Probing New Weak-scaled Charged Matter: Higgs Decays, Dark Matter, EDM

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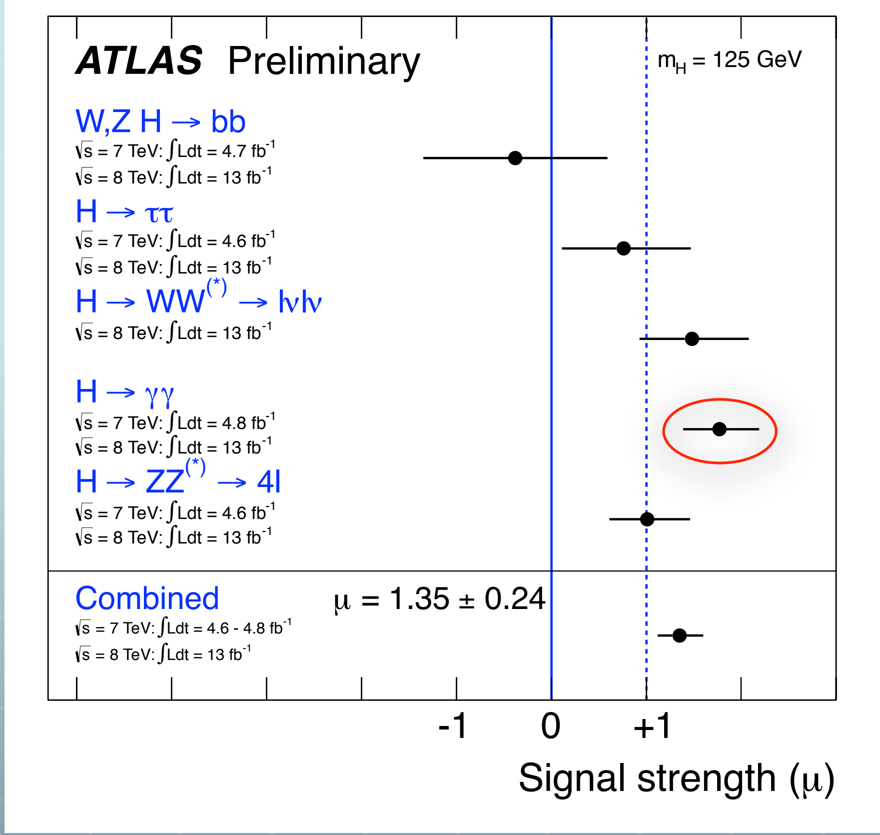
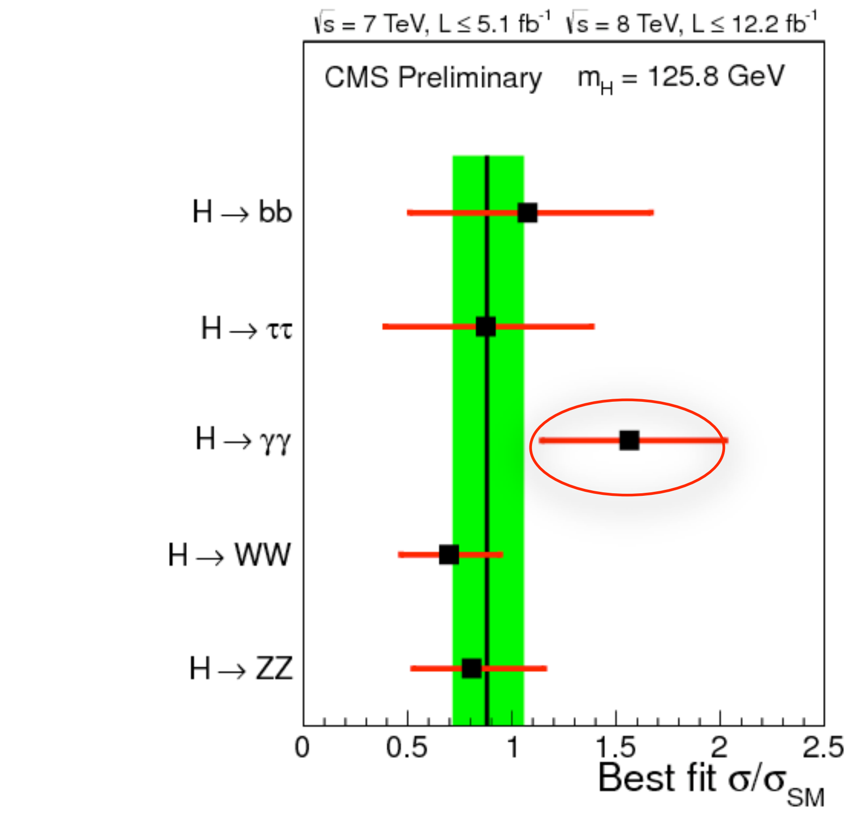
Higgs diphoton enhancement:





- **Currently the observations are consistent**

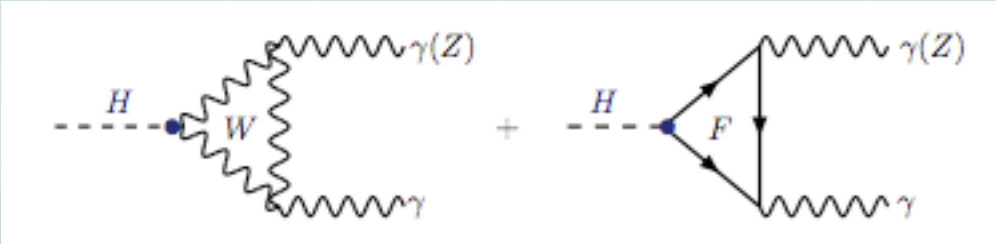
$$\mu_{\gamma\gamma} = \frac{\sigma \times BR(h \to \gamma\gamma)}{\sigma \times BR(h \to \gamma\gamma)_{SM}} \sim 1.5 - 2,$$

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

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;

Simplest way to achieve this pattern is to have weak-scale charged matter, which obtains at least part of its mass from Higgs, modifying higgs-diphoton coupling.

- **How to enhance diphoton: loop of weak-scale charged matter**
- **Add new heavy vector-like fermions**



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

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

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

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

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

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

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

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

mass eigenvalues: m2 > m1

m1 > 100 GeV LEP bound!

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

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

Vacuum instability of Higgs potential: λ |H|⁴

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

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}

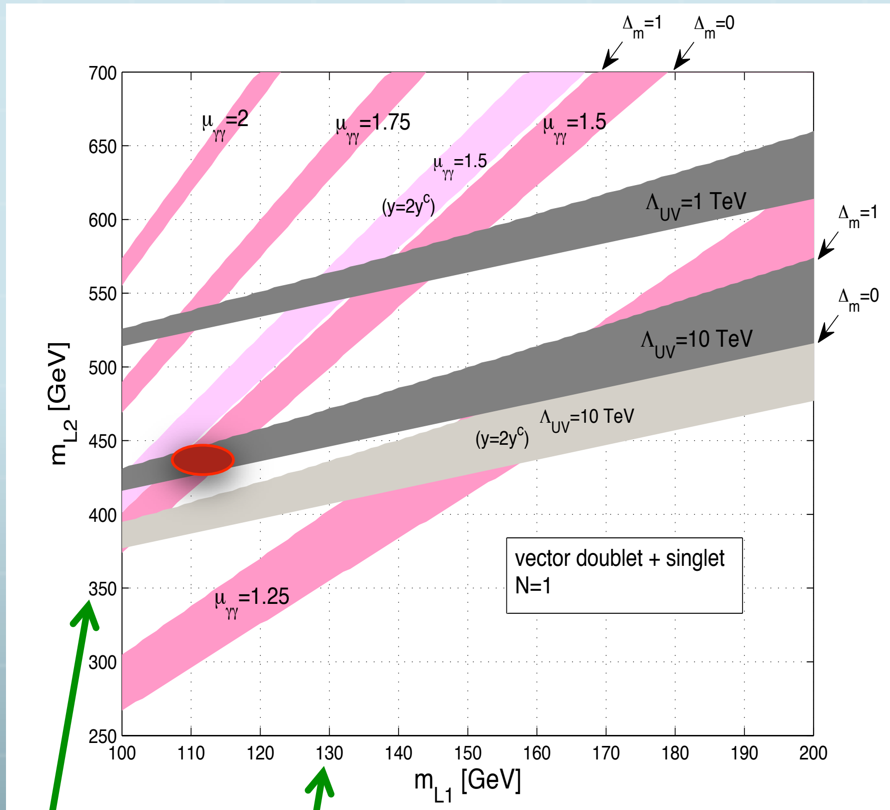
"vector – like lepton" : $\psi, \psi^c \sim (1,2)_{\pm\frac{1}{2}}, \quad \chi, \chi^c \sim (1,1)_{\mp 1}.$

