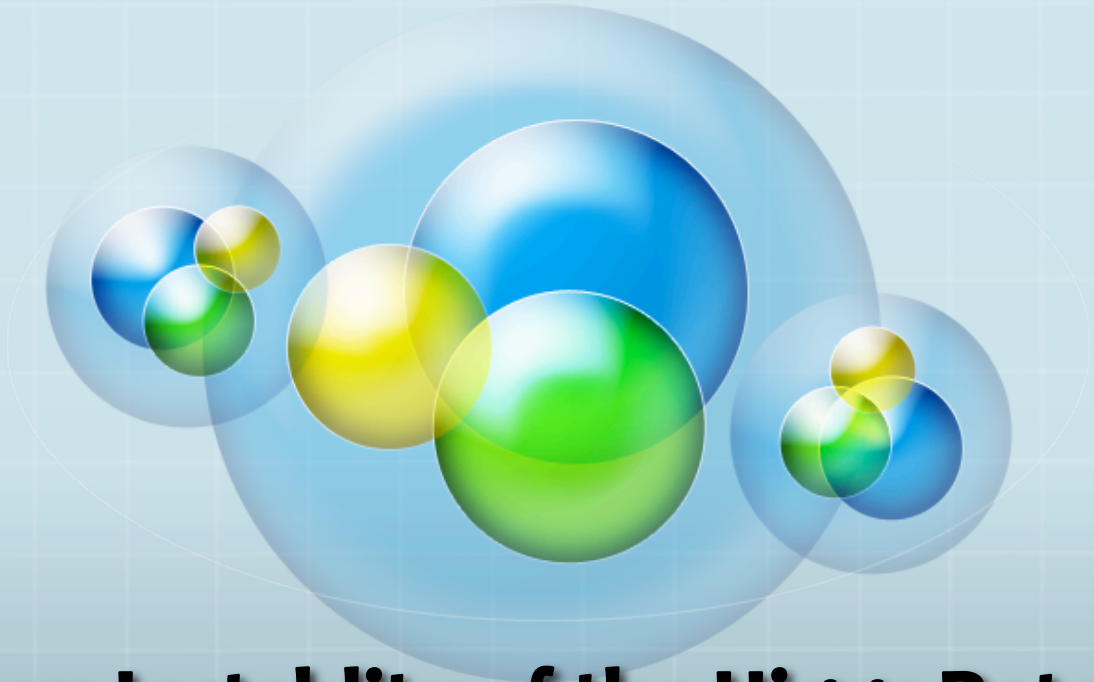
The Fate of the Universe in Light of the New Data

