Electroweak Symmetry Breaking
&
New Physics

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Questions for the LHC

- What is the dynamics of Electroweak Symmetry Breaking ?

- Is Dark Matter made of weakly interacting thermal relics?

- Why 3 families?
- Why is the electron much lighter than the top

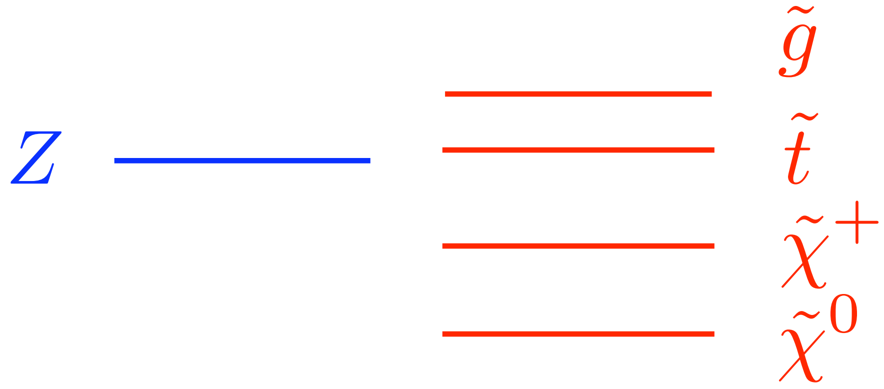
I. Supersymmetry

II. Composite Higgs

Supersymmetric Standard Model

$$V(H) \sim -m^2_{SUSY} H^2 + g^2_W H^4 \qquad m^2_Z \sim g^2_W \langle H \rangle^2 \sim m^2_{SUSY}$$

expect(ed) to find SUSY at LEP



- upper bound on physical Higgs mass

$$m^2_h \leq m^2_Z + m^2_t \frac{3\lambda^2_t}{2\pi^2} \ln m_{\tilde{t}}/m_t$$

$$m_h > 114.4\,\mathrm{GeV} \quad \Rightarrow \quad m_{\tilde{t}} \gtrsim 500 \div 1000\,\mathrm{GeV}$$

Tuning: $\frac{m^2_Z}{m^2_{\tilde{t}}} \sim 1 - 5\,\%$

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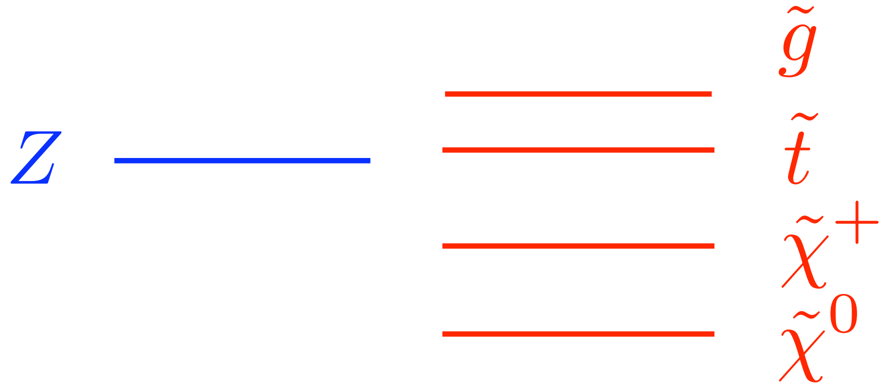

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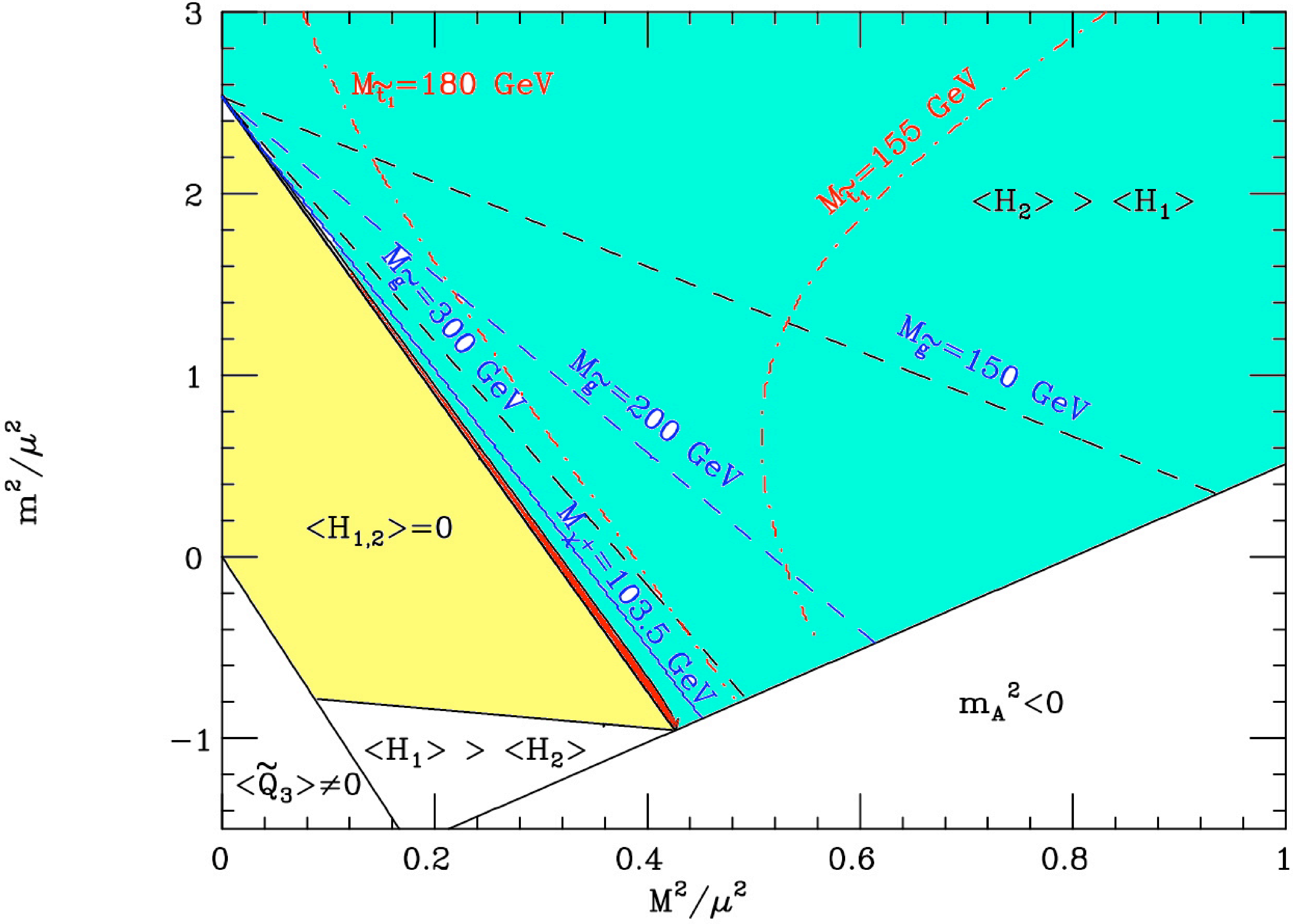
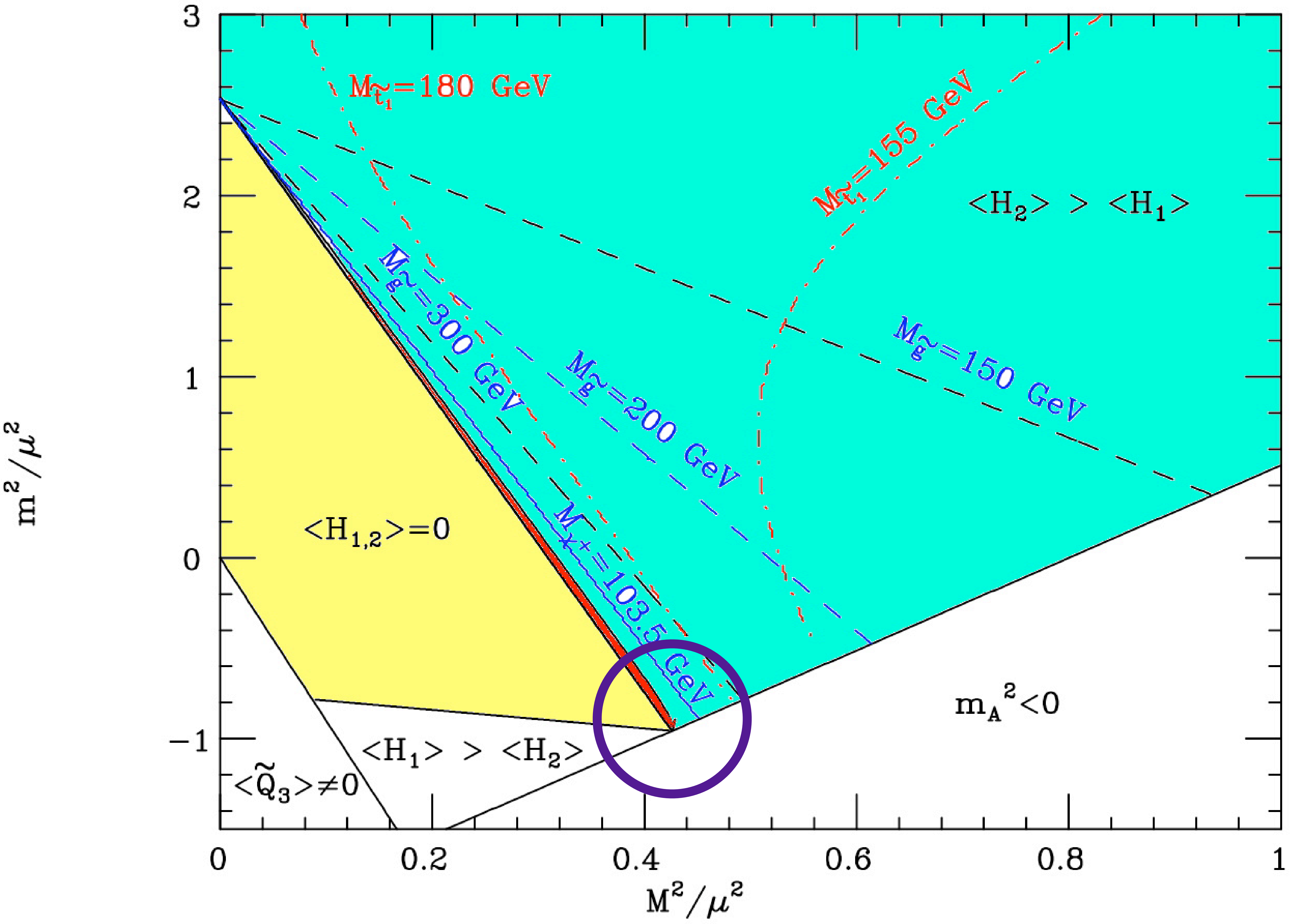


