Dark Matter at the LHC, and elsewhere

Patrick Fox

Fermilab

Lots of evidence for DM

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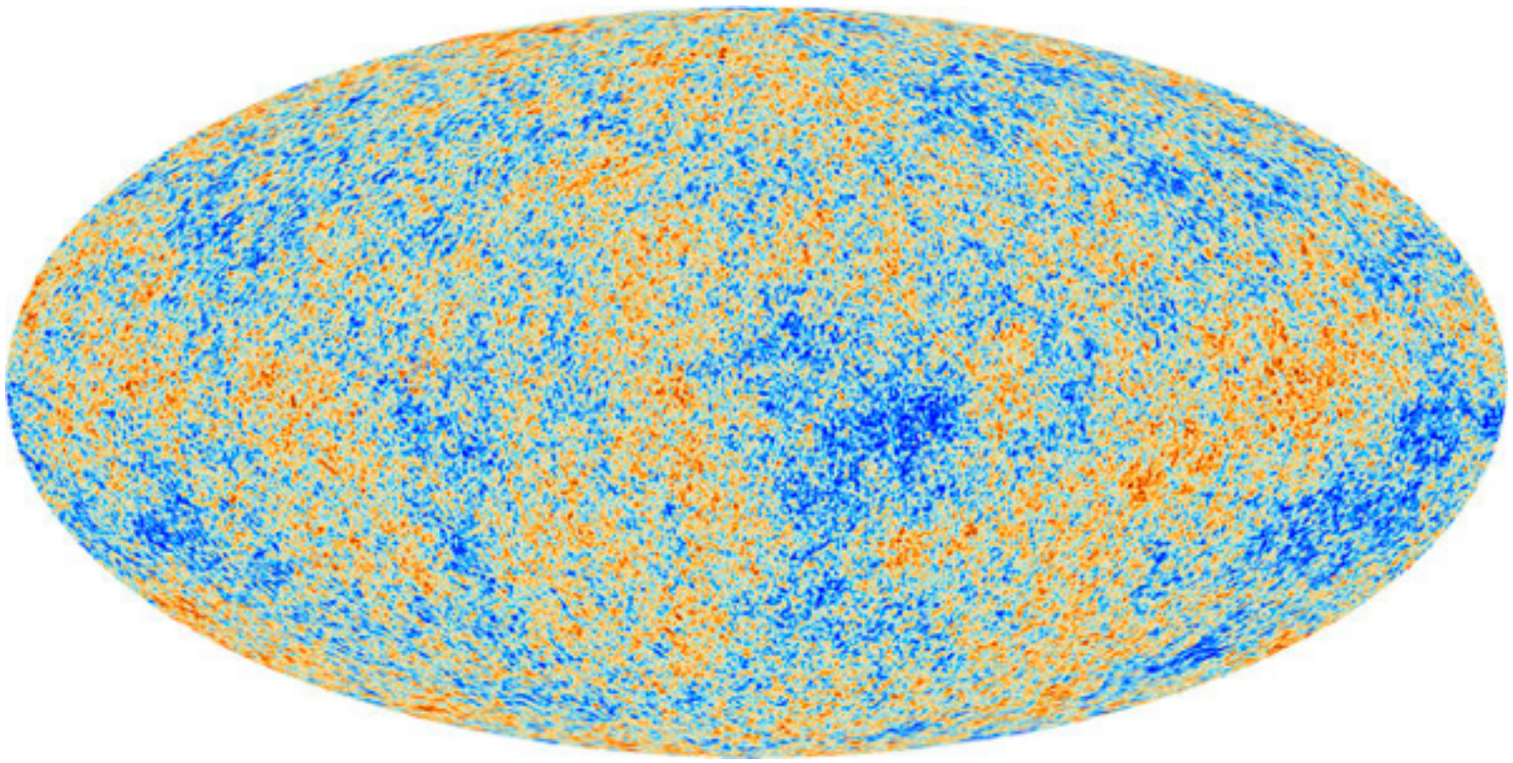
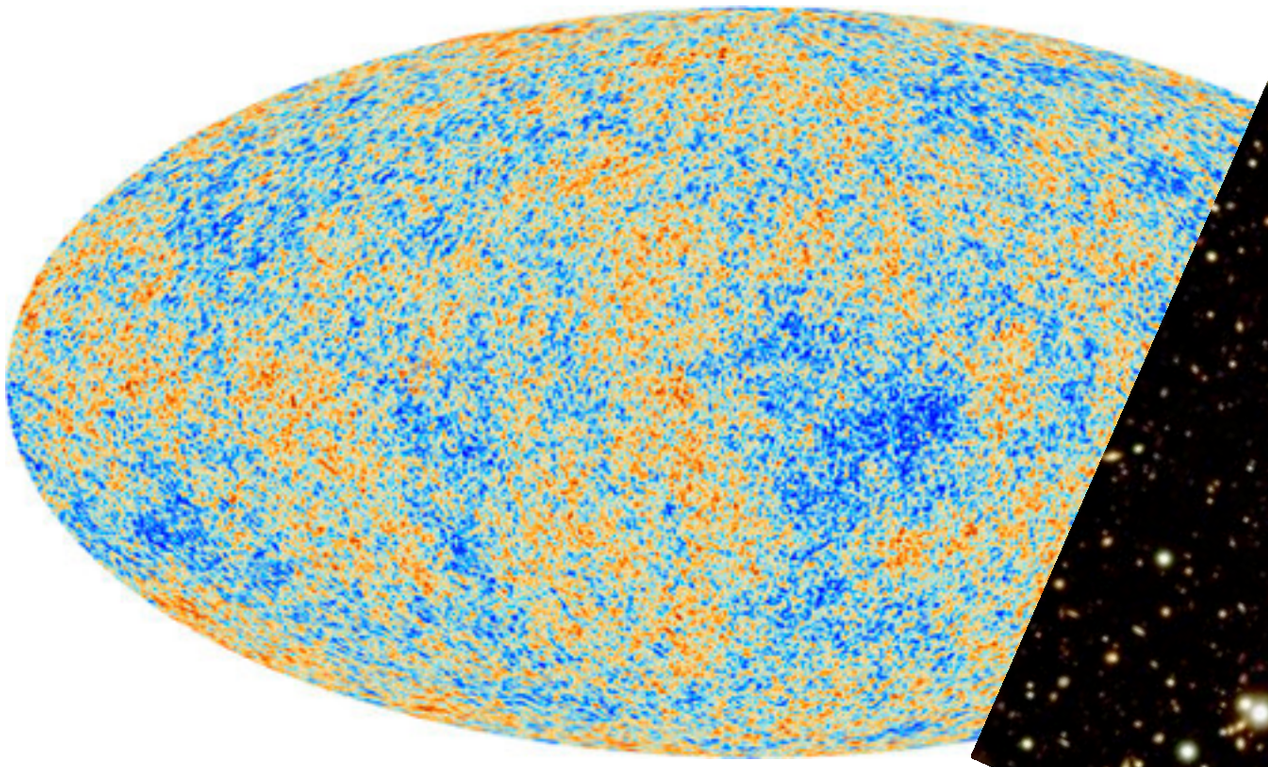


Lots of evidence for DM



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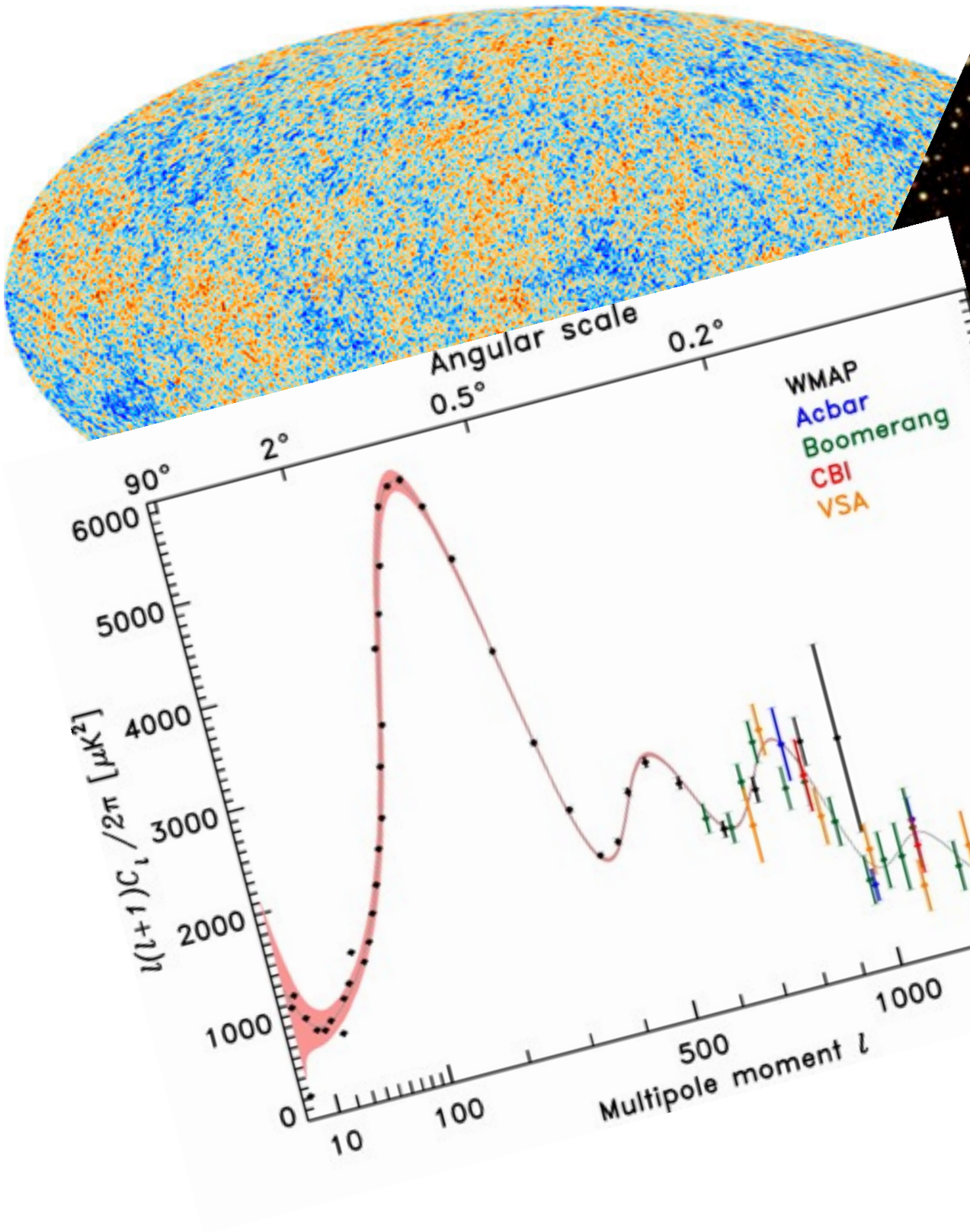

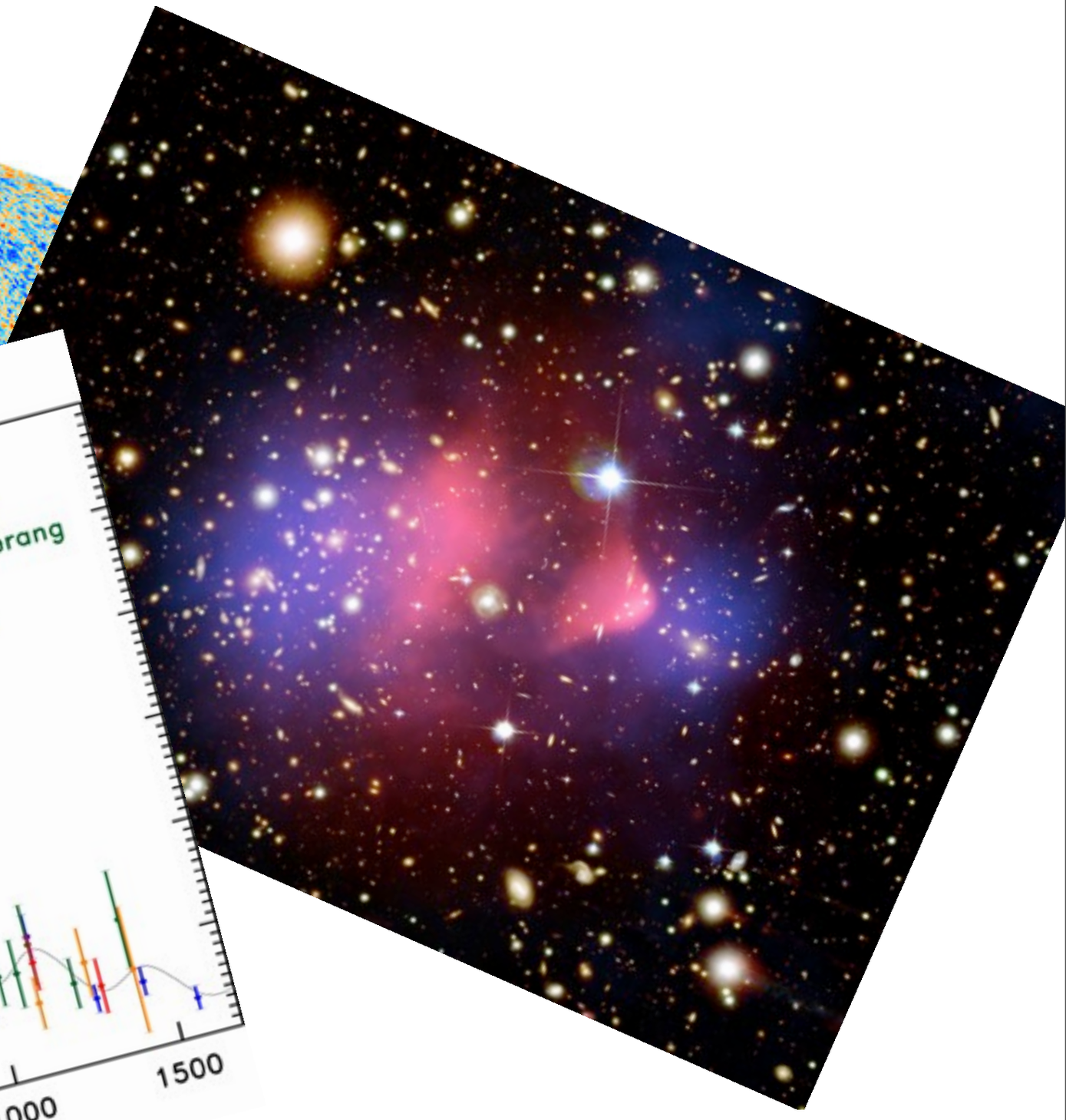

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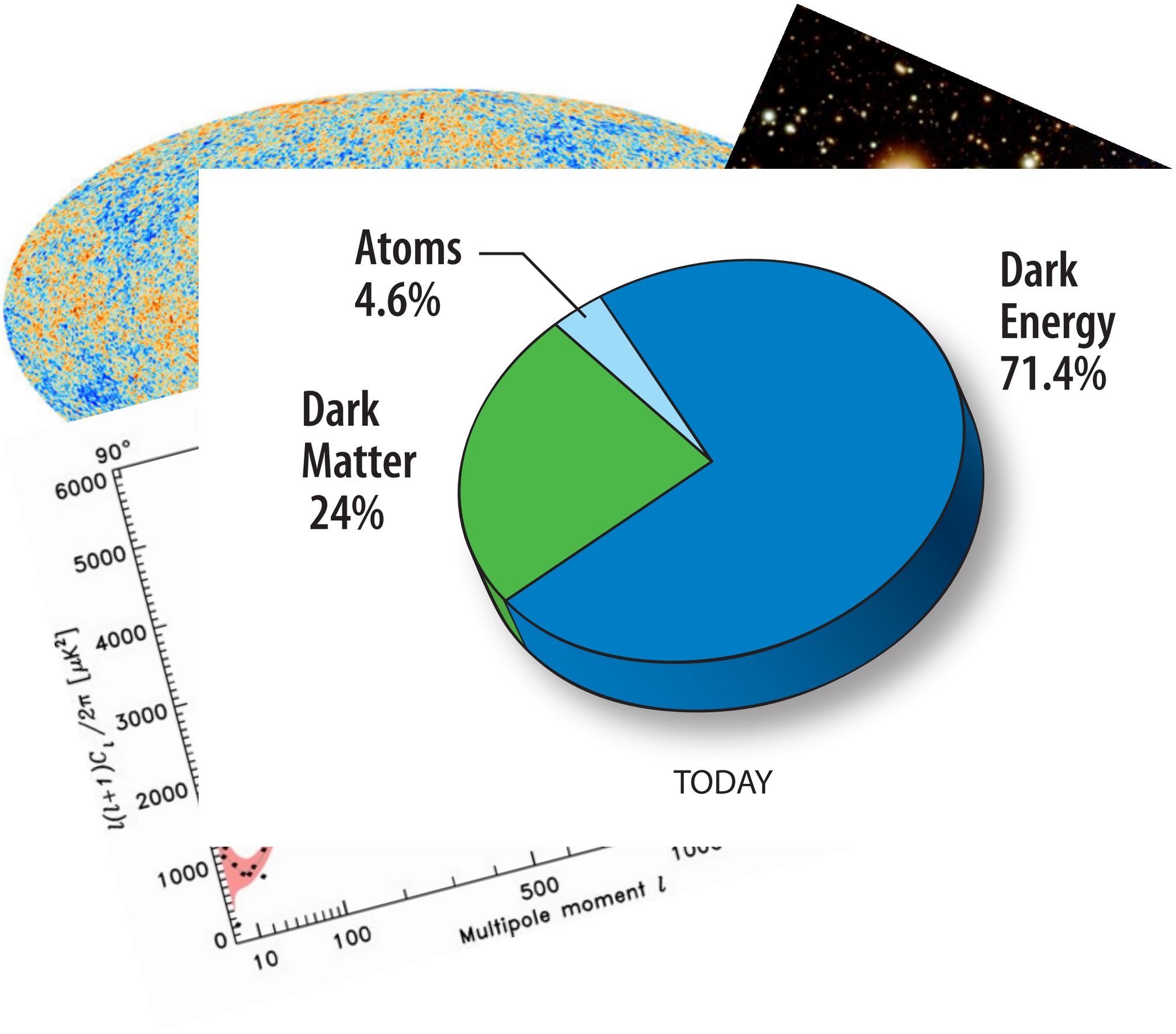
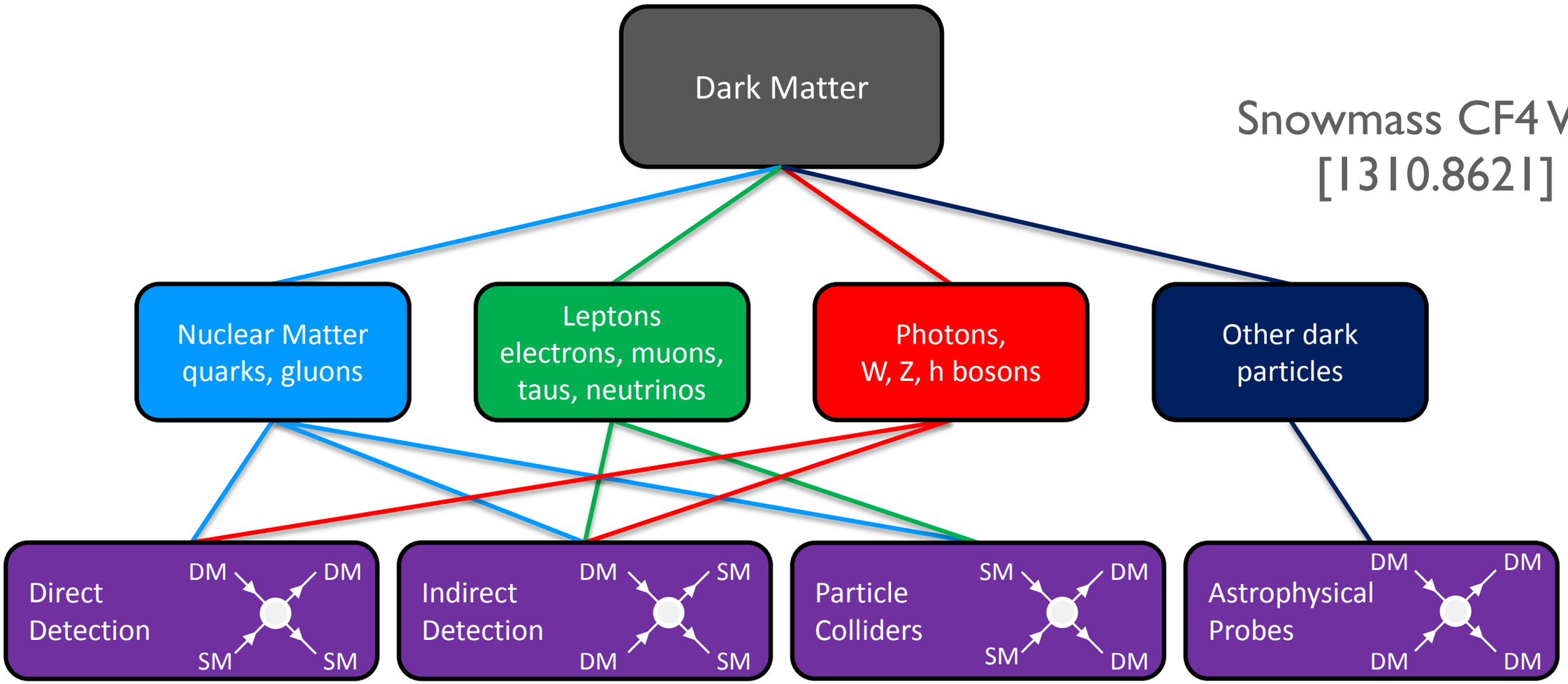
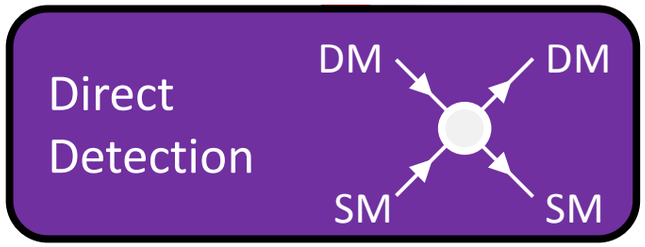


Searching for DM non-gravitationally

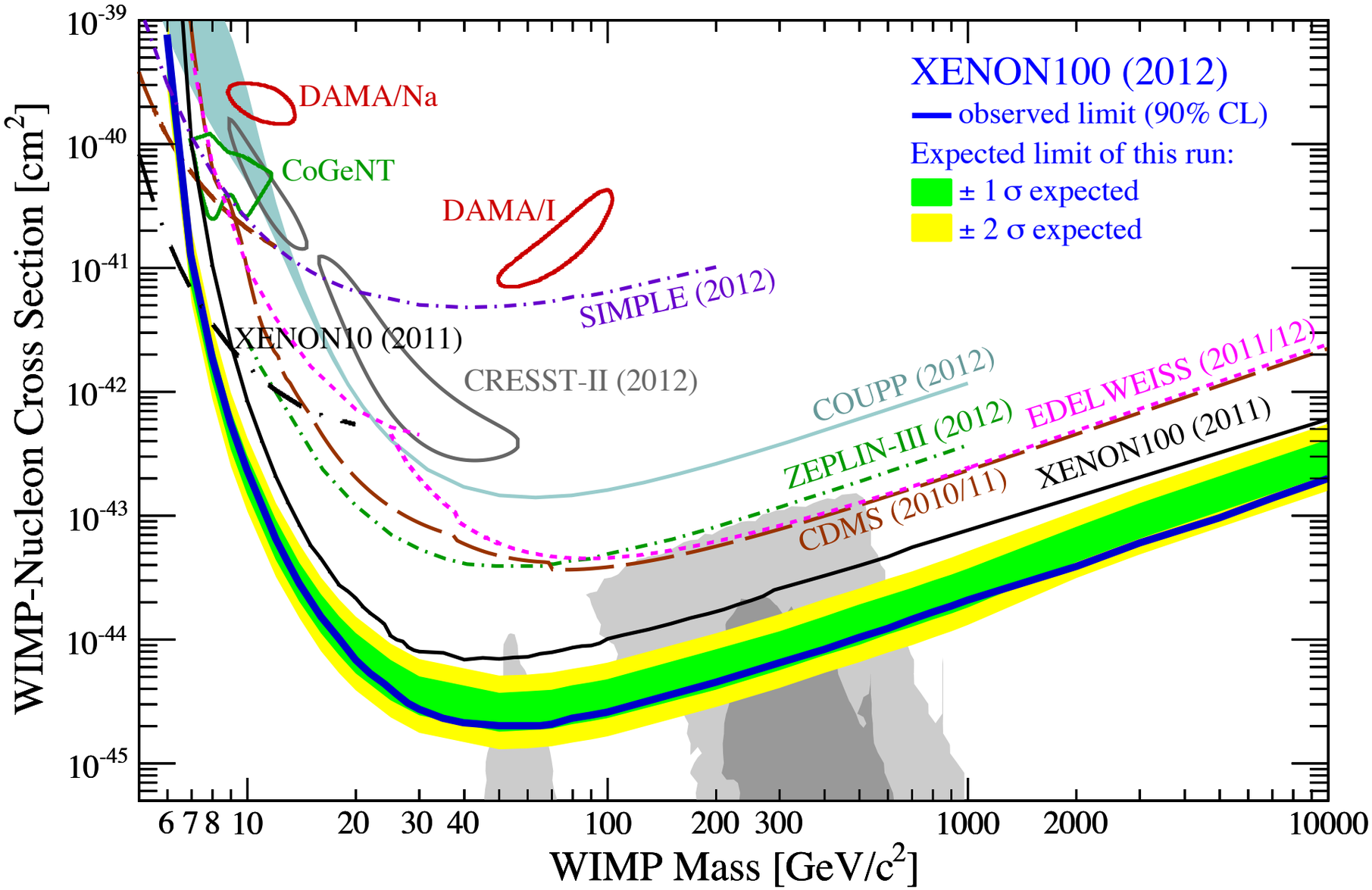


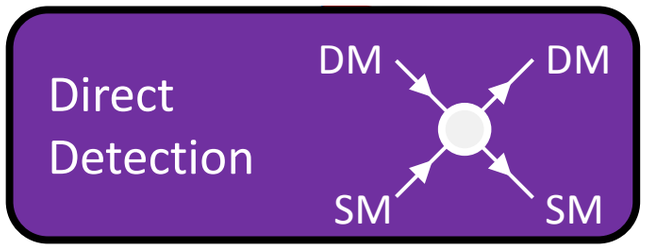
Snowmass CF4 WG
[1310.8621]

Complementary approaches
Need all four going forward



- Astrophysical assumptions
- No upper limit to mass probed
- Lower limit: astrophysics + expt. threshold
- SD, inelastic, isospin-dependence weaken bounds





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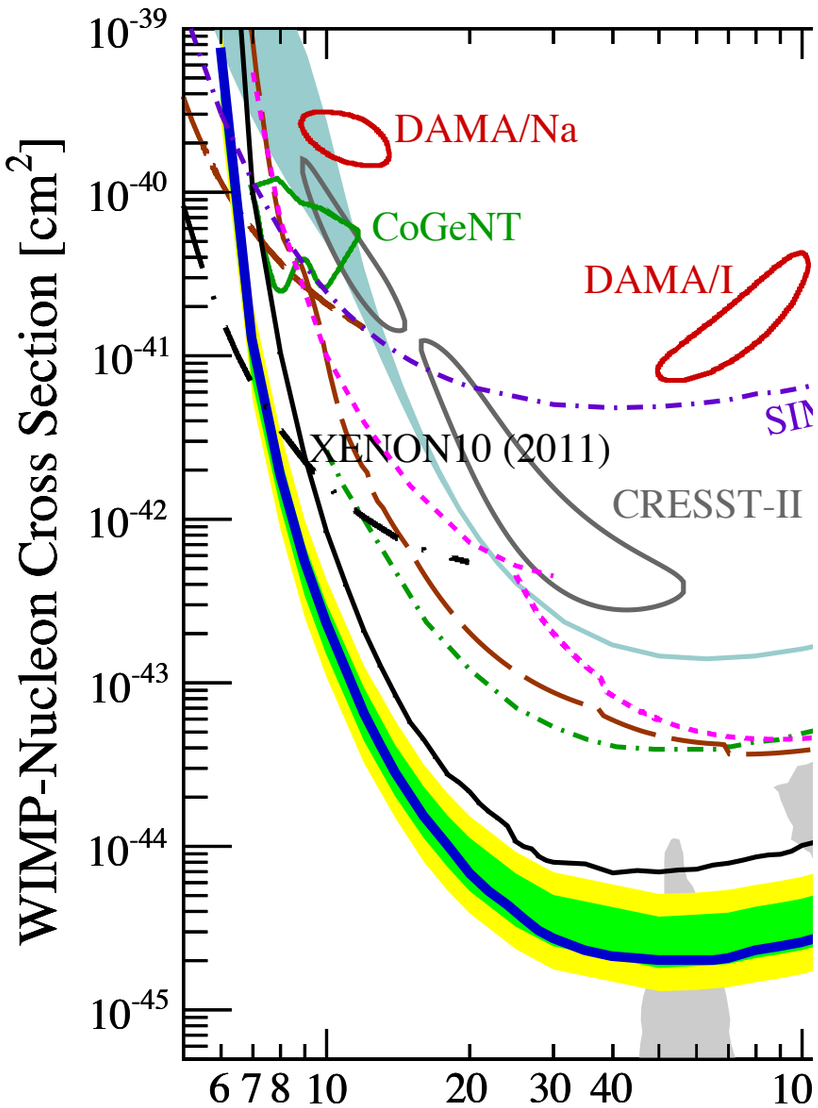

