$\mathcal{P}$recision $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays in $\mathcal{B}$SM

$\mathcal{M}$ilada $\mathcal{M}$argarete $\mathcal{M}$ühlleitner (KIT)

Higgs Couplings 2015
Lumley Castle
12-15 Oct 2015

Outline

◇ Introduction

◇ Coupling Determination - Effective Lagrangians

◇ Benchmark Model - Composite Higgs

◇ Coupling Measurements and New Physics Scales

◇ Couplings in Specific Models

  ∗ The NMSSM

    ∘ Higher order effects in couplings

    ∘ CP-violating couplings

   (∘ Higgs self-couplings)

  ∗ Composite Higgs Couplings

◇ Conclusions

Introduction

Official: Discovered Particle is the Higgs Boson

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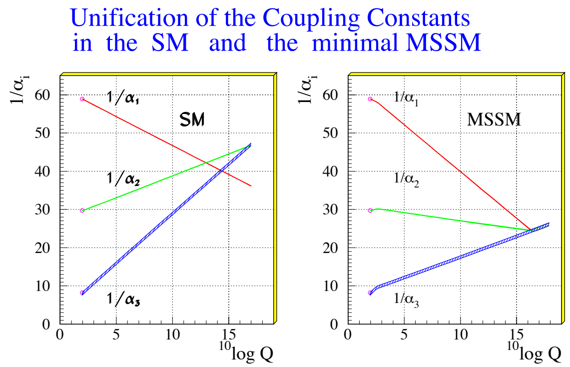
New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

𝒪pen 𝒫roblems

◇ What is the mechanism beyond EWSB? Weak or strong dynamics?

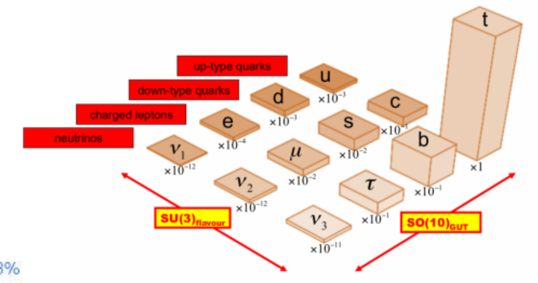


◇ Huge Higgs mass corrections - finetuning?

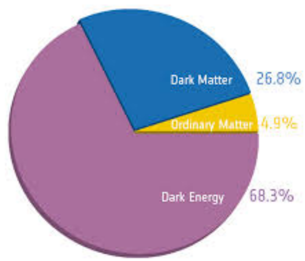
◇ Do the gauge couplings unify?

◇ Incorporation of gravity?

◇ Puzzling spectrum of fermion masses and mixings



◇ What is the nature of Dark Matter?



◇ Origin of matter-antimatter asymmetry?

◇ New sources of CP violation?

◇ ...

$\mathcal{B}$ig $\mathcal{Q}$uestions - $\mathcal{B}$ig $\mathcal{I}$deas

- What is the mechanism beyond EWSB? Weak or strong dynamics?
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- Do the gauge couplings unify?
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- What is the nature of Dark Matter?
- Origin of matter-antimatter asymmetry?
- New sources of CP violation?
- ...

Supersymmetry

Compositeness

Extra Dimensions

Extended Higgs Sectors

Top Partner W'/Z'

Minimal Dark Matter

Hidden Sector ...

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- ◇ ...

No Observation of Physics Beyond the SM so Far!

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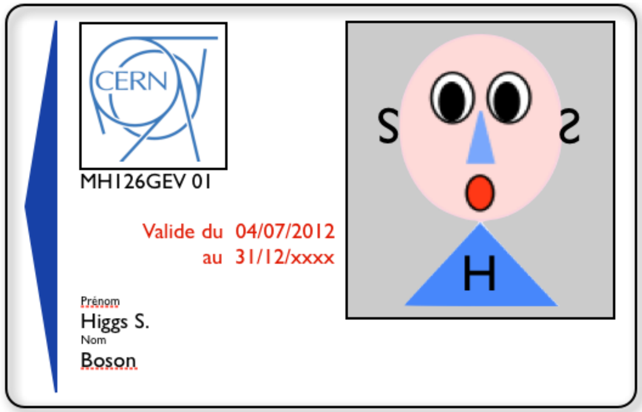
Hidden Sector ...

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

- **Naturalness: Just around the corner!**

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

  But: Discovery of new scalar particle 4th July 2012



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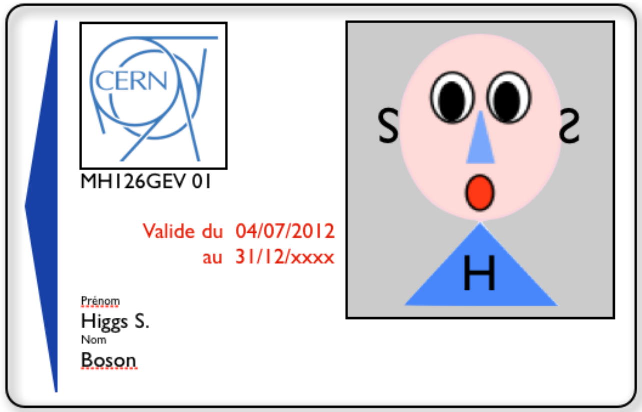

$\mathcal{W}$hat can we learn from $\mathcal{H}$iggs $\mathcal{P}$hysics in the $\mathcal{F}$uture?

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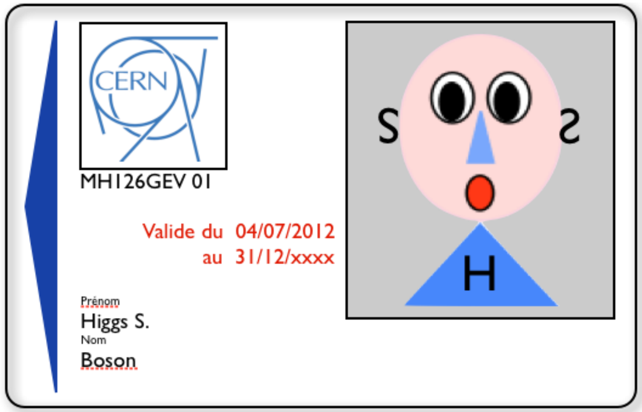


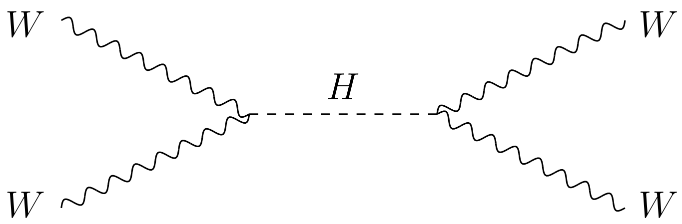
𝒲hat can we learn from ℋiggs 𝒫hysics in the ℱuture?

𝒲hat can we learn from ℋiggs 𝒞ouplings 𝒫recision ℳeasurements?

$\mathcal{W}$hat is the $\mathcal{D}$ynamical $\mathcal{O}$rigin of $\mathcal{EWSB}$?

$\mathcal{I}$s the Higgs boson $\mathcal{E}$lementary or $\mathcal{C}$omposite?

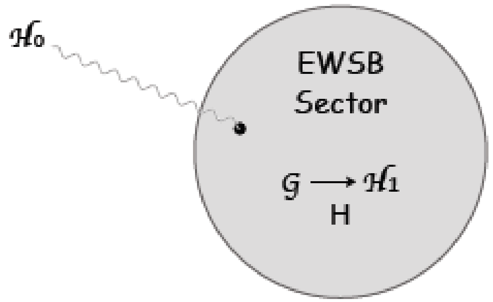
Weakly coupled models



$\mathcal{S}$M, $\mathcal{S}$USY, ...
SUSY Partner ~ 1 TeV

New particles necessary to
stabilise the Higgs boson mass

Strongly-interacting dynamics



$\mathcal{C}$omposite $\mathcal{H}$iggs
top partners $\gtrsim 700$ GeV

Resonances for unitarity
Higgs boson composite object

Cartoon from R.Contino [1005.4269]

What Can We Learn From Coupling Measurements?

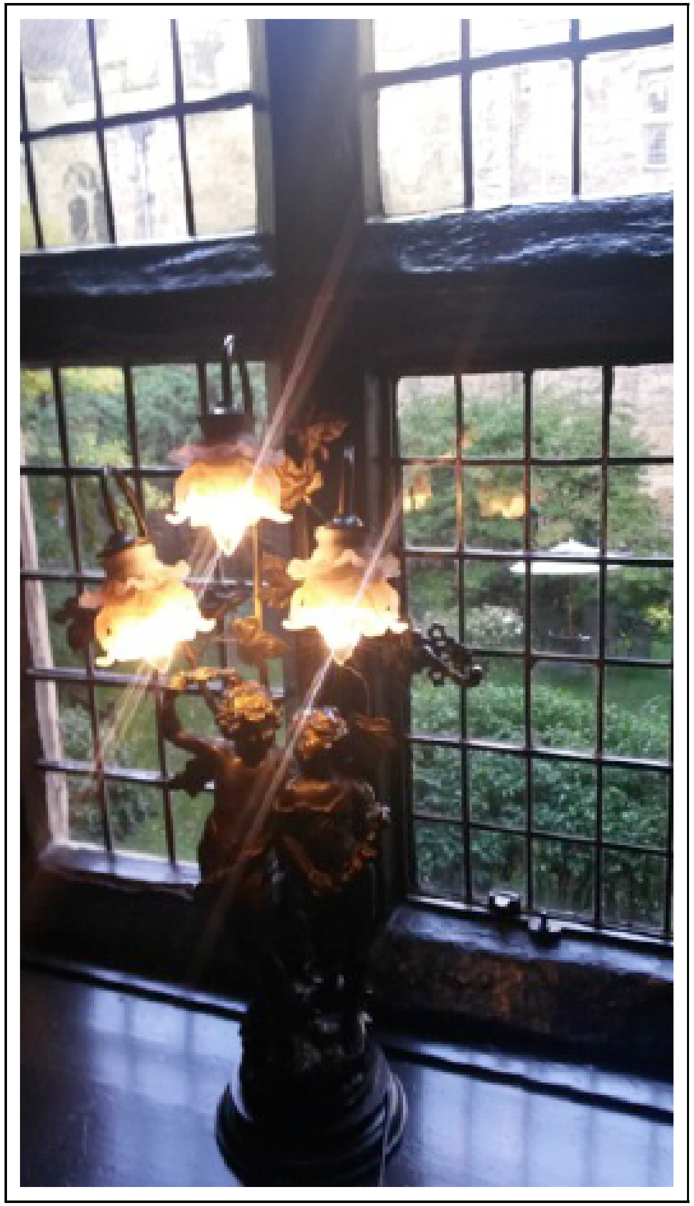
- ***The Standard Model Higgs Boson***
  - ◇ Test relation $g_{hXX} \sim m_X$ predicted by Higgs mechanism

- **Deviations from SM couplings ⟵ New Physics**
  - ◇ modified Higgs properties through mixing effects with other scalars or mixture between elementary and composite state in case of a composite particle (partial compositeness)
  - ◇ modified Higgs properties through loop effects or effective low-energy operators (strong int.)
  - ◇ modified Higgs Γ_{tot}/BRs through invisible decays and/or decays into lighter non-SM states

What is the Scale of New Physics that can be Probed?

∗ Depends on experimental precision and precision in theoretical predictions ∗

$\mathcal{C}$oupling $\mathcal{D}$etermination - $\mathcal{E}$ffective $\mathcal{L}$agrangians

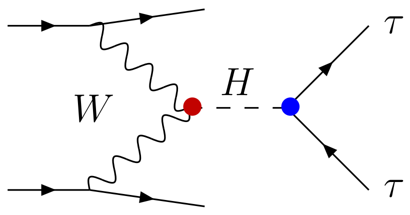


$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

E.g.:



$\sim \Gamma_{WW} \frac{\Gamma(H\to\tau\tau)}{\Gamma_{\text{tot}}}$ (narrow width approximation)

$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

$$\sigma_{\text{prod}}(H) \times \text{BR}(H \to XX) \sim \Gamma_{\text{prod}} \times \frac{\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}}$$

Coupling measurement at the LHC

- $*$ Determination of total width impossible w/o further assumptions; not all final states accessible
- $*$ $\Rightarrow$ Only ratios of couplings can be measured

- **Couplings extracted** from $\mu = (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$ values provided by experiments

- **Theoretical approach**
  - $*$ Effective Lagrangian which defines the meaning of the couplings
  - $*$ Effective Lagrangian w/ modified Higgs couplings $\to$ signal rates $\to$ fit to experimental μ values

$\mathcal{E}$ffective $\mathcal{L}$agrangians

- **Weakly interacting theories**
  - ∗ effective higher dimension operators up to dimension 6

    Burgess,Schnitzer; Leung eal ;Buchmüller,Wyler;Grzadkowski eal;Hagiwara,Ishihara,Szalapski,Zeppenfeld;Giudice eal
  - ∗ assume large Λ

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i \\ &= \mathcal{L}_{\mathrm{SM}} + \sum_i \bar{c}_i O_i \\ &= \mathcal{L}_{\mathrm{SM}} + \Delta\mathcal{L}_{\mathrm{SILH}} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2} + \Delta\mathcal{L}_{\mathrm{bos}} + \Delta\mathcal{L}_{4f} + \Delta\mathcal{L}_{\mathrm{CP}}\end{aligned}$$

- **Assumption: Higgs $SU(2)$ doublet**

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$
\begin{aligned}
\Delta\mathcal{L}_{\mathsf{SILH}} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{F_1} = {} & \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) \\
& + \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& + \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) + \frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& + \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right),
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{F_2} = {} & \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c \sigma^{\mu\nu} u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c \sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} \\
& + \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H \sigma^{\mu\nu} d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H \sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu}
\end{aligned}
$$

$\mathcal{E}$ffective $\mathcal{L}$agrangians

$$\Delta\mathcal{L}_{\text{bos}} = \frac{\bar{c}_{3W}\, g^3}{m_W^2}\, \epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} G_\rho^{c\,\mu}$$

$$+ \frac{\bar{c}_{2W}}{m_W^2}\, (D^\mu W_{\mu\nu})^i\, (D_\rho W^{\rho\nu})^i + \frac{\bar{c}_{2B}}{m_W^2}\, (\partial^\mu B_{\mu\nu})\, (\partial_\rho B^{\rho\nu}) + \frac{\bar{c}_{2G}}{m_W^2}\, (D^\mu G_{\mu\nu})^a\, (D_\rho G^{\rho\nu})^a$$

$$\Delta\mathcal{L}_{4f} = \sum_{\psi, L/R, T^a} \bar{\psi}_i \gamma^\mu T^a \psi_j\, \bar{\psi}_k \gamma_\mu T^a \psi_l + \bar{\psi}_i T^a \psi_j\, \bar{\psi}_k T^a \psi_l$$

$$\Delta\mathcal{L}_{\text{CP}} = \frac{i\tilde{c}_{HW}\, g}{m_W^2}\, (D^\mu H)^\dagger \sigma^i (D^\nu H) \tilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}\, (D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$$

$$+ \frac{\tilde{c}_\gamma\, {g'}^2}{m_W^2}\, H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

$$+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\, \epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} \tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} \tilde{G}_\rho^{c\,\mu}\,,$$

$\ast$ After using the equations of motion: 53 (59) independent dim-6 operators

$\mathcal{E}$ffective $\mathcal{L}$agrangians

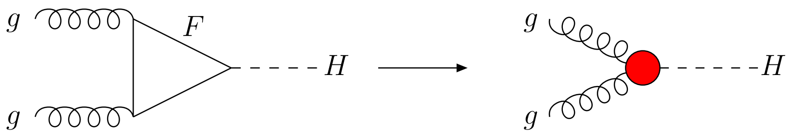
◇ **Higgs $\mathcal{L}_{\text{eff}}$:** unitary gauge, canonically normalized fields; SM: $\kappa_i = 1, \bar{\kappa}_i = 0$

Contino eal '10,'12; Azatov eal; Alonso eal;
Brivio eal; Elias-Miró eal; Isidori eal; Buchalla eal

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_3 \left(\frac{m_h^2}{2v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)} \psi^{(i)} \left(1 + \kappa_\psi \frac{h}{v} + \dots\right)$$
$$+ m_W^2\, W_\mu^+ W^{-\,\mu} \left(1 + 2\kappa_W \frac{h}{v} + \dots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2\kappa_Z \frac{h}{v} + \dots\right) + \dots$$
$$+ \left(\frac{\bar{\kappa}_{WW}\, \alpha}{\pi} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\bar{\kappa}_{ZZ}\, \alpha}{2\pi} Z_{\mu\nu} Z^{\mu\nu} + \frac{\bar{\kappa}_{Z\gamma}\, \alpha}{\pi} Z_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_\gamma\, \alpha}{2\pi}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_g\, \alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \left(\left(\bar{\kappa}_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + \bar{\kappa}_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \bar{\kappa}_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \dots$$

◇ **Remarks:** $*$ Valid for h being singlet or doublet

$*$ $\bar{\kappa}_{g,\gamma,Z\gamma}$ parametrize new physics in the hgg, $h\gamma\gamma$ and $hZ\gamma$ loop couplings



$\mathcal{S}$ILH and $\mathcal{N}$on-$\mathcal{L}$inear $\mathcal{E}$xpansion

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$$+ \left(\frac{\bar{\kappa}_{WW}\,\alpha}{\pi} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\bar{\kappa}_{ZZ}\,\alpha}{2\pi} Z_{\mu\nu}Z^{\mu\nu} + \frac{\bar{\kappa}_{Z\gamma}\,\alpha}{\pi} Z_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_\gamma\,\alpha}{2\pi}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_g\,\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \left(\left(\bar{\kappa}_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + \bar{\kappa}_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \bar{\kappa}_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \dots$$

- ◇ **Strongly Interacting Light Higgs (SILH):** E energy, M NP scale, $f \equiv M/g_*$, g_* NP couplg
  expansion in v^2/f^2, E^2/M^2, α_s/π, α/π
- ◇ **Non-Linear realization of EW symmetry** large deviations from SM couplings $\rightsquigarrow$
  expansion in E^2/M^2, α_s/π

