Dark Matter @ Accelerators

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Fermilab and UChicago

Advanced Training Institute,

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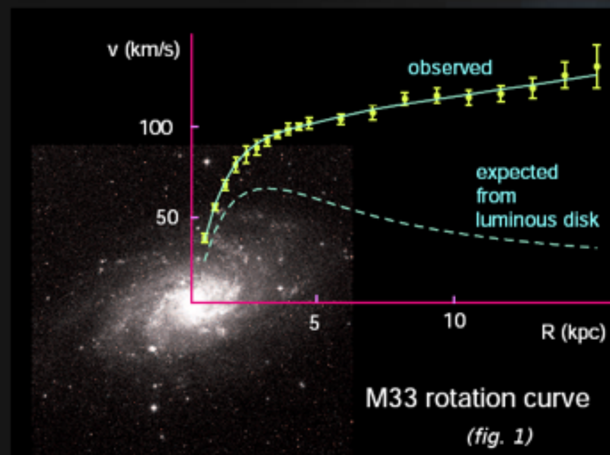
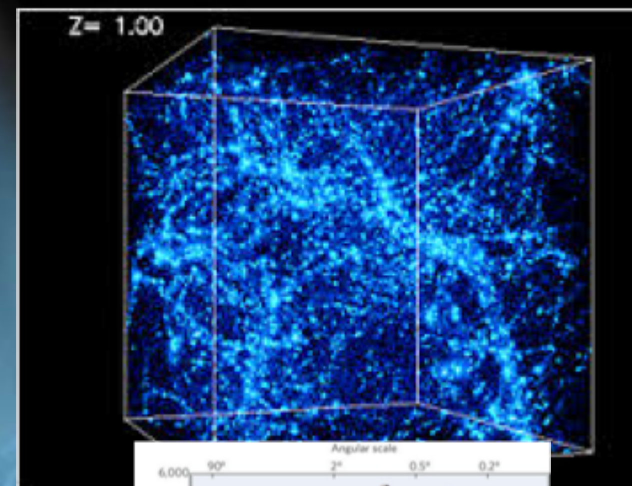
The power of the dark side

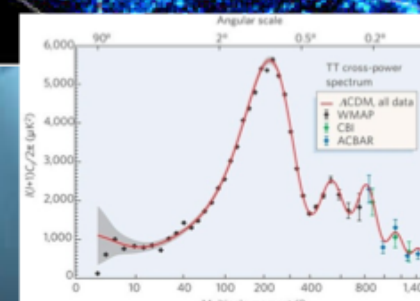
Holds the Universe together and makes *85% of all the matter in it!*

Strongest evidence for DM comes from its interactions with visible matter in the Milky Way



M33 rotation curve
(fig. 1)





What is it?

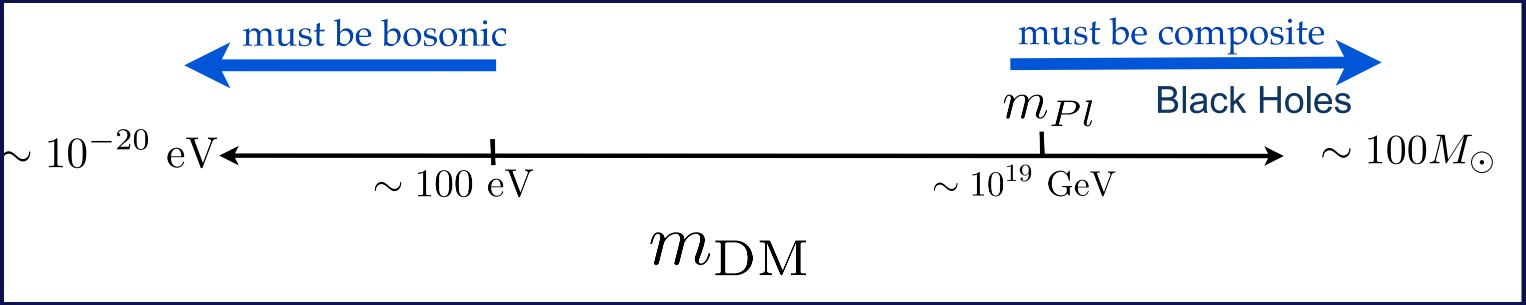
Which are its properties?

How to search for it?

Interacts very weakly → Gravity
(not charged) → Higgs-like Interactions ?

Understanding the DM Sector

Particle physics properties constrains the range of possible masses



Folding in assumptions about the evolution of the DM density in the early Universe can motivate more specific mass scales

Bad news: DM-SM interactions are not obligatory

If nature is unkind, we may never know the right scale

Good news: Most *discoverable DM candidates are in Thermal equilibrium with us in the early universe*

Why is this good?

Thermal Equilibrium:
Easily realized in the early Universe

If interaction rate exceeds Hubble expansion

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

$$H \lesssim n_\chi \sigma v \quad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \lesssim \left.\frac{g^2 T^5}{\Lambda^4}\right|_{T=m_\chi}$$

Equilibrium is easily achieved in the early universe if

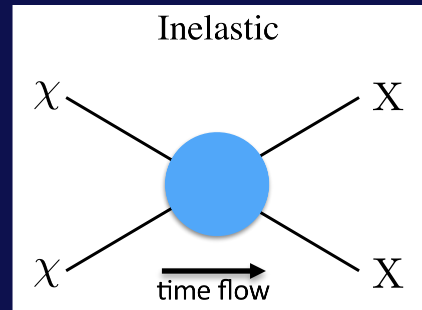
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\text{GeV}}\right)^2\left(\frac{\text{GeV}}{m_\chi}\right)^{3/2}$$

Applies to nearly all models with couplings large enough for detection (rare counter example: QCD axion DM)

Evolution of the Dark Matter Density: Thermal DM

$$\Gamma_{\mathbf{inelastic}} = n_\chi < \sigma v >$$

chemical equilibrium



At sufficiently high Temperature, the interaction $\chi\chi \longleftrightarrow XX$ is in thermal equilibrium,
DM particles are constantly replenished

$$n_{\rm DM}^{\rm (eq.)} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$

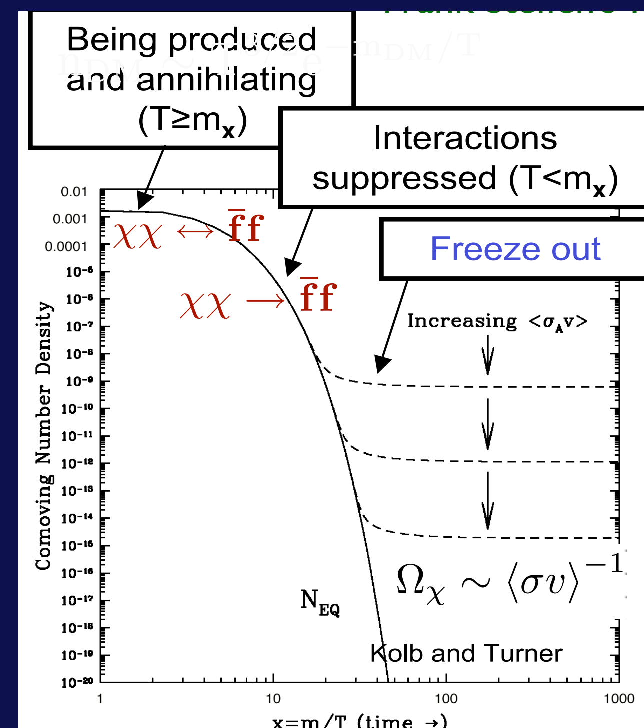
As the Universe expands & temperature decreases
number density decreases
For $T < m_{DM}$ interactions get suppressed (Cold DM)

$$n_{DM} \sim T^{3/2} e^{-m_{DM}/T}$$

Finally forward reaction stops (too hard for DM particles to find each other to annihilate)
DM density frozen in time:

$$\Gamma_{\mathbf{inelastic}} = n_\chi < \sigma v > \sim H$$

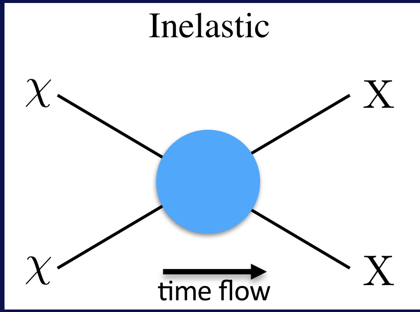
(Cold DM)

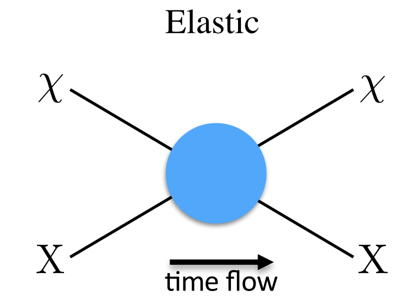


Evolution of the Dark Matter Density: Thermal DM

$\Gamma_{\mathbf{inelastic}} = n_\chi < \sigma v >$

chemical equilibrium





$\Gamma_{\mathbf{elastic}} = n_X < \sigma v >$

kinetic equilibrium

$n_X \sim T^3$

As X are relativistic

Cold Dark Matter is non-relativistic at Freeze out ➔ $n_{DM} \sim T^{3/2} e^{-m_{DM}/T}$

Hot Dark Matter is relativistic at Freeze out -➔ $n_{DM} \sim T^3$

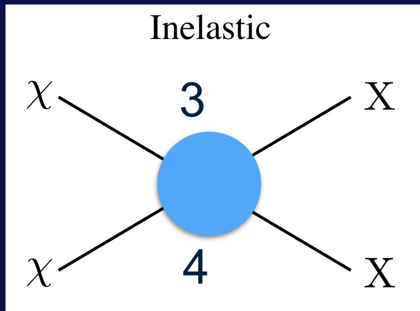
Warm dark matter is in between

After freeze out, DM is no longer in chemical eq., but it remains in thermal eq. with the surrounding plasma via elastic interactions.
After a certain point it decouples and DM is free streaming ($\Gamma_{elastic} < H$)

For Cold (Hot) Dark Matter kinetic decoupling happens only after freeze out (earlier). Detailed studies of the DM free streaming after decoupling constrain warm DM candidates, that predict less structure on small scales than actually observed.

Cold Dark Matter Preferred

Evolution of the Thermal Cold Dark Matter Density



Particles 1 and 2 are identical with number density n, while 3 and 4 are SM particles in thermal equilibrium with the photon bath.

$$\dot{n}+3Hn=-\langle\sigma v\rangle_{12}\, n^2+\langle\sigma v\rangle_{34}\, n_3 n_4$$

$H=\dot{a}/a$ is the expansion rate of the Universe and a is the scale factor

When the DM is also in eq. with the SM final states: $\langle\sigma v\rangle_{12} n^2_{eq}=\langle\sigma v\rangle_{34} n_3^{eq} n_4^{eq}$

The Boltzmann equation for the dark matter number density reduces to

$$\dot{n} + 3Hn=\langle\sigma v\rangle(n^2_{eq}-n^2)$$

Instead of using n it is better to use define the comoving number density $Y=n/s$, with s the total entropy density

and using that sa^3 is constant ➔ $\dot{s}=-3sH$ ➔ $dY/dt = \langle\sigma v\rangle s\,(Y^2_{eq}-Y^2)$

Considering the behavior of the solutions for Y in limiting cases, one can build an intuition for how the DM number density evolves with time

Evolution of the Thermal Cold Dark Matter Density

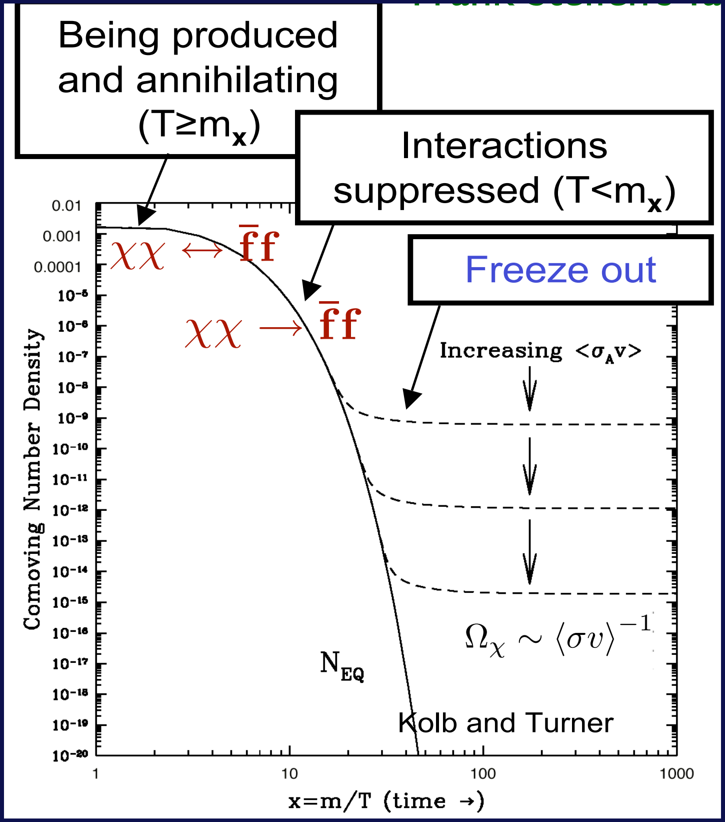
It is useful also to define a rescaled dimensionless time variable x= m/T

$$dY/dt = \langle \sigma v \rangle s \,(Y^2_{eq} - Y^2)$$

$$\downarrow$$

$$dY/dx = -xs\langle \sigma v \rangle (Y^2 - Y^2_{eq})/H(m=T)$$

Then we can plot the comoving dark matter number density Y versus the rescaled time x to see the freeze out behavior, as in this famous figure from Kolb and Turner



Evolution of the Thermal Cold Dark Matter Density:

Changes in Y arise purely from interactions of the DM with states that are in thermal equilibrium with the photon bath

Y evolution is governed by <σv>

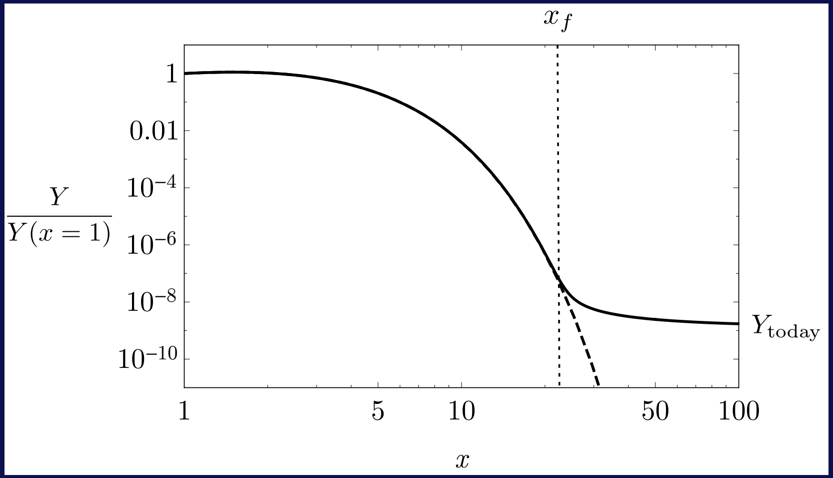
$$\langle \sigma v \rangle = \frac{1}{8m^4 T K_2^2(m/T)} \int_{4m^2}^{\infty} \sigma(\tilde{s} - 4m^2)\, \sqrt{\tilde{s}}\, K_1(\sqrt{\tilde{s}}/T)\, ds \xrightarrow{\text{non-rel.}} b_0 + \frac{3}{2} b_1 x^{-1} + \cdots$$

Where K_1 and K_2 are modified Bessel functions.
In the non-relativistic limit, the cross section can be expanded in the rescaled time variable x with coefficients $b_{0,1,\ldots}$

b_0 represents s-wave annihilation: no dependence of <σv> on x

b_1 represents p-wave annihilation: <σv> decreases as x gets larger.
Note this can be regarded as a velocity suppression, since
$1/x = T/m \sim (mv^2/2)/m \sim v^2$

The WIMP Miracle



Taking xf$\sim$10 and$\langle\sigma v\rangle \sim \alpha^2/m^2$, the fraction of critical density contributed by the DM today is

$$\Omega\chi = m\, s_{today}\, Y_{today} / \rho_{cr} \rightarrow \Omega\chi h^2 \sim (10^{-26} cm^3/s)/\langle\sigma v\rangle \simeq 0.1\ (0.01/\alpha)^2\ \ (m/100\ \text{GeV})^2$$

➔ correct abundance today as measured by Planck and WMAP,
for α ~ 0.01 and m ~ 100 GeV

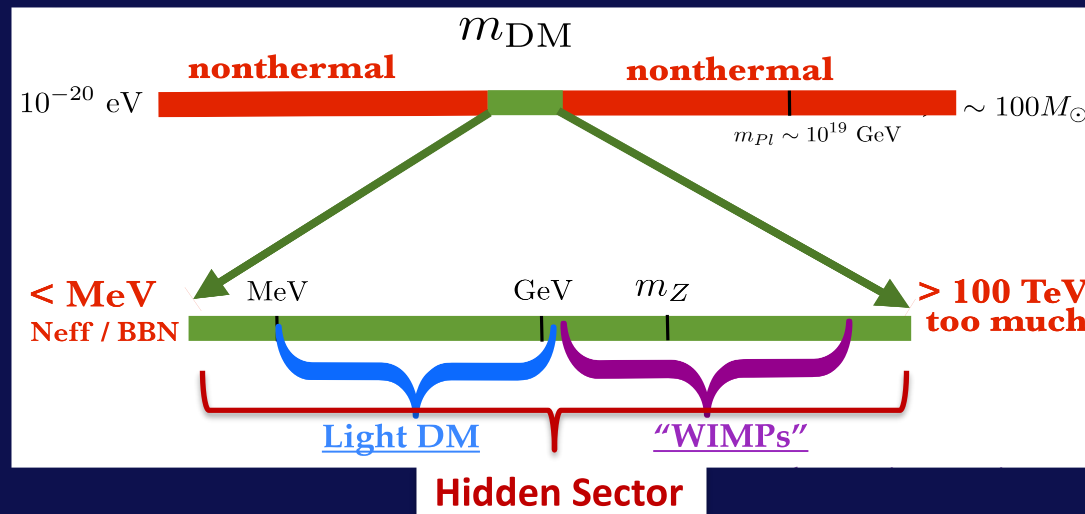
the “WIMP miracle”

Weak-scale DM naturally gives the correct DM density
Many well-motivated models, such as supersymmetry provide such candidates.
A wide-ranging of experimental programs targeted for WIMP searches

How much of a miracle are WIMPs?

What is really constrained is the ratio of the squared coupling to the mass.
It is possible to open up a wider band of allowed masses for thermal DM by taking $\alpha \ll 1$ while keeping α^2/m^2 fixed ($\alpha^2\, m^2/M^4$, if heavy mediators)

Thermal Equilibrium: Narrows viable Mass range



WIMPs:

interact through SM weak forces and for masses below ~ 2GeV or higher than several TeV the annihilation cross section is too small, hence overabundance of thermal DM expected

Hidden Sector DM:

Particles neutral under SM forces, but charged under new forces not yet discovered. Can have portal interactions with the SM.
Mass viable over a wider range than WIMPs including **Light DM down to KeV range**

Minimal Annihilation Rate for symmetric and asymmetric DM

"Symmetric" DM means the DM is its own antiparticle and its relic abundance is produced by thermal freeze out

"Asymmetric" DM is realized when the DM relic abundance is created by an asymmetry between DM particles and antiparticles, in addition to the possible one induced by thermal freeze out

$$\Omega_\chi \sim \langle \sigma v \rangle^{-1}$$

Symmetric Thermal DM:
Observed density requires →

$$\sigma v_{\rm sym} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Asymmetric Thermal DM:
Just need to deplete antiparticles

$$\sigma v_{\rm asym} > 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

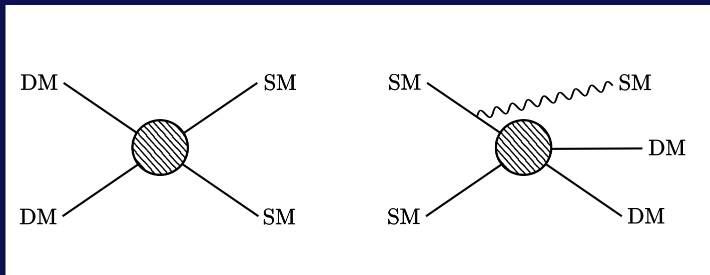
Rate can be bigger, but not smaller

Thus many searches for Symmetric DM also Asymmetric DM scenarios

Accelerator based DM searches
collider experiments and fixed target experiments

- I will cover Standard WIMP scenarios as well as Hidden Sector DM thermal freeze out scenarios
- I will also cover searches for the particles mediating the new interactions
- Low mass region Hidden Sector DM pheno is quite different from Standard WIMP pheno

Accelerator Searches Vs Direct Detection



Strong connection between Thermal Freeze out and DM searches at collider/accelerators

Accelerator searches explore the relativistic production and/or interactions of DM candidates
Direct detection experiments search for the scattering of DM in the Milky Way halo off matter, with relative velocity ~ $10^{-3}c$

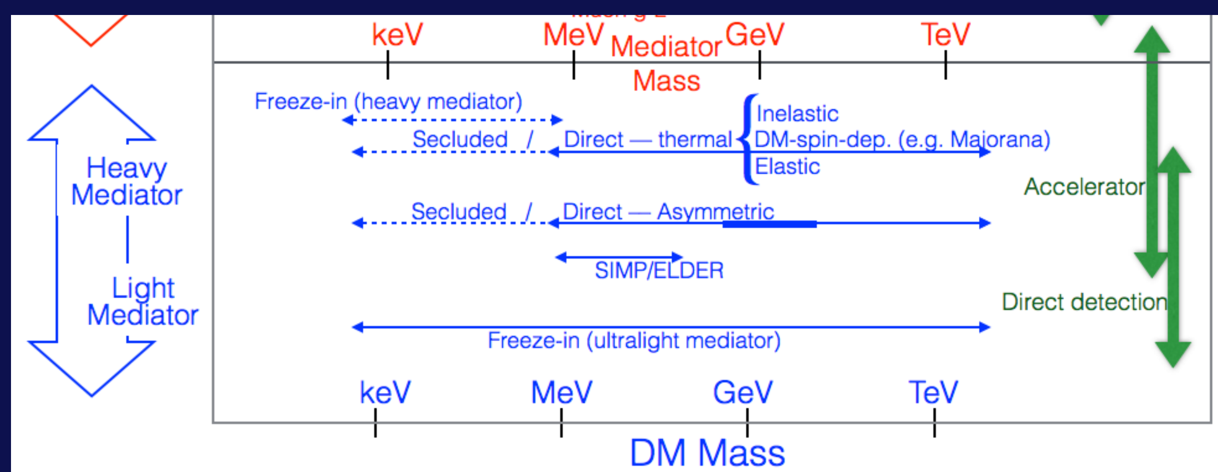
Such big kinematic difference may make DM scenarios accessible to one technique and not at the other techniques.

e.g.

