Dark Matter: Models

Tim M.P. Tait

University of California, Irvine

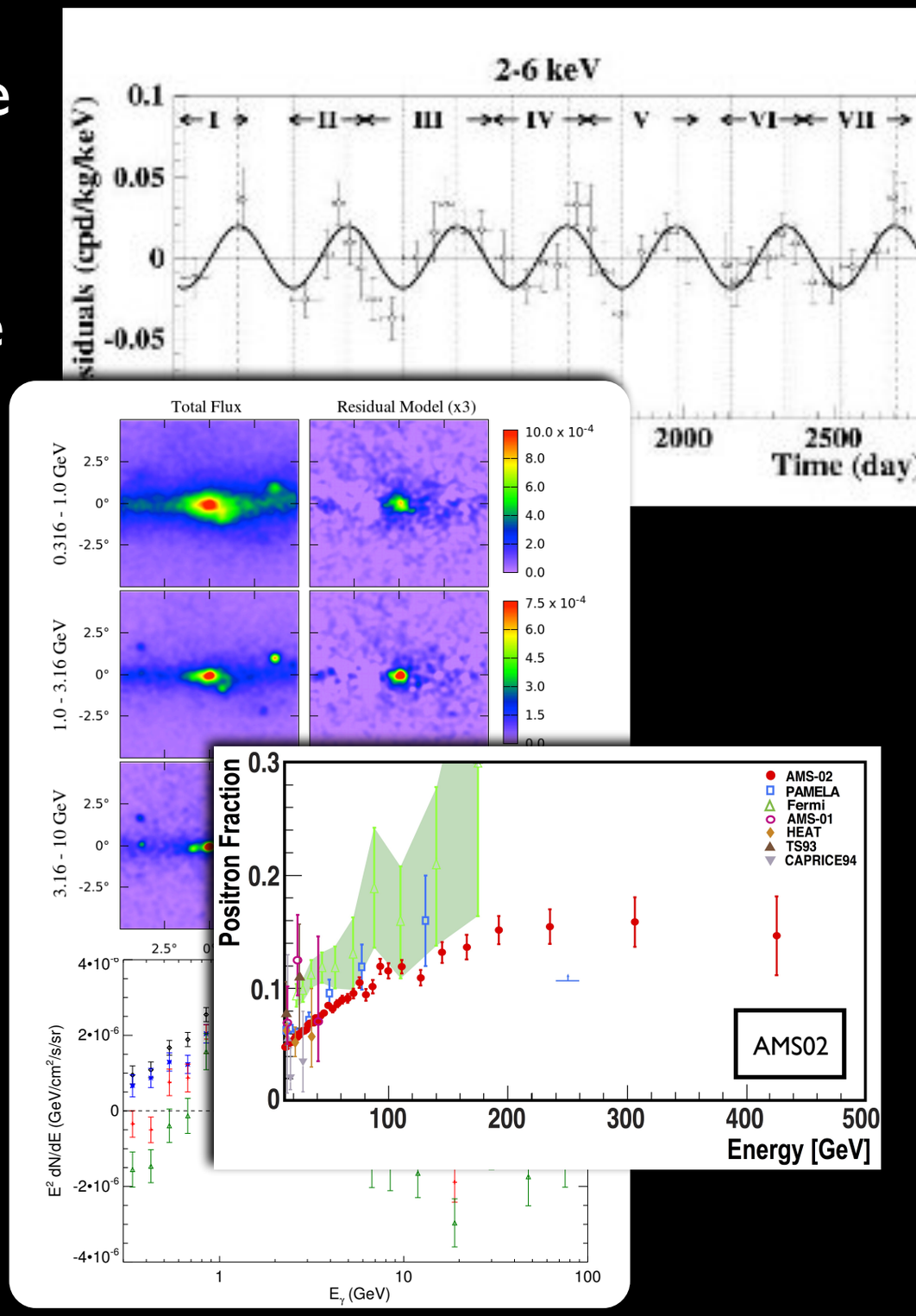
VSOP22
September 2-7, 2016

Outline

- "Designer" Dark Matter
  - Light Mediator Particles
  - Annihilation into Mediators
  - Effective Field Theories
  - Simplified Models

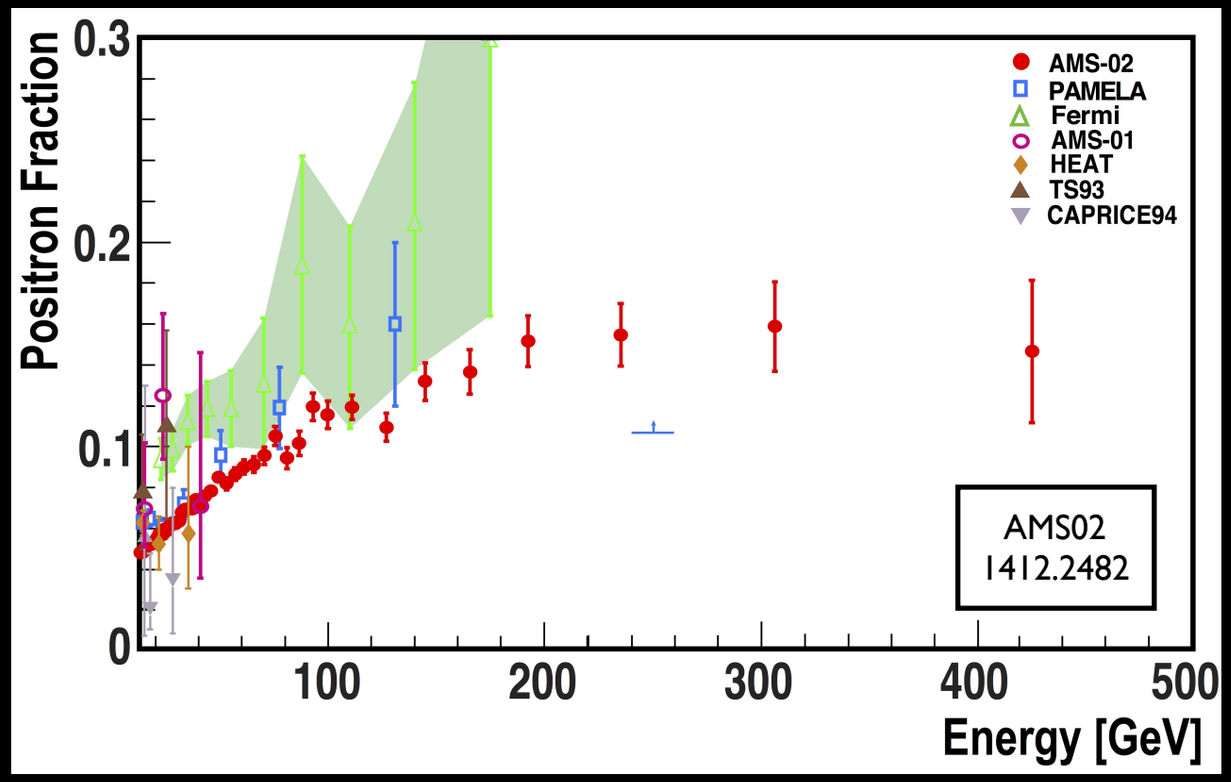
Designer Dark Matter

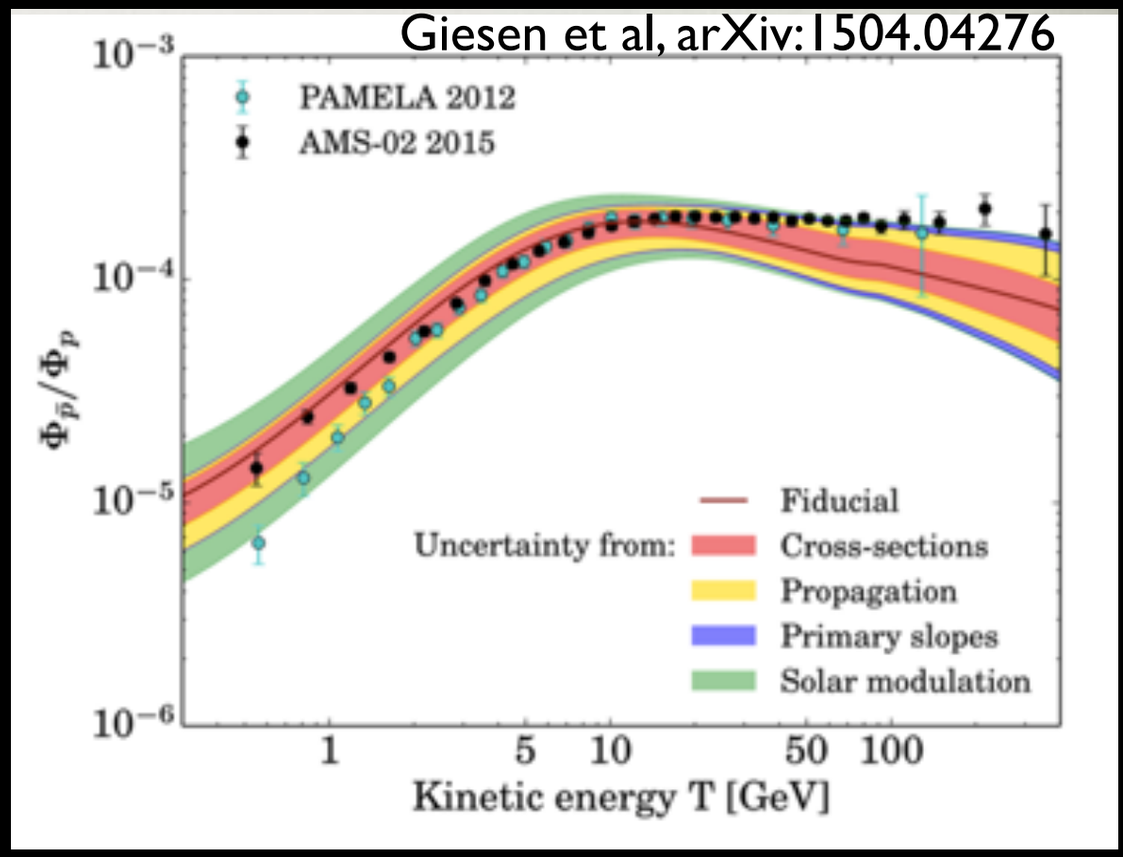
- As our searches for dark matter mature, we hope to eventually see a hint for a signal.
- There is no completely compelling evidence for an observation, but there are some tantalizing hints for things we don't understand. They might even be WIMPs!
- We can hope to eventually construct a theory of dark matter from observation.
- Even if the hints don't stand the test of time, they may inspire unconventional visions for how dark matter could work. They're still valuable to inspire new experiments and analyses.



Positron Fraction

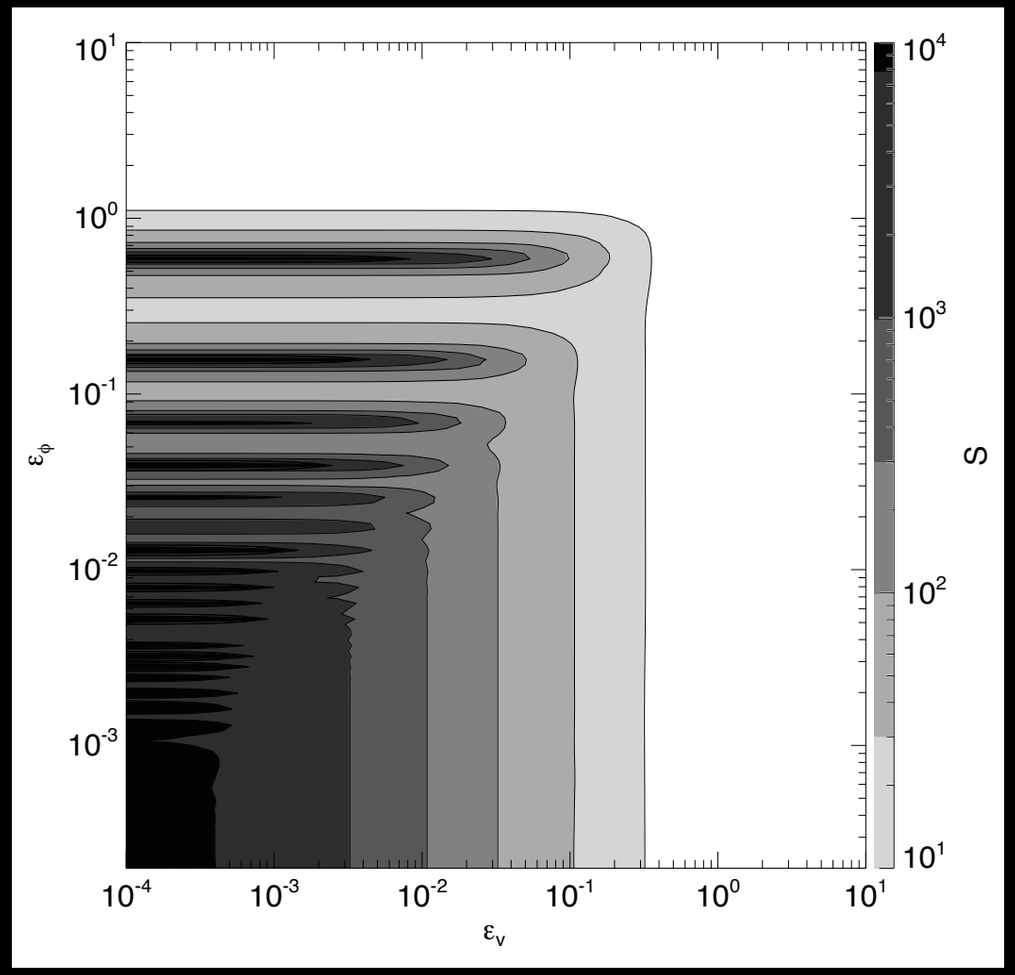
- Anti-matter is only rarely produced by astrophysical objects. An excess is a possible signature of dark matter annihilation.
- Somewhat mysteriously, the fraction of positrons increases with energy up to ~500 GeV as measured by AMS-02.
- This could be the output of a nearby pulsar, or it could be a signal of dark matter annihilation.
- If interpreted as dark matter, a cross section that is somewhat shockingly high compared to the thermal one would be required.
- Anti-proton measurements show no excess over expectations.





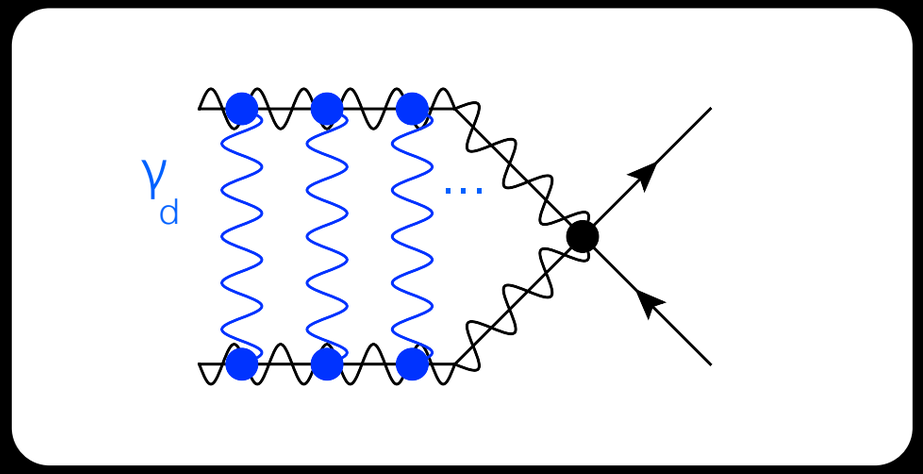
Light Mediators

- The PAMELA (and now Fermi and AMS02) positron excesses are an interesting signal that could be from dark matter annihilation/decay.
- A DM explanation runs into tension between the rate of annihilation required to produce a large enough signal compared with the relic density.
- A popular idea to reconcile the two is to introduce a light mediator (such as a dark photon) to invoke a Sommerfeld-like enhancement at small WIMP velocities.
- Summing up the effect of the mediator on the scattering can lead to a large enhancement factor compared to the leading order annihilation rate.



$$\epsilon_\phi \equiv \frac{m}{\alpha M} \qquad \epsilon_v \equiv \frac{v}{\alpha}$$

Cirelli, Kadastik, Raidal, Strumia 0809.2409
Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
...



Dark Photon

- An attractive idea which has received a lot of attention is to postulate that the new light force carrier is a "dark photon".
- The idea is that there is a new vector boson with a small mass (and thus a whole dark Higgs sector) under which dark matter is charged, but the SM is not:

$$\mathcal{L} = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}M_V^2 V^\mu V_\mu + i\overline{\chi}\left(\partial\!\!\!/ - ig\, V\!\!\!/\right)\chi + \epsilon V^{\mu\nu}B_{\mu\nu}$$

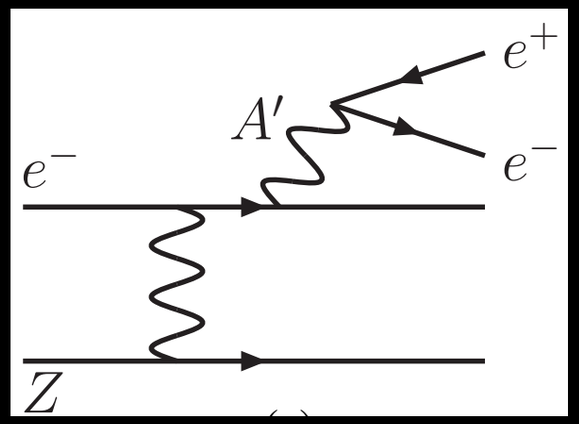
- The kinetic mixing with hyper charge changes the mass basis of the states such that the usual massless photon remains unchanged. However, the dark photon picks up a small coupling to the SM particles proportional to their electric charge times the kinetic mixing parameter ε:

$$g_{\rm eff} \sim \begin{cases} g & \chi \\ eQ_\psi\epsilon & \psi_{\rm SM} \end{cases}$$

- There is also some mixing with the Z, but for dark photon masses much less than the Z boson mass, this is extremely tiny and can usually be neglected.

A New Experimental Frontier!

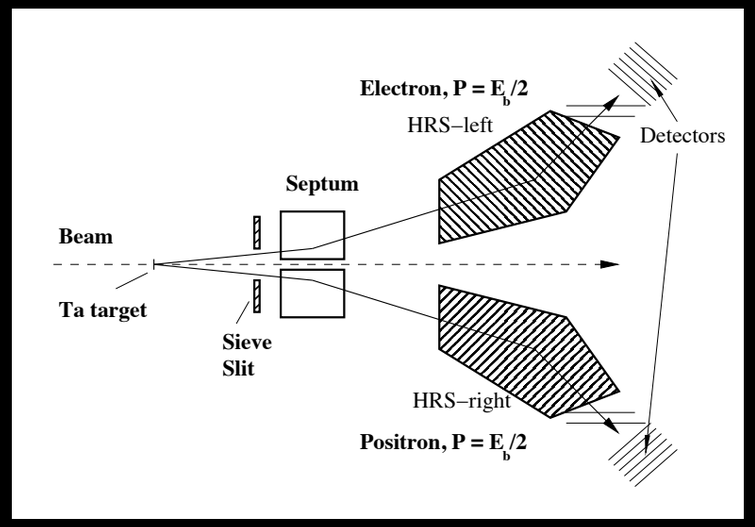
- Once people realized that light dark force carriers were interesting and under-explored, they began to devise experiments to search for them.



Abrahamyan et al, APEX 1108.2750

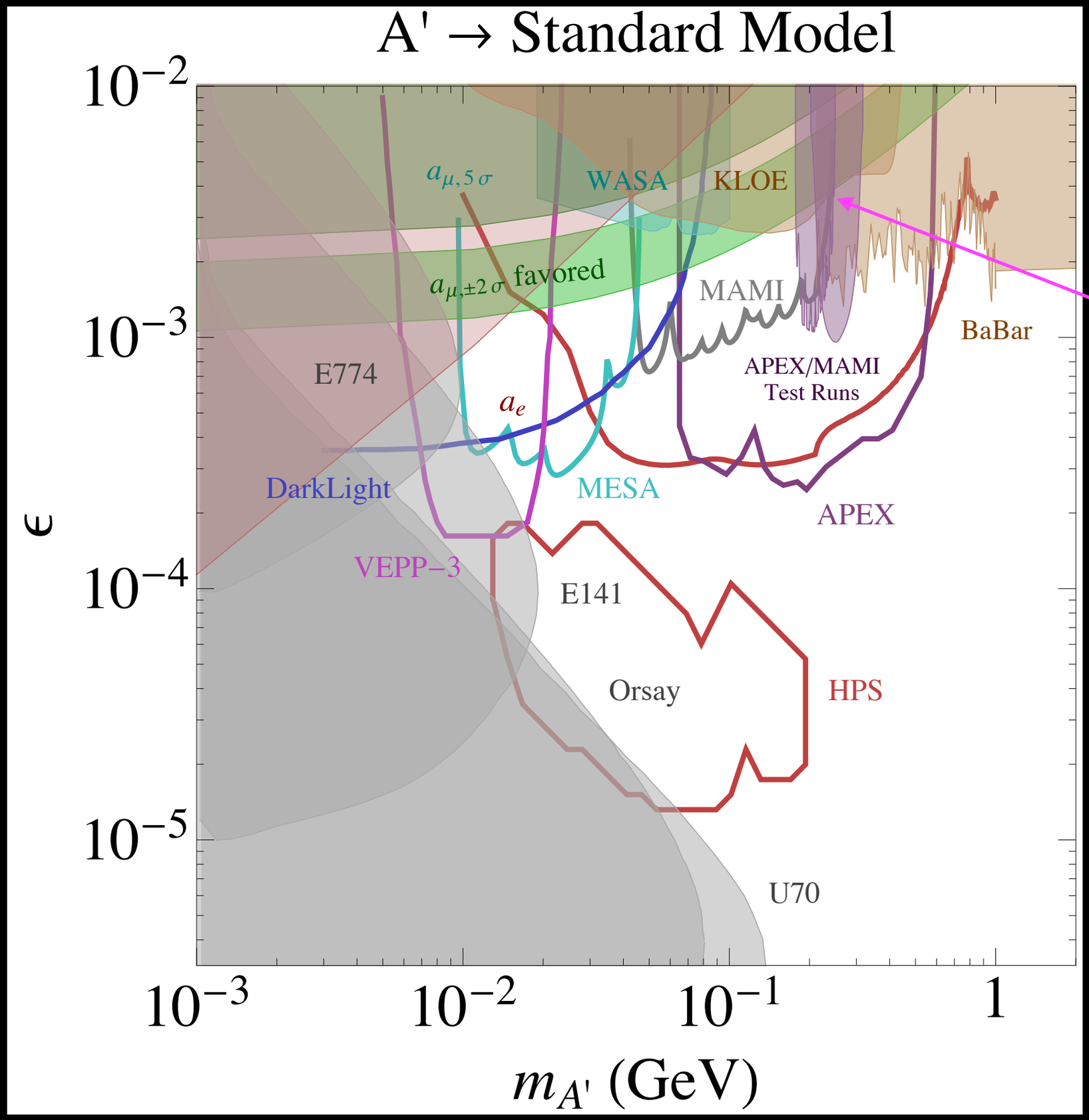
- Since the target parameter space has low masses and very weak couplings, often low energy, high luminosity facilities provide the best limits.

- High luminosity electron accelerators can produce the dark force carrier, which eventually decays into e+e- or in some cases the dark matter itself.



- There is now a whole family of experiments aimed at exploring different regions of mass / coupling.

Dark Photon Searches



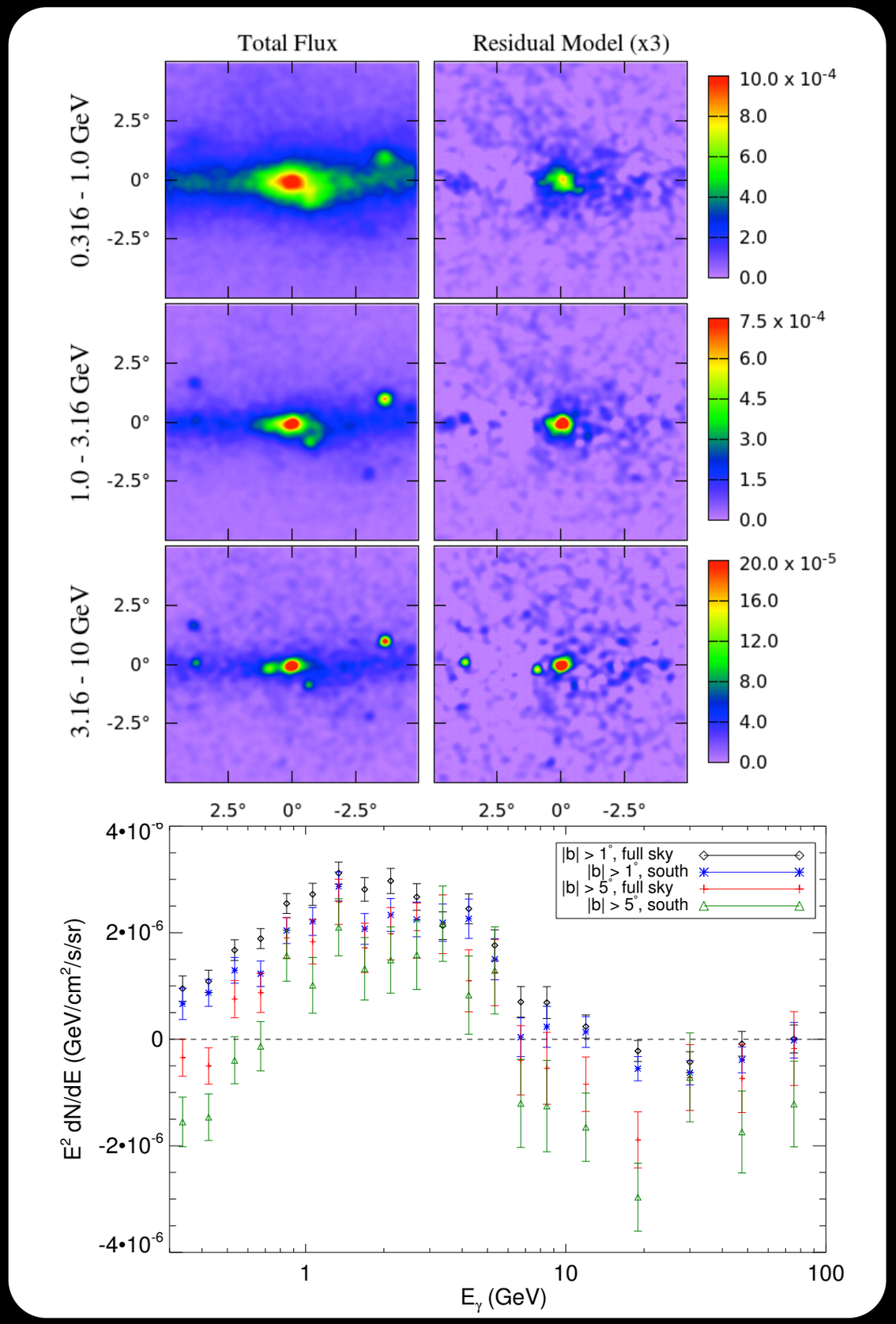
Test runs of APEX and MAMI already place new bounds on parameter space!

