Naturalness vs. the LHC

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Solving (?) the hierarchy problem

- supersymmetry
- global symmetry (little Higgs)
- strong interactions (technicolor, ex. dim.)

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- scale inv. (+ Coleman-Weinberg)
- ...

Composite Higgs

electroweak symmetry breaking by new strong dynamics

composite Higgs - PG boson

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- $SO(5)/SO(4) \;\rightarrow\; 4\pi \;\rightarrow\; H$

Minimal Composite Higgs Model
Agashe, Contino, Pomarol '04

- $SO(6)/SO(5) \;\rightarrow\; 5\pi \;\rightarrow\; H, a$
  $SU(4)/Sp(4,C) \;\rightarrow\; 5\pi \;\rightarrow\; H, s$

Next MCHM
Gripaios, Pomarol, Riva, Serra '09
Chacko, Batra '08

- $SO(6)/SO(4)xSO(2) \;\rightarrow\; 8\pi \;\rightarrow\; H_1 + H_2$

Minimal Composite Two Higgs Doublets
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Minimal composite Higgs model

Agashe, Contino, Pomarol '04

$$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$$

GB transform as a **4** of $SO(4)$, $(2, 2)$ of $SU(2)_L \times SU(2)_R$

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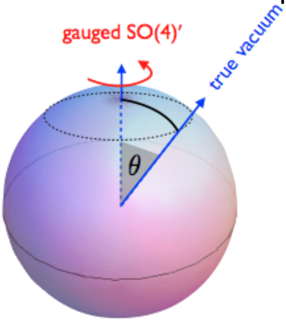

Higgs potential from $SO(5)$ breaking effects

- gauge interactions
- Yukawa interactions

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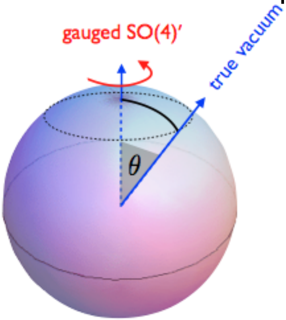

Higgs potential from $SO(5)$ breaking effects

- gauge interactions
- Yukawa interactions

$\to$ naturalness requires
top partners $\lesssim 1$ TeV
see also 1410.8555
and talk by A.Carmona
LHC searches - talk by T.Flacke

Signatures of composite Higgs

- Higgs physics

  Montull, Riva, Salvioni, Torre
  Carena, Da Rold, Ponton

- spin-1/2 resonances

  Gripaios, Muller, Parkera, Sutherland
  Matsedonskyi, Riva, Vantalon
  De Simone, Matsedonskyi, Rattazzi, Wulzer

- spin-1 resonances

  Contino, Pappadopulo, Marzocca, Rattazzi
  Panico, Wulzer
  De Curtis, Redi, Tesi
  Pappadopulo, Thamm, Torre, Wulzer

- electroweak precision data (S,T)

  Ciuchini, Franco, Mishima, Silvestrini
  Barbieri, Tesi

- flavor

  Csaki, Falkowski, Weiler
  Redi, Weiler
  Straub

Effective description of spin-1 resonances

global symmetry breaking $\mathcal{G} \to \mathcal{H}$

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- 'hidden local symmetry'

$\to$ modify the symmetry breaking pattern

$$\mathcal{G} \times \mathcal{H}_{local} \to \mathcal{H}$$

ρ_μ gauge bosons of $\mathcal{H}_{local}$ $\to$ 'vector' resonances

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3 free parameters

$$m_\rho,\ g_\rho,\ \xi = \frac{v_{EW}^2}{f^2}$$

g_ρ - gauge coupling of $\mathcal{H}_{local}$

Production and decays of ρ_L

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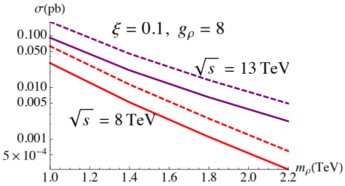
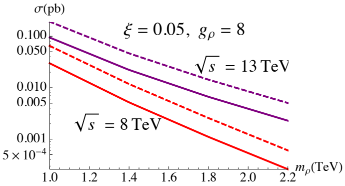
- production dominated by Drell-Yan $q\bar{q} \to \rho$





