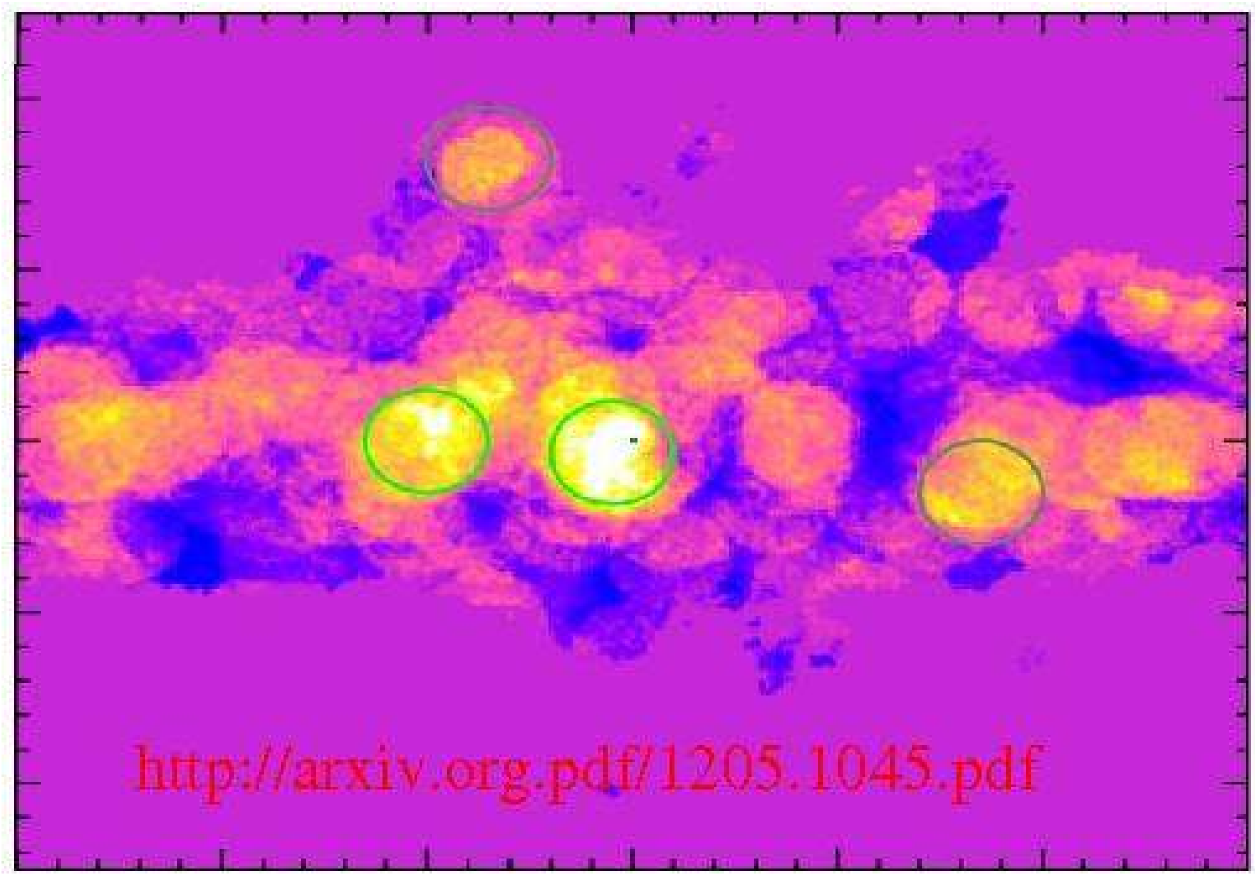
LHC constraints on dark matter with γ-ray lines or strong self-interactions



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TRIUMF, 9-11 Dec., 2013

Outline

- Hints of 130 GeV DM annihilating to $\gamma\gamma$ at the galactic center
- Challenges for model building, and two examples:
  JC, 1205.2688, loop-induced annihilation
  JC, A. Frey, G. Moore, 1208.2685, composite magnetic DM
- Constraints from LHC:
  JC, G. Dupuis, Z. Liu, 1306.3217
- Composite model of strongly interacting DM and the LHC
  JC, G. Moore, Z. Liu, W. Xue, 1312.xxxx

Part I: Hints of 130 GeV DM

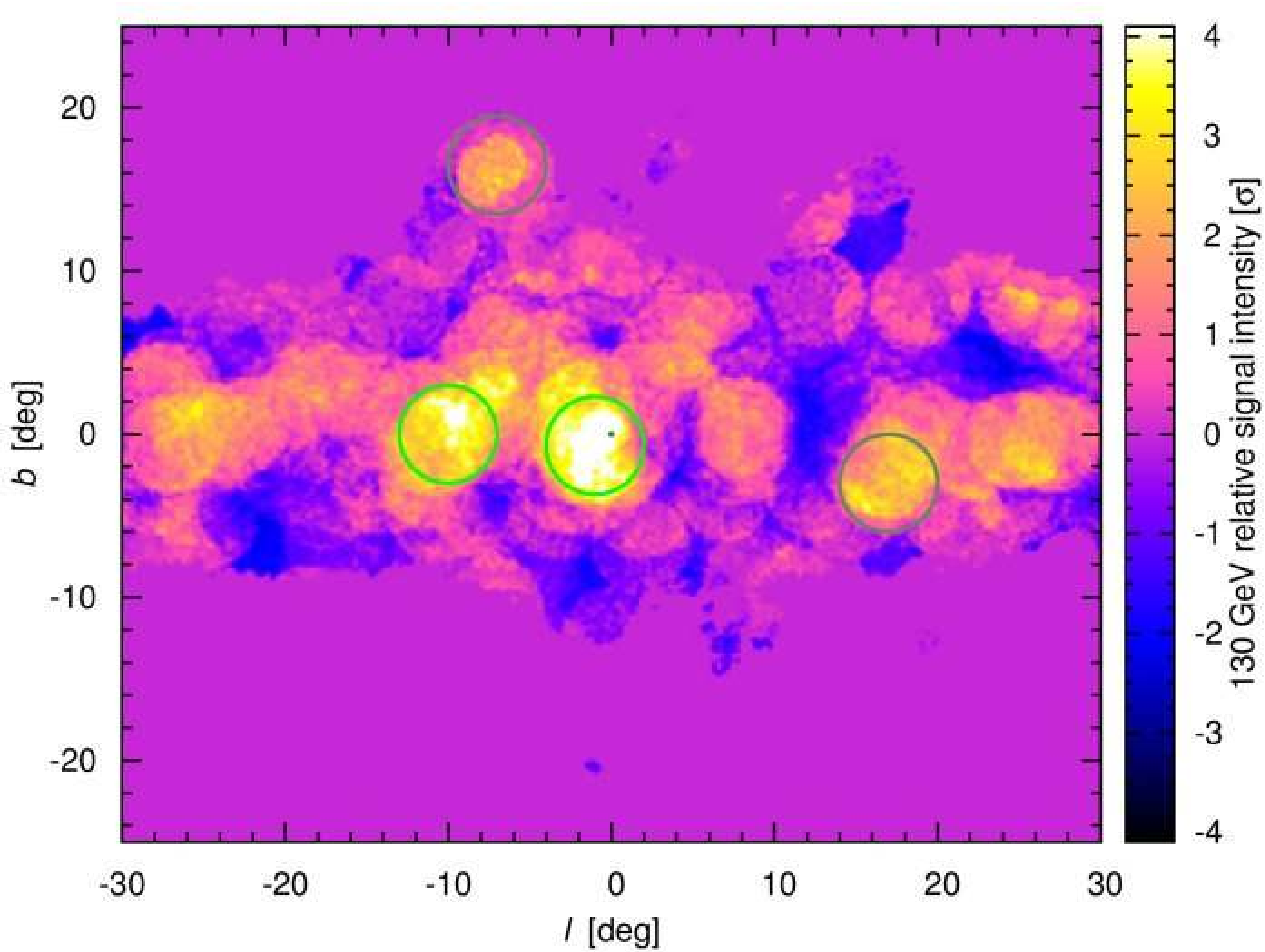
Evidence for 130 GeV DM

Hints were found of DM annihilations $\chi\chi \to \gamma\gamma$ at the galactic center from publicly available Fermi/LAT data (analyzed by theorists!):

Bringmann *et al.* 1203.1312	4.1σ (3.1σ)	galactic center
Weniger 1204.2797	4.6σ (3.3σ)	galactic center
Tempel *et al.* 1205.1045	4.5σ (4.0σ)	GC, line spect.
Su & Finkbeiner, 1206.1616	6.5σ (5.2σ)	GC, double line
Hektor *et al.* 1207.4466	(3.6σ)	galactic clusters
Su & Finkbeiner, 1207.7060	3.3σ	unassociated Fermi sources
Finkbeiner, *et al.* 1209.4562, Hektor *et al.* 1209.4548	argue against suspected instrumental background	

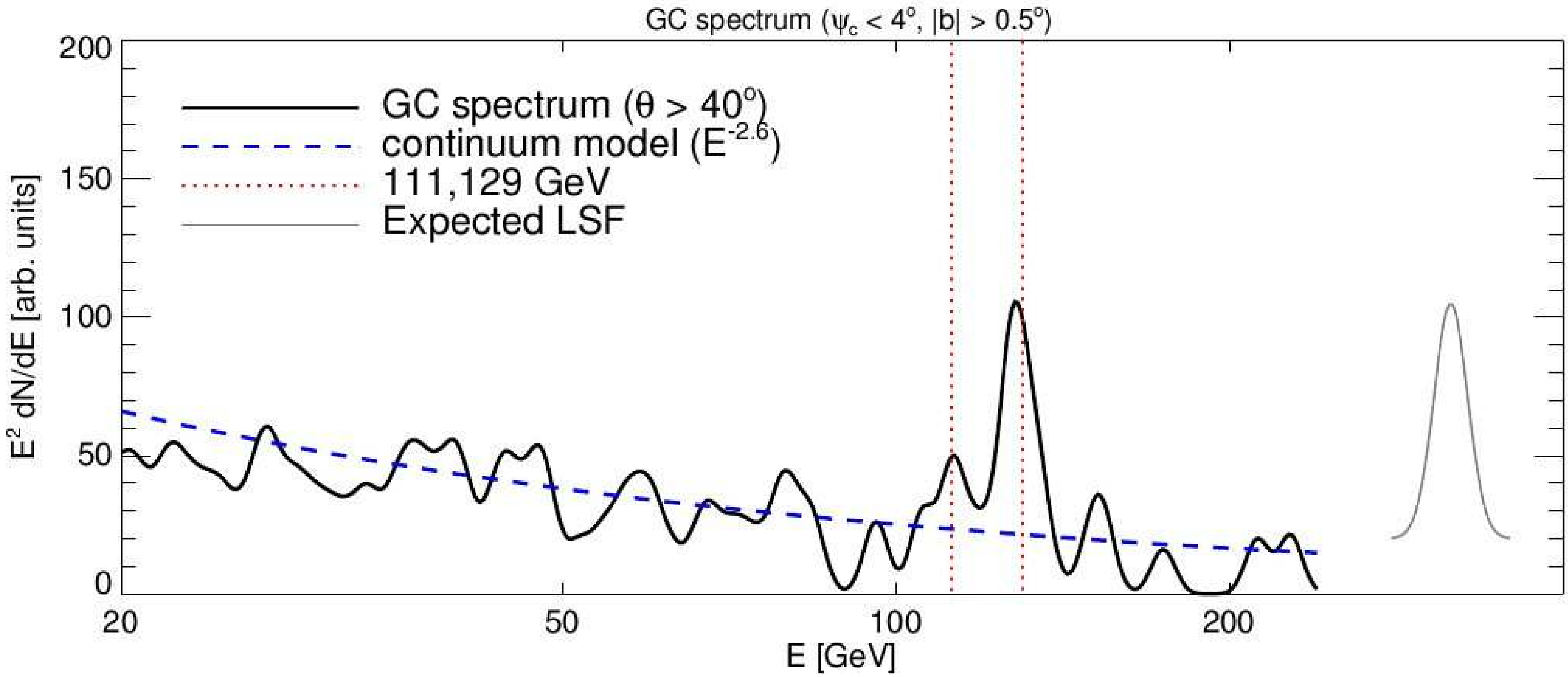
Morphology

Most significant signal is from galactic center.
Tempel, Raidal & Hektor 1205.1045:



Energy spectrum

From Su & Finkbeiner 1206.1616:



Smaller bump at 111 GeV consistent with $\chi\chi \to \gamma Z$ if $m_\chi \cong 130$ GeV.

This second line is expected in most models, including ours! (DM couples to hypercharge, not just electric charge)

Concerns with the DM interpretation

- Profumo, Linden 1204.6047 suggest astrophysical Fermi bubble source; disputed by others (Su, Finkbeiner 1206.1616)

- Boyarsky, Malyshev, Ruchayskiy 1205.4700 argue that spectral bumps can be found at other frequencies and locations;

- 130 GeV excess found in earth limb photons—detector noise contamination?

- Fermi collaboration finally does their own analysis (1305.5597), finding bump with smalller significance, 3.3σ (local), 1.5σ (global)

- Daniel Whiteson doesn't believe in it (1208.3677, 1302.0427)

On the other hand . . .

Fermi is changing its observing strategy to spend more time observing the galactic center, to settle the issue.

Perhaps H.E.S.S. II will beat them to it

Regardless of 130 GeV signal, DM models that produce gamma ray lines might be interesting in the future, so we keep an open mind

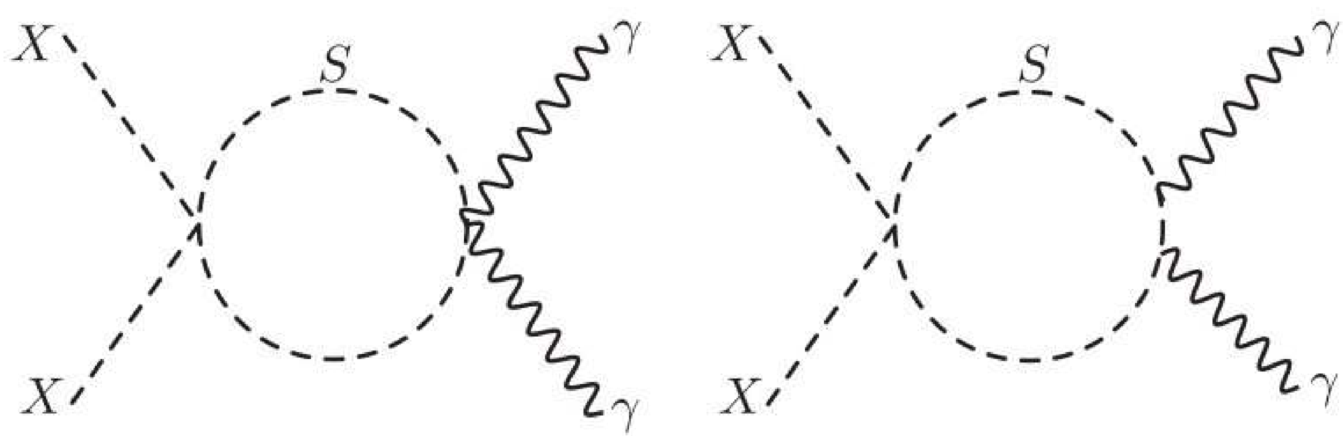
Part 2: Models of DM with γ ray lines

Challenges to model building

Generic (SUSY) dark matter models have much smaller $\sigma v(\chi\chi \to \gamma\gamma)$.

Constraints on $\chi\chi \to f\bar{f},\ WW,\ ZZ$ due to continuum photons from decays and inverse Compton ($f\gamma \to f\gamma$) Rules out neutralinos (Cohen *et al.,* 1207.0800, Buchmüller & Garny, 1206.7056)

Loop effect is generically too small to give big enough $\sigma v(\chi\chi \to \gamma\gamma)$

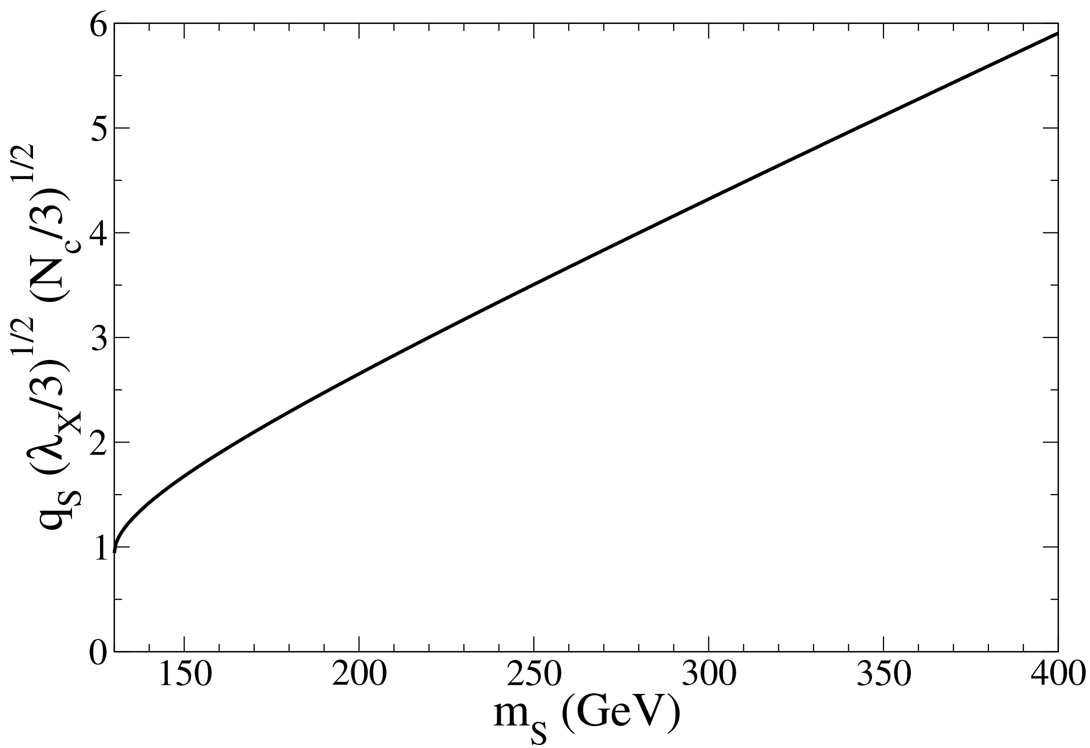


A loop model that works (Model 1)

JC, 1205.2688 proposed scalar DM X coupling to exotic charged ($q_S = 2$) and colored (under hidden SU(N)) scalar S:

$$\mathcal{L}_{\rm int} = \frac{\lambda_X}{2} X^2\,|S|^2 + \lambda_{hS}|H|^2\,|S|^2 + \frac{\lambda_{hX}}{2}|H|^2\,X^2$$

Loop (rate) is enhanced by $q_S^4 N_c^2 = 144$ for $N_c = 3$.



Relation between $q_S\sqrt{\lambda_X N_c}$ and m_S to get observed $\sigma v(\chi\chi\to\gamma\gamma)$.

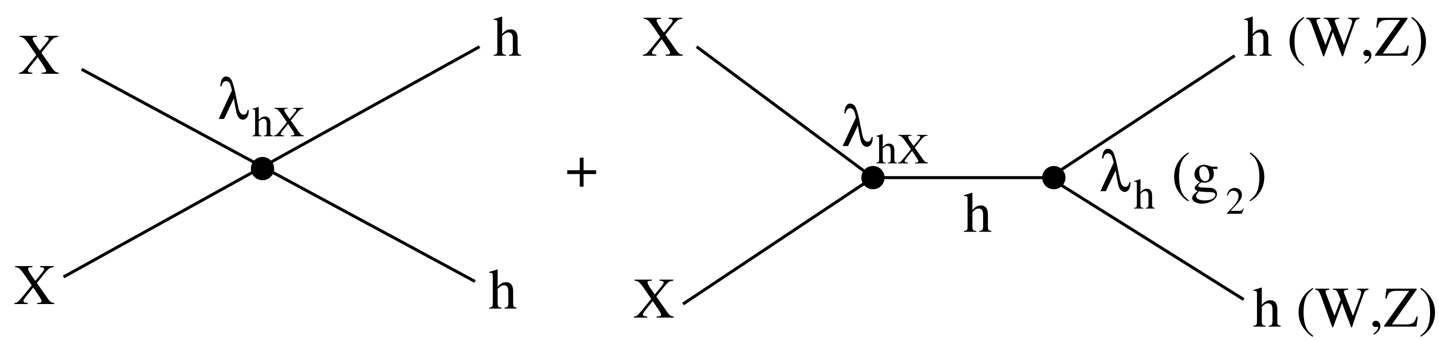
Need $m_S \gtrsim 130$ GeV, $q_S \sim 2$ for $\lambda_X \sim 1$

Relic density (loop model)

The λ_{hX} coupling can control the relic density of X,

$$\mathcal{L}_{\rm int} = \frac{\lambda_X}{2} X^2 \, |S|^2 + \lambda_{hS} |H|^2 \, |S|^2 + \frac{\lambda_{hX}}{2} |H|^2 \, X^2$$

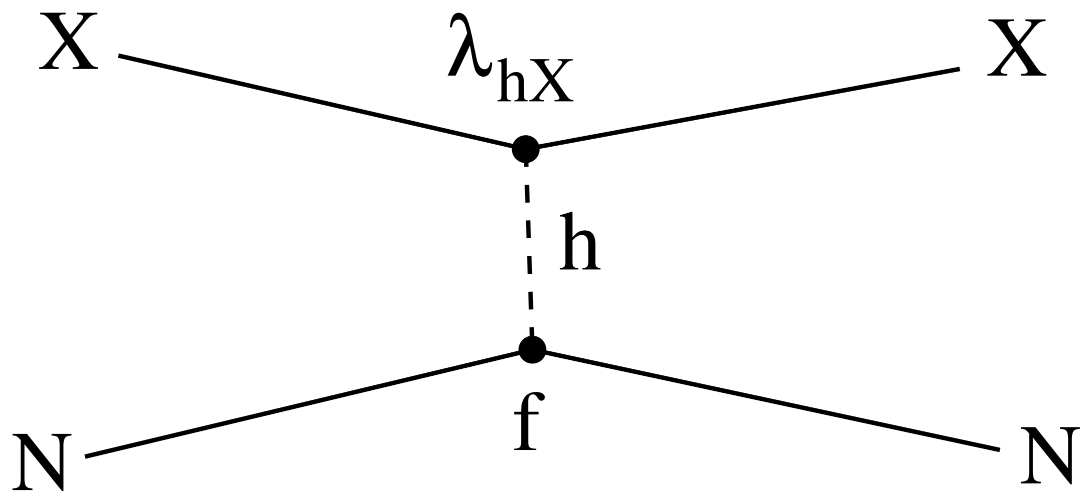
through the annihilations $XX \to hh$, WW, ZZ,



Gives right relic density if $\lambda_{hX} = 0.05$ (or less if $XX \to gg$ is important, but dark glueballs may be heavier than X).