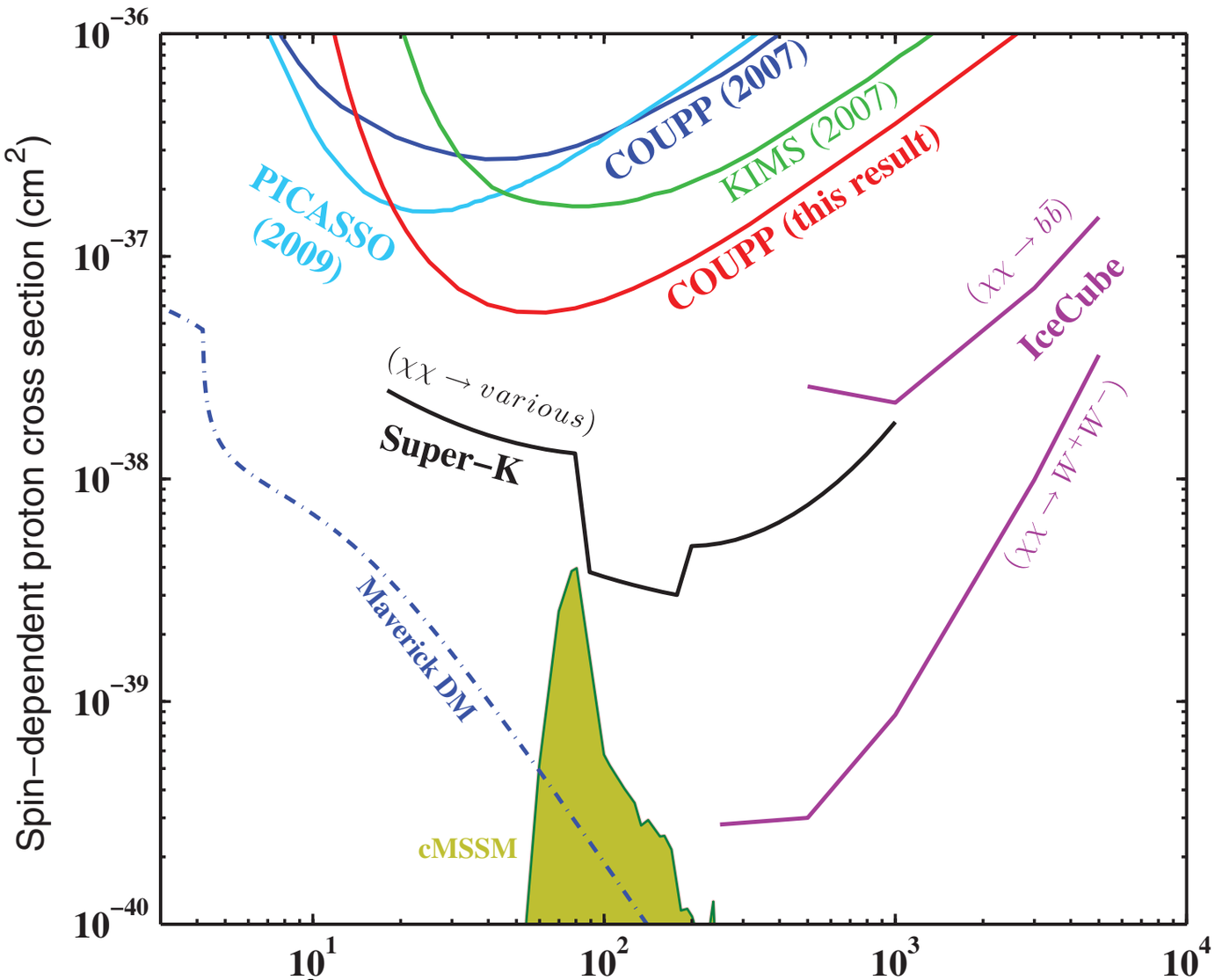

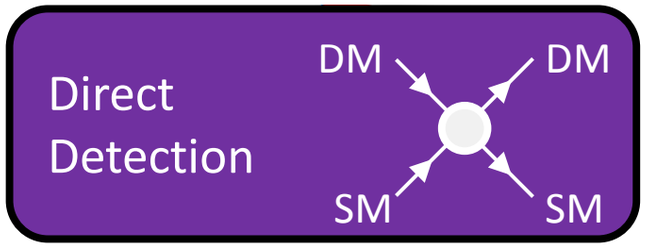

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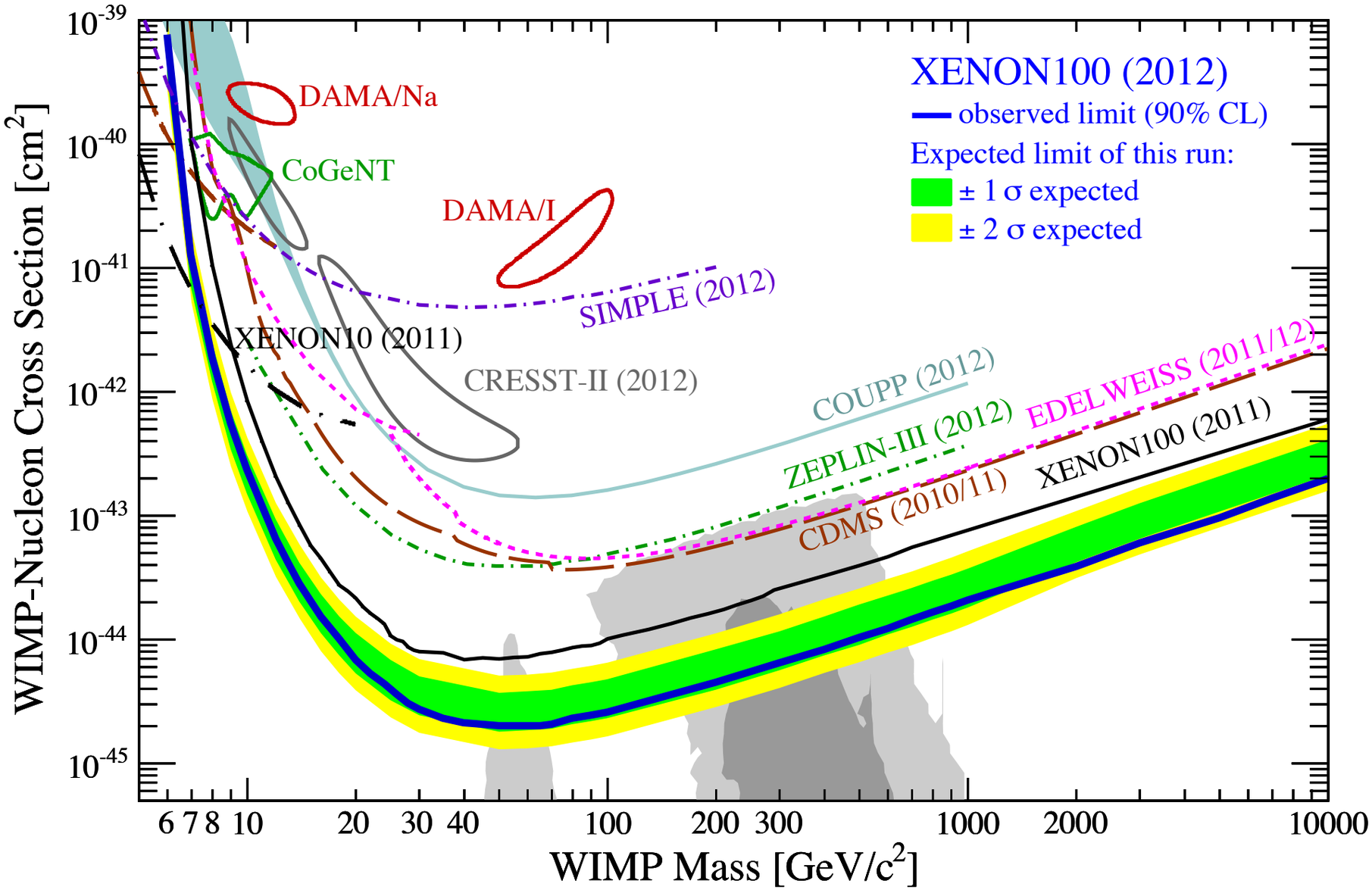
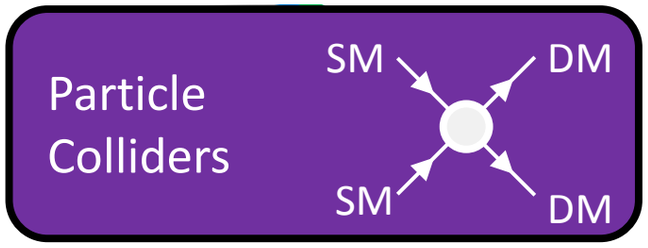
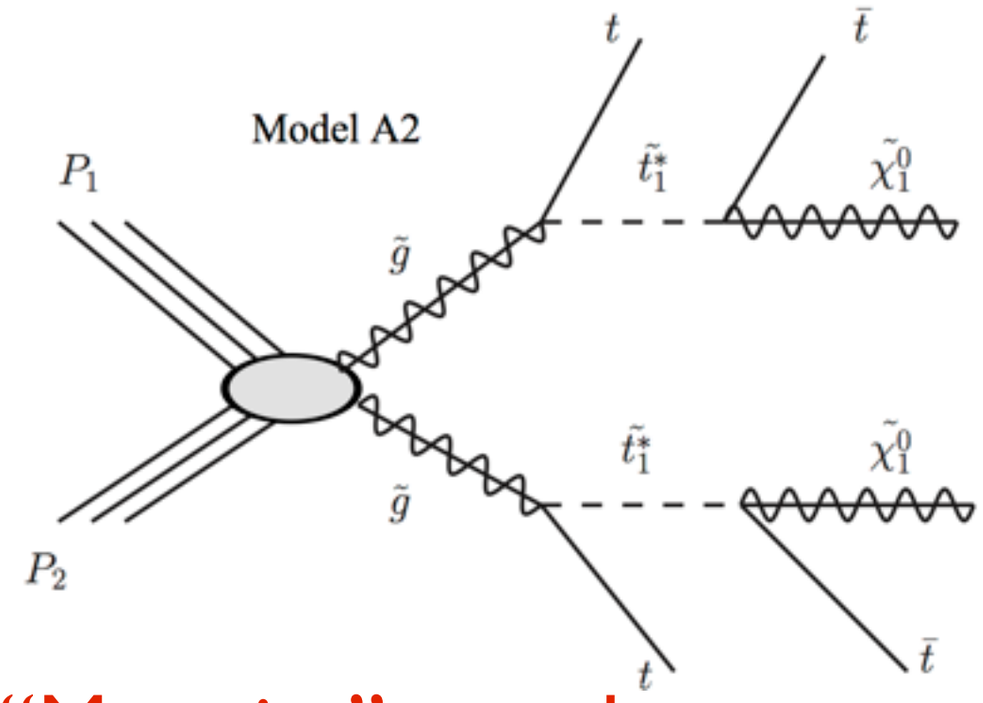




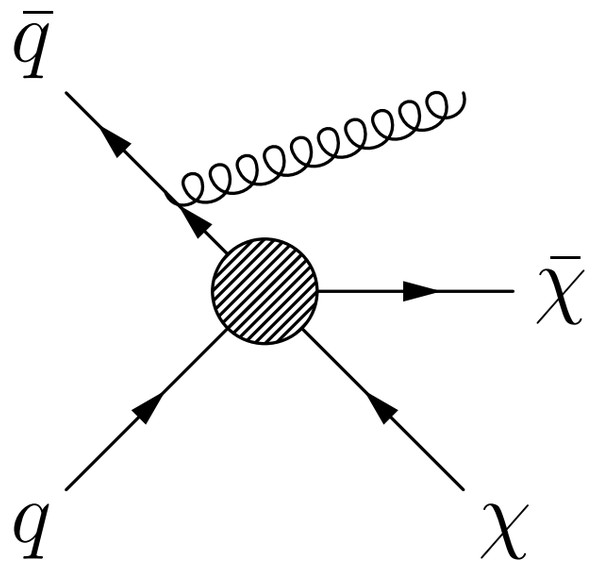
- Collider stable = cosmologically stable?
- No astrophysical assumptions
- Limited by kinematic reach

"Traditional" searches



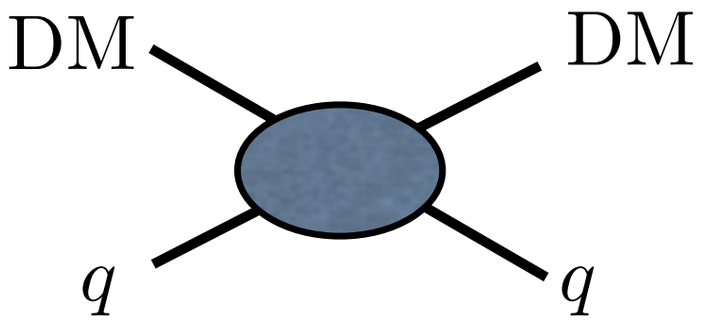
- Many models with DM (e.g. SUSY), searches are model specific
- Many kinematic quantities

"Monojet" searches

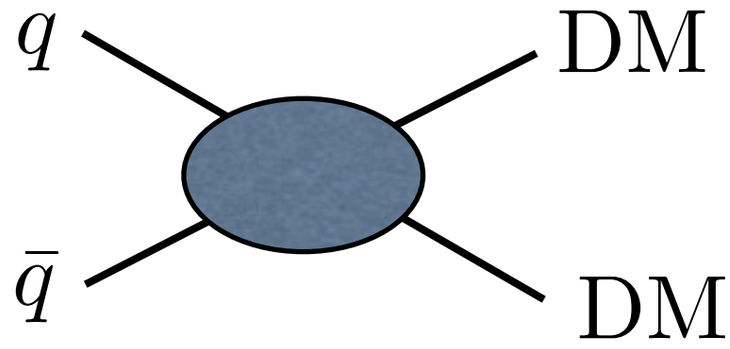


- Only search for DM, "model independent"
- Direct link to direct detection
- Few kinematic quantities

Operators



$\Leftrightarrow$



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

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

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

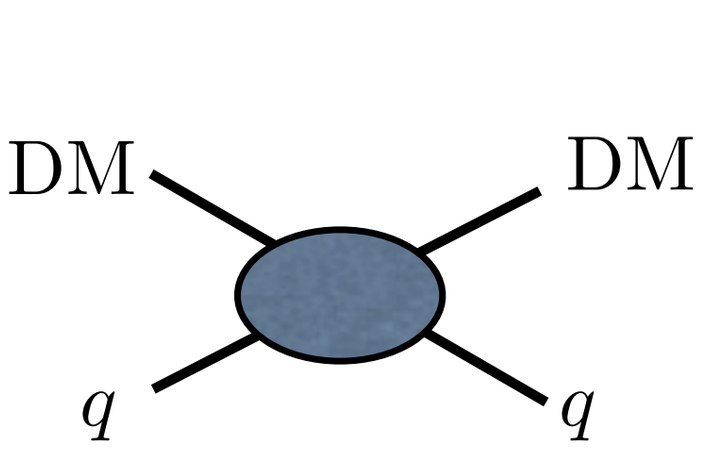
SI, scalar exchange

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

SI, scalar exchange

Typically consider each operator separately

Operators



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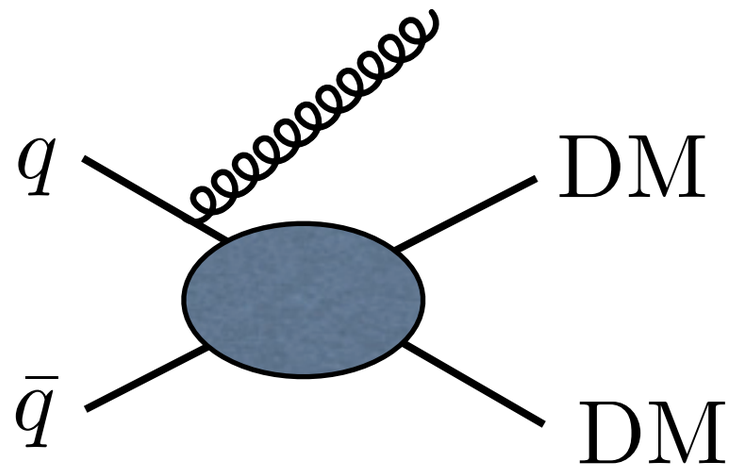

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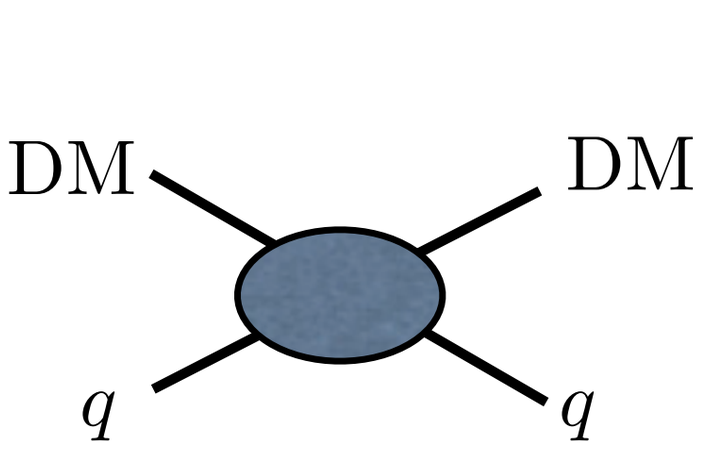

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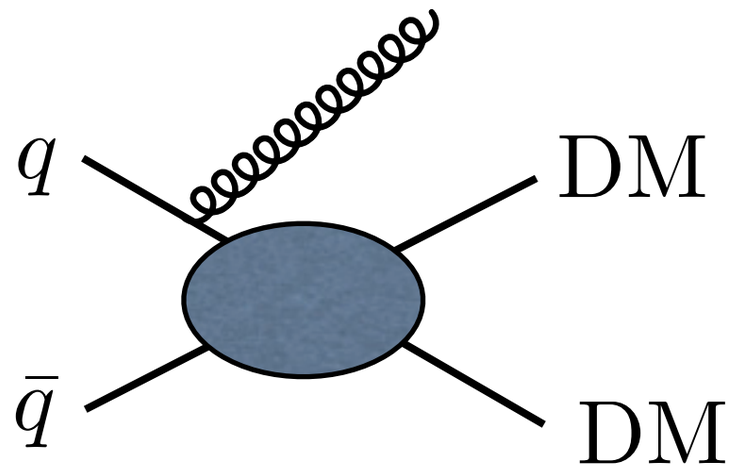

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See Goodman et al. [1008.1783] for more complete list

Typically 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

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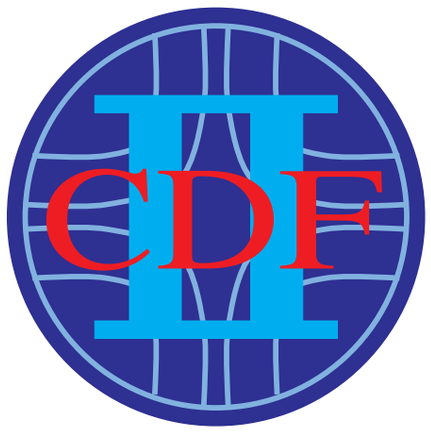
Many Experimentalists

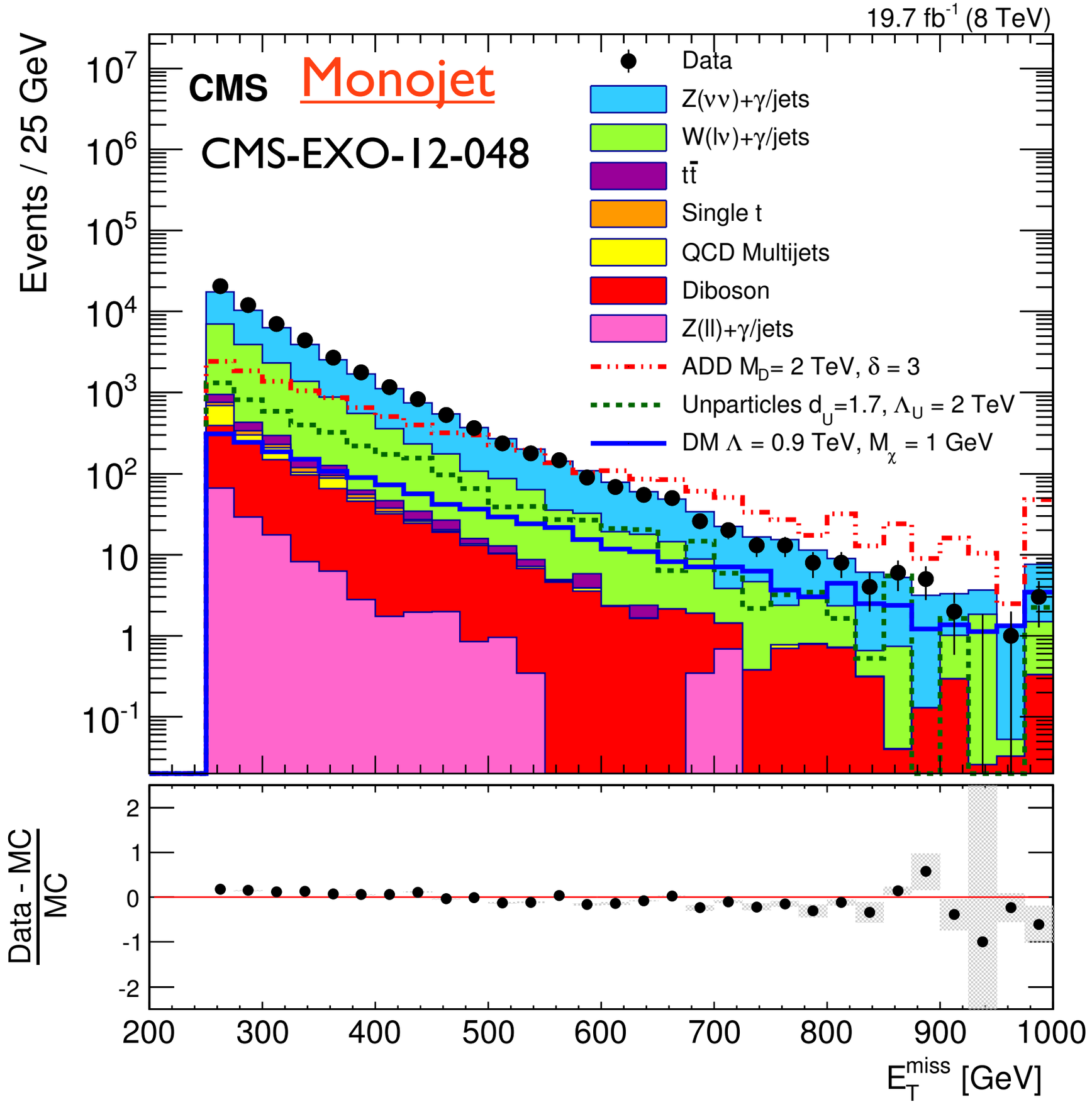
ADD extra dimension searches can be recast



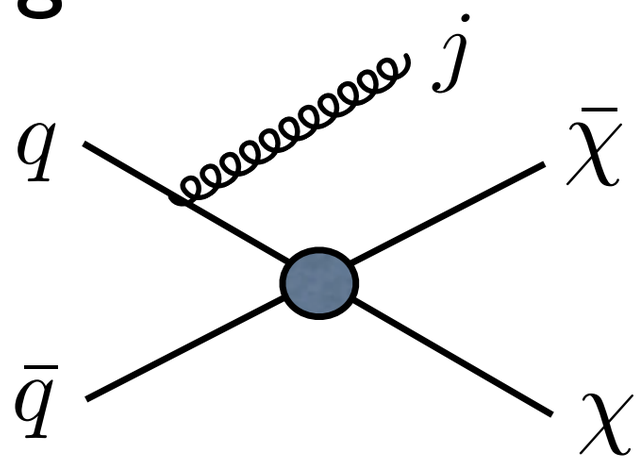
6.7/fb shape-based monojet analysis

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

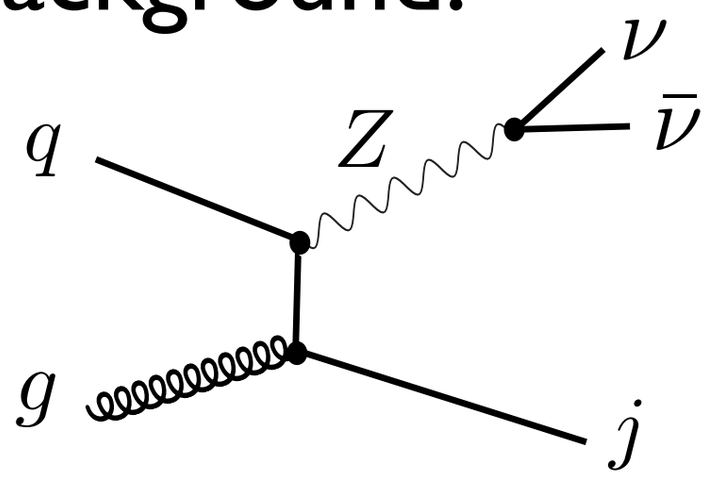
Recast of other searches for mono-W/Z/H
Theory analyses for mono-b, mono-top



Signal:

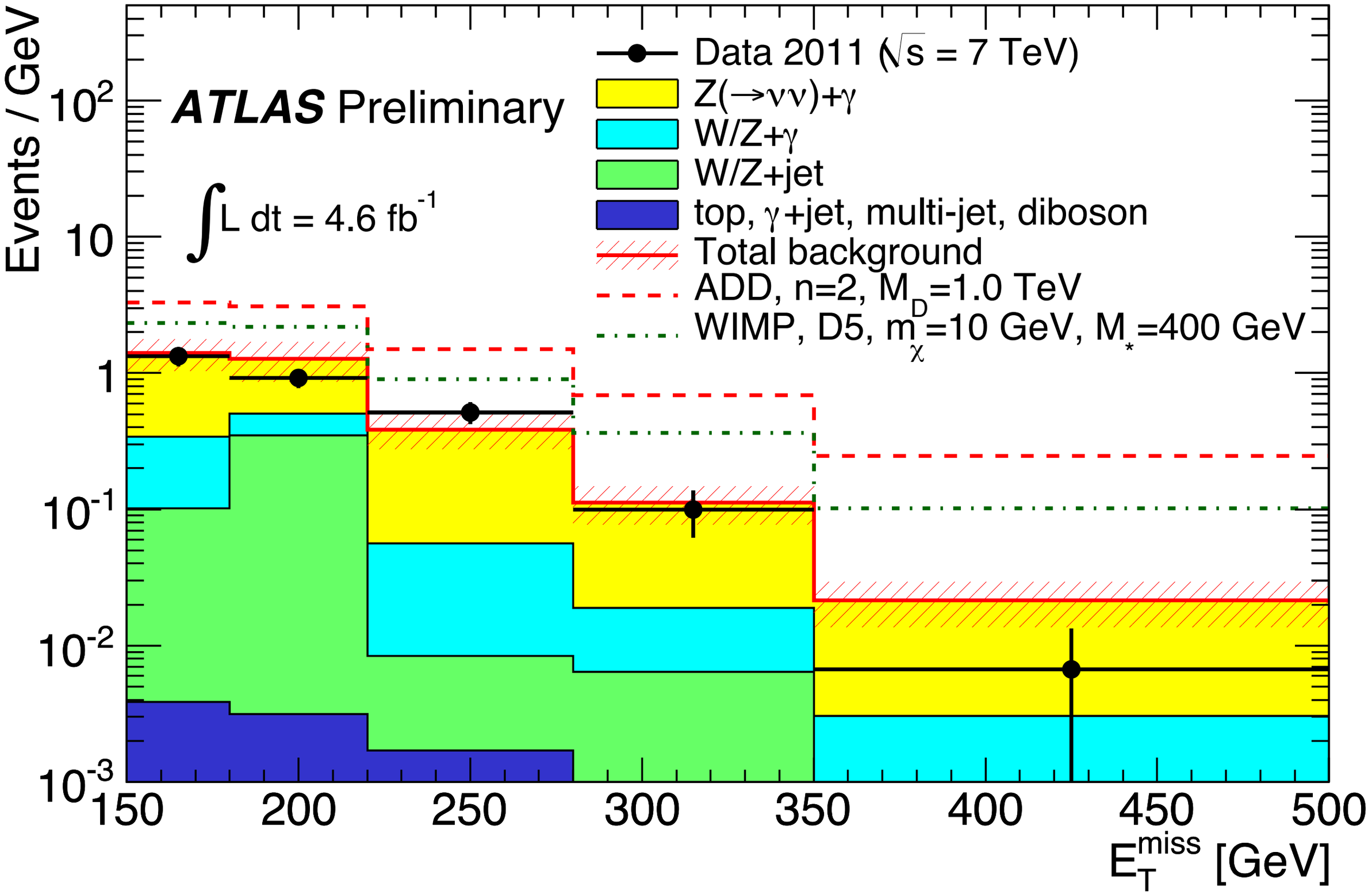


(Dominant) Background:

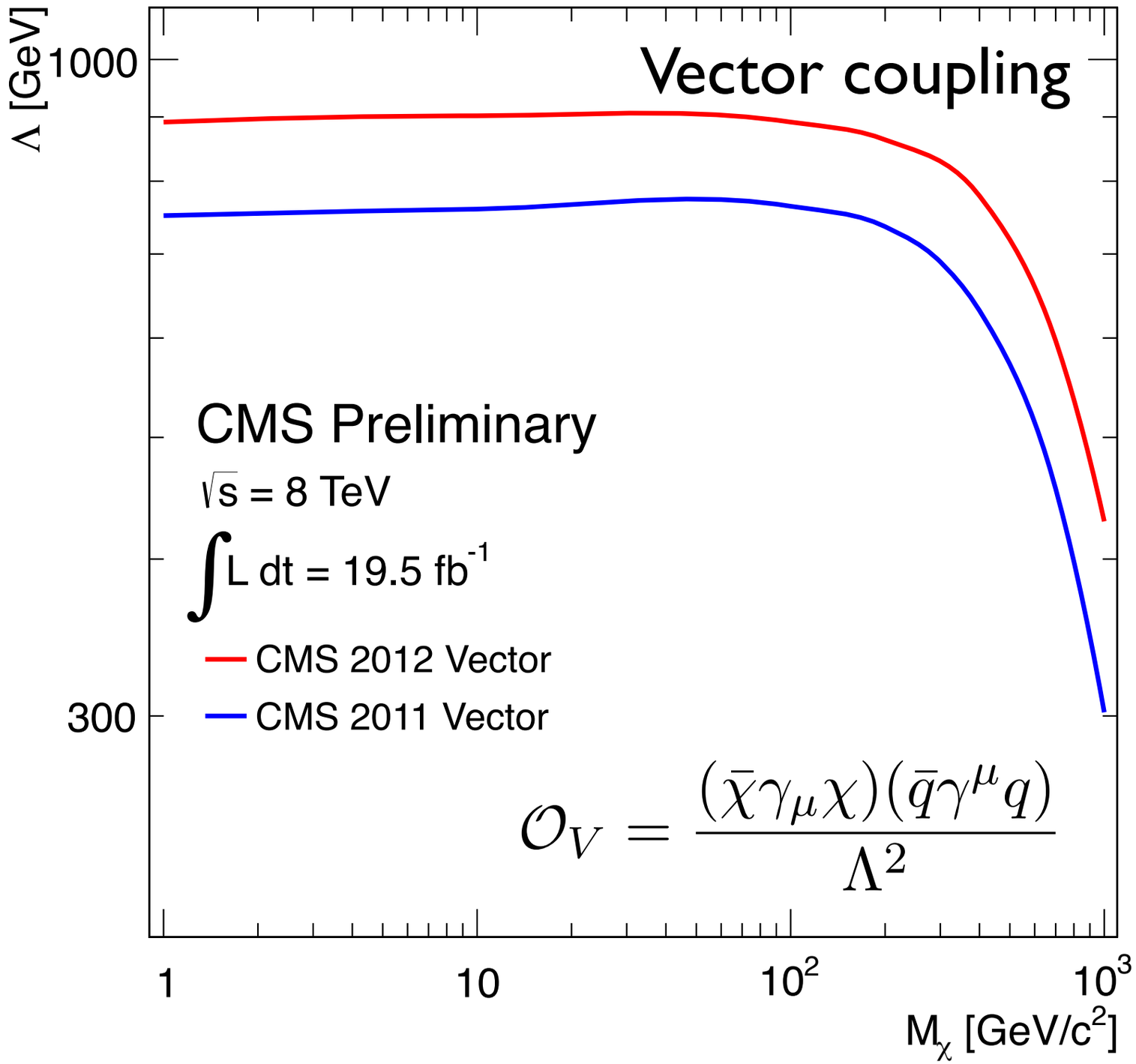


ATLAS-CONF-2012-085

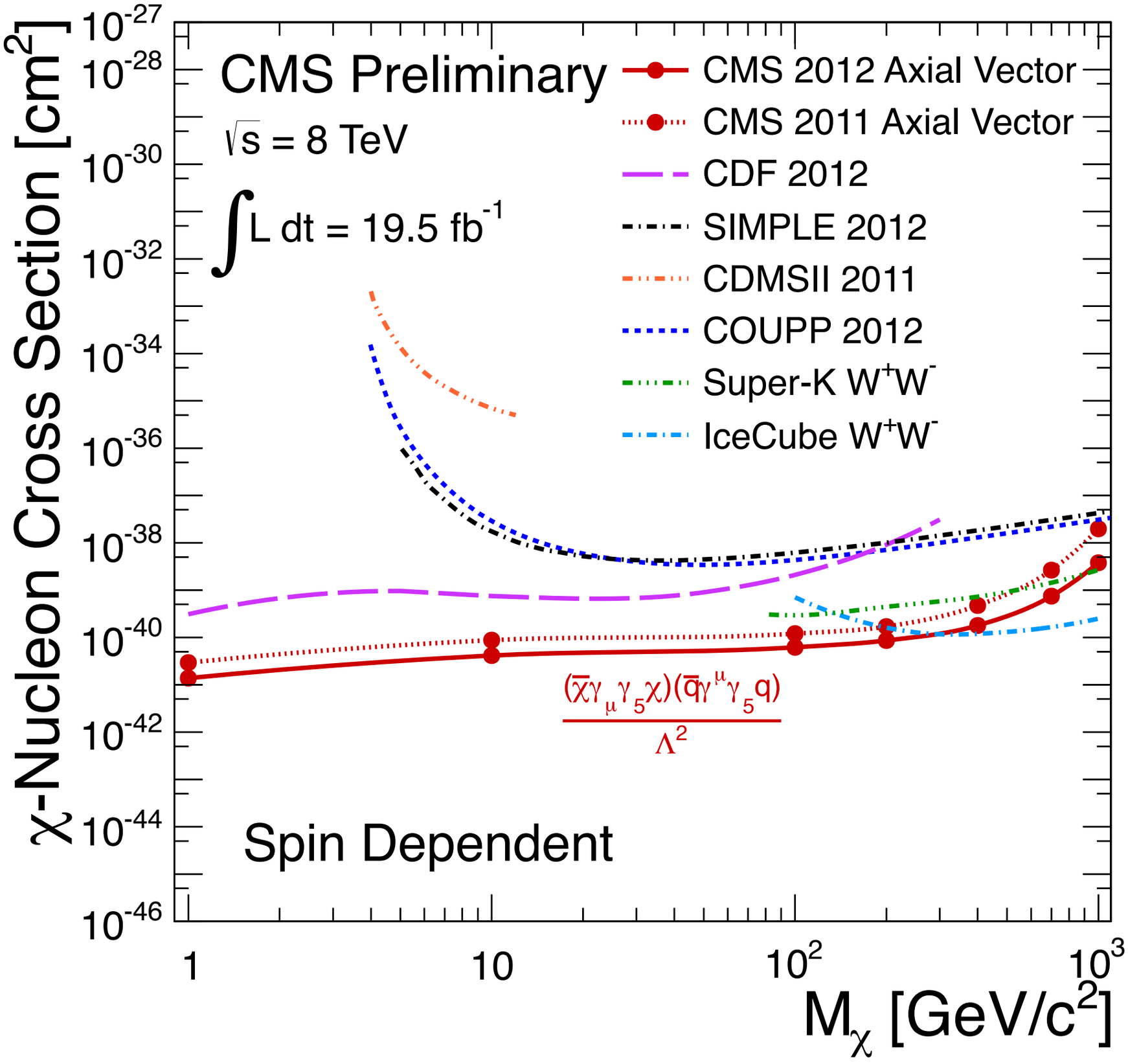
Monophoton



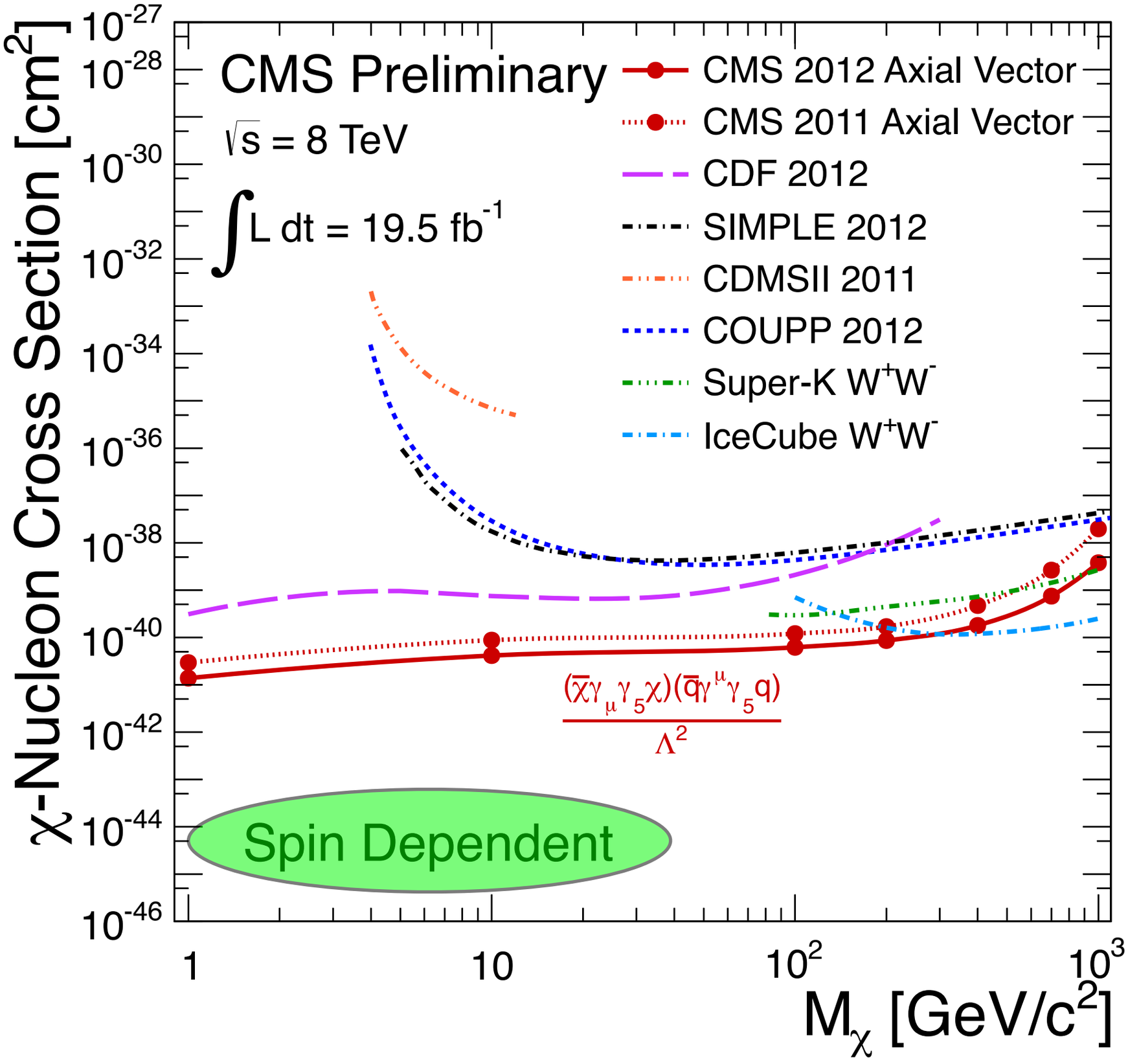
How to quantify nothing?



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-
(χ̄γμγ5χ)(q̄γμγ5q) / Λ2
Spin Dependent
χ-Nucleon Cross Section [cm2]
Mχ [GeV/c2]
10-27
10-28
10-30
10-32
10-34
10-36
10-38
10-40
10-42
10-44
10-46
1
10
10²
10³

Monojet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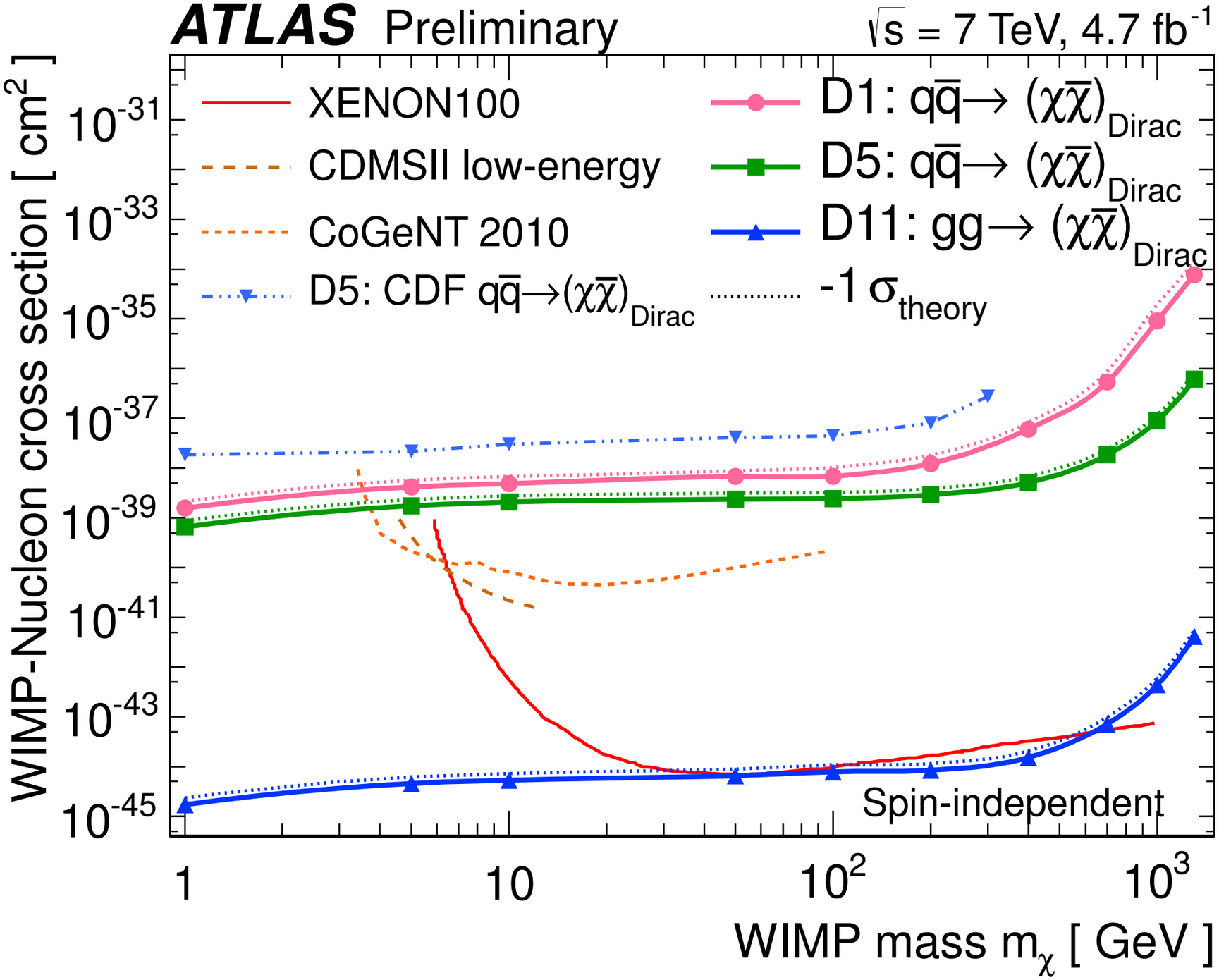
Monojet

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

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

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



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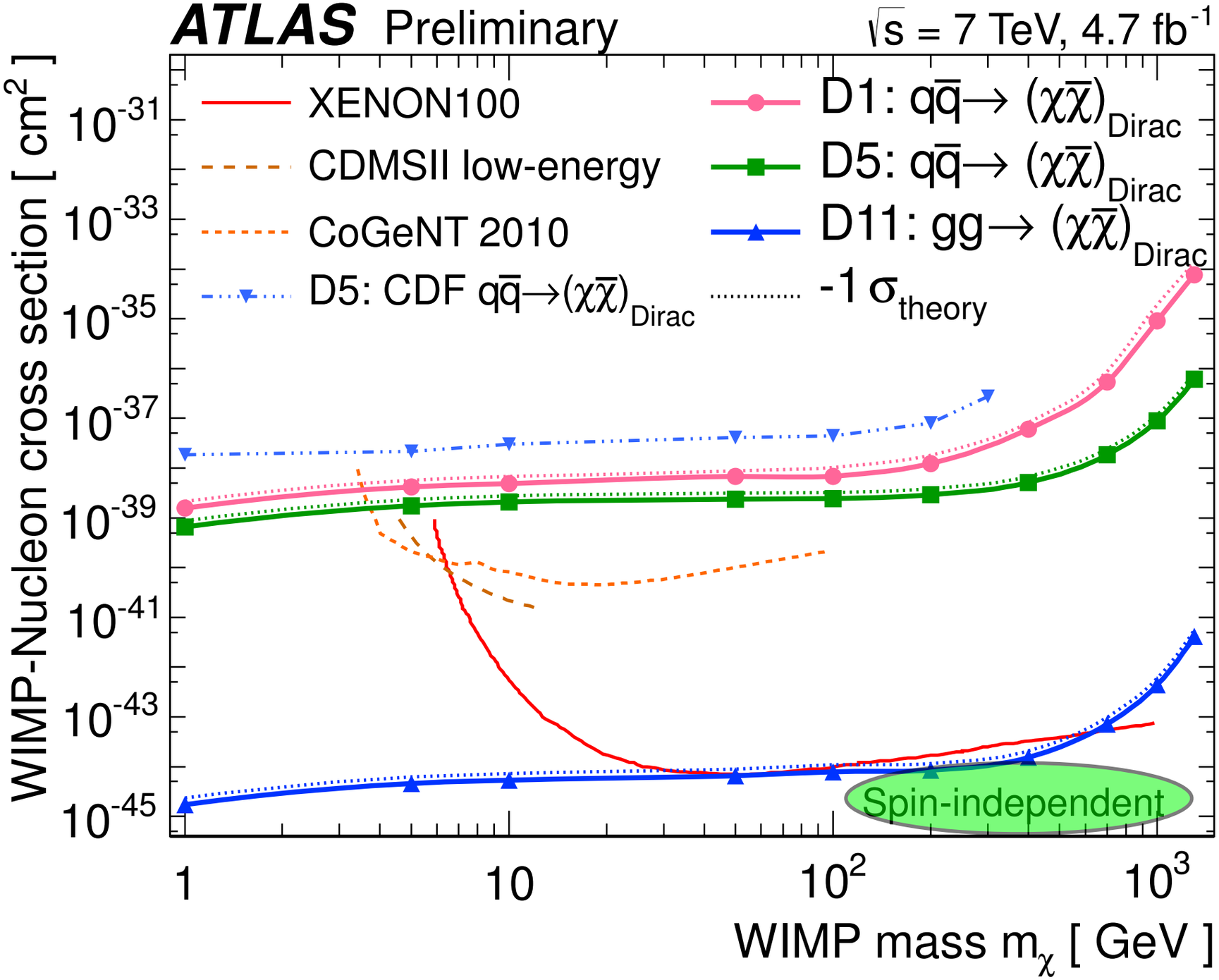
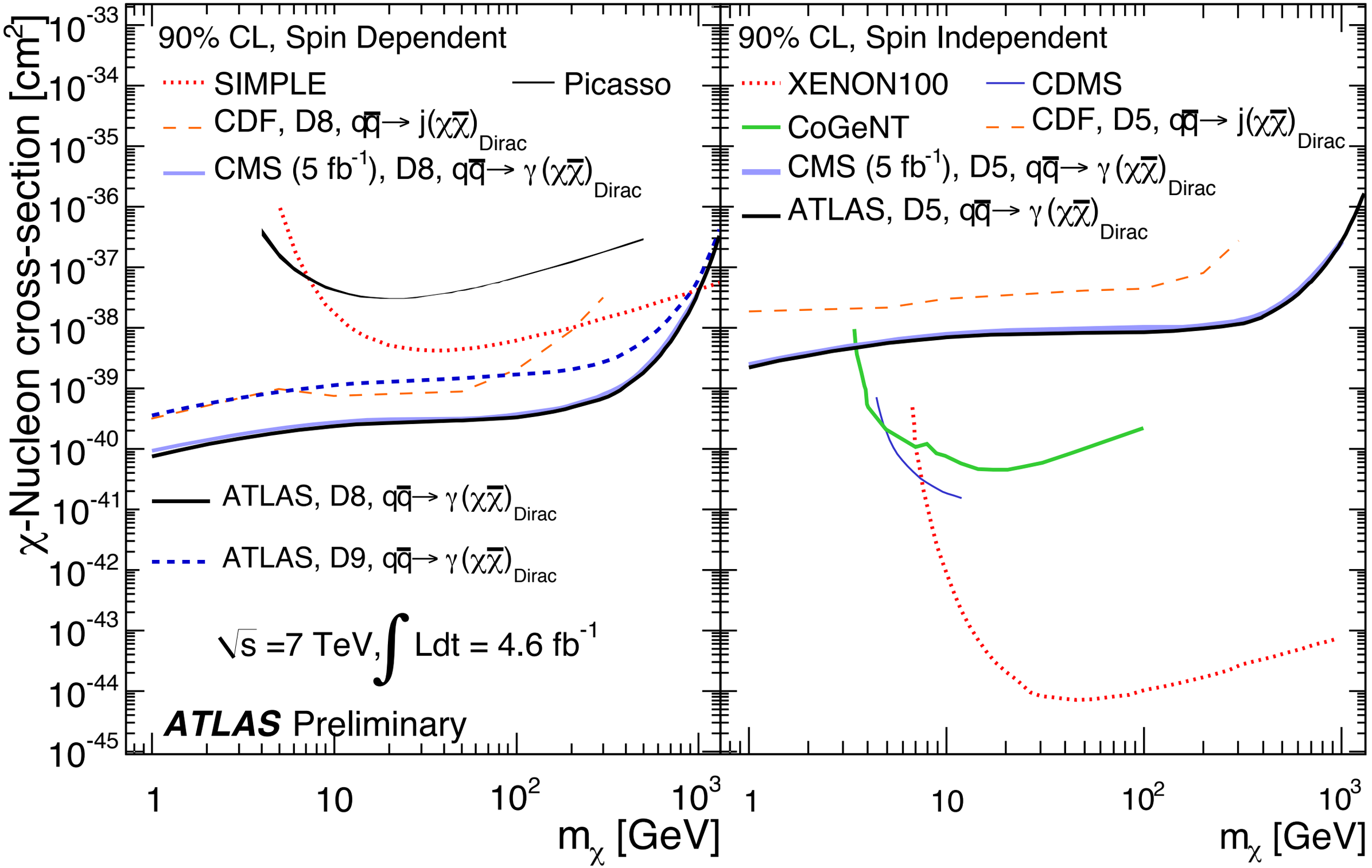


Monophoton

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

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



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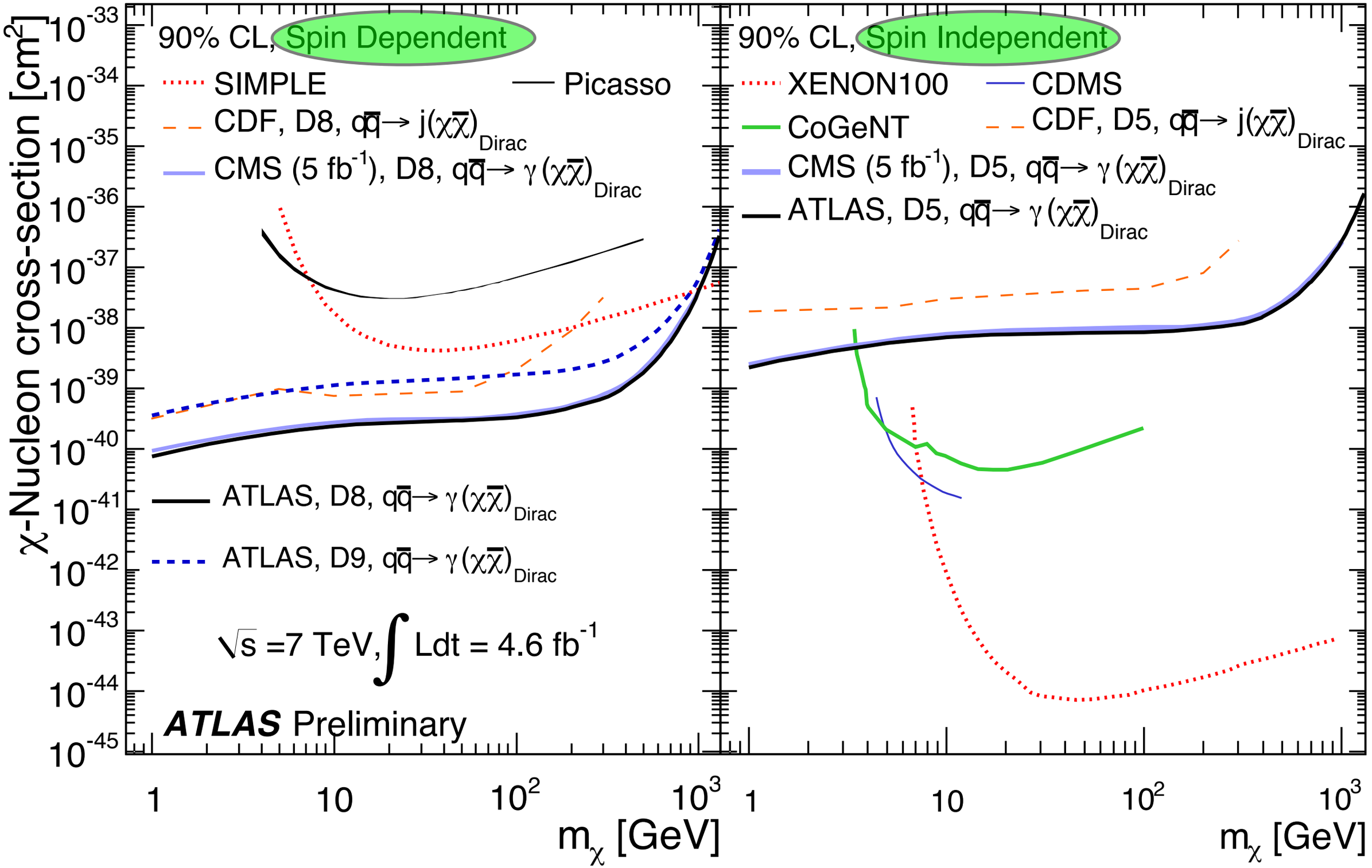
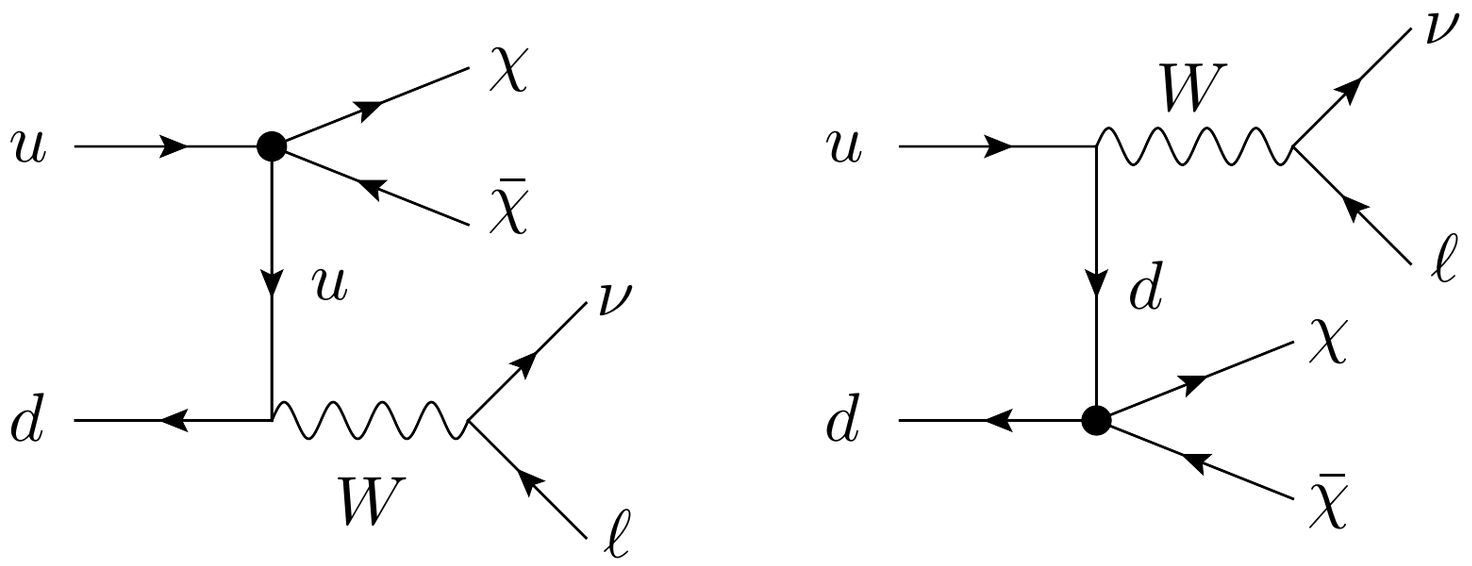
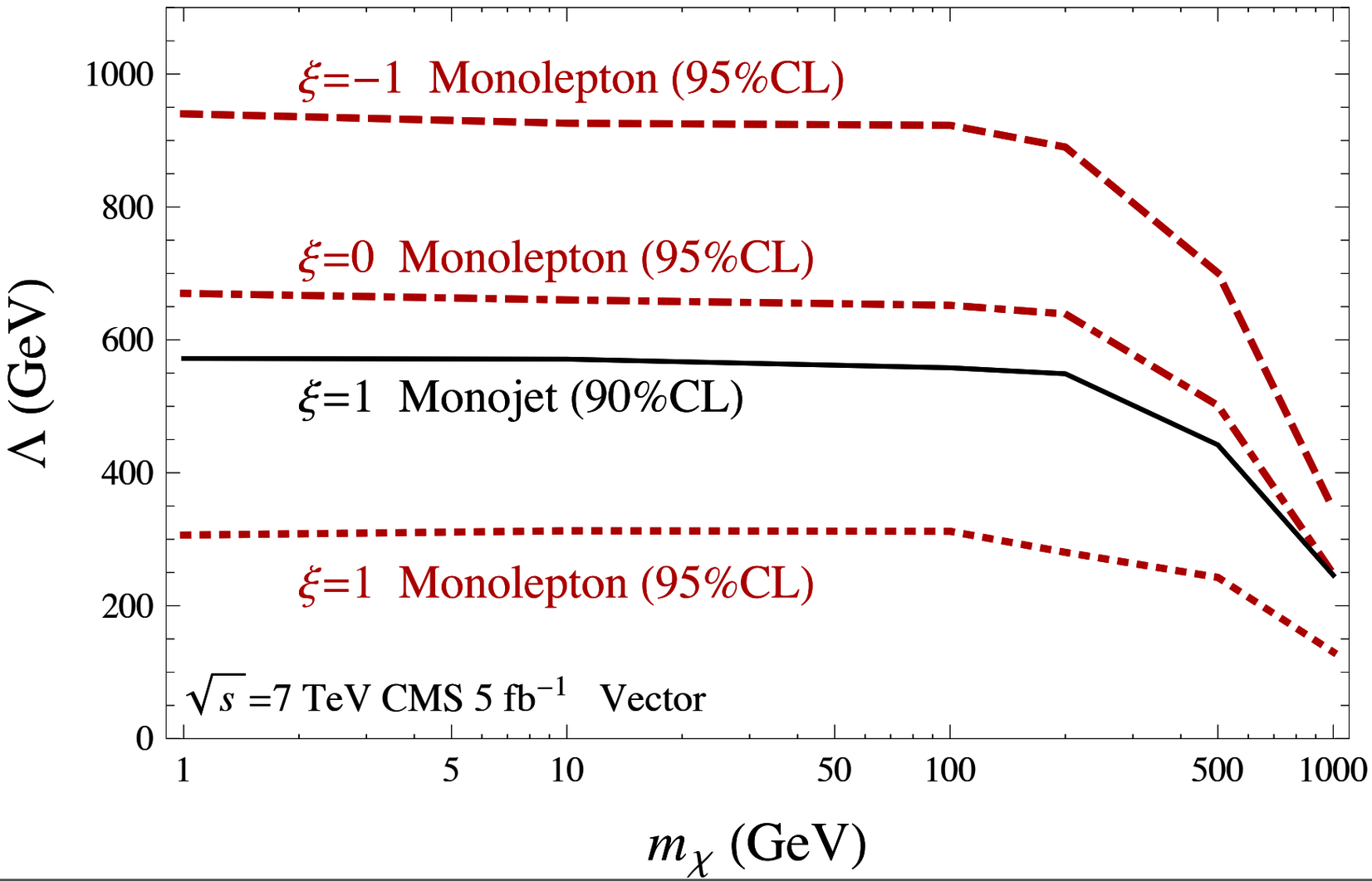


Mono-W

[Bai, Tait, 1208.4361]



