U(1)′ and Higgs in SUSY

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Work in progress, in collaboration with Tao Liu, Haipeng An

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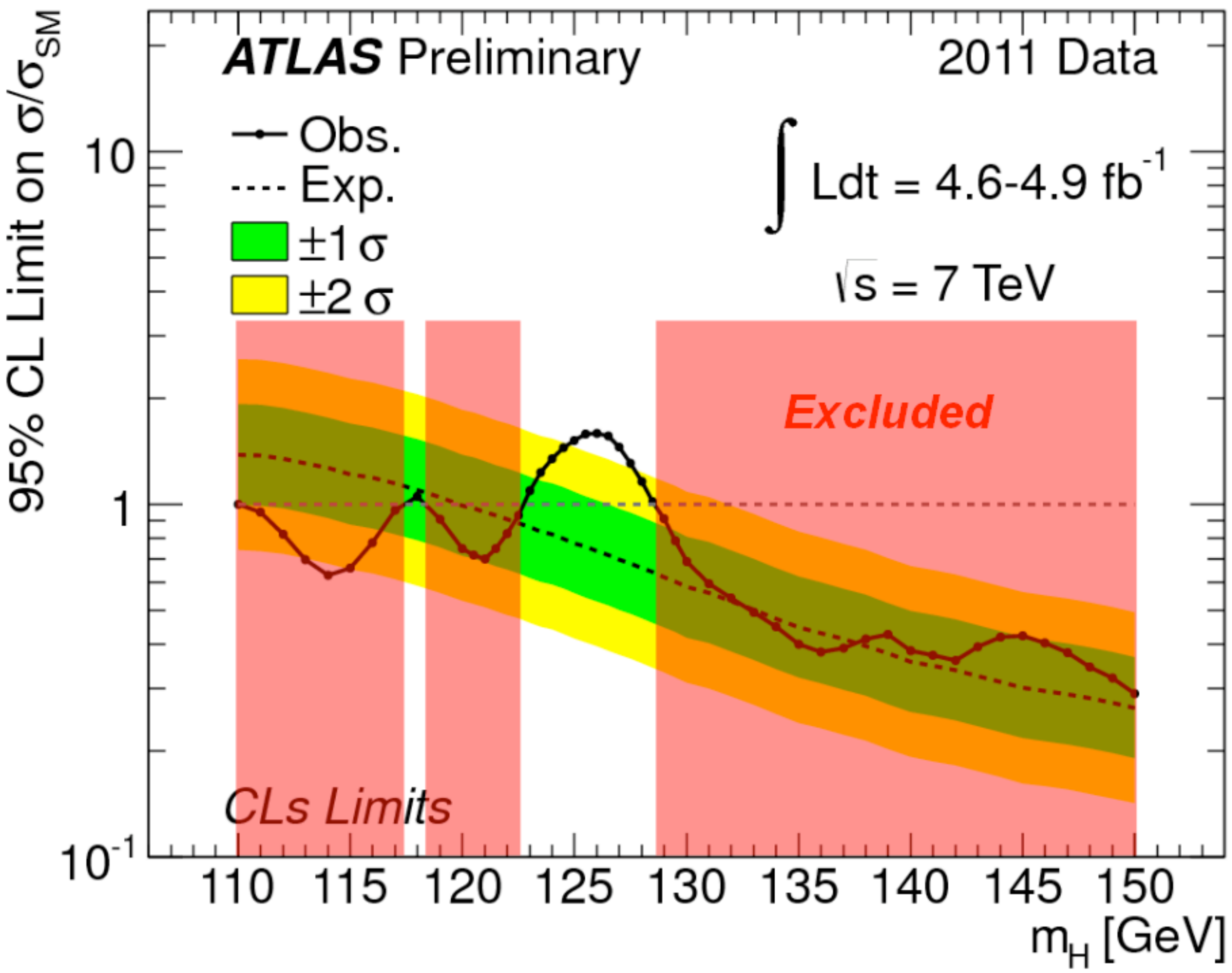
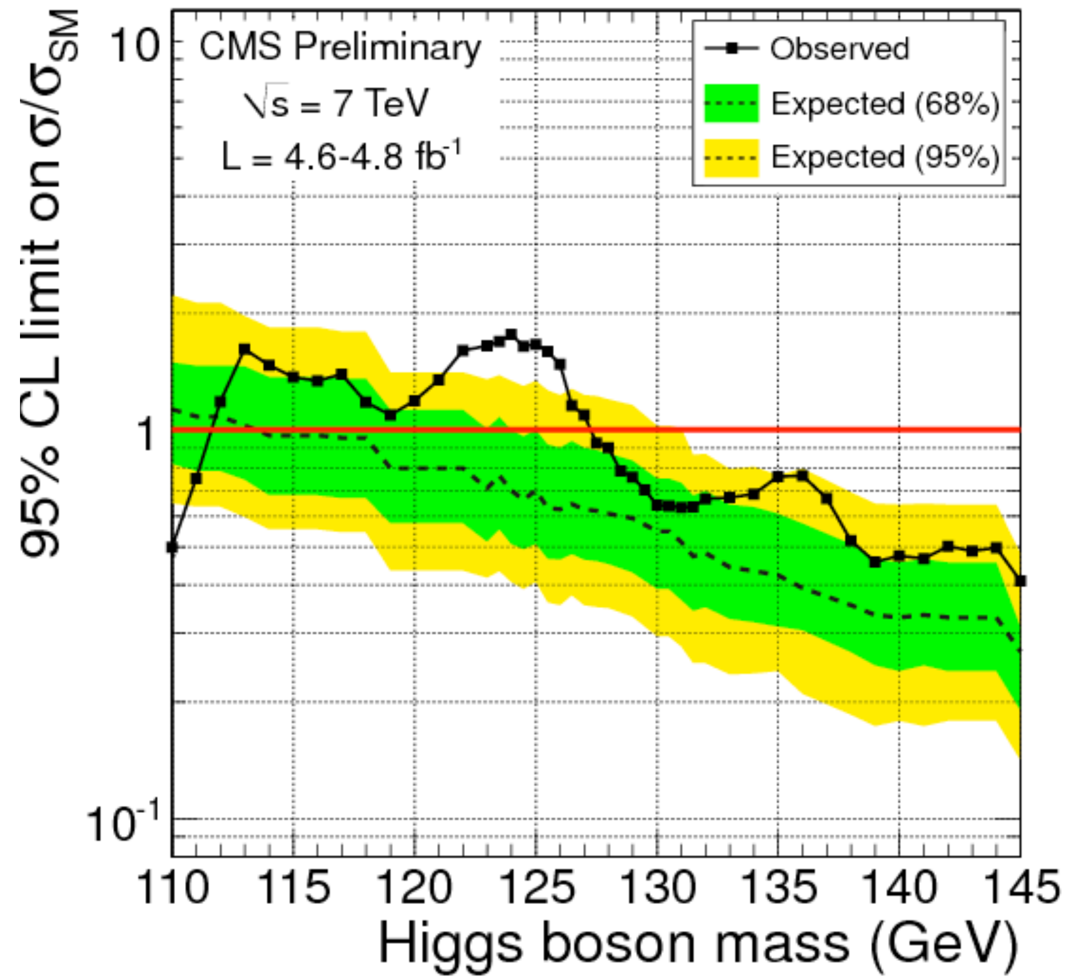
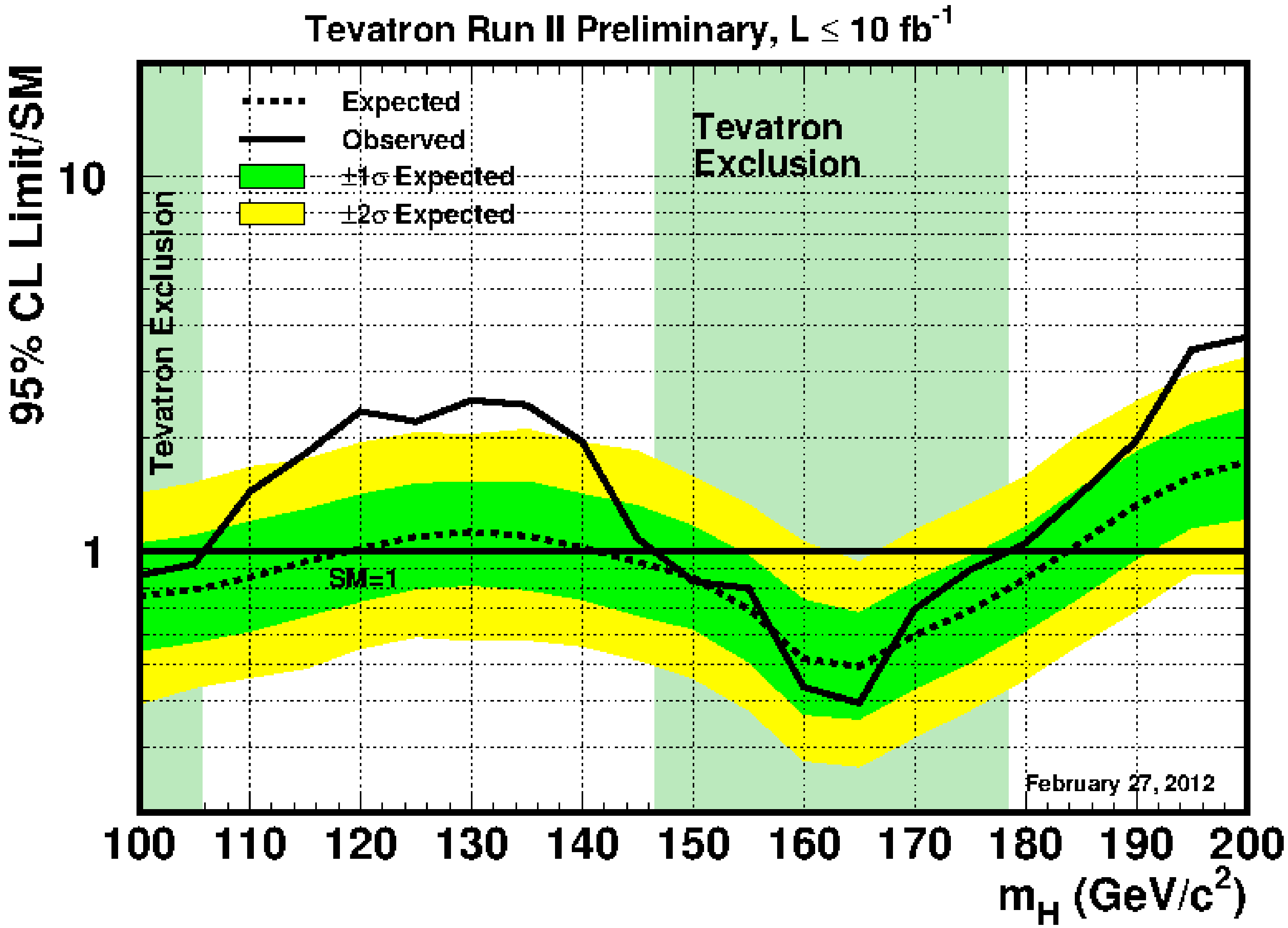
The signal





