Two topics of scale invariant extensions of the SM

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Contents

- Scale invariant extensions of the SM with strongly interacting hidden sector : EWSB and CDM from h-QCD (hidden sector TC)
- Dilaton (radion in RS I scenario) couplings to the SM fields : $SU(3)_C \times SU(2)_L \times U(1)_Y$ vs. $SU(3)_C \times U(1)_{em}$

Based on

- hep-ph/0709.1218 (PLB),0801.4284(IJMPA), 1012.0103(ICHEP),1103.2571(PRL), and a number of proceedings during 2007-2012 (with T.Hur, D.W.Jung, J.Y.Lee)
- arXiv:1402.2115 [hep-ph] (with D.W.Jung)

SM Chapter is being closed

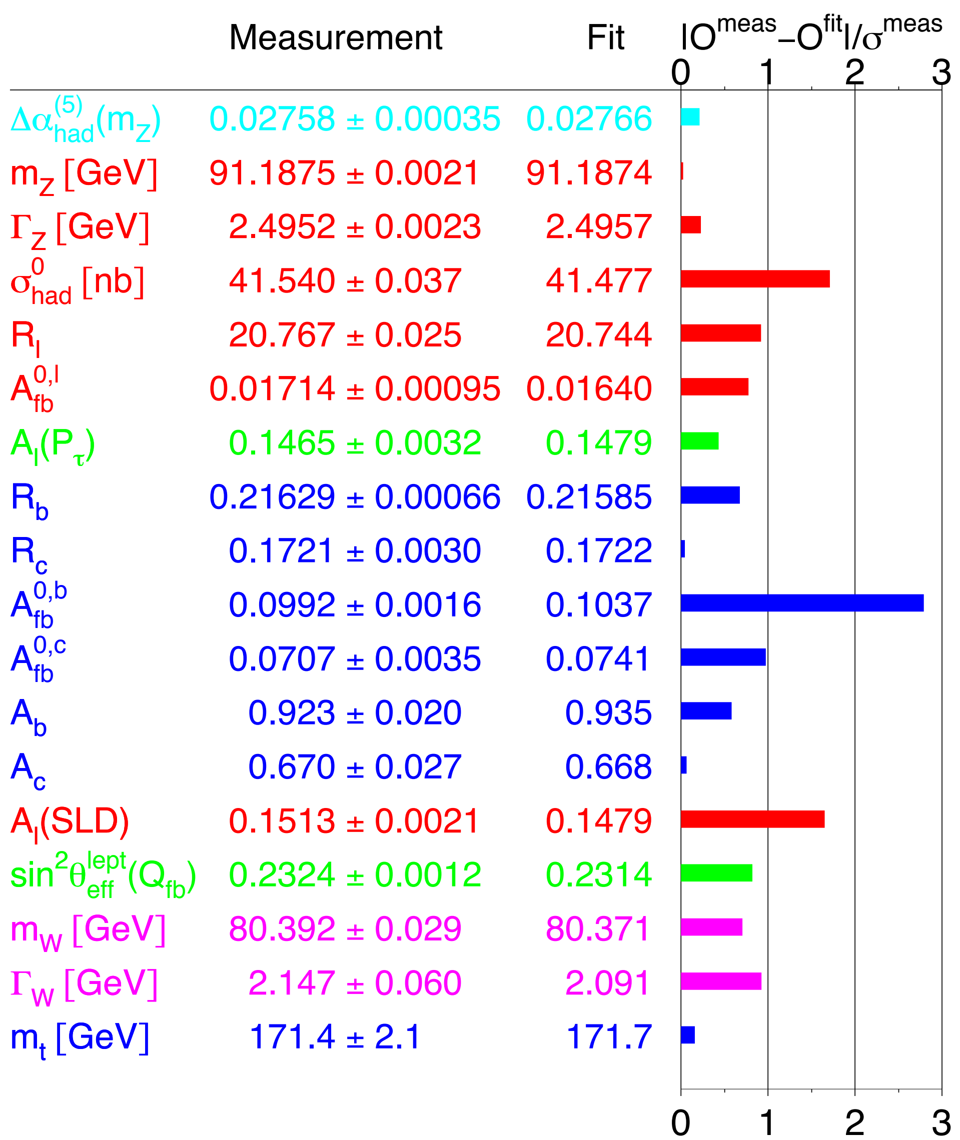
- SM has been tested at quantum level
  - EWPT favors light Higgs boson
  - CKM paradigm is working very well so far
  - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC so far

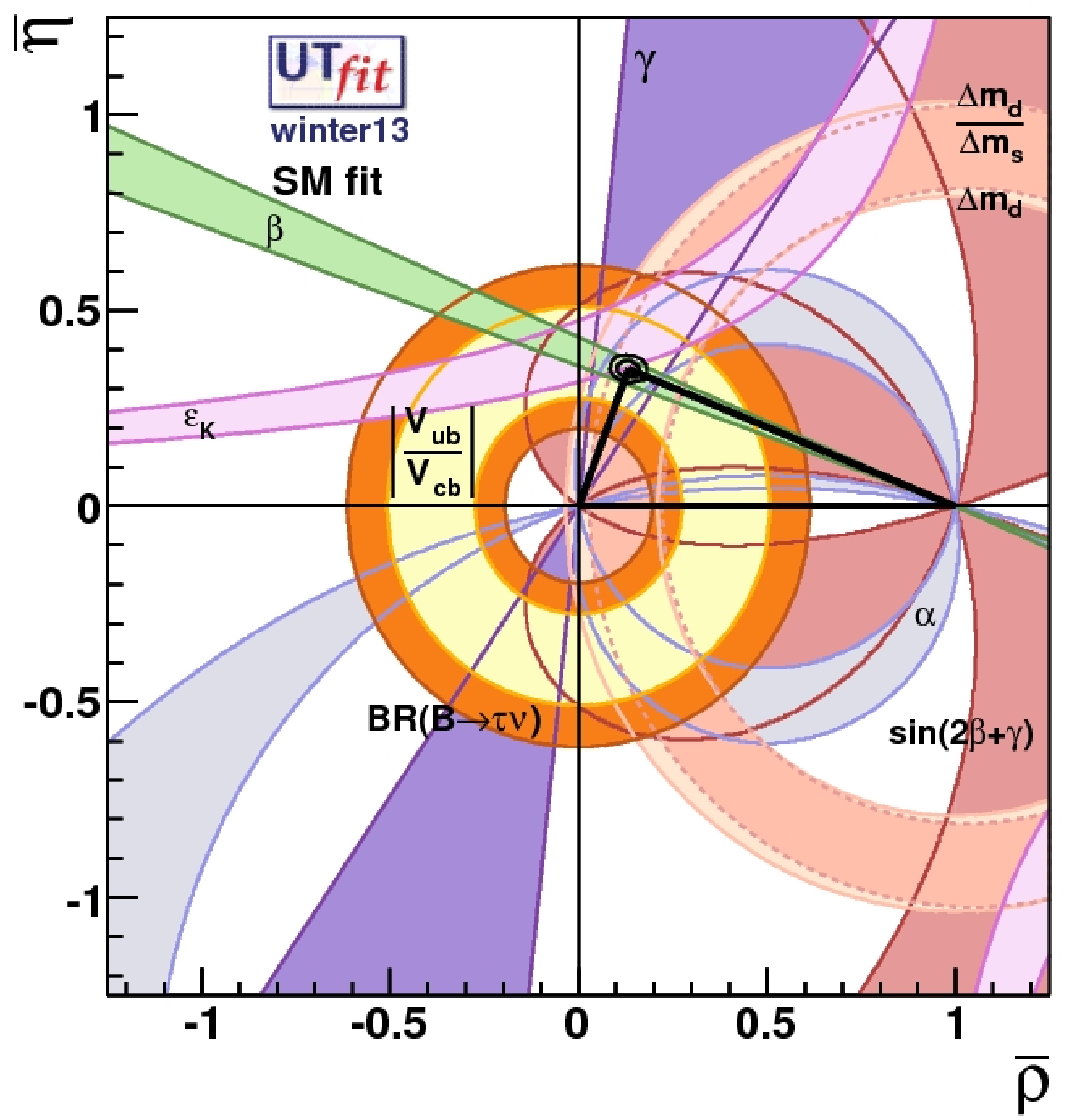
SM Lagrangian

$$
\begin{aligned}
\mathcal{L}_{MSM} = & -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
& +|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\
& +\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
& -\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) . (1)
\end{aligned}
$$

Based on local gauge principle

EWPT & CKM



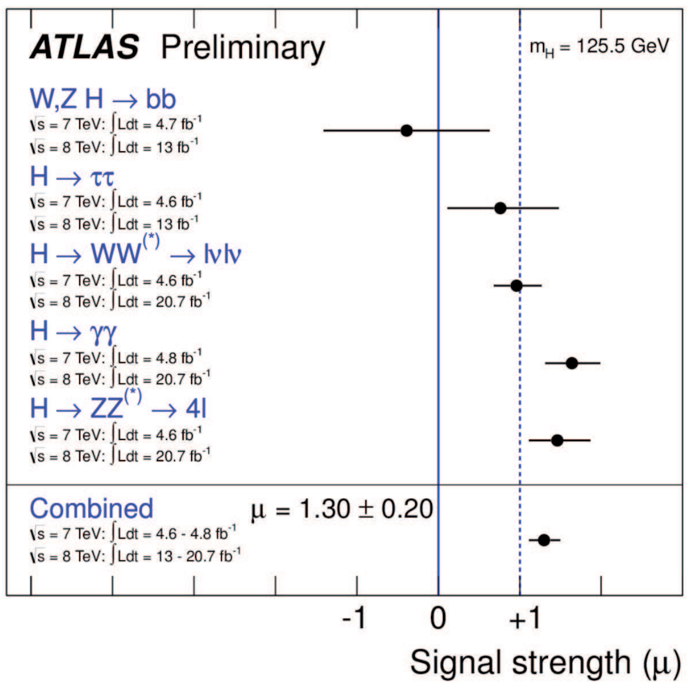


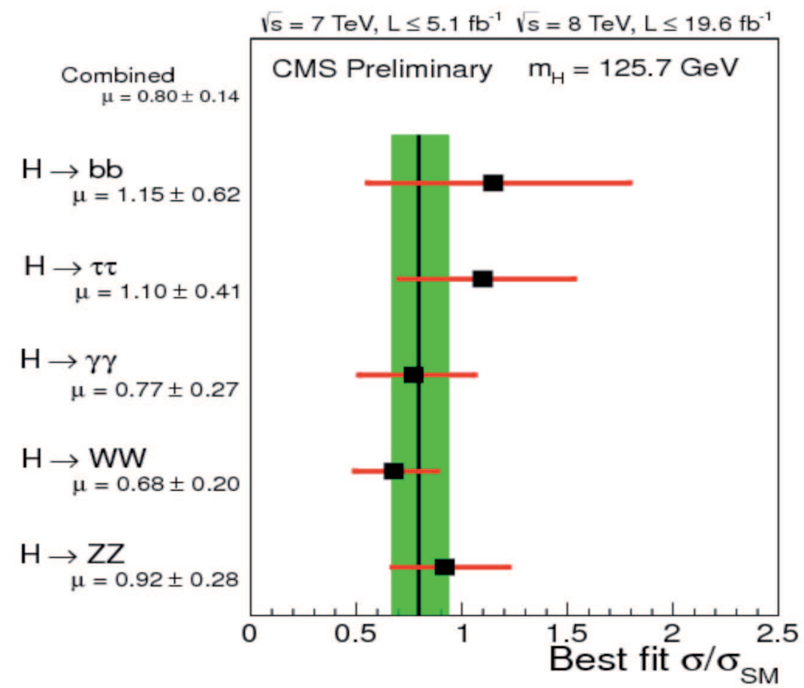
Almost Perfect !

