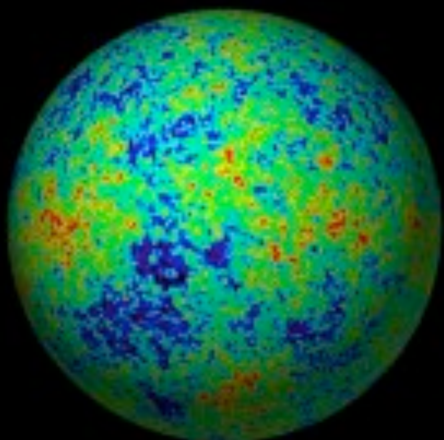
Dark Matter at Colliders

Tim M.P. Tait
University of California, Irvine

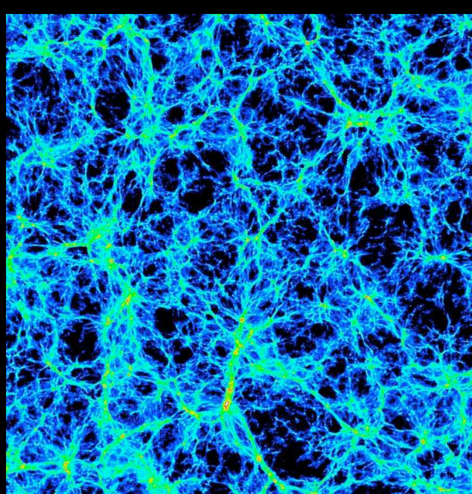
MC4BSM, Fermilab
May 19, 2015

Dark Matter

CMB



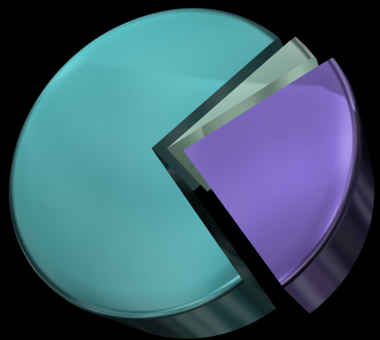
Supernova

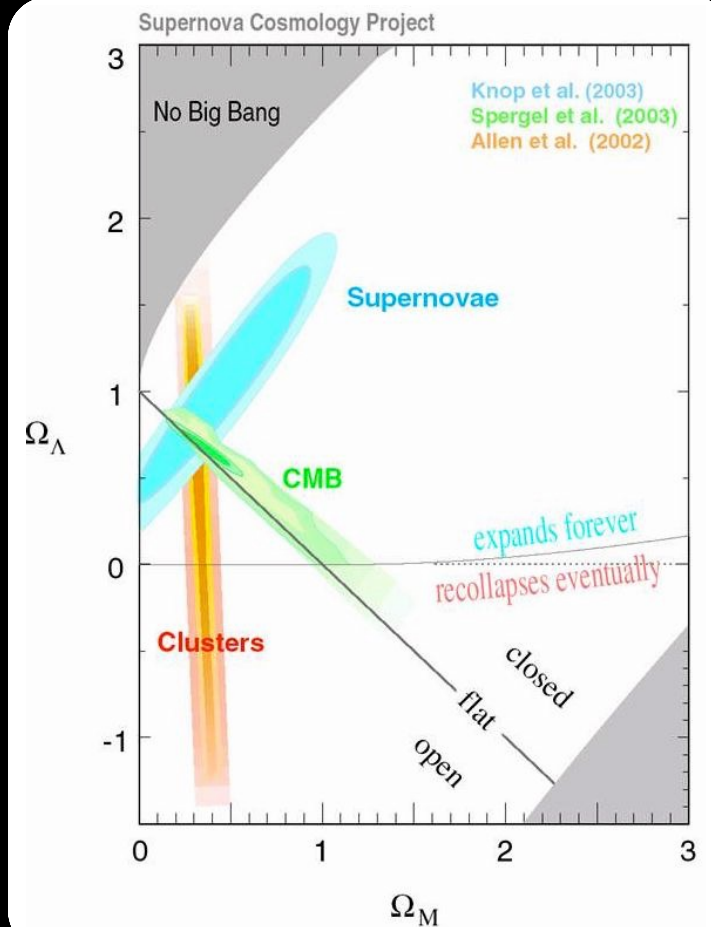


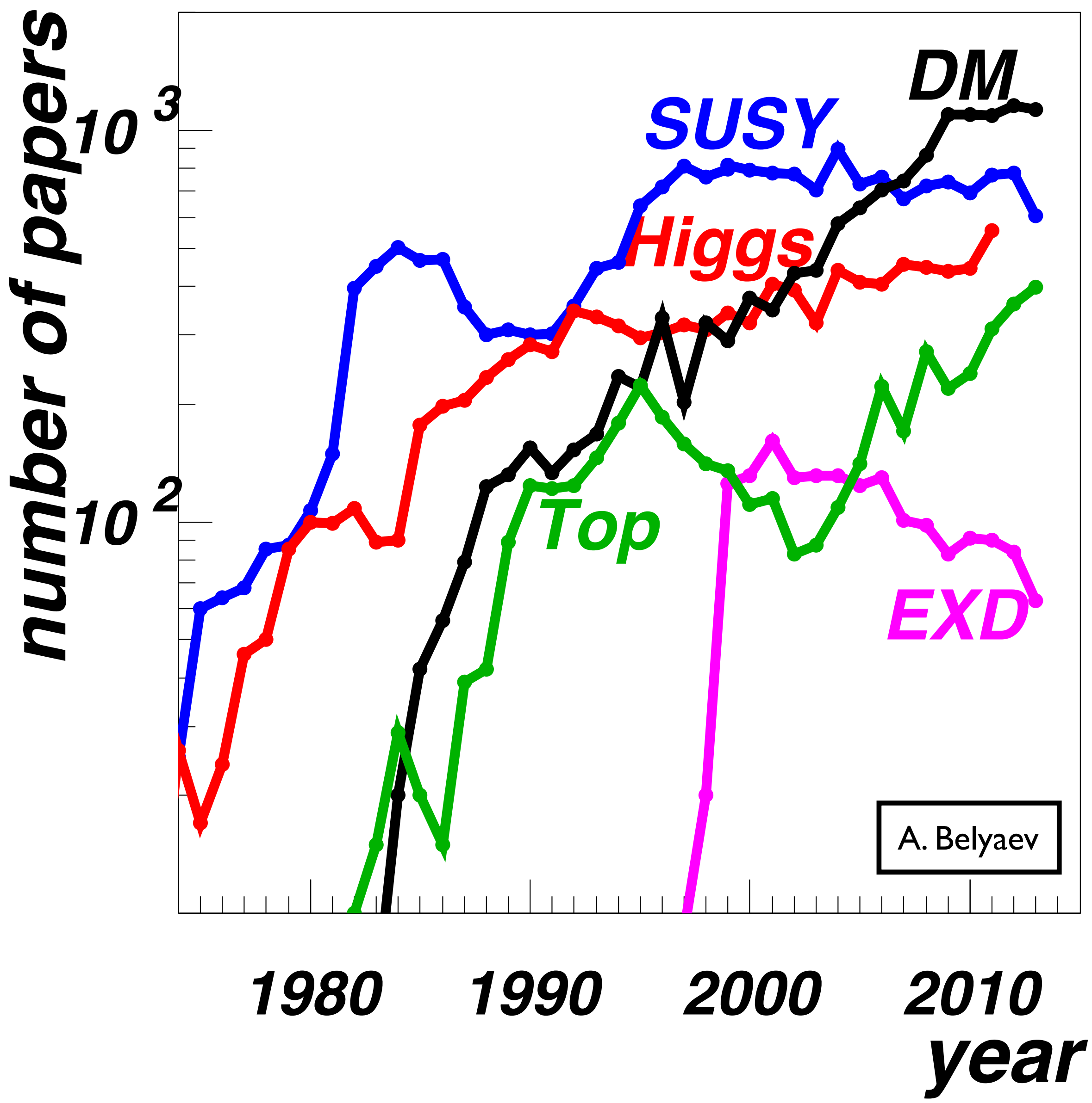
Structure

Lensing

- Ordinary Matter
- Dark Matter
- Dark Energy

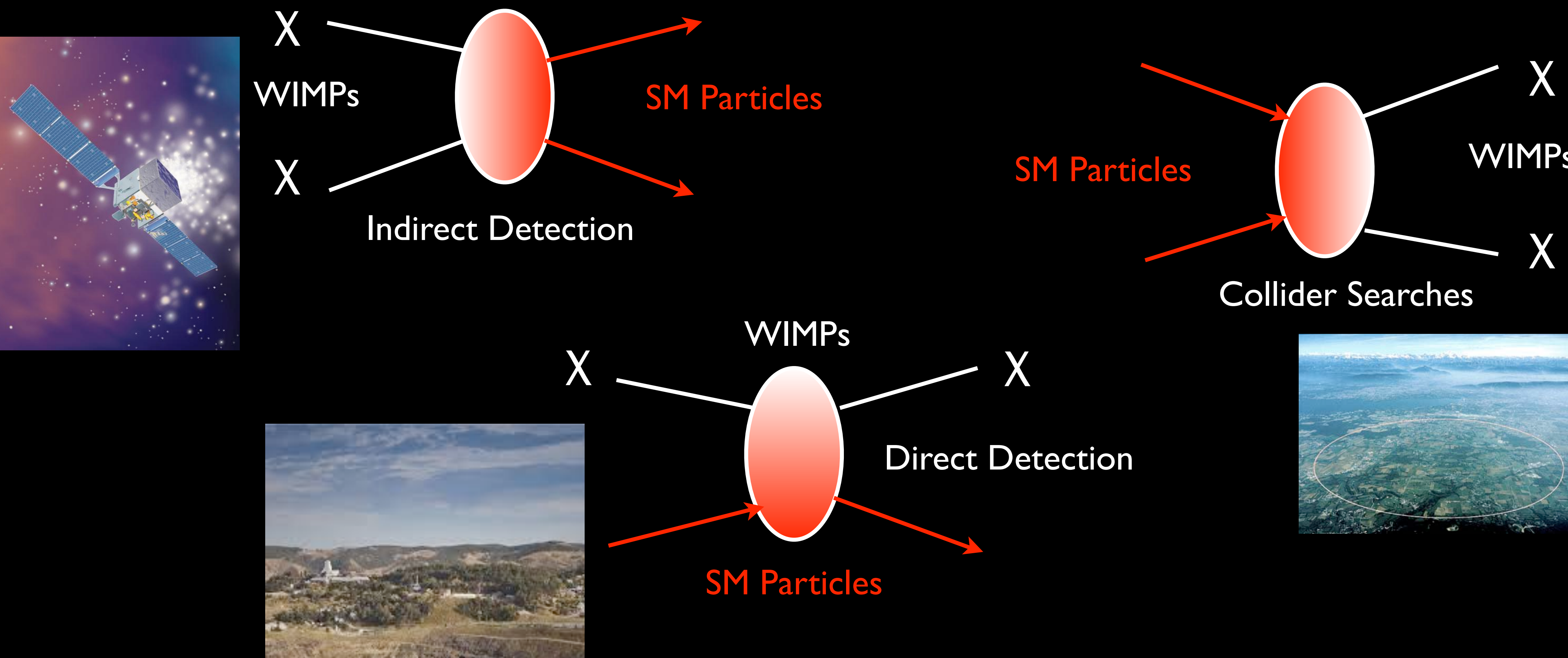






number of papers
10^3
10^2
SUSY
DM
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year

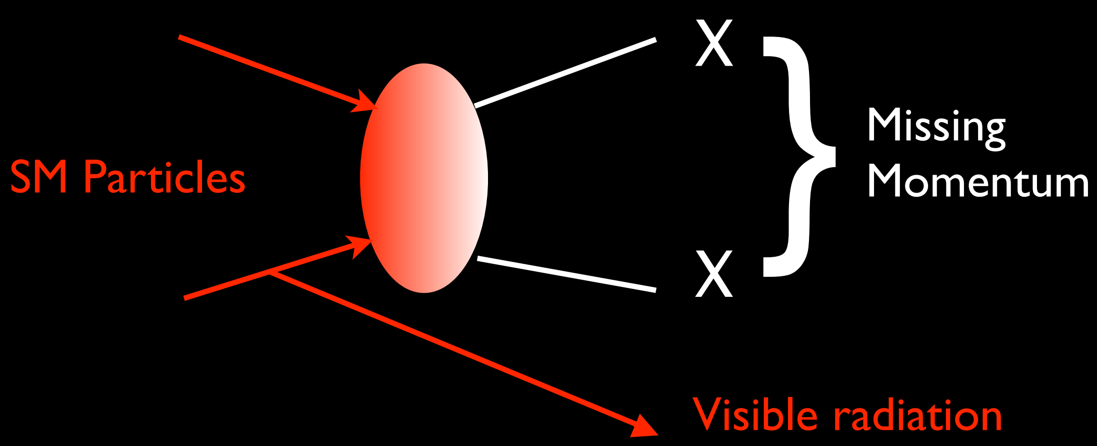
Particle Probes of DM

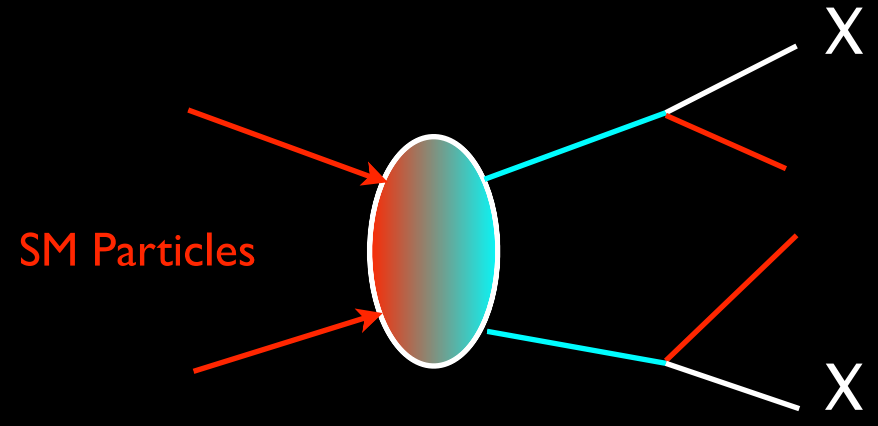


- The common feature of particle searches for WIMPs is that all of them are determined by how WIMPs interact with the Standard Model.

Seeing the Invisible?

- Dark matter interacts so weakly that it is expected to pass through the detector components without any significant interaction, making it effectively invisible (much like neutrinos).
- There are two ways we can try to "see" them nonetheless:





"KK Sgluquarkino Pair Production"

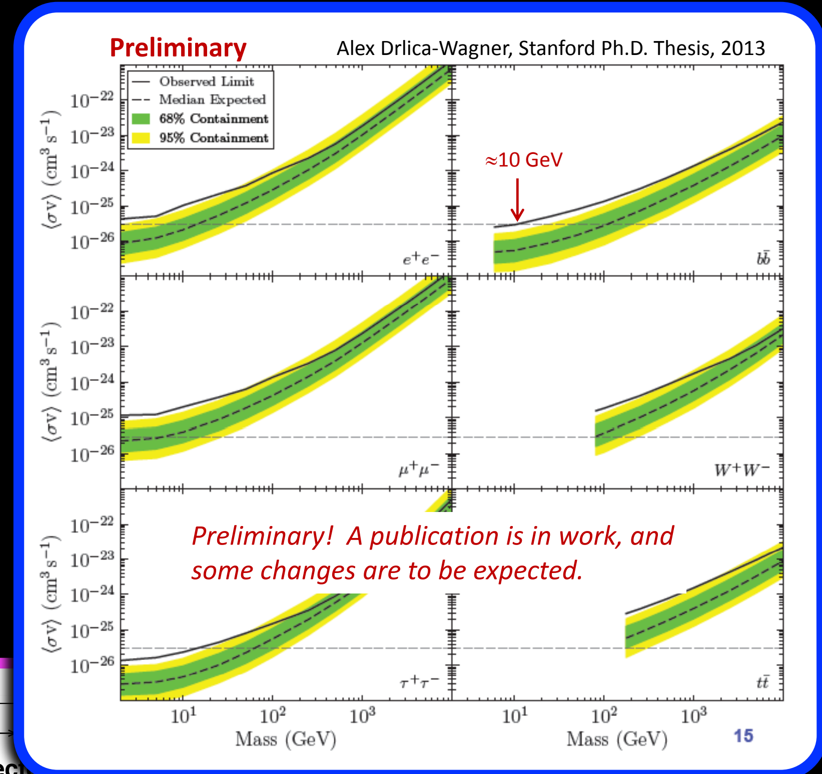
Radiation from the SM side of the reaction.

