Axion-mediated dark matter and Higgs diphoton signal

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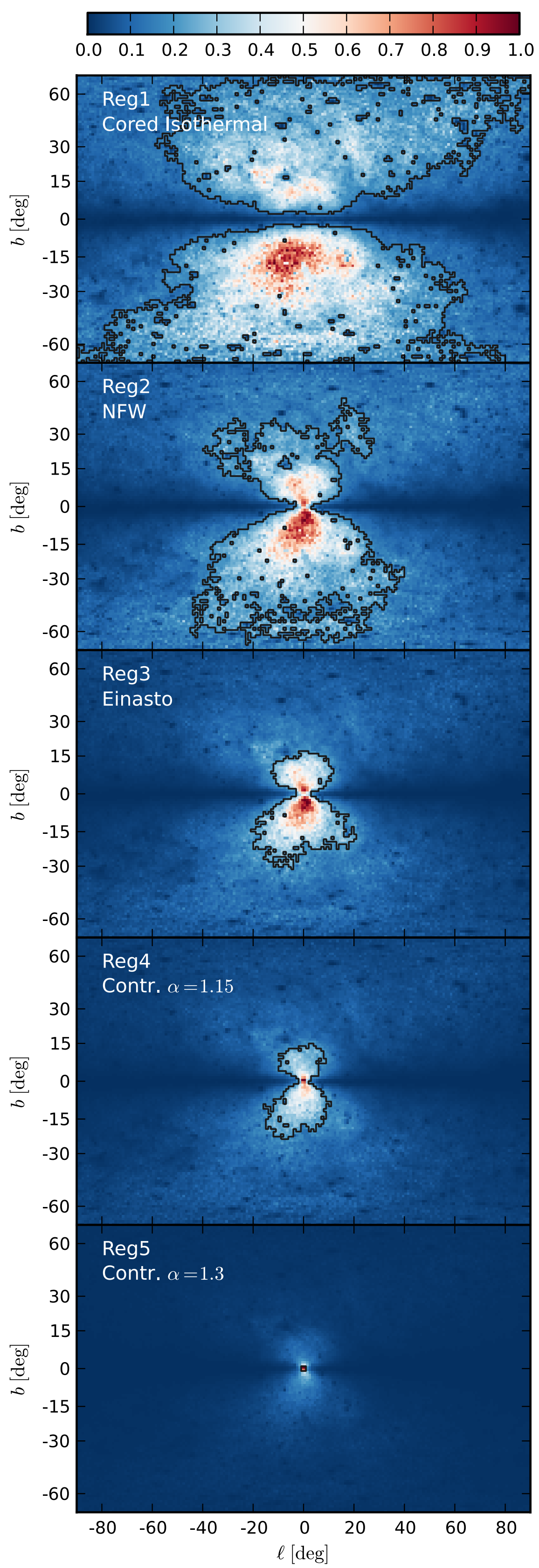
Refs: HML, M. Park, W. Park, PRD86 (2012), 103502
& 1209.1955 [hep-ph] (to appear in JHEP).

Particle Physics and Cosmology 2012
November 5, 2012

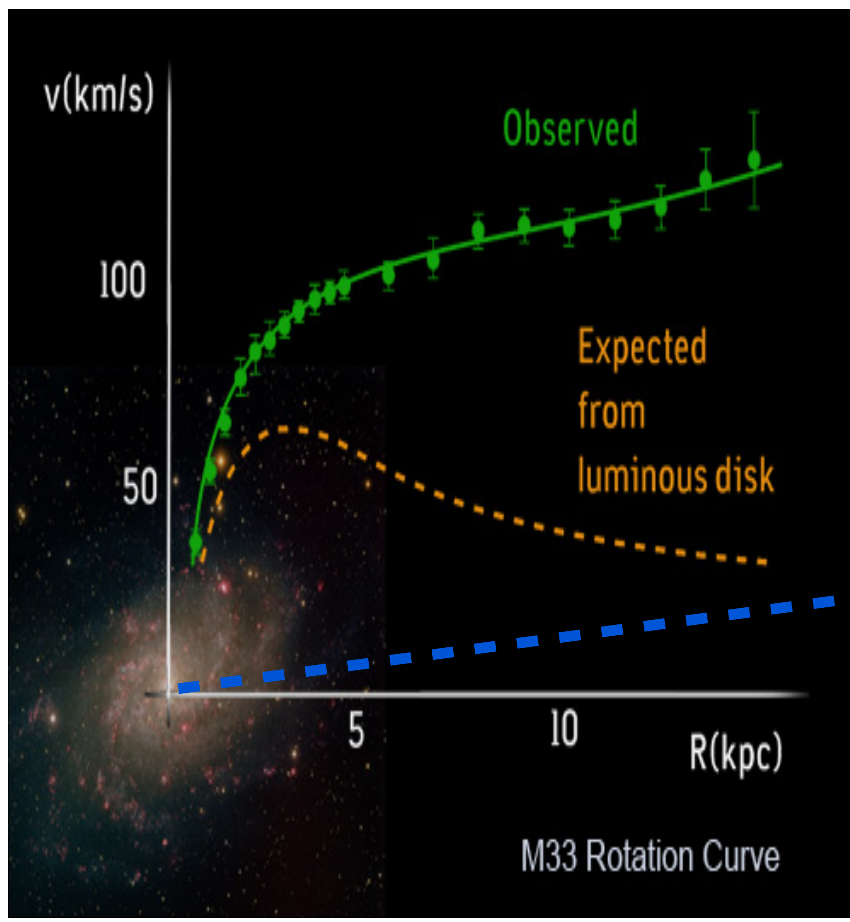
Outline

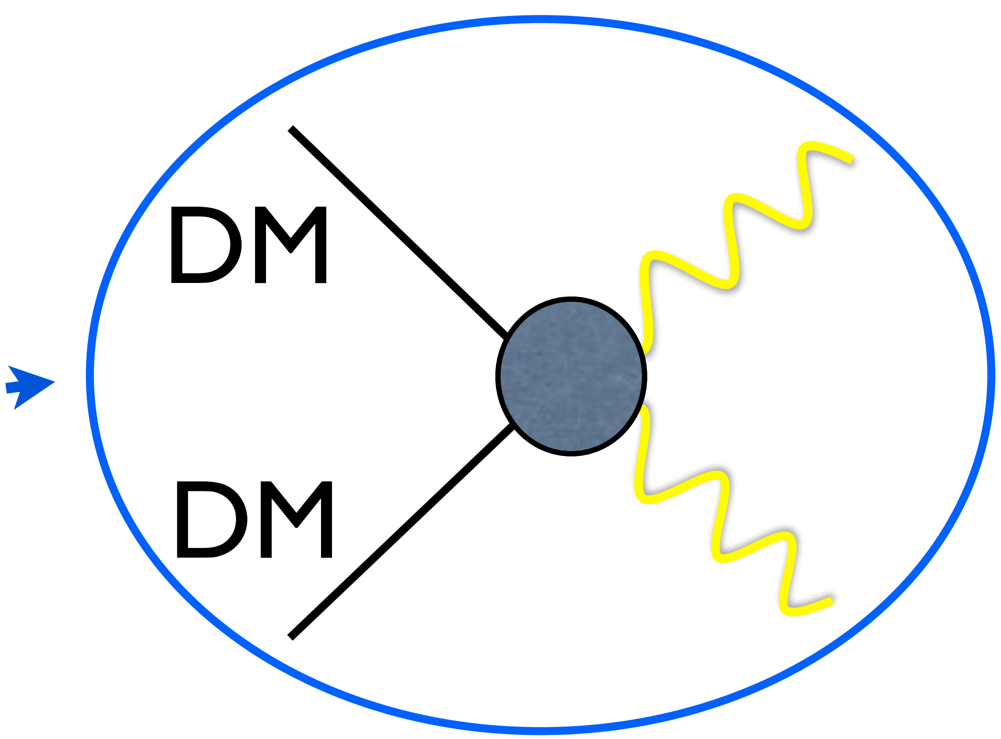
- Dark matter and Higgs boson
- Dark matter for Fermi gamma-ray line
- Extra leptons and Higgs diphoton signal
- Conclusions

Fermi gamma-ray line



- Fermi Large Area Telescope: gamma-ray line from galactic center peaked at 130 GeV. [C. Weniger (2012)]

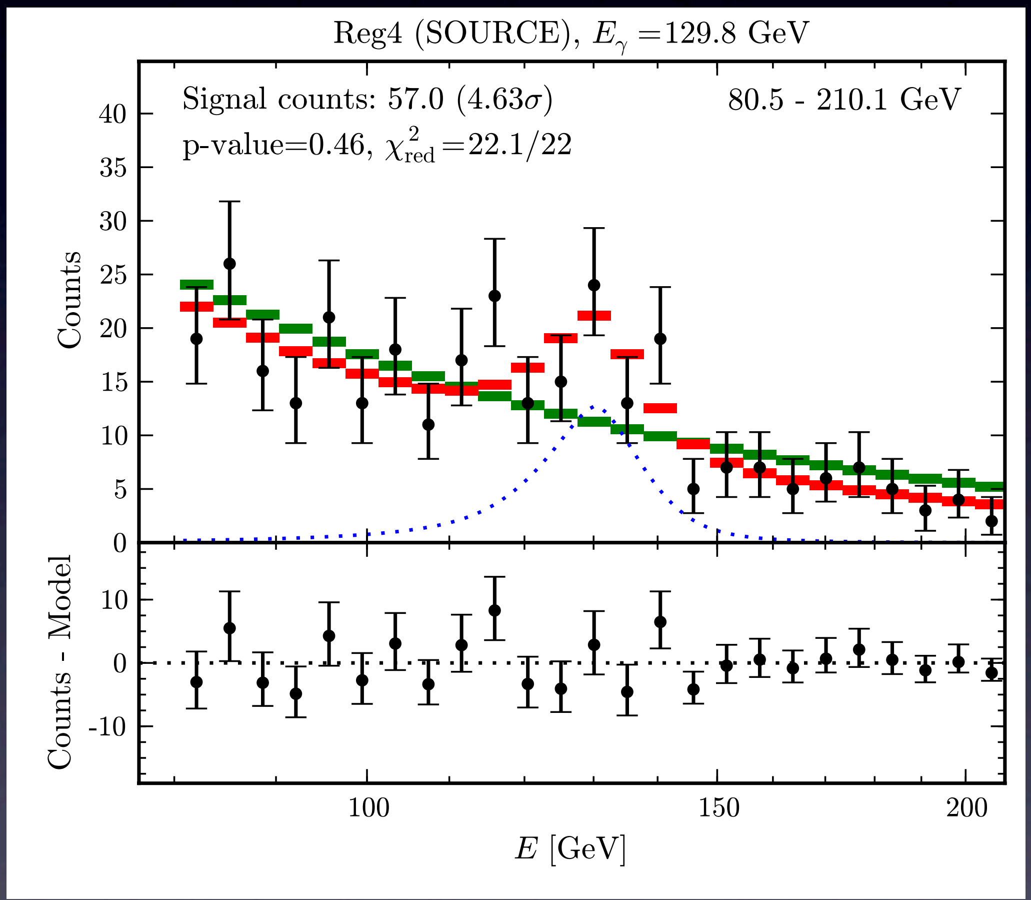


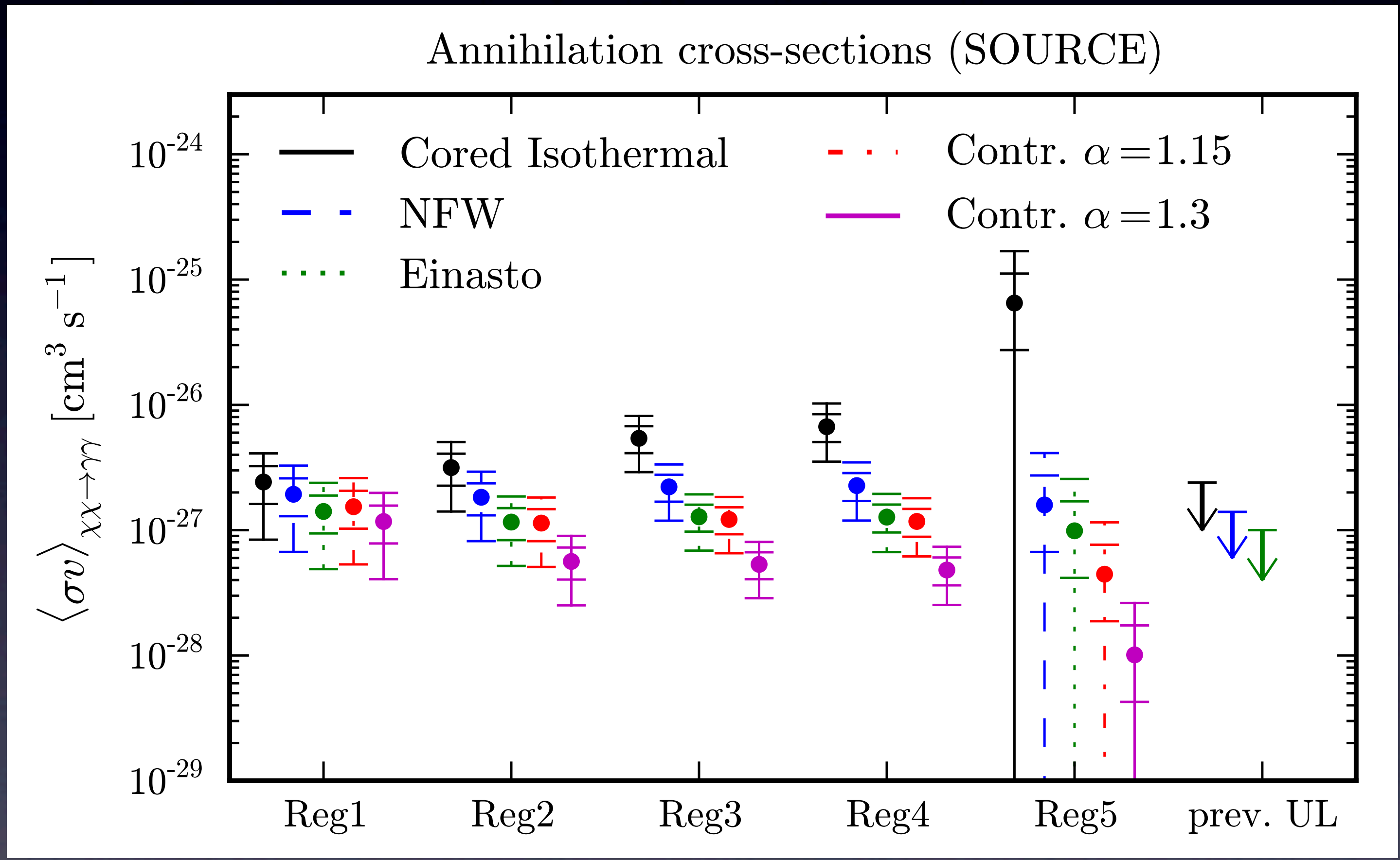


Signal of Dark Matter annihilating into photons ?