Updates@LHCP

Signal Strengths

$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$





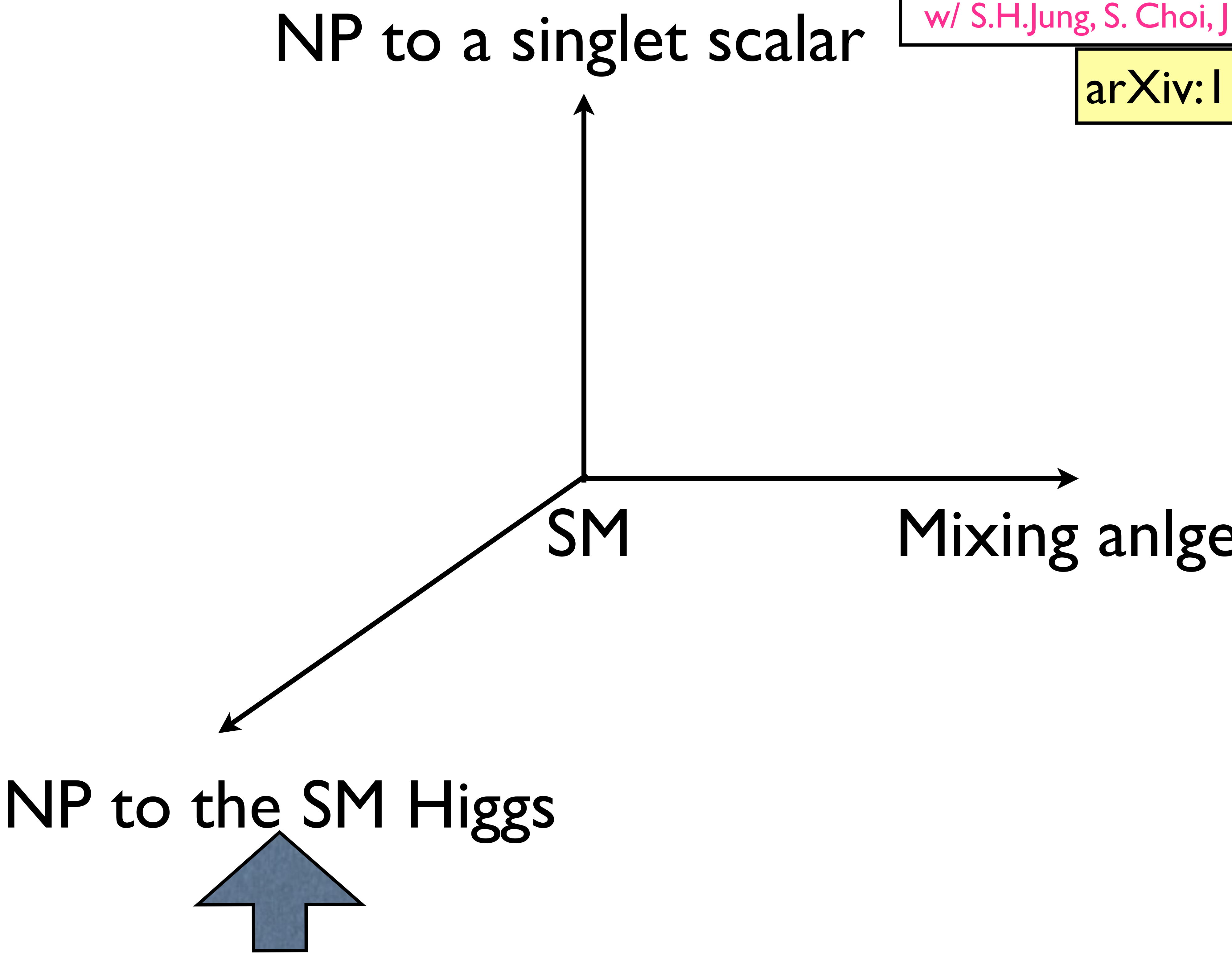
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = 0.96 \pm 0.12$$

14년 3월 7일 금요일

w/ S.H.Jung, S. Choi, JHEP (2013)

arXiv:1307.3948



Considered by the usual approaches
based on effective Lagrangian

SM Higgs

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{h,int}} &= \sum_f b_f \frac{m_f}{v} h\bar{f}f - \left\{2b_W \frac{h}{v} + b_W^{'}\left(\frac{h}{v}\right)^2\right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{b_Z \frac{h}{v} + \frac{1}{2}b_Z^{'}\left(\frac{h}{v}\right)^2\right\} m_Z^2 Z_\mu Z^\mu \\
&+ \frac{\alpha}{8\pi} r_{\mathrm{sm}}^\gamma \left\{b_\gamma \frac{h}{v} + \frac{1}{2}b_\gamma^{'}\left(\frac{h}{v}\right)^2\right\} F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\mathrm{sm}}^g \left\{b_g \frac{h}{v} + \frac{1}{2}b_g^{'}\left(\frac{h}{v}\right)^2\right\} G_{\mu\nu}^a G^{a\mu\nu} \\
&+ \frac{\alpha_2}{\pi}\left\{2b_{dW}\frac{h}{v} + b_{dW'}\left(\frac{h}{v}\right)^2\right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\alpha_2}{\pi}\left\{2b_{dZ}\frac{h}{v} + b_{dZ'}\left(\frac{h}{v}\right)^2\right\} Z_{\mu\nu}Z^{\mu\nu} \\
&+ \frac{\alpha_2}{\pi}\left\{2\widetilde{b_{dW}}\frac{h}{v} + \widetilde{b_{dW'}}\left(\frac{h}{v}\right)^2\right\} W_{\mu\nu}^+ \widetilde{W^{-\mu\nu}} + \frac{\alpha_2}{\pi}\left\{2\widetilde{b_{dZ}}\frac{h}{v} + \widetilde{b_{dZ'}}\left(\frac{h}{v}\right)^2\right\} Z_{\mu\nu}\widetilde{Z^{\mu\nu}} \\
&+ \frac{\alpha}{\pi}\left\{2b_{Z\gamma}\frac{h}{v} + b_{Z\gamma'}\left(\frac{h}{v}\right)^2\right\} F_{\mu\nu}Z^{\mu\nu} \qquad (2.1)
\end{aligned}
$$

Singlet Scalar S

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{s,int}} &= \sum_f c_f \frac{m_f}{v} s\bar{f}f - \left\{2c_W \frac{s}{v} + c_W^{'}\left(\frac{s}{v}\right)^2\right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{c_Z \frac{s}{v} + \frac{1}{2}c_Z^{'}\left(\frac{s}{v}\right)^2\right\} m_Z^2 Z_\mu Z^\mu \\
&+ \frac{\alpha}{8\pi} r_{\mathrm{sm}}^\gamma \left\{c_\gamma \frac{s}{v} + \frac{1}{2}c_\gamma^{'}\left(\frac{s}{v}\right)^2\right\} F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\mathrm{sm}}^g \left\{c_g \frac{s}{v} + \frac{1}{2}c_g^{'}\left(\frac{s}{v}\right)^2\right\} G_{\mu\nu}^a G^{a\mu\nu} \qquad (2.10) \\
&+ \frac{\alpha_2}{\pi}\left\{2c_{dW}\frac{s}{v} + c_{dW'}\left(\frac{s}{v}\right)^2\right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\alpha_2}{\pi}\left\{2c_{dZ}\frac{s}{v} + c_{dZ'}\left(\frac{s}{v}\right)^2\right\} Z_{\mu\nu}Z^{\mu\nu} \\
&+ \frac{\alpha_2}{\pi}\left\{2\widetilde{c_{dW}}\frac{s}{v} + \widetilde{c_{dW'}}\left(\frac{s}{v}\right)^2\right\} W_{\mu\nu}^+ \widetilde{W^{-\mu\nu}} + \frac{\alpha_2}{\pi}\left\{2\widetilde{c_{dZ}}\frac{s}{v} + \widetilde{c_{dZ'}}\left(\frac{s}{v}\right)^2\right\} Z_{\mu\nu}\widetilde{Z^{\mu\nu}} \\
&+ \frac{\alpha}{\pi}\left\{2c_{Z\gamma}\frac{s}{v} + c_{Z\gamma'}\left(\frac{s}{v}\right)^2\right\} F_{\mu\nu}Z^{\mu\nu} \quad - \mathcal{L}_{nonSM} \qquad (2.11)
\end{aligned}
$$

Mixing with a singlet scalar

$$H_1 = h\cos\alpha - s\sin\alpha$$
$$H_2 = h\sin\alpha + s\cos\alpha$$

$$\mathcal{M}(H_1F) = \mathcal{M}(hF)_{\rm SM} \times (b_F\cos\alpha - c_F\sin\alpha) \equiv \kappa_{1F}\mathcal{M}(hF)_{\rm SM}$$
$$\mathcal{M}(H_2F) = \mathcal{M}(hF)_{\rm SM} \times (-b_F\sin\alpha + c_F\cos\alpha) \equiv \kappa_{2F}\mathcal{M}(hF)_{\rm SM}$$

Model	Nonzero c's
Pure Singlet Extension	c_{h^2}
Hidden Sector DM	c_χ
Dilaton	$c_{h^2}, c_g, c_W, c_Z, c_\gamma$
Vectorlike Quarks	c_g, c_γ
Vectorlike Leptons	c_γ
New Charged Vector bosons	c_γ

Other c's are all zeros !

SM gives the best fit

	both	CMS	ATLAS
SM	$\chi^2/\nu = 12.01/10 = 1.20$	$2.33/5 = 0.466$	$9.69/5 = 1.94$
(Δb_γ)	(0.090) 11.19/9=1.24	(-0.117) 1.71/4=0.428	(0.28) 4.99/4=1.25
$(\Delta b_g, \Delta b_\gamma)$	(-0.018, 0.107) $11.13/8 = 1.39$	(-0.078, -0.048) $0.859/3 = 0.286$	(0.11, 0.17) $4.14/3 = 1.38$
(b_V, b_f)	(1.031, 0.962) $11.74/8 = 1.47$	(0.898, 1.021) 0.808/3=0.27	(1.345, 0.808) 4.52/3=1.51
$(b_V \leq 1, b_u, b_d)$	(1.0, 0.969, 0.938) $11.86/7 = 1.69$		
$(\Delta b_g, \Delta b_\gamma, b_V, b_f)$	(0.041, 0.117, 0.941, 0.961) $11.07/6 = 1.85$		

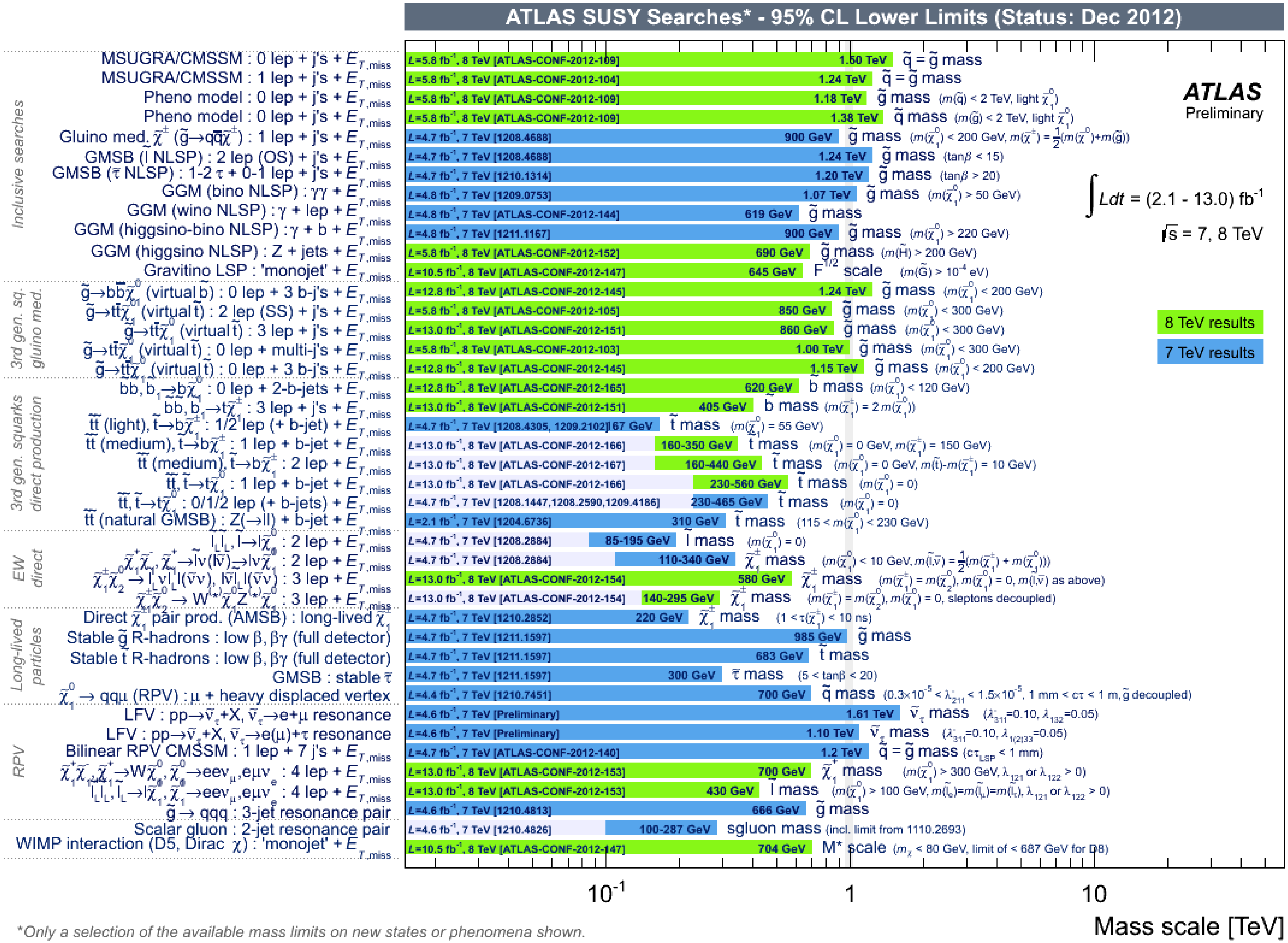
2HDMs (MSSM)

Table 5. Best-fit results using b_i only from both CMS and ATLAS data as well as individual. Errors are shown in text.

