Simple and Realistic Composite Higgs Models in Flat Extra Dimensions

G.Panico, M.S, M.Serone, JHEP 1102 (2011) 103.
arXiv: 1012.2875 [hep-ph]

Mahmoud Safari

SISSA

Planck 2011, Lisbon

Motivation

- Among various ideas proposed to address the gauge hierarchy problem is to identify the Higgs with the internal component of the gauge field in extra dimension (Gauge-Higgs Unification)
  [Farlie 1979, Manton 1979, Forgacs & Manton 1980, Hosotani 1983, 1989]

- GHU Models can be seen as weakly coupled 5D duals of Strongly Coupled 4D CFTs in which the Higgs arises as a Composite State
  [Contino, Nomura, Pomarol '03, Agashe, Contino, Pomarol 04]

- So GHU models in warped space provide calculable examples of composite Higgs models where one can perform explicit computation of the parameters relevant for EWPT

Motivation

- Among various ideas proposed to address the gauge hierarchy problem is to identify the Higgs with the internal component of the gauge field in extra dimension (Gauge-Higgs Unification)
  [Farlie 1979, Manton 1979, Forgacs & Manton 1980, Hosotani 1983, 1989]

- GHU Models can be seen as weakly coupled 5D duals of Strongly Coupled 4D CFTs in which the Higgs arises as a Composite State
  [Contino, Nomura, Pomarol '03, Agashe, Contino, Pomarol 04]

- So GHU models in warped space provide calculable examples of composite Higgs models where one can perform explicit computation of the parameters relevant for EWPT

Motivation

- Among various ideas proposed to address the gauge hierarchy problem is to identify the Higgs with the internal component of the gauge field in extra dimension (Gauge-Higgs Unification)
  [Farlie 1979, Manton 1979, Forgacs & Manton 1980, Hosotani 1983, 1989]

- GHU Models can be seen as weakly coupled 5D duals of Strongly Coupled 4D CFTs in which the Higgs arises as a Composite State
  [Contino, Nomura, Pomarol '03, Agashe, Contino, Pomarol 04]

- So GHU models in warped space provide calculable examples of composite Higgs models where one can perform explicit computation of the parameters relevant for EWPT

Motivation

Computation in warped space still challenging

Computation in warped space still challenging

But

- Low energy symmetries of the theory are independent of the specific form of the 5D metric, so:
- As far as EWSB and low energy phenomenology is concerned the background metric is irrelevant and one can rely on flat space versions of GHU models

Motivation

- Another Key ingredient is the introduction of Boundary Kinetic Terms (BKT) for the gauge fields, without which one would get too low Higgs and top masses [Scrucca, Serone, Silvestrini '03]

- Large BKT for the gauge fields (and fermions) are introduced on the UV brane which effectively defines the elementary sector of the composite Higgs model, so that these models resemble more closely their warped analogues

Motivation

- Another Key ingredient is the introduction of Boundary Kinetic Terms (BKT) for the gauge fields, without which one would get too low Higgs and top masses [Scrucca, Serone, Silvestrini '03]

- Large BKT for the gauge fields (and fermions) are introduced on the UV brane which effectively defines the elementary sector of the composite Higgs model, so that these models resemble more closely their warped analogues

Motivation

- Another Key ingredient is the introduction of Boundary Kinetic Terms (BKT) for the gauge fields, without which one would get too low Higgs and top masses [Scrucca, Serone, Silvestrini '03]
- Large BKT for the gauge fields (and fermions) are introduced on the UV brane which effectively defines the elementary sector of the composite Higgs model, so that these models resemble more closely their warped analogues

In this work we present 3 GHU models in flat space, including boundary kinetic terms for gauge fields (and fermions for 2 of the models) based on SO(5)/SO(4) symmetry breaking pattern

EWPT

- Most constraining bounds on new physics come from S and T parameters and from deviations to $Z\bar{b}_L b_L$ coupling δg_b.

- In all our models, $\mathbb{Z}_2$ (LR) symmetry has been imposed to protect δg_b from new physics corrections [Agashe, Contino, Da Rold, Pomarol '06]

- Tree level values of S, T and δg_b parameters are computed using the holographic approach [Agashe, Contino, Pomarol '04]

EWPT

- Most constraining bounds on new physics come from S and T parameters and from deviations to $Z\bar{b}_L b_L$ coupling δg_b.

- In all our models, $\mathbb{Z}_2$ (LR) symmetry has been imposed to protect δg_b from new physics corrections [Agashe, Contino, Da Rold, Pomarol '06]

- Tree level values of S, T and δg_b parameters are computed using the holographic approach [Agashe, Contino, Pomarol '04]

EWPT

- Most constraining bounds on new physics come from S and T parameters and from deviations to $Z\bar{b}_L b_L$ coupling δg_b.

- In all our models, $\mathbb{Z}_2$ (LR) symmetry has been imposed to protect δg_b from new physics corrections [Agashe, Contino, Da Rold, Pomarol '06]

- Tree level values of S, T and δg_b parameters are computed using the holographic approach [Agashe, Contino, Pomarol '04]

EWPT

- Symmetries protecting T and δg_b are not exact, so 1-Loop effects expected to be important

- Also 1-Loop corrections to S cannot totally be ignored, since the 1-Loop suppression factor is partially compensated by the mild hierarchy between lightest non SM gauge and fermion masses

- The gauge contribution to EWP observables are subdominant with respect to fermion contributions since the non-SM fermions are significantly lighter than non-SM vector mesons

- So in all 3 models 1-Loop fermion contribution to EWP observables have been computed. This is done using the standard KK approach

EWPT

- Symmetries protecting T and δg_b are not exact, so 1-Loop effects expected to be important
- Also 1-Loop corrections to S cannot totally be ignored, since the 1-Loop suppression factor is partially compensated by the mild hierarchy between lightest non SM gauge and fermion masses
- The gauge contribution to EWP observables are subdominant with respect to fermion contributions since the non-SM fermions are significantly lighter than non-SM vector mesons
- So in all 3 models 1-Loop fermion contribution to EWP observables have been computed. This is done using the standard KK approach

EWPT

- Symmetries protecting T and δg_b are not exact, so 1-Loop effects expected to be important
- Also 1-Loop corrections to S cannot totally be ignored, since the 1-Loop suppression factor is partially compensated by the mild hierarchy between lightest non SM gauge and fermion masses
- The gauge contribution to EWP observables are subdominant with respect to fermion contributions since the non-SM fermions are significantly lighter than non-SM vector mesons
- So in all 3 models 1-Loop fermion contribution to EWP observables have been computed. This is done using the standard KK approach