Dark matter for γ-ray line

- Fermi gamma-ray line needs a large cross section for dark matter annihilation to photon(s).





DM interpretation:

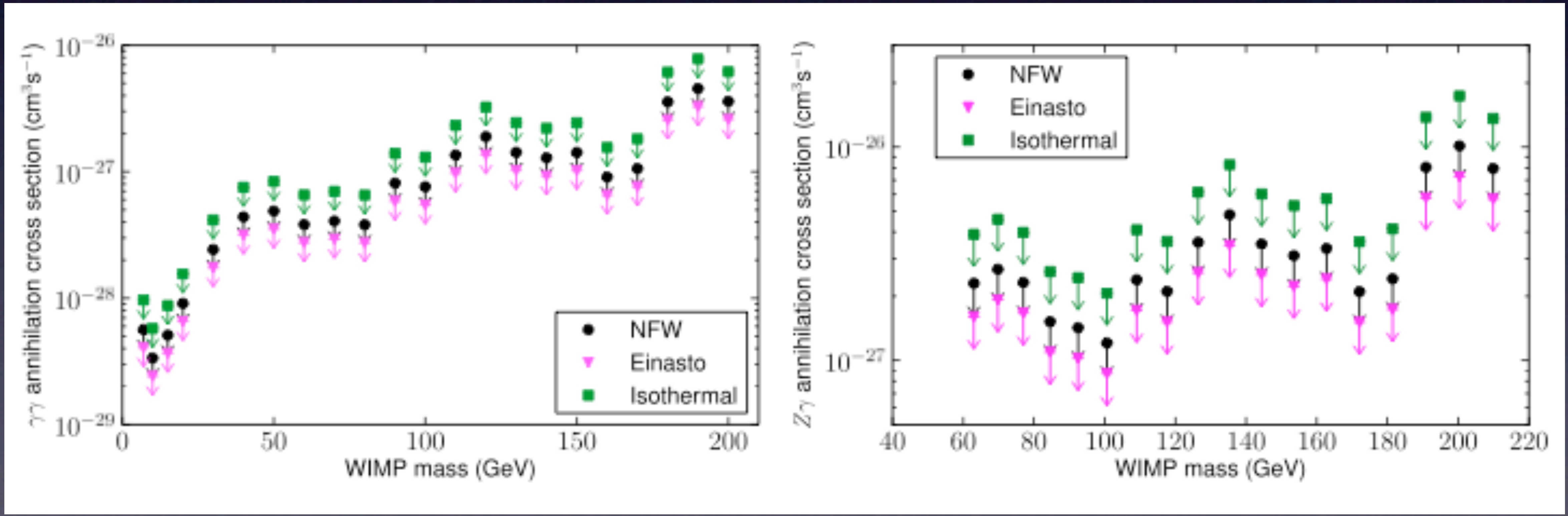
$$m_X \approx 130\,\mathrm{GeV},\ \langle\sigma v\rangle_{\gamma\gamma} = 1.3 - 2.3\times 10^{-27}\mathrm{cm}^3/\mathrm{s}\,(4.6\sigma).$$

"Einasto" "NFW"

:"4-8 % Branching fraction" of thermal cross section

γ-ray line constraints

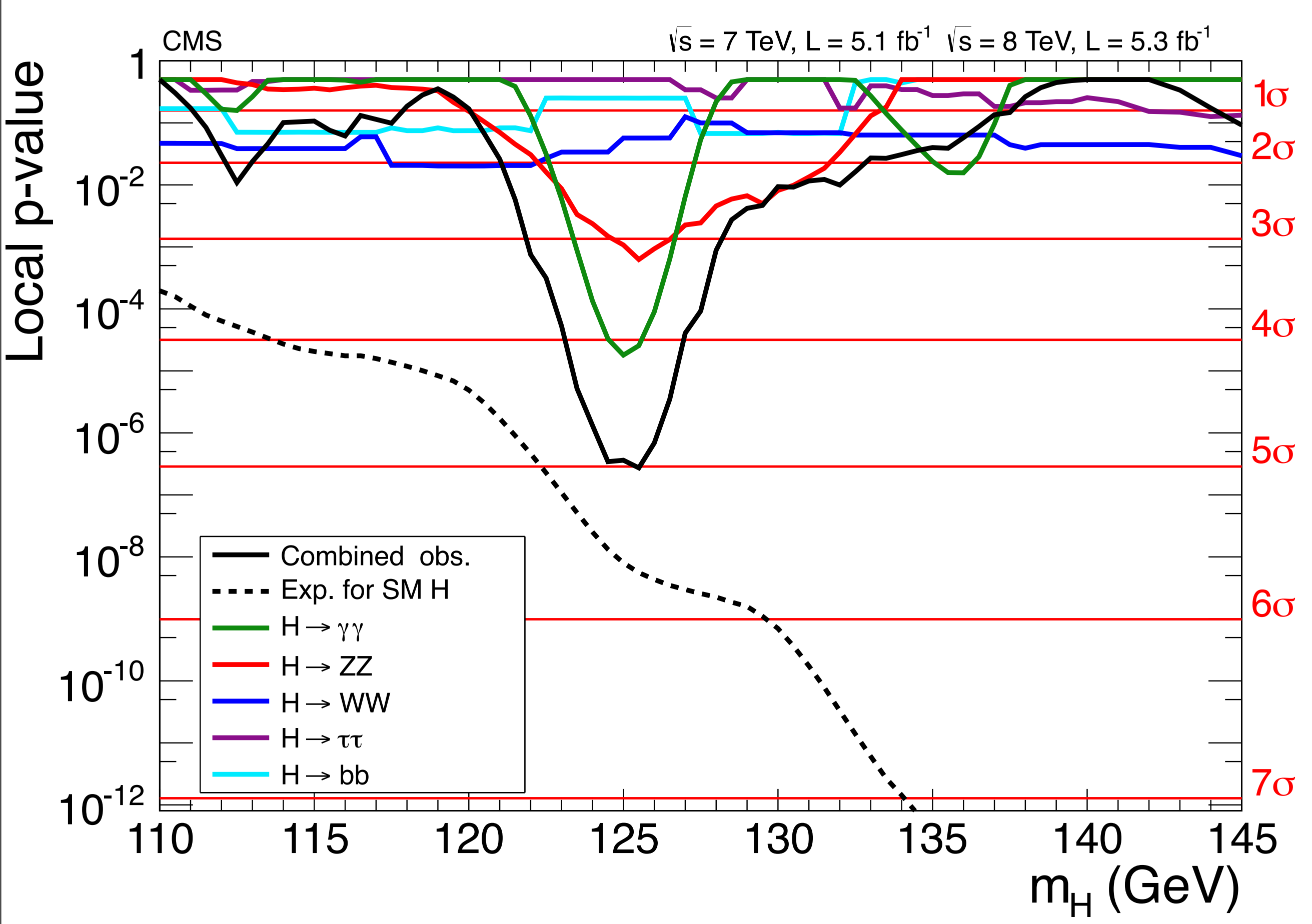
- Two years of data from Fermi LAT 20° x 20°
- 95% CL limits on DM annihilation cross sections

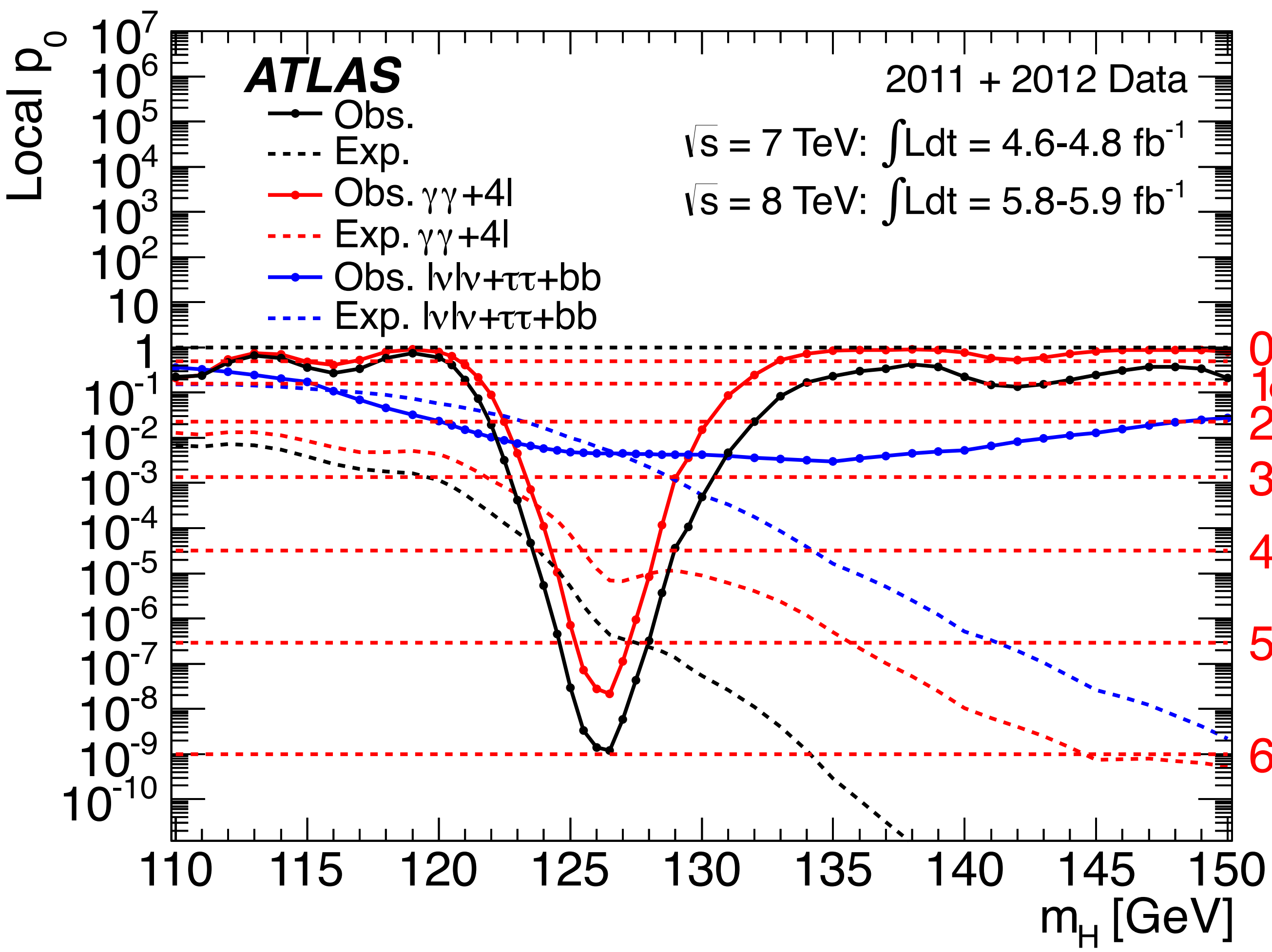


For $M_\chi \simeq 130\,\mathrm{GeV}$, limits close to $\langle \sigma v \rangle_{\gamma\gamma} \lesssim 2 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$

Discovery of 125GeV boson

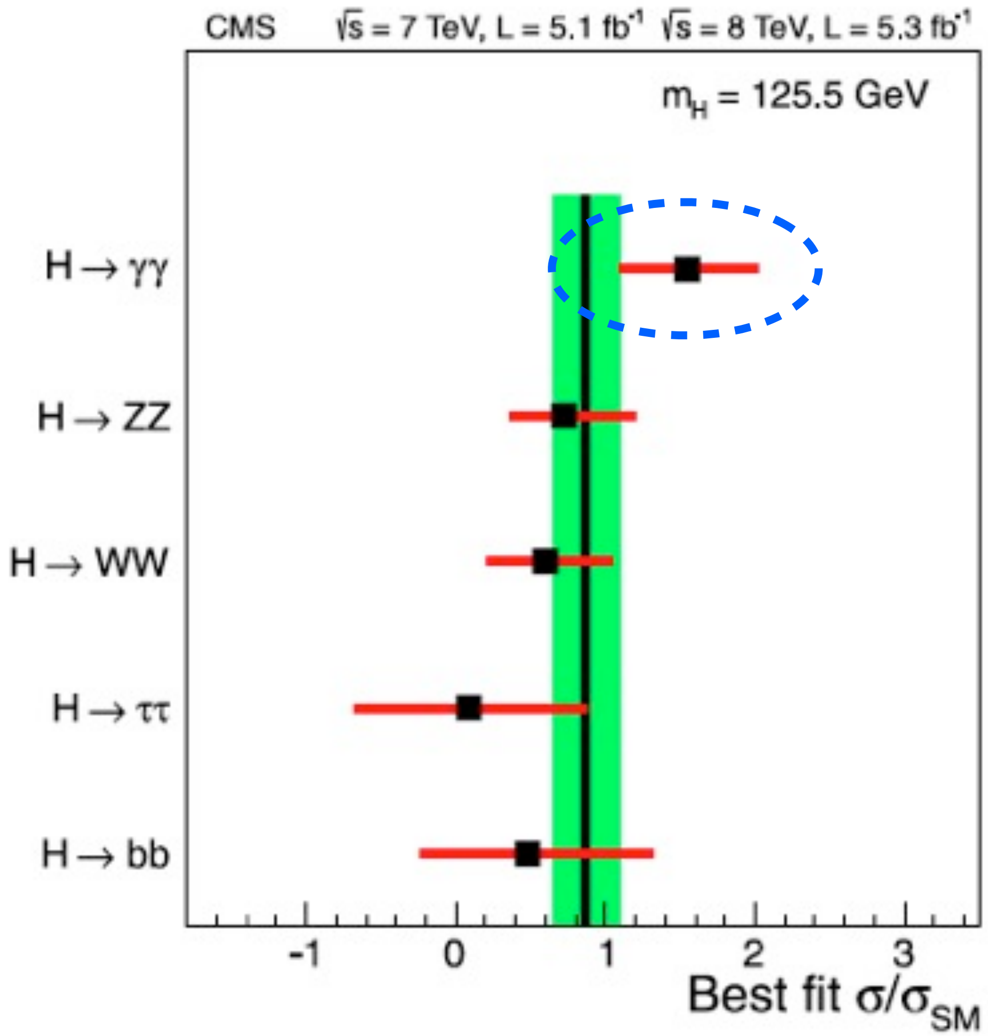
Evidences for Higgs boson at the LHC,
eventually 48 years after Higgs proposed.