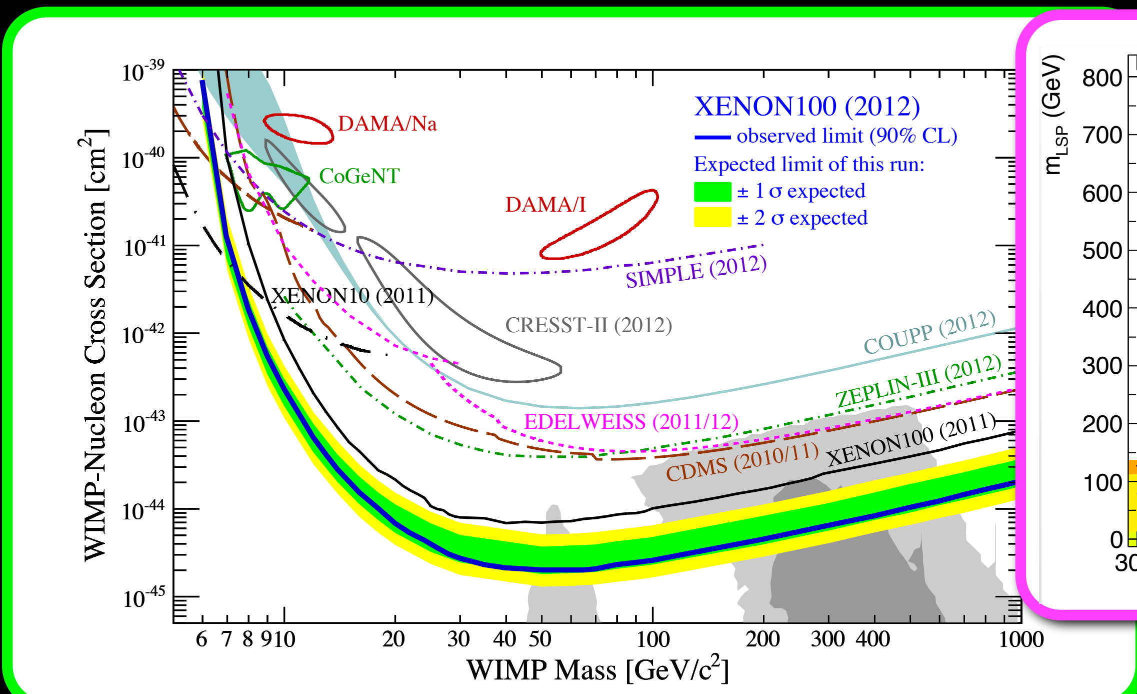
Production of "partners" which decay into WIMPS + SM particles.

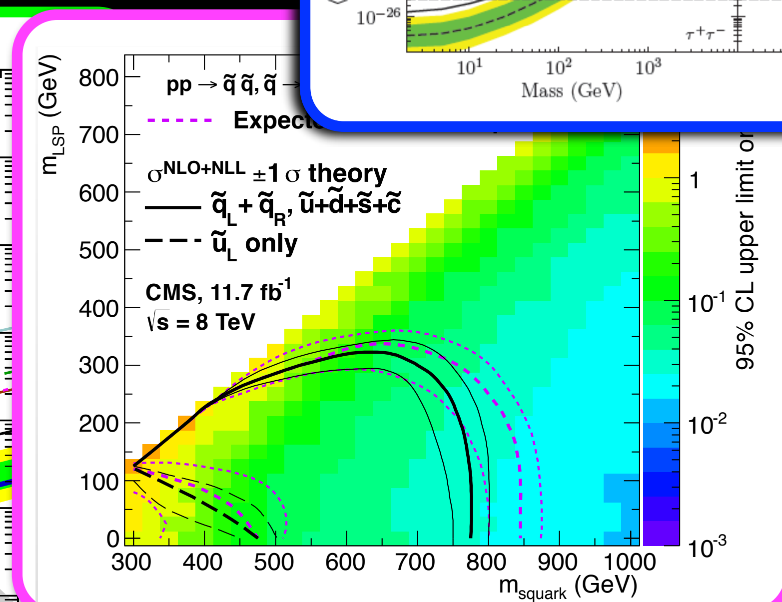
We Need (a) Theory

Individually, dark matter searches of all kinds put limits on different cross sections. Without some kind of theoretical structure, we can't compare them.

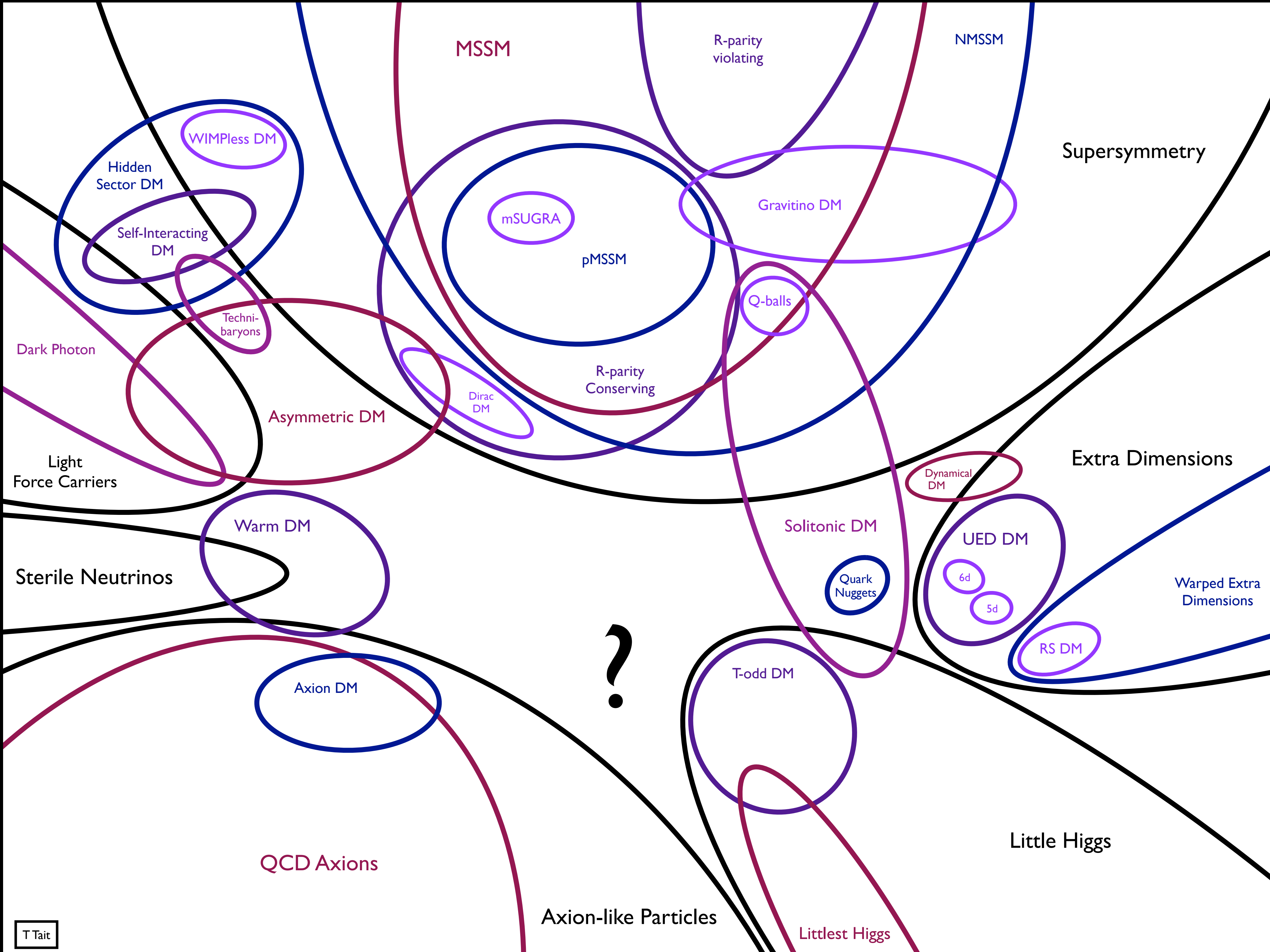
But we *know* they are all attempts to characterize the same thing(s)...

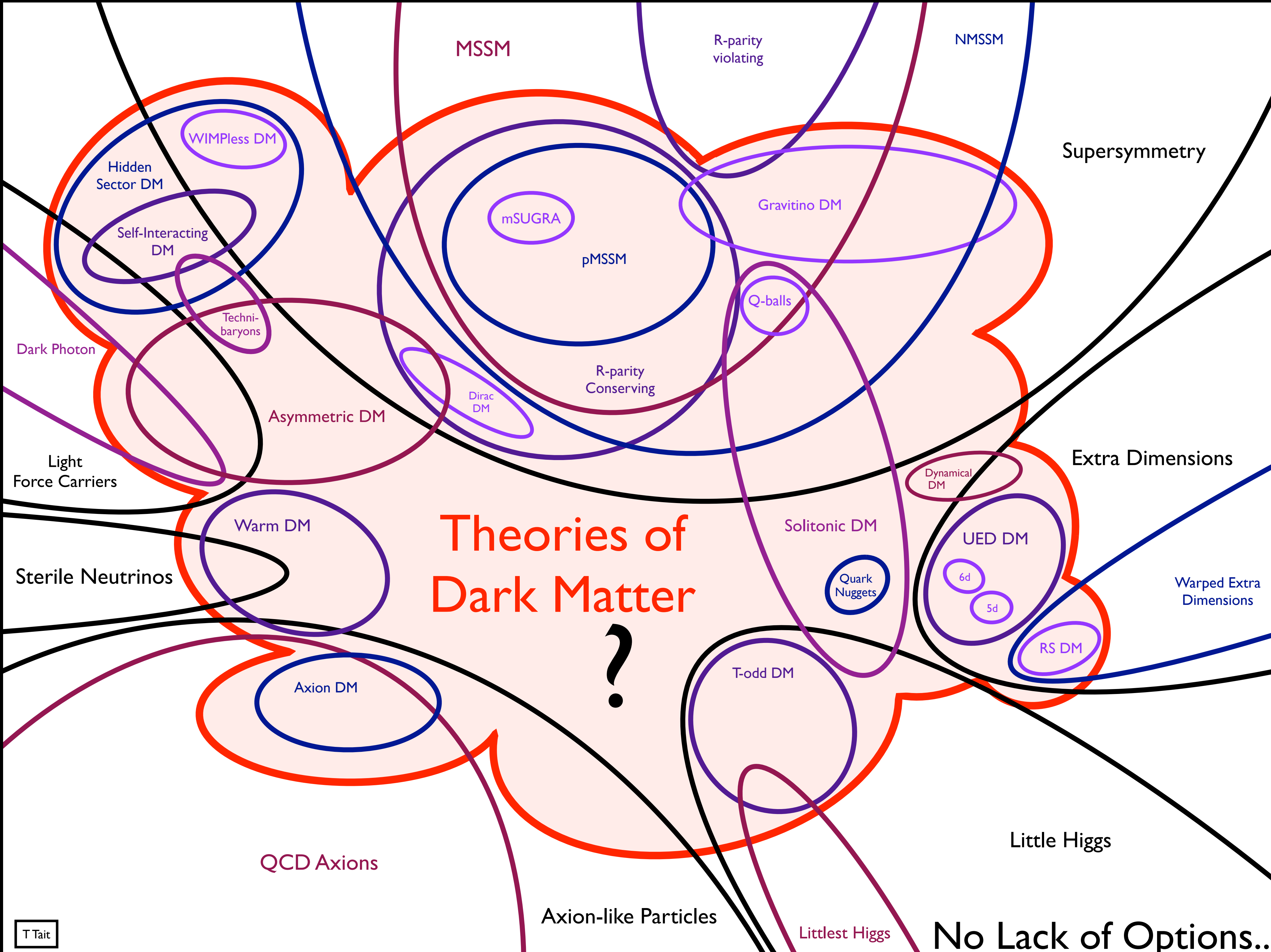






Which theory to use?


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
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
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
?
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait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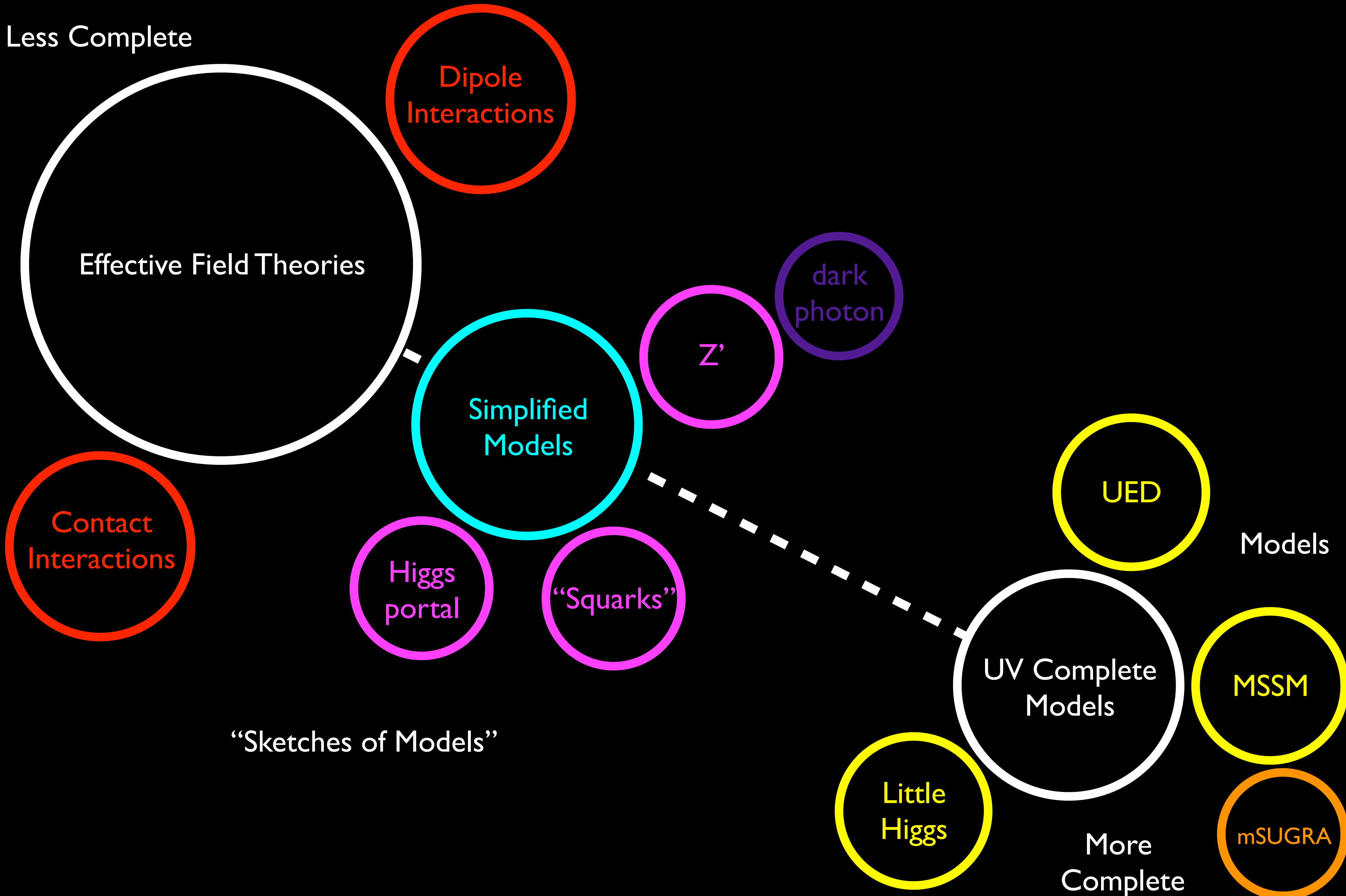
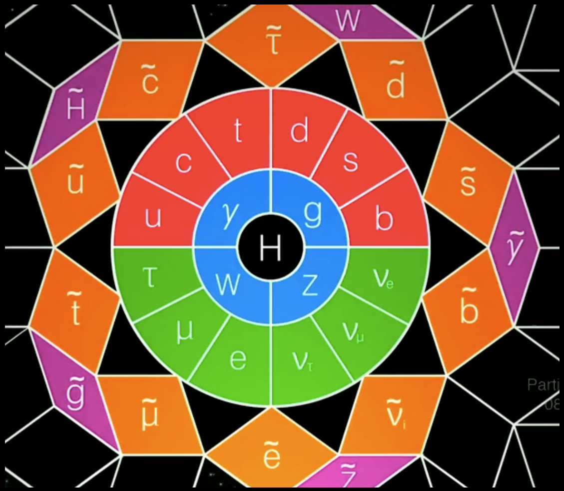
Littlest Higgs
No Lack of Options...
T Tait

