The Last Talk with Nothing New to Say

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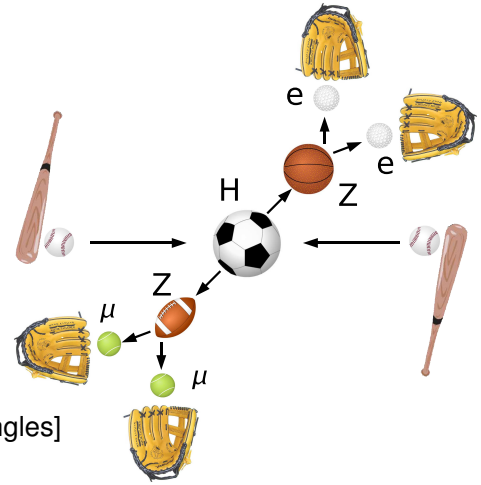
Higgs Questions

1. What is the ‘Higgs’ Lagrangian?

- psychologically: looked for Higgs, so found a Higgs
- CP-even spin-0 scalar expected, which operators?
  spin-1 vector unlikely
  spin-2 graviton unexpected
- ask flavor colleagues [Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles]



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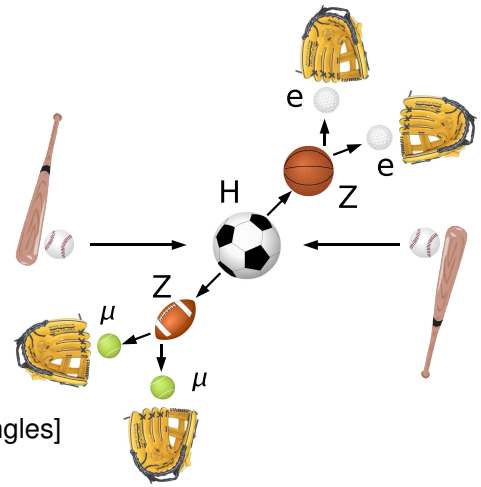

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- ‘coupling’ after fixing operator basis
- Standard Model Higgs vs anomalous couplings

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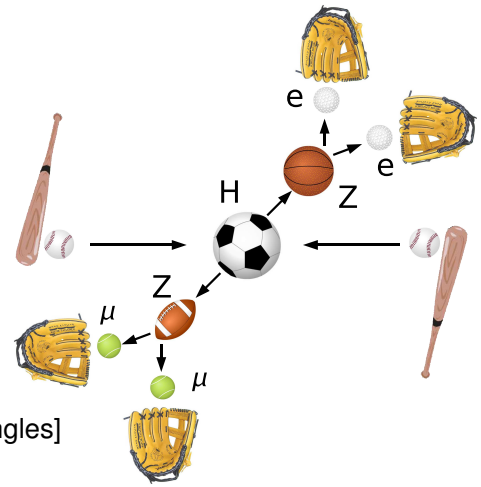

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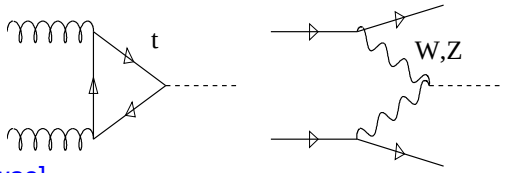
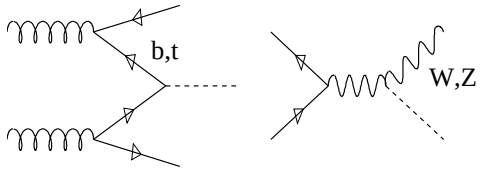
3. What does all this tell us? [Review 1403.7191]

- strongly interacting models
- TeV-scale new physics
- weakly interacting extended Higgs sectors
- Higgs portal, link to baryogenesis, dark matter,...

