

# 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

- The requirement of dark matter  $\implies$  Physics beyond the SM

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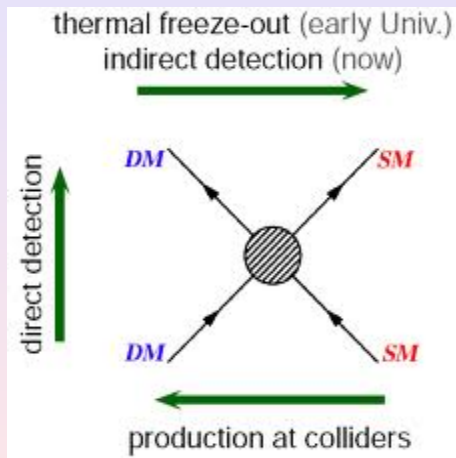
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- WIMP : Spin, Electroweak charge, Real or Complex, Majorana /Dirac ?  
We do not know !!!
- WIMPs interact with SM particles with EW strength, which is much stronger than gravitational interactions

See lectures by J. Ellis and P. Gondolo in this meeting

## Detection of Dark Matter



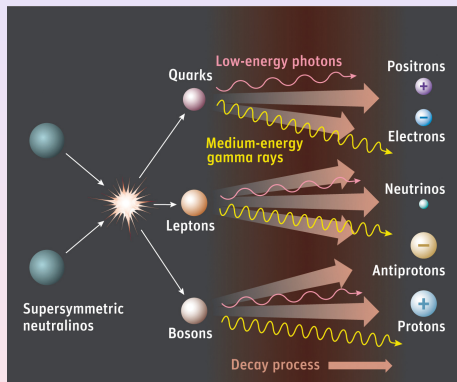
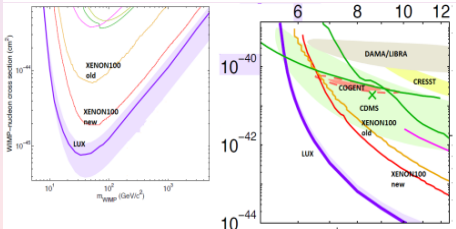
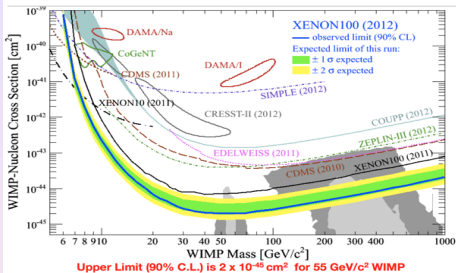


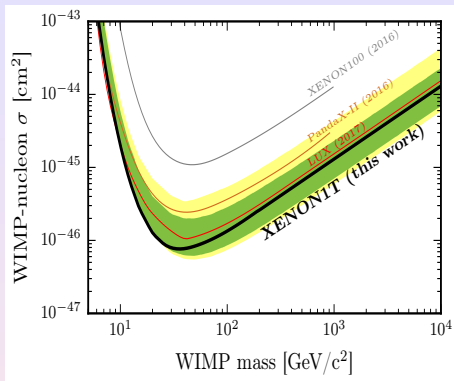
# Detection of Dark Matter

- 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

## XENON100: New Spin-Independent Results





- WIMP-nucleon interaction cross section : with a minimum of  $7.7 \times 10^{-47}$  cm<sup>2</sup> for a WIMP mass of 35 GeV/c<sup>2</sup> WIMPs at 90% confidence level.

