# Composite Higgs Models with Vector-like B-Quarks

Milada Margarete Mühlleitner
(Karlsruhe Institute of Technology)
in coll. with: Ramona Gröber, Marc Gillioz and Andreas Kapuvari

**Scalars 2013**
**Warsaw, Poland**
**12-16 September 2013**

# After Higgs Discovery: Which Higgs Boson?

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

# $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson

- **Bound state from a Strongly Interacting Sector** Kaplan,Georgi; Dimopoulos eal; Dugan eal

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

Higgs: Pseudo-Goldstone boson of strongly interacting sector

$$\text{Global symmetry of strong sector } G \quad \xrightarrow[]{\text{spontaneously broken at } f} \quad \text{subgroup } H$$

$G/H$: 4th Nambu-Goldstone Boson: Higgs boson

- **Possible symmetry patterns**

  ∗ $H$ must contain SM gauge group

  ∗ $G$ must contain an $SU(2) \times SU(2) \sim SO(4)$ symmetry $\rightsquigarrow$ PGB is a Higgs doublet

Minimal Models:

$SO(5) \times U(1)_X \to SO(4) \times U(1)_X \rightsquigarrow$ PGB: one doublet

Agashe,Contino,Pomarol; Contino,da Rold, Pomarol

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

- **Strongly Interacting Light Higgs (SILH) effective Lagrangian** Giudice,Grojean,Pomarol,Rattazzi
  - ⋆ describes phenomenology of composite Higgs boson
  - ⋆ expansion in $\xi = v^2/f^2$

- **Large $\xi$:** 5D MCHM provides completion for large $\frac{v^2}{f^2}$ $(SO(5)/SO(4))$ Contino eal; Agashe eal

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

| spinorial representations of $SO(5)$ | fundamental representations of $SO(5)$ |
|---|---|
| MCHM4 | MCHM5 |

| **MCHM4** | **MCHM5** |
|---|---|
| $g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ <br> $g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi}$ | $g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ <br> $g_{Hff} = g^{SM}_{Hff}\frac{(1-2\xi)}{\sqrt{1-\xi}}$ |
| universal factor <br> $\rightsquigarrow$ BRs unchanged | $g_{Hff}$ coupling <br> vanishes for $\xi = 0.5$ |

# $\mathcal{M}$asses

- **Higgs boson mass:**

  generated at loop level through explicit breaking of $G$ by SM interactions with strong sector $\rightsquigarrow$

  Higgs mass relation with masses of other resonances

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

- **Partial compositeness:**

  Kaplan; Contino,Kramer,Son,Sundrum

  SM fermion masses generated through
  linear mixing with partners from strong sector

  heavy top quark mass $\rightsquigarrow$ mixing with new partners important

$$\Delta\mathcal{L} = \lambda_L \bar{q}_L Q_L + \lambda_R \bar{T}_R t_R$$

# $\mathcal{E}$ffects of $\mathcal{H}$eavy $\mathcal{T}$op $\mathcal{P}$artners

- **EWPT:** Models with new vector-like fermions in full representation (fundamental) of SO(5) compatible with EWPT

  Gillioz; Lodone; Anastasiou,Furlan; ...

- **Higgs Production through gluon fusion:**

  * description of effects from heavy top partners through Low-Energy Theorem (LET)

$$\mathcal{L}_{hgg} = \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \frac{\partial}{\partial \log H} \log\det \underbrace{\mathcal{M}_t^2(H)}_{\text{top mass matrix}} |_{H=\langle H \rangle}$$

$$= \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \frac{1-2\xi}{\sqrt{1-\xi}}$$

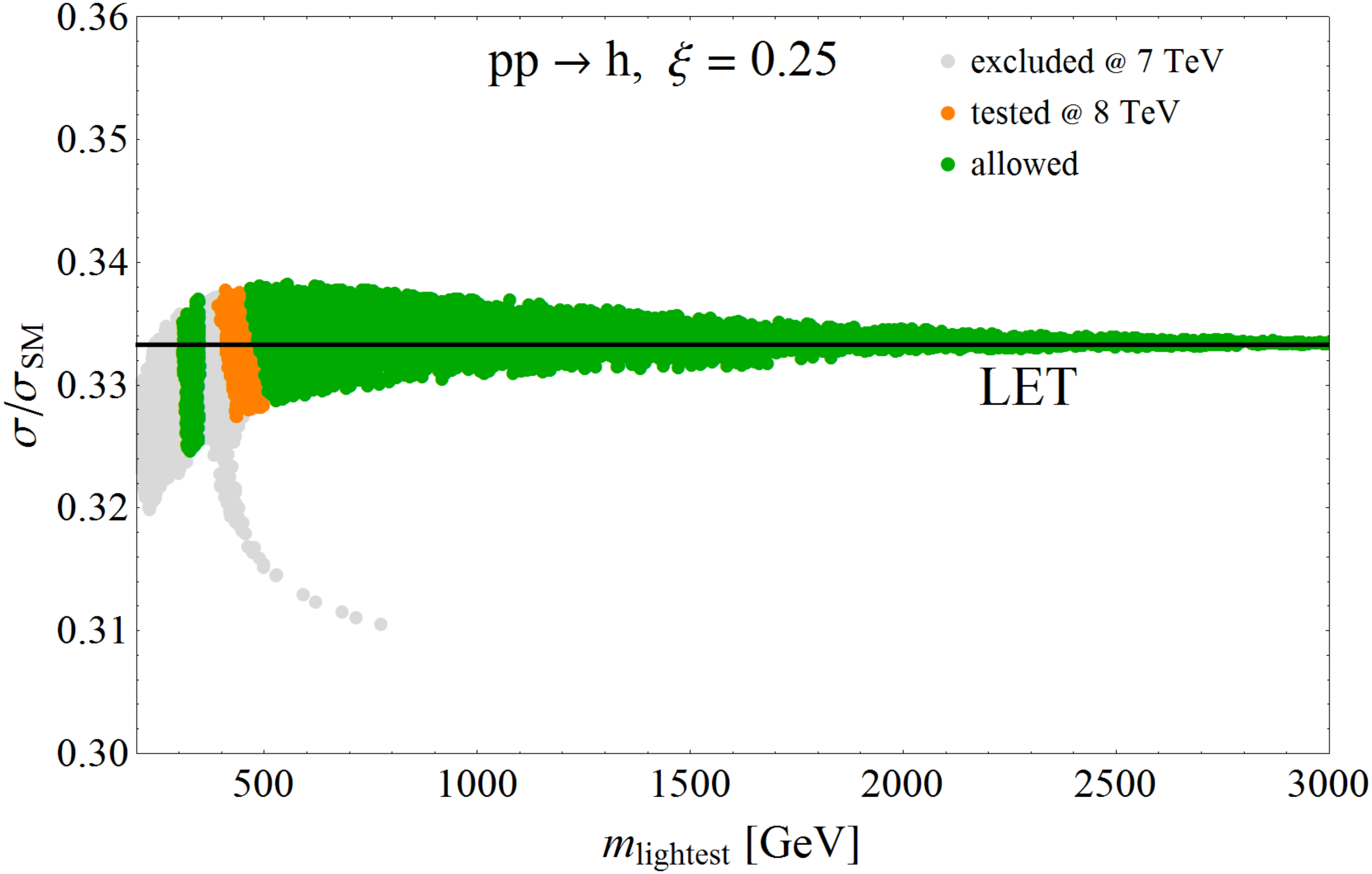
* Depends on pure Higgs non-linearities and not on details of spectrum!

