Higgs and New Physics

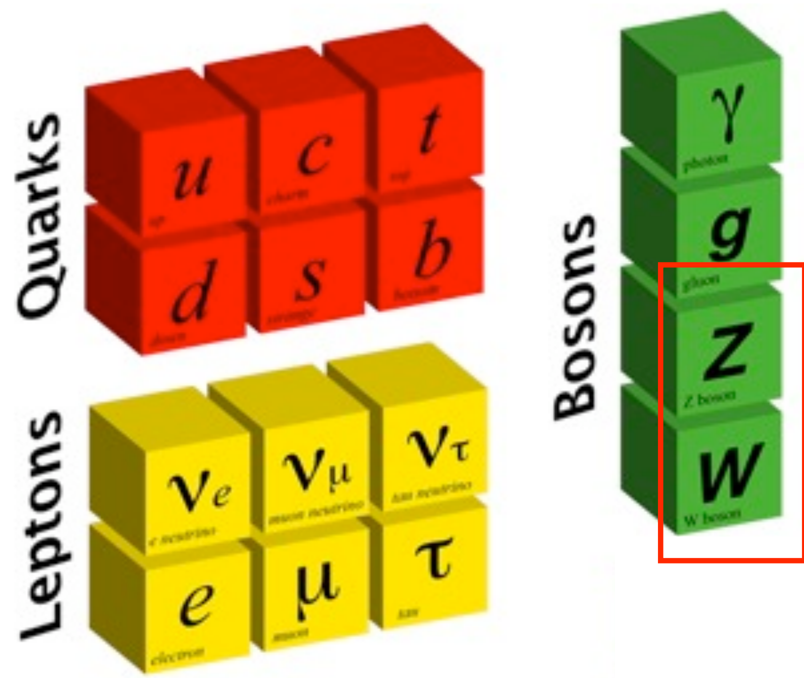
Lian-Tao Wang
University of Chicago

LPC seminar, March 28 2012

The Standard Model

Force carriers

Interaction strength



Electromagnetic $\quad e$

Strong $\quad g_{\text{strong}}$

Weak $\quad g_{\text{W}}$

$$m_{\text{W,Z}} \simeq 10^2 \text{ GeV}$$

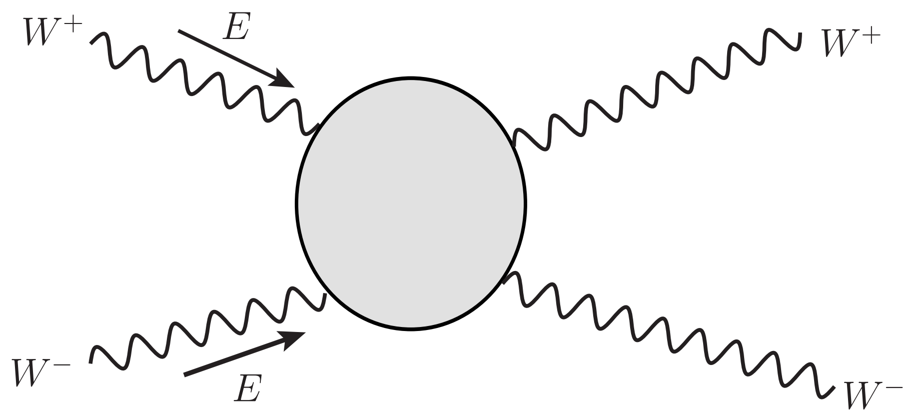
- Electroweak symmetry breaking: weak interaction has finite range

$$V_{\text{weak}}(r) \approx \frac{e^{-r/r_{\text{W}}}}{r}, \;\; r_{\text{W}} \approx m_{\text{W,Z}}^{-1} \approx 10^{-17} \text{ m}$$

Fermi, 1934

Standard Model needs to be extended.

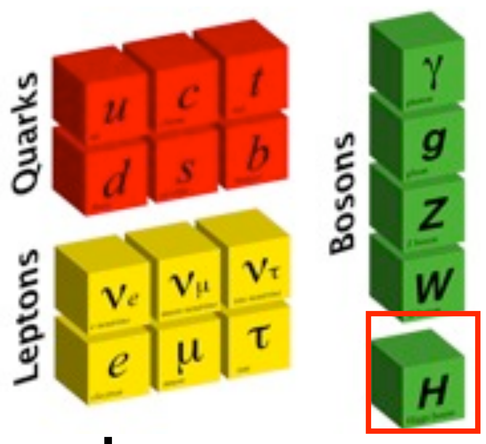
Consider:



$$\text{Amplitude} \approx g_{\mathrm{W}}^2 \frac{E^2}{m_{\mathrm{W}}^2}$$

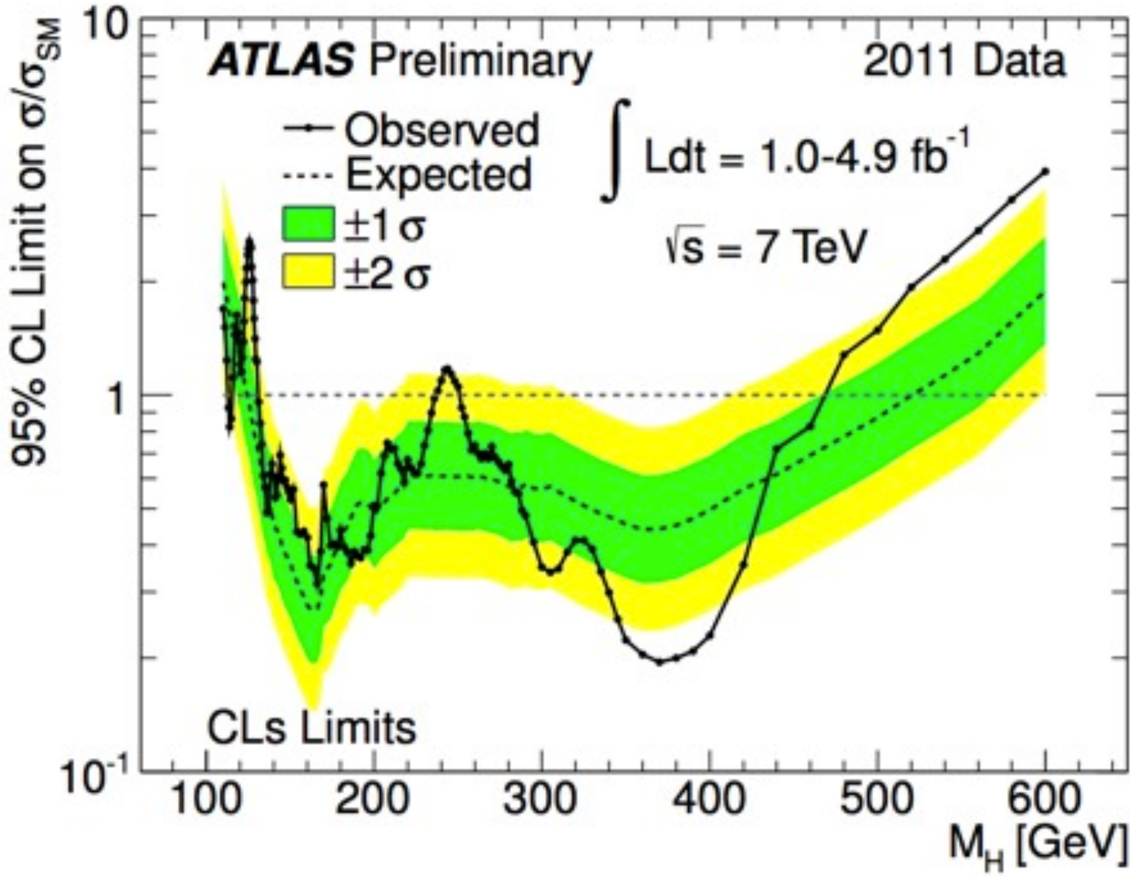
Growing stronger at higher energy.
Perturbative unitarity breaks down.

- Therefore, this picture is not valid at $E \sim 4\pi m_{\mathrm{W}}/g_{\mathrm{W}} \simeq \text{ TeV}$
- Something new must happen before TeV scale.
- Simplest new physics:
  - The Higgs boson, a spin-0 neutral particle.
  - Higgs field can give mass to both electrons and gauge bosons (W, Z).