Spectrum of Theory Space

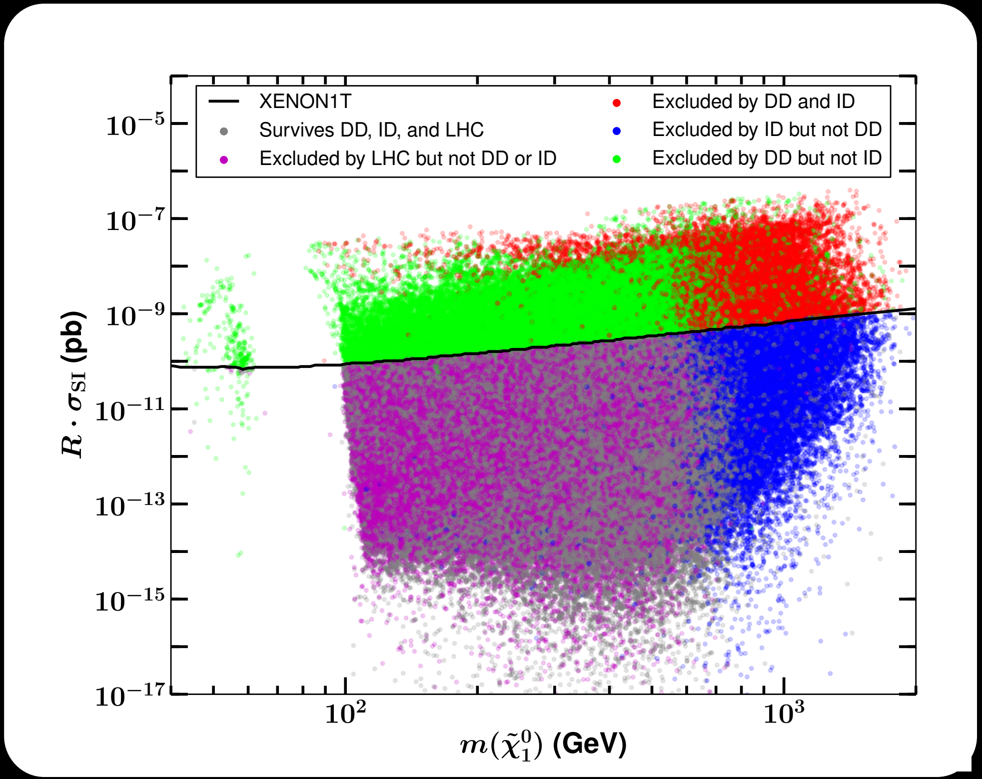


Supersymmetric Model

- An obvious first place to start would be with complete theories of dark matter, the most obvious example of which is our favorite theory: the Minimal Supersymmetric Standard Model.
- There are a huge number of free parameters. Even focusing on just the "reasonable" parameterizations leads to ~20 parameters, encompassing rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space in the plane of the WIMP mass versus the direct detection cross section.



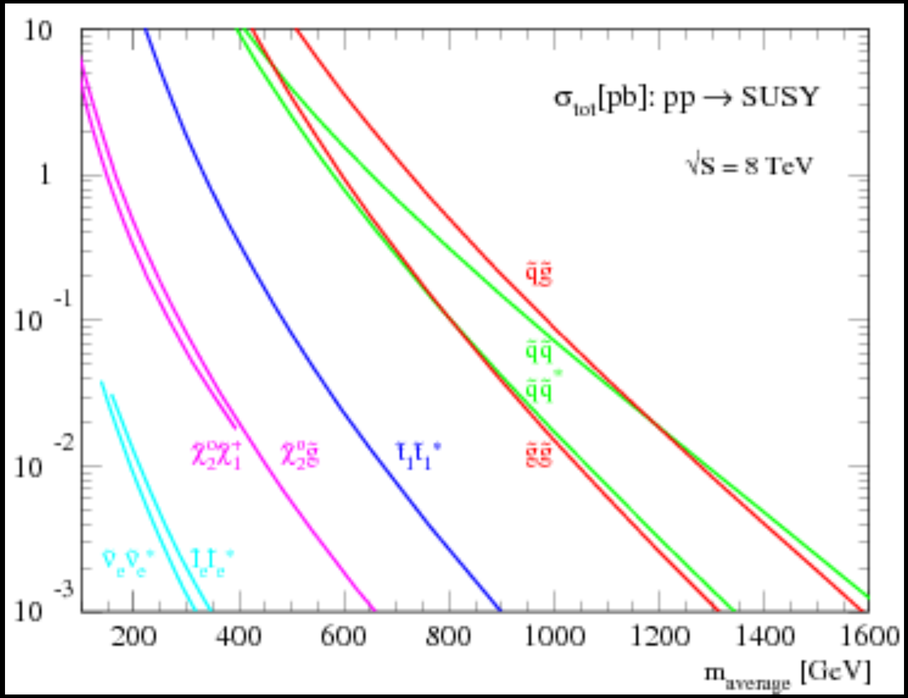
Particle Fever
D.E. Kaplan

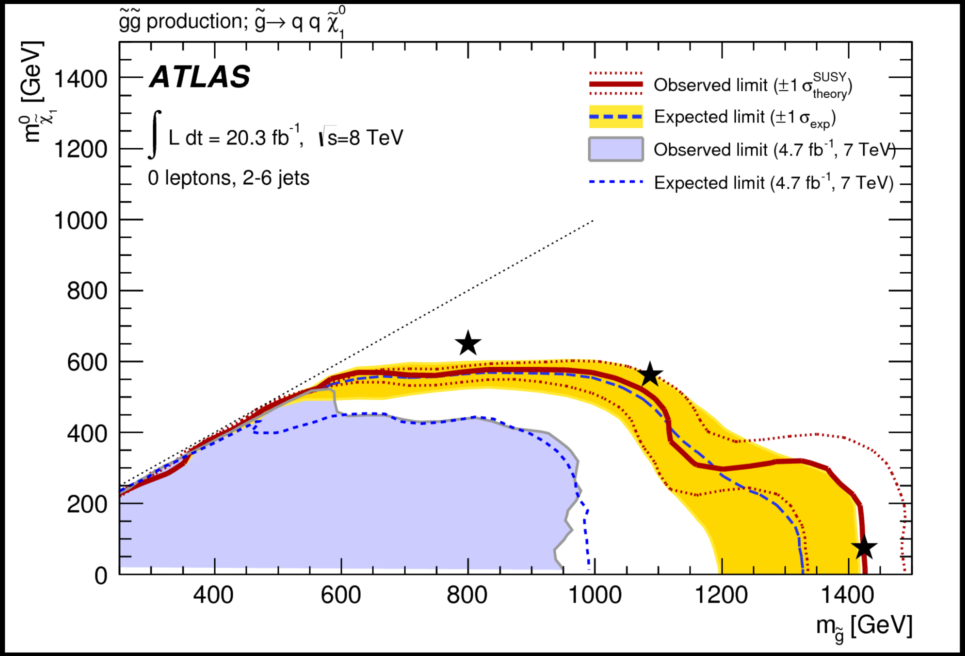


Cahill-Rowley et al, 1305.6921

MC Tools: MSSM

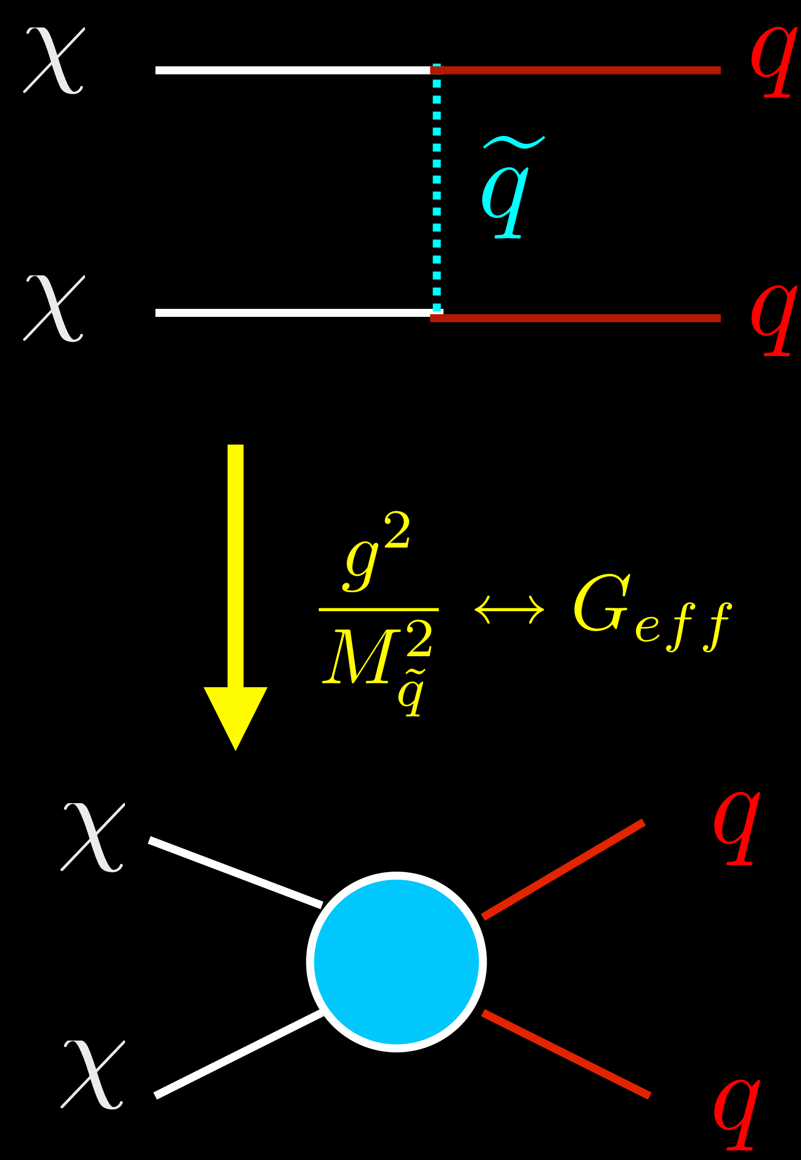
- The MSSM is the poster child for Monte Carlo tools at high energy colliders.
- All of the major production processes are known at NLO in (SUSY) QCD (and have been for > 10 years or so). (Though not always for completely generic spectra).
- Differential cross sections are available, usually in the narrow width approximation.
- In some cases, re-summed and NLO matched results are on the market.
- NLO (rates) are the standard for interpretation of experiments.





Contact Interactions

- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved.
- The drawback to a less complete theory is such a simplified description will undoubtably miss out on correlations between quantities which are obvious in a complete theory.
- And it will break down at high energies, where one can produce more of the new particles directly.



Example: Majorana WIMP

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB
see also: Bai, Fox, Harnik 1005.3797 & JHEP

- As an example, we can write down the 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.
- In principle, a realistic UV theory will turn on some combination of them, with related coefficients.

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
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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.

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

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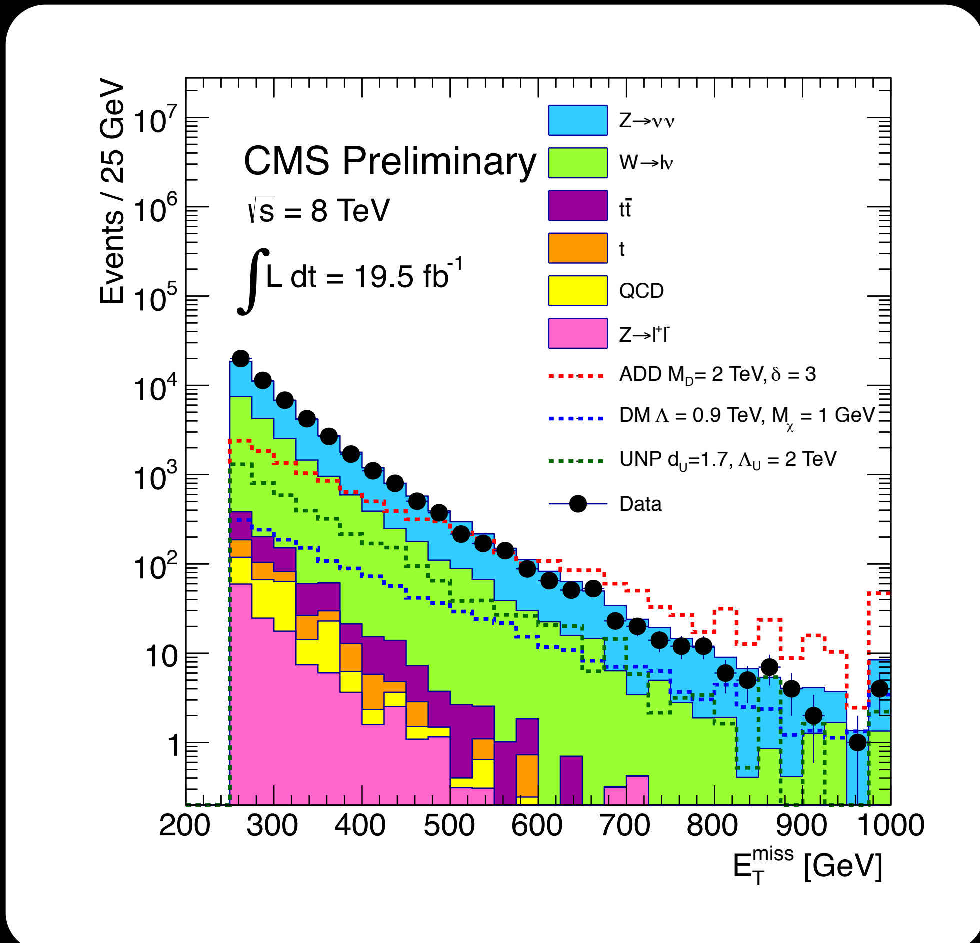
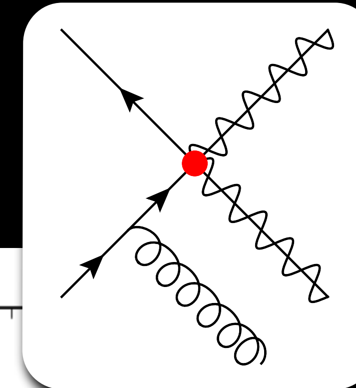
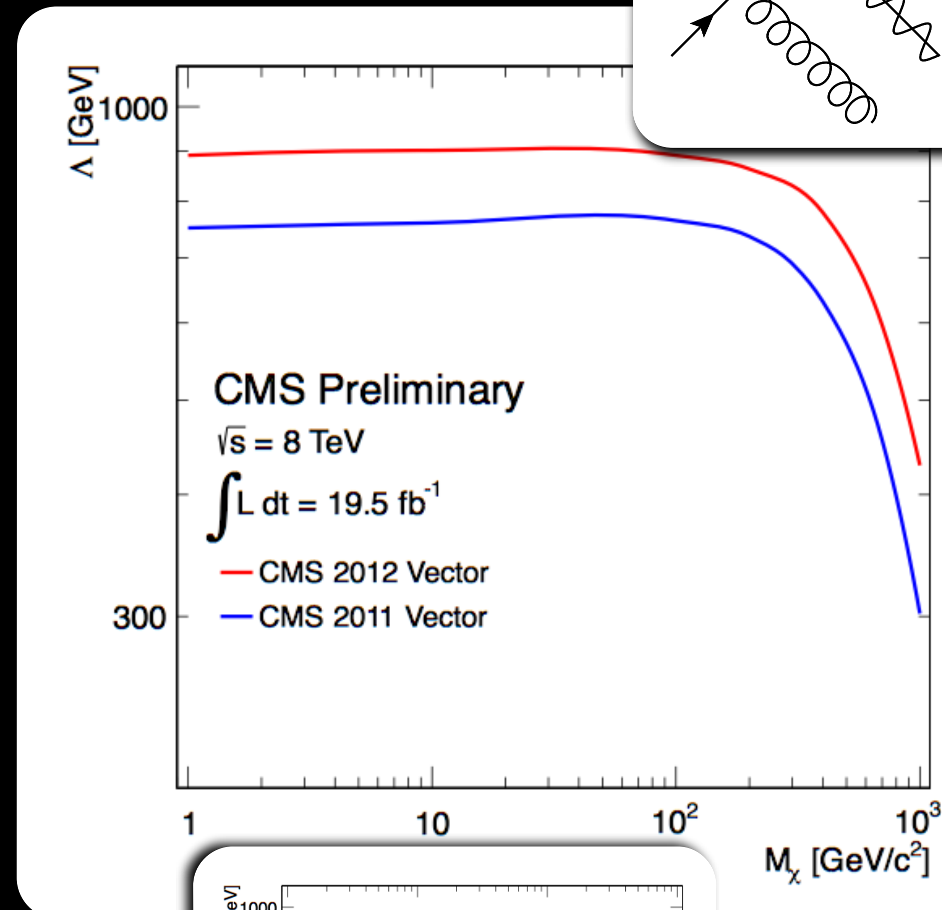
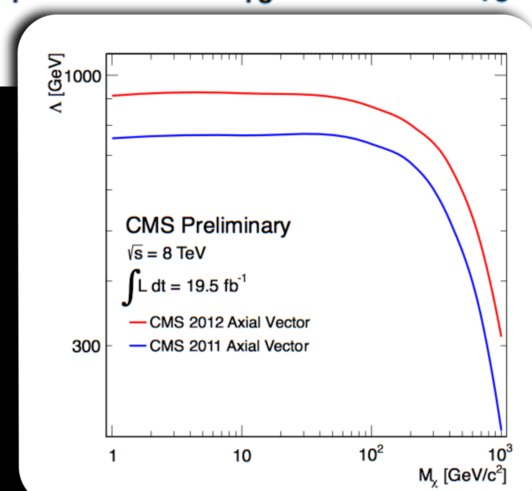
Collider Results



