Collider Constraints on Dark Matter

Patrick Fox

Fermilab

Lots of evidence for DM

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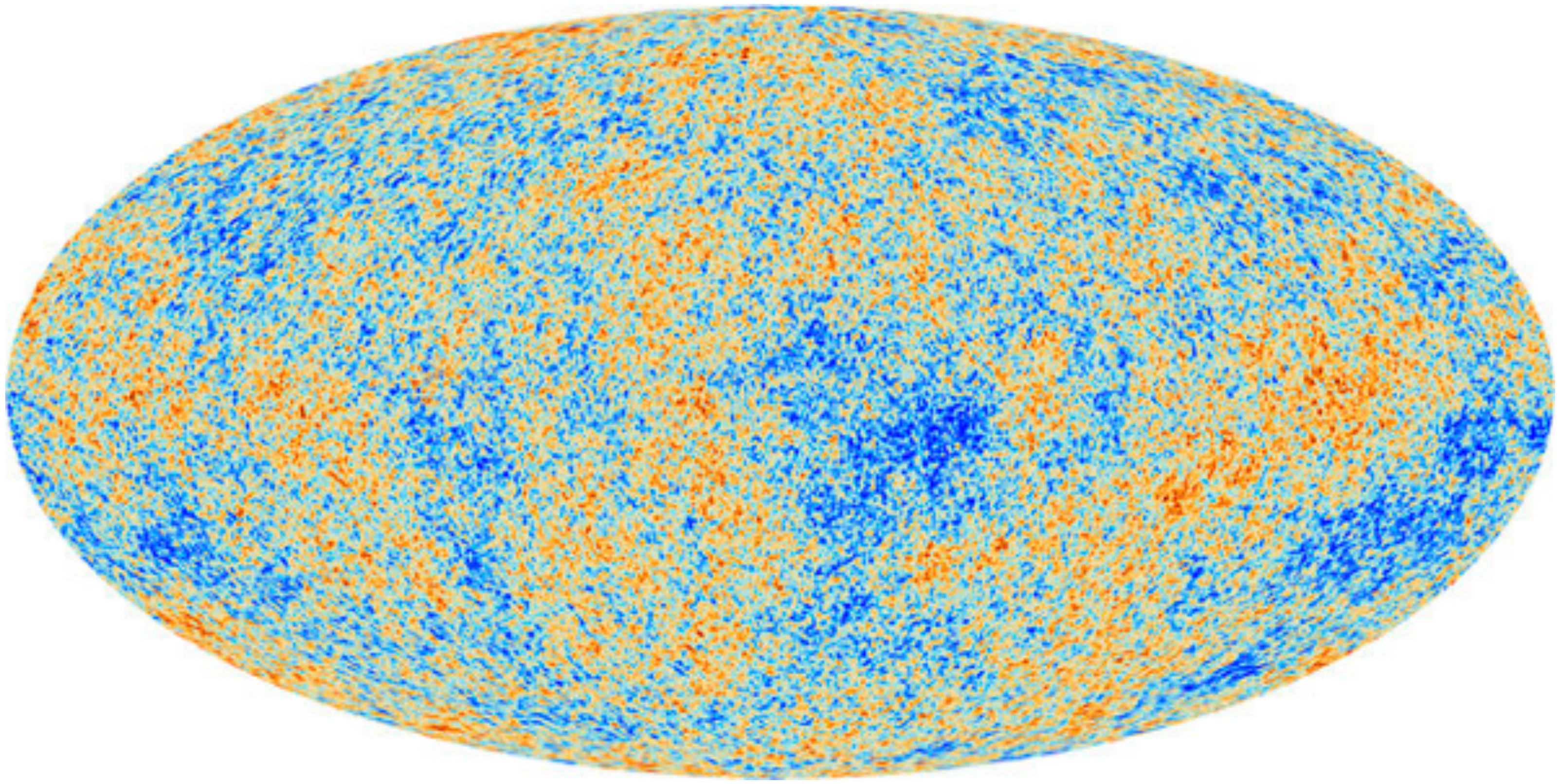

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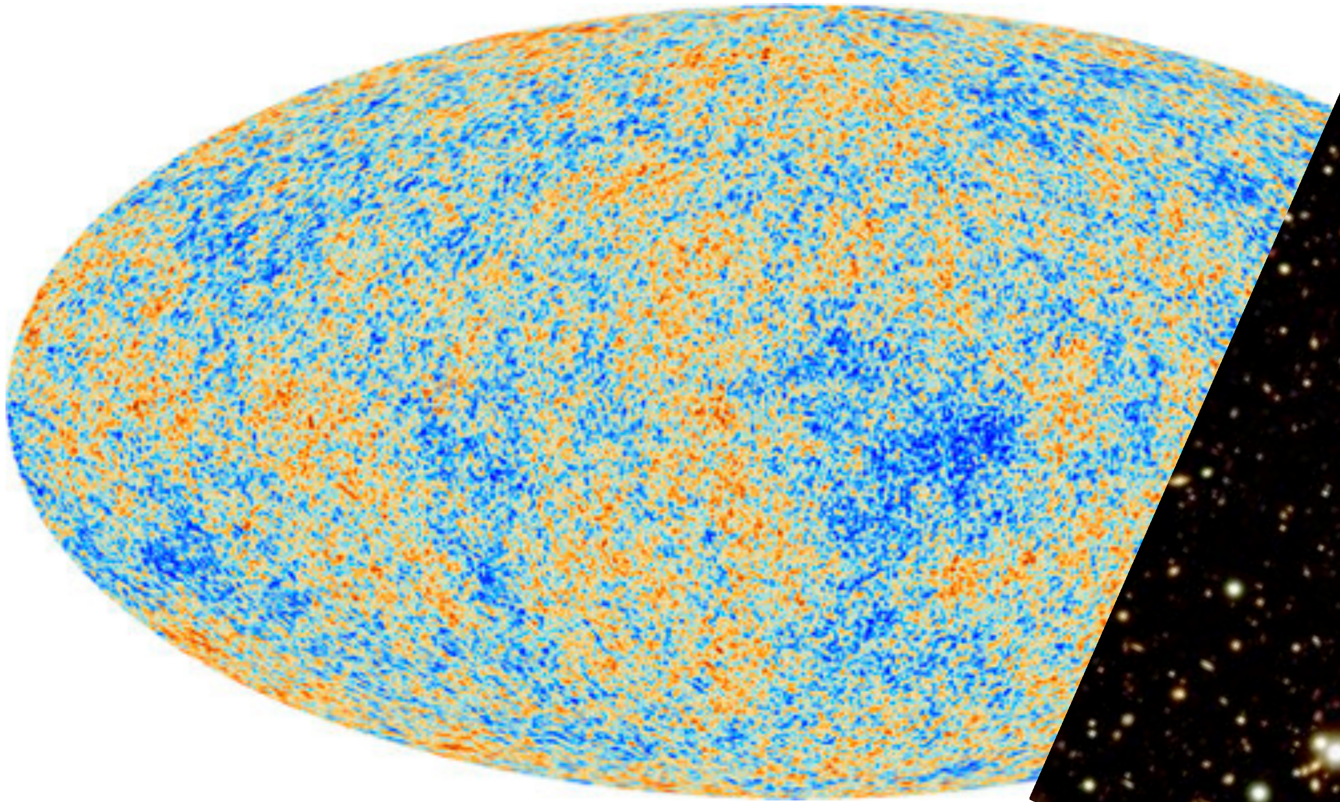

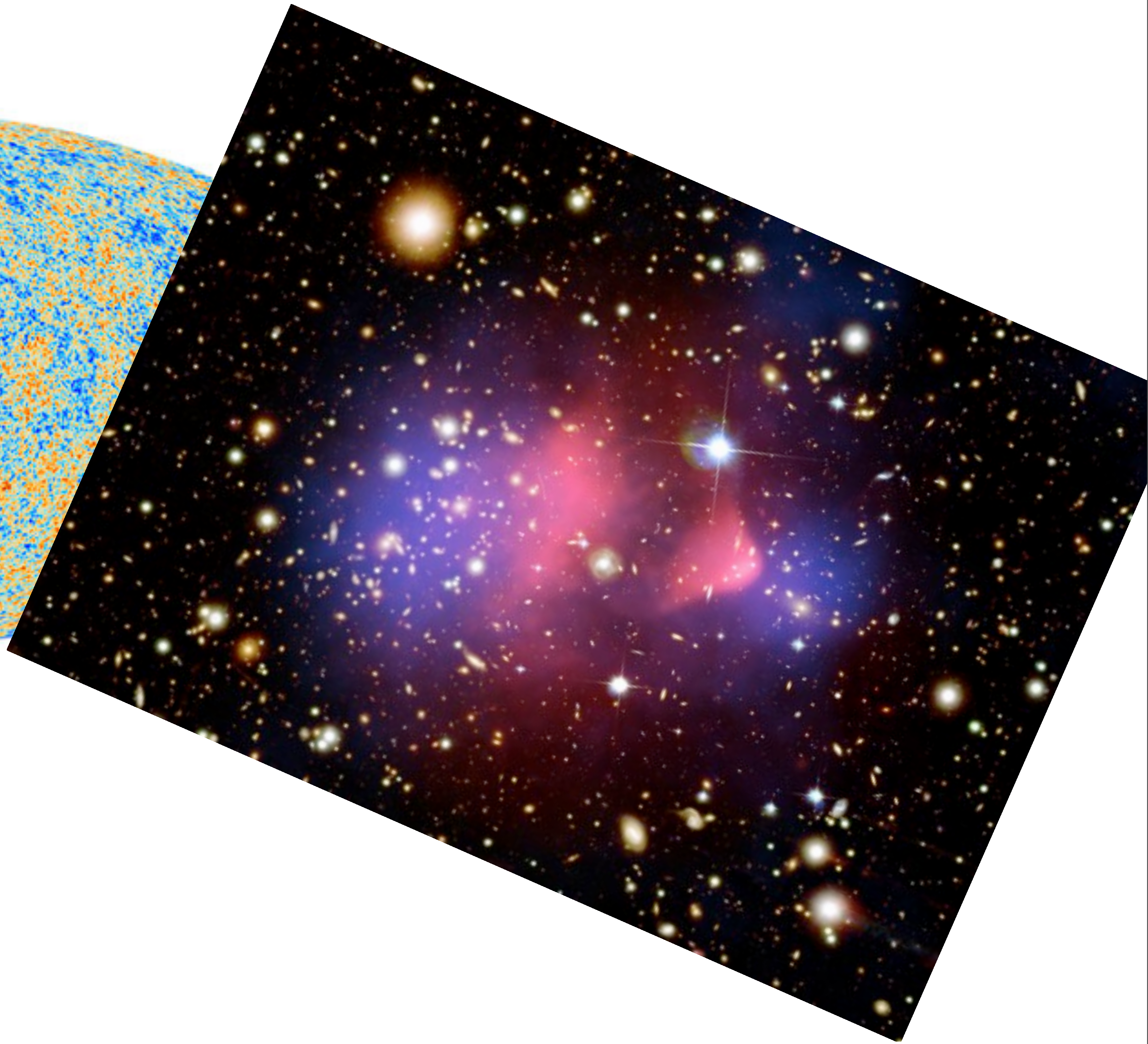

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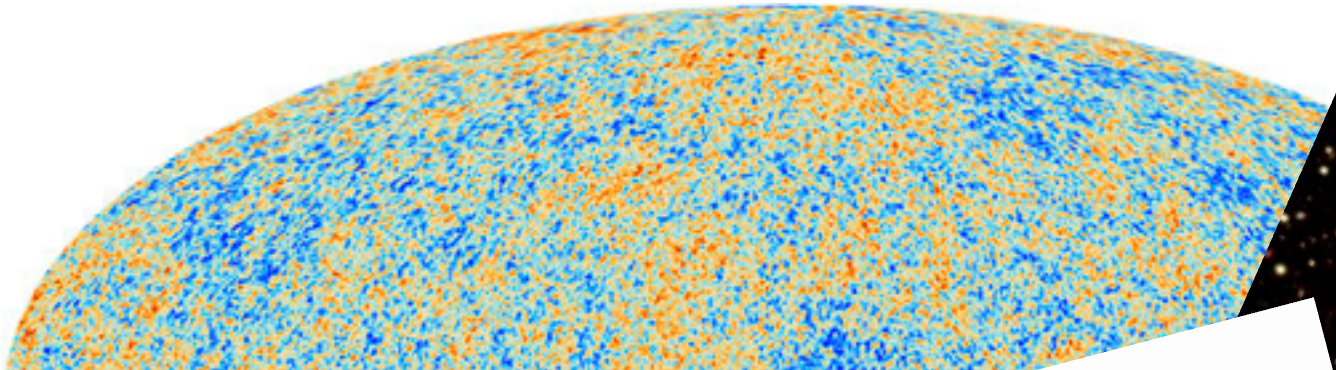

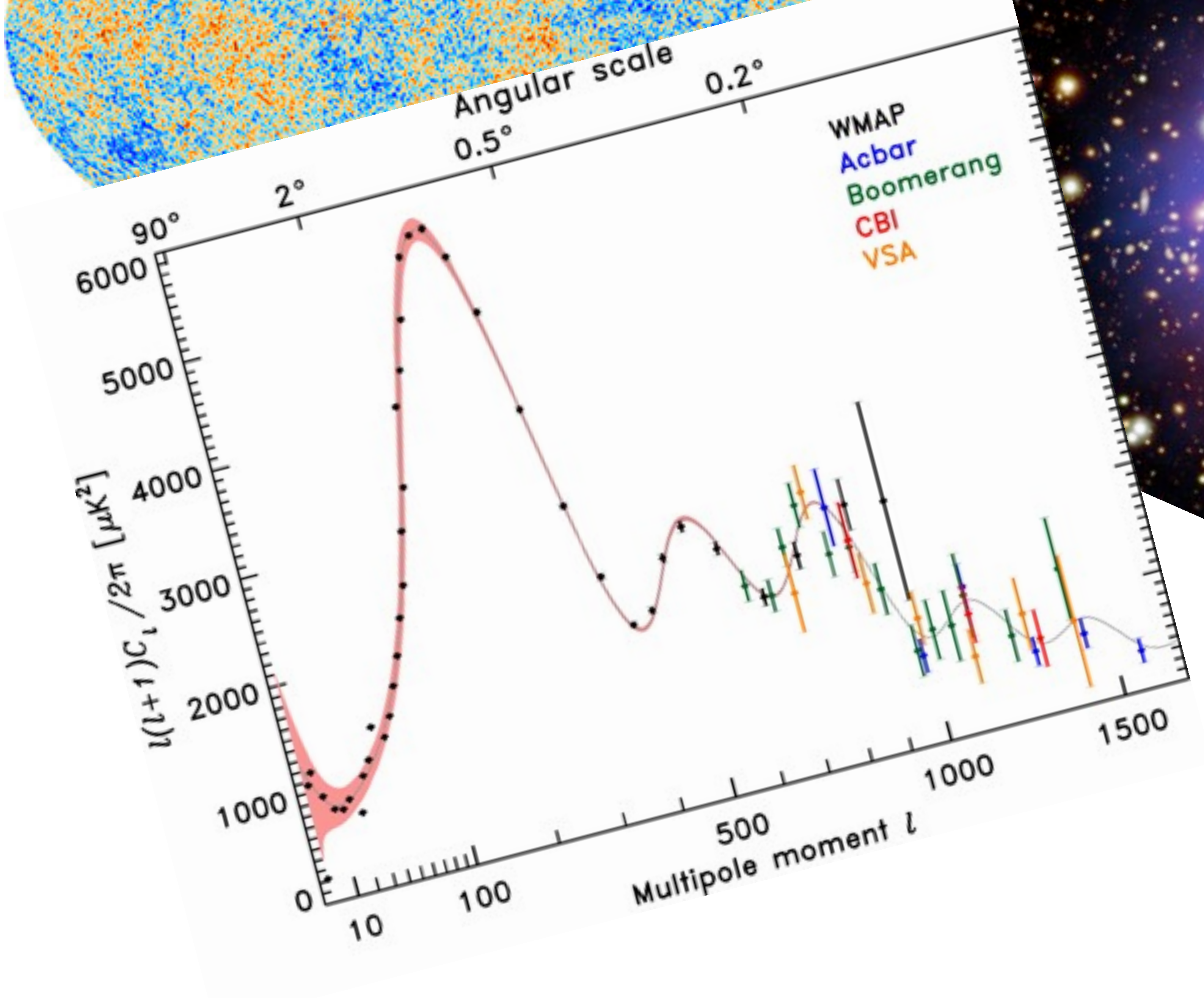

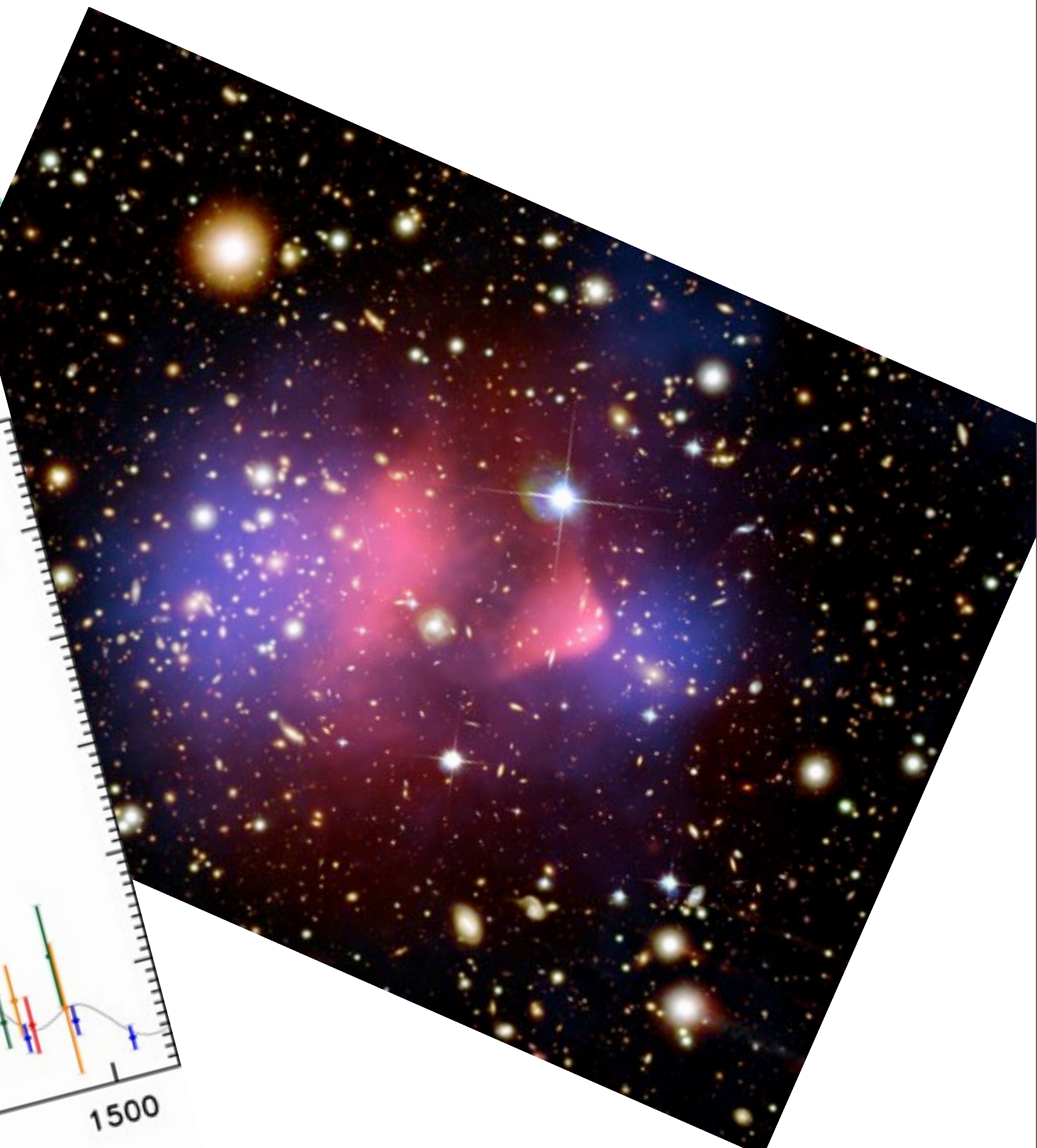

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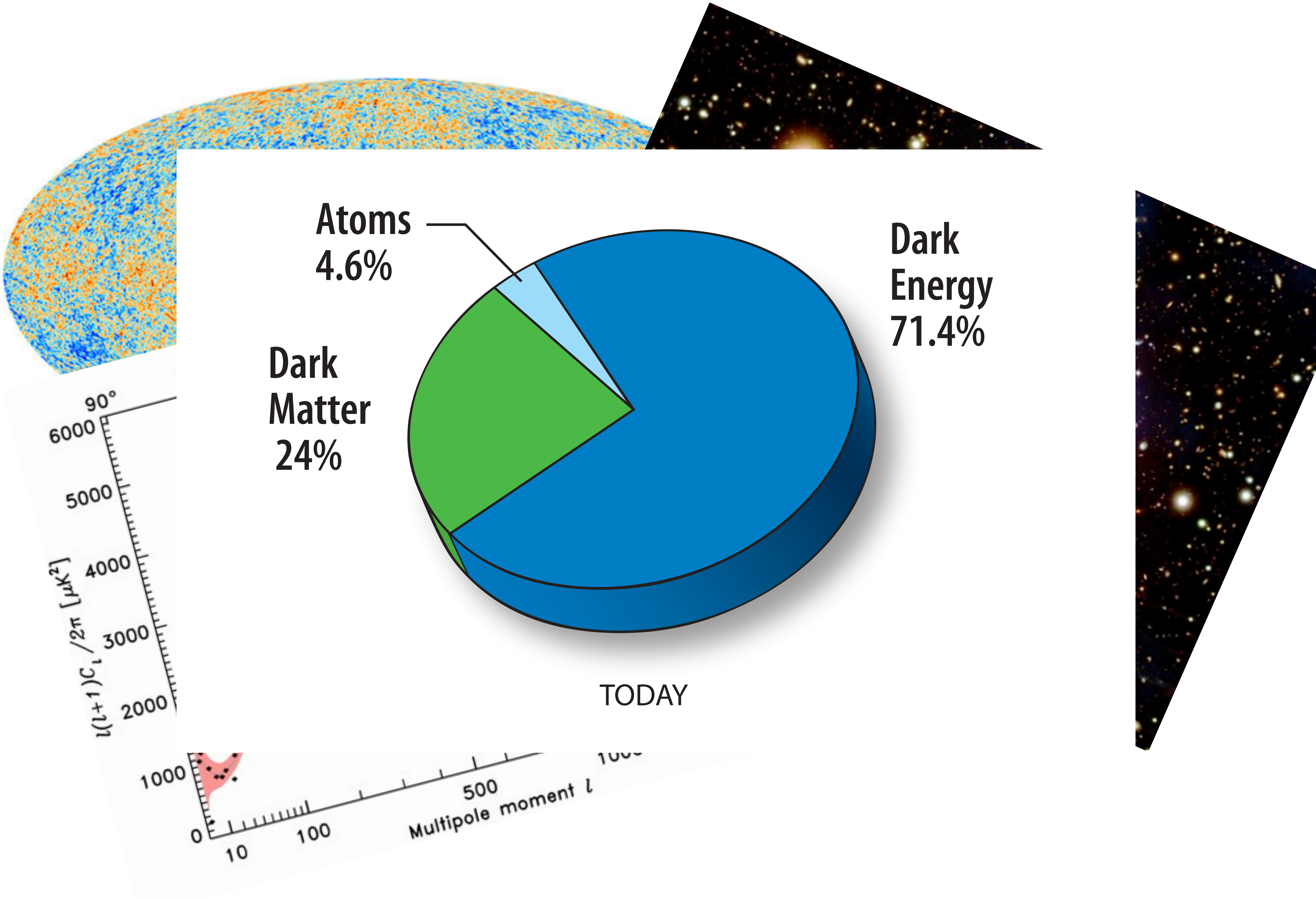
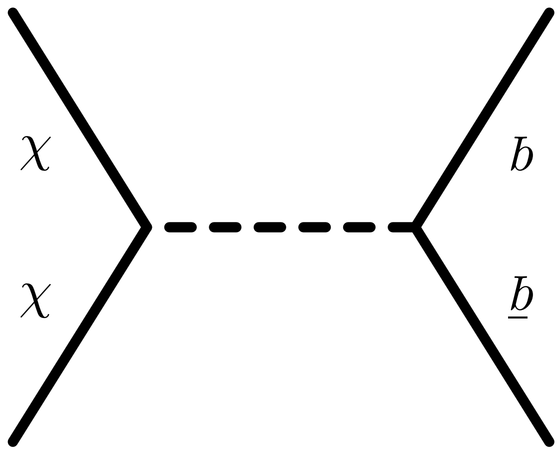
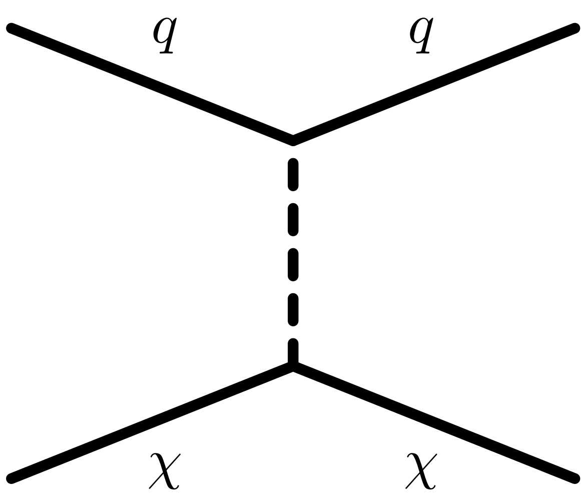
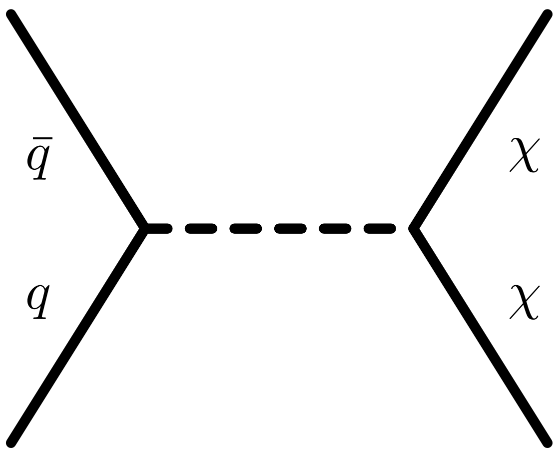


Searching for DM non-gravitationally







Indirect detection

Look up

Anti-matter excesses in cosmic rays, photons from centre of galaxy

Direct detection

Look down

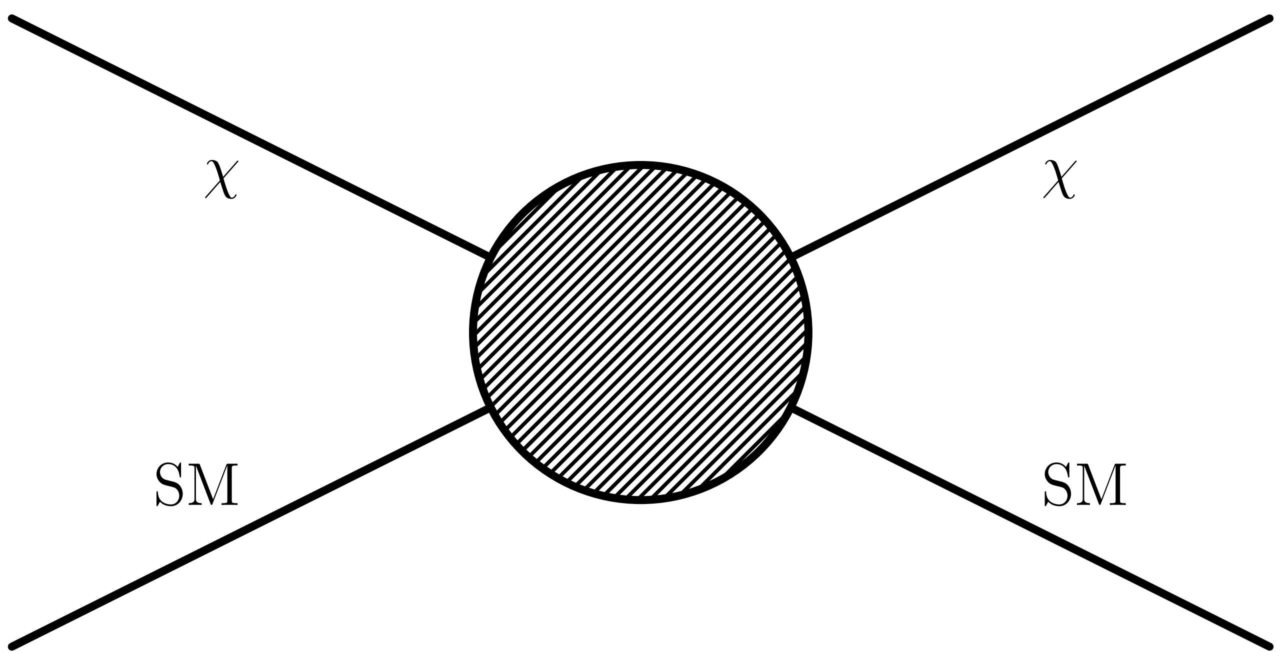
Low rate, low energy recoil events in underground labs