Direct detection (loop model)

Same coupling λ_{hX} controls rate of X interaction with nucleons in direct detection experiments



($f \cong 0.32^{+0.31}_{-0.06}$ from lattice, sum rules, χPT $\ldots$)

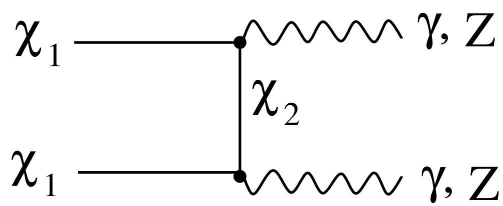
Using $\lambda_{hX} = 0.05$, Cross section for XN scattering is $1.5\times$ lower than current LUX limit

Should be discovered by improved xenon experiments

Model 2: Magnetic dark matter

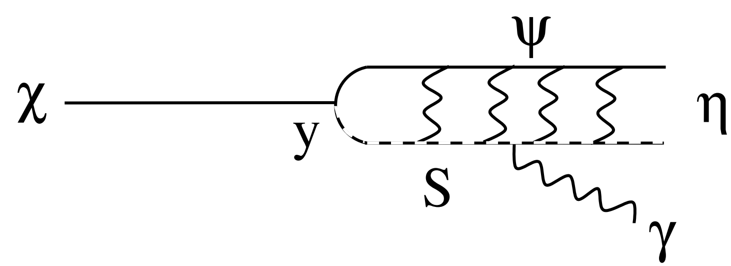
JC, Frey, Moore 1208.2685; see also Weiner, Yavin 1206.2910, 1209.1093

DM with large magnetic moment could explain Fermi line



Model is simple: new SU(2) confining gauge interaction, "quark" ψ, "squark" S, Majorana particle χ

DM is mixture of χ and ψS bound state; Dirac ψS state splits into two Majorana states $\chi_{1,2}$



Transition magnetic moment connects DM ground state and first excited state, $\mu_{12}\left(\bar{\chi}_1\sigma_{\mu\nu}\chi_2\right)F^{\mu\nu}$

Compositeness gives large $\mu_{12}\sim e/m_\psi$

Particle content of magnetic model

		state	spin	$SU(2)_g$	$U(1)_y$	$U(1)_{em}$	Z_4	constituents	
Elementary Constituents	Majorana state	χ	$\frac{1}{2}$	1	0	0	-1	-	
	"quark"	ψ_a	$\frac{1}{2}$	$\overline{2}$	-1	$-\frac{1}{2}$	i	-	
	"squark"	S^a	0	2	1	$\frac{1}{2}$	i	-	
Bound States	"mesons"	η	$\frac{1}{2}$	1	0	0	-1	$S\psi$	fermion
		$\tilde{\eta}_S$	0	1	0	0	1	S^*S	boson
		$\tilde{\eta}_\psi$	0	1	0	0	1	$\bar{\psi}\psi$	boson
	"baryons"	N^-	$\frac{1}{2}$	1	-2	-1	1	$S^*\psi$	fermion
		$\tilde{N}_\mu^+$	0	1	2	1	-1	SS	boson
		$\tilde{N}_\psi^-$	0	1	-2	-1	-1	$\psi\psi$	boson

Dark matter states $\chi_{1,2,3}$ are admixtures of χ, η, η^c

$$V = \frac{1}{2} m_\chi \bar{\chi}\chi + m_\psi \bar{\psi}\psi + m_S^2 |S|^2 + \lambda |S|^4$$
$$+ \underbrace{\bar{\chi} S^a (y + i y_5 \gamma_5) \psi_a}_{\chi-\eta \text{ mixing}} + \underbrace{y' \epsilon_{ab} S_a^* \bar{e}_R \psi_b}_{\text{charged relic decay}} + \text{h.c.}$$

parity ($\to y_5\gamma_5$)

Relic density (magnetic model)

Considering only magnetic moment coupling, annihilation diagrams are

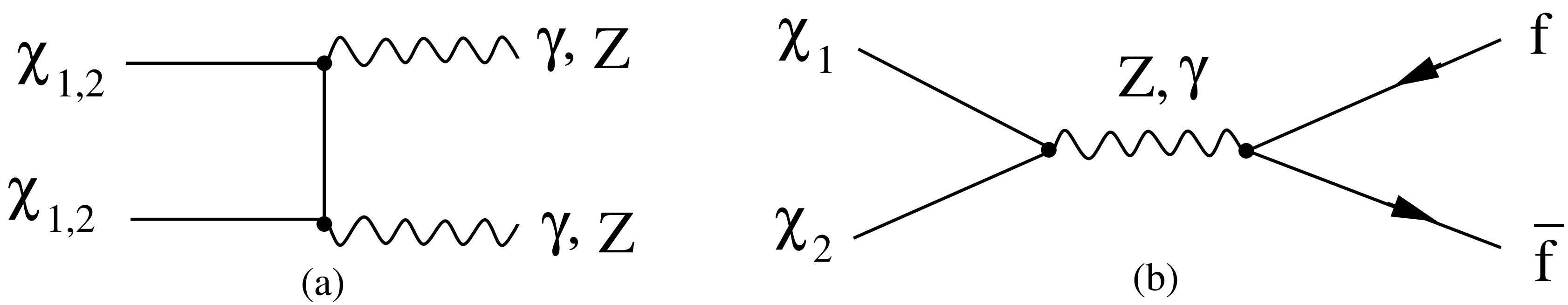


Diagram (b) suppresses relic density too much, unless $m_{\chi_2} - m_{\chi_1} \gtrsim 10$ GeV. (Then $\chi_2 \to \chi_1 \gamma$ gets rid of χ_2.)

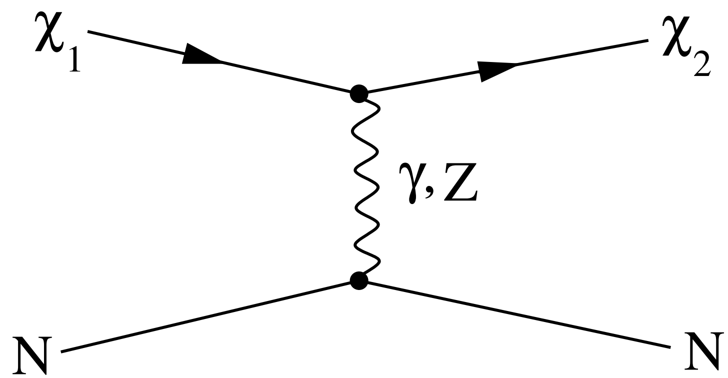
If magnetic moment $\mu_{12} \cong 2$ TeV^{-1}, relic density n_χ is $\sim 10\times$ smaller than normal, but predicted γ ray signal is still big enough:

$$2\gamma \text{ rate } \sim n_\chi^2 \, \mu_{12}^4$$

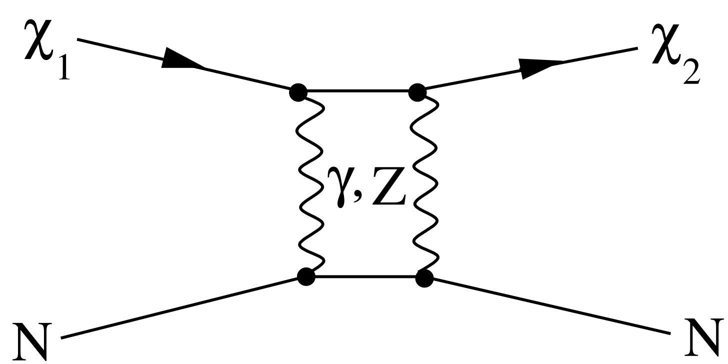
χ_1 is subdominant component of dark matter

Direct detection (magnetic model)

Because of large mass splitting $m_{\chi_2} - m_{\chi_1} \gtrsim 10$ GeV, there is no direct detection signal at tree level:



χ_1 does not have enough energy to produce χ_2.
Can have loop-induced interaction



Part 3: LHC Constraints on DM with lines

What to look for

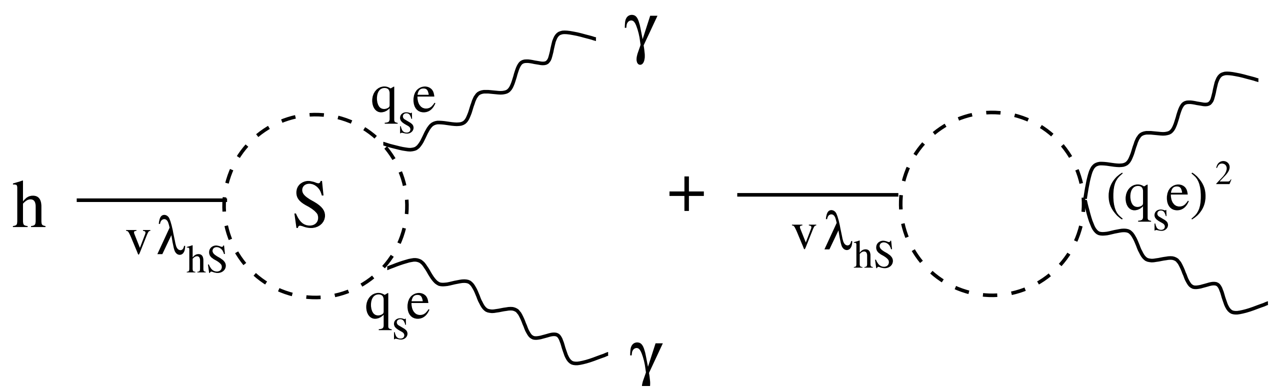
an array of exotic signals ...