Hidden-sector Dark Matter:

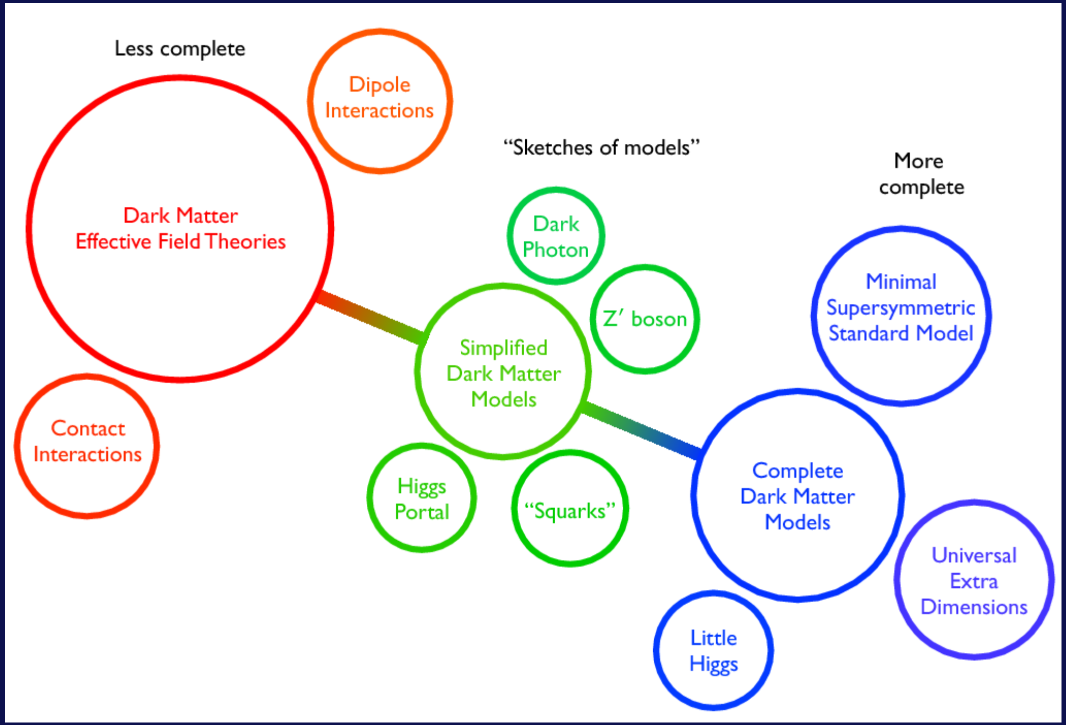
Production Mechanisms

Detection Strategies



DM Theory Space

Needed to relate information from direct and indirect detection experiments with accelerator bounds/searches



- Non–renormalizable interactions ➔Effective Field Theory (EFT) approach

Each possible interaction characterized by the DM candidate mass & the operator suppression scale

- Simplified models

(e.g. SM +DM + (a) mediator/s from extended SM or Dark Sector)
More parameters but describe correctly the full kinematics of DM production

- Specific more complete models

Even larger set of parameters, but allows for correlations between observables,

Dark Matter at Colliders: the LHC

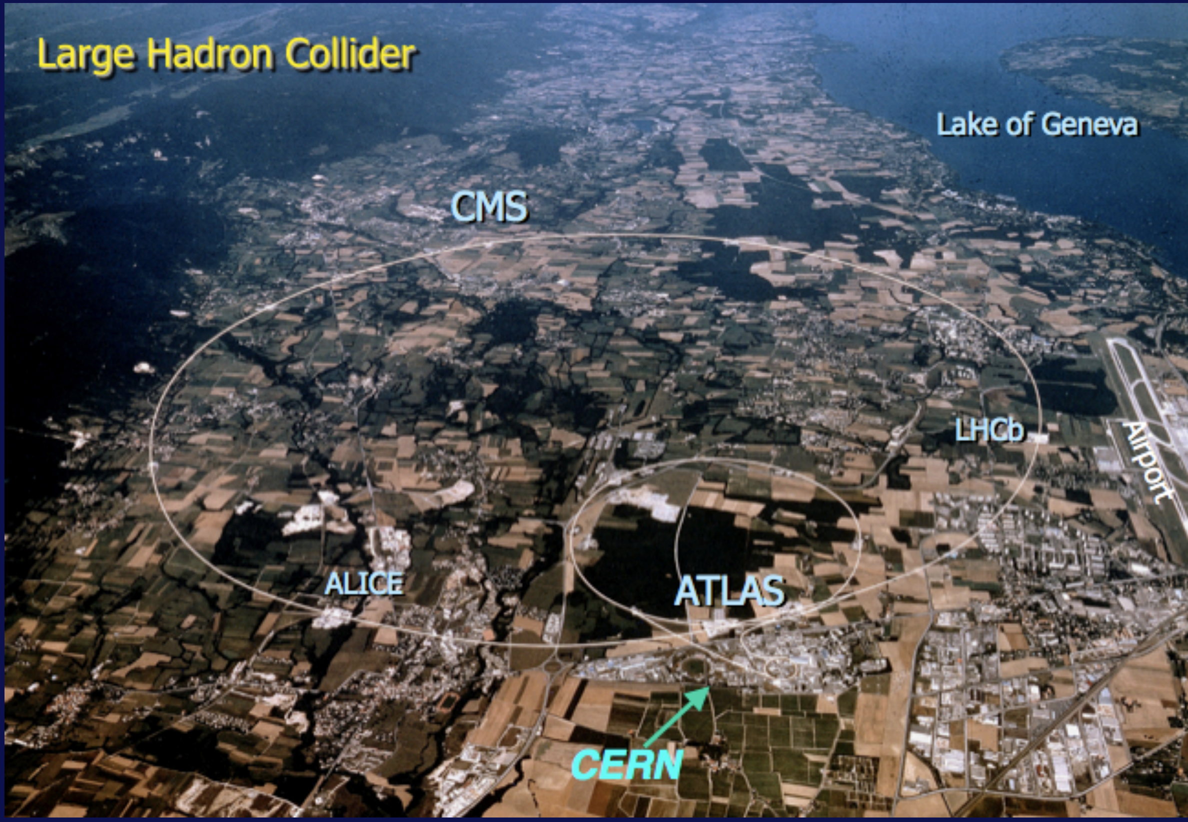
- If dark matter is light enough and has sufficiently strong non-gravitational interactions with ordinary matter, then it will be produced in proton-proton collisions at the LHC

- The LHC is running now (Run 2) with 13 TeV pp collisions, and ran 7 TeV and 8 TeV pp collisions in 2010-2012 for the discovery of the Higgs boson

- 27 km underground ring

- 31,000 tons of superconducting magnets cooled to 1.9 degrees K using 90 tons of liquid helium

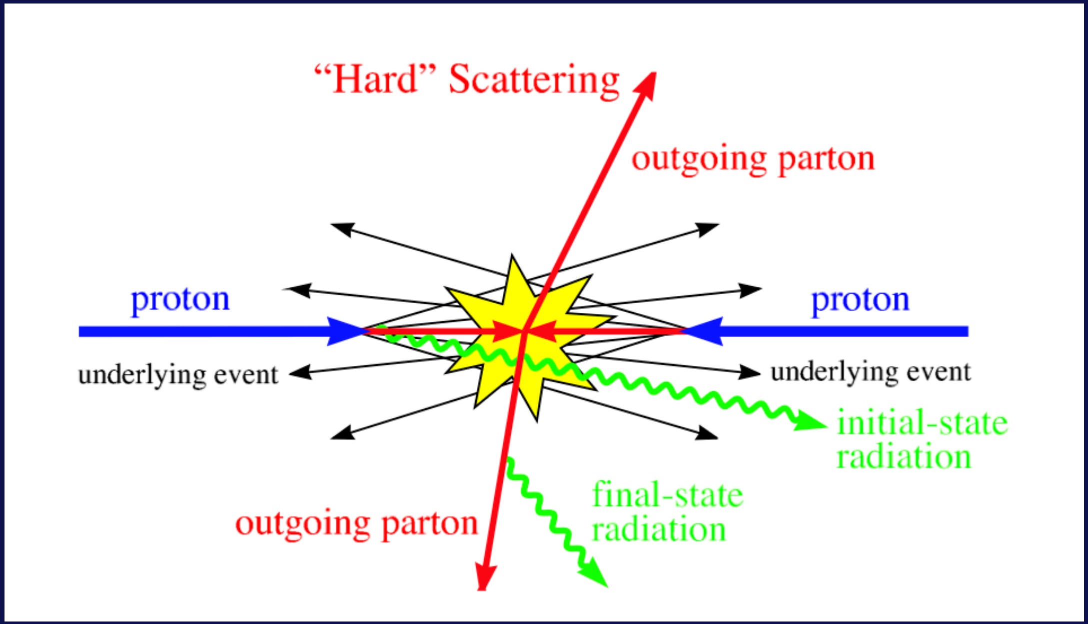
- Counter-rotating beams of protons, 360 Megajoules of energy per beam = 86 Kg of TNT



Dark Matter at Colliders: the LHC

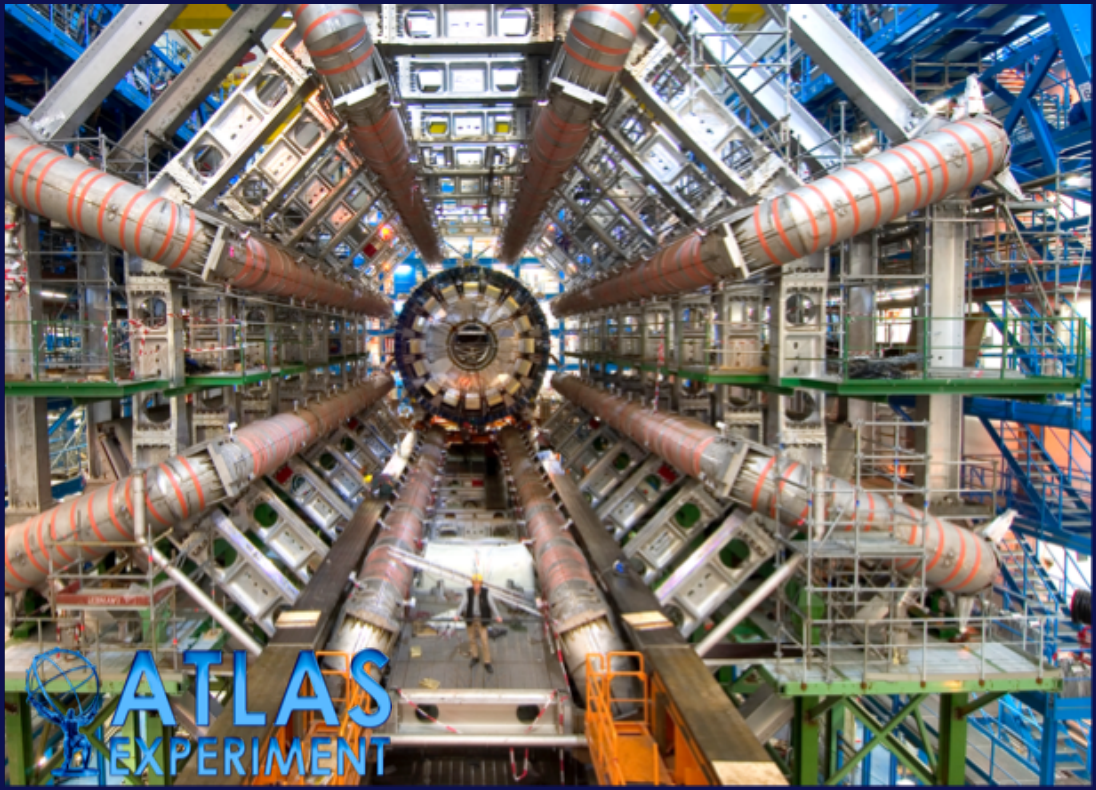
- Bad news: since the proton is a QCD composite of quarks and gluons, pp collisions at 13 TeV actually produce a distribution of quark-quark, quark-gluon, or gluon-gluon collisions at much lower center-of-mass energies

- Good news: Collisions occur every 25 nanoseconds over runs that last for years, so you have a lot of chances to make a rare event that contains dark matter particles



Dark Matter at Colliders: ATLAS and CMS detectors

Good news: The ATLAS and CMS collaborations have built and are operating the world's largest and most sophisticated particle detectors: >100 million channels of readout for collisions occurring every 25 nanoseconds

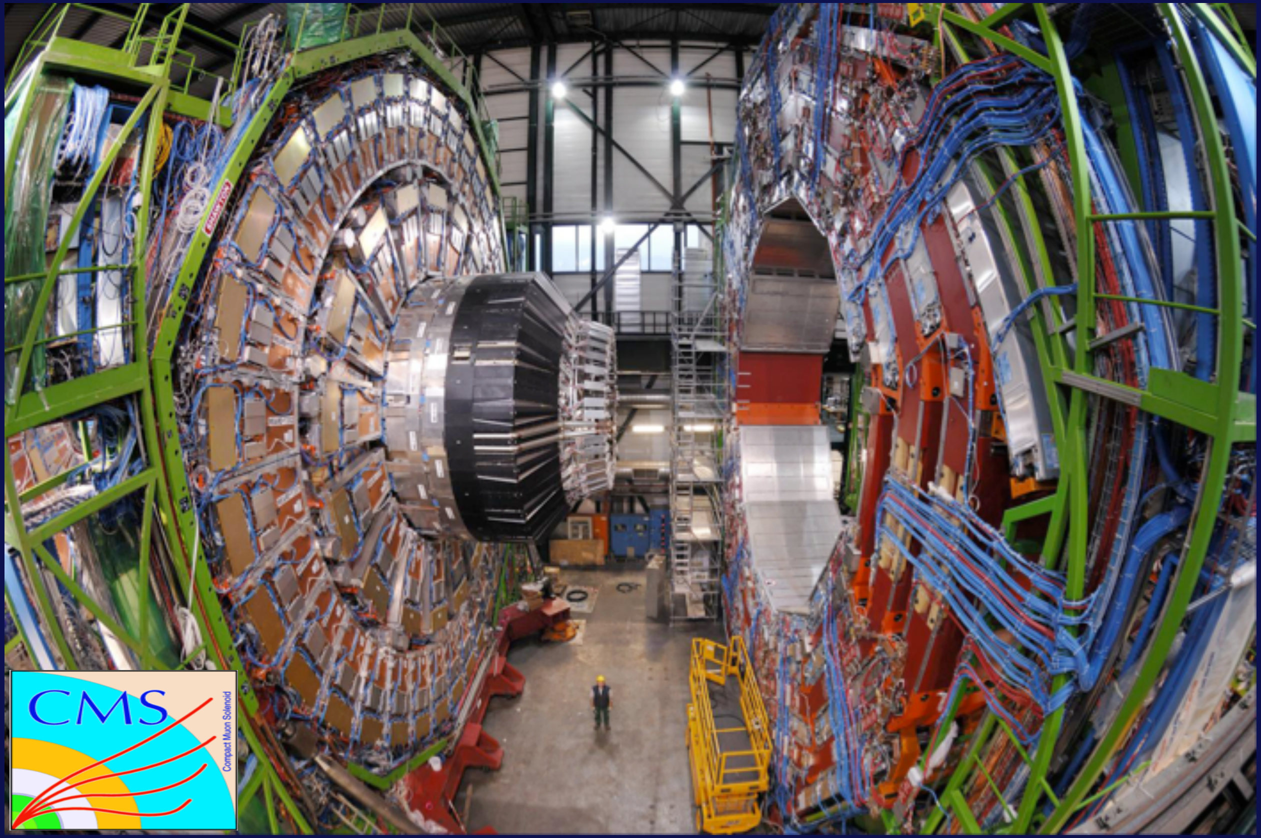


Each experiment about
3000 physicists
180 Institutes
40 countries

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

Dark Matter at Colliders: ATLAS and CMS detectors

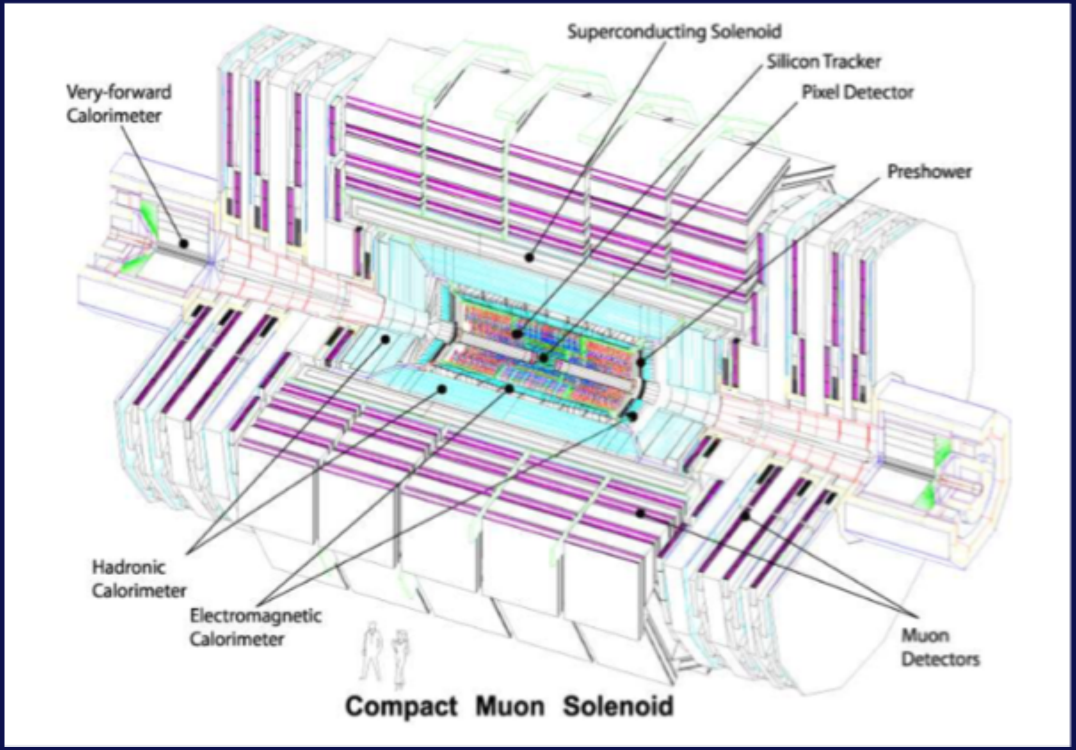
Bad news: The ATLAS and CMS detectors cannot detect dark matter particles directly, even if the LHC produces them



Dark Matter at Colliders: ATLAS and CMS detectors

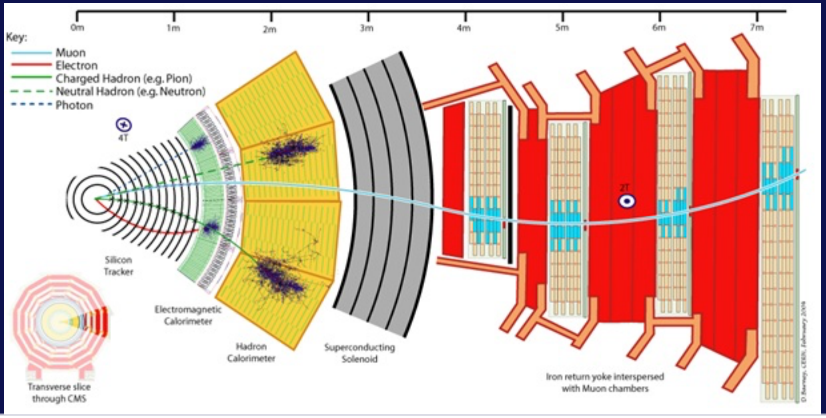
What do the ATLAS and CMS detectors detect?

