Beyond the Standard Model

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DIS

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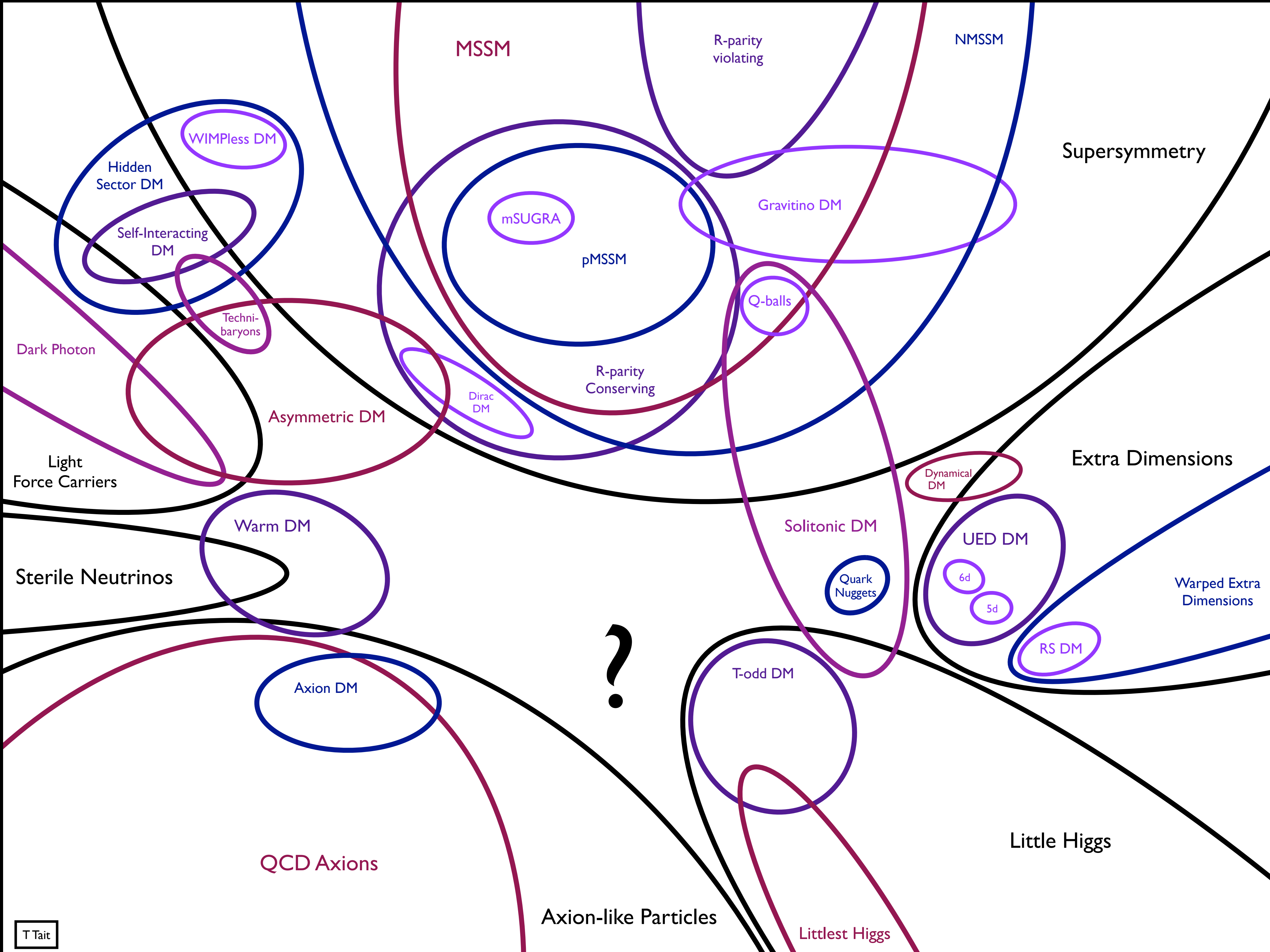
Missing Energy Signals

- Missing energy signals are a big part of the new physics menu at colliders, largely because of the potential connection to dark matter.
- We still don't know what dark matter is, but we know it is at most weakly interacting.
    - We know it should look like "nothing" to a collider detector.
- We have reason to think it should have reasonably large couplings to at least some of the Standard Model, in order to explain its abundance in the Universe.

"Cold Dark Matter: An Exploded View" by Cornelia Parker


MSSM
R-parity
violating
NMSSM
WIMPless DM
Hidden
Sector DM
Supersymmetry
Gravitino DM
mSUGRA
pMSSM
Self-Interacting
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Techni-
baryons
Q-balls
Dark Photon
R-parity
Conserving
Dirac
DM
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Dynamical
DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark
Nuggets
6d
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Warped Extra
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RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
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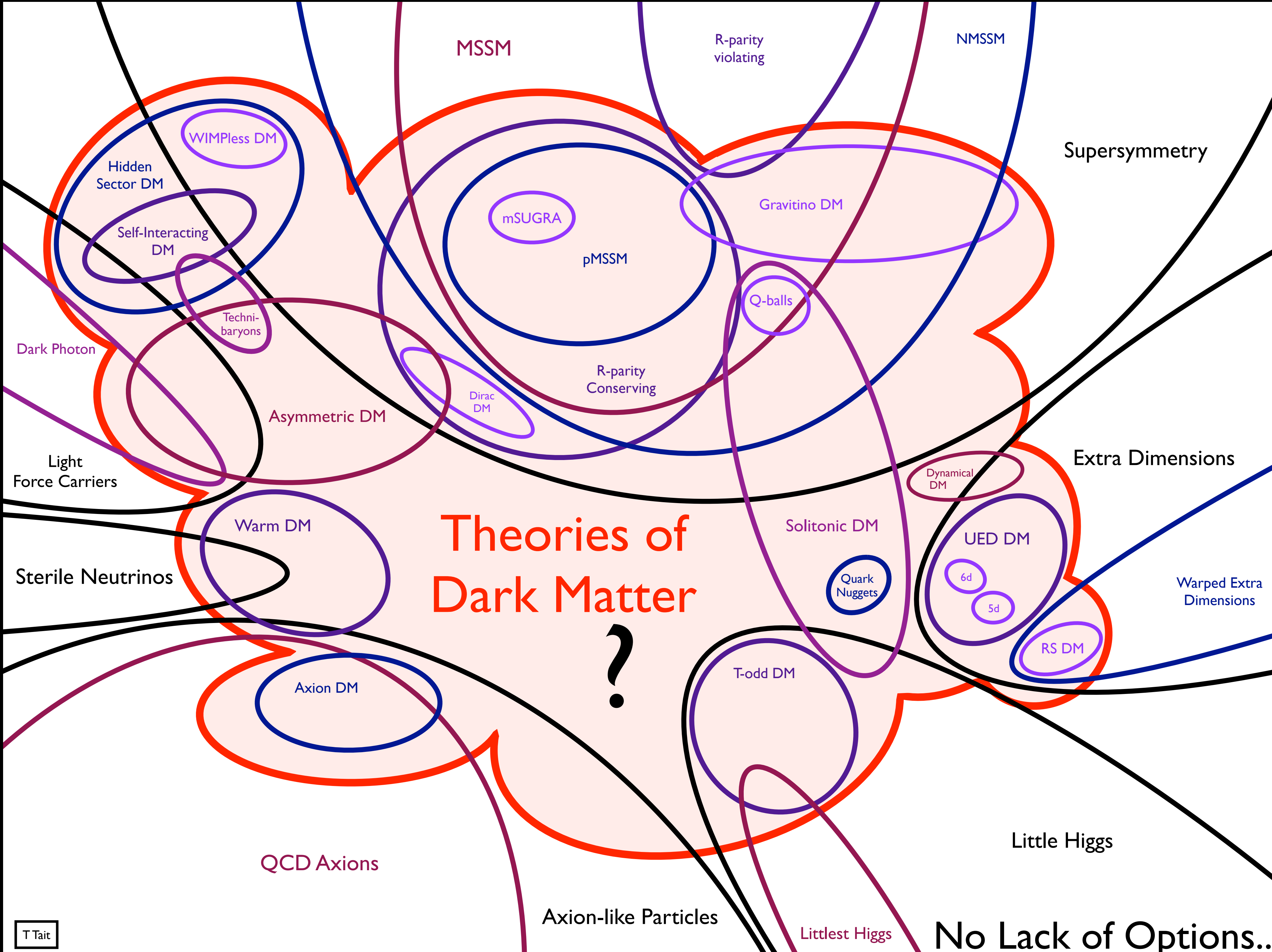
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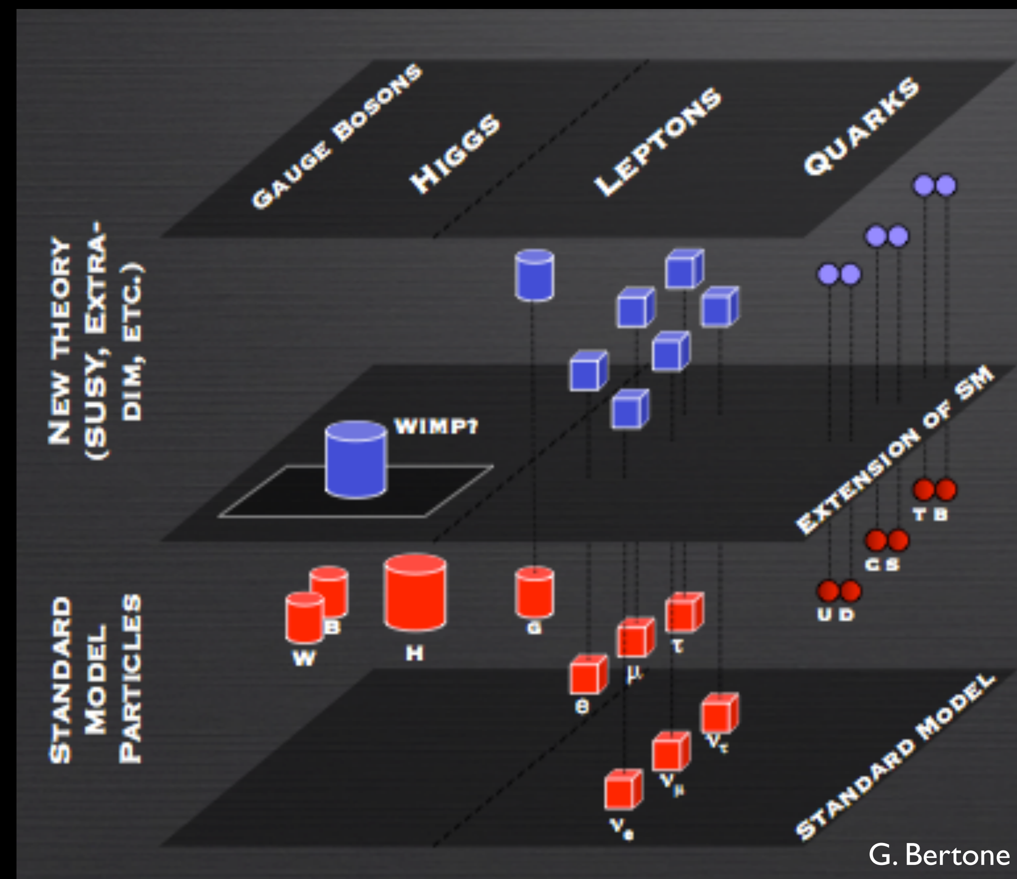
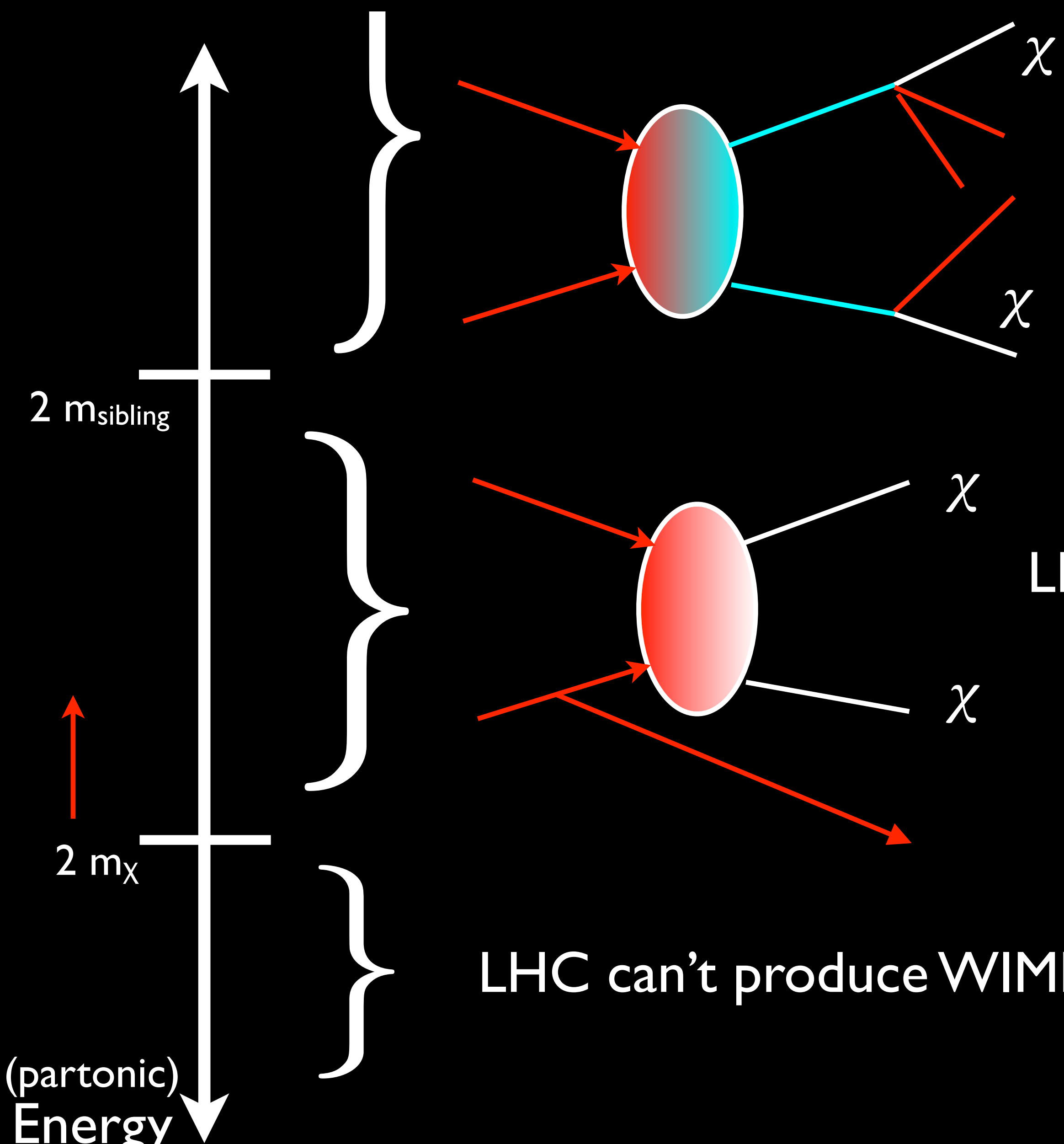
Littlest Higgs
No Lack of Options…
T Tait

