(over)Interpreting the Higgs "signal"

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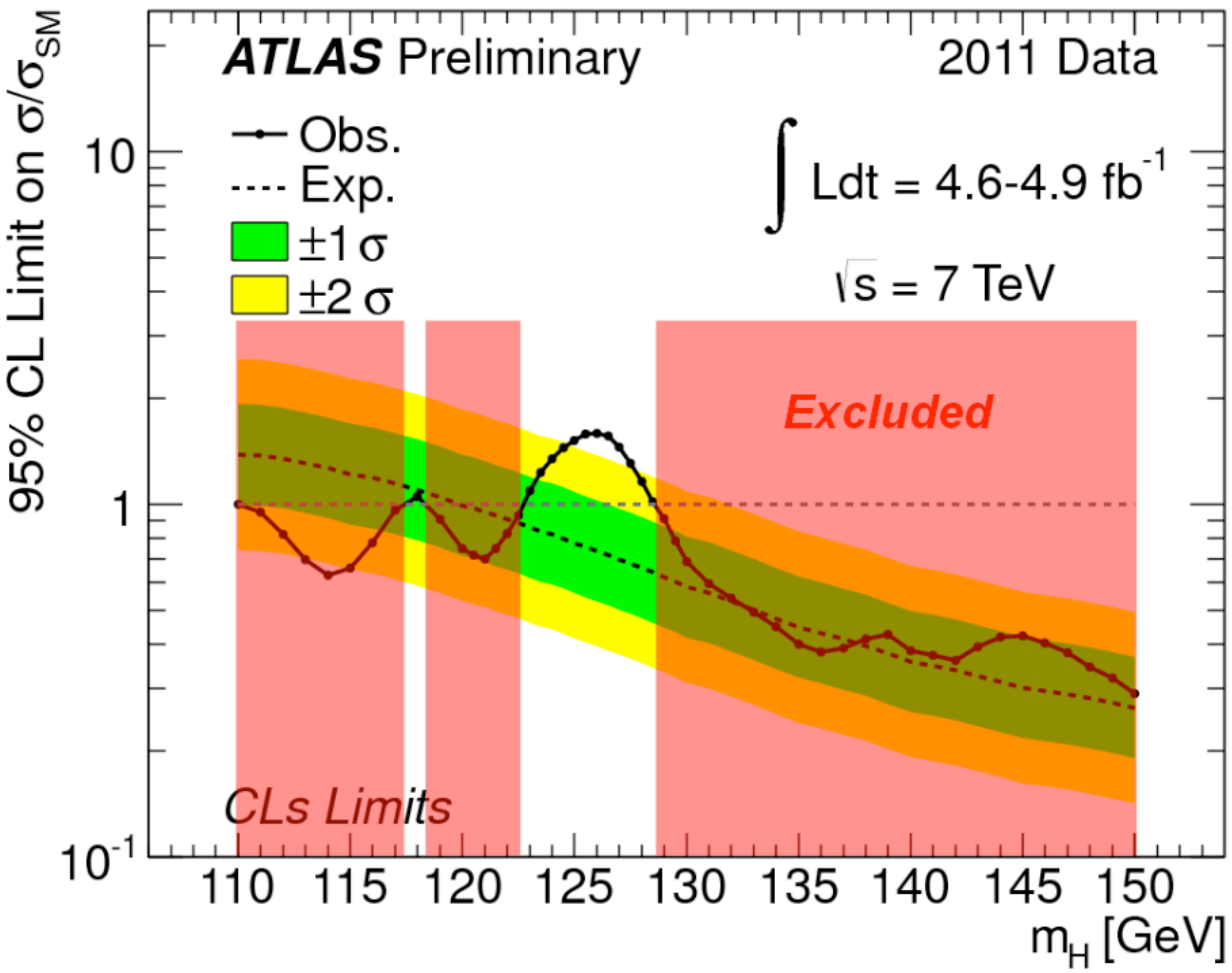
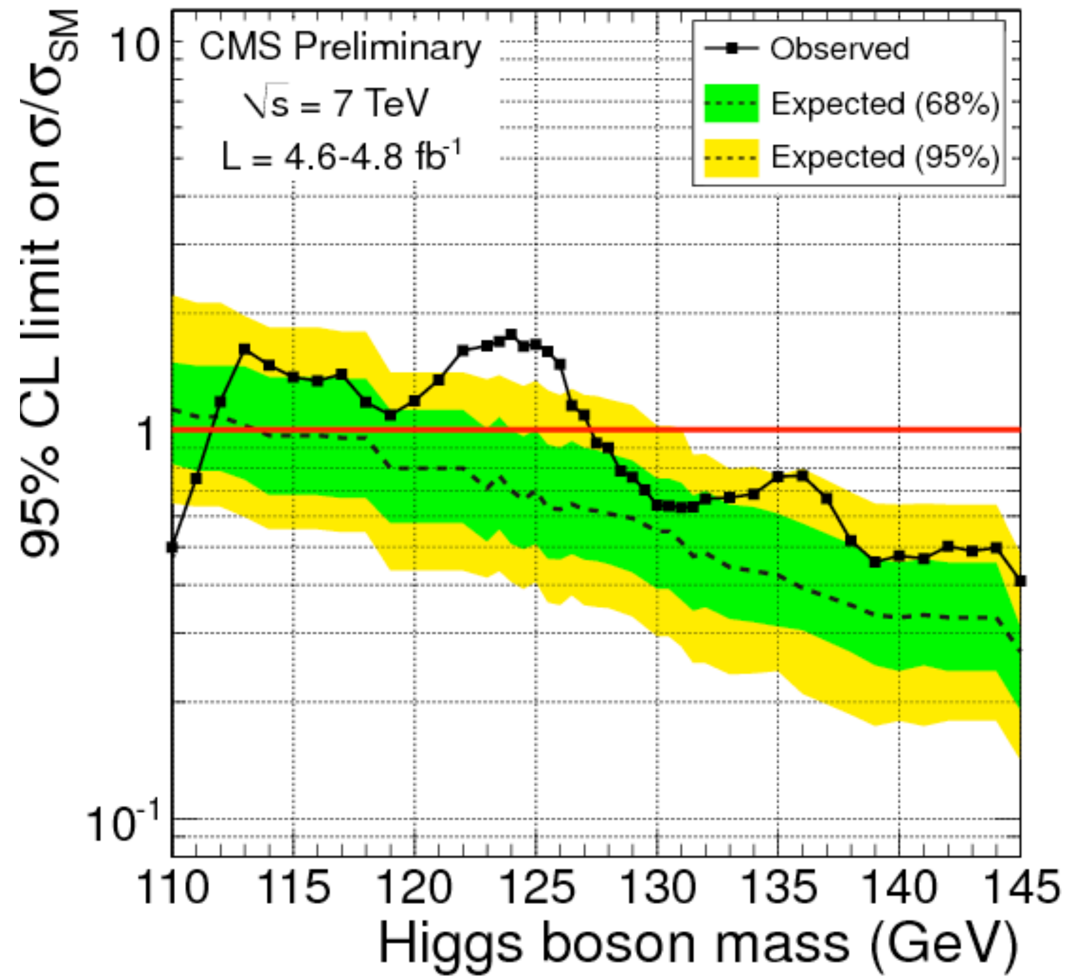
University of Chicago

Fermilab theory seminar, May 24, 2012

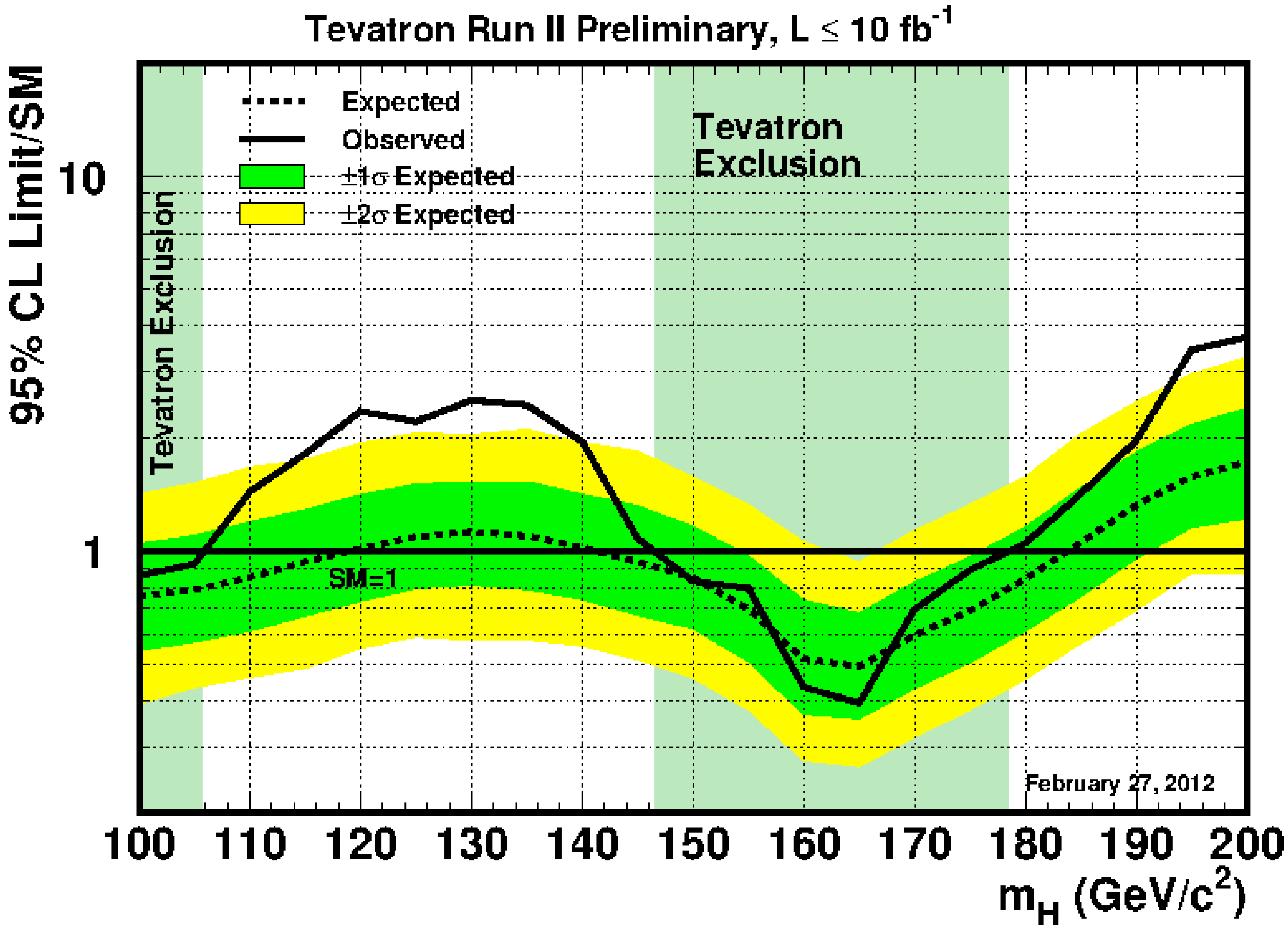
The signal





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

Tevatron



Tevatron Run II Preliminary, L ≤ 10 fb-1
95% CL Limit/SM
10
1
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron Exclusion
Tevatron Exclusion
SM=1
February 27, 2012
100
110
120
130
140
150
160
170
180
190
200
mH (GeV/c2)

Interpretation.

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- It's the Higgs boson. Measured the last parameter of the Standard Model.

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Interpretation.

- It's the Higgs boson. Measured the last parameter of the Standard Model.

This talk

- It's the Higgs boson. Implications for new physics scenarios.

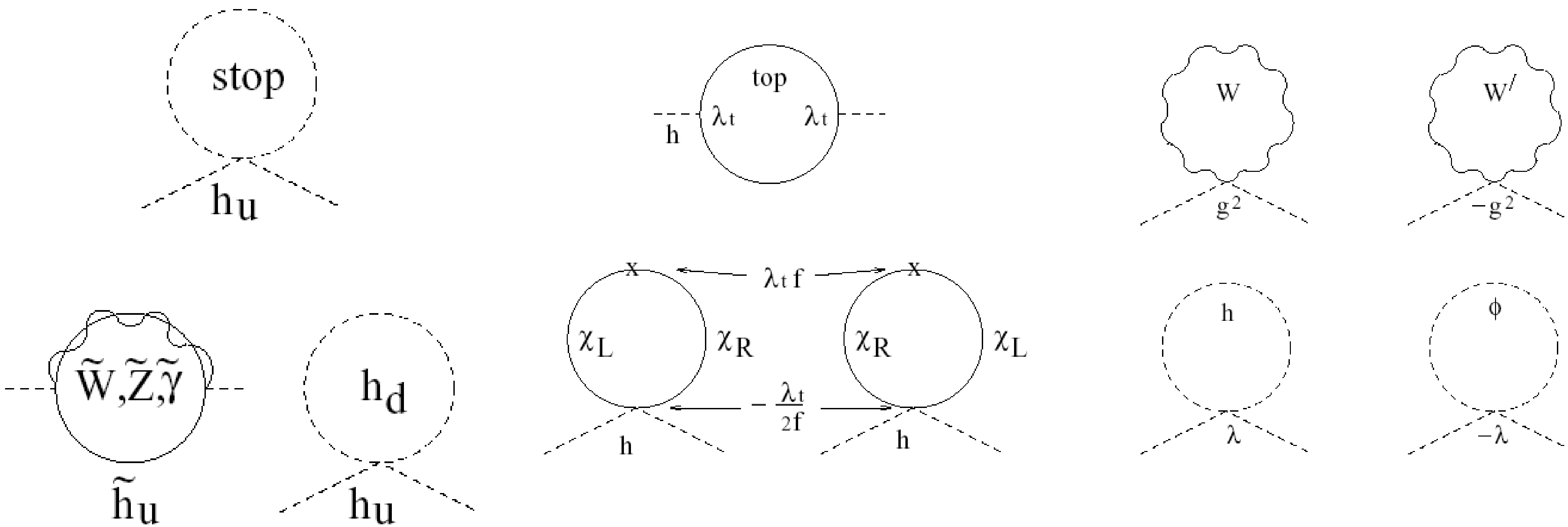
- It's not the Higgs boson. Radion, ...

- It's not a signal. Hidden Higgs, no Higgs.

Why new physics?

