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

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Outline

- Hints of 130 GeV DM annihilating to $\gamma\gamma$ at the galactic center
- Challenges for model building, and two examples: (1) J. Cline, 1205.2688, loop-induced annihilation (loop model); (2) J. Cline, A. Frey, G. Moore, 1208.2685, composite magnetic DM (magnetic model).
- LHC signatures of the photophilic DM models: J. Cline, G. Dupuis, ZL, 1306.3217
- Composite model of strongly interacting DM and the LHC: J. Cline, G. Moore, ZL, W. Xue, 1312.3325

Hints of 130 GeV DM

Hints for 130 GeV DM (2012)

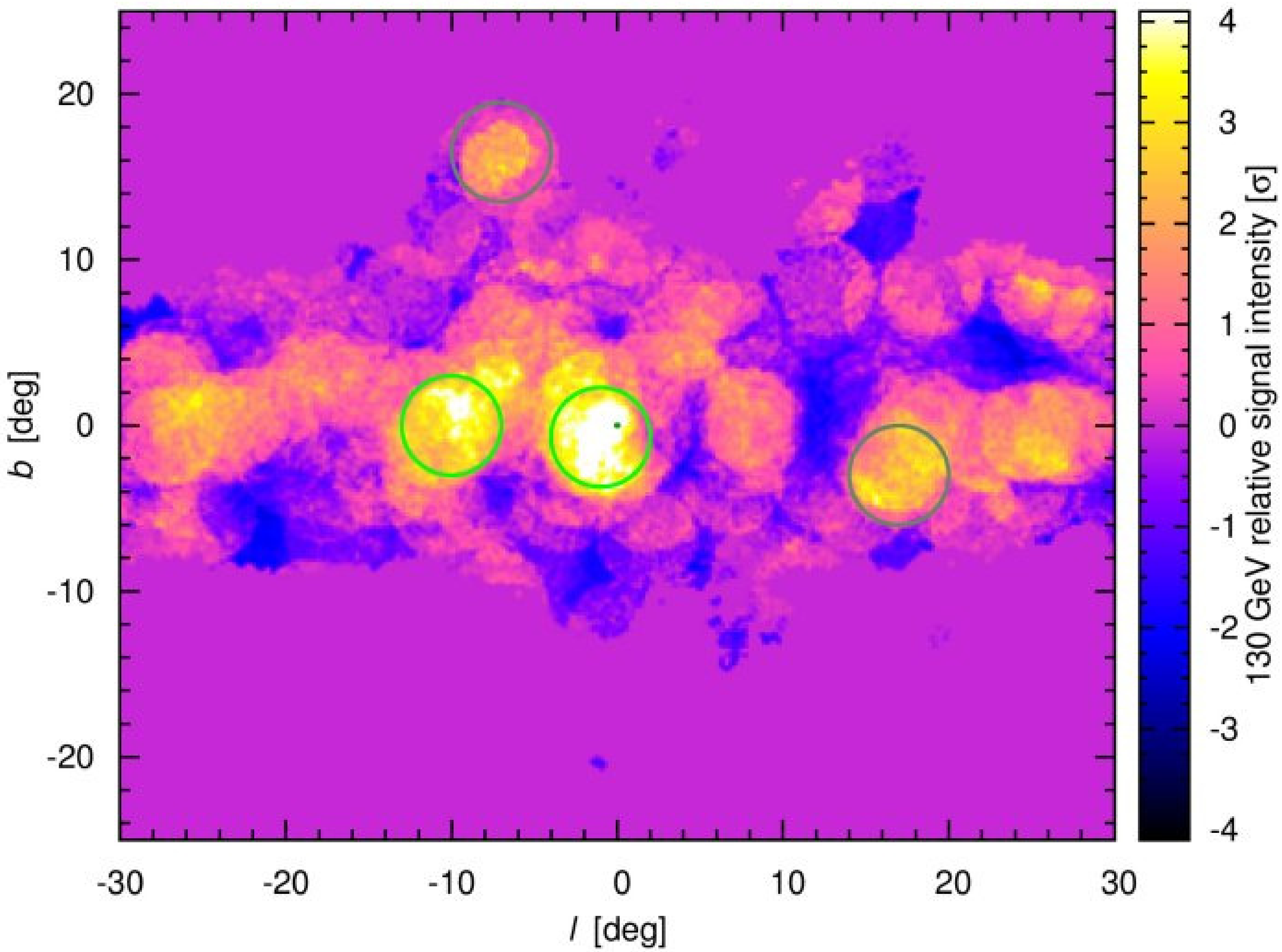
Hints were found of DM annihilation $\chi\chi \to \gamma\gamma$ near 130 GeV at the galactic center using the public Fermi/LAT data by theorists.

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

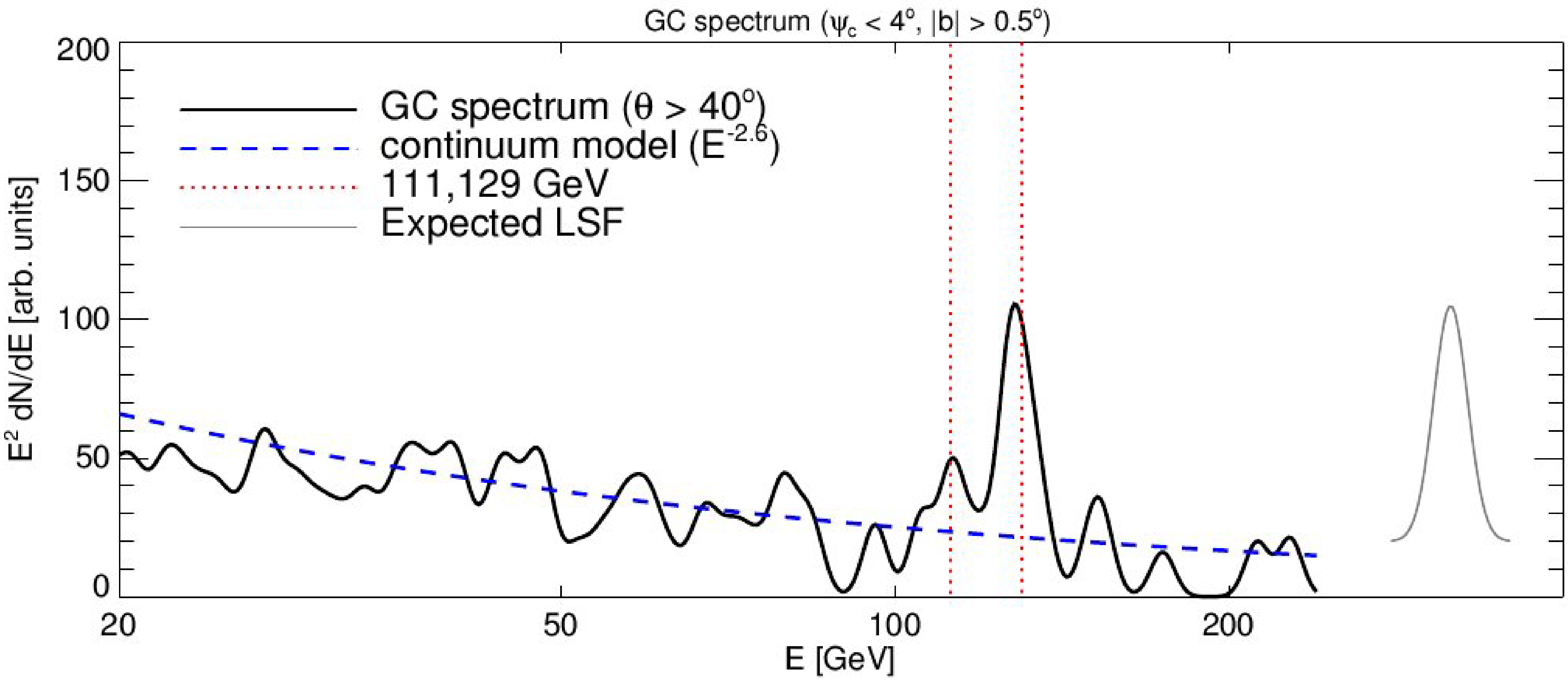
Most Significant signal is from galactic center

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 $m_\chi \simeq 130$ GeV

$E_\gamma = m_\chi(1 - \frac{m_\chi^2}{4m_Z^2}) = 112$ GeV in the $\gamma + Z$ final state, for $m_\chi = 129$ GeV

Concerns

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

Boyarsky, Malyshev, Ruchayshiy 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/LAT 1305.5597 (3.7 year data) finds smaller significance 3.3σ (local), 1.6σ (global) at 133 GeV photon energy.

Recent Fermi/LAT analysis (Andrea Albert, October 24, 2014) finds 0.72 σ (local significance) in 5.8 year dataset.

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. will resolve this issue

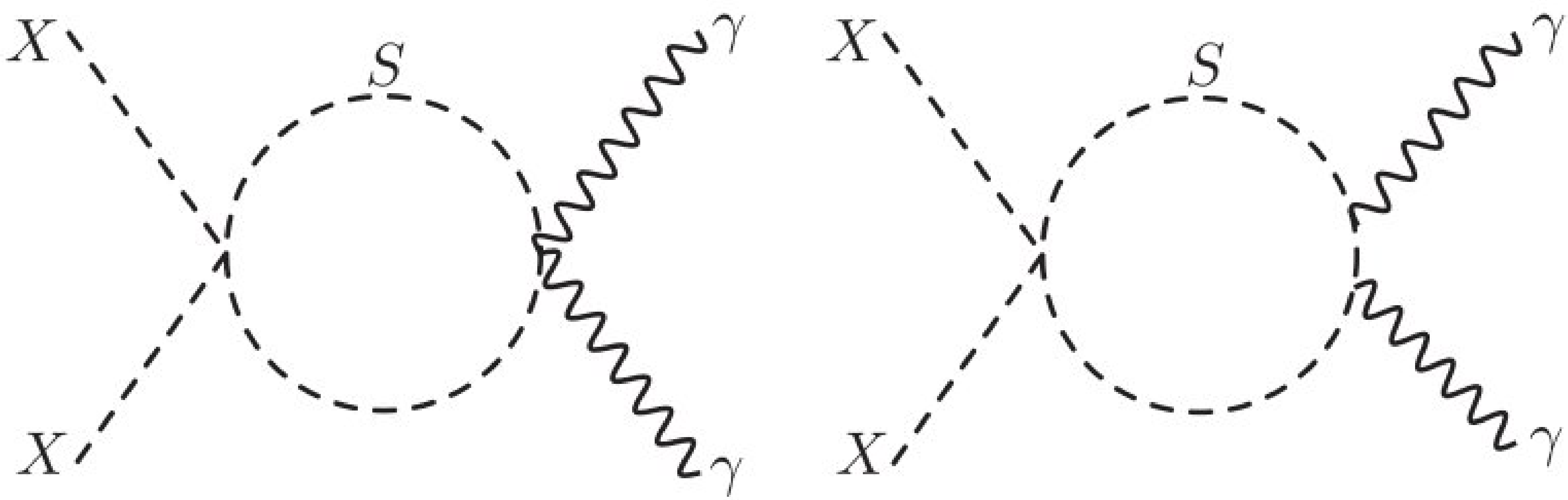
Regardless of 130 GeV signal, DM models that produce gamma rays lines might be interesting in the future, so we keep an open mind

Models of DM with γ ray lines

Challenges to model building

Photons can be produced from loop-annihilation of DM pair

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



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

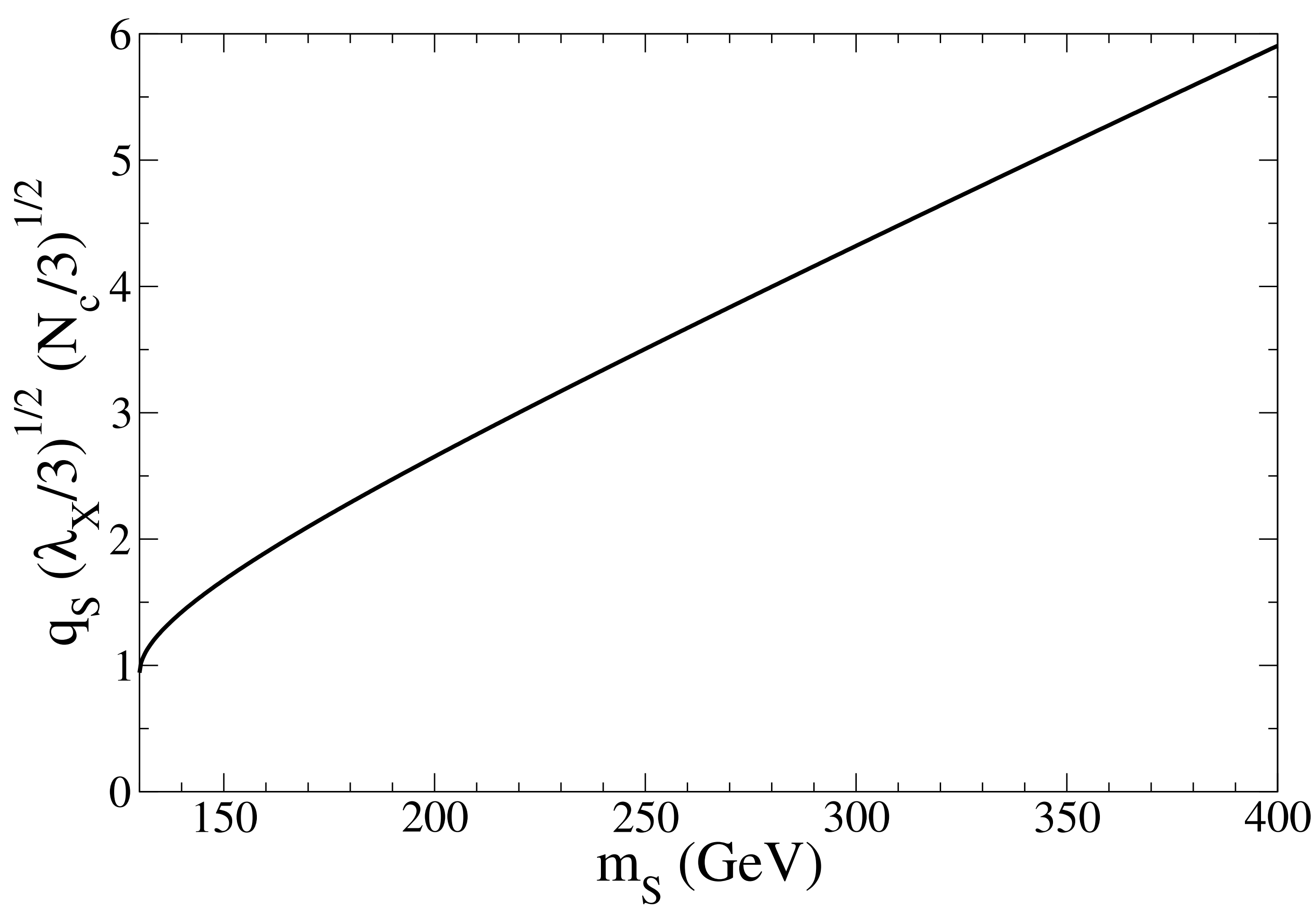
Constraints on $\chi\chi \to f\bar{f}, WW, ZZ$ due to continuum photons from decays and inverse Compton ($f\gamma \to f\gamma$) rules out neutralinos (Cohen et al., 1207.0800, Buchmüller & Garny, 1206.7056)

A loop model that works (Model 1)

J. Cline, 1205.2688: scalar DM X couplings to exotic charged ($q_S = 2$) and colored (under hidden SU(N)) scalar S, (H is the Higgs doublet)

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

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 $\sigma v(\chi\chi \to \gamma\gamma)$.

