# THE EXCEPTIONAL TWIN HIGGS

## (AKA CHARGED NATURALNESS)

CERN-CKC TH Institute on Neutral Naturalness

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In collaboration with J. Serra, to appear

# Twin Higgs: the paradigm

## The Twin Higgs mechanism and the little hierarchy problem

## A Composite Twin Higgs model

# The Twin Higgs Mechanism

- The Twin Higgs mechanism helps in reducing the sensitivity of the Higgs potential to the mass of the particles introduced to address the hierarchy problem
- It realises the Higgs as a pseudo-Goldstone boson of a global symmetry breaking G/H
- The SM symmetry structure and particle content is doubled through a $Z_2$ symmetry (at least partially) and G is chosen to accomodate a copy of the electroweak sector
- The SM particles are neutral under the twin gauge group and vice versa (at least color)
- Thanks to the $Z_2$ symmetry, the leading contribution to the quadratic part of the potential turns out to be symmetric under G and therefore vanishing
- What happens is that the sensitivity to the mass of the states to which the Higgs potential is sensitive (like "top partners" or electroweak "resonances") from the two sectors turn out to be equal and with opposite sign
- Only a sensitivity to the neutral twin partners remain, but they can be much lighter
- Fine-tuning is generally reduced by a ratio of couplings $g_*^2/g_{\rm SM}^2$

*Chacko, Goh, Harnik, hep-ph/0506256*
*Barbieri, Gregoire, Hall, hep-ph/0509242*
*Chacko, Nomura, Papucci, Perez, hep-ph/0510273*
*Chacko, Goh, Harnik, hep-ph/0512088*
*Chang, Hall, Weiner, hep-ph/0604076*

# Twin Higgs at work

## 1. Weak dynamics (Supersymmetry) + Twin Higgs

*Chang, Hall, Weiner, hep-ph/0604076*
*Craig, Howe, 1312.1341 [hep-ph]*

$G/H$

$m_{h,W,Z}$ $\quad m_{\text{twin}} \sim g_{\text{SM}} f$ $\quad m_{\text{soft}} \sim g_* f$ $\quad \Lambda_{\text{UV}}$

$$\Delta = \frac{\delta m_h}{m_h} \sim \left(\frac{m_{\text{soft}}}{500\text{GeV}}\right)^2 \log\left(\frac{\Lambda_{\text{UV}}^2}{m_{\text{soft}}^2}\right) \quad \Longrightarrow \quad \Delta \sim \left(\frac{m_{\text{twin}}}{500\text{GeV}}\right)^2 \left(1 + \log\left(\frac{m_{\text{soft}}^2}{m_{\text{twin}}^2}\right)\right)$$

$$\nearrow \qquad \Downarrow$$

$$g_*^2 \equiv \frac{m_{\text{soft}}^2}{f^2} \sim \lambda^2 \frac{16\pi^2}{3y_t^2} \log^{-1}\left(\frac{\Lambda_{\text{UV}}^2}{m_{\text{soft}}^2}\right) \qquad \Delta \sim \left(\frac{m_{\text{soft}}}{500\text{GeV}}\right)^2 \frac{g_{\text{SM}}^2}{g_*^2} \left(1 + \log\left(\frac{g_*^2}{g_{\text{SM}}^2}\right)\right)$$

## 2. Strong dynamics (Compositeness) + Twin Higgs

$G/H$

$m_{h,W,Z}$ $\quad m_{\text{twin}} \sim g_{\text{SM}} f$ $\quad \Lambda_{IR} \sim m_* \sim g_* f$ $\quad \Lambda_{\text{UV}}$

$$\Delta = \frac{\delta m_h}{m_h} \sim \left(\frac{m_*}{500\ \text{GeV}}\right)^2 \quad \Longrightarrow \quad \Delta \sim \left(\frac{m_{\text{twin}}}{500\ \text{GeV}}\right)^2 \left(1 + \log\left(\frac{m_*^2}{m_{\text{twin}}^2}\right)\right)$$

$$\nearrow \qquad \Downarrow$$

$$g_*^2 \equiv \frac{m_*^2}{f^2} \qquad \Delta \sim \left(\frac{m_*}{500\text{GeV}}\right)^2 \frac{g_{\text{SM}}^2}{g_*^2} \left(1 + \log\left(\frac{g_*^2}{g_{\text{SM}}^2}\right)\right)$$

# Twin Higgs at work

## 1. Weak dynamics (Supersymmetry) + Twin Higgs

*Chang, Hall, Weiner, hep-ph/0604076*
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$G/H$

$m_{h,W,Z}$ — $m_{\text{twin}} \sim g_{\text{SM}} f$ — $m_{\text{soft}} \sim g_* f$ — $\Lambda_{\text{UV}}$

$$\Delta = \frac{\delta m_h}{m_h} \sim \left(\frac{m_{\text{soft}}}{500\text{GeV}}\right)^2 \log\left(\frac{\Lambda^2_{\text{UV}}}{m^2_{\text{soft}}}\right) \Longrightarrow \Delta \sim \left(\frac{m_{\text{twin}}}{500\text{GeV}}\right)^2 \left(1+\log\left(\frac{m^2_{\text{soft}}}{m^2_{\text{twin}}}\right)\right)$$

$$\Downarrow$$

$$g_*^2 \equiv \frac{m^2_{\text{soft}}}{f^2} \sim \lambda^2 \frac{16\pi^2}{3y_t^2} \log^{-1}\left(\frac{\Lambda^2_{\text{UV}}}{m^2_{\text{soft}}}\right) \nearrow \quad \Delta \sim \left(\frac{m_{\text{soft}}}{500\text{GeV}}\right)^2 \frac{g^2_{\text{SM}}}{g^2_*}\left(1+\log\left(\frac{g^2_*}{g^2_{\text{SM}}}\right)\right)$$

Charged under SM

## 2. Strong dynamics (Compositeness) + Twin Higgs

Neutral under SM

$G/H$

$m_{h,W,Z}$ — $m_{\text{twin}} \sim g_{\text{SM}} f$ — $\Lambda_{IR} \sim m_* \sim g_* f$ — $\Lambda_{\text{UV}}$

$$\Delta = \frac{\delta m_h}{m_h} \sim \left(\frac{m_*}{500\text{ GeV}}\right)^2 \Longrightarrow \Delta \sim \left(\frac{m_{\text{twin}}}{500\text{ GeV}}\right)^2 \left(1+\log\left(\frac{m^2_*}{m^2_{\text{twin}}}\right)\right)$$

$$\Downarrow$$

$$g_*^2 \equiv \frac{m_*^2}{f^2} \nearrow \quad \Delta \sim \left(\frac{m_*}{500\text{GeV}}\right)^2 \frac{g^2_{\text{SM}}}{g^2_*}\left(1+\log\left(\frac{g^2_*}{g^2_{\text{SM}}}\right)\right)$$

# A Twin Composite Higgs

- The smallest global symmetry that can account for a doubling of all the SM fields and custodial symmetry should contain 4 commuting $SU(2)$ subgroups, therefore $\mathrm{rank}(G) = 4$
- In order to identify the SM Higgs with some of the NGB of $G/H$ we need the Goldstone multiplet to contain a $(2,2)$ of $SU(2)_L \times SU(2)_R$
- The smaller such coset is the 7-sphere $SO(8)/SO(7)$

*Barbieri, Greco, Rattazzi, Wulzer, 1501.07803 [hep-ph]*
*Low, Tesi, Wang, 1501.07890 [hep-ph]*
*see also talks by A. Wulzer and A. Tesi*

- As in MCHM we also have to introduce a $U(1)_X$ global symmetry necessary to correctly reproduce the hypercharge of the SM fermions $Y = T^3_R + X$
- Twin groups for $SU(3)_c$ and $U(1)_X$ also have to be introduced to get a full copy of the SM
- The global symmetry breaking pattern is therefore

$$SU(3)_c \times \widetilde{SU(3)}_c \times U(1)_X \times \widetilde{U(1)}_X \times Z_2 \times (SO(8)/SO(7))$$

- where

$$\frac{SO(8)}{SO(7)} \supset \frac{SO(4) \times \widetilde{SO(4)}}{SO(4) \times \widetilde{SO(3)}} \sim \frac{SU(2)_L \times SU(2)_R \times \widetilde{SU(2)}_L \times \widetilde{SU(2)}_R}{SU(2)_L \times SU(2)_R \times \widetilde{SU(2)}_{L+R}}$$