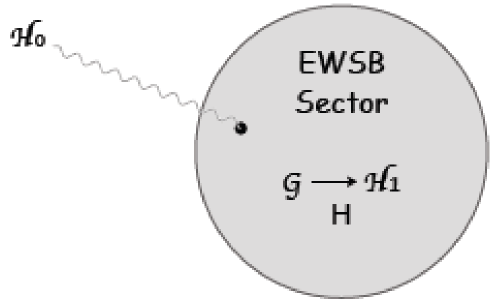
$\mathcal{C}$omposite $\mathcal{H}$iggs

$\mathcal{B}$enchmark $\mathcal{M}$odel: $\mathcal{C}$omposite $\mathcal{H}$iggs

Kaplan,Georgi; Dimopoulos eal; Dugan eal

- **Bound state from a Strongly Interacting Sector not much above weak scale**

- **How can we obtain a light composite Higgs?**



Higgs: Pseudo-Goldstone boson of strongly interacting sector

Global symmetry of strong sector $\mathcal{G}$ $\xrightarrow{\text{spontaneously broken at } f}$ subgroup $\mathcal{H}_1$

$\mathcal{G}/\mathcal{H}_1$: contains Higgs boson as Nambu-Goldstone Boson

- **Continuous interpolation between the SM and Technicolor:**

$\xi = 0$ SM limit $\longleftarrow$ $\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$ $\longrightarrow$ $\xi = 1$ "Technicolor" limit

strong sector resonances decouple, except boson

boson deccouples, vector resonances like in TC

- **No hierarchy problem** EWSB potential generated at one-loop through gauge and top loops

Higgs Anomalous Couplings

- **Large ξ?** The 5D MCHM ($SO(5)/SO(4)$) provides completion for large ξ Contino eal; Agashe eal
- **Gauge couplings**

$$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi} = g_{HVV}^{SM}\,\kappa_V$$

- **Fermion couplings** depend on embedding into representations of the bulk symmetry

spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5
$g_{Hff} = g_{Hff}^{SM}\sqrt{1-\xi} \equiv g_{Hff}^{SM}\,\kappa_\psi$	$g_{Hff} = g_{Hff}^{SM}\frac{1-2\xi}{\sqrt{1-\xi}} \equiv g_{Hff}^{SM}\,\kappa_\psi$
universal shift of couplings no modifications of BRs	BRs depend on $\xi = v^2/f^2$

- **Higgs self-couplings** also model-dependent Contino eal; Gröber,MMM; Bock eal; Barger eal

$\mathcal{H}$iggs $\mathcal{C}$ouplings $\mathcal{R}$elations

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
κ_W	$1 - \bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
κ_Z	$1 - \bar{c}_H/2 - \bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$\kappa_\psi \;\; (\psi = u, d, l)$	$1 - (\bar{c}_H/2 + \bar{c}_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
κ_3	$1 + \bar{c}_6 - 3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
κ_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar{c}_g$	0	0
$\kappa_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar{c}_\gamma$	0	0
$\kappa_{Z\gamma}$	$\left(\bar{c}_{HB} - \bar{c}_{HW} - 8\,\bar{c}_\gamma \sin^2\theta_W\right)\tan\theta_W$	0	0
κ_{WW}	$-2\,\bar{c}_{HW}$	0	0
κ_{ZZ}	$-2\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W - 4\bar{c}_\gamma \tan^2\theta_W \sin^2\theta_W\right)$	0	0
$\kappa_{W\partial W}$	$-2(\bar{c}_W + \bar{c}_{HW})$	0	0
$\kappa_{Z\partial Z}$	$-2(\bar{c}_W + \bar{c}_{HW}) - 2\,(\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W$	0	0
$\kappa_{Z\partial\gamma}$	$2\,(\bar{c}_B + \bar{c}_{HB} - \bar{c}_W - \bar{c}_{HW})\tan\theta_W$	0	0

$\mathcal{HO}$ $\mathcal{C}$orrections $\mathcal{S}$ILH and $\mathcal{N}$on-$\mathcal{L}$inear $\mathcal{E}$xpansion

- **Example Fermionic Decay:** $h \to f\bar{f}$

$$\text{SILH:} \quad \Gamma(\bar\psi\psi)|_{\text{SILH}} = \Gamma_0^{\text{SM}}(\bar\psi\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{\text{SM}}|^2}\text{Re}(A_0^{*\text{SM}} A_{1,\text{EW}}^{\text{SM}})\right][1 + \delta_\psi\, c^{\text{QCD}}]$$

$$\text{NL:} \quad \Gamma(\bar\psi\psi)|_{\text{NL}} = \Gamma_0^{\text{SM}}(\bar\psi\psi)\ \kappa_\psi^2\,[1 + \delta_\psi\, c^{\text{QCD}}]$$

A_0^{SM} : SM tree-level amplitude
$A_{1,\text{EW}}^{\text{SM}}$: SM EW amplitude (analoguous treatment of real corrections)
c^{QCD} encodes QCD corrections; $\delta_\psi = 1(0)$ for quarks (leptons)

- **Remarks:**

  * fractorization of QCD $\leftrightarrow$ EW

  * NL approach: no EW corrections!

- **Numerical Implementation:**

  Fortran code `eHDECAY` [Contino,Ghezzi,Grojean,MMM,Spira]

$\mathcal{C}$omputer $\mathcal{T}$ool for $\mathcal{H}$iggs $\mathcal{D}$ecay $\mathcal{W}$idths in the $\mathcal{E}$FT $\mathcal{A}$pproach

- **Implementation for Higgs decay widths:** `eHDECAY`

  R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira

  URL: http://www.itp.kit.edu/∼maggie/eHDECAY/

- **Implemented Parametrisations**

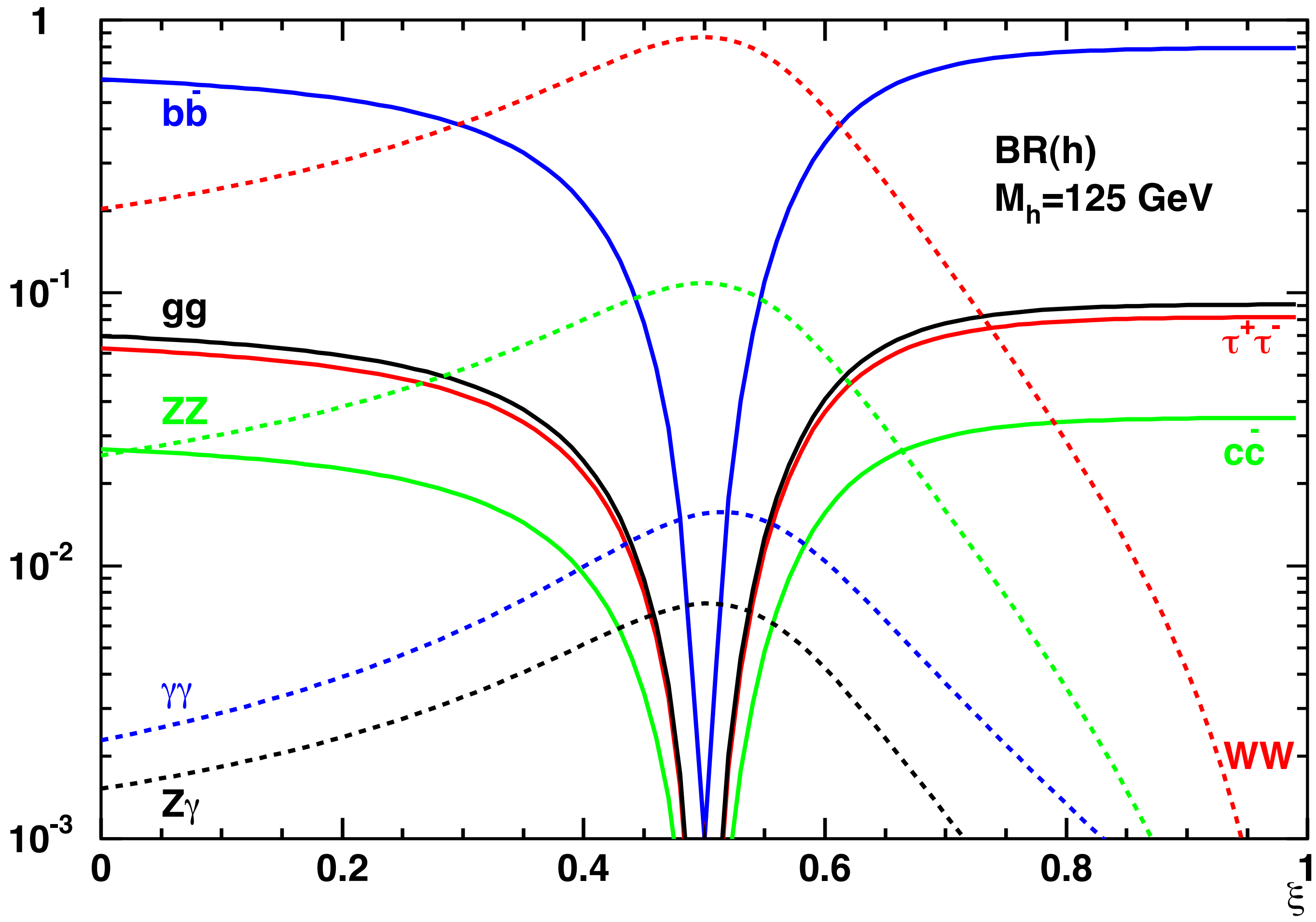
SILH:	strongly interacting light Higgs boson, SU(2) doublet
MCHM4,5:	minimal composite Higgs models
non-linear:	expansion, allows large couplg deviations from SM

- **Higher Order Corrections:**

  * $h \to gg$ and $h \to \gamma\gamma$ w/ NLO QCD mass effects
  * QCD for SILH, MCHM, NL; EW for SILH, MCHM

Composite Higgs Branching Ratios for MCHM5

Grojean,Espinosa,MMM



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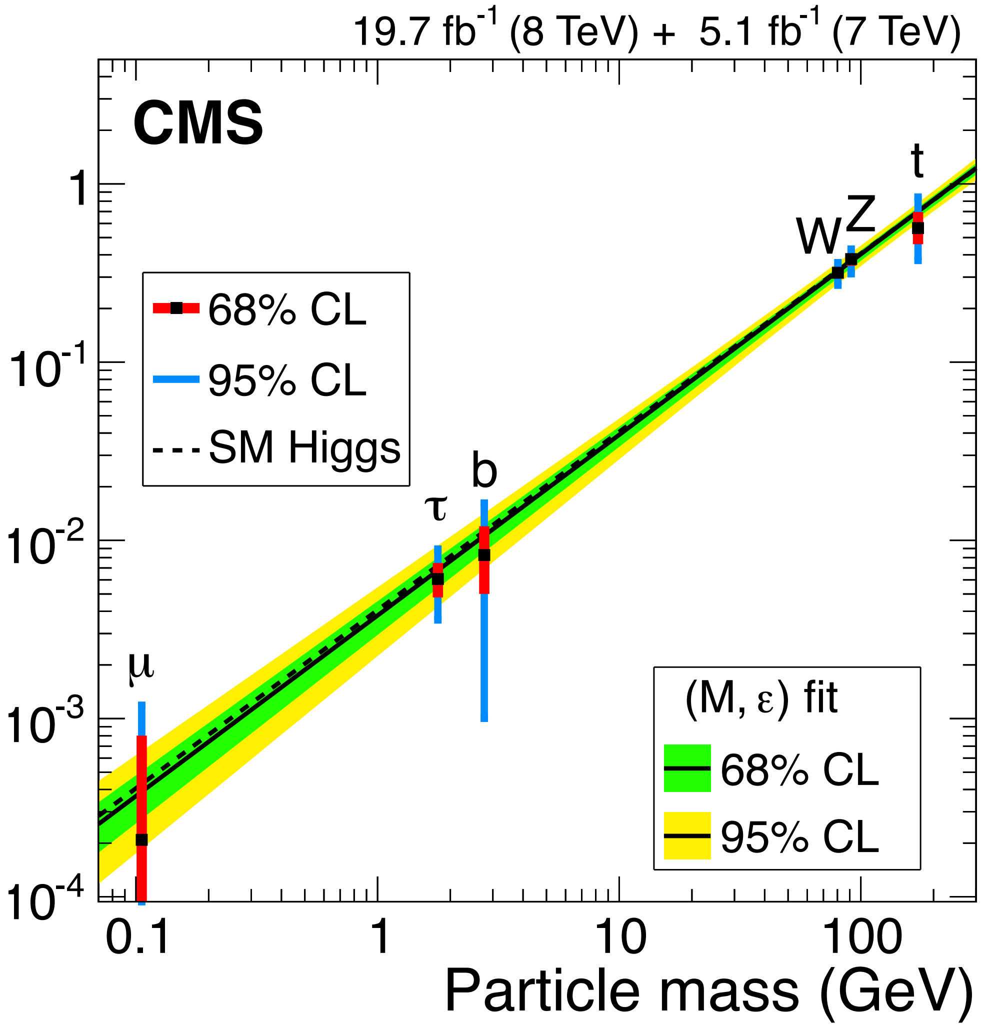


$\mathcal{C}$oupling $\mathcal{M}$easurements and $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales

$\mathcal{S}$cales $\mathcal{P}$robed $\mathcal{I}$n $\mathcal{C}$oupling $\mathcal{M}$easurements

- **Use expansions in higher dimensional operators** to describe coupling deviation $\rightsquigarrow$

$$g_{hXX} = g_{hXX}^{\text{SM}}[1+\Delta] \; : \; \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\Lambda \gg v =$ characteristic scale of Beyond the SM Physics

[caveat: violation of decoupling theorem]

- **Scales to be probed in Mixing Effects**

LHC coupling precision:	$4-15\%$	$\rightsquigarrow$	$\Lambda = 640$ GeV...1.2 TeV
HL-LHC coupling precision:	$2-10\%$	$\rightsquigarrow$	$\Lambda = 780$ GeV...1.7 TeV

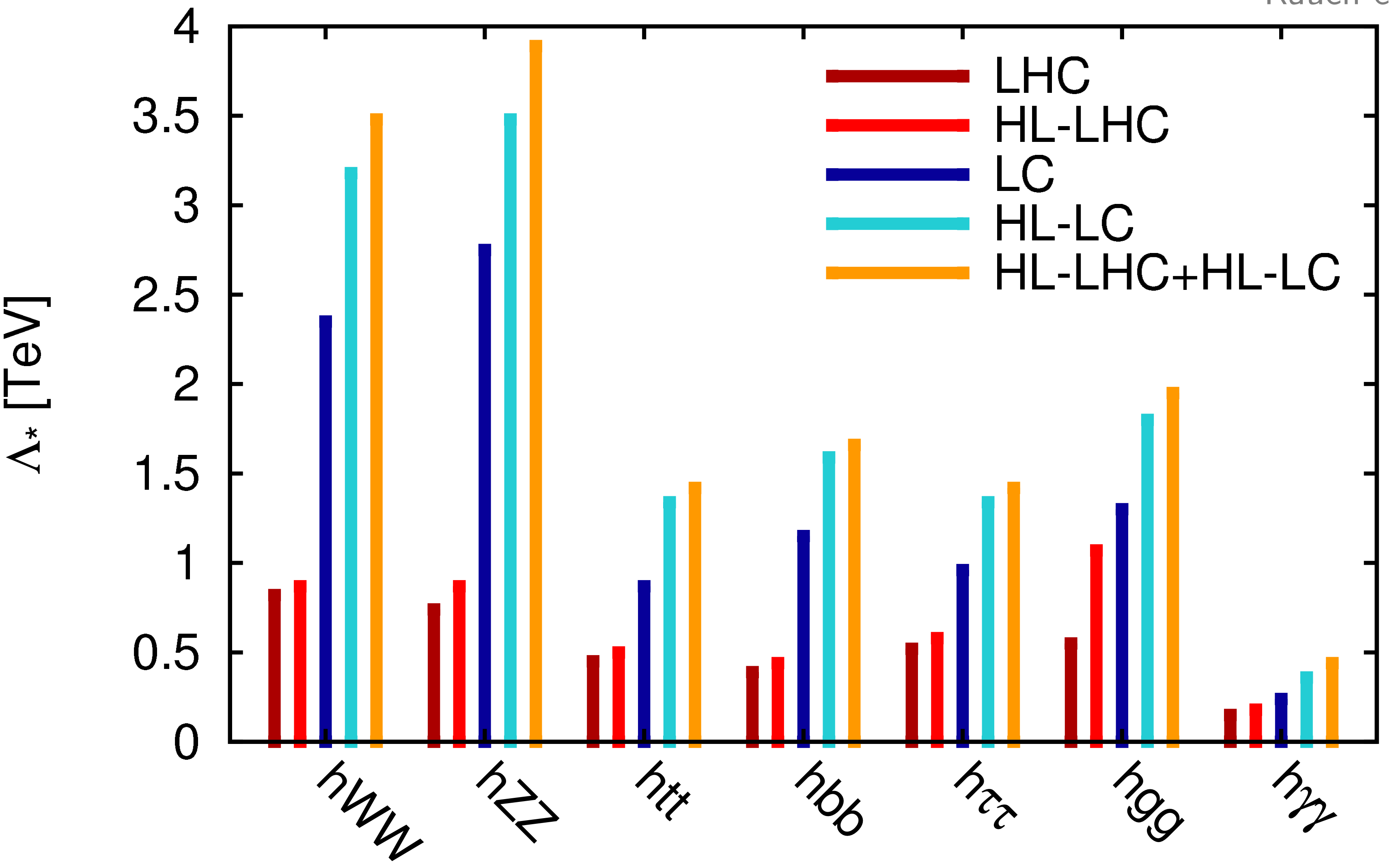
- **Scales to be probed in Loop Effects**

additional loop suppression factor $\rightsquigarrow \Delta = \frac{v^2}{16\pi^2\Lambda^2}$

$\Rightarrow$ for $\Delta = 0.02$ scale probed: $\Lambda \approx 140$ GeV

𝒫robed ℰffective 𝒩ew 𝒫hysics 𝒮cales (loop, coupling factors factored out)

Rauch et al.