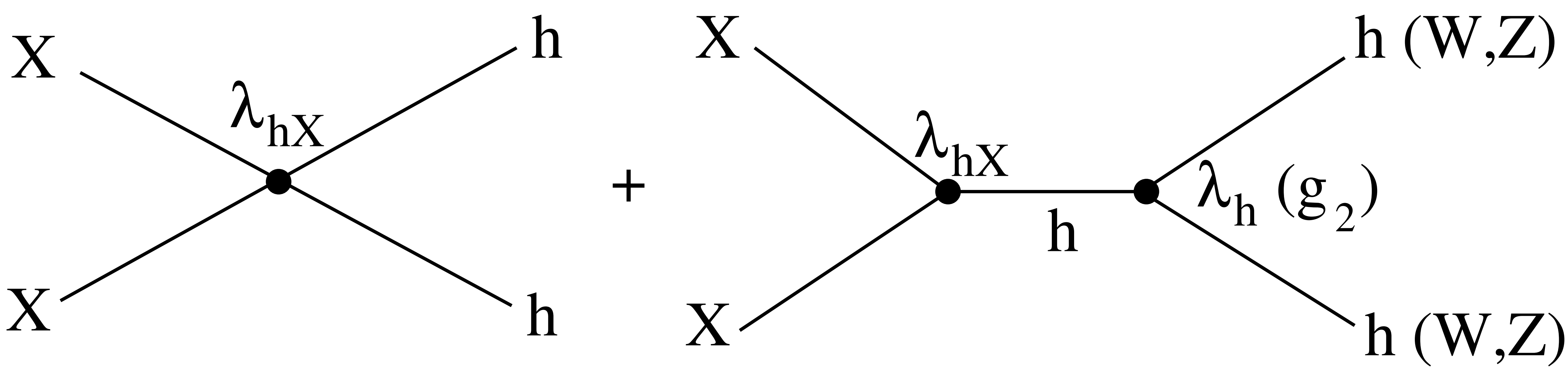
Need $m_S \gtrsim 130$ GeV, $q_S \sim 2$ for $\lambda_X \sim 1$

Relic density (loop model)

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

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

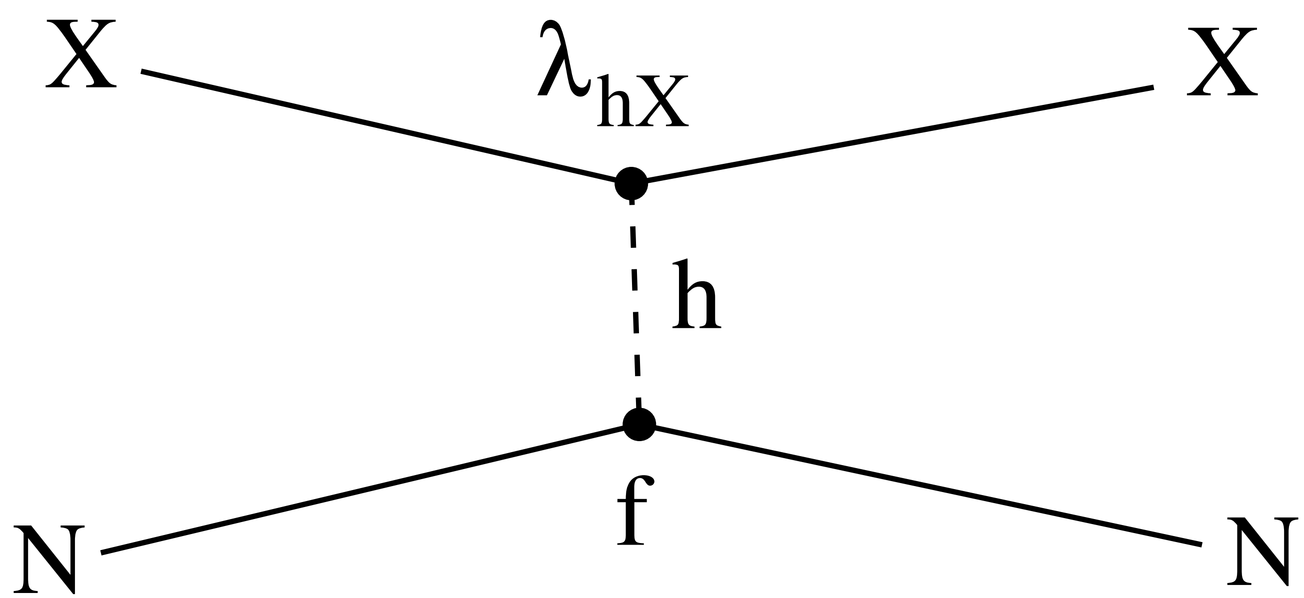
through the annihilations $XX \to hh,\ WW,\ ZZ$,



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



($f \simeq 0.32^{+0.32}_{-0.06}$ from lattice, sum rules, ...)

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

Should be discovered by upcoming LUX or XENON1T experiments!

Magnetic dark matter (model 2)

- Cline, Frey, Moore 1208.2685 propose composite DM model to generate large MDM, in analogy to neutron
- Model is simple: new SU(2) confining gauge interaction, "quark" ψ, "squark" S, Majorana particle χ
- ψ and S form a bound state, Dirac fermion ψS
- χ mixes with ψS due to mass terms, generate 3 Majorana states
- DM is mixture of χ and ψS bound state
- Transition magnetic moment connects DM ground state and first excited state $\mu_{12}(\bar{\chi}_1 \sigma_{\mu\nu} \chi_2) F^{\mu\nu}$

Particle content in model 2

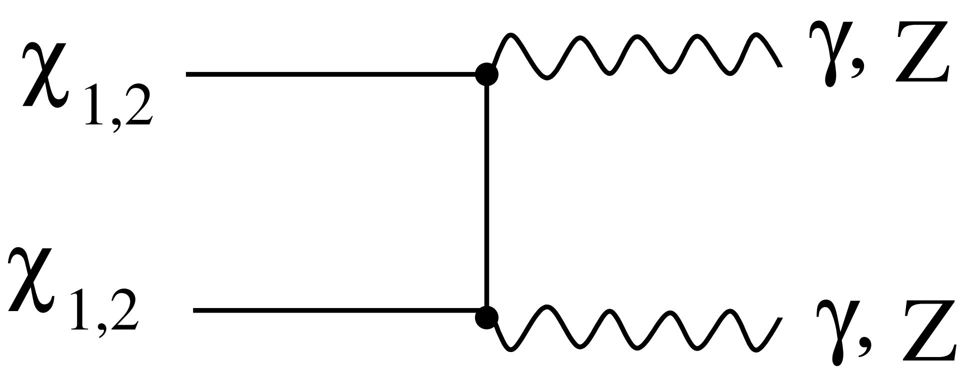
		state	spin	$\mathrm{SU}(2)_g$	$\mathrm{U}(1)_y$	$\mathrm{U}(1)_{\mathrm{em}}$	Z_4	constituents	
Elementary Constituents	Majorana state	χ	$\frac{1}{2}$	1	0	0	-1	-	
	"quark"	ψ_a	$\frac{1}{2}$	$\bar{2}$	-1	$-\frac{1}{2}$	i	-	
	"squark"	S^a	0	2	1	$\frac{1}{2}$	i	-	
Bound States	"mesons"	η	$\frac{1}{2}$	1	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

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

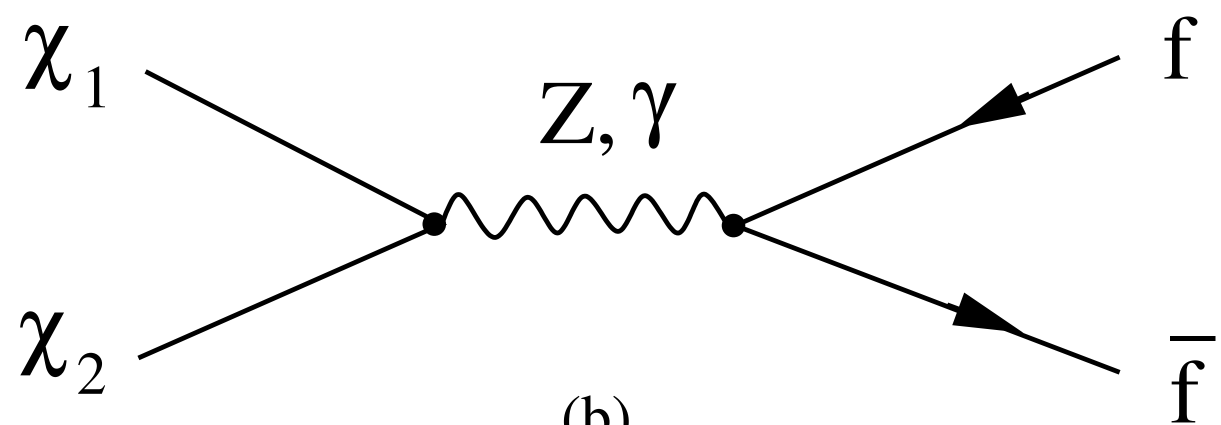
parity

Relic density (magnetic model)



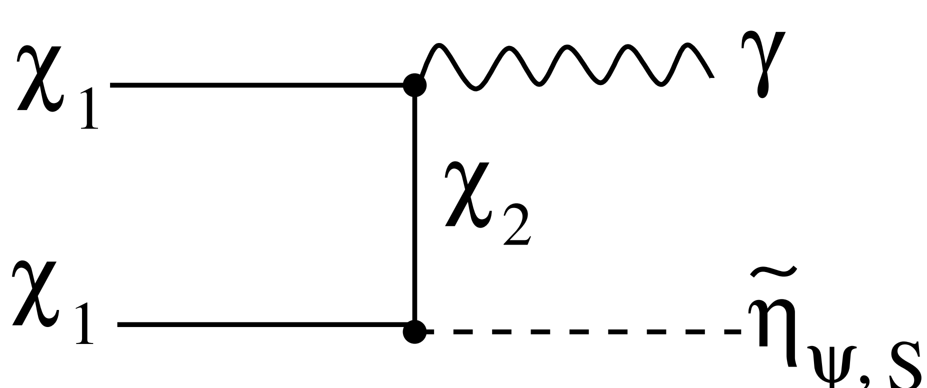
(a)

magnetic moment
to di-γ or di-Z



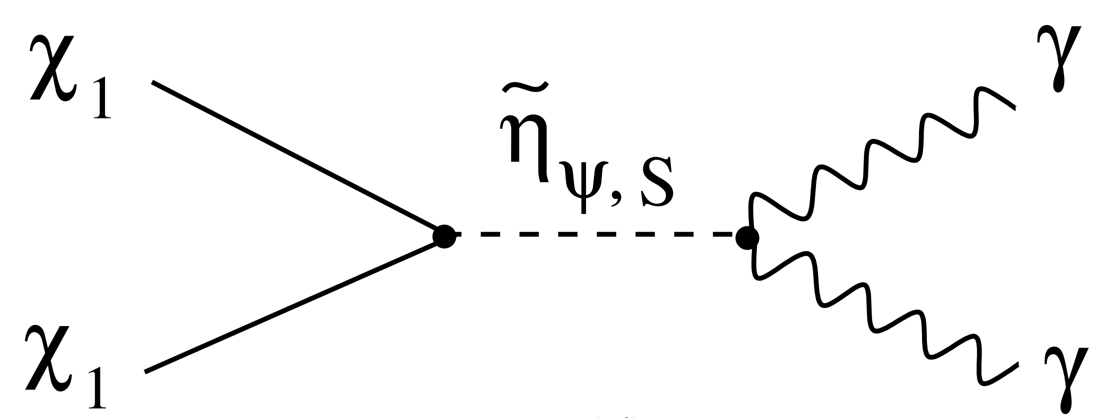
(b)

suppressed if $m_{\chi_2} - m_{\chi_1} > 10$ GeV



(c)

forbidden if $m_{\tilde{\eta}_i} > 2m_{\chi_1}$



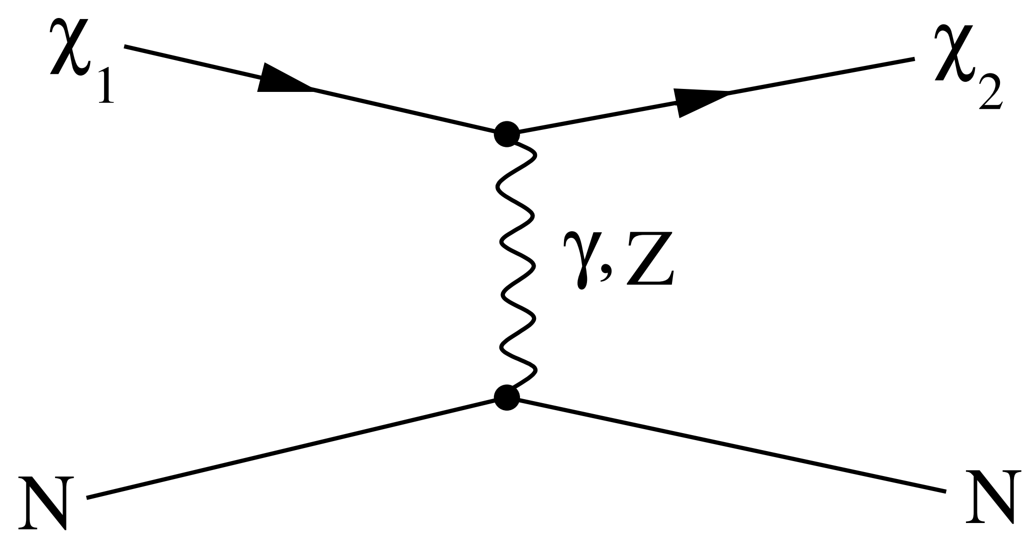
(d)

potentially new channel

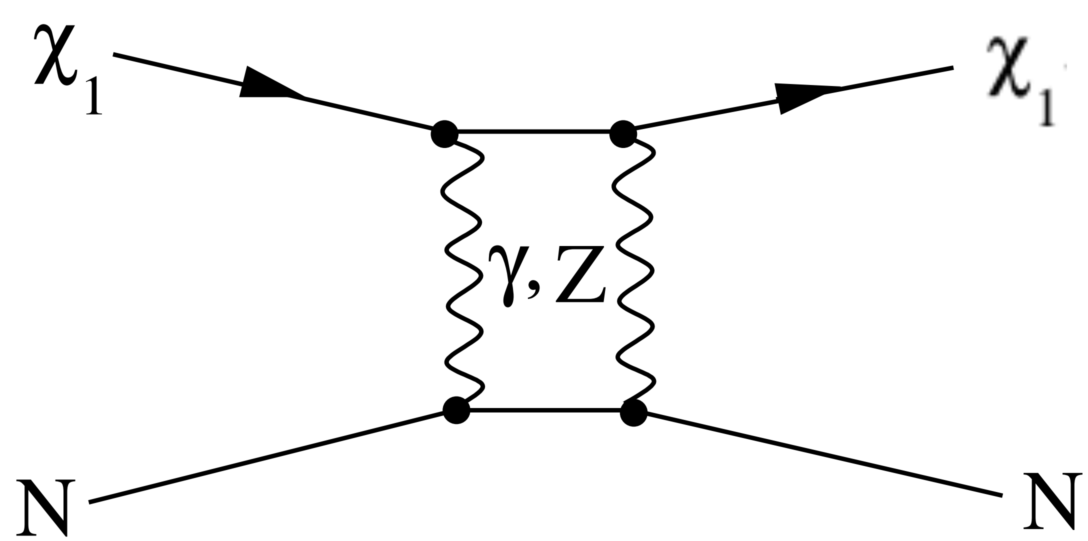
χ comprising just 10-15% of the total DM, with magnetic moment μ~2/TeV and a mass splitting of 10 GeV produces big enough photon signals

