Dark matter searches at the Colliders (LHC)

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Dark Matter

- We have clear evidence for abundance of non-luminous matter in the universe
- This excess of matter is called Dark Matter, which constitute about 27% of the content of the Universe, while the ordinary matter accounts only for at most 5%
- Existence of Dark Matter : Support comes from several Astrophysical observations
- The exact nature of this new kind of matter is still not clear

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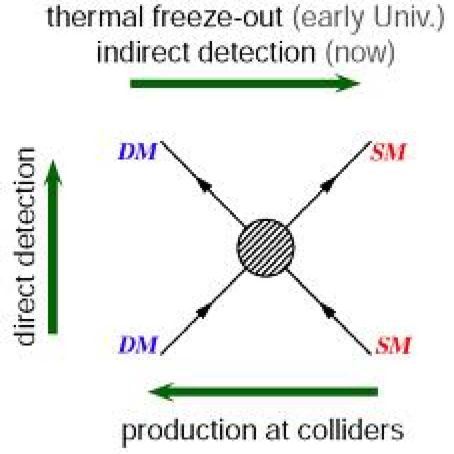
- The most attractive picture for DM : some kind of weakly interacting, massive particle (WIMP), with mass $\sim$ 100 GeV $-$ $\mathcal{O}$(TeV) with correct relic density
- WIMP : Spin, Electroweak charge, Real /Majorana or Complex /Dirac ?
- WIMPs interact with SM particles with EW strength, which is much stronger than gravitational interactions

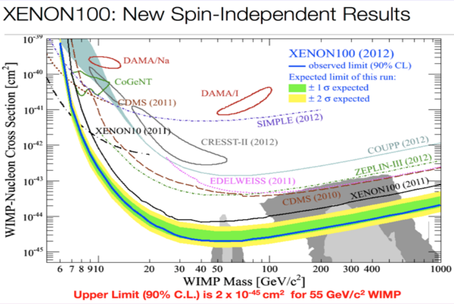
See lectures by Yann Mambrini in this meeting

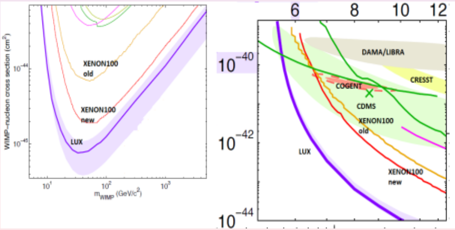
Detection of Dark Matter

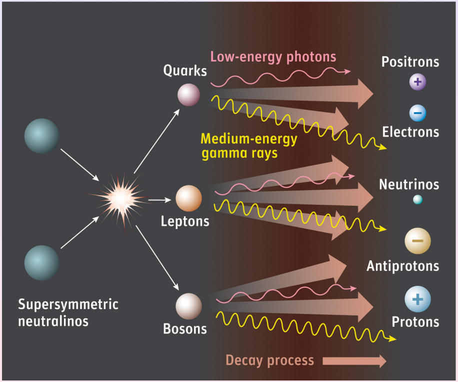


- Different ways of Dark matter detection :
  - **Direct Detection** : WIMPs would scatter elastically with nuclei of detector material and produce recoil energy. Both spin dependent and spin independent cross-sections are measured
  - **Indirect Detection** : If DM exists, then the products of DM annihilation can be detectable.
    - **Gamma-ray** : PAMELA, HESS, VERITAS etc.
    - **Neutrinos** : Super-KamioKande, IceCube.
    - **Antimatter** : PAMELA, HEAT, AMS-01 and AMS-02.
  - **Collider Searches**: Producing DM particles at colliders associated with either a photon or jet : Large missing energy $+\gamma$ or jet. It can be produced also with $W^{\pm}, Z$ and heavy fermions (t, b).

Direct and Indirect Detection







Possible WIMP candidates

- All most all the physics beyond the standard model predicts a WIMP
- In principle, WIMP can be a Dirac or a Majorana fermion, it can be a scalar as well
- Beyond the Standard Model :
  - SUSY with R-parity : Lightest neutralino $(\tilde{\chi}_1^0)$
  - Little Higgs models with T-parity : Heavy photon A_H
  - Universal Extra Dimensions with KK-parity : Lightest KK excitation

BIG question ?

How does WIMP interact with SM fields ?

We need some kind of a theory for WIMP interaction with SM fields

Theory of WIMP interactions

One needs a theory of DM interactions to interpret :

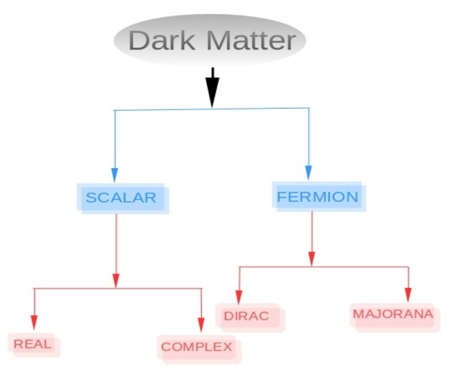
- the cross-section limits obtained from the LHC searches on $\not{E}_T$ events
- to make link between LHC limits and limits obtained from the DM direct and indirect searches

- Several DM models beyond the SM have been proposed
- Broadly they can be classified into three categories :

1. Effective theory of DM interactions
2. Simplified models of DM interactions
3. Complete model of DM

[Ref:J.Abdallah *et al.*, arXiv:1506.03116v3[hep-ph]]

Effective theory of Dark Matter interactions

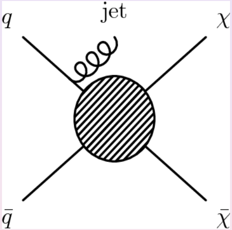


- Situation : DM (χ) + SM (No other new particles in the spectrum)
- Interactions of DM with SM particles are governed by the underlying gauge symmetry.

- Additional symmetry is needed to make DM stable : χ is odd under Z_2, while all SM fields are even $\Longrightarrow$ stable WIMP & at colliders WIMPs are pair produced
- WIMP is singlet under the SM gauge groups $\Longrightarrow$ No tree-level couplings with the E-W gauge bosons. It can couple to W, Z by integrating out intermediate heavy particles.
- The flavour structure is such that WIMP does not introduce FCNC or CP violation.
- The LHC limits on the cross-sections is a function of only one parameter, the scale of new physics Λ. Processes with higher powers of Λ are highly suppressed

[Ref:arXiv:0912.4511,1005.1286,1005.3797,1008.1783,1009.0008, 1108.1196,1109.4398]

Effective theory of Dark Matter interactions



- In this approach, the interactions between the DM and the SM fields are described by a non-renormalizable operators:
- $\mathcal{L}_{\rm EFT} = \frac{1}{M_*^2}(\bar{q}q)(\bar{\chi}\chi)$. Here, the interactions between the fermionic DM particle χ and quark q is communicated via a heavy scalar field, which has been integrated out $\Longrightarrow$ D=6 operator
- The strength of the interaction is controlled by the mass scale M_*
- The beauty of EFT : the same operator can describe DM annihilation, scattering, and production.

Effective theory of Dark Matter interactions

- The EFT operators are non-renormalizable but predictive as long as the energy scale of the interaction $E << M_*$

- The EFT is a valid prescription for the calculation :

    - indirect searches of DM. The energy scale for non-relativistic annihilation of DM particles in the halo is $\mathcal{O}(M_{\text{DM}})$

    - Direct detection of the DM : non-relativistic interaction of the DM with nucleon takes place at the energy scale of $\mathcal{O}(\text{MeV})$

Interaction between Dirac WIMP and SM quarks

- The interaction between the DM and quarks (mediated by a colorless scalar S and pseudo-scalar P:

$$\mathcal{L} \supset g^{s}_{\rm DM}(\bar{\chi}\chi)S + g^{S}_{\rm SM}\sum_q \frac{m_q}{v}(\bar{q}q)S + ig^{P}_{\rm DM}(\bar{\chi}\gamma_5\chi)P + ig^{P}_{\rm SM}\sum_q \frac{m_q}{v}(\bar{q}\gamma_5 q)P$$

- Both S & P are exact CP eigenstates and $g^{S,P}_{\rm DM}$ and $g^{S,P}_{\rm SM}$ are all real $\Longrightarrow$ No additional contributions to EDMs
- For very heavy mediator masses $M_{S,P}$ ($M_{S,P} >> E_{\rm process}$), integrating out the scalar and pseudo-scalar mediator $\Longrightarrow$

$$\mathcal{O}^q_S = \frac{m_q}{\Lambda_S^3}\left(\bar{\chi}\chi\right)\left(\bar{q}q\right), \qquad \mathcal{O}^q_P = \frac{m_q}{\Lambda_P^3}\left(\bar{\chi}\gamma_5\chi\right)\left(\bar{q}\gamma_5 q\right)$$

