A Lecture on Dark Matter at Colliders

Eduardo Pontón

Dark Matter and Neutrino Detection School, July 23-Aug. 3, 2018

ICTP-SAIFR

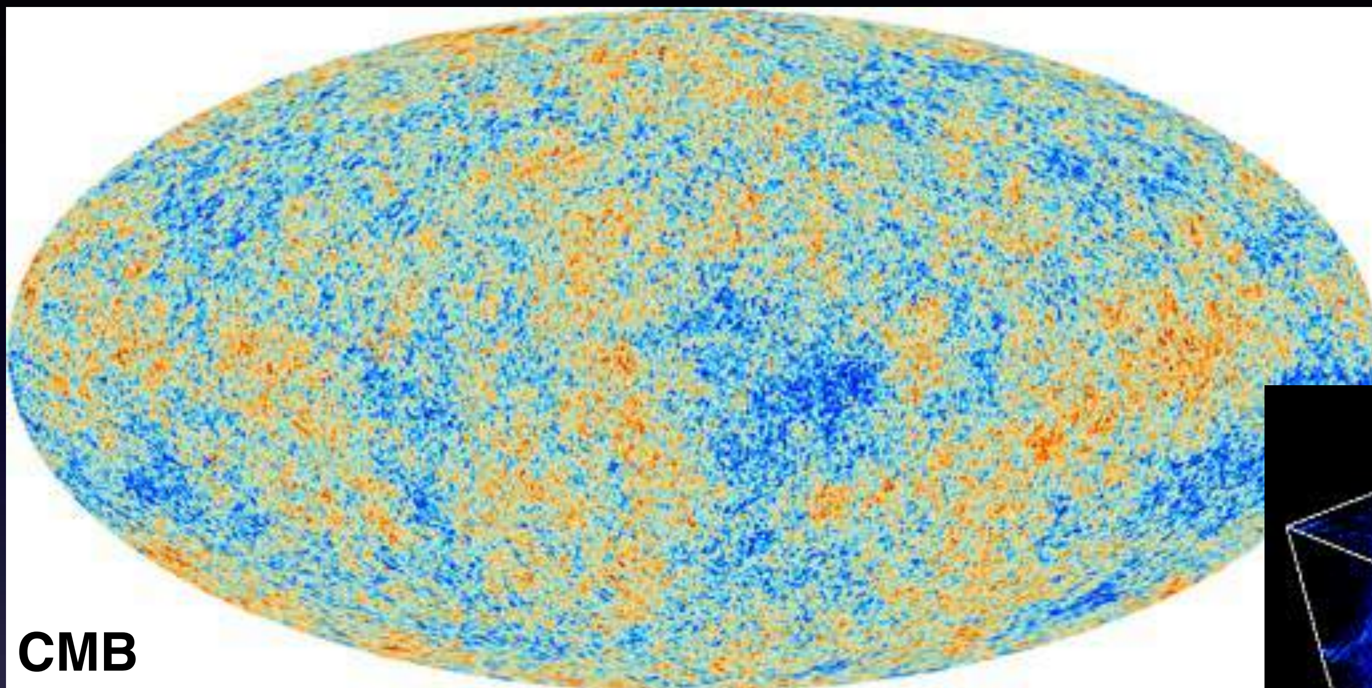
ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

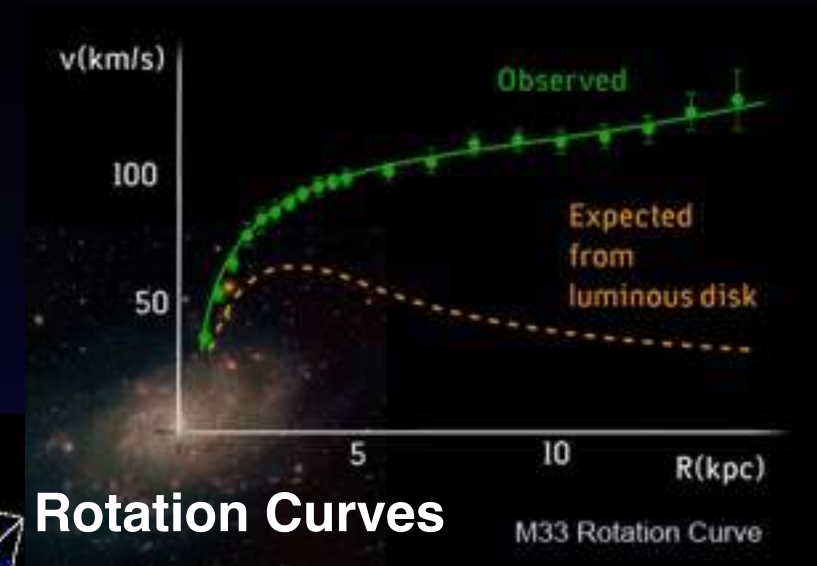
IFT - UNESP INSTITUTO DE FÍSICA TEÓRICA

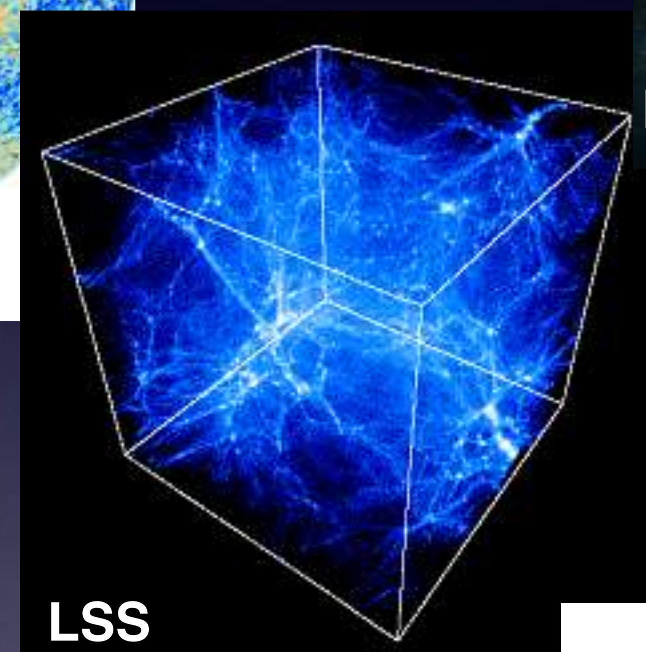
Outline

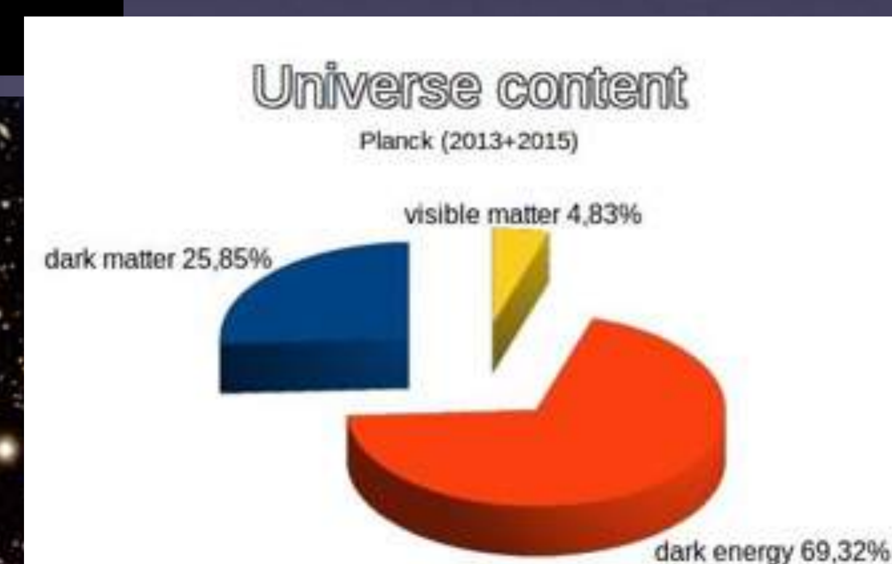
- The general picture: Searches for Dark Matter (DM)
- Colliders and DM
- The role of models
    - “UV complete” models
    - Simplified models
    - Effective Theories
- DM Search Strategies at Colliders
- Connecting to other Searches
- Further References

Evidence for DM









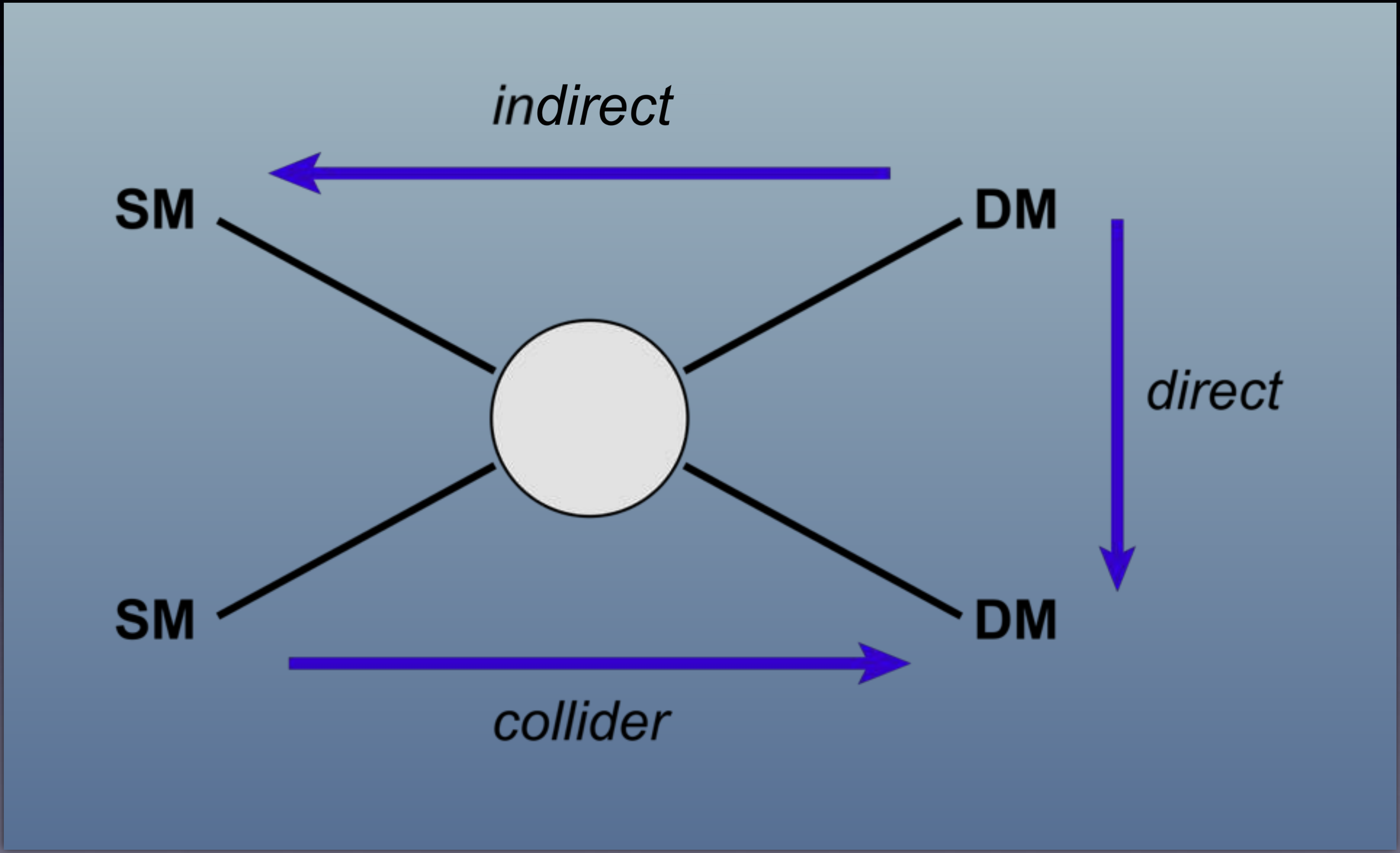
The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
    - ☐ Yes ☐ No

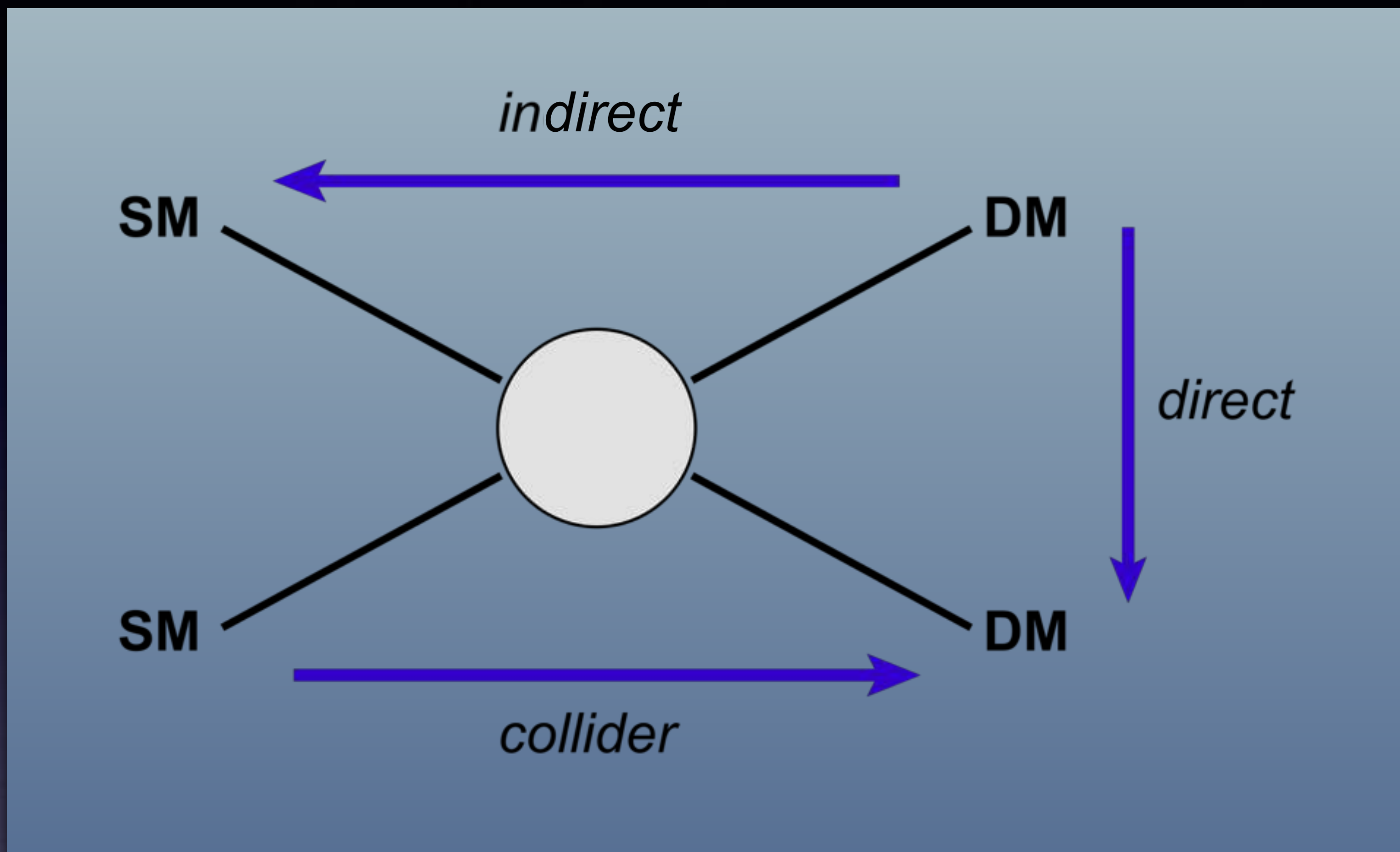
Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?
- ☐ Thermal Relic?
    - ☐ Yes ☐ No

Complementarity



Complementarity



In actuality:

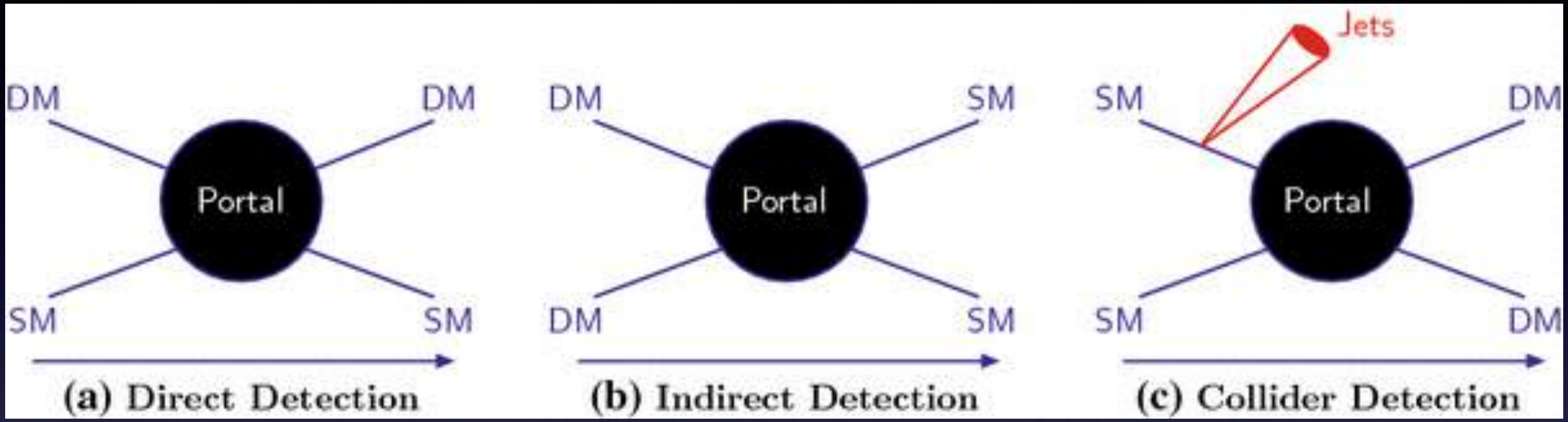
Correlations may or may not be observable

Basic caveats:

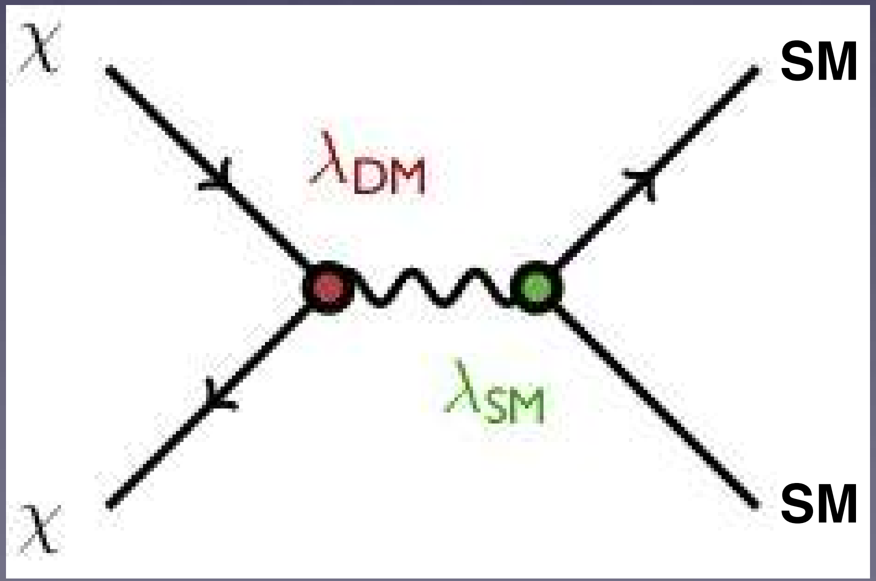
- “SM” may refer to different particles
- “DM” may also refer to different particles!

Still: having access to different aspects is a very attractive program!

Mediators/Portals



Renormalizable example



Dark Matter Candidates

Basic requirements

- Sufficiently long lived (may or may not eventually decay)
- Sufficiently weakly interacting, e.g. no electric or color charges

Perhaps additionally

- Couplings and mass constrained by relic density considerations

  (but this is subject to cosmological assumptions, for example)

Why Colliders

Thermal Relics → $$\Omega \sim \frac{1}{\langle \sigma v \rangle}$$

→ $$\langle \sigma v \rangle \sim 1 \text{ pb}$$

Typical weak scale cross section, accessible at current colliders!

Possibility to produce DM and observe properties in a controlled, well-understood environment.

But no guarantees:

- DM may lie beyond reach in mass (both high or low)
- DM may interact too weakly (e.g. axions)

- Direct/indirect DM searches bring in additional uncertainties, for example, of astrophysical nature.
- Collider experiments are “cleaner"
- However, DM sector may not be within the collider reach
- Cannot tell if signal from DM (may decay outside the detector)

In a collider environment, the “DM particle” may or may not be what is out there filling the universe. But for simplicity we will still refer to it as

“DM particle”

Models and DM Searches

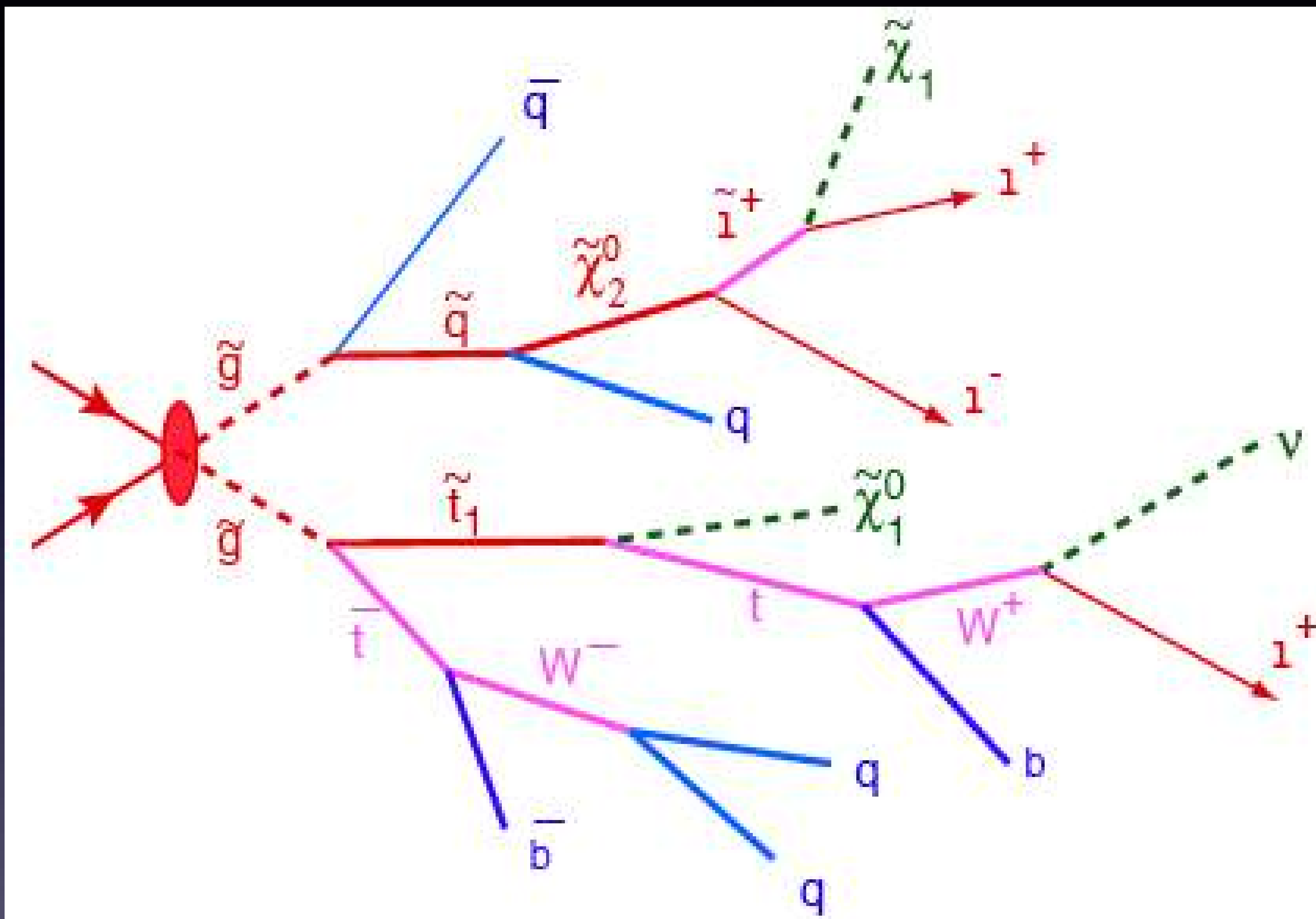
“Full-fledged” Models

Often motivated by reasons other than Dark Matter…

Guided by other considerations, such as

- Addressing questions left open by the SM of Particle Physics
- Implementations of elegant theoretical ideas
- Explorations of possible worlds…

“Full-fledged” Models



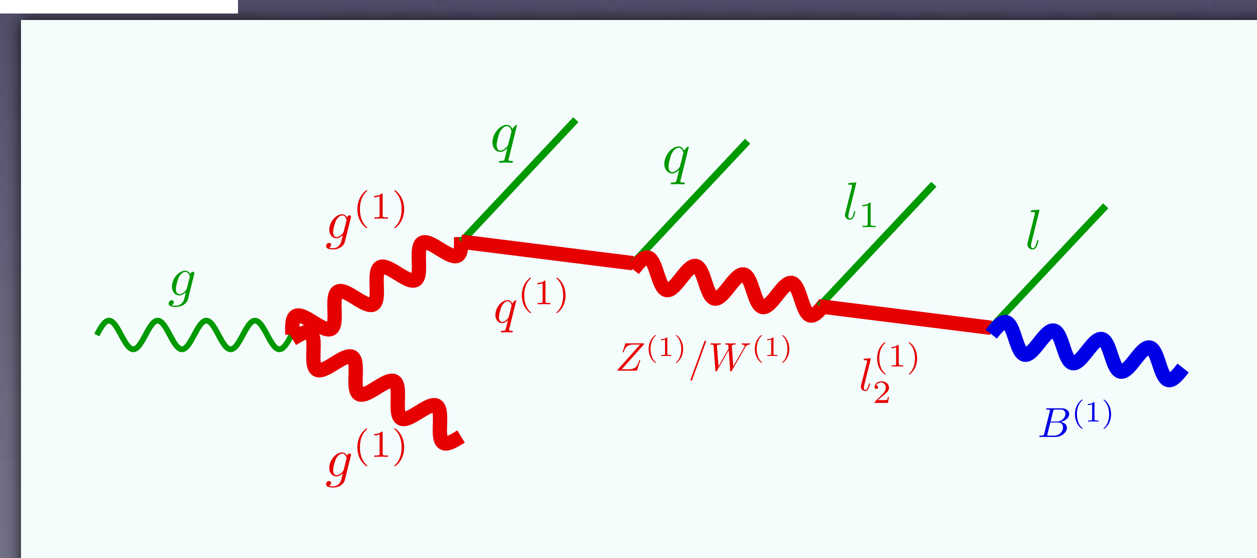
SUSY

(as in the Minimal Supersymmetric SM)

… or the “bosonic version”

UED

(Universal XDim)



“Full-fledged” Models

Can be fairly complicated (as is the SM!)

Large number of unknown parameters…

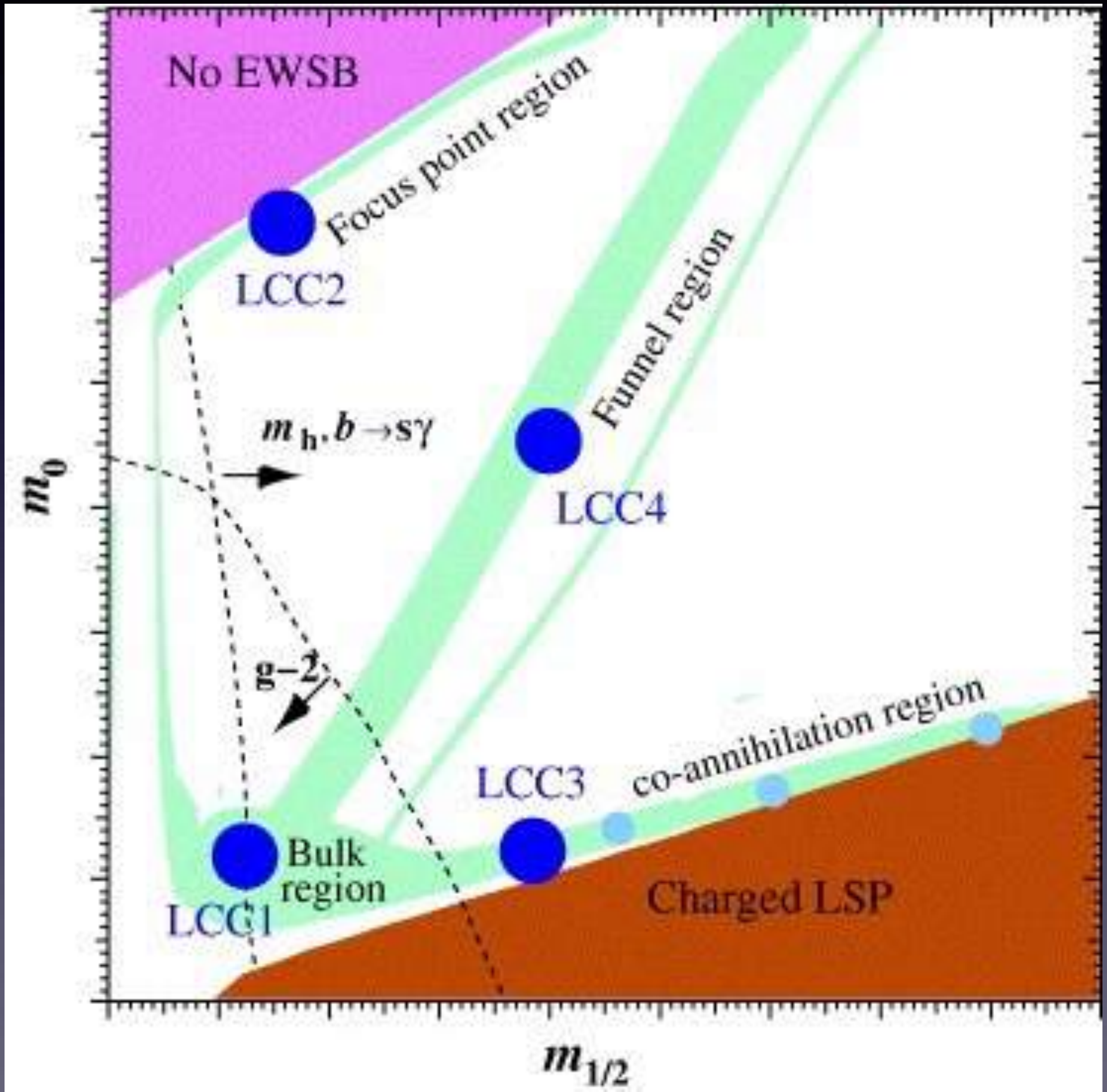
Not all of those are relevant in the context of a specific question, such as the study of the DM phenomenology

Nevertheless can still be very complicated to analyze

→ benchmarks, or brute force scans

For presentation of experimental results, drastic reduction of the parameter space necessary… often not well motivated.