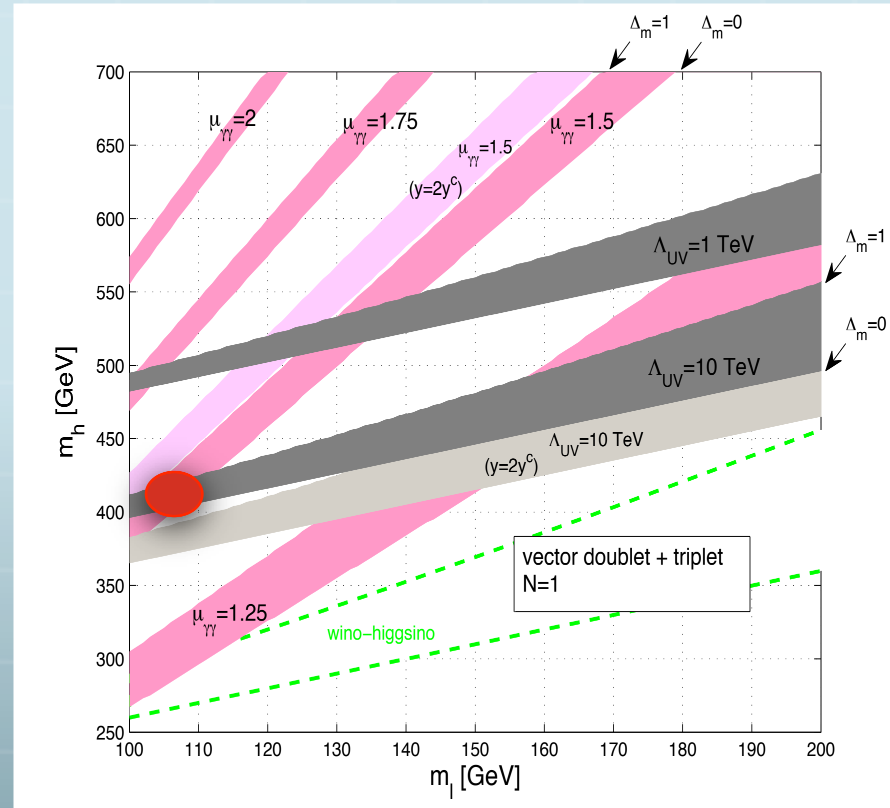
$$-\mathcal{L} = m_\psi \psi\psi^c + m_\chi \chi\chi^c + yH\psi\chi + y^c H^\dagger \psi^c \chi^c + cc.$$

"wino + Higgisino" : $\psi, \psi^c \sim (1,2)_{\pm\frac{1}{2}}, \quad \chi \sim (1,3)_0.$

$$-\mathcal{L} = m_\psi \psi\psi^c + \frac{1}{2} m_\chi \chi\chi + \sqrt{2} yH\psi\chi + \sqrt{2} y^c H^\dagger \psi^c \chi + cc.$$

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

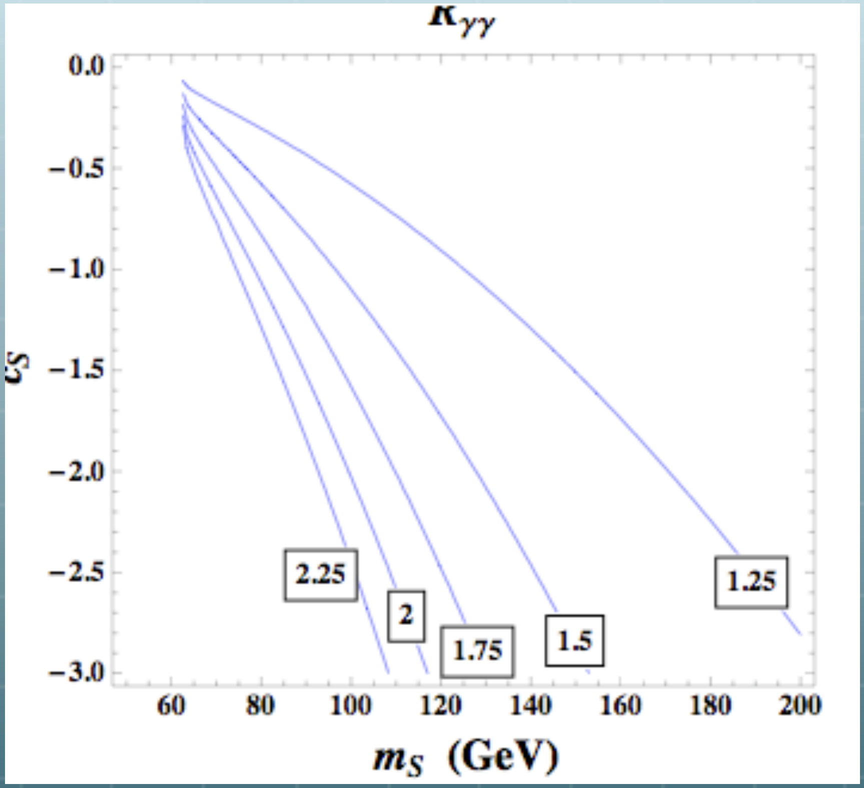
- **Split SUSY or in general, theory with low-energy effective description containing only fermions + Higgs up to 10 TeV predicts the diphoton enhancement has to disappear!**

- **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;**



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

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

Carena, Low, Wagner 1206.1082

- Light stau scenario: Carena, Gori, Low, Shah, Wagner and Wang 2011 & 2012

  Vacuum instability constraints diphoton enhancement to be about 1.5 in large tan beta region (tan β <~ 100) and light stau (m ~ 90 GeV)

Aside:

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

$$r^i_G = \frac{\mathcal{A}^i_{hgg}}{SM} = \frac{2t^i_c}{1}\frac{\partial \log m(v)}{\partial \log v}$$

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

$$r^i_G = -9.7\frac{t^i_c}{N^i_c Q^2}r^i_\gamma$$

$$\mu_{\gamma\gamma} = \frac{\sigma \times BR(h\to\gamma\gamma)}{\sigma \times BR(h\to\gamma\gamma)_{SM}} = \left|1 - 9.7\frac{t^i_c}{N^i_c Q^2}r^i_\gamma\right|^2 \left|1 + r^i_\gamma\right|^2$$

SM ~ 2 SM ~0.5

Non-colored particle:

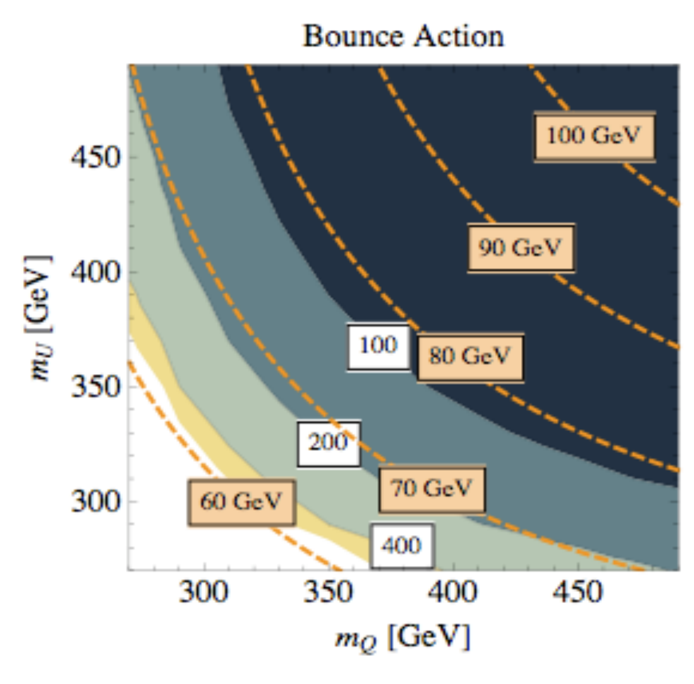
$$\mu_{\gamma\gamma} = \frac{\sigma \times BR(h\to\gamma\gamma)}{\sigma \times BR(h\to\gamma\gamma)_{SM}} = \left|1 + r^i_\gamma\right|^2$$

~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

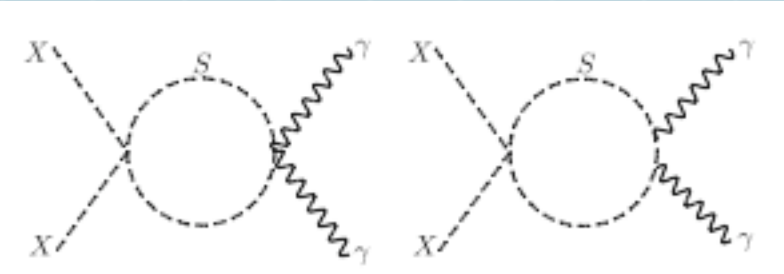
- **Similarly, vacuum instability gets worse for colored scalars, e.g., stops. Again, one could not enhance diphoton rate with stops.** **Reece, 1208.1765**

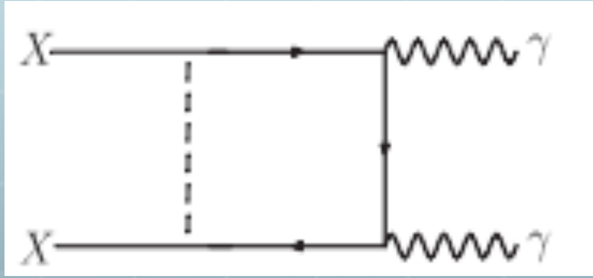


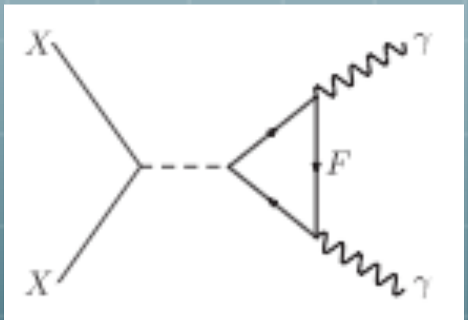
A_t adjusted to flip the sign of hGG amplitude.

- **indirect DM signal:**

It was often claimed that: "smoking-gun" signal of annihilating DM would be a monochromatic gamma-ray line (lines) in a region of high DM density, e.g., our Galactic center!

