LHC vs. Dark Matter

Roni Harnik, Fermilab

Can LHC make a *model independent* statement about DM?

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Yes!

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DM has not been found at LHC yet.

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Well, duh... anything else?

Can LHC make a *model independent* statement about DM?

Yes!

DM has not been found at LHC yet.

Well, duh... anything else?

No.

Beyond that any statement is valid within a model.

Models

* Plan: a laundry list of DM models.
* As an organizing principle, take the "Tait axis":

Lets take a tour
of the axis.

Models

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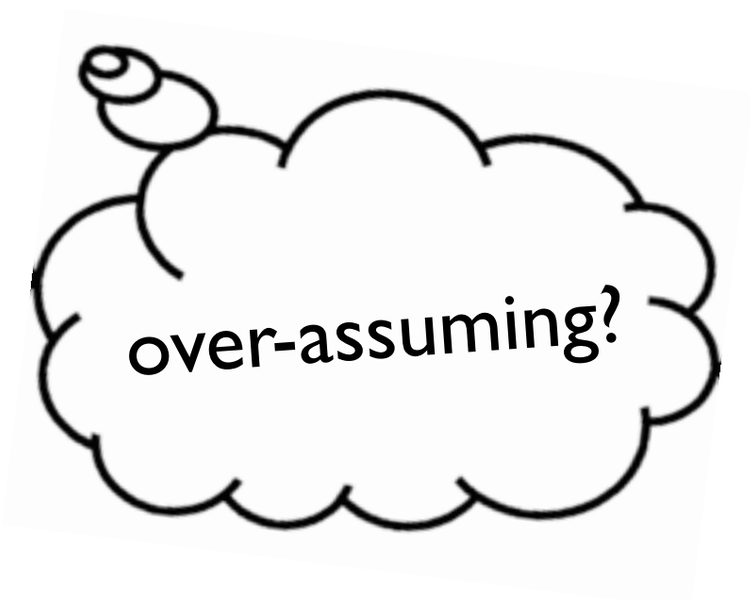

Lets take a tour
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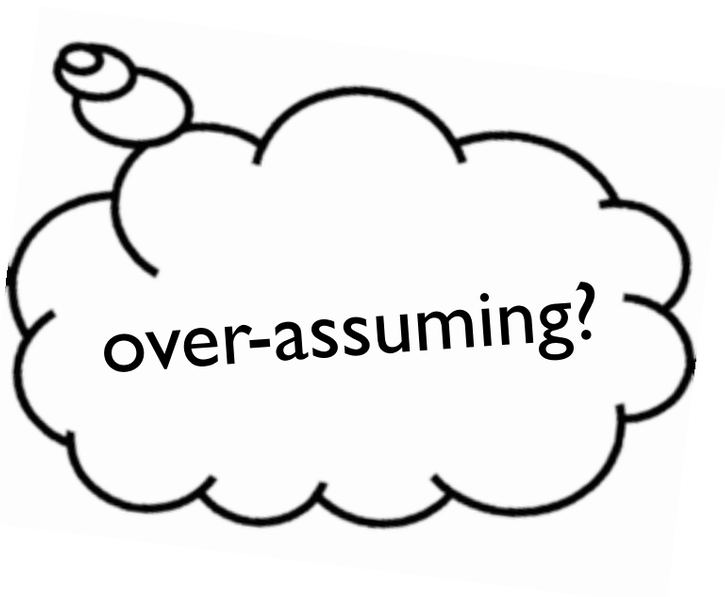
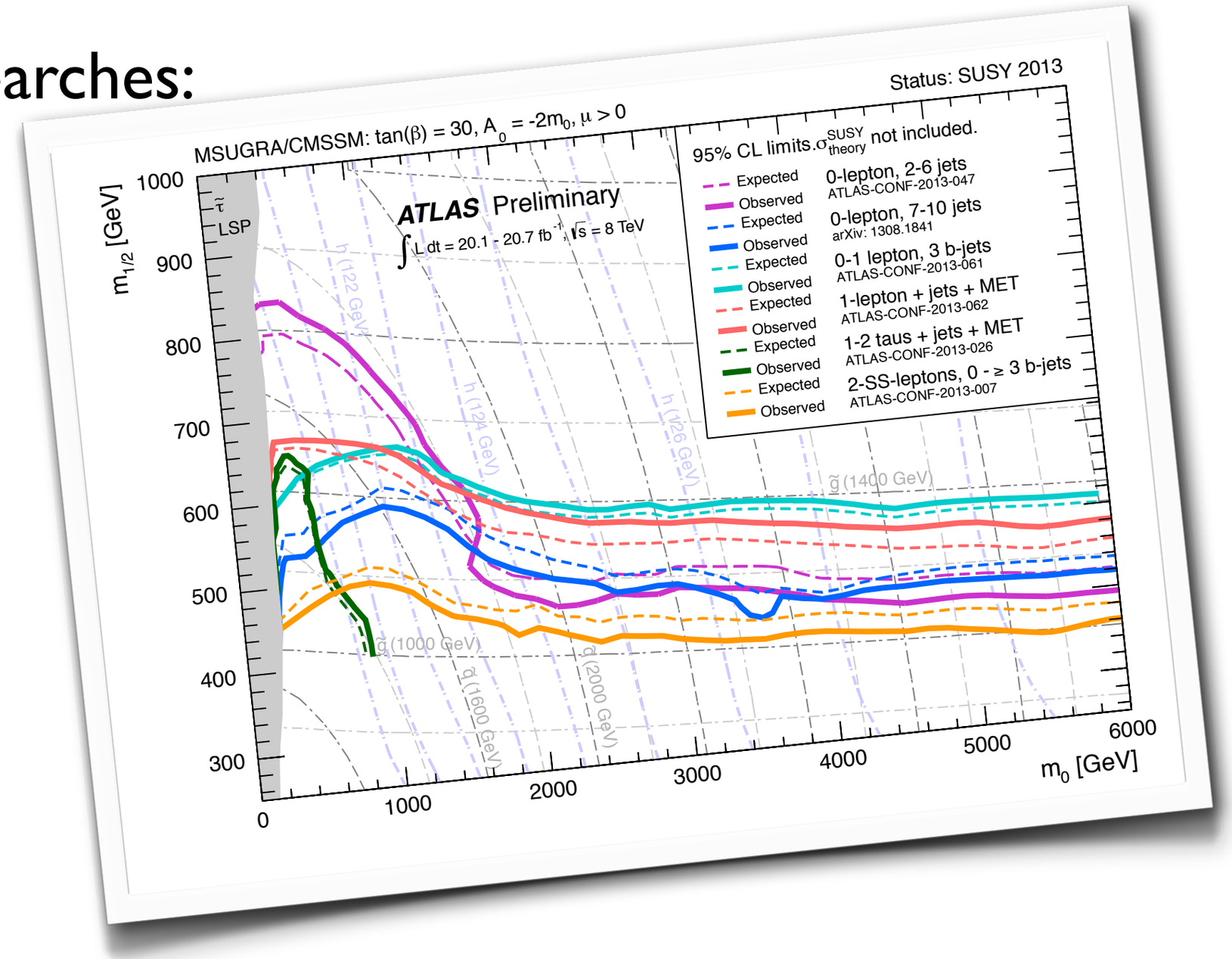


Complete Models

SUSY Searches

* Many many searches:



TeV SUSY is not looking so great.
A statement about naturalness. not DM so much.

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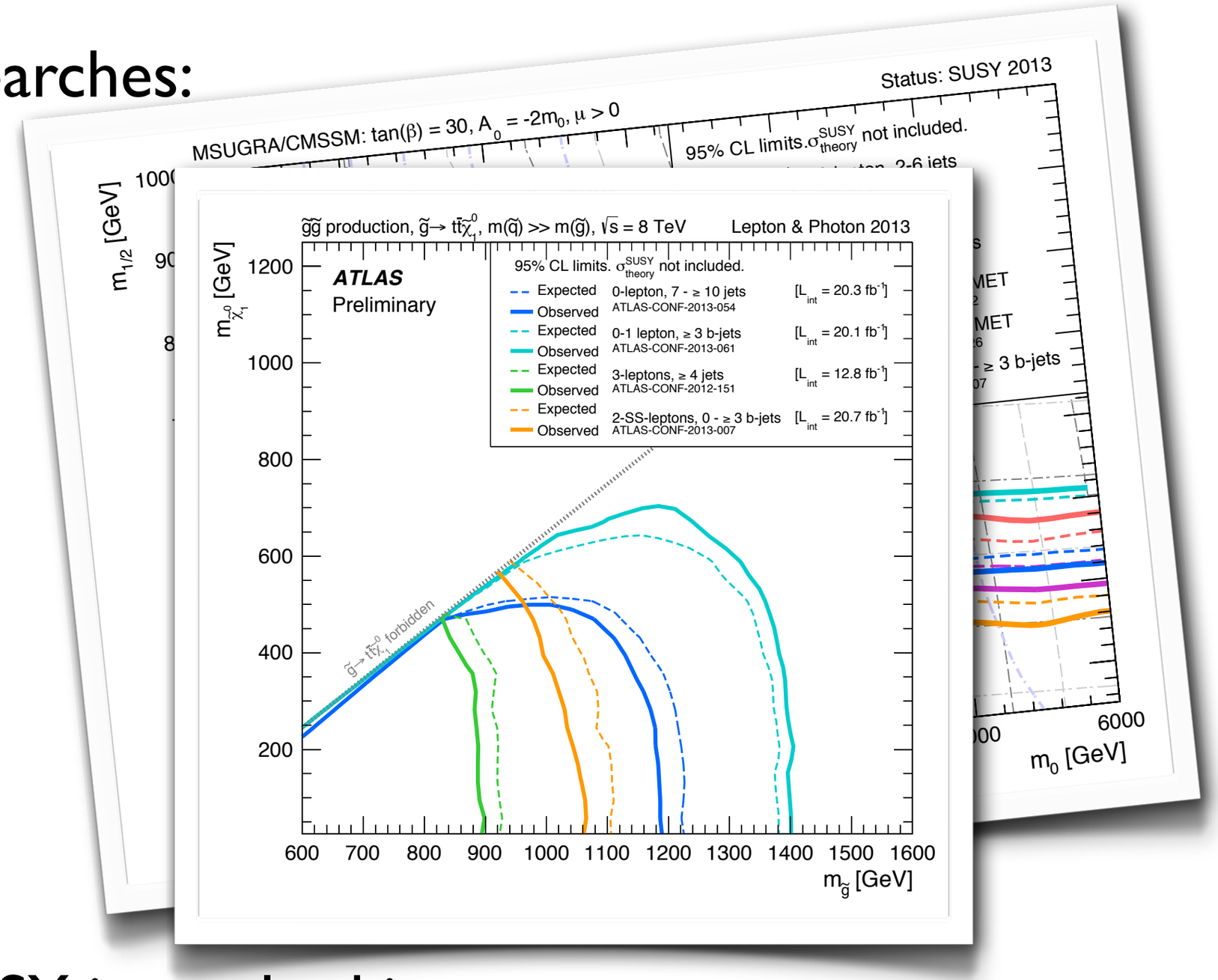

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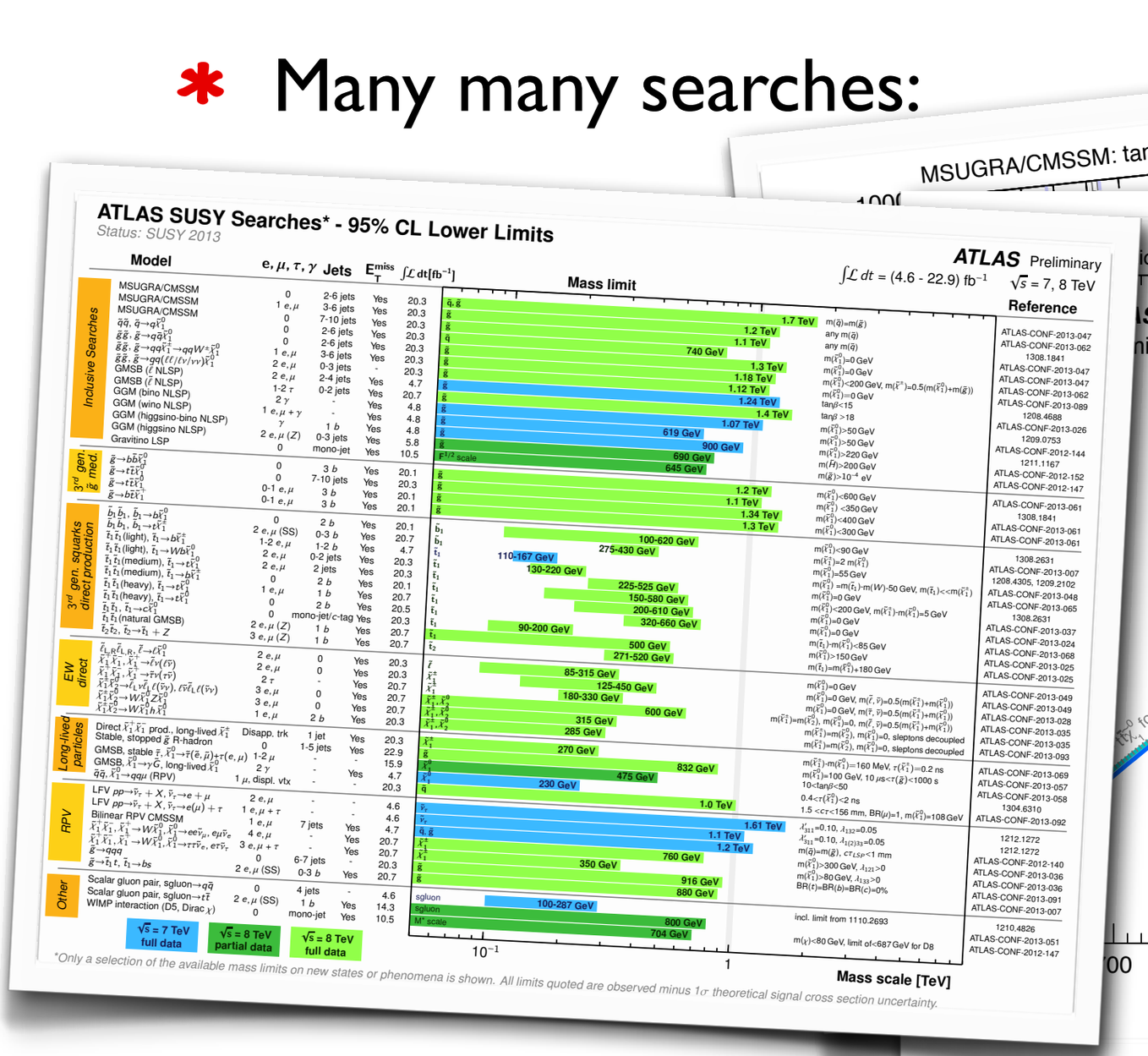

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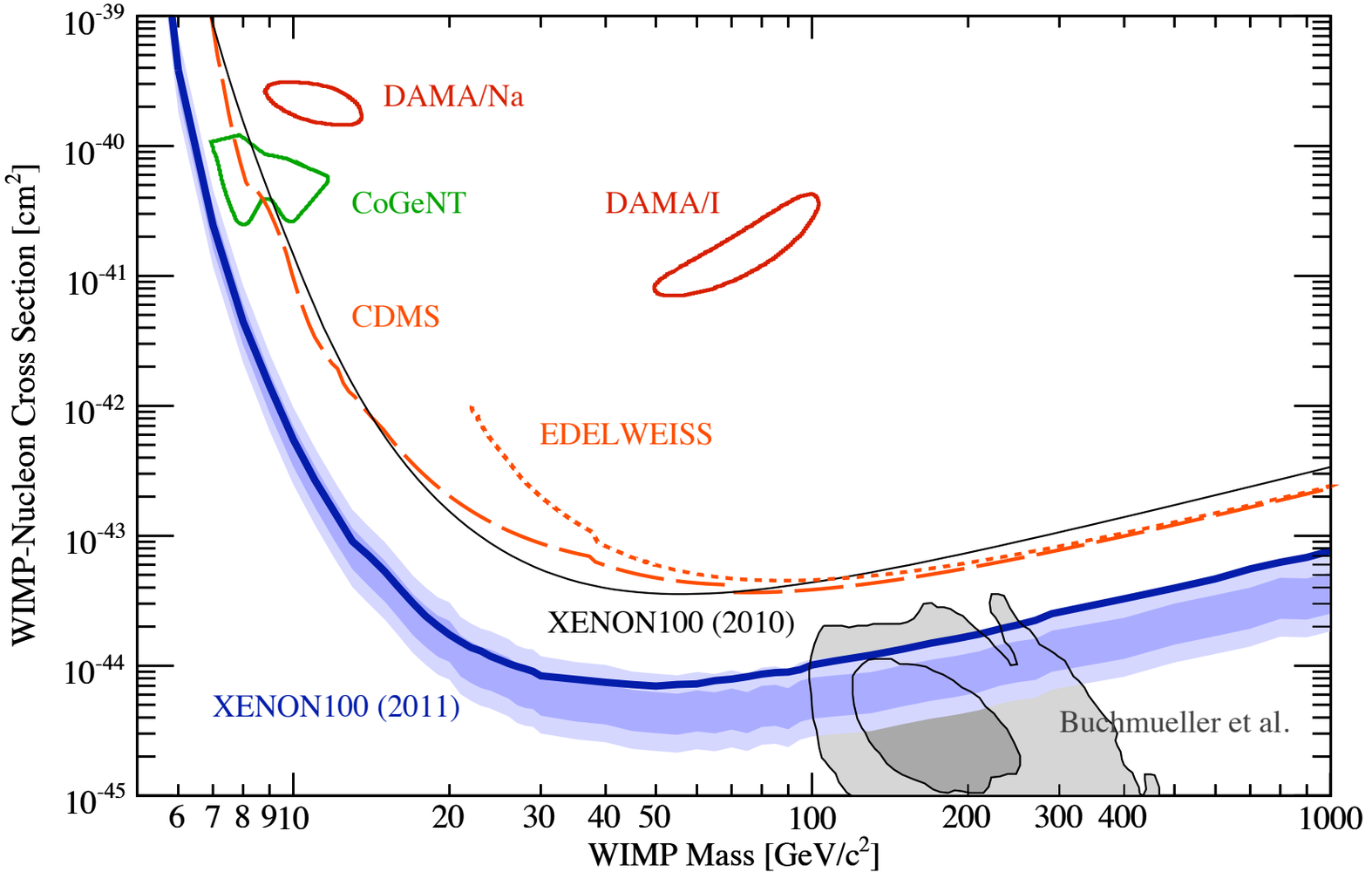
What do these models look like on a DM parameter space?

Over-Specific?

* DM constraints are often presented with amoeba-shaped parameter spaces.



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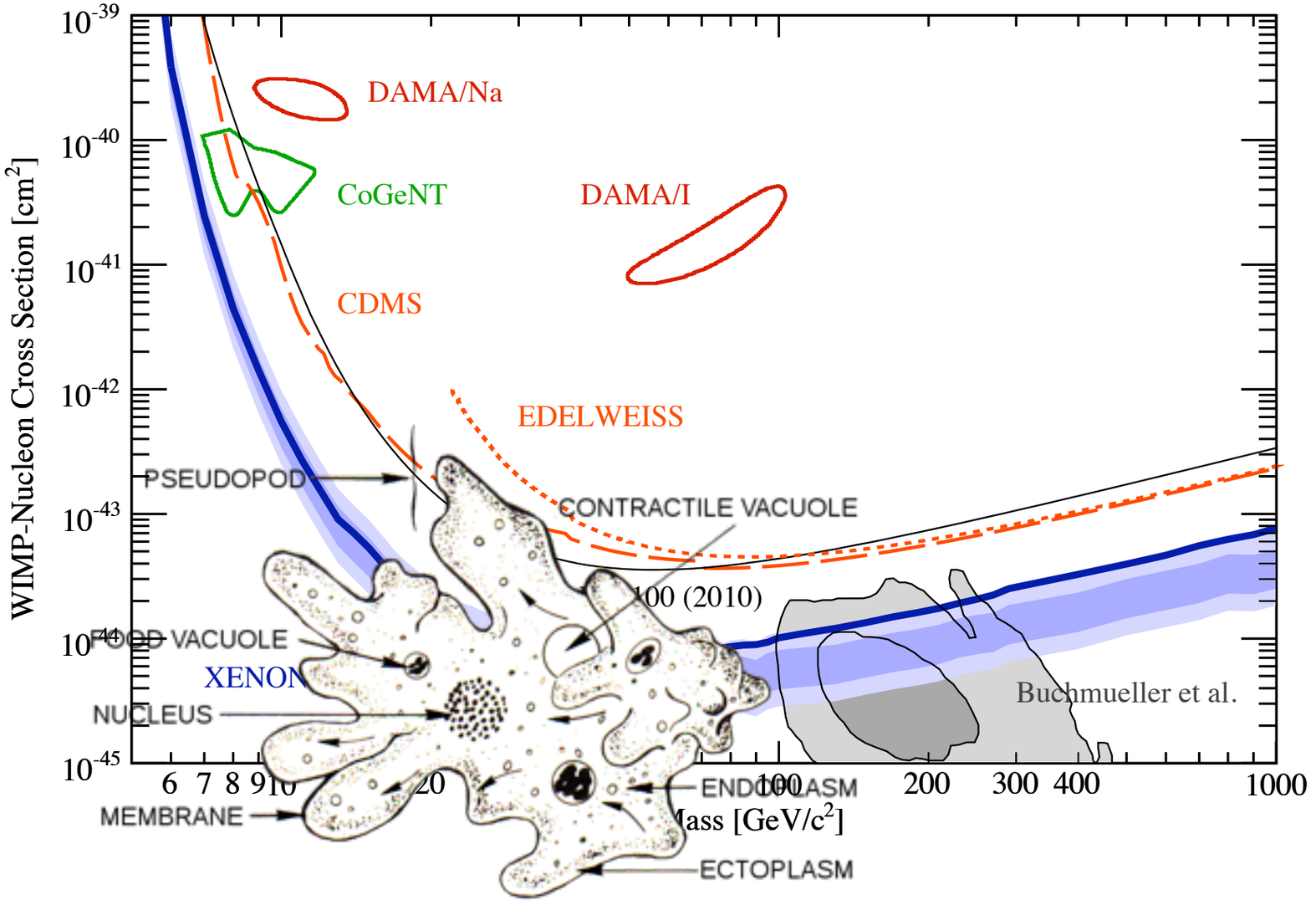

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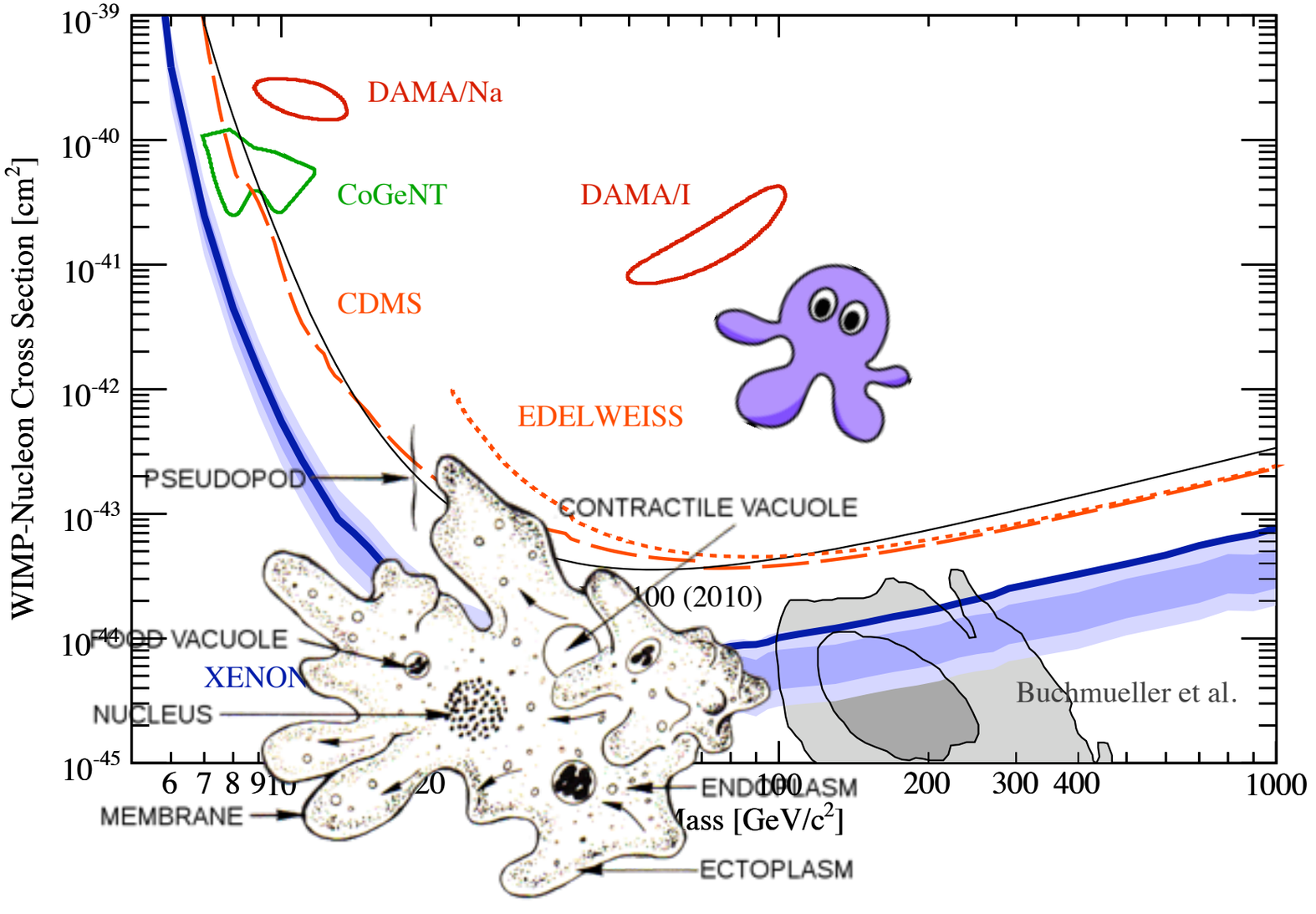

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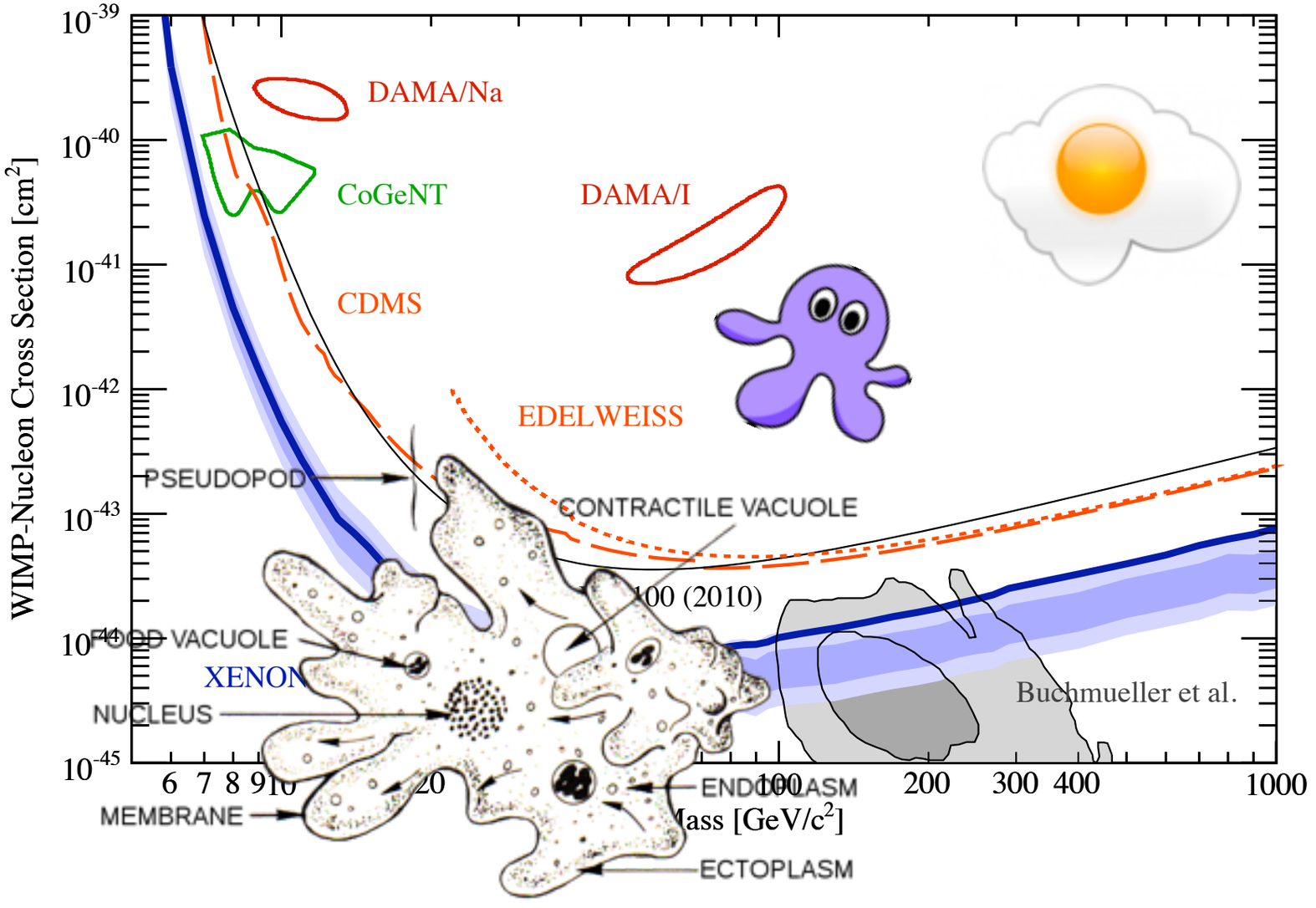

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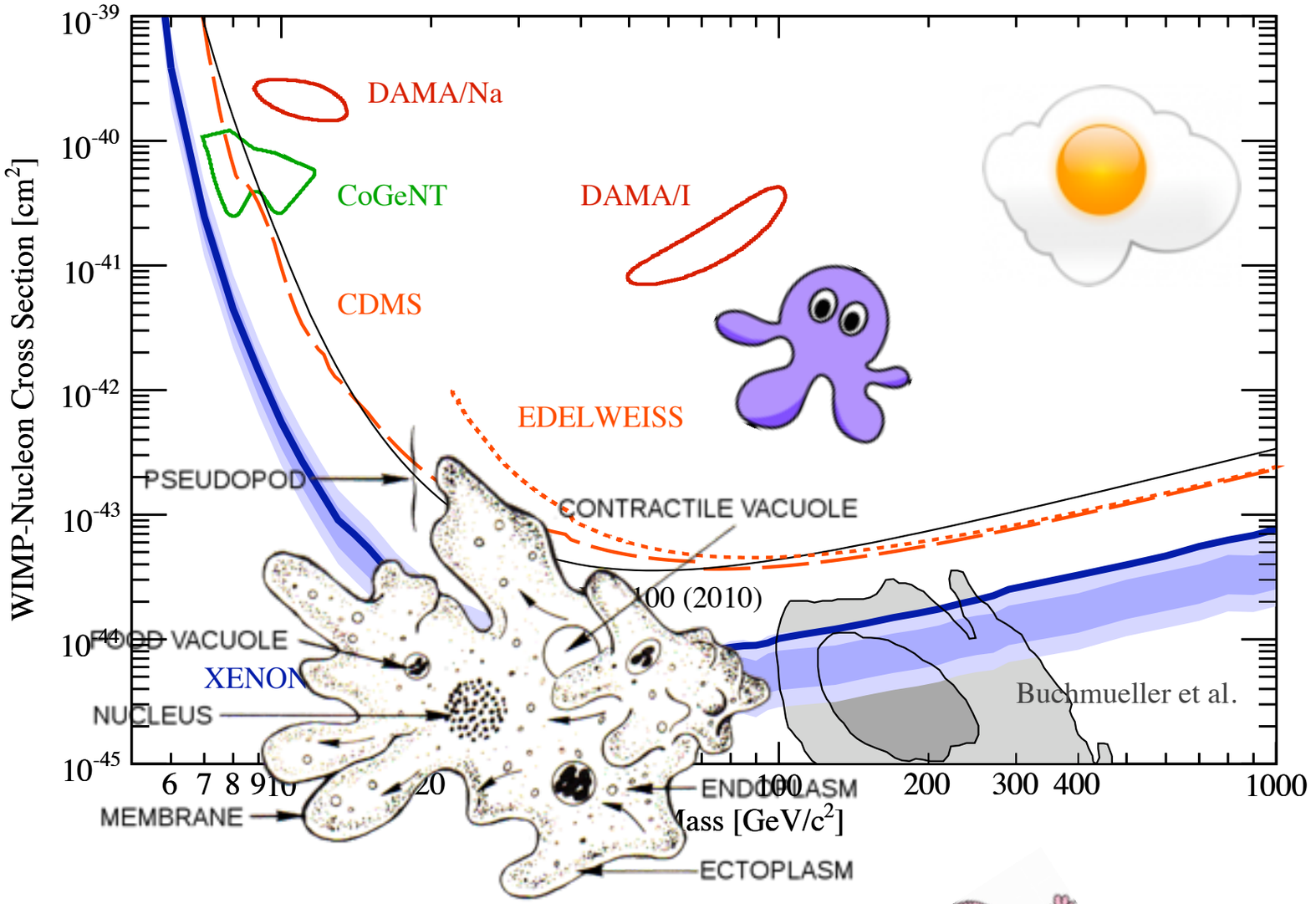

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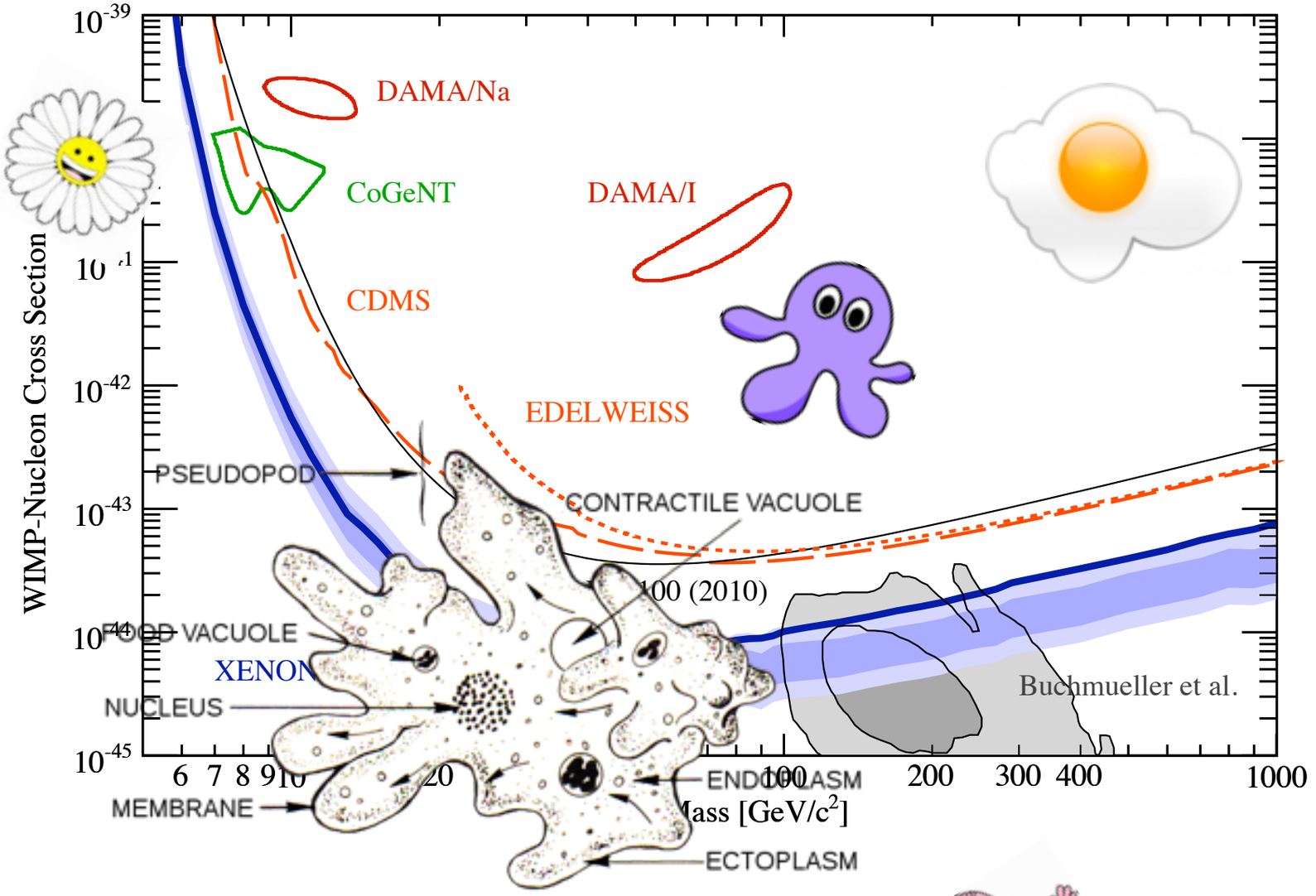
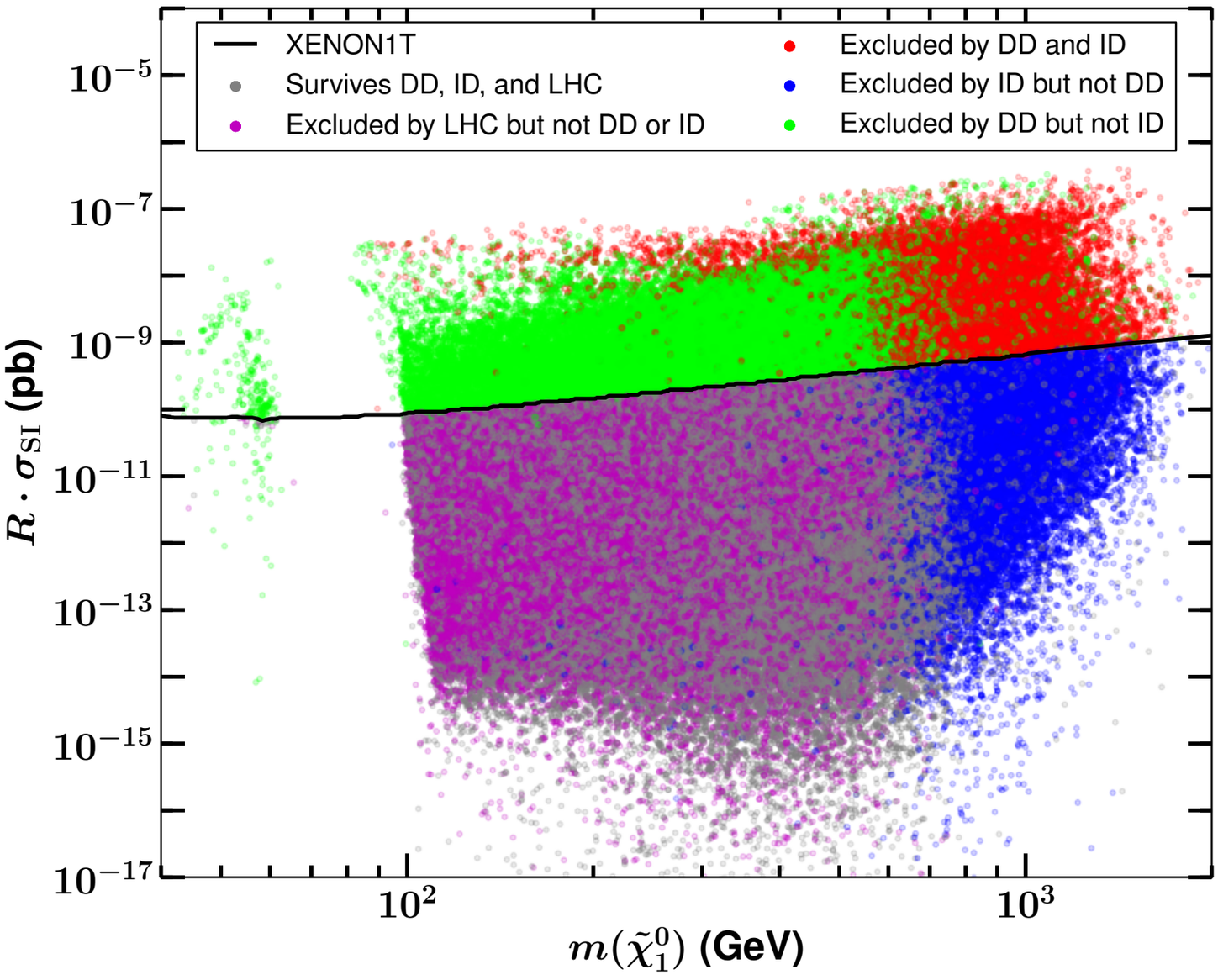


SUSY



pMSSM. Cotta & co. 1305.6921

Note:

* The plane is full.

* LHC-accessible and LHC-proof models co-exist everywhere.

* A specific model will often have a knob to turn...

DM EFT's

"Fermilab Clan":
Bai, Fox, RH - 1005.3797
Fox, RH, Kopp, Tsai -1103.0240
Fox, RH, Kopp, Tsai - 1109.4389
Fox, RH, Primulando, Yu - 1203.1662

"Irvine Clan":
Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu -1005.1286
Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu - 1008.1783
Fortin and Tait - 1103.3289
Rajaraman, Shepherd,Tait and Wijangco - 1108.1196
Shepherd and Goodman - 1111.2359

Direct Detection - EFT

* The EFT that described DM interaction in direct detection experiments:

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

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

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

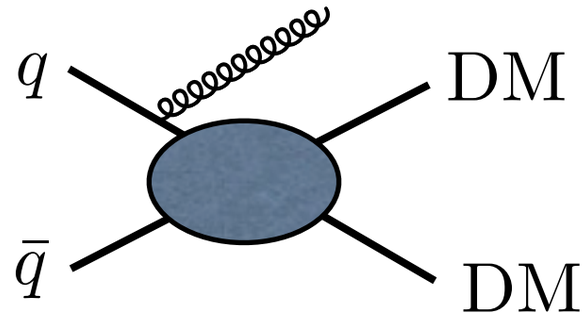
SI (or SD), t-channel "squark exchange"

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

SI gluon operator

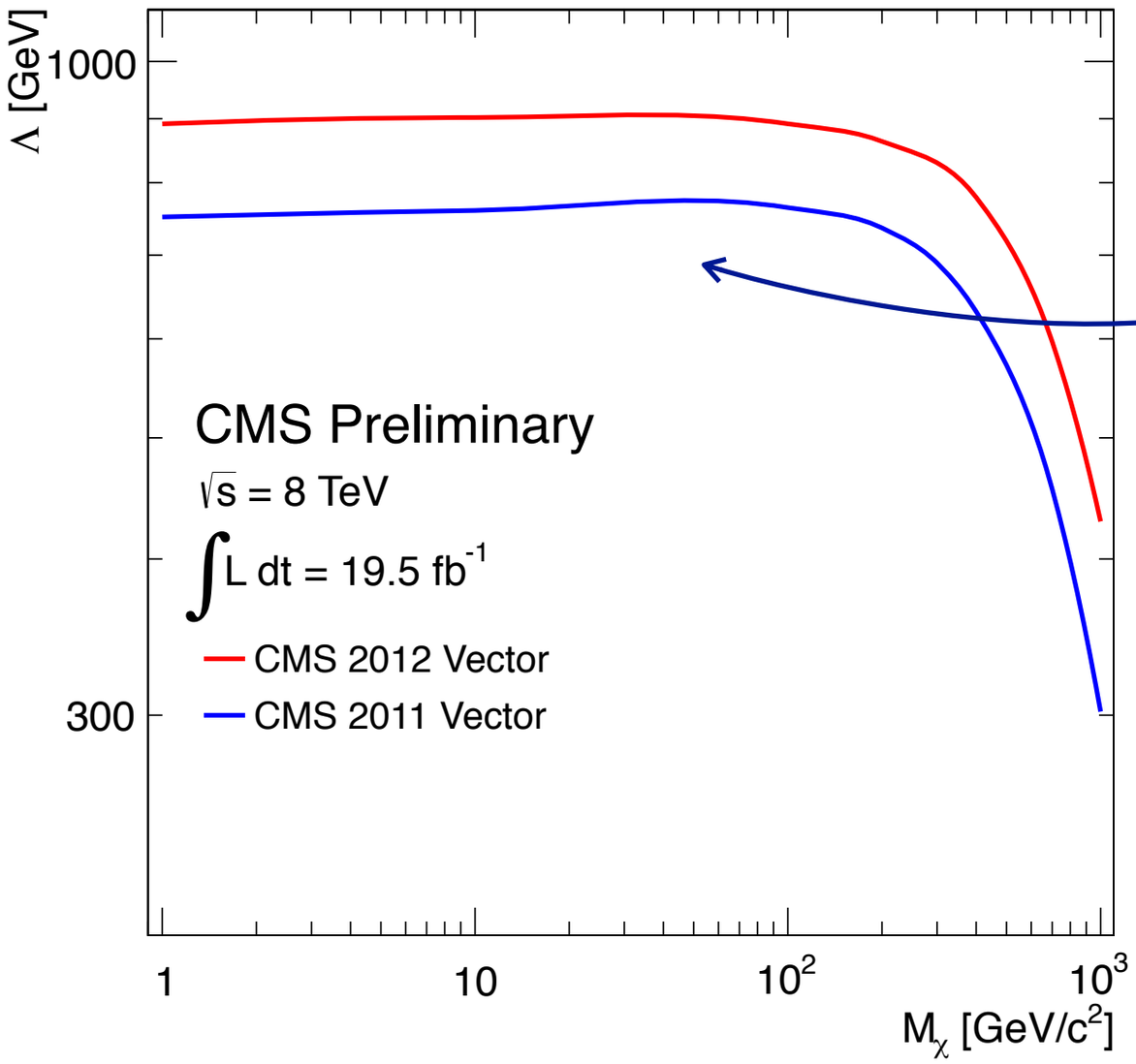
Look for mono-anything:

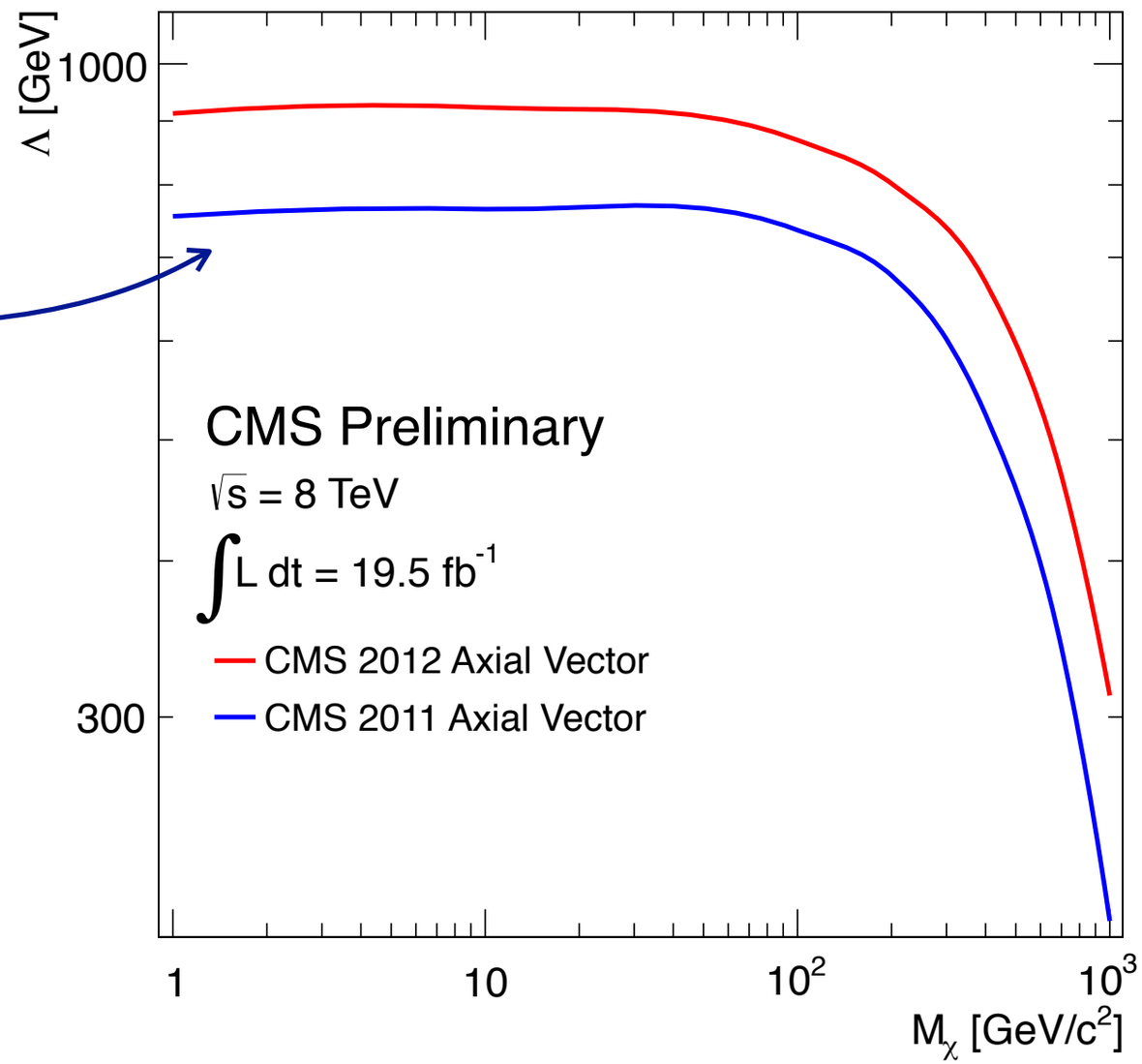
(mono-jet, mono-photon, mono-Z, mono-W, mono-di-jet...?)