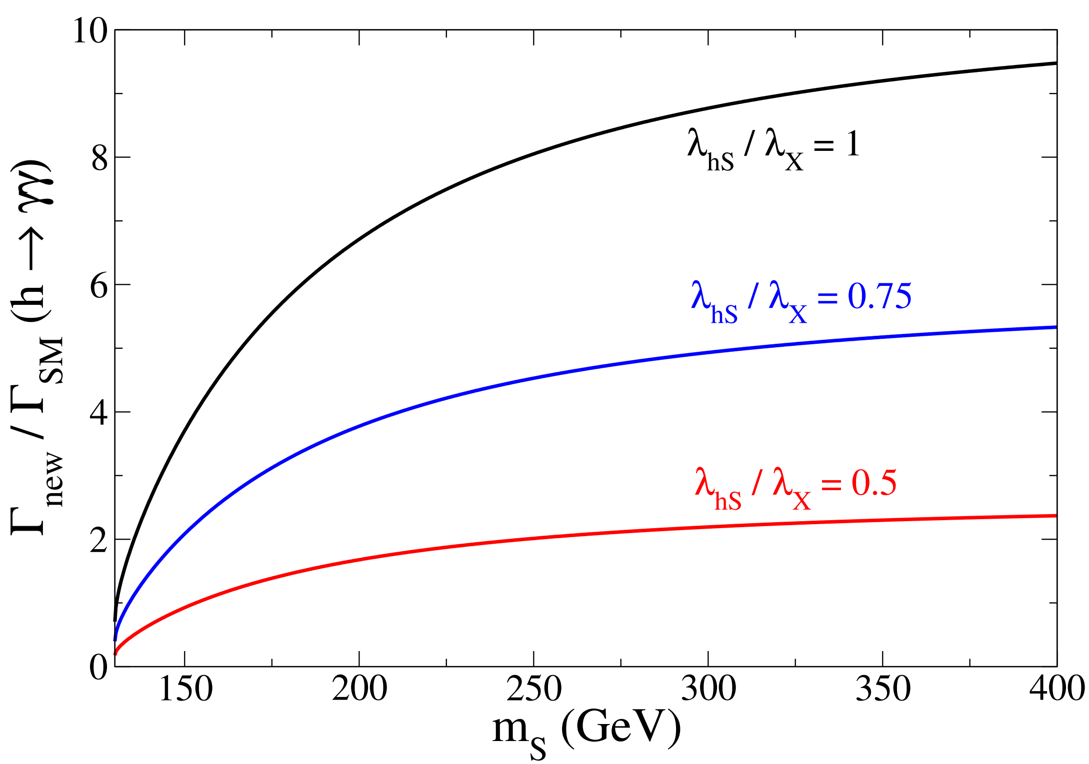
- $H \to 2\gamma$ enhancement
- Same-sign dileptons
- Resonant “vector meson” production, decay into leptons
- Excited e, μ imposters (charged mesons), $e^*, \mu^* \to e, \mu + \gamma$
- Photon pairs from neutral meson decays, 4-photon events
- monophotons

vector mesons give strongest constraint

Higgs to $\gamma\gamma$ enhancement (loop model)

In loop model, similar diagrams as for $XX \to \gamma\gamma$ contribute to $h \to \gamma\gamma$:

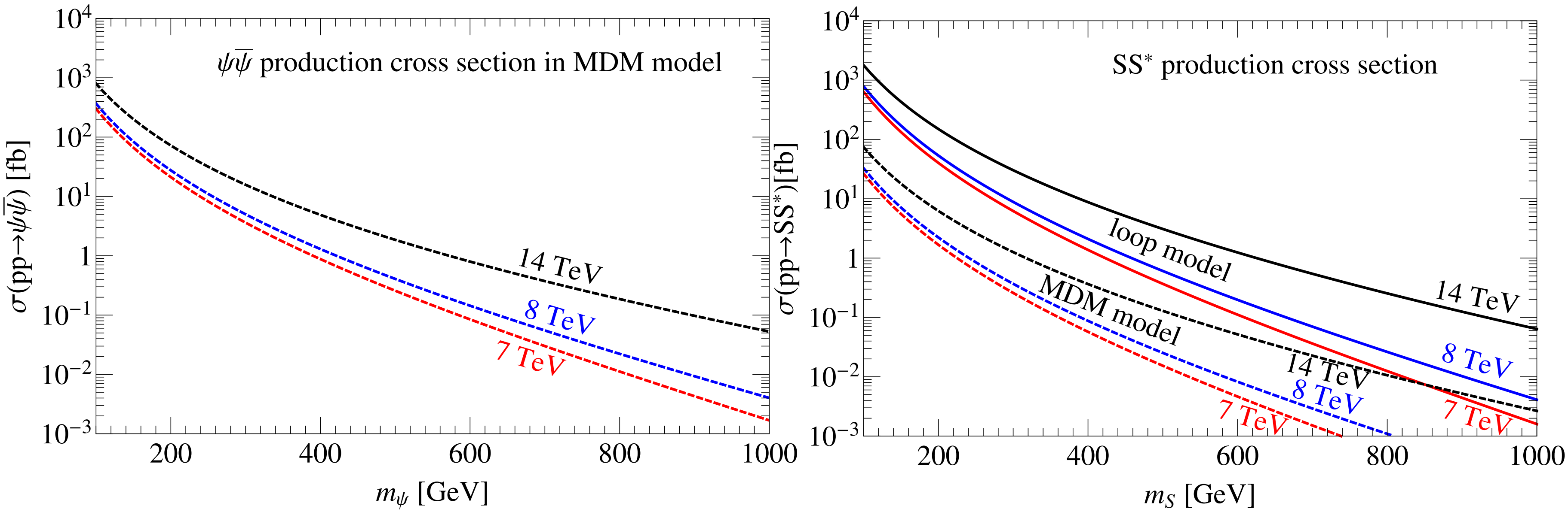




Enhancement depends on m_S and on ratio of couplings λ_{hS}/λ_X (in $\lambda_{hS}h^2|S|^2 + \lambda_X X^2|S|^2$)

Charged particles via Drell-Yan

$$pp \to \psi\bar{\psi} \text{ or SS}^*$$



But ψ and S are strongly interacting—they "hadronize" in the dark SU(N)

This makes them harder to discover!

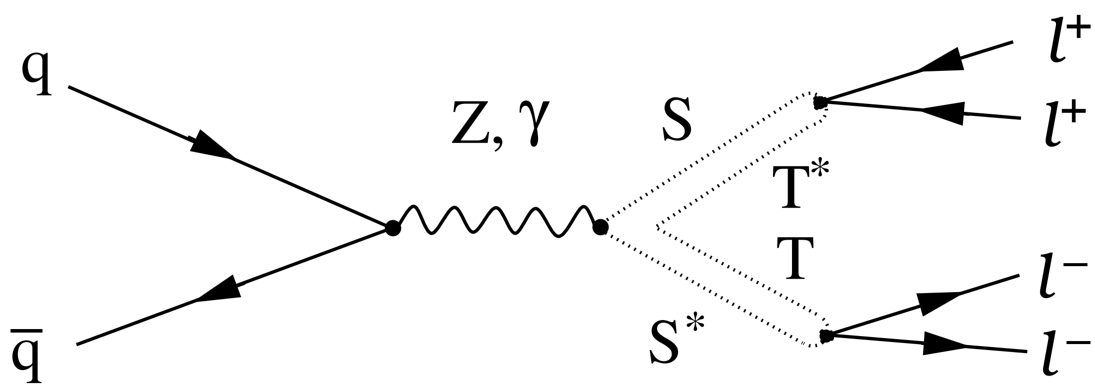
Like-sign lepton signal (loop model)

Charge ± 2 states S must not be stable—stringent constraints on charged relics.

Introduce neutral fundamental scalar T to allow $S \to T l^+ l^+$ through dimension-5 interaction

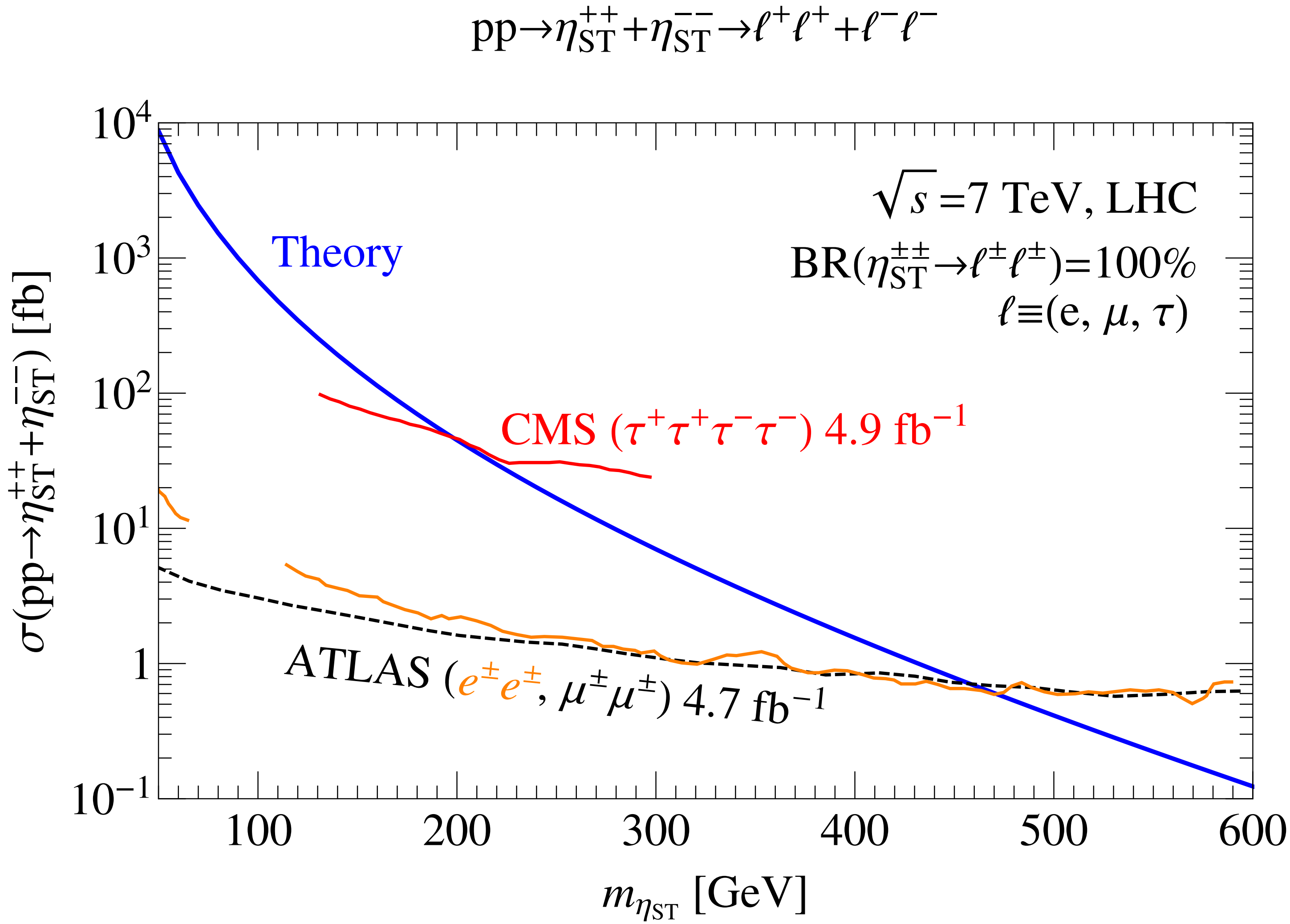
$$\Lambda^{-1}\, T^* S\, \bar{l}^c l$$

Then ST^* bound state decays into like-sign leptons.