- Charged particle tracks in the tracker
- Energy from electromagnetic showers in the ECAL
- Energy from hadronic showers in the the HCAL
- Tracks in the outer muon system



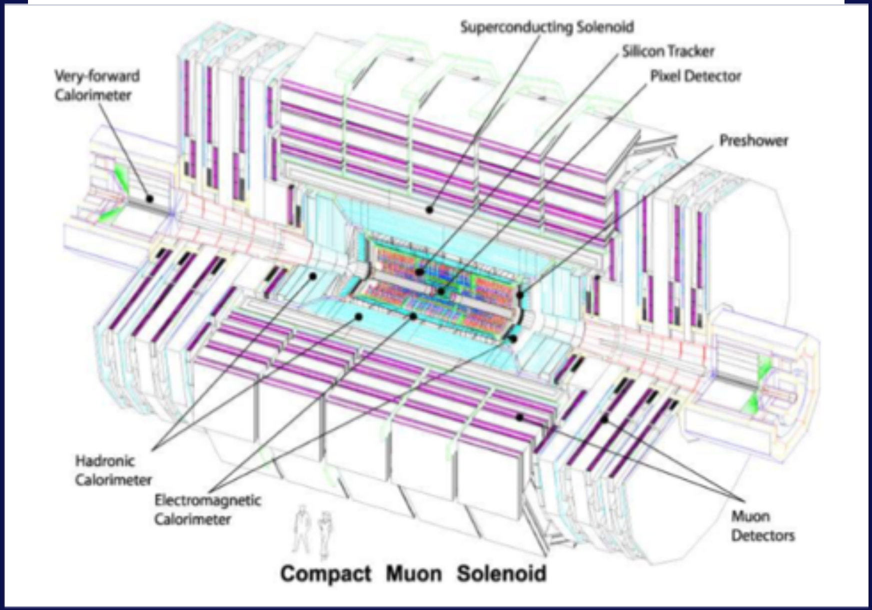
Dark Matter at Colliders: ATLAS and CMS detectors

From this basic information ATLAS and CMS reconstruct "physics objects" for "interesting" collisions events



physics objects:

- Electron
- Photon
- Muon
- Hadronically decaying tau
- Jet
- b-Jet
- Missing transverse energy (MET)



What is MET??

Dark Matter at Colliders: What is MET?

MET is a way for collider detectors to “see the invisible”

- Suppose you measured the momentum of every visible particle coming out from a particular pp collision and add up these vectors to get the total momentum transverse to the LHC beam

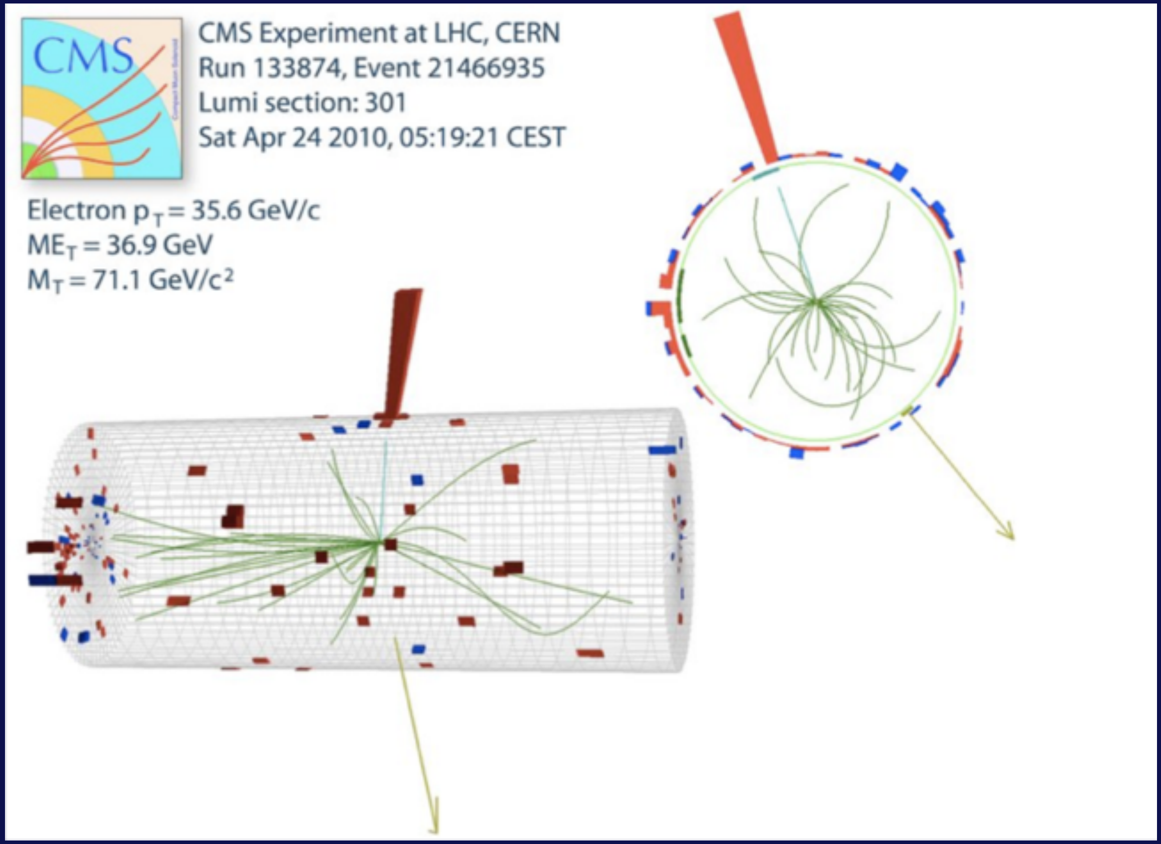
- The protons in the beam have no transverse momentum (or you would have lost them around the ring)

- Then, assuming only conservation of momentum, any large imbalance in the total transverse momentum must have been compensated by one or more invisible particles produced in the collision

Dark Matter at Colliders: What is MET?

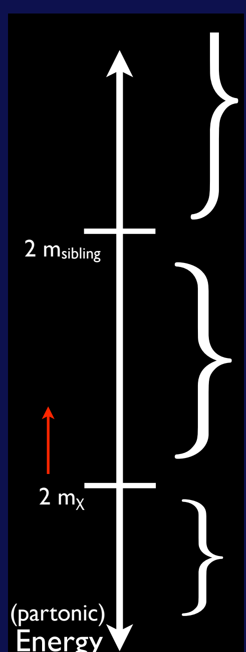
MET is a way for collider detectors to “see the invisible”

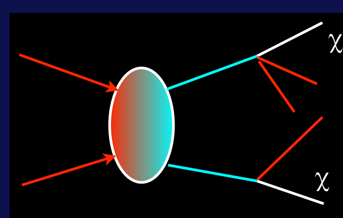
- ATLAS and CMS see lots of collisions with large MET, coming from neutrinos
- Here is a CMS event that produced a W boson, which decayed into an electron and a neutrino
- The neutrino is “seen” as MET



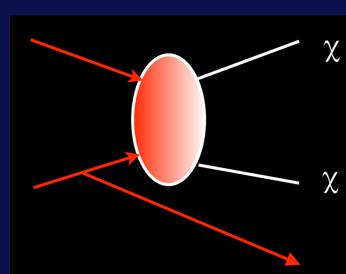
Dark Matter at Colliders: use the MET

- WIMP DM particles could be “detected” at the LHC as MET
- We could either produce the WIMP directly (in pairs), or produce a charged/colored relative of the WIMP that decays into a WIMP
- The WIMP is the lightest of the new states and must be neutral and stable
- Most of the heavier “WIMP siblings” usually are colored and/or charged, thus (for a given mass) easier to produce directly in a pp collision than the dark matter WIMP





LHC produces heavier new particles that then decay into SM particles and WIMPS, leading to more complex final sates



The most minimal assumption is that the only new state beyond the SM that is kinematically accessible at the LHC is the DM particle => LHC directly produces the WIMP

LHC has not enough energy to produce the WIMPs

Effective Field Theory Approach : Contact Interactions

- The dark matter is the only state accessible to our experiments.
- Natural place to start, since EFT implies many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved
- Each operator characterized in terms of 2 parameters: DM mass and suppression scale Λ

Drawbacks: It breaks down when energy is sufficient to produce other new particles directly
It misses correlations among observables

Example: Axial-vector operator,
X denotes a Dirac or Majorana Fermion

$$\mathcal{O} = \frac{1}{\Lambda^2}(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)$$

LHC: Stronger constraints on Λ (=M*) for effective operators involving quarks and gluons. Each operator has a separate scale Λ (=M*) that characterize its strength

10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ invariance coupling the ' WIMP (Majorana fermion) to quarks & gluons

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	-

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

Effective Field Theory Validity

Appealing factor: EFT is independent of the UV completion, BUT
it was observed that in some cases the EFT fails to describe the physics correctly. When?

How the EFT connects with the more fundamental theory?

$$\mathcal{O} = \frac{1}{\Lambda^2}(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)$$

Obtained from a theory with a spin-1 particle Vμ, THE MEDIATOR with axial vector couplings

$$\mathcal{L} \supset \frac{m_V^2}{2} V^\mu V_\mu + V^\mu g_q \bar{q}\gamma_\mu\gamma^5 q + V^\mu g_{\rm DM}\bar{\chi}\gamma_\mu\gamma^5\chi$$

s-channel exchange leads to a Matrix element that for $m_V^2 >> s$ easily connect with the EFT

$$\mathcal{M} \propto \frac{g_q\, g_{\rm DM}}{m_V^2 - s} \xrightarrow{m_V^2 >> s} \frac{1}{\Lambda^2} = \frac{g_q\, g_{\rm DM}}{m_V^2}$$

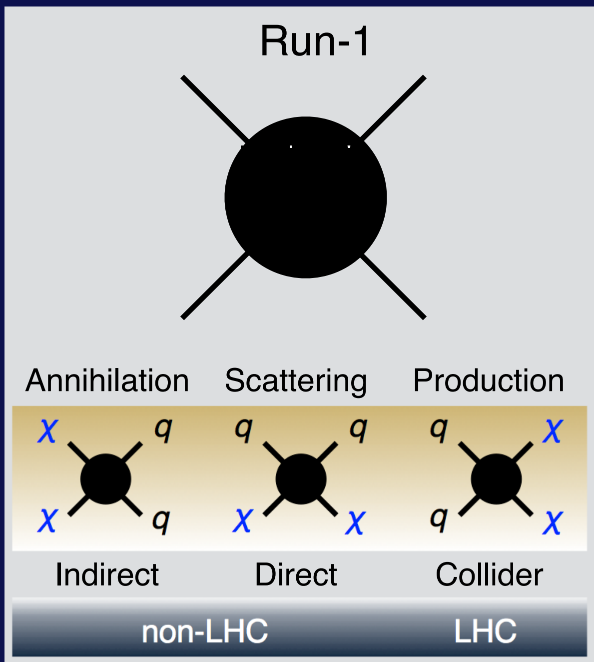
Instead if $m_V \lesssim$ TeV, effects of order s/m_V^2 are relevant and spoil validity of EFT

Also $\Lambda \lesssim$ a few TeV is needed not to make the cross section too small at the LHC
➔ For too large m_V one needs couplings too large (non-perturb) to have sensitivity.

Aditionally, the matrix element from EFT scales as s/Λ^2 and hence the perturbative unitarity of the theory demands $\sqrt{s} \lesssim (2\text{-}3)\,\Lambda$

Truncate the EFT such that only processes with small momentum transfer are considered, $E \lesssim m_V$ to allow for a reliable, model independent bounds
(For Run 1 LHC with $\sqrt{s}$ = 7-8 TeV, EFT more reliable that for 13 TeV)

EFT Complementarity among searches



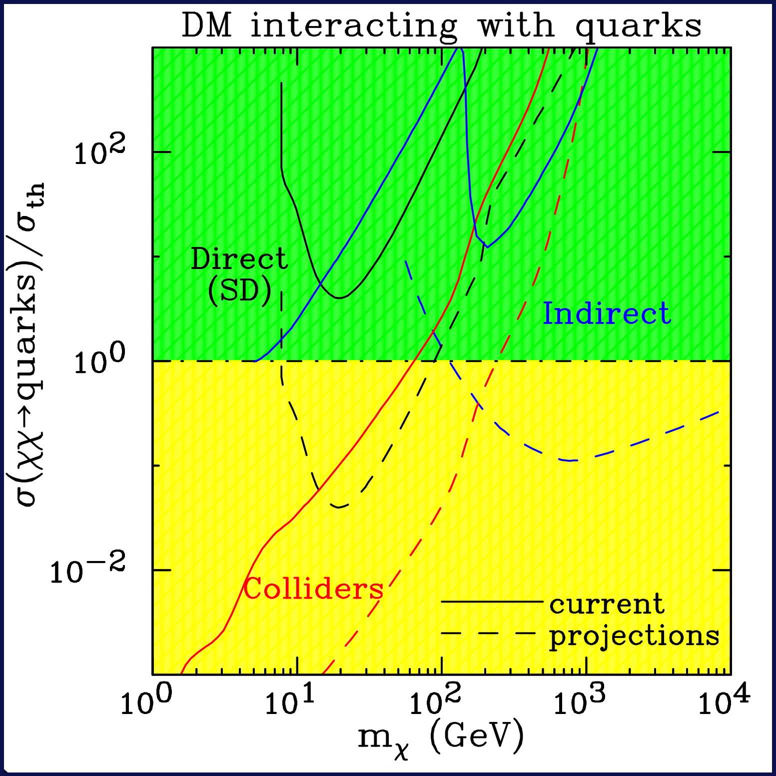
- The various types of interactions are accessible to different kinds of experiments.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation in the galactic halo
  - Collider Production

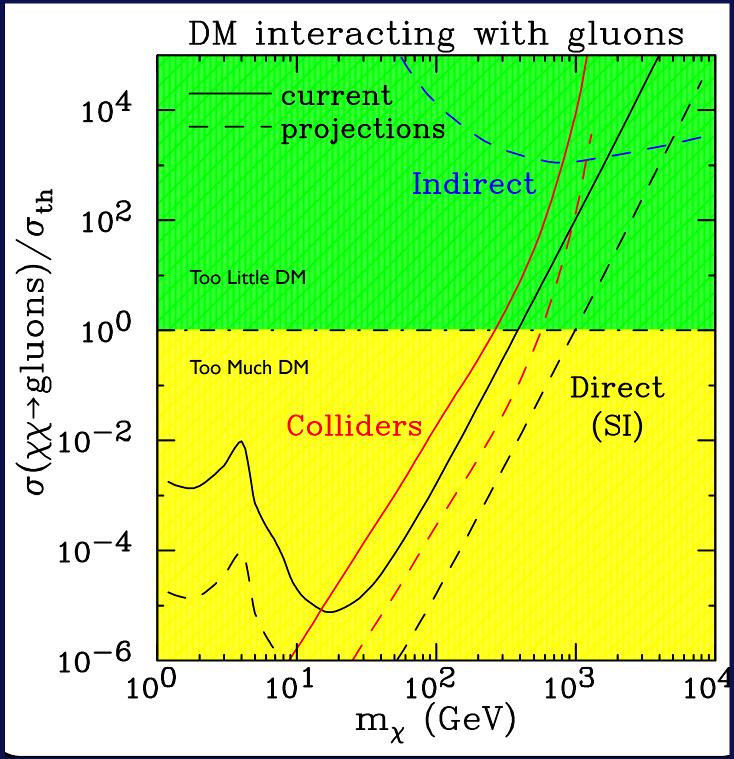
Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

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	-

EFT Complementarity among searches

Colliders do better for lighter WIMPs or p-wave annihilations whereas indirect detection is more sensitive to heavy WIMPs





DM Complementarity, arXiv:1305.1605

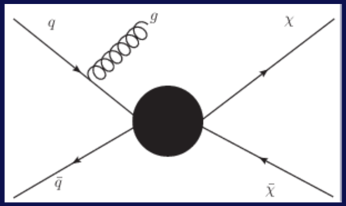
Main results from colliders come from mono-jet analyses (see below)

EFT results

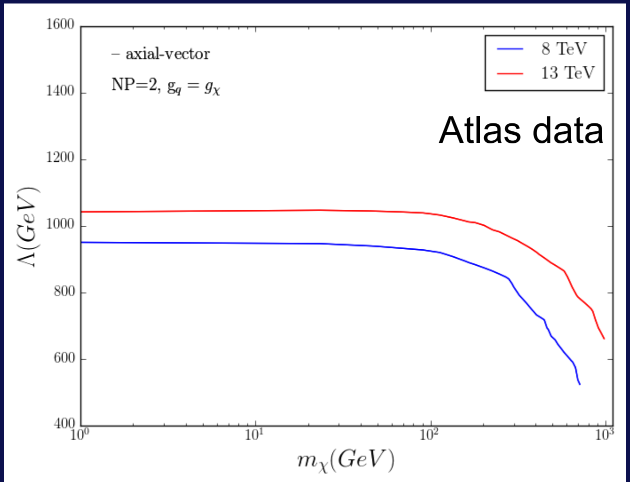
EFT is independent of UV completion; but is there a regime in which is valid?

The shape of all kinematic distributions is independent of the suppression scale Λ
For a dim-6 operator, all cross sections are simply proportional to $1/\Lambda^4$, hence, it is easy to present results in terms of Λ and m_{DM}.

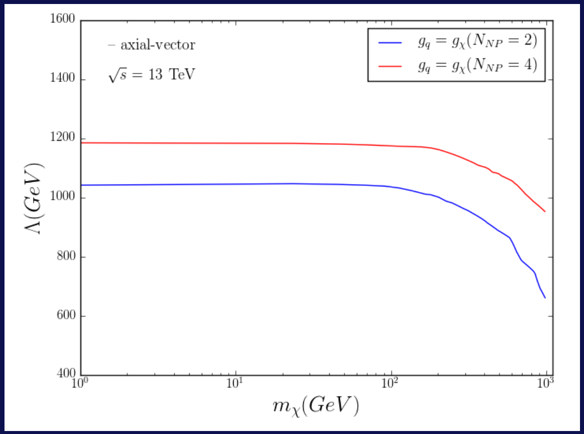
In addition, for m_{DM} smaller than the typical cut in missing transverse energy, kinematic distributions, and hence bounds, become independent of m_{DM}
➔ LHC searches are sensitive to arbitrarily low m_{DM}.



Monojet searches



60% increase in the cross sections shows bad behavior of the EFT



The analysis of LHC monojet data in the language of EFT, which was originally hoped to provide a model independent framework, actually does not seem to apply to any model.

Simplified Models

- Should be simple enough to form a credible unit within a more complicated model

Consider descriptions with (an) additional particle/s mediating the interactions between the DM candidates and the SM particles

DM candidate should be absolutely stable or live long enough to escape LHC detectors

The dark sector can be richer, but the additional states should be somewhat decoupled.

- Should be complete enough to be able to describe accurately the relevant physics phenomena at the energies that can be probed at the LHC

Unlike the DM–EFTs, simplified models are able to describe correctly the full kinematics of DM production at the LHC, because they resolve the EFT contact interactions into single-particle s-channel or t-channel exchanges.

To limit the possibilities, **consider only renormalizable interactions** and consistent with Lorentz invariance, the SM gauge symmetries, and DM stability

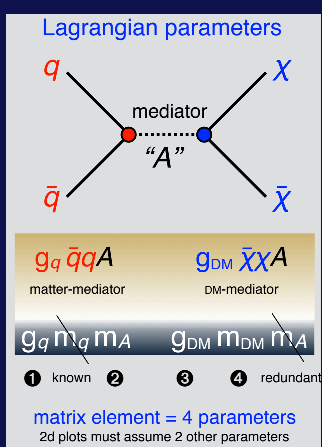
Additional interactions **should not violate the exact and approximate accidental global symmetries of the SM** ➔ interactions between the visible and the dark sector should be such that baryon and lepton number is conserved and that the custodial and flavor symmetries of the SM are not strongly broken.

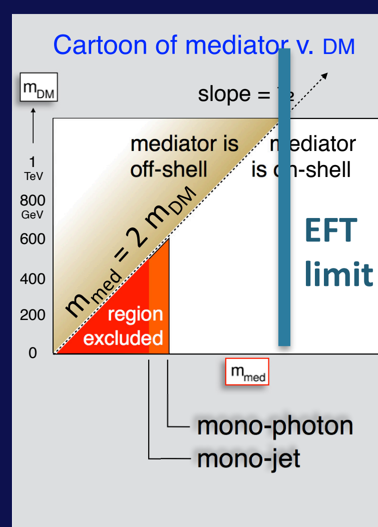
Simplified Models (cont'd)

- **Models specifically designed to involve only a few new particles and interactions**
- Can be understood as a limit of a more general new-physics scenario, where all but the lightest dark-sector states are integrated out.
- **By construction, the physics can therefore be characterized in terms of a small number of parameters such as particle masses and couplings.**

In the minimal simplified model the matrix element for the interaction involves 4 param, —gq, g_{DM}, m_{DM} and m_{med}

Testing the strength of the $\sigma_{pp\to XX}$ can be translated into probing region in a 2D space (m_{med}-m_{DM}) after assuming the values of 2 param. (g_q ,g_{DM}).





For $m_{med} < 2\ m_{DM}$, off shell mediator, DM production suppressed

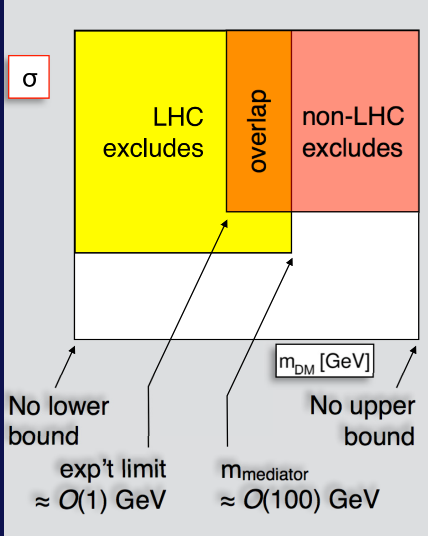
EFT limit, tricky, only valid for couplings close to perturbativity bound

LHC searches aim to explore the on-shell mediator region

Simplified Models: Complementarity among searches

One can translate the parameter region explored at the LHC into $\sigma_{p\chi\to p\chi}$ in order to compare the LHC results with non-LHC results.