EWPT

- Symmetries protecting T and δg_b are not exact, so 1-Loop effects expected to be important
- Also 1-Loop corrections to S cannot totally be ignored, since the 1-Loop suppression factor is partially compensated by the mild hierarchy between lightest non SM gauge and fermion masses
- The gauge contribution to EWP observables are subdominant with respect to fermion contributions since the non-SM fermions are significantly lighter than non-SM vector mesons
- So in all 3 models 1-Loop fermion contribution to EWP observables have been computed. This is done using the standard KK approach

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in one multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++), q'_L(-+)] \\ \left\{ \begin{array}{ll} x_L(+-) & \\ u_L(--) & T_L(+-) \\ d_L(--) & \end{array} \right. \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}, 1_{2/3}, 1_{-1/3}, 2_{1/6}, 2_{7/6}, 3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass m

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in <u>one</u> multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++), q'_L(-+)] \\ \left\{ \begin{array}{ll} x_L(+-) & \\ u_L(--) & T_L(+-) \\ d_L(--) & \end{array} \right. \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}$, $1_{2/3}$, $1_{-1/3}$, $2_{1/6}$, $2_{7/6}$, $3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass *m*

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in <u>one</u> multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++),\, q'_L(-+)] & \\ \begin{Bmatrix} x_L(+-) \\ u_L(--) \\ d_L(--) \end{Bmatrix} & T_L(+-) \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}$, $1_{2/3}$, $1_{-1/3}$, $2_{1/6}$, $2_{7/6}$, $3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass m

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in <u>one</u> multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++), q'_L(-+)] \\ \begin{cases} x_L(+-) \\ u_L(--) \quad T_L(+-) \\ d_L(--) \end{cases} \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}, 1_{2/3}, 1_{-1/3}, 2_{1/6}, 2_{7/6}, 3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass *m*

Fermions in the 10 of SO(5)

- Third generation quarks embedded in one multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++),\, q'_L(-+)] \\ \begin{cases} x_L(+-) & \\ u_L(--) & T_L(+-) \\ d_L(--) & \end{cases} \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}, 1_{2/3}, 1_{-1/3}, 2_{1/6}, 2_{7/6}, 3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass *m*

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in one multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++), q'_L(-+)] \\ \left\{ \begin{matrix} x_L(+-) & \\ u_L(--) & T_L(+-) \\ d_L(--) & \end{matrix} \right. \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}, 1_{2/3}, 1_{-1/3}, 2_{1/6}, 2_{7/6}, 3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass *m*

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in one multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++), q'_L(-+)] \\ \begin{cases} x_L(+-) \\ u_L(--) \quad T_L(+-) \\ d_L(--) \end{cases} \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}$, $1_{2/3}$, $1_{-1/3}$, $2_{1/6}$, $2_{7/6}$, $3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass m

Model 1

Fermions in the 10 of SO(5)

- Third generation quarks embedded in one multiplet, 10 of SO(5)

$$10_{2/3} = (2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$$

$$\xi_L = \begin{bmatrix} [q_L(++), q'_L(-+)] \\ \begin{cases} x_L(+-) & \\ u_L(--) & T_L(+-) \\ d_L(--) & \end{cases} \end{bmatrix}_{2/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_x \bar{x}_L i\not{D} x_L + Z_T \bar{T}_L i\not{D} T_L + Z_{q'} \bar{q}'_R i\not{D} q'_R$$

- No IR mass terms compatible with O(4) symmetry

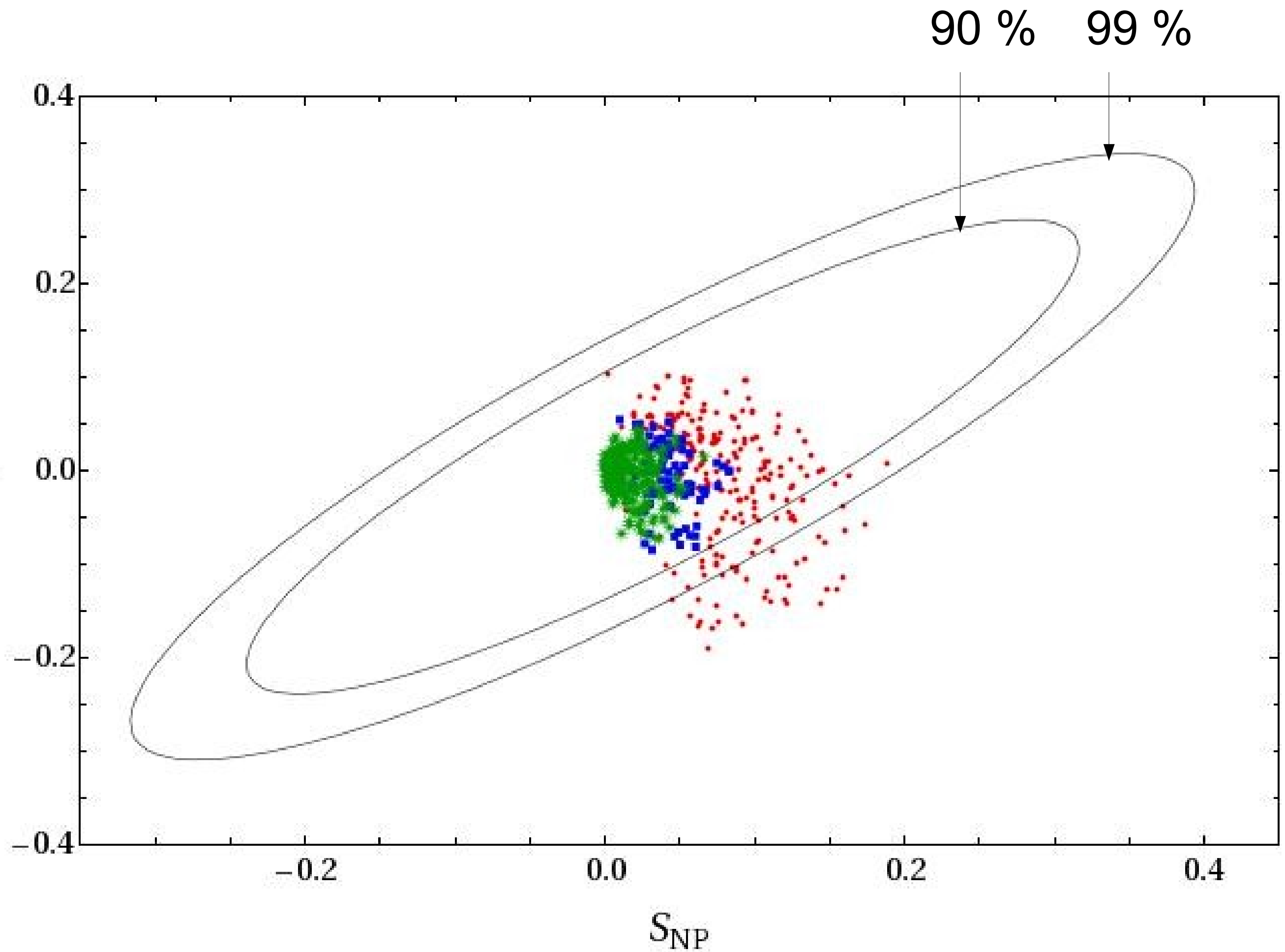
$$L_{f,L} = 0$$

- Vector like resonances with quantum numbers: $1_{5/3}$, $1_{2/3}$, $1_{-1/3}$, $2_{1/6}$, $2_{7/6}$, $3_{2/3}$

- 7 parameters in the fermion sector: $Z_q, Z_t, Z_b, Z_x, Z_T, Z_{q'}$ and a bulk mass *m*

Model 1

Results...