- where, the suppression scale Λ is related to mediator mass $M_{S/P}$ and fundamental couplings $g^S_{\rm SM}$ and $g^S_{\rm DM}$ by $\Lambda_S = \left(\frac{vM_S^2}{g^S_{\rm SM}g^S_{\rm DM}}\right)^{1/3}$, for pseudoscalar interactions: $S \to P$
- For vector mediator, $\Lambda_V = \frac{M_V}{\sqrt{g^V_{\rm SM}g^V_{\rm DM}}}$

Higher dimensional operators for Dirac Dark Matter

Label	Operator	Usual coefficients	Dimension
$\mathcal{O}_{\rm D1}$	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3	6
$\mathcal{O}_{\rm D2}$	$\bar{\chi}i\gamma_5\chi\bar{q}q$	m_q/M_*^3	6
$\mathcal{O}_{\rm D3}$	$\bar{\chi}\chi\bar{q}i\gamma_5 q$	m_q/M_*^3	6
$\mathcal{O}_{\rm D4}$	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q$	m_q/M_*^3	6
$\mathcal{O}_{\rm D5}$	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	6
$\mathcal{O}_{\rm D6}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	6
$\mathcal{O}_{\rm D7}$	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$	6
$\mathcal{O}_{\rm D8}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$	6
$\mathcal{O}_{\rm D9}$	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$	6
$\mathcal{O}_{\rm D10}$	$\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$	6
$\mathcal{O}_{\rm D11}$	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/4M_*^3$	7
$\mathcal{O}_{\rm D12}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_S/4M_*^3$	7
$\mathcal{O}_{\rm D13}$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/4M_*^3$	7
$\mathcal{O}_{\rm D14}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_S/4M_*^3$	7

[Ref: Simone *et al.*, arXiv:1603.08002v1]

Higher dimensional operators for Majorana Dark Matter

$\mathcal{O}_{\text{M1}}$	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\text{M2}}$	$\bar{\chi}i\gamma_5\chi\bar{q}q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\text{M3}}$	$\bar{\chi}\chi\bar{q}i\gamma_5 q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\text{M4}}$	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\text{M5}}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$	6
$\mathcal{O}_{\text{M6}}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/2M_*^2$	6
$\mathcal{O}_{\text{M7}}$	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/8M_*^3$	7
$\mathcal{O}_{\text{M8}}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_S/8M_*^3$	7
$\mathcal{O}_{\text{M9}}$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/8M_*^3$	7
$\mathcal{O}_{\text{M10}}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_S/8M_*^3$	7

[Ref: Simone *et al.*, arXiv:1603.08002v1]

Higher dimensional operators for Complex Scalar Dark Matter

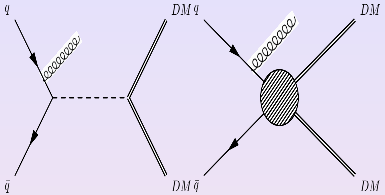
Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{C1}$	$\phi^*\phi\bar{q}q$	m_q/M_*^2	5
$\mathcal{O}_{C2}$	$\phi^*\phi\bar{q}i\gamma_5 q$	m_q/M_*^2	5
$\mathcal{O}_{C3}$	$\phi^* i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	$1/M_*^2$	6
$\mathcal{O}_{C4}$	$\phi^* i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma_5 q$	$1/M_*^2$	6
$\mathcal{O}_{C5}$	$\phi^*\phi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/4M_*^2$	6
$\mathcal{O}_{C6}$	$\phi^*\phi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/4M_*^2$	6

For Real Scalar Dark Matter:

Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{R1}$	$\phi^2\bar{q}q$	$m_q/2M_*^2$	5
$\mathcal{O}_{R2}$	$\phi^2\bar{q}i\gamma_5 q$	$m_q/2M_*^2$	5
$\mathcal{O}_{R3}$	$\phi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/8M_*^2$	6
$\mathcal{O}_{R4}$	$\phi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/8M_*^2$	6

[Ref: Simone *et al.*, arXiv:1603.08002v1]

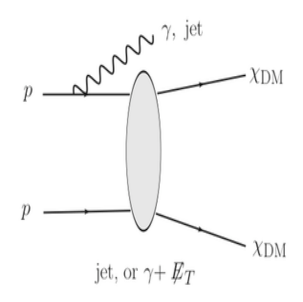
Signature of DM at the LHC



- The existing LHC studies in most cases are performed in the frame work of effective theory (EFT)
- DM - quark interactions are parametrised using EFT technique
- DM (χ)- quark (q) contact interaction is set by the scale Λ or M_*, which is related to the mediator mass M, its couplings to quark (g_q) and DM (g_χ) as $\Lambda = \frac{M}{\sqrt{g_q g_\chi}}$
- S, V, A type of interactions between $\chi - q$ are studied. The DM is a Dirac particle
- LHC results are then translated as limit in $M_{\rm DM} - \sigma_{\rm SI}$ plane in model independent way

DM searches at the LHC

- The production ($pp \to \chi\chi$) of WIMPs at the LHC would give rise to large $\not{E}_T \Longrightarrow$ hard to observe at the detector
- Signal observation requires : At least a hard jet or a photon in association with this $\not{E}_T$: (a) Mono-photon : $\gamma + \not{E}_T$ and (b) Monojet : jet + $\not{E}_T$
- Both ATLAS & CMS have looked for a variety of $\not{E}_T$ signatures involving hadronic jets, $W^{\pm}, Z, \gamma, t/b$- quarks as well as the Higgs boson in the final state



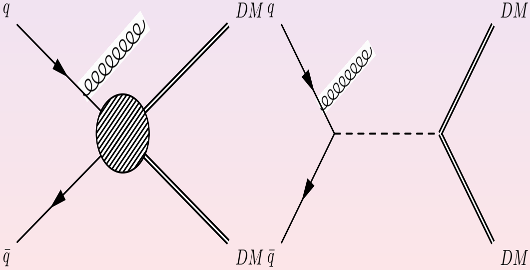
Another BIG question ?

Can we trust EFT interpretation of LHC results on DM searches ?

Yes, but with some limitations !!

Limitations of EFT of DM interactions

- The EFT description of DM interactions with the SM fields is valid as long as the mass of the heavy mediator is not within the kinematic reach of the collider
- As the heavy mediator particles mass scales and coupling strengths become accessible to the LHC, the validity of the EFT approximation can not be guaranteed



- Example:
- The heavy particle propagator in the process $q\bar{q} \to \bar{\chi}\chi + \gamma(g)$ is

$$\frac{1}{Q_{\rm tr}^2 - M_{\rm med}^2} = -\frac{1}{M_{\rm med}^2}\left(1 + \frac{Q_{\rm tr}^2}{M_{\rm med}^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M_{\rm med}^4}\right)\right)$$

- $Q_{\rm tr}^2$ is the momentum transfer in the process
- Retaining only the leading term $1/M_{\rm med}^2 \Longrightarrow$ truncation of the expansion to the lowest -dimensional EFT operator
- $M_\star = \frac{M_{\rm med}}{\sqrt{g_q g_\chi}}$ holds as long as $Q_{\rm tr} << M_{\rm med}$
- In this s-channel process : $Q_{\rm tr} > 2m_\chi$ (to produce the DM pair) $\Longrightarrow$ $M_* > \frac{Q_{\rm tr}}{\sqrt{g_q g_\chi}} > 2\frac{m_\chi}{\sqrt{g_q g_\chi}} > \frac{m_\chi}{2\pi}, \quad (g_q, g_\chi \leq 4\pi)$

[Ref. arXiv:1603.08002[hep-ph]]

- A better measure of the validity of the EFT :
  - $Q_{\rm tr}^2 < M_{\rm med}^2 \equiv g_q g_\chi M_*^2 \Longrightarrow$ EFT valid
  - $Q_{\rm tr}^2 \sim M_{\rm med}^2$: $\sigma_{\rm prod}$ receives resonant enhancement & EFT approximation gives conservative limits relative to the full theory
  - $Q_{\rm tr}^2 >> M_{\rm med}^2$: EFT expansion fails, $\sigma_{\rm prod}$ falls like $Q_{\rm tr}^{-1}$ rather than $M_{\rm med}^{-1}$ $\Longrightarrow$ EFT constraints will stronger than the actual ones
- EFT validity condition : $Q_{\rm tr}^2 < M_{\rm med}^2 = g_q g_\chi M_*^2$
- Discard events which do not pass this condition and gives a truncated signal cross section as function of

$$(m_\chi, g_q, g_\chi, M_*) \quad \text{or} \quad (m_\chi, M_{\rm med})$$

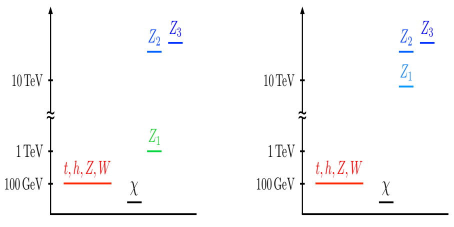
- The truncation to the lowest-dim operators of EFT expansion is accurate only if the momentum transfer is smaller than the energy scale of the order of M_* or Λ
- Compute the fraction of events with momentum transfer lower than the EFT cut off scale

$$\mathrm{R}_{\Lambda}^{\mathrm{tot}} \equiv \frac{\sigma \mid_{Q_{\mathrm{tr}}<\Lambda}}{\sigma} = \frac{\int_{p_T^{\mathrm{min}}}^{p_T^{\mathrm{max}}} dp_T \int_{-2}^{2} d\eta \frac{d^2\sigma}{dp_T d\eta} \mid_{Q_{\mathrm{tr}}<\Lambda}}{\int dp_T \int d\eta \frac{d^2\sigma}{dp_T d\eta}}$$

