Phenomenology of the Minimal pNGB Higgs

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ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

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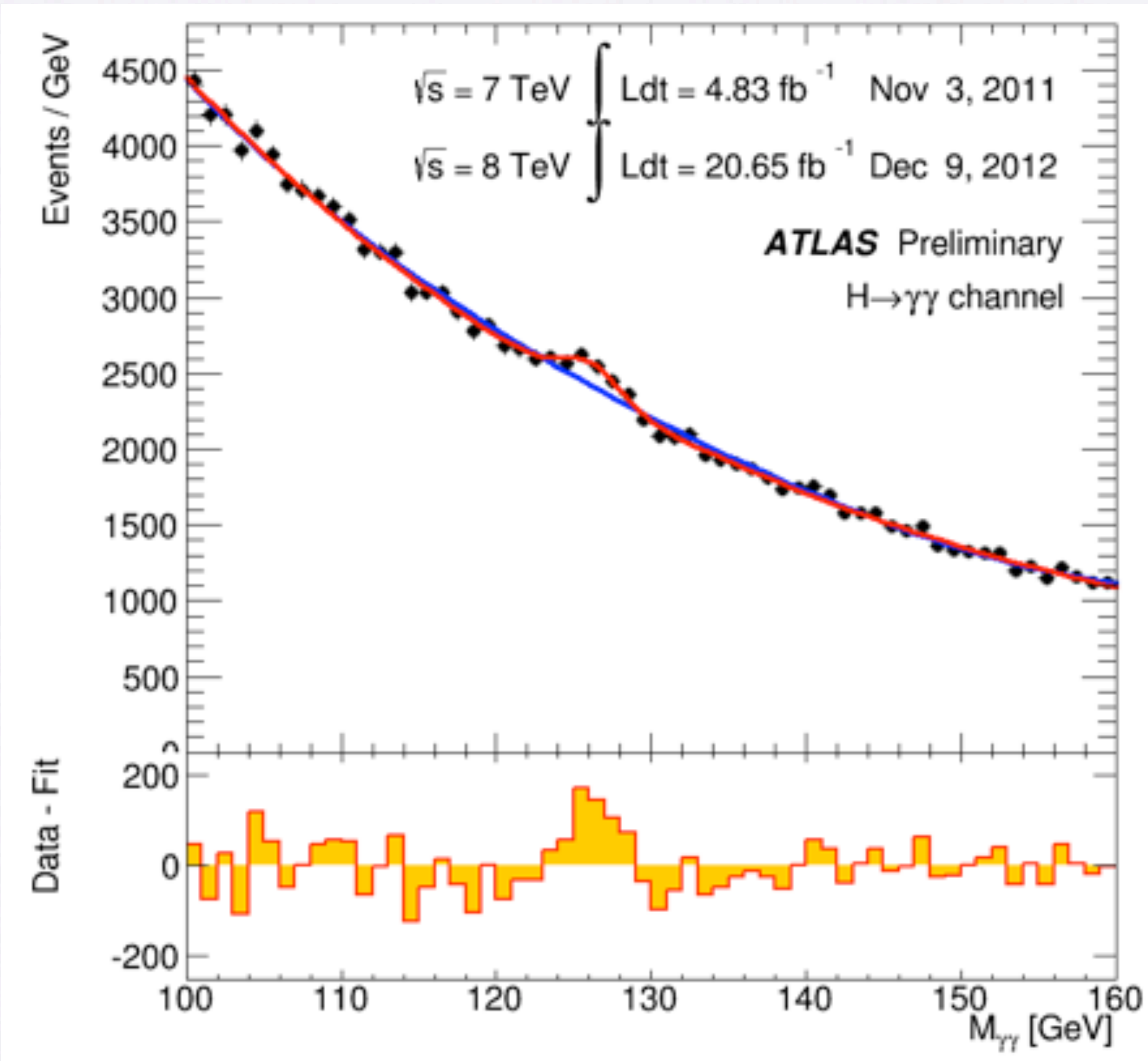
"JÚLIO DE MESQUITA FILHO"

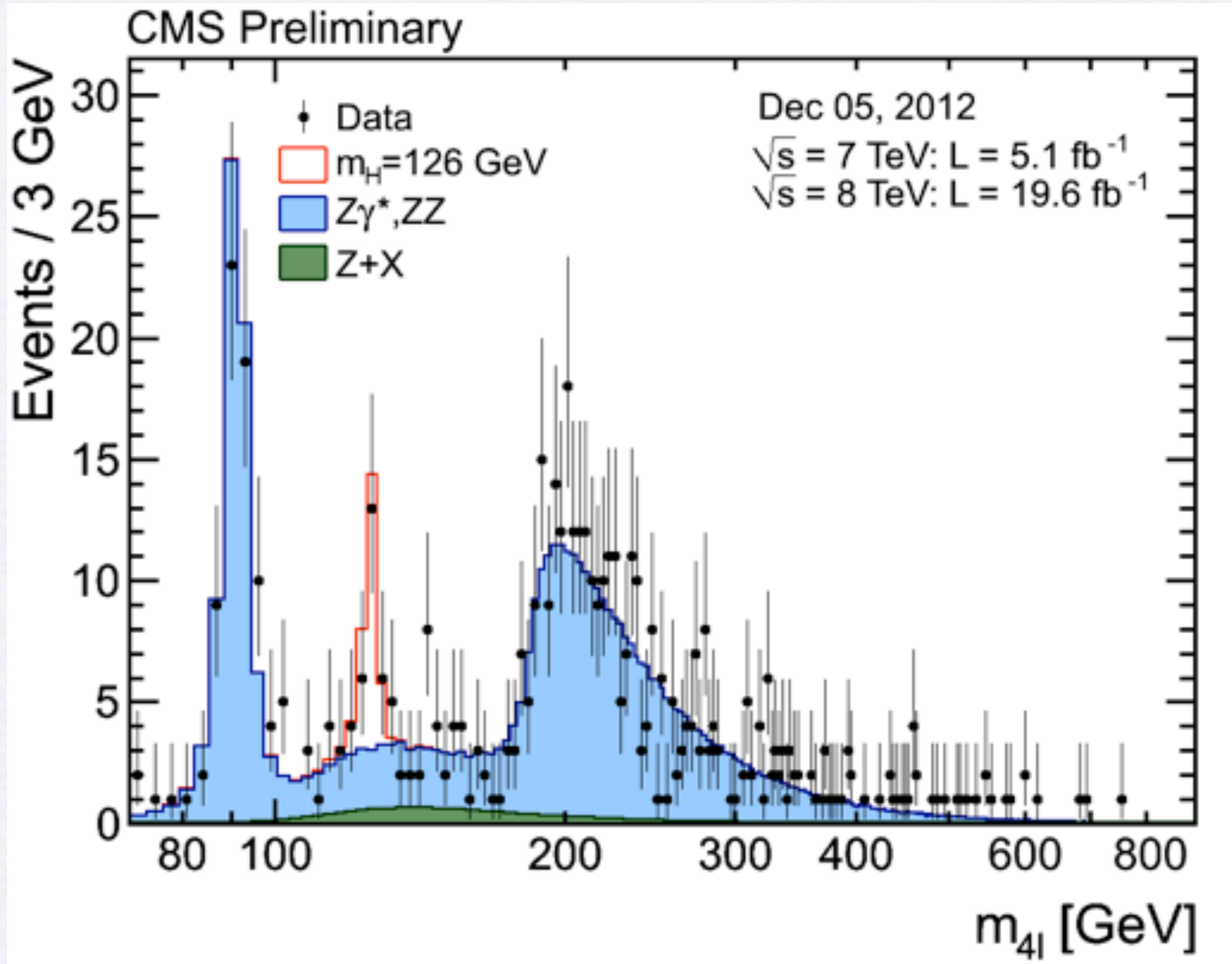
Outline

- Motivation
- The Minimal Composite Higgs Model (2-site model version)
- Higgs Phenomenology: Model Dependence
- Conclusions and Outlook