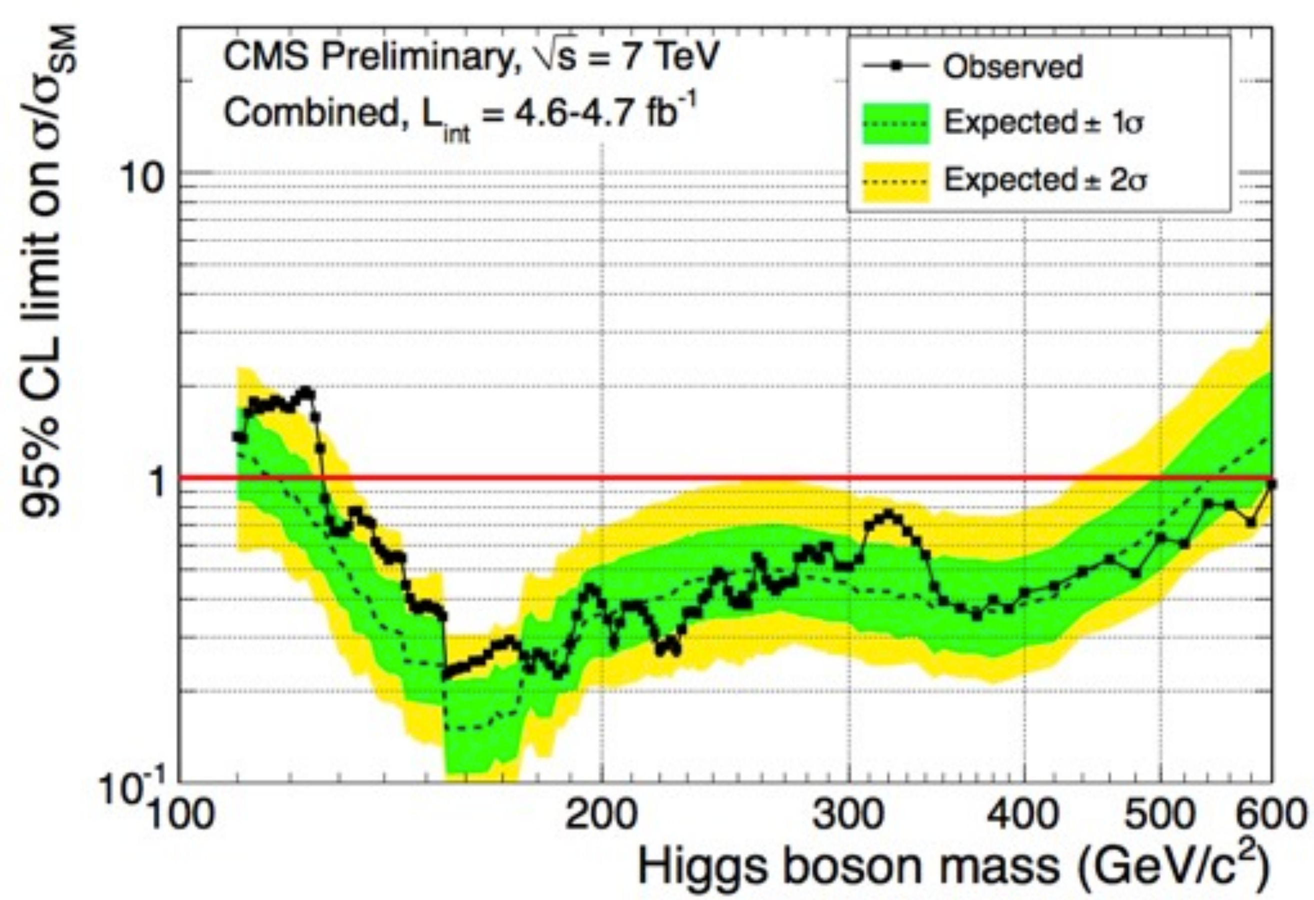


The news

ATLAS-CONF-2011-163

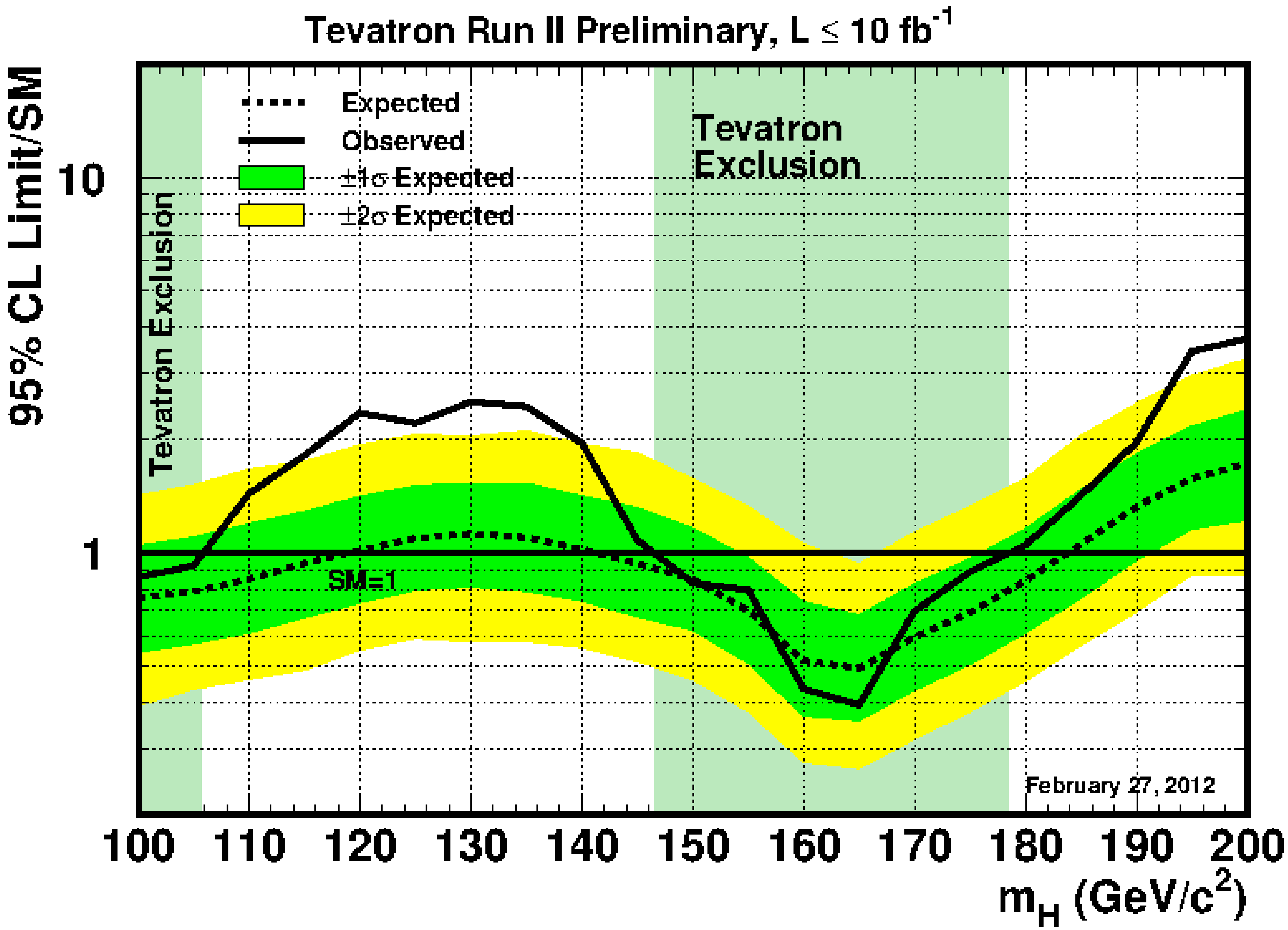


CMS PAS HIG-11-032



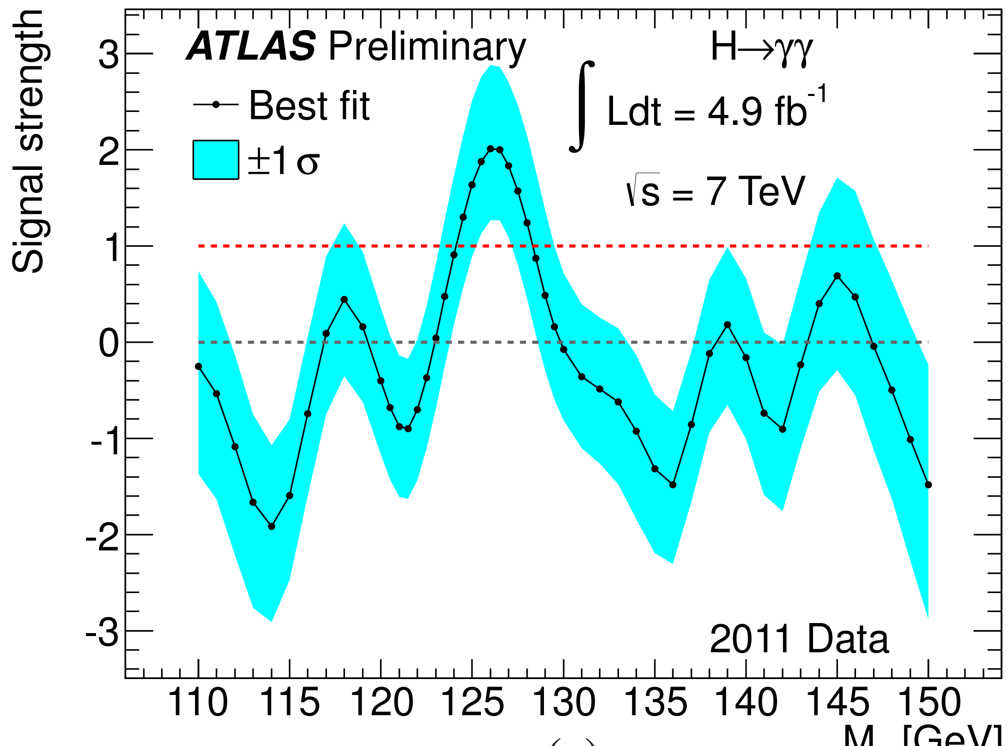
- $m_h > 130$ GeV is excluded.
- A hint of light Higgs signal around 124-126 GeV.

Tevatron

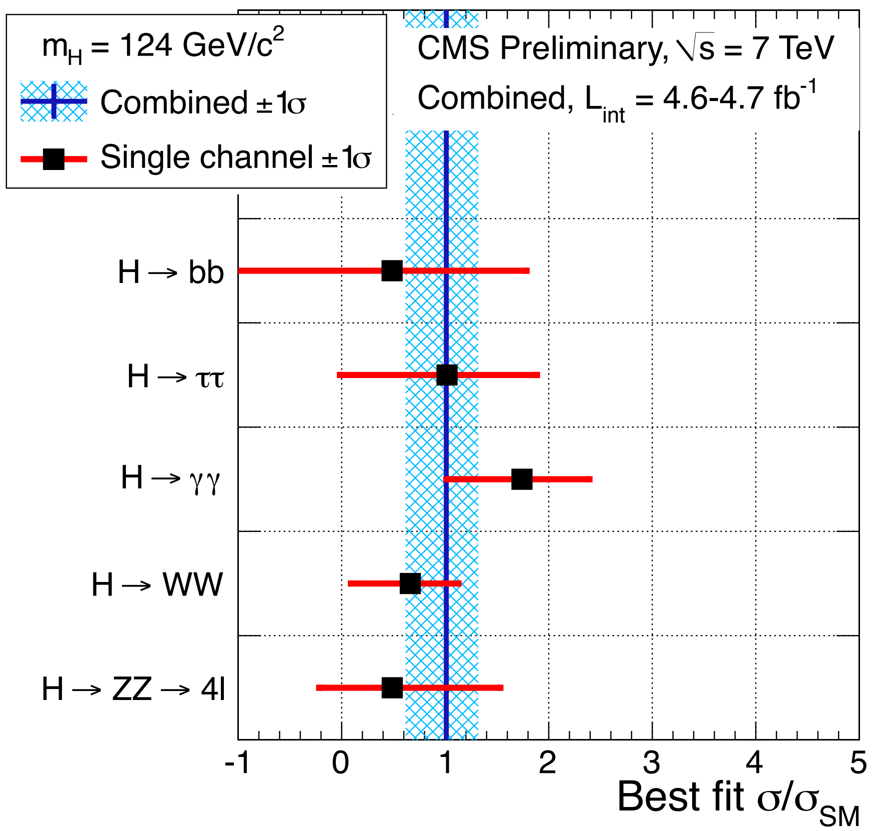


Tevatron Run II Preliminary, L ≤ 10 fb⁻¹
95% CL Limit/SM
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron Exclusion
Tevatron Exclusion
SM=1
February 27, 2012
10
1
100
110
120
130
140
150
160
170
180
190
200
m_H (GeV/c²)

h→γγ higher than SM prediction?



(a)



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  - This is not a Higgs. Radion?
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Winning lottery

Why new physics

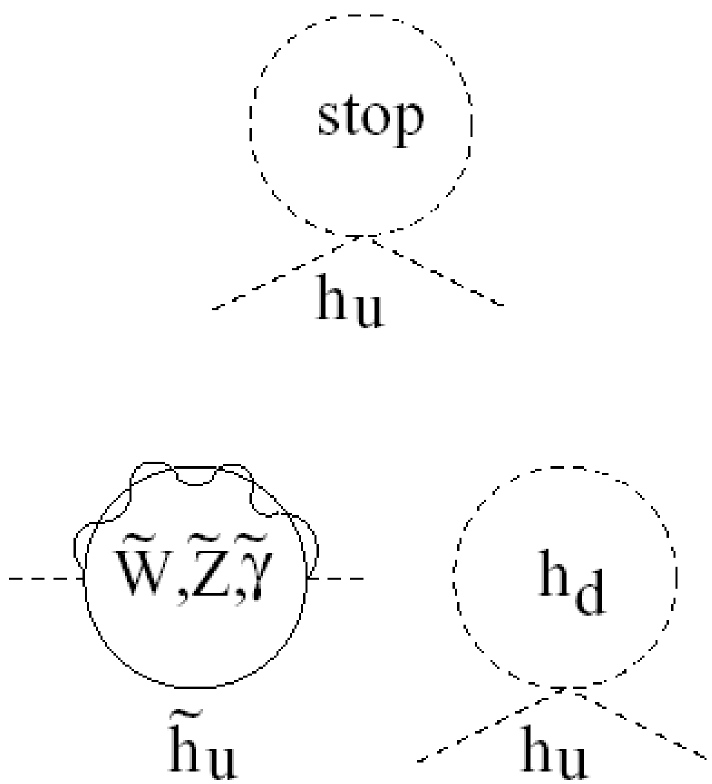
- Naturalness puzzle.
  - Why the electroweak scale, or higgs mass, so much less than other possible fundamental scales, for example, $M_{Pl} = 10^{19}$ GeV.
  - Is such a large scale separation generic in quantum theory? Due to quantum fluctuations,

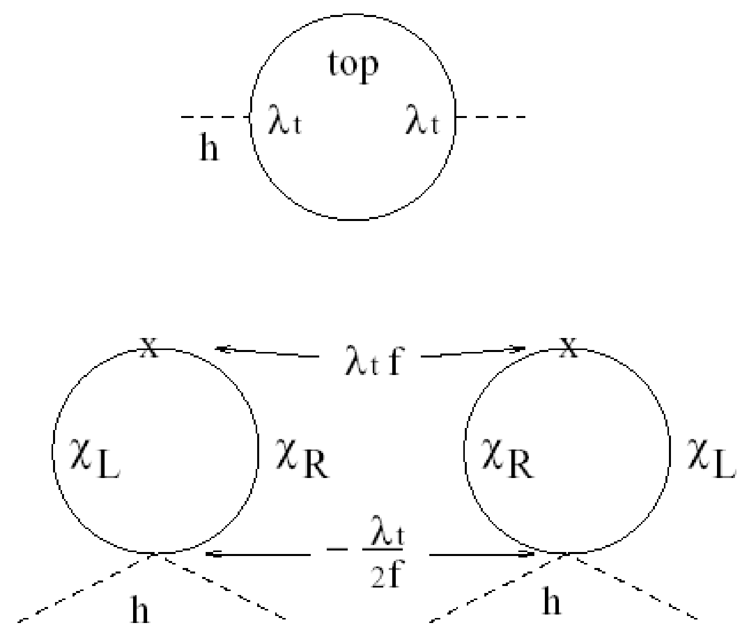
$$m_h^2 \sim m_{h0}^2 + c\Lambda^2, \quad \Lambda = M_{\mathrm{Pl}}, \ldots$$

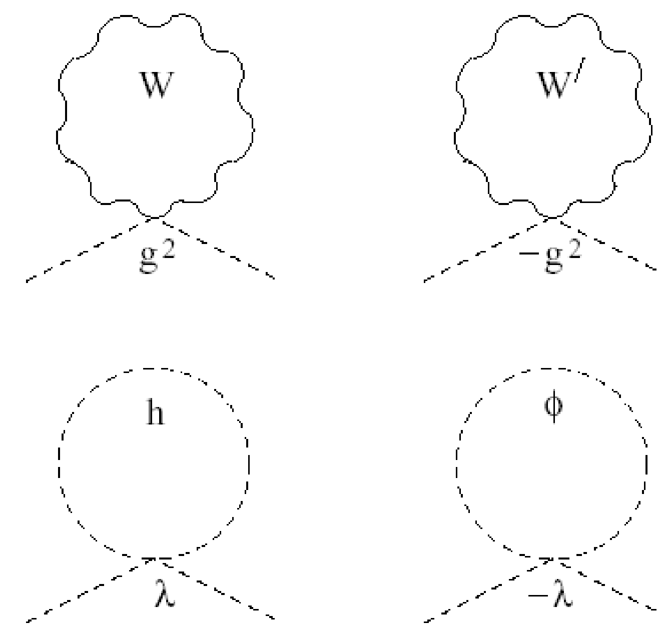
  - Large fine-tuning. Something needs to control the quantum fluctuations.

Why new physics?

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







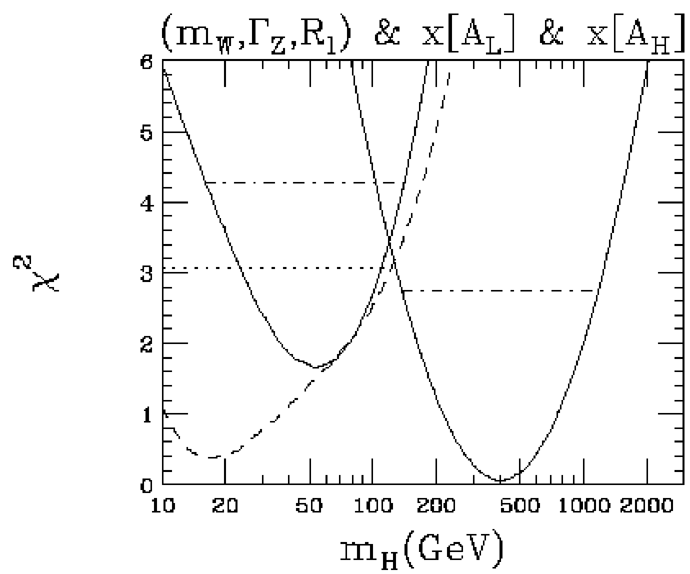
Why new physics

- Electroweak baryongenesis.
  - Strong first order EW phase transition.
  - Large CP violation.

Cohen, Morrissey, Pierce, 1203.2924
Curtin, Jaiswal, Meade, 1203.2932

Why new physics?

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



- Dark matter.
  - Perhaps Higgs has something to do with its mass.
  - Higgs-DM coupling, $\sigma_{SI} \sim 10^{-44}\text{cm}^{-2}$, being probed at direct detection. Good lamppost!

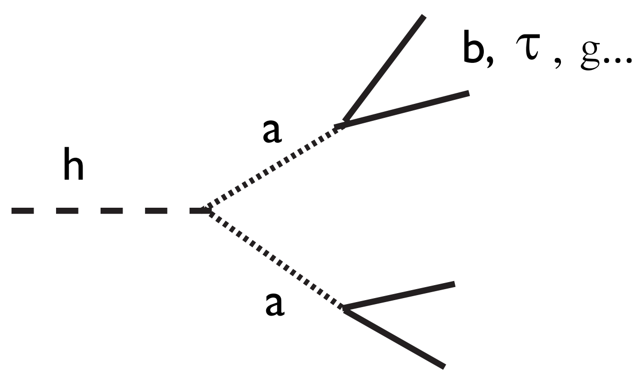
Lopez-Honorez, Schwetz, Zupan, 1203.2064

How might NP show up?

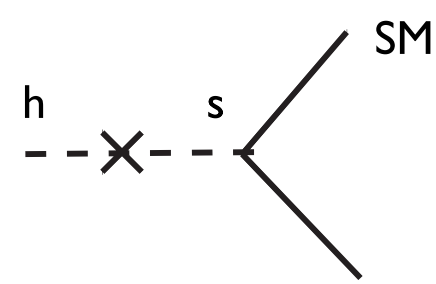
- Being directly produced and detected at the LHC.
  - SUSY: superpartners.
  - Composite Higgs (extra dim): resonances.

- Modification of Higgs production and decay.

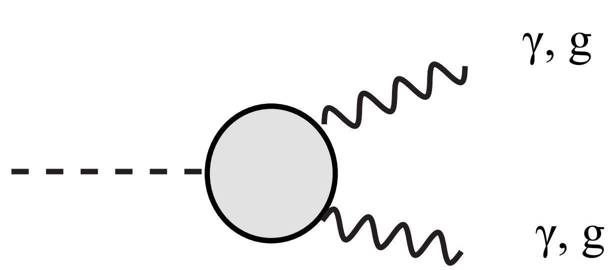
to new states



mixing



in the loop



Loop of NP

In addition to measuring Higgs properties,
We can also look for the new states.

Longer term

- Era of precision Higgs physics.
  - Independent of whether other NP are found.