- $p_T^{\mathrm{min}} = 500$ GeV, $\mid \eta \mid < 2$ for $\sqrt{s} = 8$ TeV & 14 TeV
- $p_T^{\mathrm{max}} = 1, 2$ TeV, for $\sqrt{s} = 8$ TeV & 14 TeV
- $R_{\Lambda}^{\mathrm{tot}}$ gets closer to 1 for large $\Lambda \Longrightarrow$ the effect of cut off becomes negligible
- $R_{\Lambda}^{\mathrm{tot}}$ drops for large m_χ, because the momentum transfer increases in this mass regime
- Conclusion : EFT works better for large Λ and small m_{DM}

[Ref. G. Busoni *et al.*, PLB 728 (2014), JCAP 06 (2014), JCAP 09 (2014)]

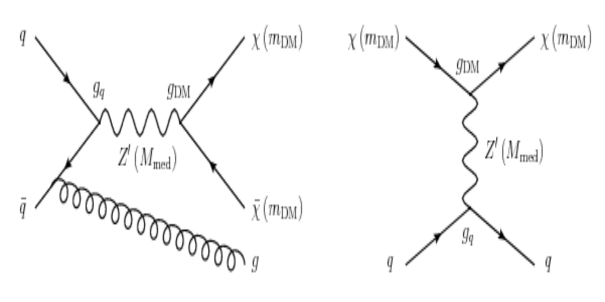
Simplified model of DM interactions



- The dark sector can have additional fields, but they should be somewhat decoupled
- The simplified Lagrangian should contain terms that are renormalizable, Lorentz & SM gauge invariant.
- four parameters : DM mass m_χ; mediator mass M_{med}, universal mediator coupling to quarks g_q; and mediator coupling to DM g_χ

[Ref: J. Abdallah *et al.*, arXiv:1503.03116, O. Buchmueller *et al.*, JHEP 01 (2014), A. De. Simone *et al.*, JHEP 06 (2014), Godbole *et al.*, arXiv:1506.01408]

Vector and axial vector *s*-channel mediator



$$\mathcal{L}_{\rm vector} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \chi \quad (1)$$

$$\mathcal{L}_{\rm axial-vector} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi \quad (2)$$

[Ref: A. Boveia *at el.*, arXiv:1603.04156]

- The coupling g_q is assumed to universal to all quarks
- Parameters : $g_q, g_\chi, m_\chi, M_{\rm med}$ controls the DM interactions with SM particles $\Longrightarrow$ LHC searches and direct detections
- At low energies $(E << M_{\rm med})$ heavy mediator Z'_μ can be integrated out to get a tower of non-renormalizable operators for the Dirac DM interactions with quarks. The lowest-dimensional $(D = 6)$ operator is of type $\mathcal{O}_{D5} = \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
- matching condition implies $\frac{1}{M_*^2} = \frac{g_q g_\chi}{M_{\rm med}^2}$

Collider search vs direct detection cross section for light mediators

- In the case of *s*-channel operators, resonance effects can increase the production cross section of DM pair
- small decay width $\Gamma \Longrightarrow$ large enhancement
- the mediator has a non vanishing decay width to jets and DM pairs
- $pp \to \bar{\chi}\chi + X$ scales as

$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(Q_{\text{tr}}^2 - M^2)^2 + \frac{\Gamma^2}{4}} E^2$$

- $E \equiv \sqrt{\hat{s}}$
- q is the four momentum flowing through this mediator

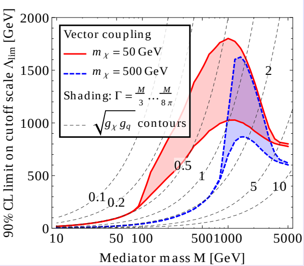
[Ref. P.J. Fox *et al.*, PRD85,056011(2012)]

- The direct detection cross section is approximately given by

$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$

- For $M^2 << q^2$, the limit that collider sets on $g_\chi^2 g_q^2$ becomes independent of M
- limit on $g_q^2 g_\chi^2$ from $\sigma(\chi N \to \chi N) \to$ stronger for smaller $M \Longrightarrow$ the collider limit on direct detection becomes weaker as M becomes smaller
- when $m_\chi < M/2$ and the condition $\sqrt{q^2} \approx M$, collider production of $\bar{\chi}\chi + X$ experiences resonant enhancement $\Longrightarrow$ improved limits on Λ is expected

[Ref. P.J. Fox *et al.*, PRD85,056011(2012)]



- $\Lambda \equiv M/\sqrt{g_q g_\chi}$
- Very large $M(\geq 5$ TeV) limits on $\Lambda \implies$ EFT frame work
- For $2m_\chi << M \leq 5$ TeV $\implies$ resonant enhancement leads to a significant improvement in the limit. Mediator is produced on shell, primary parton collision $\rightarrow$ 2 body rather than 3 body
- Strongest enhancement is possible when Γ is small
- $\Gamma = M/8\pi$ to $\Gamma = M/3$
- Below $M \approx 2m_\chi$, Z' can not decay in to DM pair, but only to $q\bar{q}$

[Ref. P.J. Fox *et al.*, PRD85,056011(2012)]

CMS study of jet + $\not{E}_T$ channel at $\sqrt{s} = 8$ TeV

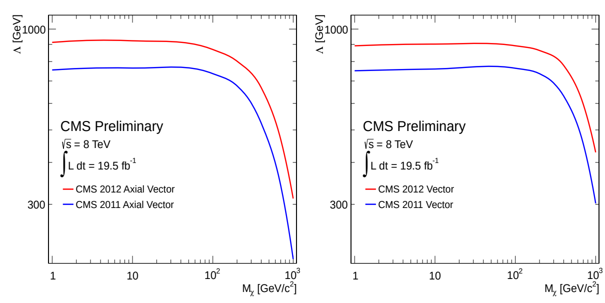
- CMS looked for jets $+\not{E}_T$ signature at $\sqrt{s} = 8$ TeV run at integrated luminosity of 19.7 fb^{-1}
- DM - quark interactions are parametrised using EFT technique
- DM (χ)- quark (q) contact interaction is set by the scale Λ, which is related to the mediator mass M, its couplings to quark (g_q) and DM (g_χ) as $\Lambda = \frac{M}{\sqrt{g_q g_\chi}}$
- S, V, A type of interactions between $\chi - q$ are studied. The DM is a Dirac particle
- S, V interactions can be related to σ_{SI}
- A interaction can be related to σ_{SD}
- Simplified model with s-channel mediator with vector interactions also considered
- Mass of the mediator M_{med} varied for two values $m_\chi = 50$ GeV and 500 GeV
- $\Gamma_V = M_V/8\pi$ and $M_V/3$

[Ref. V. Khachatryan *et al.*, CMS Collaboration, EPJC 75 (2015)]

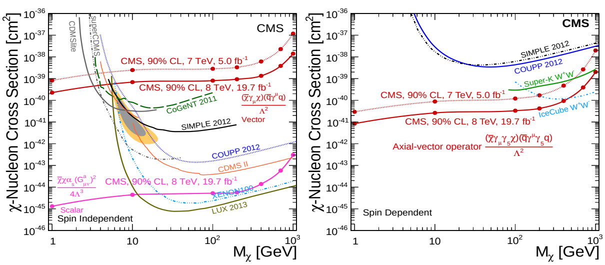
- The main SM backgrounds : $Z + \text{jets}$, $W + \text{jets}$, $t\bar{t}$
- Basic cuts : $\not{E}_T > 120$ GeV, $p_T^j > 80$ GeV, $|\ \eta_j\ | < 2.6$
- Analysis is performed in 7 regions of $\not{E}_T > 250 - 550$ GeV (in step of 50 GeV), $p_T^j(j_1) > 110$GeV, $|\ \eta_j\ | < 2.4$
- Events with $N_j > 2$ with $p_T^j > 30$ GeV and $|\ \eta_j\ | < 4.5$ are discarded
- Signal events contains jets from either ISR/FSR, a second jet (j_2) is allowed, provided $\Delta\phi(j_1, j_2) < 2.5 \implies$ suppresses QCD dijet events