Cartoon of cross-section v. DM



Results in m_{med}-m_{DM} space are converted into m_{DM}-σ^{dd}_{DM-p} space

$$\sigma^{dd}_{DM-p} \propto \left(g_q \, g_{DM} \frac{m_{DM-p}}{m^2_{med}} \right)^2$$

with $$m_{DM-p} = \frac{m_\chi m_N}{m_\chi + m_N}$$ the DM-nucleon reduced mass

We shall see that many of the mono-object results in this framework rule out a region of low m_{DM}

Important:

direct detection limits can be evaded by assuming that χ is not stable on cosmological time scales, but lives long enough to escape the ATLAS and CMS detectors. When comparing the bounds set by direct detection and the LHC, this loophole should be kept in mind.

Before diving in into experimental searches less consider some typical Simplified Models

Model Building: s- Channel Mediators

❖ Scalar s-channel mediators (spin 0 mediators)

Add a scalar gauge singlet with interactions with singlet DM particles: Dirac or Majorana fermion or a scalar itself

Scalar may be real or complex (scalar and pseudoscalar components) and couples to SM fermions

If coupling to SM fermions is via mixing with the Higgs ➔ rich Higgs and EW pheno that makes the model less simple (type of Higgs portal to DM)

MFV dictates that the coupling of a scalar to the SM fermions will be proportional to the fermion masses. However, these couplings can be scaled by separate factors for the up-quarks, down- quarks, and charged leptons.
Assuming a Dirac fermion DM χ, coupling to the SM only through a scalar ϕ or pseudoscalar a

$$\mathcal{L}_{\text{fermion},\phi} \supset -g_\chi \phi \bar{\chi} \chi - \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) ,$$

$$\mathcal{L}_{\text{fermion},a} \supset -i g_\chi a \bar{\chi} \gamma_5 \chi - \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right) .$$

In general there will be also a scalar potential coupling the scalar to the Higgs. However, this minimal case, with MFV and assuming gu = gd = gl, is only a 4 param. model

mχ, mϕ/a, gχ, gu,

Signal strength in DM production also depends on the total width also given by this 4 param.

❖ Higgs portals to DM

DM may predominantly couple to the SM particles through the SM Higgs.
Some examples

I) The *DM particle is a scalar singlet* under the SM gauge group, which couples through a quartic interaction with the Higgs (direct Higgs portal)

$$\mathcal{L}_{\text{scalar},H} \supset -\lambda_\chi \chi^4 - \lambda_p \chi^2 |H|^2$$

The self-coupling λ_χ plays no role in determining how well the portal coupling λ_p can be probed via LHC DM searches.

Adding a discrete Z2 symmetry that takes $\chi \to -\chi$ and $H \to H$ leads to stable DM, and in addition guarantees no singlet-Higgs mixing, which leaves SM Higgs couplings unaltered at tree level.

For $m_h > 2\, m_\chi$, the most obvious manifestation of the interactions is through their contributions to the invisible decay of the Higgs. Competitive results for light DM < 10 GeV

$$\Gamma(h \to \chi\chi) = \frac{\lambda_p^2 v^2}{2\pi m_h}\left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{1/2}$$

For $m_h < 2m_\chi$, the Higgs cannot decay on-shell to a pair of χ particles, so that DM pair production has to proceed off-shell. The cross section is then suppressed by an additional factor of λ_p^2 as well as the two-body phase space, ➔ rate that rapidly diminishes with m_χ

No LHC reach

❖ Higgs portals to DM (cont'd)

II) The *DM particle is a fermion singlet* under the gauge symmetries of the SM, which couples to a scalar boson which itself mixes with the Higgs.

This model class provides a specific realization of the s-channel scalar mediator case

$$\mathcal{L}_{\text{fermion},H} \supset -\mu_s s^3 - \lambda_s s^4 - y_\chi \bar{\chi} \chi s - \mu_p s|H|^2 - \lambda_p s^2 |H|^2,$$

(Higgs portal through S)

$Y\chi$ → Yukawa coupling in the dark sector μ_p and λ_p → Higgs portal between DM and SM

μ_s and λ_s play no important role in the DM pheno at the LHC (set to 0). Also set <s>=0

To make contact with the scalar mediator model, after EWSB and rotation to the mass basis

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} (\cos\theta\, h_1 - \sin\theta\, h_2) \sum_f y_f \bar{f} f - (\sin\theta\, h_1 + \cos\theta\, h_2)\, y_\chi \bar{\chi} \chi\,.$$

$$\tan(2\theta) = \frac{2 v \mu_p}{m_s^2 + \lambda_p v^2 - m_h^2},$$

$m_{h1} \simeq mh$ and $m_{h2} \simeq (m_s^2 + \lambda_p v^2)^{1/2}$

Identifying h2 with ϕ, it follows gu=gd=ge=gv= −sinθ. and $g_\chi = y_\chi \cos\theta$.

The effective Yukawa coupling between h_1 and the SM fermions is $y_f \cos\theta$.
Same, universal suppression factor cosθ appears in h_1W+W- & h_1ZZ tree-level vertices as well as in loop-induced h_1gg, $h_1\gamma\gamma$, and $h_1\gamma Z$ couplings → $\sin\theta < 0.4$ (Higgs precision meas.)

❖ Higgs portals to DM (cont'd)

II) The DM particle is a fermion singlet under the gauge symmetries of the SM, which couples to a scalar boson which itself mixes with the Higgs.

Same as in scalar DM Higgs portal, if kin. allowed, **Higgs bosons can decay into DM**

$$\Gamma(h_1 \to \chi\bar{\chi}) = \frac{y_\chi^2 \sin^2\theta \, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}$$

After replacing sinθ→cosθ and mh_1→ mh_2 the same expression holds for h_2, if it is sufficiently heavy. All partial widths of h_1 to SM particles are $\cos^2\theta$ suppressed & the decay $h_1 \to h_2 h_2$ may be allowed.

Fermion singlet DM pheno through Higgs portal is generically richer than that of the simplest scalar mediator model

- ❖ Tree level couplings of h_1 & h_2 to W, Z pairs ➔ **mono-V signals with interesting behavior**

$$\mathcal{A}(pp \to \not{E}_T + W/Z) \propto y_\chi \sin(2\theta) \times \left(\frac{1}{s_{\chi\bar{\chi}} - m_{h_1}^2 + i m_{h_1}\Gamma_{h_1}} - \frac{1}{s_{\chi\bar{\chi}} - m_{h_2}^2 + i m_{h_2}\Gamma_{h_2}}\right)$$

Opposite sign ➔MET+W/Z cross sections can depend sensitively on m_{h2} and m_χ

Destructive interference between the two scalar mediators is also at work for mono-jets, with relevant consequences in direct detection.

- ❖ The presence of the two scalar states h_1 and h_2 allowing for the trilinear s-h_1-h_2 vertix can change the mono-Higgs phenomenology compared to the simplified scalar mediator case

❖ Higgs portals to DM (cont'd)

III) The *DM particle itself may be a mixture of an electroweak singlet and doublet* as in the MSSM where it has both bino and higgsino components, or in the NMSSM where it can be bino-higgsino or singlino-higgsino.

Generically, this is referred to as "singlet–doublet" DM.

-- If in the MSSM (NMSSM), the additional Higgs doublet (and singlet) mix with the Higgs and one should be close to alignment (decoupling) to be in agreement with LHC Higgs data --

Consider a fermion singlet χ and a pair of fermion doublets with opposite hypercharge denoted by $\psi_1=(\psi_1^0, \psi_1^-)^T$ and $\psi_2=(\psi_2^+, \psi_2^0)^T$, such that the new fields are odd under a Z_2 symmetry under which the SM fields are even (MSSM in decoupling limit, $y_{1,2}$, free param)

$$\mathcal{L}_{\text{fermion,SD}} = i\left(\bar{\chi}\,\partial\!\!\!/\,\chi + \bar{\psi}_1 D\!\!\!\!/\,\psi_1 + \bar{\psi}_2 D\!\!\!\!/\,\psi_2\right) - \frac{1}{2}m_S\chi^2 - m_D\psi_1\psi_2 - y_1\chi H\psi_1 - y_2\chi H^\dagger\psi_2 + \text{h.c.},$$

After electroweak symmetry breaking, singlet and doublets mix.

The physical spectrum:
$(\chi+, \chi-)$ with mass mD
$(\chi 1, \chi 2, \chi 3)T=U\ (\chi, \psi_1^0, \psi_2^0)^T$

U is the unitary matrix diagonalizing :

$$\mathcal{M} = \begin{pmatrix} m_S & \frac{y_1 v}{\sqrt{2}} & \frac{y_2 v}{\sqrt{2}} \\ \frac{y_1 v}{\sqrt{2}} & 0 & m_D \\ \frac{y_2 v}{\sqrt{2}} & m_D & 0 \end{pmatrix}$$

The DM particle is the lightest eigenstate $\chi_1=U_{11}\,\chi+U_{12}\,\psi_1^0+U_{13}\psi_2^0$.

❖ Higgs portals to DM (cont'd)

In the singlet–doublet scenario, DM couples to the Higgs boson h and the SM gauge bosons via its doublet components

$$\mathcal{L} \supset -h\bar{\chi}_i(c^*_{h\chi_i\chi_j}P_L + c_{h\chi_i\chi_j}P_R)\chi_j - Z_\mu\bar{\chi}_i\gamma^\mu(c_{Z\chi_i\chi_j}P_L - c^*_{Z\chi_i\chi_j}P_R)\chi_j - \frac{g}{\sqrt{2}}(U_{i3}W^-_\mu\bar{\chi}_i\gamma^\mu P_L\chi^+ - U^*_{i2}W^-_\mu\bar{\chi}_i\gamma^\mu P_R\chi^+ + \text{h.c.})$$

$$c_{Z\chi_i\chi_j} = \frac{g}{4\cos\theta_w}(U_{i3}U^*_{j3} - U_{i2}U^*_{j2}),$$
$$c_{h\chi_i\chi_j} = \frac{1}{\sqrt{2}}(y_1U_{i2}U_{j1} + y_2U_{i3}U_{j1}),$$

DM can annihilate to SM fermions via s-channel Higgs or Z-boson exchange and to bosons again through a Higgs or a Z boson in the s-channel or via χi or χ+ in the t-channel. Higgs (Z-boson) exchange leads to SI (SD) DM nucleon scattering.

Same as other Higgs portal cases:

$$\Gamma(h \to \chi_1\chi_1) = \frac{m_h}{4\pi}\left(1 - \frac{4m^2_{\chi_1}}{m_h^2}\right)^{3/2}\left|c_{h\chi_1\chi_1}\right|^2$$

Also invisible Z decays (< 3MeV from LEP)

$$\Gamma(Z \to \chi_1\chi_1) = \frac{m_Z}{6\pi}\left(1 - \frac{4m^2_{\chi_1}}{m_Z^2}\right)^{3/2}\left|c_{Z\chi_1\chi_1}\right|^2$$

if kin. allowed

Besides the above, since model has 2 neutral &1 charged fermions in addition to the DM one, LHC searches for electroweak Drell–Yan production allow to set bounds on the new fermions arising in scalar-doublet scenario:

Production modes: $q\bar{q} \to \chi_i\chi_j$ & $q\bar{q} \to \chi^+\chi^-$ via Z boson or $q\bar{q}(') \to \chi^\pm\chi_i$ via W-boson exchange or gluon–gluon fusion gg→χiχi via an intermediate Higgs produced via a top-quark loop

MET plus jets & MET plus leptons signals, e.g. $pp \to \chi^\pm\chi_{2,3} \to W^\pm\chi_1 Z\chi_1$ ➔ 2l or 3l plus MET

Model Building: s- Channel Mediators

- **Vector s-channel mediators (spin-1 mediators)**

Simplest ways to add a new mediator to the SM is by extending its gauge symmetry by a new U(1)′, which is spontaneously broken such that the mediator obtains a mass M_V

Depending on whether DM is a Dirac fermion χ or a complex scalar φ,

$$\mathcal{L}_{\text{fermion},V} \supset V_\mu \, \bar{\chi}\gamma^\mu(g_\chi^V - g_\chi^A\gamma_5)\chi + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu(g_f^V - g_f^A\gamma_5)f\,,$$

$$\mathcal{L}_{\text{scalar},V} \supset ig_\varphi V_\mu(\varphi^*\partial^\mu\varphi - \varphi\partial^\mu\varphi^*) + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu(g_f^V - g_f^A\gamma_5)f\,,$$

q, l and v denote all quarks, charged leptons and neutrinos, respectively.

Under the MFV assumption the couplings of V to the SM fermions will be flavor independent, but they can depend on chirality (g_f^A non -zero)

For Majorana DM, the vector coupling g_χ^V vanishes, while a real scalar cannot have any CP-conserving interactions with V.

Simplified models assume either purely vector or axial vector mediators with 6 param.

$m_\chi, M_V, g_\chi, gu^V, gd^V, gl^V$ or $m_\chi, M_V, g_\chi A, gu^A, gd^A, gl^A$

In practice, pure axial vector case is hard to build consistent with SM Yukawa int. and MFV

❖ Vector s-channel mediators: details of the new U(1)’

Dark Higgs sector:

- Best way to give mass to vector mediator is by additional Higgs field Φ with non-zero VeV
- Dark Higgs can mix with the SM Higgs leading to Higgs portal scenario II)
- Mass of Dark Higgs close to M_V, hence most likely to be included in LHC pheno

IF DM is chiral, the dark Higgs is responsible for the DM mass

Perturbativity constrains the DM mass with respect the mediator one

$$M_\chi \lesssim \sqrt{4\pi}\, M_V / g^A_\chi$$

while EW precision measurements require

$$M_V \gtrsim 2 \text{ TeV}$$

❖ Vector s-channel mediators: details of the new U(1)'

Mixing with SM gauge bosons

Since fermions are charged under the SM gauge group & the new U(1)',
➔ loop effects induce kinetic mixing between the new vector mediator & the neutral SM gauge bosons

$$\mathcal{L}_{\text{kinetic}} \supset \frac{\epsilon}{2} F'^{\mu\nu} B_{\mu\nu}$$

Where $F'^{\mu\nu}$ and $B^{\mu\nu}$ are U(1)' and $U(1)_Y$ field strength tensors
Precision measurements imply $g_q^A \lesssim 1$ and $M_V \gtrsim 100$ GeV

In S-channel mediator models, mediators decay back in SM particles and would show up in di-jets and di-lepton searches. Di-leptons are tightly constrained by LHC. If quark-mediator couplings were also small, then SM- DM interactions would be too small to be observed.

We shall assume that SM quarks are charged under the new U(1)' but lepton couplings only arise at loop level (Leptophilic Z').
Additional fermions charged under U(1)' will be needed for Anomaly Cancellation, but one can arrange scenarios that will not change the DM pheno

Model Building: T- Channel Flavoured Mediators

For fermionic DM, the mediator can be a colored scalar or a vector particle Φ.
The scalar case connects with the squarks in Supersymmetry and has an easy UV completion

Given the interaction: Φχq, either Φ or χ need ot carry color charge to be in a MFV case
We consider the scalar to be colored in analogy to SUSY.
The mediator can couple to up (down)-right handed quarks or left handed quarks,

$$\mathcal{L}_{\text{fermion},\tilde{u}} \supset \sum_{i=1,2,3} g\phi_i^* \bar{\chi} P_R u_i + \text{h.c.}$$

$$\phi_i = \{\tilde{u}, \tilde{c}, \tilde{t}\}$$

$$\mathcal{L}_{\text{fermion},\tilde{u}} \supset \sum_{i=1,2,3} g\phi_i^* \bar{\chi} P_R u_i + \text{h.c.}$$

MFV requires both equal masses $M_{1,2,3}$ of the mediators, and universal couplings $g=g_{1,2,3}$ between the mediators and their corresponding quarks u_i= {u,c,t}.
This universality can be broken by allowing for corrections that split the mass of the third mediator (govern by the large top Yukawa coupling) from the other.

The generic parameter space is $m_\chi, M_{1,2}, M_3, g_{1,2}, g_3$

In general these simplified models are very similar to those with squarks and studies consider independently cases with light quark superpartners or stops/sbottoms (3 parameters space)

Mono-object searches for DM

The most model-independent searches for dark matter at the LHC.

The targeted interaction is pp→ χχ+X,
where the X represents the "mono" system of observable particles
recoiling against the DM pair χχ, that is identifyed as missing transverse momentum

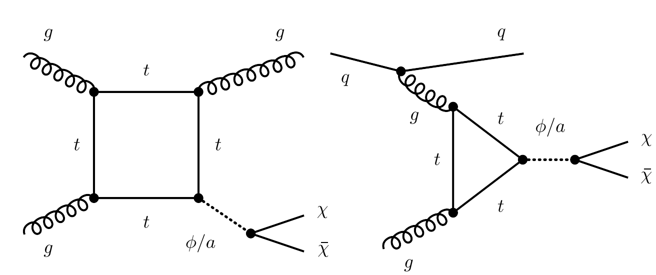
X can be a system composed of jets, photons, weak bosons (γ, W, Z),
Higgs bosons, or heavy flavor quarks (b and t)

Mono-object searches for DM

Scalar and Pseudoscalar mediator, s-channel

Monojet search

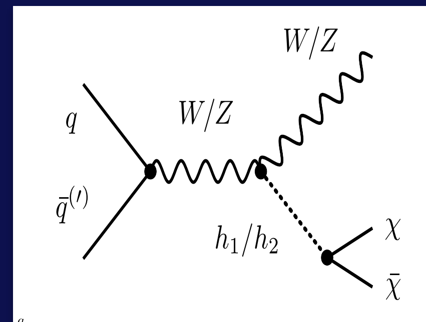
$m\chi, m\phi/a, g\chi, gu,$



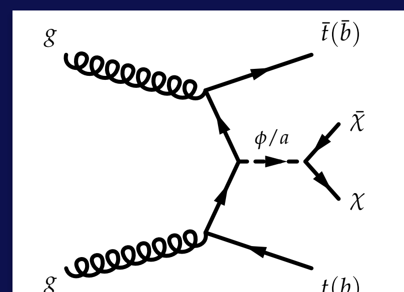
$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) .$$

$$\mathcal{L}_a = i g_\chi a \bar{\chi} \gamma_5 \chi + \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right) .$$

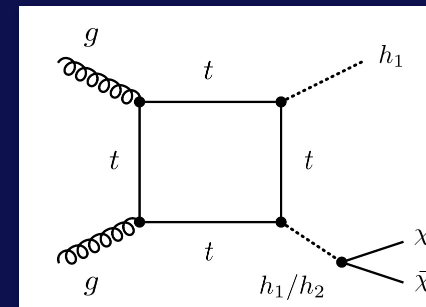
Mono-V search

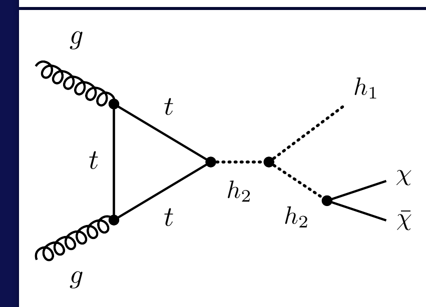


Top (bottom) pair search



Mono-Higgs search





Sensitivity of mono-boson searches (W,Z,H) to this model is low, UNLESS we consider the effects of the Higgs portal (upper middle diagram or right diagrams).

With the MFV assumption, however, the top and bottom quarks can play an important role in the phenomenology.

Spin-zero Mediator Total Width

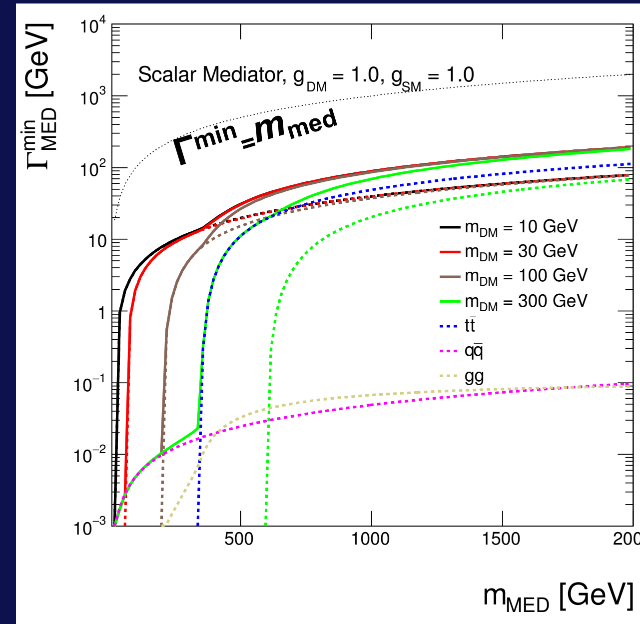
$$\Gamma_\phi = \sum_f N_c \frac{y_f^2 g_v^2 m_\phi}{16\pi}\left(1-\frac{4m_f^2}{m_\phi^2}\right)^{3/2} + \frac{g_\chi^2 m_\phi}{8\pi}\left(1-\frac{4m_\chi^2}{m_\phi^2}\right)^{3/2} + \frac{\alpha_s^2 g_v^2 m_\phi^3}{32\pi^3 v^2}\left|f_\phi\left(\frac{4m_t^2}{m_\phi^2}\right)\right|^2, \quad ($$

$$\Gamma_a = \sum_f N_c \frac{y_f^2 g_v^2 m_a}{16\pi}\left(1-\frac{4m_f^2}{m_a^2}\right)^{1/2} + \frac{g_\chi^2 m_a}{8\pi}\left(1-\frac{4m_\chi^2}{m_a^2}\right)^{1/2} + \frac{\alpha_s^2 g_v^2 m_a^3}{32\pi^3 v^2}\left|f_a\left(\frac{4m_t^2}{m_\phi^2}\right)\right|^2,$$

$$f_\phi(\tau) = \tau\left[1+(1-\tau)\arctan^2\left(\frac{1}{\sqrt{\tau-1}}\right)\right],$$

$$f_a(\tau) = \tau \arctan^2\left(\frac{1}{\sqrt{\tau-1}}\right).$$

Nc=3 for quarks and Nc=1 for leptons



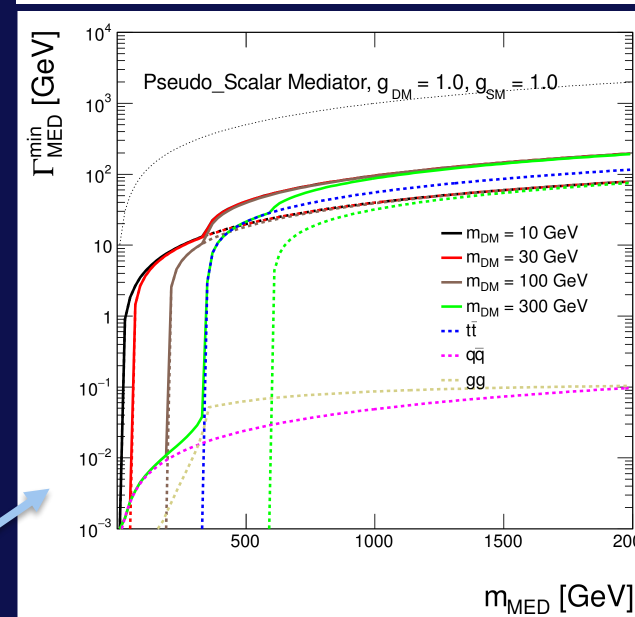
First term → decay into SM fermions

Second term → decay into DM .