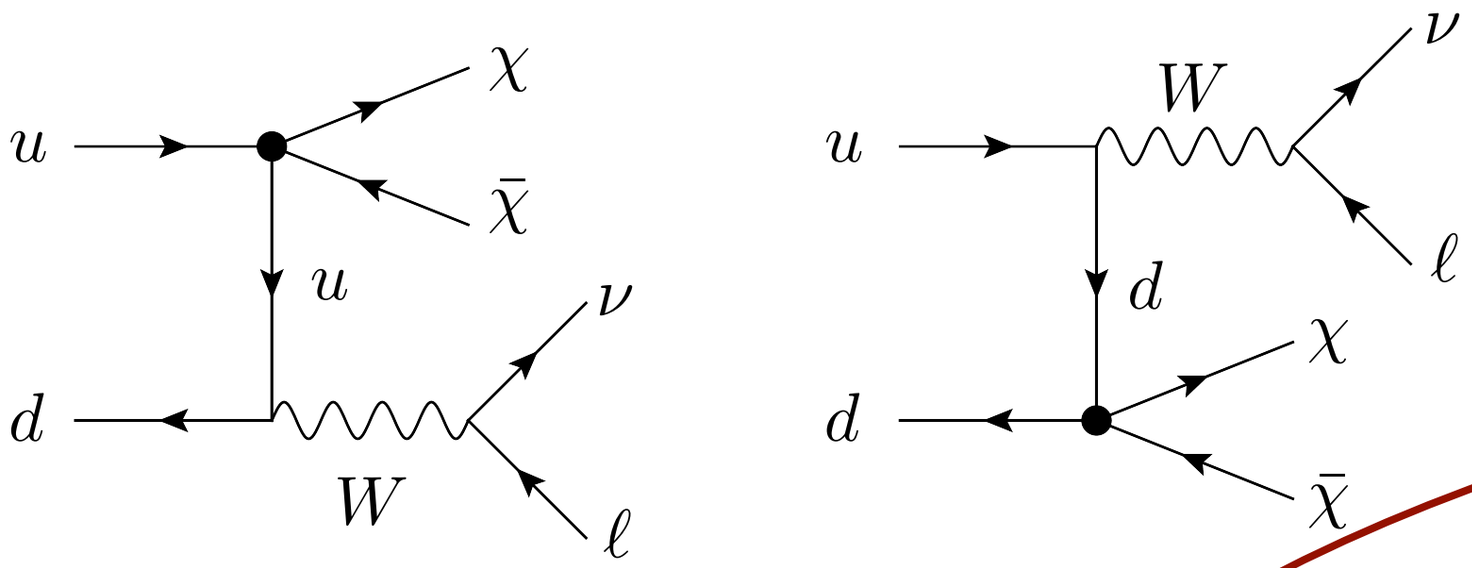
$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\;\left(\overline{u}\gamma^\mu u+\xi\;\overline{d}\gamma^\mu d\right)$$



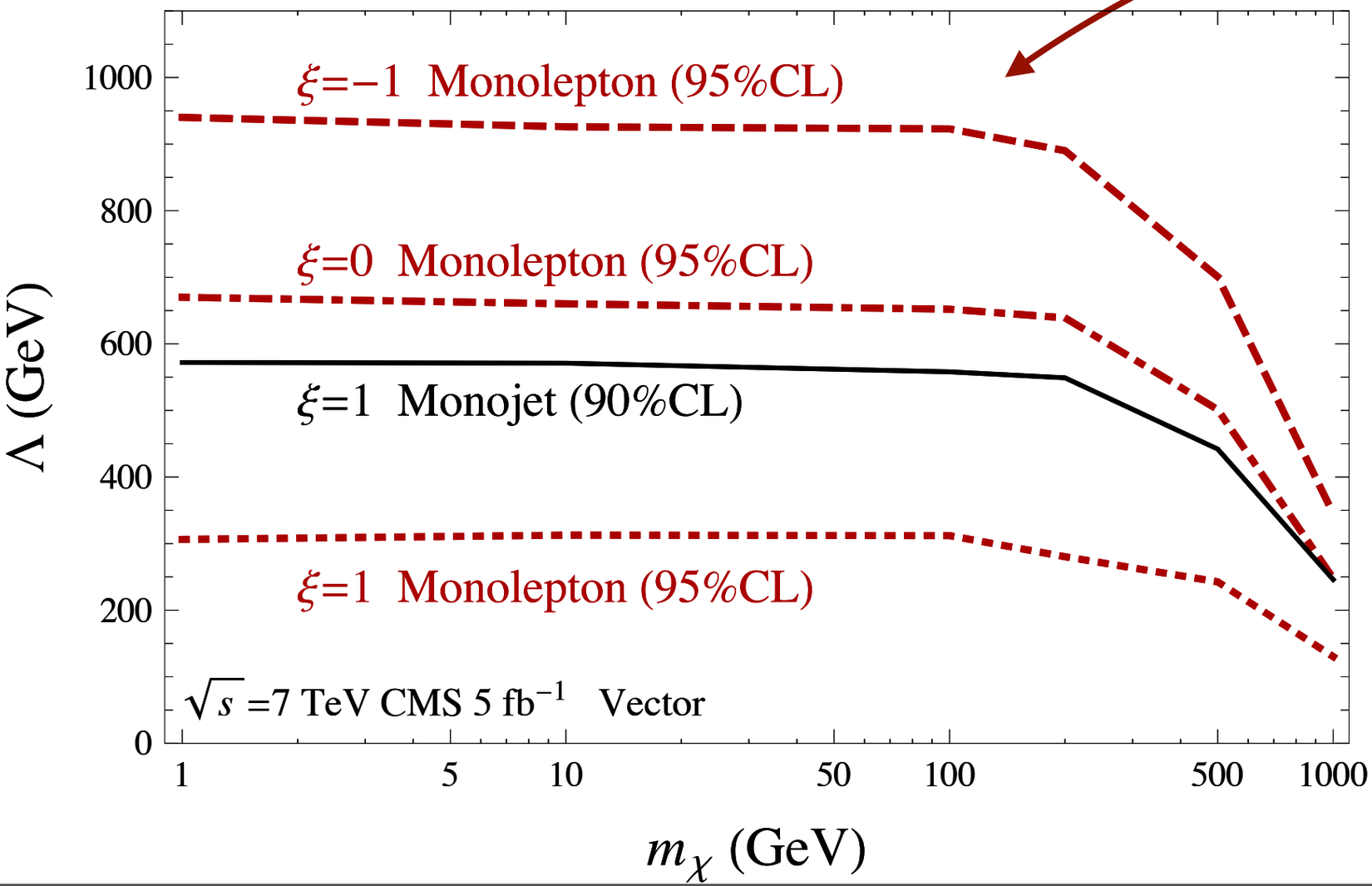
Uses CMS W' search (7 TeV 5/fb)

Mono-W

[Bai, Tait, 1208.4361]



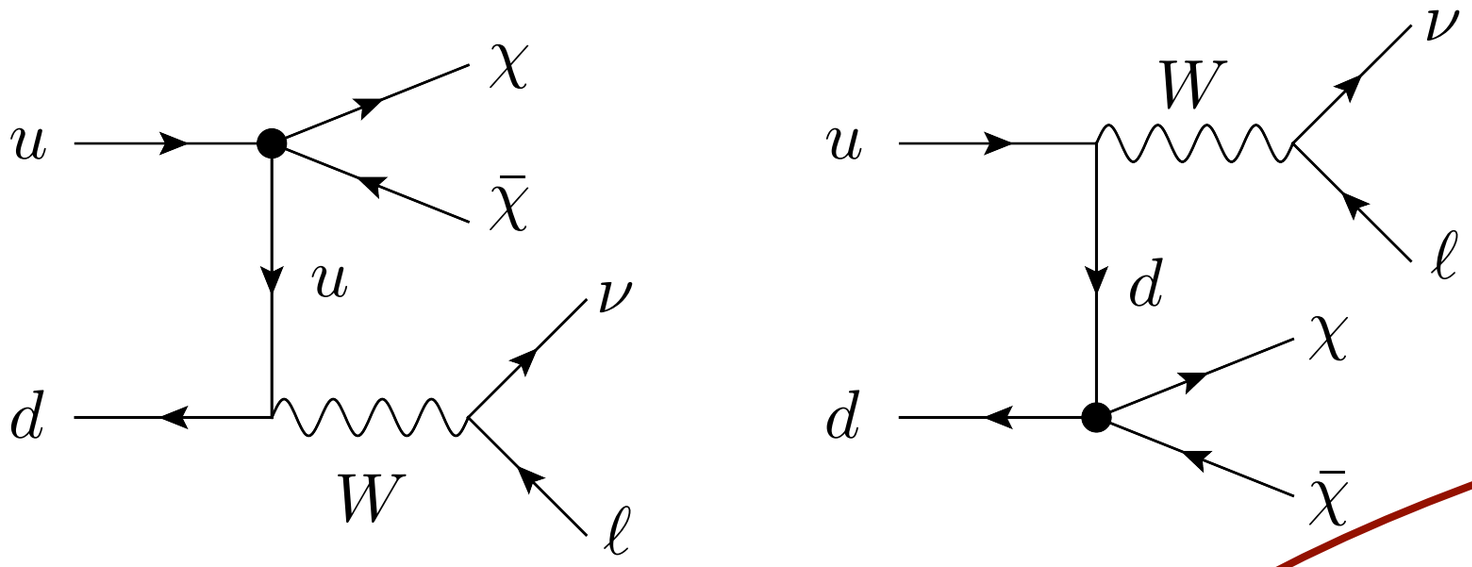
$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\,\left(\overline{u}\gamma^\mu u + \xi\,\overline{d}\gamma^\mu d\right)$$



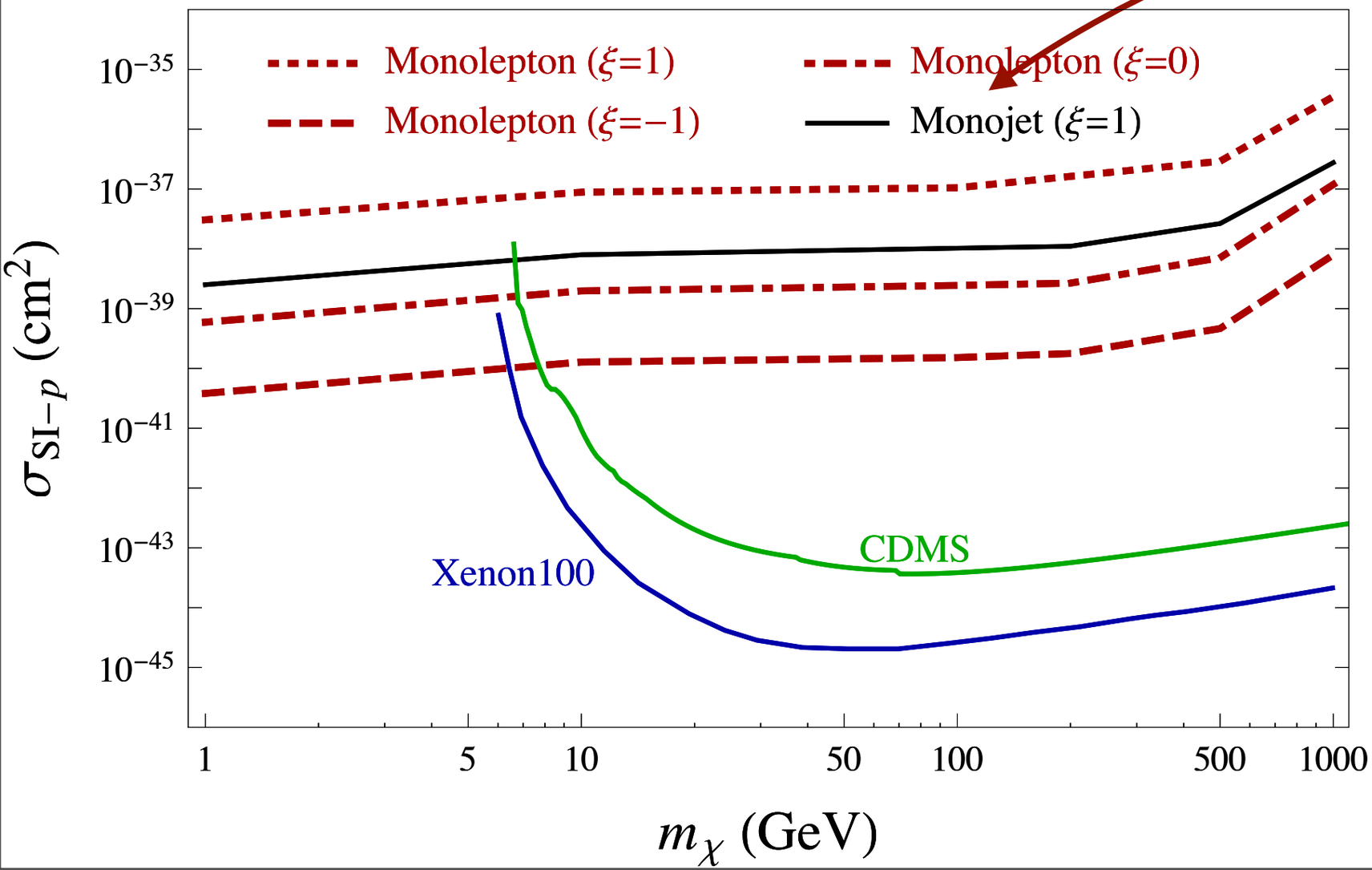
Uses CMS W' search (7 TeV 5/fb)

Mono-W

[Bai, Tait, 1208.4361]



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

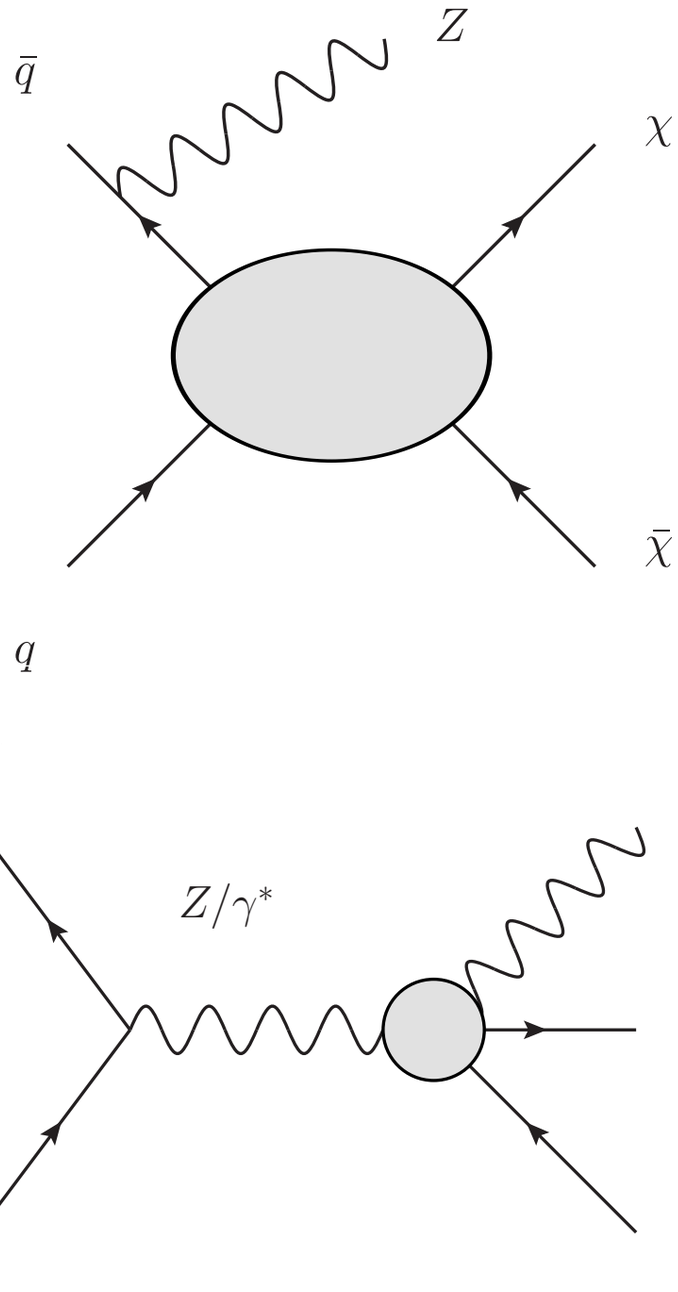


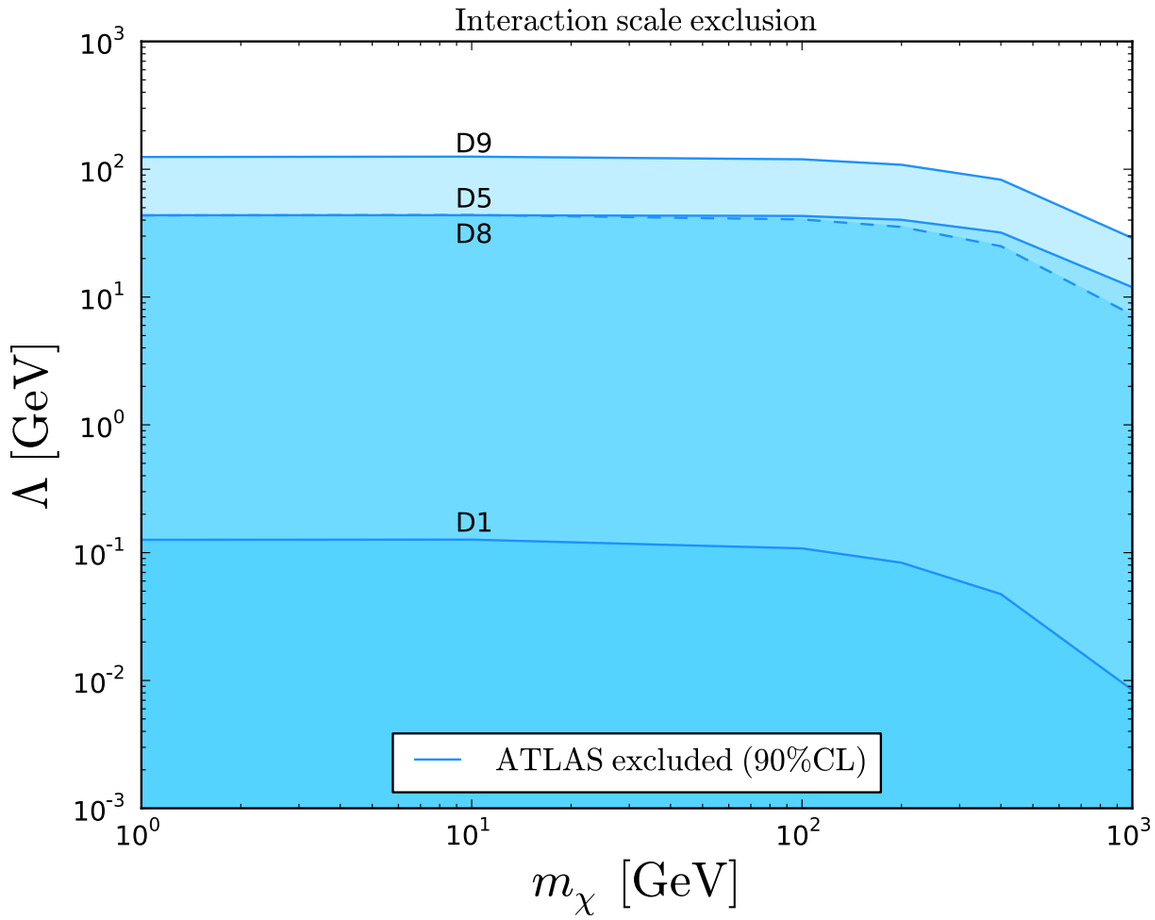
Uses CMS W' search (7 TeV 5/fb)

Mono-Z

[Carpenter et al, 1212.3352]

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





Mono-Z

[Carpenter et al, 1212.3352]

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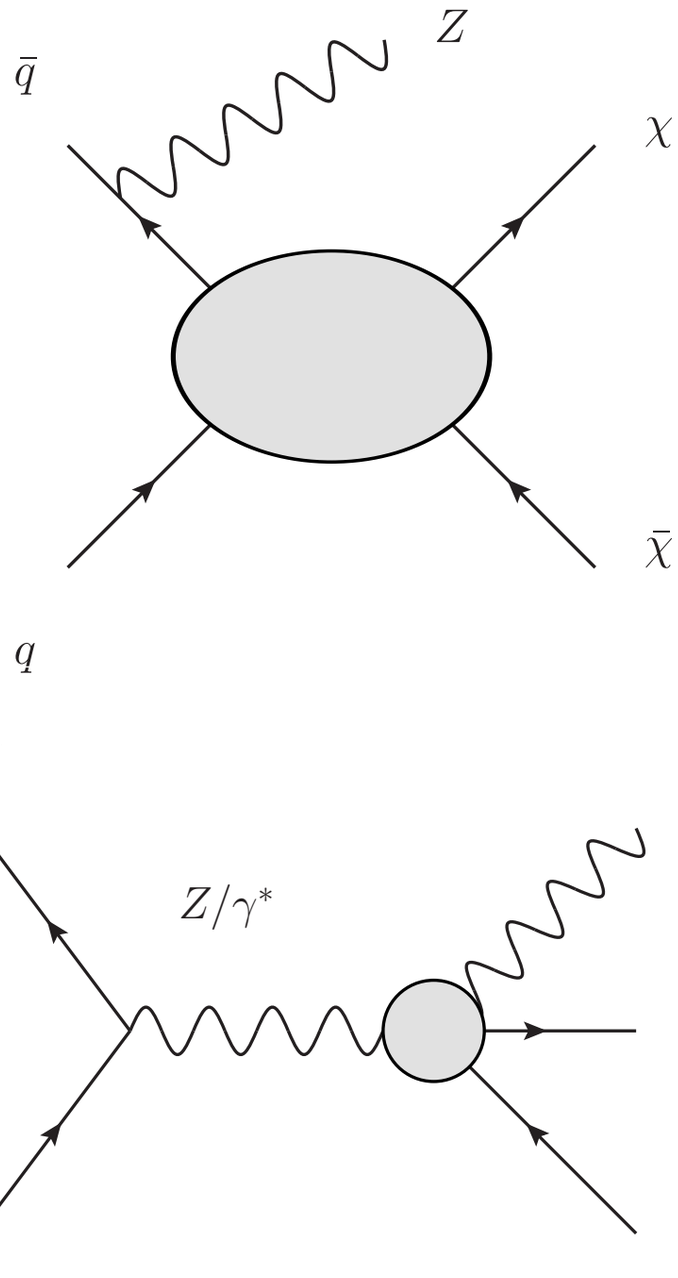
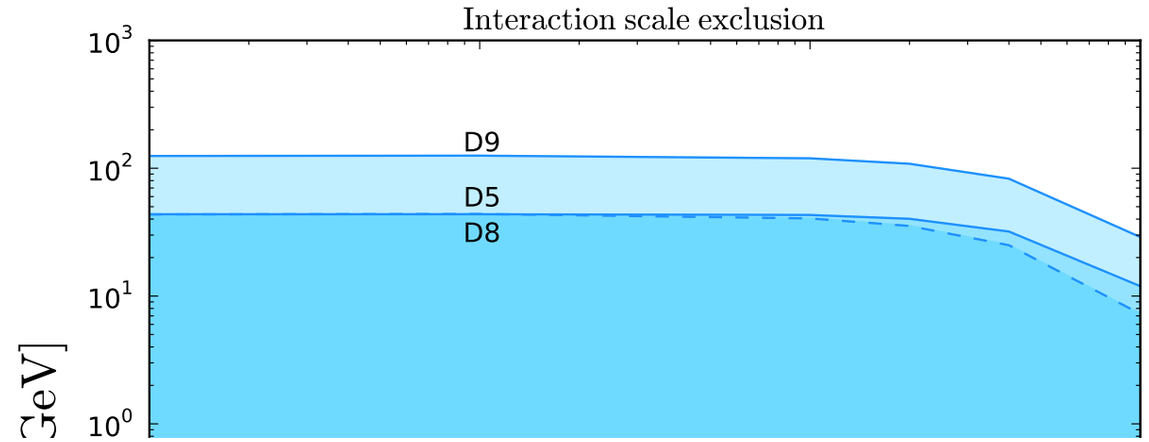
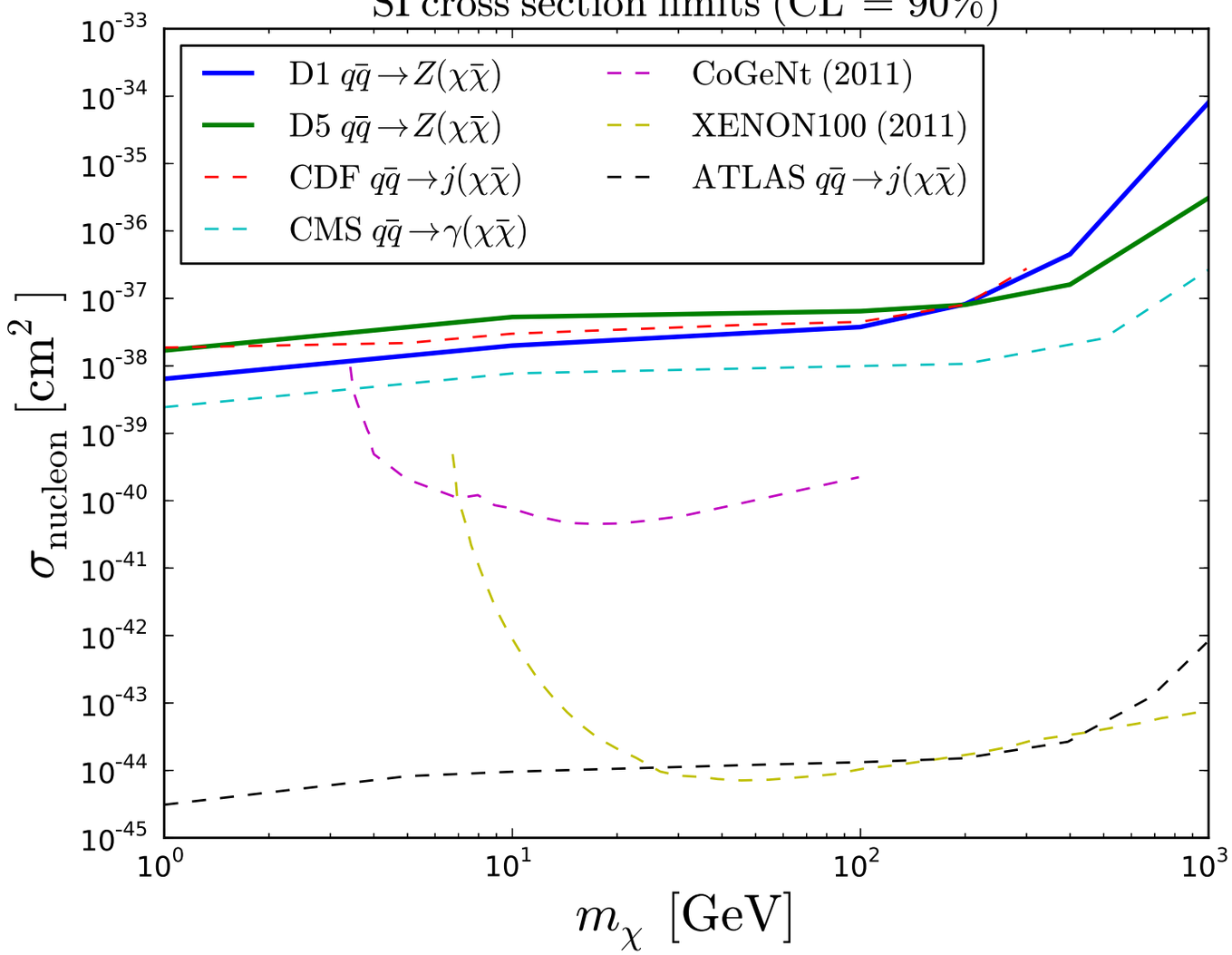






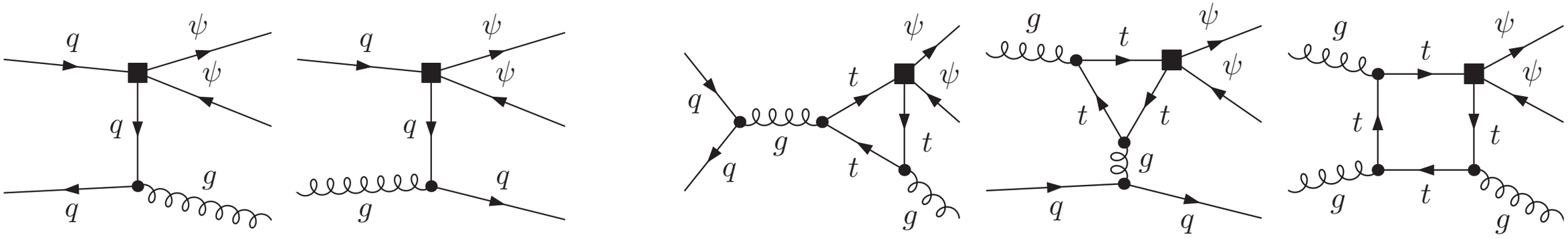
Mono- “whatever”

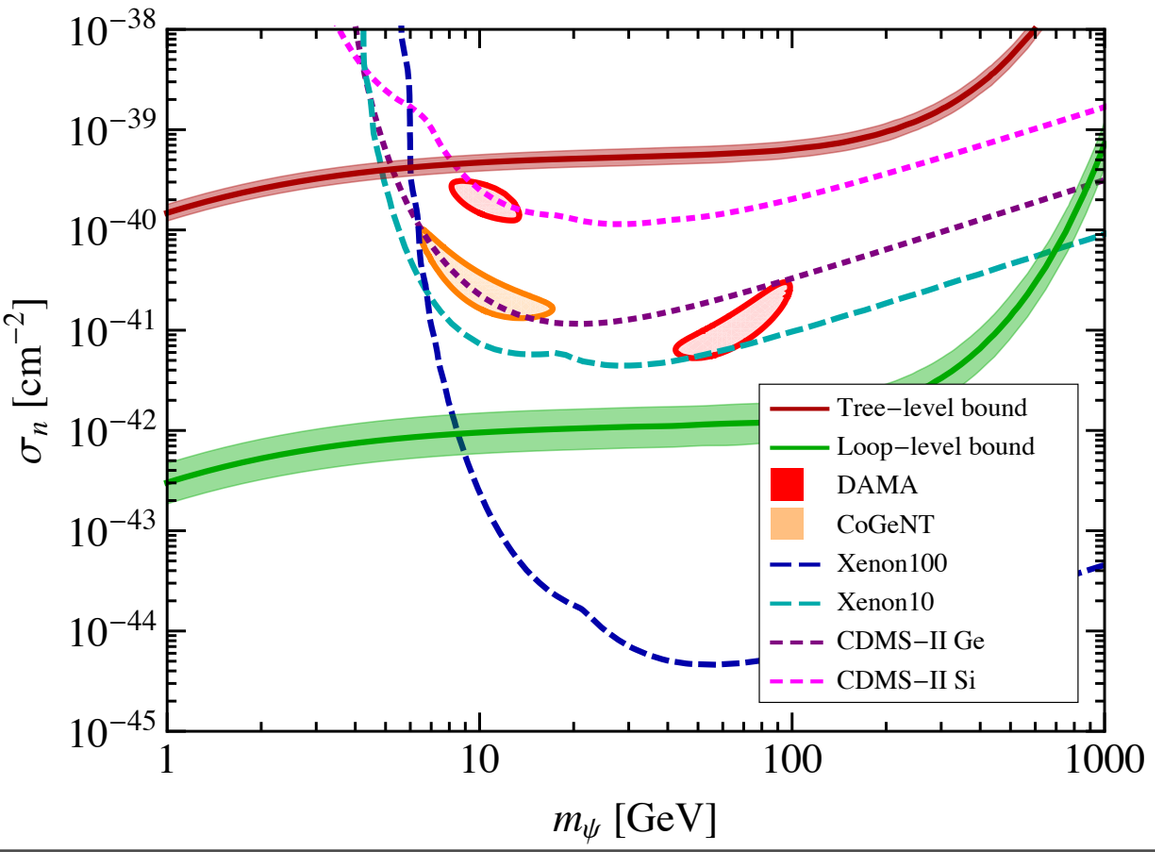
- Many search channels, combining for stronger bounds
- Must be careful about overlaps, but most orthogonal
- Bounds dominated by monojet, but others give non-trivial improvements
- See e.g. Cheung et al (1201.3402); Berge et al (1302.3619)