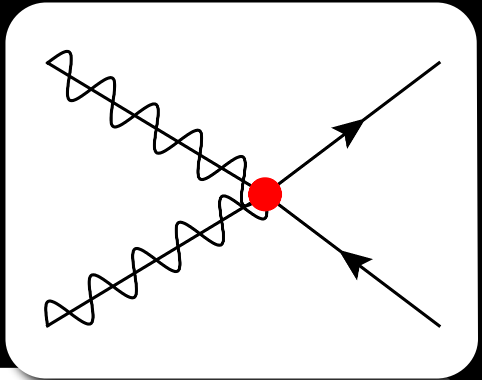




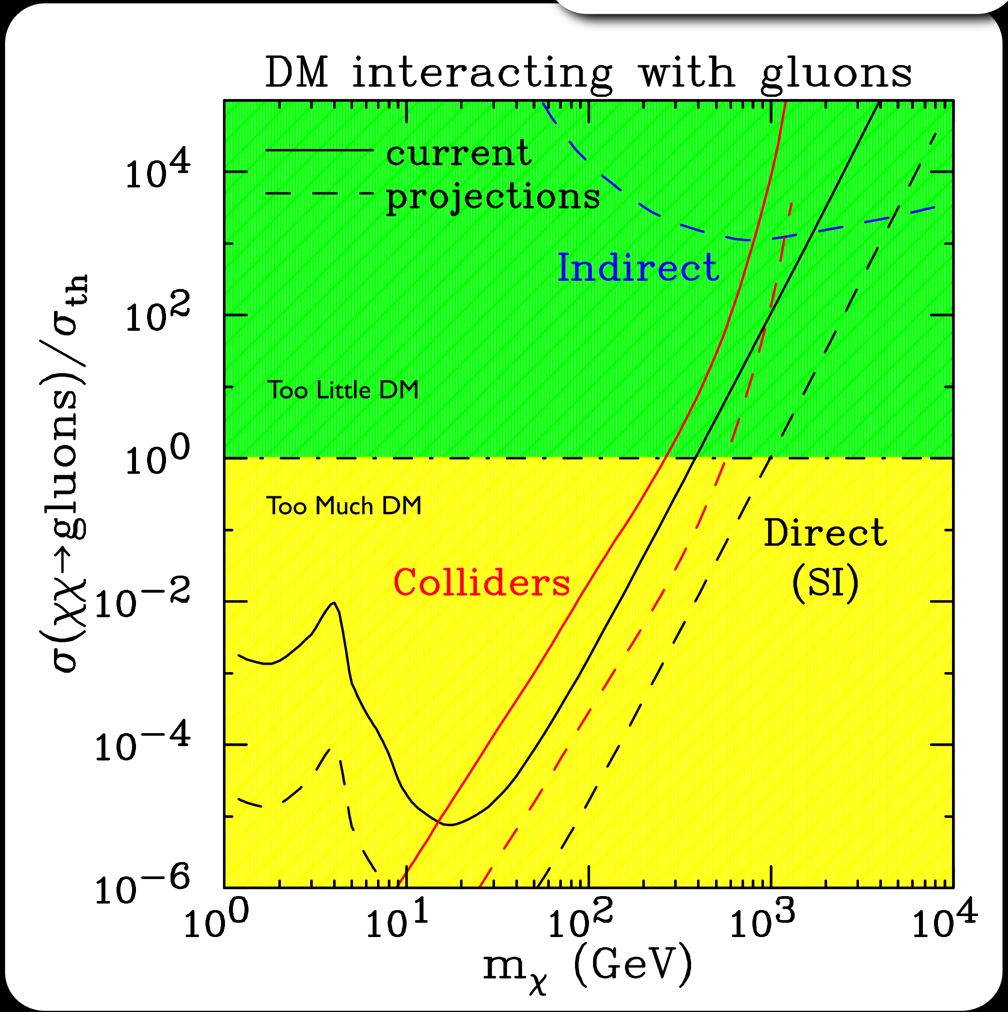


Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

Annihilation

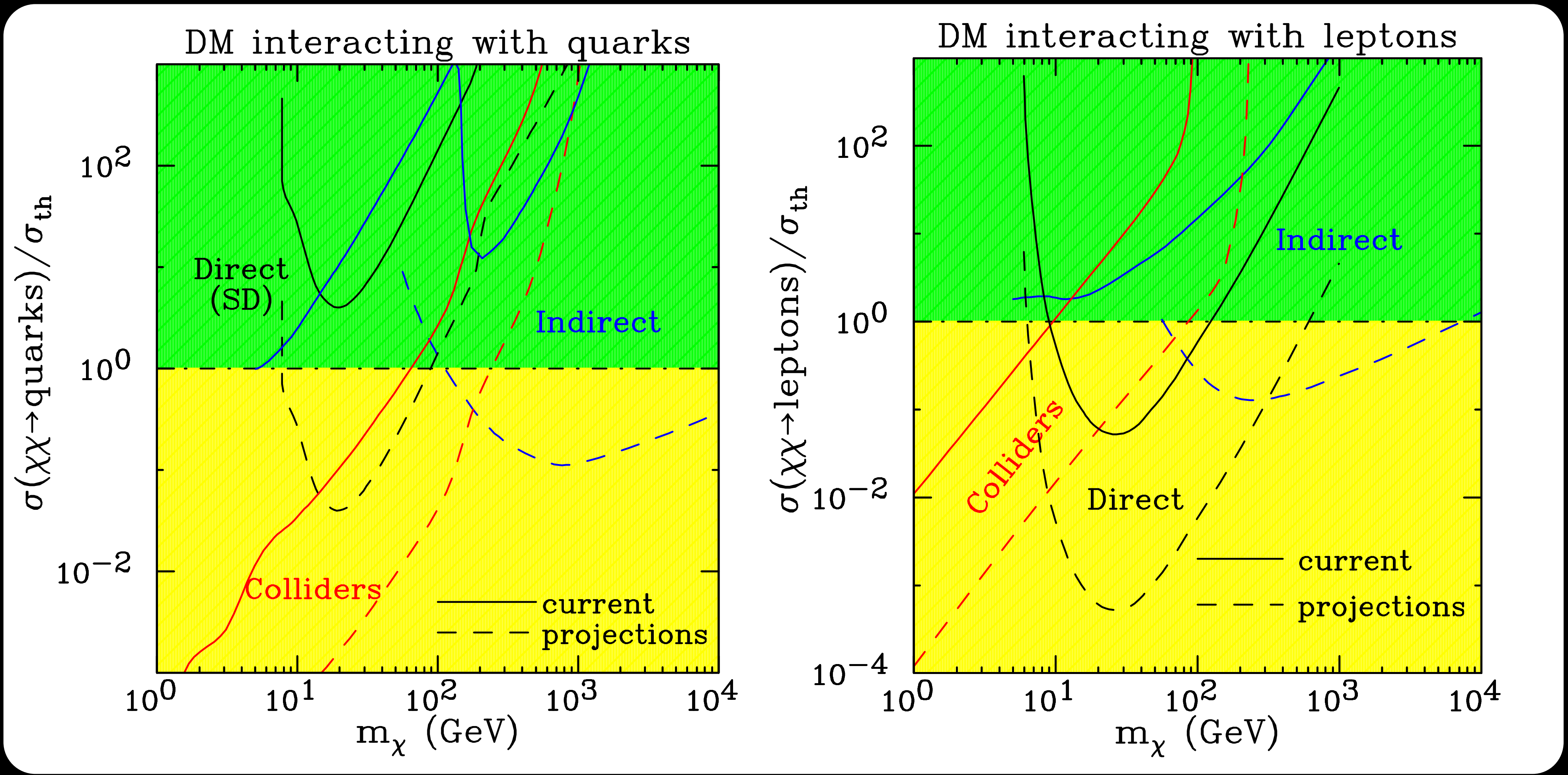


- We can map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Colliders continue to do better for lighter WIMPs or p-wave annihilations whereas indirect detection is more sensitive to heavy WIMPs.



DM Complementarity, arXiv:1305.1605 & PDU

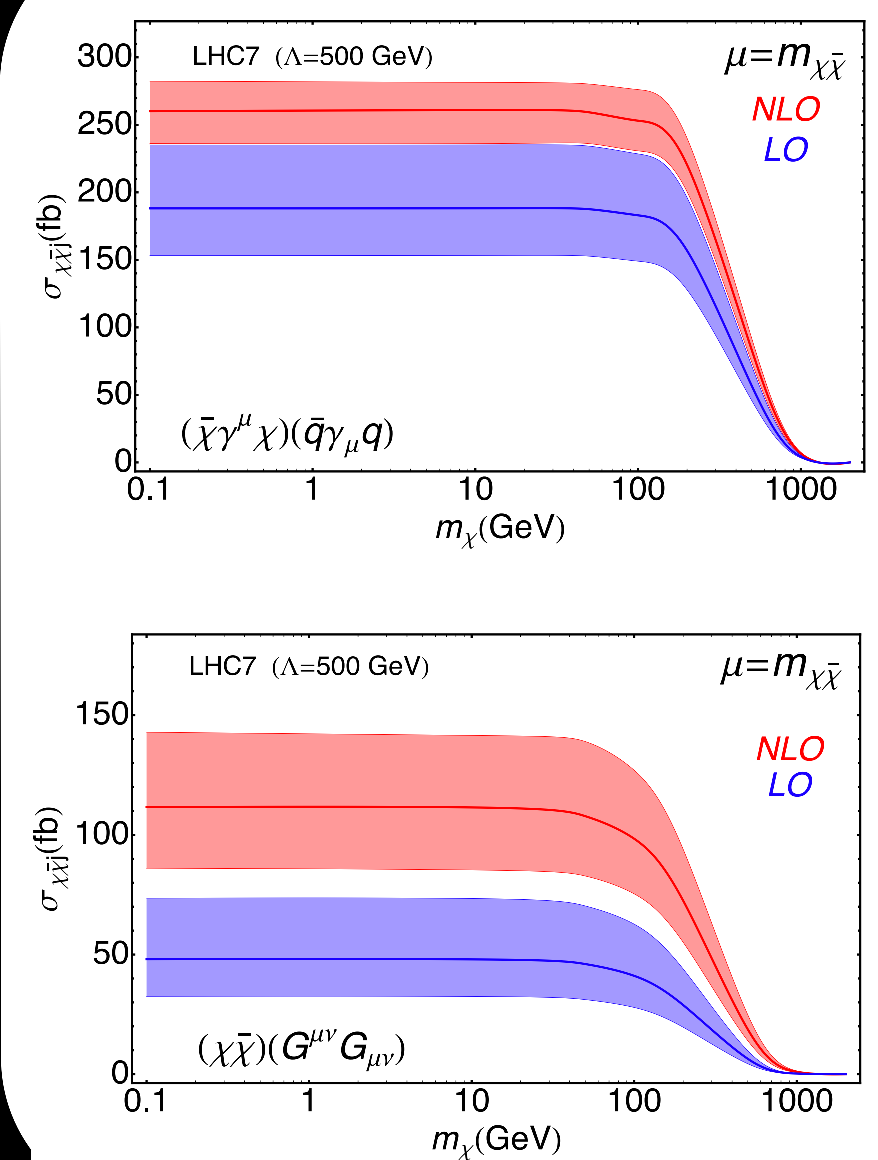
Quarks & Leptons



DM Complementarity, arXiv:1305.1605 & PDU

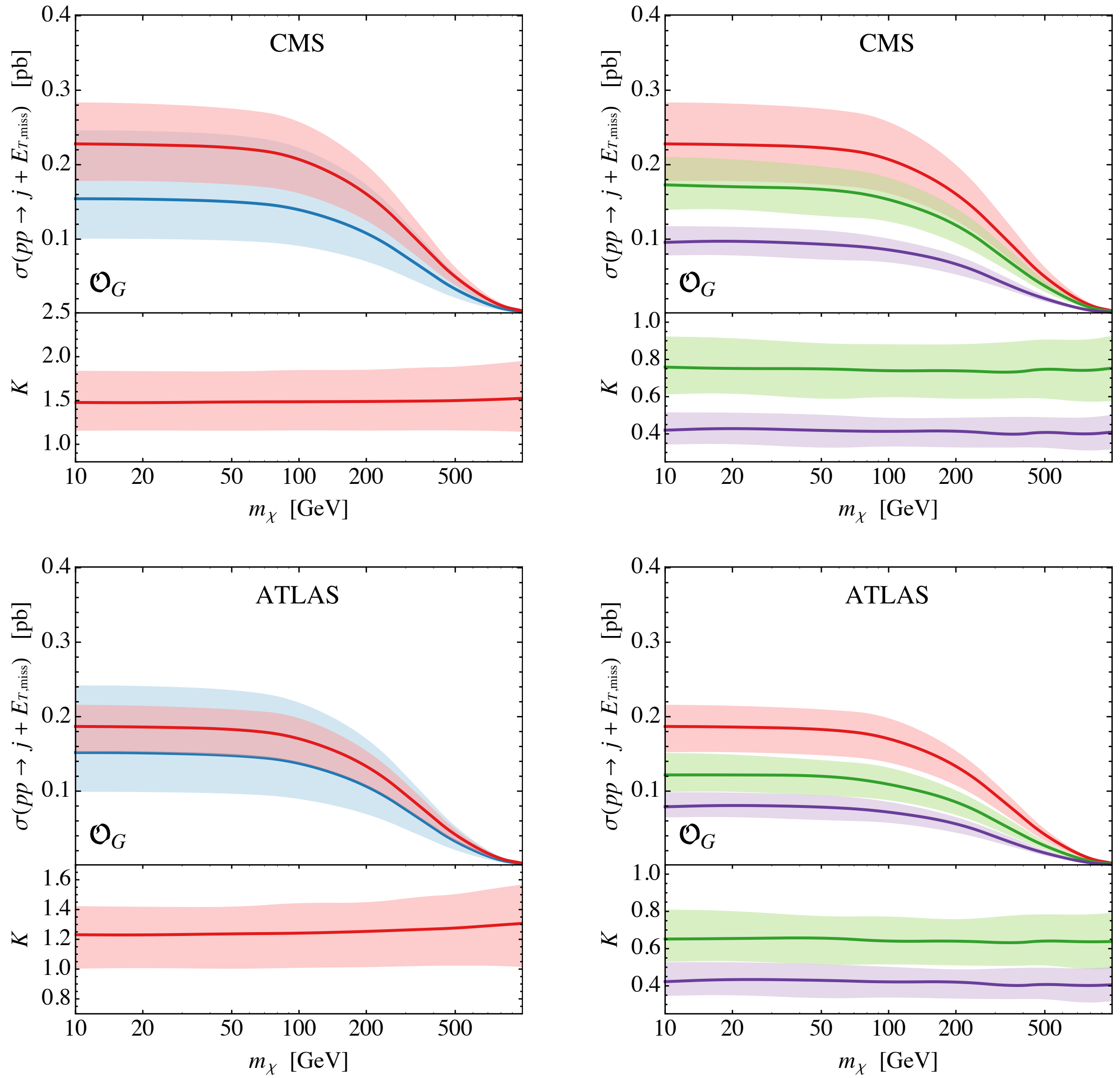
EFT : MC Tools

- The bulk of Monte Carlo studies of the signal are done at tree level.
  - Standard UFO Model file.
- In some cases, higher orders are very important, and can lead to a qualitatively different picture.
- In particular, for interactions with quarks weighted by mass, interactions with gluons mediated by virtual top quarks can be very significant.
- NLO results are available for mono-jet and mono-photon, and are included in both MCFM and an extension of POWHEG Box.



