$\mathcal{A}$3a $\mathcal{E}$xtended $\mathcal{H}$iggs $\mathcal{S}$ectors at the $\mathcal{L}$HC

$\mathcal{M}$ilada $\mathcal{M}$. $\mathcal{M}$ühlleitner (KIT)
PIs: MMM and Tilman Plehn

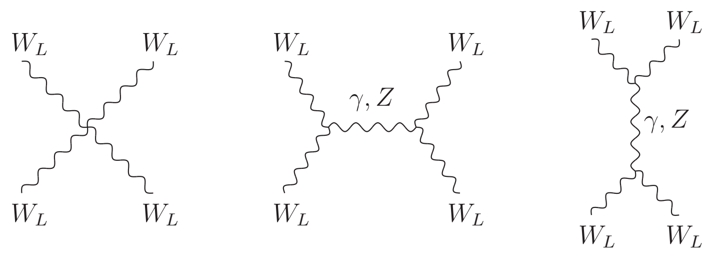
SFB Kick-Off 2019

Karlsruhe, 18-19 March 2019

Introduction

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$iscovery

- **Higgs Discovery ⇝ New Era of Particle Physics**
  - Structurally completes the Standard Model
  - Self-consistent framework to describe physics up to the Planck scale



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

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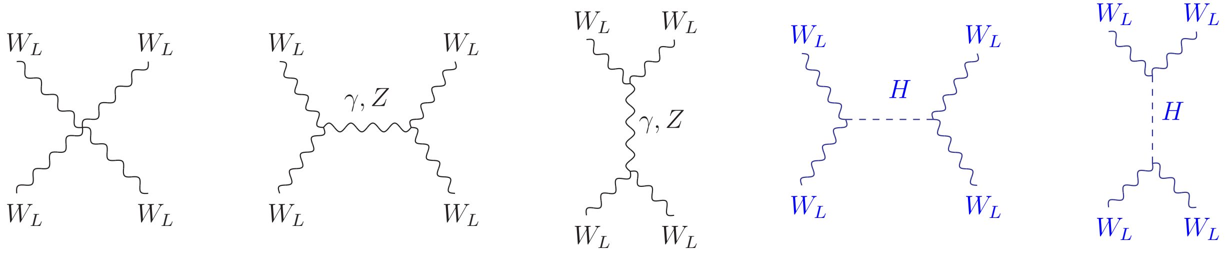

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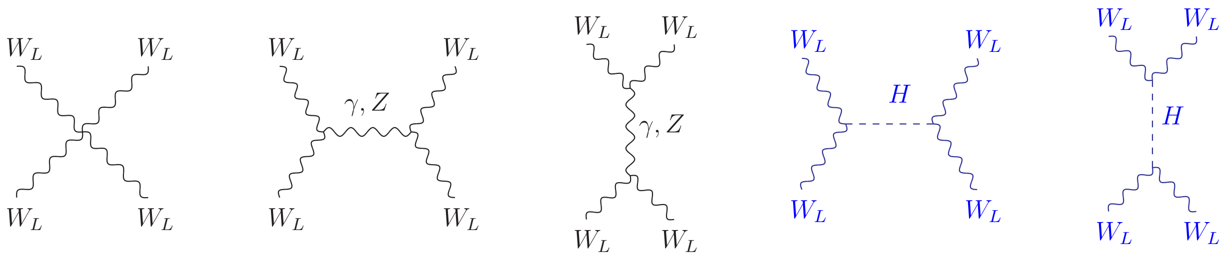

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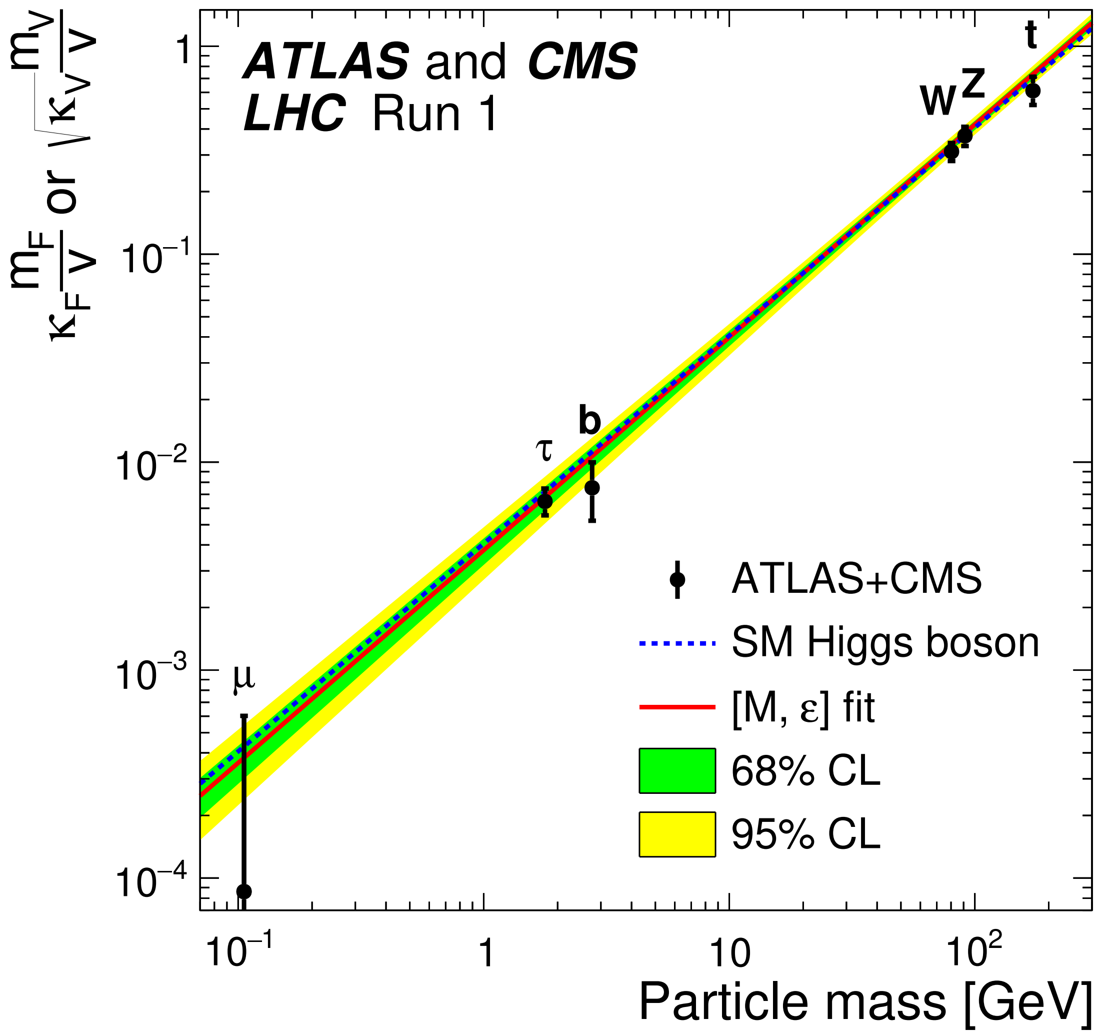
- **SM Higgs couplings:**
  - $g_{Hf\bar{f}} \sim \frac{m_f}{v}$ and $\sqrt{g_{HVV}} \sim \frac{m_V}{v}$

Higgs Boson Couplings to SM Particles

[ATLAS/CMS, JHEP08(2016)045]



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  - ∗ Behaves very SM-like
- **Open Questions:**
  - ∗ $\rightsquigarrow$ Standard Model is low-energy effective theory of more fundamental theory at some high scale

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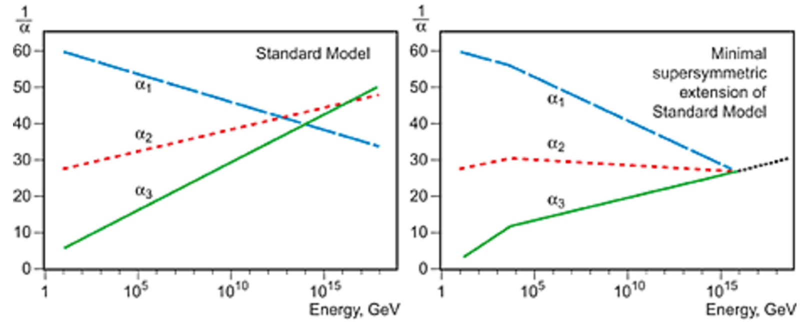

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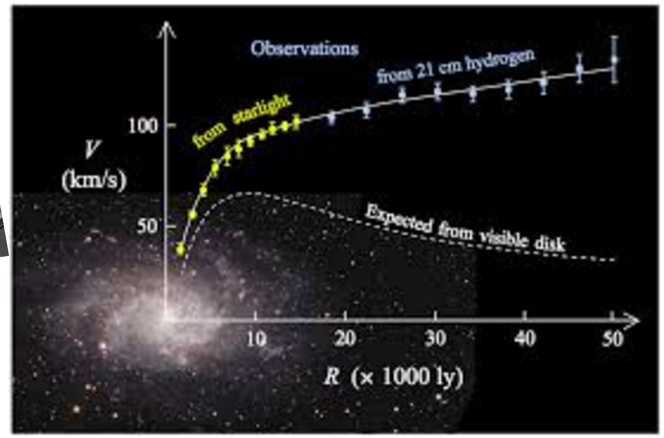