Giudice, Rattazzi ‘06



Giudice, Rattazzi '06

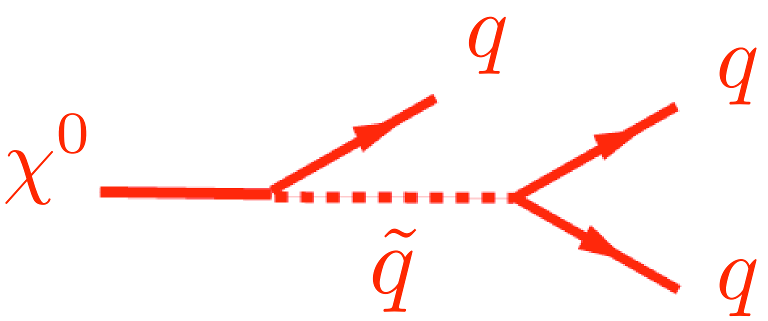
Could a supersymmetric Higgs with mass < 114.4 GeV have escaped detection at LEP by decaying exotically ?

Example N. 1

Carpenter, Kaplan, Rhee '06

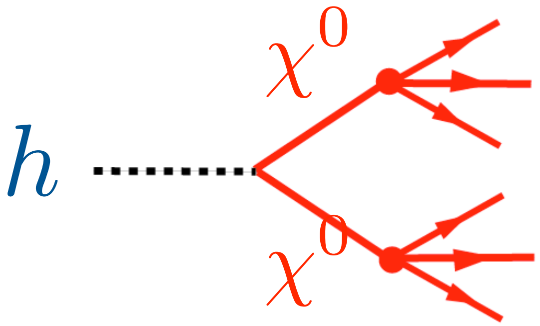
R-parity broken by $\Delta B = 1$ operators $\quad W_{\not R_p} = \lambda''_{ijk}\,\bar{U}^i\bar{D}^j\bar{D}^k$

◆ LSP not stable



$\chi^0 \rightarrow 3\,\text{jets}$

◆ If $\quad 2m_{\chi^0} < m_h$



$h \rightarrow 6\,\text{jets}$
can easily dominate

- no dedicated $h \rightarrow 6\,\text{jets}$ analysis at LEP
- all inclusive analysis $e^+e^- \rightarrow hZ$ $\quad m_h > 82\,\text{GeV}$ $\quad$ OPAL

  ↳ anything

- By estimating the efficiency with which $h \to 6\,\text{jets}$ is picked by existing analyses, one can derive a bound $m_h \gtrsim 90\,\text{GeV}$

- Can relax tuning from 1% to 10%

- SUSY signal at LHC: leptons + lots of jets *Difficult!*

- decay length of $\chi^0 \to 3\,\text{jets}$

$$L_\chi \sim 3\,\mu\text{m}\,\frac{E_\chi}{m_\chi}\left(\frac{10^{-2}}{\lambda''}\right)^2\left(\frac{m_{\tilde{q}}}{100\,\text{GeV}}\right)^2\left(\frac{30\,\text{GeV}}{m_\chi}\right)^2$$

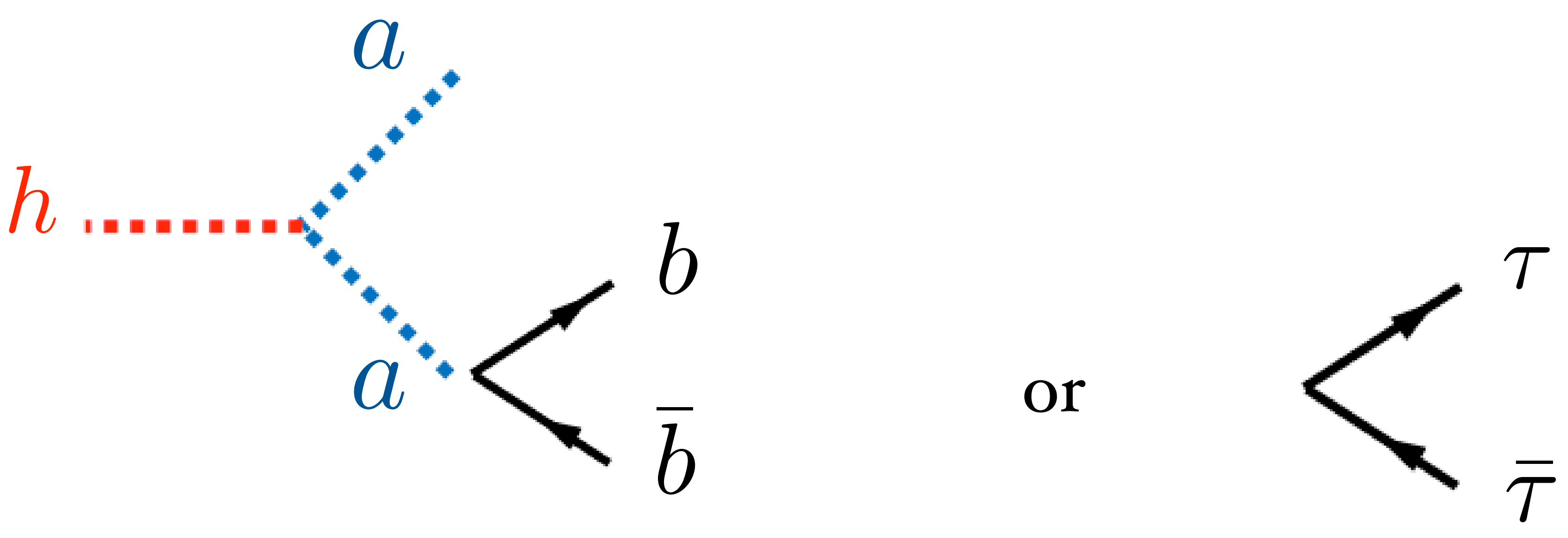
over a significant range $10^{-5} \lesssim \lambda'' \lesssim 10^{-2}$

can search for SUSY by vertex tagging ⇒ LHCb is well suited

Example N. 2: Higgs cascade decay in NMSSM

Dermísek, Gunion 05

additional complex scalar $S = s + ia$



$h \to 4b$ LHWG-2005-01 $m_h > 110\,\mathrm{GeV}$

$h \to 4\tau$ OPAL-2002 $m_h > 86\,\mathrm{GeV}$

- Extra tuning of parameters is however needed to escape LEP bounds

Schuster,Toro 05

Ex: $h \to 4\tau$ implies additional tuning to have $m_a < 11\,\mathrm{GeV}$

Example N. 3

Barbieri, Hall, Nomura, Rychkov 06

NMSSM at large trilinear:
λSUSY

$\lambda\, S H_1 H_2$

$\lambda \gg g_W$

$$m_Z^2 \sim \frac{g_W^2}{\lambda^2}\, m_{SUSY}^2$$

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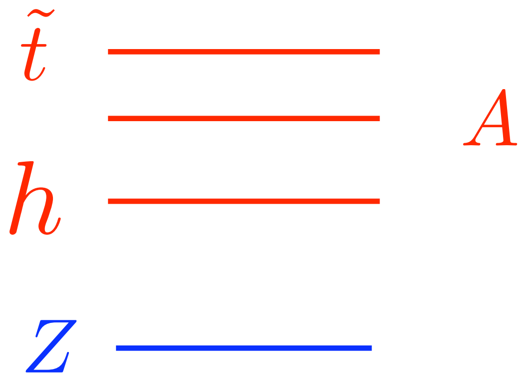