- of which the generators $T^a_L, T^3_R, \tilde{T}^a_L, \tilde{T}^3_R$ are gauged (plus color and twin color)
- In order to avoid the presence of a massless twin photon one can avoid gauging $\tilde{T}^3_R$
- For simplicity the $q_L$ is coupled with a fundamental **8** of $SO(8)$ and the $t_R$ with a singlet

# A Twin Composite Higgs

$$\frac{SO(8)}{SO(7)} \supset \frac{SO(4)\times\widetilde{SO(4)}}{SO(4)\times\widetilde{SO(3)}} \sim \frac{SU(2)_L\times SU(2)_R\times\widetilde{SU(2)}_L\times\widetilde{SU(2)}_R}{SU(2)_L\times SU(2)_R\times\widetilde{SU(2)}_{L+R}}$$

7 Goldstone bosons $\qquad (2,2,0)\sim H \qquad (1,1,3)\sim\omega$

- The $\omega$ triplet is eaten by the twin W bosons which gets a mass of order $m_{\widetilde{W}} \sim gf/2$
- The SM gauge and Yukawa couplings break explicitly the global symmetry, generating a radiative potential for the Higgs (as in CHM)
- Electroweak symmetry is broken at the scale v, the custodial $SU(2)_L\times SU(2)_R$ is broken to the vectorial $SU(2)_{L+R}$ and the $\pi^i$ are eaten by the W and the Z that get masses $m_W = gv/2$
- Analogously, fermions charged under $SO(4)$ (SM fermions) acquire a mass $m_f = y_f v/\sqrt{2}$ while fermion charged under $\widetilde{SO(4)}$ acquire a mass $m_{\widetilde{f}} \sim y_{\widetilde{f}} f/\sqrt{2}$
- Resonances from the strong sector instead lie at a scale $m_\rho \sim g_\rho f$ and $m_\Psi \sim g_\Psi f$
- To avoid constraints from direct searches we will be interested in $g_\rho \sim g_\Psi \sim g_* \gg 1$

# Higgs Potential

## 1. $Z_2$ symmetric contribution

$$V_{g^2}(H) \approx \frac{g_\rho^2 f^4}{16\pi^2}\left[g^2 \sin^2\left(\frac{H}{f}\right) + \widetilde{g}^2 \cos^2\left(\frac{H}{f}\right)\right]$$

$$V_{y_t^2}(H) \approx \frac{N_c g_\Psi^2 f^4}{16\pi^2}\left[y_t^2 \sin^2\left(\frac{H}{f}\right) + \widetilde{y}_t^2 \cos^2\left(\frac{H}{f}\right)\right]$$

- The quadratic contribution to the potential cancels in the $Z_2$ symmetric limit when

$$g = \widetilde{g}\,, \quad y_t = \widetilde{y}_t$$

- It remains a contribution to the quartic term in the breaking parameters which generates a Higgs quartic coupling of the right order to get a light Higgs with minimal tuning

$$V_{y_t^4}(H) \approx \frac{N_c f^4}{16\pi^2}\left[y_t^4 \sin^4\frac{H}{f}\log\frac{2m_\Psi^2}{y_t^2 f^2 \sin^2\frac{H}{f}} + \widetilde{y}_t^4 \cos^4\frac{H}{f}\log\frac{2m_\Psi^2}{\widetilde{y}_t^2 f^2 \cos^2\frac{H}{f}}\right]$$

- This potential cannot be "tuned" to achieve EWSB with $v \ll f$ and therefore one needs $Z_2$ breaking contributions

# Higgs Potential

## 2. $Z_2$ breaking contribution

- Consider the case where only the hypercharge breaks the $Z_2$ symmetry
- The first contribution is given by

*Barbieri, Greco, Rattazzi, Wulzer, 1501.07803 [hep-ph]*

$$V_{g_2'^2}(H) \approx \frac{g_\rho^2 f^4}{16\pi^2} g'^2 \sin^2\left(\frac{H}{f}\right)$$

- However it is too small to allow for viable EWSB
- The second contribution arises from the fact that the hypercharge breaking at some high scale $\Lambda_{\rm UV}$ contributes, through the running of $y_t$ and $\widetilde{y}_t$, to a $Z_2$ breaking in the top sector at the scale $m_*$

$$\Delta y_t(\Lambda_{\rm UV})^2 = y_t(\Lambda_{\rm UV})^2 - \widetilde{y}_t(\Lambda_{\rm UV})^2 = 0$$
$$\Delta y_t(m_*)^2 = \frac{b g_1^2}{16\pi^2} y_L(m_*)^2 \log\frac{\Lambda_{\rm UV}}{m_*}$$

$$V_{y_t^2}(H) \approx \frac{N_c g_\Psi^2 f^4}{16\pi^2} \Delta y_t(m_*)^2 \sin^2\left(\frac{H}{f}\right)$$

- To achieve a viable minimum one needs $g_\Psi \sim 4\pi$ with $b$ of order a few and a very high scale (for $b \sim 1$ one needs $\Lambda_{\rm UV} \gtrsim M_{\rm Pl}$)

# The good and the “bad” of the SO(8) Twin Higgs

## 1. The good

- EWSB can be achieved with the right Higgs mass and with minimal tuning (at least for fully composite top right)
- The explicit breaking of the $Z_2$ by hypercharge prevents the existence of a twin photon and could saturate the breaking needed for the Higgs potential (needs check in calculable models)
- No large corrections to the EWPO are generated (the twin sector is totally SM neutral)
- The model could be very hard to see at the LHC (good for tuning)

## 2. The “bad”

- The $\widetilde{SU(2)}_R$ is purely global and irrelevant for the twin mechanism
- Constraints from EWPT push the tuning $\xi \equiv v^2/f^2$ in the percent region and are hardly alleviated by additional contributions from the strong sector since the resonances are heavier than in usual CH (except for non-decoupling contributions)
- The model could be very hard to see at the LHC (bad for understanding)

# The Exceptional Twin Higgs

Symmetries and particle content

Breaking and Higgs potential

Phenomenological features and constraints

# The Exceptional Twin Higgs

- The smallest global symmetry that can account for a doubling of the SM fields related to naturalness only and for custodial symmetry should contain only 3 commuting $SU(2)$ subgroups, therefore $\mathrm{rank}(G) = 3$
- In order to identify the SM Higgs with some of the NGb of $G/H$ we need the Goldstone multiplet to contain a $(2,2)$ of $SU(2)_L \times SU(2)_R$
- The smaller such coset is the 7-sphere $SO(7)/G_2$
- The rest of the global symmetry is as before and the global symmetry breaking pattern is therefore (now $\widetilde{U(1)}_X$ is not needed)

$$SU(3)_c \times \widetilde{SU(3)}_c \times U(1)_X \times Z_2 \times (SO(7)/G_2)$$

- where

$$\frac{SO(7)}{G_2} \supset \frac{SU(2)_L \times \widetilde{SU(2)}_L \times SU(2)_3}{SU(2)_L \times SU(2)_R}$$

- of which the generators $T^a_L, \widetilde{T}^a_L, T^3_3$ are gauged
- The SM hypercharge corresponds to the combination $Y = \widetilde{T}^3_L + T^3_3 + X$
- This has the important implication that twin partners will generally be charged under the SM hypercharge and therefore, depending on the X charge, will carry electric charge

# Higgs Potential

## 1. $Z_2$ symmetric contribution

$$V_{g^2}(H) \approx \frac{g_\rho^2 f^4}{16\pi^2}\left[g^2 \sin^2\left(\frac{H}{f}\right) + \widetilde{g}^2 \cos^2\left(\frac{H}{f}\right)\right]$$

$$V_{y_t^2}(H) \approx \frac{N_c g_\Psi^2 f^4}{16\pi^2}\left[y_t^2 \sin^2\left(\frac{H}{f}\right) + \widetilde{y}_t^2 \cos^2\left(\frac{H}{f}\right)\right]$$

- The quadratic contribution to the potential cancels in the $Z_2$ symmetric limit when

$$g = \widetilde{g}\,, \quad y_t = \widetilde{y}_t$$

- It remains a contribution to the quartic term in the breaking parameters which generates a Higgs quartic coupling of the right order to get a light Higgs with minimal tuning

$$V_{y_t^4}(H) \approx \frac{N_c f^4}{16\pi^2}\left[y_t^4 \sin^4\frac{H}{f}\log\frac{2m_\Psi^2}{y_t^2 f^2 \sin^2\frac{H}{f}} + \widetilde{y}_t^4 \cos^4\frac{H}{f}\log\frac{2m_\Psi^2}{\widetilde{y}_t^2 f^2 \cos^2\frac{H}{f}}\right]$$

