Fermi γ-ray line in an axion mediated DM model

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Fermilab theory seminar (Dec. 6th 2012)

1. Fermi Gamma Ray Line at 130 GeV from Axion-Mediated Dark Matter
   with Hyun Min Lee, Wan-il Park (arXiv:1205.467)

2. Axion-mediated dark matter and Higgs diphoton signal
   with Hyun Min Lee, Wan-il Park (arxiv: 1209.1955)

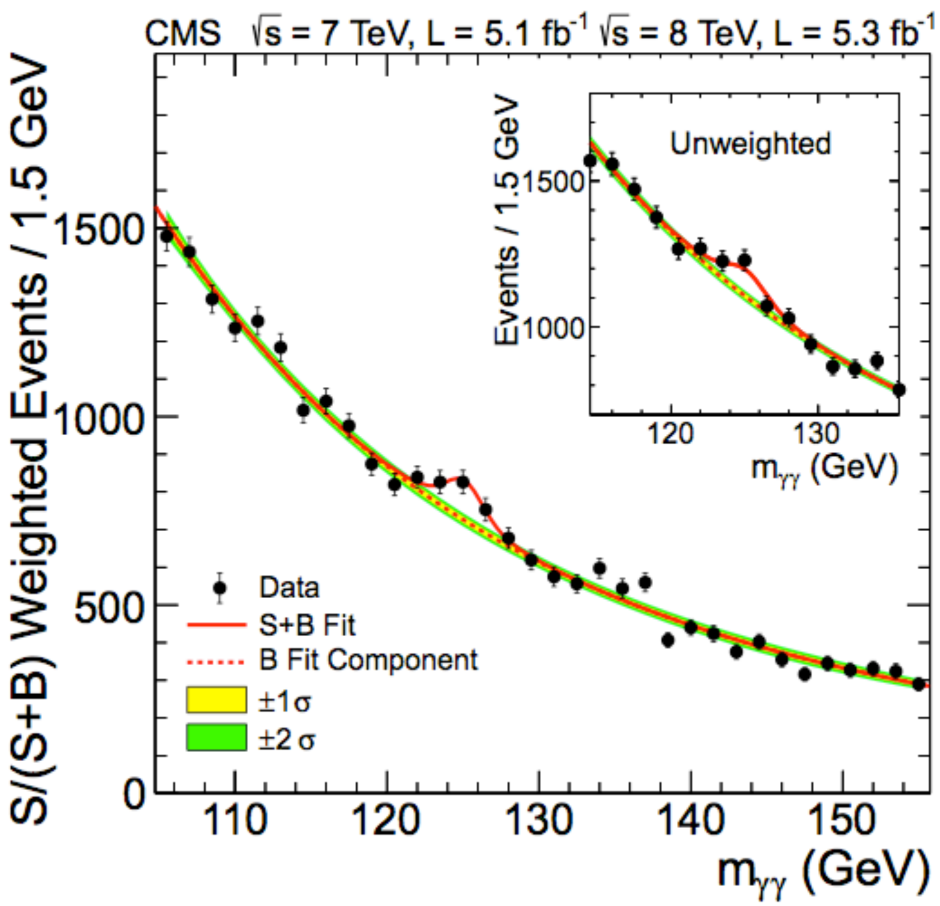
3. Interplay between Fermi gamma-ray lines and the LHC
   with Hyun Min Lee, Veronica Sanz (arxiv:12XX.XXXX)

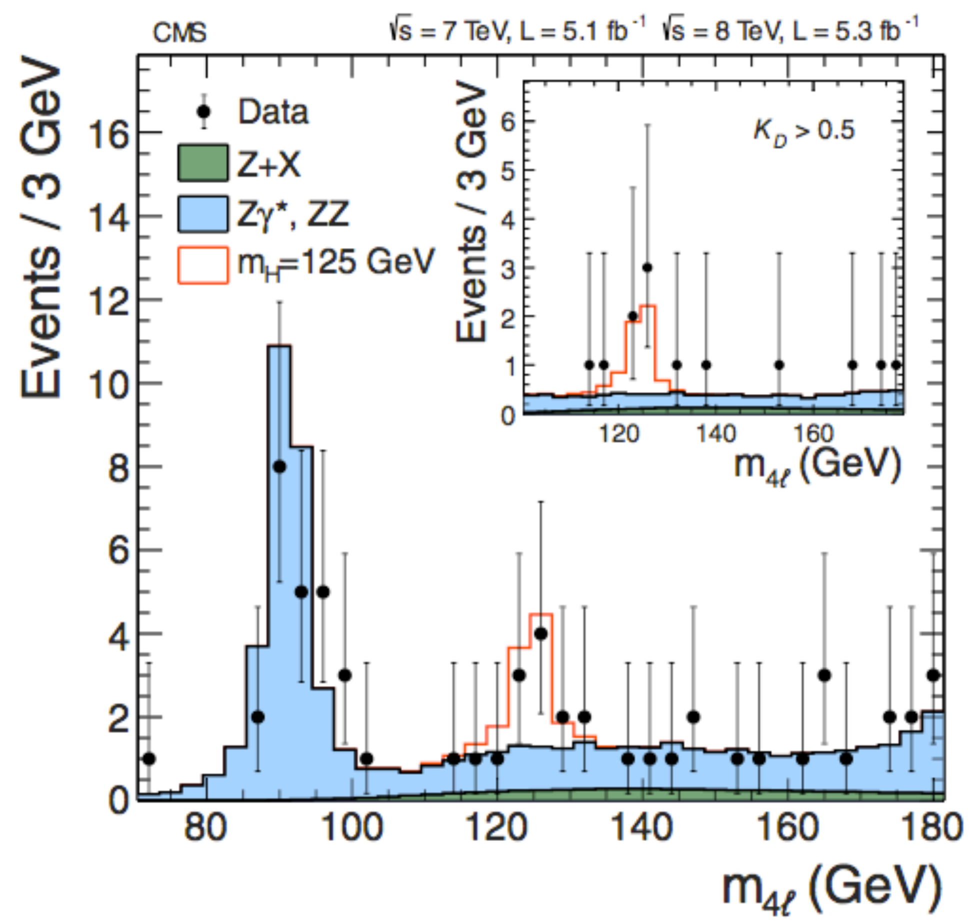
Contents

- A reminder: New boson to two photon
- Fermi γ ray line ~ 130GeV
- Axion mediated dark matter
- Extra particles in a loop.
- Link to the “higgs→diphoton”