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



LHC Signatures of DM Models with γ ray lines

Various LHC signatures

$H \to \gamma\gamma$ enhancement

same-sign dileptons

Resonant vector meson production with dilepton final states

Excited e, μ imposters (charged mesons) $e^*, \mu^* \to e, \mu + \gamma$

Photon pairs from neutral meson decays

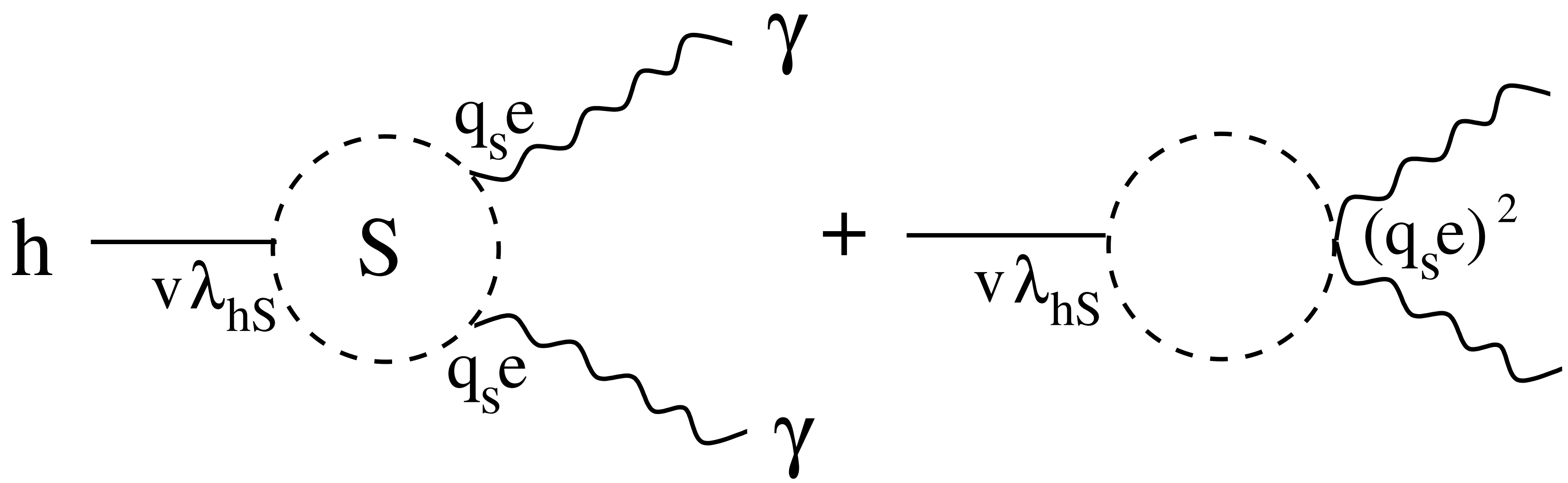
4-photon events

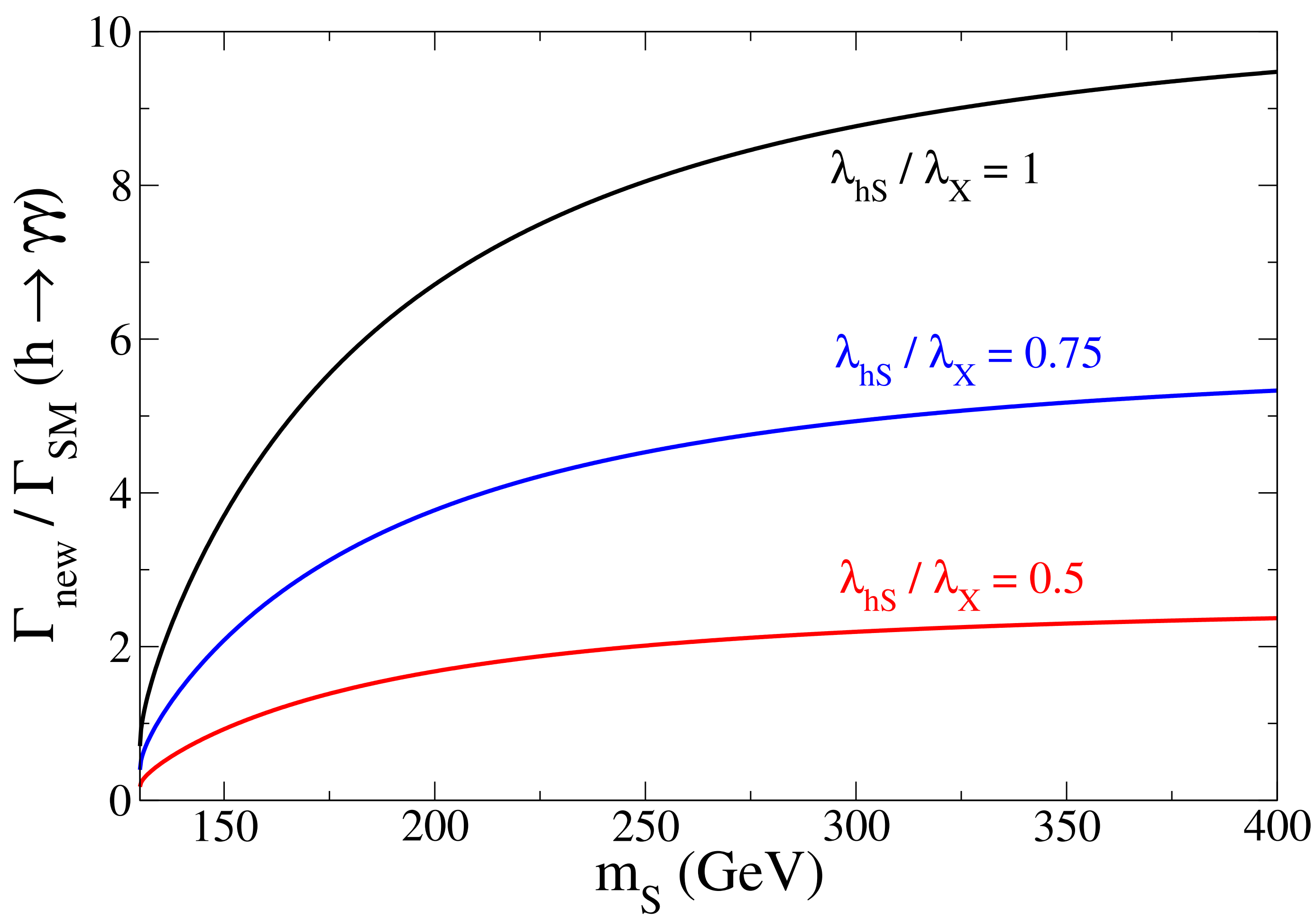
mono-photon signals

A lot of channels to look for

Higgs to γγ enhancement (loop model)

Similar diagrams as for $XX \rightarrow \gamma\gamma$ contribute to $h \rightarrow \gamma\gamma$



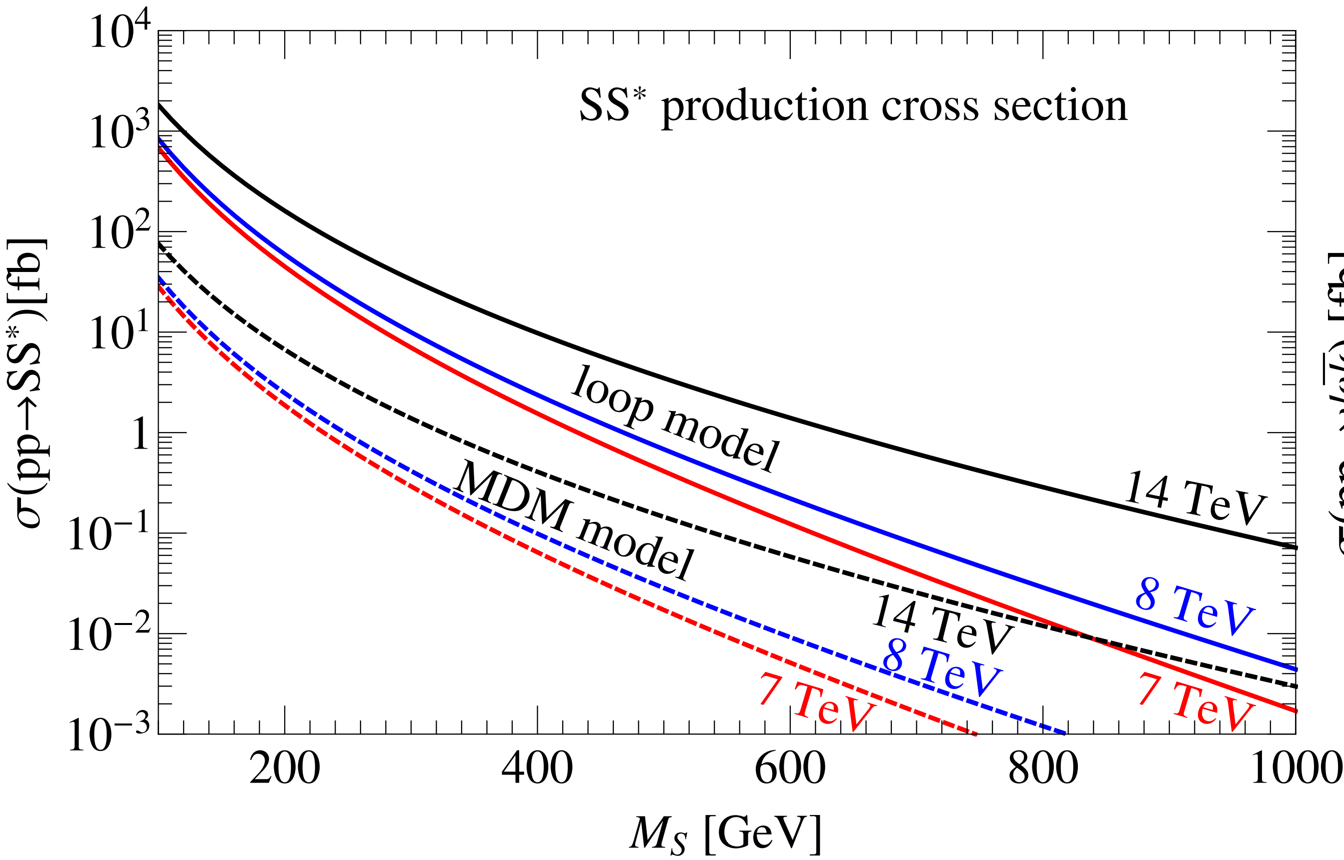


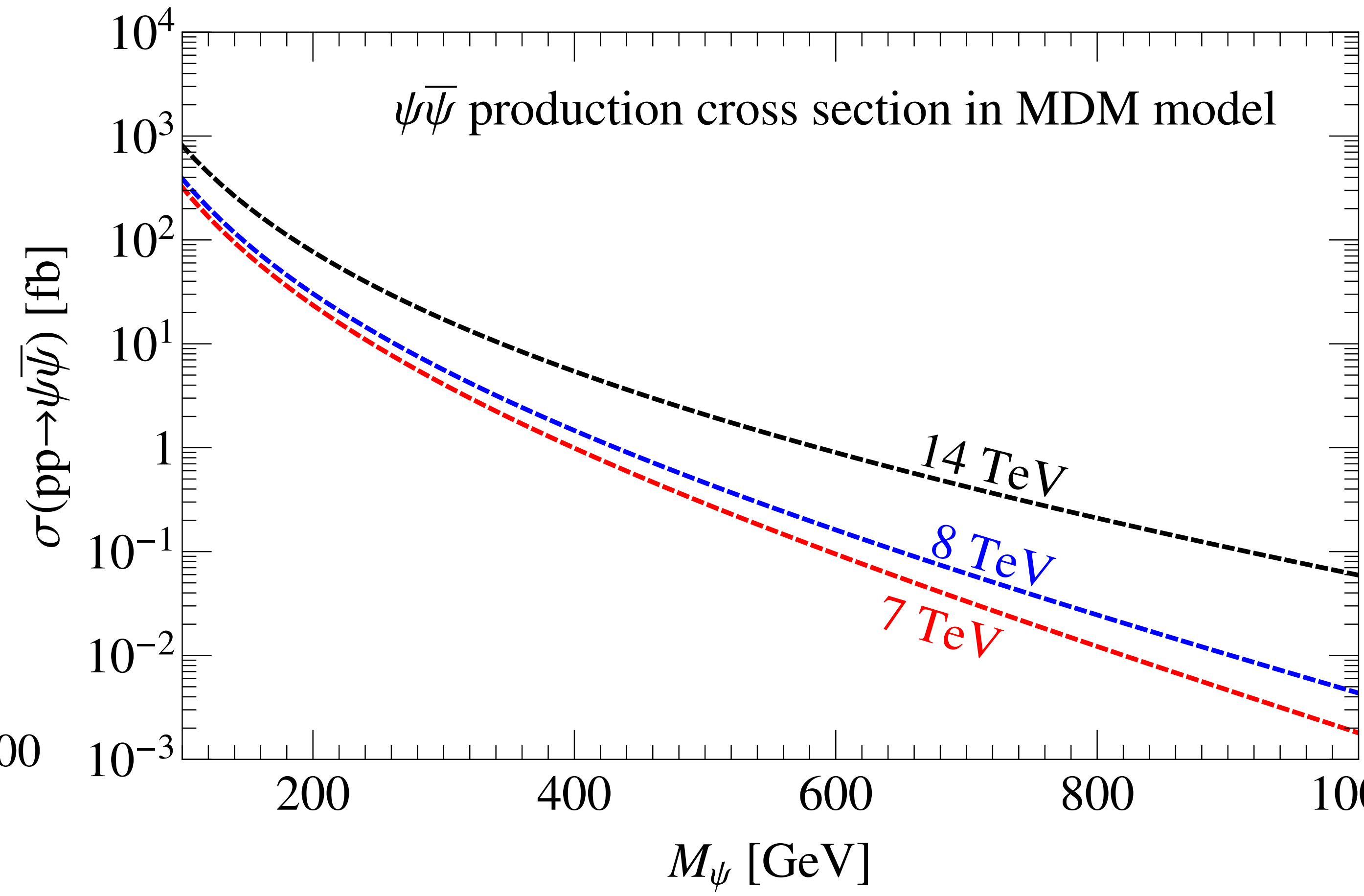
Enhancement depends on the scalar mass and the coupling to Higgs

LHC production of charged particles

Model 1: (Loop model) $q_S = 2$, $N_c = 3$

Model 2: (Magnetic model) $q_S(q_\psi) = 1/2$, $N_c = 2$





$pp \to \psi\bar{\psi}$ or SS^* via Drell-Yan

Both ψ and S are strongly interaction, "hadronize" in dark $SU(N)$

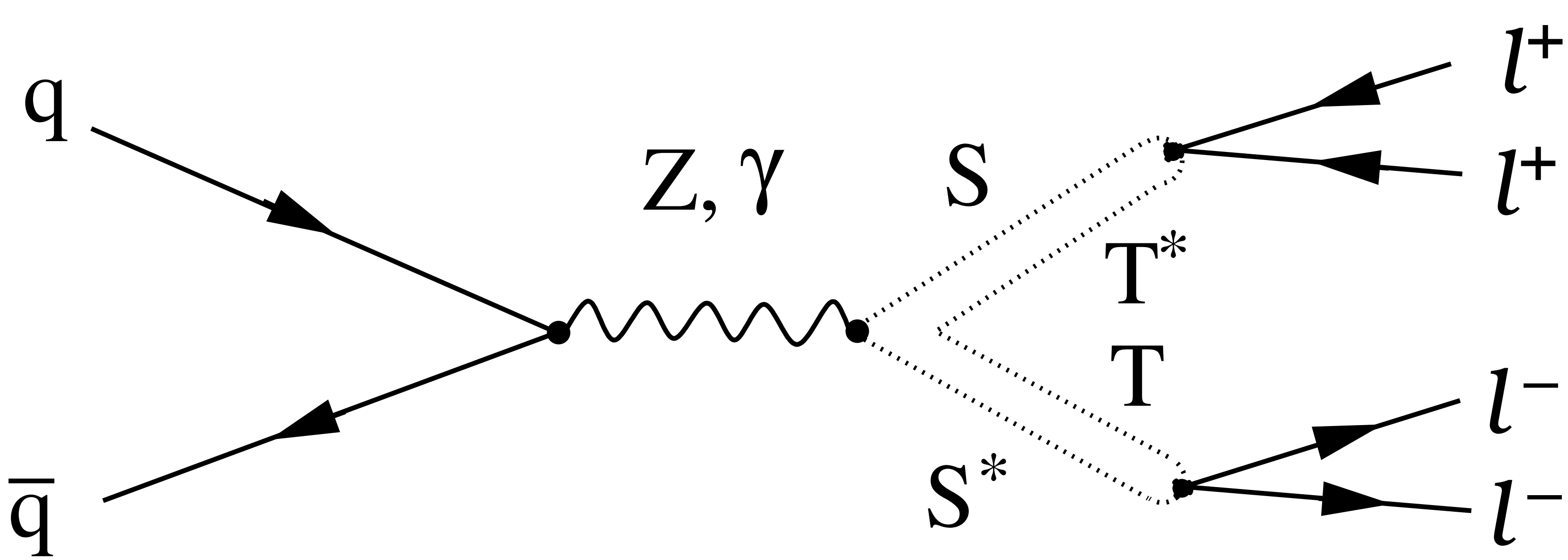
This makes them harder to find

Like-sign di-leptons (loop model)

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

Introduce neutral triplet T to allow $S \to T \ell^+ \ell^+$ through dimension-5 $T^* S \, \bar{\ell}^c \ell$ interaction.