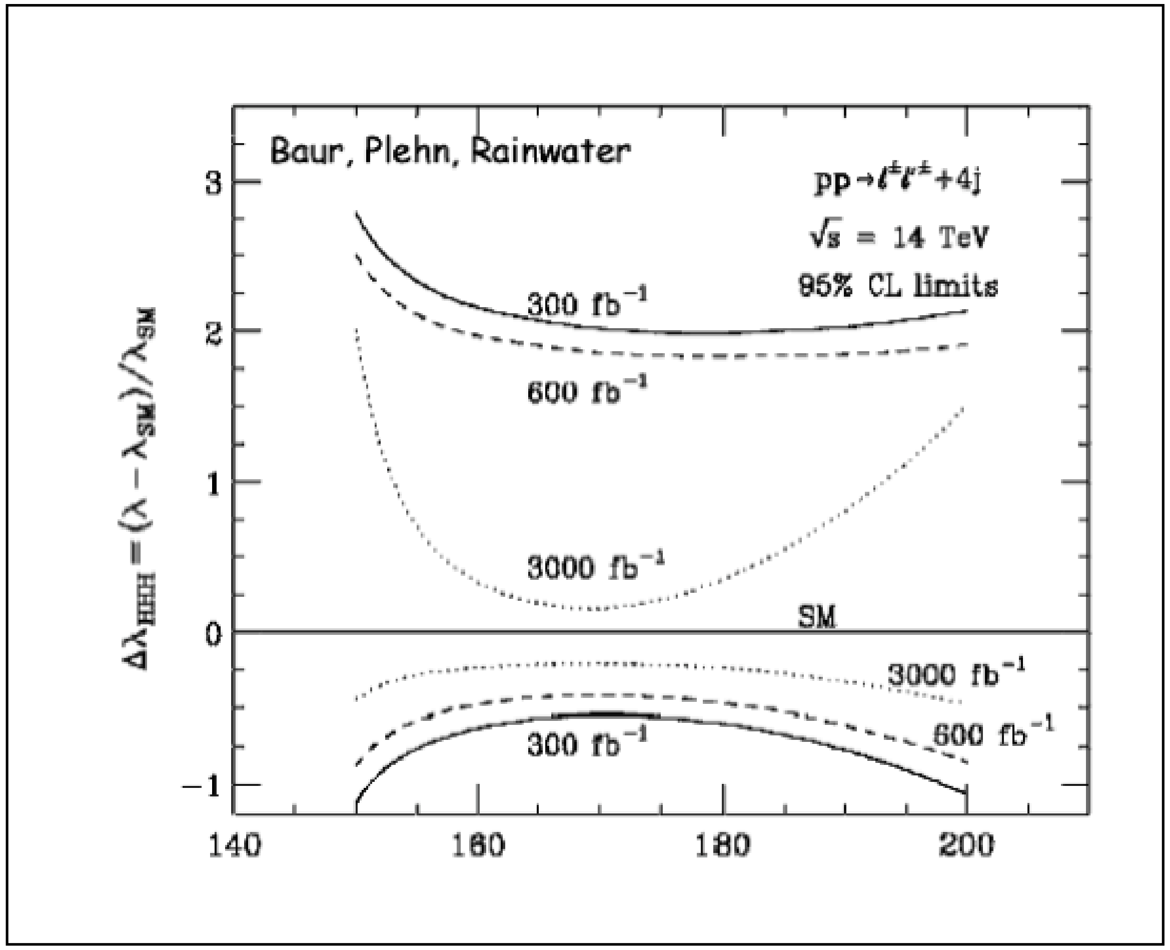
$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\,(V_\mu V^\mu)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] - m_i \bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \mathrm{h.c.} \\ &+ \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \\ &+ c_g\frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma\frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}\end{aligned}$$

Contino, Grojean, Moretti, Piccinini, RR '10

  - Measuring a, b, c, d reveal nature of Higgs and information of NP.
  - For example, in composite Higgs models, deviation on the order of

$$\frac{v^2}{f^2} \sim 10\% - \mathrm{ish}$$

Example, Higgs triple coupling.



$$gg \to hh \to 4W \to \ell\ell 4j$$

Baur, Plehn, Rainwater, 2002

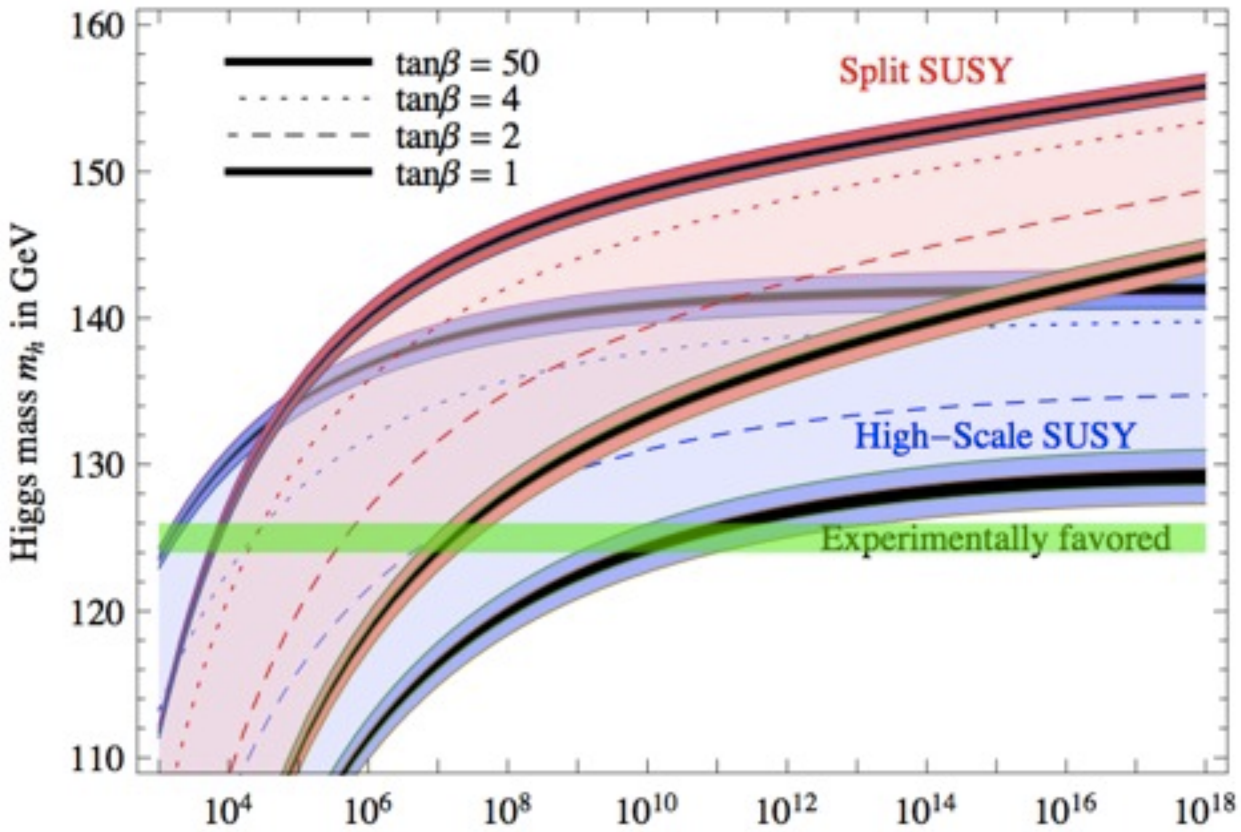
- Very hard, according to this study 10 years ago.

- But, perhaps we can do better?

Supersymmetry.

SUSY.

- $\sim$ 60 papers so far.
- 80% on SUSY. Natural. Prefer light Higgs.
  - A bit heavy for MSSM. But certainly possible.



Giudice, Strumia, 2011

  - Is heavy scalar reasonable?
  - Very strong limits on gauge mediation.

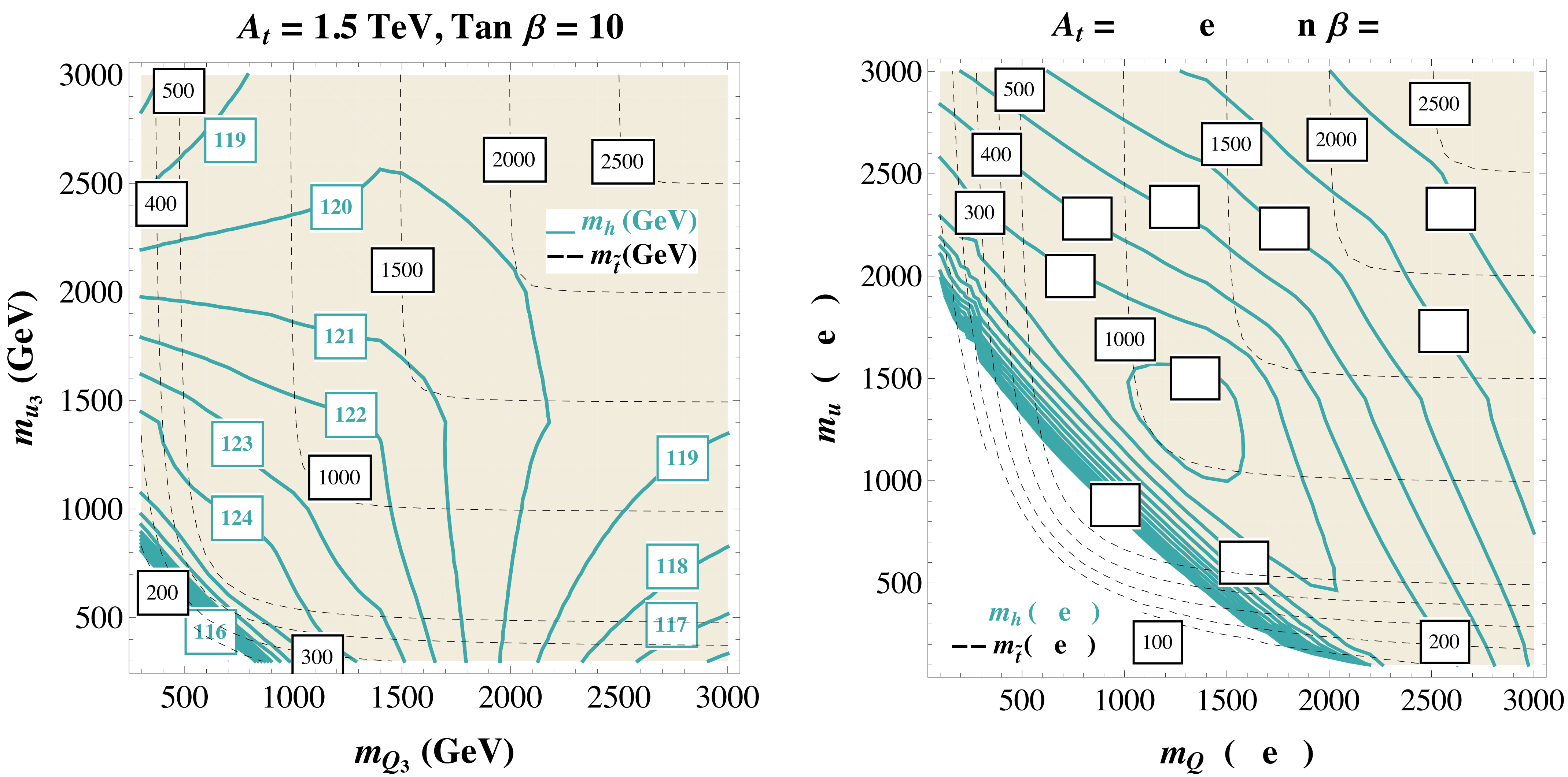
Draper, Meade, Reece, Shih, 1112.3068

SUSY.

Carena, Gori, Shah, Wagner. 1112.3336

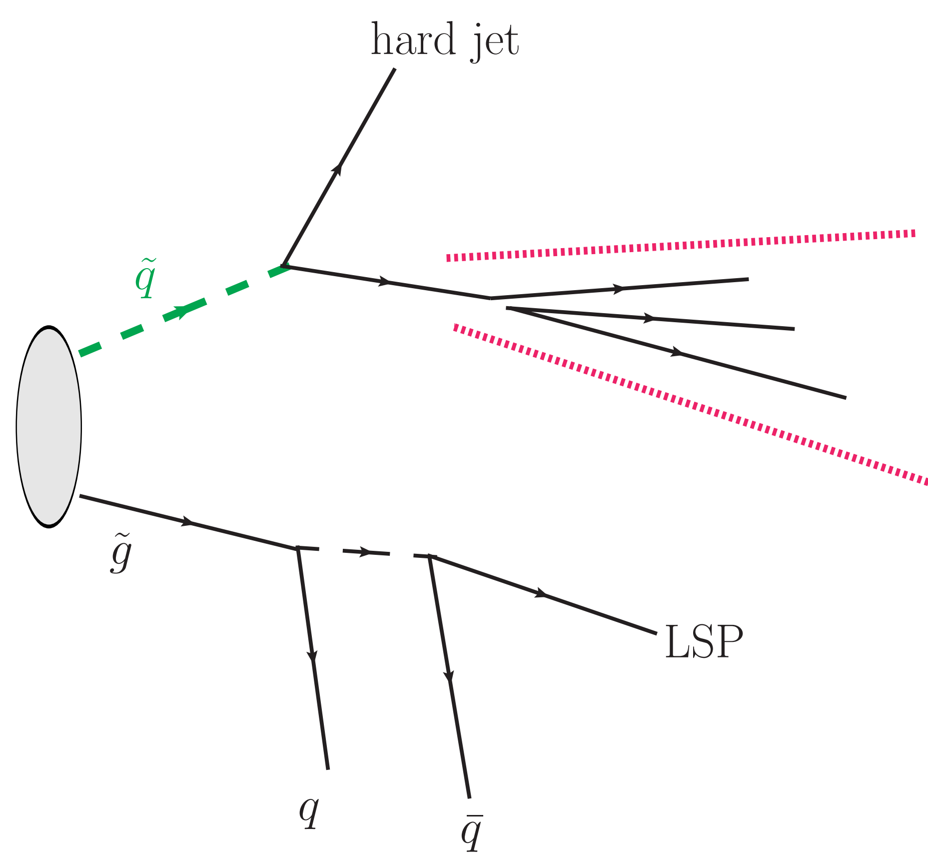
$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

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



Searching for heavy squarks

- At the LHC, the best direct search channel is



Gluino jet,
with substructure!

- Reach up to $m_{squark} \approx$ 4 TeV @ LHC 14 (2 TeV @ LHC 7).

Fan, Krohn, Thalapillil, LTW, 1102.0302

A promising, and complicated, scenario.

$> \mathrm{TeV}$ — $\tilde{u},\ \tilde{d},\ \ldots$ / $\tilde{t},\ \tilde{b}$ — Heavy squark, and $m_{\tilde{t},\tilde{b}} < m_{\tilde{u},\tilde{d}}$

$\sim 100\mathrm{s\ GeV}$ — $\tilde{g}$ / $\tilde{N}$ — Light gaugino

- Better consistency with constraints:
  - flavor, CP, Higgs mass
- A generic feature of large classes of models.
  - Scalar heavier than inos.
  - 3rd generation scalar somewhat lighter. (mixing, RGE)

Many recent models: Acharya, et al. 07; Everett, et. al. 08;
Langacker et. al. 07; Heckman et al. 08; Sundrum 09; Barbieri et. al., 10.....