JiJi Fan
Harvard University

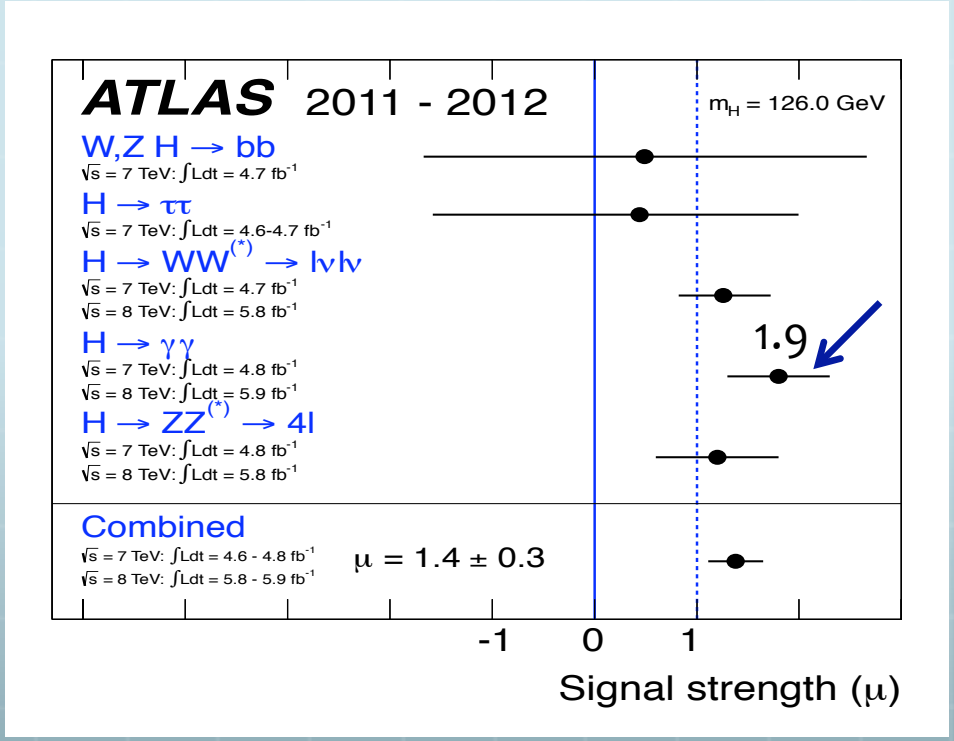
Chicago LHC 2012 Workshop, Nov. 12 - 14

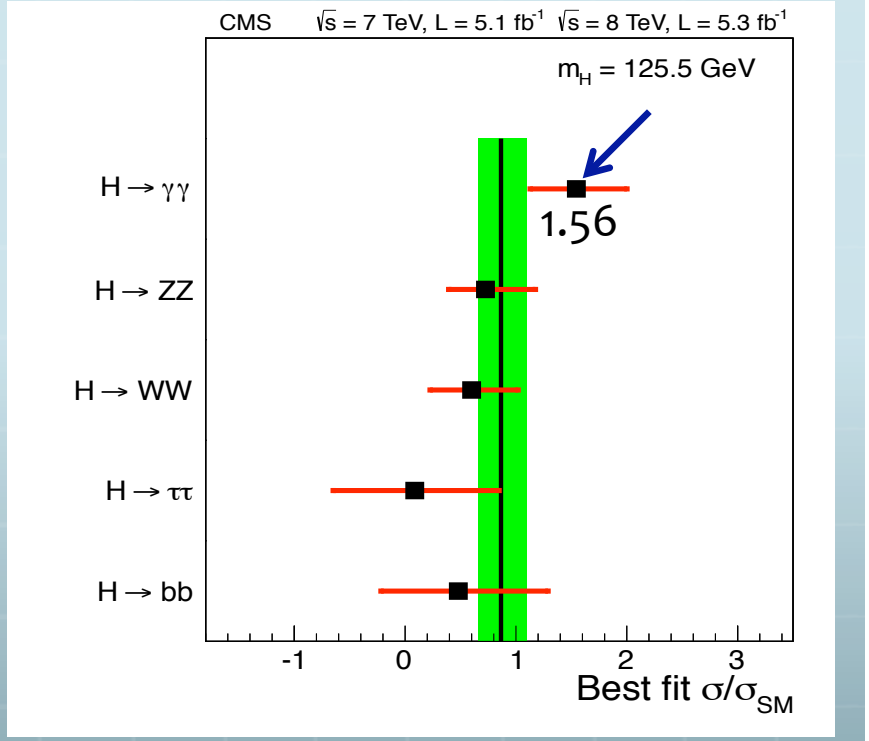


Vacuum Instablity of the Higgs Potential

JiJi Fan
Harvard University

Chicago LHC 2012 Workshop, Nov. 12 - 14



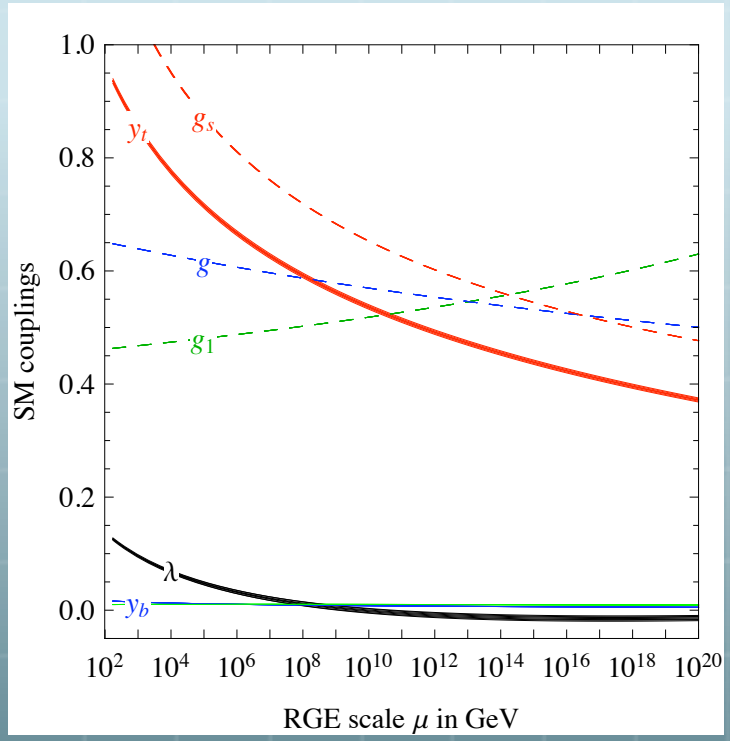


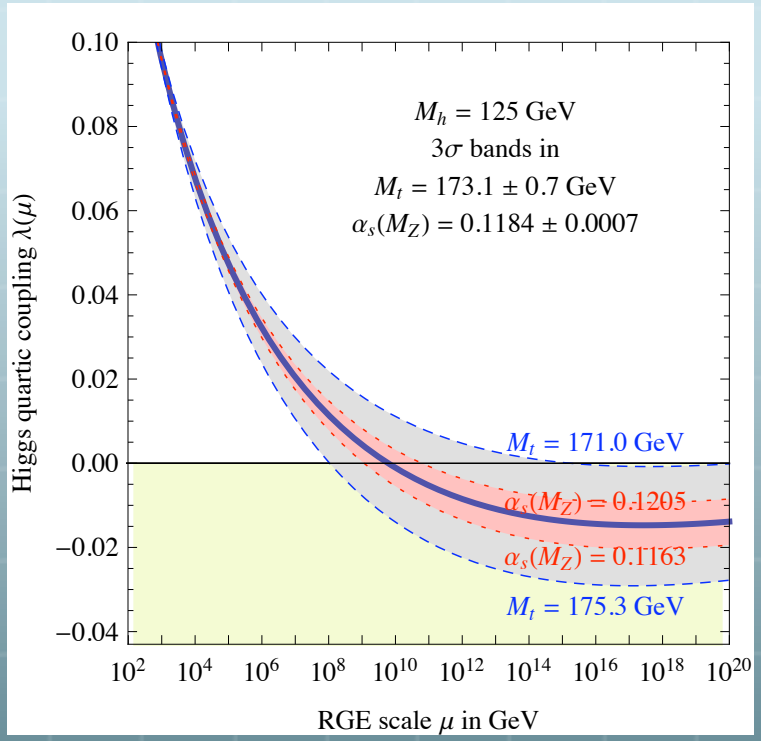
H -> WW* (8 TeV 13 fb^{-1}) $\mu = 1.5 \pm 0.6$ (7 TeV, 5 fb^{-1}; 8 TeV 12 fb^{-1}) 0.74 ± 0.25

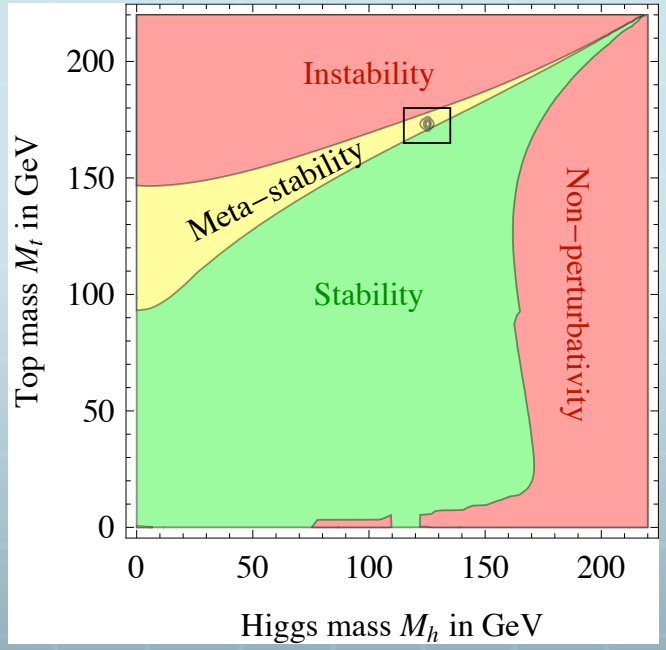
H -> ZZ* (7 TeV 5 fb^{-1}; 8 TeV 6 fb^{-1}) 1.4 ± 0.6 (7 TeV 5 fb^{-1}; 8 TeV 12 fb^{-1}) $0.8^{+0.35}_{-0.28}$