ε parameterizes the coupling, which is εeQ in "dark photon" models.

Snow mass Intensity Frontier Report 1401.6077

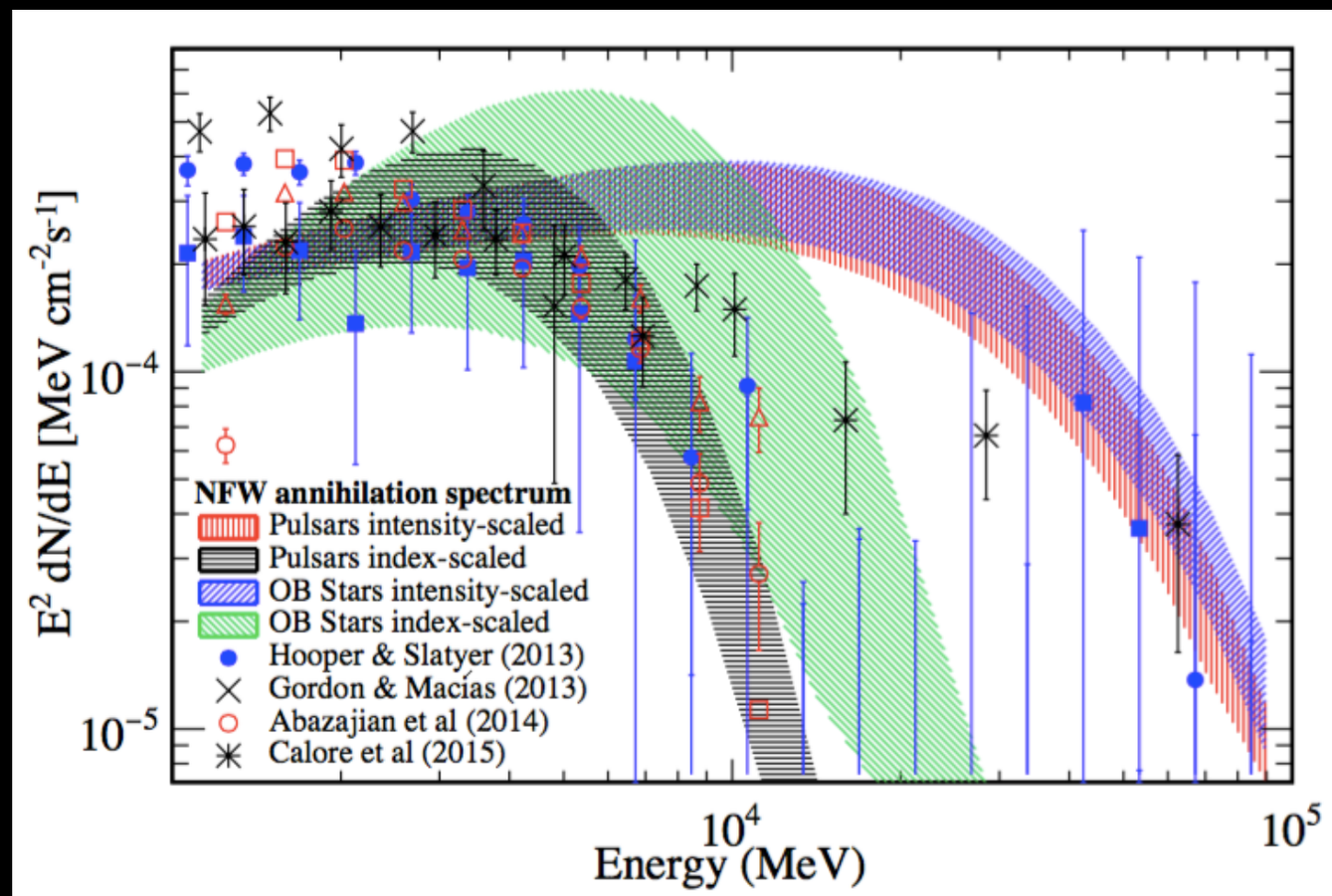
Gamma Ray GeV Excess

- A simplified model allows us to put a (possible) discovery into context and ask what a theory that could explain it should look like.
- As an example: there are hints for what could be a dark matter signal in the Fermi data from the galactic center.
- After subtracting models of the diffuse gamma ray emission, known point sources, etc, an excess remains with a distribution peaking around a few GeV, consistent with the expectations of a 40 GeV dark matter particle annihilating into bottom quarks.
- This signal is currently the most credible hint for particle dark matter we have!



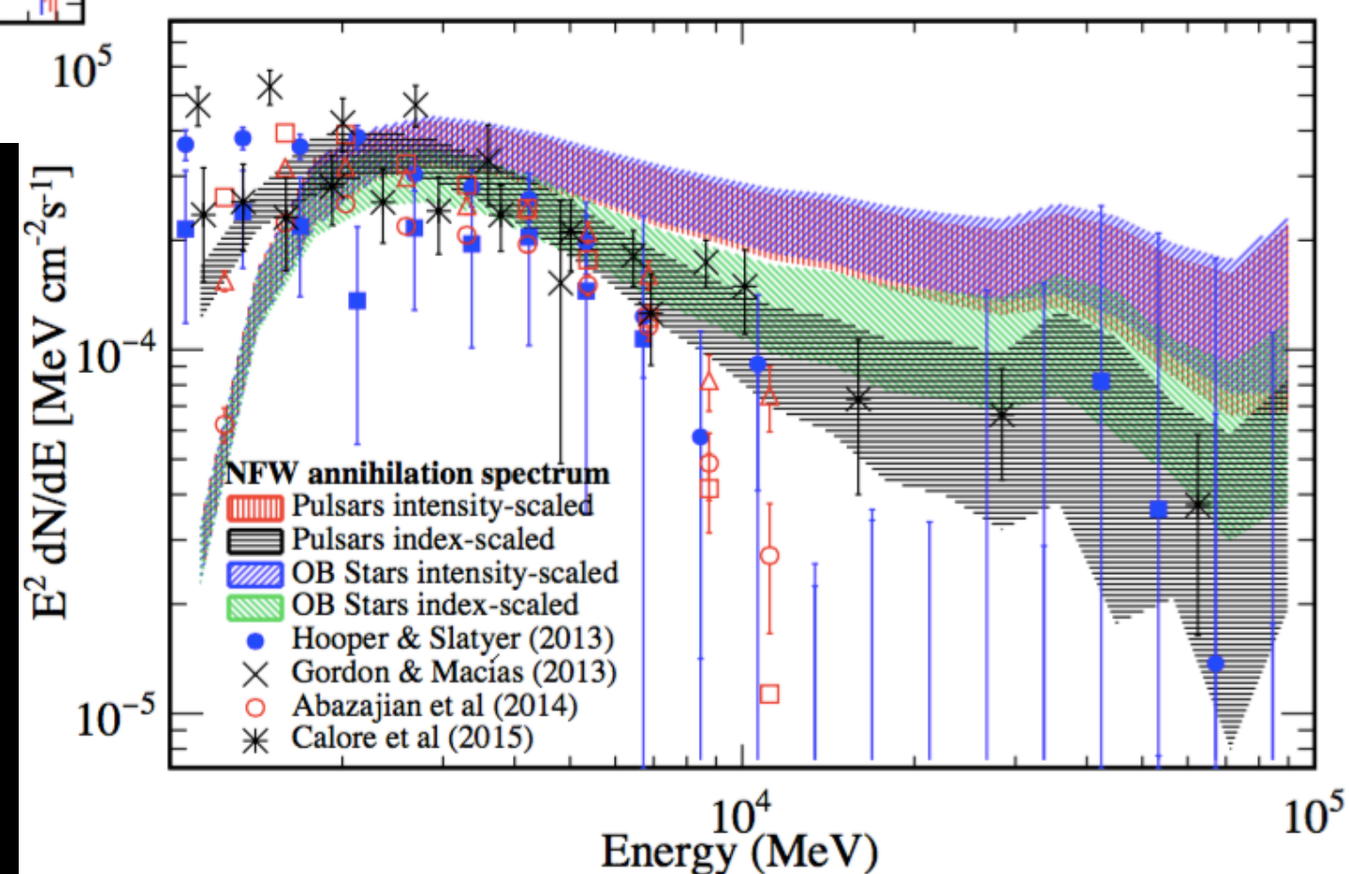
Hooper, Goodenough, 2009 + 2010
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703
see also: Abazajian, Canac, Horiuchi, Kaplinghat; Macias, Gordon

Fermi LAT Analysis



Masses favored in the 10s-100s of GeV range

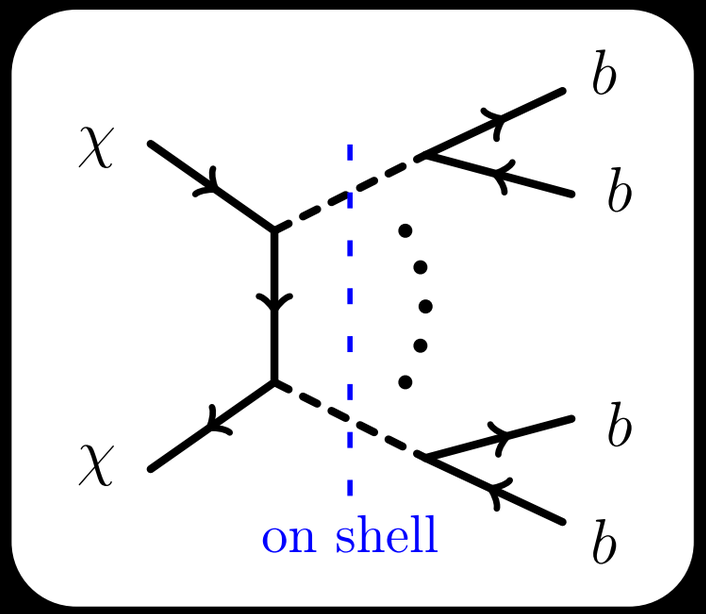
Fermi LAT collab. arXiv:1511.02938 & ApJ



Preferred cross sections turn out to be around the thermal one or a bit smaller.

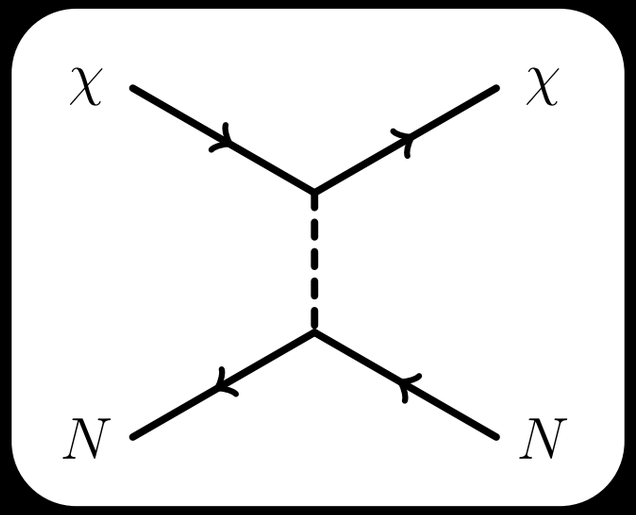
Annihilation into Mediators

- The signal is large enough that something is going to need to suppress scattering with heavy nuclei.
- For example, the particle communicating between dark matter and the SM (the "mediator") could be a pseudoscalar, leading to spin-dependent and velocity suppressed coupling to nuclei.



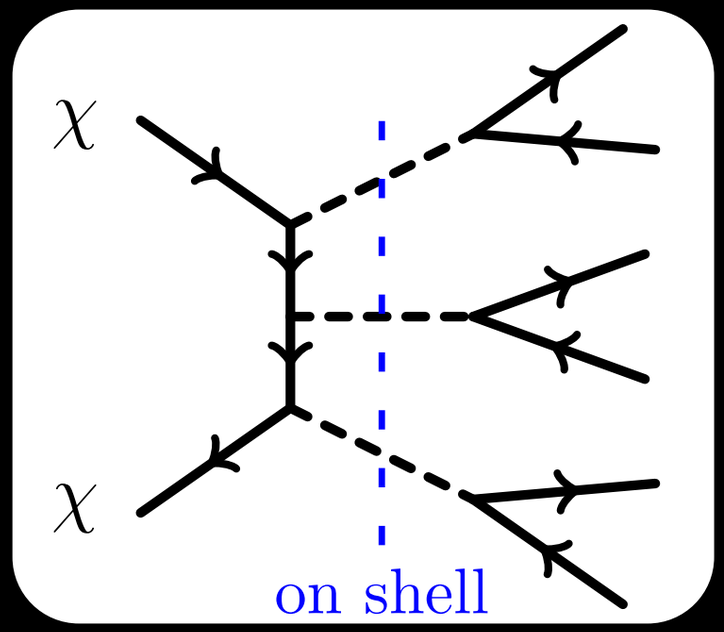
$\sigma_{\rm ann} \propto \epsilon^2 g^2$

- Another avenue is to have the dark matter annihilate into the mediators themselves. The rate for this to happen is fixed by the coupling of dark matter to the mediator, g.
- The mediator can have a MUCH smaller coupling to the SM particles, ε. It has kpc distances to travel before it needs to decay into what we observe!
- This is a generic way of getting an indirect signal while suppressing direct detection and collider constraints.



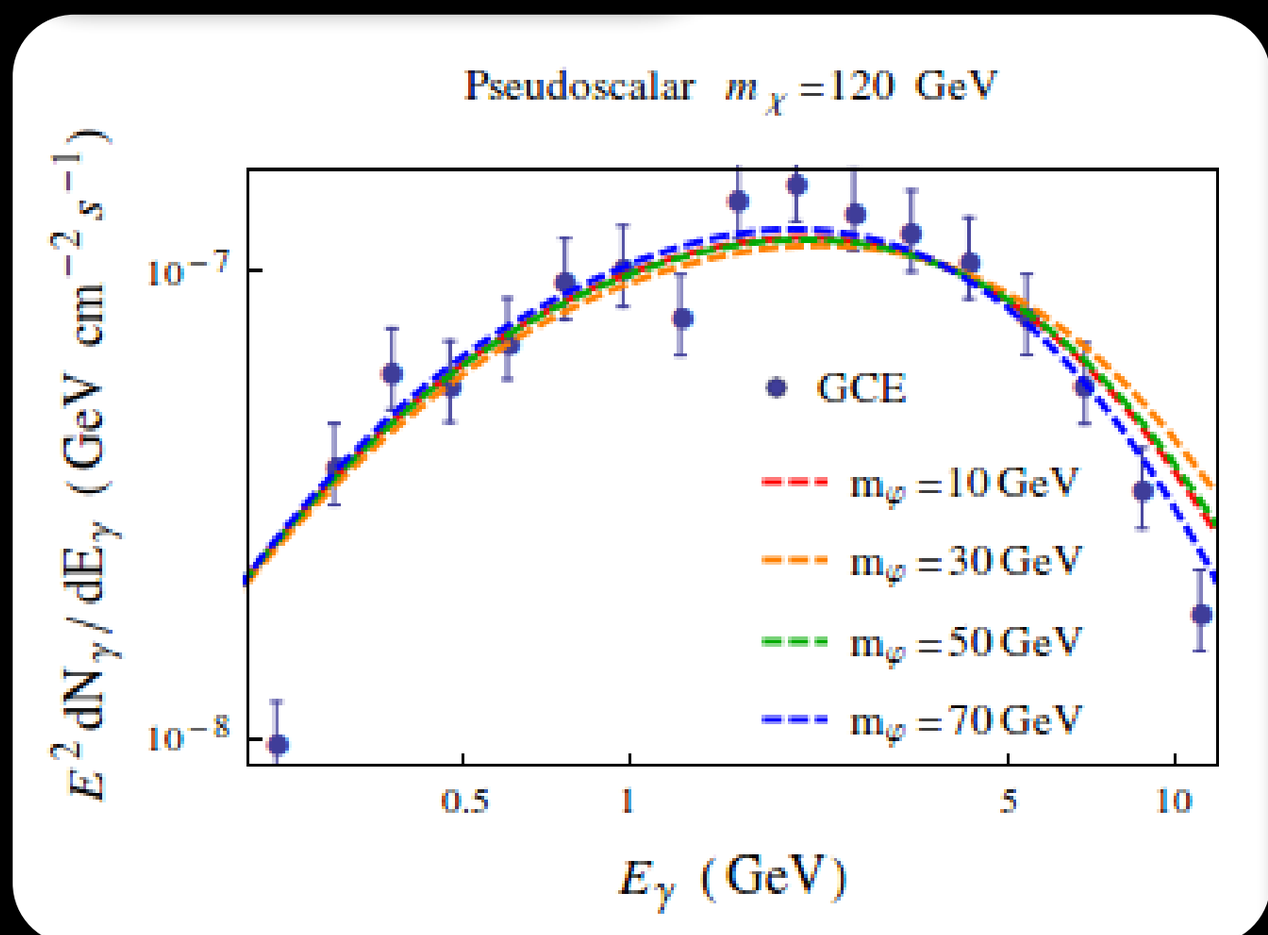
$\sigma_{\rm direct} \propto \epsilon^2 g^2$

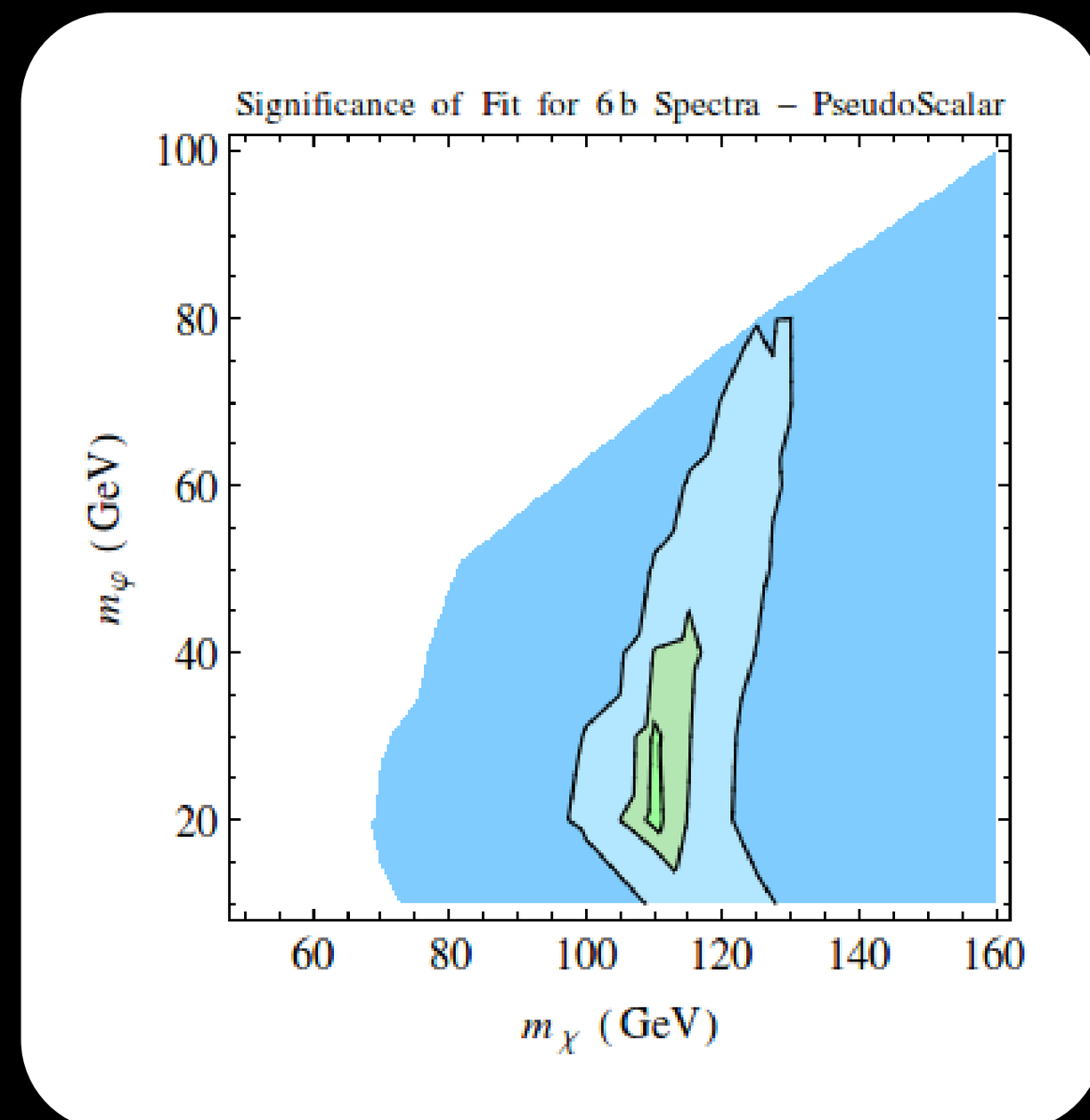
Annihilation into Mediators



Annihilation into three pseudo-scalars is not velocity-suppressed! These can then decay into a b bbar pair, whose kinematics are determined by the mass of the dark matter and the mass of the mediator itself. For appropriately chosen masses, We can fit the galactic center signal!

Abdullah, DiFranzo, Rajaraman, TMPT, Tanedo, Wijangco 1404.6528 & PRD





Recap: Designer DM

- For a given signal which might be telling us about dark matter, we can construct theories with specific properties to try to engineer something that looks like what we want.

- A few tricks I discussed here include:

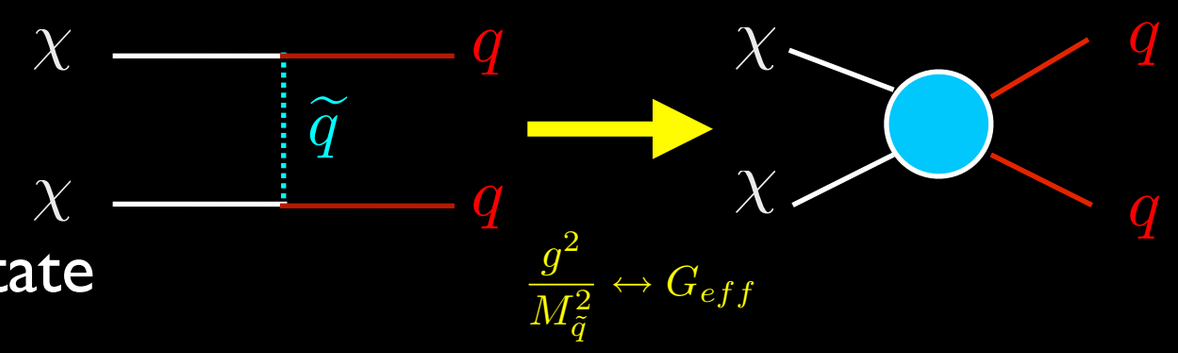
  - Sommerfeld-like enhancement: a light force carrier can enhance the rate for dark matter to annihilate when it is at low relative velocities.

  - Annihilation into mediators: Dark matter can escape from bounds from direct or collider searches if it annihilates into mediators, which themselves are very very weakly coupled to the Standard Model.

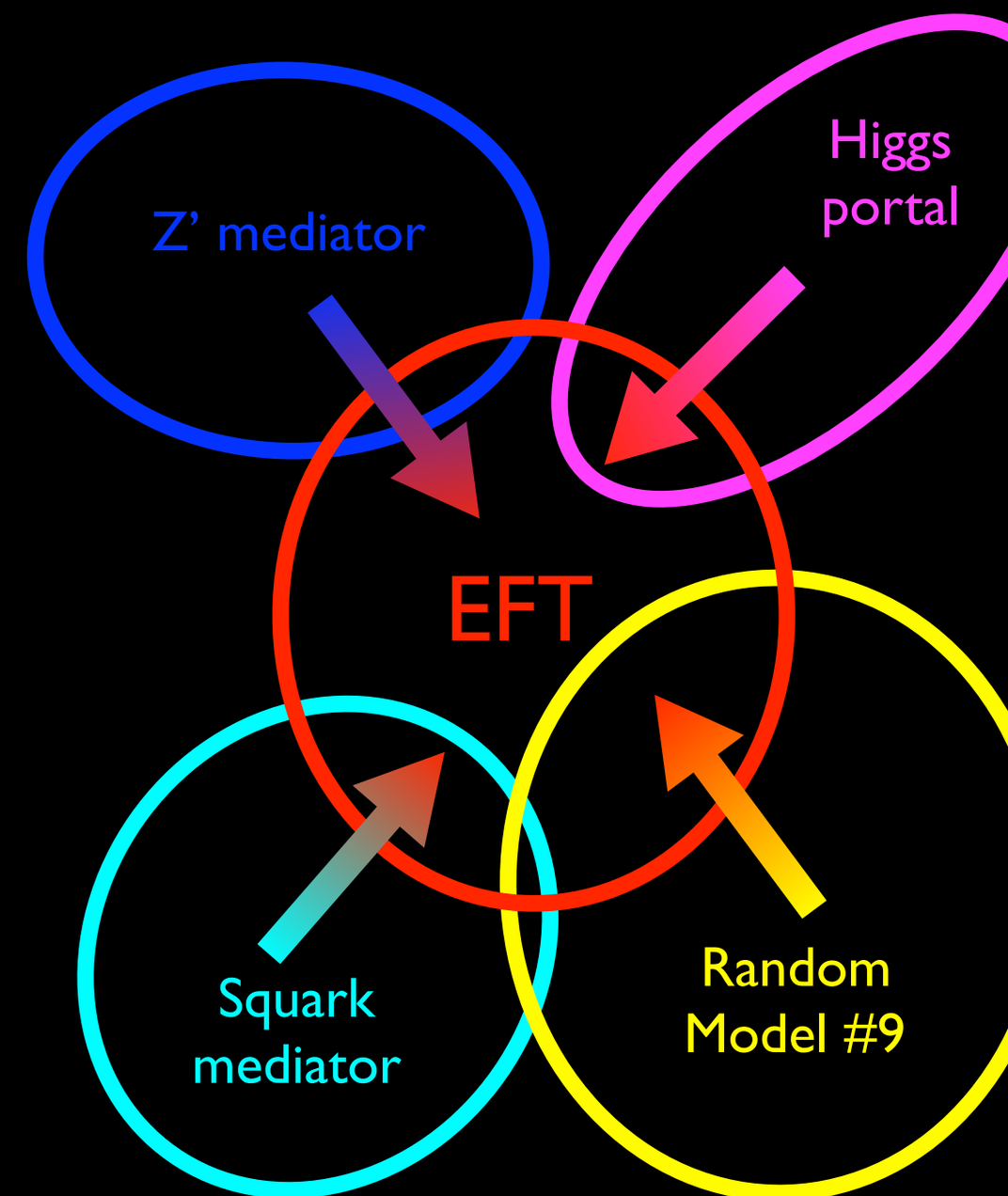
- Given a signal of dark matter, we can use these (and other) modules to build a theory that looks the way we would like. With a set of such theories in hand, we can see what other kinds of signals they predict as a way to test our hypothesis and either find another indication that the original signal is more likely to be true, or to rule out the hypothesis.