[Ref. V. Khachatryan *et al.*, CMS Collaboration, EPJC 75 (2015)]

CMS limit on $\Lambda - m_\chi$ plane

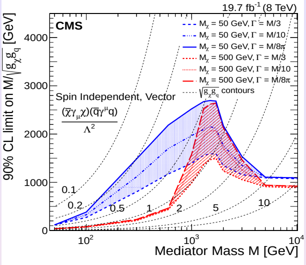


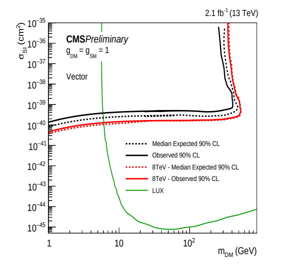
Lower limits at 90% CL on $\sigma^{\mathrm{SI}}_{\chi-N} - m_\chi$ and $\sigma^{\mathrm{SD}}_{\chi-N} - m_\chi$ plane



[Ref. V. Khachatryan *et al.*, CMS Collaboration, EPJC 75 (2015), CMS PAS EXO-15-003]

Lower limits at 90% CL on simplified model parameter space

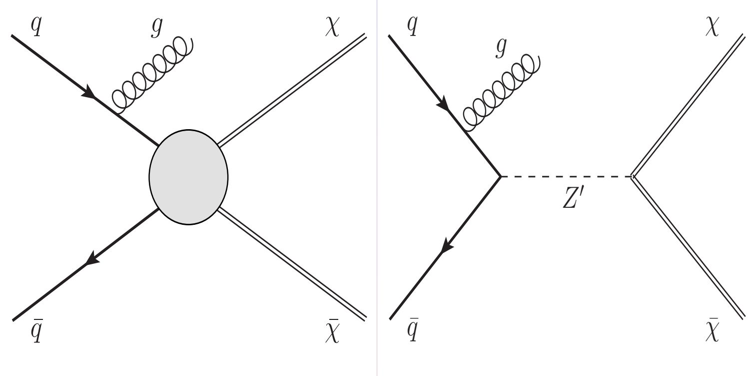




- Γ_V is varied between the extremes of $M_V/8\pi$ and $M_V/3$, where $M_V/8\pi$ corresponds to a mediator that can only decay into quark pair.
- For 13 TeV study, simplified model (vector like interactions with $g_q = g_\chi = 1$) considered. The current bound is weaker than 8 TeV results
- From 13 TeV analysis : $M_{\text{med}} > 1.3$ TeV at 90% CL

[Ref. V. Khachatryan *et al.*, CMS Collaboration, EPJC 75 (2015), CMS PAS EXO-15-003]

ATLAS study of the mono-jet signature of DM (arXiv:1502.01518)



- Jets + $\not{E}_T$ signal interpretation in terms of (a) contact interaction described by EFT operators and (b) a simplified model with s-channel Z' boson exchange

List of Effective operators considered :

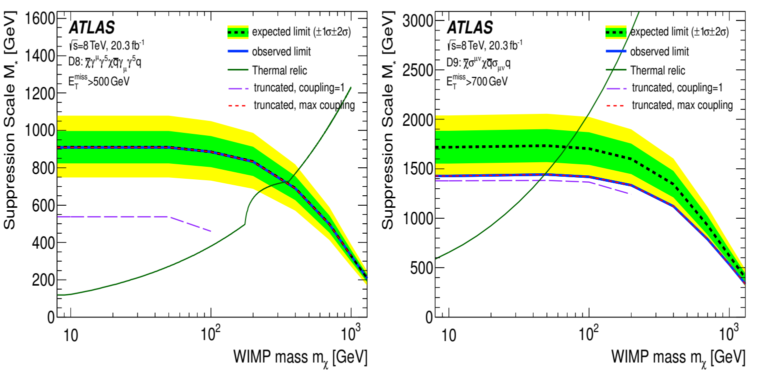
Name	Initial state	Type	Operator
C1	qq	S	$\frac{m_q}{M_*^2}\chi^\dagger\chi\bar{q}q$
C5	gg	S	$\frac{\alpha_s}{M_*^2}\chi^\dagger\chi(G^a_{\mu\nu})^2$
D1	qq	S	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	V	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	A	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$
D9	qq	T	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	S	$\frac{\alpha_s}{M_*^3}\bar{\chi}\chi(G^a_{\mu\nu})^2$

- ATLAS looked for jets $+\not{E}_T$ signature at $\sqrt{s} = 8$ TeV run at integrated luminosity of 20.3 fb^{-1}
- Mono-jet events are selected with $p(j_1)_T > 120$ GeV and $\mid \eta \mid < 2.0$, $p(j_1)_T/\not{E}_T > 0.5$
- Additional cut : $\Delta\phi(p(j_1)_T, \not{E}_T) > 1.0 \Longrightarrow$ removes the QCD multijet background
- Events with any additional jets are rejected with $p_T^j > 20$ GeV and $\mid \eta \mid < 4.5$

ATLAS study of the mono-jet signature of DM (arXiv:1502.01518)

- 9 signal regions are selected based on $\not{E}_T$ cut
- $(SR1, SR2, SR3, ..SR9) \equiv (\not{E}_T/\text{GeV} = 150, 200, 250, ..700)$
- In EFT approach, the bounds on M_* for a given DM mass (m_χ) can be converted to bounds on WIMP-nucleon scattering cross-section
- σ_{SD} limits are based on $D8$ and $D9$
- Both $D8$ and $D9$ cross-section limits are significantly stronger than those from σ_{SD}
- truncated events : events are omitted where interaction energy scale exceeds the mediator particle mass $\Longrightarrow$ events are kept for which $Q_{\text{tr}} < M_{\text{med}}$
- Perturbative limits on couplings : $0 < \sqrt{g_q g_\chi} < 4\pi$

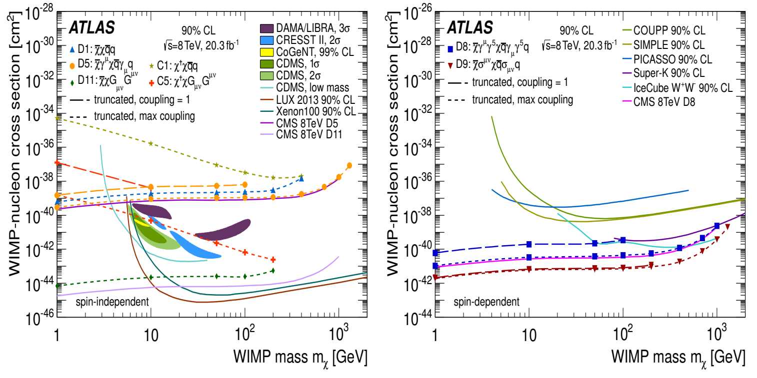
Lower limits at 95% CL on M_* as function of the WIMP mass m_χ for $D8$ & $D9$



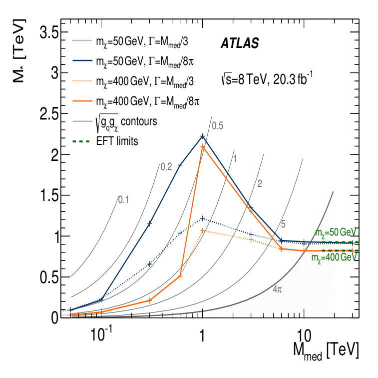
- The Thermal relic line for $D8$ has a bump feature at m_t where the annihilation channel to top quark opens.