Ongoing work with Marcela Carena and Leandro da Rold

Resonance at ~125 GeV





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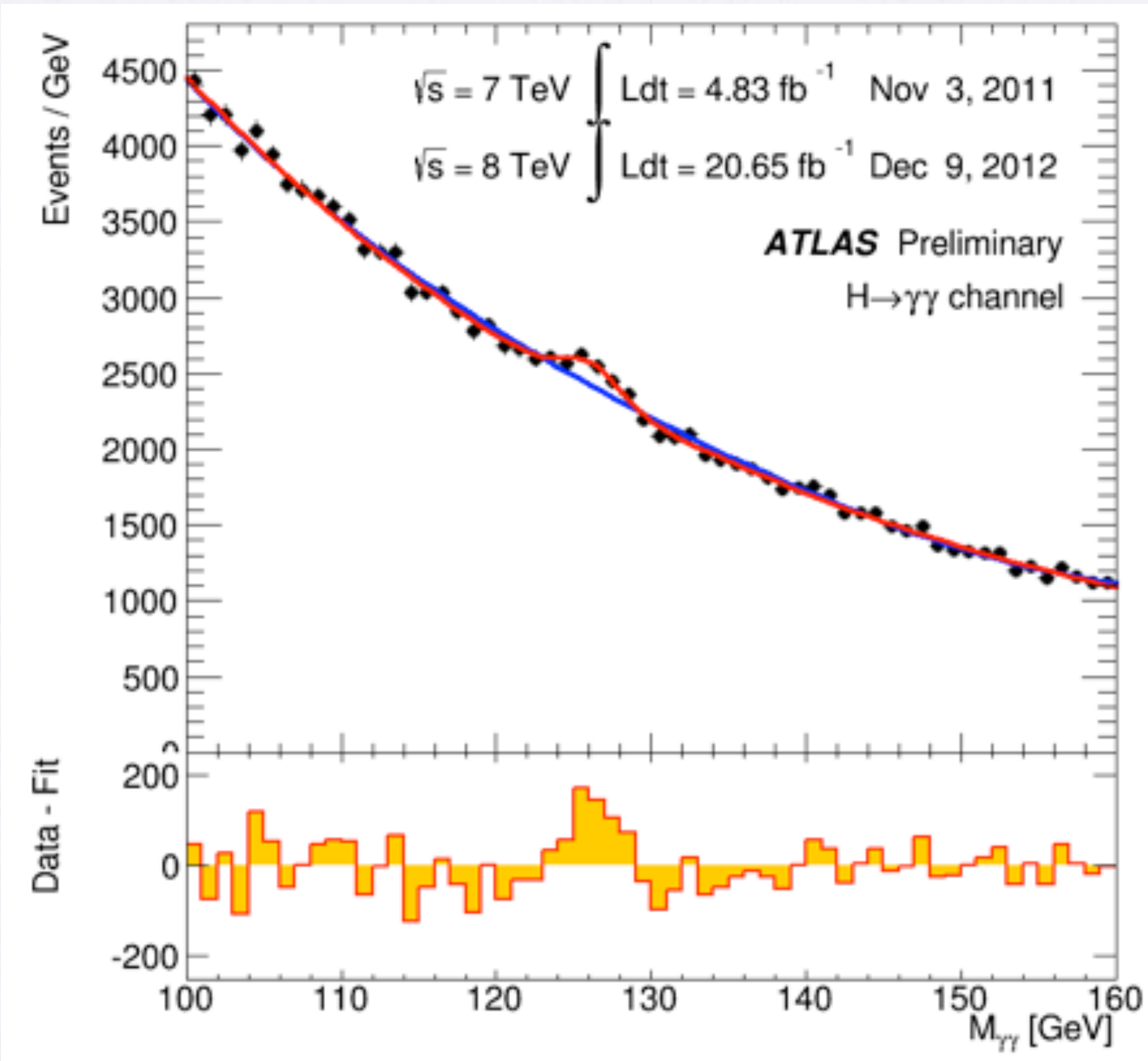
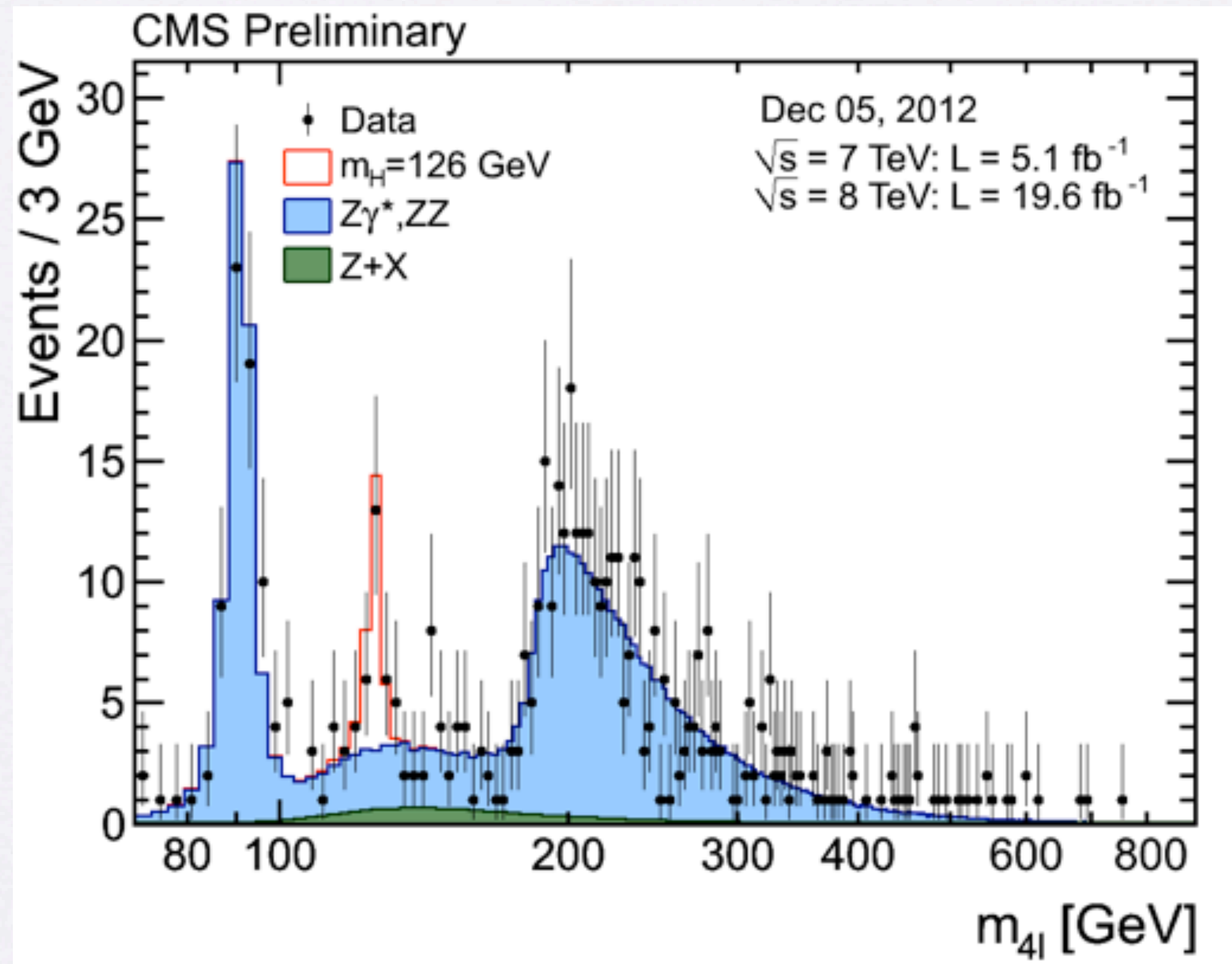
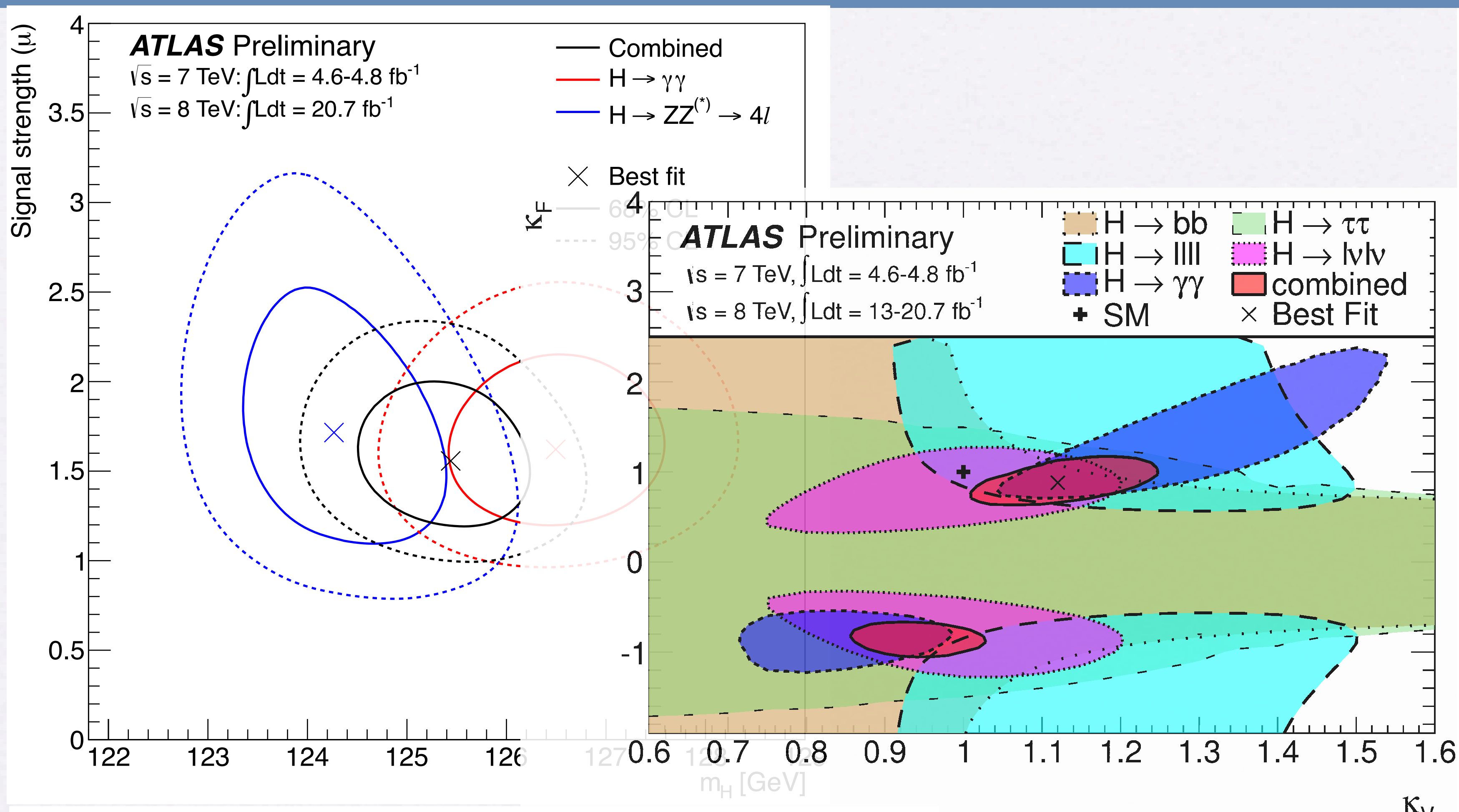
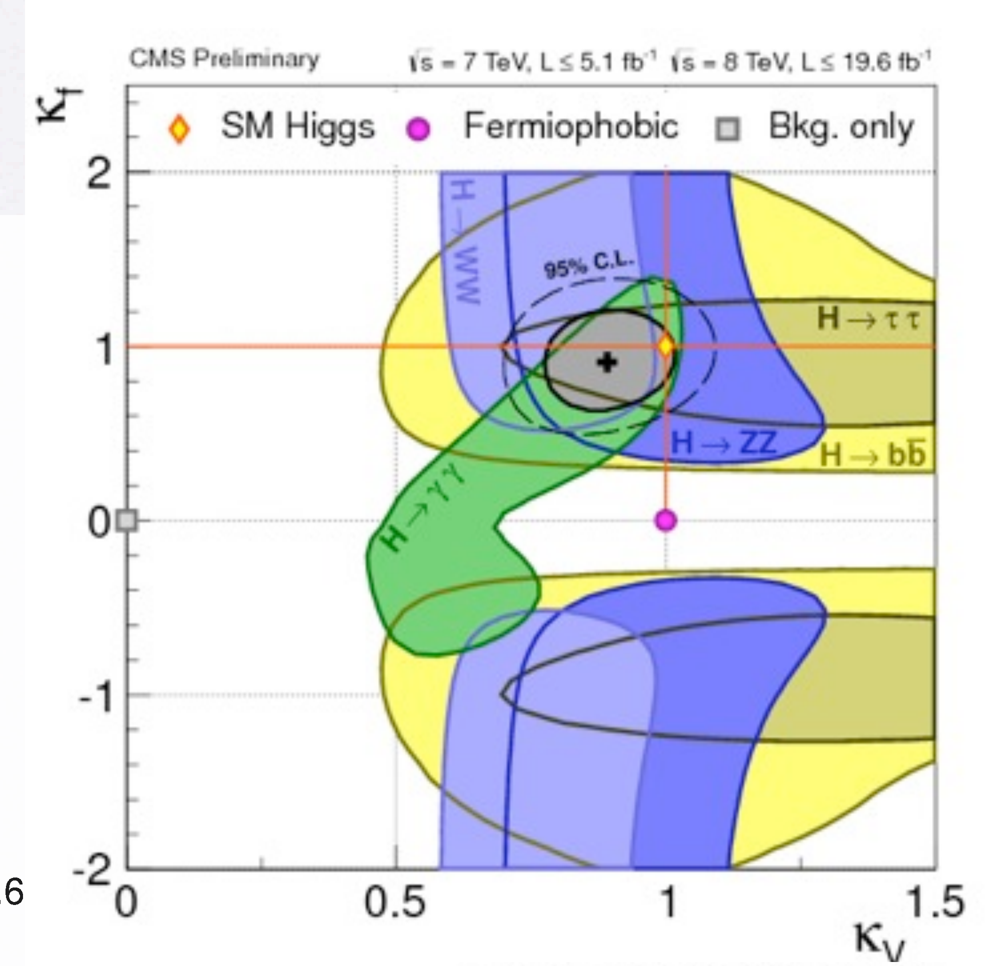


