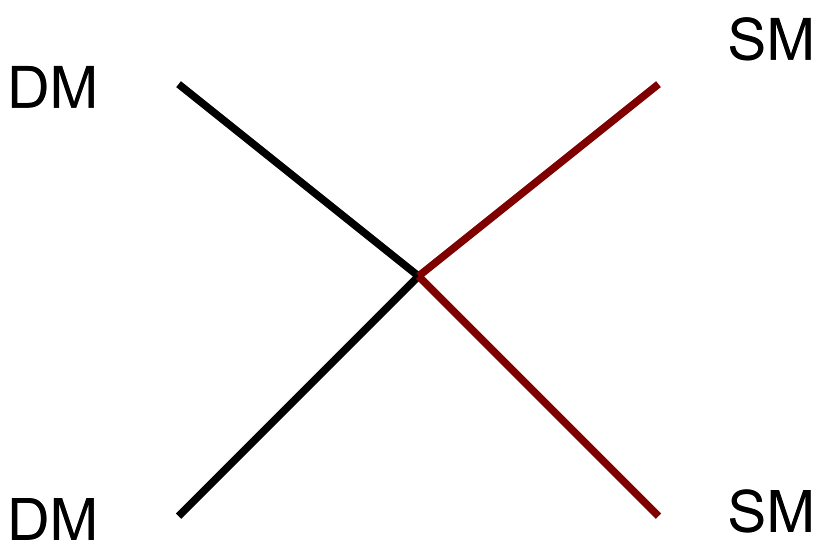
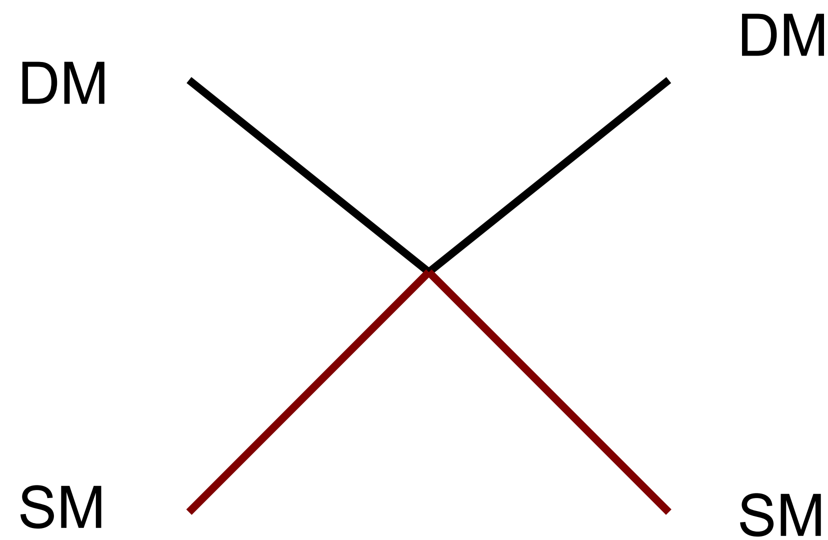
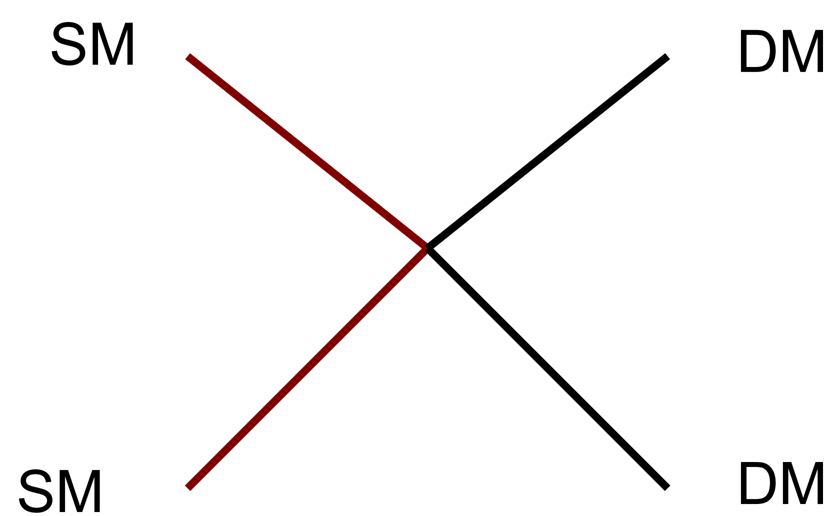
LHC searches for DM with Single Gauge Boson Events



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 gauge boson

Consider Effective operator Analysis for DM particles to couple to pairs of Z bosons

Expect process pp- $Z\chi\chi$ at LHC single Z+MET

Recast the ATLAS ZZ -ll$\nu\nu$ search as bound on DM production

For single Z events, we expect 2 kinds of operators to be relevant to this analysis

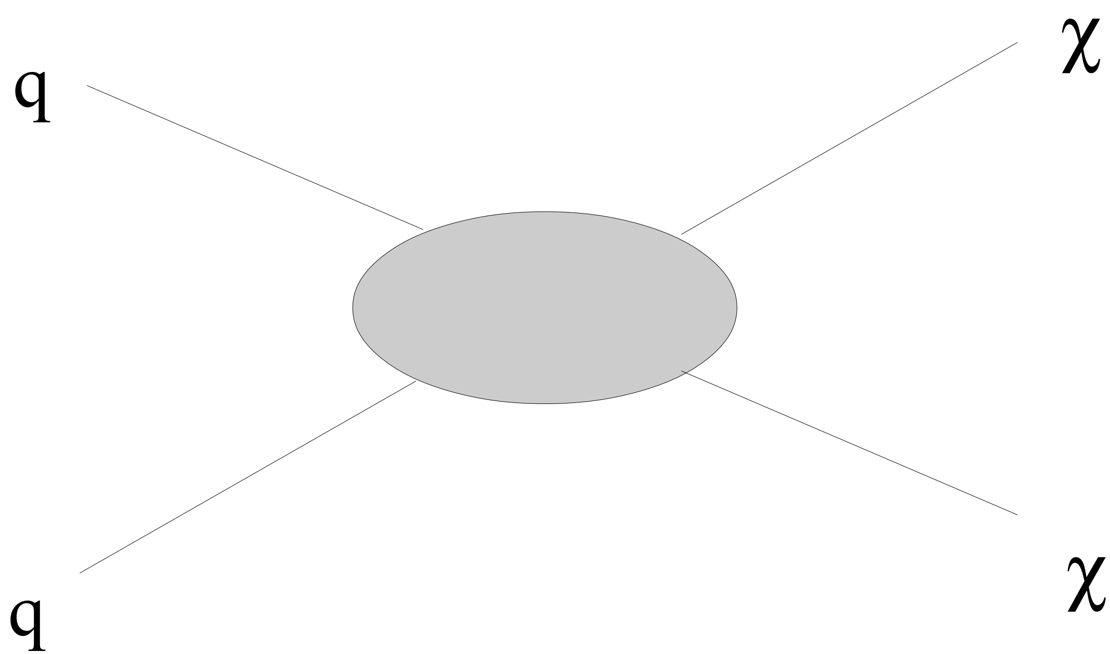
- Those where pairs of DM particles couple to pairs of quarks

And

- Those where pairs of DM particles couple to pairs of Gauge Bosons

Effective Operator Analysis: DM-Quark/Gluon Couplings

Consider all operators which contribute to the effective couplings between pairs of quarks and DM particles



Goodman, Ibe, Rajaraman, Shephard, Tait, Yu

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Fermionic DM

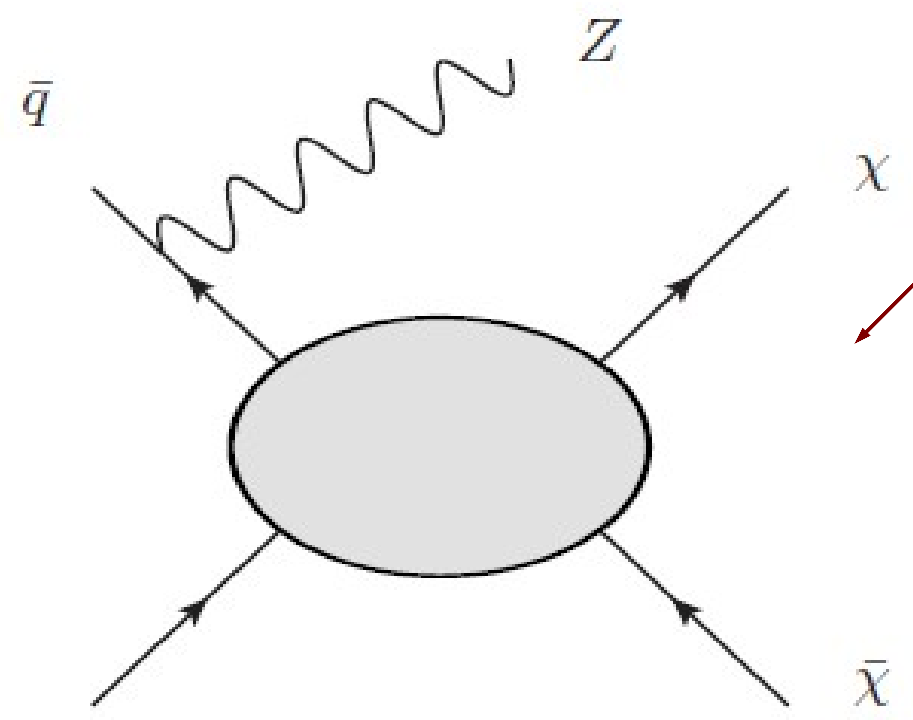
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Scalar DM