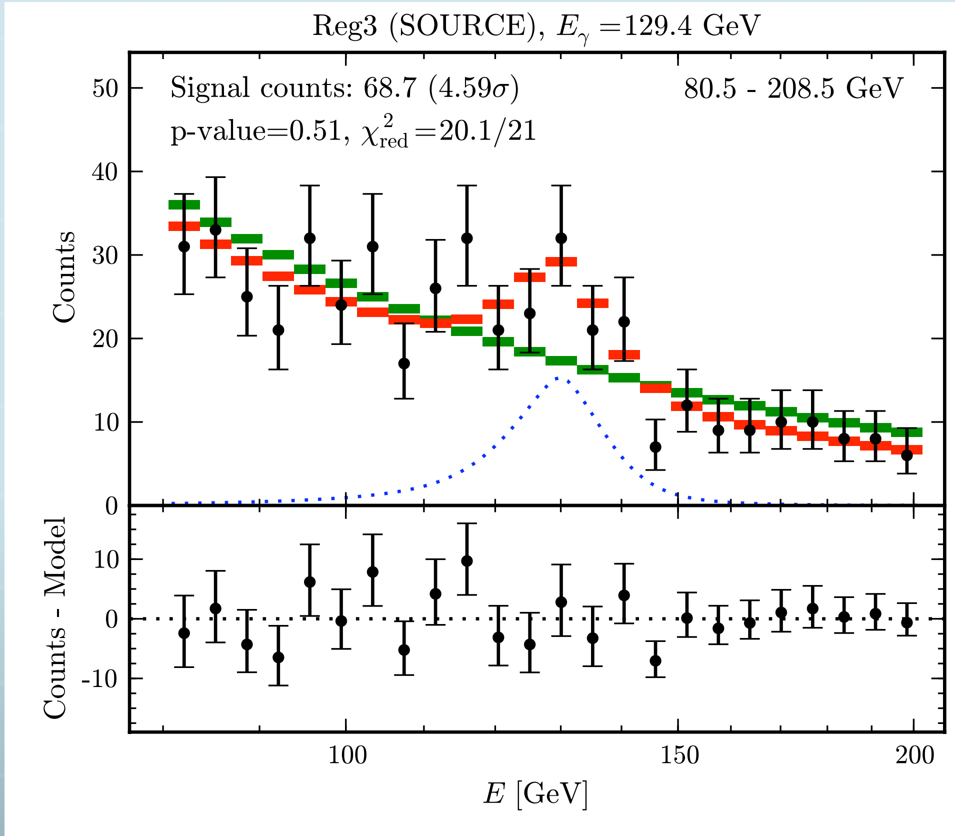


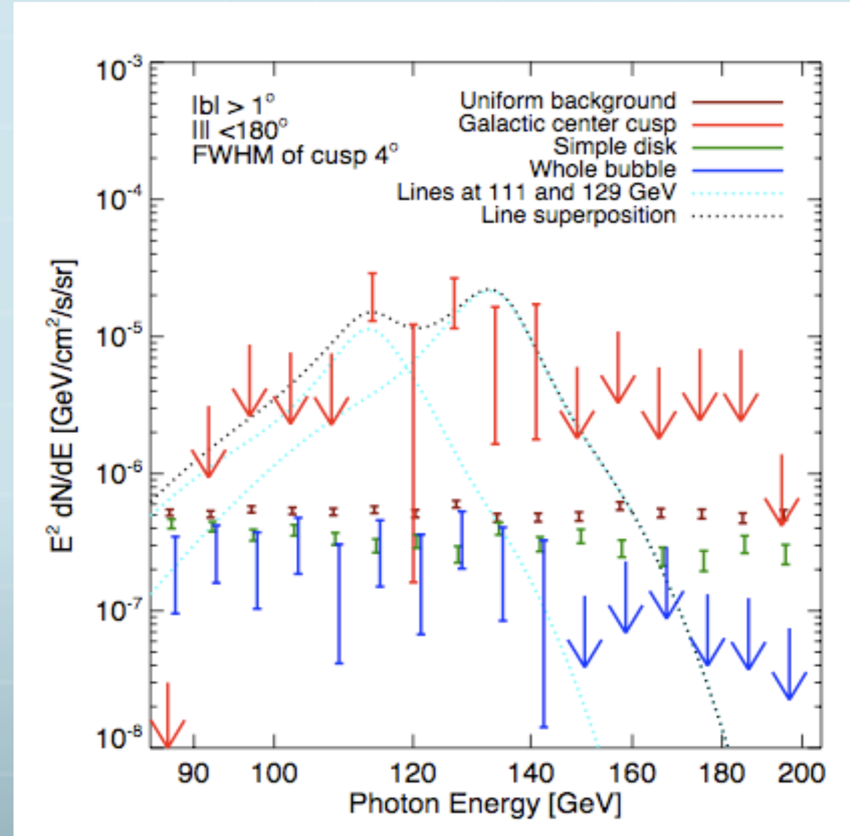




Presently DM is non-relativistic: DM + DM ➔ϒϒ

$$E_\gamma = M_{DM}$$

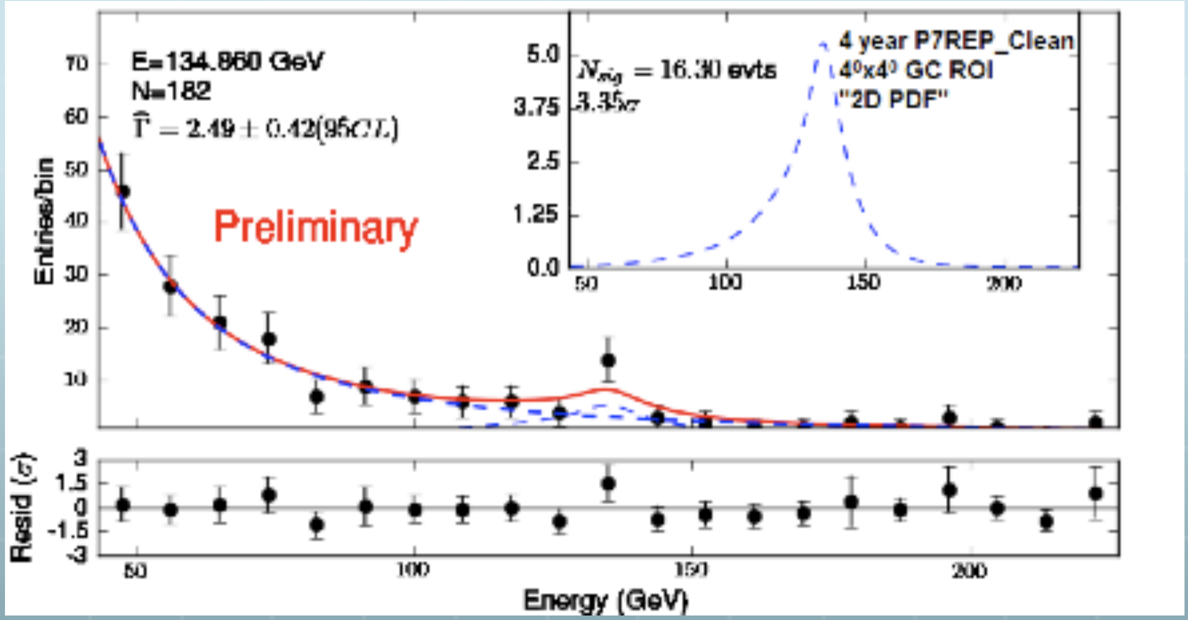




Weniger 1204.2797; claiming 4.6 σ locally (3.2 σ globally)

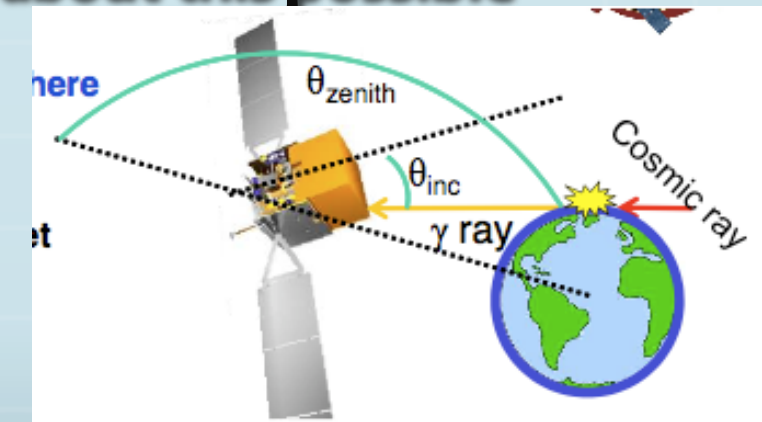
Su and Finkbiener; 1206.1616; could fit two lines γγ and γZ

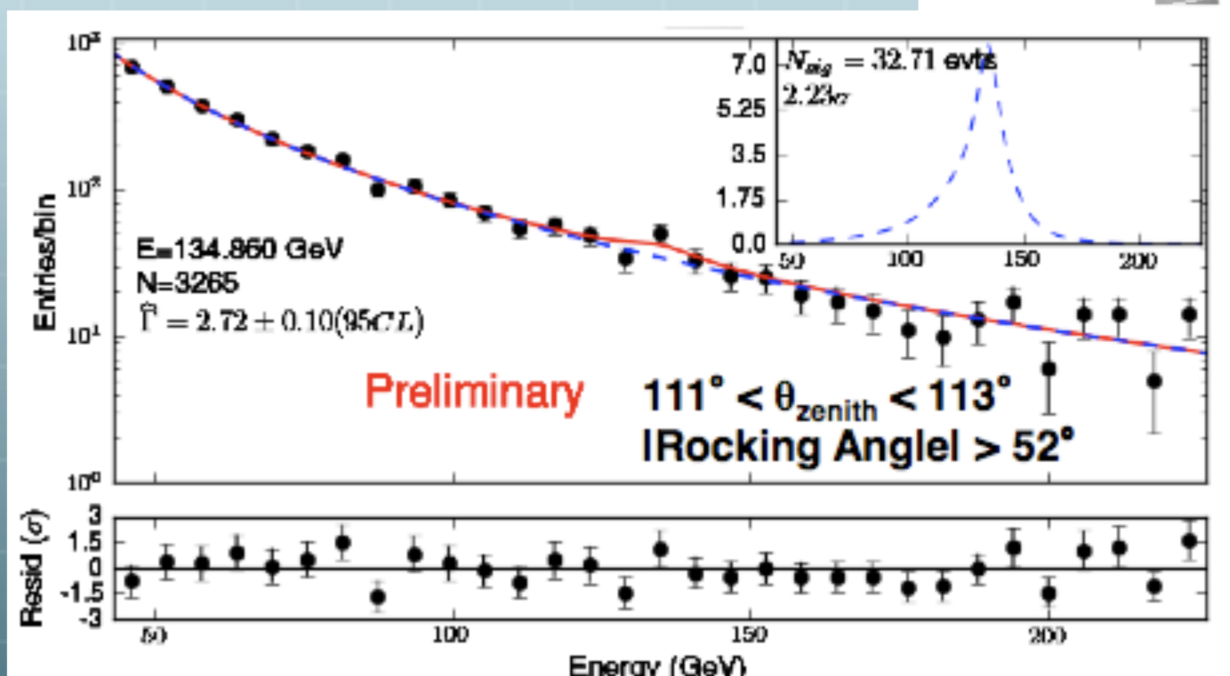
Andrea Albert on behalf of Fermi collaboration at Fermi Symposium 11/2/2012 (analysis based on 4 year reprocessed data)