SM gives the best fit

Models	Best-fit results	χ^2/ν
SM		$12.01/10 = 1.20$
universal modification $(\hat{\kappa}^2_{univ})$ (BR_{nonSM}) $(\cos\alpha)$	 (1.012) $\leq 18.8\%$ at 95%CL ≥ 0.904 at 95%CL	 $11.96/9 = 1.33$
VL lepton, W', S' (c_α, c_γ)	 (0.98, -0.55)	 $11.1/8 = 1.39$
VL quark $(c_\alpha, c_g, c_\gamma)$	 (0.947, -0.128, -0.313)	 $11.1/7 = 1.58$
$(c_\alpha, c_\gamma, Br_{nonSM})$	$BR_{nonSM} \leq 24\%$ at 95%CL	$11.1/8 = 1.39$
$(c_\alpha, c_g, c_\gamma, Br_{nonSM})$	$BR_{nonSM} \leq 39\%$ at 95%CL	$11.1/7 = 1.58$
singlet mixed-in $\hat{\kappa}$ $(\hat{\kappa}^2_g, \hat{\kappa}^2_\gamma, \hat{\kappa}^2_{mix})$	 (1.03, 1.15, 0.942)	 $11.1/7 = 1.58$
singlet mixed-in theory $(\hat{c}_g, \hat{c}_\gamma, \hat{c}_\alpha)$	 (-0.176, -0.432, 0.971)	 $11.1/7 = 1.58$

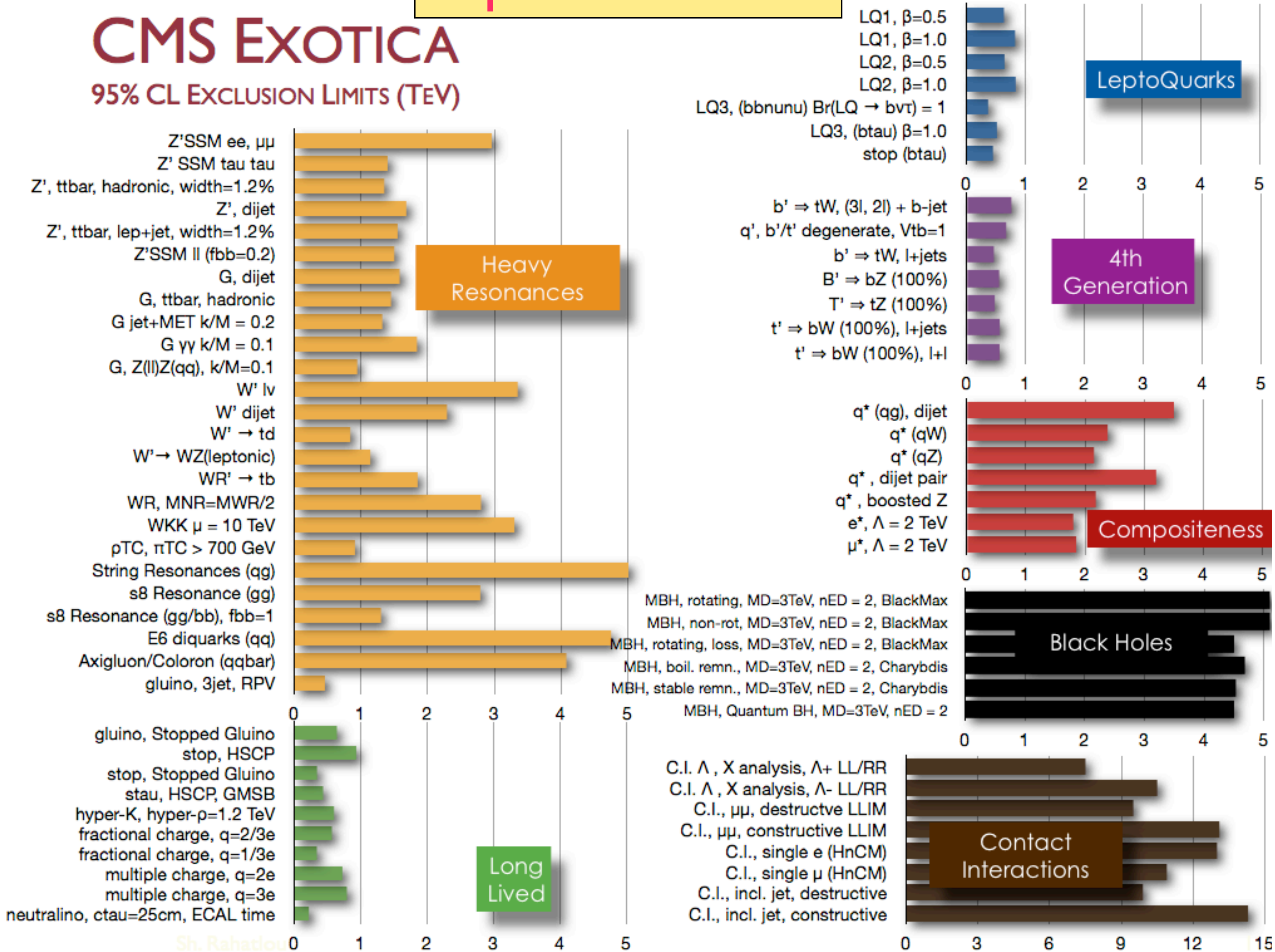
Table 7. Summary of best-fit results with scalar mixing. If BR_{nonSM} is included in fit, no unique solution is found, and its upper bound at 95%CL is presented. Only central values of best-fit are shown, and errors can be found in text.



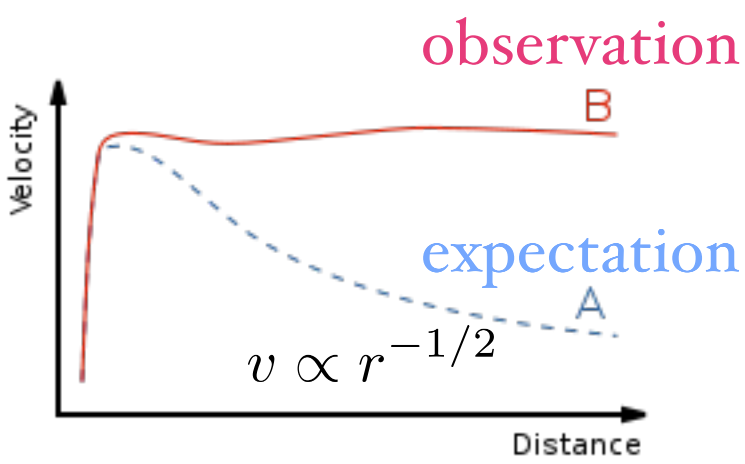
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