Collider searches

Look small

Missing energy events at colliders

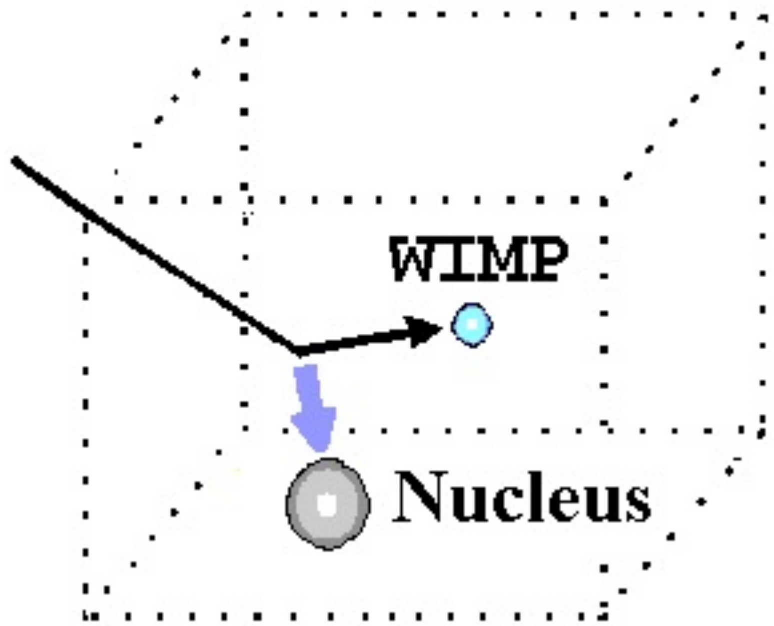
Direct Detection

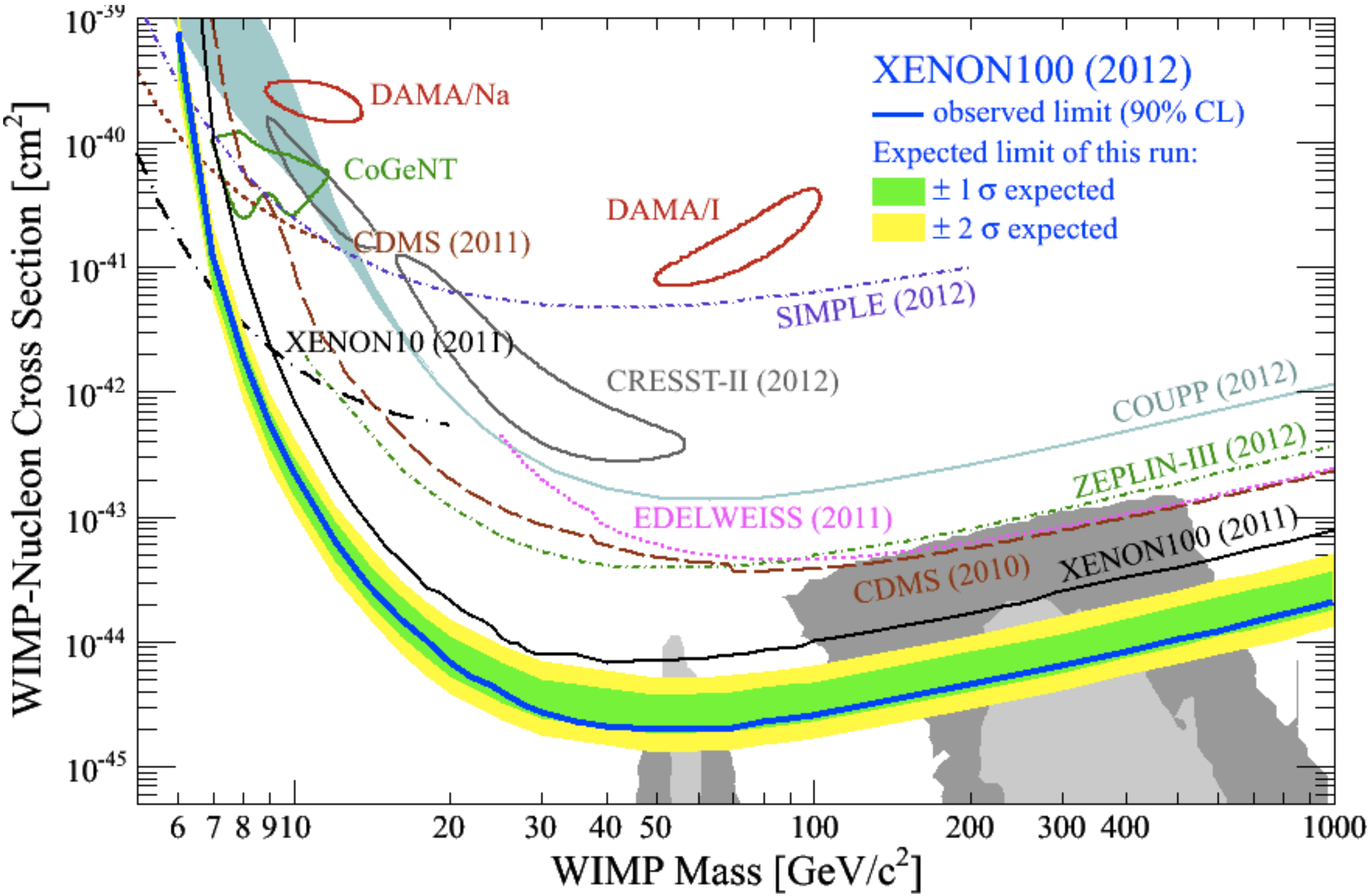


$$E_R \sim \frac{q_\chi^2}{2\,M_T} \sim 100\,\mathrm{keV}$$

$$R \sim N_T \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle$$

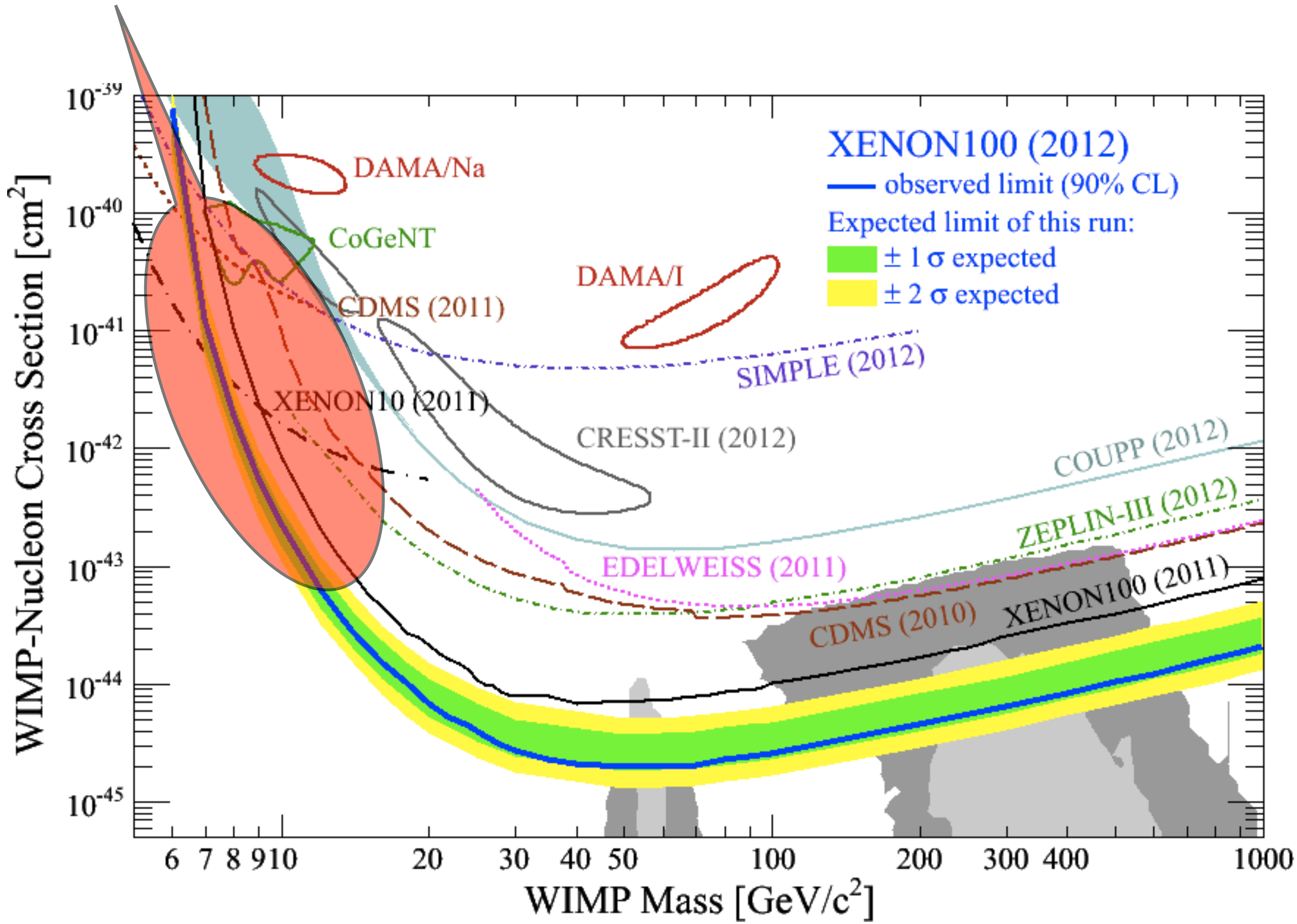
How to distinguish this small number of low energy events from backgrounds?





(Assume local abundance is 0.3 GeV/cm³)

Threshold cuts off



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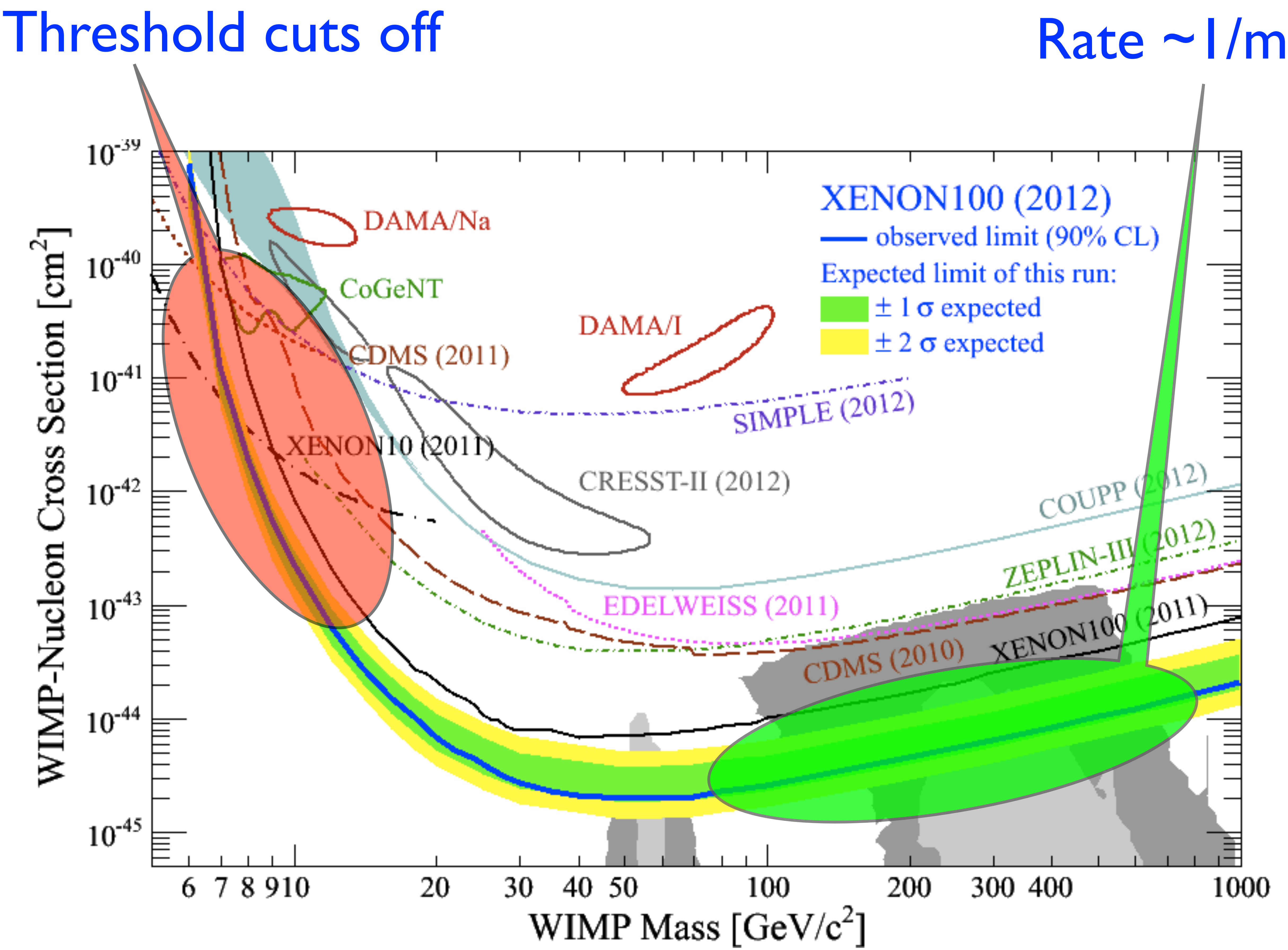

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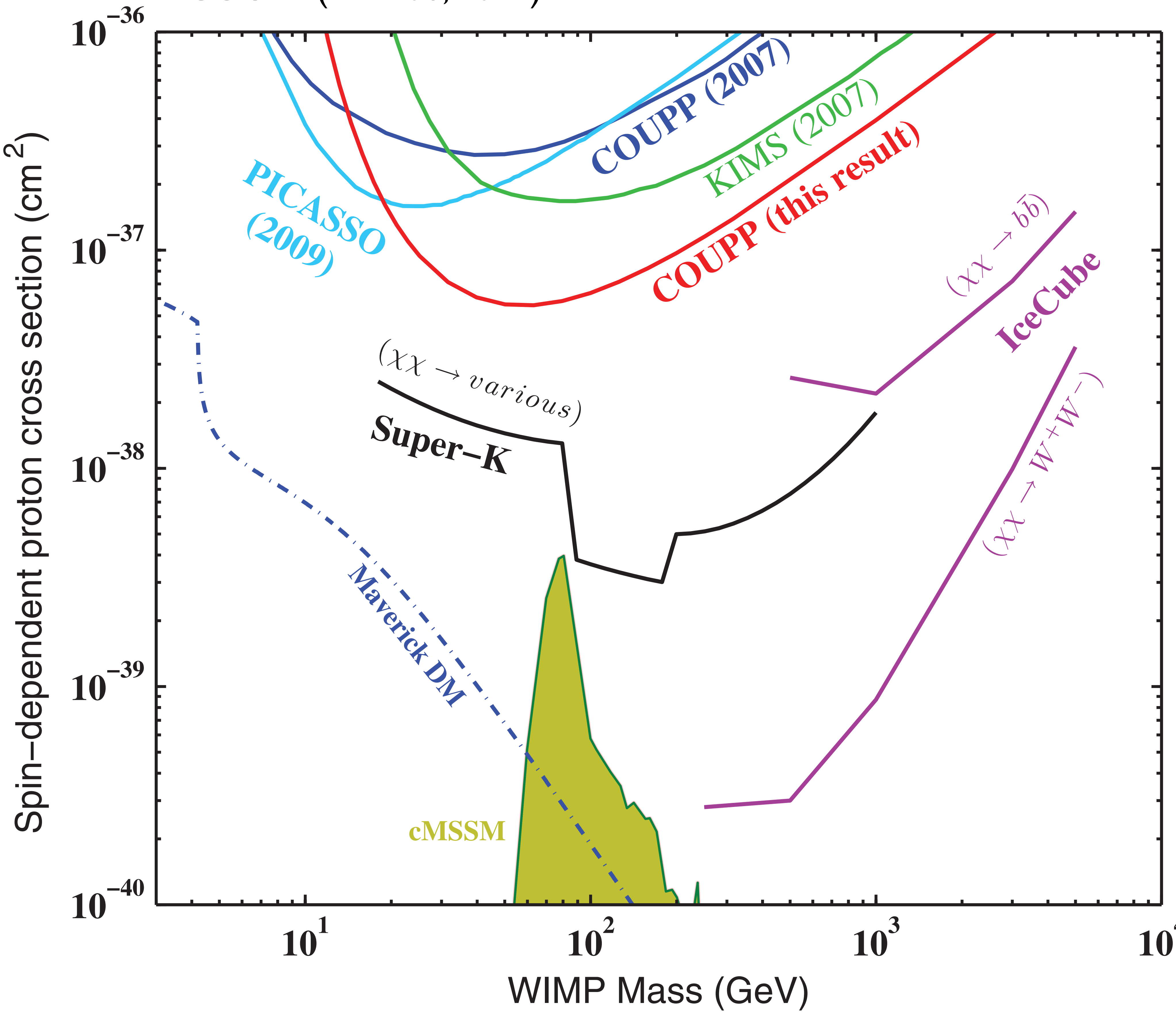
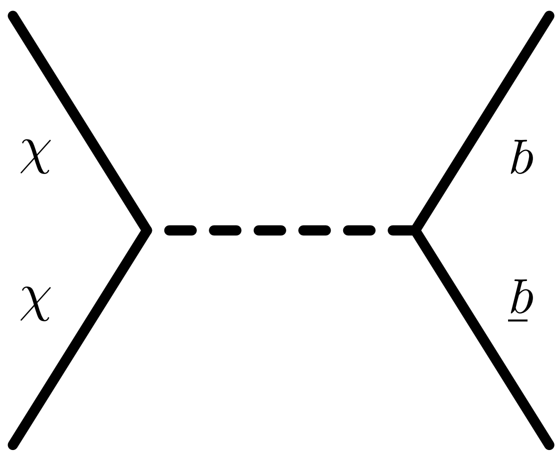
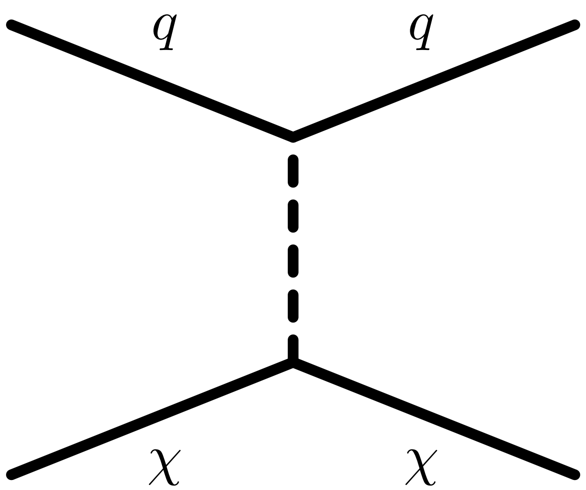
COUPP (PRL106, 2011)

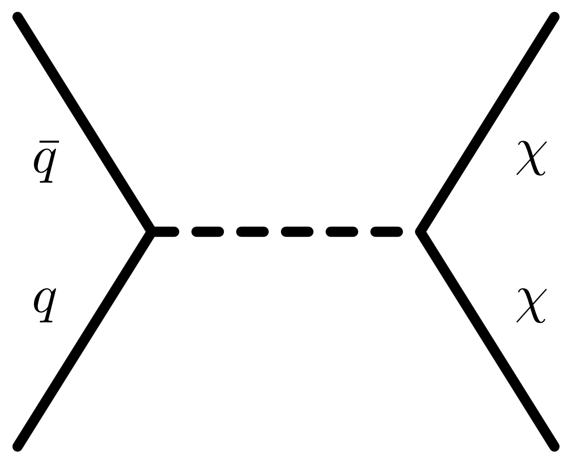


Friday, 19 July 13

Synergy

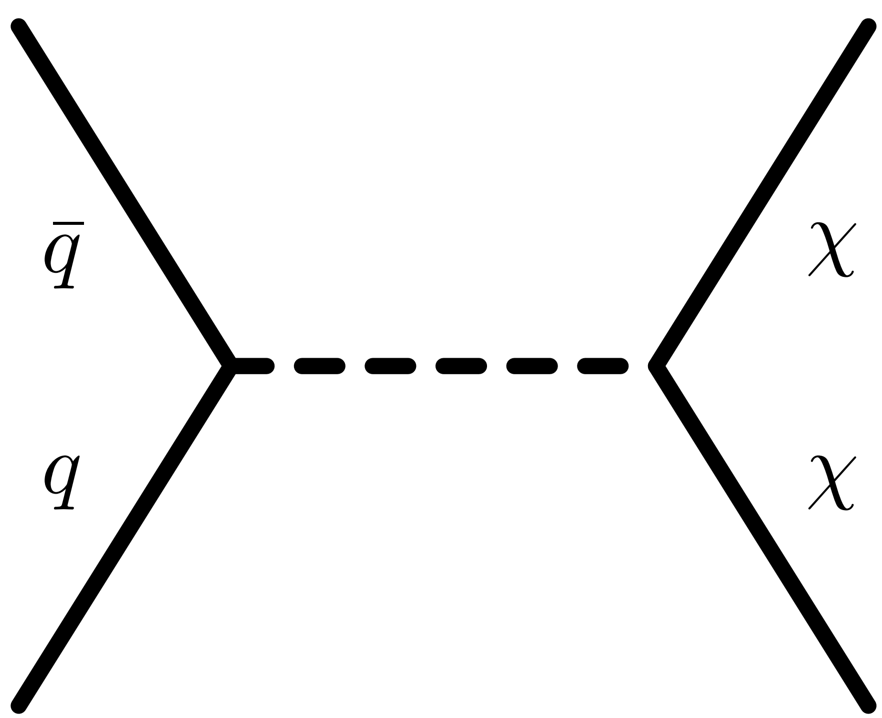




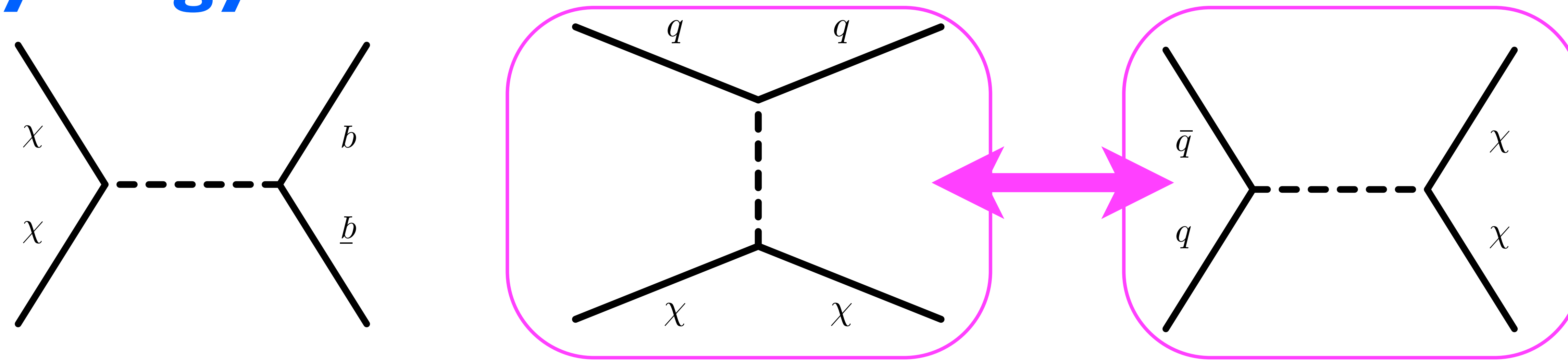


Indirect detection Direct detection Collider searches

Many BSM models contain DM, but can we be more model independent?



Synergy



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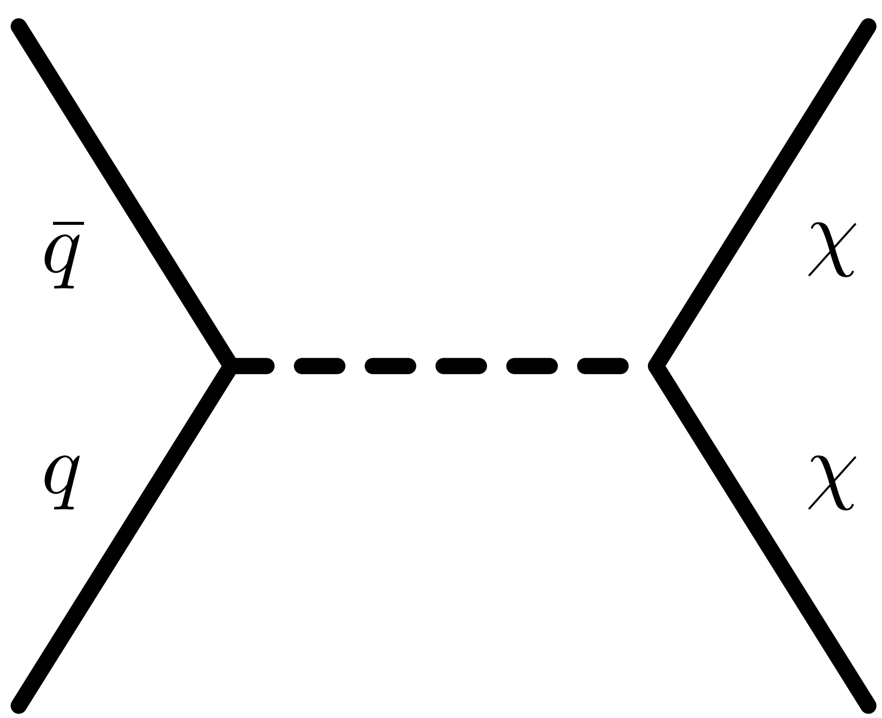

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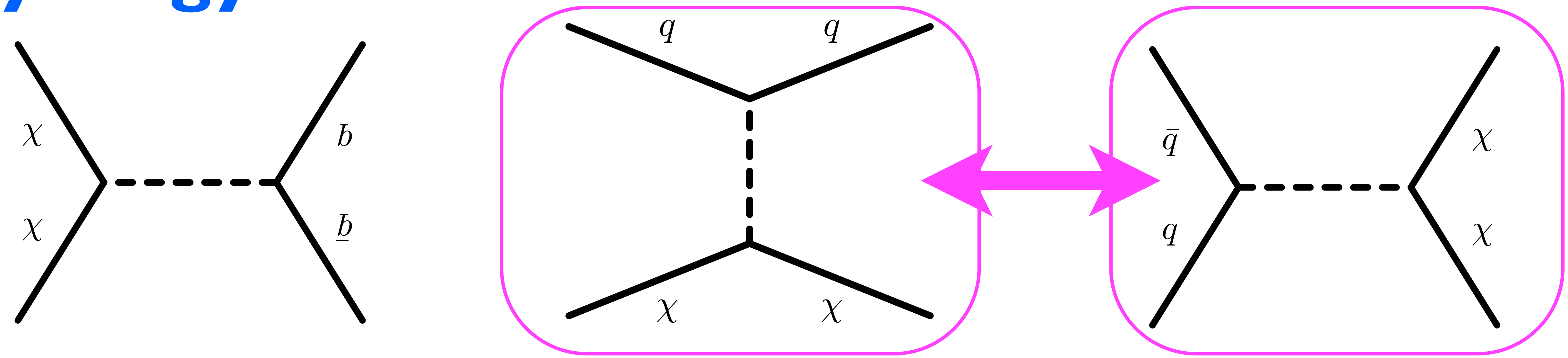

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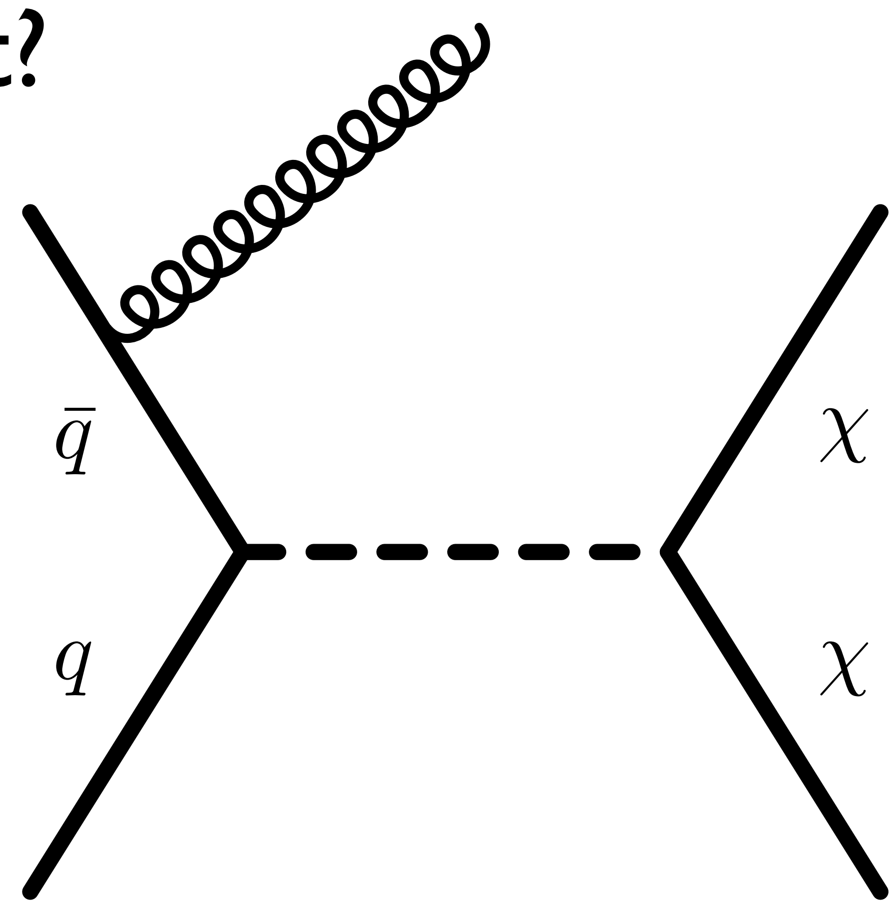
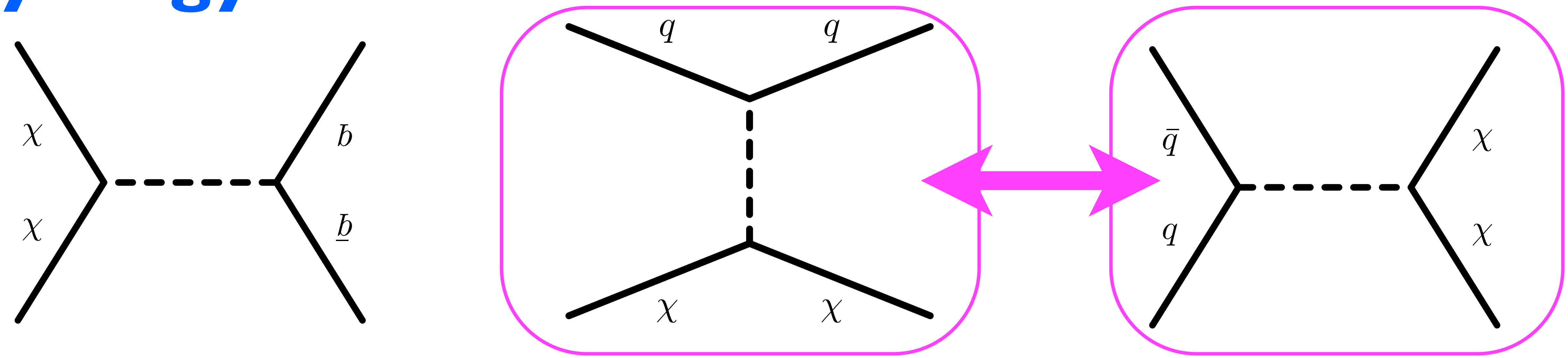