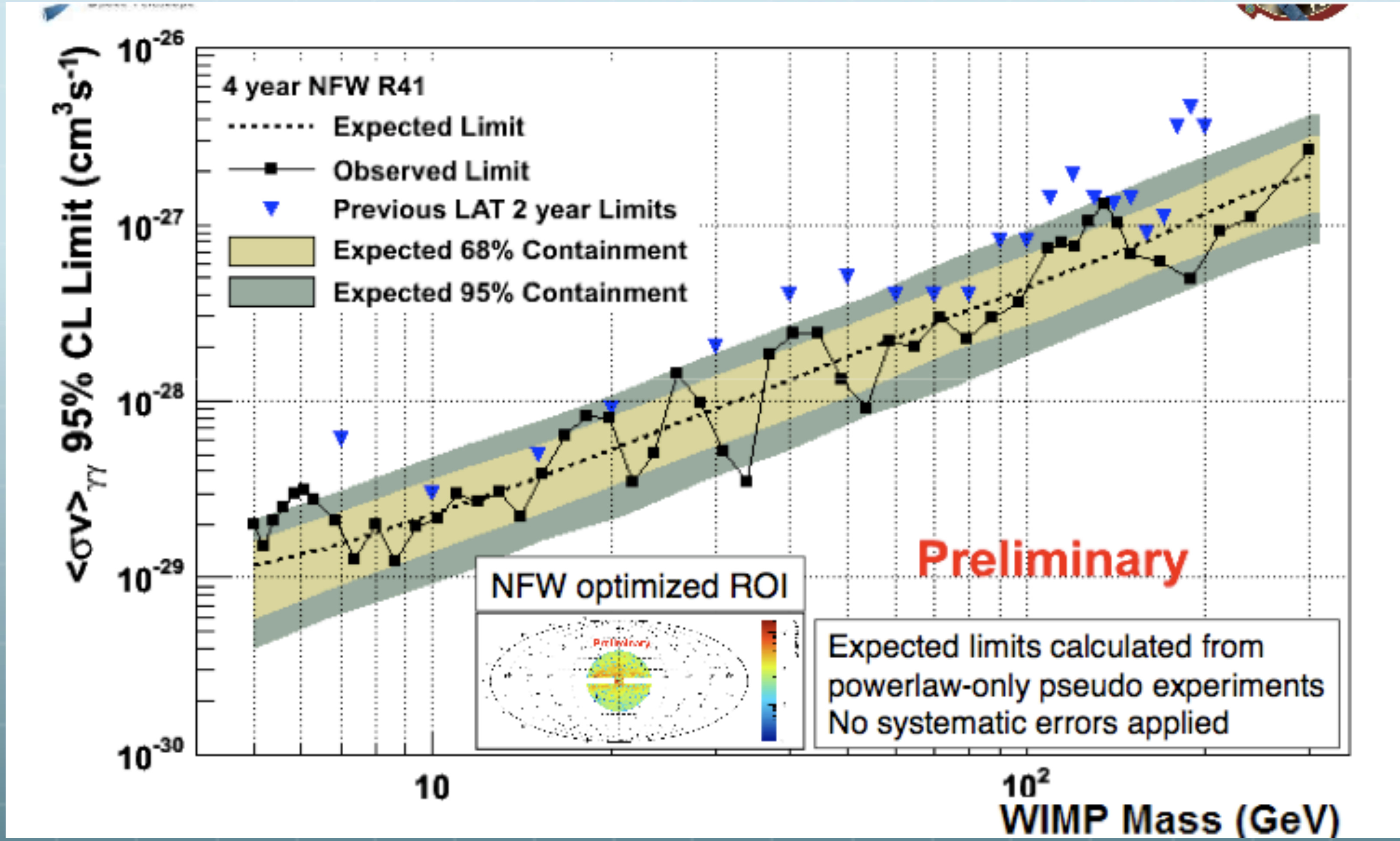
2d fit: 3.35 σ locally at 135 GeV; < 2σ globally

- **Quite a few things to worry about this possible "signal":**
- **Earth Limb Photons**

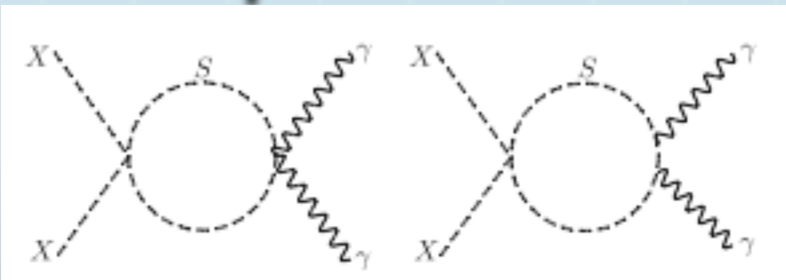


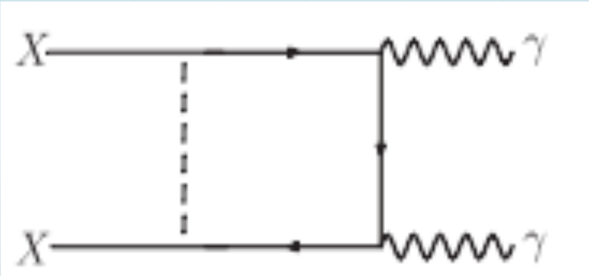


- **Similar features at other energies along the GP**



- **Assuming such a signal, the simplest possibility is to have weak-scale charged matter mediating DM+DM to two photons**

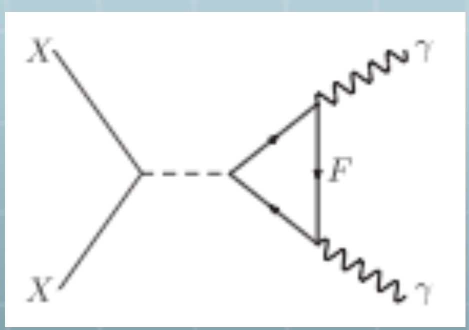




- **Theoretical difficulties to explain it:**

$$\langle \sigma v \rangle_{DM+DM \to 2\gamma} \sim 10^{-27} \mathrm{cm}^3/\mathrm{s}$$