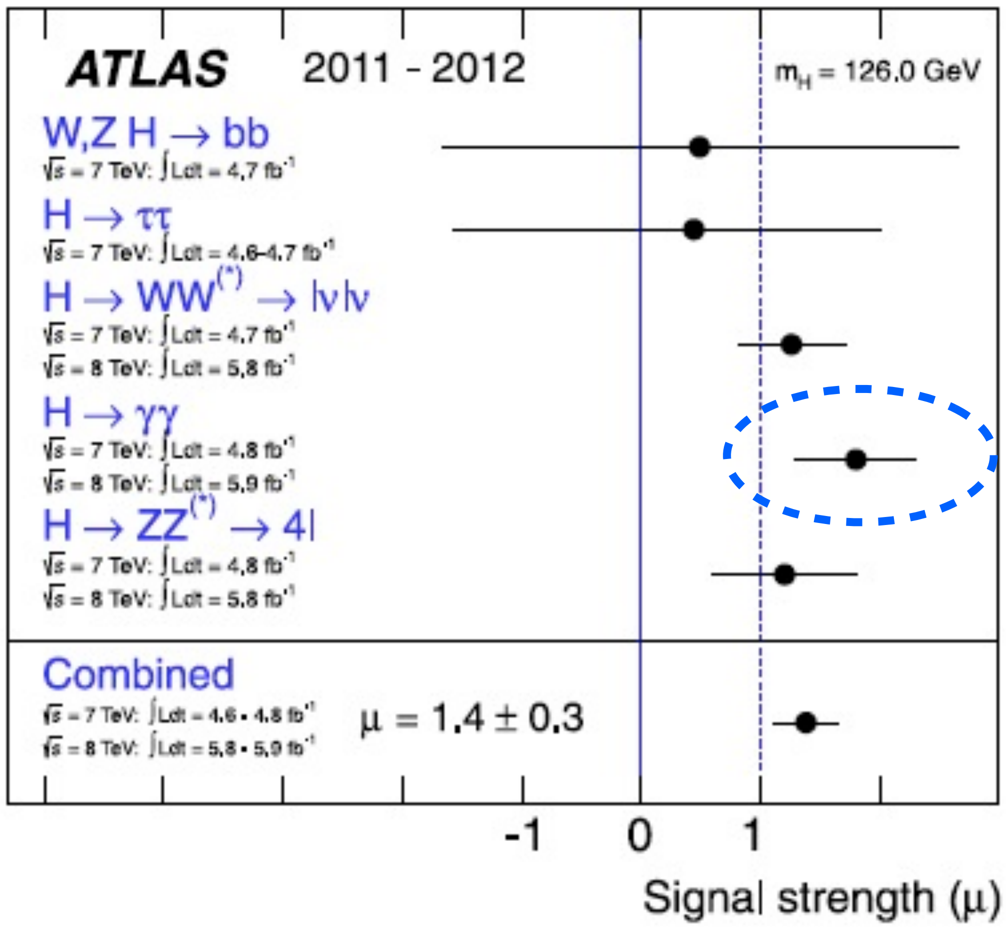




- CMS: 5.0σ at m_H=125 GeV ~125 m_p
- ATLAS: 5.9σ at m_H=126.5 GeV

Force of the 125GeV boson

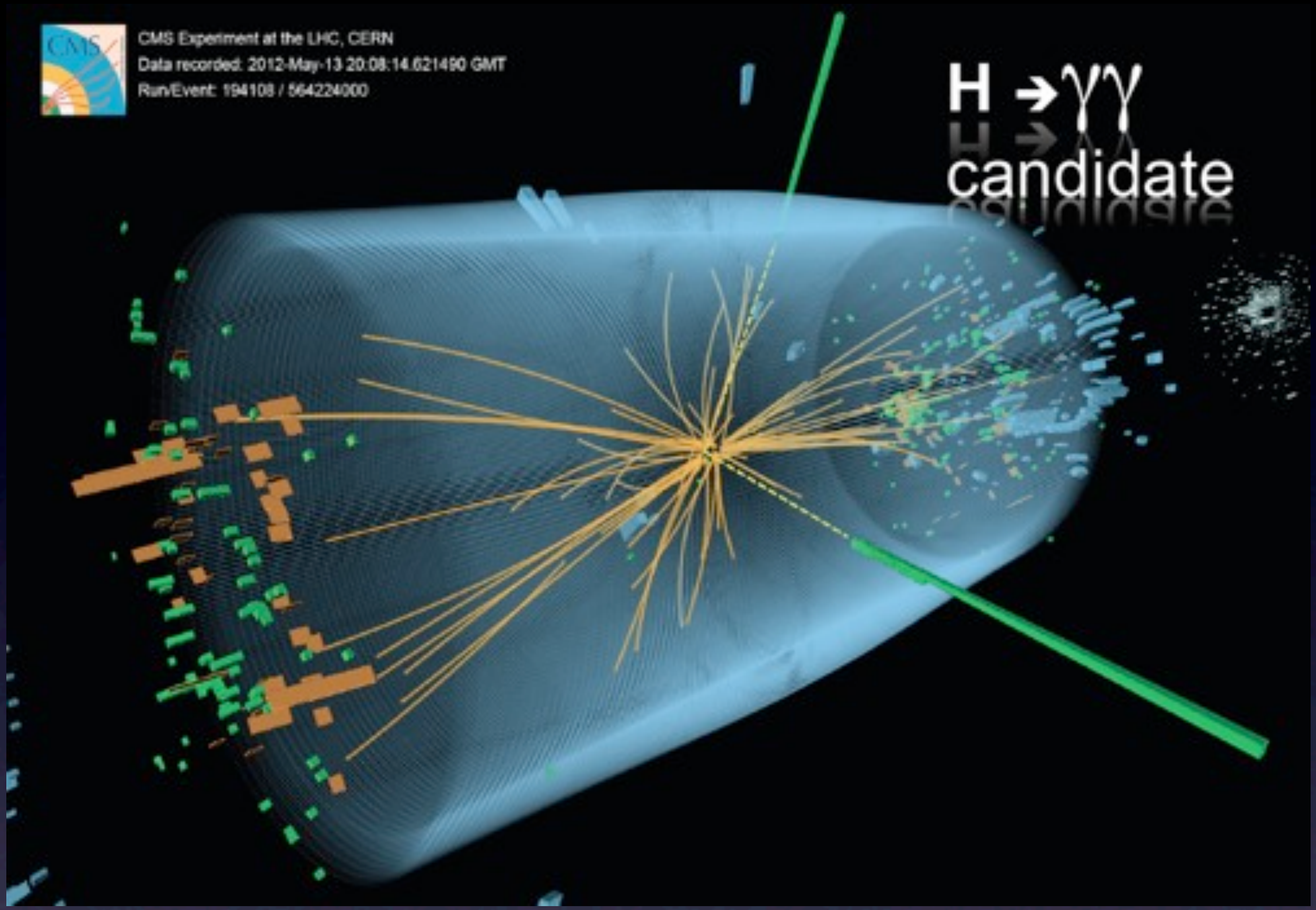




Overall signal strengths are consistent with the SM Higgs but there is an excess in Higgs-to-diphoton channel.

CMS: $\mu_{\gamma\gamma} = 1.6 \pm 0.4$ ATLAS: $\mu_{\gamma\gamma} = 1.8 \pm 0.5$

Model for DM & Higgs



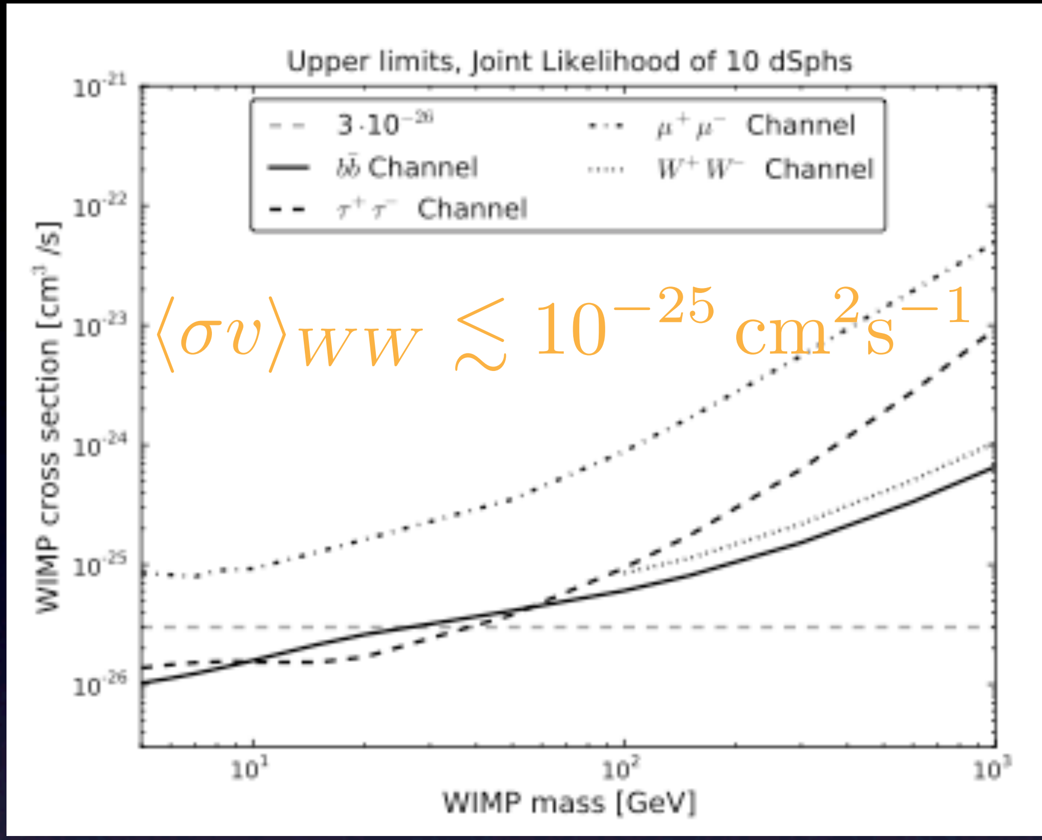
- We assume Fermi gamma-ray line is a dark matter signal.
- We assume LHC diphoton signal is due to the SM Higgs.
- We propose a DM model for explaining both Fermi gamma-ray line and Higgs diphoton rate.