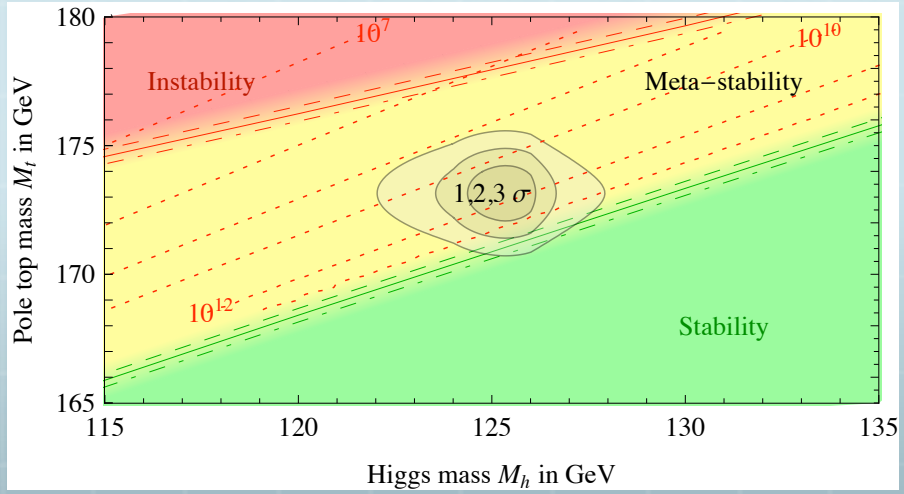
Vacuum instablity in the SM (NNLO analysis of the Higgs potential)

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori and Strumia 1205.6497









The condition of absolute stability up to the Planck scale:

$$h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$

Vacuum instability in beyond SM scenarios (with di-photon enhancement)

Joglekar, Schwaller, Wagner 1207.4235;
Arkani-Hamed, Blum, D'Agnolo, Fan 1207.4482;
Reece 1208.1765;

There are many other papers on vacuum instability of Higgs potential in different scenarios: e.g., in MSSM Altmannshofer, Carena, Shah, Yu 1211.1976;
in scenario with b-b' mixing (beautiful mirror fermion), Batell, Gori, Wang 1209.6382

Higgs radiative couplings

- **hgg, hγγ couplings**

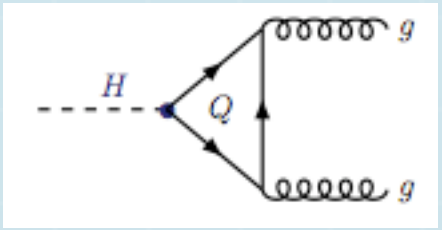
  Low energy Higgs theorem: hgg, hγγ couplings are related to beta function coefficients (Shifman et.al)

Eg: given a new heavy colored particle with mass M(v) and contribution to the QCD beta function Δb

$$\frac{\Delta b}{32\pi^2}\frac{h}{v}G^a_{\mu\nu}G^{a\mu\nu}\frac{\partial \log M(v)}{\partial \log v}$$

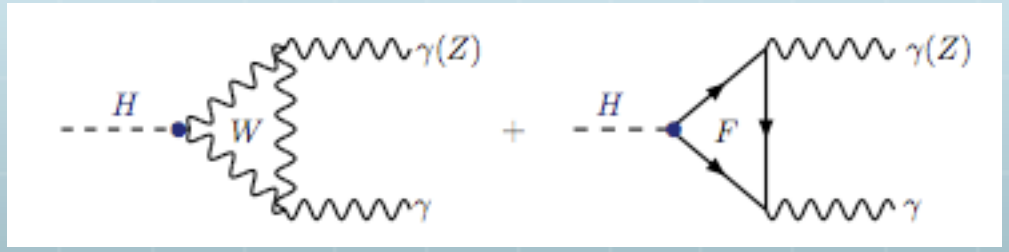
Any heavy matter with mass proportional to the Higgs VEV contribute with the same sign, whether it is a fermion or a scalar
Low energy Higgs theorem captures the leading log correction from new heavy mass threshold; there is finite mass correction, which is small

$$\frac{\Delta b}{32\pi^2}\frac{h}{v}G^a_{\mu\nu}G^{a\mu\nu}\frac{\partial \log M(v)}{\partial \log v}$$



In SM, Q=t

$$(\mathcal{A}^g_{\rm SM})_{\rm leading-log} = b_t = 4/3$$



$$(\mathcal{A}^\gamma_{SM})_{\rm leading-log} = b_t + b_W = +(4/3)^2 - 7$$

$$\mathcal{A}^\gamma_{SM} = -6.49$$

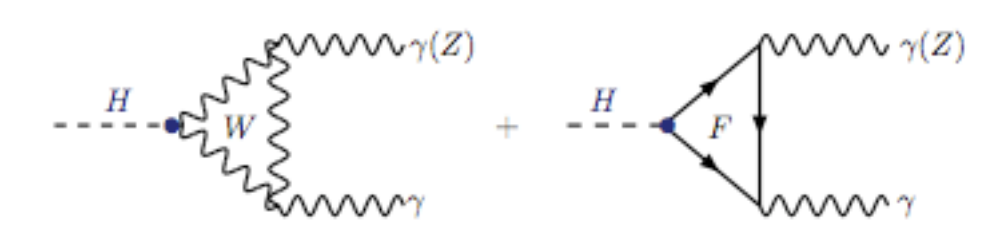
- **Currently the observations are consistent**

$$\mu_{\gamma\gamma} = \frac{\sigma \times BR(h \to \gamma\gamma)}{\sigma \times BR(h \to \gamma\gamma)_{SM}} \sim 1.5 - 2,$$

$$\mu_{VV} = \frac{\sigma \times BR(h \to VV)}{\sigma \times BR(h \to VV)_{SM}} \sim 1.$$

For this talk, we don't consider the possibility that mixing effect suppress Higgs-b-bbar coupling and enhance the rates of all the other channels

- **How to enhance diphoton: add new heavy vector-like fermions**



$$(\mathcal{A}^{\gamma}_{SM})_{\rm leading-log} = b_t + b_W = +(4/3)^2 - 7$$

$$\mathcal{A}^{\gamma}_{SM} = -6.49$$

$$\mathcal{L}_M = -\left(\psi^{+Q}\ \chi^{+Q}\right)\begin{pmatrix} m_\psi & \frac{yv}{\sqrt{2}} \\ \frac{y^c v}{\sqrt{2}} & m_\chi \end{pmatrix}\begin{pmatrix} \psi^{-Q} \\ \chi^{-Q} \end{pmatrix} + cc,$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \approx \left|1 + \frac{1}{\mathcal{A}^{\gamma}_{SM}} Q^2 \frac{4}{3}\left(\frac{\partial \log m_f}{\partial \log v}\right)\left(1 + \frac{7\, m_h^2}{120\, m_f^2}\right)\right|^2,$$

$$\mathcal{L}_M = -\left(\psi^{+Q}\ \chi^{+Q}\right)\begin{pmatrix} m_\psi & \frac{yv}{\sqrt{2}} \\ \frac{y^c v}{\sqrt{2}} & m_\chi \end{pmatrix}\begin{pmatrix} \psi^{-Q} \\ \chi^{-Q} \end{pmatrix} + cc, \qquad \text{Q: charge}$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \approx \left|1 + \frac{1}{\mathcal{A}^\gamma_{SM}} Q^2\, \frac{4}{3}\left(\frac{\partial \log m_f}{\partial \log v}\right)\left(1 + \frac{7\, m_h^2}{120\, m_f^2}\right)\right|^2,$$