Falkowski; Low,Vichi; Azatov,Galloway; Gillioz,Grober,Grojean,MM,Salvioni

(cancellation of loops of extra fermions and corrections to top Yukawa coupling due to mixing)

# Gluon Fusion with Heavy Top Partners

Gillioz,Grober,Grojean,MM,Salvioni



# Heavy Bottom Partners

- **Heavy Bottom Partners:** Study constraints from EWPT and effects on Higgs phenomenology
- **The Model:** Antisymmetric representation $[(\mathbf{10})$ under $SO(5)]$
  smallest representation giving mass to both top and bottom quarks
- **Decomposition under $SU(2)_L \times SU(2)_R$:** $(\mathbf{10})_{2/3} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$

  ∗ Triplet: $(\mathbf{3},\mathbf{1}) = \begin{pmatrix} \chi \\ u \\ d \end{pmatrix}$

  ∗ Singlet: $(\mathbf{1},\mathbf{3}) = (\chi_1, u_1, d_1)$ $\quad d_1/u_1$ mixes with $b_R/t_R$

  ∗ Bi-Doublet: $(\mathbf{2},\mathbf{2}) = \begin{pmatrix} \chi_4 & T_4 \\ t_4 & d_4 \end{pmatrix}$ $\quad T_4/d_4$ mixes with $(t_L, b_L)$

- **Charges:**

  $\chi, \chi_1, \chi_4$ : charge $5/3$ $\quad u, u_1, t_4, T_4$ : charge $2/3$ $\quad d, d_1, d_4$ : charge $-1/3$

# $\mathcal{T}$he $\mathcal{L}$agrangian

- **Lagrangian with new heavy fermions:**

$$\begin{aligned}\mathcal{L} =& i\,\mathrm{Tr}(\bar{\mathcal{Q}}_R \not{D} \mathcal{Q}_R) + i\,\mathrm{Tr}(\bar{\mathcal{Q}}_L \not{D} \mathcal{Q}_L) + i\bar{q}_L \not{D} q_L + i\bar{b}_R \not{D} b_R \\ & + i\bar{t}_R \not{D} t_R - M_{10}\mathrm{Tr}(\bar{\mathcal{Q}}_R \mathcal{Q}_L) - yf\left(\Sigma^\dagger \bar{\mathcal{Q}}_R \mathcal{Q}_L \Sigma\right) \\ & - \lambda_t \bar{t}_R u_{1L} - \lambda_b \bar{b}_R d_{1L} - \lambda_q (\bar{T}_{4R}, \bar{d}_{4R}) q_L + h.c.\end{aligned}$$

$*$ $\mathcal{Q}$ = ten-plet of new vector-like fermions
$*$ $\Sigma$ = Goldstone fields (in unitary gauge):

$$\Sigma = (0, 0, 0, \sin(H/f), \cos(H/f))$$

- **The Parameters:**

$*$ $\xi = v^2/f^2$, $y$, $M_{10}$ and $\sin\phi_L$ (with $\tan\phi_L = \lambda_q/(M_{10} + fy/2)$)
$*$ $\lambda_b/\lambda_t$ fixed by requirement of reproducing $m_t$, $m_b$ after mass matrix diagonalisation

# $\mathcal{E}$lectroweak $\mathcal{P}$recision $\mathcal{T}$ests

- **New Physics constrained** by EWPD from LEP

- **New Physics contributions** to $\epsilon_1, \epsilon_2, \epsilon_3$ and $\epsilon_b$ Altarelli,Barbieri,Caravaglios,Jadach; Grojean,Matsedonskyi,Panico

  (equivalently to $S, T, U$ Peskin,Takeuchi and $\delta g_{Zb_Lb_L}$)

  $*$ $\epsilon_1$ (or $T$):

  Modified Higgs-$VV$ couplings $\rightsquigarrow$ no cancellation of UV divergencies $\rightsquigarrow$

$$\Delta\epsilon_1^{IR} = -\frac{3\alpha(m_Z^2)}{16\pi\sin^2\theta_W}\xi\log\left(\frac{m_\rho^2}{m_Z^2}\right)$$

Barbieri,Bellazzini,Rychkov,Varagnolo

  Cut-off by mass $m_\rho$ of first vector resonance

  In addition contributions from new fermions in the loop Lavoura,Silva; Agashe,Contino; Gillioz; Anastasiou,Furlan,Santiago

# $\mathcal{E}$lectroweak $\mathcal{P}$recision $\mathcal{T}$ests

- **New Physics constrained** by EWPD from LEP
- **New Physics contributions** to $\epsilon_1, \epsilon_2, \epsilon_3$ and $\epsilon_b$ Altarelli,Barbieri,Caravaglios,Jadach

  (equivalently to $S, T, U$ Peskin,Takeuchi and $\delta g_{Z \to b_L b_L}$)

$*$ $\epsilon_3$ (or $S$):

Modified Higgs couplings $\rightsquigarrow$ divergent contributions $\rightsquigarrow$

$$\Delta\epsilon_3^{IR} = \frac{\alpha(m_Z^2)}{48\pi \sin^2\theta_W} \xi \log\left(\frac{m_\rho^2}{m_Z^2}\right)$$

Barbieri,Bellazzini,Rychkov,Varagnolo

In addition tree-level UV-contribution from mixing of SM gauge fields with new vector $\rho$ and axial vector $a$ resonances