A Cartoon WIMP Theory

- A typical WIMP theory has a whole "layer" of new particles.
    - E.g. SUSY, UED, Little Higgs, ...
- The WIMP is the lightest of these new states, and must be neutral and ~stable to be viable dark matter.
- Most of the heavier "WIMP siblings" usually are coloured and/or charged, and thus interact much more strongly with the Standard Model particles than the WIMP does.
- They decay into the WIMP itself plus Standard Model particles.



LHC WIMP Production

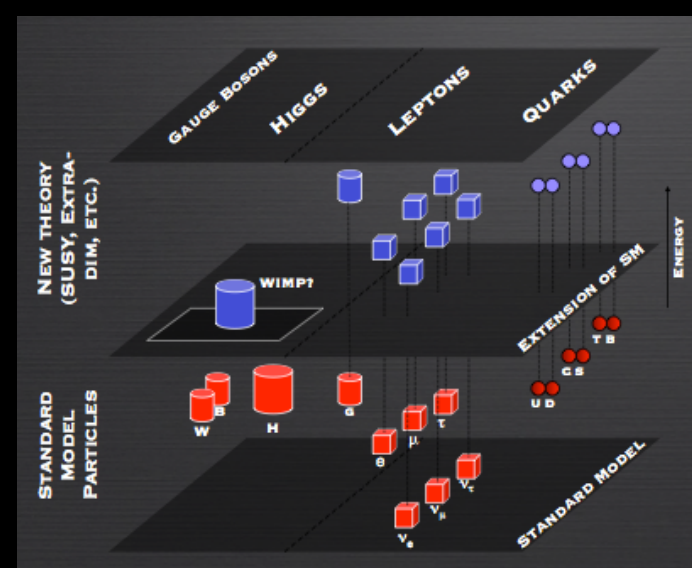


LHC can produce WIMP siblings, which decay into WIMPs and other SM particles.

"KK Sgluquarkino Pair Production Followed by Decay into WIMPs"

LHC can directly produce WIMP pairs.

LHC can't produce WIMPs.

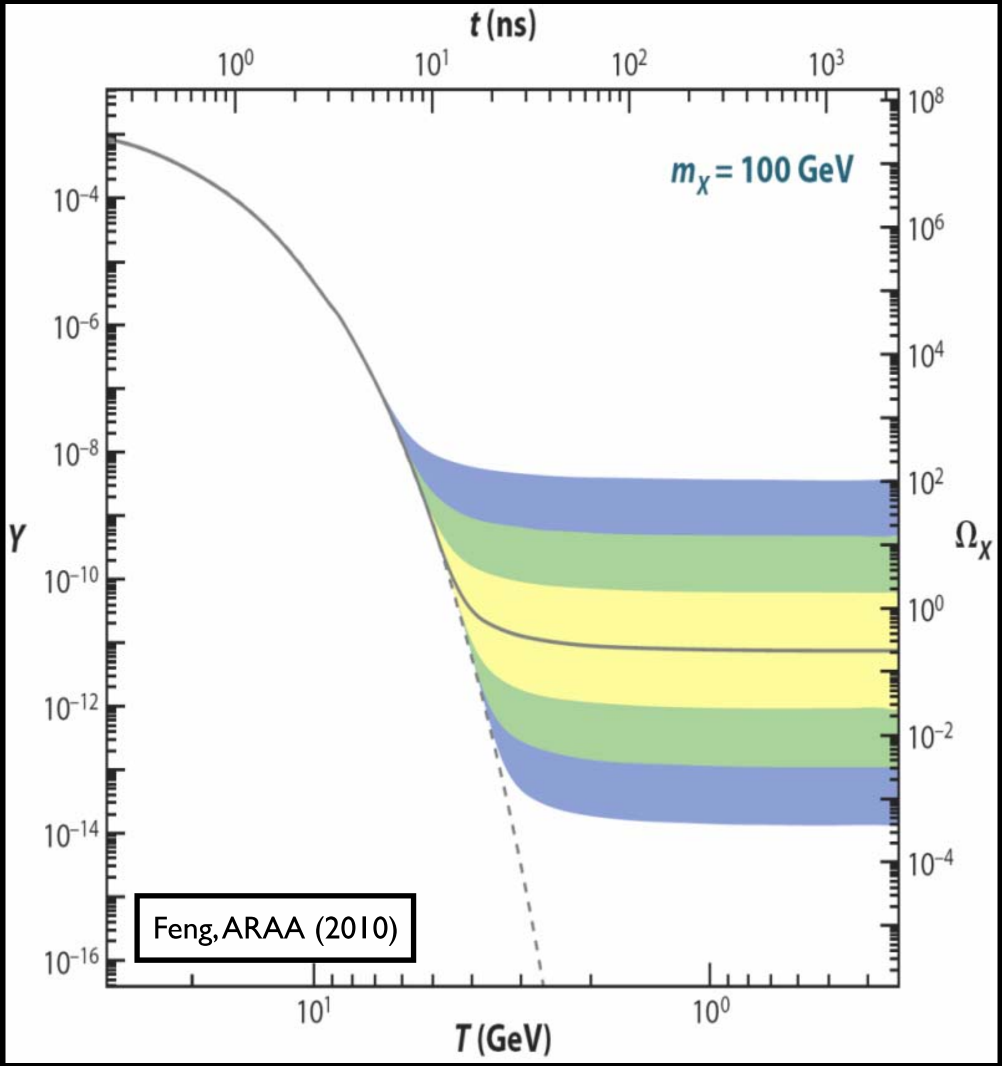


Relic Density

- If dark matter is a thermal relic, annihilation into the SM control its abundance in the Universe.
  - The observed relic abundance is suggestive of a cross section:

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

  - Without a detailed model, it isn't clear how to translate it into an LHC or direct detection rate.
  - The dark matter could also be produced non-thermally, or the history of the Universe could be non-standard.