Contact Interactions (EFT) and Simplified Models

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: Beltran, Hooper, Kolb, Krusberg 0808.3384 & PRD
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
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.

Example: Majorana WIMP

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

- The various types of interactions are accessible to different kinds of experiments. (Technically meaning: the observables are unsuppressed by the small dark matter velocity in our halo, v ~ 10^{-3}.
  - 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.

Example: Majorana WIMP

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

- The various types of interactions are accessible to different kinds of experiments. (Technically meaning: the observables are unsuppressed by the small dark matter velocity in our halo, v ~ 10^{-3}.
- 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.

Example: Majorana WIMP

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

- The various types of interactions are accessible to different kinds of experiments. (Technically meaning: the observables are unsuppressed by the small dark matter velocity in our halo, v ~ 10^{-3}.
- 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.

Example: Majorana WIMP

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

- The various types of interactions are accessible to different kinds of experiments. (Technically meaning: the observables are unsuppressed by the small dark matter velocity in our halo, v ~ 10^{-3}.

- 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	-

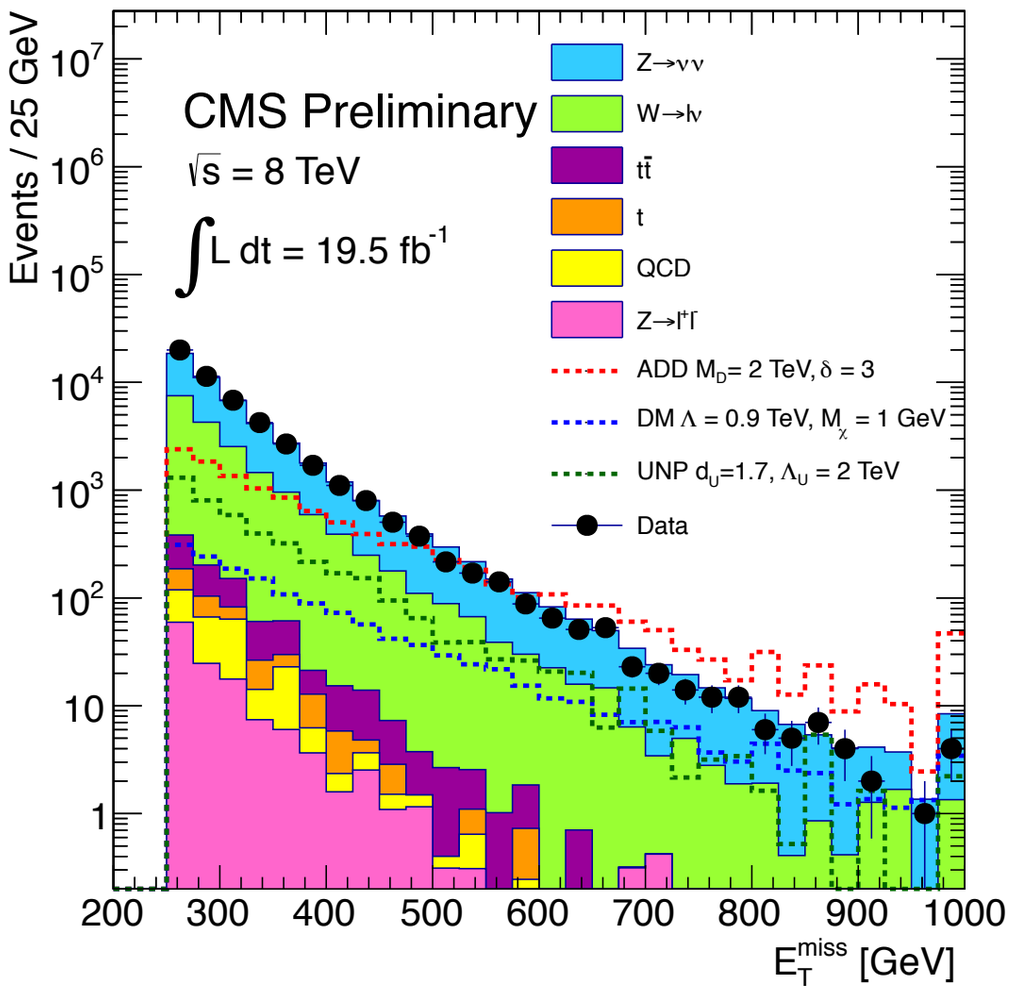
$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

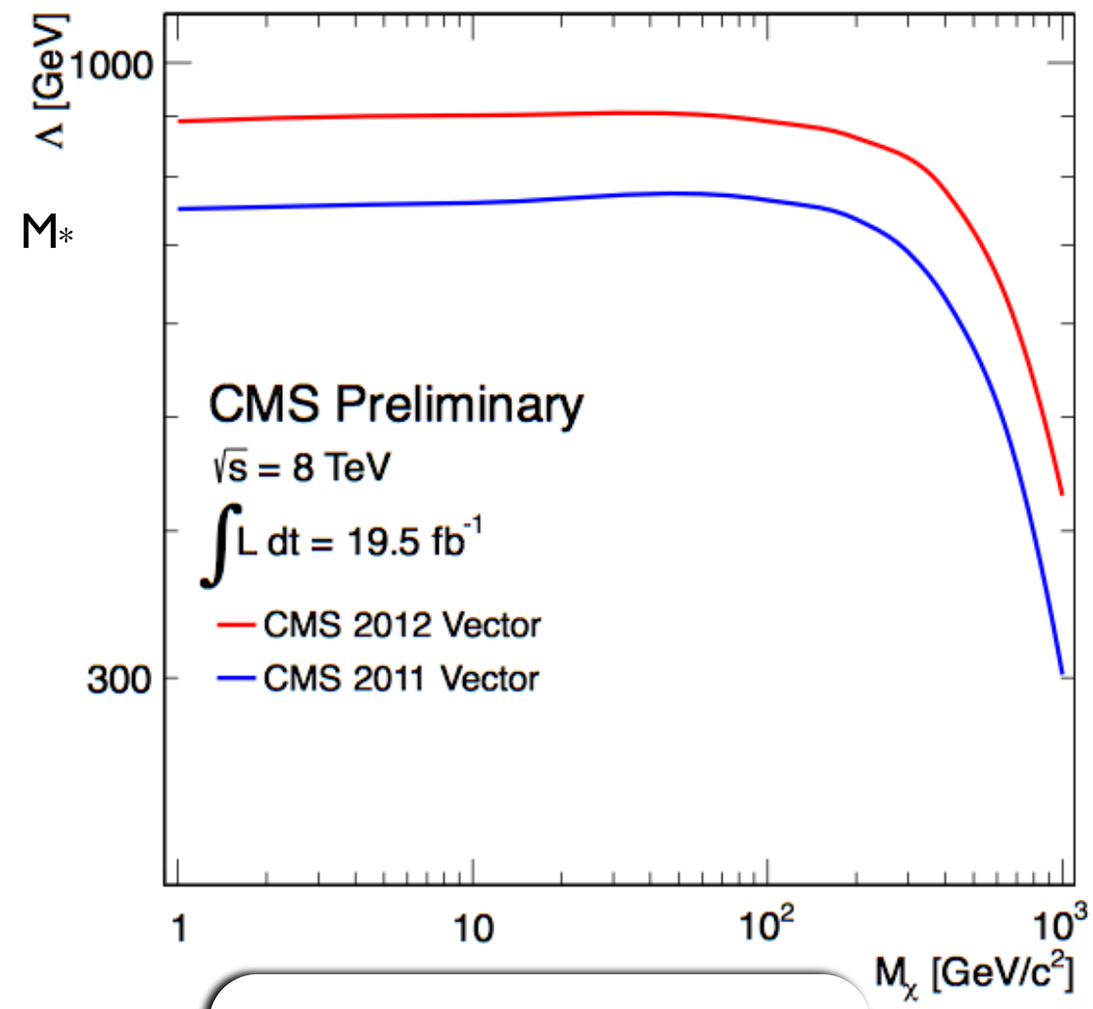
$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

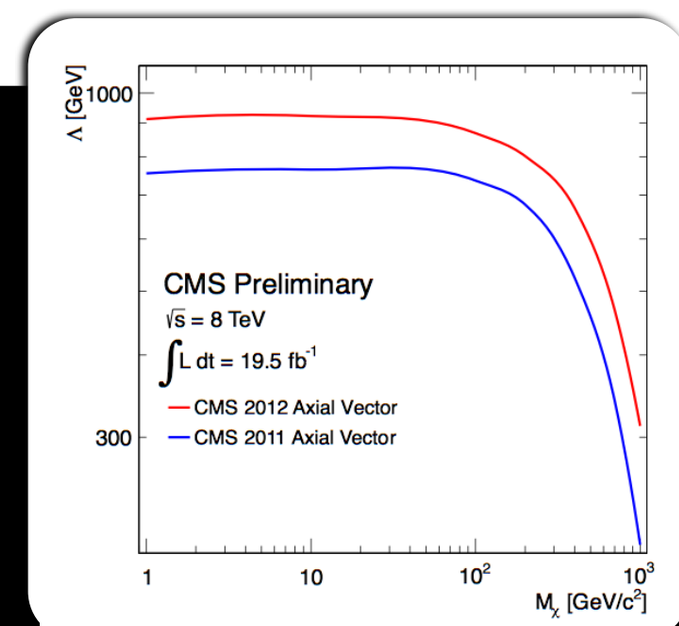
Other operators may be rewritten in this form by using Fierz transformations.

Collider Searches help fill in regions of theory-space where direct and indirect detection are challenged by velocity-suppression. Colliders produce DM relativistically, and thus have v ~ 1.

Collider Results



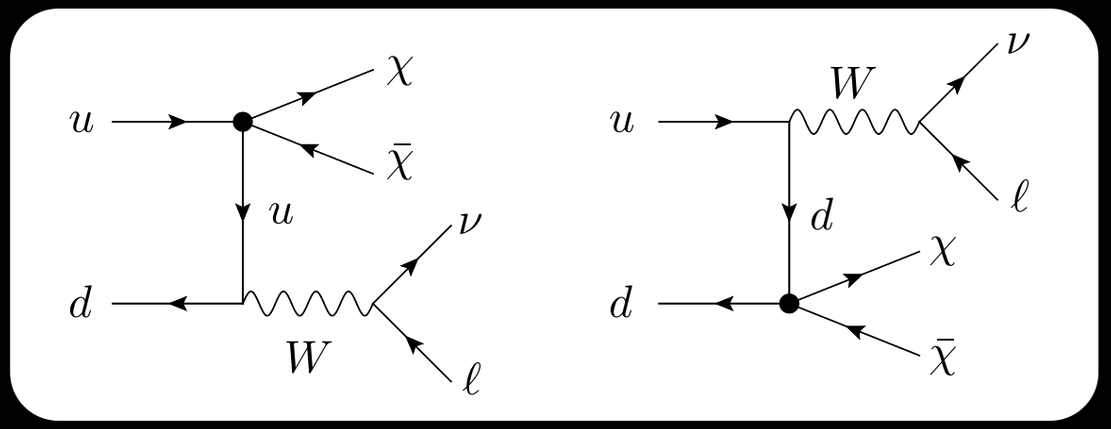




Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

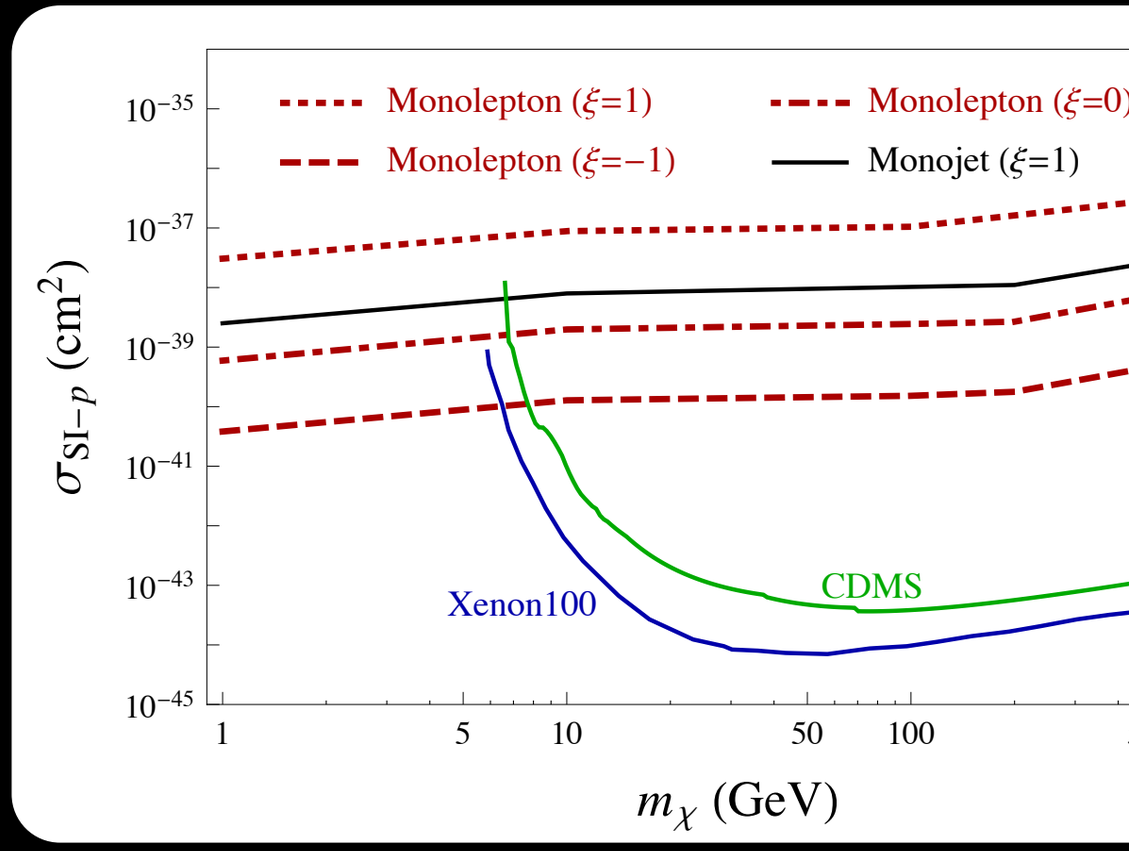
Mono-Whatever

- 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

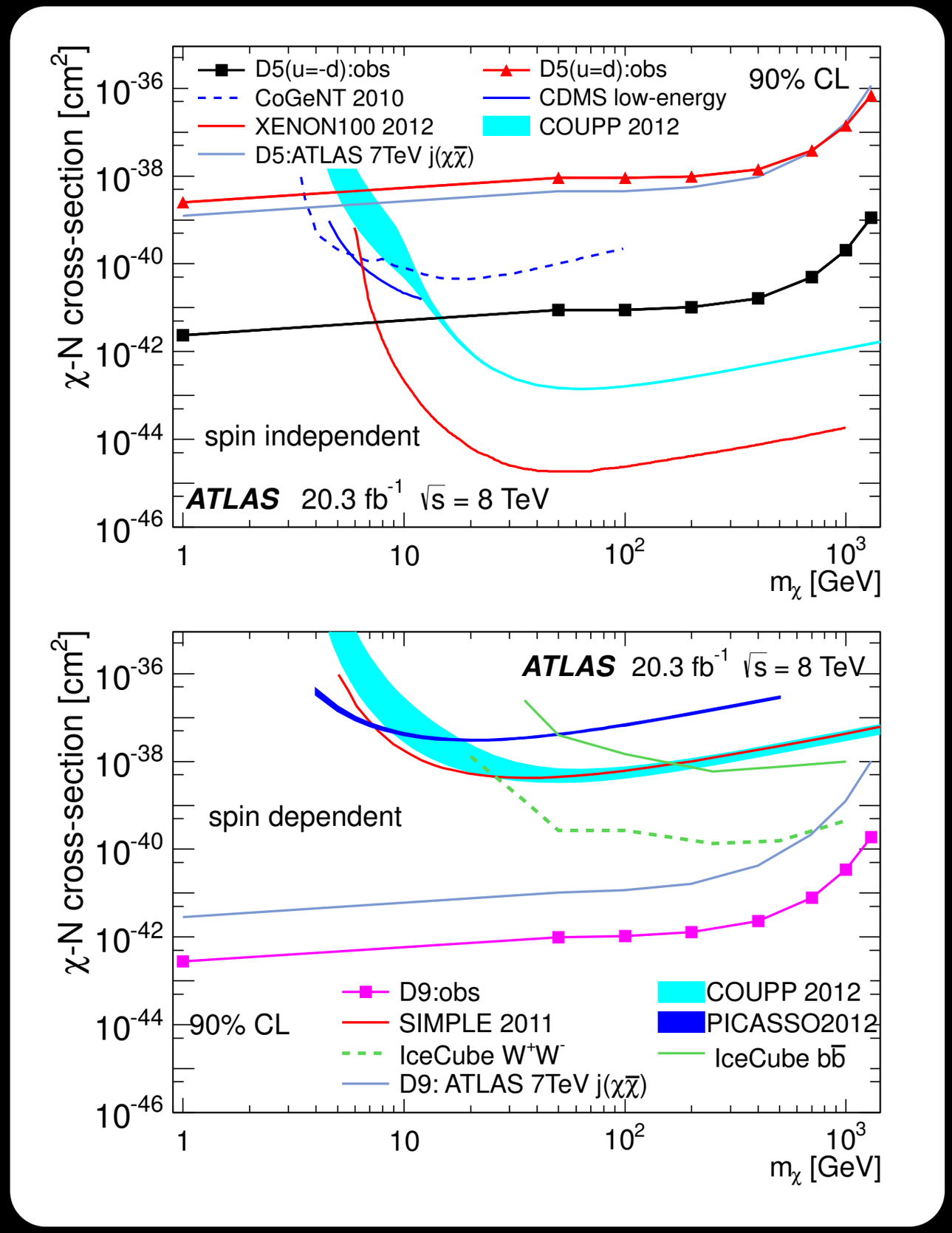
Y. Bai, TMPT, 1208.4361 & PLB



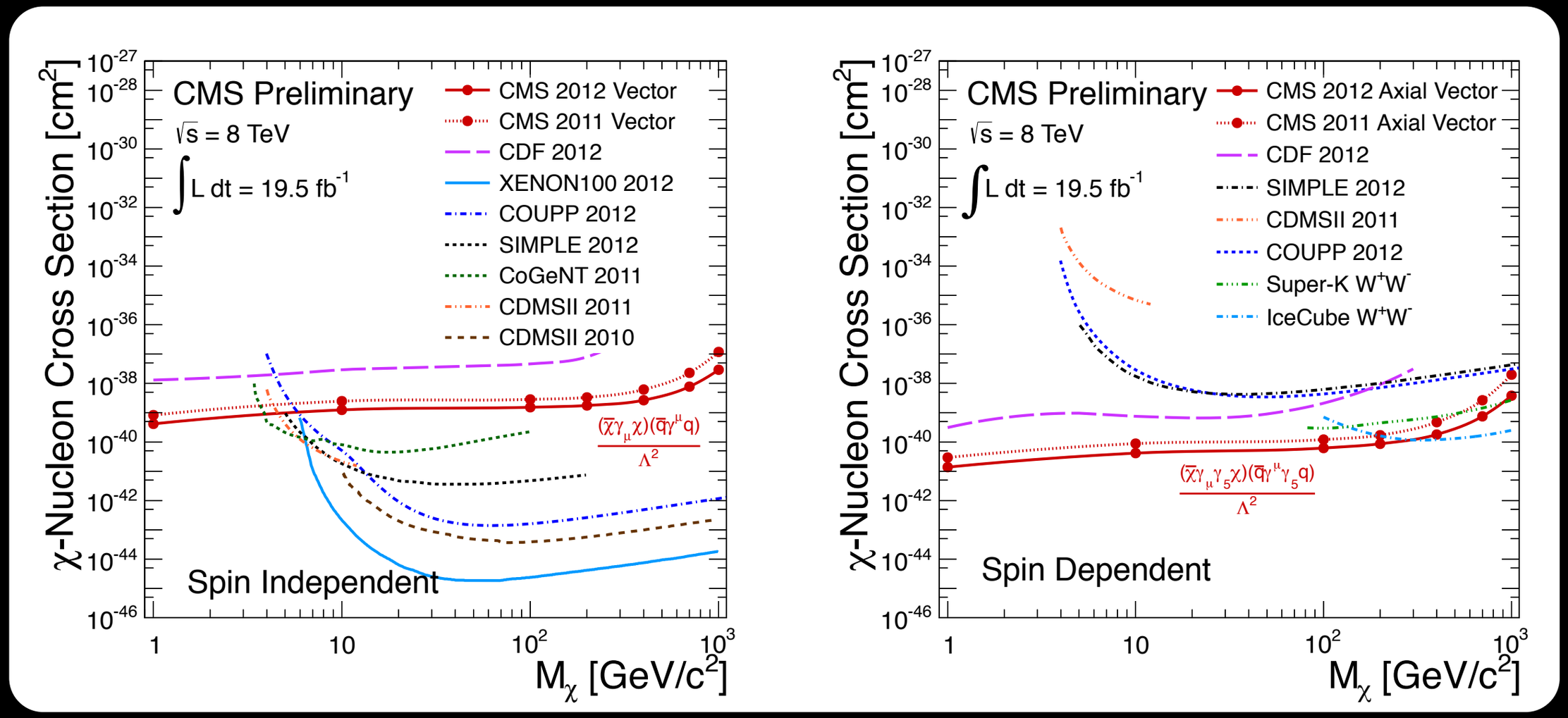
(d coupling) = ξ x (u coupling)

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!



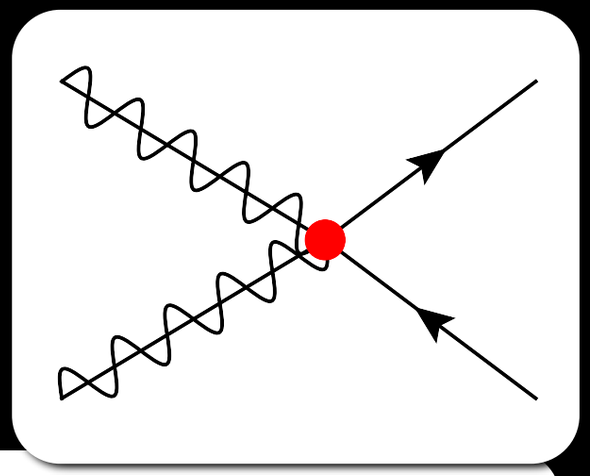
Translation to Elastic Scattering



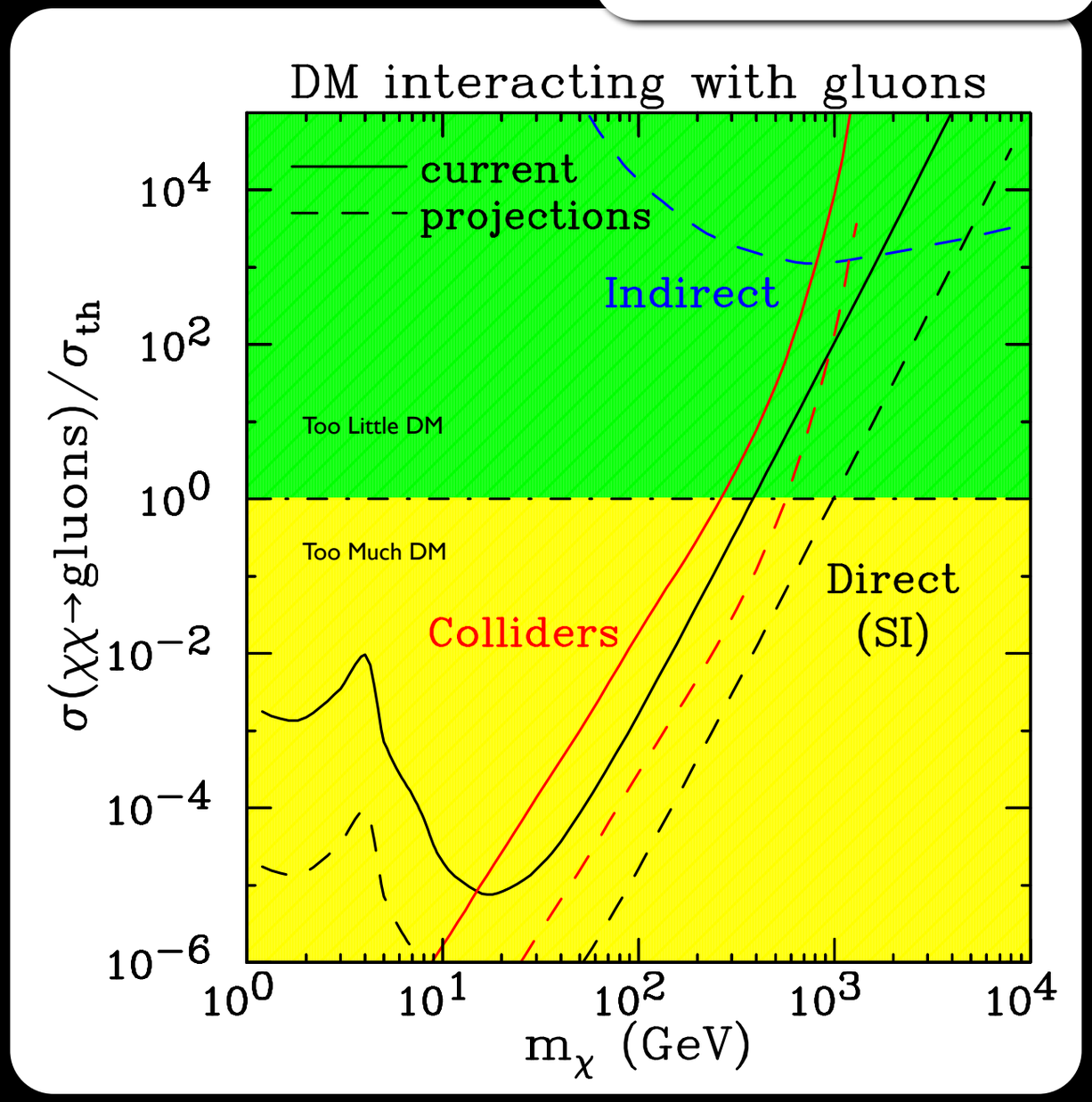
See: Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB; Bai, Fox, Harnik 1005.3797 & JHEP; and lots of other papers…

- 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).