A bump hunting

- We got the “bump” at the LHC on the 4th of July

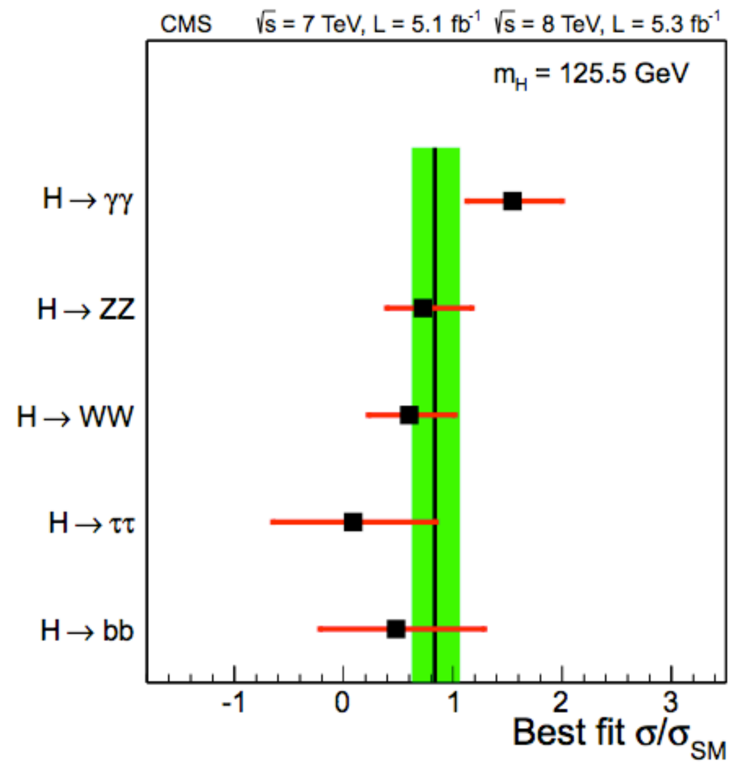


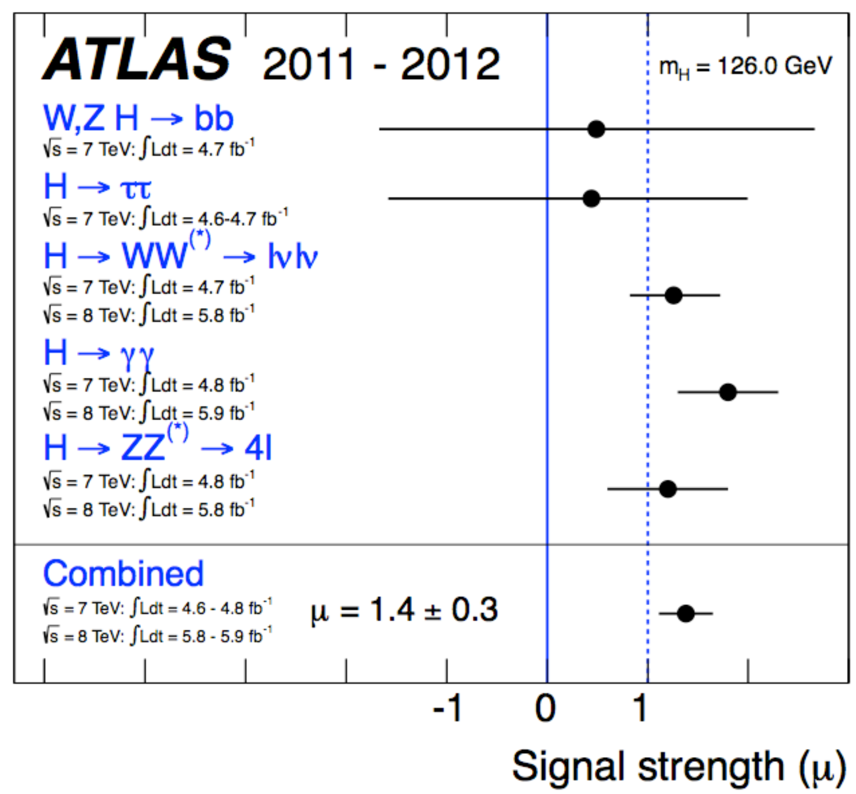


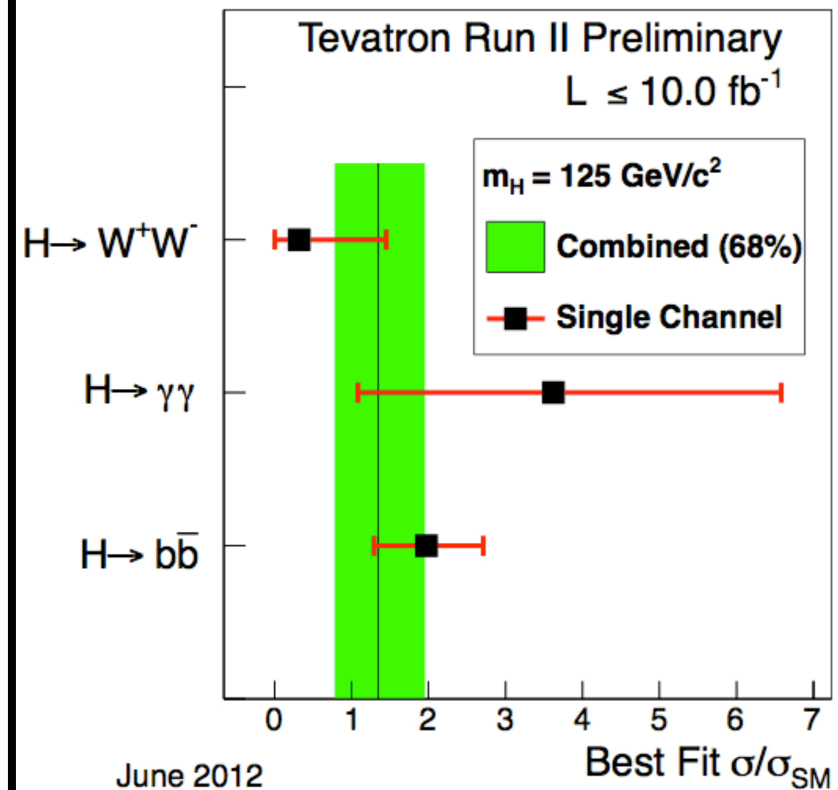
Four lepton channel is the golden channel to study the property of newly discovered boson, but a di-photon channel was problematic (compared to “expected higgs boson”)