If $l = e$ or μ, this is constrained by recent CMS (1207.2666) and ATLAS (1210.5070) analyses

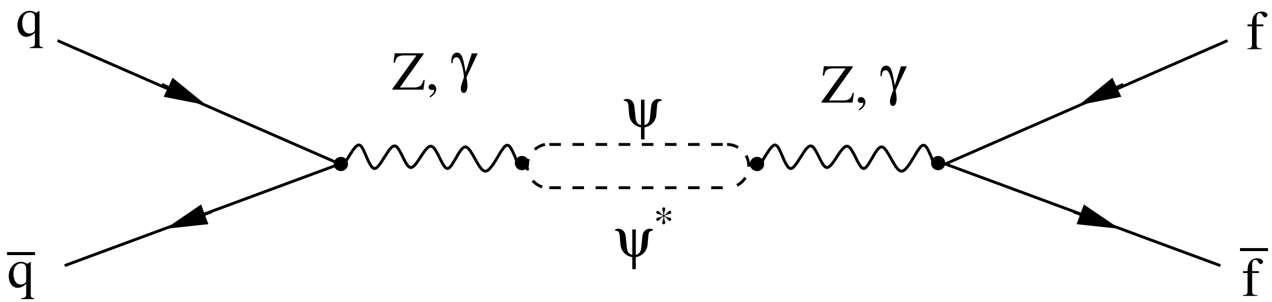
Like-sign lepton constraints



Charge-2 meson η_{ST} must be heavier than $470\ \mathrm{GeV}$ ($210\ \mathrm{GeV}$) if it decays into e, μ (τ).

Vector meson production

Spin-1 meson ϕ_ψ analogous to J/ψ:



Production depends on wave function at origin,

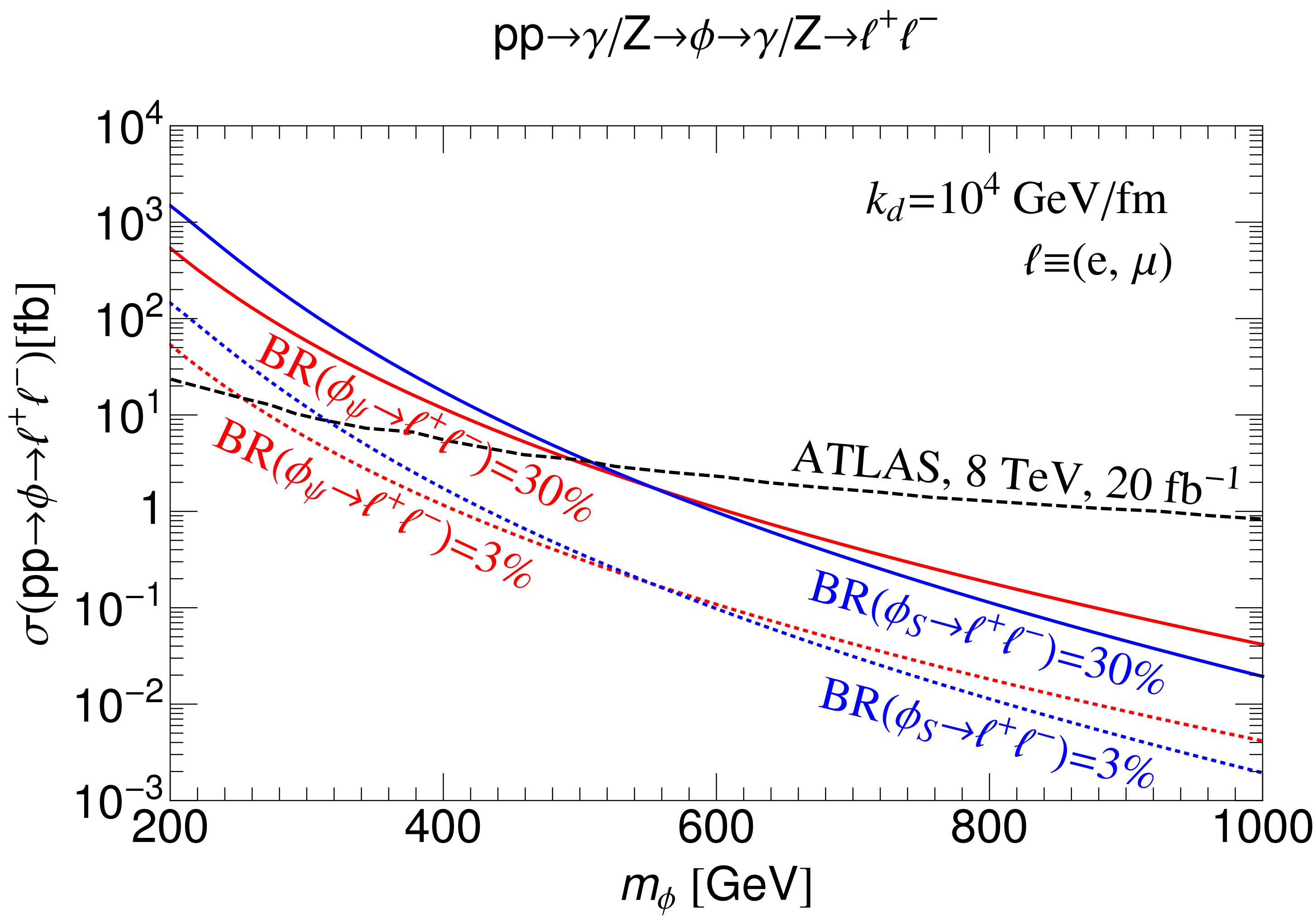
$$|\psi(0)|^2 \sim m_\psi k_d$$

where k_d is string tension of dark SU(N).

Vector meson $\phi_S = SS^*$ has $\ell = 1$, so $\psi(0) = 0$; production goes like $|\vec{\nabla}\psi(0)|^2$

Vector meson constraints

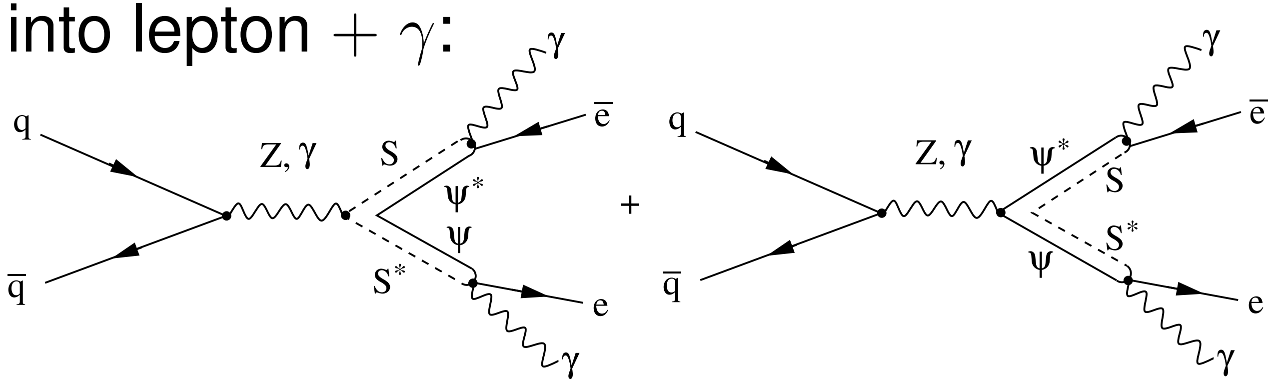
Constraints depend on BR($\phi \to e^+e^-$ or $\mu^+\mu^-$) and k_d



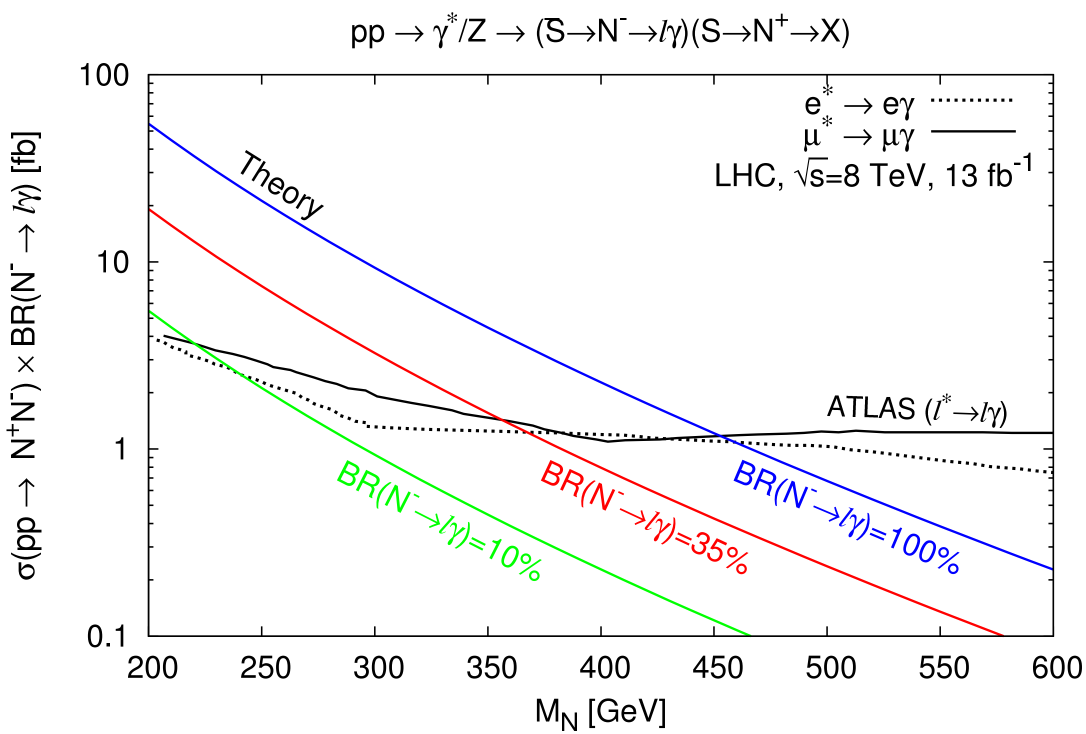
Bound on meson mass is $m_\phi \gtrsim 250 - 500$ GeV

Excited electrons and muons

Singly charged mesons $S^*\psi = N^-$ in magnetic DM model have same quantum numbers as charged leptons; they decay into lepton $+\ \gamma$:



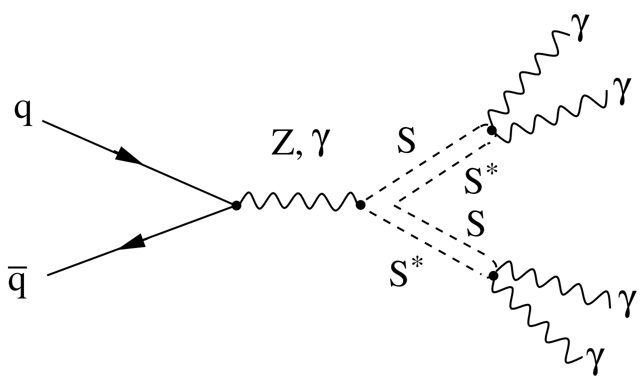
(recall $y' S^* \bar{e} \psi$ interaction to avoid charged relics)



Limits depend on BR$(N^- \to e/\mu + \gamma)$.