N: # of species of fermions

$$\mu_{\gamma\gamma} = \frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \approx \left|1 + 0.1\,\mathcal{N}\, Q^2\, \frac{2yy^c v^2}{m_1 m_2}\right|^2$$

$$m_2 = m_1\left(1 + \sqrt{\Delta_v^2 + \Delta_y^2 + \Delta_m^2}\right), \quad \Delta_v^2 = \frac{2yy^c v^2}{m_1^2}, \quad \Delta_y^2 = \frac{(y-y^c)^2\, v^2}{2m_1^2}, \quad \Delta_m^2 = \frac{(m_\psi - m_\chi)^2}{m_1^2}$$

mass eigenvalues: m2 > m1

m1 > 100 GeV LEP bound!

$$\mu_{\gamma\gamma} \geq 1.5 \to yy^c \geq \left(\frac{0.86}{\mathcal{N}\, Q^2}\, \frac{m_1}{100\ \text{GeV}}\right)^2.$$

To get a large enhancement, one needs large Yukawa couplings!

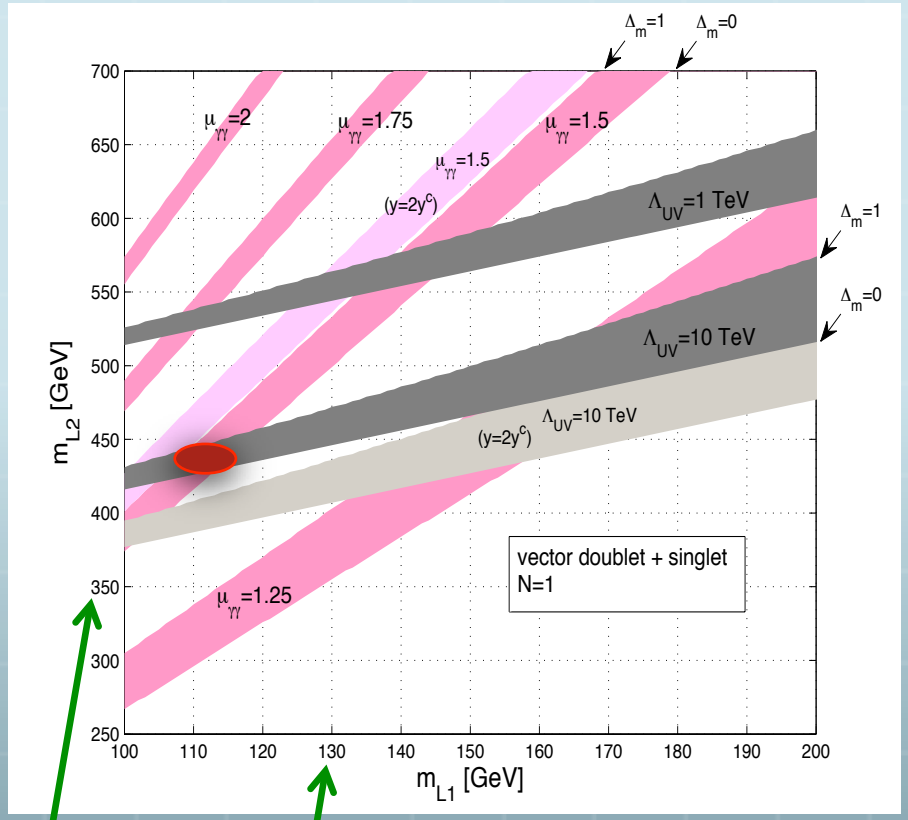
Vacuum instability of Higgs potential: $\lambda |H|^4$

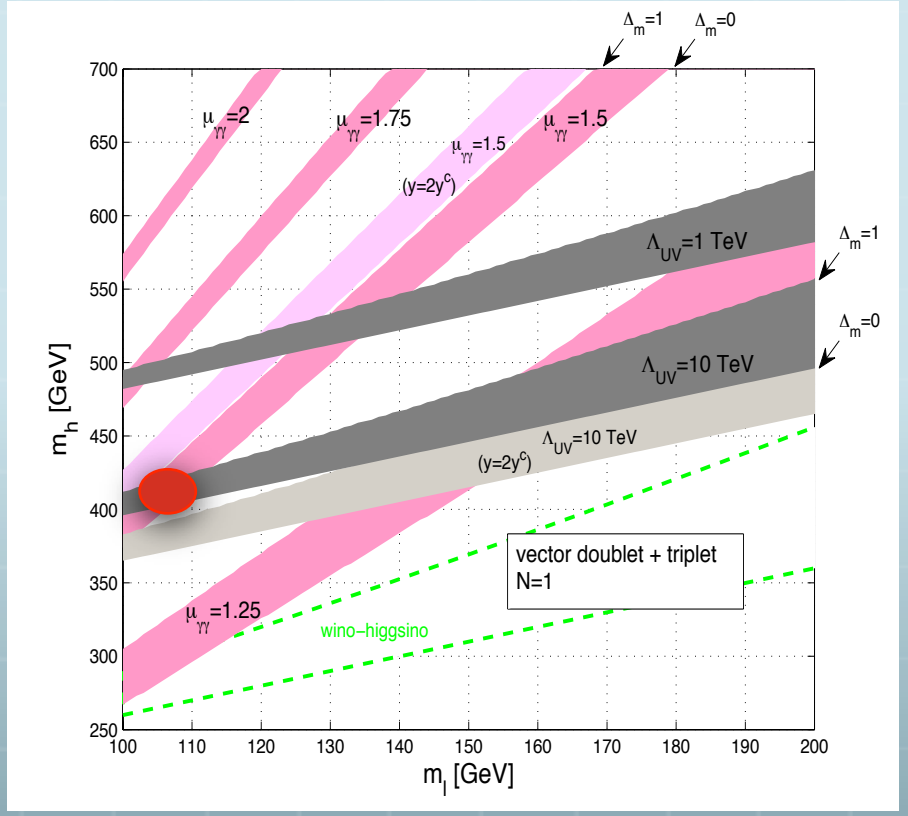
$$16\pi^2\frac{d\lambda}{dt} = \lambda\left(24\lambda - 9g_2^2 - \frac{9g_1^2}{5} + 12y_t^2 + 4\mathcal{N}\left(y_n^2 + y_n^{c2} + y^2 + y^{c2}\right)\right) - 2\mathcal{N}\left(y^4 + y^{c4} + y_n^4 + y_n^{c4}\right) - 6y_t^4$$
$$+\frac{3}{8}\left(2g_2^4 + \left(g_2^2 + \frac{3g_1^2}{5}\right)^2\right). \qquad \text{(A.1)}$$