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]

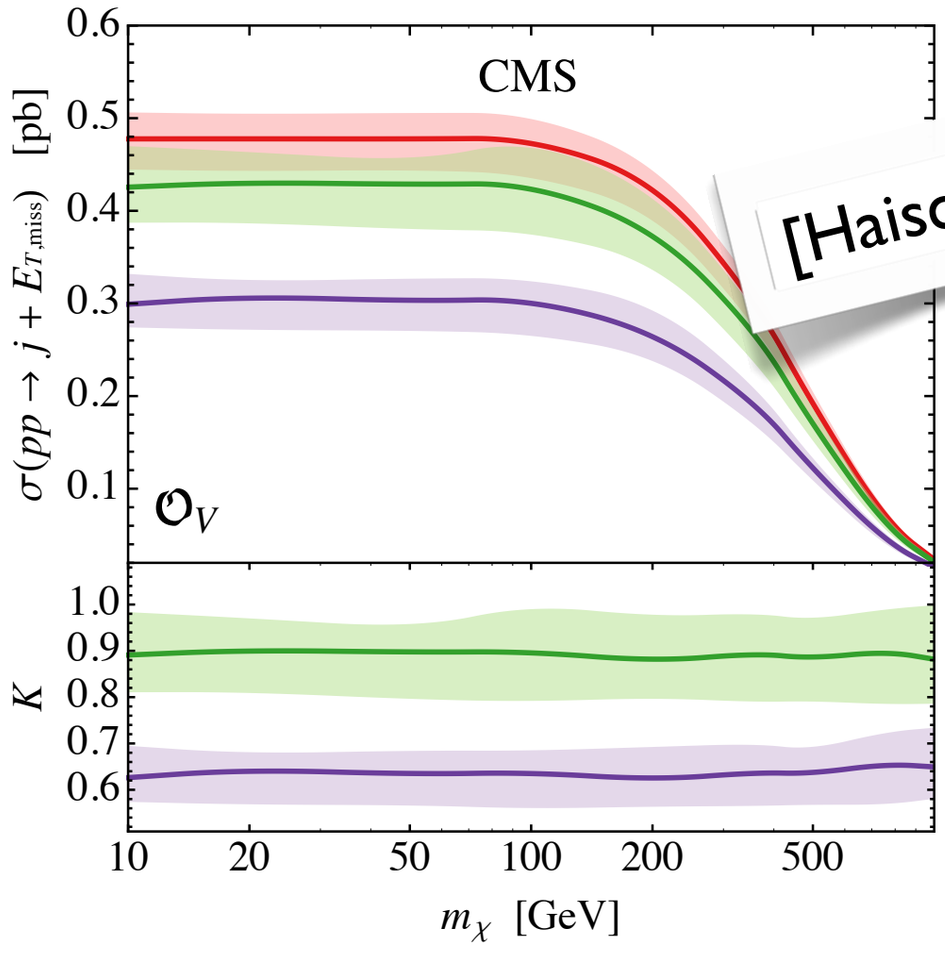




DM@NLO

[Haisch et al, 1208.4605,1310.4491]
[PJF and Williams, 1211.6390]

- Analyses are becoming systematics limited
- Reduce theory uncertainty by calculating at NLO (S+B)
- 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
- MCFM and POWHEG implementations



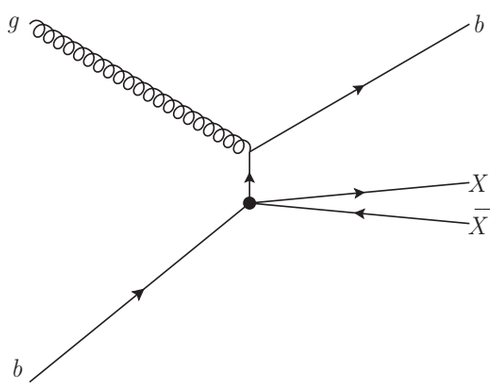
[Haisch et al, 1310.4491]

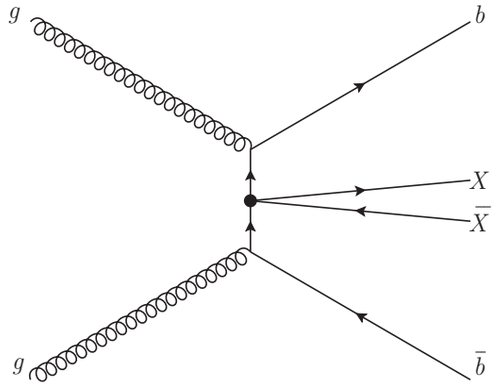
The scalar operator

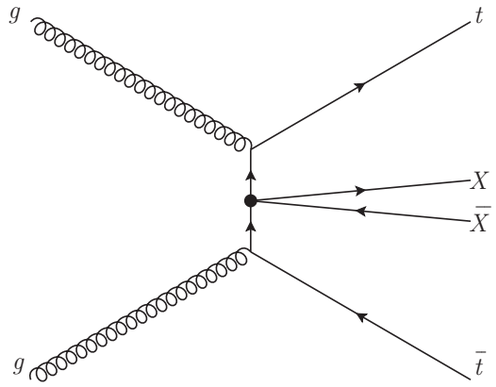
[Kamenik, Zupan, 1107.0623]

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

[Lin, Kolb, Wang, 1303.6638]





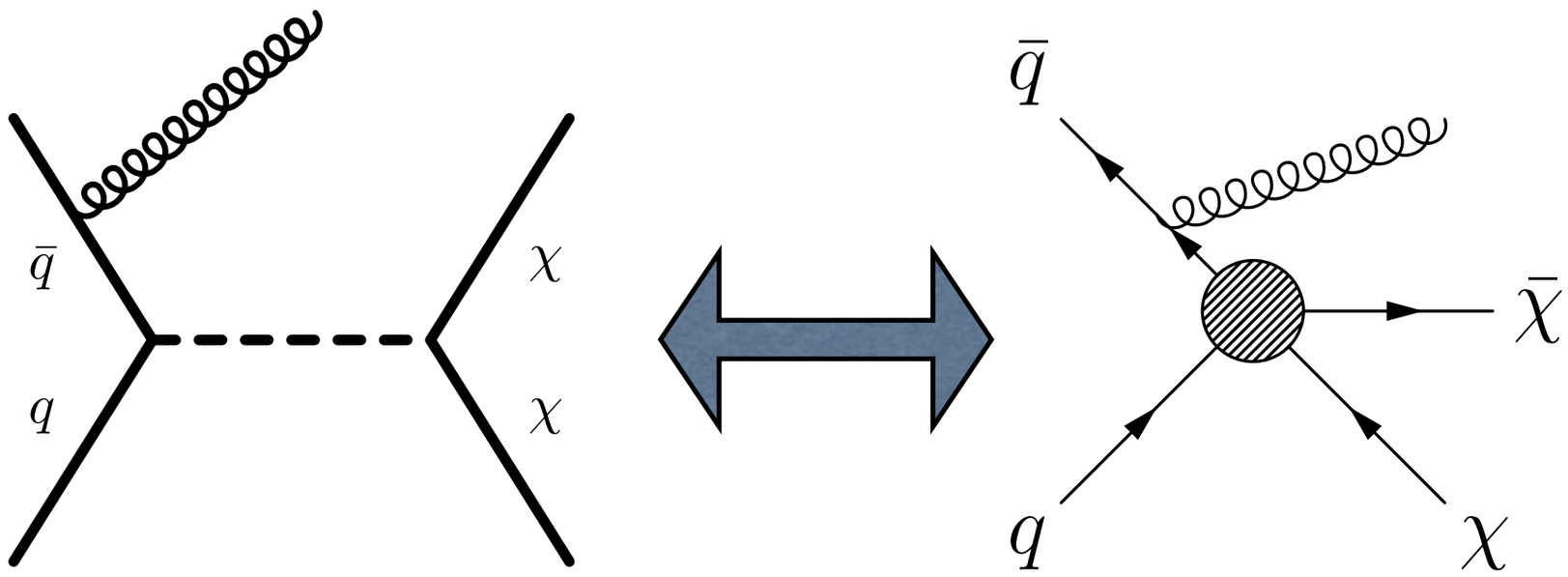


Light Mediators

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

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

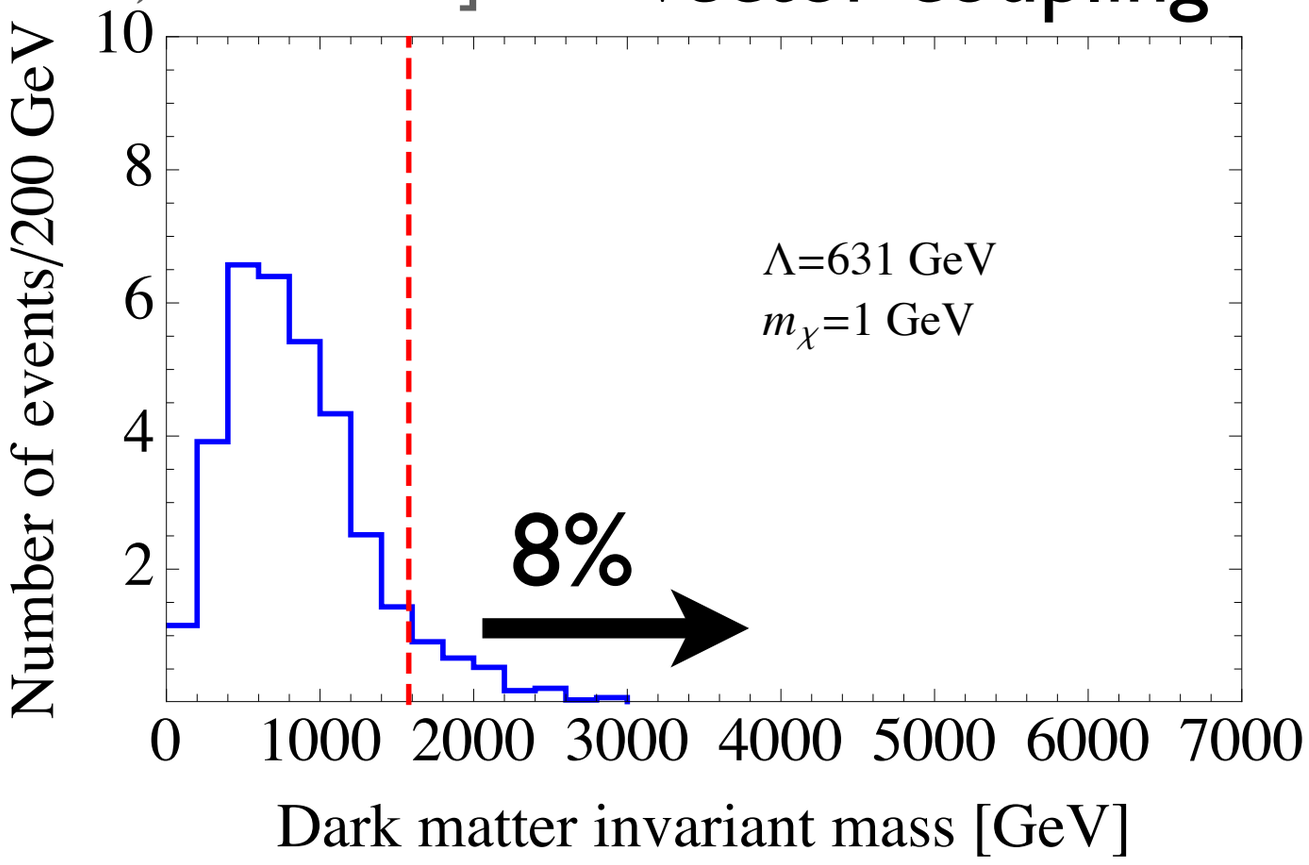
What fraction of collider events have momentum transfers sufficient to probe the UV completion?



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

[PJF et al, 1203.1662]

Vector coupling

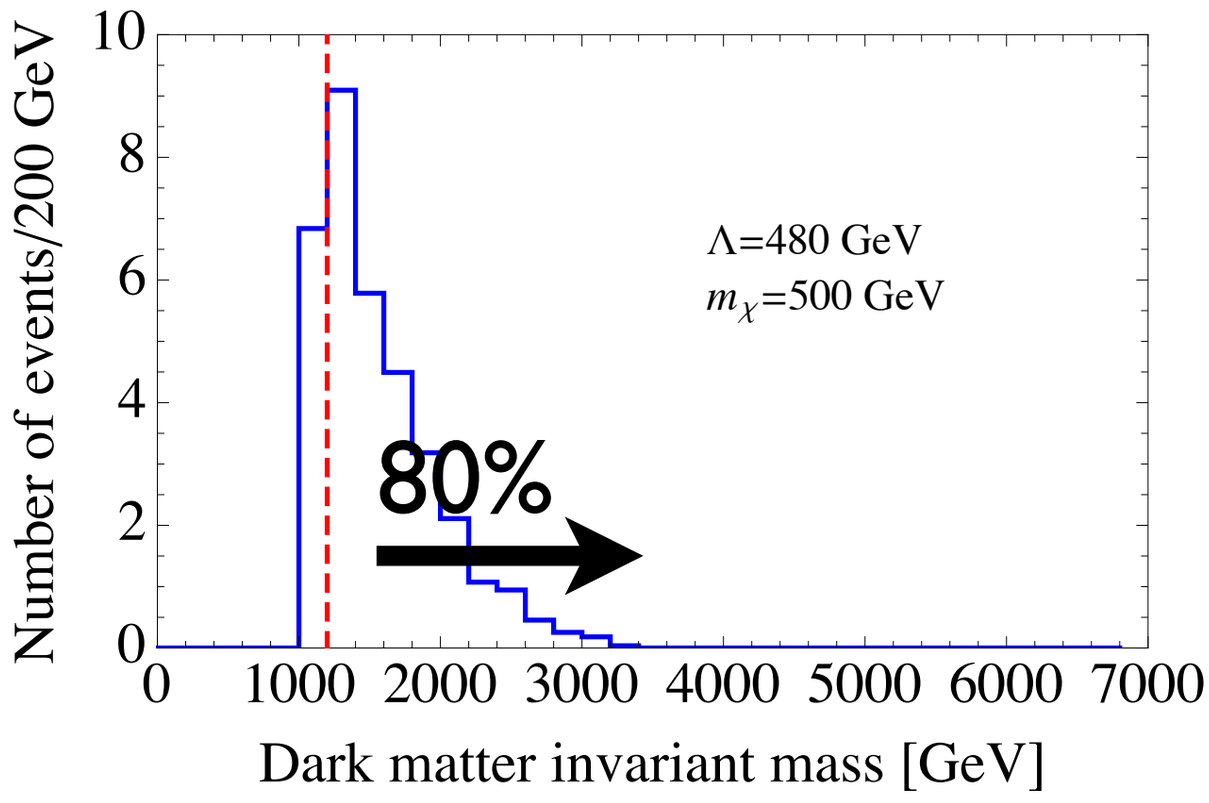


Unitarity bound $m_{\chi\chi} < \frac{\Lambda}{0.4}$

[Shoemaker and Vecchi, 1112.5457]

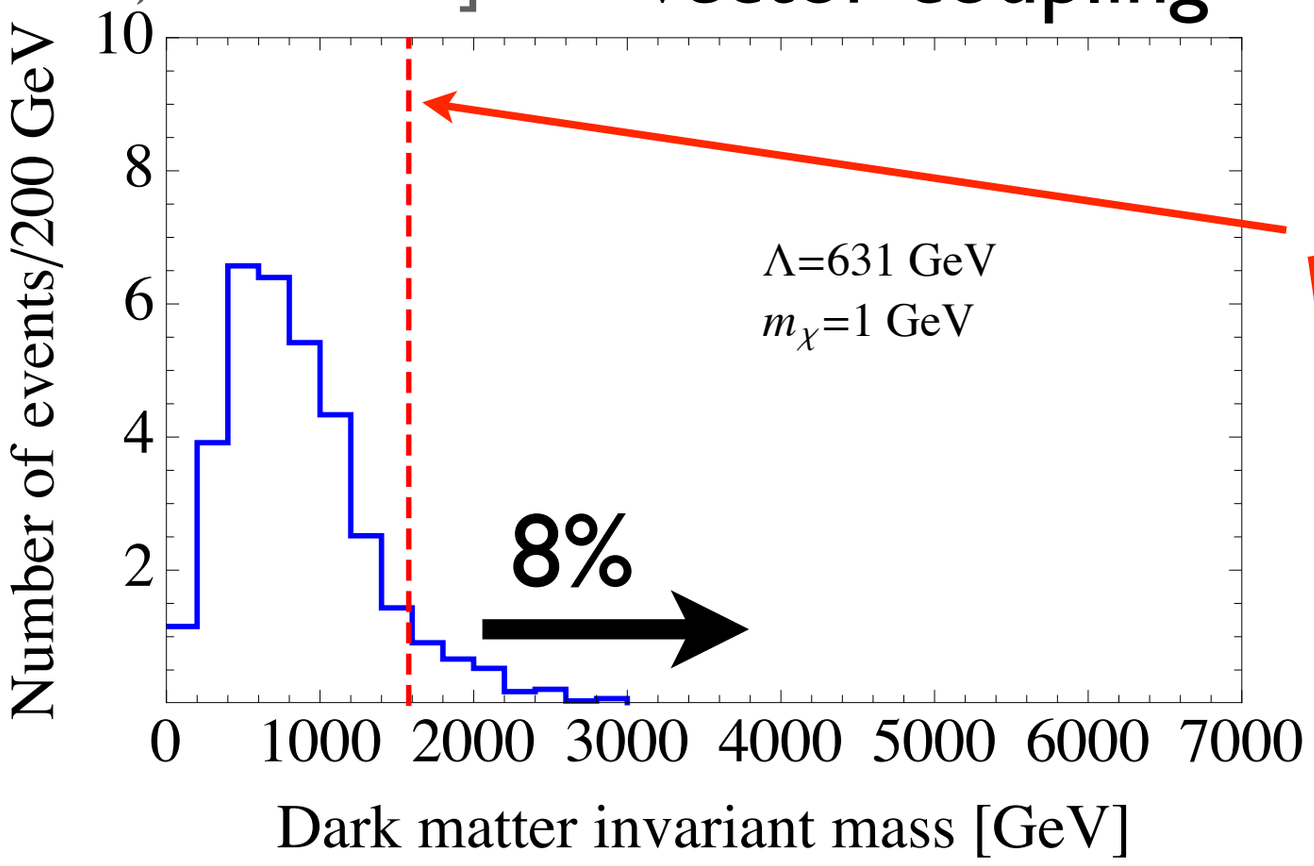
Fraction of events where EFT breaks down may be non-negligible

Depends on DM mass



[PJF et al, 1203.1662]

Vector coupling



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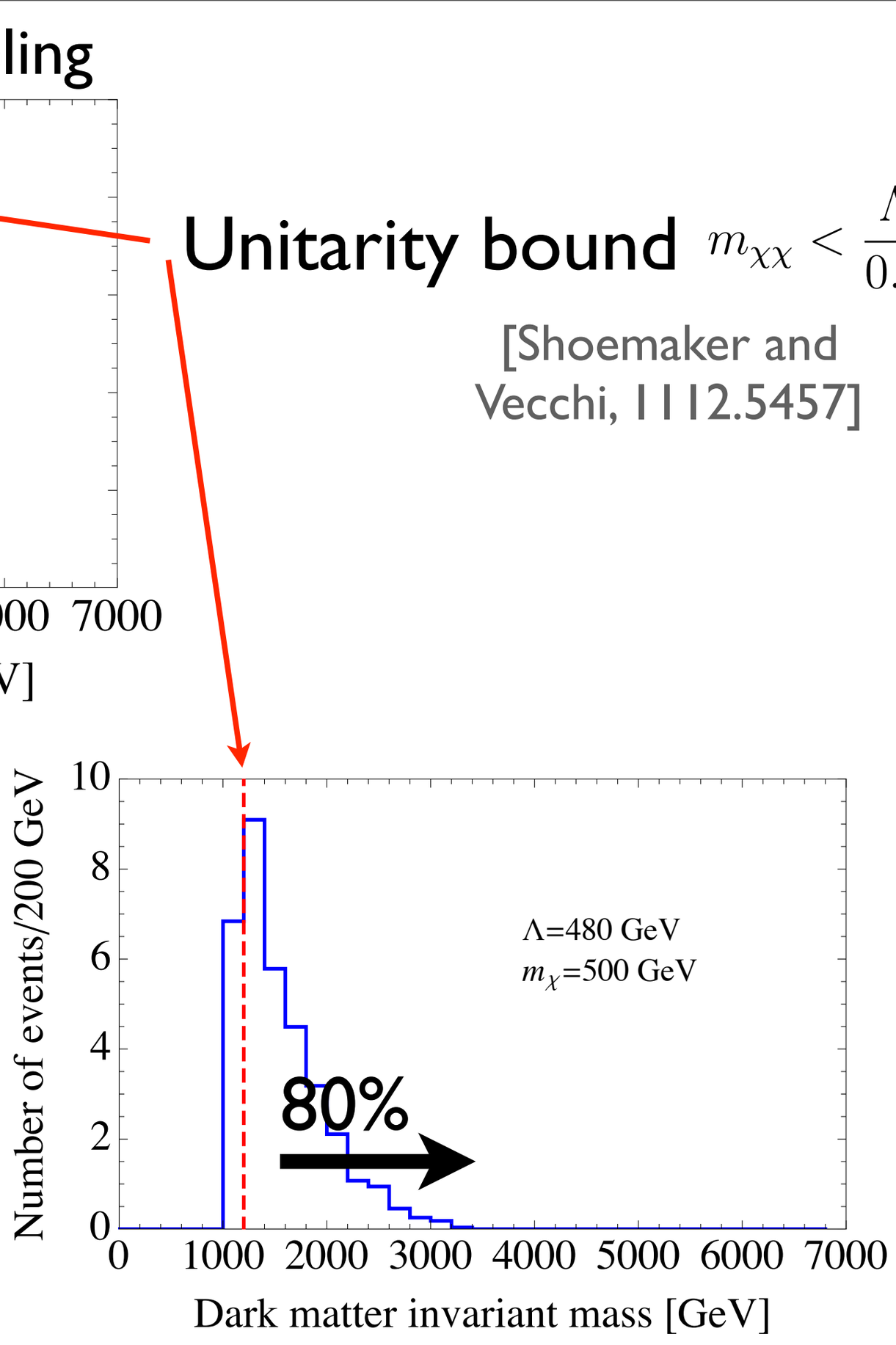

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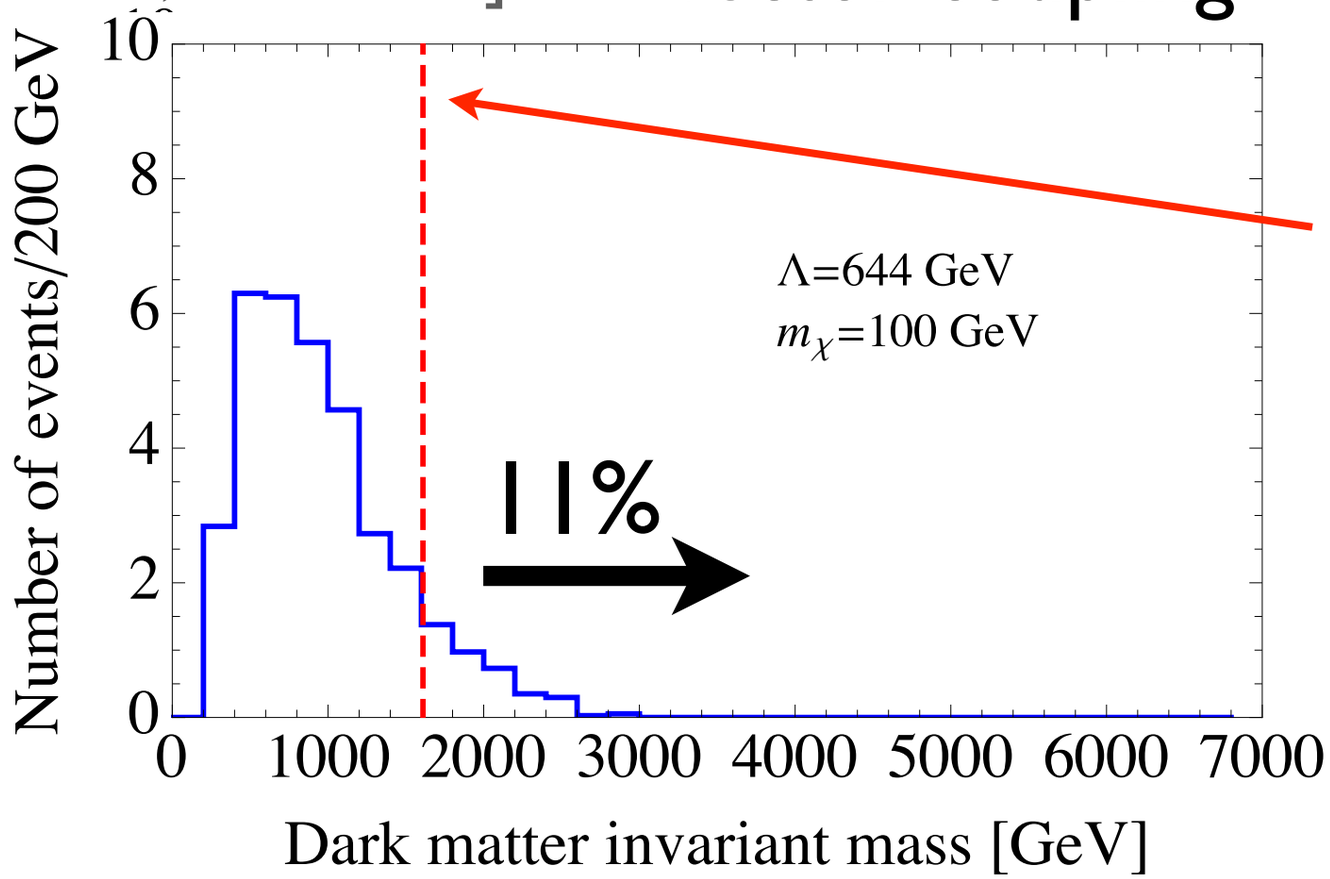

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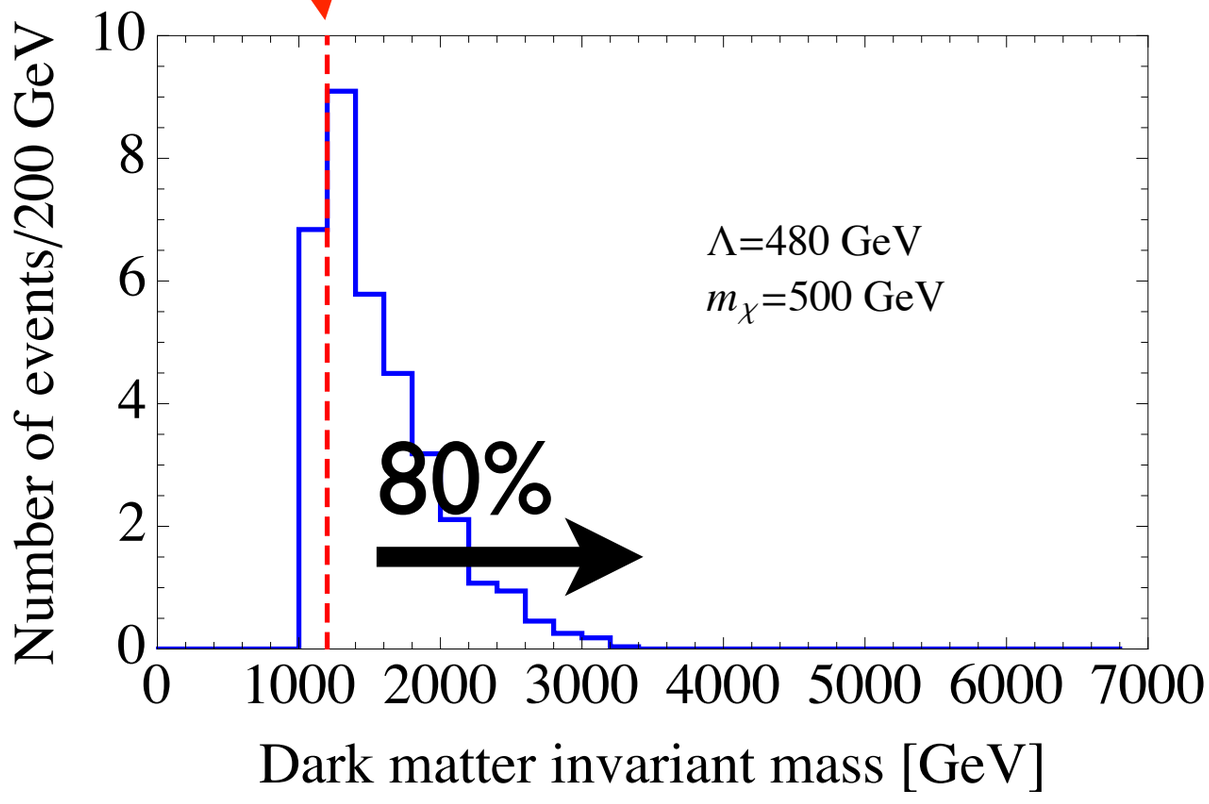
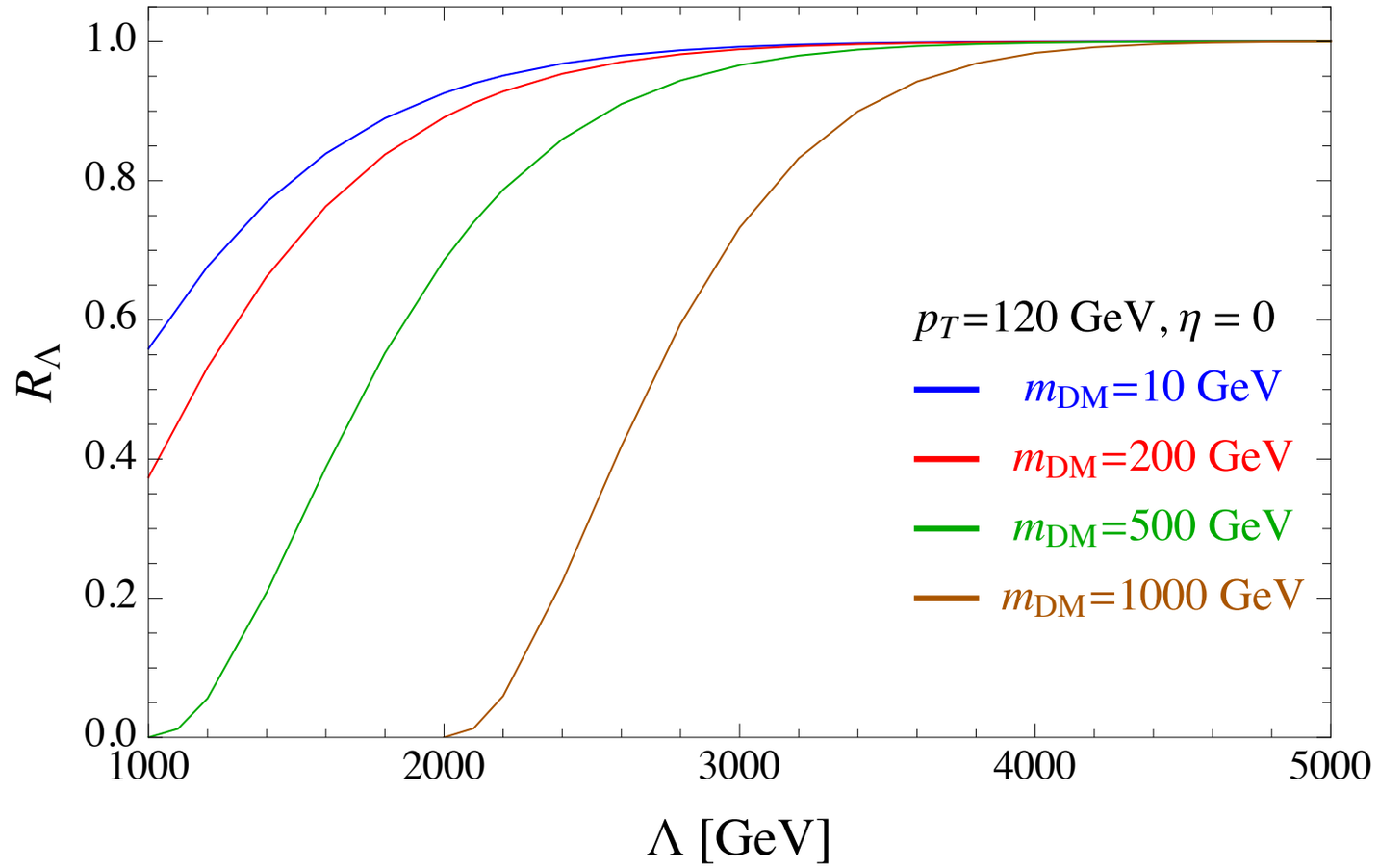


What fraction of events have momentum transfers sufficient to probe the UV completion?