14년 3월 7일 금요일

Aspen this March

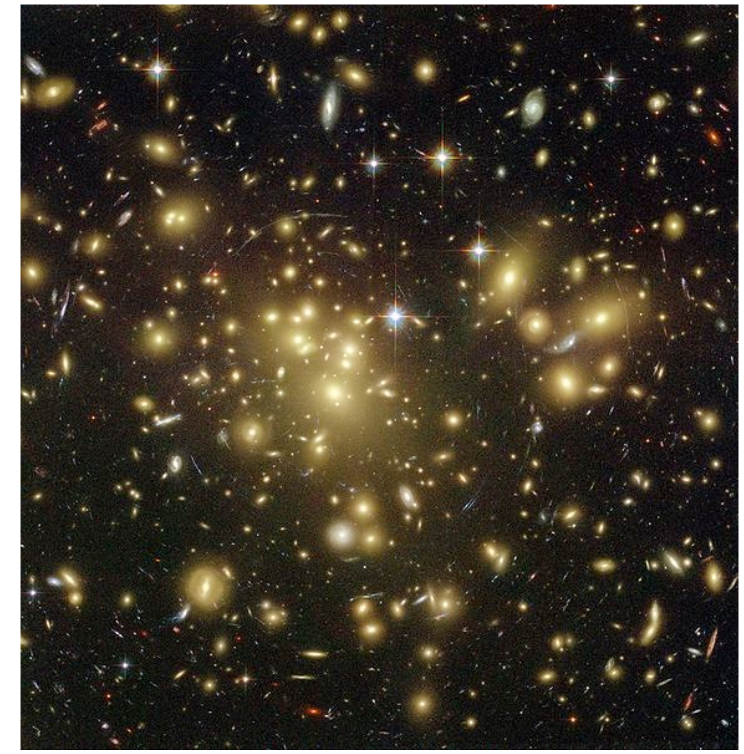


- Dark & visible matter and dark energy, neutrinos

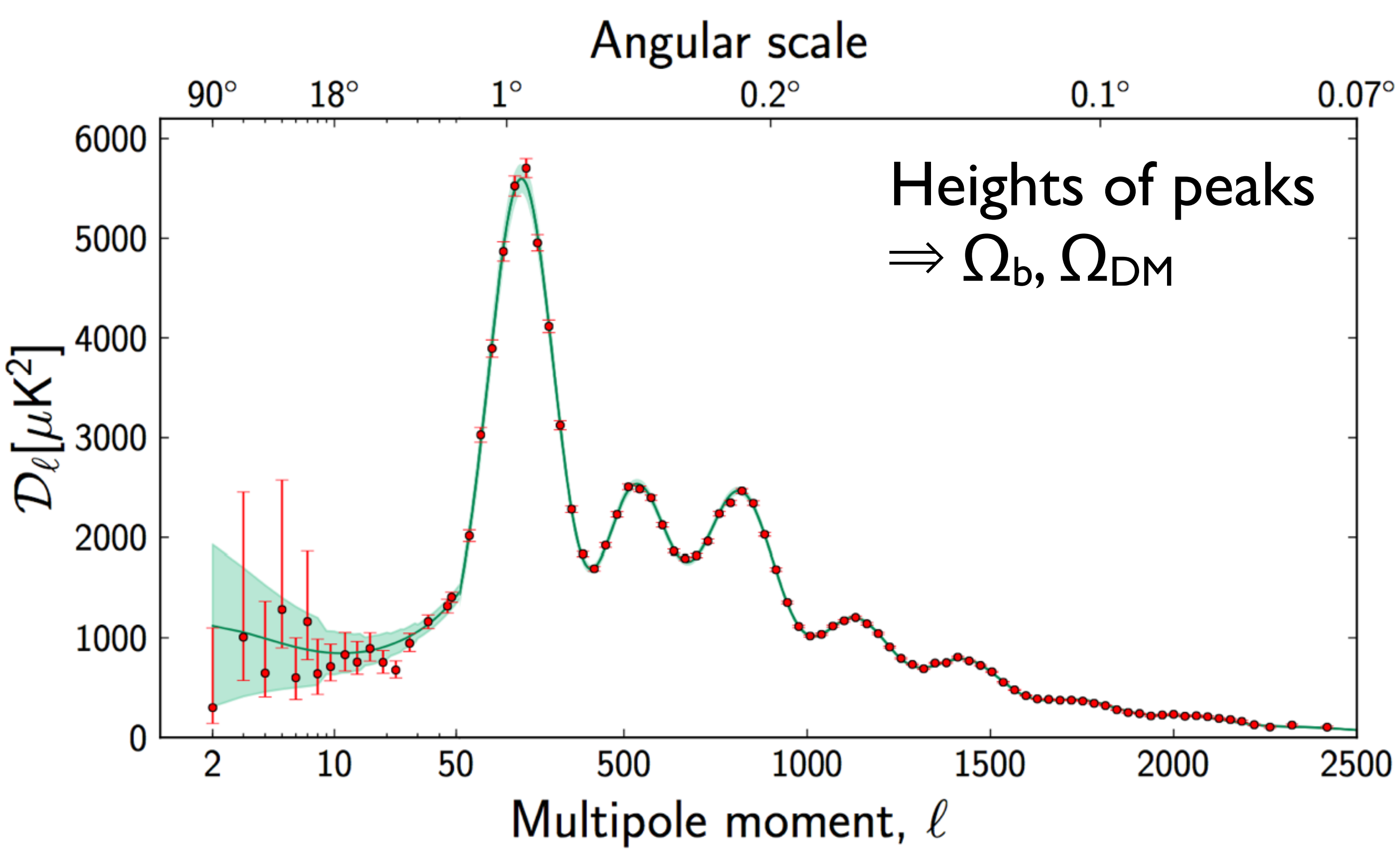


Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster



Strong gravitational lensing in Abell 1689

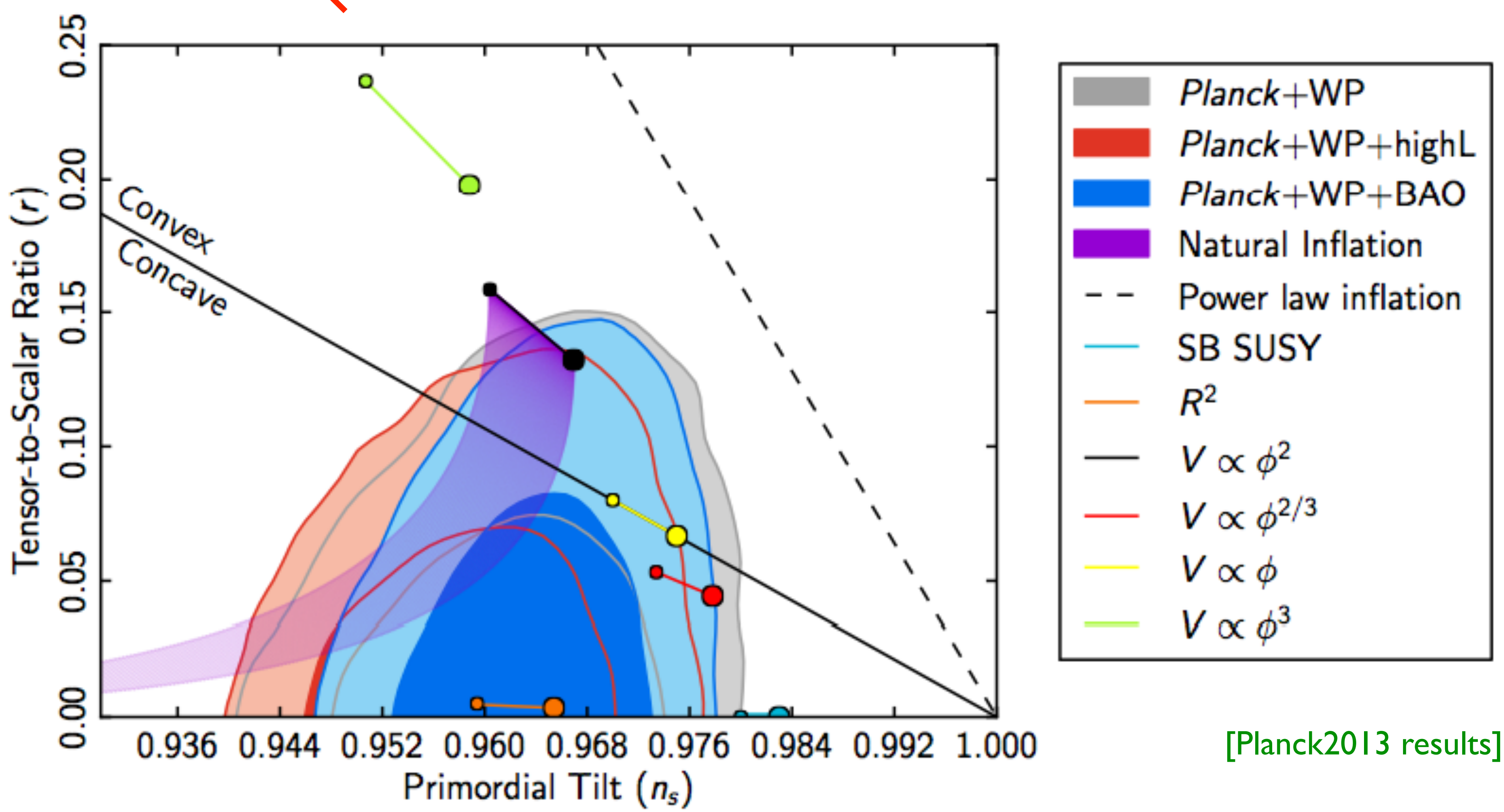


$$\Omega_b \simeq 0.048$$
$$\Omega_{DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

Inflation models in light of Planck2013 data

$$V \propto \phi^4$$



[Planck2013 results]

Only Higgs (~SM) & Nothing Else So Far

Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky & Higgs Inflations

Many candidates

Can we attack these problems ?

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Lessons for Model Building

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- One may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

(3,2,1) or SU(3)cXU(1)em ?

- Well below the EW sym breaking scale, it may be fine to impose SU(3)c X U(1)em
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different results (work in preparation with D.W.Jung)
- Singlet mixing with SM Higgs

Digression on Higgs-dilaton system

arXiv:1402.2115 [hep-ph]

Dilaton interactions

- Dilaton/radion (in RS I scenario) couples to the trace of energy-momentum tensor
- But which form ?

$$T_\mu{}^\mu(\mathrm{SM})^{\mathrm{tree}} = \left[\sum_f m_f \bar{f} f - 2m_W^2 W_\mu^+ W^{-\mu} - m_Z^2 Z_\mu Z^\mu + \left(2m_h^2 h^2 - \partial_\mu h \partial^\mu h\right) + \ldots\right]$$

OR

$$T^\mu_\mu(\mathrm{SM}) = 2\mu_H^2 H^\dagger H + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu}$$

Effective Lagrangian

$$
\begin{aligned}
\mathcal{L} = \quad & \mathcal{L}_{\rm SM}(\mu_H^2 = 0) + \frac{1}{2} f_\phi^2 \partial_\mu \chi \partial^\mu \chi - \mu_H^2 \chi^2 H^\dagger H - \frac{f_\phi^2 m_\phi^2}{4} \chi^4 \left\{ \log \chi - \frac{1}{4} \right\}, \\
- & \log \left(\frac{\chi}{S(x)} \right) \left\{ \frac{\beta_{g_1}(g_1)}{2 g_1} B_{\mu\nu} B^{\mu\nu} + \frac{\beta_{g_2}(g_2)}{2 g_2} W^i_{\mu\nu} W^{i\mu\nu} + \frac{\beta_{g_3}(g_3)}{2 g_3} G^a_{\mu\nu} G^{a\mu\nu} \right\} \\
+ & \log \left(\frac{\chi}{S(x)} \right) \left\{ \beta_u \left(\mathbf{Y_u} \right) \bar{Q}_L \tilde{H} u_R + \beta_d \left(\mathbf{Y_u} \right) \bar{Q}_L H d_R + \beta_l \left(\mathbf{Y_u} \right) \bar{l}_L H e_R + H.c. \right\} \\
+ & \log \left(\frac{\chi}{S(x)} \right) \frac{\beta_\lambda(\lambda)}{4} \left(H H^\dagger \right)^2
\end{aligned}
$$

- **Minimizing the extended potential generally gives**

$$\langle H \rangle = (0, v/\sqrt{2})^T, \quad \langle \phi \rangle = \bar{\phi}.$$

- **From tadpole condition for Higgs boson and dilaton,**

$$\begin{aligned} \lambda v^2 &= \mu^2 \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}}, \\ \mu^2 v^2 &= f_\phi m_\phi^2 \bar{\phi}\ \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}}. \end{aligned}$$

- **Similar to the singlet extended SM, but the structures are different.**

Mass Formula

- **The Higgs-Dilaton mass matrix becomes**

$$\mathcal{M}^2(h,\phi) = \begin{pmatrix} m^2_{hh} & m^2_{h\phi} \\ m^2_{\phi h} & m^2_{\phi\phi} \end{pmatrix} = \begin{pmatrix} 2\lambda v^2 & -2\frac{\lambda v^3}{f_\phi} e^{-2\frac{\bar\phi}{f_\phi}} \\ -2\frac{\lambda v^3}{f_\phi} e^{-2\frac{\bar\phi}{f_\phi}} & m^2_\phi e^{2\frac{\bar\phi}{f_\phi}}\left(1+2\frac{\bar\phi}{f_\phi}\right) \end{pmatrix} \equiv \begin{pmatrix} m^2_h & -m^2_h \frac{v}{f_\phi} e^{-2\frac{\bar\phi}{f_\phi}} \\ -m^2_h \frac{v}{f_\phi} e^{-2\frac{\bar\phi}{f_\phi}} & \tilde m^2_\phi e^{2\frac{\bar\phi}{f_\phi}} \end{pmatrix}$$

where

$$\tilde m^2_\phi = m^2_\phi\left(1+2\frac{\bar\phi}{f_\phi}\right).$$

- **Mass eigenvalues and mixing angle :**

$$m^2_{H_{1,2}} = \frac{m^2_h + \tilde m^2_\phi e^{2\frac{\bar\phi}{f_\phi}} \mp \sqrt{\left(m^2_h - \tilde m^2_\phi e^{2\frac{\bar\phi}{f_\phi}}\right)^2 + 4 e^{-4\frac{\bar\phi}{f_\phi}} \frac{v^2}{f^2_\phi} m^4_h}}{2}$$

with

$$\tan\alpha = \frac{-m^2_h \frac{v}{f_\phi} e^{-2\frac{\bar\phi}{f_\phi}}}{\tilde m^2_\phi e^{\frac{2\bar\phi}{f_\phi}} - m^2_{H_1}}.$$

$$\mathcal{L}(f,\bar{f},H_{i=1,2}) = -\frac{m_f}{v}\overline{f}fh = -\frac{m_f}{v}\overline{f}f(H_1c_\alpha + H_2s_\alpha),$$

vs. $$\mathcal{L}(f,\bar{f},\phi) = -\frac{m_f}{f_\phi}\bar{f}f\phi\ \mathrm{e}^{-\bar{\phi}/f_\phi}$$

Note that there is no limit where we recover the usual form of the dilaton coupling

$$
\begin{aligned}
\mathcal{L}(g,g,H_{i=1,2}) &= -\frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \frac{\beta_3(g_3)}{2g_3}G_{\mu\nu}G^{\mu\nu}\phi \\
&= -\frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \frac{\beta_3(g_3)}{2g_3}G_{\mu\nu}G^{\mu\nu}(-H_1 s_\alpha + H_2 c_\alpha). \qquad (15)\\
\mathcal{L}(W,W,H_{i=1,2}) &= \frac{2m_W^2}{v}W_\mu^+ W^{-\mu} h - \frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \frac{\beta_2(g_2)}{2g_2}W_{\mu\nu}W^{\mu\nu}\phi \\
&= \frac{2m_W^2}{v}W_\mu^+ W^{-\mu}\,(H_1 c_\alpha + H_2 s_\alpha) \\
&- \frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \frac{\beta_2(g_2)}{2g_2}W_{\mu\nu}W^{\mu\nu}(-H_1 s_\alpha + H_2 c_\alpha). \qquad (16)\\
\mathcal{L}(Z,Z,H_{i=1,2}) &= \frac{m_Z^2}{v}Z_\mu Z^\mu h - \frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \left\{c_W^2\frac{\beta_2(g_2)}{2g_2} + s_W^2\frac{\beta_1(g_1)}{2g_1}\right\} Z_{\mu\nu}Z^{\mu\nu}\phi \\
&= \frac{m_Z^2}{v}Z_\mu Z^\mu\,(H_1 c_\alpha + H_2 s_\alpha) \\
&- \frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \left\{c_W^2\frac{\beta_2(g_2)}{2g_2} + s_W^2\frac{\beta_1(g_1)}{2g_1}\right\} Z_{\mu\nu}Z^{\mu\nu}(-H_1 s_\alpha + H_2 c_\alpha). \qquad (17)\\
\mathcal{L}(\gamma,\gamma,H_{i=1,2}) &= -\frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \left\{s_W^2\frac{\beta_2(g_2)}{2g_2} + c_W^2\frac{\beta_1(g_1)}{2g_1}\right\} F_{\mu\nu}F^{\mu\nu}\phi \\
&= -\frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ \left\{s_W^2\frac{\beta_2(g_2)}{2g_2} + c_W^2\frac{\beta_1(g_1)}{2g_1}\right\} F_{\mu\nu}F^{\mu\nu}(-H_1 s_\alpha + H_2 c_\alpha). \qquad (18)\\
\mathcal{L}(\gamma,Z,H_{i=1,2}) &= -\frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ 2s_W c_W \left\{\frac{\beta_2(g_2)}{2g_2} - \frac{\beta_1(g_1)}{2g_1}\right\} Z_{\mu\nu}F^{\mu\nu}\phi \\
&= -\frac{\mathrm{e}^{-\bar{\phi}/f_\phi}}{f_\phi}\ 2s_W c_W \left\{\frac{\beta_2(g_2)}{2g_2} - \frac{\beta_1(g_1)}{2g_1}\right\} Z_{\mu\nu}F^{\mu\nu}(-H_1 s_\alpha + H_2 c_\alpha). \qquad (19)
\end{aligned}
$$

$(m_{H2} > m_{H1} = 126\text{GeV})$

- **Allowed range is highly constrained-coincides with SM results.**
- **Precise Heavy scalar boson phenomenology is required.**