Apply Effective Operator method to other LHC collider signals outside of monojet singals

Use Mono Z searches to constrain DM parameter-space of effective operators where where DM particle couple to pairs of Z bosons,or to pairs of quarks

Pair of DM particles produced

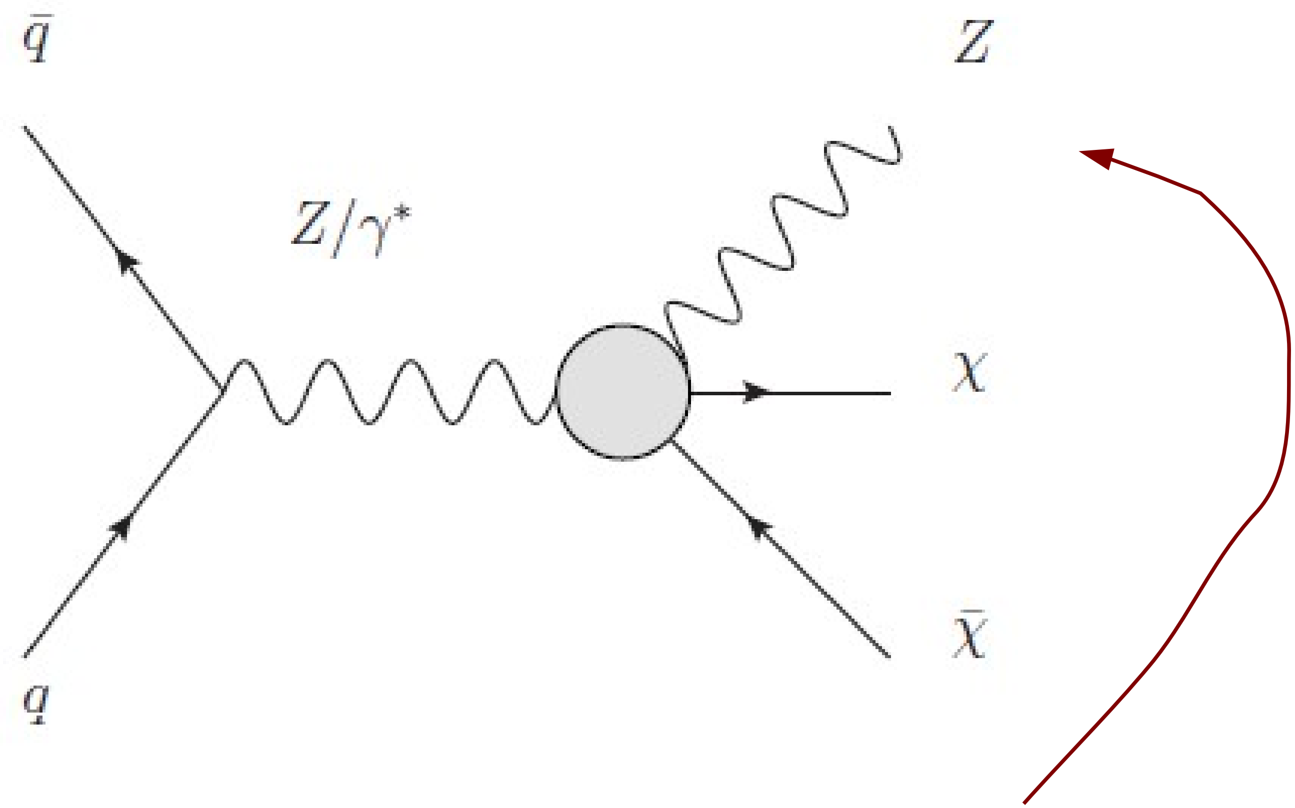


Quark radiates Z boson in initial state

Quark-DM Effective Interactions

$$\sum_q \left\{ \frac{m_q}{\Lambda_{\mathrm{D1}}^3} \bar{q}q \; \bar{\chi}\chi + \frac{1}{\Lambda_{\mathrm{D8}}^2} \bar{q}\gamma^\mu \gamma_5 q \; \bar{\chi}\gamma_\mu \gamma_5 \chi + \frac{1}{\Lambda_{\mathrm{D5}}^2} \bar{q}\gamma^\mu q \; \bar{\chi}\gamma_\mu \chi + \frac{1}{\Lambda_{\mathrm{D9}}^2} \bar{q}\sigma^{\mu\nu} q \; \bar{\chi}\sigma_{\mu\nu}\chi \right\}$$

ZZ-DM Effective Interactions



Pair of DM particles produced in association with a Z boson

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, $\gamma\gamma$ and γZ couplings at loop order.

Dim 7 Operators

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)

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

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

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

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

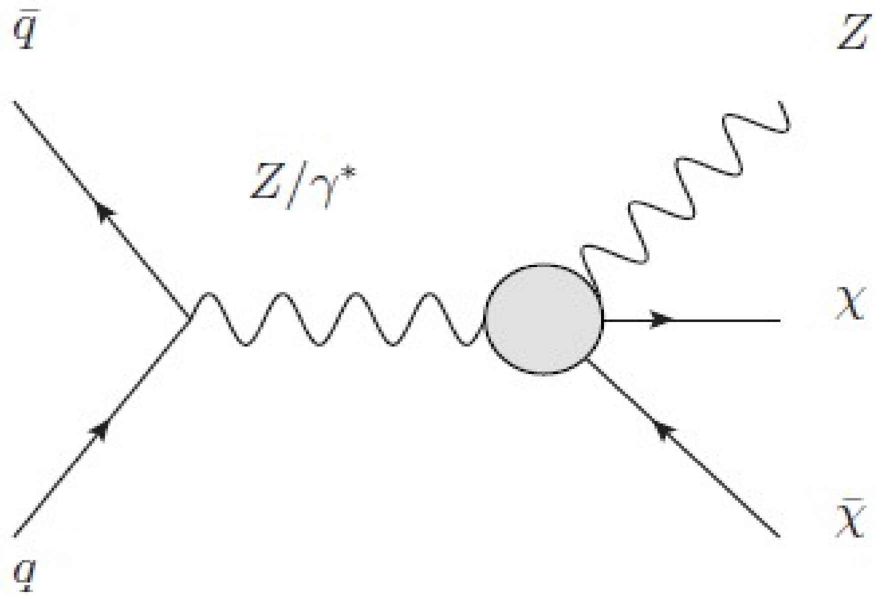
Related by Gauge invariance, determined by 2 coefficients

Production xsec varies with DM particle mass

Production xsec's vary from operator to operator, Each type of operator means different momentum dependence in Feynmann Rules.

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

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



xsec has 2 contributions

Xsec varies over 2 parameter space

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

There is a region where photon
Contribution is zero

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

ATLAS ZZ Search

7 TeV, 4.6 inverse fb of data

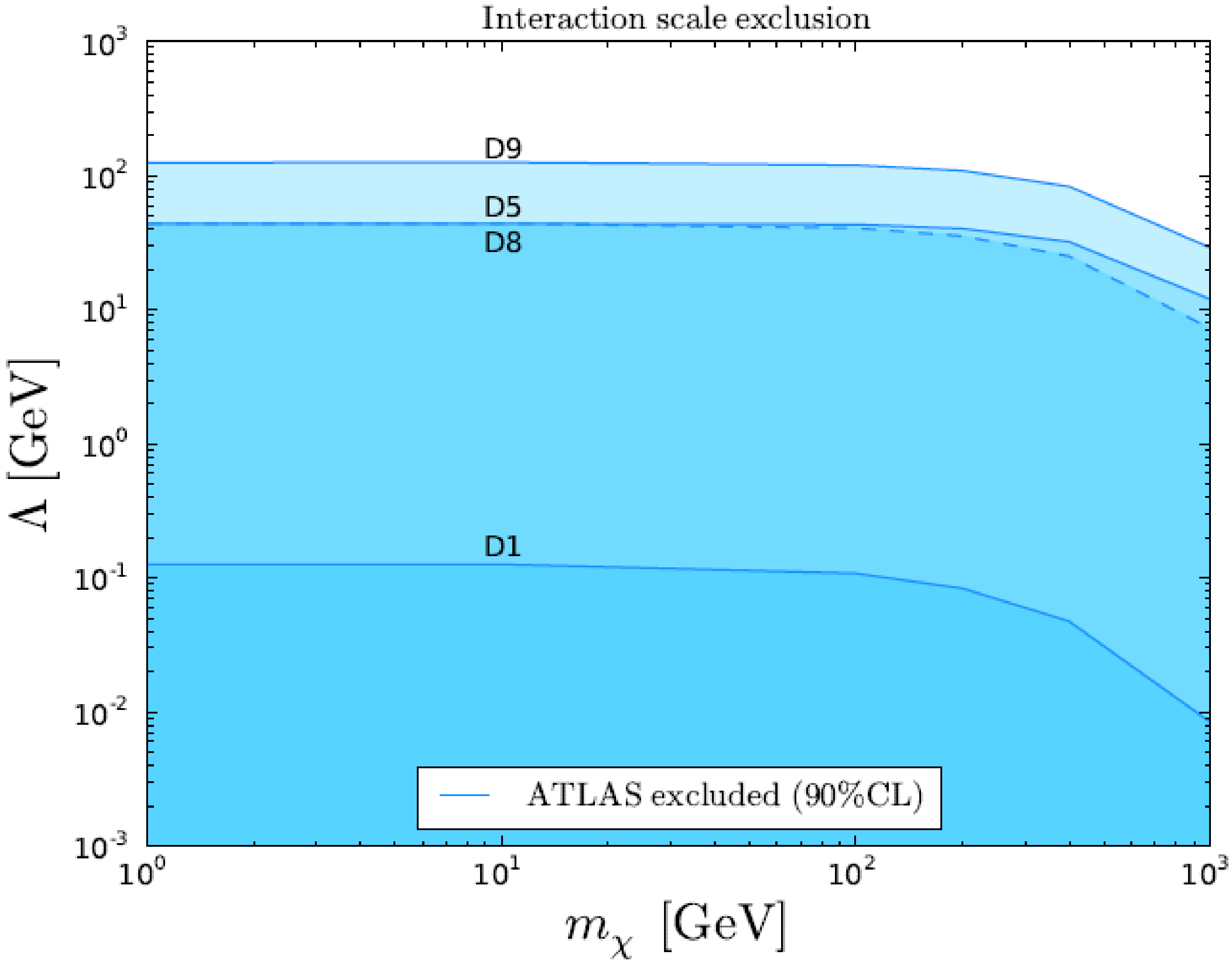
- two same-flavor opposite-sign electrons or muons, each with $p_{\mathrm{T}}^{\ell} > 20$ GeV, $|\eta^{\ell}| < 2.5$;
- dilepton invariant mass close to the Z boson mass: $m_{\ell\ell} \in [76, 106]$ GeV;
- no particle-level jet with $p_{\mathrm{T}}^{j} > 25$ GeV and $|\eta^{j}| < 4.5$;
- $(|p_{\mathrm{T}}^{\nu\bar{\nu}}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