Need large coupling and/or mass coincidences



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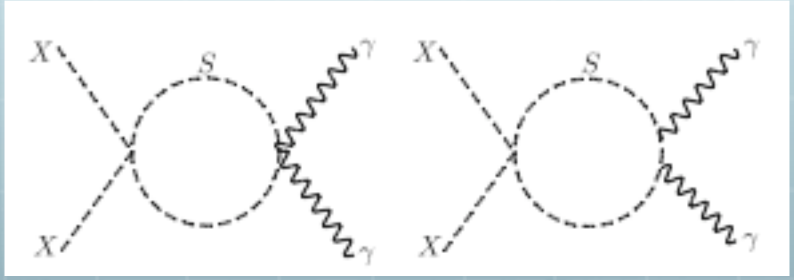
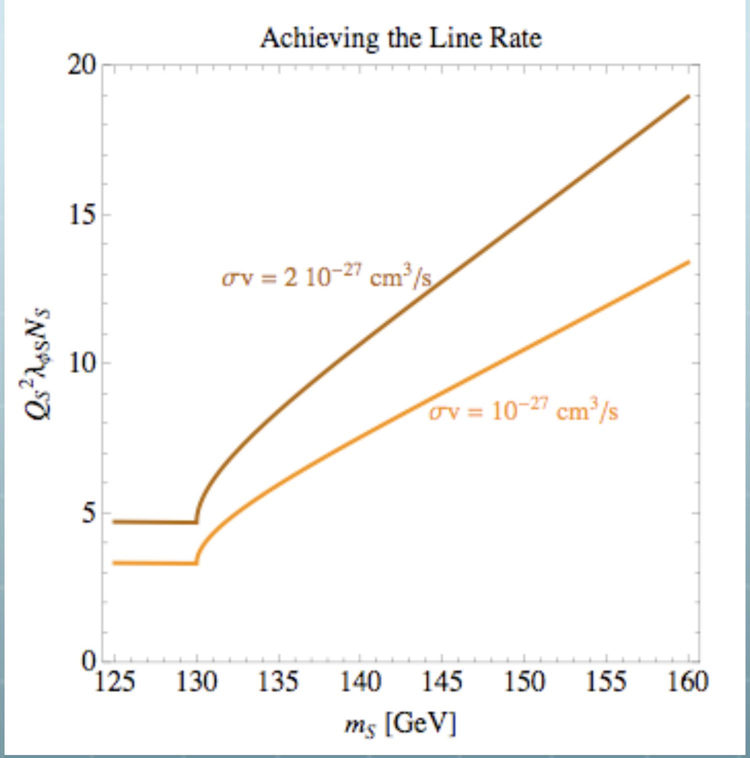
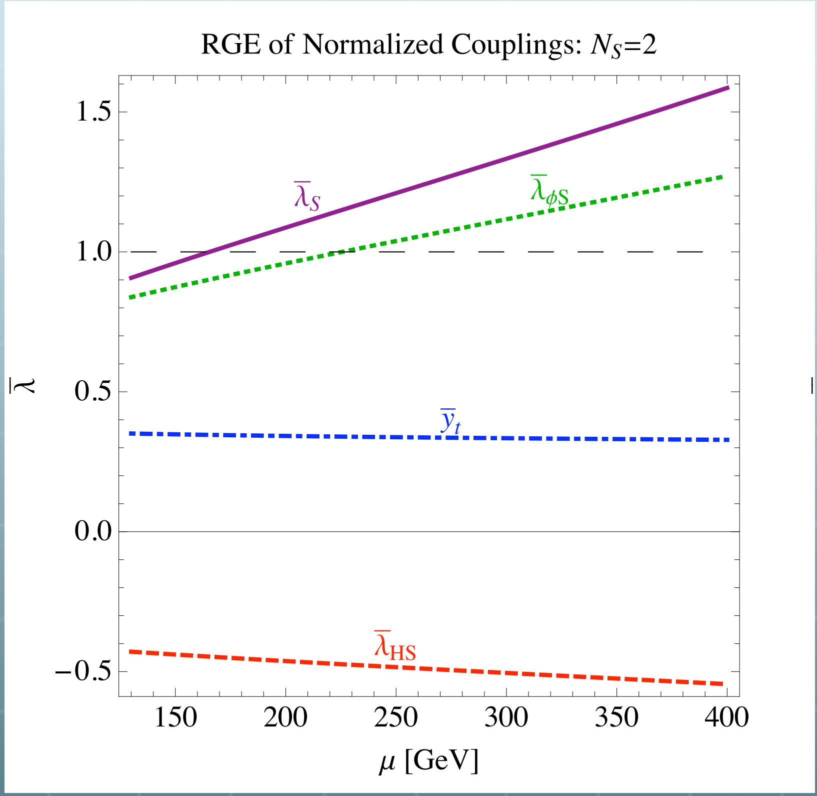
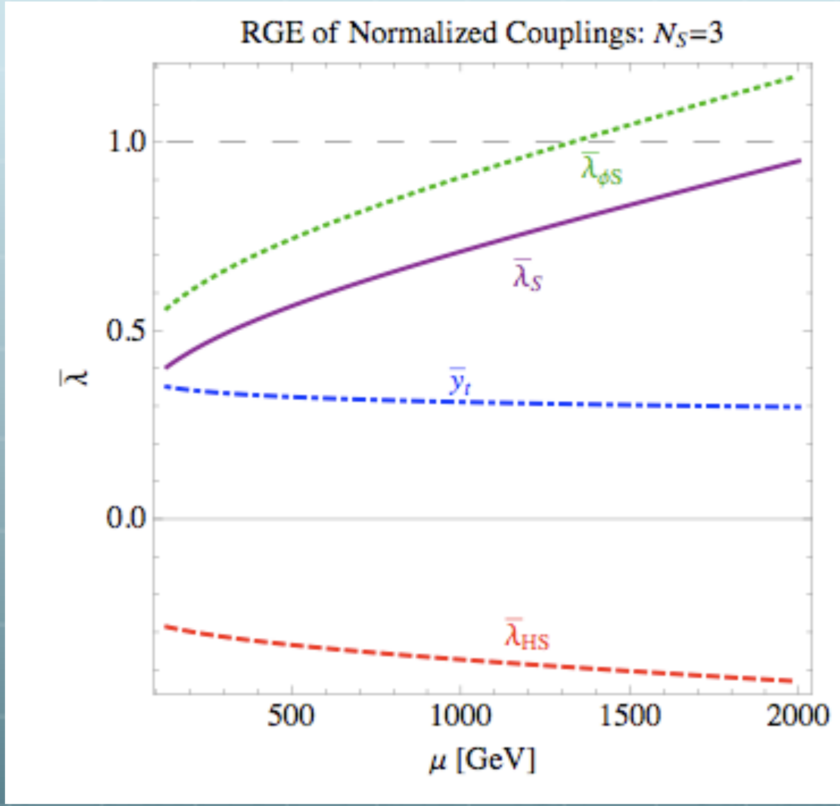




$$-\mathcal{L} \supset \lambda_{\phi S}\phi^2|S|^2 + \lambda_{HS}|S|^2|H|^2 + \lambda_{\phi H}\phi^2|H|^2 + m_{S;0}^2|S|^2 + \lambda_S|S|^4 + \frac{1}{2}m_\phi^2\phi^2 + \lambda_\phi\phi^4$$
$$- \mu_H^2|H|^2 + \lambda_H|H|^4$$

Couplings become non-perturbative quickly

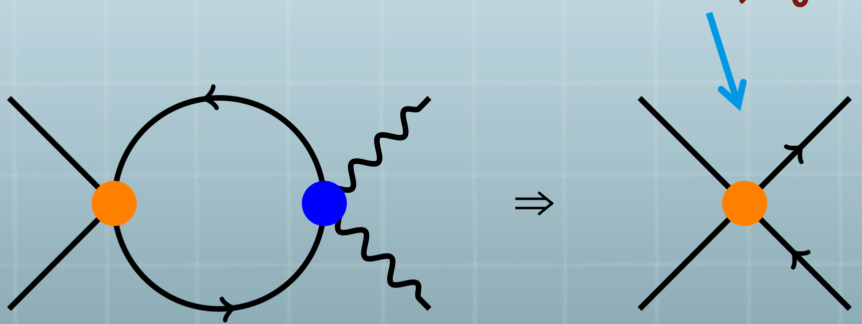




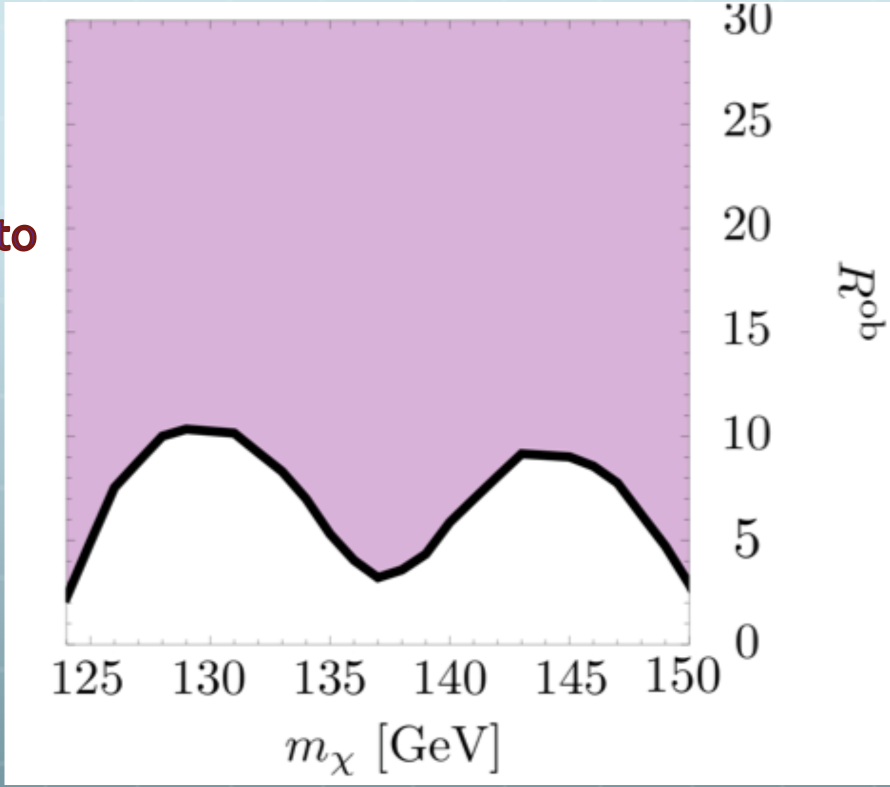
- **Continuum constraint** Buchmuller and Garny; Cohen, Lisanti , Slatyer and Wacker; Cholis, Tavakoli and Ullio 2012;

Cross sections of processes contributing to the continuum is no more than 5 – 10 times that of loop-level;

Charged matter can decay to showers of hadrons, π_0



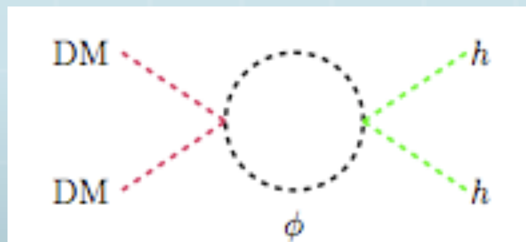
charged matter loop (W, …)

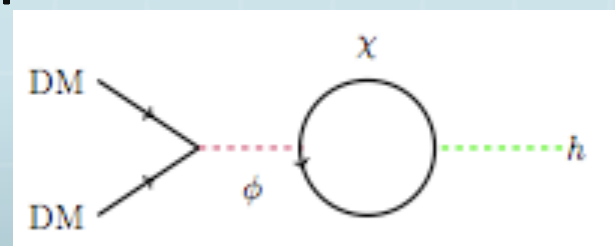


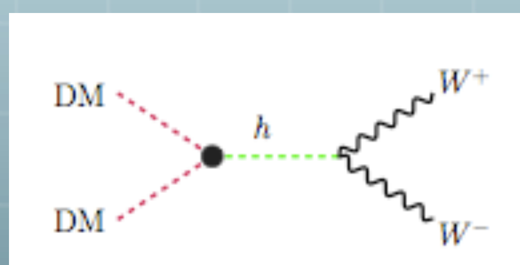
Rules out almost all MSSM neutralino DM explanations for the photon line (except internal bremsstrahlung)

Intriguingly, both anomalies are related to weak-scaled charged matter with mass ~ 100 GeV;
could they be related ?