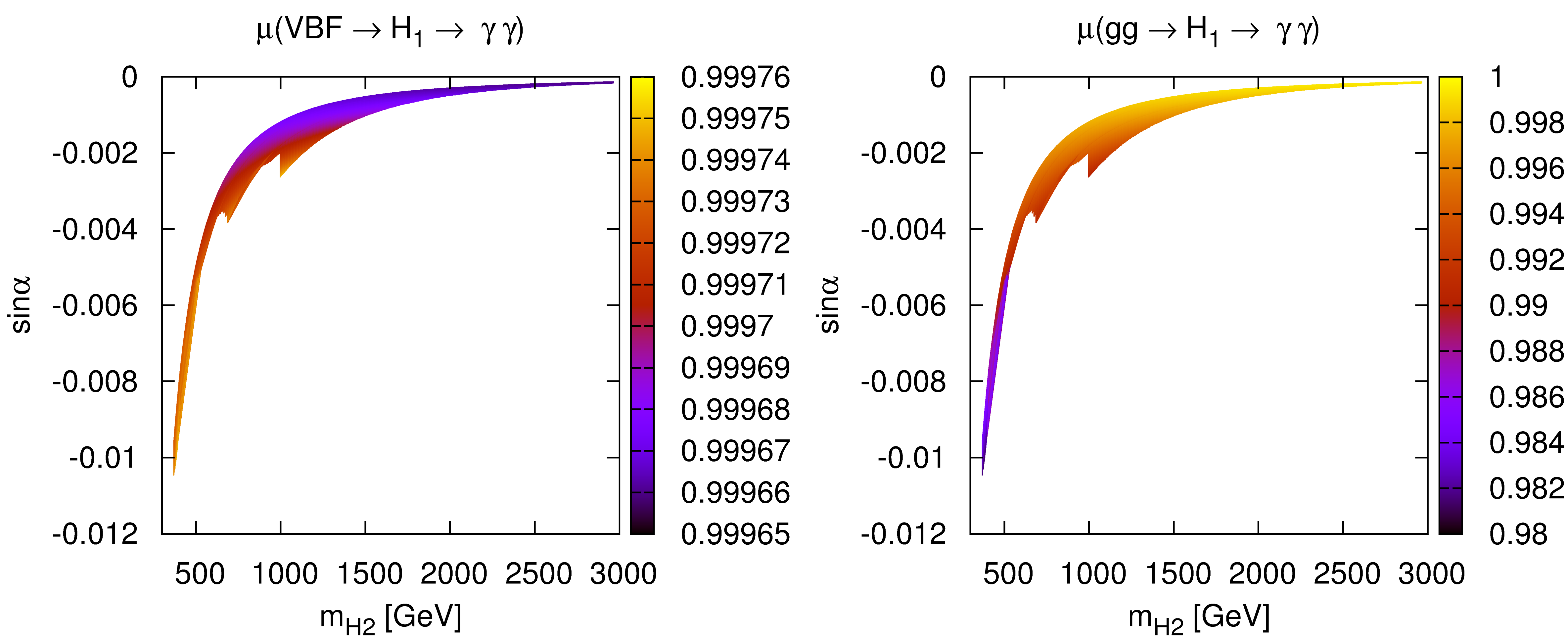


Figure: Rates relative to the SM values: ggF and VBF

$(m_{H1} < m_{H2} = 126\text{GeV})$

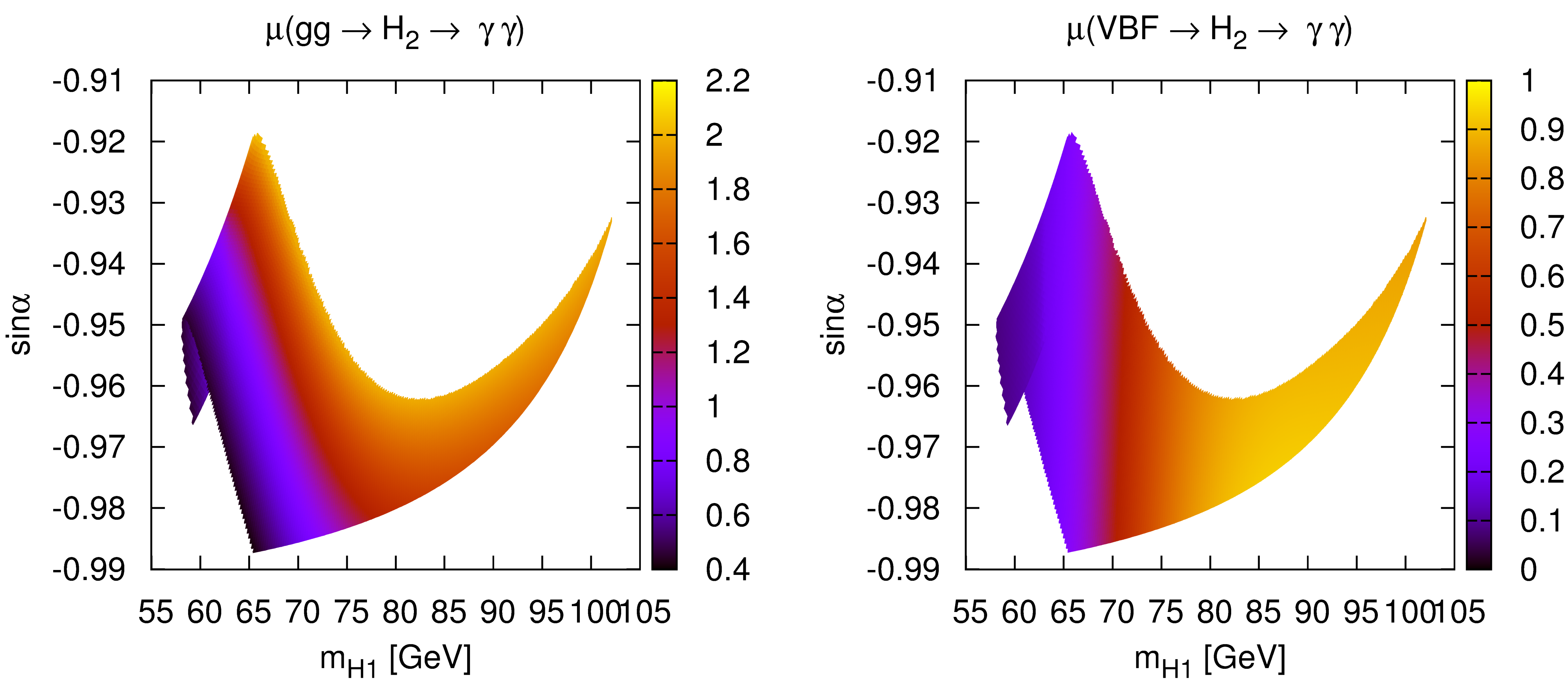


Figure: Rates relative to the SM values: ggF and VBF

Typical prediction II

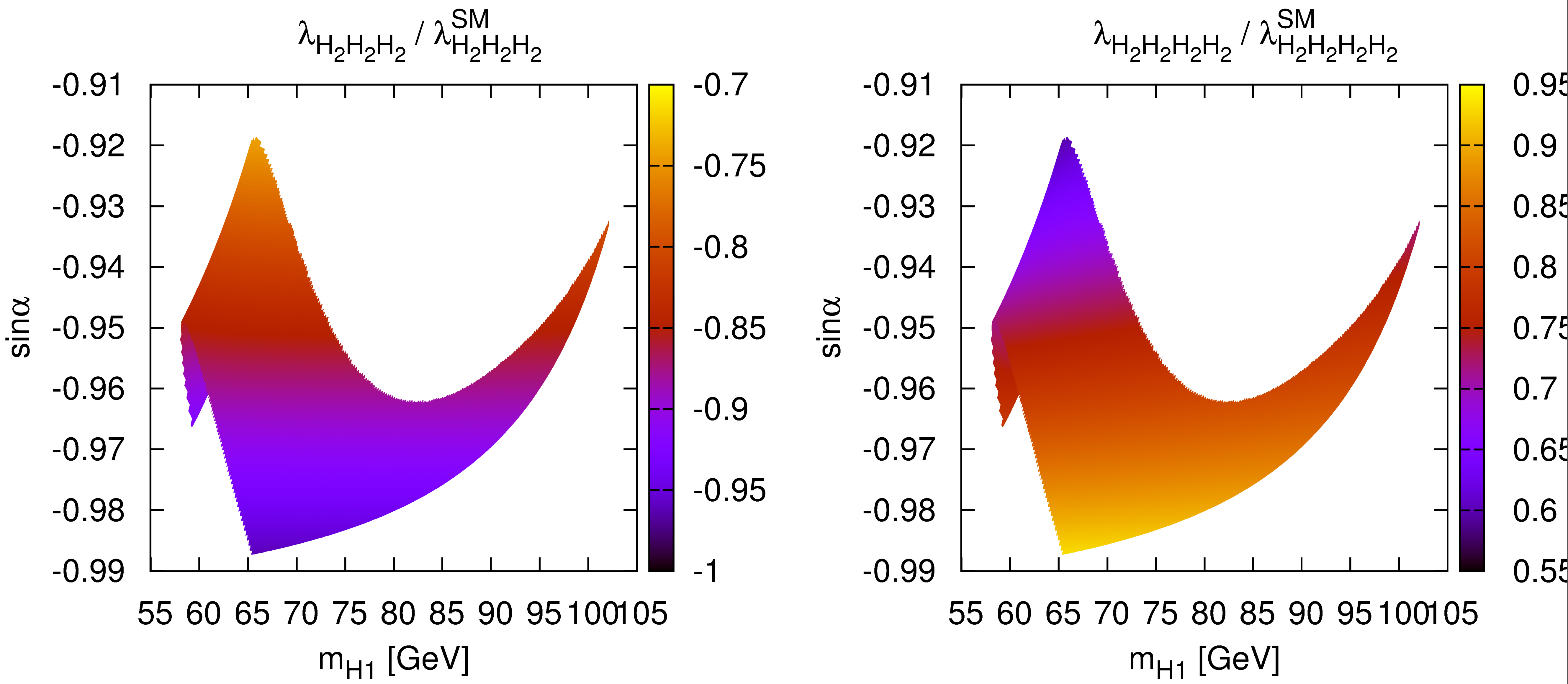


Figure: Triple and Quartic couplings.

Back to the main theme

Origin of EWSB ?

- LHC discovered a scalar ~ SM Higgs boson
- This answers the origin of EWSB within the SM in terms of the Higgs VEV, v
- Still we can ask the origin of the scale "v"
- Can we understand its origin by some strong dynamics similar to QCD or TC ?

Origin of Mass

- Massive SM particles get their masses from Higgs mechanism or confinement in QCD
- How about DM particles ? Where do their masses come from ?
- SM Higgs ? SUSY Breaking ? Extra Dim ?
- Can we generate all the masses as in proton mass from dim transmutation in QCD ? (proton mass in massless QCD)

Questions about DM

- Electric Charge/Color neutral
- How many DM species are there ?
- Their masses and spins ?
- Are they absolutely stable or very long lived ?
- How do they interact with themselves and with the SM particles ?
- Where do their masses come from ? Another (Dark) Higgs mechanism ? Dynamical SB ?
- How to observe them ?

Underlying Principles

- Hidden Sector CDM
- Singlet Portals
- Renormalizability (with some caveats)
- Local Dark Gauge Symmetry (unbroken or spontaneously broken) : Dark matter feels gauge force like most of other particles & DM is stable for the same reason as electron is stable

(Alternative models by Asaka, Shaposhnikov et al.)

Hidden Sector

- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could be CDM
- Generic in many BSM's including SUSY models
- E8 X E8' : natural setting for SM X Hidden
- SO(32) may be broken into G_{SM} X G_h

Hidden Sector

- Hidden sector gauge symmetry can stabilize hidden DM
- There could be some contributions to the dark radiation from unbroken dark sector
- Consistent with GUT in a broader sense
- Can address "QM generation of all the mass scales from strong dynamics in the hidden sector" (alternative to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

How to specify hidden sector ?

- Gauge group (G_h) : Abelian or Nonabelian
- Strength of gauge coupling : strong or weak
- Matter contents : singlet, fundamental or higher dim representations of G_h
- All of these can be freely chosen at the moment : Any predictions possible ?
- But there are some generic testable features in Higgs phenomenology and dark radiation

Hidden sector DM

- Hidden sector DM with its own dark gauge sym : Natural candidates & Generic in many BSM including SUSY, Superstring theory
- E8 x E'8 , SO(32) --> $G_{SM} \times G_{hidden}$
- Dark gauge sym can guarantee the stability or the longevity of DM
- Can be thermalized through singlet portals

Known facts for hCDM

- Strongly interacting hidden sector
  - CDM : composite h-mesons and h-baryons
  - All the mass scales can be generated from hidden sector
  - No long range dark force
  - CDM can be absolutely stable or long lived

T. Hur, D. -W. Jung, P. Ko and J. Y. Lee, Phys. Lett. B **696**, 262 (2011) [arXiv:0709.1218 [hep-ph]]; T. Hur and P. Ko, Phys. Rev. Lett. **106**, 141802 (2011) [arXiv:1103.2571 [hep-ph]].

P. Ko, Int. J. Mod. Phys. A **23**, 3348 (2008) [arXiv:0801.4284 [hep-ph]]; P. Ko, AIP Conf. Proc. **1178**, 37 (2009); P. Ko, PoS ICHEP **2010**, 436 (2010) [arXiv:1012.0103 [hep-ph]]; P. Ko, AIP Conf. Proc. **1467**, 219 (2012).