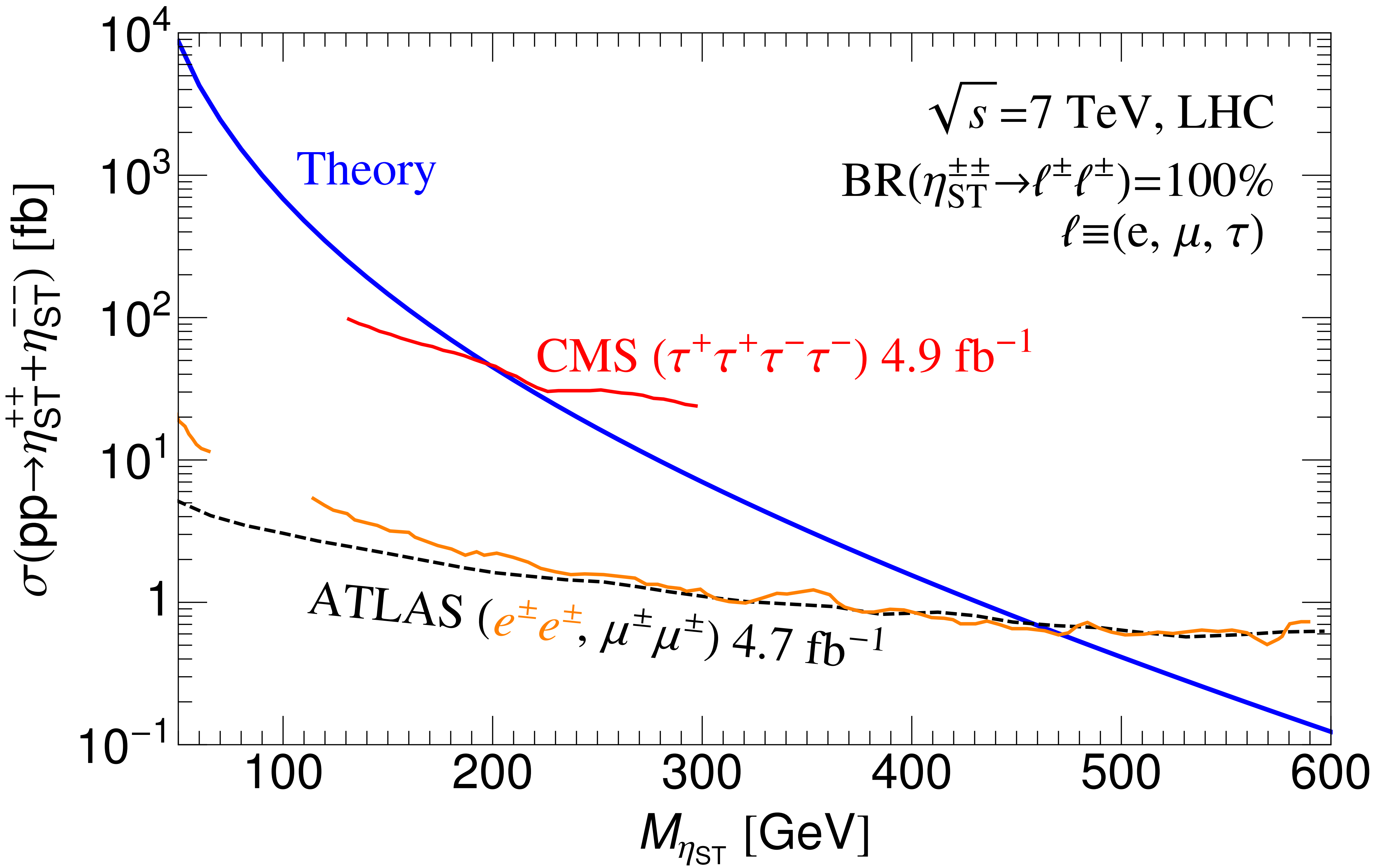
Then $\eta_{ST} \equiv \langle S T^* \rangle$ bound state decays into like-sign leptons.



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

Like-sign di-lepton constraints

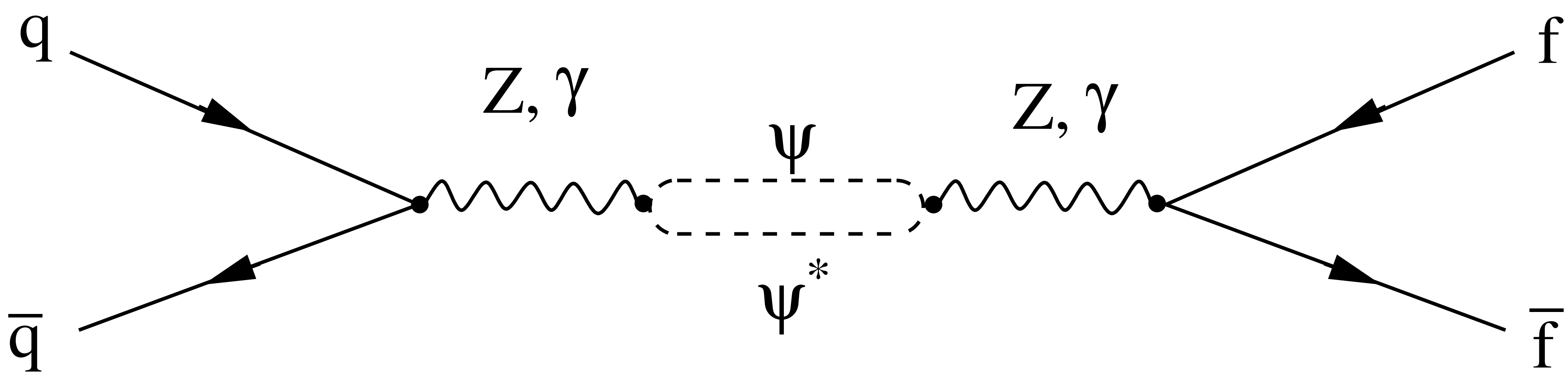
$$pp \to \eta_{ST}^{++} + \eta_{ST}^{--} \to \ell^+\ell^+ + \ell^-\ell^-$$



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

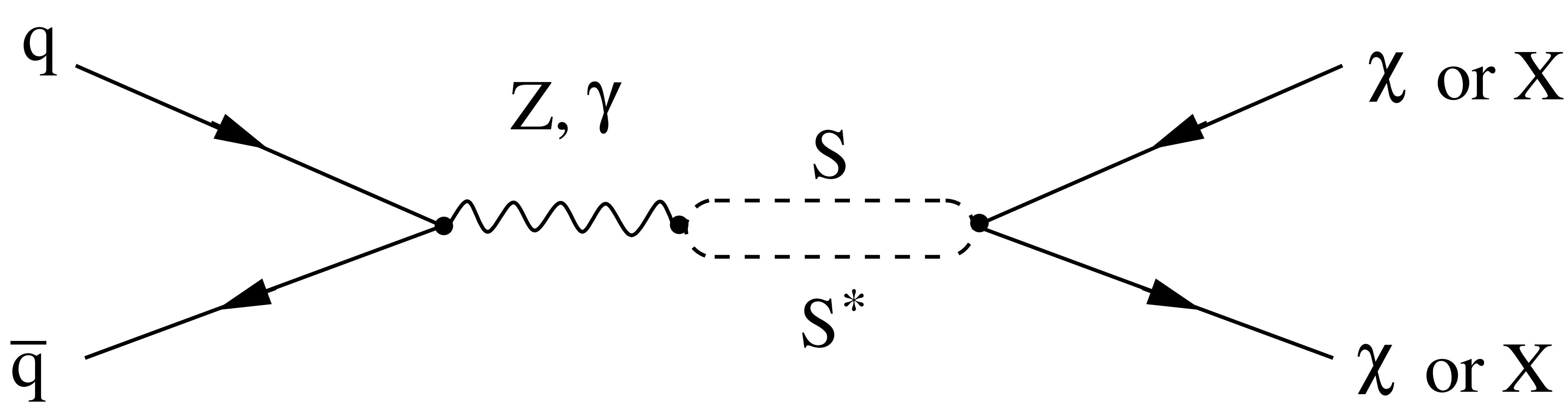
Vector meson production

Analogous to ϕ or J/ψ production, $\psi\bar{\psi}$ and SS^* bound state can be produced resonantly



Angular momentum $J = 1$ (charge conjugation of photon is -1):
$\phi_\psi \equiv \langle\psi\bar{\psi}\rangle$ from spins of the constituents, orbital $\ell = 0$
$\phi_S \equiv \langle SS^*\rangle$ with scalar constituents must have $\ell = 1$

LHC sensitivity depends upon branching ratio of ϕ_ψ (ϕ_S) to dark matter,



dark (scalar) Quarkonium decay

fermion bound state, dark "quarkonium" decay (S-wave)

$$\mathcal{M}(\phi_\psi \to e^+ e^-) \propto \hat{n} \cdot \epsilon^* \; \Psi(0)$$

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

scalar bound state, dark "squarkonium" decay (P-wave)

$$\mathcal{M}(\phi_S \to e^+ e^-) \propto \epsilon^* \cdot \vec{\nabla}\Psi(0)$$

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

P-wave (l=1) gives non-vanishing results for the scalar case

$$\vec{\nabla}\Psi_{n00}(0) = 0$$

$$\vec{\nabla}\Psi_{210}(0) = \sqrt{3/4\pi}\; \hat{z}$$

$$\vec{\nabla}\Psi_{211}(0) = -\sqrt{3/4\pi}\; \hat{\epsilon}_+$$

$$\vec{\nabla}\Psi_{21-1}(0) = \sqrt{3/4\pi}\; \hat{\epsilon}_-$$

$$\epsilon_+ = (\hat{x} + i\hat{y})/\sqrt{2}$$
$$\epsilon_- = (\hat{x} - i\hat{y})/\sqrt{2}$$

ϵ_+: circular polarization in $+\hat{z}$

ϵ_-: circular polarization in $-\hat{z}$

Bohr model for dark meson

$\langle\psi\bar{\psi}\rangle$: $\Gamma(\phi_\psi \to e^+e^-) \propto |\Psi_{1\mathrm{S}}(0)|^2$

$\langle SS^*\rangle$: $\Gamma(\phi_S \to e^+e^-) \propto |\vec{\nabla}\Psi_{1\mathrm{P}}(0)|^2 \sim |\vec{p}\Psi_{1\mathrm{S}}(0)|^2$

Total energy: $E_{\text{total}} = 2\sqrt{p^2+m^2} + 2kr$, where p is momentum, r is the distance from origin, k is the string tension of the confining potential, m is the mass of the 2 constitutes.

Bohr quantization $L = 2pr = n$

NR: $E = 2m + p^2/m + nk/p$; $\frac{dE}{dp} = 0 \Rightarrow p = (mnk/2)^{1/3}$

$r = (n/2)^{2/3}(mk)^{-1/3}$; $|\Psi|^2 r^3 \simeq 1 \Rightarrow |\Psi|^2 \propto mk$

Relativistic: $E = 2p + nk/p$; $\frac{dE}{dp} = 0 \Rightarrow p = \sqrt{nk/2}$

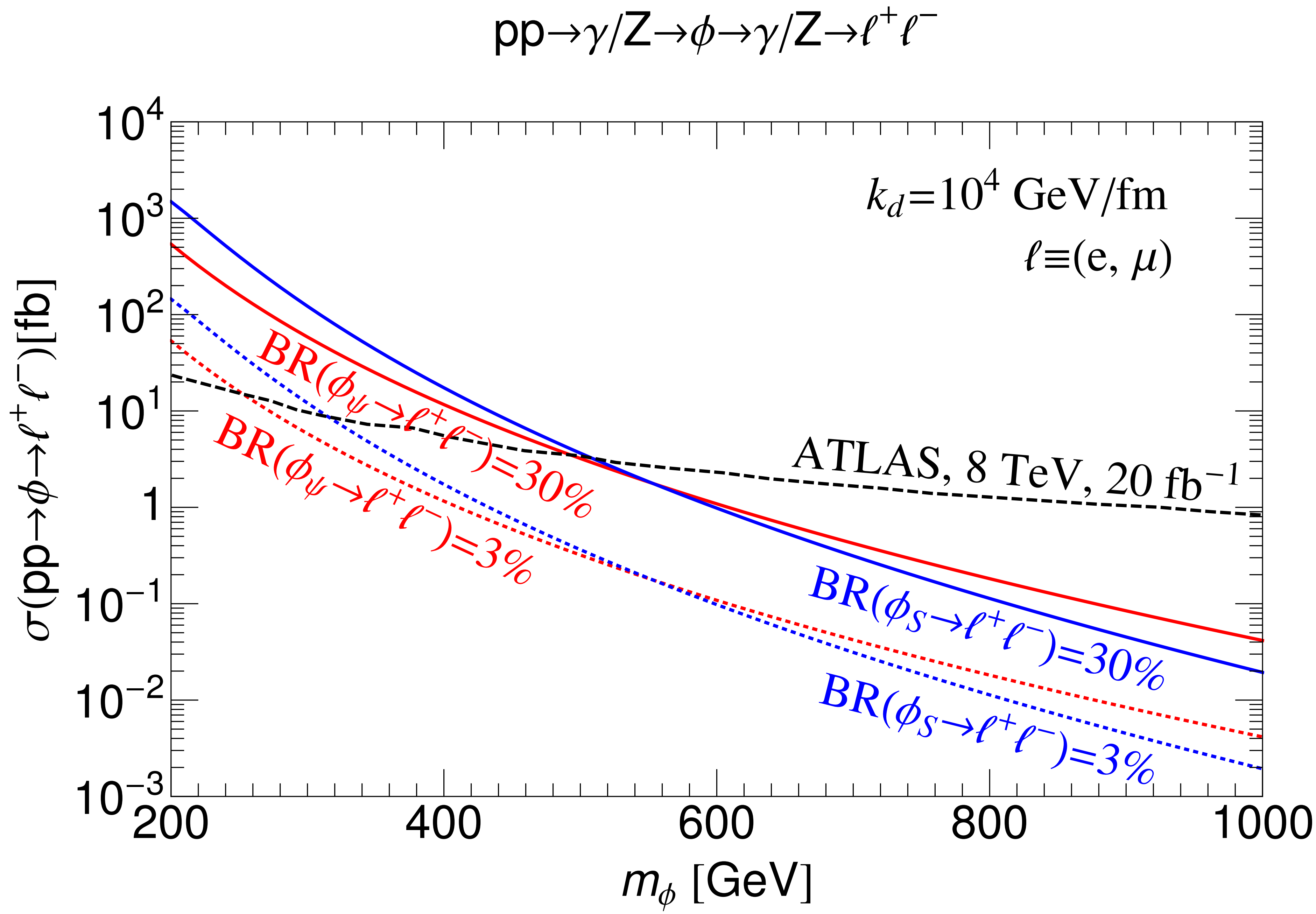
$r = \sqrt{n/2k}$; $|\Psi|^2 r^3 = 1 \Rightarrow |\Psi|^2 \propto k^{3/2}$

Conjecture: $|\Psi(0)|^2 = ak^{3/2} + bmk$

Fitting QCD (ϕ, J/ψ, Υ), we get $a = 0.022$ and $b = 0.13$

Constraint from OSSF dileptons

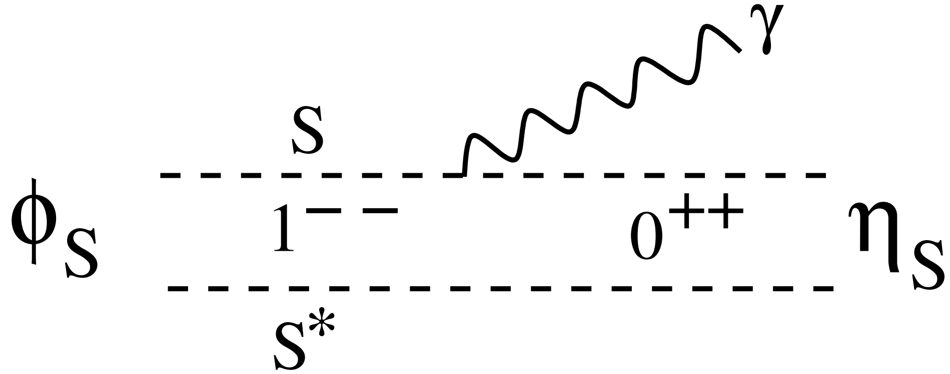
Constraints depend on $BR(\phi \to \ell^+\ell^-)$ and k_d

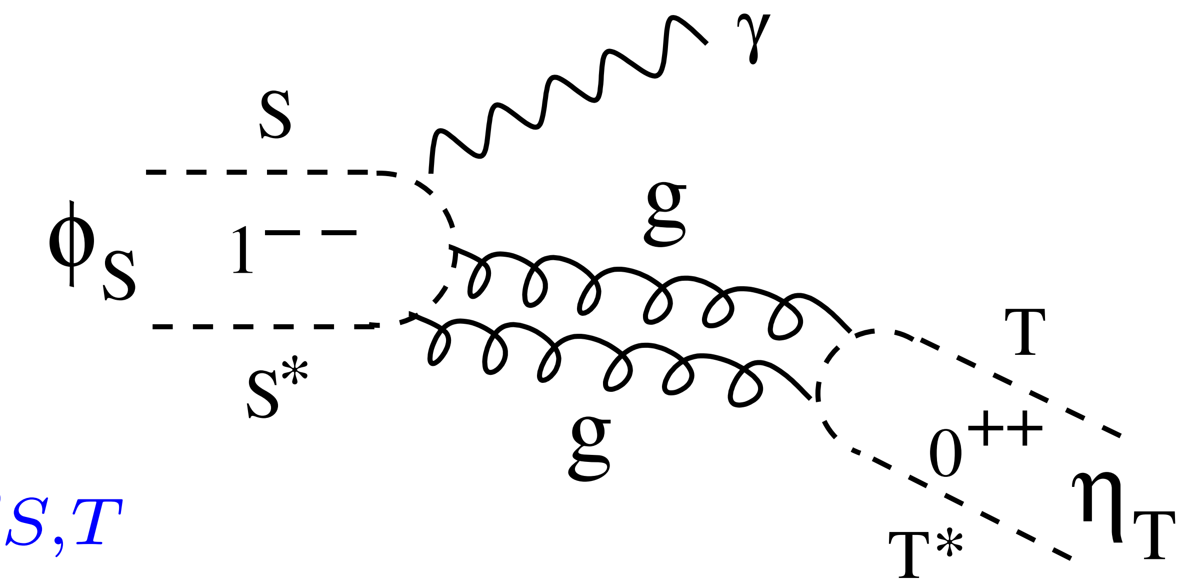


Bound on the vector meson mass is $m_\phi > 250 - 500$ GeV

Other decay modes can dominate

$$\phi_S(1P) \to \eta_S(1S) + \gamma \qquad \phi_S(1P) \to \eta_T(1S) + \gamma$$





$$g_{S,T}(eq_S/m_\phi)\phi^{\mu\nu}F_{\mu\nu}\eta_{S,T}$$

$g_S = 1.5$ by modeling the charmonium radiative decay processes, $\chi_{c0} \to \gamma J/\psi$, $J/\psi \to \gamma\eta_c$, and $\psi(2S) \to \gamma\chi_{c0}$.