- This potential cannot be “tuned” to achieve EWSB with $v \ll f$ and therefore one needs $Z_2$ breaking contributions

# Particle content

- For simplicity and to avoid constraints we consider the twin symmetry to be realised only on the fields related to naturalness

*see also Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph] and talk by A. Katz*

- Twin symmetry is therefore respected by third generation quarks and non-abelian gauge fields
- It is broken by light fermions and hypercharge sector
- The quantum numbers of the relevant fields are (all charges are fixed by anomaly cancellation)

| | SO(7) | $SU(2)_L$ | $SU(2)_{\widetilde{L}}$ | $SU(2)_3$ | $SU(2)_R$ | $U(1)_X$ | $U(1)_Q$ |
|---|---|---|---|---|---|---|---|
| $W$ | **21** | **3** | **1** | **1** | **1** | 0 | $0, \pm 1$ |
| $\widetilde{W}$ | **21** | **1** | **3** | **1** | **3** | 0 | $0, \pm 1$ |
| $B$ | **21** | **1** | **1** | **3** | **3** | 0 | 0 |
| $q_L$ | **8** | **2** | **1** | **2** | **2** | $+\frac{2}{3}$ / $-\frac{1}{3}$ | $+\frac{2}{3}, -\frac{1}{3}$ |
| $t_R$ | **1** | **1** | **1** | **1** | **1** | $+\frac{2}{3}$ | $+\frac{2}{3}$ |
| $b_R$ | **1** | **1** | **1** | **1** | **1** | $-\frac{1}{3}$ | $-\frac{1}{3}$ |
| $\widetilde{q}_L$ | **8** | **1** | **2** | **2** | **3** | $+\frac{1}{2}/-\frac{1}{2}$ | $\pm\frac{1}{2}$ |
| $\widetilde{t}_R$ | **1** | **1** | **1** | **1** | **1** | $+\frac{1}{2}$ | $+\frac{1}{2}$ |
| $\widetilde{b}_R$ | **1** | **1** | **1** | **1** | **1** | $-\frac{1}{2}$ | $-\frac{1}{2}$ |

# Higgs Potential

## $Z_2$ breaking contribution

*Barbieri, Greco, Rattazzi, Wulzer, 1501.07803 [hep-ph]*
*see also talk by A. Wulzer*

- Again we have a contribution

$$V_{g_2'^2}(H) \approx \frac{g_\rho^2 f^4}{16\pi^2} g'^2 \sin^2\left(\frac{H}{f}\right)$$

- However, again, it is too small to allow for viable EWSB
- We need an additional contribution of the form

$$V_{y_t^2}(H) \approx \frac{N_c g_\Psi^2 f^4}{16\pi^2} \Delta y_t(m_*)^2 \sin^2\left(\frac{H}{f}\right)$$

| | SO(7) | SU(2)$_L$ | SU(2)$_{\widetilde{L}}$ | SU(2)$_3$ | SU(2)$_R$ | U(1)$_X$ | U(1)$_Q$ |
|---|---|---|---|---|---|---|---|
| $W$ | **21** | **3** | **1** | **1** | **1** | $0$ | $0, \pm1$ |
| $\widetilde{W}$ | **21** | **1** | **3** | **1** | **3** | $0$ | $0, \pm1$ |
| $B$ | **21** | **1** | **1** | **3** | **3** | $0$ | $0$ |
| $q_L$ | **8** | **2** | **1** | **2** | **2** | $+\frac{2}{3} \,/\, -\frac{1}{3}$ | $+\frac{2}{3}, -\frac{1}{3}$ |
| $t_R$ | **1** | **1** | **1** | **1** | **1** | $+\frac{2}{3}$ | $+\frac{2}{3}$ |
| $b_R$ | **1** | **1** | **1** | **1** | **1** | $-\frac{1}{3}$ | $-\frac{1}{3}$ |
| $\widetilde{q}_L$ | **8** | **1** | **2** | **2** | **3** | $+\frac{1}{2}/-\frac{1}{2}$ | $\pm\frac{1}{2}$ |
| $\widetilde{t}_R$ | **1** | **1** | **1** | **1** | **1** | $+\frac{1}{2}$ | $+\frac{1}{2}$ |
| $\widetilde{b}_R$ | **1** | **1** | **1** | **1** | **1** | $-\frac{1}{2}$ | $-\frac{1}{2}$ |

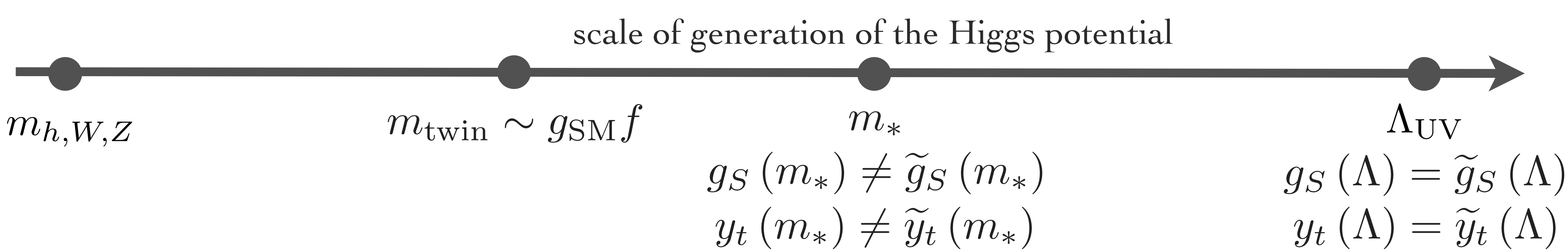
# Running effects

$Z_2$ breaking effects are induced by the different running of the strong couplings

*see also Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph] and talk by A. Katz*

$$\frac{dy_t}{d\log\mu} = \frac{9y_t^3}{32\pi^2} - \frac{y_t g_S^2}{2\pi^2} \qquad \frac{d\widetilde{y}_t}{d\log\mu} = \frac{9\widetilde{y}_t^3}{32\pi^2} - \frac{\widetilde{y}_t \widetilde{g}_S^2}{2\pi^2}$$

$$\frac{dg_S}{d\log\mu} = -\frac{7g_S^3}{16\pi^2} \qquad \frac{d\widetilde{g}_S}{d\log\mu} = -\frac{29\widetilde{g}_S^3}{48\pi^2}$$




$$\Delta y_t(m_*)^2 = y_t(m_*)^2 - \widetilde{y}_t(m_*)^2 \approx \frac{g_S(m_*)^4\, y_t(m_*)^2}{(16\pi^2)^2} \log^2\left(\frac{\Lambda}{m_*}\right)$$

# Higgs Potential

## $Z_2$ symmetric contribution

$$V_{y_t^4}(H) \approx \frac{N_c f^4}{16\pi^2}\left[y_t^4 \sin^4\frac{H}{f}\log\frac{2m_\Psi^2}{y_t^2 f^2 \sin^2\frac{H}{f}} + \widetilde{y}_t^4 \cos^4\frac{H}{f}\log\frac{2m_\Psi^2}{\widetilde{y}_t^2 f^2 \cos^2\frac{H}{f}}\right]$$

## $Z_2$ breaking contribution

$$V_{y_t^2}(H) \approx \frac{N_c g_\Psi^2 f^4}{16\pi^2}\frac{g_S^4 y_t^2}{(16\pi^2)^2}\log^2\left(\frac{\Lambda}{m_*}\right)\sin^2\left(\frac{H}{f}\right)$$