- Weakly interacting hidden sector
    - Long range dark force if Gh is unbroken
    - If Gh is unbroken and CDM is DM, then no extra scalar boson is necessary (*)
    - If Gh is broken, hDM can be still stable or decay, depending on Gh charge assignments
- More than one neutral scalar bosons with signal strength = 1 or smaller (indep. of decays) except for the case (*)
- Vacuum is stable up to Planck scale

S.Baek, P.Ko, W.I.Park, E.Senaha, JHEP (2012)

Higgs signal strength/Dark radiation/DM

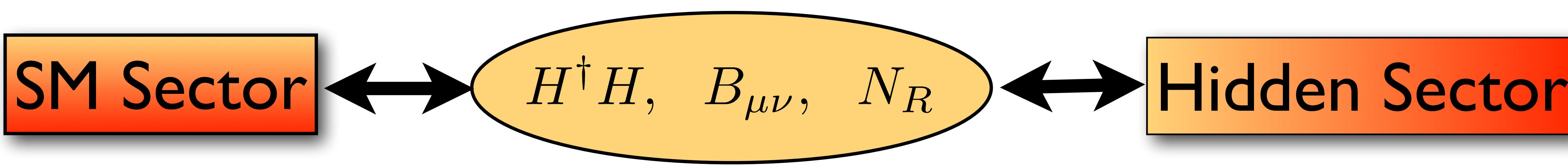
in preparation with Baek and W.I. Park

Models	Unbroken U(1)X	Local Z2	Unbroken SU(N)	Unbroken SU(N) (confining)
Scalar DM	1 0.08 complex scalar	<1 ~0 real scalar	1 ~0.08*# complex scalar	1 ~0 composite hadrons
Fermion DM	<1 0.08 Dirac fermion	<1 ~0 Majorana	<1 ~0.08*# Dirac fermion	<1 ~0 composite hadrons

:The number of massless gauge bosons

Singlet Portal

- If there is a hidden sector, then we need a portal to it in order not to overclose the universe
- There are only three unique gauge singlets in the SM + RH neutrinos



$$\boxed{N_R \leftrightarrow \widetilde{H} l_L}$$

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture

Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

Warming up with a toy model

- Reinterpretation of 2 Higgs doublet model
- Consider a hidden sector with QCD like new strong interaction, with two light flavors
- Approximate SU(2)L X SU(2)R chiral symmetry, which is broken spontaneously
- Lightest meson π_h : Nambu-Goldstone boson -> Chiral lagrangian applicable
- Flavor conservation makes π_h stable -> CDM

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

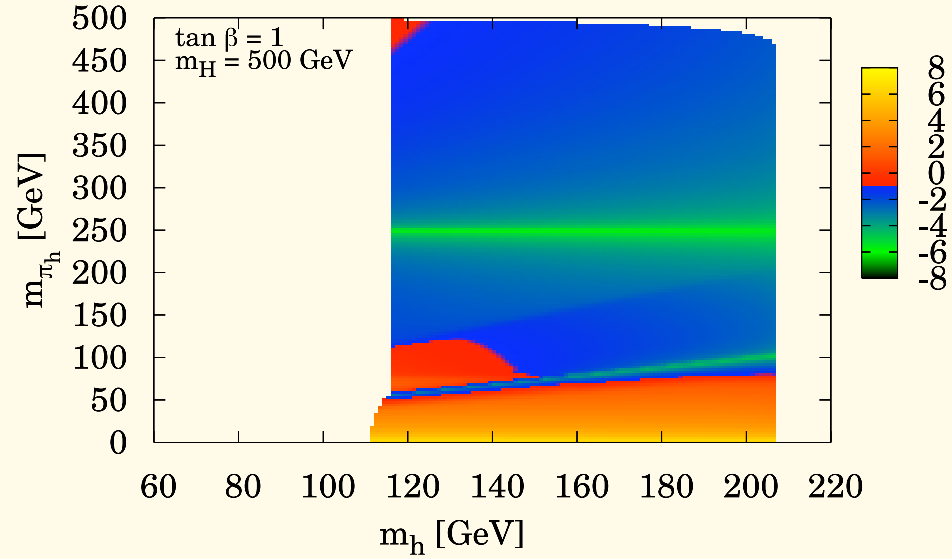
Not present in the two-Higgs Doublet model

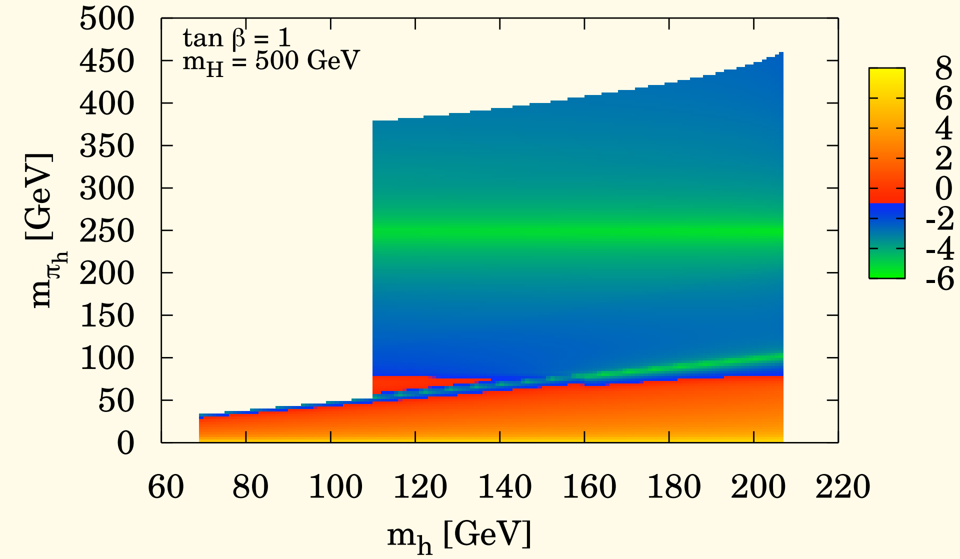
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1\lambda_2' > \lambda_3^2$

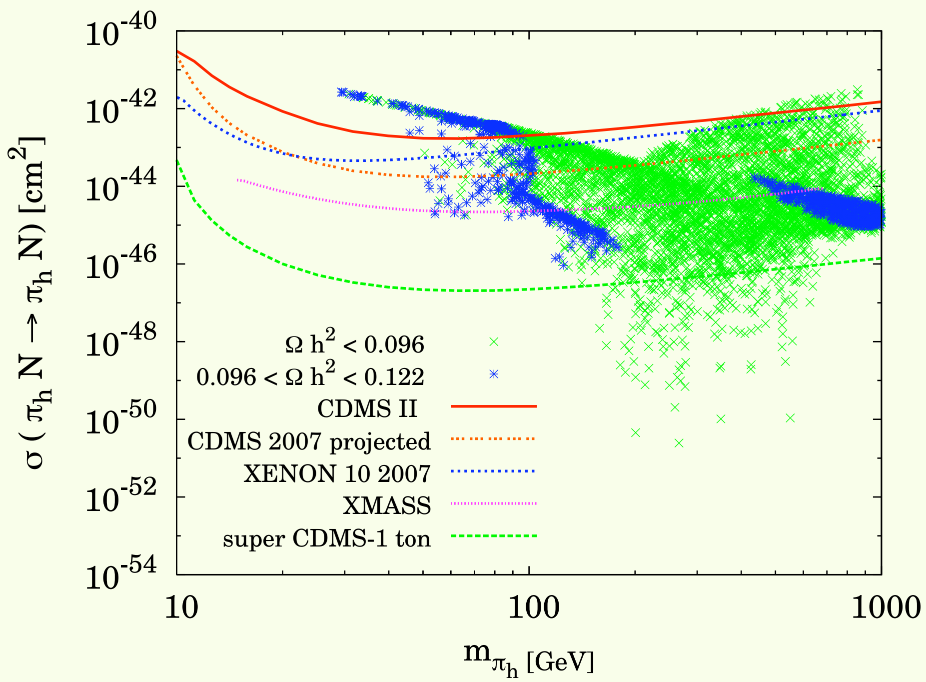
Relic Density

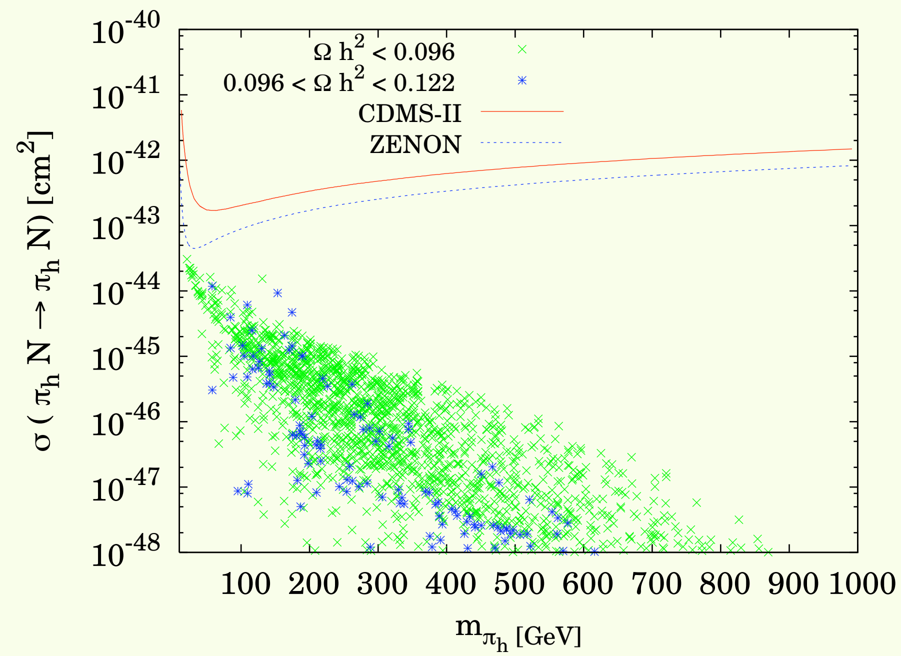




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

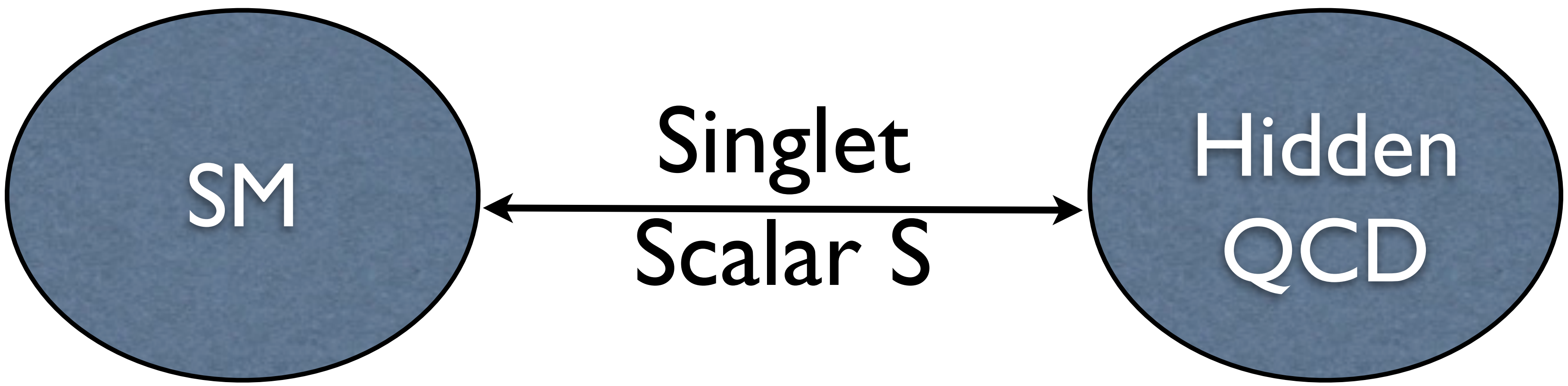




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by “S”

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \\ &+ \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c.\Big)\end{aligned}$$

Hidden sector lagrangian with new strong interaction

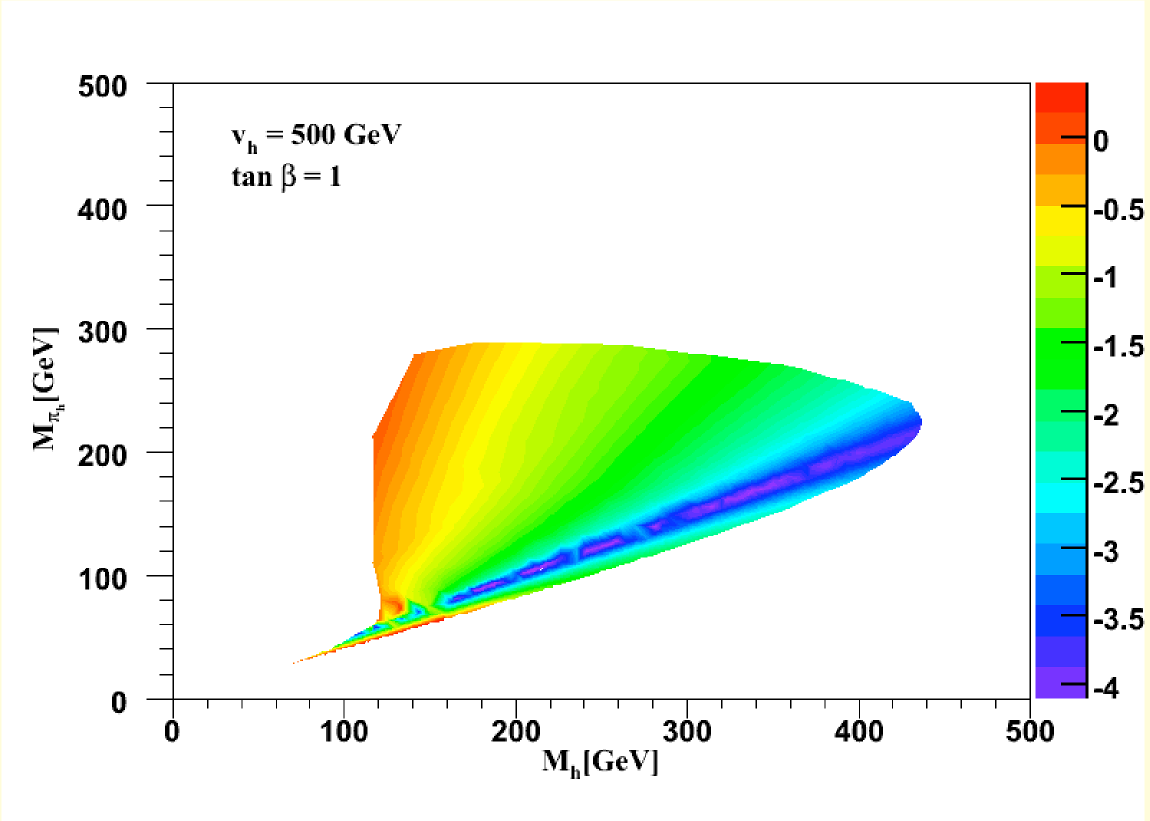
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