Strongly Interacting Light Higgs (SILH)

- **SILH Lagrangian:** first term of an expansion in $\xi = v^2/f^2$ [f: typical scale of strong sector]
  Higgs couplings modified in terms of ξ Giudice,Grojean,Pomarol,Rattazzi

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
universal	0.076	0.051	0.008	0.0052	0.0052
non-universal	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
universal	0.89	1.09	2.82	3.41	3.41
non-universal	0.94	1.98	5.13	5.65	5.65

universal: fermions in spinorial representation Agashe,Contino,Pomarol
non-universal: fermions in fundamental representation Contino,Da Rold,Pomarol

Couplings in Specific Models

Effective Theory Approach Versus Specific Models

- **Effective Field Theory (EFT) Approach**
  - ∗ assume few basic principles (e.g. field content, SM gauge symmetries)
  - ∗ parametrize SM deviations by higher-dimensional operators

Advantage:	study large class of models
Disadvantage:	cannot account for effects from light particles in the loops, Higgs decays into non-SM particles
Solution:	study EFT and specific BSM models capturing these features

Going Beyond the SM

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

Effective Theory Approach Versus Specific Models

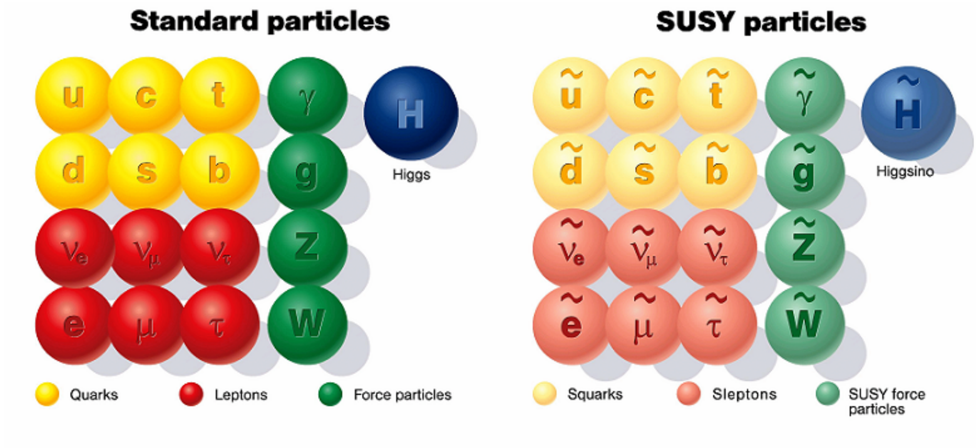
- **Effective Field Theory (EFT) Approach**
  - ∗ assume few basic principles (e.g. field content, SM gauge symmetries)
  - ∗ parametrize SM deviations by higher-dimensional operators

Advantage:	study large class of models
Disadvantage:	cannot account for effects from light particles in the loops, Higgs decays into non-SM particles
Solution:	study EFT and specific BSM models capturing these features

- **Remainder of this talk:**
  - ◇ Next-to-Minimal Supersymmetric extension of the SM (NMSSM)
  - ◇ Composite Higgs Model

Supersymmetry

Supersymmetry: relates fermions and bosons



Virtues of supersymmetry:

- ∗ solves hierarchy problem
- ∗ Higgs mechanism generated radiatively
- ∗ gauge coupling unification (MSSM)
- ∗ Cold Dark Matter candidate ($\leftarrow$ R-parity) ...

Consequences:

- ♢ new particles (*e.g.* running in the loops)
- ♢ extended Higgs sectors (scalar, pseudoscalar or no definite CP quantum number)
- ♢ couplings affected by mixing and loop effects, BRs by new non-SM decays

$\mathcal{T}$he $\mathcal{N}$MSSM

$\mathcal{I}$nterpretation within $\mathcal{SUSY}$: The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Supersymmetric Higgs Sector:** SUSY & anomaly-free theory $\Rightarrow$ 2 complex Higgs doublets

- **Most economic version:** Minimal Supersymmetric Extension of the SM (MSSM):

  2 complex Higgs doublets

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

  2 complex Higgs doublets plus one complex singlet field $\rightsquigarrow$

- **Solution of the μ-problem:** μ must be of $\mathcal{O}$(EWSB scale) Kim,Nilles

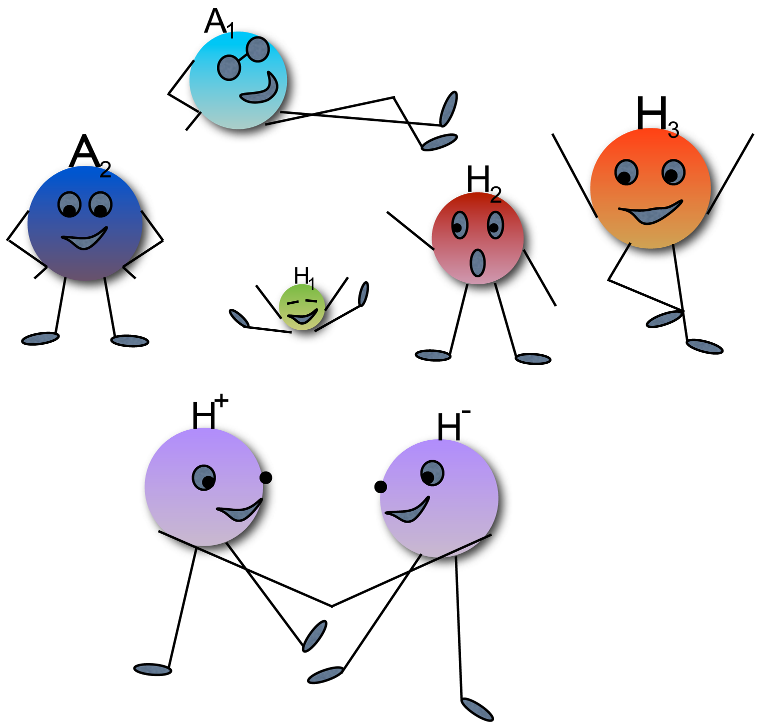
  μ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Enlarged Higgs and neutralino sector:** 2 complex Higgs doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Higgs mass eigenstates:**
  superpositions of doublet and singlet components $\rightsquigarrow$
  the more singlet-like
  the smaller couplings to SM particles



- **Significant changes of Higgs boson phenomenology**
  - ∗ light Higgses not excluded, Higgs-to-Higgs decays
  - ∗ degenerate Higgs bosons around 125 GeV possible
  - ∗ very light singlino-like lightest SUSY particle (LSP)
  - ∗ $\rightsquigarrow$ invisible Higgs decays
  - ∗ tree-level CP violation ...

$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections $\mathcal{M}$asses and $\mathcal{C}$ouplings

- **NMSSM Higgs boson masses given in terms of Higgs potential parameters**
- **Higher order corrections:**
  - $*$ important to shift SM-like NMSSM Higgs boson mass to $\sim$ 125 GeV;
  - $*$ Higgs masses enter production cxn's and BR's $\rightsquigarrow$
  - $*$ need to be known at highest possible accuracy for proper interpretation of exp results, for distinction of Higgs sectors of different BSM models

$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections $\mathcal{E}$ffects on $\mathcal{C}$ouplings

- **Mass eigenstates (CP-violating):** at tree-level

$$\underbrace{(h_1, h_2, h_3, h_4, h_5, G)^T}_{\text{mass eigenstates}} = \underbrace{\mathcal{R}^{(0)}_{ij}}_{\text{mixing matrix}} \underbrace{(h_d, h_u, h_s, A, a_s, G)^T}_{\Phi^T\text{: interaction eigen.}}$$

- **Mass matrix:** at tree-level

$$\mathcal{D}^{(0)}_H = \text{diag}\left((M^{(0)}_{H_1})^2, ..., (M^{(0)}_{H_5})^2, 0\right) = \mathcal{R}^{(0)}\, M^{(0)}_{\Phi\Phi}\, \mathcal{R}^{(0),T}$$

$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections $\mathcal{E}$ffects on $\mathcal{C}$ouplings

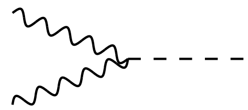
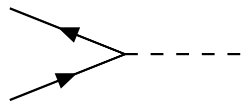
- **Mass eigenstates (CP-violating):** at loop level

$$\underbrace{(H_1, H_2, H_3, H_4, H_5, G)^T}_{\text{mass eigenstates}} = \underbrace{\mathcal{R}_{ij}^{(l)}}_{\text{mixing matrix}} \underbrace{(h_d, h_u, h_s, A, a_s, G)^T}_{\Phi^T\text{,interaction eigen.}}$$

- **Mass matrix:** at loop level

$$\mathcal{D}_H^{(l)} = \text{diag}\left((M_{H_1}^{(l)})^2, ..., (M_{H_5}^{(l)})^2, 0\right) = \mathcal{R}^{(l)}\, M_{\Phi\Phi}^{(l)}\, \mathcal{R}^{(l),T}$$

- **Higgs couplings:**

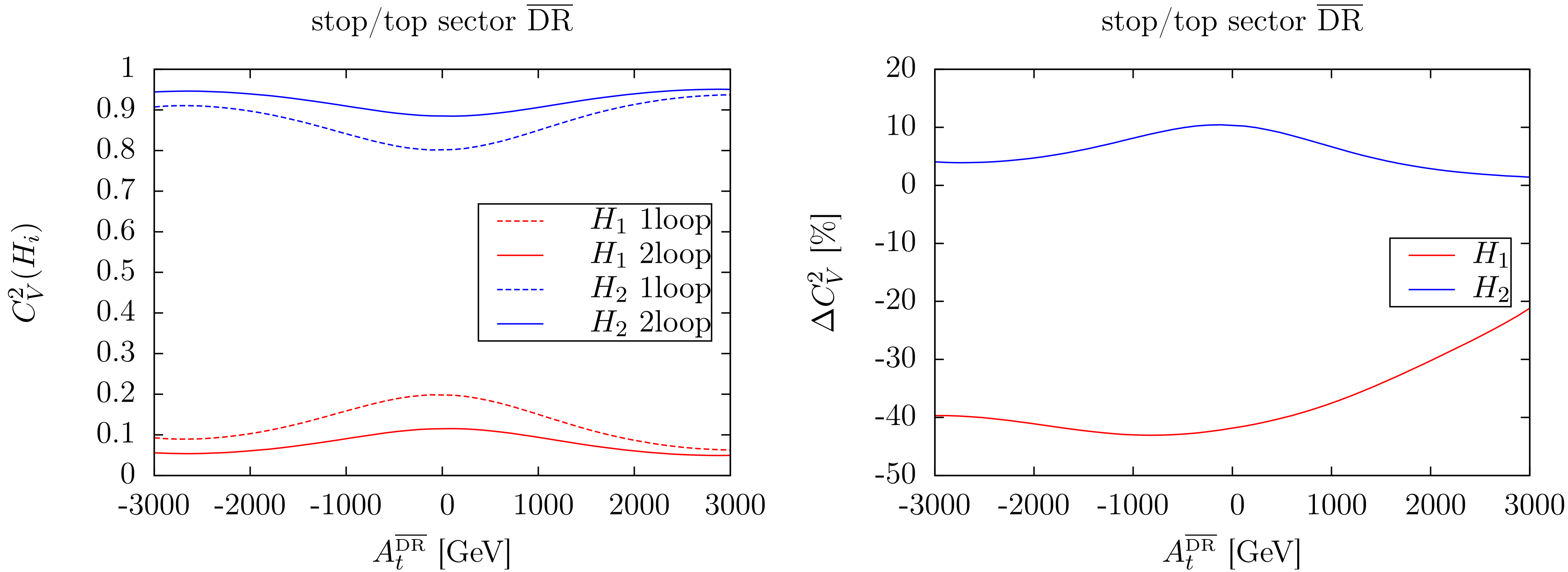
$\mathcal{C}$ouplings to gauge bosons	$g_{VVH_i} \quad = \quad [\mathcal{R}_{i1}^{(l)} \cos\beta + \mathcal{R}_{21}^{(l)} \sin\beta]\, g_{VVH}^{\text{SM}}$	
$\mathcal{Y}$ukawa couplings	$g_{ddH_i} \quad = \quad \frac{\mathcal{R}_{i1}^{(l)}}{\cos\beta} g_{ffH}^{\text{SM}} \qquad g_{uuH_i} = \frac{\mathcal{R}_{i2}^{(l)}}{\sin\beta} g_{ffH}^{\text{SM}}$	

NMSSM Higgs Boson Mass

- **Status of higher order corrections:**
  - Real NMSSM:
    - ◇ leading one-loop [Ellwanger;Elliott eal; Pandita;Ellwanger,Hugonie]
    - ◇ full one-loop in $\overline{\text{DR}}$ scheme [Degrassi,Slavich;Staub eal]
    - ◇ full one-loop in mixed $\overline{\text{DR}}$-OS scheme [Ender(→Walz),Graf,MMM,Rzehak]
    - ◇ $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ $\overline{\text{DR}}$ w/ zero external momentum [Degrassi,Slavich]
    - ◇ first results beyond this [Goodsell eal]
  - Complex NMSSM:
    - ◇ various one-loop contributions in effective potential approach [Ham,Kim,Oh,Son;Ham,Oh,Son;Ham,Jeong,Oh;Funakubo,Tao;Ham,Kim,Oh,Son]
    - ◇ full one-loop & leading two-loop in effective potential approach [Cheung,Hou,Lee,Senaha]
    - ◇ full one-loop in diagrammatic approach [Graf,Gröber,MMM,Rzehak,Walz]
    - ◇ $\mathcal{O}(\alpha_t\alpha_s)$ mixed $\overline{\text{DR}}$-OS scheme w/ zero external momentum [MMM,Nhung,Rzehak,Walz]

$\mathcal{I}$mpact on $\mathcal{H}$iggs $\mathcal{C}$ouplings

MMM,Nhung,Rzehak,Walz '14

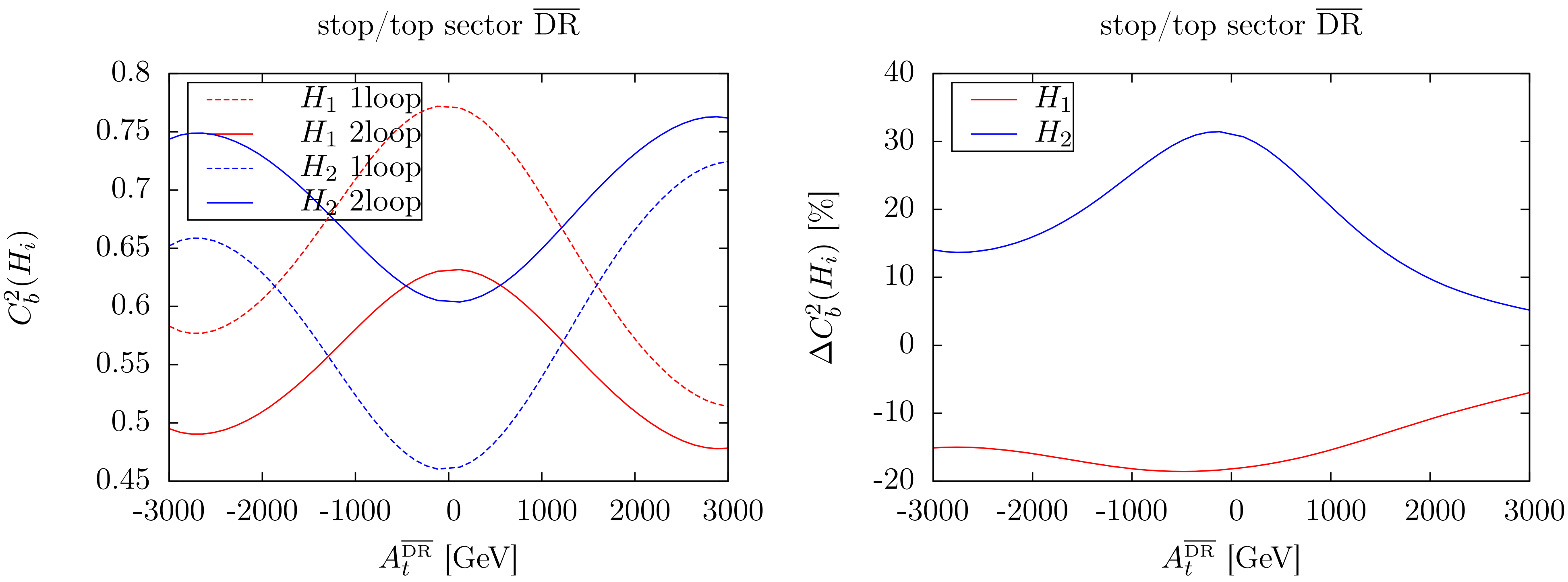


$* \; C_V(H_i) = \mathcal{R}^l_{i1}\cos\beta + \mathcal{R}^l_{i2}\sin\beta$

$* \; \Delta C_V^2 = [(C_V^2)^{\rm 2loop} - (C_V^2)^{\rm 1loop}]/(C_V^2)^{\rm 1loop}$