"Monojets"

Synergy



Indirect detection　Direct detection　Collider searches

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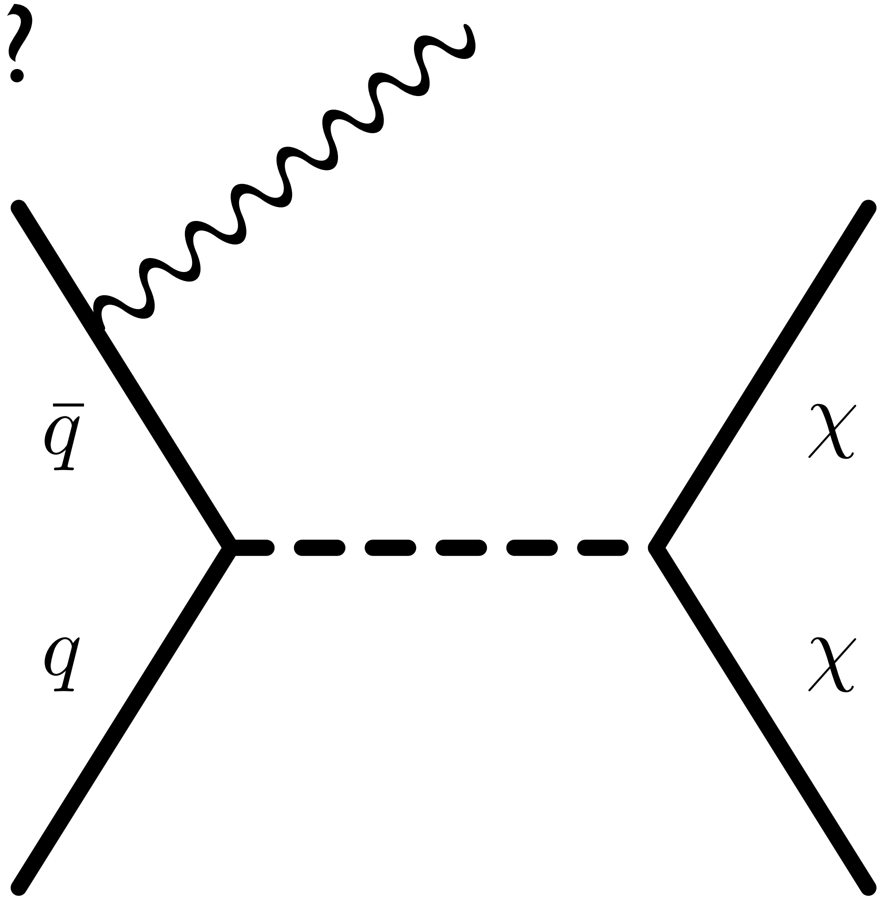


"Monophotons"

The Naturalness Dogma: caveat emptor

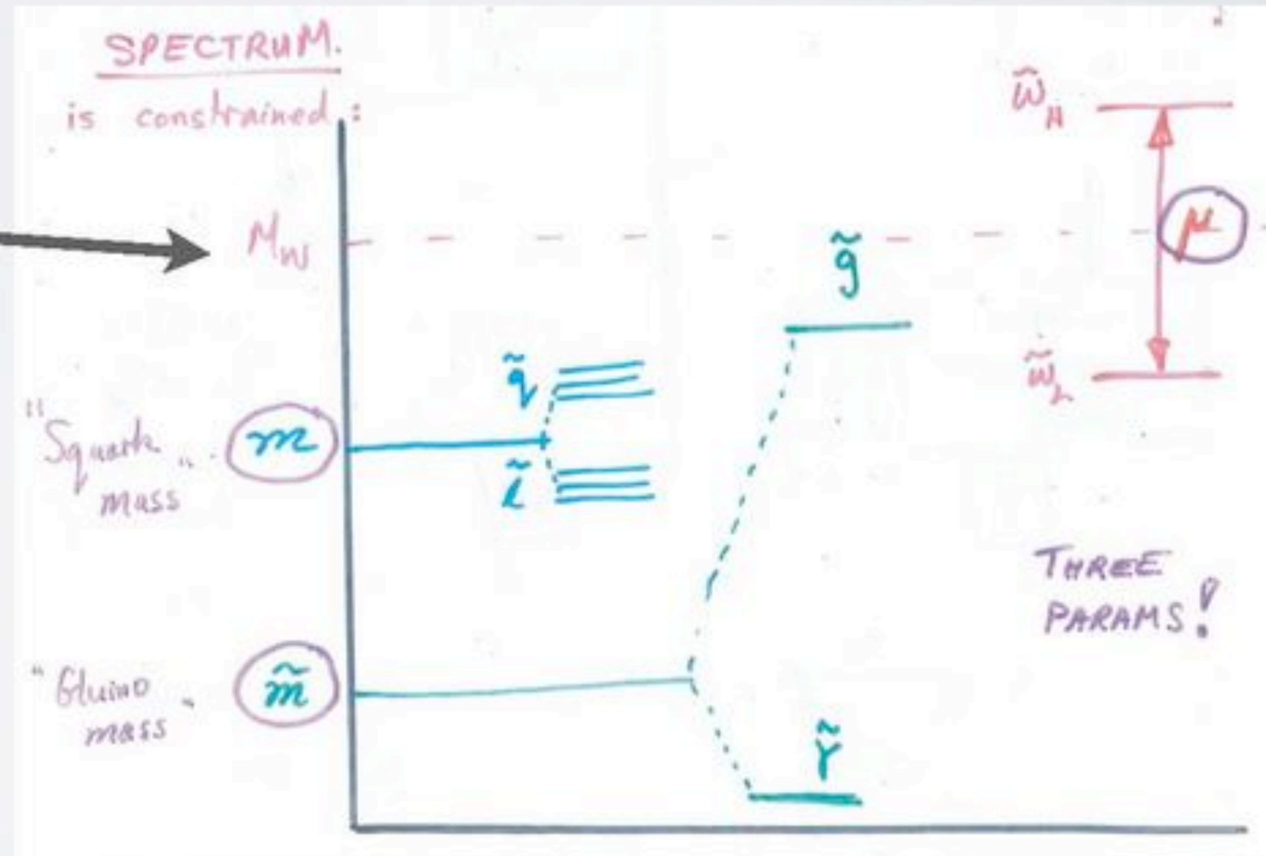
NATURAL SUSY, 1984

From Lawrence Hall's talk at SavasFest

W boson near the top of the spectrum....

1984 was a utopian year for SUSY.

Times have changed!



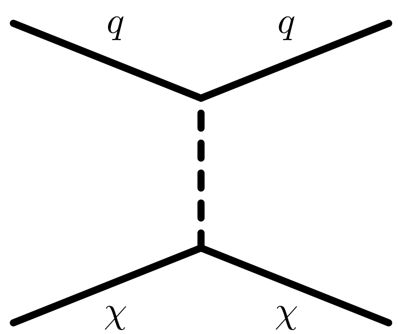
Talk by Matt Reece at LHCP 2013

Joseph Lykken — *KITP Santa Barbara, July 12, 2013*

Move beyond simple models?

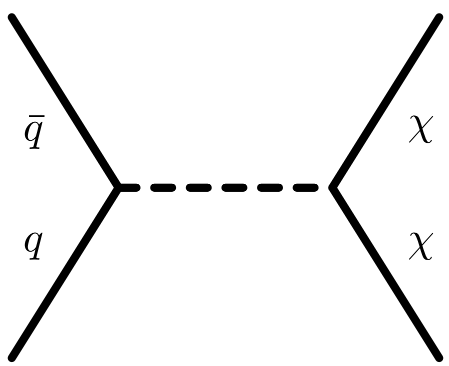
Neal Weiner, Invisibles13

"EFT"



$$\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

$$\mu = \frac{m_\chi m_n}{m_\chi + m_n}$$



Mono-jet + $\not{E}_T$

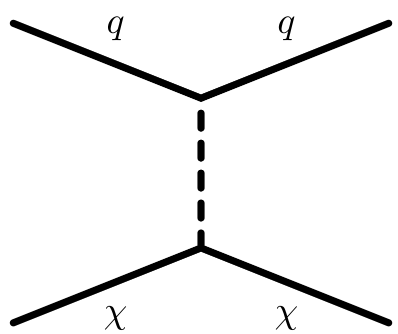
$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2}{M^4}$$

Bounds are "model independent", and <u>astrophysics independent</u>

No low mass threshold

Unaffected by iDM, momentum/velocity suppression

"EFT"



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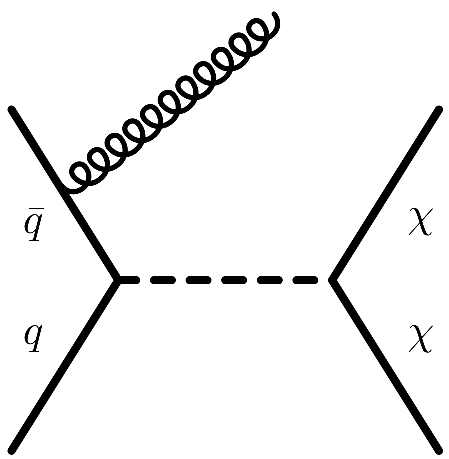

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Operators

See Goodman et al. [1008.1783]
for more complete list

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2},$$

SI, vector exchange

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2},$$

SD, axial-vector exchange

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R),$$

SI, scalar exchange

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}$$

SI, scalar exchange

- DM a Dirac fermion
- Consider each operator separately

Many Theorists

Goodman, Jessica et al. Phys.Lett. B695 (2011) 185-188
Goodman, Jessica et al. Phys.Rev. D82 (2010) 116010
Goodman, Jessica et al. arXiv:1111.2359
Rajaraman, Arvind et al. Phys.Rev. D84 (2011) 095013
Fortin, Jean-Francois et al. Phys.Rev. D85 (2012) 063506
Bai, Yang et al. JHEP 1012 (2010) 048
PJF, Harnik, et al. Phys.Rev. D85 (2012) 056011
PJF, Harnik et al. Phys.Rev. D84 (2011) 014028
PJF, Harnik et al arXiv:1203.1662
Shoemaker, Vecchi arXiv:1112.5457
An, Jia and Wang: arXiv:1202.2894

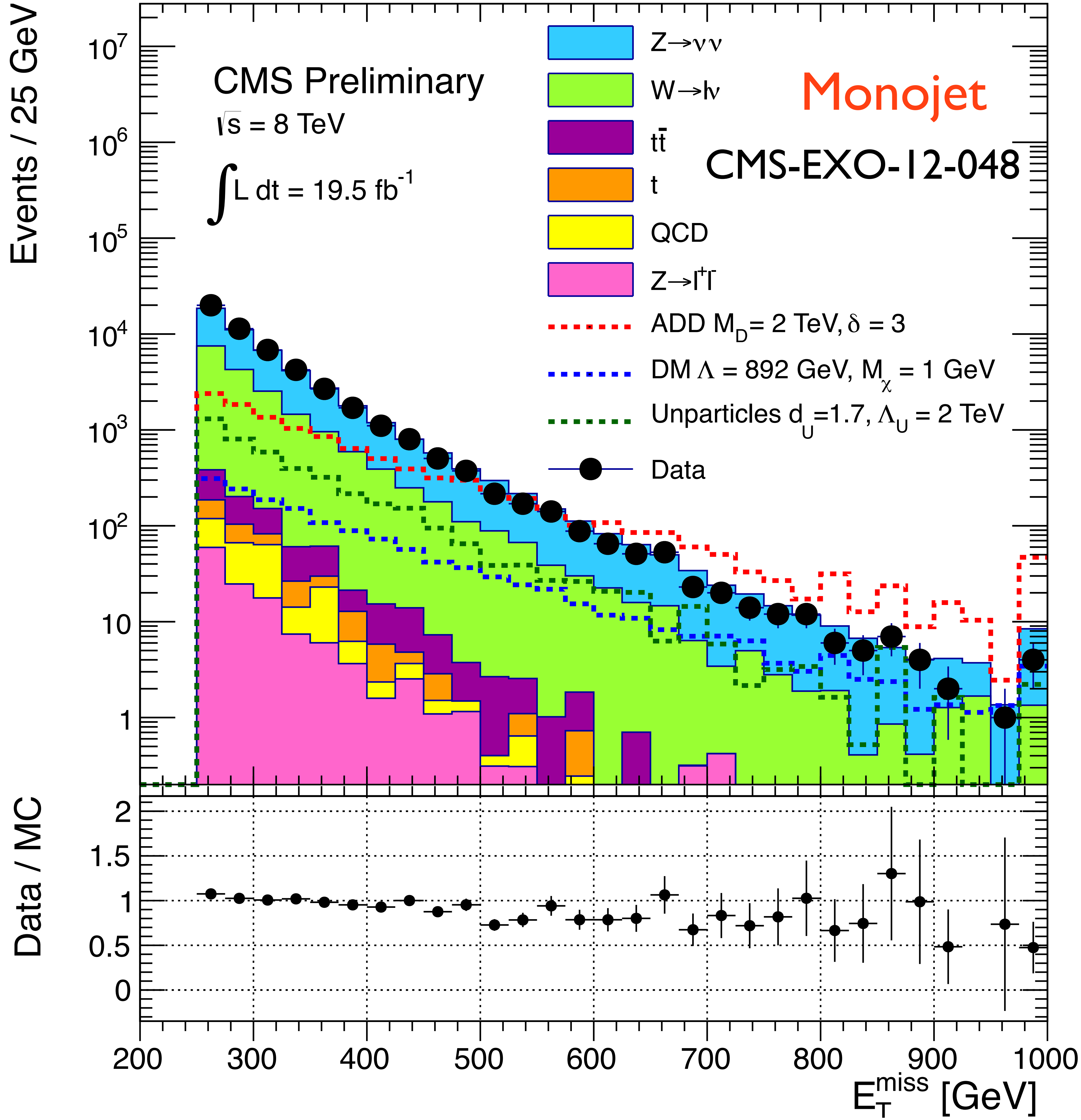
⋮

Many Experimentalists

ADD extra dimension searches can be "recast"

6.7/fb shape-based monojet analysis

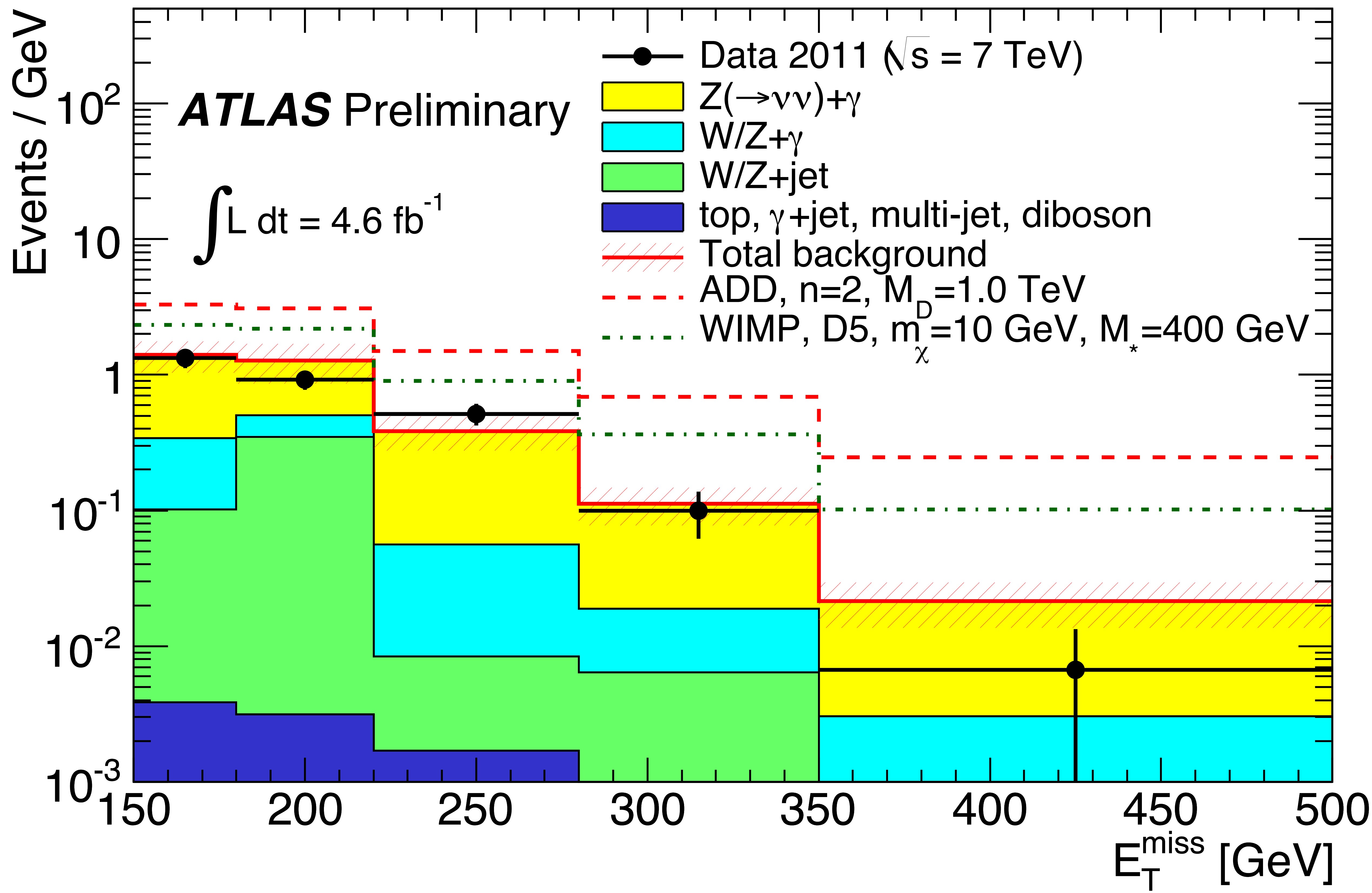
5~20/fb cut and count monojet and monophoton analyses



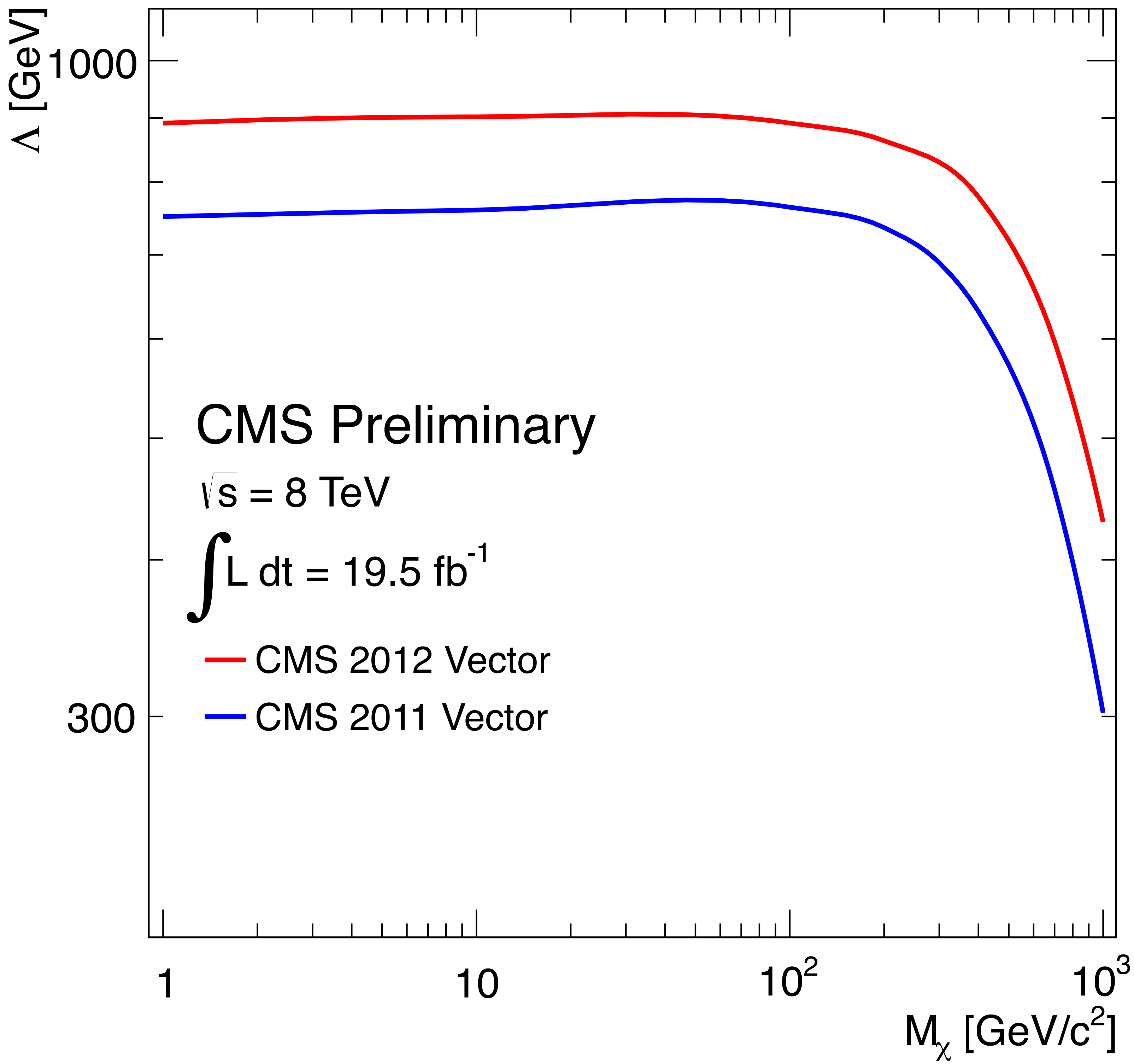
CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb⁻¹
Monojet
CMS-EXO-12-048
Z→νν
W→lν
tt̄
t
QCD
Z→l⁺l⁻
ADD M_D = 2 TeV, δ = 3
DM Λ = 892 GeV, M_χ = 1 GeV
Unparticles d_U=1.7, Λ_U = 2 TeV
Data
Events / 25 GeV
Data / MC
E_T^miss [GeV]

ATLAS-CONF-2012-085

Monophoton

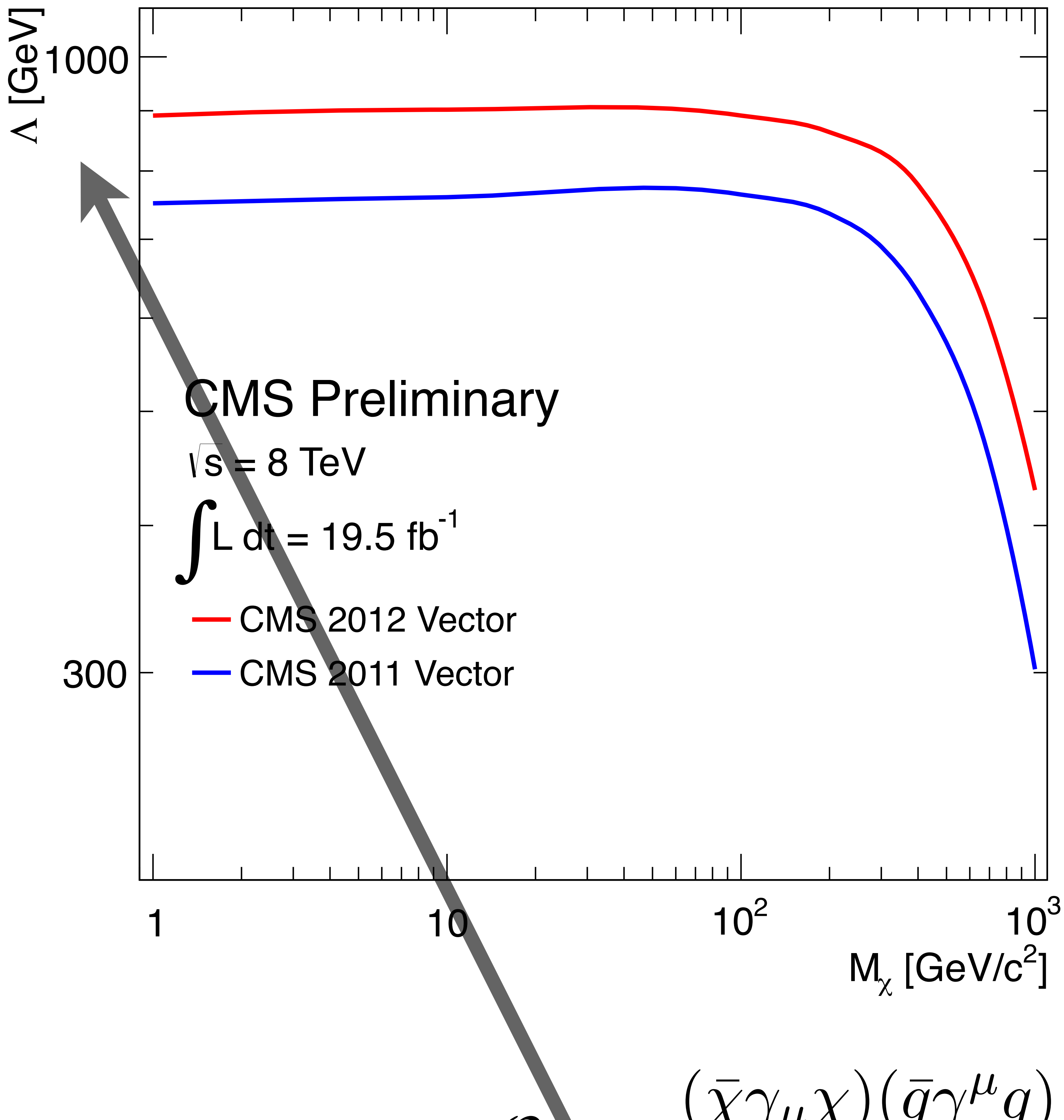


Vector coupling



$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Vector coupling



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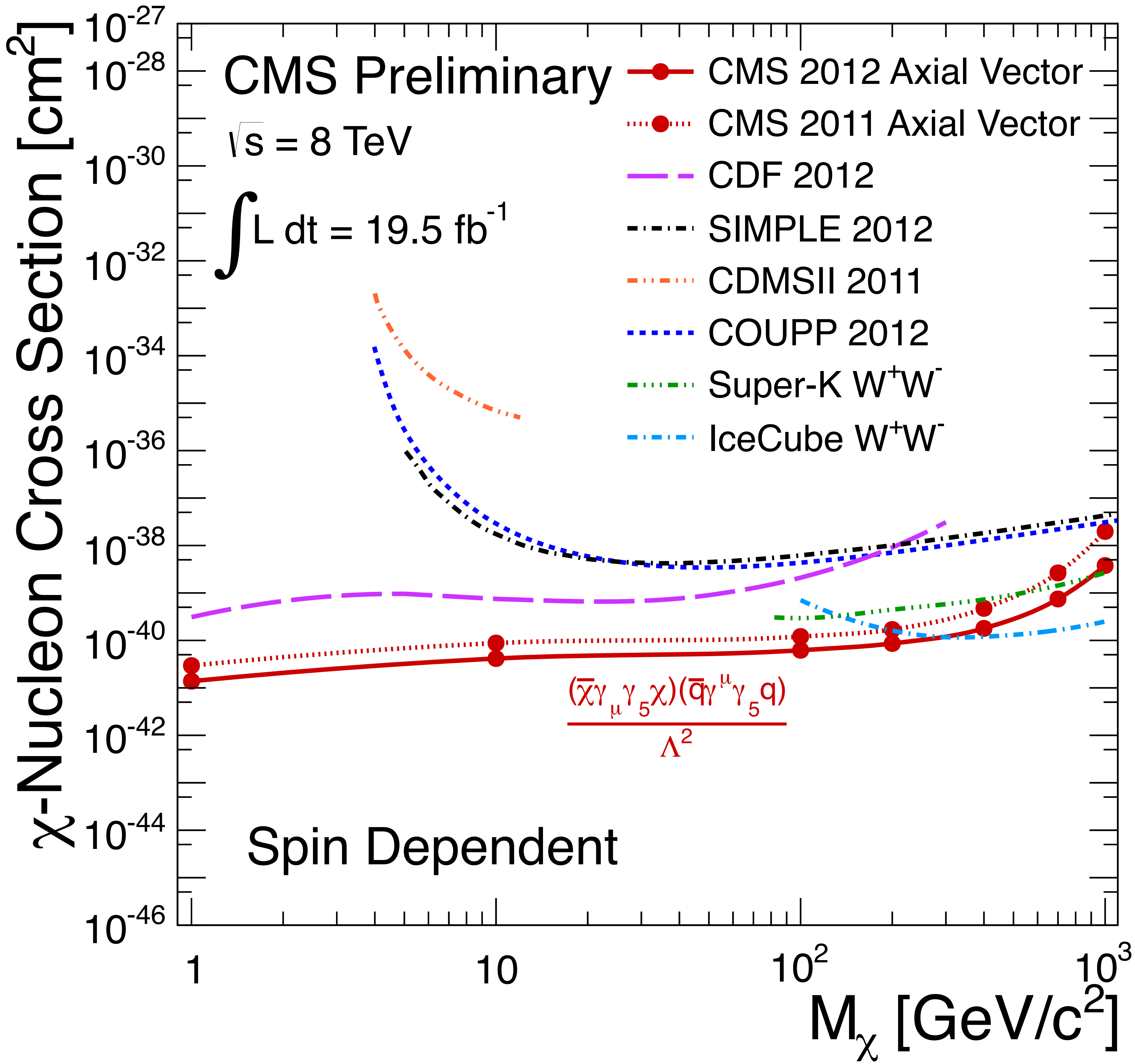
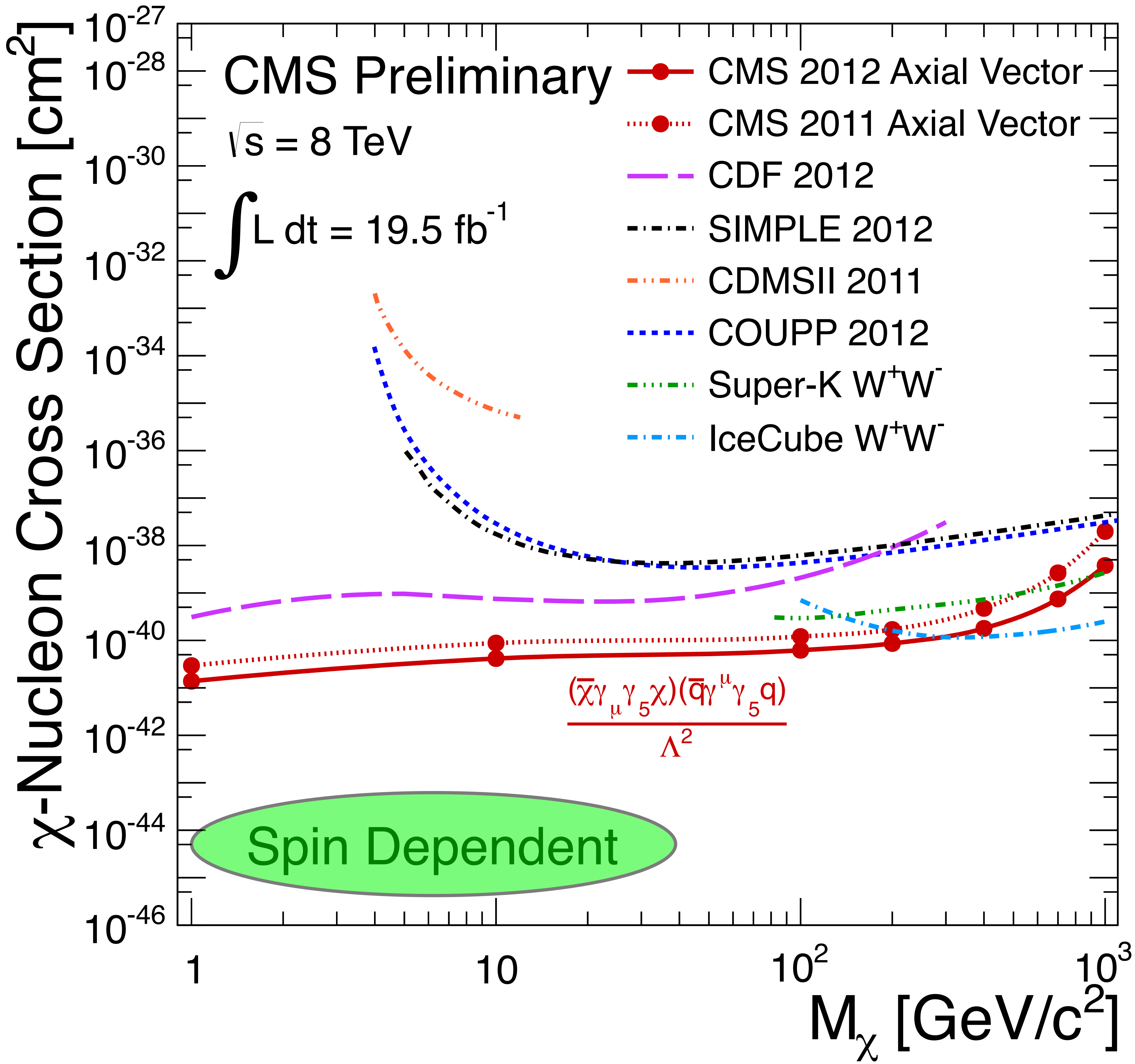
Monojet



CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb-1
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W+W-
IceCube W+W-
$\frac{(\bar{\chi}\gamma_{\mu}\gamma_{5}\chi)(\bar{q}\gamma^{\mu}\gamma_{5}q)}{\Lambda^2}$
Spin Dependent
χ-Nucleon Cross Section [cm2]
Mχ [GeV/c2]

Monojet



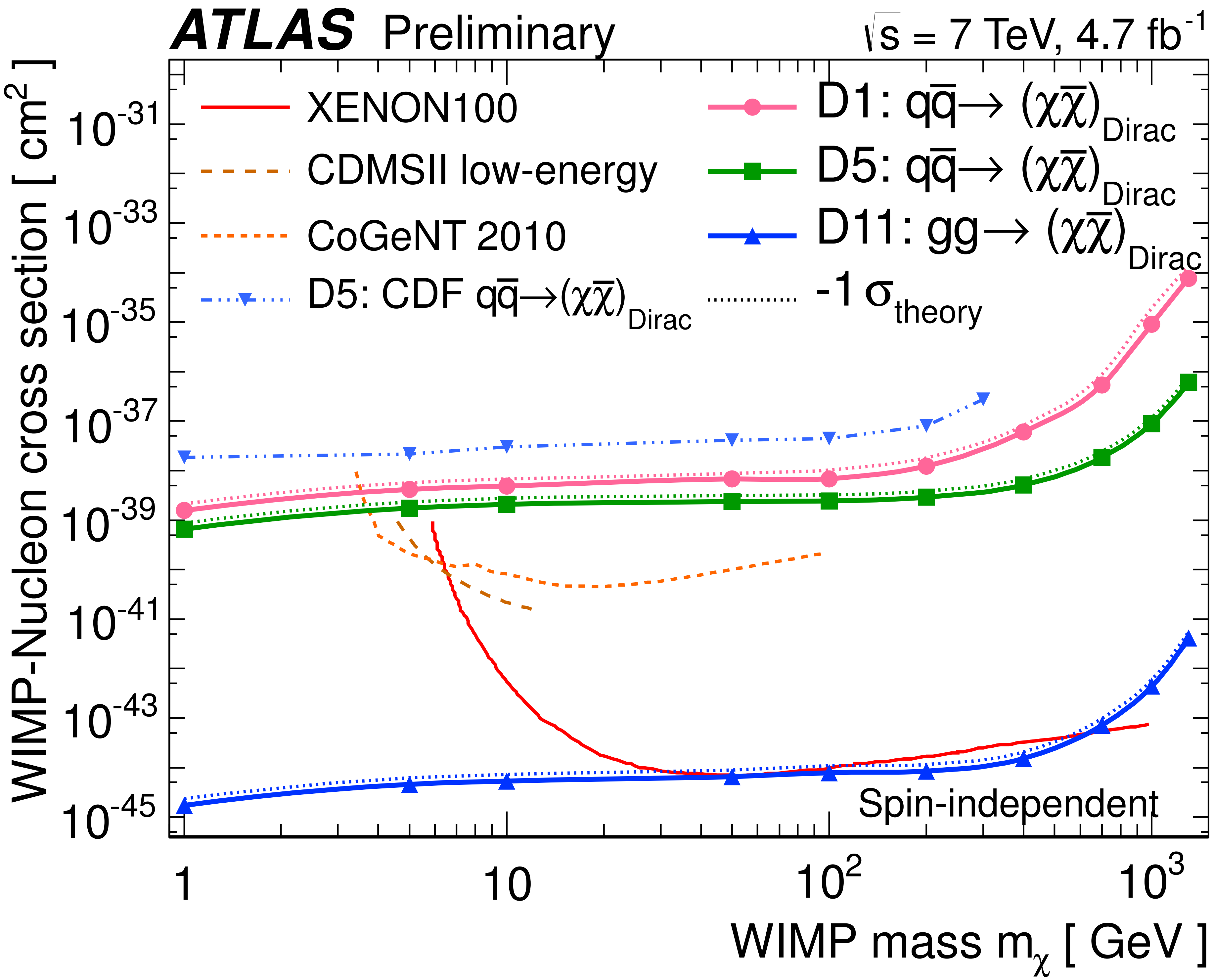
CMS Preliminary
$\sqrt{s}$ = 8 TeV
$\int$L dt = 19.5 fb^{-1}
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W^+W^-
IceCube W^+W^-
$\frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$
Spin Dependent
χ-Nucleon Cross Section [cm^2]
M_χ [GeV/c^2]
10^{-27}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
1
10
10^2
10^3

Monojet

$$D1 = \bar{\chi}\chi\bar{q}q$$

$$D5 = \bar{\chi}\gamma^{\mu}\chi\gamma_{\mu}\bar{q}q$$

$$D11 = \bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$$



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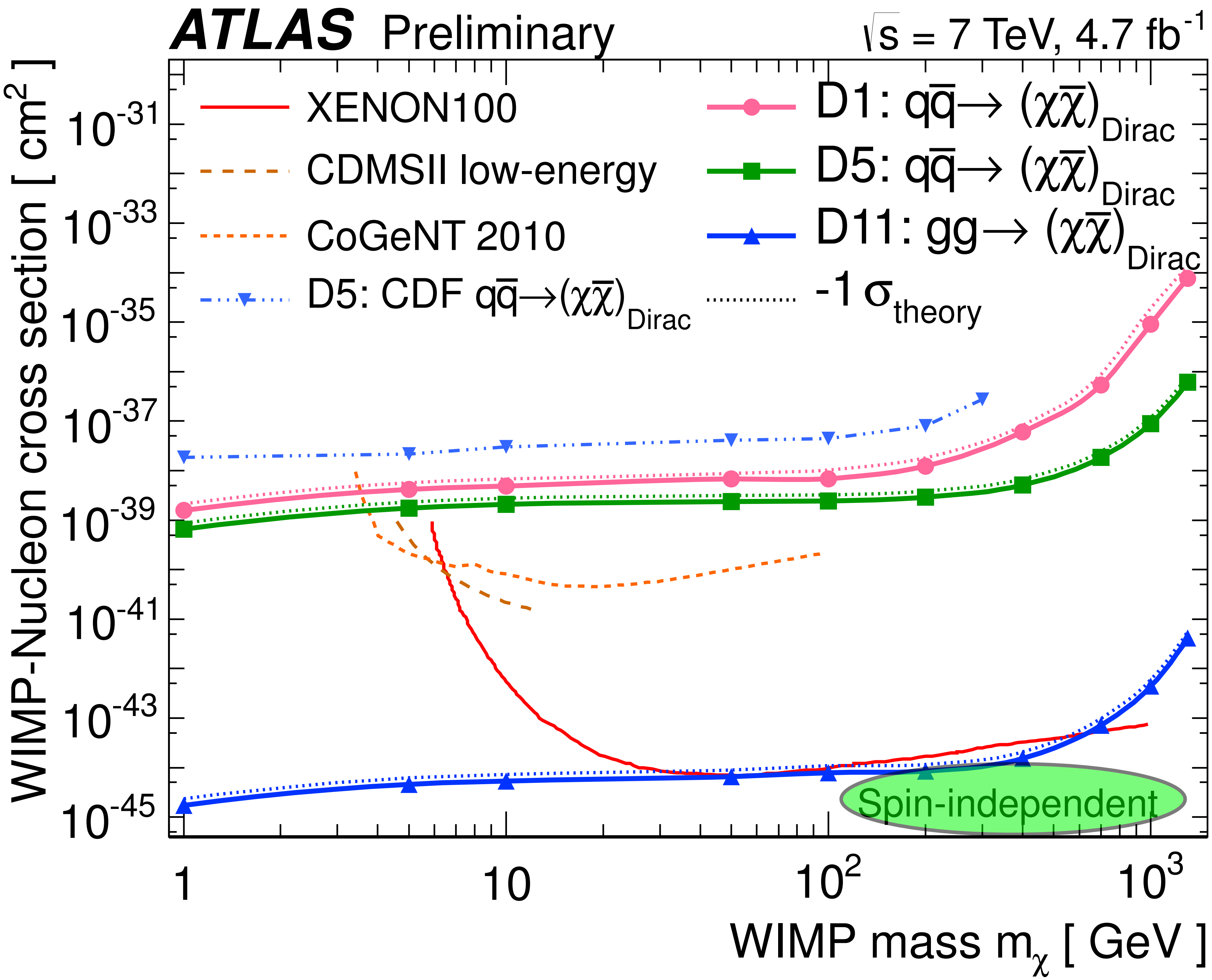
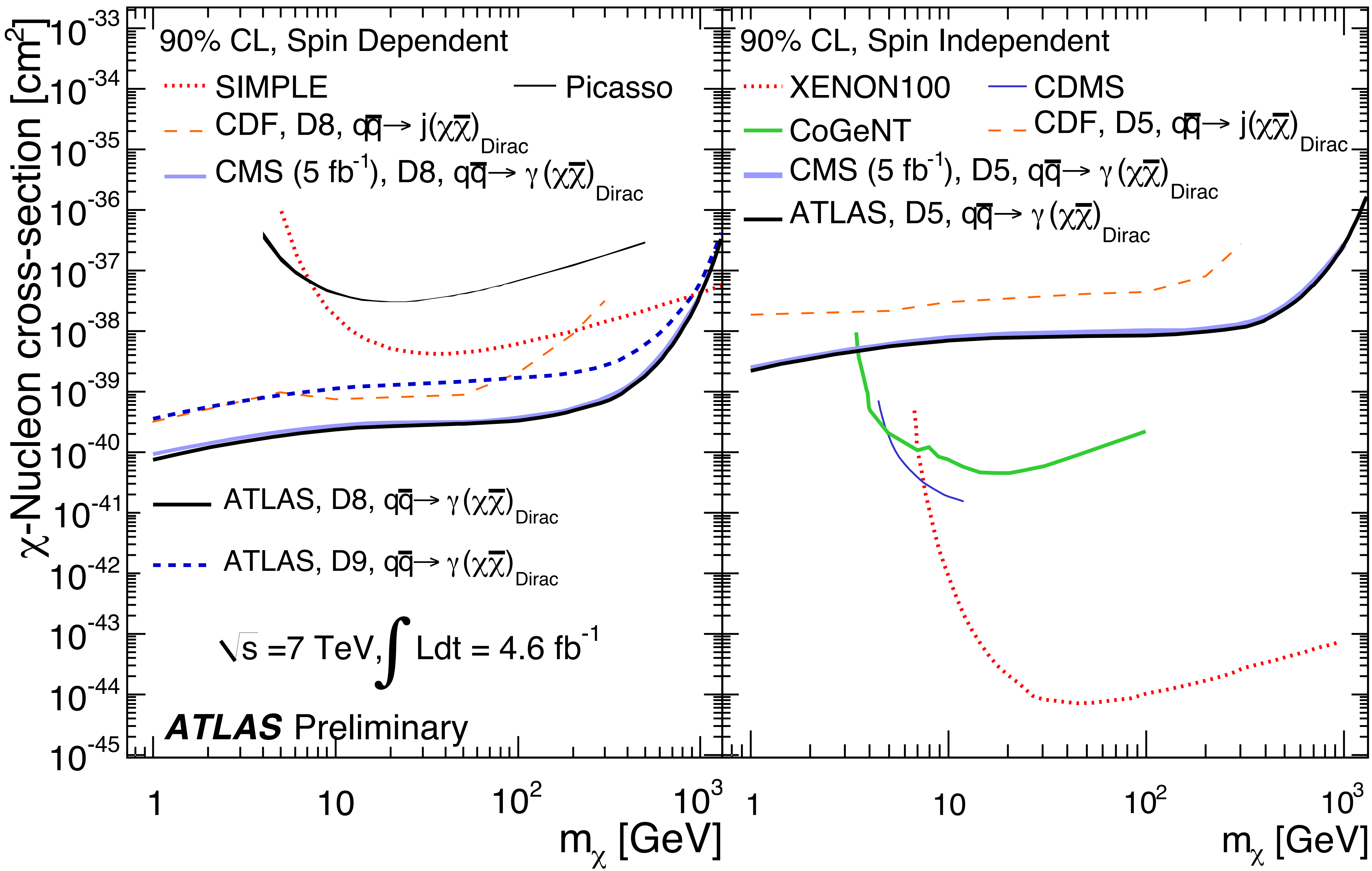


Monophoton

$$D8 = \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma^{\mu}\gamma_5 q$$

$$D5 = \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma^{\mu}q$$



Monophoton

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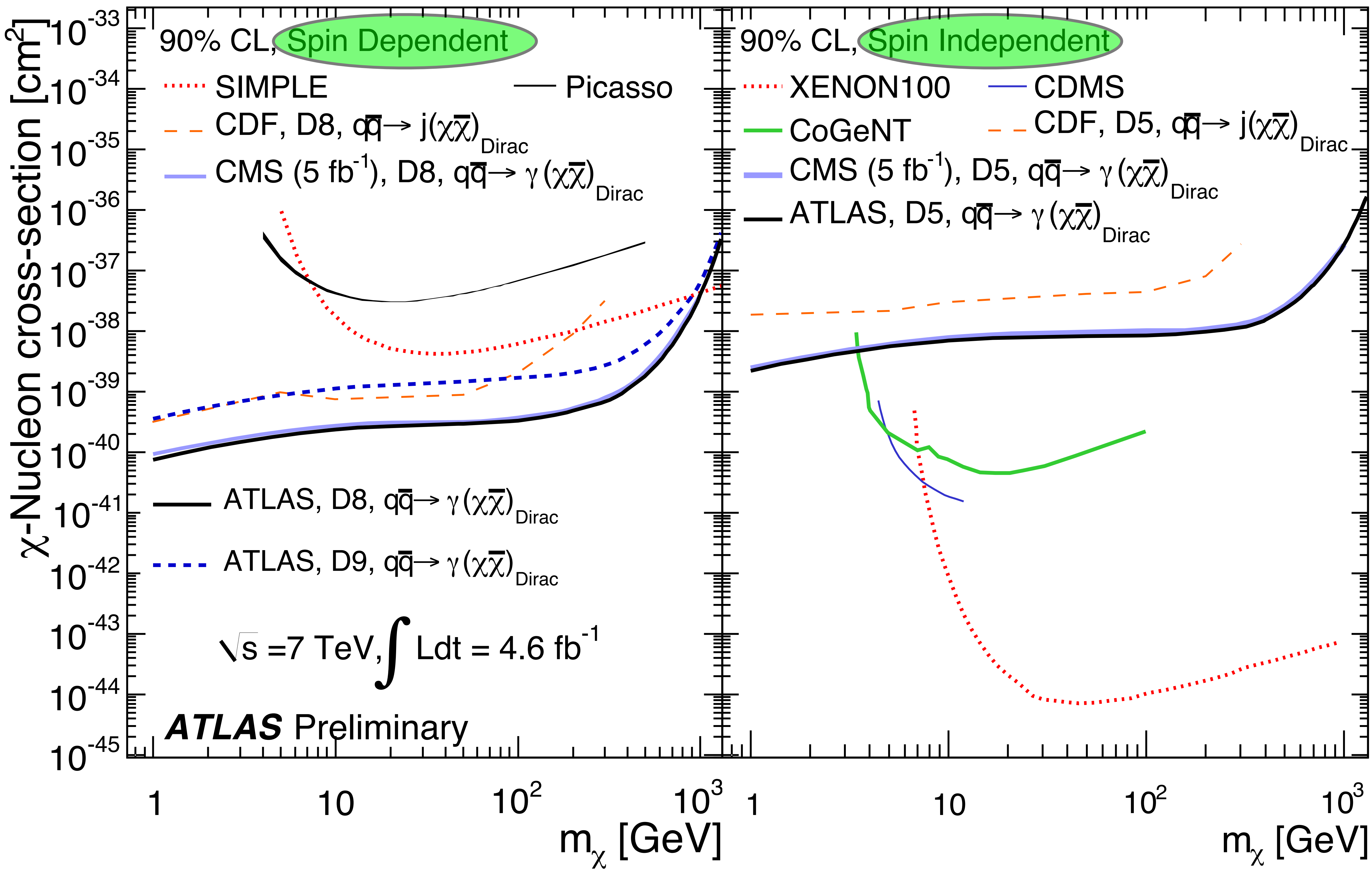


What next?

"Mono" searches: $\Delta\phi(j_1, j_2) < 2.5 \quad N_{jet} \leq 2$

LHC is a jets "factory", can we do better?

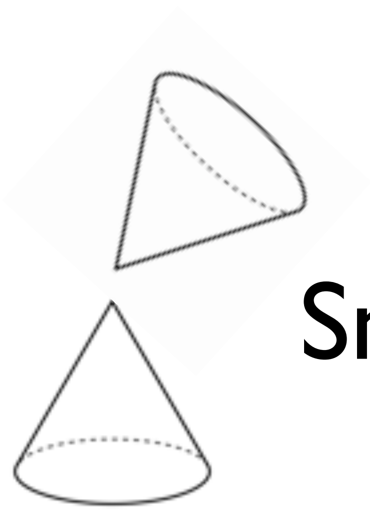
Steal from SUSY jets+MET analyses

$$M_R = \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

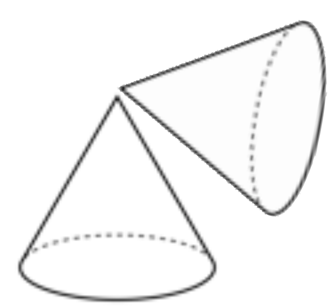
$$M_R^T = \sqrt{\frac{\not{E}_T(p_T^{j_1} + p_T^{j_2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

[Rogan 1006.2727]

$$R = \frac{M_R^T}{M_R}$$

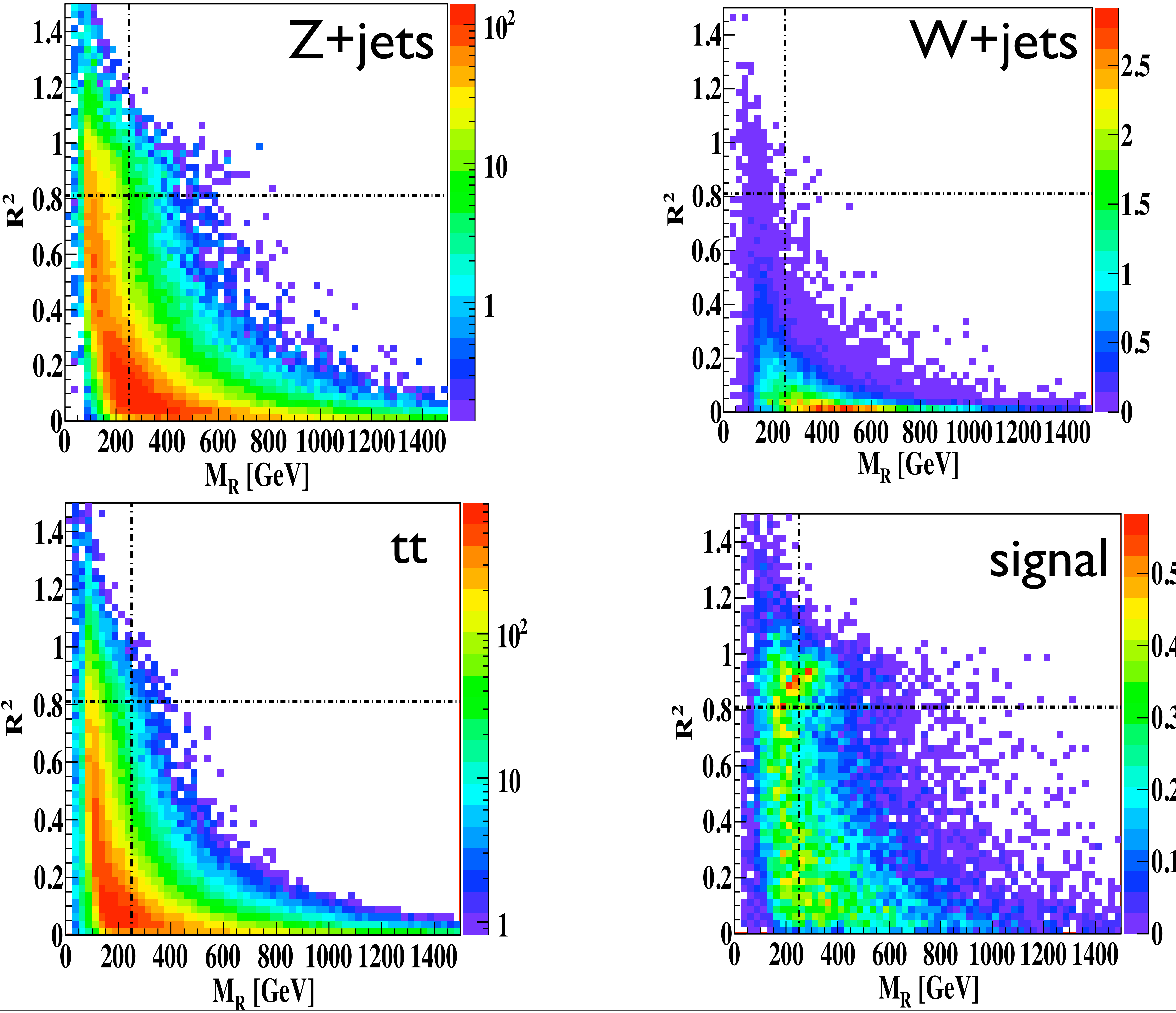


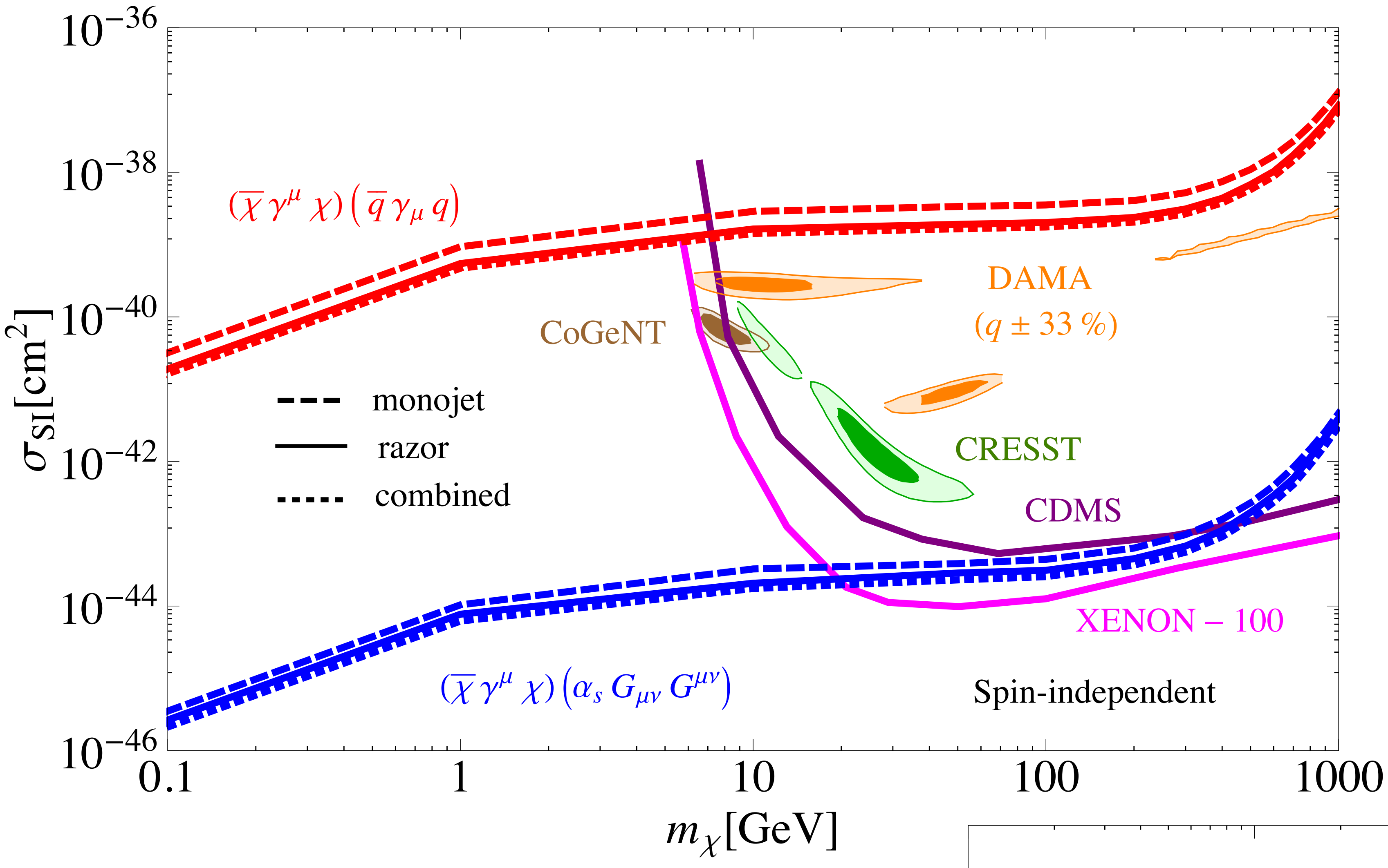
Small R



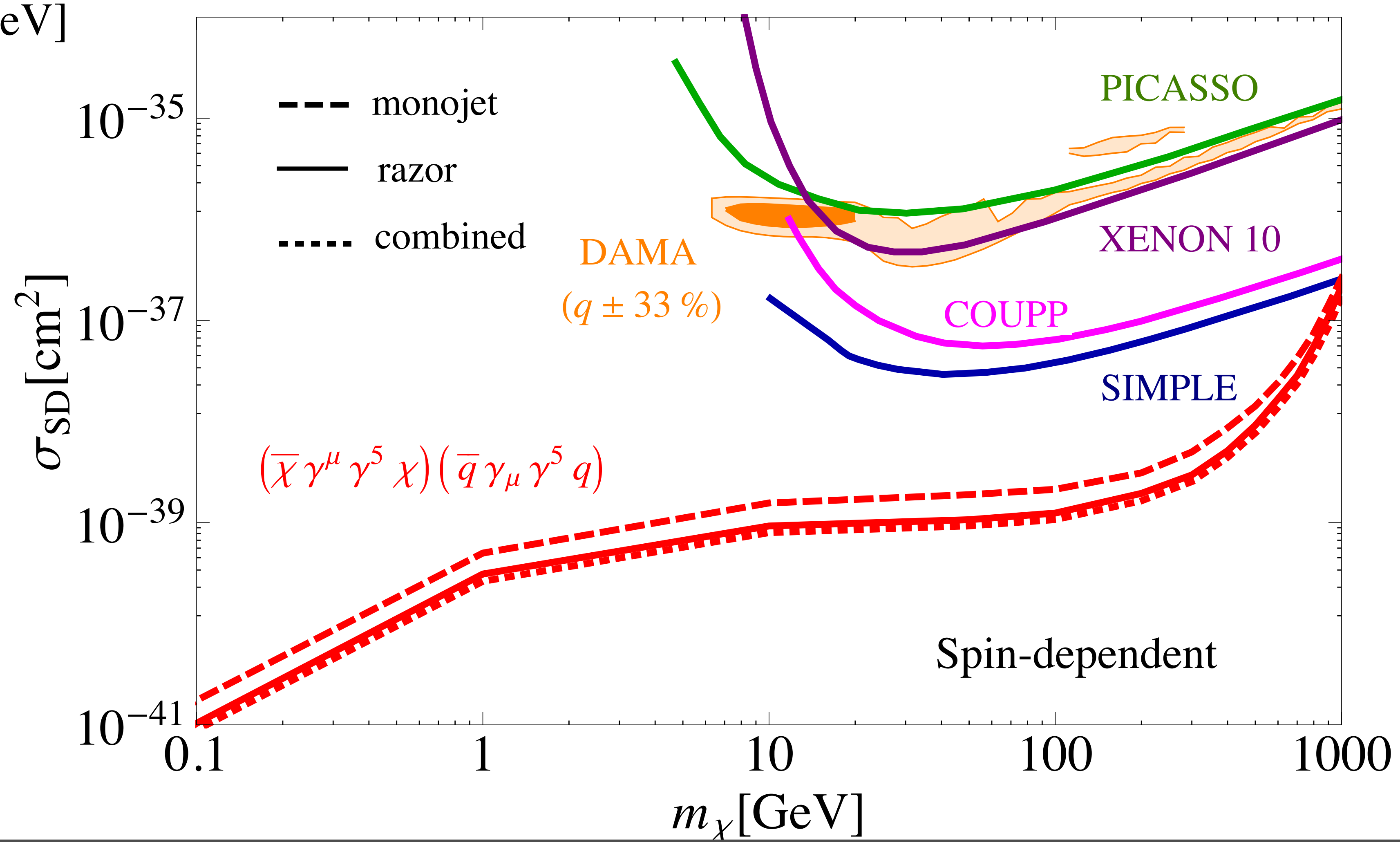
Large R

Friday, 19 July 13


Z+jets
W+jets
tt
signal
R^2
M_R [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
200
400
600
800
1000
1200
1400
1
10
10^2
0.5
1.5
2
2.5
0.1
0.2
0.3
0.4