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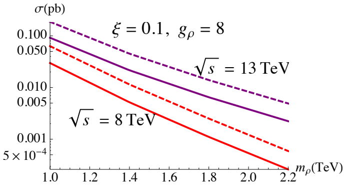
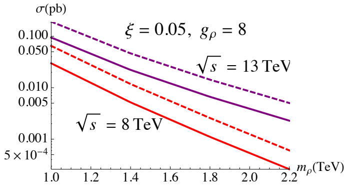
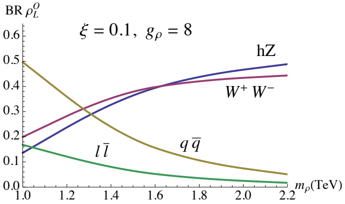
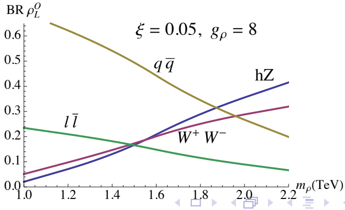




- decays mainly to hZ and WW, but ff non-negligible





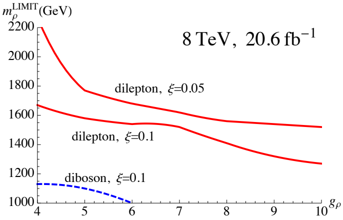
Direct searches

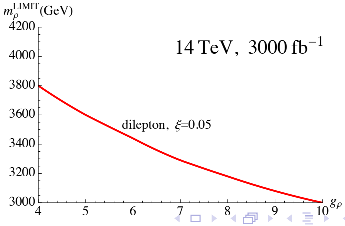
$$\Gamma\left(\rho^0 \to W^+W^-\right) \approx \Gamma\left(\rho^0 \to Zh\right) \approx \frac{m_\rho^5 \xi^2}{192\pi g_\rho^2 v^4}.$$

$$\Gamma\left(\rho^0 \to e^+e^-\right) \approx \Gamma\left(\rho^0 \to \mu^+\mu^-\right) \approx \frac{g^4 m_\rho \left(1+\sqrt{1-\xi}\right)^2}{96\ 4\pi g_\rho^2}$$

$$\Gamma\left(\rho^0 \to q_i\bar{q}_i\right) \approx \frac{g^4 m_\rho \left(1+\sqrt{1-\xi}\right)^2}{32\ 4\pi g_\rho^2}$$

present strongest exclusions - CMS search for ll resonances

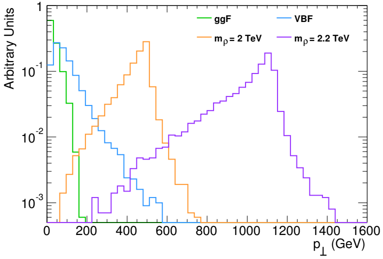


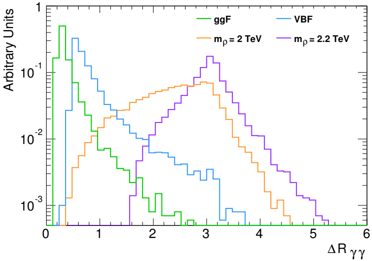


Searching for $\rho \rightarrow Vh$

M.Hoffmann, AK, R.Nikolaidou, S.Paganis

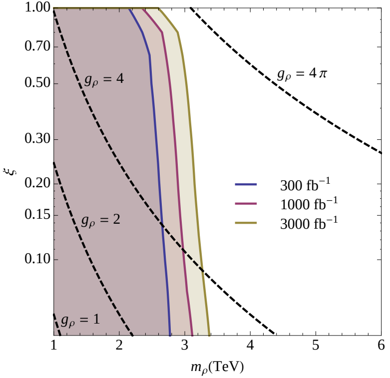
$h \to \gamma\gamma$, $h \to ZZ^{(*)} \to 4\ell$, where $\ell = e, \mu$, $(h \to b\bar{b})$, $V \to jj$





suppress the SM Higgs background by $p_\perp \geq 550$ GeV cut
$\rightarrow$ probing $m_\rho \sim 3\,\mathrm{TeV}$ in the next LHC run

here assumed $m_\rho = g_\rho f = g_\rho v_{EW}/\sqrt{\xi}$



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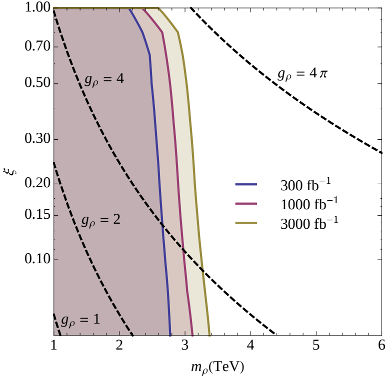