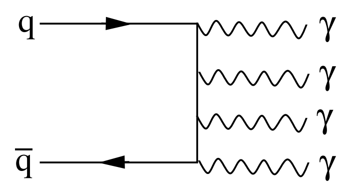
Decays to τ are less constrained

Diphotons (from 4-photon events)

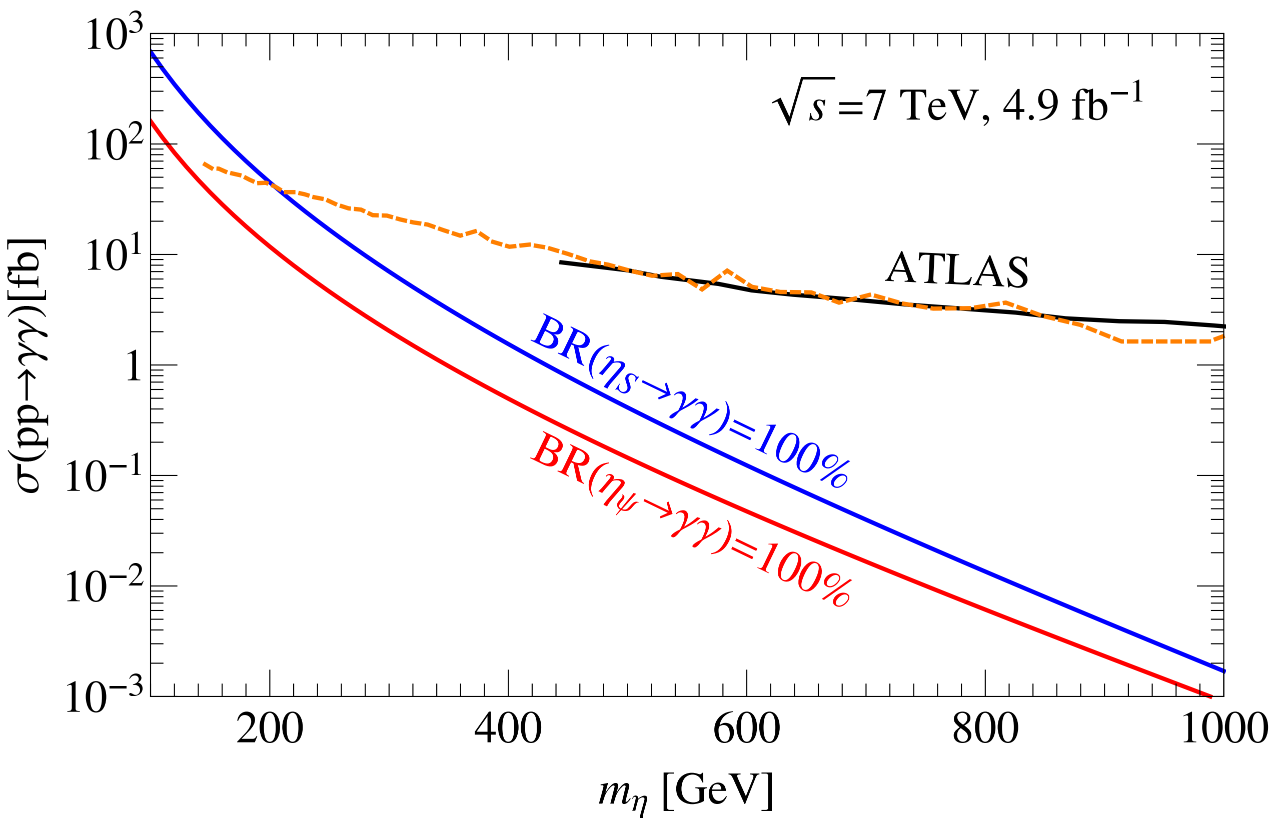


$pp \to \eta\eta \to \gamma\gamma + X$

From production of η meson pairs;
SM background due to



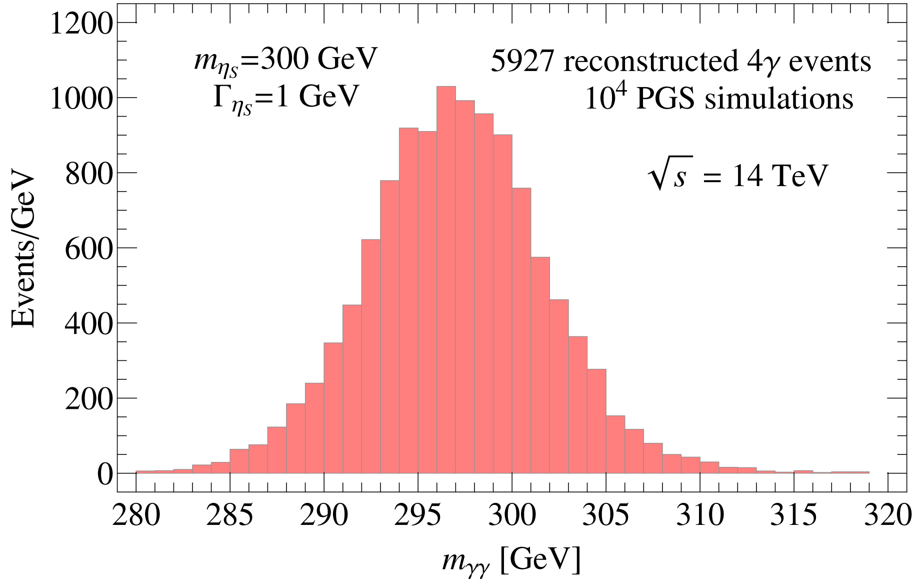
is very small



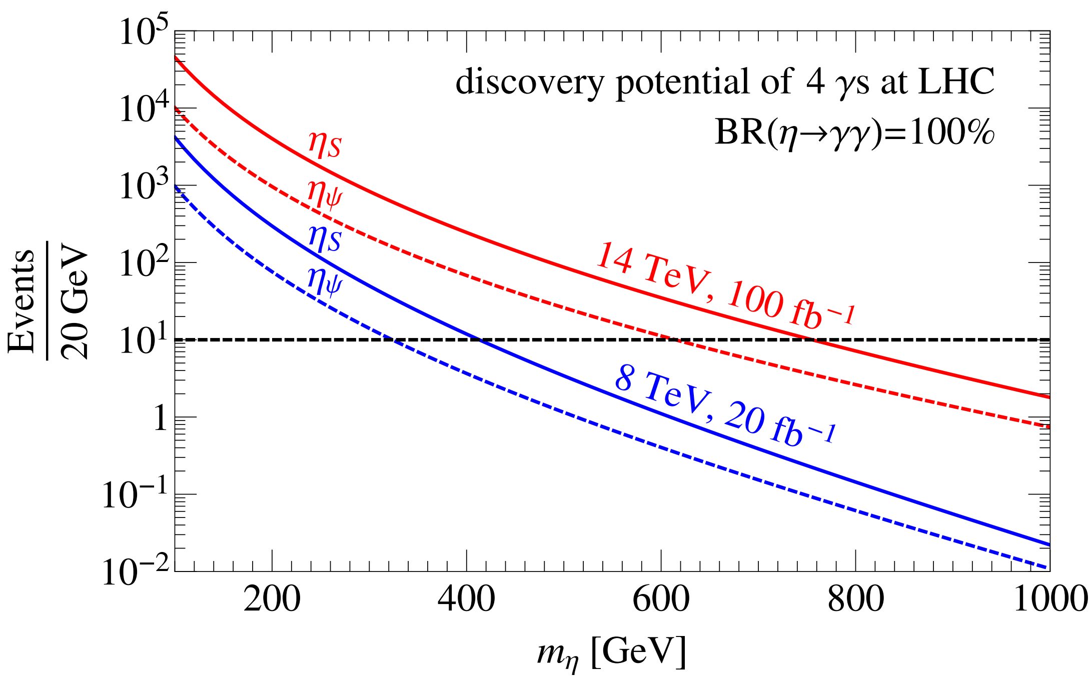
Our limits on $\eta \to \gamma\gamma$ decays from ATLAS diphoton search:

$m_\eta \gtrsim 200$ GeV

4-photon events



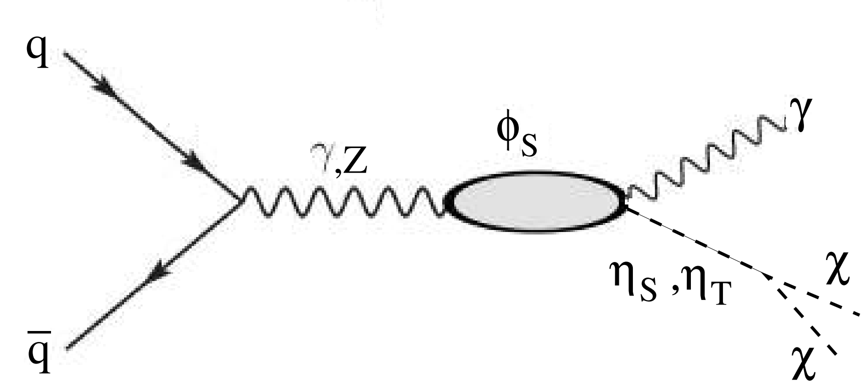
Reconstructed events for $m_{\eta_S} = 300$ GeV, $\Gamma = 1$ GeV, $\sqrt{s} = 14$ TeV