Annihilation

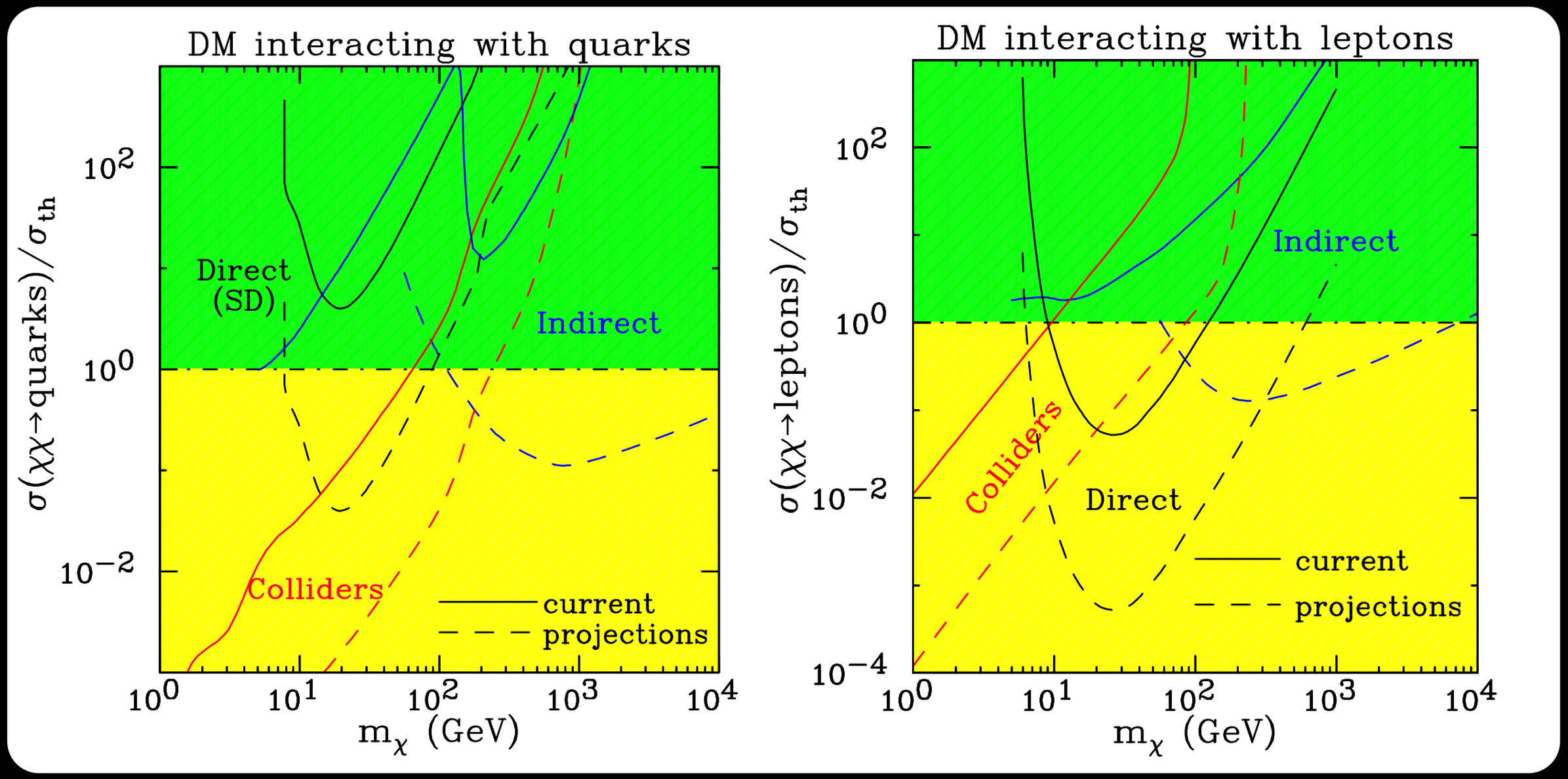


- We can also map interactions into predictions for WIMPs annihilating.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Here, the cross section has been normalized to the thermal cross section for a thermal relic at a given mass.
- 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

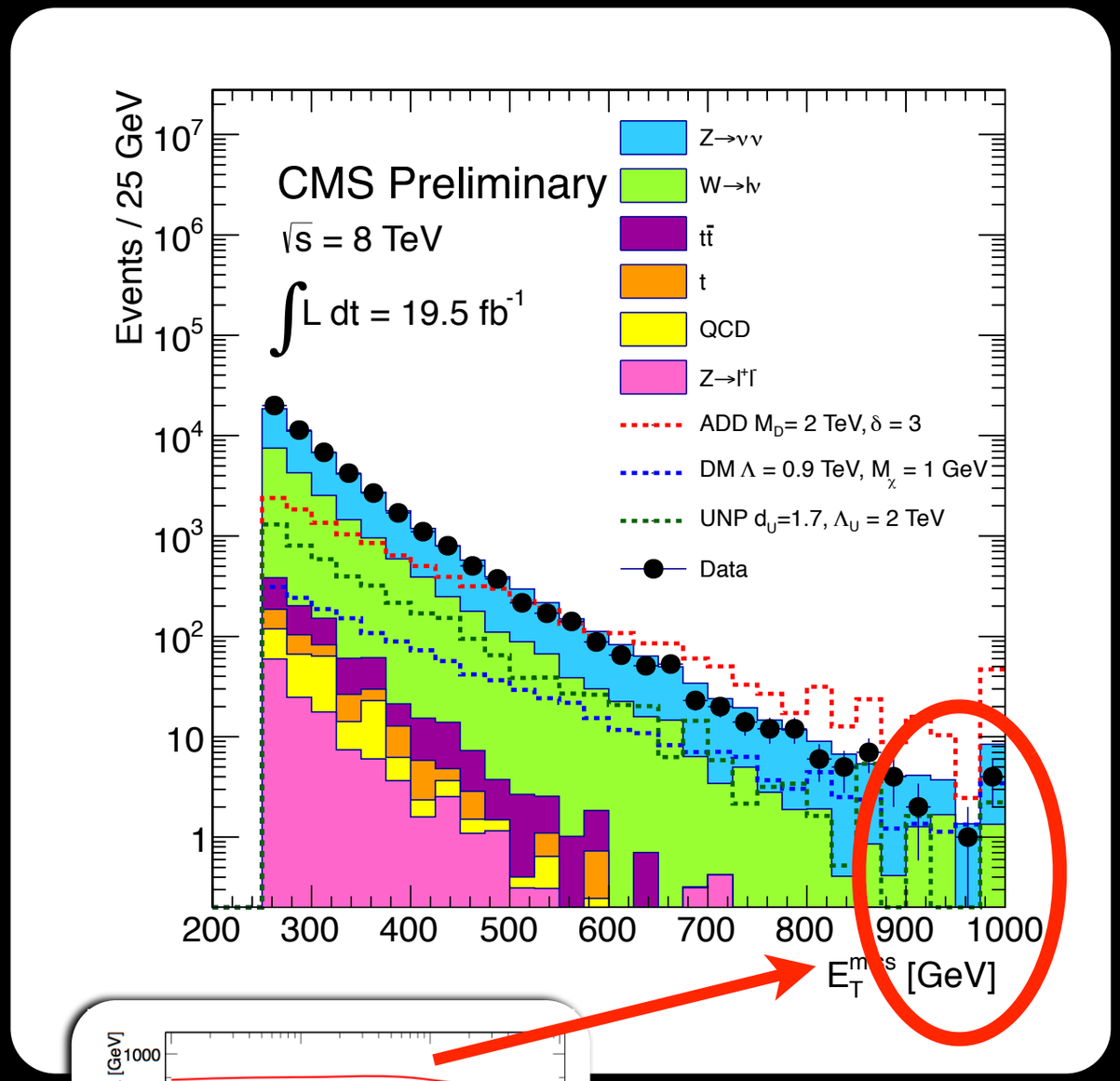
Quarks & Leptons

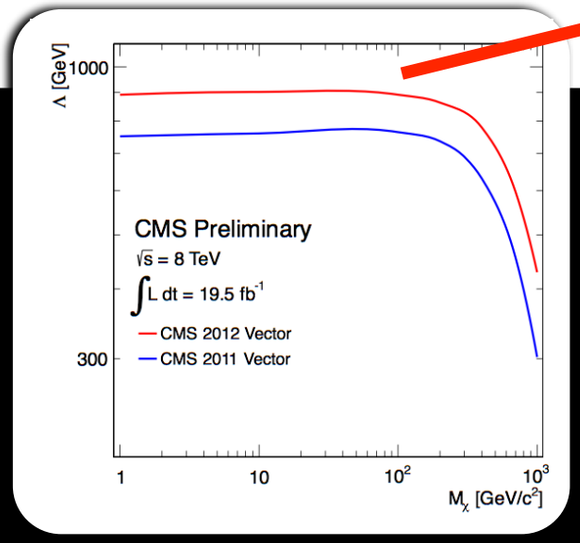


DM Complementarity, arXiv:1305.1605

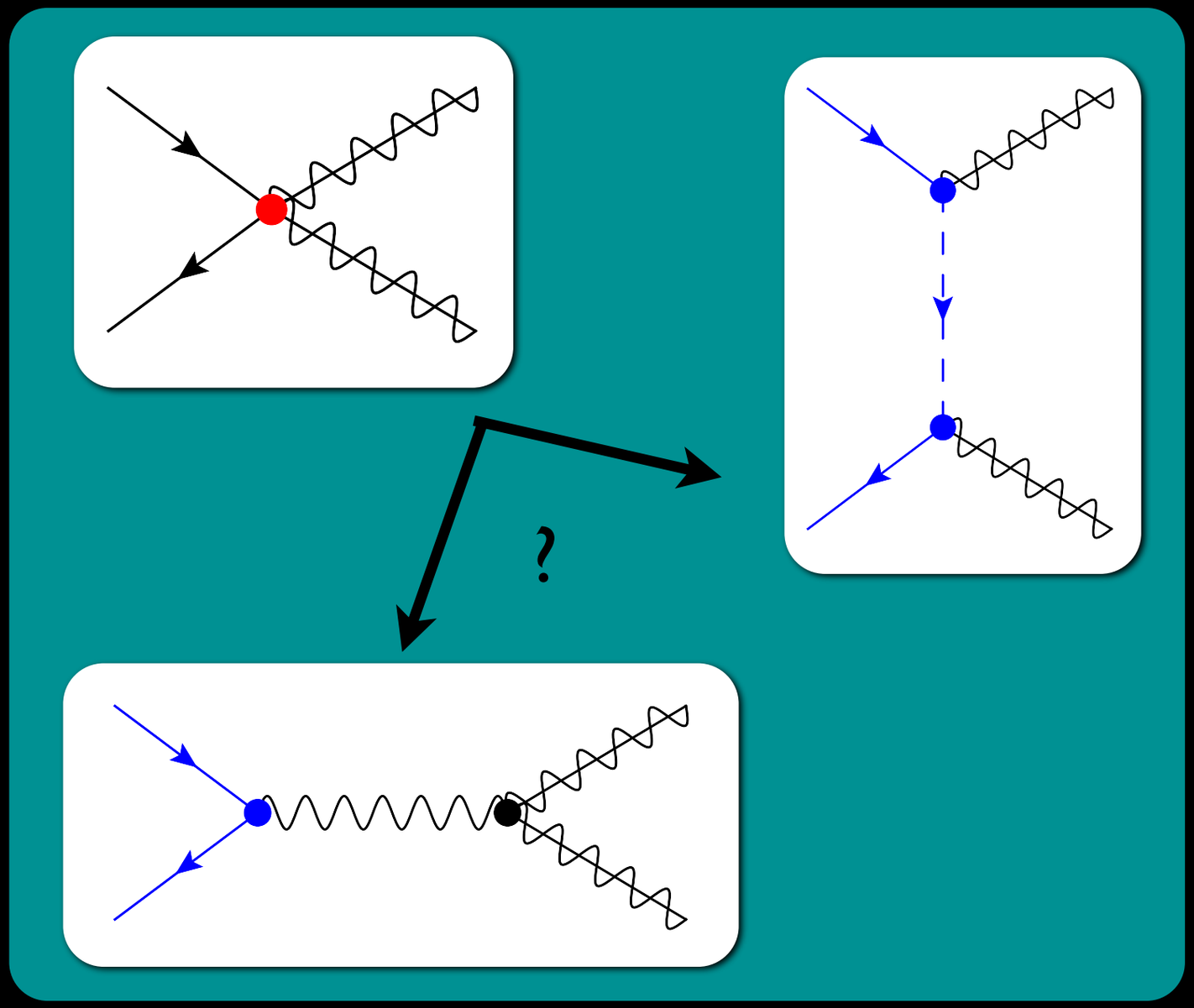
How Effective a Theory?

- 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 might be 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.]
- More generally, the correct statement is that *the EFT cannot describe theories with light mediators, and those theories are also very interesting!*





Simplified Models?



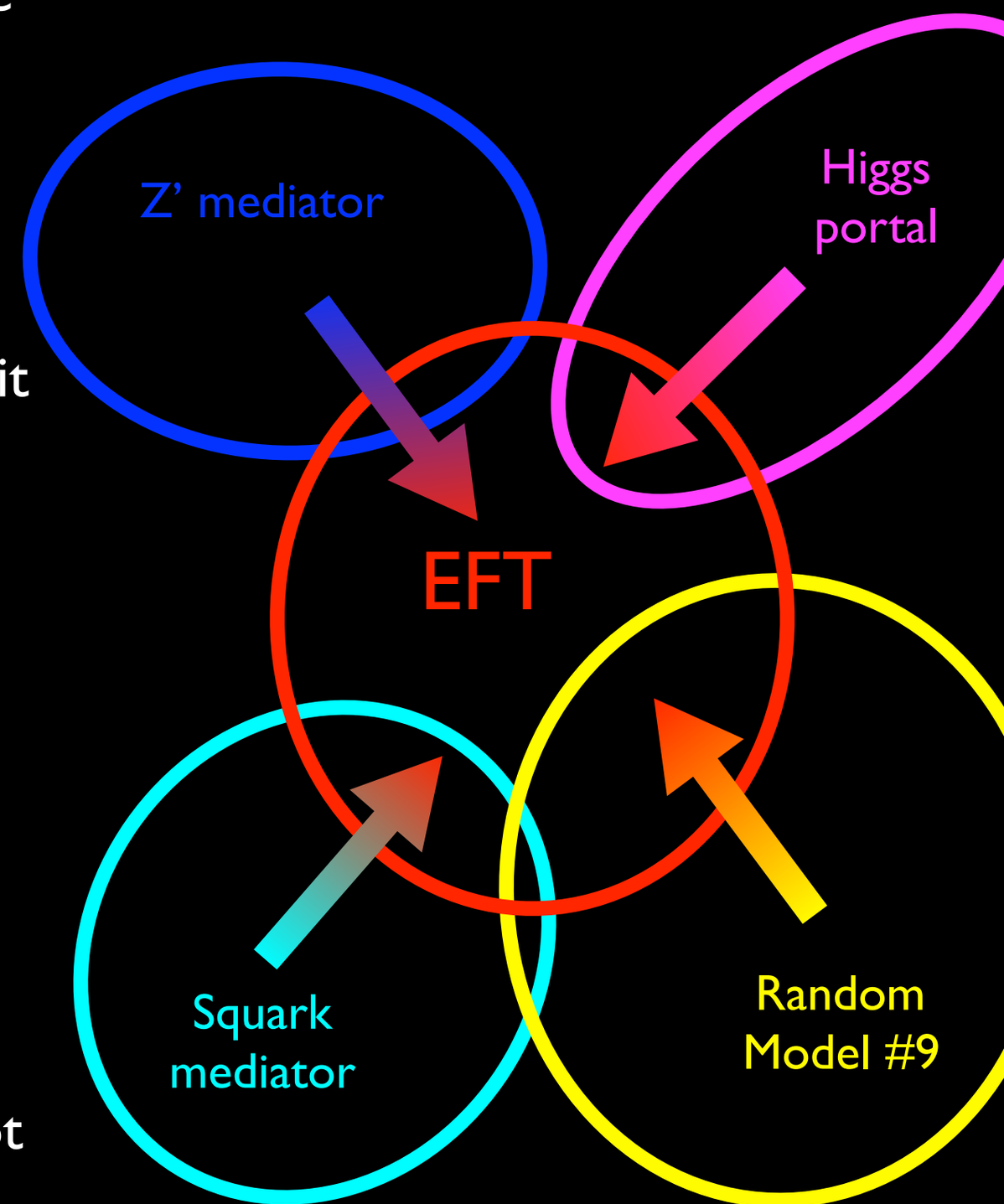
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

"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.

One strategy is to try to write down theories with mediators explicitly included.

"EFT Doesn't Work at LHC"

- One sometimes hears the statement that the EFT doesn't work at the LHC because it corresponds to a strongly coupled simplified model.
  - This is inspired to some extent by the fact that the EFT is the universal large mass limit of any simplified model.
  - One should remember that the EFT is a superset of a limit of all simplified models: any one of them does not typically characterize all of them.
  - It is logistically impossible to rule out application of the EFT *in general* based on one *specific* model.
  - Instead, this reminds us that the EFT cannot itself describe all the possibilities!



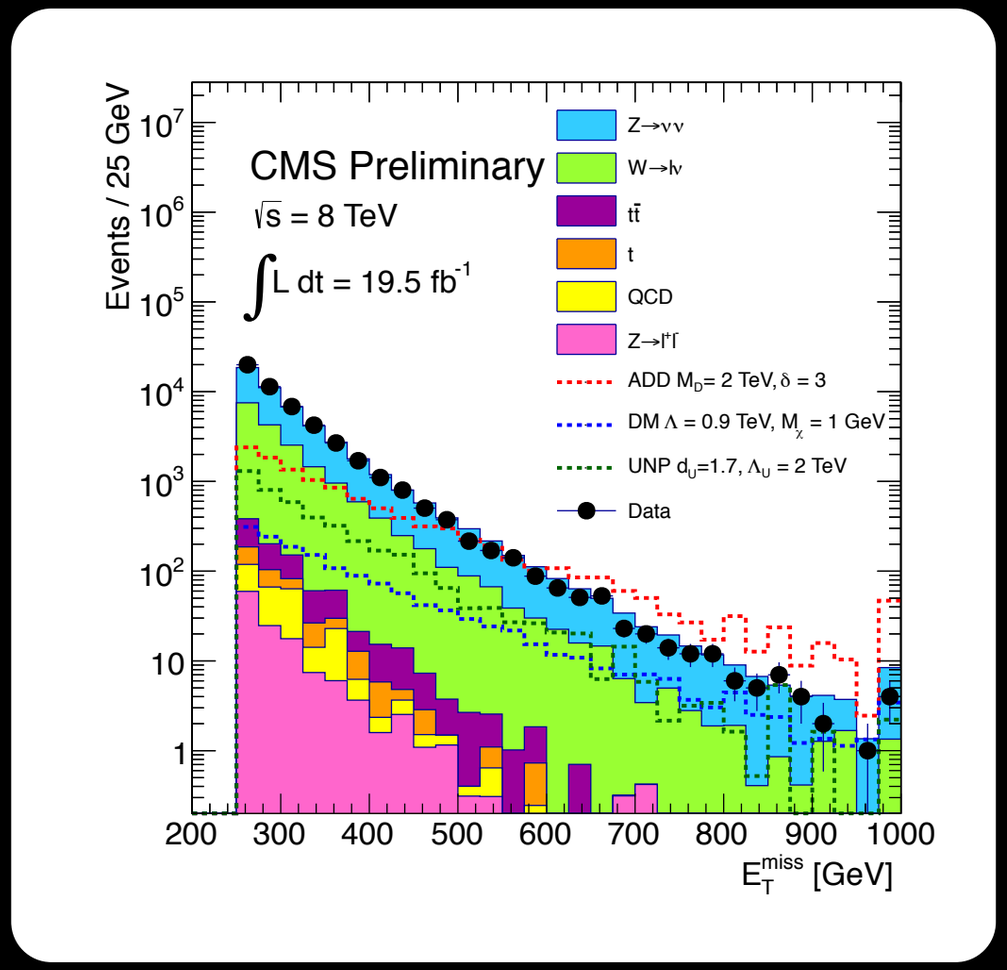
"EFT Doesn't Work at LHC"

- So what can we learn from the EFT itself?
- The EFT is an expansion in energy: E / M∗.
  - If E is too large, loop contributions to the observables will contribute as much as the tree level, and the theory ceases to be predictive.
  - Where that happens for fixed M∗ is somewhere around:

$$E \gtrsim 4\pi \; M_*$$

(We can argue about whether this should be 4π or 2π or some other number. One is as indefensible as another.)

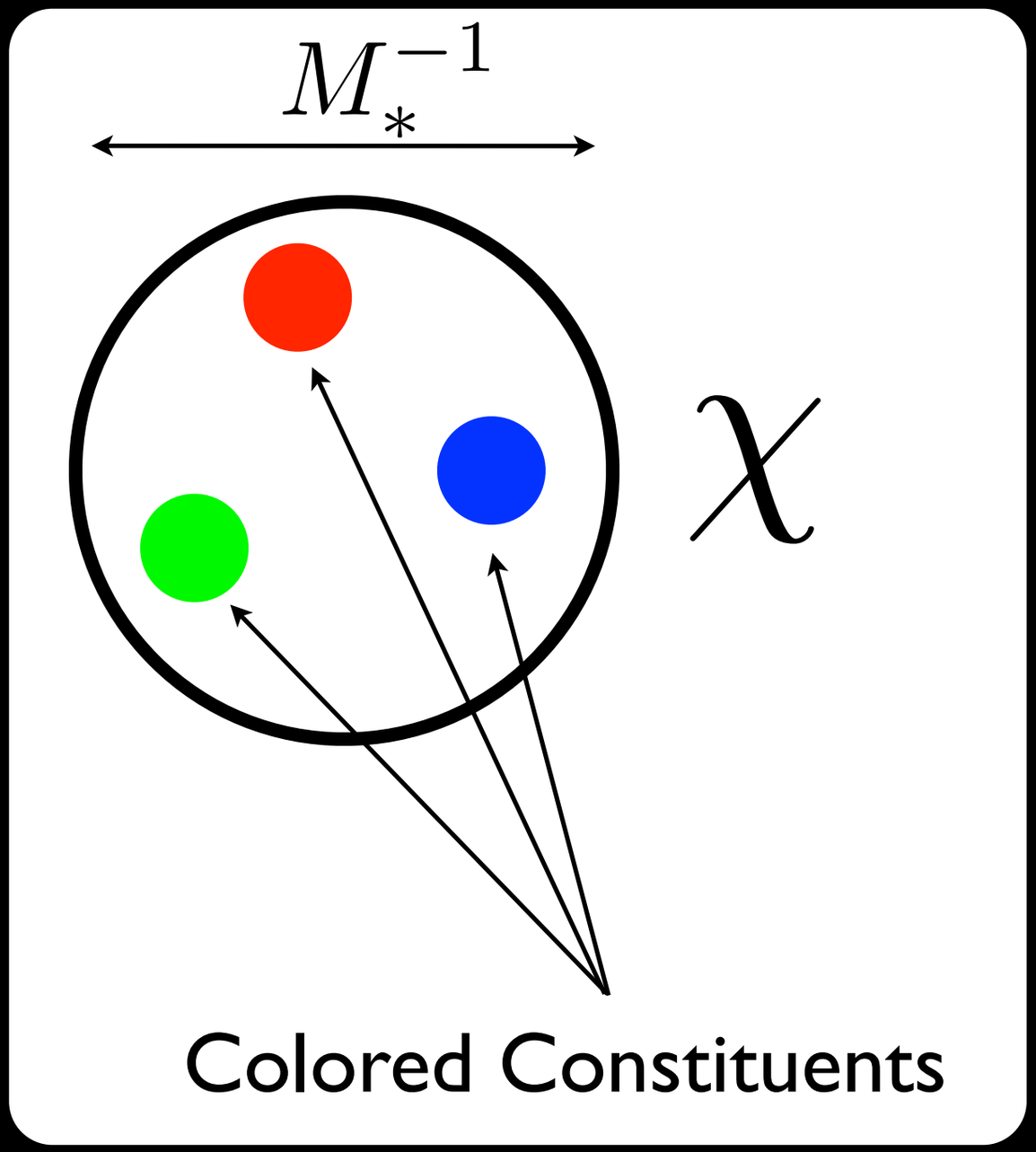
  - For the Run I limits of M∗ ~ 1 TeV, this forbids us from using events with energies larger than about 10 TeV.



Not a big problem at Run I…

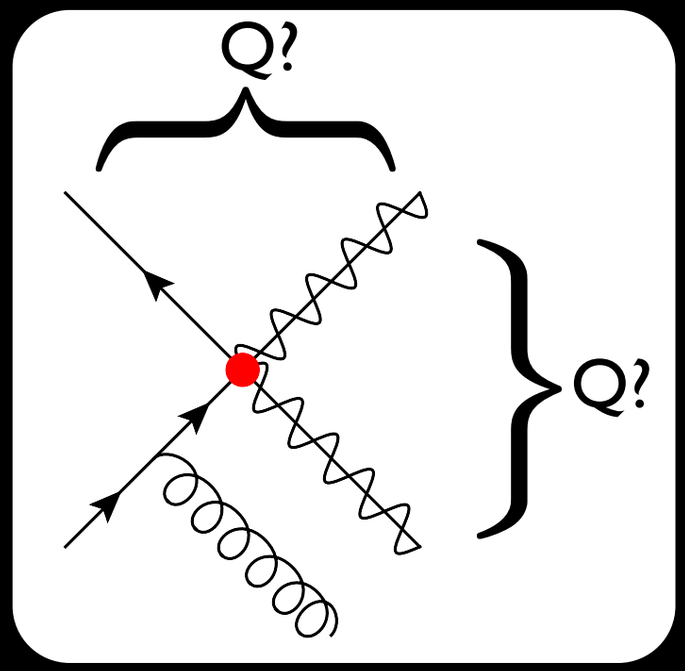
(even in the limit 4π -> ~1!)

A Composite WIMP?