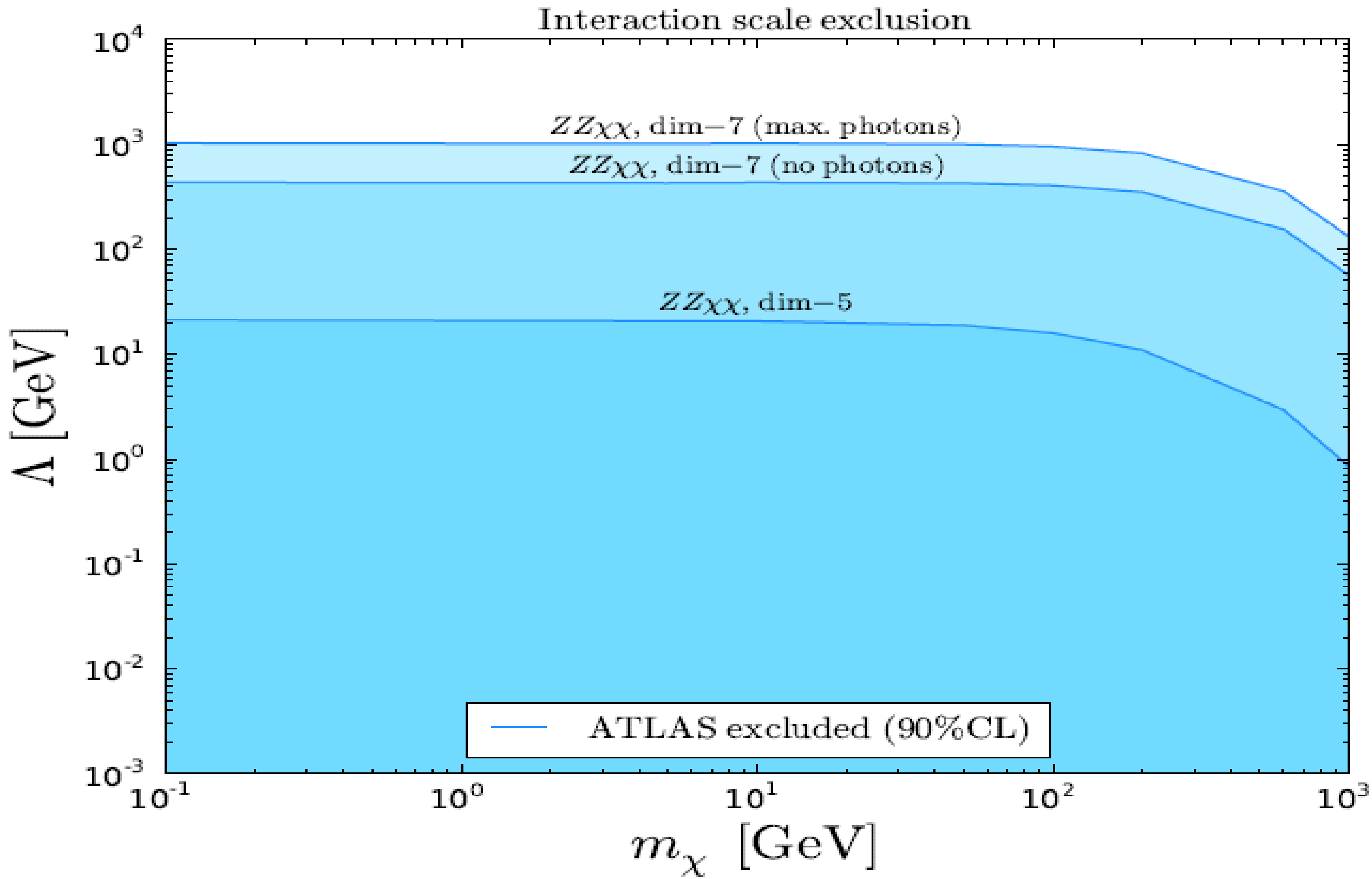
No signif. Deviation over SM process is observed.
Limits on DM operators may be set

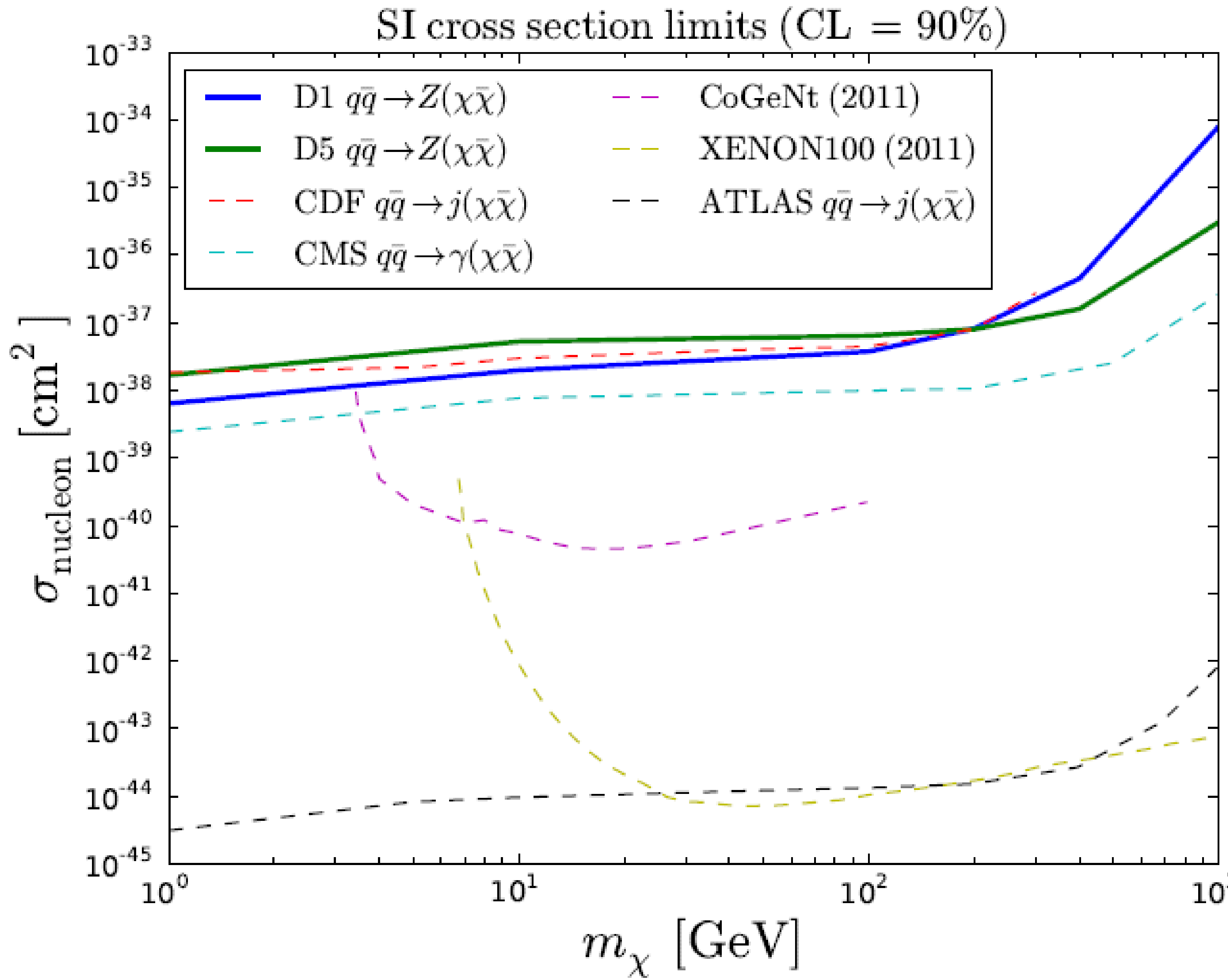
Total # of events N<18 at 90% confidence