Possible pitfall: induced Higgs-DM coupling constrained by continuum and direct detection   **JF, Reece, to appear**







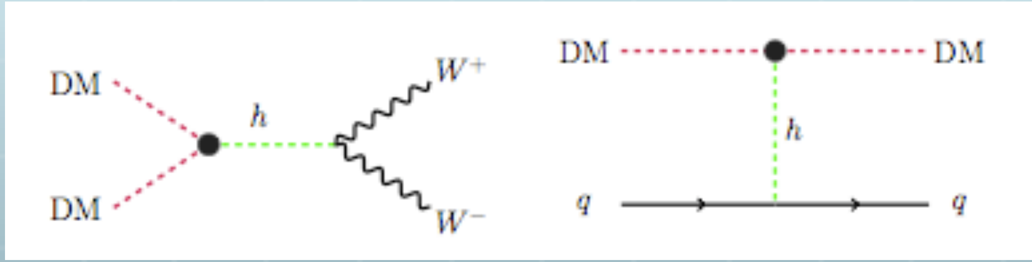
For example:

$$
\begin{aligned}
-\mathcal{L} \quad &\supset \quad \lambda_{\phi S}\phi^2|S|^2 + \lambda_{HS}|S|^2|H|^2 + \lambda_{\phi H}\phi^2|H|^2 + m_{S;0}^2|S|^2 + \lambda_S|S|^4 + \frac{1}{2}m_\phi^2\phi^2 + \lambda_\phi\phi^4 \\
&- \quad \mu_H^2|H|^2 + \lambda_H|H|^4
\end{aligned}
$$

Continuum constraint on induced Higgs-DM coupling: E.g., scalar DM model

$$\langle \sigma v \rangle = \sum_{i=W,Z} n_i \frac{|\lambda_{\phi H}|^2}{2\pi m_\phi^2} \sqrt{1 - \frac{m_i^2}{m_\phi^2}} \frac{m_i^4}{\left(4m_\phi^2 - m_h^2\right)^2} \left(2 + \frac{(2m_\phi^2 - m_i^2)^2}{m_i^4}\right)$$

$$= \left|\frac{\lambda_{\phi H}}{0.028}\right|^2 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1},$$



Direct detection constraint

$$\sigma_{SI} = \frac{|\lambda_{\phi H}|^2 m_n^4 f^2}{\pi m_h^4 m_\phi^2}$$

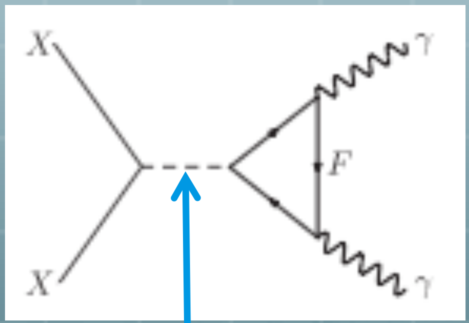
$$= \left(\frac{\lambda_{\phi H}}{0.05}\right)^2 5 \times 10^{-45} \mathrm{cm}^2,$$

- **Even if DM-Higgs coupling is set to zero, it could be generated radiatively**

$$\lambda_{\phi H} \approx \frac{\lambda_{HS}\lambda_{\phi S}N_S}{8\pi^2}\log\frac{\Lambda}{m_S} \approx -0.24\frac{\lambda_{\phi S}N_S}{4.3}\frac{\lambda_{HS}N_S}{-2.2}\frac{1}{N_S}\frac{\log(\Lambda/m_S)}{2.0}.$$

5 times the bound; need a tuning ~ 10% between tree-level and loop-level DM-Higgs couplings

- **Caveat: Q>1**



Pseduo-scalar

Correlation between CP-even and CP-odd observables

A CP-odd version of low-energy theorem

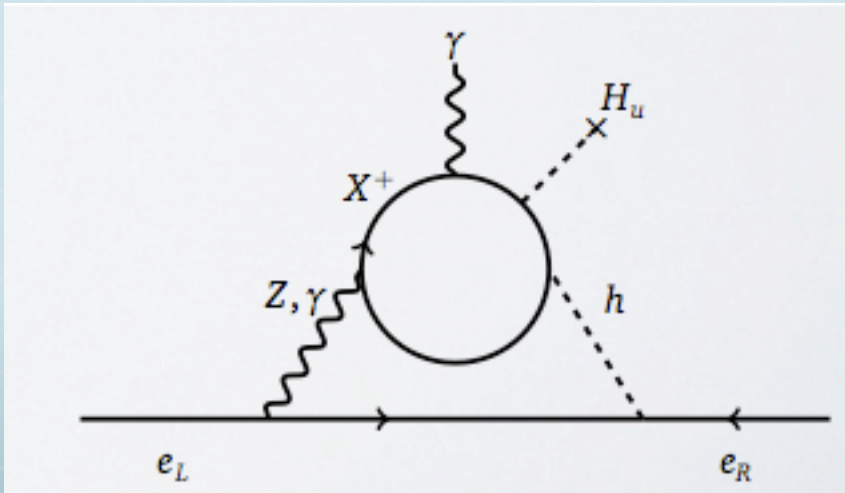
$$\frac{\alpha}{4\pi} \arg\det \mathcal{M} F_{\mu\nu}\tilde{F}^{\mu\nu} \to \frac{\alpha}{4\pi} \frac{\partial \arg\det \mathcal{M}}{\partial v} h F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Higgs CP-violating decay (Voloshin 1208.4303); and CP-odd TGCs; more importantly, it results in EDM through the RGE mixing:

$$\frac{c}{\Lambda^2} H^\dagger H F_{\mu\nu}\tilde{F}^{\mu\nu} \text{ and } d_f L H \sigma_{\mu\nu} \bar{e} \tilde{F}^{\mu\nu}$$

$$\frac{d_f}{e} = -\frac{Q_f m_f c}{4\pi^2 \Lambda^2} \log \frac{\Lambda^2}{m_h^2}$$

Bar-Zee type diagram



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

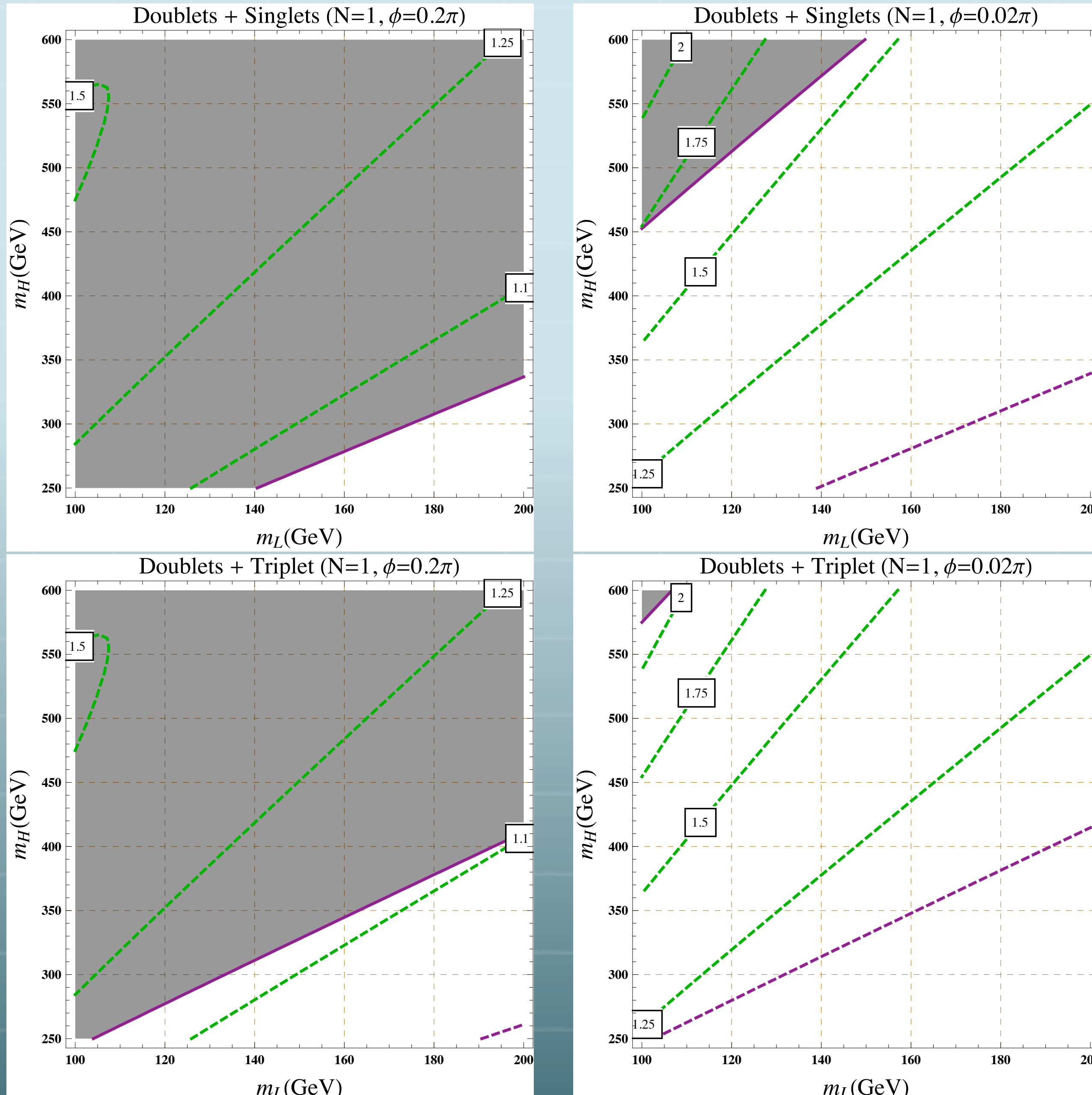
$$\phi \;=\; \arg\left(m_\psi^* m_\chi^* y y^c\right)$$