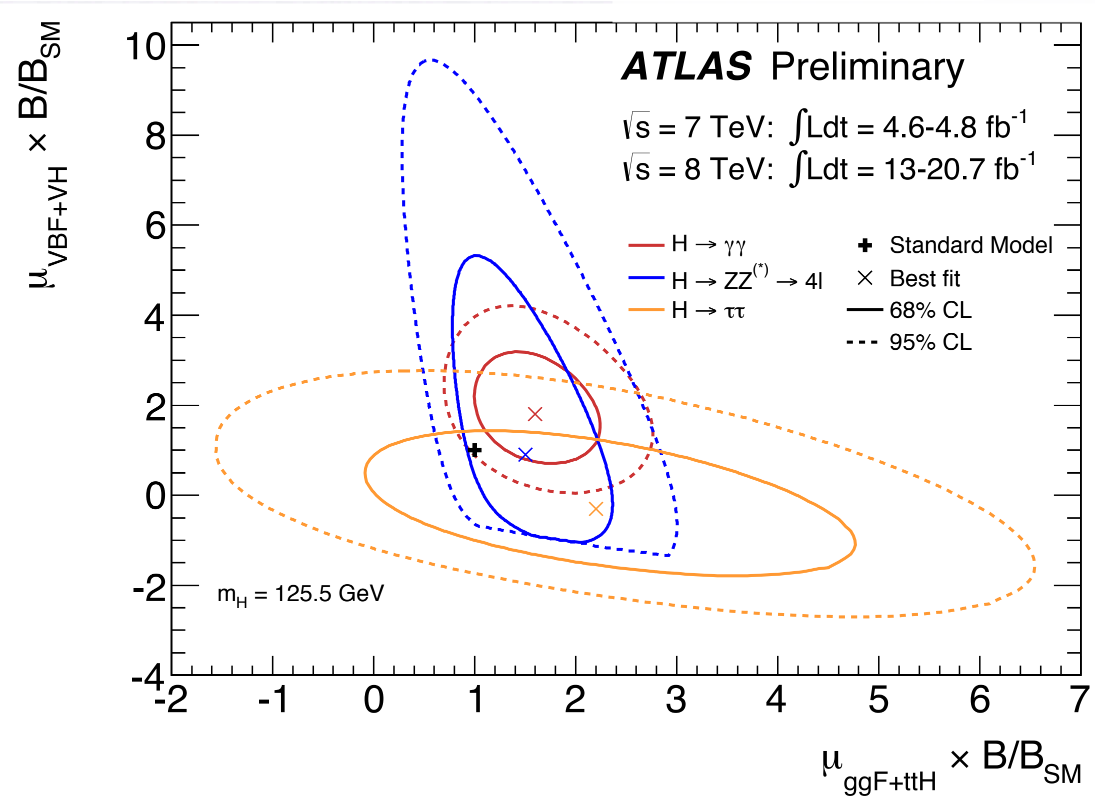


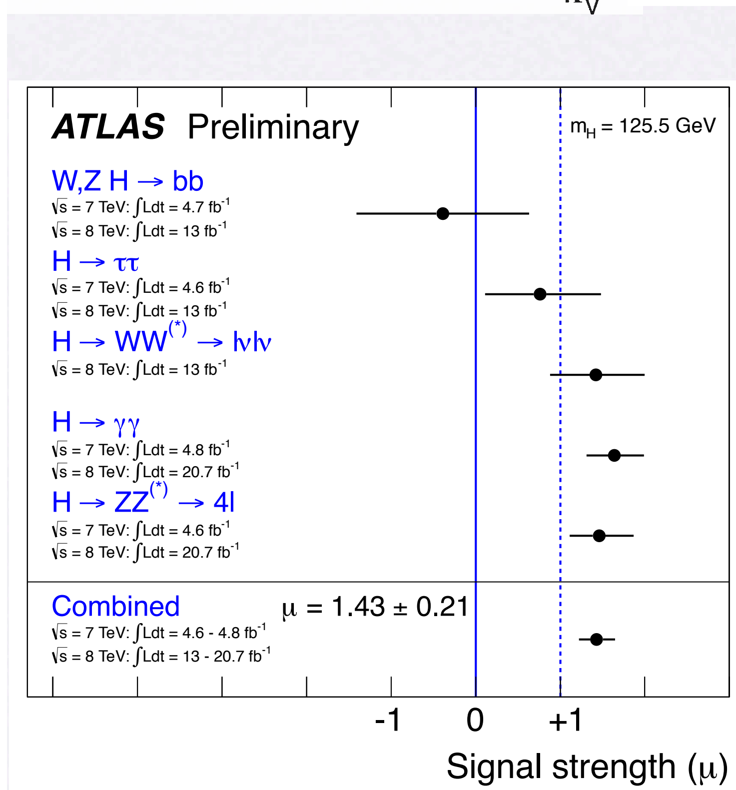
... and no deviations from the SM anywhere!

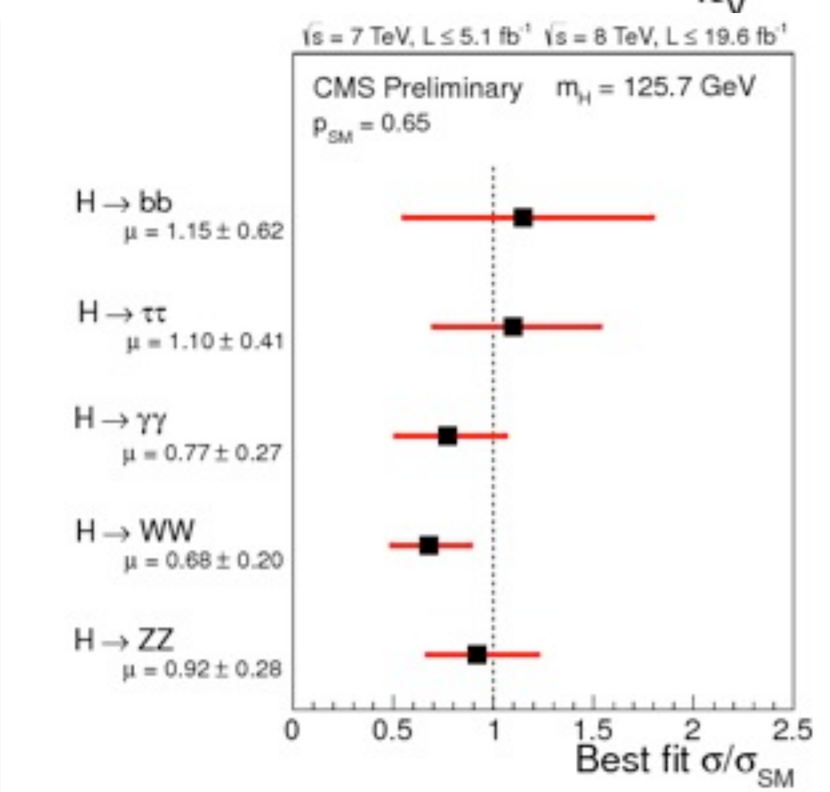
Signal Strengths











The Higgs Boson: A Milestone

- Is it elementary (up to scales parametrically larger than the weak scale)?

  → would be the first *elementary scalar* we know of!

- Or rather a composite scalar state of some underlying dynamics?

  → unlike other examples (e.g. pions), here inherits dynamics that gives it a vev, also a first...

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The Higgs as a pNGB

Elementary sector:
SM gauge bosons,
quarks & leptons

SM gauge interactions
↔
Mixing

New strong sector:
resonances +
Higgs bound state

But why would the Higgs resonance be lighter than the rest?

Natural to interpret the composite Higgs as a (pseudo) Nambu-Goldstone boson

Higgs in $G/\mathcal{H}$

Georgi & Kaplan '84
Agashe et. al '03

Inspiration from pions in QCD (with 2 flavors): $SU(2)_L \times SU(2)_R / SU(2)_{L+R}$

$\pi^0, \pi^\pm$ **are NGB's of spontaneous breaking**

Acquire masses from explicit breaking:

- $m_q \neq 0 \;\Rightarrow\; m_\pi^2 \simeq m_q B_0$
- $e \neq 0 \;\Rightarrow\; m_{\pi^\pm}^2 - m_{\pi^0}^2 \sim \frac{e^2}{16\pi^2}\Lambda^2$

The MCHM

(i.e. Minimal Composite Higgs Model)

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Pattern of symmetry breaking in the EW sector:

Gauge: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

$\cap$

Global: $SO(5) \xrightarrow[E \sim f]{} SU(2)_L \times SU(2)_R \xrightarrow[E \sim v]{} SU(2)_{L+R}$ custodial

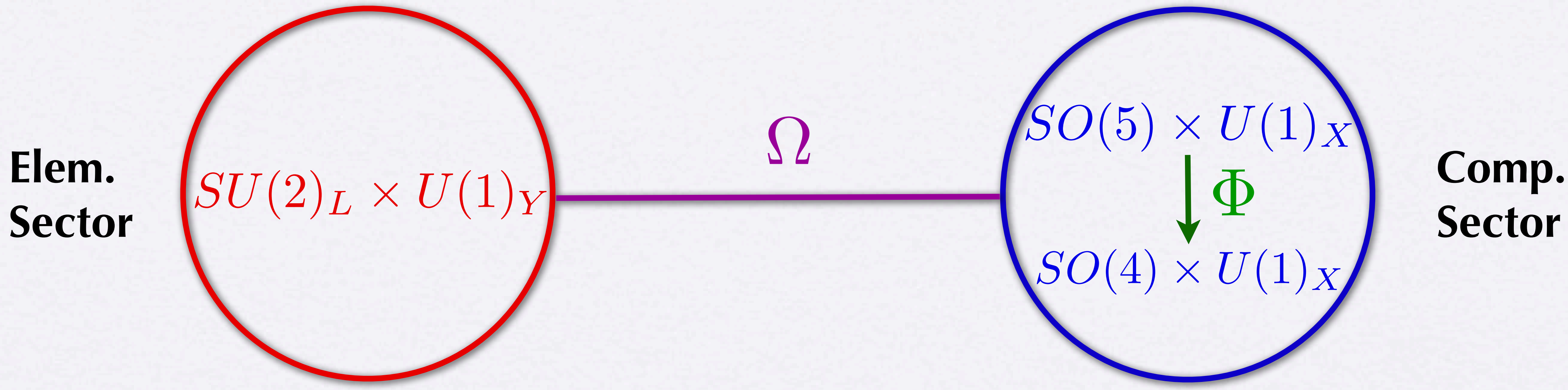
$SO(5) \times U(1)_X$ **smallest group** $\supset SU(2)_L \times U(1)_Y$ **& cust. symm. & H = pNGB**

Agashe, Contino, Pomarol '04;

2-Site Model

Contino, Kramer, Son & Sundrum, 2006

de Curtis, Redi & Tesi, 2011



$$\mathcal{L} = \mathcal{L}_{\rm el} + \mathcal{L}_{\rm mix} + \mathcal{L}_{\rm cp}$$