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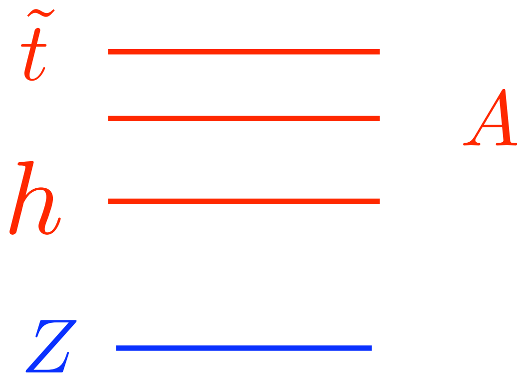
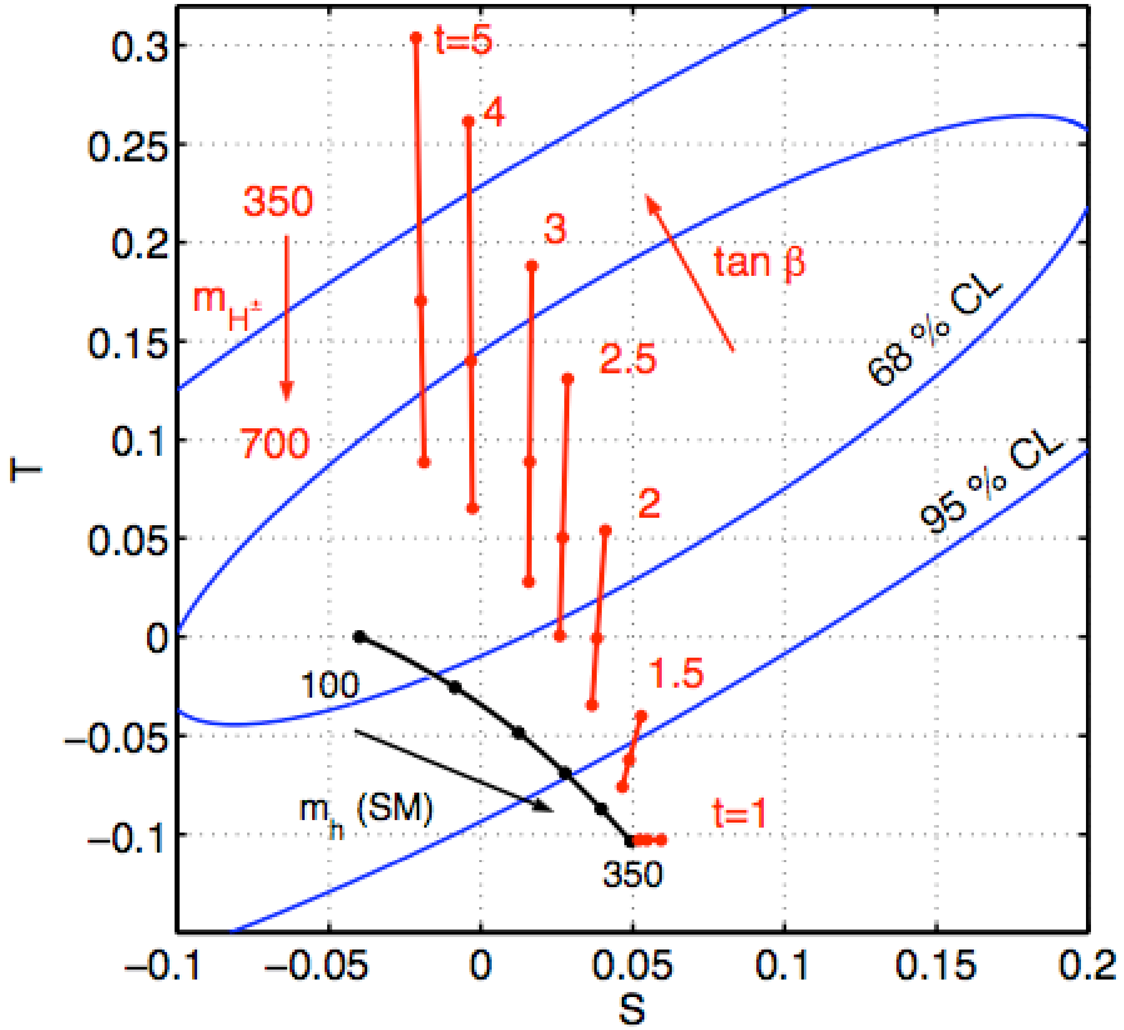


$m_h \sim 300\,\mathrm{GeV}$
can be compatible with
electroweak precision tests
thanks to compensating loop effects
(due to large splittings within Higgs
and Higgsino doublets)



- Natural mass range

$$200\,\mathrm{GeV} < m_{\mathrm{Higgses}} < 700\,\mathrm{GeV}$$

$$500\,\mathrm{GeV} < m_{\mathrm{sparticles}} < 2\,\mathrm{TeV}$$

- Higgs spectrum in λSUSY $m_h < m_{H^+} < m_H < m_A$

while in MSSM $m_h < m_A < m_{H^+}, m_H$

- Theoretical ***price*** of λSUSY: λ becomes strong just above 10 TeV
  - must complete theory above this scale
  - what about gauge unification?
  - is the Higgs composite above 10 TeV?