Large Yukawa drives Higgs quartic coupling negative at higher energy scale; At Λ_{UV}, λ is so negative that the tunneling rate through false vacuum bubbles of size Λ_{UV}^{-1} is less than the age of the Universe; the theory is thus cut off at Λ_{UV}

$$\text{“vector}-\text{like lepton”}: \quad \psi, \psi^c \sim (1,2)_{\pm\frac{1}{2}}, \;\; \chi, \chi^c \sim (1,1)_{\mp 1}.$$
$$-\mathcal{L} = m_\psi \psi\psi^c + m_\chi \chi\chi^c + yH\psi\chi + y^c H^\dagger \psi^c \chi^c + cc.$$
$$\text{“wino} + \text{Higgisino”}: \quad \psi, \psi^c \sim (1,2)_{\pm\frac{1}{2}}, \;\; \chi \sim (1,3)_0.$$
$$-\mathcal{L} = m_\psi \psi\psi^c + \frac{1}{2} m_\chi \chi\chi + \sqrt{2} yH\psi\chi + \sqrt{2} y^c H^\dagger \psi^c \chi + cc.$$

N=1





Fermion mass eigenvalues

Arkani-Hamed, Blum, D'Agnolo and JF 1207.4482

Recap:

- To get a diphoton enhancement >~ 1.5, one needs to have a light charged state with mass below 150 GeV (N=2) and a very low cutoff below 10 TeV.
- This light charged state, if exists, is within reach of LHC 8 TeV running; at worst, 14 TeV running.
- Bosonic degrees of freedom must kick in below or about 10 TeV to cure the theory
- The vacuum instability constraint could be relieved by allowing N>1 and/or Q>1; give up gauge coupling unification and could be constrained more easily experimentally

Some theoretical implications

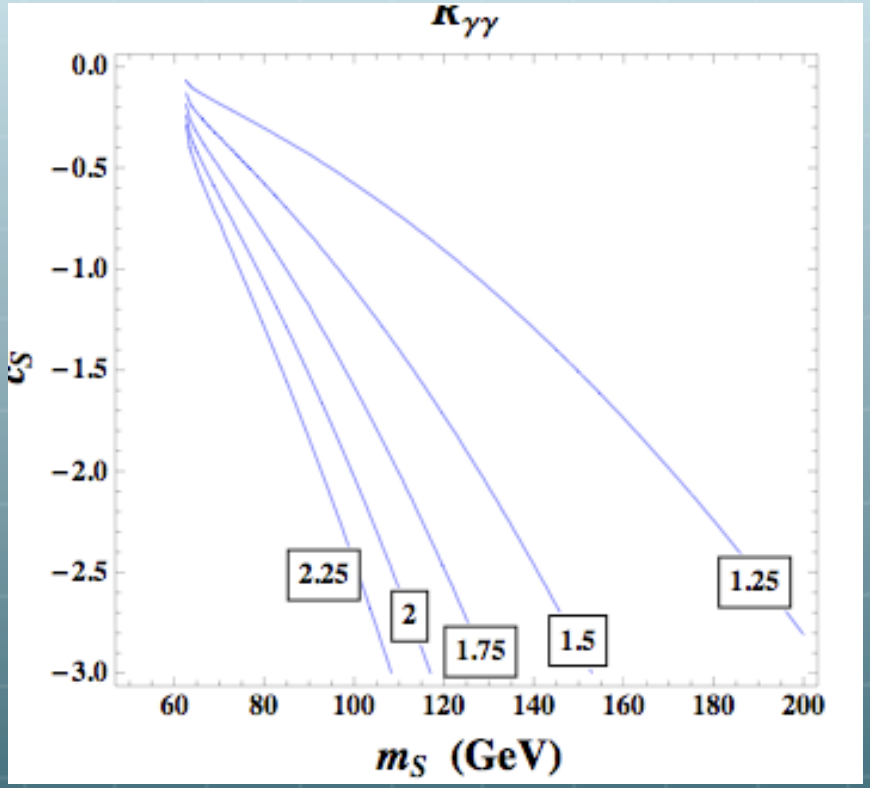
- **Split SUSY or in general, theory with low-energy effective description containing only fermions + Higgs up to 10 TeV predicts the diphoton enhancement has to disappear!**

- **Alternatively, diphoton enhancement, if true, will rule out split SUSY and its variants**

- **One could also add scalars: e.g., S with a large negative quartic coupling to the Higgs**

$$c_s |S|^2|H|^2 + \lambda_S |S|^4 + \lambda_H |H|^4$$

- **Again, one needs to worry about vacuum instability;**



$$\lambda_S \geq \frac{c_s^2}{4\lambda_H} \quad \lambda_H \sim 0.13$$

Large $|c_s|$ leads to either strong coupling or vacuum instability

Low, Carena, Wagner 1206.1082

Things one should not do: Add colored and charged particles to generate a large diphoton enhancement;

$$r_G^i = \frac{\mathcal{A}^i_{hgg}}{SM} = \frac{2t_c^i}{1}\frac{\partial \log m(v)}{\partial \log v}$$

$$r_\gamma^i = \frac{\mathcal{A}^i_{h\gamma\gamma}}{SM} = \frac{\frac{1}{3}N_c^i Q^2}{-6.49}\frac{\partial \log m(v)}{\partial \log v}$$

$$r_G^i = -9.7\frac{t_c^i}{N_c^i Q^2} r_\gamma^i$$

$$\mu_{\gamma\gamma} = \frac{\sigma \times BR(h \to \gamma\gamma)}{\sigma \times BR(h \to \gamma\gamma)_{SM}} = \left|1 - 9.7\frac{t_c^i}{N_c^i Q^2} r_\gamma^i\right|^2 \left|1 + r_\gamma^i\right|^2$$