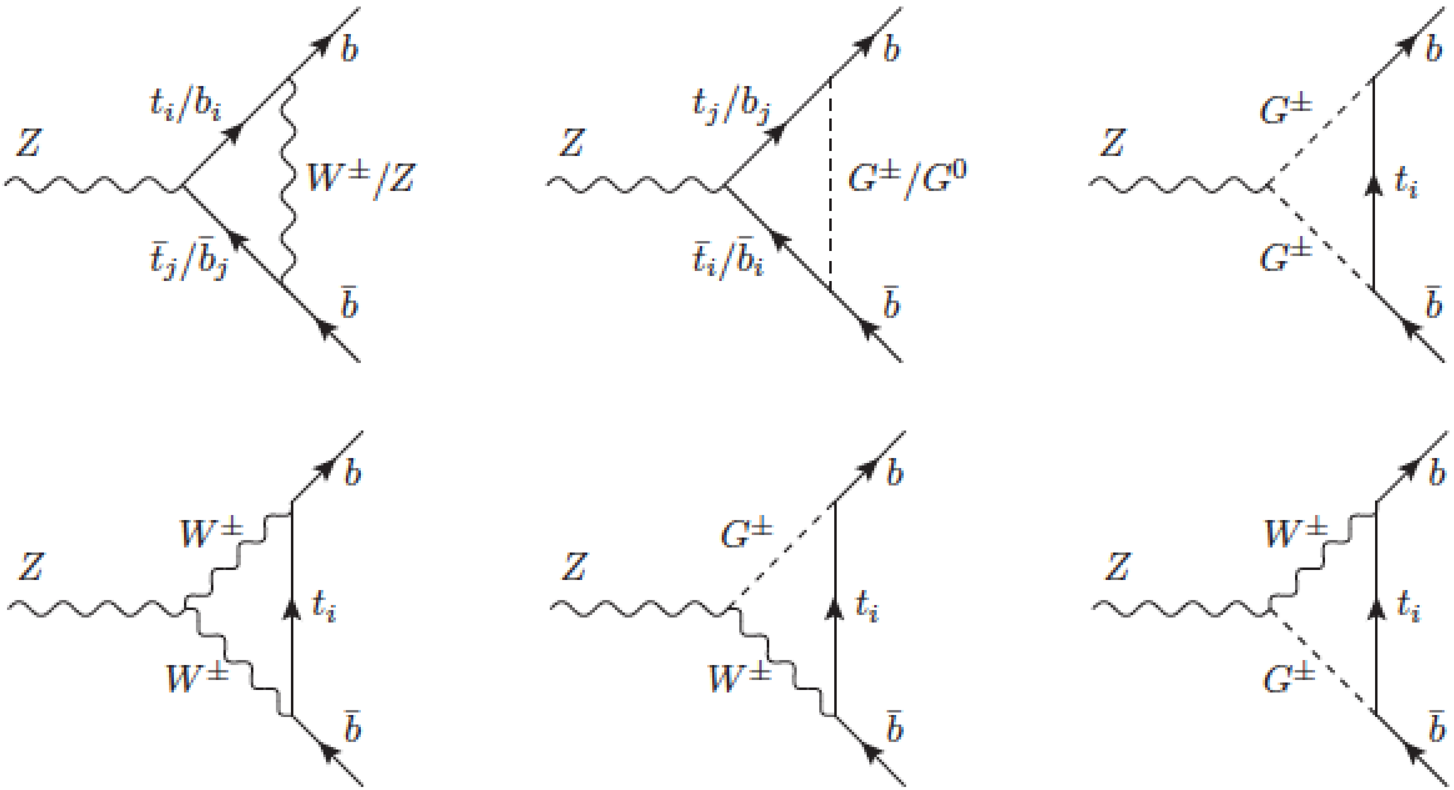
$$\Delta\epsilon_3^{UV} = \frac{m_W^2}{m_\rho^2}\left(1 + \frac{m_\rho^2}{m_a^2}\right)$$

Contino

# $\mathcal{C}$ontributions to $\epsilon_b$

- **New Physics contributions** to $Zb_Lb_L$

[no tree-level contributions to $\delta g_L$ due to left-right symmetry Agashe,Contino,da Rold,Pomarol]
[previous works: no mixing of $b$-quark with partners e.g. Anastasiou,Furlan,Santiago]




New: $*$ full mixing with bottom partners
$*$ additional counterterms necessary

## $\mathcal{R}$enormalisation

- **Bare Lagrangian:**

$$\mathcal{L}_{Z\bar{b}_L b_L} = -\frac{e}{s_W c_W} \bar{b}^0_{L,i} \gamma_\mu U^{0L}_{ij} \left(T_{3,L} - 2 s_W^2 Q\right)_{jj} U^{0L\,\dagger}_{jk} b^0_{L,k} Z^\mu$$

- **Field renormalisation:**

$$b^0_{L,i} \longrightarrow \left(\delta_{ij} + \frac{1}{2}\delta Z_{ij}\right) b_{L,j}$$

- **Renormalisation of the mixing matrix**

$$U^0_{ij} \longrightarrow (\delta_{ik} + \delta u_{ik}) U_{kj}$$

- **Counterterm:** defined anti-Hermitian $\rightsquigarrow$ ensures unitarity

Denner,Sack; Gambino,Grassi,Madricardo; Kniehl,Madricardo,Steinhauser; Barroso,Brucher,Santos; Yamada

$$\delta u^L_{b,ij} = \frac{1}{4}\left(\delta Z^L_{ij} - \delta Z^{L\,\dagger}_{ij}\right)$$

# $\mathcal{R}$enormalisation

- **Field renormalisation:**

$$b^0_{L,i} \to \left(\delta_{ij} + \frac{1}{2}\delta Z_{ij}\right) b_{L,j}$$

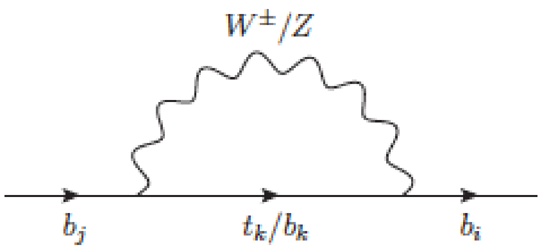
- **Renormalisation of the mixing matrix**

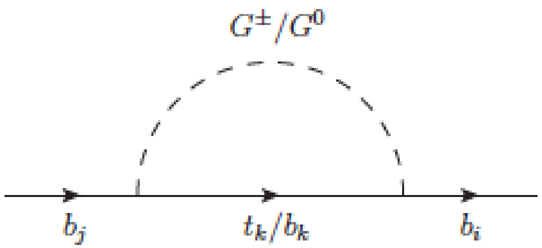
$$U^0_{ij} \to (\delta_{ik} + \delta u_{ik}) U_{kj}$$

- **Counterterm:** defined anti-Hermitian $\rightsquigarrow$ ensures unitarity

Denner,Sack; Gambino,Grassi,Madricardo; Kniehl,Madricardo,Steinhauser; Barroso,Brucher,Santos; Yamada

$$\delta u^L_{b,ij} = \frac{1}{4}\left(\delta Z^L_{ij} - \delta Z^{L\,\dagger}_{ij}\right)$$



# $\mathcal{C}$onstraints from $\mathcal{EWPT}$

* Scan over:

$$0 \le \xi \le 1 \;, \quad 0 < \sin\phi_L \le 1 \;, \quad |y| < 4\pi \;, \quad 0 \le M_{10} \le 10 \text{ TeV}$$