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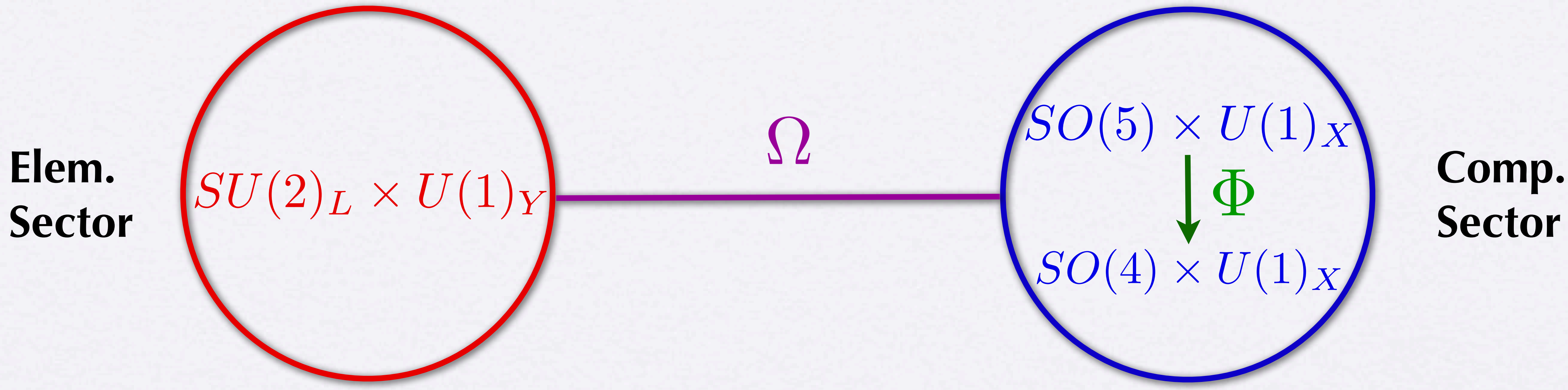

$$\mathcal{L} = \mathcal{L}_{\rm el} + \mathcal{L}_{\rm mix} + \mathcal{L}_{\rm cp}$$

- **Elementary sector**

$$\mathcal{L}_{\rm el} = \mathcal{L}_{\rm SM}(\psi_L^{\rm el}, \tilde{\psi}_R^{\rm el}, A_\mu^{\rm el})$$

- **Gauge symmetry:** G_{SM}
- **massless fermions**
- **no Higgs field**

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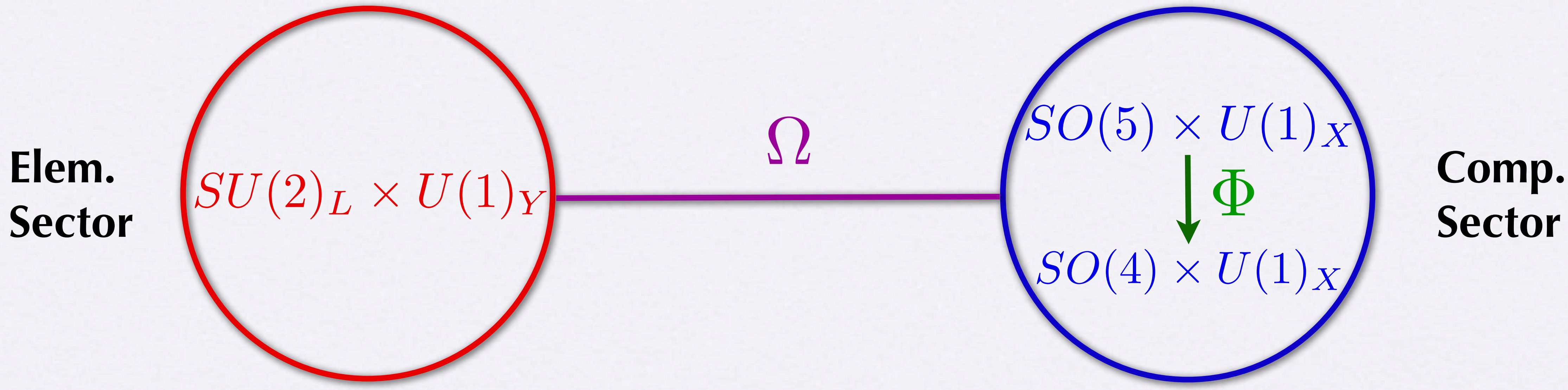

$$\mathcal{L} = \mathcal{L}_{\rm el} + \mathcal{L}_{\rm mix} + \mathcal{L}_{\rm cp}$$

- **Effective description of the composite sector:** $\rho_\mu^{\rm cp}, \psi^{\rm cp} + \Phi$

$$\mathcal{L}_{\rm cp}^{\rm eff} = -\frac{1}{4}(F_{\mu\nu}^{\rm cp})^2 + \bar{\psi}^{\rm cp}(i\not{D}^{\rm cp} - M_{\rm cp})\psi^{\rm cp} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_\Phi$$

- **Include one set of spin-1 resonances [in adjoint of SO(5)]**
- ***Vector-like* fermions with quantum numbers of SM fermions**
- **Spontaneous breaking parametrized by Φ**

characterized by

$g_{\rm cp} \gg g_{\rm SM}$

scale f

$(M_{\rm cp} \sim g_{\rm cp} f)$

2-Site Model

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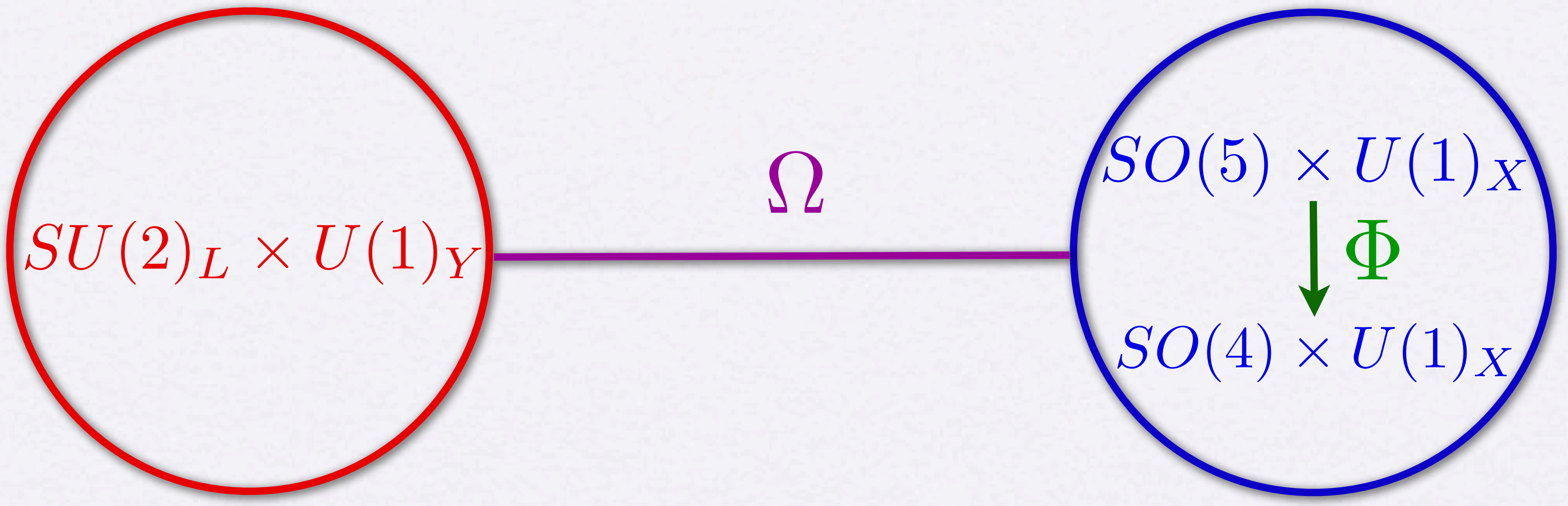
Elem. Sector



Comp. Sector

$$\mathcal{L} = \mathcal{L}_{\rm el} + \mathcal{L}_{\rm mix} + \mathcal{L}_{\rm cp}$$

- **Non-linear sigma model connecting the two sites** $\Omega \to g_{\rm el} \Omega g_{\rm cp}^\dagger$

$$G^{\rm el} \times G^{\rm cp} \to G_{\rm SM}$$

$$\mathcal{L}_{\rm mix}^{\rm eff} \supset \frac{1}{4} f_\Omega^2 {\rm Tr}|D_\mu \Omega|^2 + \Delta\, \bar{\psi}_L^{\rm el}\, \Omega\, \mathcal{P}_\psi \psi_R^{\rm cp} + \tilde{\Delta}\, \bar{\tilde{\psi}}_R^{\rm el}\, \Omega\, \mathcal{P}_{\tilde{\psi}} \tilde{\psi}_L^{\rm cp}$$

$\Delta, \tilde{\Delta}$: explicit breaking of SO(5) $\longrightarrow$ small numbers from small mixings

$$\tan\theta_\psi = \Delta / M_{\rm cp}$$

EWSB

Effective description of $SO(5) \to SO(4)$ **breaking:**

$$\Phi = e^{i\Pi/f_\pi}(0,0,0,0,1)^T$$

$$\Pi = \sum_{a=1}^{4} \Pi^{\hat{a}} T^{\hat{a}}$$

$T^{\hat{a}}$ **the** $SO(5)/SO(4)$ **generators**

In unitary gauge

- **Before EWSB:** $\Phi = \frac{1}{h}\sin(h/f_\pi)\,\{h_1, h_2, h_3, h_4, h\cot(h/f_\pi)\}^T$ $\quad h \equiv \sqrt{h_1^2 + h_2^2 + h_3^2 + h_4^2}$

- **After EWSB:** $\langle h_3 \rangle = v$ $\quad \langle \Phi \rangle = (0, 0, \epsilon, 0, \sqrt{1-\epsilon^2})^T$

New parameter: $\epsilon = \sin(v/f_\pi)$

EWSB

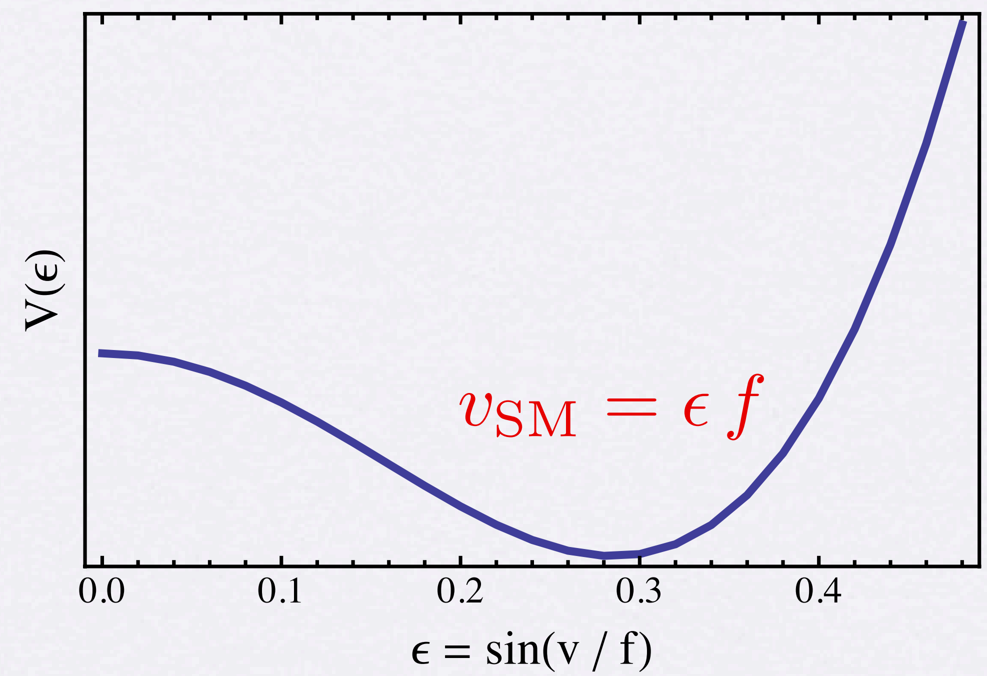
In the limit that $g, g' \to 0$ & $\Delta, \tilde{\Delta} \to 0$, the $\Pi' s$ are exact NGB's

⟶ Higgs potential generated by gauge and ``Yukawa" interactions

In the 2-site model, the 1-loop potential is calculable if we allow only

$$y_u \bar{Q}_L \Phi U_R + y_d \bar{Q}_L \Phi D_R$$ (not the opposite chiral structure)

- Gauge interactions: prefer ``vacuum alignment" (no EWSB)
- Yukawa interactions (dominated by top): can induce EWSB



EWSB

Higgs potential depends on SO(5) representations of fermionic resonances

$$\psi^{\rm cp} = 1, 4, 5, 10, 14, \ldots$$

- **Large top mass requires large θ_q ⟶ Impact on bottom sector**

- **Protection of $Zb\bar{b}$ coupling restricts the choice of fermion rep's** Agashe, Contino, da Rold Pomarol, 2006

  e.g. t_L **embedded in** $5_{2/3}, 10_{2/3}, 14_{2/3}, \ldots$ of $SO(5) \times U(1)_X$

- **This work:** $q_L - t_R - b_R =$ **5-5-5, 10-10-10**

  5-5-10, 5-10-10, 10-5-10

  14-14-1, 14-14-10

Higgs Phenomenology

Goals

- Explore implications for Higgs phenomenology in several realization of the MCHM

  How can we distinguish between different models, hence learn something about the strongly interacting sector (through Higgs measurements)?