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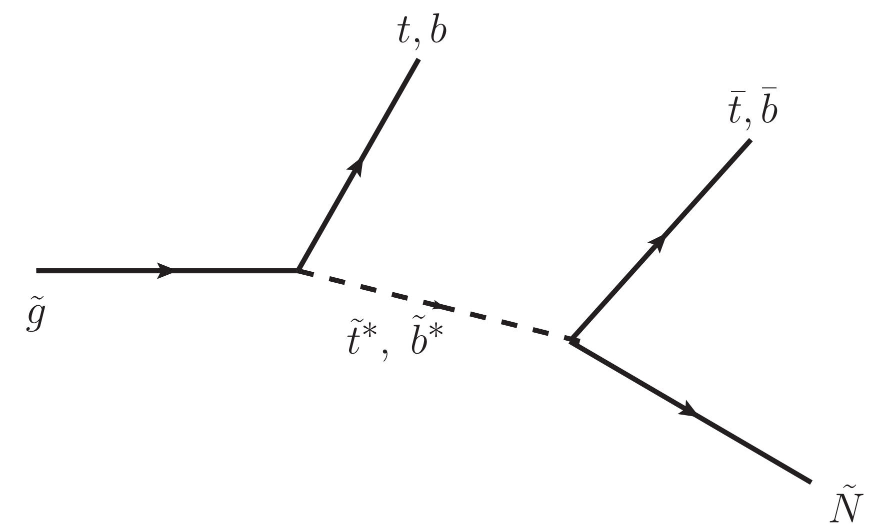


The Dominant channel

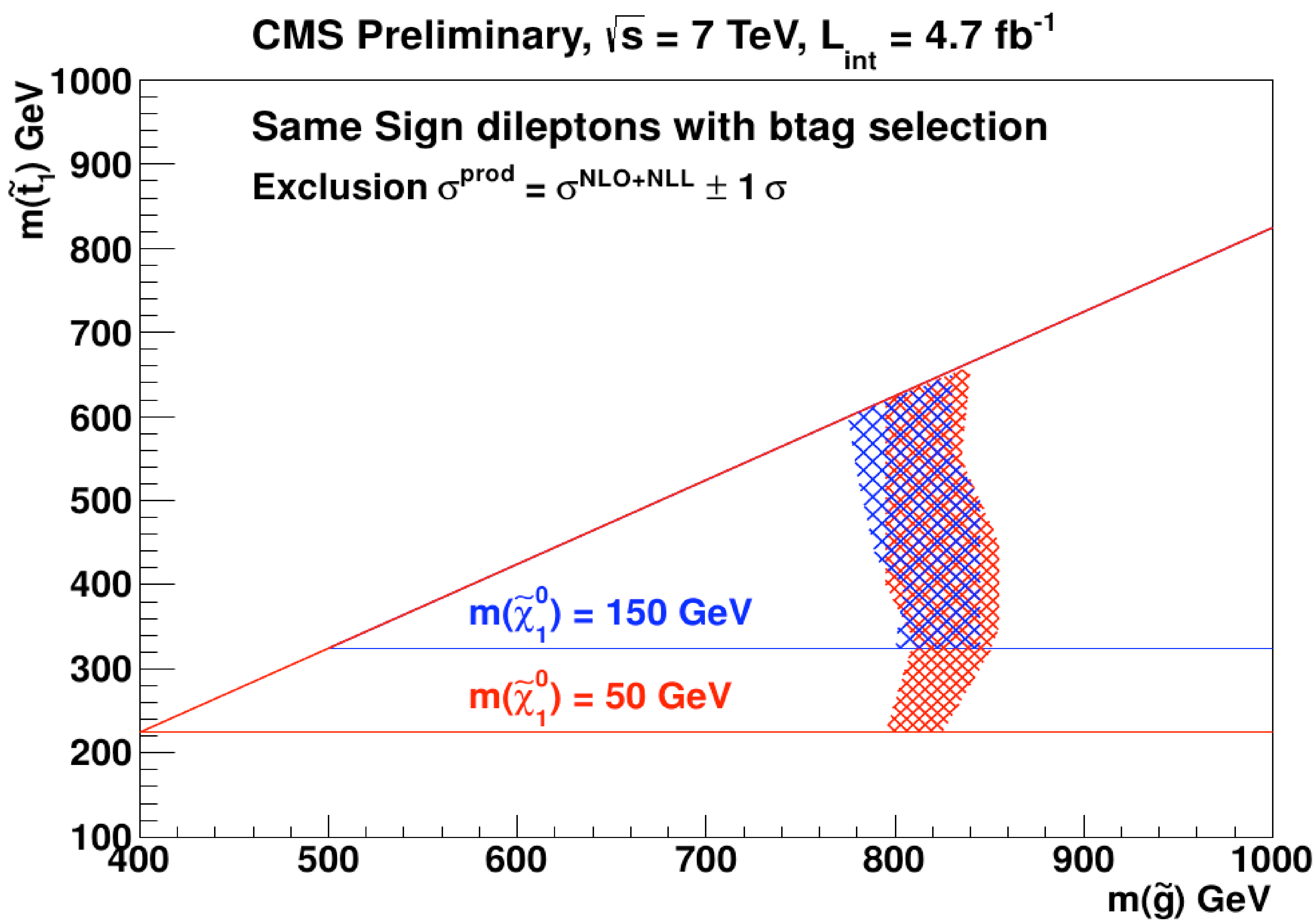
$$p\,p \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}(\text{or } t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots)$$

$$\tilde{g} \to t\bar{t}(b\bar{b}) + \tilde{N},\ \text{or}\ \ t\bar{b} + \tilde{C}^- \quad t \to b\ell^+\nu$$

- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction difficult.

Acharya, Grajek, Kane, Kuflik, Suruliz, LTW 0901.3367
Kane, Kuflik, Lu, LTW, 1101.1963

Example: 4 top final state



Extensions of MSSM

- MSSM
  - Higgs quartic from SM D-term

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

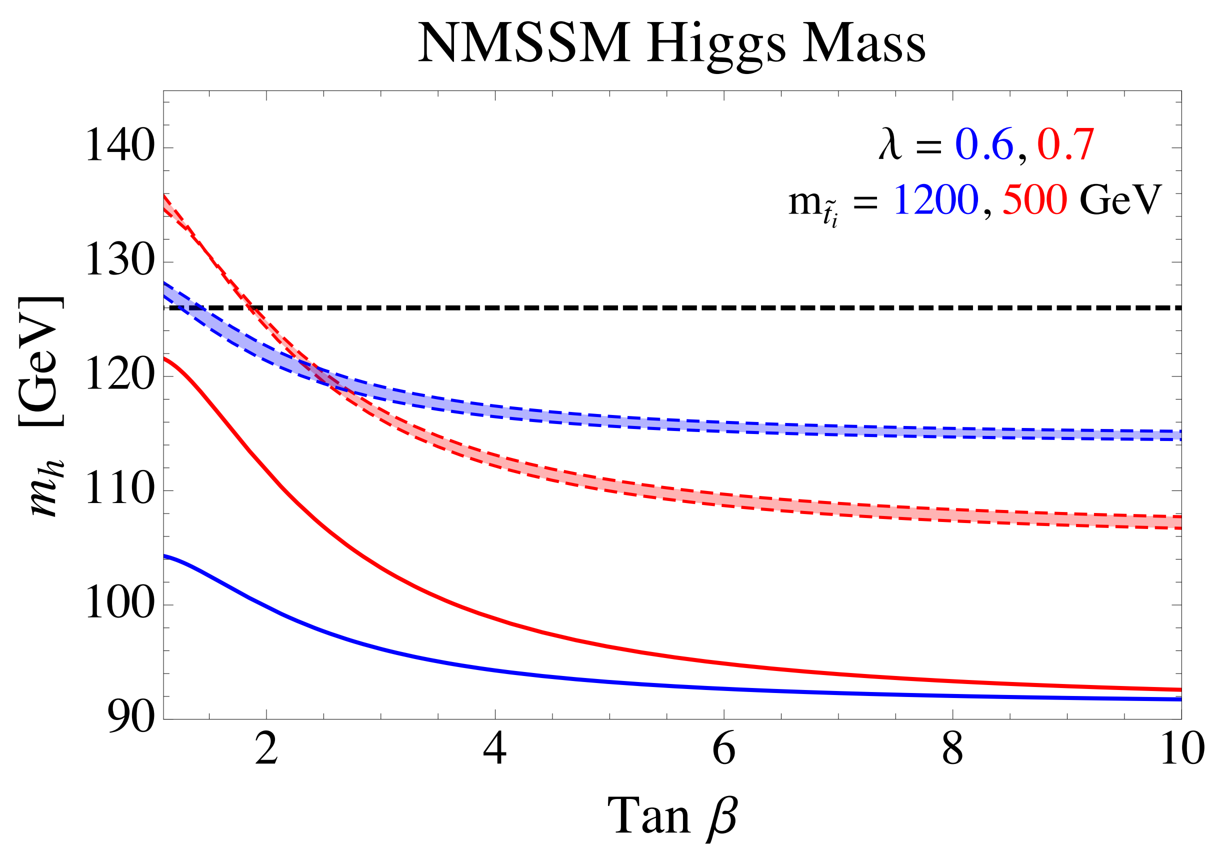
  - m_h = 125 GeV needs $M_{SUSY} \gg M_{top}$

- Extensions → new quartic coupling?

Extended Higgs sector with SUSY?

Hall, Pinner, Ruderman, 1112.2703

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$



- NMSSM. $L = L_{\text{MSSM-matter}} + \lambda S H_u H_d$
- Very large λ?

Extended gauge symmetry

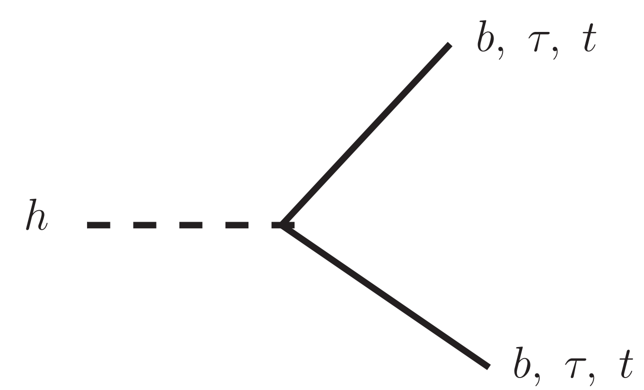
- New D-term.

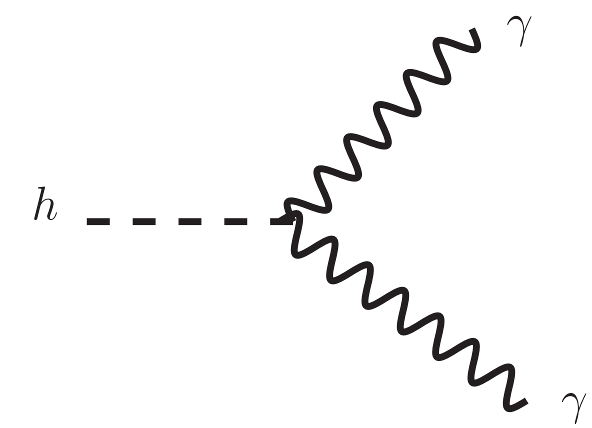
Batra, Delgado, Kaplan, Tait, hep-ph/0309149
Maloney, Pierce, Wacker, hep-ph/0409127
Zhang, An, Ji, Mohapatra, 0804.0268

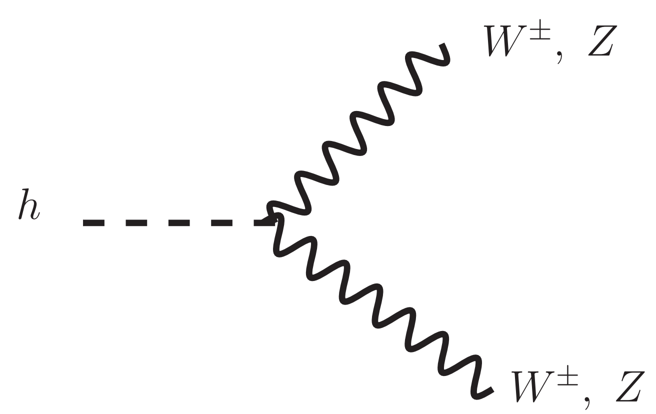
- Simplest possibility, a new U(1)′.
  - SSB near weak scale.
  - Higgs charged under this U(1)′.
- A new U(1)′ also implies additional states.
  - New Higgs field for the U(1)′.
  - New exotics from anomaly cancellation.

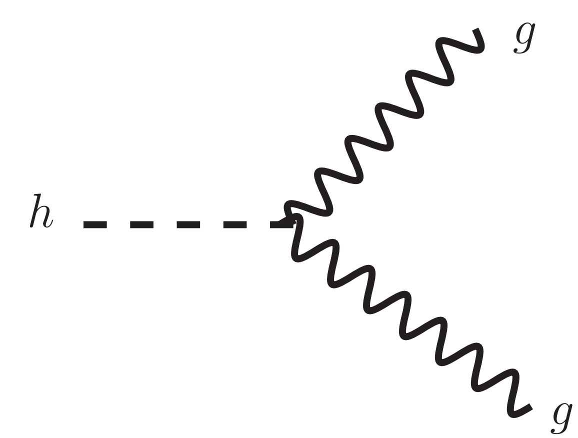
Modifying Higgs phenomenology

Is the Higgs SM like?









- Crucial couplings to measure (constrain).
  - Enters both production and decay, sensitivity early on.

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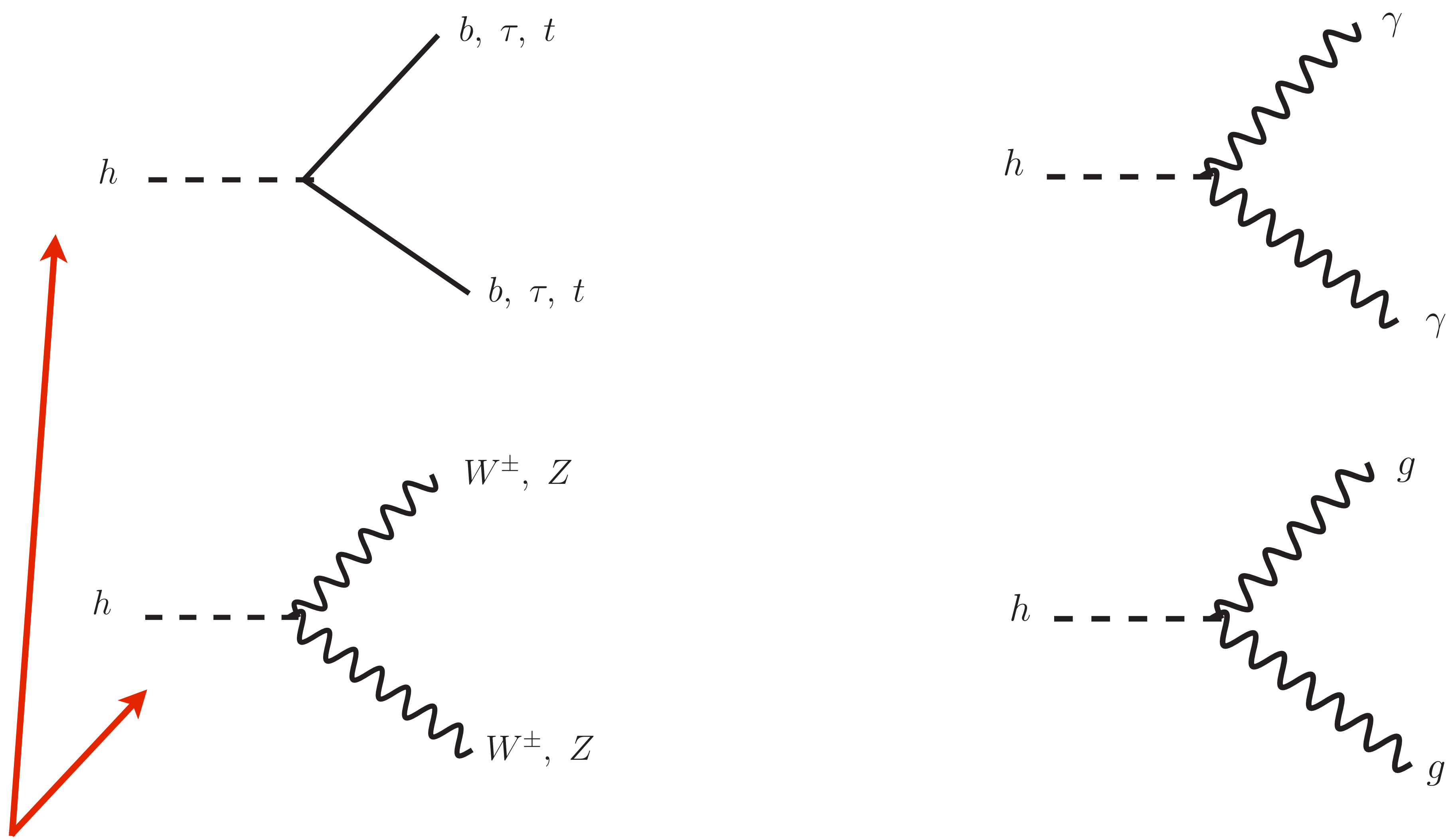

