Blended Models of Electroweak Symmetry Breaking

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At 2011, still two paradigm for EWSB:

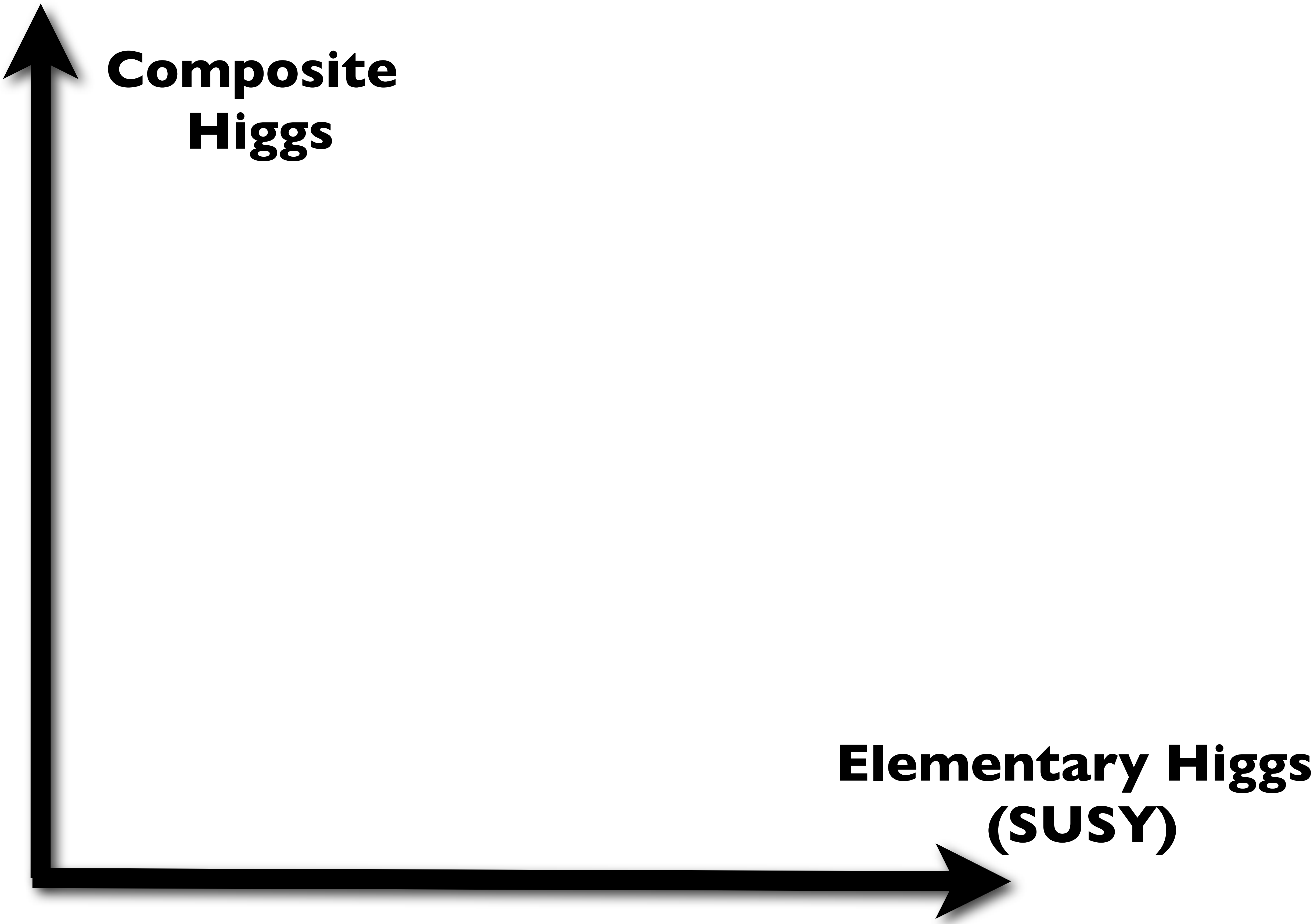
- Weakly coupled (Elementary) Higgs = SM

  Naturalness ➠ Supersymmetric SM

- Strongly-coupled "Higgs" ➠ Composite Higgs or Higgsless (e.g. Technicolor)

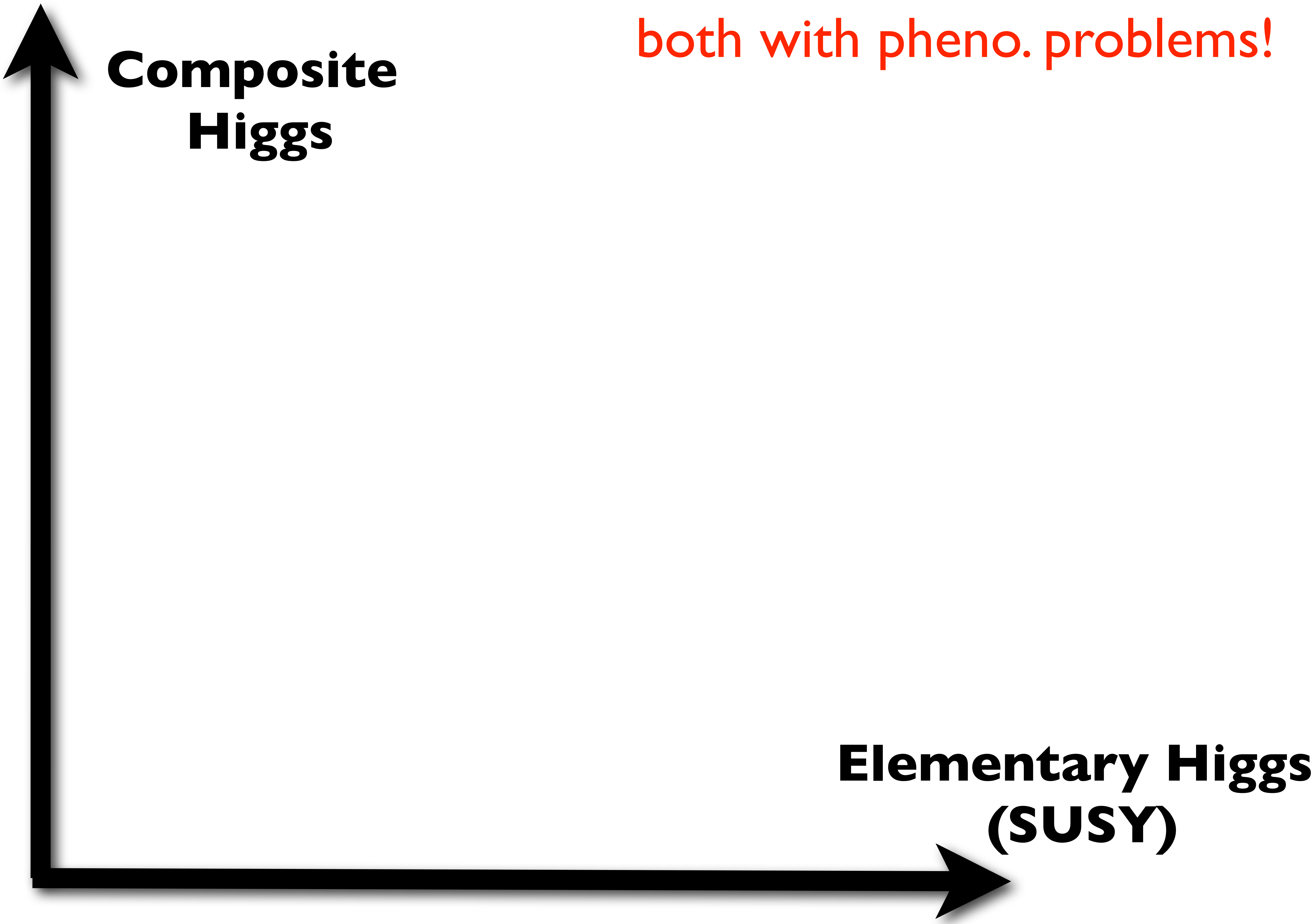
At present, <u>no serious hints</u> for one or the other!

Two schools with “orthogonal” approaches



Two schools with "orthogonal" approaches

both with pheno. problems!



Two schools with “orthogonal” approaches

both with pheno. problems!

Composite Higgs

Elementary Higgs (SUSY)

GOOD: No constrains from EWPT
BAD: New particles expected at LEP and Tevatron (e.g. Higgs) no found

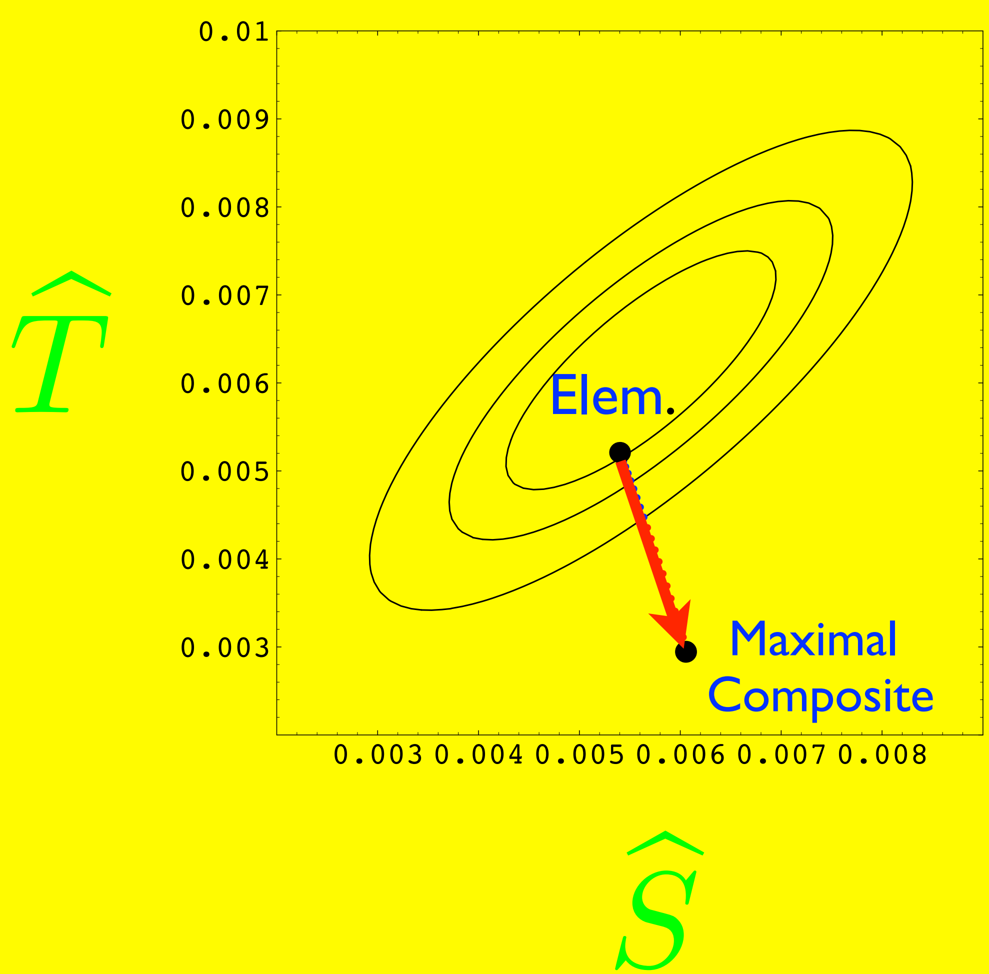
Two schools with "orthogonal" approaches

both with pheno. problems!

Composite Higgs

GOOD: New particles expected above the TeV (resonances)

BAD: Constrained by EWPT :



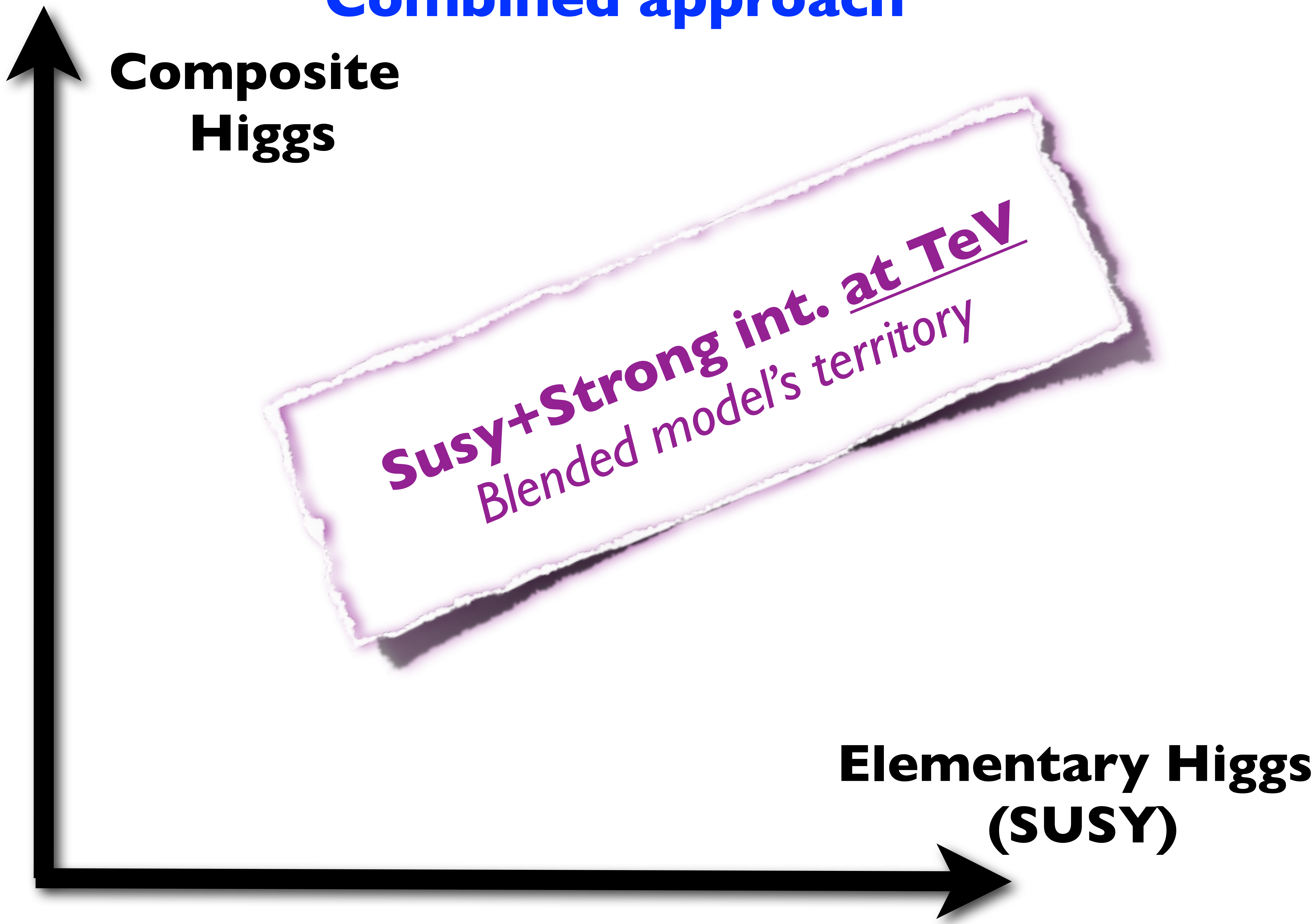
Elementary Higgs (SUSY)