$$\frac{c}{\Lambda^2} H^\dagger H F_{\mu\nu}\tilde{F}^{\mu\nu}$$

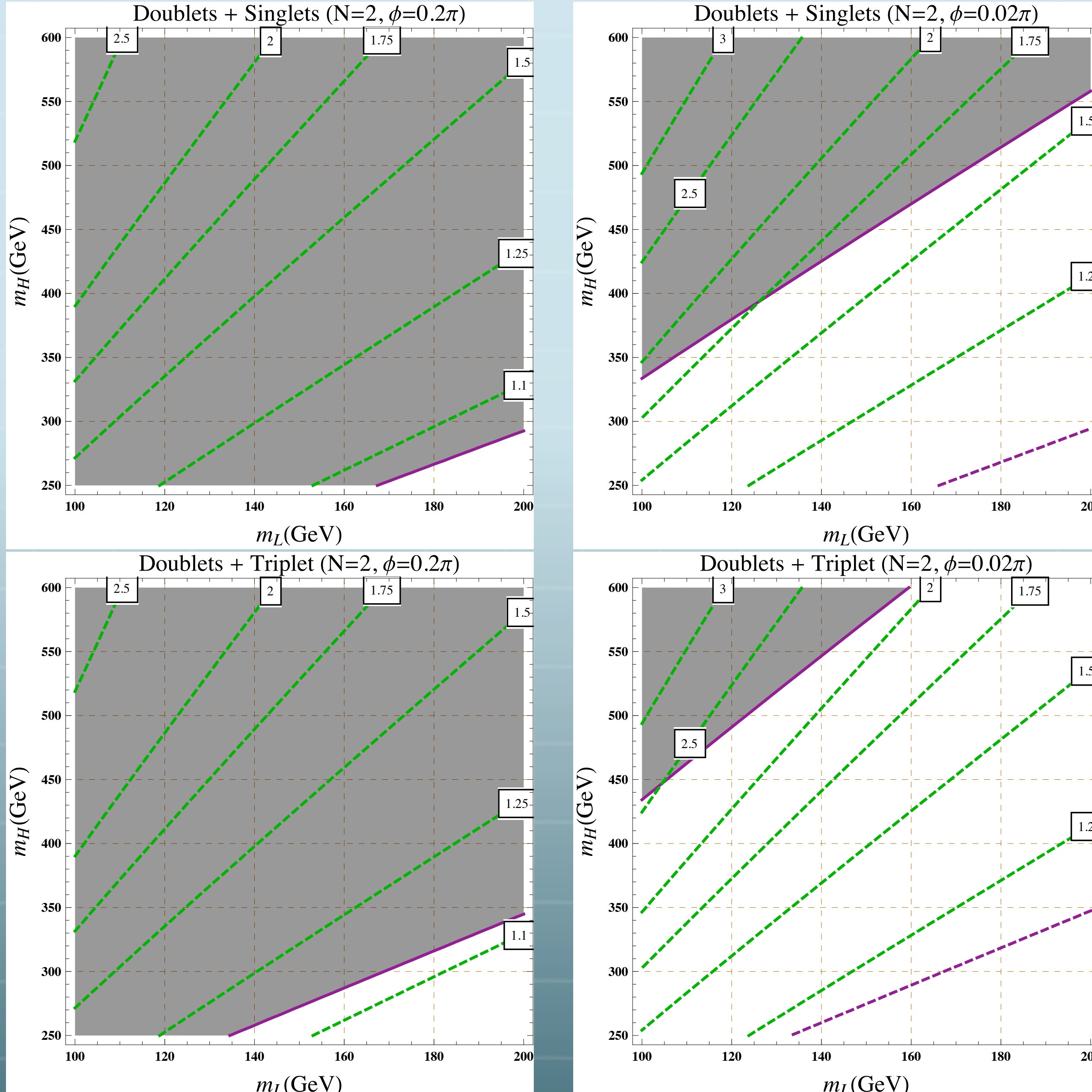
$$c = \frac{\alpha}{4\pi} y y^c \sin\phi;\ \Lambda^2 = m_\psi m_\chi$$

$$\frac{d_e}{e} < 10^{-27}\,\mathrm{cm} \to \Lambda \geq 700\mathrm{GeV}\sqrt{\frac{yy^c \sin\phi}{1}}$$

In split context:
Arkani-Hamed, Dimopoulous, Giudice, Romanino; …
Recently, McKeen, Pospelov and Ritz 1208.4597;



Doublets + Singlets (N=1, ϕ=0.2π)
Doublets + Singlets (N=1, ϕ=0.02π)
Doublets + Triplet (N=1, ϕ=0.2π)
Doublets + Triplet (N=1, ϕ=0.02π)
m_H(GeV)
m_L(GeV)
600
550
500
450
400
350
300
250
100
120
140
160
180
200
1.5
1.25
2
1.75


Doublets + Singlets (N=2, ϕ=0.2π)
Doublets + Singlets (N=2, ϕ=0.02π)
Doublets + Triplet (N=2, ϕ=0.2π)
Doublets + Triplet (N=2, ϕ=0.02π)
m_H(GeV)
m_L(GeV)
2.5
2
1.75
1.5
1.25
1.1
3
100
120
140
160
180
200
250
300
350
400
450
500
550
600

To evade current EDM and have diphoton enhancement > 1.5, the physical CP phase has to be small < 0.06; -> Higgs CP problem!

Exception: A singlet with mass ~ Higgs mass (mass difference ~ a few GeV)

McKeen, Pospelov and Ritz

The ACME collaboration (Yale-Harvard group) will potentially improve the bound by an order of magnitude in a few years or measure it!

Conclusion

- Higgs couplings would be a powerful indirect probe of beyond SM physics!
- Diphoton rate could have deep implications for naturalness.
- DM: difficult to explain a large line rate; more difficult to relate this to Higgs diphoton enhancement.
- EDM: models responsible for diphoton enhancement has to have small CP-violating phase generically; if diphoton enhancement persists, Higgs CP problem!

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**

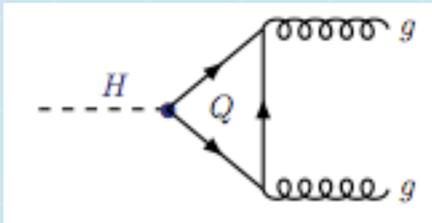
$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu} \qquad \frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2}\log\frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2}\log\frac{\Lambda}{M}$$

$$M(h)|_{\langle h\rangle = v}$$

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

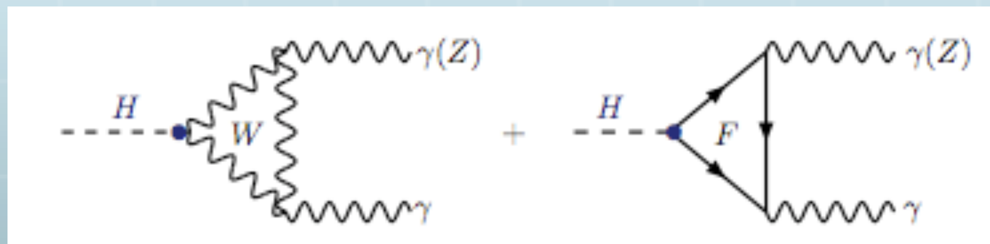
Any heavy matter with mass proportional to the Higgs VEV contribute with the same sign, whether it is a fermion or a scalar
Low energy Higgs theorem captures the leading log correction from new heavy mass threshold; there is finite mass correction, which is small

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



In SM, Q=t

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



$$\begin{aligned}(\mathcal{A}^\gamma_{SM})_{\rm leading-log} &= b_t + b_W = +(4/3)^2 - 7\\ \mathcal{A}^\gamma_{SM} &= -6.49\end{aligned}$$

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

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

t_c: Dykin index;
N_c: dimension

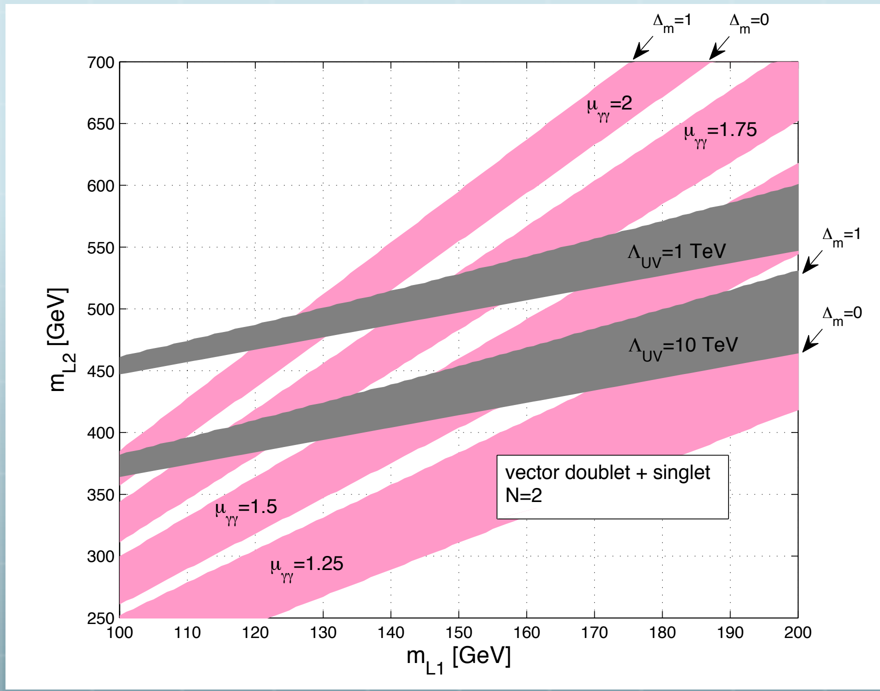
$$r_\gamma^i = \frac{\mathcal{A}^i_{h\gamma\gamma}}{SM} = \frac{\frac{1}{3}N_c^i Q^2}{-6.49}\frac{\partial \log m(v)}{\partial \log v}$$