“Full-fledged” Models



Still, may learn that special situations might be required…

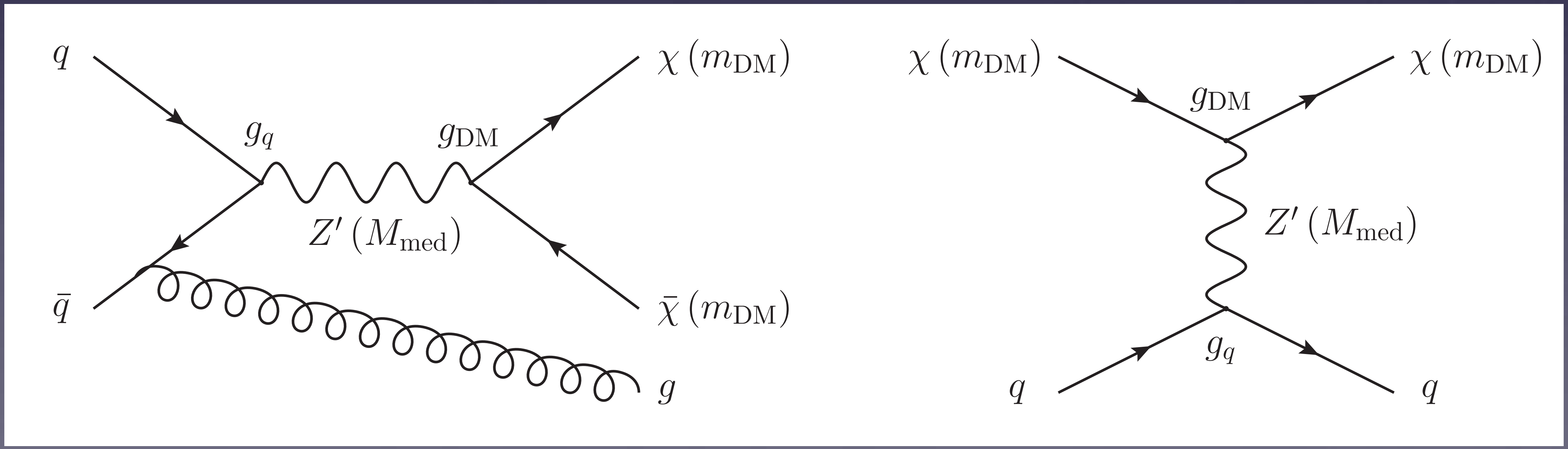
A more practical approach

Simplified Models

Keep only the relevant (few) degrees of freedom

Manageable number of parameters, treated in a theoretically consistent manner (a well-defined field theory)

A reasonably good way to present the experimental information



<u>*See "Simplified Models for DM Searches at the LHC" (2015)*</u> LHC DM Working Group

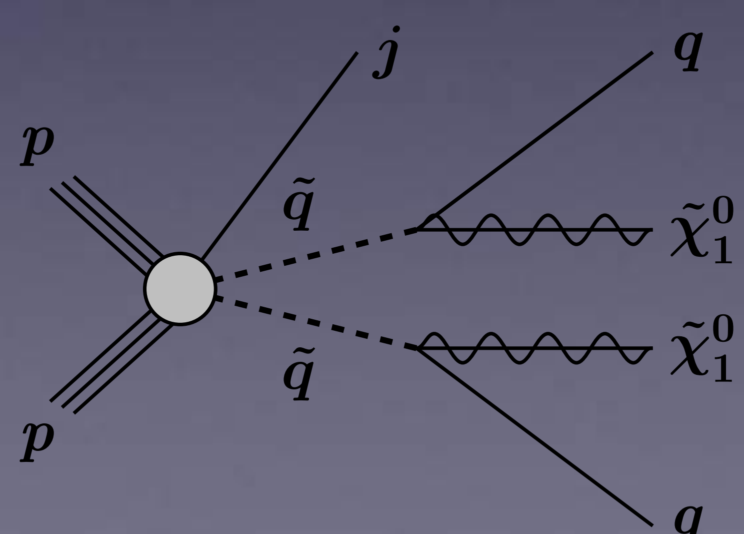
Simplified Models

Colliders are primary "mediator discovery" machines

→ Tighter constraints on mediator mass than DM mass

Classes of mediators:

- Known mediators, e.g. "Higgs Portal"
- Exotic mediators, e.g. "SUSY" like models

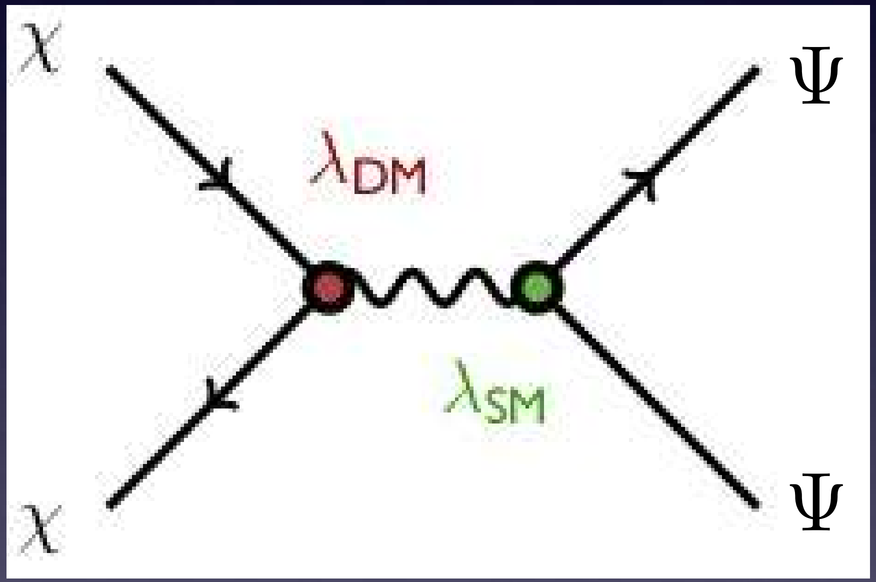


Often SUSY notation used more generically

One More Simplification?

Effective Theories

If the mediators are heavier than the relevant energies, may integrate them out and analyze the physics in an effective theory



$$\frac{1}{\Lambda^2}\chi\chi\Psi\Psi$$

$$\frac{1}{\Lambda^2} = \frac{\lambda_{\rm DM}\lambda_{\rm SM}}{M_{\rm med}^2}$$

Details of operator(s) reflect the properties of underlying interaction

Effective Theories

Name	Operator
scalar	$\bar{\chi}\chi\bar{q}q$
pseudo-scalar	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$
vector	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
axial-vector	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
tensor	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

see Goodman et. al. (1008.1783) for more

Effective Theories

Such effective contact terms usually well-justified (for given models) in low-energy environments, such as in direct/indirect signals

They have also been used at the LHC, to derive bounds on Λ

Not surprisingly, the bounds are of the same order as the available energies, i.e. 100 GeV to TeV

Note that the effective scale depends on a single combination of couplings and mass

$$\frac{1}{\Lambda^2} = \frac{\lambda_{\rm DM}\lambda_{\rm SM}}{M^2_{\rm med}}$$

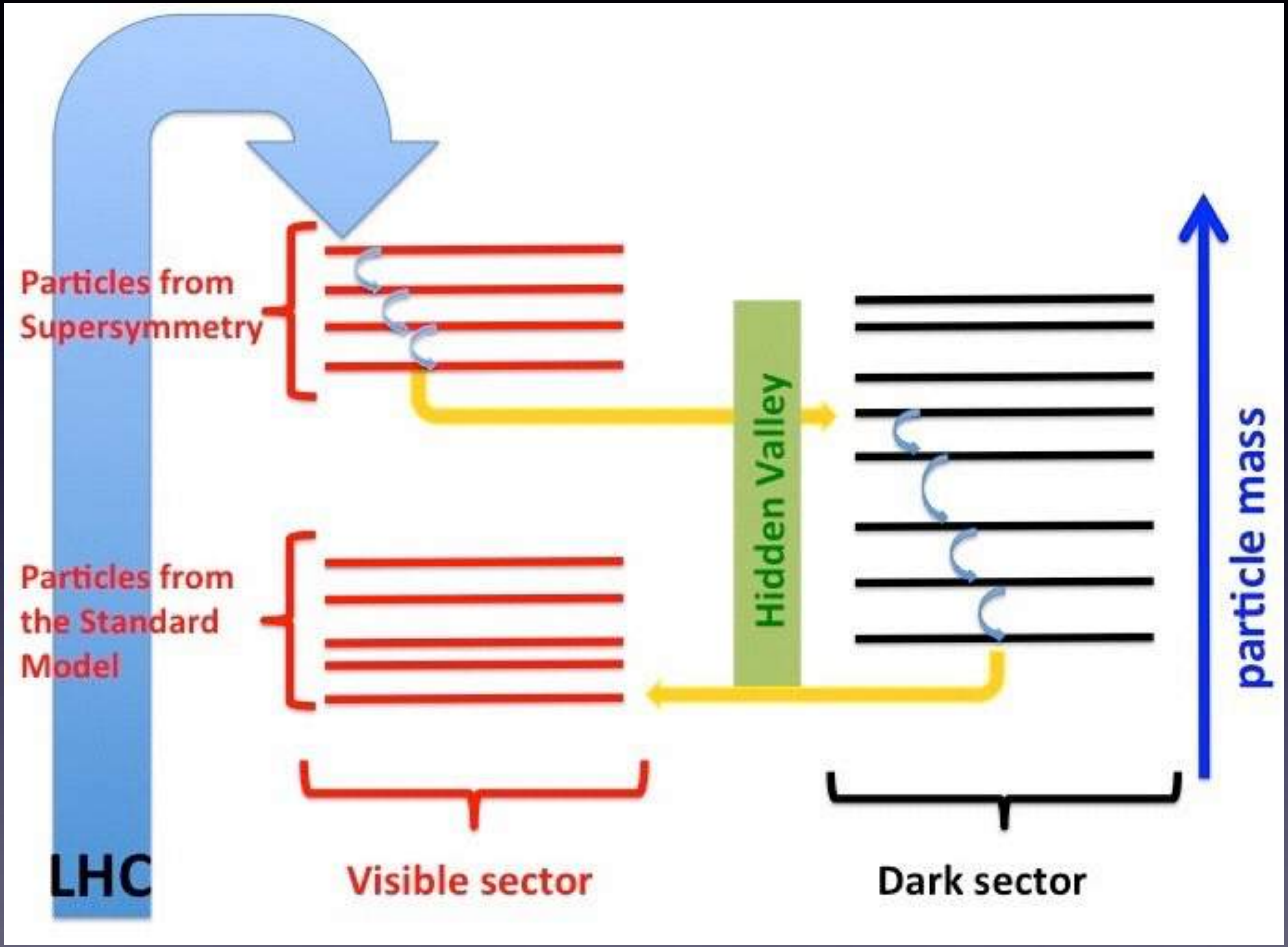
For couplings of order one: $\Lambda \sim M_{\rm med}$ → Analysis is not self-consistent!

But if $\lambda_{\rm DM} \sim 4\pi$ can have $\Lambda \ll M_{\rm med}$

Simplified model approach may not work for such “strong coupling” scenarios!

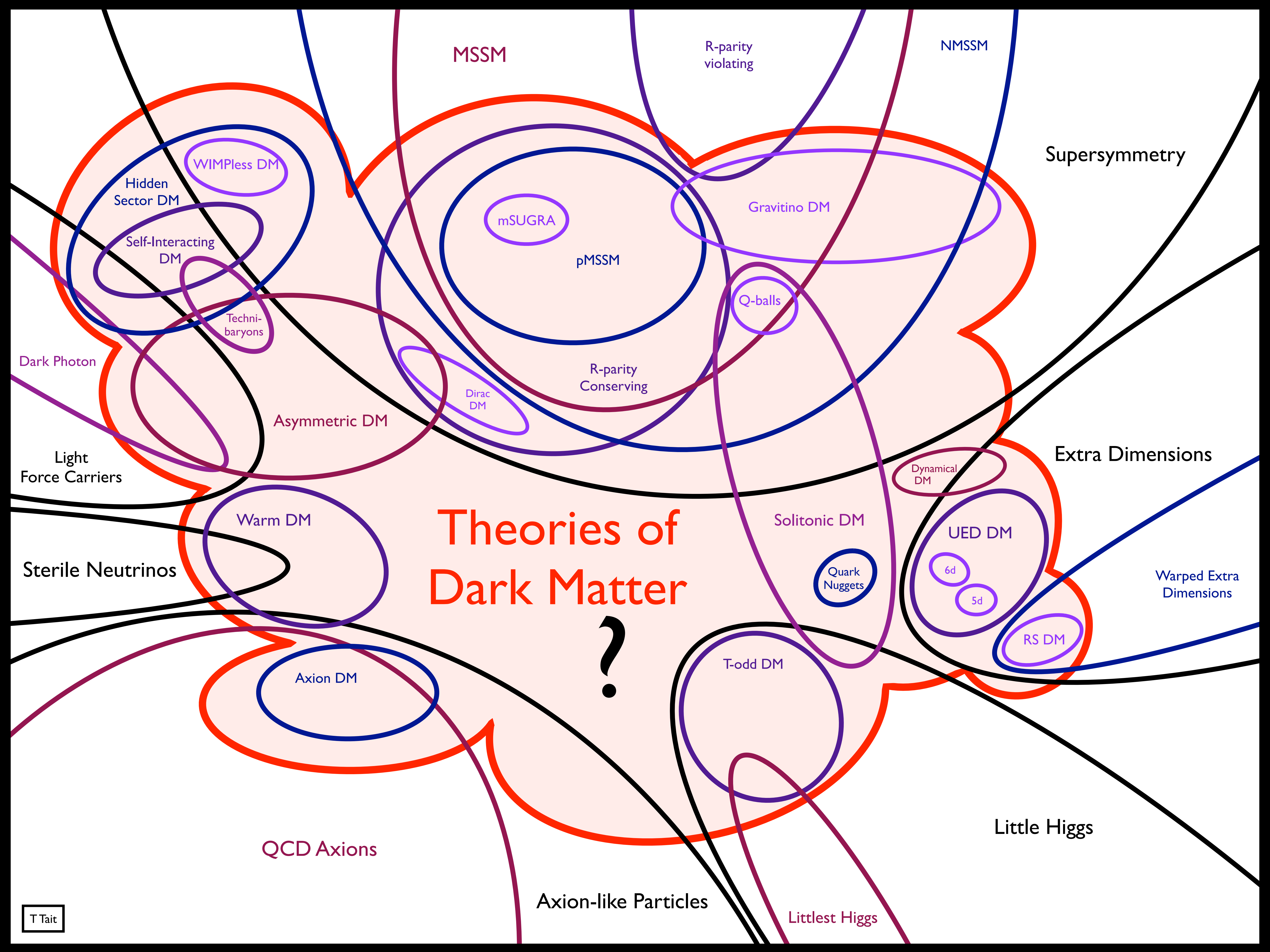
Nature may be significantly more complex than naively imagined…

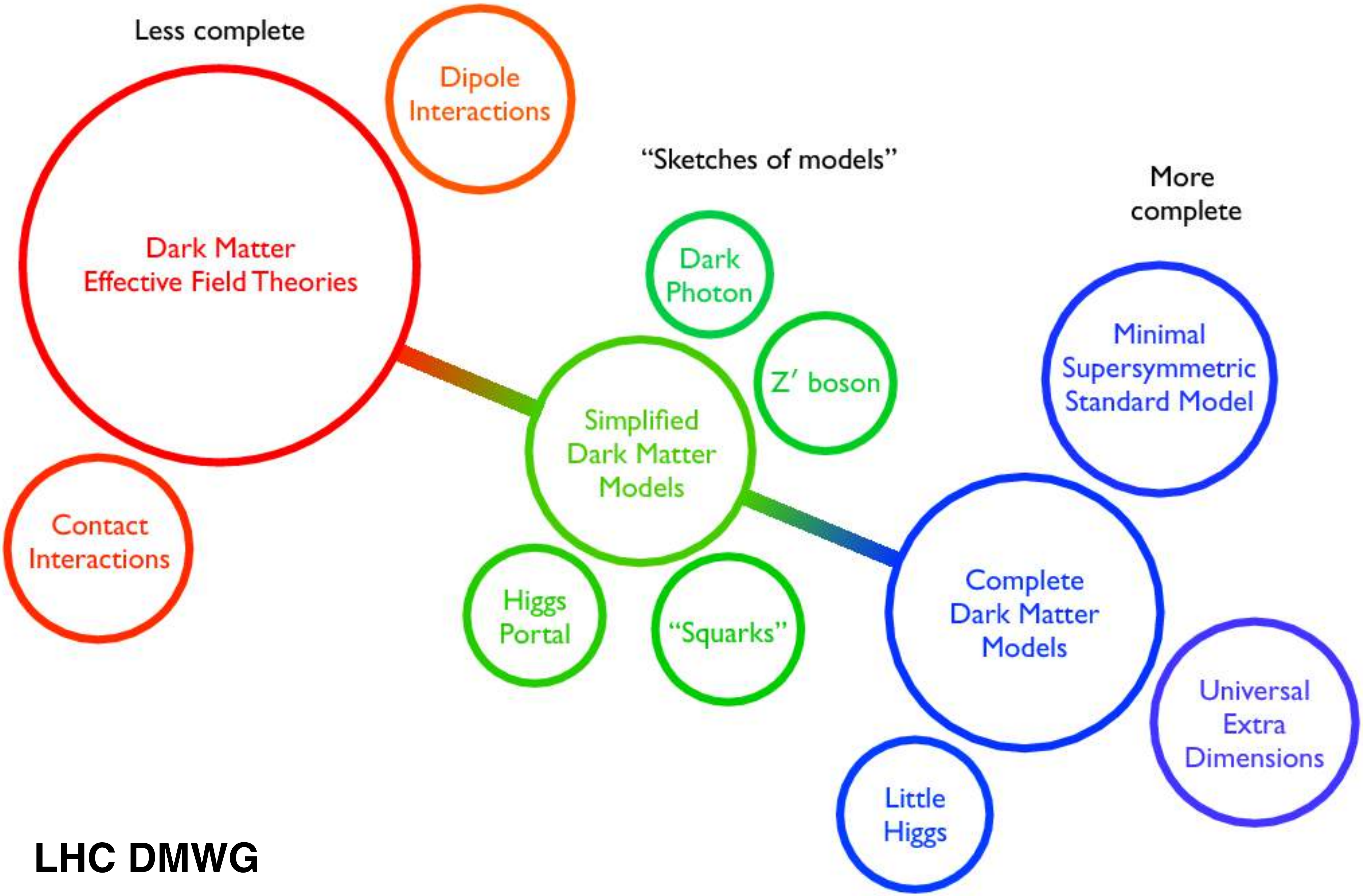
Hidden Valleys



Echoes of a Hidden Valley at Hadron Colliders (Strassler & Zurek)

A Theory of Dark Matter (Arkani-Hamed et.al.)


MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac
DM
R-parity
Conserving
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Dynamical
DM
Warm DM
Theories of
Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark
Nuggets
6d
5d
Warped Extra
Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait


Less complete
Dipole Interactions
"Sketches of models"
More complete
Dark Matter Effective Field Theories
Dark Photon
Minimal Supersymmetric Standard Model
Z′ boson
Simplified Dark Matter Models
Contact Interactions
Complete Dark Matter Models
Higgs Portal
"Squarks"
Universal Extra Dimensions
Little Higgs

LHC DMWG

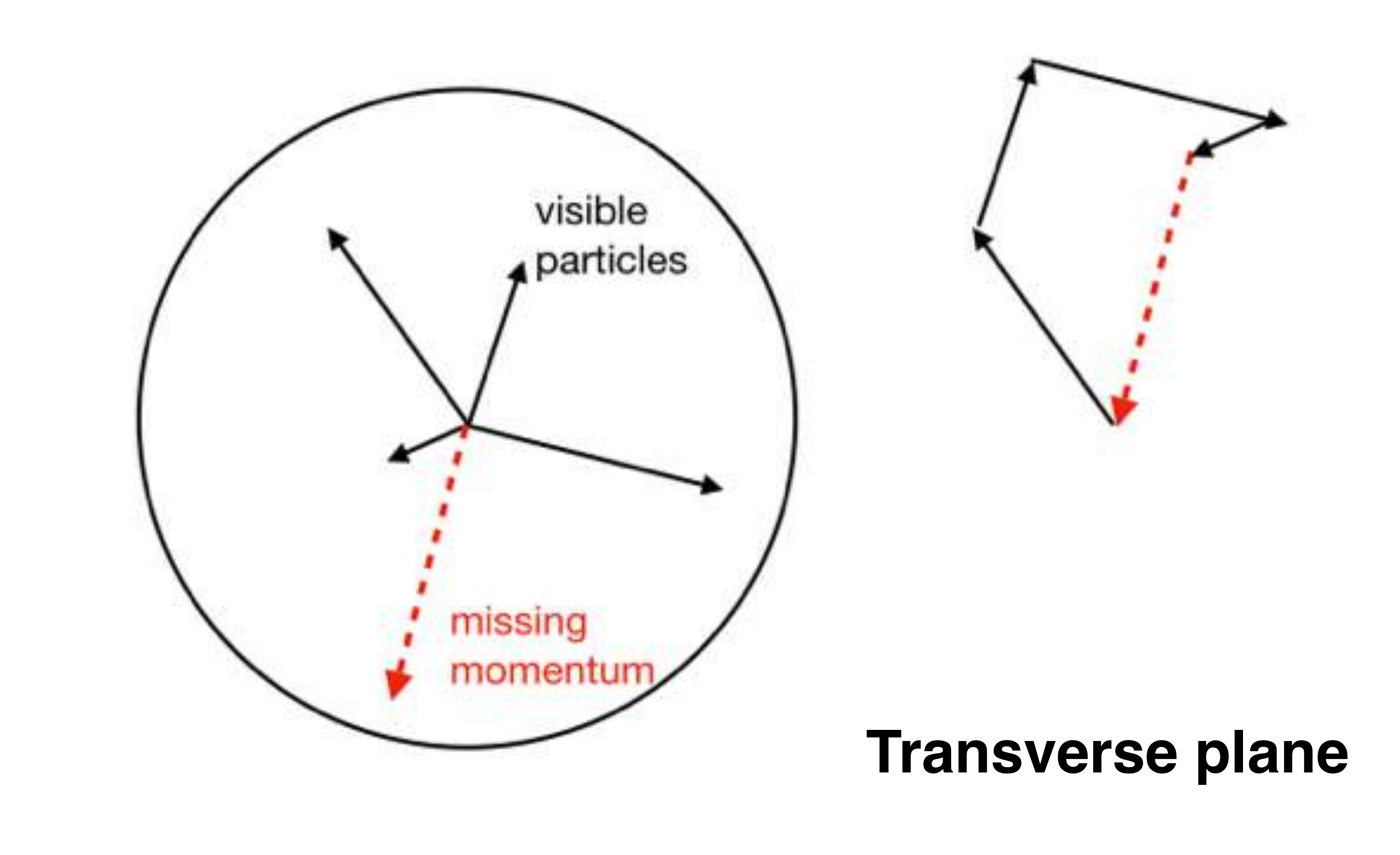
Collider DM Search Strategies

(Transverse) Missing Energy

Hard collision between partons: longitudinal momentum unknown

→ Look for momentum imbalance in transverse plane

$$\vec{\not{E}}_T = -\sum_i \vec{E}^i_{\mathrm{T}}$$



Dark Matter Searches at the LHC

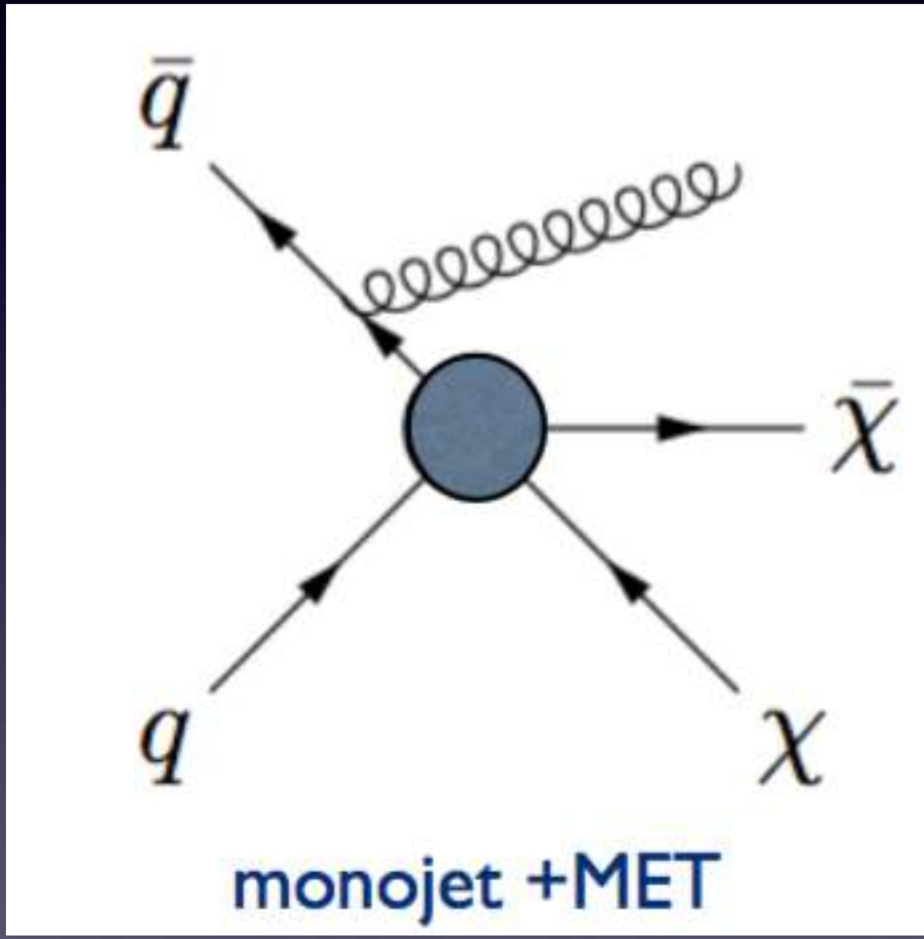
Two broad categories:

- Dark Matter Particle appears in the final state
- Dark Matter Particle does not appear in the final state

→ Searches for the mediator

Seeing the Invisible?

If only DM is produced, we won't know!



Initial State Radiation (ISR)

- Jets
- Photons
- W/Z Gauge Bosons
- Higgs

Used to tag the event as "interesting"

Mono-X Searches, but can also look at higher-multiplicities

"Mono-X Searches"

Types of Searches

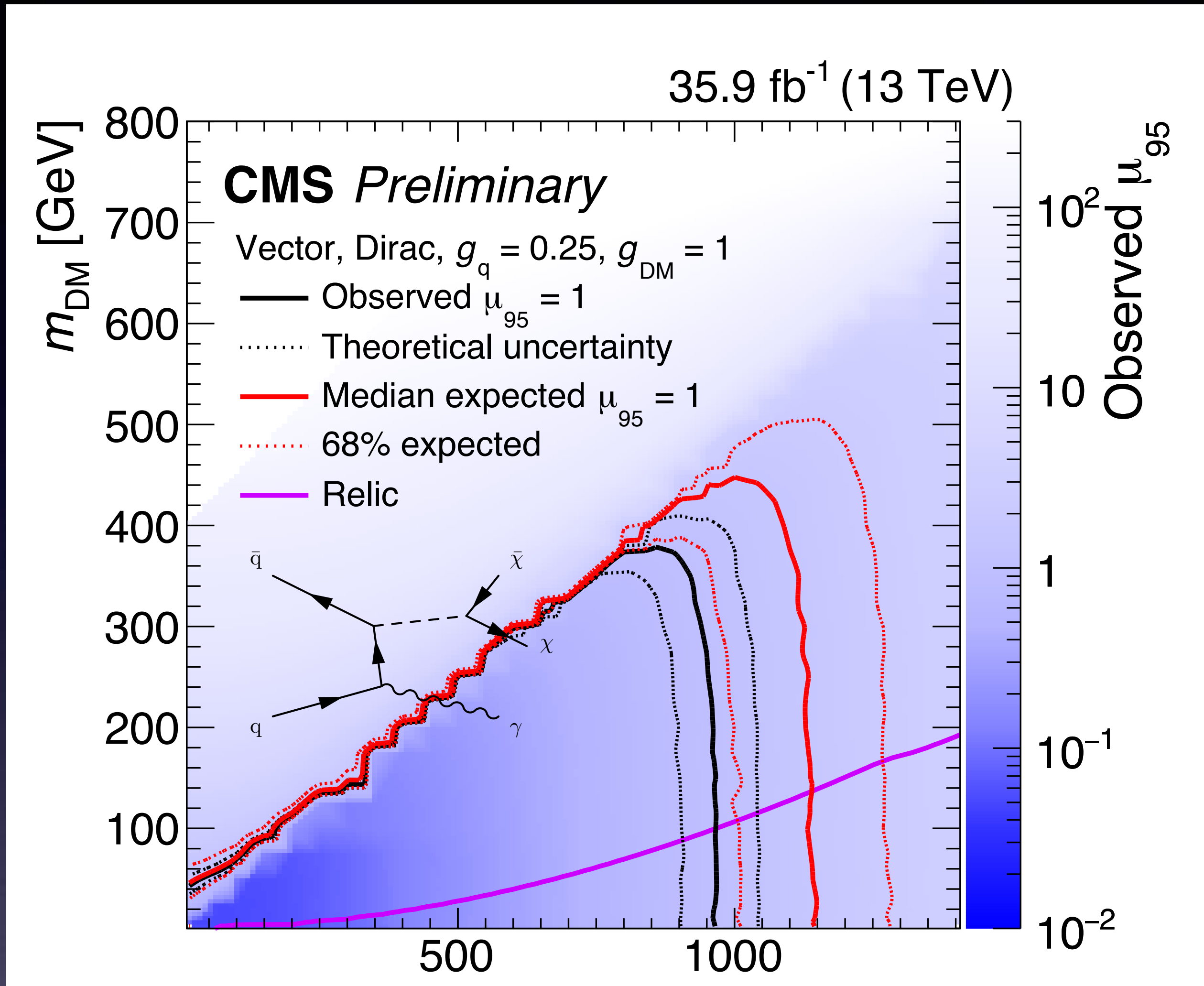
- When the DM particle is light compared to the mediator, it will be highly boosted, and the X back-to-back to the $\vec{\not\!\!E}_T$

→ Classic Mono-X configuration

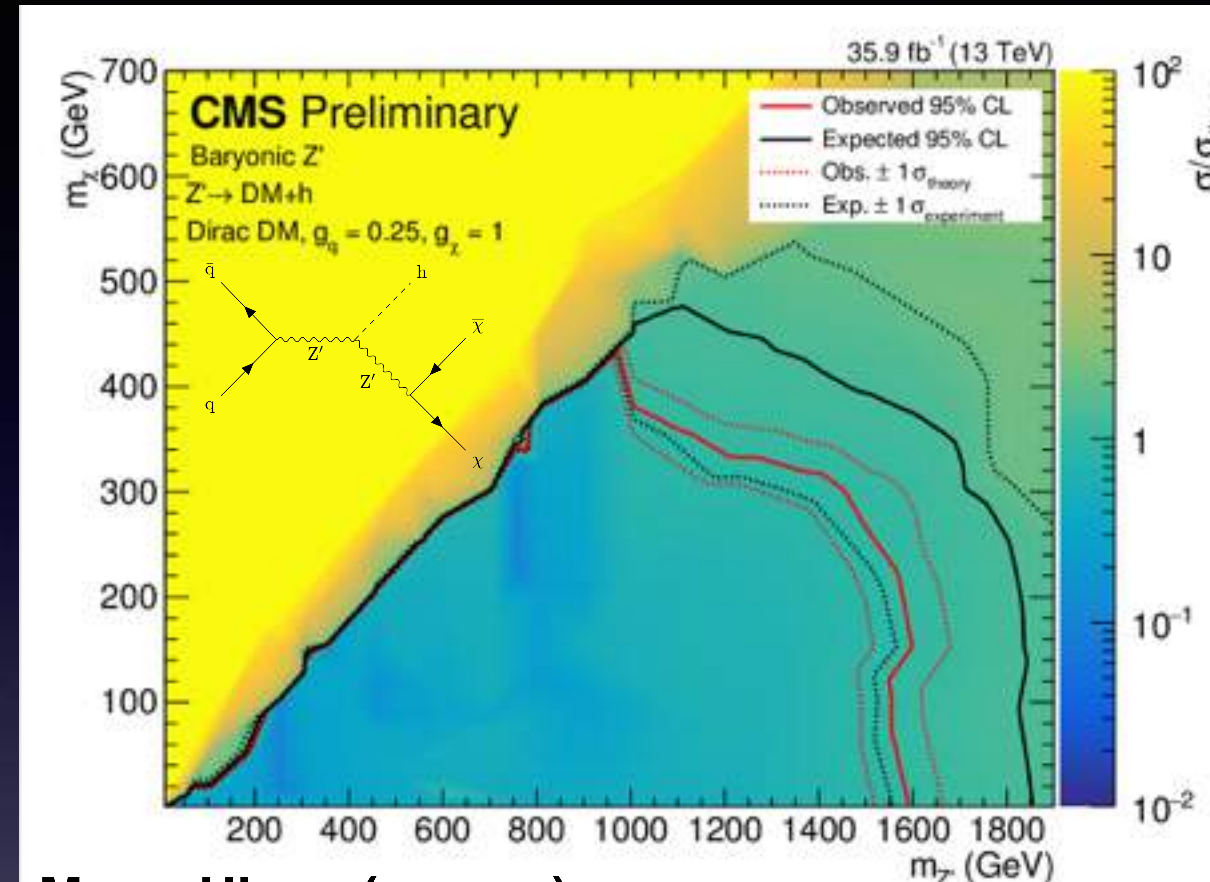
- Traditional $\vec{\not\!\!E}_T$ + anything (SUSY-like) searches