Naive Higgs Couplings



Standard Model operators [SFitter: Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]



- assume: narrow CP-even scalar
  Standard Model operators
  couplings proportional to masses?
- couplings from production & decay rates

$$\boxed{\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \end{array}}$$

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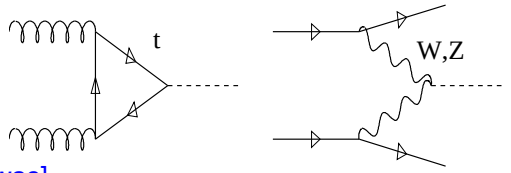

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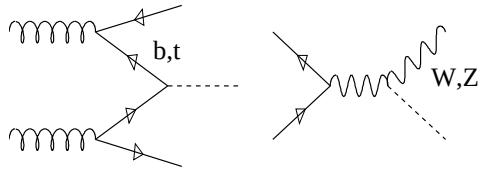

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Total width

- non-trivial scaling

$$N = \sigma \; BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}} \; \frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}} \sim \frac{g^4}{g^2 \dfrac{\sum \Gamma_i(g^2)}{g^2} + \Gamma_{\text{unobs}}} \overset{g^2 \to 0}{\longrightarrow} = 0$$

  gives constraint from $\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \to \Gamma_H|_{\text{min}}$
- $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \to \Gamma_H|_{\text{max}}$ [HiggsSignals]
- SFitter assumption $\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j$ [plus generation universality]

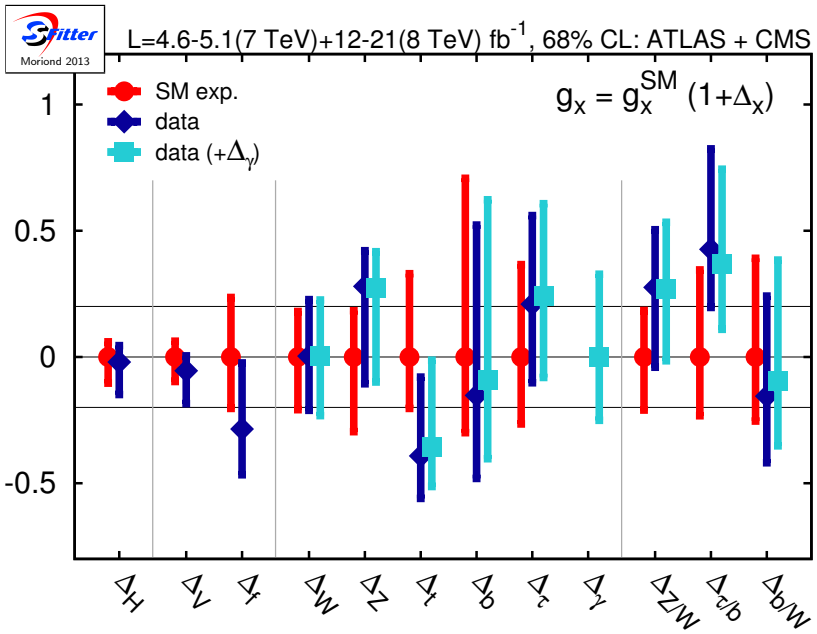
Now and in the future

Now [Aspen/Moriond 2013; Lopez-Val, TP, Rauch]

- focus SM-like [secondary solutions possible]
- tree couplings consistent in loops
- six couplings and ratios from data

  g_g vs g_t not yet good

  [similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]
- assumptions help: $\Delta_H, \Delta_V, \Delta_f$



