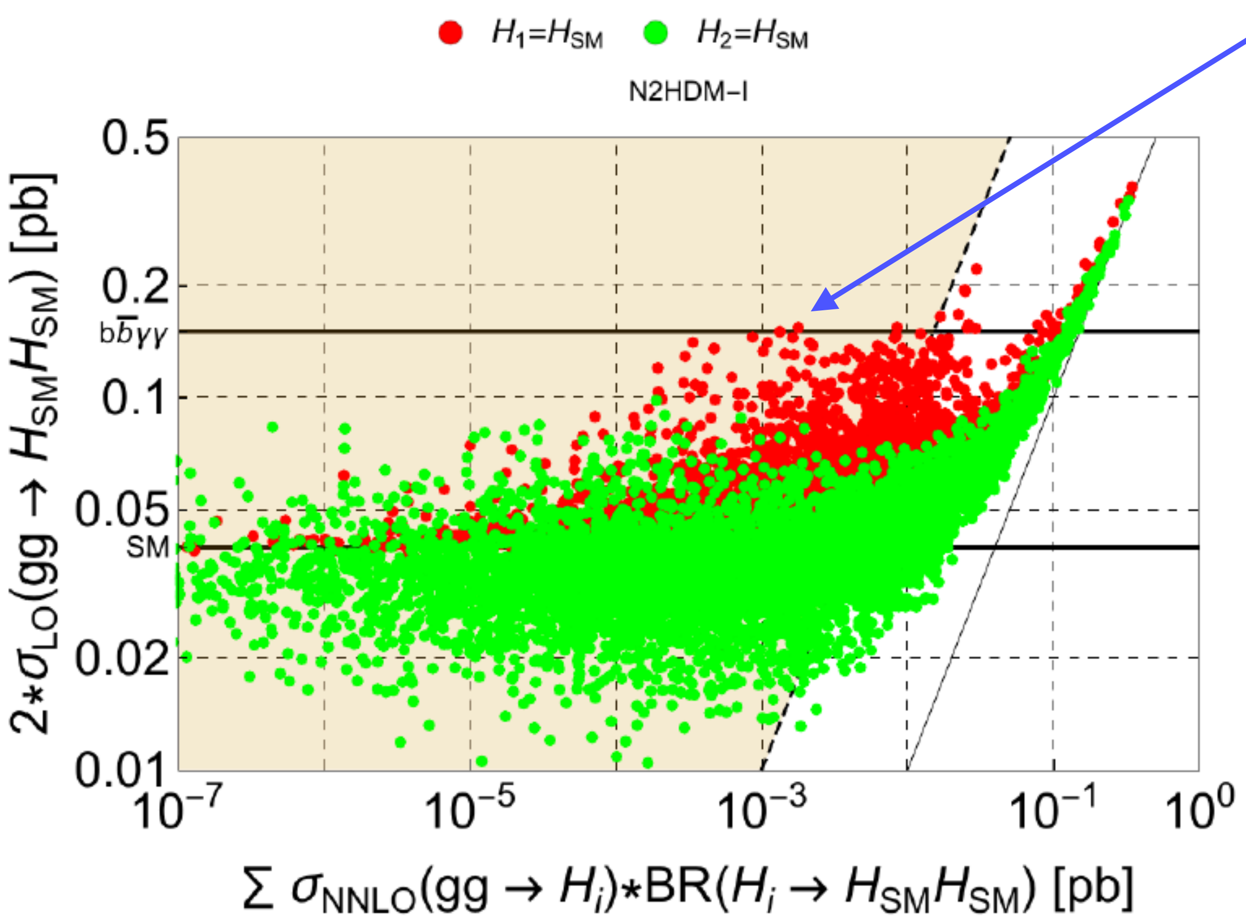
* HiggsBounds turned off for di-Higgs
* Use SusHi to calculate $\sigma(H_k)$ for all possible intermediate resonances H_k at NNLO QCD
* Calculate $\sigma(H_k)$ x BR(H_k -> H_{SM} H_{SM}) and compare it with experiment
* Exception: exp. limits assume narrow resonance -> we keep points if $(\Gamma_{tot}(H_k)/m_{Hk})_{limit} > 5\%$

