Collider Searches for DM in Mono-Everything Final States

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arXiv:1312.2592
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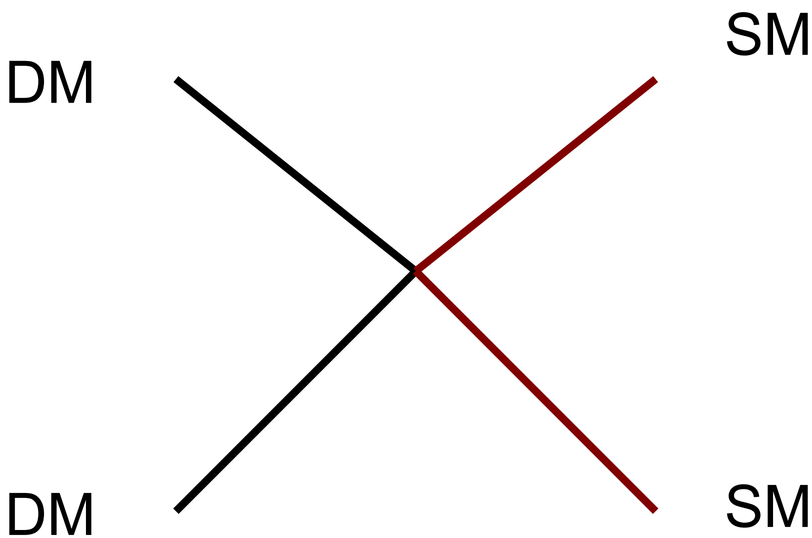
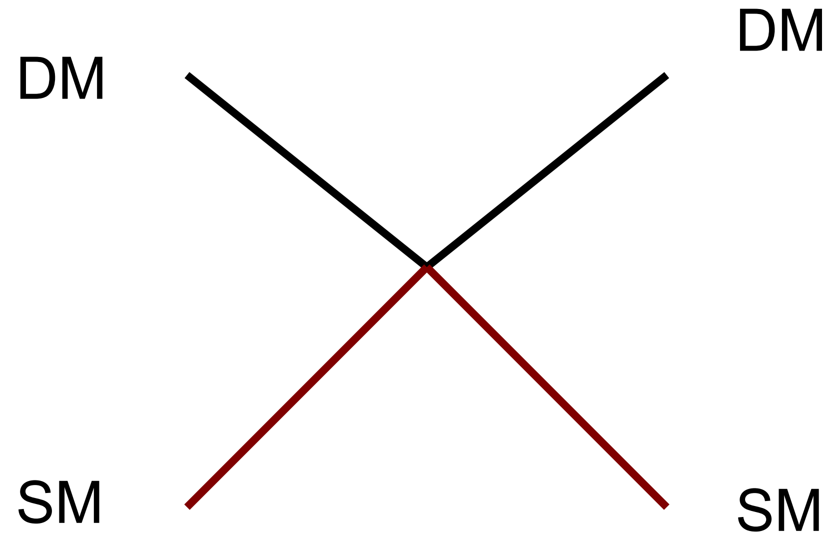
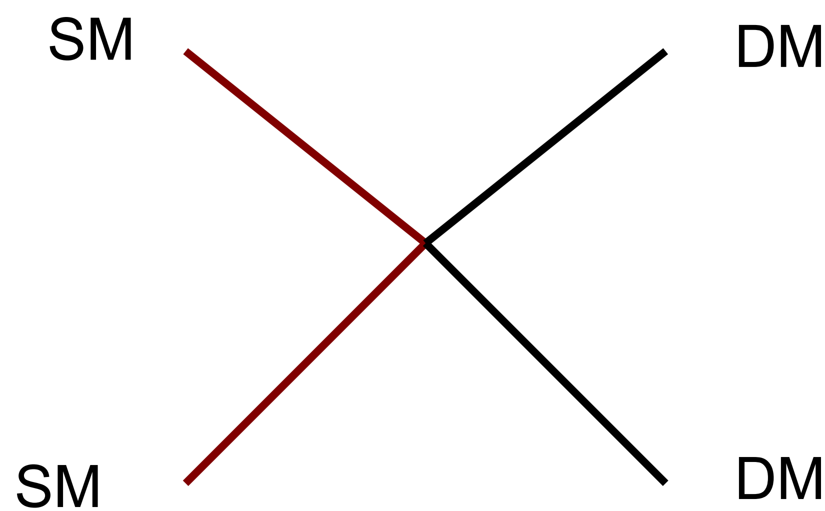
with Whiteson, Frate, Zhou, Nelson, Cotta, Shimmin, Tait, DiFranzo, Mulhearn



DM Annihilation



DM Scattering



DM Pair Production at Colliders

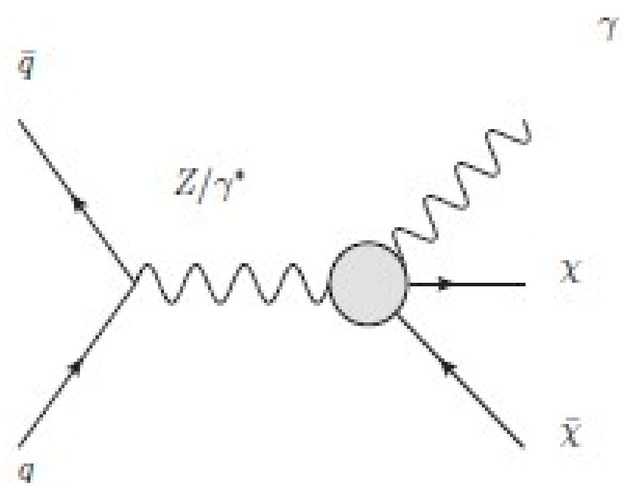
Use colliders to constrain parameters in models of DM in this case by considering the pair production of DM particles along with a single boson

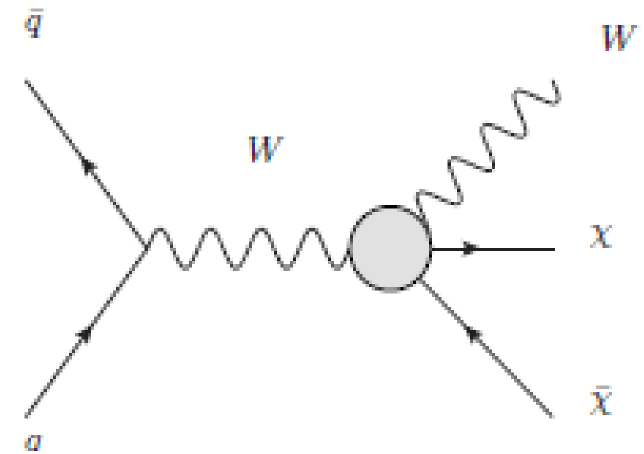
Consider all effective operator for DM particles to couple to EW bosons

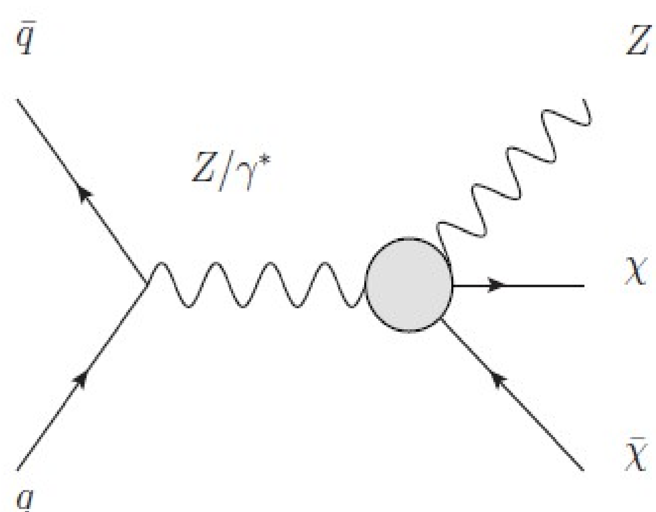
Expect process pp - Boson+$\chi\chi$ at LHC, Mono-something +MET

Recast the Existing searches bound models

Synthesize Data with Indirect Searches







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Operators of Effective Dim 5

$$\frac{1}{\Lambda_5^3}\,\bar{\chi}\chi\,(D_\mu H)^\dagger D^\mu H$$

Inserting Higgs vevs and expanding the covariant derivative yields

$$\frac{m_W^2}{\Lambda_5^3}\,\bar{\chi}\chi\,W^{+\mu}W_\mu^- + \frac{m_Z^2}{2\Lambda_5^3}\,\bar{\chi}\chi\,Z^\mu Z_\mu$$

Notice a single parameter determines ratio of DM couplings to W's and Z's. $\gamma\gamma$ a γZ couplings genrated at higher at loop order.

Dimension 6 and 7 Operators

$$\mathcal{L} = \frac{1}{\Lambda^3_{C1,2}} \bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu} +$$
$$\frac{1}{\Lambda^3_{C3,4}} \bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} \tilde{F^i_{\mu\nu}}$$

Fermionic DM

$$\mathcal{L} = \frac{1}{\Lambda^3_{C5,6}} \bar{\chi}\gamma^5\chi \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu} +$$
$$\frac{1}{\Lambda^3_{C7,8}} \bar{\chi}\gamma^5\chi \sum_i k_i F_i^{\mu\nu} \tilde{F^i_{\mu\nu}},$$

Fermionic DM, pseudoscalar current

$$\mathcal{L} = \frac{1}{\Lambda^2_{B1,2}} \bar{\phi}\phi \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu}$$
$$+ \frac{1}{\Lambda^2_{B3,4}} \bar{\phi}\phi \sum_i k_i F_i^{\mu\nu} \tilde{F^i_{\mu\nu}}$$

Scalar DM

A Note on Gauge Invariance

The general gauge invariant operators are given by

$$L = \frac{1}{\Lambda_7^3}\,\bar{\chi}\chi\,\sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu}$$

3 independent couplings for 3 SM gauge groups

$$g_{gg} = \frac{k_3}{\Lambda_7^3}$$

One independent coupling for SU(3)

$$g_{WW} = \frac{2k_2}{s_w^2 \Lambda_7^3}$$

$$g_{ZZ} = \frac{1}{4 s_w^2 \Lambda_7^3} \left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2} \right)$$

$$g_{\gamma\gamma} = \frac{1}{4 c_w^2} \frac{k_1 + k_2}{\Lambda_7^3}$$

$$g_{Z\gamma} = \frac{1}{2 s_w c_w \Lambda_7^3} \left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2} \right)$$