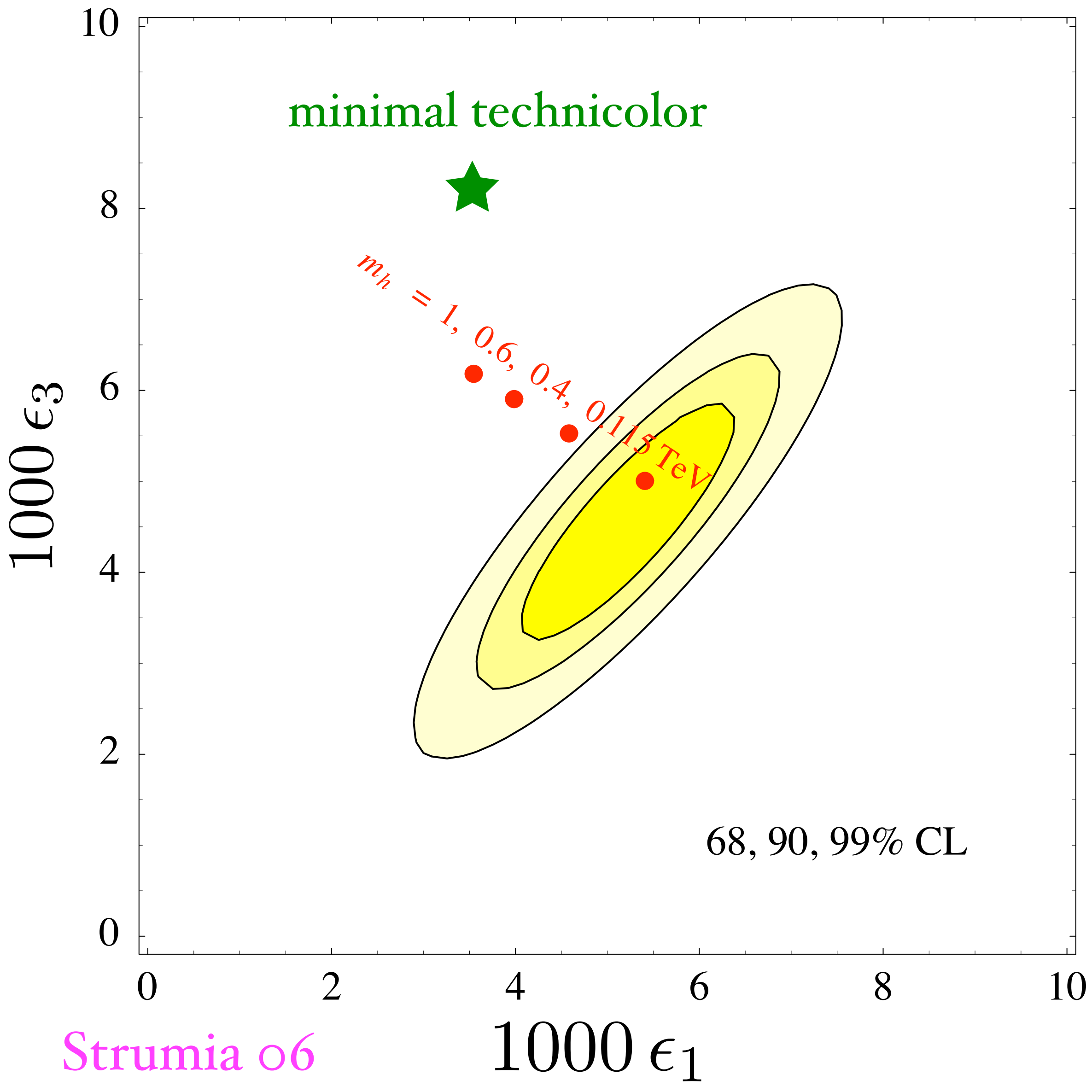
I. Supersymmetry

II. Composite Higgs

Technicolor: simplest possibility

Weinberg, Susskind ‘79

but most dramatic in that there is not even a narrow Higgs resonance



Strumia 06

$$\Delta\epsilon_3 \equiv \widehat{S} = \widehat{S}_{UV} + \frac{g^2}{96\pi^2}\ln(m_h/m_Z)$$

$$\widehat{S}_{UV} \sim \frac{g^2}{96\pi^2} N_{TF} N_{TC}$$

Peskin, Takeuchi ‘89

Minimal TC has no parameter to play with in order to reduce $\widehat{S}$

★ **Next to minimal TC**: light Higgs exists as a 4th pseudo-Goldstone boson

Georgi, Kaplan '84
Banks '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

Electroweak Precision tests are helped in two ways

- light Higgs screens IR contribution to $\widehat{S}, \widehat{T}$
- $\widehat{S}_{UV} \simeq \frac{g^2 N}{96\pi^2} \times \frac{v^2}{f^2}$

$$\begin{cases} \langle H \rangle \equiv v \\ f = \text{pseudo-Goldstone decay const.} \end{cases}$$

$\frac{v^2}{f^2}$ depends on extra parameters → can in principle be tuned to be a little bit smaller than 1

Compositeness scale $4\pi f$ could still be as low as a few TeV

Structure of the Models

Strong sector
H = Goldstone doublet
Ex. : $H = SO(5)/SO(4)$

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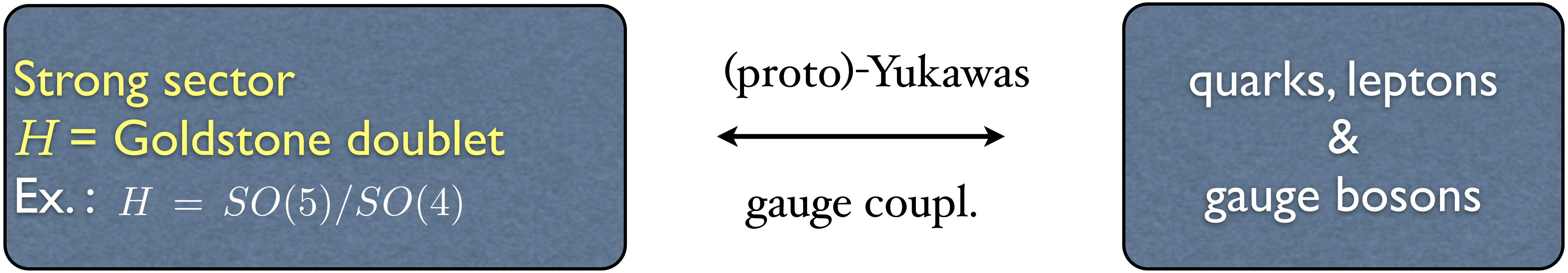

Strong sector
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Ex. : $H = SO(5)/SO(4)$

(proto)-Yukawas
$\longleftrightarrow$
gauge coupl.

quarks, leptons
&
gauge bosons

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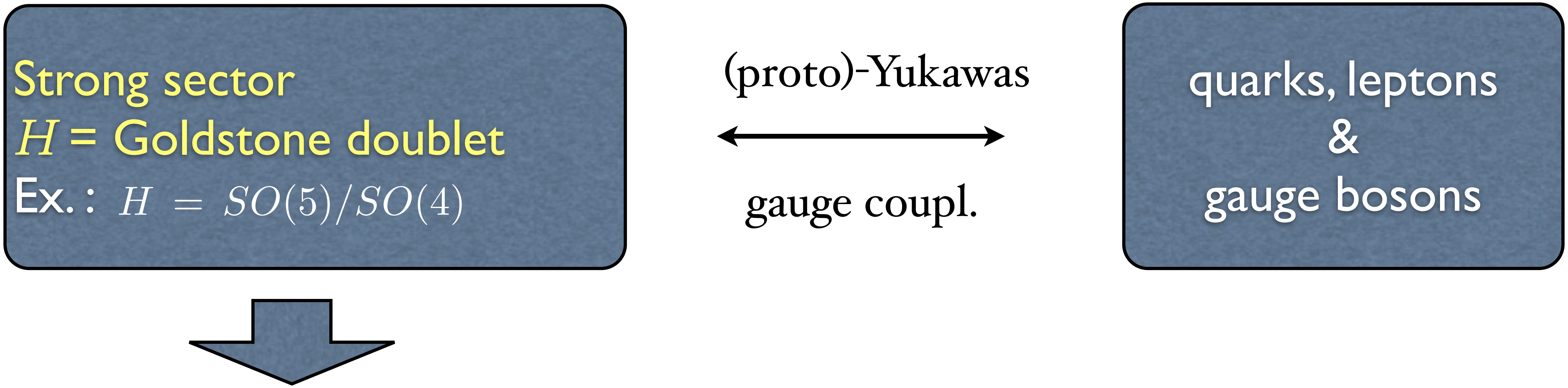

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m_ρ	mass of resonances
g_ρ	coupling of resonances

$$f = \frac{m_\rho}{g_\rho}$$

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↔
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Examples

- Technicolor type $g_\rho \sim \frac{4\pi}{\sqrt{N_{TC}}}$
- 5D models $m_\rho \sim m_{KK}$ $g_\rho \sim g_{KK}$
- Little Higgs $(m_\rho,\ g_\rho)$ mass and coupling of 'regulators'

Collider Signals of Composite Higgs

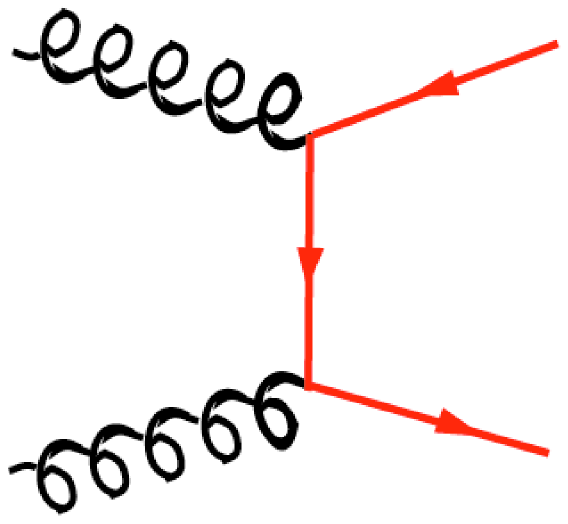
I) Direct: production of resonances,
in particular colored fermions associated to the top quark