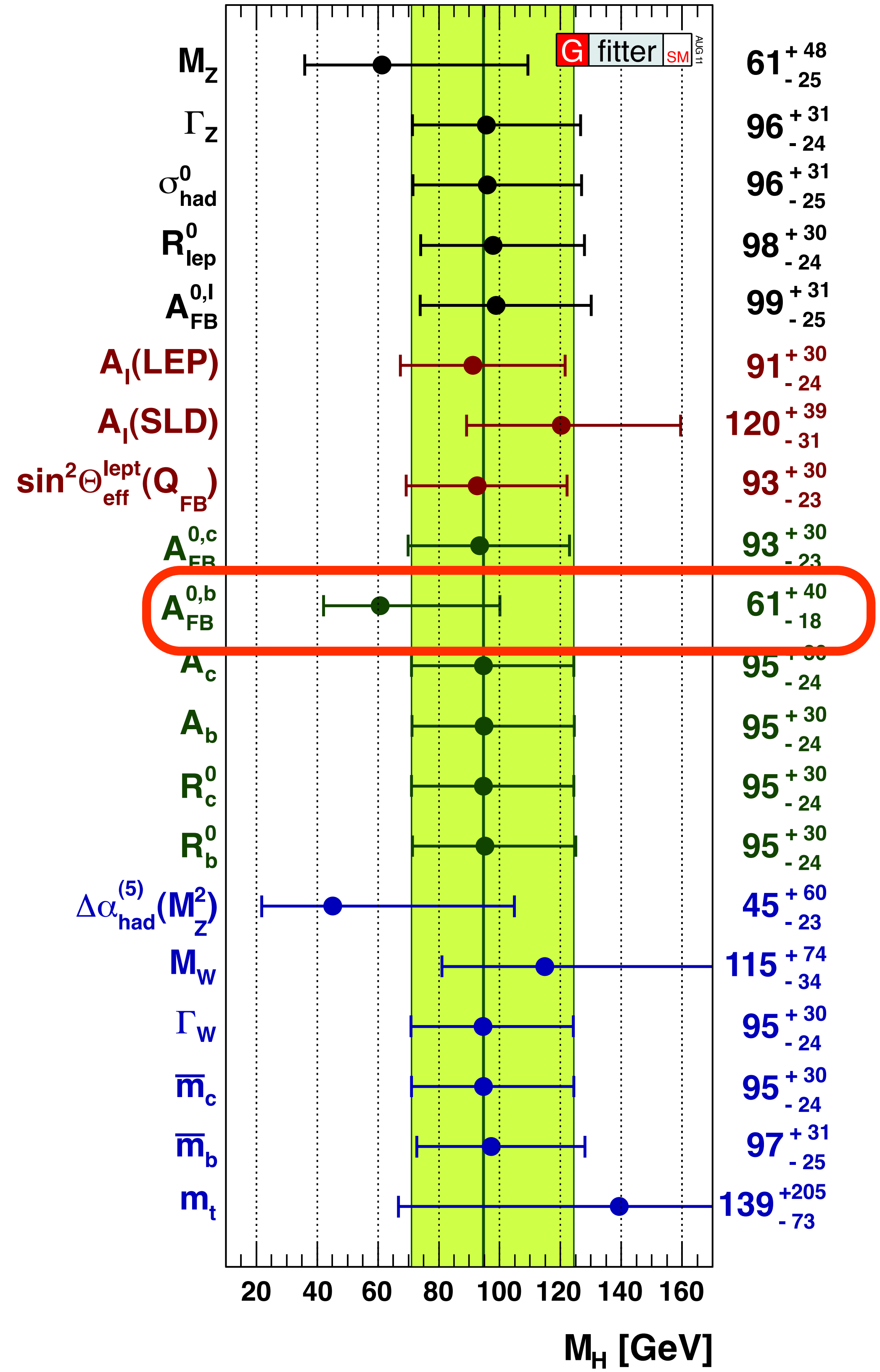
- Large classes of new physics models have partners: SUSY, little Higgs, etc.

- Partners couples to Higgs.



Why new physics?

- Electroweak precision.
  - 125 GeV is fine, but somewhat more uncomfortable than 115 or 90. NP to fix it?



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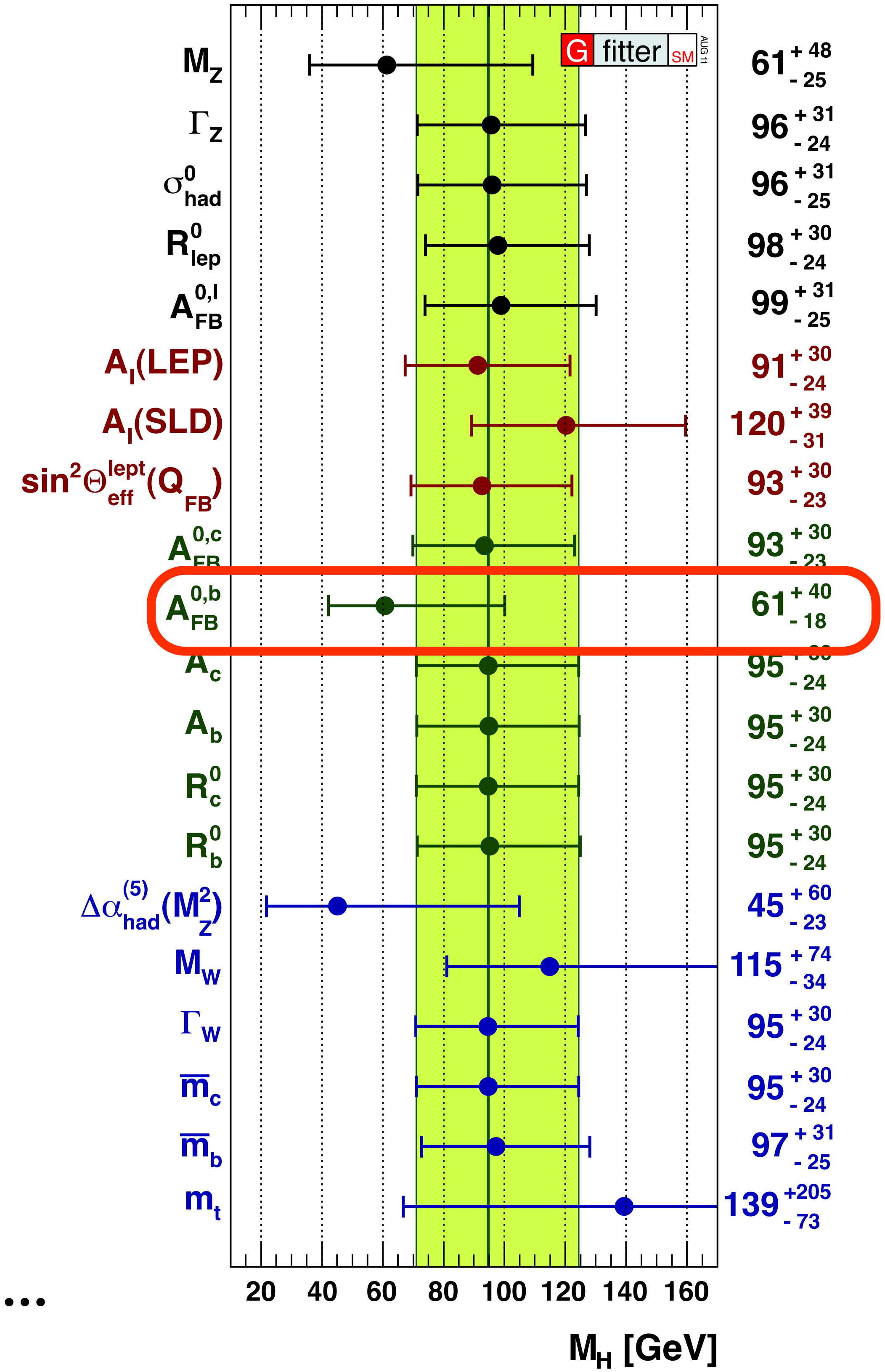


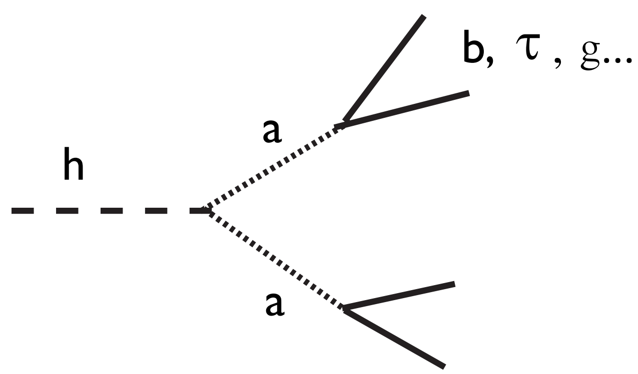
More: Dark matter, baryogensis ....

How might NP show up?

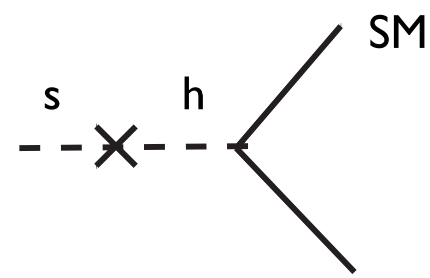
- Being directly produced and detected at the LHC.
  - SUSY: superpartners.
  - Composite Higgs (extra dim): resonances.

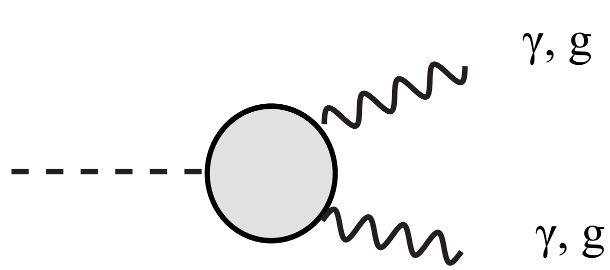
- Modification of Higgs production and decay.

hiding Higgs



mixing





Loop of NP

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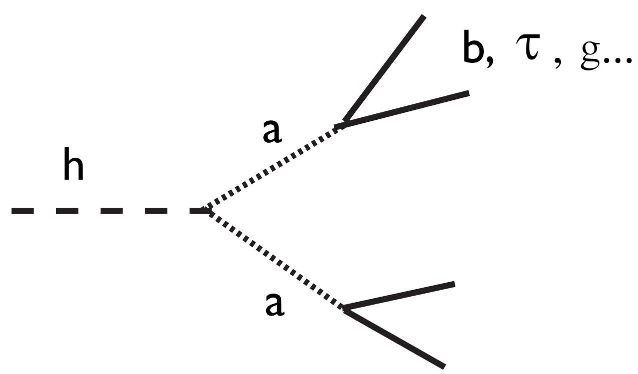

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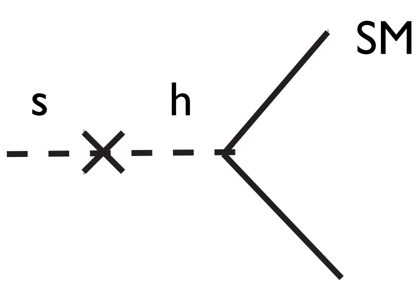
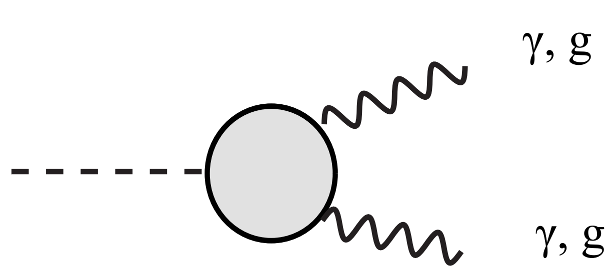
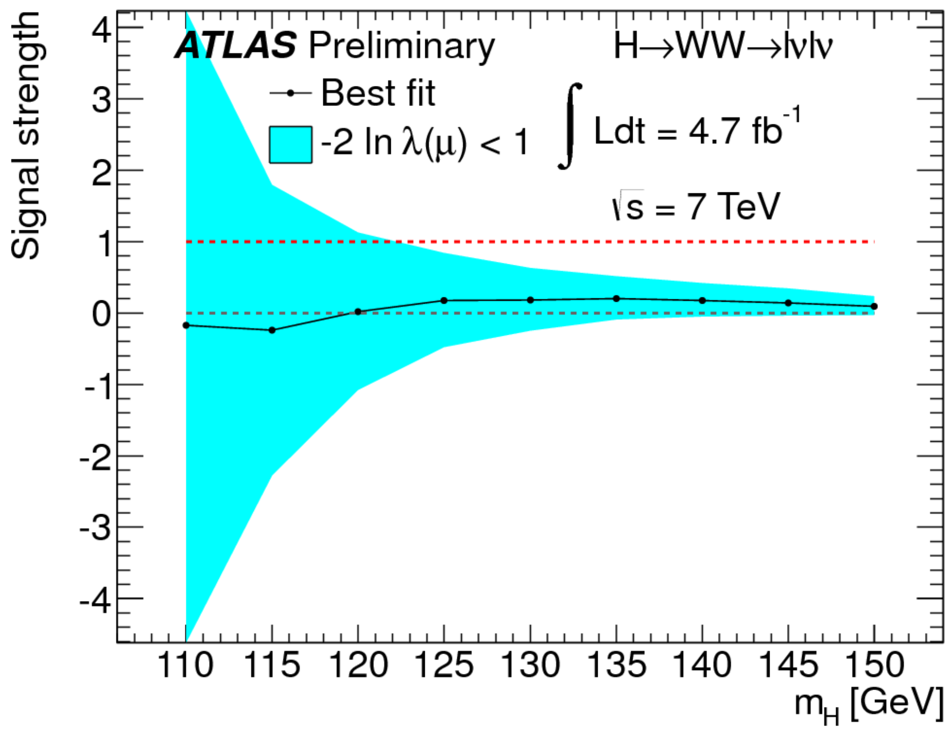


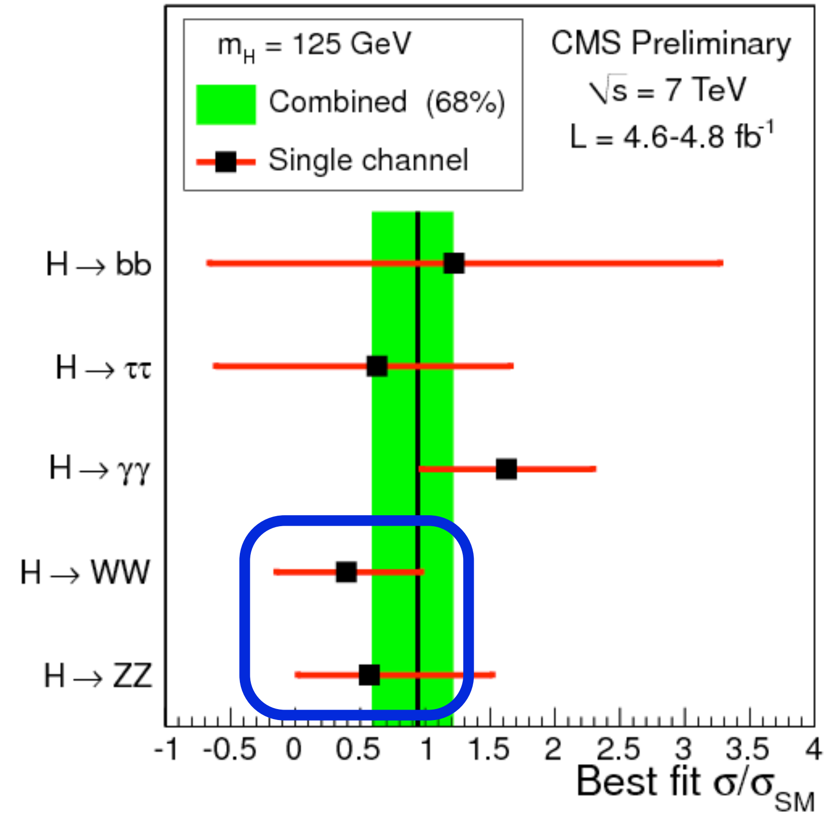


Loop of NP

Any hints?