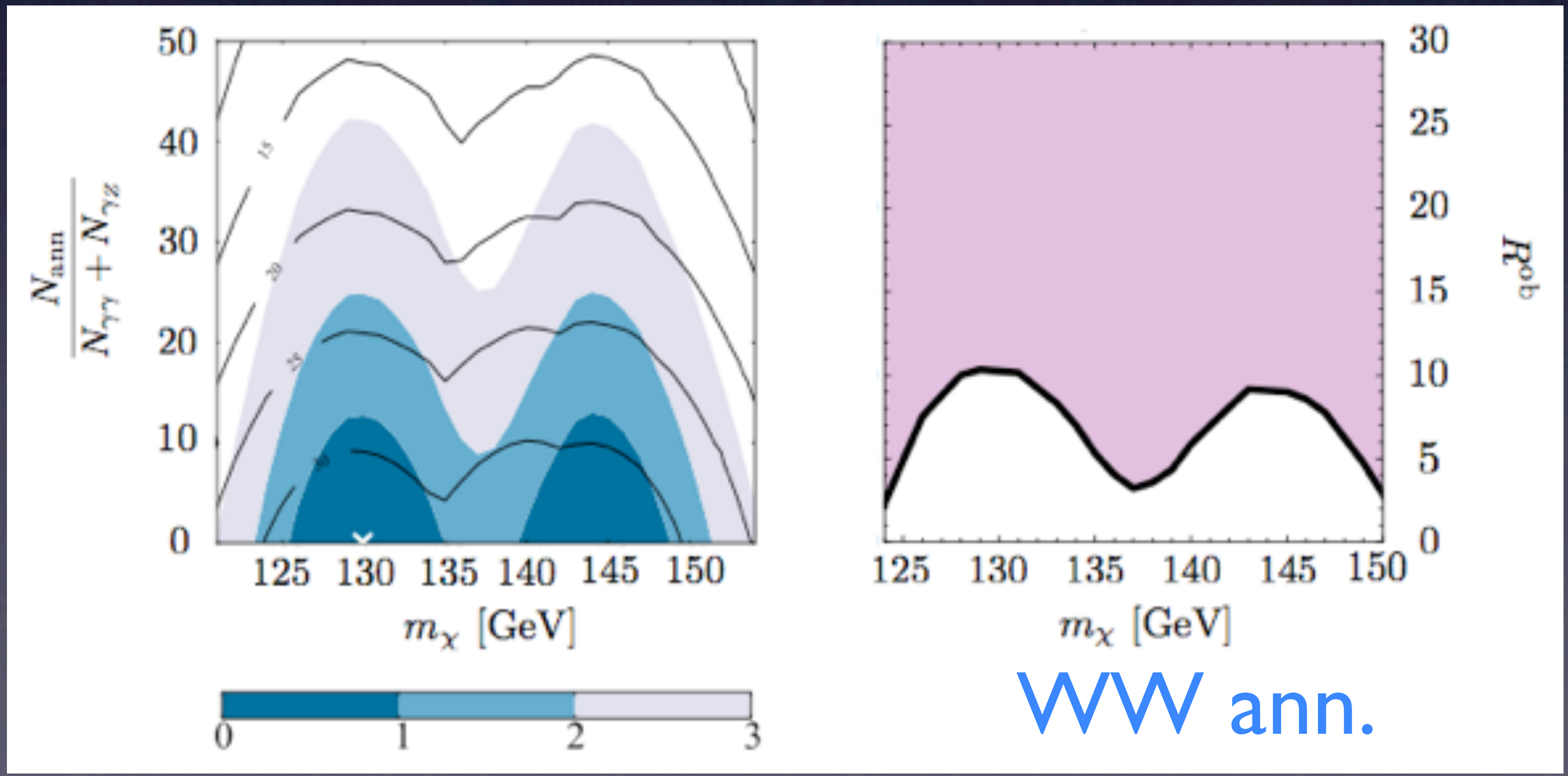
Dark matter for Fermi gamma-ray line

Bounds on continuum

- Fermi dwarf galaxies, Anti-proton from PAMELA, etc.
- Line + shape of the continuum spectrum:

[T. Cohen et al (2012); Buchmuller, Garny (2012)]





$$R^{\rm ob} \equiv \frac{1}{n^{\gamma}_{\rm ann}} \frac{N_{\rm ann}}{N_{\gamma\gamma}+N_{\gamma Z}}$$

$$R^{\rm th} \equiv \frac{\sigma_{\rm ann}}{2\,\sigma_{\gamma\gamma}+\sigma_{\gamma Z}}$$

$R^{\rm ob}_{\rm max} \simeq 10$ [95% C.L.]

→ $\sigma^{\rm max}_{\rm ann} \simeq 20\,\sigma_{\gamma\gamma}$

"2-photon"

Similar bounds on $b\bar{b},\ \mu^+\mu^-,\ \tau^+\tau^-$.

Effective theory for DM

[Rajaraman, Tait, Whiteson (2012)]

- Unknown DM interactions can be parametrized by effective operators.
- Effective operators for DM annihilations:
  - Scalar DM: $\left\{B_{\mu\nu}B^{\mu\nu},\ W^a_{\mu\nu}W^{a\mu\nu},\ B_{\mu\nu}\tilde{B}^{\mu\nu},\ W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\right\}$ $\times X^2$
  - Fermion DM: $\bar{\chi}\gamma^{\mu\nu}\chi\, B_{\mu\nu}$ and $\bar{\chi}\gamma^{\mu\nu}\chi\, \tilde{B}_{\mu\nu}$

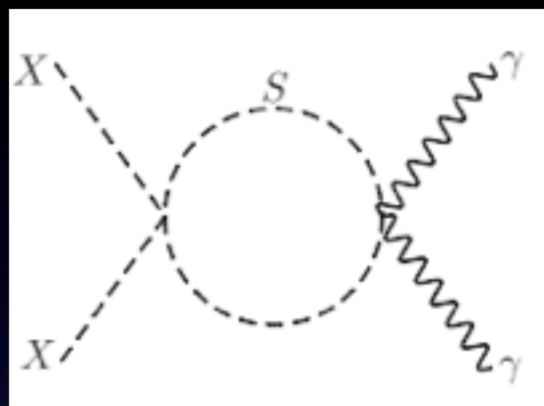
    $\left\{B_{\mu\nu}B^{\mu\nu},\ W^a_{\mu\nu}W^{a\mu\nu},\ B_{\mu\nu}\tilde{B}^{\mu\nu},\ W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\right\}$ $\times \{\bar{\chi}\chi,\ \bar{\chi}\gamma^5\chi\}$

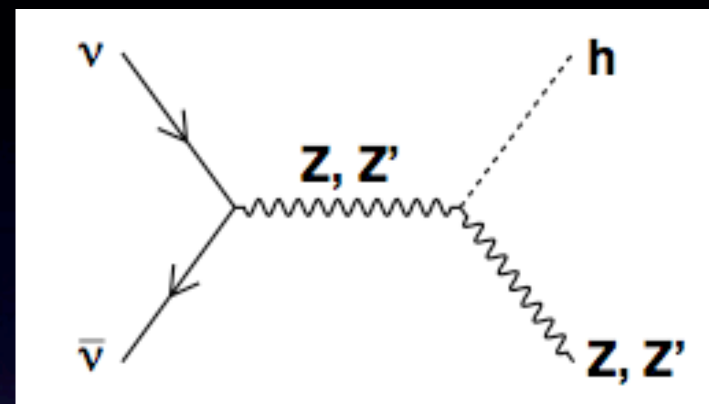
“Dirac” $\left\{B_{\mu\alpha}\tilde{B}^{\alpha\nu},\ W^a_{\mu\alpha}\tilde{W}^{a\alpha\nu}\right\}$ $\left\{B_{\mu\nu}|\Phi|^2,\ \tilde{B}_{\mu\nu}|\Phi|^2,\ \Phi^\dagger W^a_{\mu\nu}T^a\Phi,\ \Phi^\dagger\tilde{W}^a_{\mu\nu}T^a\Phi\right\}$ $\times \bar{\chi}\gamma^{\mu\nu}\chi$

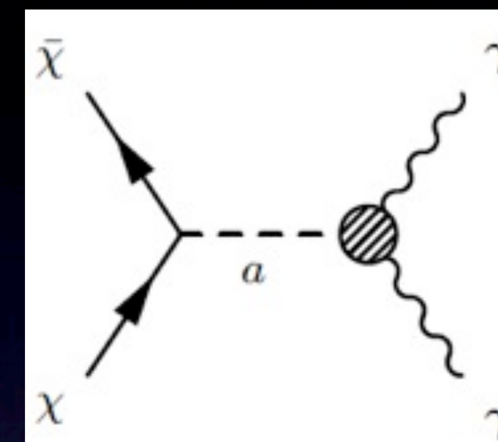
- But, EFT does not capture a resonance effect or fix the ratio of two lines to one line.

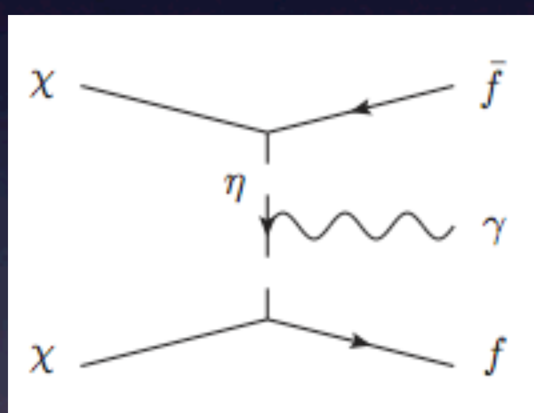
Models for gamma-ray line

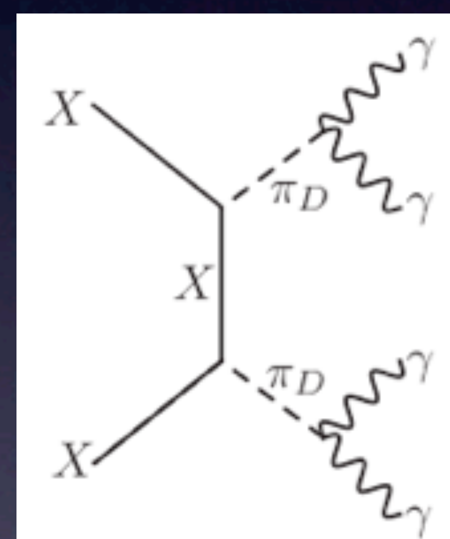
- Dark matter annihilation

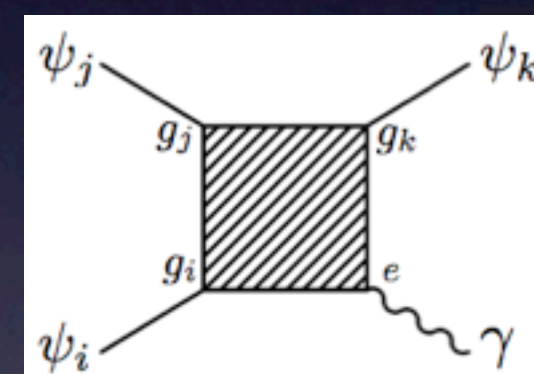




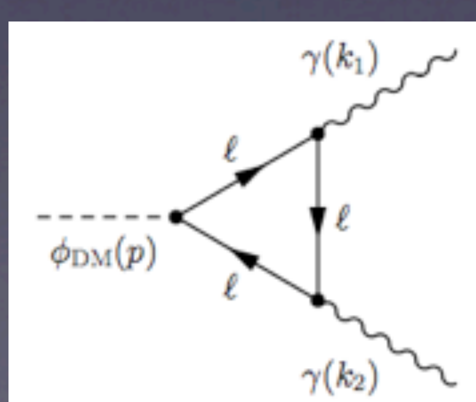


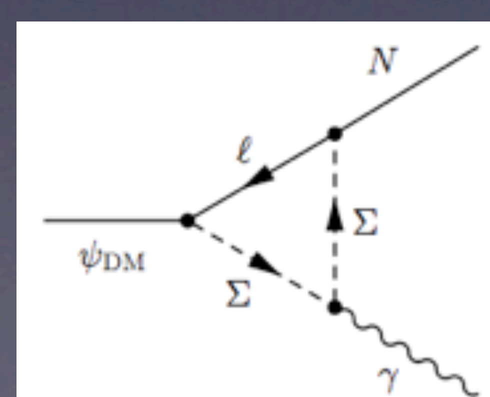






- Dark matter decay

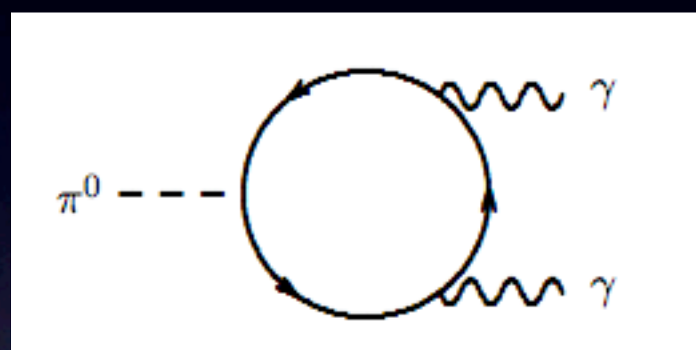




See talk by J.C. Park.

Photons from axion

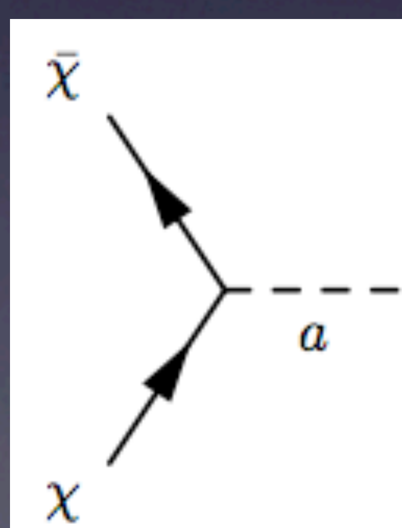
- Neutral pion, a pseudo-Goldstone boson of QCD, decays 98.8% into two photons by EM anomalies.



$-ig\,\bar{\psi}\gamma_5 T_a \pi_a \psi$

$$\Gamma(\pi^0 \to 2\gamma) = \frac{\alpha^2 m_{\pi^0}^3}{64\pi^3 f_\pi^2}$$

- How about "axion" as DM mediator from new global symmetry in hidden sector ?