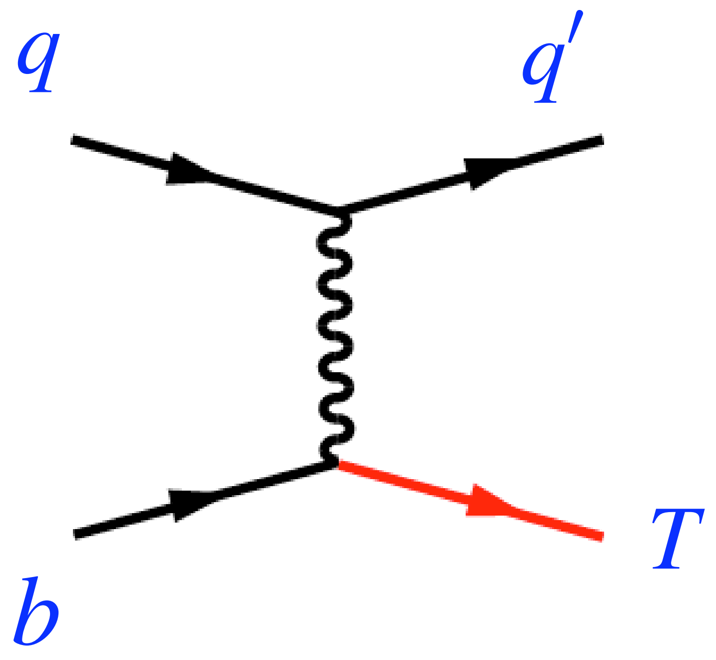
talk di Contino

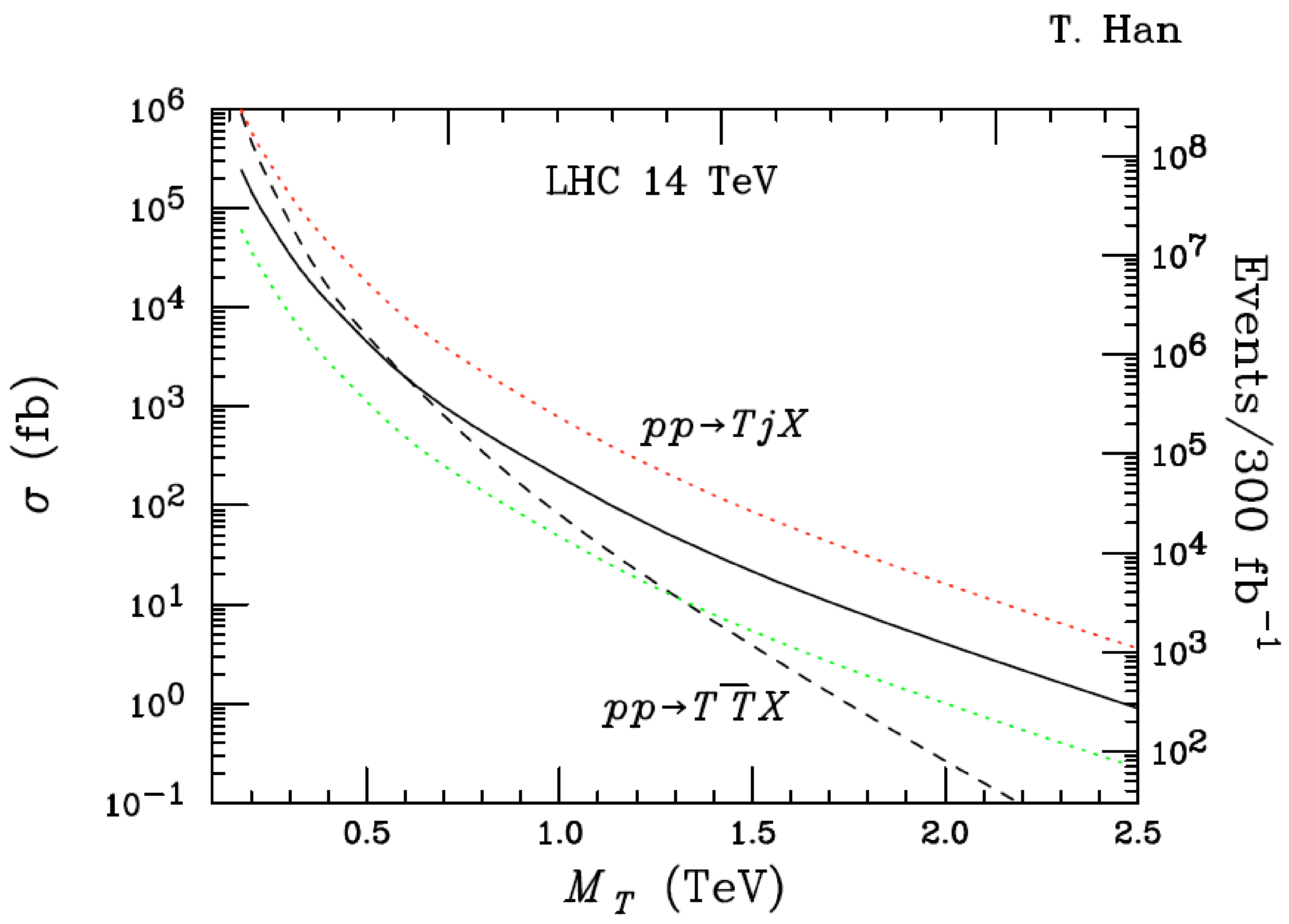
II) Indirect: deviations from the Standard Model in Higgs production
rates and branching ratios

Production of top partner(s): $T_{(Q=\frac{2}{3})} + \ldots$

Perelstein, Peskin, Pierce '04
Han, Logan, Wang '05





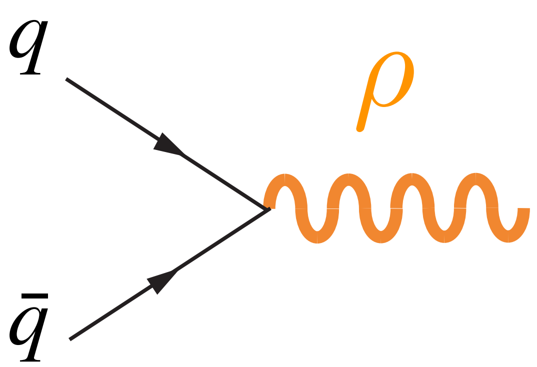


cleanest mass peak: $T \longrightarrow Zt \longrightarrow \ell^+\ell^- b\ell \not{E}_T$

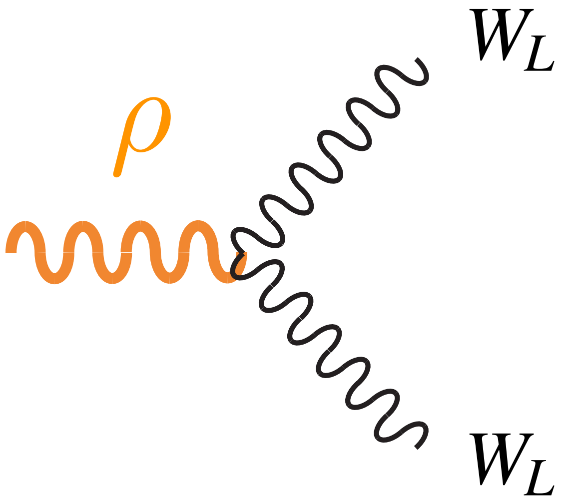
Naturalness suggests these states should be detected at LHC