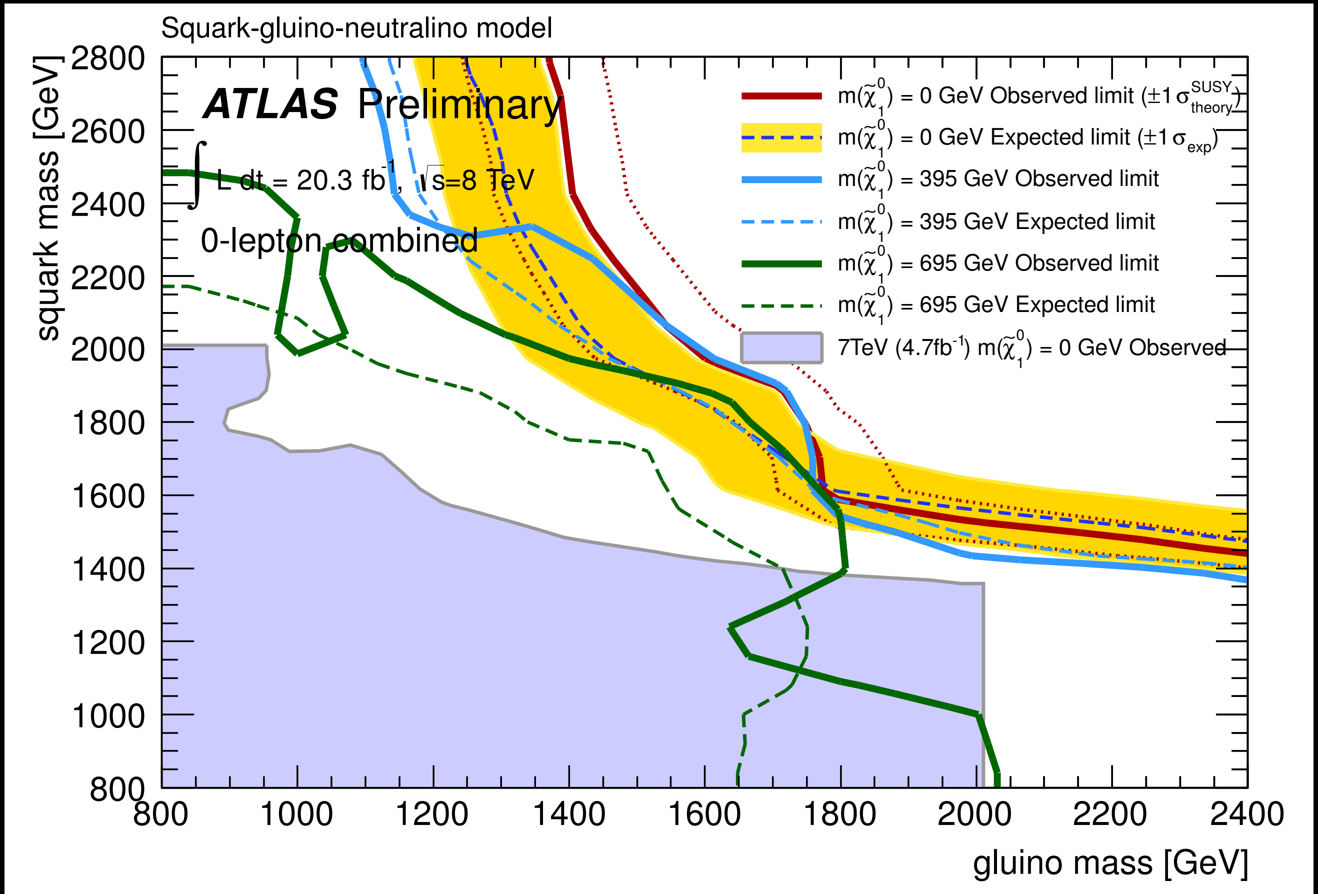


53,40 Euro for 20 servings

Available in Blue Raspberry, Fruit Punch, and Grape flavors....

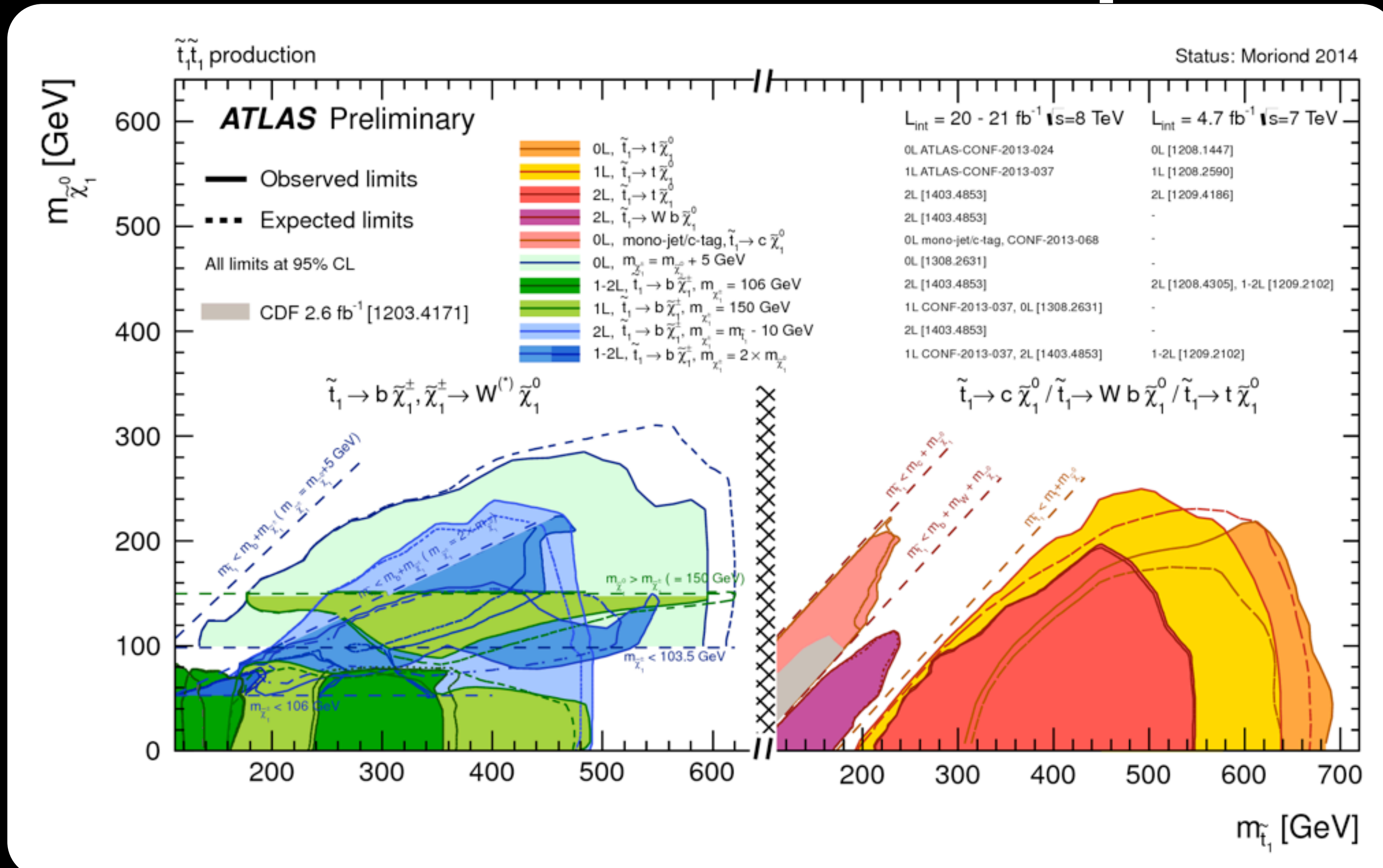
WIMP Sibling Production

Squarks and Gluinos



- Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino (“coloured sibling”) production.
  - Gluinos decay to two jets + WIMP
  - Squarks into one jet + WIMP
- For equal masses, searches require them to be larger than about 1.8 TeV and are > 1 TeV when one or the other is very heavy.

3rd Generation Squarks

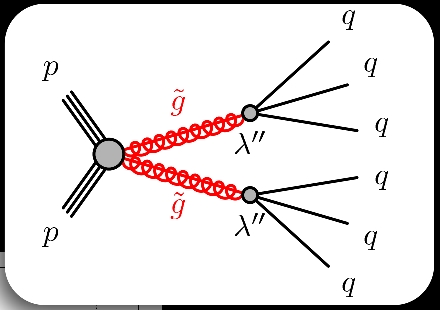


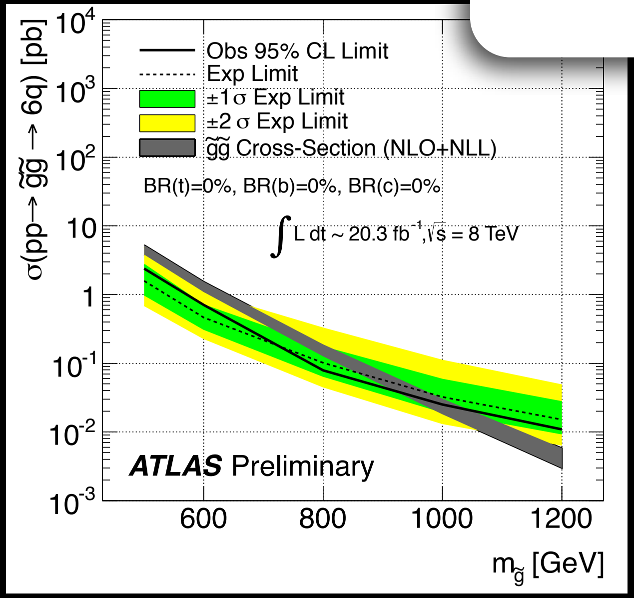
- Naturalness requires SUSY to have light(ish) stops. This should be balanced by the fact that in the MSSM, the Higgs mass is calculable, suggesting the stops aren't *too* light.

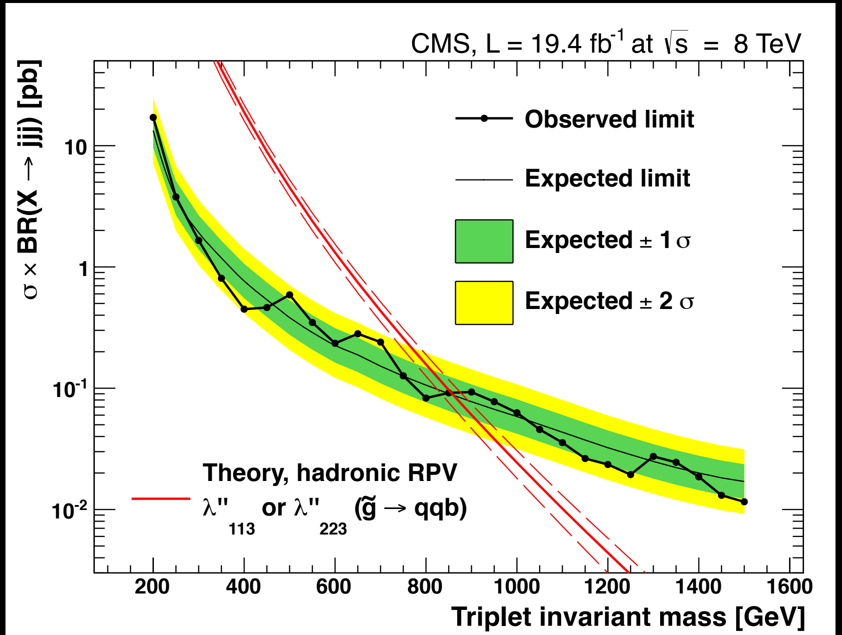
- Searches for stops are starting to reach 600-700 GeV, and carving out the natural regions of supersymmetry!

Hiding SUSY?

- Maybe SUSY dark matter is a red herring. We can get all of the naturalness properties we like from SUSY without asking it to explain dark matter as well.
- Turning on R-parity violating interactions quickly runs into strong constraints. There should be some organizing principle such as minimal flavour violation. Csaki, Grossman, Heidenreich, 1111.1239
- The baryon-number-violating interaction can lead coloured superpartners to decay entirely into jets, e.g. $\tilde{g}$ > qqq.
- This is very challenging, but searches show amazing progress!