"definition" of the Higgs boson

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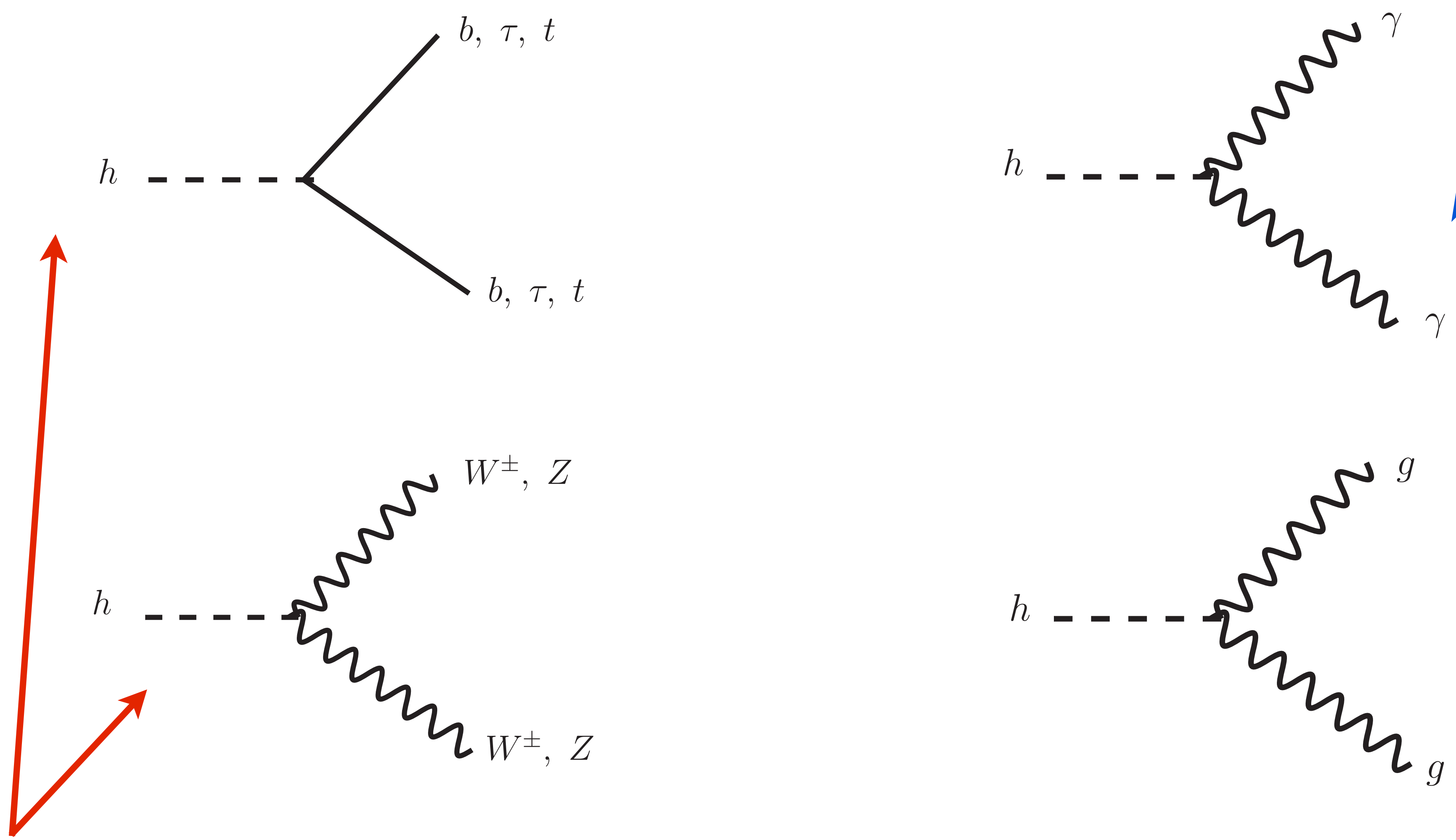

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"easier" to modify

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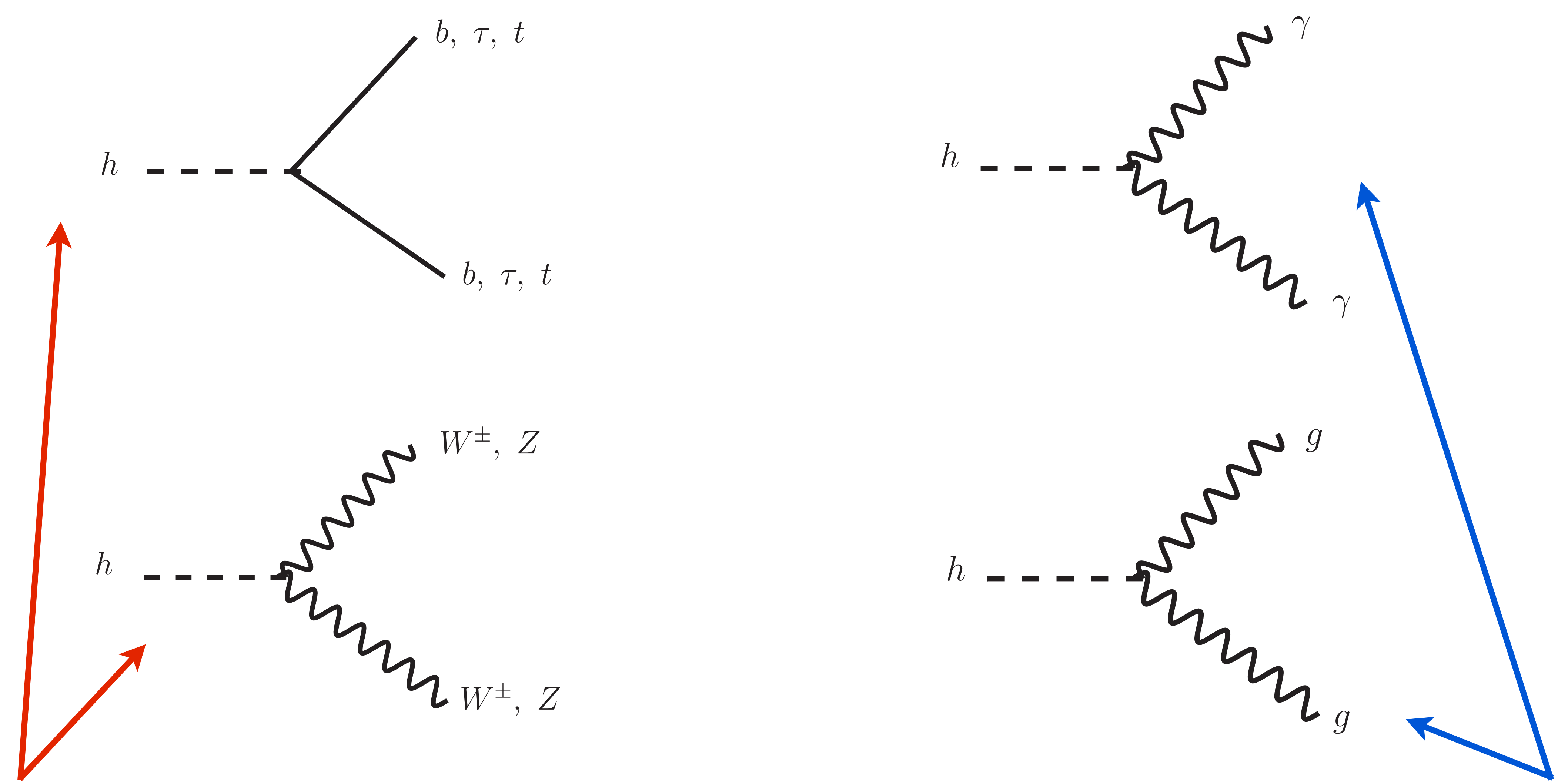


"definition" of the Higgs boson

Focus on these

"easier" to modify

- Crucial couplings to measure (constrain).
  - Enters both production and decay, sensitivity early on.

Considering two possibilities

- A. We take the hint of a light Higgs (in the range of 124-126 GeV) seriously, and study the implication for new physics.

$\frac{\sigma^{\rm obs}}{\sigma_{\rm SM}}$		$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb
	ATLAS ($m_h = 126$ GeV)	2.0 ± 0.9	1.2 ± 1.2	1.2 ± 0.9	–	–
	CMS ($m_h = 124$ GeV)	1.7 ± 0.8	0.5 ± 1.1	0.7 ± 0.6	1.0 ± 1.1	0.5 ± 1.5

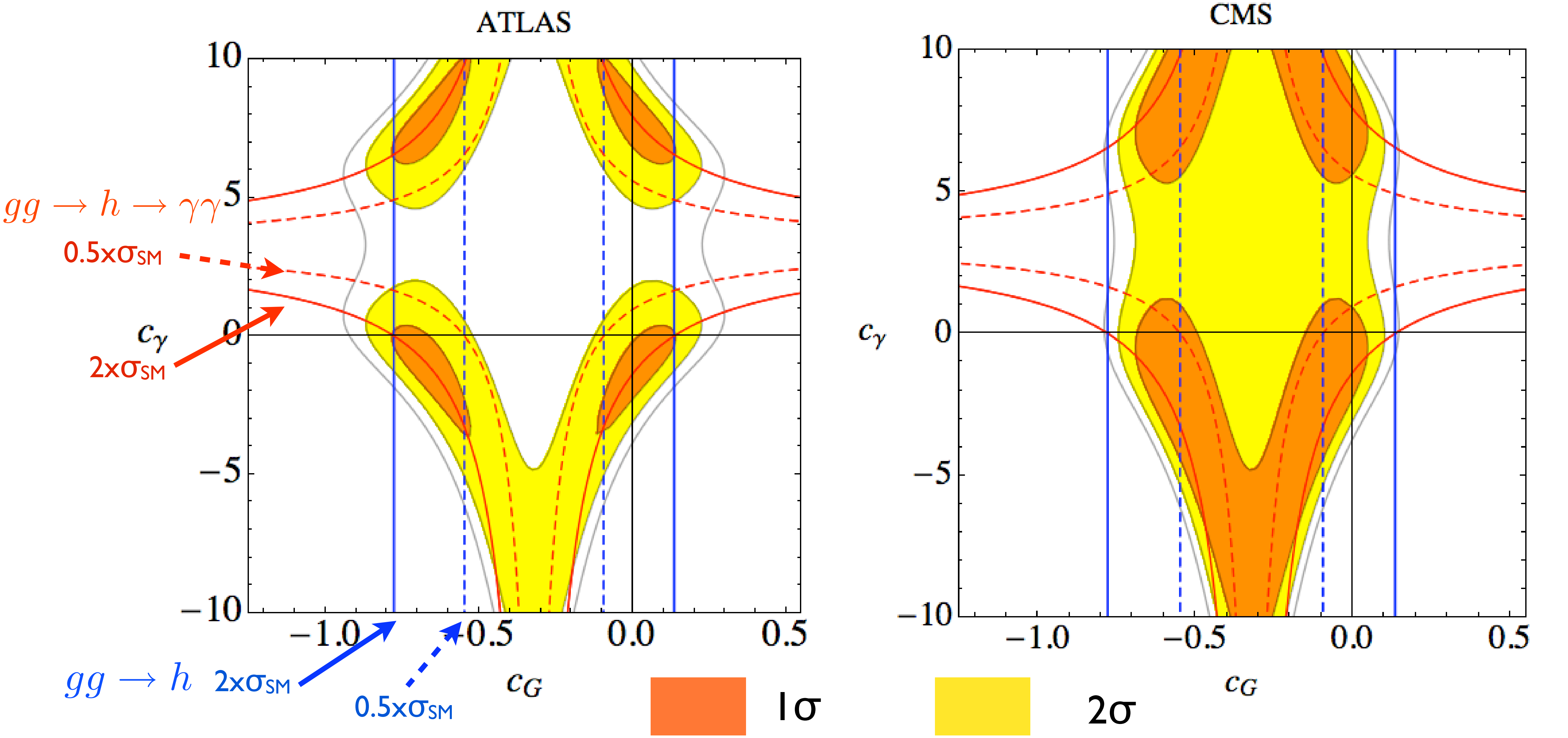
- B. There is a hidden heavy Higgs (m_h > 140 GeV)
  - New physics plays the role of change production and decay of Higgs.

Effective operator approach.

- NP couples to Higgs can carry SM gauge quantum number.
  - Integrating them out generates effective couplings

$$\mathcal{L} \supset c_G \frac{\alpha_s}{4\pi v^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} + c_\gamma \frac{\alpha}{4\pi v^2} H^\dagger H F_{\mu\nu} F^{\mu\nu}.$$