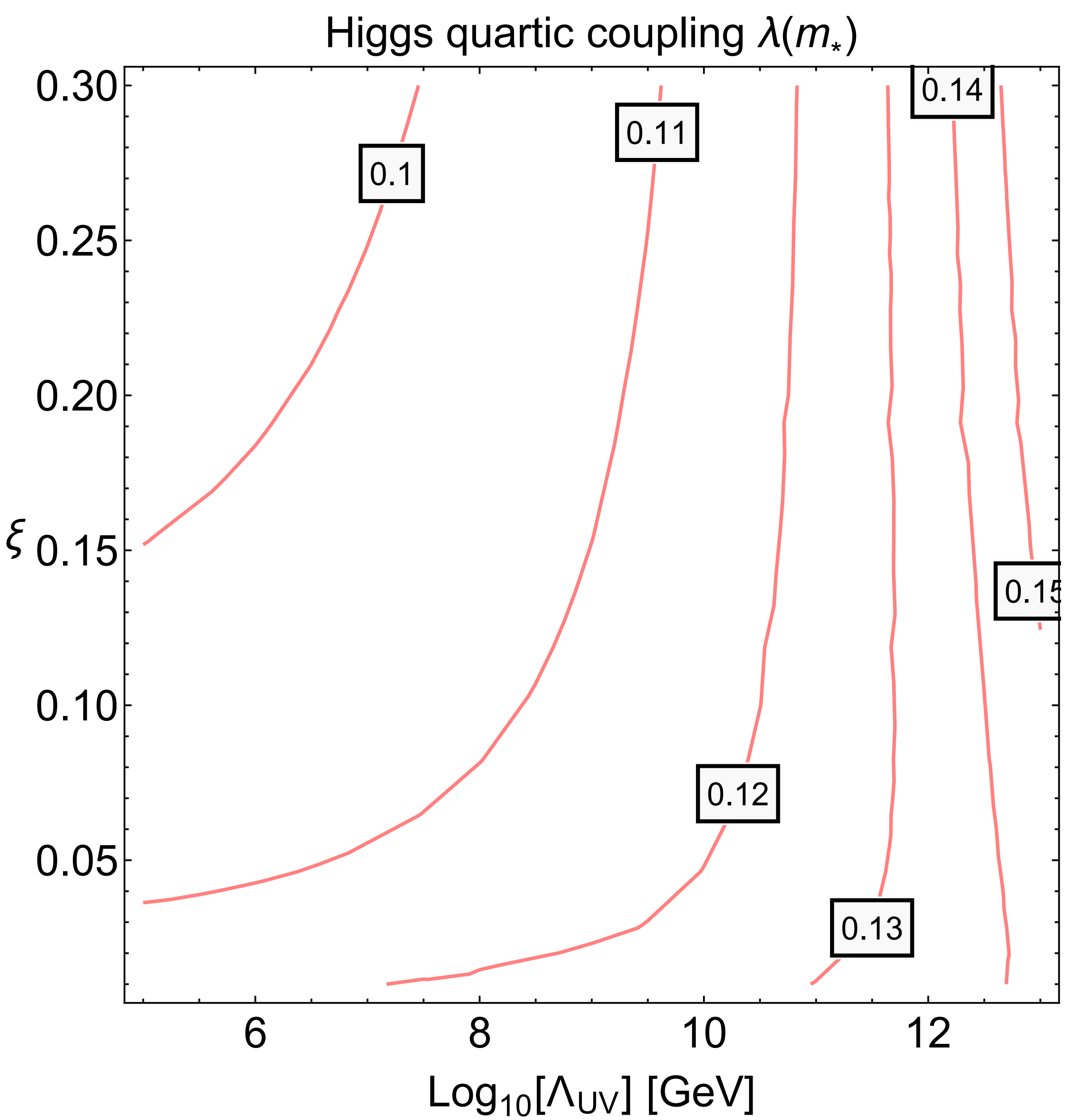
## Full potential

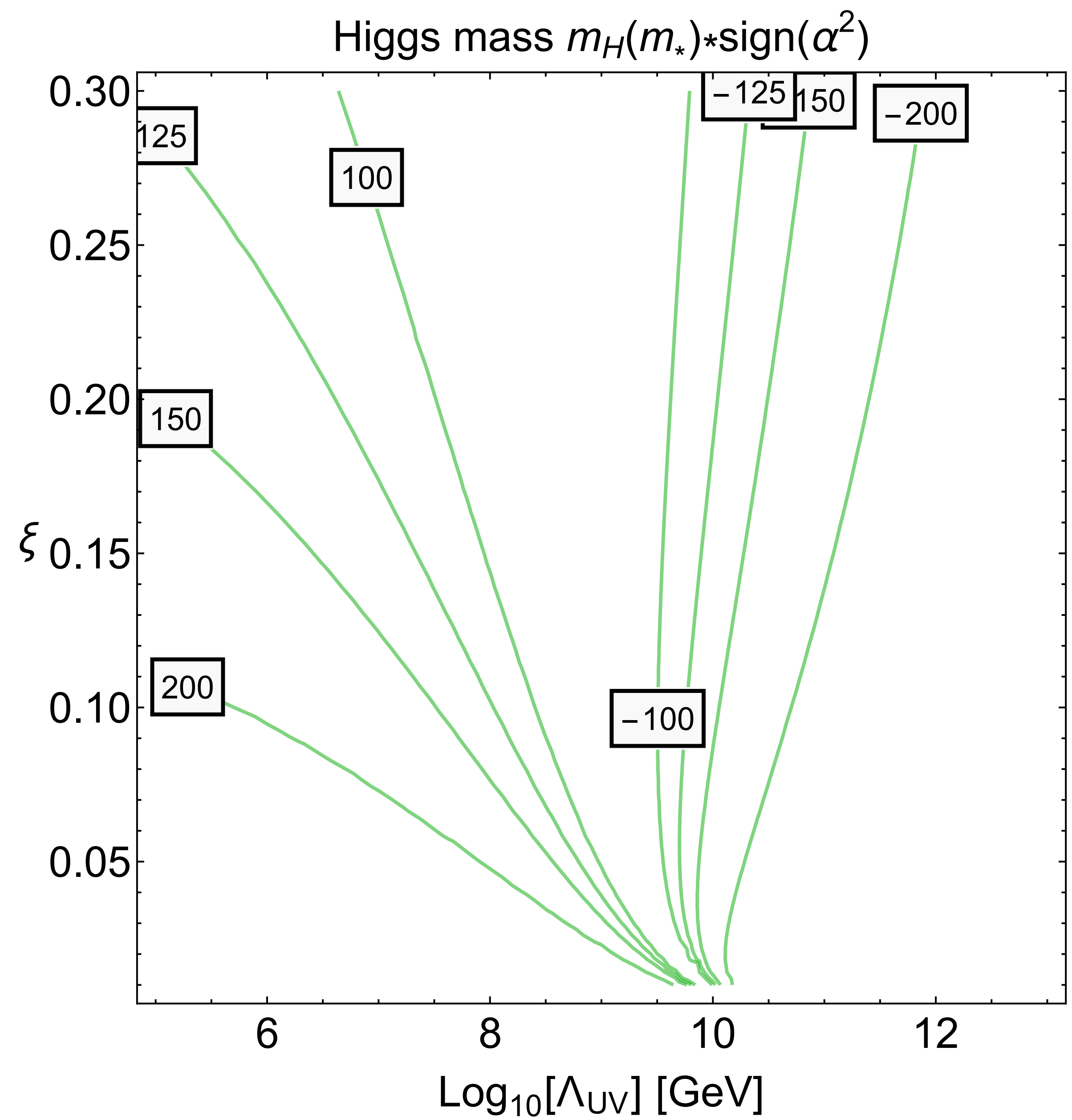
$$V(H) \approx \alpha \sin^2\left(\frac{H}{f}\right) + \beta \sin^4\left(\frac{H}{f}\right)$$

- Notice that both $\alpha$ and $\beta$ have an additional suppression compared to usual Composite Higgs models, i.e. only the vev needs to be tuned while the quartic is already of the right order

# Higgs Potential

$$V(H) \approx \alpha \sin^2\left(\frac{H}{f}\right) + \beta \sin^4\left(\frac{H}{f}\right)$$




- The potential can be tuned with minimal tuning independently of $f$
- The minimum value of $f$ is determined by experimental constraints