$\mathcal{I}$mpact on $\mathcal{H}$iggs $\mathcal{C}$ouplings

MMM,Nhung,Rzehak,Walz '14

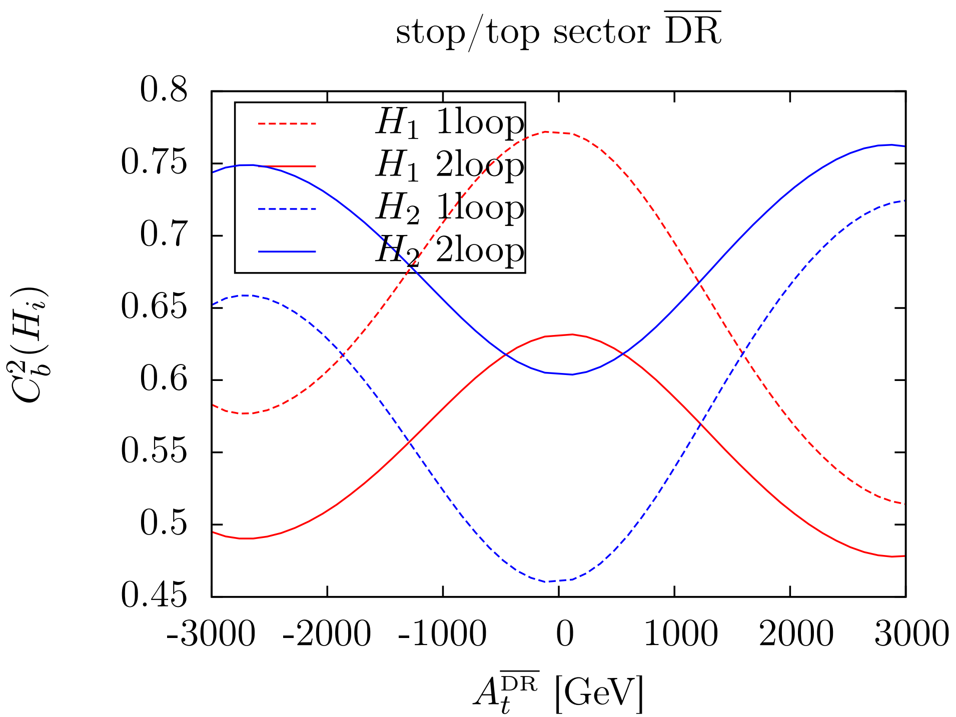


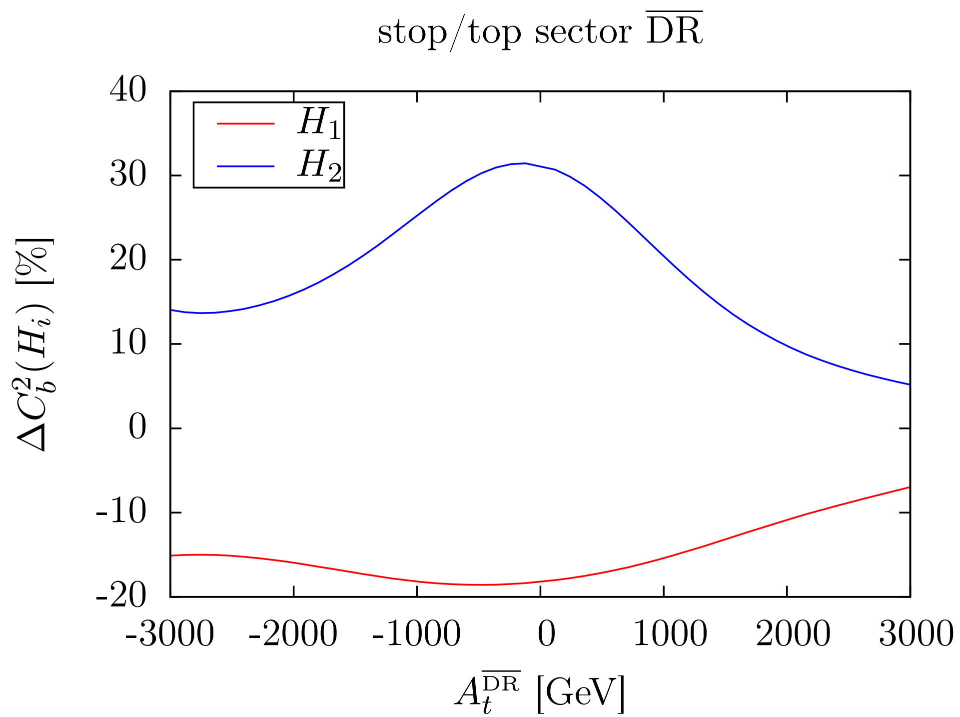
$*$ $C_b(H_i) = \mathcal{R}^l_{i1}/\cos\beta$

$*$ $\Delta C_b^2 = [(C_b^2)^{\text{2loop}} - (C_b^2)^{\text{1loop}}]/(C_b^2)^{\text{1loop}}$

$\mathcal{I}$mpact on $\mathcal{H}$iggs $\mathcal{C}$ouplings

MMM,Nhung,Rzehak,Walz '14





Influence of 2-loop corrections on couplings sizeable

$\rightsquigarrow$ significant effects on phenomenology

$\mathcal{C}$P-$\mathcal{V}$iolating $\mathcal{C}$ouplings

$\mathcal{CP}$ $\mathcal{V}$iolation in the $\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{S}$ector

- **Possibility of CP violation in the tree-level Higgs sector**

- **Several sources of CP violation:**
  * CP-violating parameters $\lambda, \kappa, A_\lambda, A_\kappa$
  * CP-violating vacuum expectation values $v_s e^{i\varphi_s}$, $v_u e^{i\varphi_u}$

- **Only one possible phase combination at tree level**

$$\varphi_2 - \varphi_1 \quad \text{with} \quad \begin{array}{rcl} \varphi_1 & = & \varphi_\lambda + \varphi_s + \varphi_u \\ \varphi_2 & = & \varphi_\kappa + 3\varphi_s \end{array}$$

[after exploiting the tadpole conditions]

- **At higher order in Higgs masses:** φ_1 and φ_2 not related any more
  * φ_1 and φ_2 independent in neutralino sector, φ_1 in chargino and up-type squark sector
  * $\rightsquigarrow$ φ_1 and φ_2 independent phases

$\mathcal{C}$onstraints from $\mathcal{EDM}$s

- **Included constraints on CP-violating phases from:** [King,MMM,Nevzorov,Walz,1508.03255]

Electron EDM	:	$\sim 1 \cdot 10^{-28} e\,\text{cm}$
Thallium EDM	:	$\sim 9 \cdot 10^{-25} e\,\text{cm}$
Neutron EDM	:	$\sim 3 \cdot 10^{-26} e\,\text{cm}$
Mercury EDM	:	$\sim 3.1 \cdot 10^{-29} e\,\text{cm}$,

- **Most stringent constraint from:** electron EDM
- **Computation of EDMs in the NMSSM** implemented in `NMSSMCALC`

  [Baglio,Gröber,MMM,Nhung,Rzehak,Spira,Streicher,Walz; King,MMM,Nevzorov,Walz] http://www.itp.kit.edu/∼maggie/NMSSMCALC

NMSSMCALC
Calculator of One-Loop and O(alpha_t alpha_s) Two-Loop Higgs Mass Corrections and of Higgs Decay Widths in the CP-conserving and the CP-violating NMSSM
Now with the computation of the EDMs in the complex NMSSM

The program package NMSSMCALC calculates the one-loop and O(alpha_t alpha_s) corrected Higgs boson masses and the Higgs decay widths and branching ratios within the CP-conserving and the CP-violating NMSSM.
The decay calculator is based on an extension of the program HDECAY 6.10 now.

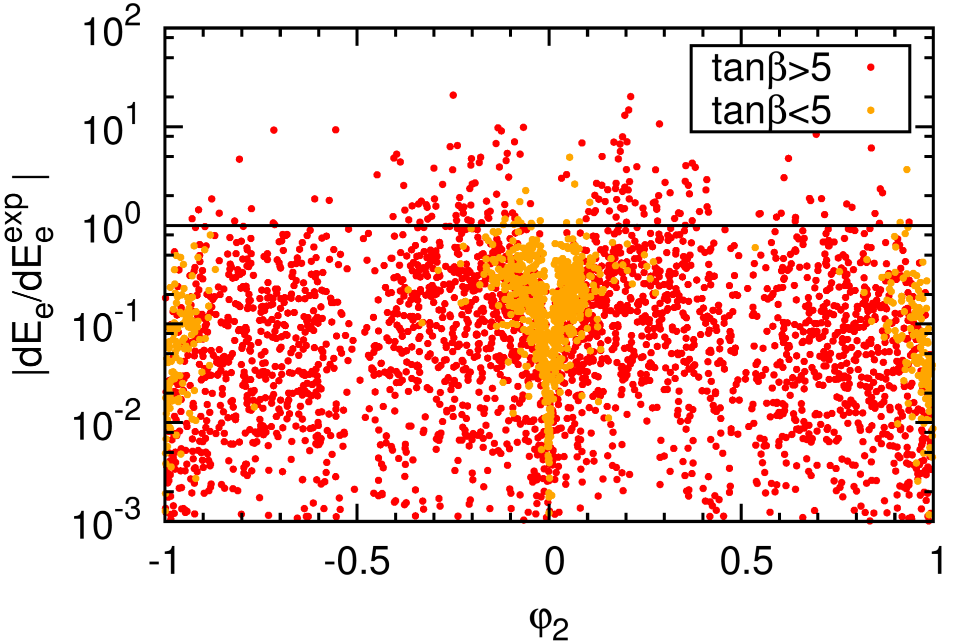
Released by: Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz
Program: NMSSMCALC version 2.00 NEW! Computation of the EDMs in the complex NMSSM

When you use this program, please cite the following references:

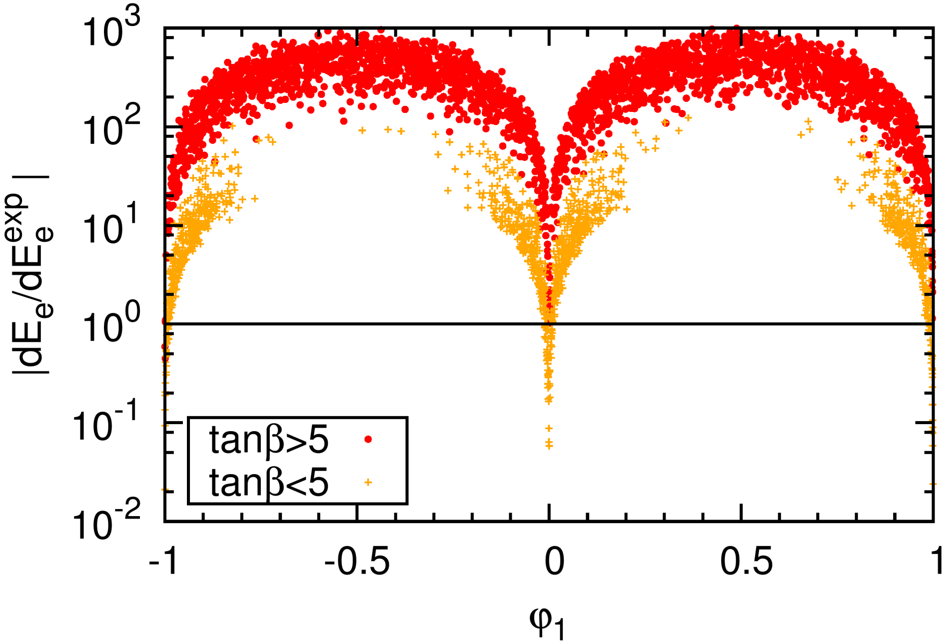
NMSSMCALC:	Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz, in Comput. Phys. Commun. 185 (2014) 12
One-Loop Masses:	K. Ender, T. Graf, M. Mühlleitner, H. Rzehak, in Phys. Rev. D85 (2012)075024
	T. Graf, R. Gröber, M. Mühlleitner, H. Rzehak, K. Walz, in JHEP 1210 (2012) 122
O(alpha_t alpha_s) Mass Corrections:	M. Mühlleitner, D.T. Nhung, H. Rzehak, K. Walz, in JHEP 1505 (2015) 128
Computation of the EDMs in the cNMSSM:	S.F. King, M. Mühlleitner, R. Nevzorov, K. Walz, in arXiv:1508.03255
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Constraints from $\mathcal{EDM}$s

[King,MMM,Nevzorov,Walz,1508.03255]



'NMSSM-type CP violation'



'NMSSM-type and MSSM-type CP violation'

Remember: $\varphi_1 = \varphi_\lambda + \varphi_s + \varphi_u$
$\varphi_2 = \varphi_\kappa + 3\varphi_s$

$\mathcal{CP}$ $\mathcal{V}$iolation in $\tau^+\tau^-$ $\mathcal{D}$ecays

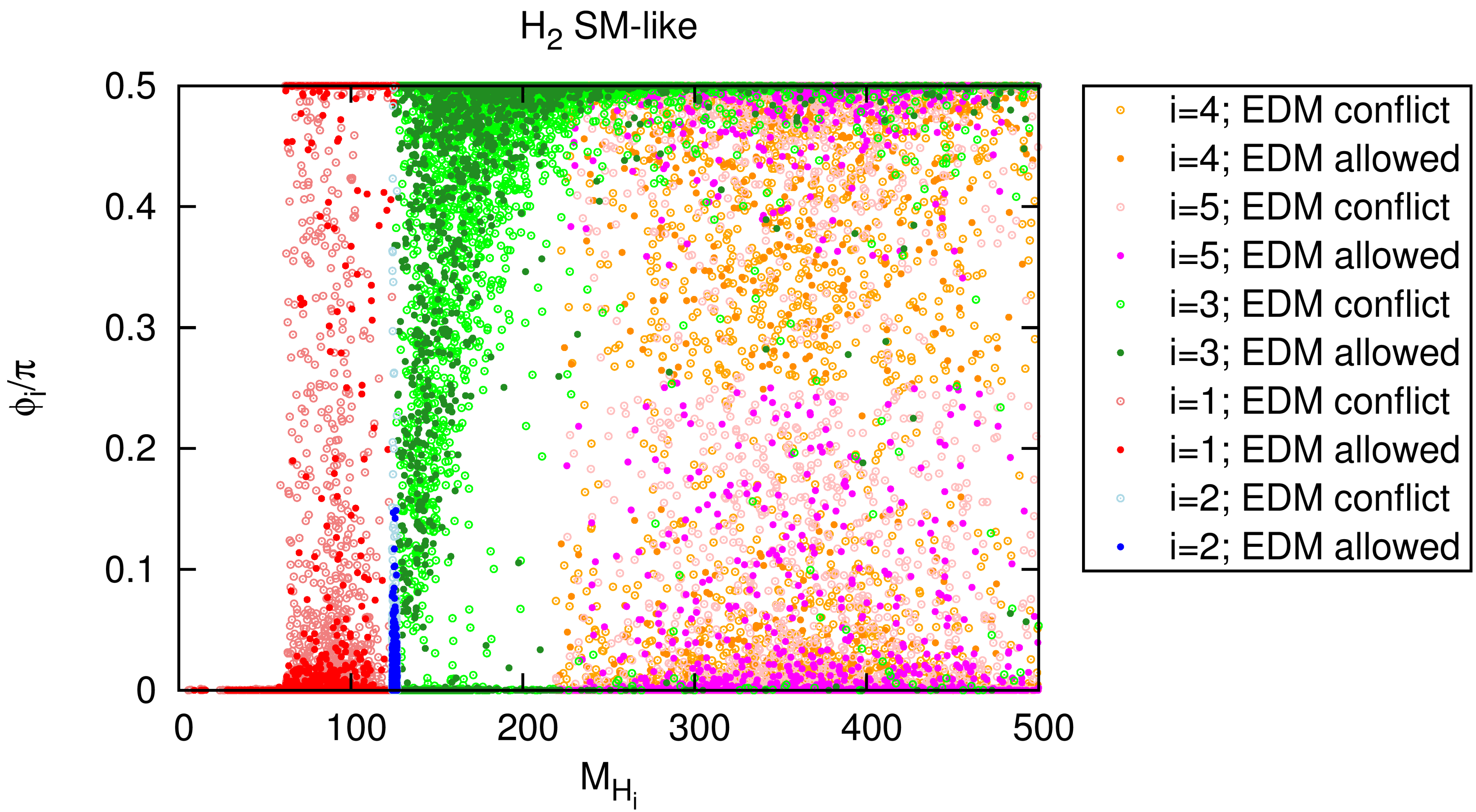
- **CP-violating Higgs coupling to tau's** [Berge,Bernreuther,Kirchner; Berge,Bernreuther,Spiesberger]

$$\mathcal{L}_{H_i\tau\tau} = -\frac{m_\tau}{v}\,\tau^+\left(c_\tau^S + i c_\tau^P \gamma_5\right)\tau^- H_i$$

$$= -\frac{m_\tau}{v}\sqrt{(c_\tau^S)^2 + (c_\tau^P)^2}\;\tau^+\left(\cos\phi_i + i\sin\phi_i\,\gamma_5\right)\tau^- H_i \qquad \text{with } \tan\phi_i = \frac{c_\tau^P}{c_\tau^S}$$

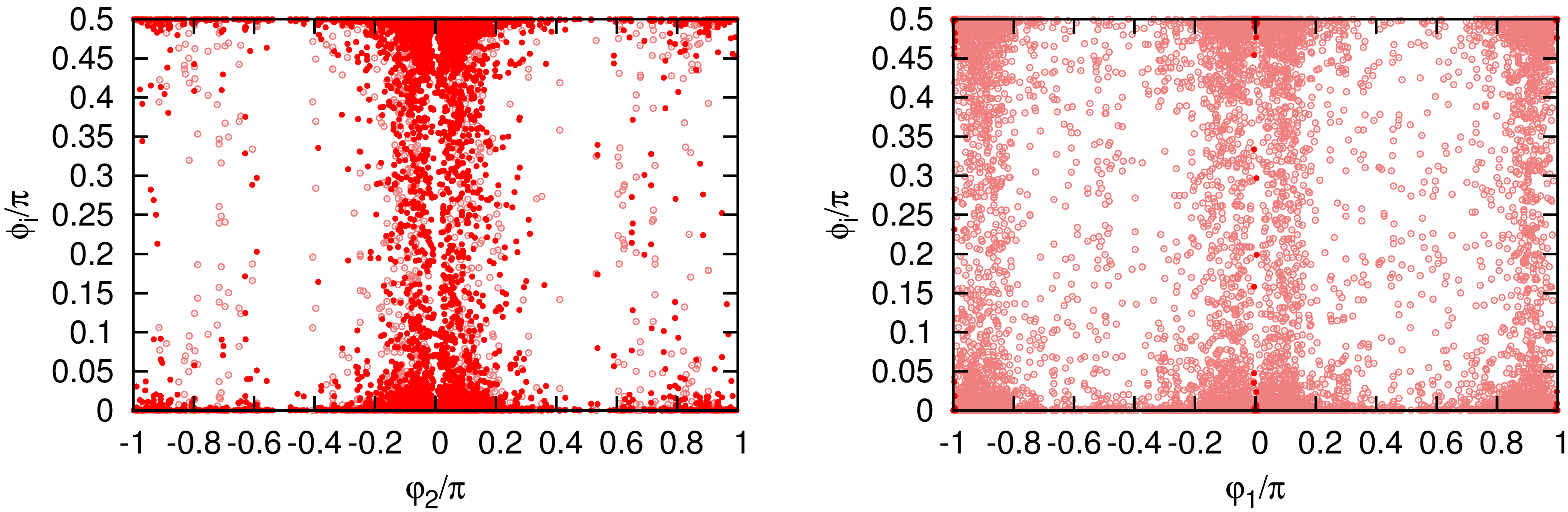
$\mathcal{CP}$ Violation in $\tau^+\tau^-$ Decays