Exclusions for Effective Quark Operators

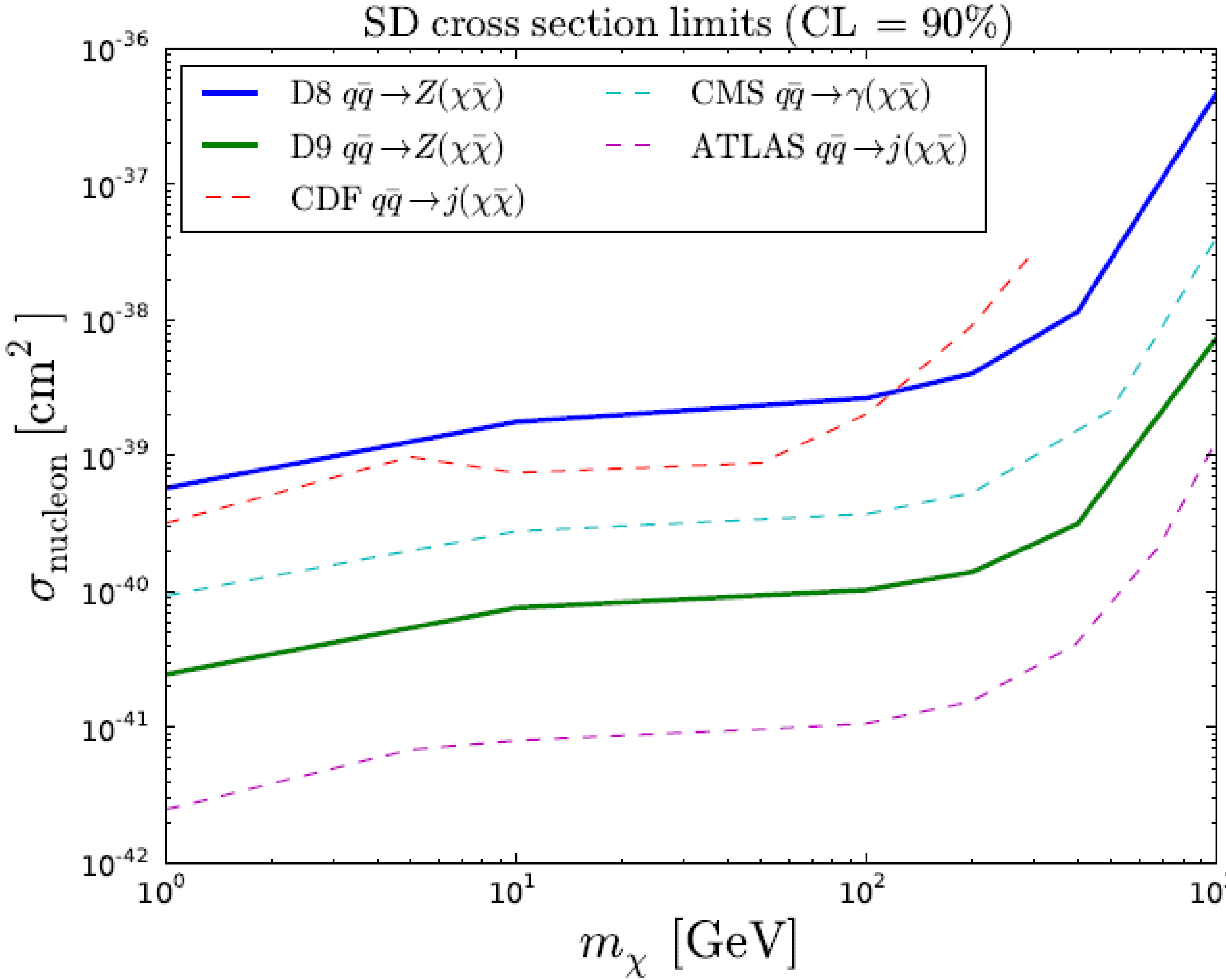


Exclusions for Effective Gauge-Boson Operators





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

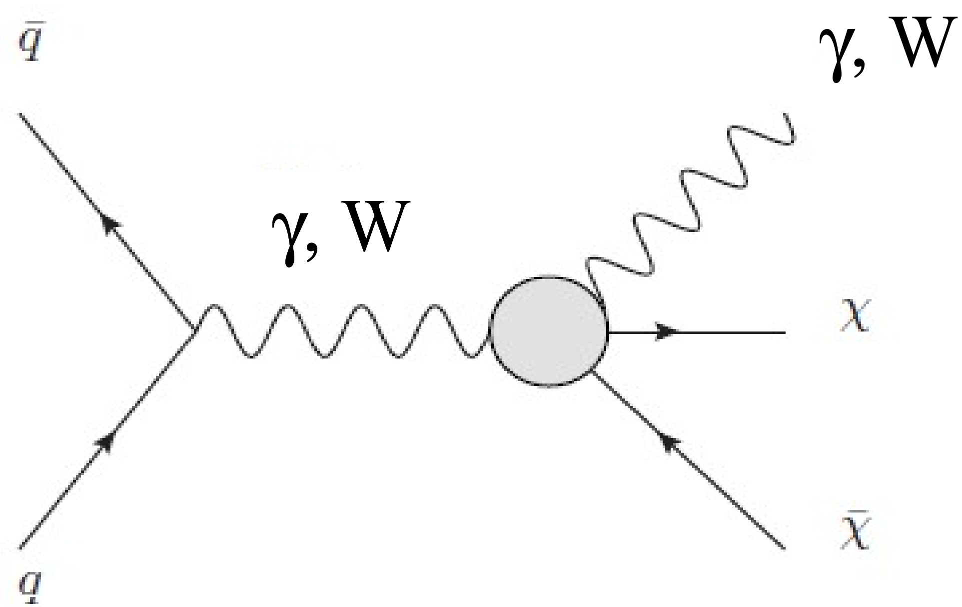


SD cross section limits (CL = 90%)
D8 $q\bar{q} \to Z(\chi\bar{\chi})$
D9 $q\bar{q} \to Z(\chi\bar{\chi})$
CDF $q\bar{q} \to j(\chi\bar{\chi})$
CMS $q\bar{q} \to \gamma(\chi\bar{\chi})$
ATLAS $q\bar{q} \to j(\chi\bar{\chi})$
σ_{nucleon} [cm^2]
m_χ [GeV]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}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

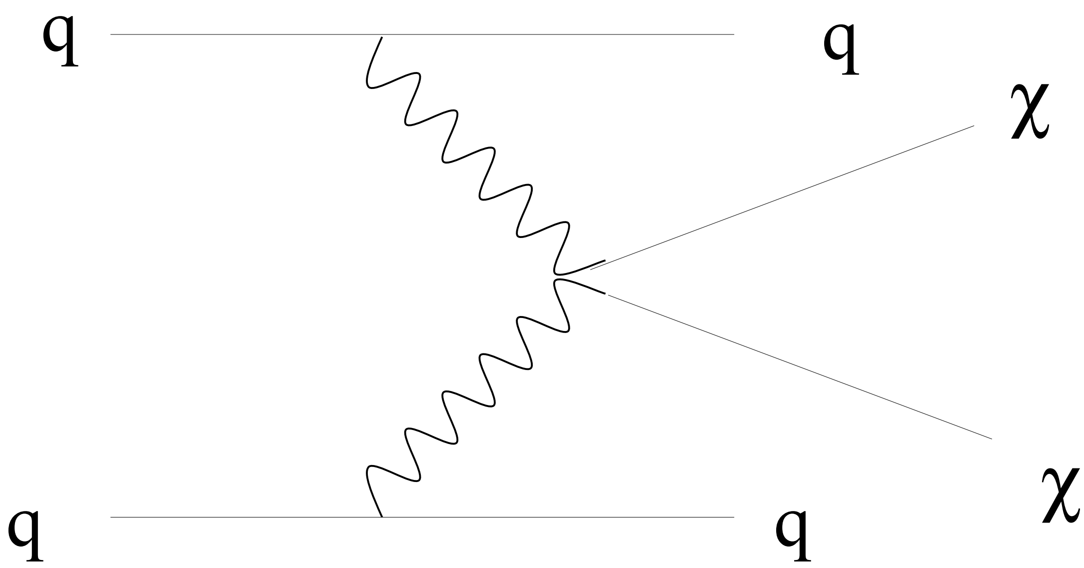
Extensions

- Consider Bounds on Scalar DM

-Extend effective operator analysis to make further exclusions for DM-gauge boson pair effective operators, e.g. mono-photon events, events with missing energy and forward jets.