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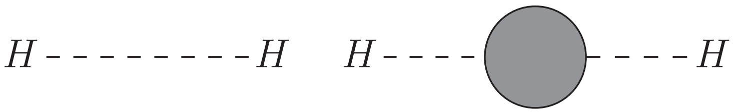
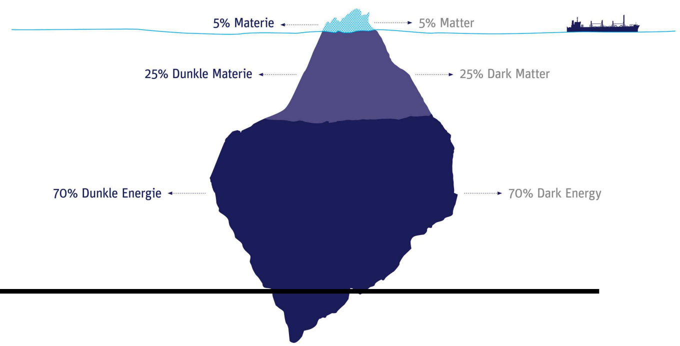
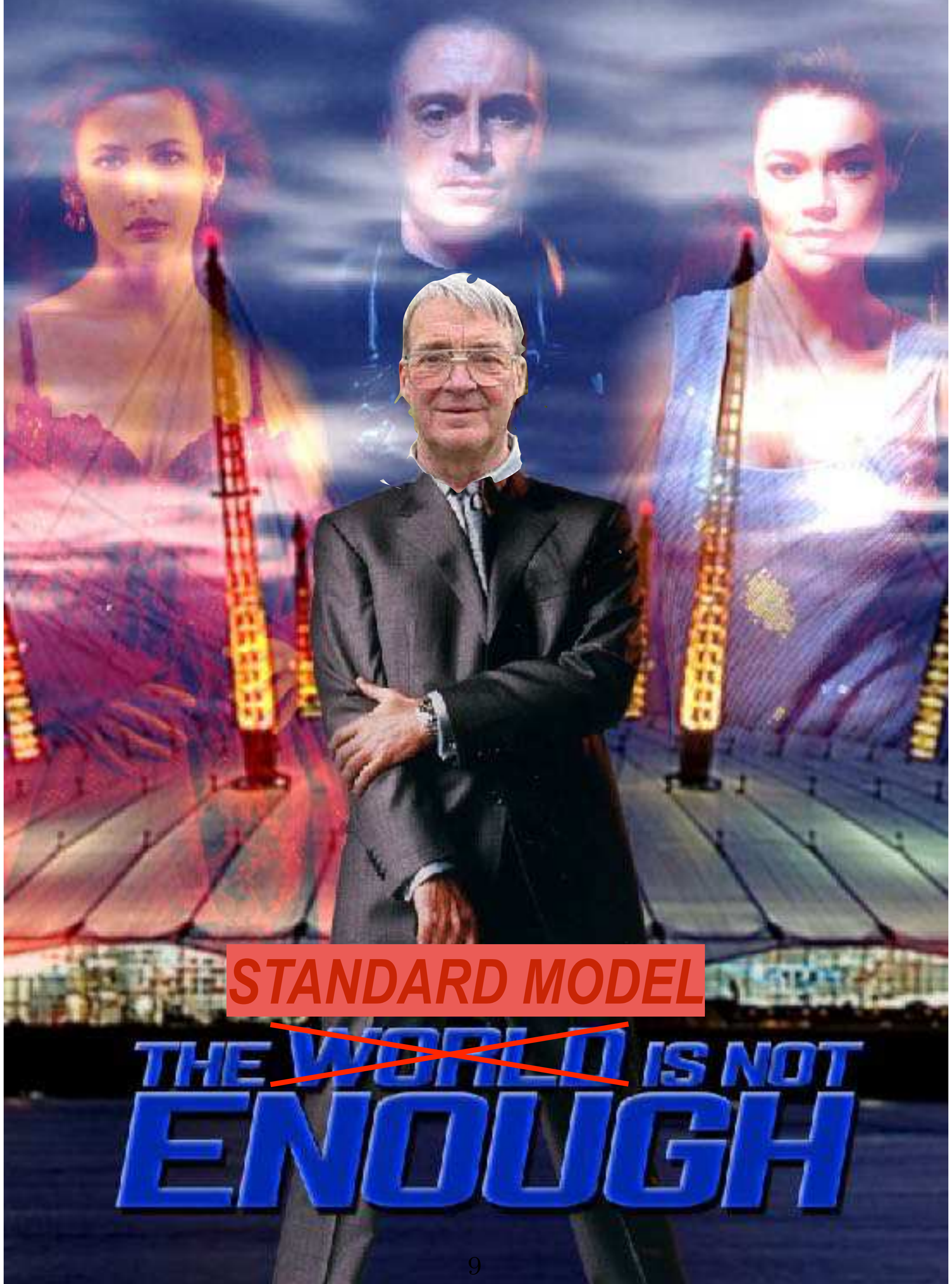


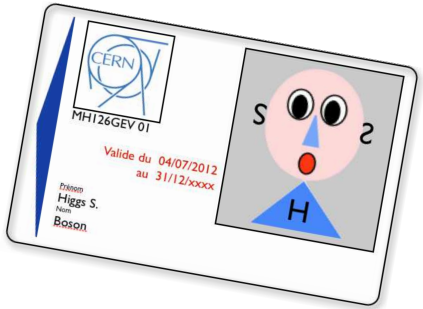



STANDARD MODEL
THE WORLD IS NOT ENOUGH

$\mathcal{W}$here is $\mathcal{N}$ew $\mathcal{P}$hysics?

- **Naturalness: Just around the corner!**
- **Experimental reality:** No Beyond the Standard Model Physics discovered so far!

  Guido Altarelli, 16/1/2012, KIT: *'The situation is depressing, but not desperate.'*



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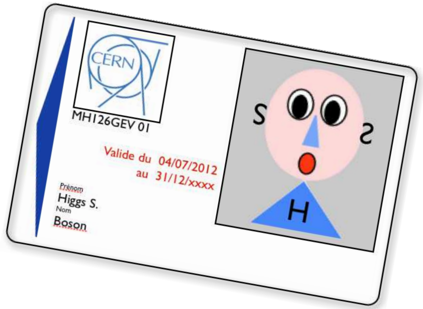

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  ◇ Additional Higgs bosons from extended Higgs sectors - lighter or heavier than SM-like Higgs

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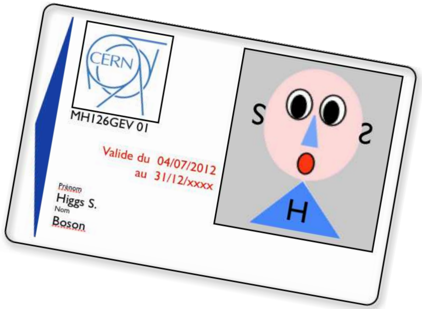


- **Direct detection of new physics:**
  - ◇ Additional Higgs bosons from extended Higgs sectors - lighter or heavier than SM-like Higgs
- **Indirect detection of new physics: e.g. deviations from SM couplings**
  - ◇ through mixing effects with other Higgs bosons - e.g. singlet, doublet, CP admixtures
  - ◇ modified Higgs properties through loop effects
  - ◇ modified $\Gamma_{\rm tot}$ and BRs through invisible decays and/or decays into lighter non-SM states

$\mathcal{E}$xtended $\mathcal{H}$iggs $\mathcal{S}$ectors

- **Why extended Higgs sectors?**
  - Extended Higgs sectors: help to
    - alleviate metastability
    - provide DM candidate
    - additional sources of CP-violation
    - enable successful baryogenesis
    - ...
  - Many models of new physics require extended Higgs models ← Supersymmetry!

$\mathcal{R}$ole of $\mathcal{P}$recision $\mathcal{P}$hysics

- **Precision in theory predicions of Higgs observables indispensable:**
  - SM-like behaviour of discovered Higgs $\rightsquigarrow$ small indirect new physics effects
  - identification of underlying model $\leftarrow$ different new physics models lead to similar effects
- **Required:**
  - Precision predictions of Higgs observables and backgrounds
  - Tools w/ modern analysis methods efficiently including precision predictions and a global Higgs sector analysis

Hadron Collider Phenomenology:

direct production of new particles $\rightarrow$ precision physics and indirect searches

$\mathcal{G}$oals of $\mathcal{P}$roject $\mathcal{A}$3a

- **Project Goal:**
  - ∗ Systematic analysis of extended Higgs sectors guided by
    - ⋄ fundamental properties
    - ⋄ precision computations
    - ⋄ phenomenology
  - ∗ Identify and exploit so far unexplored LHC signatures & observables
  - ∗ Provide theoretical model including new propagating states for aready exisiting LHC signatures

- **Course of Action:**

  (I) Precision studies of electroweak vacuum

  (II) Precision predictions for LHC phenomenology

  (III) Phenomenology and Analysis

$\mathcal{B}$eyond the $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ectors

Beyond SM Higgs Sectors

2Higgs-Doublet-Model

Multi-Higgs

CP-violating 2HDM

PortalHiggs

Next-2HDM

TwinHiggs

Singlet Extensions

LittlestHiggs

MSSM

3HDM

NMSSM

Georgi-Machachek

CompositeHiggs

- **How select the models? Guidelines:**
  - ∗ Simplicity
  - ∗ Compatible w/ relevant experimental and theoretical constraints → see next slides
  - ∗ Solve (some) of the flaws of the SM
  - ∗ (Part) of the Higgs spectrum accessible at the LHC
  - ∗ Properties testable at the LHC

$\mathcal{E}$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.* 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 (← check *e.g.* w/ `HiggsBounds`, `HiggsSignals`)

  ∗ Direct searches for new particles

  ∗ Low-energy observables

  ∗ Relic density (← models w/ DM candidate)

  ∗ EDM constraints (← models w/ CP violation)

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

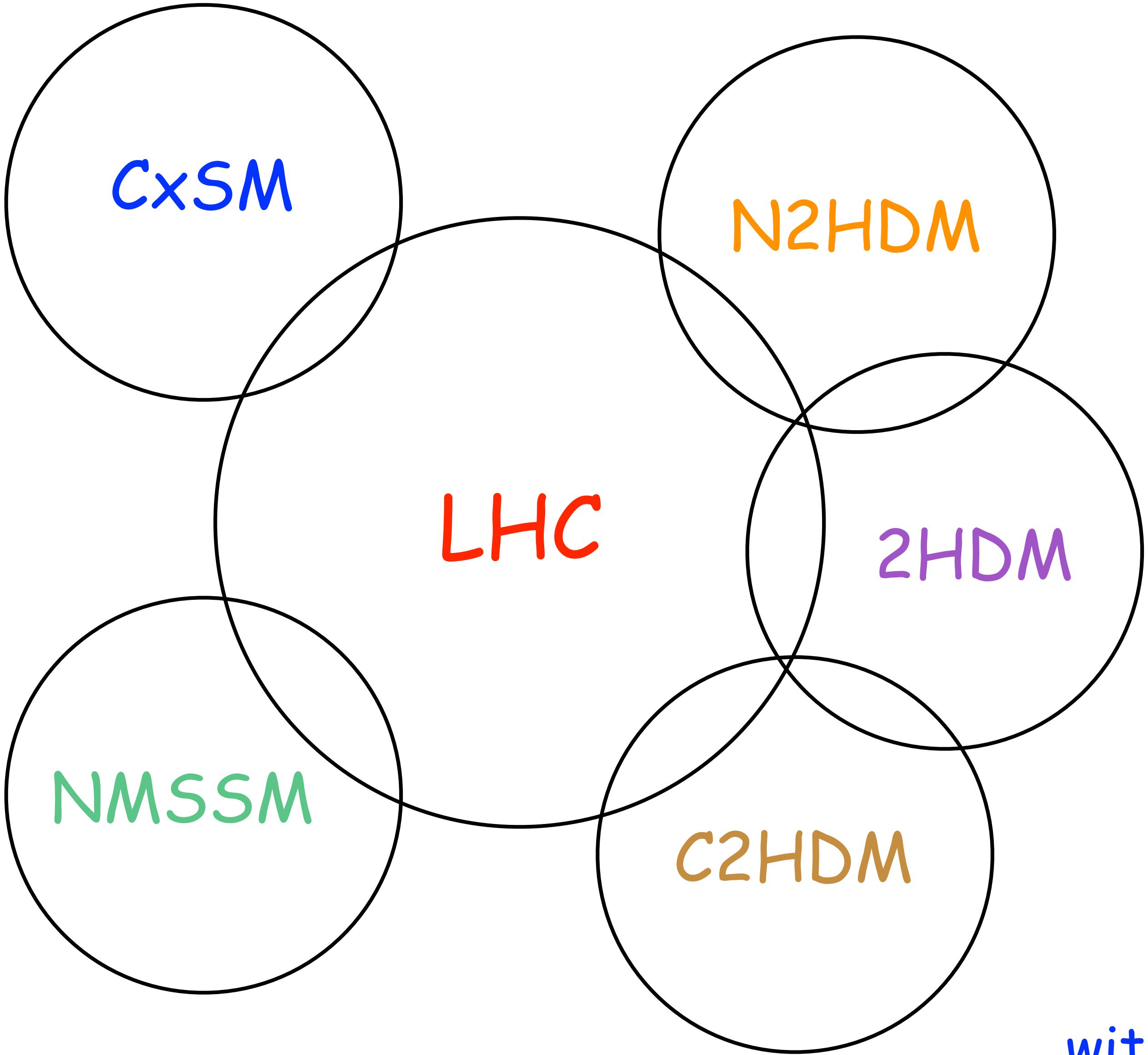
- **Higgs potential bounded from below**
- **EW vacuum global minimum**
- **Perturbative unitarity**

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

Some of the simplest non-SUSY models and the NMSSM

How can we distinguish them ....