Estimate $g_T/g_S \simeq \alpha_d^2/\pi$ (OZI suppression encoded) using $J/\psi \to \gamma\eta_c$ and $J/\psi \to \gamma\eta'$ in QCD

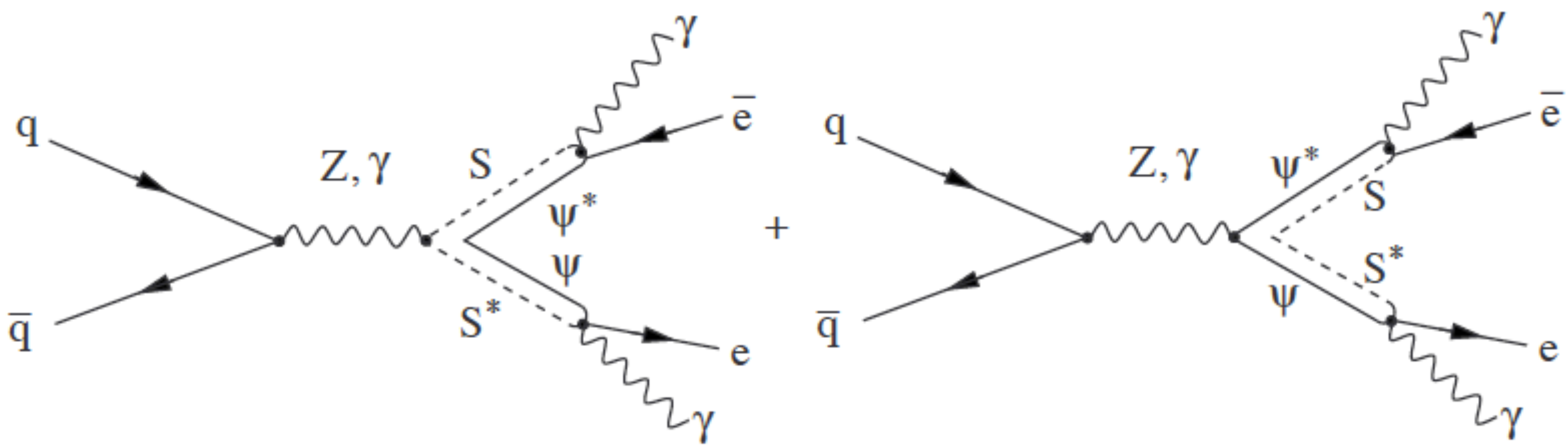
$$\alpha_d(Q^2) = \frac{12\pi}{32\ln(Q^2/\Lambda_d^2)}$$

T is the only light matter relevant in SU(3).

$\Lambda_d \sim k_d^{1/2}/2$ inferred from QCD.

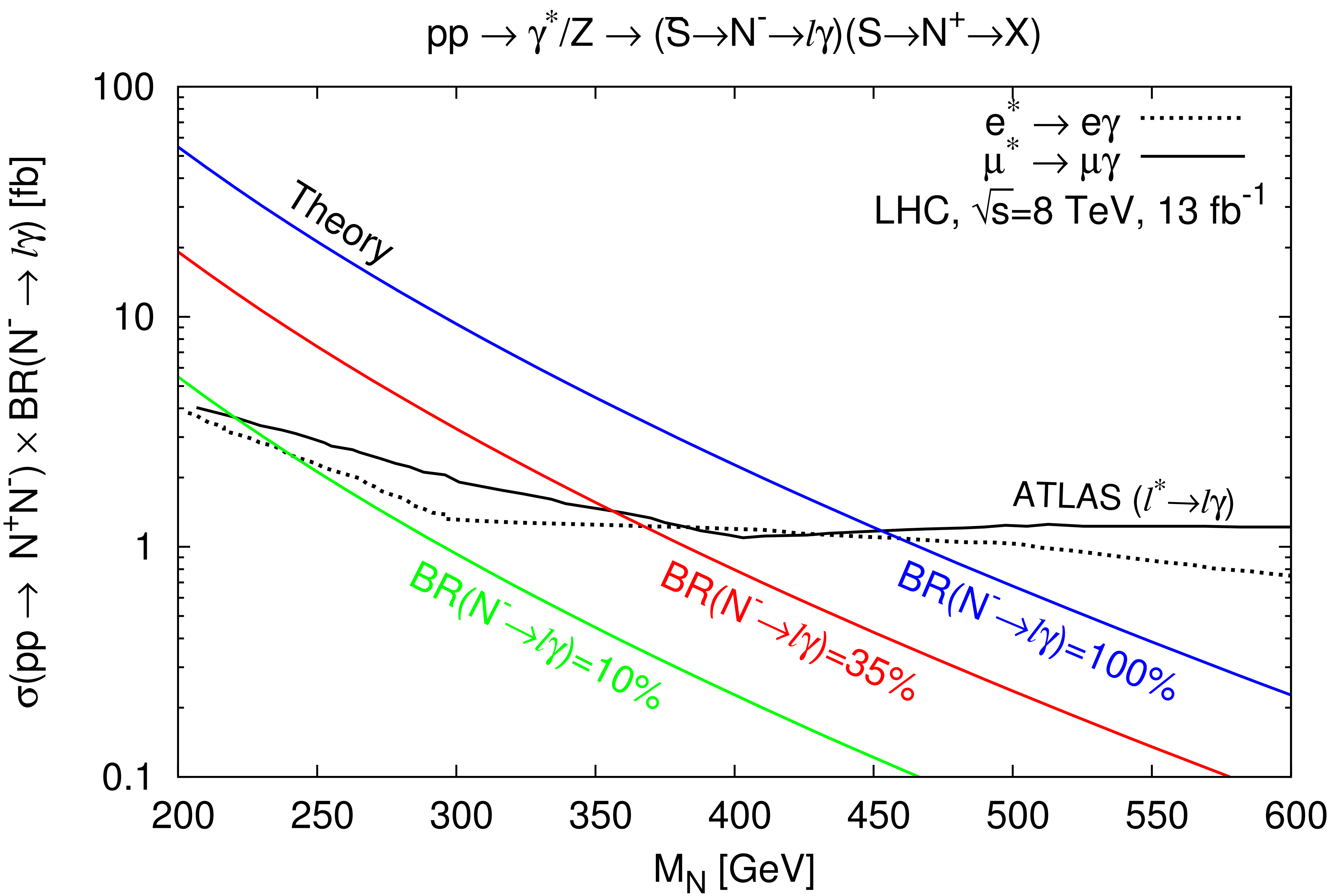
Charged "baryon" decay

singly charged particle $N^- \equiv S^*\psi$ in magnetic model
can decay via transition magnetic moment, $N^- \to e^- + \gamma$



mimic the excited electron/muon signal in Kaluza-Klein states

Excited e/μ limits



$m_N > 367$ GeV for the flavor-democratic case

4-photon signal

Meson pairs, either $2\eta_\psi$ or $2\eta_S$ produced via an s-channel γ/Z can generate 4-photon final states

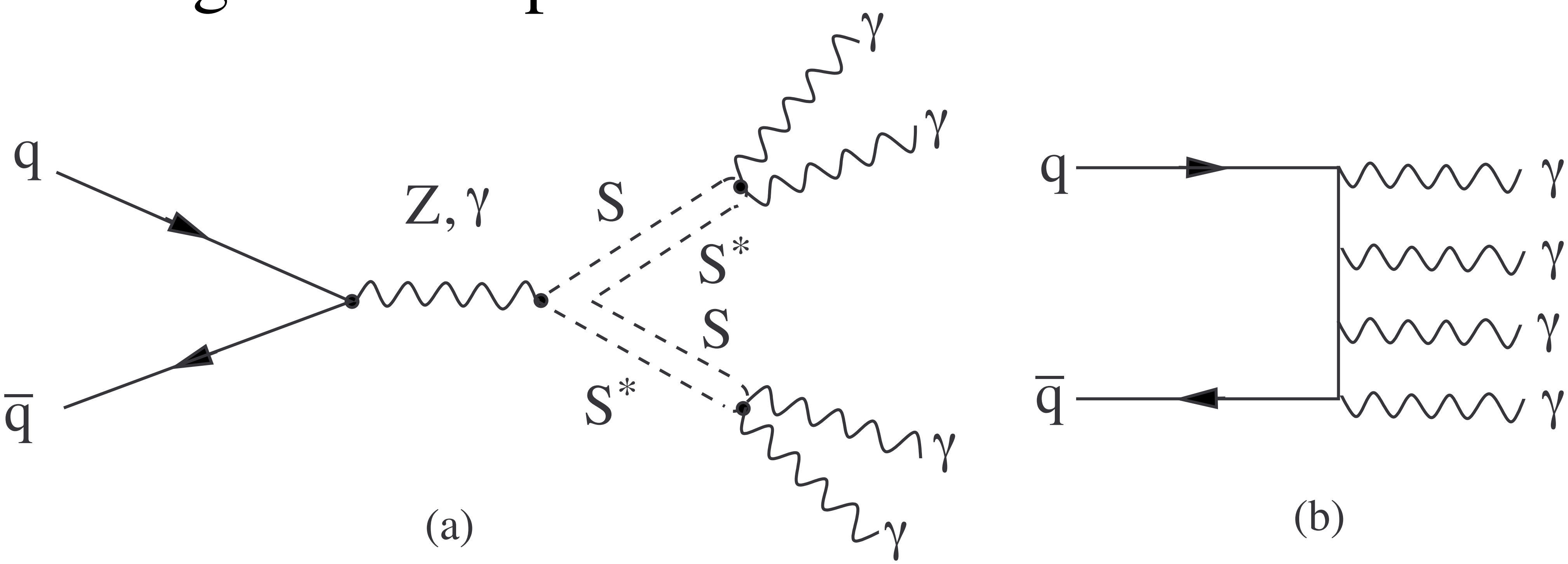


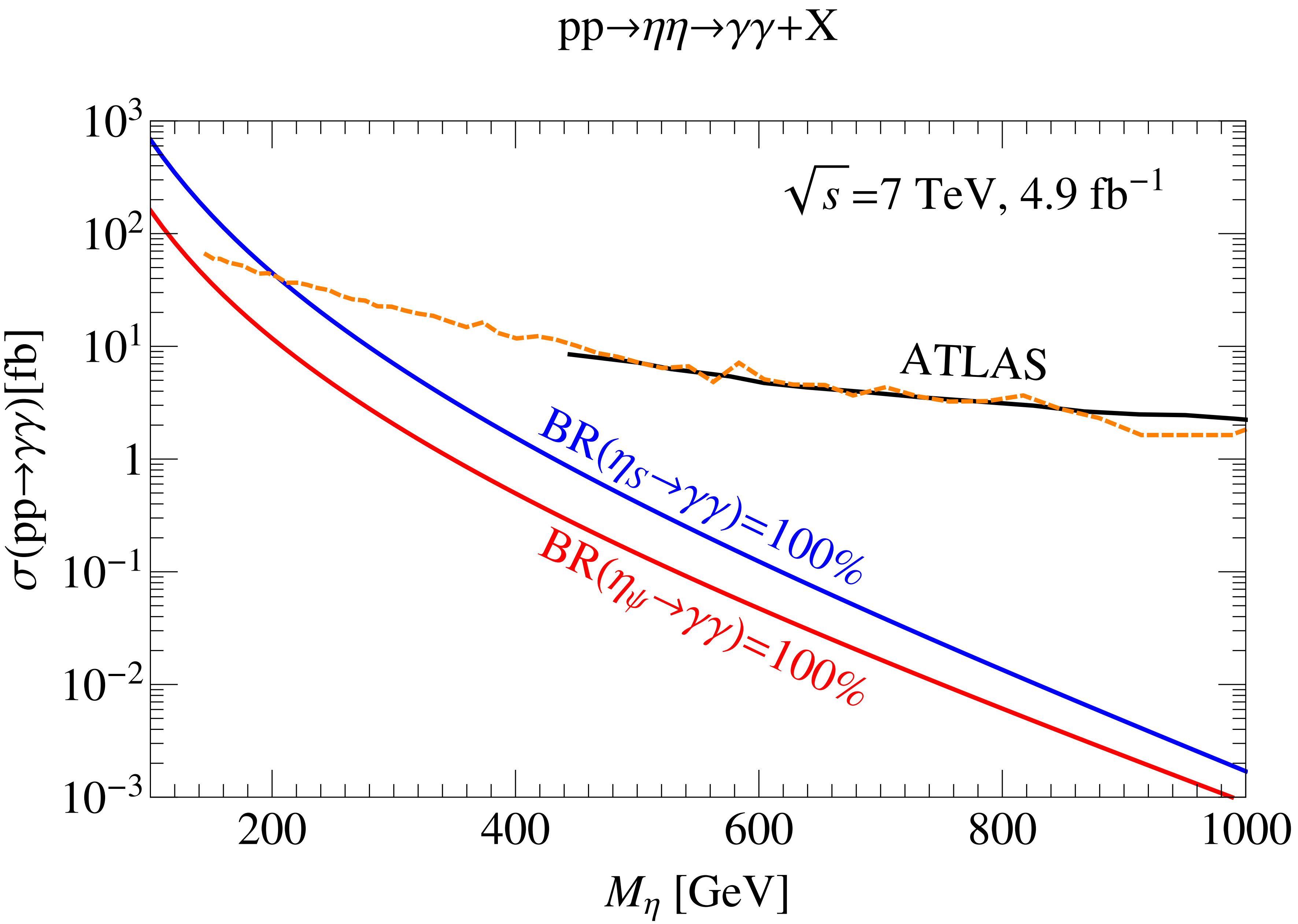
diagram (a): reconstruction of the invariant masses of photon pairs exhibits peaks around the hidden meson mass.

diagram (b): SM process shows no invariant mass resonance

$\sigma_b(pp \to 4\gamma) \sim$ (0.1-0.2) fb for $\sqrt{s} = 8 - 14$ TeV with $p_T > 10$ GeV

diphotons out of 4-photon events

No exiting 4 photon searches at LHC



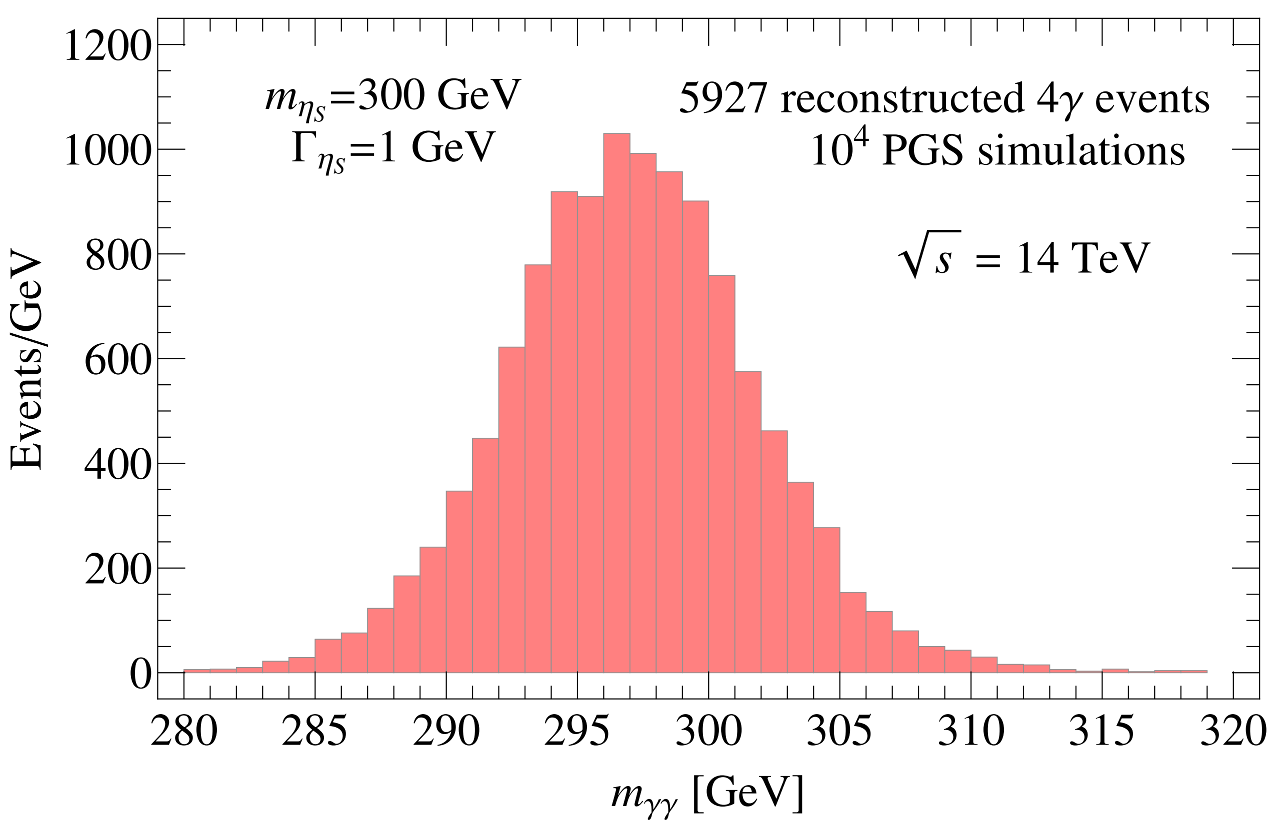
$m_\eta > 200$ GeV

di-photon data analysis (ATLAS+CMS) also constrains the 4-photon final states.