- Projection on $T_{NP} - S_{NP}$ plane
- Points with $m_H > 114$ GeV have been chosen
- $M_{H,eff} = 120$ GeV has been taken as a reference point

* Pass EWPT at 90% C.L
■ Pass EWPT at 99% C.L
● Do not pass EWPT at 99% C.L

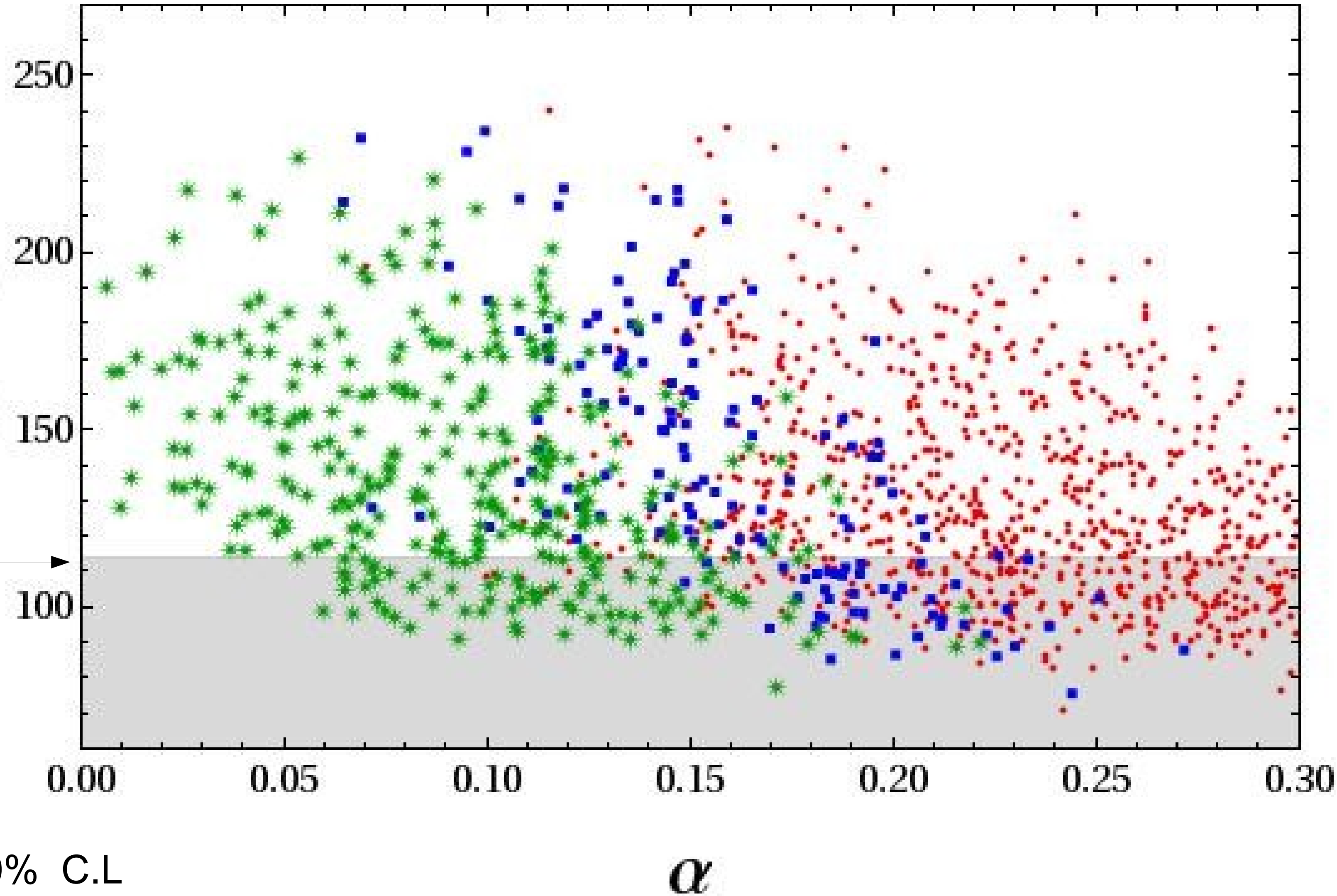
5 d.o.f

In this model the $W \bar{t}_R b_R$ coupling at tree level is nonzero. This is taken into account in the fit

Model 1

Results...