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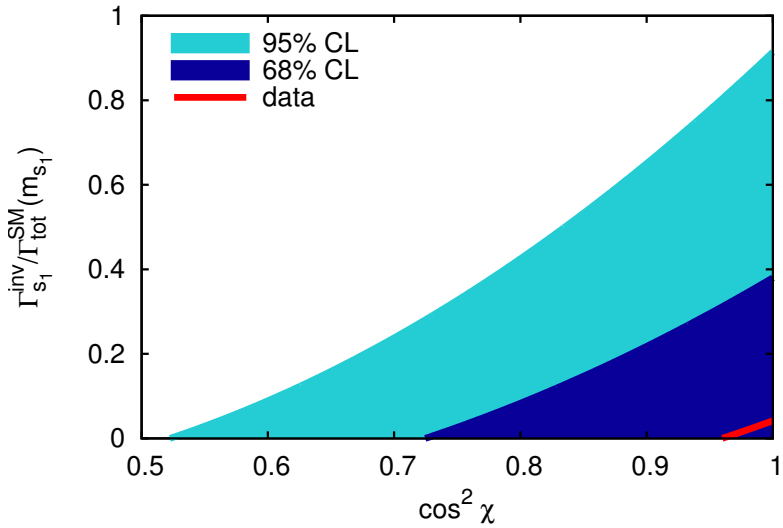
Higgs portal [Michael's talk]

- model–specific fits next step
- why not Higgs portal
  mixing angle vs invisible width



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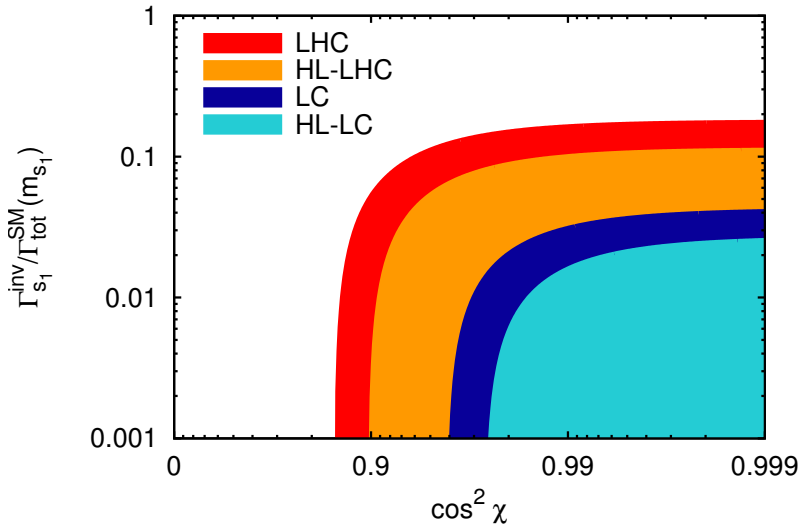

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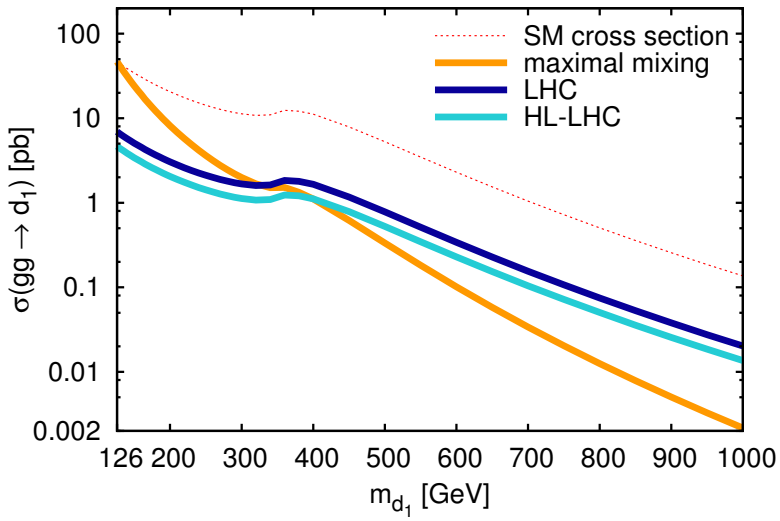

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  mixing angle vs invisible width
- translated into heavy Higgs rate
- direct invisible searches numerically irrelevant

$\Rightarrow$ remember your model hypothesis

2HDM as a consistent UV completion

How to think of coupling measurements [constant couplings, see Spanno's talk]