Related by Gauge invariance, determined by 2 coefficients

X-Section Dependence

Production xsec varies with DM particle mass

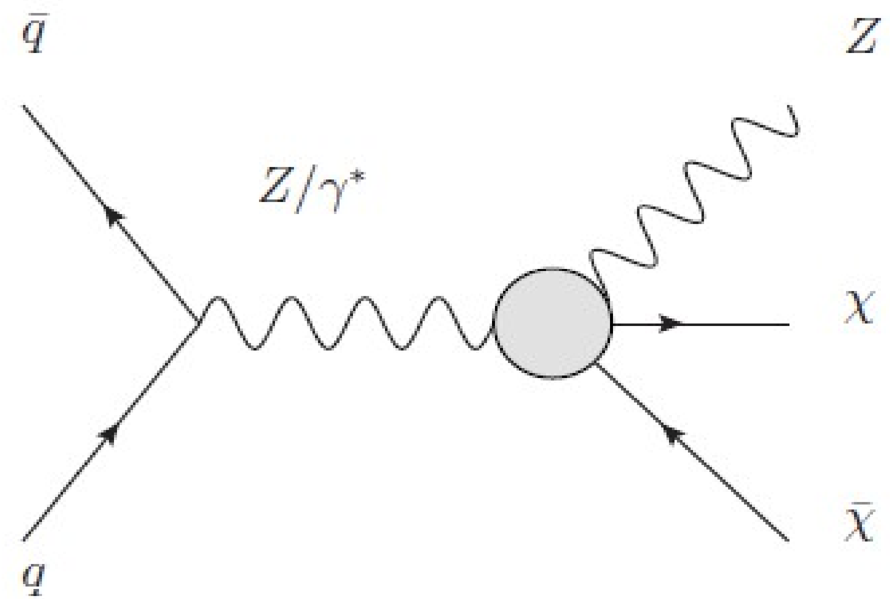
Production xsec varies with effective cut-off of operator

Production xsec's vary with momentum dependence of operator

*Gauge invariance demands correlations across channels

$$L = \frac{1}{\Lambda_7^3} \bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} F_{\mu\nu}^i$$

Mono Z depends on 3 parameters



xsec has 2 contributing diagrams

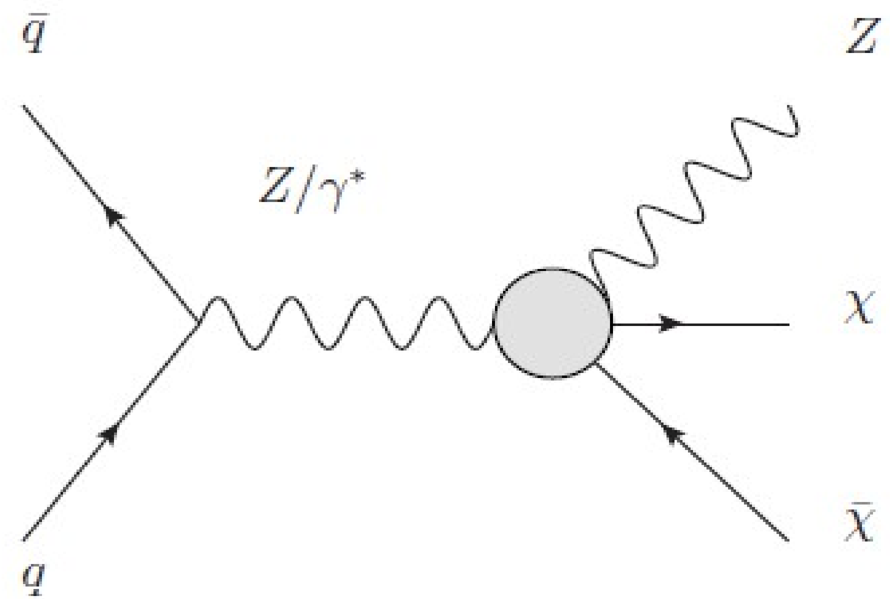
There is a region where photon Contribution is zero

$$g_{Z\gamma} = \frac{1}{2 s_w c_w \Lambda_7^3} \left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2} \right)$$

$$g_{ZZ} = \frac{1}{4 s_w^2 \Lambda_7^3} \left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2} \right)$$

$$L = \frac{1}{\Lambda_7^3} \bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} F_{\mu\nu}^i$$

Mono Z depends on 3 parameters



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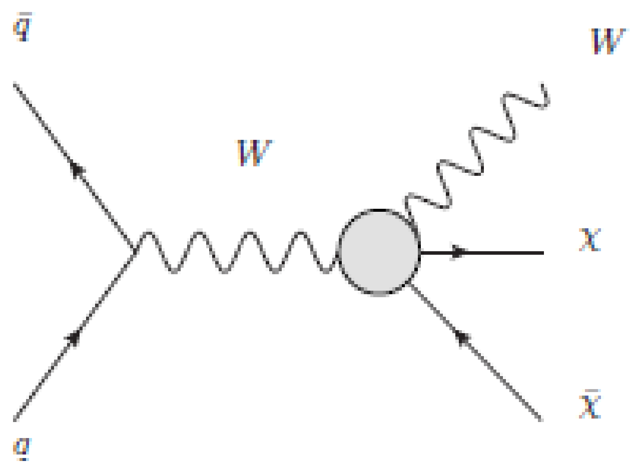
$$g_{Z\gamma} = \frac{1}{2 s_w c_w \Lambda_7^3}\left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2}\right)$$

$$g_{ZZ} = \frac{1}{4 s_w^2 \Lambda_7^3}\left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2}\right)$$

$$L = \frac{1}{\Lambda_7^3}\ \bar{\chi}\chi\ \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu}$$

Mono W depends on 2 parameters



$$\begin{aligned}
g_{gg} &= \frac{k_3}{\Lambda_7^3} \\
g_{WW} &= \frac{2k_2}{s_w^2 \Lambda_7^3} \\
g_{ZZ} &= \frac{1}{4 s_w^2 \Lambda_7^3}\left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2}\right) \\
g_{\gamma\gamma} &= \frac{1}{4 c_w^2}\frac{k_1 + k_2}{\Lambda_7^3} \\
g_{Z\gamma} &= \frac{1}{2 s_w c_w \Lambda_7^3}\left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2}\right)
\end{aligned}$$

ATLAS ZZ Search

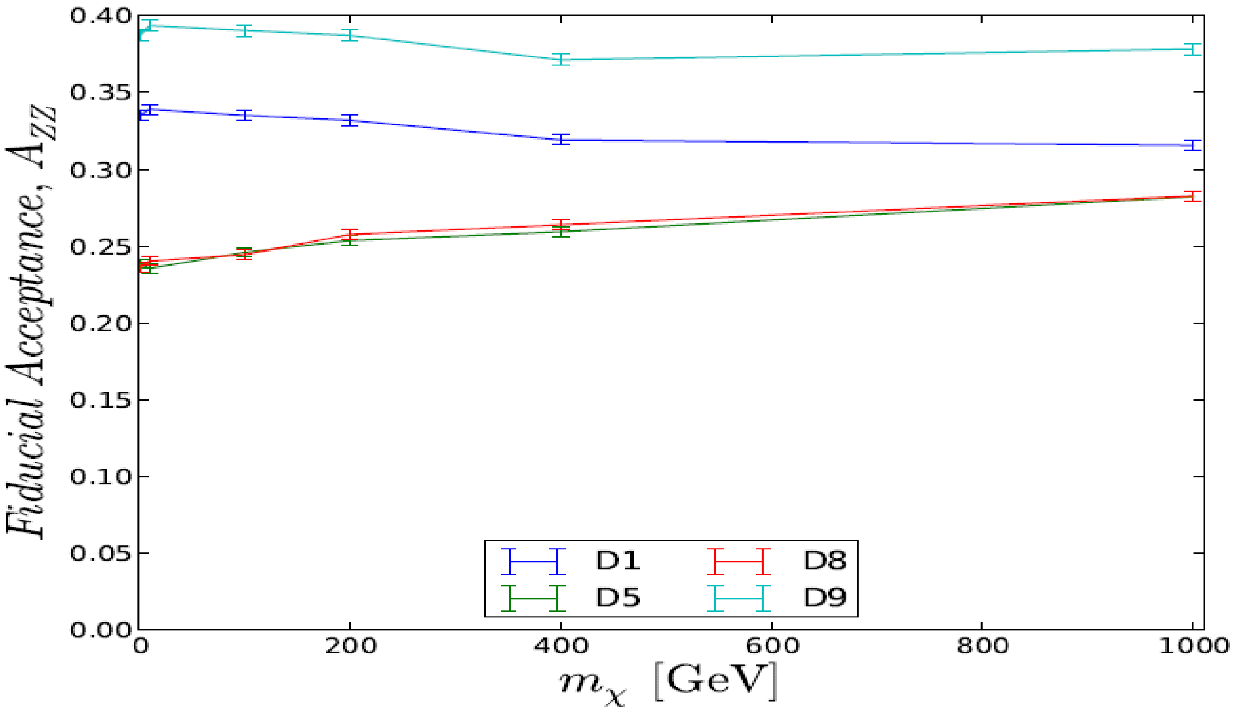
7 TeV, 4.6 inverse fb of data

- two same-flavor opposite-sign electrons or muons, each with $p_{\mathrm{T}}^{\ell} > 20$ GeV, $|\eta^{\ell}| < 2.5$;
- dilepton invariant mass close to the Z boson mass: $m_{\ell\ell} \in [76, 106]$ GeV;
- no particle-level jet with $p_{\mathrm{T}}^{j} > 25$ GeV and $|\eta^{j}| < 4.5$;
- $(|p_{\mathrm{T}}^{\nu\bar{\nu}} - p_{\mathrm{T}}^{Z}|)/p_{\mathrm{T}}^{Z} < 0.4$;
- $-p_{\mathrm{T}}^{\nu\bar{\nu}} \times \cos(\Delta\phi(p_{\mathrm{T}}^{\nu\bar{\nu}}, p_{\mathrm{T}}^{Z})) > 75$ GeV.