Last term →decay into gluons.

Assumed gv=gu=gd=gl, in the partial decay widths, hence Γ(ϕ/a→gg) includes only top loop contributions, which provide the by far largest corrections (yt ≫ yb)

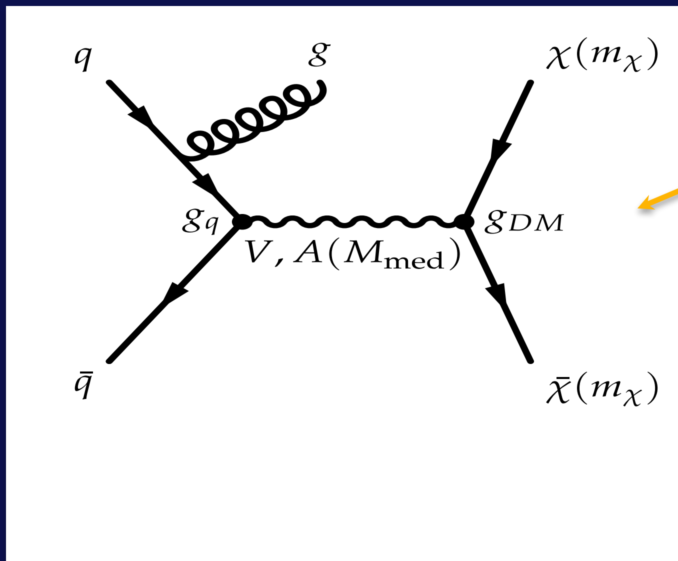
Notice that if mϕ/a > 2 m_t and gu ≳ gχ the φ/a total widths will typically be dominated by the partial widths to tops



We set gq = gχ = 1. Contrary to the vector and axial-vector models, these values lead to Γ_{min}/m_{med}<~0.1, ensuring the narrow width approximation is applicable.

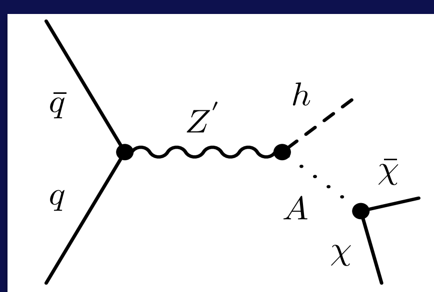
Mono-object searches for DM

Vector and axial Vector mediator, s-channel



Monojet search

A photon, W/Z boson or a Higgs boson can be radiated from the initial state partons instead of a gluon



$\bar{\chi}\gamma^{\mu}\chi$

$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}\gamma^{5}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi.$$

Mono Higgs signals can appear in models with Vector mediators and an additional Higgs doublet Z'-2HDM

Spin-one Mediator Total Width

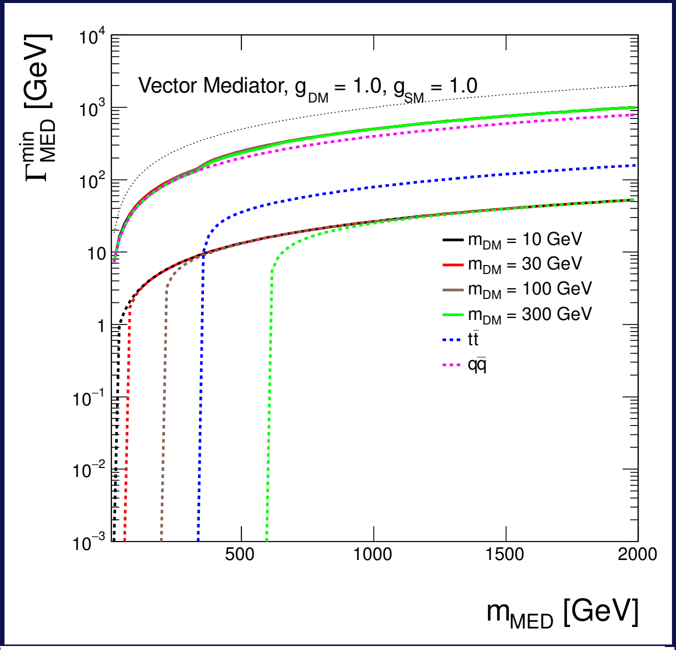
As mentioned before, when no additional visible or invisible decays contribute to the width of the mediator, the minimal width is fixed by the choices of couplings *gq* and *gχ*.
For arbitrary vector and axial vector couplings

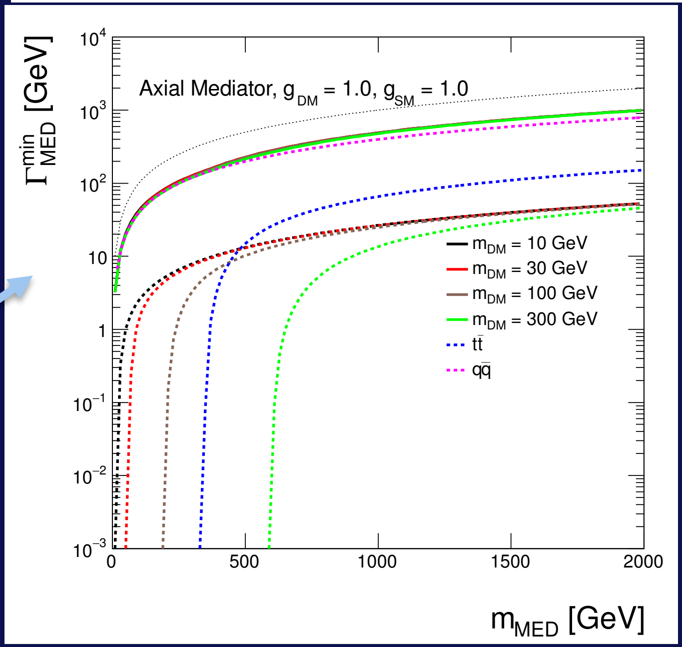
$$\Gamma_V = \frac{M_V}{12\pi} \sum_{i=f,\chi} N_c^i \left(1 - \frac{4m_i^2}{M_V^2}\right)^{1/2} \times \left[(g_i^V)^2 + (g_i^A)^2 + \frac{m_i^2}{M_V^2}\left(2(g_i^V)^2 - 4(g_i^A)^2\right)\right].$$

The sum extends over all fermions I that are above threshold, while Nc_i=3 for quarks and Nc_i=1 for leptons and DM.

We set gq = gχ = 1 and assume no mediator coupling to leptons. Such a coupling would have a minor effect in increasing the mediator width, but would set strong constraints from Drell-Yan process

Later on we will take gq=0.25 to avoid di-jet bounds





Spin one- Mediator Total Width and collider searches

For a perturbative description to be valid $\Gamma_V/M_V<1$ ➔ maximum size of couplings

Assuming $M_V \gg m_i$ and setting for simplicity $gq^V = g\chi^V = g$ and $gl^V = gi^A=0$
➔ $\Gamma_V/M_V \simeq 0.5g^2$ hence $g < 1.4$ for a perturbative desprition
And much smaller for a Narrow Width Approximation ($\Gamma_V/M_V<10.25$) to be applicable

When NWA can be used, production & decay factorizes $\sigma(pp\rightarrow Z+\chi\bar{\chi}) = \sigma(pp\rightarrow Z+V)\times Br(V\rightarrow\chi\,\bar{\chi})$.
The resulting LHC phenomenology is determined by the leading decay mode of the mediator.

Considering $gl^V = gi^A=0$ on has

- decays into quarks dominate if $g\chi^V/gi^V \lesssim 4$ ➔ strong constraints from di-jet resonances.
- invisible decays dominate if $g\chi^V/gi^V \gtrsim 4$ ➔ strongest collider signal in MET + SM particles
- have comparable branching rations for $g\chi^V/gi^V \simeq 4$

Scaling laws as a function of the mediator couplings can be obtained depending on the mediator and DM particle masses can render the production cross sections invariant under rescaling of one of the couplings or the couplings ratio.

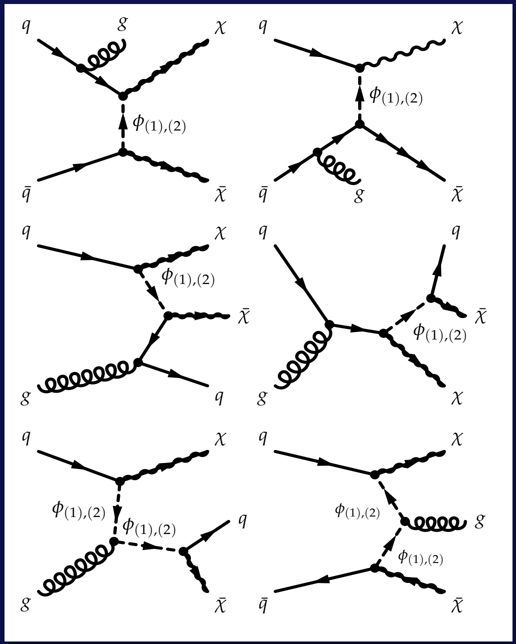
Mono-object searches for DM

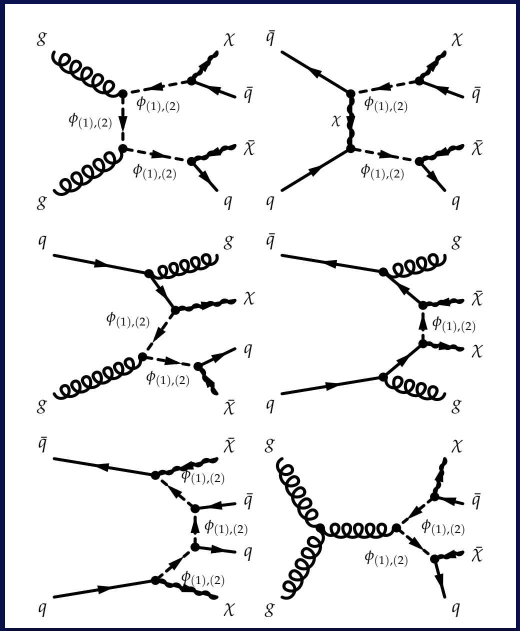
Colored Scalar mediator, t-channel

$$\mathcal{L}_{\text{int}} = g \sum_{i=1,2} (\phi_{(i),L} \bar{Q}_{(i),L} + \phi_{(i),u,R} \bar{u}_{(i),R} + \phi_{(i),d,R} \bar{d}_{(i),R}) \chi$$

Monojet search

Generic parameter space $m\chi, M_{1,2}, M_3, g_{1,2}, g_3$





For V + E_{Tmiss}, a representative Feynman diagram can be Constructed by replacing a final-state gluon in with a γ, W, Z boson, but radiation of electroweak bosons directly from the mediator also leads to a mono-boson signature.

Colored scalar Mediator Total Width

$$\Gamma(\phi_i \to \chi \bar{u}_i) = \frac{g_i^2}{16\pi M_i^3}(M_i^2 - m_{u_i}^2 - m_\chi^2) \times \sqrt{M_i^4 + m_{u_i}^4 + m_\chi^4 - 2M_i^2 m_{u_i}^2 - 2M_i^2 m_\chi^2 - 2m_\chi^2 m_{u_i}^2}$$

$$= \begin{cases} \frac{g_i^2}{16\pi} M_i \left(1 - \frac{m_\chi^2}{M_i^2}\right)^2, & M_i, m_\chi \gg m_{u_i}. \\ \frac{g_i^2}{16\pi} M_i, & M_i \gg m_\chi, m_{u_i}. \end{cases}$$

Unless the final-state quark u_i is a top quark, the given limiting cases are always very good approximations to the exact widths.

The production channels that lead MET plus jet signal are uū→χχ̄+g, ug→χχ̄+u and ūg→χχ̄+ū.

Additionally, if the colored mediator ũ is sufficiently light it may be pair produced from both gg or uū initial states, leading to a MET + 2 jets signature

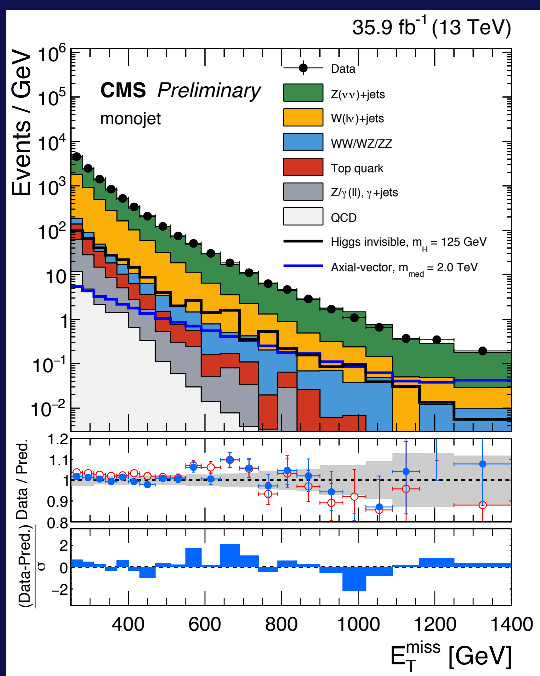
If the DM particle is a Majorana fermion also the uu and ūū initial states contribute to the production of mediator pairs. (A qq initial state gives a large enhancement at the LHC)

Squarks: The above is very similar to squark pair production in SUSY (MSSM) with a decoupled gluino. One important difference is that in SUSY the coupling between the squarks and the neutralino χ is necessarily. The cross section for squark pair production through t-channel exchange of DM is therefore negligible,

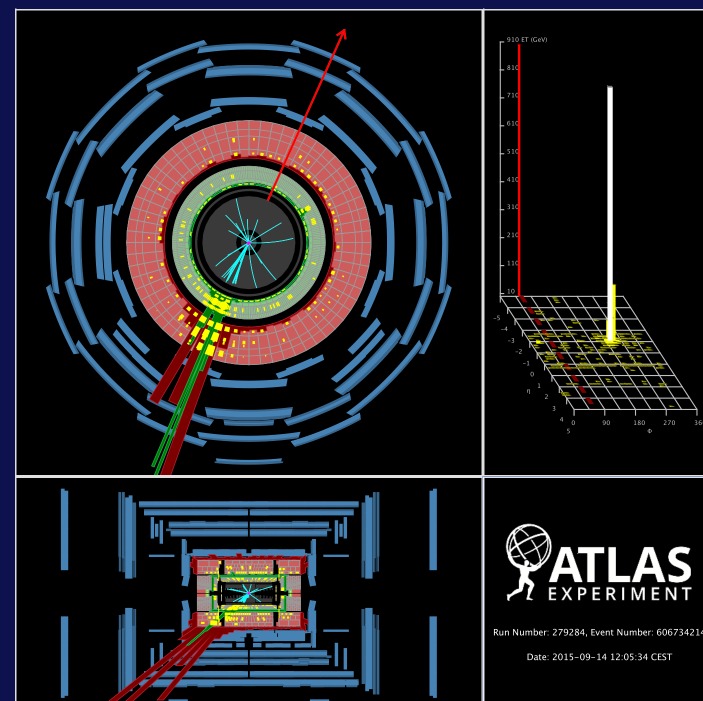
Mono-jet/s Searches at the LHC

Produce DM in proton proton collisions in association with QCD jets from ISR

Search for a jet with high transverse momentum p_T recoiling against a DM pair, the latter which manifest itself as missing transverse momentum $E_{T,miss}$



Monojet $E_{T,miss}$ distribution



Mono-jet event display. Jet (downward bars) is balanced by E_{tmiss} (upward arrow), both 1TeV

Mono-jet/s Searches at the LHC (cont'd)

Caveat: the probability to produce just one highly energetic jet is rather low: Mono-jet searches therefore typically only impose a strict veto on events containing leptons, but do include events with several high pT jets.

❖ With increasing LHC center-of-mass energy searches become more and more inclusive.

- ATLAS analysis allows up to 4 jets with pT > 30 GeV and pseudorapidity $|\eta| < 2.8$, while the leading (i.e.most energetic) jet is required to have pT>250 GeV and $|\eta| < 2.4$.
- CMS does not constrain the total number of jets at all and only requires that the leading jet satisfy pT>100 GeV and $|\eta| < 2.5$.

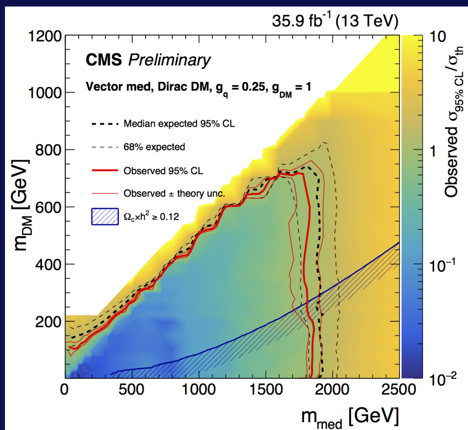
❖ Is challenging to model distributions with increasing number of jets and is necessary to use data-driven estimation of backgrounds based on control regions
e.g. pertinent background from pp →Z(→νν)+ jets can be inferred from analogous events in which the Z boson decays leptonically.

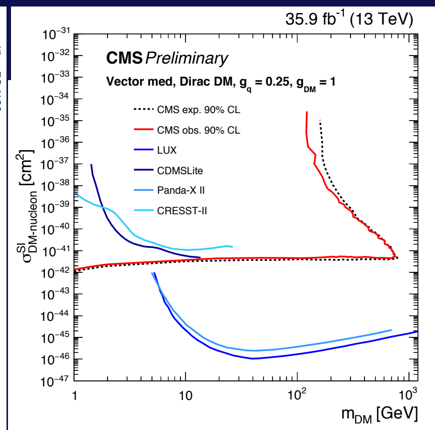
❖ Detector effects (jet mismeasurement) also leads to events that appear to have unbalanced transverse momentum: *such multi-jet backgrounds, however, are suppressed by requiring that the p_{Tmiss} vector does not point into the direction of any of the leading jets*

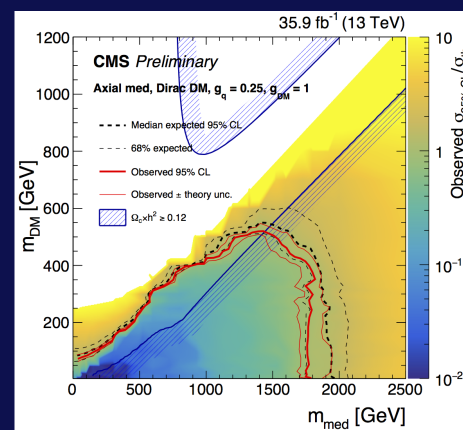
Background distributions can be well described by these methods, but systematic uncertainties remain a limiting factor, hard to improve with more luminosity.
Better understanding of EW corrections on the W+ jets to Z+ jets ratio would be crucial

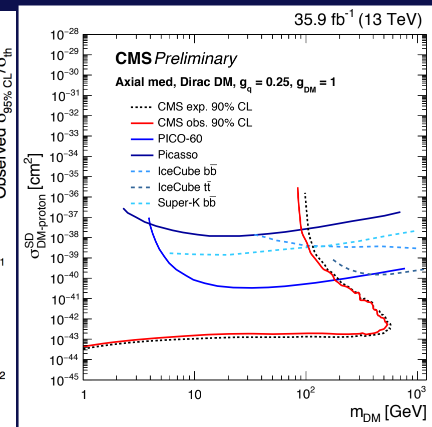
Mono-jet/s Searches at the LHC (cont'd)

Vector and axial vector mediators, s-channel

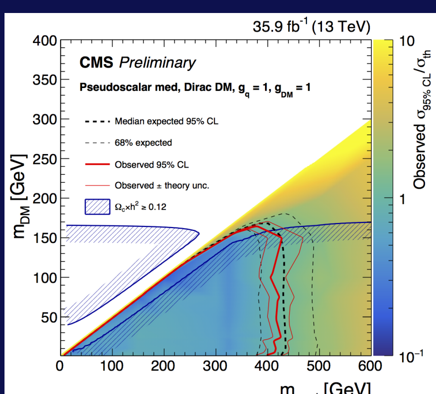


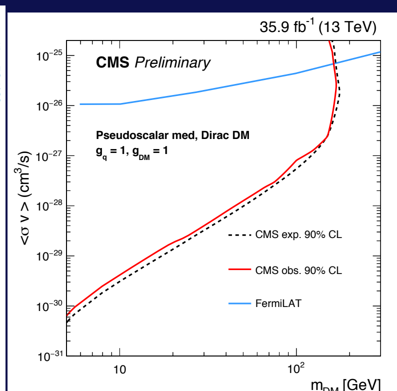




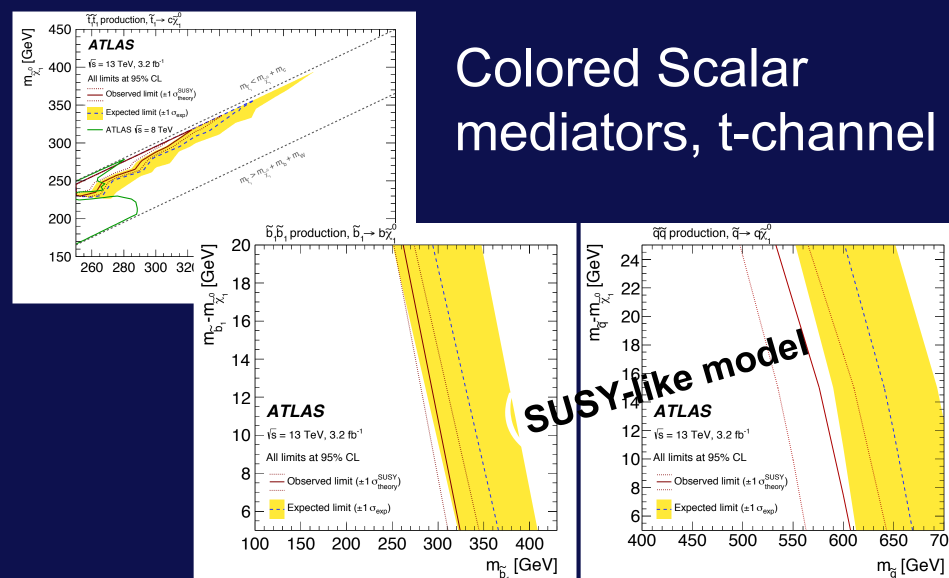


PseudoScalar mediator, s-channel





Colored Scalar mediators, t-channel



Mono-V (γ,Z,W) Searches at the LHC

Similar to mono-jet, DM is produced with a vector boson radiated off a quark in the initial state

The corresponding cross section is significantly smaller than for QCD radiation,
BUT,
the process is much cleaner & can therefore be searched for with higher sensitivity.