Drell-Yan production of vector resonances

$$\Delta\epsilon_3 \sim 10^{-3}\,(\frac{2.5\,\mathrm{TeV}}{m_\rho})^2$$



$$= \frac{g^2}{g_\rho}$$



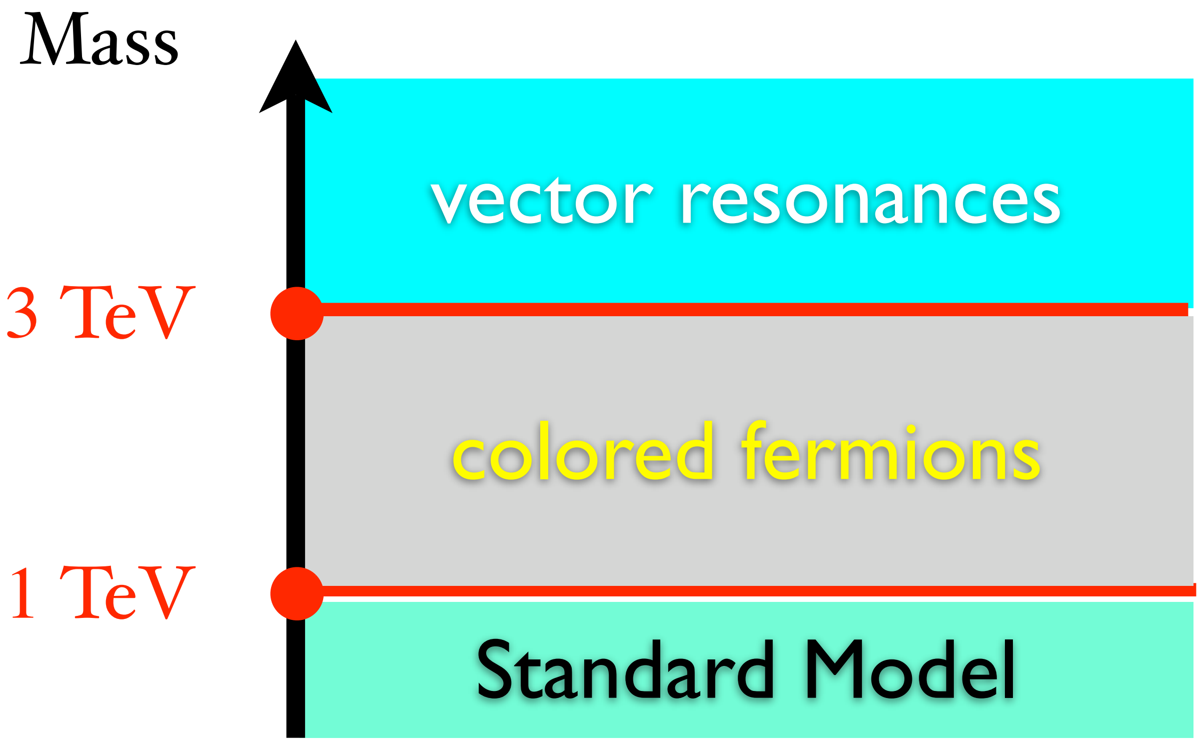
$$= g_\rho$$

$$\sigma\left(pp \to \rho_H^\pm + X\right) = \left(\frac{4\pi}{g_\rho}\right)^2 \left(\frac{3\ \mathrm{TeV}}{m_\rho}\right)^6\ 0.5\ \mathrm{fb}$$

resonances are increasingly harder to detect as $g_\rho \longrightarrow 4\pi$

- broad & heavy
- couple weakly to SM fermions

If



Mass

vector resonances

3 TeV

colored fermions

1 TeV

Standard Model

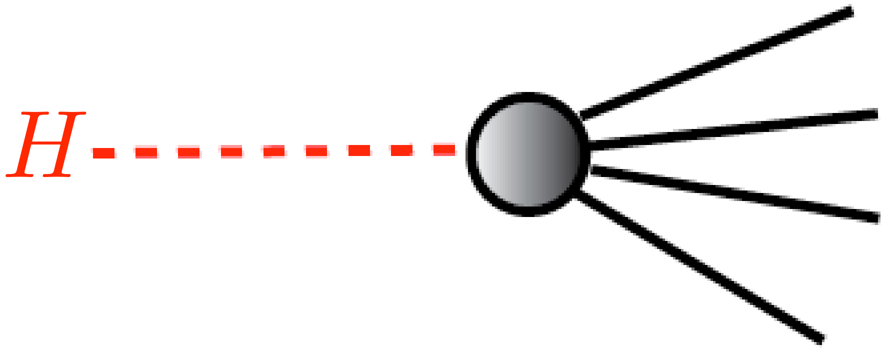
A ‘precision’ study of Higgs properties would in principle help understanding the origin of the weak scale

Effective Lagrangian

Principles & Rules to build the effective Lagrangian

Giudice, Grojean, Pomarol, Rattazzi 07

- Custodial & Goldstone symmetry
- Minimal Flavor Violation: no-mixing other than CKM
- each extra H leg costs $\frac{g_\rho}{m_\rho}$



- each extra ∂_μ costs $\frac{1}{m_\rho}$

$$\partial_\mu \to \partial_\mu + iA_\mu$$

$$\frac{\partial^2}{m_\rho^2} \to \frac{F_{\mu\nu}}{m_\rho^2}$$

- Operators testing the ***strong*** self coupling of the Higgs $\frac{1}{f} \equiv \frac{g_\rho}{m_\rho}$

$$\mathcal{L}_{NC} = \frac{c_H}{2f^2} \partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) - \frac{c_6 \lambda}{f^2} \left(H^\dagger H\right)^3 + \left(\frac{c_y y}{f^2} H^\dagger H \, \bar{\psi}_L H \psi_R + \text{h.c.} \right)$$

$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{v^2}{f^2}$$

- ‘Form Factors’: sensitive to the scale m_ρ

$$\mathcal{L}_{FF} = \frac{i c_W}{2 m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) \left(D^\nu W_{\mu\nu} \right)^i + \frac{i c_B}{2 m_\rho^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(\partial^\nu B_{\mu\nu} \right)$$
$$+ \frac{c_\gamma g^2}{16 \pi^2 m_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g y_t^2}{16 \pi^2 m_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{E^2}{m_\rho^2}$$

‘Special Form Factors’

$$\frac{ic_{HW}}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB}}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

in principle they test
the strong dynamics

$$\frac{\delta\Gamma(h \to \gamma Z)}{\Gamma(h \to \gamma Z)_{SM}} \sim (c_{HW} - c_{HB})\frac{v^2}{f^2}$$

however this process is hard to measure and the well measured observables are affected as

$$\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{E^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}$$

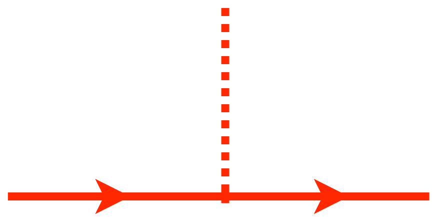
Effects in Higgs production & decay

$$c_H \longrightarrow \mathcal{L}_{kin} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) \partial_\mu h \partial^\mu h$$

all couplings rescaled by

$$\frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \simeq 1 - c_H \frac{v^2}{2f^2}$$