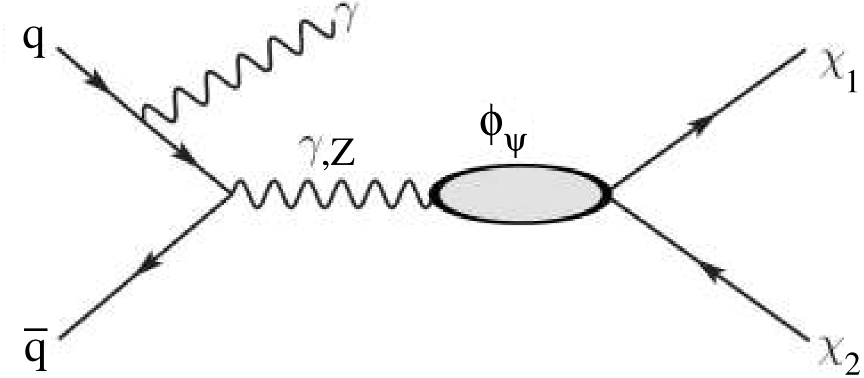


Discovery potential for 4-γ signal after upgrade of beam

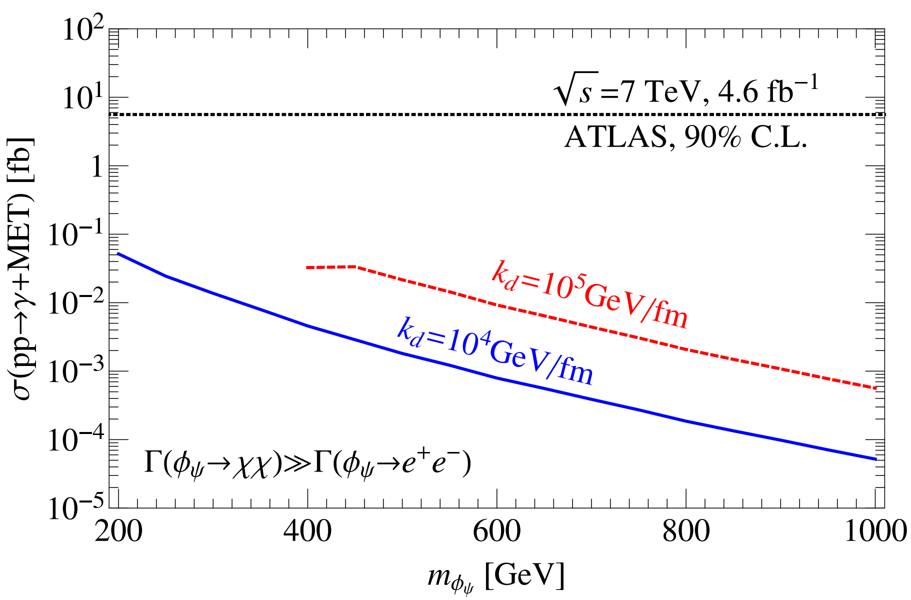
Monophotons

From vector meson production/decay:

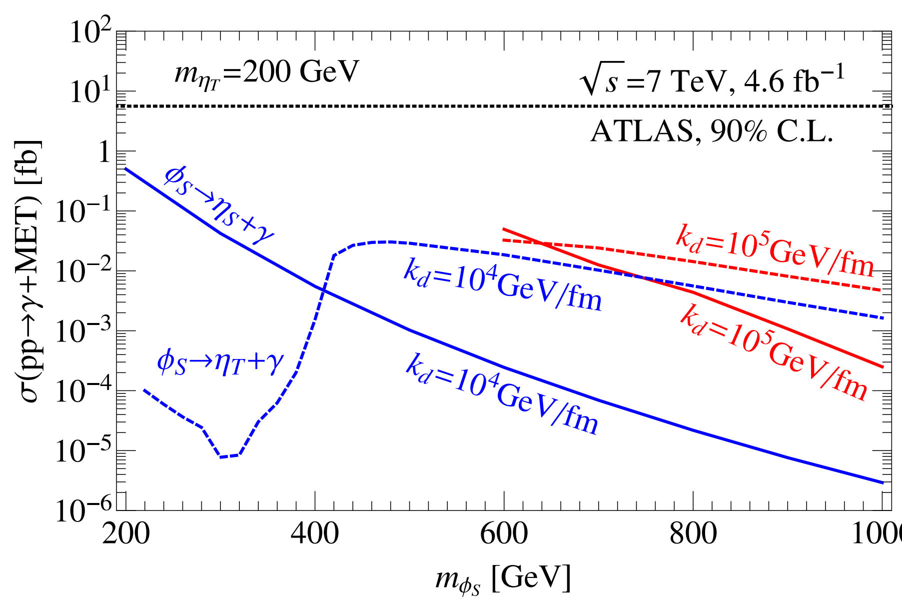




Predicted signals are far below current constraints:



Loop model



Magnetic DM model

Summary of LHC constraints

LHC Observable	Constraint (loop model)	Constraint (MD model)
$h \to \gamma\gamma$	$\lambda_h/\lambda_X < 0.25$	–
same-sign dileptons	BR($\eta_{ST} \to ee, \mu\mu) \ll 1$ or $m_{\eta_{ST}} > 200$ GeV	–
vector meson production	$m_{\phi_S} > 310$ GeV $\Lambda_d >$ few $\times\, m_S$	$m_{\phi_\psi} > 250$ GeV $\Lambda_d \gtrsim 300$ GeV
excited lepton searches	–	$m_N > 370$ GeV
diphoton production	$m_{\eta_S} > 220$ GeV	$m_{\eta_\psi} > 140$ GeV
4-photon events (14 TeV, 100 fb^{-1})	$m_{\eta_S} > 750$ GeV	$m_{\eta_\psi} > 600$ GeV
monophotons	–	–

Summary of LHC constraints for 130 GeV dark matter. 4-photon constraints based on the ultimate reach of LHC.

Part 4:

Strongly Interacting Dark Matter @ LHC

Hints for DM self-interactions

DM with elastic self-interaction

$$\sigma/m \cong 0.6\ \mathrm{cm}^2/\mathrm{g}$$

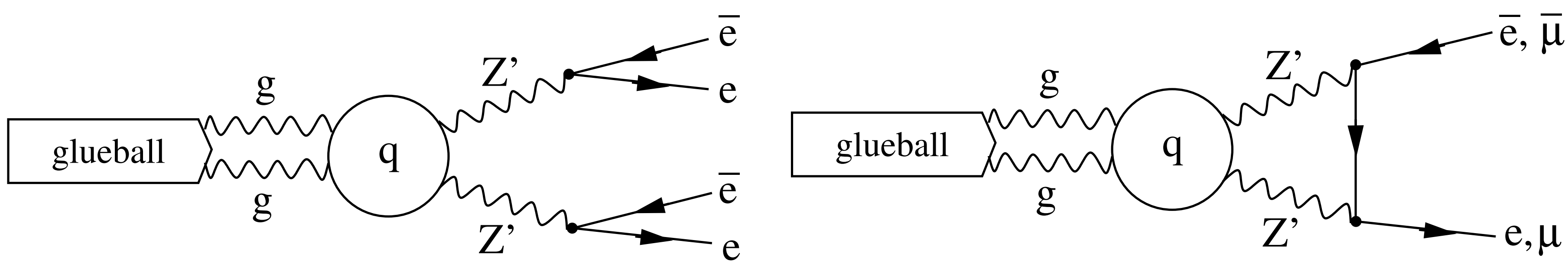
can help resolve some problems of structure formation:

- Predicted halo profiles more cuspy than observed
- Too many large satellite galaxies predicted by simulations
- JC, Moore, Liu, Xue 1312.xxxx study composite DM models that naturally have large σ
- Dark glueballs with $m \cong 500$ MeV have right σ/m
- Can have associated LHC signal

Dark glueballs interacting with Z'

If dark sector has SU(N) with only heavy quarks, glueballs can be dark matter

Assume quarks have U(1)$'$ with Z' that couples to leptons; then glueballs are metastable:

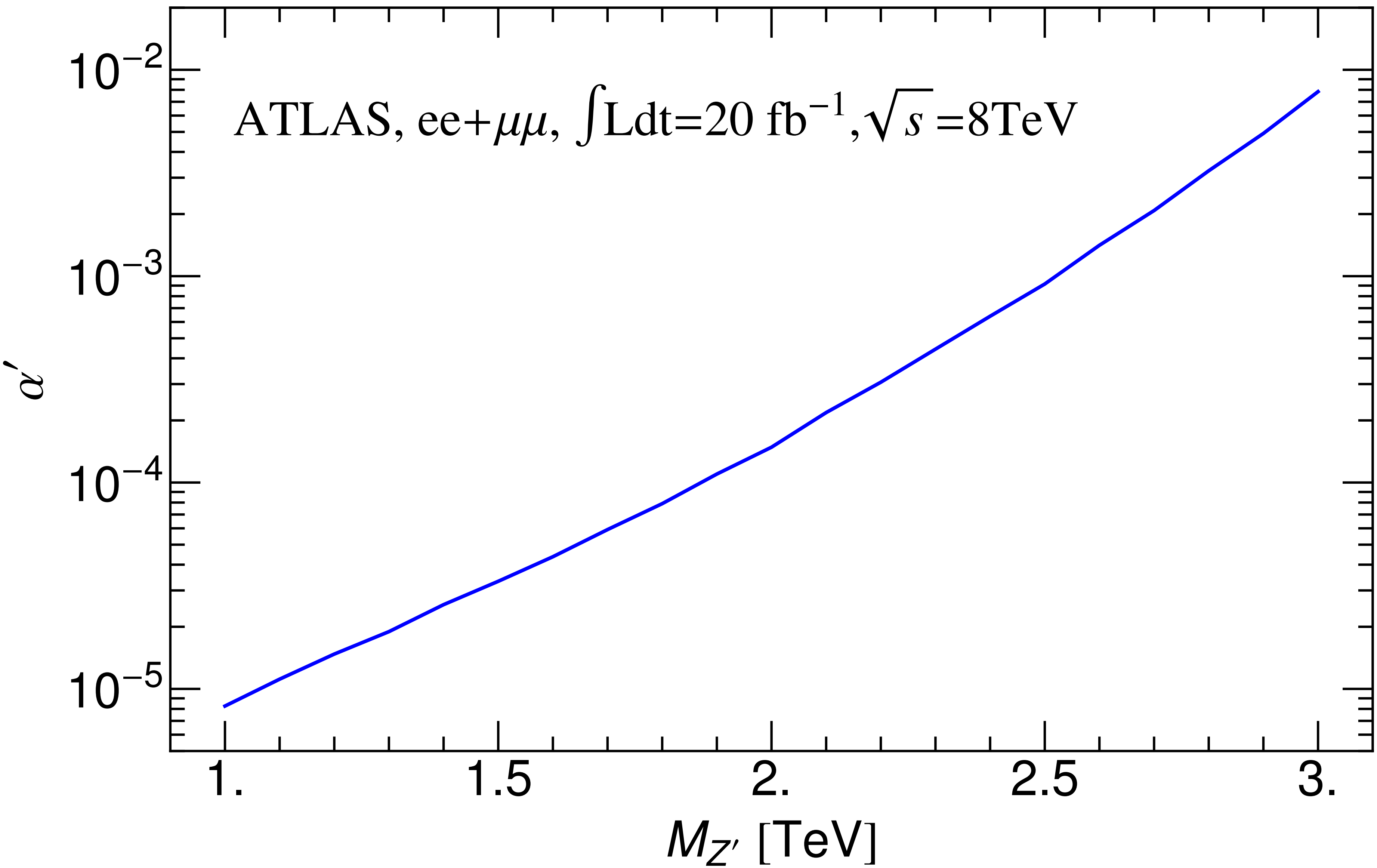


CMB constrains $m_{Z'}$ (lifetime $> 4 \times 10^{24}\,\mathrm{s}$):

$$m_{Z'} \gtrsim 2.3\ \mathrm{TeV} \left(\frac{\alpha'^2 \alpha_N}{10^{-5}}\right)^{1/4} \begin{cases} x^{-1}, & x < 1 \\ 1, & x > 1 \end{cases}$$

where $x = m_q / 700\ \mathrm{MeV}$.