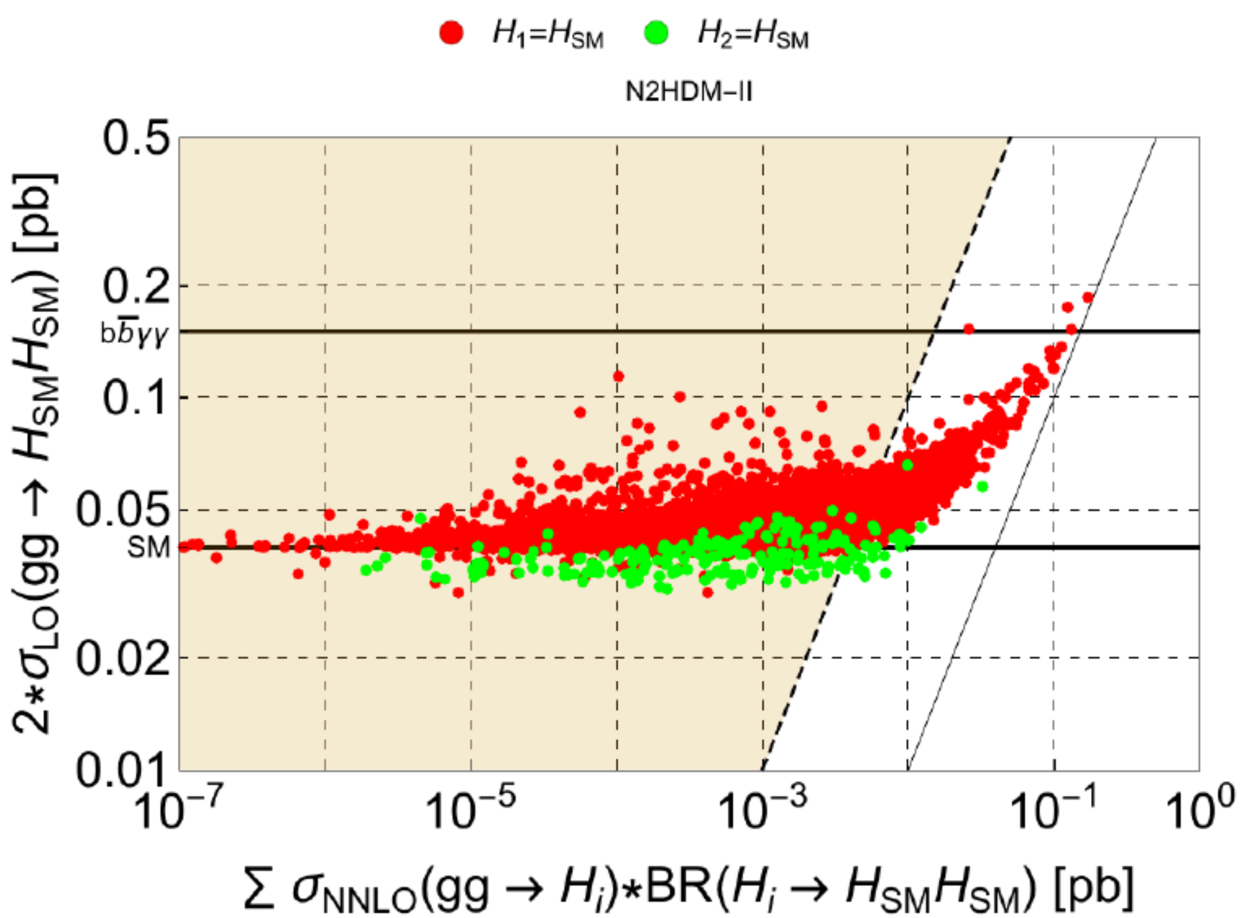
Provided final states on request: 4b, (2b)(2tau), (2b)(2gamma), (2b)(2W), (2b)(2Z), (2W)(2gamma), 4W

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

Impact of Di-Higgs Searches on N2HDM parameter space

Non-resonant experimental searches start cutting in N2HDM parameter space





Cross section resonantly dominated if $\sigma(H_k) \times BR(H_k \to H_{SM}\, H_{SM}) > 0.1\, \sigma(H_kH_k)$

Non-resonant experimental search limits applied

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