Limits on $\Lambda \equiv \dfrac{M}{\sqrt{g_\chi g_1}}$:

same limit for SI and SD





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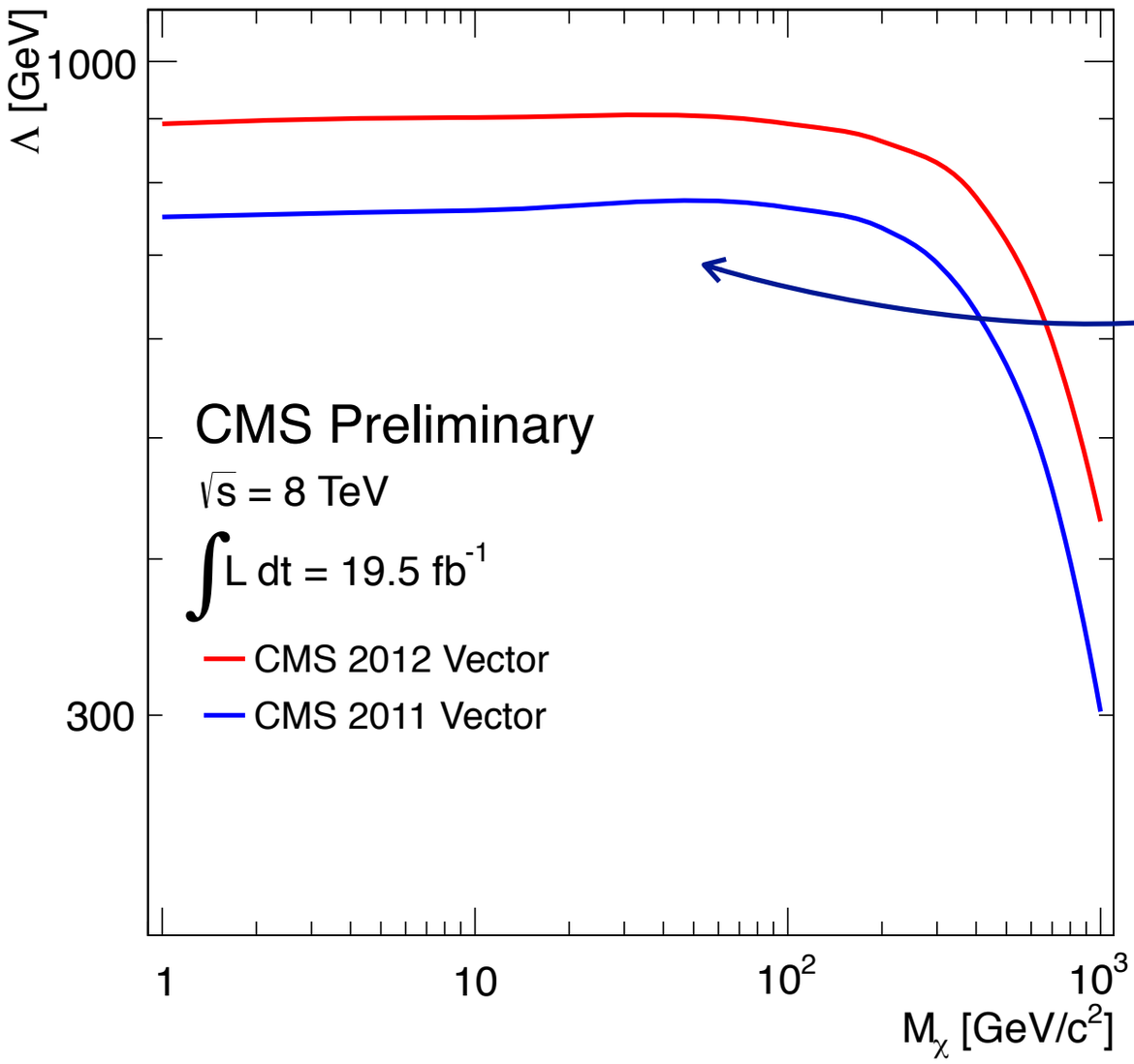
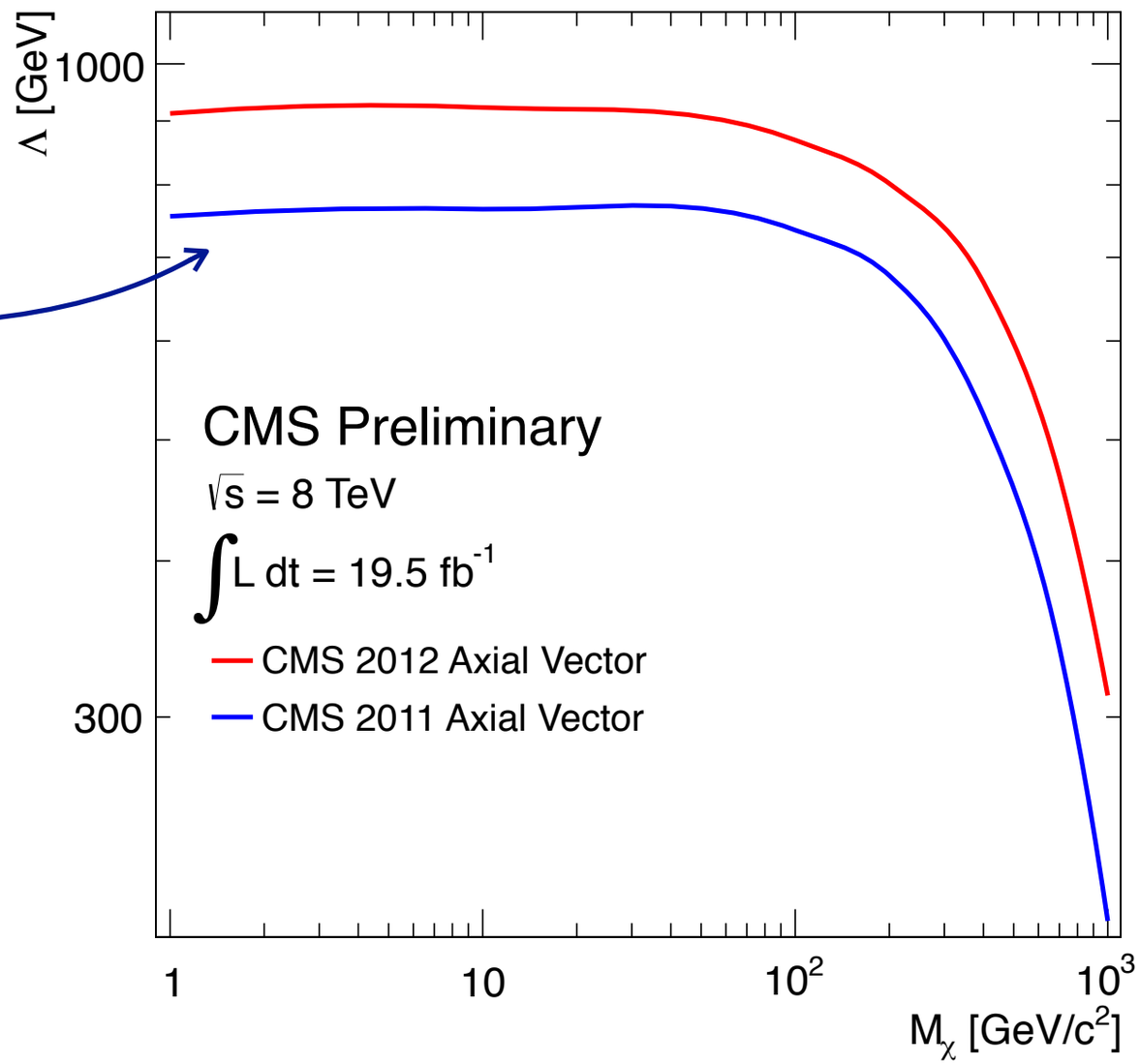
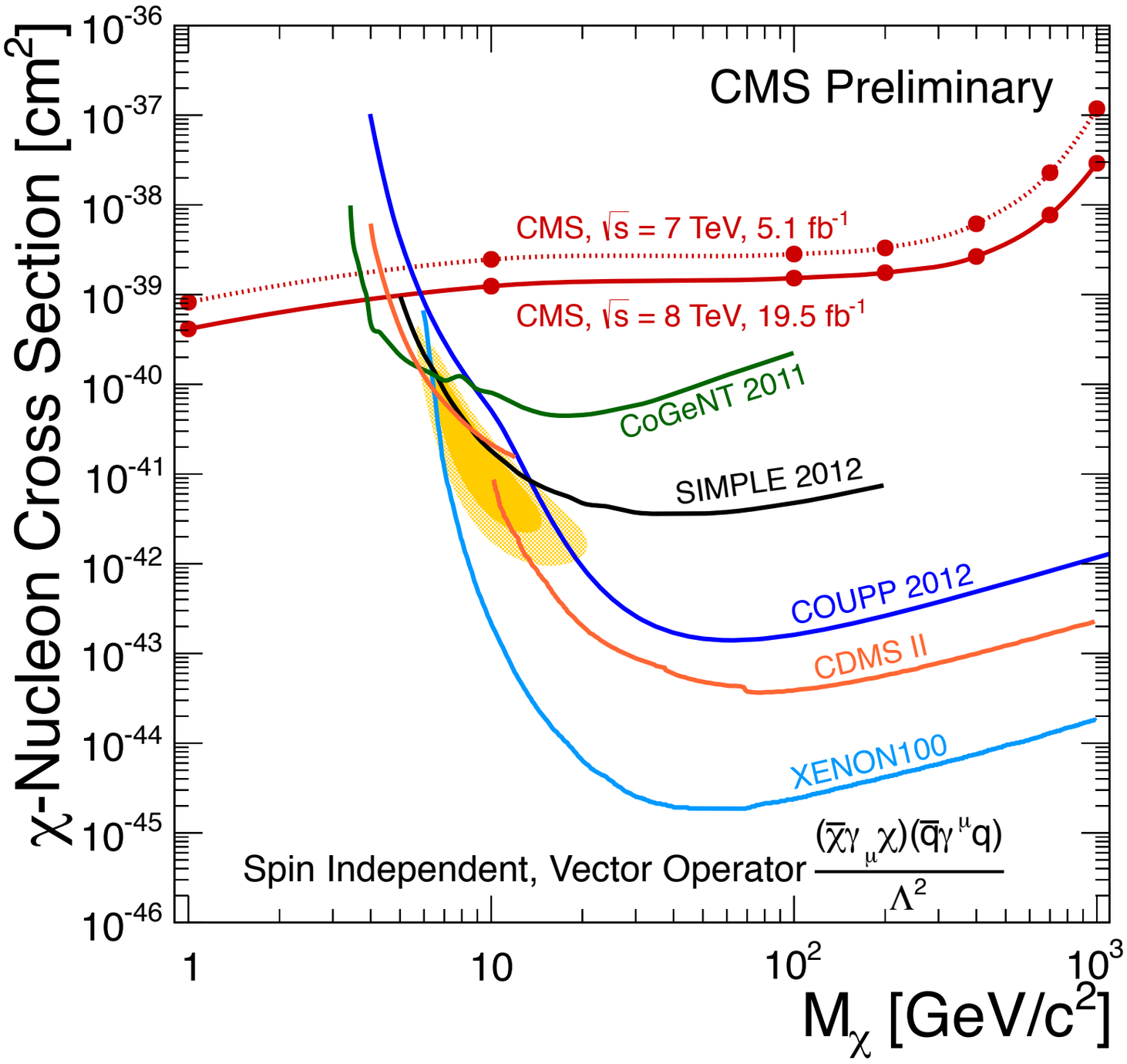




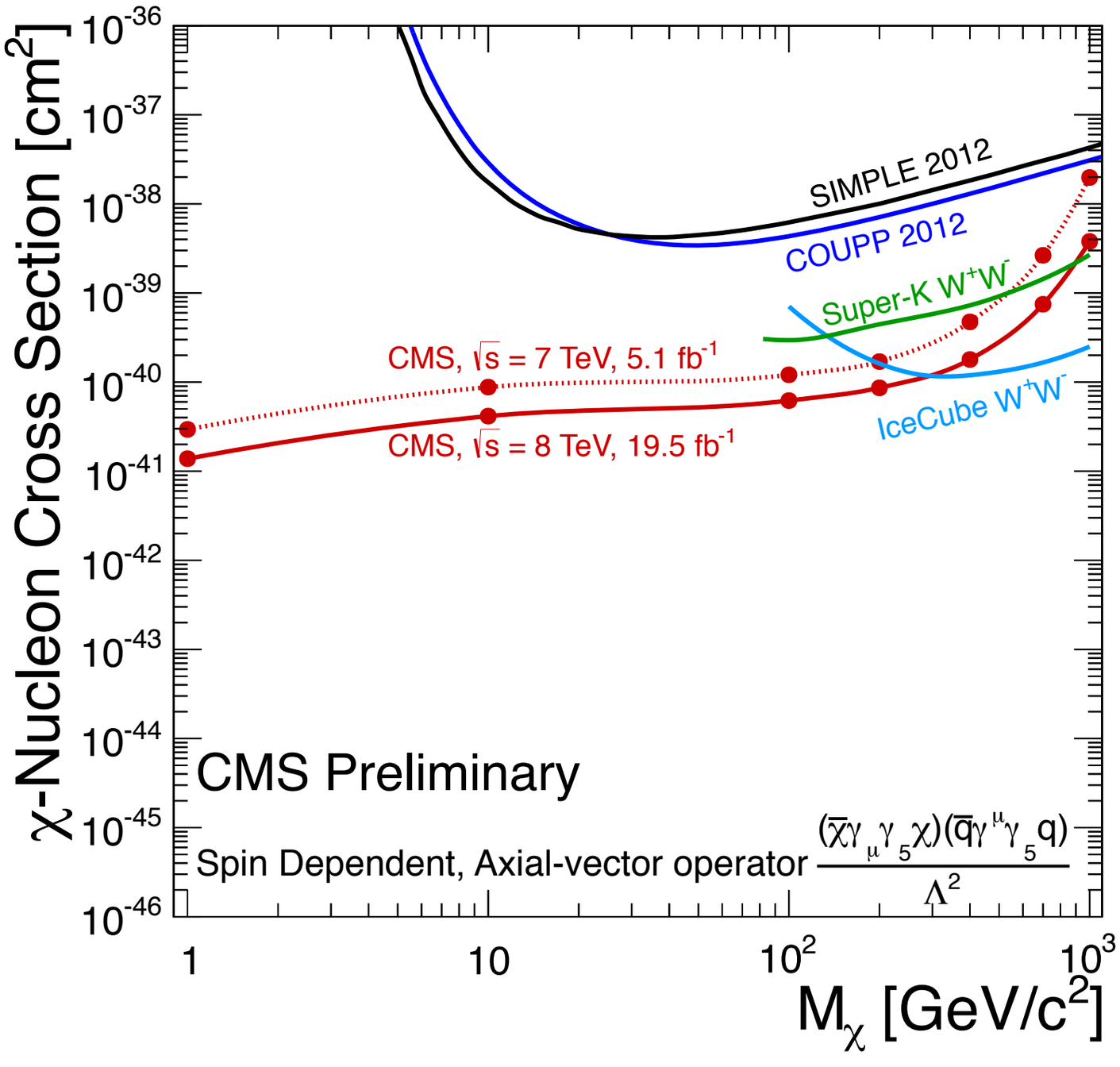
The limit is flat at low mass.

SI Limit



Strong limit at low mass

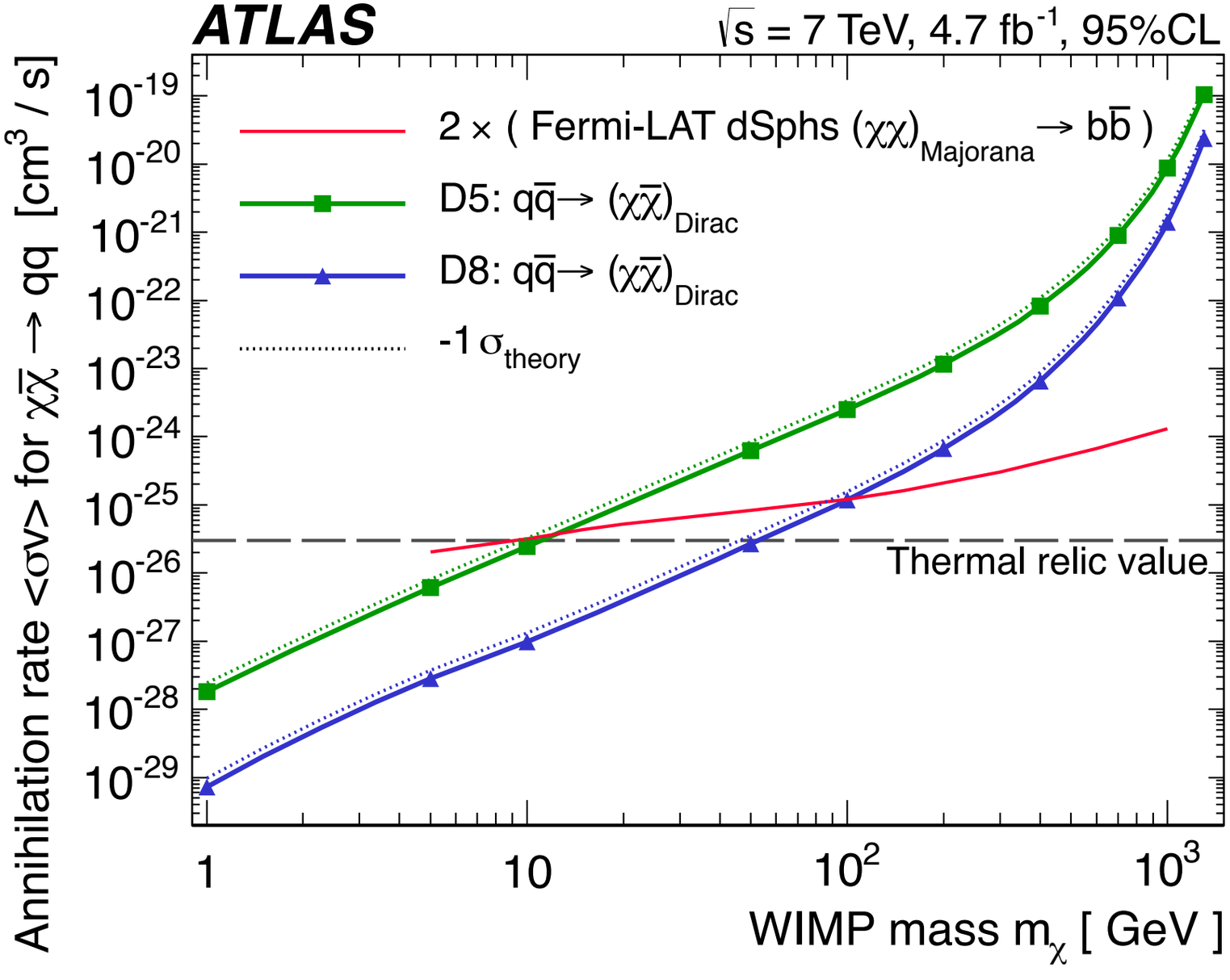
SD Limit



Strong spin dependent limit.

Annihilation

* A minimal light thermal relic is constrained:



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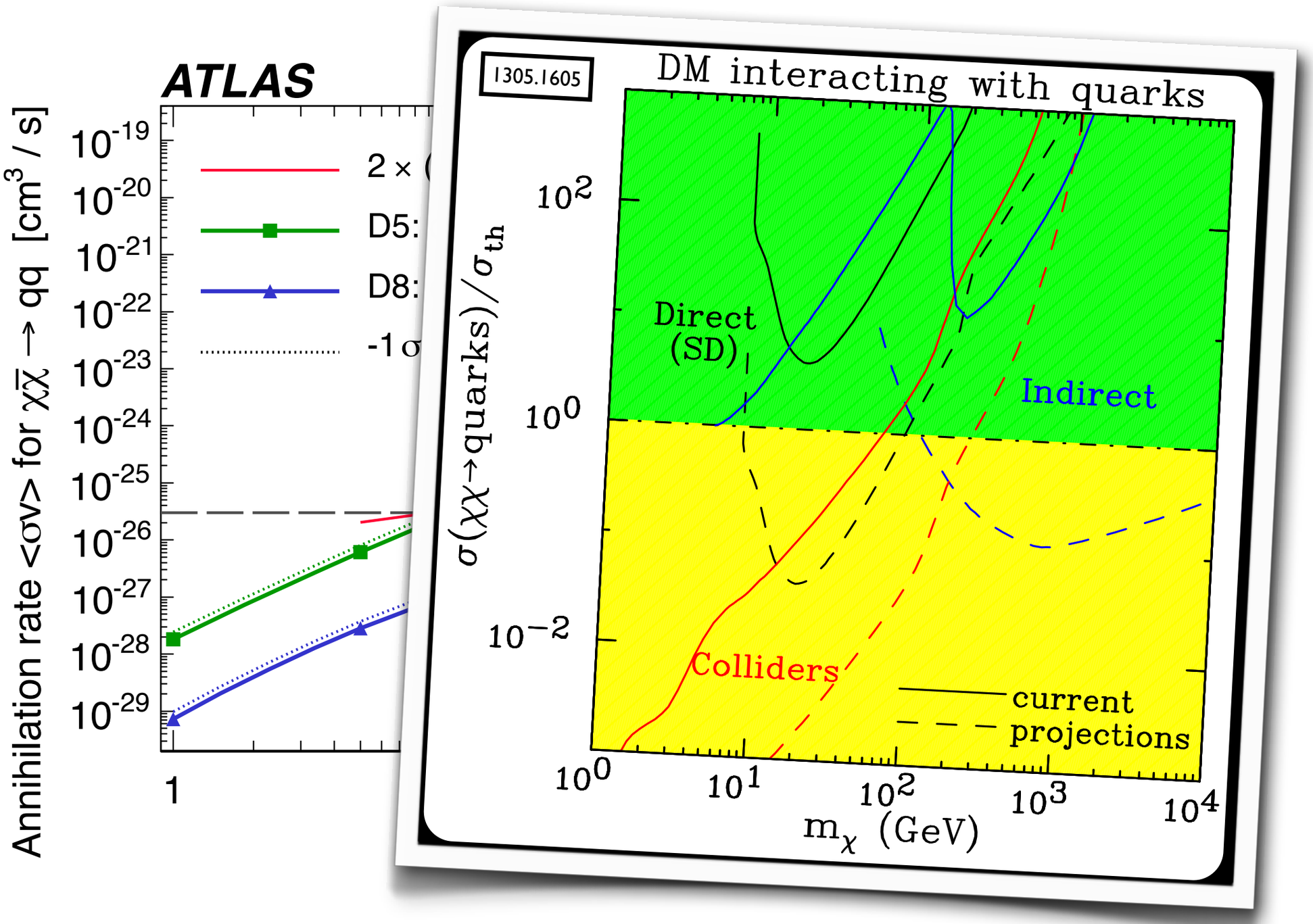


Is the EFT a valid description at LHC?

Two possibilities:

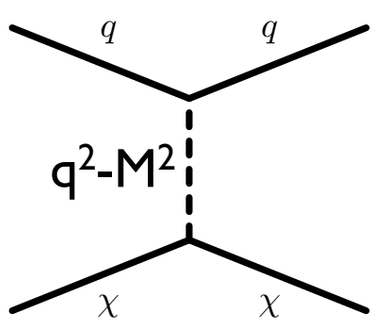
Is the EFT a valid description at LHC?

<u>Two possibilities:</u>

1) EFT is valid at LHC.
2) It's not.

EFT vs Light Mediator

* The EFT is valid for direct detection($q \sim 100\ \mathrm{MeV}$):

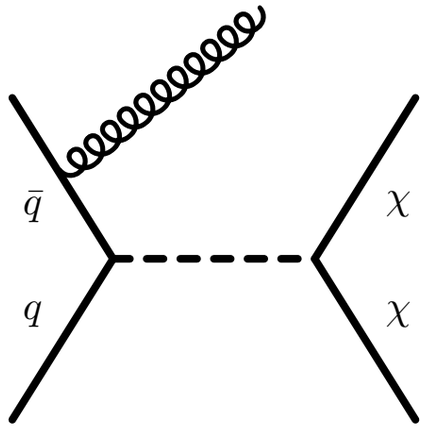


$$\sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

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

$$\Lambda \equiv \frac{M}{\sqrt{g_q g_\chi}}$$

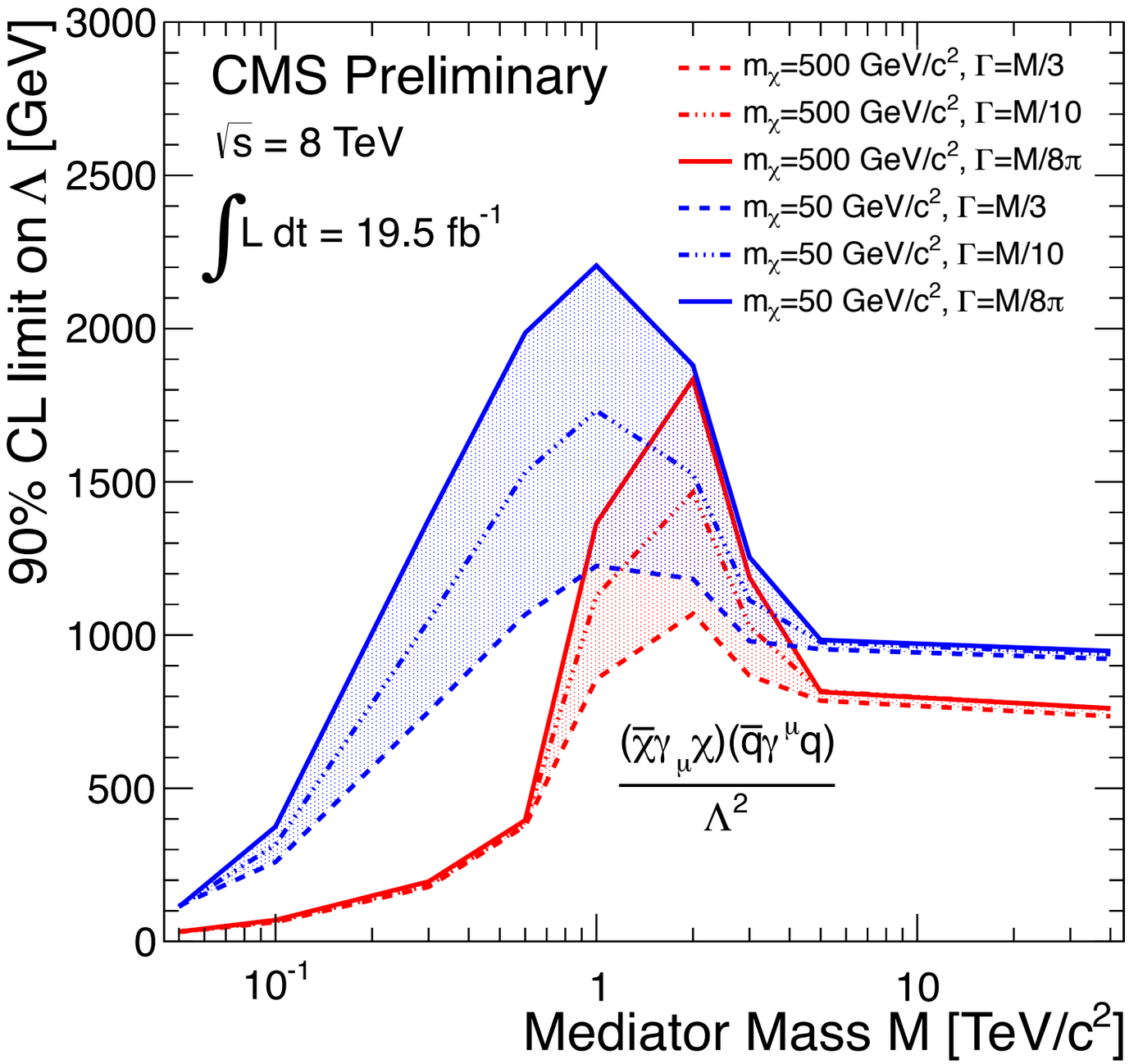
* At a collider consider two extreme limits:



$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \ll \sqrt{s_*} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M > \sqrt{s_*} \end{cases}$$

Light Madiator

* The limit become better before it gets worse:



EFT limits are **conservative** so long as the mediator is above ~ twice DM mass.

They are not valid for light mediator.

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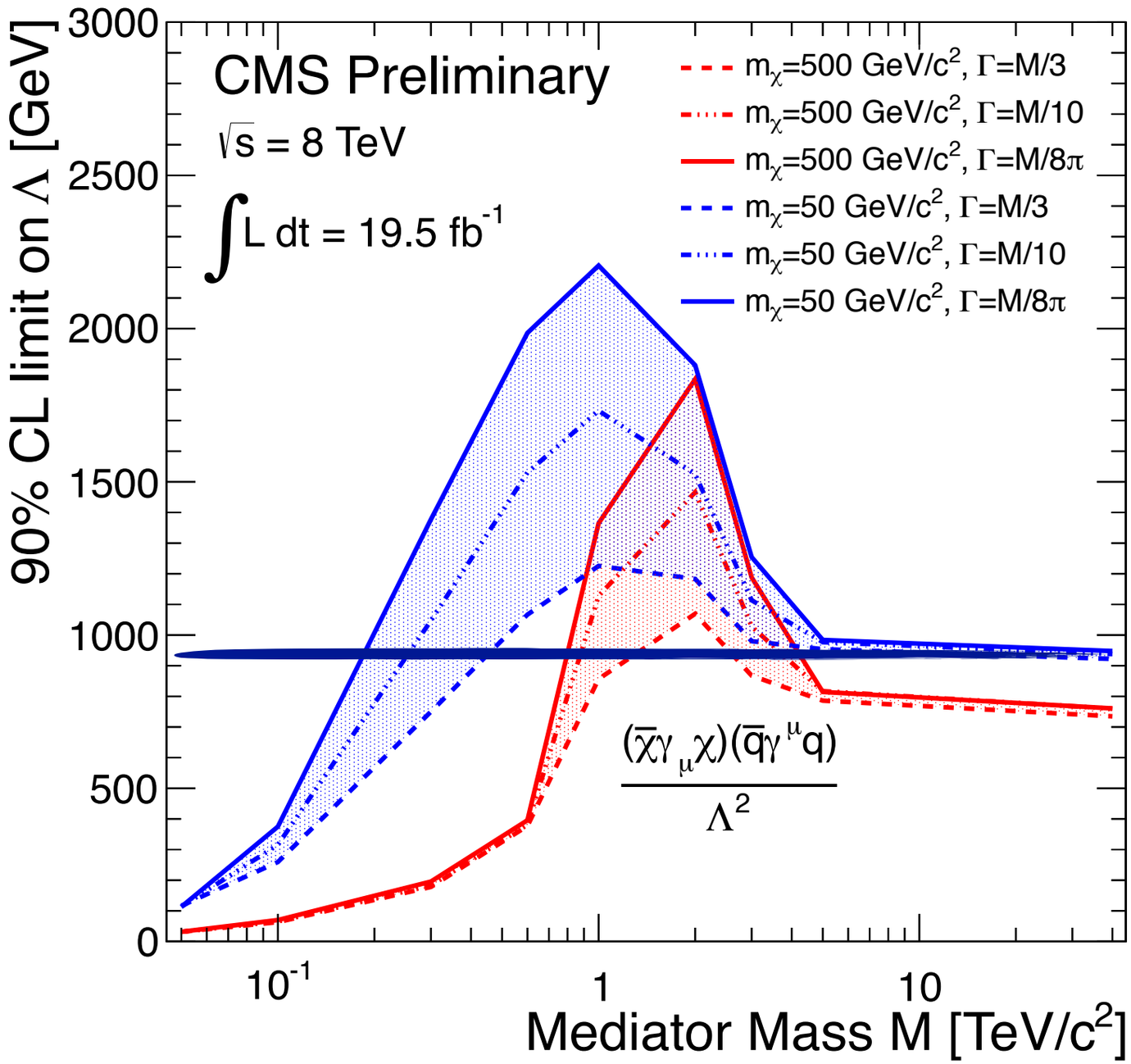

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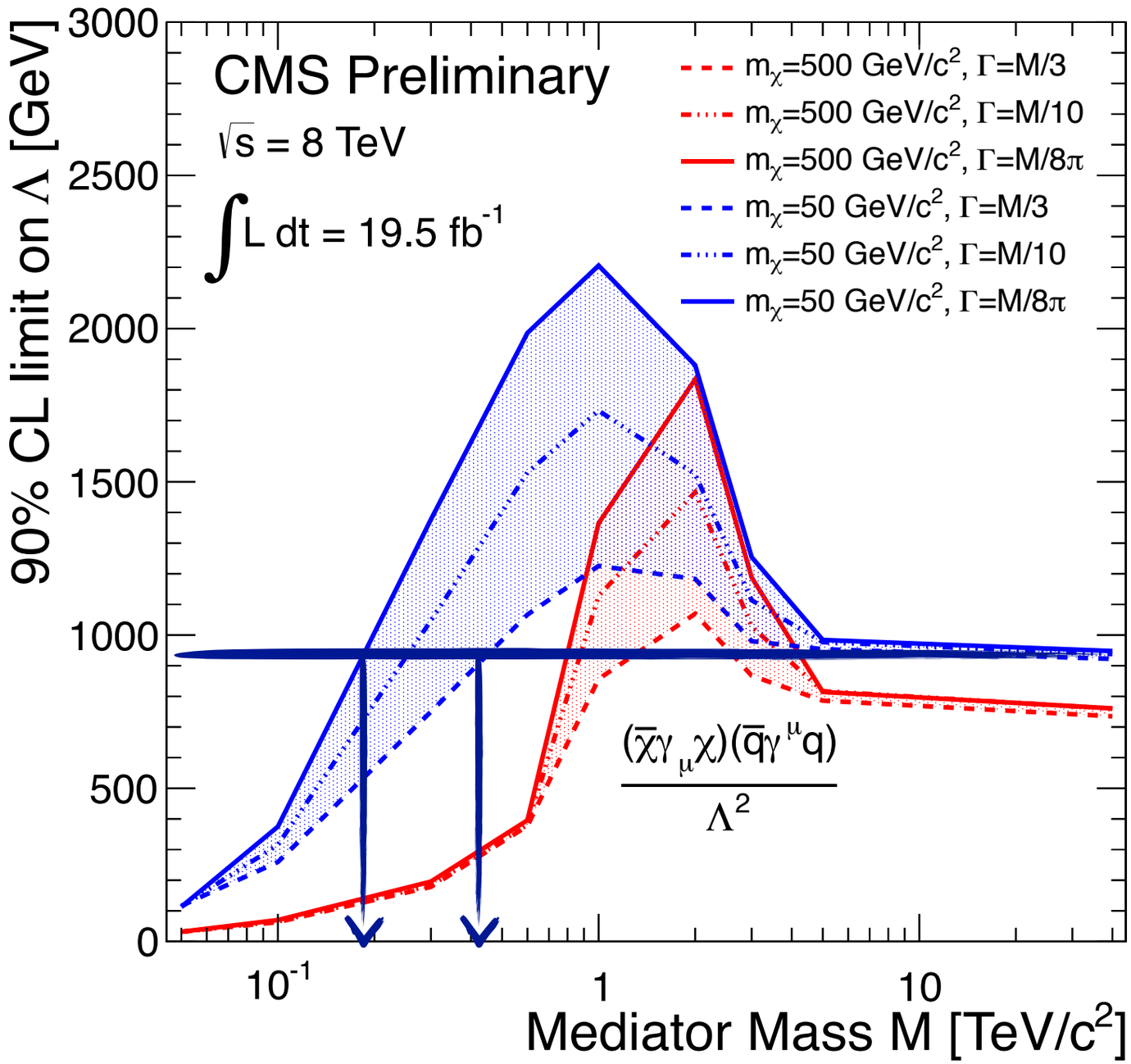

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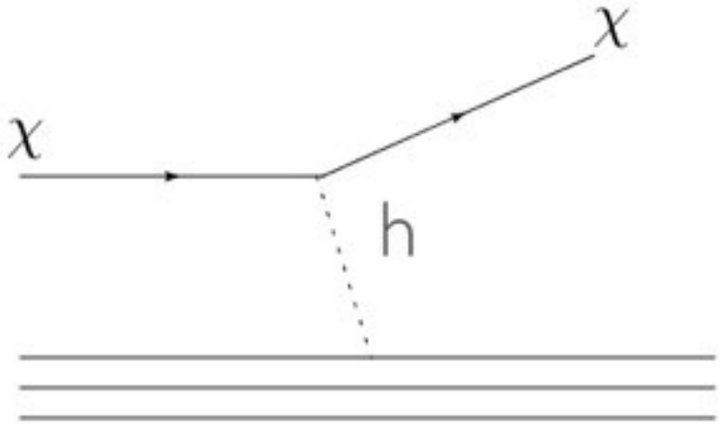
Simplified Model: Higgs

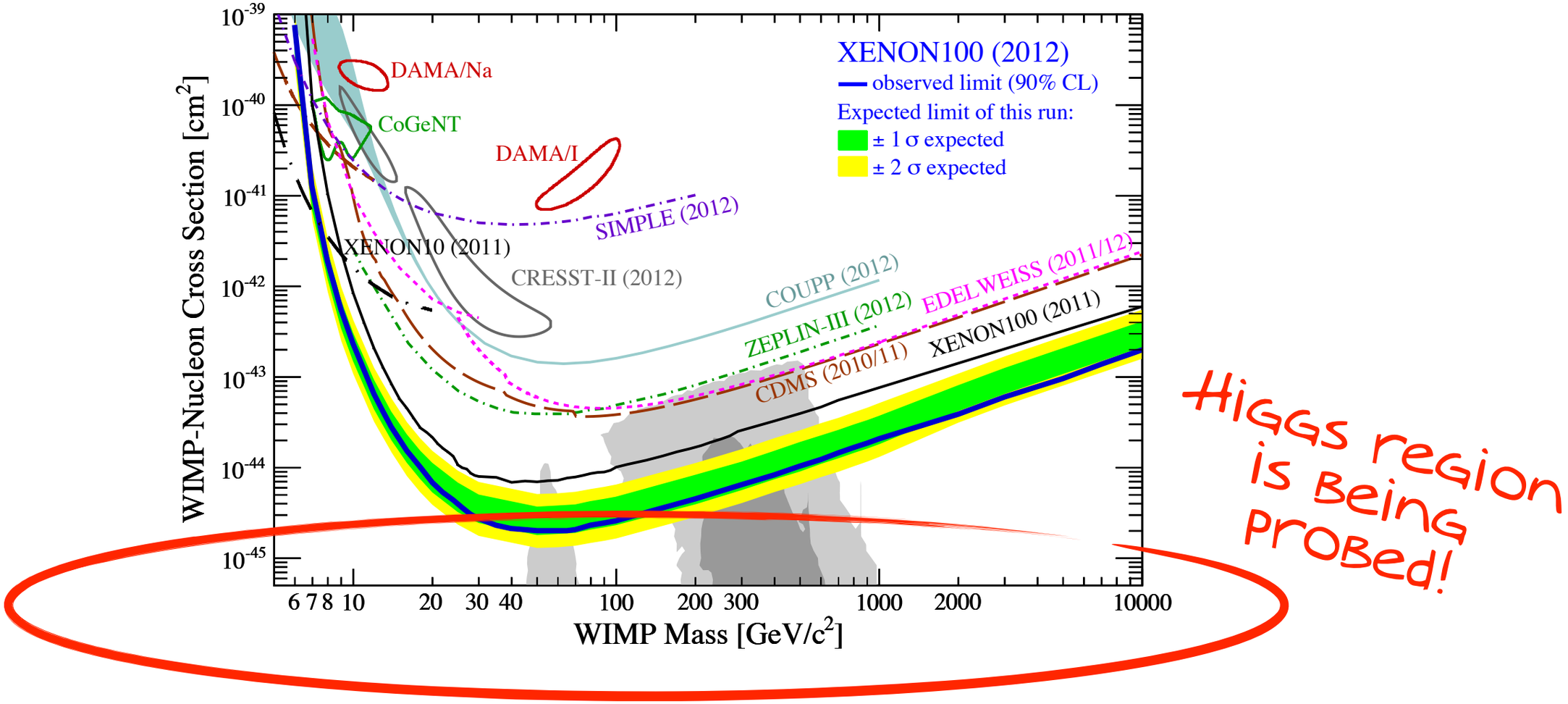
For other examples see talk
By Di Franzo this afternoon.

Higgs Mediation

DM exists
+
Higgs exists

$\stackrel{?}{=}$



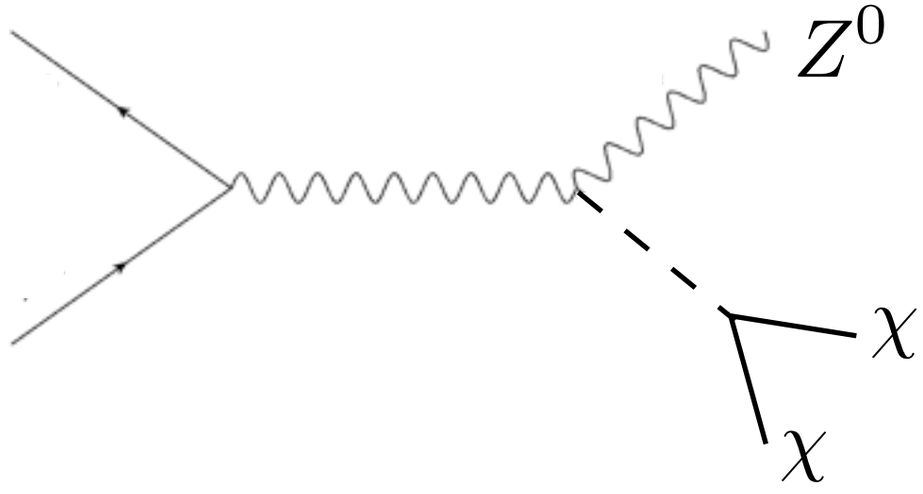


Higgs mediation

* Direct detection will not cover light DM. But...

DM is light
+
couples to Higgs

= Invisible h decay!

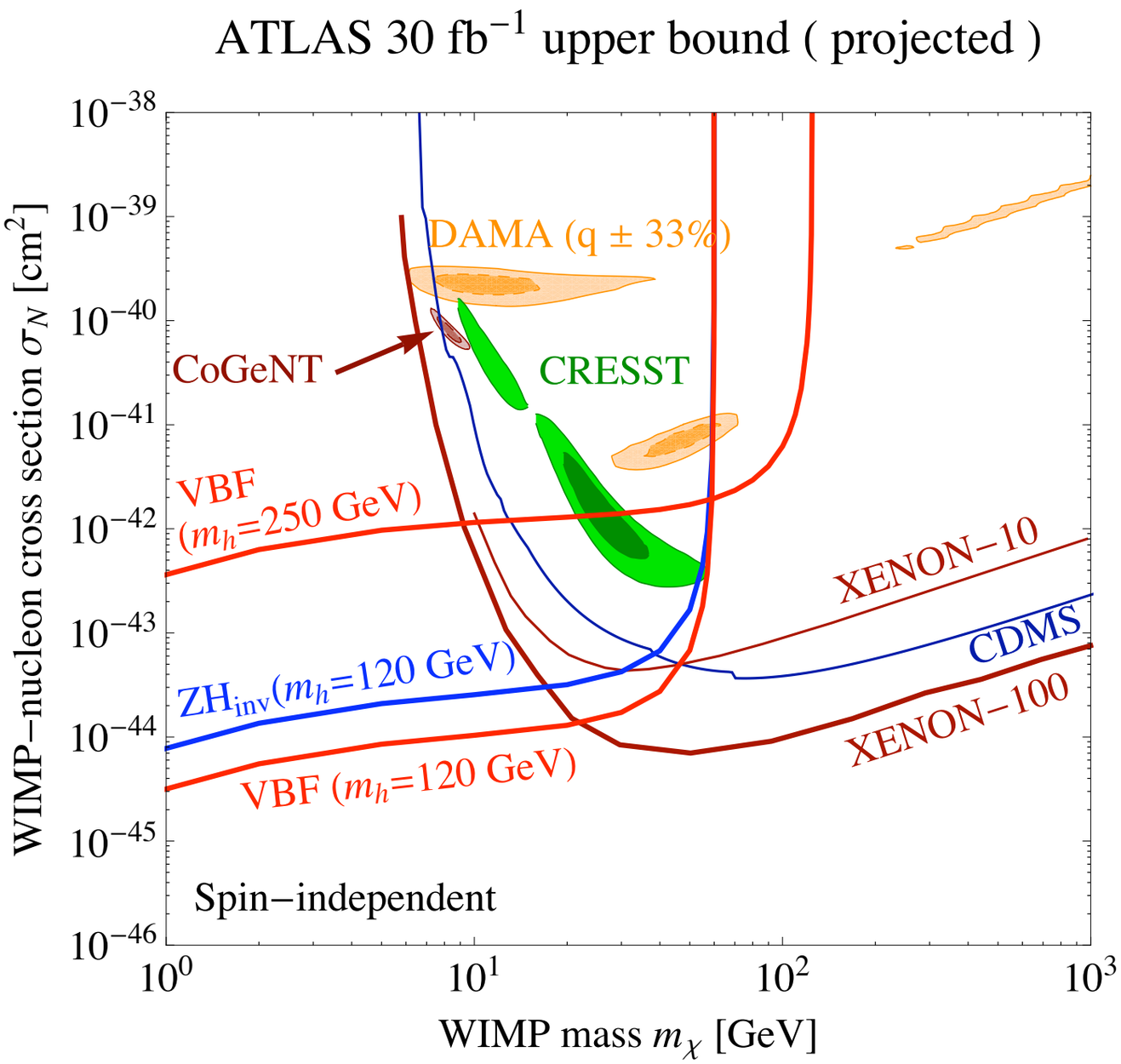


current ATLAS limit:
BR(h→inv)<65%

(David's Talk)

(Higgs is narrow!
a strong limit on
h-DM coupling)

Higgs Mediation



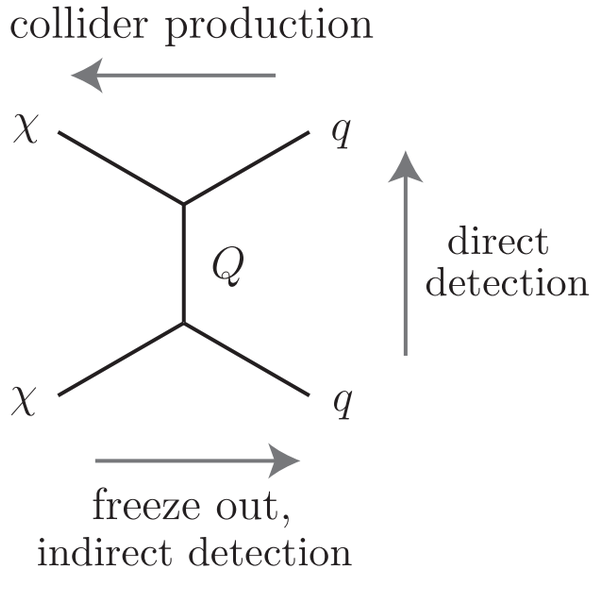
Complementary.

Higgs window will be fully covered!