$\bar{q}$
γ, W
γ, W
χ
$\bar{\chi}$
q


q
q
χ
χ
q
q

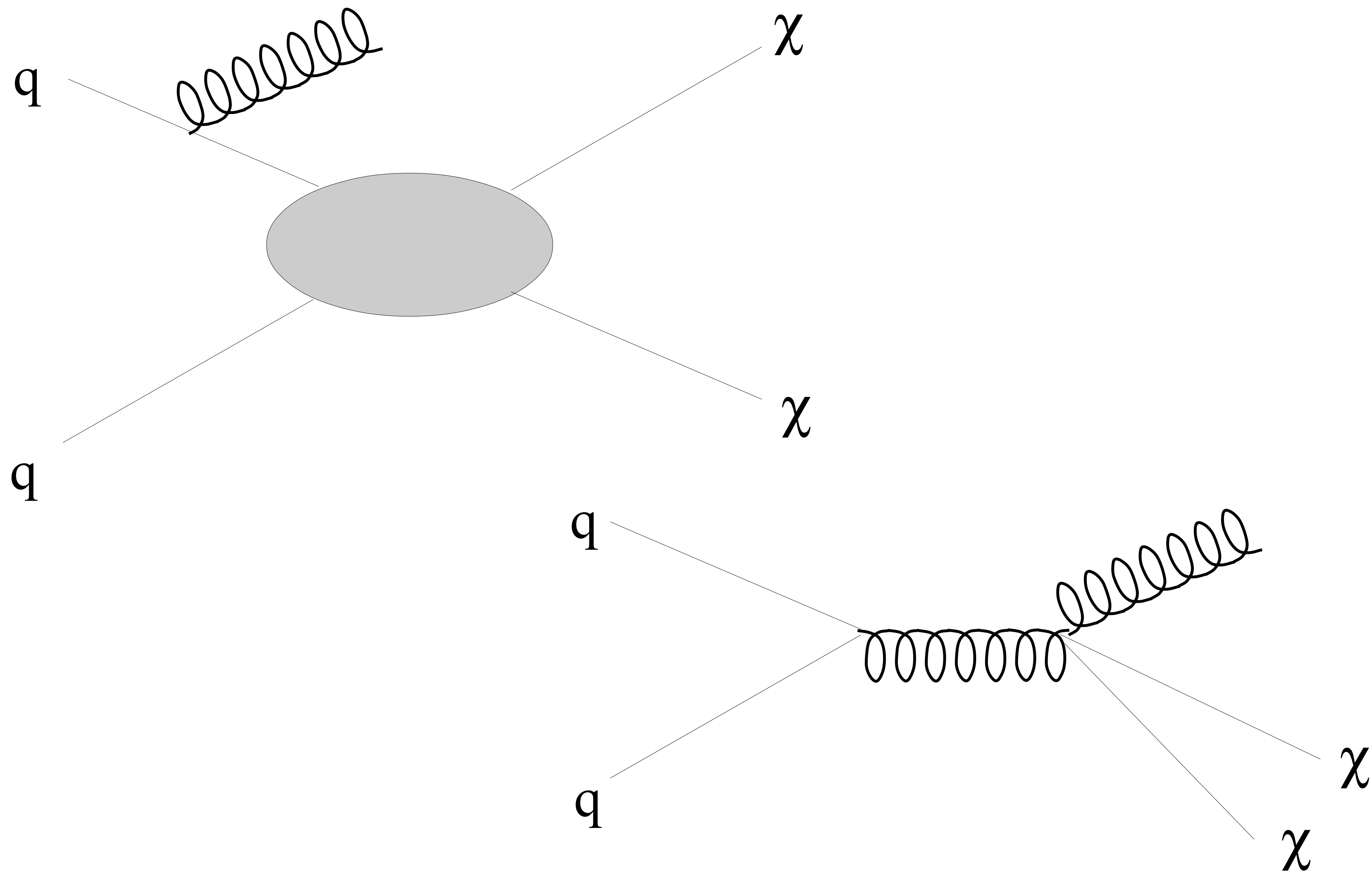
Collider searches for signals with a single gauge boson may be a useful tool in constraining a variety of DM models

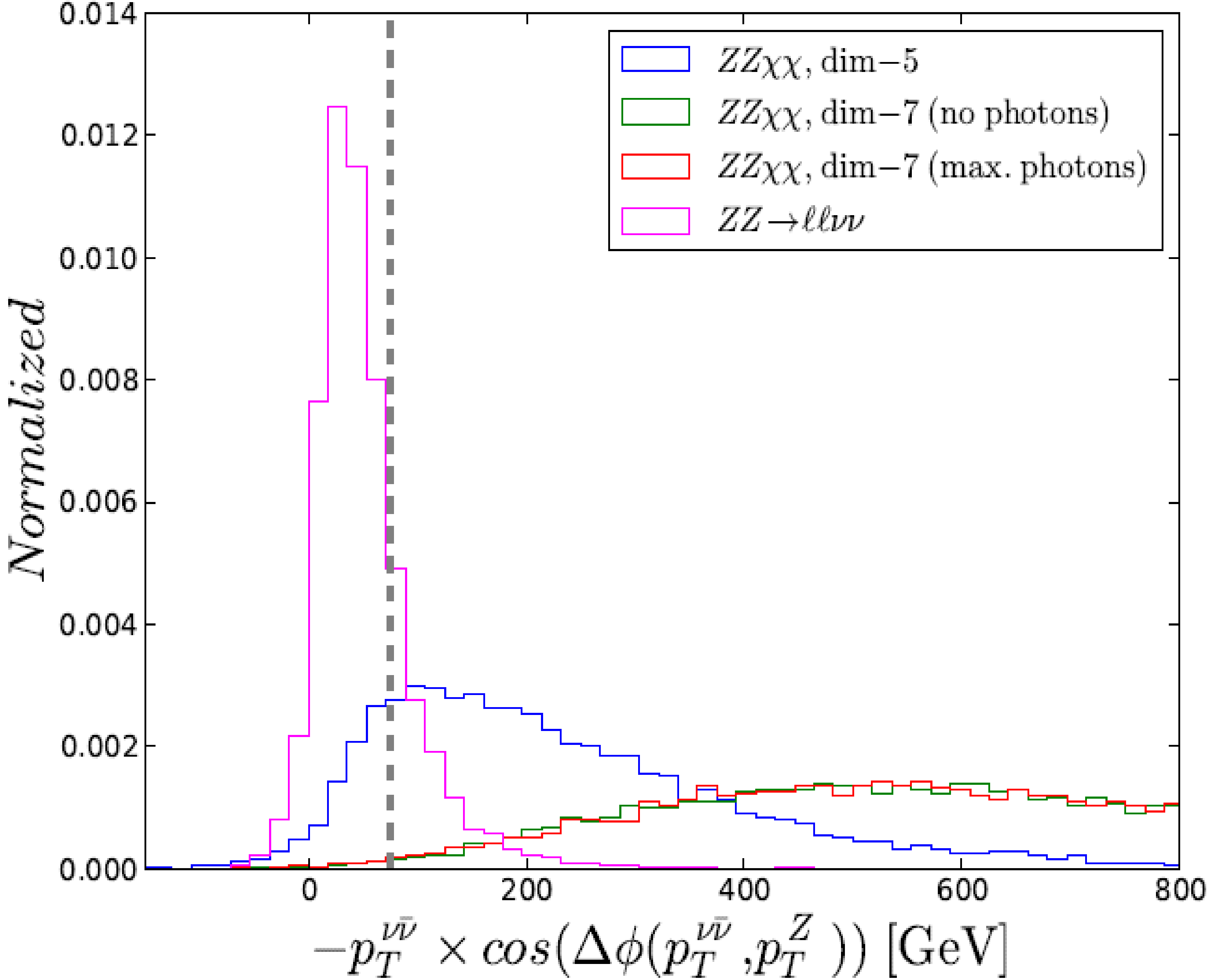
Exclusions may be made right now using existing searches which can be recast, new dedicated searches will be even better