# The Twin Z: indirect constraints

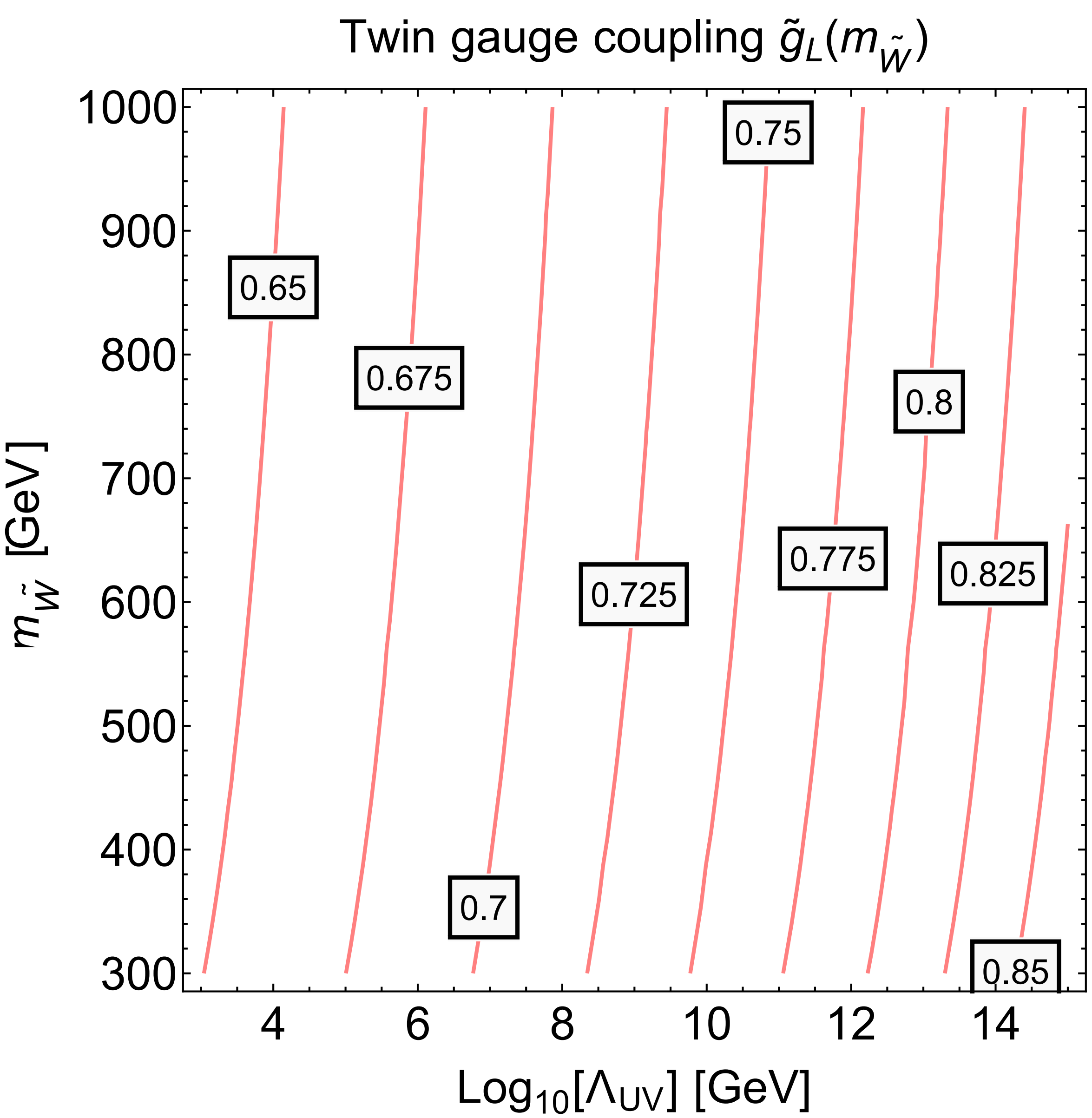
- The spectrum of our model in the gauge sector is determined from the sigma-model Lagrangian that in the unitary gauge reads

$$\mathcal{L} = \frac{3f^2}{32} d_\mu^a d^{\mu\, a} \supset \frac{f^2}{8}\left[\sin^2\frac{h}{f}\left(\left(g_3 B - g_L W^3\right)^2 + 2g_L^2 W^+W^-\right) + \cos^2\frac{h}{f}\left(\left(g_3 B - \tilde{g}_L \widetilde{W}^3\right)^2 + 2\tilde{g}_L^2 \widetilde{W}^+\widetilde{W}^-\right)\right]$$

- The mixing of the $B$ with the $\widetilde{W}^3$ generates a contribution to the Y parameter

$$\frac{1}{\widetilde{g}_Y^2} = \frac{1}{\widetilde{g}_3^2} + \frac{1}{\widetilde{g}_L^2}$$

$$Y \approx \frac{g_Y^2 m_W^2}{\widetilde{g}_L^2 \widetilde{m}_W^2} \approx \frac{g_Y^2 g_L^2}{\widetilde{g}_L^4}\xi \quad \lesssim \quad 2\cdot 10^{-3} \text{ @ } 95\% \text{ CL}$$




- Unless we invoke rather large threshold corrections at the high scale (**or additional contributions from loops of twin fermions**) this indirect constraint would push $\xi \lesssim 0.01$
- This may also suggest a hard breaking of the twin symmetry from the $SU(2)_L$ gauge interactions analogous to the one of the hypercharge
- Additional contributions to T may also be present from loops of twin fermions

# The Twin Z: direct constraints

- The twin $Z$ couples to twin bottom quarks (and twin tops) and after eliminating the mixing with the hypercharge, also to SM fermions and gauge bosons with strengths

$$g_{\widetilde{Z}ff} \approx Y_f \frac{g_Y^2}{\widetilde{g}_L \sqrt{1 - \frac{g_Y^2}{\widetilde{g}_L^2}}}$$

$$g_{\widetilde{Z}\widetilde{b}\widetilde{b}} \approx \widetilde{g}_L$$

$$g_{\widetilde{Z}WW} \sim g_{\widetilde{Z}Zh} \approx \frac{g_Y^2}{\widetilde{g}_L \sqrt{1 - \frac{g_Y^2}{\widetilde{g}_L^2}}}$$

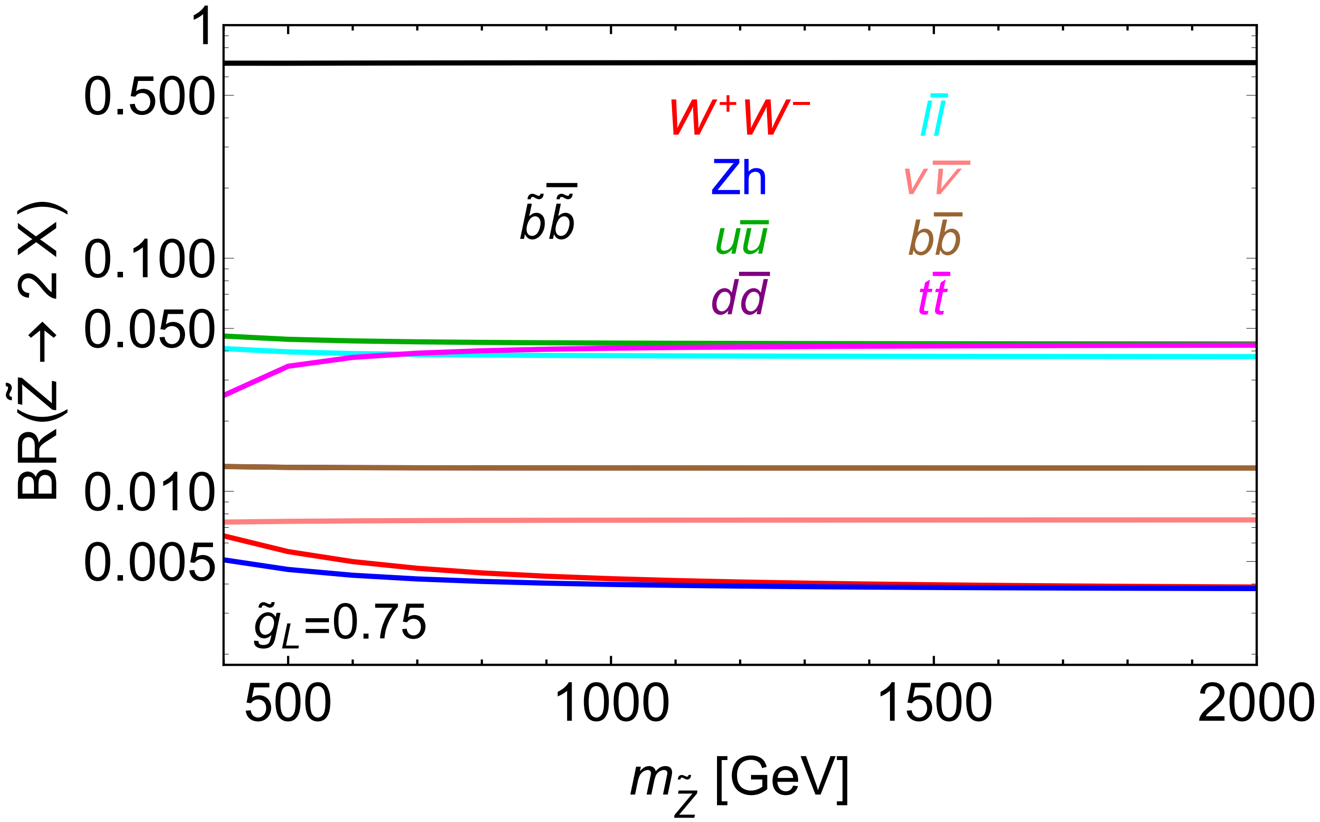
$$\Gamma_{V^0 \to u\bar{u}} \approx 3 \frac{g_Y^4}{\widetilde{g}_L^2 \left(1 - \frac{g_Y^2}{\widetilde{g}_L^2}\right)} \left(Y_Q^2 + Y_U^2\right) \frac{M_{V^0}}{24\pi}\,, \quad \Gamma_{V^0 \to l\bar{l}} \approx \frac{g_Y^4}{\widetilde{g}_L^2 \left(1 - \frac{g_Y^2}{\widetilde{g}_L^2}\right)} \left(Y_L^2 + Y_E^2\right) \frac{M_{V^0}}{24\pi}\,,$$