Other Simplified Models

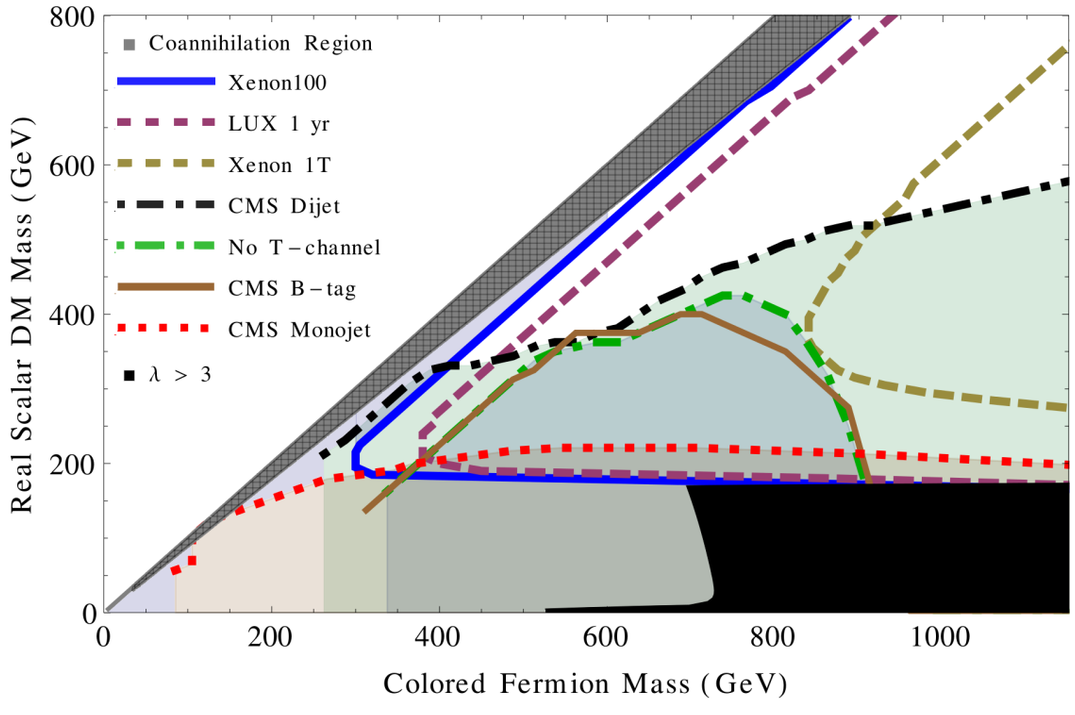
* "Squark mediator":

  Chang et al. 1307.8120
  Bai and Berger 1308.0612
  Di Franzo et al 1308.2679



* Small parameter space:

  (e.g. can fix coupling from relic density)



Conclusion

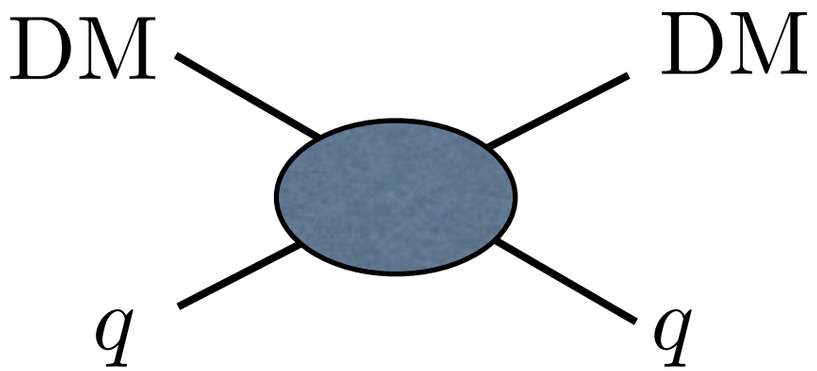
* **The LHC is also looking for DM.**
* The precise mapping of limits is model dependent.
* LHC searches are often **complementary**:
  - Low mass.
  - Spin dependent.
  - Invisible Higgs.

Sales Pitch.

Probes of DM Interactions

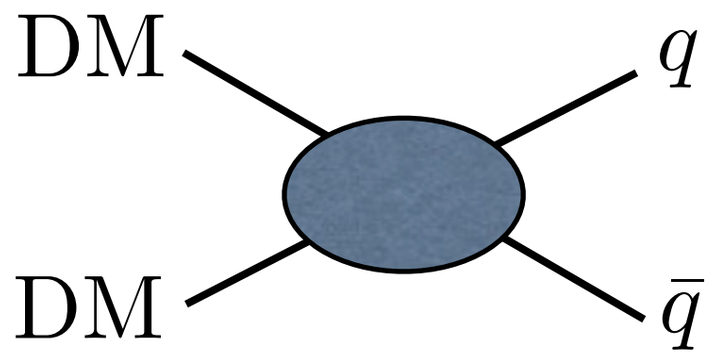
* "WIMP coincidence" hints that DM has is an interaction w/ matter. picobarn-ish cross sections!?
* We hope to probe dark matter in several ways:

DM-nucleus scattering



direct

DM annihilation

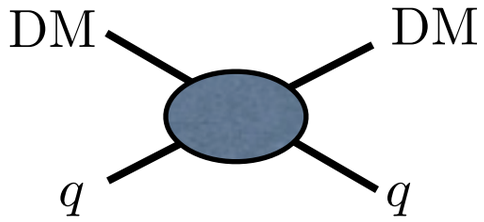


indirect

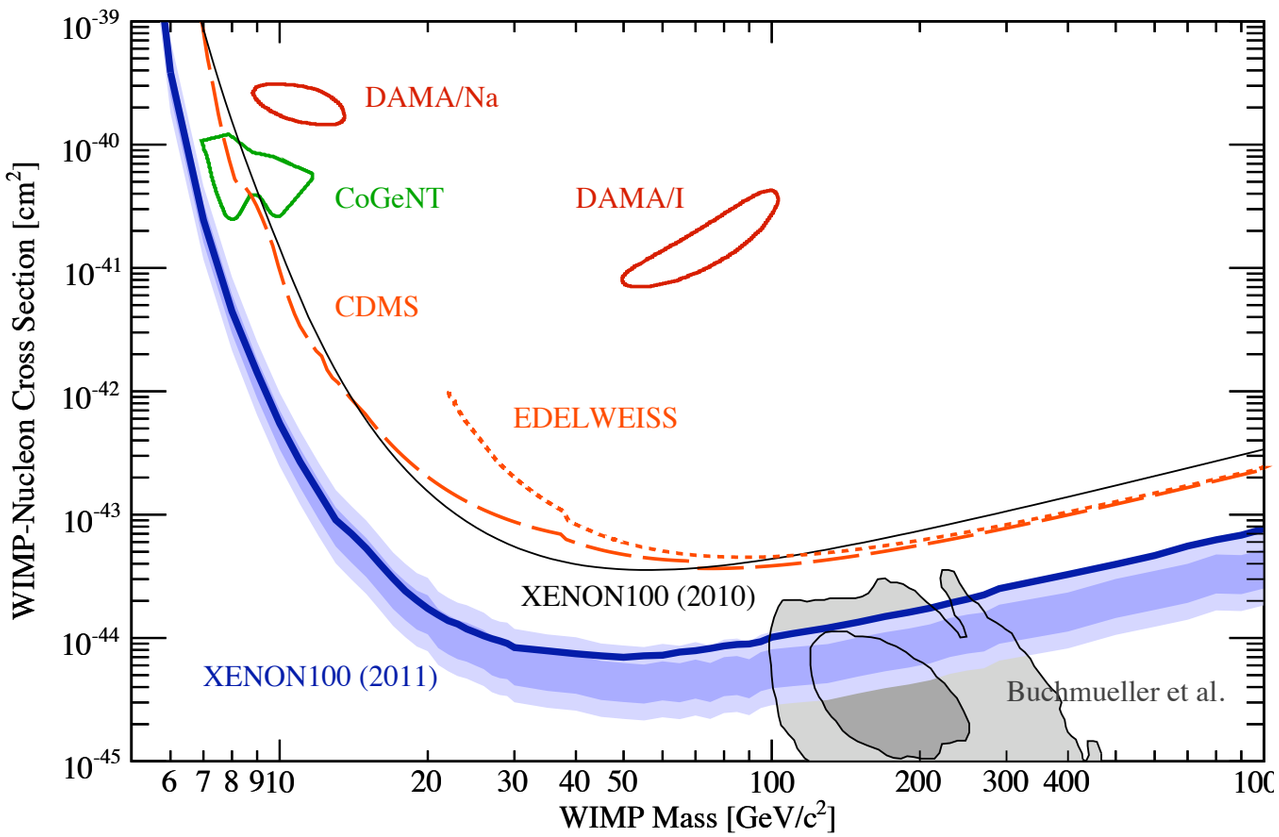
Focus on direct detection in this talk.

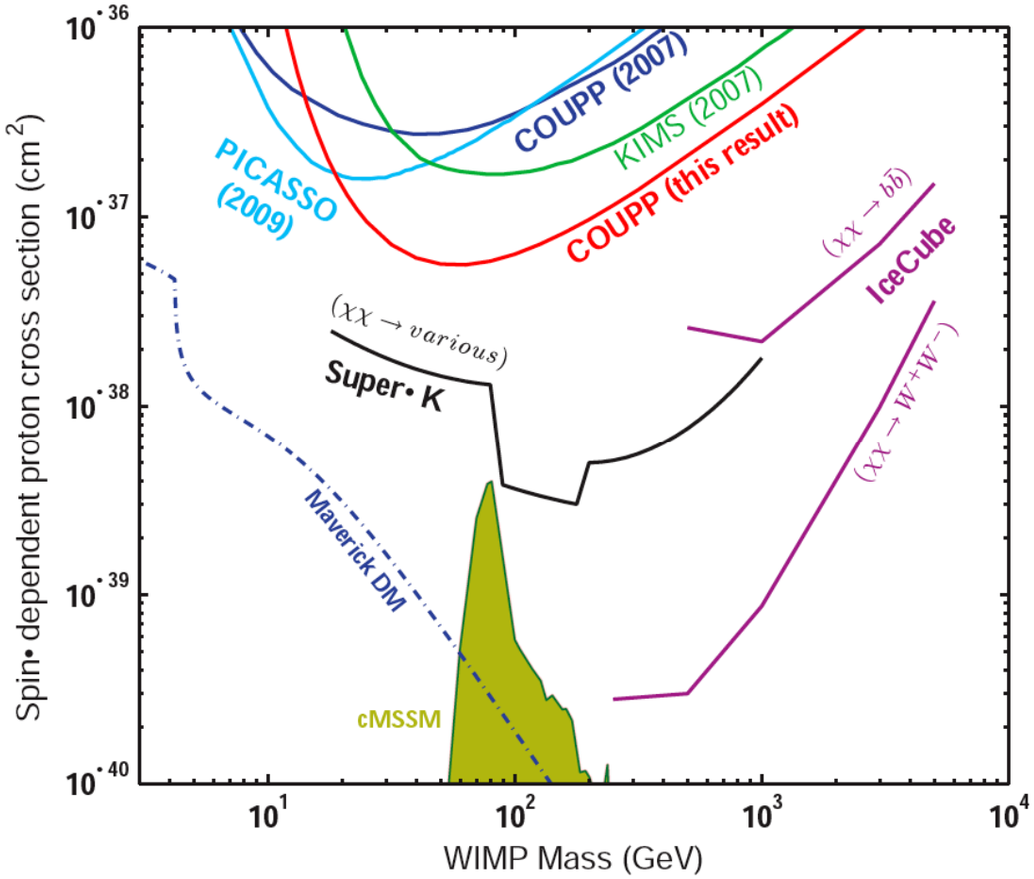
(a similar game can be played for indirect)

Direct detection



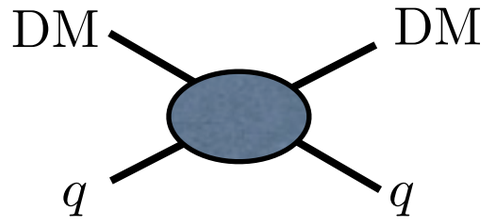
* Direct detection places limits on .
* Heroic effort with remarkable results.
* DD has some weaknesses.





What do colliders tell us about this parameter space?

Direct detection



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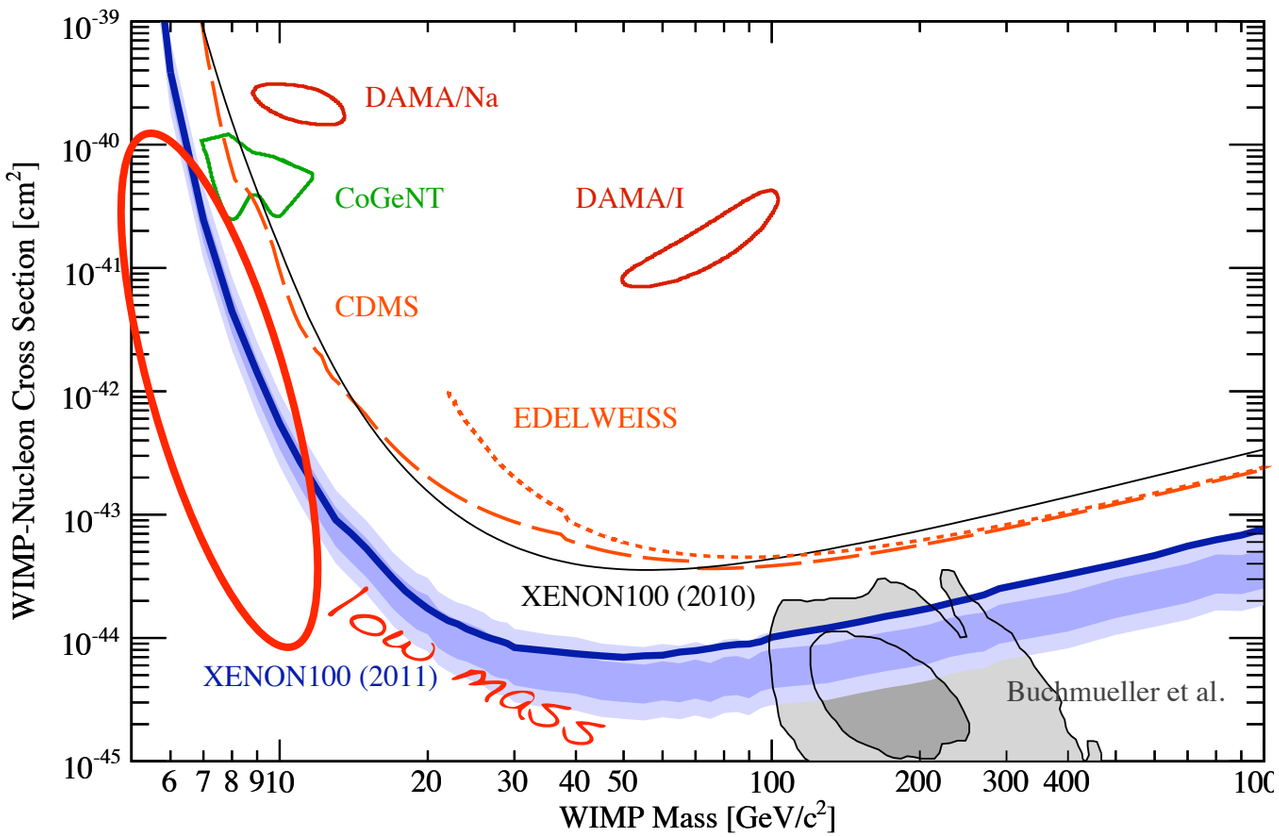

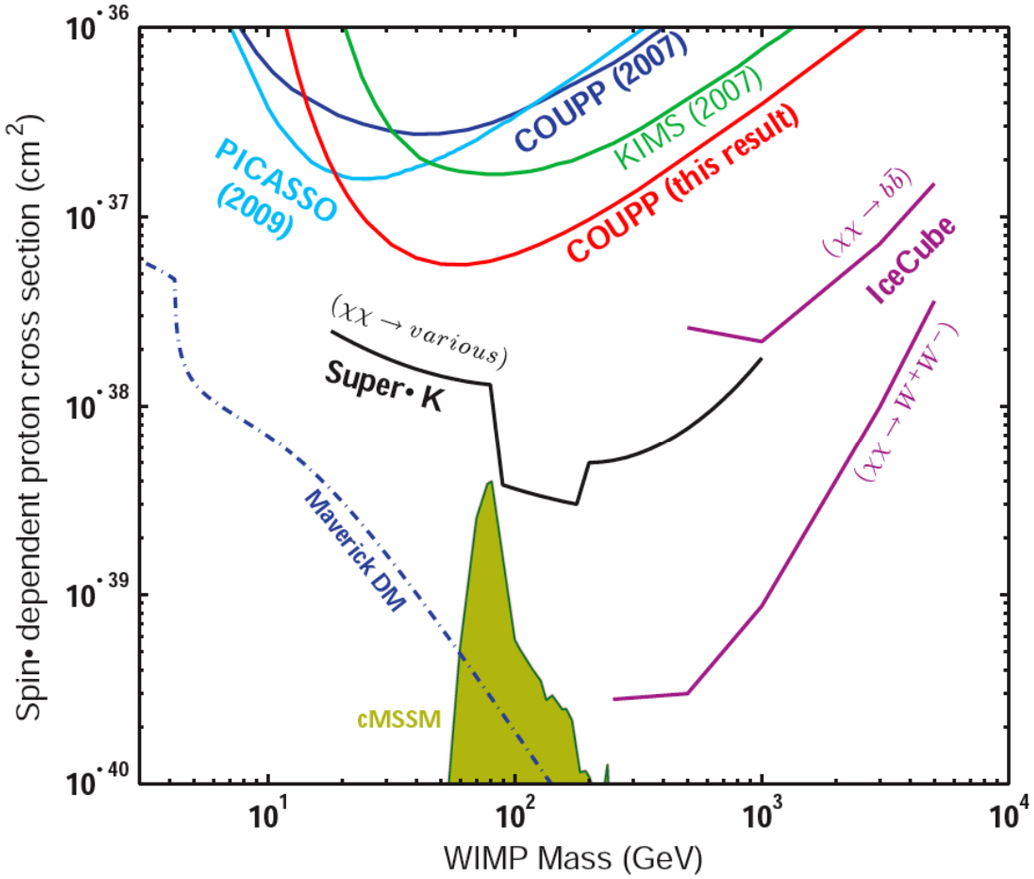

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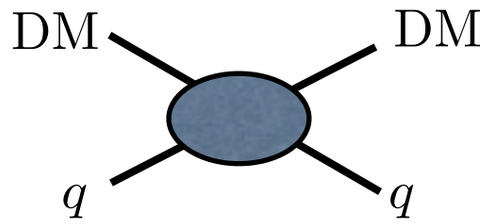

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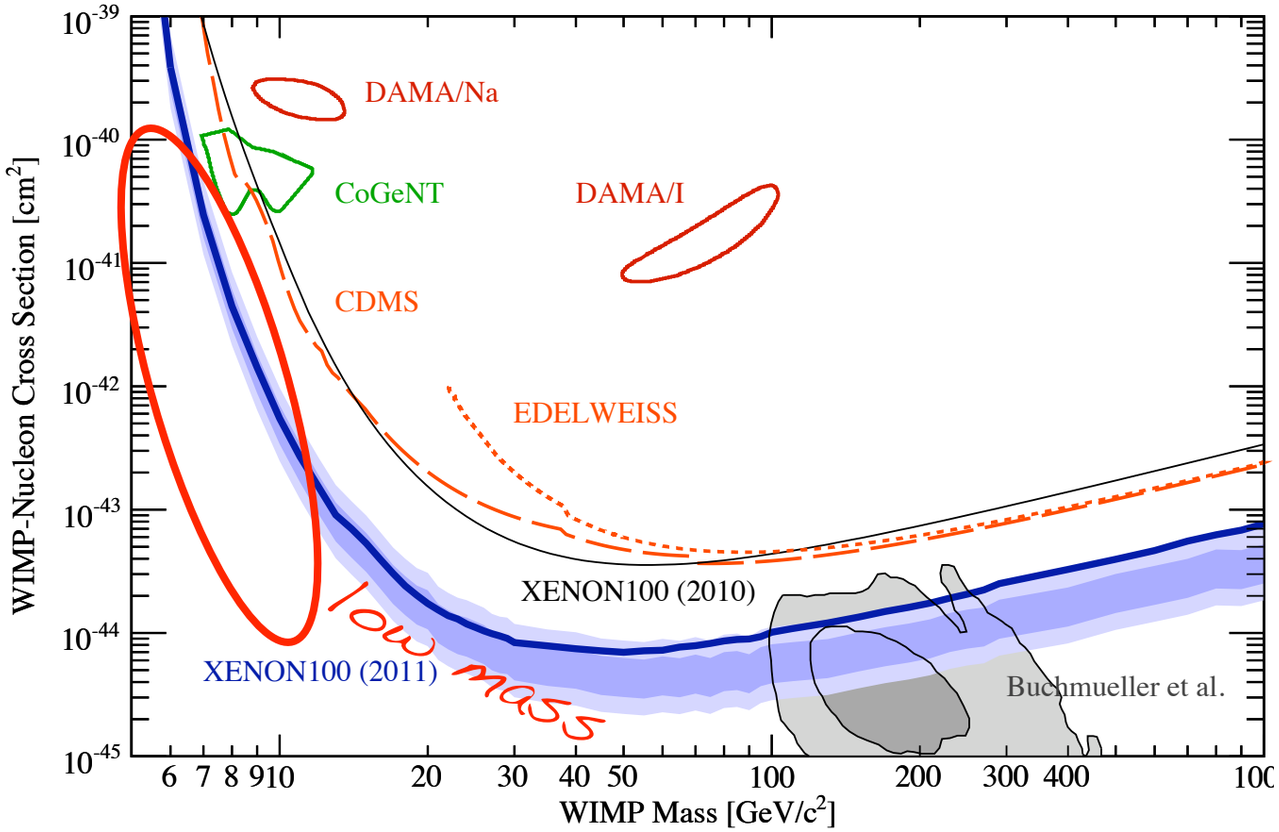
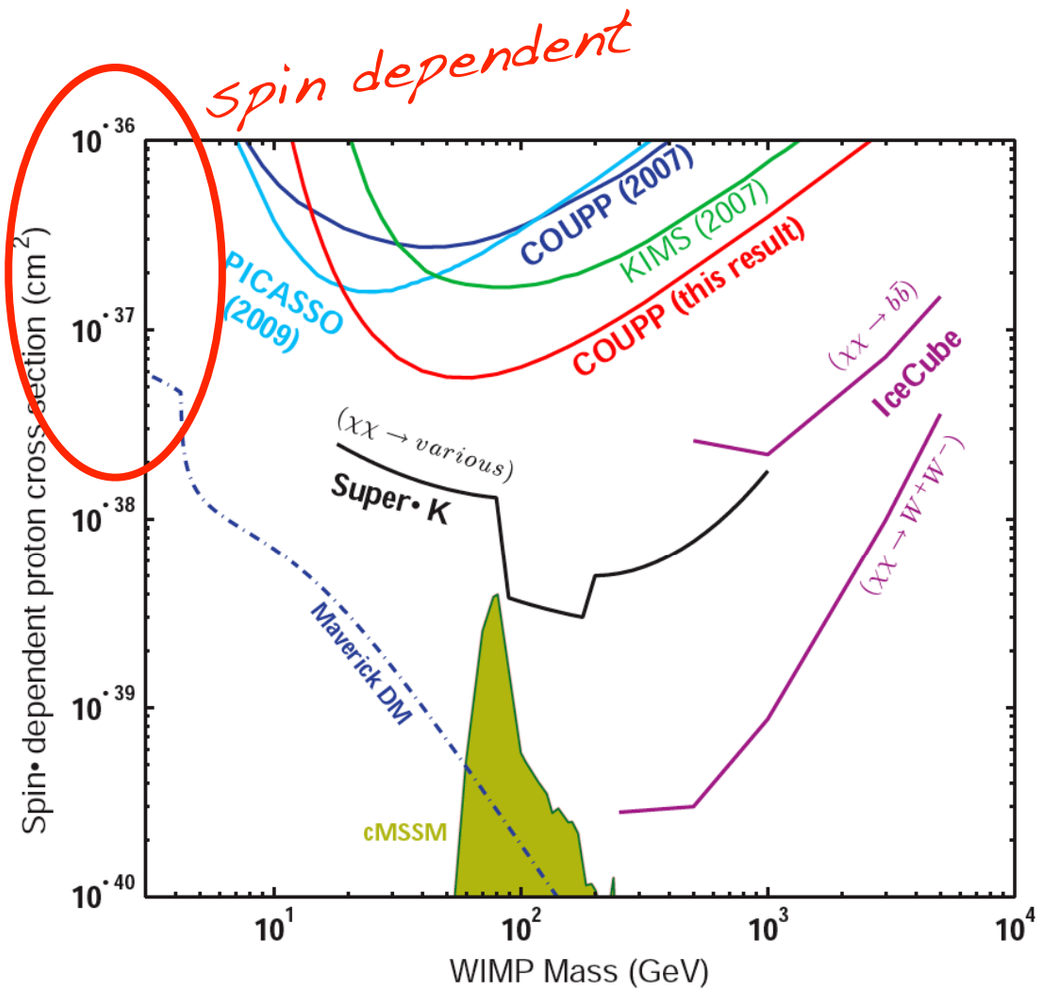
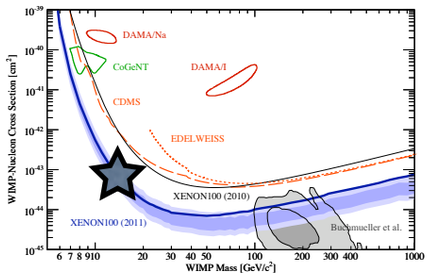
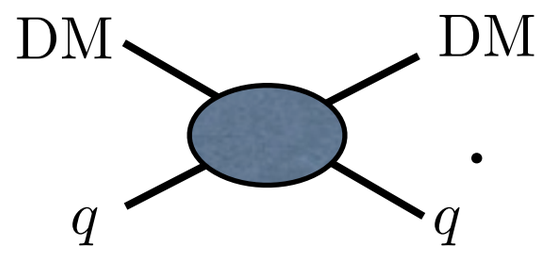




What do colliders tell us about this parameter space?

A Simple Point

* In order to get a particular DM-nucleon cross section, 

, we assume the existence of a DM-hadron interaction, 

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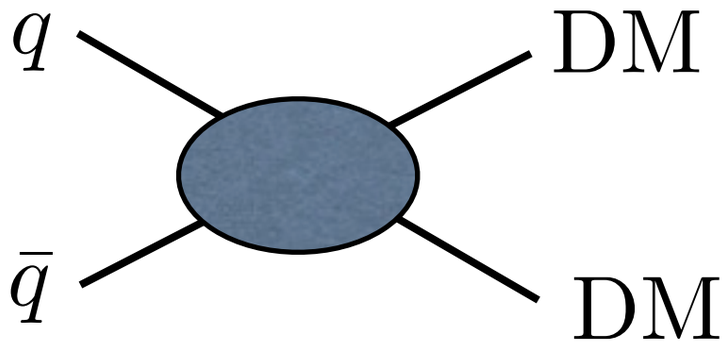
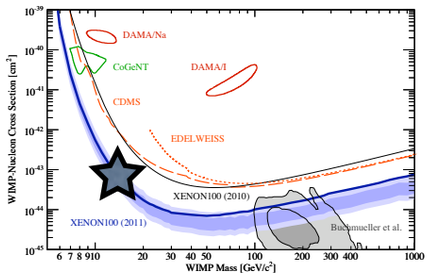
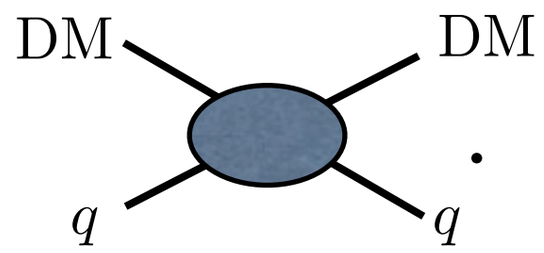
* The same interaction can lead to DM production at a hadron machine.



$$p\bar{p} \rightarrow \text{ nothing}$$

A Simple Point

* In order to get a particular DM-nucleon cross section, 

, we assume the existence of a DM-hadron interaction, 

.

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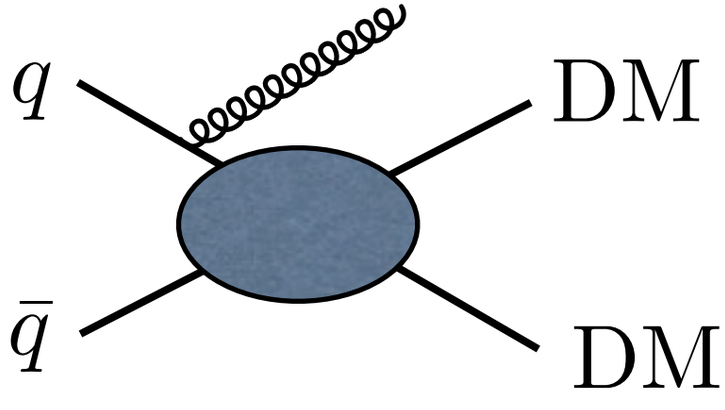
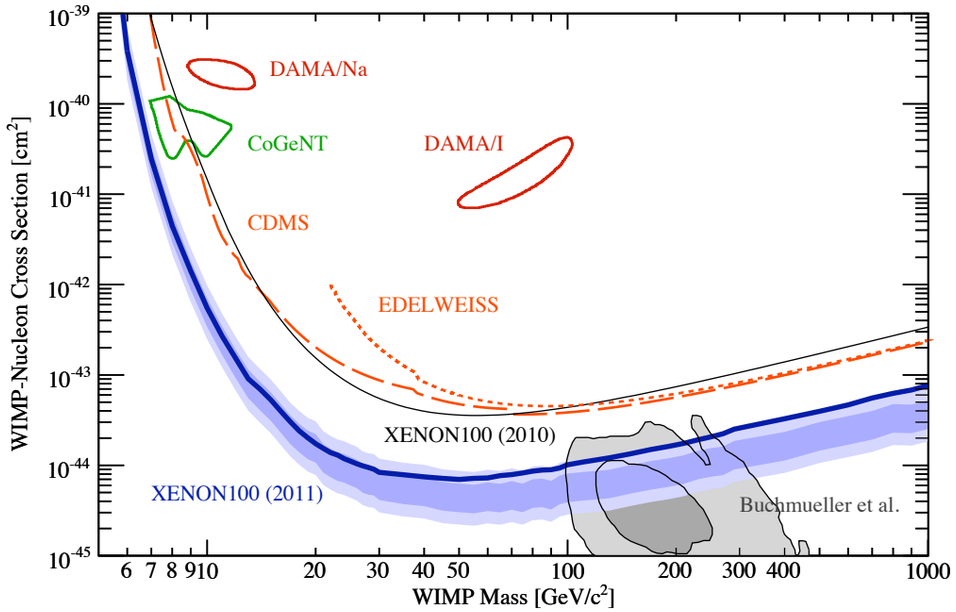
* The same interaction can lead to DM production at a hadron machine.

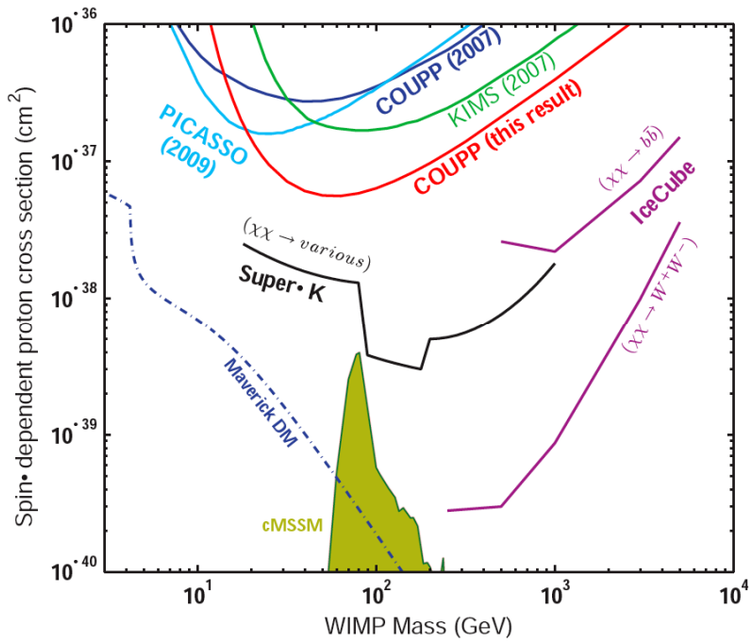


$$p\bar{p} \longrightarrow j + \not{E}_T$$

A Simple Point

* **Mono-jet searches can place limits on the direct detection plane.**



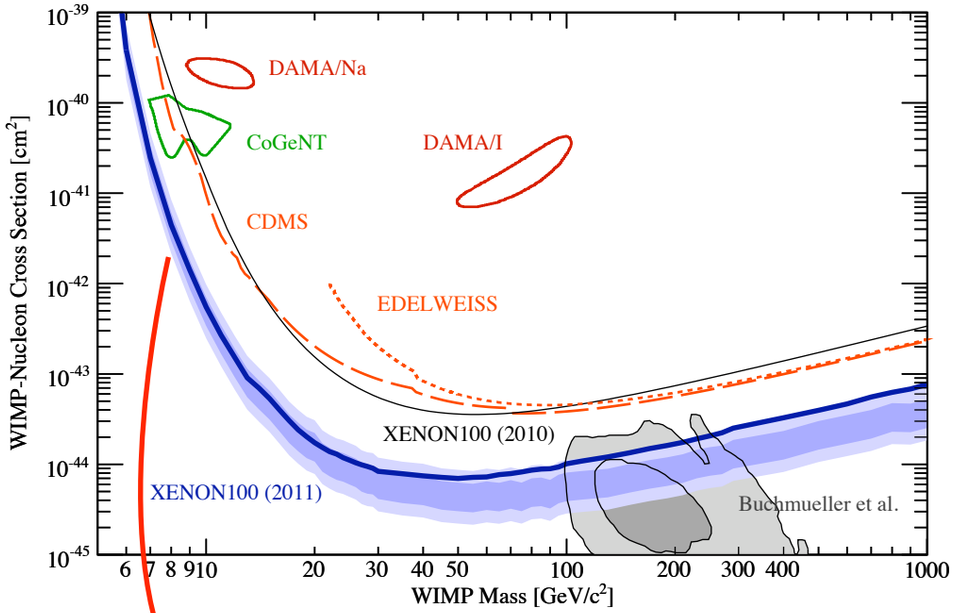


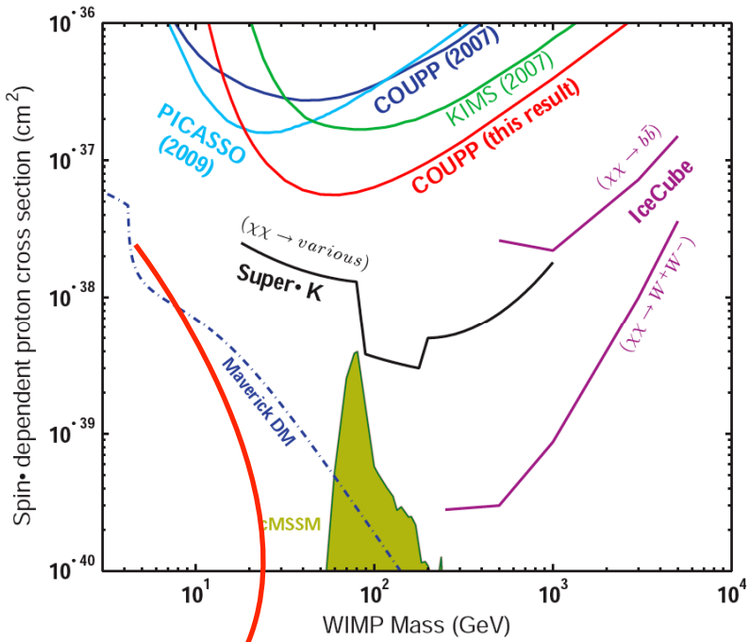
* These are **conservative** limits.
  In a specific model there may be other ways to produce DM, e.g. through cascades from heavy colored states.

But mono-jet are certainly good to set bounds.

A Simple Point

- **Mono-jet searches can place limits on the plane.**





The collider does not have a low energy threshold

The collider does not pay a price for spin dependence

Direct Detection - EFT

* The EFT that described DM interaction in direct detection experiments:

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}\,,$$ 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 (or SD), t-channel "squark exchange"

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

---

Two possibilities:

Direct Detection - EFT

* The EFT that described DM interaction in direct detection experiments:

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

SI, vector exchange

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SI (or SD), t-channel "squark exchange"

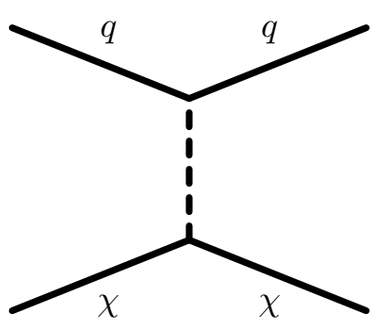
$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}$$

SI gluon operator

Two possibilities: 1) EFT is valid at LHC.
2) It's not.

EFT vs Light Mediator

* The EFT is valid for direct detection($q \sim 100\ \mathrm{MeV}$):

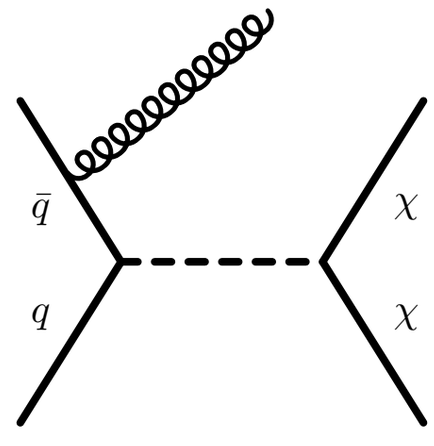


$$\sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

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

$$\Lambda \equiv \frac{M}{\sqrt{g_q g_\chi}}$$

* At a collider consider two extreme limits:



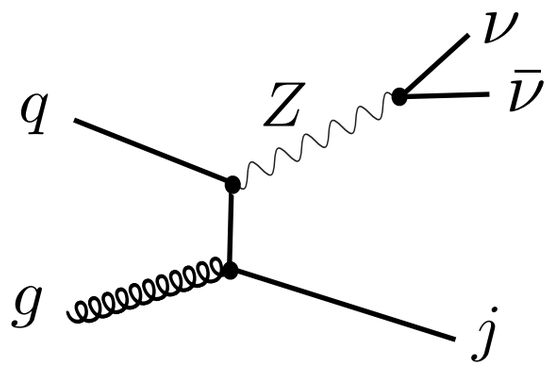
$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \ll \sqrt{s_*} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M > \sqrt{s_*} \end{cases}$$

Handles for S vs B
&
Inclusive Jets plus MET

Mono-Jet

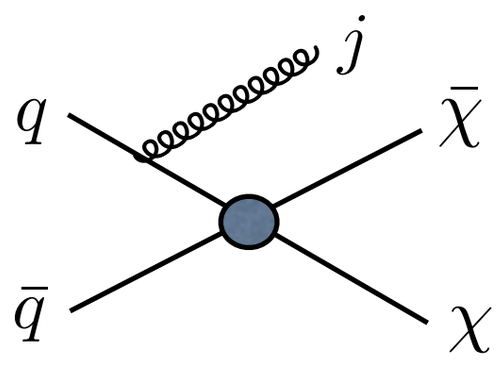
* *Assume* the EFT is valid at the LHC.
* Consider contact operator involving u or d.
* The signal spectrum is harder than backgrounds.

<u>dominant background</u>:
Z plus jet (qg initial state).



Z is typically emitted forward, with low p_T.

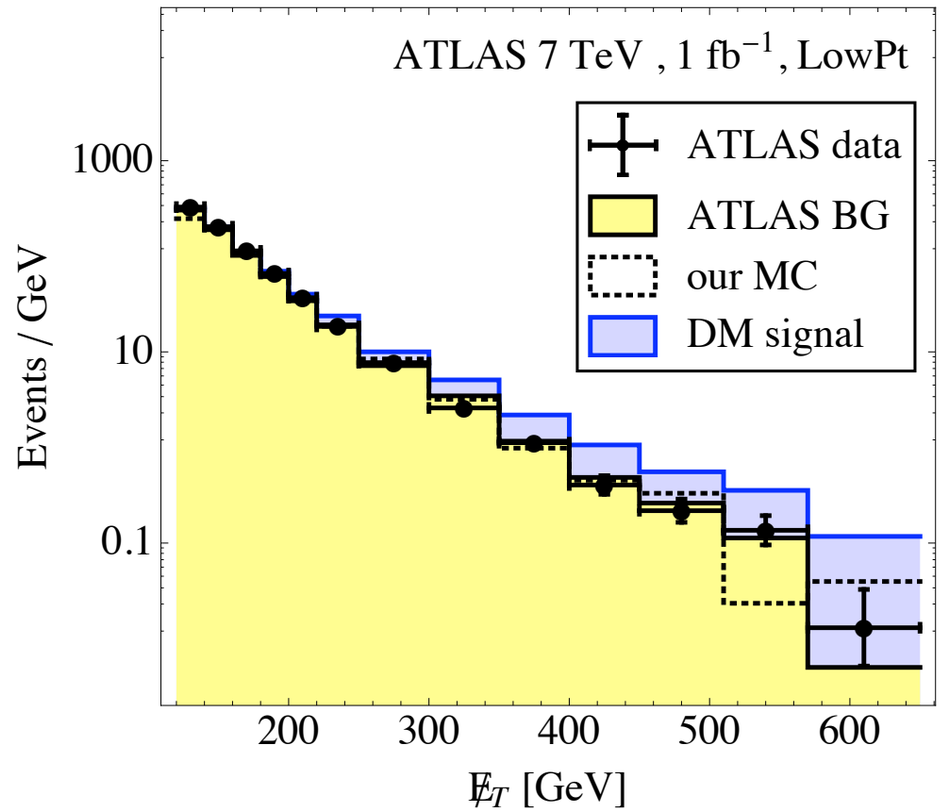
<u>dominant signal</u>:
$q\bar{q}$ initial state.



DM system emitted isotropically.

Mono-Jet

* Signal is **harder** and **more central** (unless DM couples to sea quarks).



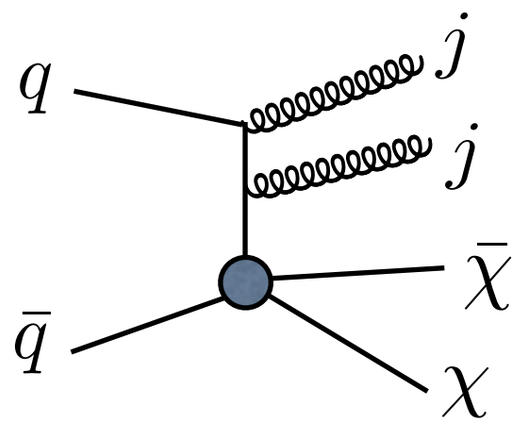
* Add angular info to mono-jet analyses? (could improve ADD limits as well)

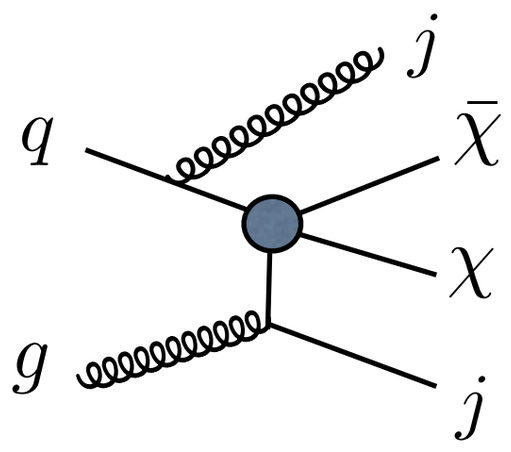
More Jets

* Applying a veto on the second jet reduces signal efficiency, and increases theory uncertainty.

* Indeed, most recent CMS (and upcoming ATLAS) mono-jet searches allow for a **hard second jet**, so-long as its not back to back with first jet.

* Inclusive jets plus MET searches for SUSY exist. Can we use them as searches for dark matter?

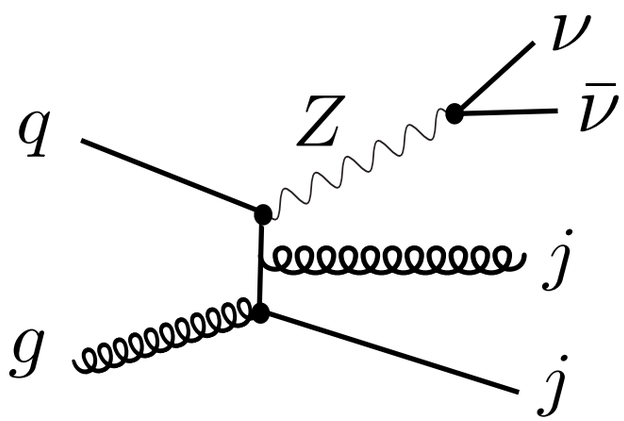


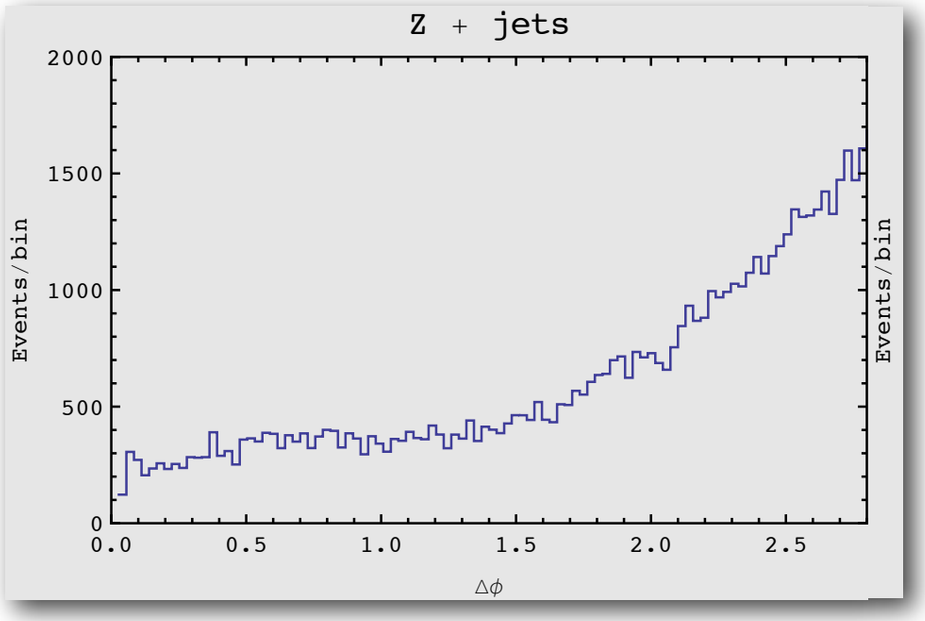


(with Fox, Primulando and Yu, 1203.1662)

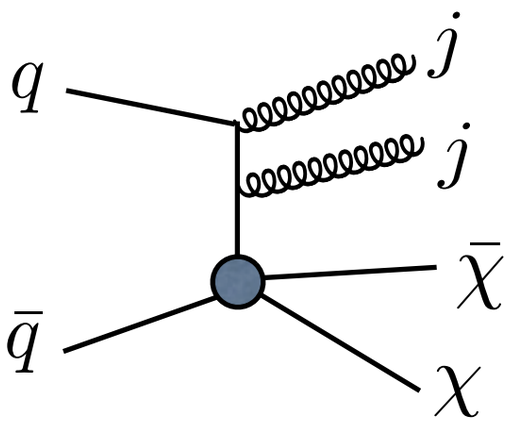
More Jets

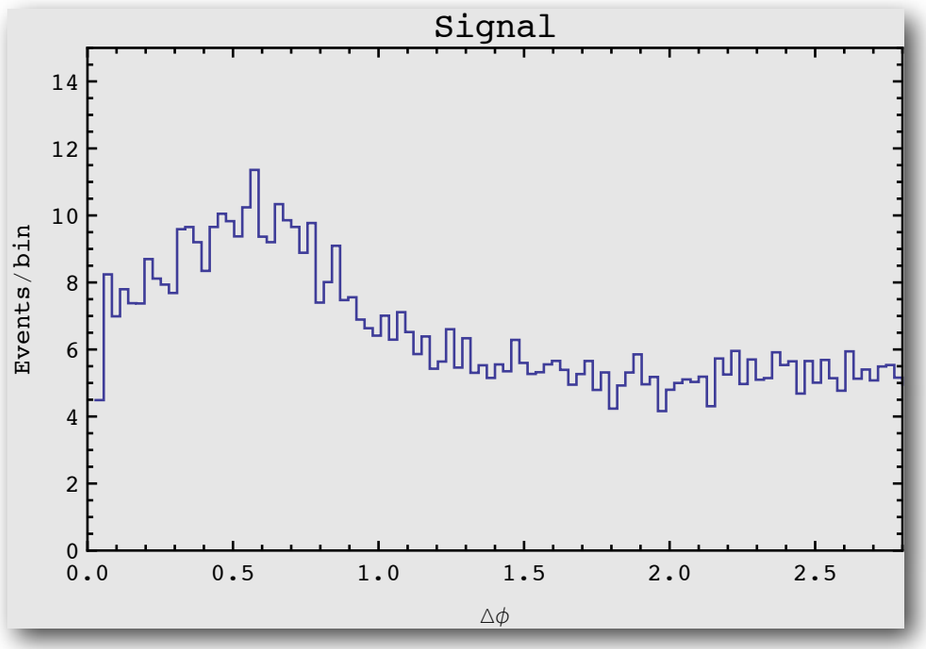
* Signal and Background have different dominant initial states, different angular distributions:





Azimuthal angle b/w jets





Razor

* We would like an analysis that is also sensitive to the angular distribution of jets and to MET.
* CMS's Razor analysis limits SUSY by inspecting a 2D distribution of two kinematic variables.
* The Razor variables follow simple exponential distributions - a data driven analysis.