.... if a scalar is found.



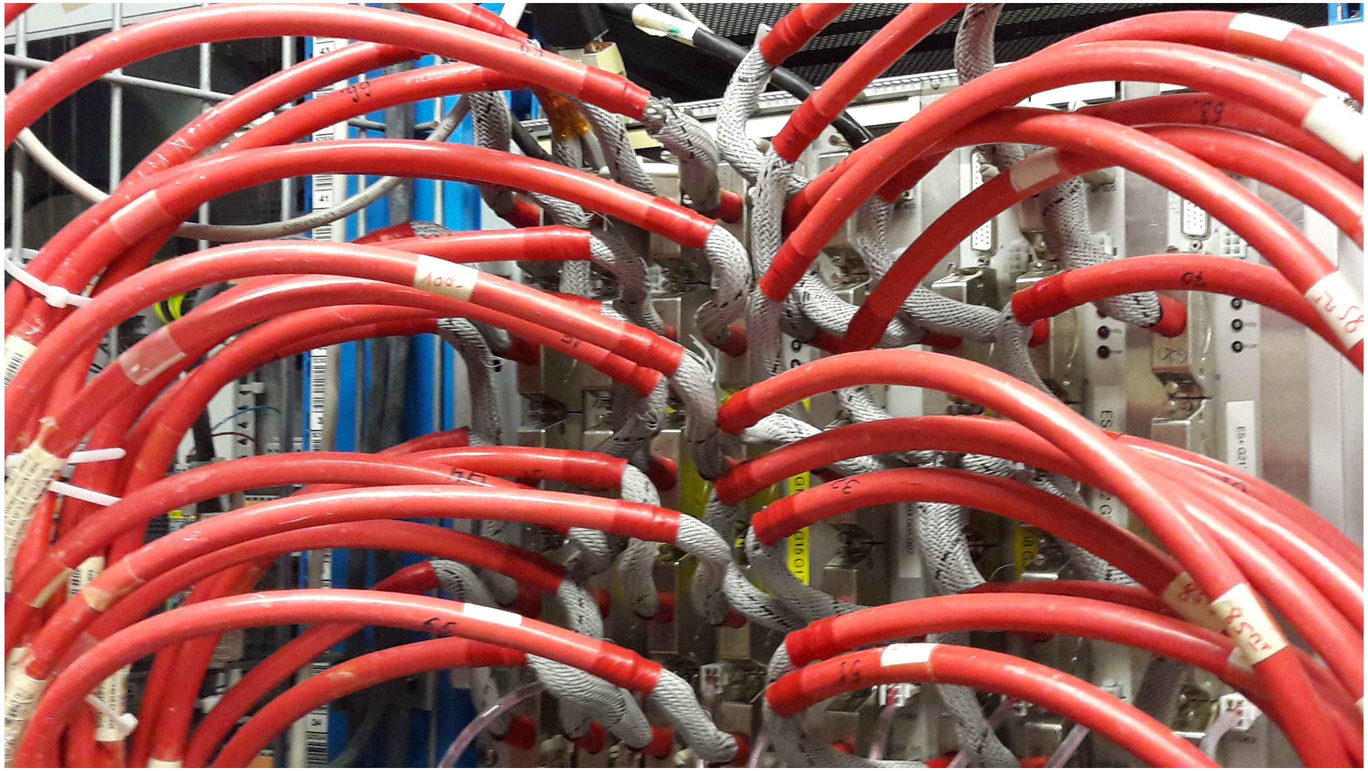
.... with precision measurements.

The Models

	CxSM	2HDM	C2HDM	N2HDM
Model	SM+complex singlet	2 Higgs doublets	CP-violating 2HDM	2HDM+real singlet
Particle content	3 CP-even $H_{1,2,3}$ (broken phase)	2 CP-even h,H 1 CP-odd A charged $H^\pm$	3 CP-mixed $H_{1,2,3}$ charged $H^\pm$	3 CP-even $H_{1,2,3}$ 1 CP-odd A charged $H^\pm$
Motivation	minimal model for DM & baryogenesis benchmark for Higgs-to-Higgs decays	additional sources for for CP-violation; DM candidate (inert 2HDM) benchmark for MSSM	2HDM benefits + explicit CP violation in the Higgs sector	benchmark model for the NMSSM DM candidate

- **The $\mathcal{N}$MSSM:** 3 CP-even $H_{1,2,3}$, 2 CP-odd $A_{1,2}$, charged $H^\pm$

Precision Studies of the Electroweak Vacuum



Precision Studies of the Electroweak Vacuum

- **Relevance:**
  - ∗ Interplay stability of SM vacuum and SM parameters
  - ∗ Extended Higgs sectors $\rightsquigarrow$ more complex vacuum structure
  - ∗ Understanding crucial to guarantee vacuum stability and proper electroweak symmetry breaking

- **Example: 2-Higgs-Doublet-Model (2HDM):**
  - ∗ three types of minima: normal EW, CP breaking, charge breaking (CB)
  - ∗ also possible two coexisting normal EW minima (different VEVs); tunneling possible [Barroso,Ferreira,Ivanov,Santos,2013]
  - ∗ if normal minimum exists all CP or CB stationary points proven to be saddle points [Ferreira,Santos,Barroso,2004]

- **Example: Next-2HDM (N2HDM):**
  - ∗ minimum conditions of 2HDM do not apply to N2HDM
  - ∗ possibility of CP and CB-breaking minima [MMM,Sampaio,Santos,Wittbrodt]

$\mathcal{V}$acuum $\mathcal{S}$tability and $\mathcal{L}$oop $\mathcal{C}$orrections

- **Example: Inert 2HDM:** two types of EW minima at tree level can coexist
  - points allowed a tree level excluded at one-loop level and vice versa [Ferreira,Swiezewska,2006]
- **Example: CP-violating 2HDM:**
  - points allowed at tree level excluded at NLO [Basler,MMM,Wittbrodt,2018]
  - Loop-corrected effective potential at $T \neq 0 \rightsquigarrow$ test for a strong first order phase transition (SEWPT)
  - SEWPT testable through measurement of trilinear Higgs self-couplings [Grojean,Servant,Wells] [Noble,Perelstein 2008; Huang,No,Pernié,Ramsey-Musolf,2017; Basler,MMM,Wittbrodt,2018; Reichert,Eichhorn,Gies,Pawlowski,TP,Scherer,2018] link to gravitational waves
- **Vacuum Study of SUSY Models:**
  [Hollik,Weiglein,Wittbrodt (tree), '19; `Vevacious`, Camargo-Molina eal, '13 (loop)]

Fundamental properties of Higgs potential imply limits on mass ranges of additional scalars and affects their possible production and decay patterns as well as the Higgs self-interaction strengths

$\mathcal{V}$acuum $\mathcal{L}$ink to $\mathcal{H}$igh-$\mathcal{E}$nergy $\mathcal{S}$cales

- **High-energy scales:**
  - Link between vacuum stability and high-energy scales $\rightarrow$ T (perturbative studies)
  - Higher-dimensional operators can lead to measurable effects below actual thresholds
  - Systematic study of these effects wrt vacuum stability, DM, nature of EWPT complements perturbative approach
    [Eichhorn,Gies,Jaeckel,TP,Scherer,2015; Reichert,Eichhorn,Gies,Pawlowski,TP,Scherer,2018]

Project Plan - *Vacuum Stability*

- **Precision studies:**
  - ∗ Investigation of vacuum stability of models w/ additional scalar states ($\leftarrow$ successful baryogenesis) at NLO in the effective potential approach (SUSY and non-SUSY models)
  - ∗ Study changes wrt to tree-level results, study impact on allowed parameter space
  - ∗ First steps to consider also metastability conditions $\rightarrow$ extension beyond current CRC

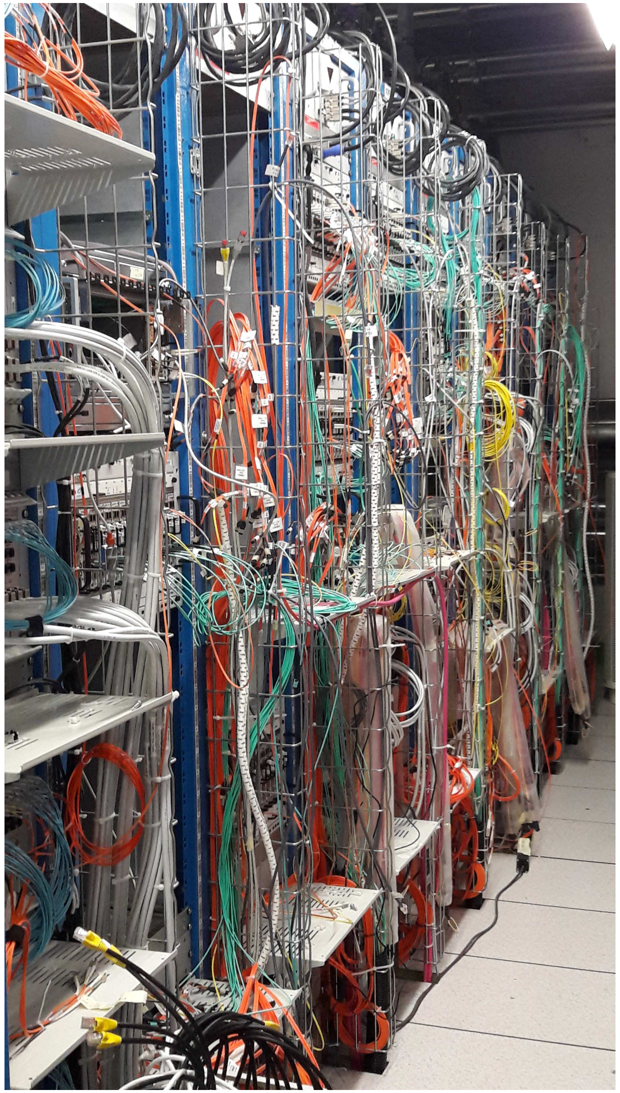
- **Models w/ DM candidates:**
  - ∗ Investigate how Z_2 symmetry ($\leftarrow$ DM quantum number) can be guaranteed beyond tree level
  - ∗ Study how preferred parameter choices impact extrapolation to high-energy scales