- Take into account full minimization of dynamically generated Higgs potential

- Incorporate $m_h \sim 126~\mathrm{GeV}$ (as well as m_t and m_b)

Strategy

- **Random scan over parameters** (with a common heavy scale)
- **Minimize resulting Higgs potential. If EWSB, normalize to reproduce** M_Z
- **Select points with**

$$m_h \approx [120-130]\ \mathrm{GeV} \qquad m_t \in [150-170]\ \mathrm{GeV} \qquad m_b \approx 4\ \mathrm{GeV}$$

For example, in the model based on 10's of SO(5), in addition to f_π **and** g_ρ **:**

Mixing terms

$$\mathcal{L}_f = \sum_{\psi=q_L,u_R,d_R} \bar{\psi} i \not{D} \psi + \overbrace{\bar{q}_L \Delta_q Q_R + \bar{u}_R \Delta_u U_L + \bar{d}_R \Delta_d D_L}^{\text{Mixing terms}} + \text{h.c.}$$

$$+ \sum_{\Psi=Q,U,D} \bar{\Psi}(i\not{D} - M_\Psi)\Psi + m_{y_u} \bar{Q}_L U_R + m_{y_d} \bar{Q}_L D_R + \text{h.c}$$

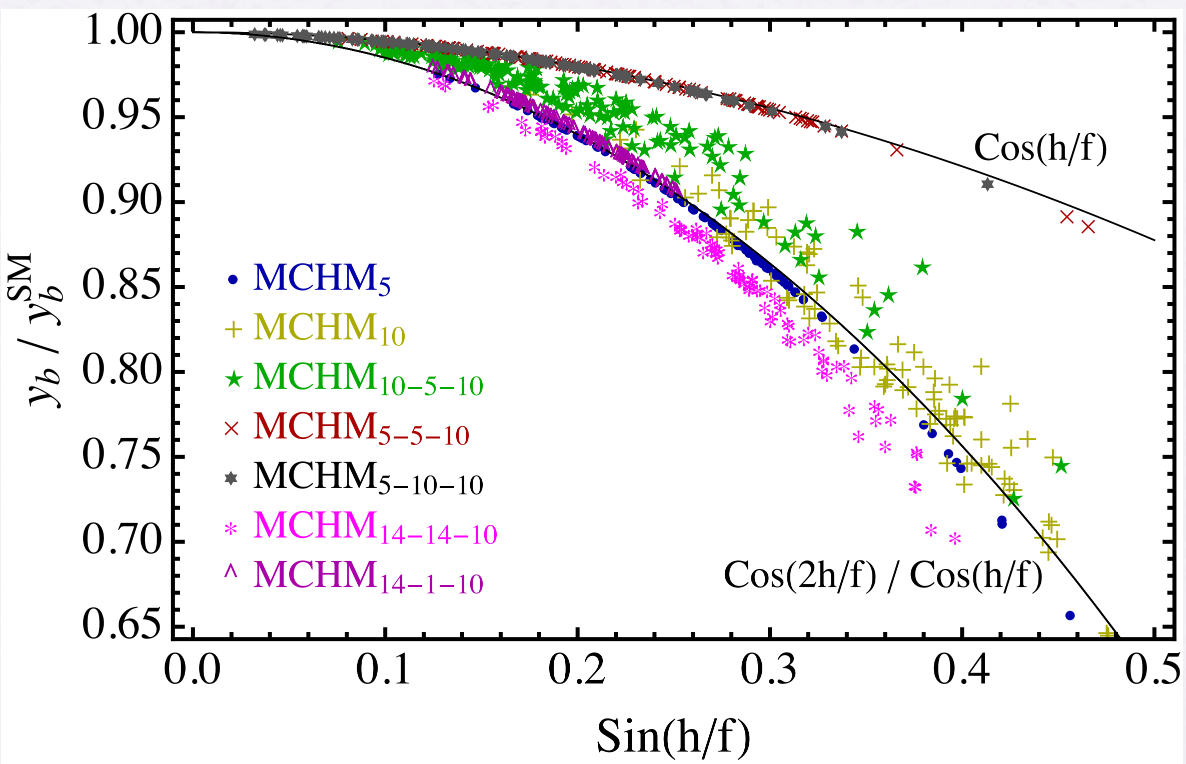
$$+ y_u \Phi^\dagger \bar{Q}_L U_R \Phi + y_d \Phi^\dagger \bar{Q}_L D_R \Phi + \text{h.c.}$$

← **Yukawa terms**

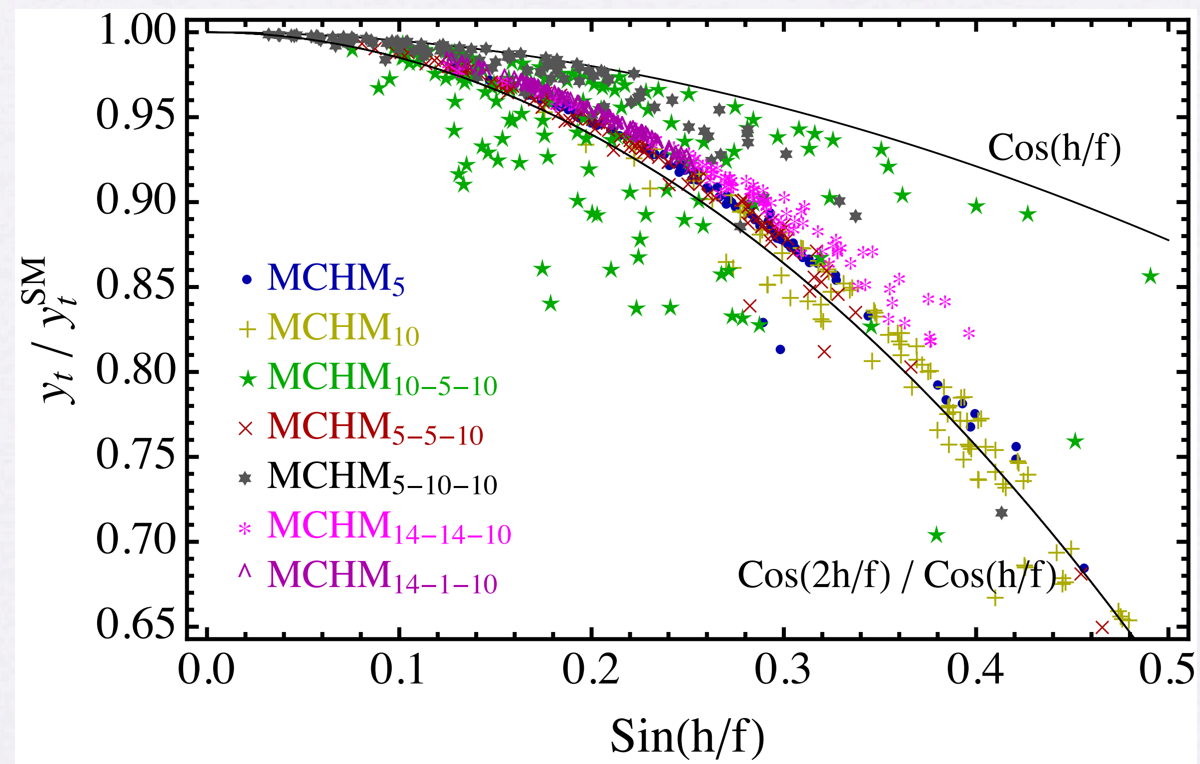
Deviations in SM Yukawa Int's

Depending mainly on $\epsilon = \sin(v/f)$, deviations up to 20%

Bottom Yukawa



Top Yukawa



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$$\sum_n \frac{y_n^\psi}{m_n^\psi} = \mathrm{Tr}(Y_\psi M_\psi^{-1}) = \frac{d}{dh}\log\det(M_\psi^\dagger M_\psi) = \frac{1}{\epsilon f}F^\psi(\epsilon)$$

$$= \frac{y_0^\psi}{m_0^\psi} + \sum_{n>0}\frac{y_n^\psi}{m_n^\psi}$$

→ **Small unless light states**

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$$\frac{y_0^\psi}{m_0^\psi} = \frac{1}{\epsilon f}F^\psi(\epsilon)\left[1+\mathcal{O}(\epsilon^2\times\sin^2\theta_{\psi_L},\epsilon^2\times\sin^2\theta_{\psi_R})\right]$$

→

$$\frac{y_0^\psi}{y_{SM}^\psi} = v\times\frac{y_0^\psi}{m_0^\psi} \approx F^\psi(\epsilon)$$

MCHM/SM	10-5-10	5-5-10	5-10-10	5, 10, 14-14-10, 14-1-10
c_g	F_2	F_1	F_2	F_1
y_t	F_2	F_1	F_2	F_1
y_b	F_1	F_2	F_2	F_1
c_V	F_2	F_2	F_2	F_2