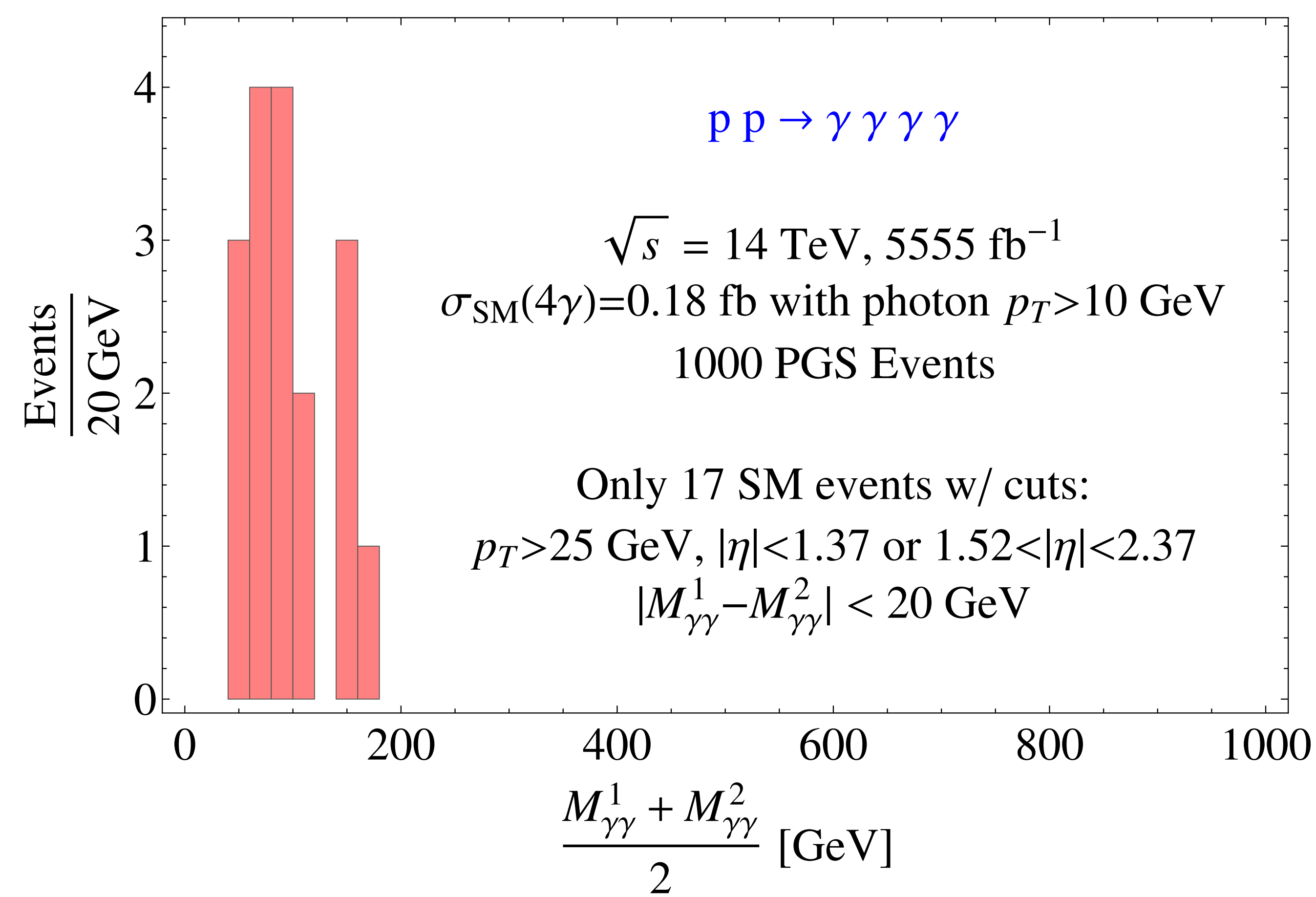
4-photon reconstruction

Photon selection: $p_T > 25$ GeV, and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$,
The invariant masses requirement: $|M^1_{\gamma\gamma} - M^2_{\gamma\gamma}| < 20$ GeV

loop model



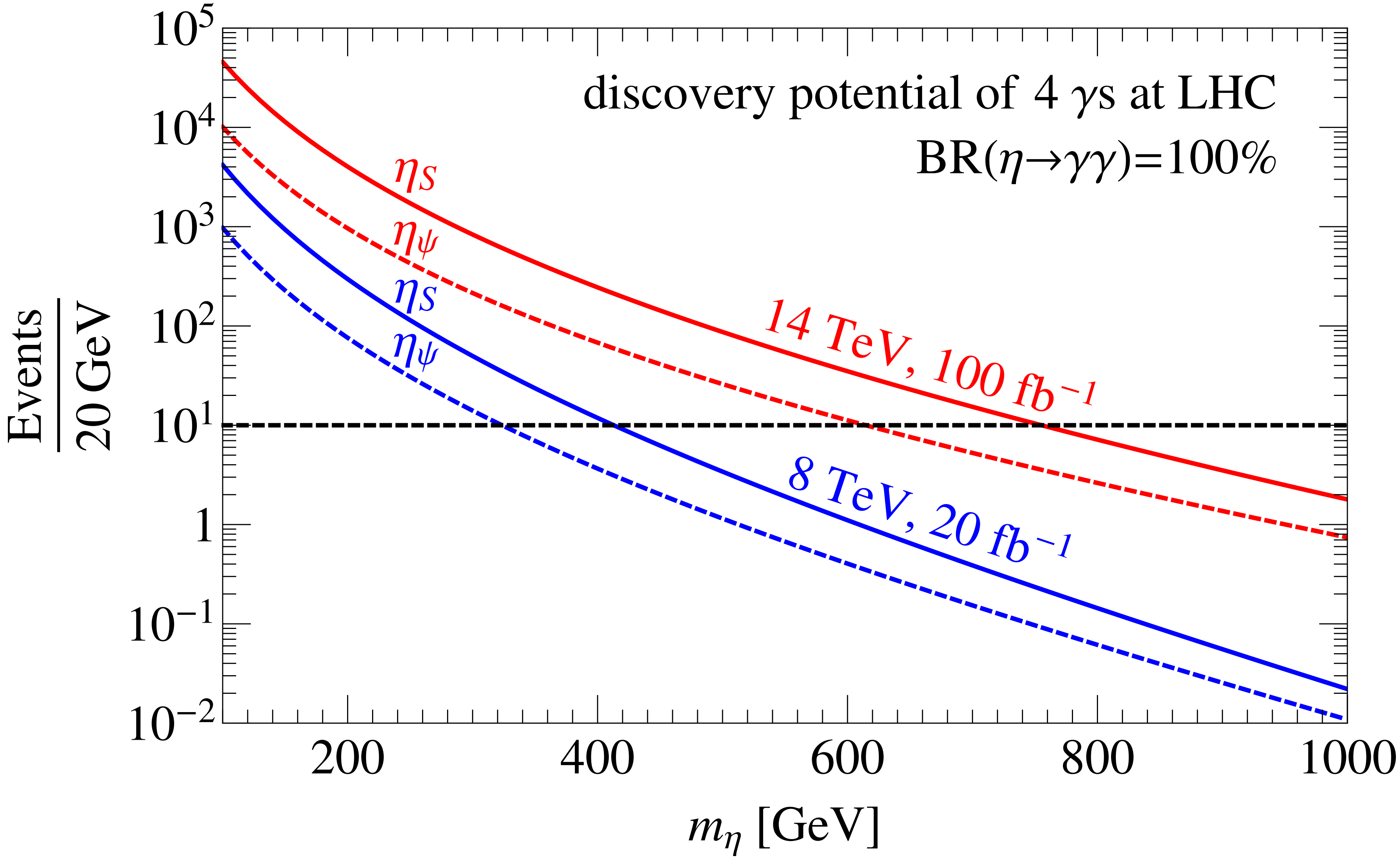
standard model



invariant mass width is smeared by the detector resolution

LHC discovery potential

SM background is negligible. N=10 for discovery criterion.



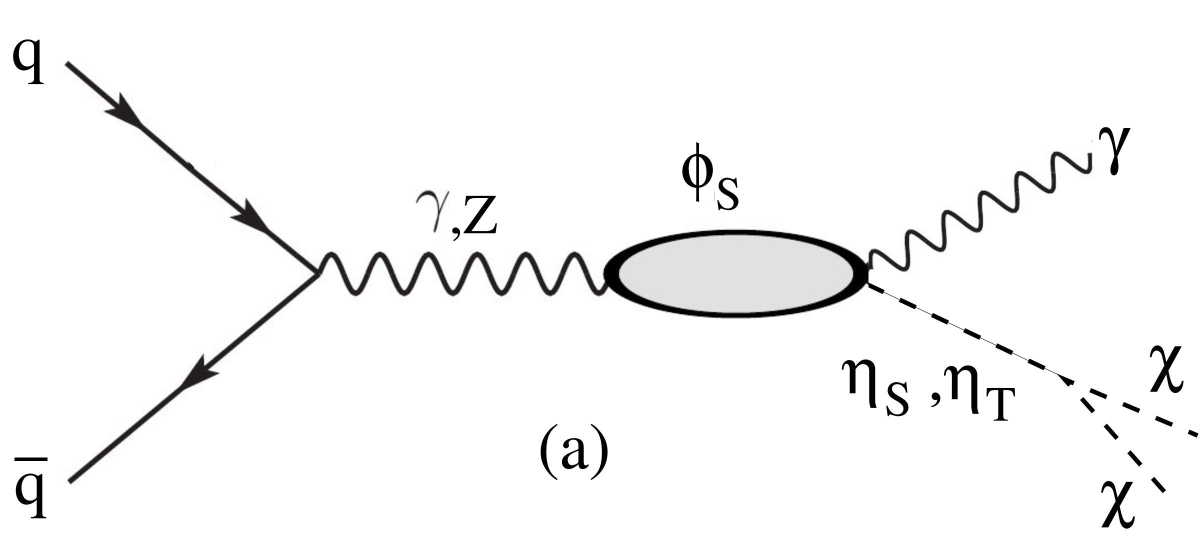
$$\sim 400\ \text{GeV}\ @\ \sqrt{s} = 8\ \text{TeV},\ \mathcal{L} = 20\ \text{fb}^{-1}$$

$$\sim 750\ \text{GeV}\ @\ \sqrt{s} = 14\ \text{TeV},\ \mathcal{L} = 100\ \text{fb}^{-1}$$

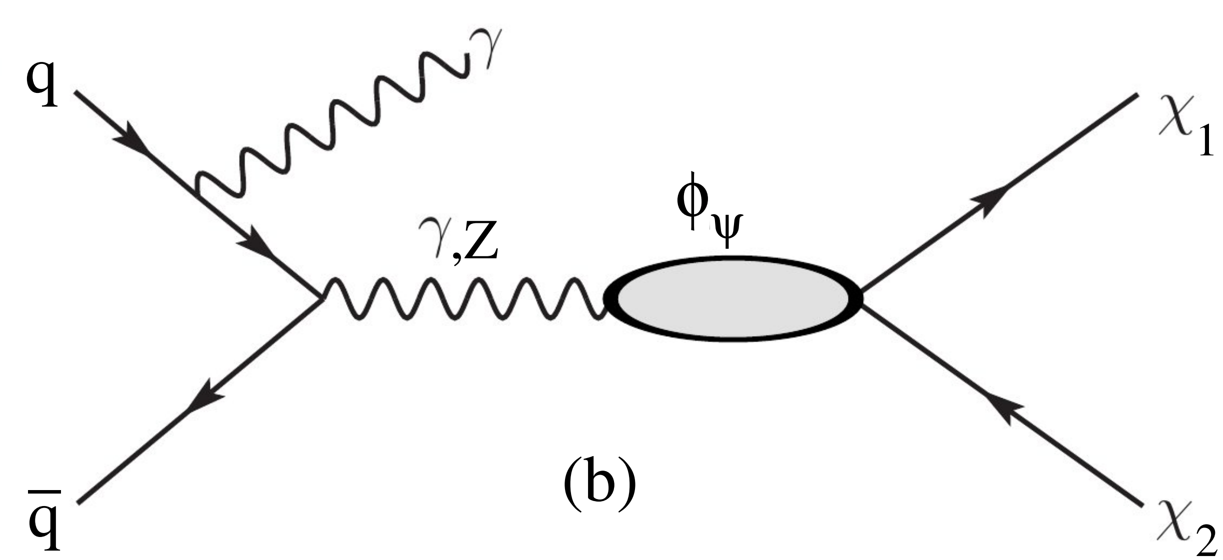
Monophotons

The constraints in the OS dilepton channel could be evaded if the vector meson decays into DM or other hidden sector states dominate

A complementary constraint then arises from the mono-photon (or mono-jet) final state plus larger MET