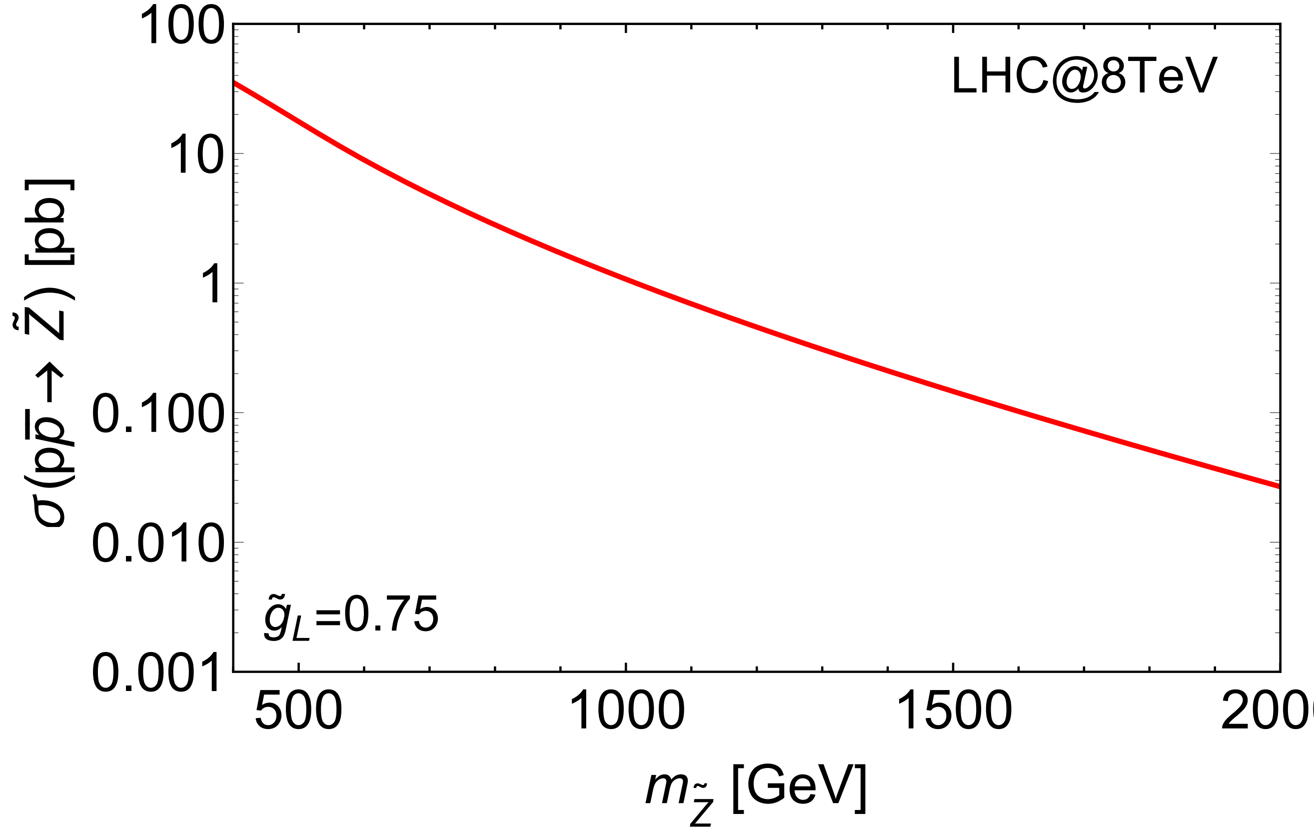
$$\Gamma_{V^0 \to d\bar{d}} \approx 3 \frac{g_Y^4}{\widetilde{g}_L^2 \left(1 - \frac{g_Y^2}{\widetilde{g}_L^2}\right)} \left(Y_Q^2 + Y_D^2\right) \frac{M_{V^0}}{24\pi}\,, \quad \Gamma_{V^0 \to \nu\bar{\nu}} \approx \frac{g_Y^4}{\widetilde{g}_L^2 \left(1 - \frac{g_Y^2}{\widetilde{g}_L^2}\right)} Y_L^2 \frac{M_{V^0}}{24\pi}\,,$$

$$\Gamma_{V^0 \to \widetilde{b}\bar{\widetilde{b}}} \approx 3 \widetilde{g}_L^2 \frac{M_{V^0}}{48\pi}\,,$$

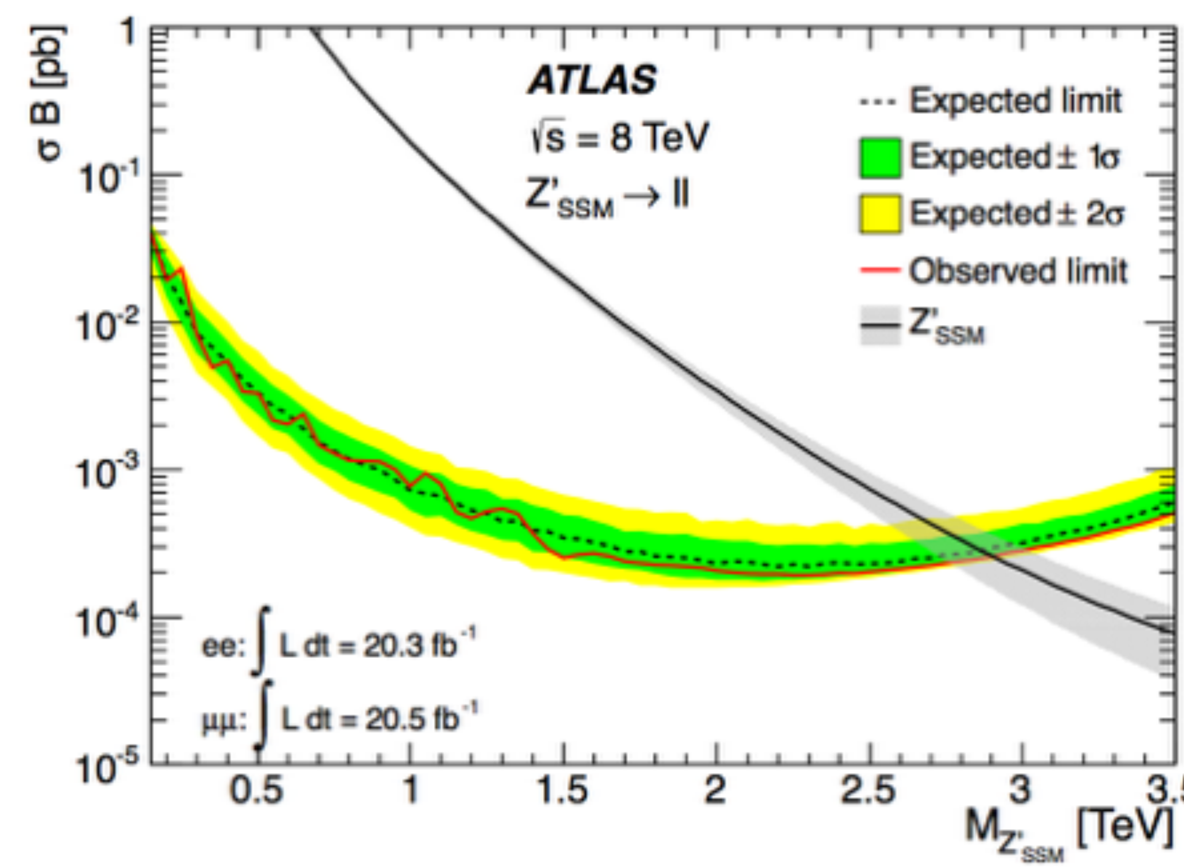
$$\begin{aligned} \Gamma_{V^0 \to W_L^+ W_L^-} &\approx \frac{g_Y^4}{\widetilde{g}_L^2 \left(1 - \frac{g_Y^2}{\widetilde{g}_L^2}\right)} \frac{M_{V^0}}{192\pi} \\ \Gamma_{V^0 \to Z_L h} &\approx \frac{g_Y^4}{\widetilde{g}_L^2 \left(1 - \frac{g_Y^2}{\widetilde{g}_L^2}\right)} \frac{M_{V^0}}{192\pi} \end{aligned}$$