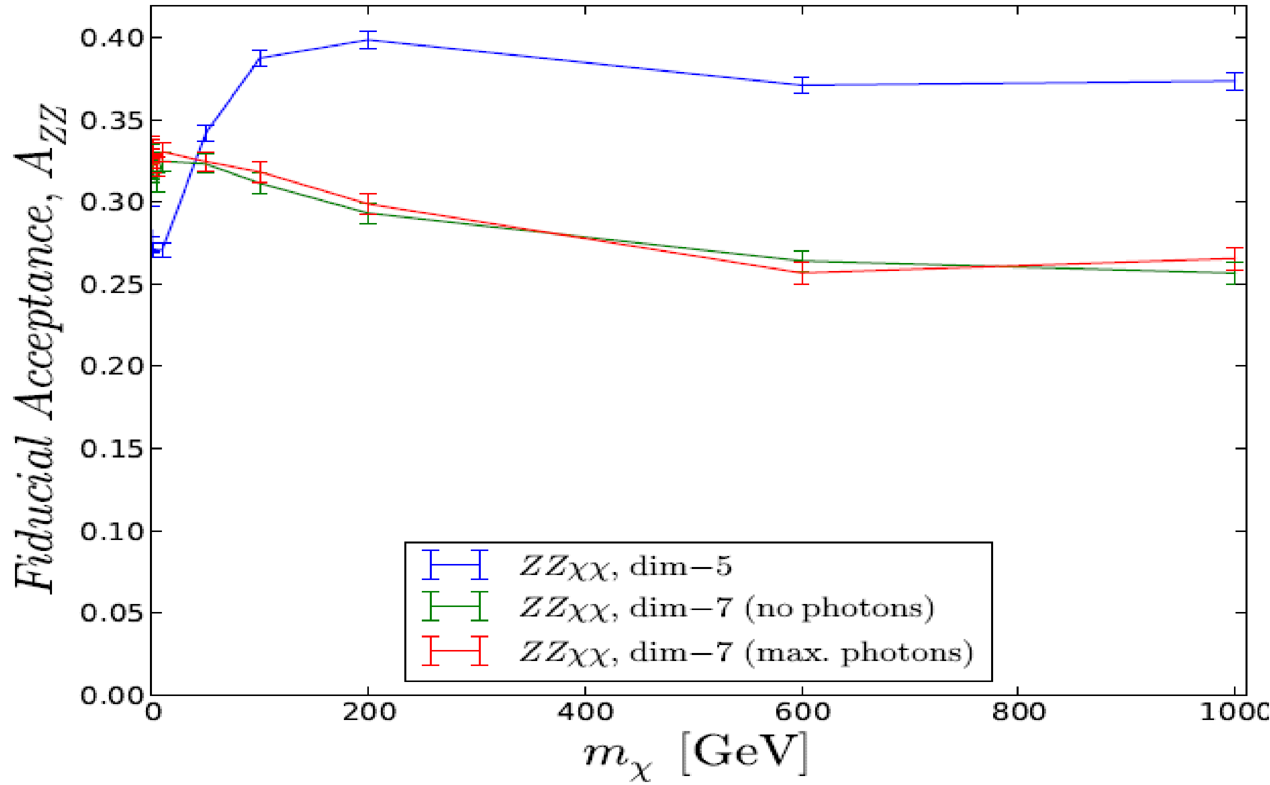
	$ee\nu\nu$	$\mu\mu\nu\nu$	$\ell\ell\nu\nu$
Background	20.8 ± 2.7	26.1 ± 3.3	46.9 ± 5.5
SM $ZZ \to \ell\ell\nu\nu$	17.8 ± 1.8	21.6 ± 2.2	39.3 ± 4.0
Total	38.6 ± 3.8	47.7 ± 4.6	86.2 ± 7.2
Data	35	52	87

No signif. Deviation over SM process is observed.
Limits on DM operators may be set

Total # of events N<18 at 90% confidence

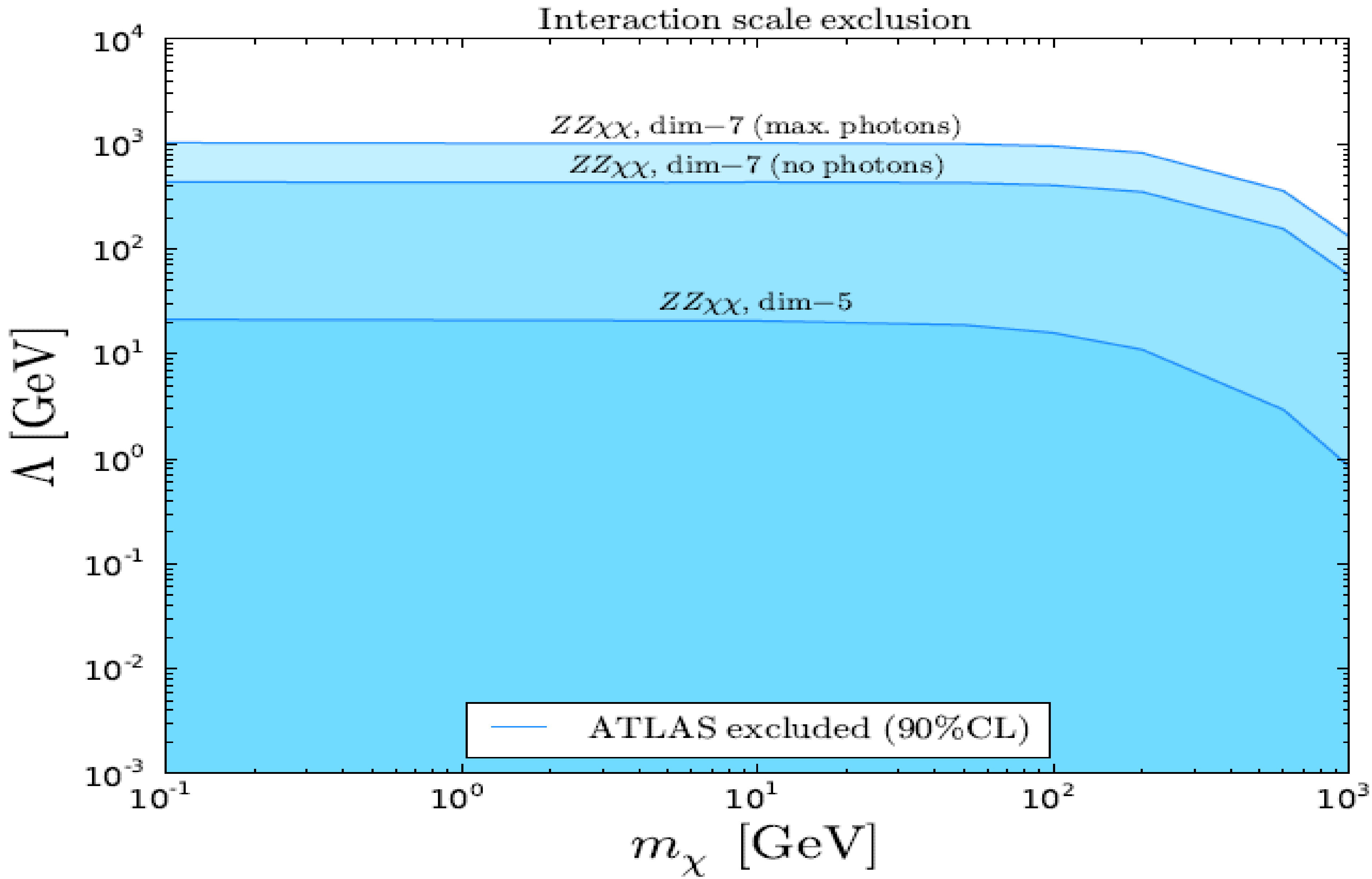


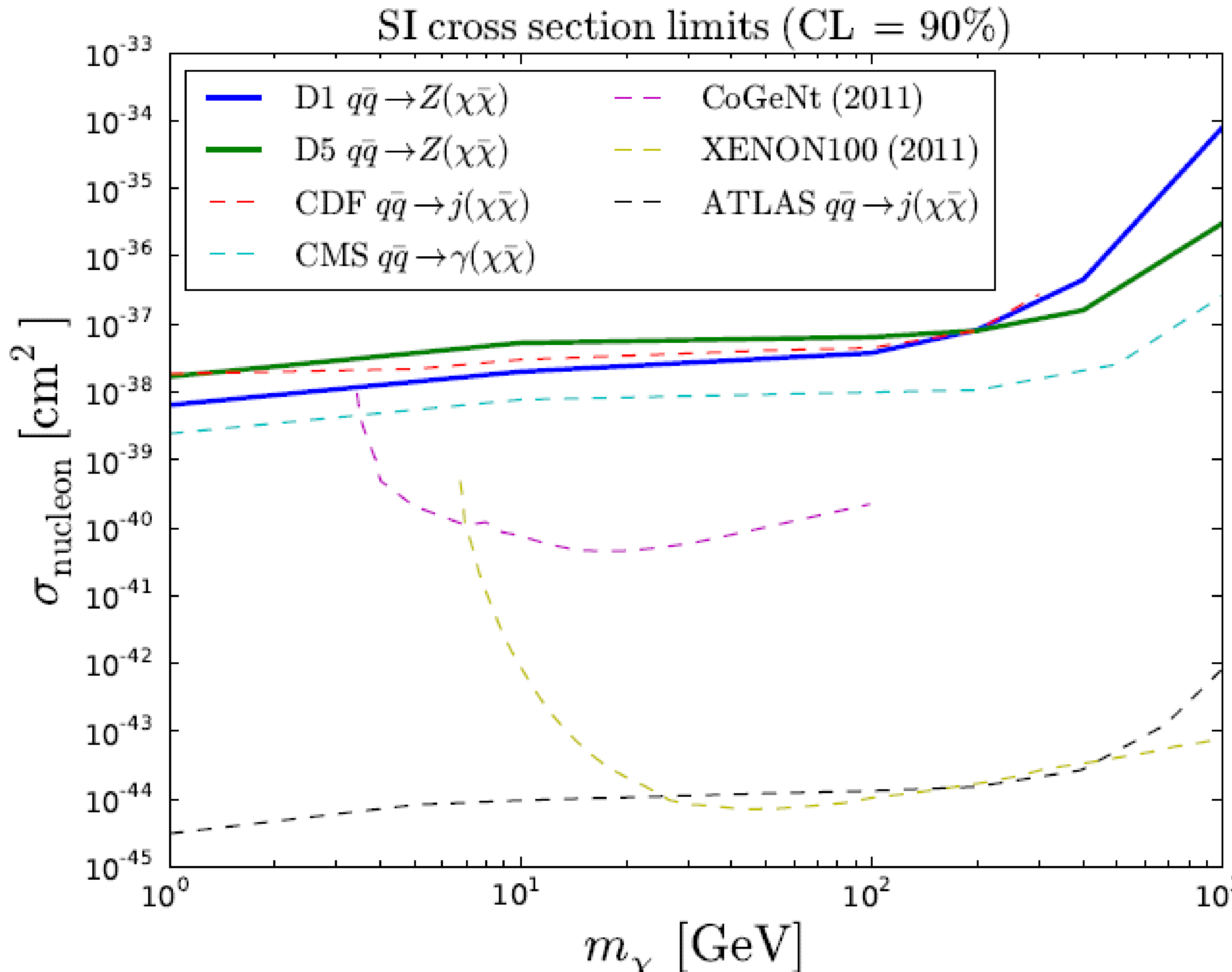
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Fiducial Acceptance, A_{ZZ}
0
200
400
600
800
1000
m_χ [GeV]
D1
D5
D8
D9