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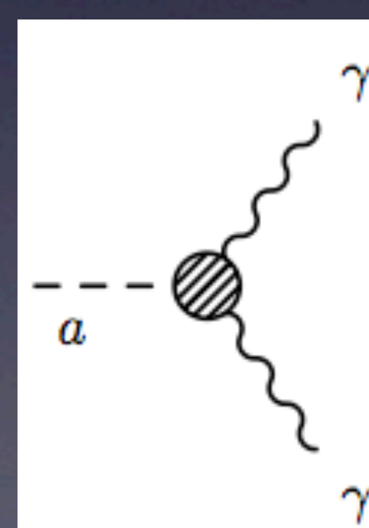


$\bar{\chi}\chi \to \gamma\gamma$:

large fraction

cf. Z' mediator: [Jackson et al (2009); Dudas et al (2012)]

Fermion DM + axion

[HML, Park, Park (2012)]

- Consider the effective axion interactions to a Dirac fermion DM and EW gauge bosons,

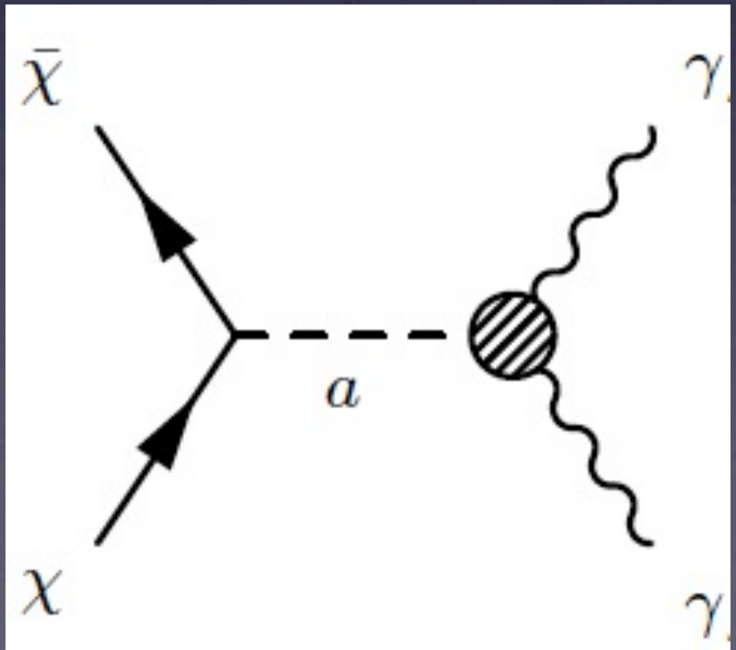
$$\mathcal{L}_{\rm int} = -\frac{\lambda_\chi}{\sqrt{2}} a\,\bar{\chi}\gamma^5\chi + \sum_{i=1,2}\frac{c_i\alpha_i}{8\pi f_a}\,a\,F^i_{\mu\nu}\tilde{F}^{i\mu\nu}.$$

- DM annihilation cross section into a photon pair:

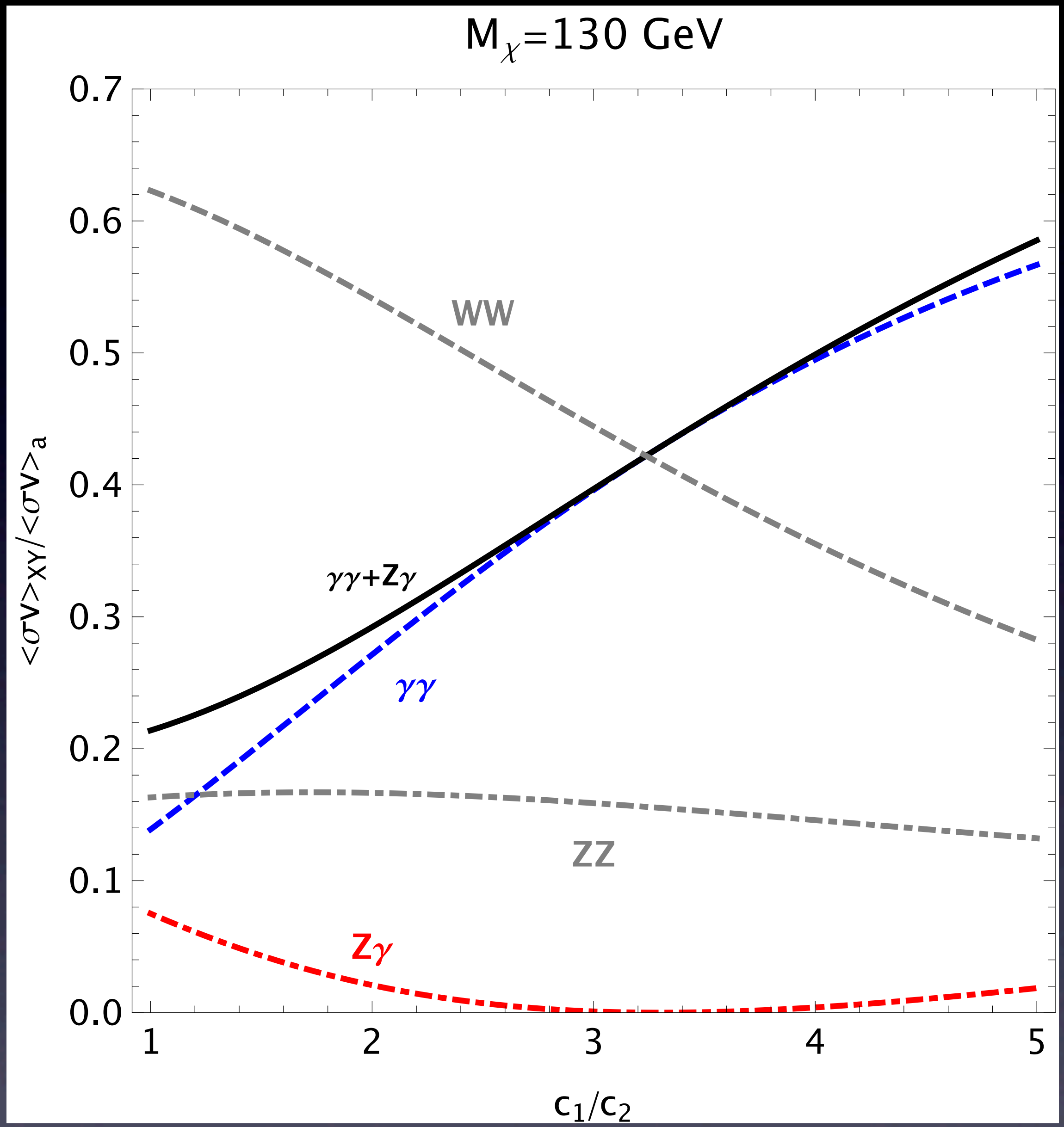
$$\langle\sigma v\rangle_{\gamma\gamma} = \frac{1}{16\pi}|\lambda_\chi|^2|c_{\gamma\gamma}|^2\frac{16M_\chi^4}{(4M_\chi^2-m_a^2)^2+m_a^2\Gamma_a^2},$$

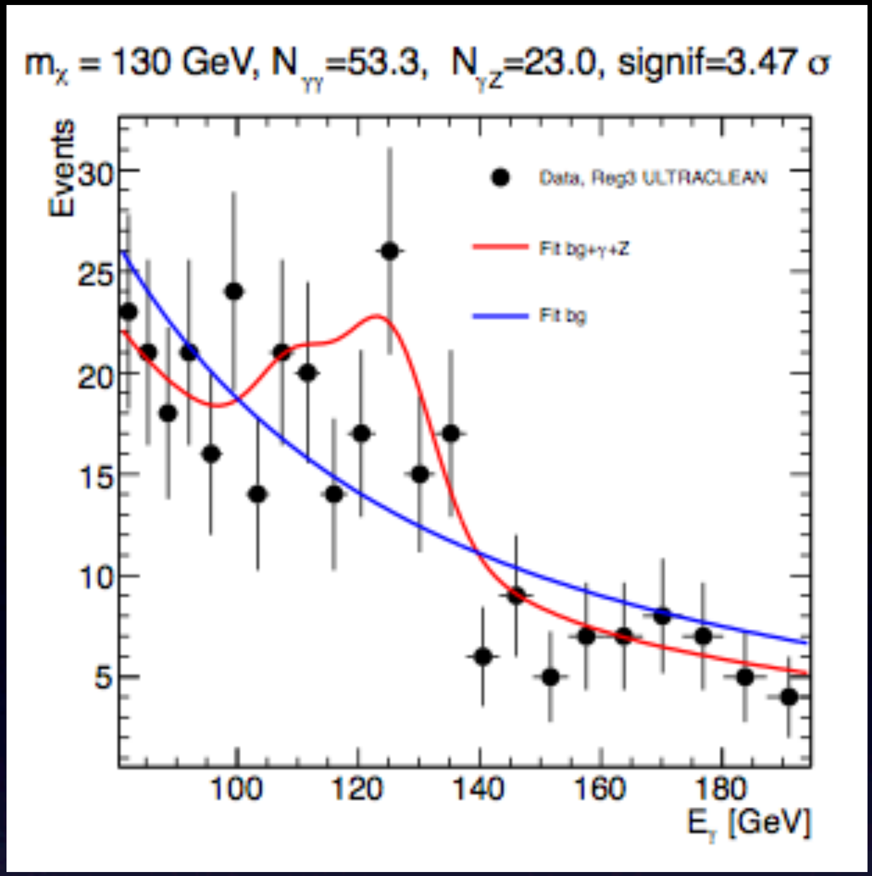
$$c_{\gamma\gamma} = \frac{(c_1+c_2)\alpha}{16\pi f_a}$$

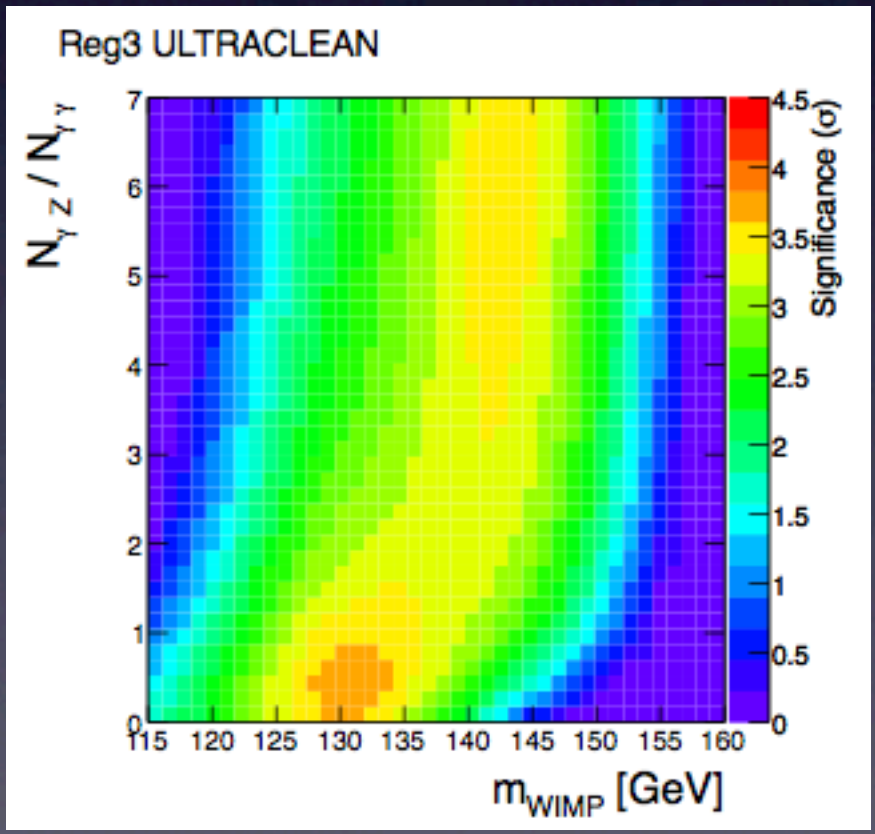
Resonance effect near $m_a \sim 2M_\chi$ enhances the cross section.



Two γ-ray lines







- Two γ-ray lines:

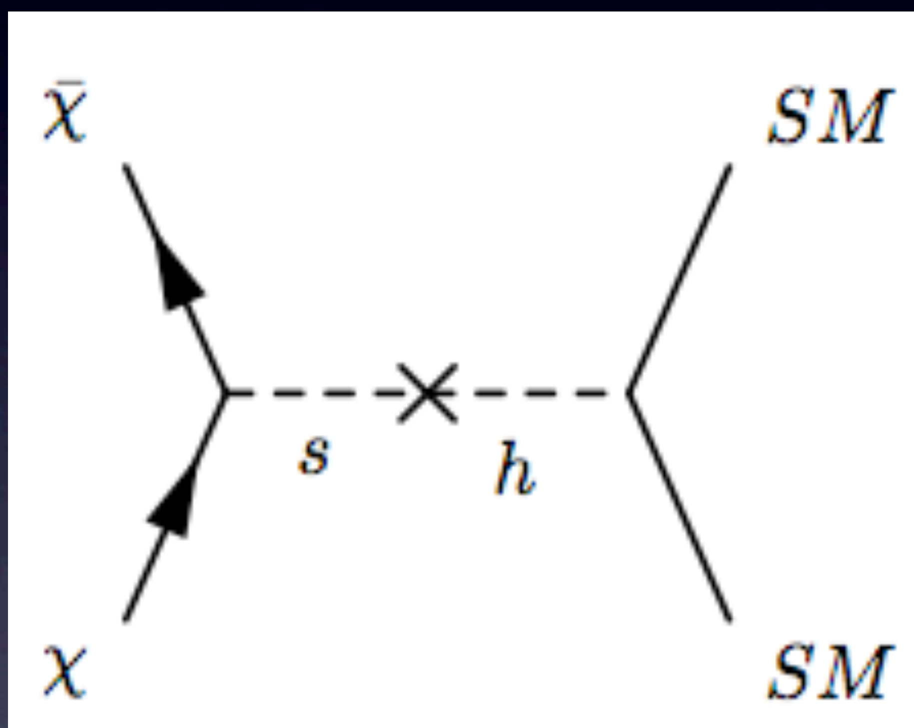
$$E_\gamma = M_\chi, \quad E_\gamma = M_\chi\left(1 - \frac{M_Z^2}{4M_\chi^2}\right).$$