Di-photon

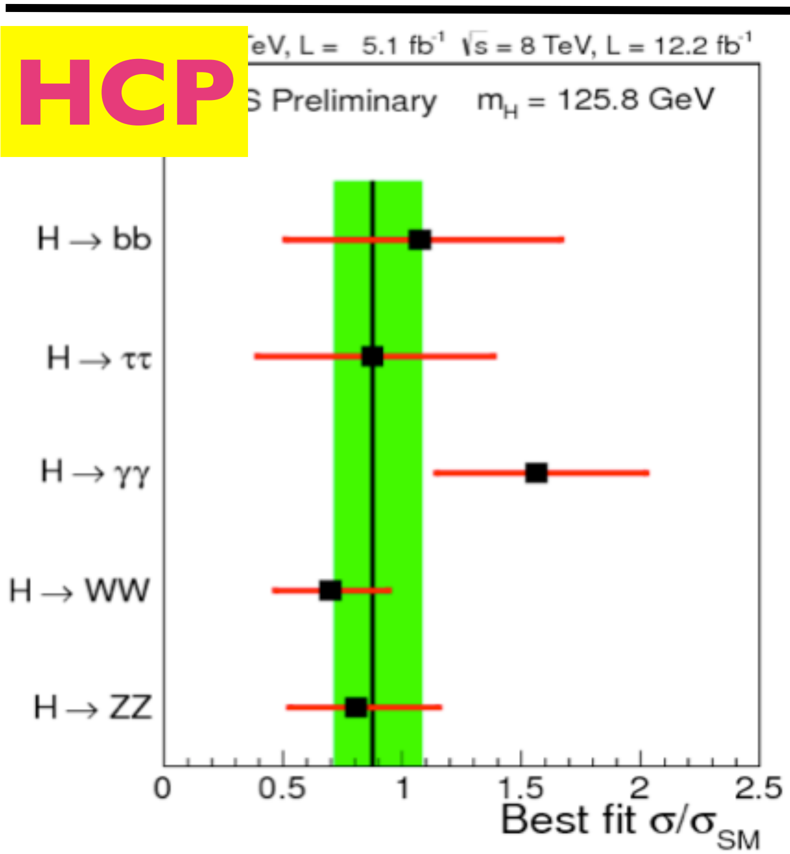
4th of July

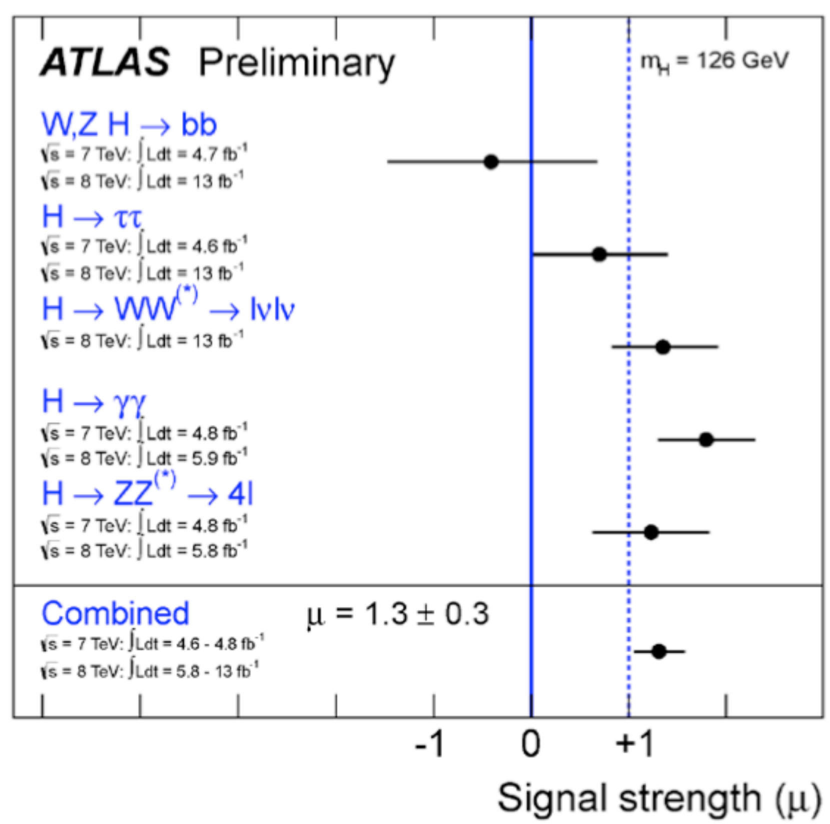


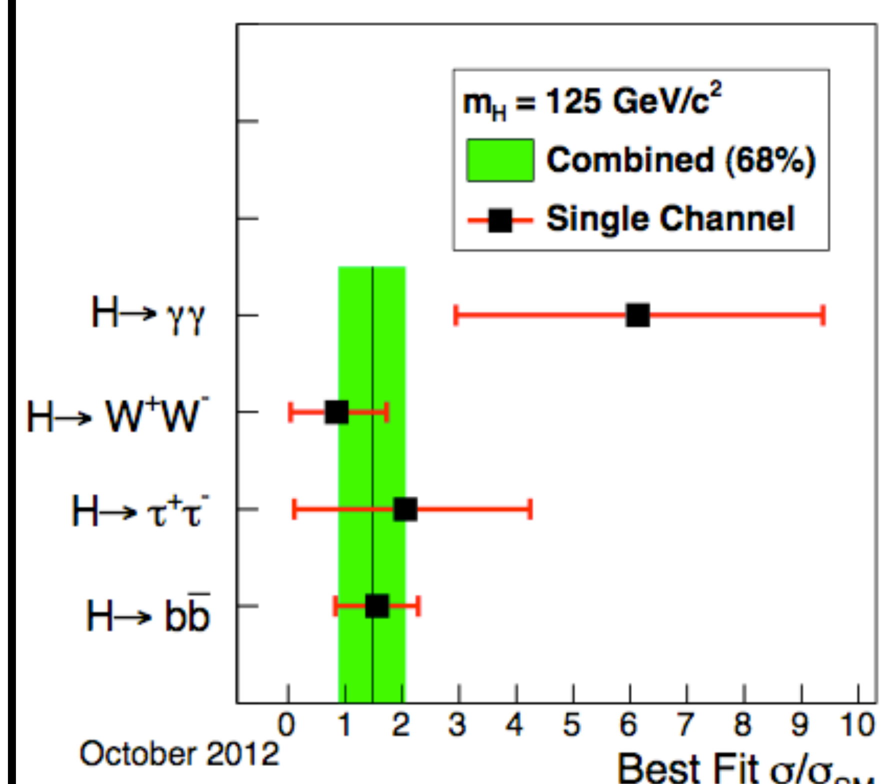




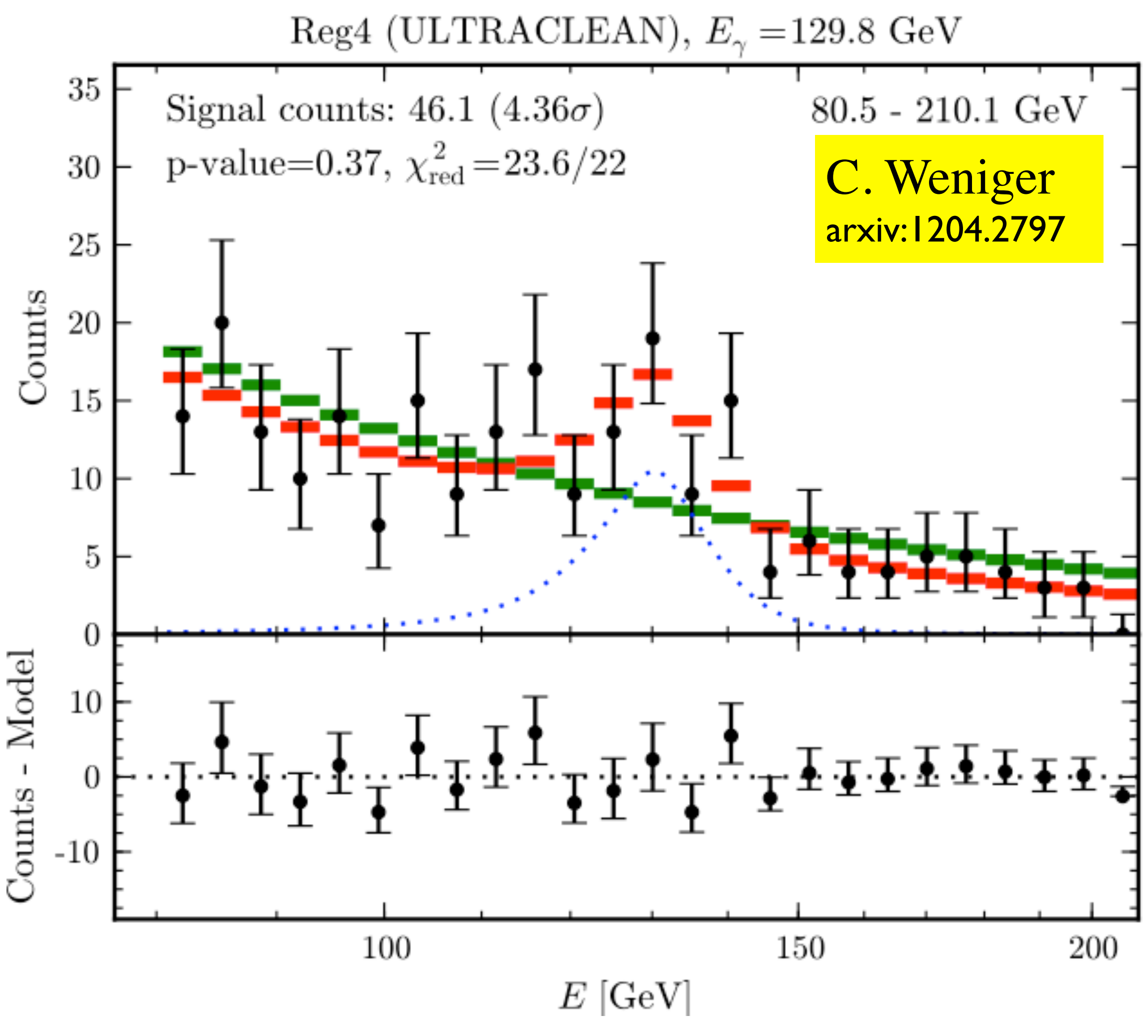
HCP







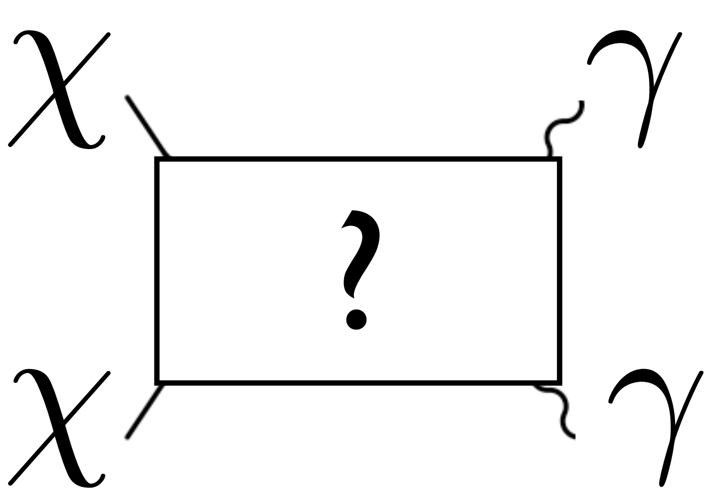
Fermi γ ray line

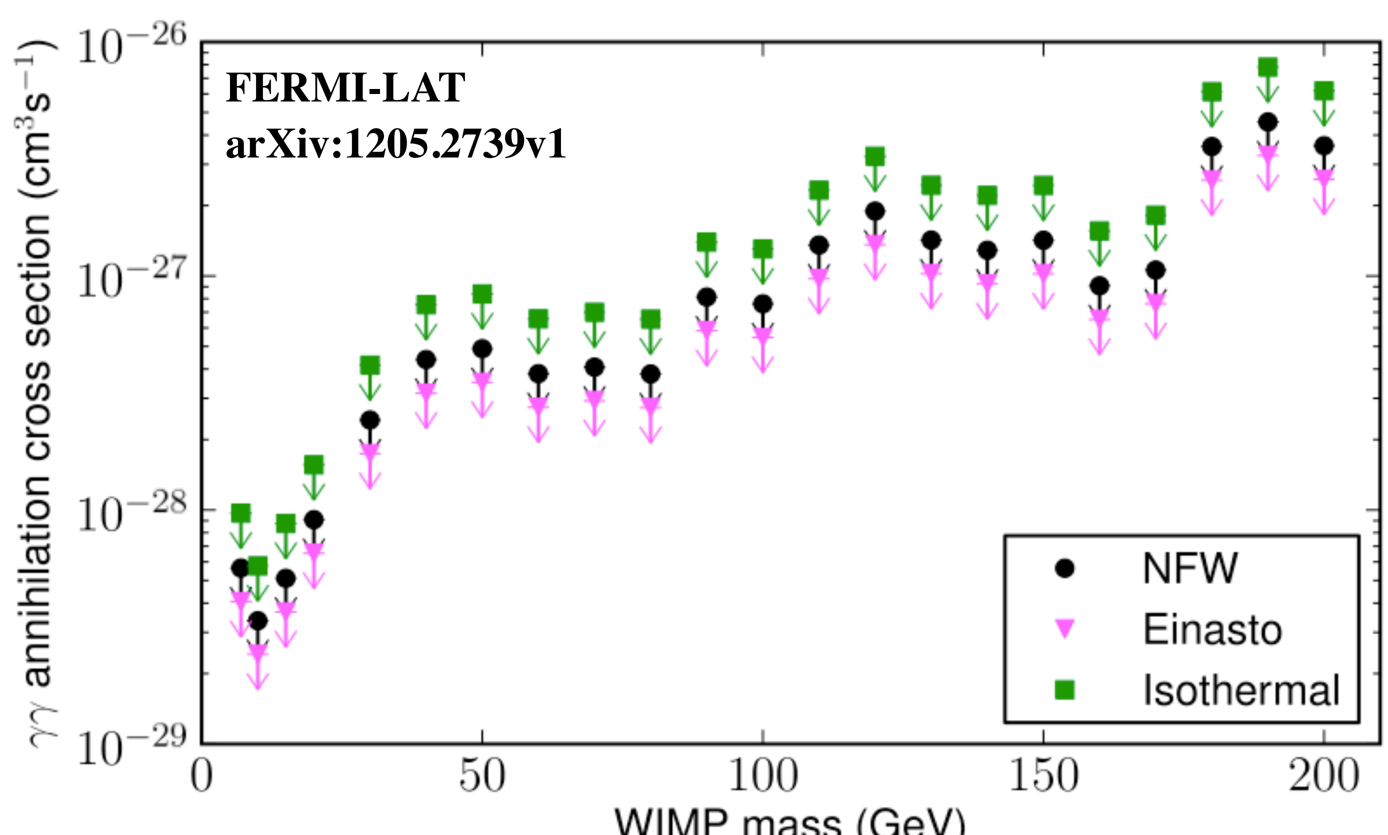


- An excess of Eγ around 130GeV have been reported from Fermi Large Area Telescope (Fermi LAT) based on the data; from Aug. 4 2008 to Mar. 8,2012

- Interpretation with dark matter annihilation provides:

$$< \sigma v >_{\gamma\gamma} = (1.27 \sim 2.27) \times 10^{-27} cm^3 s^{-1}$$





Set up

- We required a s-channel annihilation
  to explain a photon line ~ 130GeV
- Fermion dark matter + pseudo scalar "a"
  in s-channel (s-wave)
- We used "electro-weak" axion to avoid
  large annihilation of dark matter pair to gluon.
- We included a CP-even singlet in our consideration.
- An axion gets a weak scale mass →
  Cross section enhancement by a resonance effect
  (e.g. high scale PQ breaking)

Axion Mediated model

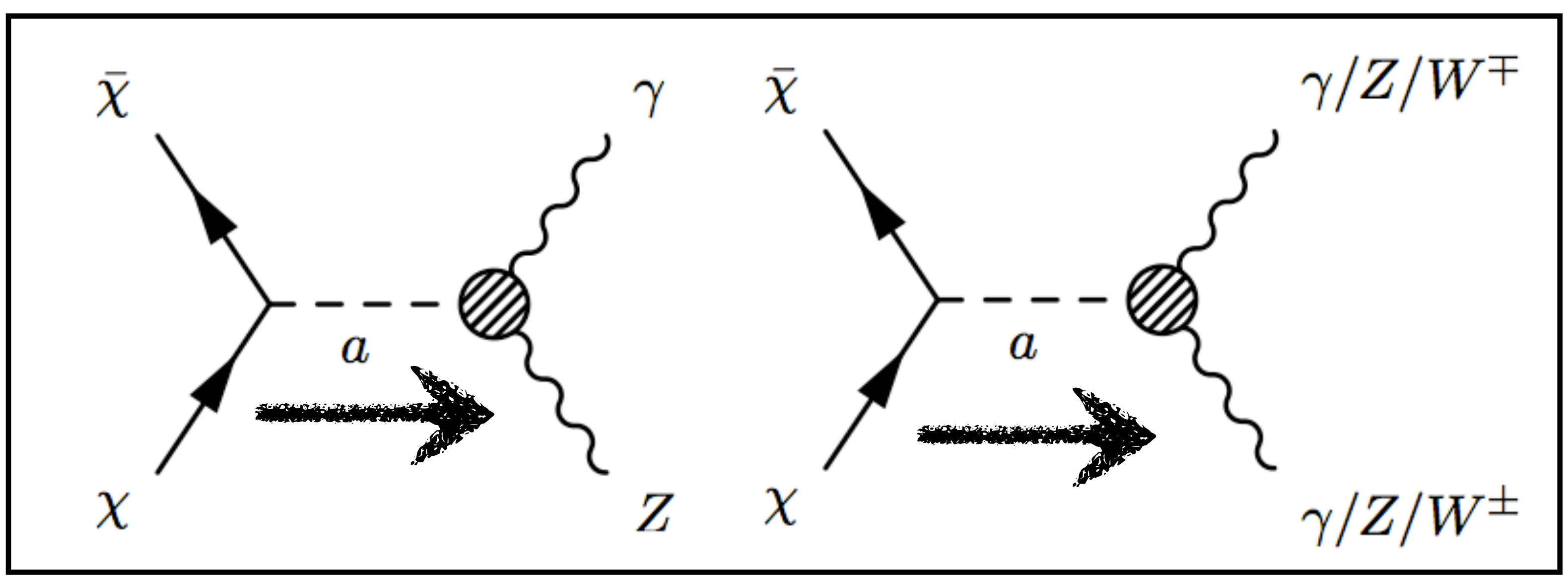
- Dark matters to the photons (SM)

$$\mathcal{L}_{\rm int} = \lambda_\chi(S\bar{\chi}P_L\chi + S^*\bar{\chi}P_R\chi) + \sum_{i=1,2} \frac{c_i\alpha_i}{8\pi v_s} aF^i_{\mu\nu}\tilde{F}^{i\mu\nu}$$