[Busoni, De Simone, Morgante, Riotto, 1307.2253, 1402.1275, 1405.3103]

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



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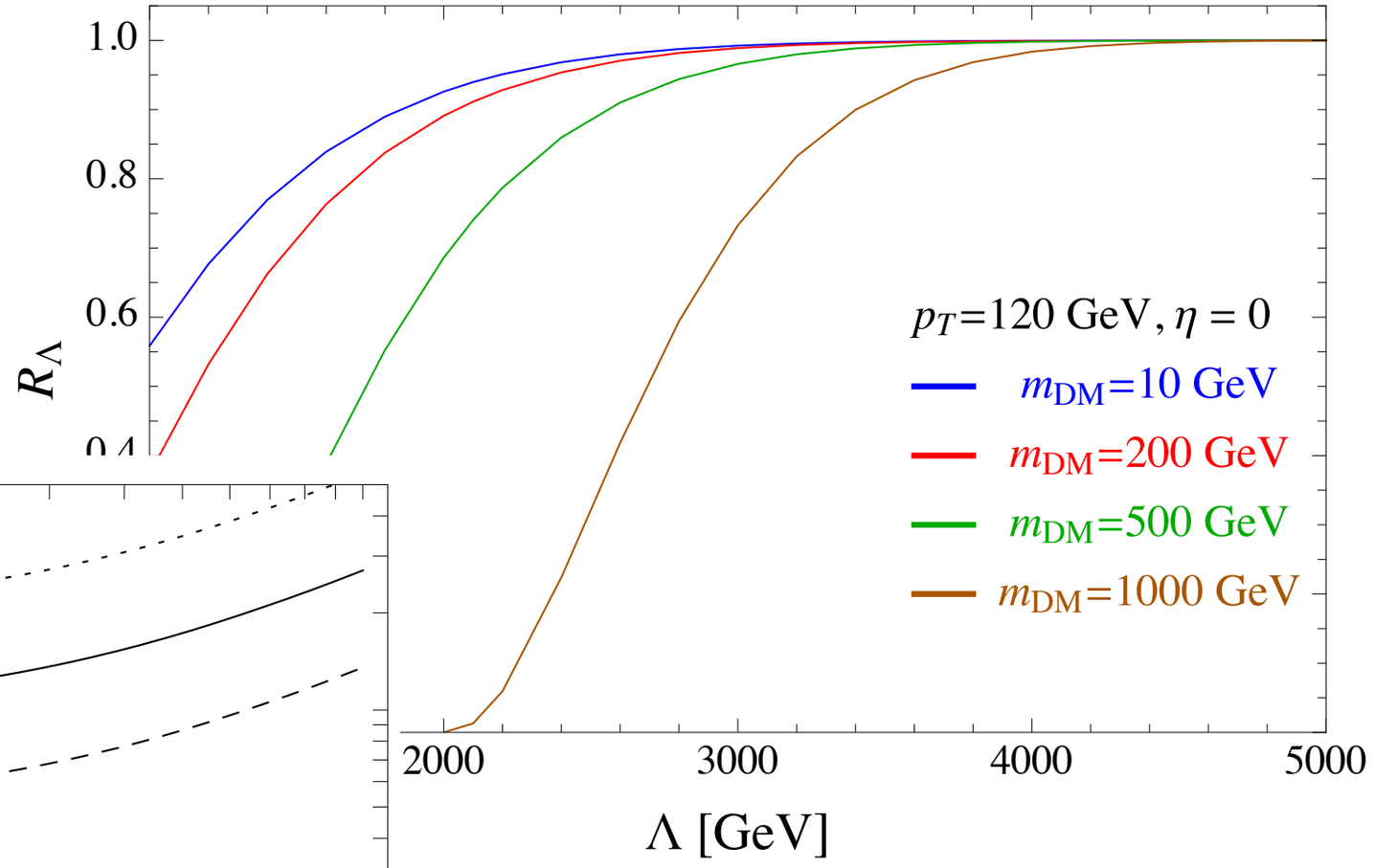
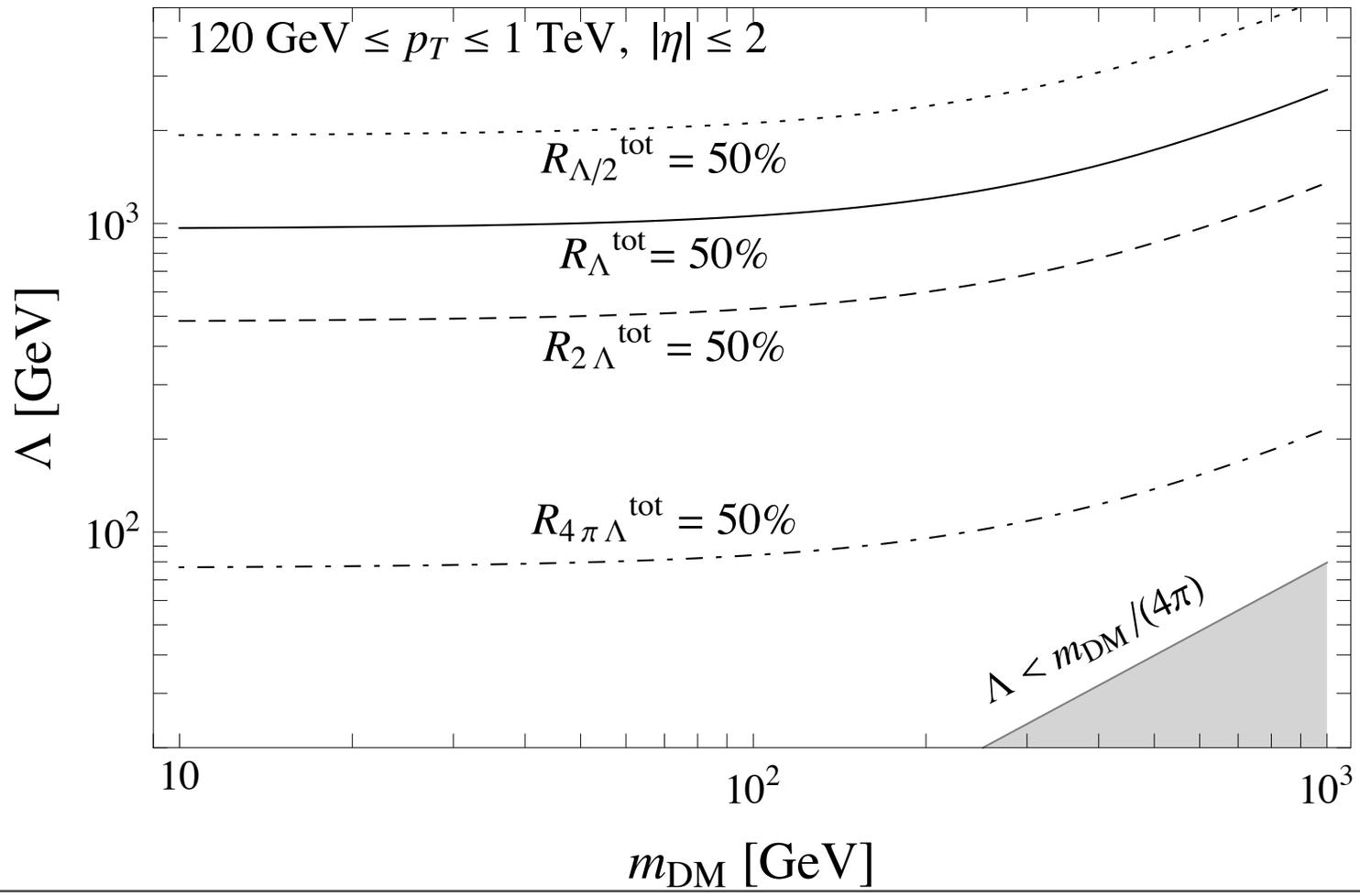
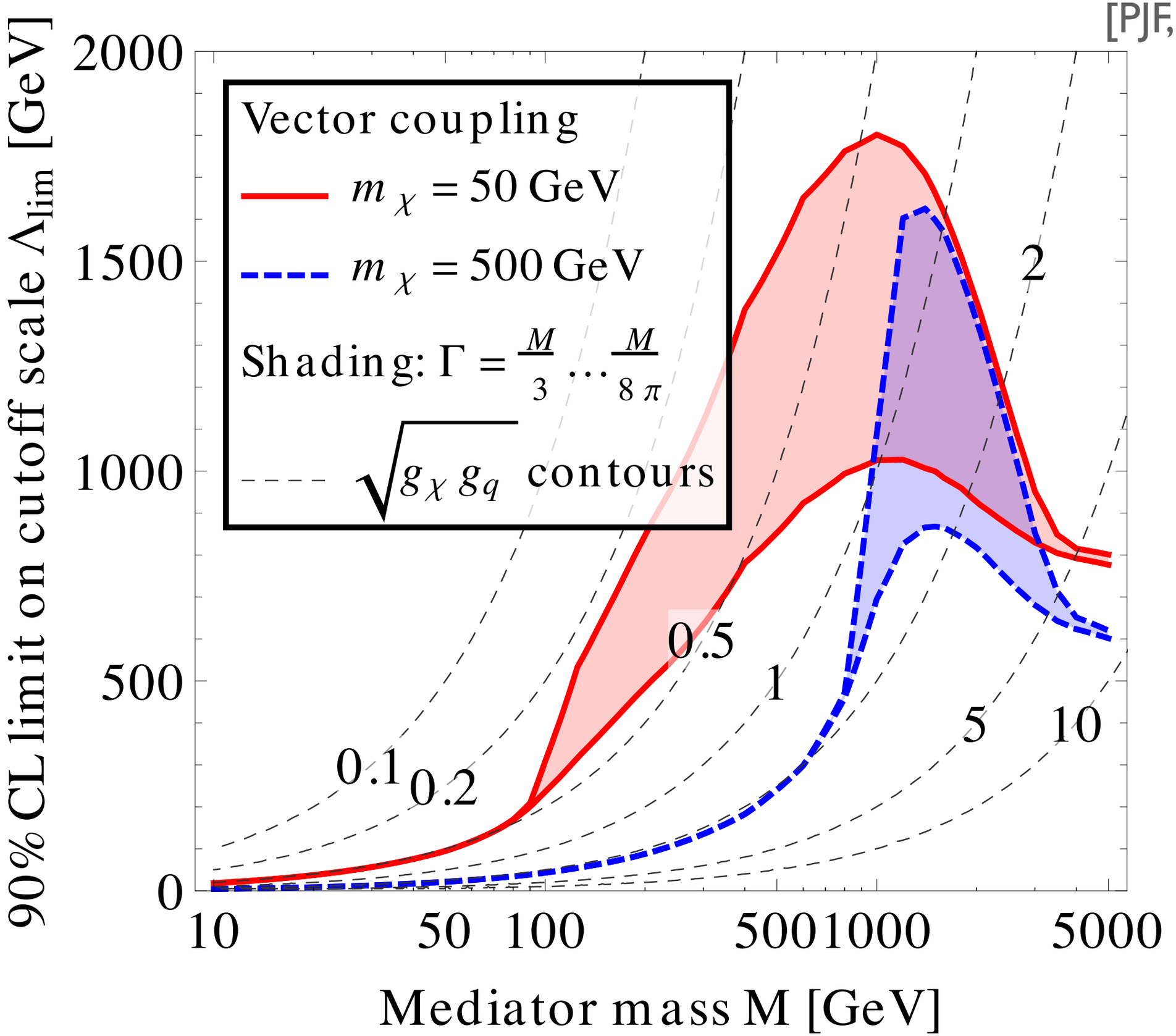




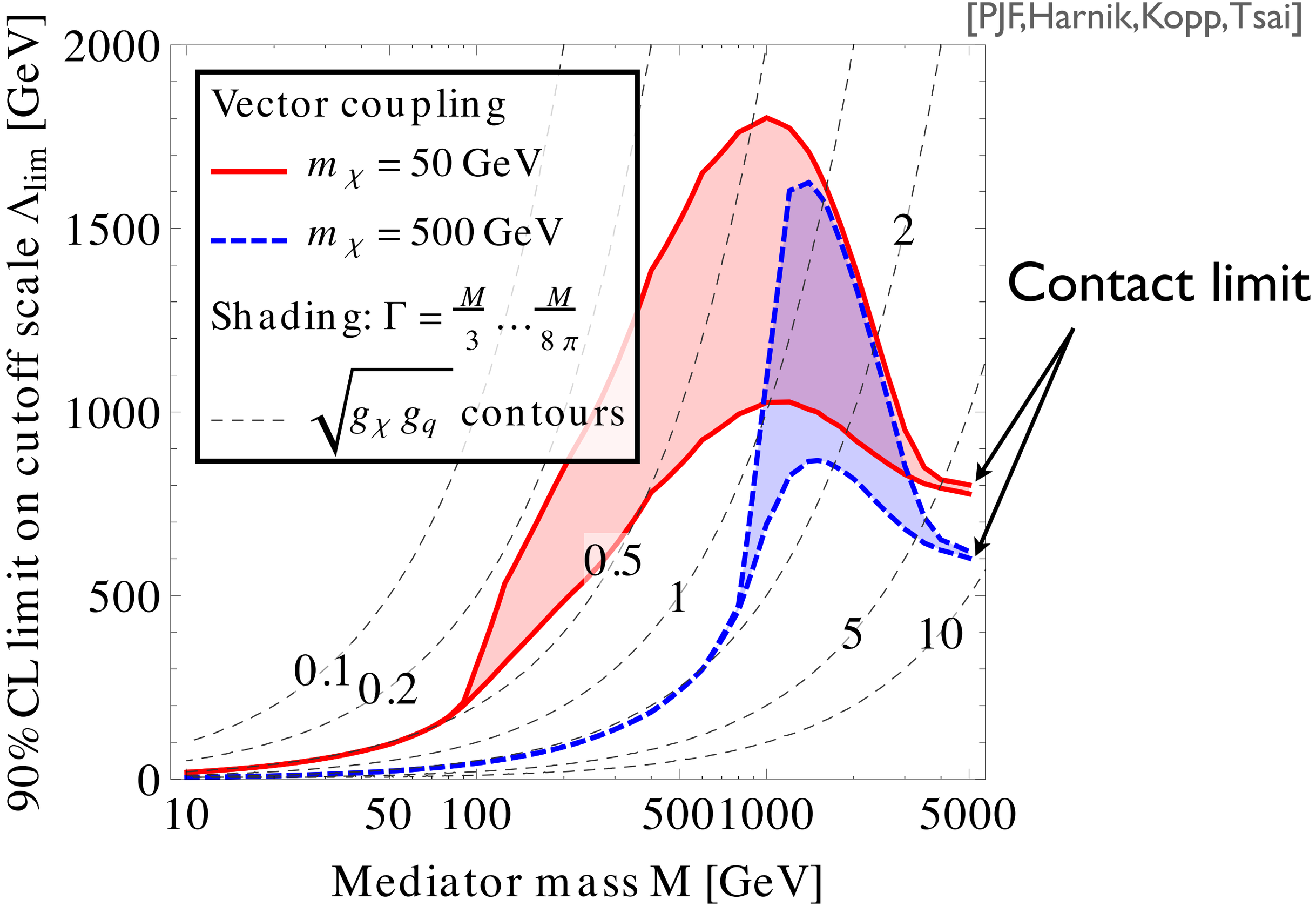
How full is the glass?

How full is the glass?

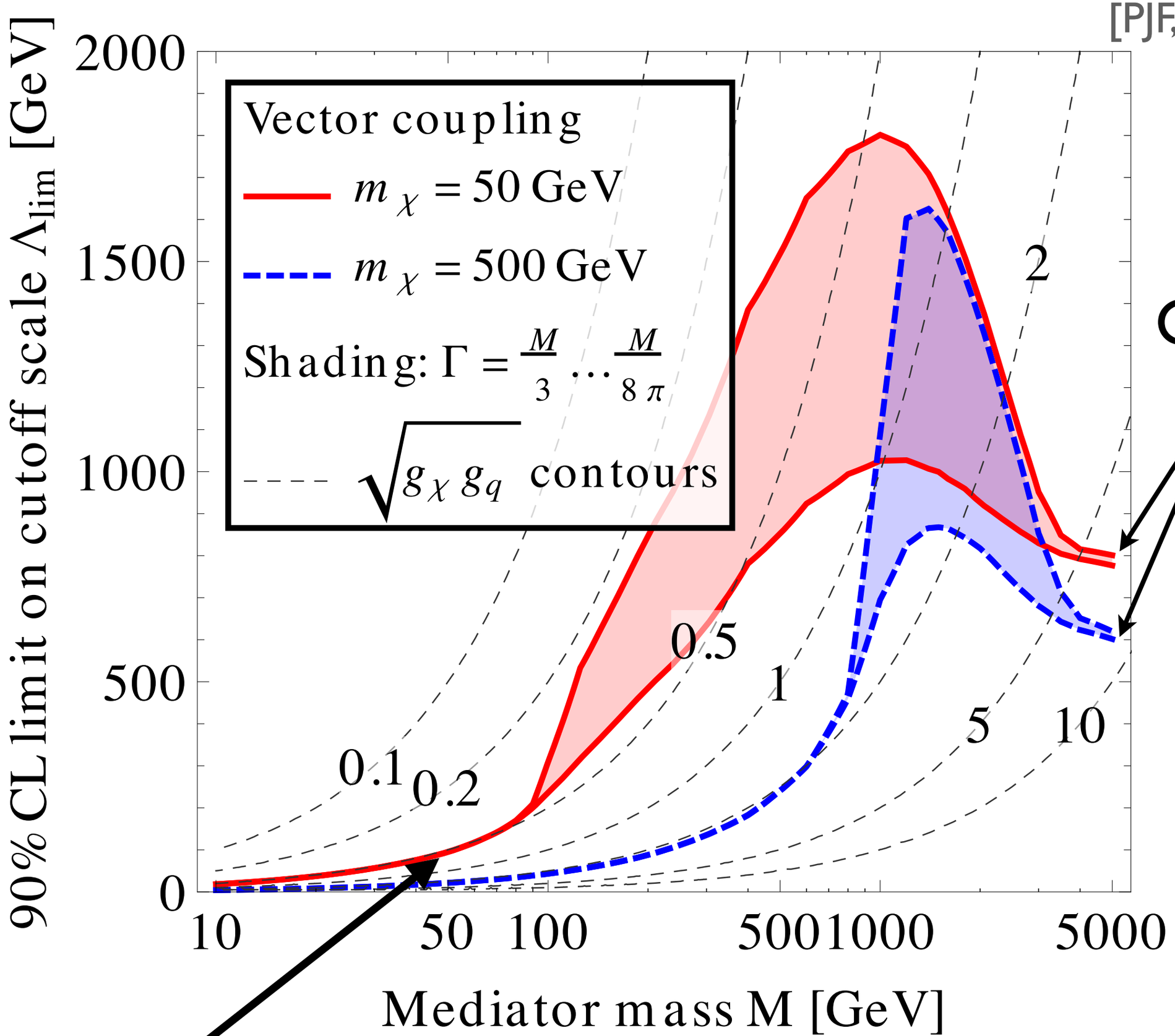
[PJF,Harnik,Kopp,Tsai]



[PJF,Harnik,Kopp,Tsai]



[PJF,Harnik,Kopp,Tsai]



Contact limit

Light mediator severely weakens limit

[PJF,Harnik,Kopp,Tsai]

90% CL cutoff scale Λ_{lim} [GeV]

90% CL limit on Λ [GeV]

CMS Preliminary

$\sqrt{s}$ = 8 TeV

$\int L\,dt = 19.5\ fb^{-1}$

m_χ=500 GeV/c^2, Γ=M/3

m_χ=500 GeV/c^2, Γ=M/10

m_χ=500 GeV/c^2, Γ=M/8π

m_χ=50 GeV/c^2, Γ=M/3

m_χ=50 GeV/c^2, Γ=M/10

m_χ=50 GeV/c^2, Γ=M/8π

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

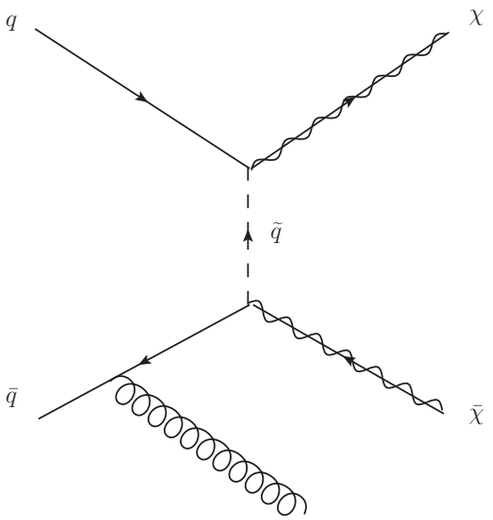
Mediator Mass M [TeV/c^2]

tact limit

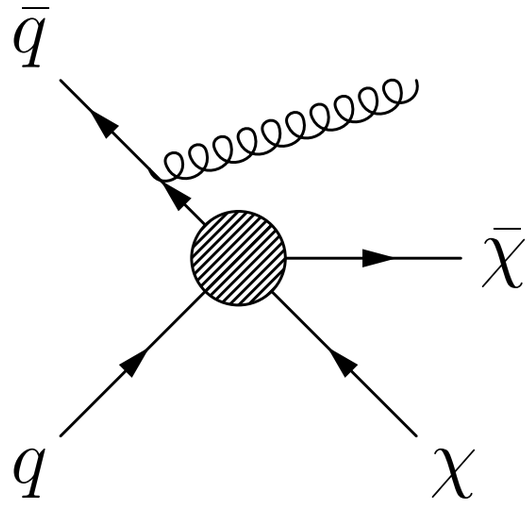
Simplified Models

"Integrate in" the mediator

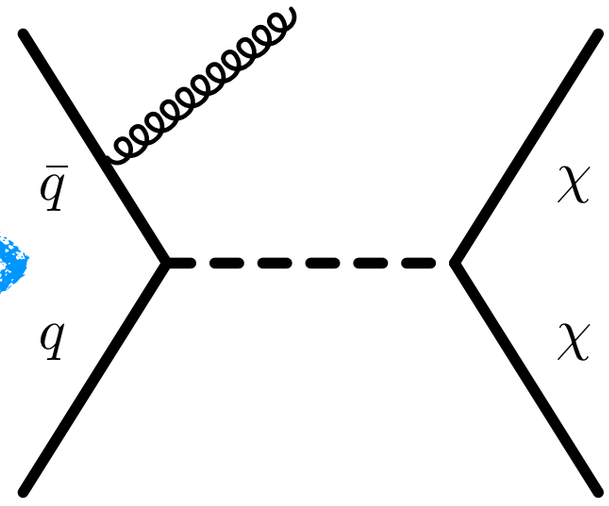
t-channel



EFT



s-channel



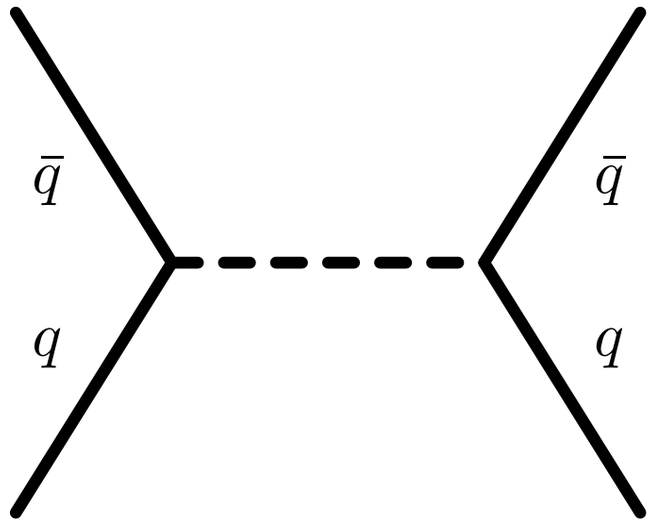
$$\Lambda,\, m_\chi \longrightarrow m_\chi,\, M,\, \Gamma,\, \sqrt{g_q g_\chi}$$

New channels to search for!

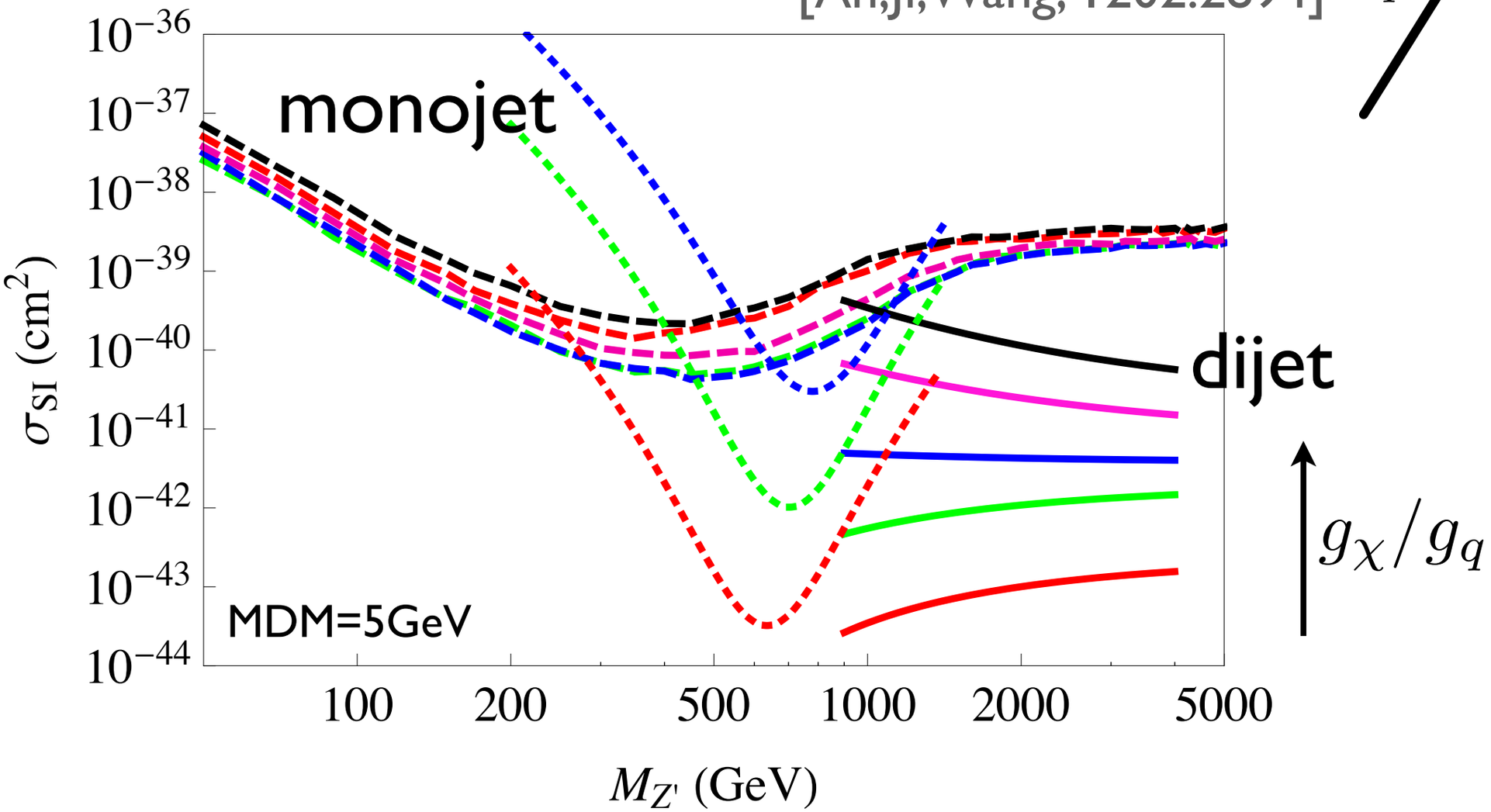
Light Mediators

[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]