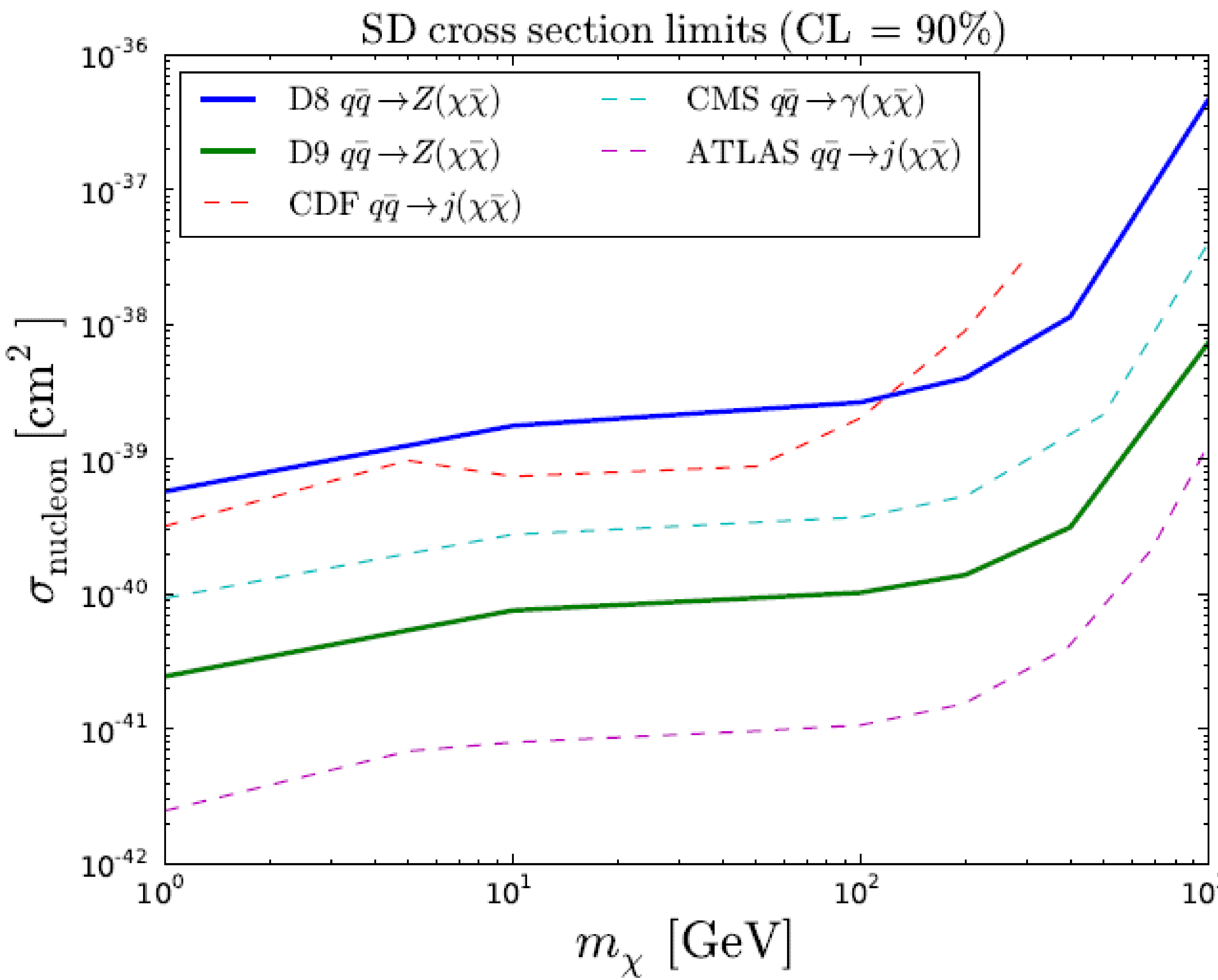
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Fiducial Acceptance, A_{ZZ}
0
200
400
600
800
1000
m_χ [GeV]
$ZZ\chi\chi$, dim−5
$ZZ\chi\chi$, dim−7 (no photons)
$ZZ\chi\chi$, dim−7 (max. photons)

Exclusions for Effective Gauge-Boson Operators





SI cross section limits (CL = 90%)
D1 $q\bar{q} \to Z(\chi\bar{\chi})$
D5 $q\bar{q} \to Z(\chi\bar{\chi})$
CDF $q\bar{q} \to j(\chi\bar{\chi})$
CMS $q\bar{q} \to \gamma(\chi\bar{\chi})$
CoGeNt (2011)
XENON100 (2011)
ATLAS $q\bar{q} \to j(\chi\bar{\chi})$
$\sigma_{\rm nucleon}$ [cm^2]
m_χ [GeV]
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{0}
10^{1}
10^{2}
10^{3}

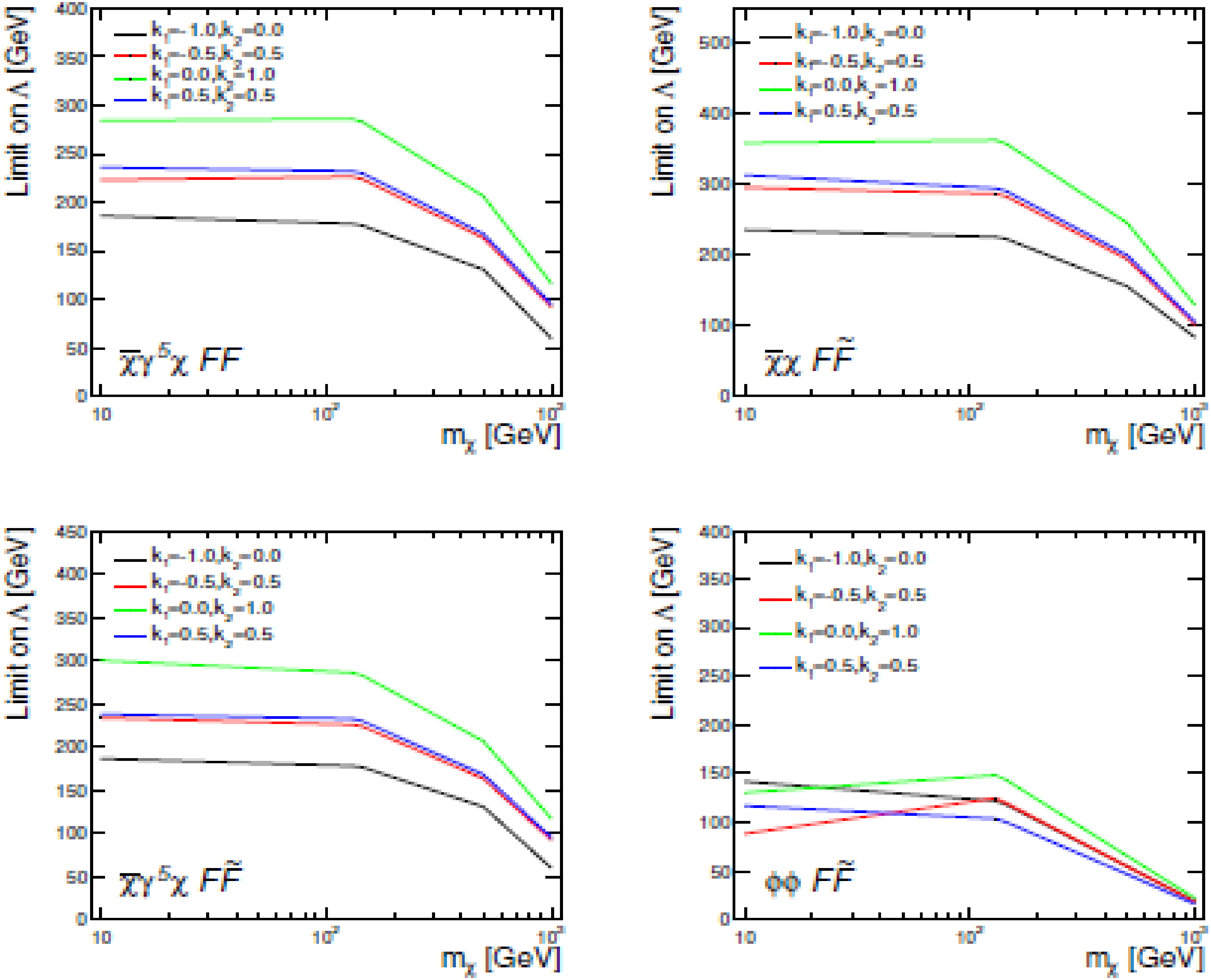


SD cross section limits (CL = 90%)
D8 $q\bar{q} \to Z(\chi\bar{\chi})$
D9 $q\bar{q} \to Z(\chi\bar{\chi})$
CDF $q\bar{q} \to j(\chi\bar{\chi})$
CMS $q\bar{q} \to \gamma(\chi\bar{\chi})$
ATLAS $q\bar{q} \to j(\chi\bar{\chi})$
$\sigma_{\rm nucleon}$ [cm^2]
m_χ [GeV]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^0
10^1
10^2
10^3

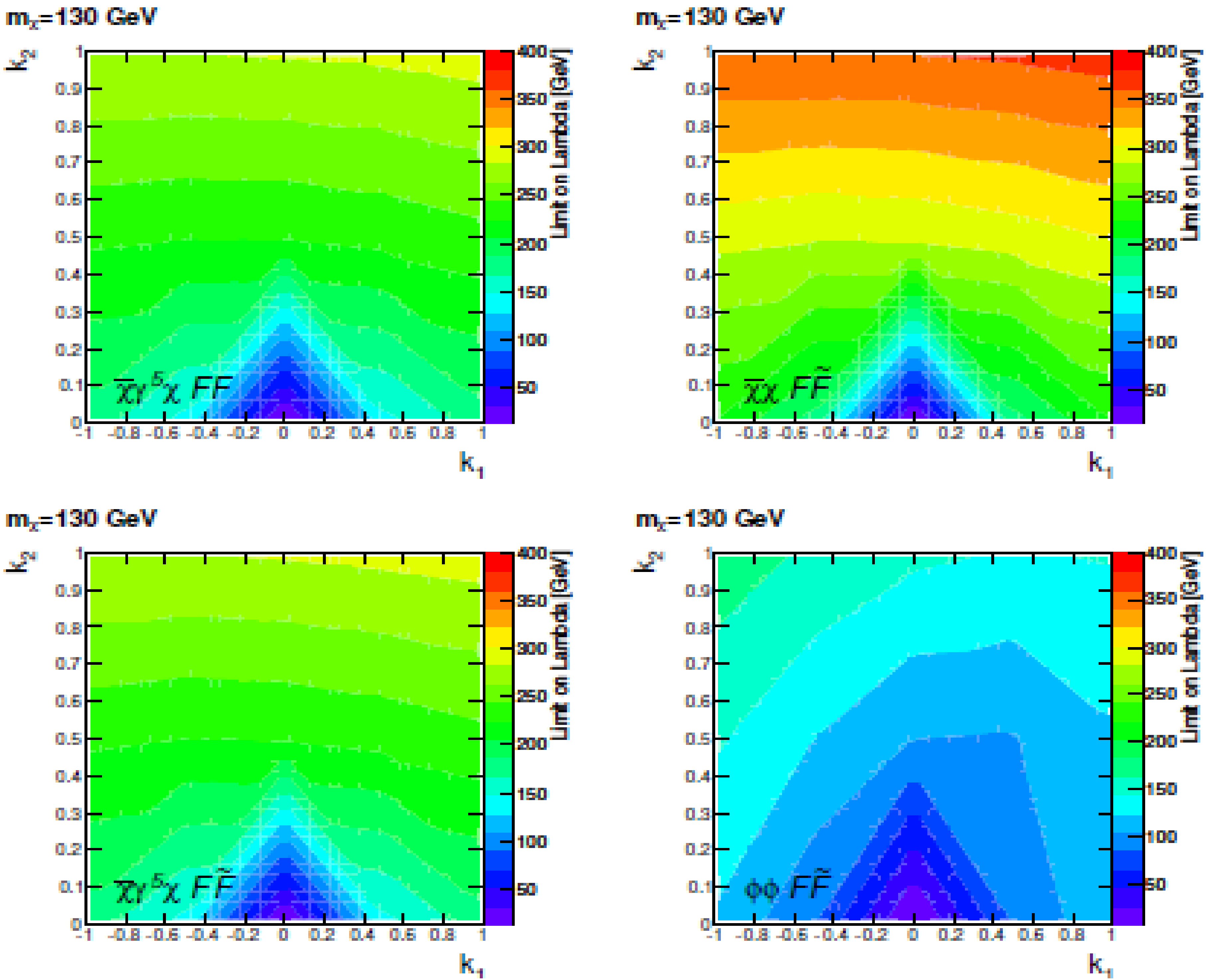
Mono-photon ATLAS 7 TeV 4.6 inv fb

- 1 photon, $p_{\mathrm{T}} > 150$ GeV
- $\not{E}_T > 150$ GeV
- ≤ 1 jet with $p_{\mathrm{T}} > 30$ GeV
- $\Delta\phi(\gamma, \not{E}_T) > 0.4$
- $\Delta\phi(j_1, \not{E}_T) > 0.4$
- No electrons (muons) with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.47$ ($p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.4$)