No constrains from EWPT

ew particles expected at LEP

d Tevatron (e.g. Higgs)

Blended Models for EWSB: Combined approach



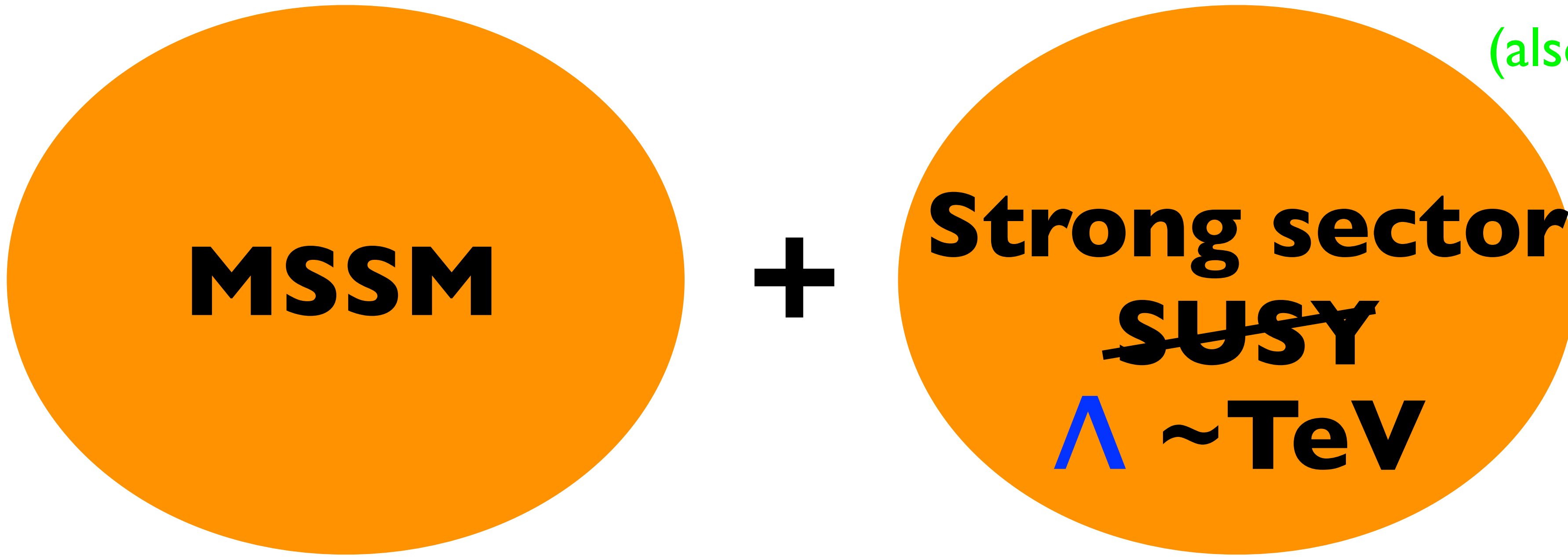
Why blending?

- Cure problems of both MSSM and composite Higgs: Try to have a **heavier Higgs** by making it more composite **without conflicts with EWPT**

- In the MSSM approach a strong sector is always needed for Susy-Breaking (we usually hide it → "*hidden sector*") **Why not being visible?**

Simplest *blended model* for EWSB:

Gherghetta, AP
arXiv:1107.4697
(also Azatov, Galloway, Luty)



We will assume *linear* MSSM couplings to the strong sector:

$$\mathcal{L}_{\rm int} = g_i \Phi_i \mathcal{O}_i$$

MSSM field (Φ_i)

Operator of the strong sector ($\mathcal{O}_i$)

Vectors: $\int d^4\theta \; g_i V_i \mathcal{J}_i$

Chiral: $\int d^2\theta \; g_i \Phi_i \mathcal{O}_i$

Currents of the strong sector ($\mathcal{J}_i$)

in GMSB: current made of messenger superfields

The **Higgs** will be **elementary** but will exhibit properties of **compositeness** due to their mixing with the strong sector

Possibility of...

- Higgs heavier that 130 GeV:
- MSSM with only one Higgs
- EWSB broken from the susy-breaking sector itself

Obvious problems:

- EWPT + FCNC (as in TC!)
- Generating realistic soft masses

Assumptions on the Susy-breaking sector (SBS)

Strongly coupled theory generically defined by:

- Energy scale (mass gap): Λ ~TeV
- "Number of colors": N (number of messengers in GMSB)
- Susy breaking of order one:
  - ➥ Susy-breaking splittings also of order ~ Λ
  - ➥ hard and soft Susy-breaking terms of the same order

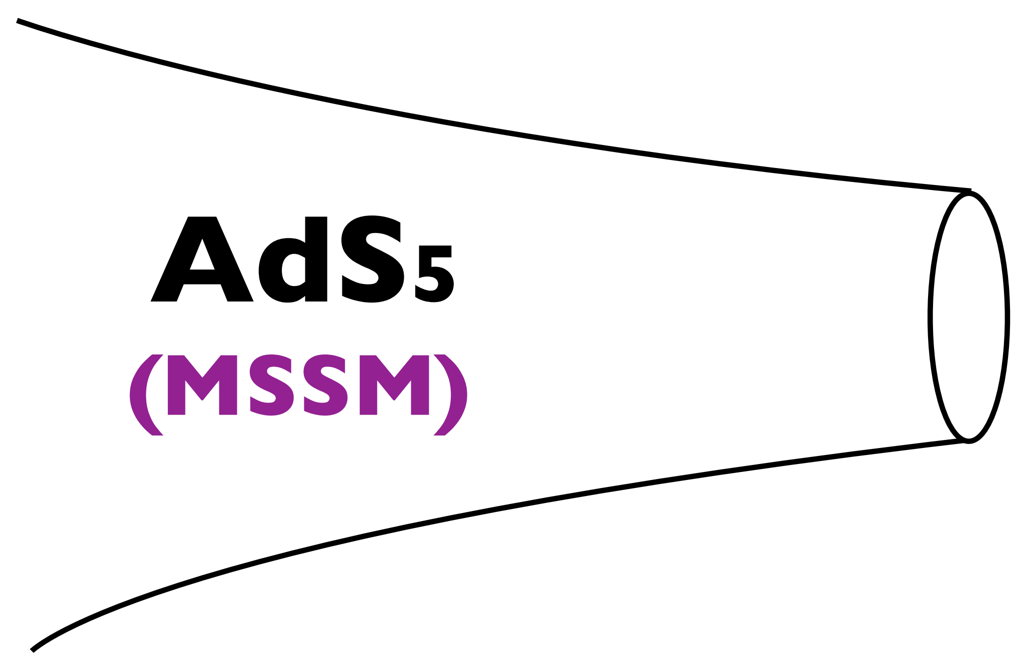
To get predictions, beyond NDA estimates, we will use the AdS/CFT correspondence:

Strong sector ➠ Warped Extra-dimension

MSSM + **Strong ~~SUSY~~** Λ **~TeV**

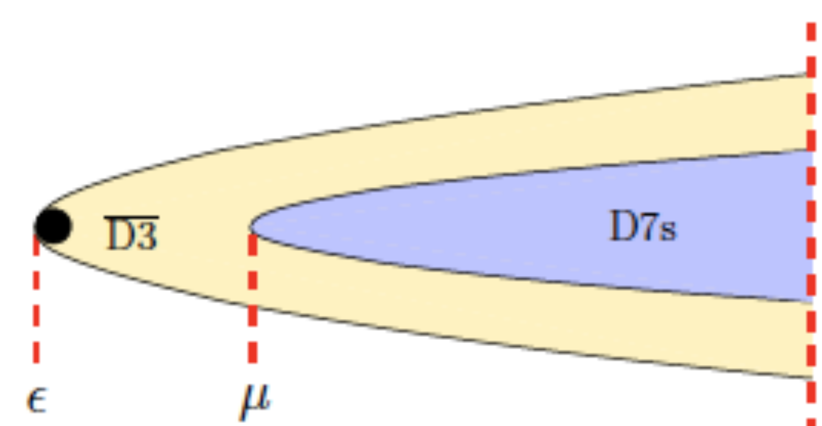
5D Prototype:

Susy broken
at the end
of an AdS throat
(hard-wall or RS setup)



Susy breaking TeV

Stringy constructions on the way...



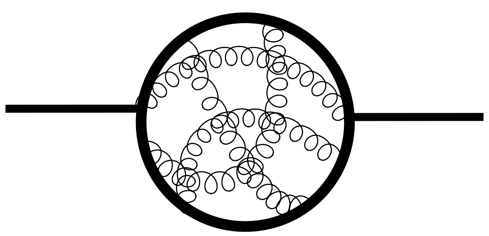
F.Benini, A.Dymarsky, S.Franco, S.Kachru, D. Simic, H.Verlinde 09

Higgs sector

1) MSSM Higgs doublets coupled to the SBS:

$$g_i \int d^2\theta \; H_i \mathcal{O}_i$$

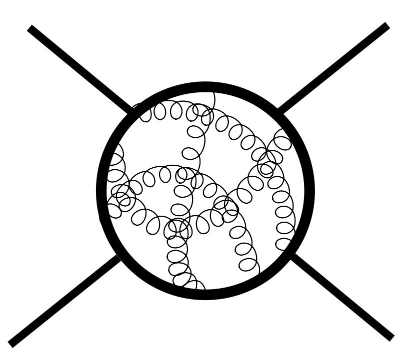
Higgs potential terms:



$$m_i^2 \sim \frac{g_i^2 N \Lambda^2}{16\pi^2} \simeq \Lambda^2 \epsilon_{H_i}^2$$

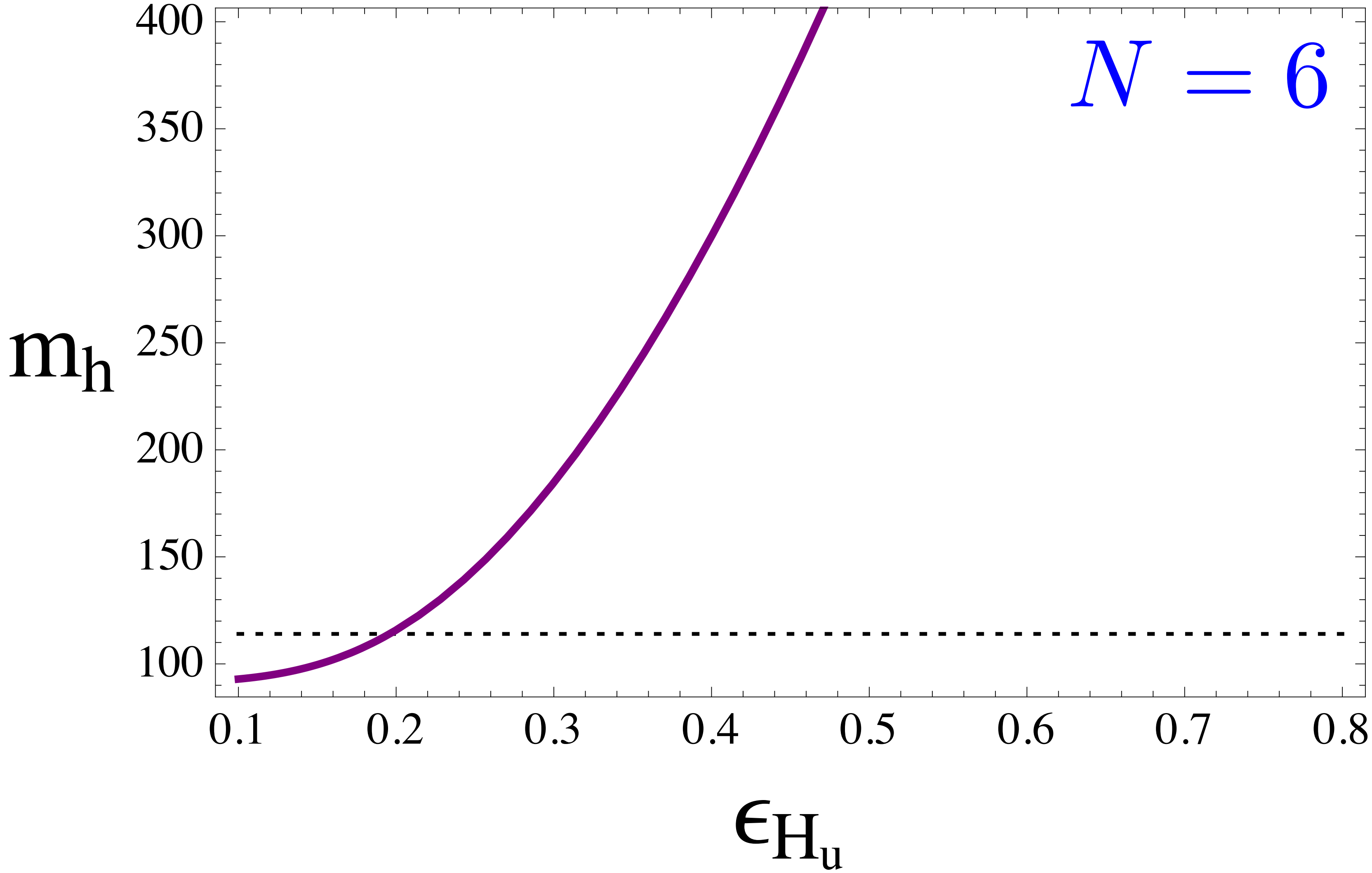
$$\epsilon_{H_i} \sim \frac{g_i}{g_{st}} \qquad g_{st} \sim 4\pi/\sqrt{N}$$

degree of mixing with the strong sector



$$\Delta\lambda_i \sim \frac{g_i^4 N}{16\pi^2} \simeq \frac{16\pi^2}{N}\epsilon_{H_i}^4$$

Lightest MSSM Higgs mass



tree-level!