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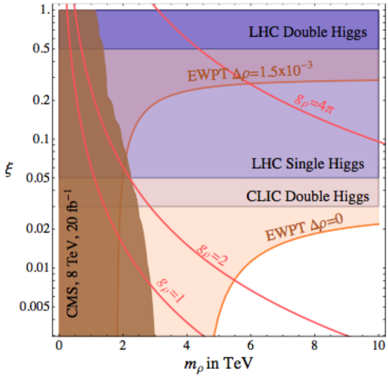

Contino, Grojean, Pappadopulo, Rattazzi, Thamm

Impact of composite fermions

spin-1 resonances may couple directly to fermion resonances

$$-i\bar{\psi} g_\rho \gamma^\mu T^a \rho^a_\mu \psi$$

partial compositeness $\rightarrow$ mass mixing with SM fermions

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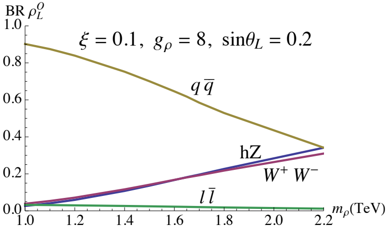
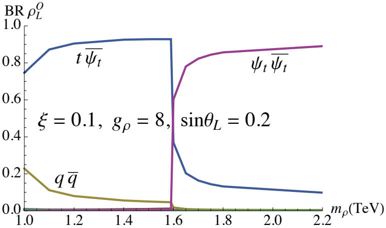
partial compositeness → mass mixing with SM fermions → modified BR of spin-1 resonances

- 3 gen. resonances only,
  $m_T \gtrsim 2\,\mathrm{TeV}$ (left) and $m_T \sim 0.8\,\mathrm{TeV}$ (right)





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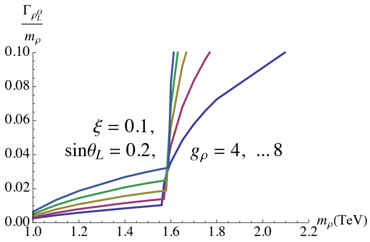

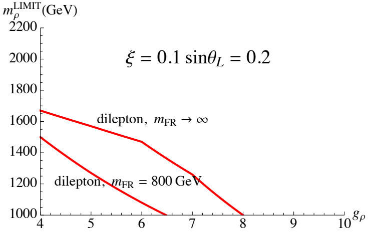

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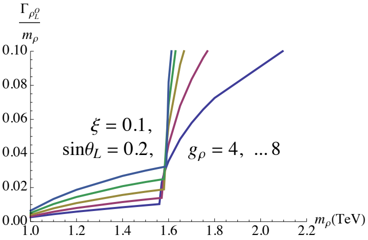
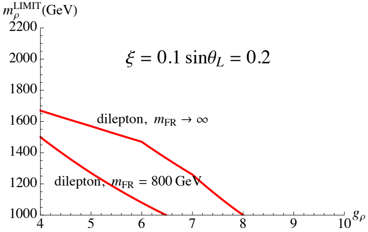
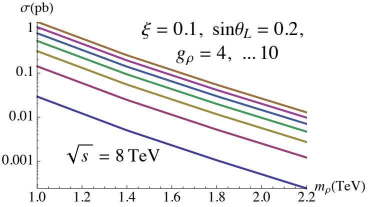
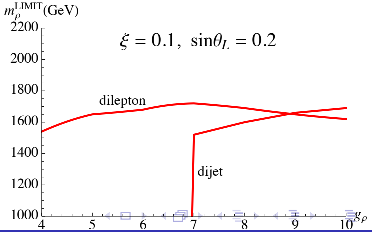




if we allow for significant partial compositeness of light quarks





SUSY

naturalness strained by non-observation of supersymmetric partners at the LHC

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idea: use a gaugino "focus" point in RGE running