[Ref: E. Aprile et al (XENON Collaboration), arXiv:1705.06655v2]

## Possible WIMP candidates

- All most all the physics beyond the standard model predicts a WIMP
- 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

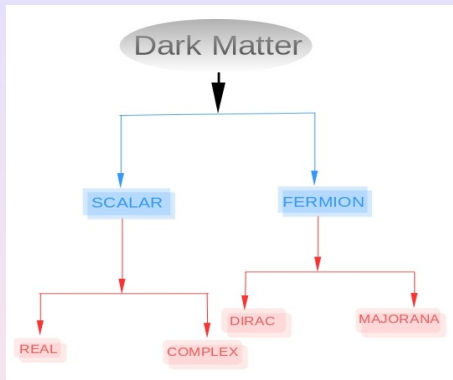
One needs a theory of DM interactions to interpret :

- the cross-section limits obtained from the LHC searches on  $\cancel{E}_T$  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 ( $\chi$ ) + SM ( No other new particles in the spectrum )
- Interactions of DM with SM particles are governed by the underlying gauge symmetry.

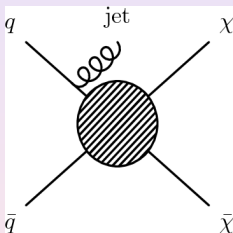
## Assumptions of EFT of Dark Matter interactions

- Additional symmetry is needed to make DM stable :  $\chi$  is odd under  $Z_2$ , while all SM fields are even  $\implies$  stable WIMP & at colliders WIMPs are pair produced
- WIMP is singlet under the SM gauge groups  $\implies$  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  $\Lambda$ . Processes with higher powers of  $\Lambda$  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:
- $\mathcal{L}_{\text{EFT}} = \frac{1}{M_*^2} (\bar{q}q)(\bar{\chi}\chi)$ . Here, the interactions between the fermionic DM particle  $\chi$  and quark  $q$  is communicated via a heavy scalar field, which has been integrated out  $\implies$  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  $E \ll M_*$
- 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  $P$ ):

$$\mathcal{L} \supset g_{\text{DM}}^S (\bar{\chi}\chi) S + g_{\text{SM}}^S \sum_q \frac{m_q}{v} (\bar{q}q) S + ig_{\text{DM}}^P (\bar{\chi}\gamma_5\chi) P + ig_{\text{SM}}^P \sum_q \frac{m_q}{v} (\bar{q}\gamma_5 q) P$$

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

$$\mathcal{O}_S^q = \frac{m_q}{\Lambda_S^3} (\bar{\chi}\chi) (\bar{q}q), \quad \mathcal{O}_P^q = \frac{m_q}{\Lambda_P^3} (\bar{\chi}\gamma_5\chi) (\bar{q}\gamma_5 q)$$

- where, the suppression scale  $\Lambda$  is related to mediator mass  $M_{S/P}$  and fundamental couplings  $g_{\text{SM}}^S$  and  $g_{\text{DM}}^S$  by  $\Lambda_S = \left( \frac{v M_S^2}{g_{\text{SM}}^S g_{\text{DM}}^S} \right)^{1/3}$ , for pseudoscalar interactions:  $S \rightarrow P$
- For vector mediator,  $\Lambda_V = \frac{M_V}{\sqrt{g_{\text{SM}}^V g_{\text{DM}}^V}}$

## Higher dimensional operators for Dirac Dark Matter

Label	Operator	Usual coefficients	Dimension
$\mathcal{O}_{D1}$	$\bar{\chi}\chi\bar{q}q$	$m_q/M_*^3$	6
$\mathcal{O}_{D2}$	$\bar{\chi}i\gamma_5\chi\bar{q}q$	$m_q/M_*^3$	6
$\mathcal{O}_{D3}$	$\bar{\chi}\chi\bar{q}i\gamma_5q$	$m_q/M_*^3$	6
$\mathcal{O}_{D4}$	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5q$	$m_q/M_*^3$	6
$\mathcal{O}_{D5}$	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	6
$\mathcal{O}_{D6}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	6
$\mathcal{O}_{D7}$	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5q$	$1/M_*^2$	6
$\mathcal{O}_{D8}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5q$	$1/M_*^2$	6
$\mathcal{O}_{D9}$	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$	6
$\mathcal{O}_{D10}$	$\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$	6
$\mathcal{O}_{D11}$	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/4M_*^3$	7
$\mathcal{O}_{D12}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_S/4M_*^3$	7
$\mathcal{O}_{D13}$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/4M_*^3$	7
$\mathcal{O}_{D14}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_S/4M_*^3$	7