[King,MMM,Nevzorov,Walz,1508.03255]



$\mathcal{CP}$ $\mathcal{V}$iolation in $\tau^+\tau^-$ $\mathcal{D}$ecays

[King,MMM,Nevzorov,Walz,1508.03255]



Expected Accuracy at the LHC: [Berge,Bernreuther,Kirchner]

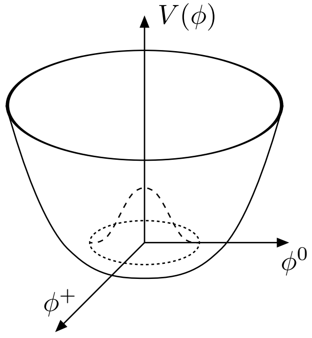
$\sqrt{s} = 14$ TeV, $\int \mathcal{L} = 150$ fb^{-1}, 500 fb^{-1}, 3 ab^{-1}: $\Delta\Phi_\tau = 27°, 14.3°, 5.1°$

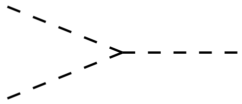
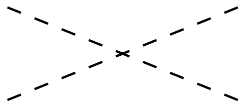
Higgs Self-Couplings

$\mathcal{I}$mportance of $\mathcal{D}$etermination of the $\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{S}$elf-$\mathcal{C}$ouplings

The EWSB potential:

$$V(H) = \frac{1}{2!}\lambda_{HH}H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4$$



$\mathcal{T}$rilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
$\mathcal{Q}$uartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

$\mathcal{M}$easurement of the scalar boson self-couplings
and
$\mathcal{R}$econstruction of the EWSB potential
} $\mathcal{E}$xperimental verification $\mathcal{O}$f the scalar sector of the $\mathcal{E}$WSB mechanism

Determination of the scalar boson self-couplings at colliders:

$\boldsymbol{\lambda_{HHH}}$ via pair production
$\boldsymbol{\lambda_{HHHH}}$ via triple production

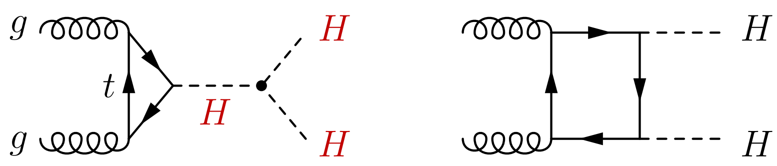
radiation off W/Z, WW/ZZ fusion, gg fusion

$\mathcal{T}$he $\mathcal{T}$rilinear $\mathcal{S}$elf-$\mathcal{C}$oupling at the $\mathcal{LHC}$ - Example SM

Determination of λ_{HHH} at the LHC

double radiation of W/Z:	$q\bar{q}$	$\longrightarrow$	$W/Z + HH$	Barger,Han,Phillips
WW/ZZ fusion:	qq	$\longrightarrow$	$qq + HH$	Dicus,Kallianpur,Willenbrock Abbasabadi,Repko,Dicus,Vega Dobrovolskaya,Novikov Eboli,Marques,Novaes,Natale
gluon gluon fusion:	gg	$\longrightarrow$	HH	Glover,van der Bij Plehn,Spira,Zerwas Dawson,Dittmaier,Spira

gluon gluon fusion - dominant process



$\mathcal{L}$oop $\mathcal{C}$orrected $\mathcal{T}$rilinear $\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling

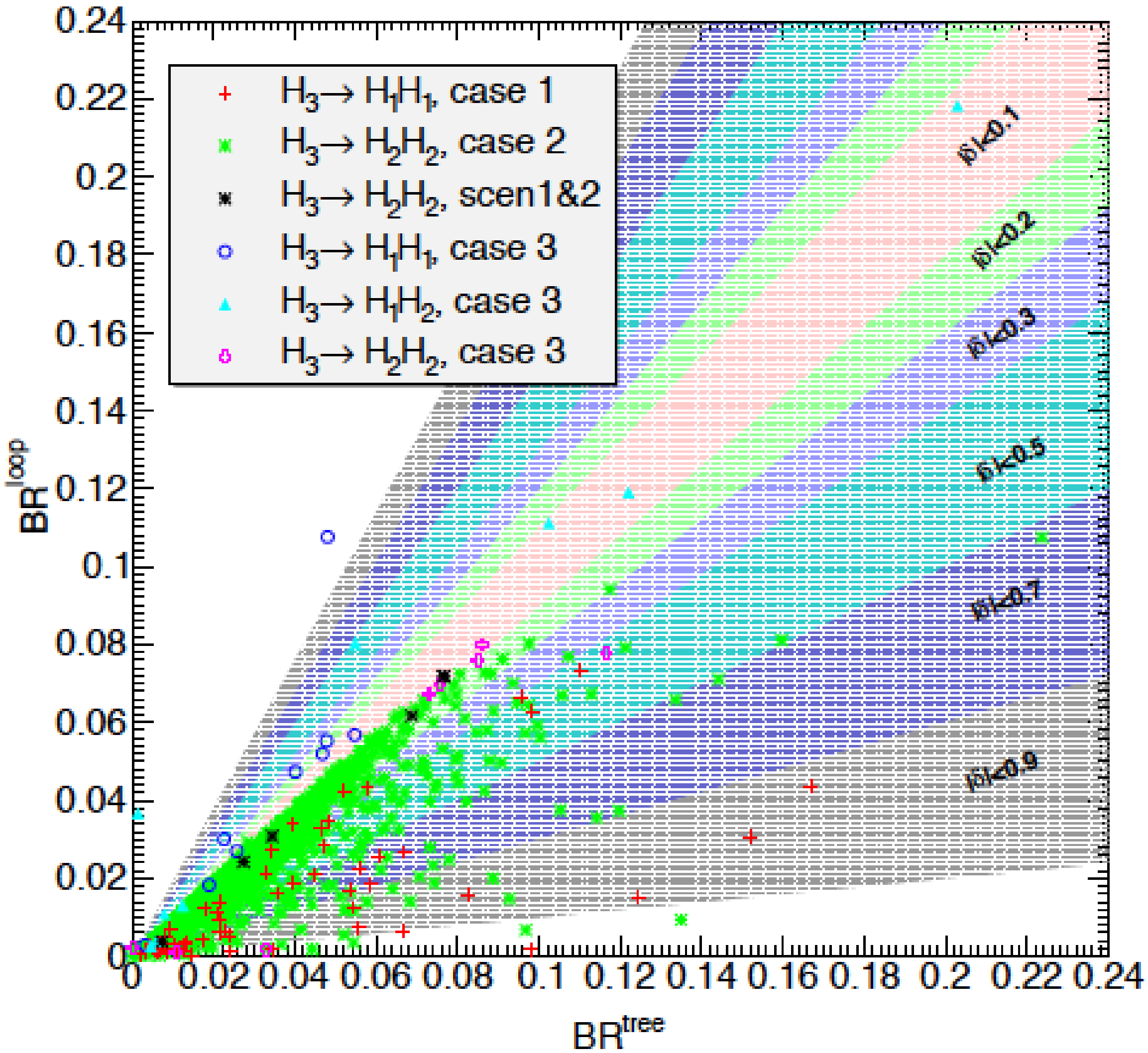
- **Higgs mass and self-couplings:** determined from Higgs potential $\rightsquigarrow$ consistent description of Higgs sector at higher order requires loop corrections to masses and self-couplings

$\Rightarrow$ determination of higher order corrections to trilinear Higgs self-couplings

$*$ one-loop corrections in real NMSSM [Dao,MMM,Streicher,Walz '13]

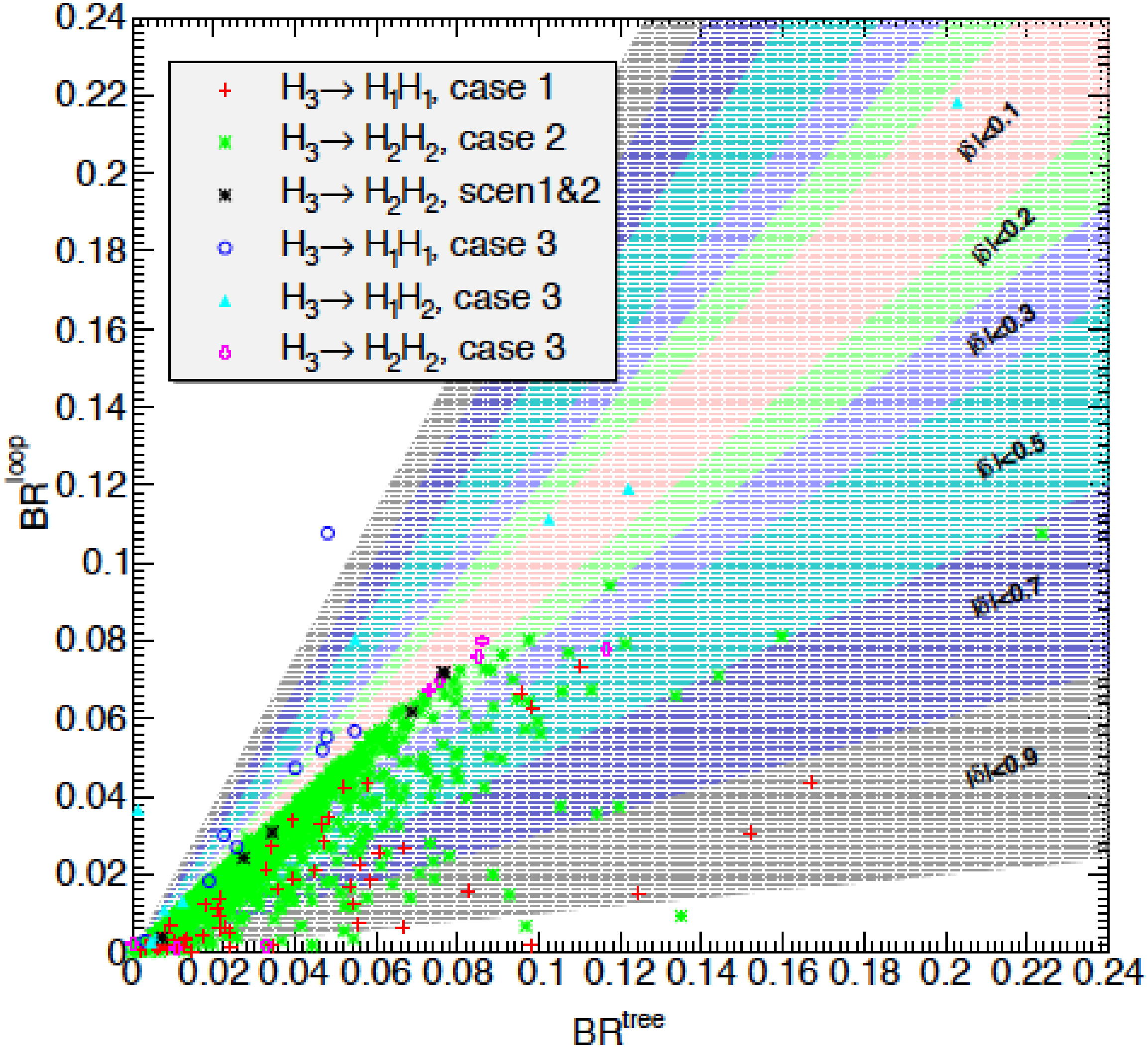
$*$ two-loop corrections in complex NMSSM [MMM,Nhung Dao,Ziesche '15]

Dao,MMM,Streicher,Walz '13



$$\delta \equiv \frac{BR^{loop} - BR^{tree}}{BR^{tree}}$$

Dao,MMM,Streicher,Walz '13

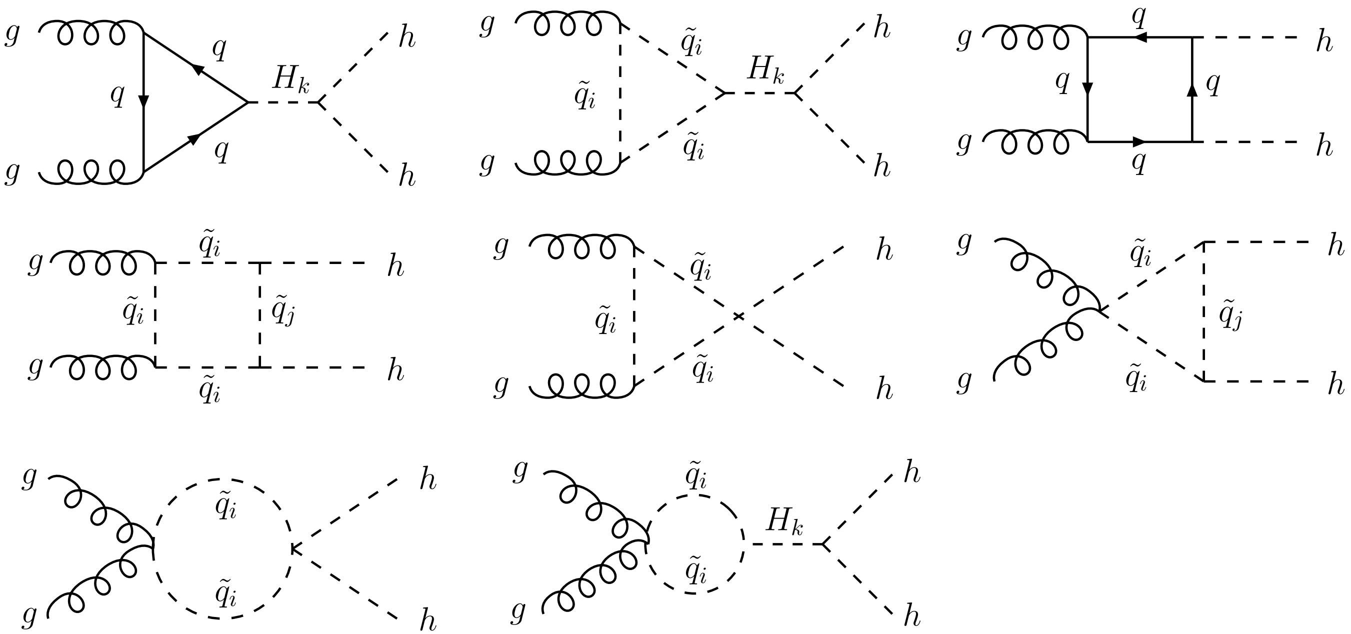


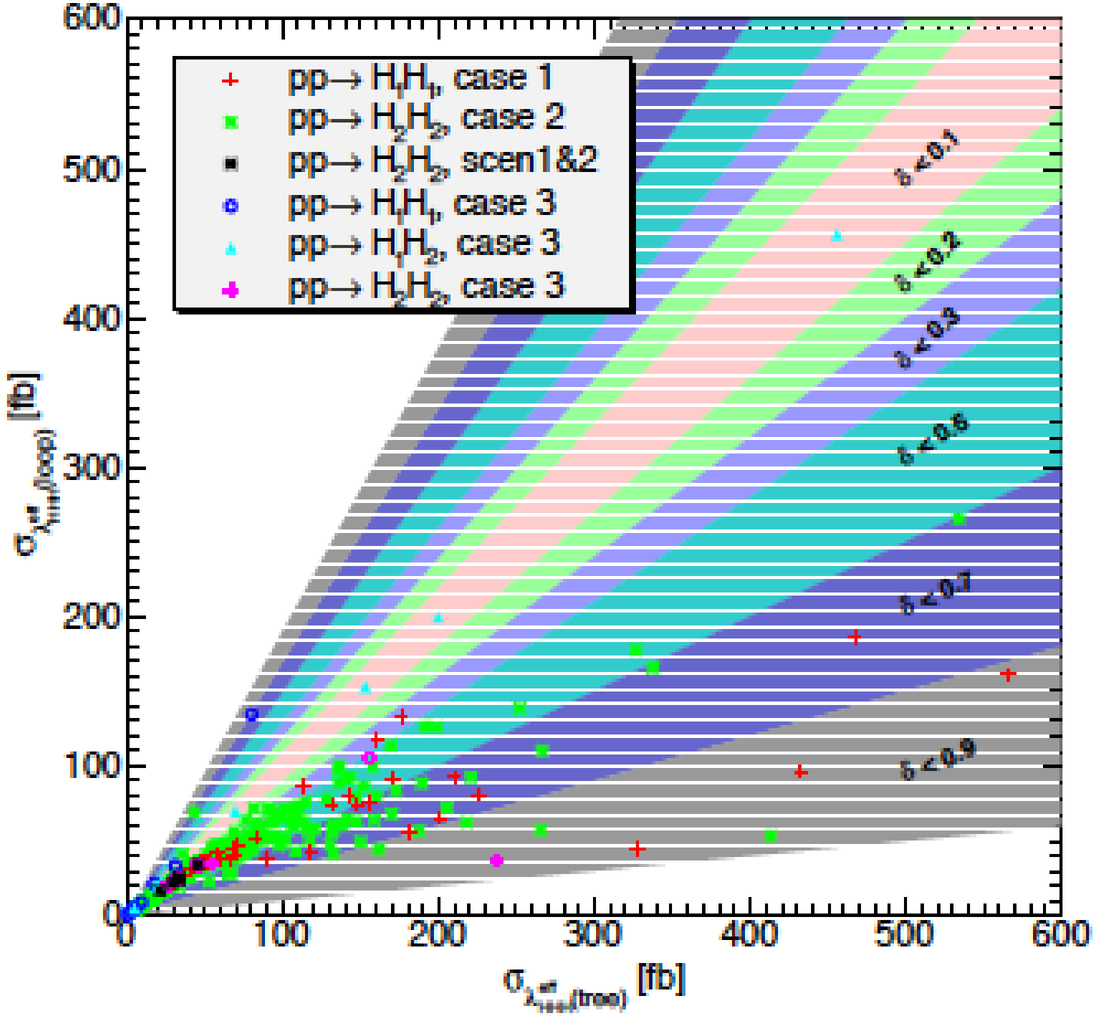
* Effect of higher order corrections on branching ratios can be up to 90% and higher
* Black points: excluded if only tree-level BR considered