Fox, Williams 1211.6390 & PRD

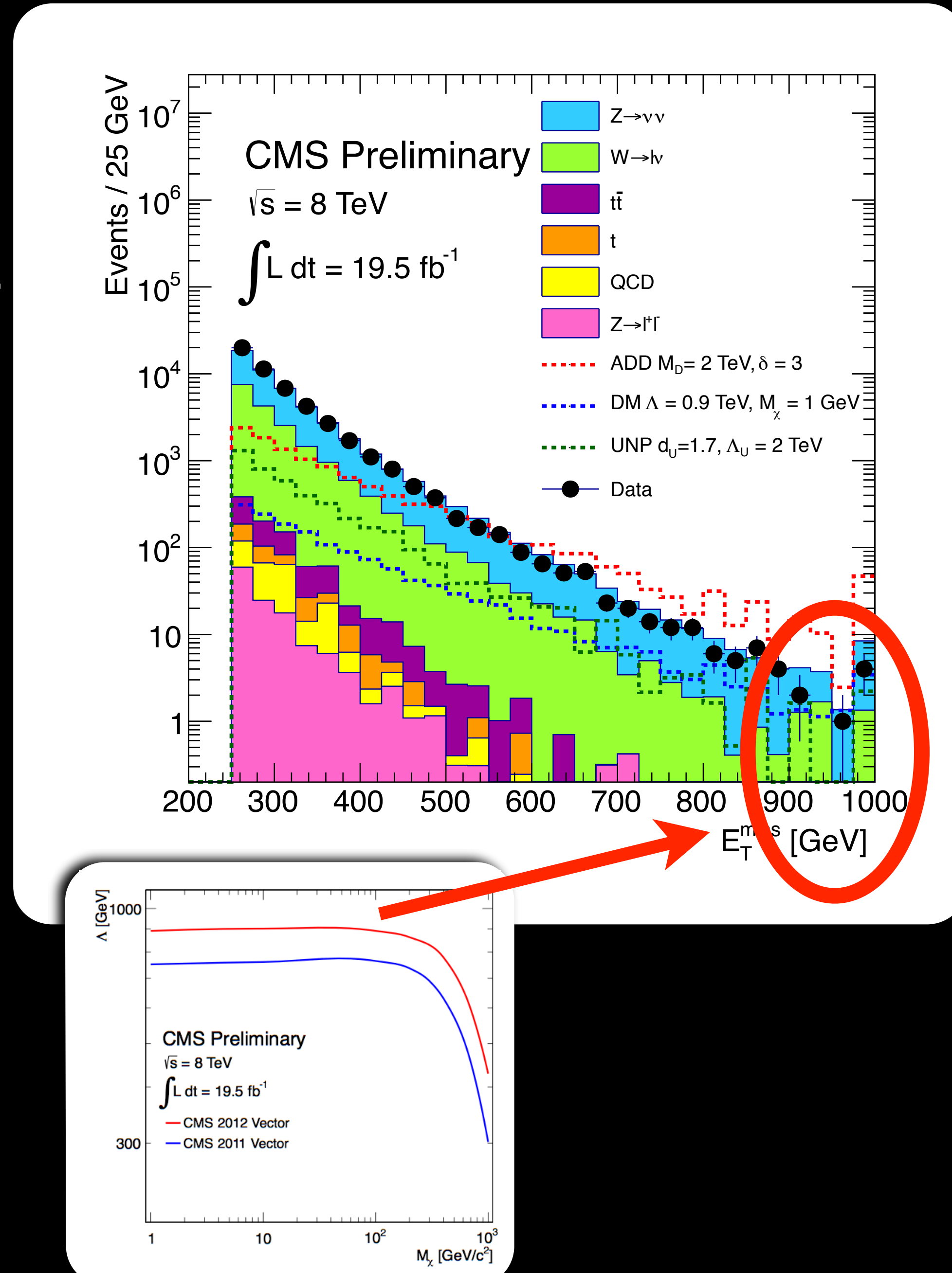
EFT : MC Tools



Haisch, Kahlhoefer, Re 1310.4491 & JHEP

How Effective a Theory?

- We should worry a little bit about whether what we are doing makes sense.
- The bounds on the scale of the contact interaction are ~ 1 TeV, and we know that LHC collisions are capable of producing higher energies.
- For the highest energy events, we are almost certainly using the wrong theory description.
- It is difficult to be quantitative about precisely where the EFT breaks down, because the energies probed by the LHC depend on the parton distribution functions. [The answer is time-dependent in that sense.]



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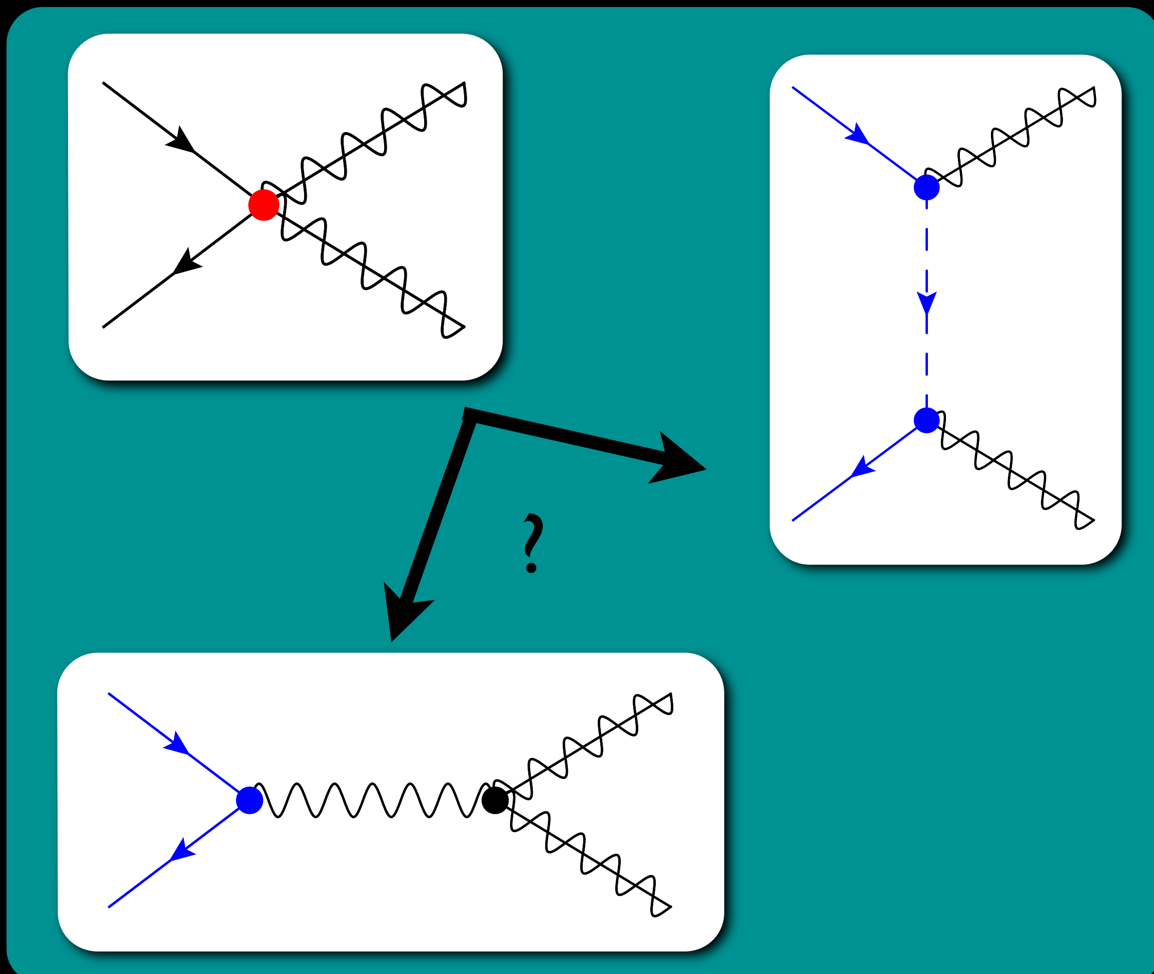


“t-channel” mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

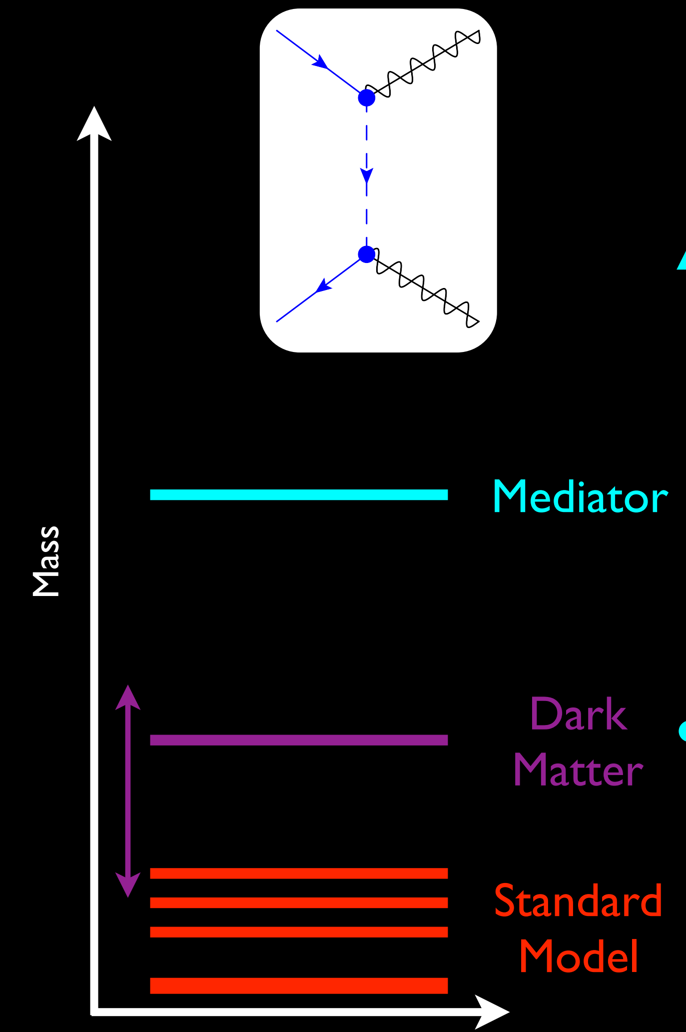
“s-channel” mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

Where things can go wrong, and by how much, depends on the actual UV-completion.

One way to understand this issue would be to try to explore the space of reasonable UV completions and see how things look.

Simplified Model

- Moving toward a more complete theory, we can also consider a model containing the dark matter as well as the most important particle mediating its interaction with the Standard Model.
- For example, if we are interesting in dark matter interacting with quarks, we can sketch a theory containing a colored scalar particle which mediates the interaction.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, etc.
- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

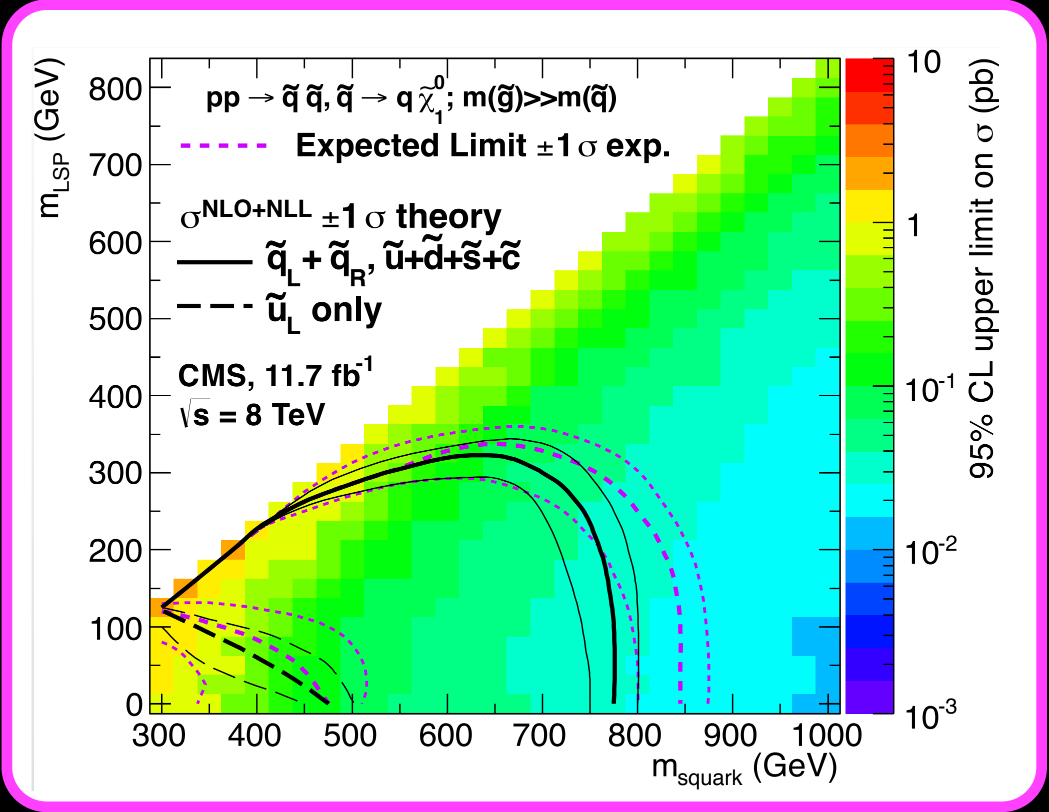


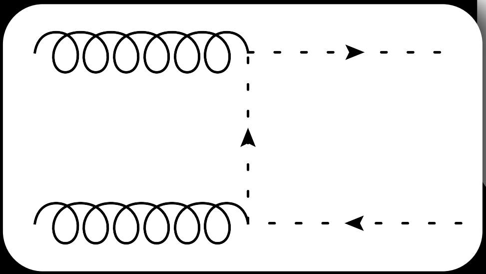
Lots of Recent Activity:

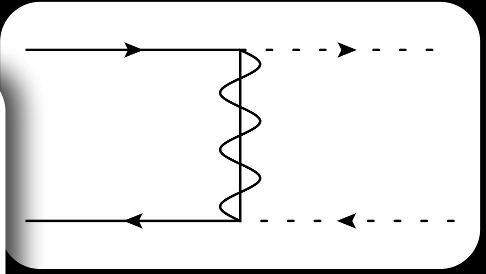
Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679
Papucci, Vichi, Zurek 1402.2285
+ follow ups.

$\tilde{u}_R$ Model

- To start with, consider a theory where a Dirac DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force (QCD; mostly from initial gluons) or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.
- This is effectively a simplified model the collaborations already consider in searching for squark-like particles.





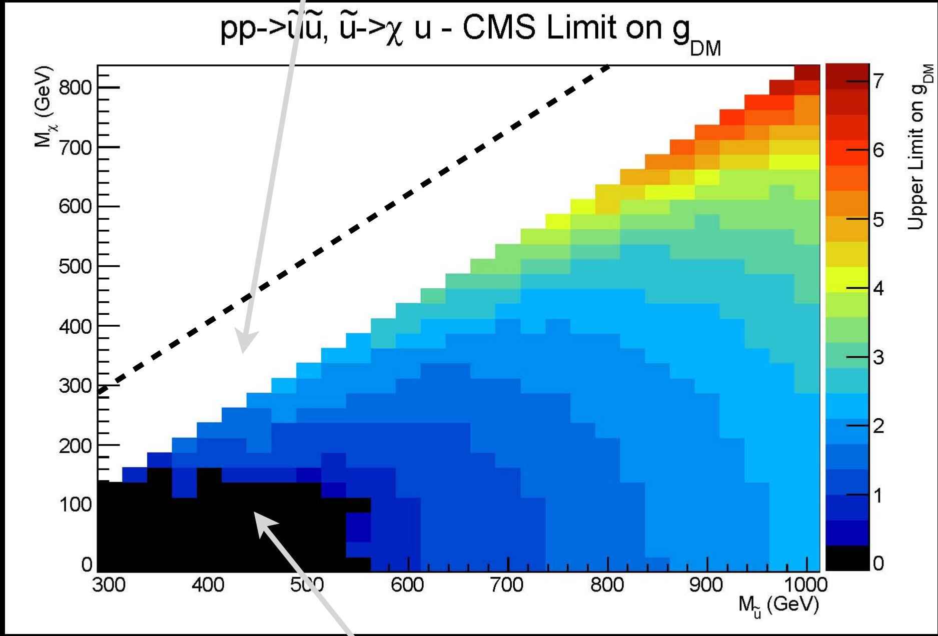


$\tilde{u}_R$ Model

- In order to avoid strong flavor constraints, we implement minimal flavor violation by promoting the colored mediator to a flavor triplet.
- MFV would suggest that the first two generations have almost equal couplings, but is more agnostic about the coupling of the top quark to its mediator.
- Similarly, the masses of the first two generation mediators should be close to degenerate, and there is more freedom for the top-mediator.
- 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.