- $\Delta_x \neq 0$ violating renormalization, unitarity,...
- EFT approach:

  (1) define consistent 2HDM, decouple heavy states
  (2) fit 2HDM model parameters, plot range of SM couplings
  (3) compare to free SM couplings fit

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Yukawa-aligned 2HDM

- $\Delta_V \leftrightarrow (\beta - \alpha) \qquad \Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\} \qquad \Delta_\gamma \leftrightarrow m_{H^\pm}$
- Δ_g not free parameter, top partner?
  custodial symmetry built in at tree level $\Delta_V < 0$
- Higgs-gauge quantum corrections
  enhanced $\Delta_V < 0$
- fermion quantum corrections
  large for $\tan\beta \ll 1$
  $\Delta_W \neq \Delta_Z > 0$ possible

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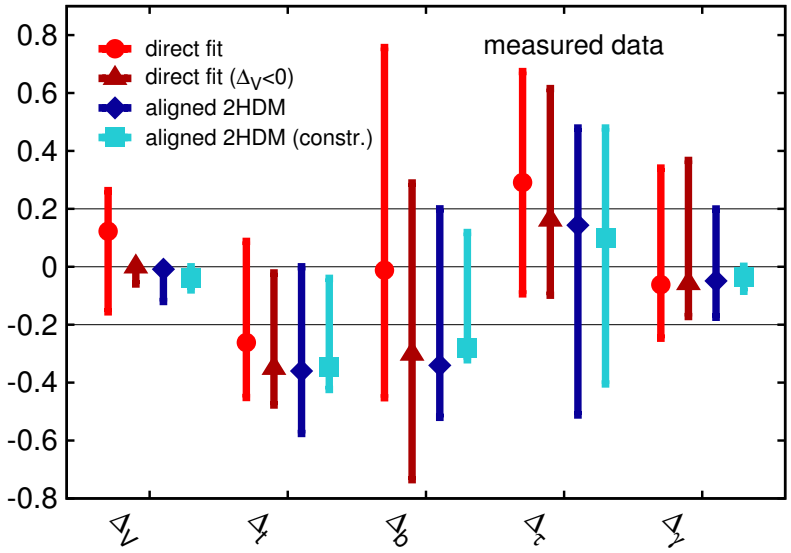
UV-complete vs SM coupling fits

- 2HDM close to perfect at tree level
- $\Delta_W \neq \Delta_Z > 0$ through loops
- ignote constraints on UV completion

$\Rightarrow$ free SM couplings well defined



Error analysis

Sources of uncertainty [Cranmer, Kreiss, Lopez-Val, TP]

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian [no statistical interpretation, just a range]
- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong
- theory likelihood flat centrally and zero far away
- profile likelihood construction: RFit [CKMFitter]

$$-2 \log \mathcal{L} = \chi^2 = \vec{\chi}_d^T \; C^{-1} \; \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\ \dfrac{|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})}}{\sigma_i^{(\text{exp})}} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})} \end{cases}$$

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Combination in profile likelihood [RFit, CKMFitter]

- Gaussian $\otimes$ Gaussian: half width added in quadrature
- Gaussian/Poisson $\otimes$ flat: linear
- flat $\otimes$ flat: linear

Higher-dimensional operators

Light Higgs as a Goldstone boson [Contino, Giudice, Grojean, Pomarol, Rattazzi]

- strongly interacting models predicting heavy broad resonance(s)
- light state if protected by Goldstone's theorem [Georgi & Kaplan]
- interesting if $v \ll f < 4\pi f \sim m_\rho$ [little Higgs $v \sim g^2 f/(2\pi)$]

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\begin{aligned}
\mathcal{L}_{\text{SILH}} = & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) \\
& + \frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
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Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