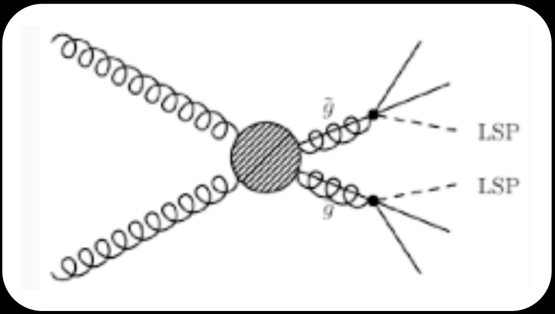


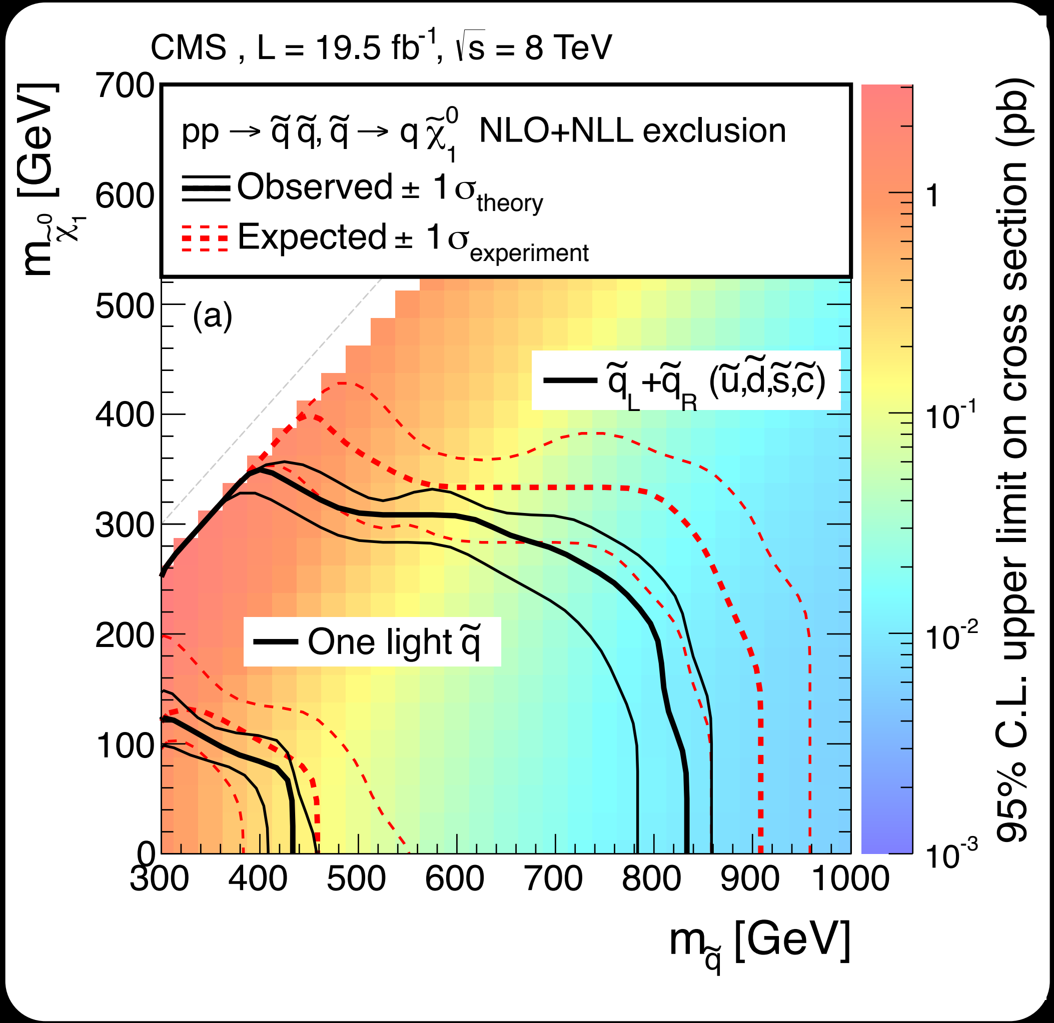




Simplified Models

- One can step away from specific MSSM assumptions by working with simplified models.
  - These are phenomenological sketches of theories with some basic particles and decays built into them.
- The experimental collaborations have been willing to explore casting their SUSY searches into this framework, allowing for a much more flexible interpretation of limits.



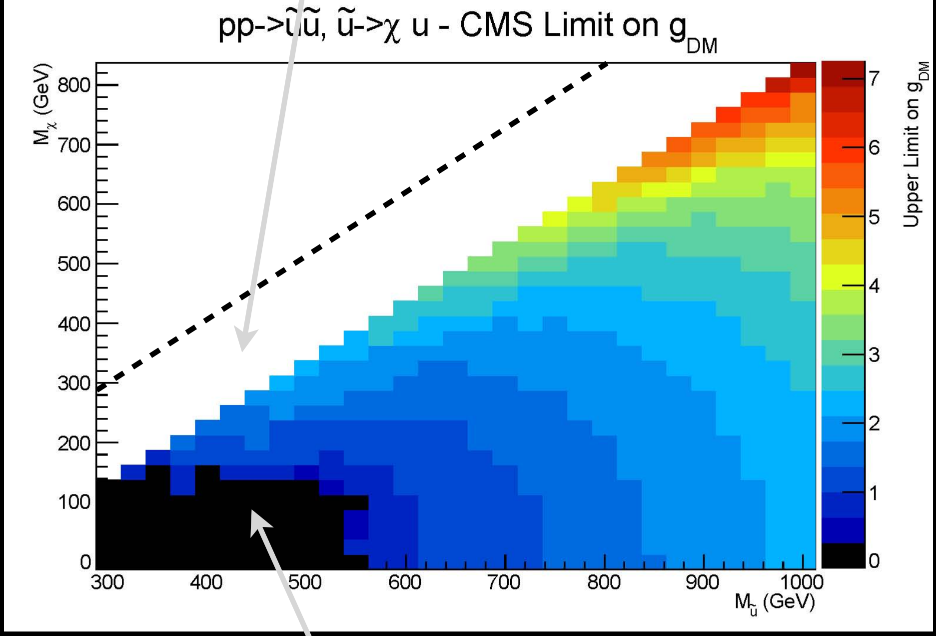


$\tilde{u}_R$ Model

- What do these results tell us about dark matter?
- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
- For simplicity, we set the couplings equal for all three generations.
    - This is motivated to avoid generating large flavor-violation at one loop.
- In the parameter plane of the mass of the dark matter and mass of the mediators, we can determine a limit on the coupling strength in the plane of the masses of the dark matter and the mediators.

Mono-jet searches will help fill in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

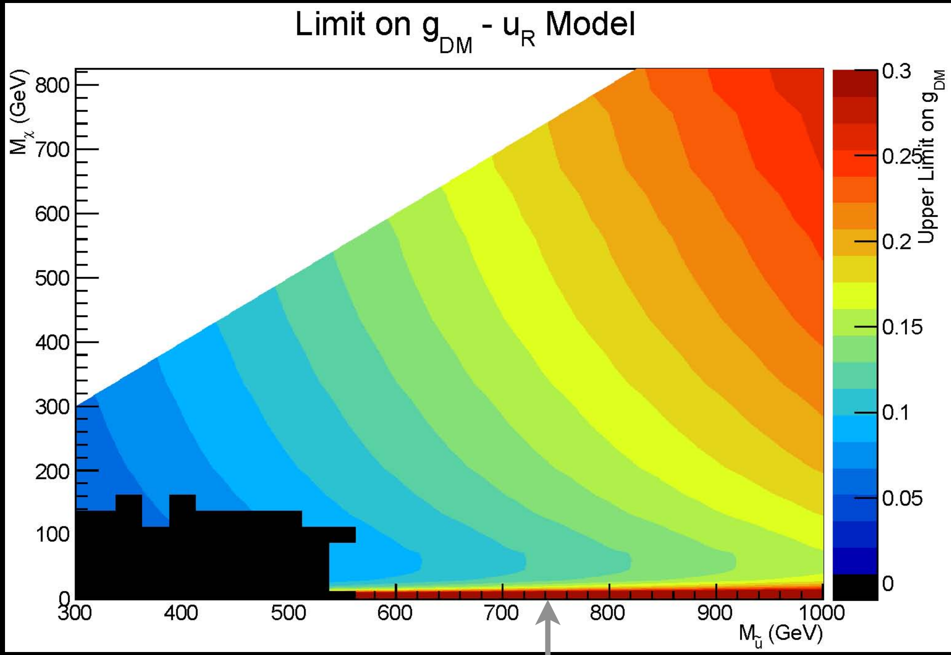


QCD production saturates the CMS limits, resulting in no allowed value of g.

$\tilde{u}_R$ Model

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

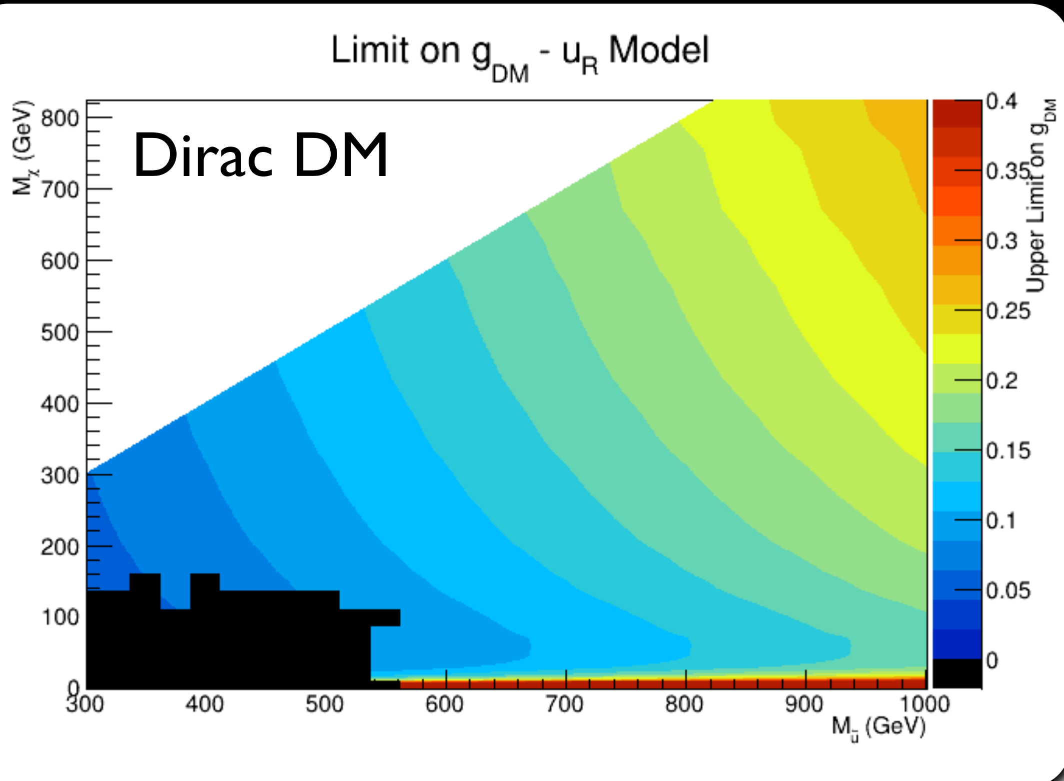
- A Dirac WIMP also has spin-independent scattering with nucleons. For most of the parameter space, there are bounds from the Xenon-100 experiment. (And recently LUX has said something as well...).
- Elastic scattering does not rule out any parameter space, but it does impose stricter constraints on the coupling in the regions CMS left as allowed.