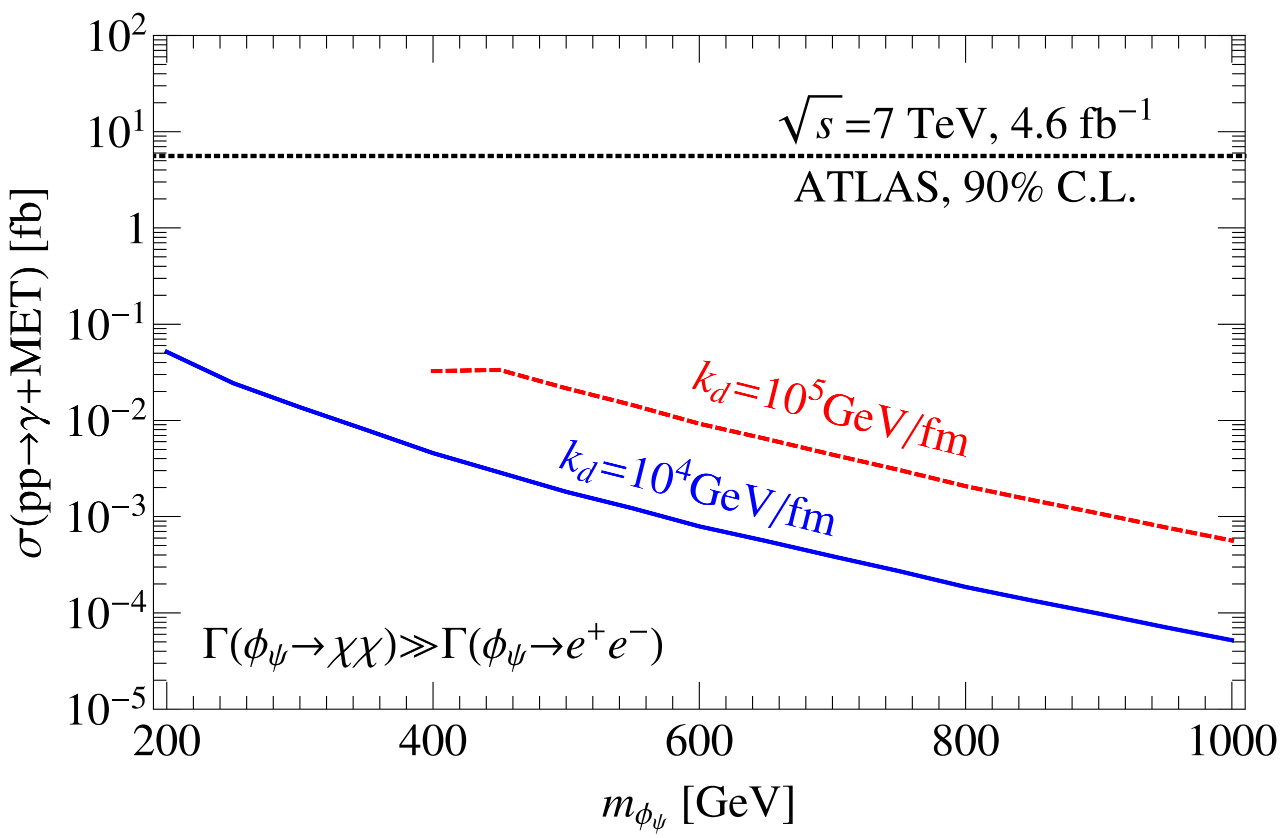
loop model



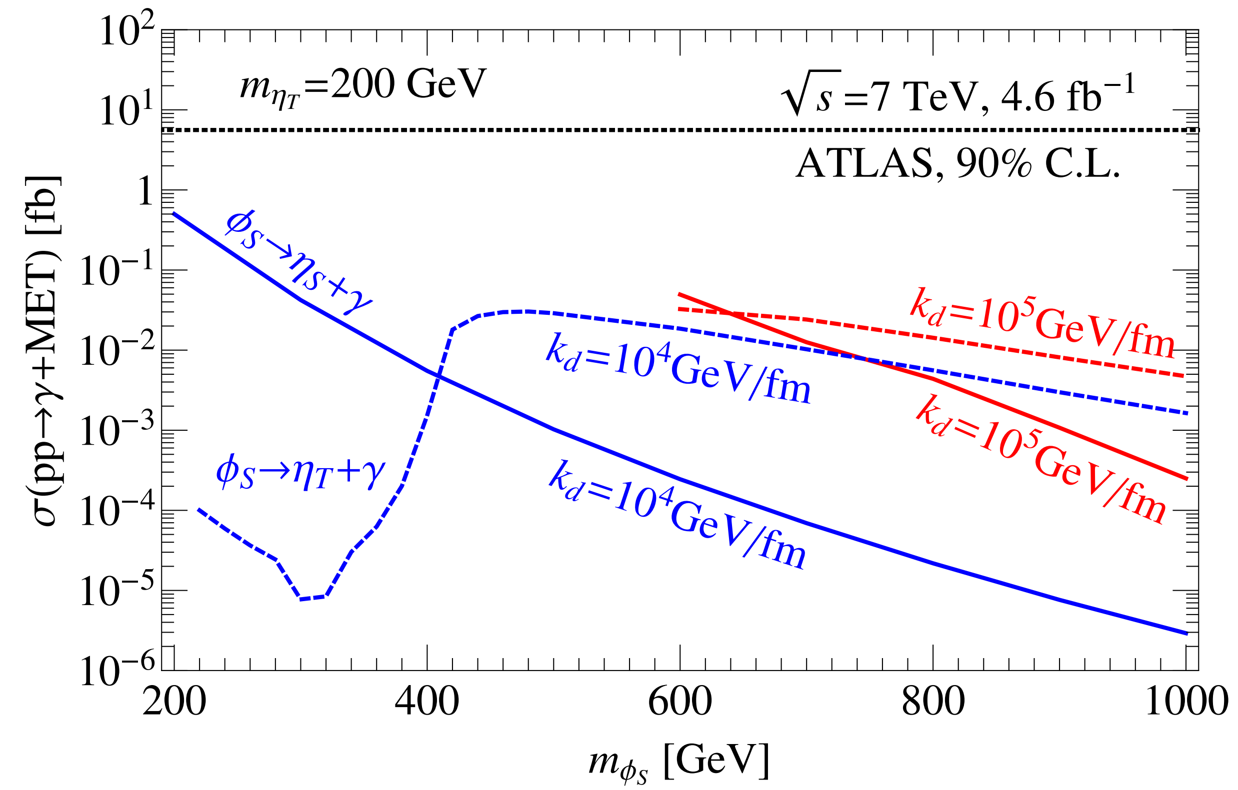
magnetic model

Monophoton constraints at LHC

magnetic model



loop model



Analyzed using the same detector cuts as ATLAS

MET $>$ 150 GeV and photon $P_T > 150$ GeV along with other cuts

far below current limits

Summary of LHC constraints

LHC Observable	Constraint (loop model)	Constraint (MD model)
same-sign dileptons	$\mathrm{BR}(\eta_{ST} \to ee, \mu\mu) \ll 1$ 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	–	–

4-photon constraints are the projected limits

Strongly Self-Interacting Dark Matter

Hints of DM self-interaction

Standard cold dark matter seems to get structure wrong at small scales.

N-body simulations predict cuspy density profiles, while observations suggest core structure.

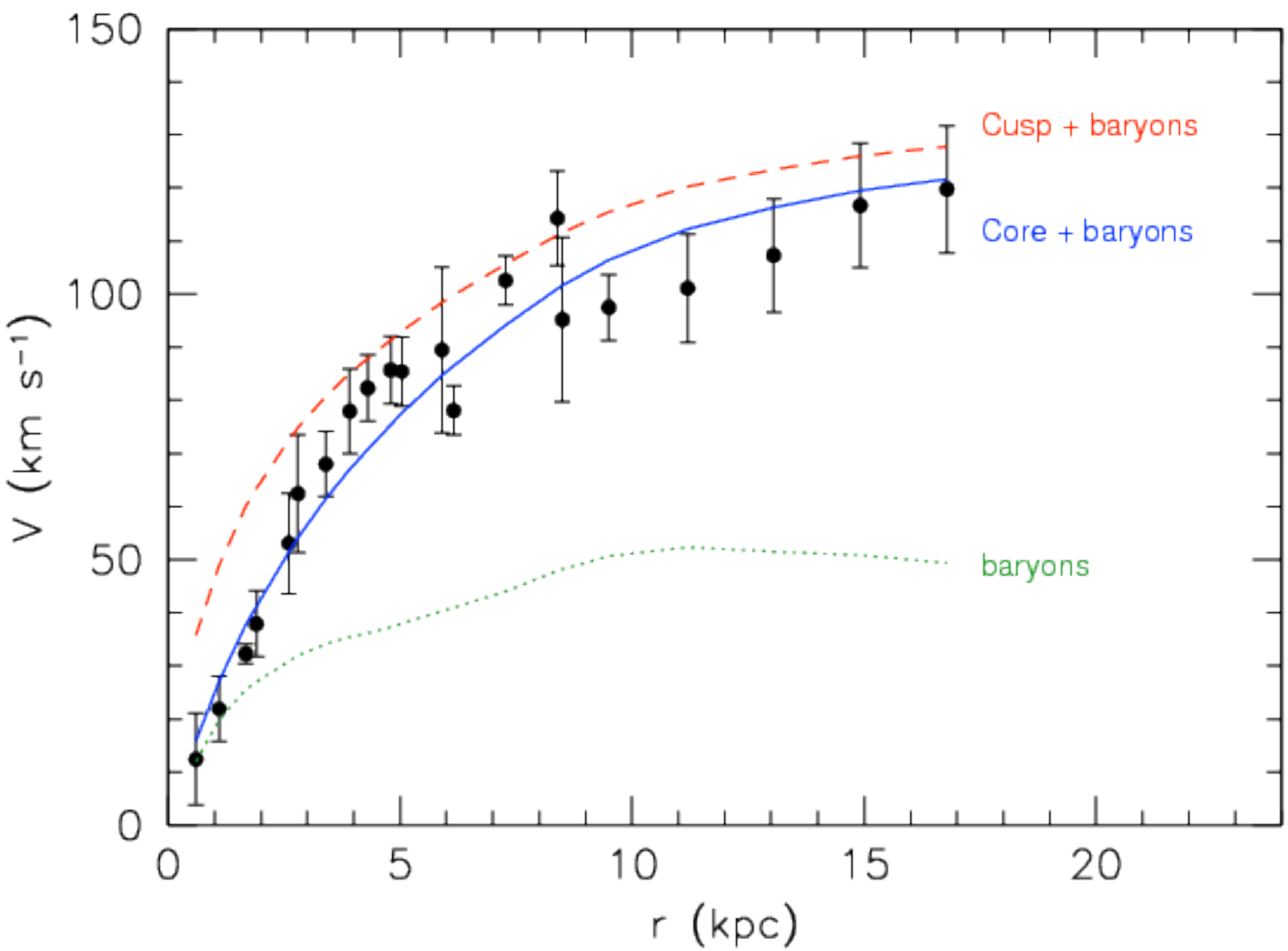
Less satellite galaxies are observed in Milky Way than predicted. The so-called "missing satellite" problem.

If DM scatters with itself elastically, with

$$\sigma/m \sim \ 1\ \mathrm{barn/GeV}$$

these problems are ameliorated.

Cusp versus Core



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baryons are subdominant.

core+baryons fits the data well.

cuspy profile has too much matter in the central region.

Too big to fail problem

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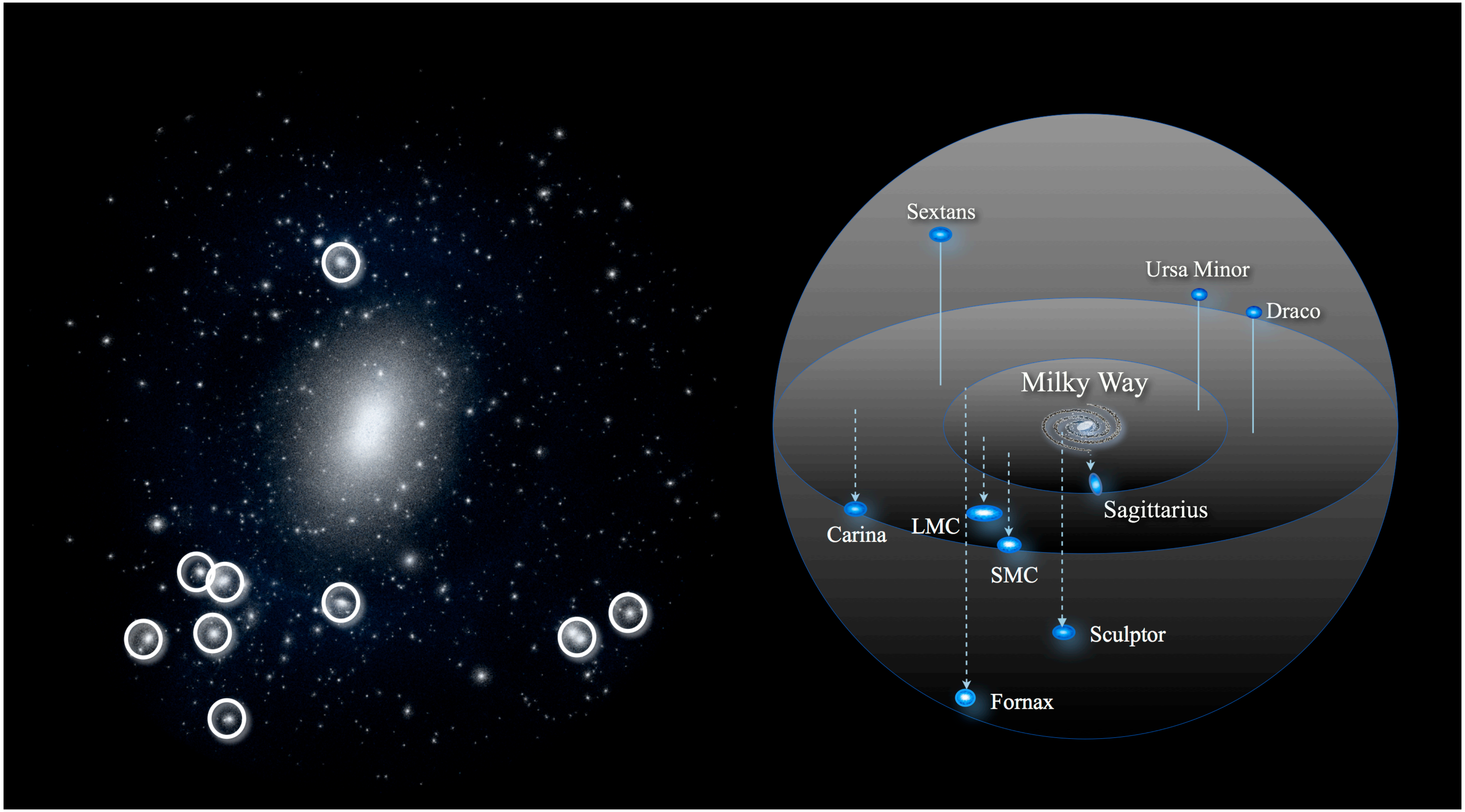
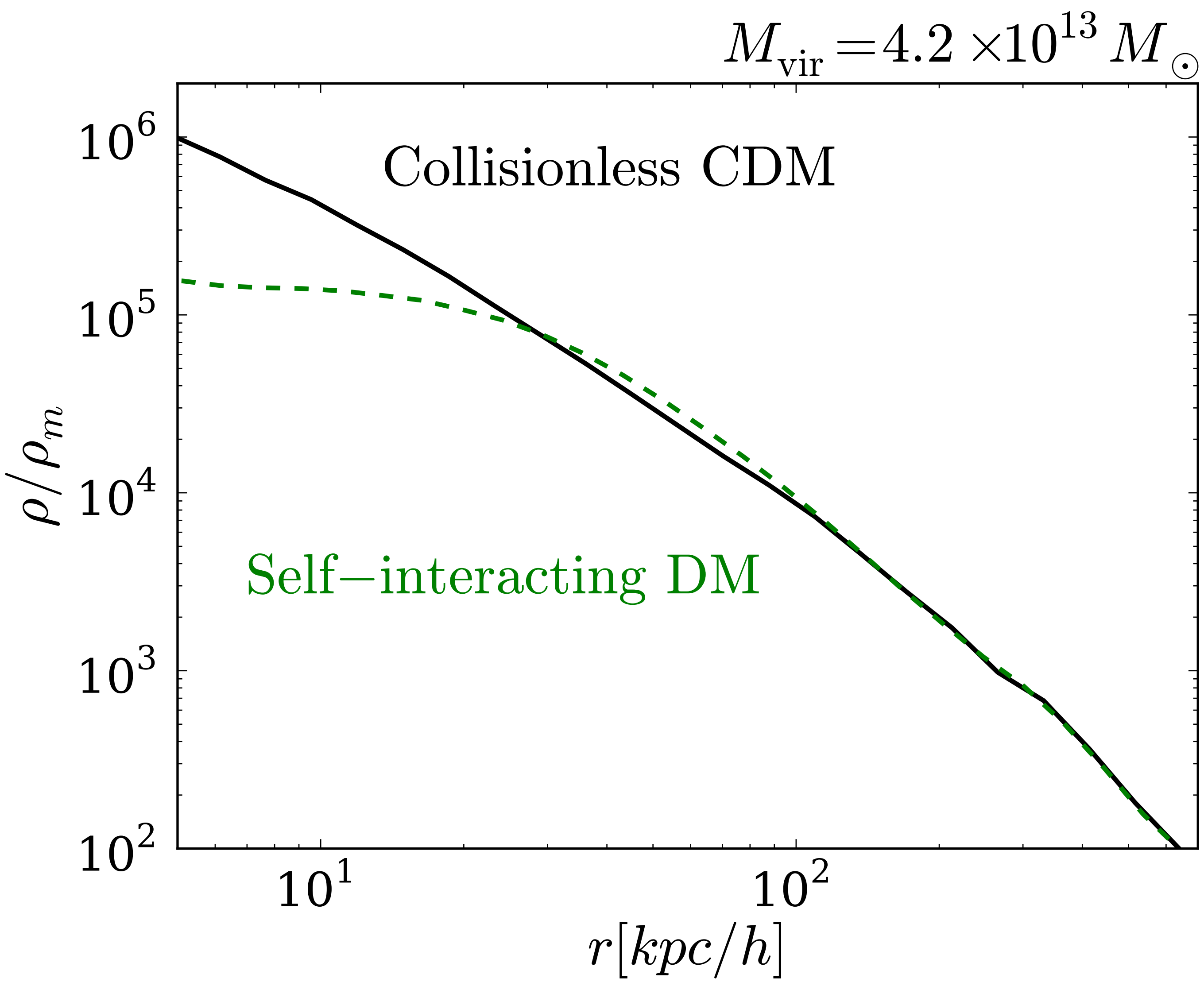


Largest predicted dwarf satellites (left) have too high central densities to match the observed ones (right).

self-interaction produces a core

DM at large radii have larger velocity. They scatter with DM at smaller radii, heating them up. Essentially the cuspy profile gets puffed up.