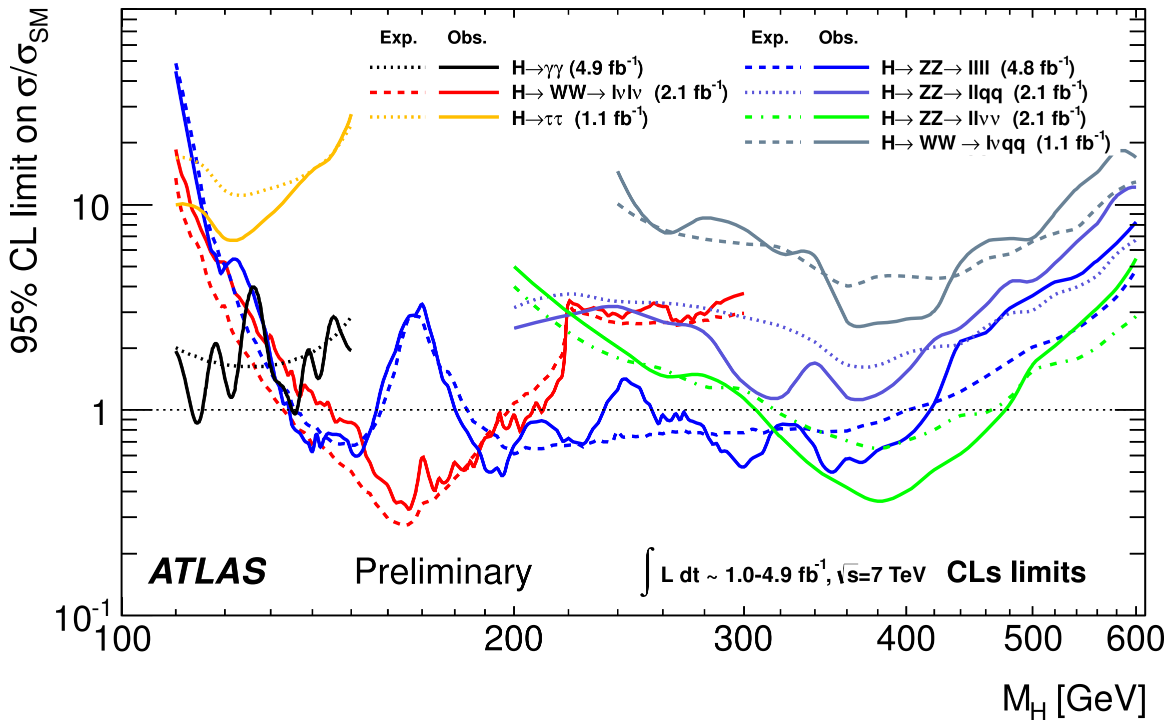
Fit in the light Higgs signal scenario

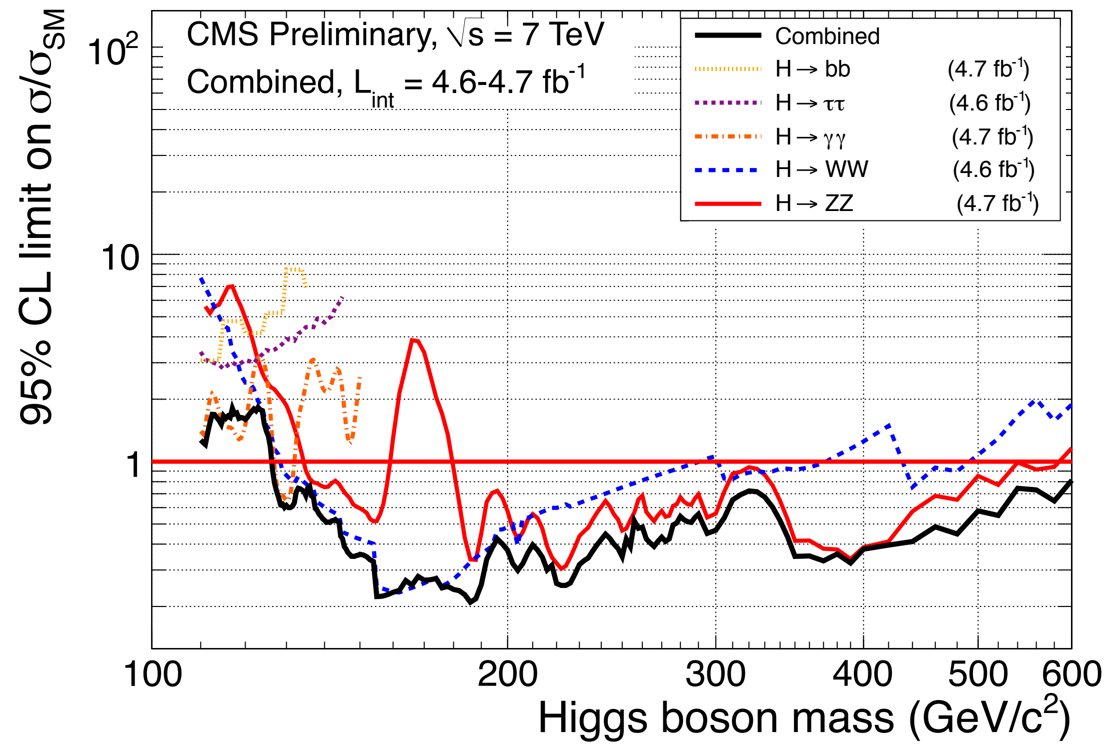


B. Batell, S. Gori, LTW, 1112.5180

- ATLAS "prefers" more NP (higher di-photon rate)
- CMS more consistent with SM.

Heavy Higgs.

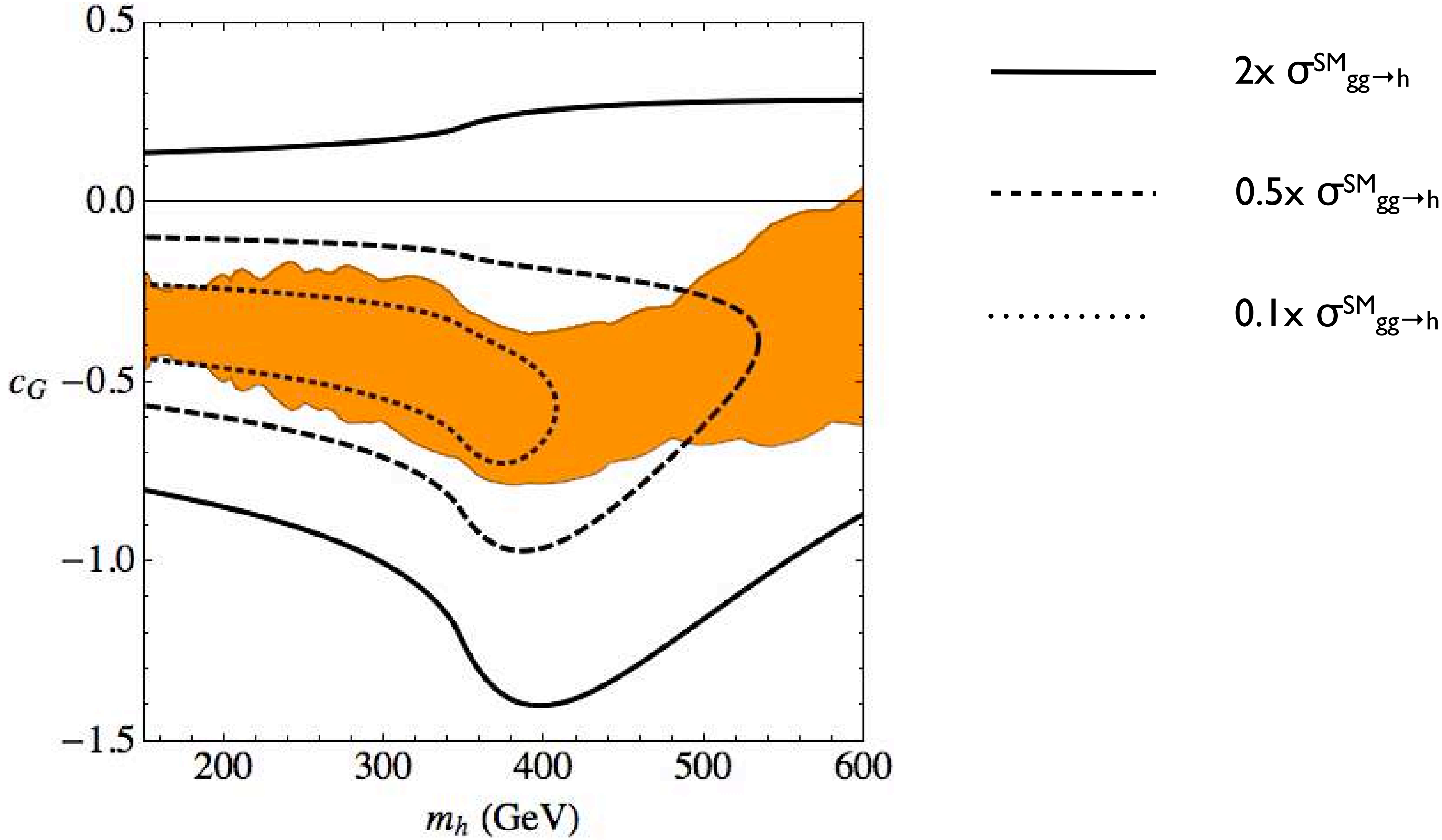




- Main relevant channels are WW and ZZ, strong constraints for $m_h < 200$.

- Only the gg fusion production channel can be modified by $$c_G \frac{\alpha_s}{4\pi v^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Hiding Heavy Higgs



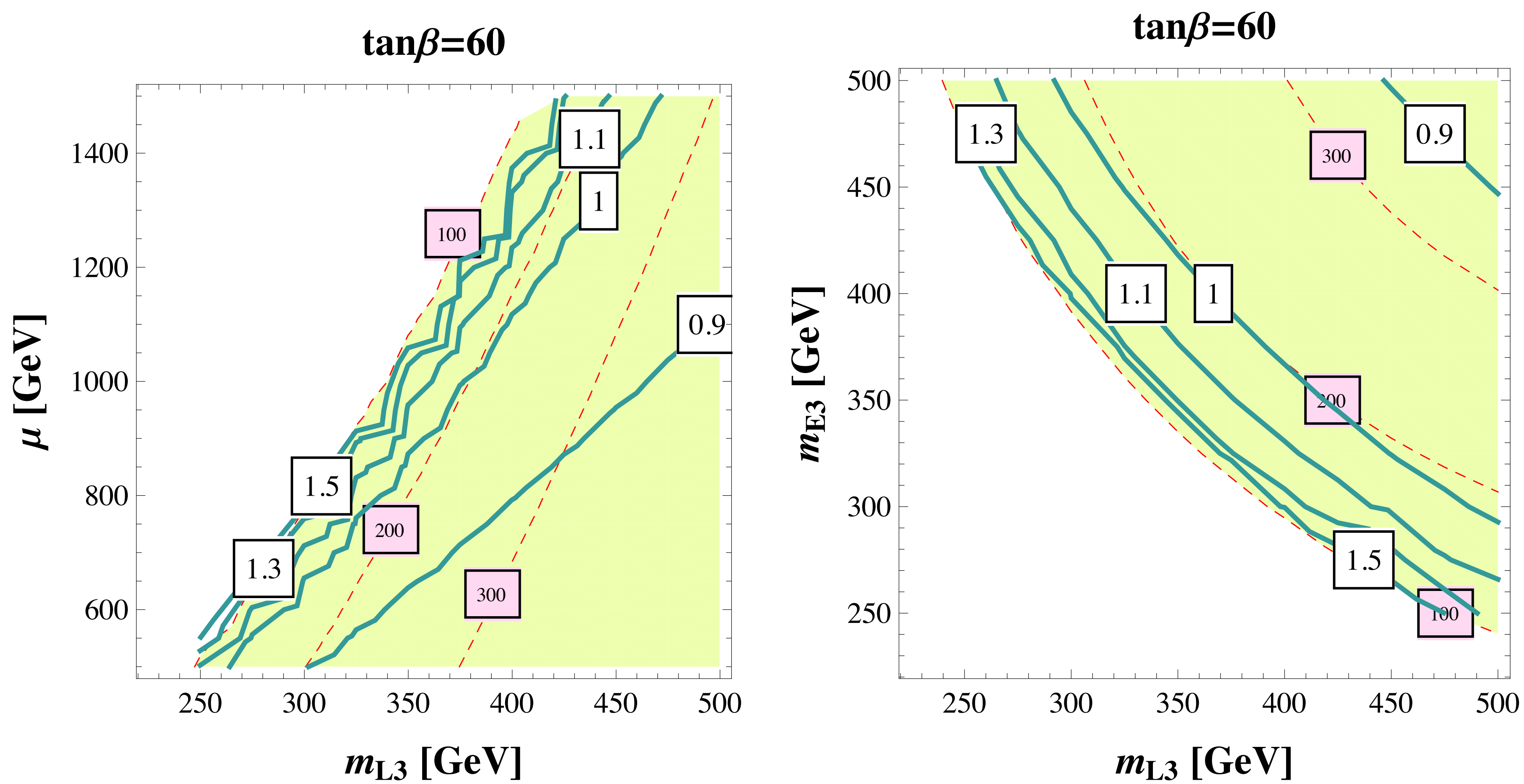
Connecting to NP models: $h \to \gamma\gamma$

- SM $\Gamma(h \to \gamma\gamma)$ dominated by $W^{\pm}$ and top, all with large couplings to the Higgs boson.

- Significant modification of $BR(h \to \gamma\gamma)$ would require
  - Charged NP with similar mass ~ 100 GeV, with large coupling to h, and satisfying all the constraints (EWPT).
  - Or, changing the total width of h.
    - New states with mass ~ m_h .

- Either way is not very easy.
  - Unlikely but exciting?

Boosting the di-photon mode in MSSM?



- light stau!
  - Need ~ 120 GeV stau to have 2 × $\Gamma(h \to \gamma\gamma)_{SM}$

The Higgs portal

B. Batell, S. Gori, LTW, 1112.5180

- $HH^\dagger$ is a unique gauge and Lorentz invariant op. A straightforward possibility of coupling to NP

$$\mathcal{L} \supset \lambda H^\dagger H \mathcal{O}_{\rm NP}$$

$\mathscr{O}_{\rm NP}$ Lorentz Inv. gauge singlet

- $\mathscr{O}_{\rm NP}$ can be made of NP states carry $SU(3)\times SU(2)_L\times U(1)_Y$ quantum numbers.

- Simple, no splitting in new $SU(2)_L$ multiplet.

- Many examples, including Higgs-partner coupling in natural theories.

Manohar, Wise, 2006
Hur, Jung, Ko, Lee, 2007
Low, Vichi, 2010
Bai, Fan, Hewett, 2011
Dobrescu, Kribs, Martin, 2011
....

Higgs portal

- $\mathscr{O}_{\mathrm{NP}}$ can be made of scalars, fermions, vectors
  - Ferimion, vector

$$\frac{\lambda}{\Lambda} H^\dagger H \bar{F} F \quad \frac{\lambda}{\Lambda^2} H^\dagger H F^{\mu\nu} F^{\mu\nu}$$

Need low cut-off to have large effect

$$\lambda H^\dagger H A^\mu A_\mu$$

Mixing between SM and new gauge boson

  - Scalar

$$\lambda H^\dagger H S^\dagger S$$

Renormalizable, perhaps the simplest, and least constrained, possibility.

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← will focus on this here

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Higgs portal to exotic scalars

- We consider Higgs portal coupling

$$\mathcal{L} \supset - \lambda |S|^2 H^\dagger H$$

- Free parameters
  - Coupling constant λ
  - Mass of the exotic scalar m_S ($m_S^2 = m_0^2 + \lambda v^2$)
  - $SU(3)_C \times SU(2)_L \times U(1)_Y$ representations.
    - We considered SU(3) octet, sextet, triplet, singlet
    - SU(2) triplet, doublet, singlet
    - Choices of Hypercharge.

Model	Couplings	Signatures
$(\mathbf{1},\mathbf{1},1)$	LL	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
$(\mathbf{1},\mathbf{1},2)$	e_Re_R	$(\ell^-\ell^+)(\ell^-\ell^+)$
$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$\bar{u}_RQ$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (t\bar{t})(t\bar{t})$
	$\bar{Q}d_R$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (b\bar{b})(b\bar{b})$
	$\bar{L}e_R$	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
$(\mathbf{1},\mathbf{3},1)$	LL	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	QQ, u_Rd_R	$(jj)(jj),\ (tj)(\bar{t}j),\ (bj)(\bar{b}j),\ (tb)(\bar{t}\,\bar{b})$
	$\bar{Q}\bar{L}$	$(\ell^-j)(\ell^+j), (\ell^-t)(\ell^+\bar{t}), 2j + \not{E}_T, b\bar{b} + \not{E}_T$
	$\bar{u}_R\bar{e}_R$	$(\ell^-j)(\ell^+j), (\ell^-t)(\ell^+\bar{t})$
$(\mathbf{3},\mathbf{1},\frac{2}{3})$	d_Rd_R	$(jj)(jj), (bj)(\bar{b}j)$
$(\mathbf{3},\mathbf{1},-\frac{4}{3})$	u_Ru_R	$(jj)(jj), (tj)(\bar{t}j)$
	$\bar{d}_R\bar{e}_R$	$(\ell^-j)(\ell^+j), (\ell^-b)(\ell^+\bar{b})$
$(\mathbf{6},\mathbf{1},\frac{1}{3})$	$\bar{Q}\bar{Q}$	$(jj)(jj),\ (tj)(\bar{t}j),\ (bj)(\bar{b}j)$
	$\bar{u}_R\bar{d}_R$	$(jj)(jj),\ (tj)(\bar{t}j),\ (bj)(\bar{b}j),\ (tb)(\bar{t}\,\bar{b})$
$(\mathbf{6},\mathbf{1},-\frac{2}{3})$	$\bar{d}_R\bar{d}_R$	$(jj)(jj), (bj)(\bar{b}j), (bb)(\bar{b}\bar{b})$
$(\mathbf{6},\mathbf{1},\frac{4}{3})$	$\bar{u}_R\bar{u}_R$	$(jj)(jj), (tj)(\bar{t}j), (tt)(\bar{t}\bar{t})$
$(\mathbf{8},\mathbf{1},0)$	loop decay	$(jj)(jj)$
$(\mathbf{3},\mathbf{2},\frac{1}{6})$	$\bar{d}_RL$	$(\ell^-j)(\ell^+j), (\ell^-\bar{b})(\ell^+b), 2j + \not{E}_T, b\bar{b} + \not{E}_T$
$(\mathbf{3},\mathbf{2},\frac{7}{6})$	$\bar{u}_RL$	$(\ell^-j)(\ell^+j), (\ell^-\bar{t})(\ell^+t), 2j + \not{E}_T, t\bar{t} + \not{E}_T$
	$\bar{Q}e_R$	$(\ell^-j)(\ell^+j), (\ell^-\bar{t})(\ell^+t), (\ell^-\bar{b})(\ell^+b)$
$(\mathbf{8},\mathbf{2},\frac{1}{2})$	$\bar{u}_RQ$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (t\bar{t})(t\bar{t})$
	$\bar{Q}d_R$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (b\bar{b})(b\bar{b})$
$(\mathbf{3},\mathbf{3},-\frac{1}{3})$	QQ	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j)$
	$\bar{Q}\bar{L}$	$(\ell^-j)(\ell^+j), (\ell^-t)(\ell^+\bar{t}), (\ell^-b)(\ell^+\bar{b}), jj + \not{E}_T, t\bar{t} + \not{E}_T, b\bar{b} + \not{E}_T$
$(\mathbf{6},\mathbf{3},\frac{1}{3})$	$\bar{Q}\bar{Q}$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (tt)(\bar{t}\bar{t}), (bb)(\bar{b}\bar{b}), (tb)(\bar{t}\bar{b})$
$(\mathbf{8},\mathbf{3},0)$	loop decay	$(W^+j)(W^-j), (\gamma j)(\gamma j), (Zj)(Zj), (\gamma j)(Zj)$

- Choice of Y to allow simple renormalizable couplings to SM fields.
- Motived mainly by simplicity.
- Does give us interesting variations on Higgs decay.