- A hint of light Higgs signal around 124-126 GeV.

Tevatron



Tevatron Run II Preliminary, L ≤ 10 fb^{-1}
95% CL Limit/SM
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron Exclusion
Tevatron Exclusion
SM=1
February 27, 2012
10
1
100 110 120 130 140 150 160 170 180 190 200
m_H (GeV/c^2)

Why new physics

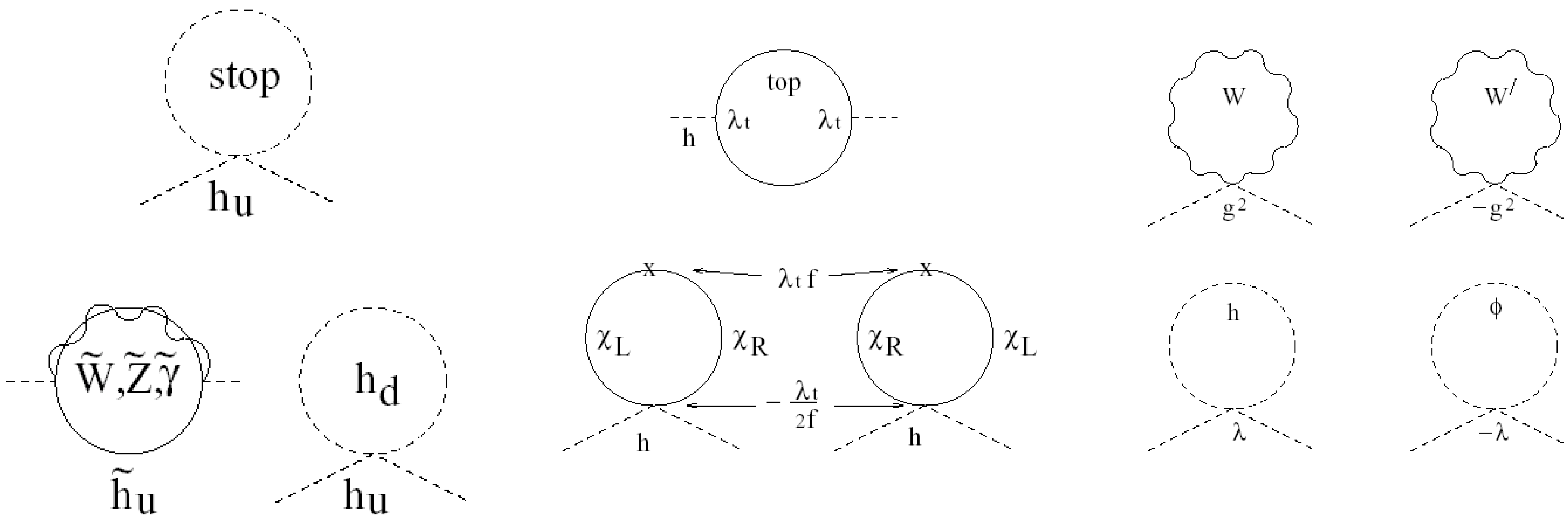
- Naturalness puzzle.
  - Why the electroweak scale, or higgs mass, so much less than other possible fundamental scales, for example, $M_{Pl} = 10^{19}$ GeV.
  - Is such a large scale separation generic in quantum theory? Due to quantum fluctuations,