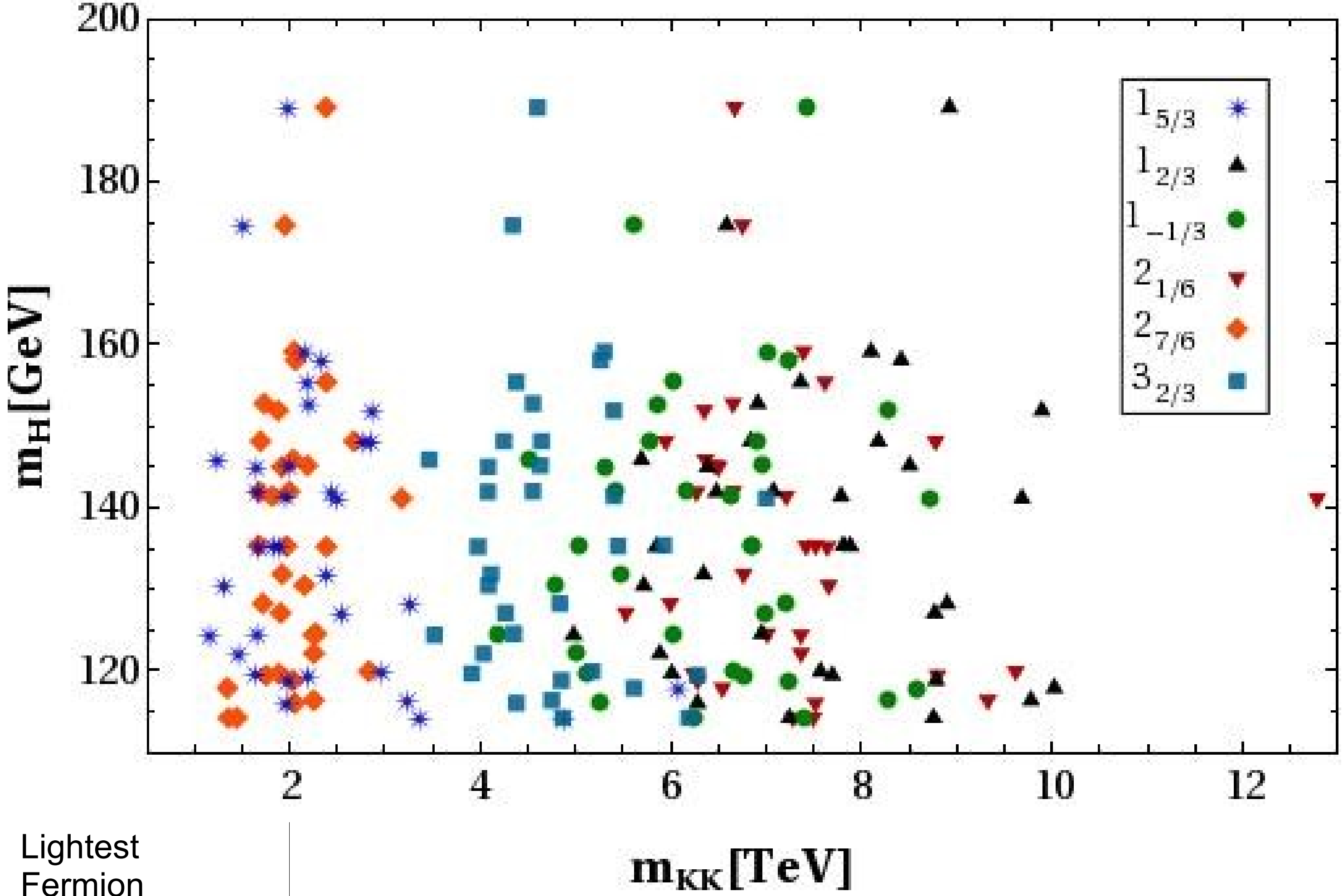
114 GeV



- * Pass EWPT at 90% C.L
- ■ Pass EWPT at 99% C.L
- ● Do not pass EWPT at 99% C.L

Model 1

Results...



Lightest Fermion Resonances

$2_{7/6}$

$1_{5/3}$

Points which pass EWPT at 99% C.L with $\alpha \in [0.16, 0.23]$

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

- Vector like resonances

$1_{2/3},\ 1_{-1/3},\ 2_{-5/6},\ 2_{1/6},\ 2_{7/6}$

- 7 Parameters in the Fermion Sector:

$Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$

and 2 Bulk Masses m_t and m_b

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- Vector like resonances

$1_{2/3},\ 1_{-1/3},\ 2_{-5/6},\ 2_{1/6},\ 2_{7/6}$

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

- 7 Parameters in the Fermion Sector:

$Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$

and 2 Bulk Masses m_t and m_b

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- Vector like resonances

$1_{2/3},\ 1_{-1/3},\ 2_{-5/6},\ 2_{1/6},\ 2_{7/6}$

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

- 7 Parameters in the Fermion Sector: $Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$ and 2 Bulk Masses m_t and m_b

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- Vector like resonances $1_{2/3}, 1_{-1/3}, 2_{-5/6}, 2_{1/6}, 2_{7/6}$

- 7 Parameters in the Fermion Sector: $Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$ and 2 Bulk Masses m_t and m_b

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

- Vector like resonances
$1_{2/3},\ 1_{-1/3},\ 2_{-5/6},\ 2_{1/6},\ 2_{7/6}$

- 7 Parameters in the Fermion Sector:
$Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$
and 2 Bulk Masses
m_t and m_b

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

- Vector like resonances $1_{2/3},\ 1_{-1/3},\ 2_{-5/6},\ 2_{1/6},\ 2_{7/6}$

- 7 Parameters in the Fermion Sector: $Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$ and 2 Bulk Masses m_t and m_b

Model 2

Fermions in the 5 of SO(5)

- Third generation quarks Embedded in Two Fundamentals of SO(5)

$$5 = (2,2) + (1,1)$$

$$\xi_{tL} = \begin{bmatrix} [q_{1L}(++), q'_{1L}(-+)] \\ u_L(--) \end{bmatrix}_{2/3}, \quad \xi_{bL} = \begin{bmatrix} [q'_{2L}(-+), q_{2L}(++)] \\ d_L(--) \end{bmatrix}_{-1/3}$$

- UV Brane Kinetic Terms

$$L_{f,0} = Z_q \bar{q}_L i\not{D} q_L + Z_t \bar{u}_R i\not{D} u_R + Z_b \bar{d}_R i\not{D} d_R + Z_{R2} \bar{q}'_{2R} i\not{D} q'_{2R} + Z_{R1} \bar{q}'_{1R} i\not{D} q'_{1R}$$

- No IR Mass Terms Allowed By Symmetries

$$L_{f,L} = 0$$

- Vector like resonances

$1_{2/3},\ 1_{-1/3},\ 2_{-5/6},\ 2_{1/6},\ 2_{7/6}$

- 7 Parameters in the Fermion Sector:

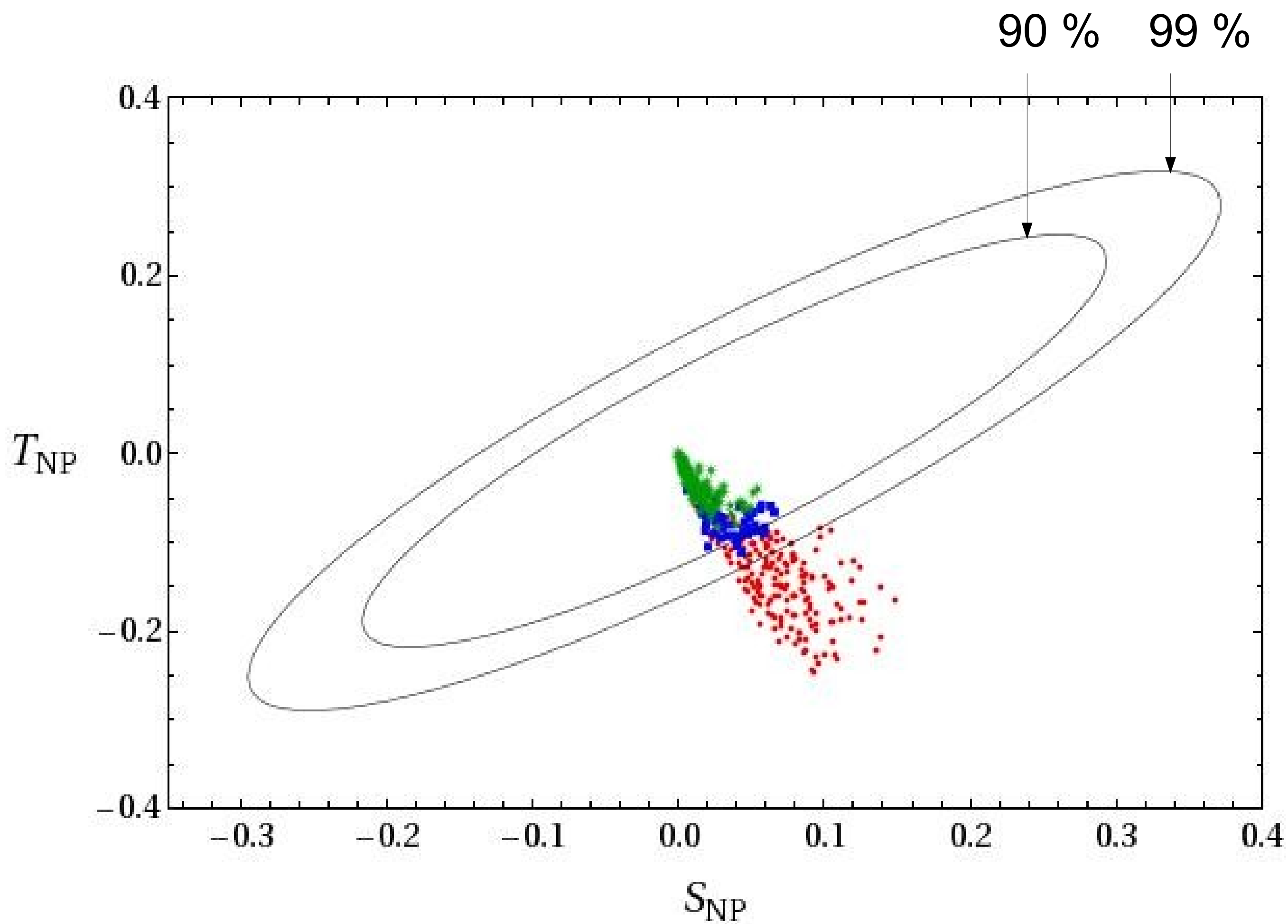
$Z_q, Z_t, Z_b, Z_{R1}, Z_{R2}$

and 2 Bulk Masses m_t and m_b

Model 2

Results...

- Projection on $T_{NP} - S_{NP}$ plane
- Points with $m_H > 114$ GeV have been chosen
- $M_{H,eff} = 120$ GeV has been taken as a reference point



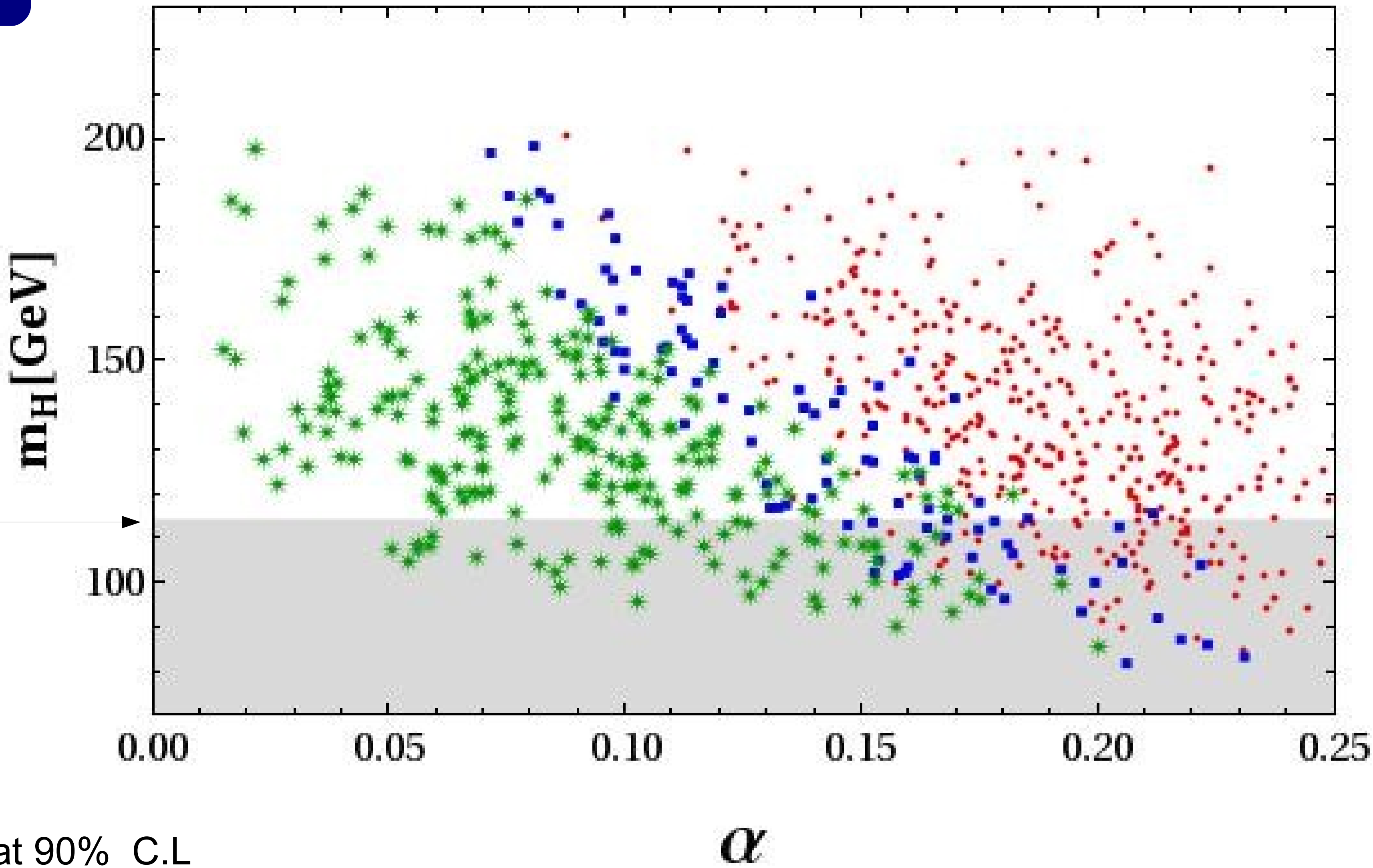
- * Pass EWPT at 90% C.L
- ■ Pass EWPT at 99% C.L
- ● Do not pass EWPT at 99% C.L

4 d.o.f

Model 2

Results...