Weak bounds in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



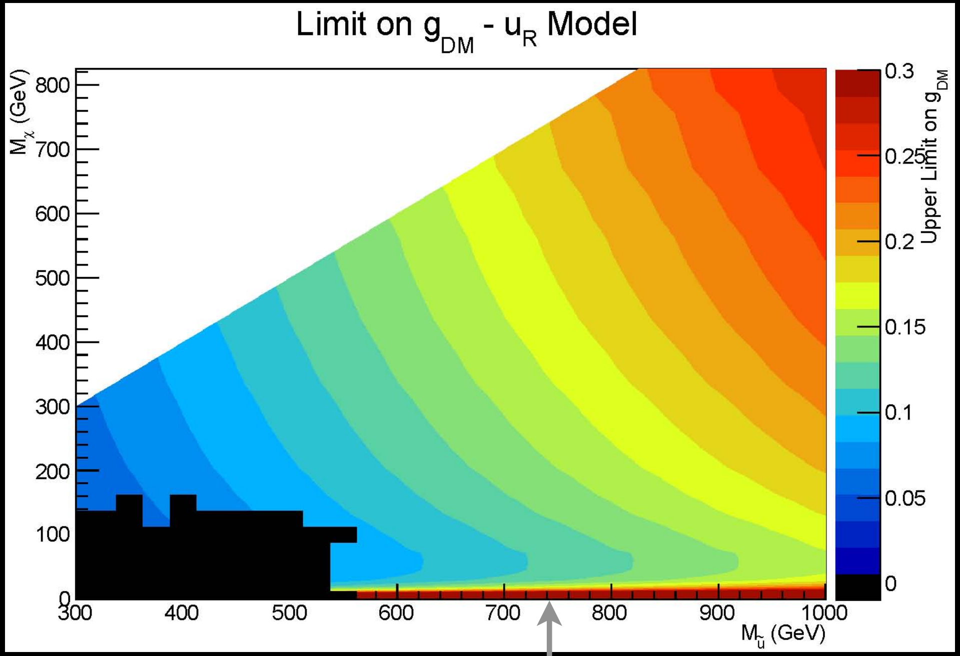
QCD production saturates the CMS limits, resulting in no allowed value of g.

All mediator masses and couplings assumed equal.

$\tilde{u}_R$ Model

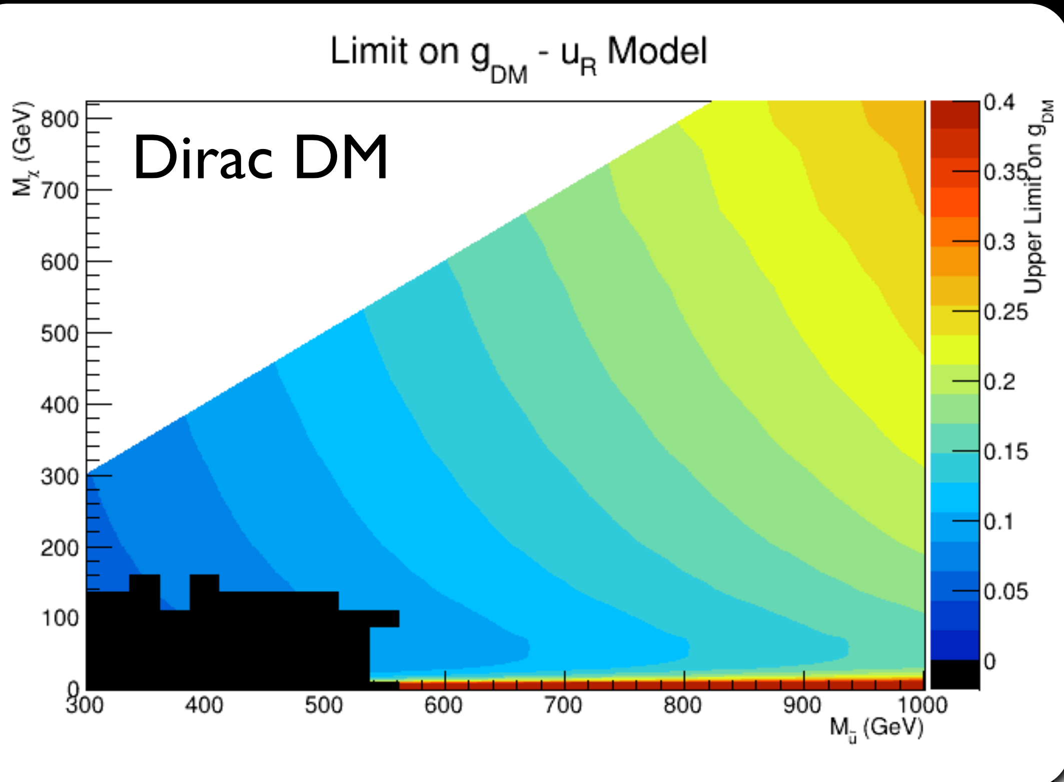
DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

- 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 LUX has recently improved these bounds by roughly a factor of two for dark matter masses around 100 GeV).
- Elastic scattering does not rule out any parameter space, but it does impose much stricter constraints on the coupling in the regions the LHC left as allowed.



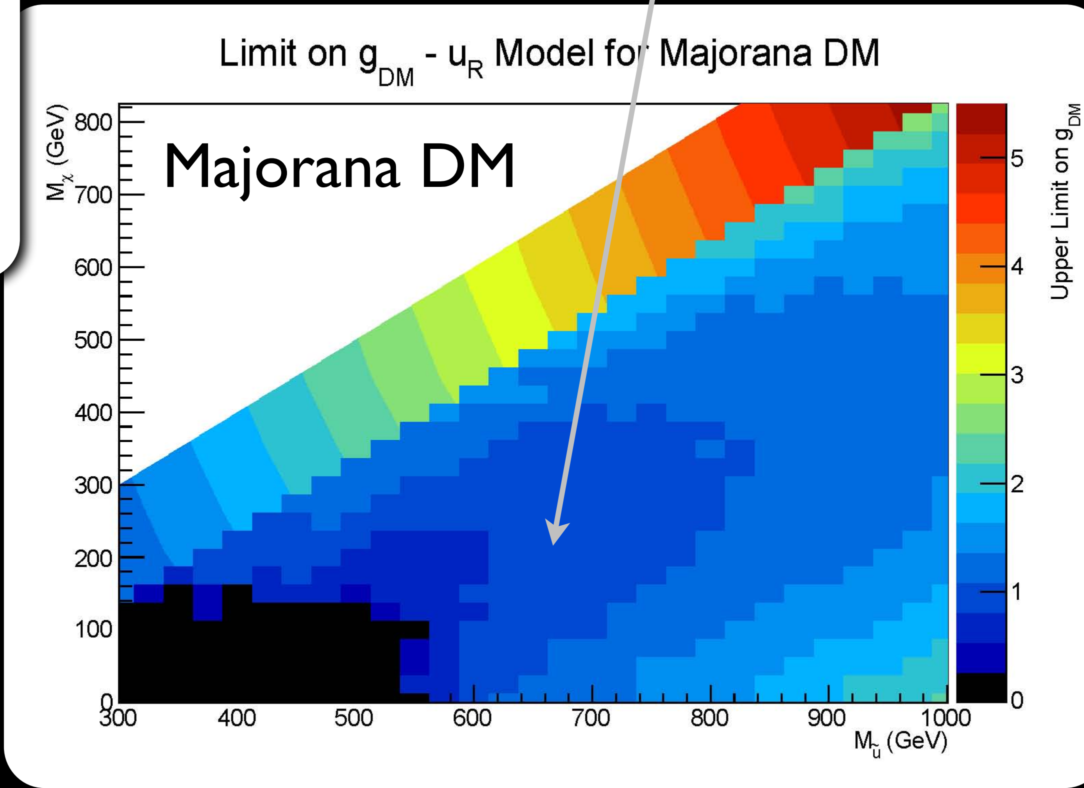
Traditional direct detection searches peter out for masses below about 10 GeV.

$\tilde{u}_R$ Model: Results



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

Collider bounds tend to dominate for Majorana DM at tree level.



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: Results

DiFranzo, Nagao, Rajaraman, TMPT
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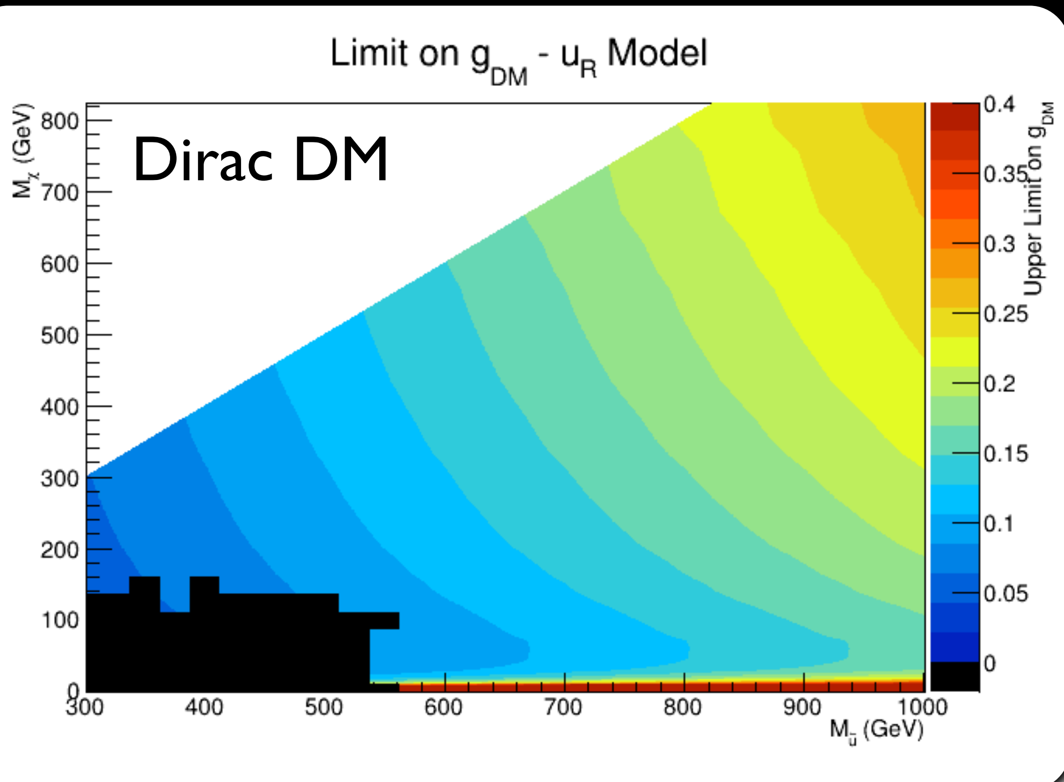

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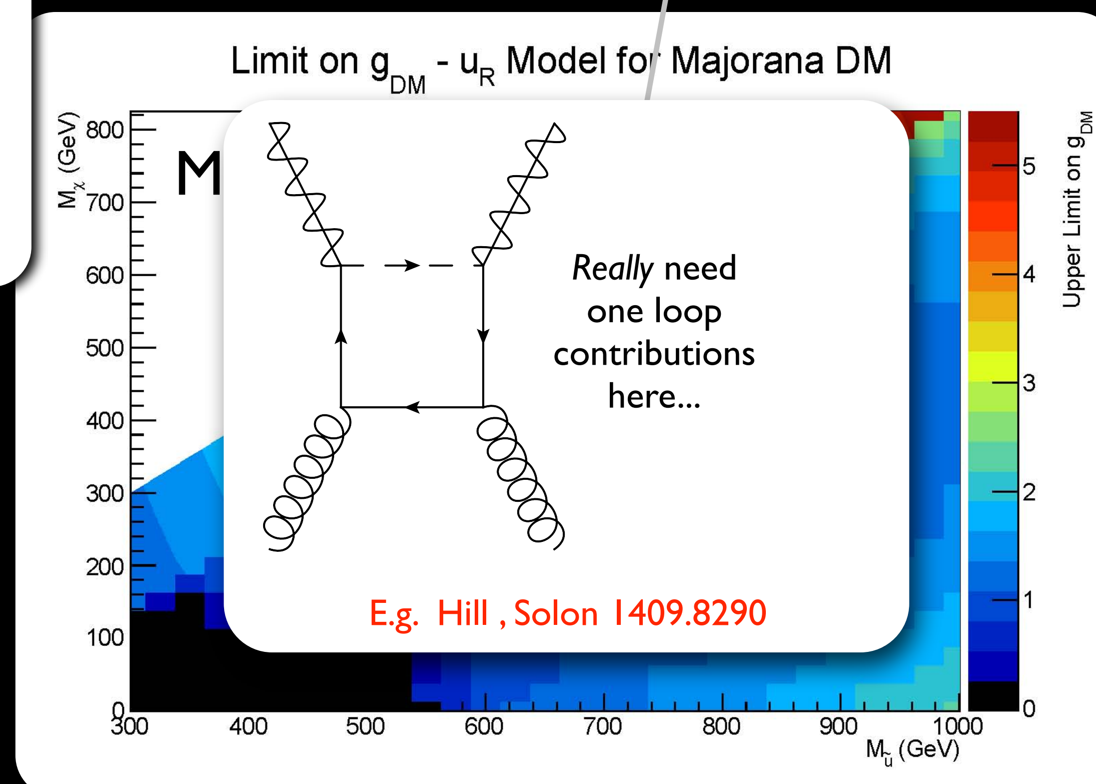

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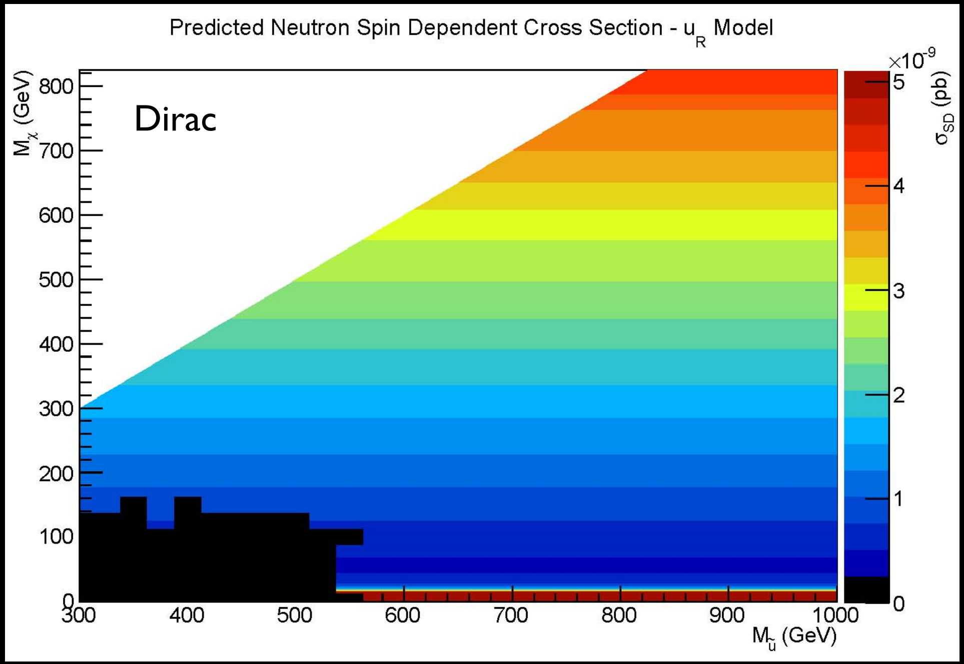
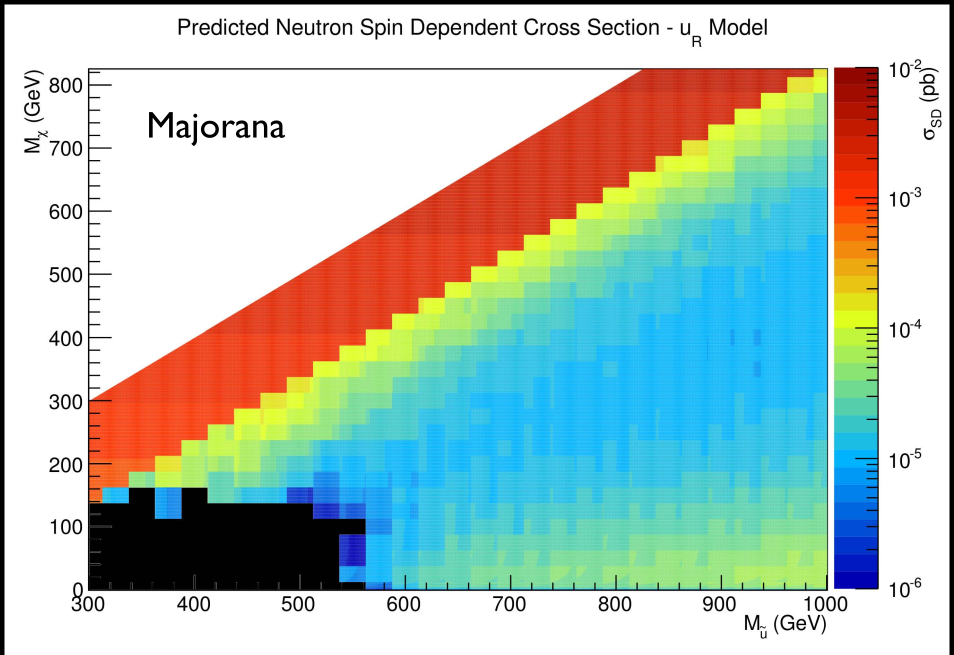
$\tilde{u}_R$ Model: Forecasts

- 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 the LHC constraints and Xenon-100 in this simplified model.
- Again, Dirac versus Majorana dark matter look very different from one another!