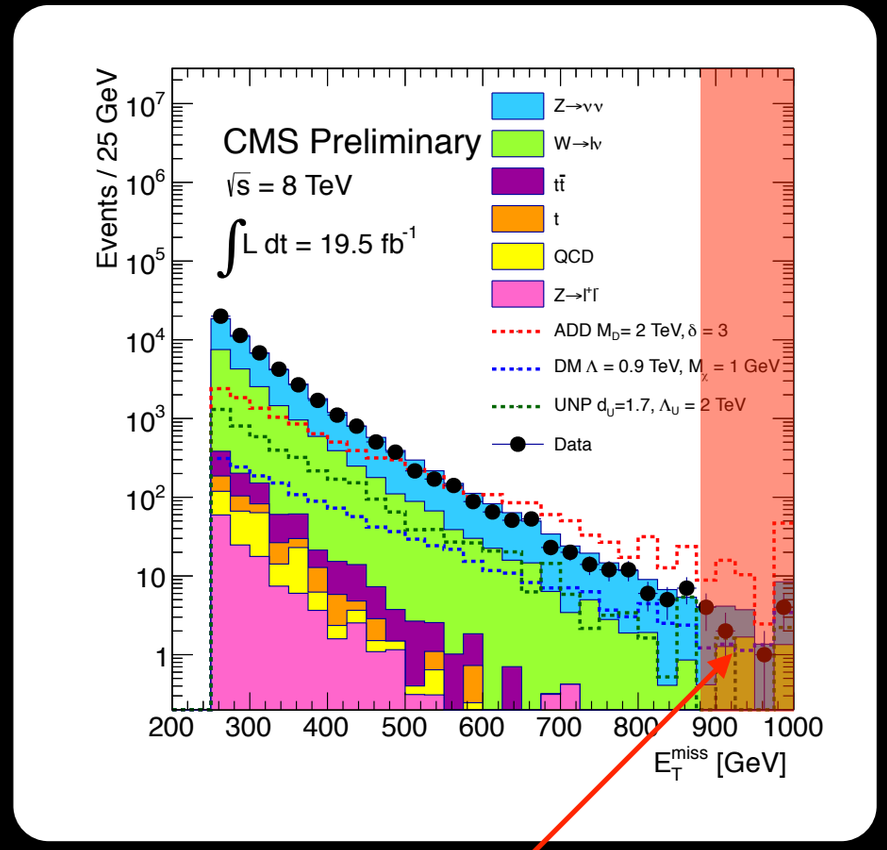


- There are cases where an EFT still says something even when there is no perturbative simplified model that can describe the physics.
- If the dark matter is a (neutral) confined bound state (confined by some dark gauge force, say) of colored constituents, we should expect its coupling to quarks and 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.

Truncation



- An interesting idea is to present EFT bounds using "truncation".
- The idea is to exclude the events with the largest momentum transfer from the bound, since they are the most likely to be badly modeled by the EFT.
- If one imagines a simple t-channel or s-channel model, two different quantities ("Q") characterize the momentum through the implicit propagator.
  - The EFT can't tell you which one to use.
  - (Neither really can be measured anyway).
- Events with Q larger than some cut value Q_{cut} are excluded from the analysis bounding M_*.



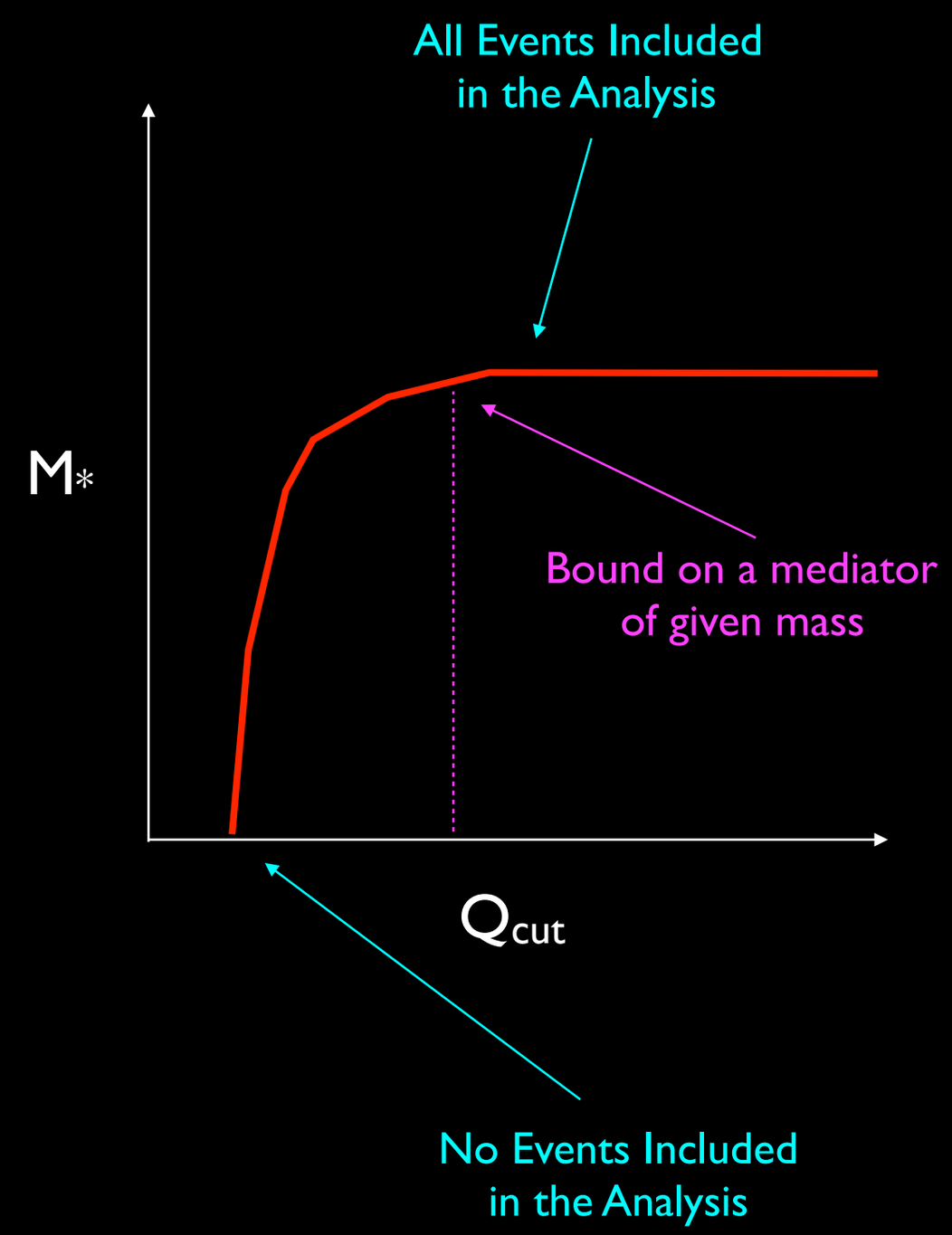
Exclude "these" Events for Q_{cut} = 900 GeV.

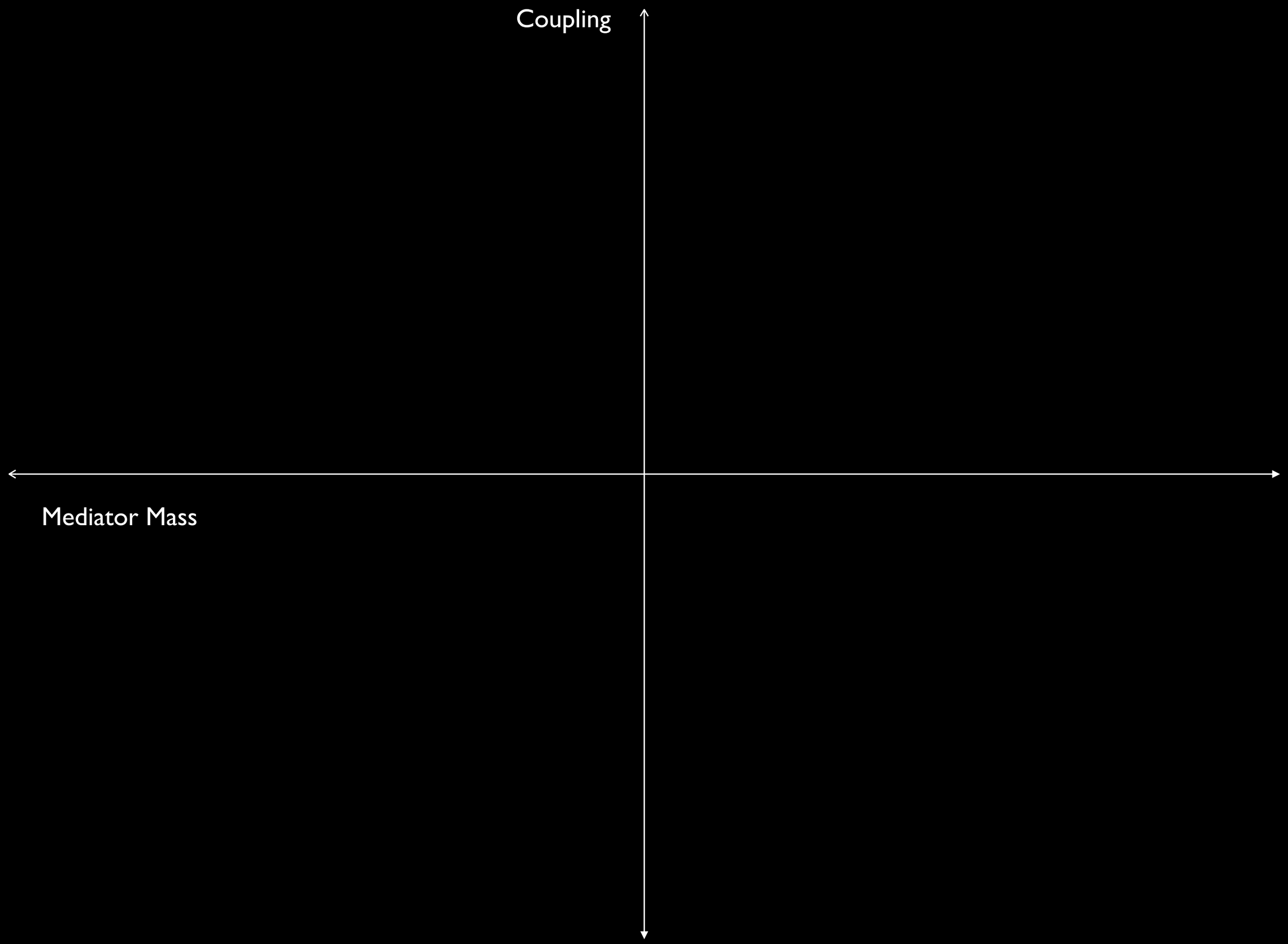
Busoni, De Simone, Gramling, Jacques, Morante Riotto, arXiv:1307.2253 & PLB arXiv:1402.275 & 1405.3101 & JCAP

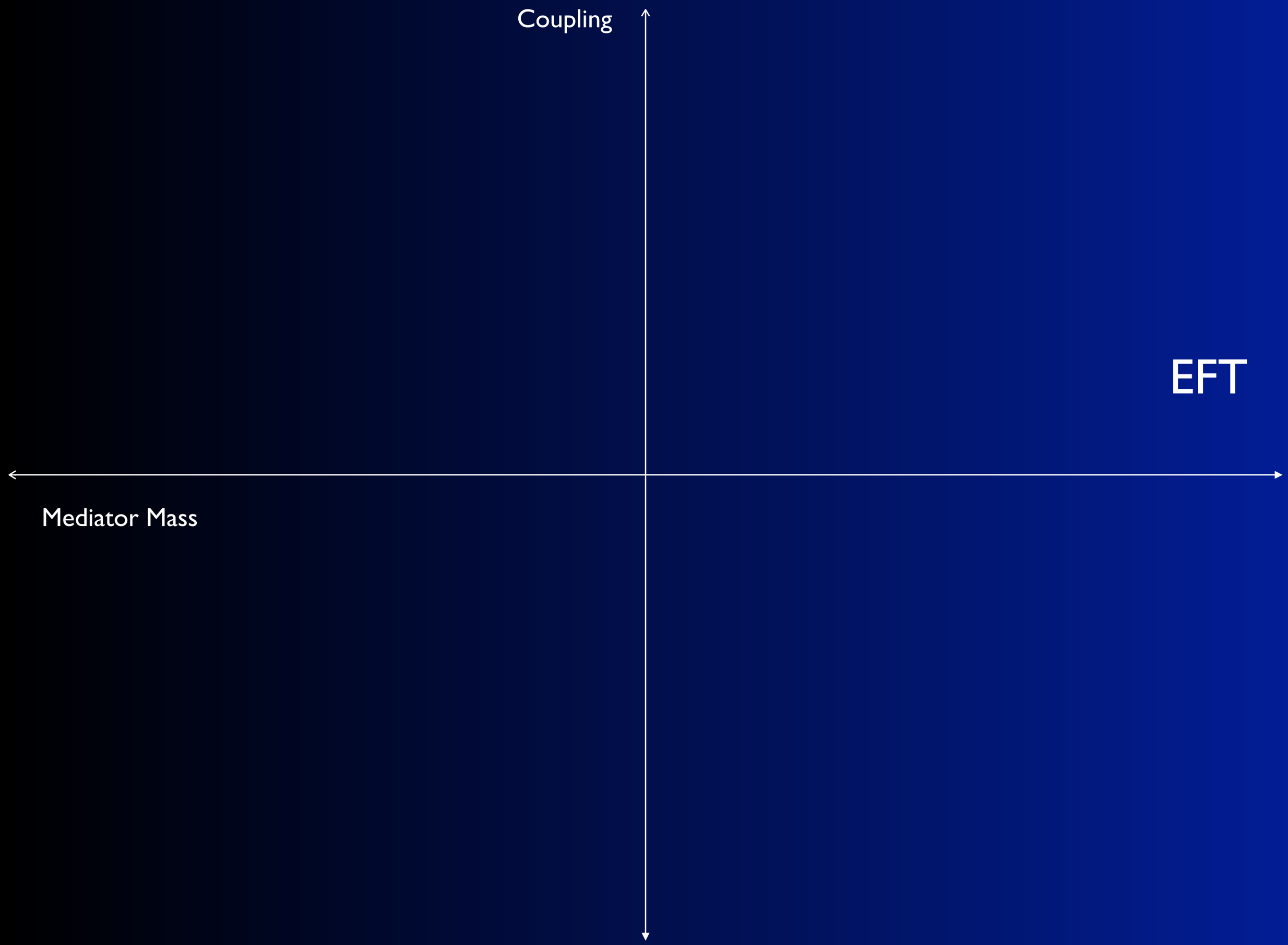
Truncation

Racco, Wulzer, Zwirner, arXiv:1502.04701

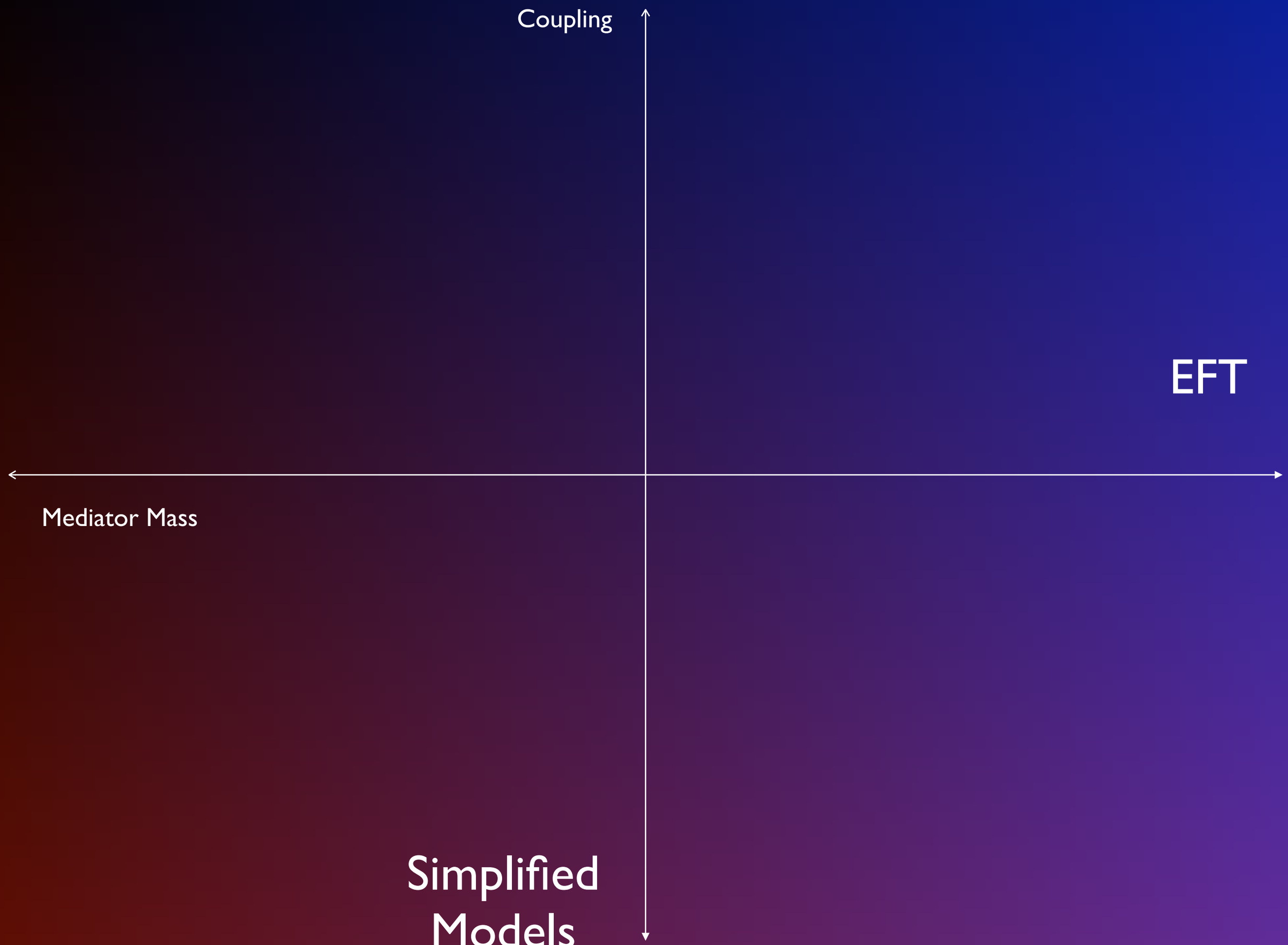
- One way to implement is to apply the cut at the generator level when defining a theory template to compare with, and then use all of the experimental data in the analysis.
- Probably the most useful way to present results would be to show the resulting bound on M_* as a function of Q_{cut}.
- That way, the end user can decide (based on the masses of the particles in her theory) what value of Q_{cut} is appropriate, and find the conservative limit on her model.
- (And of course dedicated searches for mediators will be important, too).
- This was the final recommendation made by the "ATLAS/CMS Dark Matter Forum", 1507.00966 for presenting the results in terms of EFT parameterizations.

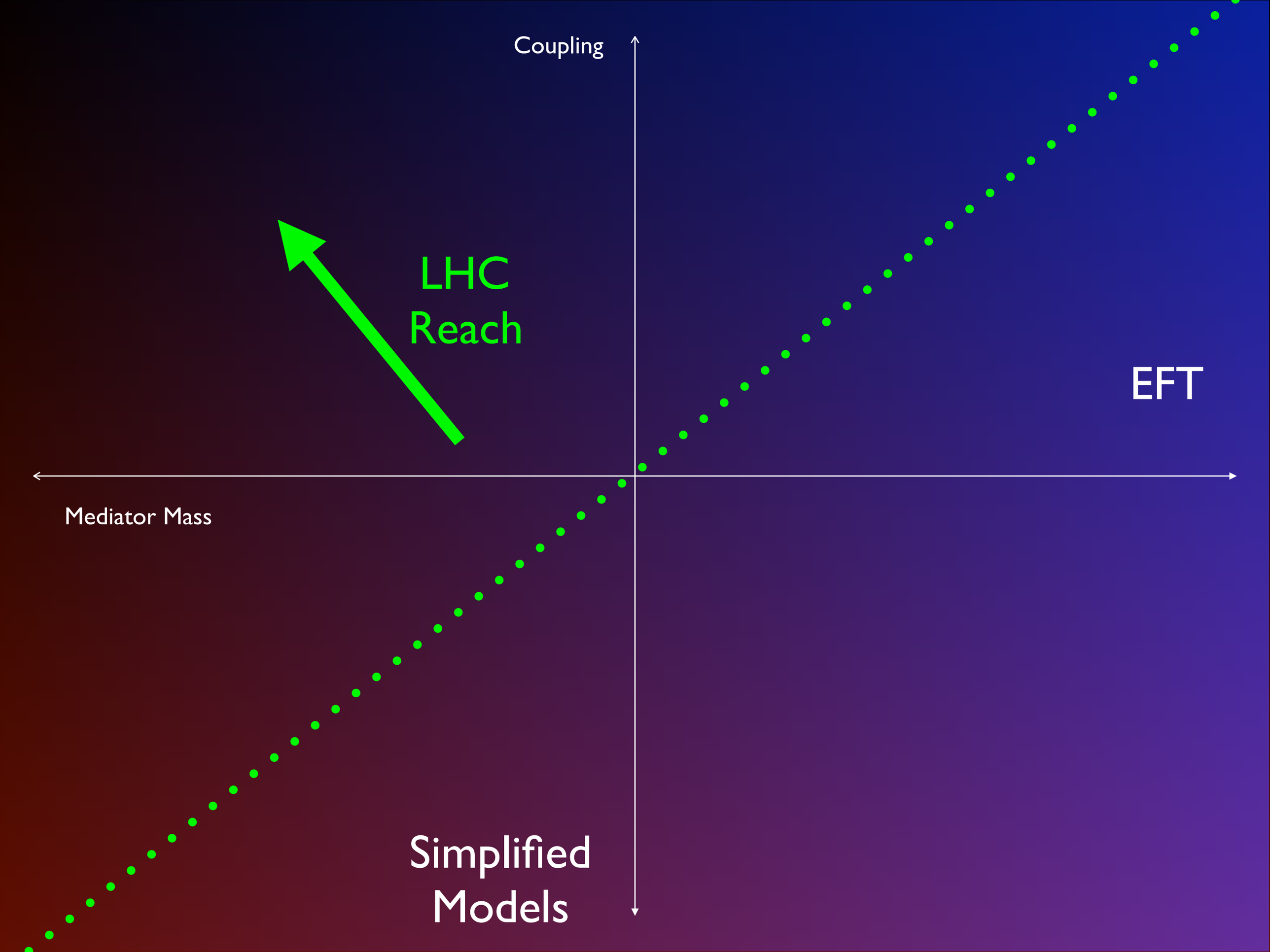



Coupling
Mediator Mass


Coupling
EFT
Mediator Mass


Coupling
Mediator Mass
Simplified
Models


Coupling
EFT
Mediator Mass
Simplified
Models


Coupling
LHC
Reach
EFT
Mediator Mass
Simplified
Models

Simplified Models

Simplified Models

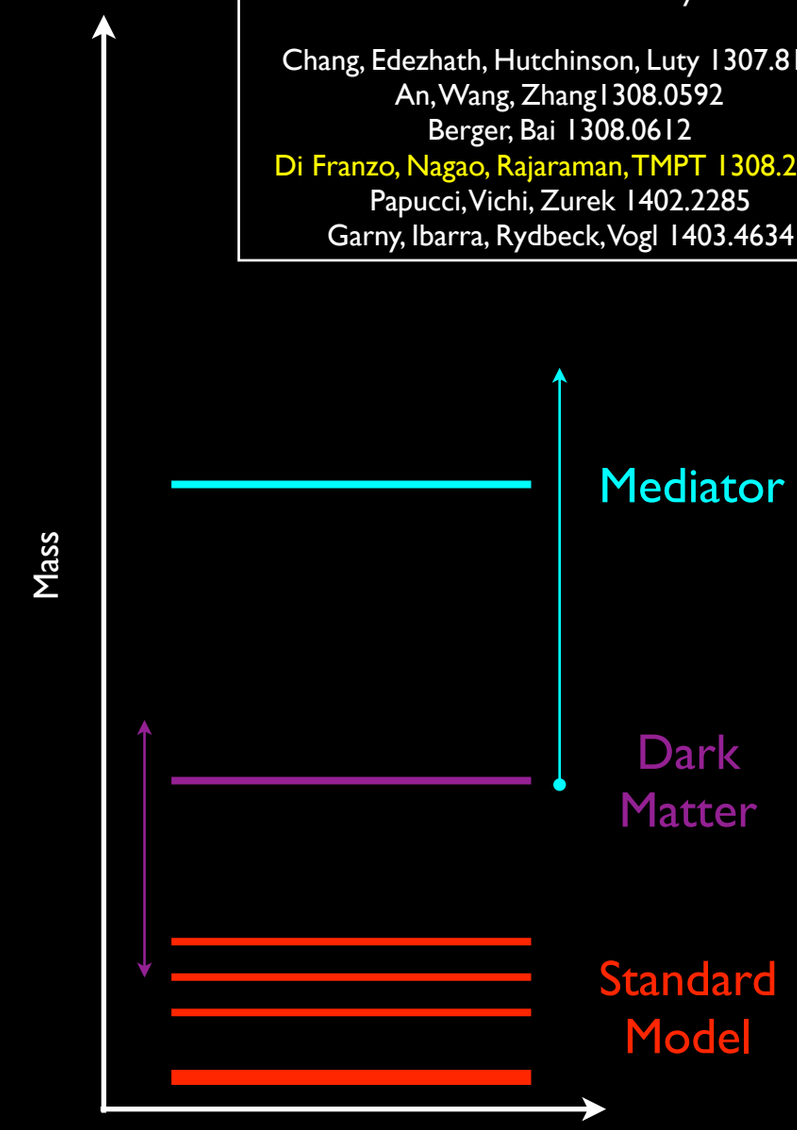
- Since the EFT limit cannot describe particles whose masses are accessible at the LHC, it is also fruitful to explore theories which include the mediator particles explicitly.
  - In many cases, new and interesting phenomena become accessible!
- Of course, the number of possible constructions increases as one includes more states. I choose to organize the description of such models according to a few simple properties:
  - The model should be UV complete at the level of LHC phenomenology.
    - This typically means it should be gauge invariant under the full SU(3)xSU(2)xU(1) symmetry and at least acknowledging all renormalizable interactions.
- I choose to impose minimal flavor violation, so that the bulk of the parameter space will tend to be consistent with flavor-violating observables.
  - That doesn't mean that some regions of parameter space aren't ruled out by precision measurements.
  - It's not the most general possibility and some alternate constructions are still interesting to think about.