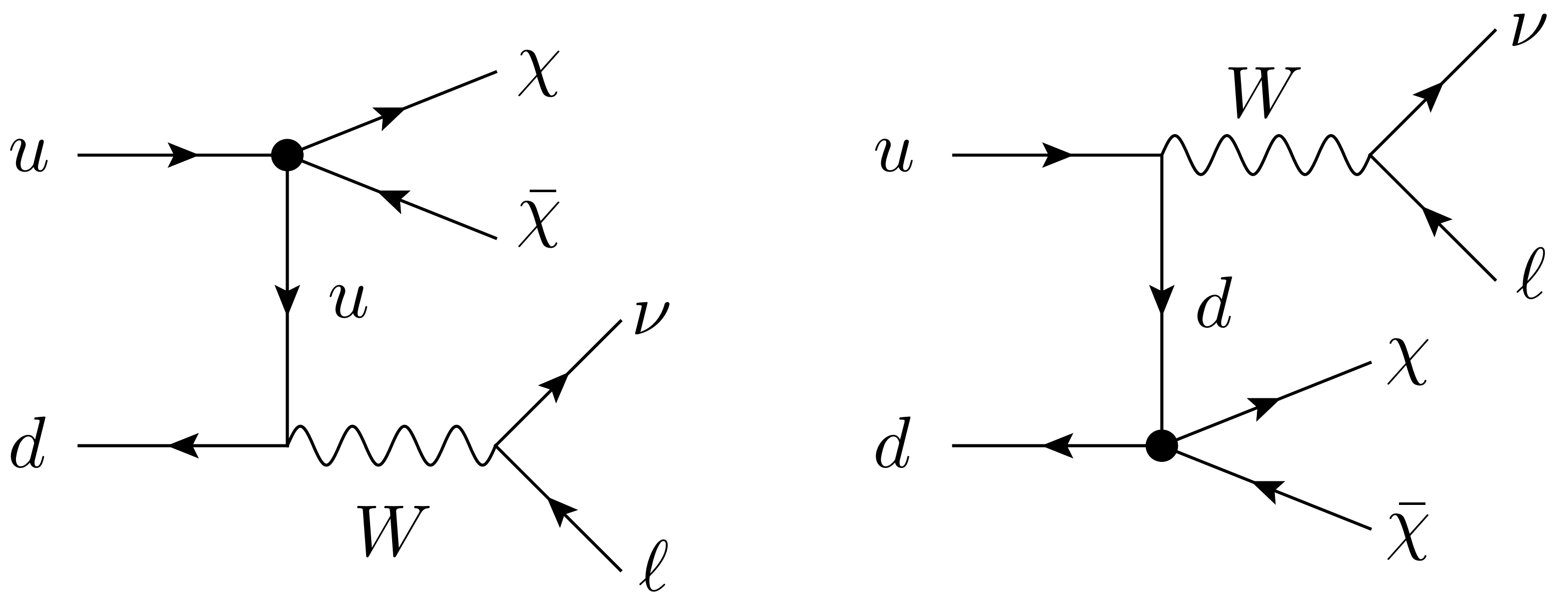


[PJF, Harnik, Primulando, Yu, 1203.1662]

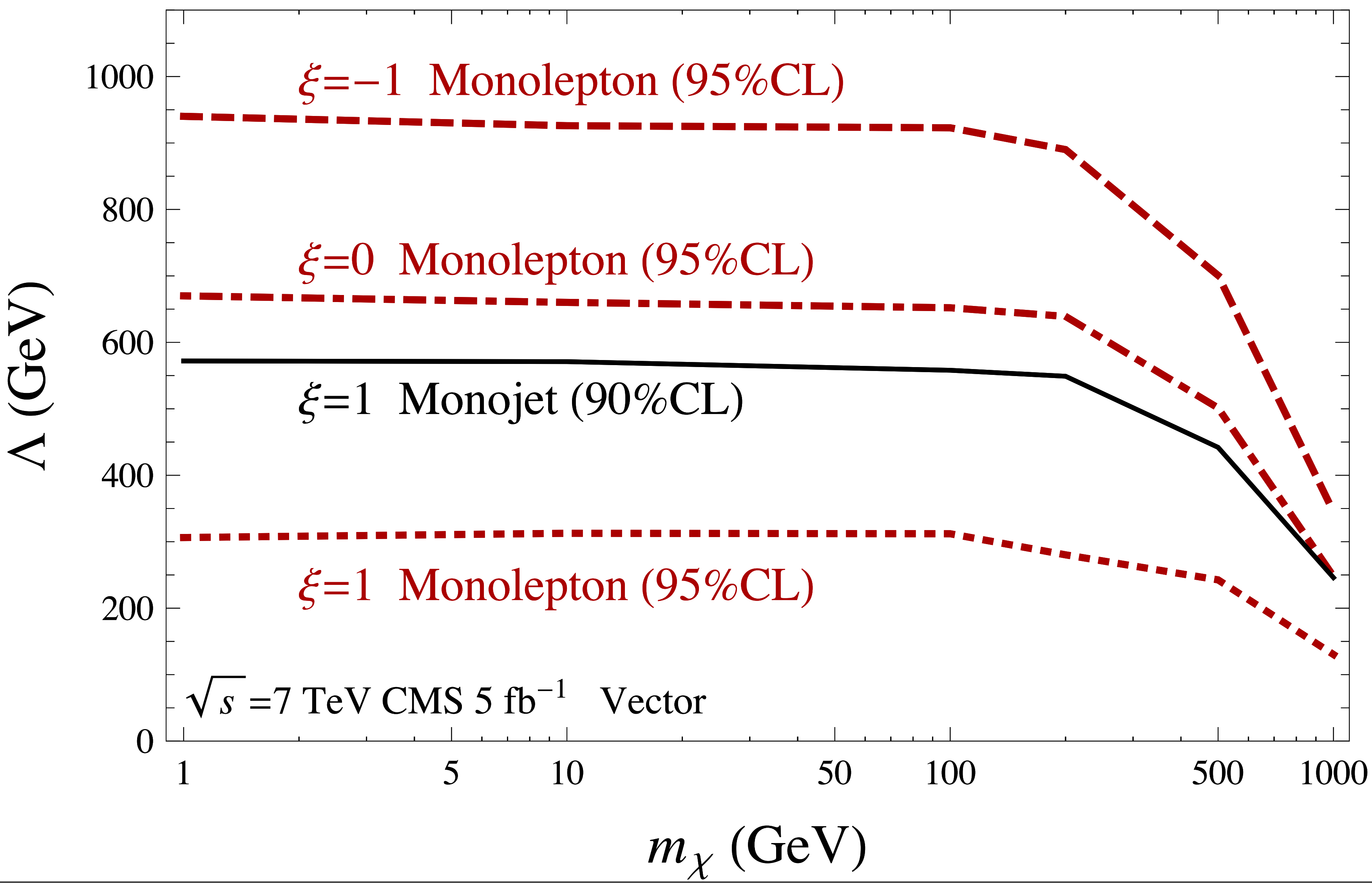


Mono-W

[Bai, Tait, 1208.4361]



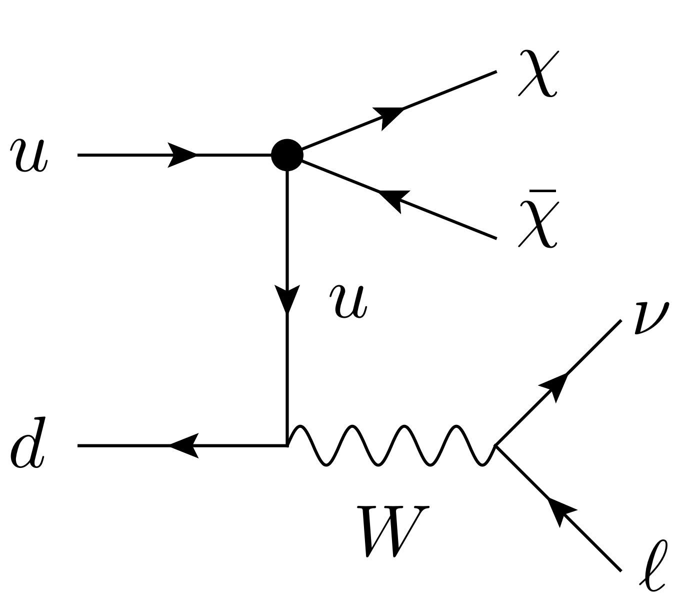
$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\;\left(\overline{u}\gamma^\mu u + \xi\,\overline{d}\gamma^\mu d\right)$$

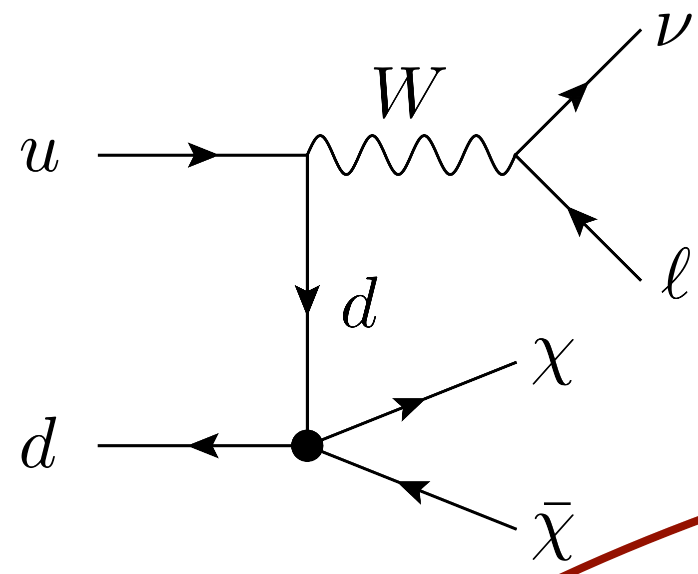


Uses CMS W' search (7 TeV 5/fb)

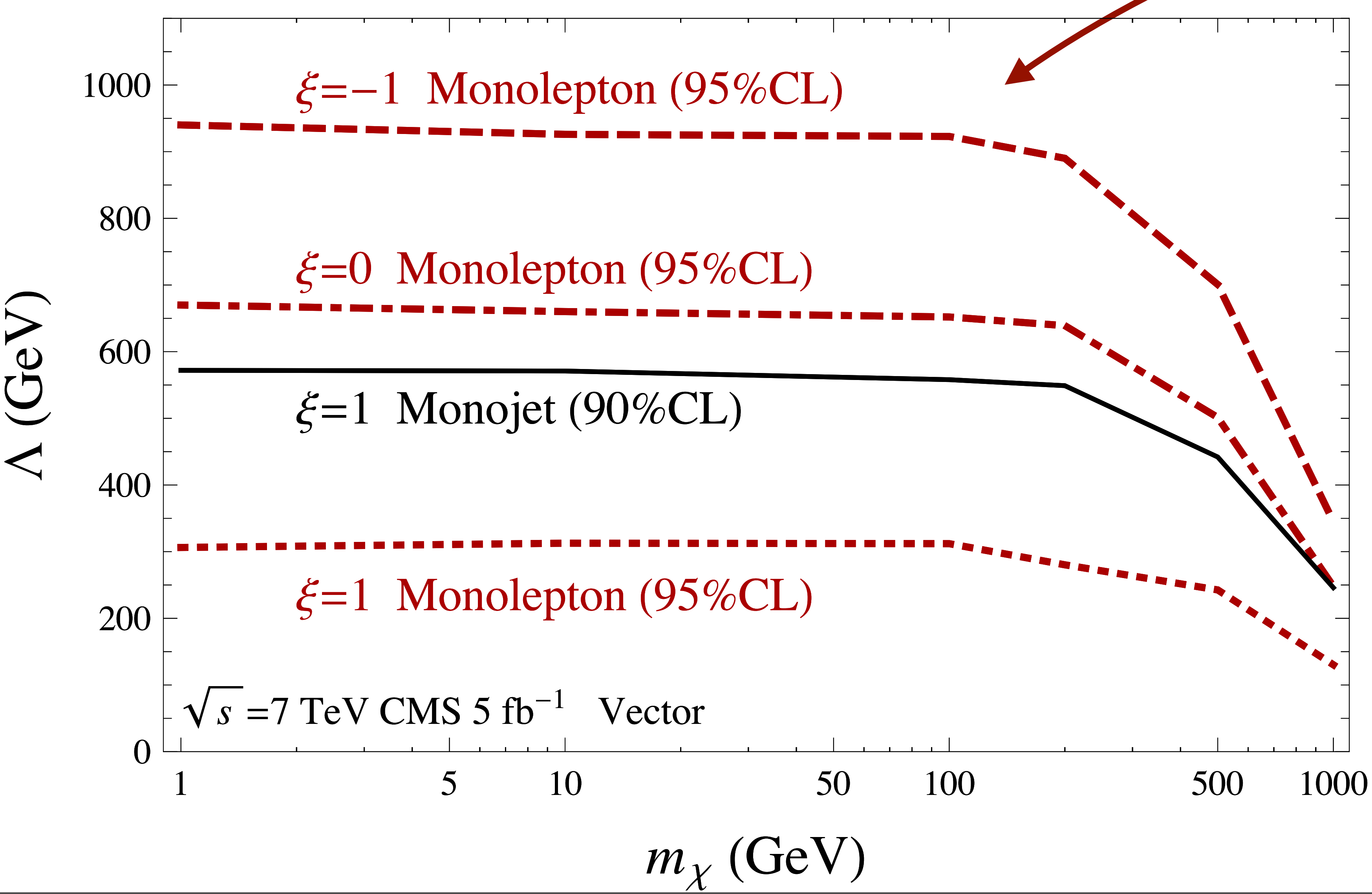
Mono-W

[Bai, Tait, 1208.4361]





$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\;\left(\overline{u}\gamma^\mu u + \xi\,\overline{d}\gamma^\mu d\right)$$



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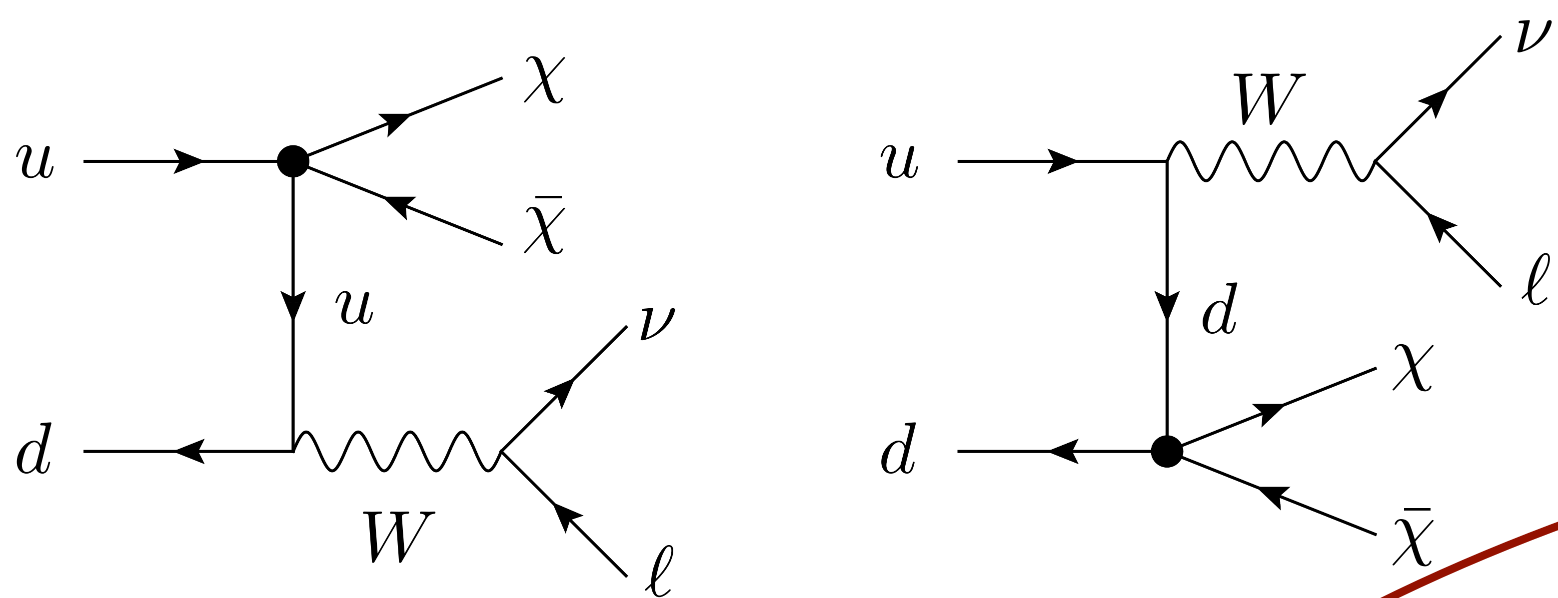
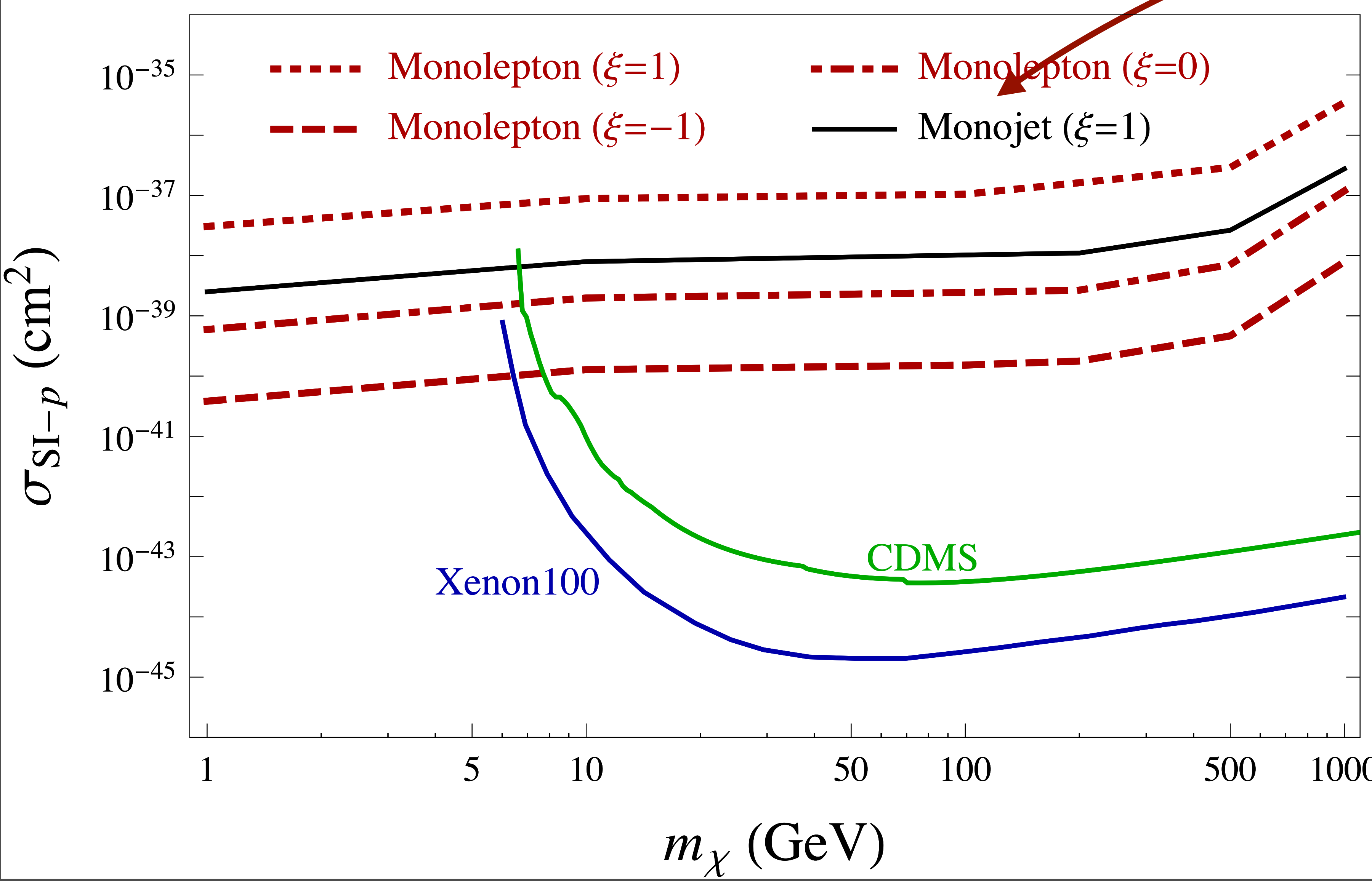
Mono-W

[Bai, Tait, 1208.4361]



$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\;\left(\overline{u}\gamma^\mu u+\xi\,\overline{d}\gamma^\mu d\right)$$

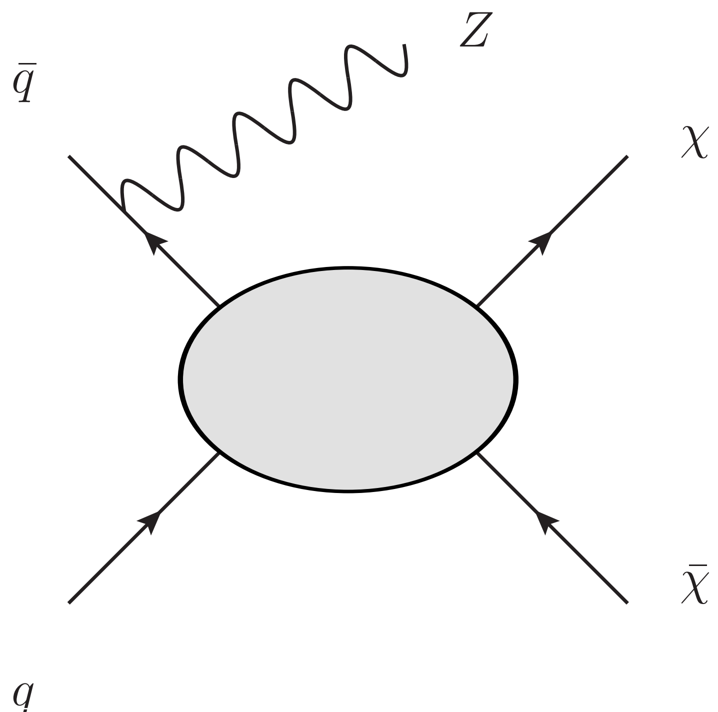


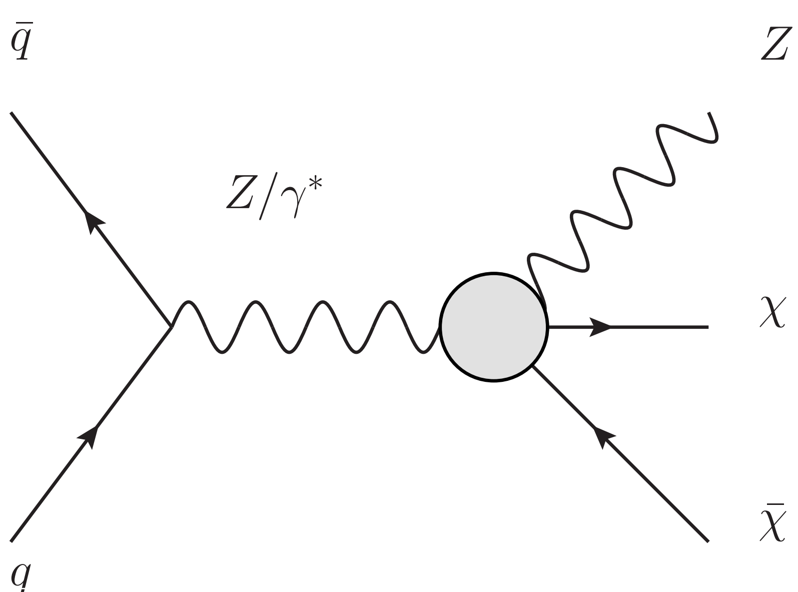
Uses CMS W' search (7 TeV 5/fb)

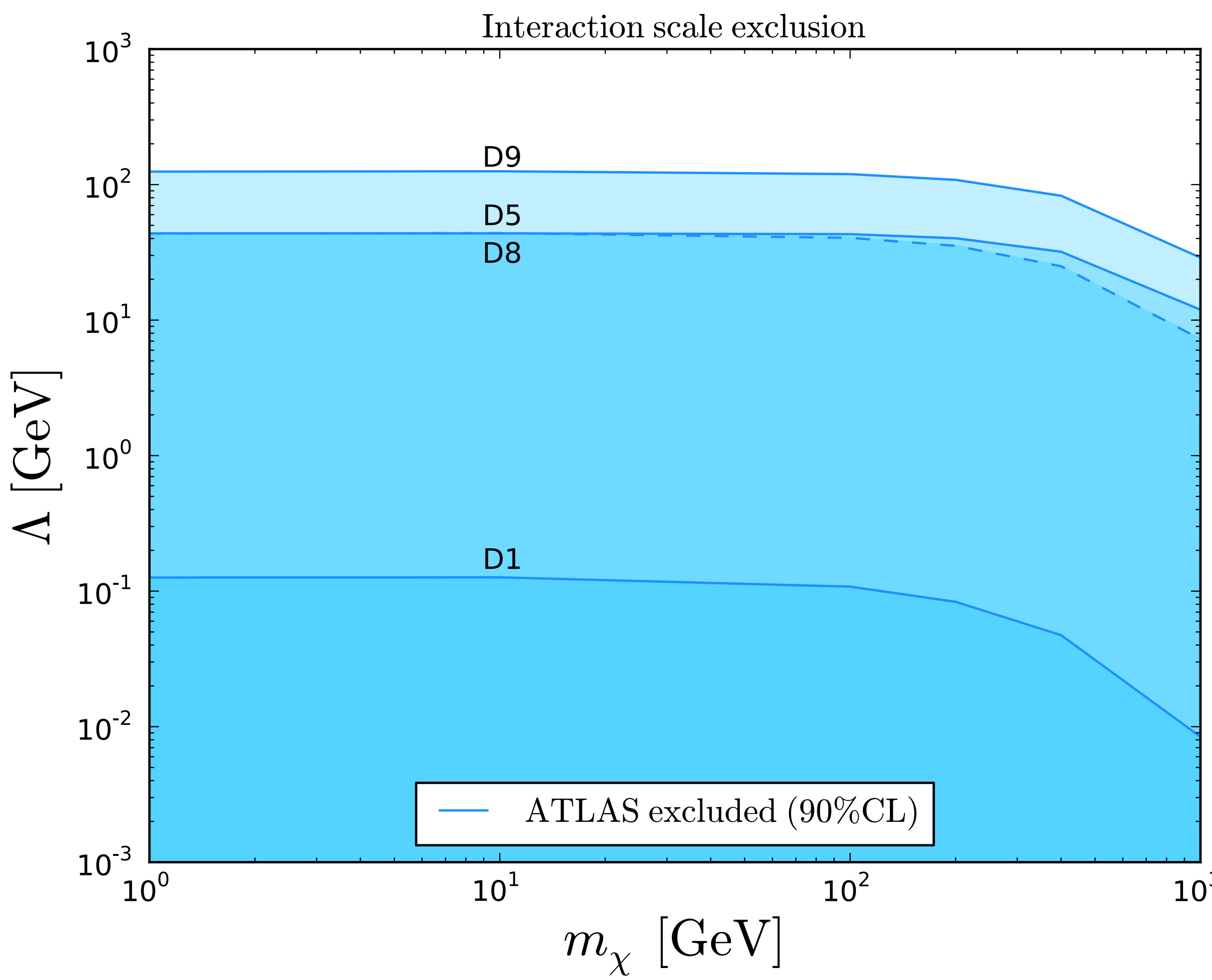
Mono-Z

[Carpenter et al, 1212.3352]

Uses ATLAS $\ell\ell\nu\nu$ x-sec measurement (7 TeV 4.6/fb)







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[Carpenter et al, 1212.3352]