Project Plan Continued - Vacuum Stability

- **Evolution to High-Energy Scales:**
  - Complement perturbative approach by functional renormalization group $\rightsquigarrow$ possible to evolve general Higgs potentials to higher energies, including higher-dimensional operators
  - Study inherent uncertainties in perturbative approach
  - (i) Include full set of Higgs and Goldstone fields w/ full set of running gauge couplings, confirm arpproximate results for vacuum stability and baryogenesis;

    (ii) Add more scalar fields, covering their full mass range; study their decoupling from dynamical description of EWPT or their treatment as part of the effective Lagrangian
  - Challenge: keep track of all parameters in the coupled numerical RGE $\rightsquigarrow$ application of maching learning techniques $\rightarrow$ link to project A2a

$\mathcal{P}$recision $\mathcal{P}$redictions for $\mathcal{L}$HC $\mathcal{P}$henomenology



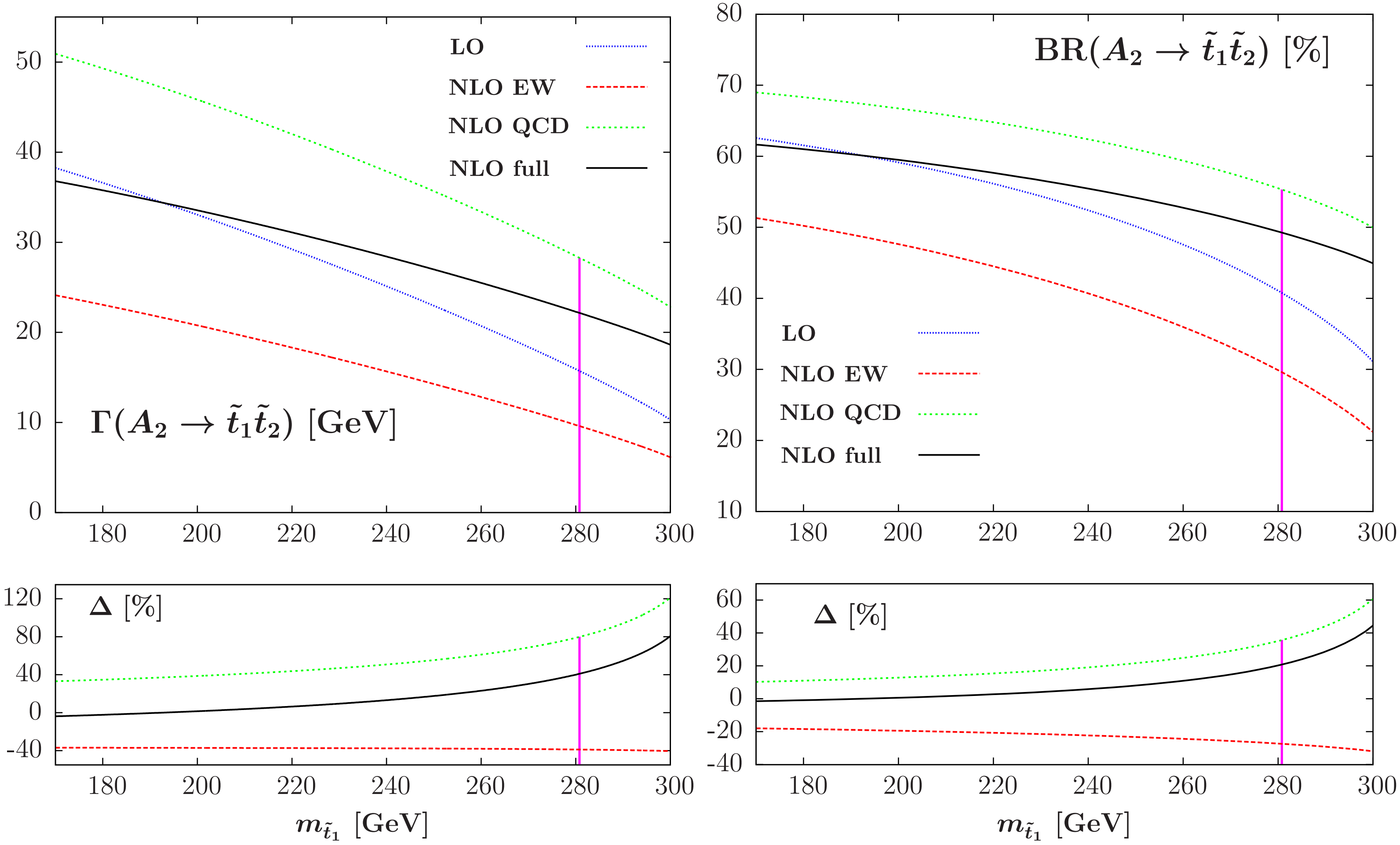
$\mathcal{S}$tatus of $\mathcal{E}$W $\mathcal{H}$igher-$\mathcal{O}$rder $\mathcal{C}$orrections to $\mathcal{B}$SM $\mathcal{H}$iggs $\mathcal{D}$ecays

- **BSM Higher-Order Corrections to Higgs Production and Decay:**
  - QCD corrections can be adapted to BSM models, EW corrections cannot!
  - EW corrections to Higgs decay widths typically of $\mathcal{O}(10\%)$; but can be considerably larger:
    - ◇ Impact important if of same size as QCD corrections and of opposite sign
    - ◇ NLO corrections important if LO width is small
    - ◇ Corrections can be parametrically enhanced
    - ◇ Light Higgs particles in the loop can enhance loop corrections

- **Higher-Order Corrections to NMSSM Higgs Decays:**
  - NLO SUSY-EW and SUSY-EW corrections to Higgs decays into stop pairs: EW corrections can be of same order as QCD corrections and of opposite sign [Baglio,Krauss,MMM,Walz] $\rightarrow$ T
  - For the one-loop renormalization of the NMSSM Higgs sector, see also [Bélanger,Bizouard,Boudjema,Chalons]
  - Higher-order corrections can be parametrically enhanced $\rightarrow$ Δ_b corrections [Hempfling; Hall,Rattazzi,Sarid; Carena eal; Pierce eal; Nierste eal; Guasch eal; Noth eal; Ghezzi eal] implemented in `NMSSMCALC` [Baglio,Grober,MMM,Nhung,Rzehak,Streicher,Spira,Walz]

$\mathcal{N}$MSSM $\mathcal{P}$seudoscalar $\mathcal{D}$ecay into $\mathcal{S}$tops

[Baglio,Krauss,MMM,Walz,'15]



◇ Parameter point: $M_{A_2} = 1012$ GeV, $m_{\tilde{t}_1} = 281$ GeV, $m_{\tilde{t}_2} = 709$ GeV

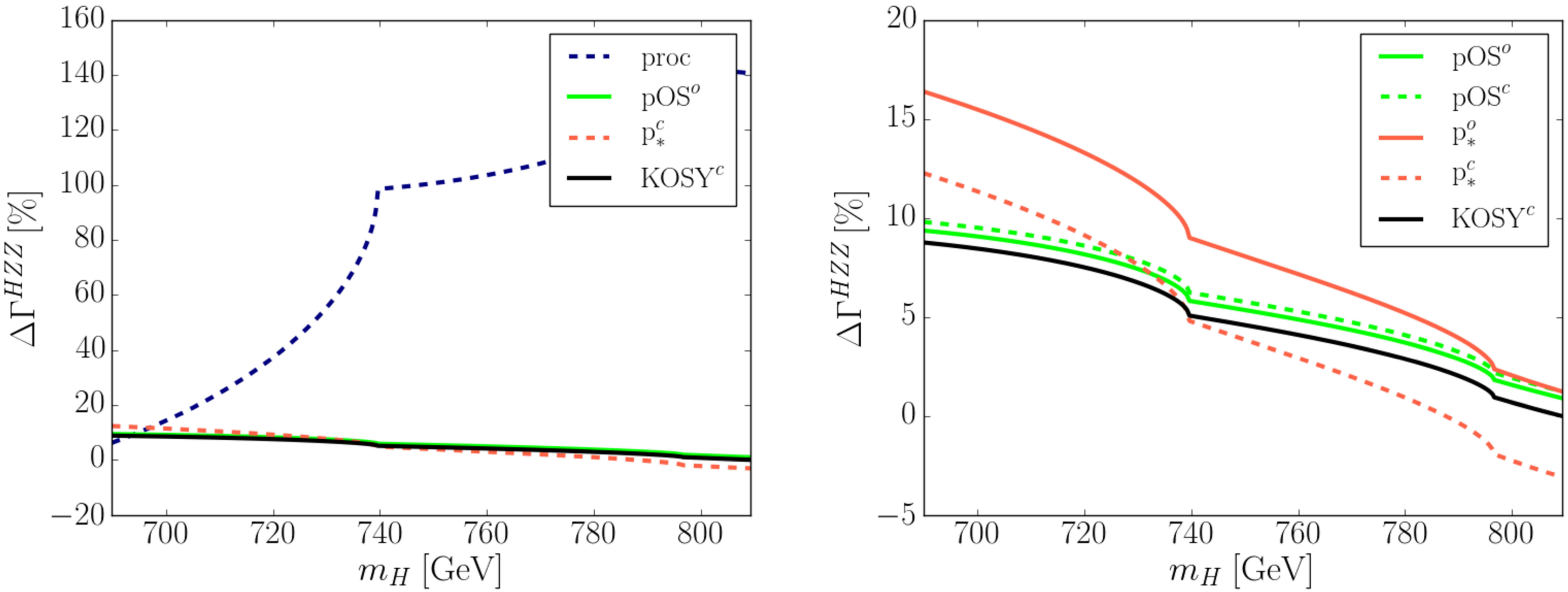
Status of EW Higher-Order Corrections to BSM Higgs Decays

- **Higher-Order Corrections to 2HDM Higgs Decays:**
  - Gauge parameter independent renormalization scheme first developed by [Krause,Lorenz,MMM,Santos,Ziesche,'16]
    see also [Denner,Jenisches,Lang,Sturm,'16;Altenkamp,Dittmaier,Rzehak,'17;Denner,Dittmaier,Lang,'18]
  - EW corrections to Higgs decays of up to $\mathcal{O}(20\%)$ → T
  - Large EW corrections in Higgs-to-Higgs decays possible [Kanemura eal; Krause,MMM,Santos,Ziesche,'16] → link to project A3b
  - Code `2HDECAY` including EW and state-of-the-art QCD correction to 2HDM Higgs decays in various renormalization schemes [Krause,MMM,Spira,'18]