114 GeV



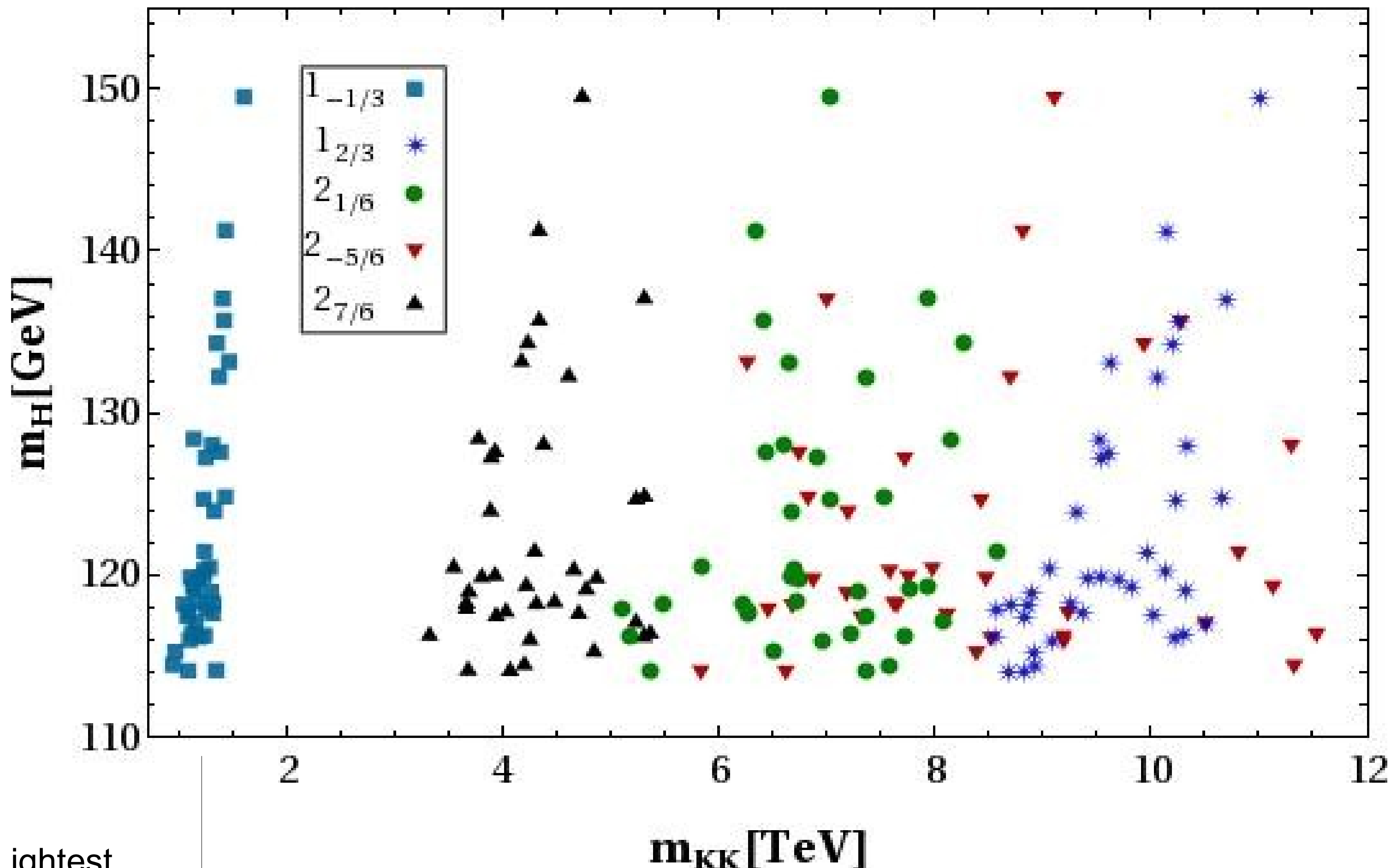
* Pass EWPT at 90% C.L

■ Pass EWPT at 99% C.L

● Do not pass EWPT at 99% C.L

Model 2

Results...



Lightest Fermion Resonance

$1_{-1/3}$

Points which pass EWPT at 99% C.L with $\alpha \in [0.16, 0.22]$

Model 3

Modified MCHM5

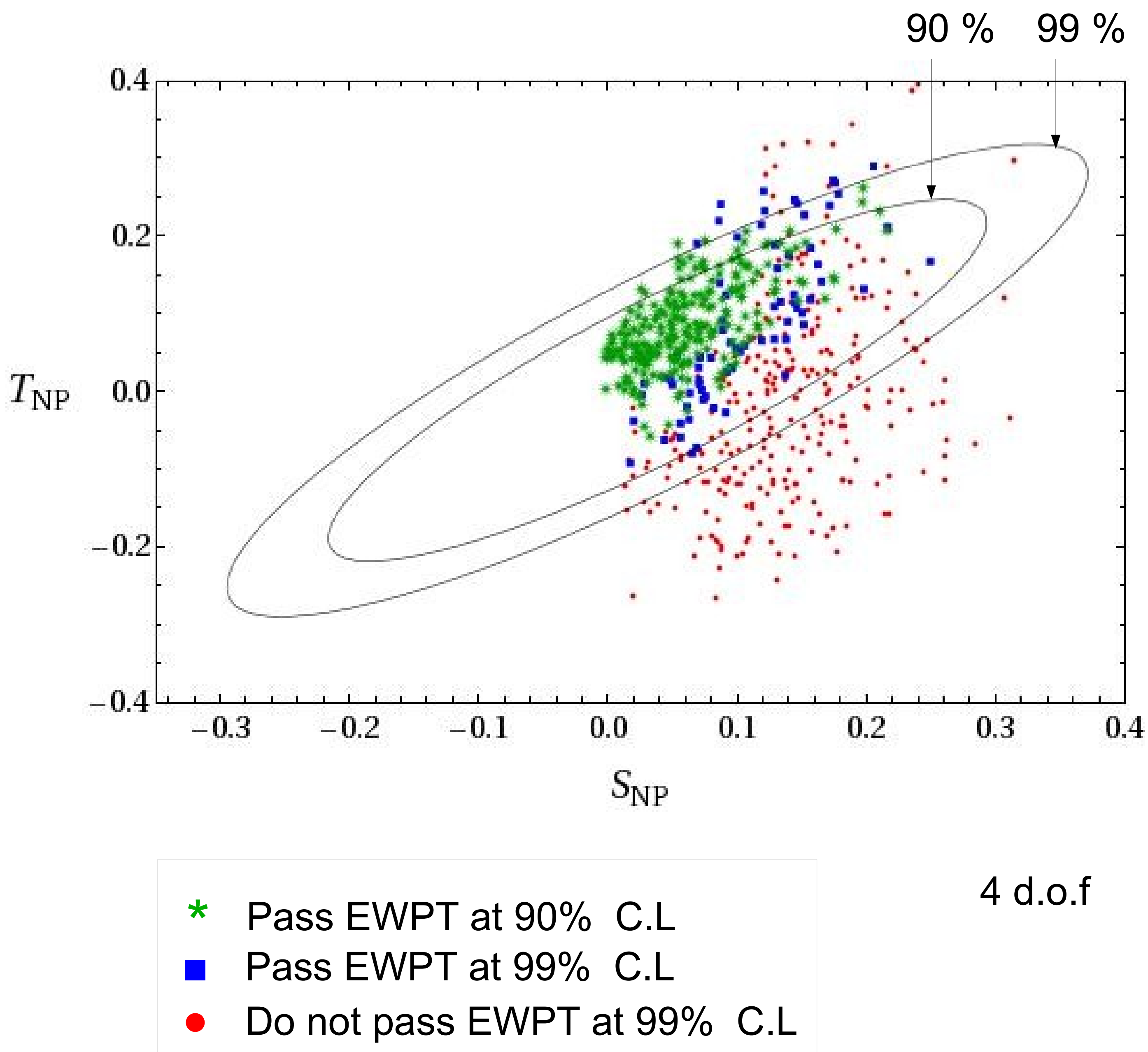
This model is the flat space version of the Minimal Composite Higgs Model (MCHM5) [Agashe, Contino, Pomarol '04]