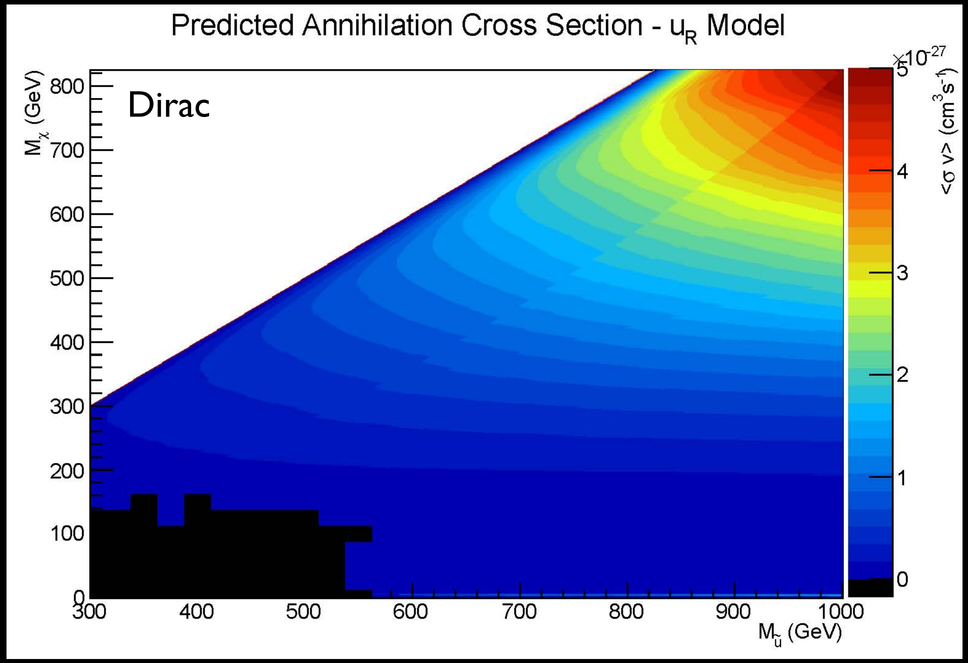


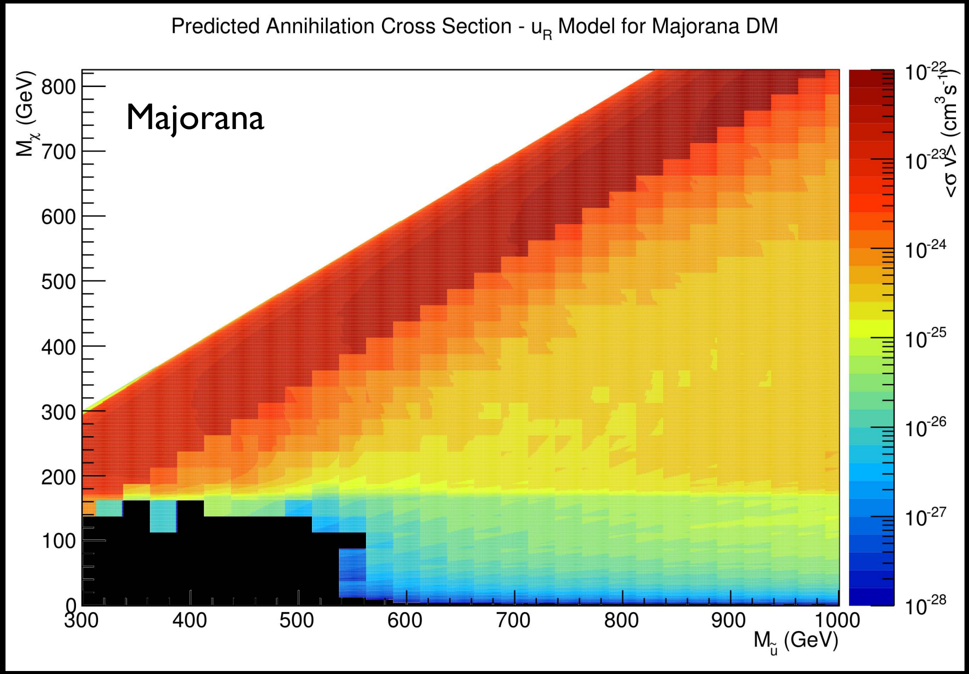


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

$\tilde{u}_R$ 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. 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.

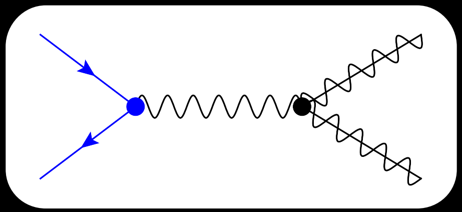


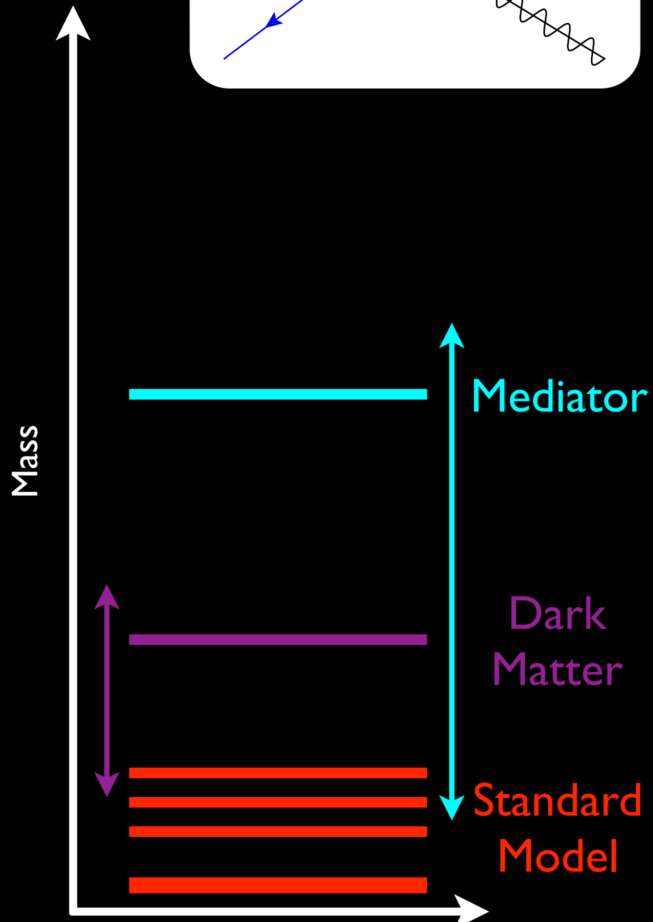


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

S-Channel : Vector

- Vector models have more parameters consistent with MFV.
- uR, dR, qL, eR, lL all have family-universal but distinct charges, as does H.
  - We would like to be able to write down the SM Yukawa interactions.
  - Quarks need not have universal couplings.
- There could be kinetic mixing with $U(1)_Y$.
- There is a dark Higgs sector. It may not be very important for LHC phenomenology.
- Gauge anomalies must cancel, which also may not be very important for LHC phenomenology.



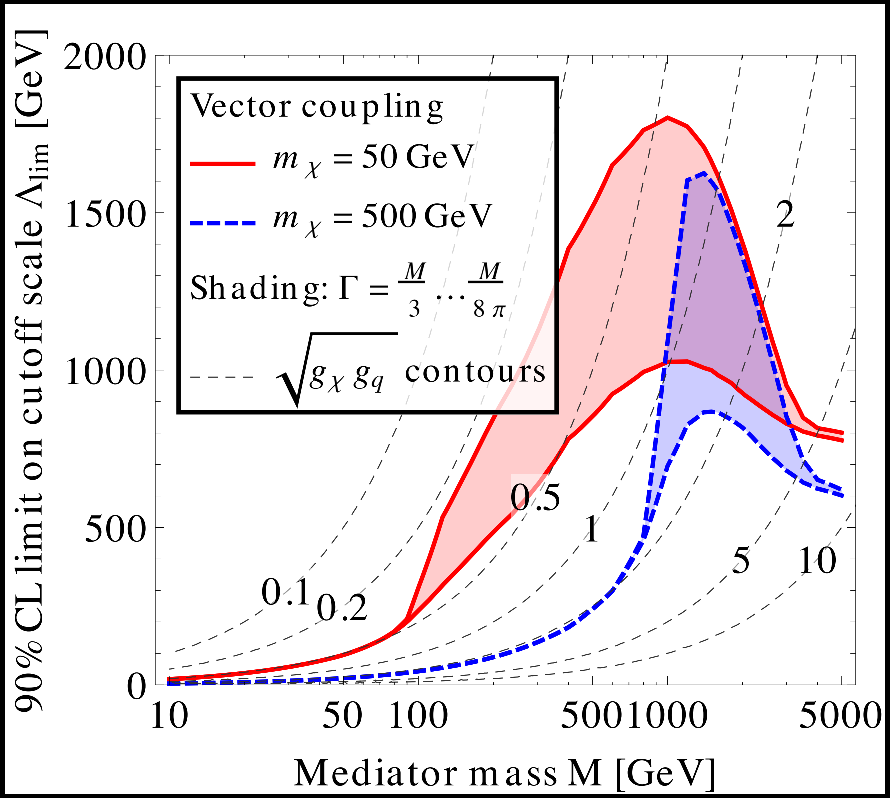


Parameters: $\{M_{\rm DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H, \eta\}$ + ...

How Effective a Theory?

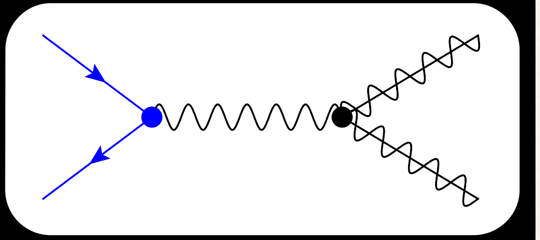
- There is a large literature asking how simplified models match up with the EFT, starting with some of the original EFT papers themselves.

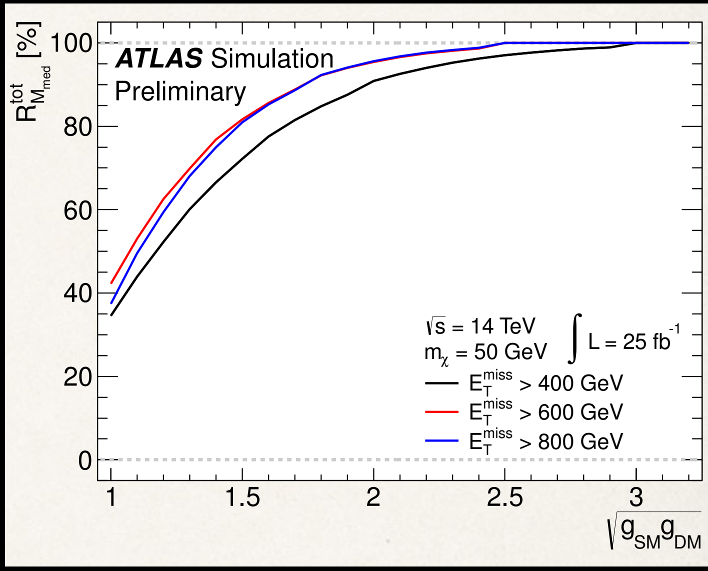
Fox, Harnik, Kopp, Tsai
1109.4398 & PRD



- Pushing the mass of the mediator higher for fixed EFT coupling corresponds to assuming the mediator is more strongly coupled.

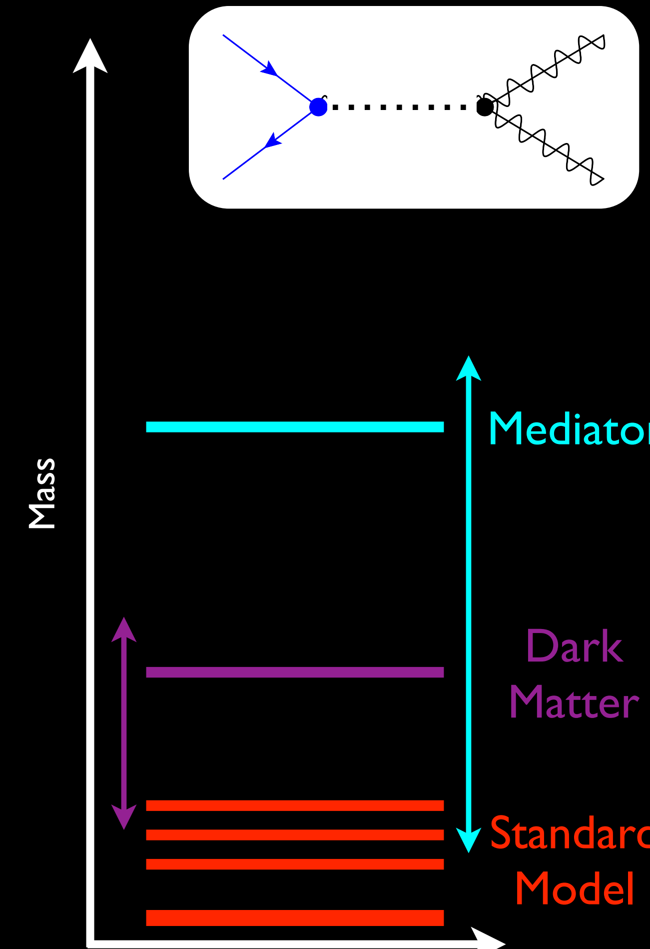
- Depending on how they are implemented, there are additional constraints from processes like dijet resonance searches, or Z'-like searches for dilepton resonances.





S-Channel : Scalar

- A singlet scalar could be real or complex.
- Scalar couplings are chirality flipping. The scalar mediator consistent with MFV couples proportionally to Yukawa couplings.
- In the SM, the only relevant parameters are the masses, and the degree of mixing with the SM Higgs through electroweak breaking.
- If the SM is extended to a two (or more) Higgs doublet model, the coupling to up-quarks, down-quarks, and/or leptons become de-correlated.
- Much like the Higgs itself, there can be important coupling to gluons induced at loop level.