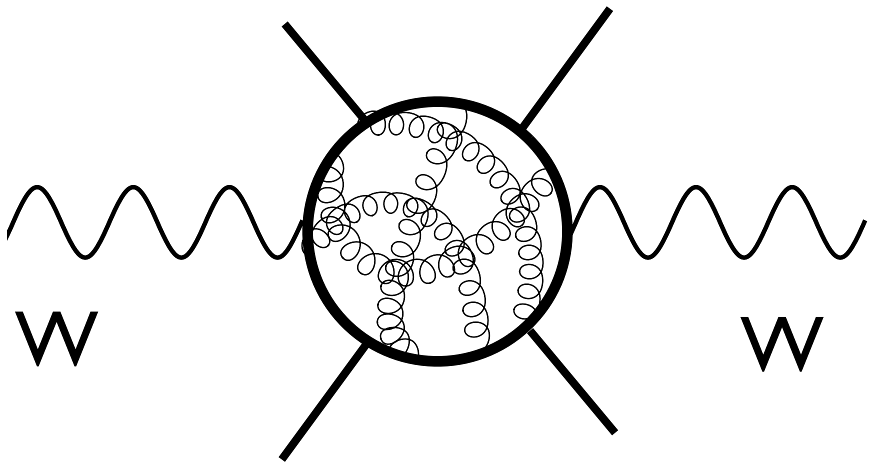
$\tan\beta \to \infty$

Large modifications without extra light states!

EWPT

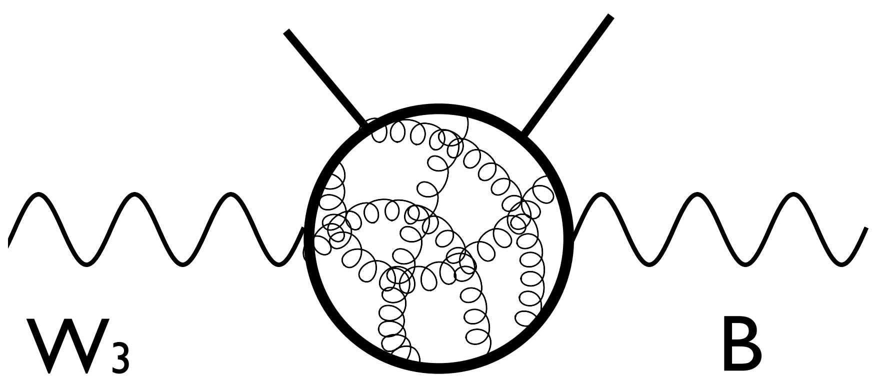
As the Higgs couples stronger to the (strong) sector that breaks susy, modifications of EW observables become sizable.
Main contributions:

W-masses



$$\widehat{T} = c_T \tan^2\theta_W \frac{16\pi^2 v^2 \epsilon_{H_2}^4}{N\Lambda^2}$$

Kin. mixing



$$\widehat{S} = c_S \frac{m_W^2 \epsilon_{H_2}^2}{\Lambda^2}$$

coefficients c_T, $c_S \sim 1$. From AdS/CFT:

$$\begin{cases} c_S \simeq \dfrac{9\pi^2((\epsilon_{H_2}^2+1)^2-1)}{32(\epsilon_{H_2}^2+1)^2\epsilon_{H_2}^2} \\ c_T \simeq \dfrac{9\pi^2}{64(\epsilon_{H_2}^2+1)(2\epsilon_{H_2}^2+1)} \end{cases}$$

M. Round'10

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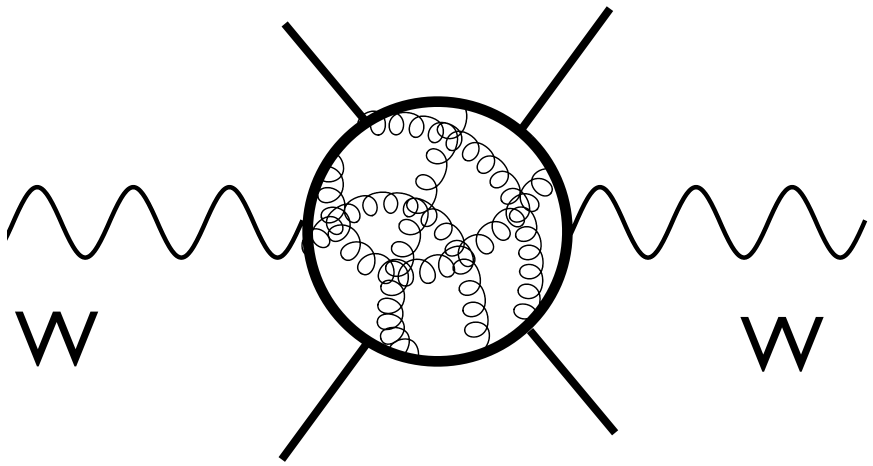
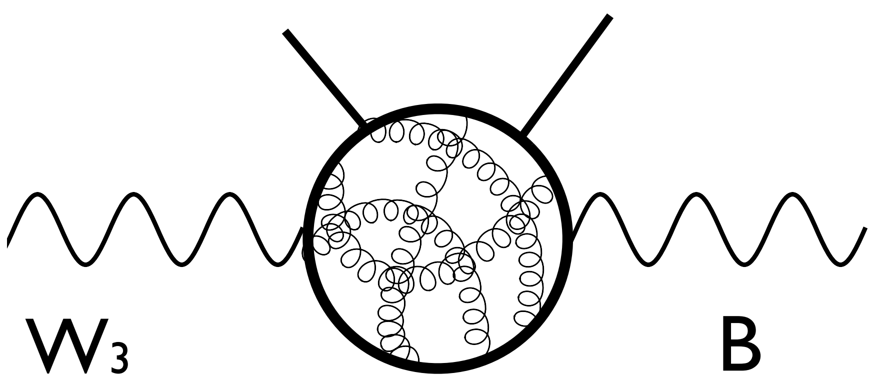


$$\widehat{T} = c_T \tan^2\theta_W \frac{16\pi^2 v^2 \epsilon_{H_2}^4}{N\Lambda^2}$$

N will be needed to be large ~ 6!

Kin. mixing



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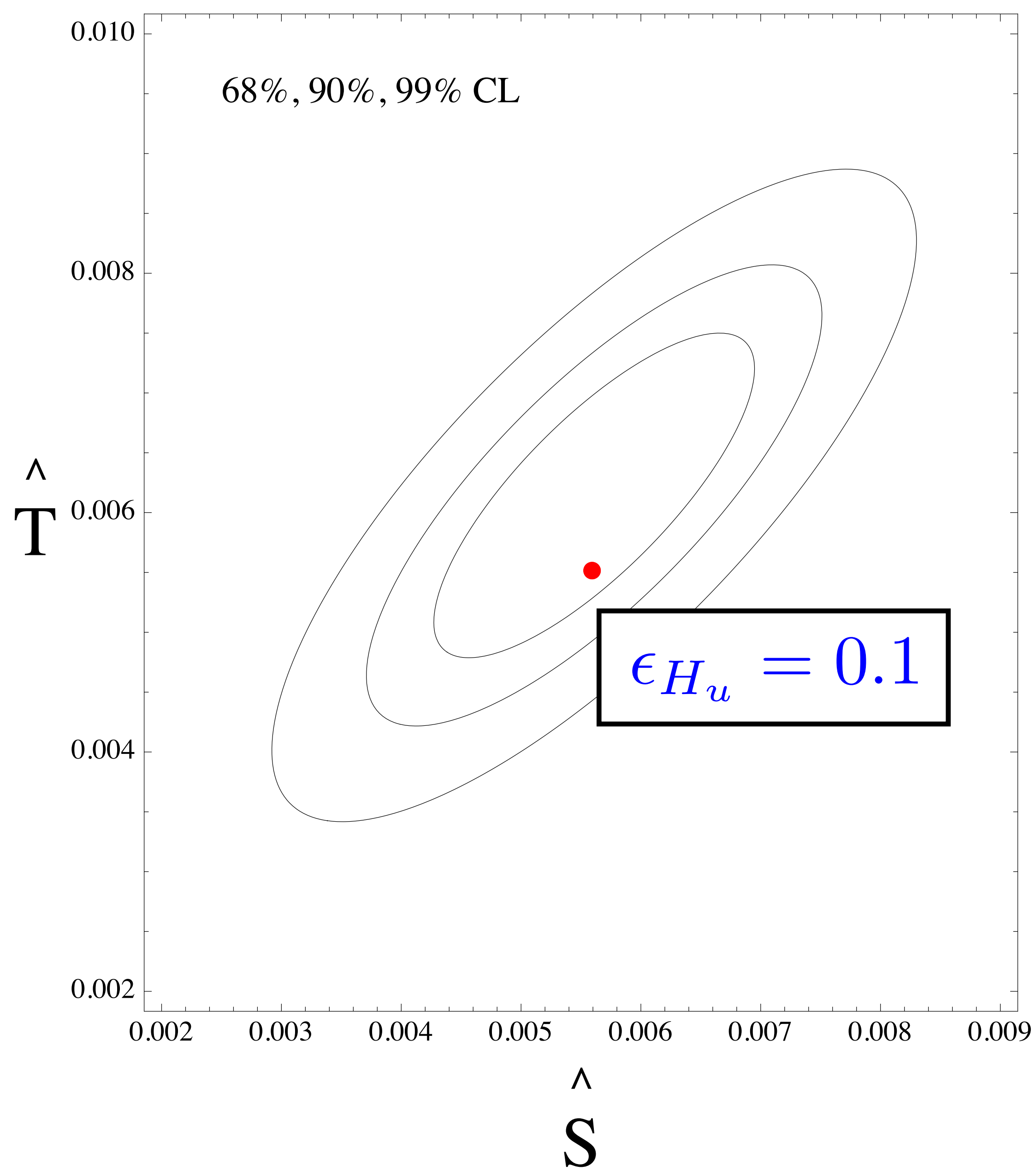
M. Round'10

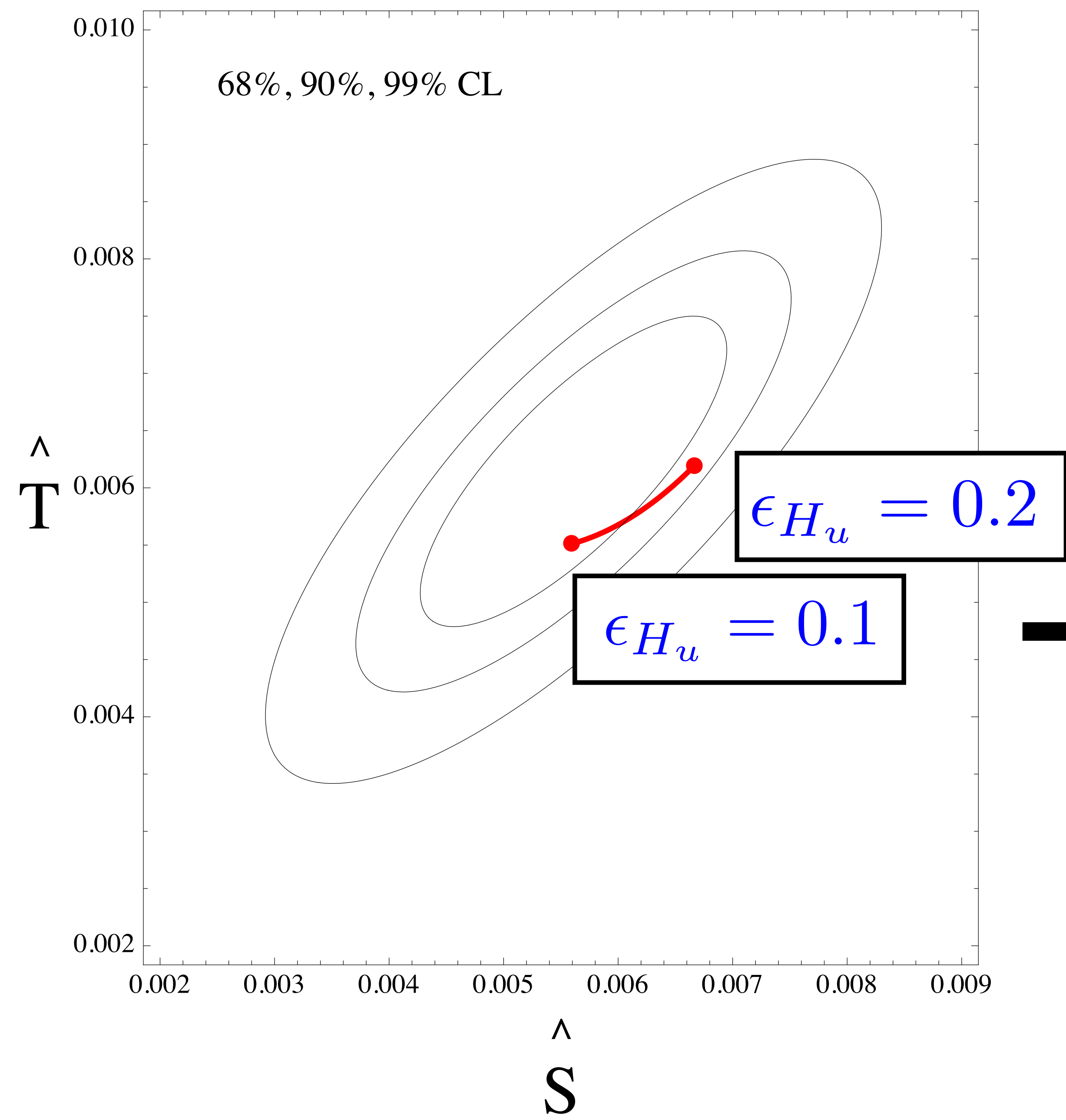
$N = 6$ $\Lambda = 1$ TeV



$m_h \sim 91$ GeV

at tree-level!