Razor

* Consider events

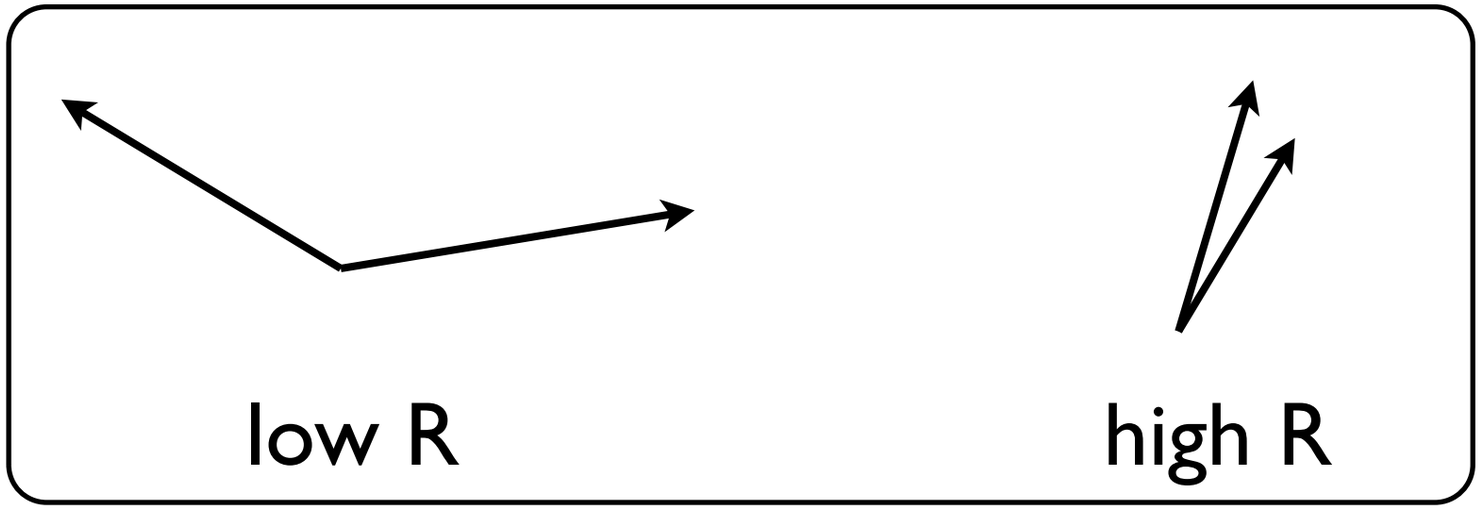
$$M_R = \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

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

Estimators for characteristic scale in the event

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

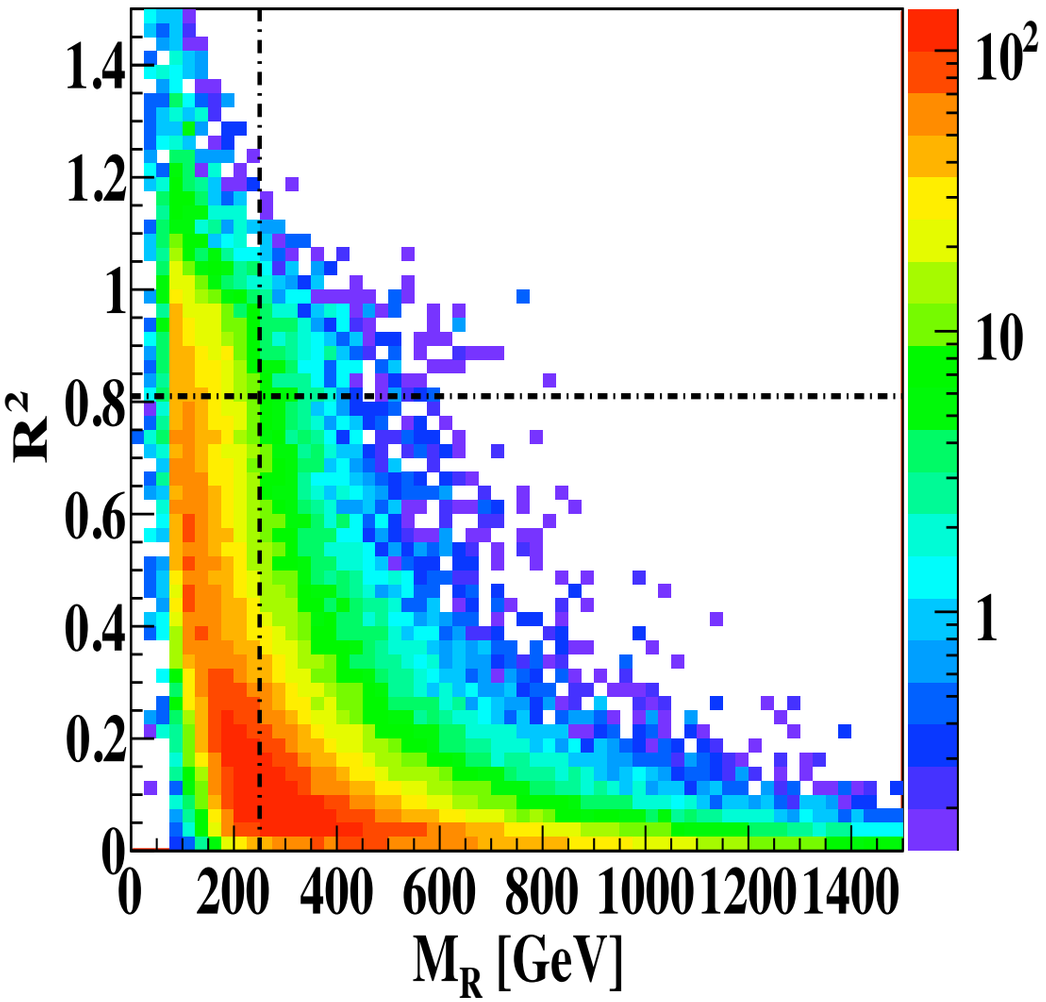
roughly: R=ratio of MET to visible.



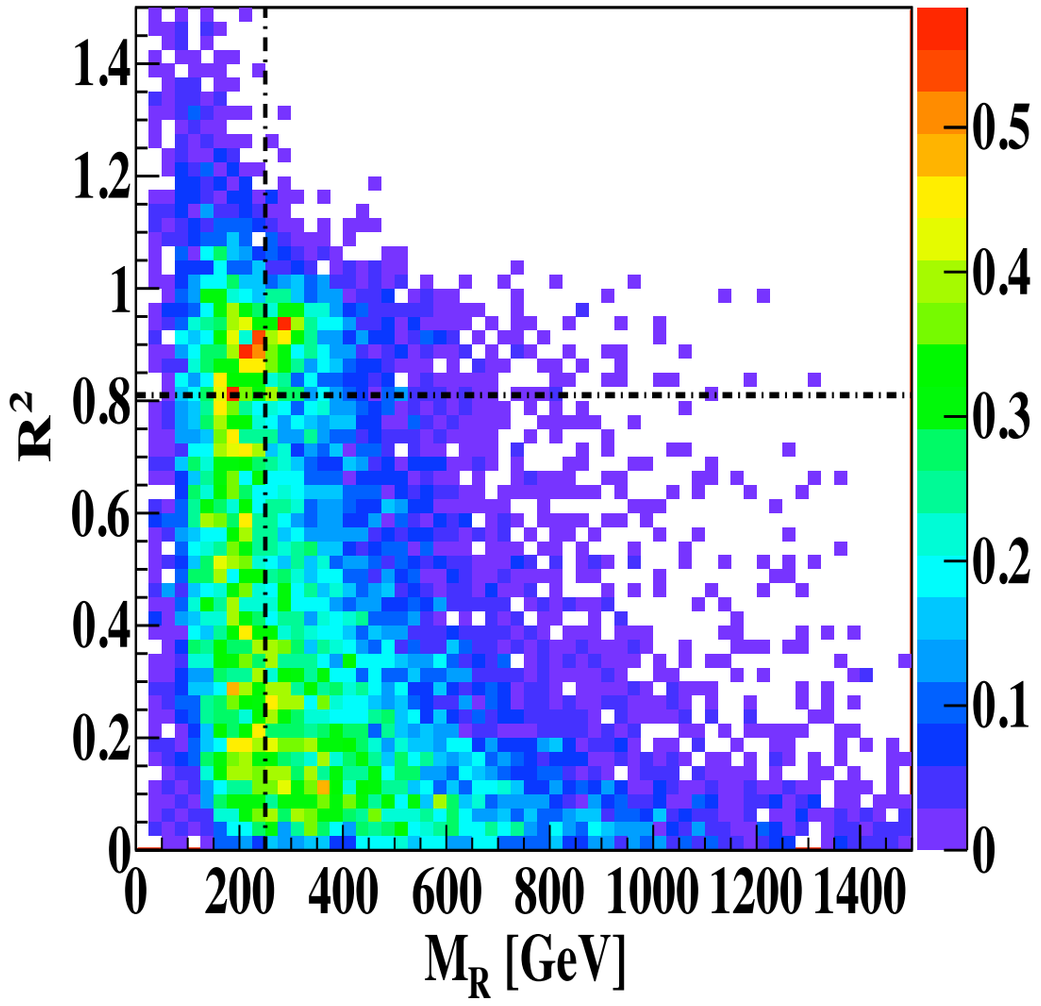
Razor

* Background and Signal shapes in M_R vs R:

Z+jets

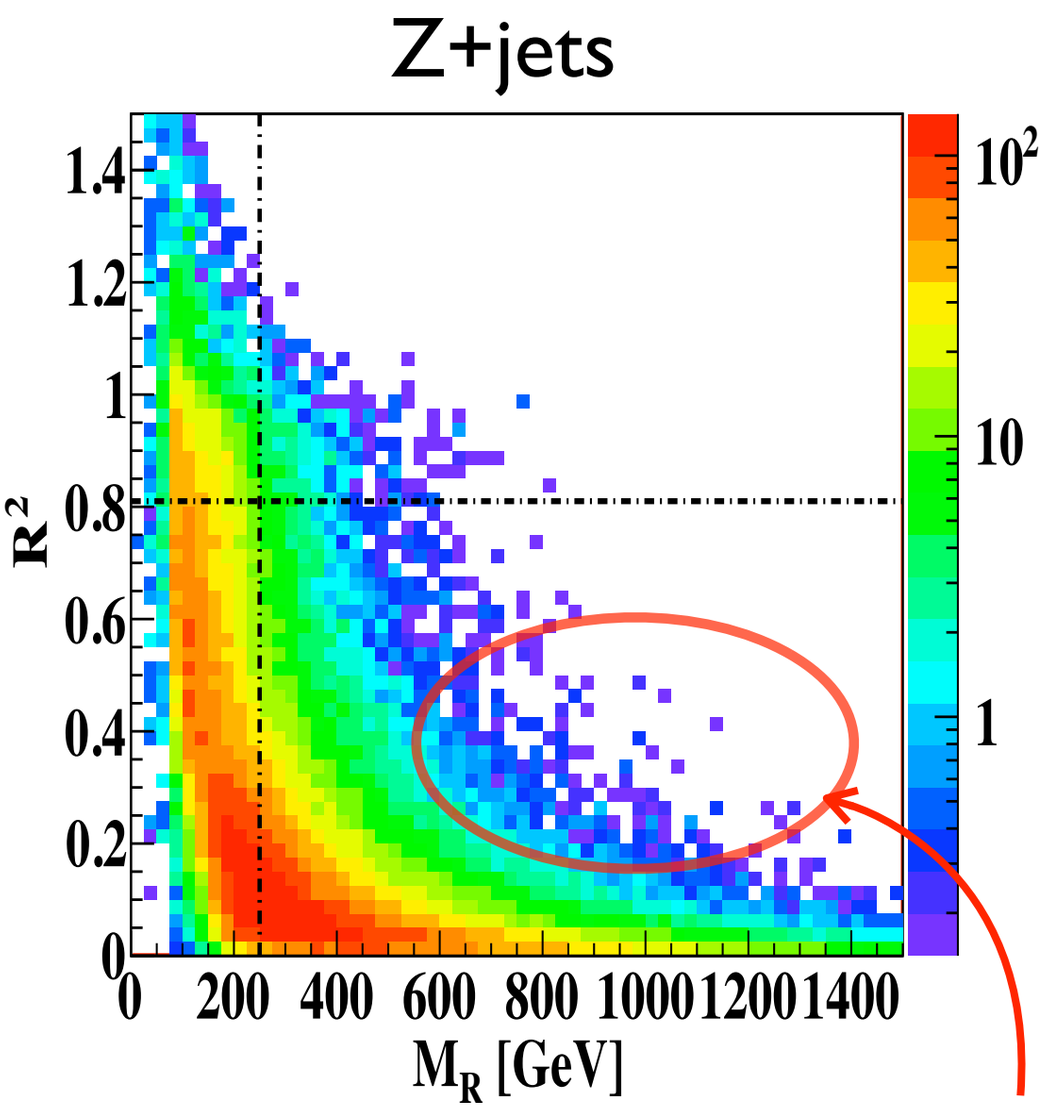


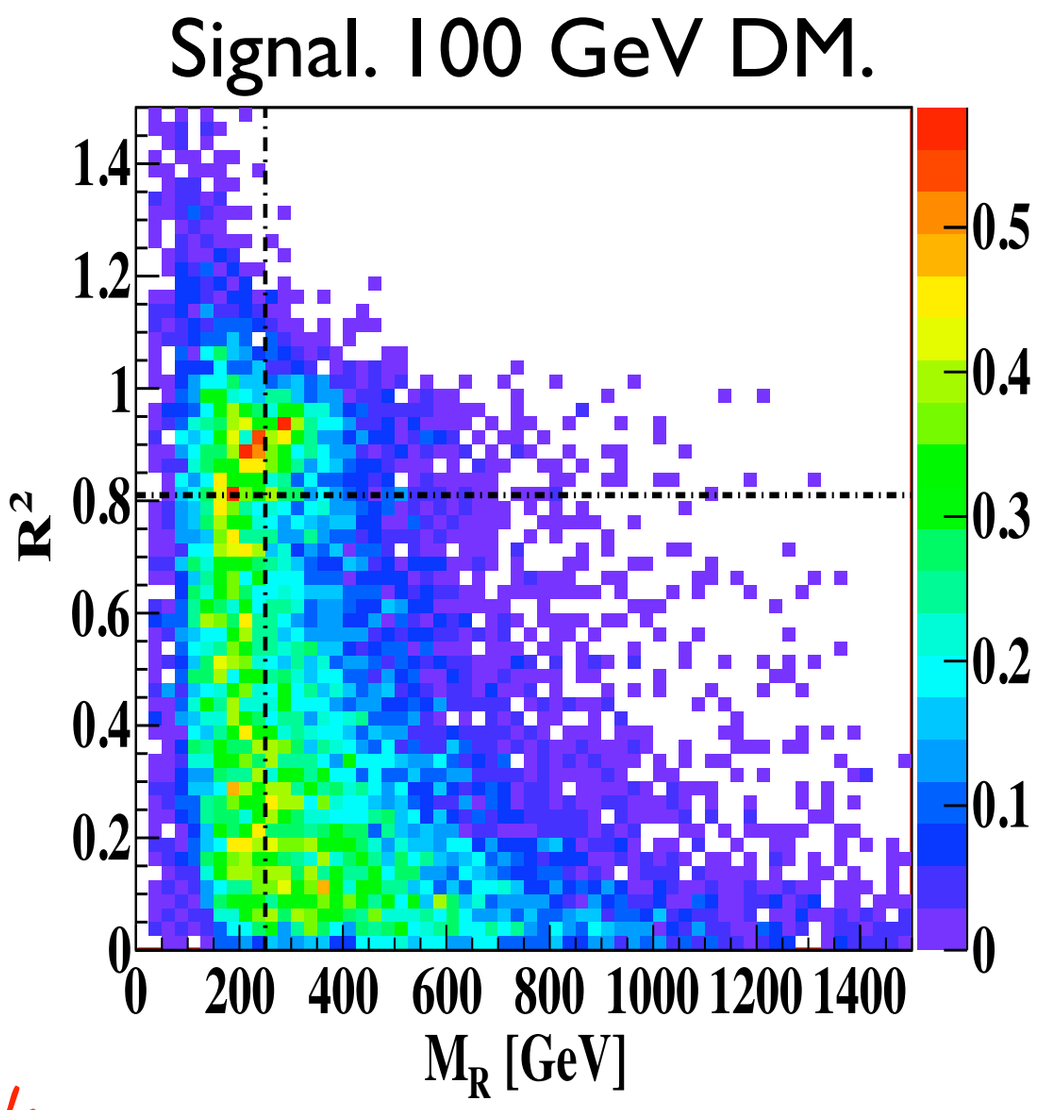
Signal. 100 GeV DM.



Razor

* Background and Signal shapes in M_R vs R:



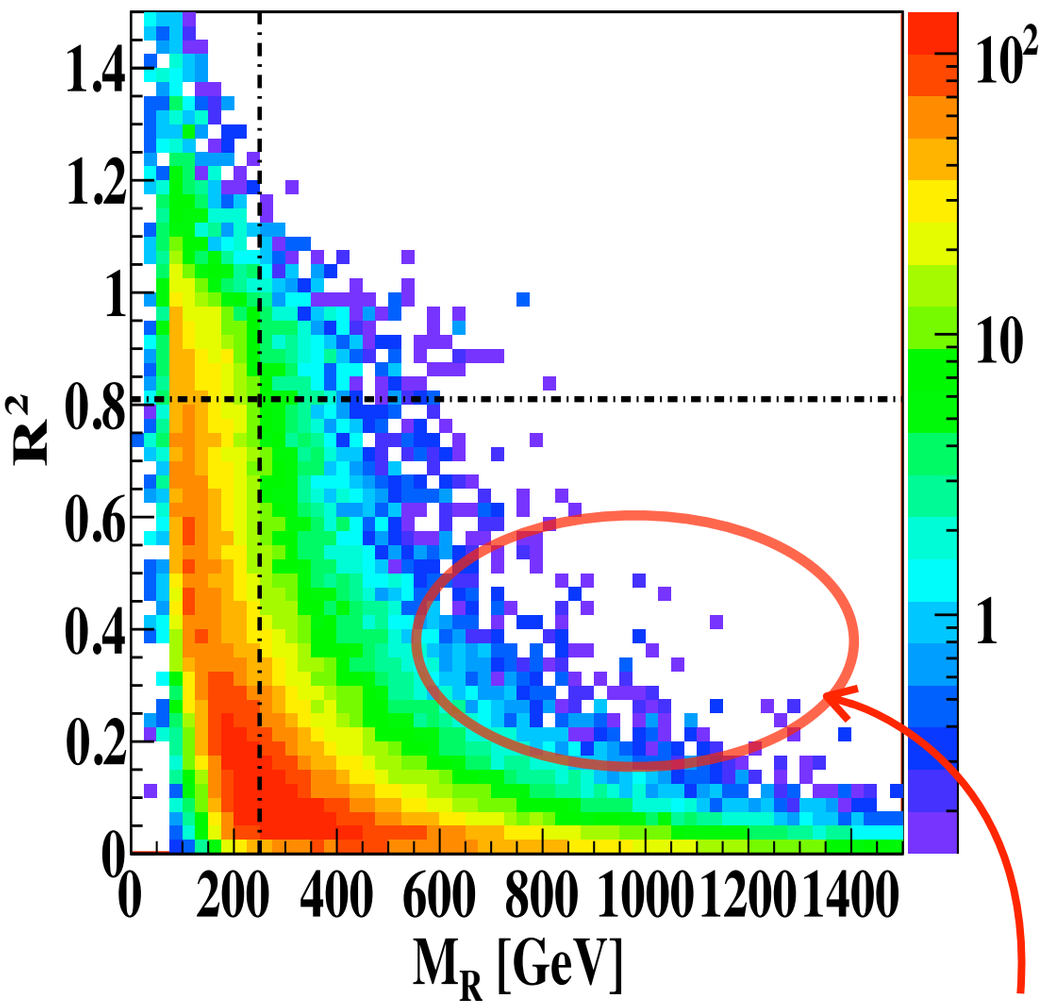


SUSY search

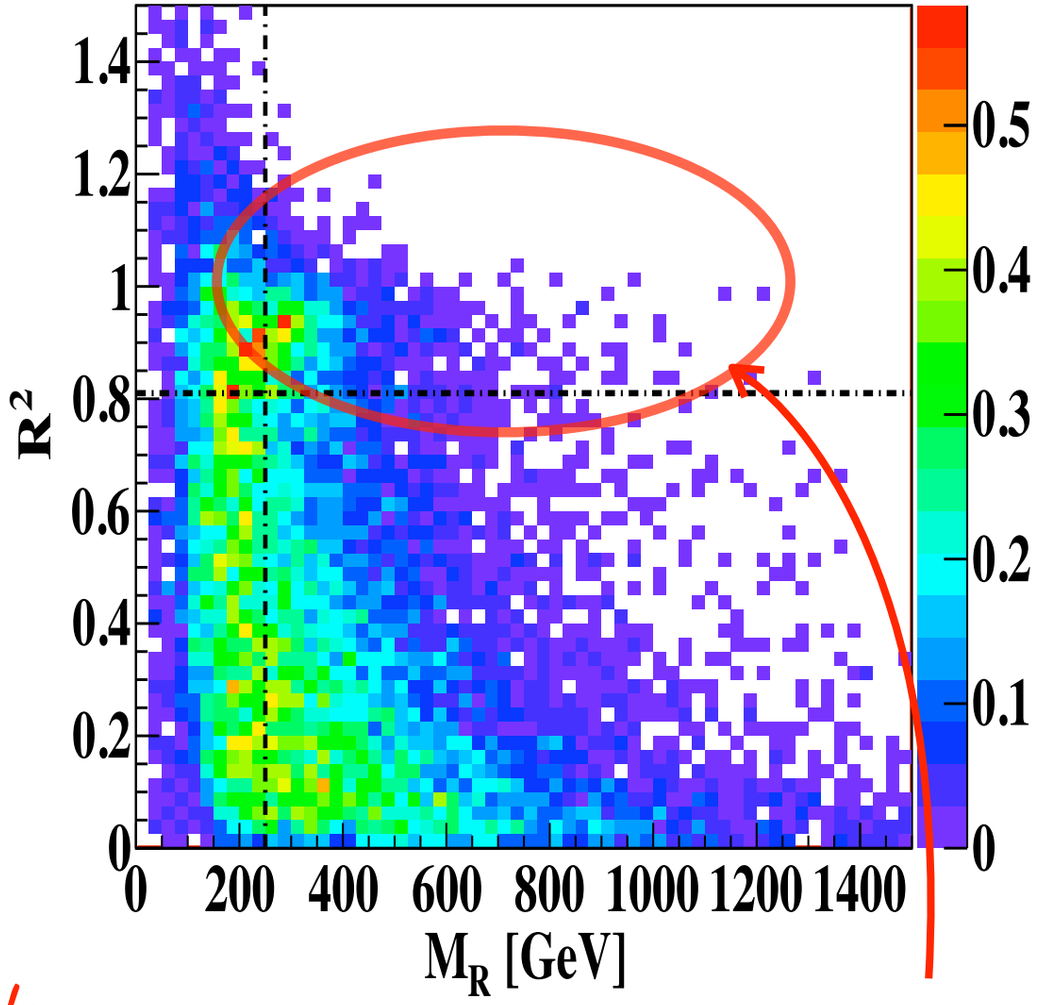
Razor

* Background and Signal shapes in M_R vs R:

Z+jets



Signal. 100 GeV DM.

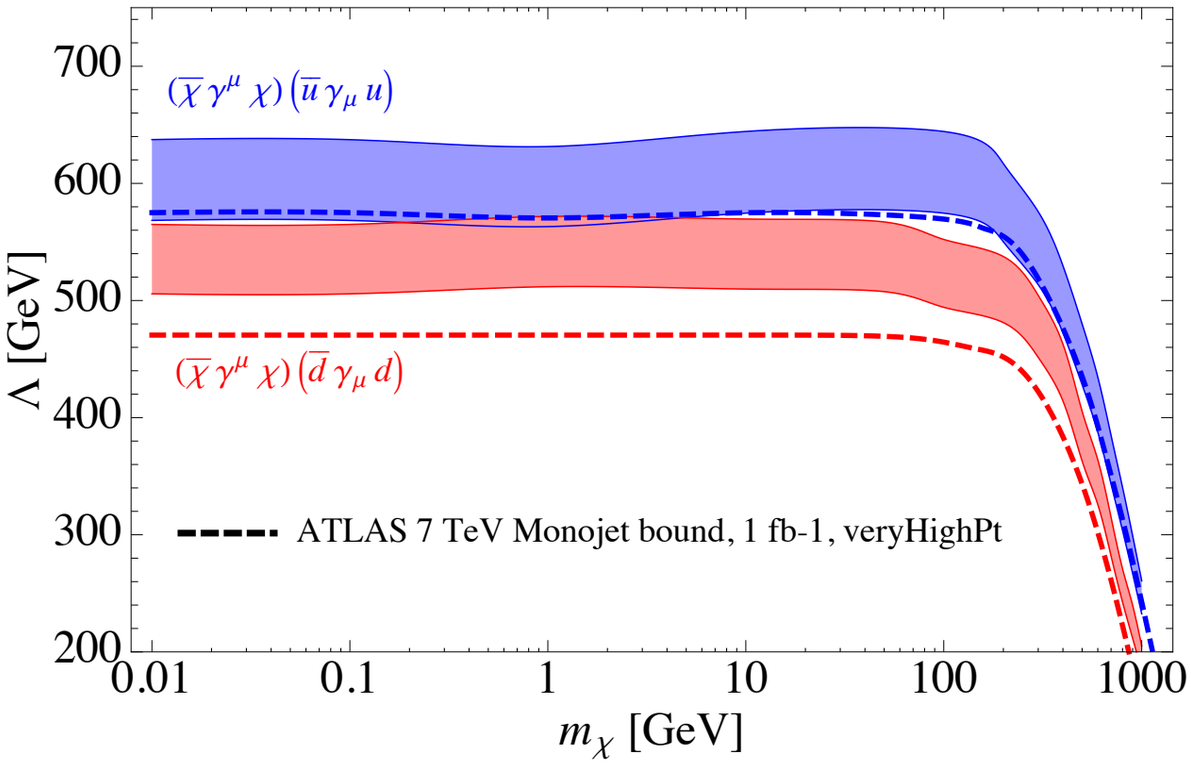


SUSY search

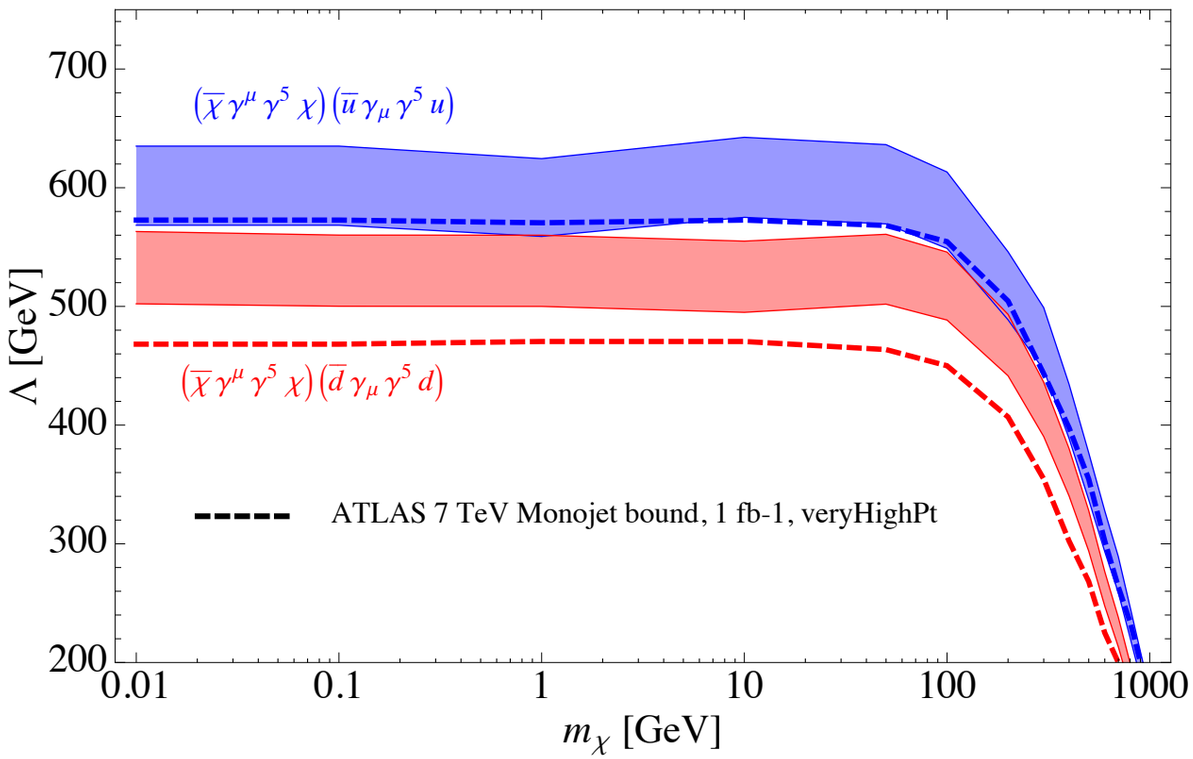
our search

Razor Limits

* With 800 fb^{-1}:



(a) Vector couplings.

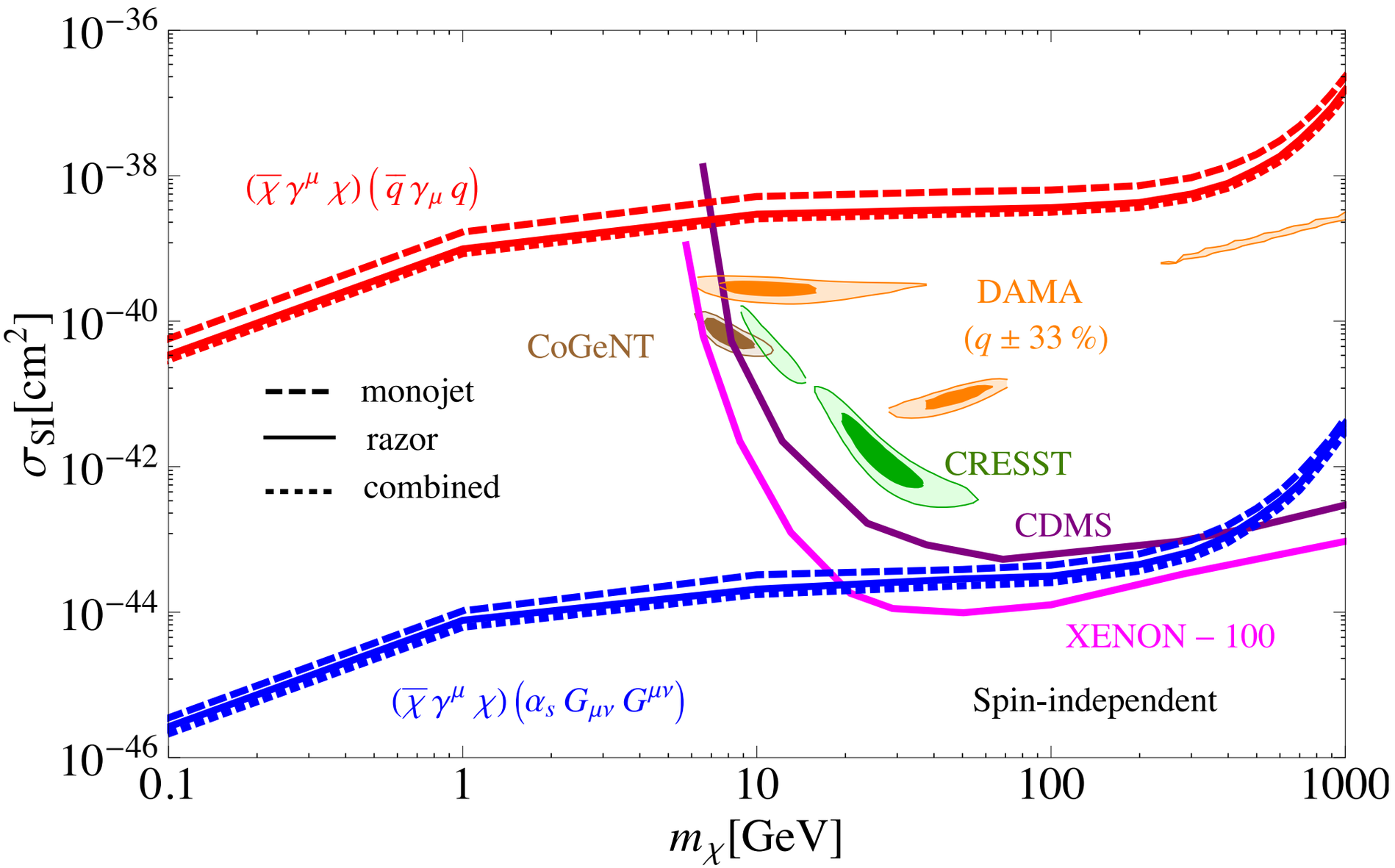


(b) Axial couplings

* The band represents two assumption about uncertainties:
(1) statistics only, and (2) systematic=statistic.
truth is probably closer to (1).

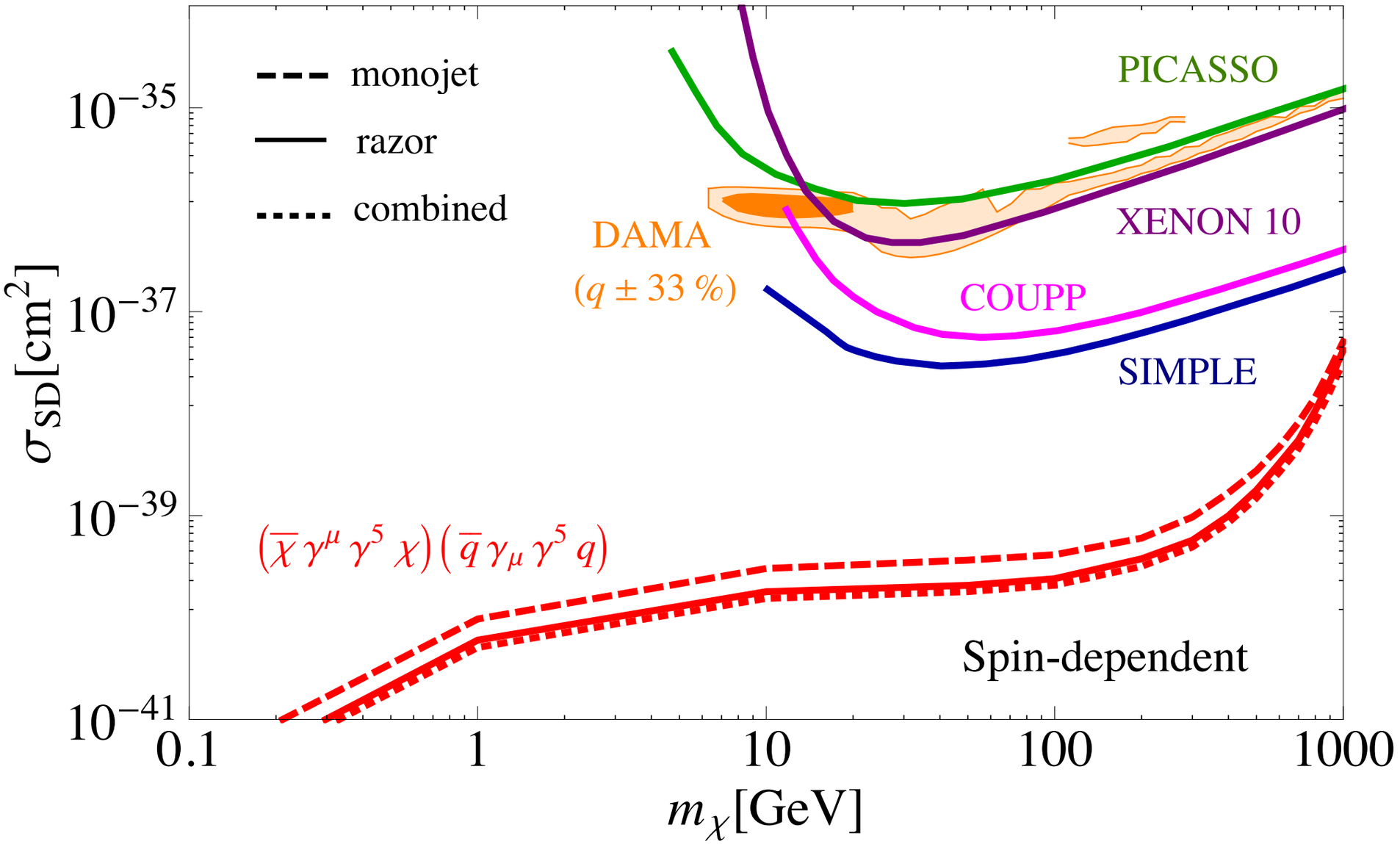
Razor Limits

* Spin-Independent (with 800 fb^{-1}):



Razor Limits

* Spin-Dependent:



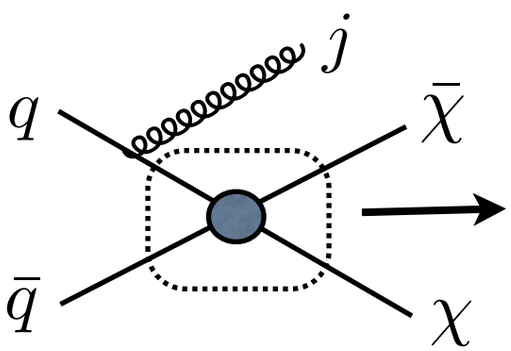
EFT

Is it always valid?
"Model independent"?
Certainly not.

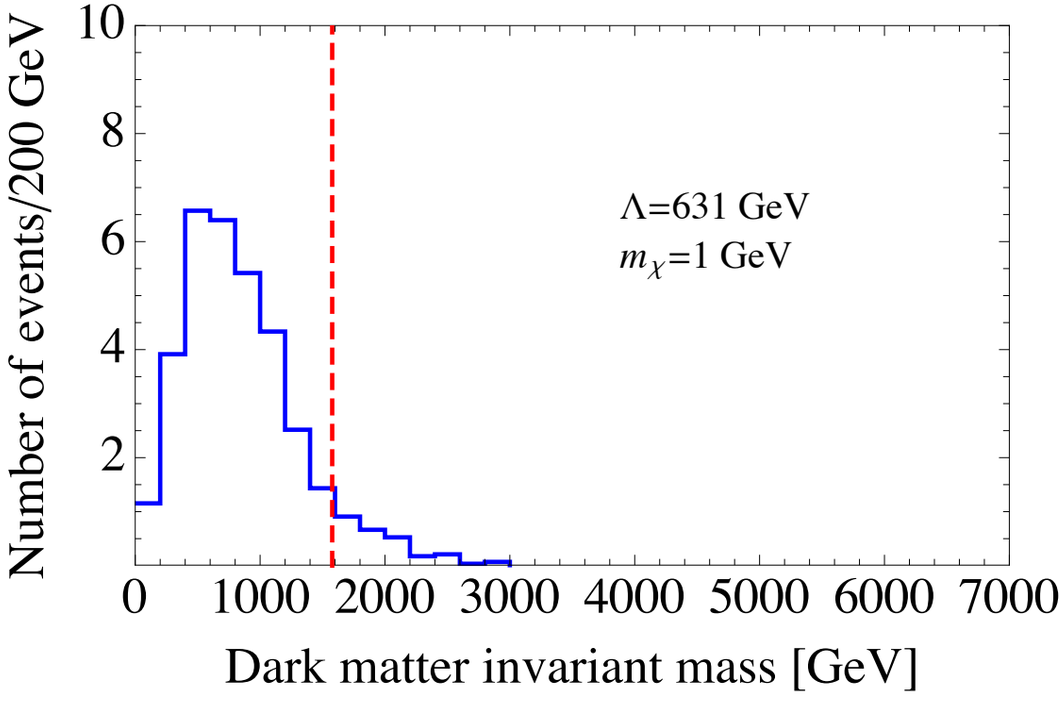
Is it useful?
Certainly.

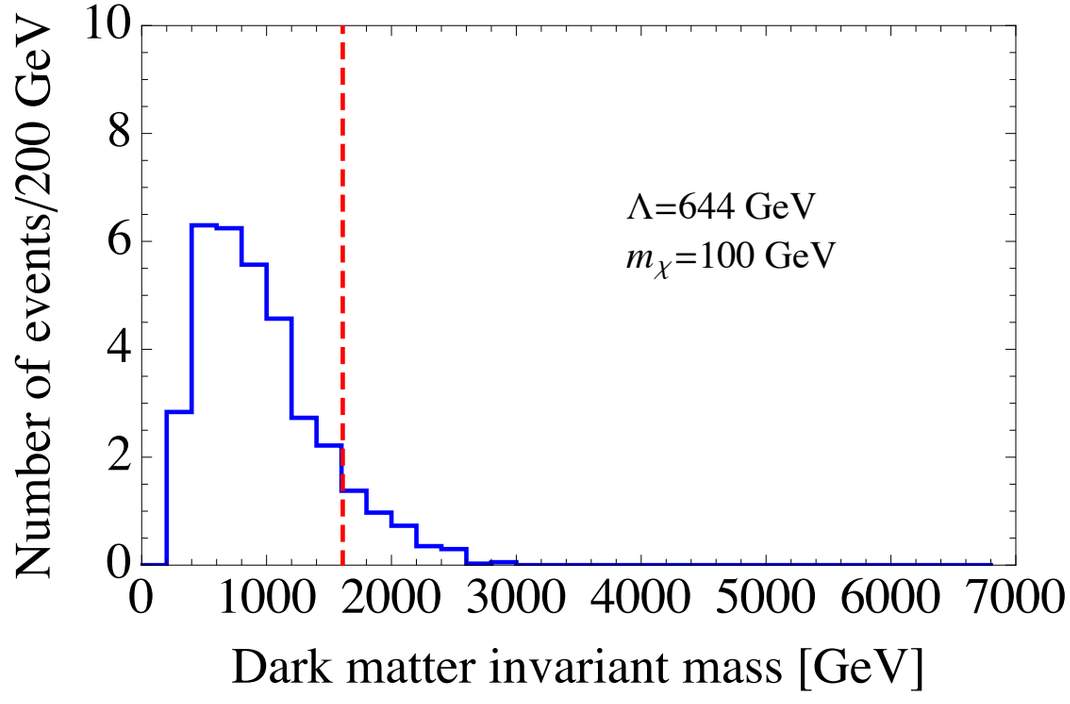
Unitarity

* Vechi and Shoemaker point to a unitarity limit:



$$\Lambda \gtrsim 0.4\sqrt{\beta(\hat{s})\hat{s}} \longrightarrow m_{\chi\chi} < \frac{\Lambda}{0.4}$$

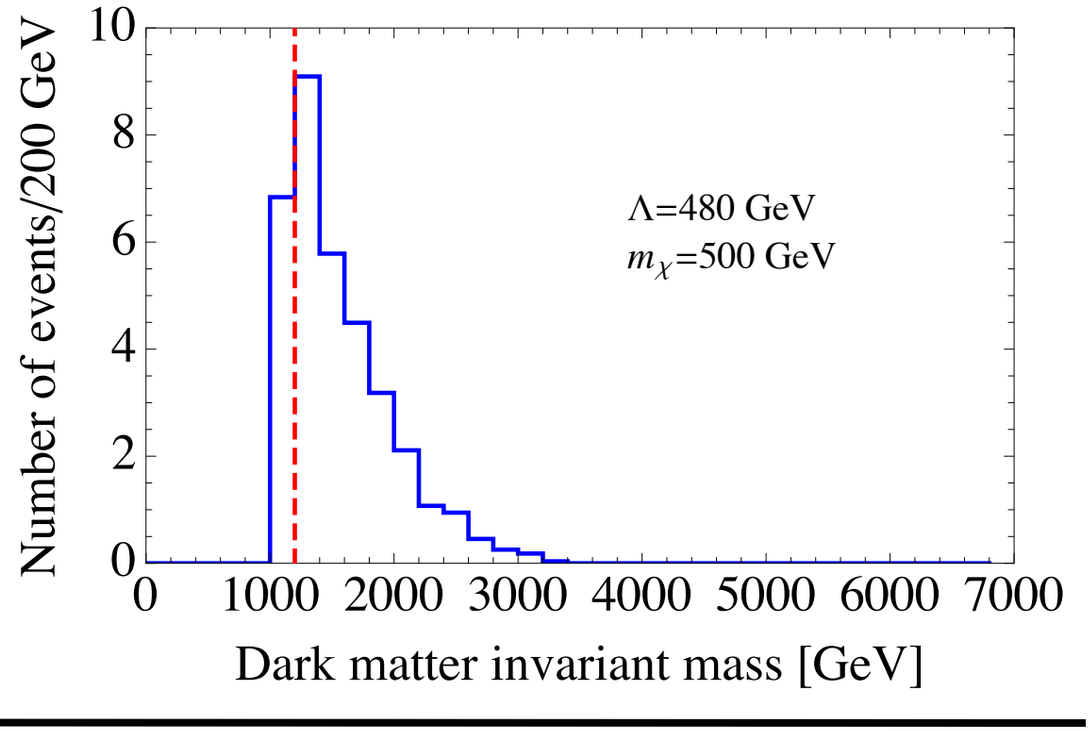




The EFT may be accurate to ~10% for light DM.