# The Twin Z: direct constraints




- The conclusion is similar (or even stronger) than the one from indirect constraints
- We need large threshold corrections to push $\tilde{g}_L \gtrsim 1$
- Again, this may suggest a hard breaking of the twin symmetry from the $SU(2)_L$ gauge interactions analogous to the one of the hypercharge



# Not gauging the twin $SU(2)_L$

- Constraints due to the presence of a light, not enough weakly coupled Z' (both direct and indirect) can be alleviated if we assume a hard breaking of the $Z_2$ symmetry from $SU(2)_L$
- The global breaking pattern remains the same, but the gauging changes in order to correctly gauge the generator corresponding to the hypercharge

$$\frac{SO(7)}{G_2} \supset \frac{SU(2)_L \times \widetilde{SU(2)}_L \times SU(2)_3}{SU(2)_L \times SU(2)_R}$$

- Now only the generators $T_L^a$, $T_R^3$ are gauged with $Y = T_R^3 + X$
- Now the gauging of the hypercharge explicitly breaks $\widetilde{SU(2)}_L \times SU(2)_3$ so that the charged component of the $\omega$ triplet of $SU(2)_R$ naturally gets a mass
- This mass is generated at loop level and is of order $m_{\omega^\pm}^2 \sim g'^2 g_\rho^2 f^2/(16\pi^2)$
- To give a mass to the neutral component one needs further assumptions about the breaking
- An option is offered by the twin bottom sector: embedding the twin bottom right in an irrep other than singlet (with $X = -1/3$) and giving it a large compositeness would generate a mass for all the $\omega$ of order $m_{\omega^{\pm,0}}^2 \sim N_c y_{b_R}^2 g_\Psi^2 f^2/(16\pi^2)$
- Since the $\omega$'s have no charge under $SU(2)_L$ they don't have Yukawa couplings with SM fermions and only the neutral will couple after mixing with the Higgs

# Not gauging the twin $SU(2)_L$

## $Z_2$ breaking contribution from $SU(2)_L$ interactions

- Consider the case where $SU(2)_L$ interactions also break the $Z_2$ symmetry
- The first contribution is given by

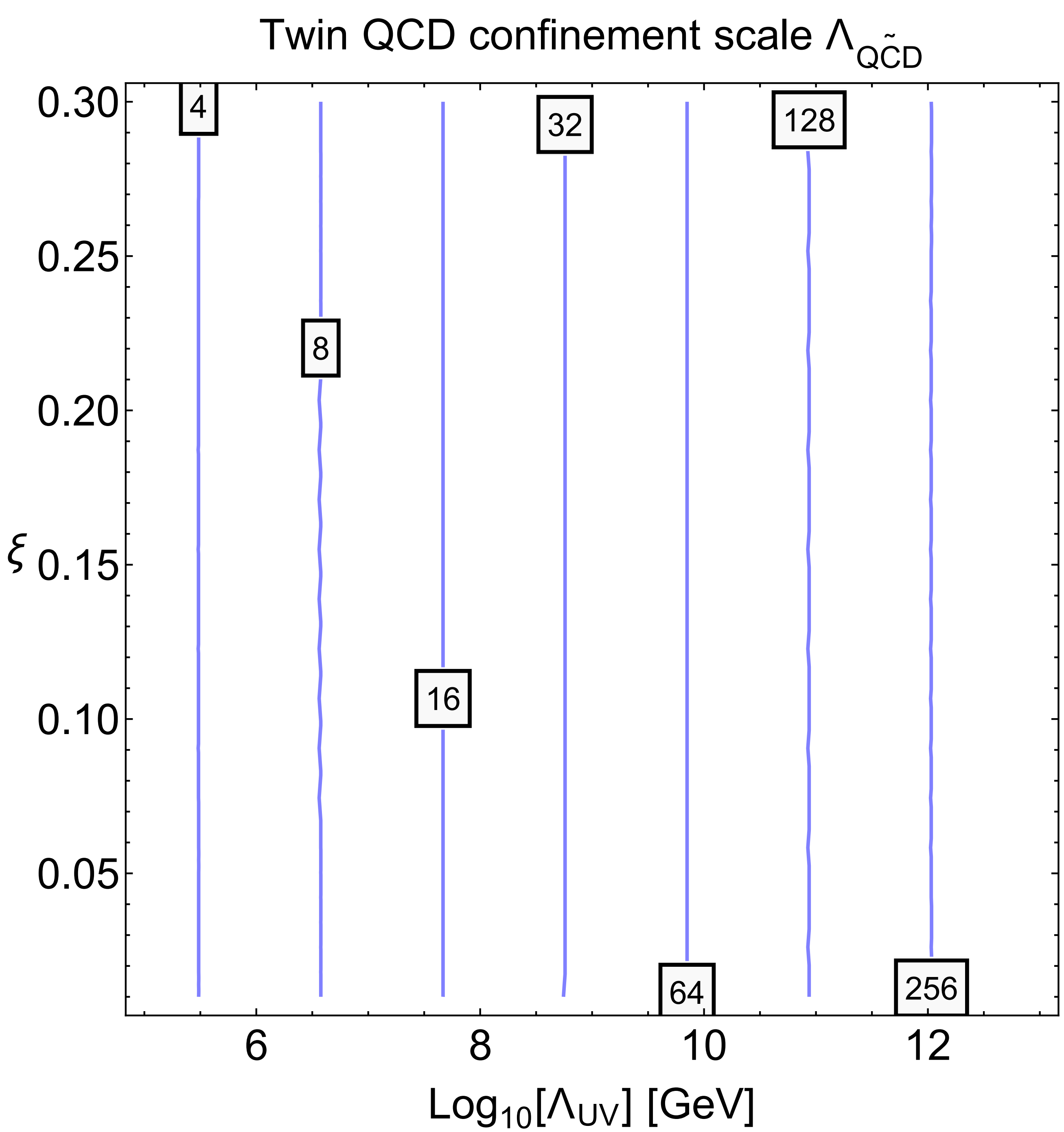
$$V_{g_2'^2, g_2^2}(H) \approx \frac{g_\rho^2 f^4}{16\pi^2}\left(g'^2 + g^2\right)\sin^2\left(\frac{H}{f}\right)$$

- Now the positive contribution is larger (but still not log-enhanced, so still typically too small to allow for the needed tuning)
- Now the contributions from running of $SU(2)_L$ (1-loop) and colors (2-loops) can be comparable

$$\frac{b_2 g^2}{16\pi^2}\log\frac{\Lambda_{\mathrm{UV}}}{m_*} \sim \frac{b_S g_S^4}{\left(16\pi^2\right)^2}\log^2\frac{\Lambda_{\mathrm{UV}}}{m_*} \qquad \text{for} \qquad \Lambda_{\mathrm{UV}} \sim 10^8\ \mathrm{GeV}$$

- A calculable model (e.g. an holographic realisation) is necessary to identify the larger contribution to the potential
- However the estimates we made in the case of the gauged model should still give an idea of the size of the potential

# The twin QCD and $\Lambda_{\widetilde{\mathrm{QCD}}}$




$$\widetilde{g}_S\left(\Lambda_{\widetilde{\mathrm{QCD}}}\right) \equiv 4\pi$$

- This scale has to be compared with the scale $f = v/\sqrt{\xi}$ setting the mass of the twin fermions
- Twin fermions will generally have a mass of the order of $\widetilde{y}_f f$