$\mathcal{I}$mpact of $\mathcal{L}$oop $\mathcal{C}$orrected $\lambda_{\phi_i\phi_j\phi_k}$ on $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction

- **Dominant process at LHC:** $gg \to \phi_i\phi_k$ Dao,MMM,Streicher,Walz '13

  $\phi_i, \phi_k = 1, ..., 5$

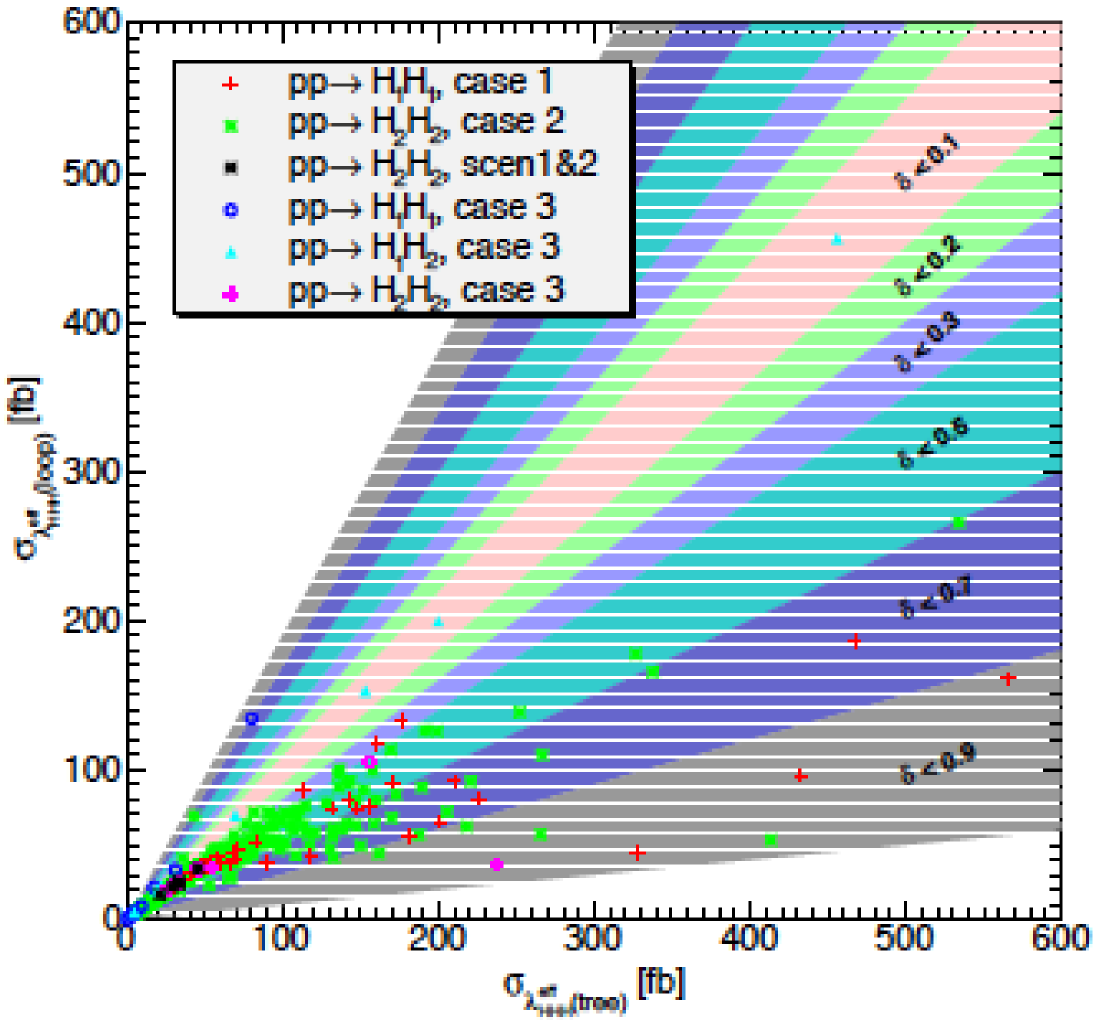




Loop corrected Higgs pair production cross section σ_L versus tree-level σ_T

$$\delta \equiv \frac{\sigma_L - \sigma_T}{\sigma_T}$$

Dao,MMM,Streicher,Walz ’13



Large deviations (up to 90%) due to large deviations between tree-level and loop-corrected $BR(H_3 \to hh)$.

$\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{C}$ouplings

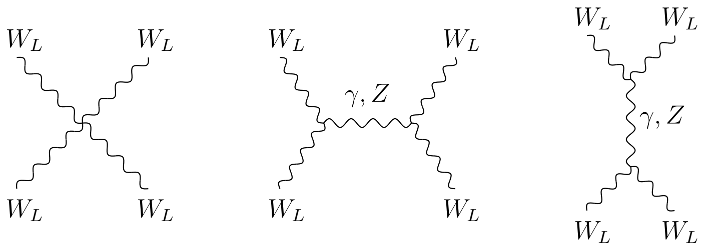
$\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{C}$ouplings - $\mathcal{P}$henomenological $\mathcal{I}$mplications

▷ Modified Higgs couplings to SM gauge bosons and fermions

- Unitarity not restored any more in $V_L V_L$ scattering

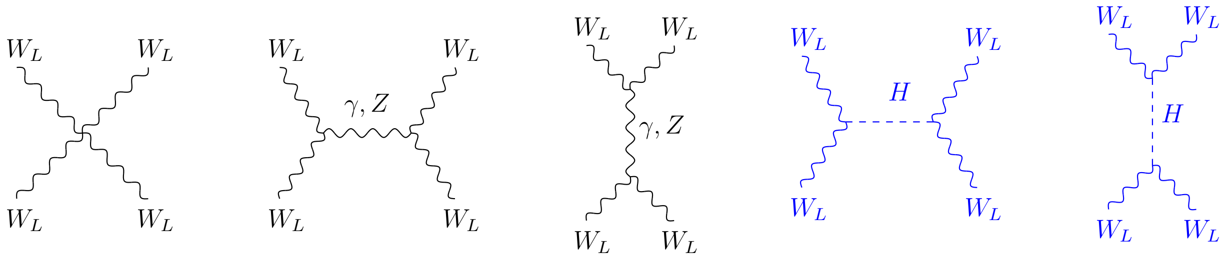
$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{s}{v^2}$$

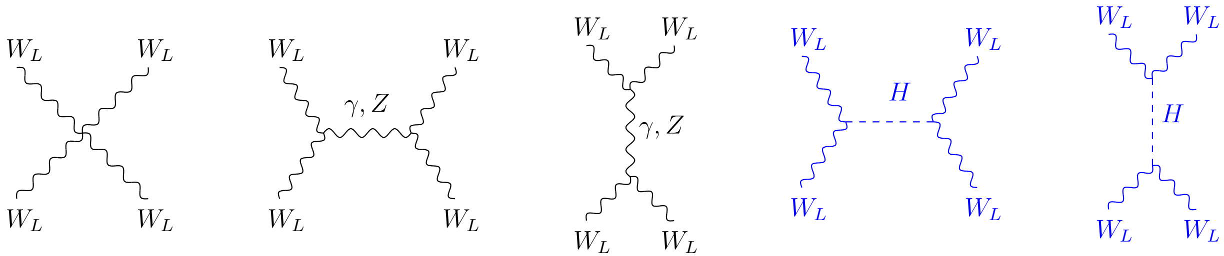
- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{\kappa_V^2 s^2}{s-m_h^2}\right)$$

$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{\kappa_V^2 s^2}{s - m_h^2}\right)$$

$\kappa_V = 1$ perturbative unitarity in $WW \to WW$

- **Higgs couplings deviate from SM couplings** $\Rightarrow$ $VV \to VV$ and $VV \to hh$ grow with E^2

Giudice,Grojean,Pomarol,Rattazzi; Contino eal '10,'13

$\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{C}$ouplings - $\mathcal{P}$henomenological $\mathcal{I}$mplications

▷ Modified Higgs couplings to SM gauge bosons and fermions

- Unitarity not restored any more in $V_L V_L$ — Giudice eal; Contino eal '10,'13
- Higgs production and decay rates changed — Espinosa,Grojean,MMM
- Influences compatibility with EWPT — Giudice eal; Barbieri eal; Contino; Agashe eal; Gillioz; Lavoura,Silva; Lodone; Anastasiou eal; Grojean eal; Gröber eal

▷ New couplings

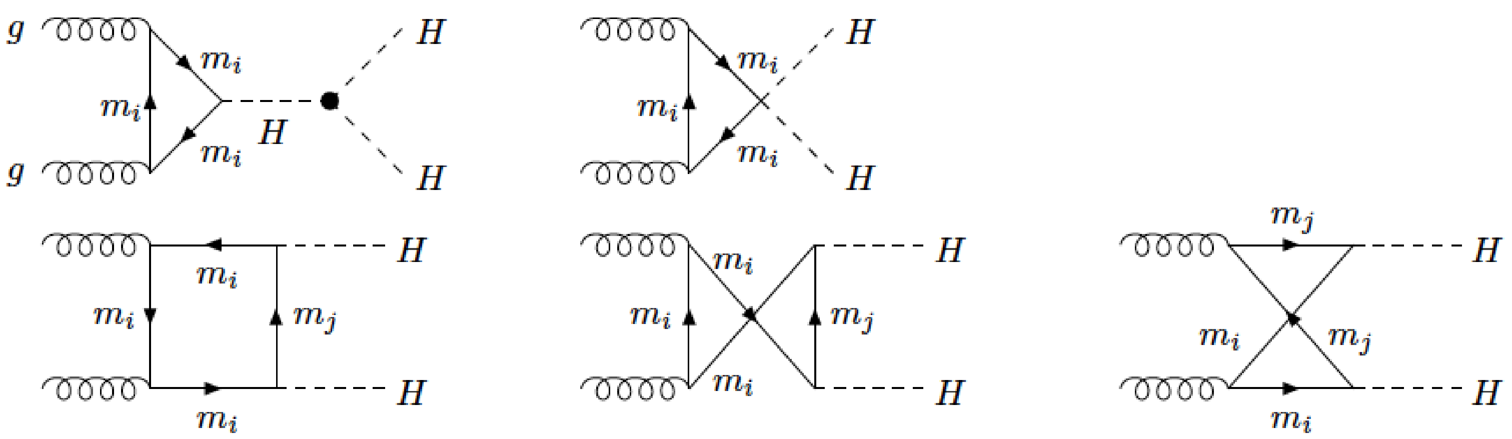
- Compatibility with Flavour Constraints — Agashe,Perez,Soni; Csaki eal; Blanke eal; Bauer eal; Redi,Weiler; Keren-Zur eal; Barbieri eal; Redi; Vignaroli; Da Rold eal; Delaunay eal
- Influences Double Higgs Production — Gröber,MMM; Contino eal; Gillioz eal

$\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{I}$mplications on $\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction

- **Double Higgs production through gluon fusion:**

  ∗ sensitive to trilinear Higgs self-coupling — Baur,Glover; Spira eal; Djouadi,Kilian,MMM,Zerwas;Gröber,MMM

  ∗ access to anomalous $HHf\bar{f}$ coupling — Contino eal '12



▷ Can be enhanced compared to the SM process

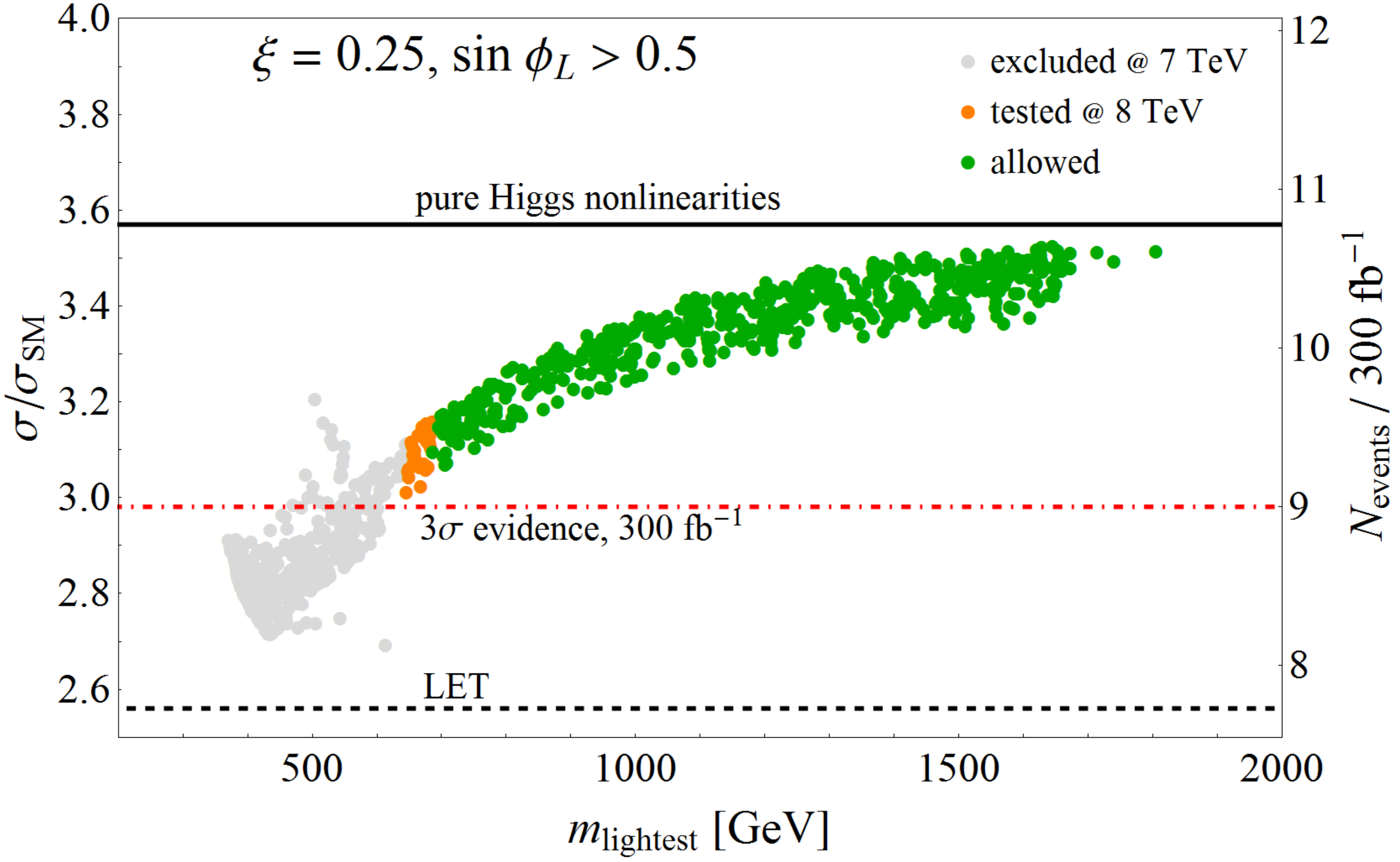
▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

▷ Different fermions can contribute within one loop

▷ Sensitivity to details of heavy composite sector?

$\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction in $\mathcal{MCHM}$5 w/ $\mathcal{T}$op $\mathcal{P}$artners

Gillioz,Gröber,Grojean,MMM,Salvioni



only top; partners

⟵ integrated out

top and partners

⟵ integrated out

Summary

- **Higgs Discovery**
  - ∗ Higgs Signal compatible with SM-like Higgs Boson
  - ∗ Interpretation within numerous BSM physics models possible
- **Effective Lagrangian Approach $\leftrightarrow$ Specific Models**
  - ∗ EFT covers a large class of models
  - ∗ Has to be complemented by investigations in specific models
- **NMSSM**
  - ∗ 2-loop corrections to Higgs couplings and self-couplings are sizeable
  - ∗ Large tree-level CP violation in couplings is possible
- **Composite Higgs Models**
  - ∗ Perturbative unitarity in VV scattering violated
  - ∗ Higgs pair production cxn can be enhanced wrt SM

Thank You For Your Attention!