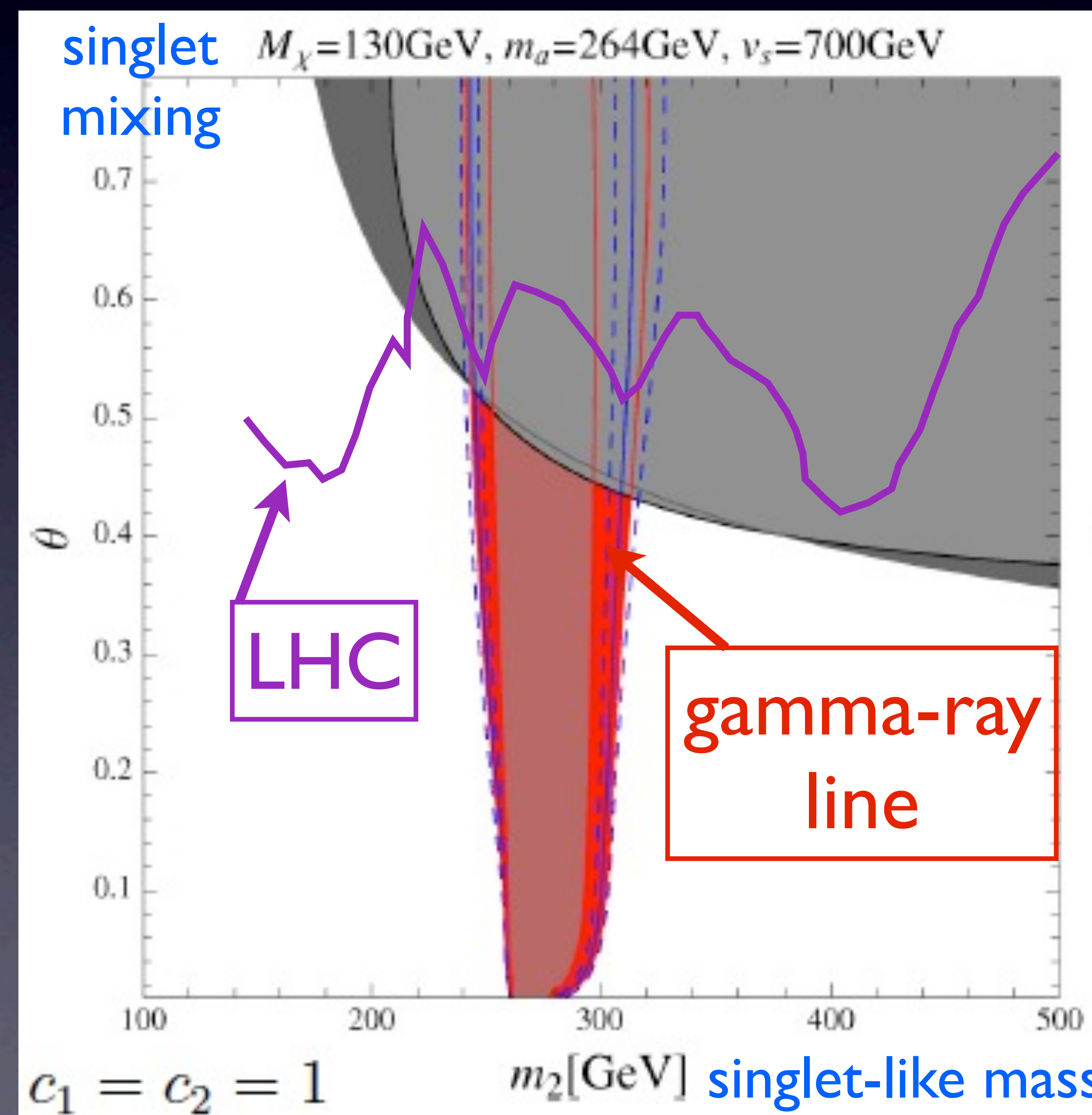
$$M_\chi = 130\,\mathrm{GeV}, \quad \text{another peak at } 114\,\mathrm{GeV}.$$

[Rajaraman et al (2012)]

Axion-partner mediation

- CP-even scalar partner (from $S=s+ia$) opens extra p-wave channels, determining the relic density.
- Directly detectable by XENON*1T* & LHC.



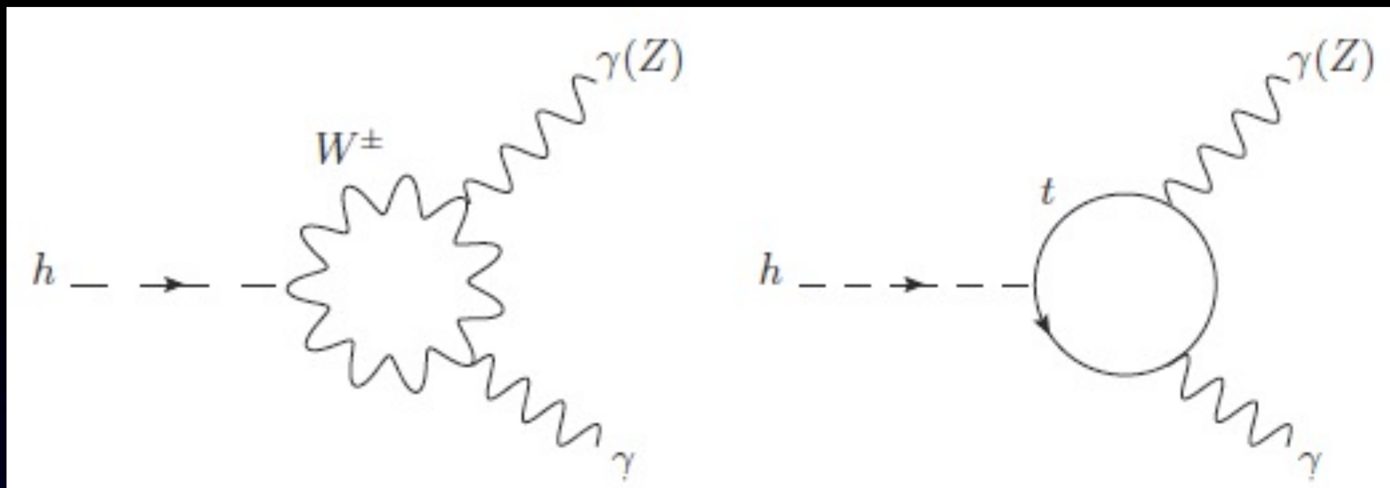


$$\lambda_\chi (S\,\bar\chi P_L \chi + S^*\,\bar\chi P_R \chi) \rightarrow \lambda_\chi\, s\, \bar\chi\chi$$

$$\lambda_{HS} |S|^2 |H|^2 \rightarrow \lambda_{HS}\, v_s v_h\, s\, h$$

Extra leptons and Higgs diphoton signal

Higgs diphoton rate

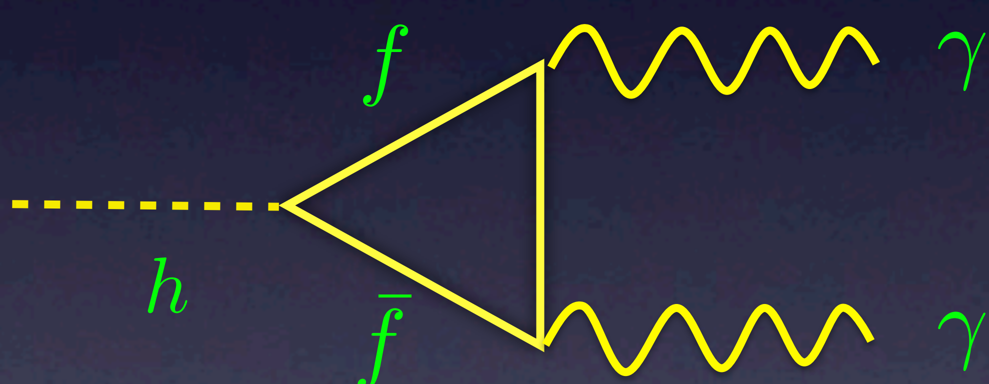


SM: $$\mathcal{L}_{\gamma\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\sum_i \frac{b_i e^2}{16\pi^2}\log\frac{\Lambda^2}{m_i^2}$$

$$\mathcal{L}_{\gamma\gamma} = \frac{\alpha}{8\pi}\left(-7+\frac{4}{3}N_c Q_t^2\right)\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$

"destructive interference"

- New charged fermion can enhance diphoton rate:



$$\mathcal{L}_{\rm eff} = -\frac{c_f}{M}|H|^2\bar{f}f$$

[Carena, Low, Wagner (2012)]

- Higgs diphoton rate:

$$\Gamma_{h\to\gamma\gamma} = \frac{G_F\alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left|A_1(\tau_W)+N_c Q_t^2 A_{1/2}(\tau_t)+\frac{c_f v^2}{M m_f}A_{1/2}(\tau_f)\right|^2$$

-8.32   1.84   new fermion

For $\mu_{\gamma\gamma}\simeq 1.7,\quad M=v,\ m_f=100\,\mathrm{GeV}$: $c_f \simeq -3.27$

Leptons shed light !

[HML, M. Park, W. Park (2012)]

- Higgs couplings need two vector-like leptons:

$$\mathcal{L}_{\gamma\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \sum_i \frac{b_i e^2}{16\pi^2} \log \frac{\Lambda^2}{m_i^2}$$

$$m_{1,2}(h) = m_0 \mp |\lambda_f| h.$$

$$\mathcal{L}_{\rm eff} = -\frac{\alpha|\lambda_f|}{6\pi}\left(\frac{1}{m_1} - \frac{1}{m_2}\right) h\, F_{\mu\nu} F^{\mu\nu}.$$

"constructive interference"

- Leptons couple to the axion to generate anomalies:

$$\mathcal{L}_{a,\rm eff} = \sum_{i=1,2} \frac{c_i \alpha_i}{8\pi v_s} a F^i_{\mu\nu} \tilde{F}^{i\mu\nu}$$

$$c_1 = {\rm Tr}(q_{\rm PQ} Y^2),\ \ c_2 = {\rm Tr}(q_{\rm PQ} l(r)).$$

- Leptons shed light: no change in Higgs production; no DM annihilation to gluon.

PQ symmetry for extra leptons

- Extra leptons with PQ charges acquire masses from $U(1)_{PQ}$ breaking (i.e. VEV of singlet $S=s+ia$).
- PQ-invariant potential respects extra $U(1)_H$:

$$V = \mu_1^2|H_d|^2 + \mu_2^2|H_u|^2 + \frac{1}{2}\lambda_1|H_d|^4 + \frac{1}{2}\lambda_2|H_u|^4 + \lambda_3|H_u|^2|H_d|^2 + \lambda_4|H_uH_d|^2$$

$$+\lambda_S|S|^4 + m_S^2|S|^2 + \lambda_{H_uS}|S|^2|H_u|^2 + \lambda_{H_dS}|S|^2|H_d|^2$$

- PQ & $U(1)_H$ breaking soft masses lift two massless axions: "singlet axion" becomes DM mediator.

$$\Delta V = \frac{1}{2}m_S'^2 S^2 - \mu_3^2 H_u H_d + \text{h.c.}$$

High-scale PQ breaking can generate them:

$$\frac{1}{M_P^2}\Phi_1^4 S^2 + \frac{1}{M_P^2}\Phi_2^4 H_u H_d, \quad \langle\Phi_1\rangle \sim \langle\Phi_2\rangle \sim 10^{10}\,\text{GeV}.$$

2012년 11월 5일 월요일

Models with extra leptons

- Minimal content for Higgs couplings:

  EW doublet + "singlet" (I,II); EW doublet + "triplet" (III)

- Model I: $-\mathcal{L}_{\rm Yukawa} = \lambda_\chi S\chi\tilde{\chi} + \lambda_l S l_4 \tilde{l}_4 + \lambda_e S e^c_4 \tilde{e}^c_4 + y_l H_d l_4 e^c_4 - \tilde{y}_l H_u \tilde{l}_4 \tilde{e}^c_4 + {\rm h.c.}$
- Model II: $-\mathcal{L} = \lambda_\chi S\chi\tilde{\chi} + \lambda_l S l_4 \tilde{l}_4 + m_e e^c_4 \tilde{e}^c_4 + y_l H_d l_4 e^c_4 - \tilde{y}_l H_u \tilde{l}_4 \tilde{e}^c_4 + {\rm h.c.}$
- Model III: Similar to Model I but

$$-\mathcal{L}_{\rm Yukawa} = \cdots + y_l H_d l_4 T - \tilde{y}_l H_u \tilde{l}_4 T + {\rm h.c.}$$

	Model I	Model II	Model III
(c_1, c_2)	$(3,1)$	$(1,1)$	$(1,3)$
$\mathrm{Br}(\bar{\chi}\chi \to \gamma\gamma)$	40%	14%	6.5%
$\mathrm{Br}(\bar{\chi}\chi \to WW)$	44%	62%	65%
$\mathrm{Br}(\bar{\chi}\chi \to ZZ)$	16%	16%	15%
(r, R)	$(1.15 \times 10^{-3}, 0.56)$	$(0.27, 1.77)$	$(1.01, 2.51)$