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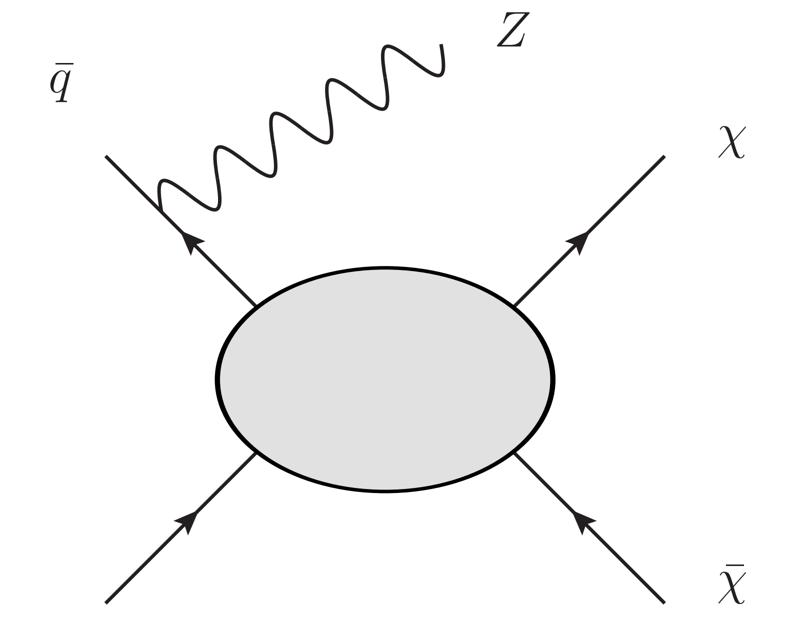
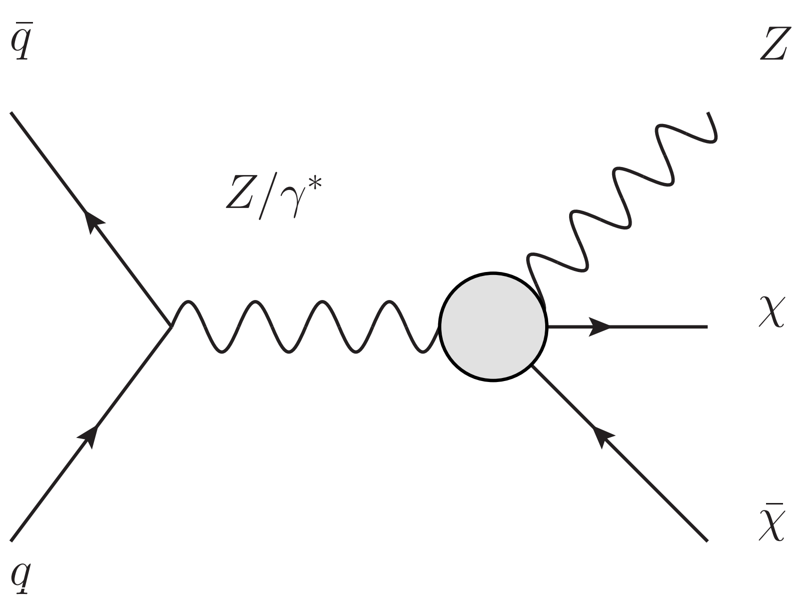
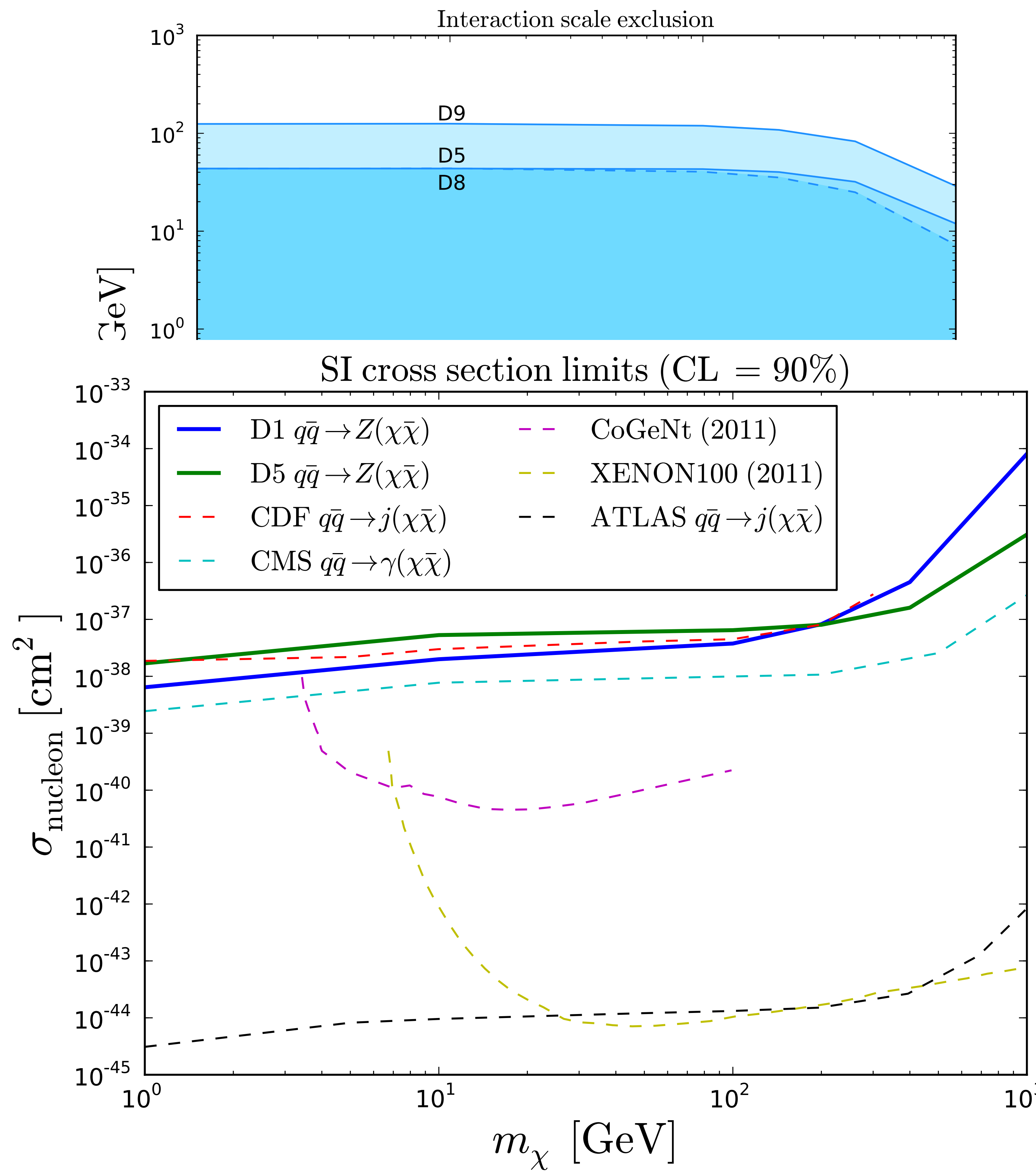






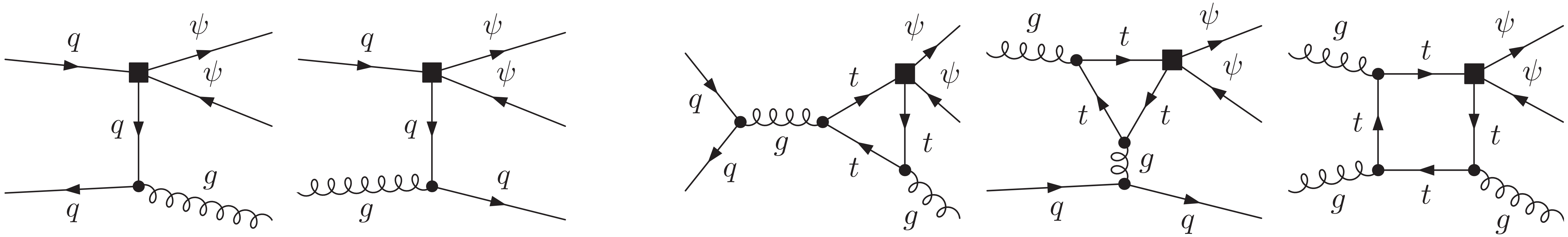
Mono- “whatever”

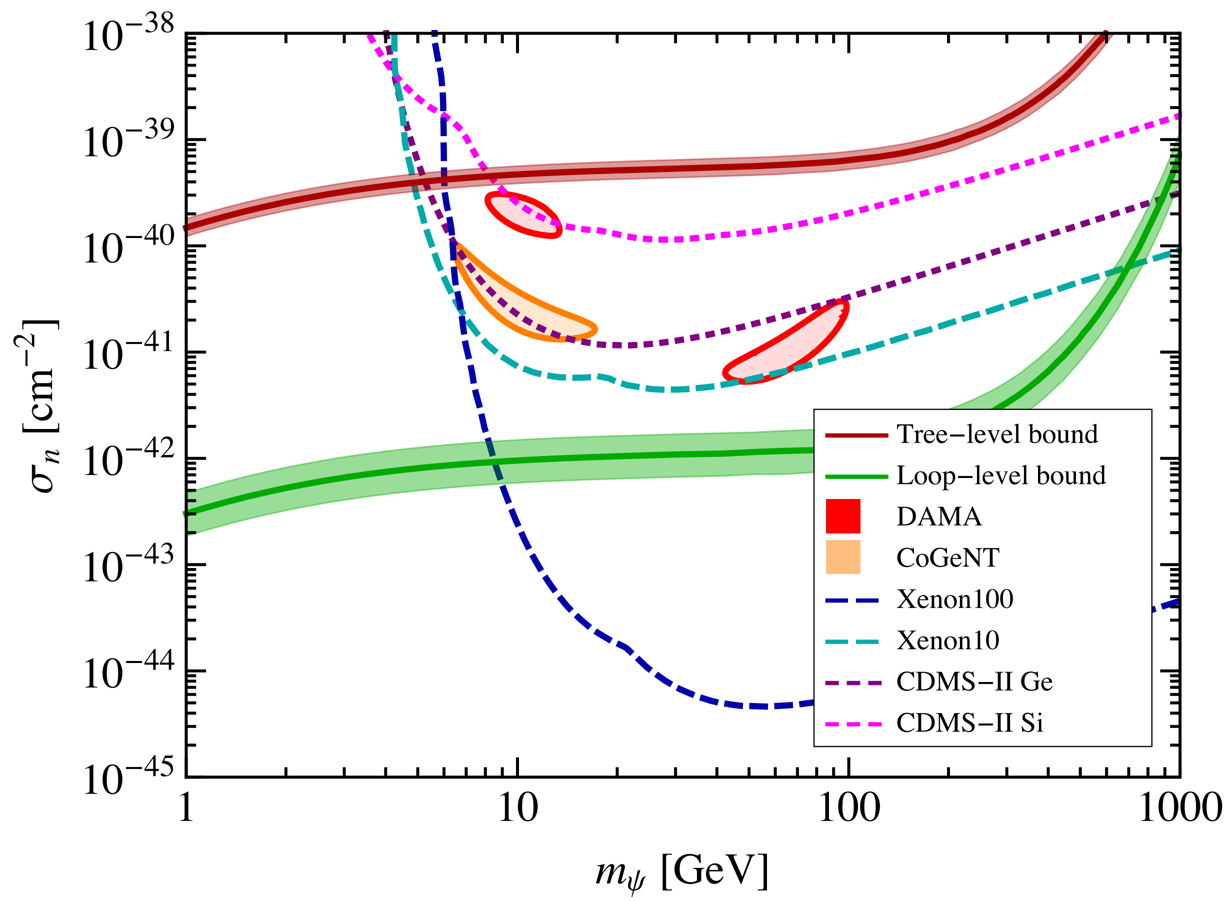
- Many search channels, combining for stronger bounds
- Must be careful about overlaps, but most orthogonal
- Bounds dominated by monojet, but others give non-trivial improvements
- See e.g. Cheung et al (1201.3402); Whiteson et al (1302.3619)

The scalar operator $\mathcal{O} = \frac{m_q}{M_*^3} \bar{q} q \bar{X} X$

Large corrections to production cross section

[Haisch, Kahlhoefer, Unwin, 1208.4605]





DM@NLO

[PJF and Williams, 1211.6390]

Analyses are becoming systematics limited

Reduce theory uncertainty by calculating at NLO (S+B)

Happy byproduct of larger x-sec, stronger bounds

Mismatch in MET and jet(pT) cuts, combined with "monojet" allowing >1 jet opens up phase space at NLO

Some operators (e.g. scalar) that have suppressed rate at LO can have very large "NLO" corrections

[Haisch et al, 1208.4605]

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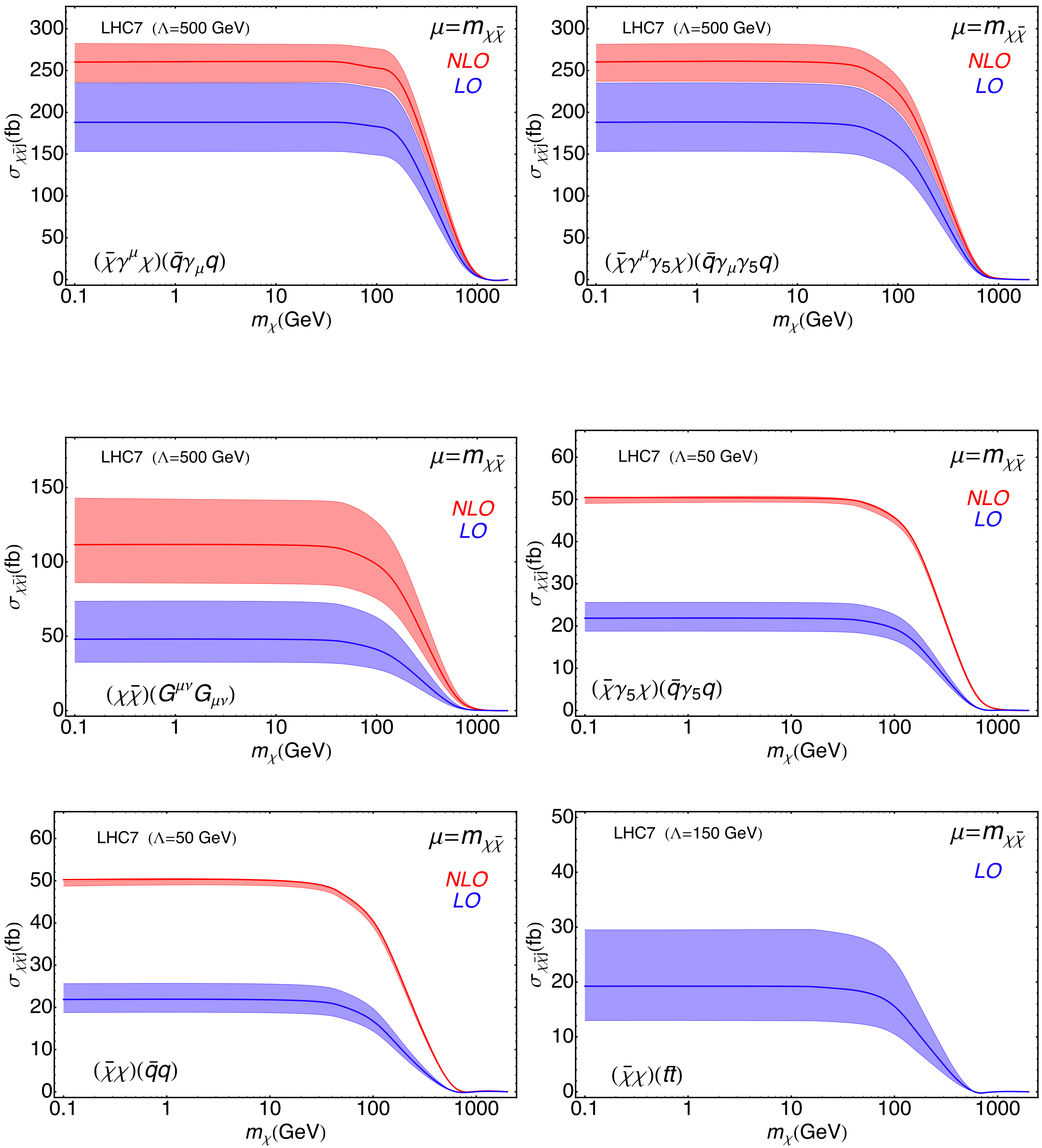
MCFM-dark

DM@NLO



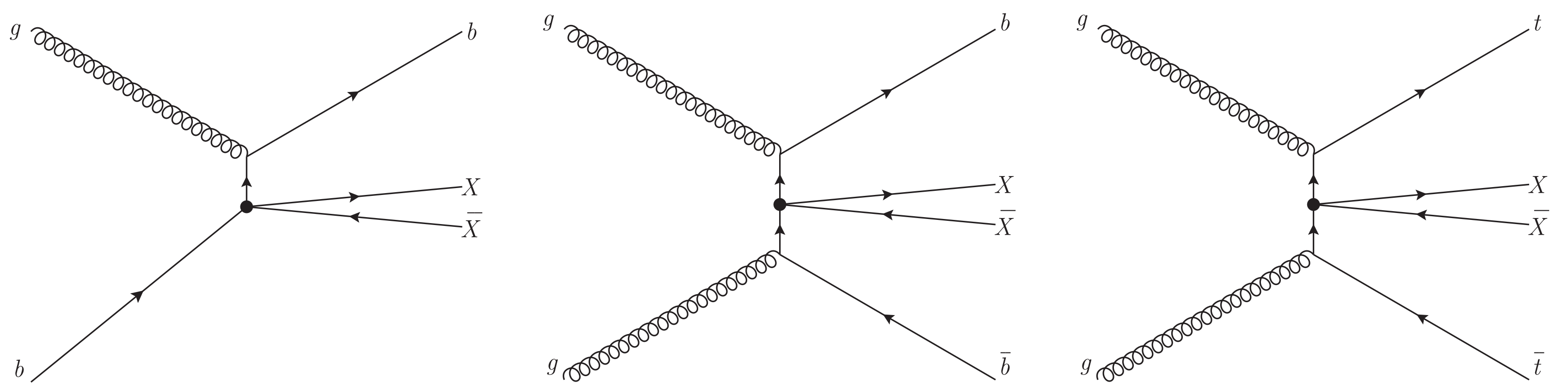
LHC7 (Λ=500 GeV)
μ=m_χχ̄
NLO
LO
σ_χχ̄j(fb)
m_χ(GeV)
(χ̄γ^μχ)(q̄γ_μq)
LHC7 (Λ=500 GeV)
μ=m_χχ̄
NLO
LO
(χ̄γ^μγ5χ)(q̄γ_μγ5q)
LHC7 (Λ=500 GeV)
μ=m_χχ̄
NLO
LO
(χχ̄)(G^μν G_μν)
LHC7 (Λ=50 GeV)
μ=m_χχ̄
NLO
LO
(χ̄γ5χ)(q̄γ5q)
LHC7 (Λ=50 GeV)
μ=m_χχ̄
NLO
LO
(χ̄χ)(q̄q)
LHC7 (Λ=150 GeV)
μ=m_χχ̄
LO
(χ̄χ)(t̄t)

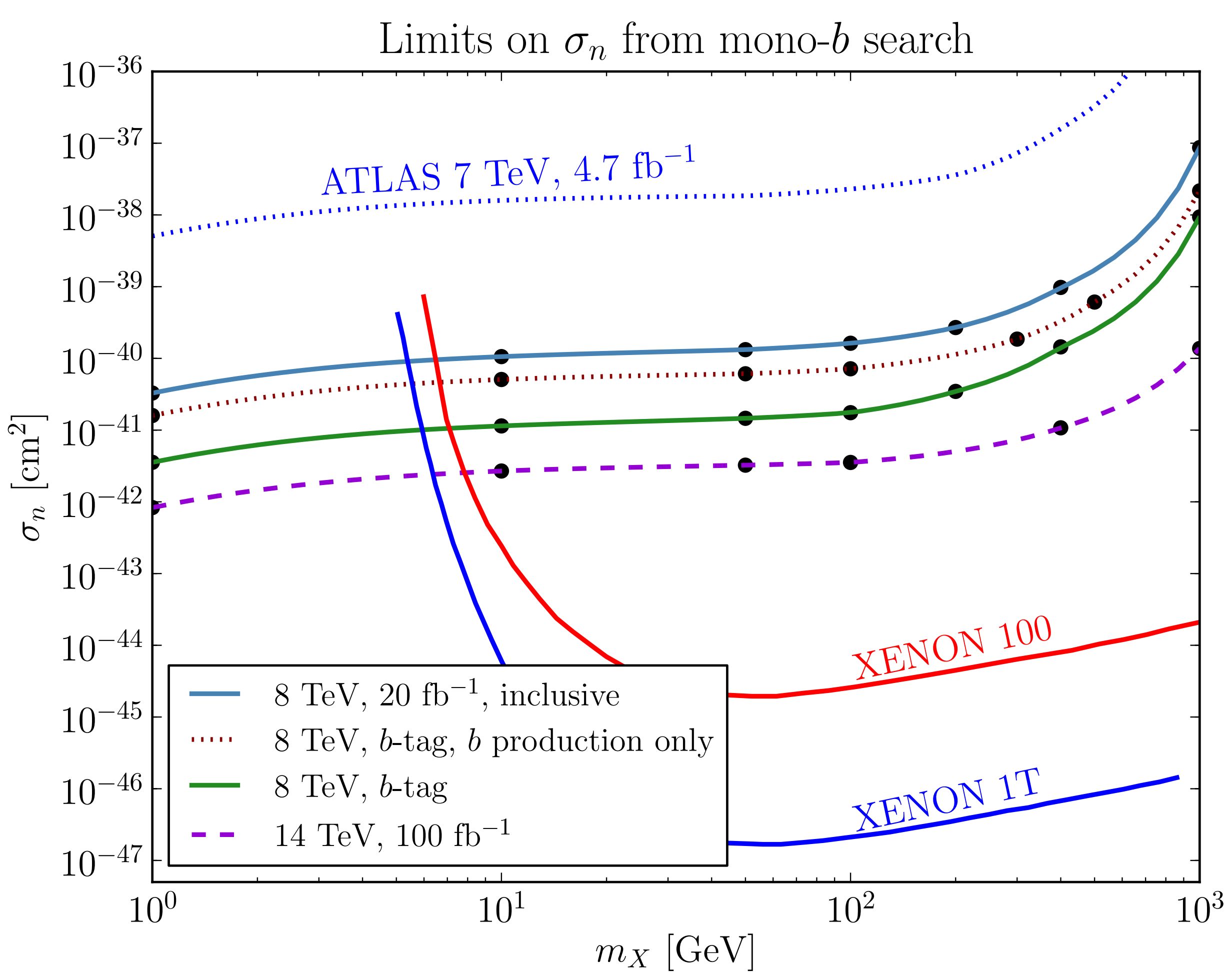
The scalar operator

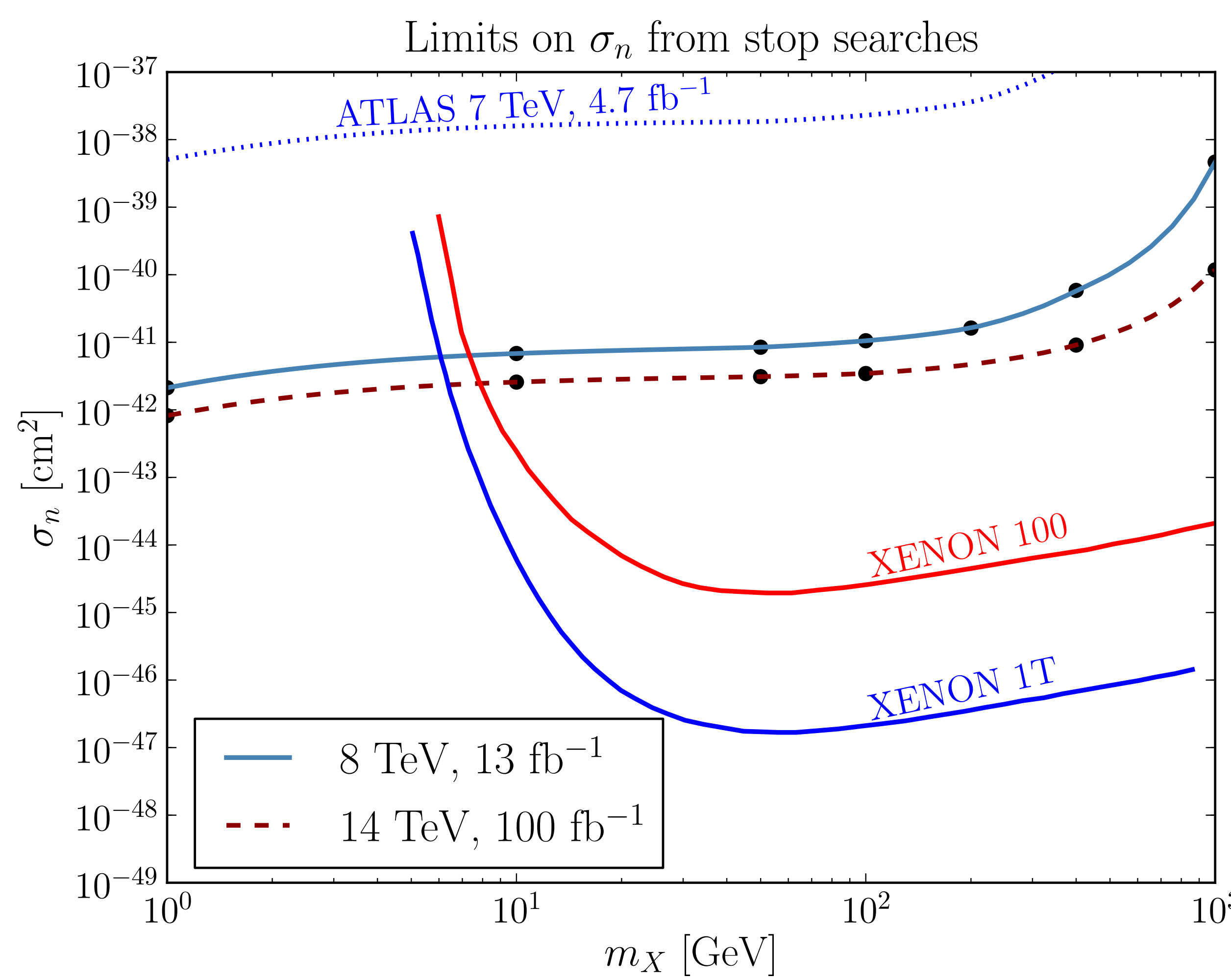
[Kamenik, Zupan, 1107.0623]

Look at heavy flavour in the final state: mono-b, stop searches

[Lin, Kolb, Wang, 1303.6638]



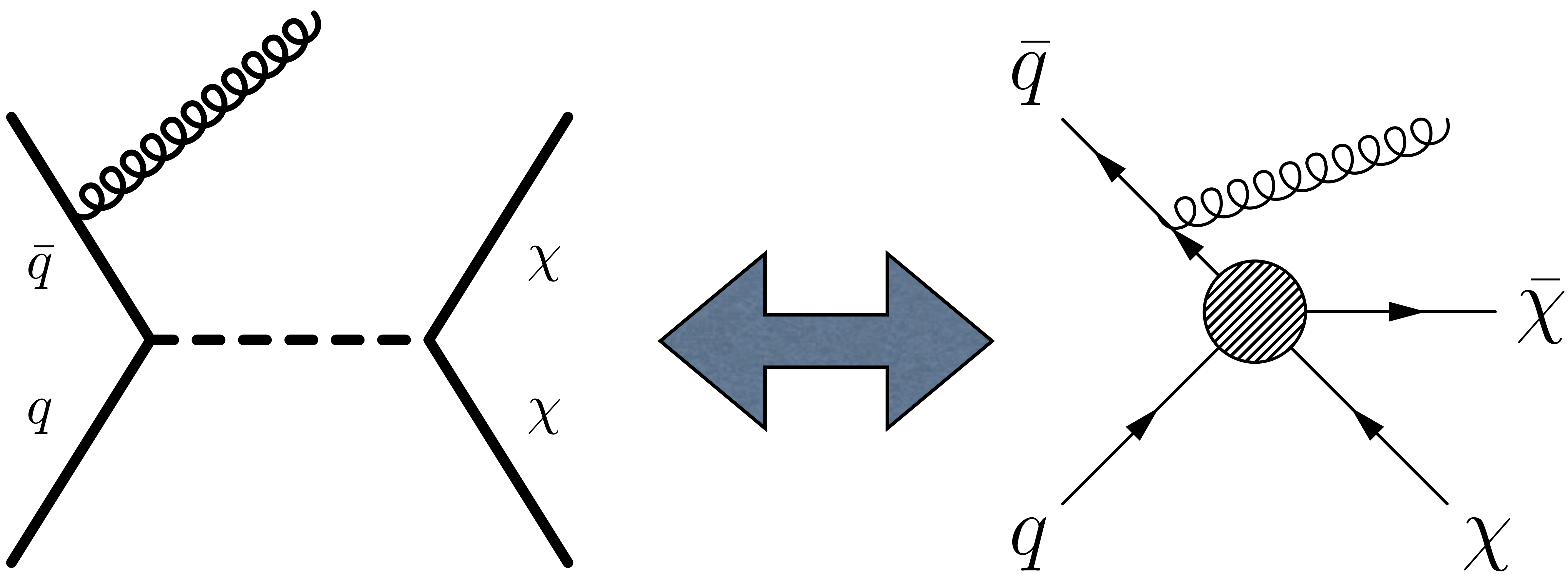




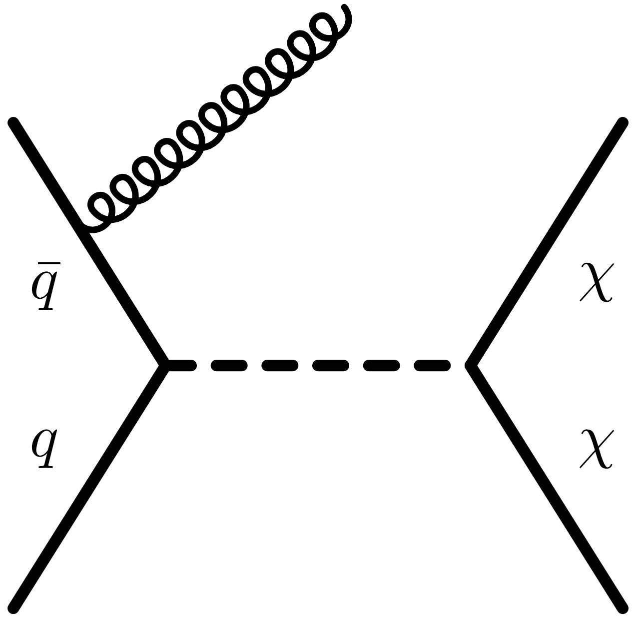
Light Mediators

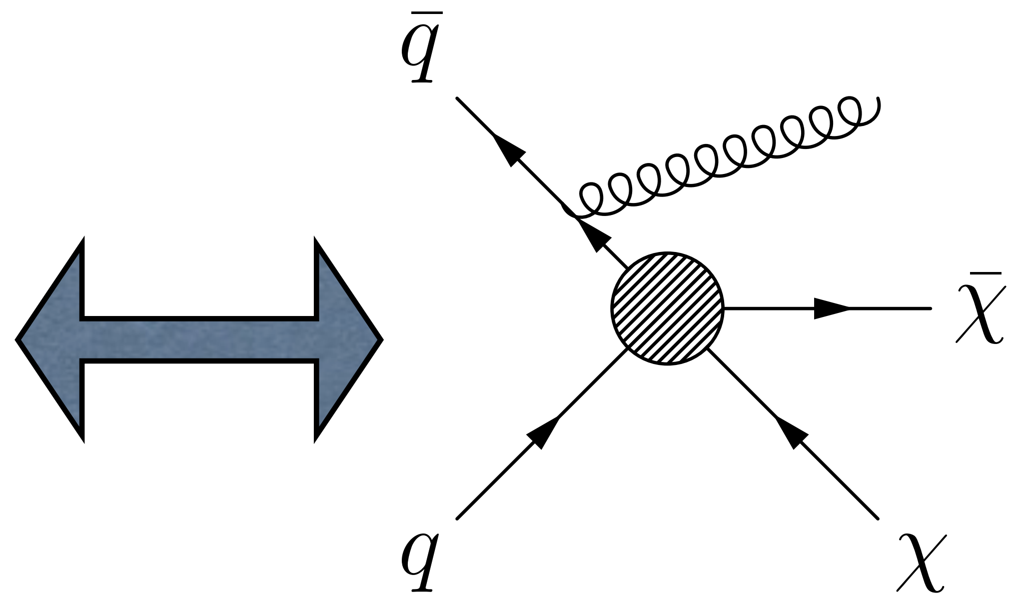
For all but the lightest mediators EFT is good for direct detection