$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections $\mathcal{E}$ffects on $\mathcal{C}$ouplings

- **Mass eigenstates (CP-violating):** at loop level

$$\underbrace{(H_1, H_2, H_3, H_4, H_5, G)^T}_{\text{mass eigenstates}} = \underbrace{\mathcal{R}_{ij}^{(l)}}_{\text{mixing matrix}} \underbrace{(h_d, h_u, h_s, A, a_s, G)^T}_{\Phi^T\text{,interaction eigen.}}$$

- **Mass matrix:** at loop level

$$\mathcal{D}_H^{(l)} = \text{diag}\left((M_{H_1}^{(l)})^2, ..., (M_{H_5}^{(l)})^2, 0\right) = \mathcal{R}^{(l)}\, M_{\Phi\Phi}^{(l)}\, \mathcal{R}^{(l),T}$$

- **Loop-corrected mass matrix:**

$$\left(M_{\Phi\Phi}^{(l)}\right)_{ij} = \mathcal{D}_H^{(0)} - \Sigma_{ij}^{(l)} + \frac{1}{2}\left[\mathcal{R}^{(0)}\,(\delta^{(l)}\mathcal{Z}^\dagger\, M_{\Phi\Phi}^{(0)} + M_{\Phi\Phi}^{(0)}\,\delta^{(l)}\mathcal{Z})\,\mathcal{R}^{(0),T}\right]_{ij} + \left[\mathcal{R}^{(0)}\,\delta^{(l)} M_{\Phi\Phi}\,\mathcal{R}^{(0),T}\right]_{ij}$$

Σ: self-energy, $\delta\mathcal{Z}$: wave-function renormalization, δM: mass counterterm, ext. mom. $p^2 = 0$

$\mathcal{C}$oupling $\mathcal{A}$ccuracies

Englert eal

coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—	0.008	0.004	0.004

* accuracy at 68% CL; deviations: $g = g_{\text{SM}}[1 \pm \Delta]$
* LHC/HL-LHC: $\int \mathcal{L} = 300$ fb^{-1} and 3000 fb^{-1}
* LC/HL-LC: 250+500 GeV/250+500 GeV+1 TeV, $\int\mathcal{L} = 250 + 500$ fb^{-1}/1150+1600+2500 fb^{-1}

$\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales (loop, coupling factors factored out)

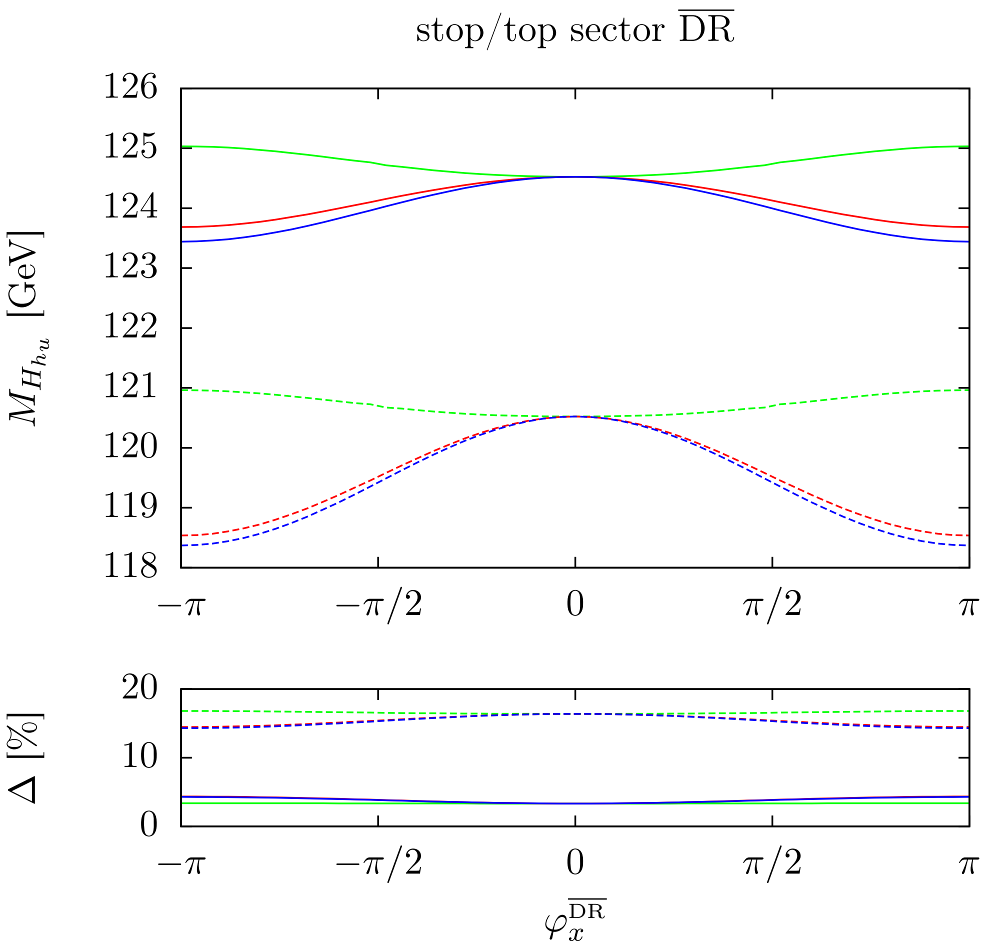
- **Effective New Physics scales Λ_*** extracted from coupling measurements

Λ_* [TeV]	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.82	0.87	2.35	3.18	3.48
hZZ	0.74	0.87	2.75	3.48	3.89
htt	0.45	0.50	0.87	1.34	1.42
hbb	0.39	0.44	1.15	1.59	1.66
$h\tau\tau$	0.52	0.58	0.96	1.34	1.42
hgg	0.55	1.07	1.30	1.80	1.95
$h\gamma\gamma$	0.15	0.18	0.24	0.36	0.44

Loop-induced couplings to gluons and photons contain only the contribution of the contact terms

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass 2-$\mathcal{L}$oop $\mathcal{C}$orrections

MMM,Nhung,Rzehak,Walz '14



$m_t^{pole} = 173.5$ GeV

$m_t^{\overline{\text{DR}}} = 143.14$ GeV at $Q = 1.25$ TeV

dashed: one-loop, full: two-loop

variation of φ_{A_t}, φ_{M_3}, φ_μ

$\varphi_\kappa = \varphi_u = 0$, $\varphi_\lambda = 2\varphi_s = 2/3\varphi_\mu \rightsquigarrow$ tree-level phase $\varphi_y = 0$

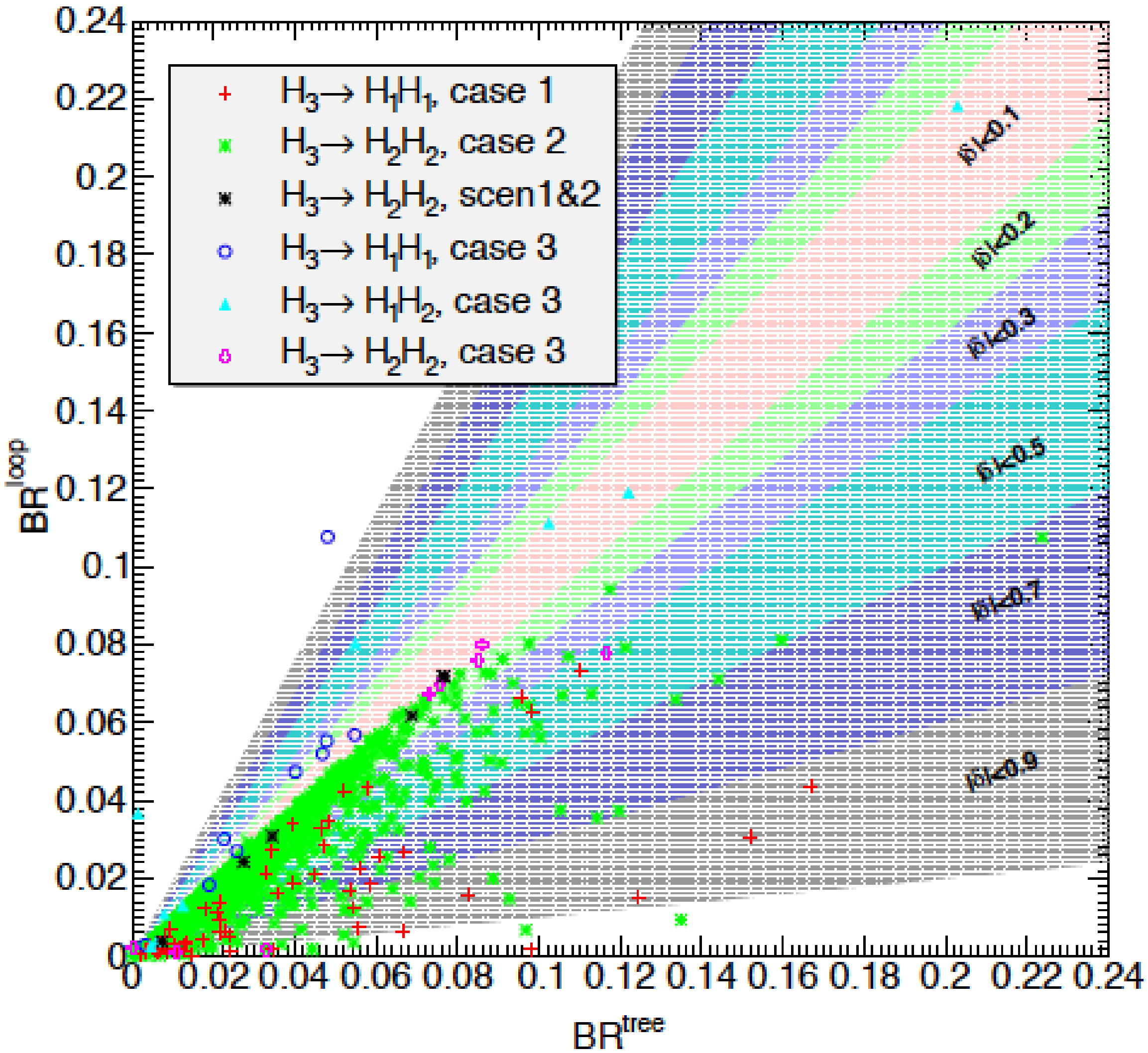
φ_{M_3} dependence at 1-loop $\leftarrow$ m_t conversion OS to $\overline{\text{DR}}$

$\Delta = |M_{H_{h_u}}^{(n)} - M_{H_{h_u}}^{(n-1)}|/M_{H_{h_u}}^{(n-1)}$

dashed: $n = 1$, solid: $n = 2$

difference in $\overline{\text{DR}}$ and OS masses:
one-loop: $\mathcal{O}(15 - 25\%)$
two-loop: $\mathcal{O}(\lesssim 1.5\%)$

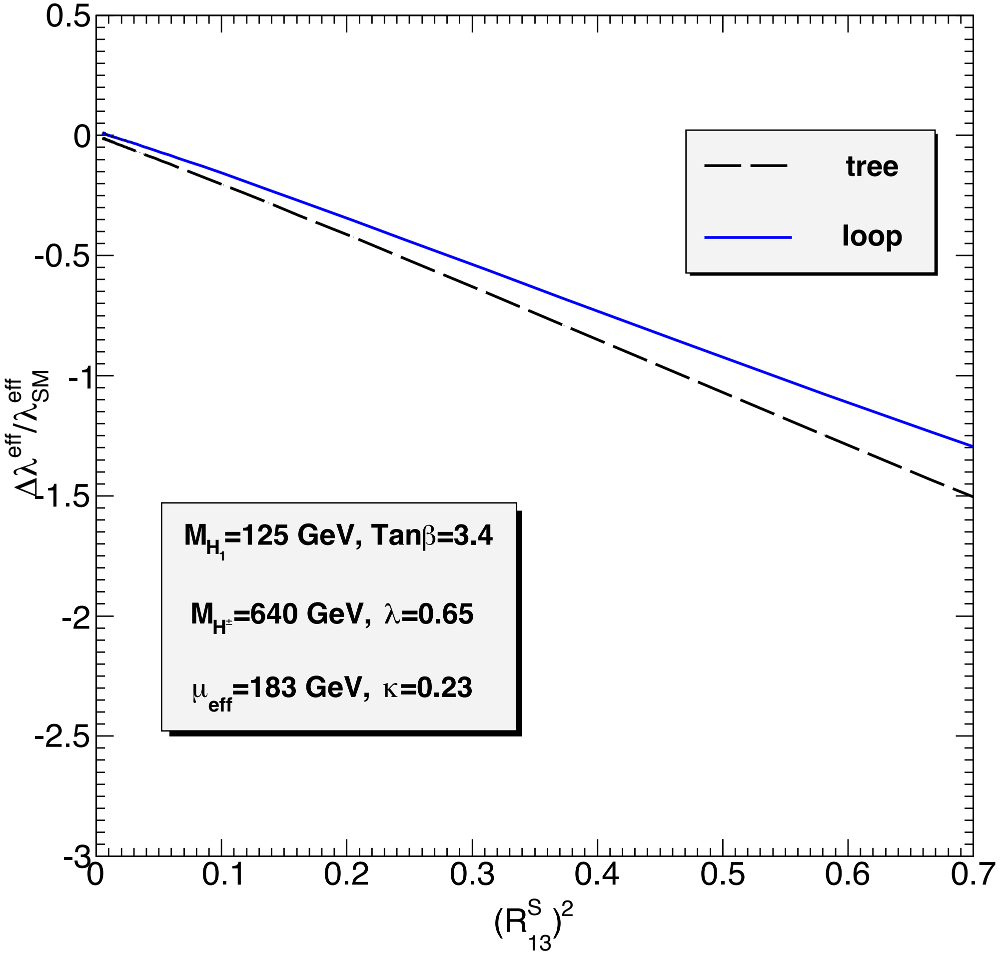
Dao,MMM,Streicher,Walz '13



$*$ H_3 decays into SM-like Higgs bosons h: $h = H_{1,2}$ (case 1,2); H_1, H_2 degenerate in mass (case 3)

$\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{T}$rilinear $\mathcal{N}$MSSM $\mathcal{C}$oupling - $\mathcal{S}$M $\mathcal{L}$imit

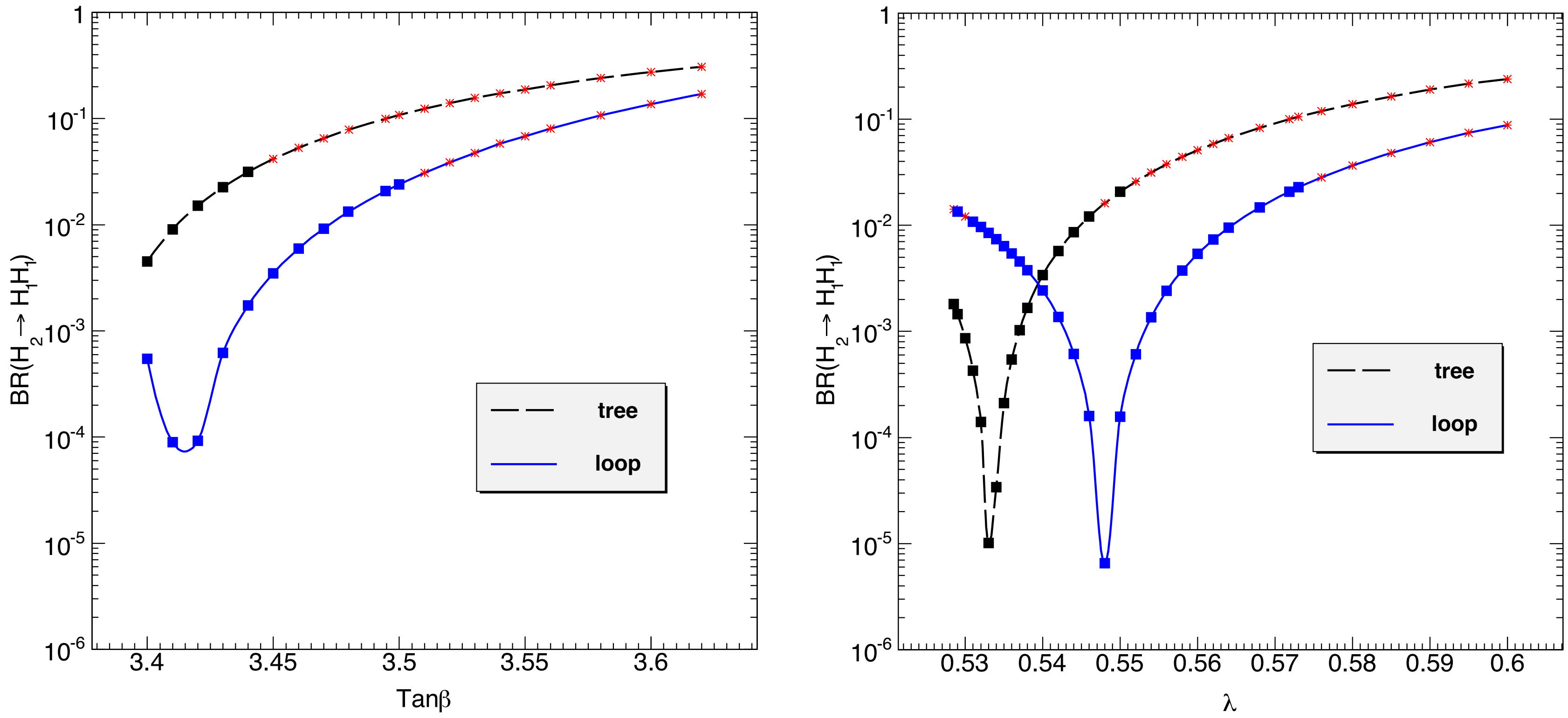
[Dao,MMM,Streicher,Walz]



$\Delta^{\text{eff}} = \lambda^{\text{eff}}_{hhh} - \lambda^{\text{eff}}_{\text{SM}}$ ($h \equiv H_1$ 125-GeV NMSSM Higgs); $(R^S_{13})^2$ (singlet admixture)^2 of H_1

$\mathcal{I}$mpact of $\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{S}$elf-$\mathcal{C}$oupling on ($\mathcal{N}$on-)$\mathcal{E}$xclusion