[Ref: ATLAS Collaboration, arXiv:1502.01518]

Lower limits at 90% CL on $\sigma^{SI}_{\chi-N}$ and $\sigma^{SD}_{\chi-N}$ as a function of WIMP mass (m_χ)

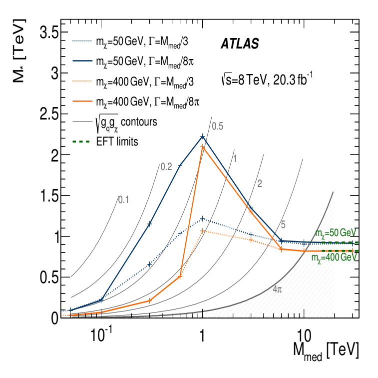


Interpretation in terms of simplified model



- Dirac WIMP interacts with SM particles via Z'
- For each WIMP mass, mediator particle mass M_{med} between 50 GeV and 30 TeV are considered each for two values of mediator particle width ($\Gamma = M_{\text{med}}/3$ & $M_{\text{med}}/8\pi$)
- $M_* = M_{\text{med}}/\sqrt{g_q g_\chi}$
- For a given M_{med} and two values of Γ, the real value of the mass suppression scale would compare to the M_* value derived assuming a contact interaction (dashed lines in the figure)

- This contact interaction regime is reached for $M_{\text{med}} \simeq 5$ TeV

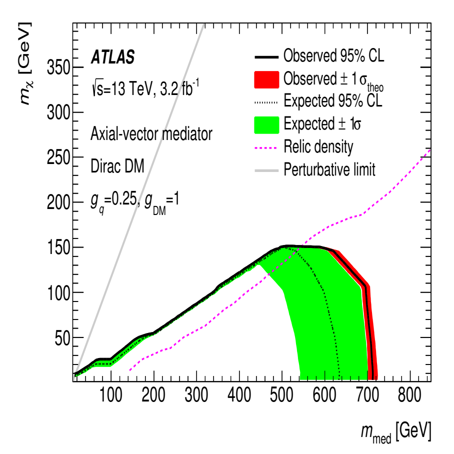


- This contact interaction regime is reached for $M_{\rm med} \simeq 5$ TeV
- For (700 GeV $< M_{\rm med} <$ 5 TeV), the mediator Z' produced resonantly and actual M_* value is higher than in the contact interaction regime
- In this case, the contact interaction limits would be pessimistic; they would underestimate the actual values
- For small $M_{\rm med}$ mass $<$ 700 GeV, very small M_* limits because the WIMP would be than the mediator $\Longrightarrow$ WIMP pair production via Z' would be kinematically suppressed
- In this limit, the contact interaction limit would be optimistic and overestimate the actual M_* values.

ATLAS study of $\gamma + \not{E}_T$ channel at $\sqrt{s} = 13$ TeV

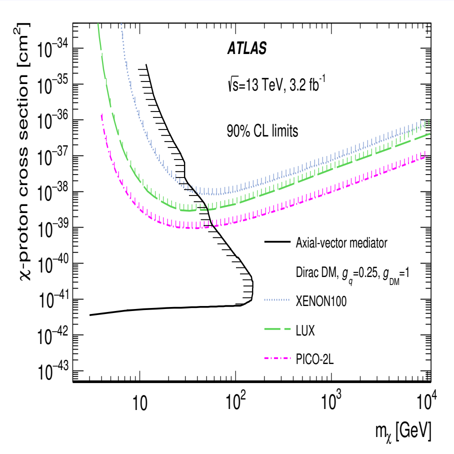
- $\gamma + \not{E}_T$ process studied using 3.2fb^{-1} data
- Events are selected based on
  1. $\not{E}_T > 150$ GeV
  2. $p_T^{\gamma} > 150$ GeV
  3. $\mid \eta \mid < 2.37$
  4. $\Delta\phi(\gamma, \not{E}_T) > 0.4$
  5. Events with more than one jet or with a jet with $\Delta\phi(\text{jet}, \not{E}_T) < 0.4$ are rejected
- Two scenarios are considered to interpret the results in the context of DM:
  1. Dirac DM produced via *s*-channel mediator with axial-vector interactions
     Five parameters : $m_\chi, M_{\text{med}}, g_q, g_\chi, \Gamma_{\text{med}}$
  2. $\gamma\gamma\bar{\chi}\chi$ D=7 EFT operator: DM is produced via $q\bar{q} \to \gamma \to \gamma\bar{\chi}\chi$,no need for ISR photons. four free parameters : $k_1, k_2, m_\chi, \Lambda$

[Ref: ATLAS Collaboration, arXiv:1604.01306]



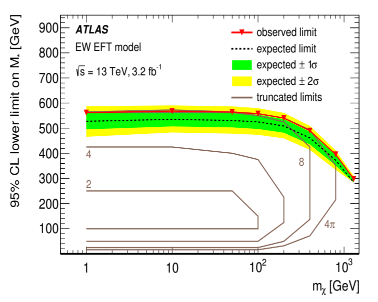
- perturbative unitarity limit : $m_\chi = \sqrt{\pi/2} M_{\text{med}}$
- $M_{\text{med}} > 710$ GeV @ 95% CL for m_χ masses up to 150 GeV

[Ref: F. Kahlhoefer *et al.*, JHEP 016 (2016), ATLAS Collaboration, arXiv:1604.01306]



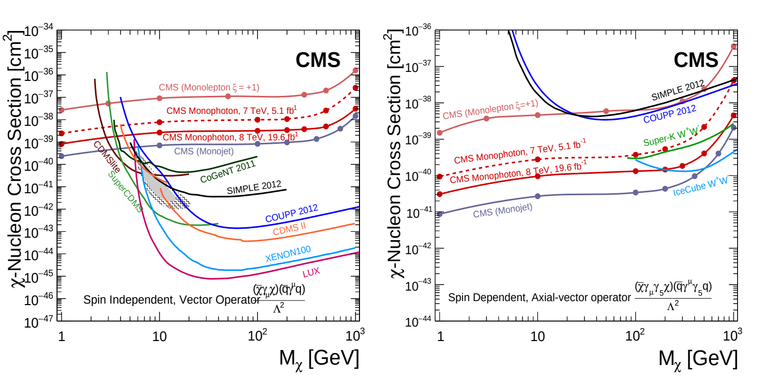
- Assuming $g_q = 0.25$ and $g_\chi = 1$ for both collider and direct detection
- stringent limits on $\sigma_{\chi-p} \sim \mathcal{O}(10^{-41}\text{cm}^2)$ up to $m_\chi \sim 150$ GeV
- Note that PICO-2L expt. provides stringent limit on $\sigma^{\rm SD}_{\chi-p}$ for WIMP masses < 50 GeV

[Ref: ATLAS Collaboration, arXiv:1604.01306, C. Amole *et al.*, PICO-2L Run 2 Collaboration, arXiv:1601.03729]



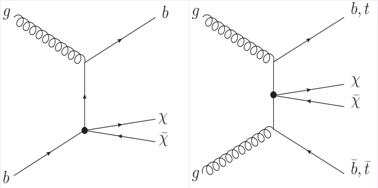
- For $\gamma\gamma\bar{\chi}\chi$ interactions, lower limits are put on $M_* - m_\chi$ plane
- Truncated limits are given, the scale at which EFT description is invalid $(M_{\rm cut})$ is assumed to be related to M_* through $M_{\rm cut} = g^* M_*$, where g^* is the EFT couplings
- Events with $\sqrt{s} > M_{\rm cut}$ are removed and limits is recomputed
- For various values g^* limits are shown
- search excludes $M_* < 570$ GeV

CMS lower limits at 90% CL on σ_{SI} and σ_{SD} as a function of WIMP mass (m_χ) ($\gamma + \not{E}_T$)



[Ref: CMS Collaboration, arXiv:1410.8812]

$\bar{\chi}\chi + QQ$ $(Q = t, b)$ at the LHC



- Integrating out heavy scalar & pseudo-scalars one can generate following set of the most simplest EFT operators, suppressed by the scale M_*:

$$\mathcal{O}_S^Q = \frac{m_Q}{M_*^3}(\bar{\chi}\chi)\bar{Q}Q; \quad \mathcal{O}_P^Q = \frac{m_Q}{M_*^3}(\bar{\chi}\gamma_5\chi)\bar{Q}\gamma_5 Q; \quad (Q = t, b)$$

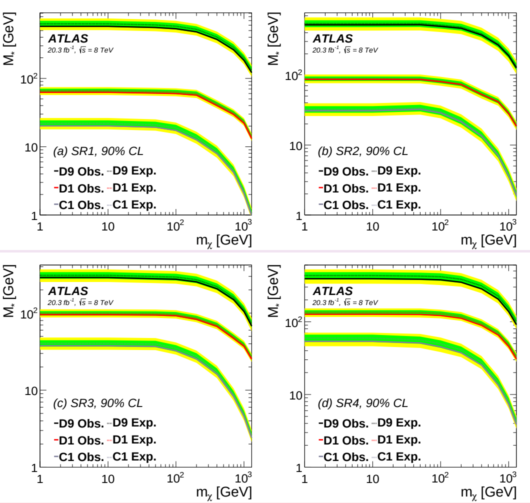
- ATLAS collaboration has looked into this channel. They have also considered Tensor operator in addition to $\mathcal{O}_S, \mathcal{O}_P$. $\mathcal{O}_\mathrm{T} = \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{Q}\sigma_{\mu\nu}Q$

[Ref: ATLAS Collaboration, arXiv:1410.4031, for other details, see Q.-H. Cao *et al.*, JHEP 1108, 018(2011), Beltran *et al.*, JHEP 1009, 037 (2010), J. Goodman *et al.*, PLB695, 185 (2011); PRD 82, 11610 (2010), Bhattacherjee *et al.*, arXiv:1212.5013]