Background source	Events		
$Z(\rightarrow \nu\nu)\gamma$	93	±16	±8
$Z/\gamma^*(\rightarrow \ell\ell)\gamma$	0.4	±0.2	±0.1
$W(\rightarrow \ell\nu)\gamma$	24	±5	±2
W/Z+jets	18	±6	
Top	0.07	±0.07	±0.01
Diboson	0.3	±0.1	±0.1
γ+jets and multi-jet	1.0	±0.5	
Total	137	±18	±9
Data	116		



Limit on Λ [GeV]
m_χ [GeV]
k1=-1.0,k2=0.0
k1=-0.5,k2=0.5
k1=0.0,k2=1.0
k1=0.5,k2=0.5
χ̄γ5χ FF
χ̄χ FF̃
χ̄γ5χ FF̃
φφ FF̃



m_χ=130 GeV
$\bar{\chi}\gamma^5\chi\, FF$
m_χ=130 GeV
$\bar{\chi}\chi\, F\tilde{F}$
m_χ=130 GeV
$\bar{\chi}\gamma^5\chi\, F\tilde{F}$
m_χ=130 GeV
$\phi\phi\, F\tilde{F}$
k_1
k_2
Limit on Lambda [GeV]

Annihilation Rate to Photons

$$\langle \sigma v \rangle^{\gamma\gamma}_{B1,2} = \frac{2m_\chi^2}{\pi \Lambda_s^4} \left(k_1 c_w^2 + k_2 s_w^2\right)^2$$

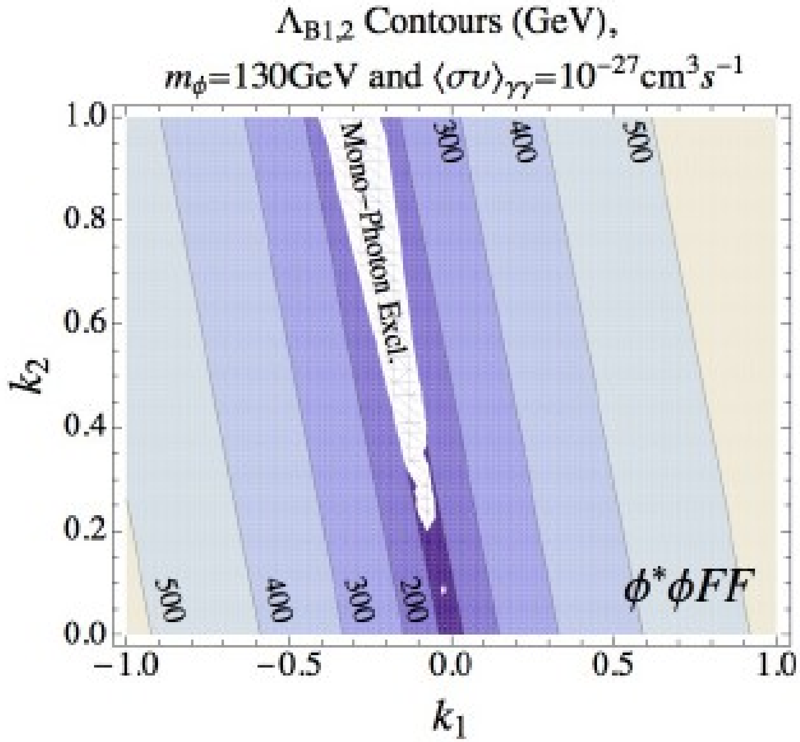
$$\langle \sigma v \rangle^{\gamma Z}_{B1,2} = \frac{3(4m_\chi^2 - m_Z^2)^3 c_w^2 s_w^2}{64 \pi m_\chi^4 \Lambda_s^4} \left(k_1 - k_2\right)^2$$

$$\langle \sigma v \rangle^{\gamma\gamma}_{C5,6} = \frac{4m_\chi^4}{\pi \Lambda_{f5}^6} \left(k_1 c_w^2 + k_2 s_w^2\right)^2$$

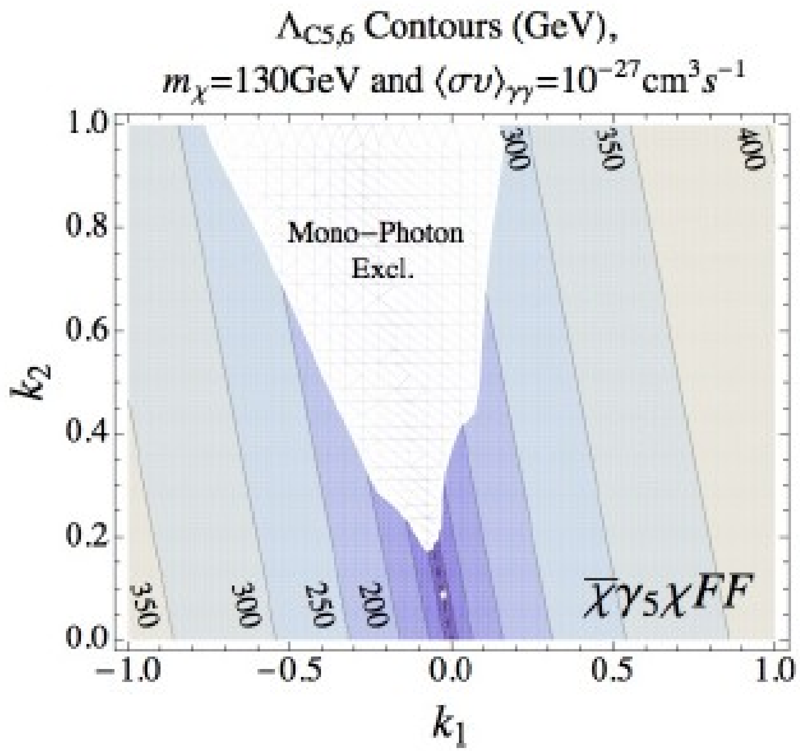
$$\langle \sigma v \rangle^{\gamma Z}_{C5,6} = \frac{3(4m_\chi^2 - m_Z^2)^3 c_w^2 s_w^2}{32 \pi m_\chi^2 \Lambda_{f5}^6} \left(k_1 - k_2\right)^2$$

$$\langle \sigma v \rangle^{\gamma\gamma}_{C7,8} = \frac{8m_\chi^4}{\pi \Lambda_{f5}^6} \left(k_1 c_w^2 + k_2 s_w^2\right)^2$$

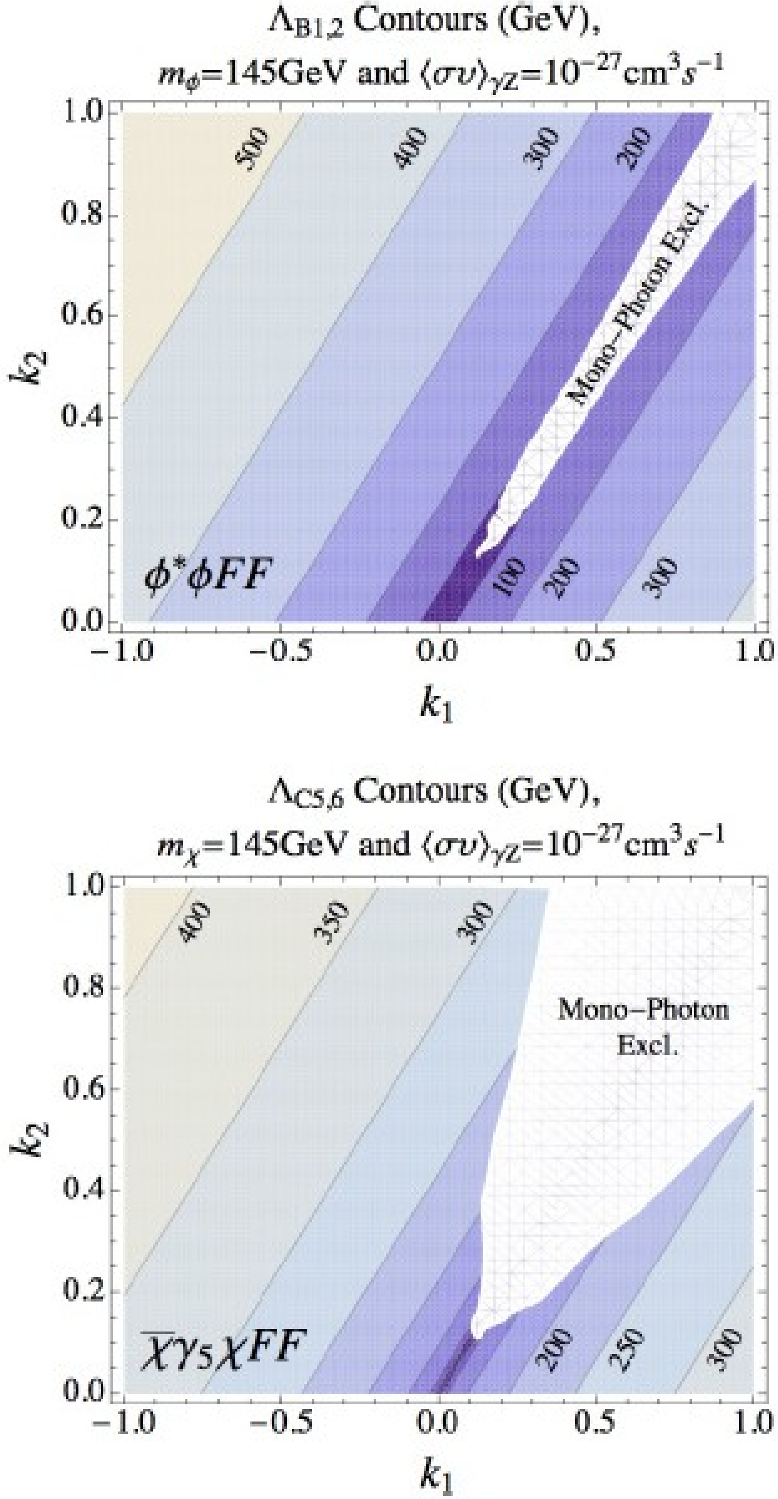
$$\langle \sigma v \rangle^{\gamma Z}_{C7,8} = \frac{(4m_\chi^2 - m_Z^2)^3 c_w^2 s_w^2}{4 \pi m_\chi^2 \Lambda_{f5}^6} \left(k_1 - k_2\right)^2 .$$