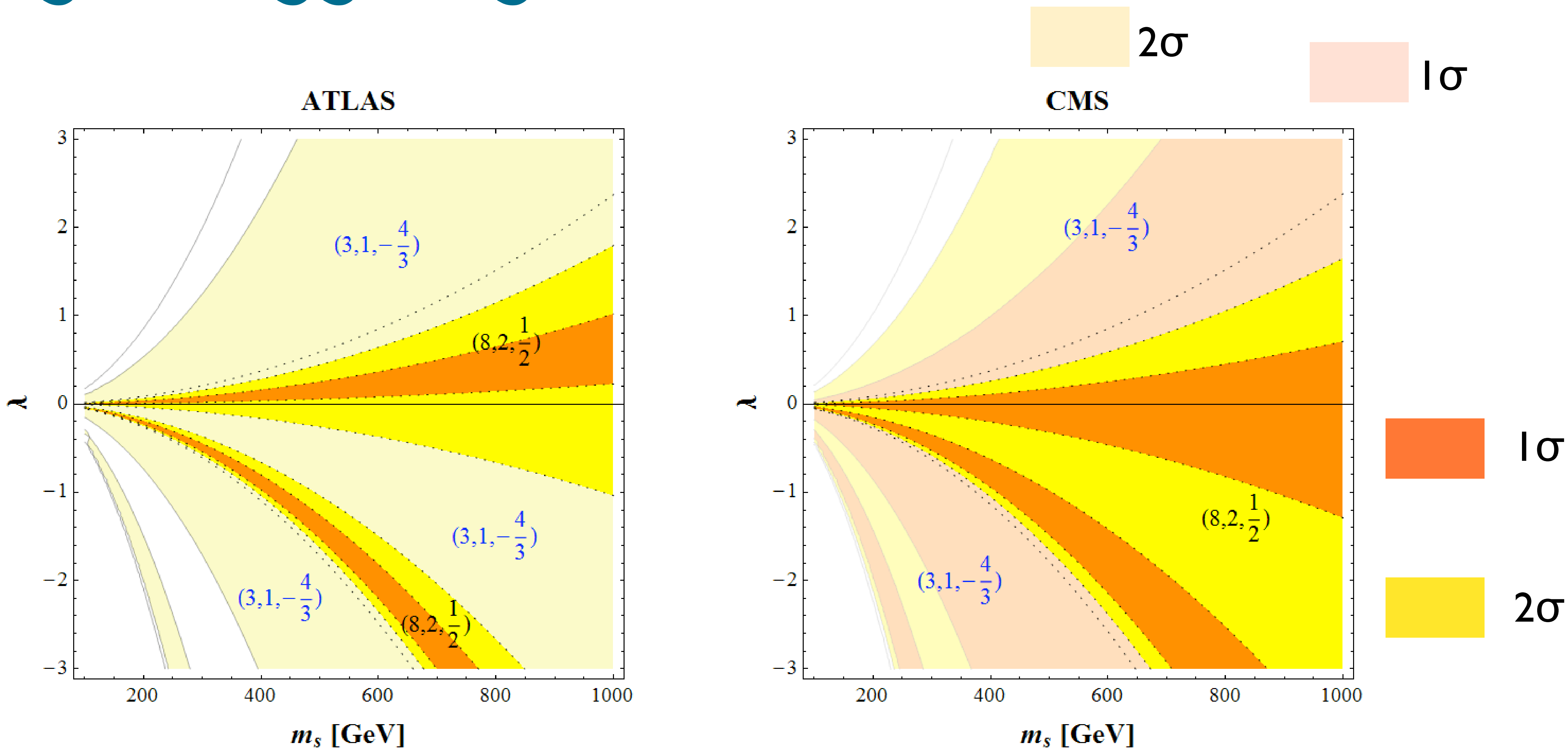
Modification of rate.

$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \sim \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}} = \left| 1 + Kc \frac{4\lambda\, C(r) A_0(\tau_S) \frac{v^2}{m_S^2}}{\sum_f A_{1/2}(\tau_f)} \right|^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = \left| 1 - c \sum_i \frac{2\lambda\, d(r) Q_{S_i}^2 A_0(\tau_S) \frac{v^2}{m_S^2}}{A_1(\tau_W) - \sum_f N_f Q_f^2 A_{1/2}(\tau_f)} \right|^2$$

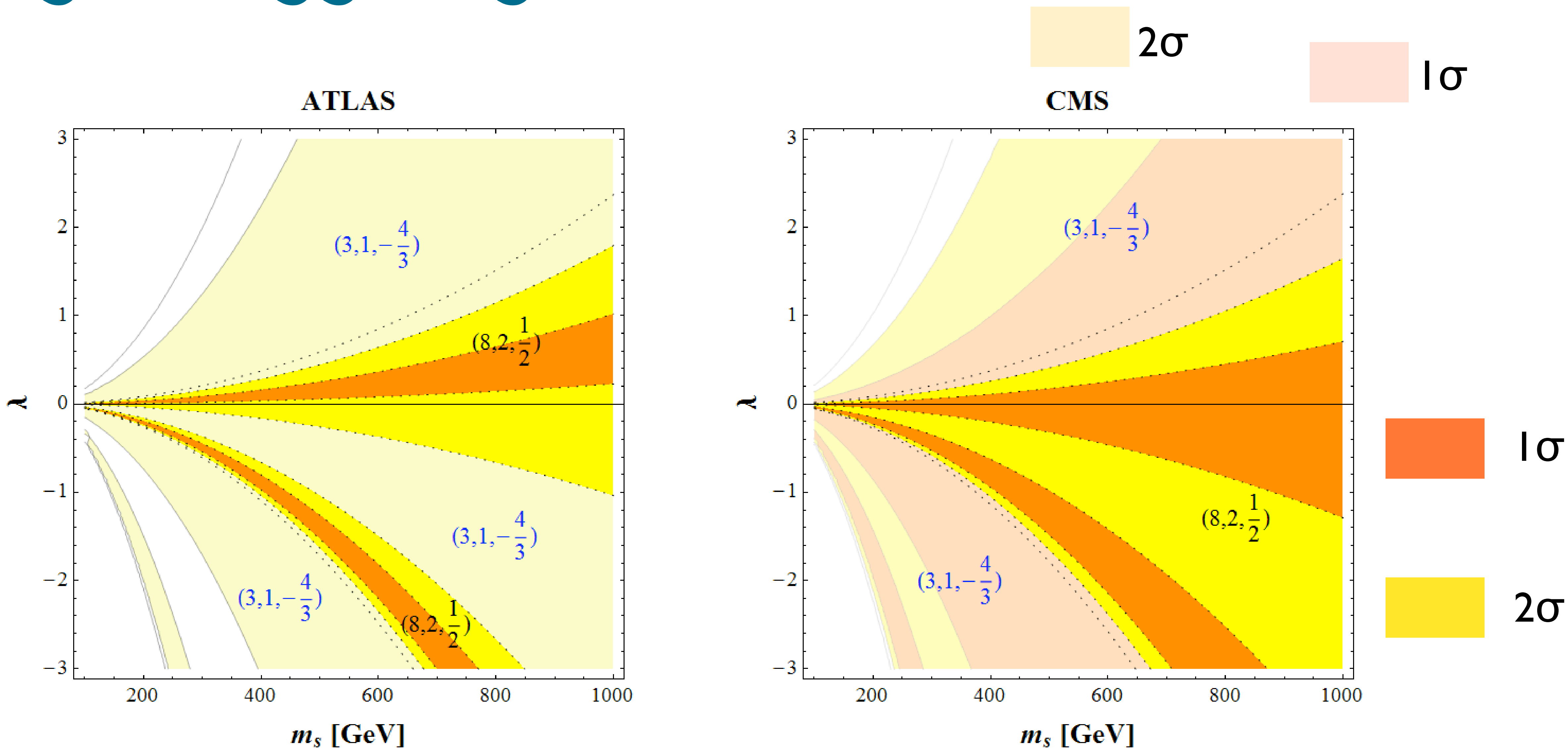
- **Negative** NP effect in partial width to 2 photons ($\lambda>0$) corresponds to a **positive** effect in gluon fusion.

Light Higgs signal



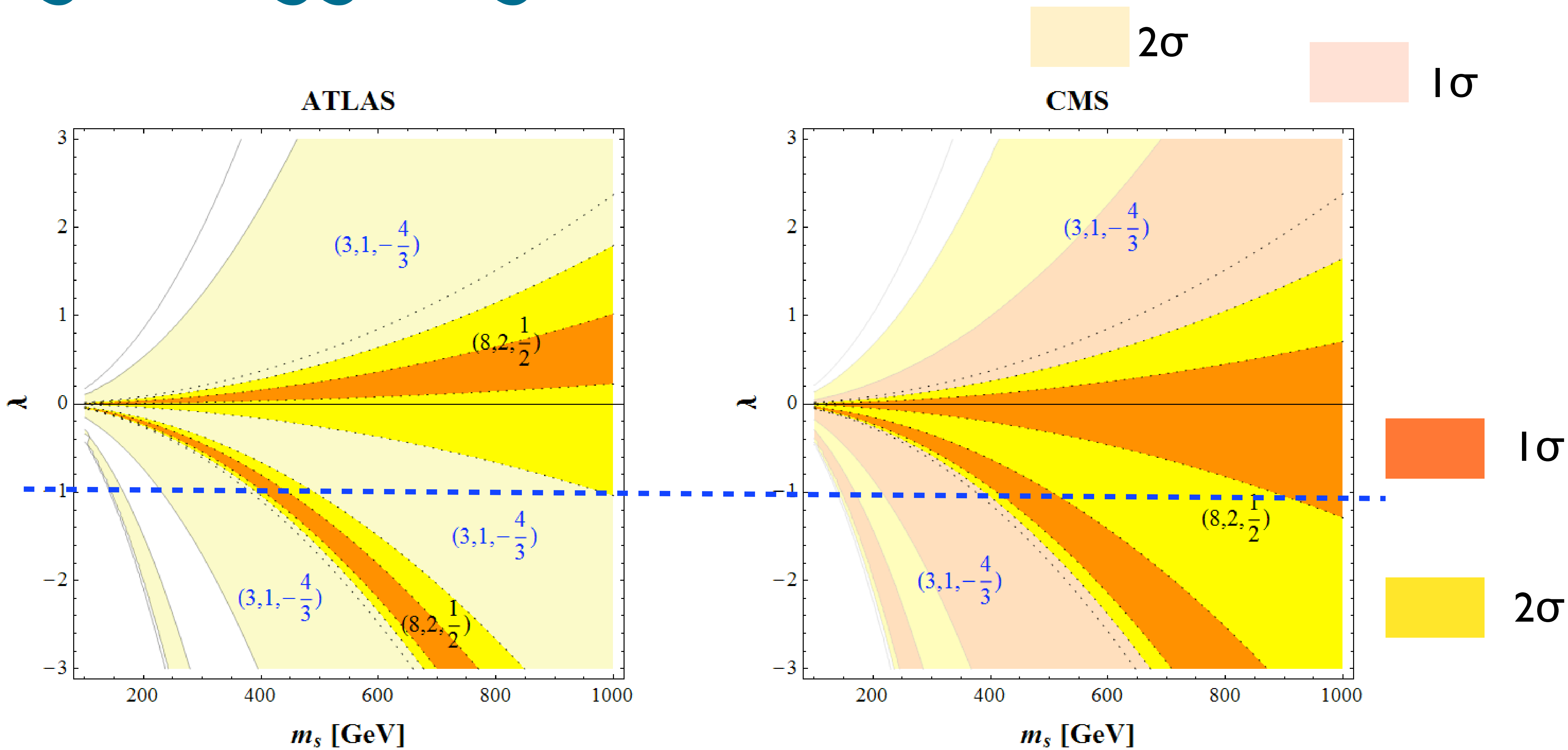
- For ATLAS, this triplet is not a very good fit.
- λ=0 not a very good fit. Higher di-photon rate.