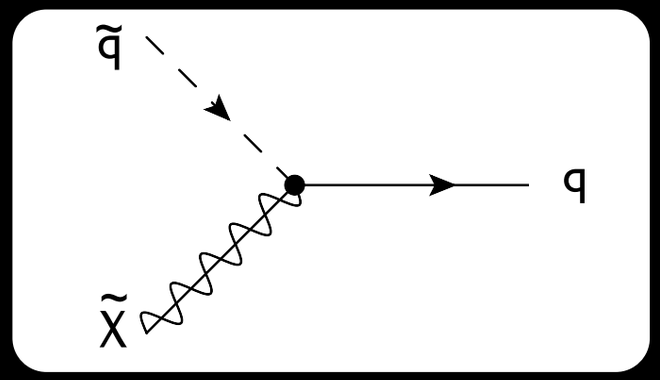
Simplified Model

- 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.
- Minimal flavor violation suggests we consider mediators with a flavor index corresponding to {uR,cR,tR},{dR,sR,bR}, or {Q1,Q2,Q3} and/or combinations.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, 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.

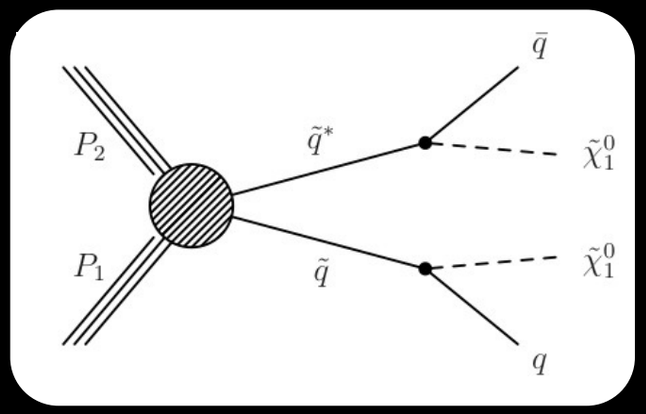
Lots of Recent Activity:

Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679
Papucci, Vichi, Zurek 1402.2285
Garny, Ibarra, Rydbeck, Vogl 1403.4634

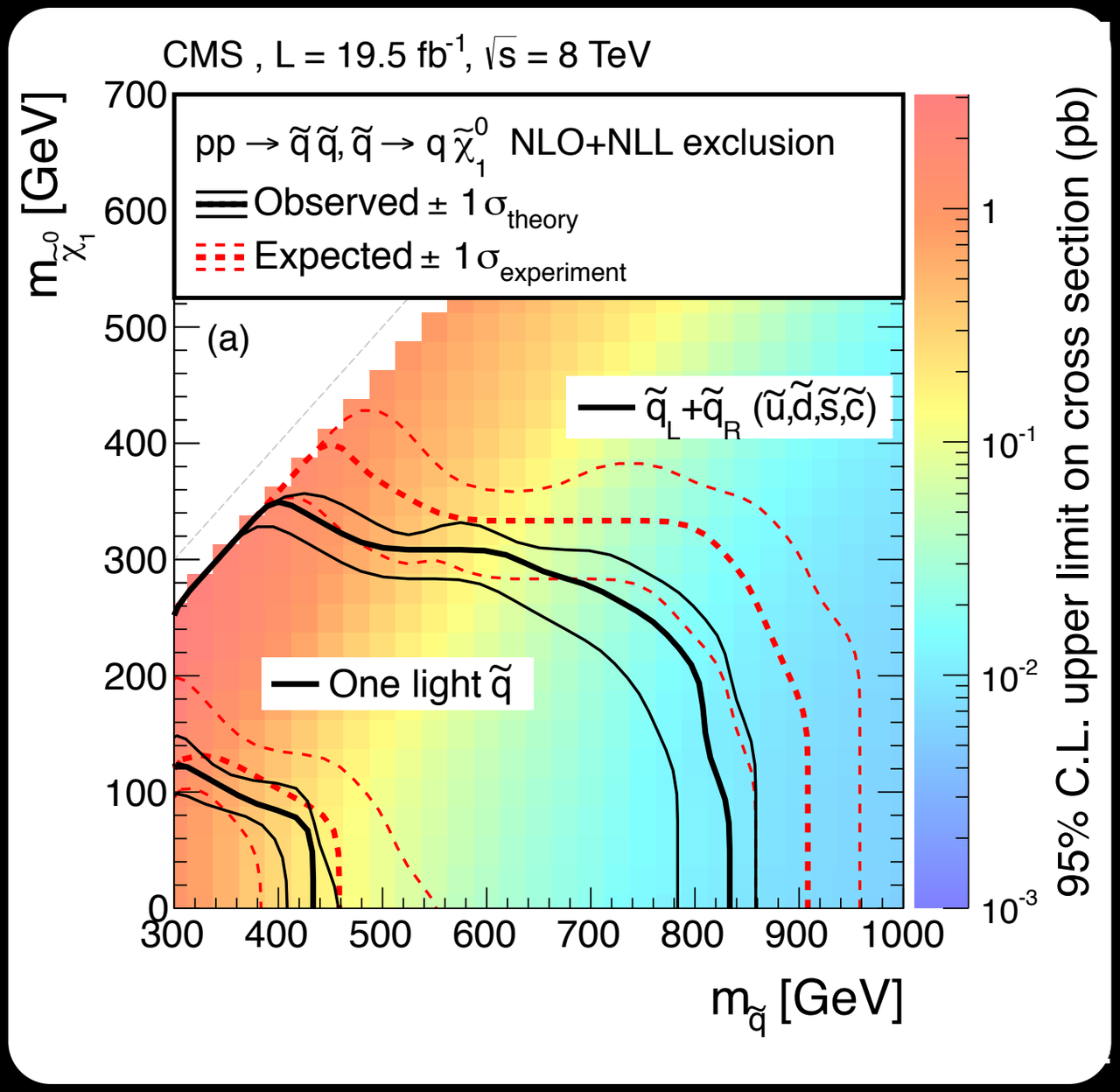




Simplified Model



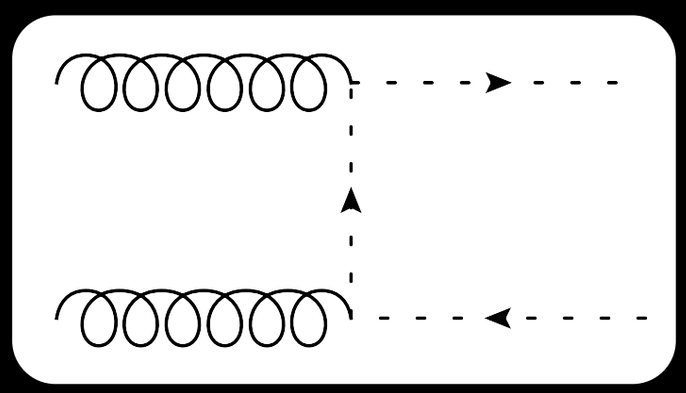
- This is a model that is used by the LHC collaborations as a way of presenting more generic searches for a colored particle which decays into a single jet and missing energy.
- If we exchange the LHC production cross section for the mediator coupling to quarks, we can translate the LHC bounds into dark matter properties.

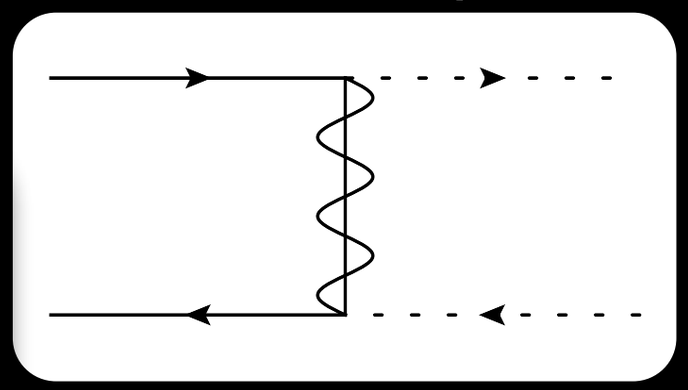


Of course, we can also consider a wider variety of WIMP properties and mediators and get away from MSSM-like theories.

$\tilde{u}_R$ Model

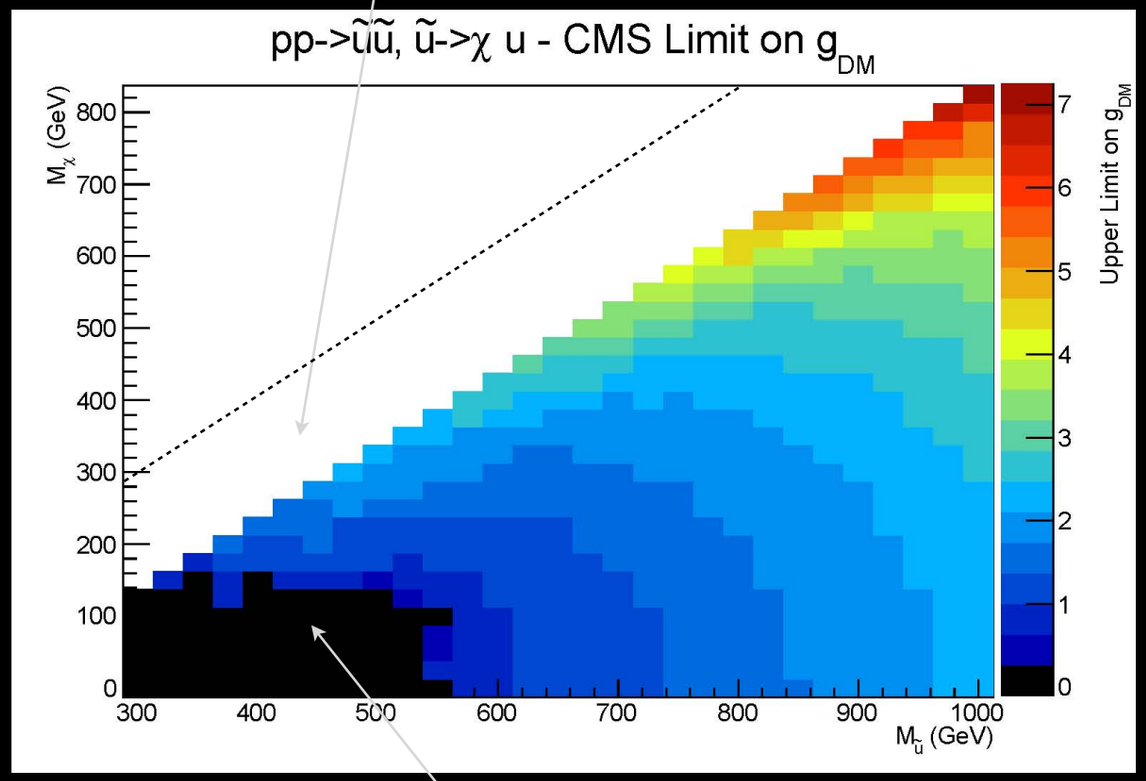
- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
  - (This is just a simple starting point!)
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force (QCD; mostly from initial gluons) or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.





Weak bounds in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

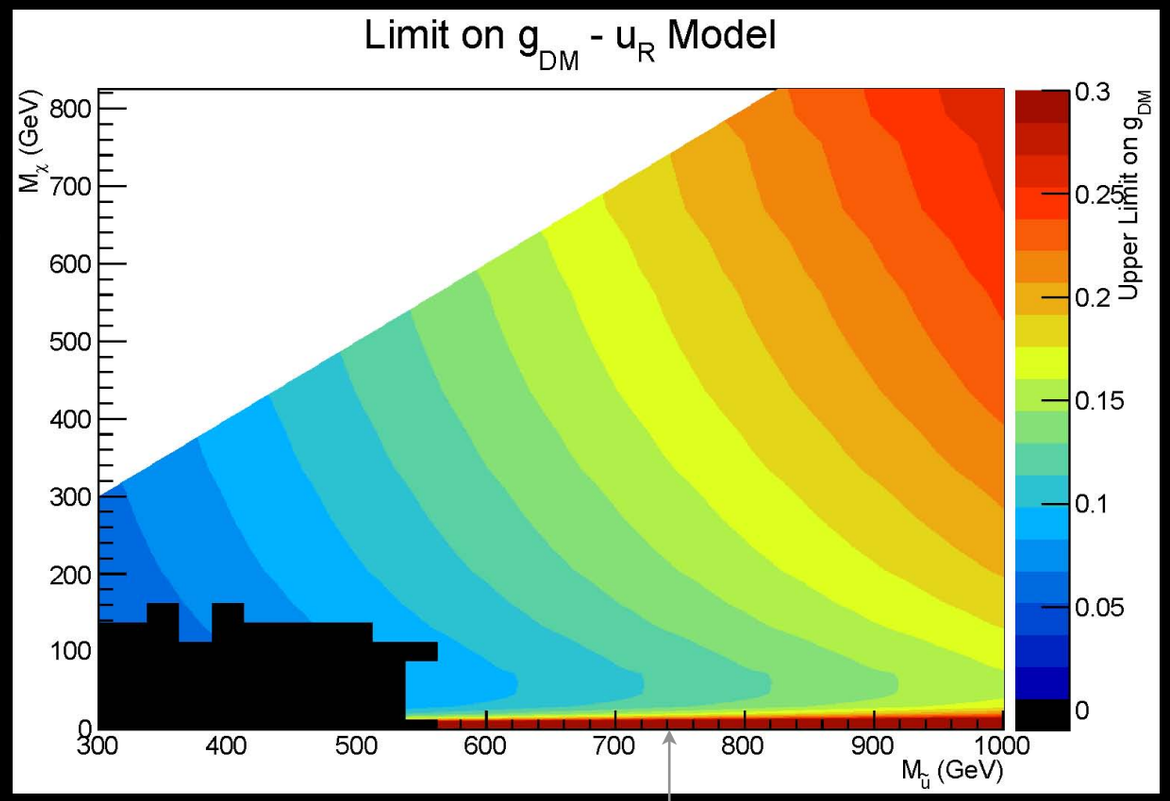


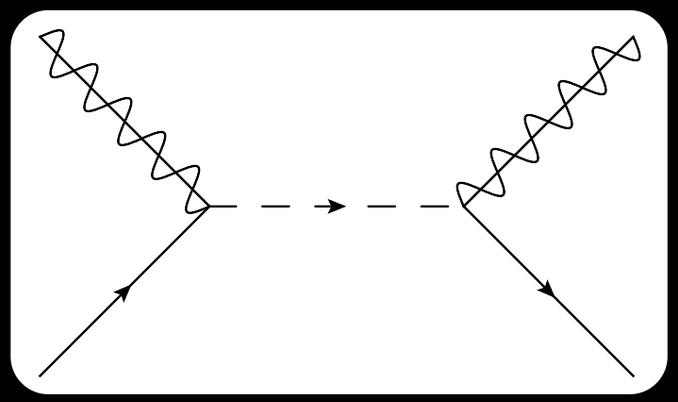
QCD production saturates the CMS limits, resulting in no allowed value of g.

$\tilde{u}_R$ Model

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

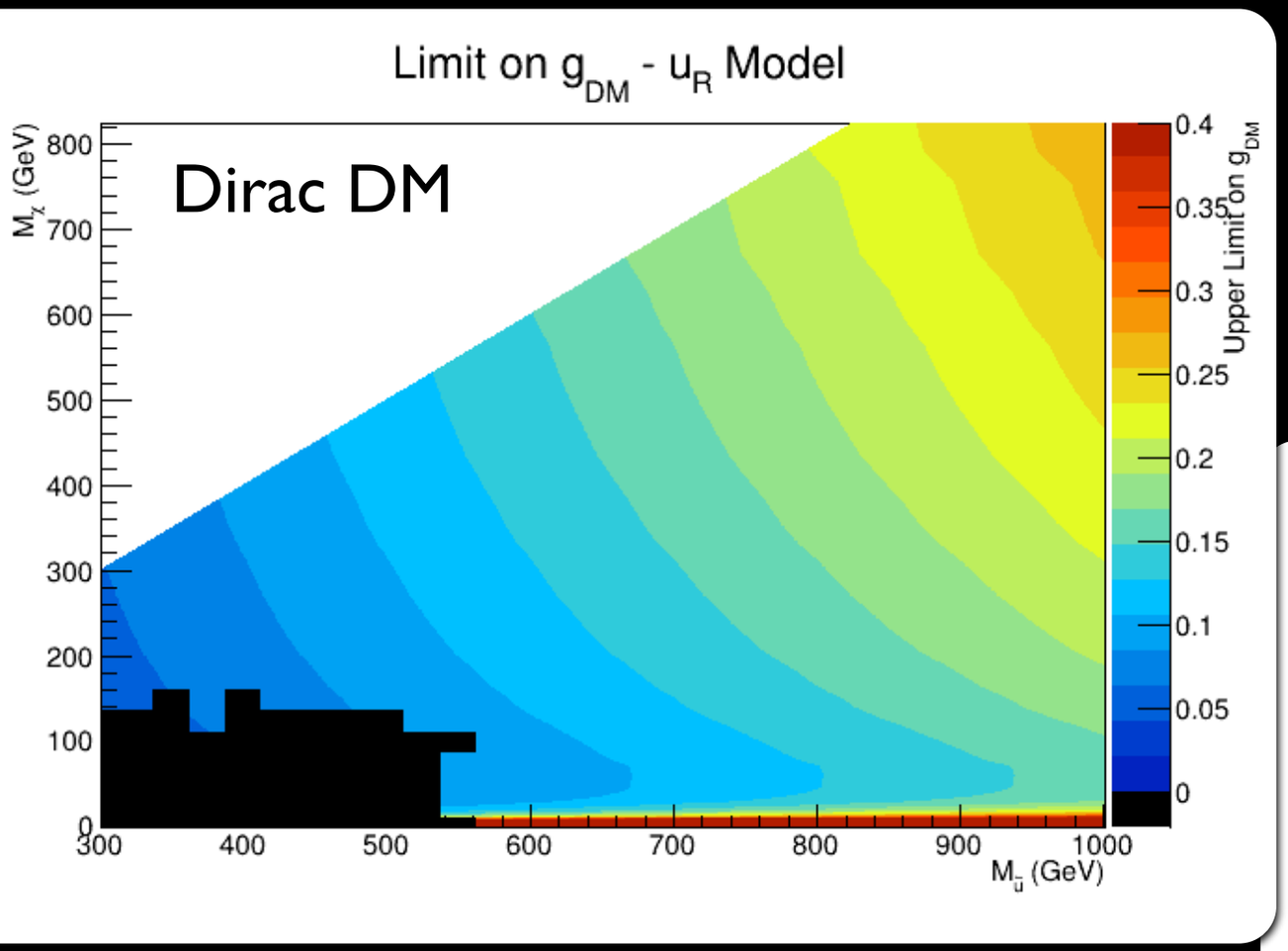
- A Dirac WIMP also has spin-independent scattering with nucleons. For most of the parameter space, there are bounds from the Xenon-100 experiment. (And recently LUX has improved these limits by about a factor of two...).
- Elastic scattering does not rule out any parameter space, but it does impose stricter constraints on the allowed size of the coupling in the regions the LHC left as allowed.





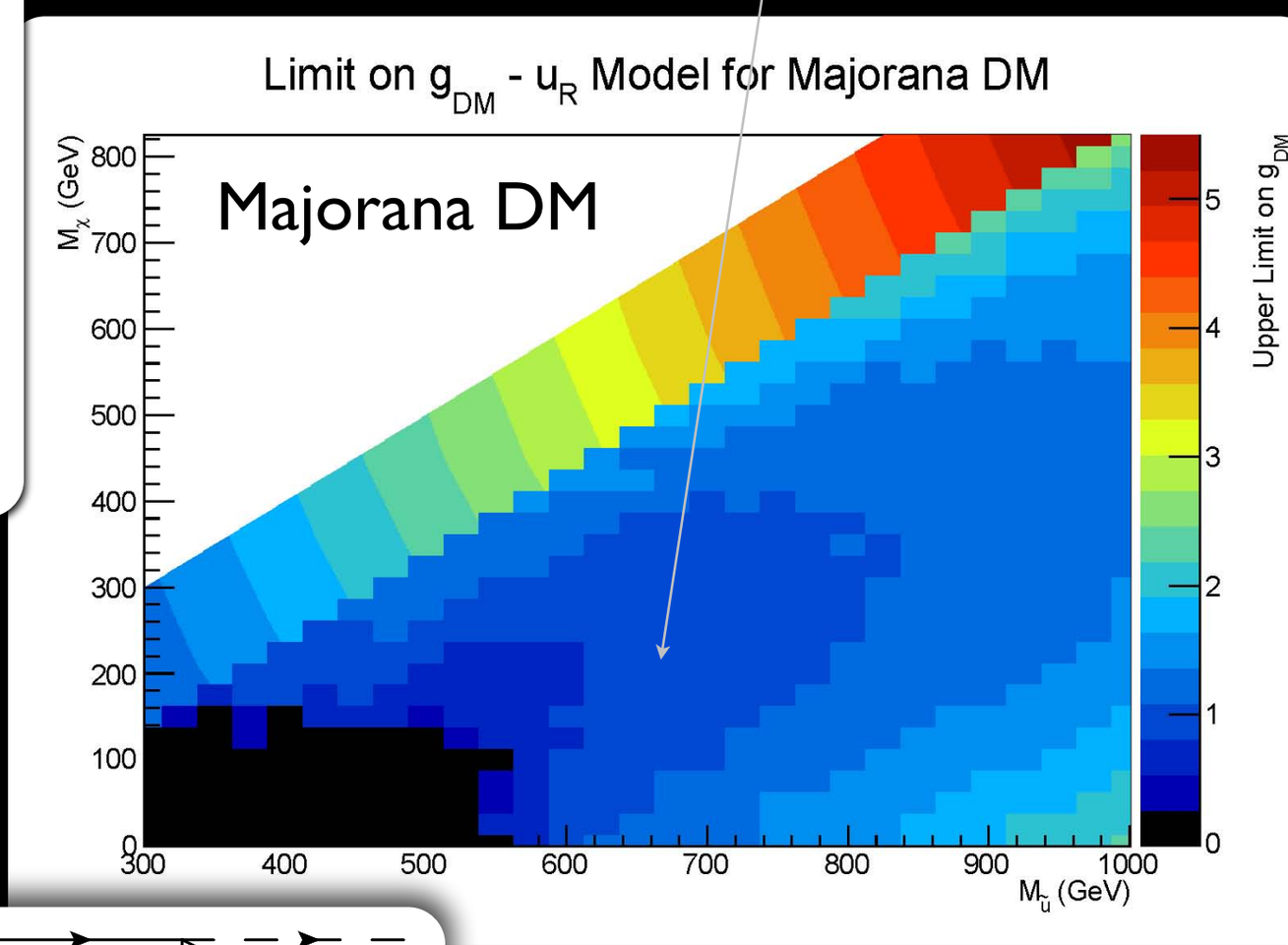
Traditional direct detection searches peter out for masses below about 10 GeV.

Majorana versus Dirac



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

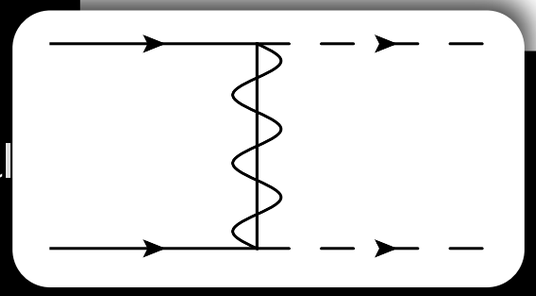
Collider bounds tend to dominate for Majorana DM.



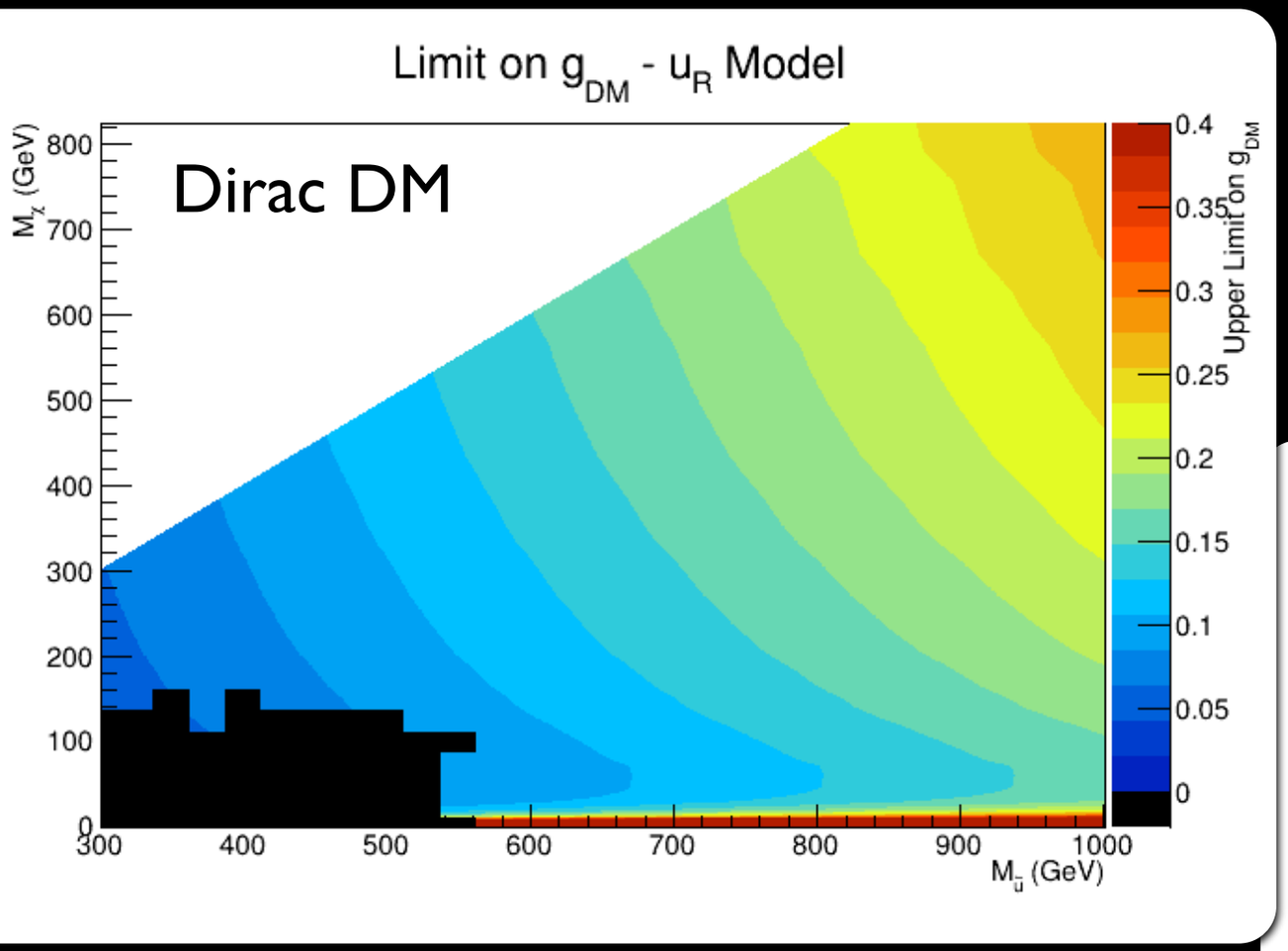
There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

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.