- assume Higgs is largely Standard Model
- additional higher-dimensional couplings

$$\begin{aligned}\mathcal{L}_{\text{eff}} = &- \frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}(\Phi^\dagger\Phi)G_{\mu\nu}G^{\mu\nu} + \frac{f_{WW}}{\Lambda^2}\Phi^\dagger W_{\mu\nu}W^{\mu\nu}\Phi \\ &+ \frac{f_W}{\Lambda^2}(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) + \frac{f_B}{\Lambda^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) + \frac{f_{WWW}}{\Lambda^2}\text{Tr}(W_{\mu\nu}W^{\nu\rho}W^\mu_\rho) \\ &+ \frac{f_b}{\Lambda^2}(\Phi^\dagger\Phi)(\overline{Q}_3\Phi d_{R,3}) + \frac{f_\tau}{\Lambda^2}(\Phi^\dagger\Phi)(\overline{L}_3\Phi e_{R,3})\end{aligned}$$

- plus e-w precision data and triple gauge couplings
- remember what Lagrangian you assume
- not best approach for renormalizable models

Extended Higgs sectors

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

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$$\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}} \qquad\qquad \mu_{p,d} = \frac{\Gamma_{\text{SM}}}{\Gamma_{\text{SM}} + \Gamma_{\text{inv}}} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

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- additional doublet [type-X fermion sector]

$$1 + \Delta_V = \sin(\beta - \alpha) = \sqrt{1 - \xi^2}$$

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$$1 + \Delta_V = \sin(\beta - \alpha) = \sqrt{1 - \xi^2}$$

- MSSM [plus tan β]

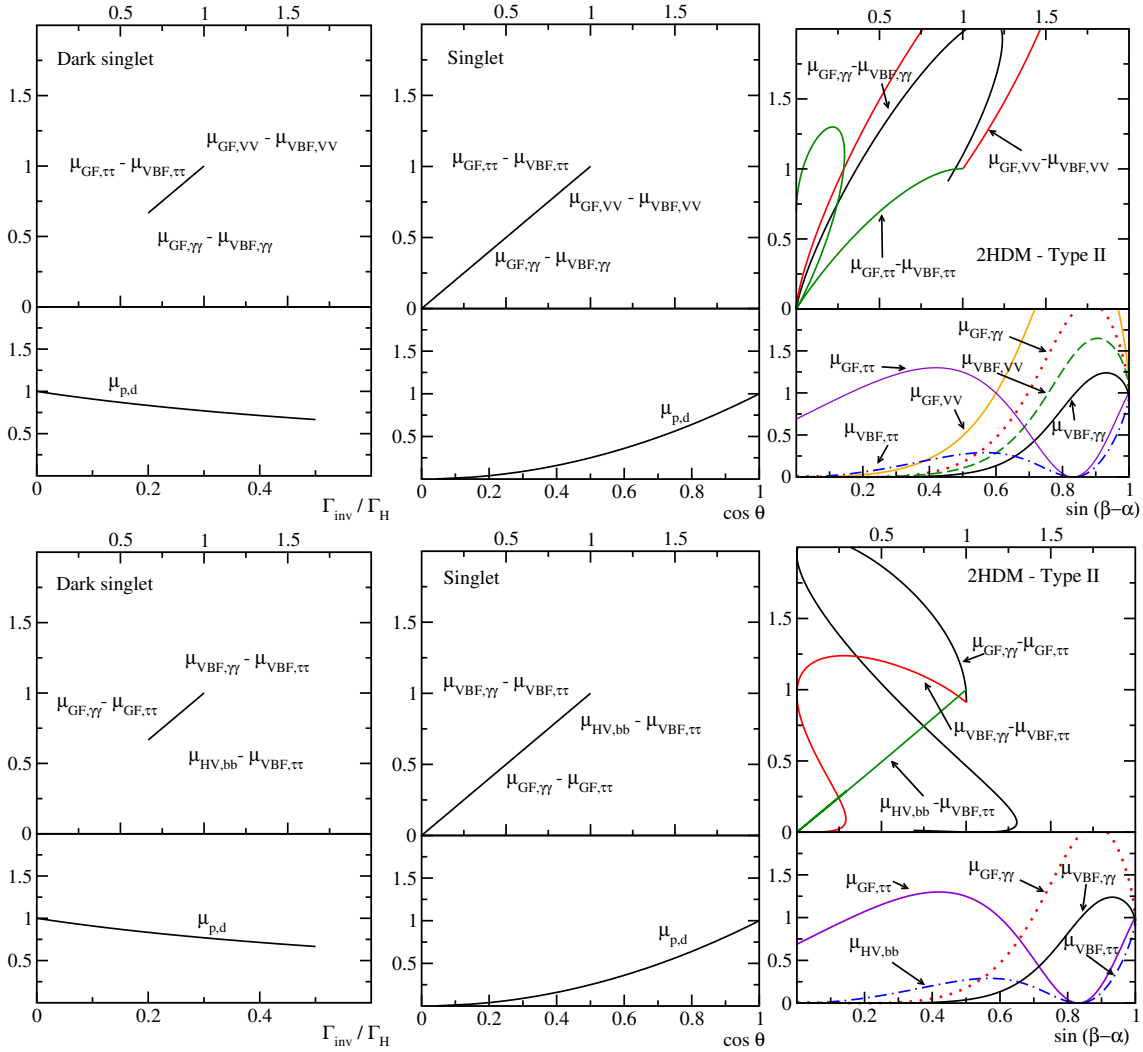
$$\xi^2 =\simeq \frac{m_h^2\,(m_Z^2 - m_h^2)}{m_A^2 (m_H^2 - m_h^2)} \sim \frac{m_Z^4\,\sin^2(2\beta)}{m_A^4}$$