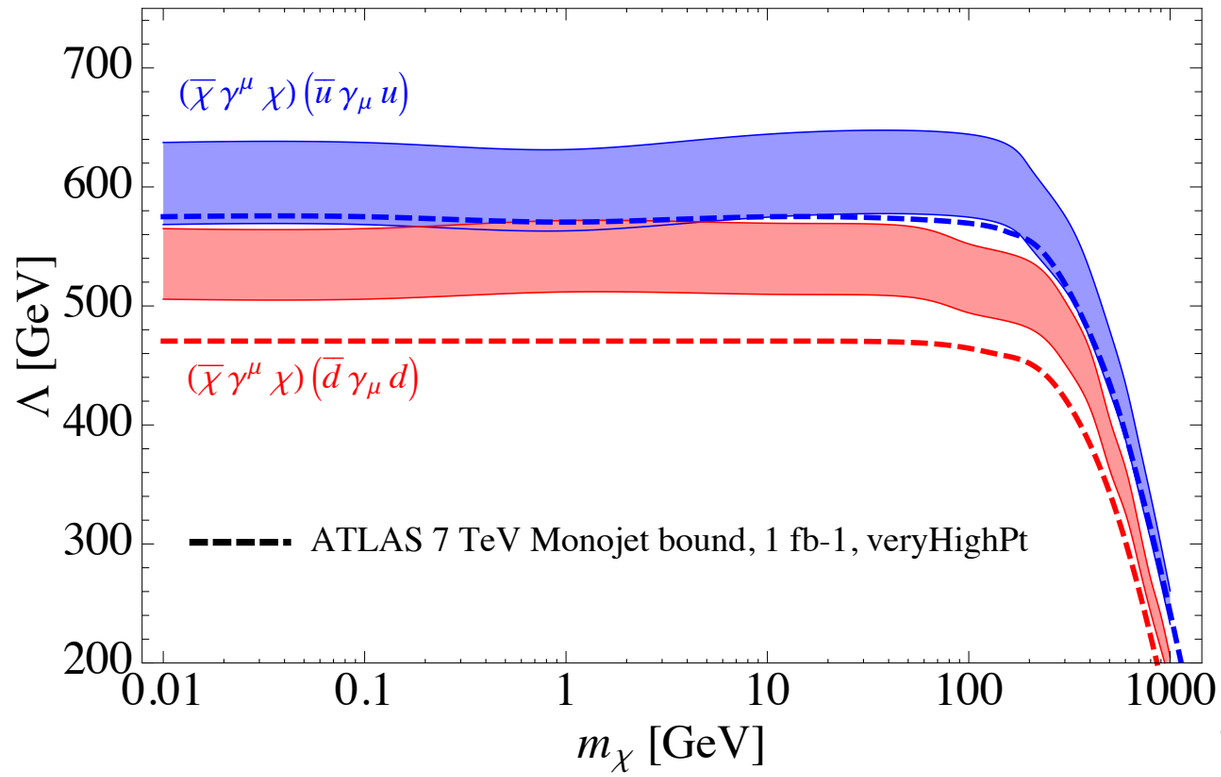
Unitarity

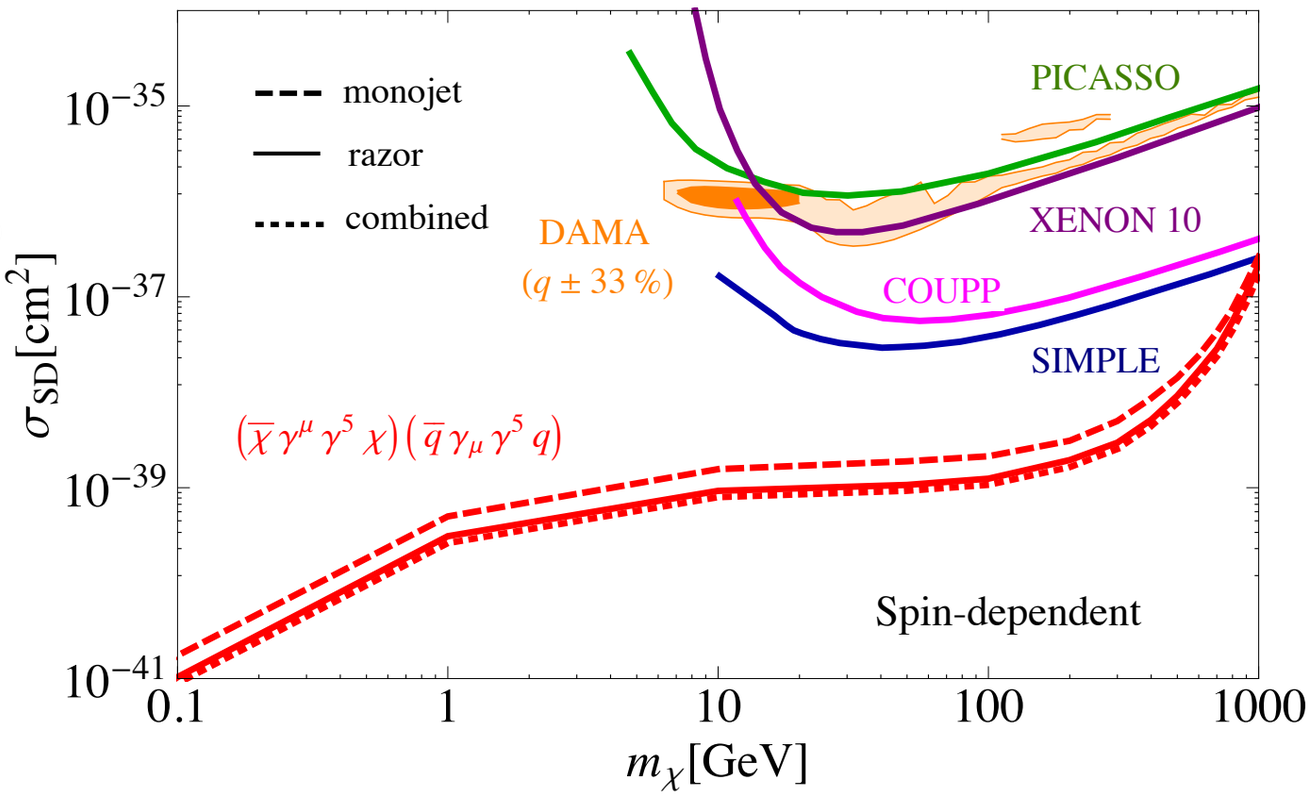
* For heavy dark matter the EFT is not valid:



Unitarity

- Strictly speaking, the EFT analysis is not valid at small Λ.





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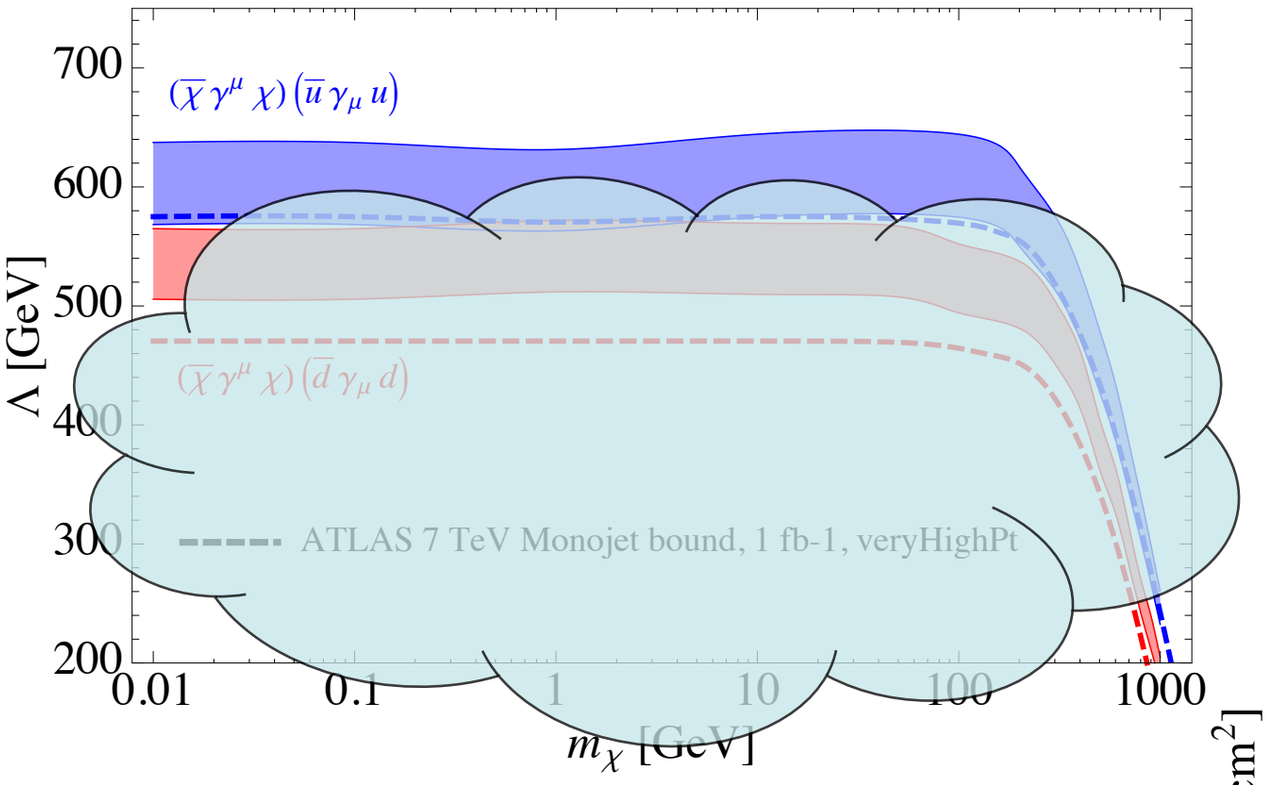

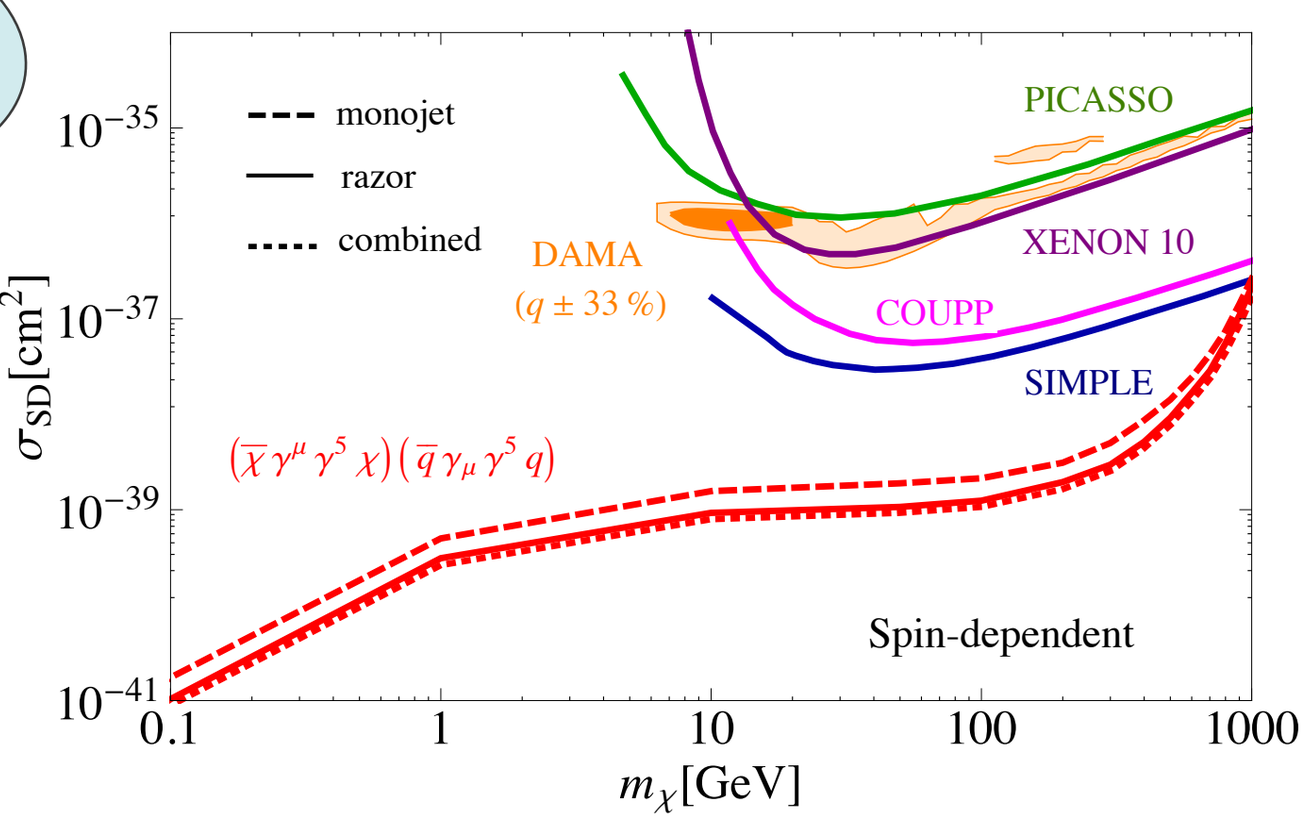

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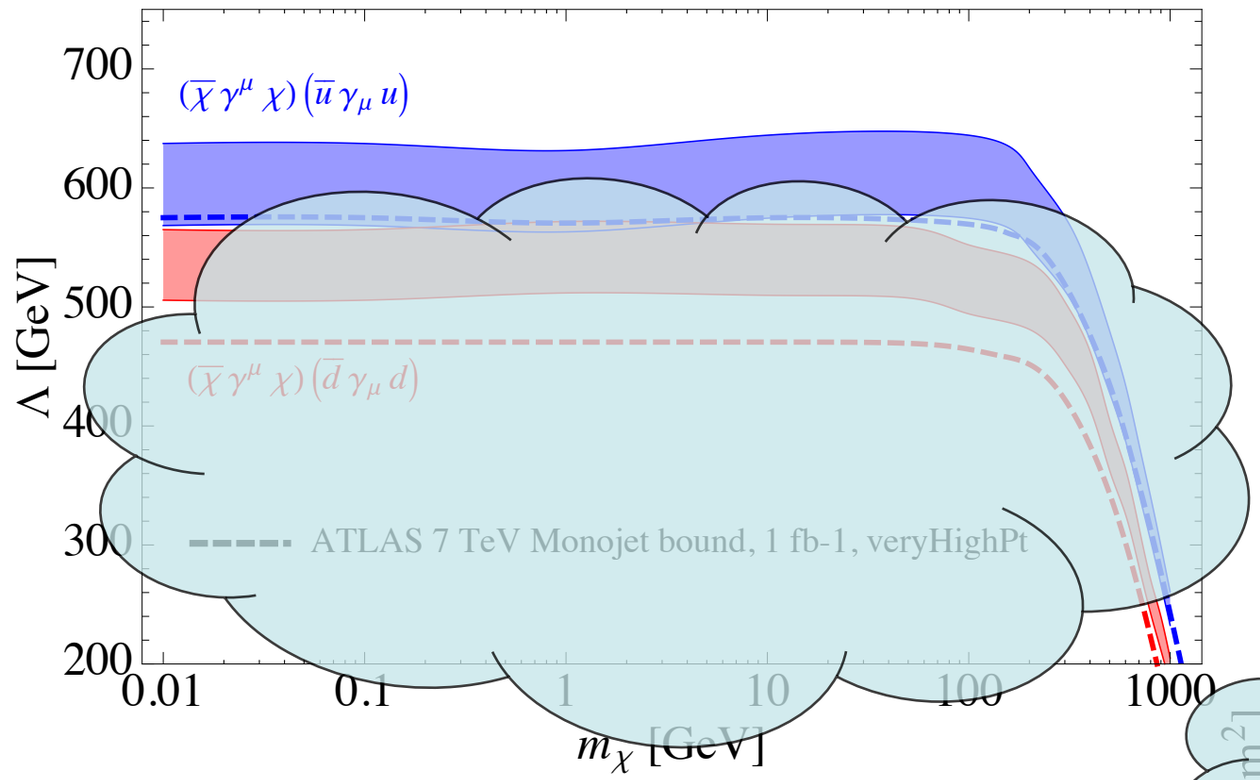

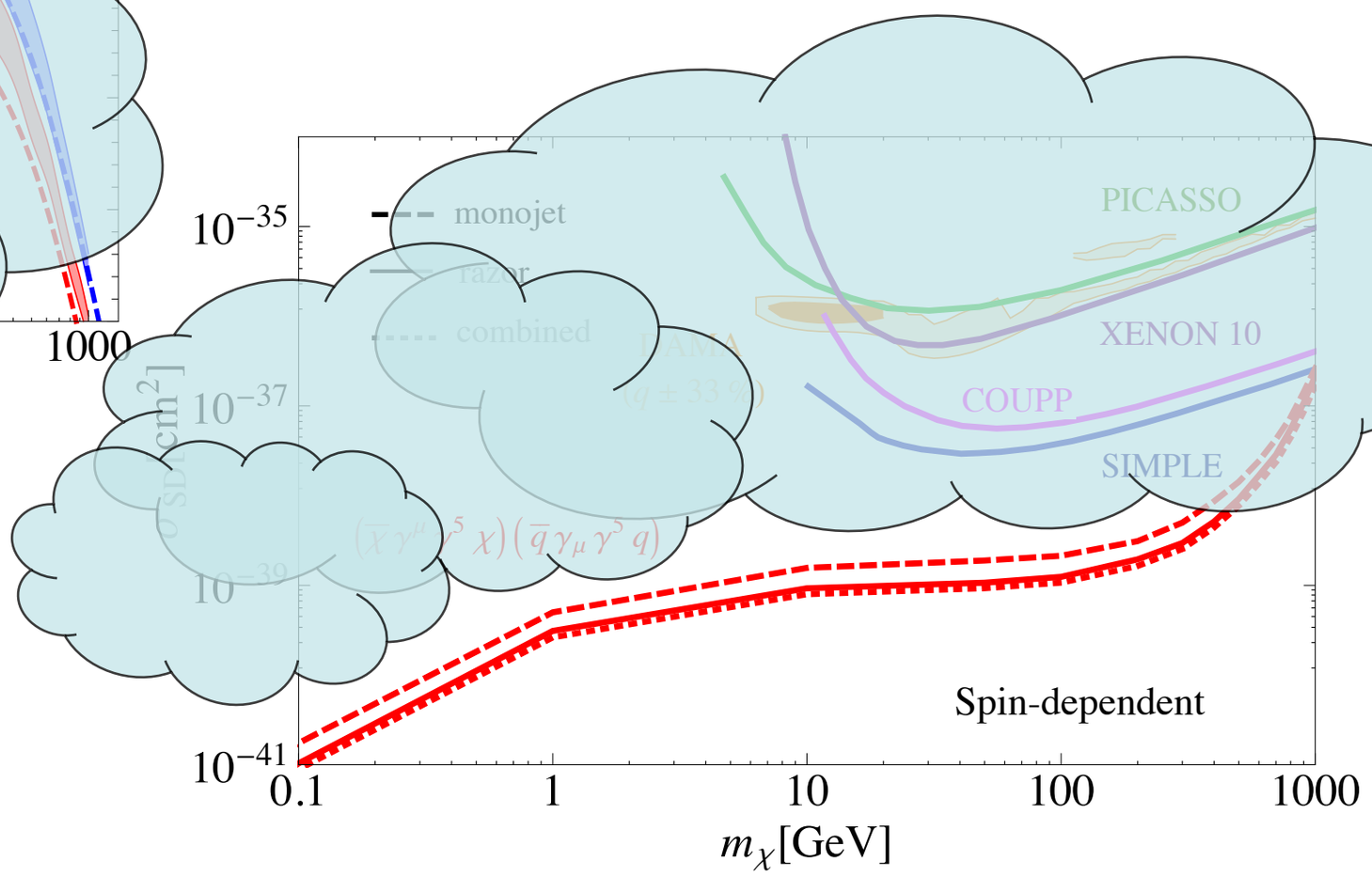

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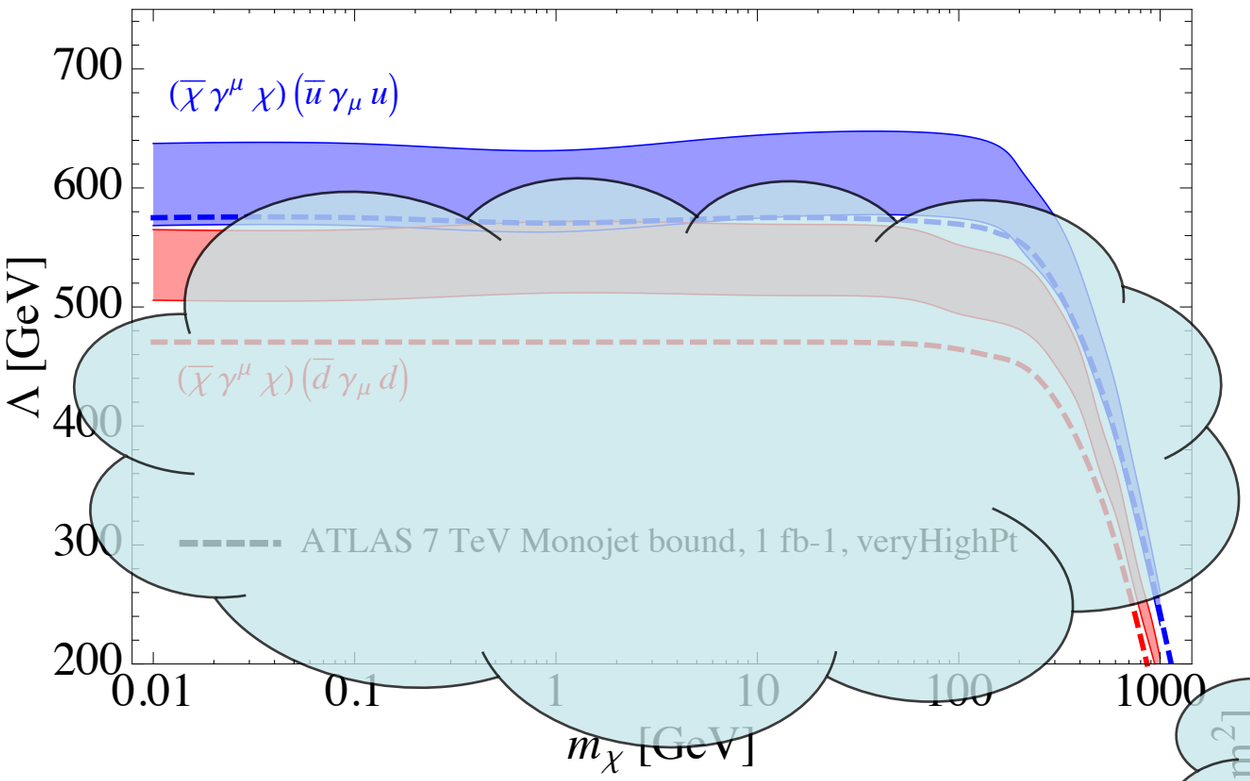
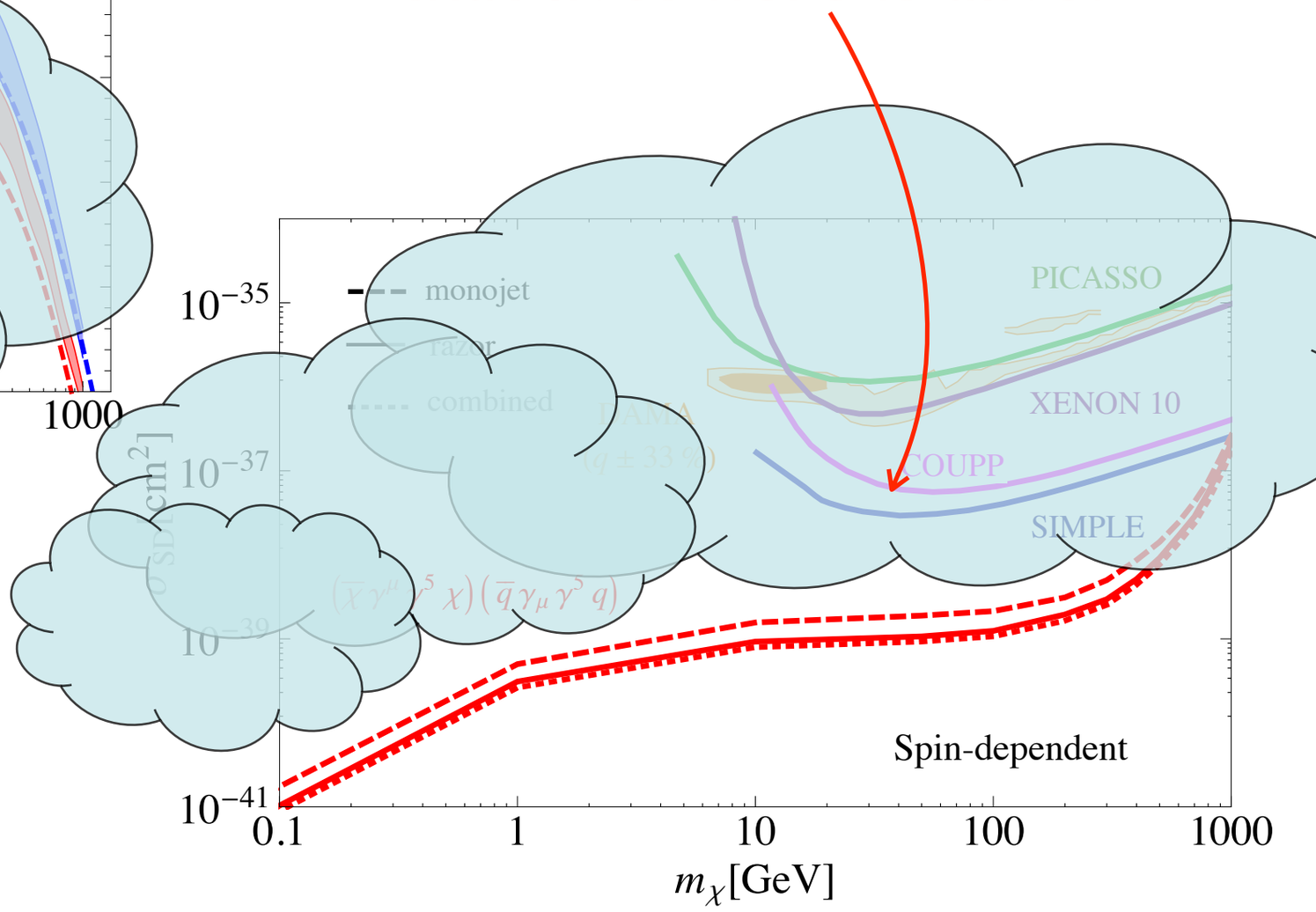


Does this mean a theory that lives here is alive?



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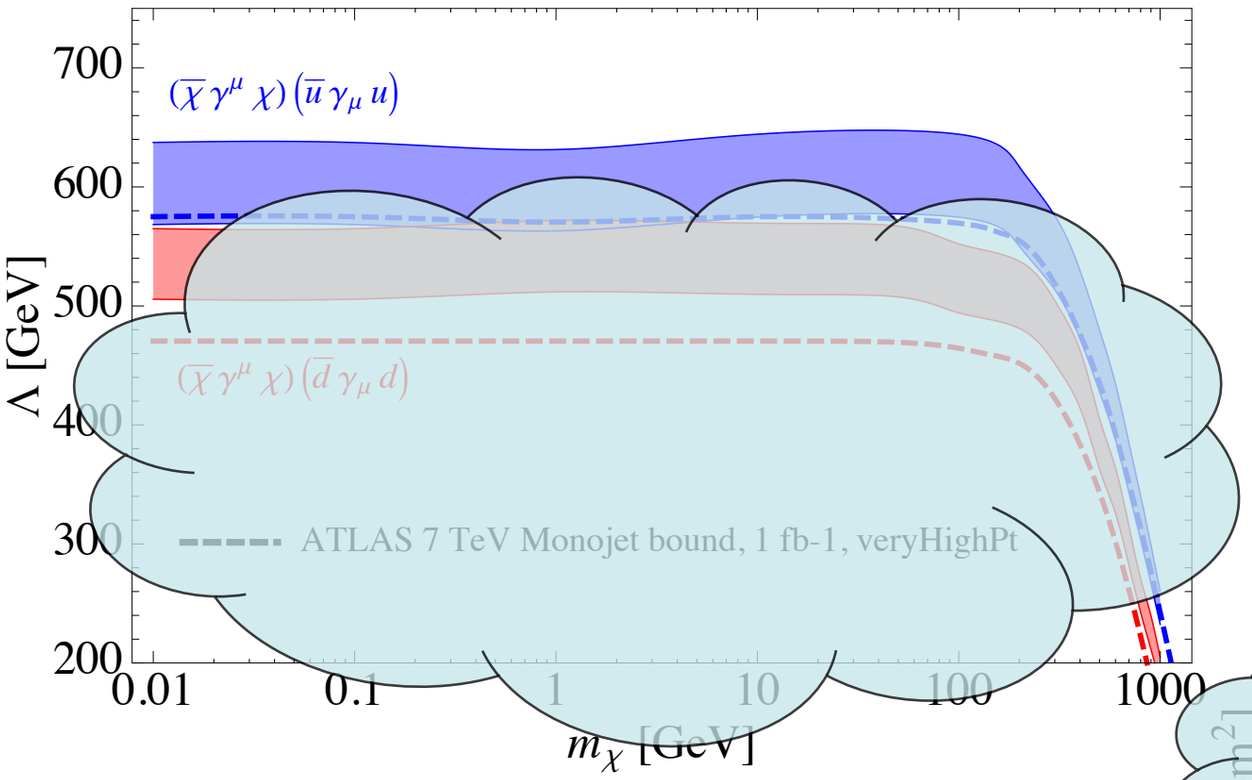

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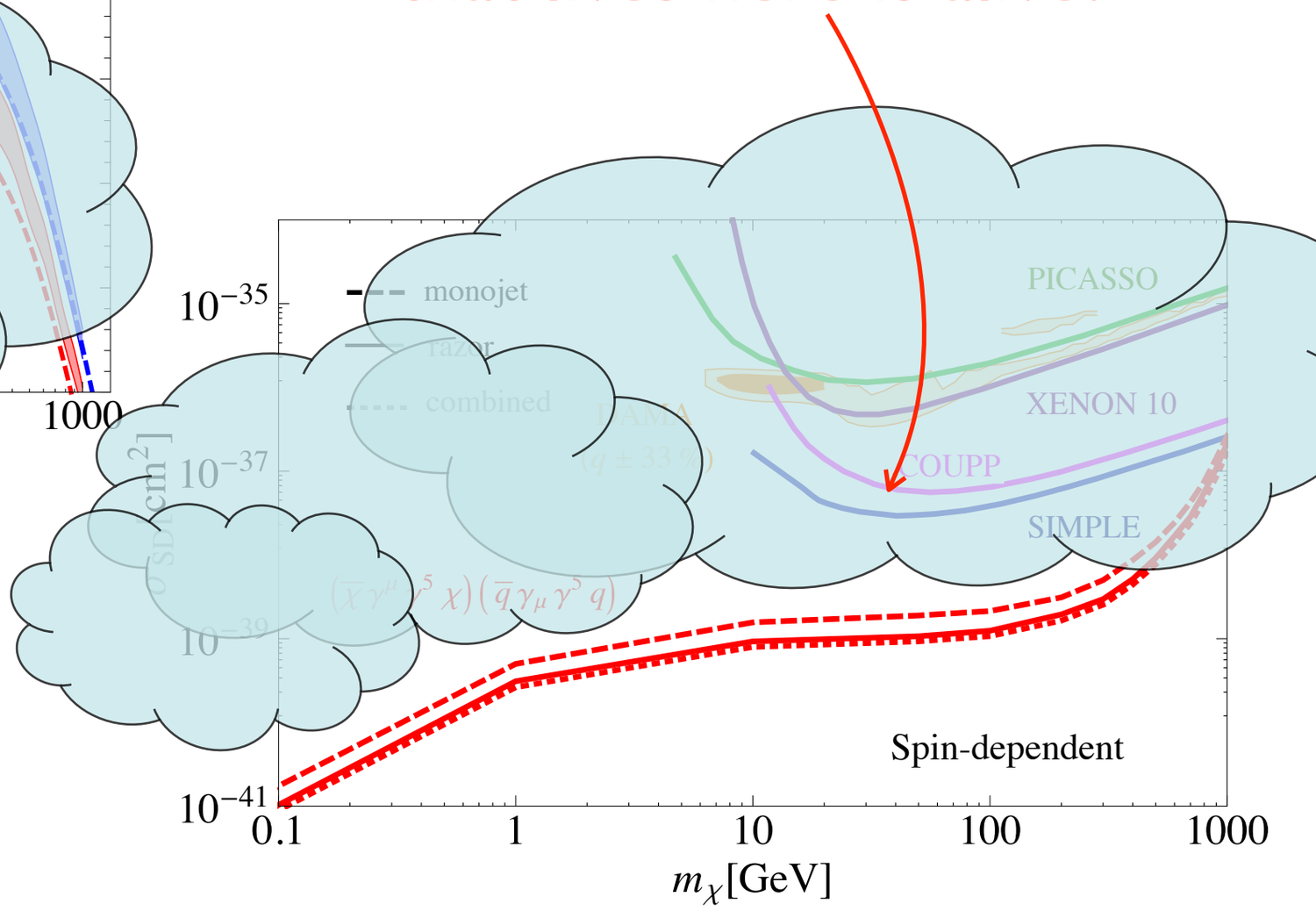
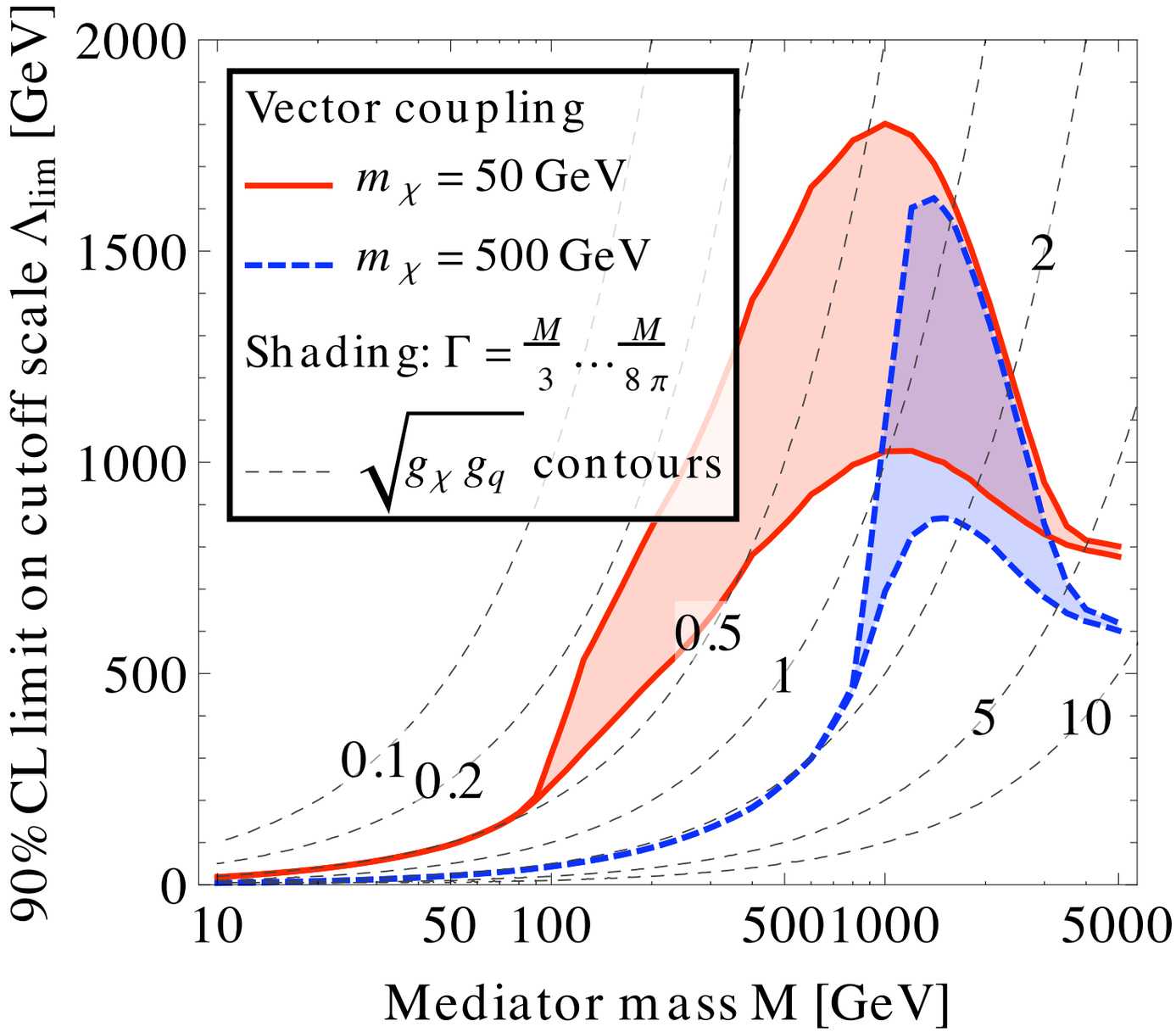


No.

In fact it may be even more dead.

Light Madiator

* The limit become better before it gets worse:



EFT limits are **conservative** so long as the mediator is above a few hundred GeV (and the mediator decays to DM).

Light Madiator

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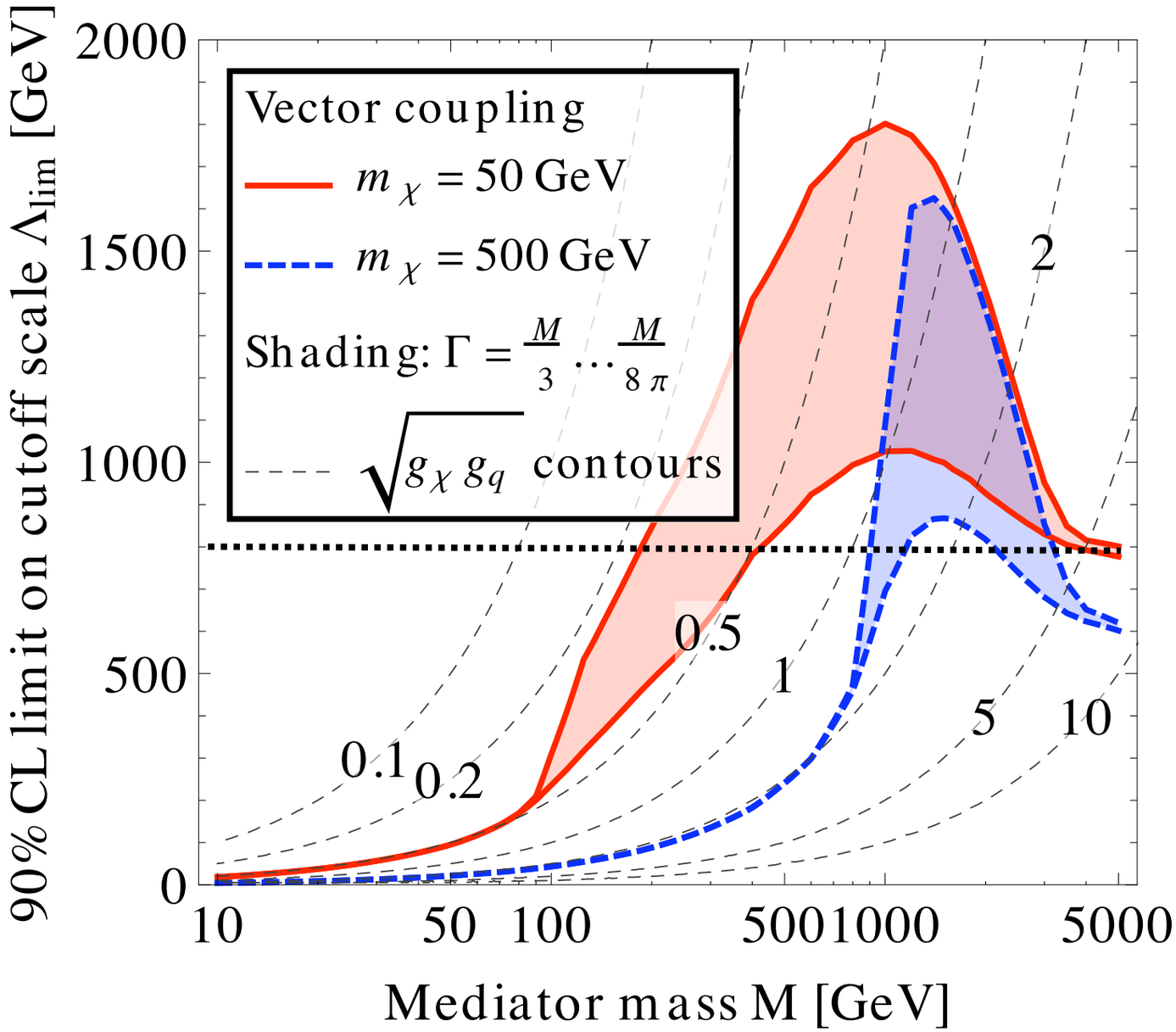

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Light Madiator

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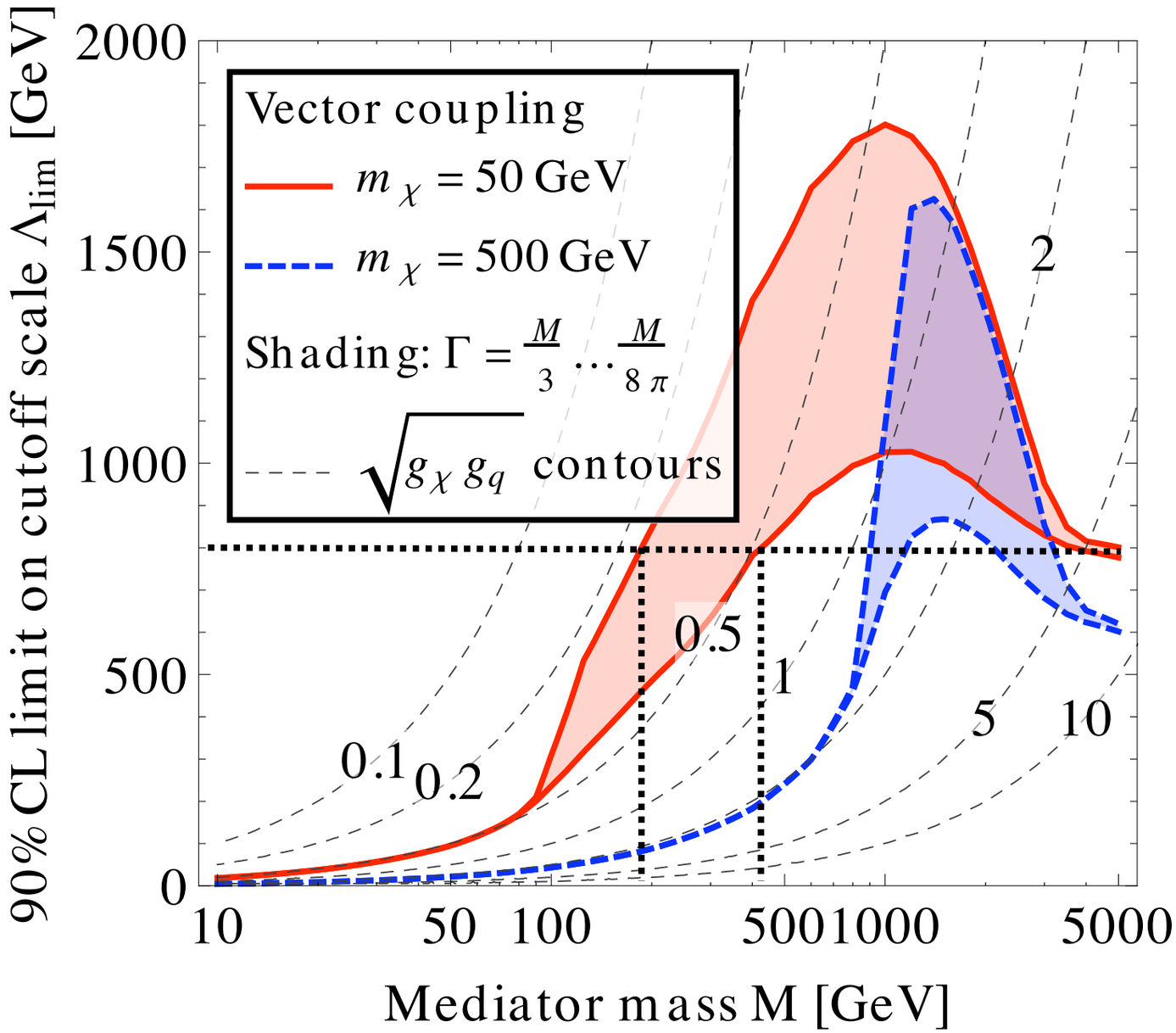


EFT limits are **conservative** so long as the mediator is above a few hundred GeV (and the mediator decays to DM).

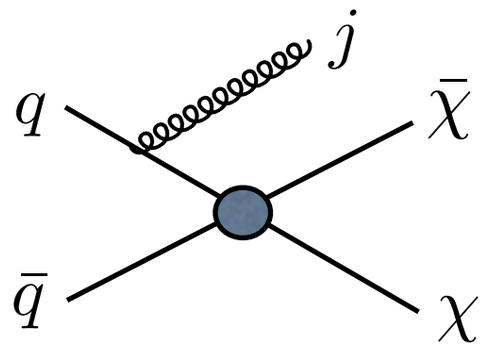
Questions

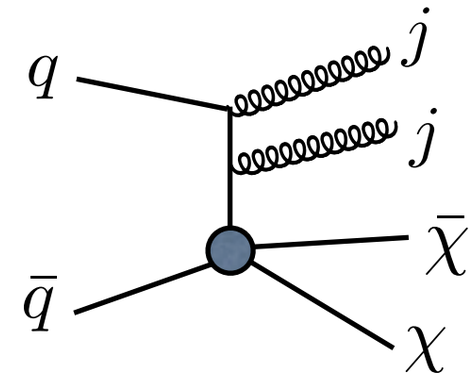
* How can we improve these bounds?
* Are there other LHC searches that are relevant?

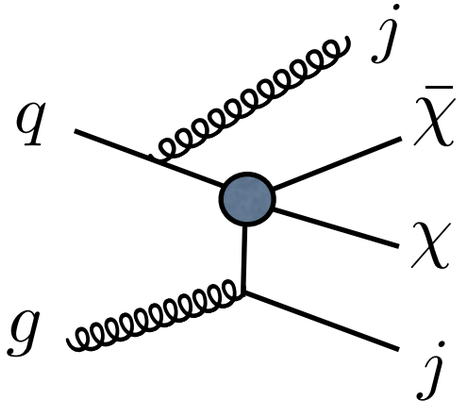
* What theoretical assumptions go into the bounds?
* How can collider bounds be evaded?

Outline

* Setup - operators and mediators
* Mono-Jets & Mono-photons.
* Multi-jets plus MET.
  - Handles on S vs B.
  - Razor analysis.
* Note on validity of EFT.
* DM Higgs interplay?