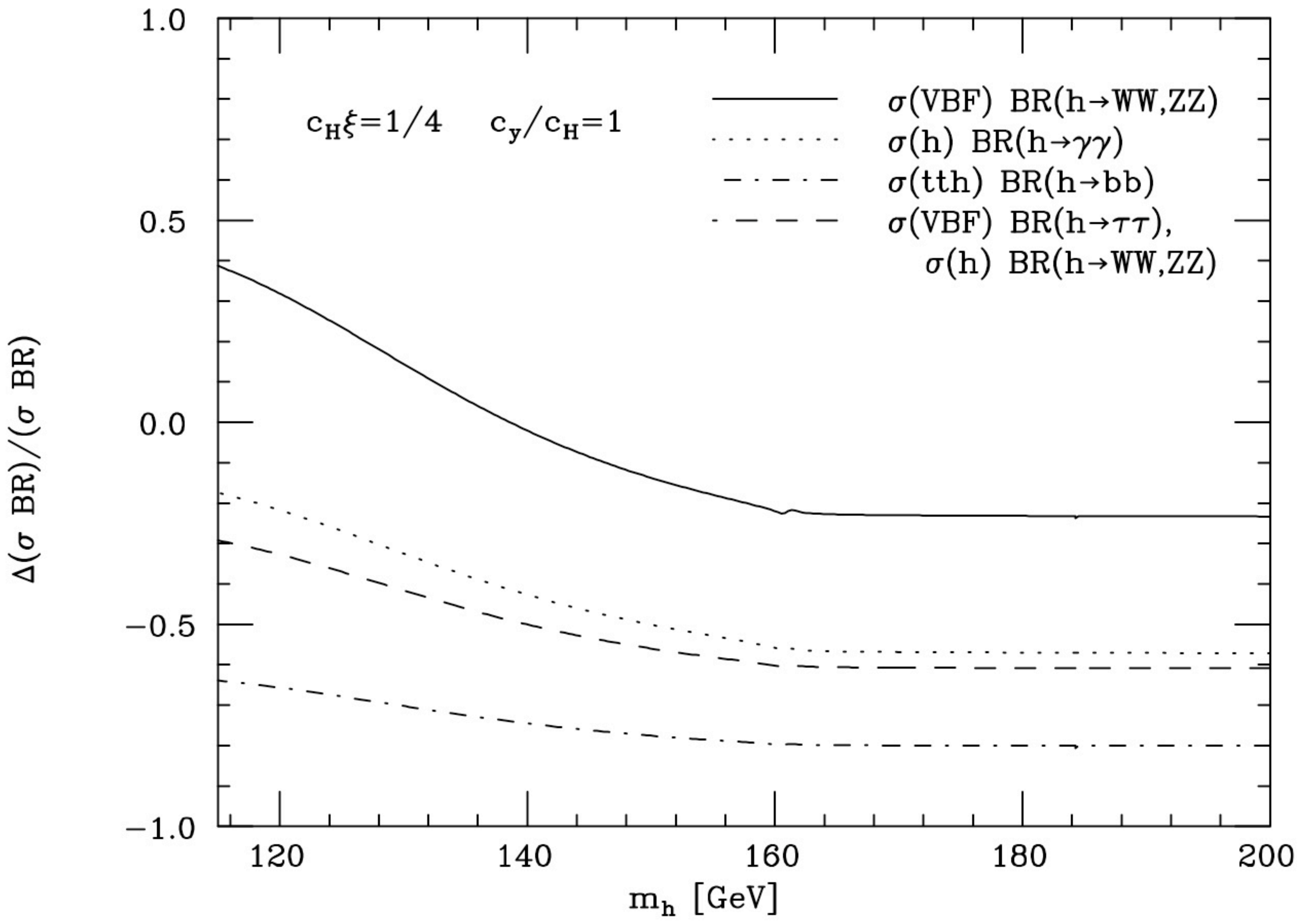
$$c_y \longrightarrow$$



$$\frac{m_\psi}{v}\left(1 - c_y \frac{v^2}{f^2}\right)$$

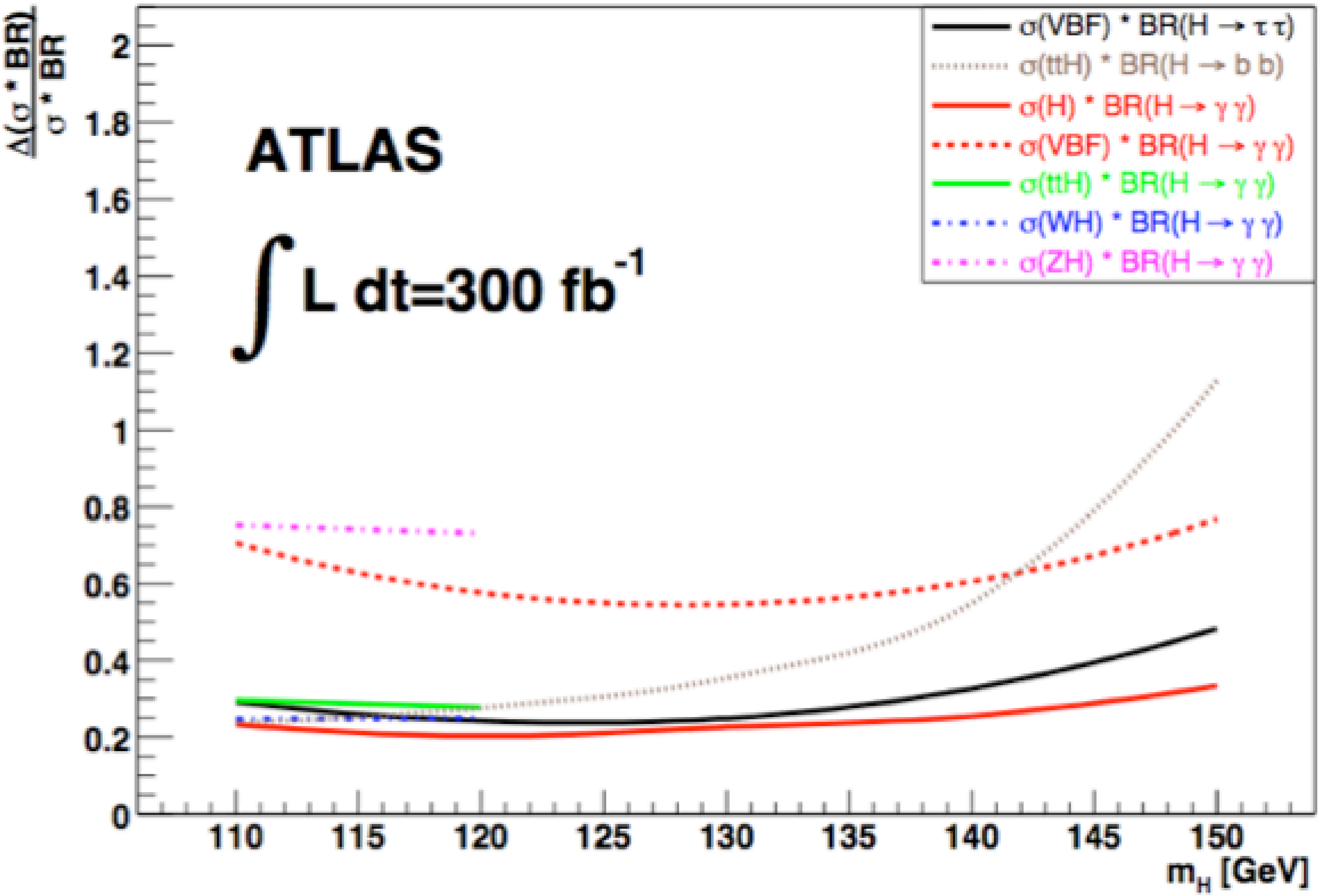
$$\frac{\Delta\left(\sigma(\text{prod}) \times \text{Br}\right)}{\left(\sigma(\text{prod}) \times \text{Br}\right)_{SM}}$$

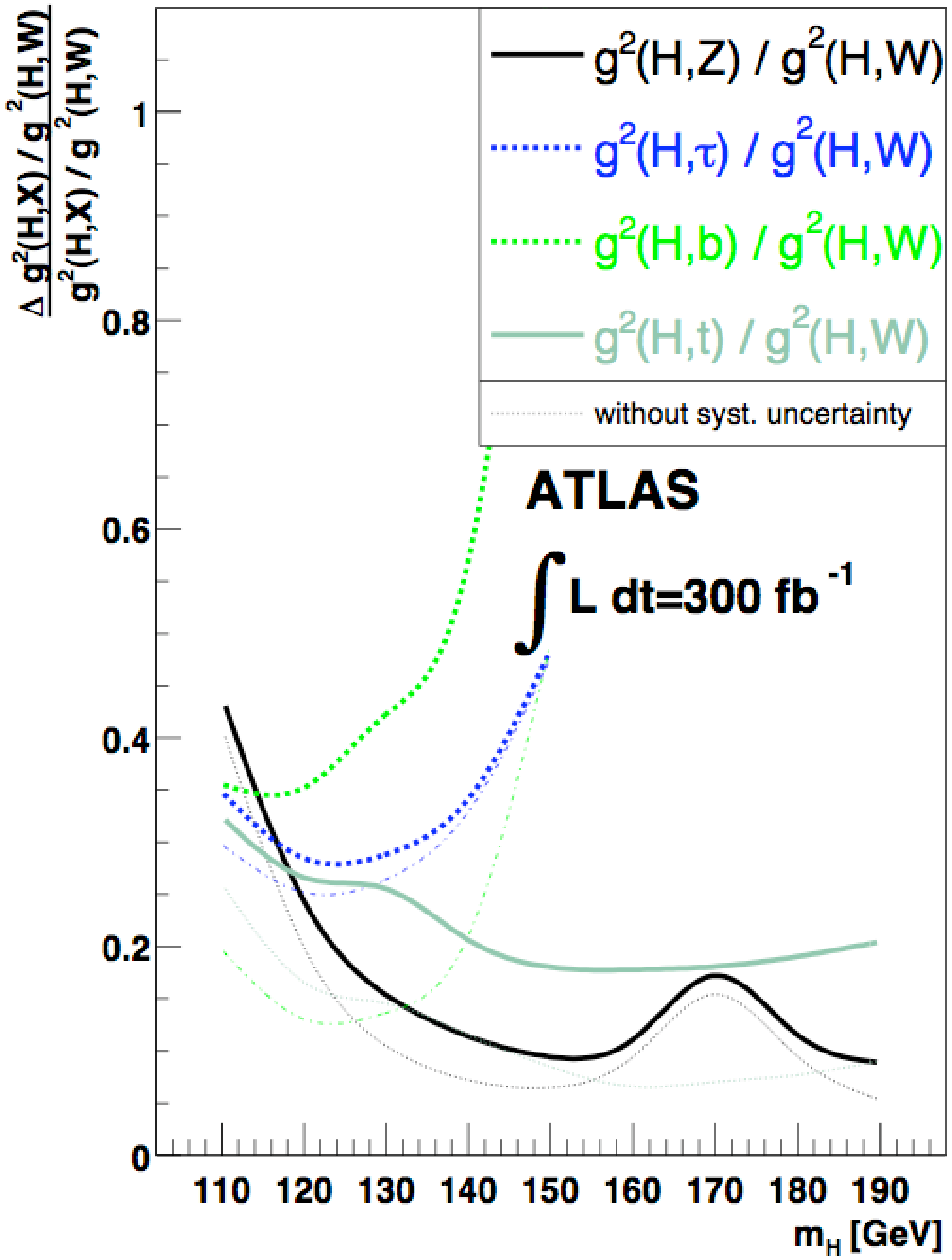
$$= \# c_H \frac{v^2}{f^2} + \# c_y \frac{v^2}{f^2}$$