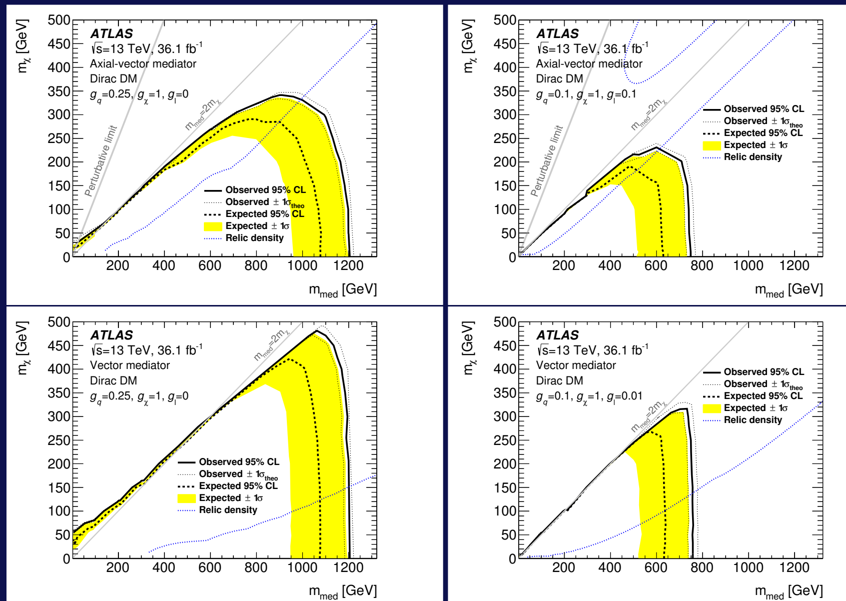
If DM couples directly to a pair of gauge bosons, mono-V processes may in fact be the dominant way in which DM is produced at the LHC.

Mono-Photon

- Mono-photon searches are among the conceptually simplest searches for DM
- Require only the presence of a high pT photon and no isolated leptons.

Although both detector effects (for example electron or jet misidentification) and beam-induced events can potentially fake mono-photon events, background levels are typically very low and experimental sensitivity is limited only by statistics

DM- Mono-photon Searches by ATLAS



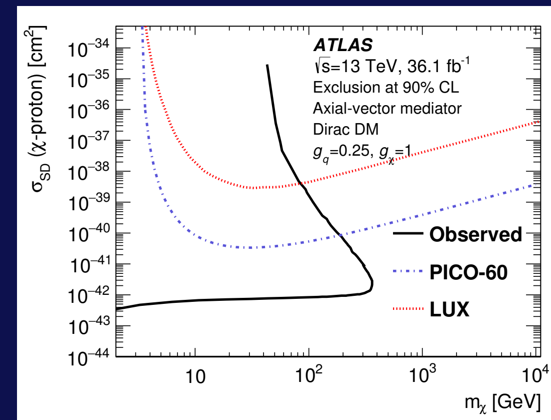
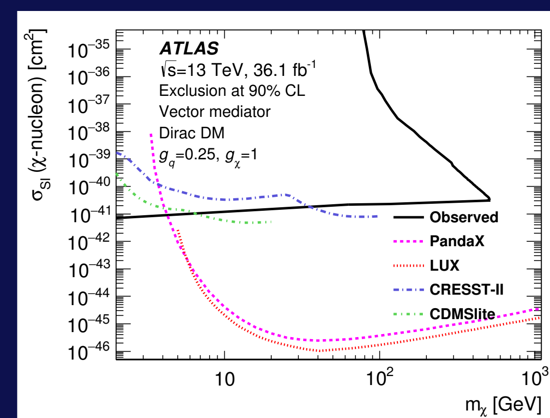


Table 8: Observed limits at 95% CL on the mediator mass and the DM particle mass for the four models considered. The mediators and couplings to quarks, to dark-matter particles and to leptons are specified for each model.

Model	Mediator	g_q	g_χ	g_ℓ	Limit on m_{med} [GeV] for low m_χ	Limit on m_χ [GeV] reaching as high as
A1	axial-vector	0.25	1	0	1200	340
A2	axial-vector	0.1	1	0.1	750	230
V1	vector	0.25	1	0	1200	480
V2	vector	0.1	1	0.01	750	320



Complementary limits to be set on the χ–proton scattering cross section in the low DM mass region where the direct DM search experiments have less sensitivity due to the very low energy recoils that such low-mass dark-matter particles would induce

Mono-Z and Mono-W

- Z bosons decaying into a lepton pair (e-e- or μ+μ-) yield a very clean signal

  -- Require the transverse momentum of the di-lepton system to be opposite in azimuthal direction & similar in magnitude to the missing transverse momentum

  -- Require the di-lepton invariant mass to be close to the Z boson mass,

  ➔ suppress backgrounds, besides the irreducible backgrounds from di-boson production with a Z decaying invisibly (Z → νν)

- W bosons decaying leptonically, the neutrino adds to the missing transverse momentum and one obtains a so-called mono-lepton event.

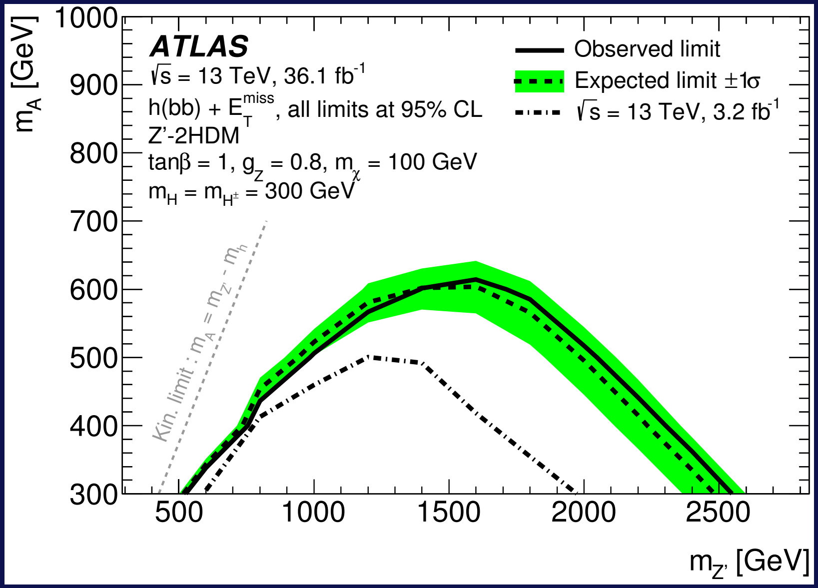
  ➔ experimental signature almost identical to the leptonic decay of an off-shell W -- background suppression is challenging and requires an accurate estimate of the transverse mass distribution --

- Hadronically decaying W or Z boson in association with missing transverse momentum. Similar to mono-jet searches but use a larger distance parameter for the leading jet and employ additional criteria such as requiring the mass of the fat jet to be consistent with a W or Z boson.

Mono-Higgs

Searches for H → b̄b and γγ Higgs in a Z' 2HDM (additional U(1) & Higgs doublet)

- In the b̄b final state, (chosen for its BR (H→b̄b) ~ 60%), background rejection is crucial
  Uses new techniques developed to identify Higgs bosons with high pT.
  → SM Higgs boson produced with sufficiently high transverse momentum such that the two b-jets from its decay merge into a single fat jet.



e.g., ATLAS → MET > 500 GeV in a single fat jet with R= 1.0; pT > 250 GeV containing two b-tagged sub-jets with R= 0.2
(High b tagging efficiency of 40 %)

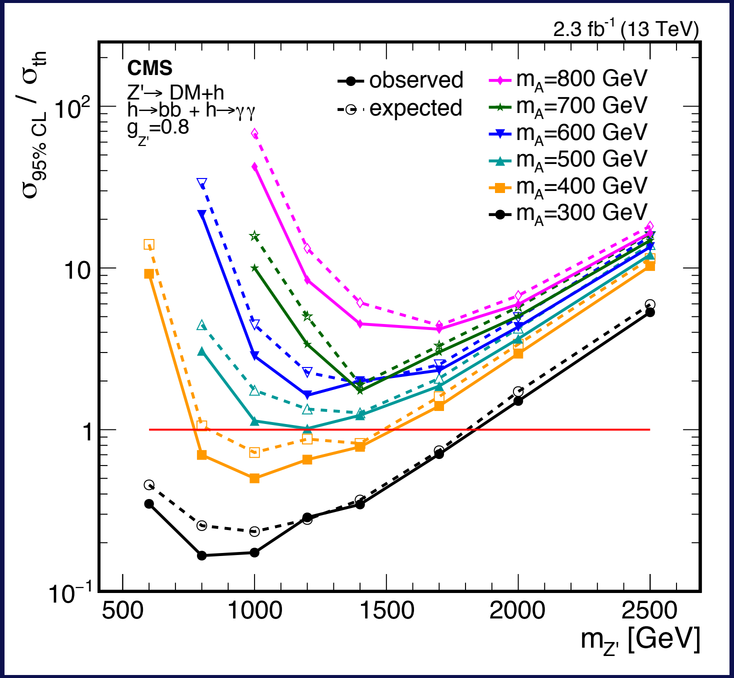
The dominant backgrounds (tt̄ and Z, W+ jets) are non-resonant, so that the invariant mass of the fat jet can be used to discriminate signal from background. (still statistically limited)

Mono-Higgs

Searches for H → $\bar{b}b$ and γγ Higgs in a Z′ 2HDM (additional U(1) & Higgs doublet)

- In the γγ final state, backgrounds are very small and hence only a relatively loose cut on MET is necessary (e.g. CMS search requires MET >105 GeV).
  Searches profit of the excellent resolution in the $\mathbf{m_{\gamma\gamma}}$ to suppress non-resonant backgrounds from SM processes with mis-measured MET . (only statistically lim.)

The exclusion expected and observed 95% CL limits on the signal strength for Combined h→bb and h→*γγ*, for *m*A= 300–800 GeV and fixed *mχ*=100 GeV, tan*β*= *gχ* =1. *σ*th is calculated for *gZ′*=0.8.

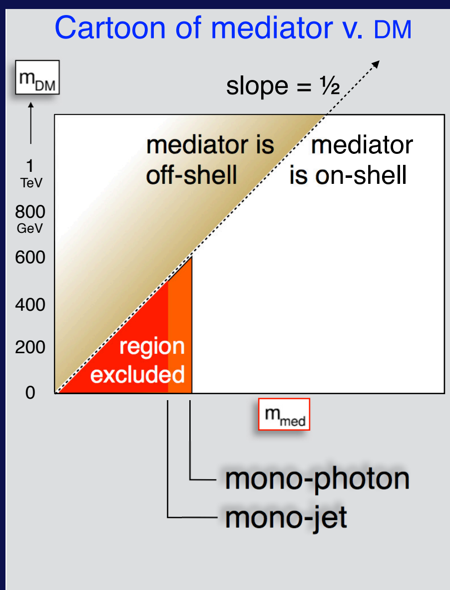


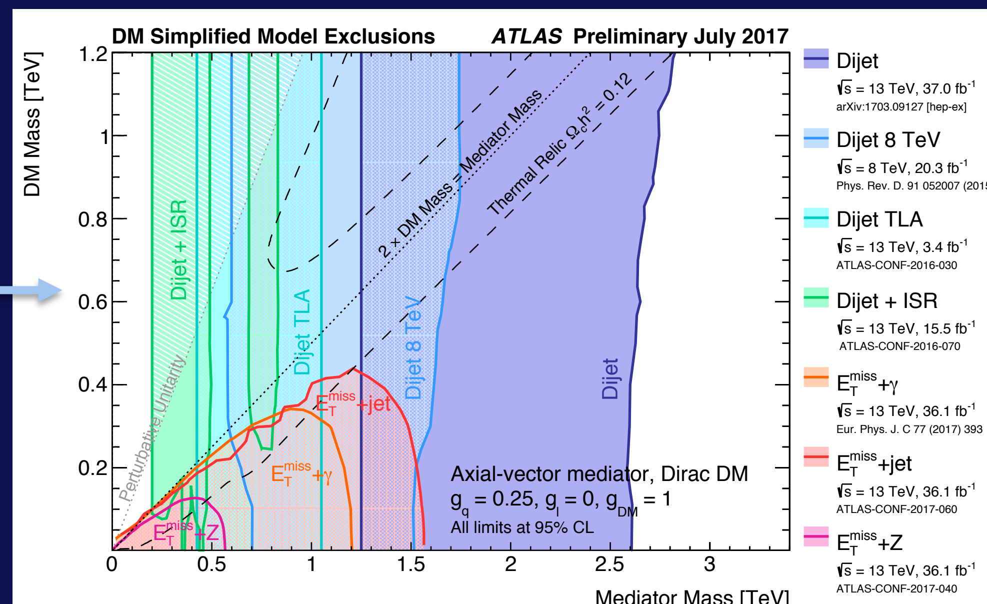
Searches for Dark Matter mediators

Examples: spin-1 mediator in di-jet.

Abundant jet production limits amount of events with two or more jets one can save to disk.

ATLAS/CMS developed new techniques to lower the threshold on di-jet invariant mass



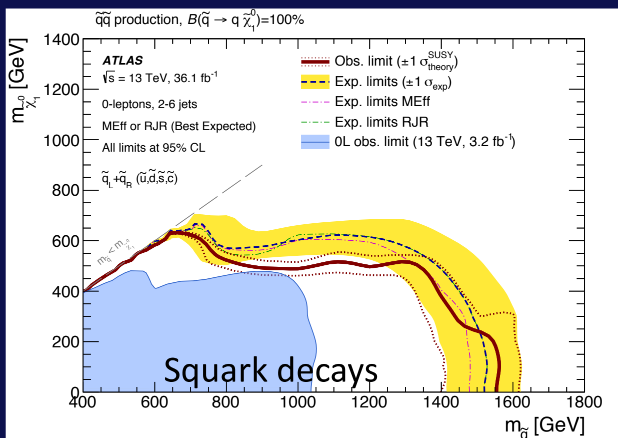


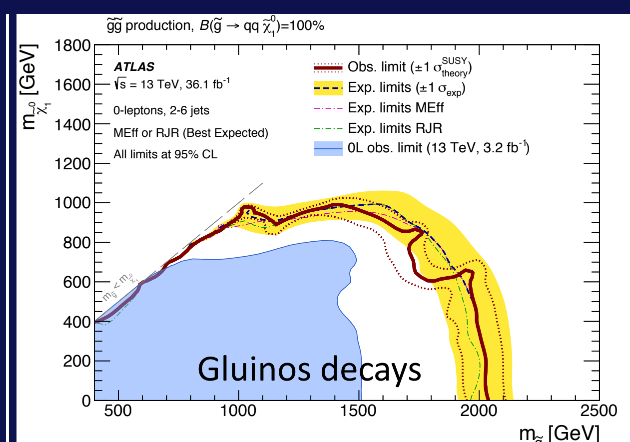
Overlay of leptophobic axial-vector mediator exclusions from dijet and mono-object searches

Squark and Gluinos decaying to DM

Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino ("colored sibling") production.

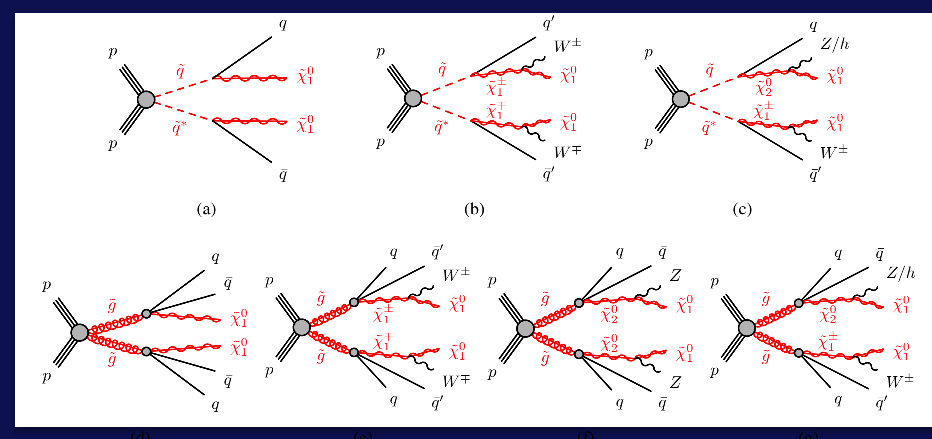
- Gluinos decay to two jets + WIMP
- Squarks into one jet + WIMP [Assuming degenerate "light" squarks]



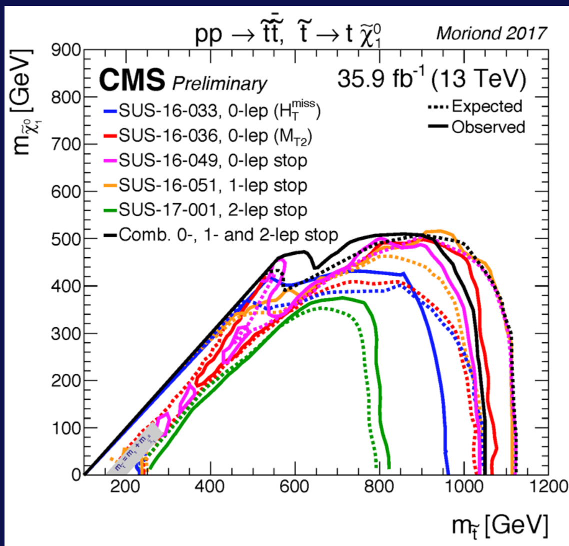


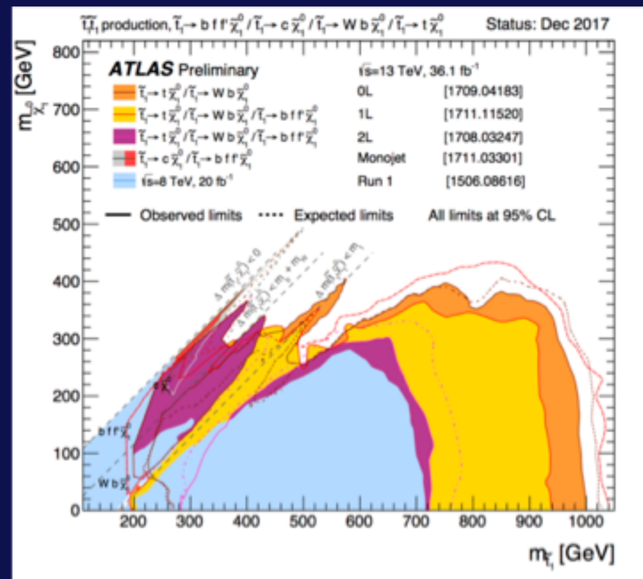
These are important constraints on SUSY.
The specific message for dark matter depends very much on the model parameters

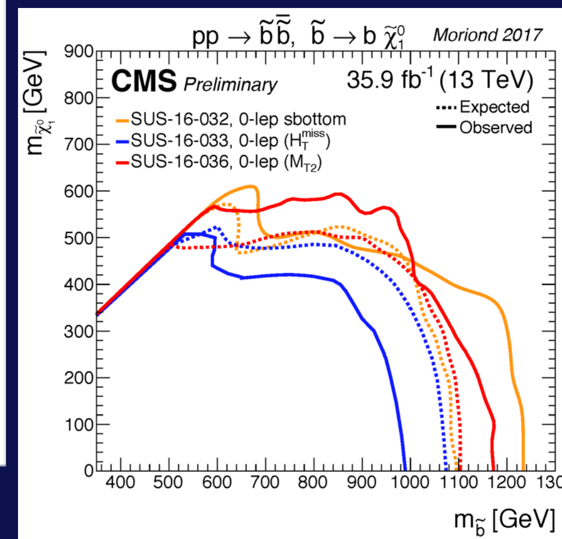
Quark/Gluinos mya have direct or one-step decays adding complexity to the searches