ATLAS constrains α' via dileptons

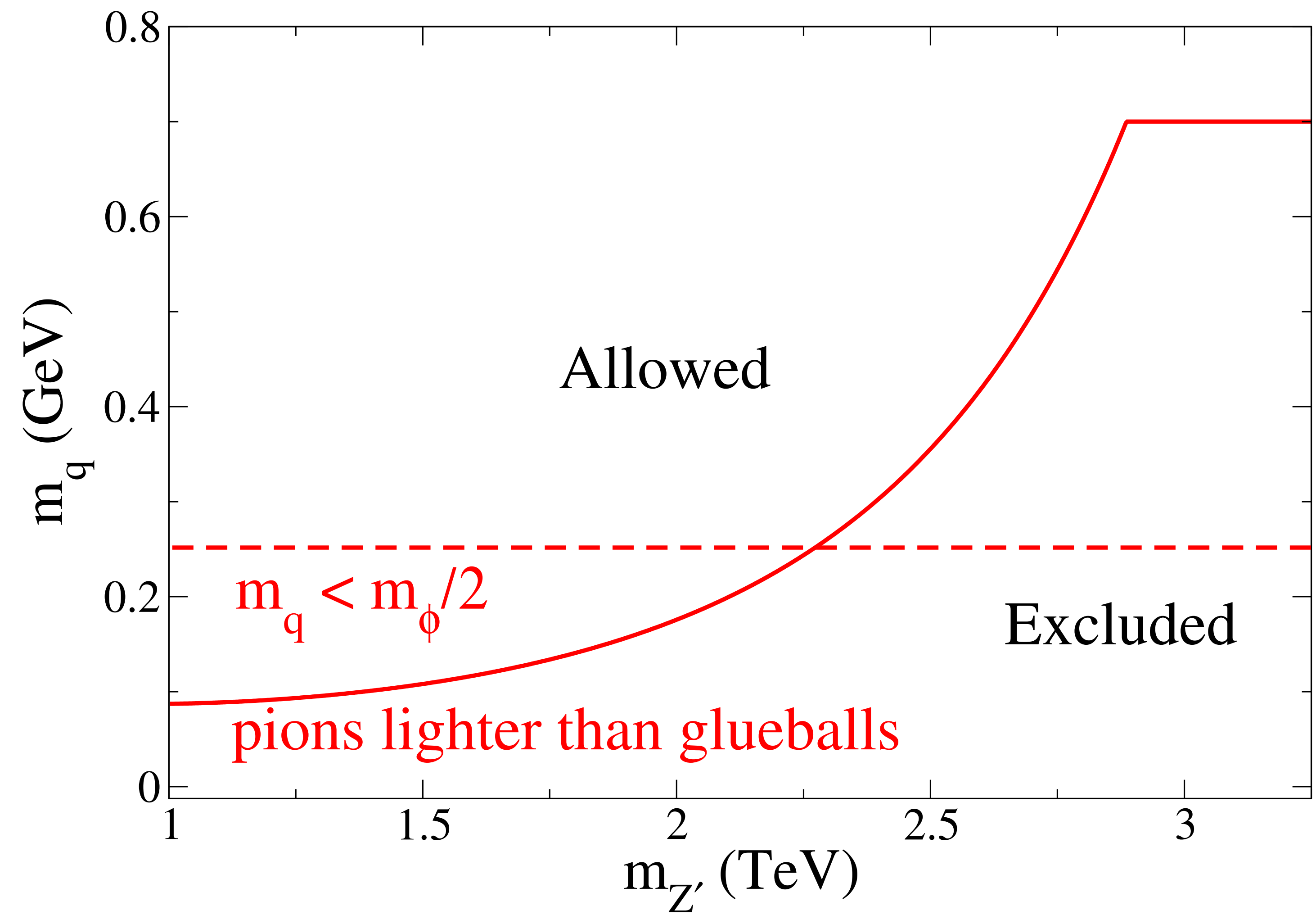


(assuming same Z' coupling to leptons and dark quarks)

Combining ATLAS + CMB constraints

If m_q is not far above dark confinement scale, LHC and CMB have comparable sensitivity;

CMB bound assuming ATLAS constraint on α' is saturated:



Conclusions

- Secret theme of this talk: dark sector with confining SU(N) – why not? We have SU(3) in visible sector.
- Compositeness/strong dynamics can help to produce large DM annihilation cross section into photons
- 130 GeV DM will be definitively probed in coming year or two. Maybe γ-ray lines at other energies will be found?
- Confinement makes relatively light charged particles harder to find at LHC than otherwise
- Resonant production of vector "mesons" is the most sensitive probe, but several other exotic signals predicted
- Dark glueball DM might be indirectly probed at LHC through discovery of Z' with enhanced invisible width (from decays into dark quarks).

extra slides

$\chi\chi \to \gamma\gamma$ cross section in loop model

It was shown that a cross section for $\chi\chi \to \gamma\gamma$ consistent with the value determined in ref. [2] for 130 GeV dark matter could be obtained for parameter values $q_s = 2$, $\lambda_{s\chi} = 3$, $N_c = 3$, $m_s = 170$ GeV, for example. More generally, one can express the cross section $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ in terms of the mass ratio $r = m_s/m_\chi$ as

$$\frac{\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}}{0.1\langle\sigma v\rangle_0} = 0.44\left(\frac{q_s}{2}\right)^4\left(\frac{\lambda_{s\chi}}{3}\right)^2\left(\frac{N_c}{3}\right)^2\left(\frac{m_\chi}{130\text{ GeV}}\right)^{-2} r^{-4} f(r) \tag{2.2}$$

where $f(r) = 9r^4(1 - r^2(\sin^{-1}(1/r))^2)^2 \to 1$ for large r and is numerically fit by the formula $f(r) \cong 1 + 0.4/(r - 0.972)$ which is good to 6% for any value of $r > 1.001$. (We define f in this way so that the r dependence in (2.2) is all transparently in the r^{-4} factor for $r \gg 1$.) The combination $r^{-4}f(r)$ reaches its maximum value $\cong 19.4$ when $r = 1$. Recall that $\langle\sigma v\rangle_0 = 1$ pb$\cdot c$ is the nominal relic density cross section.

$\chi\chi \to \gamma\gamma$ cross section in magnetic model

$$\langle \sigma v \rangle_{\rm eff} \cong 0.1\, \langle \sigma v \rangle_0 \left(\frac{f(r)}{\cos\theta} \right)^4 \left(\frac{m_\psi}{100\ \mathrm{GeV}} \right)^4$$

where $r = m_{\chi_2}/m_{\chi_1}$, $f(r) = \sqrt{(r + 1/r)/2}$,
$\theta =$ mass mixing angle

Vector meson $\to$ dilepton cross section

$$\sigma(q\bar{q} \to \phi \to e^+e^-) = \frac{4\pi\, q_q^2}{\cos^4(\theta_W)} \frac{\Gamma^2(\phi \to e^+e^-)}{(\hat{s} - m_\phi^2)^2 + m_\phi^2\, \Gamma^2(\phi \to \text{any})}$$

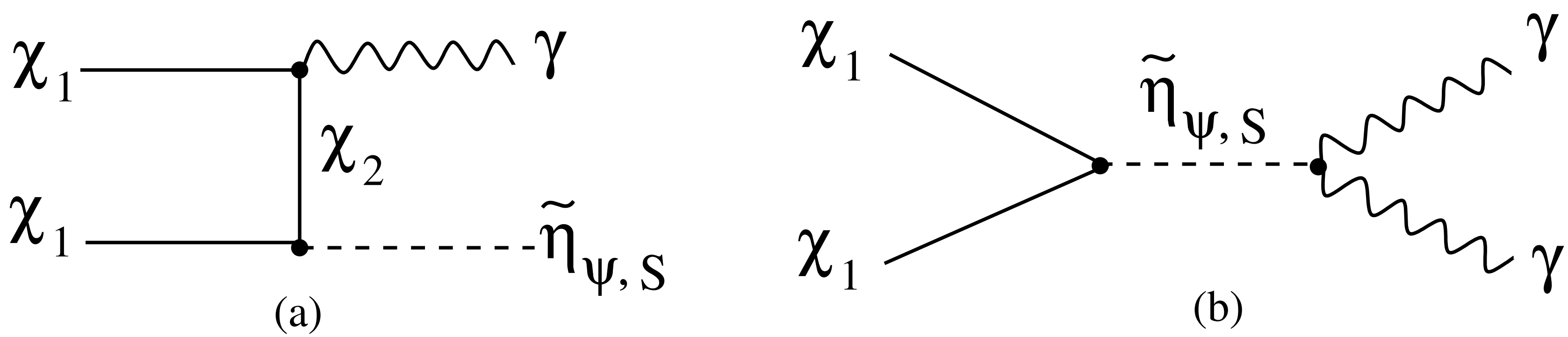
where

$$\Gamma(\phi_\psi \to e^+e^-) = \frac{4\pi\, N_c}{3} \frac{\alpha^2 q_\psi^2}{E_\psi^2} |\Psi(0)|^2$$

$$\Gamma(\phi_S \to e^+e^-) = \frac{8\pi N_c}{3} \frac{\alpha^2 q_S^2}{E_S^2\, m_\phi^2} |\vec{\nabla}\Psi(0)|^2$$

Relic density (magnetic DM model)

Additional possible contributions to annihilation from bound states should be suppressed to avoid making n_χ too small



Can arrange for $m_{\tilde\eta_i} > 2m_{\chi_1}$ to block diagram (a).

Diagram (b) is estimated to be small unless resonantly enhanced.

Alternatively, diagram (b) could be used to help get the observed $\chi\chi \to \gamma\gamma$ in the galactic center