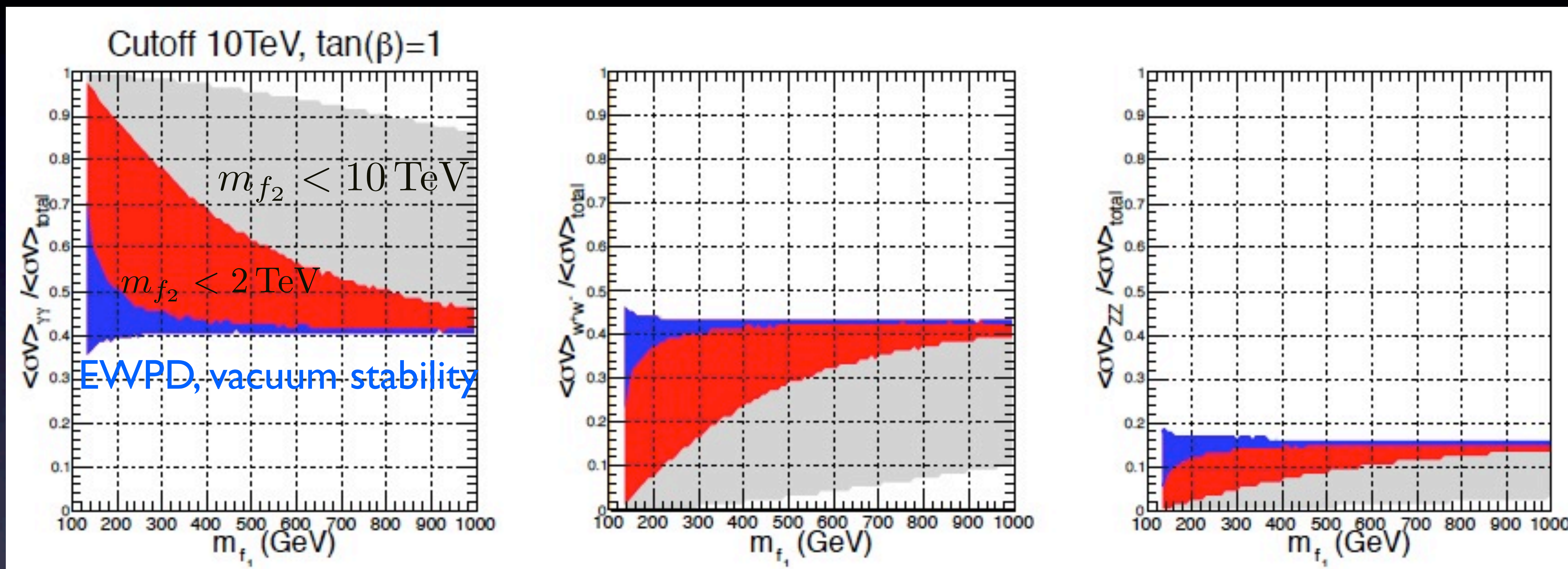
$$r \equiv \langle\sigma v\rangle_{Z\gamma} / (2\langle\sigma v\rangle_{\gamma\gamma})$$

$$R \equiv \langle\sigma v\rangle_{WW} / (2\langle\sigma v\rangle_{\gamma\gamma} + \langle\sigma v\rangle_{Z\gamma})$$

Fermi gamma-ray line explained by 130 GeV DM in all models.

Mass dependent ann.

(Model I)

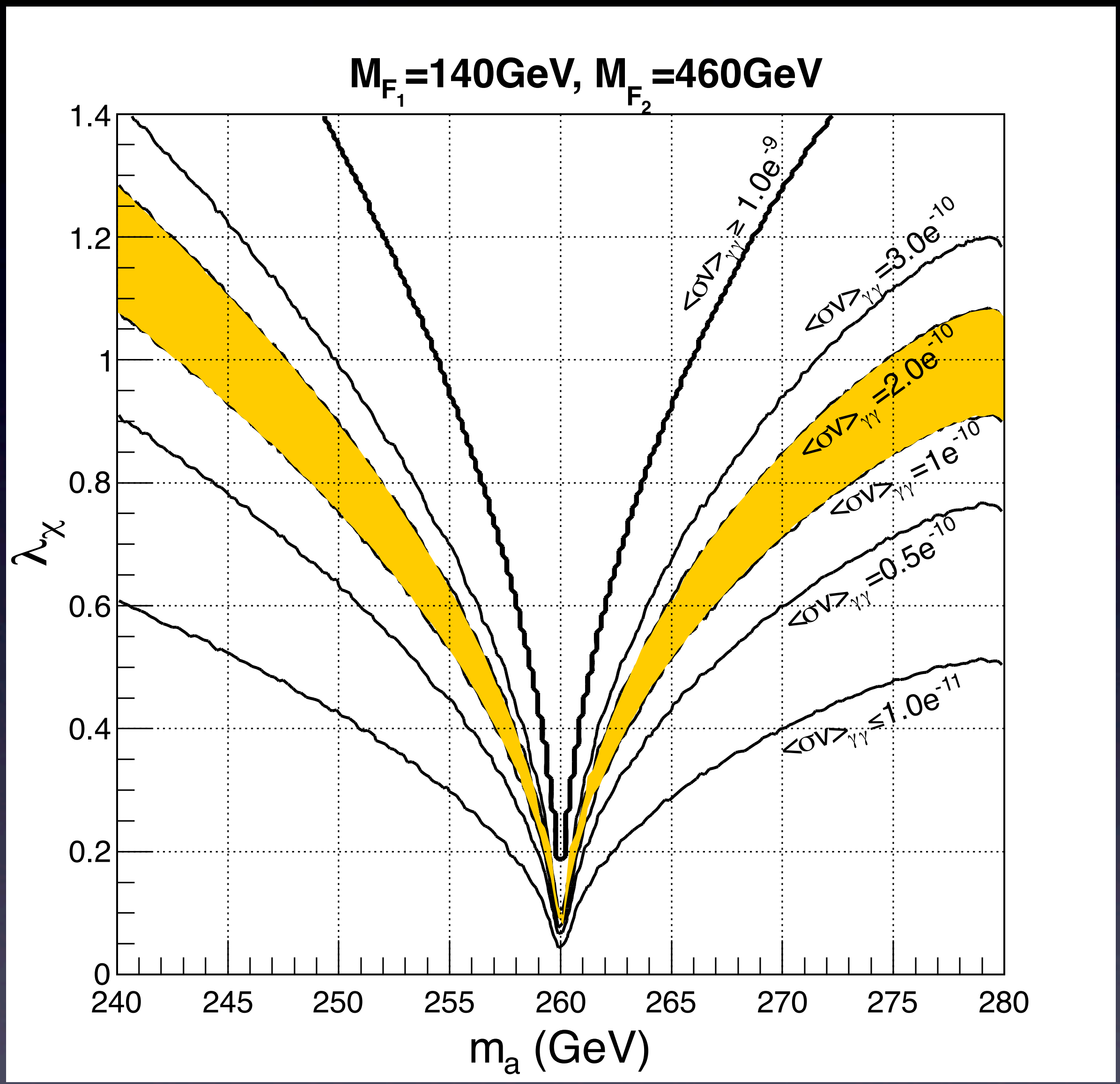


$$\langle\sigma v\rangle_{\gamma\gamma} = \frac{|\lambda_\chi|^2\alpha^2}{512\pi^3}\frac{s^2}{(s-m_a^2)^2+\Gamma_a^2 m_a^2}\left|\frac{\lambda_1 A_1(\tau_1)}{m_{f_1}}+\frac{\lambda_2 A_2(\tau_2)}{m_{f_2}}\right|^2,$$

$$A_1(x) = x\arcsin^2(1/\sqrt{x}).$$

- Large lepton mixing changes the branching fractions significantly for $m_{f_1} < 200\,\mathrm{GeV}$.

Resonant annihilation



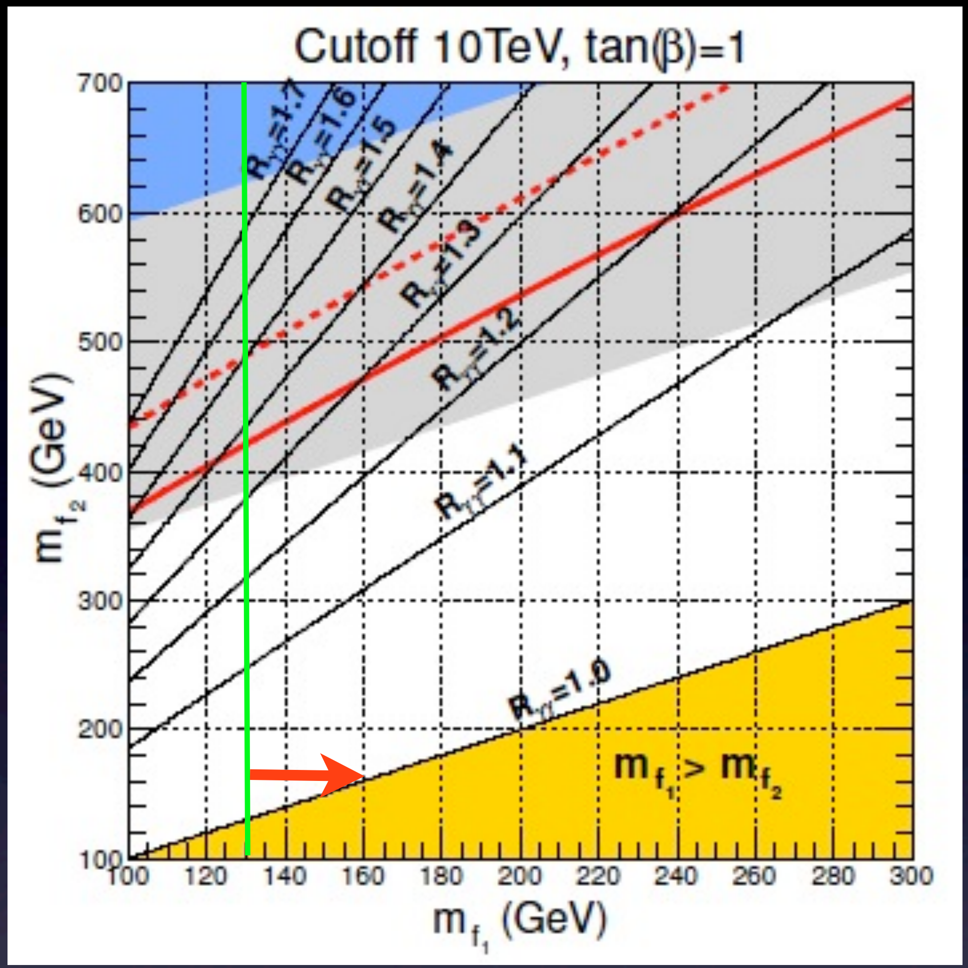
$R_{\gamma\gamma} \simeq 1.4$

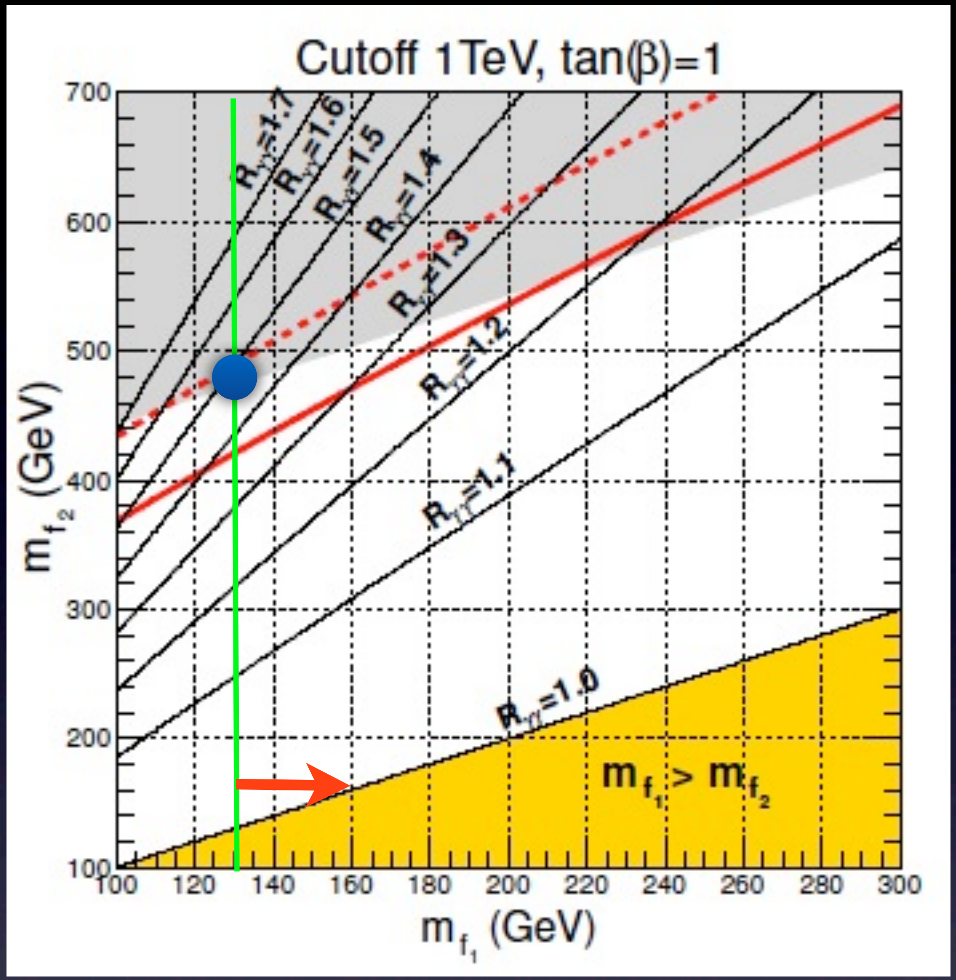
Consistent with 1 TeV cutoff, EWPD @ 95%

- DM annihilation cross section into a photon pair is obtained for

$$|m_a - 2m_\chi| \lesssim 10\,\mathrm{GeV} \quad \text{for } \lambda_\chi \lesssim 0.8.$$

Model constraints





- Assume that the SM Higgs mixes with others little.
- EWPT(68,95%), Perturbativity; Vacuum stability bound (triplet model: more stringent).
- No tree-level DM annihilation: $m_{f_1} > 130\,\mathrm{GeV}.$