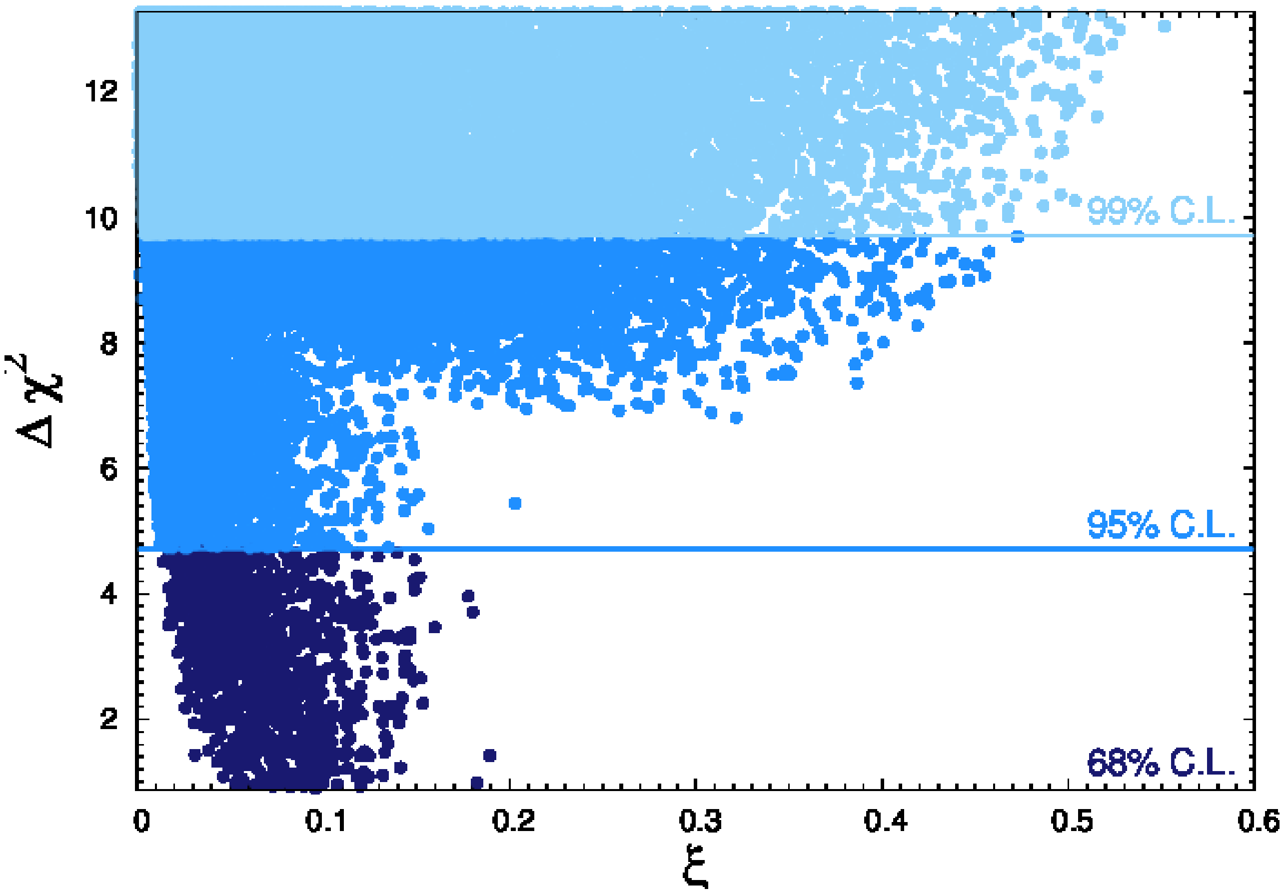
* $\chi^2$ Test:

$$\chi^2 = \sum_{i,j=1,2,3,b} \left(\epsilon_i^{th} - \epsilon_i^{exp}\right) C_{ij}^{-1} \left(\epsilon_j^{th} - \epsilon_j^{exp}\right) \qquad \Delta\chi^2 = \chi^2 - \chi^2_{min} \le 13.28$$

* Additional constraint: $|V_{tb}| > 0.92$ [CMS]

# Constraints from $\mathcal{EWPT}$

Gillioz,Grober,Kapuvari,MM




Fair blue to dark blue: Points fulfill EWPT at 99%, 95%, 68% CL and $|V_{tb}| > 0.92$

## $\mathcal{C}$ompatibility with $\mathcal{H}$iggs $\mathcal{S}$earch $\mathcal{R}$esults

- **Main production channel - gluon fusion:**
  Bottom quark contributions cannot be described by LET $\leftarrow m_b \ll m_h \rightsquigarrow$

$$\mathcal{L}_{hgg} = \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \left( \frac{\partial}{\partial \log H} \log \det \mathcal{M}^2(H)|_{H=\langle H \rangle} - \sum_{m_i < m_h} \frac{y_{ii}}{M_i} \right)$$

  $\rightsquigarrow$ dependence on spectrum Azatov,Galloway

- **Determination of Higgs rates:**
  - $*$ Heavy quark loop contributions to $gg \to h$ implemented in `HIGLU` (at NLO QCD) Spira
  - $*$ Production cross section (at NLO QCD)

$$\sigma_{prod} = \sigma_{gg\to h} + \sigma_{hq\bar{q}}^{SM}(1-\xi) + \sigma_{Wh/Zh}^{SM}(1-\xi) + \sigma_{t\bar{t}h}^{SM}(g_{ht\bar{t}}/g_{ht\bar{t}}^{SM})^2$$

  - $*$ Modified Higgs decays, including contributions from vector-like fermions in loop-mediated decays, implemented in `HDECAY` Djouadi,Kalinowski,MMM,Spira; Contino,Ghezzi,Grojean,MMM,Spira

# $\mathcal{C}$ompatibility with $\mathcal{H}$iggs $\mathcal{S}$earch $\mathcal{R}$esults

- **Scan over parameter space:**

$$0 \le \xi \le 1 \,, \qquad 0 \le \sin\phi_L \le 1 \,, \qquad |y| < 4\pi \,, \qquad 0 \le M_{10} \le 10 \text{ TeV}$$

- **Constraints from direct heavy fermion searches** ATLAS;CMS: Point rejected if excluded by directed searches for new fermions (analoguously to Gillioz,Grober,Grojean,MM,Salvioni)

- **Global $\chi^2$ fit:**

$$\chi^2 = \sum_i \frac{(\mu_i^{exp} - \mu_i^{theo})^2}{(\Delta\mu_i^{exp})^2 + (\Delta\mu_i^{theo})^2} + \chi^2_{EWPT} + \frac{(|V_{tb}^{exp}| - |V_{tb}^{theo}|)^2}{(\Delta V_{tb})^2}$$