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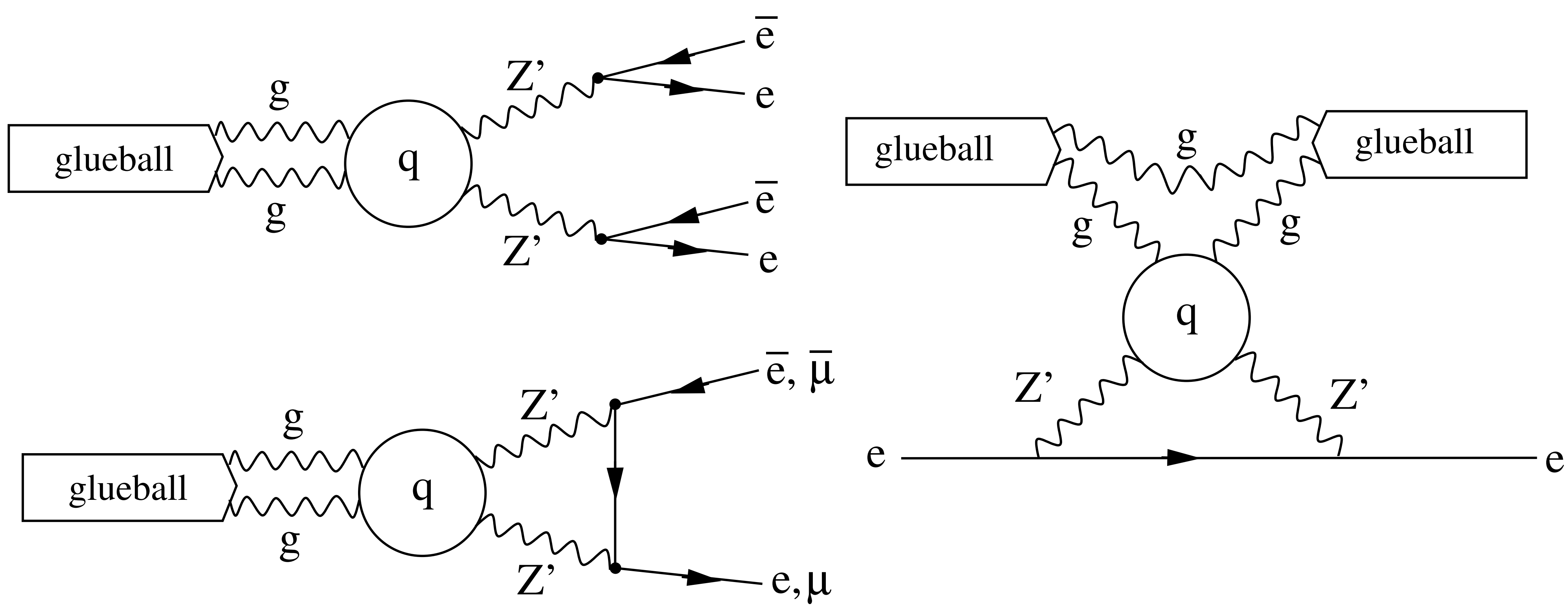
Meanwhile, self-interacting dark matter (SIDM) predicts less satellites than collisionless CDM.

dark glueball DM

Dark glueball can be dark matter in hidden SU(N) with heavy quarks. Dark glueballs can have the right self-interacting cross section with mass ~ 500 MeV

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

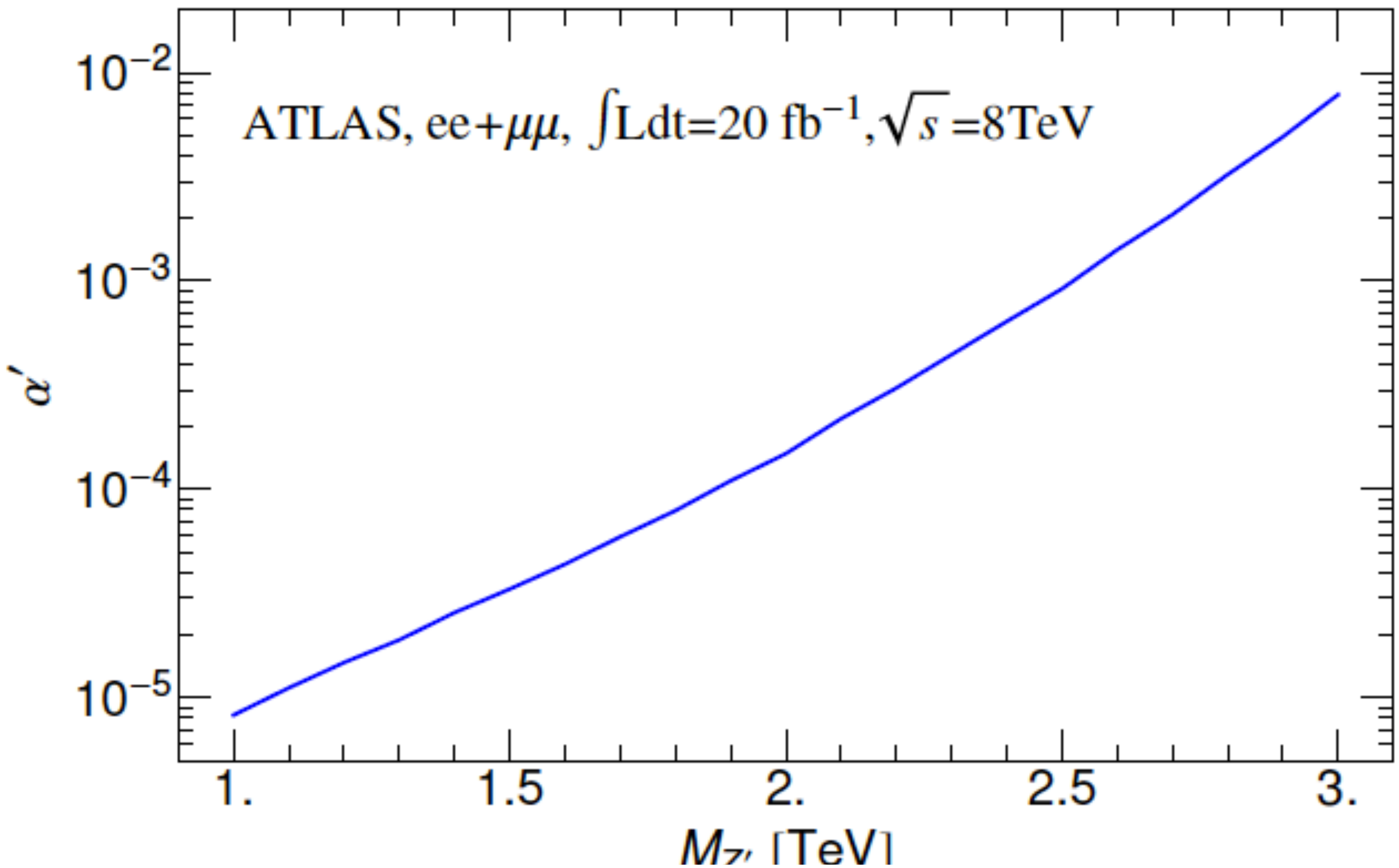


CMB and LHC constraints

CMB constrains $m_{Z'}$ (lifetime $> 4 \times 10^{24}$ s) ($x \equiv m_q/700$ MeV)

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

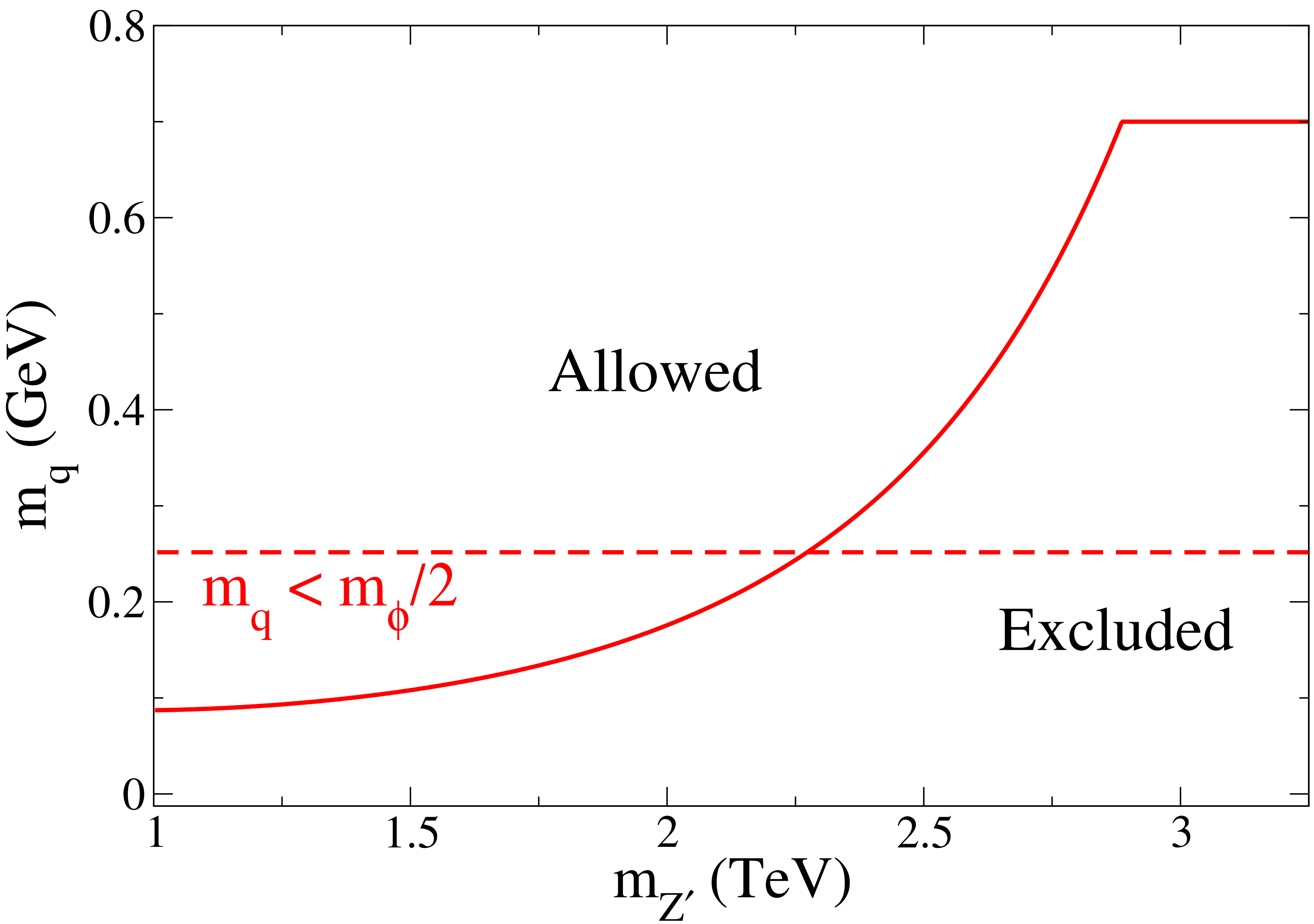
ATLAS constrains α' via dileptons



Combing ATLAS and CMB

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



Summary

- Hints for 130 GeV dark matter in Fermi/LAT data seemed strong, but now it starts to disappear. HESS-II and future Fermi-LAT will definitively resolve this issue, maybe with photon excess at other energies
- Composite states with strong dynamics in hidden SU(N) can enhance the gamma ray cross section.
- Decays of charged bound states can produce like-sign leptons, opposite-sign leptons, lepton plus photon, and multi-photon final states at LHC
- The mono-photon (mono-jet) plus large MET search at LHC provides a complementary constraint if the charged bound states decaying into dark matter dominates
- Dark glueball DM might be indirectly probed at LHC

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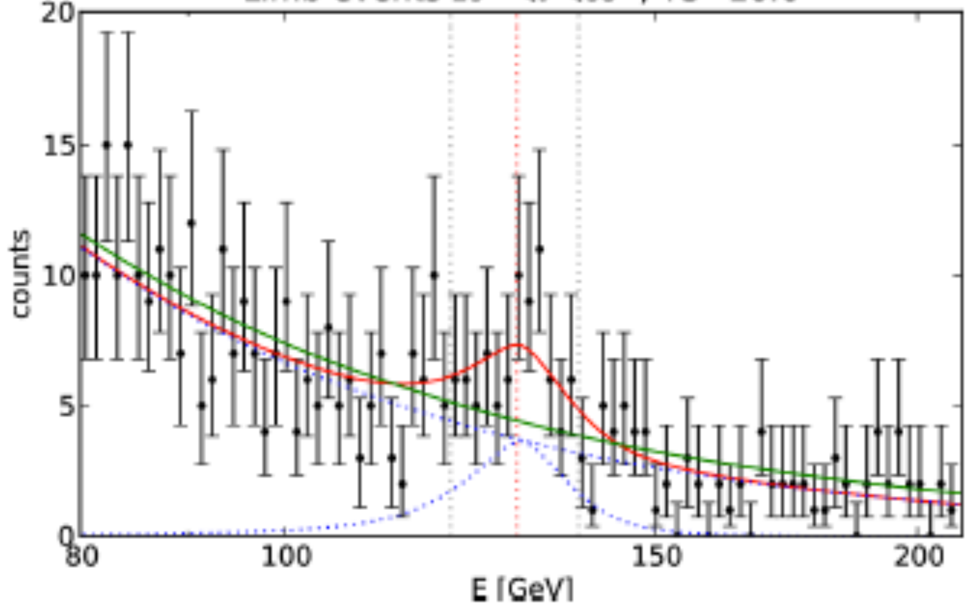
Additional Slides

The Earth Limb Line

The Earth Limb Line



[Finkbeiner et al., Hektor et al.,2012; Ackermann et al., 2013]

~3sigma line in low-incidence angle events from the Earth limb.

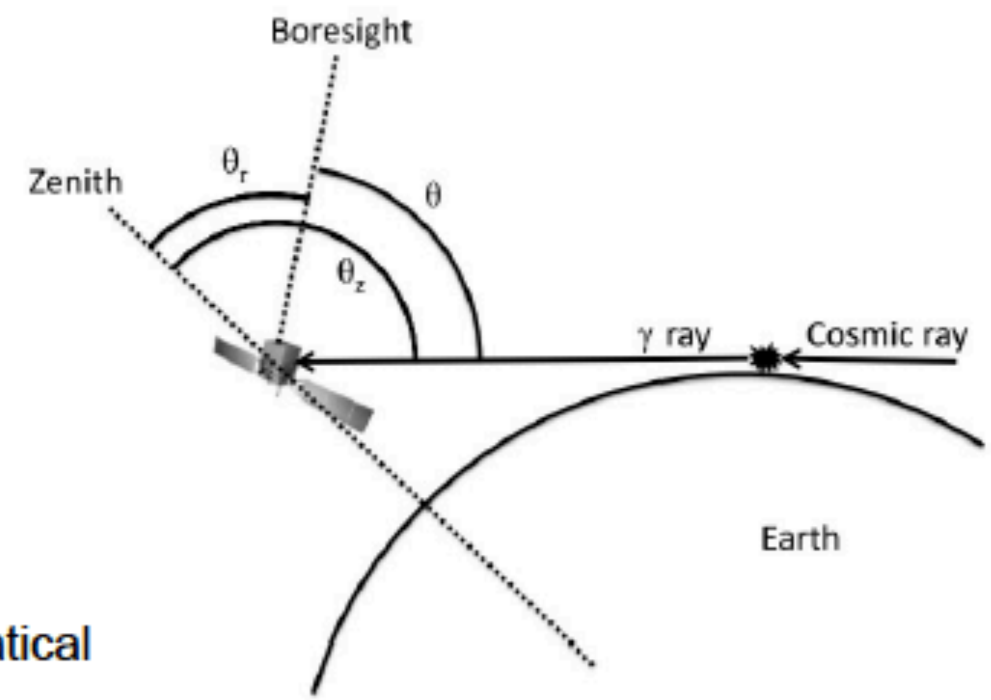


Fig. from 1305.5597

This is the strongest argument for a systematical cause of 130 GeV features in the LAT data.

from Weniger's talk