Extended Higgs sectors

Effect on signal strengths

– decay–diagonal and production–diagonal correlations

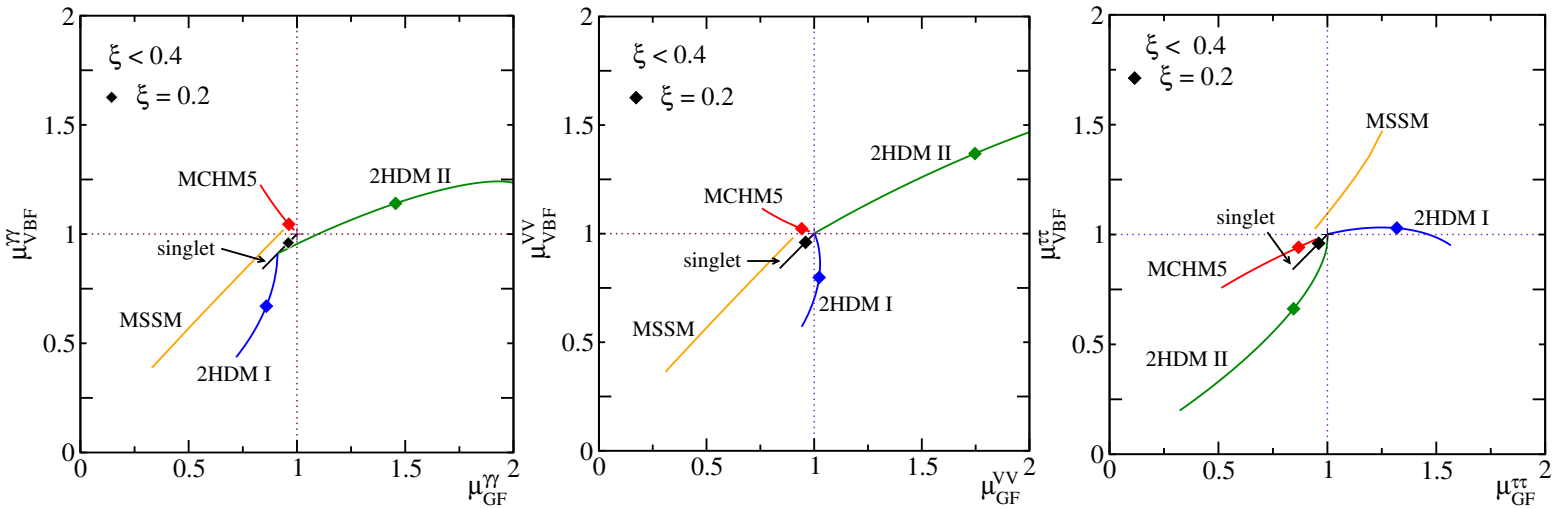
– for dark singlet
for mixing singlet
for type-II 2HDM