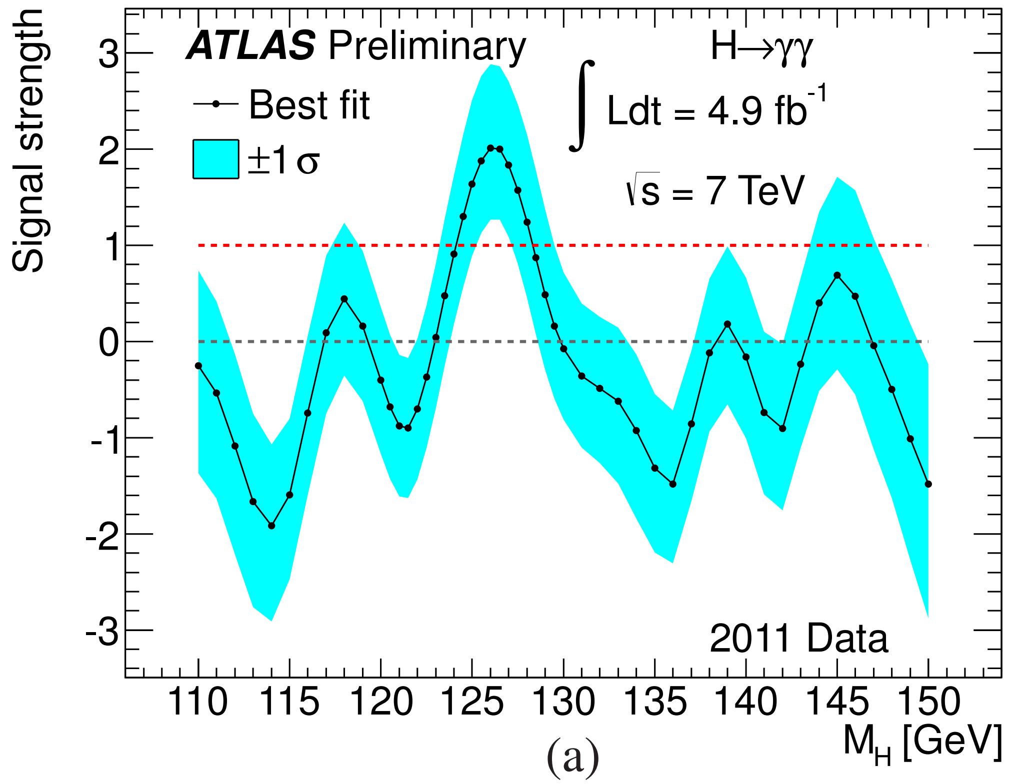
gg→h enhancement?

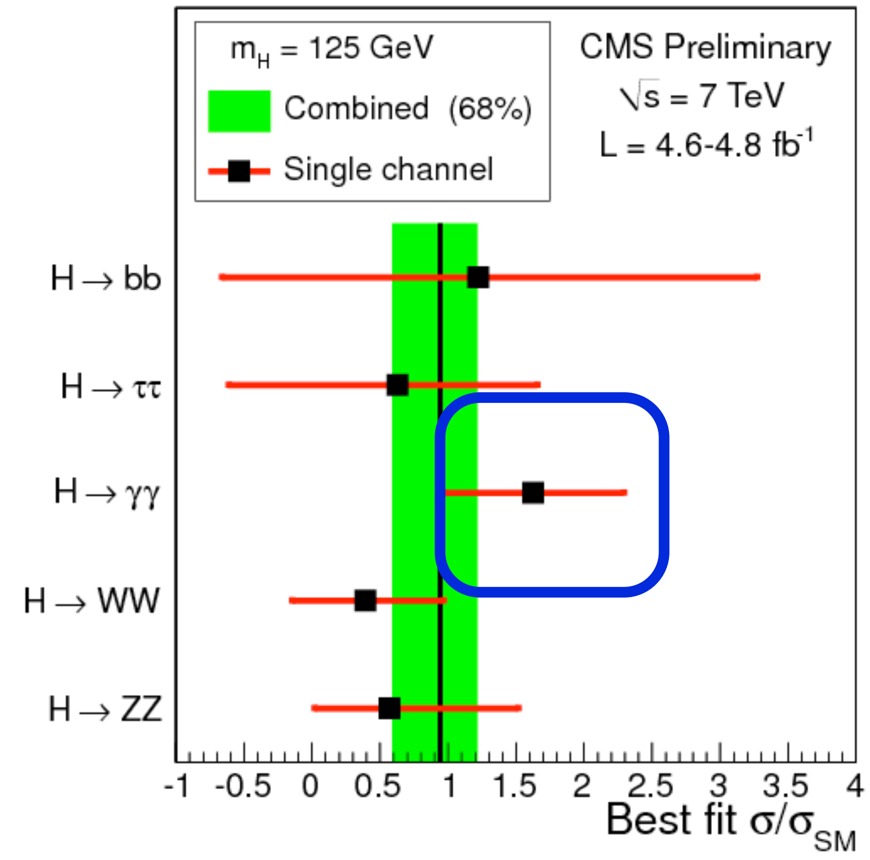




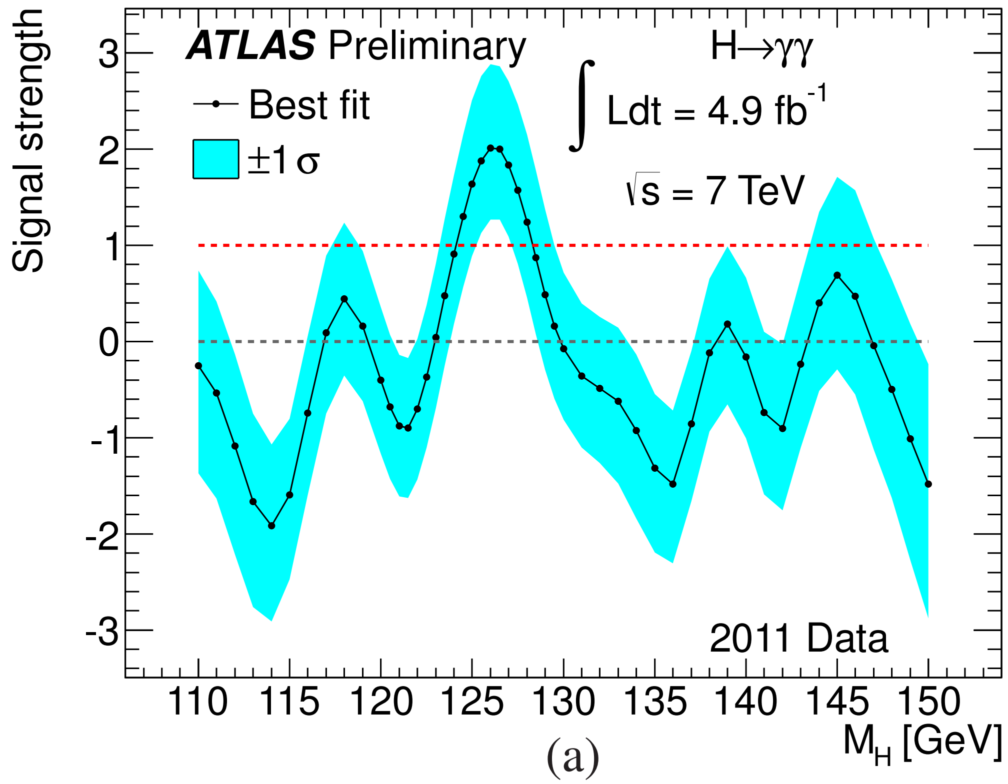
- Maybe not.
- No excess in WW.

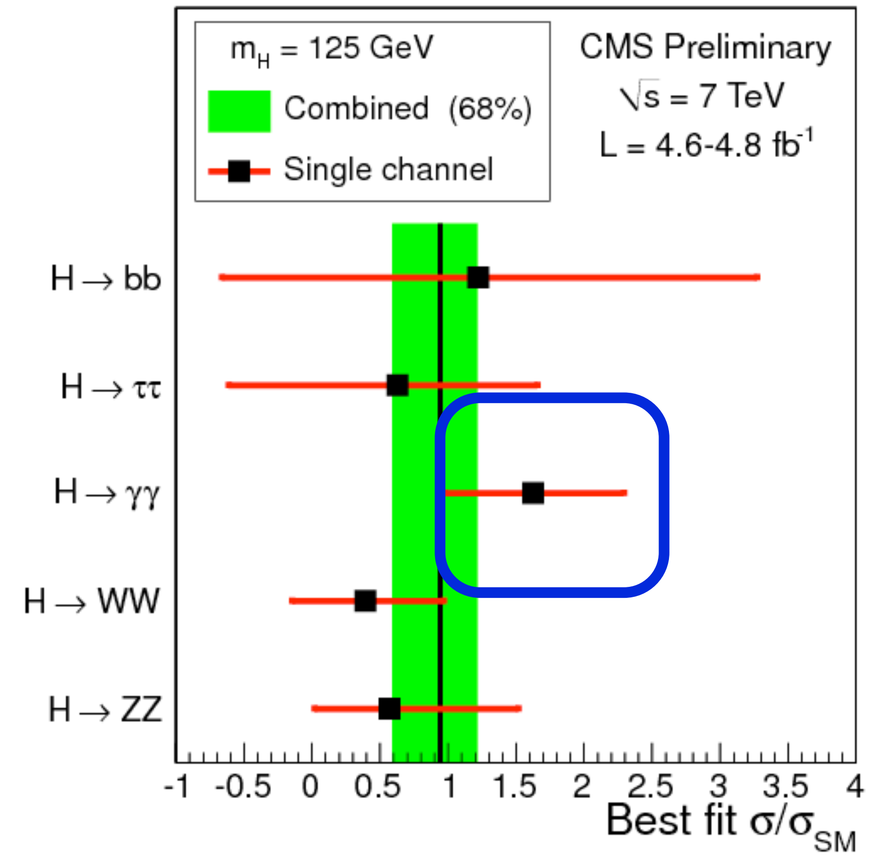
h→γγ higher than SM prediction?





h→γγ higher than SM prediction?





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

This talk.

- Higgs mass in SUSY.
- Enhancement of $h \to \gamma\gamma$.
- A possible connection with EWPT.

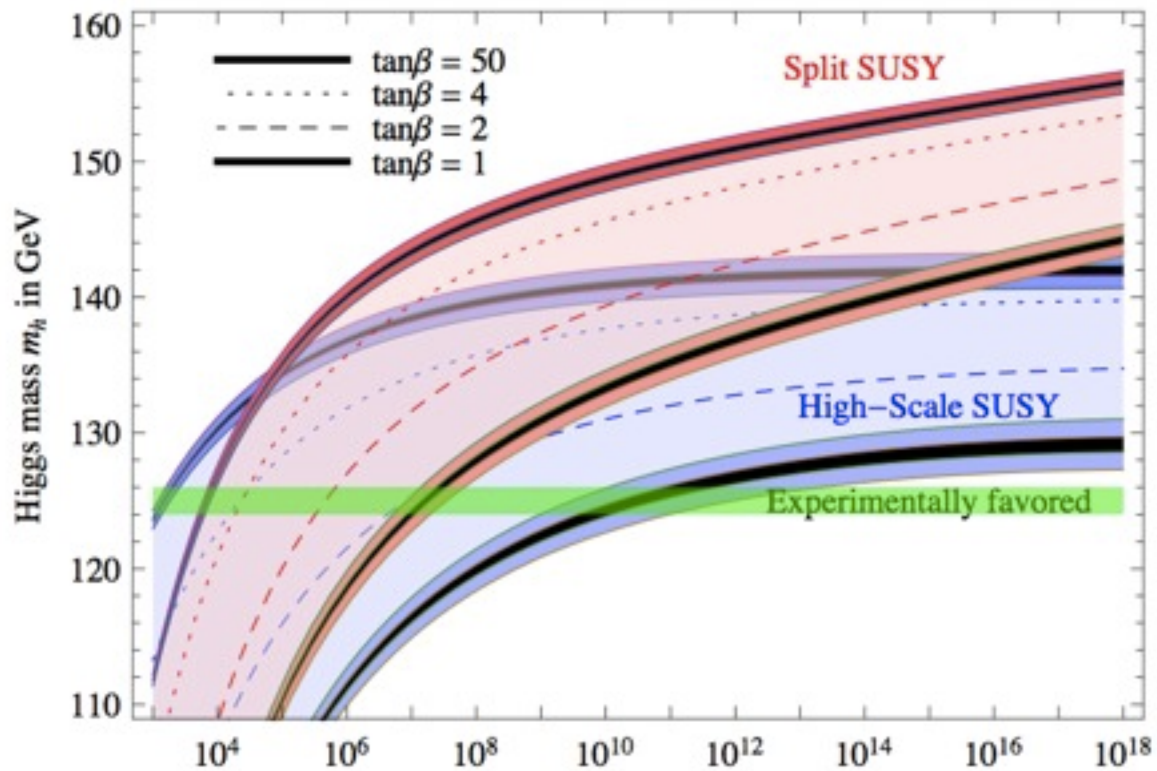
Higgs in SUSY.

~ 70 papers so far, > 80% on SUSY

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

SUSY and m_h = 125 GeV

- SUSY prefers light Higgs.
  - A bit heavy for MSSM. But certainly possible.