$\Lambda_{B1,2}$ Contours (GeV),
m_ϕ=130GeV and $\langle\sigma v\rangle_{\gamma\gamma}=10^{-27}\text{cm}^3 s^{-1}$
Mono−Photon Excl.
300
400
500
500
400
300
200
$\phi^*\phi FF$
k_2
k_1



$\Lambda_{C5,6}$ Contours (GeV),
m_χ=130GeV and $\langle\sigma v\rangle_{\gamma\gamma}=10^{-27}\text{cm}^3 s^{-1}$
Mono−Photon Excl.
300
350
400
350
300
250
200
$\overline{\chi}\gamma_5\chi FF$
k_2
k_1



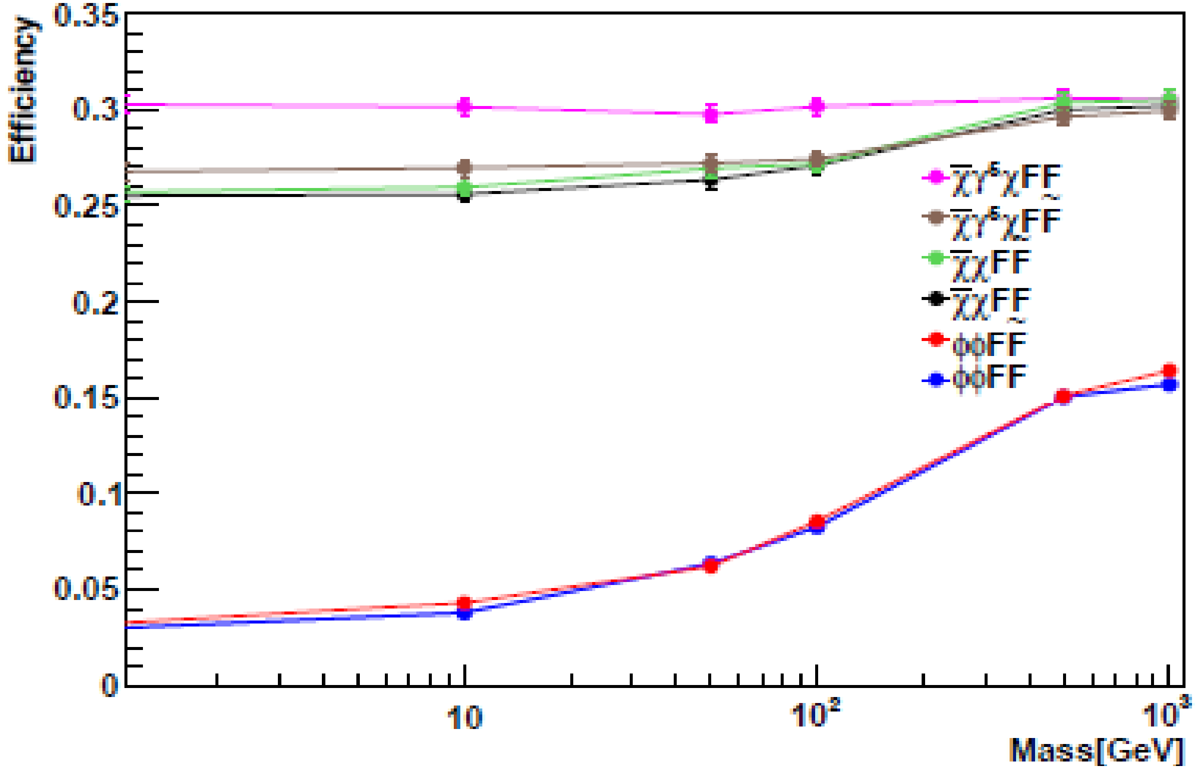
$\Lambda_{B1,2}$ Contours (GeV),
m_ϕ=145GeV and $\langle\sigma v\rangle_{\gamma Z}=10^{-27}\mathrm{cm}^3 s^{-1}$
500
400
300
200
100
200
300
Mono−Photon Excl.
$\phi^*\phi FF$
k_2
k_1
$\Lambda_{C5,6}$ Contours (GeV),
m_χ=145GeV and $\langle\sigma v\rangle_{\gamma Z}=10^{-27}\mathrm{cm}^3 s^{-1}$
400
350
300
200
250
300
Mono−Photon
Excl.
$\overline{\chi}\gamma_5\chi FF$
k_2
k_1

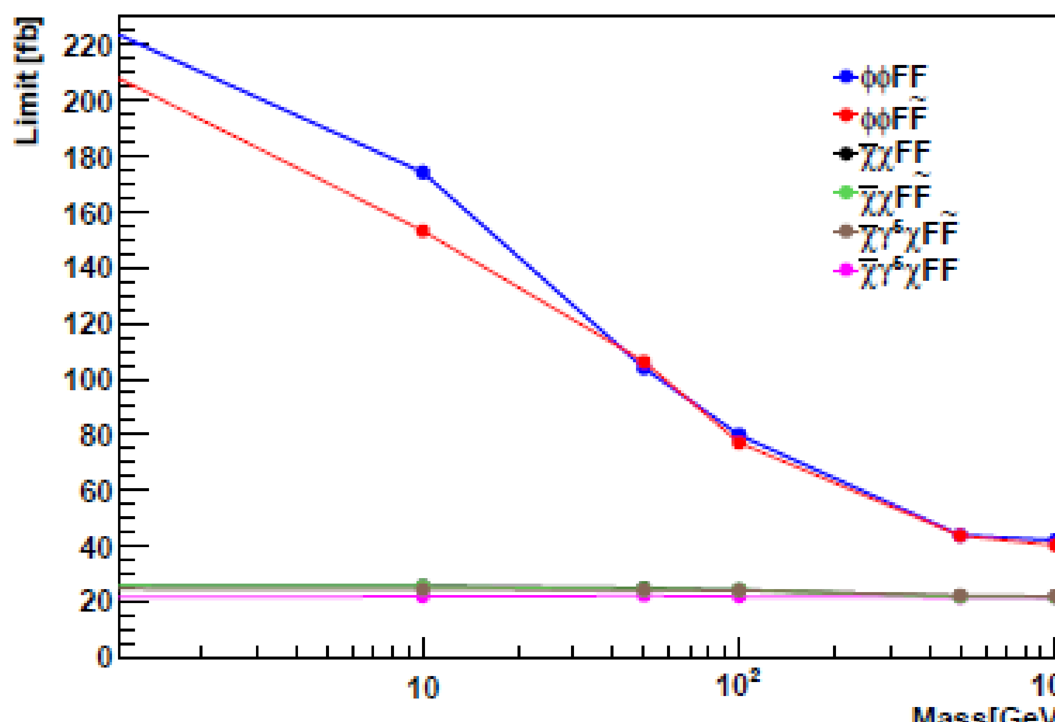
Mono-W ATLAS 8 TeV 20.3 inv fb

- 1 Cambridge-Aachen jet with $R = 1.2$, $p_{\mathrm{T}} > 250$ GeV, $|\eta| < 1.2$, $\sqrt{y} > 0.4$
- $\not\!\!E_T > 350$ GeV
- $\leq$ 1 narrow jet with $p_{\mathrm{T}} > 40$ GeV,$|\eta| < 4.5$, ΔR(narrow jet, fat jet) > 0.9
- No electrons, muons, or photons with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.47$, $|\eta| < 2.5$, and $|\eta| < 2.37$ respectively