- Searches for resonances, such as dijets, can be recast as searches for the mediator

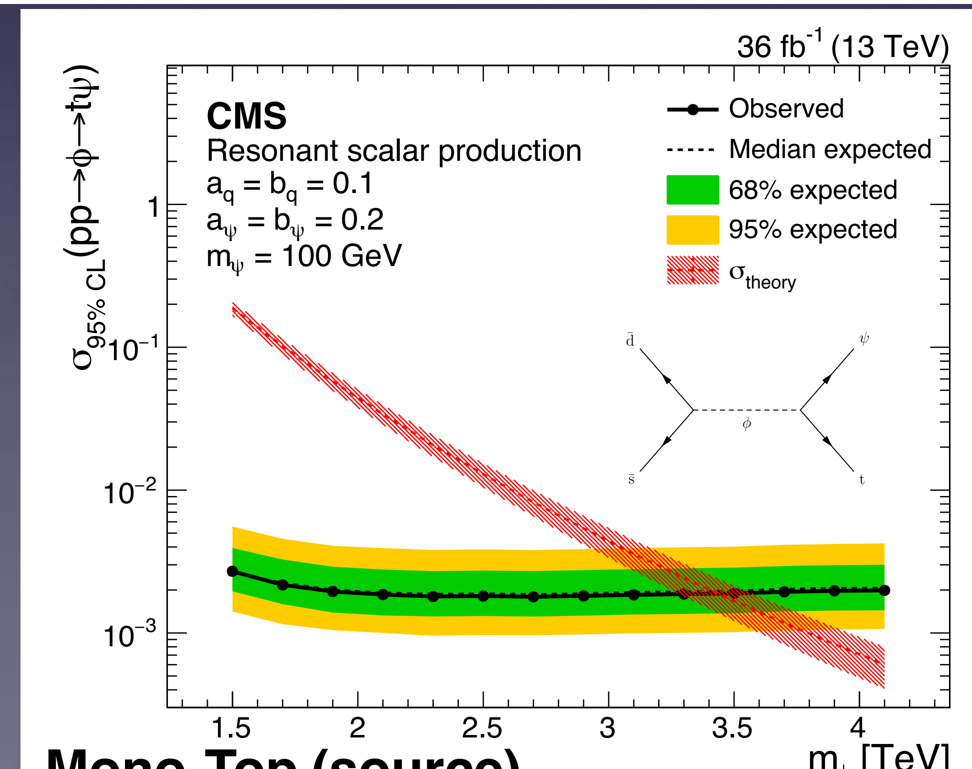
Mono-X Searches



Mono-Photon (source)



Mono-Higgs (source)

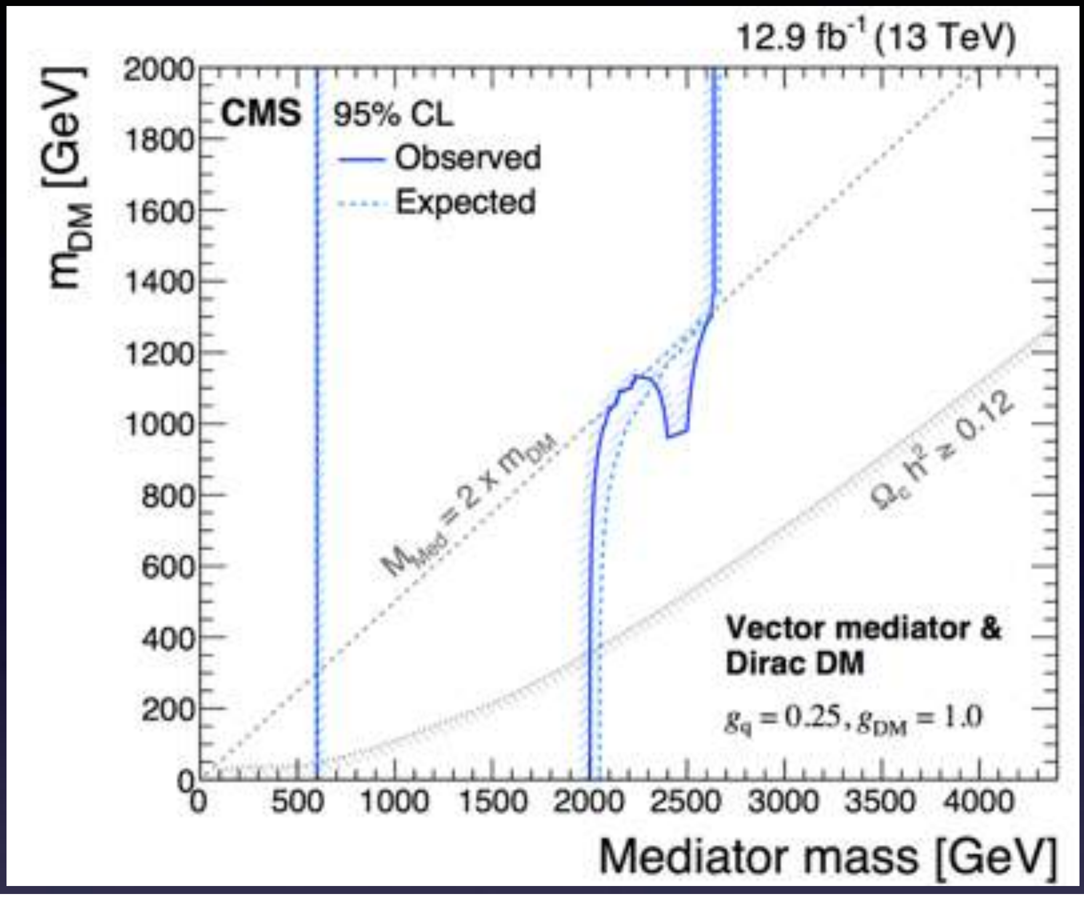


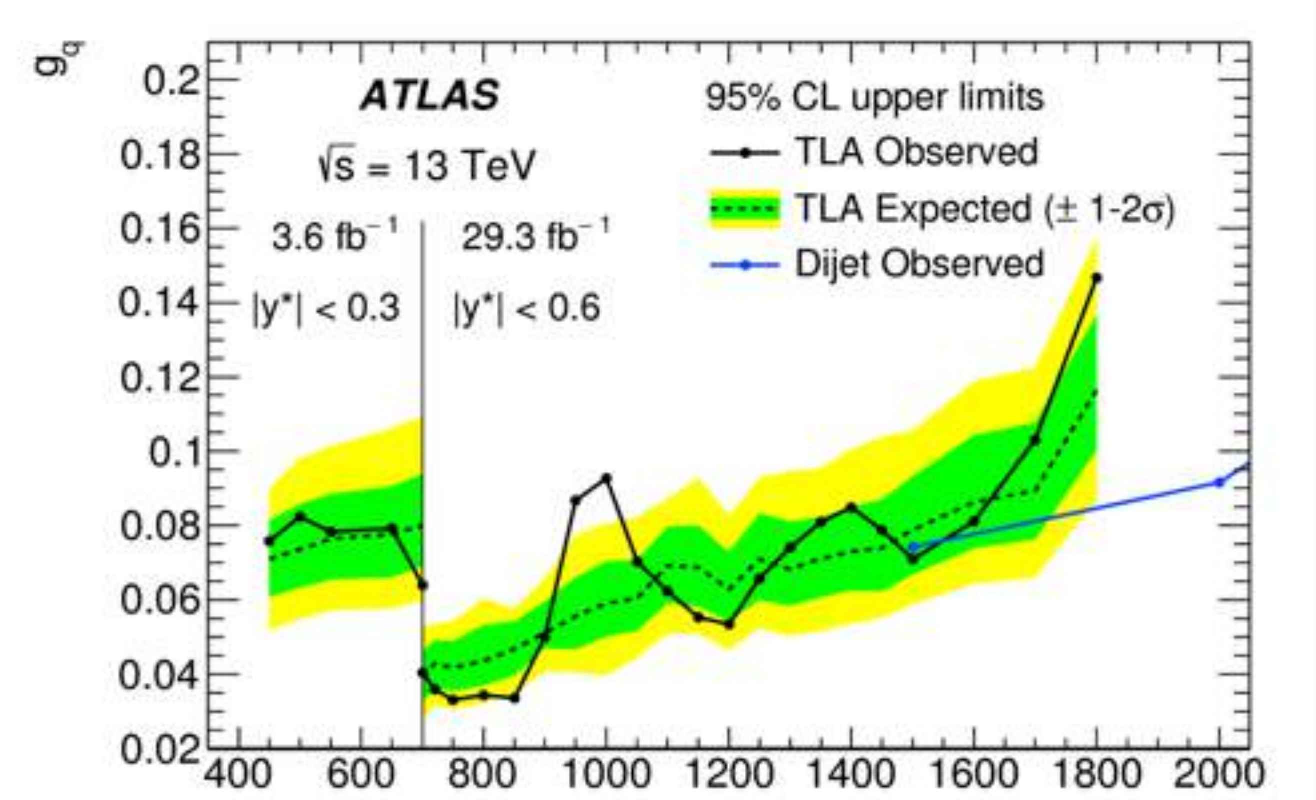
Mono-Top (source)

A Plethora of Searches

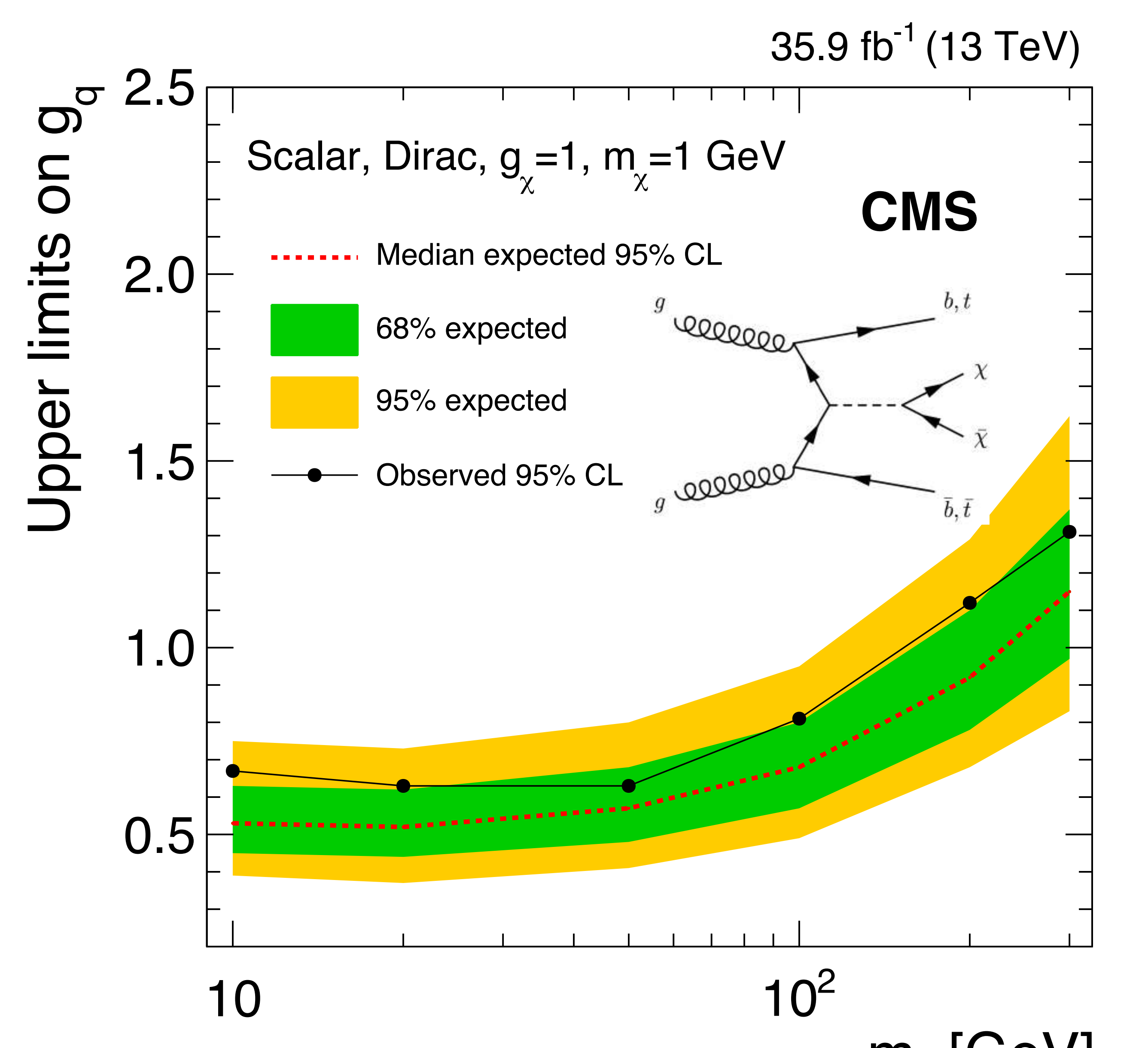
(similar analyses from ATLAS)

Di-X Searches





Di-Jet **(source)**



Di-Top **(source)**

Connecting to Other Searches

One would like to translate the findings in one type of search, i.e. direct, indirect or collider, in a way that can usefully inform the others

Doing this in a generic, model-independent way seems unfeasible:

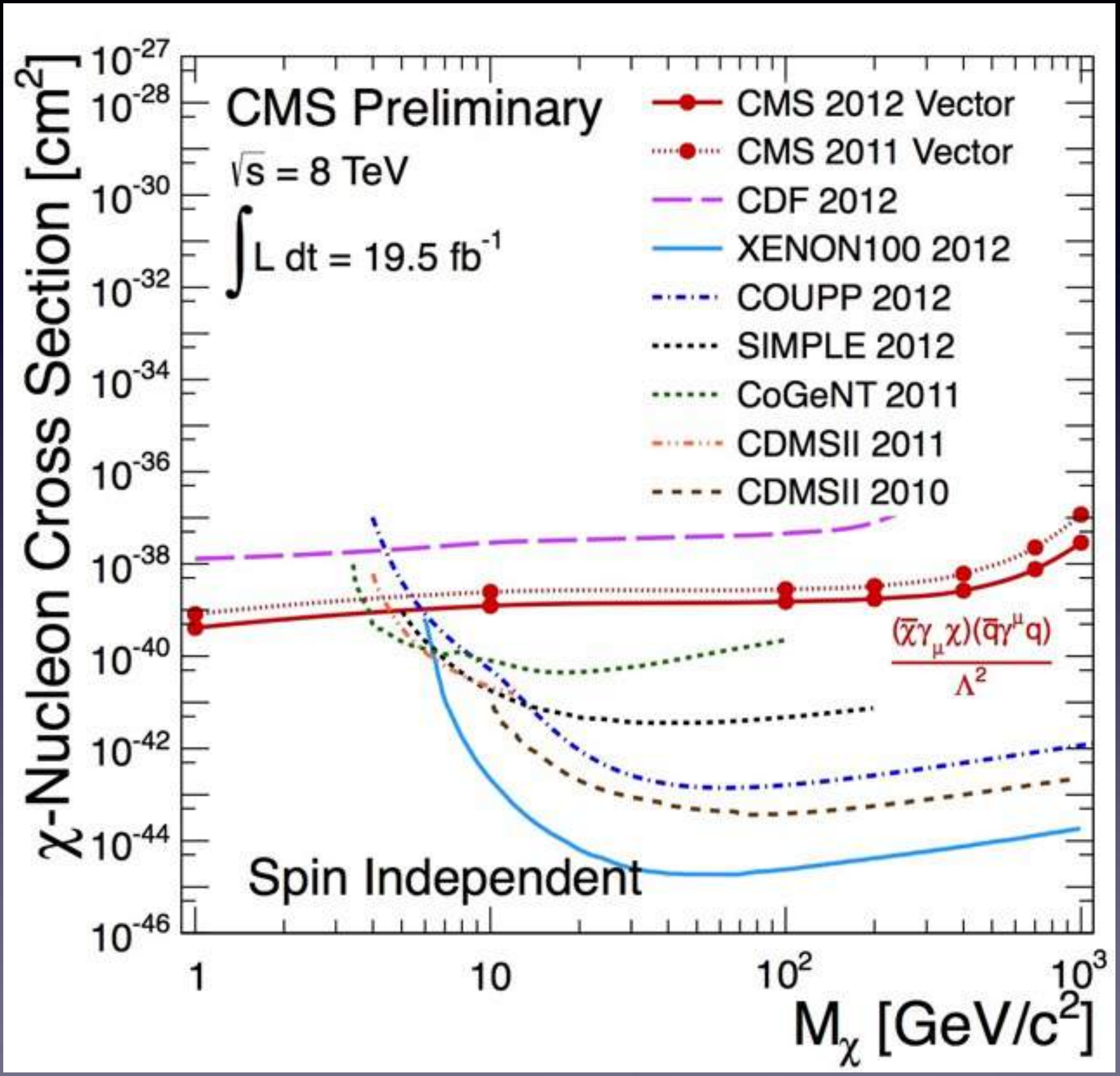
The relevant issues at play in these search strategies are not the same

But within a given model, better-defined connections can be established

Need to be aware of the model-dependence when making statements about the implications of a search on another…

Expect that establishing a final picture will require all the information available, plus theoretical considerations

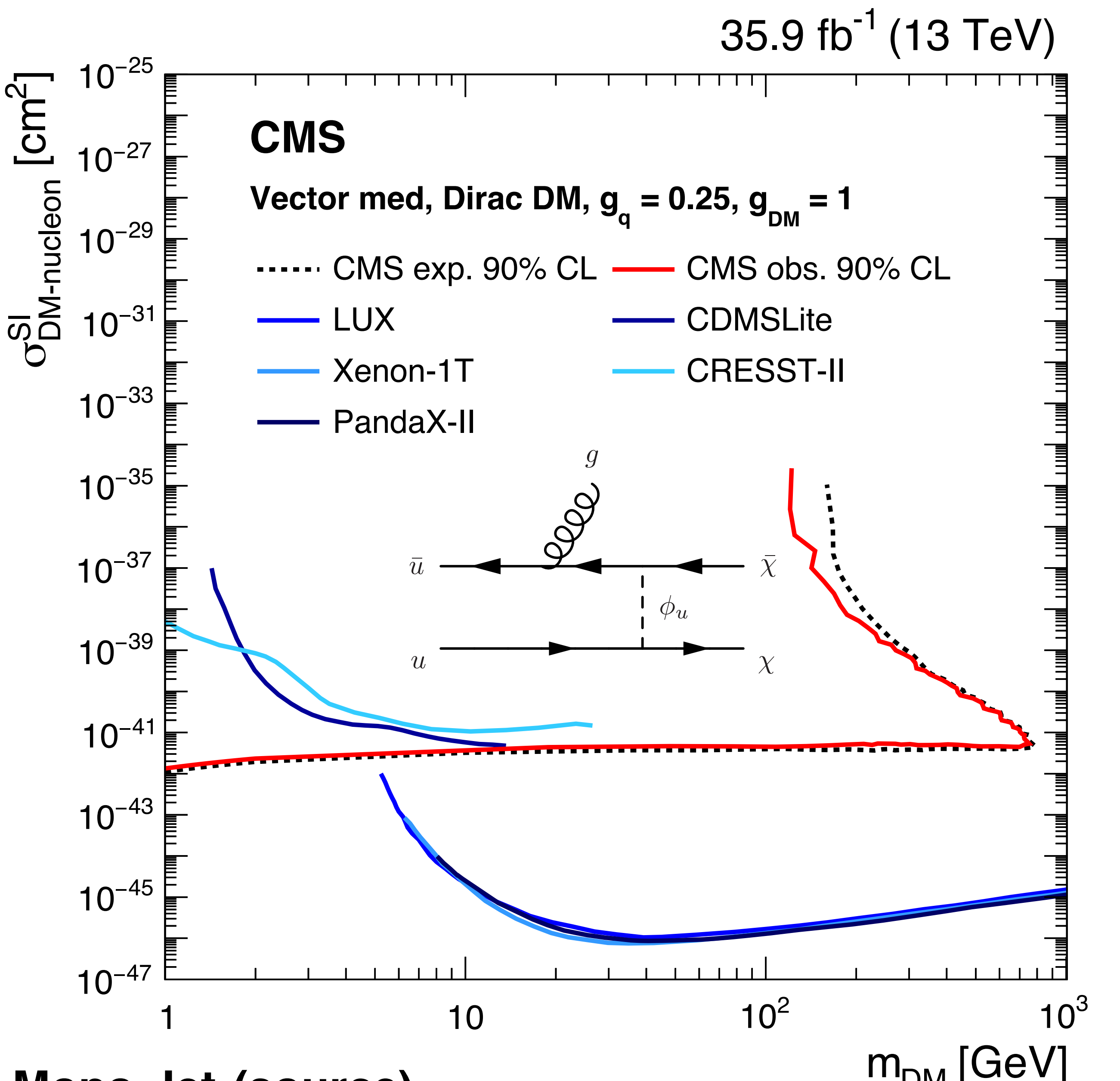
Comparison to Direct Detection



Comparison to Direct Detection

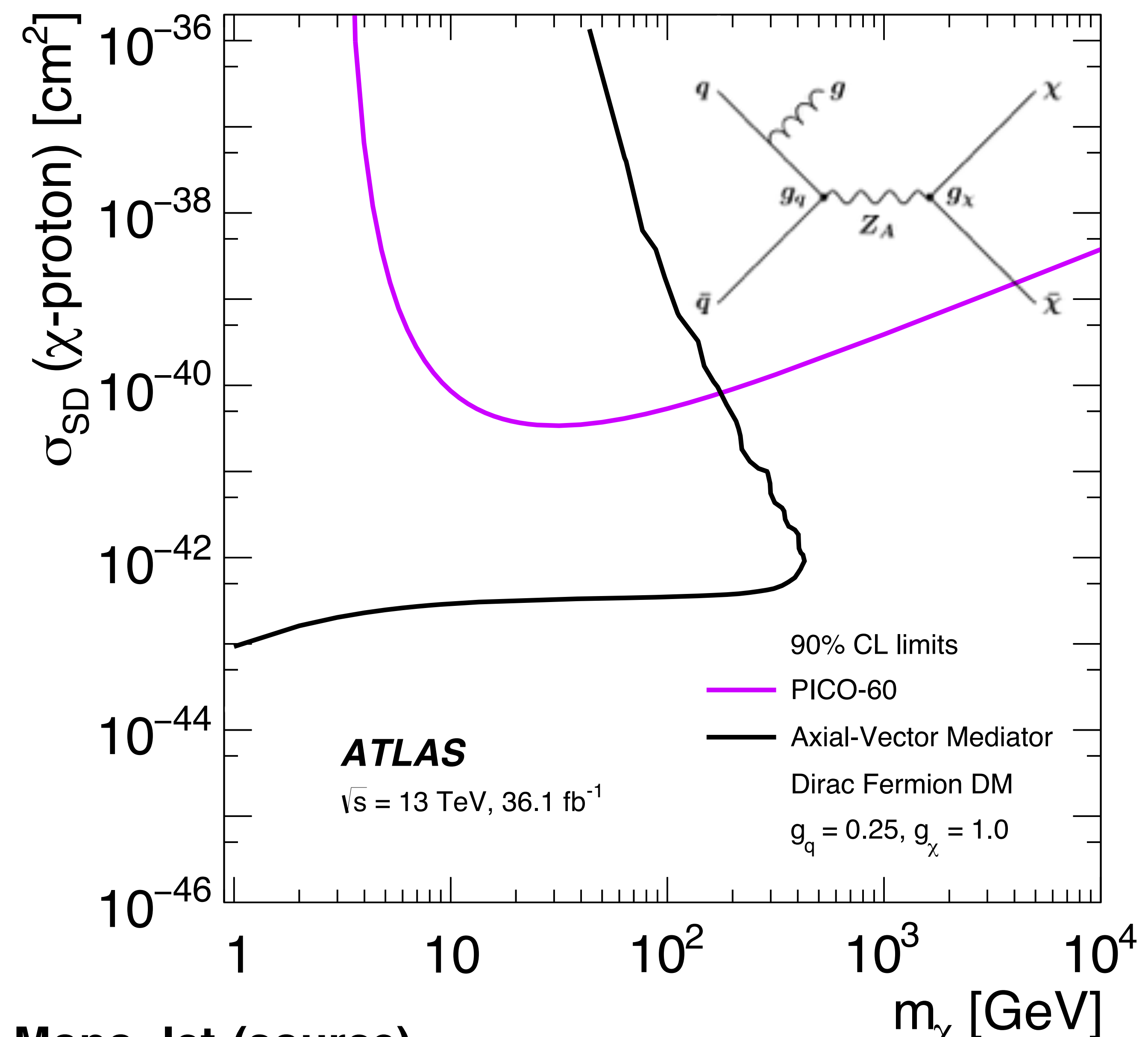
Most sensitivity at the LHC from Mono-Jet Searches

Spin-Independent



Mono-Jet (source)

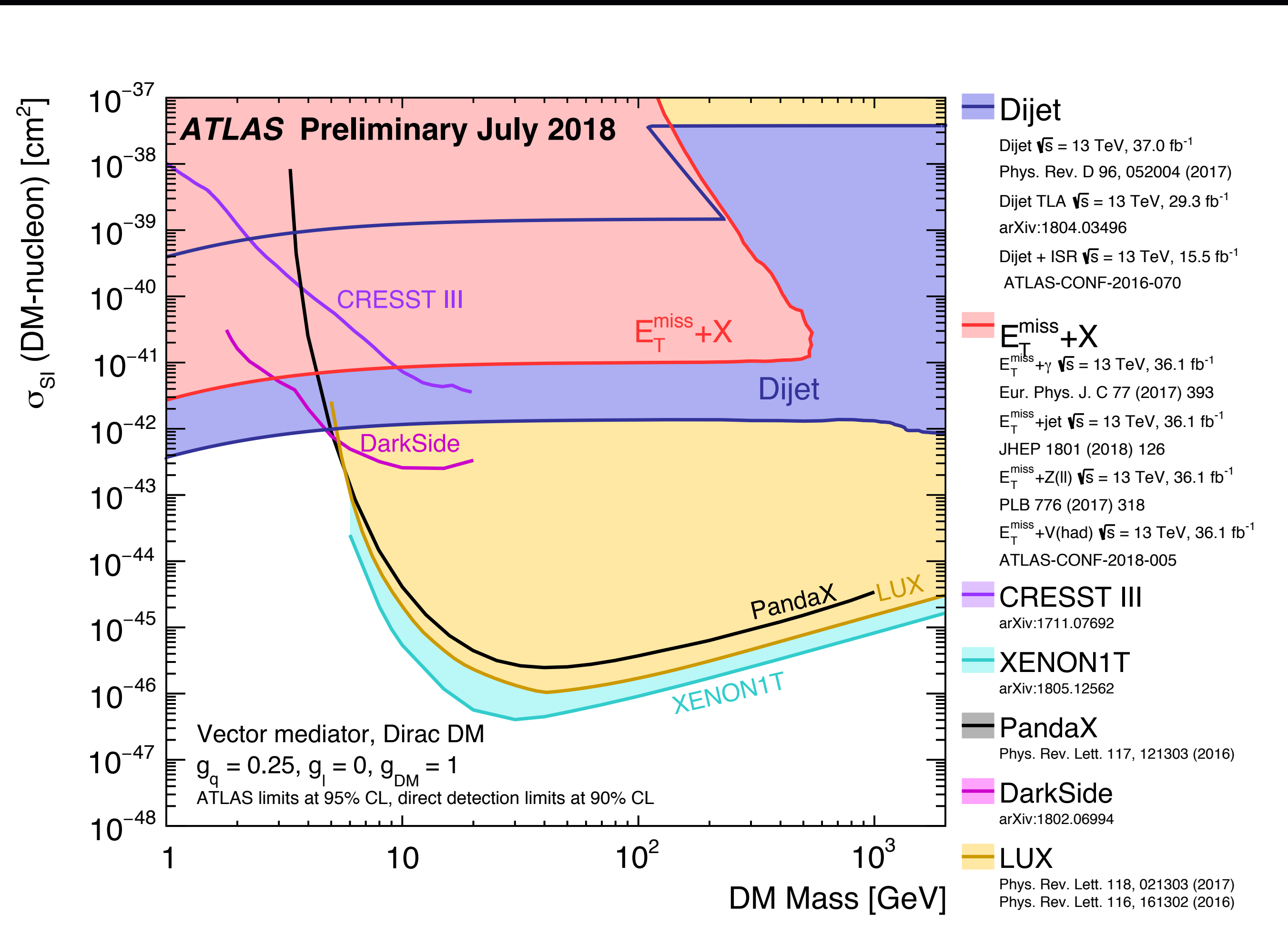
Spin-Dependent

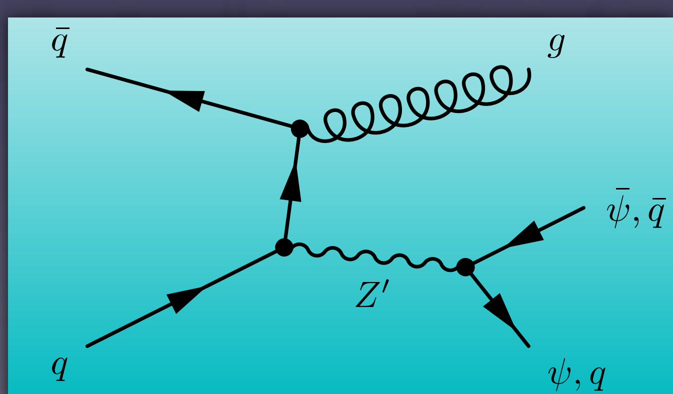


Mono-Jet (source)