Extended Higgs sectors

Effect on signal strengths

- decay–diagonal and production–diagonal correlations
- for dark singlet
  for mixing singlet
  for type-II 2HDM
- new physics scenarios in 2 dimensions



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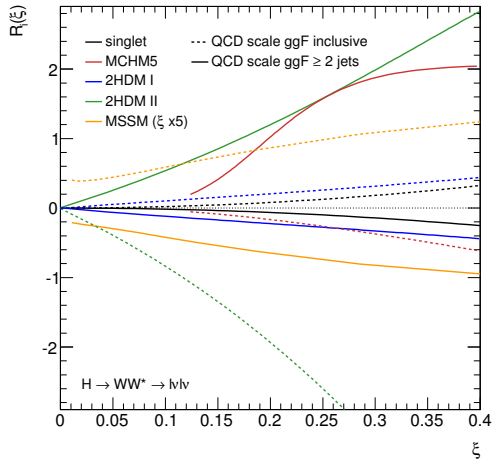

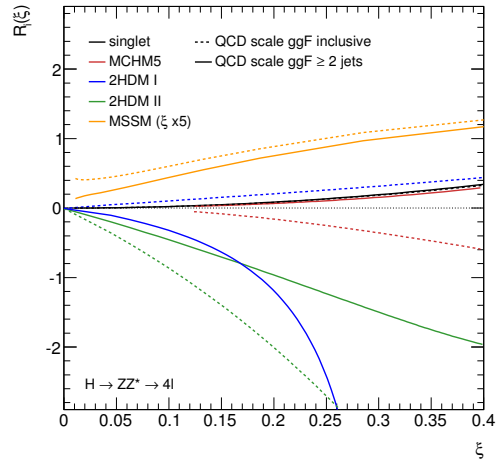

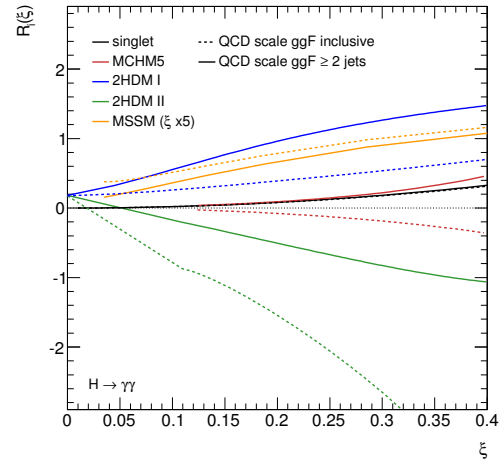

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$\Rightarrow$ only for illustration at this stage...

Questions

Big questions

- what is the Higs Lagrangian?
- what are the coupling values?
- what does all this tell us?

Small questions

- what are good alternative model hypotheses?
- go for renormalizable or EFT completions?
- how can we improve the couplings fit precision?
- how can we measure the quark Yukawas?
- how can we measure the Higgs self coupling?
- how do we avoid theory dominating uncertainties
- who wants to work on backgrounds?
- can QCD be fun?

Lectures on LHC Physics, Springer, arXiv:0910.4182 updated under `www.thphys.uni-heidelberg.de/~plehn/`

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