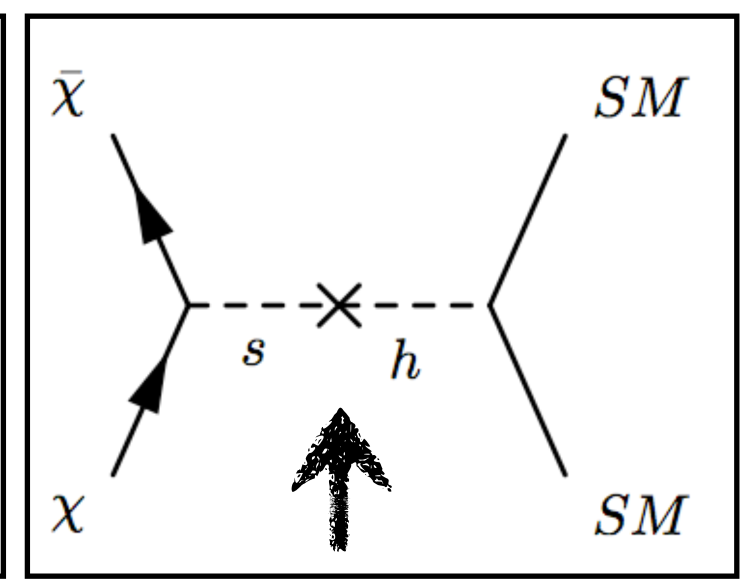
with $S = (s+ia)/\sqrt{2}$

and potential (+ mixing between s and h)

$$V(H,S) = \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|S|^2|H|^2 + m_H^2|H|^2 + m_S^2|S|^2 - \left(\frac{1}{2}m_S'^2 S^2 + \text{h.c.}\right)$$

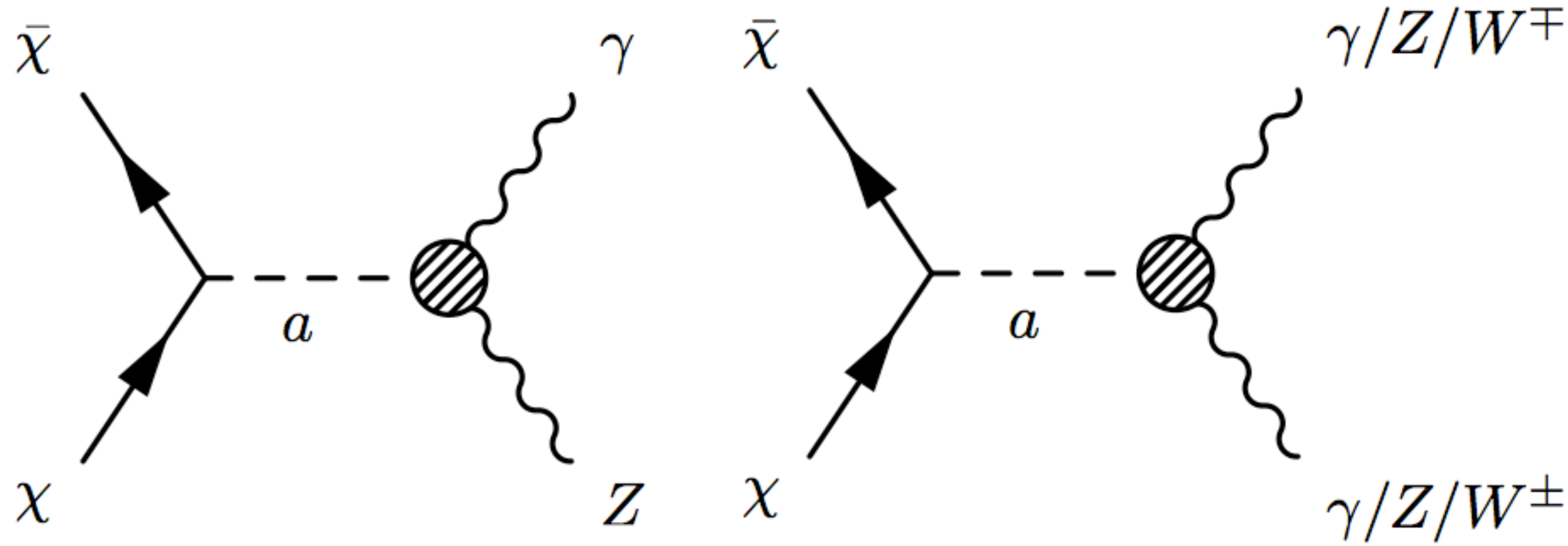


Fermi γ ray



Direct detection

Photon line(s)

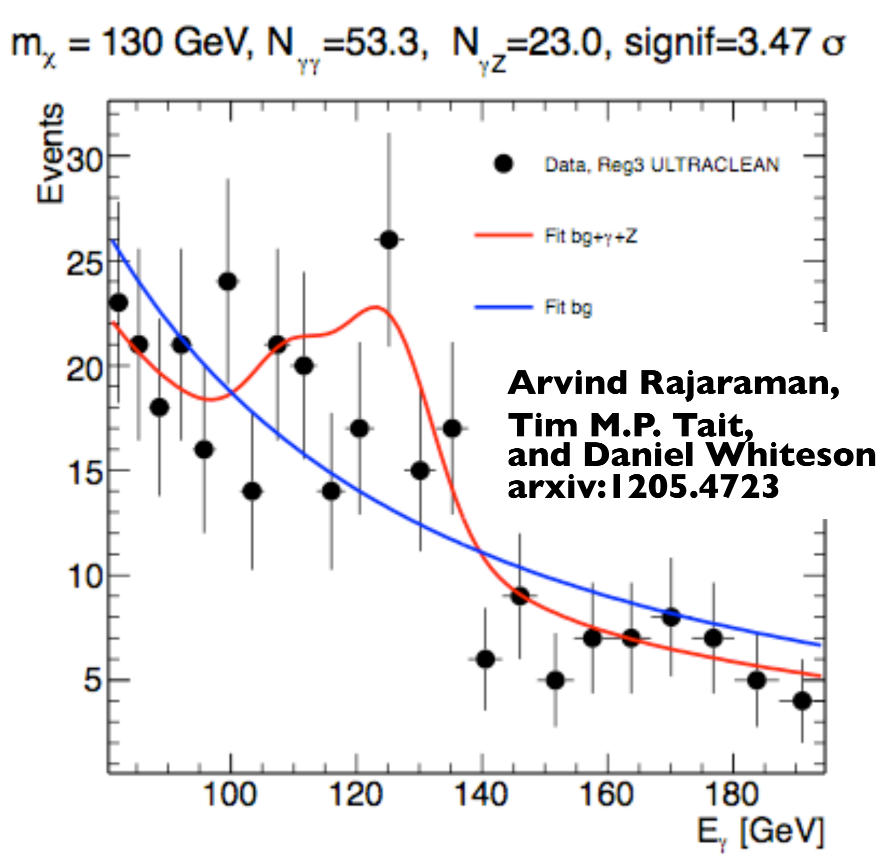


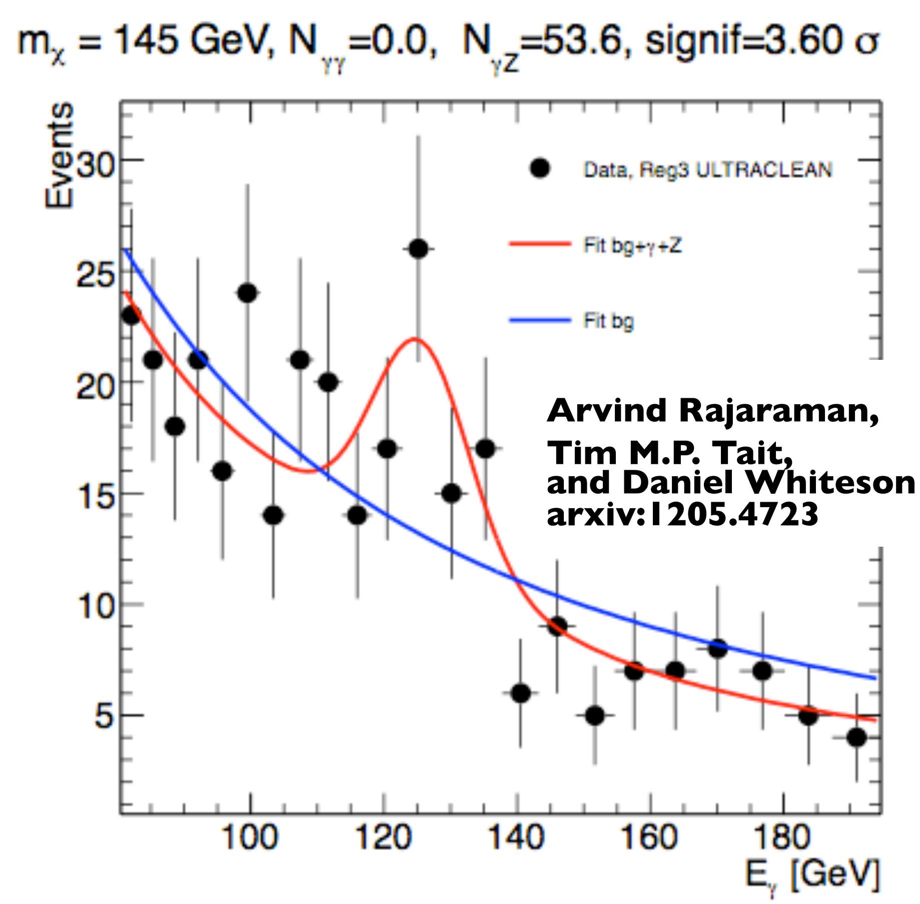
- We have:
  1. DM+DM → photon+photon $E_\gamma = M_\chi$
  2. DM+DM → photon+Z $E_\gamma = M_\chi \left(1 - \frac{m_Z^2}{4M_\chi^2}\right)$
  3. DM+DM → (Z, Z) (W,W): continuum spectrum

Photon line(s)