Giudice, Strumia, 2011

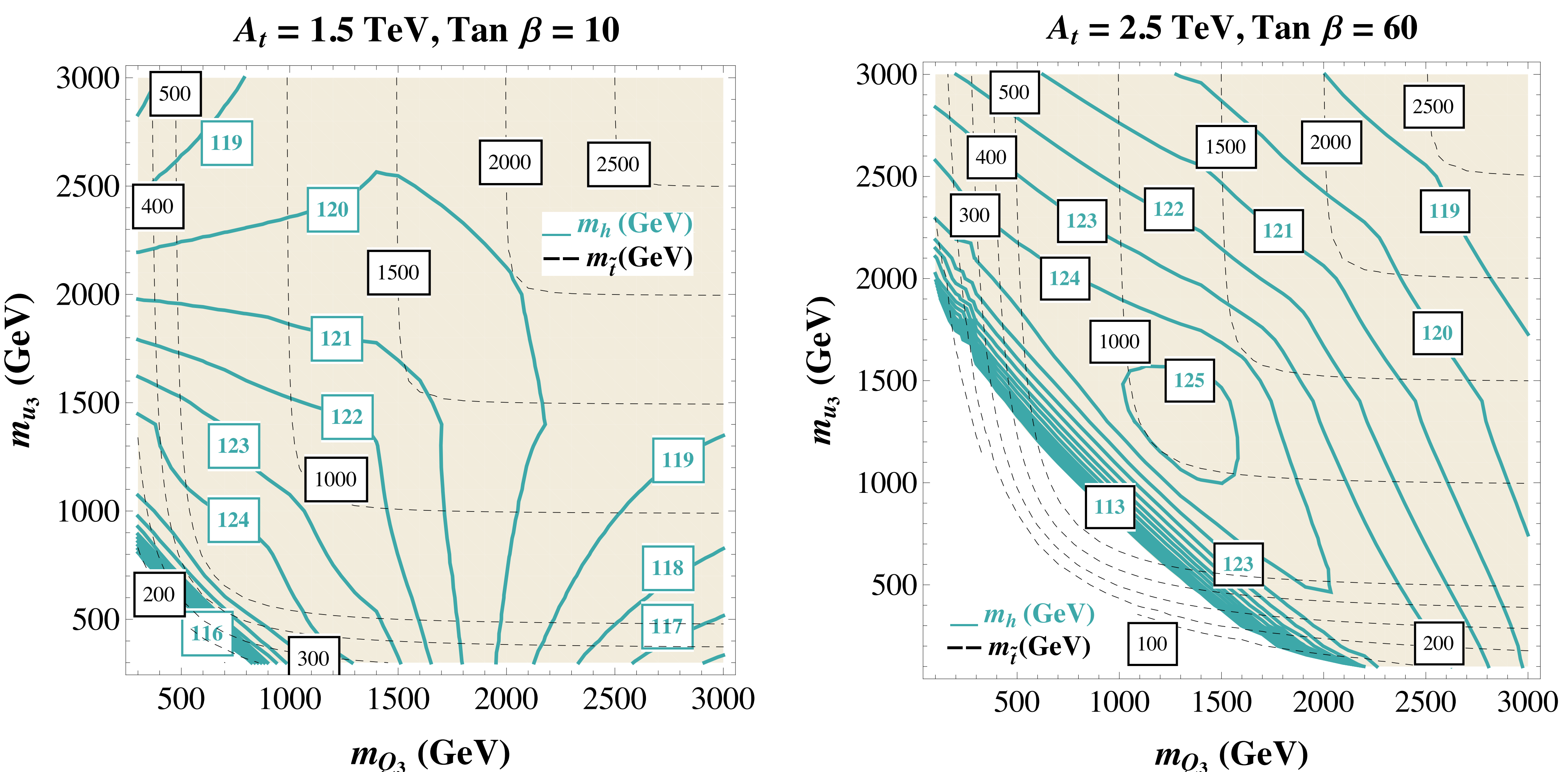
  - Is heavy scalar reasonable? Maybe.
  - Could have benefits: flavor, CP.

In detail:

Carena, Gori, Shah, Wagner. 1112.3336

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$t = \log\frac{M_{\rm SUSY}^2}{m_t^2} \qquad \tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{\tilde{A}_t^2}{12 M_{\rm SUSY}^2}\right)$$



Less tuned?

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?
  - F-term models NMSSM, ...

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.

Work in progess with Haipeng An and Tao Liu

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).

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

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

SUSY limit

- Massive vector multiplet in the SUSY limit.

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

- Higgs quartic couplings

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

- Effective Kahler potential after integrating out massive U(1) in SUSY limit

$$\mathcal{K}_{\rm eff} = -\frac{g^2}{M_V^2}\left[\sum_a q_a \phi_a^\dagger \phi_a\right]^2 + \frac{g^2}{8M_V^4}\left[\bar{D}_{\dot{\alpha}} D_\alpha \left(\sum_a q_a \phi_a^\dagger \phi_a\right)\right]^2$$

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

$$a_1 = \mathcal{O}(\lambda^2)\ ,\quad a_2 = \frac{g_{\rm PQ}^2 q_{H_u}^2 \Delta M_s^2}{2M_s^2}\ ,\quad \Delta M_s^2 \sim \Lambda_{\rm soft}^2$$

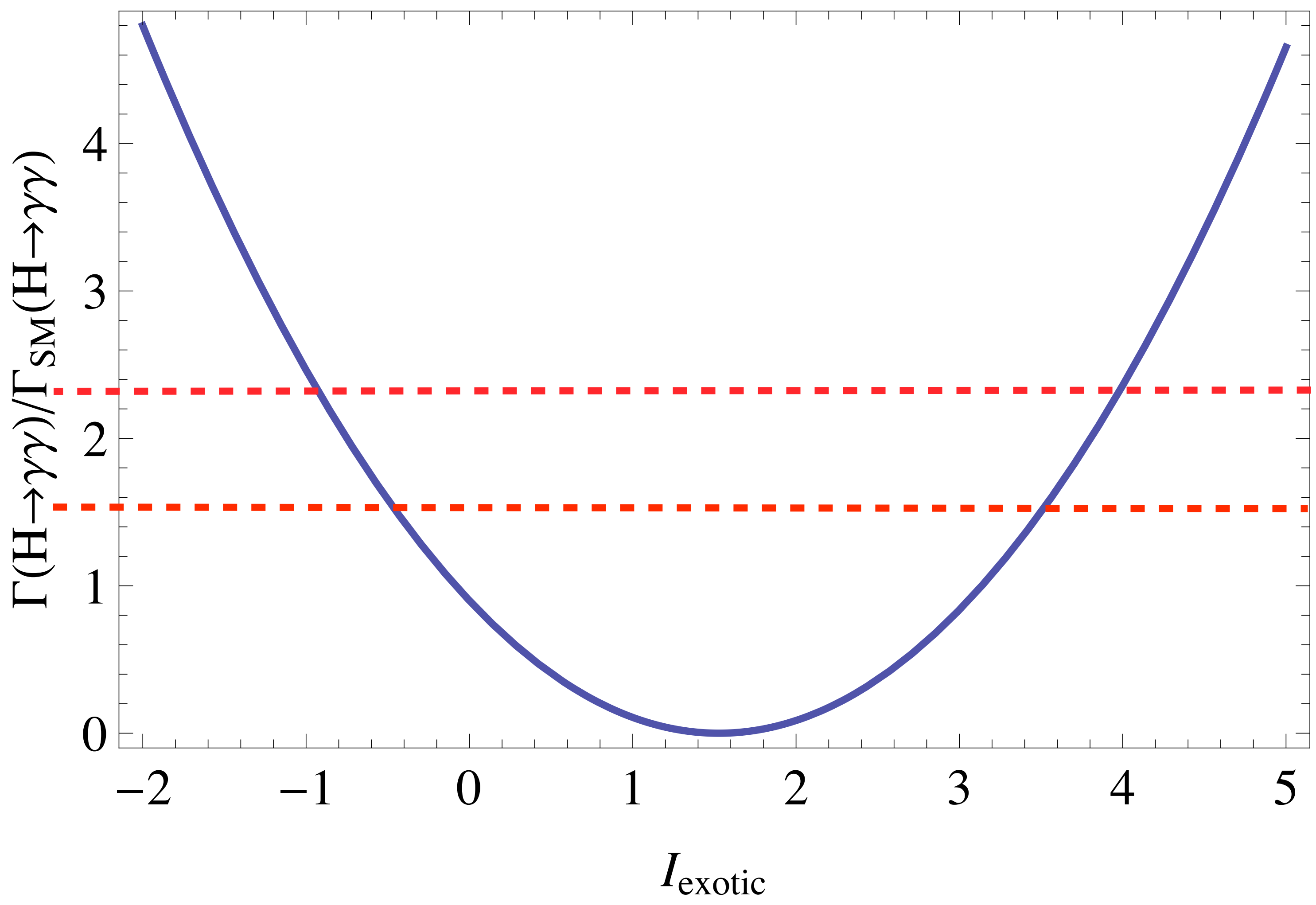
$$a_3 = \frac{-4A_\lambda \lambda g_{\rm PQ}^2 q_{H_u}^2 f_S}{M_s^2}$$

- 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 $h \to \gamma\gamma$

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



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

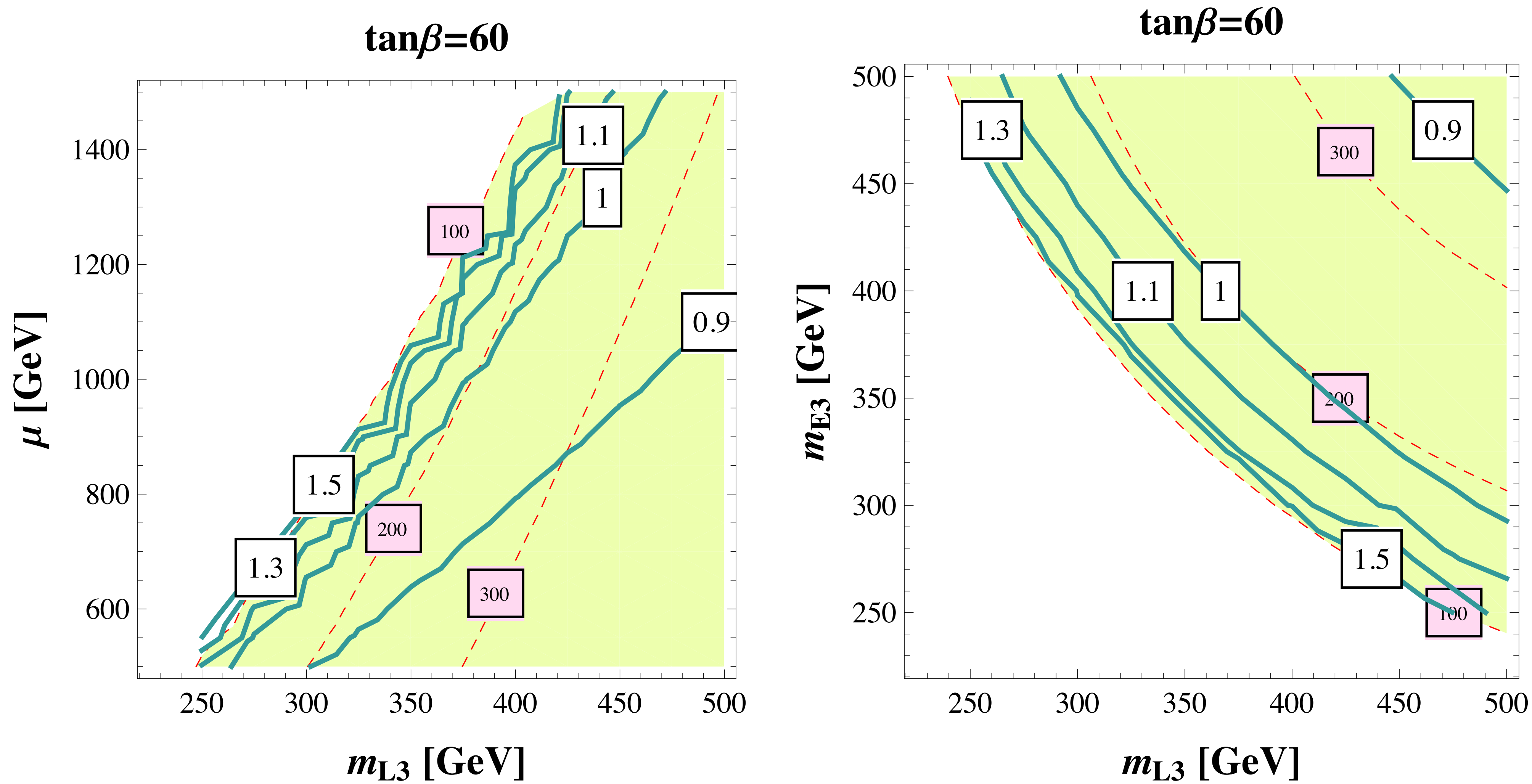
$$-\frac{\alpha}{2\pi}\frac{h}{v}\delta I F_{\mu\nu}F^{\mu\nu} \qquad \delta I \propto \frac{\partial}{\partial h}\log(\det M_{\tilde{f}}(h))$$

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

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

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

boosting the di-photon mode in



- light stau!

Carena, Gori, Shah, Wagner. 1112.3336

Signal

$$m_{L_3} = m_{e_3} = 280 \text{ GeV}, \ \tan\beta = 60, \qquad \mu = 650 \text{ GeV}, \ M_1 = 35 \text{ GeV}$$

$$m_{\tilde{\tau}_1} \sim 95 \text{ GeV}, \ m_{\tilde{\nu}_\tau} \sim 270 \text{ GeV}$$

Maybe

Possible!

	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \to \tilde{\tau}_1\tilde{\tau}_1$	$2\tau, \not{E}_T$	55.3	124.6
$pp \to \tilde{\tau}_1\tilde{\tau}_2$	$2\tau, Z, \not{E}_T$	1.0	3.2
$pp \to \tilde{\tau}_2\tilde{\tau}_2$	$2\tau, 2Z, \not{E}_T$	0.15	0.6
$pp \to \tilde{\tau}_1\tilde{\nu}_\tau$	$2\tau, W, \not{E}_T$	14.3	38.8
$pp \to \tilde{\tau}_2\tilde{\nu}_\tau$	$2\tau, W, Z, \not{E}_T$	0.9	3.1
$pp \to \tilde{\nu}_\tau\tilde{\nu}_\tau$	$2\tau, 2W, \not{E}_T$	1.6	5.3

- Signature.

$$pp \to \tilde{\tau}_1[\tilde{\nu}_\tau(\to W^\pm \tilde{\tau}_1^\mp)] \to \ell^\pm \tau\bar{\tau} + \text{MET}$$

$$pp \to \tilde{\tau}_1\tilde{\tau}_1 \to \tau\bar{\tau} + \text{MET}$$

- Existing searches focus either on long cascades, or chargino-neutralino production.