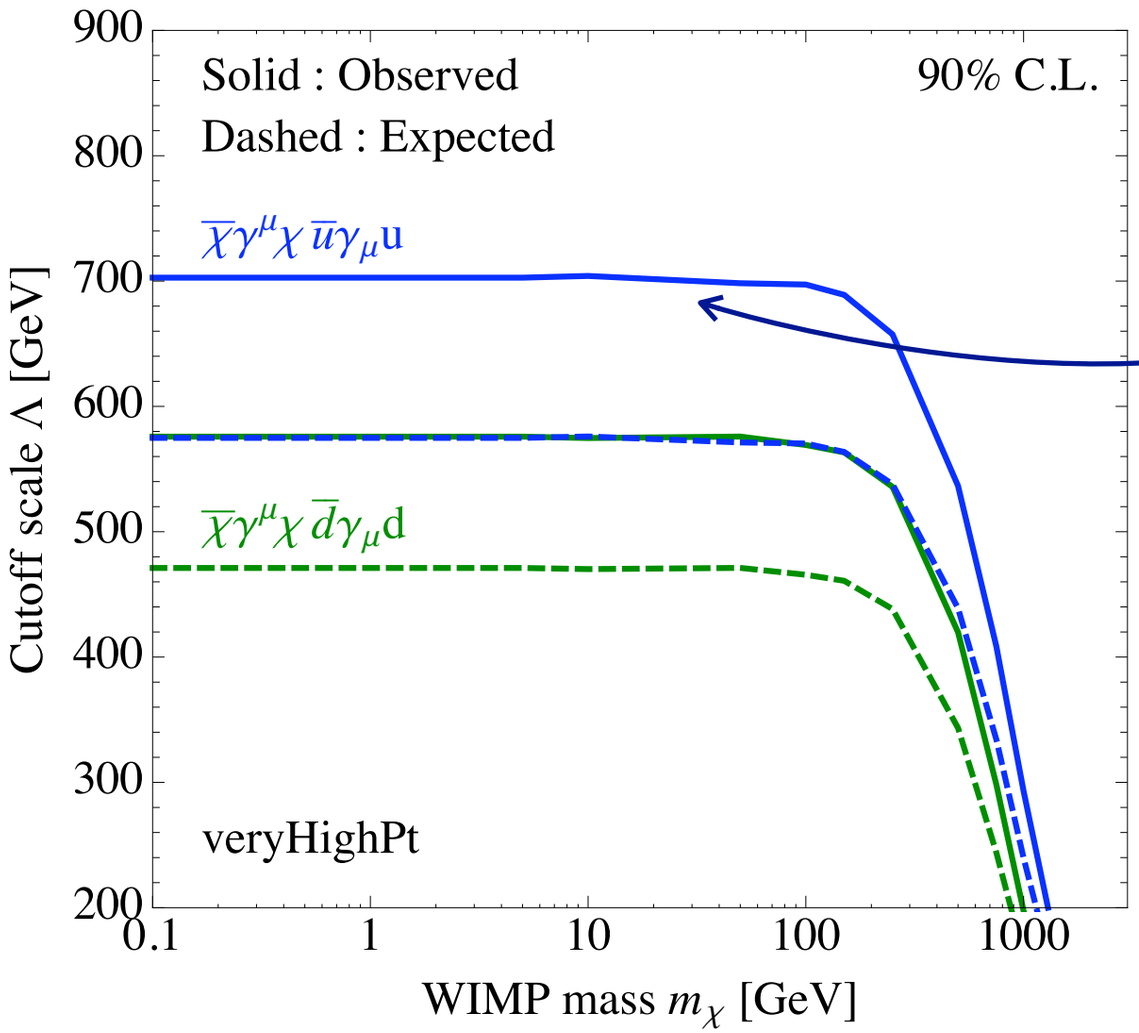


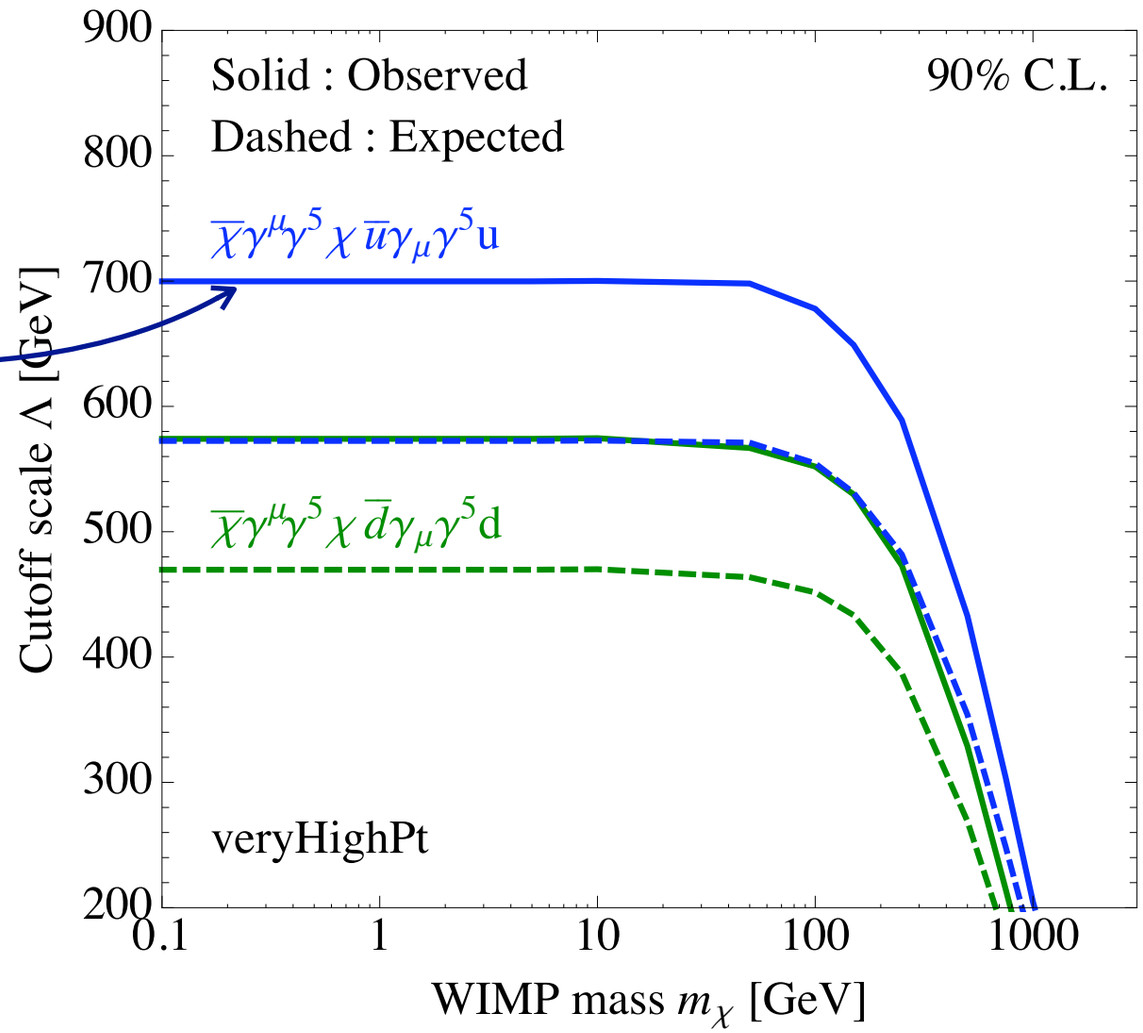


Mono-Jet

Limits on $\Lambda \equiv \dfrac{M}{\sqrt{g_\chi g_1}}$:

same limit for SI and SD





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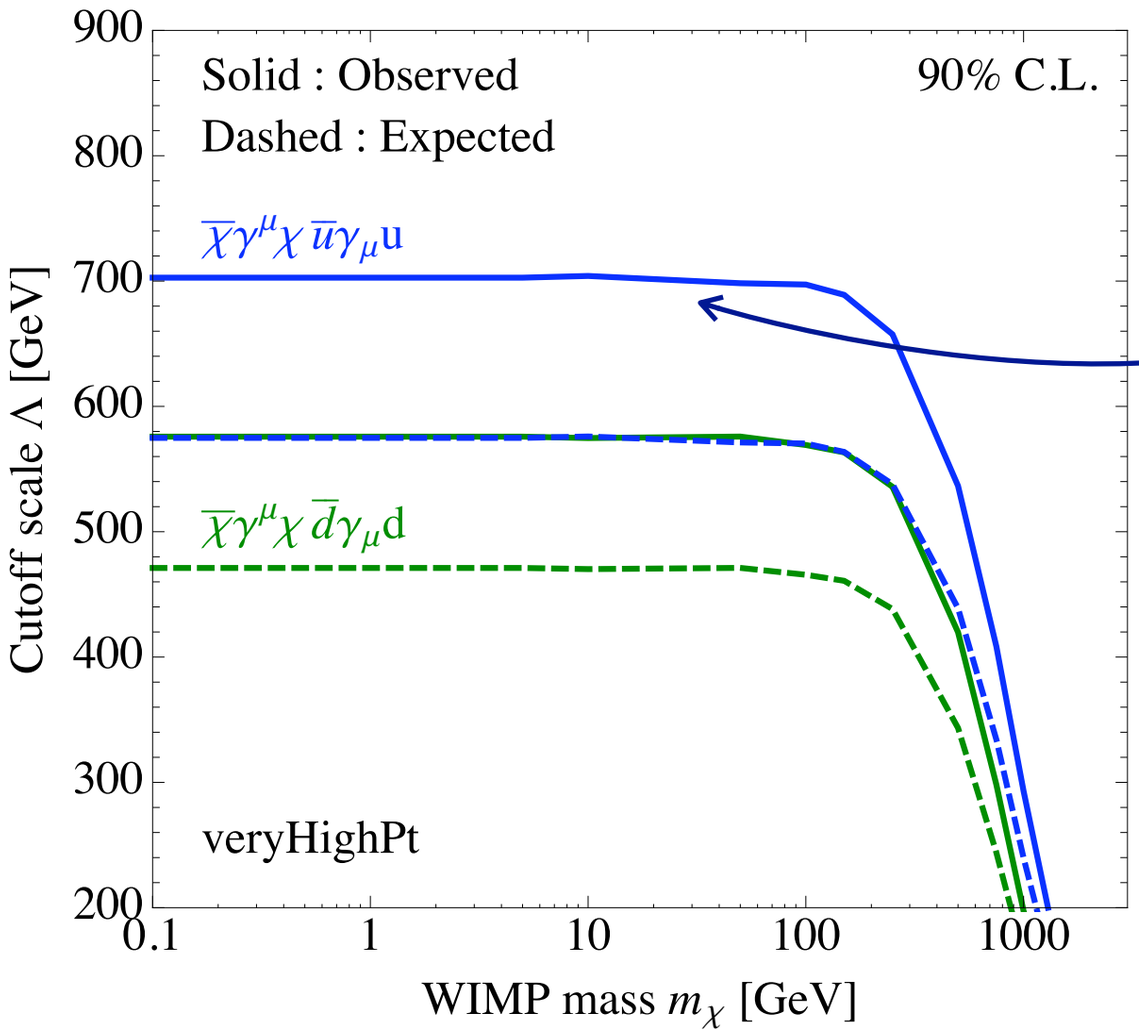
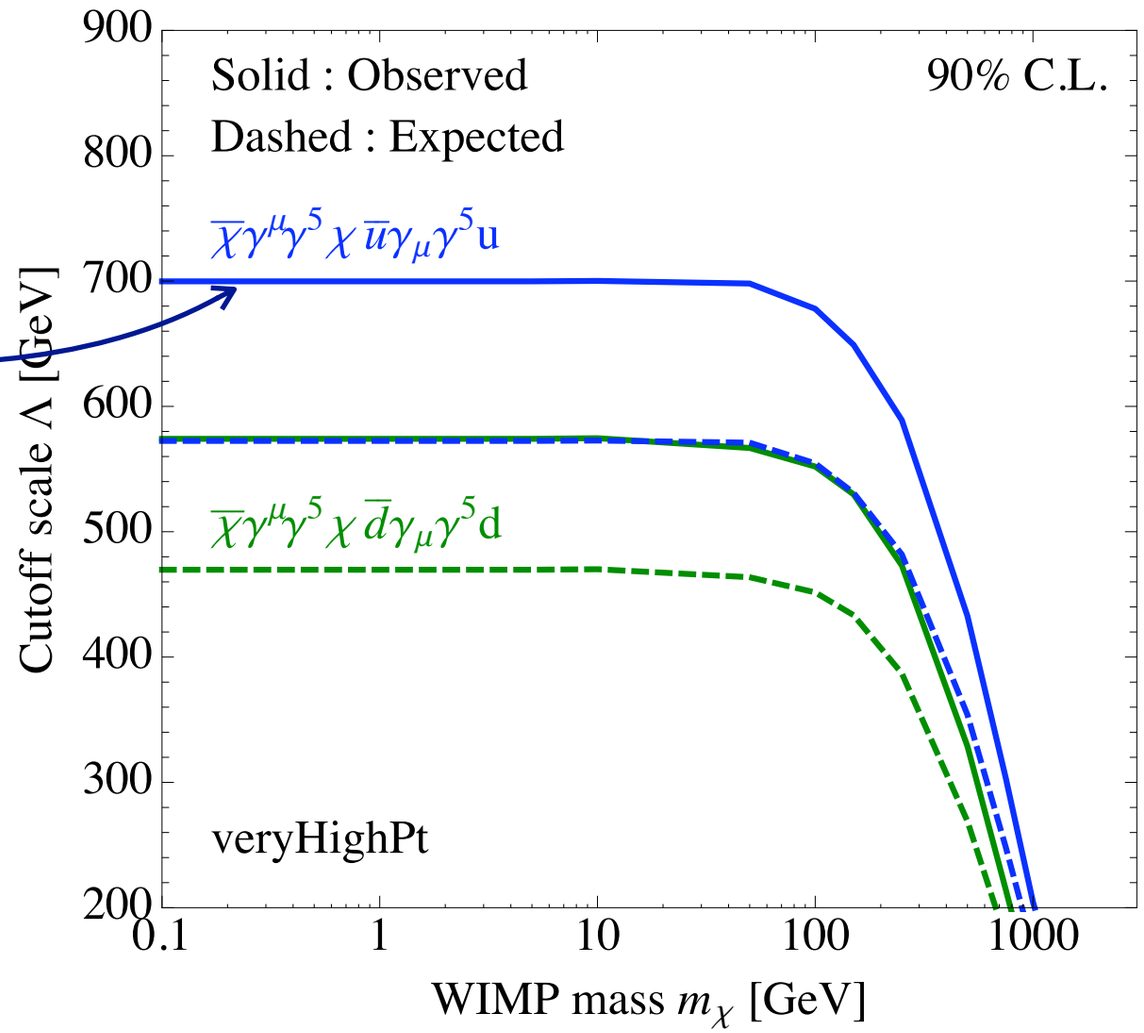
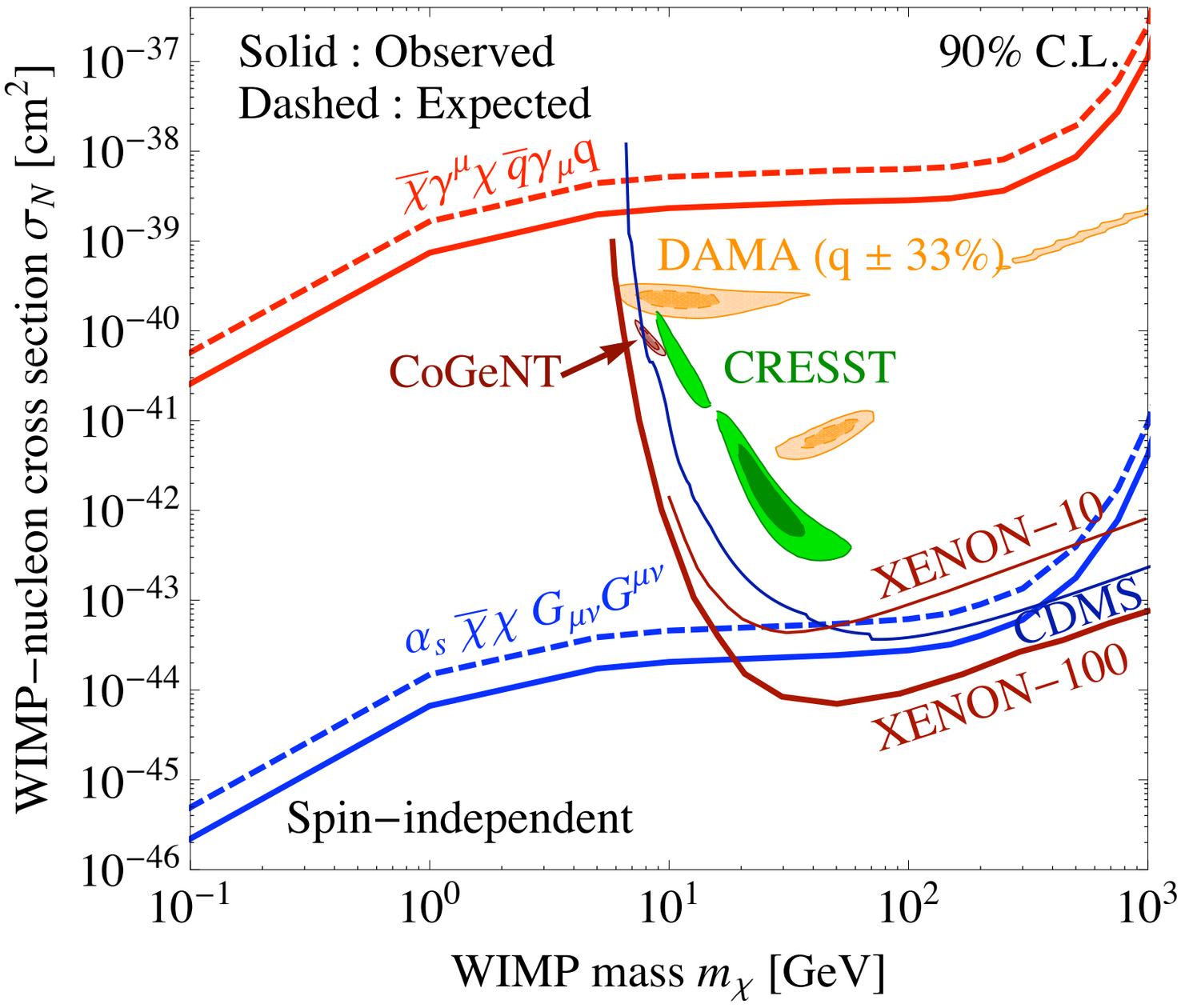




The limit is flat up to ~200 GeV.
Goes all the way to zero.

SI Limit

$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2 ,$$
$$\sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2 ,$$



Best limit at low mass

SI Limit

$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2 ,$$
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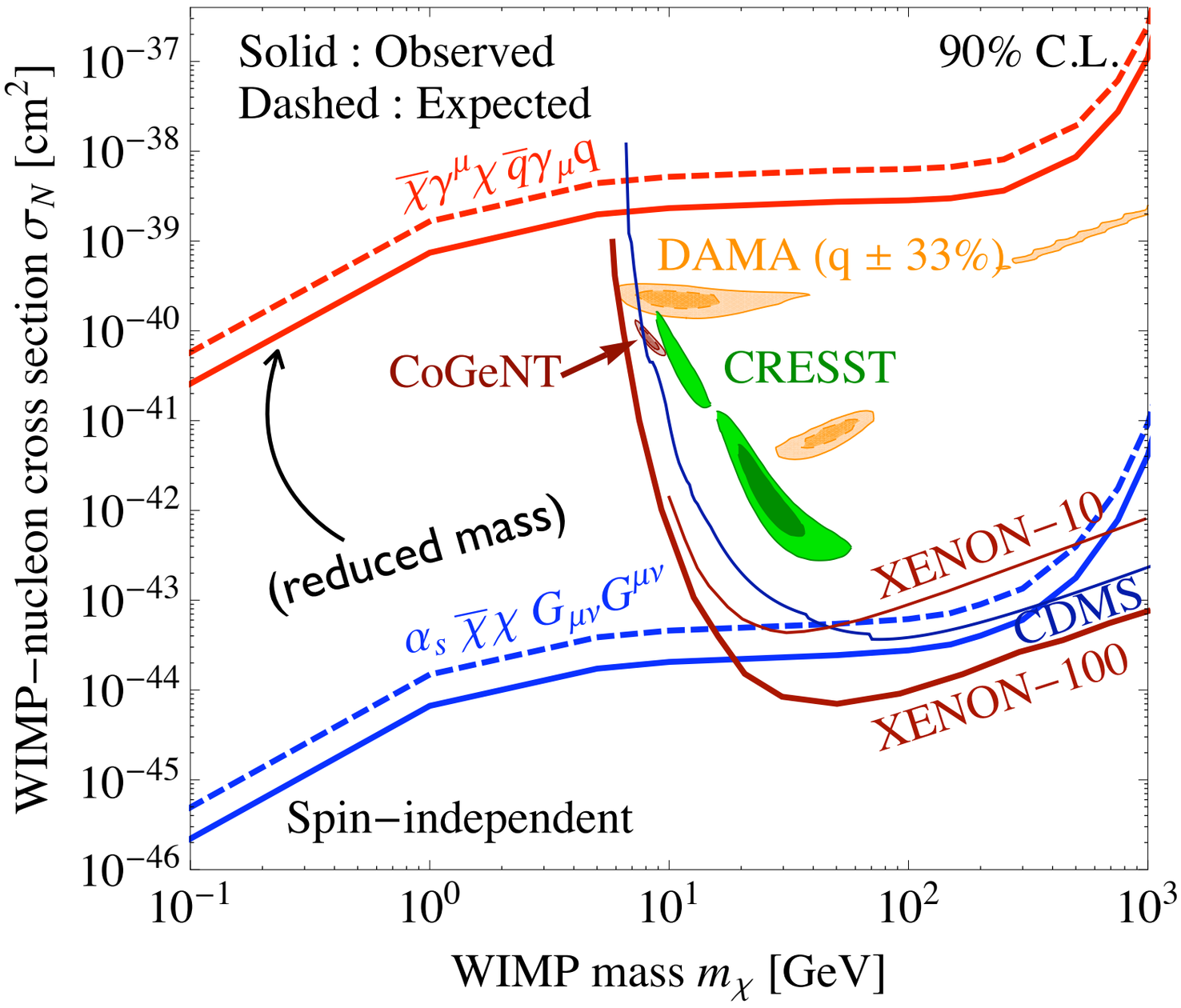
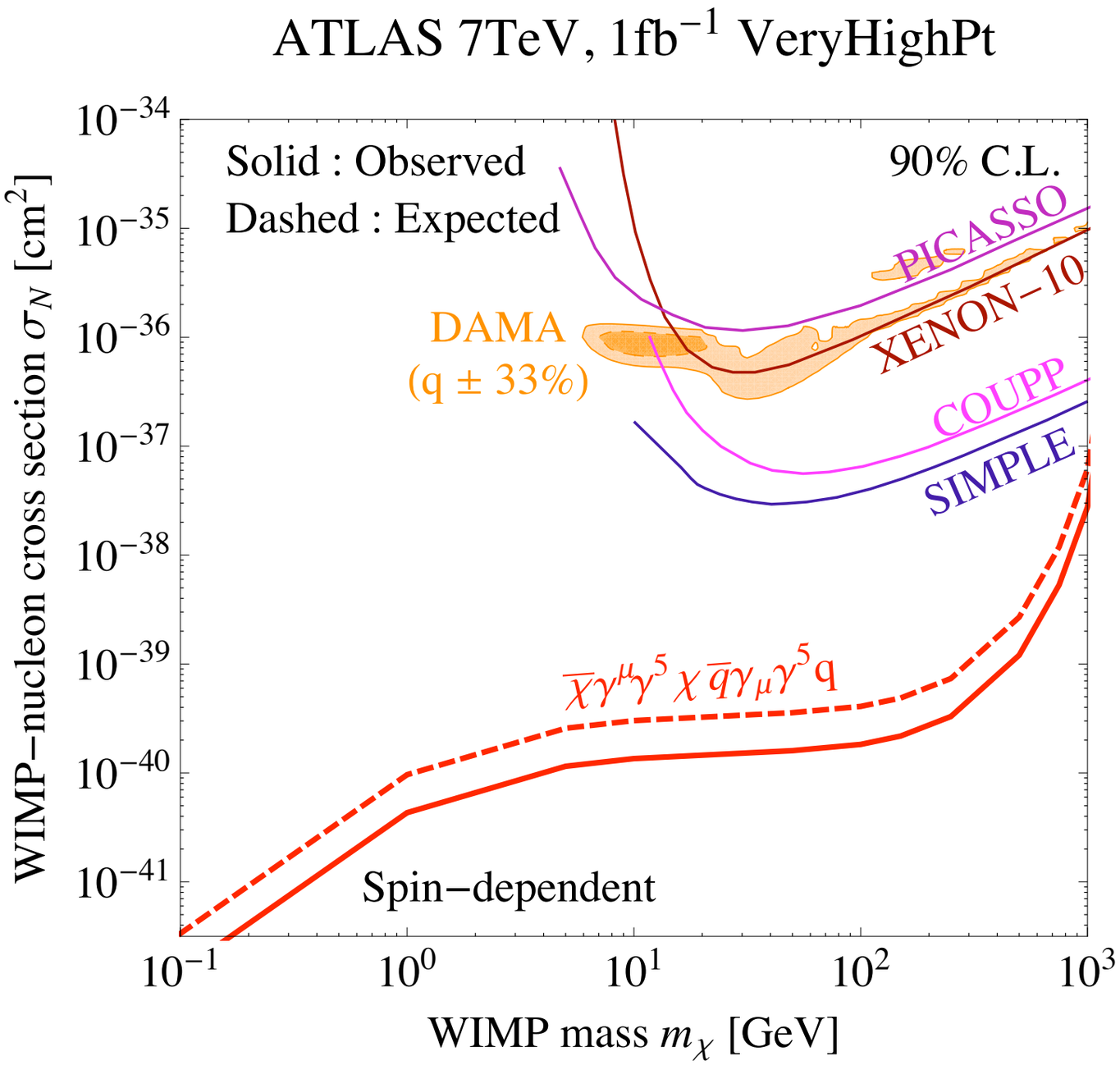
ATLAS 7TeV, 1fb^{-1} VeryHighPt



Best limit at low mass

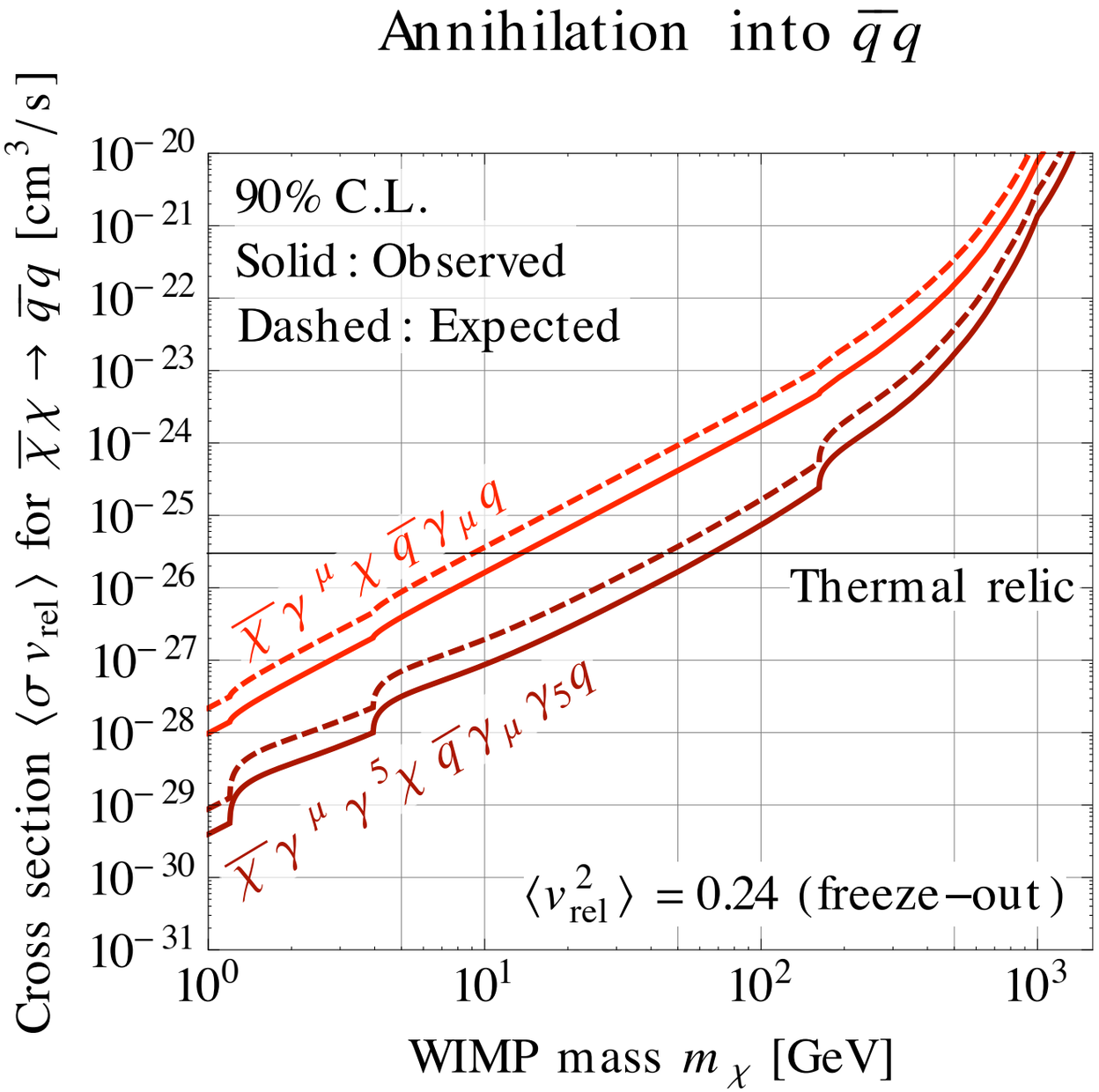
SD Limit



Best spin dependent limit.

Annihilation

* A minimal light thermal relic is ruled out:



Can we evade bounds?

* Lets fix $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \dfrac{\mu^2}{M^4}$ and lower M.

  The couplings must be decreased to compensate.

* Then for very small M we get to the regime where

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

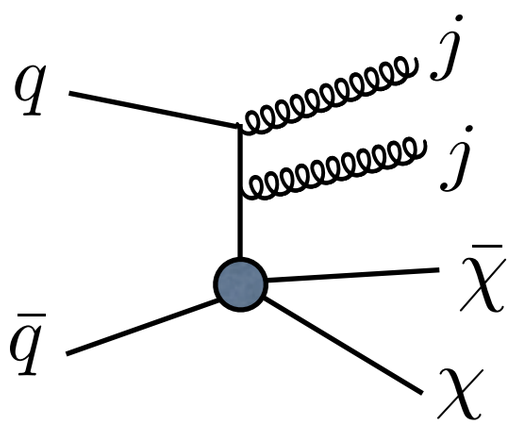
* The cross section drops as M^4.

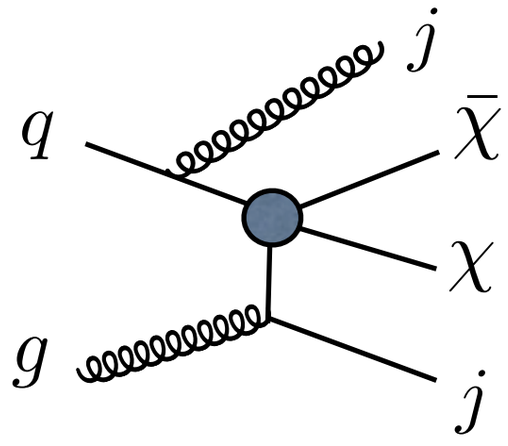
* **Theories with light mediators always evade the collider bound.**

  (**But**....more on the intermediate regime later)

Jets plus MET

(with Fox, Primulando and Yu, 1203.1662)

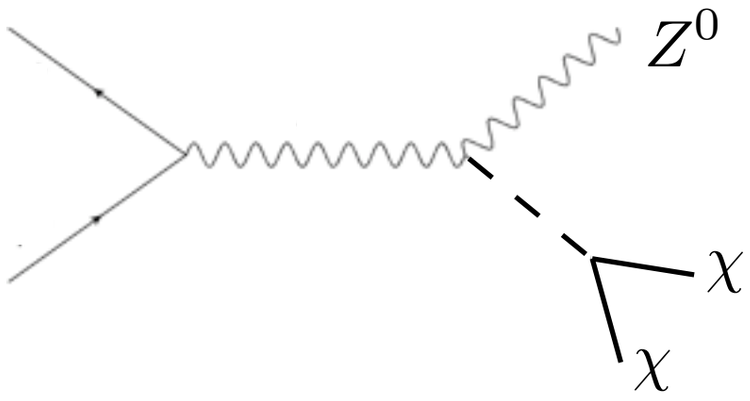




Higgs Portal DM

* For specific models, we can probe the identity of the mediator with other mono-somthings.

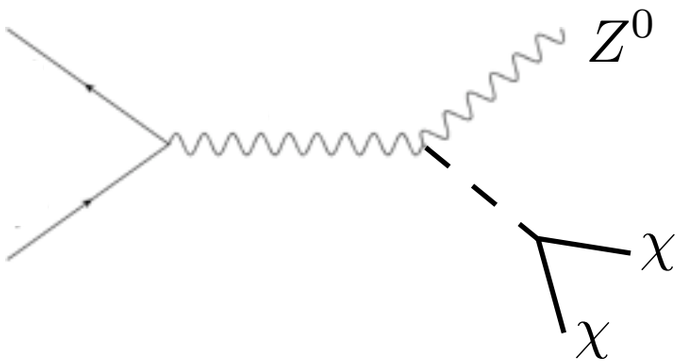
* In many models DM couples via the **Higgs**. **Mono-Z** (and **VBF**) may be sensitive to this.



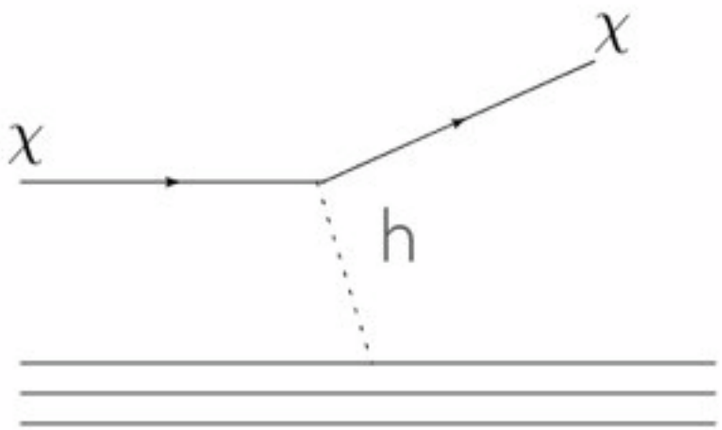
Invisible Higgs searches can be interpreted as "direct detection" experiments!

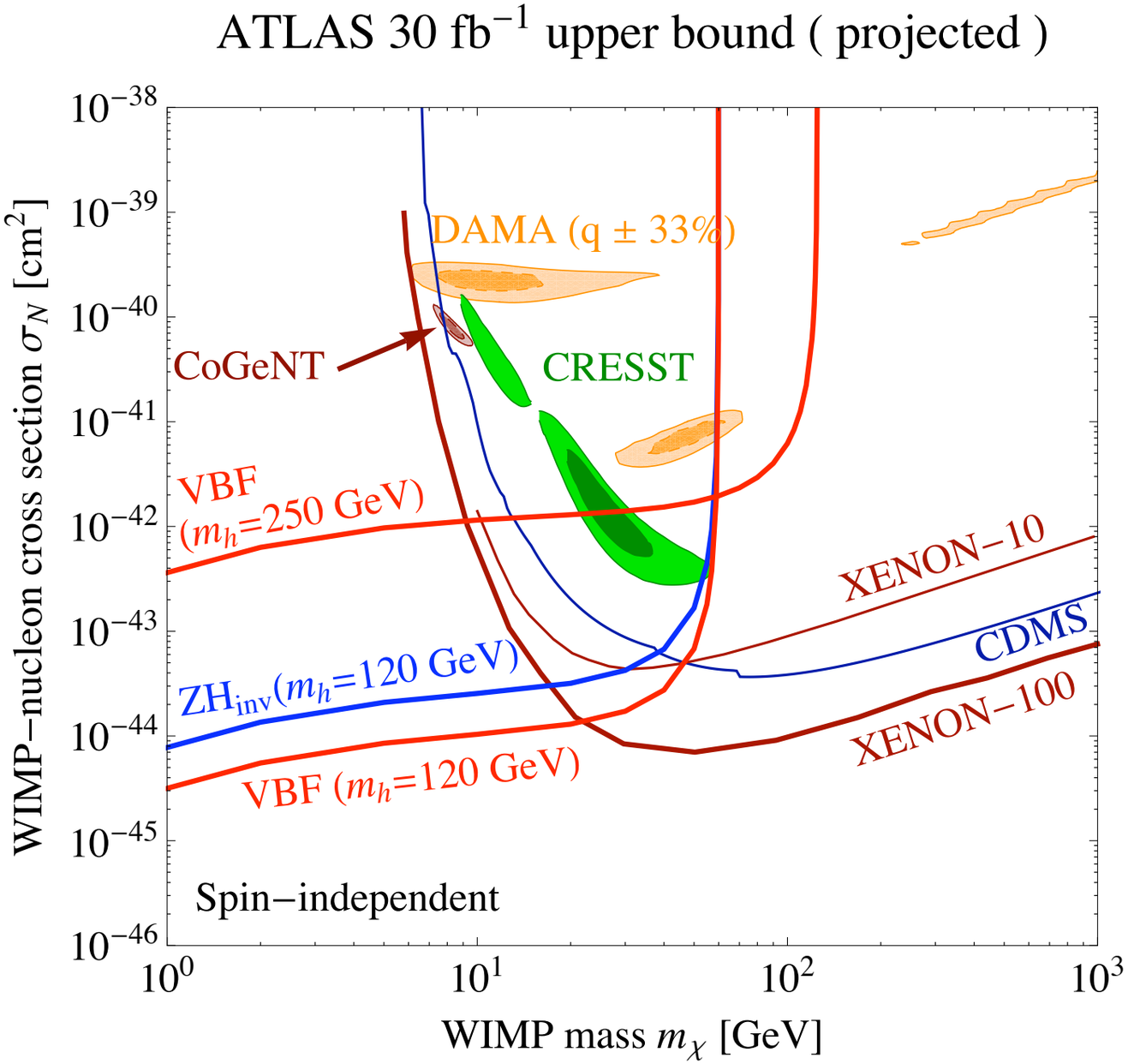
A Characteristic Higgs Channel can confirm Higgs mediation!

Higgs Mediator



vs.





Direct detection is parametrically smaller!

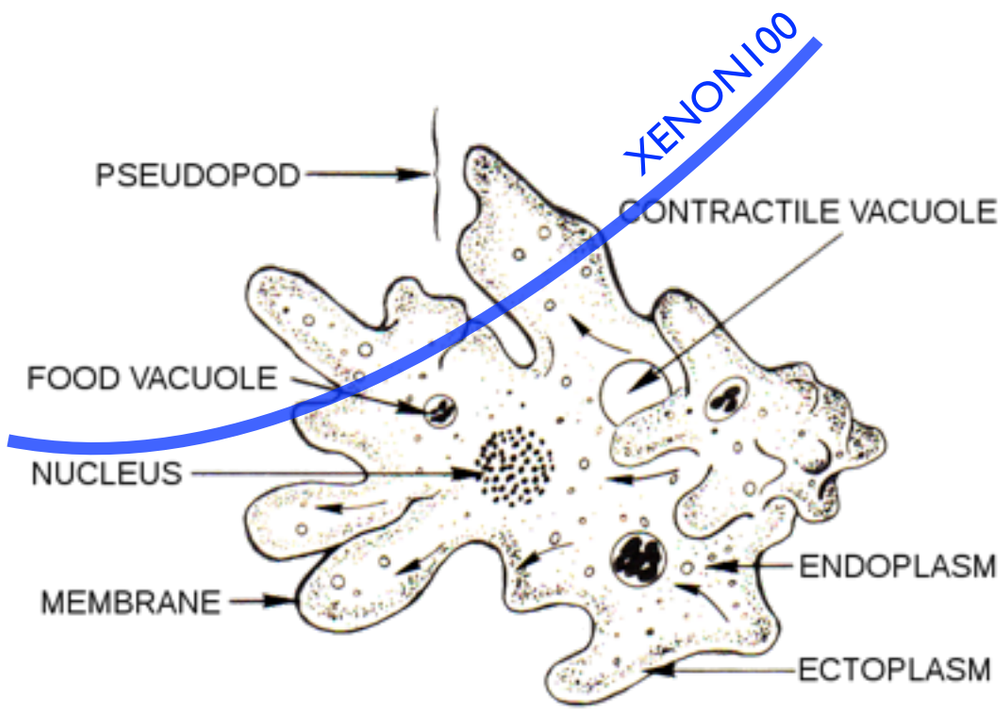
Fox,RH, Kopp and Tsai

To Conclude:

Colliders are placing competitive and complementary bounds to direct and to indirect detection:

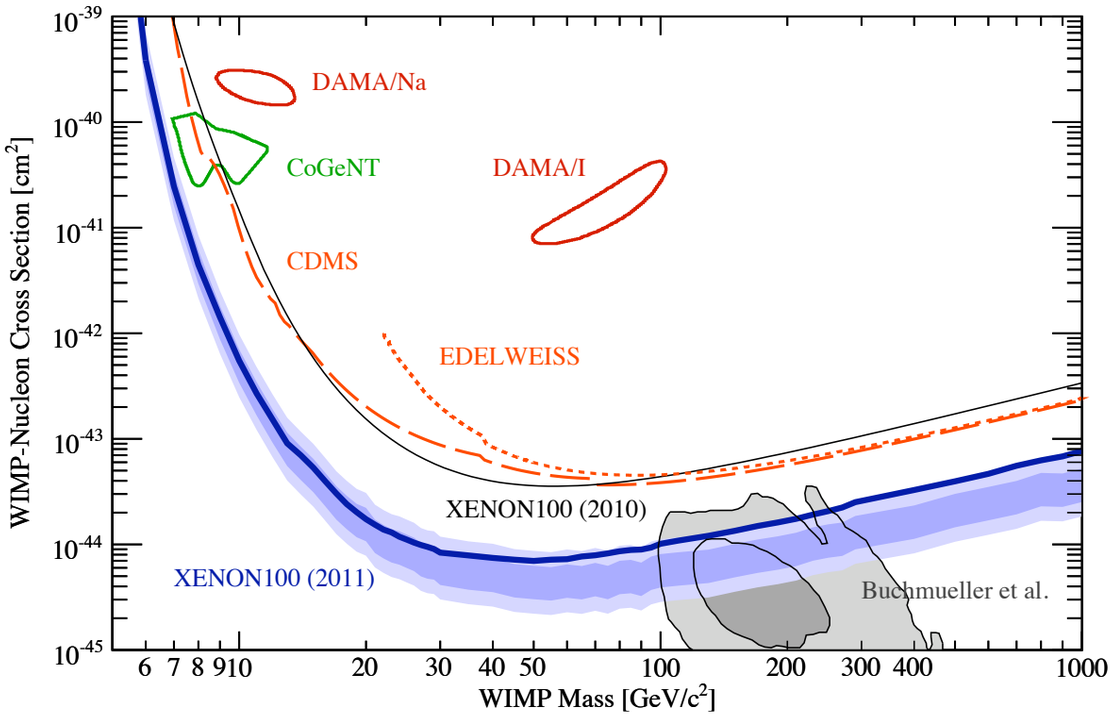
* The **Tevatron** (LHC) is the world record holder for light dark matter and for spin dependent.
* Dedicated CDF, CMS, and ATLAS **mono-jet** studies are out (or underway). CMS **mono-photon** too.
* Inclusive Jets plus MET studies may have additional discriminating power (Razor).
* **Higgs** and **DM** play nicely together.

Deleted Scenes



Collider Connections?

* DM experiments and colliders are often said to be related *in a specific framework* (SUSY).



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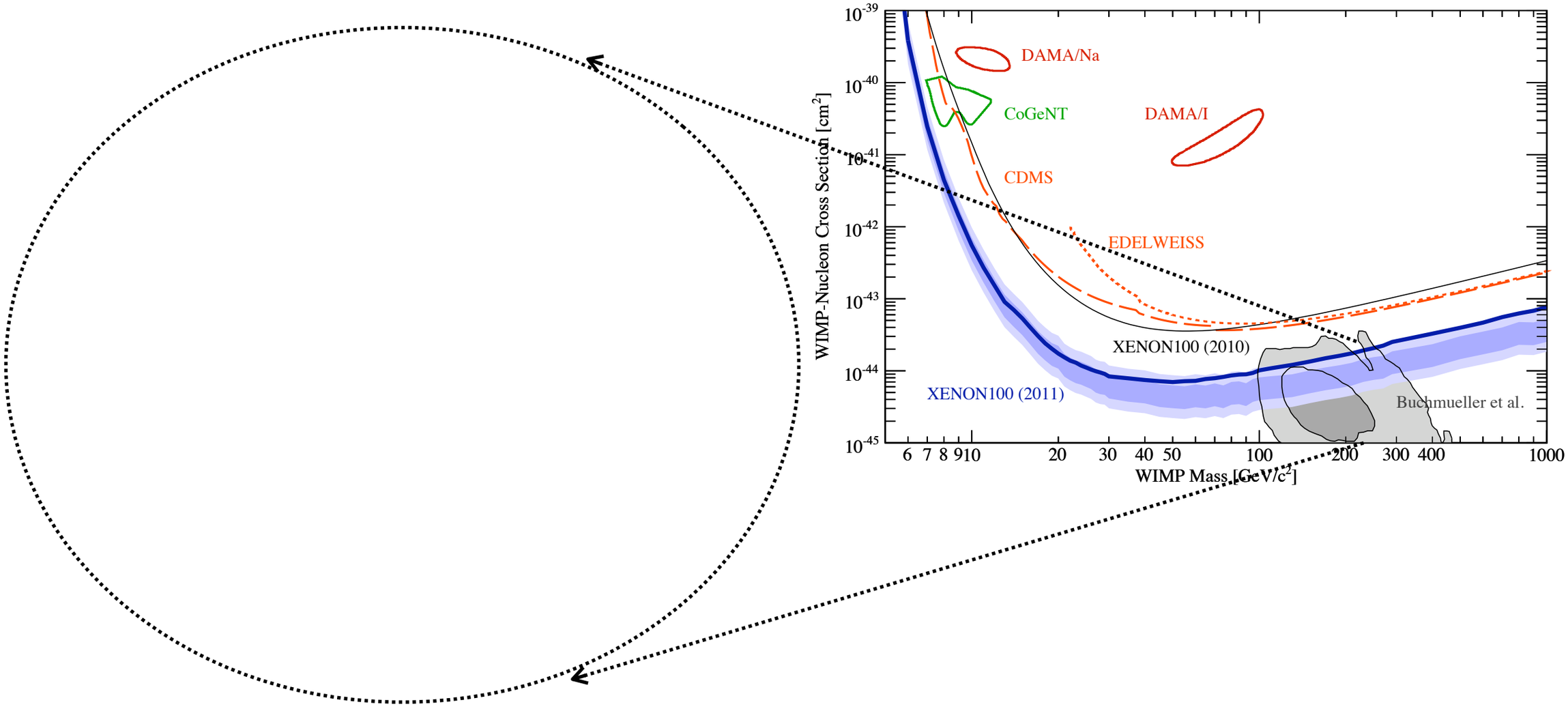

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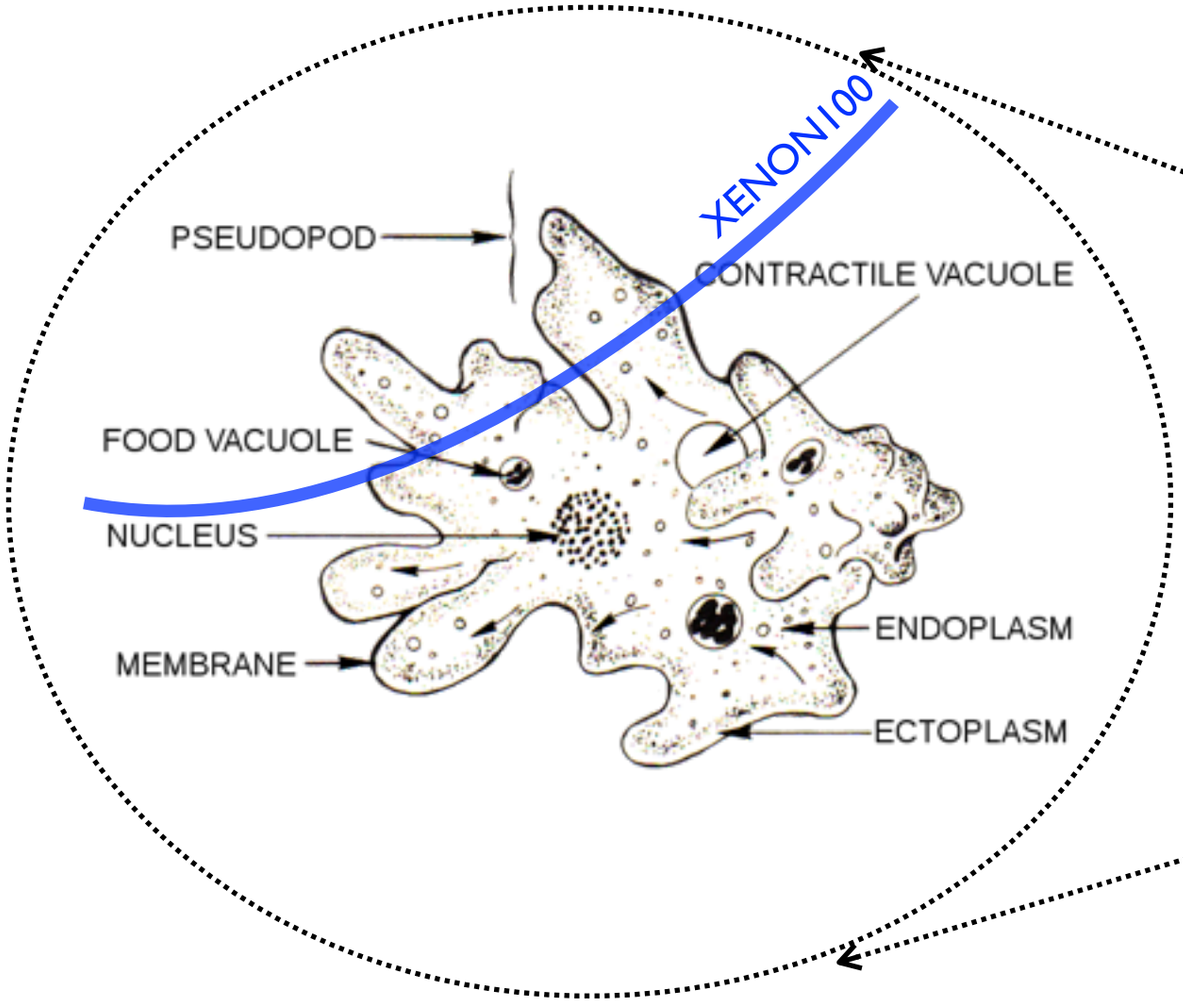