$N = 6$ $\Lambda = 1$ TeV

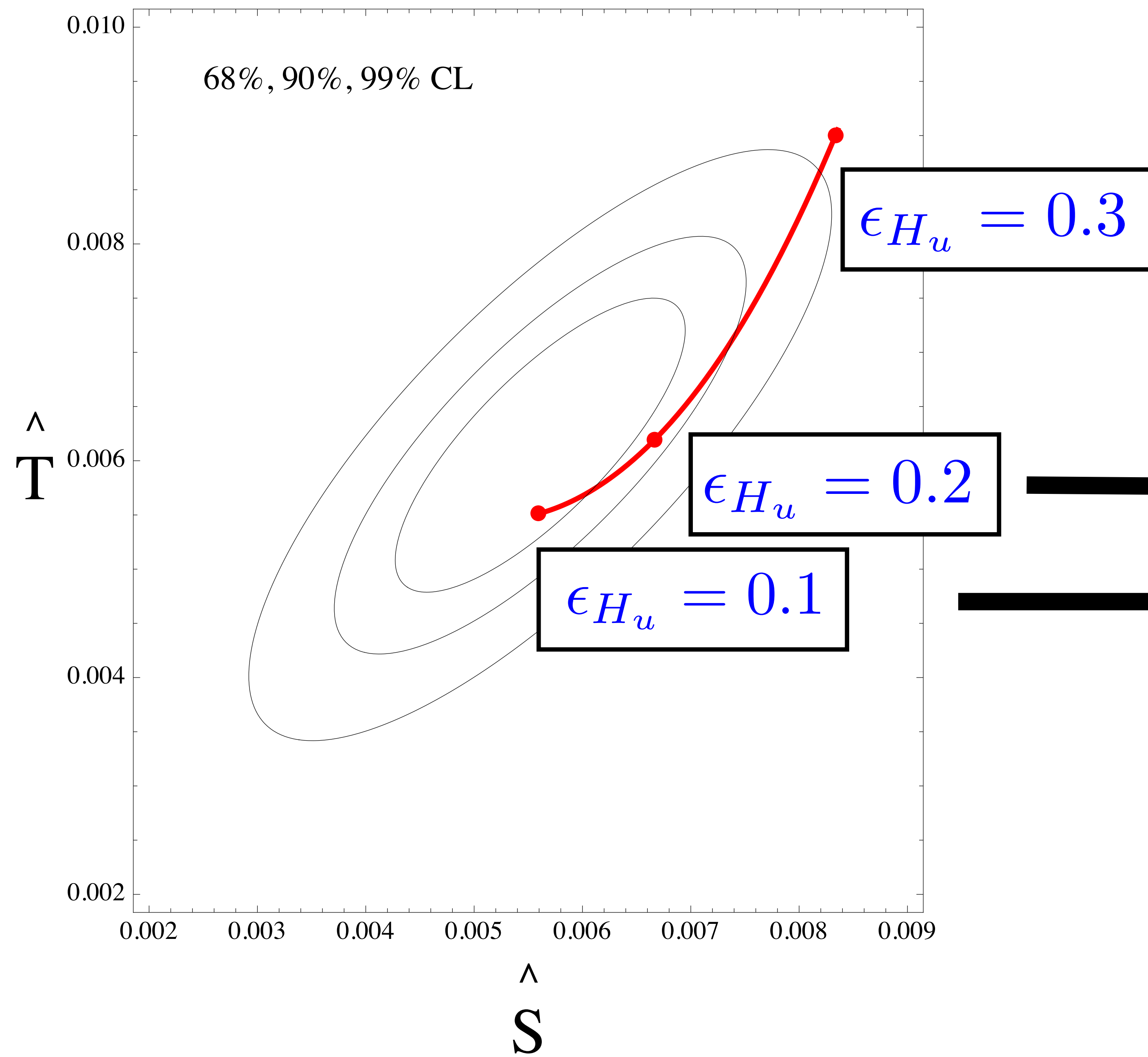


$m_h \sim 120$ GeV

$m_h \sim 91$ GeV

at tree-level!

$N = 6$ $\Lambda = 1$ TeV

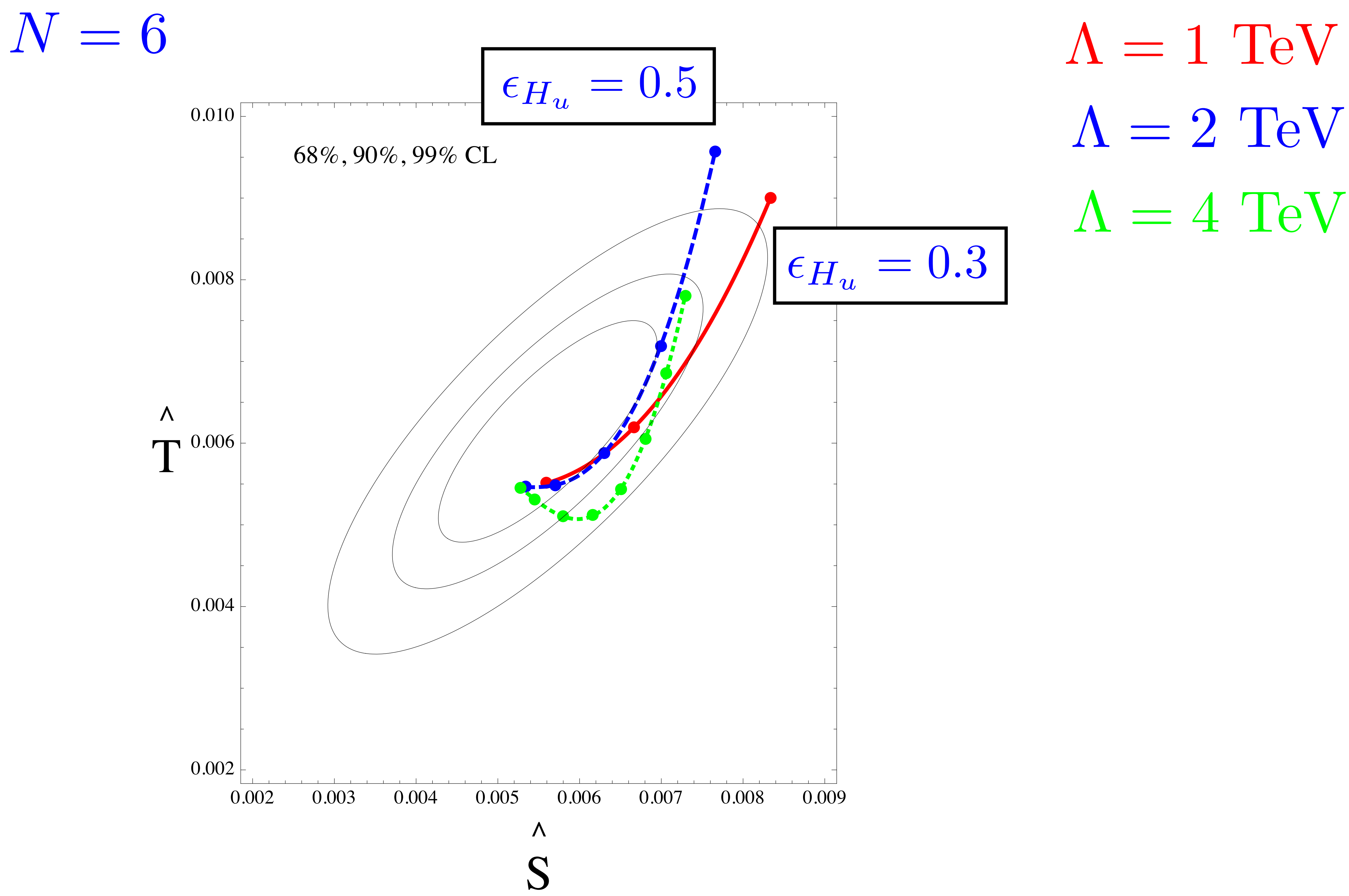


$m_h \sim 193$ GeV

$m_h \sim 120$ GeV

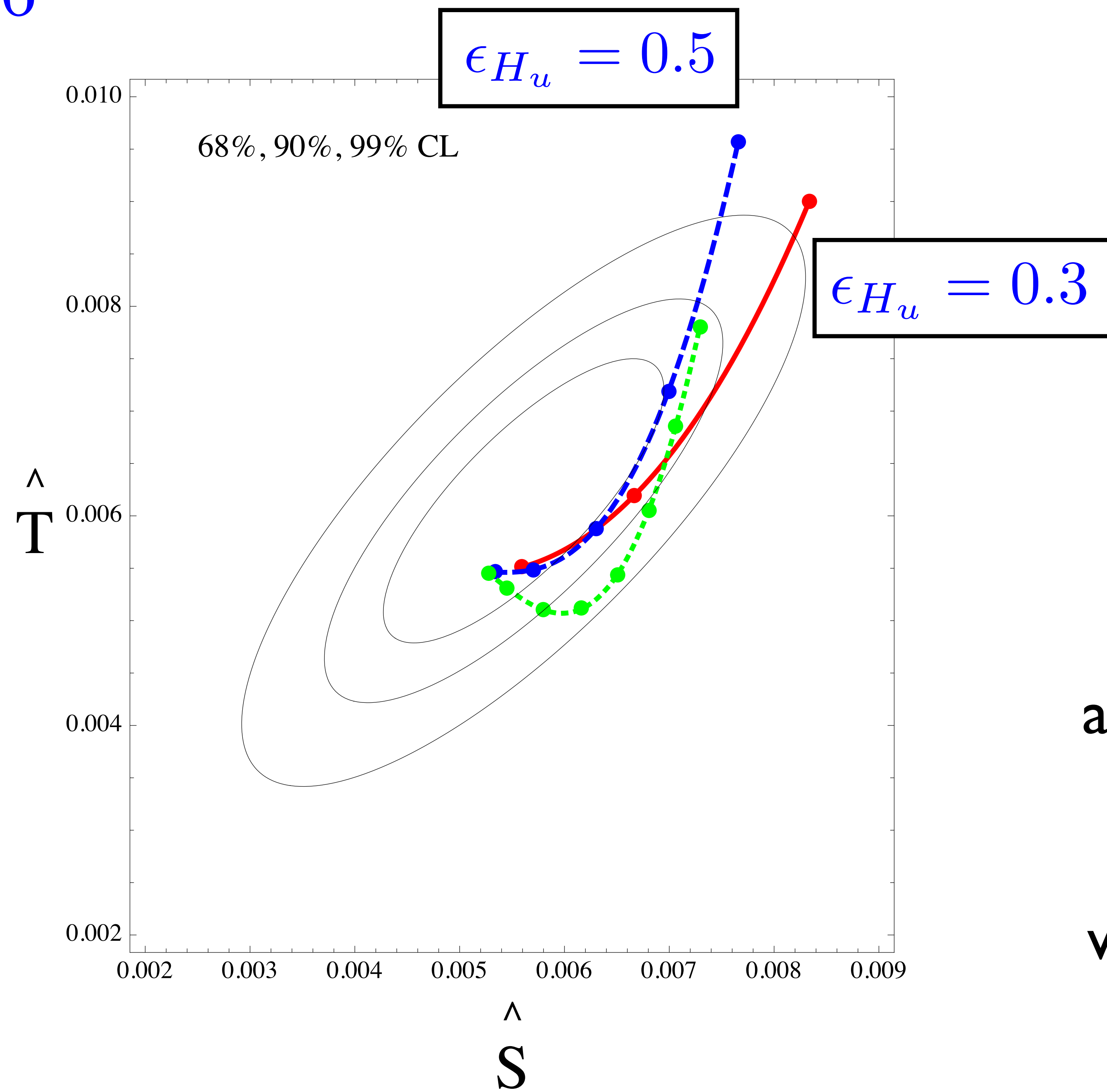
$m_h \sim 91$ GeV

at tree-level!