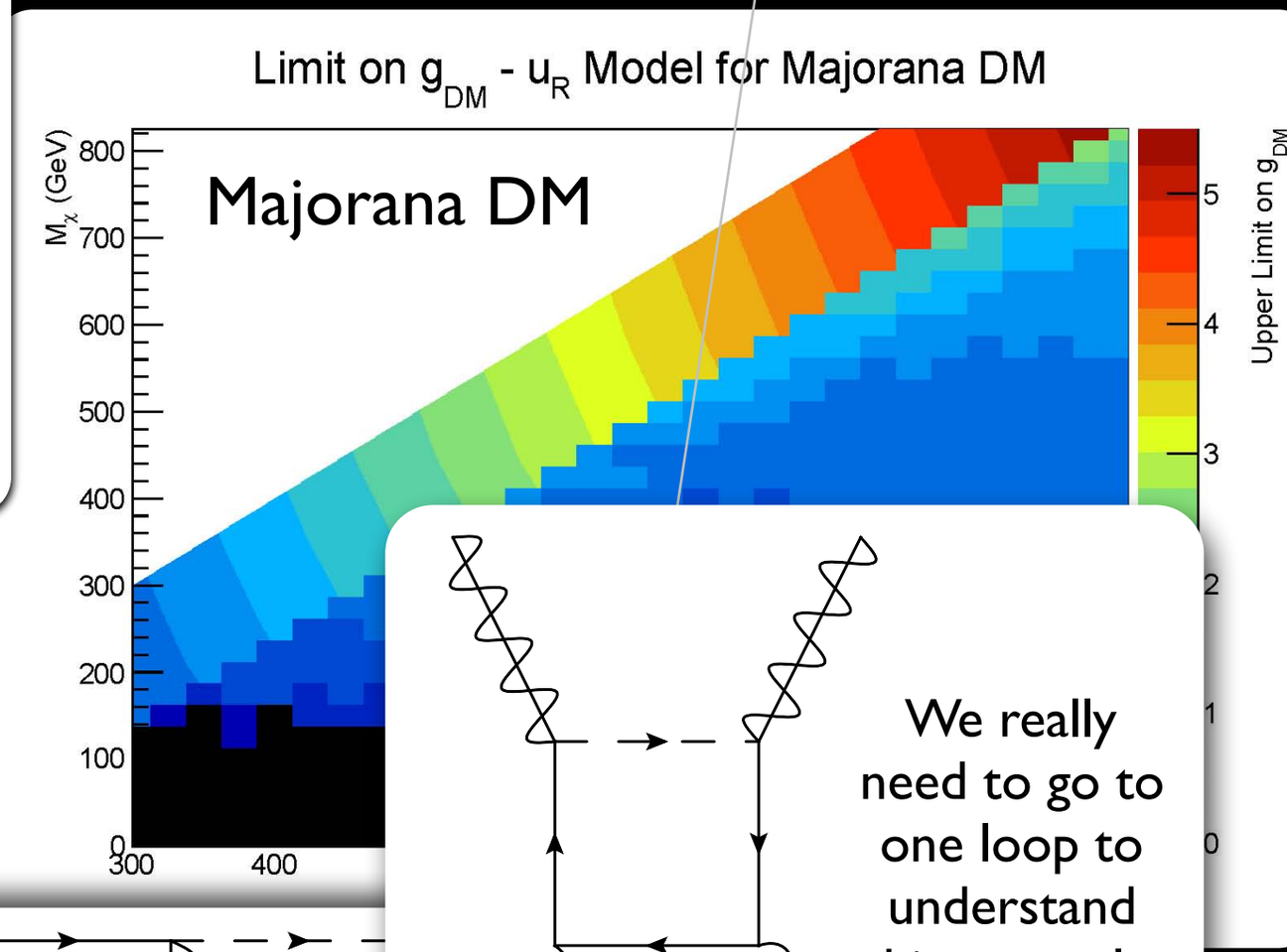


Majorana versus Dirac



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

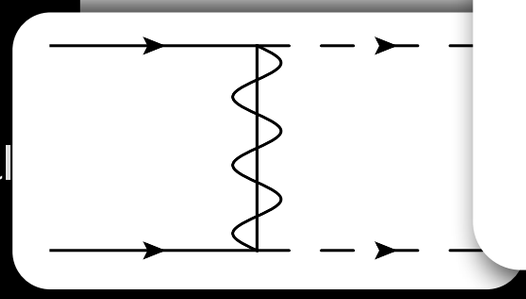
Collider bounds tend to dominate for Majorana DM.

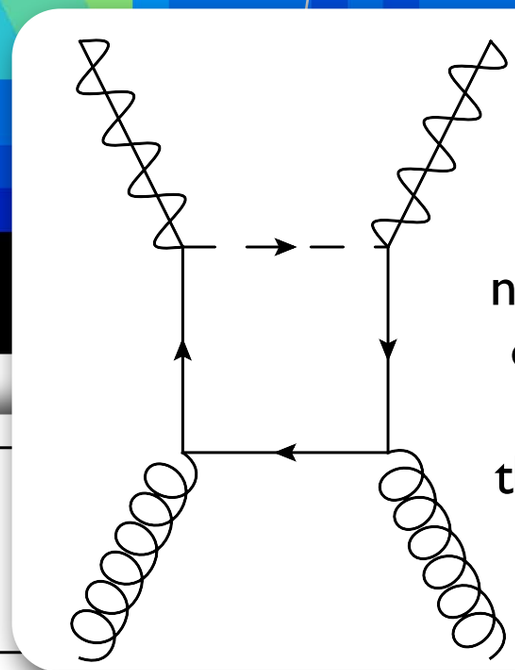


There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

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.

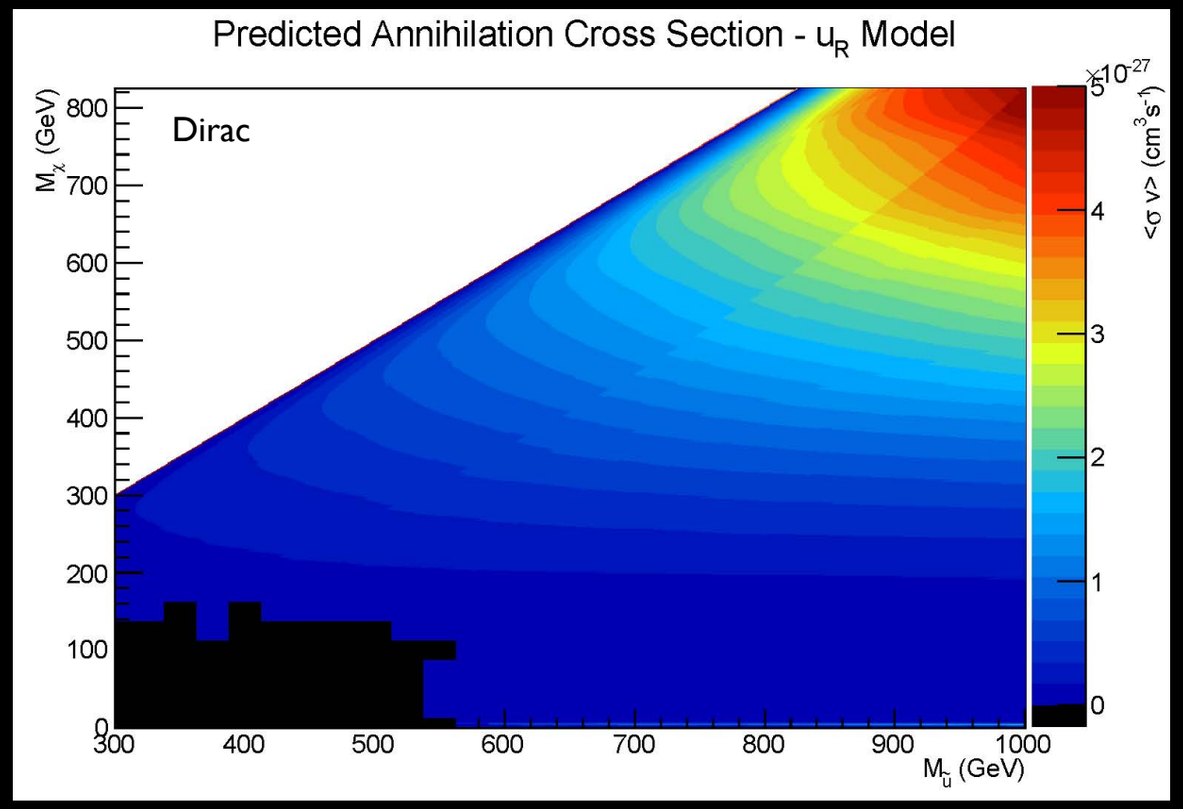


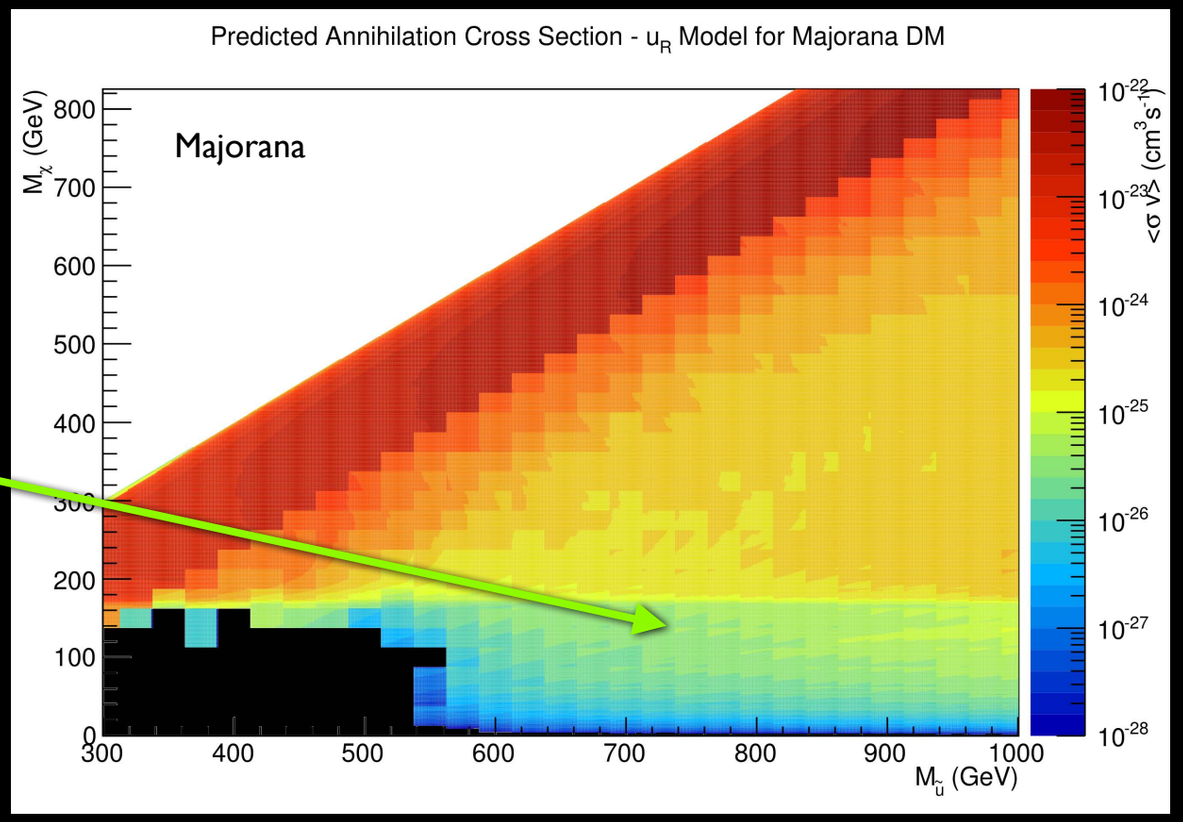


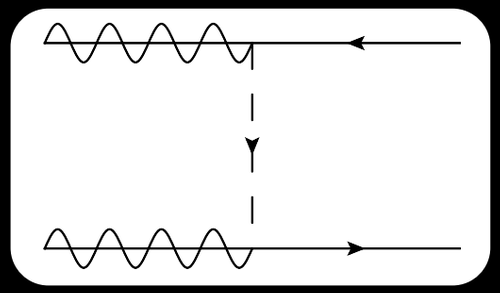
We really need to go to one loop to understand this properly.

$\tilde{u}_R$ 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).

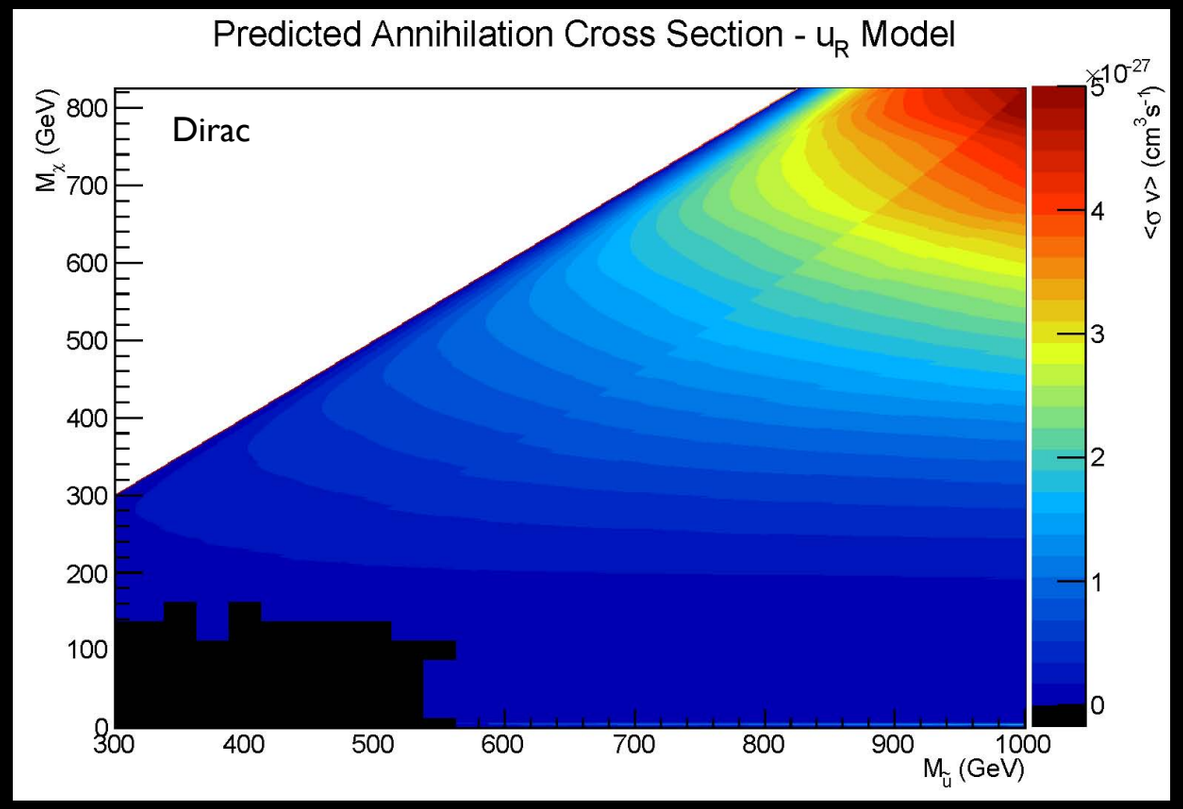


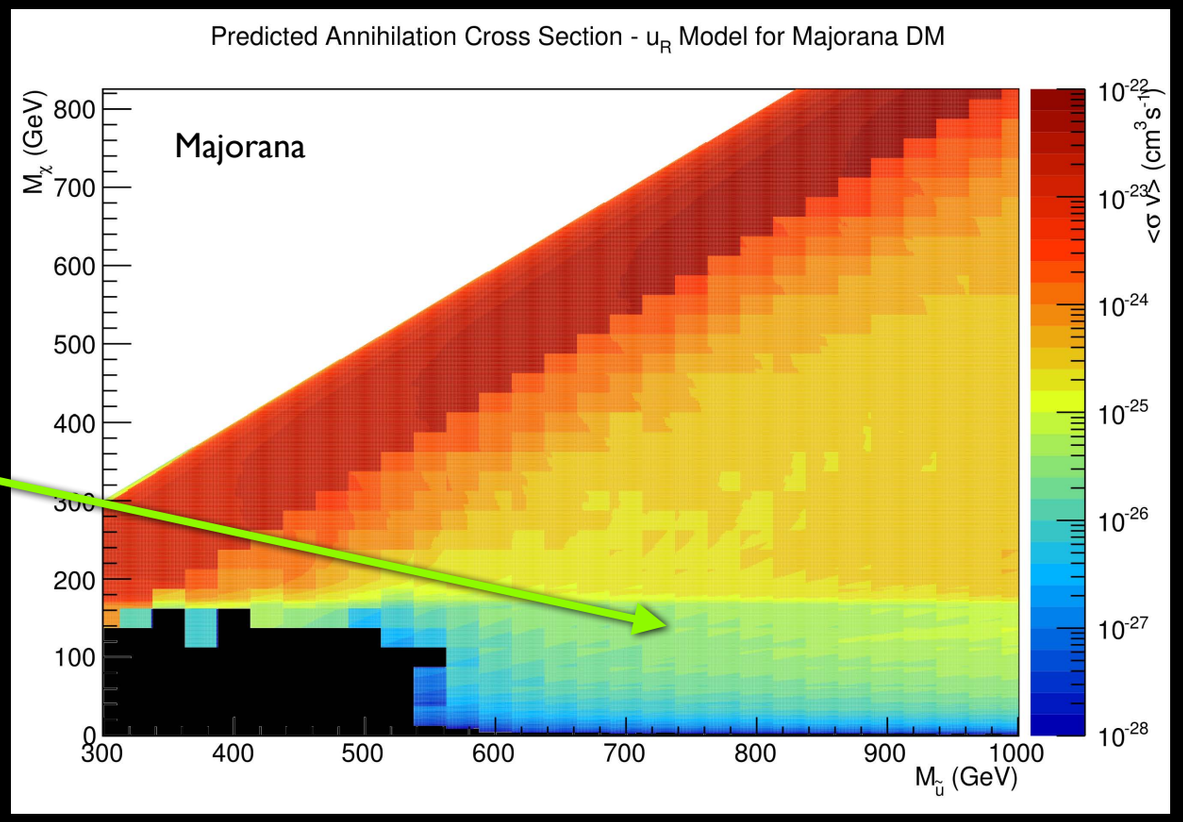


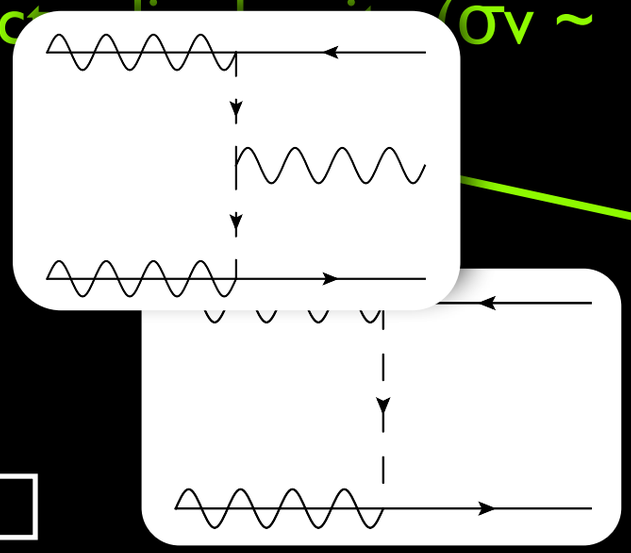


$\tilde{u}_R$ Model: Forecasts

- 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).



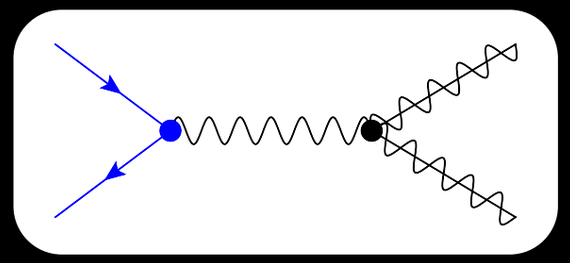




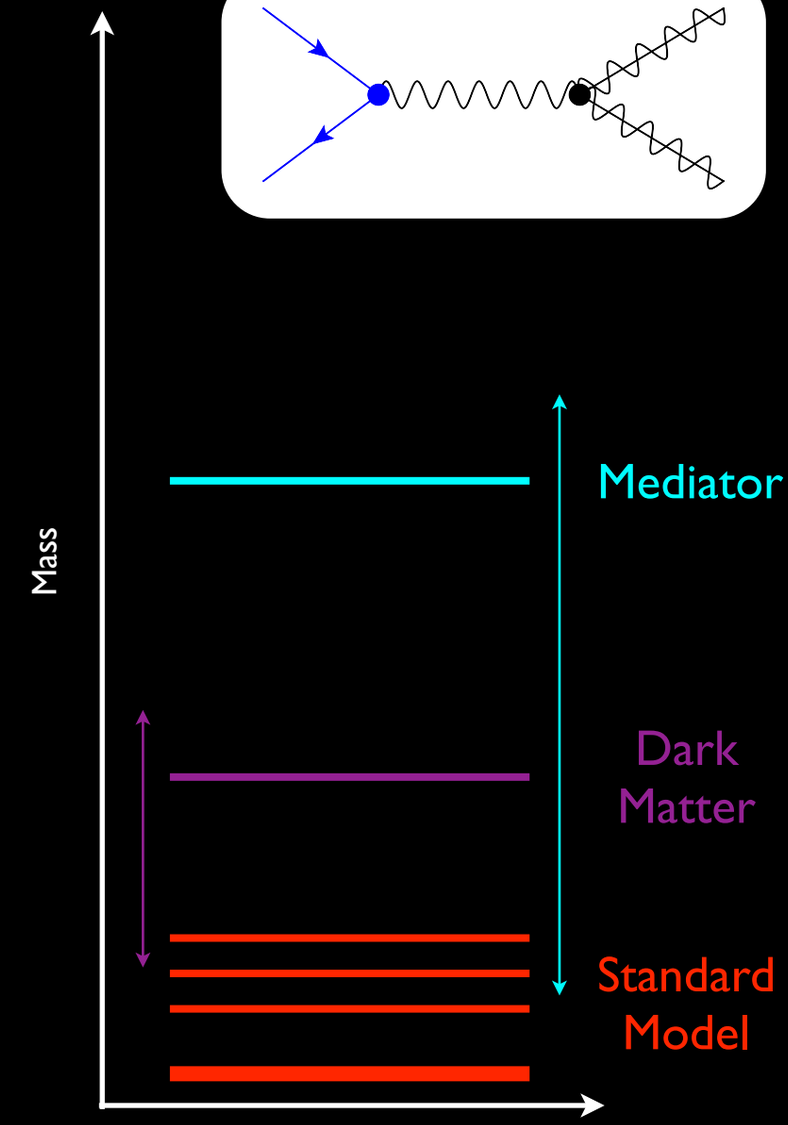
For the Majorana case, radiative corrections can be very significant...

Garny, Ibarra, Rydbeck, Vogl 1403.4634

S-Channel :Vector

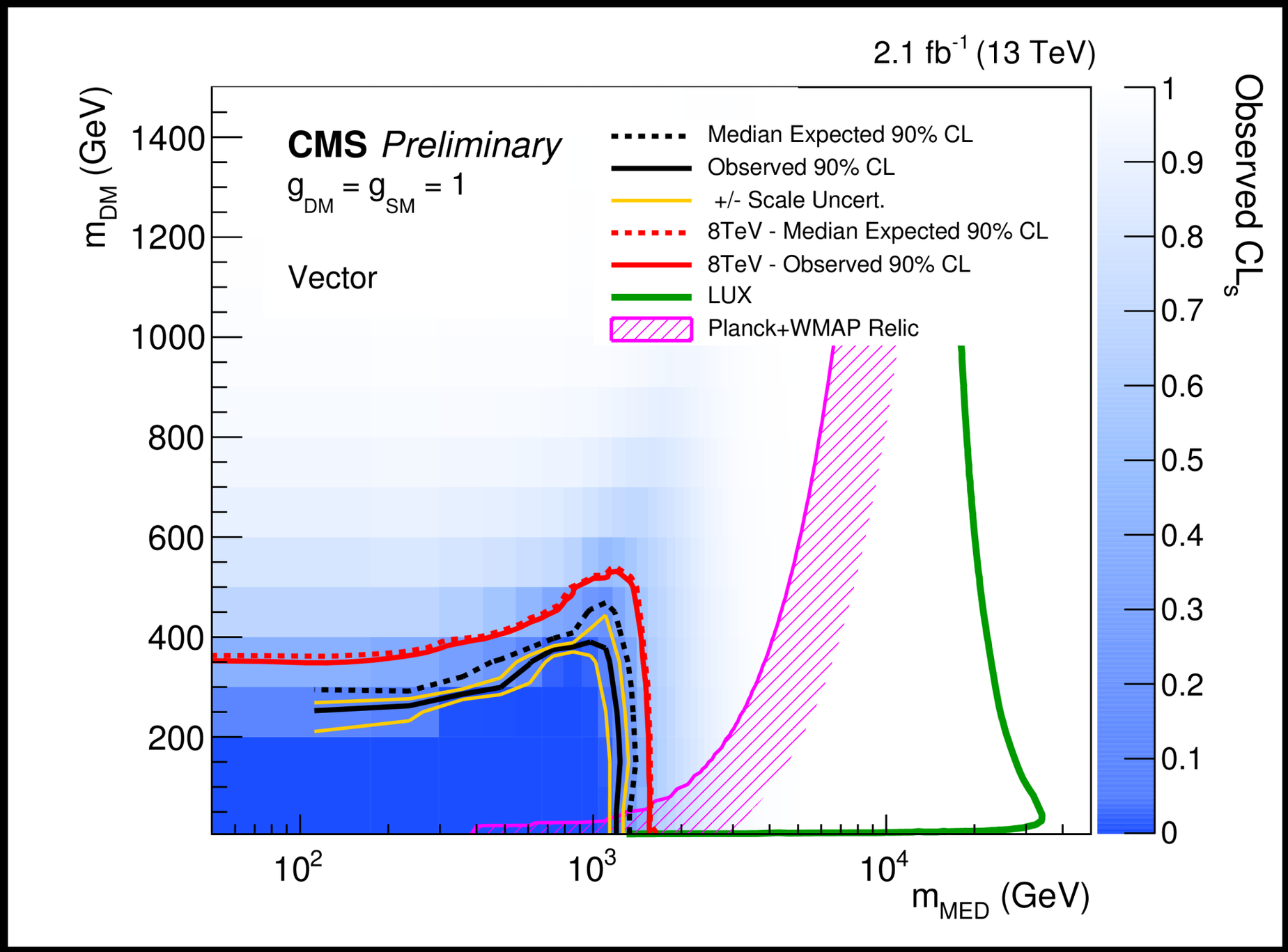


- Vector models have more parameters consistent with MFV.
- uR, dR, qL, eR, lL all have family-universal but distinct charges, as does H.
  - We would like to be able to write down the SM Yukawa interactions.
  - Quarks need not have universal couplings.
- There could be kinetic mixing with $U(1)_Y$.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



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

S-Channel :Vector



NB: These quark couplings are excluded by dijet resonance searches for mediator masses < about 1 TeV.!