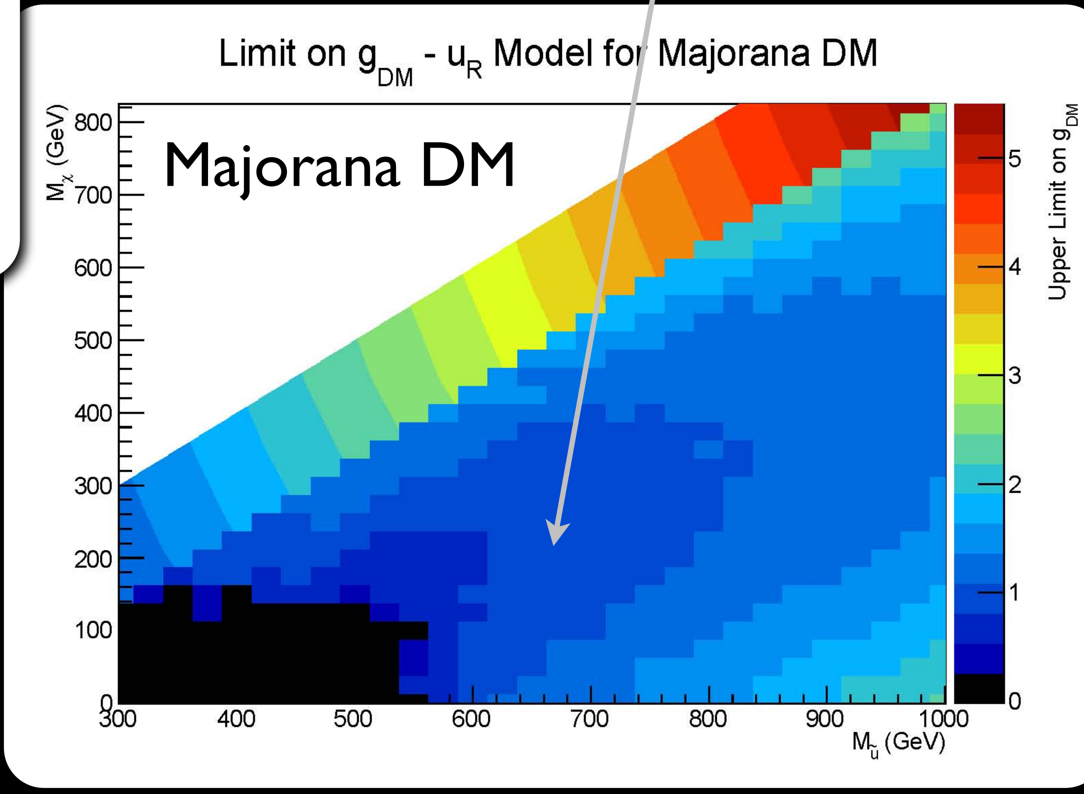
Traditional direct detection searches peter out for masses below about 10 GeV.

Majorana versus Dirac

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



Collider bounds tend to dominate for Majorana DM.



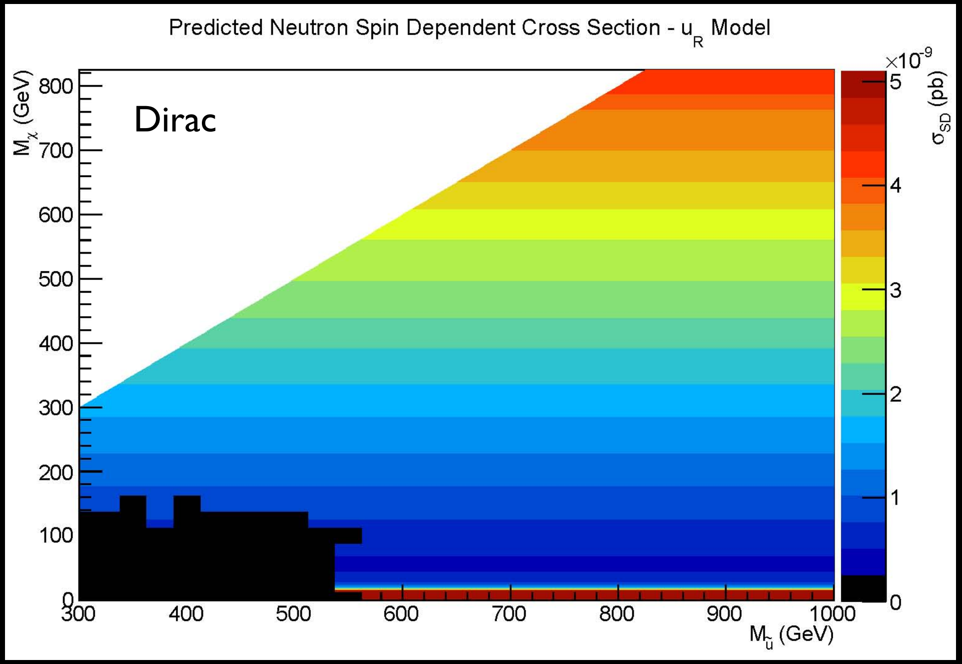
There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

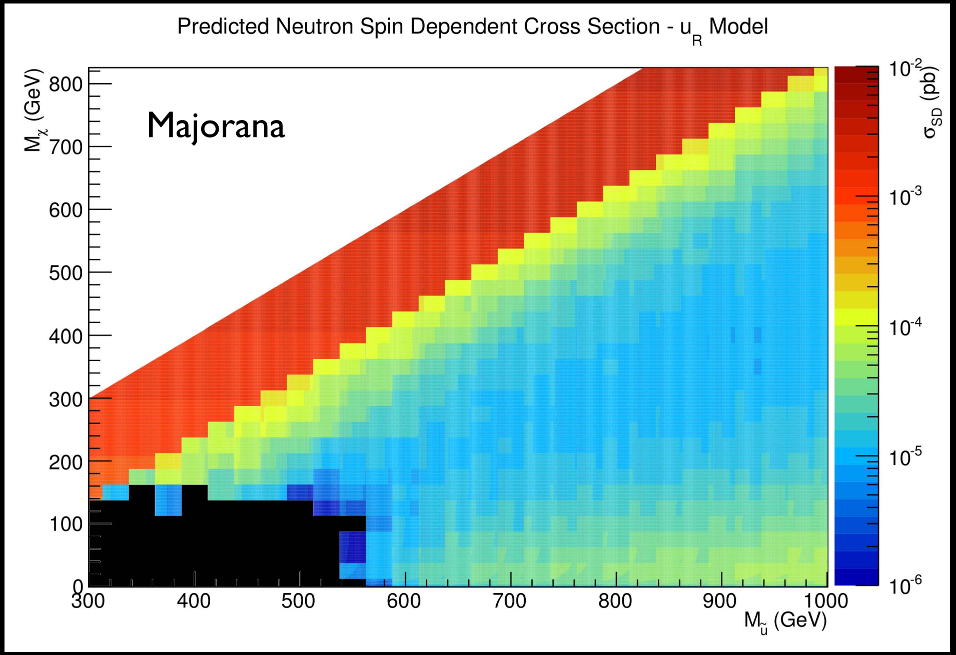
Majorana WIMPs have no tree-level spin-independent scattering in this model.

At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.

$\tilde{u}_R$ Model: Forecasts

- Now that we understand the current bounds, we can forecast what this implies for future searches.
- For example, we can plot the largest spin-dependent cross sections that are consistent with CMS and Xenon in this simplified model.
- Again, Dirac versus Majorana dark matter look very different from one another!





DiFranzo, Nagao, Rajaraman, TMPT
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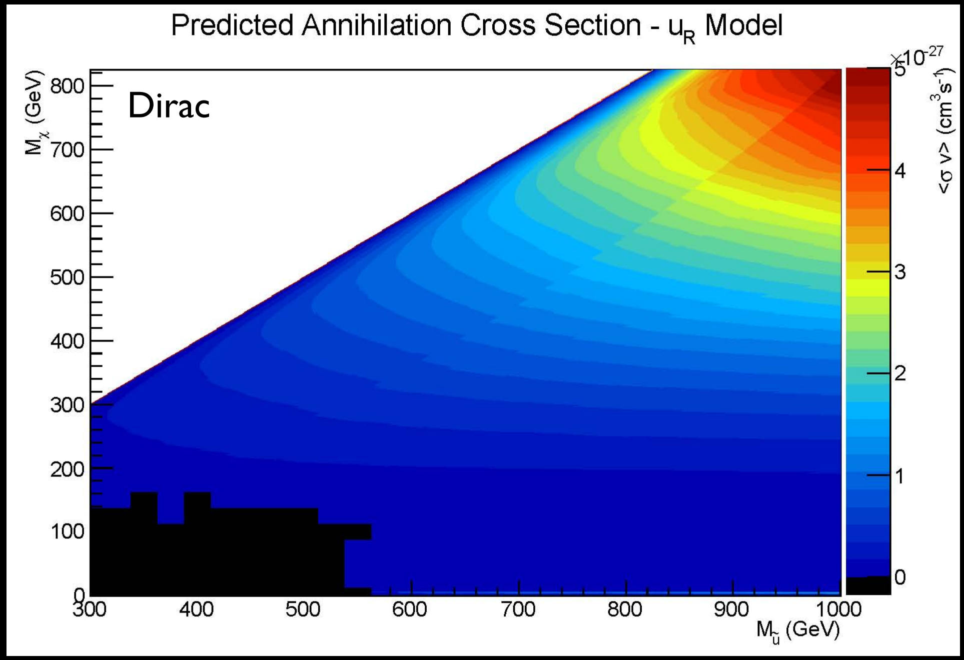
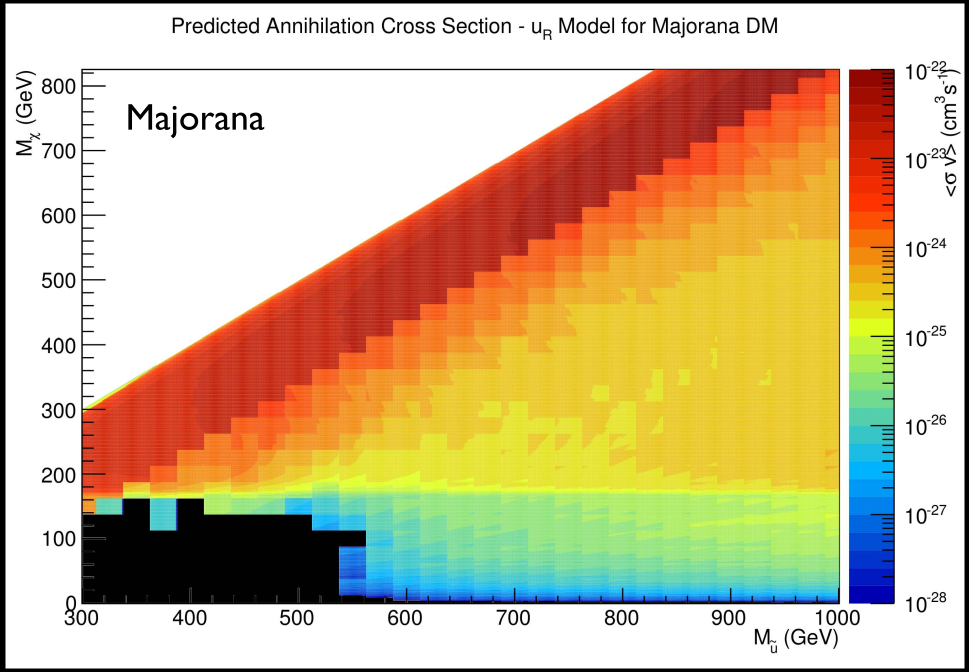
$\tilde{u}_R$ Model: Forecasts

- Similarly, we can forecast for the annihilation cross section.
- The Fermi LAT does not put very interesting constraints at the moment, but it is very close to doing so, and limits from dwarf satellite galaxies are likely to be relevant in the near future for Majorana DM.
- We can also ask where in parameter space this simple module would lead to a thermal relic with the correct relic density ($\sigma v \sim 10^{-26}$ cm^3/s).