Light Higgs signal



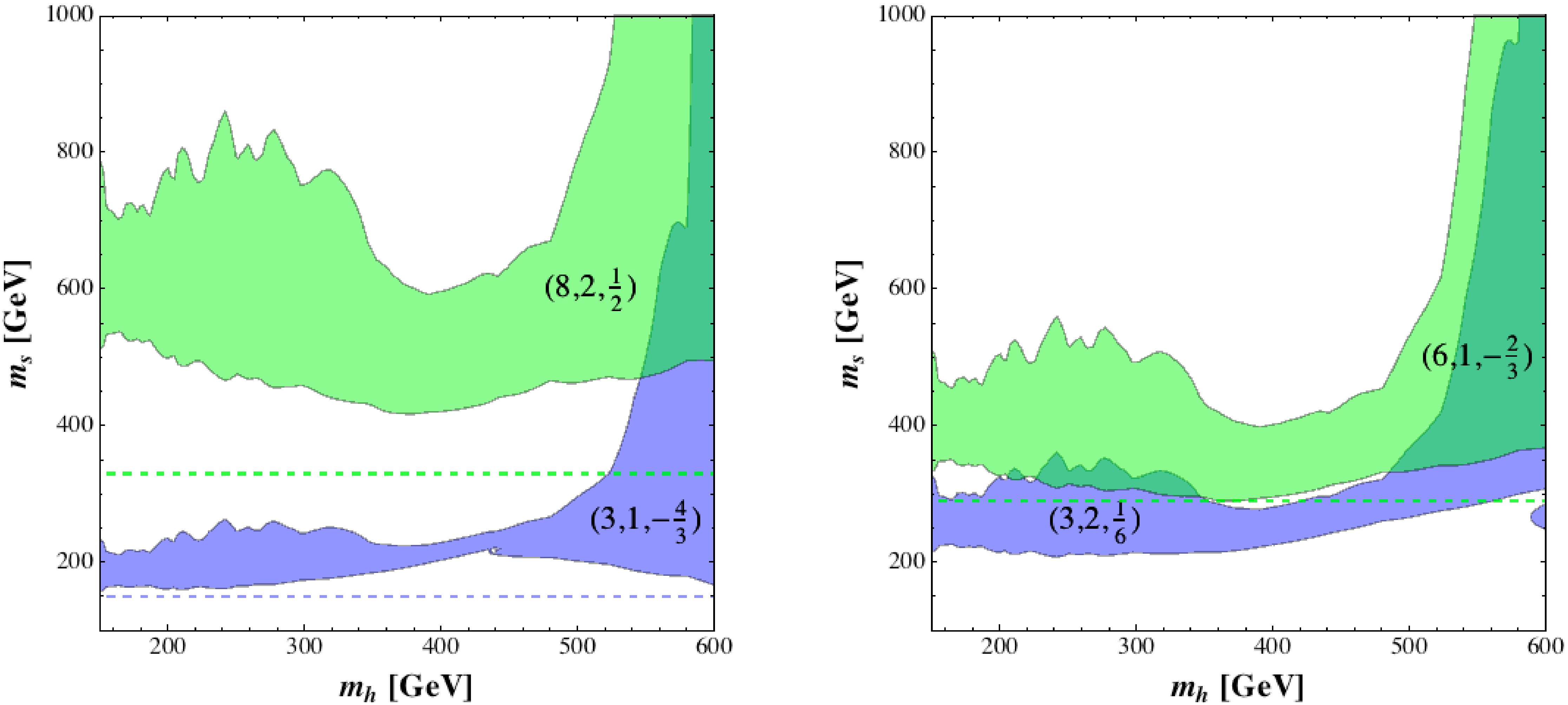
- CMS more consistent with SM.
    - λ=0 gives a good fit.
- Triplet fits better.

Light Higgs signal



- For λ=O(1), triplet ∼200 GeV and octet ∼500 GeV are allowed.

Hiding Heavy Higgs.



Fixed λ=-1

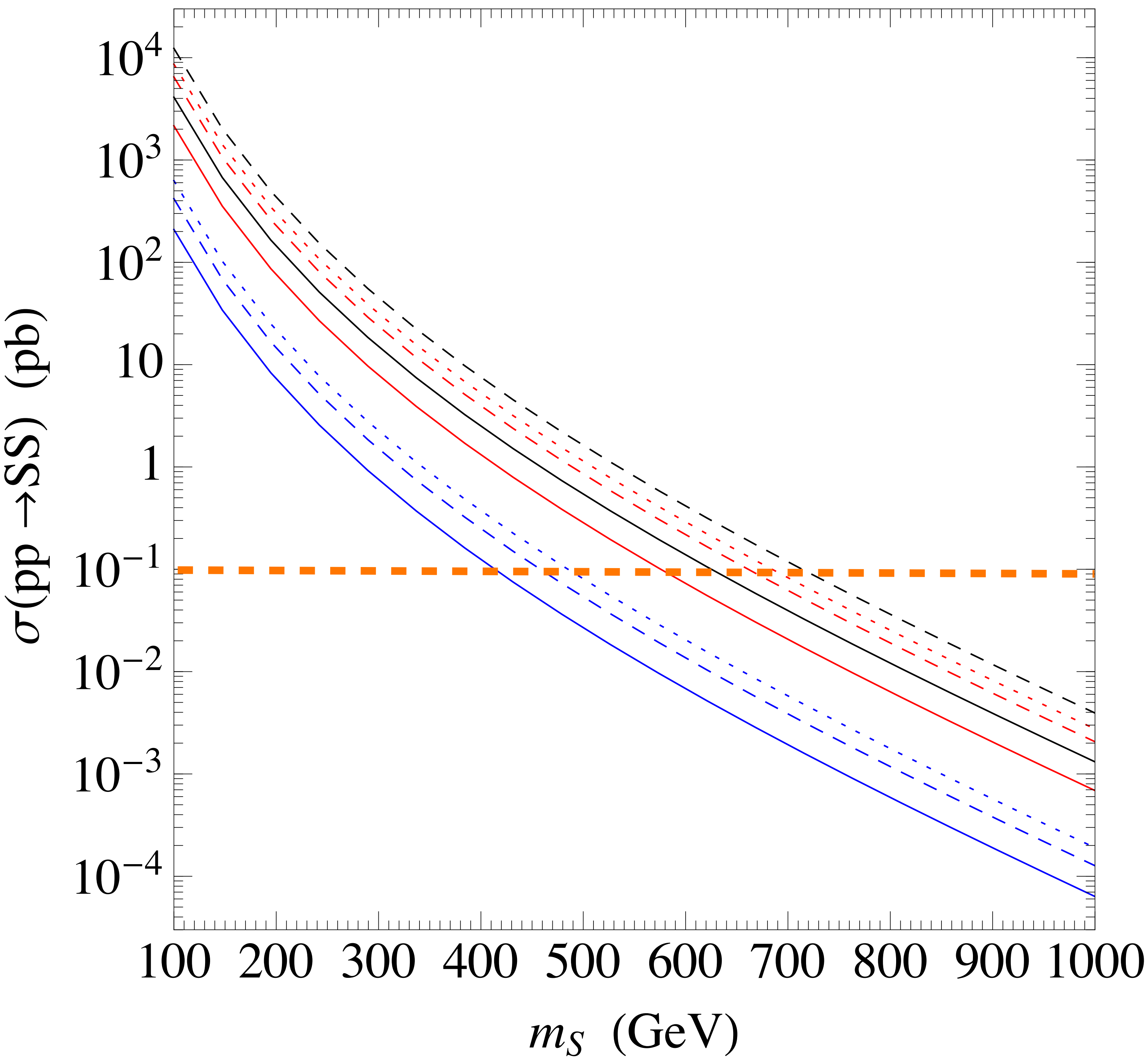
Collider searches

- Higgs phenomenology are consistent (possible even favor) lighter NP.

- These states can be searched for at the LHC.
  - Complementary to measurement in the Higgs sector.

- Production. $pp \to SS^{(*)}$.
  - Decent rate for colored NP.

Production rates of colored scalars



blue: triplet
black: sextet
red: octet

Different SU(2) rep:
multiplicative factor

10^3 events at 10 fb^{-1}

Decay modes

- We mainly focus on decay from couplings

$$\mathcal{L} \supset \eta S \bar{\psi}_1^{\mathrm{SM}} \psi_2^{\mathrm{SM}} + \mathrm{h.c.}$$

- We could impose MFV.
  - (8, 2, 1/2) can have MFV coupling. Manohar, Wise, 2006
  - Others must be in a larger multiplet. Arnold, Pospelov, Trott, Wise, 2010
  - Prefers to decay into 3rd gen.
- Also, we can choose small η.
  - Decay can be democratic.
  - Prompt as long as $\eta > 10^{-7}$

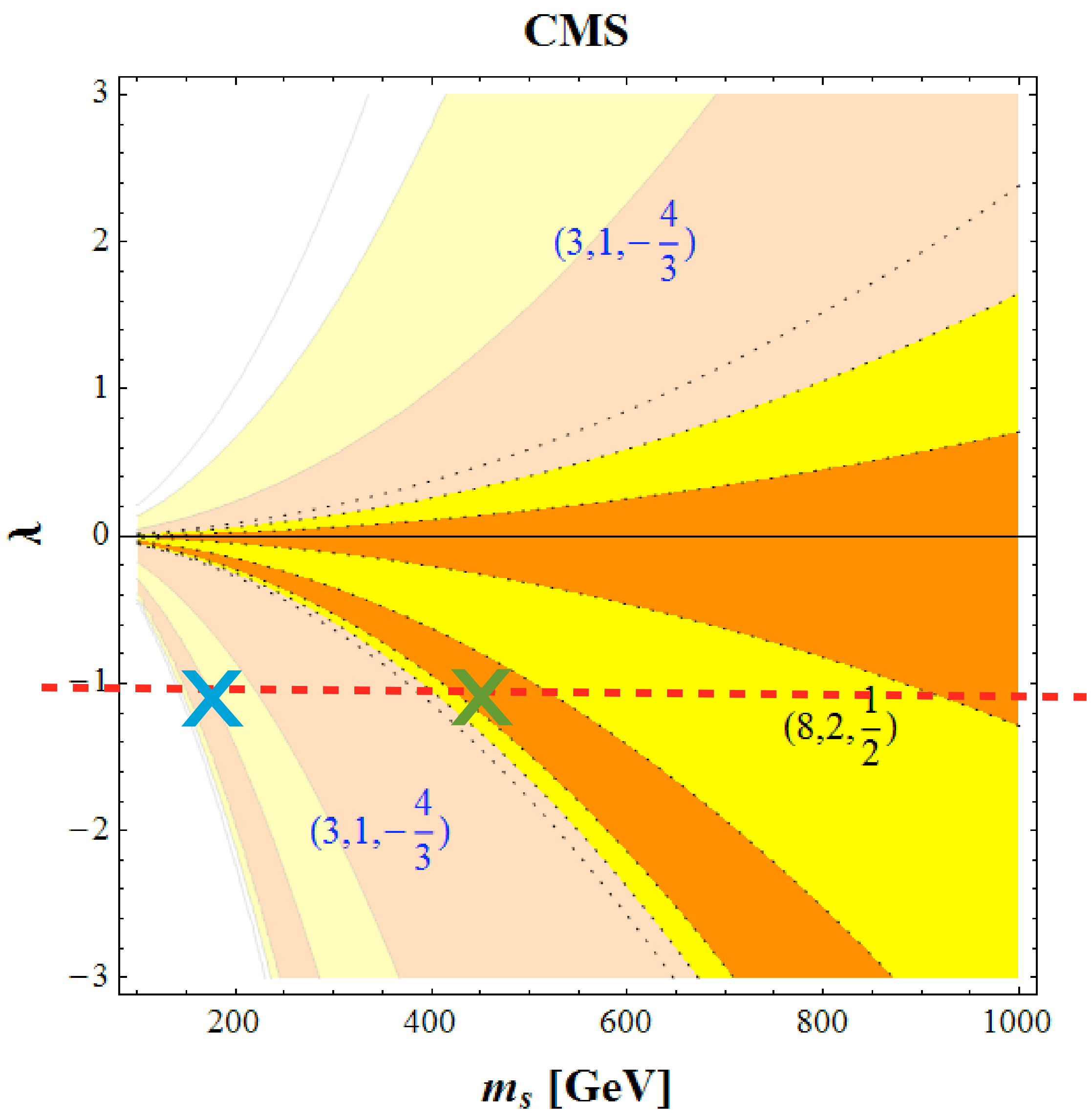
LHC constraints.

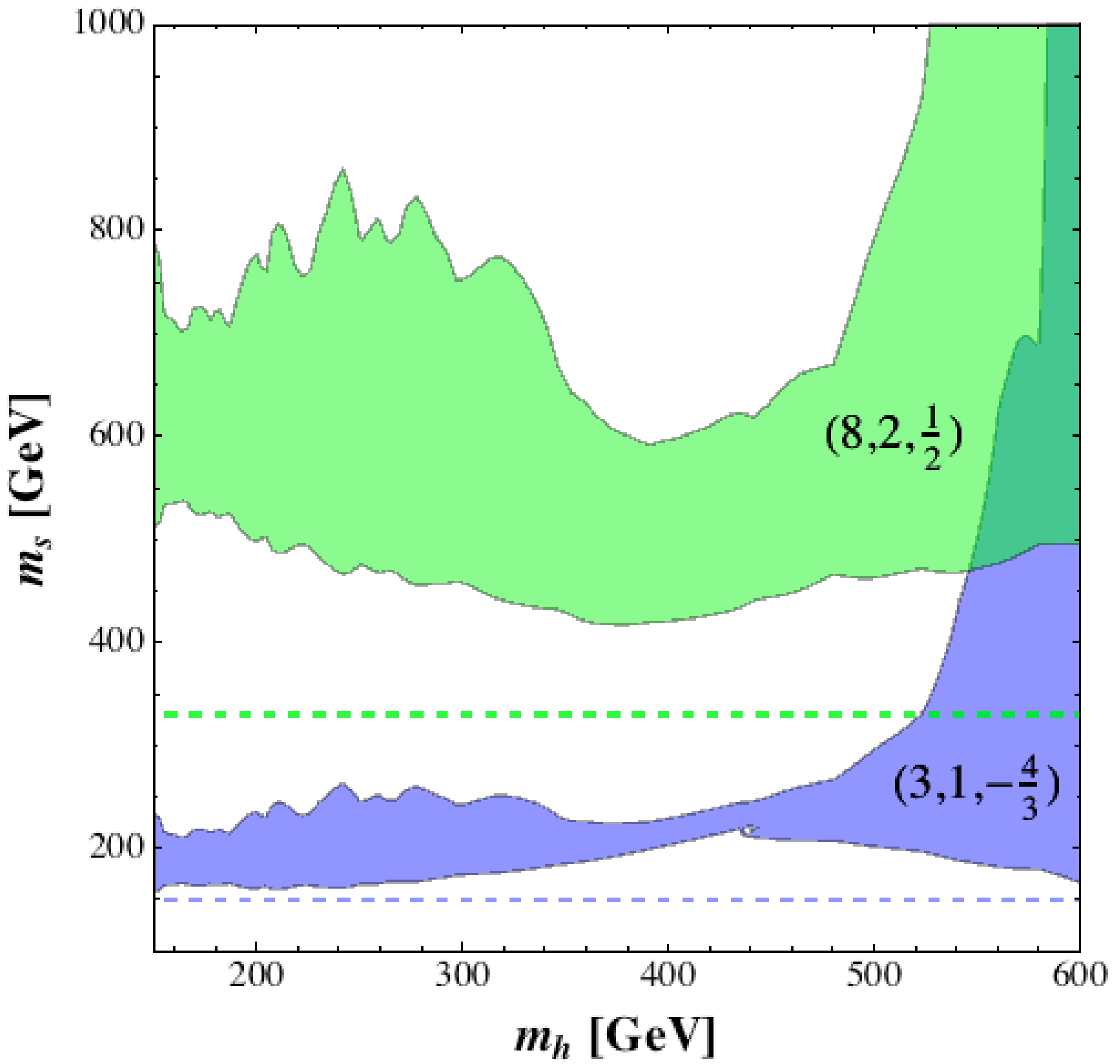
- No dedicated search in most cases.
- We will just estimate based on search for other NP with similar final states.
  - Rough. Kinematics can be different.
  - More complete analysis certainly necessary.

LHC constraints, an example

- 4jet final states: $S\ S^* \to jjjj$
  - Common. Can come from octet, sextet, and triplet.
- ATLAS at 35 pb^{-1} (arXiv:1110.2693)
  - Ruled out between 100-185 → (8,1,0)>160 GeV
  - Naively scale up the luminosity by 100 → (8,1,0)> 250 GeV, (8,2,Y) > 300 GeV
  - Similar reach on sextet
  - Triplet: bound about 150 GeV with 10 fb^{-1}
  - New CMS 2.2 fb^{-1} : octet:550, triplet:250
- Potential at 14 TeV: ∼ bounds x 2.

Interplay with Higgs pheno





Conclusion

- 2012 is going to be a year of Higgs.
  - Confirm a light Higgs signal, or
  - Rule out SM-like weakly coupled Higgs.
- Rich implications for new physics.
  - Connection with LHC NP searches.
  - Modifying Higgs phenomenology.
  - Inspiring new models.