$N = 6$
$\epsilon_{H_u} = 0.5$
$\epsilon_{H_u} = 0.3$
$\Lambda = 1$ TeV
$\Lambda = 2$ TeV
$\Lambda = 4$ TeV
68%, 90%, 99% CL
0.010
0.008
0.006
0.004
0.002
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
$\hat{T}$
$\hat{S}$

$N = 6$



$\Lambda = 1$ TeV

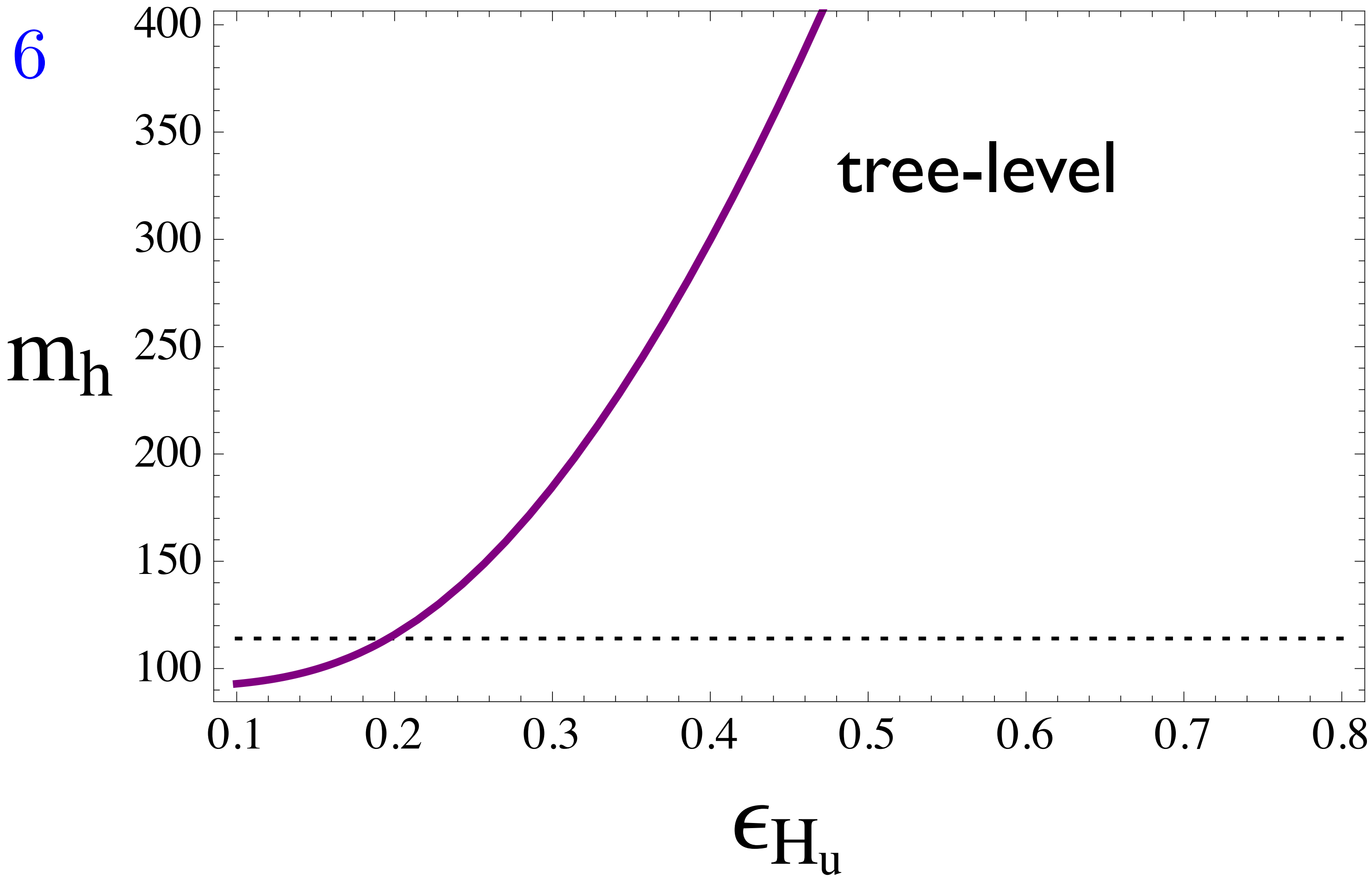
$\Lambda = 2$ TeV

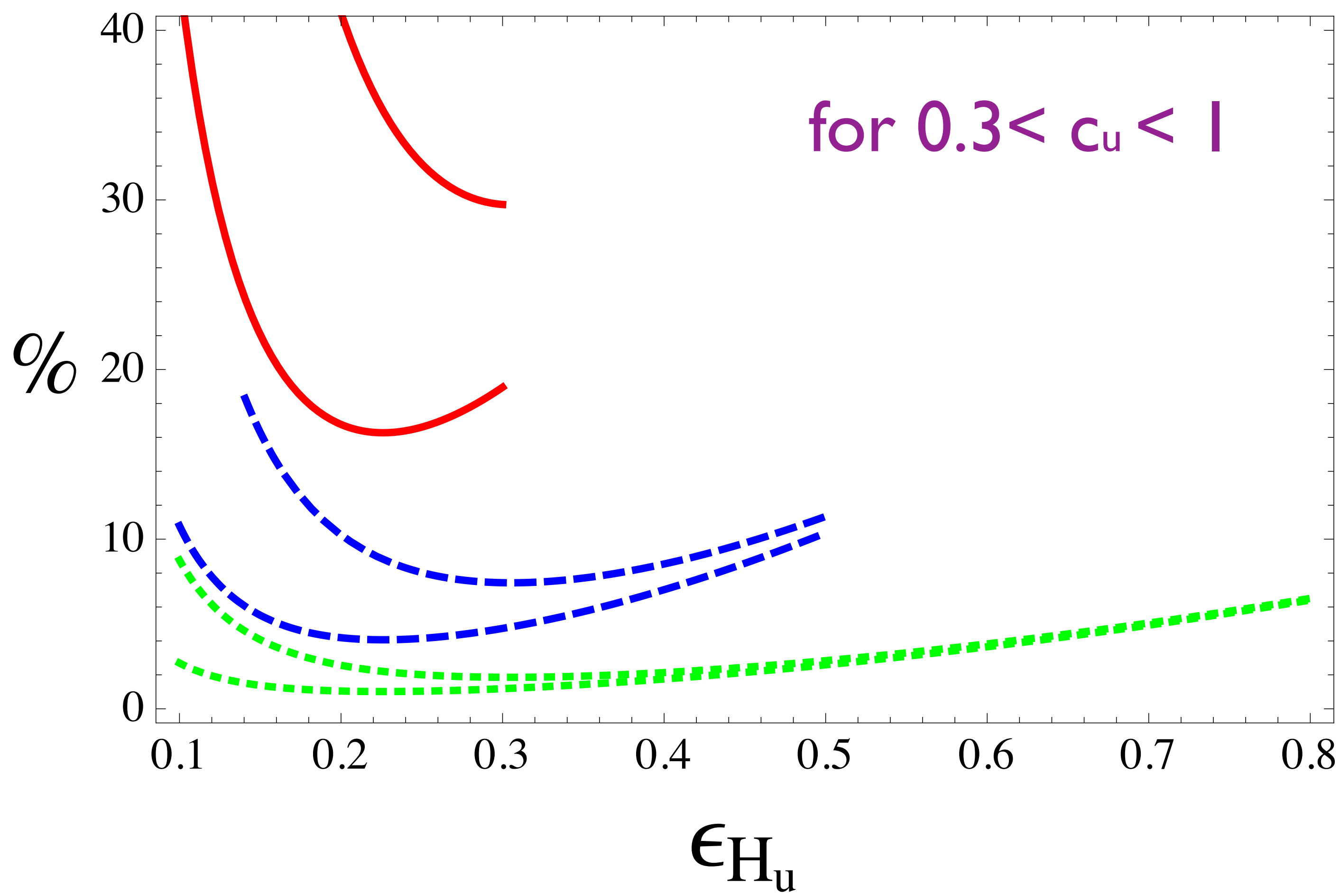
$\Lambda = 4$ TeV

Stronger coupling to the susy-breaking sector allowed for larger Λ but at the price of tuning:
As we increase Λ
we increase the EW scale:

$$v^2 = \frac{m^2_{H_u}}{\lambda_{H_u}} = c_u \frac{\epsilon^2_{H_u} \Lambda^2}{\lambda_{H_u}}$$

$N = 6$





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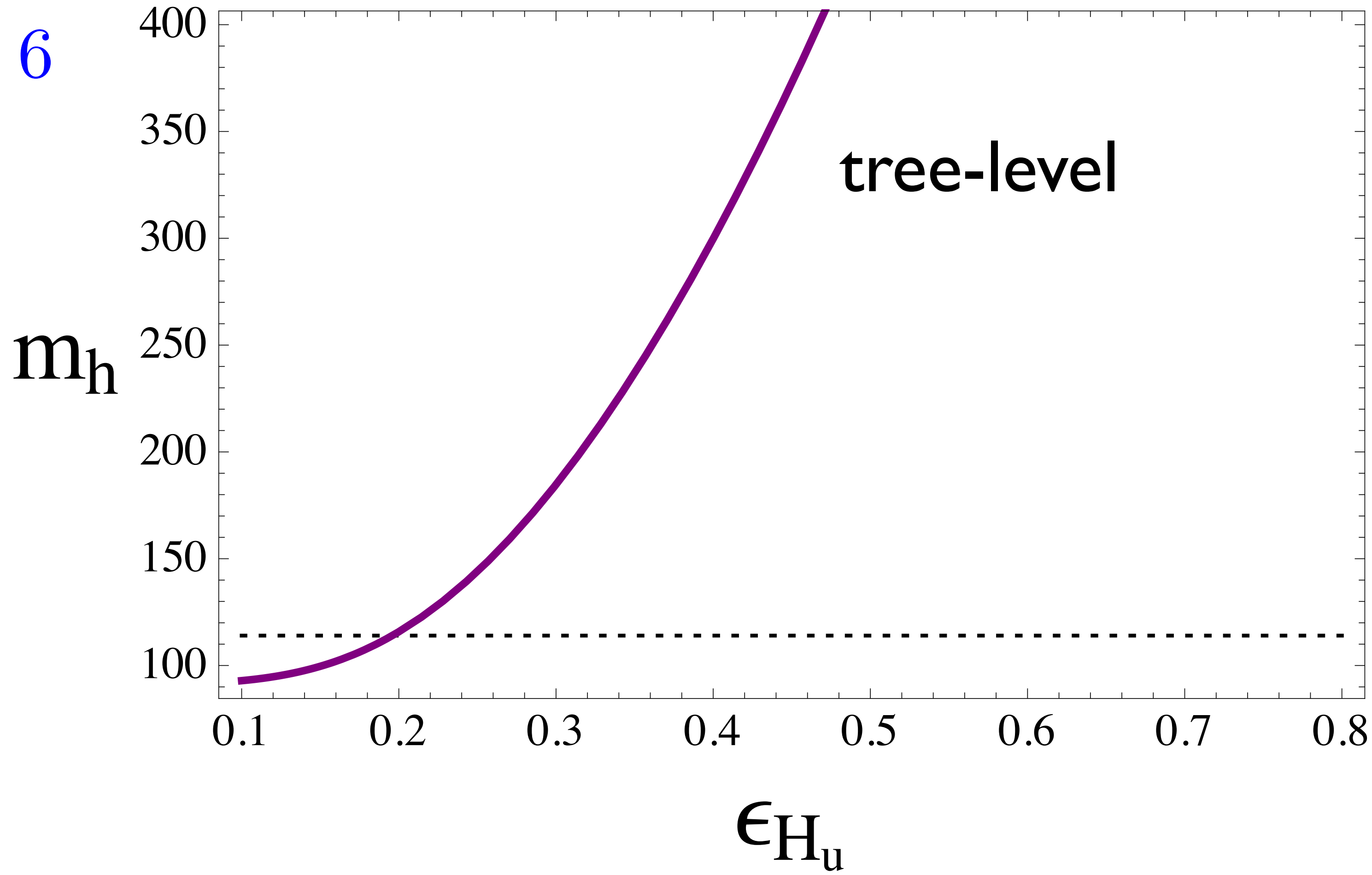

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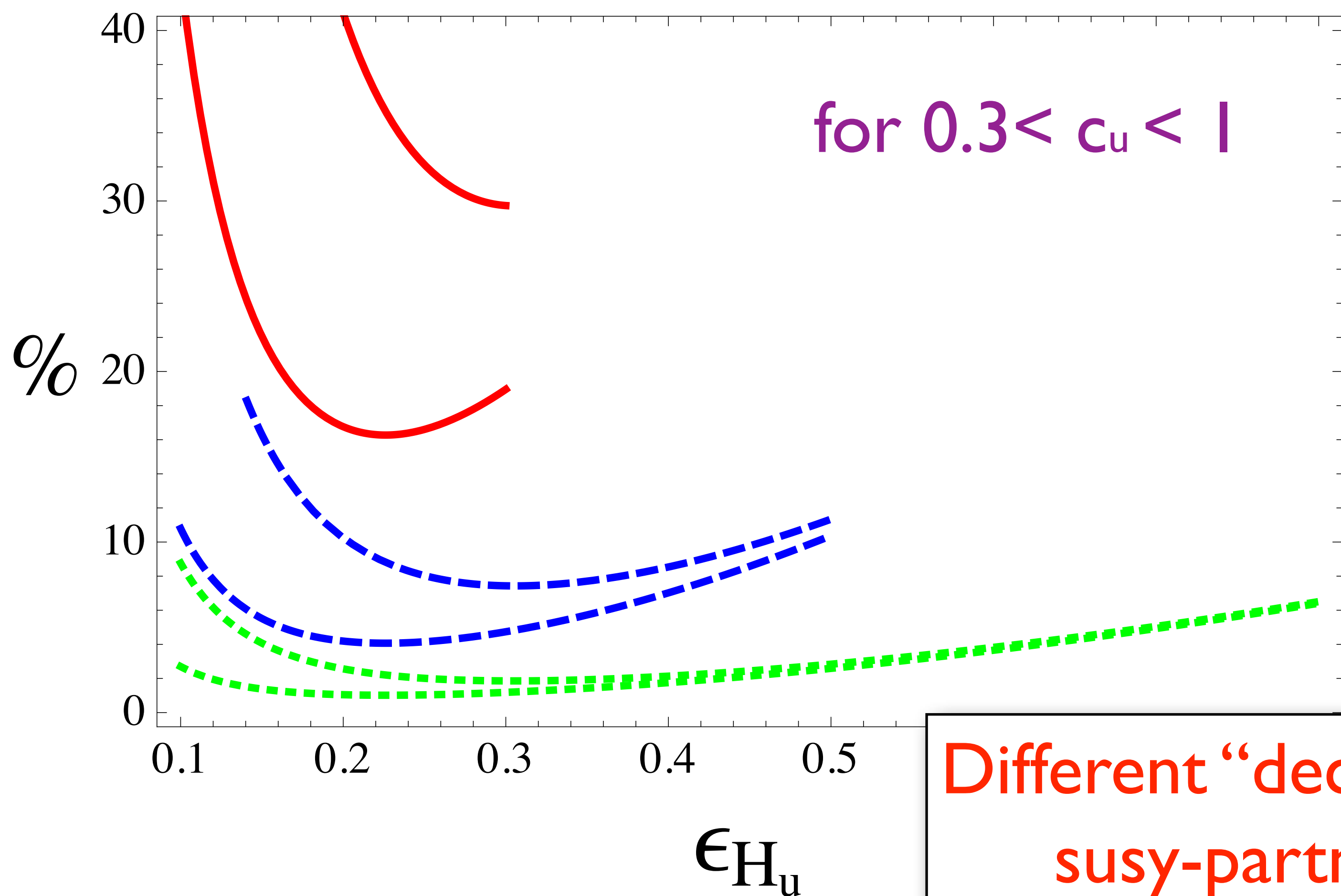