ATLAS study of DM in association with heavy flavours (arXiv:1410.4031)

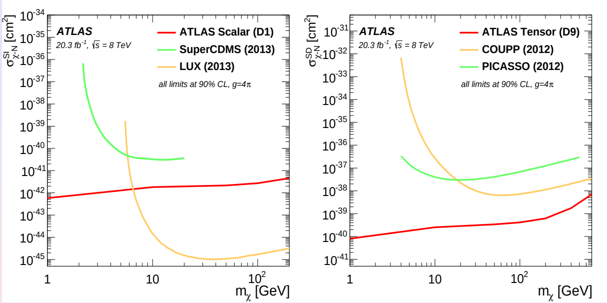
- Two types of signals are studied :
  - $pp \to \bar{\chi}\chi + \bar{b}b$; $SR1$ & $SR2$
  - $pp \to \bar{\chi}\chi + \bar{t}t$; $SR3$ & $SR4$
- $SR1$: DM produced in association with one b-quark in the final state
- $SR2$: DM produced in association with two b-quark in the final state
- $SR3$: DM produced in association with top pair, where both top decay hadronically
- $SR4$: DM produced in association with top pair, where one top decays hadronically other one decays leptonically

Lower limits at 90% CL on M_* as function of m_χ for $C1$, $D1$ and $D9$ operators (arXiv:1410.4031)



- These limits are then converted into limits on $\sigma_{\chi N}$

Lower limits at 90% CL on $\sigma^{SI}_{\chi-N}$ and $\sigma^{SD}_{\chi-N}$ as function of m_χ for $D1$ and $D9$ operators (arXiv:1410.4031)

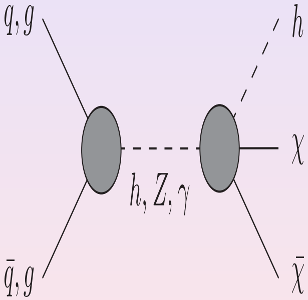


- Limits are strong for low mass region
- The couplings is assumed to be $g_q g_\chi = g = 4\pi$
- The sensitivity for $D1$ operator is approximately $\sigma^{SI}_{\chi-N} = 10^{-42}\text{cm}^2$ for $m_\chi = 10$ GeV.

ATLAS study of DM in association with a Higgs $(\to b\bar{b})$ (arXiv:1510.06218)

- Dark matter pair production in association with a Higgs boson decaying to a pair of bottom quarks.
- $\sqrt{s} = 8$ TeV and with 20.3 fb^{-1} data
- Signal : $b\bar{b} + \not{E}_T$
- The Higgs boson is reconstructed as a high p_T $b\bar{b}$ system with a pair of small radius jets canonical search or a single fat jet with jet-substructure
- Results are presented based :
  1. EFT operators describing interaction between the DM-Higgs
  2. Simplified model : 2HDM + Z'

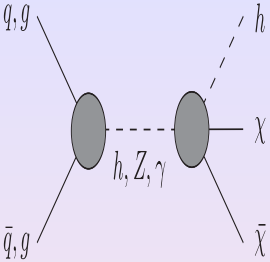
Set of EFT operators studied by ATLAS:



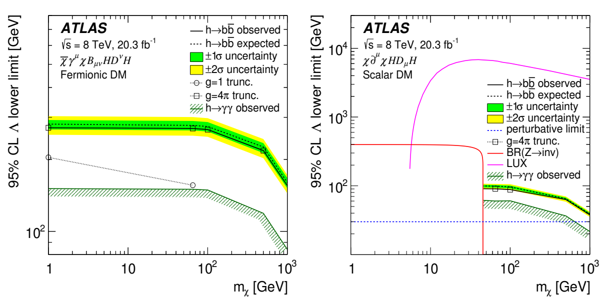
$$\lambda \mid \chi \mid^2 \mid H \mid^2 \quad (S, D = 4)$$
$$\frac{1}{M_*} \bar{\chi} i \gamma_5 \chi \mid H \mid^2 \quad (F, D = 5)$$
$$\frac{1}{M_*^2} \chi^\dagger \partial^\mu \chi H^\dagger D_\mu H \quad (S, D = 6)$$
$$\frac{1}{M_*^4} \bar{\chi} \gamma^\mu \chi B_{\mu\nu} H^\dagger D^\nu H \quad (F, D = 8)$$

- χ is the DM particle (S/F), which is SM gauge singlet
- $D_\mu(^\nu)$ is the covariant derivative for the full SM gauge group
- $B_{\mu\nu}$ is the $U(1)_Y$ field strength tensor
- parameters : DM mass m_χ, the coupling λ and the suppression scale M_*

[Ref: L. Carpenter et al. PRD 89 (2014)]

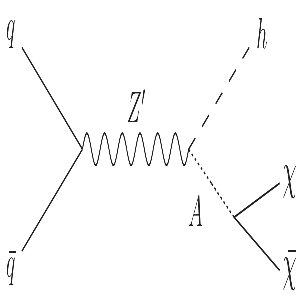


- χ is the DM, h is the 125 GeV observed Higgs boson
- the left dark circle denotes the coupling from $q\bar{q}$ or gg to h, Z, γ that mediates the $DM + h$ production
- the right dark circle represents the contact interaction in EFT framework between DM, the Higgs and the mediator
- Mediator can be a spin 1 heavy gauge boson
- signal : $b\bar{b} + \not{E}_T$
- SM backgrounds : $Z(\rightarrow \nu\bar{\nu}) + \text{jets}, W + \text{jets}, t\bar{t}$ as well as single top events



- Limits at 95% CL in $\Lambda - m_\chi$ plane for EFT operators $\bar{\chi}\gamma^\mu \chi B_{\mu\nu} H^\dagger D^\nu H$ (left) and $\chi^\dagger \partial^\mu \chi H^\dagger D_\mu H$ (right)
- Solid black line : $h(\to b\bar{b}) + \not{E}_T$: regions below the line is excluded
- The solid green line with hash marks indicates regions excluded by collider searches for $h(\to \gamma\gamma) + \not{E}_T$
- On right figure, the regions below the dashed blue line fails the perturbativity requirement
- red line indicates regions excluded by the limits on the $\mathrm{Br}(Z \to \nu\bar{\nu})$
- the magenta line indicates regions excluded by the LUX Collaboration

Simplified model ($Z' - 2\text{HDM}$) interpretation

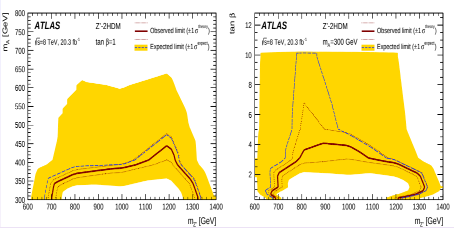


- Z' gauge boson with 2HDM where the DM particle is coupled to the heavy pseudoscalar Higgs boson Ai
- the Z' is produced resonantly
- $Z' \to h + A$ in a Type 2 two-Higgs-doublet model
- h is the observed Higgs boson, and A has a large BR to DM pair
- $Z' \to Z + h$ also possible, followed by $Z \to \nu\nu \Longrightarrow$ mimicking the expected signature.
- Ah decay mode is dominant for most of the parameter space probed in this analysis

[Ref. G. Aad *et al.*, ATLAS Collaboration, arXiv:1510.06218, A.Berlin *et al.*, PRD 89 (2014); G.C. Branco *et al.*, Phys. Rept 516 (2012)]

- results presented are for the alignment limit, $\alpha = \beta - \pi/2$.
- regions of parameter space consistent with precision electroweak constraints on the ρ_0 parameter and with constraints from direct searches for dijet resonances are considered.
- Z' does not couple to leptons in this model
- the A boson is produced on-shell and decays into DM, the mass of the DM particle does not affect the kinematic properties or cross-section of the signal process when it is below half of the A boson mass.
- Hence, the Z'-2HDM model is interpreted in the parameter spaces of $m_{Z'}$, m_A, and $\tan\beta$, with the Z' coupling fixed to its 95% confidence level (CL) upper limit per Z' mass and $\tan\beta$ value from the aforementioned electroweak and dijet search constraints.