SM ~2 SM ~0.5

Non-colored particle:

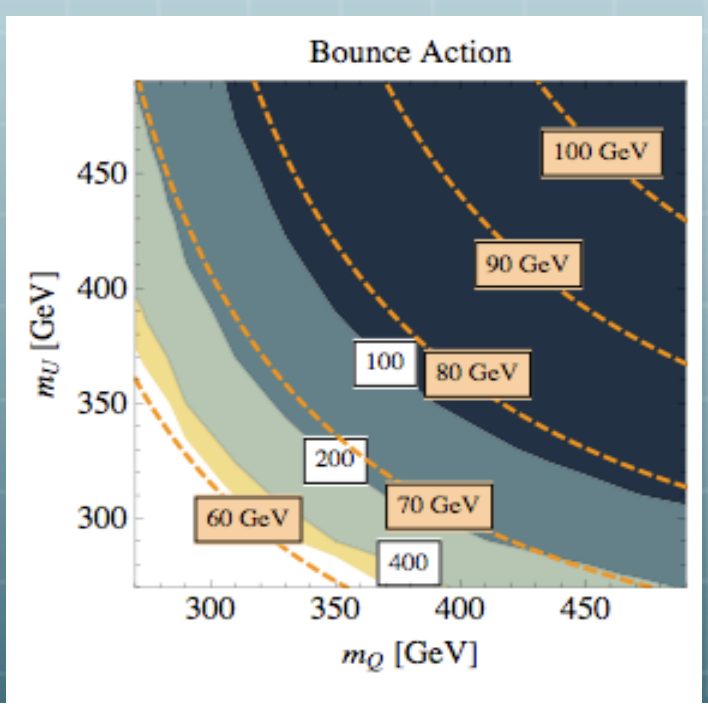
$$\mu_{\gamma\gamma} = \frac{\sigma \times BR(h \to \gamma\gamma)}{\sigma \times BR(h \to \gamma\gamma)_{SM}} = \left|1 + r_\gamma^i\right|^2$$

~0.2

- **Even more severe vacuum instability problem for colored fermions: could not enhance diphoton rate at all requiring the UV cutoff is bigger than 1 TeV.**

  Arkani-Hamed, Blum, D'Agnolo and JF 1207.4482

- **Similarly, vacuum instability gets worse for colored scalars, e.g., stops. Again, one could not enhance diphoton rate with stops.** **Reece, 1208.1765**



A_t adjusted to flip the sign of hGG amplitude.

Conclusion

- Higgs couplings would be a powerful indirect probe of beyond SM physics!
- Vacuum instability leads to interesting and important implications for SM and BSM physics;

Thank you!

Higgs couplings

- Radiative effect: hgg, hγγ couplings

  Low energy Higgs theorem: hgg, hγγ couplings are related to beta function coefficients (Shifman et.al)

Gauge theory $\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu}$

Run the gauge coupling from Λ to μ with an intermediate scale M, at which the beta function coef. changes from b to b+Δb

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2}\log\frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2}\log\frac{\Lambda}{M}$$

- **Suppose the intermediate mass threshold M is a function of the Higgs field M=M(h(x)) , one can extract from the gauge kinetic term the Higgs coupling**

$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu} \qquad \frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2}\log\frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2}\log\frac{\Lambda}{M}$$

$$\frac{\Delta b}{32\pi^2}\frac{h}{v} G^a_{\mu\nu} G^{a\mu\nu} \frac{\partial \log M(v)}{\partial \log v}$$

$M(h)|_{<h>=v}$

Any heavy matter with mass proportional to the Higgs VEV contribute with the same sign, whether it is a fermion or a scalar

Low energy Higgs theorem captures the leading log correction from new heavy mass threshold; there is finite mass correction, which is small

Example: a heavy beyond SM scalar, labeled by i, that carries both color and EM charges Q

$$r_G^i = \frac{\mathcal{A}_{hgg}^i}{SM} = \frac{2t_c^i}{1}\frac{\partial \log m(v)}{\partial \log v}$$

$$r_\gamma^i = \frac{\mathcal{A}_{h\gamma\gamma}^i}{SM} = \frac{\frac{1}{3}N_c^i Q^2}{-6.49}\frac{\partial \log m(v)}{\partial \log v}$$

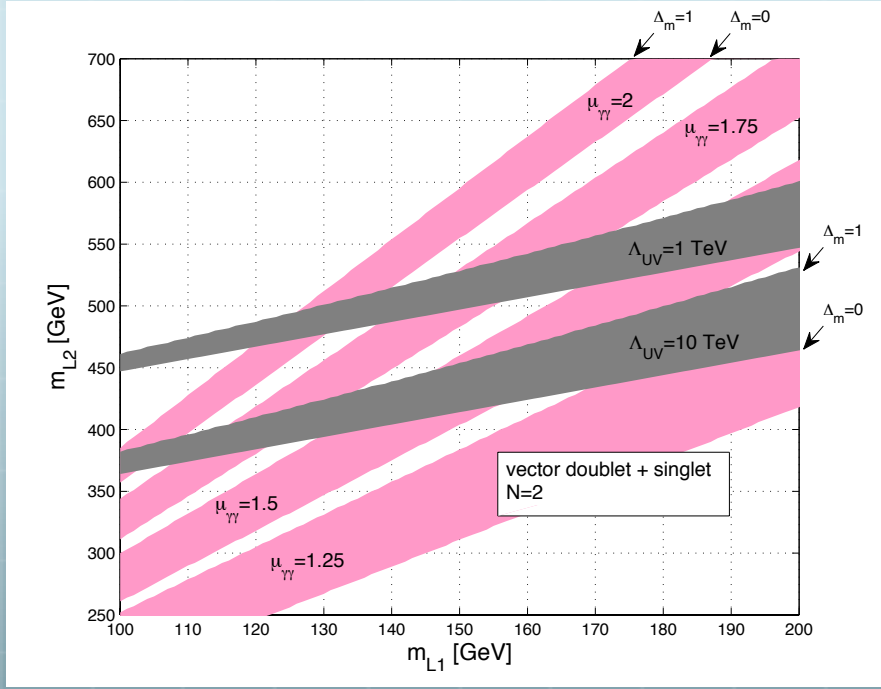
$$r_G^i = -9.7\frac{t_c^i}{N_c^i Q^2} r_\gamma^i$$