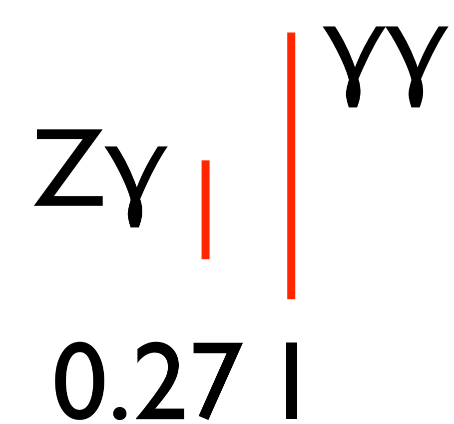
- If $M_\chi = E_\gamma \sim 130GeV$, then

$$E_\gamma = M_\chi\left(1 - \frac{m_Z^2}{4M_\chi^2}\right) \sim 114GeV$$





In our case, when $c_1=c_2$ the intensity ratio will be



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

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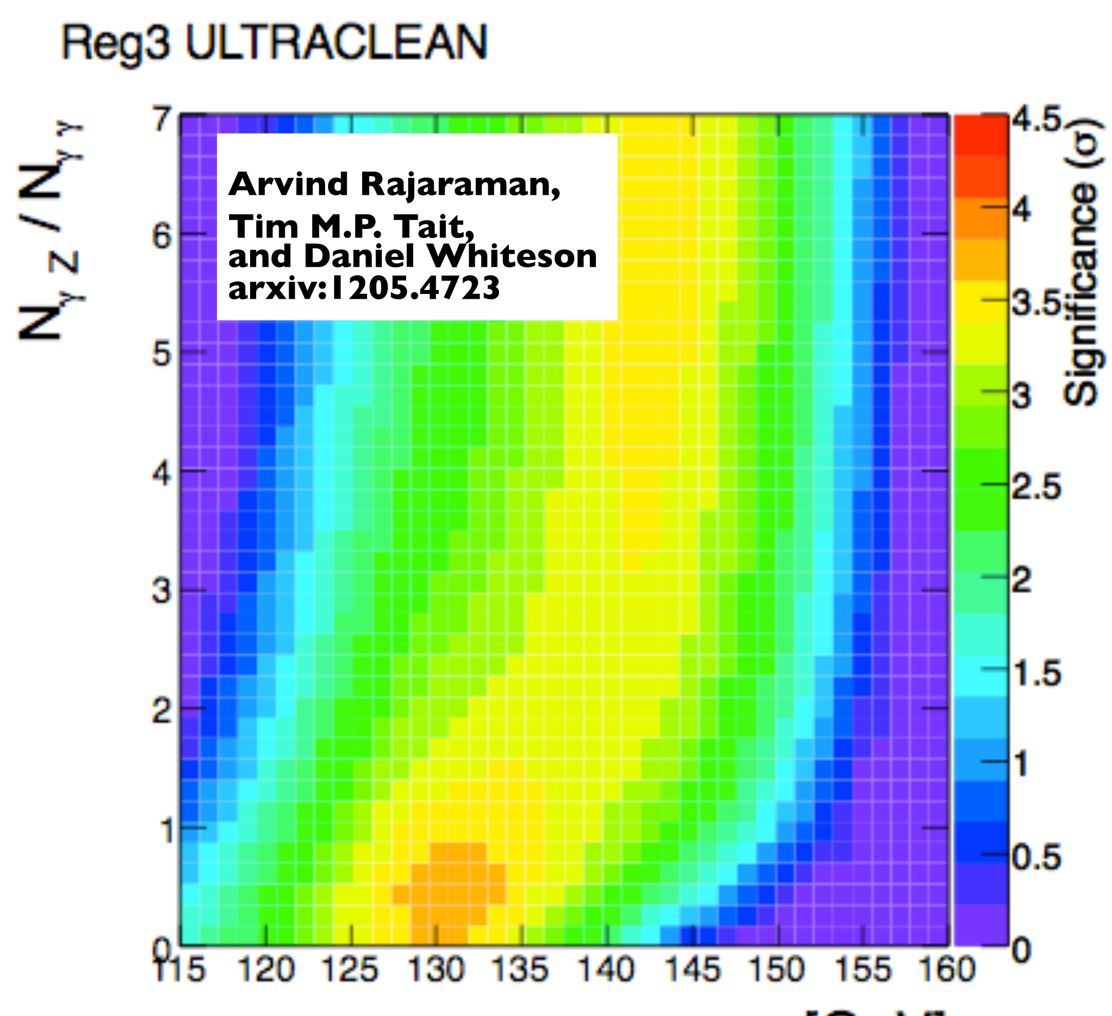

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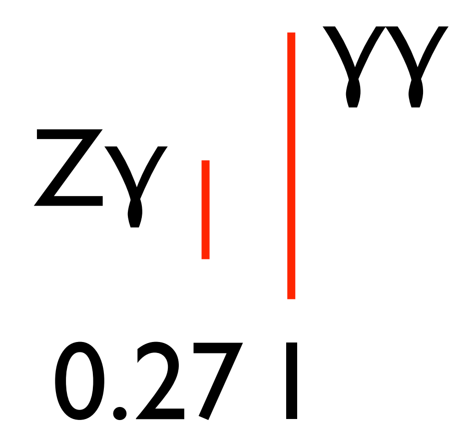


$$\sum_{i=1,2} \frac{c_i \alpha_i}{8\pi v_s} a F^i_{\mu\nu} \tilde{F}^{i\mu\nu}$$

Constraints

- Branch ratio of (DM,DM→γγ) are estimated by $<\sigma v>_{\gamma\gamma} = (1.27 \sim 2.27) \times 10^{-27} cm^3 s^{-1}$ ~ 4-8%

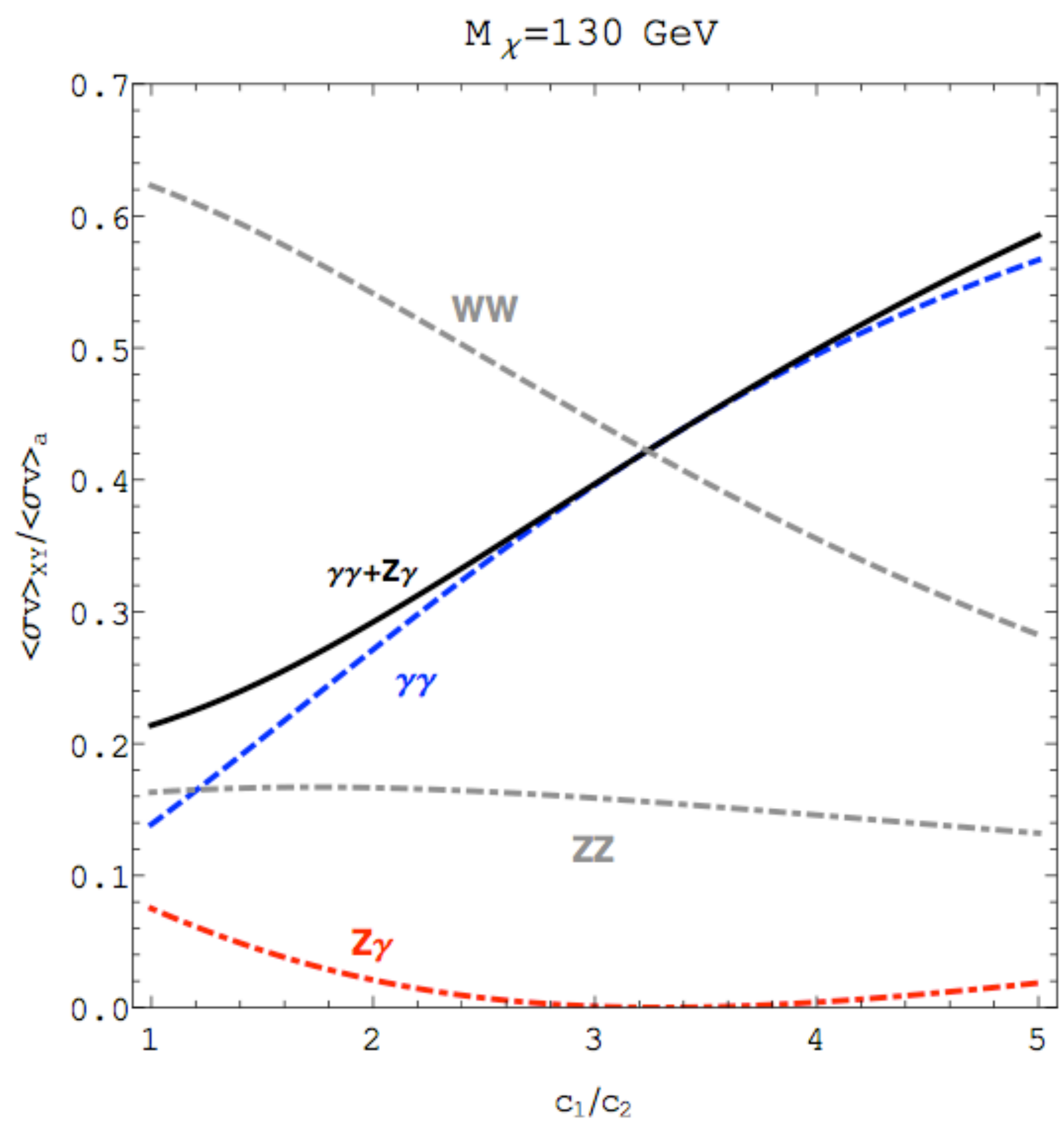
$$\mathrm{Br}(\bar{\chi}\chi \to XY)_a \equiv \frac{\langle \sigma v \rangle_{XY}}{\langle \sigma v \rangle_a} \sim 14\ \%$$

$$\langle \sigma v \rangle|_{\mathrm{fr}} \simeq \langle \sigma v \rangle_a|_{\mathrm{fr}} + \langle \sigma v \rangle_s|_{\mathrm{fr}}$$

$$4\sim8\% = \frac{<\sigma v>_{XY}}{<\sigma v>_{fr}} = \frac{Br(\bar{\chi}\chi \to XY)_a}{1 + \frac{<\sigma v>_s}{<\sigma v>_a}|_{fr}}$$