DiFranzo, Nagao, Rajaraman, TMPT
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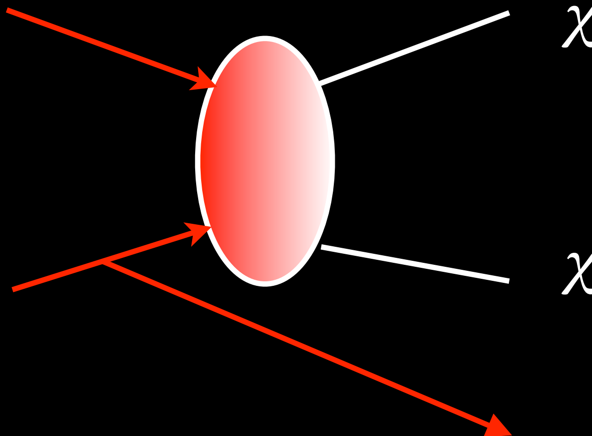
Direct WIMP Production

Maverick WIMP Production

- Producing WIMPs directly requires there to be some initial radiation from the incoming quarks or gluons: a “monojet” event.
- We’re not very sensitive to the details of how the WIMP couples to quarks and gluons: we can use effective field theories to parameterize all leading contributions.
- We can recycle existing ADD graviton searches (though they are not perfectly optimized).
- This kind of process works best for very light WIMPs, because they can be produced easily with a lot of kinetic energy, leading to large missing energy.

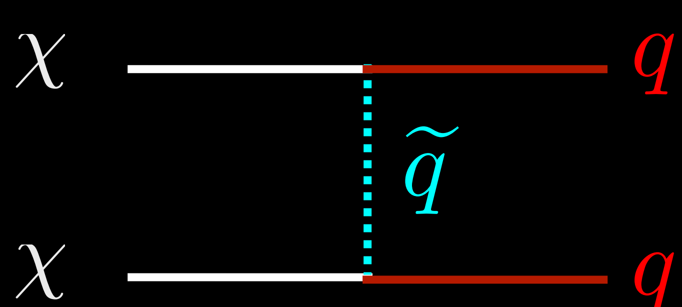


Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037

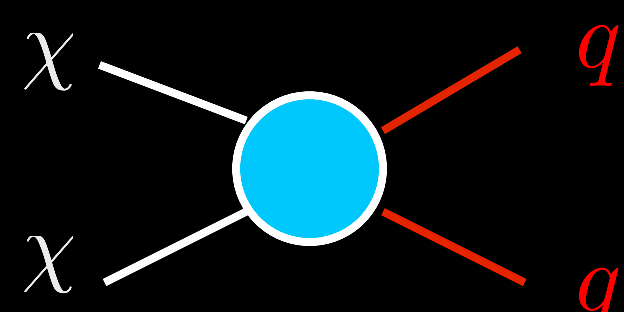
Example EFT: Majorana WIMP

- As an example, we can write down operators of interest for a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ gauge invariance coupling the WIMP to quarks and gluons.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-



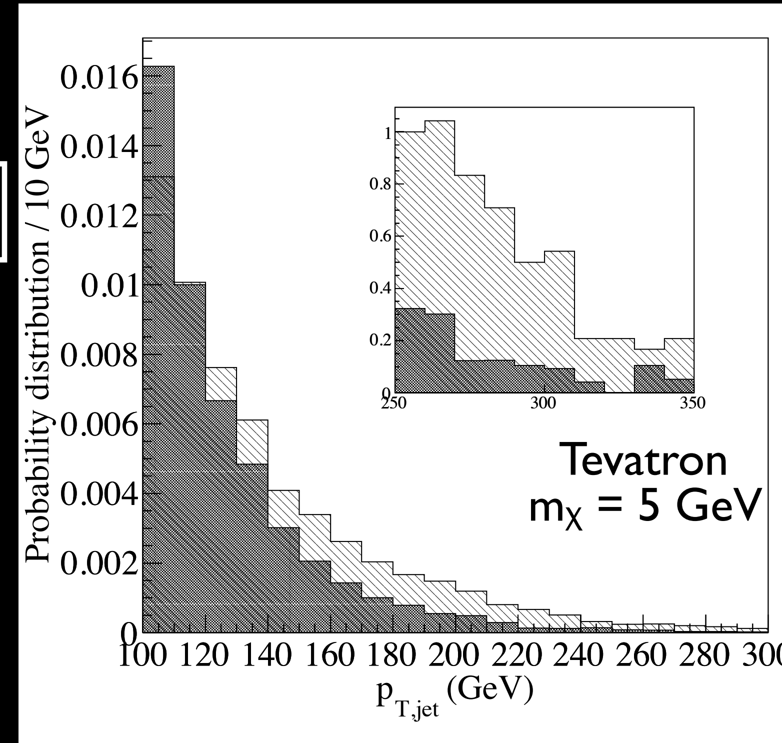
$$\frac{g^2}{M_{\tilde{q}}^2} \leftrightarrow \frac{1}{M_*^2}$$

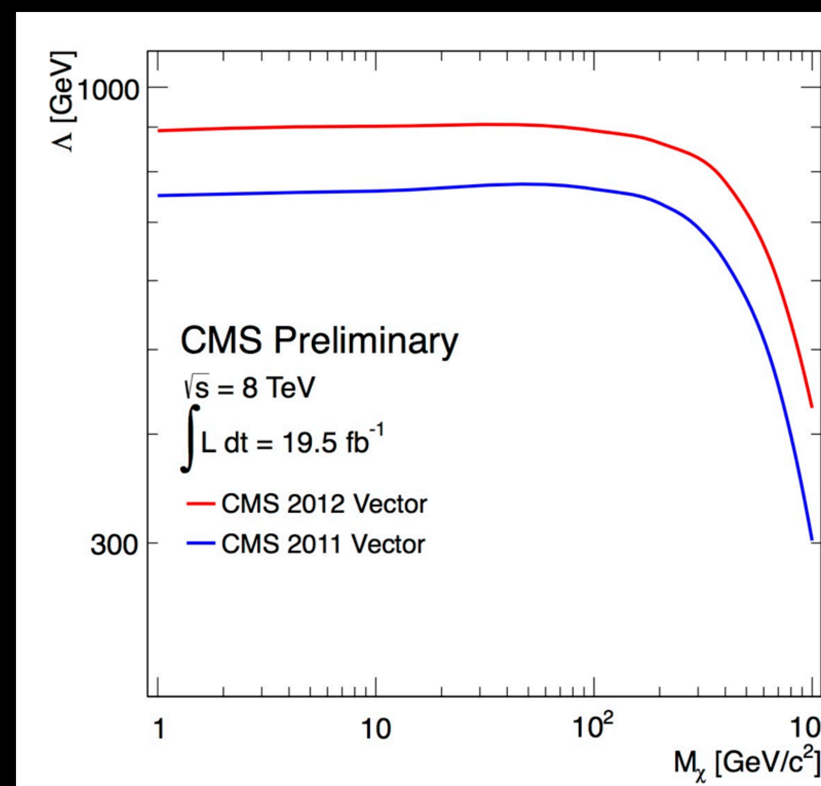


Monojets

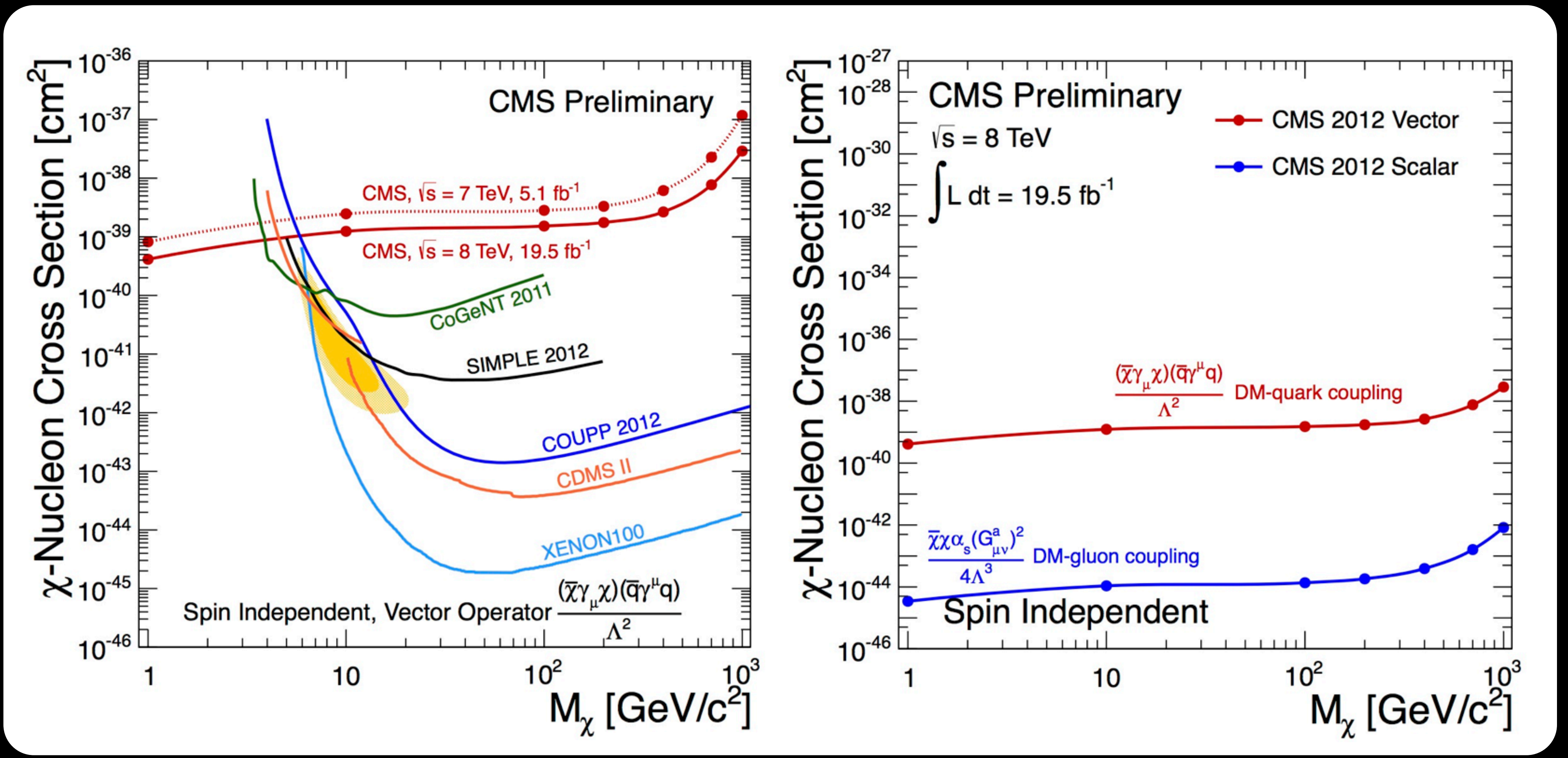
Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

- In terms of the WIMP mass and its interaction with quarks and/or gluons, we can predict the rate of monojet production.
- There are SM backgrounds from producing a Z which decays into neutrinos plus a jet of hadrons as well as fakes.
- The EFT also allows a more model-independent mapping from collider signals into direct and indirect searches.
- Other analyses such as e.g. razor can help with sensitivity.