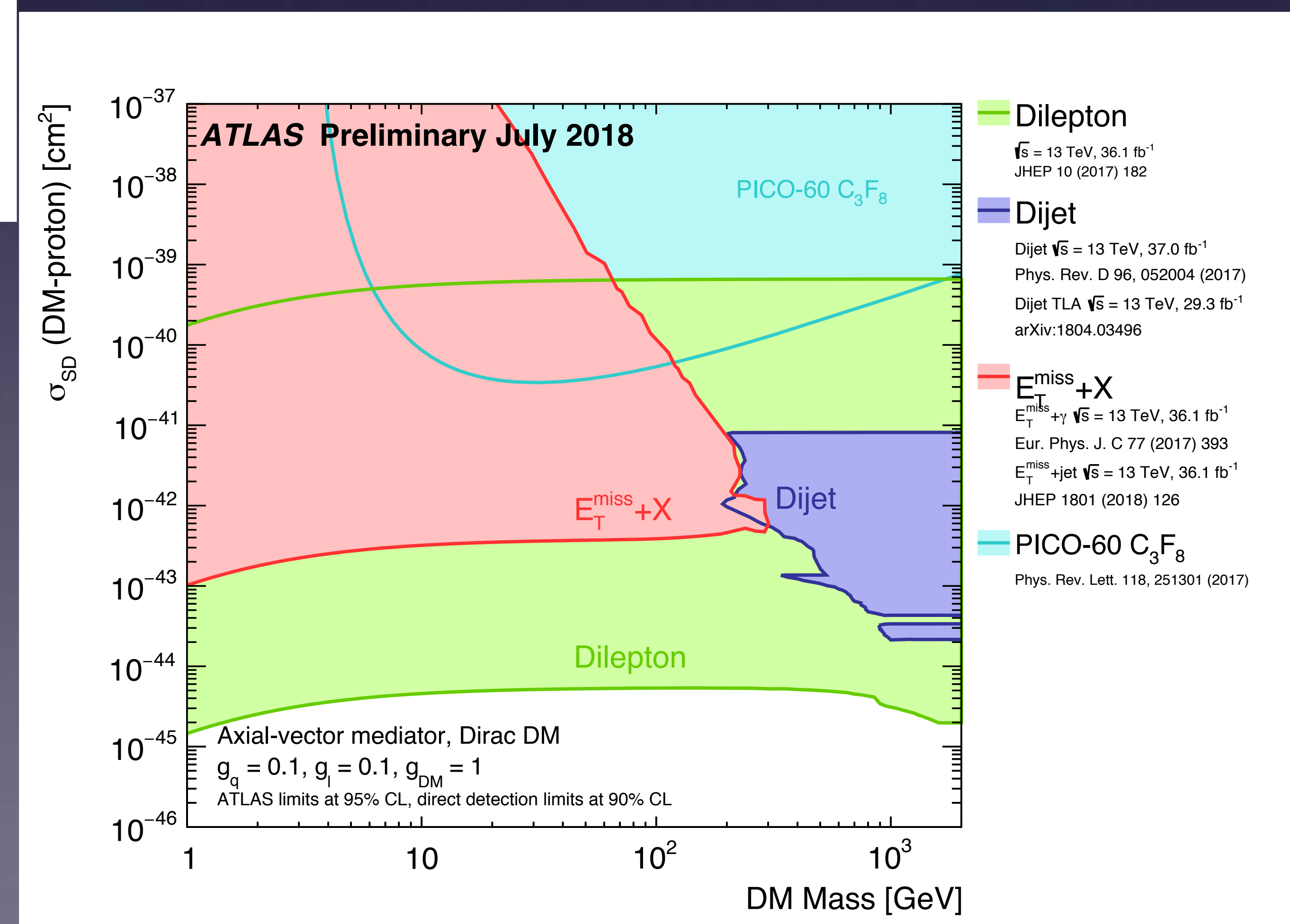
Comparison to Direct Detection

For more ATLAS plots…

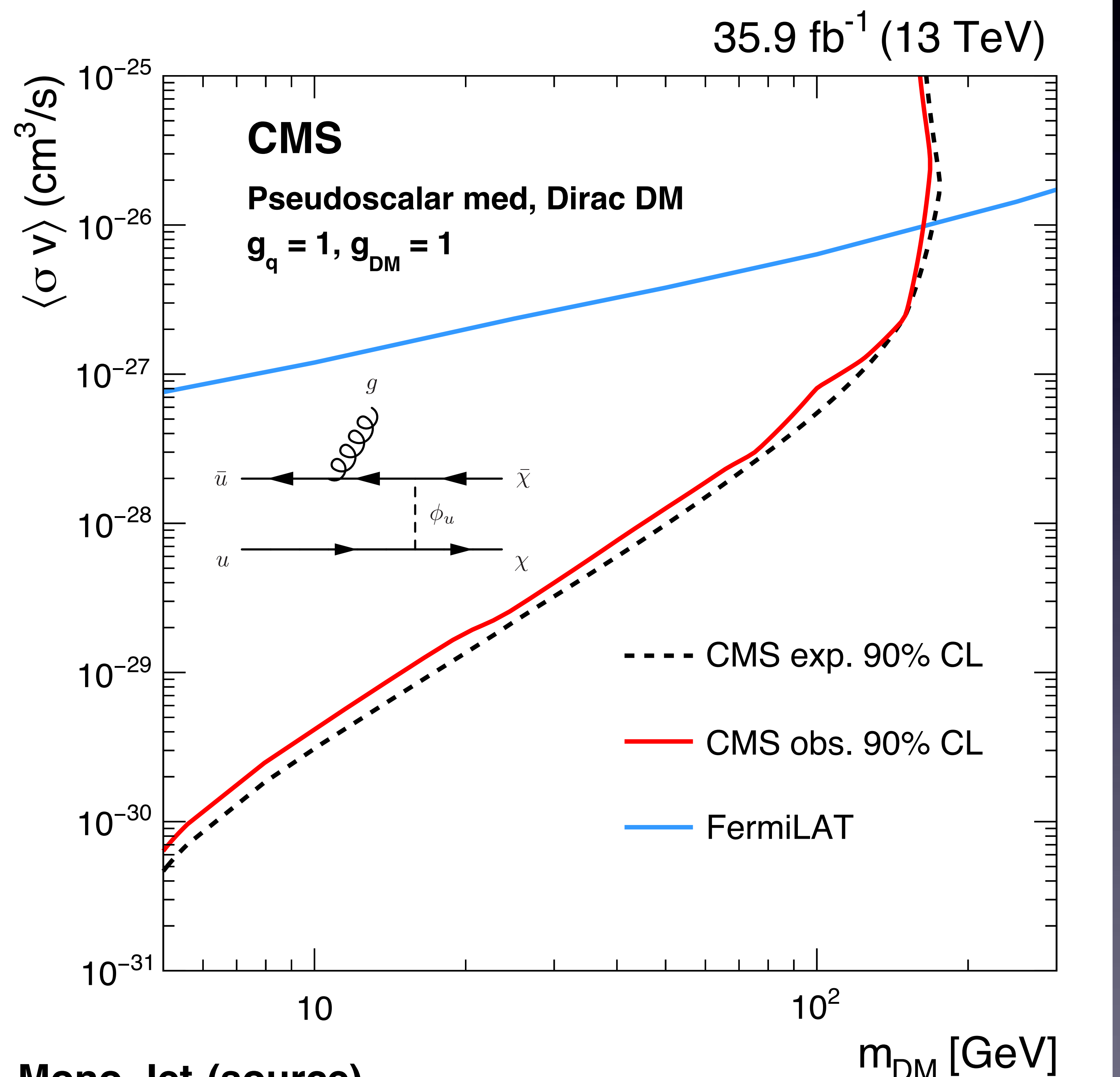




$$\mathcal{L} \supset g_{\rm DM}\, \overline{\psi}\gamma_\mu\gamma_5\psi\, Z'^\mu + g_q \sum_q \bar{q}\gamma_\mu q\, Z'^\mu$$



A Comparison to Indirect Detection



Mono-Jet **(source)**

A Comparison: Examples

EW couplings (Spin 1)	**Vector:** $g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi$ Direct detection more sensitive than colliders except at very low dark matter masses.	**Axial-Vector:** $g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$ Direct detection and colliders about equally sensitive in different regions of parameter space.
Yukawa couplings (mass dependent)	**Scalar**: $g_{\mathrm{DM}} S \bar{\chi}\chi$ Direct detection and collider about equally sensitive in different regions of parameter space.	**Pseudo-Scalar**: $g_{\mathrm{DM}} S \bar{\chi}\gamma^5 \chi$ No limits from direct detection, only from indirect. Colliders provide limits comparable to scalar couplings.

Colliders vs Direct/Indirect Detection

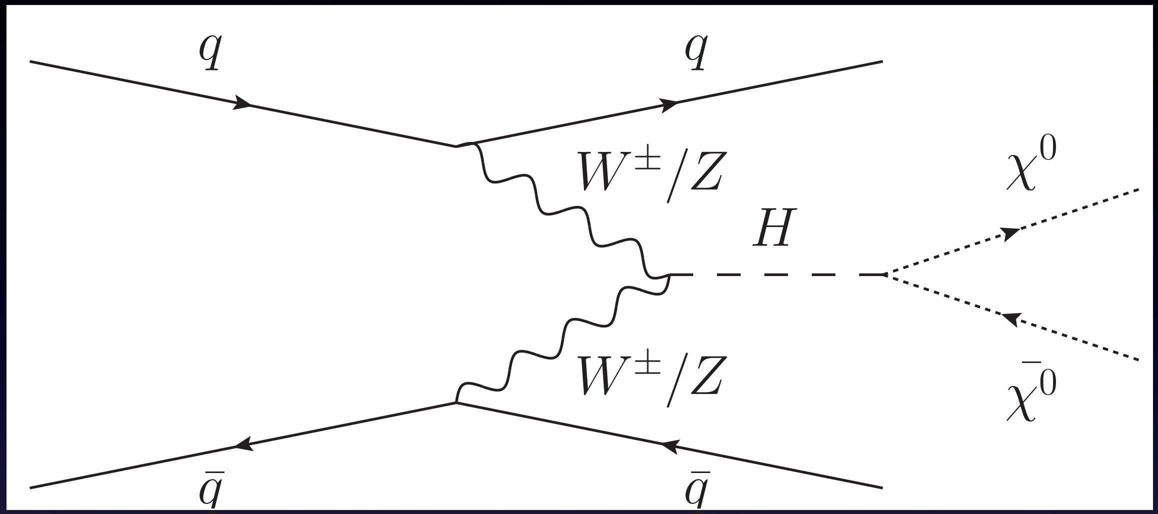
- More sensitive in the small mass region (one to several GeV)
- Less sensitive in the intermediate and high mass region

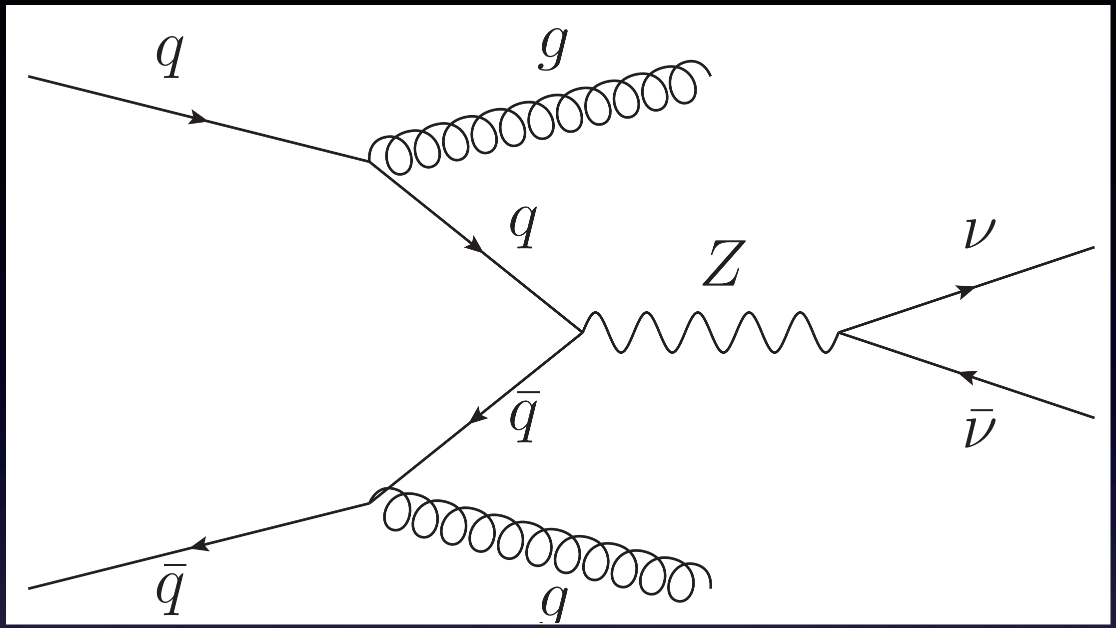
  Note: still important since independent of astrophysics

- Direct detection depends also strongly on the structure of interactions (spin-dependent vs spin-independent), which gives an edge to the collider interpretation in the spin-dependent case.
- Also strong dependence on detector technology in direct searches
- Indirect detection depends on astrophysics, as well as on annihilation channels

Back to the complementarity concept!

Invisible Higgs Decays

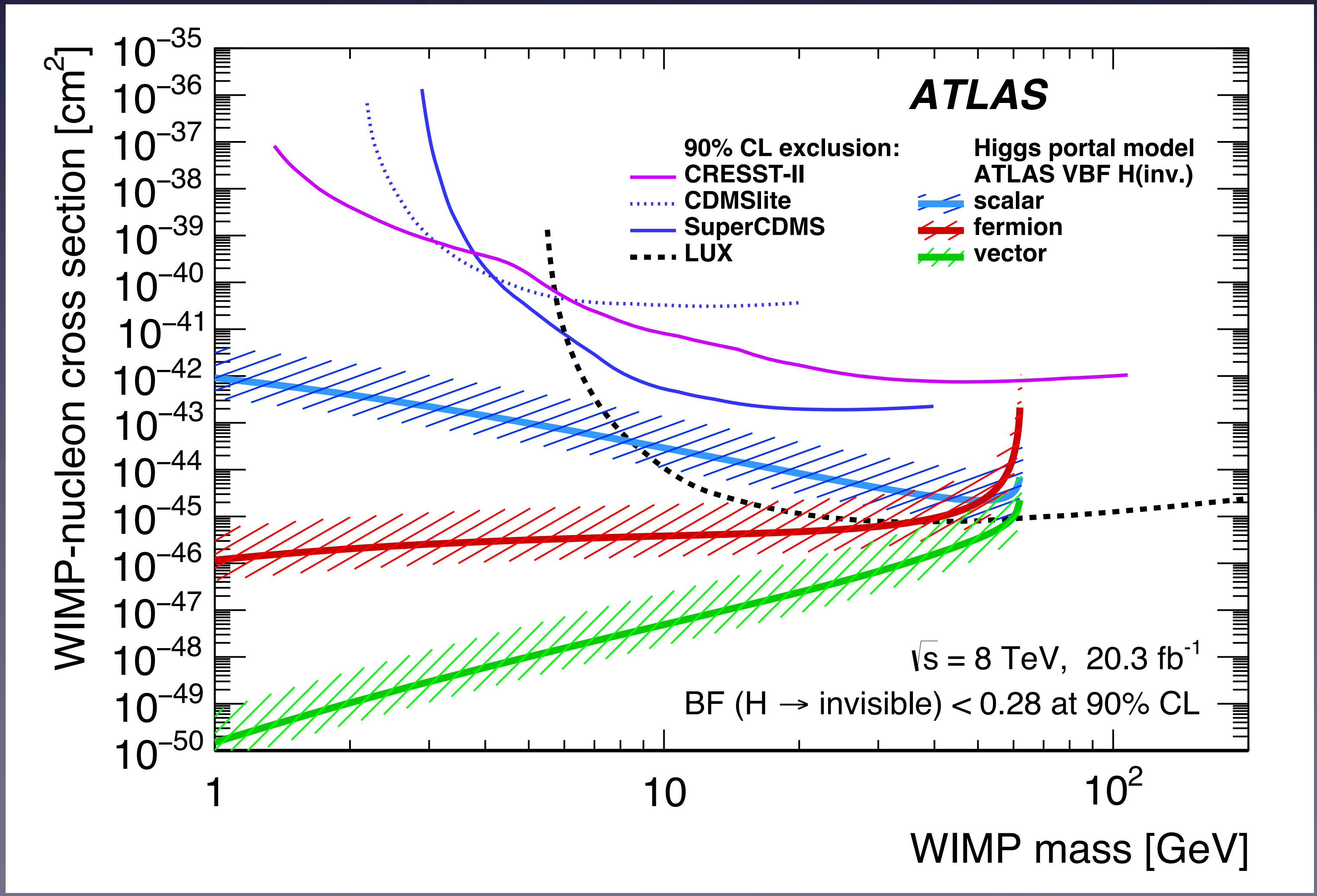




Assumption:

- Single new particle (DM)
- A SM singlet, coupled to H
- Mediator for the WIMP-nucleon interaction
- $m_{\mathrm{DM}} < m_H/2$

From ATLAS: arXiv: 1508.07869



What about very Light Mediators?