- at LHC can measure $c_y \frac{v^2}{f^2}, \; c_H \frac{v^2}{f^2}$ up to 20-40 %

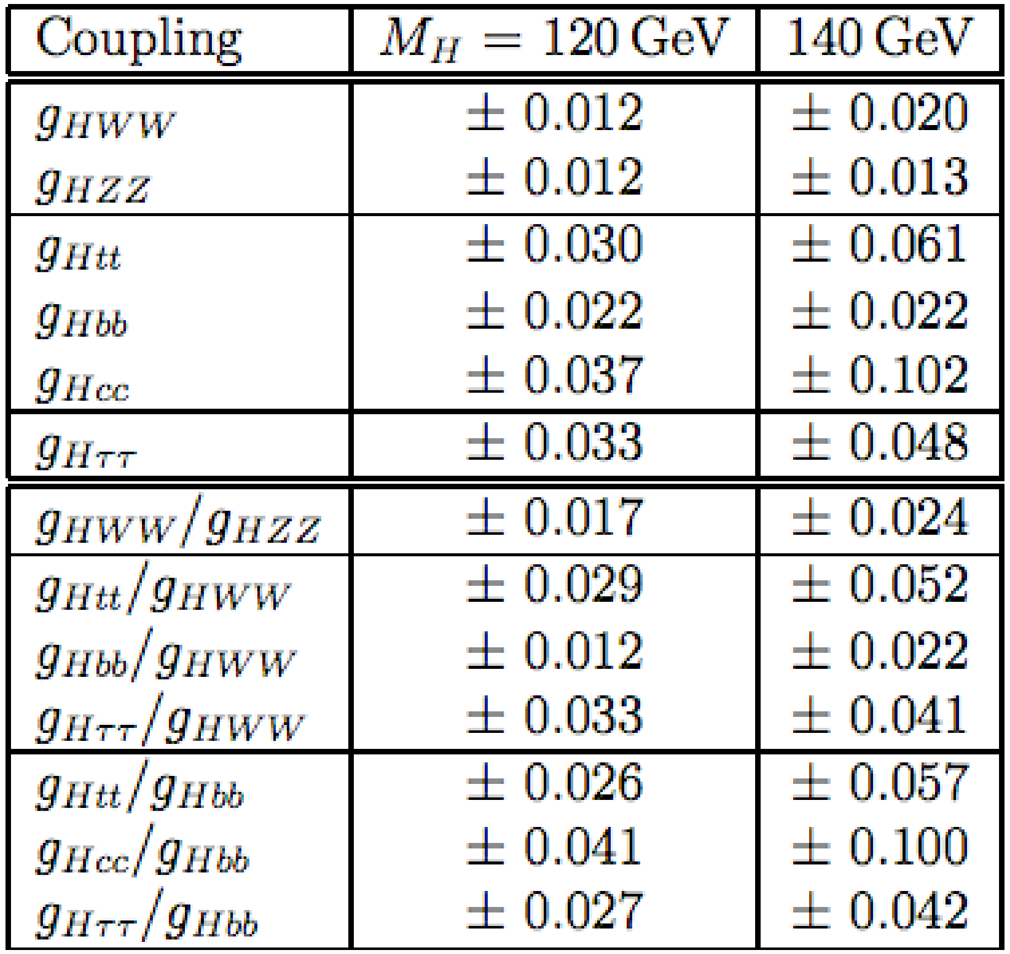
Duhrssen 03





- A sizeable deviation from SM in the absence of new light states would be indirect evidence for the composite nature of the Higgs

- At ILC one would test $\frac{v^2}{f^2}$ at % level



Coupling	$M_H = 120$ GeV	140 GeV
g_{HWW}	$\pm\,0.012$	$\pm\,0.020$
g_{HZZ}	$\pm\,0.012$	$\pm\,0.013$
g_{Htt}	$\pm\,0.030$	$\pm\,0.061$
g_{Hbb}	$\pm\,0.022$	$\pm\,0.022$
g_{Hcc}	$\pm\,0.037$	$\pm\,0.102$
$g_{H\tau\tau}$	$\pm\,0.033$	$\pm\,0.048$
g_{HWW}/g_{HZZ}	$\pm\,0.017$	$\pm\,0.024$
g_{Htt}/g_{HWW}	$\pm\,0.029$	$\pm\,0.052$
g_{Hbb}/g_{HWW}	$\pm\,0.012$	$\pm\,0.022$
$g_{H\tau\tau}/g_{HWW}$	$\pm\,0.033$	$\pm\,0.041$
g_{Htt}/g_{Hbb}	$\pm\,0.026$	$\pm\,0.057$
g_{Hcc}/g_{Hbb}	$\pm\,0.041$	$\pm\,0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\,0.027$	$\pm\,0.042$

Barger, Han,Langacker,
McElrath,Zerwas 03

J.A. Aguilar Saavedra et al.
[ECFA/DESY LC Physics WG]

ILC can rule out Higgs compositeness scale $4\pi f$ below 30 TeV

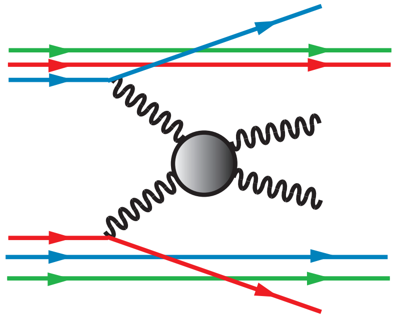
Genuine signal of Higgs compositeness

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)$$

equivalence theorem

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H\, s}{f^2}$$

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H(s+t)}{f^2}$$



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not{H}}$$

leptonic and semileptonic
vector decay channels
with 300 fb^{-1}

$\xrightarrow{\text{sensitivity}}$

$$c_H \frac{v^2}{f^2} = 0.5 - 0.7$$

Bagger et al., ‘95
Butterworth et al., ‘02

$O(4)$ symmetry: Higgs is approximately a 4th (uneaten) Goldstone

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}$$

$$\Big\Downarrow$$

sum rule

$$2\sigma_{\Delta\eta}\left(pp \to hhX\right)_{c_H} = \sigma_{\Delta\eta}\left(pp \to W_L^+ W_L^- X\right)_{c_H} + \frac{1}{6}\left(9 - \tanh^2\frac{\Delta\eta}{2}\right)\sigma_{\Delta\eta}\left(pp \to Z_L^0 Z_L^0 X\right)_{c_H}$$

$$= O(\text{fb}) \times \left(c_H \frac{v^2}{f^2}\right)^2 \qquad \text{for} \qquad m_{hh} > 1\,\text{TeV}$$

◆ $hh \to bbbb$ tough QCD background, but worth a try

- high p_T of b jets
- signal rather clean from minijets
- can use forward jet tag
- can use jet structure

Butterworth, Cox, Forshaw 02

Baur, Plehn, Rainwater 03
Pierce, Thaler, Wang 06

◆ $hh \to 4W \to \ell^\pm \ell^\pm \nu\nu jets$ more promising

Summary

- 30 years of speculations on the origin of the weak scale are coming to an end

- The *sentiment* never seemed more uncertain
  - supersymmetry ?
  - strong dynamics ?
  - just SM Higgs ?

- Important to learn to profit as much as possible of the LHC rain of data
  - studying the specific signatures of many classes of models is one way to train ourselves
  - but model independent approaches should be attempted whenever possible and meaningful

☑ Example: effective Lagrangian description of composite light Higgs

3 leading operators

$$\frac{c_H}{2f^2}\left[\partial_\mu\left(H^\dagger H\right)\right]^2 \qquad \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 \qquad \frac{c_y y_{ij}}{f^2} H^\dagger H\,\bar{\psi}_L^i H \psi_R^j$$

Most analyses focus instead on $H^\dagger H\, F_{\mu\nu}F^{\mu\nu}$ Manohar, Wise 06

- Single Higgs production with 300 fb-1 → $\frac{v^2}{f^2} \lesssim 0.2$
- $W_L W_L$ scattering emerges as a relevant process to study even in the presence of a light Higgs
- $W_L W_L \rightarrow hh$
- ILC, with 500 fb-1 and $\sqrt{s} = 500\,\mathrm{GeV}$ → $\frac{v^2}{f^2} \lesssim 10^{-2}$

$$4\pi f \gtrsim 30\,\mathrm{TeV}$$