To be consistent with observation

$$\langle \sigma v \rangle_s / \langle \sigma v \rangle_a = 0.8 - 2.3$$



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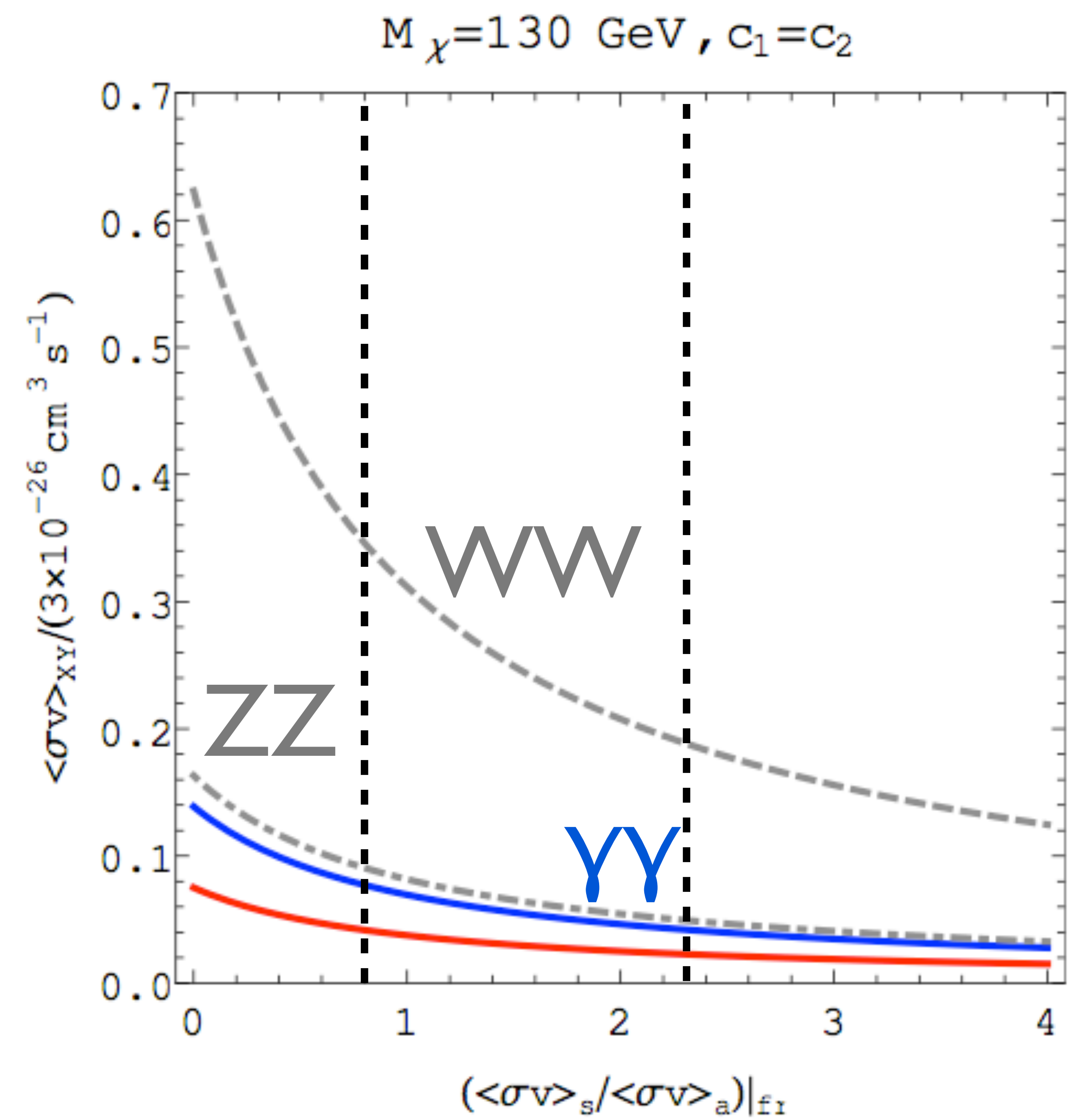
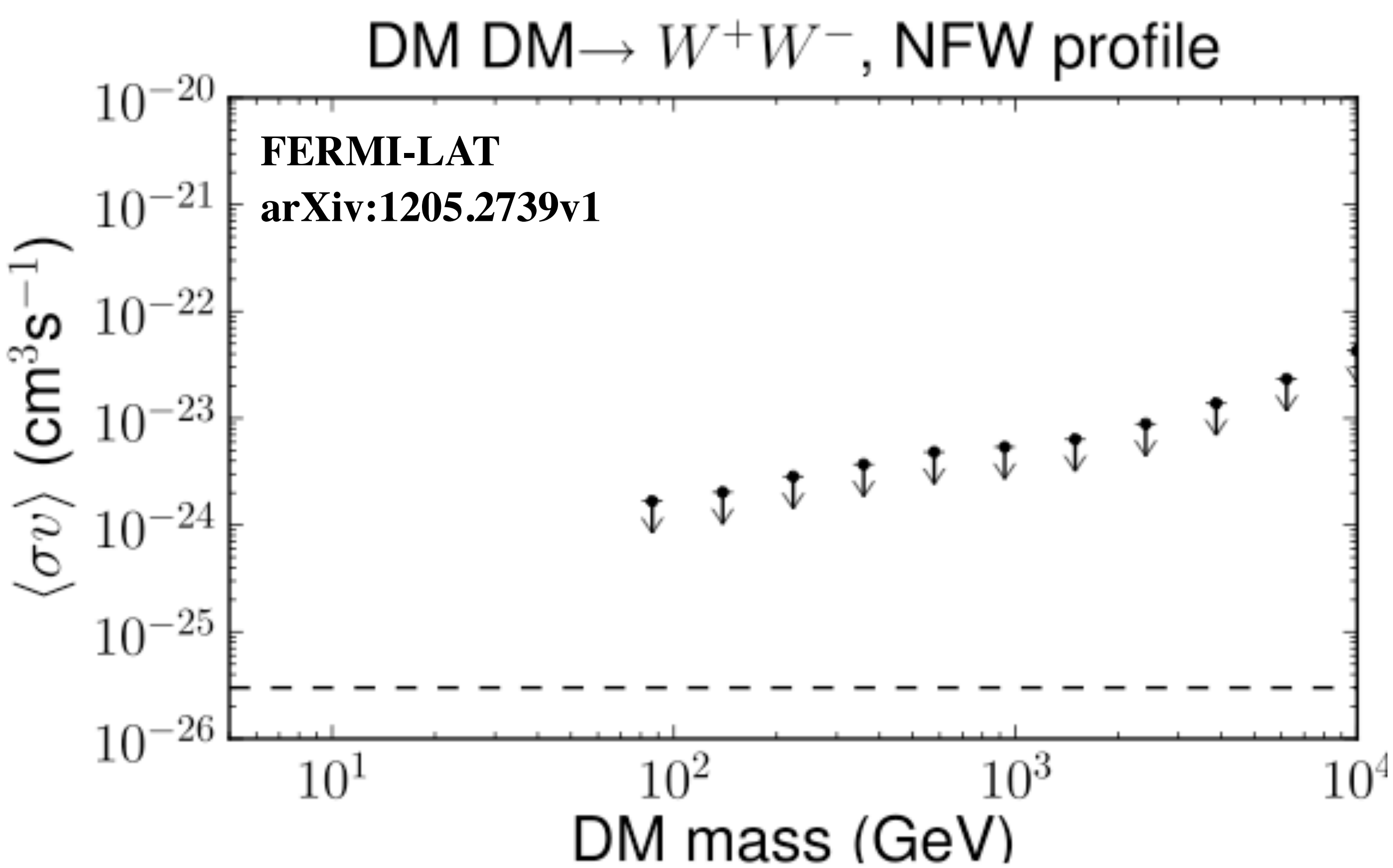
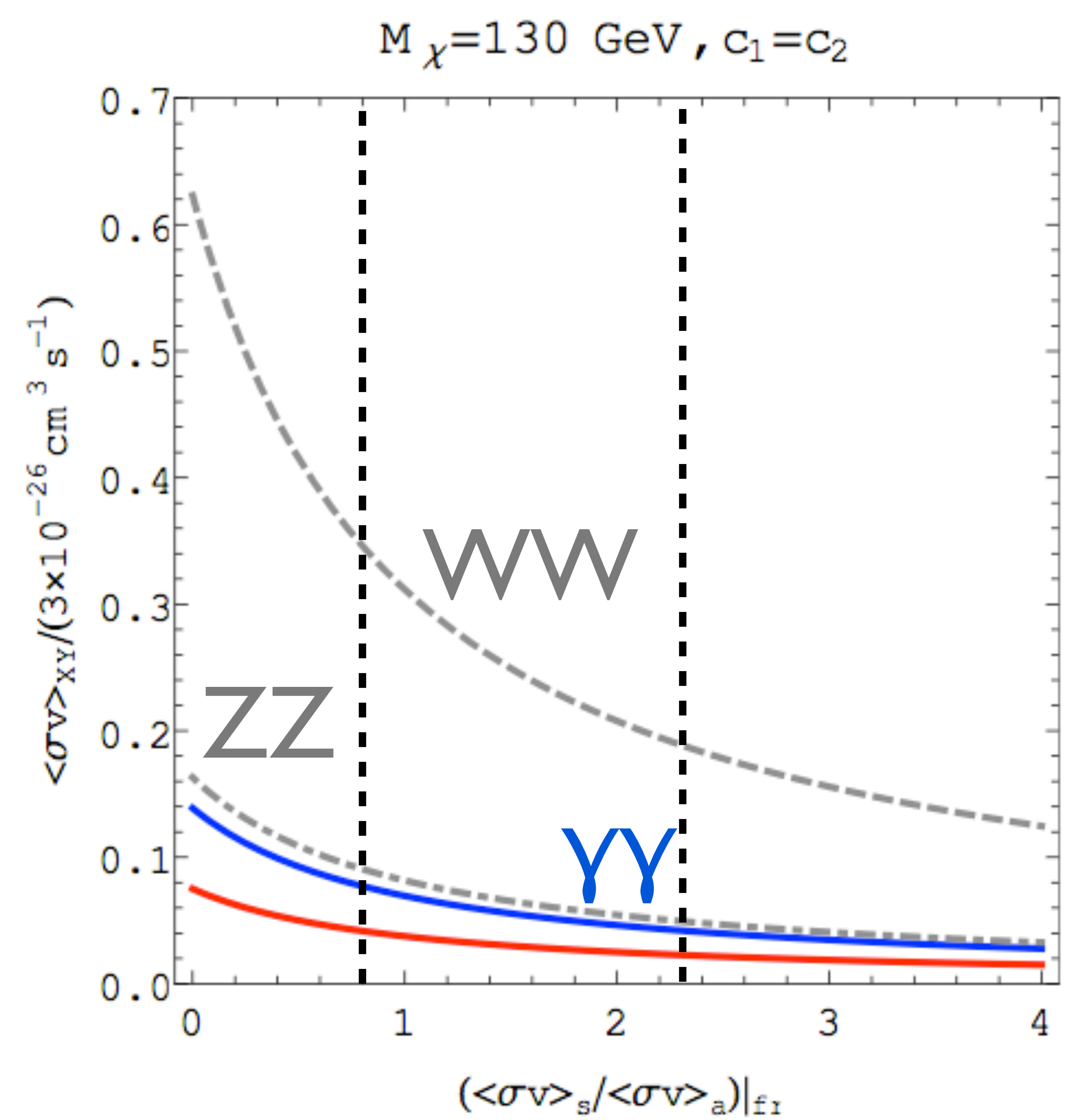


Constraints

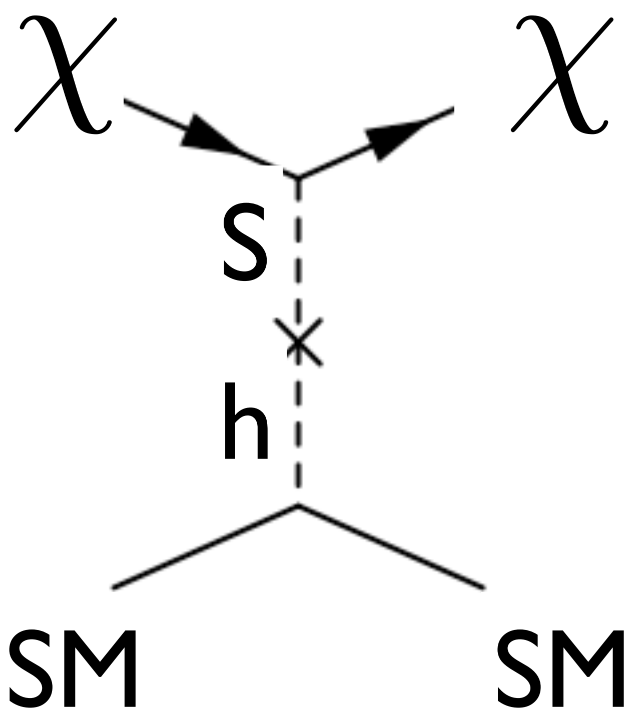
- (DM,DM→WW) channel satisfies the current upper limit by Fermi LAT.