There is lots left to explore both in single GB scenarios and beyond

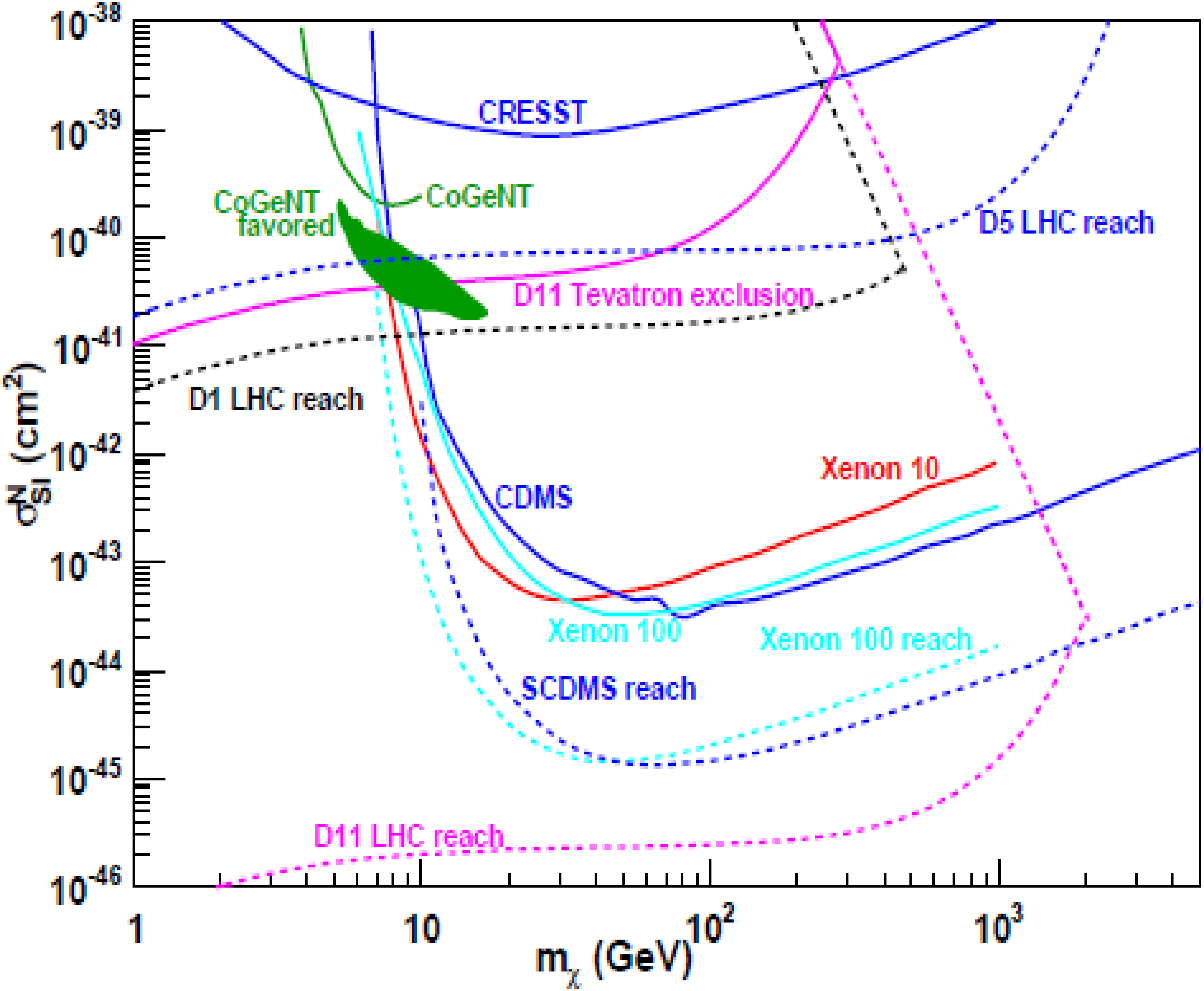
Extra Slides

Operators Constrained by Monojet Searches

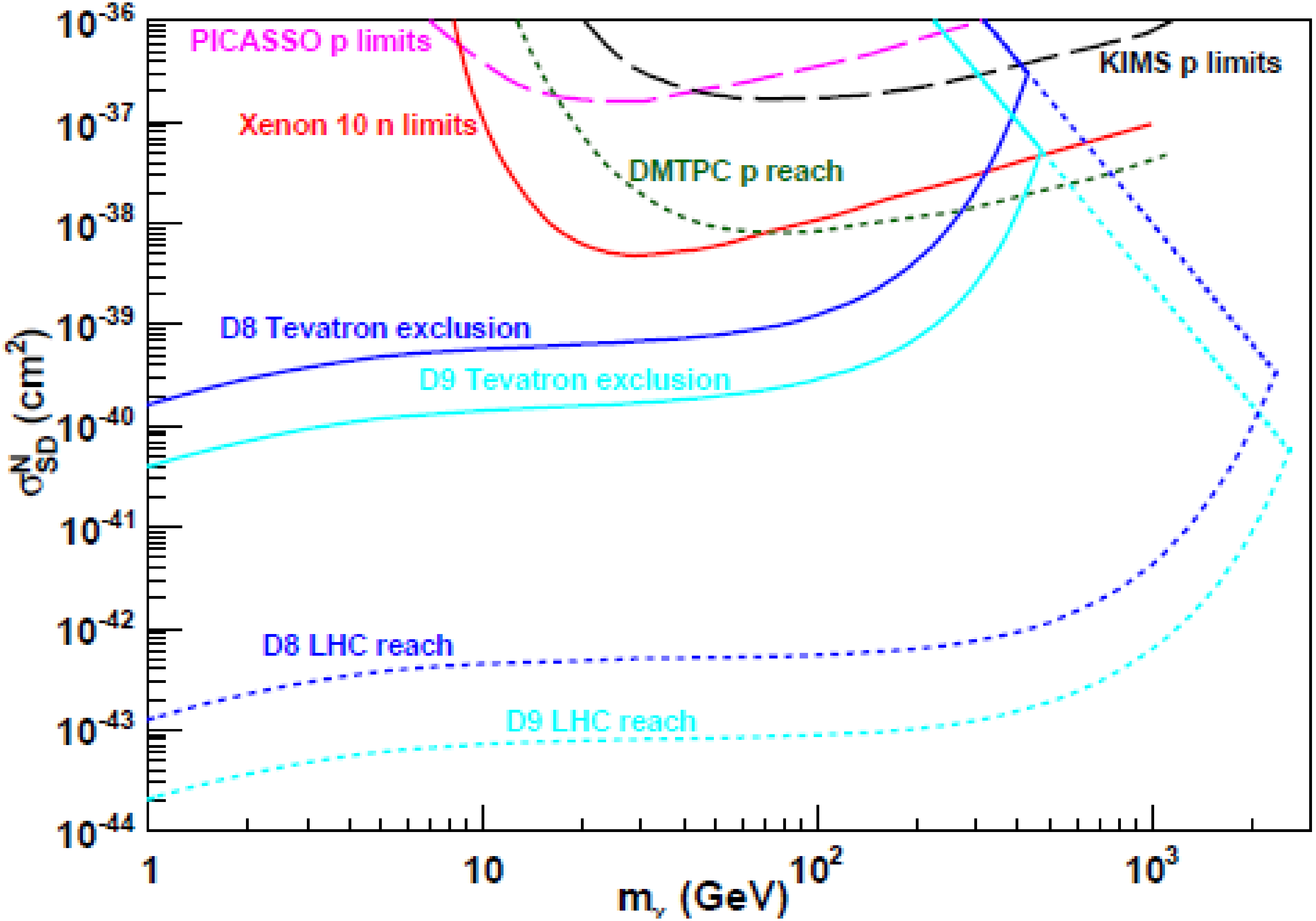




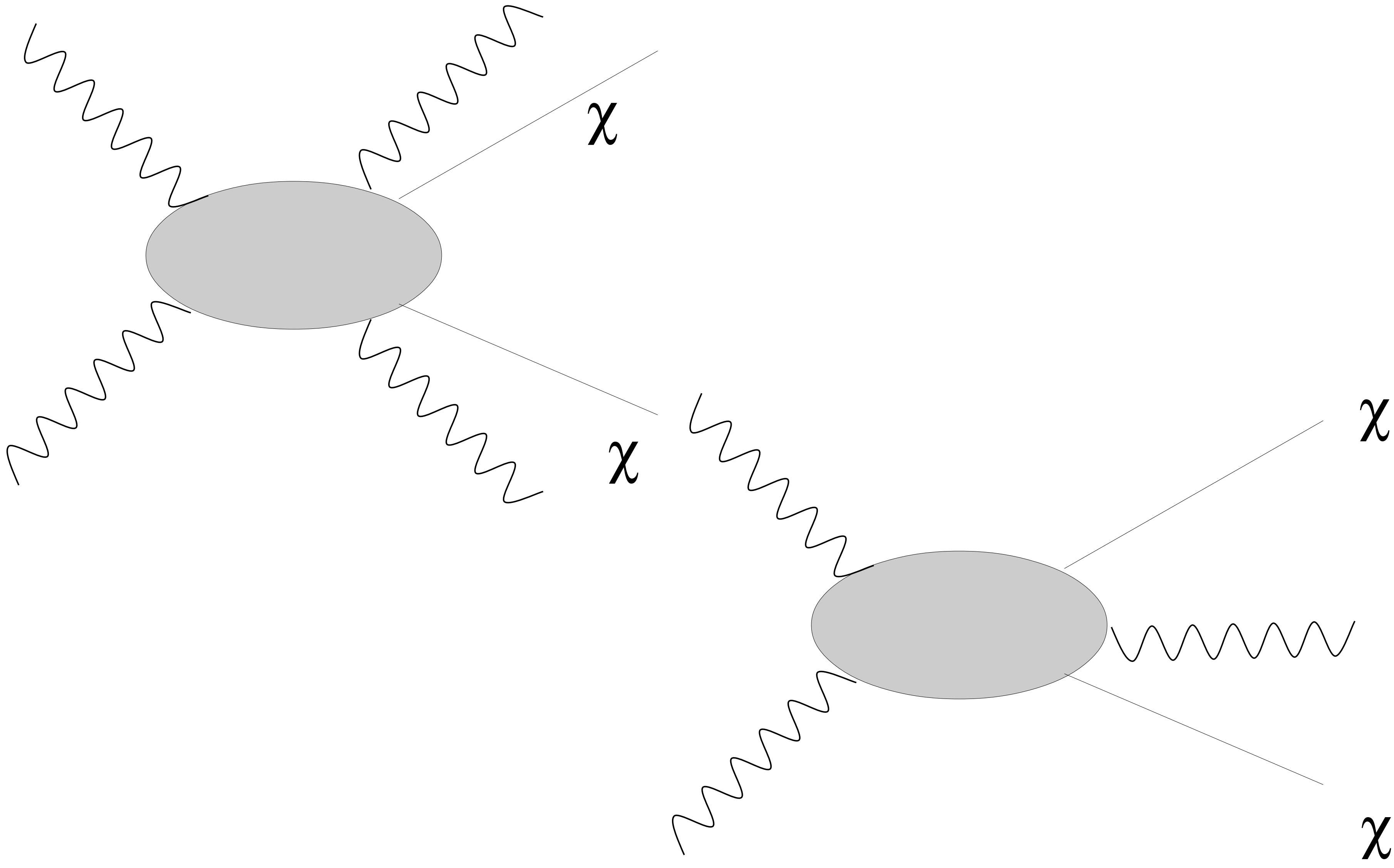
$ZZ\chi\chi$, dim−5
$ZZ\chi\chi$, dim−7 (no photons)
$ZZ\chi\chi$, dim−7 (max. photons)
$ZZ\rightarrow\ell\ell\nu\nu$
Normalized
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
$-p_T^{\nu\bar{\nu}} \times cos(\Delta\phi(p_T^{\nu\bar{\nu}}, p_T^{Z}))$ [GeV]