Different "decoupling limit" from the MSSM: susy-partners and Higgs mass $\to \infty$

2) SBS assume to break also the EW symmetry (one Higgs belongs to the SBS)

similarities with Bosonic TC
(S. Samuel 90, see also C.D.Carone, J.Erlich, J.A.Tan 06)

$$\Sigma = \frac{1}{\sqrt{2}} f_v e^{i\sigma_i \frac{\pi_i}{f_v}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Higgs potential:

$$V = m_{H_u}^2 |H_u|^2 + \lambda_{H_u} |H_u|^4 - (m_{H_u\Sigma}^2 H_u^\dagger \Sigma + h.c.) + \cdots$$

Elementary Higgs VEV from a tadpole:

$$\langle H_u \rangle \sim \frac{f_v m_{H_u\Sigma}^2}{m_{H_u}^2} \sim \frac{f_v}{\epsilon_{H_u}} \gg f_v$$

Physical Higgs mass:

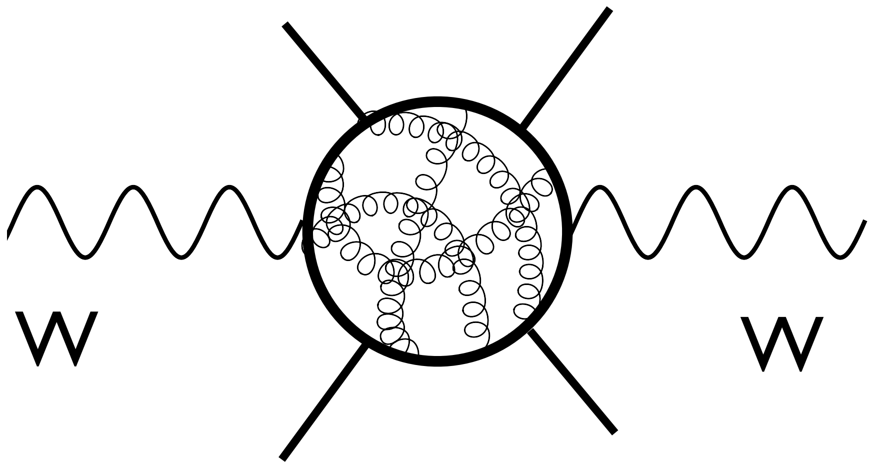
$$m_h^2 = 3\lambda_{H_u} v_u^2 + m_{H_u}^2$$

→ extra Higgs mass term

EWPT

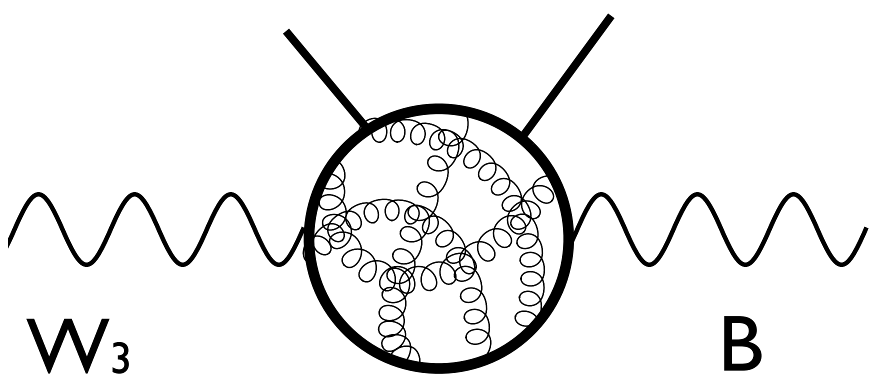
Modifications of EW observables from from <Σ> ~ f_v become sizable:

W-masses



$$\hat{T} \;=\; c_T \tan^2\theta_W \frac{16\pi^2 f_v^4}{N\Lambda^2 v^2}$$

Kin. mixing



$$\hat{S} \;=\; c_S \frac{m_W^2}{\Lambda^2}\frac{f_v^2}{v^2}$$

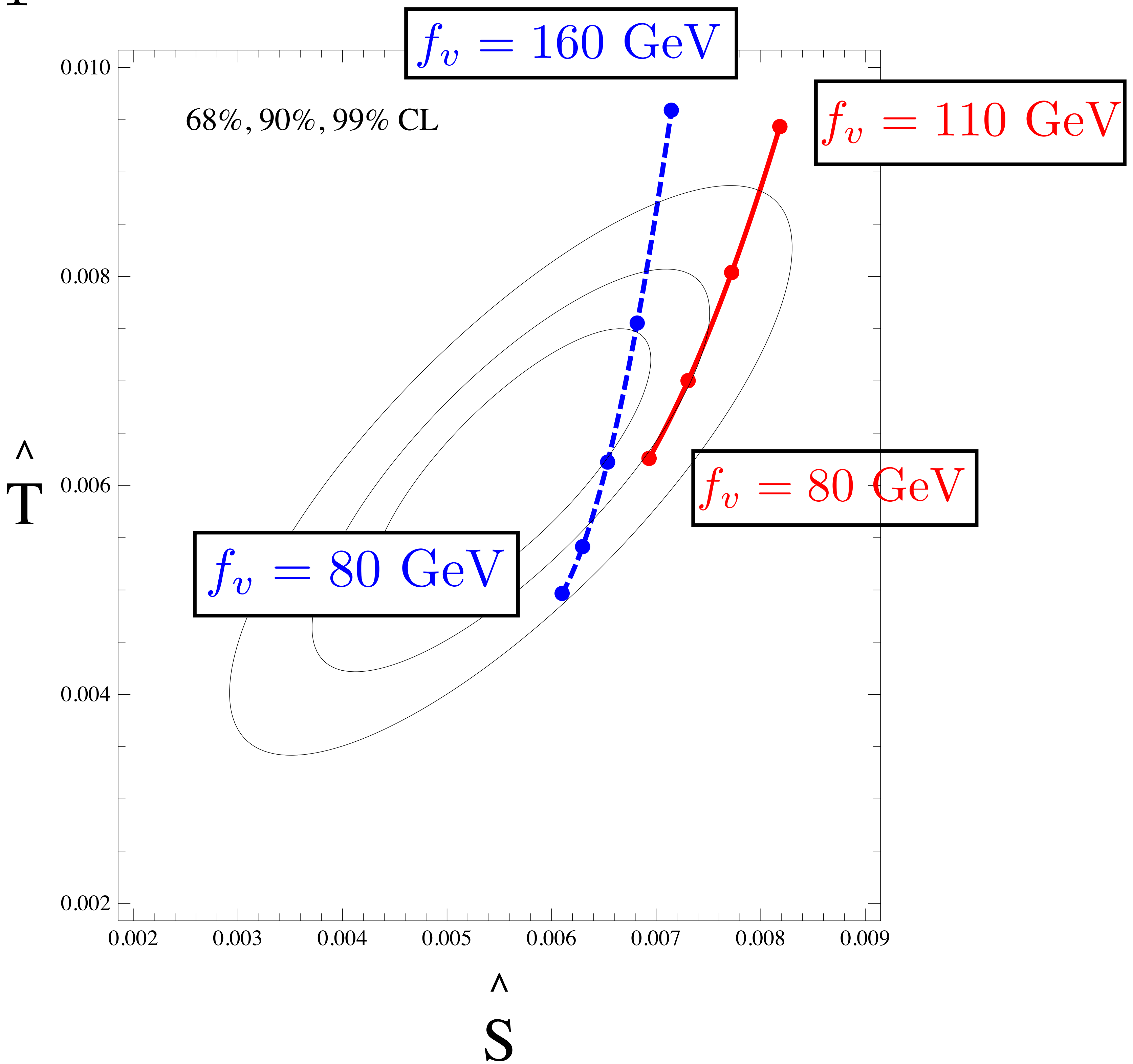
coefficents c_T, c_S ~ 1. From AdS/CFT: $c_T \simeq \frac{1}{9} c_S \simeq \frac{3\pi^2}{128}$

$N = 6$

$\epsilon_{H_2} \sim 0.1$

$\Lambda = 1$ TeV

$\Lambda = 2$ TeV



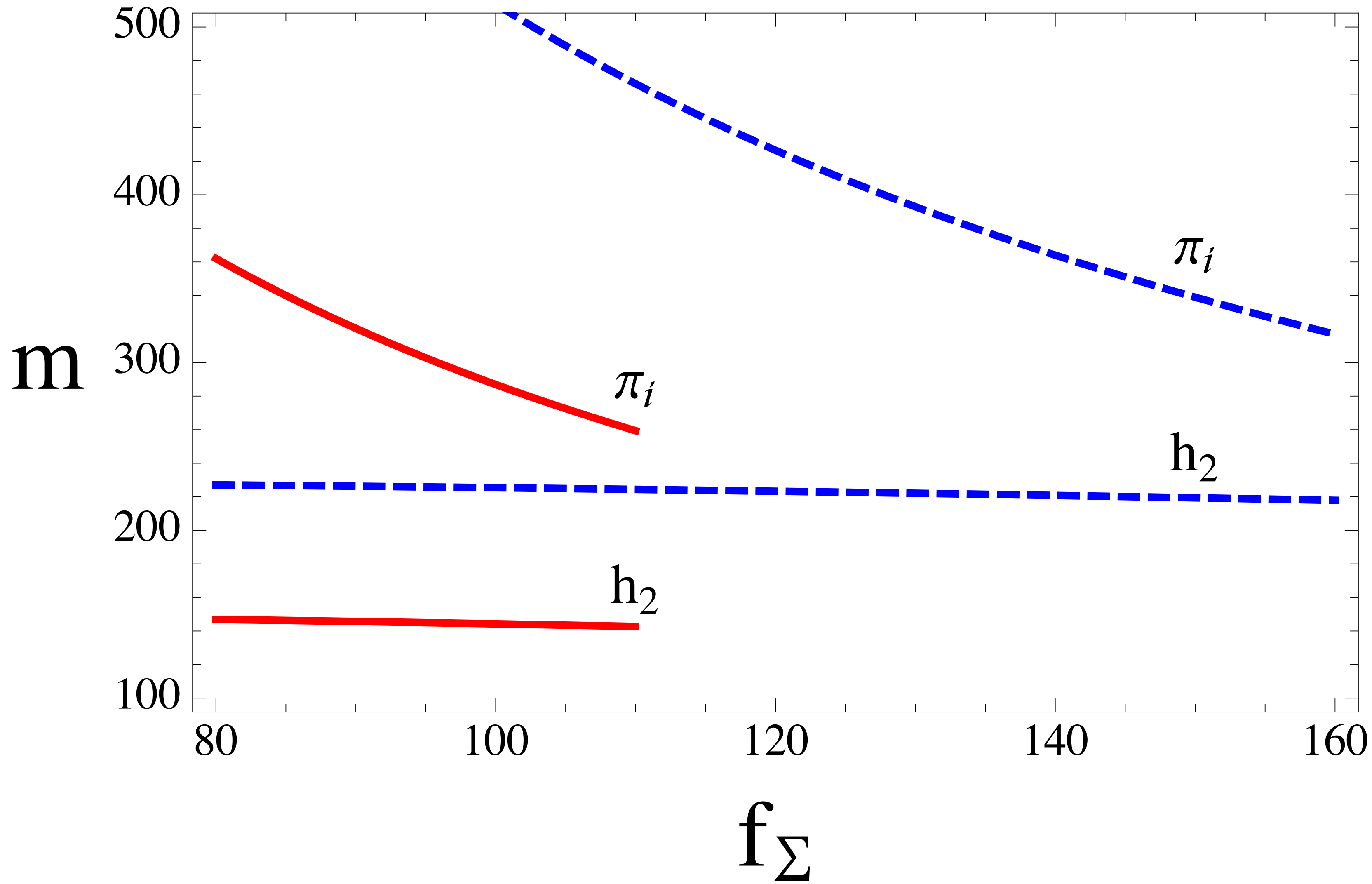
Higgs spectrum (in GeV):

$N = 6$

$\epsilon_{H_2} \sim 0.1$

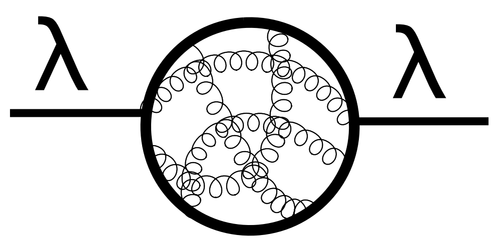
$\Lambda = 1$ TeV

$\Lambda = 2$ TeV

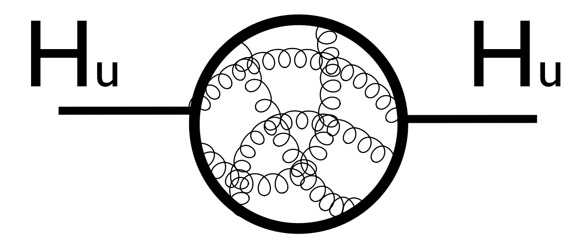


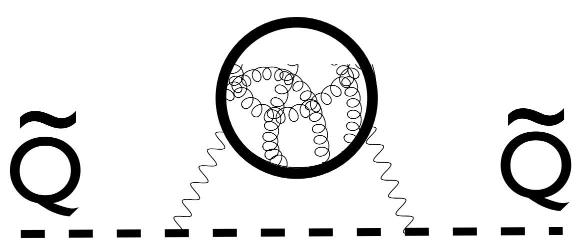
Sparticle Spectrum

Ordinary gauge-mediated soft-mass contributions too small as compared to the Higgs soft-mass



$$\sim \frac{g_i^2 N}{16\pi^2}\Lambda \quad << \quad \epsilon_{H_u}\Lambda$$

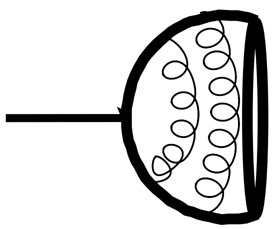




Gaugino masses:

<u>Dirac gauge-mediated contributions needed</u>

Marriage of MSSM gauginos with composite ones: 8+3+(1)

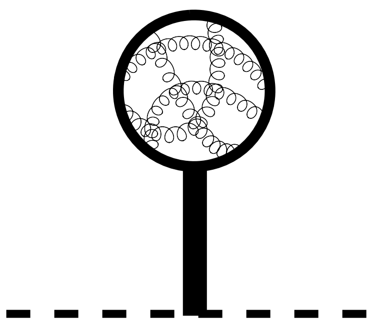
λ  **λ´** $$m_{\lambda_i} \sim \frac{g_i N}{4\pi}\Lambda \simeq 200\ \mathrm{GeV}\sqrt{\frac{N}{6}}\left(\frac{\Lambda}{\mathrm{TeV}}\right) g_i$$

An *approximate* R-symmetry must be present to avoid Majorana masses for **λ´** of order ~ Λ

Squark masses:

A) Matter not directly coupled to the SBS

Only possible origin of soft-masses from D-terms of an extra U(1) that communicate from the SBS to the MSSM:



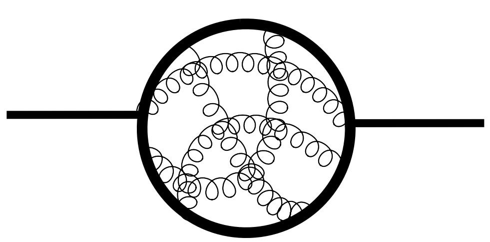
$$m_i^2 \sim q_i \frac{N}{16\pi^2}\Lambda^2 \sim m_\lambda^2$$

U(1) must be broken by the SBS

No FCNC if charges family universal

B) Matter directly coupled to the SBS a the Higgs

$$\int d^2\theta \; g_i \Phi_i \mathcal{O}_i$$



$$m_i^2 \sim g_i^2 \frac{N}{16\pi^2}\Lambda^2$$

SBS must preserve a flavor symmetry $SU(3)_Q \times SU(3)_D \times SU(3)_U$

$$g_i \equiv g = \mathcal{O}(1)$$

Yukawa sector:

A) Two Higgs Doublet Model:

Yukawas as in the MSSM: $W = Y_u H_u Q U + Y_d H_d Q D$

$R[H_i] = 0 \quad R[Q, U, D] = 1$

No FCNC !

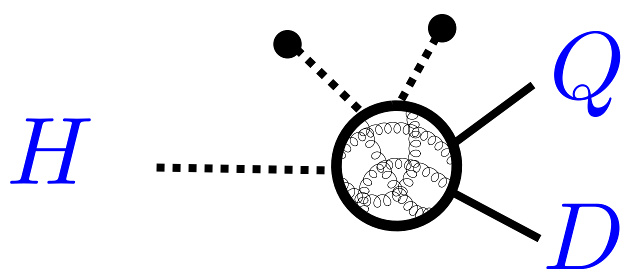
B) One Higgs Doublet Model:

$$Y_u \int d^2\theta H_u Q U + Y_d \int d^4\theta\, H_u^\dagger Q D \frac{\eta^\dagger}{\Lambda^2} \qquad \eta = F\theta^2$$

$$R[\eta] = 2$$

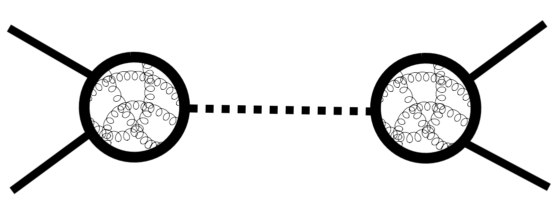
see also
R.Davies,J.March-Russell,
M.McCullough

Flavor violating Higgs interactions:



$$Y'_d \int d^4\theta\, H_u^\dagger Q D \frac{H_u H_u^\dagger \eta^\dagger}{\Lambda^4}$$

Higgs mediated FCNC. Main impact on εK :



$$C_2(\bar{s}_R d_L)^2 \; : \qquad C_2 \sim \left(Y_s V_{us} \frac{\epsilon_{H_u}^2 g_{st}^2 v^2}{\Lambda^2} \right)^2 \frac{1}{m_h^2}$$

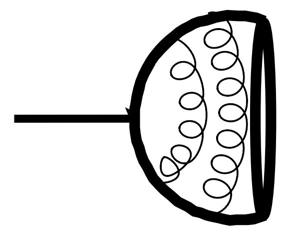
$$Y'_d \sim Y_d$$

Contribution around
the exp. value

Higgsino masses: (no μ/Bμ problem as in GMSB)

In the 1HDM an extra fermion doublet $\tilde{H}'$ must be present in the SBS for anomaly cancellation.

If it has opposite R-charge than $\tilde{H}_u$:

$\tilde{H}_u$  $\tilde{H}'$ $$m_{\tilde{H}_u} \sim \epsilon_{H_u} \Lambda$$

In 2HDM two extra fermions with opposite R-charges needed:

$$m_{\tilde{H}_i} \sim \epsilon_{H_i} \Lambda$$

As in GMSB, the LSP is the Gravitino:

$$m_{3/2} \simeq \frac{F}{M_P} \sim \frac{\sqrt{N}\Lambda^2}{4\pi M_P} \sim 10^{-4}\ \text{eV}\sqrt{\frac{N}{6}}\left(\frac{\Lambda}{1\ \text{TeV}}\right)^2$$

Much lighter than in GMSB!

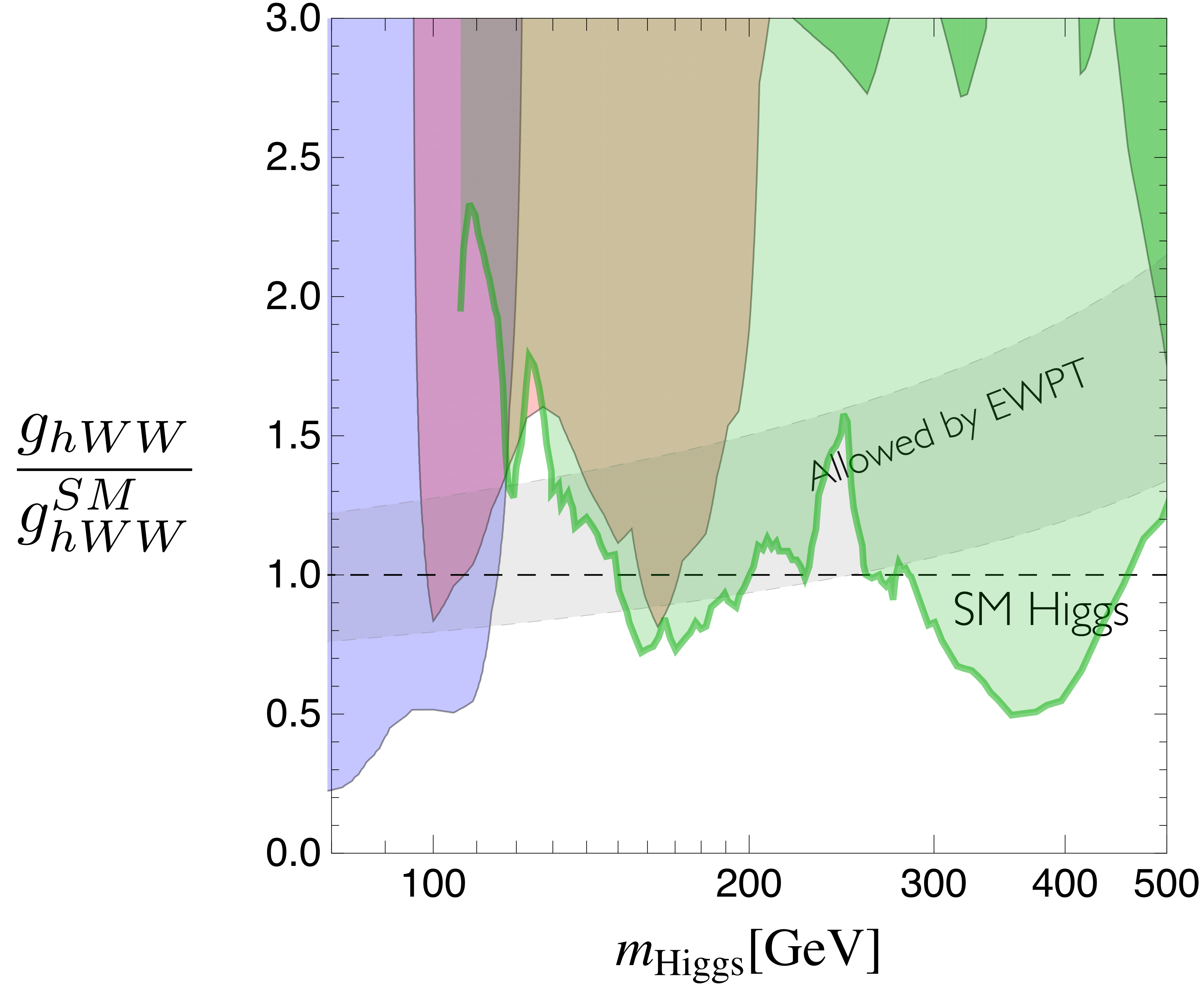
Pheno Implications

Higgs physics

1HDM: One Higgs SM-like with mass a > 130 GeV

- Possible decay to WW/ZZ
- Due to its coupling to the SBS, deviations from the SM couplings
- Tevatron and LHC Higgs bounds do not apply if the Higgs couplings to the WW/ZZ and SM fermions are smaller

in progress...



Contino
at "Higgs hunting"
Paris 2011

Exclusion Regions:

Blue = LEP

Red = Tevatron

Green = LHC

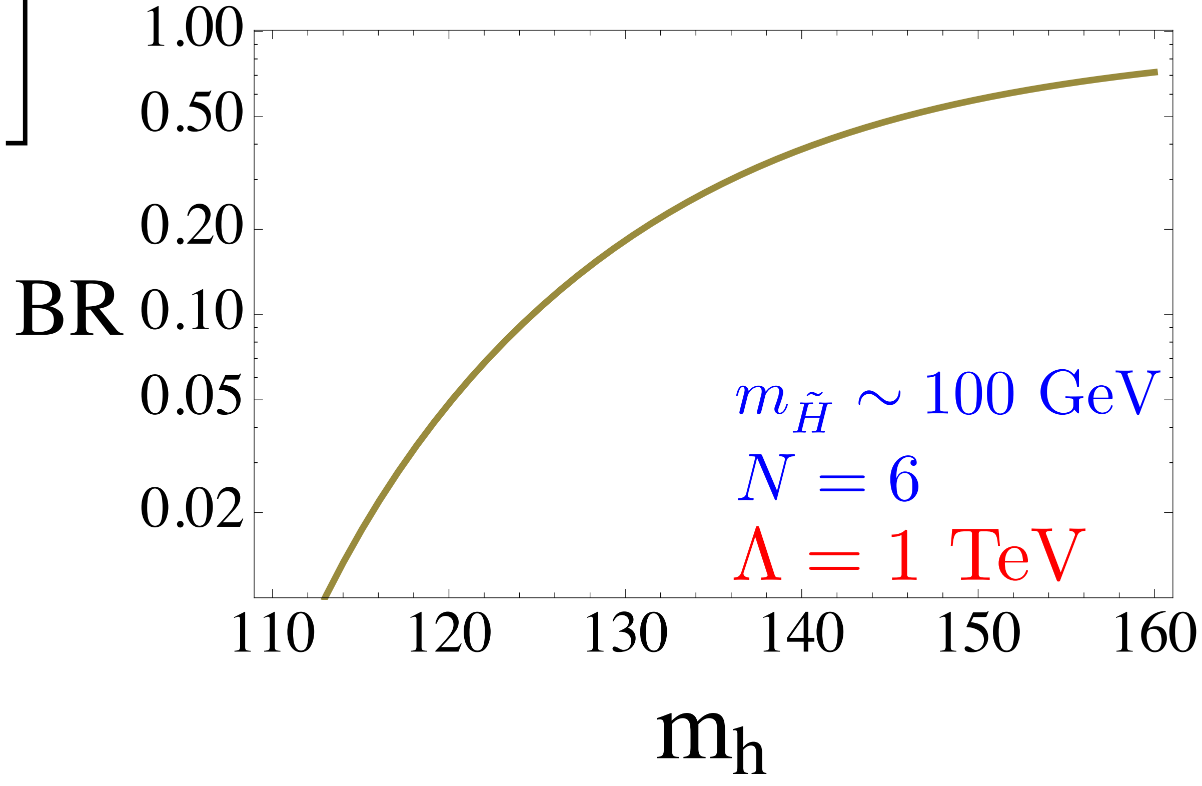
$$\frac{g_{hff}}{g_{hff}^{SM}} \approx \frac{g_{hWW}}{g_{hWW}^{SM}}$$

- New decay to Gravitino+Neutralino sizable:

$$\Gamma(h \to \tilde{G}\tilde{\chi}) \simeq \frac{1}{16\pi}\frac{m_h^5}{F^2}\left[1 - \left(\frac{m_{\tilde{\chi}}}{m_h}\right)^2\right]^4$$

Signal: photon+Missing E_T

The Smoking Gun !