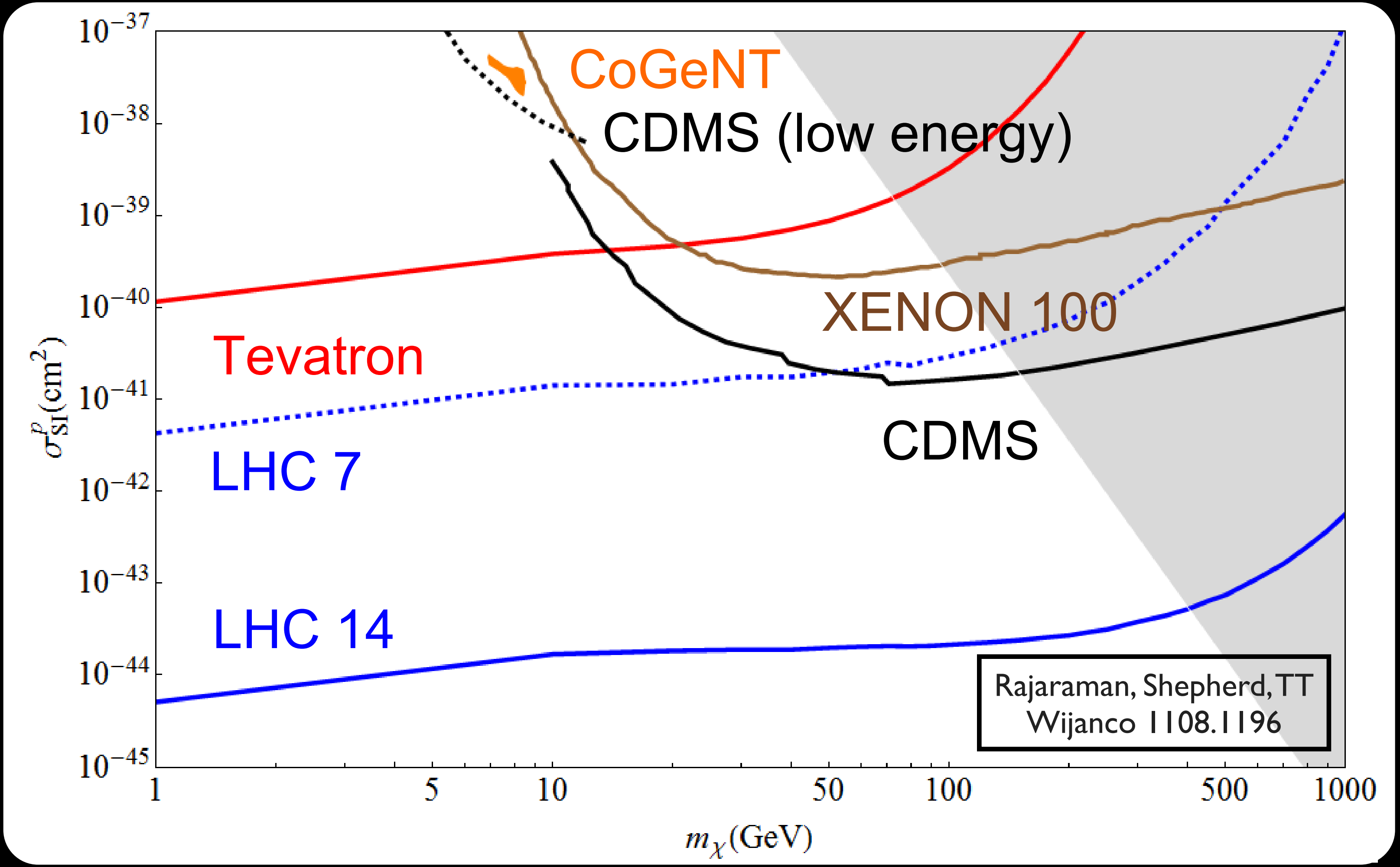




From Colliders to Direct Detection



Iso-spin Violating Couplings

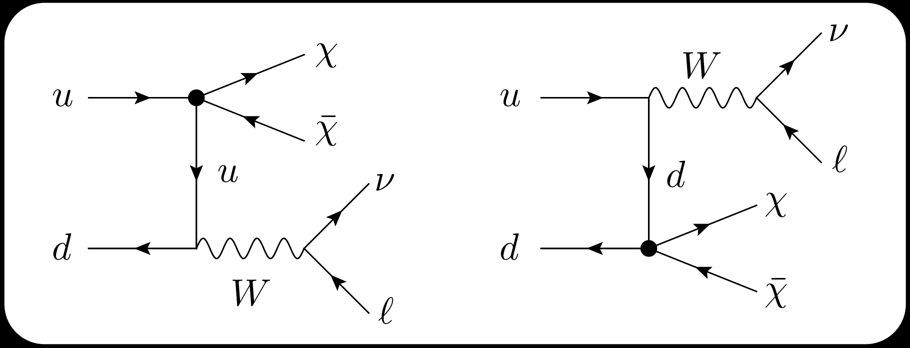


- For up- and down-quark couplings adjusted such that fn ~ -0.7 fp, constraints from Xenon are much weaker than the CoGeNT signal.
- Naive MFV implementations are ruled out by colliders, but specific non-MFV constructions survive.

Feng, Kumar, Marfatia, Sanford 1102.4331 (see also: Chang, Pierce, Weiner 1004.0697)

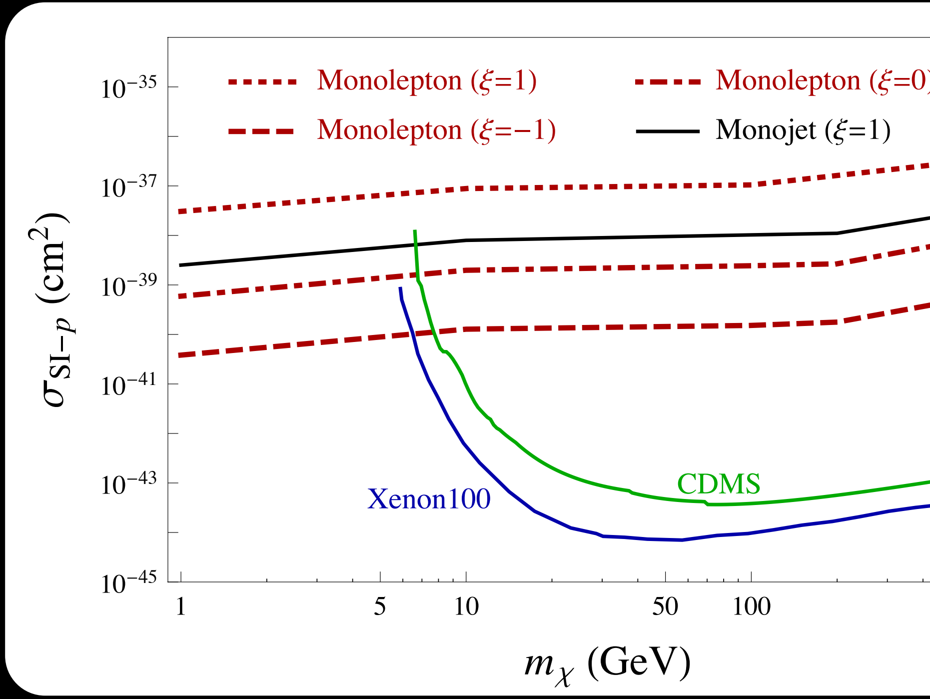
Mono-Whatever

- We can go beyond mono-jets and mono-photons.
- One can imagine similar searches involving other SM particles, such as mono-Ws (leptons), mono-Zs (dileptons), or even mono-Higgs.
- If we're just interested in the interactions of WIMPs with quarks and gluons, these processes are not going to add much.
- But they are also sensitive to interactions directly involving the bosons.
- And even for quarks, if we do see something, they can dissect the couplings to different quark flavors, etc.



CMS W' Search

Y. Bai, TMPT, 1208.4361 & PLB



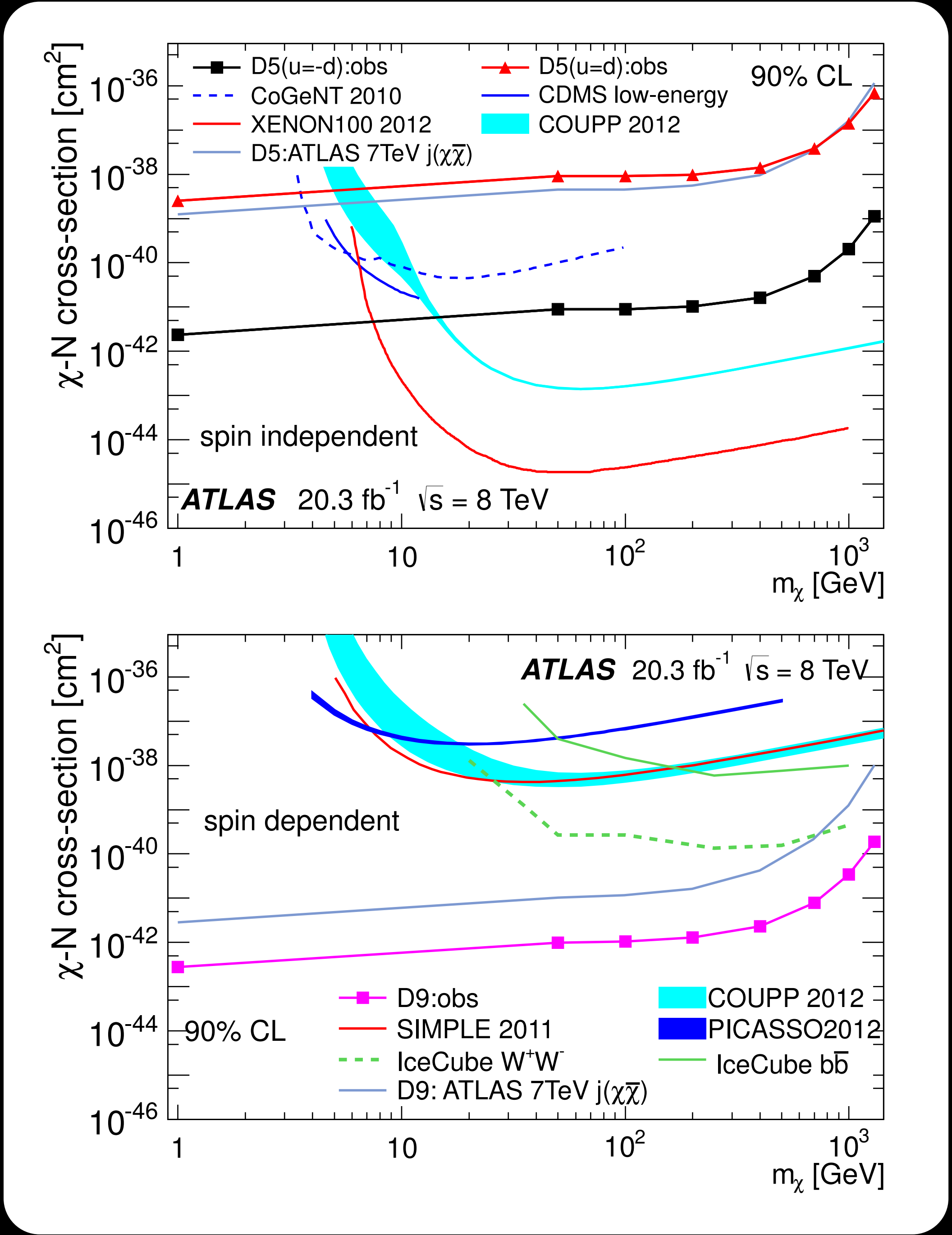
(d coupling) = ξ x (u coupling)

Jet Substructure!