- **Higher-Order Corrections to further Singlet/Doublet Extensions:**
  - Generic one-loop two-body decay widths [Goodsell,Liebler,Staub,'17]
  - EW corrections to Higgs decays in singlet extensions [Kanemura eal,'15; Bojarski eal,'15; Goodsell eal,'17; Altenkamp eal,'18]
  - Gauge-independent renormalization of the N2HDM [Krause,Lopez-Val,MMM,Santos,'17]

2$\mathcal{H}$DM $\mathcal{H}$igher-$\mathcal{O}$rder $H \to ZZ$ $\mathcal{D}$ecay

[Krause,Lorenz,MMM,Santos,Ziesche,'16]



- ◇ Left/Right: with/without process-dependent renormalization ($\leftarrow H/A \to \tau\tau$)
- ◇ gauge-parameter independent renormalization: pOS^{c,o}, p$_*^{o,c}$; dependent: KOSY^c
- ◇ $\Delta = (\Gamma^{\text{NLO}} - \Gamma^{\text{LO}})/\Gamma^{\text{LO}}$

$\mathcal{S}$tatus $\mathcal{M}$SSM $\mathcal{H}$iggs $\mathcal{P}$roduction through $\mathcal{G}$luon $\mathcal{F}$usion

- **HO Corrections to MSSM Higgs Boson Production:**
  Small $\tan\beta$: gluon fusion dominant; QCD corrections to SM loops can be taken over for scalar production; however additional squarks in the loops

  $*$ QCD corrections to (s)top and (s)bottom loops including the resummation of soft and collinear gluon effects available [Krämer eal; Djouadi eal; Graudenz eal; Spira eal; Dawson eal; Schmidt eal] NLO corrections (including the full top quark and Higgs mass dependence but not the bottom and squark mass dependence) of O(100%)

  $*$ NLO QCD corrections to quark and squark loops including the full mass dependence of top and squarks [MMM,Spira]; mass effects of $\mathcal{O}(20\%)$

  $*$ Analytic results for virtual quark and squark loops [Anastasiou eal; Aglietti eal]

  $*$ Genuine SUSY-QCD corrections in the limit of heavy loop particle masses [Harlander eal; Degrassi eal]

  $*$ Investigation of proper decoupling of heavy gluino contributions [MMM,Spira,Rzehak]

$\mathcal{P}$roject $\mathcal{P}$lan - $\mathcal{P}$recision $\mathcal{P}$redictions

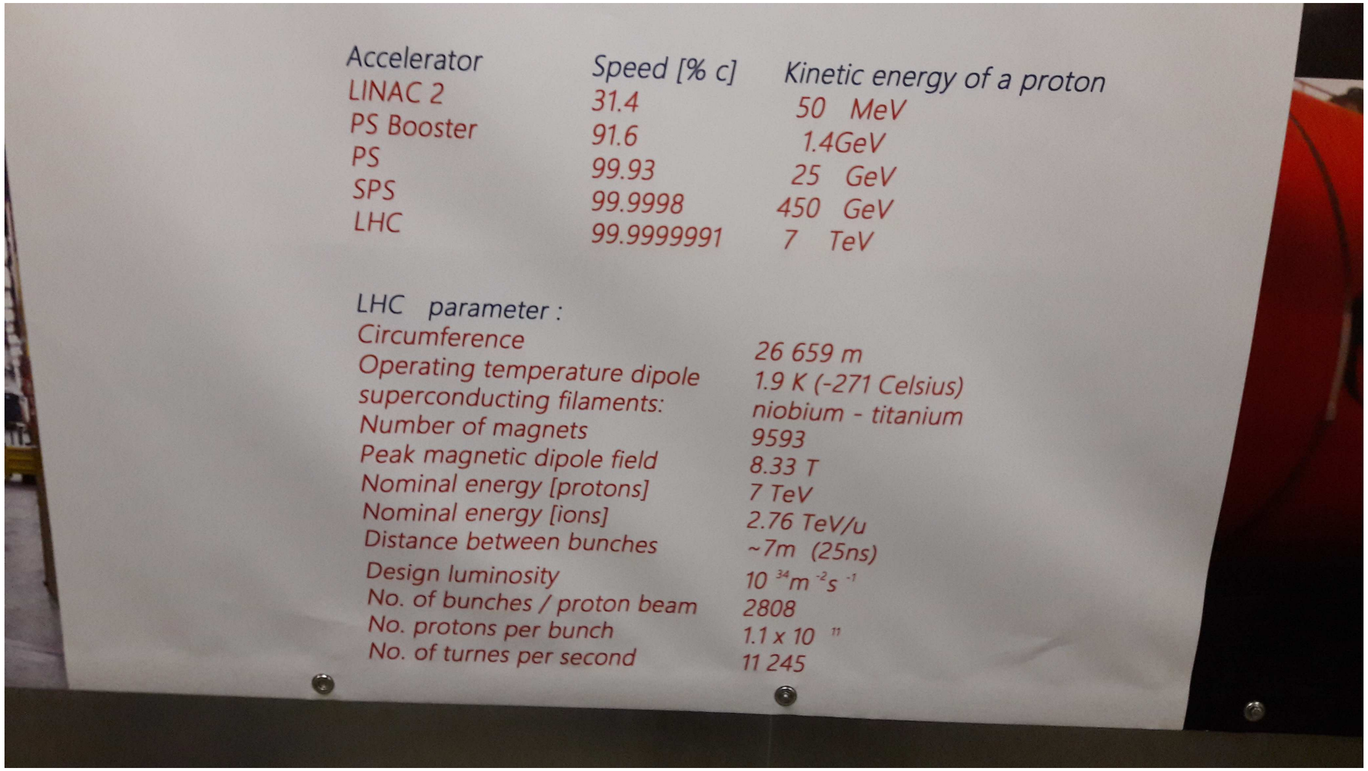
- **Higher-Order Correction to the Decays:**
  - ∗ compute missing higher-order (HO) corrections to BSM Higgs decays
  - ∗ provide suitable renormalization schemes, estimate size of remaining theoretical uncerstainties
  - ∗ investigate gauge dependencies
  - ∗ investigate size and impact of HO corrections on LHC phenomenology
  - ∗ for the following models
    - ◇ SUSY-EW and SUSY-QCD corrections to charged Higgs decays in the CP-violating NMSSM (neutral Higgs decays - being finalized)
    - ◇ EW corrections in the C2HDM
    - ◇ EW corrections in the N2HDM w/ singlet and doublet DM sectors
  - ∗ Approach: Feynman diagrammatic approach using the usual tools (`FeynArts`, `FeynCalc`, `FormCalc`, `LoopTools`); in general R_ξ gauge; make codes publicly available

Project Plan Continued - Precision Predictions

- **Pseudoscalar MSSM Higgs Production in Gluon Fusion**
  NLO SUSY-QCD corrections to $gg \to A$; approach:
  - * Numerical integration of five-dimensional Feynman integrals
  - * Separation of UV singularities through suitable endpoint substractions (there are no IR nor collinear singularities) $\rightsquigarrow$ separate integrals for divergent and finite pieces
  - * Stabilation of numerical integration above virtual particle thresholds through integration by part

  Future beyond current CRC: translation to NMSSM, to 2HDM

$\mathcal{P}$henomenology and $\mathcal{A}$naylsis

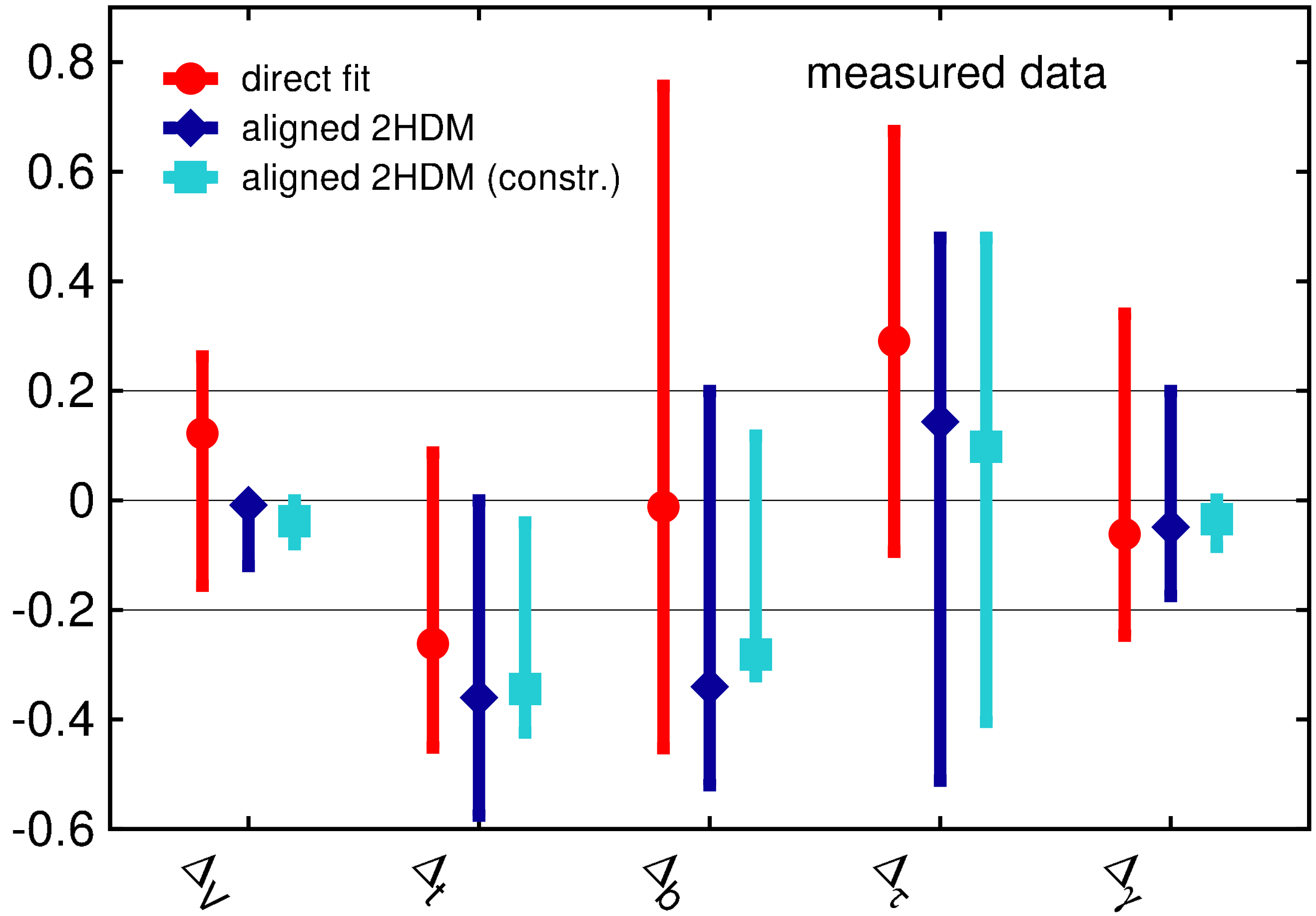


𝓡ole and 𝓒hallenges of 𝓖lobal 𝓐nalysis

- **Why a Global Analysis?**
  - ∗ Global analysis of all LHC and other relevant constraints - both theoretical and experimental - crucial to
  - ∗ properly scrutinize New Physics models ← link to projects B2b,B3a,C3a,C3b
  - ∗ Impact:
    - ◇ models may be completely or partially ruled out
    - ◇ impact on mass hierarchies of non-SM Higgs bosons
    - ◇ impact on size of higher-order corrections
    - ◇ impact on possible distinction of BSM models
    - ◇ impact on possible LHC signatures and observables; ...
  - ∗ See e.g. analysis of 2HDM alignment region [Bernon eal,'15]; comparison of singlet extensions and NMSSM [Costa,MMM,Sampaio,Santos]; scrutinization of N2HDM parameter space [MMM,Sampaio,Santos,Wittbrodt], phenomenological comparison of extended Higgs sectors [MMM,Sampaio,Santos,Wittbrodt], Re-investigation of C2HDM [Fontes,MMM,Romao, Santos,Silva,Wittbrodt]; `SFitter` [Biekötter,Butter,TP,Rauch] → T
  - ∗ Systematic inclusion of HO effects in Higgs observables is crucial