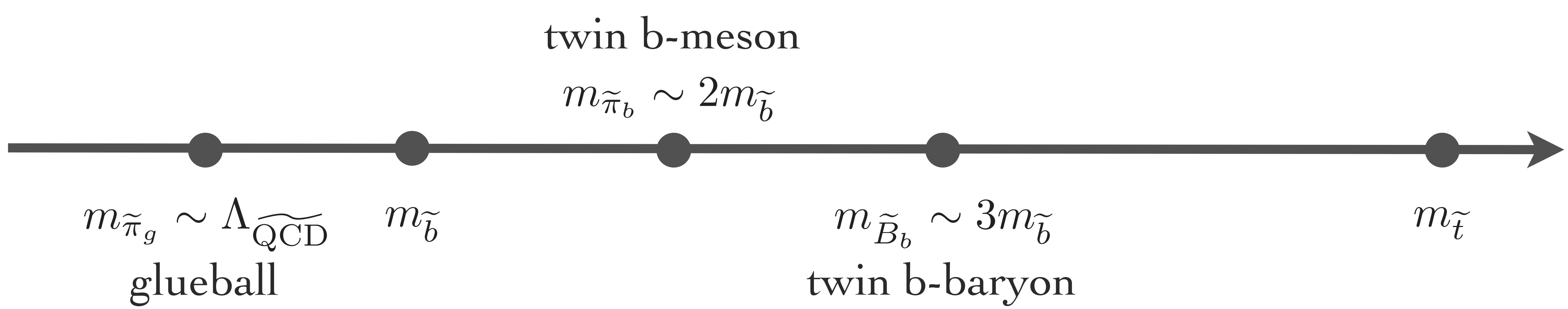
*see also Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph] and talk by A. Katz*

# Spectrum of twin fermions

- The twin QCD is has only 2 flavours and 1 family
- The twin top will have a $\Gamma/m$ similar to the top's one (decay into twin W and twin bottom) so the width will be in the tens of GeV region depending on $f$
- Depending on the exact value of $f$ and of $\Lambda_{\widetilde{\mathrm{QCD}}}$ it may or may not decay before hadronizing
- The twin bottom and twin gluons do certainly make twin hadrons
- In particular there will be unstable neutral twin mesons (glueballs and a twin b-meson) and (possibly) a stable charged twin baryon with charge 3/2
- The bottom Yukawa coupling is not related to naturalness so that the twin-b mass is a free parameter and can be substantially larger (or smaller) than the bottom mass

**Case 1:** $\widetilde{y}_b \gtrsim y_b$

*see also Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph] and talk by A. Katz*



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**Case 2:** $\widetilde{y}_b \ll y_b$

*see also Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph] and talk by A. Katz*

# Twin QCD phenomenology

- The mesons are only produced in pairs, through Higgs, photon and Z exchange, and will typically decay into (or through) photons
- They could give rise to peculiar Higgs decays or final states with four not extremely energetic photons (tens of GeV)
- The phenomenology is similar to the one of a Dark Sector with a Higgs portal like the one studied in the "Fraternal Twin Higgs" *see also Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph] and talk by A. Katz*
- The twin baryon (if it exists) is stable and carries charge 3/2 (cosmology?)
- Bounds on electrically charged particles would push its mass in the 100 GeV region
- However, it is produced only through a charge 1/2 interaction (pair production of twin b's)
- To assess the number of produced baryons one would need to know the number of baryons vs number of mesons in a twin QCD jet and this needs a modeling of hadronization in the twin QCD sector (which we do not have)
- One can compare with usual QCD jets (very naive comparison)

# Twin QCD phenomenology

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- They could … xtremely energetic p
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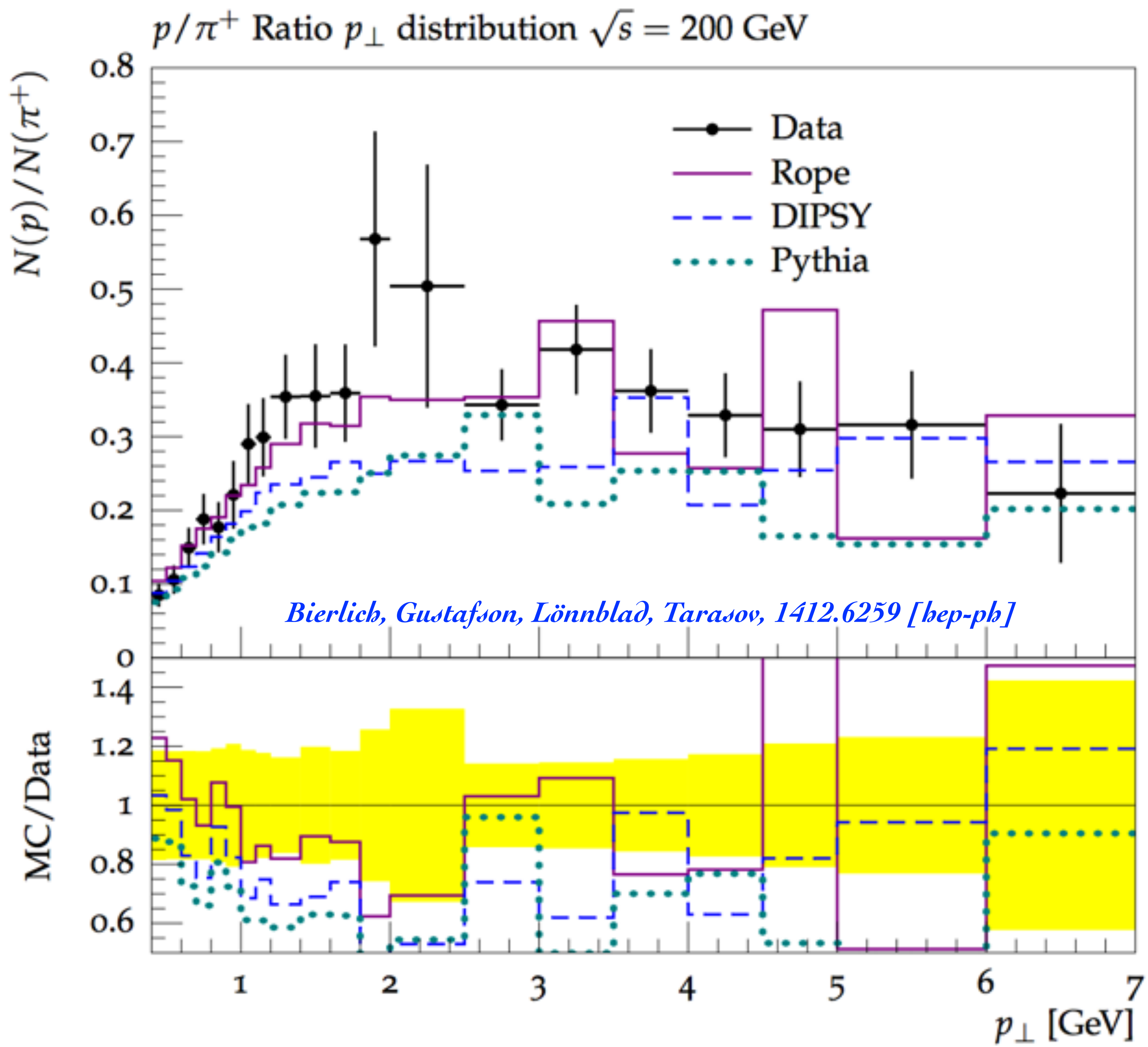

# Conclusion

# CONCLUSIONS

- The Twin Higgs mechanism, joined with a UV completion explaining the big hierarchy of scales, offers a compelling mechanism to relax fine-tuning in the light of the negative LHC results in searches for new physics

- In the most optimistic/pessimistic case (depends on the point of view) twin particles are totally neural under the SM gauge group and can elude LHC@14TEV searches while leaving fine-tuning almost unchanged

- We consider a more minimal scenario (**exceptional both from the group theory and phenomenological points of view**) where the twin particles can be electrically charged and therefore clearly visible at LHC

- This makes the model more testable: a dedicated experimental program at the LHC could lead at ruling out the idea that naturalness of the electroweak scale is guaranteed by uncoloured states only carrying electric charge (charged naturalness)

# THANK YOU