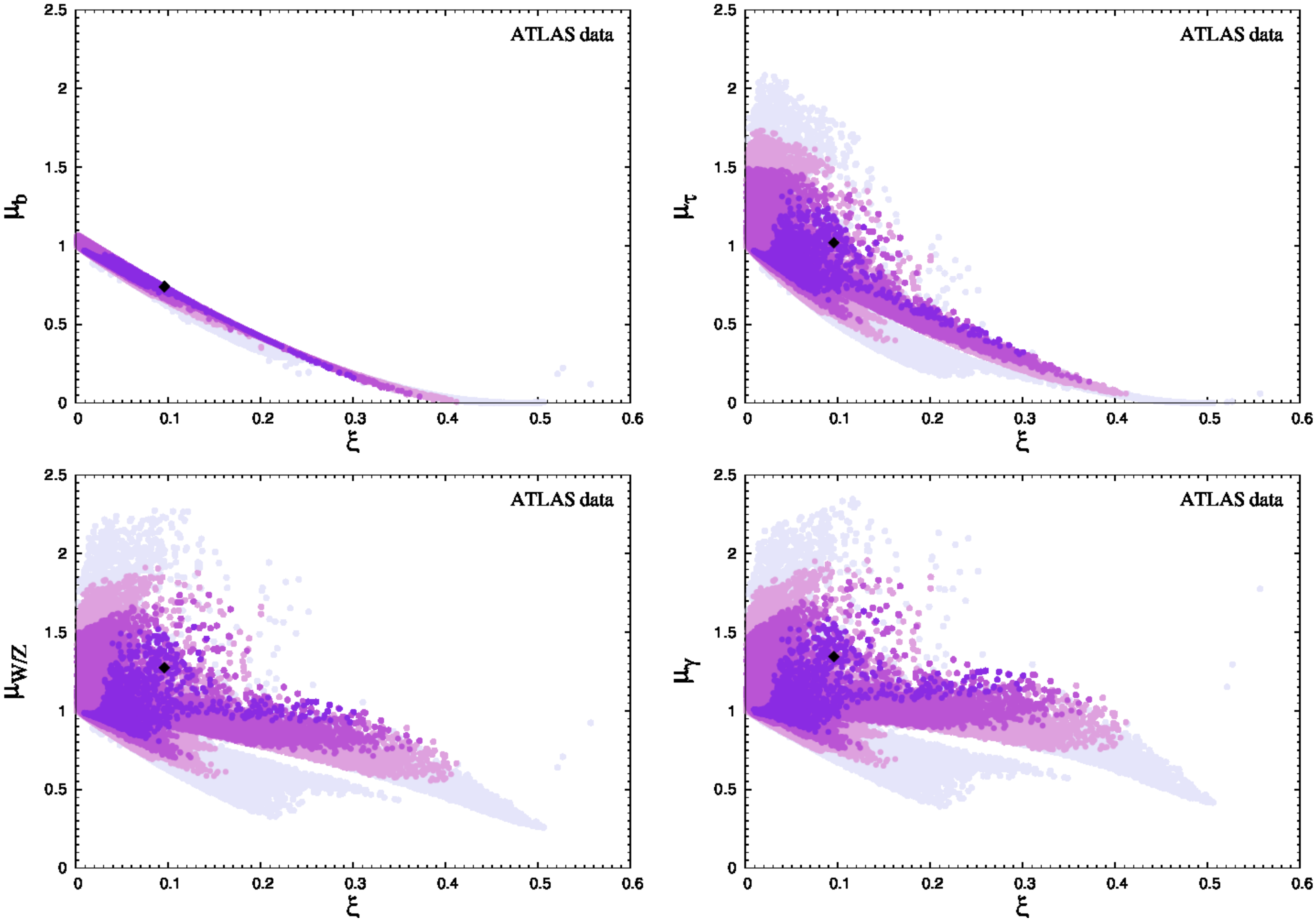
with the signal strength modifiers

$$\mu_i = \frac{\sigma_{prod}\, BR(H \to ii)}{\sigma_{prod}^{SM}\, BR^{SM}(H \to ii)}$$

for $i = b\bar{b}, WW, ZZ, \gamma\gamma, \tau\bar{\tau}$

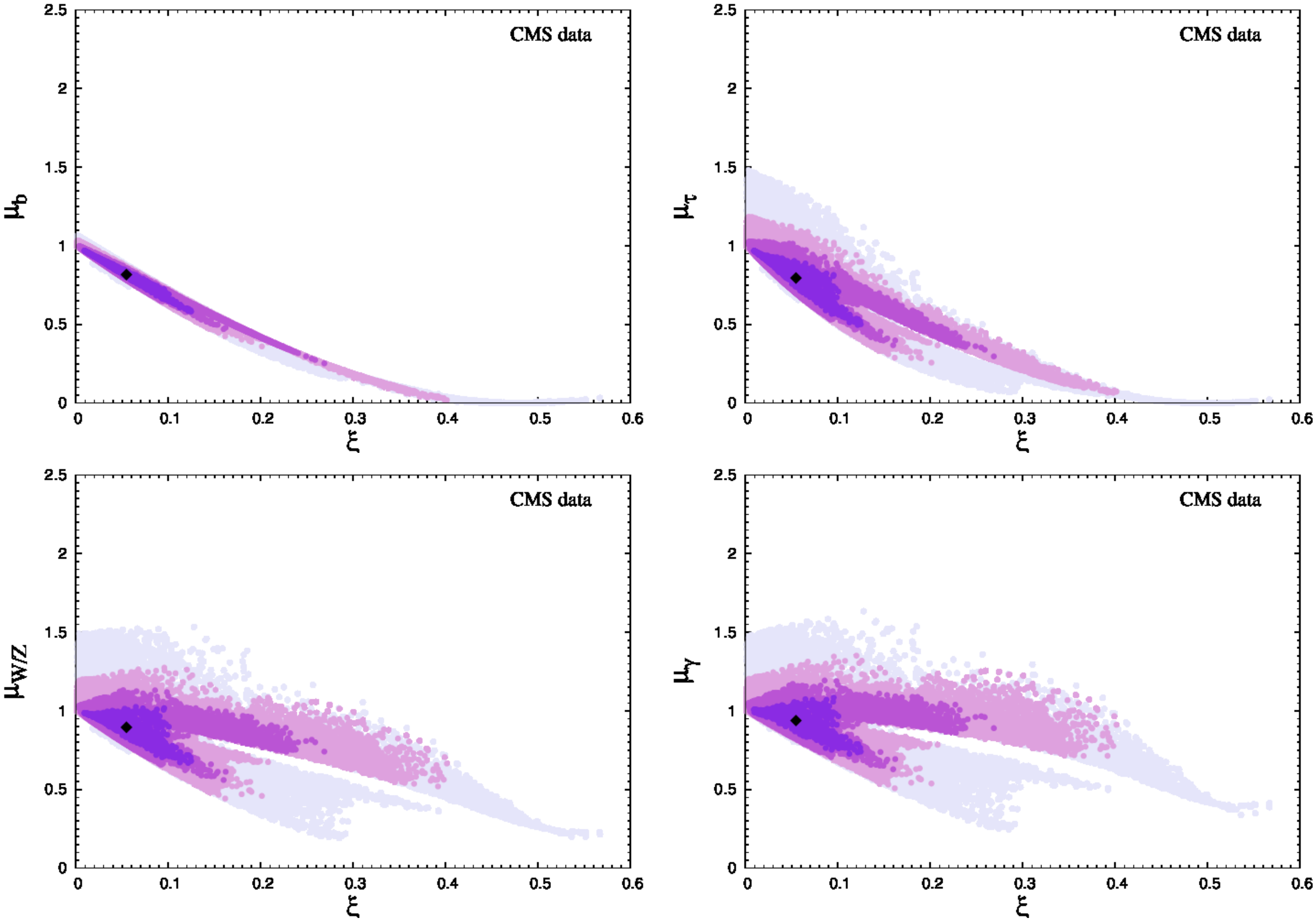
- **Compatibility with ATLAS results - Moriond 2013**