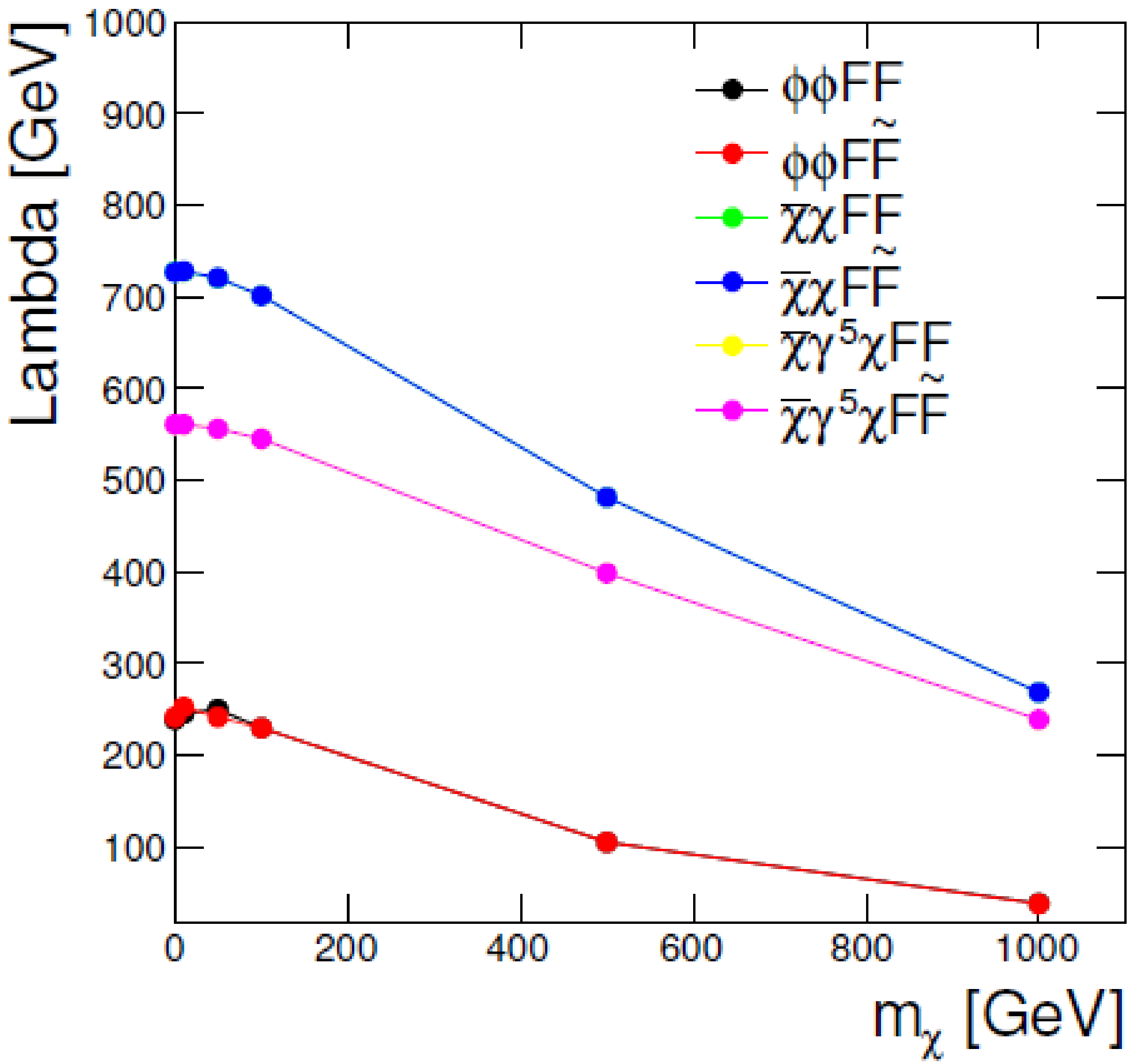
Look for Hadronically decaying W boson

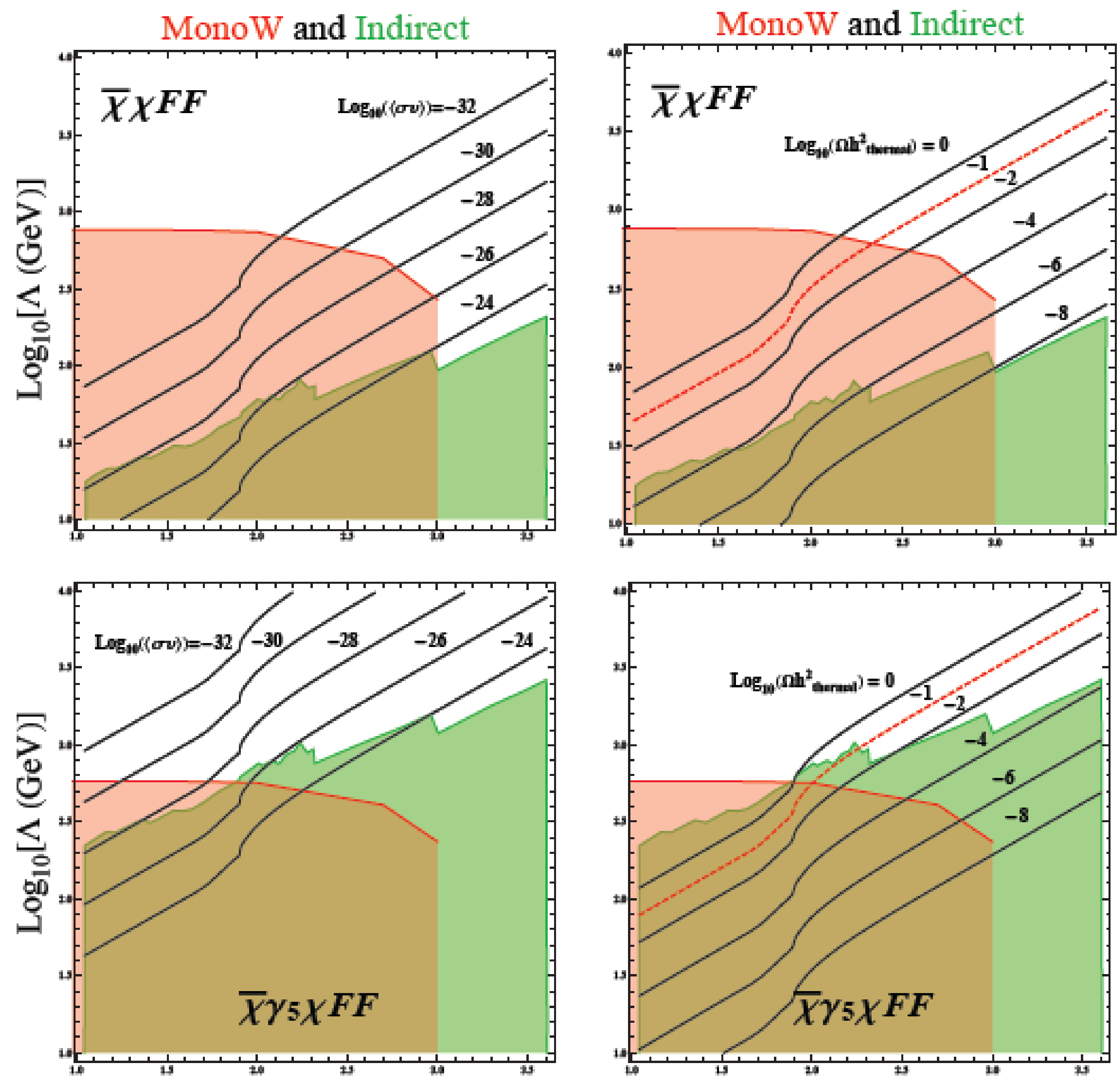
Process	$\not\!\!E_T > 350$ GeV	$\not\!\!E_T > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu$, $Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89


Efficiency
Mass[GeV]
χ̄γ⁵χFF
χ̄γ⁵χFF̃
χ̄χFF
χ̄χFF̃
φφFF̃
φφFF


Limit [fb]
Mass[GeV]
φφFF
φφFF̃
χ̄χFF
χ̄χFF̃
χ̄γ⁵χFF̃
χ̄γ⁵χFF

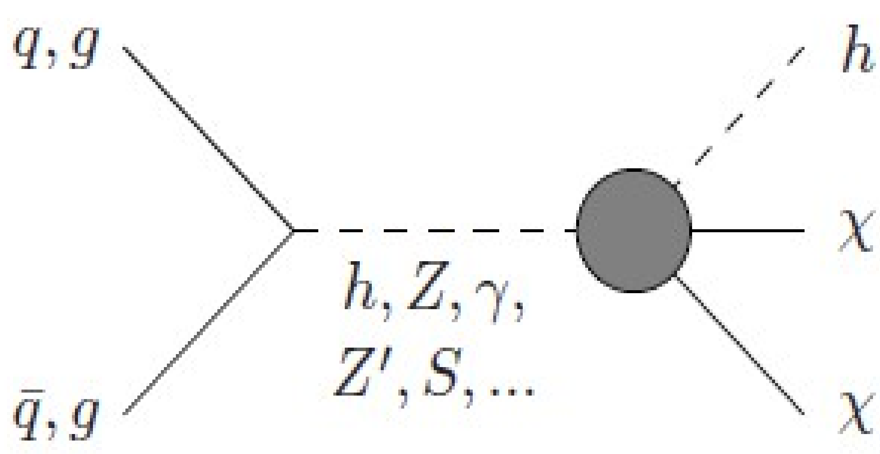
Limits on effective cut-off





Indirect bounds from WW, ZZ Annhilation Fermi-LAT and VERITAS using NFW profile

Mono Higgs



Higgs signals in four final state channels for h: $b\bar{b}$, $\gamma\gamma$, and $ZZ^* \to 4\ell$ and $ZZ^* \to \ell\ell jj$.

arXiv:1312.2592 LMC, DiFrazio, Mulhearn, Shimmon, Tulin, Whiteson

A Menagerie of Models

$$\lambda|H|^2\chi^2$$

Dimenion 4

$$\frac{1}{\Lambda}|H|^2\bar{\chi}\chi\,,\quad \frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi$$

Dimenion 5

$$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H$$

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi H^\dagger iD_\mu H\,,\quad \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi H^\dagger iD_\mu H\,.$$

Dimenion 6

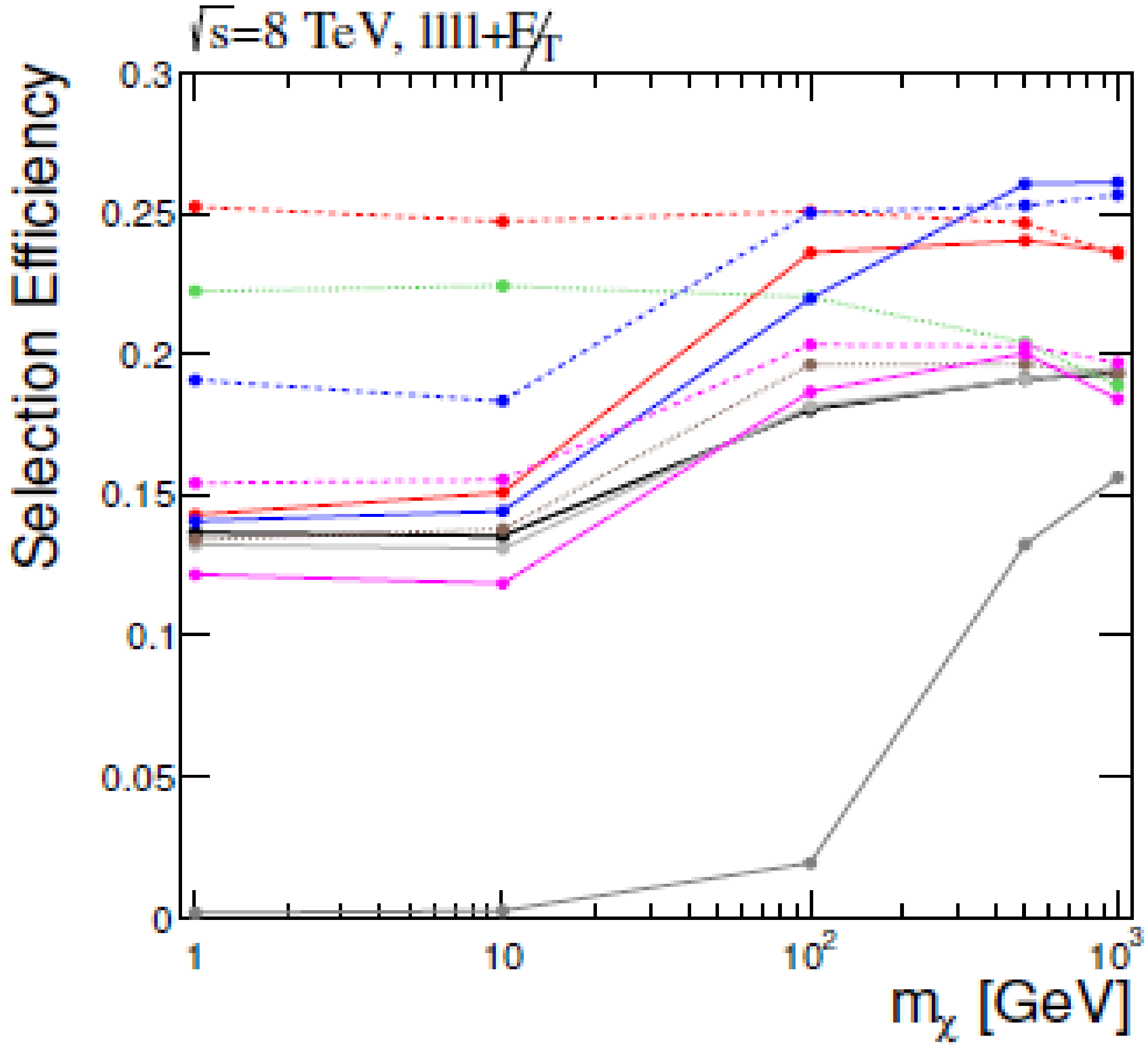
$$\frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H\,,\quad \frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi W^a_{\mu\nu}H^\dagger t^a D^\nu H$$

$$\frac{1}{\Lambda^4}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}H^\dagger H\,,\quad \frac{1}{\Lambda^4}\bar{\chi}\sigma^{\mu\nu}\chi W^a_{\mu\nu}H^\dagger t^a H$$