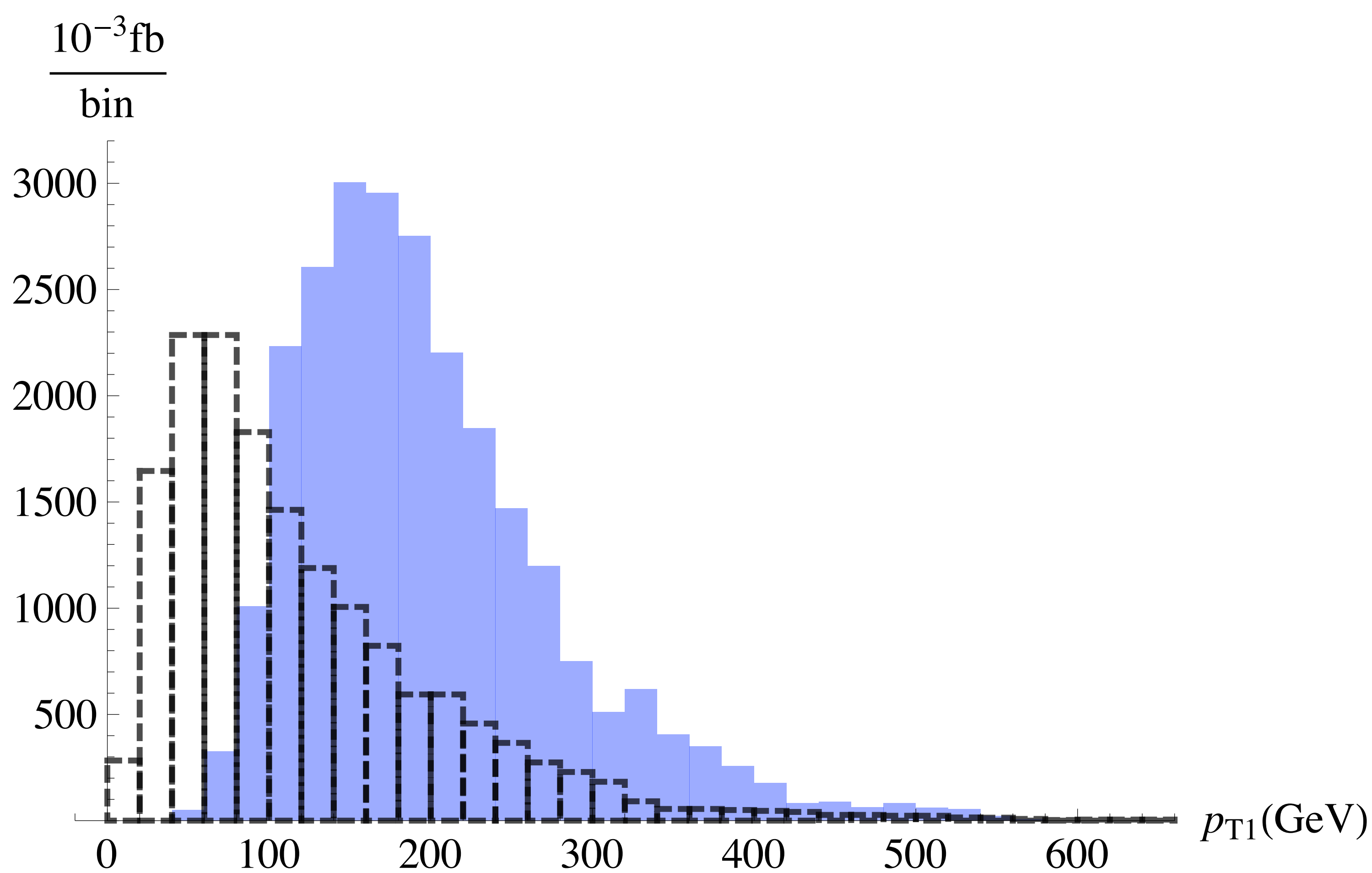
Associated production: $pp \to \tilde{\tau}_1 \tilde{\nu}_\tau$

- Background
  - W+Z/γ*
  - W+ jets (jets faking τ).
    - τ eff: ∼60%, jet rejection ∼ 50
- Basic cuts

$$p_T^{\tau(j)} > 10 \text{ GeV}, \ \Delta R > 0.4 \quad |\eta| < 2.5$$

$$p_T^{\ell} > 70 \text{ GeV} \qquad \not{E}_T > 70$$

Additional cuts for W+jets



hard tau veto $p_T^\tau < 75$ GeV

LHC Reach

Carena, Gori, Shah, Wagner, LTW, to appear

LHC 8 TeV

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	0.6	0.16	0.07
Physical background, $W + Z/\gamma^*$	15	0.25	$\lesssim 10^{-3}$
$W+$ jets background	4×10^3	26	0.3

LHC 14 TeV

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

Using exotics in $U(1)_{PQ}$ scenario

- $U(1)_{PQ}$ 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 $h \to \gamma\gamma$
  - 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
$\mathbf{L_i}$	$(1;\ 2;\ -1/2;\ 1/2)$	$\mathbf{Q_i}$	$(3;\ 2;\ 1/6;\ 1/2)$
$\mathbf{\bar{N}_i}$	$(1;\ 1;\ 0;\ 1/2)$	$\mathbf{\bar{u}_i}$	$(\bar{3};\ 1;\ -2/3;\ 1/2)$
$\mathbf{\bar{e}_i}$	$(1;\ 1;\ 1;\ 1/2)$	$\mathbf{\bar{d}_i}$	$(\bar{3};\ 1;\ 1/3;\ 1/2)$
$\mathbf{H_d}$	$(1;\ 2;\ -1/2;\ -1)$	$\mathbf{H_u}$	$(1;\ 2;\ 1/2;\ -1)$
$\mathbf{T_1}$	$(3;\ 1;\ 1/3;\ -1)$	$\mathbf{T_1^c}$	$(\bar{3};\ 1;\ -1/3;\ -1)$
$\mathbf{T_2}$	$(3;\ 1;\ 2/3;\ -1)$	$\mathbf{T_2^c}$	$(\bar{3};\ 1;\ -2/3;\ -1)$
$\mathbf{T_3}$	$(3;\ 1;\ 2/3;\ -1)$	$\mathbf{T_3^c}$	$(\bar{3};\ 1;\ -2/3;\ -1)$
$\mathbf{D_1}$	$(1;\ 2;\ 1/2;\ -1)$	$\mathbf{D_1^c}$	$(1;\ 2;\ -1/2;\ -1)$
$\mathbf{D_2}$	$(1;\ 2;\ 1/2;\ -1)$	$\mathbf{D_2^c}$	$(1;\ 2;\ -1/2;\ -1)$
$\mathbf{X}$	$(1;\ 1;\ 1;\ 2)$	$\mathbf{X^c}$	$(1;\ 1;\ \text{-}1;\ 2)$
$\mathbf{N}$	$(1;\ 1;\ 0;\ 2)$	$\mathbf{N^c}$	$(1;\ 1;\ 0;\ 2)$
$\mathbf{S}$	$(1;\ 1;\ 0;\ 2)$	$\mathbf{S^c}$	$(1;\ 1;\ 0;\ -2)$
$\mathbf{S_1}$	$(1;\ 1;\ 0;\ -4)$	$\mathbf{S_1^c}$	$(1;\ 1;\ 0;\ 4)$

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; -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)
$\mathbf{S_1}$	(1; 1; 0; −4)	$\mathbf{S_1^c}$	(1; 1; 0; 4)

Can couple to Higgs

Exotics, an example

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

Particles	Gauge charges	Particles	Gauge charges
$\mathbf{L_i}$	$(1;\ 2;\ -1/2;\ 1/2)$	$\mathbf{Q_i}$	$(3;\ 2;\ 1/6;\ 1/2)$
$\mathbf{\bar{N}_i}$	$(1;\ 1;\ 0;\ 1/2)$	$\mathbf{\bar{u}_i}$	$(\bar{3};\ 1;\ -2/3;\ 1/2)$
$\mathbf{\bar{e}_i}$	$(1;\ 1;\ 1;\ 1/2)$	$\mathbf{\bar{d}_i}$	$(\bar{3};\ 1;\ 1/3;\ 1/2)$
$\mathbf{H_d}$	$(1;\ 2;\ -1/2;\ -1)$	$\mathbf{H_u}$	$(1;\ 2;\ 1/2;\ -1)$
$\mathbf{T_1}$	$(3;\ 1;\ 1/3;\ -1)$	$\mathbf{T_1^c}$	$(\bar{3};\ 1;\ -1/3;\ -1)$
$\mathbf{T_2}$	$(3;\ 1;\ 2/3;\ -1)$	$\mathbf{T_2^c}$	$(\bar{3};\ 1;\ -2/3;\ -1)$
$\mathbf{T_3}$	$(3;\ 1;\ 2/3;\ -1)$	$\mathbf{T_3^c}$	$(\bar{3};\ 1;\ -2/3;\ -1)$
$\mathbf{D_1}$	$(1;\ 2;\ 1/2;\ -1)$	$\mathbf{D_1^c}$	$(1;\ 2;\ -1/2;\ -1)$
$\mathbf{D_2}$	$(1;\ 2;\ 1/2;\ -1)$	$\mathbf{D_2^c}$	$(1;\ 2;\ -1/2;\ -1)$
$\mathbf{X}$	$(1;\ 1;\ 1;\ 2)$	$\mathbf{X^c}$	$(1;\ 1;\ -1;\ 2)$
$\mathbf{N}$	$(1;\ 1;\ 0;\ 2)$	$\mathbf{N^c}$	$(1;\ 1;\ 0;\ 2)$
$\mathbf{S}$	$(1;\ 1;\ 0;\ 2)$	$\mathbf{S^c}$	$(1;\ 1;\ 0;\ -2)$
$\mathbf{S_1}$	$(1;\ 1;\ 0;\ -4)$	$\mathbf{S_1^c}$	$(1;\ 1;\ 0;\ 4)$

Can couple to Higgs

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

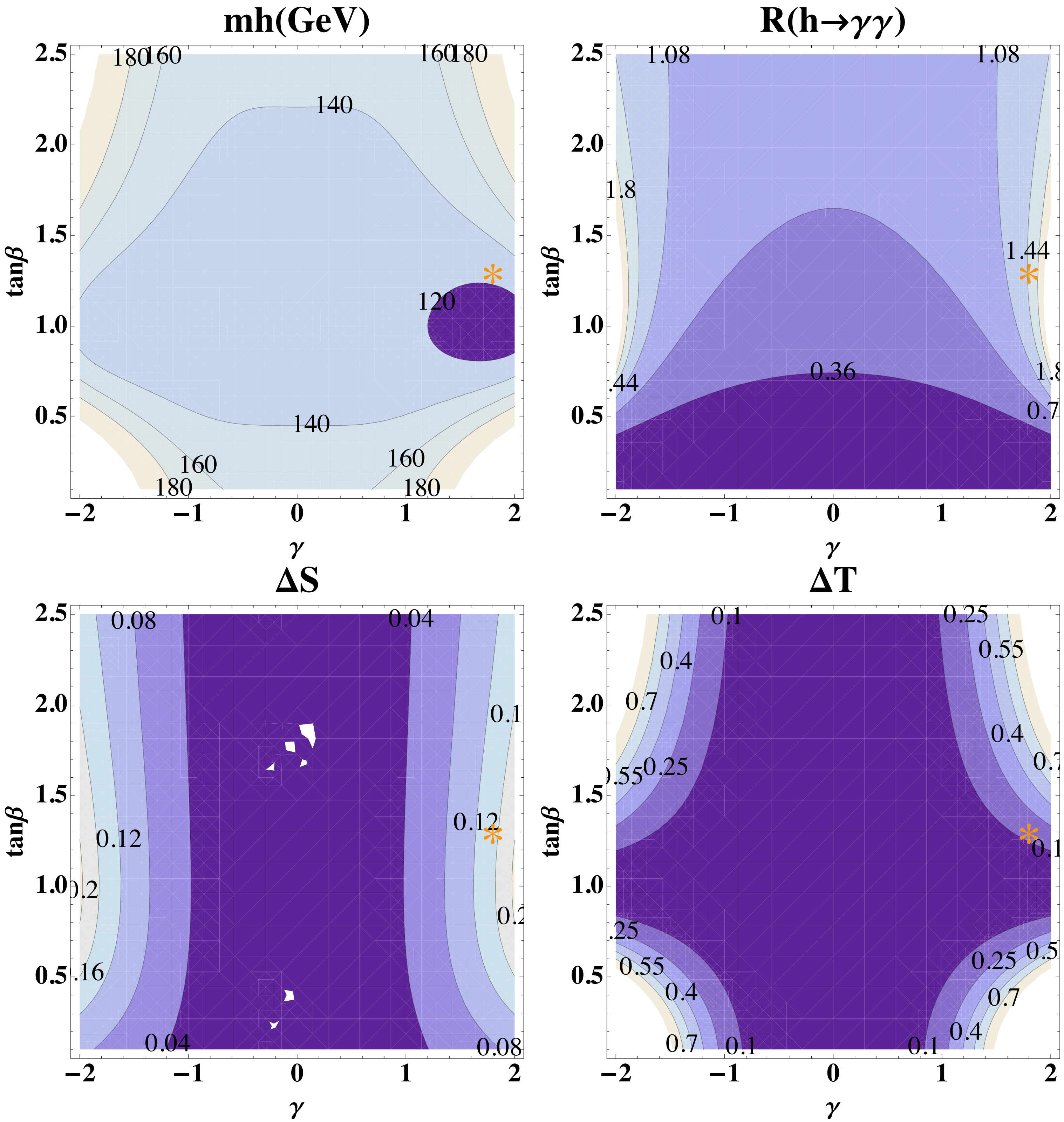
Exampls: light scalar

- g_{PQ} = 0.6, f_{PQ} = 4 TeV, λ=0.2, $\tan\beta$ = 5
- A_λ/f_{PQ} =0.4, $\Delta m_s/M_s$ =0.4
- $\gamma_{1,2}$ = 0.1, γA_1 = -950 GeV, M_D= 600 GeV, $M_{x,N}$ = 400 GeV
- m_{stop} = 400 GeV.
- m_h = 125 GeV, $h\rightarrow\gamma\gamma \approx 1.5 \times$ 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.

Light fermion scenario in more detail



Couplings of the light states.