Higgs physics

2HDM: Extra H^+, A, H Higgses

- Important deviations to $m^2_{H^+} = m^2_A + m^2_W$:

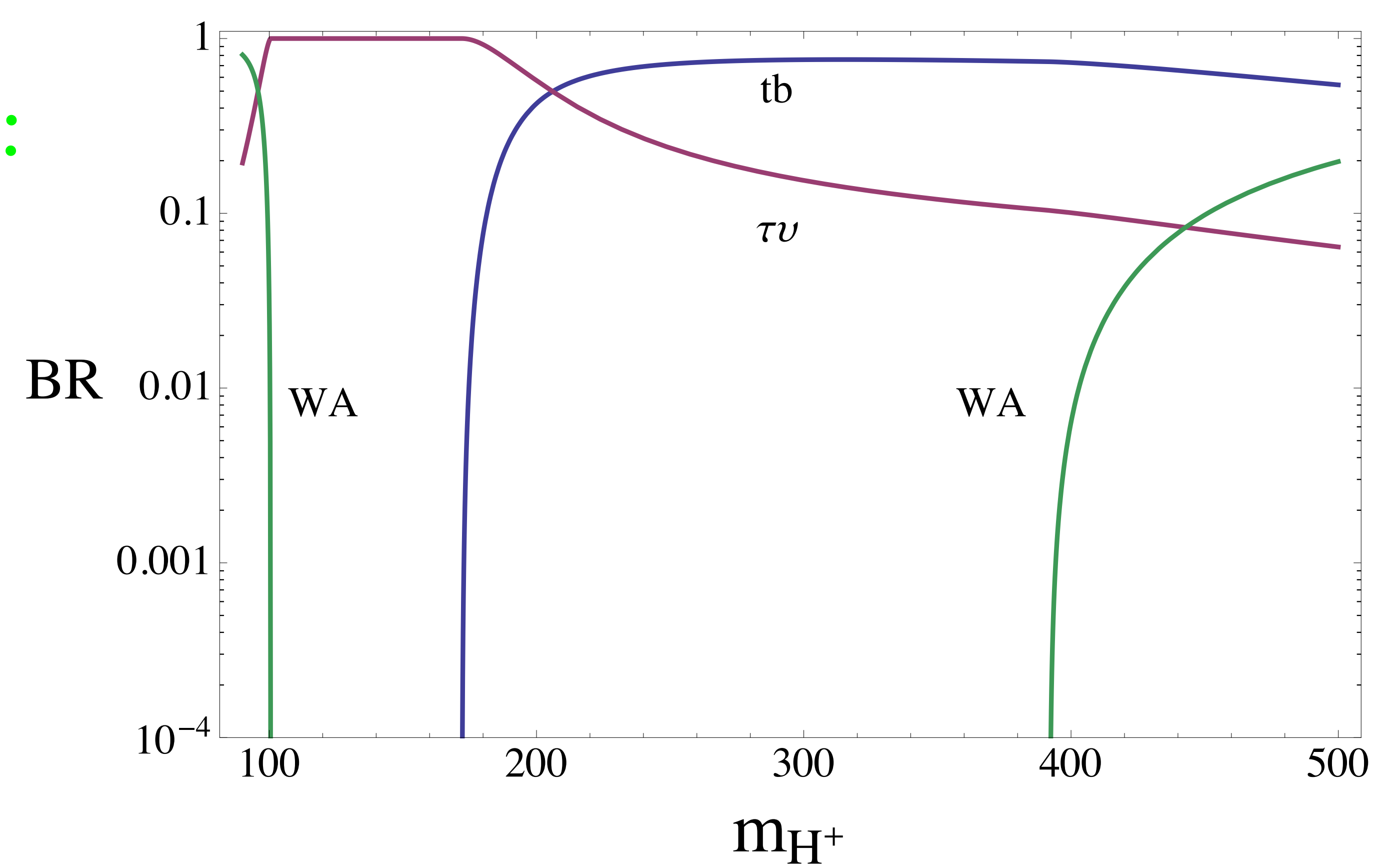
(H⁺- A splitting needs breaking of SU(2)L and custodial sym.)

$$\frac{m^2_{H^+} - m^2_A}{m^2_A} \sim \frac{v^2}{\Lambda^2} g^2_{st} \epsilon^2_{H_2}$$

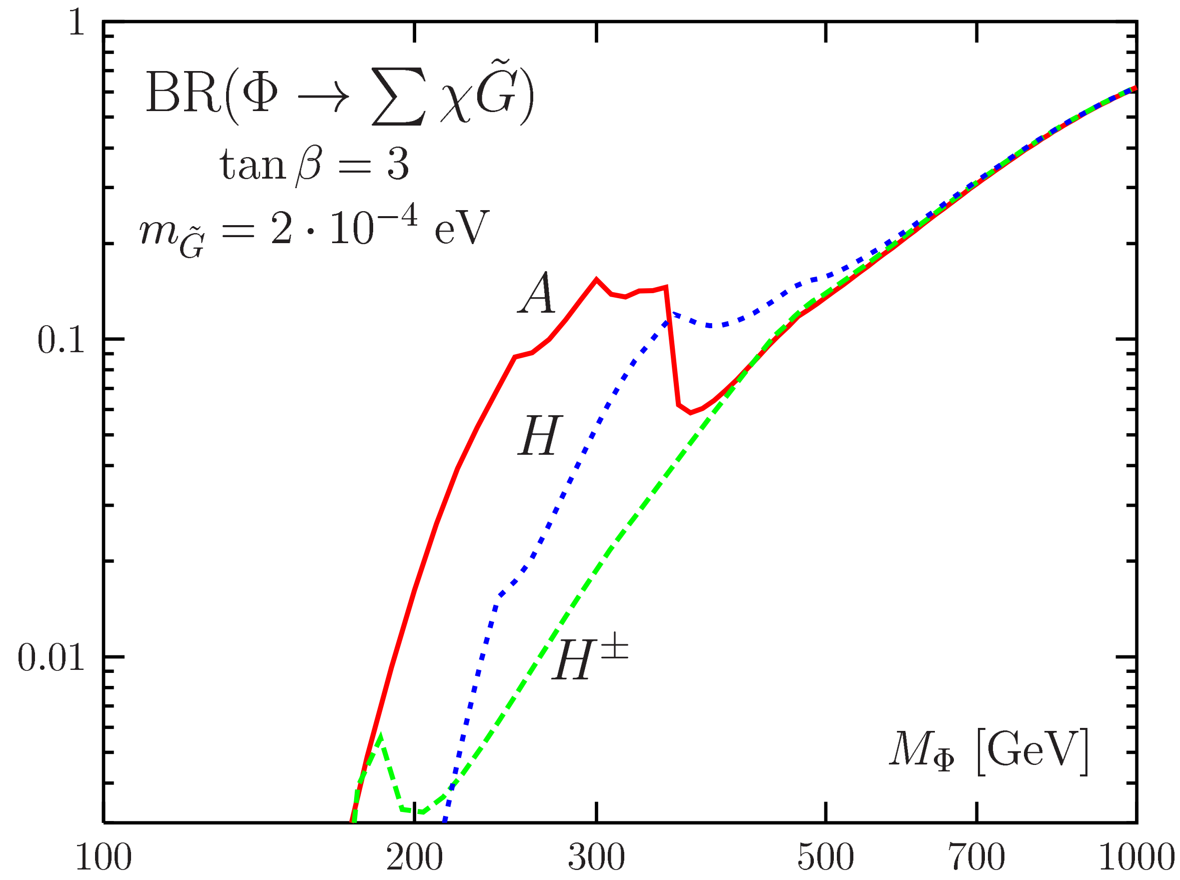
➥ gives the possibility of $H^+ \to WA$

$\tan\beta = 10$

For a splitting of 30%:



- Sizable decay of A, H (H^+) to Gravitino+Neutralino (chargino)



A. Djouadi

Sparticles at the LHC

in progress...

Main implications on the spectrum:

- Compressed Spectrum: $m \sim \frac{\sqrt{N}}{4\pi}\Lambda$
- Only Bino allowed to be lighter than EW scale (being a singlet no important pheno constraints)

  Here could be the case if there is no singlet fermion to marry with.
  It will get Majorana mass from explicit R-breaking

LHC signals similar to GMSB, but:

- No displaced vertex signatures: $\Gamma(\psi_{\rm NLSP} \to \tilde{G}) \sim \frac{m_\psi^5}{F^2} \sim \mathrm{MeV}$
- Dirac nature of gauginos change cross-section and decays

  $\sigma(qq \to \tilde{q}\tilde{q}) = \sigma(qq' \to \tilde{q}\tilde{q}') = 0$ S.Y.Choi, M.Drees, A. Freitas, P.Zerwas
- Double Gravitino production: pp →GGg or pp →GGγ

  Monojet+Missing E_T or Photon+Missing E_T

  Tevatron bound $\sqrt{F} \gtrsim 200~\mathrm{GeV}$. LHC?

A.Brignole, F.Feruglio, M.Mangano, F.Zwirner

Majorana-Dirac discrimination by like-sign lepton pairs

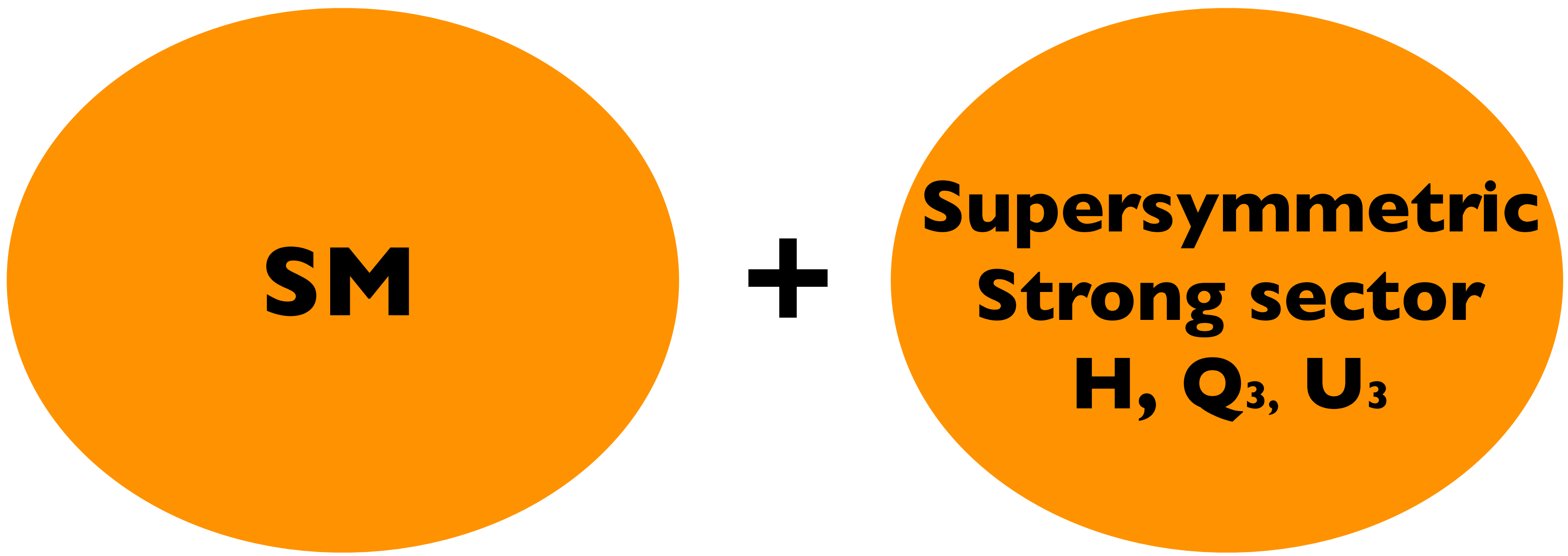
Process	Majorana			Dirac		
	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^+\ell^-$	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^+\ell^-$
$u_L u_L \to \tilde{u}_L \tilde{u}_L$	49	1	46	$\times$	$\times$	$\times$
$d_L d_L \to \tilde{d}_L \tilde{d}_L$	1	49	46	$\times$	$\times$	$\times$
$u_L d_L \to \tilde{u}_L \tilde{d}_L$	7	7	82	$\times$	$\times$	$\times$
$u_L q_R \to \tilde{u}_L \tilde{q}_R$	0	0	36	0	0	36
$q_L \bar{q}_L \to \tilde{q}_L \tilde{q}_L^*$	7	7	82	7	7	82
$u_L \bar{d}_L \to \tilde{u}_L \tilde{d}_L^*$	49	1	46	49	1	46
$u_L \bar{q}_R \to \tilde{u}_L \tilde{q}_R^*$	0	0	36	$\times$	$\times$	$\times$
$g u_L \to \tilde{g}_{(D)} \tilde{u}_L$	14	2	50	14	2	50
$g \bar{u}_L \to \tilde{g}_{(D)}^{(c)} \tilde{u}_L^*$	2	14	50	2	14	50
$g q_R \to \tilde{g}_{(D)}^{(c)} \tilde{q}_R$	0	0	18	0	0	18
$g \bar{q}_R \to \tilde{g}_{(D)} \tilde{q}_R^*$	0	0	18	0	0	18
$g g \to \tilde{g}_{(D)} \tilde{g}_{(D)}^{(c)}$	4	4	34	4	4	34

S.Y.Choi,M.Drees,A. Freitas,P.Zerwas

Other Blended models

Gherghetta,AP
Sundrum,
Redi,Gripaios
Gherghetta,Harling,Setzer

Partly supersymmetric models:



Sparticles: **Higgsino and Stops**

Signal: $gg \to \tilde{t}\,\tilde{t} \to (t\,\tilde{H})\,(t\,\tilde{H})$

Conclusions

- **Supersymetry** and **strong dynamics** could both have an important role at ~TeV

  ➥ favored by (the absence) of present data

- Example presented here:
  MSSM with Susy-broken by a strong sector at the TeV scale

- Important impact in MSSM Higgs physics:
  - Lightest MSSM Higgs can be heavier
  - Different Higgs mass splittings
  - Possibility of a MSSM with only one Higgs doublet
  - EW breaking from the SBS

- Implications on the Sparticles:
  - Dirac Gauginos and Higgsinos (approx. R-symmetry):
    "Marriage" with composite states
  - Squark masses from extra D-terms or
    by (flavor universal) direct coupling to SBS