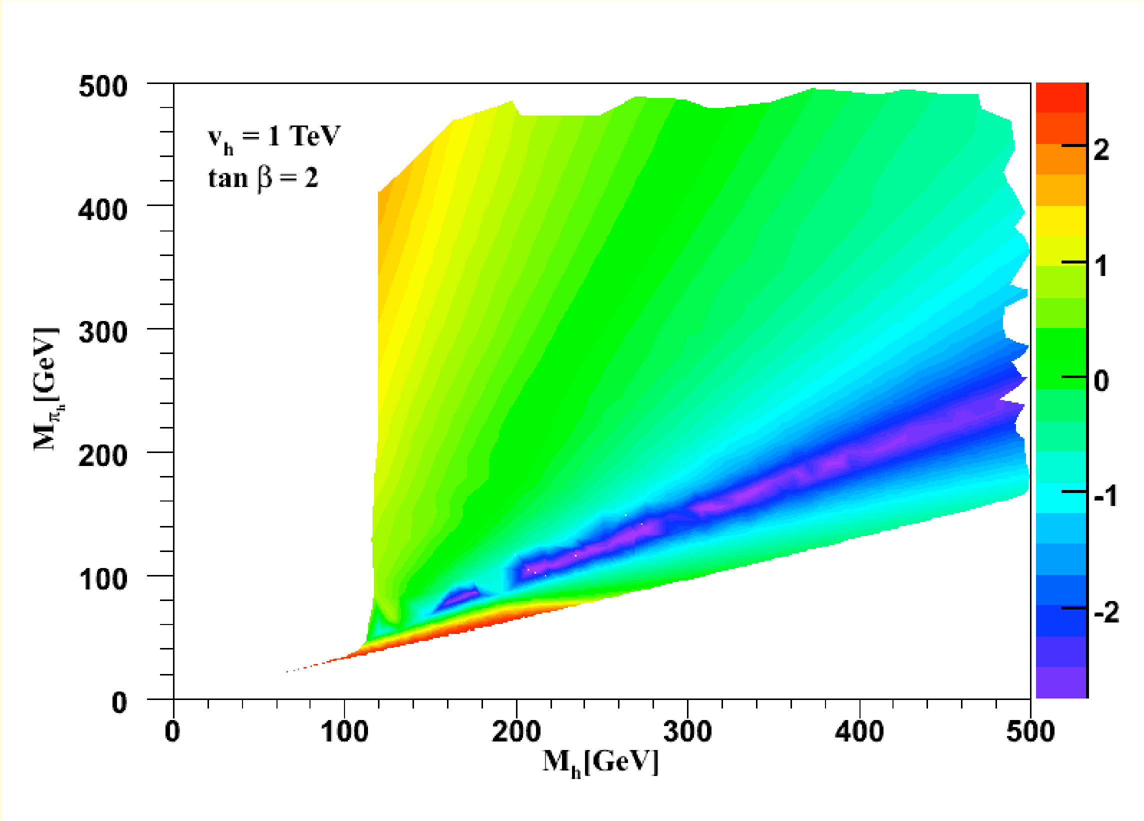
3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}$$

Relic density

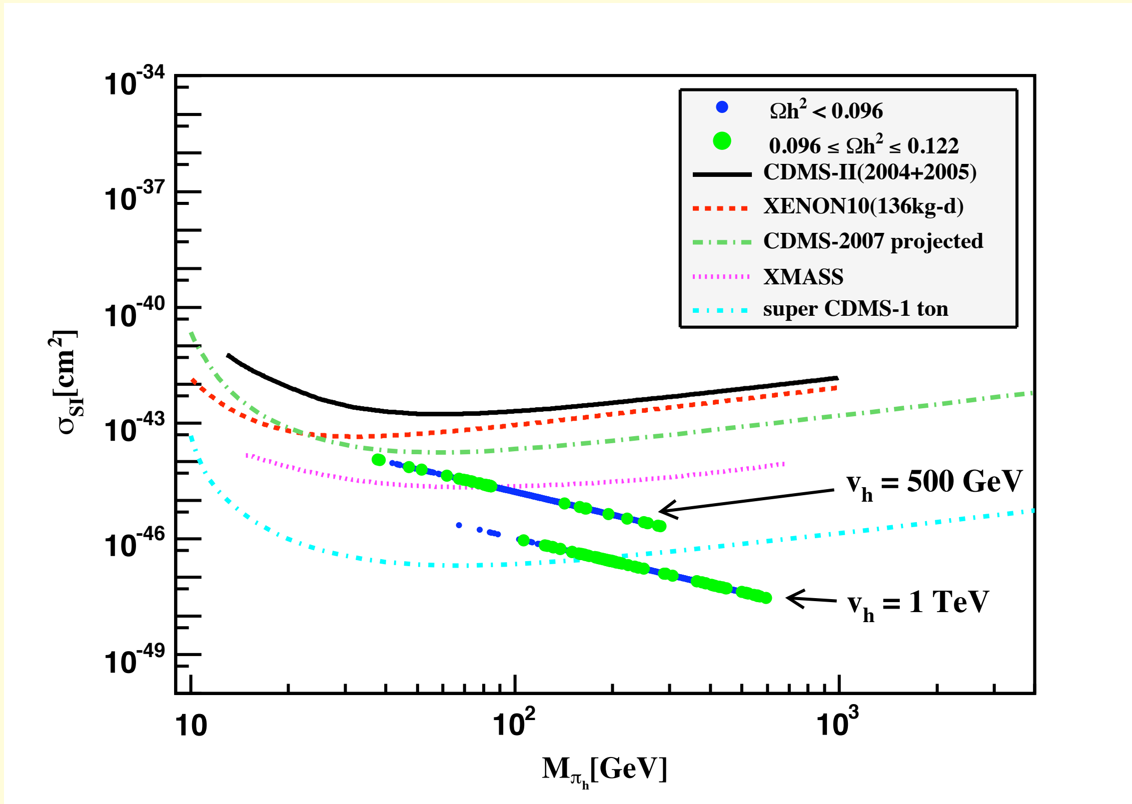




$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for
(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate

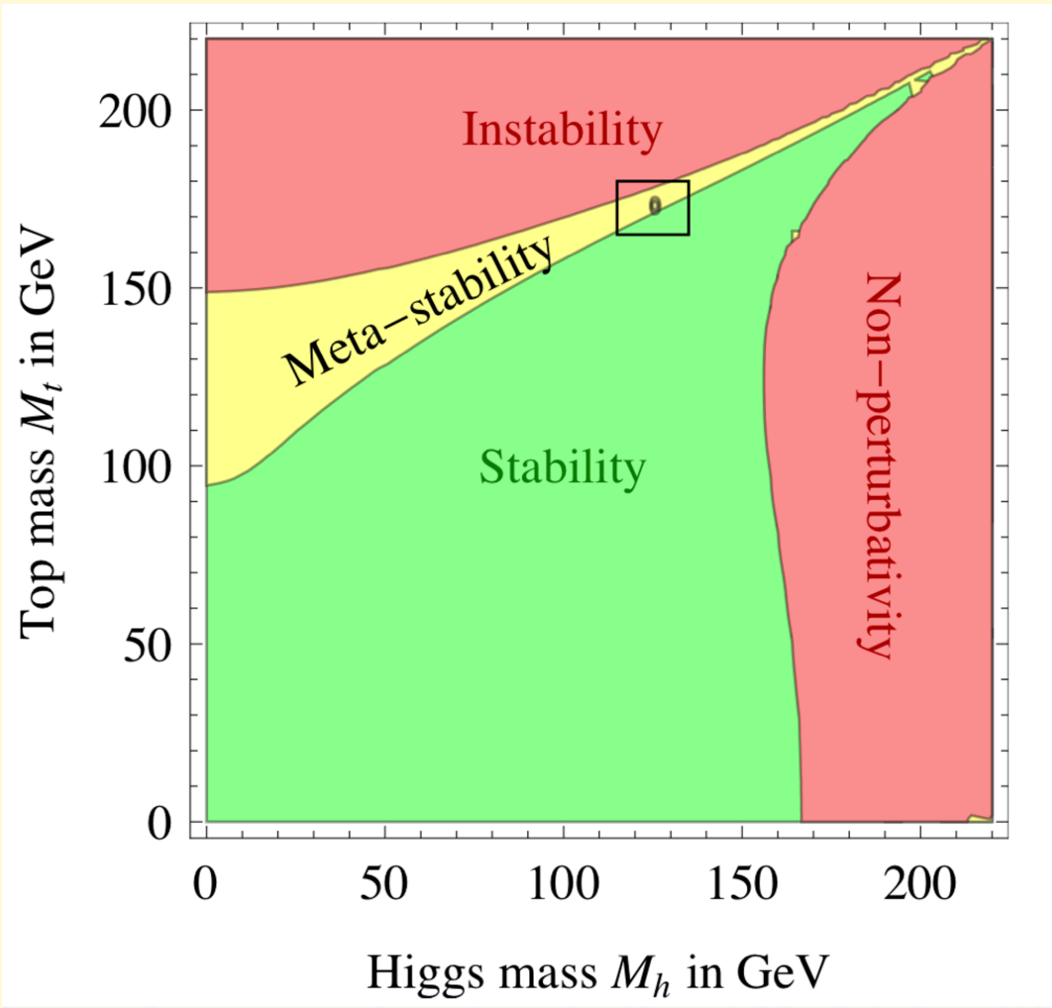


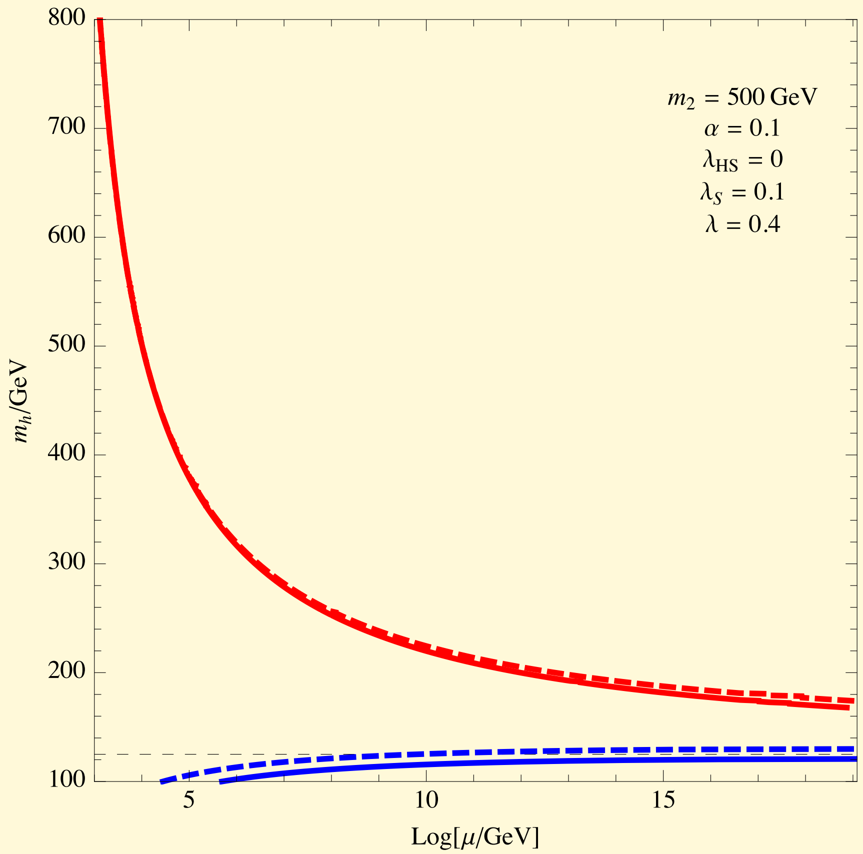
$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Vacuum Stability Improved by the singlet scalar S