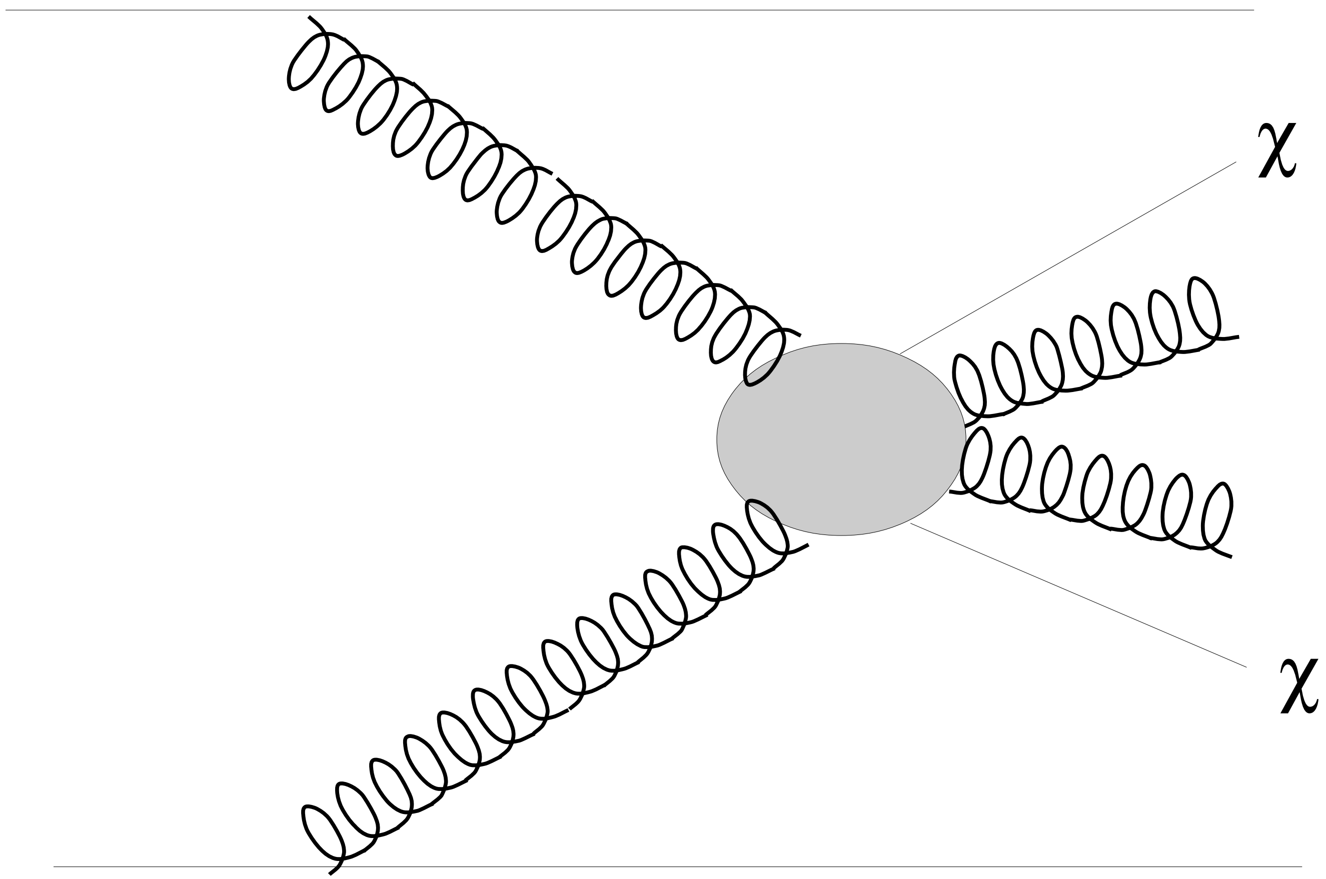


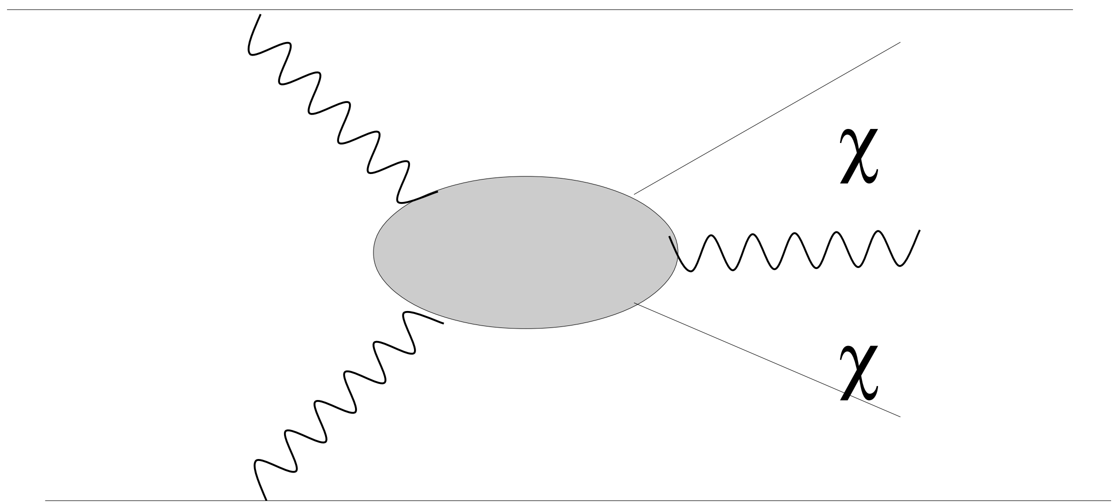
CRESST
CoGeNT
CoGeNT favored
D5 LHC reach
D11 Tevatron exclusion
D1 LHC reach
Xenon 10
CDMS
Xenon 100
Xenon 100 reach
SCDMS reach
D11 LHC reach
σ^N_{SI} (cm^2)
m_χ (GeV)


PICASSO p limits
KIMS p limits
Xenon 10 n limits
DMTPC p reach
D8 Tevatron exclusion
D9 Tevatron exclusion
D8 LHC reach
D9 LHC reach
σ^N_{SD} (cm^2)
m_χ (GeV)
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
1
10
10^2
10^3