Higgs, Higgsino-like

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

Singlet, singlino-like

$$H_uH_uX^c \quad H_dH_uN^c$$

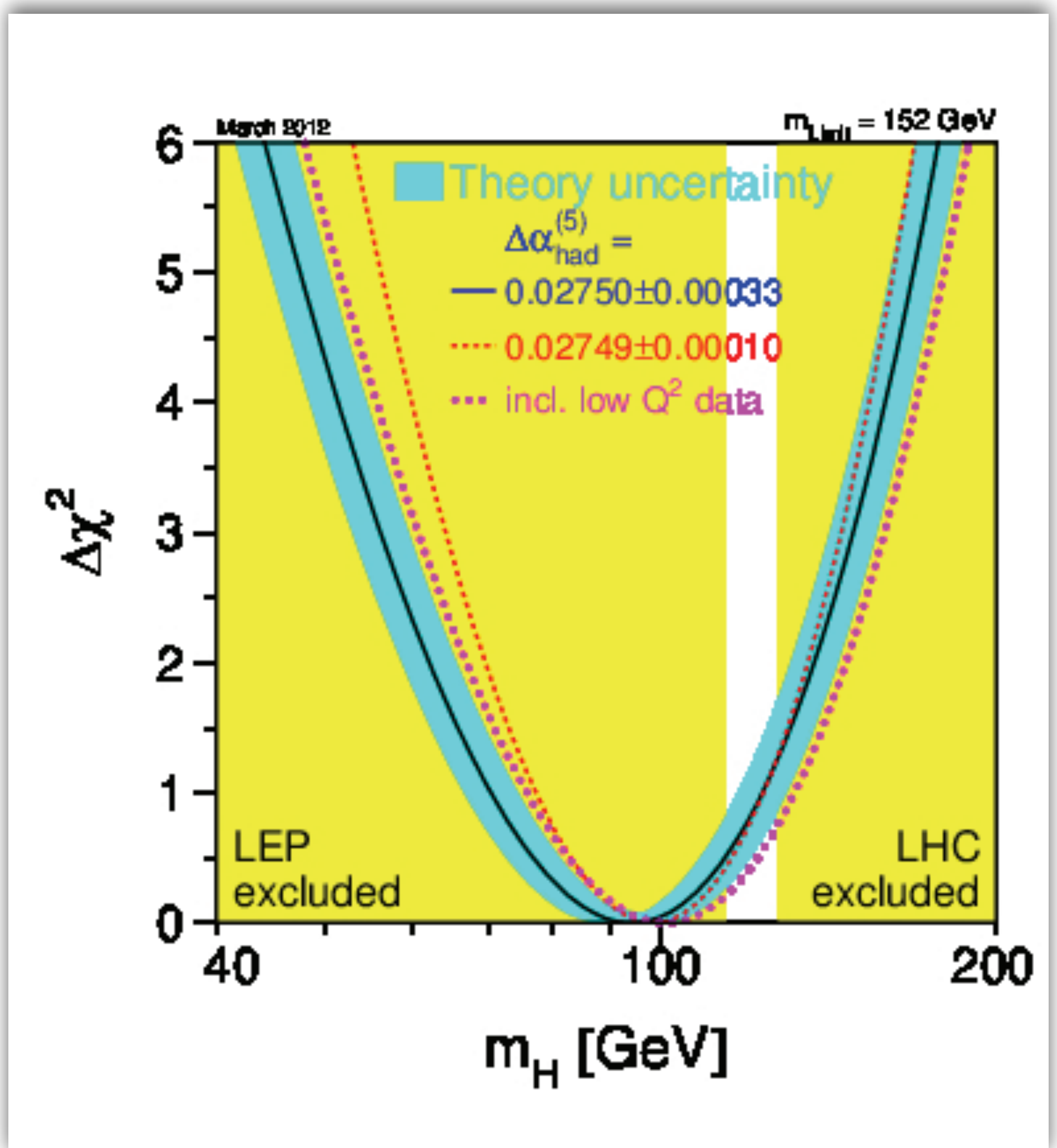
- Discovery in direct SUSY searches might be difficult.

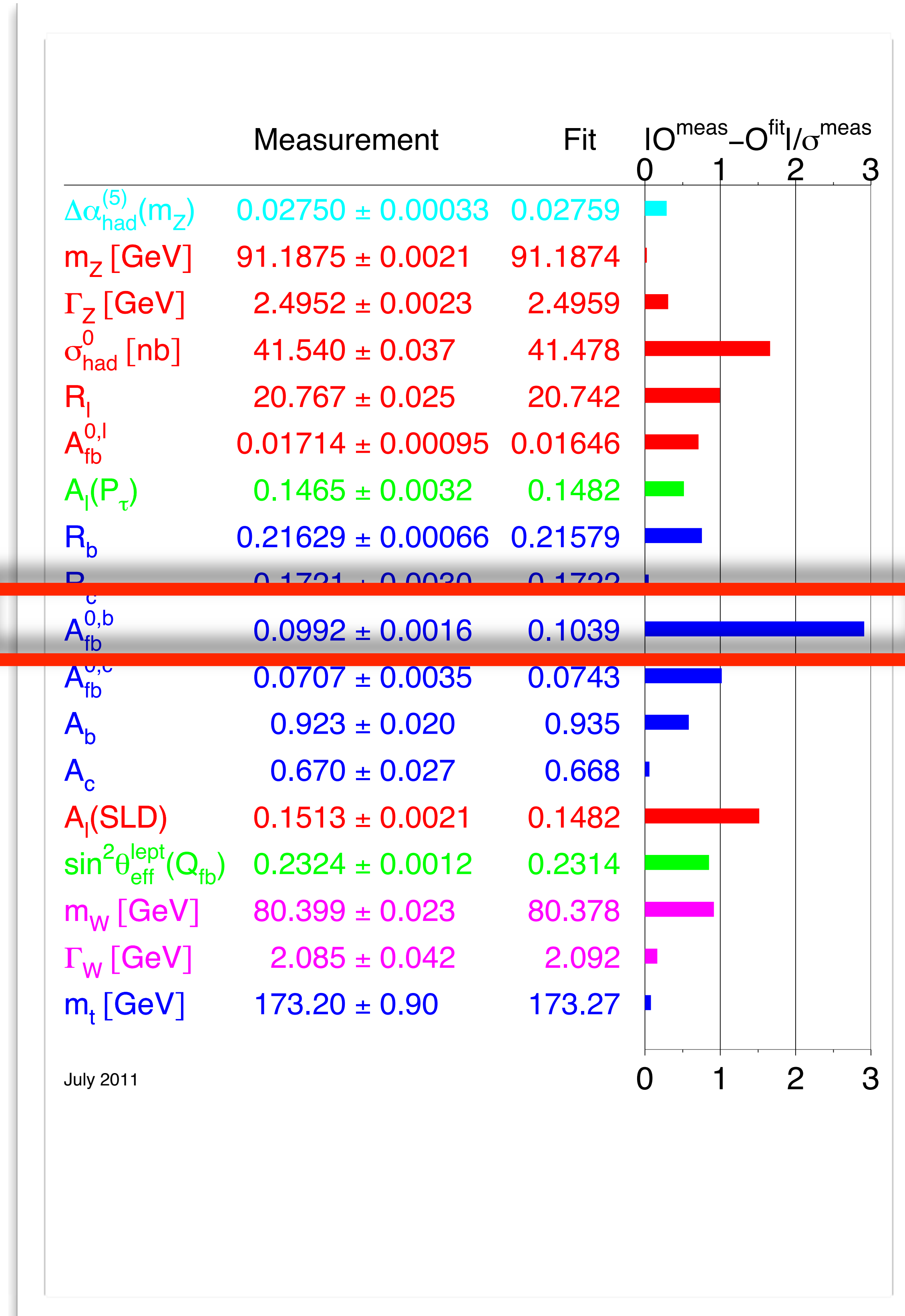
- Modification of Higgs decay maybe their first signal.

Connection to EWPT

Work in progress with B. Batell and S. Gori

Precision Electroweak Data





Consider two possibilities

- New physics gives rise to A_{FB}
- A_{FB} is "wrong" (fluctuation, ...)
  - new physics fix the EWPT fit.
- Possible connection to higgs pheno, $h \to \gamma\gamma$?

“fix” A_{FB} with new physics

Beautiful Mirrors

Choudhury, Tait, Wagner '01

Basic idea: Mix new vector-like quark with bottom quark

$$\mathcal{L} \supset -\,(\bar{b}'_L \;\; \bar{B}'_L) \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} b'_R \\ B'_R \end{pmatrix} + \text{h.c.}$$

Diagonalize mass matrix via rotations of $b_{i(L,R)}$, with angles $\theta_{L,R}$

Z boson interactions: $\mathcal{L} \supset \frac{g}{c_w} Z_\mu \sum_{ij} \bar{b}_i \gamma^\mu (L_{ij} P_L + R_{ij} P_R) b_j$

Shifts in $Z\bar{b}b$ couplings:

$$\boxed{\delta g_{Lb} = \left(t_{3L} + \frac{1}{2}\right) s_L^2, \qquad \delta g_{Rb} = t_{3R} s_R^2,}$$

Singles out 3 vector-like representations:

$$\Psi_{L,R} \sim (3,2,1/6), (3,2,-5/6), (3,3,2/3)$$

Slides from Brian Batell

Example: $\Psi \sim (3, 2, -5/6) \sim \begin{pmatrix} B \\ X \end{pmatrix}$

$t_{3R}^B = \frac{1}{2}$ ➡ $\delta g_{Rb} = \frac{1}{2} s_R^2 = 0.02$ ➡ $\sin\theta_R \approx 0.2$

Consider EFT with general Higgs couplings:

$$\mathcal{L} \supset -y_1 \bar{Q} H b_R - y_2 \bar{\Psi}_L H^\dagger b_R - M \bar{\Psi}_L \Psi_R \ + \text{h.c.}$$

$$-a\frac{|H|^2}{\Lambda}\bar{\Psi}_L\Psi_R - b\frac{|H|^2}{\Lambda^2}\bar{Q}Hb_R - c\frac{|H|^2}{\Lambda^2}\bar{\Psi}_L H^\dagger b_R + \dots \quad + \text{h.c.}$$

$$\to -\left(\bar{b}_L \ \bar{B}_L\right)\left\{\begin{pmatrix} Y_1 + \frac{bv^3}{2\sqrt{2}\Lambda^2} & 0 \\ Y_2 + \frac{cv^3}{2\sqrt{2}\Lambda^2} & M + \frac{av^2}{2\Lambda} \end{pmatrix} + h\begin{pmatrix} \frac{Y_1}{v} + \frac{3bv^2}{2\sqrt{2}\Lambda^2} & 0 \\ \frac{Y_2}{v} + \frac{3cv^2}{2\sqrt{2}\Lambda^2} & \frac{av}{\Lambda} \end{pmatrix}\right\}\begin{pmatrix} b_R \\ B_R \end{pmatrix} + \text{h.c.}$$

Diagonalize mass matrix via rotations...

Higgs physics

see also Wagner, Morrissey '03 for $(3, 2, 1/6)$

$$\mathcal{L}_{hqq} \supset -\xi_{hbb}\frac{m_b}{v}h\bar{b}b - \xi_{hBB}\frac{m_B}{v}h\bar{B}B$$
$$-\xi_{hXX}\frac{m_X}{v}h\bar{X}X$$

$$\xi_{hbb} \approx c_R^2 + \frac{bv^3}{\sqrt{2}m_b\Lambda^2} - \frac{c\, s_R v^3}{\sqrt{2}m_B\Lambda^2}$$

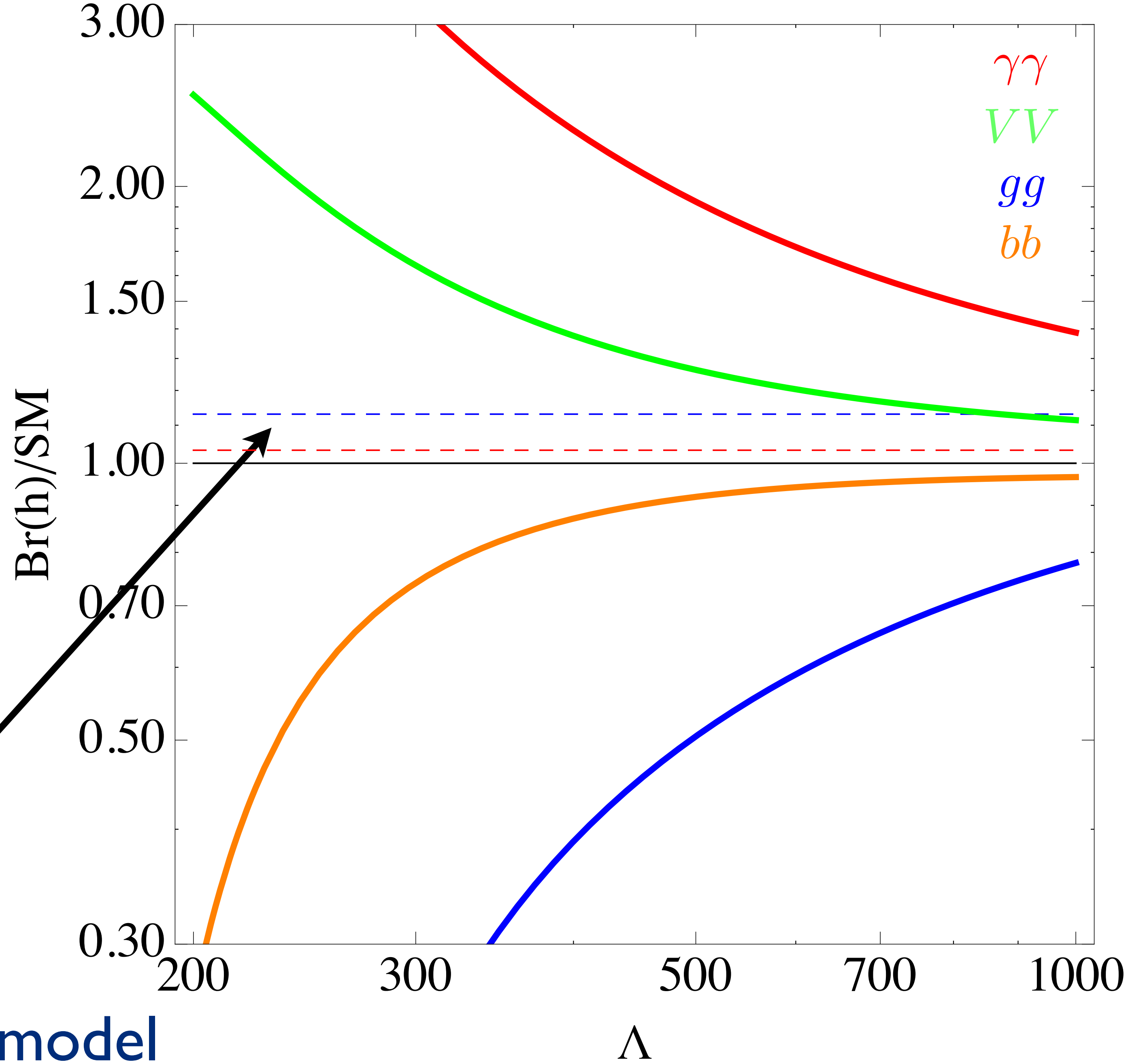
$$\xi_{hBB} \approx s_R^2 + \frac{av^2}{m_B\Lambda} + \frac{c\, s_R v^3}{\sqrt{2}m_B\Lambda^2}$$

$$\xi_{hXX} = \frac{av^2}{m_X\Lambda}$$

To enhance $\gamma\gamma$ rate:

- Suppress $h \to b\bar{b}$ partial width: $\xi_{hbb} < 1$
- Heavy quarks interfere constructively with SM $h \to \gamma\gamma$ amplitude: $\xi_{hBB}, \xi_{hXX} < 0$

$a = -1,\ b = -0.01,\ c = 0,\ m_B = 600\,\mathrm{GeV}$



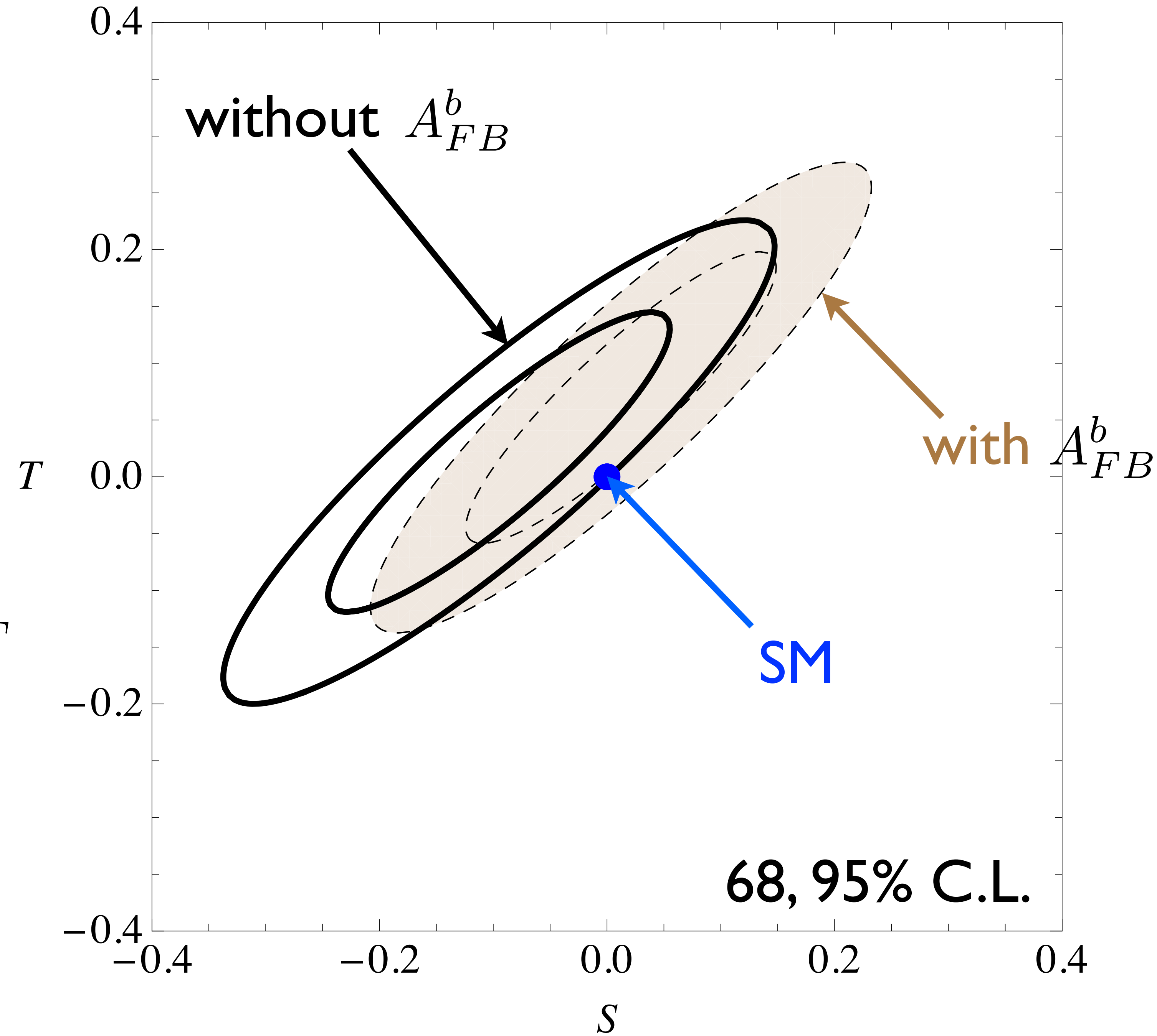
Renormalizable model
$(a = b = c = 0)$

- Enhancement in $\gamma\gamma$
- Suppression in gluon fusion
- "Acceptable" suppression in $b\bar{b}$

Ignore A_{FB}

$S-T$ fit without A^b_{FB}

$$A^b_{FB} - (A^b_{FB})_{\rm SM} \simeq -0.020\,S + 0.014\,T$$



Electroweak data (w/o A^b_{FB}) indicate a positive T, negative S

Simplest example: a second scalar doublet

$$S \sim (1,2,1/2) = \begin{pmatrix} S^+ \\ \frac{1}{\sqrt{2}}(S_0^R + i S_0^I) \end{pmatrix}$$

$$V \supset m^2|S|^2 + \lambda_1 |S|^2|H|^2 + \lambda_2 (H^\dagger S)(S^\dagger H) + [\lambda_3 (H^\dagger S)(H^\dagger S) + \text{h.c.}] + \dots$$

hS^+S^- coupling

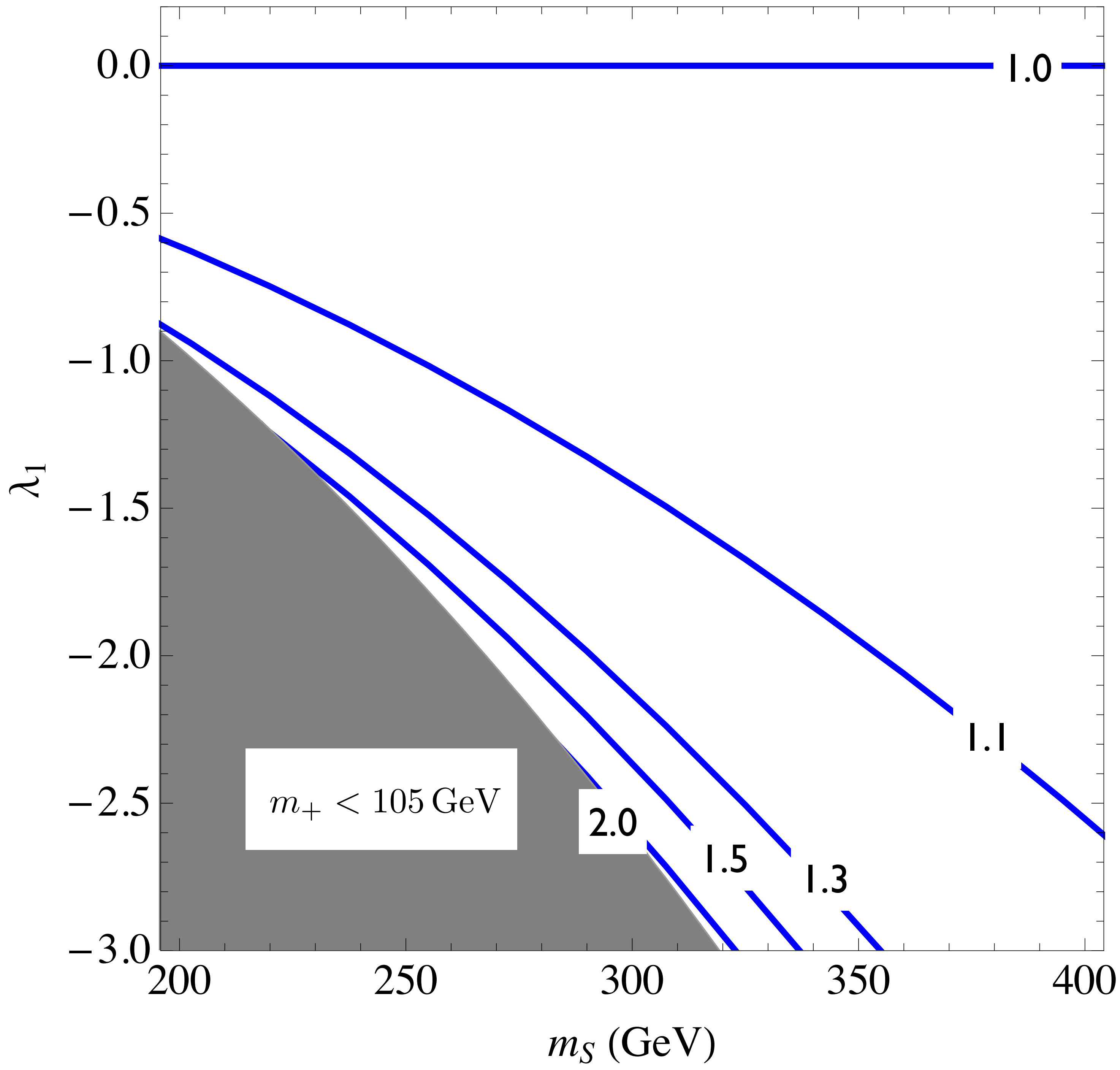
contribution to $h \to \gamma\gamma$

Custodial breaking

$$S \simeq \frac{\lambda_2 v^2}{24\pi m^2}$$

$$T \simeq \frac{v^4}{192\pi s_w^2 M_W^2 m^2}[(\lambda_2)^2 - 4(\lambda_3)^2]$$

$\mathrm{Br}(h \to \gamma\gamma)/\mathrm{SM}$

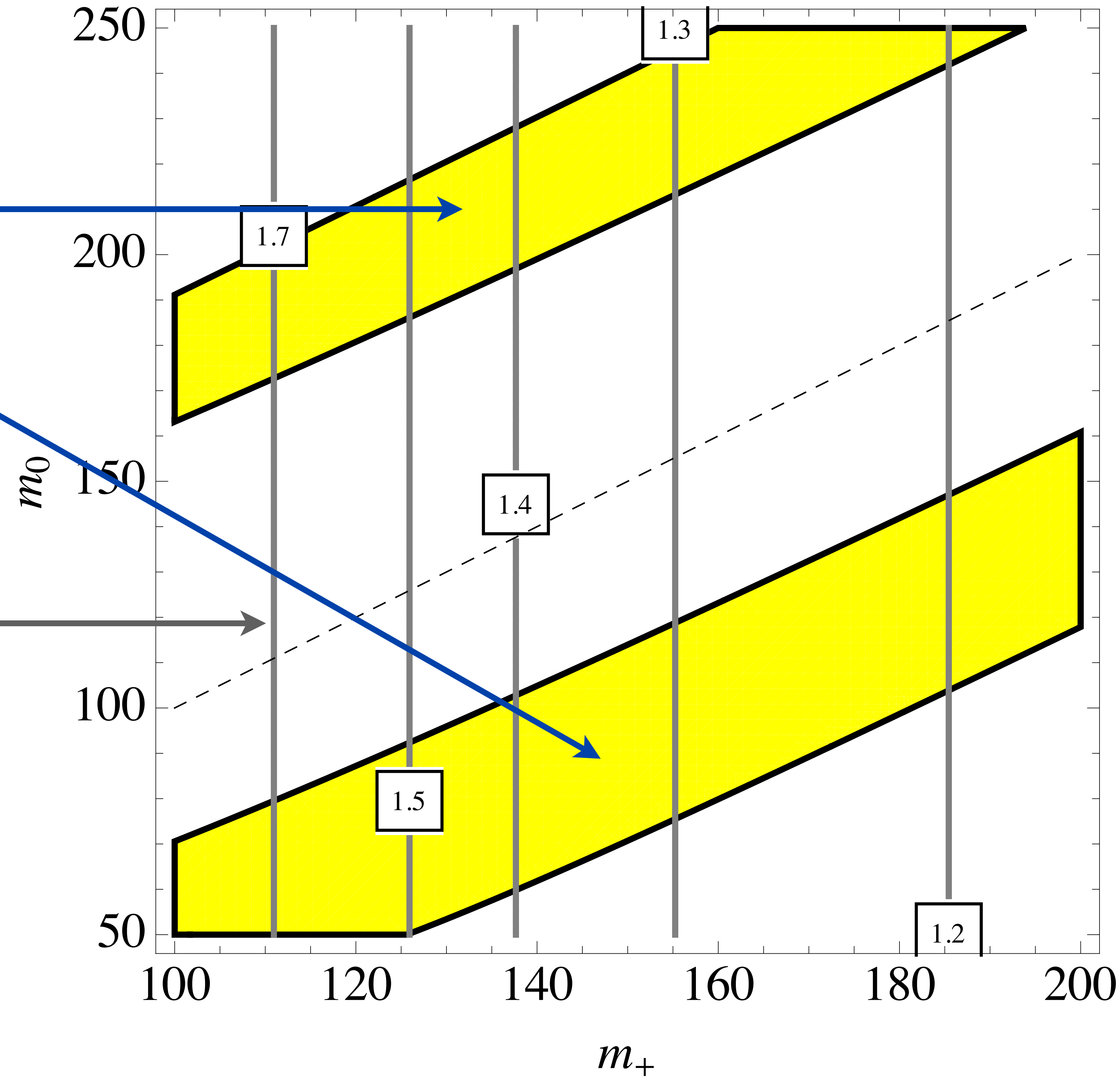


Require light charged scalars for big enhancement

e.g. $\lambda_1 = -2,\ \lambda_3 = 0$

$S - T$

preferred regions



$\mathrm{Br}(h \to \gamma\gamma)/\mathrm{SM}$

Requires mass splittings ~ 60-70 GeV

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.