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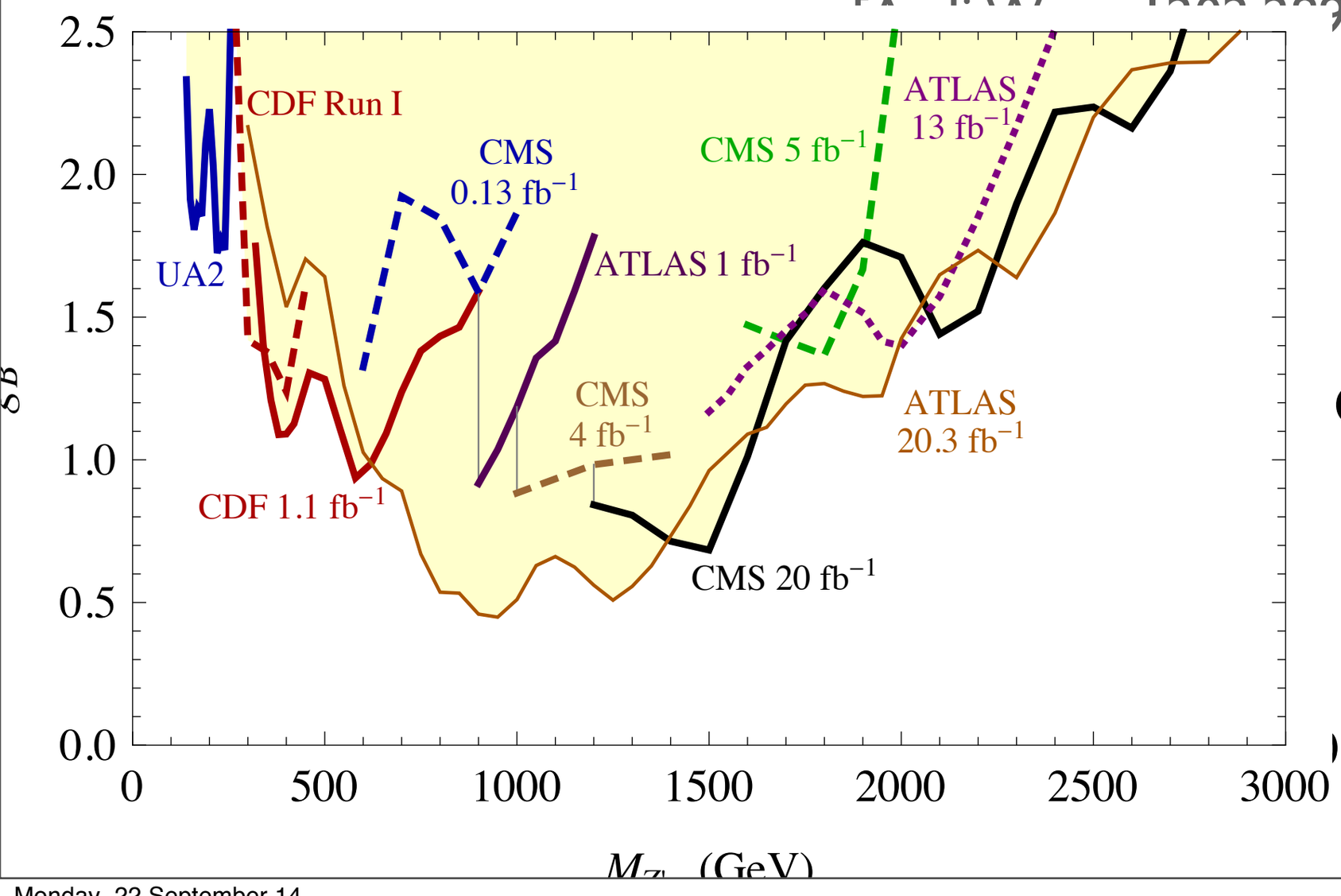

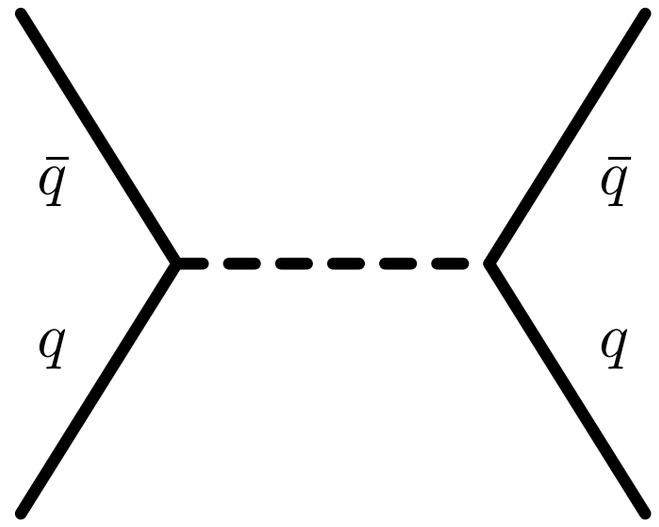

et

g_χ / g_q

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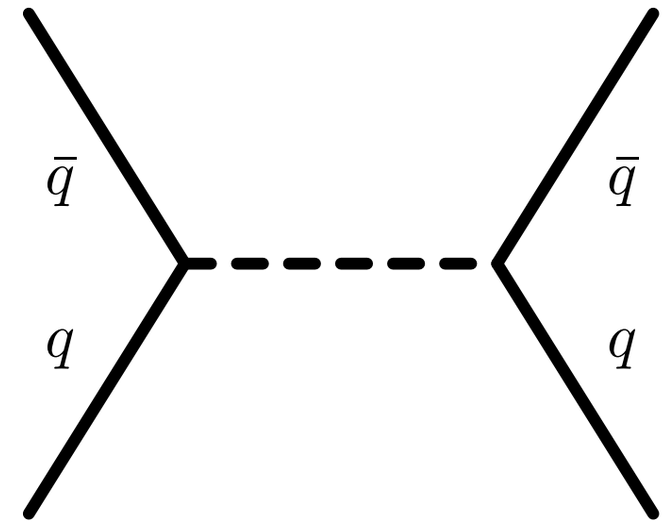

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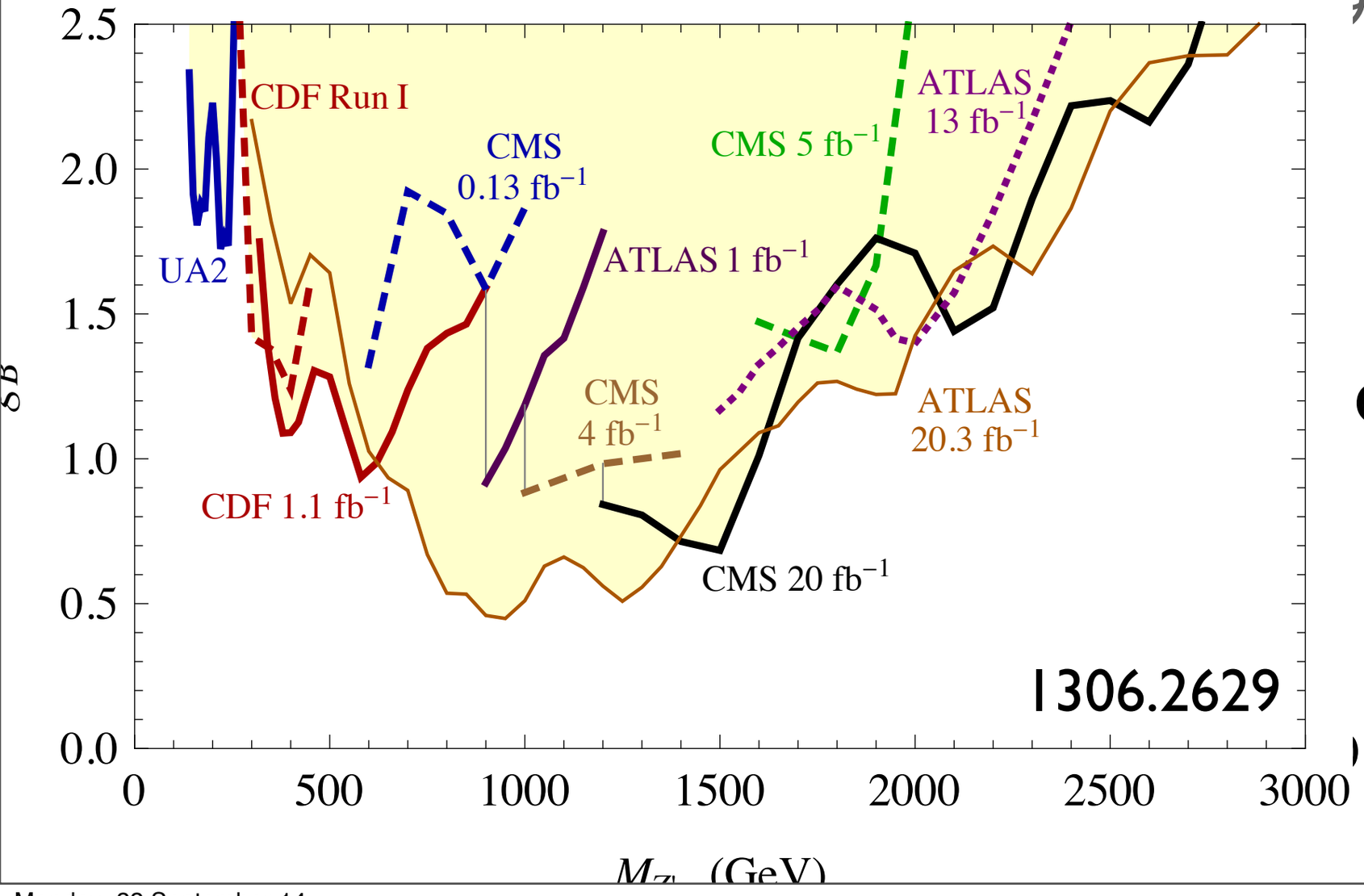


et

g_χ / g_q

Higgs and DM

[Fox, Harnik, Kopp, Tsai]

- The Higgs exists. DM exists.
- The Higgs is a motivated candidate for mediator of DM interaction. a.k.a. the **Higgs Portal**.
- Assuming Standard Higgs production:

Limit on invisible Higgs.

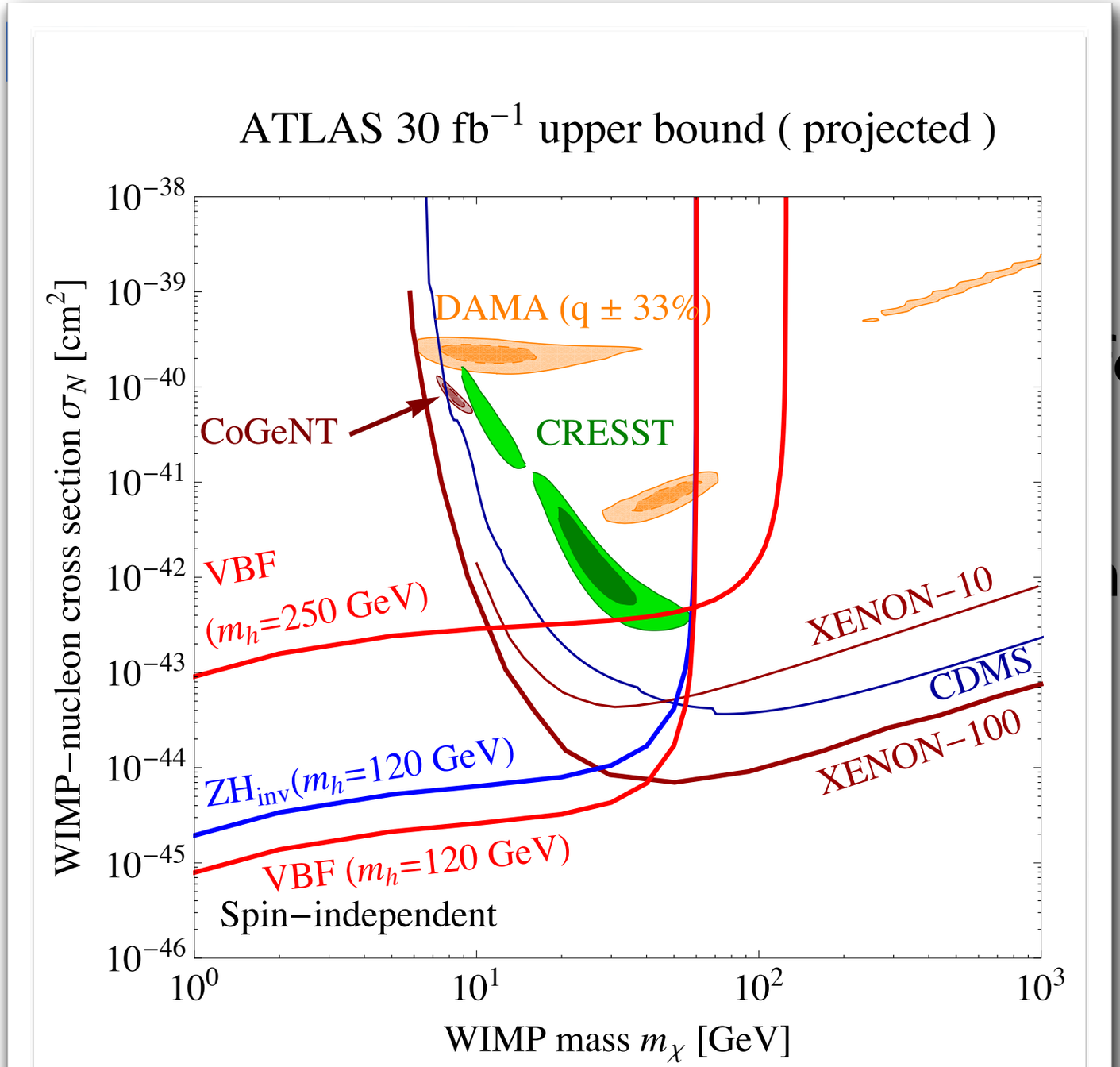
↓

Limit on Higgs-DM coupling.

↓

Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]



or mediator of DM

n:

Higgs.

Limit on Higgs-DM coupling.

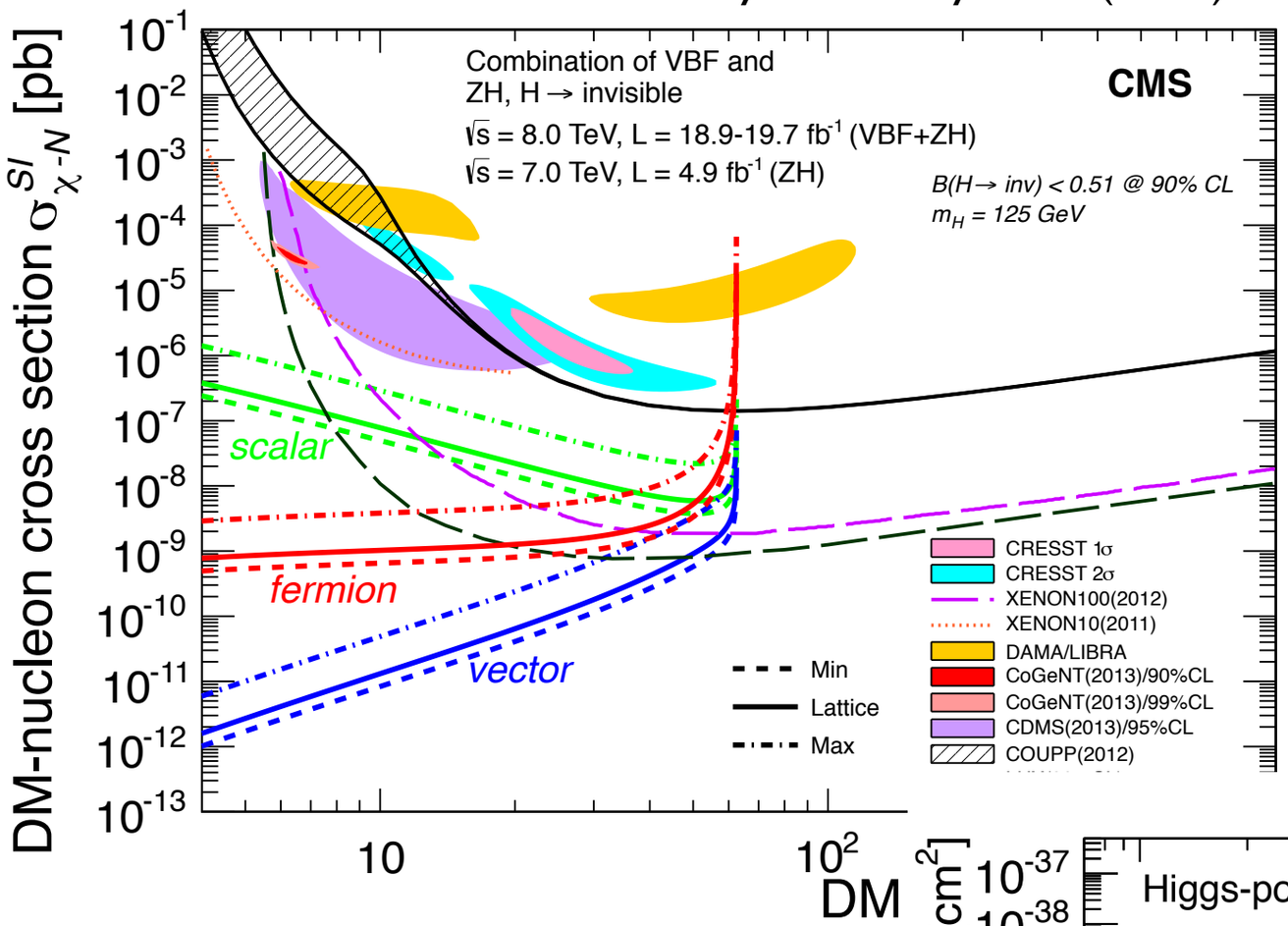
↓

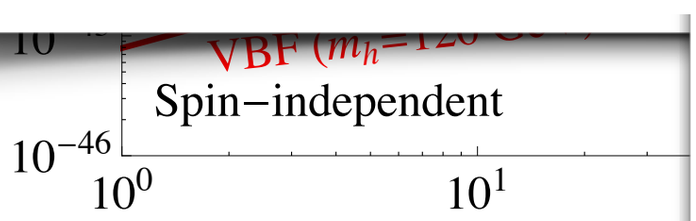
Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]

r mediator of DM

Invisible decay combo by CMS (2014)

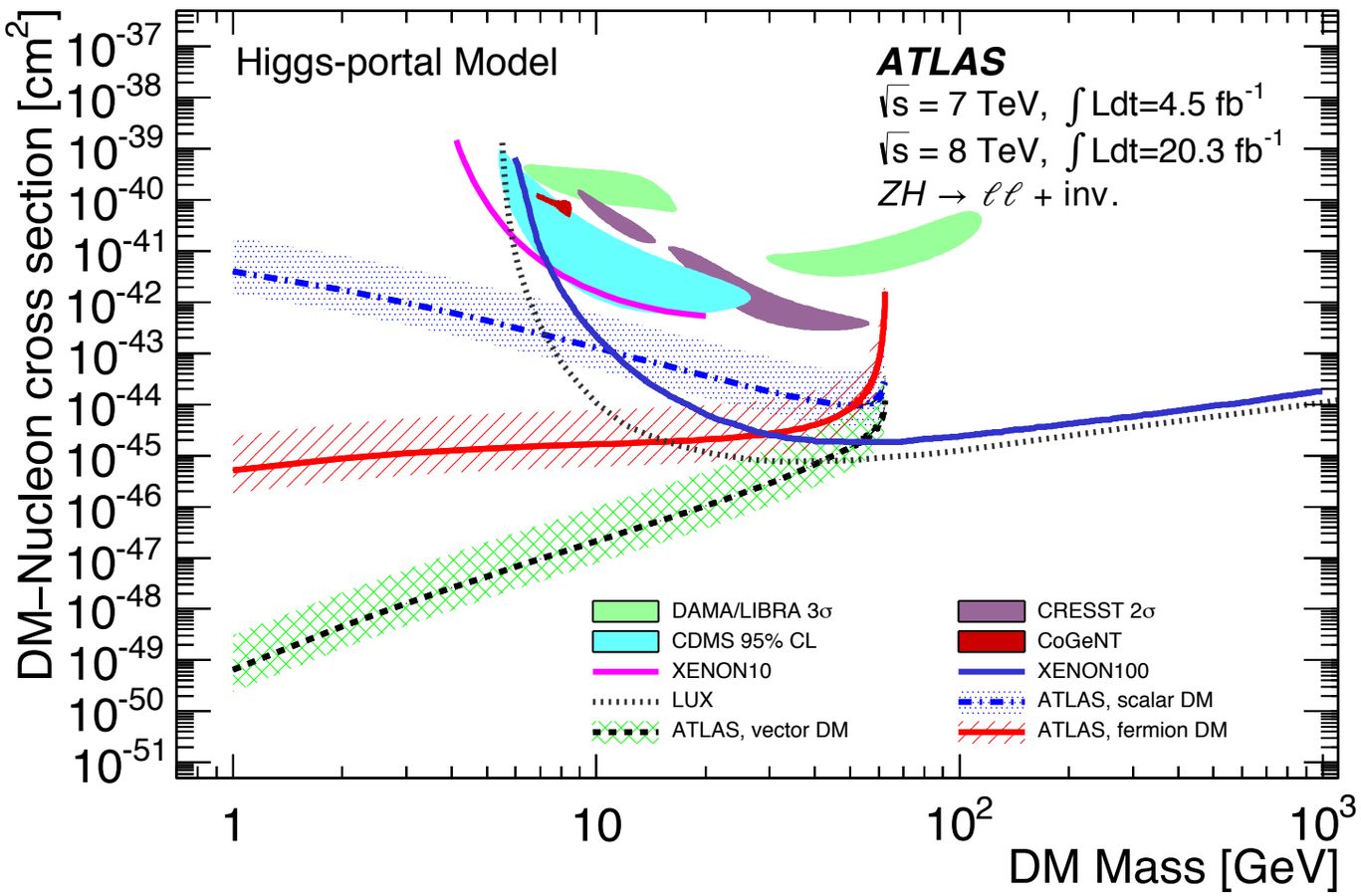




Limi

Lim

PRL on invisible decay by ATLAS (2014)

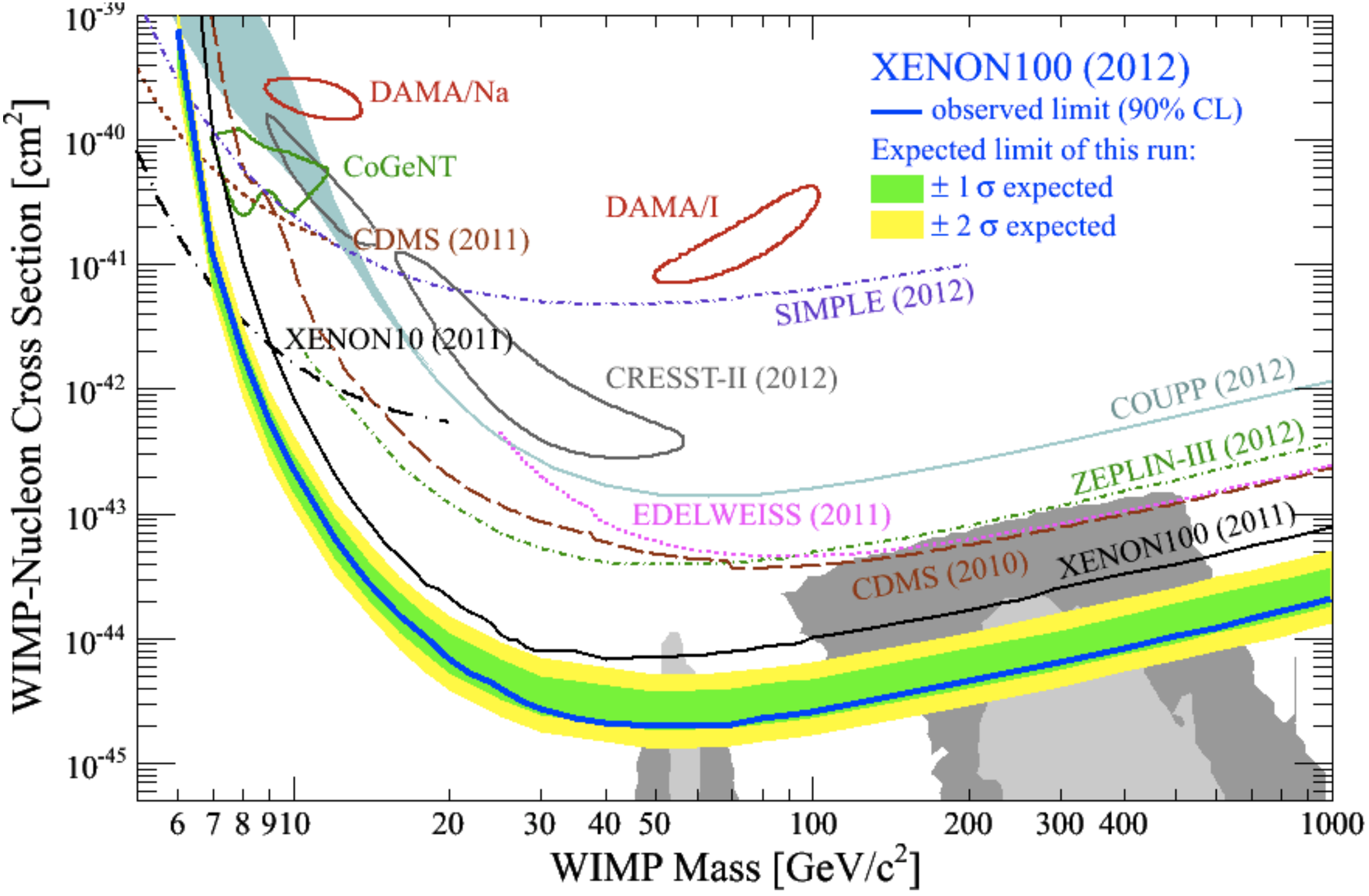


Conclusions

- Colliders can place strong constraints on dark matter
- Competitive with direct detection searches
  - Light DM
  - Spin dependent
  - *Independent of all astrophysics uncertainties*
- Light mediators alter collider bounds, more parameters
- Simplified models provide a good framework
- Beware of model dependence
- Correlated searches (mono-X, jets+MET, dijets,...)

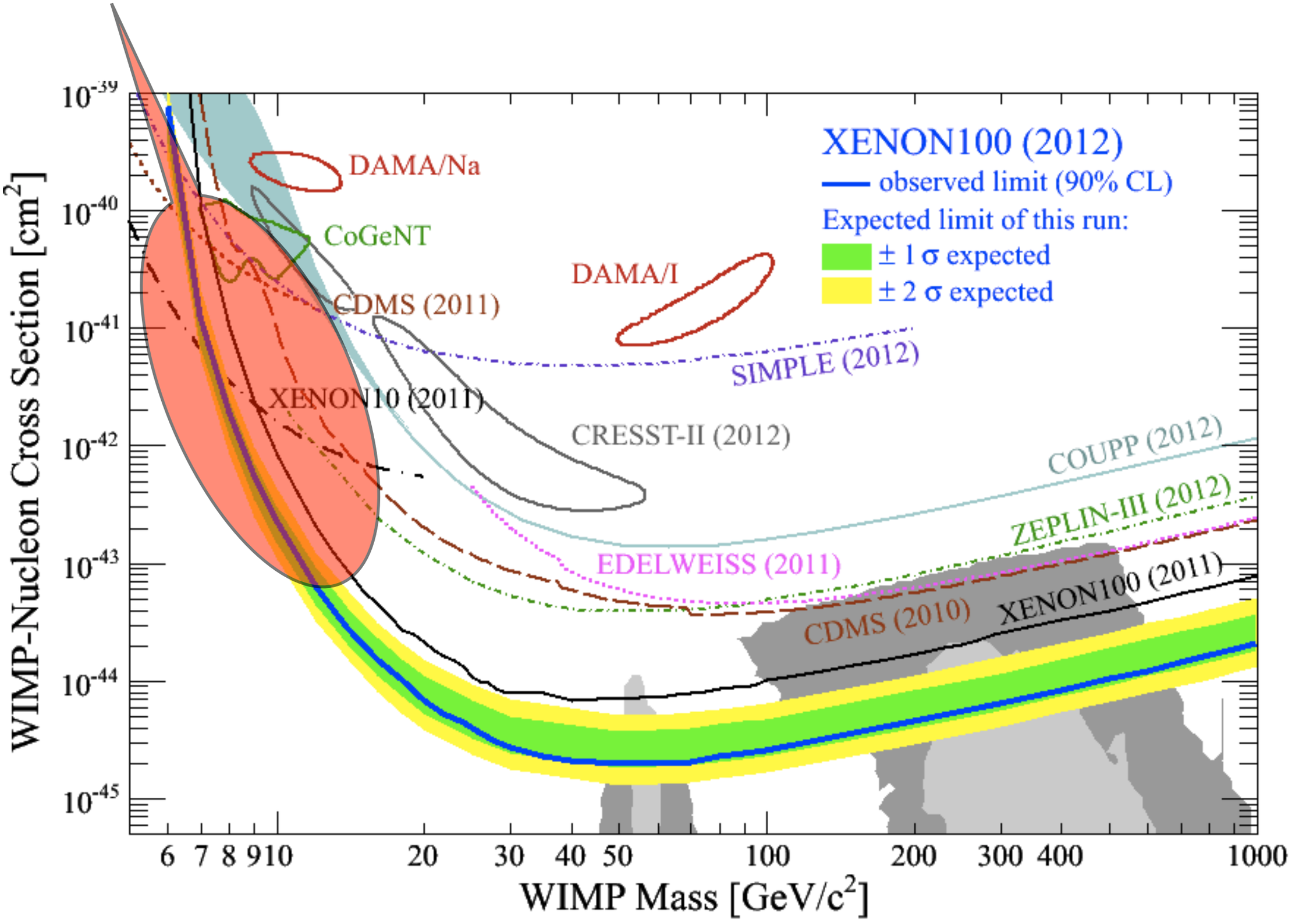
Lots of work to do!