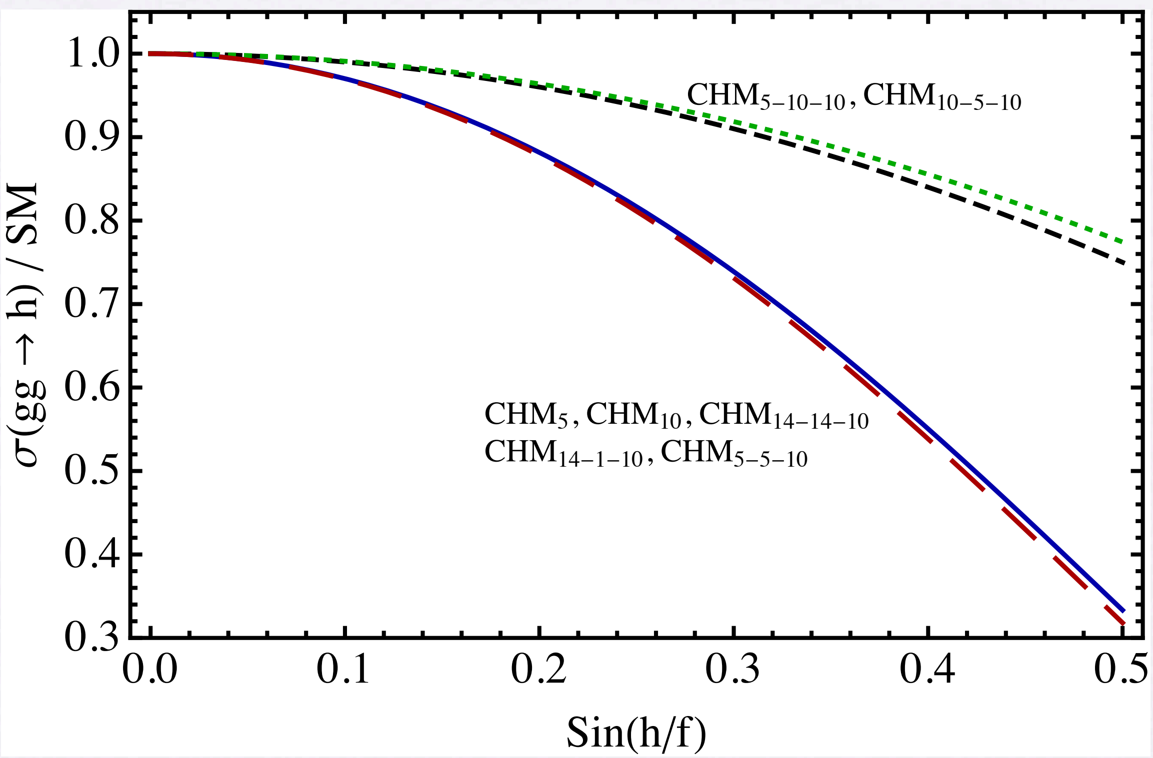
$$F_1 = \frac{1-2\epsilon^2}{\sqrt{1-\epsilon^2}}$$

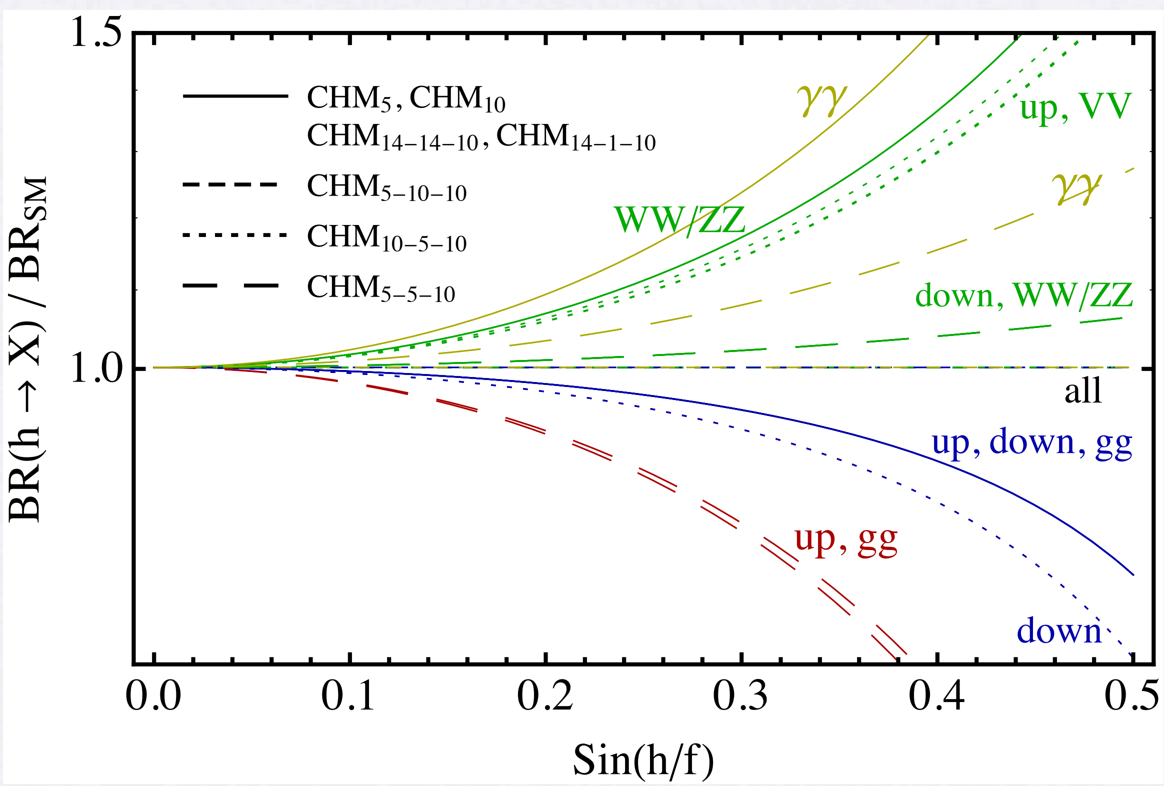
$$F_2 = \sqrt{1-\epsilon^2}$$

Higgs Production and BR's

- **Production always suppressed**
- **BR's can be enhanced or suppressed, depending on model and decay channel**

→ **Phenomenology determined by interplay of opposing effects**

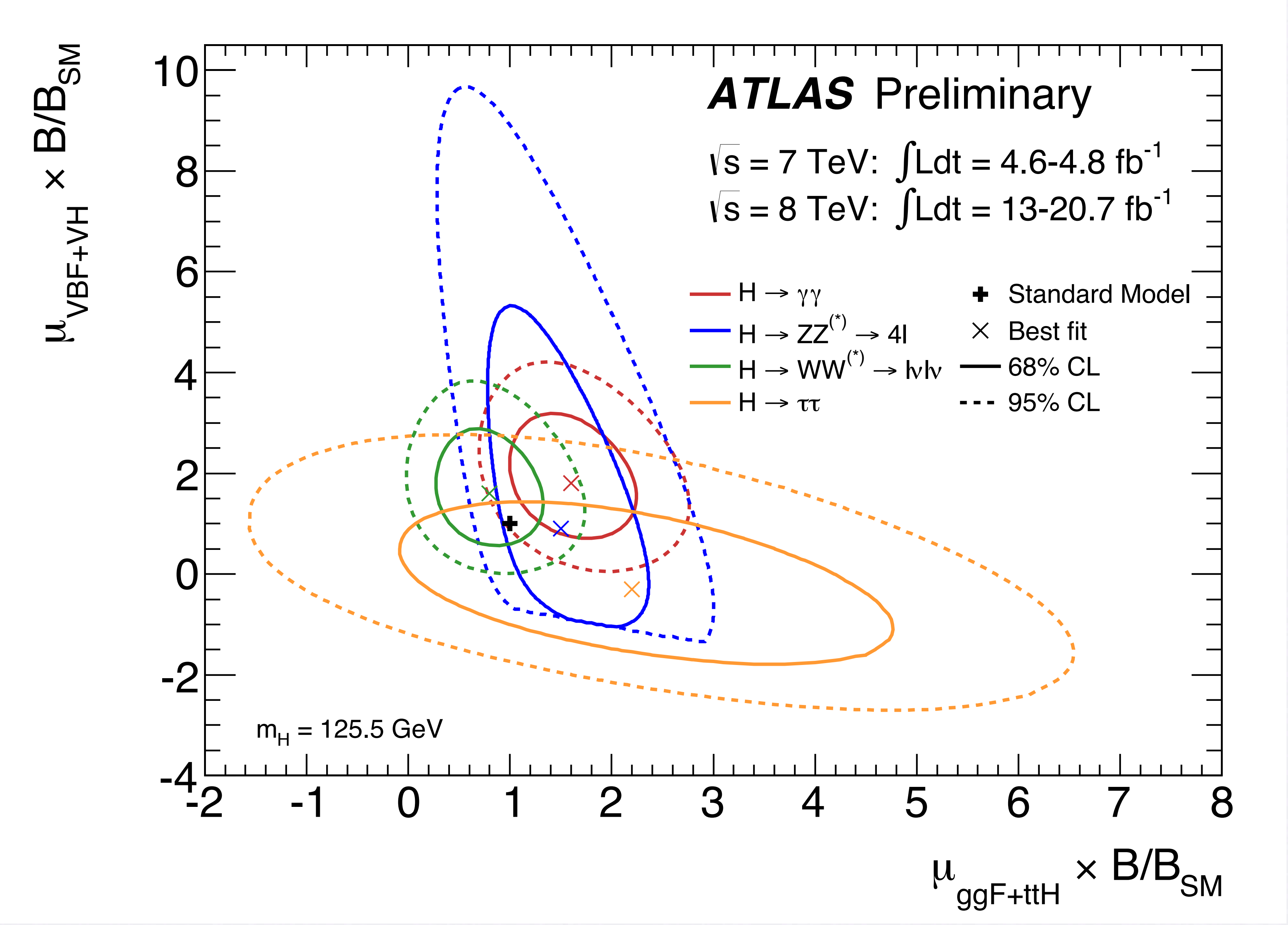




Note: VBF governed also by upper curve

LHC Constraints

Consider the ATLAS constraints in the (gluon fusion + tth) vs (VBF + hW/Z) plane



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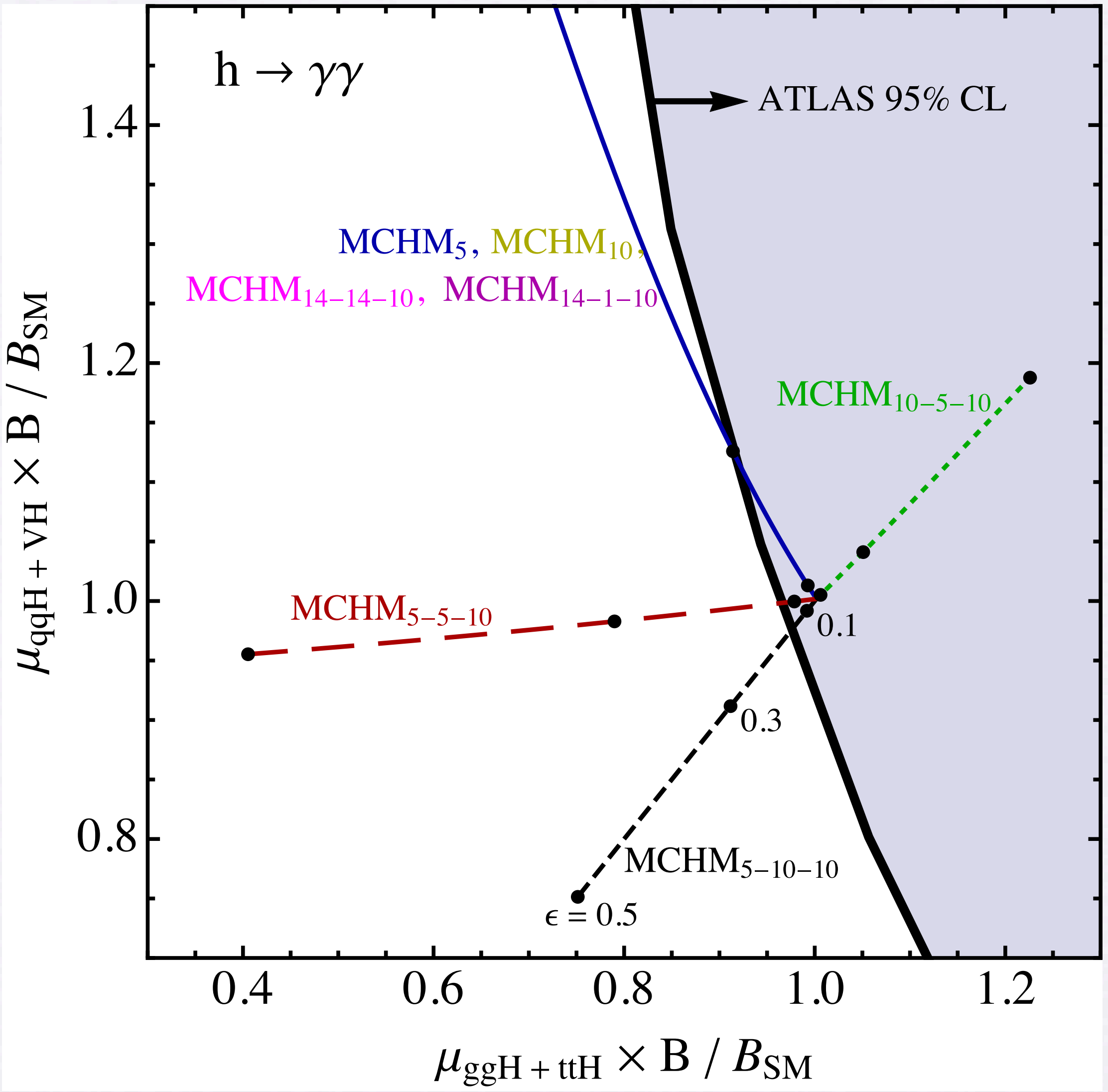