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

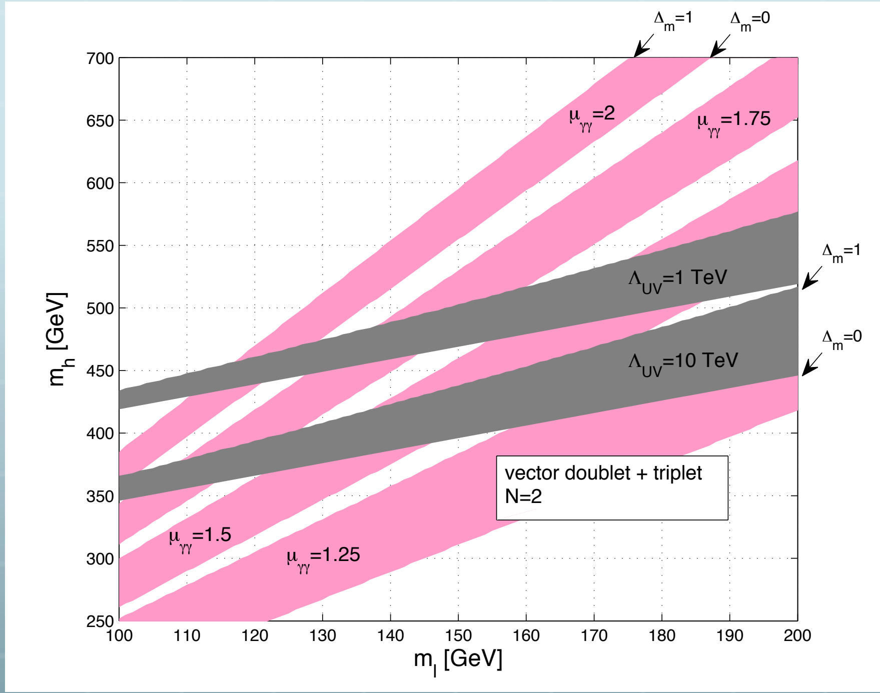
$$\text{stop}: \quad t_c = 1/2, N_c = 3, Q = 2/3;$$

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

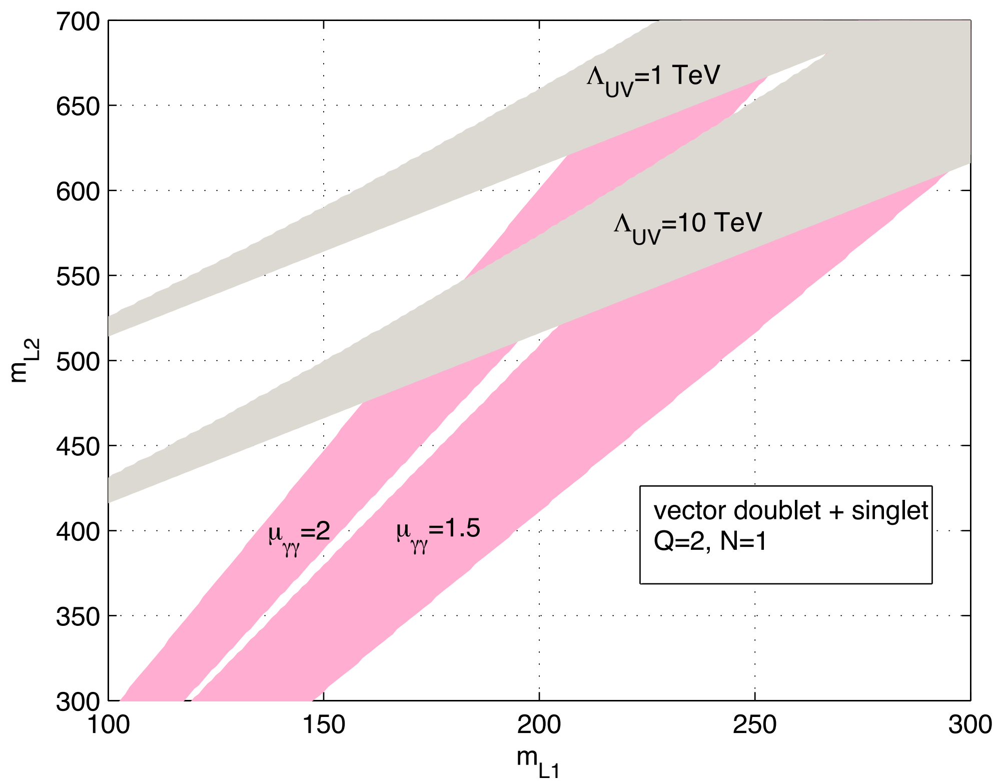
N=2



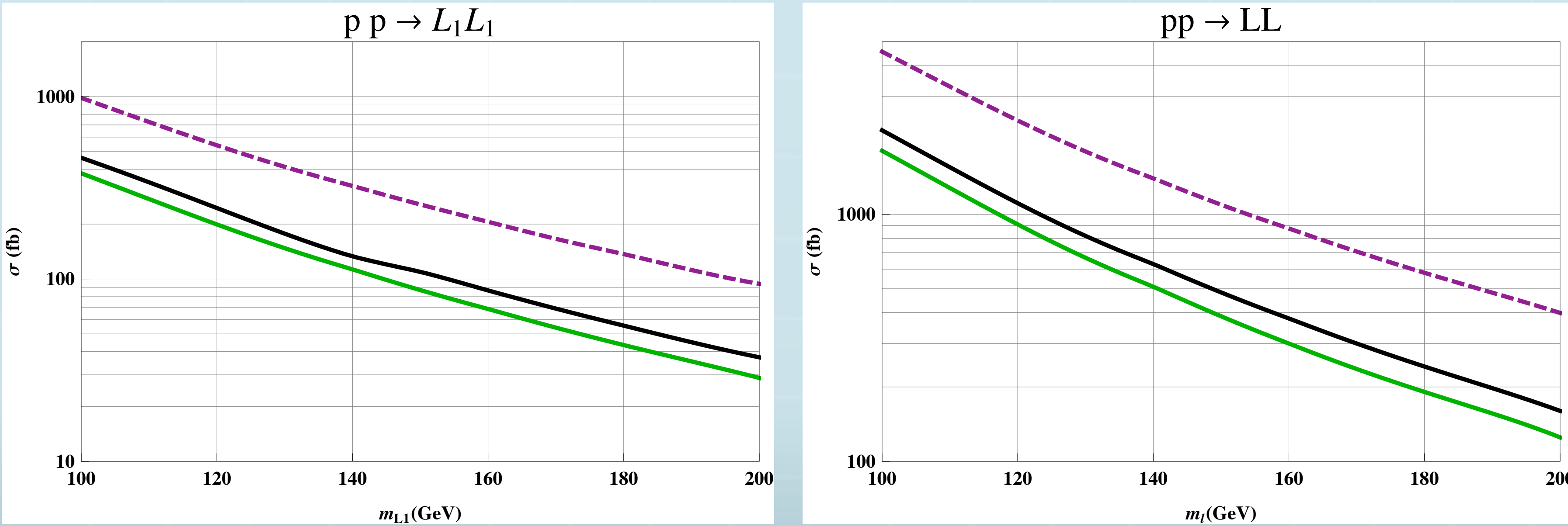
Δm=1
Δm=0
μγγ=2
μγγ=1.75
ΛUV=1 TeV
ΛUV=10 TeV
μγγ=1.5
μγγ=1.25
vector doublet + singlet
N=2
mL2 [GeV]
mL1 [GeV]

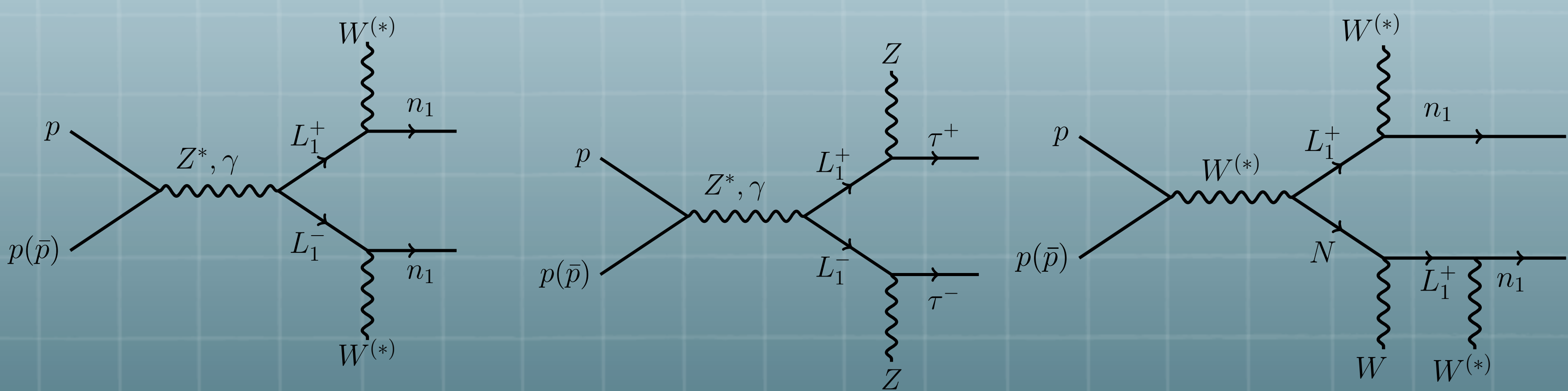


Δm=1
Δm=0
μγγ=2
μγγ=1.75
ΛUV=1 TeV
ΛUV=10 TeV
μγγ=1.5
μγγ=1.25
vector doublet + triplet
N=2
mh [GeV]
ml [GeV]



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
μ_γγ=2
μ_γγ=1.5
vector doublet + singlet
Q=2, N=1


p p → L_1L_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)


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