$$m_h^2 \sim m_{h0}^2 + c\Lambda^2, \quad \Lambda = M_{\mathrm{Pl}}, \ldots$$

  - Large fine-tuning. Something needs to control the quantum fluctuations.
- Well known scenarios: SUSY and compositeness

Why new physics?

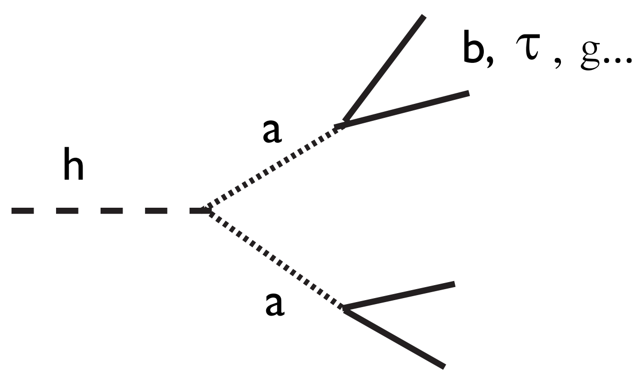
- Naturalness, new physics must couple to the Higgs.
  - Higgs mass is the one to protect.



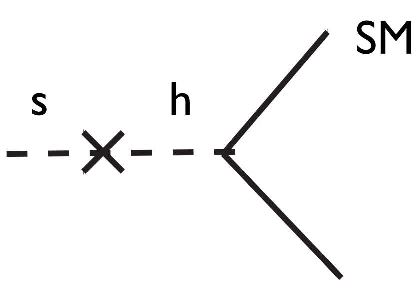
How might NP show up?

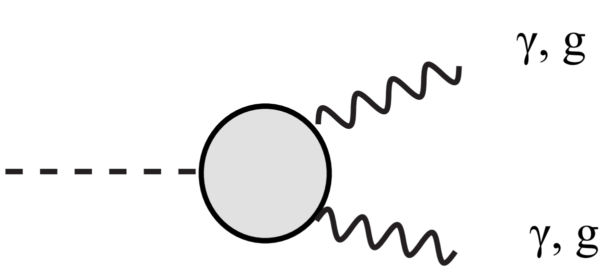
- Being directly produced and detected at the LHC.
  - SUSY: superpartners.
  - Composite Higgs (extra dim): resonances.
- Modification of Higgs production and decay.

hiding Higgs



mixing





Loop of NP

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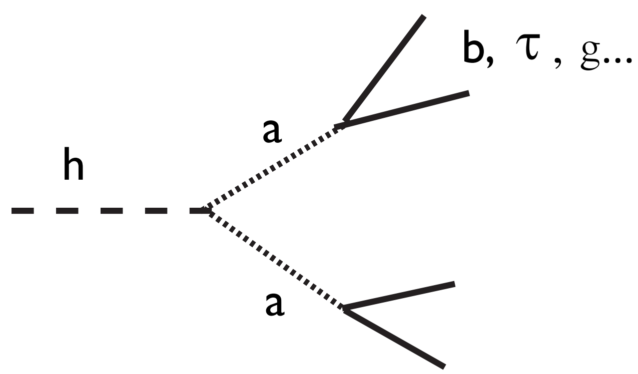

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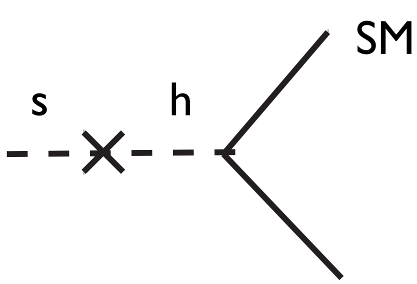
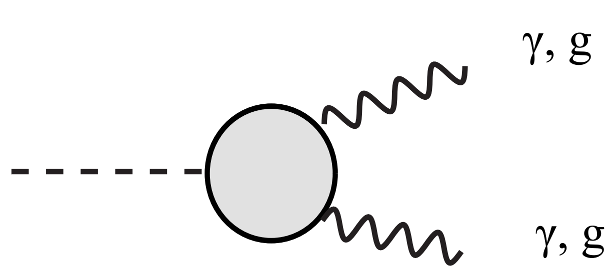
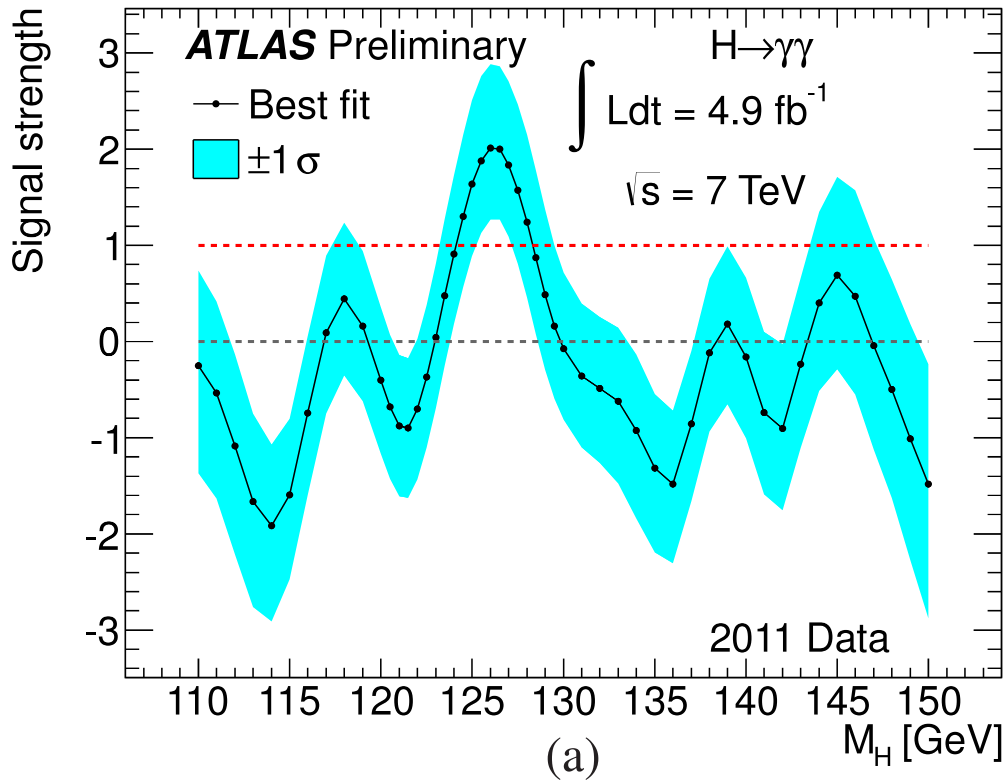