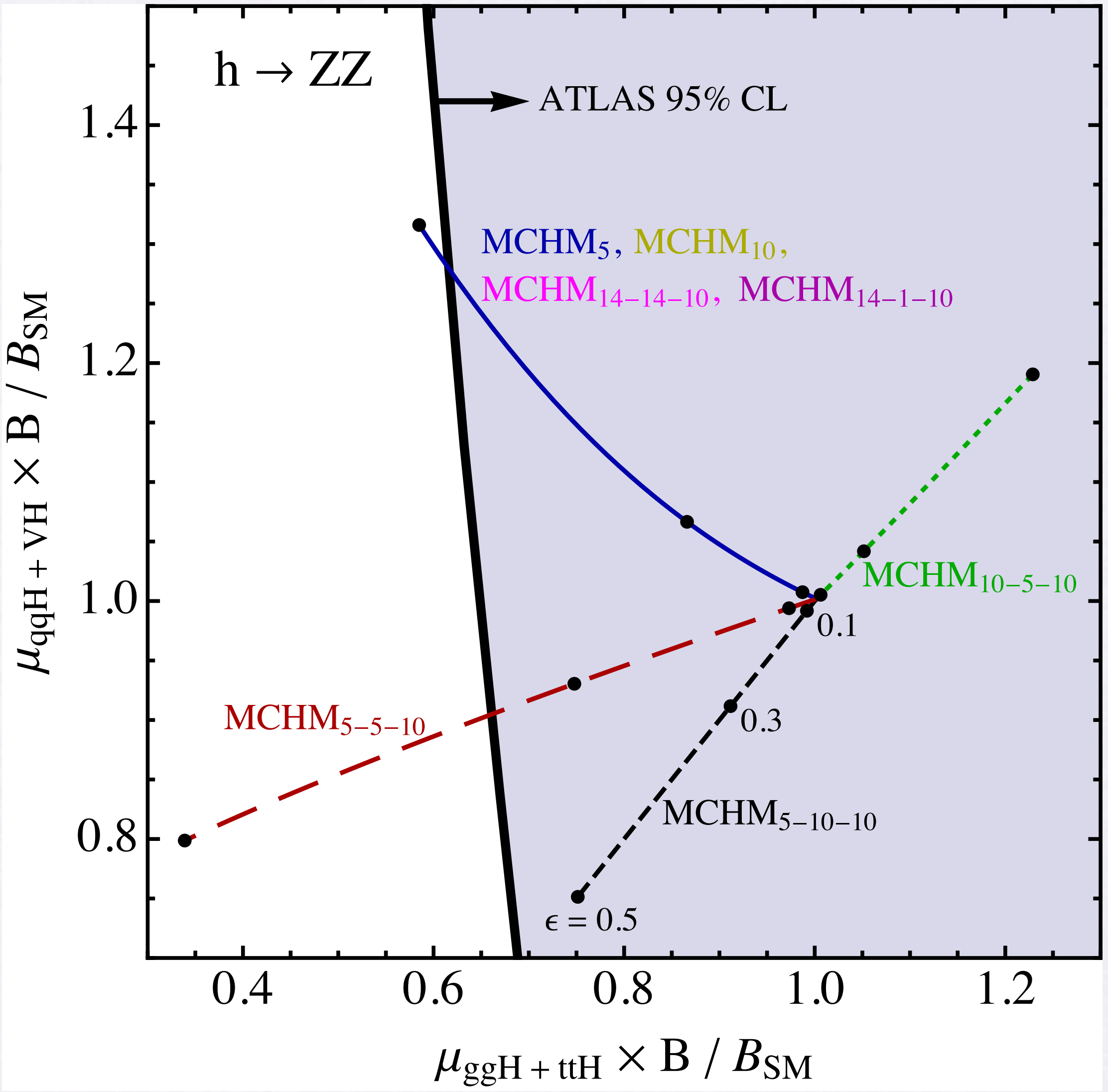

Deviations in $h \to Z\gamma$ very similar in these models.

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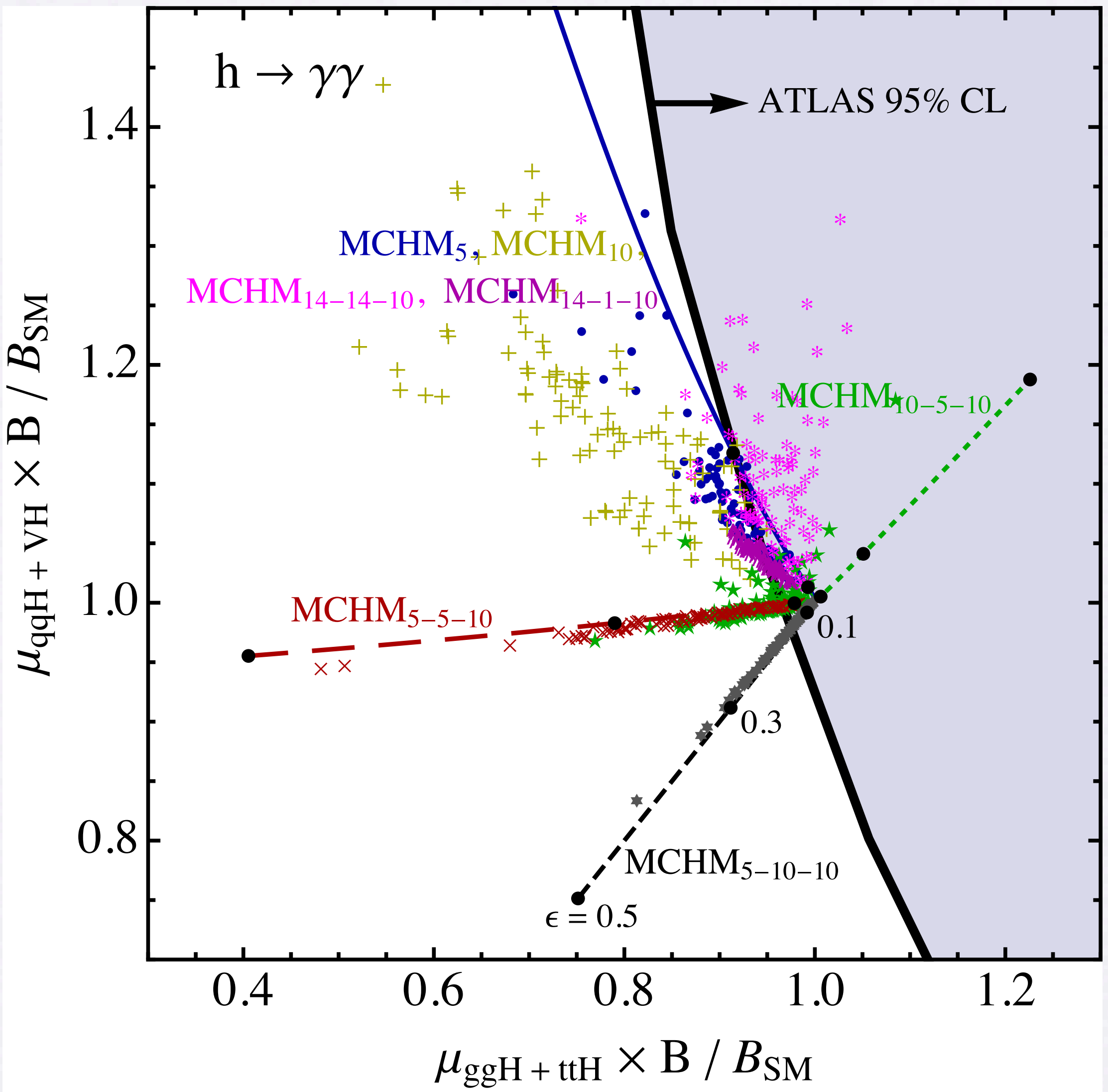