[Ref. G. Aad *et al.*, ATLAS Collaboration, arXiv:1510.06218, A.Berlin *et al.*, PRD 89 (2014); G.C. Branco *et al.*, Phys. Rept 516 (2012)]



- 95% CL upper limit on the σ is derived and used to exclude regions of parameter space in $m_{Z'} - m_A$ and $m_{Z'} - \tan\beta$ plane
- For a particular value of $m_{Z'}$ and $\tan\beta$ value the Z' gauge coupling satisfy the 95% CL upper limit from EW precision constraints and dijet searches
- $m_A \geq 300$ GeV in accordance with $b \to s\gamma$ limit
- For $\tan\beta = 1$, $m_{Z'} = 700 - 1300$ GeV is excluded for m_A up to 350 GeV
- $0.3 \leq \tan\beta < 10$, the lower bound comes from perturbative requirement of the Y_t, and the upper limit is based on direct searches for the A
- For $m_A = 300$ GeV, where $A \to \bar{\chi}\chi$, $m_{Z'} = 700 - 1300$ is excluded for $\tan\beta < 2$

Higgs Portal DM

- The SM Higgs boson couples with a particle that constitutes all or part of the dark matter in the universe.
- The dark matter sector communicates with matter/ gauge sector of the SM through the SM Higgs boson
- Higgs boson plays key role in the dark matter annihilation, direct detection and production at colliders
- DM: could be scalar(s), vector (V) or fermion (Majorana) (χ)
- DM: SM gauge singlet.

[Ref: C.P. Burgess *et al.*, NPB 619(2001), V. Barger *et al.*, PRD77 (2008), A. Djuadi *et al.*, PLB 709 (2012), EPJC 73 (2013), J. Abdallah *et al.*, arXiv:1506.03116[hep-ph]]

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_s^2 s^2 - \frac{\lambda_s}{4}s^4 - \frac{\lambda_{hss}}{4}s^2 \mid H \mid^2 \quad (3)$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{\lambda_v}{4}(V_\mu V^\mu)^2 + \frac{\lambda_{hVV}}{4}V_\mu V^\mu \mid H \mid^2 \quad (4)$$

$$\Delta\mathcal{L}_F = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{\lambda_{hff}}{4\Lambda} \mid H \mid^2 \bar{\chi}\chi \quad (5)$$

- Impose Z_2 parity $\Longrightarrow$ stable DM
- After EWSB

$$M_s^2 = m_s^2 + \frac{1}{2}\lambda_{hss}v^2 \quad (6)$$

$$M_V^2 = m_v^2 + \frac{1}{2}\lambda_{hVV}v^2 \quad (7)$$

$$M_F = m_f + \frac{1}{2\Lambda}\lambda_{hff}v^2 \quad (8)$$

[Ref: C.P. Burgess *et al.*, NPB 619(2001), V. Barger *et al.*, PRD77 (2008), A. Djuadi *et al.*, PLB 709 (2012), EPJC 73 (2013), J. Abdallah *et al.*, arXiv:1506.03116[hep-ph]]

- For $M_H > 2M_{\rm DM}$:

$$\Gamma(H \to ss) = \frac{\lambda_{hss}^2 v^2 \beta_s}{128\pi M_H} \quad (9)$$

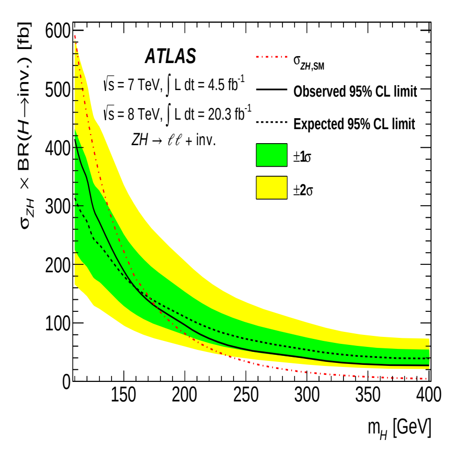
$$\Gamma(H \to \bar{\chi}\chi) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 M_H}{64\pi} \quad (10)$$

$$\Gamma(H \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_v M_H^3}{512\pi M_V^4} \times \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \quad (11)$$

where, $\beta_{\rm DM} = (1 - \frac{4M_{\rm DM}^2}{M_H^2})^{1/2}$ and the scale Λ is set well above the TeV scale

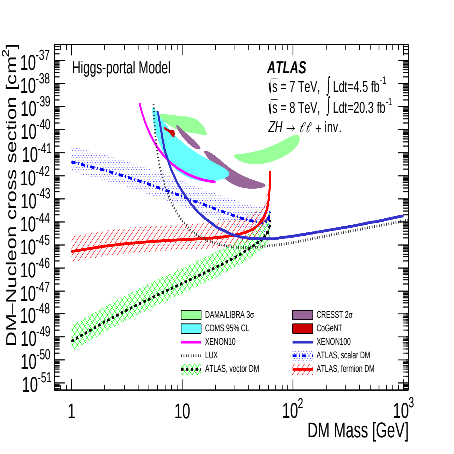
- AT colliders this would lead to invisible decay of the SM Higgs boson. Both ATLAS & CMS have studied this channel. For $M_s \leq 10$ GeV, the collider limits are stronger than the SI results.

[Ref: C.P. Burgess *et al.*, NPB 619(2001), V. Barger *et al.*, PRD77 (2008), A. Djuadi *et al.*, PLB 709 (2012), EPJC 73 (2013)]



- $pp \to ZH$ with $H \to ss$ give rise $\ell\ell + \not{E}_T$ signal
- 95% CL upper limits on $\sigma_{ZH} \times \mathrm{BR}(H \to \mathrm{inv.})$ in the mass range $110 < M_H < 400$ GeV for the combined 7 & 8 TeV data

[Ref. G. Aad *et al.*, ATLAS Collaboration, PRL 112 (2014), 201802]



- $\sigma^{SI}_{S-N} = \frac{\lambda^2_{hss}}{16\pi M_H^4}\frac{M_N^4 f_N^2}{(M_s+M_N)^2}$
- Limits on the DM-nucleon scattering cross section at 90% CL

[Ref. G. Aad *et al.*, ATLAS Collaboration, PRL 112 (2014), 201802]

Summary

- Different astrophysical observations $\Longrightarrow$ DM exists
- WIMPs are good candidate for the cold dark matter
- WIMPs require physics beyond the SM
- The existance of WIMPs can be tested in direct detection, indirect detection experiments
- WIMPs can also leave its footprint at colliders as large $\not{E}_T$ signature, but it is very difficult to confirm
- jets $+\not{E}_T$ and $\gamma + \not{E}_T$ are the two most popular search channels for the WIMP at the LHC

- EFT technique is the simplest way to interpret the results
- Collider results can be translated on $\sigma_{\chi N-\chi N} - m_\chi$ plane
- EFT has limitations : valid for energy scale $E << M_{\rm med}$
- To resolve this, several simplified scenarios have been proposed to interpret the collider and direct detection results
- So far no signature of WIMP
- For low WIMP mass ($m_\chi \leq 10$ GeV) collider limits are stronger than direct detection limits
- It is very hard to confirm the existance of DM even if the LHC finds a large $\not{E}_T$ signal

Thank You!

Backups

Implications for direct detection

- Some of these EFT operator can have contribution to WIMP-direct detection process in the limit of low momentum transfer
- WIMP-nucleon cross-section (cm^2):

$$\sigma^{D1} = 1.60 \times 10^{-37} \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right) \left(\frac{20\mathrm{GeV}}{M_*}\right)^6 \quad (12)$$

$$\sigma^{D5,C3} = 1.38 \times 10^{-37} \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right) \left(\frac{300\mathrm{GeV}}{M_*}\right)^4 \quad (13)$$

$$\sigma^{D8,D9} = 9.18 \times 10^{-40} \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right) \left(\frac{300\mathrm{GeV}}{M_*}\right)^4 \quad (14)$$

Implications for direct detection

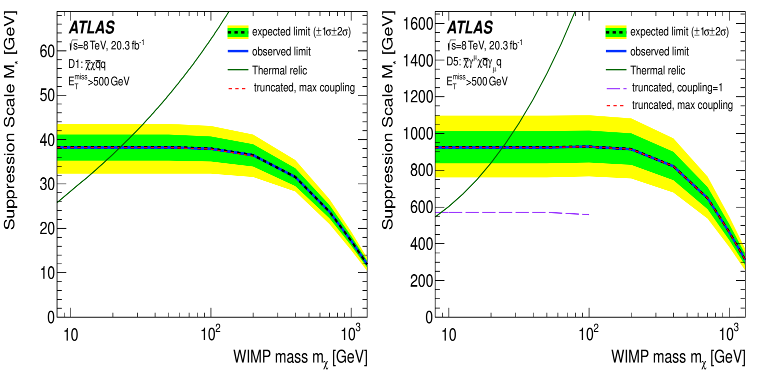
$$\sigma^{D11} = 3.83 \times 10^{-41} \left(\frac{\mu_\chi}{1\text{GeV}}\right) \left(\frac{100\text{GeV}}{M_*}\right)^6 \quad (15)$$

$$\sigma^{C1,R1} = 2.56 \times 10^{-36} \left(\frac{\mu_\chi}{1\text{GeV}}\right) \left(\frac{10\text{GeV}}{M_*}\right)^4 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \quad (16)$$

$$\sigma^{C5,R3} = 7.40 \times 10^{-39} \left(\frac{\mu_\chi}{1\text{GeV}}\right) \left(\frac{60\text{GeV}}{M_*}\right)^4 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \quad (17)$$