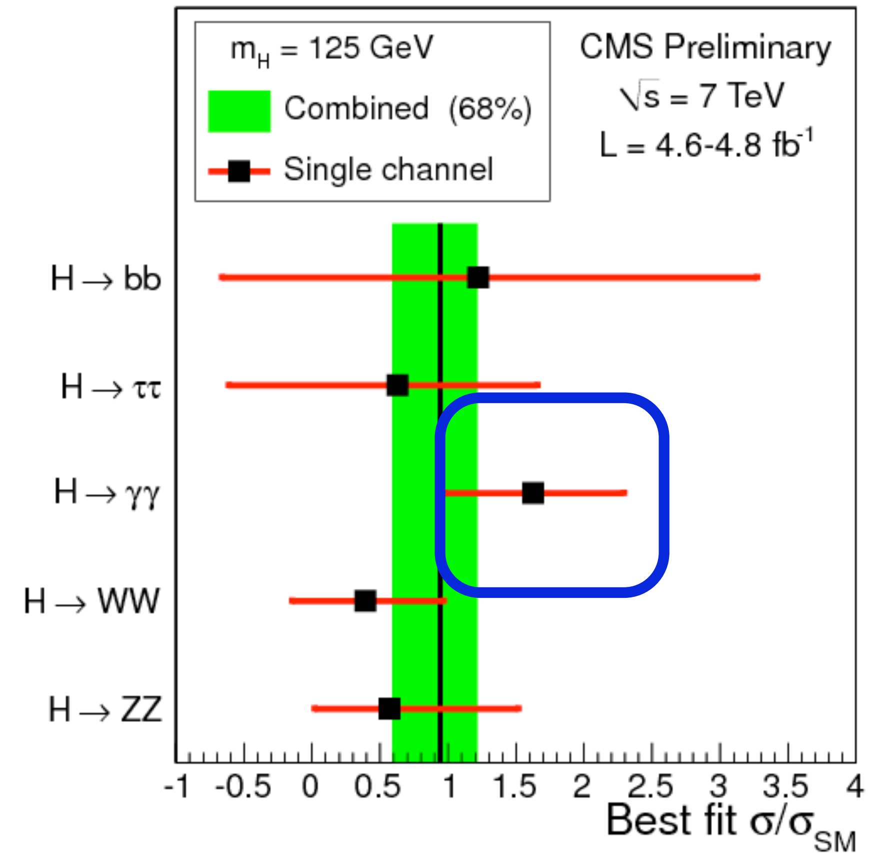
Loop of NP

Any hints?

h→γγ higher than SM prediction?