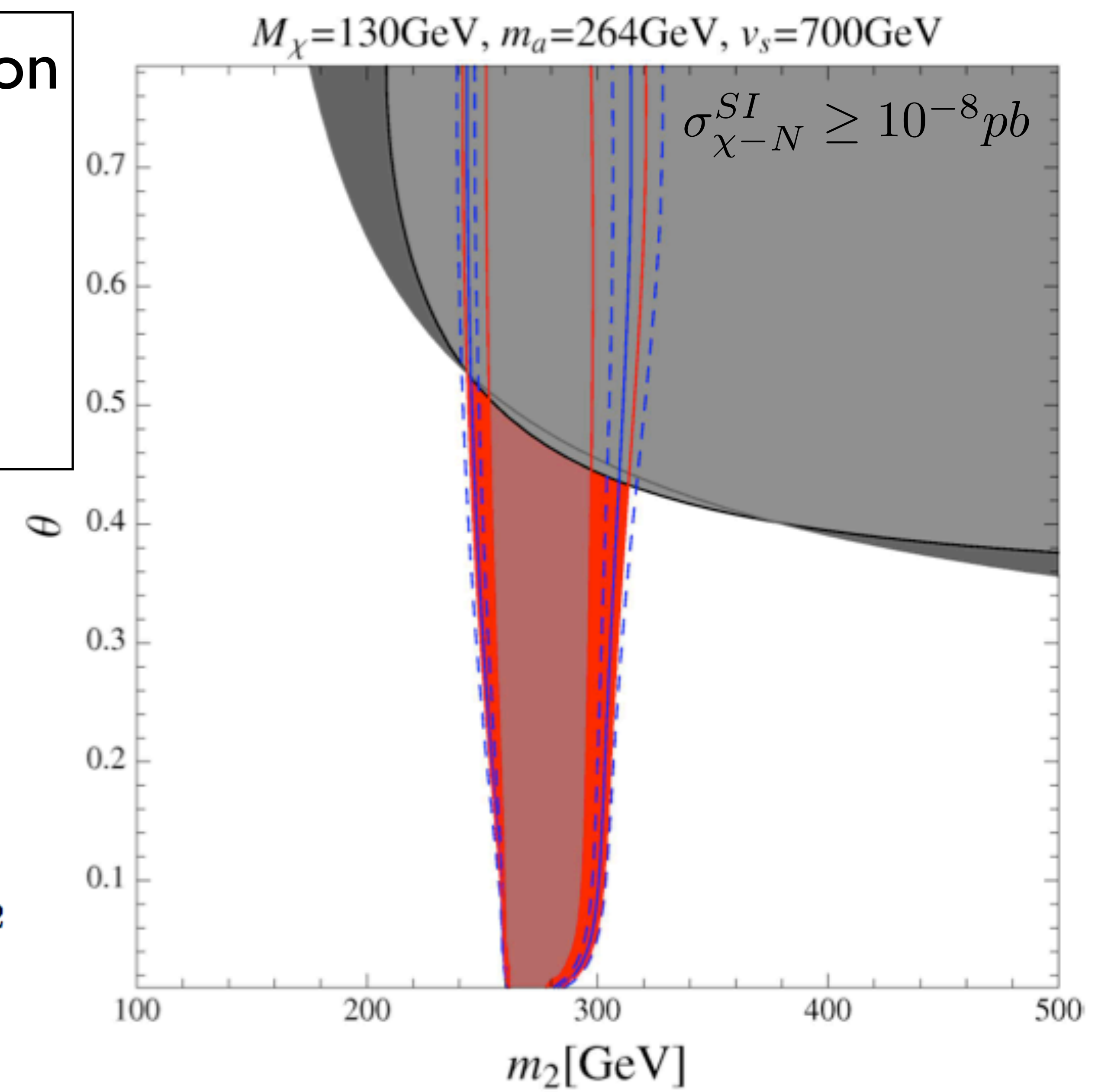


Constraints

- Direct dark mater detection



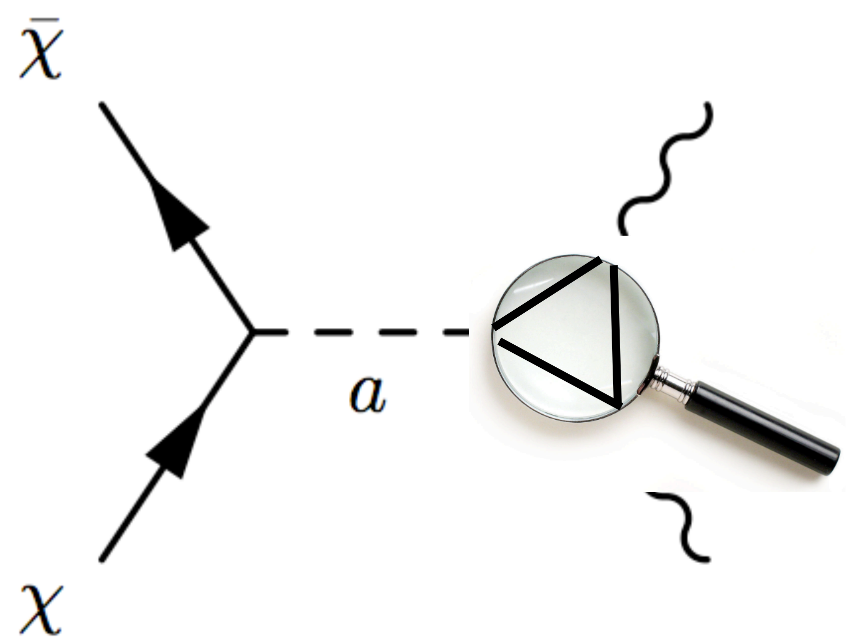
Grey: Direct detection
DGrey: EWPD
Blue: WMAP 3σ
Red: γγ 4-8%
Pink: γγ<4%



$m_1 \sim 125GeV$

$$\sigma^{\rm SI}_{\chi-N} = |\lambda_\chi|^2 \sin^2(2\theta) \cdot \frac{m_r^2 f_N^2}{8\pi}\left(\frac{m_N}{v}\right)^2\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)^2$$

There are extra leptons



- We introduce extra vector-like leptons to generate an anomaly.
- We have two higgs doubles to have Yukawa couplings for extra leptons

vector-like lepton doublets, $l_4, \tilde{l}_4$
vector-like lepton singlets, $e_4^c, \tilde{e}_4^c$

There are three types;

1. vector-like doublet and singlet with PQ charge
2. vector-like doublet and PQ neutral singlet
3. vector-like doublet and triplet with PQ charge

$$\mathcal{L}_{a,\mathrm{eff}} = \sum_{i=1,2} \frac{c_i \alpha_i}{8\pi v_s} a F^i_{\mu\nu} \tilde{F}^{i\mu\nu} \longrightarrow c_1 = \mathrm{Tr}(q_{PQ} Y^2) \text{ and } c_2 = \mathrm{Tr}(q_{\mathrm{PQ}} l(r))$$

Models with extra leptons

Model I: $-\mathcal{L}_{\text{Yukawa}} = \lambda_\chi S\chi\tilde{\chi} + \lambda_l S l_4 \tilde{l}_4 + \lambda_e S e_4^c \tilde{e}_4^c + y_l H_d l_4 e_4^c - \tilde{y}_l H_u \tilde{l}_4 \tilde{e}_4^c + \text{h.c.}$

Majorana mass for neutrino

$\frac{1}{M}(l_i H_u)(l_j H_u)$

	q_i	u_i^c	d_i^c	l_i	e_i^c	l_4	e_4^c	$\tilde{l}_4$	$\tilde{e}_4^c$	H_u	H_d	S	χ	$\tilde{\chi}$
PQ	1	1	1	2	0	1	1	1	1	-2	-2	-2	1	1
Z_2	$+$	$+$	$-$	$+$	$-$	$-$	$+$	$+$	$+$	$+$	$-$	$-$	$-$	$+$

Table 1: PQ charges and Z_2 parities for Majorana neutrino case

only dirac mass for neutrino

	q_i	u_i^c	d_i^c	l_i	e_i^c	N_i^c	l_4	e_4^c	$\tilde{l}_4$	$\tilde{e}_4^c$	H_u	H_d	S	χ	$\tilde{\chi}$
PQ	1	1	1	1	1	1	1	1	1	1	-2	-2	-2	1	1
Z_2	$+$	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$+$	$+$	$+$	$-$	$-$	$-$	$+$

Table 2: PQ charges and Z_2 parities for Dirac neutrino case

Possible mixing between leptons by $H_d l_i e_4^c$ exist. We introduced Z_2 to protect mixings.

$$\mathcal{L}_{a,\text{eff}} = \sum_{i=1,2} \frac{c_i \alpha_i}{8\pi v_s} a F^i_{\mu\nu} \tilde{F}^{i\mu\nu} \longrightarrow c_1 : c_2 = 3, 1$$

Models with extra lepton

Model 2: vector-like doublet and PQ neutral singlet

$$-\mathcal{L} = \lambda_\chi S \chi \tilde{\chi} + \lambda_l S l_4 \tilde{l}_4 + m_e e_4^c \tilde{e}_4^c + y_l H_d l_4 e_4^c - \tilde{y}_l H_u \tilde{l}_4 \tilde{e}_4^c + \text{h.c.}$$

$$\mathcal{L}_{a,\text{eff}} = \sum_{i=1,2} \frac{c_i \alpha_i}{8\pi v_s} a F^i_{\mu\nu} \tilde{F}^{i\mu\nu} \longrightarrow c_1 : c_2 = 1, 1$$