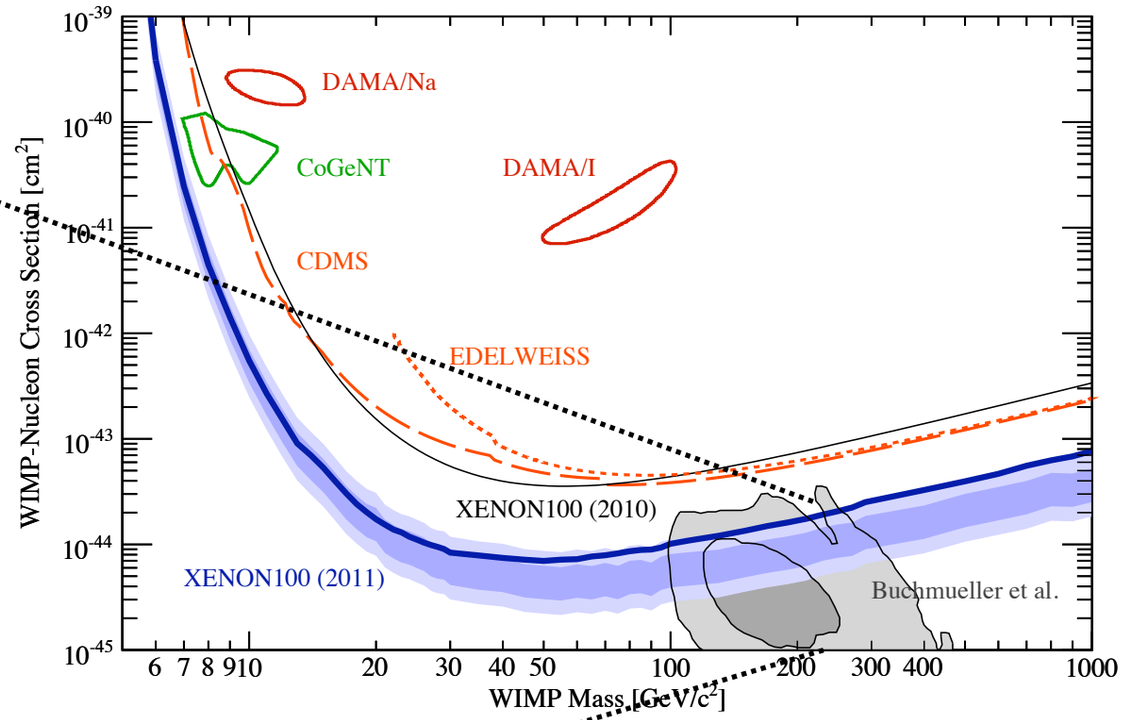

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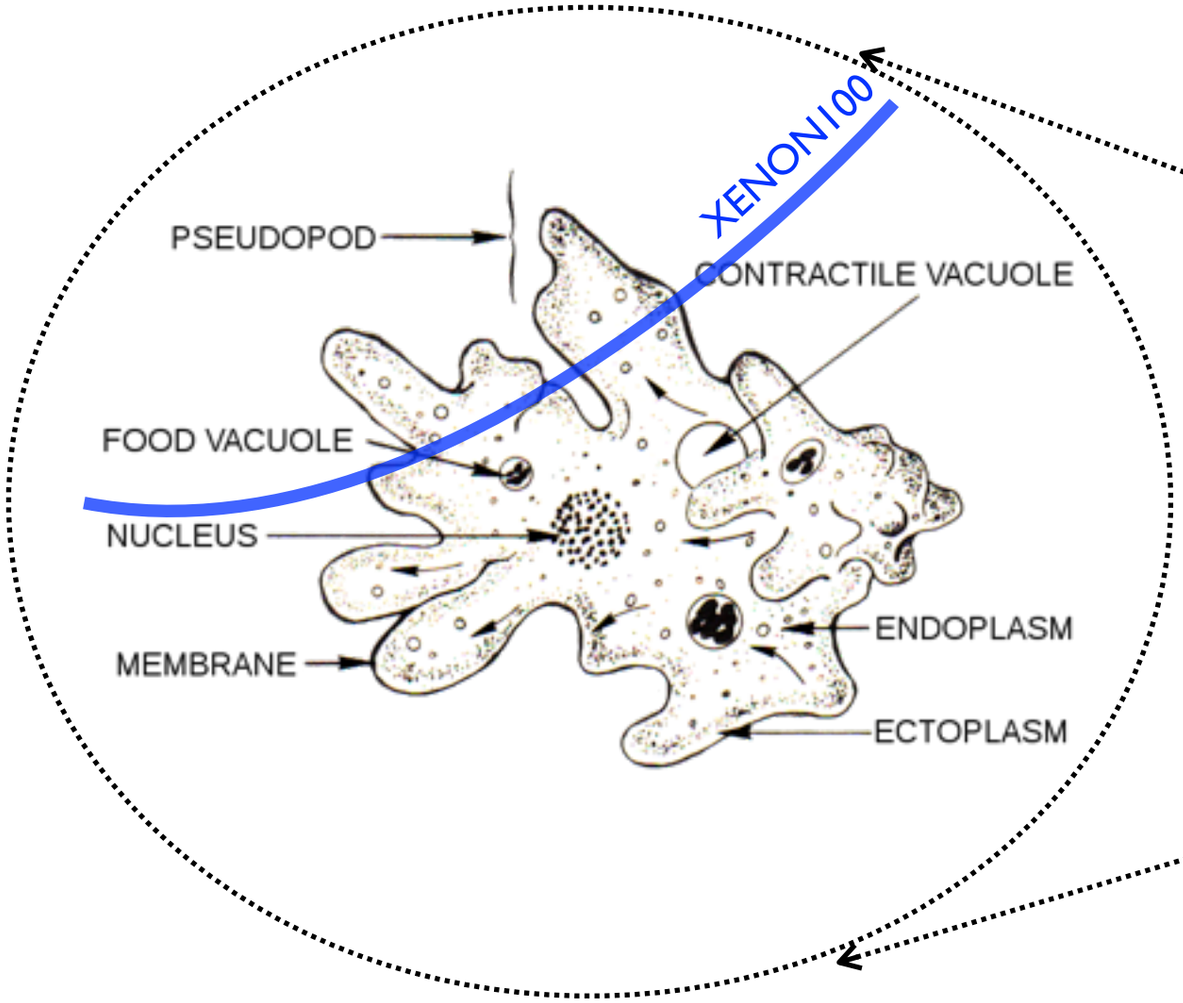

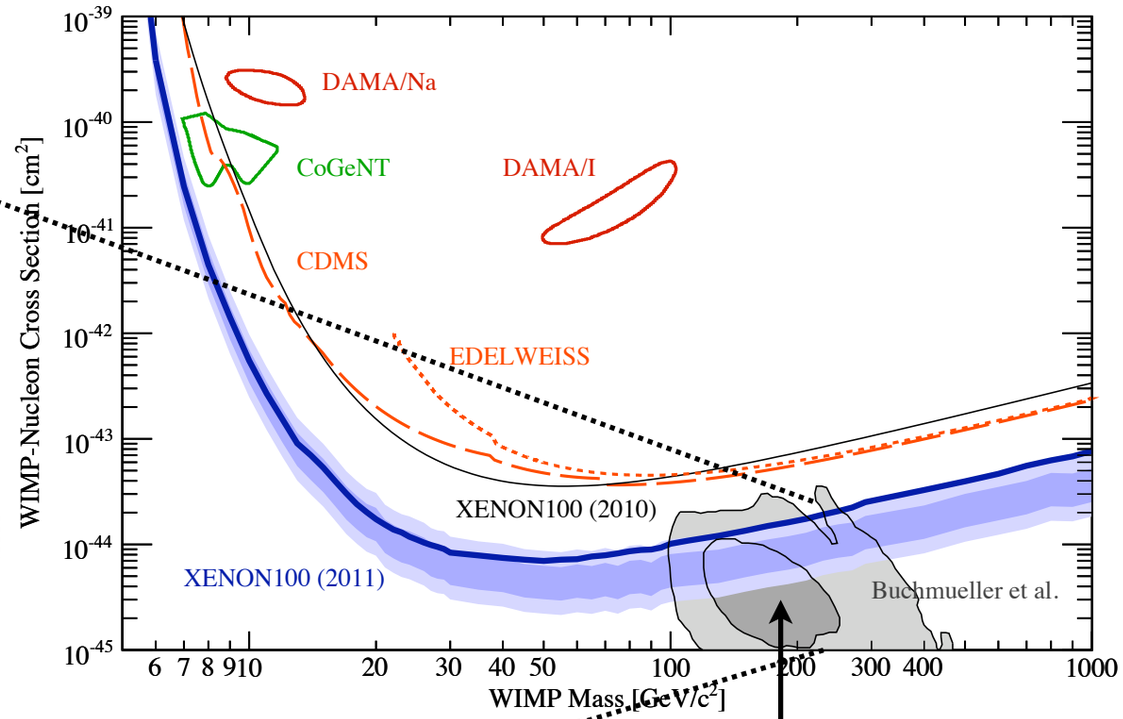

tri-leptons+
jets + MET

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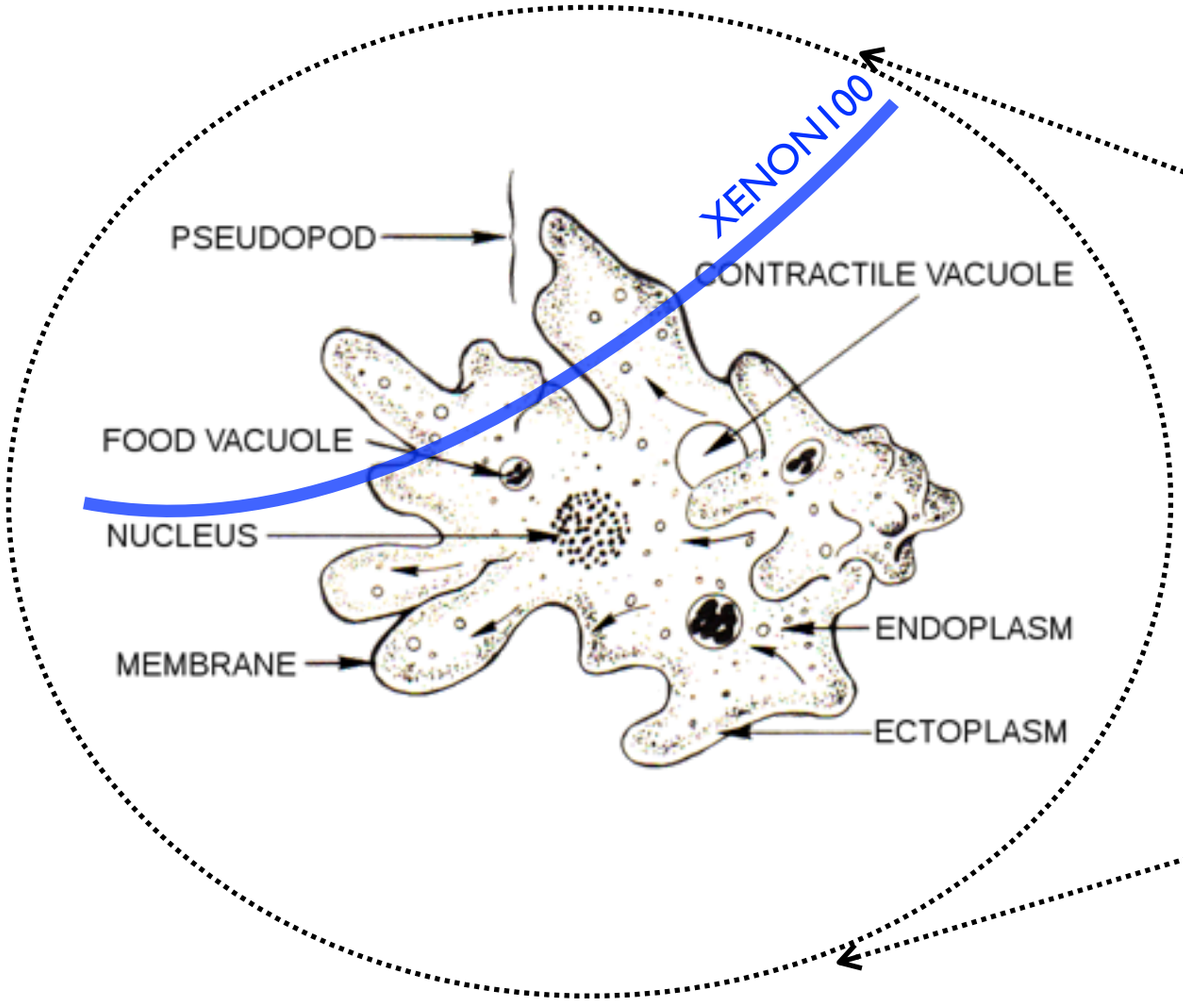

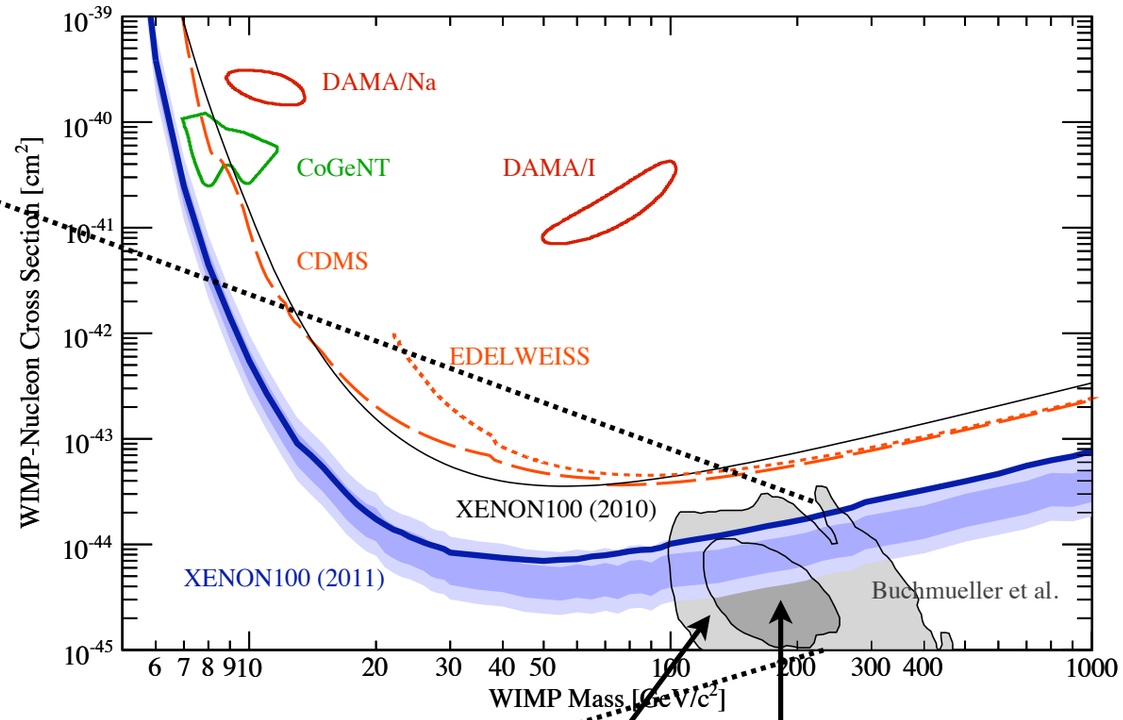

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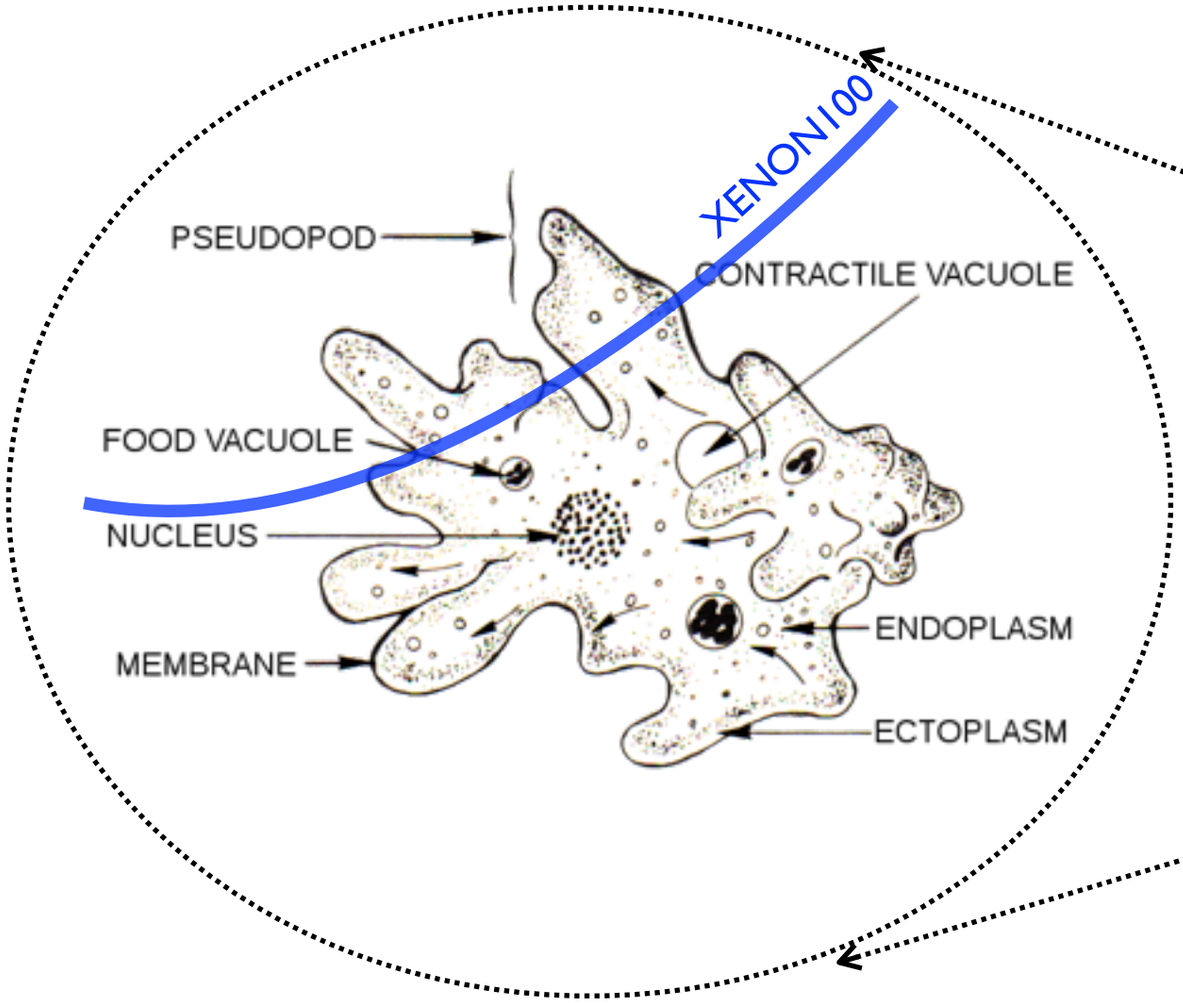

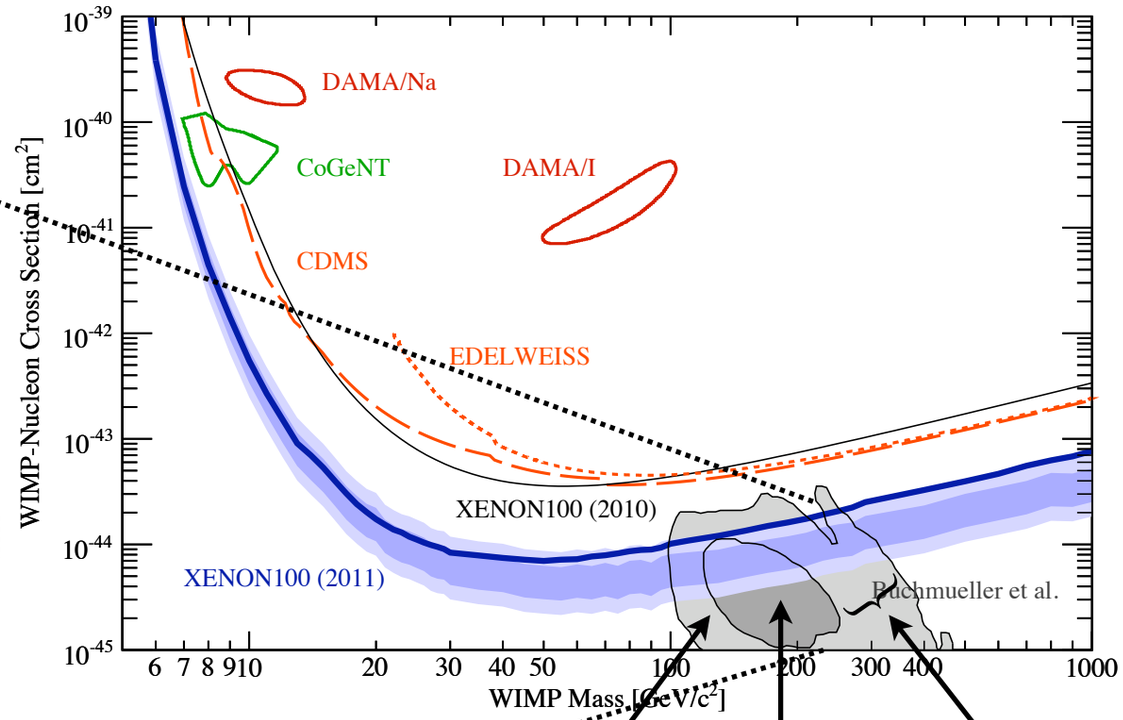

jets + MET

tri-leptons+ jets + MET

same-sign di-leptons +MET

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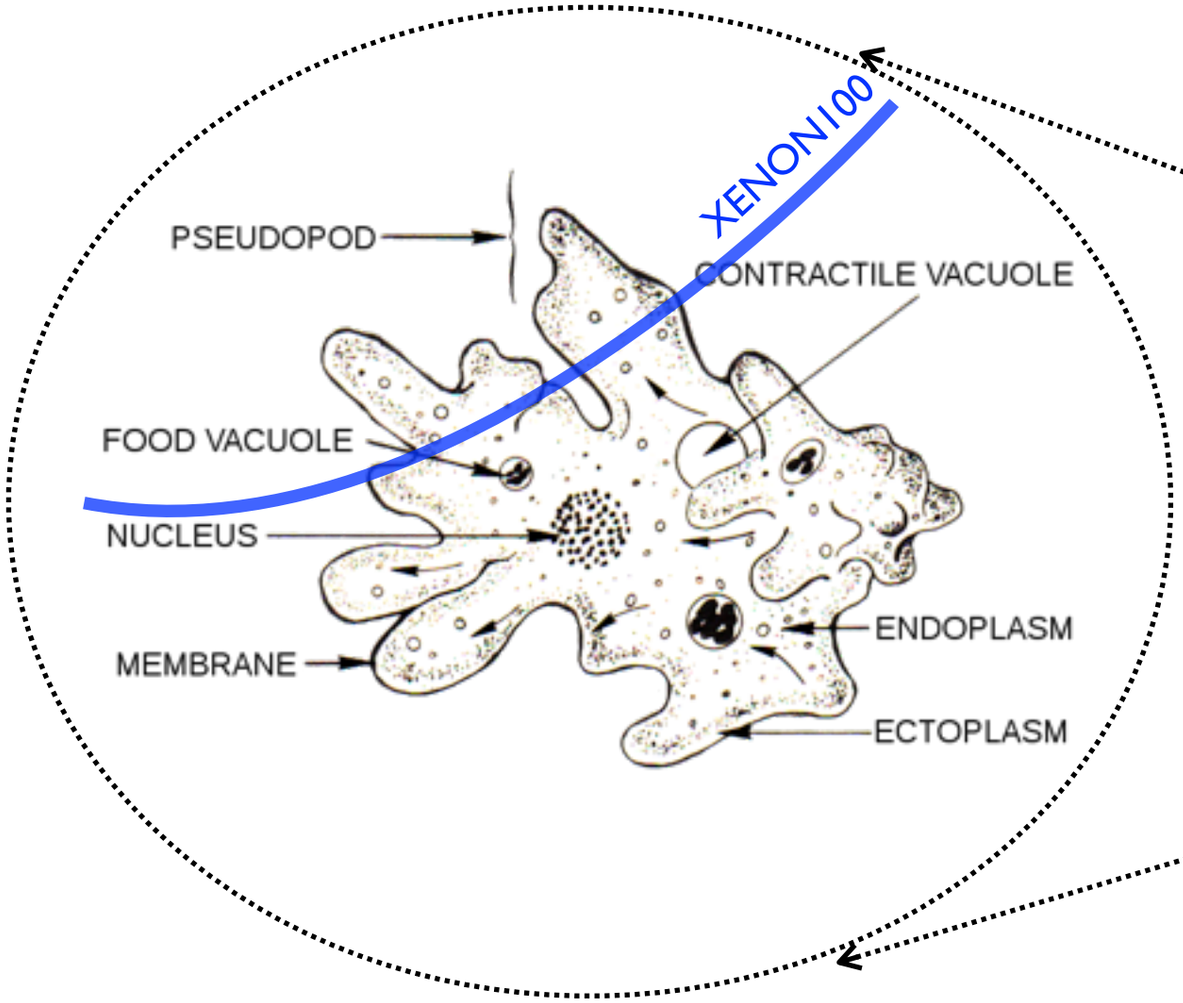
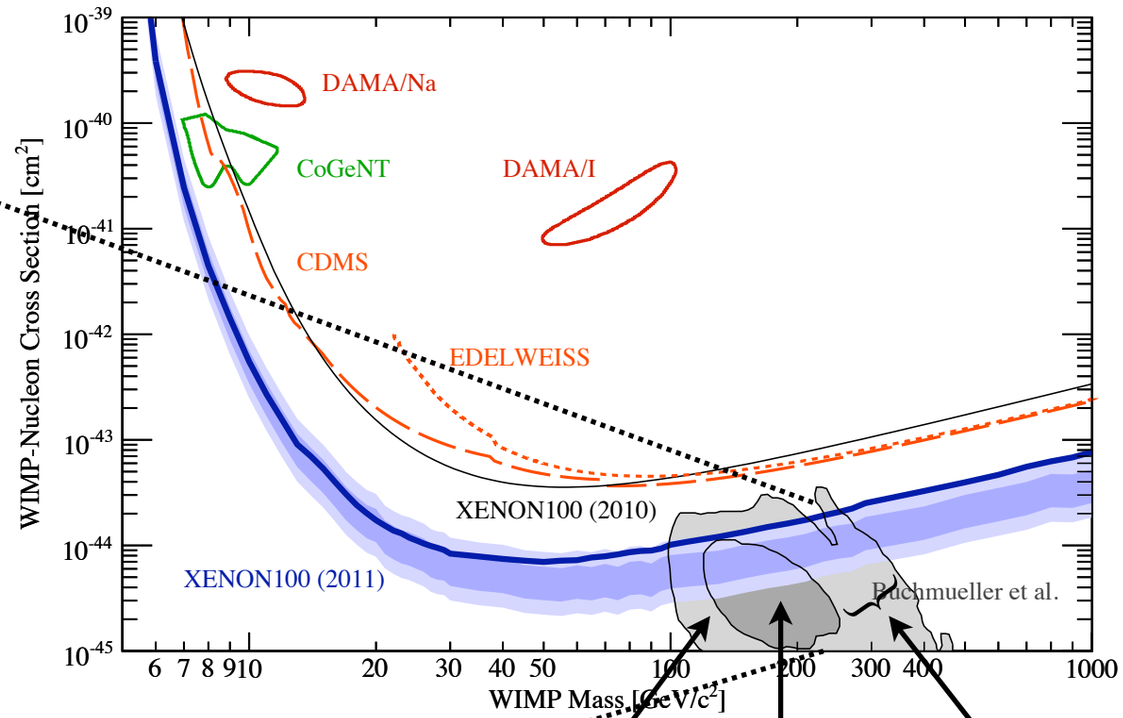




jets + MET

tri-leptons+ jets + MET

same-sign di-leptons +MET

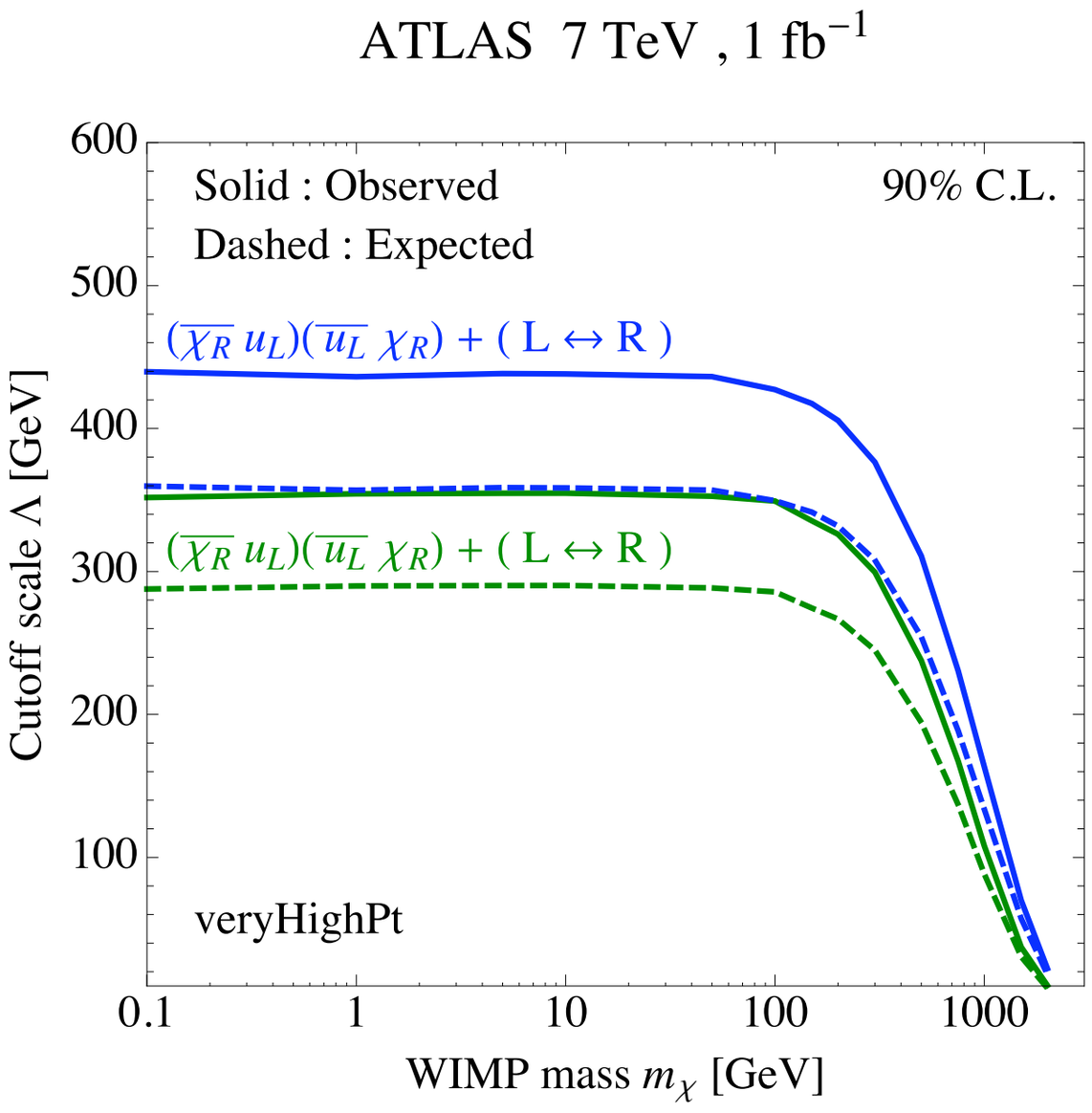
"XENON100 is starting to probe the MSSM's pseudopod, LHC killed the Membrane, but the ectoplasm is still safe." [submitted to nature]

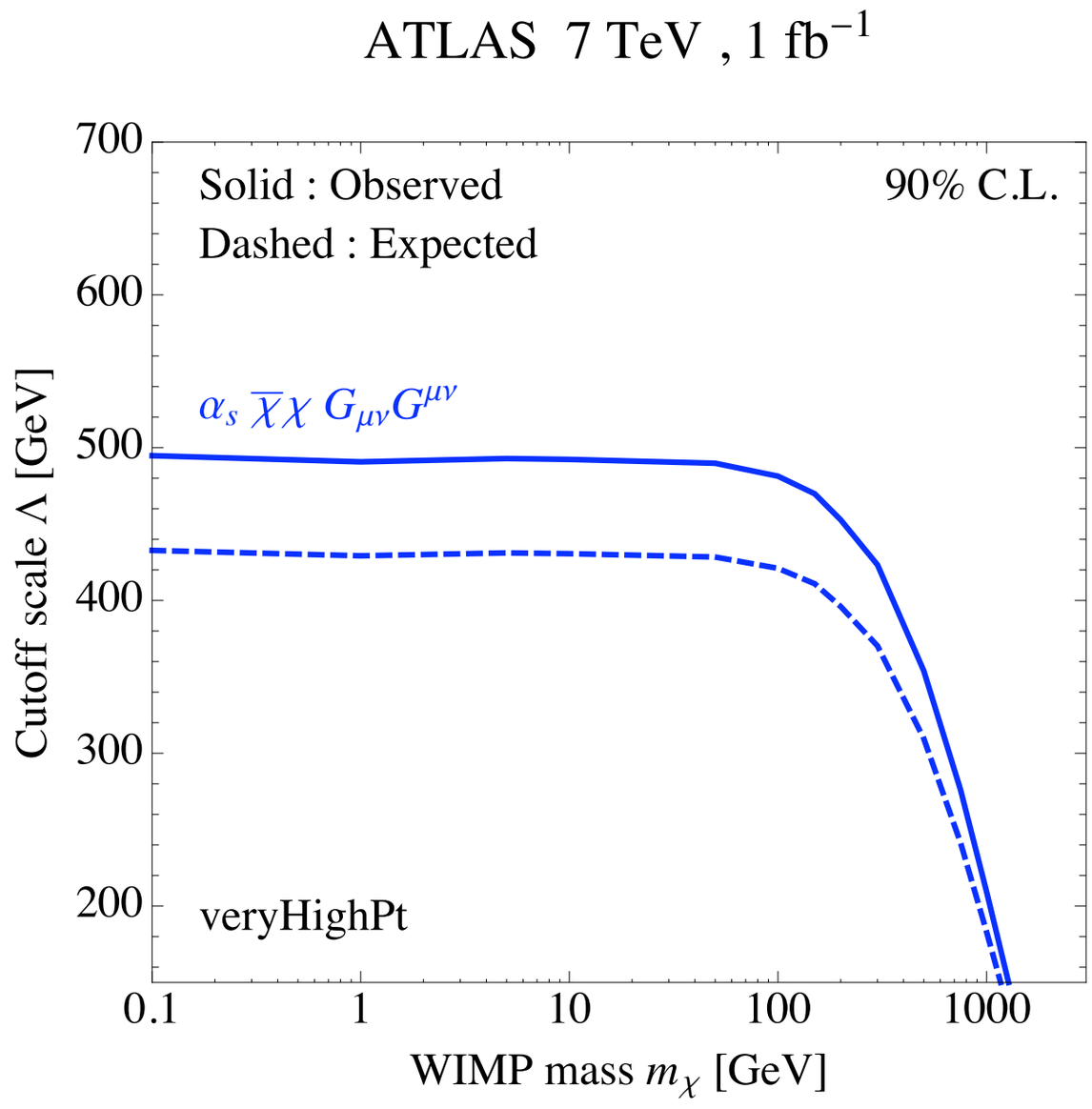
Games: Higgs searches & DM

* *Assume* the Higgs hint is real w/ SM production.
* The fact that is was seen in di-photon with the rate that is has, places limits on competing modes, e.g. Higgs to invisible.
* Places **upper** limit on higgs mediated direct detection.

* *Assume* a Higgs mass that is already excluded for SM.
* *Assume* the reason it was excluded is an invisible branching fraction.
* This places a lower limit on the invisible BR.
  Places a **lower** limit on higgs mediated direct detection.

Other Operators:

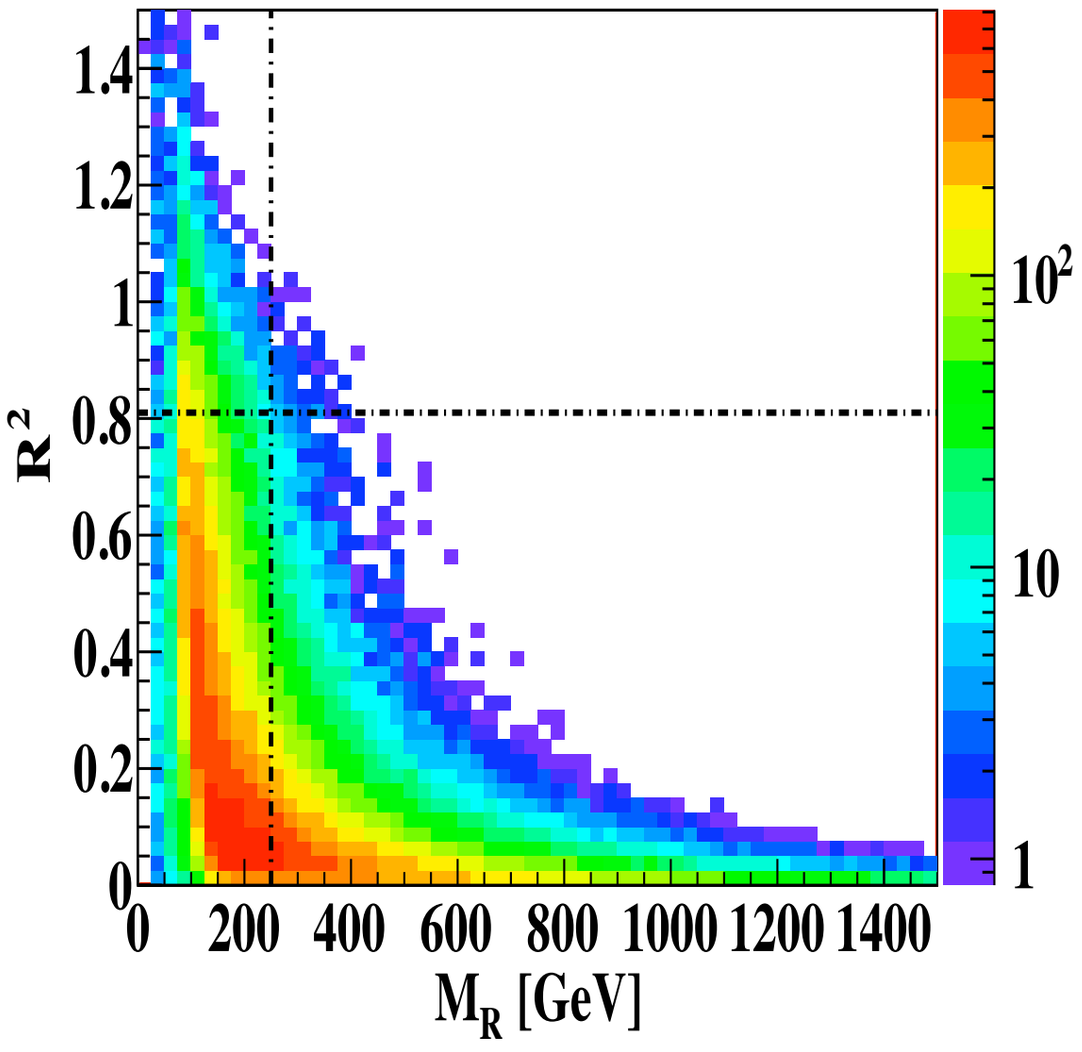




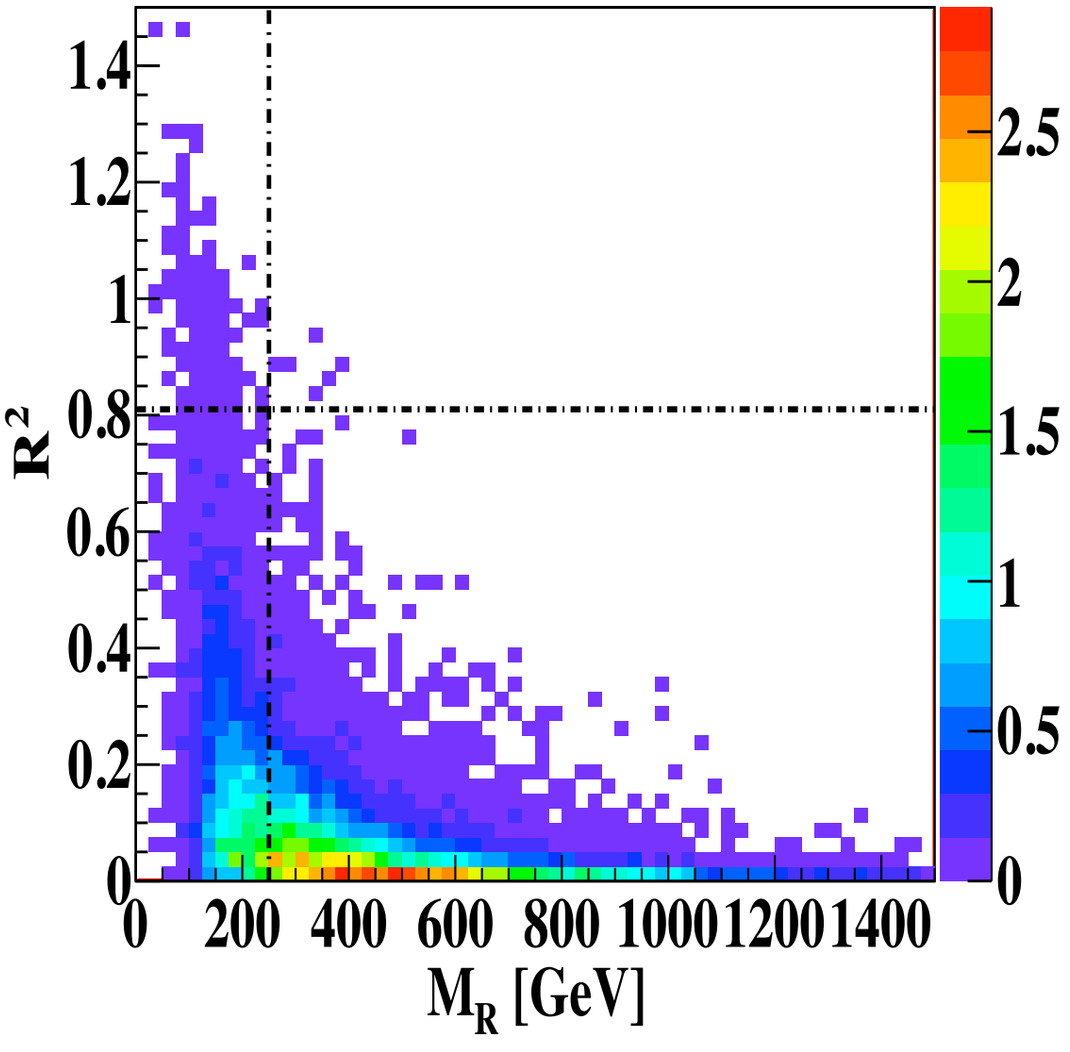
The limit is flat up to ~200 GeV.
Goes all the way to zero.

Razor Shapes

* Other Backgrounds:

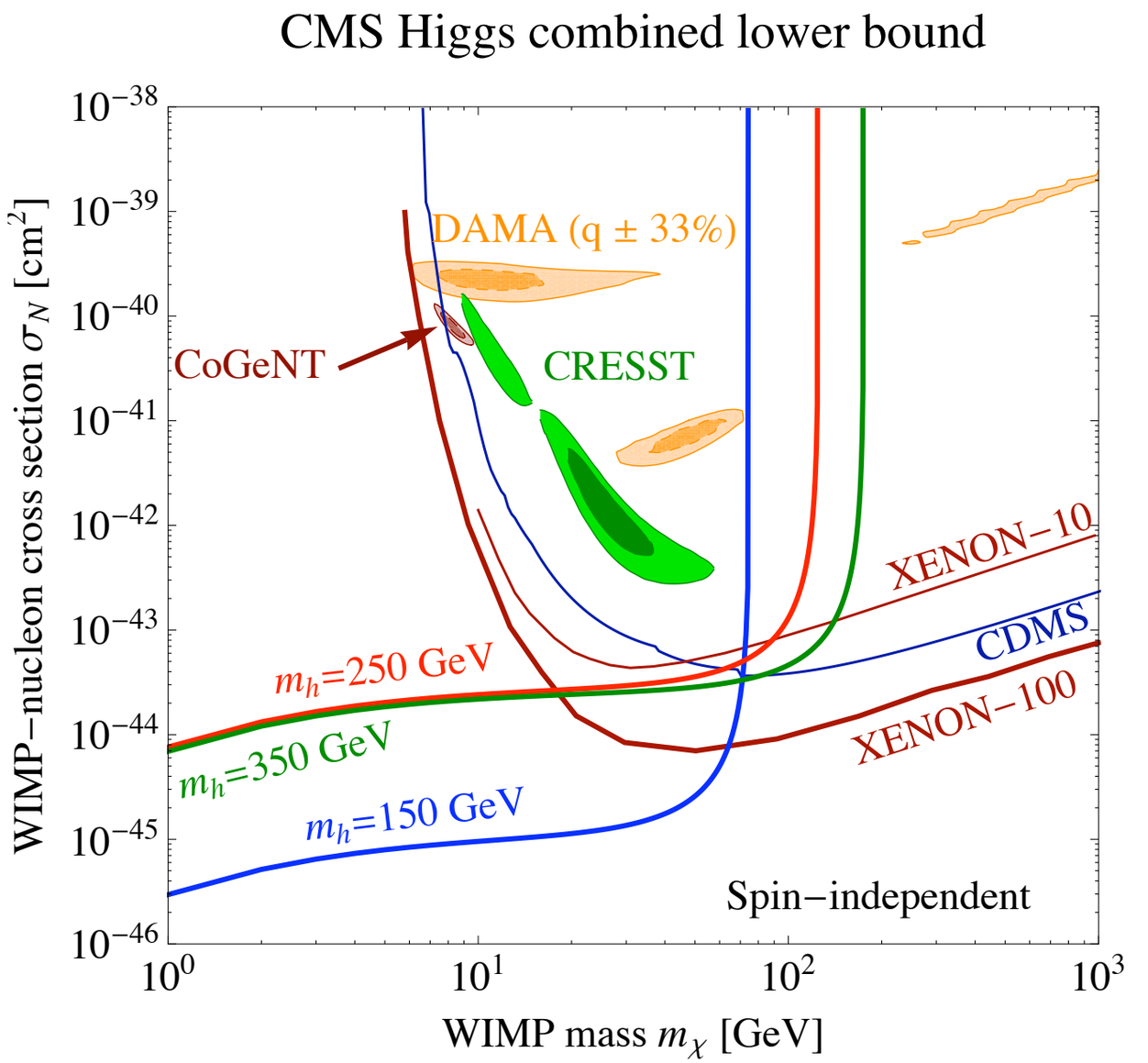


(b) W+jets.



(c) $t\bar{t}$.

Current Higgs limits vs DM

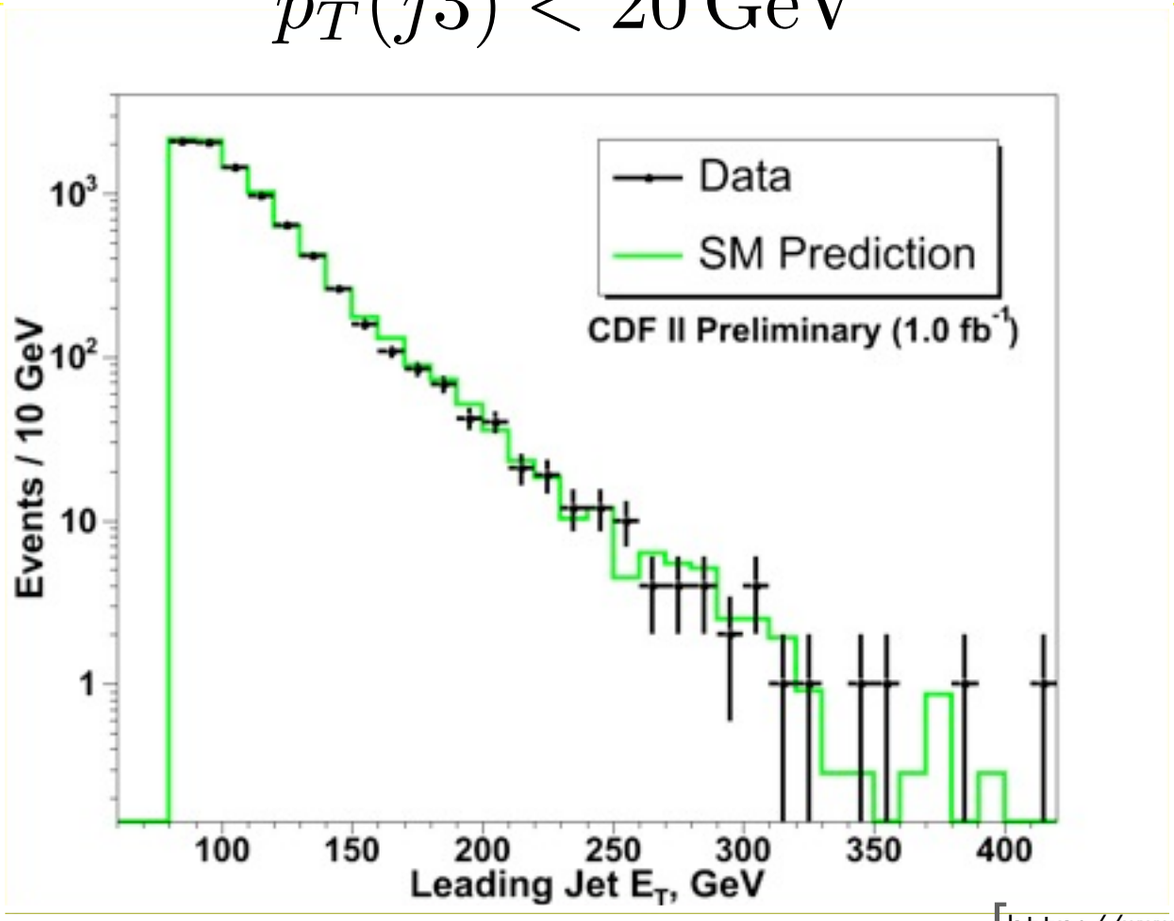


Also, if a light SM Higgs is discovered, an upper limit on DD can be extracted.