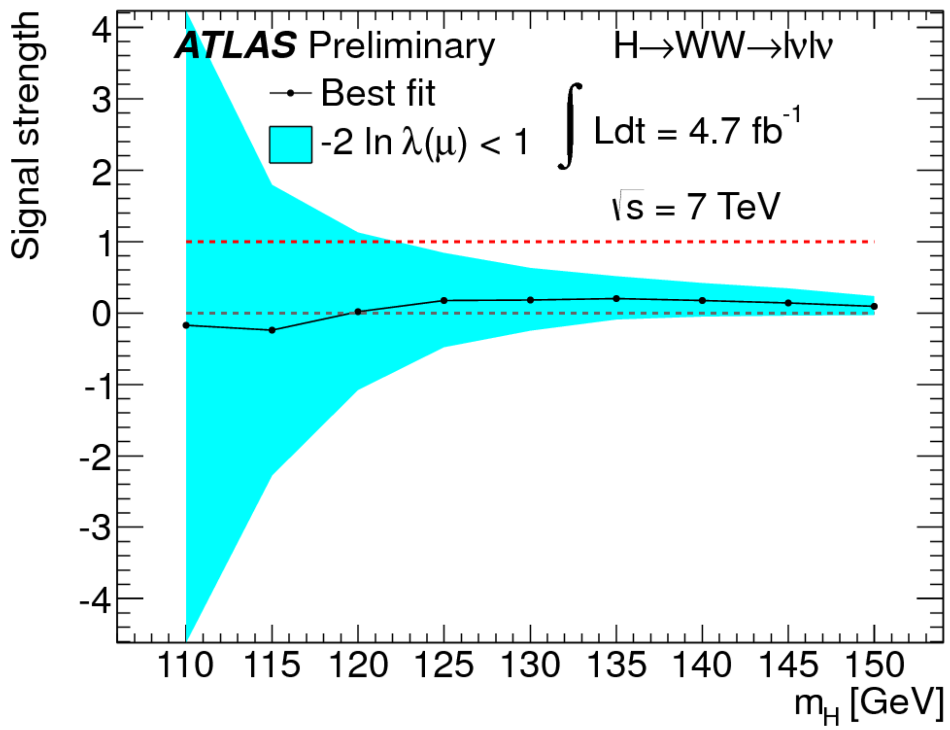


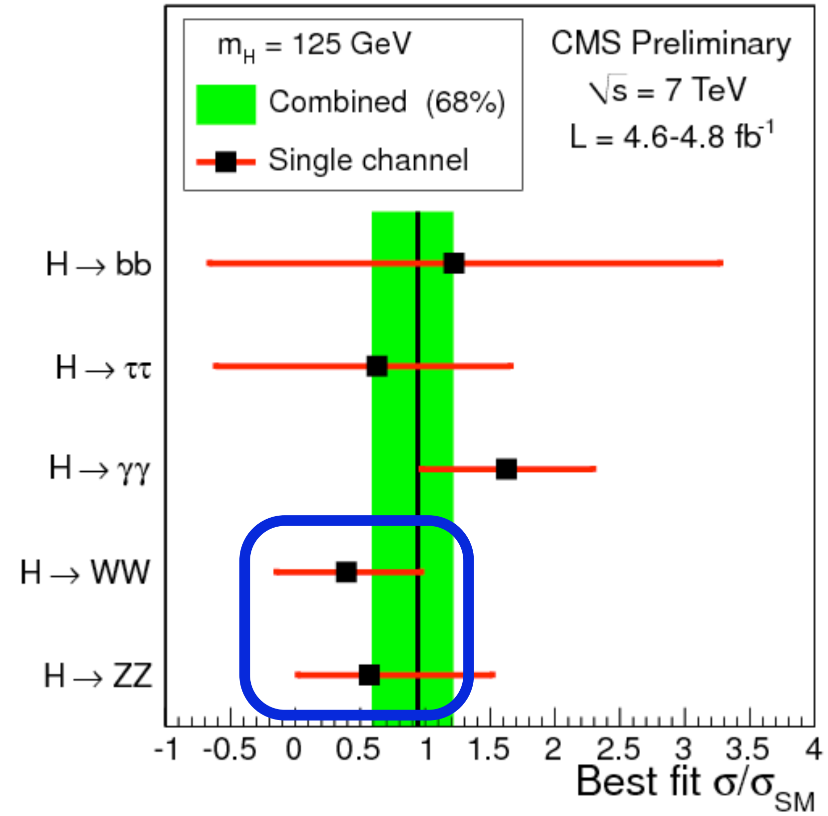
(a)



- Over interpreting, of course.
- But, it is fun to see what it might mean if this is true.

gg→h enhancement?





- Maybe not.
- No excess in WW.

In the framework of a natural theory:

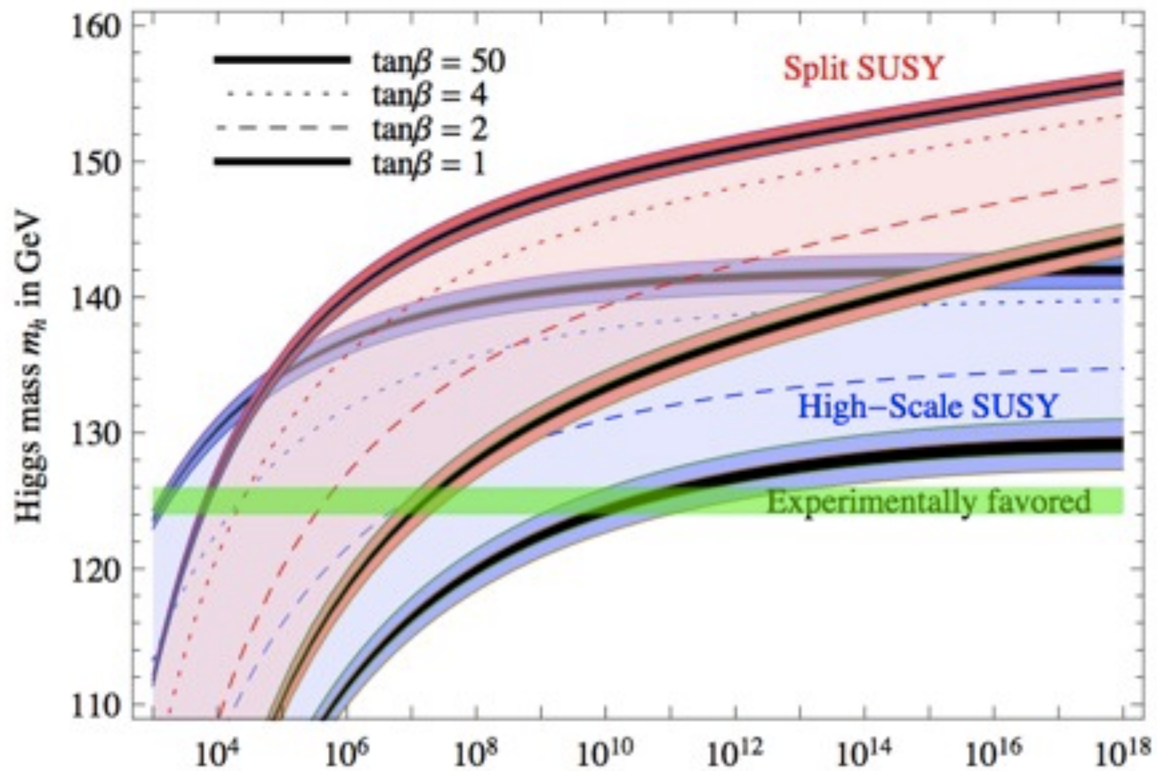
- Implications of m_h = 125 GeV?
- Accommodate significant modifications of Higgs pheno?

Higgs in SUSY.

~ 70 papers so far, > 80% on SUSY

SUSY and m_h = 125 GeV

- Natural. Prefer light Higgs.
  - A bit heavy for MSSM. But certainly possible.



Giudice, Strumia, 2011

  - Is heavy scalar reasonable? Maybe.

Extensions of MSSM

- MSSM
  - Higgs quartic from SM D-term

$$m_h^2 = m_Z^2 \cos^2 2\beta + \text{loop} \qquad \text{loop} \propto \log\left(\frac{M_{\text{SUSY}}}{M_{\text{top}}}\right)$$

  - m_h = 125 GeV needs $M_{SUSY} \gg M_{top}$
- Extensions → new quartic coupling?
  - NMSSM, sister Higgs...

Extended gauge symmetry

- New non-decoupling D-term.
- Simplest possibility, a new U(1)′.
  - SSB near weak scale.
  - Higgs charged under this U(1)′, $q_h \neq 0$.
- A new U(1)′ also implies additional states.
  - New Higgs field for the U(1)′.
  - Could have new exotics from anomaly cancellation.