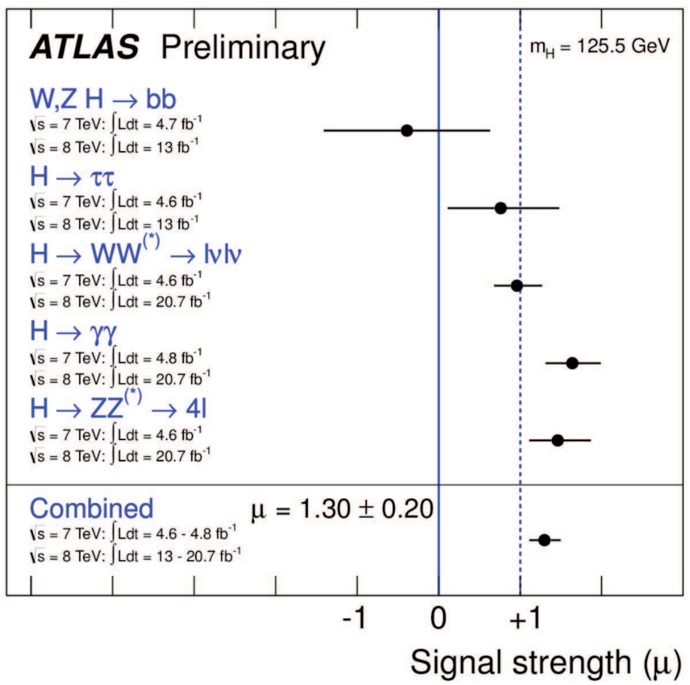
A. Strumia, Moriond EW 2013

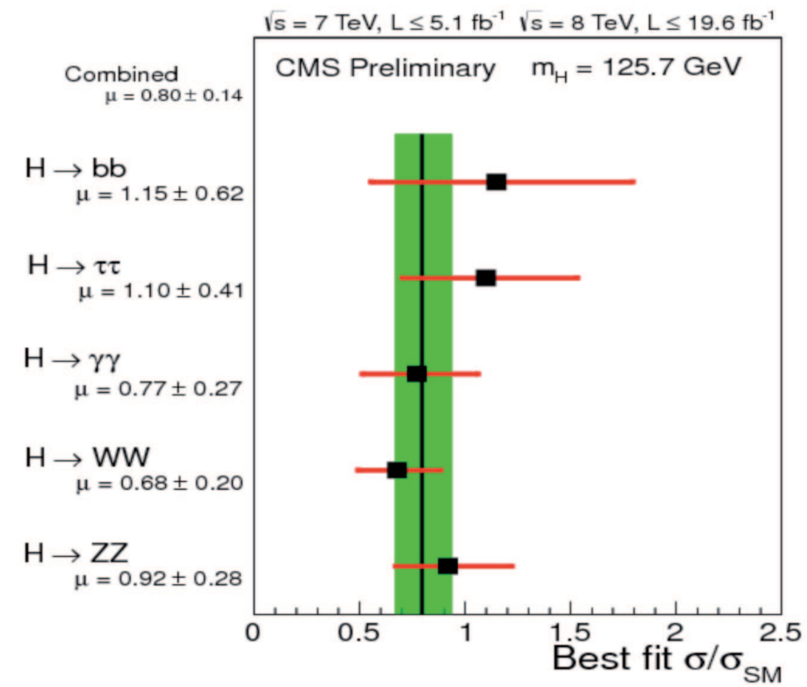
Baek, Ko, Park, Senaha (2012)

Updates@LHCP

Signal Strengths

$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$





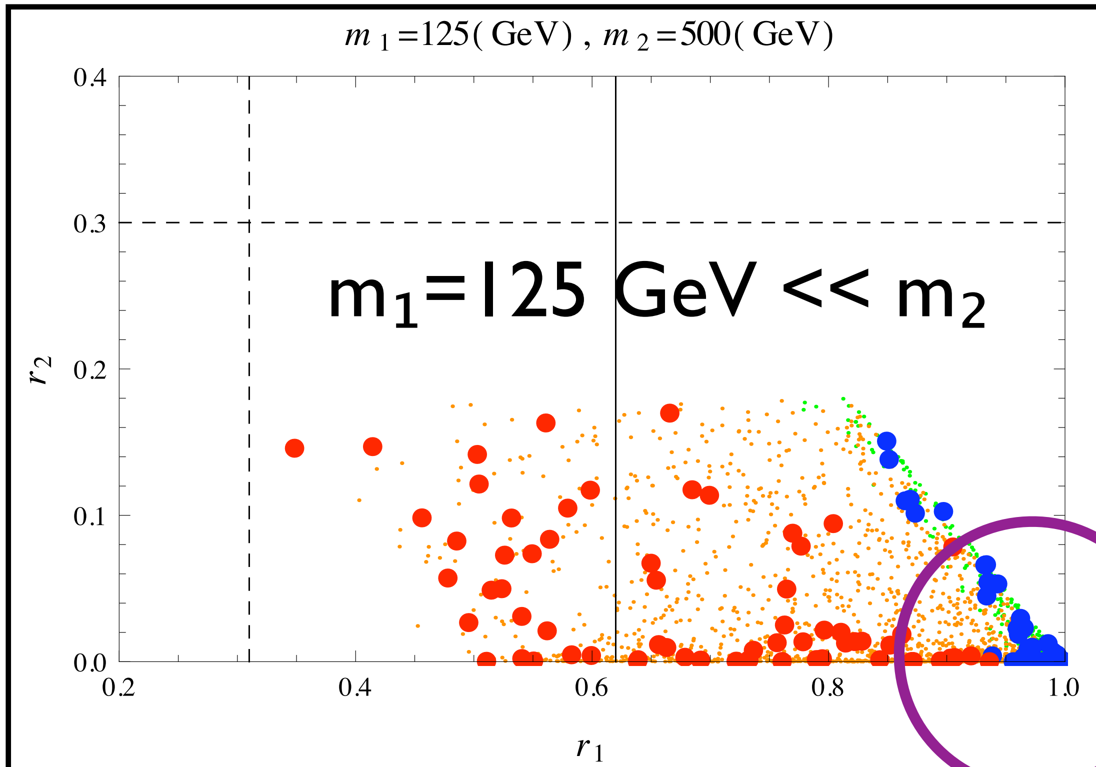
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

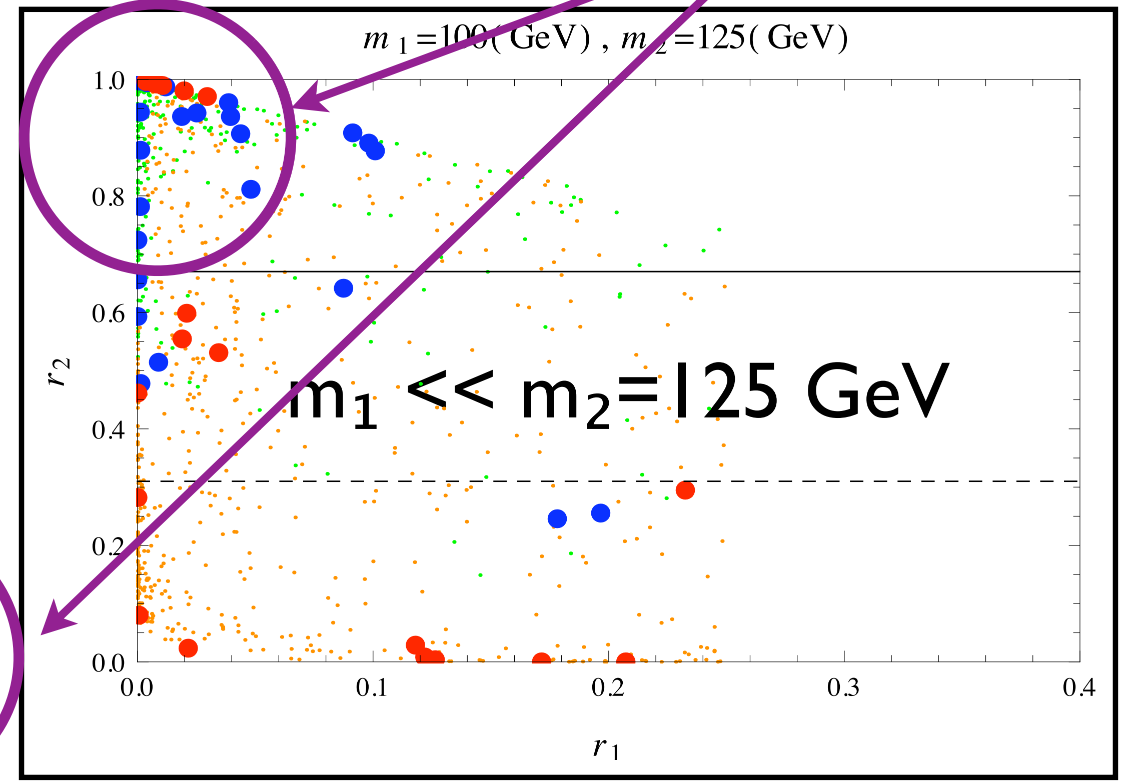
$$\langle \mu \rangle = 0.96 \pm 0.12$$

Discovery possibility

- Signal strength (r_2 vs r_1)

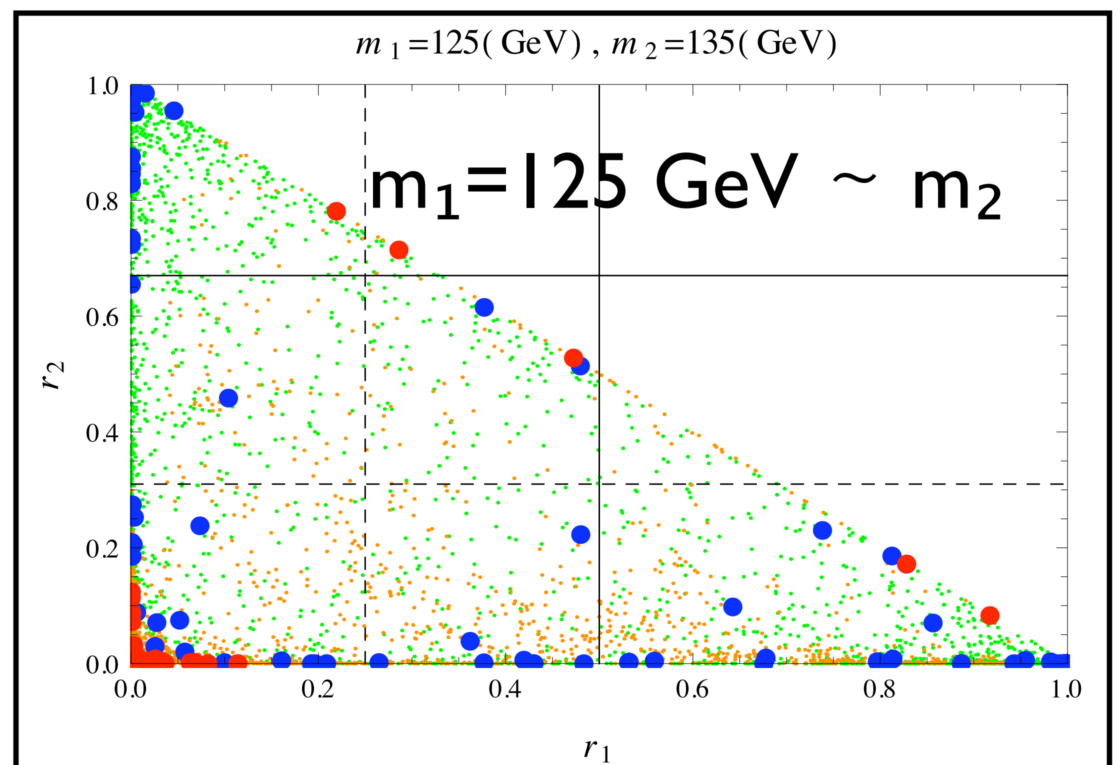
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.



- : Ω(x),σ_p(x)
- : Ω(x),σ_p(o)
- : Ω(o),σ_p(x)
- : Ω(o),σ_p(o)

- The 2nd scalar is very very elusive
- Small mixing limit is the interesting region
- How can we find the 2nd scalar at experiments ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

Naturalness Problem ?

- Scale Symmetry is explicitly broken only by dim-4 operators (beta functions)
- Our model is renormalizable when dim regularization is used, and no quadratic divergence
- Logarithmic sensitivity to high energy scale
- OK up to Planck scale as long as no new particles at high energy scale

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is absolutely stable), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without finetuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example
- Could consider SUSY version of it

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations (T. Asaka's talk)
- Better approach for hQCD ? (For example, Kugo, Lindner et al use NJL approach)

Conclusions

- We constructed a model where all the mass scales (including the DM mass) are generated by dimensional transmutation in a new strong dynamics in the hidden sector
- DM : Lightest mesons and baryons in the hidden sector (composite h-hadrons) which can have large self interacting cross section
- Higgs signal strengths < 1 (universally)