Extra Slides



(Assume local abundance is 0.3 GeV/cm³)

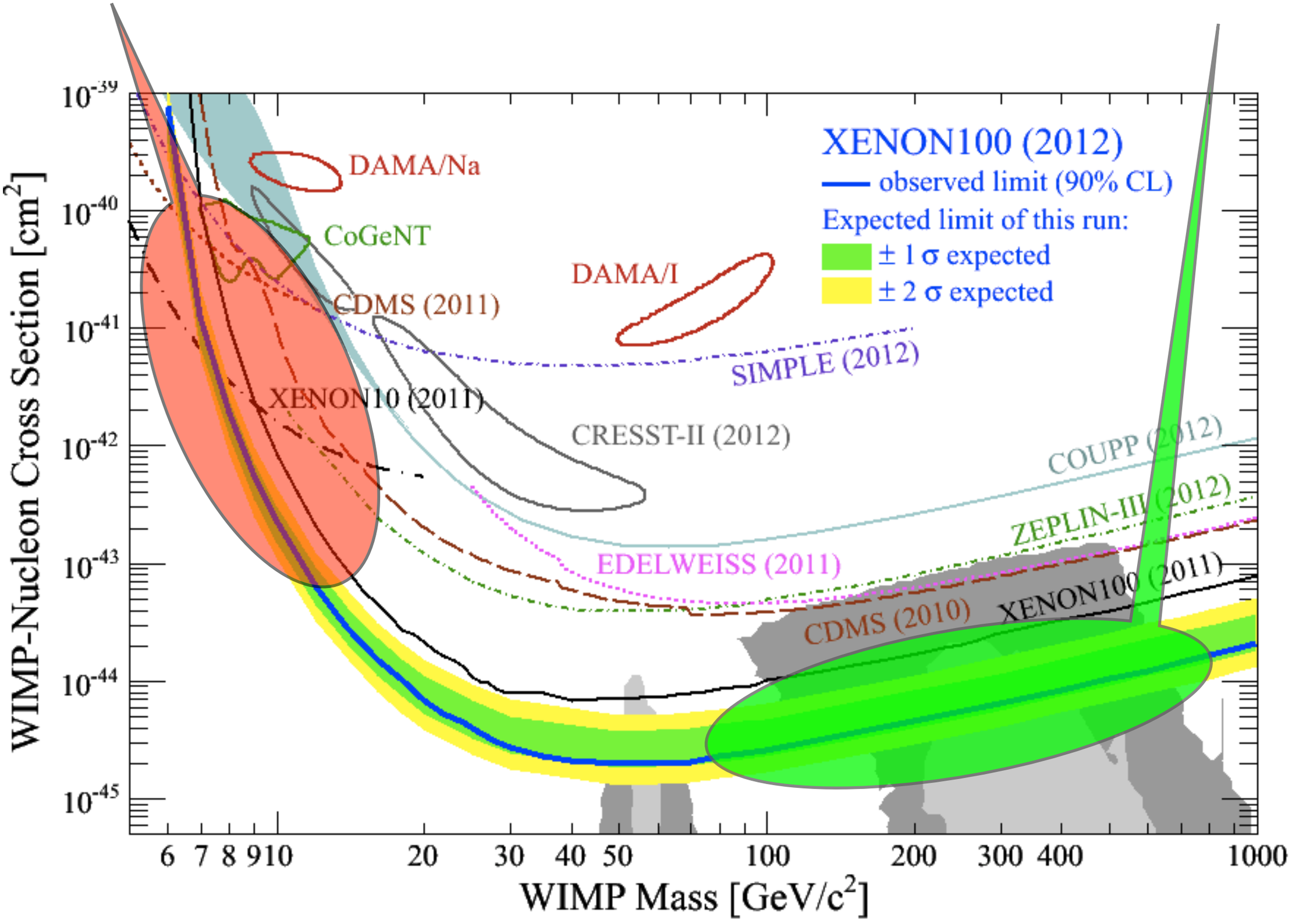
Threshold cuts off



(Assume local abundance is 0.3 GeV/cm³)

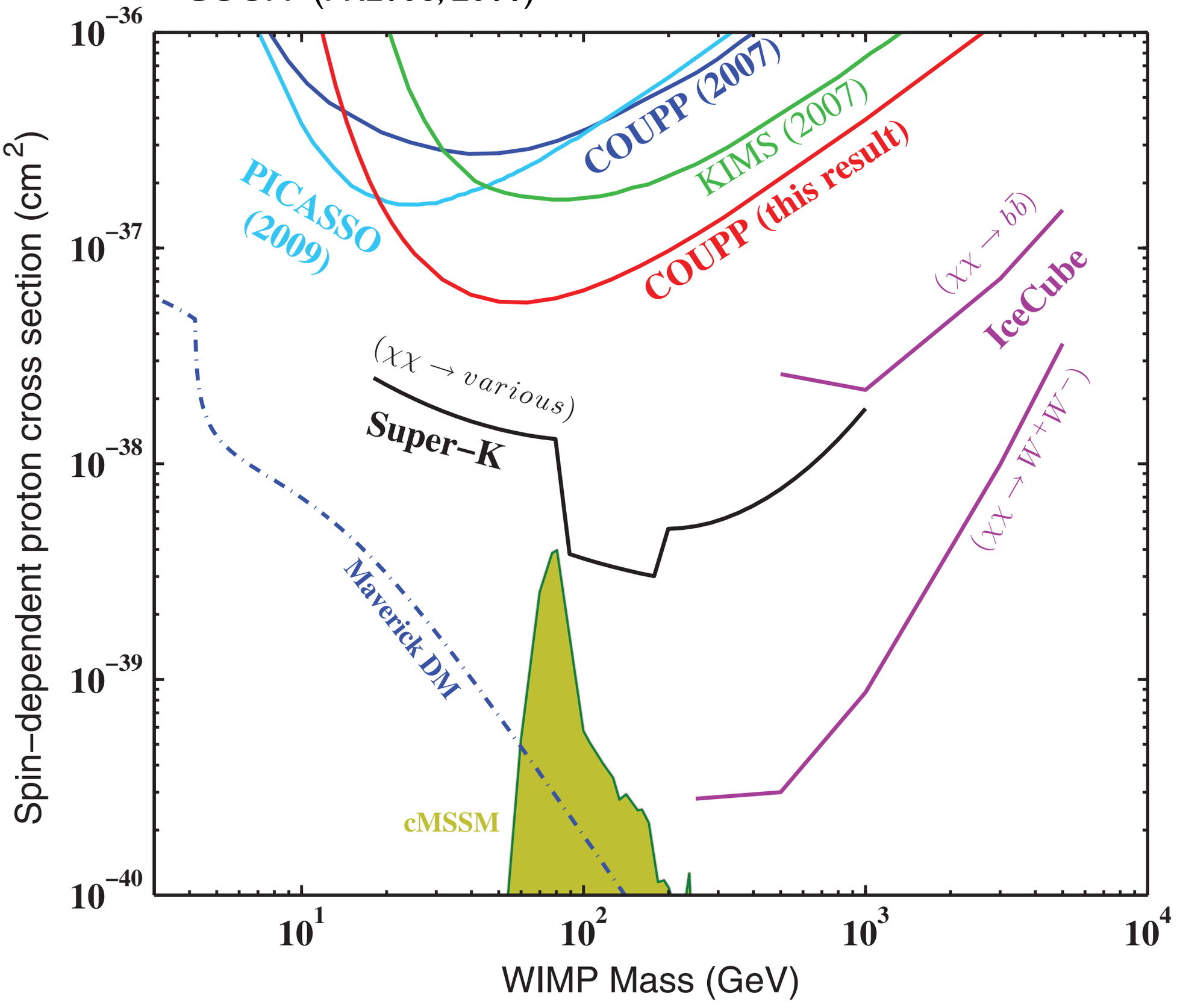
Threshold cuts off

Rate ~1/m



(Assume local abundance is 0.3 GeV/cm³)

COUPP (PRL106, 2011)



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

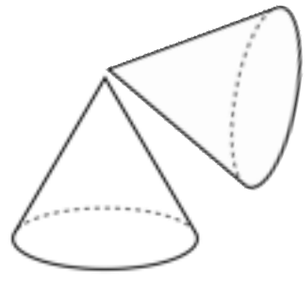
[Rogan 1006.2727]

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

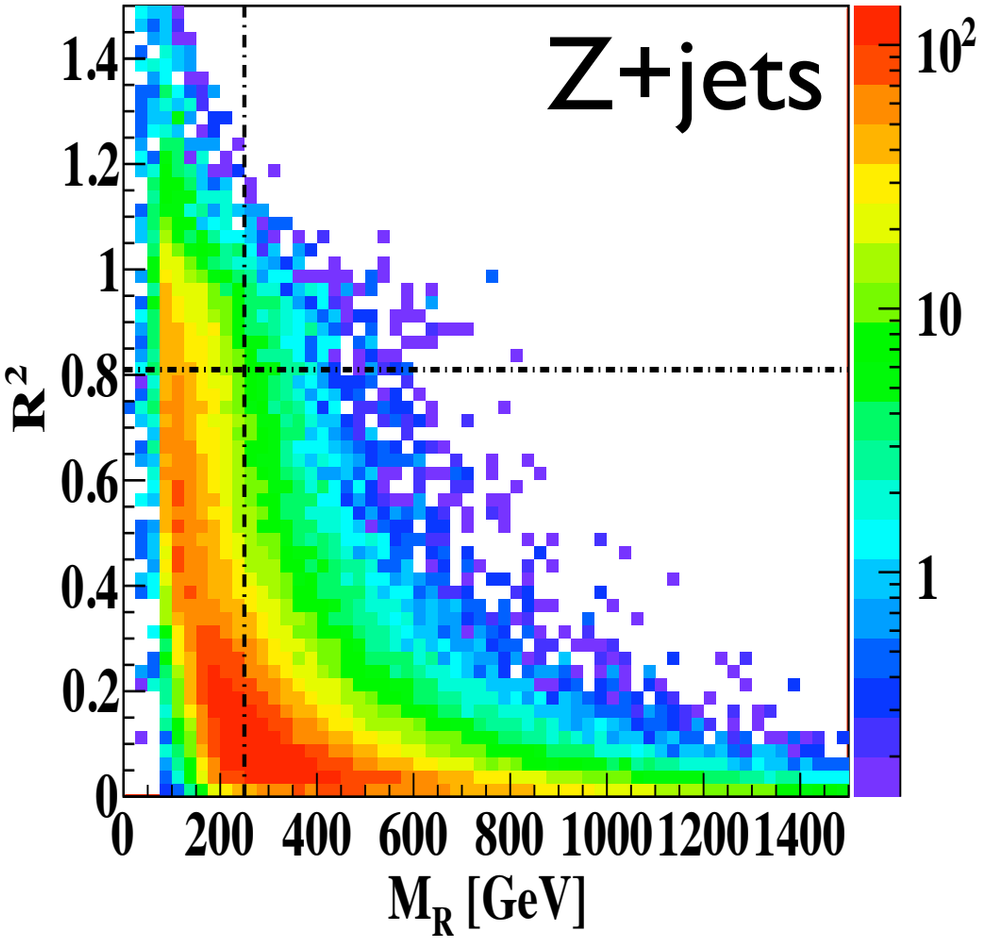
$$M_R^T = \sqrt{\frac{\not{E}_T(p_T^{j_1} + p_T^{j_2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

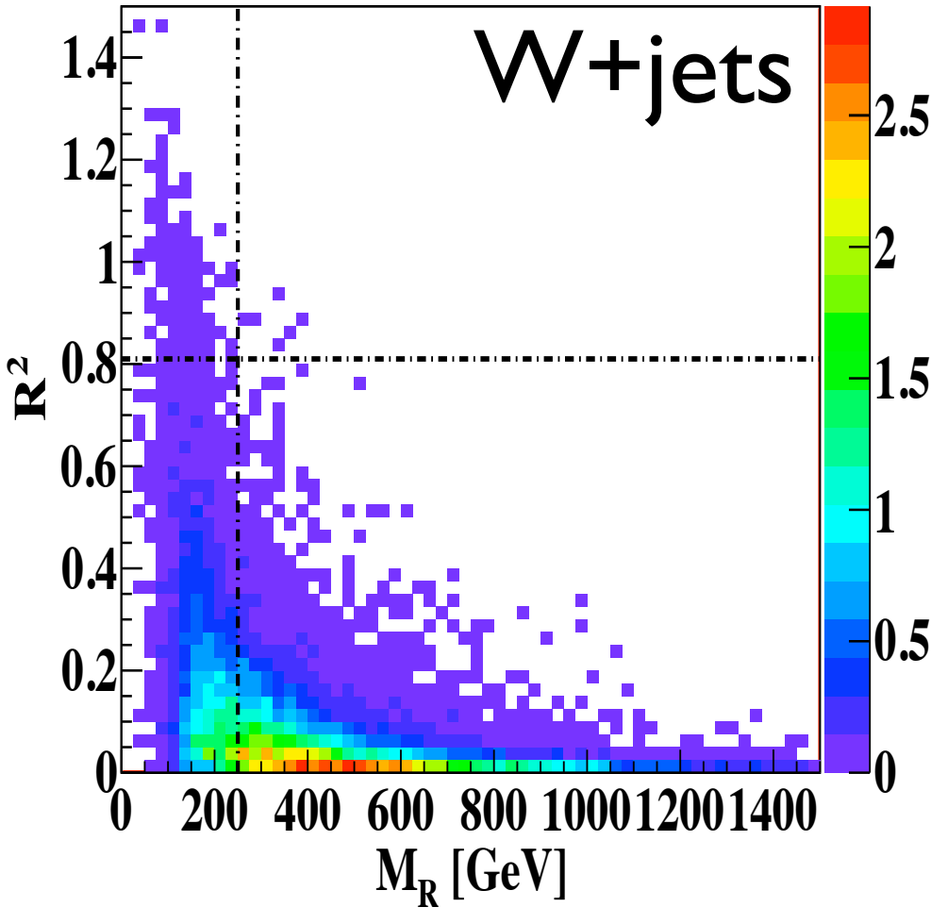
$$R = \frac{M_R^T}{M_R}$$

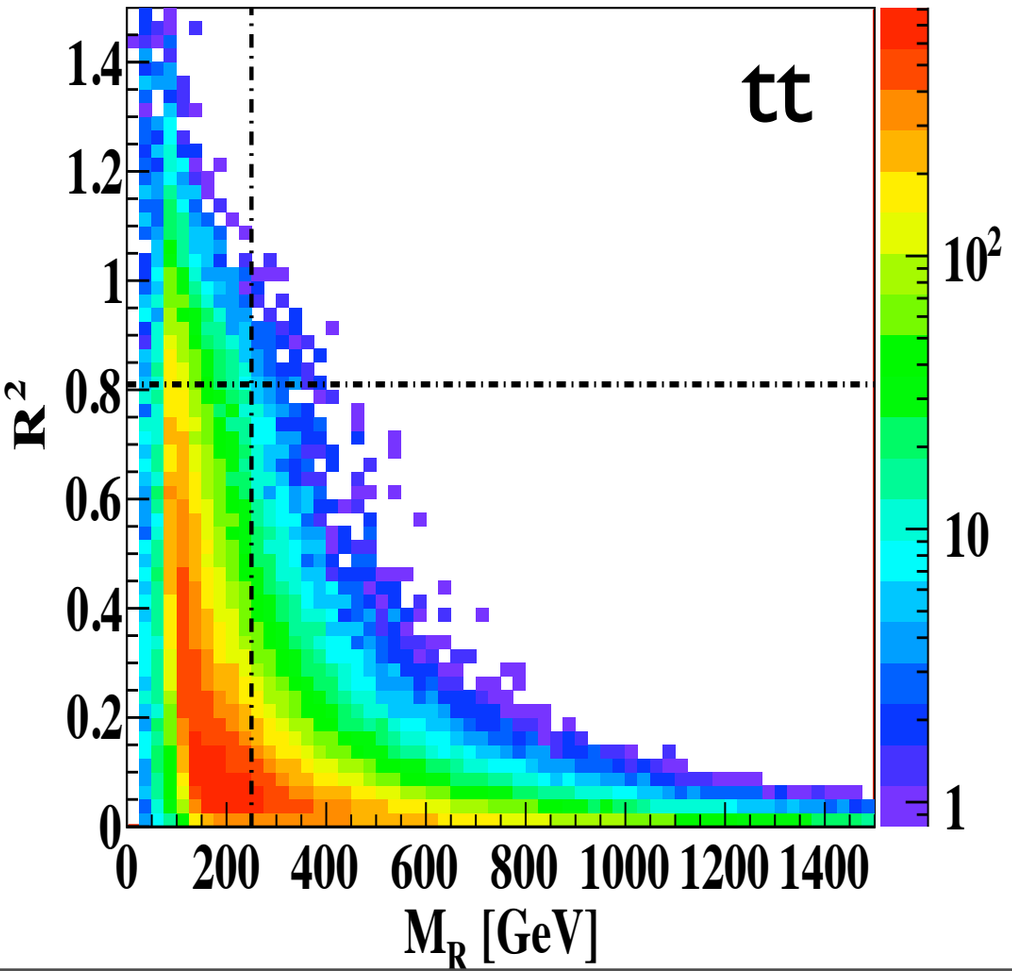
Small R

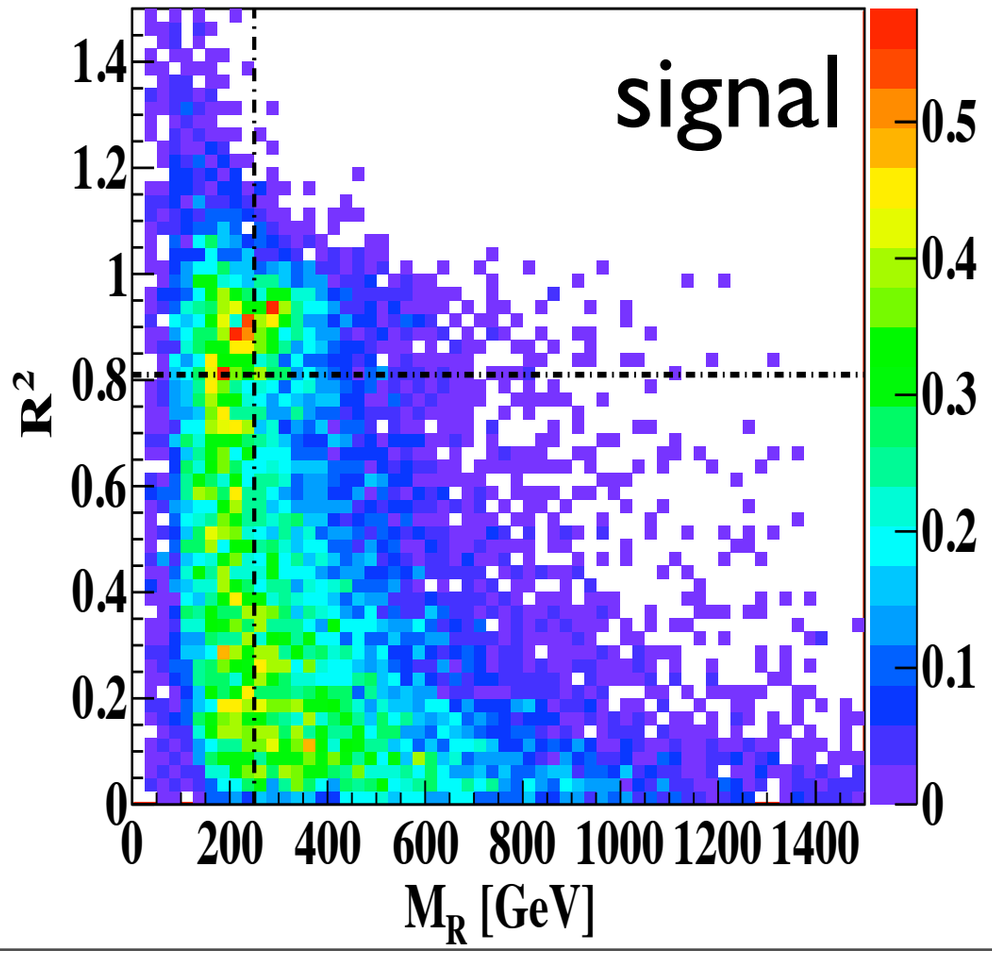


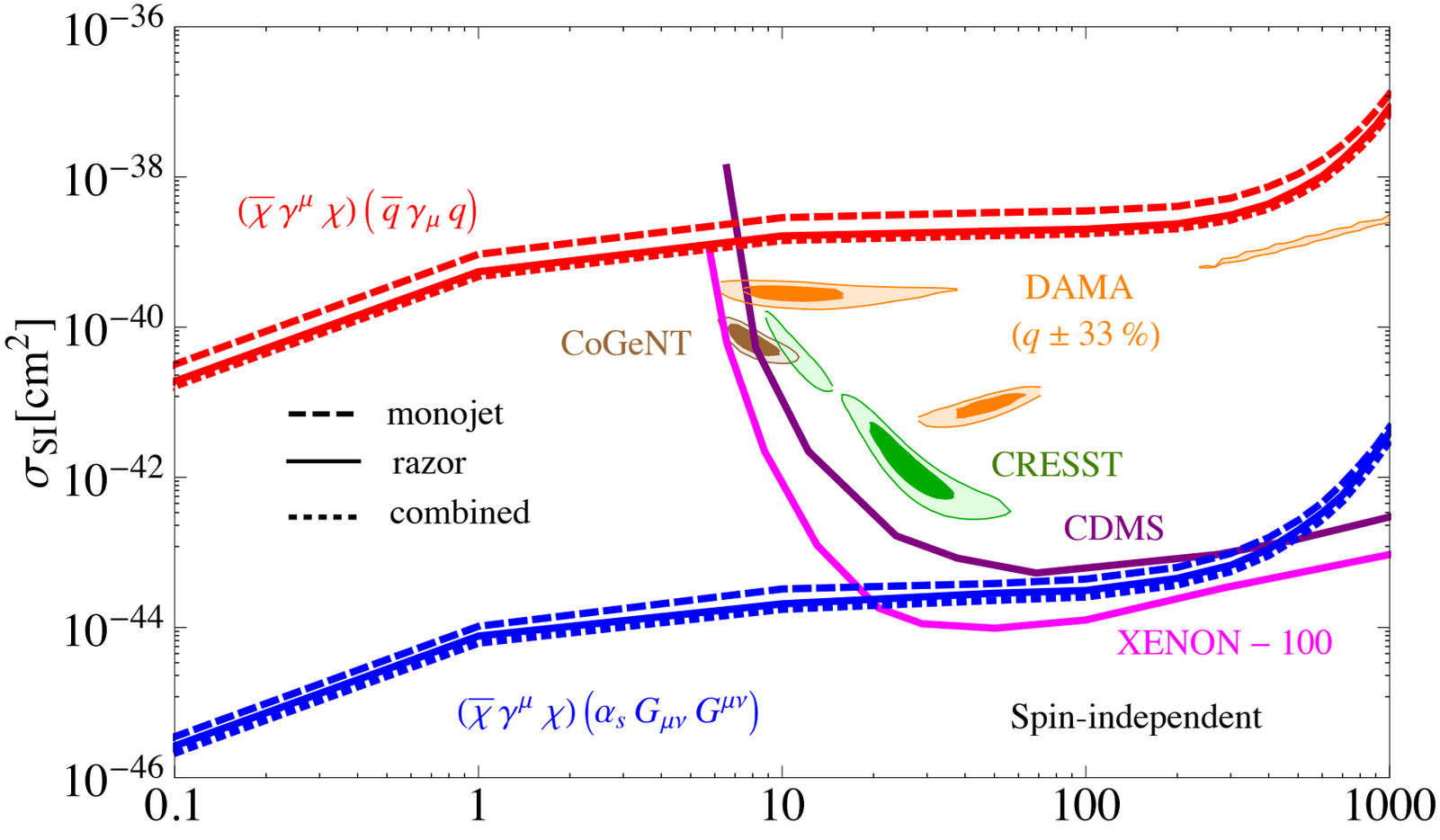
Large R


Z+jets
R^2
M_R [GeV]

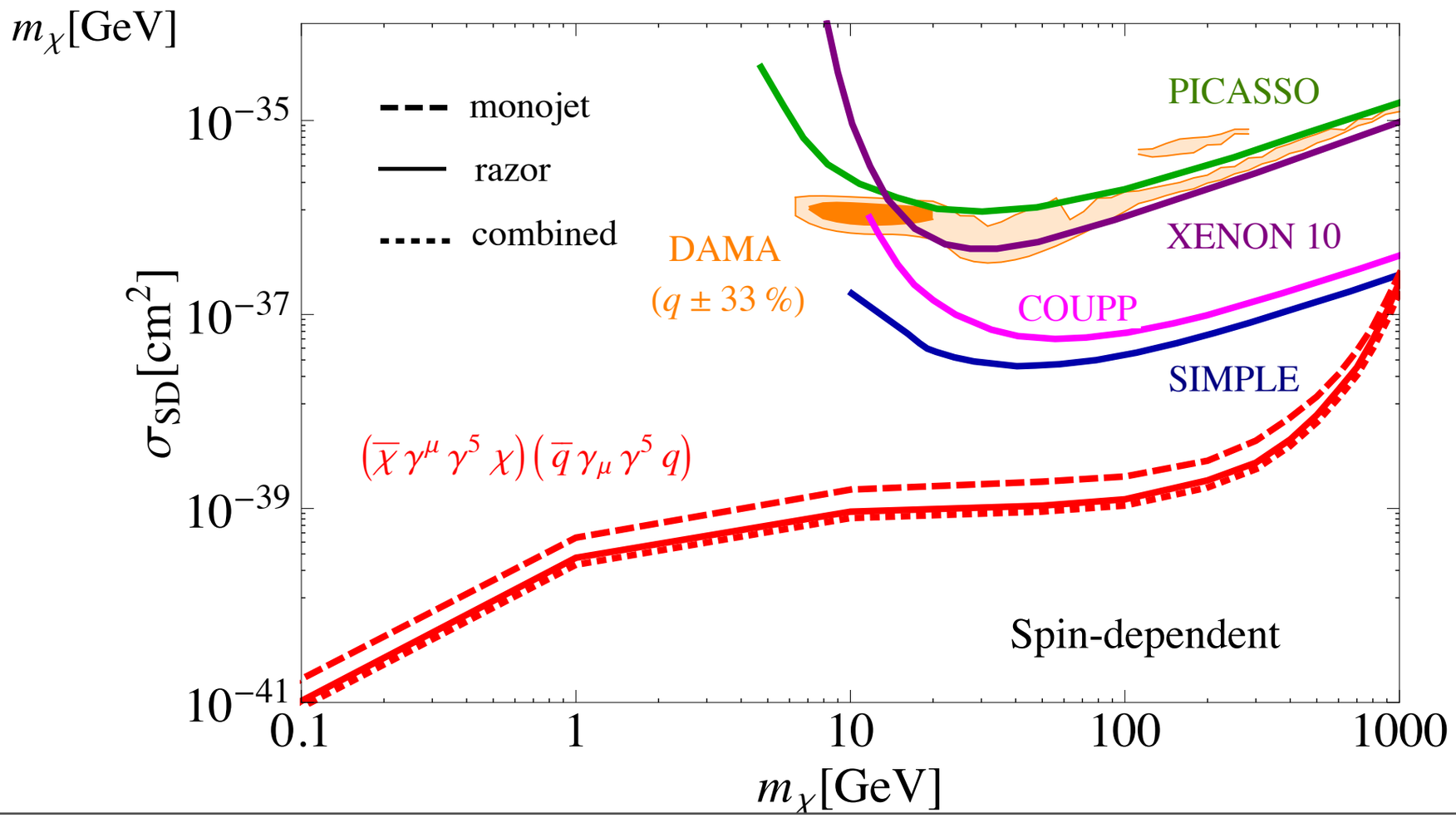

W+jets
R^2
M_R [GeV]


tt
R^2
M_R [GeV]


signal
R^2
M_R [GeV]



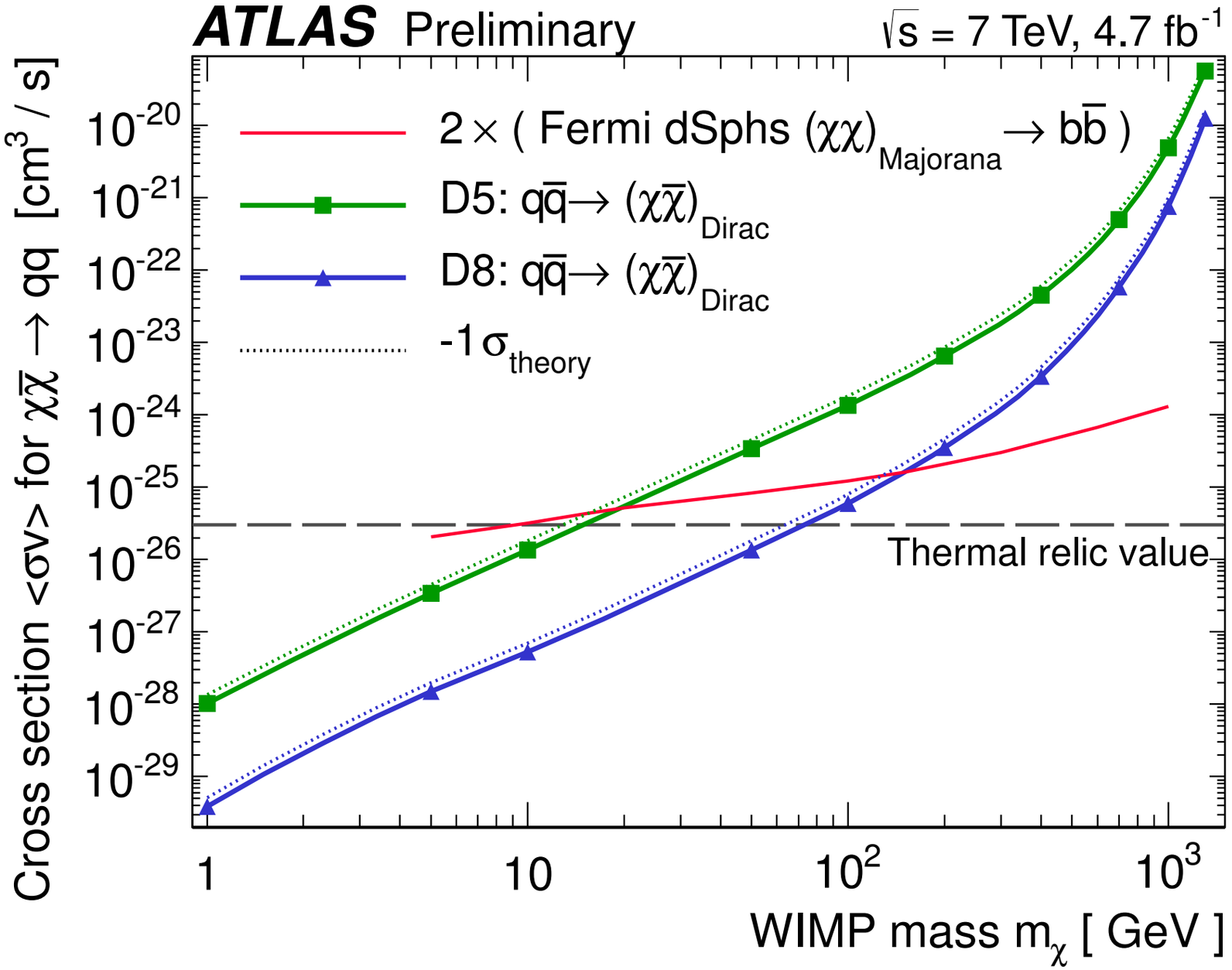
[PJF, Harnik, Primulando, Yu, 1203.1662]



DM annihilation

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

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



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

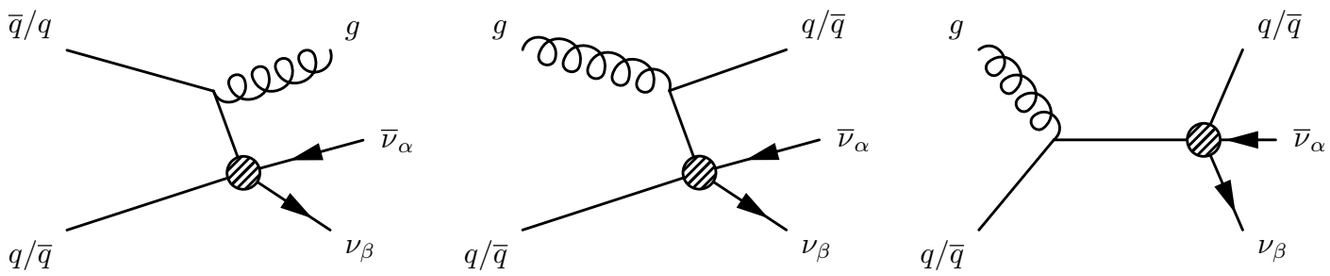
$$D5 = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma^\mu q$$

Monojets and other invisibles

[Friedland et al., 1111.5331]

Nonstandard neutrino interactions

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



	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