Batra, Delgado, Kaplan, Tait, hep-ph/0309149
Maloney, Pierce, Wacker, hep-ph/0409127
Zhang, An, Ji, Mohapatra, 0804.0268

Choice of U(1)′

- Many candidates for U(1)′.
- $U(1)_{PQ}$ is interesting.
  - Connection to the μ-problem.
  - $q_h \neq 0$, by definition.
- $U(1)_{PQ}$ breaking can be quite involved. We focus on a simplified scenario.
  - PQ symmetry breaking scale $f_{PQ} > M_{Z'}$
  - Integrate out the radial modes.

Effect of vector multiplet

- SSB by Ψ_i

$$\mathbf{\Psi_i} = f_i e^{q_i \mathbf{A}/f_{\rm PQ}}\,, f_{\rm PQ}^2 = \sum_i q_i^2 f_i^2$$
$$\mathbf{A} = \frac{1}{\sqrt{2}}(s+ia) + \sqrt{2}\theta\tilde{a} + \theta^2 F$$
$$\mathbf{K}_{\rm PQ} \;=\; \sum_i f_i^2 \exp\left(\frac{q_i(\mathbf{A}+\mathbf{A}^\dagger)}{f_{\rm PQ}} + 2g_{\rm PQ}q_i\mathbf{V}_{\rm PQ}\right) - 2\kappa\mathbf{V}_{\rm PQ}$$
$$W_H = \lambda S H_u H_d,\; V_{\rm soft} = A_\lambda \lambda S H_u H_d$$

- We will further integrate out the saxion and the vector.

Effective Higgs potential

- Integrating out saxion and massive U(1).

$$
\begin{aligned}
V &= (|\mu_{\rm eff}|^2 + m_{H_u}^2)|H_u|^2 + (|\mu_{\rm eff}|^2 + m_{H_d}^2)|H_d|^2 - 2B_\mu|H_uH_d| \\
&\quad + \frac{1}{8}(g^2 + g'^2)(|H_u|^2 - |H_d|^2)^2 - g_{\rm PQ}q_{H_u}\langle D_{\rm PQ}\rangle(|H_u|^2 + |H_d|^2) \\
&\quad + a_1|H_uH_d|^2 + a_2(|H_u|^2 + |H_d|^2)^2 + a_3|H_uH_d|(|H_u|^2 + |H_d|^2)\ .
\end{aligned}
$$

$$
\begin{aligned}
a_1 &= \frac{1}{2}\lambda^2 - \frac{4A_\lambda^2\lambda^2 q_{H_u}^2 f_S^2}{M_s^2 f_{\rm PQ}^2}\ , \\
a_2 &= \frac{1}{2}g_{\rm PQ}^2 q_{H_u}^2 - \frac{f_{\rm PQ}^2 q_{H_u}^2}{M_s^2}\left(g_{\rm PQ}^2 - \frac{2\lambda^2 f_S^2}{f_{\rm PQ}^2}\right)^2\ , \\
a_3 &= \frac{-4A_\lambda \lambda q_{H_u}^2 f_S}{M_s^2}\left(g_{\rm PQ}^2 - \frac{2\lambda^2 f_S^2}{f_{\rm PQ}^2}\right)
\end{aligned}
$$

Correction to Higgs mass

- Massive vector multiplet in SUSY limit.

$$M_s^2 = M_{\tilde{a}}^2 = M_a^2 = 2g_{\rm PQ}^2 f_{\rm PQ}^2$$

- For $\lambda < \Lambda_{\rm soft}/M_s$

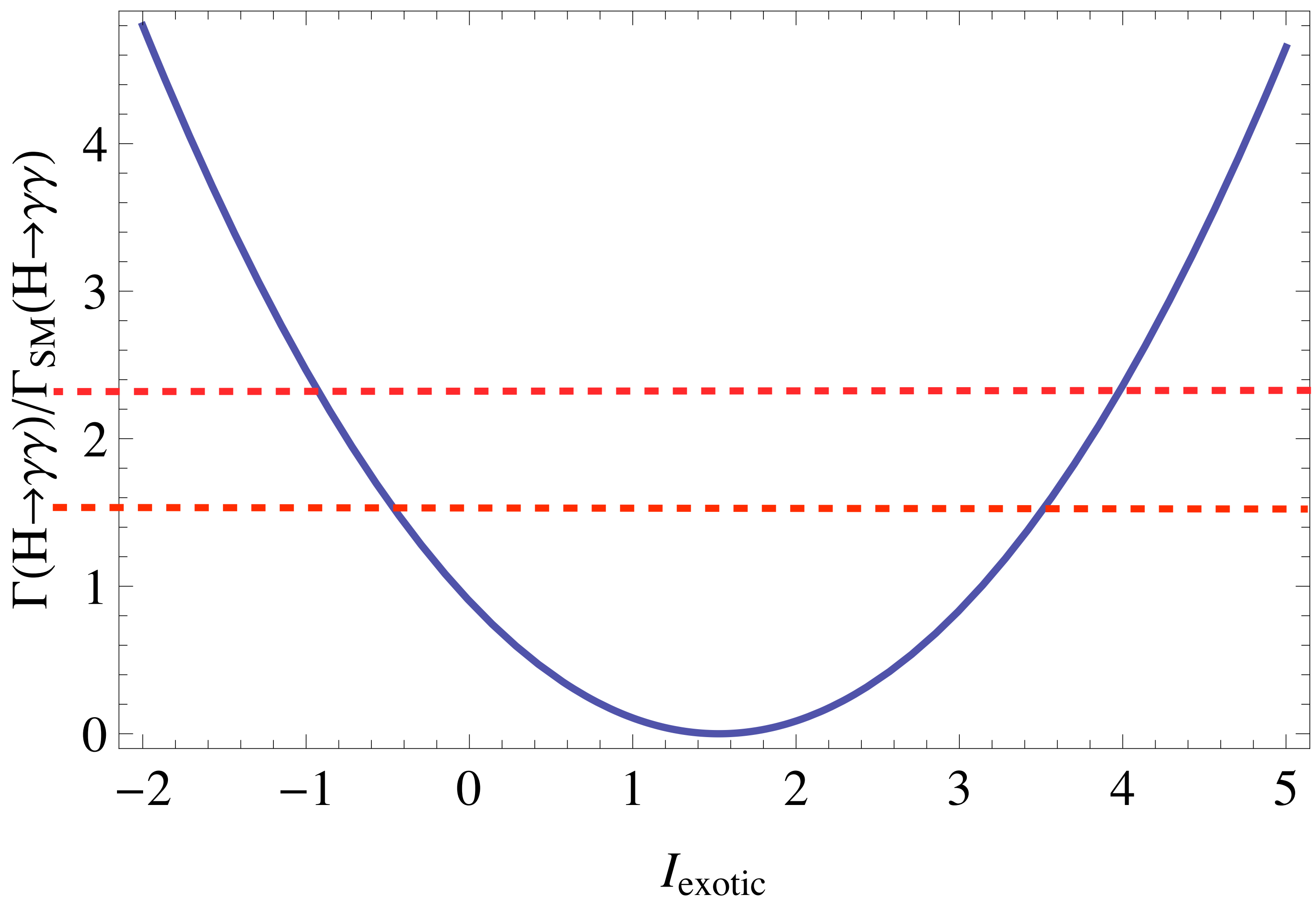
$$\begin{aligned} a_1 &= \mathcal{O}(\lambda^2)\ , \quad a_2 = \frac{g_{\rm PQ}^2 q_{H_u}^2 \Delta M_s^2}{2M_s^2}\ , \ \Delta M_s^2 \sim \Lambda_{\rm soft}^2 \\ a_3 &= \frac{-4A_\lambda \lambda g_{\rm PQ}^2 q_{H_u}^2 f_S}{M_s^2} \end{aligned}$$