- Fermions are embedded in 4 fundamentals of SO(5)
- Possible mass terms are added in the IR, but no Fermion kinetic terms are introduced in the UV.
- The Fermion Sector of this model includes 8 Parameters: 4 bulk masses and 4 IR masses.

Model 3

Results...

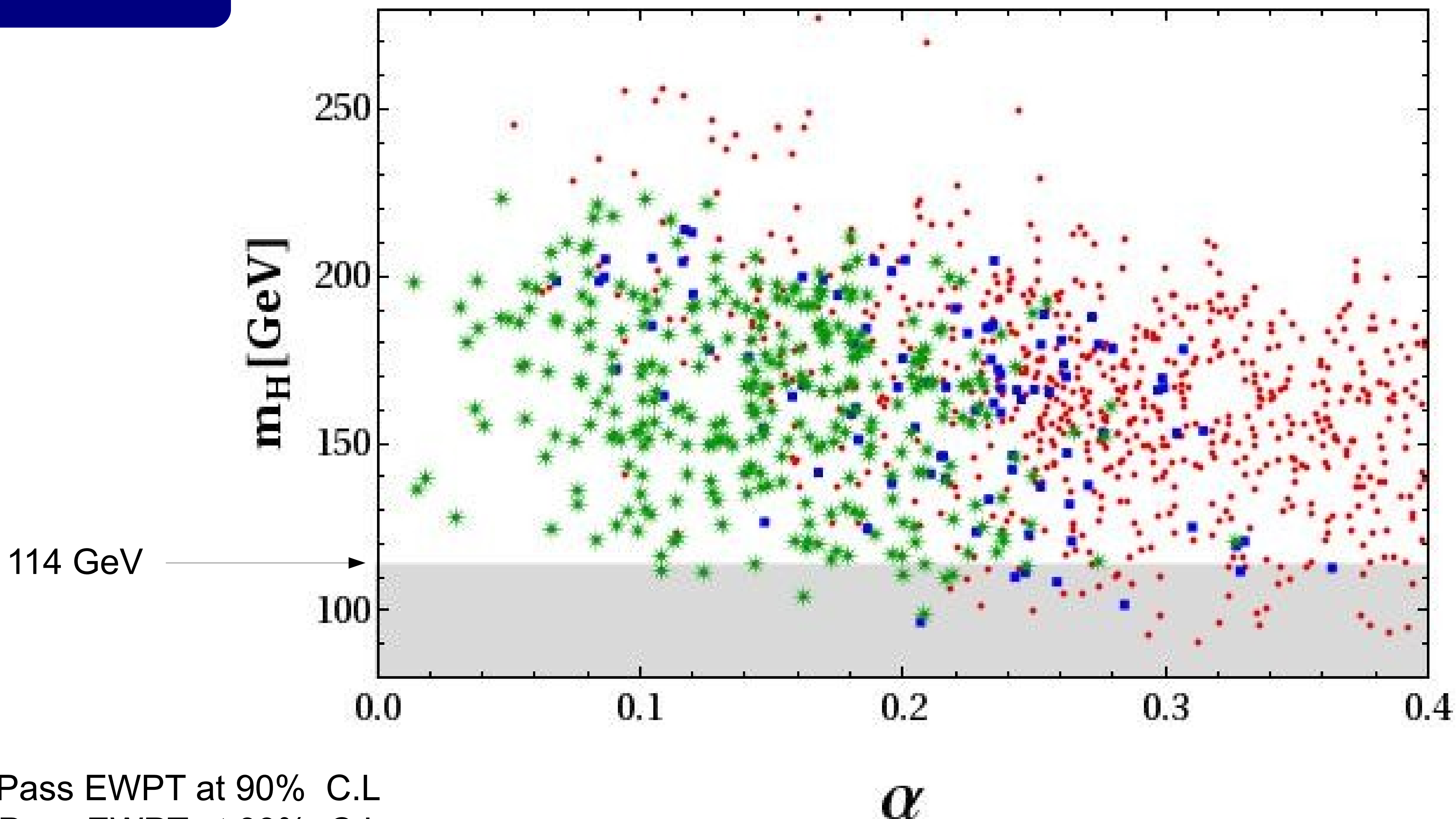
- Projection on $T_{NP} - S_{NP}$ plane
- Points with $m_H > 114$ GeV have been chosen
- $M_{H,eff} = 120$ GeV has been taken as a reference point



4 d.o.f

Model 3

Results...



* Pass EWPT at 90% C.L

■ Pass EWPT at 99% C.L

● Do not pass EWPT at 99% C.L

Conclusions

- Model building in flat space is significantly simpler than in warped space, and if accompanied by BKT and suitable custodially symmetric gauge groups, can give rise to realistic models

- Three Composite-Higgs/GHU models of this sort based on SO(5)/SO(4) have been constructed. Analysis of EWPT has been done, and EWSB and EWPT are shown to be compatible with each other.

Conclusions

- Model building in flat space is significantly simpler than in warped space, and if accompanied by BKT and suitable custodially symmetric gauge groups, can give rise to realistic models

- Three Composite-Higgs/GHU models of this sort based on SO(5)/SO(4) have been constructed. Analysis of EWPT has been done, and EWSB and EWPT are shown to be compatible with each other.