Gillioz,Grober,Kapuvari,MM



- **Compatibility with CMS results - Moriond 2013**

Gillioz, Grober, Kapuvari, MM



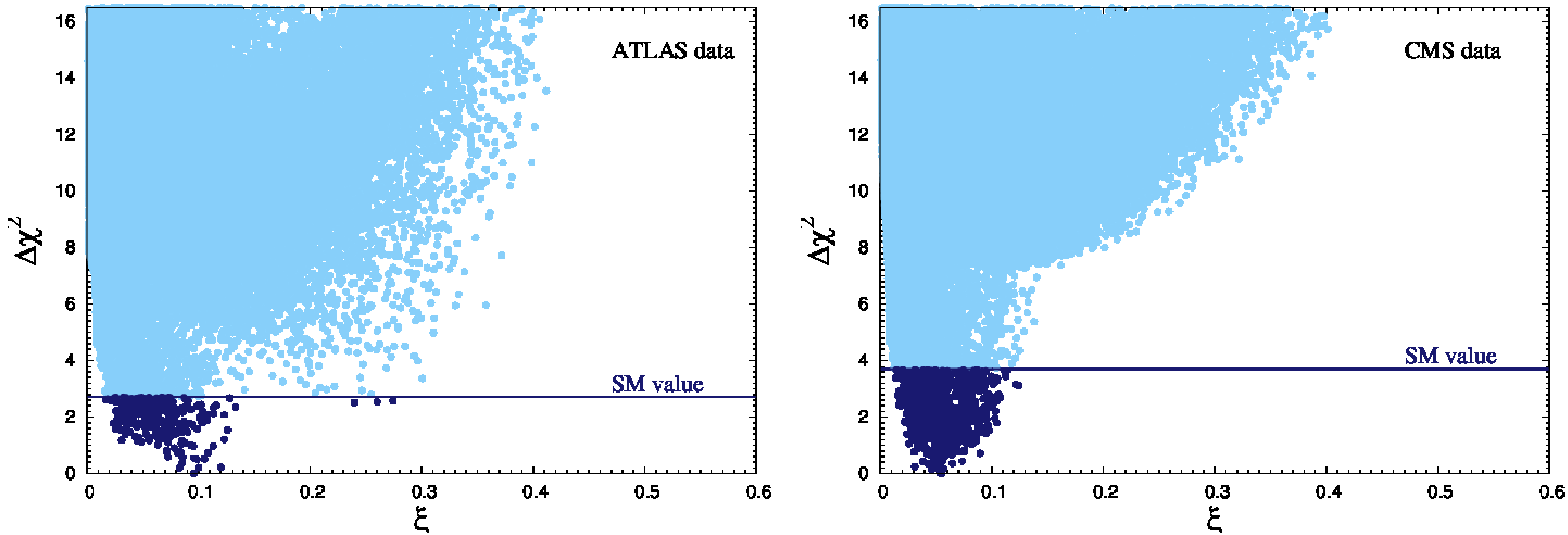
# $\mathcal{C}$onclusions and $\mathcal{O}$utlook

- ◇ Effects of heavy vector-like bottom partners investigated in composite Higgs models with partial compositeness
- ◇ Bottom partners enter in EWPO through loops
- ◇ Heavy bottom partner contributions in $Zb_Lb_L$ require renormalisation of mixing matrix
- ◇ Bottom partners: dependence of gluon fusion production cxn on spectrum
- ◇ Compatibility of simple model with EWPT, direct searches for new fermions, constraint from $|V_{tb}|$ and recent Higgs search results
- ◇ To be done: correlations between $gg$ fusion and $WW$ fusion production channels; replace direct search limits with newest limits given by ATLAS and CMS

Thank you for your attention!

# $\mathcal{C}$omparison with the $\mathcal{SM}$

Gillioz,Grober,Kapuvari,MM



# Relation Light Higgs - Light Resonance

⋆ Light Higgs boson requires light top partners

⋆ Approximate formula

Pomarol,Riva

$$m_Q \leq \frac{m_h \pi v}{m_t \sqrt{N_c}\sqrt{\xi}}$$

Best fit points

| Experiment | $\xi$ | $\chi^2$ |
|---|---|---|
| ATLAS | 0.096 | 8.83 |
| CMS | 0.073 | 4.55 |