- Tree level correction to Higgs mass

$$(m_h^2)_{\rm tree} \approx m_Z^2 \cos^2 2\beta + \left(\frac{a_1}{2}\sin^2 2\beta + 2a_2 + a_3 \sin 2\beta\right) v_{\rm EW}^2$$

O(1) corrections to $h \rightarrow \gamma\gamma$

$$-\frac{\alpha}{2\pi}\frac{h}{v}\delta I F_{\mu\nu}F^{\mu\nu} \qquad \delta I_{\mathrm{top}} \simeq 0.5 \quad \delta I_W \simeq -2.1$$



Why is it not so easy?

- SM $h \to \gamma\gamma$ is given by W and top loops.
  - W, t: light (~100 GeV), large coupling to the Higgs.
  - New states must be similar.
- In SUSY, new particles can be either fermion or boson.
- New fermion:
  - Yukawa like coupling: $h_{u,d}$ DN.
  - Need to check EWPT.

Light scalar?

- Safest way: $\lambda H^\dagger H\, S^\dagger S$ (Higgs portal).
  - $\lambda<0$, opposite to the top contribution, enhance $h\to\gamma\gamma$
- However, this does not work for SUSY.
  - $H^\dagger H\, S^\dagger S$ is of the form of F-term coupling to sfermions.
  - However, cancellation of quadratic divergence fixes $\lambda>0$. For example, for stop, $\lambda=|y_t|^2$.

More specifically

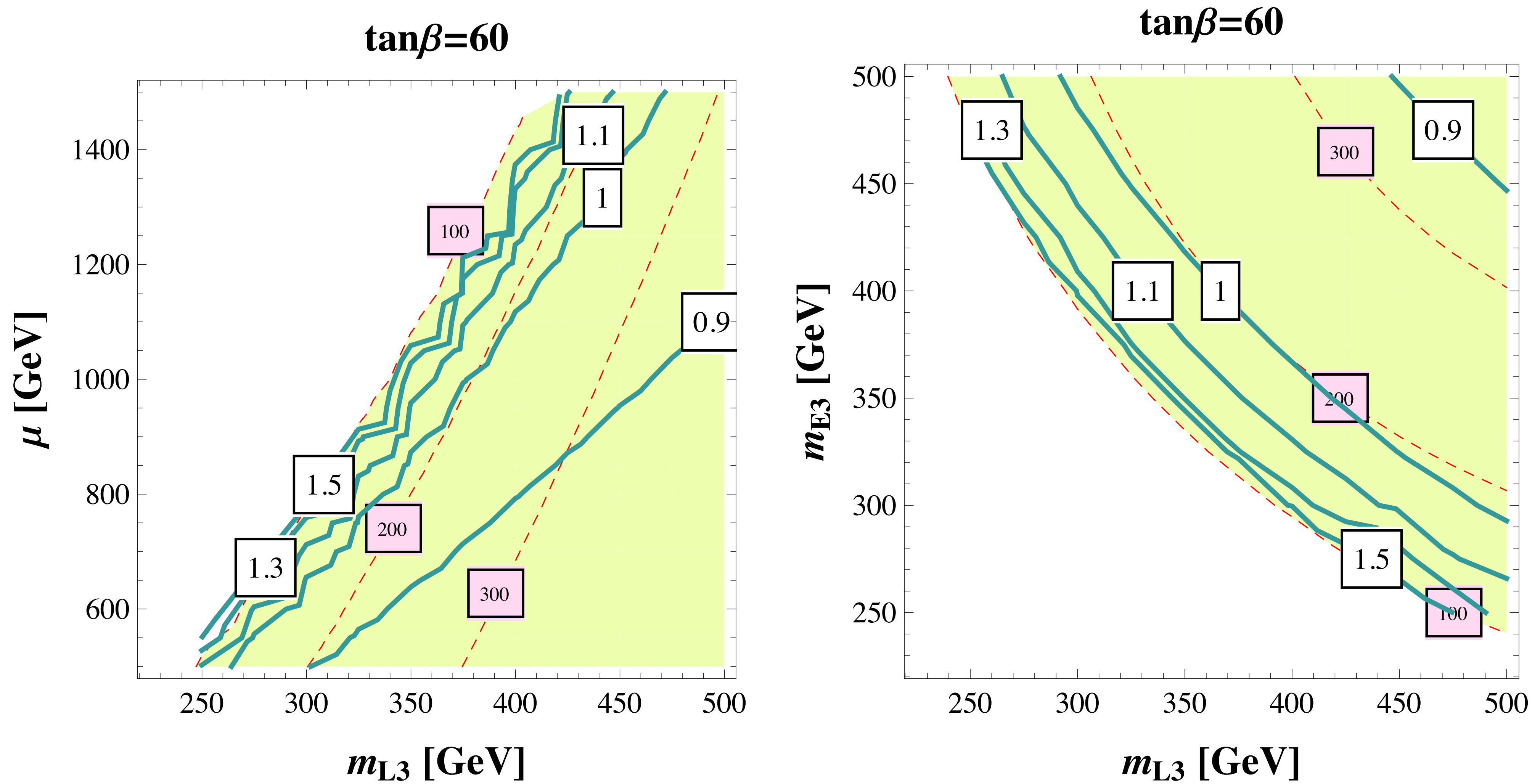
$$-\frac{\alpha}{2\pi}\frac{h}{v}\delta I F_{\mu\nu}F^{\mu\nu} \qquad \delta I \propto \frac{\partial}{\partial h}\log(\det M_{\tilde{f}}(h))$$

$$M_{\tilde{f}}(h) = \begin{pmatrix} m^2_{\tilde{f}_L} + \frac{y^2}{2}h^2 + \ldots & yhX_f \\ yhX_f & m^2_{\tilde{f}_R} + \frac{y^2}{2}h^2 + \ldots \end{pmatrix}$$

$$\frac{\partial}{\partial h}\log(\det M_{\tilde{f}}(h=v)) \propto \frac{m^2_{\tilde{f}_L} + m^2_{\tilde{f}_R} - X_f^2}{m^2_{\tilde{f}_L} + m^2_{\tilde{f}_R} - X_f^2(yv)^2}$$

- Large off-diagonal mixing, X_f, necessary for enhancement.
- Split scalar spectrum.

boosting the di-photon mode?