Direct DM Searches efficient above above multi-GeV region:

Energy Transfer $\sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 10^{-6} m_{\rm DM} \sim {\rm keV}$ (threshold)

Collider Searches can extend this down to ~ 1 GeV.

Below that, large (QCD) backgrounds bury the signal

Viable options that can go down to the MeV region:

- LHCb
- B-factories, such as BaBar and Belle-II
- Beam Dump experiments (including e^+e^- colliders)

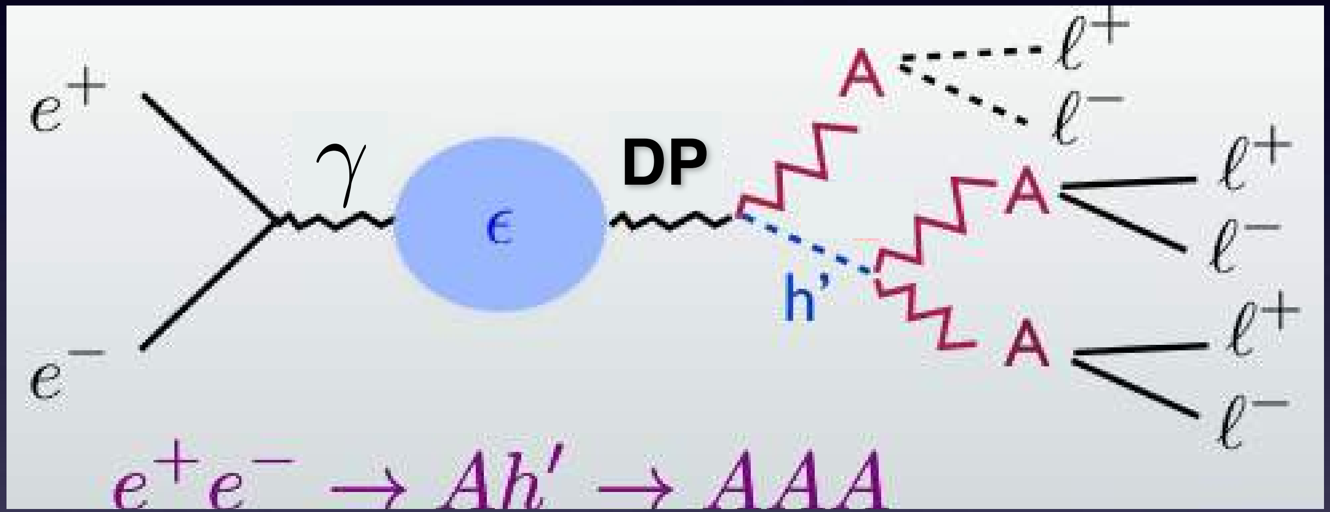
Example: Dark Photons

See e.g. 1608.08632

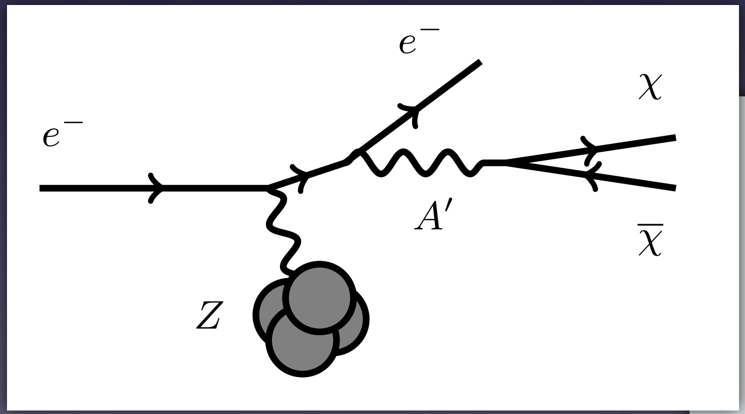
Interactions induced through kinetic mixing with the hypercharge gauge boson:

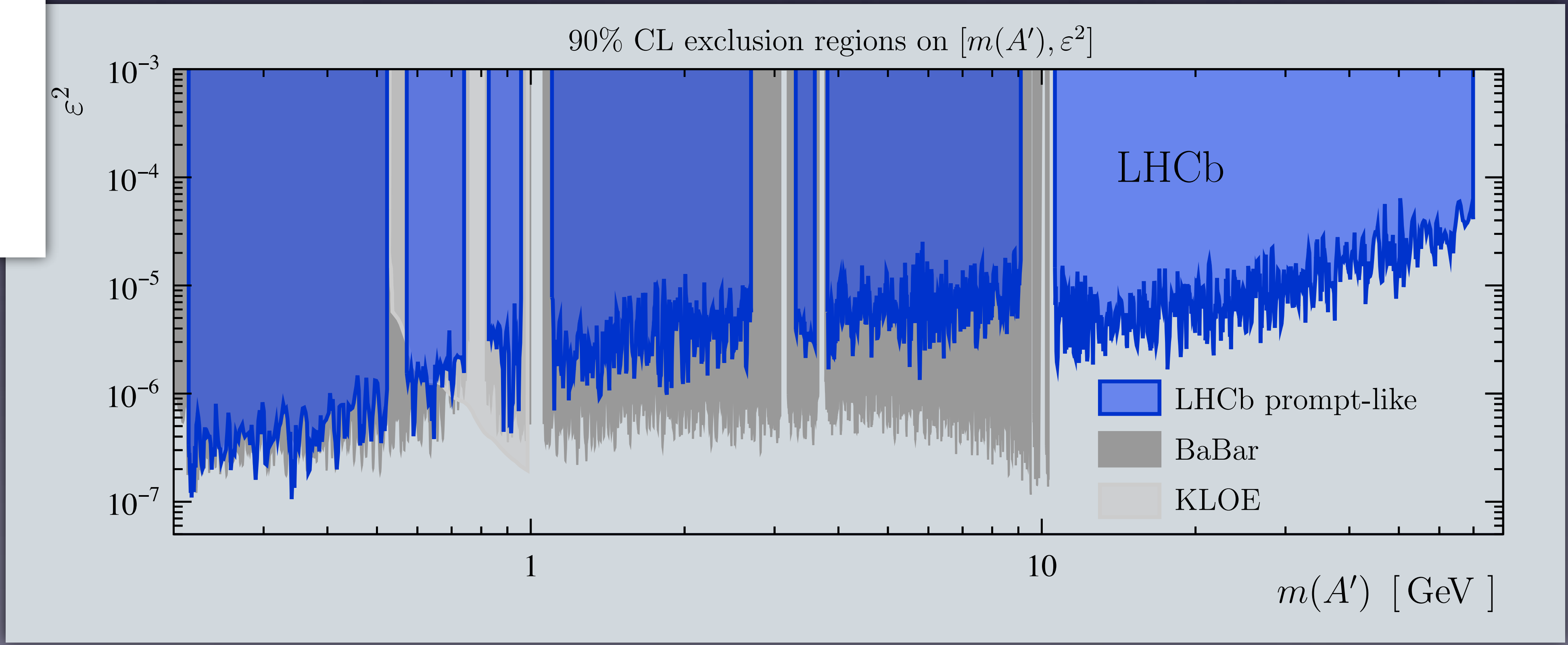
$$\mathcal{L} = -\frac{1}{4}F'^{\,\mu\nu}F'_{\mu\nu} + \frac{1}{2}\,m^2_{\rm DP}\,A'_\mu A'^{\,\mu} + \frac{1}{2}\,\epsilon B^{\mu\nu}F'_{\mu\nu}$$

At B-factories



Beam Dump Experiments



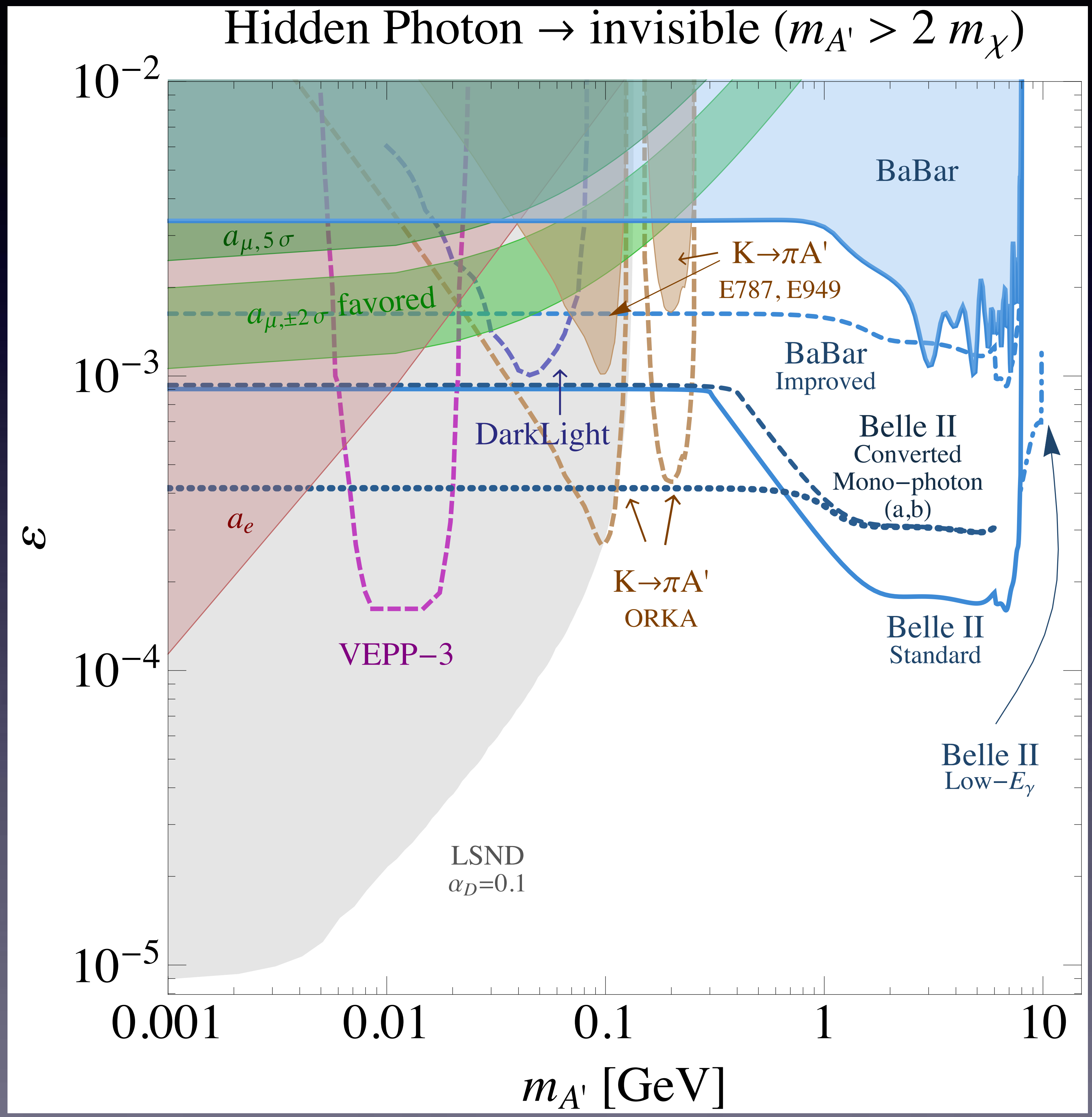


Search for Dark Photons

LHCb Collaboration

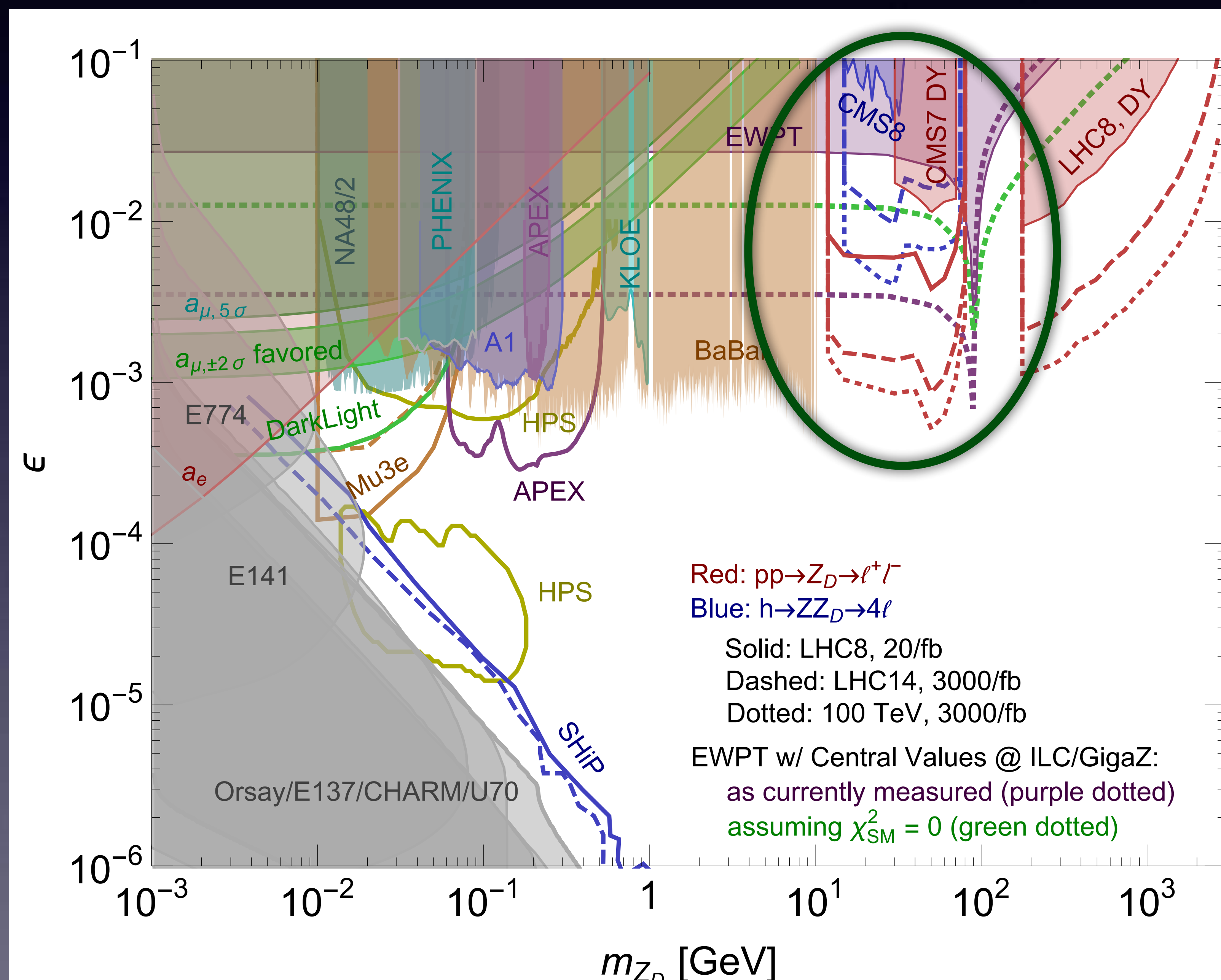
1710.02867

Example: Dark Photons



Example: Dark Photons

And at high-energy (future) colliders:



Curtin et. al. *1412.0018*

Further Topics of Interest

We barely (or did not) mention a number of topics the students may want to check out

- SUSY searches
- Super-weakly interacting DM (e.g. gravitinos)
- Searches for exotic physics motivated by Dark Sectors
- Long-lived particle searches
- Axion Searches (different techniques from colliders)

Some References

Most of the DM searches at the LHC have been carried out by the ATLAS and CMS collaborations

ATLAS Exotica (you can filter by “Dark Matter” and “Dark Sector”)

CMS Exotica (DM Searches) (Summary Plots)

Check also the Particle Data Group: Dark Matter Review