3^{rd} Generation squarks decaying to DM



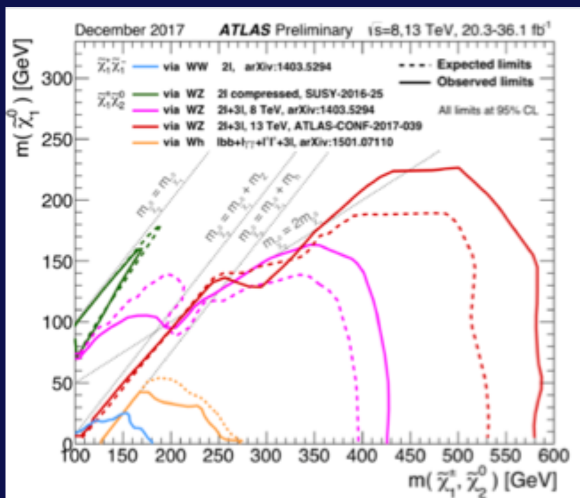


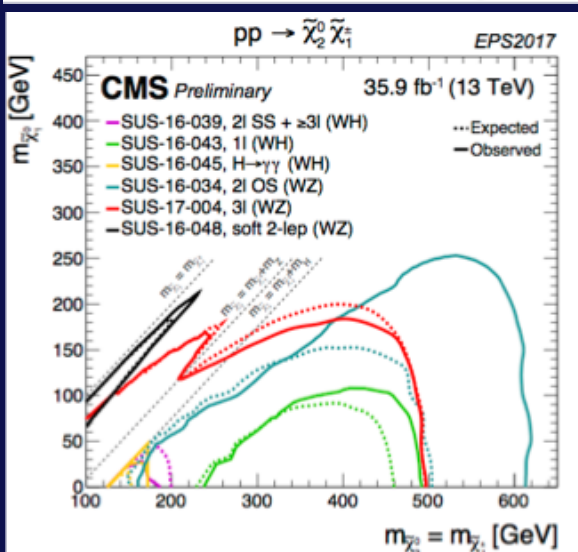


- Naturalness would suggest SUSY would like light(ish) stops.
  The Higgs mass is calculable and put constrains stop parameter space. In the minial model (MSSM) this suggests that at least one stop should be in the TeV region or higher . Extended models (NMSSM) significantly relax bounds on stop sector
- Searches for stops are starting to reach 600-700 GeV, and carving out the natural regions of supersymmetry

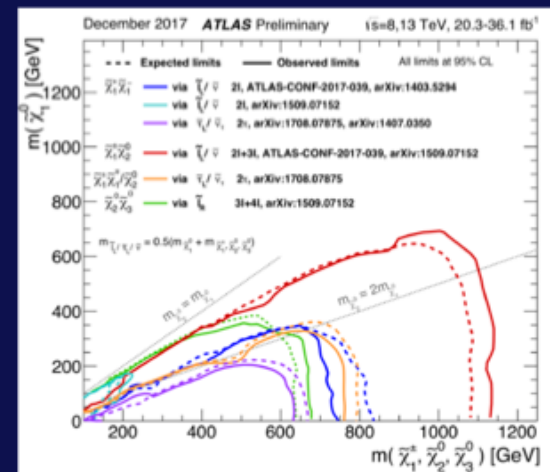
Producing SUSY DM directly at the LHC

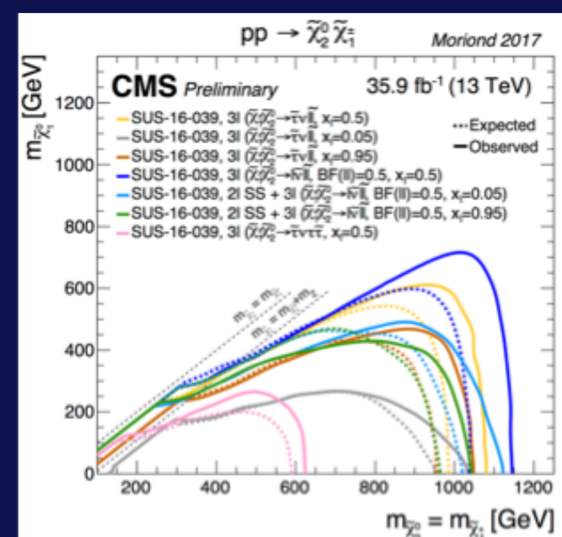
Limits on chargino-neutralino pair production with decays via W/Z/H





Limits on chargino-neutralino pair production with decays via sleptons





Broad variety of searches with specific model assumptions

NMSSM and blind spots

Light Dark Matter

< GeV model Building

Lighter scales can be derived from *v via loops or mixing*

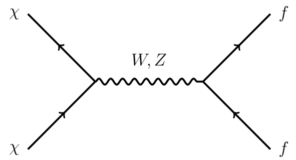
$$\mathrm{GeV}^2 \sim \frac{\alpha v^2}{16\pi^2}$$

DM must be a SM singlet

(else would have been discovered (LEP...)

Freeze out needs new forces

DM overproduced unless there are light new "mediators"



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Lee/Weinberg '79

observables signatures of Hidden Sector Light DM will depend on the type of force between DM & SM matter, and the nature of the DM coupling to that force

Back to Simplified Models

Already introduced models for (axial) vector mediator and (pseudo) scalar mediator, without specifying **how** the mediator coupling to SM matter arises

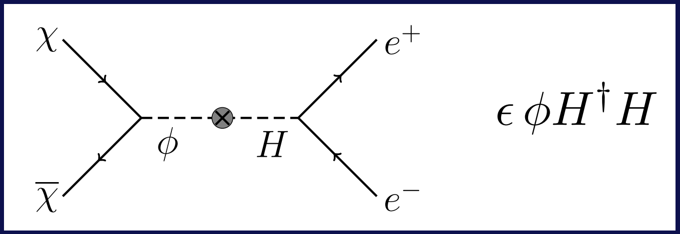
❖ high-energy SM extensions open up such options, e.g. ,
vector couplings to anomalous SM global symmetries like B or L number;
chiral couplings with non-zero g_f^A from Z-mixing models, extended Higgs sectors

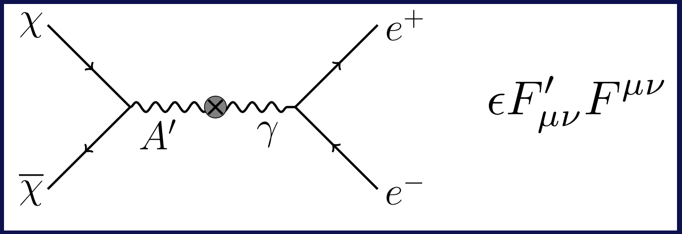
Consider the unique renormalizable interactions of an SM-neutral boson compatible with all SM symmetries

$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} & \text{vector portal} \quad \Rightarrow \quad g_f^V \approx \epsilon e q_f \\ (\mu\phi + \lambda\phi^2) H^\dagger H & \text{Higgs portal} \quad \Rightarrow \quad g_f^S = \mu m_f / m_h^2 \end{cases}$$

$e\, q_f \rightarrow$ SM electric charges

$B_{\mu\nu}, F'_{\mu\nu} \rightarrow U(1)_Y$, $U(1)_{DM1}$





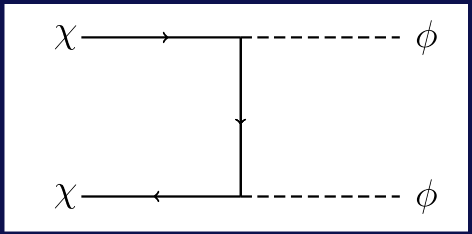
New scalar mediator mixing w/ Higgs

New vector mediator A′mixing w/ photon

ε small enough to have escaped detection, still induce right relic DM density

Who's Heavier? The DM or the Mediator?

"Secluded" Annihilation : $m\chi > m\varphi$

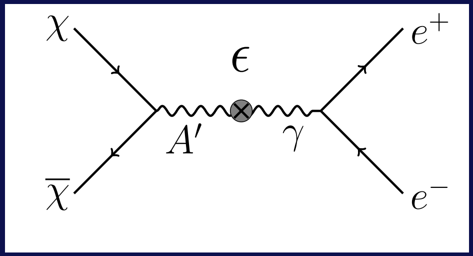


$\langle\sigma v\rangle \propto g_{DM}^4 / m_\chi^2$

- **No info on mediator-SM coupling (<σv> independent of the mixing)**
  ➔ No target @ Accelerators
- **Mediator decays to SM particles , not to DM**
- **Scalar mediator ➔ annihilation rate v^2 suppressed**
  ➔ phenomenologically viable, provided the DM Yukawa couplings are suitably small to achieve right thermal relic (e.g. $\sim 3\cdot 10^5$ -$3\cdot 10^3$ for MeV–GeV dark matter)
- **Vector mediator ➔ annihilation rate unsuppressed**
  ➔ excluded by Planck data constraining power injected by late –time DM annihilation (at Temperatures ~ eV).

Who's Heavier? The DM or the Mediator?

Direct Annihilation: mχ < mφ



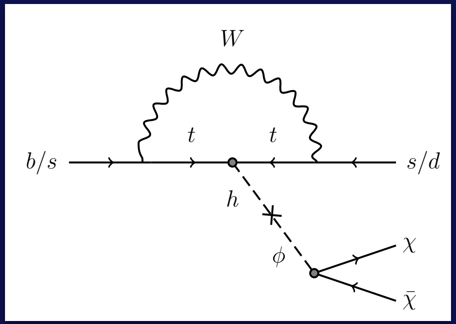
$<\sigma v> \propto g_{DM}^2\, g_{SM}^2\, m_\chi^2/m_{MED}^4$ (excluded by meson constraints)

S-channel annihilation into SM particles ➔ Minimum SM coupling

g_{DM} & $m_\chi/m_{A'}$ at most O(1) ➔ min g_{SM} compatible with Ωχ

Predictive, falsifiable target@ accelerators

- **Ok for vector like mediators but ruled out for scalar mediators due to required large mixing to offset small Yukawa couplings**



If ϕ decays invisibly, this scenario induces rare meson decays B+→K+ϕ, K+→π+χ̄χ and is constrained by limits B+→K+νν̄ and K+→π+ νν branching fractions.

Planck CMB power spectrum

➔ ok for scalar or Majorana fermion via a vector mediator

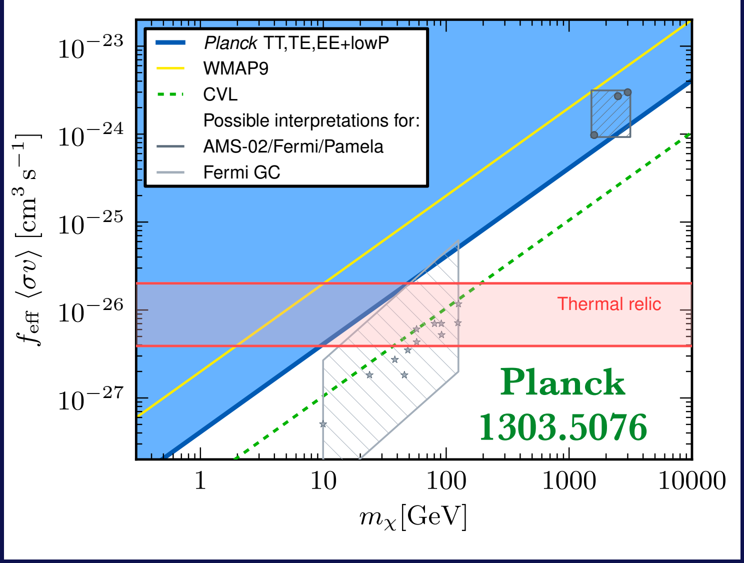
CMB power spectrum: Simplest DM candidate

Thermal DM candidate is frozen out well before recombination, **BUT**, out of equilibrium annihilation still re-ionize hydrogen and modify the CMB power spectrum

Low thermal DM is strongly constrained by this through Planck data

$$p_{ann} = f_{\rm eff}\langle\sigma v\rangle_{T\sim \rm eV}/m_{DM} < 3.5\times10^{-11}\,\rm GeV^{-3} \rightarrow \langle\sigma v\rangle_{cmb}/m\chi <\sim 3\times10^{-28}\,cm^3s^{-1}GeV^{-1}$$

Annihilation rate must be factor 1-5 below at CMB Temperature that at T/ m_χ ~20 for Sub-GeV DM ➔ s wave annihilation is ruled out



Simplest **Particle/antiparticle symmetric Dirac fermion is ruled out**

Viable models:

(1) p-wave annihilation

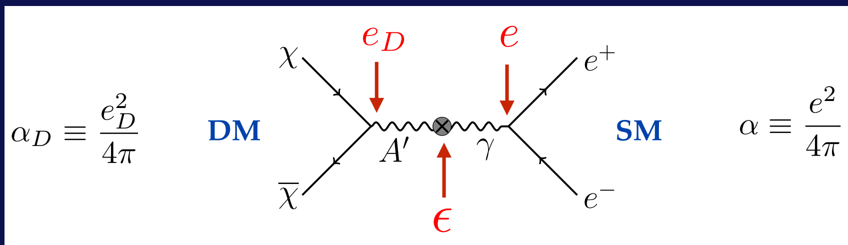
(2) annihilation shuts off before CMB

(no indirect detection!)

Population suppression ➔ (no X2 left at recombination time

Asymmetric DM ➔ no antiparticle left

Representative Model: Dark QED

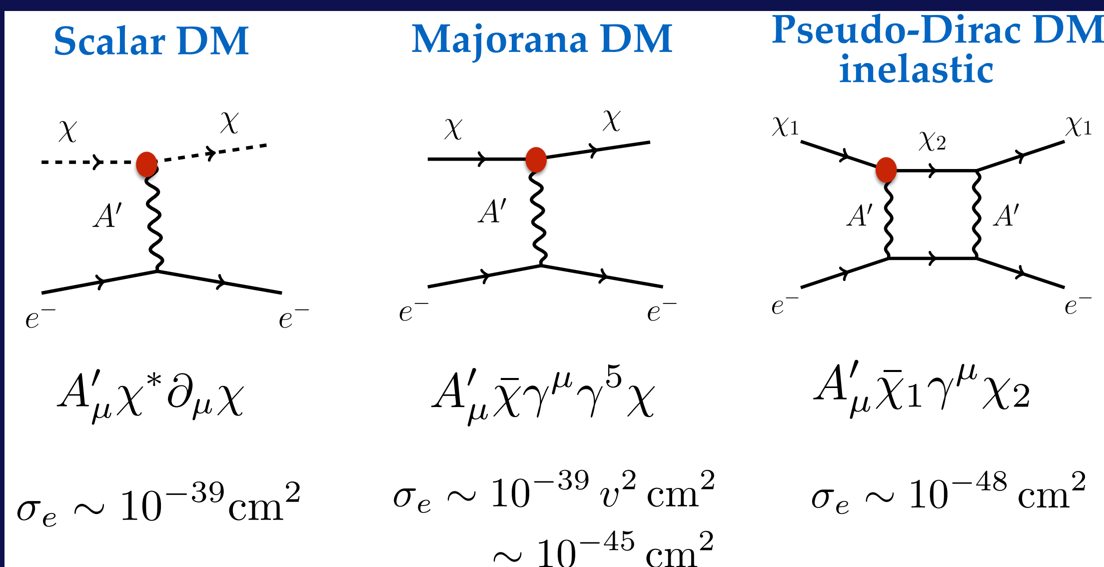


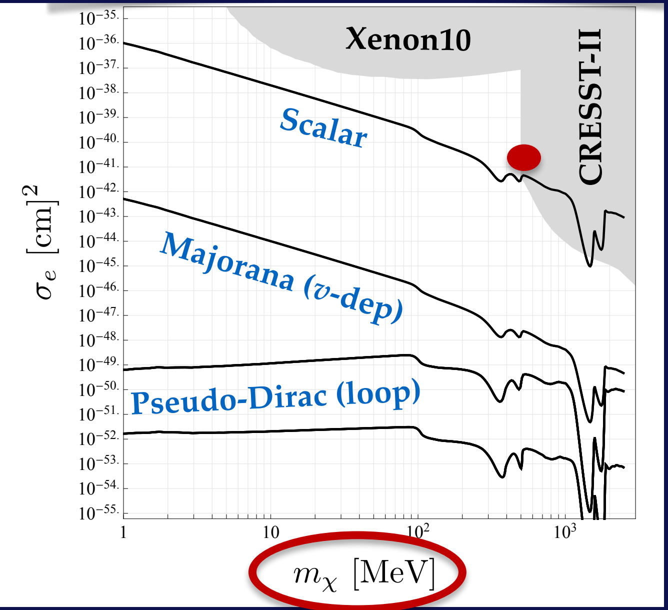
DM charged under new force: e_D ~ e

Allowed small A'-photon mixing: ε << 1

SM acquires small charge under A' : *eε*

Viable models by Direct Detection Scattering





Each ● interaction can realize thermal annihilation at T ~ M

Light Dark Matter Searches at Accelerators

Accelerators offer key advantages in the search of MeV-GeV thermal DM

- **Reduced sensitivity to details of the DM nature**

  -- Being relativistically produced, the DM scattering cross section is only weakly dependent on the velocity.

  -- In missing energy/missing momentum exp., the DM presence is inferred via energy/momentum imbalance, almost entirely insensitive to the DM velocity.

- **Overcome kinetic thresholds in the Dark Sector**

  -- DM accompanied by a heavier excited state featuring mainly off diagonal couplings with the mediator ($\chi_1\chi_2A'$) may have too low Kinetic energy to produce the excited state in DD and go only through off-shell loop processes.

  ➔ At accelerators the ground state can efficiently up-scatter into the excited state when detected through scattering off a SM target.

- **Sensitivity to Dark Sector Structure**

  -- Mediator can be not only searched for in SM particle decays but also in specific type of invisible decays.

Light Dark Matter Searches at Accelerators

- Mono-photon + MET at Lepton colliders

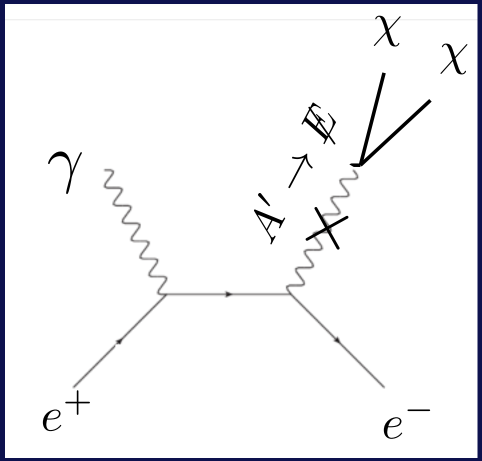
  analogous to LHC searches
- Electron and Proton Beam Dump Experiments
- Missing Energy/momentum at fixed target experiments

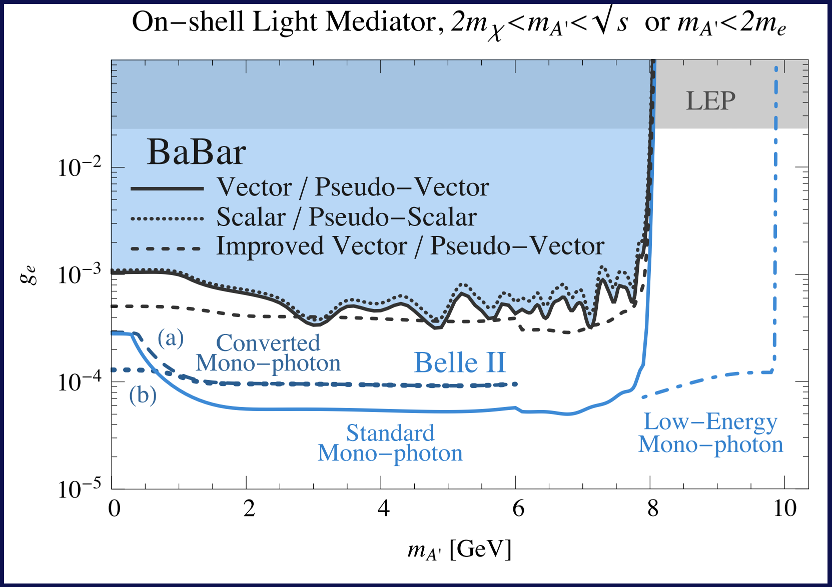
Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam
Future US initiatives							
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$	
Future international initiatives							
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020
Current and completed initiatives							
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done

Signatures @ B-Factories

mono photon + missing energy

e+e- → γ (A'→χχ)



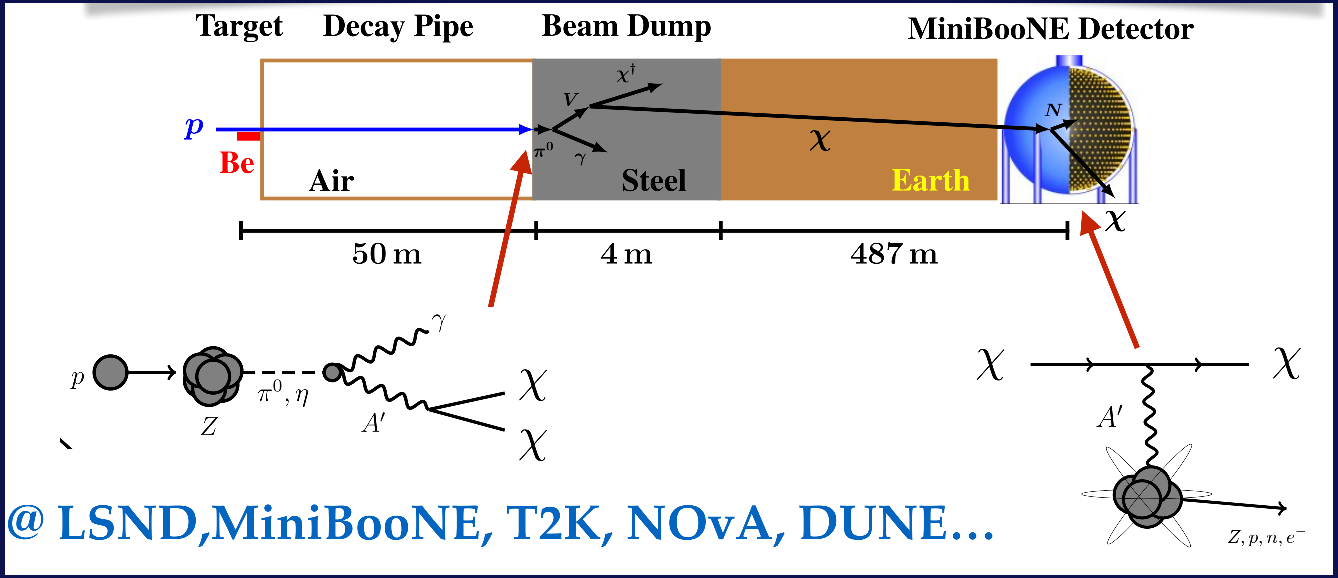


- Identified as a narrow resonance over a smooth background.
- Requires a well-known initial state & reconstruction of all particles besides the DM.
- A large background usually arises from reactions in which particle(s) escape undetected → detectors with good hermeticity required.