- light stau!

Carena, Gori, Shah, Wagner. 1112.3336

Exotics

- $U(1)_{PQ}$ is anomalous. We need to add exotics to cancel anomaly.

- It is possible that exotics can couple to the Higgs, and carry electric charge.

- We explore the possibility of having light exotics with sizable coupling to the Higgs.
    - Enhanced $h \rightarrow \gamma\gamma$
    - Consistent with constraints (precision, collider)

Exotics, an example

gauge charge under $SU(3)_C$ $SU(2)_L$ $U(1)_Y$ $U(1)_{PQ}$

Particles	Gauge charges	Particles	Gauge charges
$\mathbf{L_i}$	$(1;\ 2;\ -1/2;\ 1/2)$	$\mathbf{Q_i}$	$(3;\ 2;\ 1/6;\ 1/2)$
$\mathbf{\bar{N}_i}$	$(1;\ 1;\ 0;\ 1/2)$	$\mathbf{\bar{u}_i}$	$(\bar{3};\ 1;\ -2/3;\ 1/2)$
$\mathbf{\bar{e}_i}$	$(1;\ 1;\ 1;\ 1/2)$	$\mathbf{\bar{d}_i}$	$(\bar{3};\ 1;\ 1/3;\ 1/2)$
$\mathbf{H_d}$	$(1;\ 2;\ -1/2;\ -1)$	$\mathbf{H_u}$	$(1;\ 2;\ 1/2;\ -1)$
$\mathbf{T_1}$	$(3;\ 1;\ 1/3;\ -1)$	$\mathbf{T_1^c}$	$(\bar{3};\ 1;\ -1/3;\ -1)$
$\mathbf{T_2}$	$(3;\ 1;\ 2/3;\ -1)$	$\mathbf{T_2^c}$	$(\bar{3};\ 1;\ -2/3;\ -1)$
$\mathbf{T_3}$	$(3;\ 1;\ 2/3;\ -1)$	$\mathbf{T_3^c}$	$(\bar{3};\ 1;\ -2/3;\ -1)$
$\mathbf{D_1}$	$(1;\ 2;\ 1/2;\ -1)$	$\mathbf{D_1^c}$	$(1;\ 2;\ -1/2;\ -1)$
$\mathbf{D_2}$	$(1;\ 2;\ 1/2;\ -1)$	$\mathbf{D_2^c}$	$(1;\ 2;\ -1/2;\ -1)$
$\mathbf{X}$	$(1;\ 1;\ 1;\ 2)$	$\mathbf{X^c}$	$(1;\ 1;\ \text{-}1;\ 2)$
$\mathbf{N}$	$(1;\ 1;\ 0;\ 2)$	$\mathbf{N^c}$	$(1;\ 1;\ 0;\ 2)$
$\mathbf{S}$	$(1;\ 1;\ 0;\ 2)$	$\mathbf{S^c}$	$(1;\ 1;\ 0;\ -2)$
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Can couple to Higgs

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Can couple to Higgs

$$\begin{aligned} W &= \gamma_{1,2}(H_u D_{1,2} X^c + H_d D_{1,2} N^c) + (D \to D^c, X^c \to X, N^c \to N) \\ &+ M_D D_{1,2} D^c_{1,2} + M_X X X^c + M_N N N^c + \ldots \end{aligned}$$

Exampls: light scalar

- $g_{PQ} = 0.6$, $f_{PQ} = 2.5$ TeV, $\lambda=0.25$, $\tan\beta = 5$
- $A_\lambda/f_{PQ} = 0.4$, $\Delta m_s/M_s = 0.4$
- $\gamma_{1,2} = 0.1$, $\gamma A_1 = -950$ GeV, $M_D = 600$ GeV, $M_{X,N} = 400$ GeV
- $m_{stop} = 200$ GeV.
- $m_h = 125$ GeV, $h \to \gamma\gamma \approx 1.5 \times$ SM
- lightest charged scalar: 130 GeV.

Examples: light fermion

- g_{PQ} = 0.6, f_{PQ} = 2.5 TeV, λ=0.25, $\tan\beta$ = 1.3
- A_λ/f_{PQ} =0.4, $\Delta m_s/M_s$ =0.4
- $\gamma_{1,2}$ = 1.6, γA_1 = 300 GeV,
  M_D= 500 GeV, $M_{x,N}$ = 300 GeV
- m_{stop} = 200 GeV.
- m_h = 125 GeV, $h\to\gamma\gamma \approx 2 \times$ SM
- lightest charged fermion: 108 GeV.

Couplings of the light states.

Higgs, Higgsino-like

$DQu^c \quad D^cQd^c$

Singlet, singlino-like

$H_uH_uX^c \quad H_dH_uN^c$

- Discovery in direct SUSY searches might be difficult.

- Modification of Higgs decay maybe their first signal.

Conclusion

- 2012 is going to be a year of Higgs.
  - Confirm a light Higgs signal, or
  - Rule out SM-like weakly coupled Higgs.
- 125 GeV Higgs has significant implications on SUSY parameter space
  - Heavy scalar.
  - Extension of MSSM.
- Watch for deviations of Higgs properties.
  - Special, complicated, models.

SUSY limit

- Massive vector multiplet in the SUSY limit.

$$M_s^2 = M_{\tilde{a}}^2 = M_a^2 = 2g_{\mathrm{PQ}}^2 f_{\mathrm{PQ}}^2$$

- Higgs quartic couplings

$$a_1 = \frac{1}{2}\lambda^2 \ , \ a_2 = \frac{2q_{H_u}^2 \lambda^2 f_S^2}{f_{\mathrm{PQ}}^2} + \mathcal{O}(\lambda^4) \ , \ a_3 = 0$$