# Higher dimensional operators for Majorana Dark Matter

$\mathcal{O}_{M1}$	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$	6
$\mathcal{O}_{M2}$	$\bar{\chi}i\gamma_5\chi\bar{q}q$	$m_q/2M_*^3$	6
$\mathcal{O}_{M3}$	$\bar{\chi}\chi\bar{q}i\gamma_5q$	$m_q/2M_*^3$	6
$\mathcal{O}_{M4}$	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5q$	$m_q/2M_*^3$	6
$\mathcal{O}_{M5}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$	6
$\mathcal{O}_{M6}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5q$	$1/2M_*^2$	6
$\mathcal{O}_{M7}$	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/8M_*^3$	7
$\mathcal{O}_{M8}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_S/8M_*^3$	7
$\mathcal{O}_{M9}$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/8M_*^3$	7
$\mathcal{O}_{M10}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_S/8M_*^3$	7

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

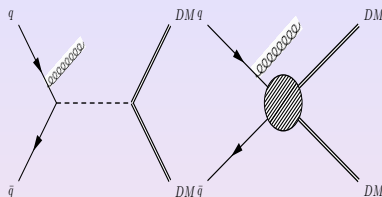
## Higher dimensional operators for Complex Scalar Dark Matter

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

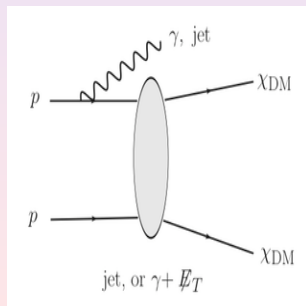
## Signature of DM at the LHC



- 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 ( $\chi$ )- quark ( $q$ ) contact interaction is set by the scale  $\Lambda$  or  $M_*$ , which is related to the mediator mass  $M$ , its couplings to quark ( $g_q$ ) and DM ( $g_\chi$ ) 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  $M_{DM} - \sigma_{SI}$  plane in model independent way

## DM searches at the LHC

- The production ( $pp \rightarrow \chi\chi$ ) of WIMPs at the LHC would give rise to large  $\cancel{E}_T \Rightarrow$  hard to observe at the detector
- Signal observation requires : At least a hard jet or a photon in association with this  $\cancel{E}_T$  : (a) **Mono-photon** :  $\gamma + \cancel{E}_T$  and (b) **Monojet** :  $\text{jet} + \cancel{E}_T$
- Both ATLAS & CMS have looked for a variety of  $\cancel{E}_T$  signatures involving hadronic jets,  $W^\pm$ ,  $Z$ ,  $\gamma$ ,  $t/b$ - quarks as well as the Higgs boson in the final state





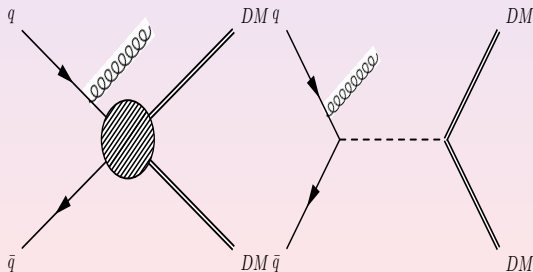
Another BIG question ?

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  $q\bar{q} \rightarrow \bar{\chi}\chi + \gamma(g)$  is

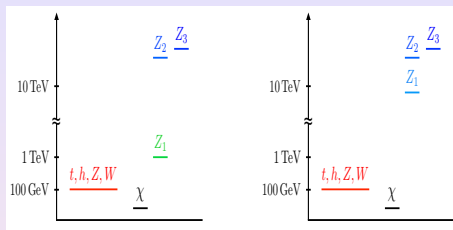
$$\frac{1}{Q_{\text{tr}}^2 - M_{\text{med}}^2} = -\frac{1}{M_{\text{med}}^2} \left( 1 + \frac{Q_{\text{tr}}^2}{M_{\text{med}}^2} + \mathcal{O}\left(\frac{Q_{\text{tr}}^4}{M_{\text{med}}^4}\right) \right)$$