Conclusions

- The Higgs is predicted to be light with mass < 200 GeV
- The lightest new physics particles are colored fermions with masses as low as 500 GeV in the MCHM5 and 1 TeV in models with fermion BKT.
- Their electroweak quantum numbers depend on the model and the region of parameter space, but they are always particles with electric charges -1/3, 2/3, 5/3

Conclusions

- The Higgs is predicted to be light with mass < 200 GeV
- The lightest new physics particles are colored fermions with masses as low as 500 GeV in the MCHM5 and 1 TeV in models with fermion BKT.
- Their electroweak quantum numbers depend on the model and the region of parameter space, but they are always particles with electric charges -1/3, 2/3, 5/3

Conclusions

- The Higgs is predicted to be light with mass < 200 GeV
- The lightest new physics particles are colored fermions with masses as low as 500 GeV in the MCHM5 and 1 TeV in models with fermion BKT.
- Their electroweak quantum numbers depend on the model and the region of parameter space, but they are always particles with electric charges -1/3, 2/3, 5/3

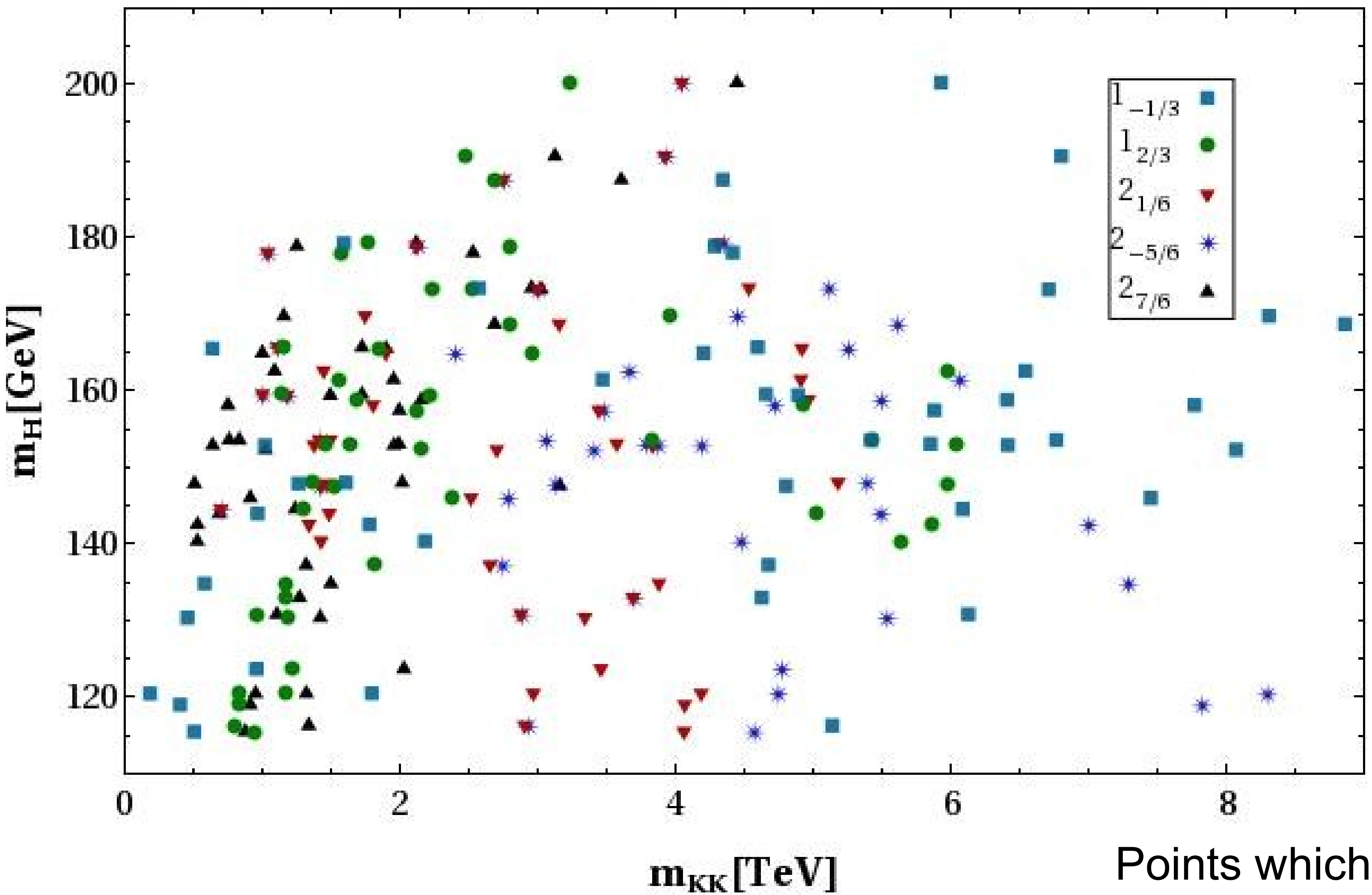
Conclusions

- The Higgs is predicted to be light with mass < 200 GeV
- The lightest new physics particles are colored fermions with masses as low as 500 GeV in the MCHM5 and 1 TeV in models with fermion BKT.
- Their electroweak quantum numbers depend on the model and the region of parameter space, but they are always particles with electric charges -1/3, 2/3, 5/3

Thank you

Back up slides: Model 3

Results...



Points which pass EWPT at 99% C.L with $\alpha \in [0.26, 0.34]$

Back up slides: χ^2 Fit

$$\epsilon_1 = (5.64 - 0.86\; lh) \times 10^{-3} + \alpha_{em} T_{NP}$$

$$\epsilon_2 = (-7.10 + 0.16\; lh) \times 10^{-3}$$

$$\epsilon_3 = (5.25 + 0.54\; lh) \times 10^{-3} + \frac{\alpha_{em}}{4 \sin(\theta_W)^2} T_{NP}$$

$$\epsilon_b = -6.47 \times 10^{-3} - 2\delta g_{b,NP}$$

$$lh \equiv \log\left(\frac{M_{H,eff}}{M_Z}\right)$$

$$M_{H,eff} \equiv M_H \left(\frac{1}{M_H L}\right)^{\sin^2(\alpha)}$$

Due to Modified Higgs Coupling to Gauge Bosons

[Barbieri, Bellazzini, Rychkov, Varagnolo, '07]

$$\epsilon_1^{exp} = (5.03 \pm 0.93) \times 10^{-3}$$

$$\epsilon_2^{exp} = (-7.73 \pm 0.95) \times 10^{-3}$$

$$\epsilon_3^{exp} = (5.44 \pm 0.87) \times 10^{-3}$$

$$\epsilon_b^{exp} = (-6.36 \pm 1.3) \times 10^{-3}$$

$$\rho = \begin{pmatrix} 1 & 0.72 & 0.87 & -0.29 \\ 0.72 & 1 & 0.46 & -0.26 \\ 0.87 & 0.46 & 1 & -0.18 \\ -0.29 & -0.26 & -0.18 & 1 \end{pmatrix}$$

$$g_{bt,R} = (9 \pm 8) \times 10^{-4}$$ arXiv: 0801.1800 [hep-ph]

arXiv: hep-ex/0412015

arXiv: hep-ex/0612034