$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$



$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$



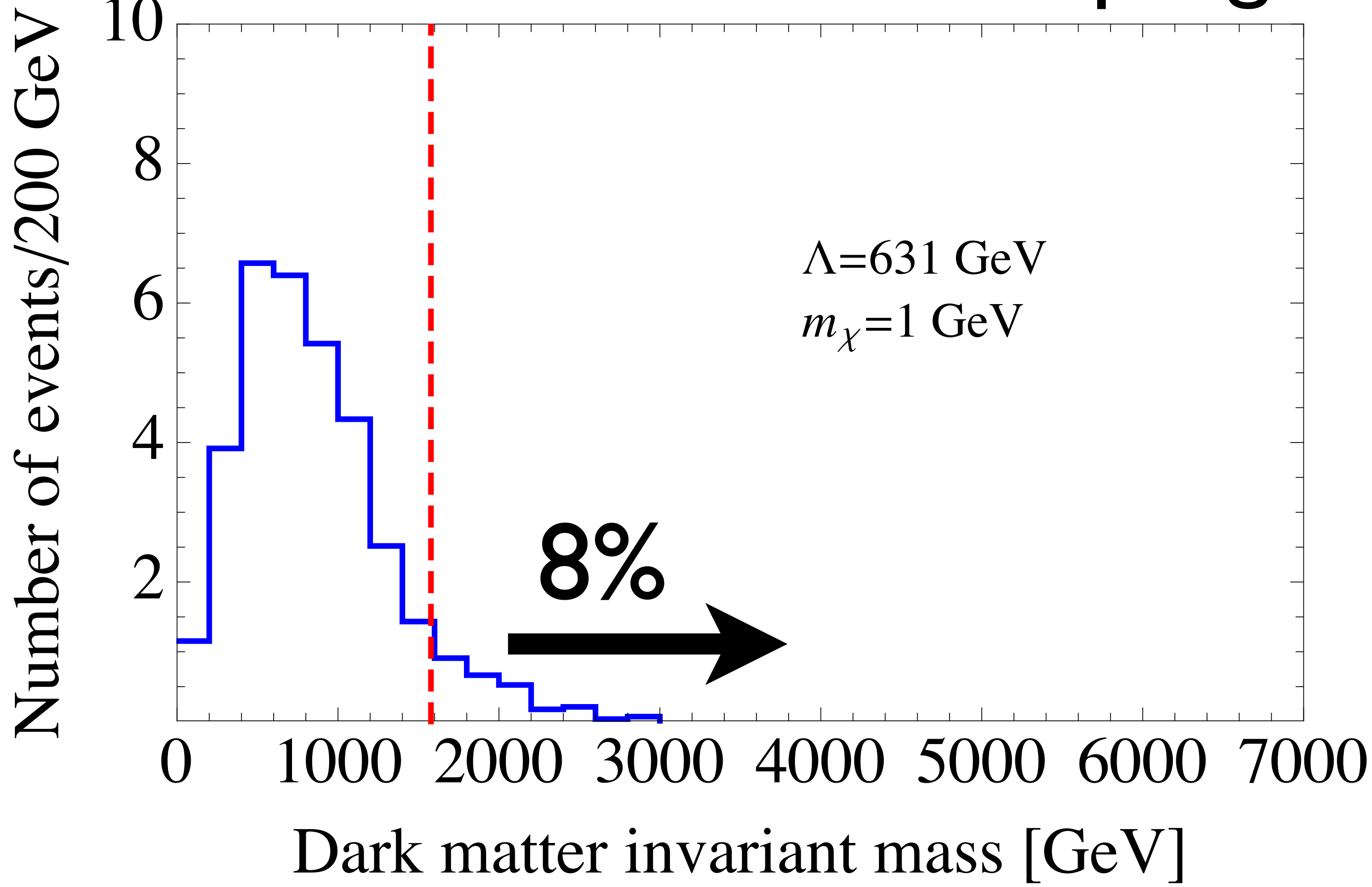


$$\frac{g_q g_\chi}{q^2 - M^2} \xrightarrow{q^2 \ll M^2} \frac{1}{\Lambda^2} \qquad \Lambda^2 = \frac{M^2}{g_q g_\chi}$$

What fraction of events have momentum transfers sufficient to probe the UV completion?

[PJF et al, 1203.1662]

Vector coupling

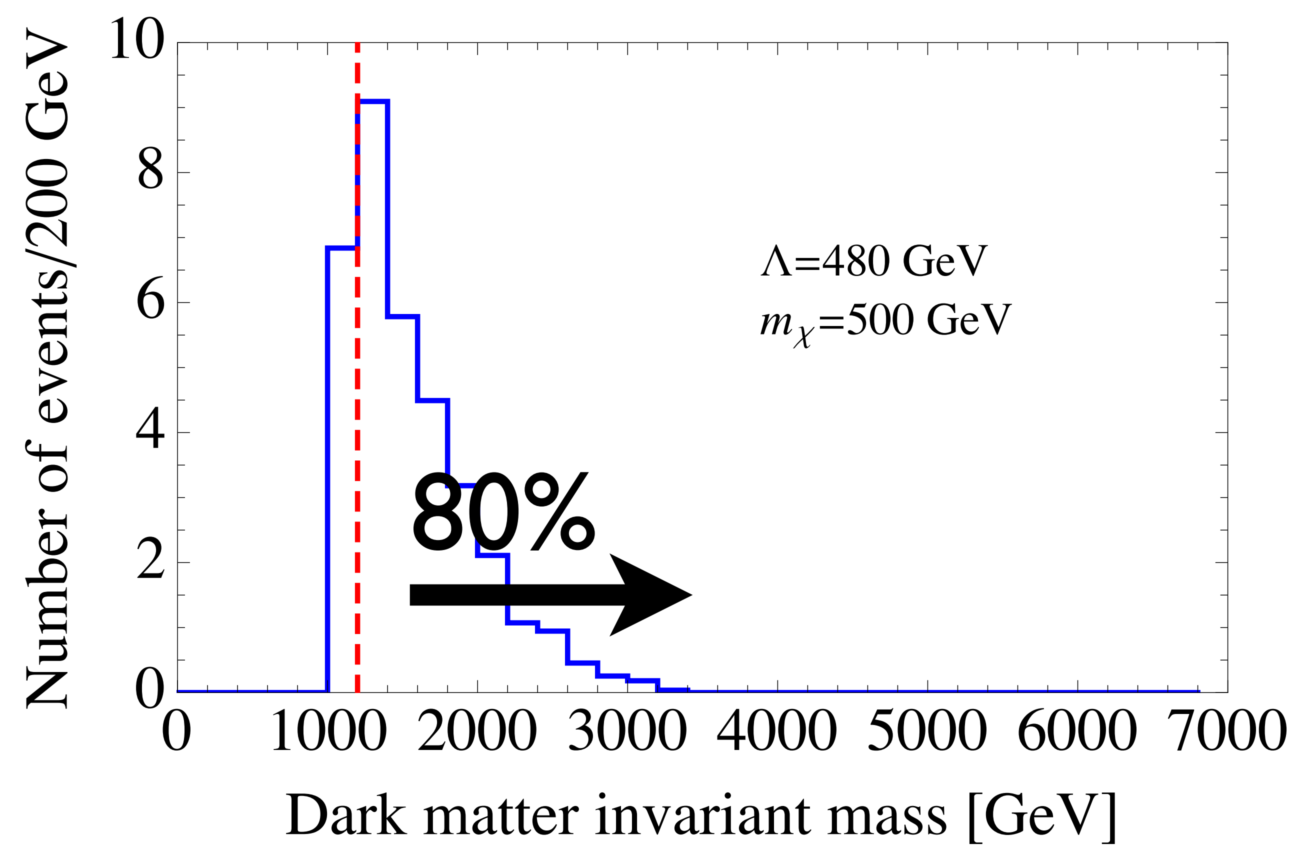


Unitarity bound $m_{\chi\chi} < \frac{\Lambda}{0.4}$

[Shoemaker and Vecchi, 1112.5456]

Fraction of events where EFT breaks down may be non-negligible

Depends on DM mass



[PJF et al, 1203.1662]

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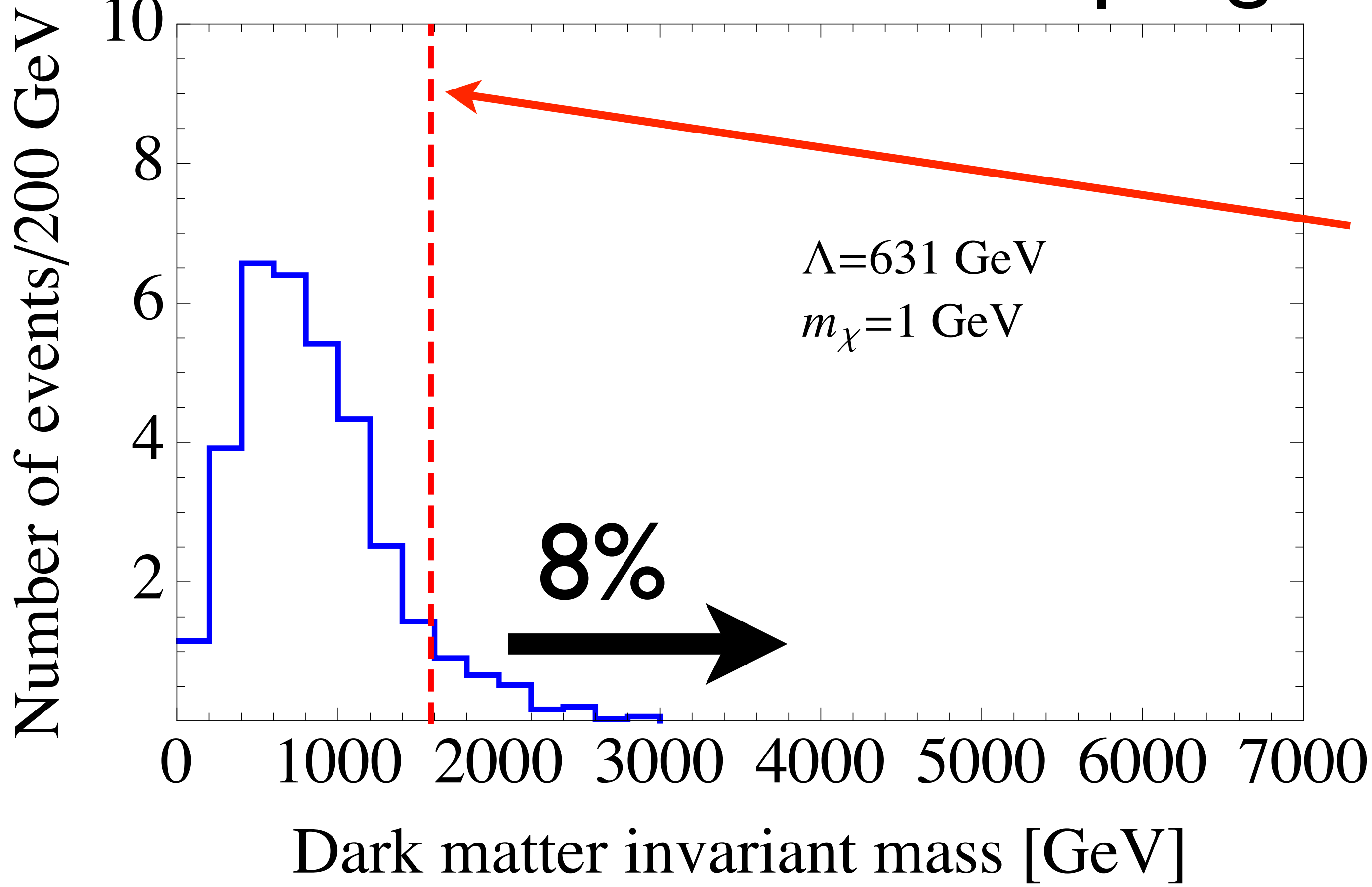

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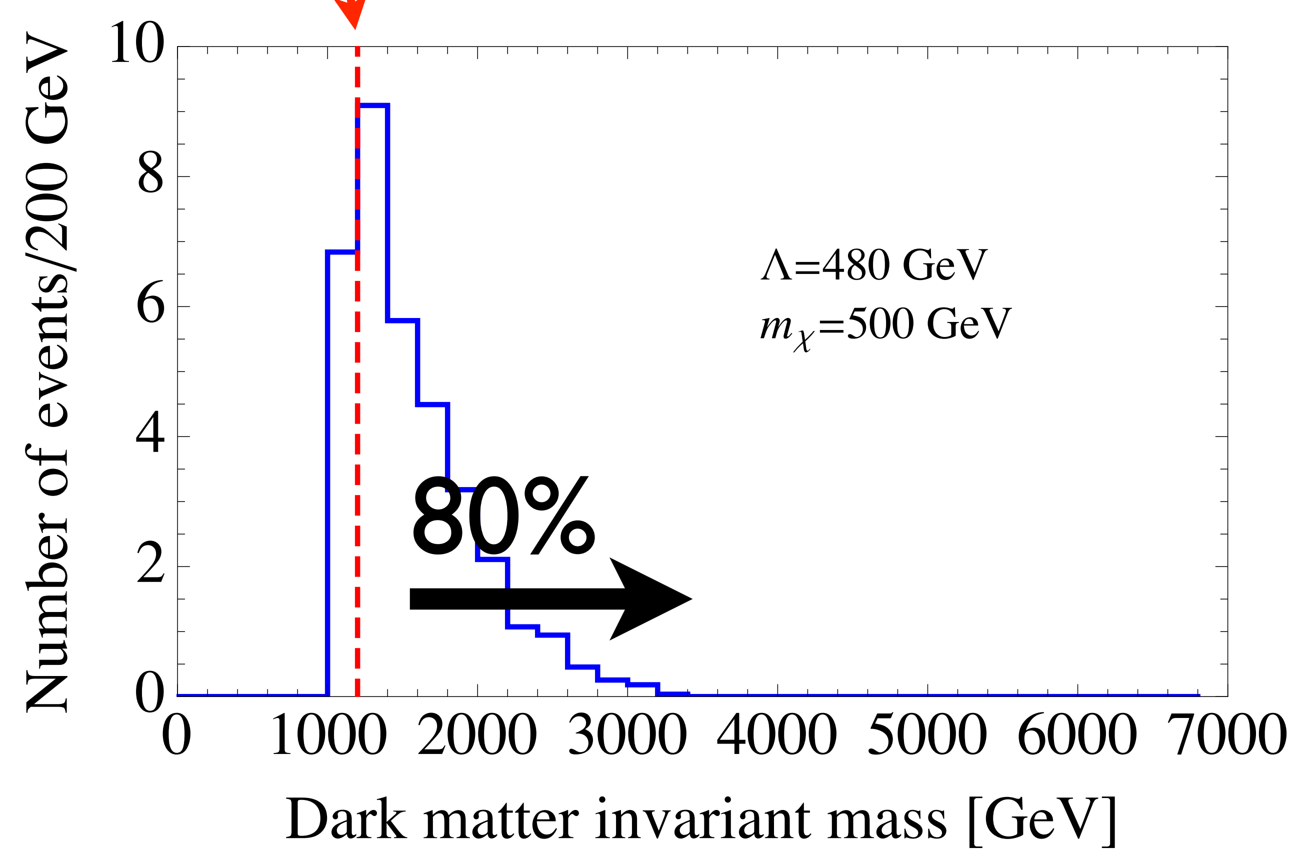
[Shoemaker and Vecchi, 1112.5456]



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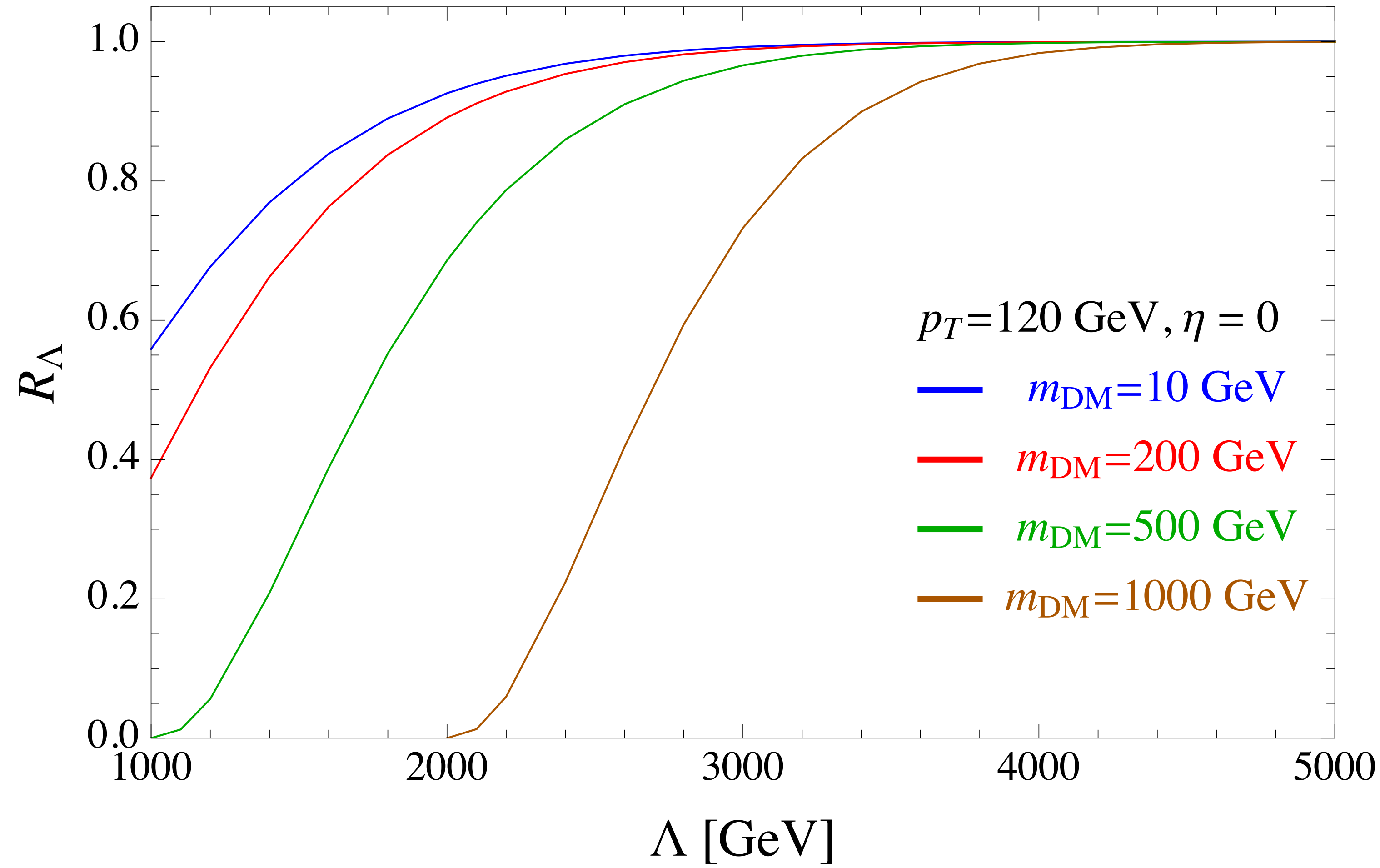
What fraction of events have momentum transfers sufficient to probe the UV completion?

[Busoni, De Simone, Morgante, Riotto, 1307.2253]

$$R_\Lambda \equiv \frac{\left.\dfrac{d^2\sigma_{\rm eff}}{dp_T d\eta}\right|_{Q_{\rm tr}<\Lambda}}{\dfrac{d^2\sigma_{\rm eff}}{dp_T d\eta}}$$



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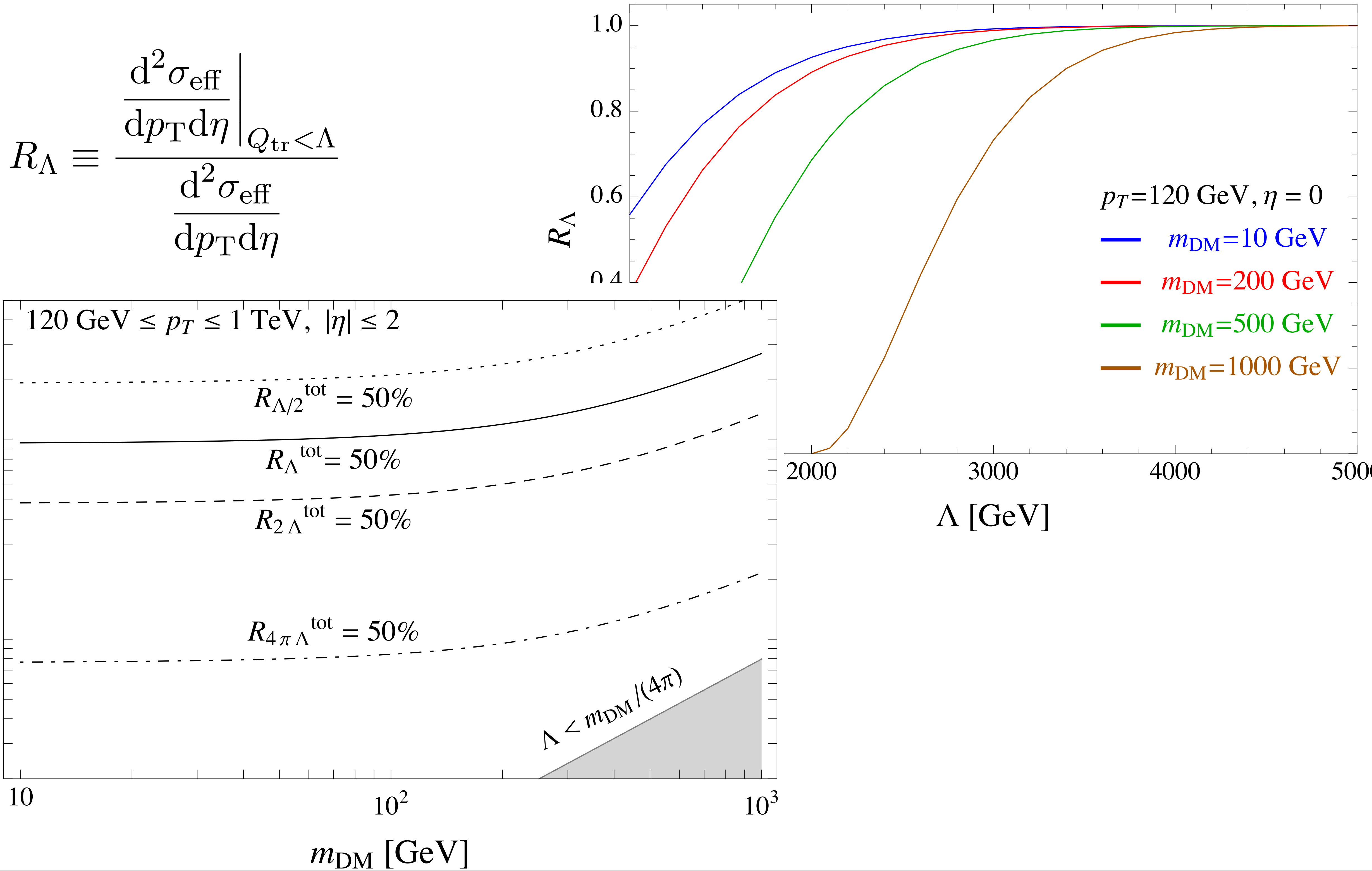
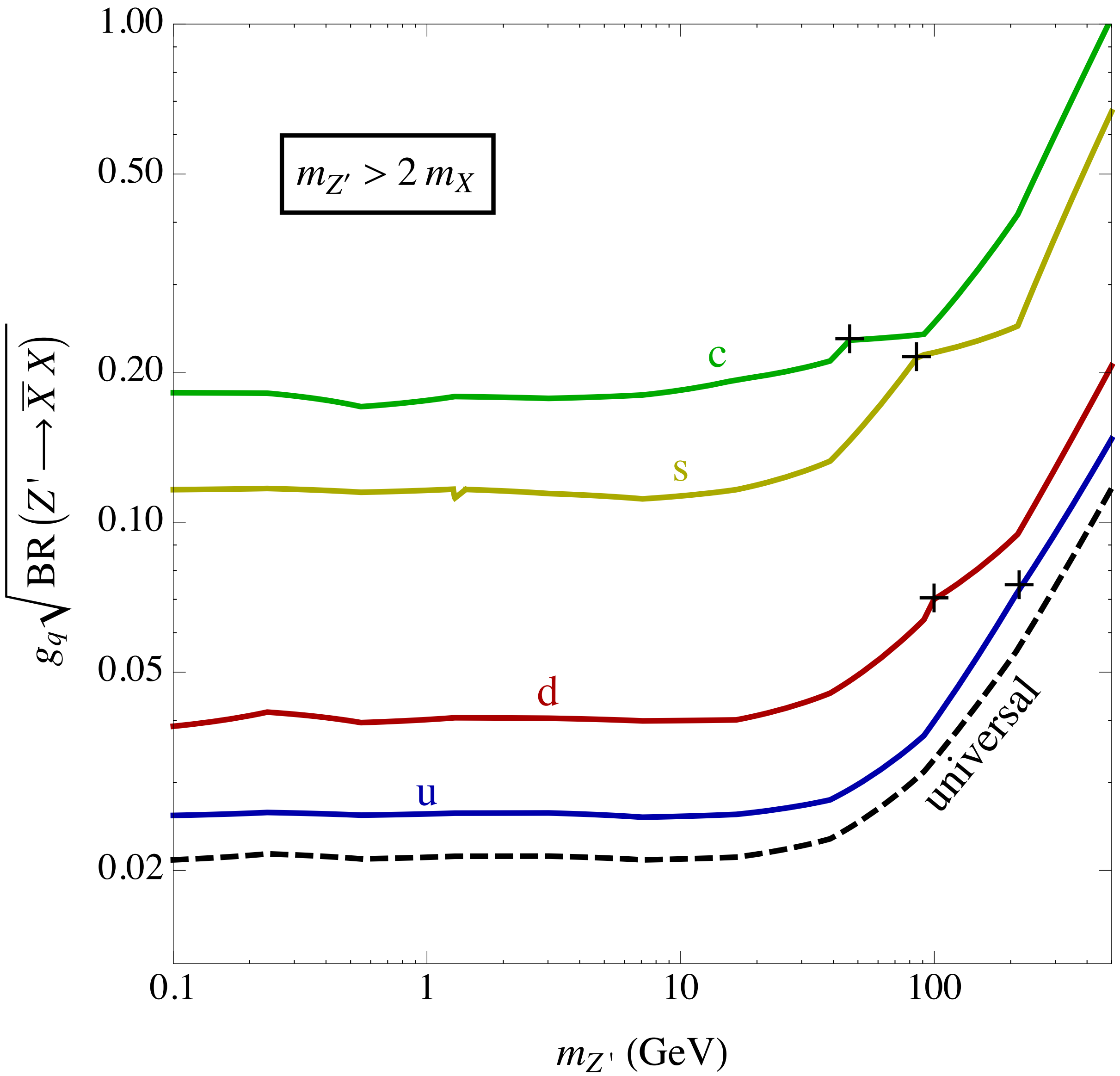