Multi GB DM verticies




χ
χ


χ
χ

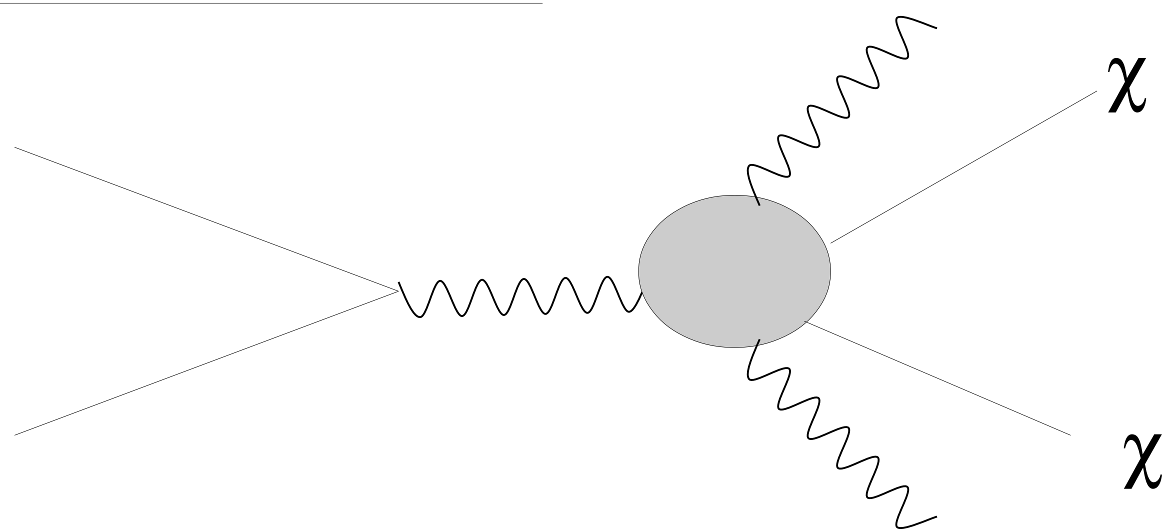
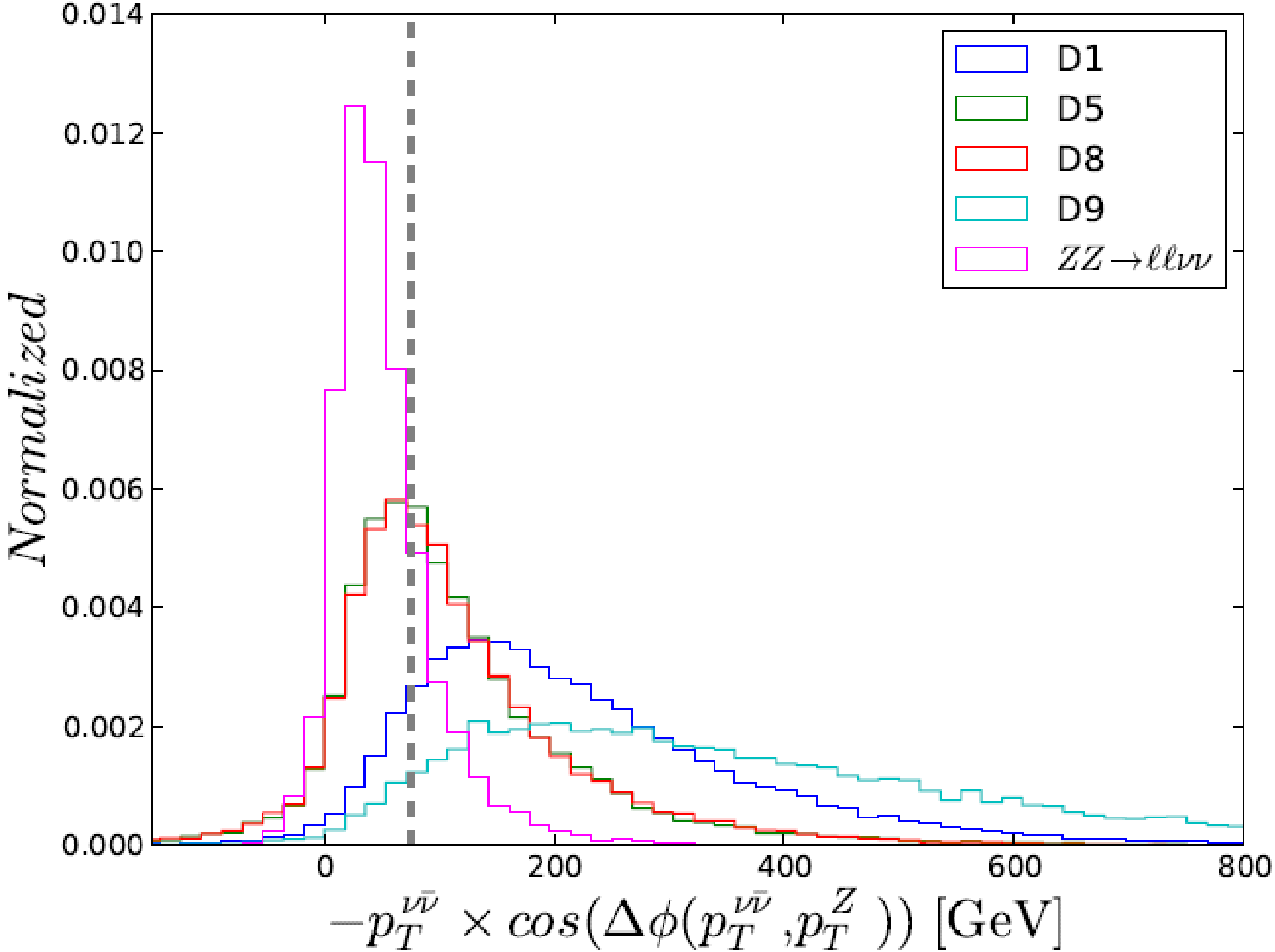
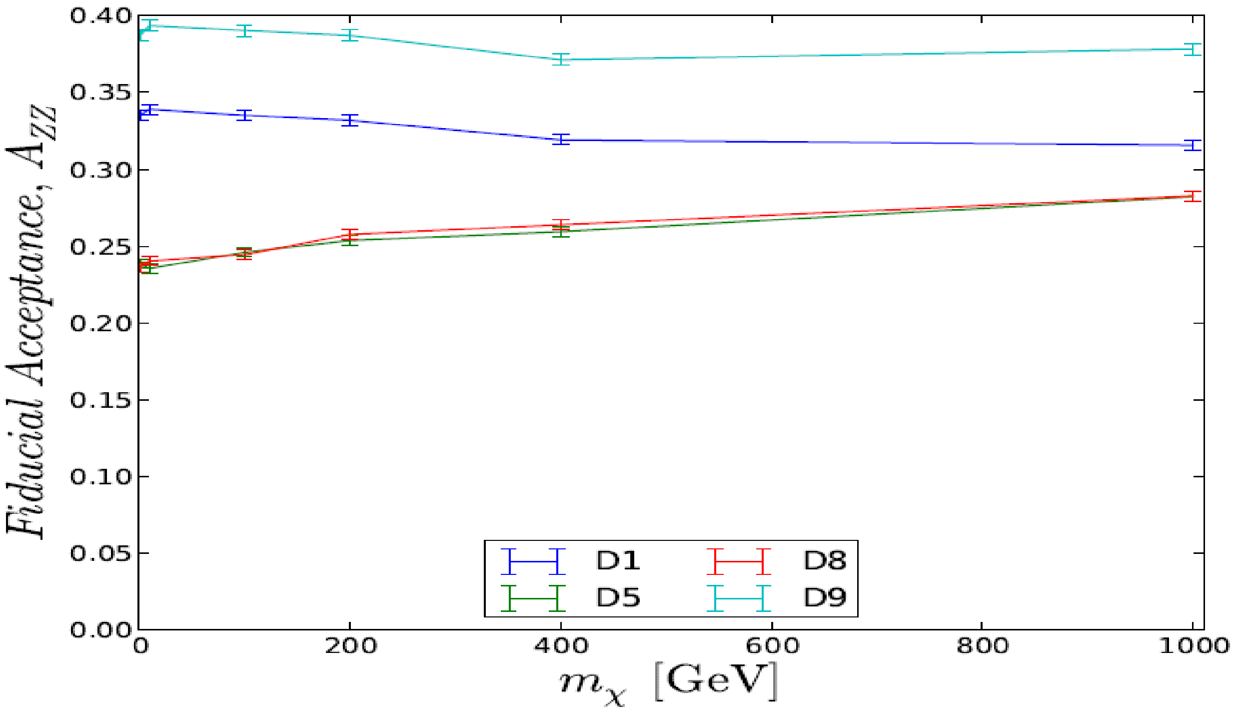

χ
χ

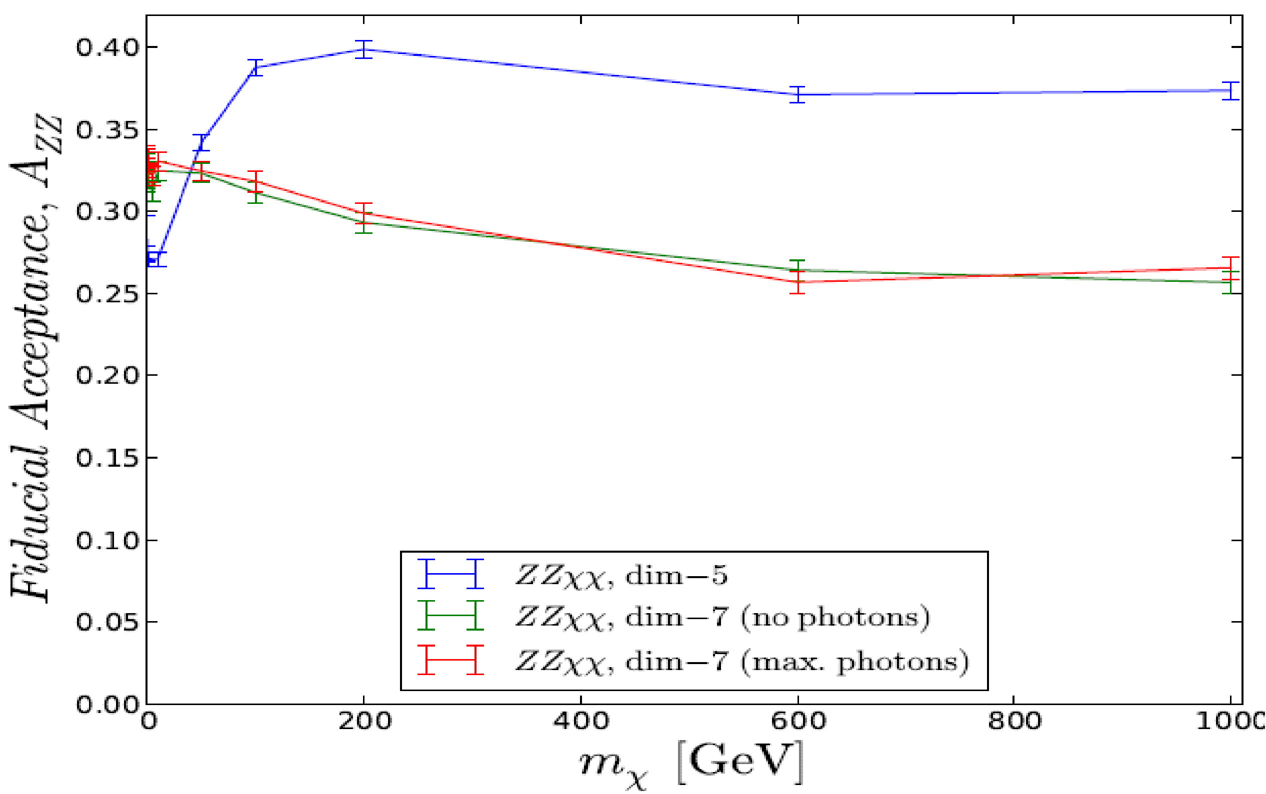
TABLE I: Production cross sections (in fb) for pair production of WIMPs in association with a Z boson, $pp \to Z\chi\bar{\chi} \to \ell^+\ell^-\chi\bar{\chi}$, in theories where the dark matter interacts primarily with quarks, for $\Lambda_i = 1$ TeV and $\sqrt{s} = 7$ TeV.

m_χ (GeV)	D1 $[\times 10^{-8}]$	D5	D8	D9
≤ 10	0.94	0.56	0.55	7.9
100	0.59	0.51	0.42	6.9
200	0.28	0.40	0.27	5.2
400	0.05	0.20	0.09	2.4
1000	3×10^{-4}	0.01	0.002	0.1


0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
$Normalized$
0
200
400
600
800
$-p_T^{\nu\bar{\nu}} \times cos(\Delta\phi(p_T^{\nu\bar{\nu}}, p_T^{Z}))$ [GeV]
D1
D5
D8
D9
$ZZ \rightarrow \ell\ell\nu\nu$



Fiducial Acceptance, A_{ZZ}
m_χ [GeV]
D1
D8
D5
D9



Fiducial Acceptance, A_{ZZ}
m_χ [GeV]
$ZZ\chi\chi$, dim−5
$ZZ\chi\chi$, dim−7 (no photons)
$ZZ\chi\chi$, dim−7 (max. photons)