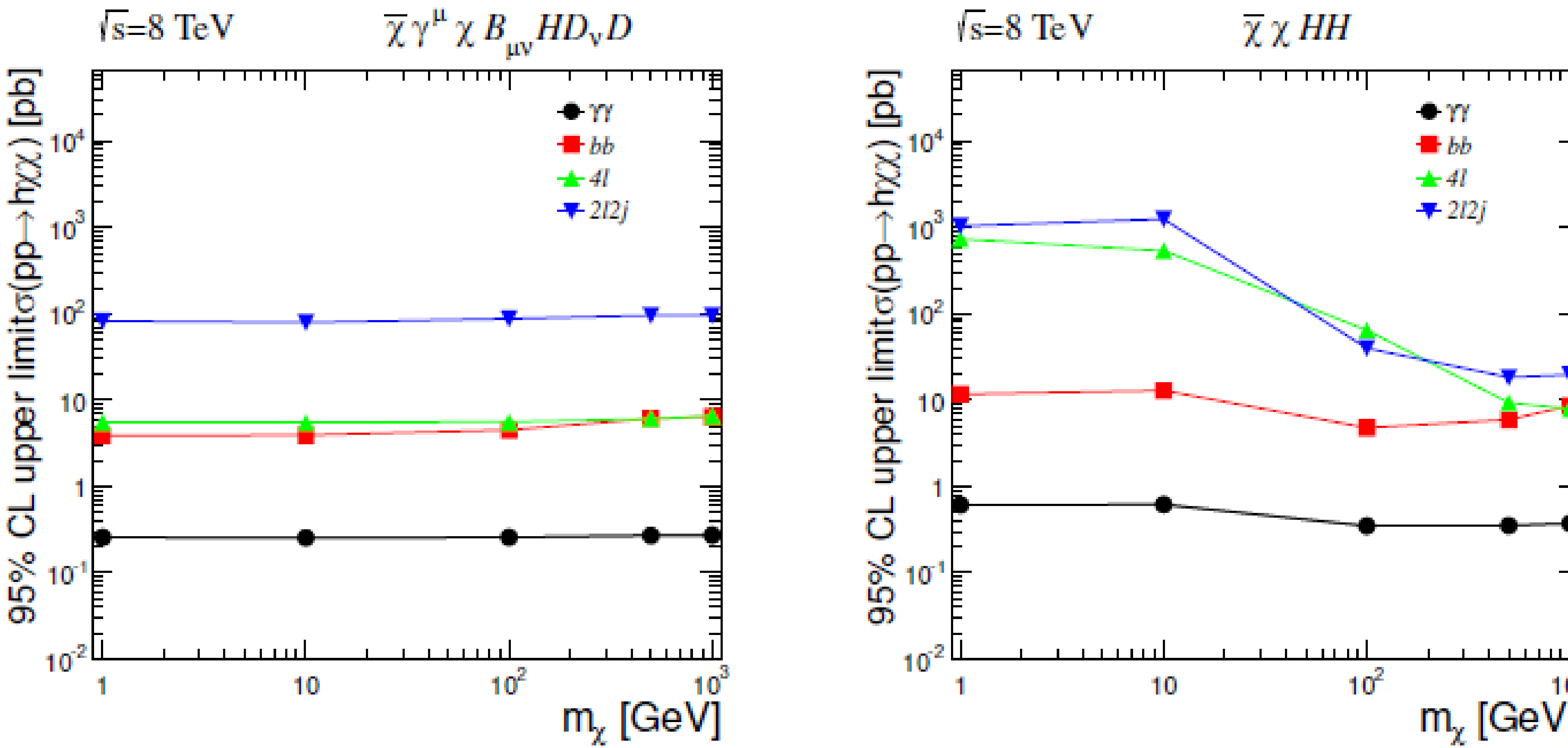
Dimenion 8

10 operators
And 4 higgs final state
Event topologies

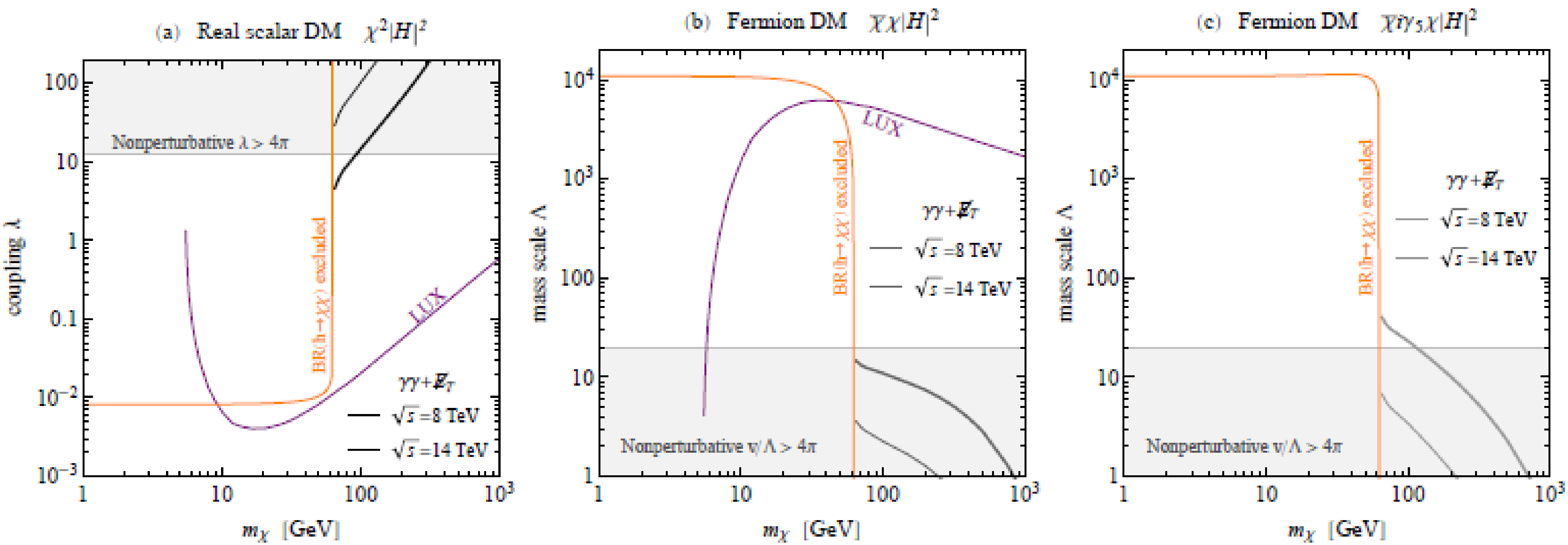
Example ZZ plus missing energy final state



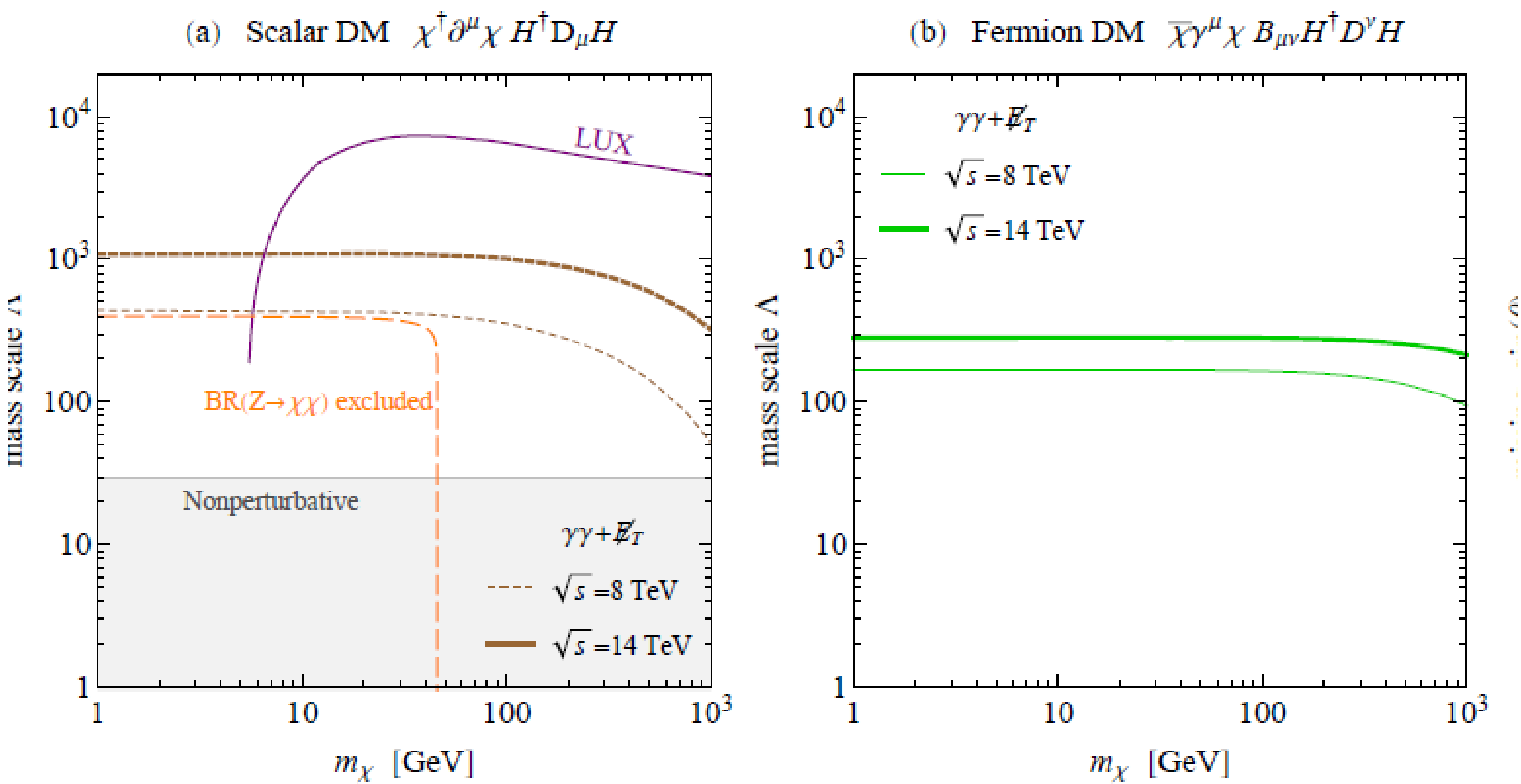
Cross section sec limits for example operators



Results: Not So Great Models



Results: Pretty Good Models



Mono-Boson Searches provide probes for interesting models of DM in many possible portals in key low background channels

Such Collider Searches Complement and/or Supersede Indirect Searches

Many extensions are yet to be explored