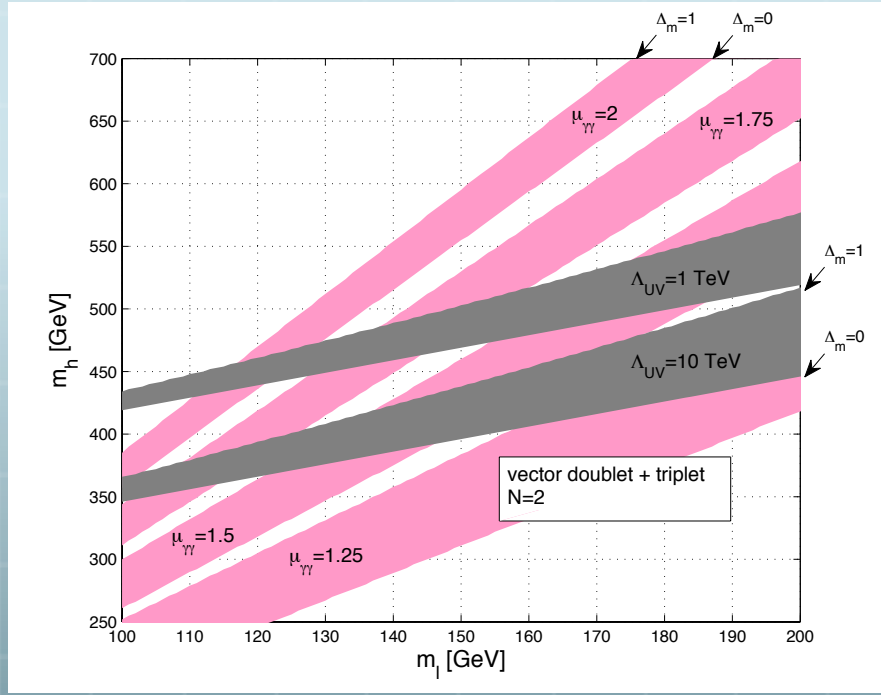
t_c: Dykin index;
N_c: dimension

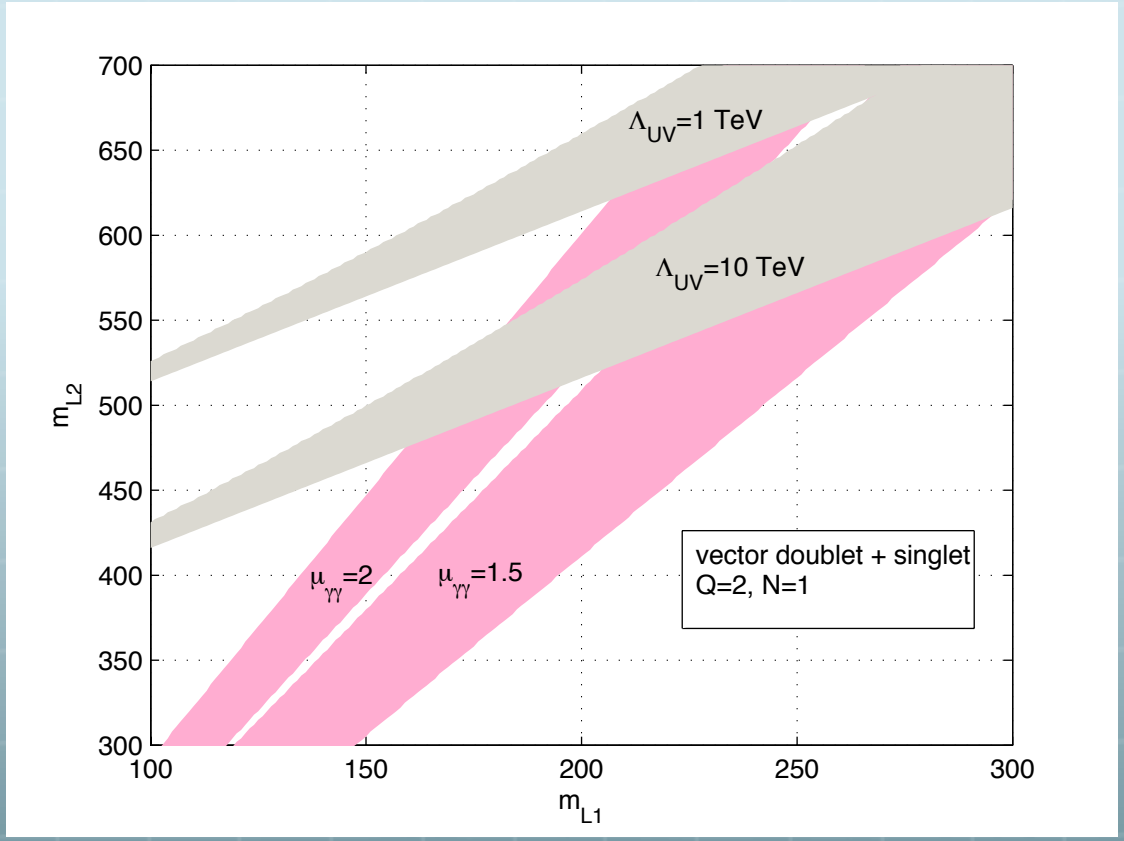
$$\text{stop}: \quad t_c = 1/2, N_c = 3, Q = 2/3;$$

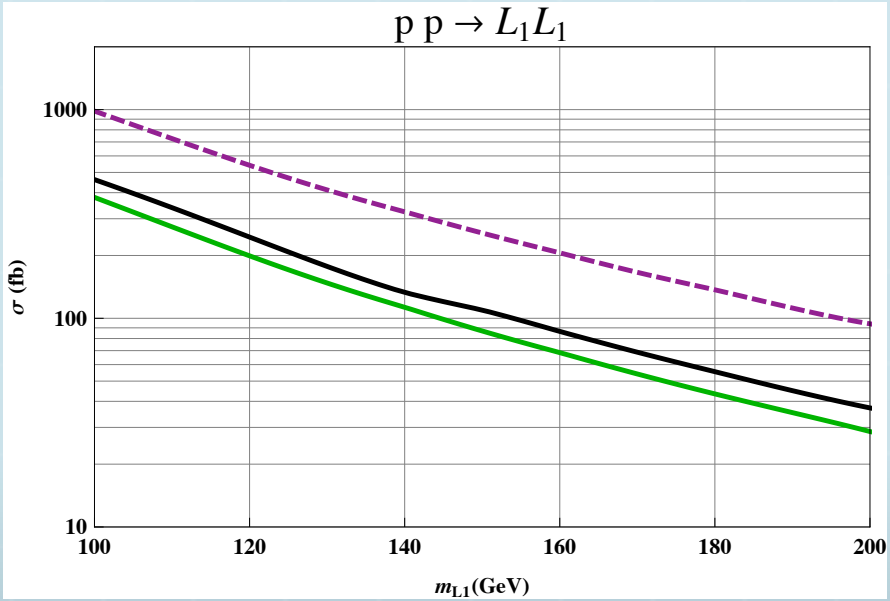
$$r_G^{\tilde{t}} \approx -3.65 r_\gamma^{\tilde{t}}$$