AK, G.G.Ross, K.Schmidt-Hoberg, F.Staub

$$\begin{aligned} m^2_{h_u}(Q) &= z^{m_0}_{h_u}(Q)m_0^2 + z^{m_{1/2}}_{h_u}(Q)m^2_{1/2} + z^{A_0}_{h_u}(Q)A_0^2 + 2z^{m_{1/2}A_0}_{h_u}(Q)m_{1/2}A_0 \\ m^2_{h_d}(Q) &= z^{m_0}_{h_d}(Q)m_0^2 + z^{m_{1/2}}_{h_d}(Q)m^2_{1/2} + z^{A_0}_{h_d}(Q)A_0^2 + 2z^{m_{1/2}A_0}_{h_d}(Q)m_{1/2}A_0 \end{aligned}$$

electroweak scale in the MSSM

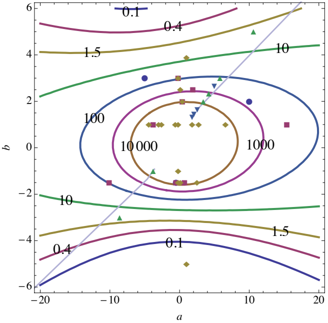
$$\lambda^{(0)}v^2 = -\frac{\tan^2\beta}{\tan^2\beta - 1}\bar{m}^2_{h_u} + \frac{1}{\tan^2\beta - 1}\bar{m}^2_{h_d} - |\mu|^2$$

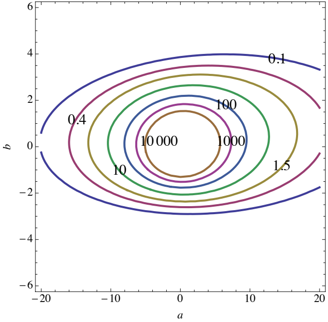
gaugino focus point

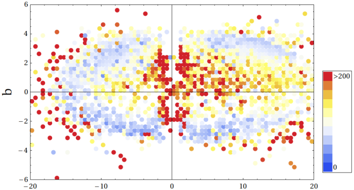
$$0 = \frac{\tan^2\beta}{\tan^2\beta - 1} z^{m_{1/2}}_{h_u}(Q_{FP}) - \frac{1}{\tan^2\beta - 1} z^{m_{1/2}}_{h_d}(Q_{FP})$$

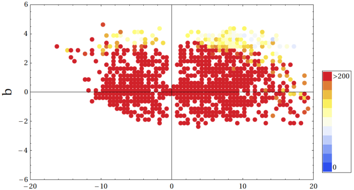
Gaugino focus point - MSSM

$$M_1 = a \cdot m_{1/2}, M_2 = b \cdot m_{1/2} \text{ and } M_3 = m_{1/2}$$



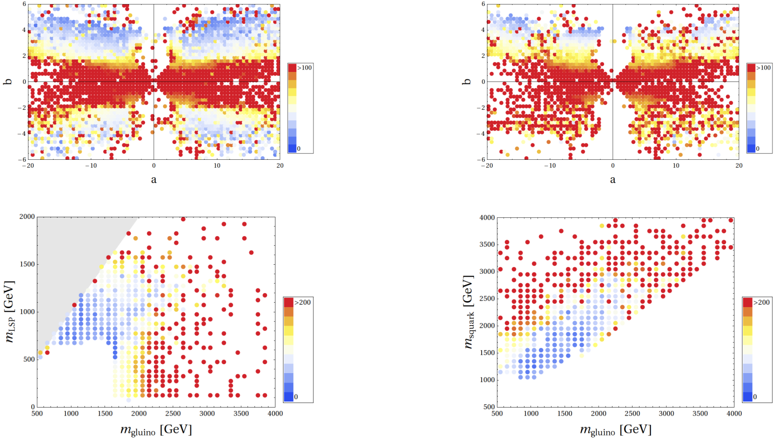






Gaugino focus point - GNMSSM

$$\mathcal{W} = \mathcal{W}_{\text{Yukawa}} + \frac{1}{3}\kappa S^3 + (\mu + \lambda S) H_u H_d + \xi S + \frac{1}{2}\mu_s S^2$$



Conclusion

It is not yet time to give up on naturalness!