$\mathcal{S}$Fitter $\mathcal{A}$nalysis

[Lopez-Val,TP,Rauch,'13]



◇ red: coupling modifiers (non-linear EFT); aligned 2HDM w/o (blue), with (light blue) EWPO, flavor, theory constraints

Role and Challenges of Global Analysis Continued

- **Challenges and Approaches for Global Analysis:**
  - ∗ Definition of Lagrangian behind global study is crucial (including particle content and symmetry structure ← determined from dedicated observables) [Brehmer,Kling,TP,Tait,'17]
  - ∗ `MADMAX` approach to understand sensitivity of multivariate analyses to specific phase space patterns; is based on discrete hypothesis tests and Neyman-Pearson lemma
  - ∗ New `MADMINER` approach based on information geometry; applied to effective Higgs operators [Brehmer,Cranmer,Kling,TP,'17] and CP properties of SM-like Higgs boson in EFT framework [Brehmer,Kling,TP,Tait,,'17]
  - ∗ Likelihood-free analysis techniques [Brehmer eal] and the matrix element method [Martini,Uwer] challenge for the proper understanding of LHC searches, the proper description of detector effects and irreducible bkgs ← important for BSM Higgs searches
  - ∗ Possible Solution: Generative Adversarial Networks (GANs) [Paganini eal; Erdmann eal] - provides fast and flexible numerical description of detector effects and of precision predictions

$\mathcal{P}$roject $\mathcal{P}$lan - $\mathcal{P}$henomenology and $\mathcal{A}$nalysis

- **Further Development of `MADMINER` tool:**
  - introduced to extract fundamental particle properties
  - further developments: go beyond effective theories, focus on signatures w/ new particles
  - goal: systematic identification of ways to extract fundamental properties from dedicated observables and state-of-the-art analyses with global phase space coverage
  - goal: public version of the tool as part of `MADGRAPH`

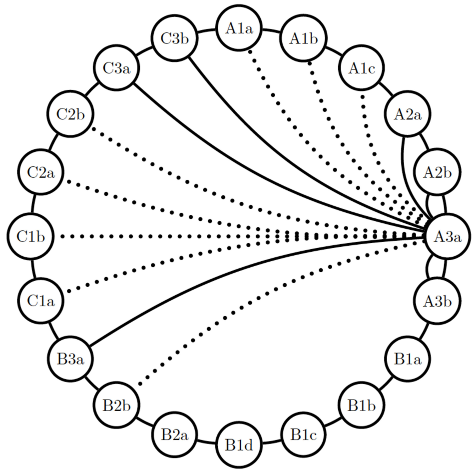
$\mathcal{P}$roject $\mathcal{P}$lan - $\mathcal{P}$henomenology and $\mathcal{A}$nalysis $\mathcal{C}$ontinued

- **Improvements through Machine Learning Applications (MLA):**
  - $*$ extended Higgs sector searches combined w/ our developed precision predictions $\rightarrow$ perfect framework for improvements of BSM physics searches through MLA
  - $*$ Approach: matrix element method w/ efficient detector resolution modelling; improvement through GANs
  - $*$ goal: efficient description of detector effects and efficient interpolation between phase space regions
  - $*$ goal: possibility to invert effects of detector smearing and to statistically relate observable phase space features with parton-level structures
  - $*$ program: train GANs for simple processes, develop scalable approach; tackle complicated phase space configurations; develop publicly available GAN tool

Project Plan - Phenomenology and Analysis Continued

- **Final Goal:** Combination of high-precision predictions for Higgs observables with theoretical and experimental constraints into a coherent analysis
  - links all aspects of A3a and adds other constraints from electroweak precision data and from flavour physics (→ CP violation!) → link to project area C
  - builds on `SFITTER` analysis [Lopez-Val,TP,Rauch] → link to A2a
  - supplemented by automated simulation of cross sections and major kinematic distributions through `MADGRAPH`
  - code gives access to wide range of LHC observables, indirect constraints and an advanced statistical treatment

Links to Other Projects



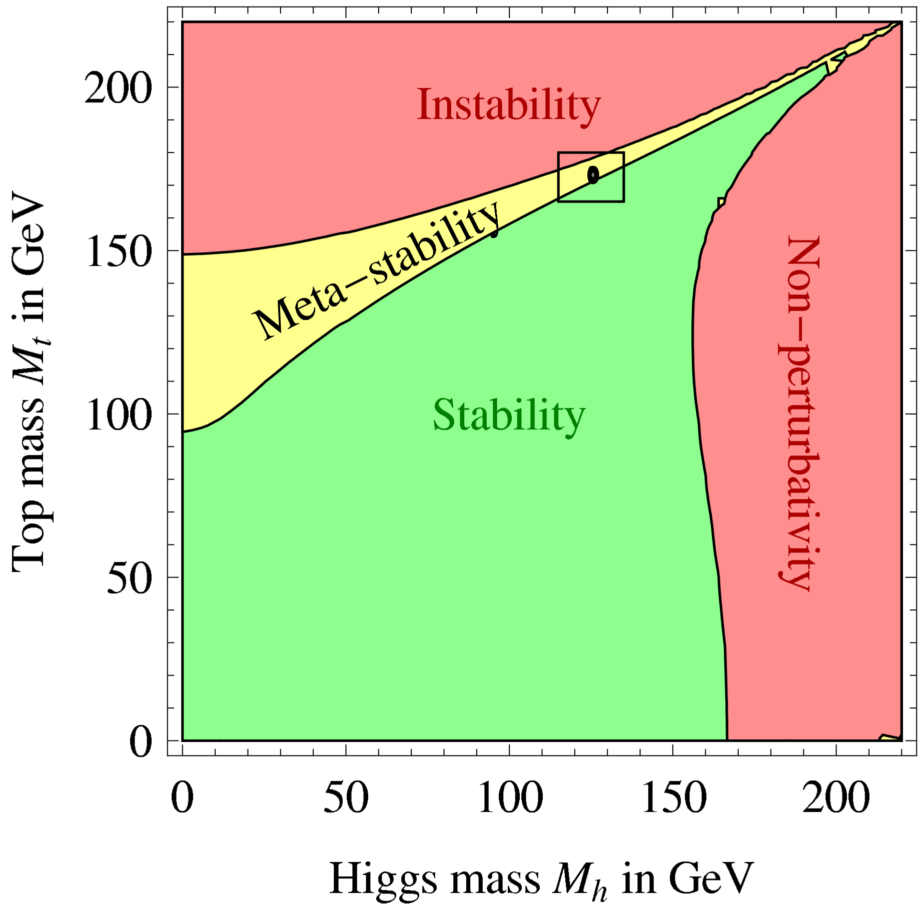
- ◇ precision predictions for Higgs production (A1a,A1c) crucial for determin. of Higgs properties
- ◇ EFT analyses of A2a, A2b can be mapped onto complete models of A3a; use SFITTER results from A2a
- ◇ insights gained in A3b (Higgs potential parameters) feed back into A3a and vice versa
- ◇ relevance for interpretation of top-quark results of B2b in New Physics scenarios
- ◇ DM results from B3a feed back into A3a
- ◇ insights on additional heavy top partners from C3a feed back into A3a

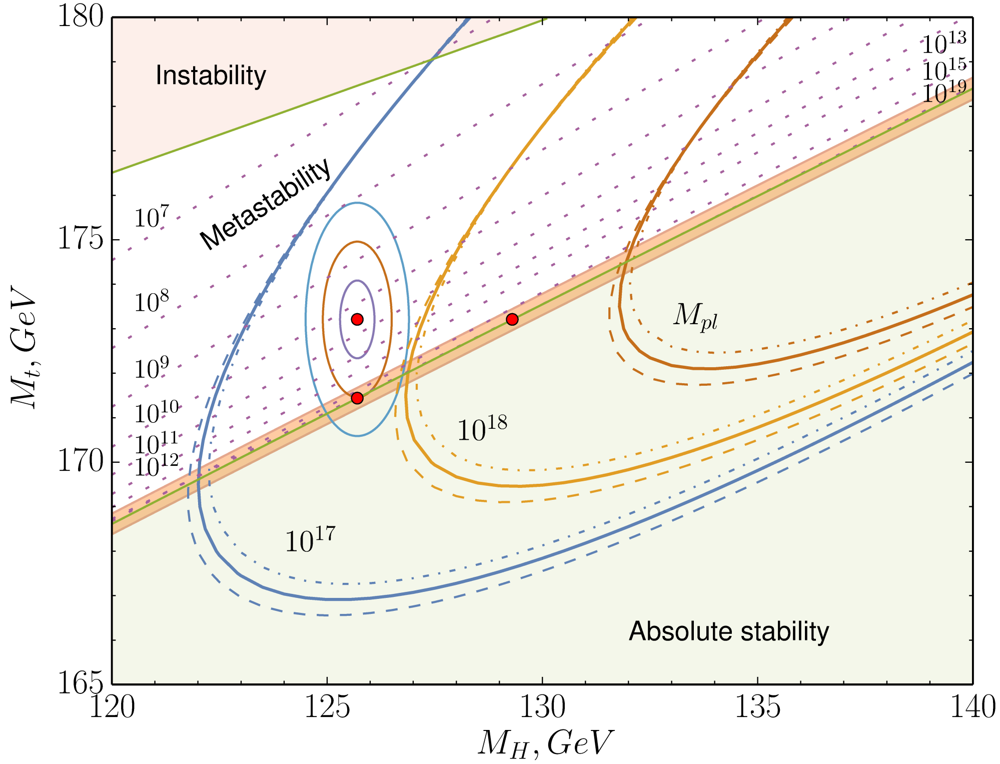
Thank You For Your Attention!