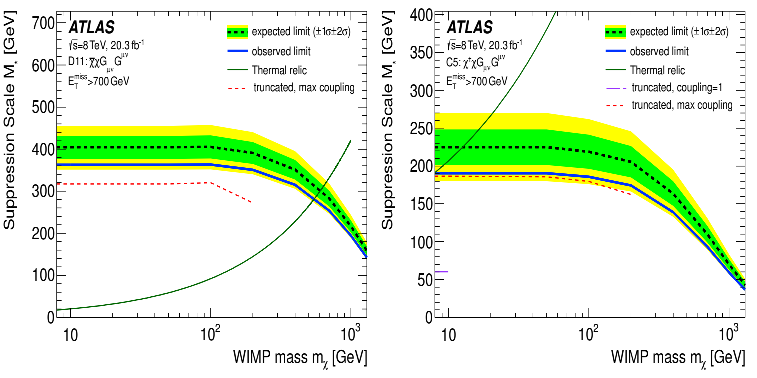
[Ref. G. Belanger *et al.*,arXiv:0803.2360, J.Goodman *et al.*, PRD 82, (2010)]

Lower limits at 95% CL on M_* as function of the WIMP mass m_χ for $D1$ & $D5$



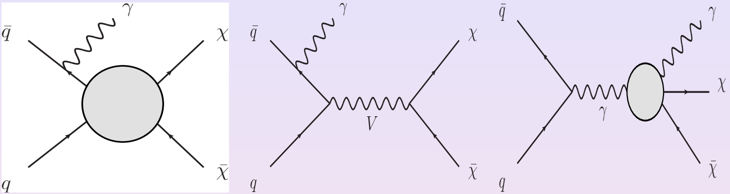
[Ref: ATLAS Collaboration, arXiv:1502.01518]

Lower limits at 95% CL on M_* as function of the WIMP mass m_χ for $D11$ & $C5$



[Ref: ATLAS Collaboration, arXiv:1502.01518]

ATLAS study of the mono-photon signature of DM (arXiv:1411.1559) at $\sqrt{s} = 8$ TeV



- EFT approach : m_{DM} and M_*
- Simplified model : Mediator $V = Z'$, $M_* = m_V/\sqrt{g_q g_\chi}$, Four parameters : m_χ, m_V, Γ_V and overall coupling $\sqrt{g_q g_\chi}$
- $\gamma\gamma\bar{\chi}\chi$ effective vertex : D= 7 operator
- $\mathcal{L} = \frac{1}{\Lambda^3_{C1,2}} \bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu} + \frac{1}{\Lambda^3_{C3,4}} \bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} \tilde{F}^i_{\mu\nu}$
- parameters k_1 and k_2 which controls the strength of DM coupling to $U(1)$ and $SU(2)$ gauge fields

[Ref. A. Nelson *et al.*, PRD 89 (2014)]

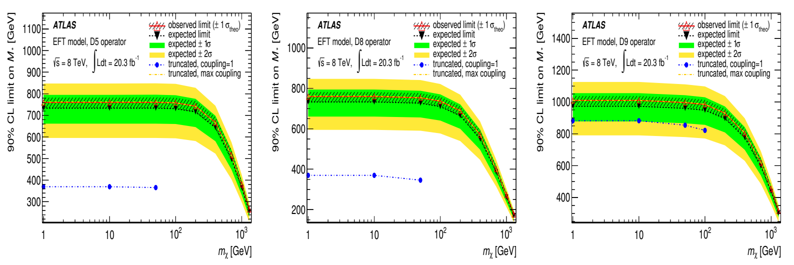
- $\gamma + \not{E}_T$ signal at $\sqrt{s} = 8$ TeV with an integrated luminosity of 20.3 fb^{-1}
- $Z(\rightarrow \nu\bar{\nu}) + \text{ISR}\ \gamma$: the main SM background
- Secondary background come from $W\gamma$ and $Z\gamma$ with unidentified leptons, WZ production where leptons or a jet is misidentified as a photon

- Signal events are selected with these set of cuts:

  - $\not{E}_T > 150$ GeV
  - $p_T^\gamma > 125$ GeV
  - $\mid \eta \mid < 1.37$
  - $\Delta\phi(\gamma, \not{E}_T) > 0.4$
  - Events with more than one jet or with a jet with $\Delta\phi(\text{jet}, \not{E}_T) < 0.4$ are rejected

[Ref: ATLAS Collaboration, arXiv:1411.1559]

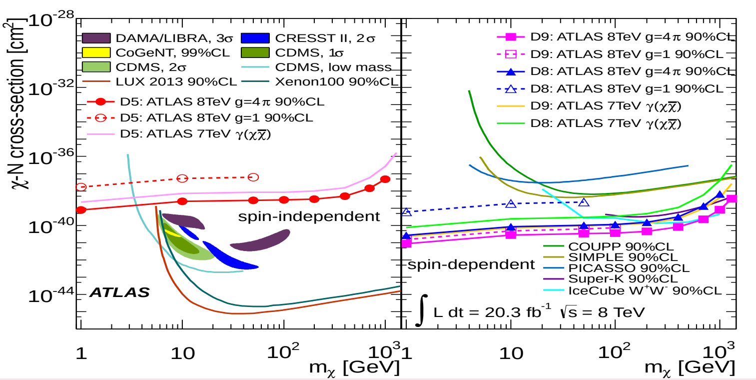
90% CL lower limits on $M_* - m_\chi$ plane



- EFT truncation is applied assuming couplings values $\sqrt{g_q g_\chi} = 1, 4\pi$
- For unit coupling, the truncated limits are less stringent than the non-truncated limits at low m_χ
- For unit coupling truncated case : For $D5\&D8$: sample generated up to $m_\chi = 50$ GeV, for $D9$: up to $m_\chi = 100$ GeV
- Lower limits on M_* now translated into upper limits on $\sigma_{\chi-N}$ as a function of m_χ

[Ref: ATLAS Collaboration, arXiv:1411.1559]

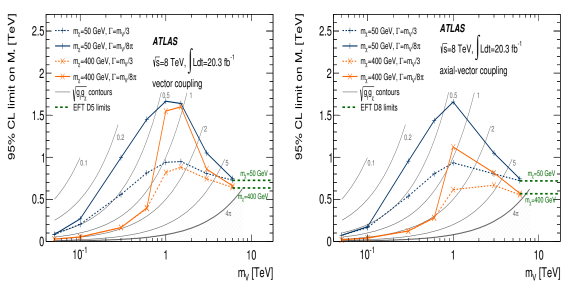
Lower limits at 90% CL on σ_{SI} and σ_{SD} as a function of WIMP mass (m_χ) ($\gamma + \not{E}_T$)



[Ref: ATLAS Collaboration, arXiv:1411.1559]

Result interpretation using simplified model

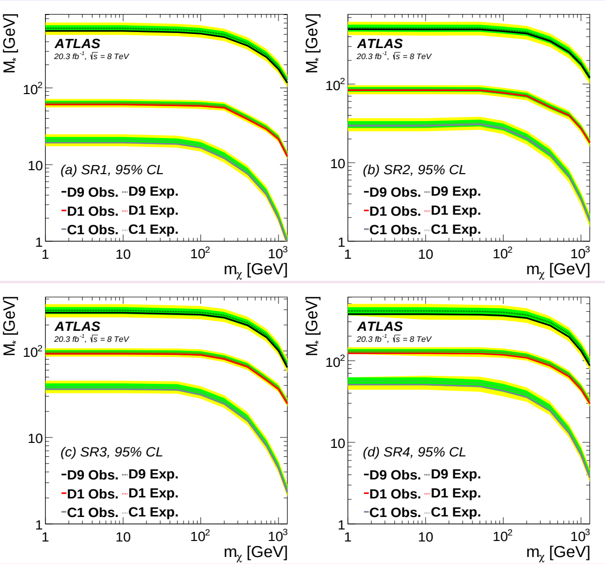
- For the simplified model : Z' model with vector & axial-vector interactions are considered



- 95%CL limits on the EFT suppression scale M_* as a function of m_V.
- When $m_V >> \sqrt{\hat{s}}_{\mathrm{LHC}}$, the EFT provides a good approximation of the simplified model with $M_* = m_V/\sqrt{g_f g_\chi}$

[Ref: ATLAS Collaboration, arXiv:1411.1559]

Lower limits at 95% CL on M_* as function of m_χ for $C1$, $D1$ and $D9$ operators (arXiv:1410.4031)



Lower limits at 95% CL on $\sigma_{\chi N}$ as function of m_χ for $D1$ and $D9$ operators
arXiv:1410.4031