CDF: jet + MET (1 fb^{-1})

counting experiment:

$$\not\!\!E_T > 80\,\mathrm{GeV}$$
$$p_T(j1) > 80\,\mathrm{GeV}$$
$$p_T(j2) < 30\,\mathrm{GeV}$$
$$p_T(j3) < 20\,\mathrm{GeV}$$



Background	Number of Events
Z -> nu nu	3203 +/- 137
W -> tau nu	2010 +/- 69
W -> mu nu	1570 +/- 54
W -> e nu	824 +/- 28
Z -> ll	87 +/- 3
QCD	708 +/- 146
Gamma plus Jet	209 +/- 41
Non-Collision	52 +/- 52
Total Predicted	8663 +/- 332
Data Observed	8449

Observed: 8449 events

[http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html]

ATLAS Analysis

* ATLAS's 1fb analysis employs 3 sets of cuts

`LowPT` Selection requires $\not\!\!E_T > 120$ GeV, one jet with $p_T(j_1) > 120$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if they contain a second jet with $p_T(j_2) > 30$ GeV and $|\eta(j_2)| < 4.5$.

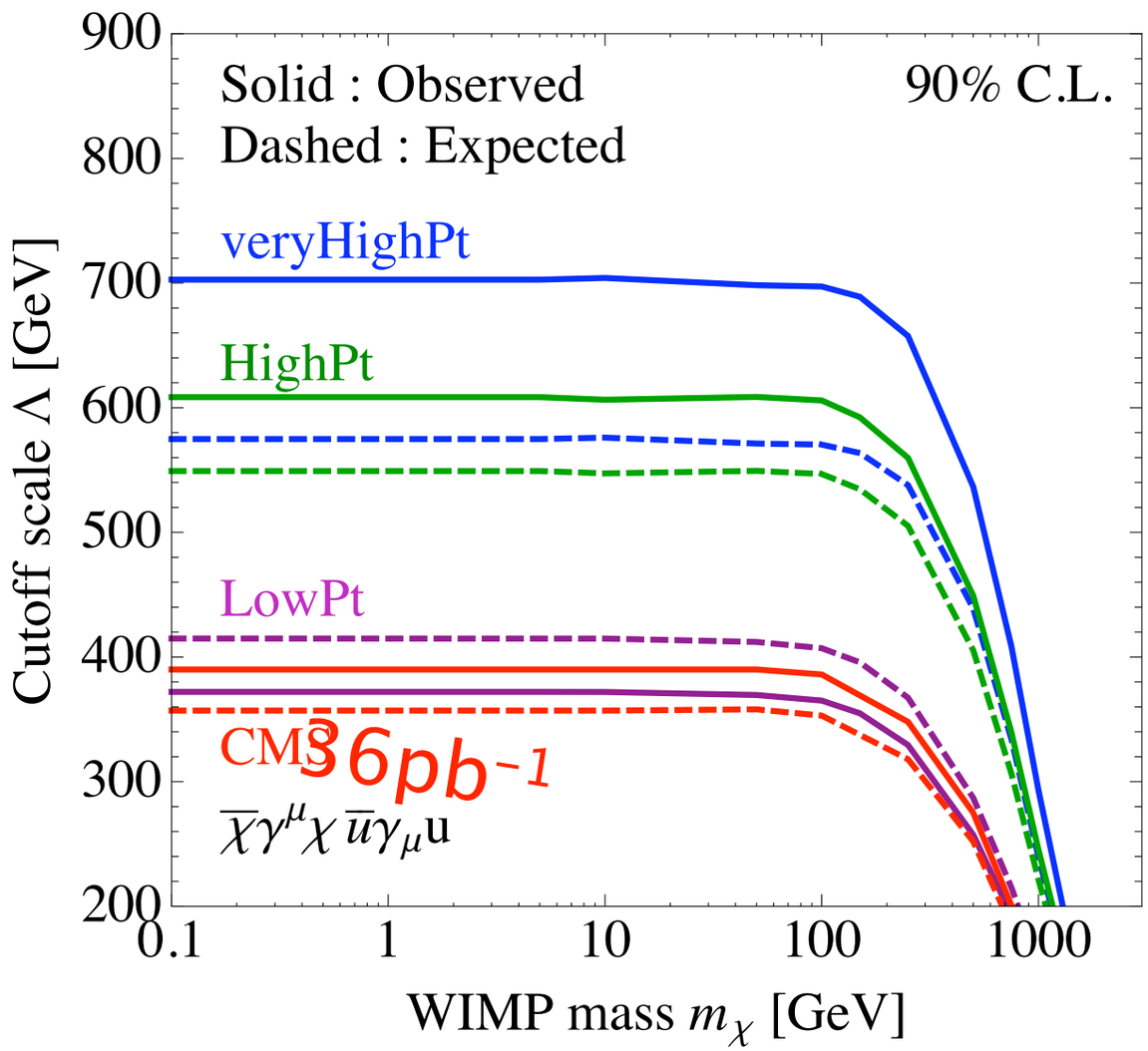
`HighPT` Selection requires $\not\!\!E_T > 220$ GeV, one jet with $p_T(j_1) > 250$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not\!\!E_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.

`veryHighPT` Selection requires $\not\!\!E_T > 300$ GeV, one jet with $p_T(j_1) > 350$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not\!\!E_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.

	ATLAS `LowPT` 1.0 fb^{-1}	ATLAS `HighPT` 1.0 fb^{-1}	ATLAS `veryHighPT` 1.0 fb^{-1}
Expected	15100 ± 700	1010 ± 75	193 ± 25
Observed	15740	965	167

Limits on $\Lambda \equiv \dfrac{M}{\sqrt{g_\chi g_1}}$:

* Set 90% CL limits: $\chi^2 \equiv \dfrac{[\Delta_N - N_{\rm DM}(m_\chi, \Lambda)]^2}{N_{\rm DM}(m_\chi, \Lambda) + N_{\rm SM} + \sigma^2_{\rm SM}} = 2.71\,.$



$$\Delta_N = \begin{cases} 0 & \text{expected bound} \\ N_{\rm obs} - N_{\rm SM} & \text{observed bound} \end{cases}$$

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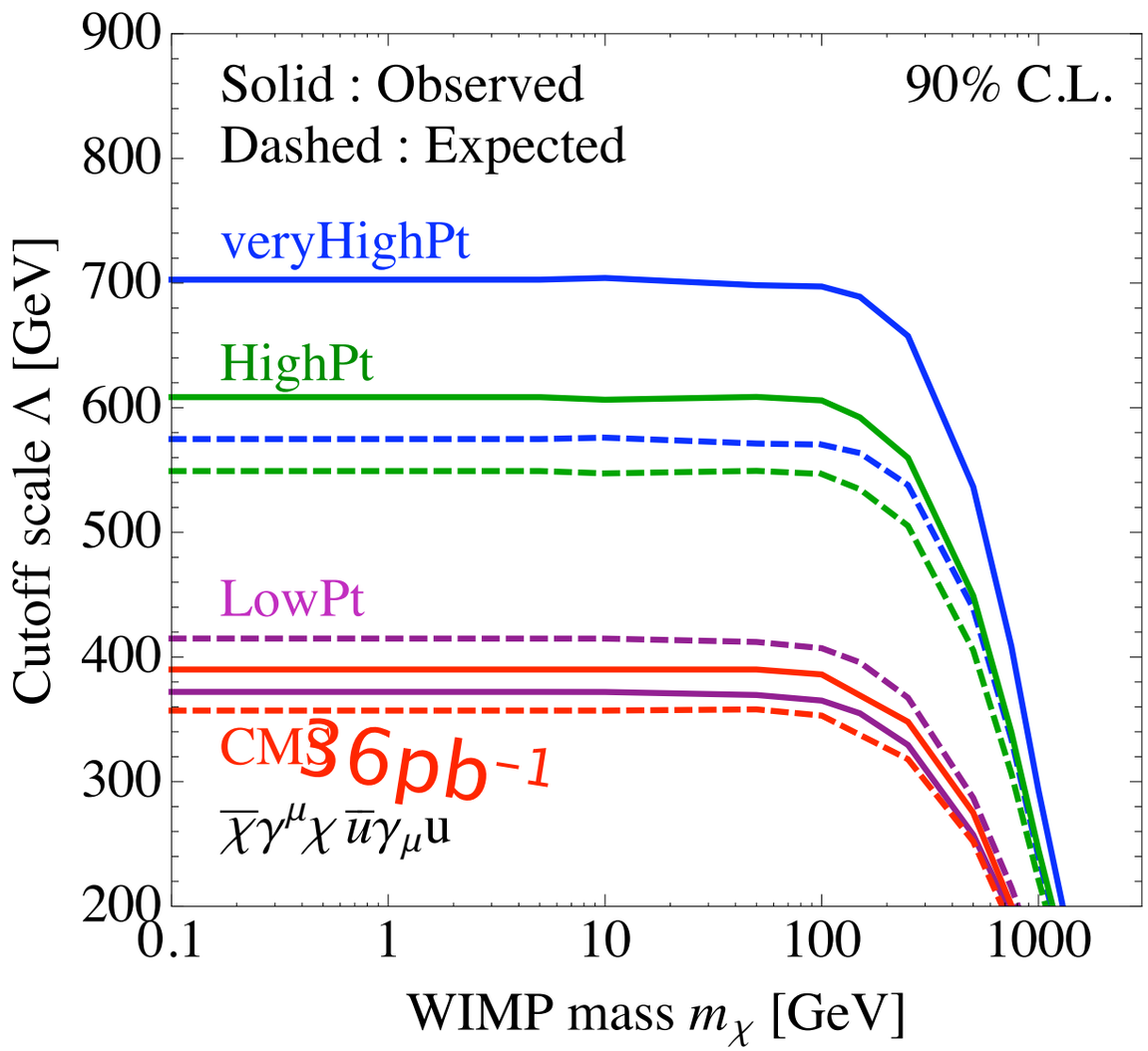
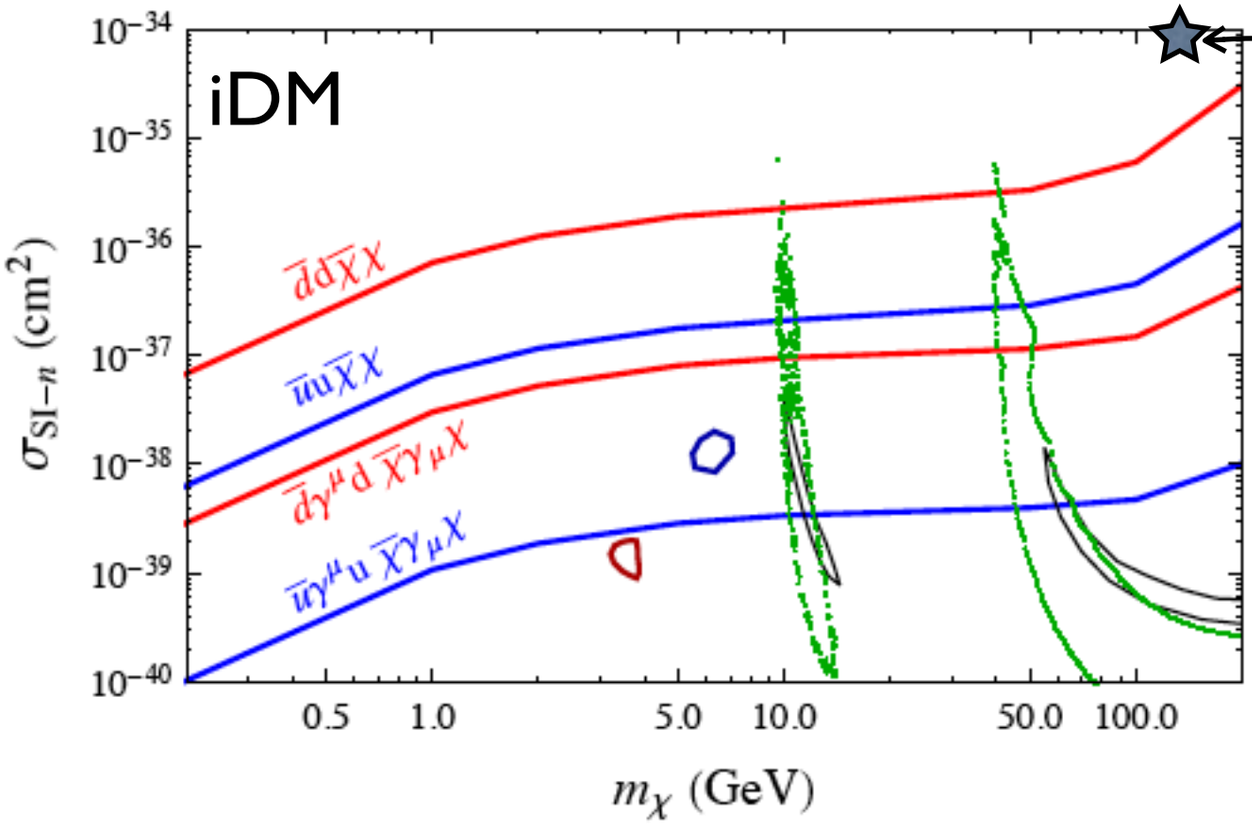


$$\Delta_N = \begin{cases} 0 & \text{expected bound} \\ N_{\rm obs} - N_{\rm SM} & \text{observed bound} \end{cases}$$

Harder is better.
in the future:
populate the tail
and keep cutting harder

iDM, MDDM, ...

* There are other scenarios in which DD is suppressed, but colliders don't care:



impure thoughts... can survive with light mediator.

LEP mono-photon

w/ Fox, Kopp and Tsai
arXiv:1103.0240

LEP

* Directly constrain DM coupling to electrons.
* **But**, in many models quark and lepton coupling are related (consider 2 benchmarks).
* LEP is a clean environment. Ability to measure missing mass.
* Places non-trivial limits also on indirect searches in lepton channels (e.g. the Hooperon).

Operators

* Same story w/ leptons (assume universality)

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2}\,, \qquad \text{(vector, } s\text{-channel)}$$

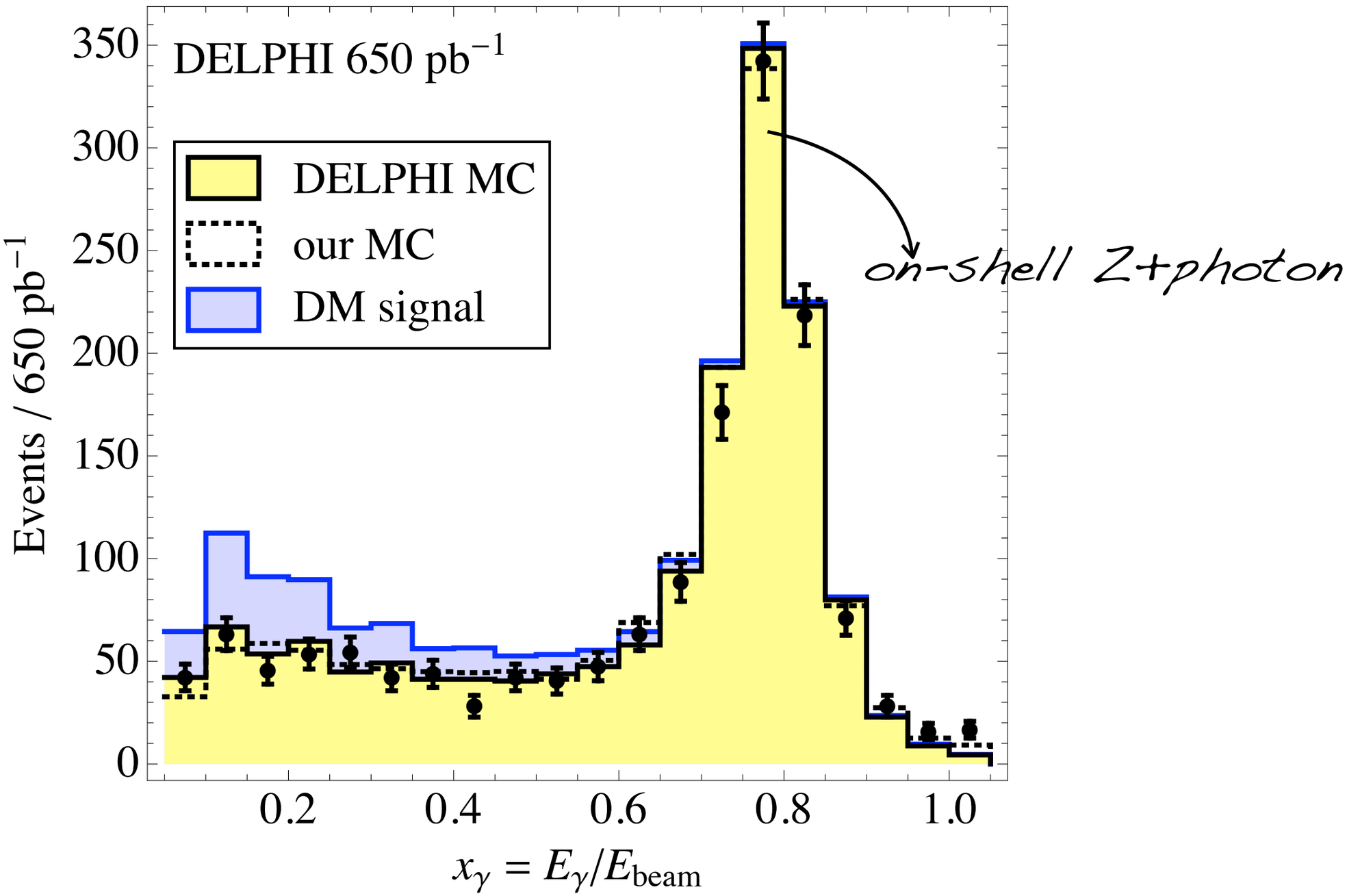
$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}\,, \qquad \text{(scalar, } s\text{-channel)}$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2}\,, \qquad \text{(axial vector, } s\text{-channel)}$$

$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2}\,, \qquad \text{(scalar, } t\text{-channel)}$$

Mono-photon

* Use spectrum shape to reject background peak.

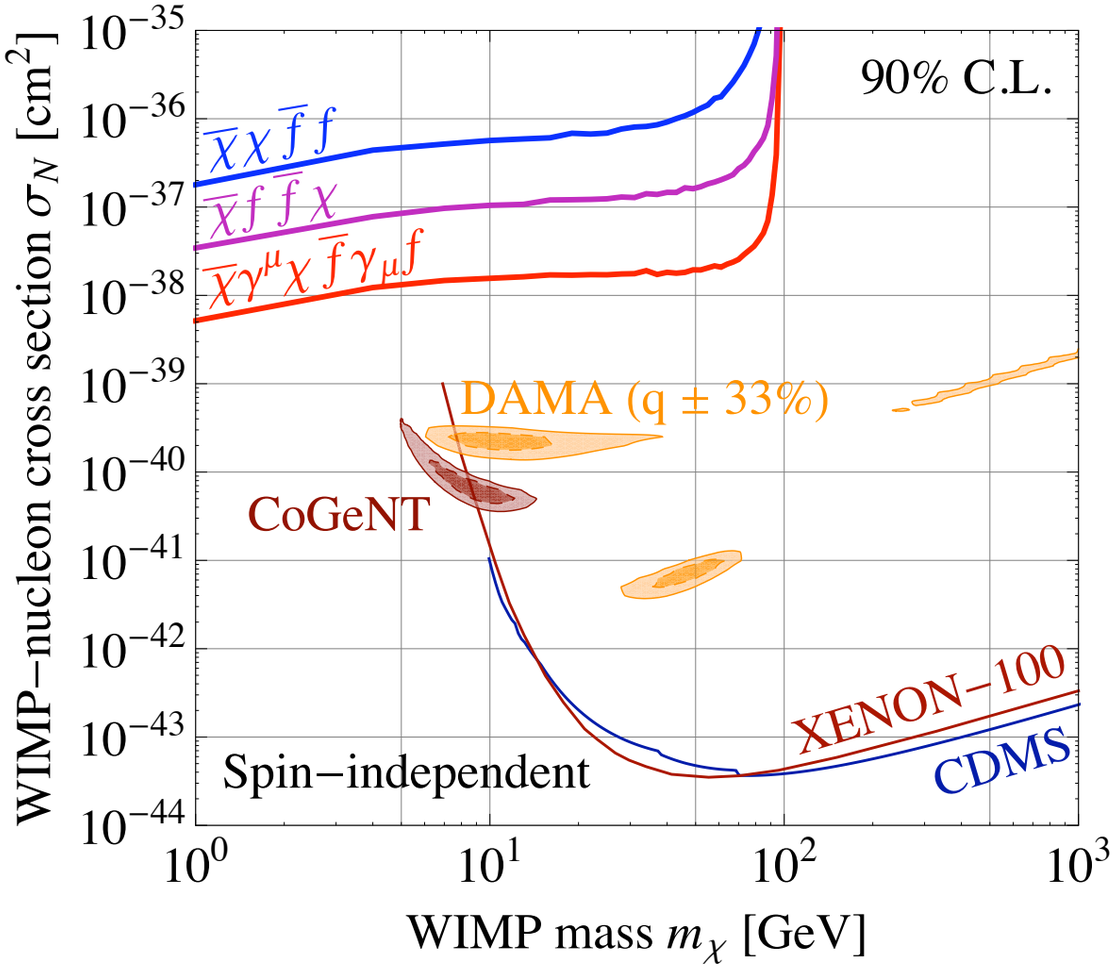


Model Dependence

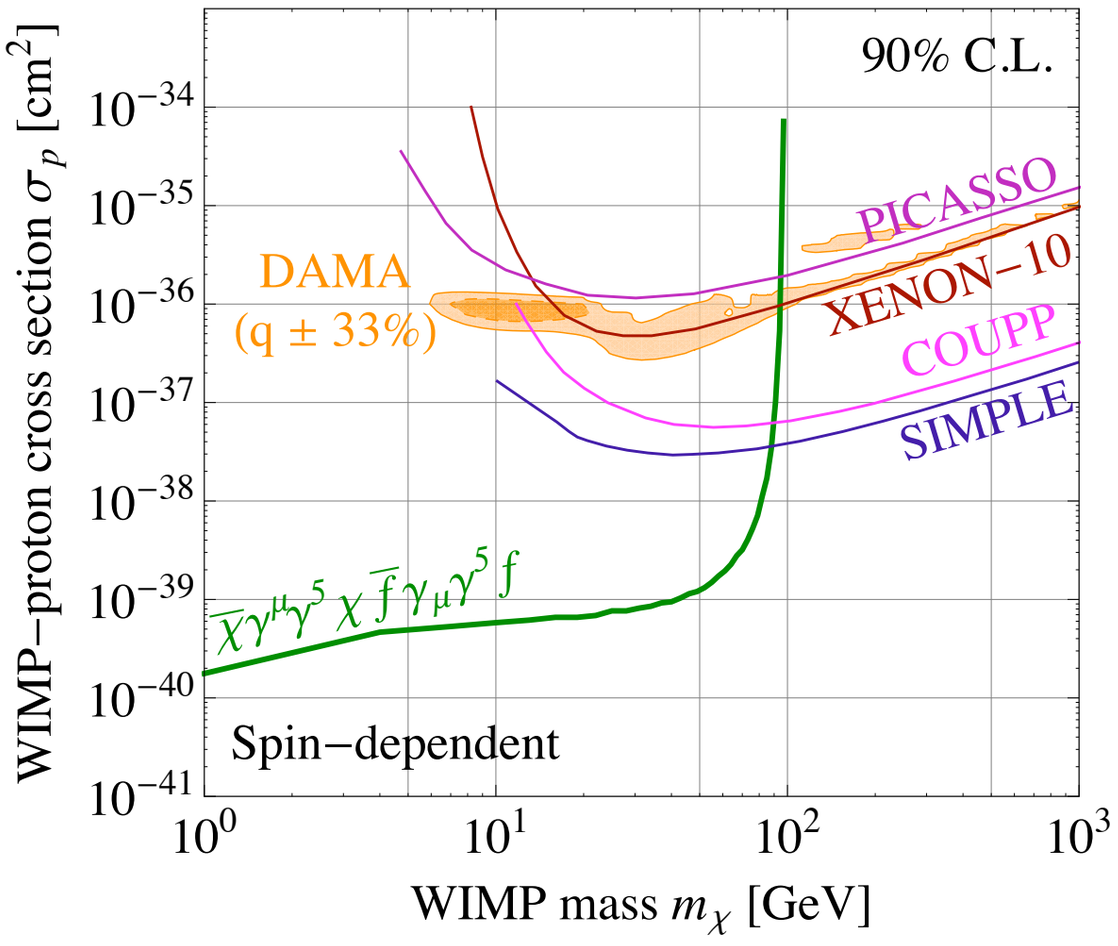
* We limit lepton couplings.
* But how does DM couple to quarks?
* Consider 2 extreme cases:
  - Couplings to **quarks are same as leptons**.
  - Couplings to quarks are **zero**.
* *Any* other case can be derived from these two.

DD Limits

Equal couplings to all SM fermions

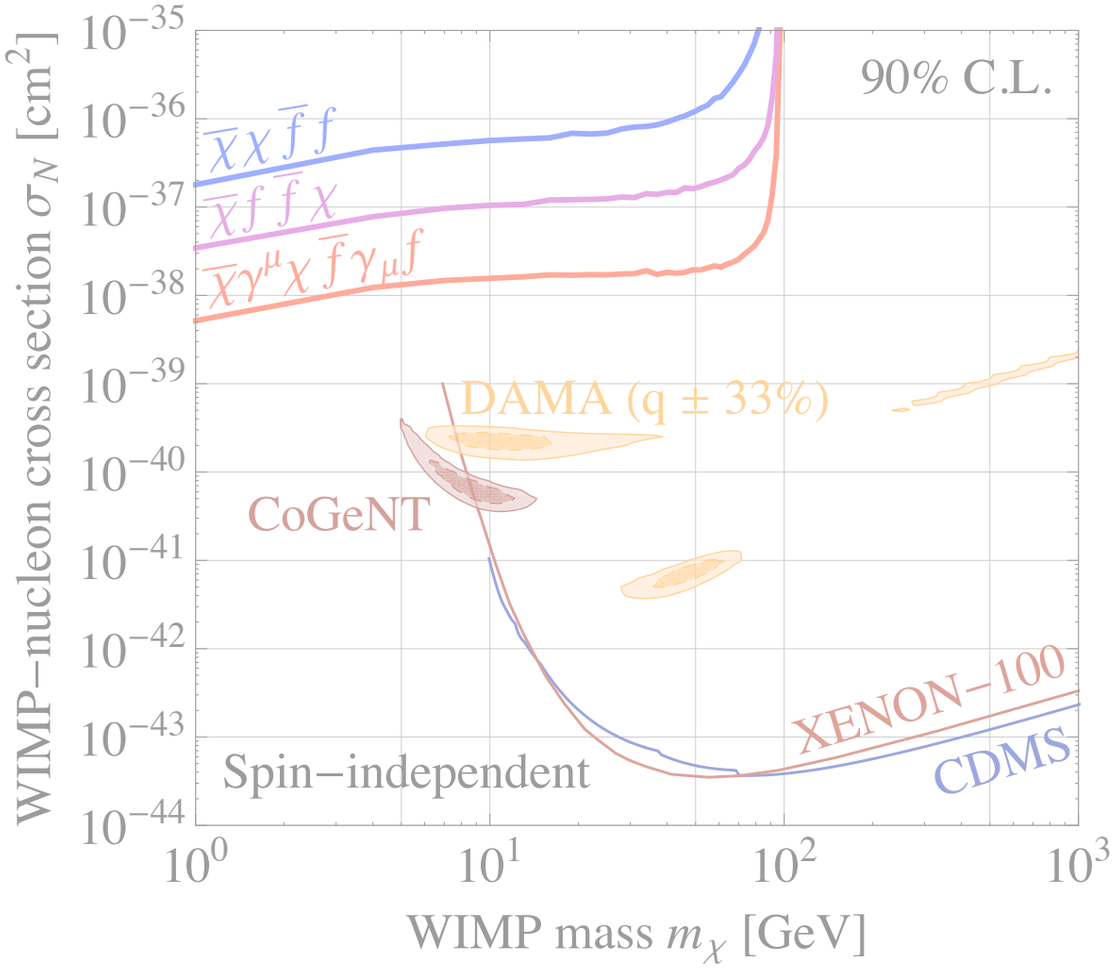


Equal couplings to all SM fermions

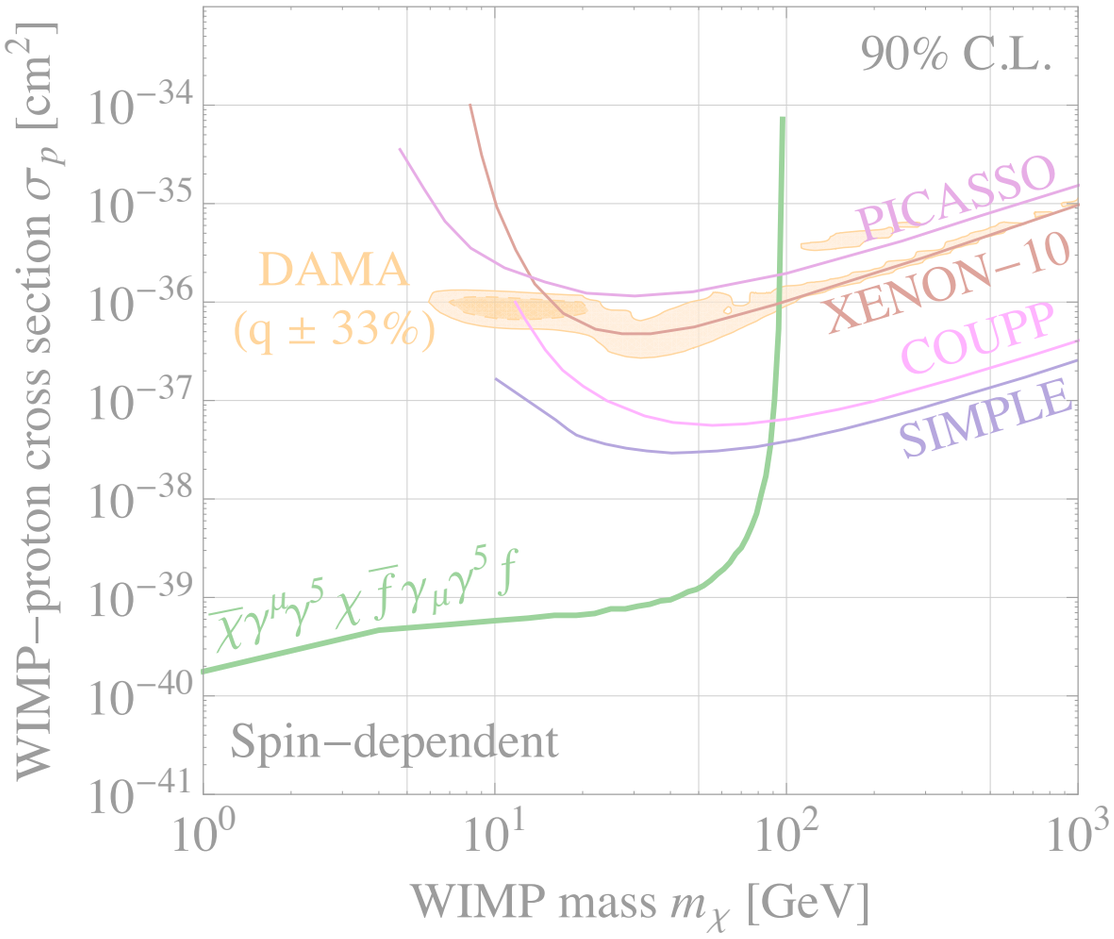


DD Limits

Equal couplings to all SM fermions

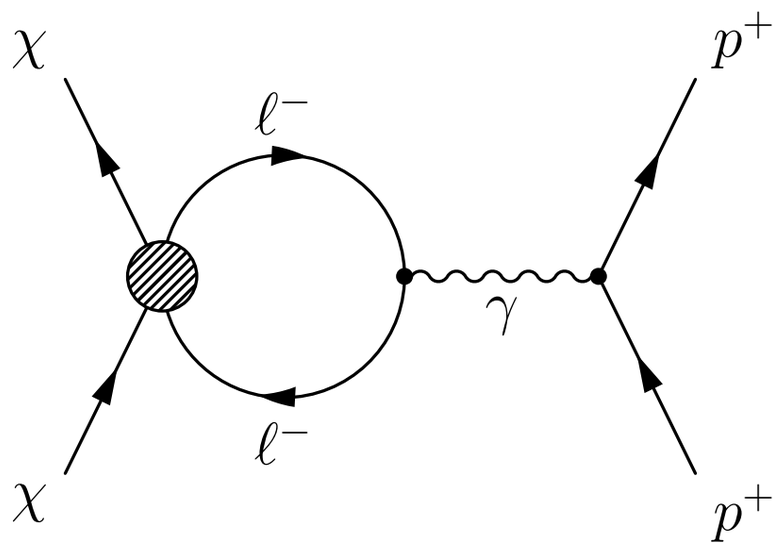


Equal couplings to all SM fermions

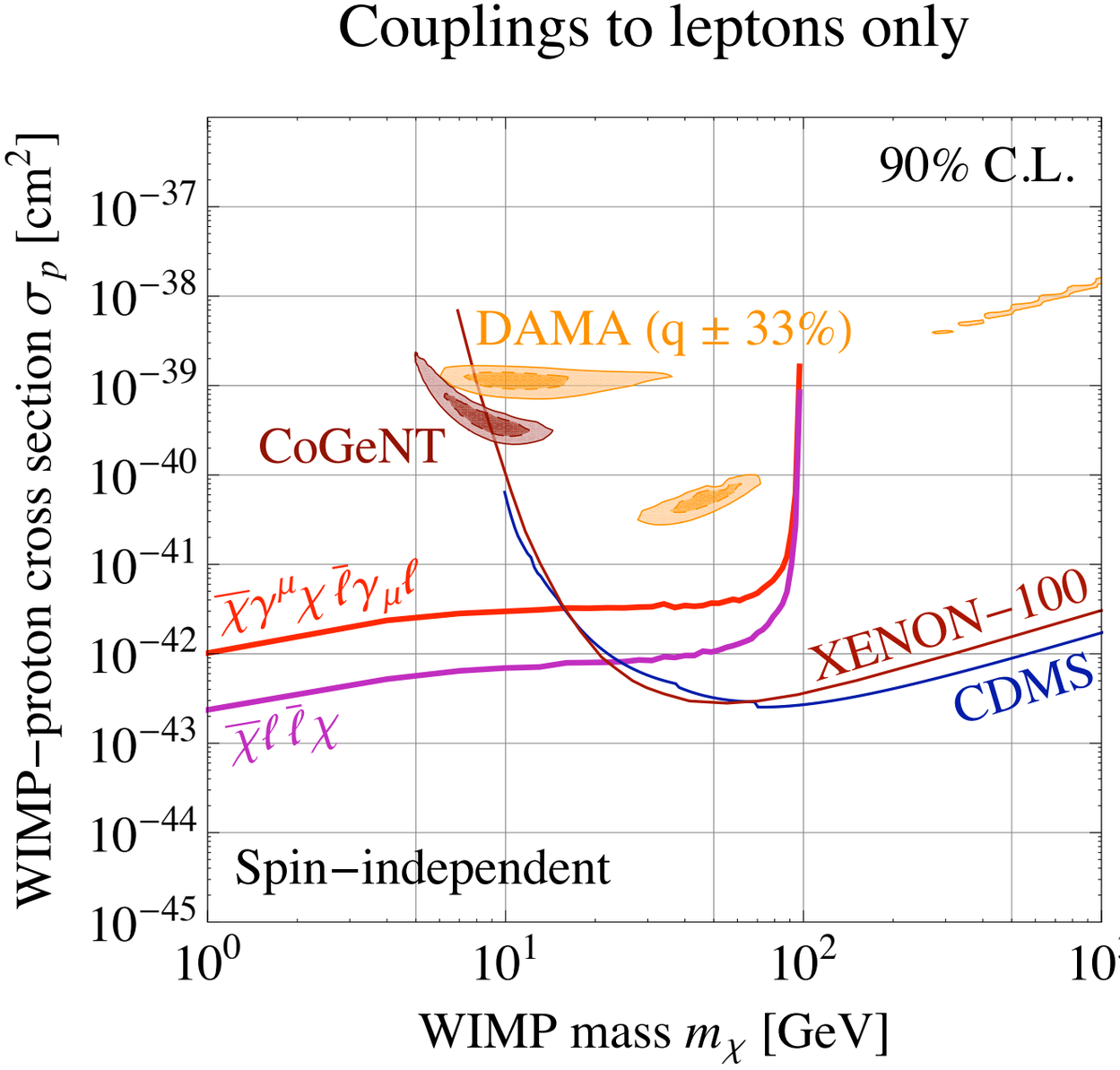


Leptophilic DM

* Consider zero couplings to quarks.

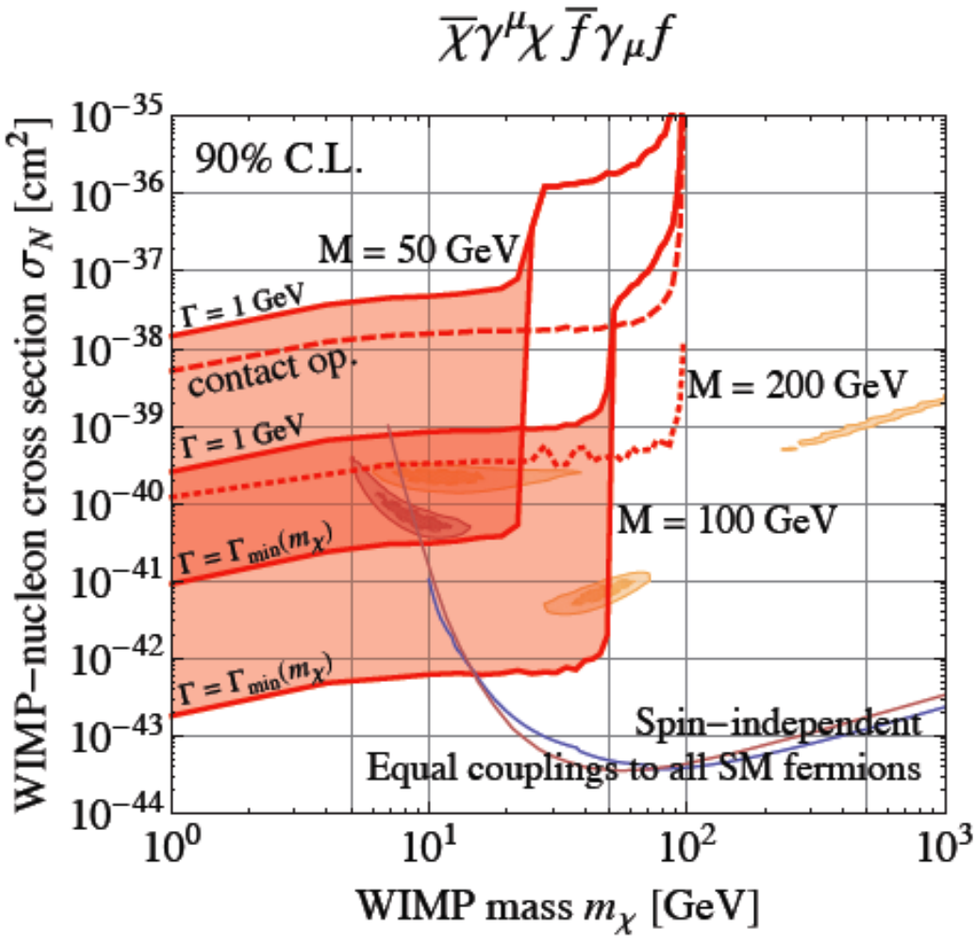


Direct detection
pays a big price.
Collider limits are strong.

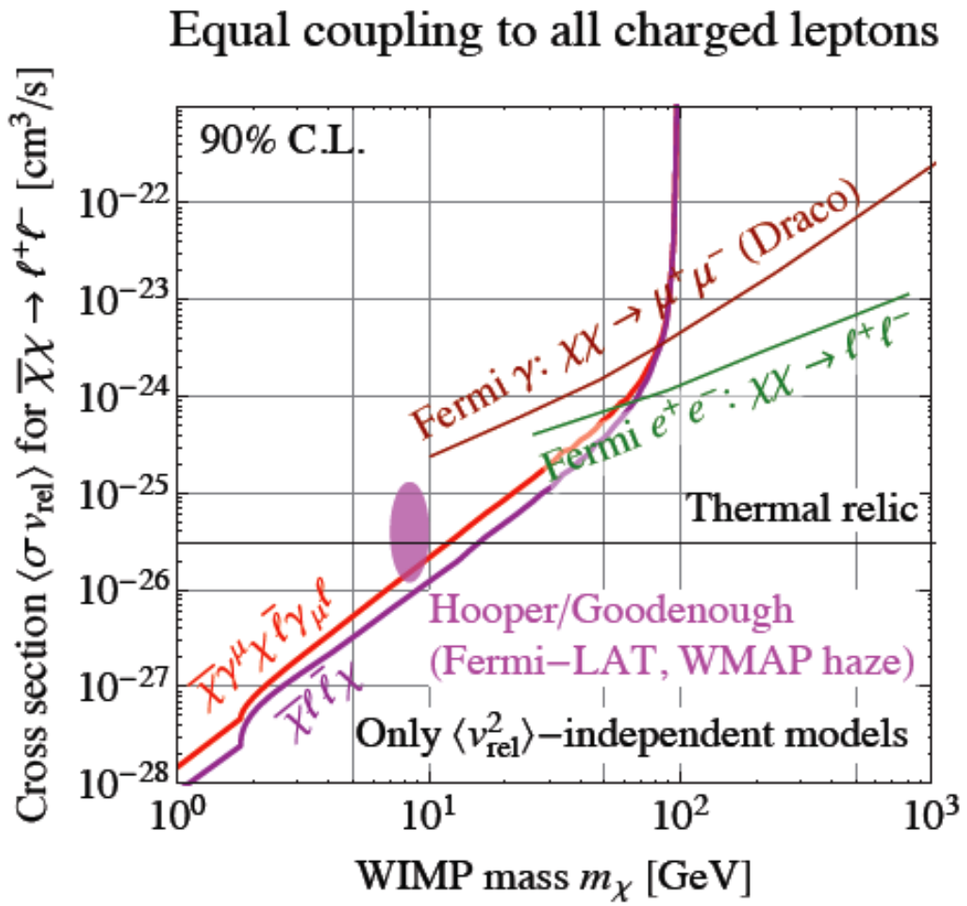


Many more..

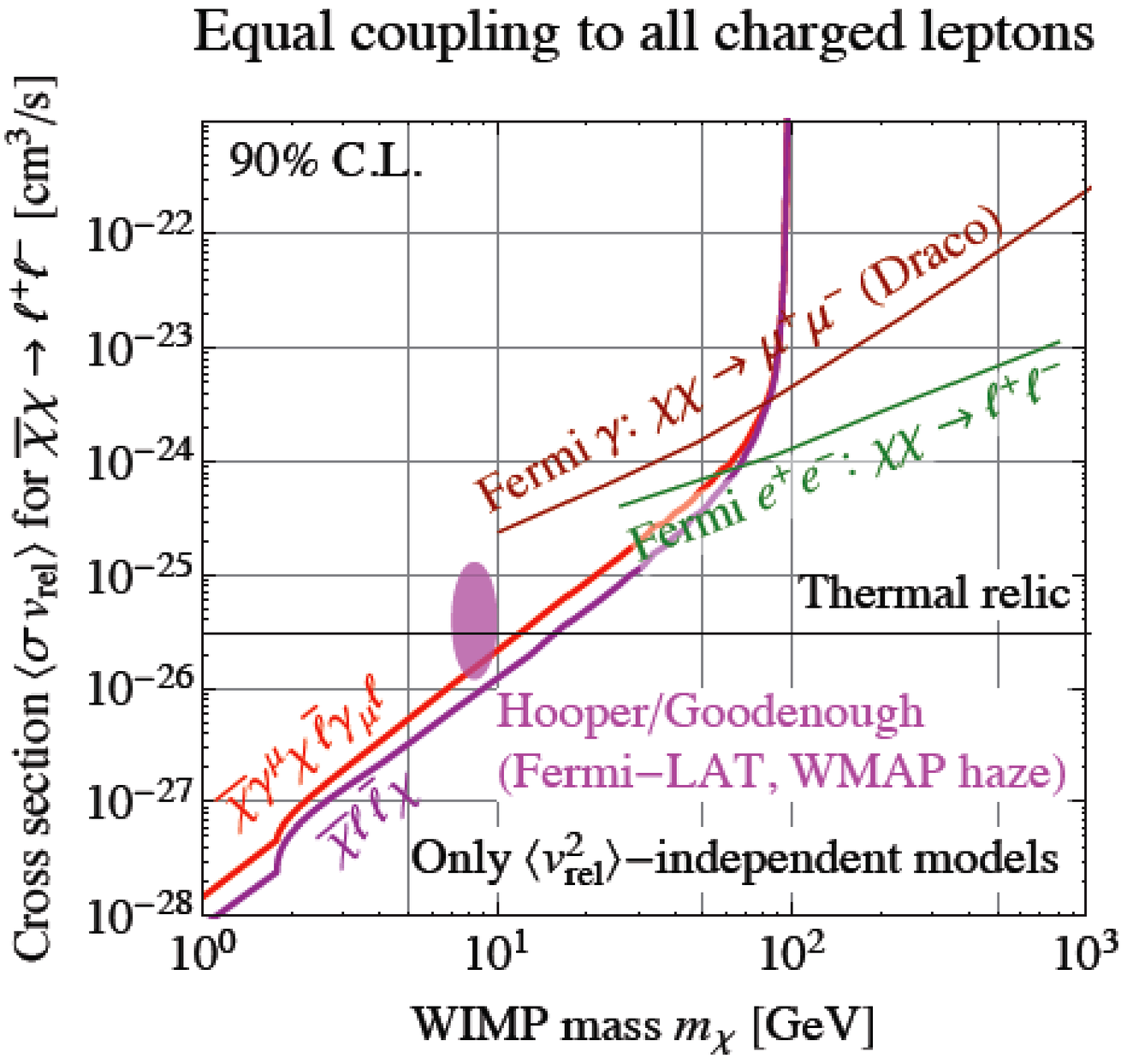
* Light mediators:



* Indirect detection:



Indirect Detection



Tension with the "Hooperon". Light thermal relic ruled out.

Light Mediators

* Lets fix $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \dfrac{\mu^2}{M^4}$ and lower M.

  The couplings must be decreased to compensate.

* Then for very small M we get to the regime where

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

* The cross section drops as M^4.

* **But what happens in the intermediate regime?**

Dark Matter @ Colliders

Roni Harnik, Fermilab

Bai, Fox, RH - 1005.3797
Fox, RH, Kopp, Tsai -1103.0240
Fox, RH, Kopp, Tsai - 1109.4389
Fox, RH, Primulando, Yu - 1203.1662

Very related work by the “Irvine Clan”:
Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu -1005.1286
Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu - 1008.1783
Fortin and Tait - 1103.3289
Rajaraman, Shepherd,Tait and Wijangco - 1108.1196
Shepherd and Goodman - 1111.2359

A Search For Dark Matter in the Monojet + Missing Transverse Energy Signature in $6.7\,\mathrm{fb}^{-1}$

S.Z. Shalhout[1], T. Schwarz[2], R. Erbacher[1], J. Conway[1], P. Fox[2], R. Harnik[2], Y. Bai[2]
UC Davis[1] **Fermilab**[2]

A neural net with our name on it ?! :-0