→ $R_{\gamma\gamma} \lesssim 1.5\,(1.4)$

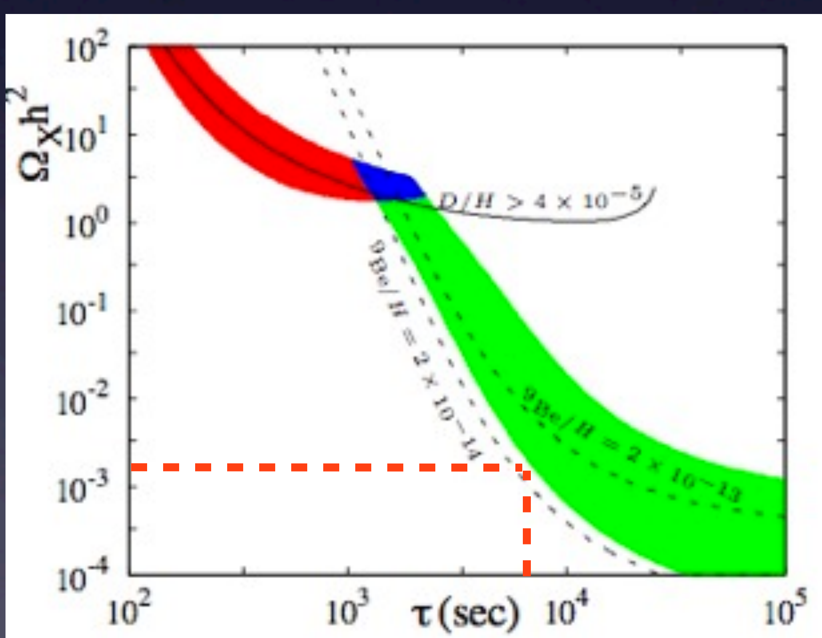
Model predictions

	Model I	Model II	Model III
(c_1, c_2)	$(3, 1)$	$(1, 1)$	$(1, 3)$
$\mathrm{Br}(\bar{\chi}\chi \to \gamma\gamma)$	$\gtrsim 40\%$	$\gtrsim 14\%$	$\gtrsim 6\%$
$R_{\gamma\gamma}$	$\lesssim 1.5$	$\lesssim 1.5$	$\lesssim 1.4$

- Singlet models predict larger Higgs diphoton rate but require extra annihilation channels.
- Triplet model leads to smaller Higgs diphoton rate but there is no need for extra annihilations.
- Model predictions are generic for other axion-mediated models. [Box-shaped gamma-ray: Fan, Reece (2012)]

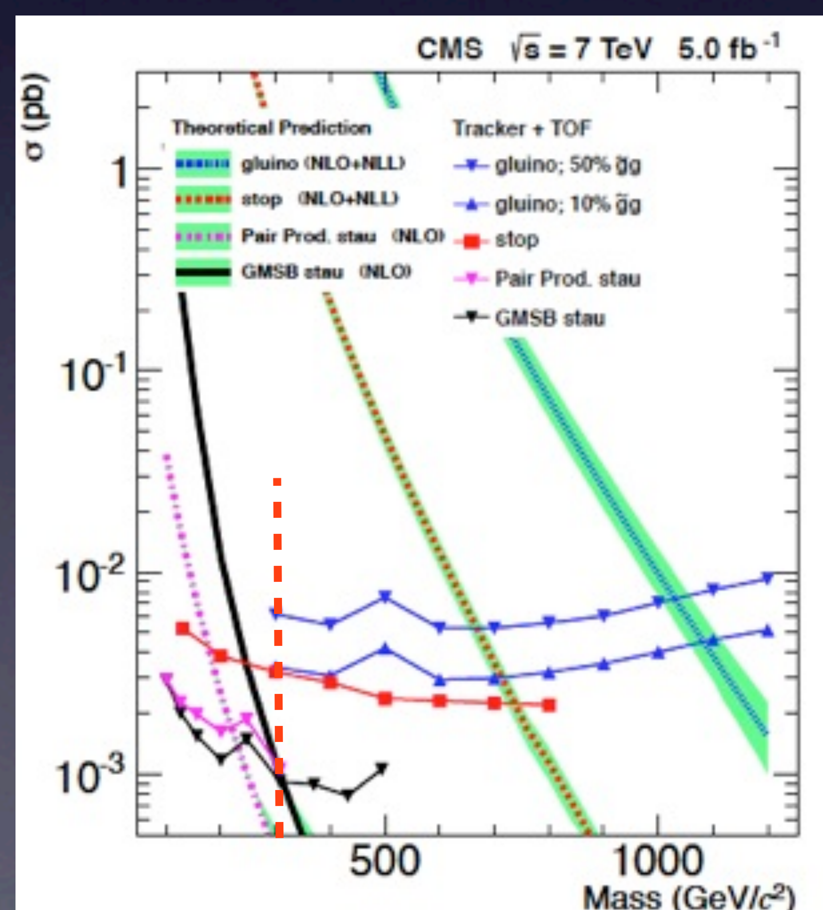
Stable leptons

- Lighter charged lepton is the lightest among extra leptons and would be stable.
- It is strongly constrained by Big Bang Nucleosynthesis and tracker search at the LHC.

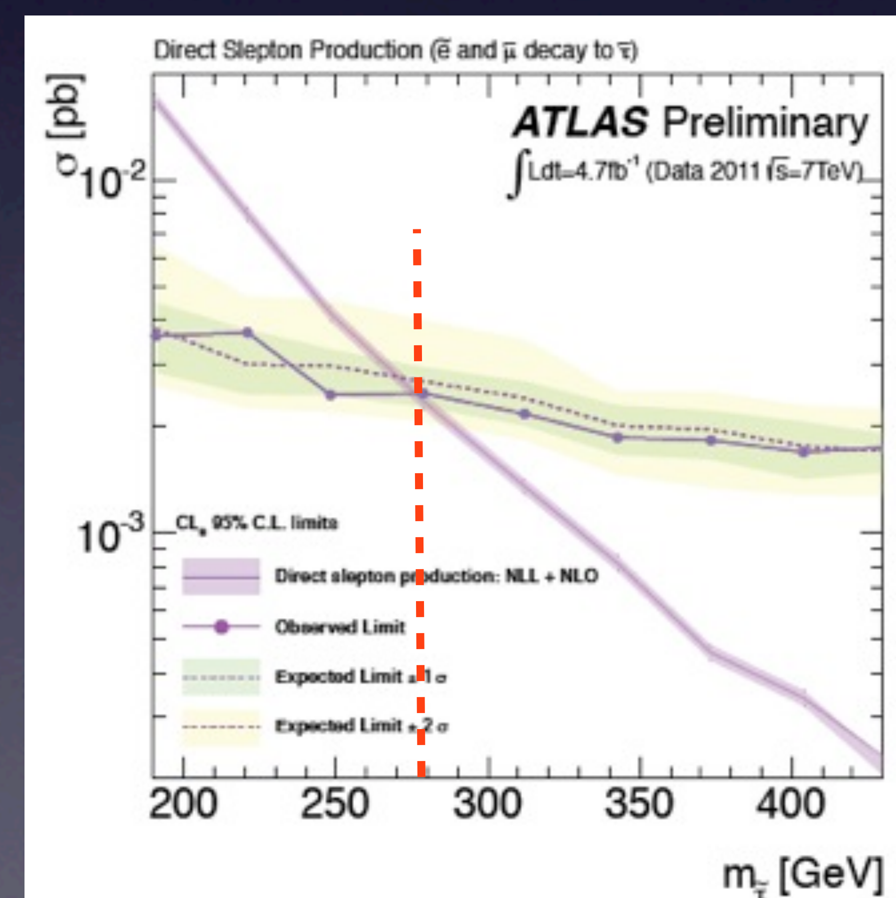


$$\Omega_{\tilde{\tau}} h^2 \approx (2.2 - 4.4) \times 10^{-1} \left(\frac{m_{\tilde{\tau}_1}}{1\mathrm{TeV}} \right)^2$$

[Pospelov(2006); Bailly et al (2008)]

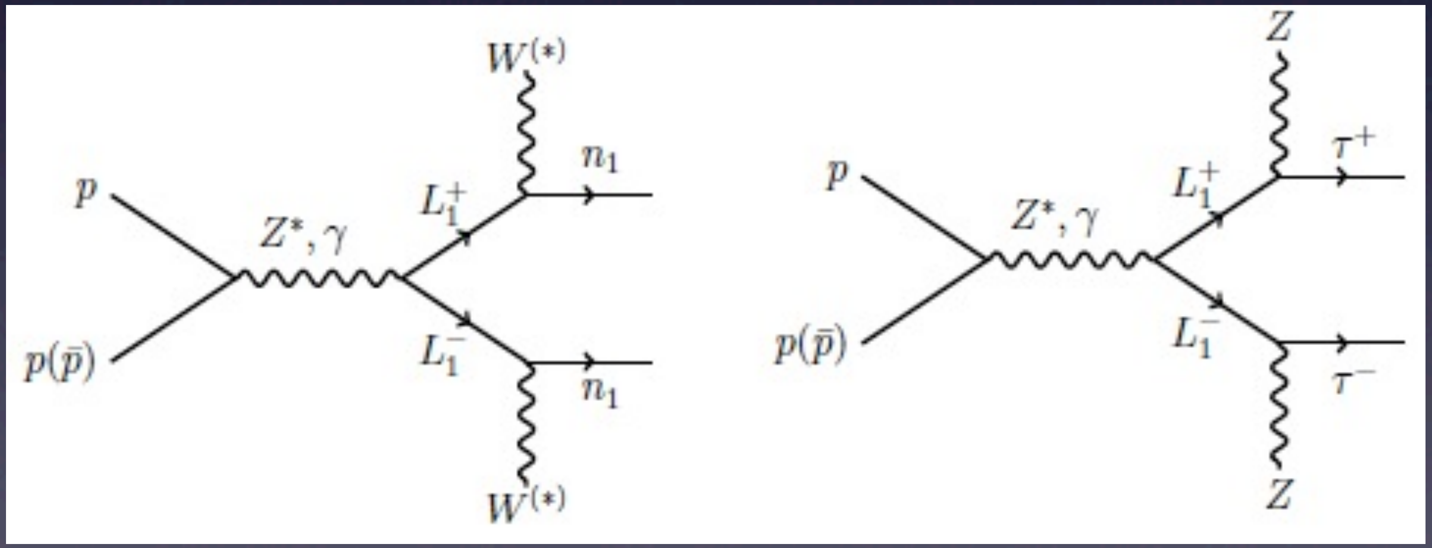


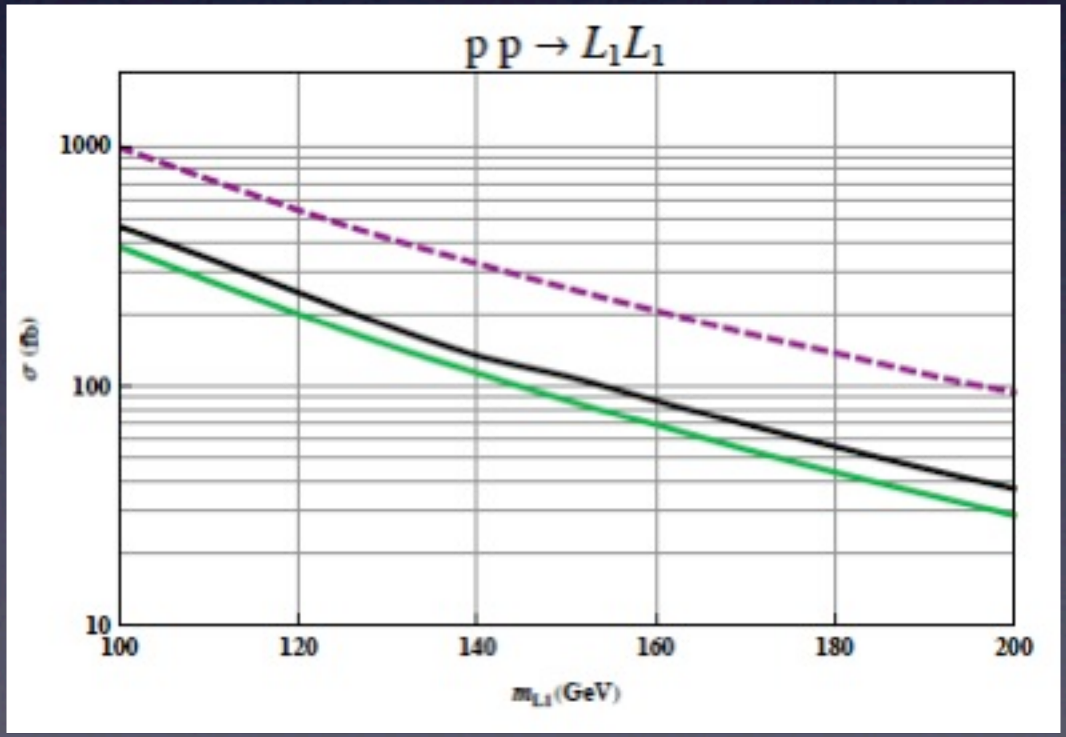
$m_{\tilde{\tau}} > 223\,\mathrm{GeV}$



Bounds on leptons

- Extra charged lepton can decay by mixing with 1) the SM charged lepton or 2) extra singlet neutrino.
- 1) "Lepton flavor violation" constrains the mixing to $|U_{iL_1}| \lesssim 0.01$: prompt decay, small enough not to exceed the 2-photon DM ann. cross section.
- 2) "Continuum photon" constraint leads to mixing $\delta \lesssim 0.06.$





[Arkani-Hamed et al (2012)]

Br($L_l \rightarrow Z$+l)≈100%,   70% efficiency times acceptance

m_{Ll}=100-120 GeV could be already excluded by a single channel 4l.

Conclusions

- In the singlet fermion dark matter model with axion mediator, electroweak anomalies lead to the photon line consistent with Fermi LAT data.
- Models of extra leptons determine the branching fraction of Fermi photons and also enhance the Higgs diphoton rate.
- Suppression of tree-level DM ann. channel constrains the Higgs diphoton rate.
- Decaying charged lepton could be probed at the LHC.