Dreiner, Schleier, Tattersall
1303.3348 & EPL

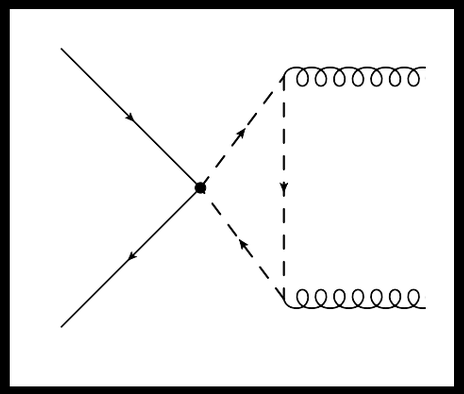
All couplings set equal to 1.
Current understanding is dominated by σ_{SI} for most masses, though CMS wins at the smallest masses, as usual.

Dark Matter Coupled to Gluons

Godbole, Mendiratta, TMPT 1506.01408 & JHEP
+Shivaji 1605.04756
Bai, Osborne 1506.07110 & JHEP

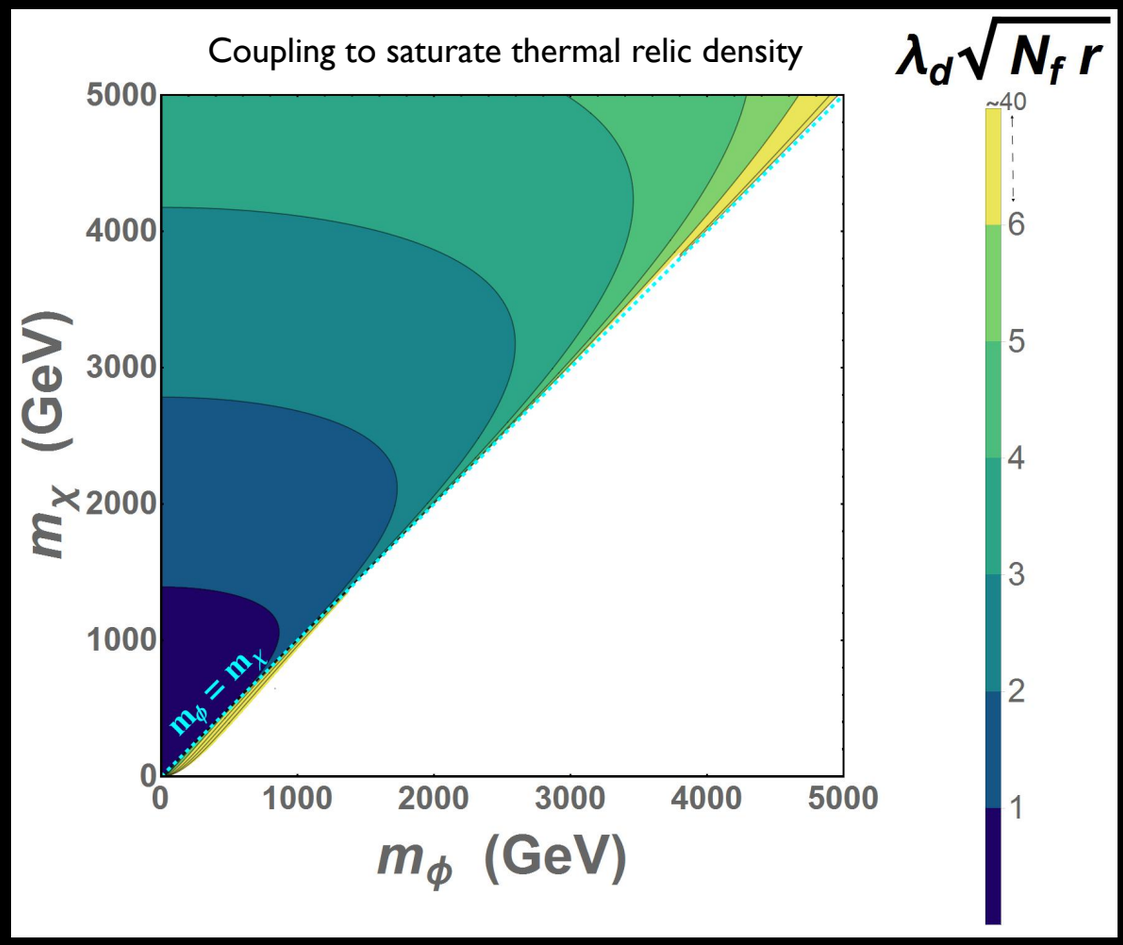
- An interesting variation is possible when both the dark matter and the colored mediator are scalars.
- In that case, a quartic interaction can connect the two.

$$\lambda_d \; |\chi|^2 |\phi|^2$$



The dominant coupling to the SM is often at one loop to gluons!

- This interaction does not require the scalar to be Z_2-stabilized, and (given an appropriate choice of EW charges) it can decay into a number of quarks, looking (jn some cases) more like an R-parity violating squark.
- The color and flavor representations (r, Nf) of the mediator are free to choose.
- For perturbative λ, a thermal relic actually favors $m_\varphi < m_\chi$ so annihilation into $\varphi\varphi^*$ is open.

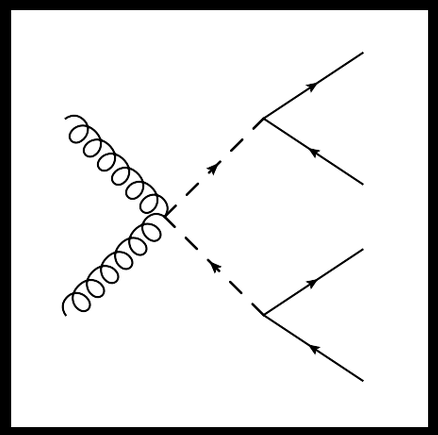


Mediator Searches

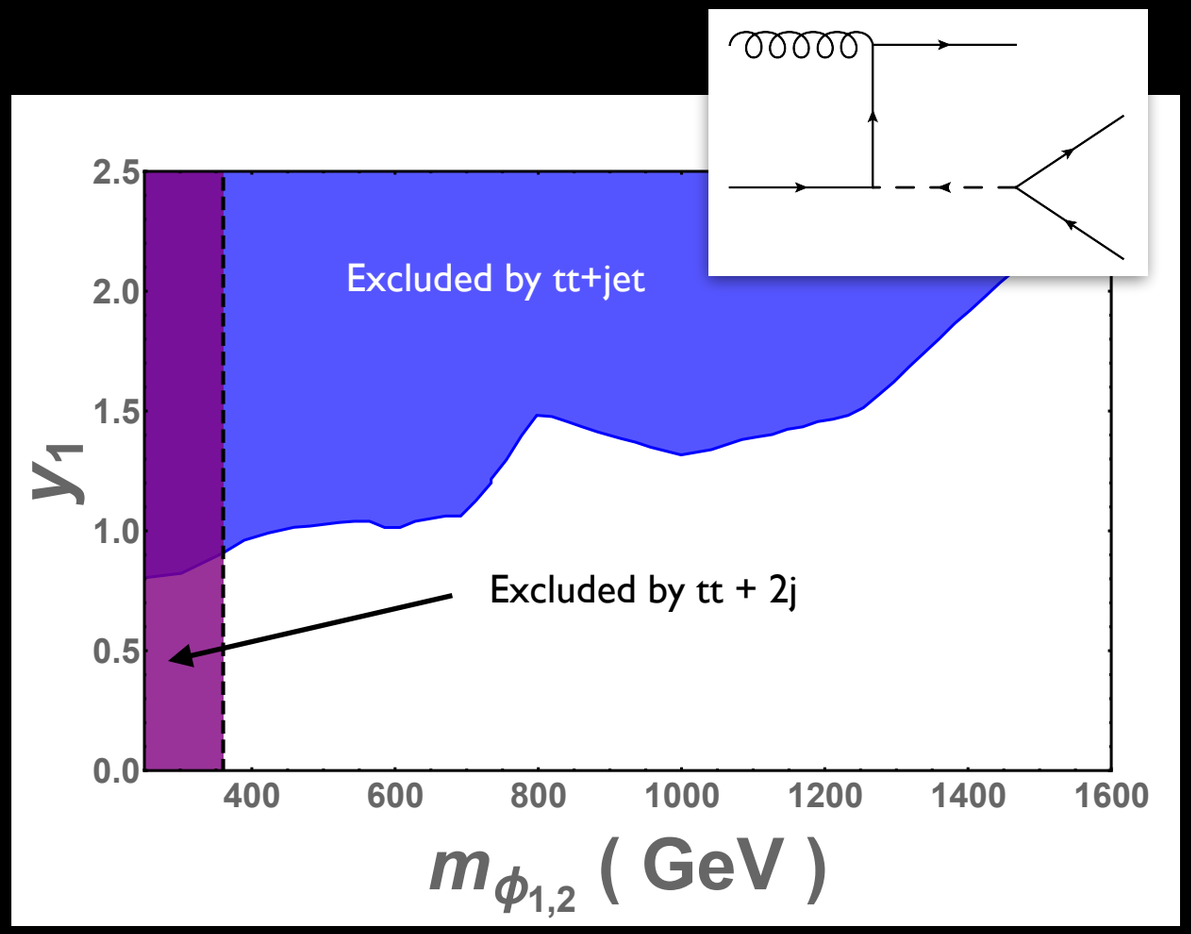
- The physics of the mediators is model-dependent, depending on the color and EW representation.
- As a starting point, we considered mediators of charge 4/3 coupling to 2 uR quarks.
- In this case, a MFV theory can be obtained by coupling anti-symmetrically in flavor indices:

$$y\epsilon^{ijk}\phi_i\bar{u}_j u^c_k + h.c.$$

- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.
- All of these constraints are rather weak.

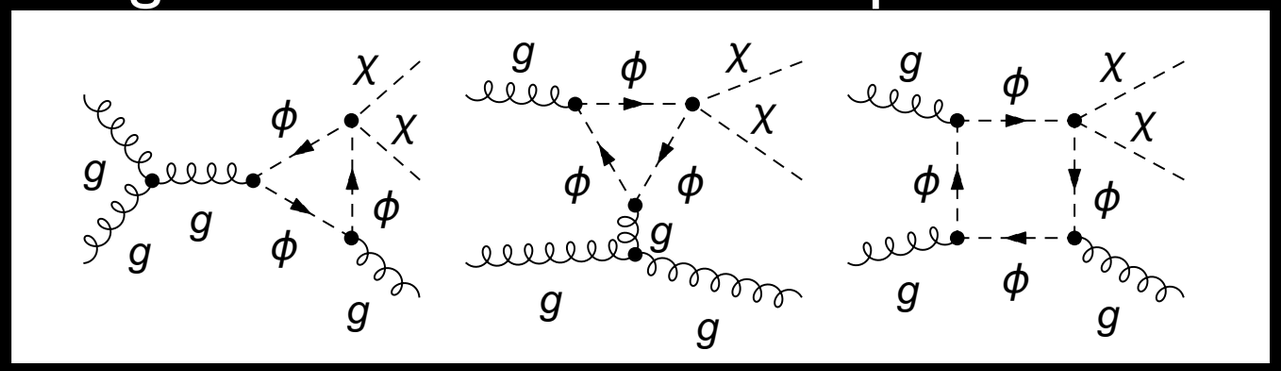


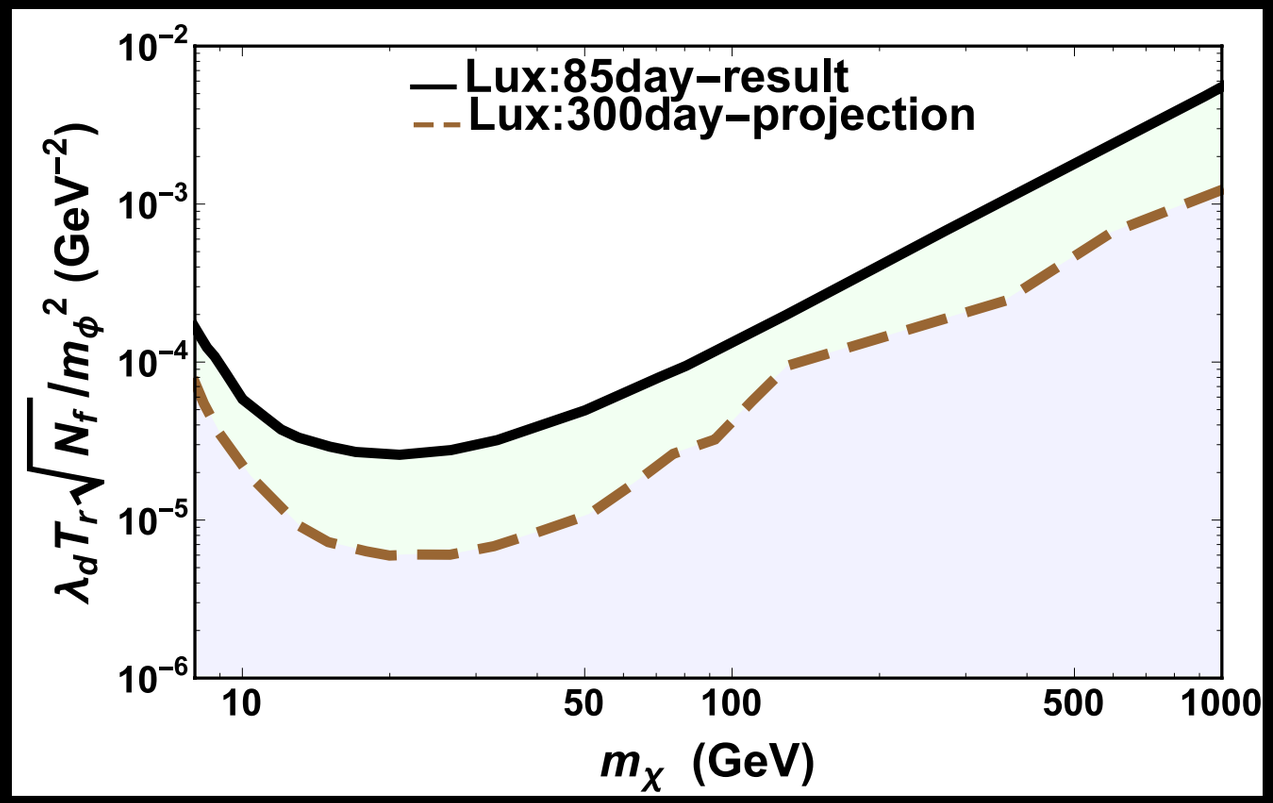
Decays into unflavored jets are bounded by m_φ > 350 GeV.



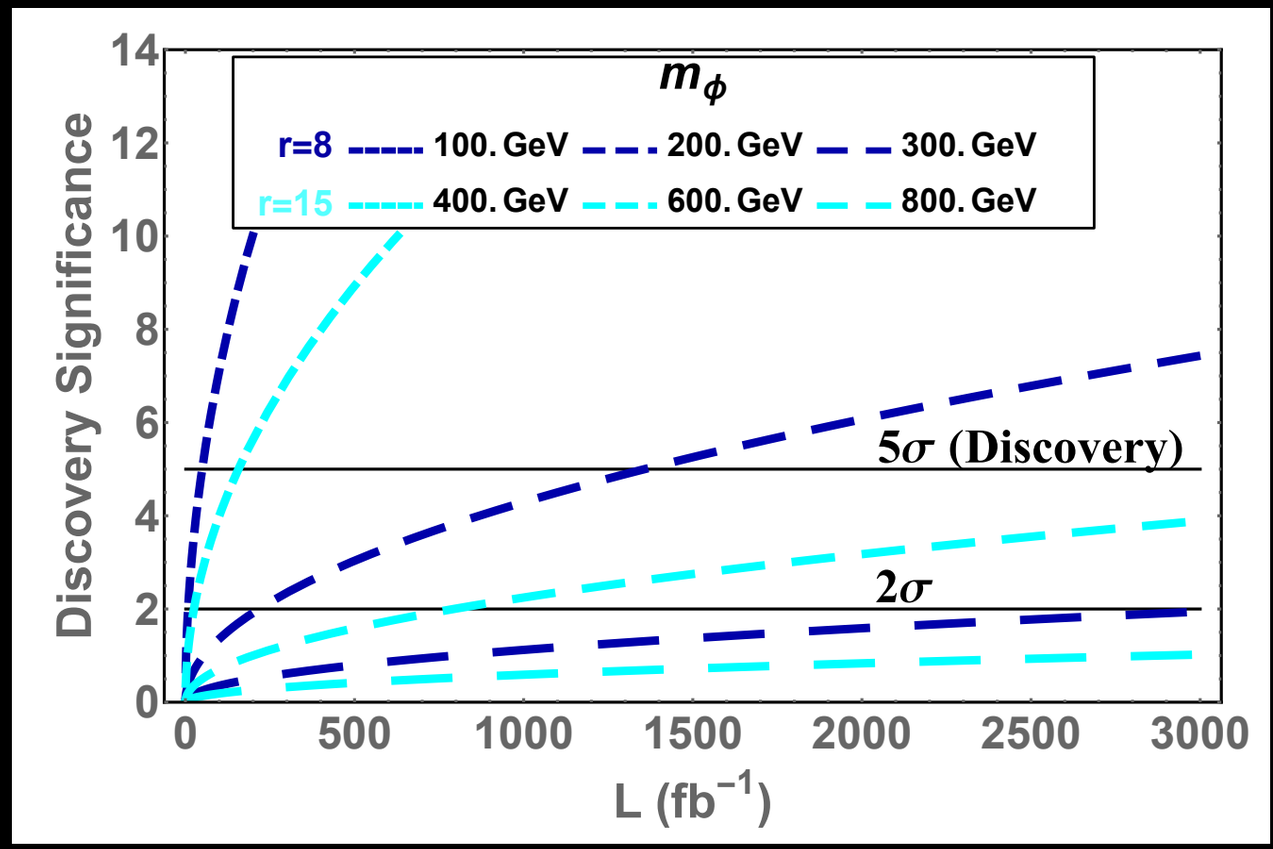
DM Searches

- Direct detection generally provides a strong bound unless the dark matter mass is particularly small.
- At a hadron collider, the mono-jet signature occurs at one loop.





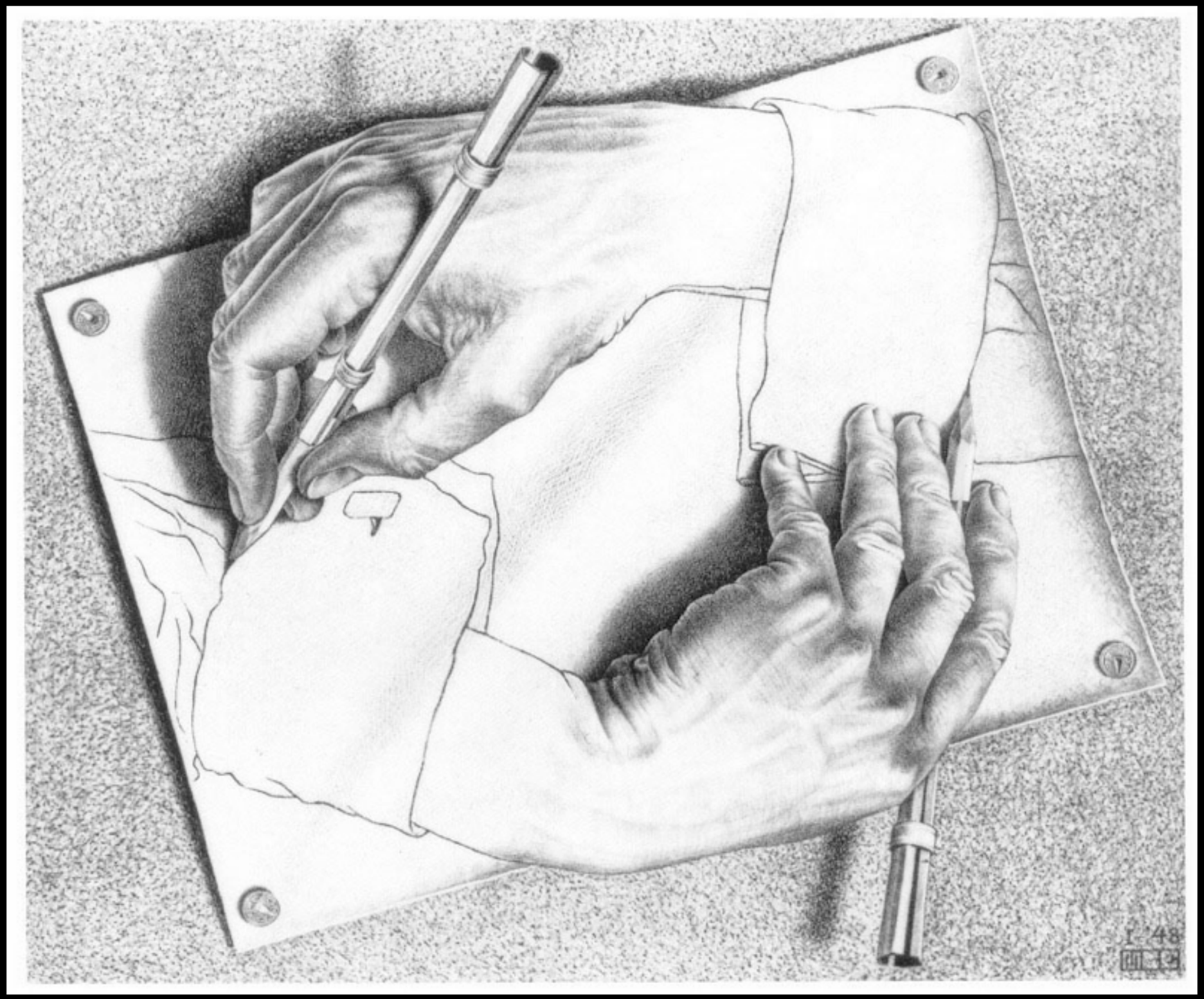
- As a result, prospects at the LHC are not particularly hopeful, though for large enough r and λ, it is possible to see something with a very large data set.
- A 100 TeV pp collider would do better…



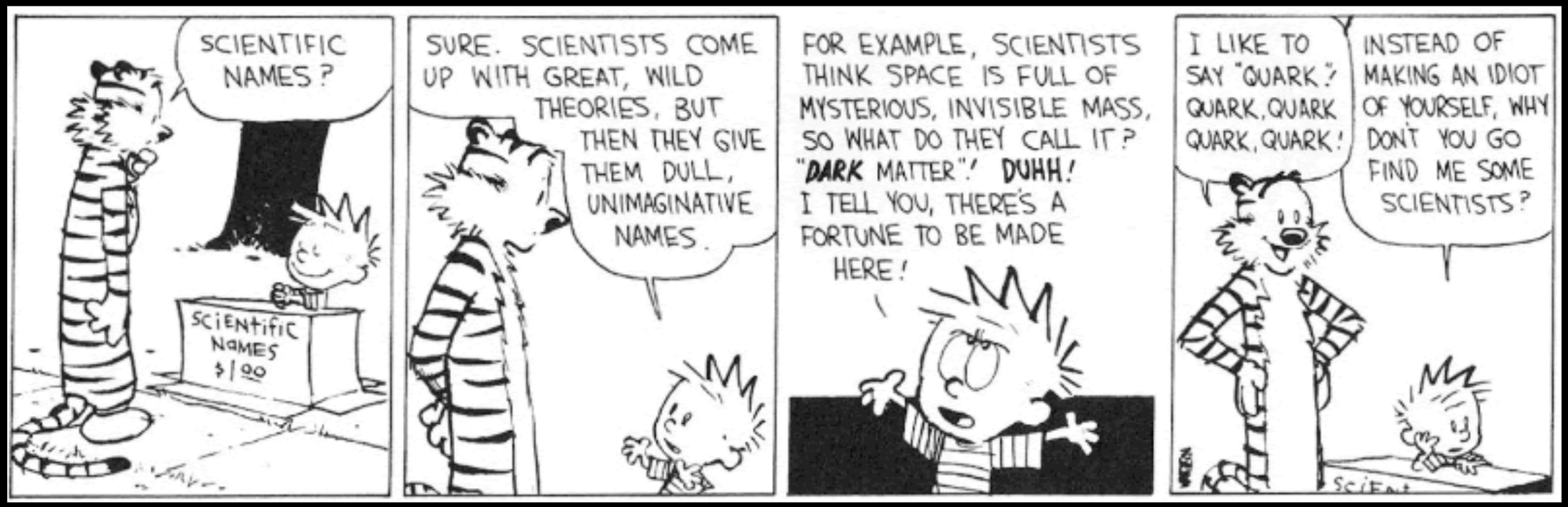
Recap: EFTs and Simplified Modes

- It can be interesting explore less complete theories, which may not describe all of Nature, but perhaps can still capture some of the most important features of dark matter.
- Contact interactions cover theories where the mediating particle is heavy, and some interesting cases where the dark matter is a dark composite.
- Simplified models fill a niche between complete theories like the MSSM and effective field theories which assume the mediators are inaccessible.
- All three theoretical constructions reveal the importance of indirect searches, direct searches and the LHC, to cover the widest range of dark matter parameter space.
- These searches complement each other, and give more information together than any single one can provide separately.

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?