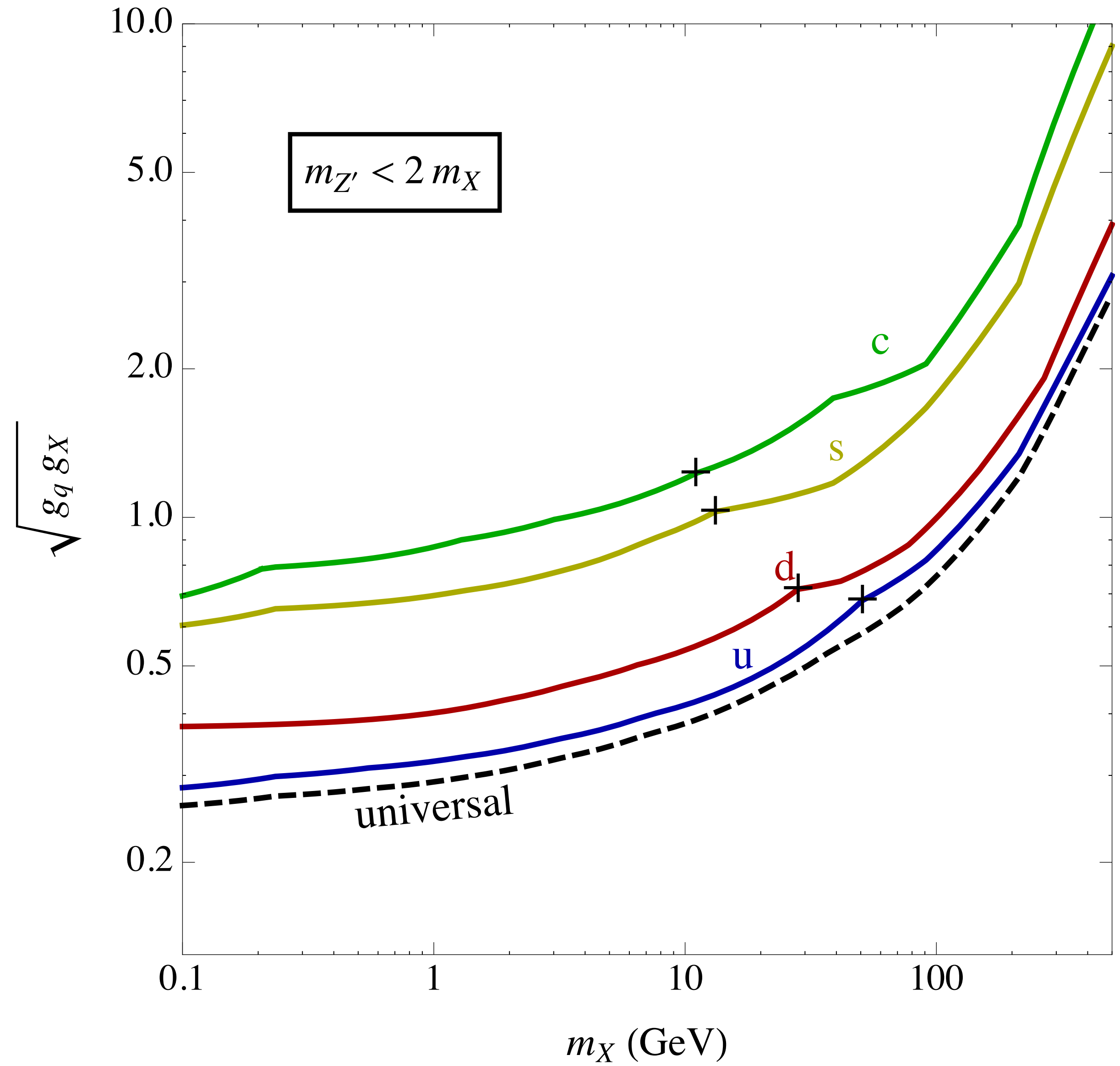
Light mediators

[Shoemaker,Vecchi 1112.5457]

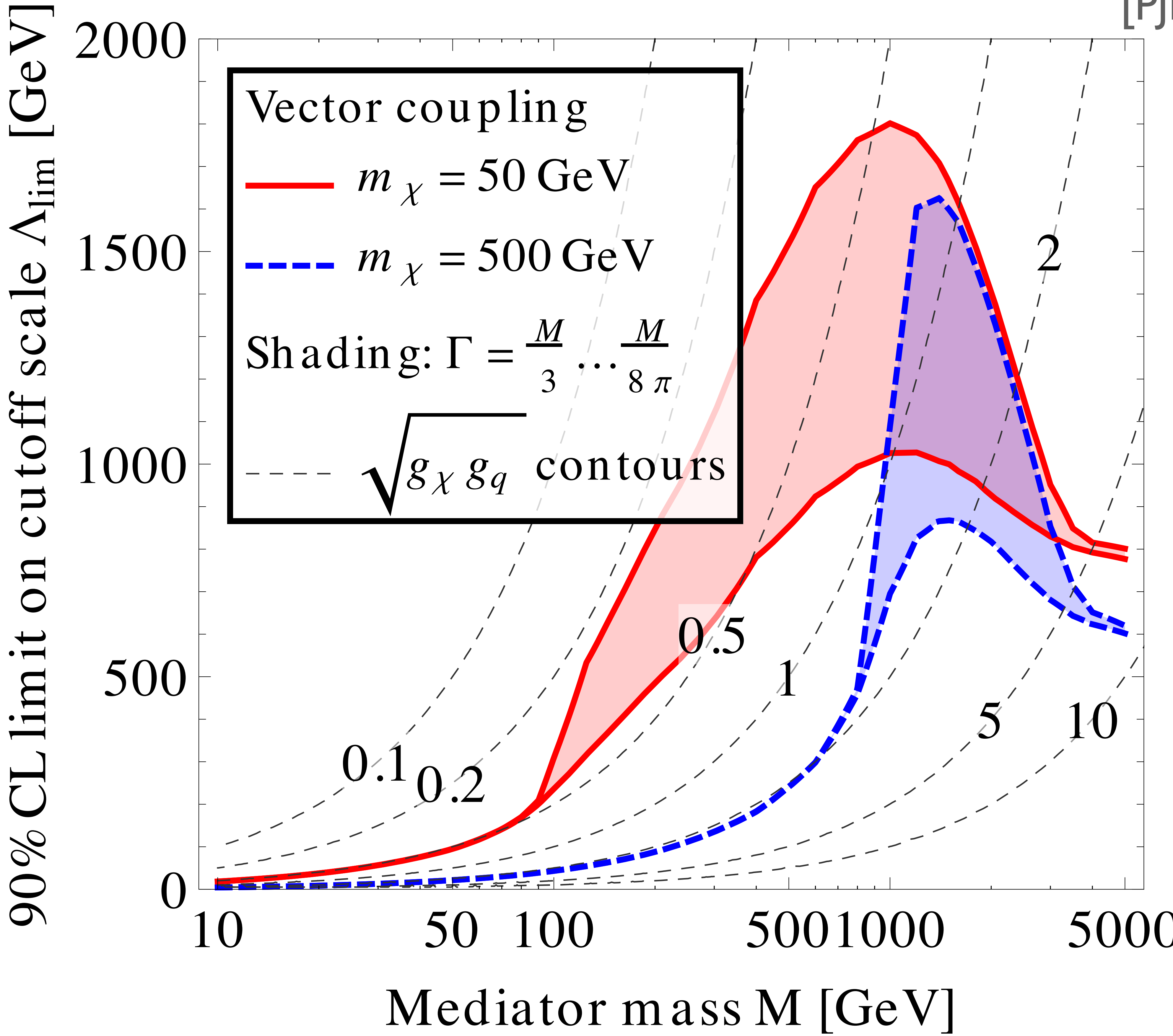
$$\Lambda,\ m_\chi \longrightarrow m_\chi,\ M,\ \Gamma,\ \sqrt{g_q g_\chi}$$

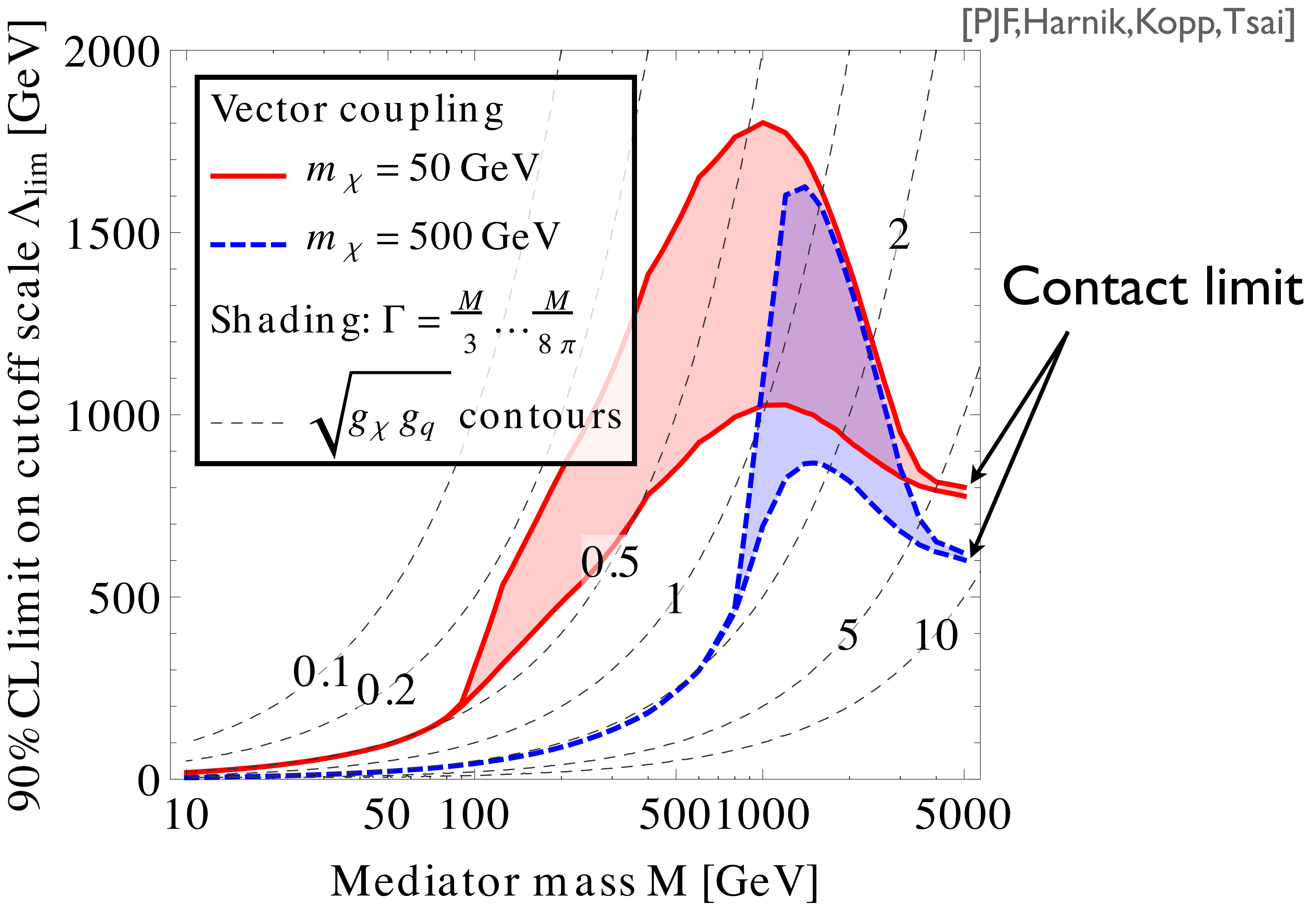
Except in tuned region depends on fewer



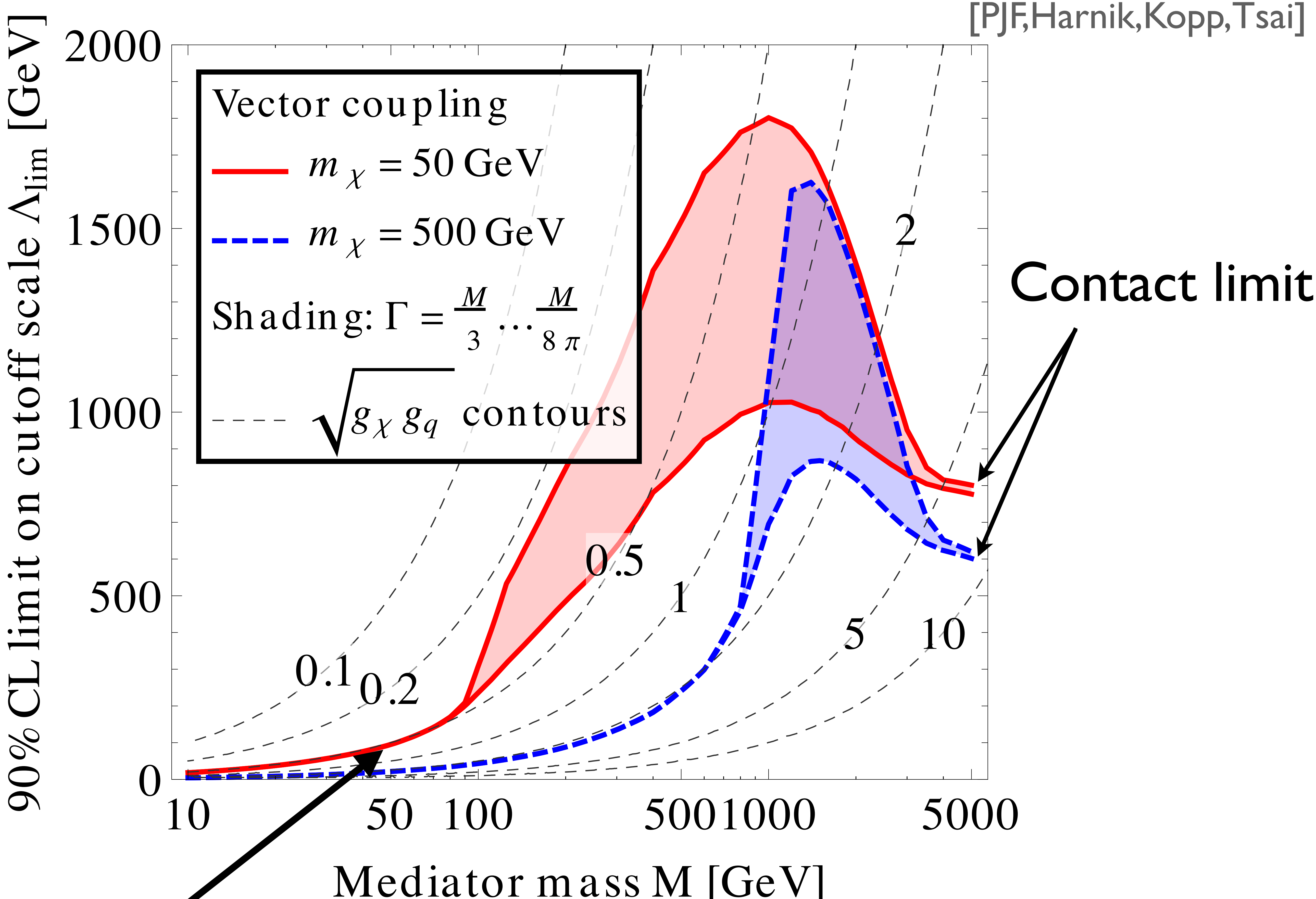


[PJF,Harnik,Kopp,Tsai]



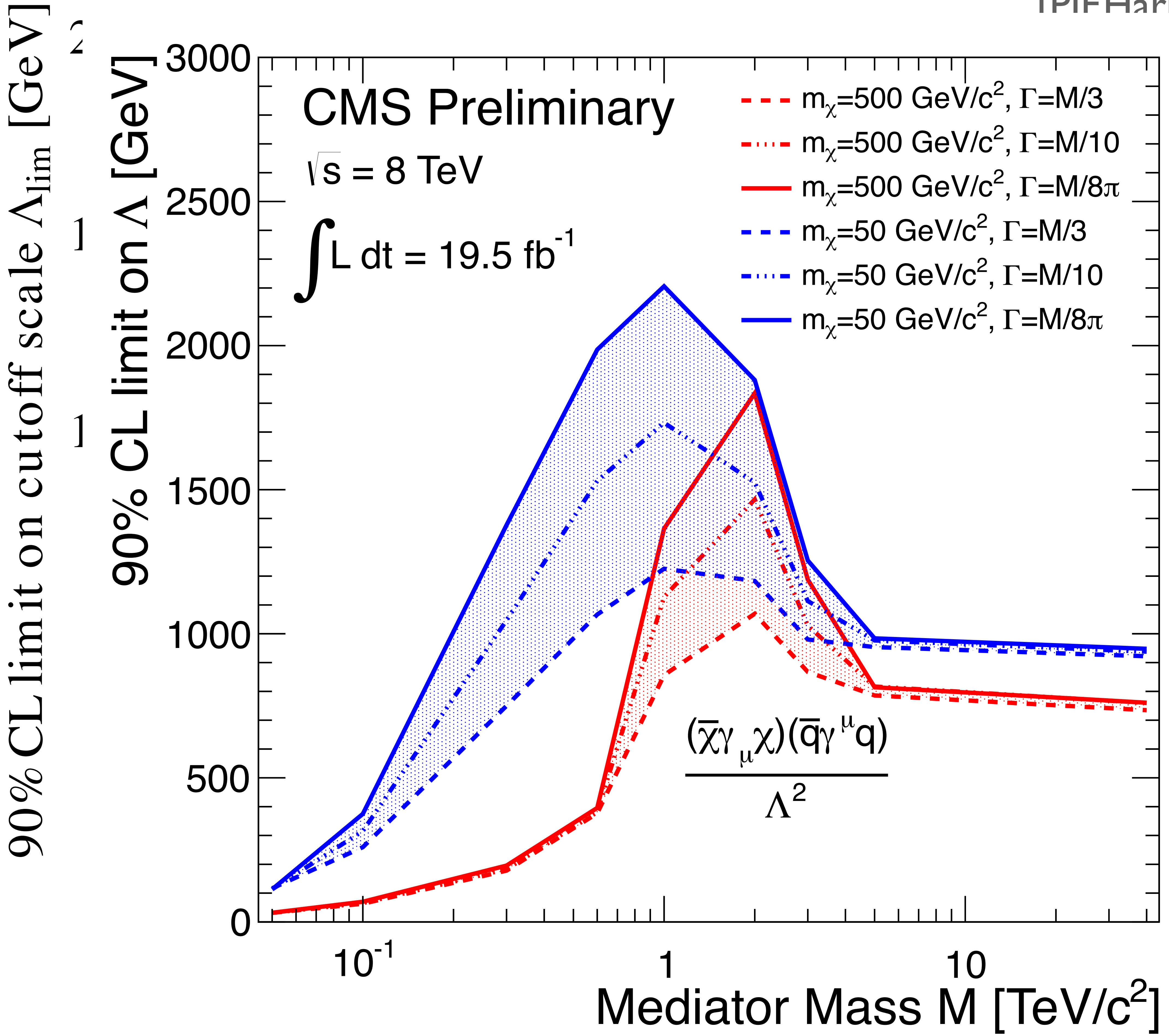


[PJF,Harnik,Kopp,Tsai]
Vector coupling
$m_\chi = 50$ GeV
$m_\chi = 500$ GeV
Shading: $\Gamma = \frac{M}{3} \dots \frac{M}{8\pi}$
$\sqrt{g_\chi g_q}$ contours
Contact limit
0.1
0.2
0.5
1
2
5
10
90% CL limit on cutoff scale $\Lambda_{\rm lim}$ [GeV]
Mediator mass M [GeV]
0
500
1000
1500
2000
10
50
100
500
1000
5000



Light mediator severely weakens limit

[PIF Harnik,Kopp,Tsai]



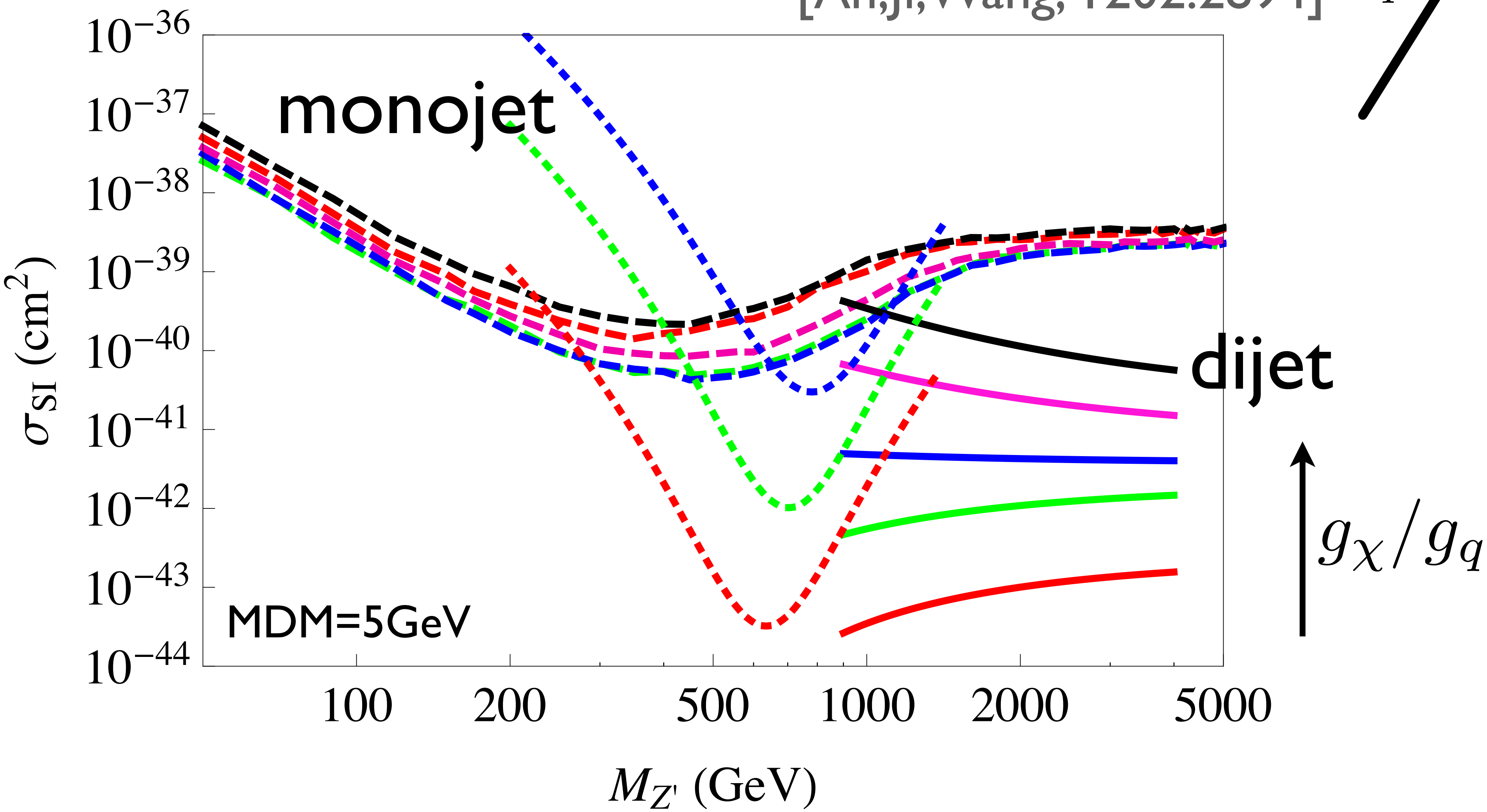
ntact limit

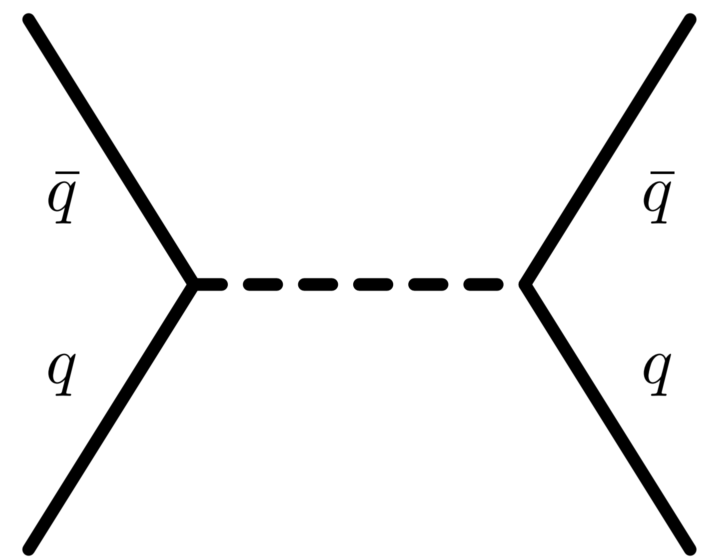
Light Mediators

[An, Ji, Wang: 1202.2894; March-Russell, Unwin, West: 1203.4854]

Look for the light mediator directly-dijet resonance/angular distributions

[An, Ji, Wang, 1202.2894]





Conclusions

- DM is being squeezed on all fronts
- Mono-jet/di-jet searches at colliders already place strong constraints on dark matter
- Competitive with direct detection searches
  - Light DM
  - Spin dependent
- *Independent of all astrophysics uncertainties*

Light mediators weaken collider bounds

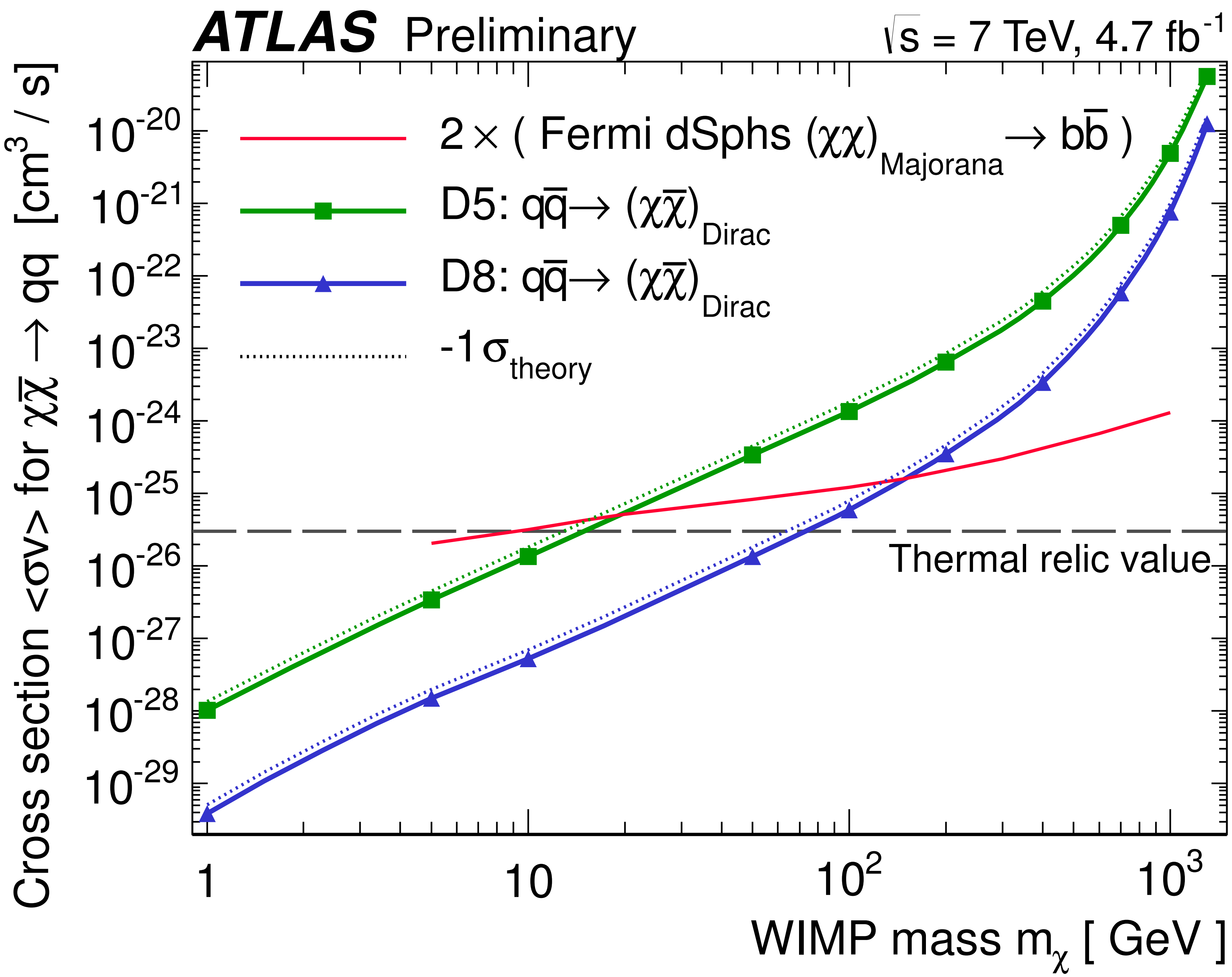
If we see a DD signal in a region ruled out by colliders we have discovered 2 particles

Extra Slides

DM annihilation

$$\sigma_V v_{\rm rel} = \frac{1}{16\pi\Lambda^4}\sum_q \sqrt{1-\frac{m_q^2}{m_\chi^2}}\left(24(2m_\chi^2+m_q^2)+\frac{8m_\chi^4-4m_\chi^2m_q^2+5m_q^4}{m_\chi^2-m_q^2}\,v_{\rm rel}^2\right),$$

$$\sigma_A v_{\rm rel} = \frac{1}{16\pi\Lambda^4}\sum_q \sqrt{1-\frac{m_q^2}{m_\chi^2}}\left(24m_q^2+\frac{8m_\chi^4-22m_\chi^2m_q^2+17m_q^4}{m_\chi^2-m_q^2}\,v_{\rm rel}^2\right).$$



$$D8 = \bar\chi\gamma^\mu\gamma_5\chi\bar q\gamma^\mu\gamma_5 q$$

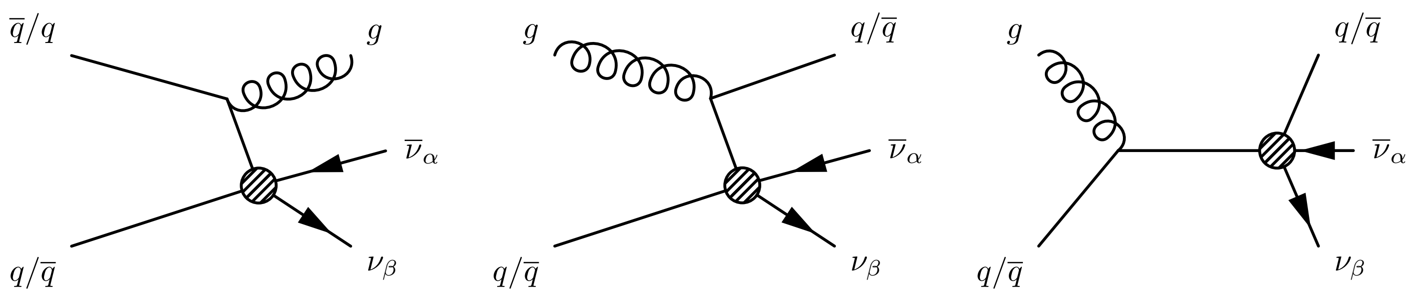
$$D5 = \bar\chi\gamma^\mu\chi\bar q\gamma^\mu q$$

Monojets and other invisibles

[Friedland et al., 1111.5331]

Nonstandard neutrino interactions

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\, G_F \varepsilon^{fP}_{\alpha\beta} \left(\overline{\nu}_\alpha \gamma_\rho \nu_\beta\right) \left(\overline{f}\gamma^\rho P f\right)$$



	CDF		ATLAS [31]		
	GSNP [32]	ADD [4, 5]	LowPt	HighPt	veryHighPt
$\varepsilon^{uP}_{\alpha\beta=\alpha}$	0.45	0.51	0.40	0.19	0.17
$\varepsilon^{dP}_{\alpha\beta=\alpha}$	1.12	1.43	0.54	0.28	0.26
$\varepsilon^{uP}_{\alpha\beta\neq\alpha}$	0.32	0.36	0.28	0.13	0.12
$\varepsilon^{dP}_{\alpha\beta\neq\alpha}$	0.79	1.00	0.38	0.20	0.18