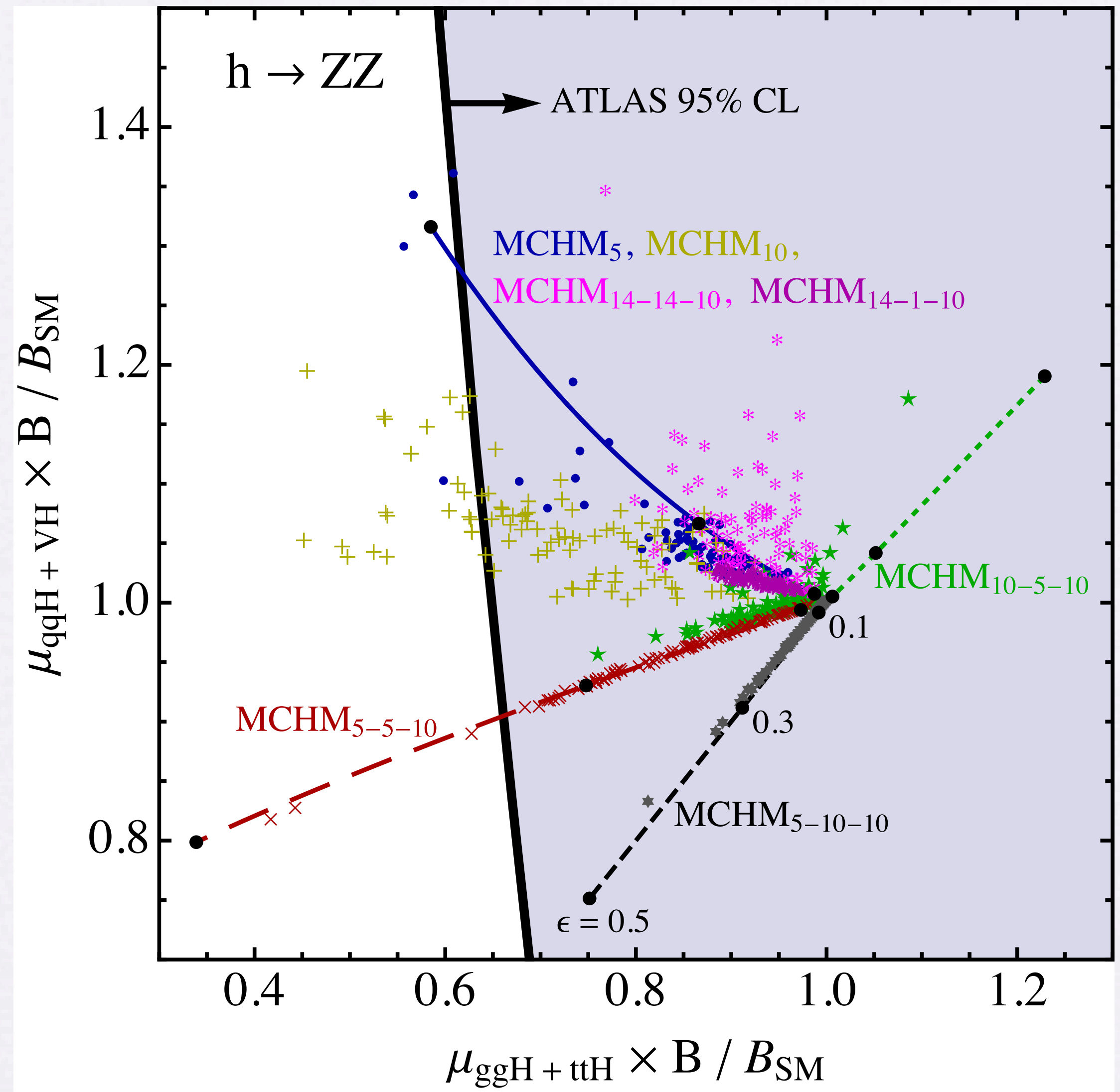

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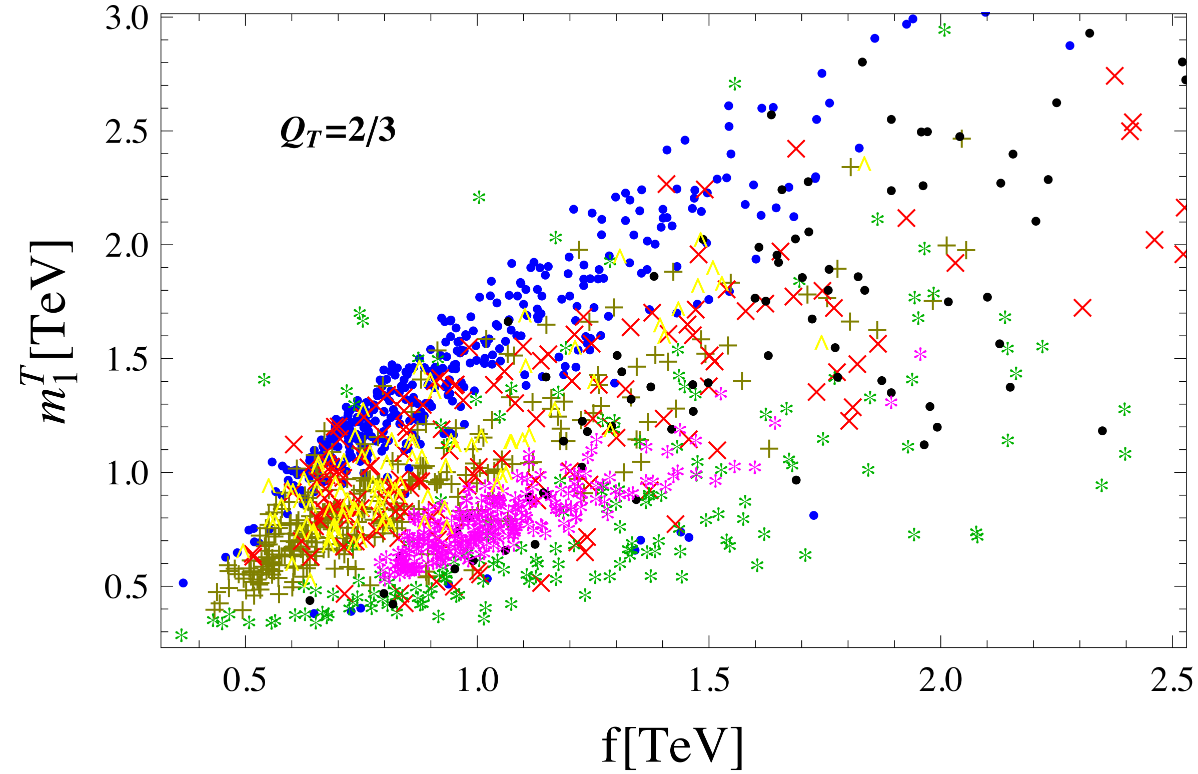
Predictions: light fermions

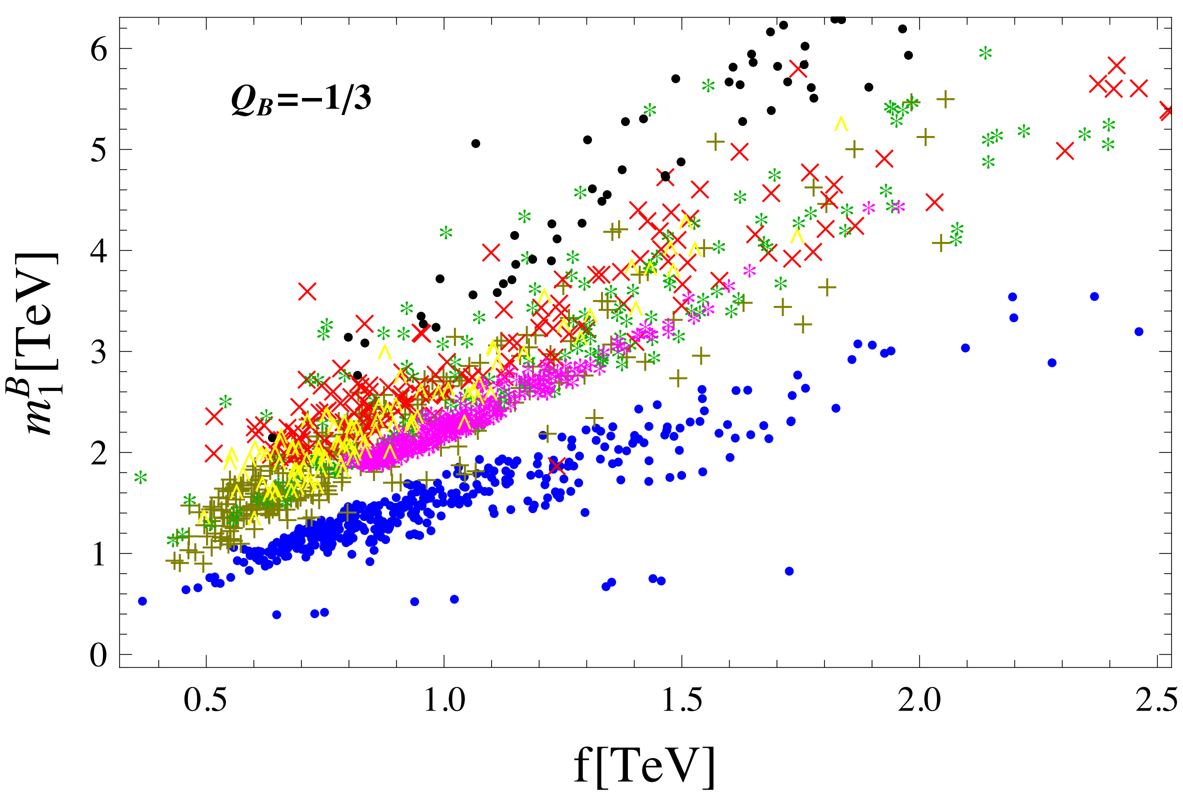
Composite models with extended symmetry predict light fermionic res.

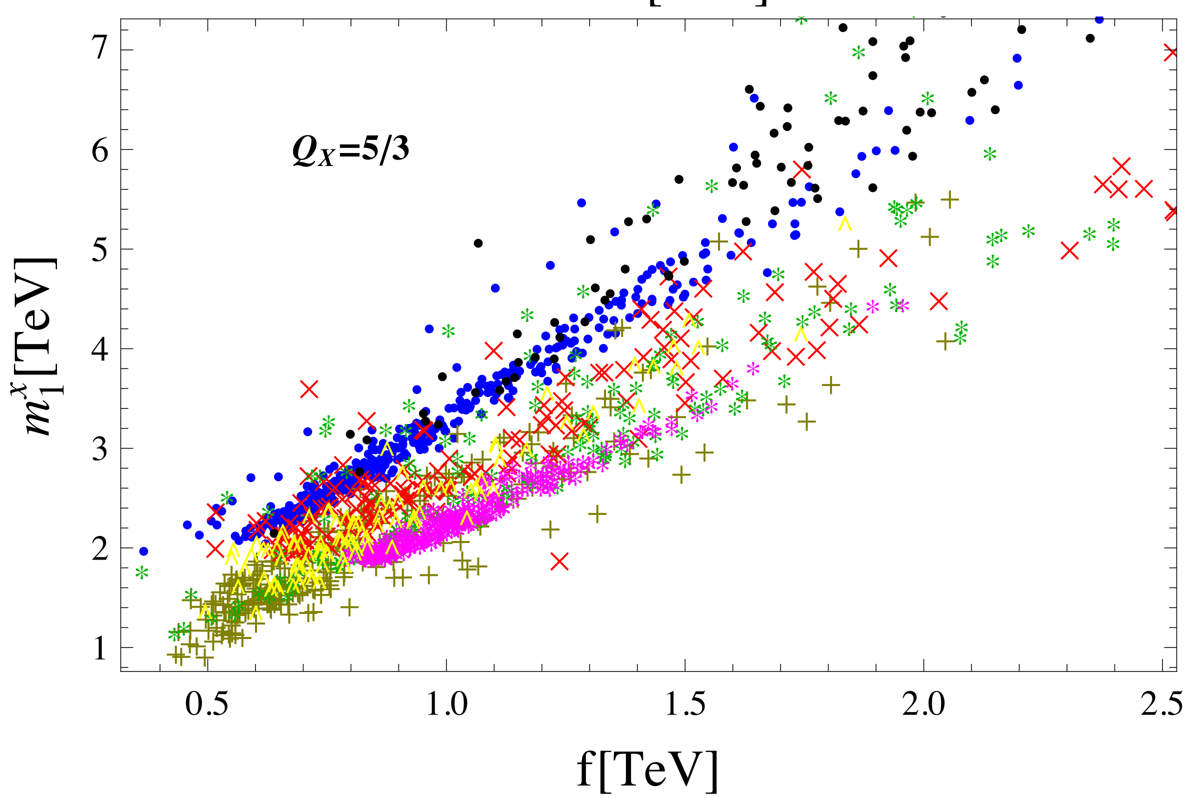
custodians: $m_{cust} < M_{cp}$

custodians can have charges
$Q = 2/3(T), -1/3(B), 5/3, 8/3, -4/3$

$\Rightarrow$ double and single QCD production
(Contino et al, Wulzer et al, Aguilar)







Summary

- A composite (pNGB) Higgs should display deviations from the SM expectations
- Even if the new resonances are hard to see at the LHC, they may have an observable effect on Higgs couplings
- Higgs branching fractions can display suppressions or enhancements w.r.t. the SM
- The pattern of deviations can illuminate the structure of the strong sector, in particular the more model-dependent fermionic sector