$\mathcal{S}$tability of the $\mathcal{SM}$ $\mathcal{V}$acuum

Degrassi,Di Vita,Elias-Miro,Espinosa '12

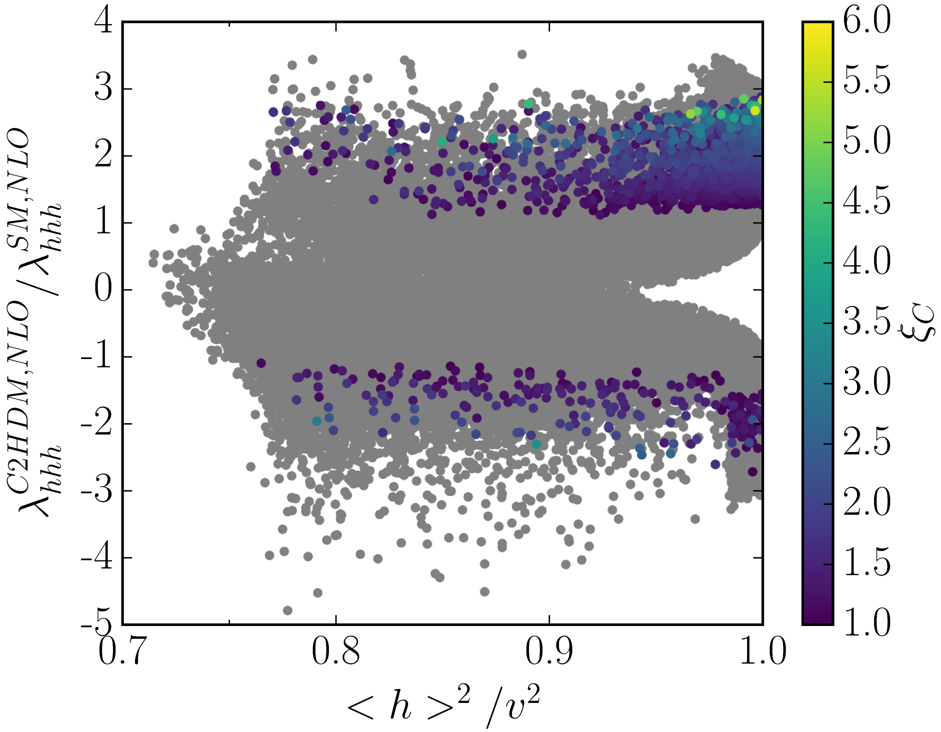
Bednyakov,Kniehl,Pikelner,Veretin '15

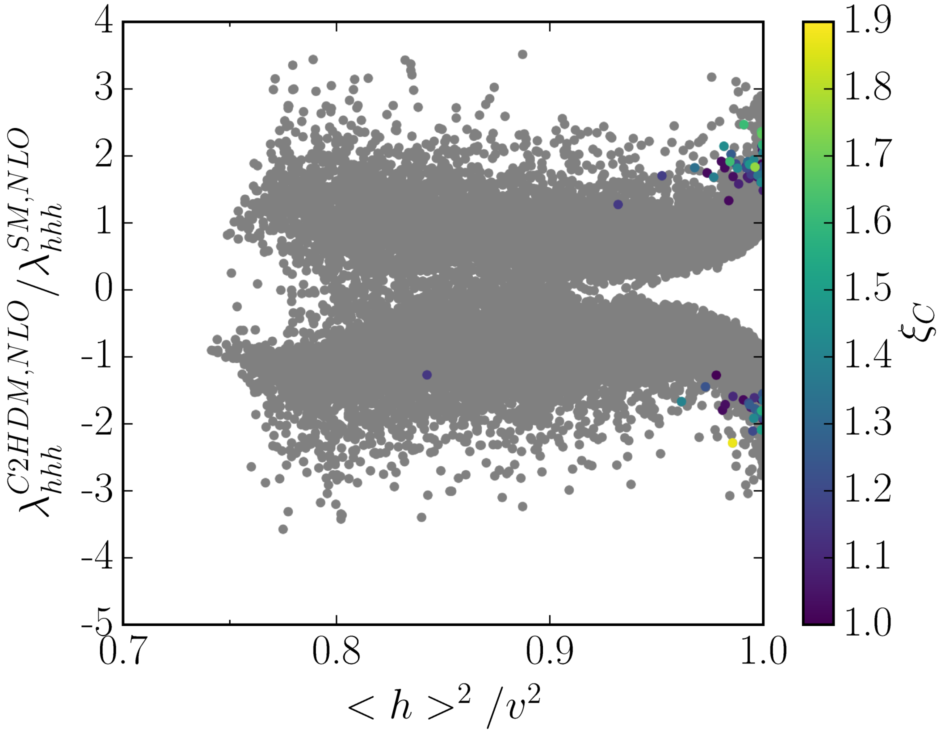




$\mathcal{E}$ffects on the $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling - $\mathcal{C}$2HDM

Type I, $H_1 = h$ - right plot: only CP-violating points [Basler,MM,Wittbrodt '17]



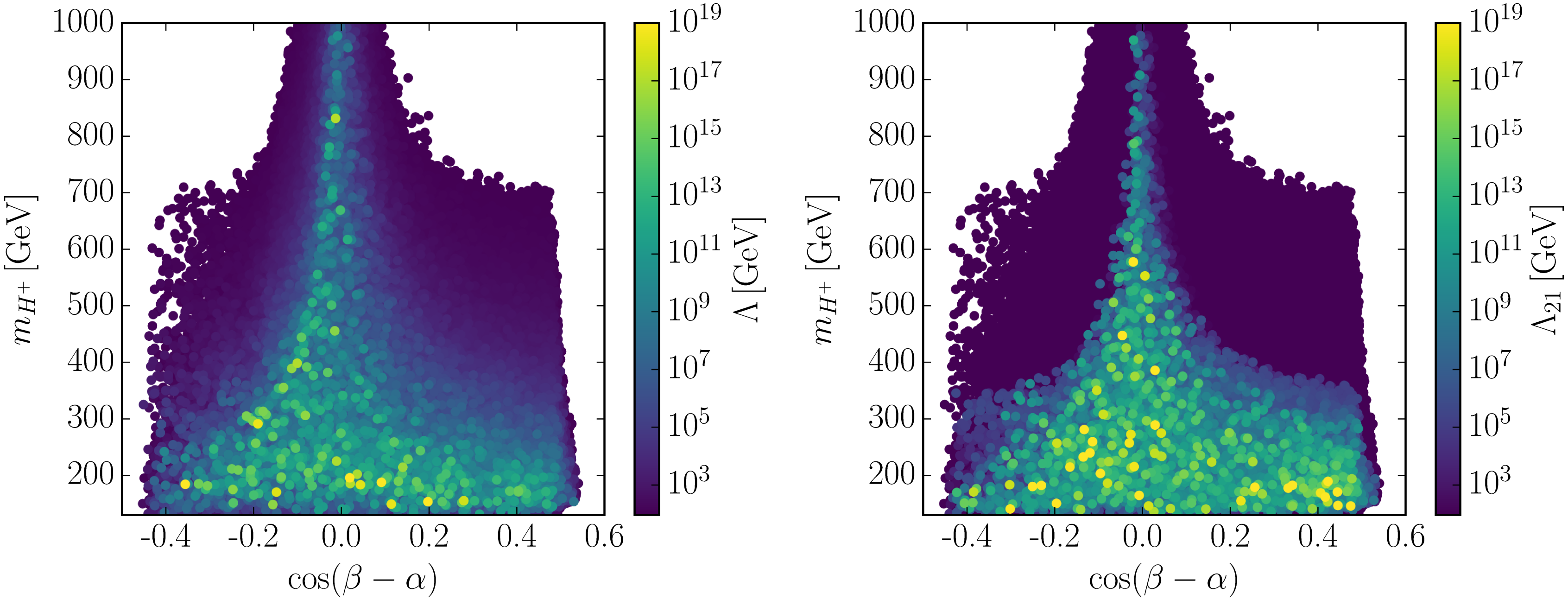


* Grey: exp+theor constraints, colour $\xi_c \geq 1$
* $1.1 \lesssim \left| \frac{\lambda_{hhh}^{\text{C2HDM,NLO}}}{\lambda_{hhh}^{\text{SM,NLO}}} \right| \lesssim 2.9$
* CP-odd part of $h \lesssim 24\% \xrightarrow{\text{EWPT}} \sim 2.5\%$

$\mathcal{T}$heory $\mathcal{C}$onstraints and $\mathcal{H}$igher-$\mathcal{O}$rder $\mathcal{C}$orrections

Impact of theory constraints, perturbative unitarity, LHC data on 2HDM (plot type 1 2HDM)

[Basler,Ferreira,MM,Santos,17]

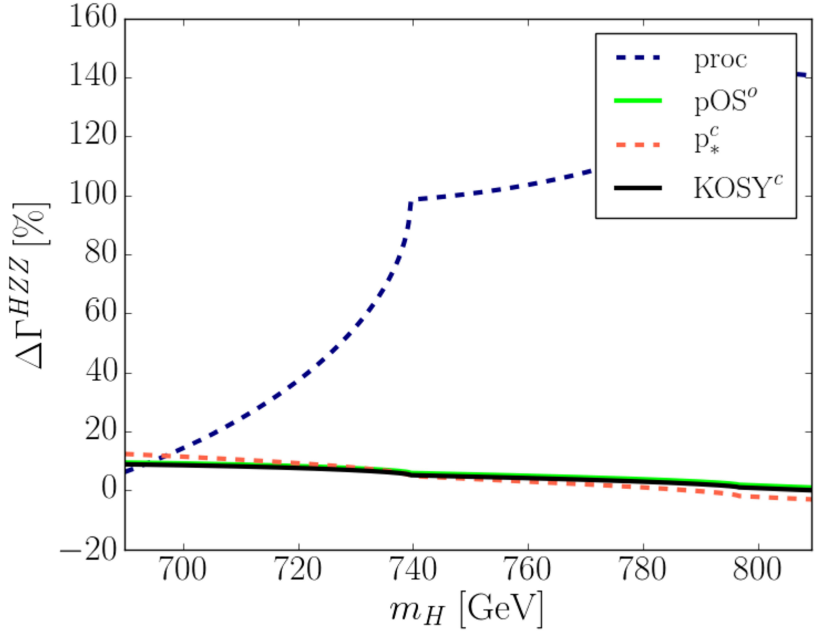


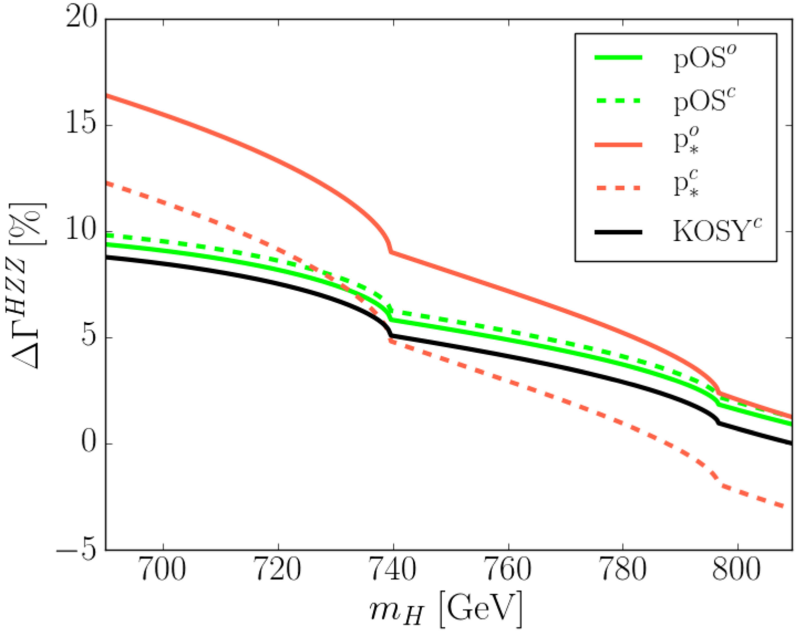
- ⋄ Left: 1-loop RGE, tree-level matching, right: 2-loop RGE, 1-loop matching of Higgs parameters
- ⋄ Alignment for $m_{H^\pm} \gtrsim 500$ GeV and validity up to $\Lambda =$ Planck scale