Anomaly only comes from vector-like doublet lepton

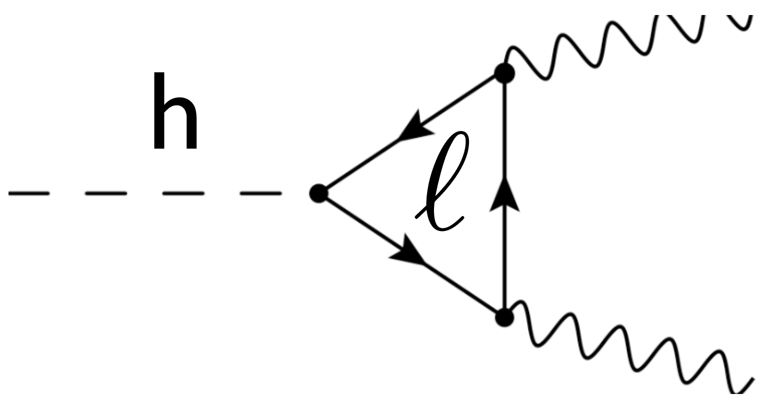
Model 3: vector-like doublet and triplet with PQ charge

$$-\mathcal{L}_{\text{Yukawa}} = \lambda_\chi S \chi \tilde{\chi} + \lambda_l S l_4 \tilde{l}_4 + \lambda_e S e_4^c \tilde{e}_4^c + y_l H_d l_4 T - \tilde{y}_l H_u \tilde{l}_4 T + \text{h.c.}$$

$$\mathcal{L}_{a,\text{eff}} = \sum_{i=1,2} \frac{c_i \alpha_i}{8\pi v_s} a F^i_{\mu\nu} \tilde{F}^{i\mu\nu} \longrightarrow c_1 : c_2 = 3, 1$$

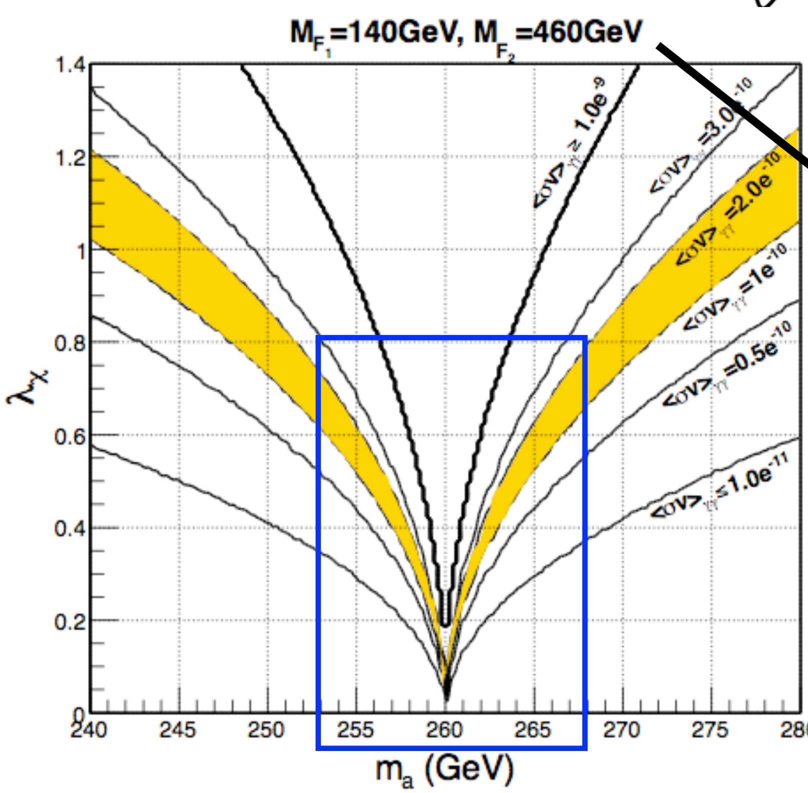
Link to higgs

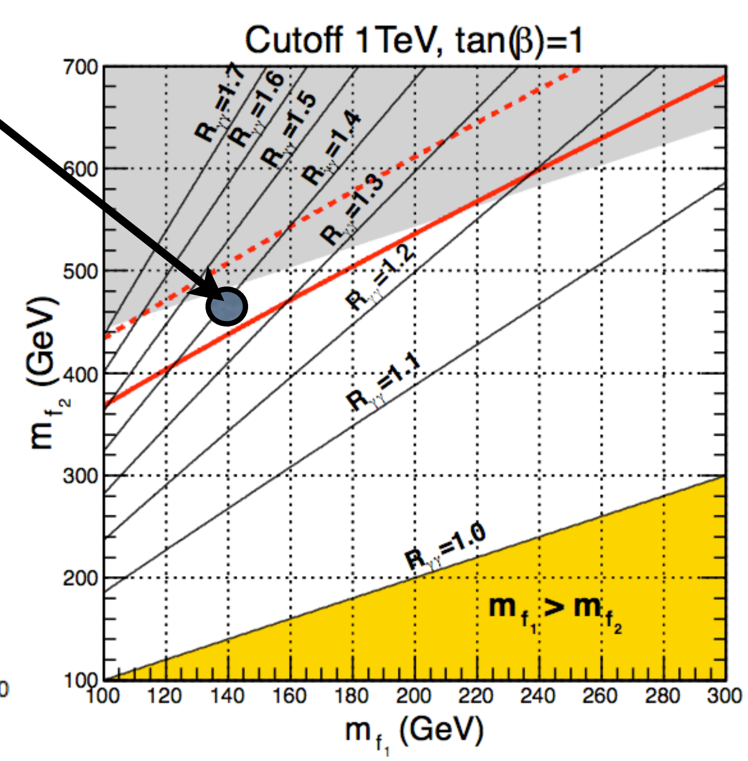
- New charged leptons are inside the higgs to two photon loop.



$$R_{\gamma\gamma} = \left|1 + y_f \frac{v}{m_f} \frac{A_f(\tau_f)}{A_V(\tau_W) + N_c Q_t^2 A_f(\tau_t)}\right|^2$$

is the ratio of the higgs to diphoton ratio compared to SM value





model I

Grey: vacuum metastability

Red: EWPD(1σ,2σ)

we see the resonant enhancement for the two photon production.

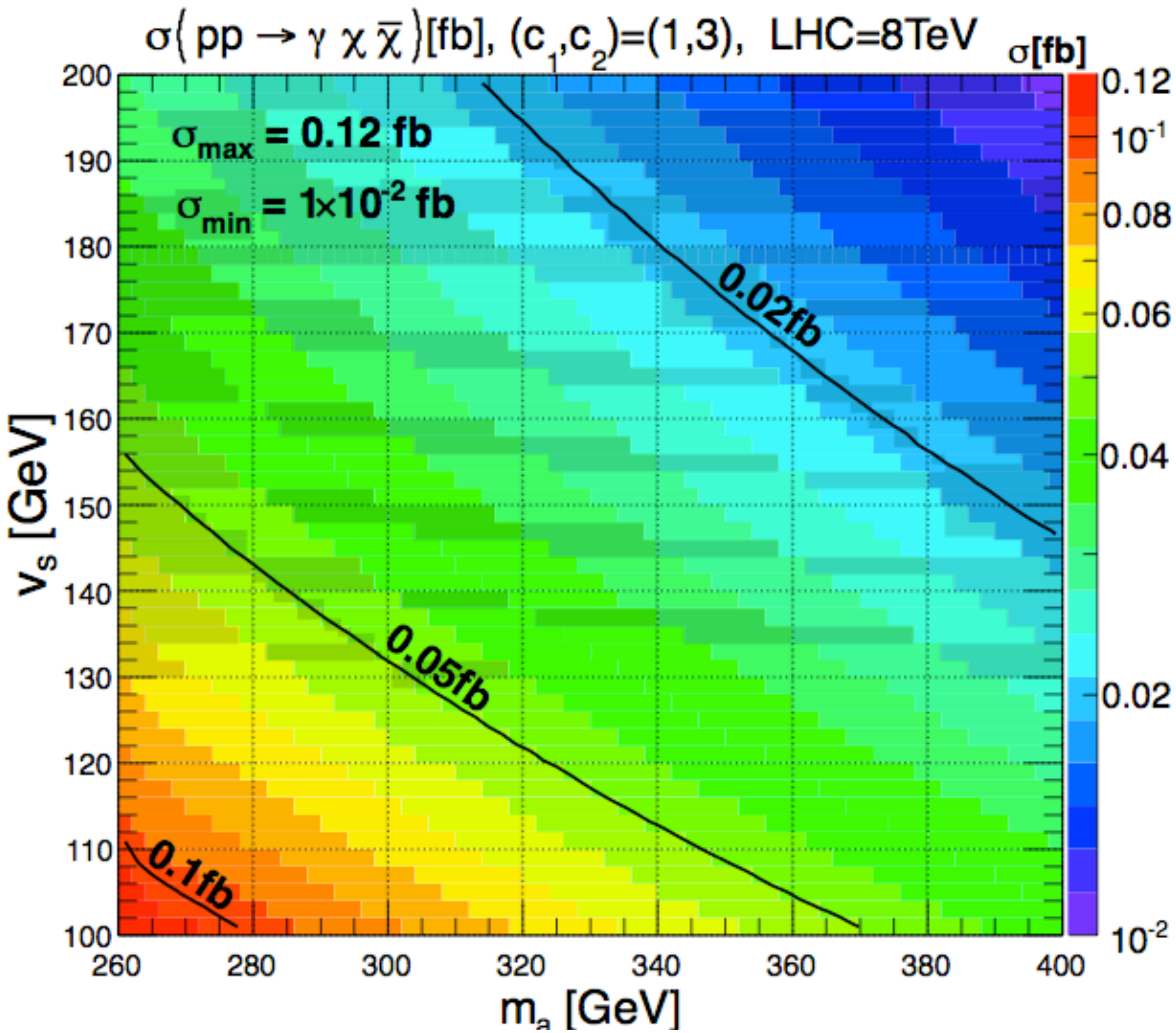
Summary of model prediction

	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 model (I, II) have larger higgs to two photon enhancement. But for the Fermi gamma ray, they require extra annihilation channels.
- Triplet model (III) does not require extra annihilation channels. It has smaller higgs to two phton enhancement compared to other models.

Conclusions

- We proposed a singlet fermion dark matter to explain recent Fermi LAT data.
- Extra vector-like leptons can explain Fermi LAT data and higgs to two photon enhancement.
- But we can not see the trace of axion at the LHC yet.



Thank you.

$$\mathcal{L}_{\text{axion}} = i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F^i_{\mu\nu}F^{i\mu\nu} + \frac{1}{\sqrt{2}}\lambda_\chi i a\,\bar{\chi}\gamma^5\chi + \sum_{i=1,2}\frac{c_i\alpha_i}{8\pi v_s}\,aF^i_{\mu\nu}\tilde{F}^{i\mu\nu}$$