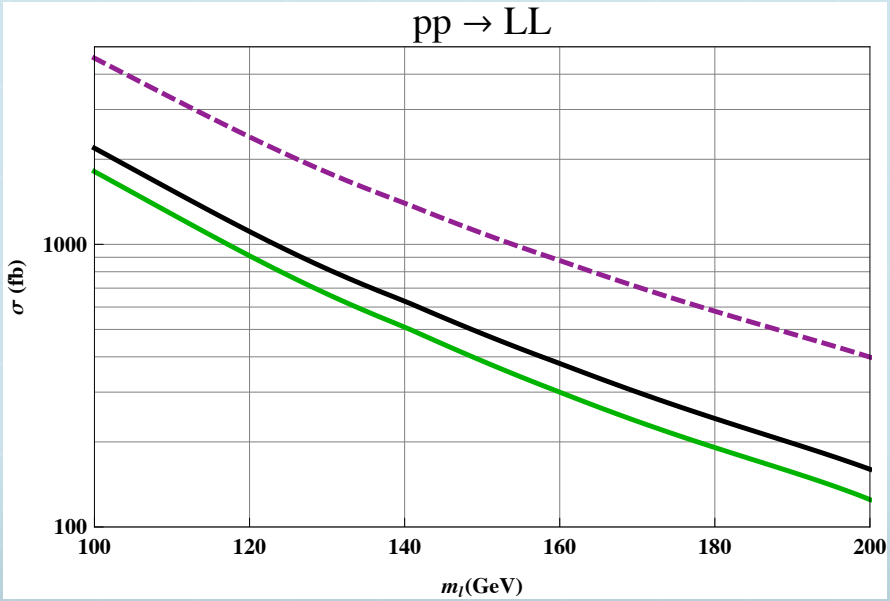
N=2

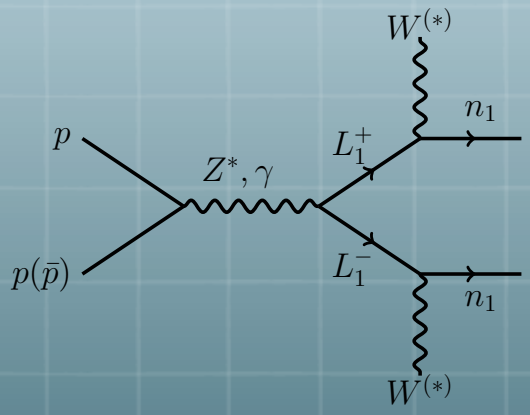

Δm=1
Δm=0
μγγ=2
μγγ=1.75
ΛUV=1 TeV
ΛUV=10 TeV
μγγ=1.5
μγγ=1.25
vector doublet + singlet
N=2
mL2 [GeV]
mL1 [GeV]

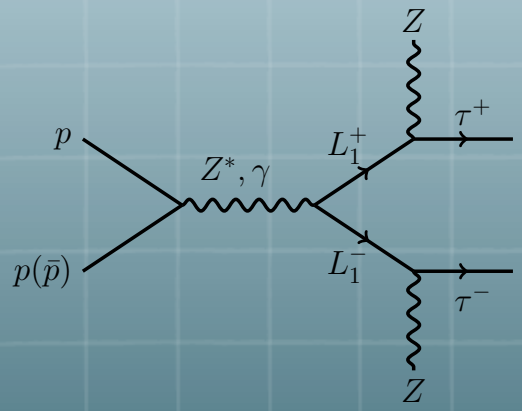

Δm=1
Δm=0
μγγ=2
μγγ=1.75
ΛUV=1 TeV
ΛUV=10 TeV
μγγ=1.5
μγγ=1.25
vector doublet + triplet
N=2
mh [GeV]
ml [GeV]

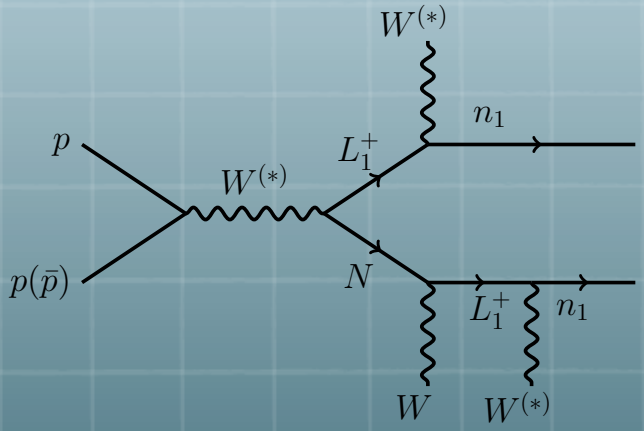

700
650
600
550
500
450
400
350
300
100
150
200
250
300
m_{L2}
m_{L1}
Λ_{UV}=1 TeV
Λ_{UV}=10 TeV
$\mu_{\gamma\gamma}$=2
$\mu_{\gamma\gamma}$=1.5
vector doublet + singlet
Q=2, N=1


p p → $L_1 L_1$
1000
100
10
σ (fb)
100
120
140
160
180
200
m_{L1}(GeV)


pp → LL
1000
100
σ (fb)
100
120
140
160
180
200
m_l(GeV)


$W^{(*)}$
n_1
p
L_1^+
Z^*, γ
$p(\bar{p})$
L_1^-
n_1
$W^{(*)}$


Z
τ^+
p
L_1^+
Z^*, γ
$p(\bar{p})$
L_1^-
τ^-
Z


$W^{(*)}$
n_1
p
L_1^+
$W^{(*)}$
$p(\bar{p})$
N
L_1^+
n_1
W
$W^{(*)}$

Theoretical implications

- **In natural SUSY, one cannot only get** Blum, D'Agnolo and JF 1206.5303

$$\frac{\mu_{\gamma\gamma}}{\mu_{ZZ^*}} \leq 1.4$$

- **One could get a sizable diphoton enhancement through light and highly-mixed staus with about percentage fine-tuning** Carena, Gori, Shah, Wagner and Wang 1112.3336; 1205.5842;

- **Split SUSY or in general, theory with low-energy effective description containing only fermions + Higgs up to 10 TeV predicts the diphoton enhancement has to disappear!**

- **Alternatively, diphoton enhancement, if true, will rule out split SUSY and its variants**