Can explore/test Scalar, Majorana, & pseudo-Dirac DM

Signatures @ Proton Beam Dumps

DM is produced pZ → pZ(A' → χχ) or, if kinematically allowed in $\pi^0/\eta' \to \gamma(A' \to \chi\chi)$



Typically detected via eχ→eχ or Nχ → Nχ scattering in a downstream detector.

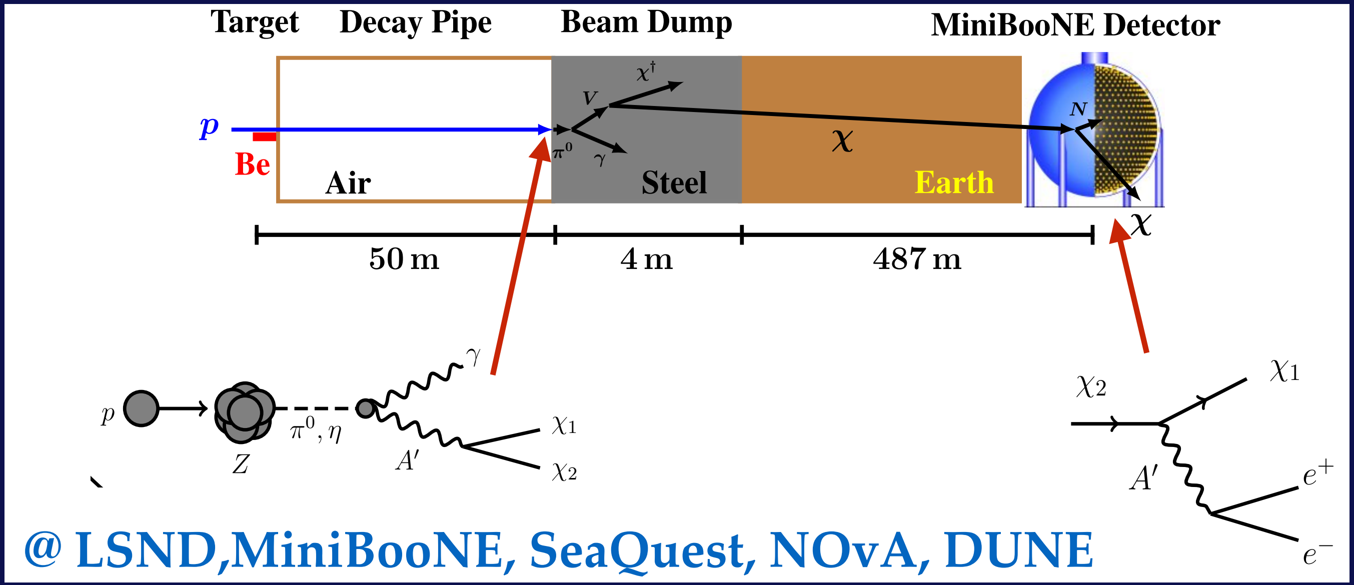
- Advantage: probes DM interaction twice, providing sensitivity to DM-mediator coupling
- Requires a large proton flux to compensate for the reduced yields.
- Signature similar to that of neutrino interactions → limiting factor on sensitivity.

Can explore/test Scalar, Majorana DM

Signatures @ Proton Beam Dumps

Inelastic scattering & decays

DM is produced $pZ \rightarrow pZ(A' \rightarrow \chi_1\chi_2)$ or, if kinematically allowed in $\pi^0/\eta' \rightarrow \gamma(A' \rightarrow \chi_1\chi_2)$



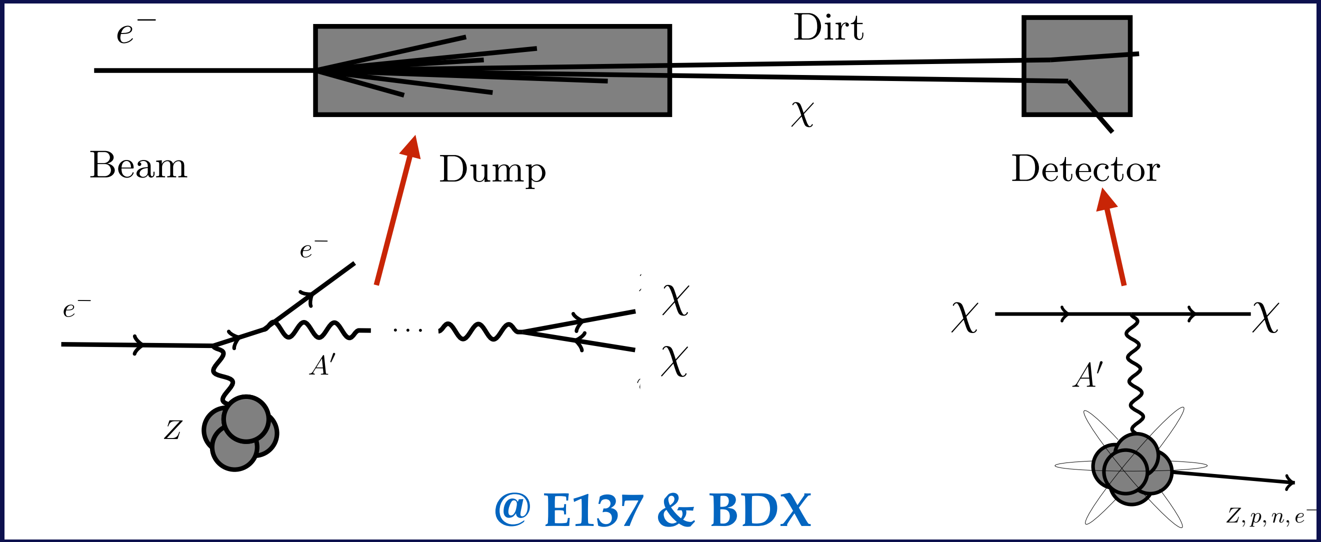
Beam-dump experiments also sensitive to the decay of excited states in the DS

- Advantage: probes DM interaction twice, providing sensitivity to the Dark sector-mediator coupling
- Requires a large proton flux to compensate for the reduced yields.

Can explore/test pseudo-Dirac DM

Signatures @ Electron Beam Dumps

DM is produced $e^- Z \rightarrow e^- Z(A' \rightarrow \chi\chi)$



Typically detected via $e\chi \rightarrow e\chi$ or $N\chi \rightarrow N\chi$ scattering in a downstream detector.

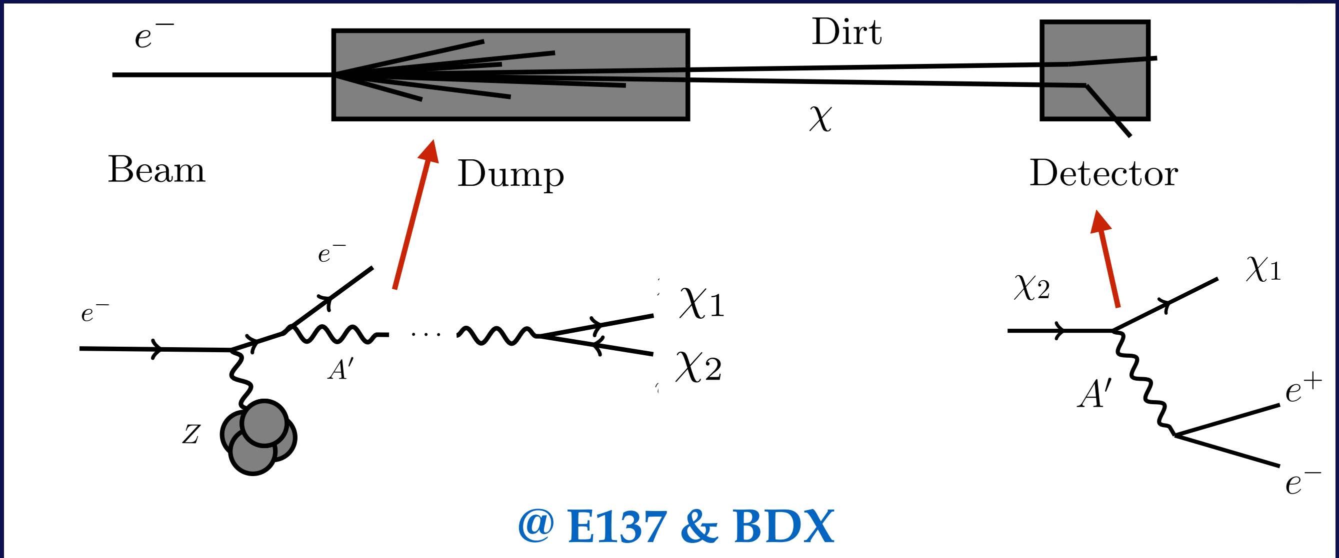
- Advantage: probes DM interaction twice, providing sensitivity to DM-mediator coupling
- Requires a large proton flux to compensate for the reduced yields.
- Signature similar to that of neutrino interactions ➔ limiting factor on sensitivity.

Can explore/test Scalar, Majorana DM

Signatures @ Electron Beam Dumps

Inelastic scattering & decays

DM is produced $e^-Z \rightarrow e^-Z(A' \rightarrow \chi\chi)$



Beam-dump experiments also sensitive to the decay of excited states in the DS

- Advantage: probes DM interaction twice, providing sensitivity to the Dark sector-mediator coupling
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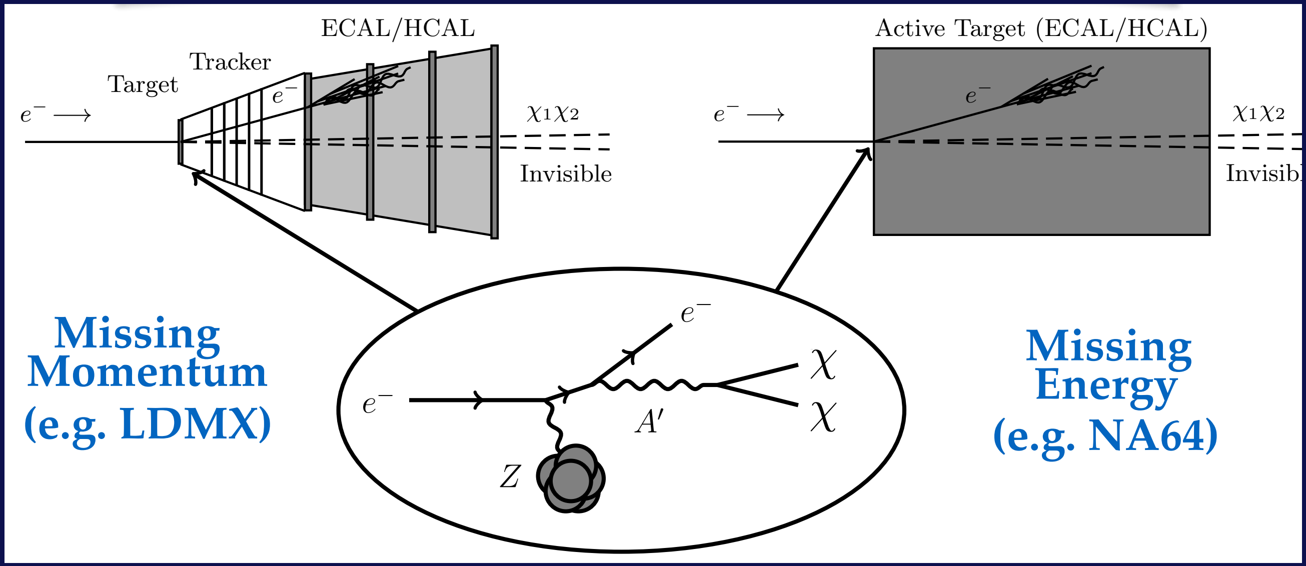
Can explore/test pseudo-Dirac DM

Signatures @ Fixed Target Experiments

Missing Energy and Missing Momentum



Observe recoiling electron and compared it to the energy of the beam
If $E_R << E_B$ ➔ missing energy/momentum carried away by the escaping particles

- Critical relevance of the detector hermeticity to achieve excellent background rejection . May be important to measure the incoming electrons individually.
- Better signal yield than beam dump experiments for similar luminosity, as the DM particles are not required to scatter in the detector.

Useful variables to compare experiments

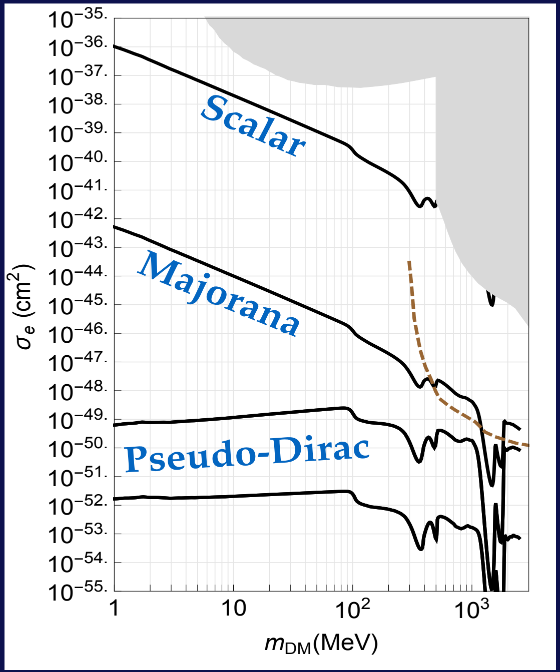
- Define new variable to optimize thermal targets

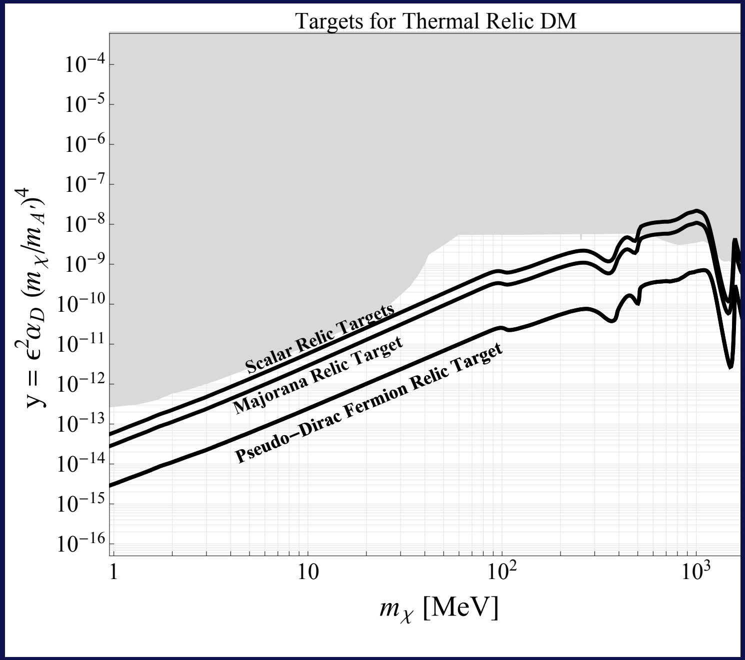
$$\sigma v \propto \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} = \left[\alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4\right] \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

Insensitive to ratios of inputs, unique "y" for given mass (up to subleading corrections)

- Direct detection Experiment

$$\sigma^{dd}_{DM-p} \propto \left(g_q \, g_{DM} \frac{m_{DM-p}}{m^2_{med}}\right)^2 \rightarrow \sigma^{dd} \propto y / m_\chi^4$$





Comparing Experiments

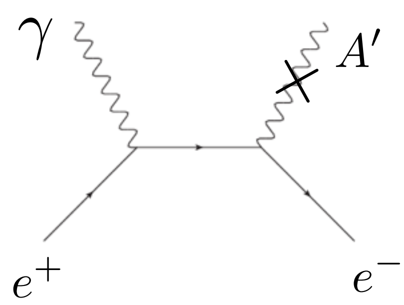
$$\sigma v \propto \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4 \equiv y$$

Some experiments only bound ... independently of this

Example: *B*-factory signal $\sigma \sim \frac{\epsilon^2}{E^2_{\mathrm{cm}}}$

Conservative "Y" sensitivity

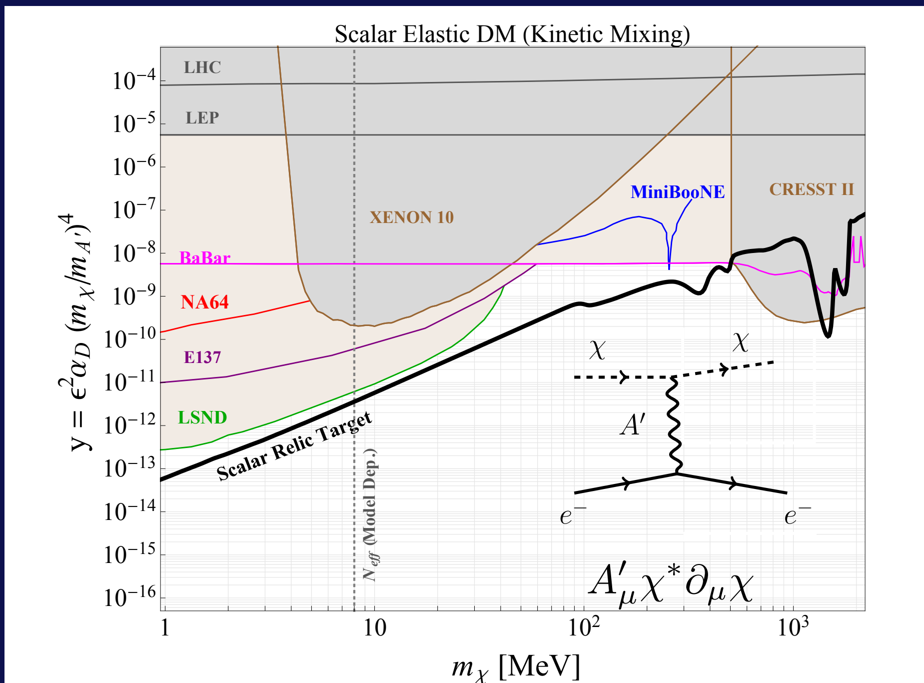
$$y_{\mathrm{exp.}} = \epsilon^2_{\mathrm{exp.}} \times \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

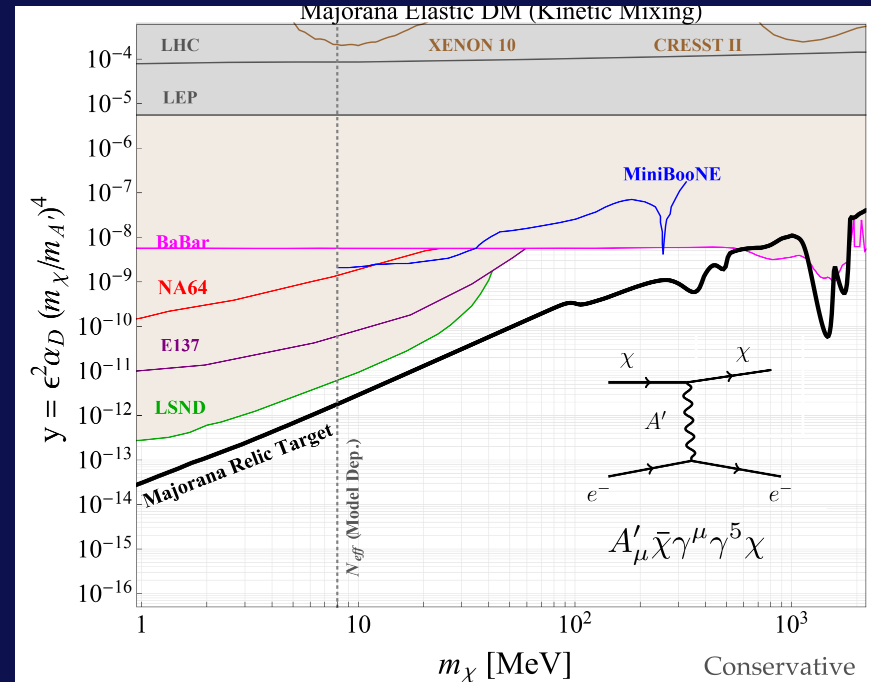


Weakest limit on **y** by demanding the largest value of $\alpha_D\,(m_\chi / m_{A'})^4$

➔ $\alpha_D \sim O(1)$ and $m_{A'} = 2\, m_\chi$

Comparing Experiments





Next gen DD & accelerator exp. will crush this

Conservative

$$\alpha_D = 0.5\ ,\ m_{A'} = 3m_\chi$$