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

2$\mathcal{H}$DM $\mathcal{H}$igher-$\mathcal{O}$rder $H \to ZZ$ $\mathcal{D}$ecay

[Krause,Lorenz,MMM,Santos,Ziesche,'16]

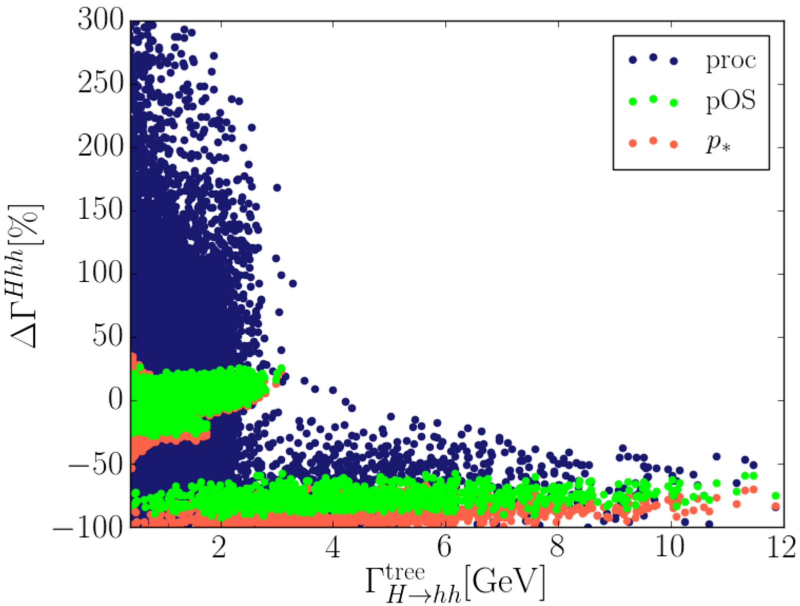


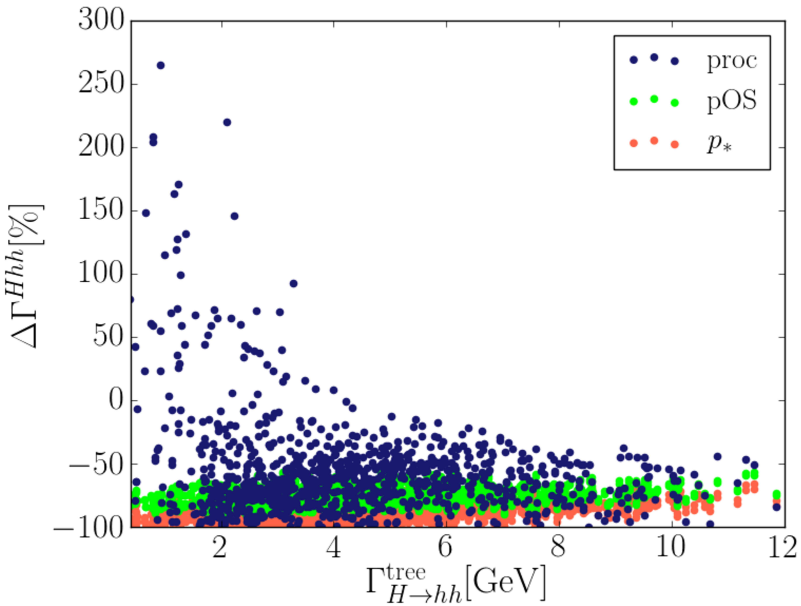


- ⋄ Left/Right: with/without process-dependent renormalization ($\leftarrow H/A \to \tau\tau$)
- ⋄ gauge-parameter independent renormalization: pOS^{c,o}, p$_*^{o,c}$; dependent: KOSY^c
- ⋄ $\Delta = (\Gamma^{\text{NLO}} - \Gamma^{\text{LO}})/\Gamma^{\text{LO}}$

2HDM Higher-Order Higgs-toHiggs Decays

[Krause,MMM,Santos,Ziesche,'16]





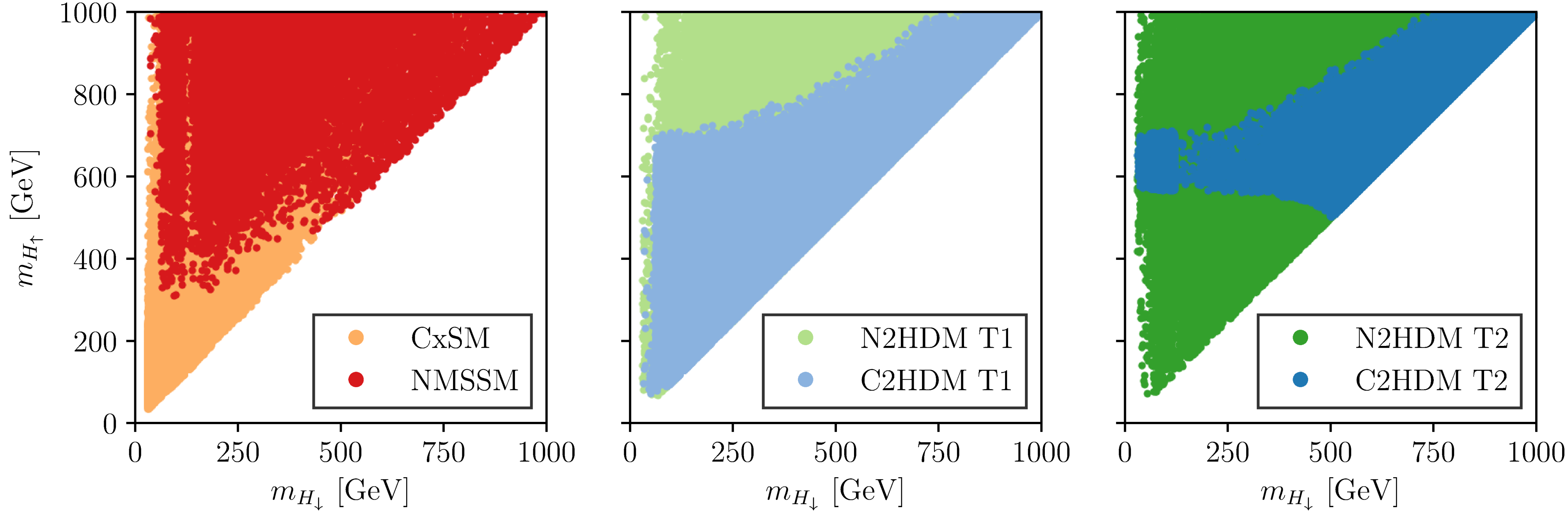
◇ Points pass theoretical and experimental constraints

◇ Three different renormalization schemes: two pinched, one process-dependent scheme

◇ Right: Only strong-coupling regime

$\mathcal{M}$ass $\mathcal{D}$istributions

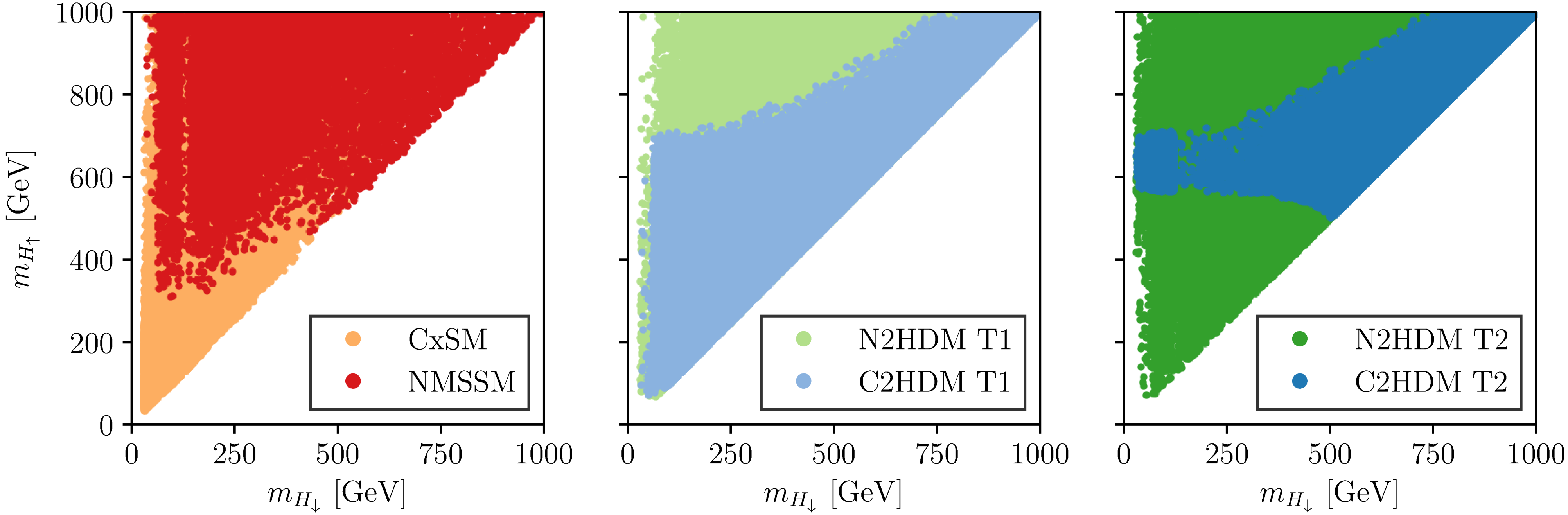
[MM,Sampaio,Santos,Wittbrodt '17]



- Tools for scan: `ScannerS`, `sHDECAY`, `N2HDECAY`
- Degenerate Higgs bosons around 125 GeV not included
- Includes latest bound on $M_{H^\pm}$(2HDM II) > 580 GeV [Misiak,Steinhauser '17]

Mass Distributions

[MM,Sampaio,Santos,Wittbrodt '17]



- All models: $m_{H_\downarrow} < m_{h_{125}}$ possible (C2HDM: only in the real 2HDM limit)
- Type I N2HDM, CxSM, C2HDM: $m_{H_\uparrow} < m_{h_{125}}$ possible
- Pseudoscalars (N2HDM, NMSSM) can be lighter than 125 GeV