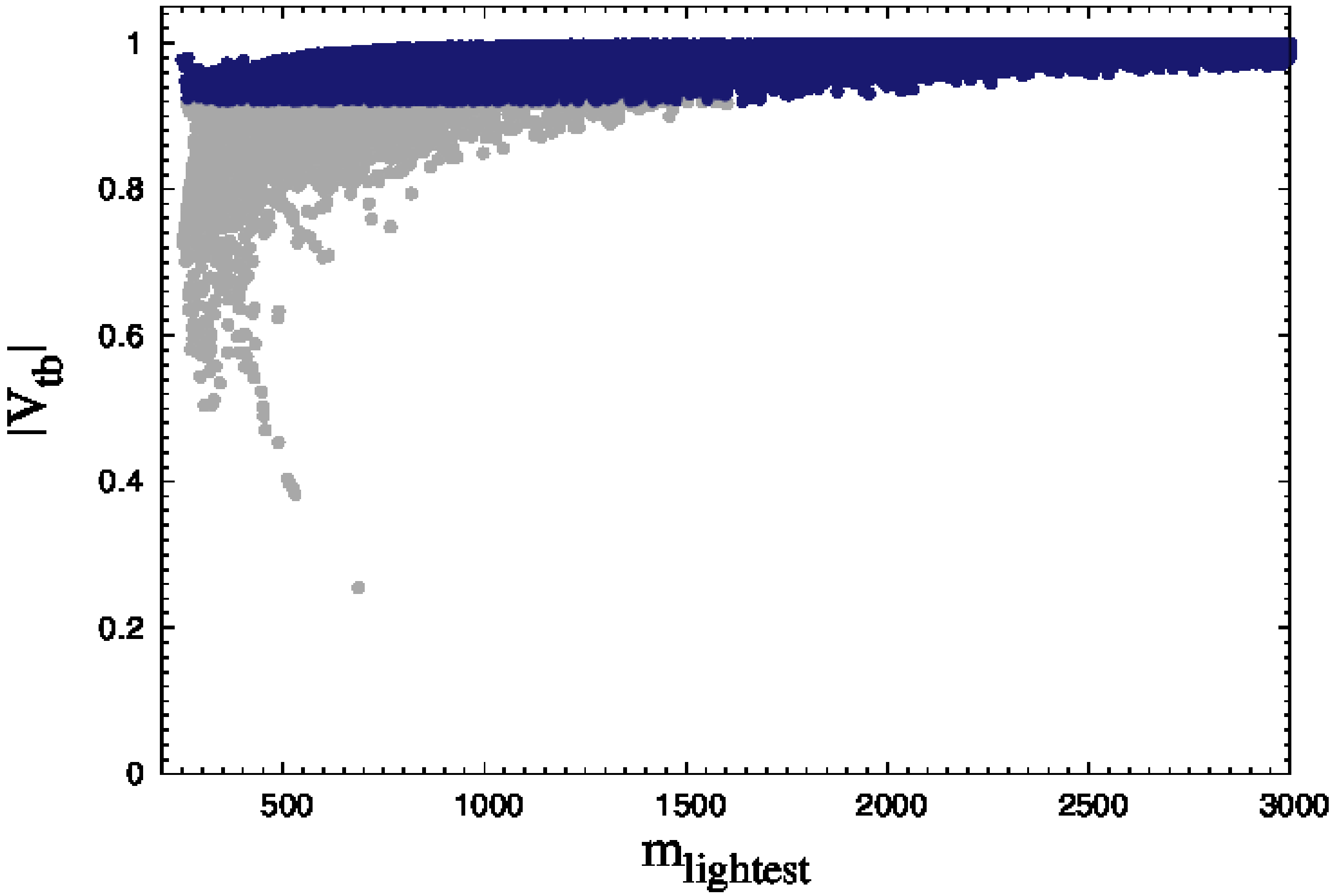
$\Longrightarrow$

Best fit points (using approximate formula)

| Experiment | $\xi$ | $\chi^2$ |
|---|---|---|
| ATLAS | 0.067 | 10.07 |
| CMS | 0.066 | 5.30 |

# $\mathcal{C}$onstraint from $|V_{tb}|$

Gillioz,Grober,Kapuvari,MM



# $\mathcal{M}$ass $\mathcal{M}$atrices

$$-\mathcal{L}_{m_t} = \overline{\begin{pmatrix} t_L \\ u_L \\ u_{1L} \\ t_{4L} \\ T_{4L} \end{pmatrix}} \begin{pmatrix} 0 & 0 & 0 & 0 & \lambda_q \\ 0 & \tilde{m_a} & -\frac{1}{4}fys_H^2 & -\frac{1}{4}fyc_H\, s_H & -\frac{1}{4}fyc_H s_H \\ \lambda_t & -\frac{1}{4}fys_H^2 & \tilde{m_a} & \frac{1}{4}fyc_H\, s_H & \frac{1}{4}fyc_H s_H \\ 0 & -\frac{1}{4}fyc_H s_H & \frac{1}{4}fyc_H s_H & \tilde{m_b} & -\frac{1}{4}fys_H^2 \\ 0 & -\frac{1}{4}fyc_H s_H & \frac{1}{4}fyc_H s_H & -\frac{1}{4}fys_H^2 & \tilde{m_b} \end{pmatrix} \begin{pmatrix} t_R \\ u_R \\ u_{1R} \\ t_{4R} \\ T_{4R} \end{pmatrix} + h.c.$$

$$-\mathcal{L}_{m_b} = \overline{\begin{pmatrix} b_L \\ d_L \\ d_{1L} \\ d_{4L} \end{pmatrix}} \begin{pmatrix} 0 & 0 & 0 & \lambda_q \\ 0 & \tilde{m_a} & -\frac{1}{4}fys_H^2 & fy\frac{c_H s_H}{2\sqrt{2}} \\ \lambda_b & -\frac{1}{4}fys_H^2 & \tilde{m_a} & -fy\frac{c_H s_H}{2\sqrt{2}} \\ 0 & fy\frac{c_H s_H}{2\sqrt{2}} & -fy\frac{c_H s_H}{2\sqrt{2}} & \tilde{m_c} \end{pmatrix} \begin{pmatrix} b_R \\ d_R \\ d_{1R} \\ d_{4R} \end{pmatrix} + h.c.\ ,$$

with

$$\tilde{m_a} = \frac{1}{4}fys_H^2 + M_{10}\ , \qquad \tilde{m_b} = \frac{1}{2}fy(1-\frac{1}{2}s_H^2) + M_{10} \quad \text{and} \quad \tilde{m_c} = \frac{1}{2}fyc_H^2 + M_{10}$$

and $s_H \equiv \sin(H/f)$, $c_H \equiv \cos(H/f)$

# $\mathcal{A}$pproximate $\mathcal{M}$ass $\mathcal{F}$ormulae

Rotation to mass eigenstates for $v = 0$ ($Q_L = (T_{4L}, d_{4L})$):

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} \rightarrow \begin{pmatrix} \cos\phi_L & \sin\phi_L \\ -\sin\phi_L & \cos\phi_L \end{pmatrix} \begin{pmatrix} q_L \\ Q_L \end{pmatrix} \qquad \tan\phi_L = \lambda_q/(M_{10} + fy/2) \ ,$$

$$\begin{pmatrix} t_R \\ u_{1R} \end{pmatrix} \rightarrow \begin{pmatrix} \cos\phi_{Rt} & \sin\phi_{Rt} \\ -\sin\phi_{Rt} & \cos\phi_{Rt} \end{pmatrix} \begin{pmatrix} t_R \\ u_{1R} \end{pmatrix} \qquad \tan\phi_{Rt} = \lambda_t/M_{10} \ ,$$

$$\begin{pmatrix} b_R \\ d_{1R} \end{pmatrix} \rightarrow \begin{pmatrix} \cos\phi_{Rb} & \sin\phi_{Rb} \\ -\sin\phi_{Rb} & \cos\phi_{Rb} \end{pmatrix} \begin{pmatrix} b_R \\ d_{1R} \end{pmatrix} \qquad \tan\phi_{Rb} = \lambda_b/M_{10} \ ,$$

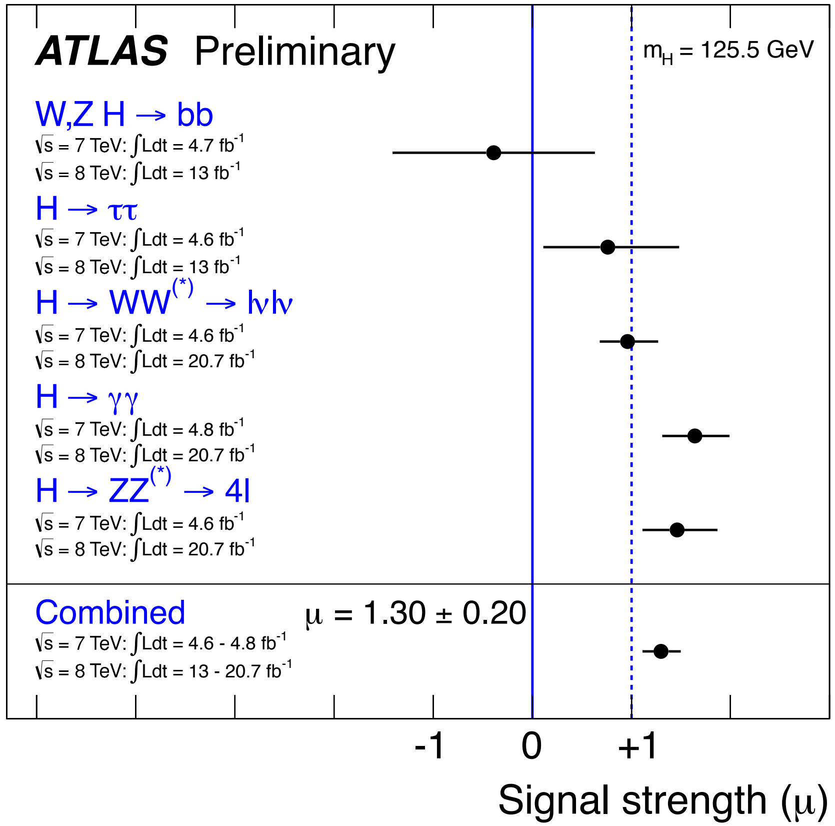
Masses of new fermions:

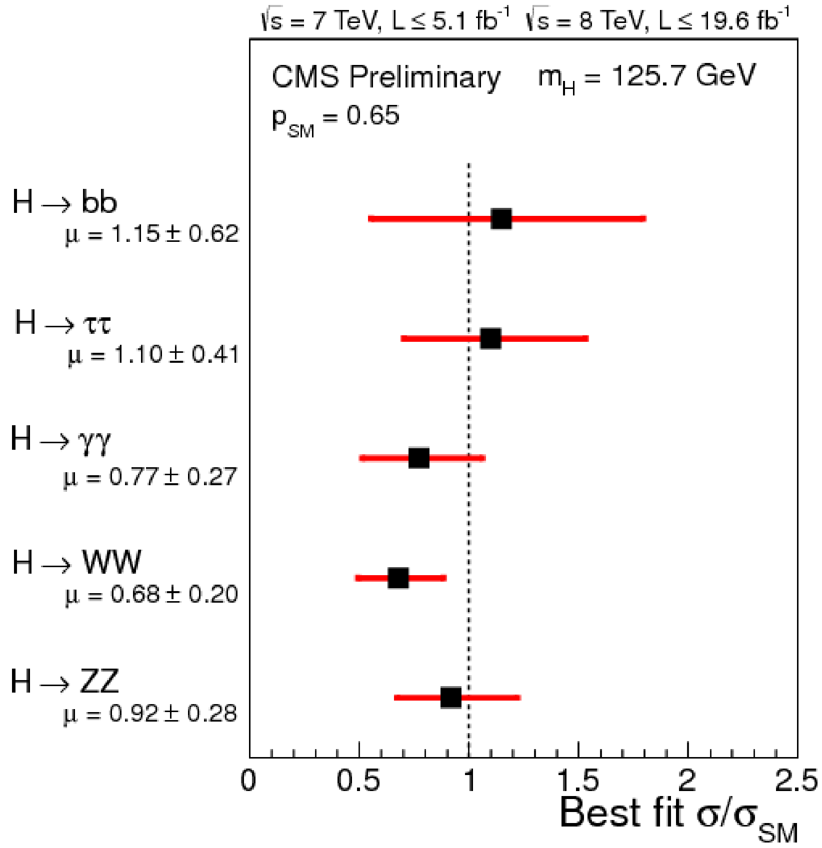
$$\underbrace{M_{10},\ \frac{M_{10}}{\cos\phi_{R,t}},\ M_{10} + \frac{fy}{2},\ \frac{M_{10} + \frac{fy}{2}}{\cos\phi_{L},}}_{\text{top partners}}\underbrace{M_{10},\ \frac{M_{10}}{\cos\phi_{R,b}},\ \frac{M_{10} + \frac{fy}{2}}{\cos\phi_L}}_{\text{bottom partners}},\underbrace{M_{10},\ M_{10},\ M_{10} + \frac{fy}{2}}_{\chi' s}$$

Top and bottom quark masses at LO in $v/f$:

$$m_{top} = \frac{y\ v}{4} \sin\phi_L \sin\phi_{R,t} \ , \qquad m_{bot} = \frac{y\ v}{2\sqrt{2}} \sin\phi_L \sin\phi_{R,b}$$

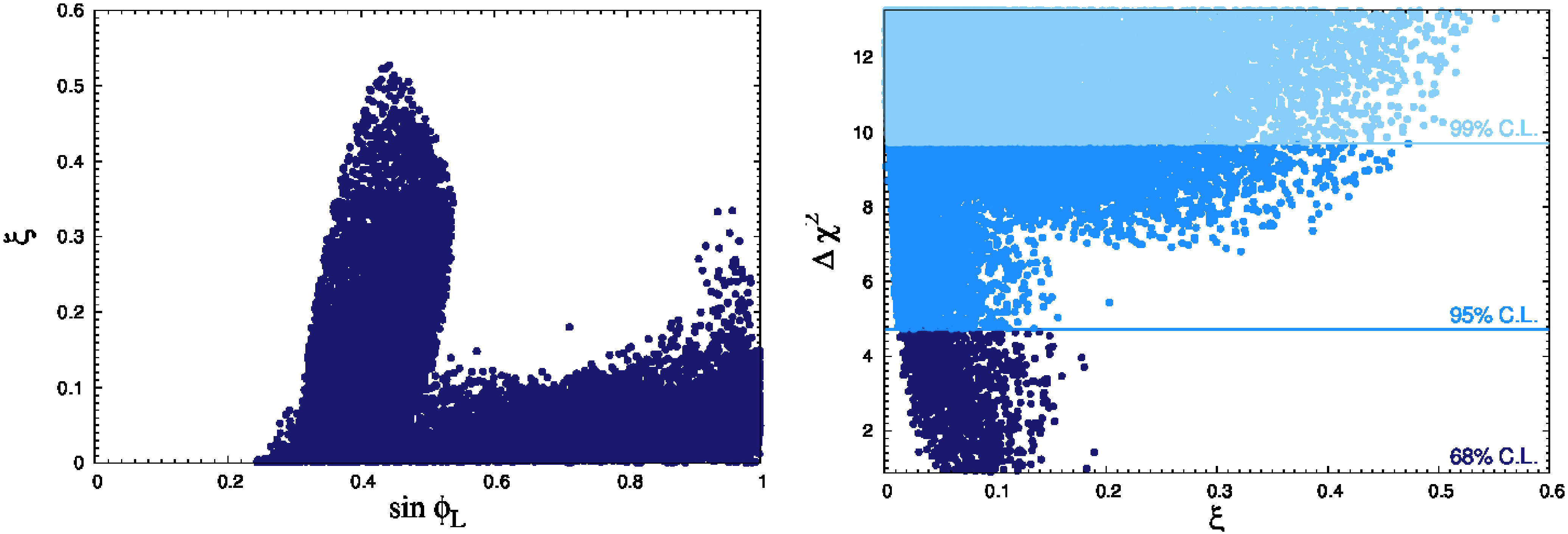
# $\mathcal{E}$xperimental $\mathcal{H}$iggs $\mathcal{S}$earch $\mathcal{R}$esults



# $\mathcal{C}$onstraints from $\mathcal{EWPT}$

Gillioz,Grober,Kapuvari,MM




Left: Points fulfill EWPT at 99% CL and $|V_{tb}| > 0.92$