Since the events of interest have boosted Ws, one can use substructure techniques to try to capture hadronically decaying Ws.

This helps increase statistics, and ultimately gives a better limit than the lepton channel.

A recent ATLAS study puts this idea into practice!

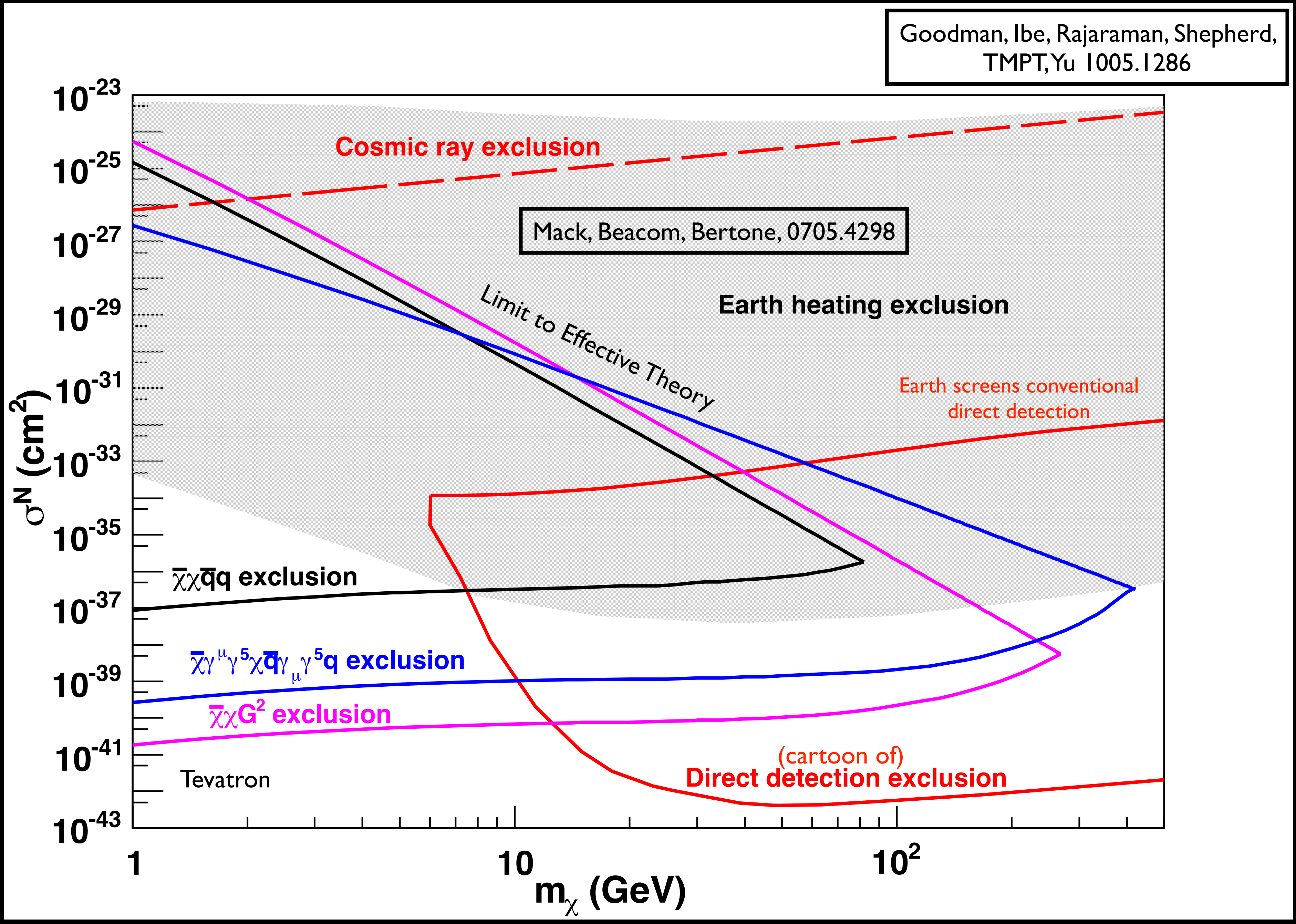


Outlook

- LHC Searches for new phenomena are going strong!
- Already big statements are being made about missing energy, dark matter, and supersymmetric theories with R-parity conservation.
- The next years will get into very interesting territory, with sensitivity to scalar stops and gluinos which should cover the most well-motivated regions of SUSY parameter space.
    - (And to say nothing about the Higgs mass and the MSSM...)
- More direct maverick production of dark matter is less effective than traditional SUSY searches if we can produce coloured mediator particles directly. If they are too heavy, maverick production will be how we fall back to quantify limits on dark matter interactions, and make contact between accelerator data and (in)direct searches.

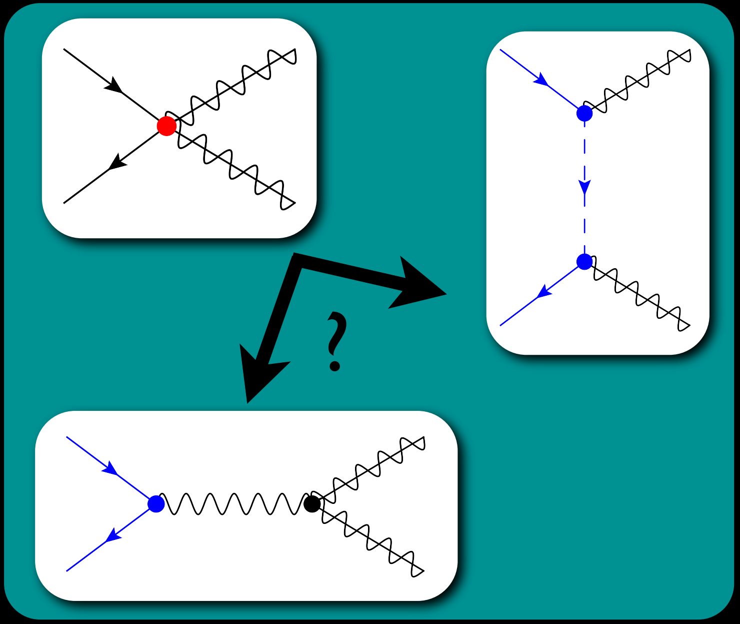
Bonus Material

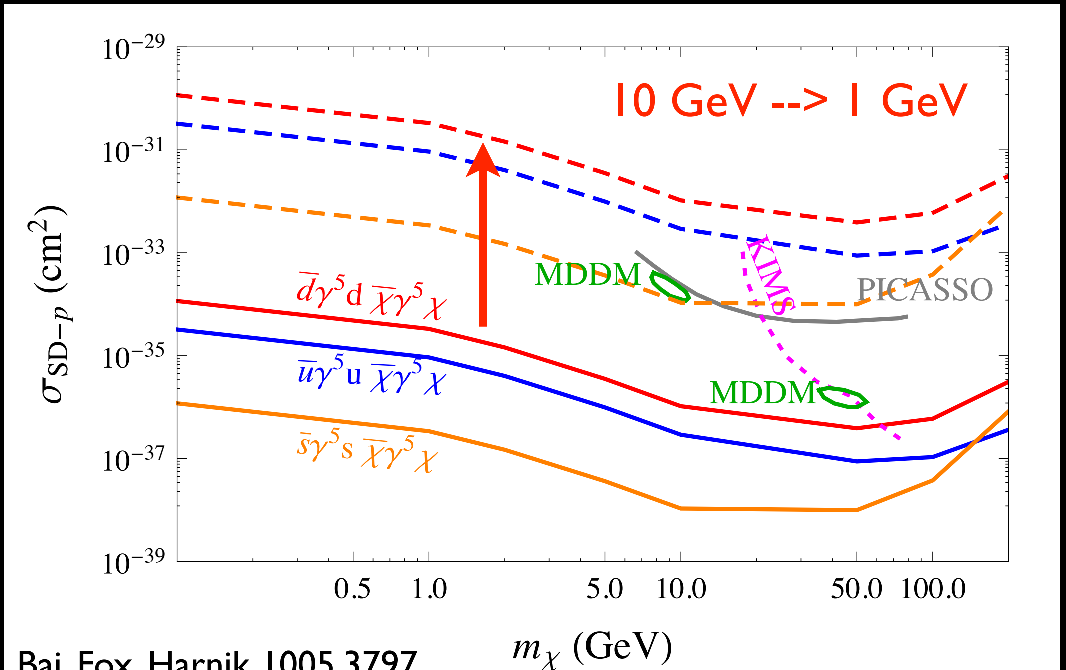
From WIMPs to SIMPs...



- How good is the EFT approximation?

- It depends on the momentum transfer of the process.
- Direct Detection: $Q^2 \sim (50\ \text{MeV})^2$.
  - EFT should work well unless you have ultralight mediators.
- Annihilation: $Q^2 \sim M^2$.
  - Fine in SUSY-like theories, problematic for quirky WIMPs or maybe coannihilators.
- Colliders: $Q^2 \sim p_T^2$
  - Bounds are generically too conservative for colored mediators.



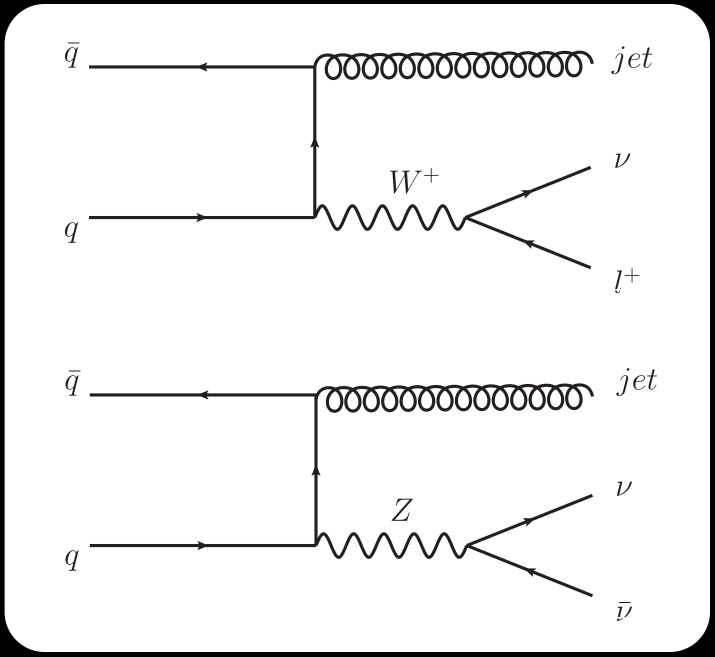


Bai, Fox, Harnik 1005.3797

Backgrounds

- To calibrate our simulations, we reproduce the CDF background using MadEvent with PYTHIA and PGS [CDF detector Model].
  - Including NLO k-factors, we succeeded at the % level.
- The dominant physics backgrounds are:
  - Z + jets (with Z-> νν).
  - W + jets (W->eν with the e

Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)



Example: Majorana WIMP

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

- The various types of interactions are accessible to different kinds of experiments.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation in the galactic halo
  - Collider Production

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

Other operators may be rewritten in this form by using Fierz transformations.