Buckley, Feld, Goncalves 1410.6497
Harris, Khoze, Spannowsky, Williams 1411.0535
+ others

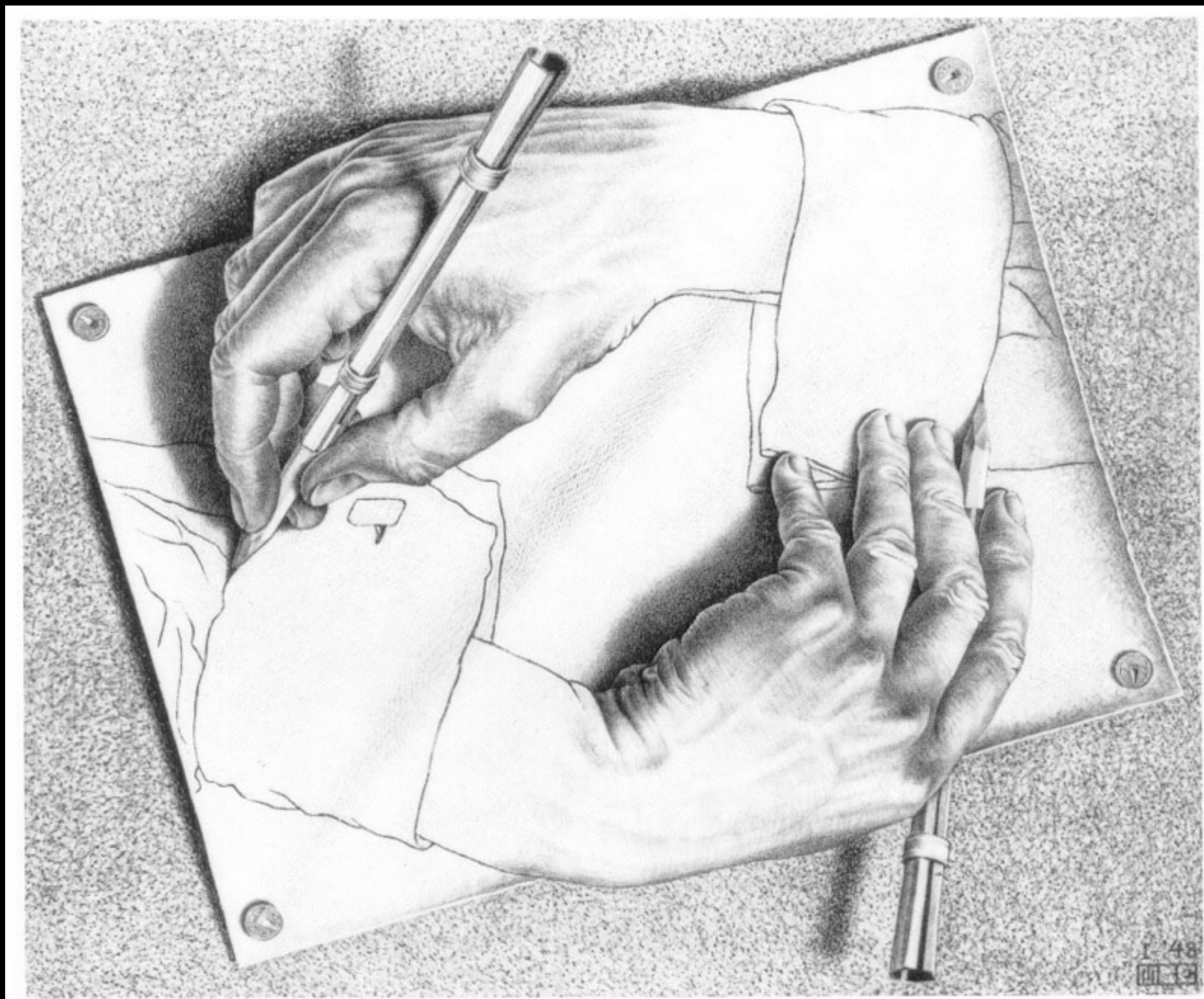
Simplified Models: MC Tools

- The vector and scalar s-channel mediators were included as part of the NLO work on contact interactions.
  - General vector case like a Z', also can be repurposed from Drell Yan.
- Colored scalars look fairly squark-like, and at least dumb k-factors are included in some analyses.
  - Would be good to have "clean" tools, free from distractions like gluinos and perhaps organized differently with regard to the scalar flavor.
  - Especially to give to experimentalists…
- Higher orders improvements are also needed to map to observables for direct and indirect searches for dark matter. The technology exists, but few general purpose tools…

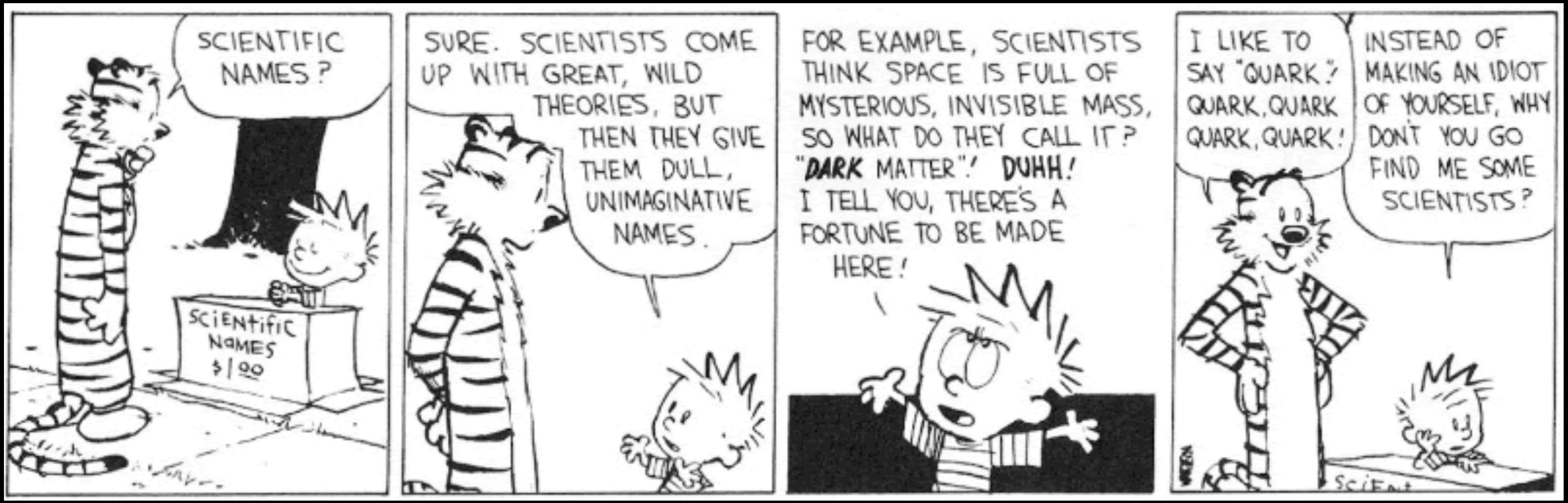
Outlook

- Colliders have important things to say about dark matter. But to understand what they are saying requires a theoretical structure.
- These could be complicated and complete like the MSSM, or simpler sketches of theories like simplified models or their EFT limits.
- I’ve discussed several levels and versions of sketches of theories.
- The tools needed to interpret the results are largely at tree level, moving toward NLO.
  - In many cases they lead to quantitative differences from tree level.
  - It would be helpful to have some general purpose, easy-to-use tools.
- Ultimately, experiment needs to bring theories of dark matter to life!

From Sketch to Life



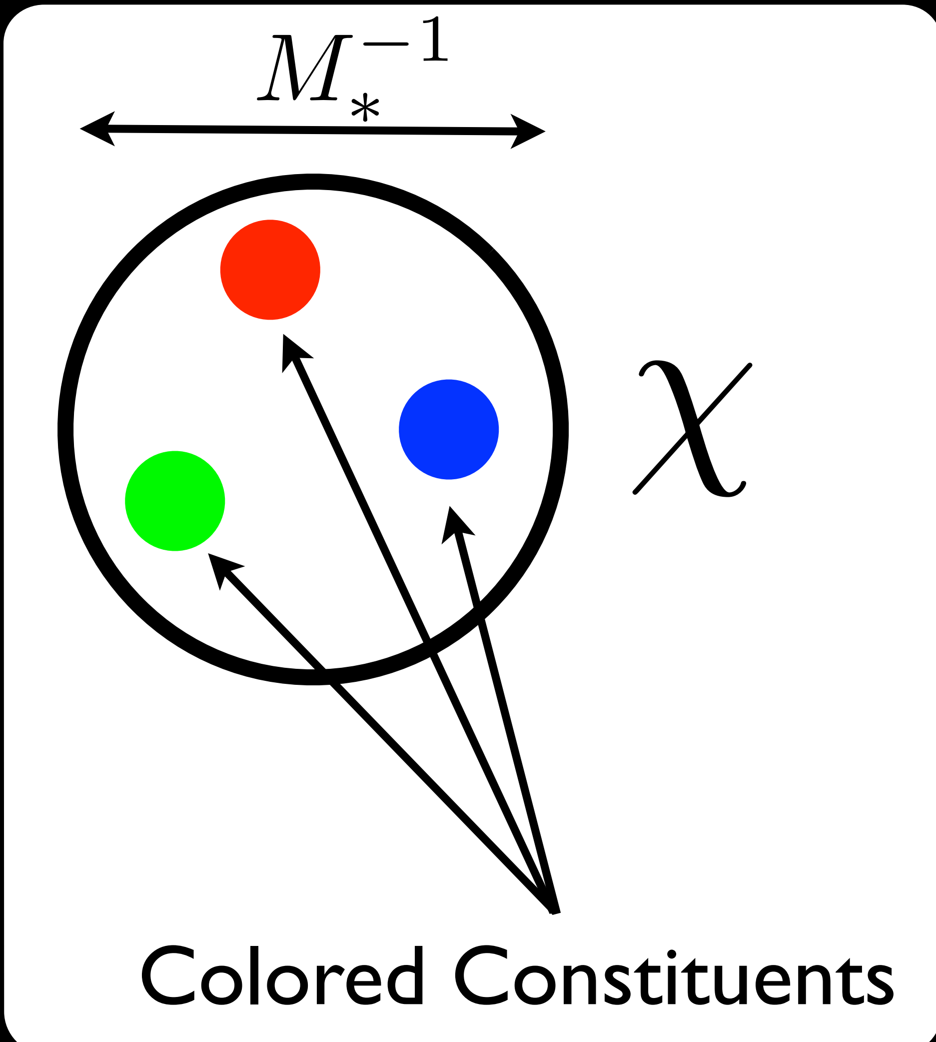
Sketches of ....



SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
I LIKE TO SAY "QUARK." QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?

Bonus Material

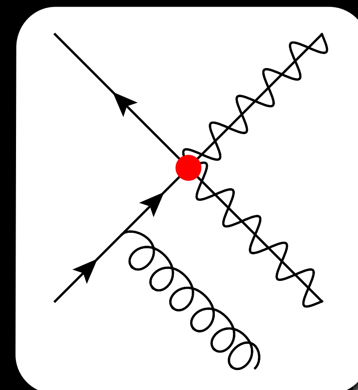
A Composite WIMP?

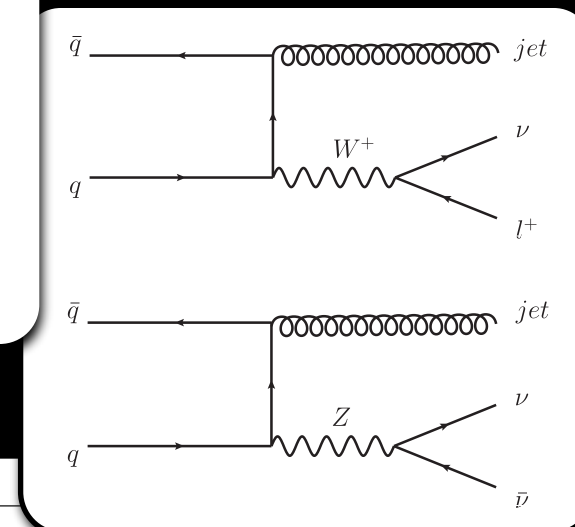


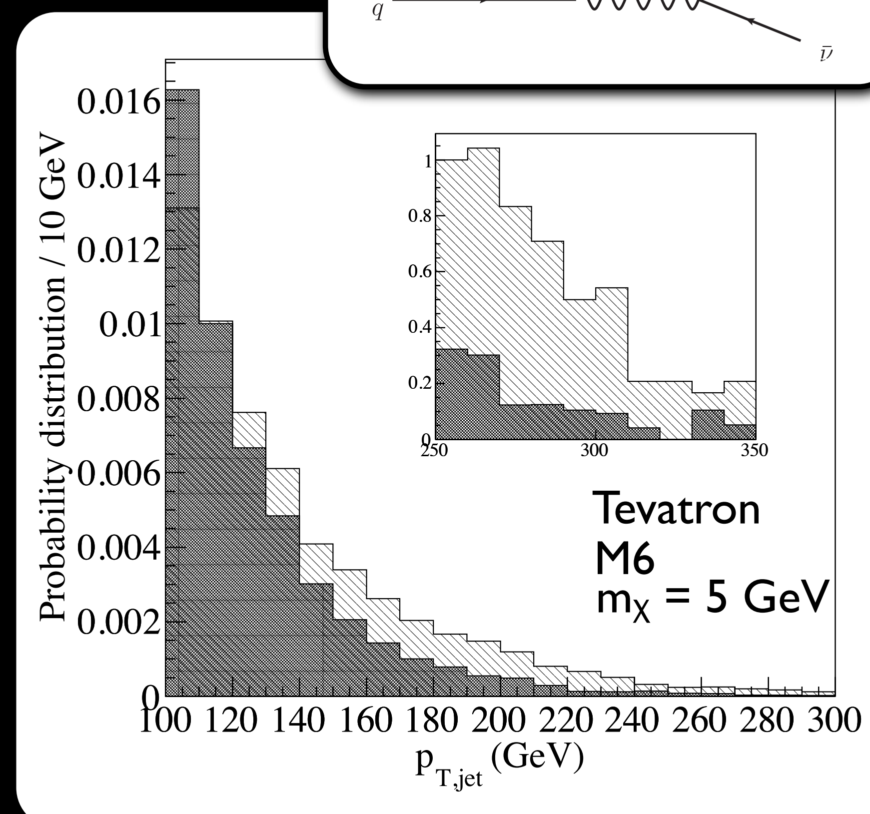
- Even when EFTs are only constraining rather strongly coupled theories, they say something interesting about some (perhaps exotic) visions of dark matter.
- If the dark matter is a (neutral) confined bound state (confined by some dark gauge force, say) of colored constituents, we should expect its coupling to quarks and gluons to be represented by higher dimensional operators whose strength is characterized by the new confinement scale.
- Bounds on EFTs constrain the dark confinement scale -- the "radius" of the dark matter.

Collider Searches

- At colliders, one searches for this type of theory by producing the dark matter directly.
- Since the detector needs something to trigger on, one looks for processes with additional final state particles, and infers the presence of dark matter based on the missing momentum it carries away from the interaction.
- There are the usual SM backgrounds from Z + jets, as well as fake backgrounds from QCD, etc.
- Contact interactions grow with energy, generically leading to a harder MET spectrum than the SM backgrounds.

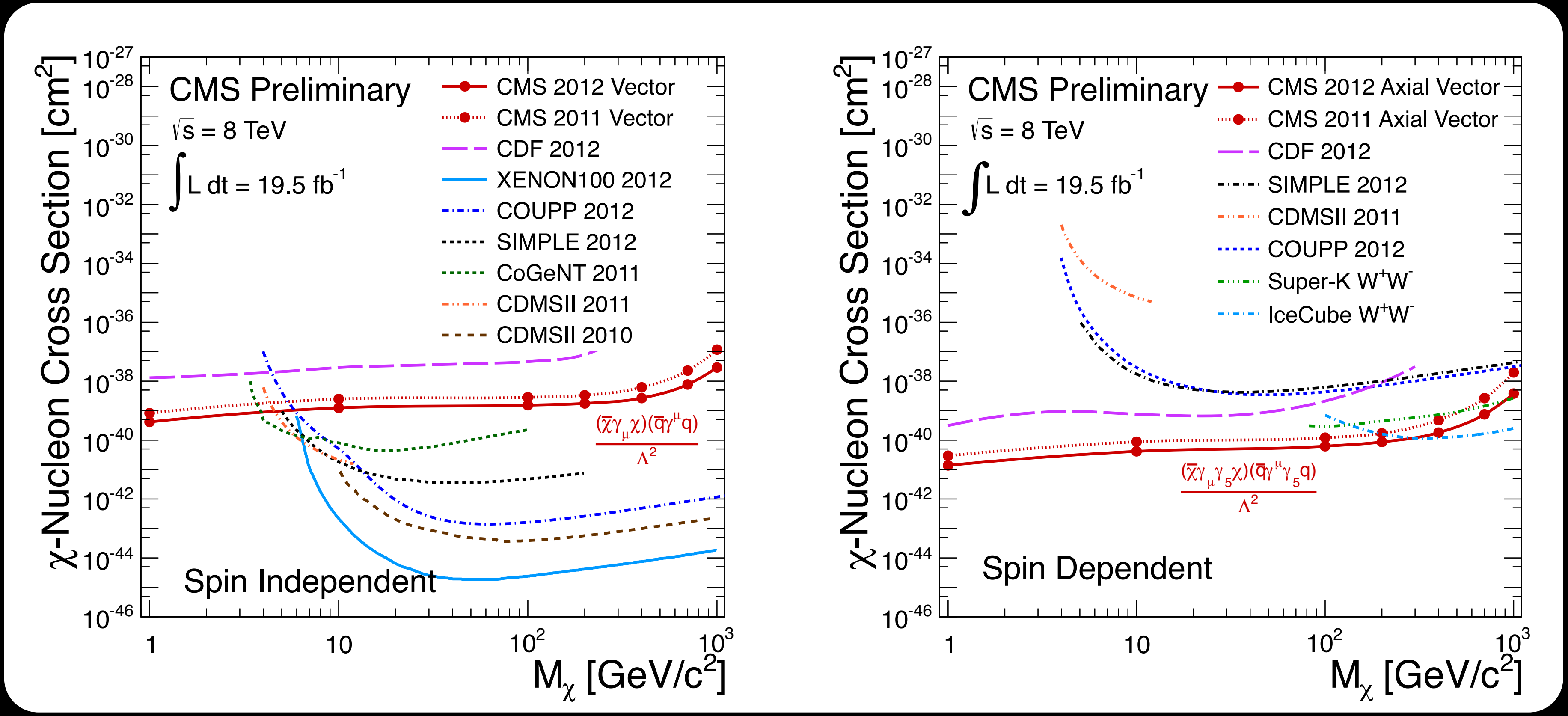






Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP

Translation to Elastic Scattering



- Colliders can help fill in a challenging region of low dark matter mass and spin-dependent interactions.
- Since they see individual partons, rather than the nucleus coherently, collider results offer a complementary perspective on DM interactions with hadrons.
- The translation assumes a heavy mediating particle (contact interaction).