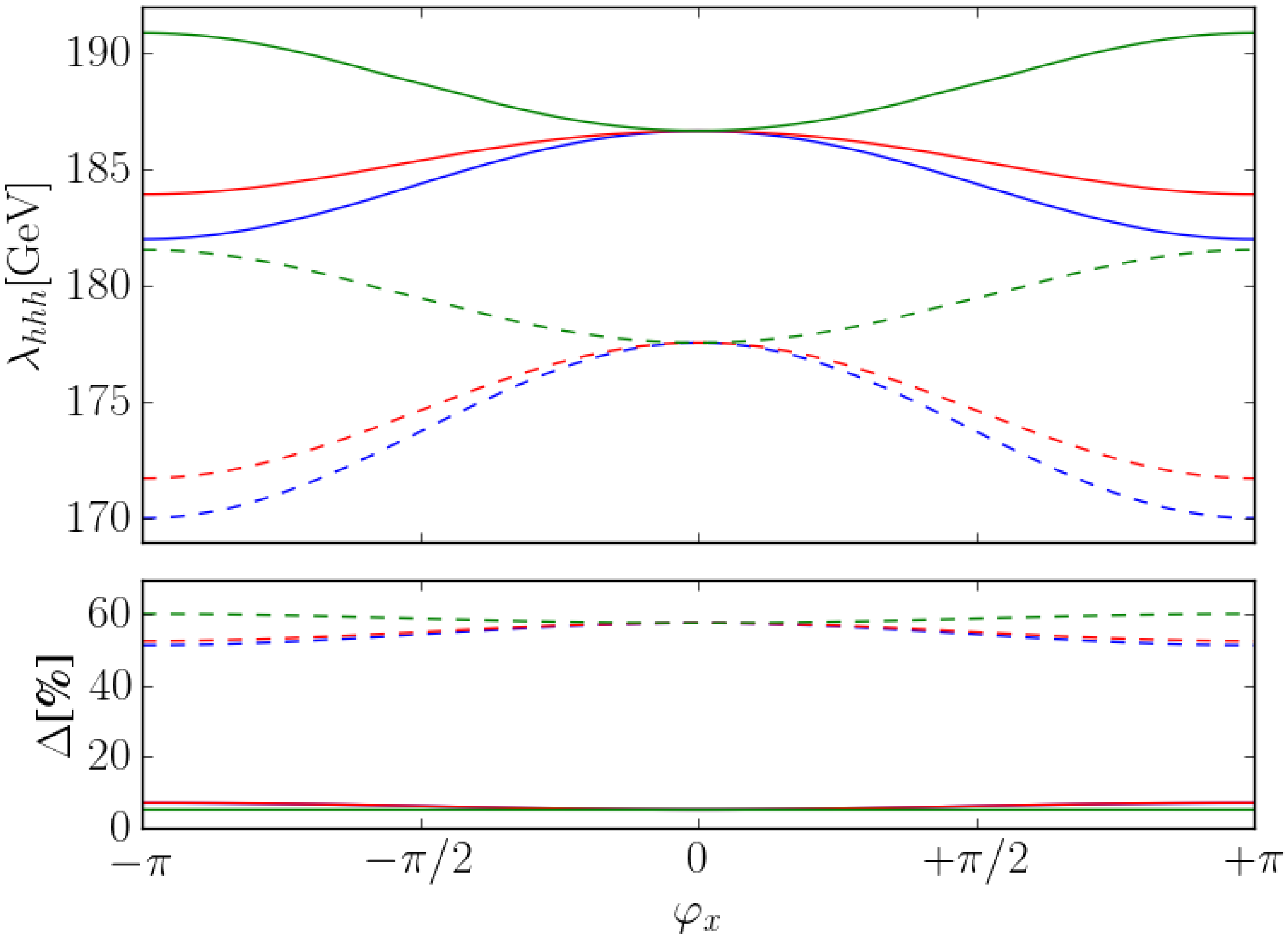
[Dao,MMM,Streicher,Walz]



$H_2 \equiv 125$ GeV Higgs; dashed - tree-level; full - loop-corrected; red - excluded

$\mathcal{T}$wo-$\mathcal{L}$oop $\mathcal{C}$orrected $\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$ouplings

MMM,Nhung Dao,Ziesche '15



dashed: 1-loop

full: 2-loop

φ_μ, φ_{A_t}, φ_{M_3}

$$\Delta = \frac{|\lambda^{(2)}_{hhh} - \lambda^{(1)}_{hhh}|}{\lambda^{(1)}_{hhh}}$$

$\mathcal{I}$nvestigation of $\mathcal{NMSSM}$ $\mathcal{D}$iscovery $\mathcal{P}$rospects - $\mathcal{S}$can

Mixing angle $\tan\beta$ and NMSSM couplings λ, κ:

$$1 \le \tan\beta \le 30 \;, \qquad 0 \le \lambda \le 0.7 \;, \qquad -0.7 \le \kappa \le 0.7$$

with perturbativity requirement

$$\sqrt{\lambda^2 + \kappa^2} \le 0.7$$

Soft SUSY breaking trilinear NMSSM couplings and μ_{eff}:

$$-2 \text{ TeV} \le A_\lambda \le 2 \text{ TeV} \;, \; -2 \text{ TeV} \le A_\kappa \le 2 \text{ TeV} \;, \; -1 \text{ TeV} \le \mu_{\text{eff}} \le 1 \text{ TeV}$$

Remaining Parameters:

$$-2 \text{ TeV} \le A_U, A_D, A_L \le 2 \text{ TeV}$$

$$600 \text{ GeV} \le M_{\tilde{t}_R} = M_{\tilde{Q}_3} \le 3 \text{ TeV} \;, \; 600 \text{ GeV} \le M_{\tilde{\tau}_R} = M_{\tilde{L}_3} \le 3 \text{ TeV} \;, \; M_{\tilde{b}_R} = 3 \text{ TeV}$$

$$M_{\tilde{u}_R,\tilde{c}_R} = M_{\tilde{d}_R,\tilde{s}_R} = M_{\tilde{Q}_{1,2}} = M_{\tilde{e}_R,\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 3 \text{ TeV}$$

$$100 \text{ GeV} \le M_1 \le 1 \text{ TeV} \;, \; 200 \text{ GeV} \le M_2 \le 1 \text{ TeV} \;, \; 1.3 \text{ TeV} \le M_3 \le 3 \text{ TeV}$$

$\mathcal{NMSSM}$ $\mathcal{S}$can

- **Conditions on the parameter scan:**

  * At least one CP-even Higgs boson $H_i \equiv h$ with: 124 GeV $\lesssim M_h \lesssim 127$ GeV
  * Compatibility with μ_{XX}^{exp} $(X = b, \tau, \gamma, W, Z)$: $|\mu_{XX}^{\text{scan}}(h) - \mu_{XX}^{\text{exp}}| \leq 2\sigma$
  * Relic density $\Omega_c h^2$ below PLANCK result $(\Omega_c h^2)^{\text{NMSSM}} \leq 0.1187 \pm 0.0017$ [PLANCK]

Constraints from low-energy observables, from LEP, Tevatron and LHC searches [NMSSMTools]

- **Signal can be superposition of two Higgs boson rates close in mass:** h **and** $\Phi = H_i, A_j$

$$\mu_{XX}(h) \equiv R_\sigma(h)\, R_{XX}^{BR}(h) \; + \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi)\, R_{XX}^{BR}(\Phi)\, F(M_h, M_\Phi, d_{XX})$$

δ : mass resolution in the respective XX final state

$F(M_h, M_\Phi, d_{XX})$: Gaussian weighting function

d_{XX}: experimental resolution of final state XX [NMSSMTools]

$\mathcal{E}$xperimental $\mathcal{S}$ignal $\mathcal{R}$ates

Based on: ATLAS-CONF-2013-034; CMS-PAS-HIG-13-005; combination à la Espinosa,MMM,Grojean,Trott

channel	best fit value	$2 \times 1\sigma$ error
$VH \to Vbb$	0.97	± 1.06
$H \to \tau\tau$	1.02	± 0.7
$H \to \gamma\gamma$	1.14	± 0.4
$H \to WW$	0.78	± 0.34
$H \to ZZ$	1.11	± 0.46

$\mathcal{P}$artial $\mathcal{C}$ompositeness

- **Partial Compositeness**

  Kaplan; Contino,Kramer,Son,Sundrum

  ◇ Elementary fermions couple linearly to heavy states of strong sector w/ same quantum numbers

$$\mathcal{L}_{pc} = -\Delta_L \bar{q}_L Q_R - \Delta_R \bar{T}_L t_R + h.c.$$

  ◇ Fermions acquire mass through mixing with new vector-like strong sector fermions

  ◇ Linear couplings violate $\mathcal{G}$ explicitly ⇝ Higgs potential induced

  ◇ Large top Yukawa couplings ⇝ top largely composite

  ◇ Light Higgs boson requires light top partners

  Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu; Pomarol,Riva

$\mathcal{D}$istinction of $\mathcal{M}$odels through $\mathcal{C}$ouplings

$\mathcal{NMSSM}$ $\mathcal{C}$oupling $\mathcal{M}$easurement - $\mathcal{D}$istinction of $\mathcal{M}$odels

- **What can we learn from coupling measurements?**

  Test coupling sum rules

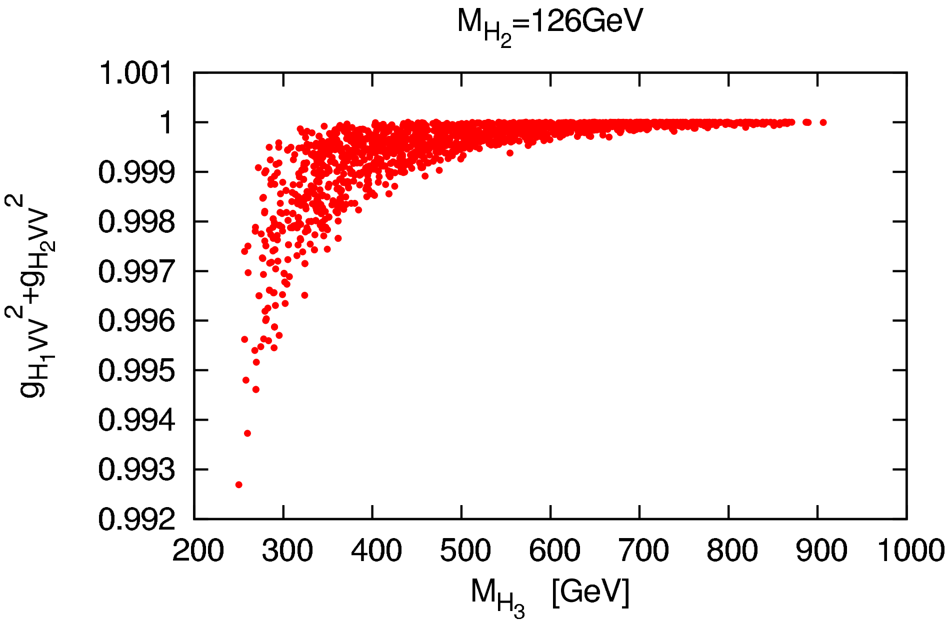
$$
\begin{aligned}
\sum_{i=1}^{3} g^2_{H_i VV} &= 1 && \underline{\text{Higgs-gauge couplings}} \\
\frac{1}{\sum_{i=1}^{3} g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^{3} g^2_{H_i bb}} &= 1 && \underline{\text{Higgs-fermion couplings}}
\end{aligned}
$$

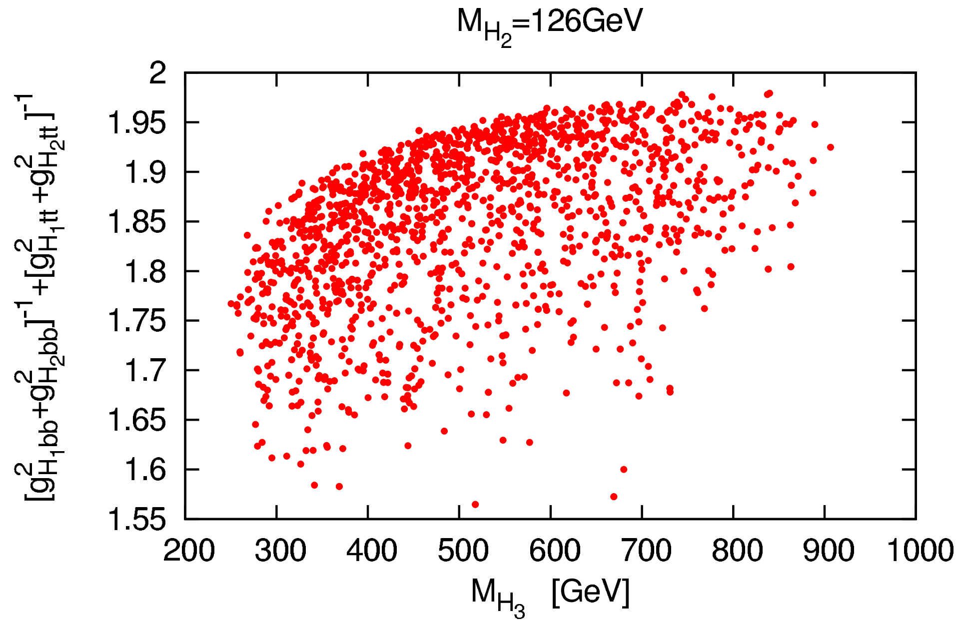
[in units of SM couplings].

- **Scenario 1** H_2 SM-like, only two lightest CP-even bosons discovered

  Deviation of sum rules: distinguish NMSSM from MSSM

Walz,MMM





H_2 is SM-like and only H_1, H_2 have been discovered

$\mathcal{NMSSM}$ $\mathcal{C}$oupling $\mathcal{M}$easurement - $\mathcal{D}$istinction of $\mathcal{M}$odels

- **What can we learn from coupling measurements?**

  Test coupling sum rules

$$\begin{aligned} \textstyle\sum_{i=1}^3 g^2_{H_i VV} &= 1 \qquad \underline{\text{Higgs-gauge couplings}} \\ \frac{1}{\sum_{i=1}^3 g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^3 g^2_{H_i bb}} &= 1 \qquad \underline{\text{Higgs-fermion couplings}} \end{aligned}$$

[in units of SM couplings].

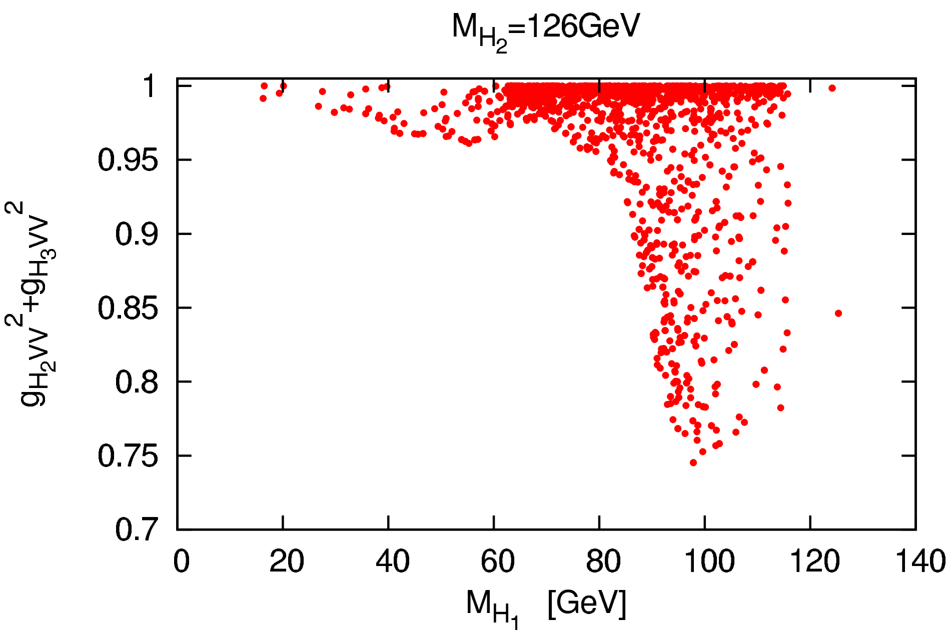
- **Scenario 1** H_2 SM-like, only two lightest CP-even bosons discovered

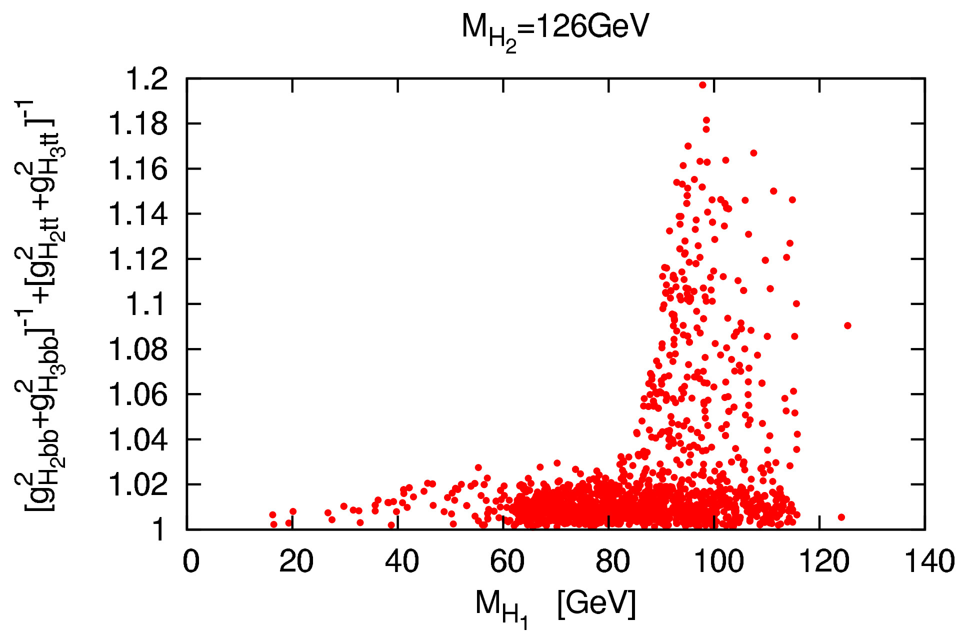
- **Scenario 2** H_2 SM-like and only H_2 and H_3 have been discovered

Deviation of sum rules: distinguish NMSSM from MSSM

$\mathcal{V}$iolation of $\mathcal{S}$um $\mathcal{R}$ules

Walz,MMM





H_2 is SM-like and only H_2, H_3 have been discovered

around 100 GeV H_1 and H_2 close in mass $\rightsquigarrow$ large mixing

$\mathcal{NMSSM}$ $\mathcal{C}$oupling $\mathcal{M}$easurement - $\mathcal{D}$istinction of $\mathcal{M}$odels

- **What can we learn from coupling measurements?**

  Test coupling sum rules

$$\begin{aligned} \textstyle\sum_{i=1}^{3} g^2_{H_i VV} &= 1 && \underline{\text{Higgs-gauge couplings}} \\ \frac{1}{\sum_{i=1}^{3} g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^{3} g^2_{H_i bb}} &= 1 && \underline{\text{Higgs-fermion couplings}} \end{aligned}$$

[in units of SM couplings].

- **Scenario 1** H_2 SM-like and only two lightest CP-even bosons discovered

- **Scenario 2** H_2 SM-like and only H_2 and H_3 have been discovered

  Deviation of sum rules: distinguish NMSSM from MSSM

- **What can be learn about high mass scale?**

  some dependence of sum rule on heavy mass can be seen, however large spreading of points

  large number of parameters at tree-level influence mixing $\rightsquigarrow$ couplings of the Higgs bosons