Modify $Zb_R\bar{b}_R$ coupling

Haber, Logan '99
Choudhury, Tait, Wagner '01

$$\mathcal{L} = \frac{g}{c_w}\bar{b}\gamma^\mu\left(g_{Lb}P_L + g_{Rb}P_R\right)b$$

$$g_{Lb} = -\frac{1}{2} + \frac{1}{3}s_w^2 \approx -0.43$$
$$g_{Rb} = \frac{1}{3}s_w^2 \approx 0.0771$$

Goal: shift A_{FB}^b without affecting R_b

$$A_{FB} = \frac{3}{4}\frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2}\frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2}$$

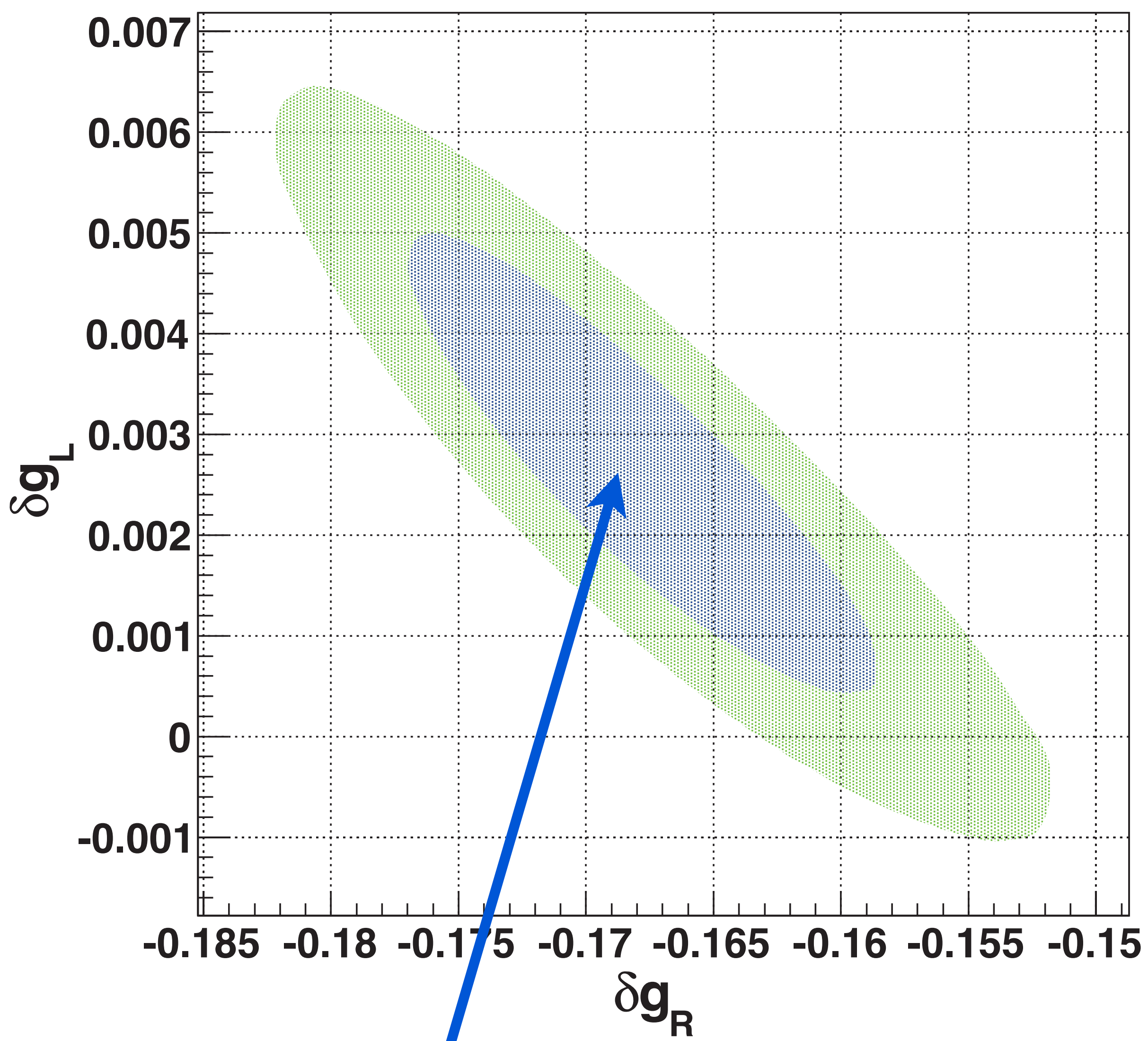
$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \simeq \frac{g_{Lb}^2 + g_{Rb}^2}{\sum_q [g_{Lq}^2 + g_{Rq}^2]}$$

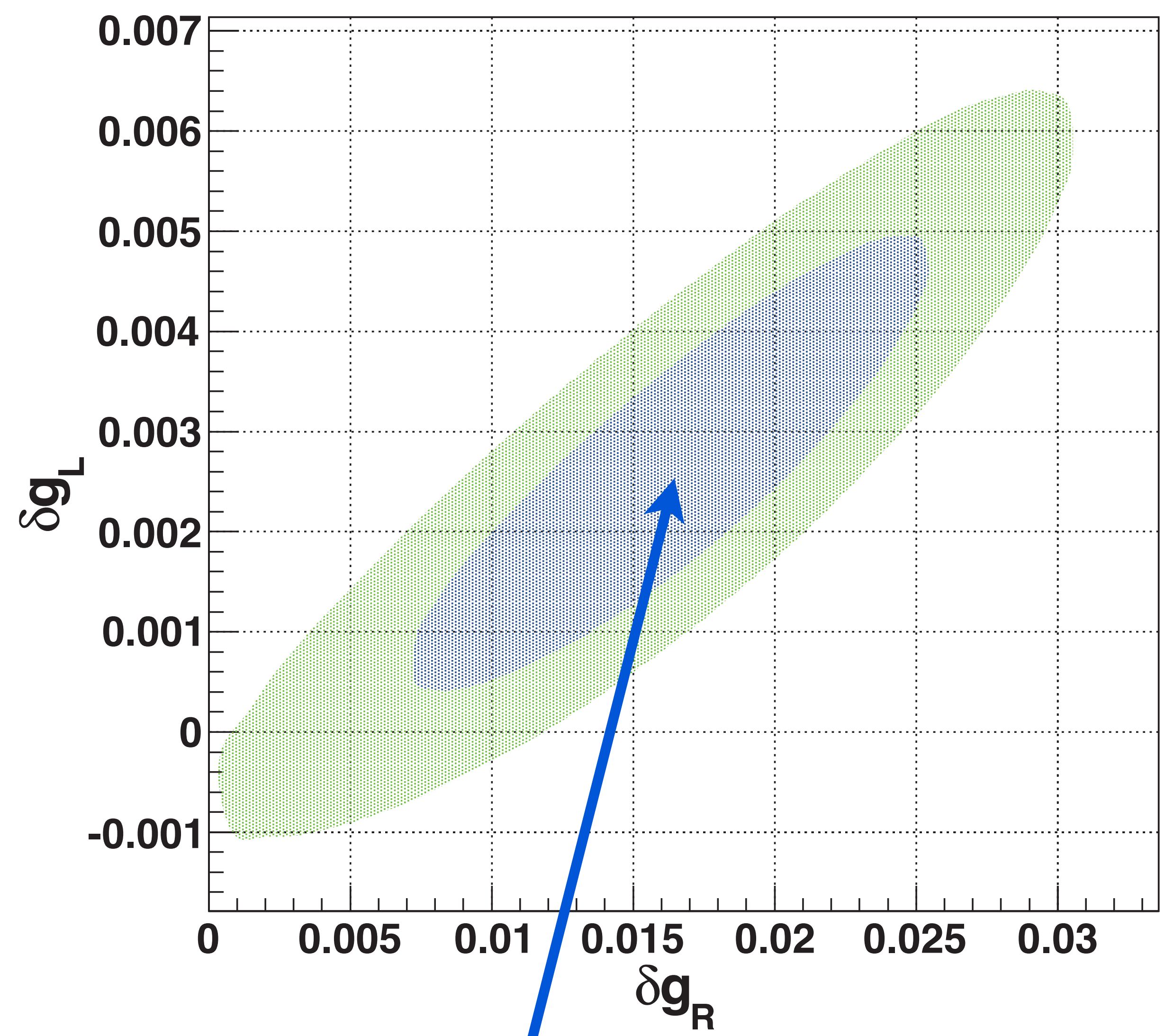
Z-pole data allows 4 solutions in $(\delta g_{Lb}, \delta g_{Rb})$, off-peak data for A_{FB}^b eliminate 2 possible solutions

Data prefers a bigger shift in δg_{Rb}, smaller shift in δg_{Lb}

Fit: 2 solutions

Kumar, Shepherd, Tait, Vega-Morales '10





Large negative δg_R^b solution

Small positive δg_R^b solution

$\delta g_{Lb} \sim 0.003 \qquad \delta g_{Rb} \sim -0.17$

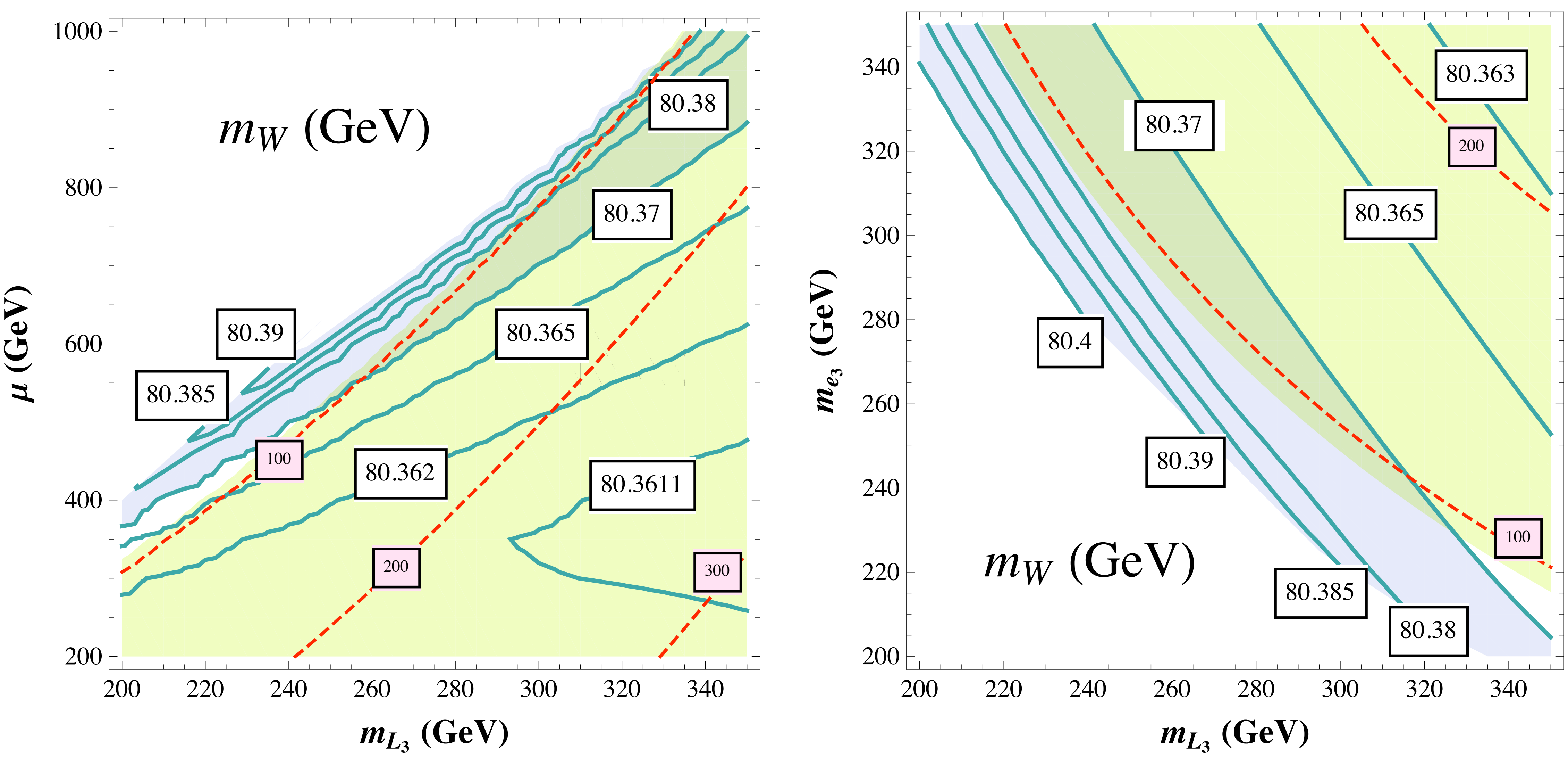
$\delta g_{Lb} \sim 0.003 \qquad \delta g_{Rb} \sim 0.02$

Direct constraints on mirror quarks

see also Kumar, Shepherd, Tait, Vega-Morales '10

$B \to bZ$	ATLAS, 1204.1265	400 GeV
$B \to tW$	CMS, 1204:1088 (3l or 2SSl+b-jet)	611 GeV
$B \to bh$	—	—
$X \to bW$	CMS, PAS-EXO-11-099 (lepton + jets)	560 GeV

Precise bounds depend on branching ratios (in progress)


m_W (GeV)
80.38
80.37
80.39
80.385
80.365
100
80.362
80.3611
200
300
1000
800
600
400
200
μ (GeV)
200
220
240
260
280
300
320
340
m_{L_3} (GeV)
80.363
80.37
200
80.365
80.4
80.39
100
m_W (GeV)
80.385
80.38
340
320
300
280
260
240
220
200
m_{e_3} (GeV)
200
220
240
260
280
300
320
340
m_{L_3} (GeV)

Light fermion benchmark

$g_{\rm PQ}$	$f_{\rm PQ}$ (GeV)	$f_S/f_{\rm PQ}$	$A_\lambda/f_{\rm PQ}$	λ
0.6	3750	0.4	0.4	0.2
$\tan\beta$	A_γ (GeV)	A_{γ_c} (GeV)	γ, γ_c	M_D (GeV)
1.3	300	300	1.8	480
M_X (GeV)	$m_{\tilde{D},\tilde{X},\tilde{N}}$ (GeV)	δ	X_t (GeV)	$M_{\tilde{t}}$ (GeV)
360	900	0.5	600	300
a_1	a_2	a_3	B_μ (10^4 GeV^2)	$\mu_{\rm eff}$ (GeV)
0.02	0.11	-0.01	45	300
m_h (GeV)	$m_{\psi 1^c}$ (GeV)	$m_{\psi 1^0}$ (GeV)	$m_{\phi 1^c}$ (GeV)	$m_{\phi 1^0}$ (GeV)
125	106	106	882	882
$R(h\to\gamma\gamma)$	ΔS	ΔT		
1.5	0.15	0.14		

Light scalar benchmark

$g_{\rm PQ}$	$f_{\rm PQ}$ (GeV)	$f_S/f_{\rm PQ}$	$A_\lambda/f_{\rm PQ}$	λ
0.6	3750	0.4	0.4	0.2
$\tan\beta$	A_γ (GeV)	A_{γ_c} (GeV)	γ, γ_c	M_D (GeV)
5	-950	100	0.2	600
M_X (GeV)	$m_{\tilde{D},\tilde{X},\tilde{N}}$ (GeV)	δ	X_t (GeV)	$M_{\tilde{t}}$ (GeV)
400	100	0.5	800	400
a_1	a_2	a_3	B_μ (10^4 GeV^2)	$\mu_{\rm eff}$ (GeV)
0.017	0.106	-0.014	45	300
m_h (GeV)	$m_{\psi 1^c}$ (GeV)	$m_{\psi 1^0}$ (GeV)	$m_{\phi 1^c}$ (GeV)	$m_{\phi 1^0}$ (GeV)
124	396	396	120	382
$R(h\to\gamma\gamma)$	ΔS	ΔT		
1.9	0.03	0.11		