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

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

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

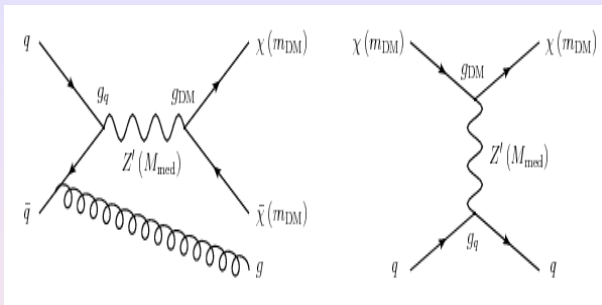
# Simplified model of DM interactions



- 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  $m_\chi$ ; mediator mass  $M_{\text{med}}$ , universal mediator coupling to quarks  $g_q$ ; and mediator coupling to DM  $g_\chi$

[Ref: J. Abdallah *et al.*, arXiv:1503.03116, O. Buchmuller *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



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

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

- The coupling  $g_q$  is assumed to be universal to all quarks
- Parameters :  $g_q, g_\chi, m_\chi, M_{\text{med}}$  controls the DM interactions with SM particles  $\implies$  LHC searches and direct detections
- At low energies ( $E \ll M_{\text{med}}$ ) heavy mediator  $Z'_\mu$  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  $\frac{1}{M_*^2} = \frac{g_q g_\chi}{M_{\text{med}}^2}$

## CMS study of jet + $\cancel{E}_T$ channel at $\sqrt{s} = 8$ TeV

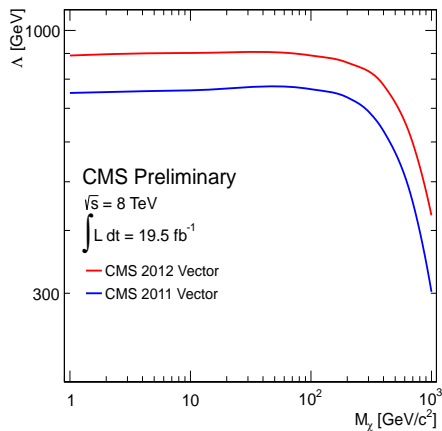
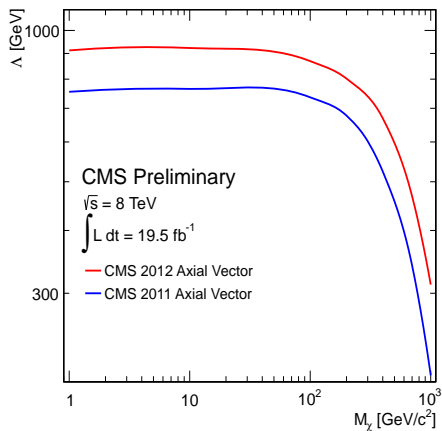
- CMS looked for **jets +  $\cancel{E}_T$**  signature at  $\sqrt{s} = 8$  TeV run at integrated luminosity of  $19.7 \text{ fb}^{-1}$
- DM - quark interactions are parametrised using EFT technique
- DM ( $\chi$ )- quark ( $q$ ) contact interaction is set by the scale  $\Lambda$ , which is related to the mediator mass  $M$ , its couplings to quark ( $g_q$ ) and DM ( $g_\chi$ ) 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  $\sigma_{\text{SI}}$
- $A$  interaction can be related to  $\sigma_{\text{SD}}$
- Simplified model with  $s$ -channel mediator with vector interactions also considered
- Mass of the mediator  $M_{\text{med}}$  varied for two values  $m_\chi = 50 \text{ GeV}$  and  $500 \text{ GeV}$
- $\Gamma_V = M_V/8\pi$  and  $M_V/3$



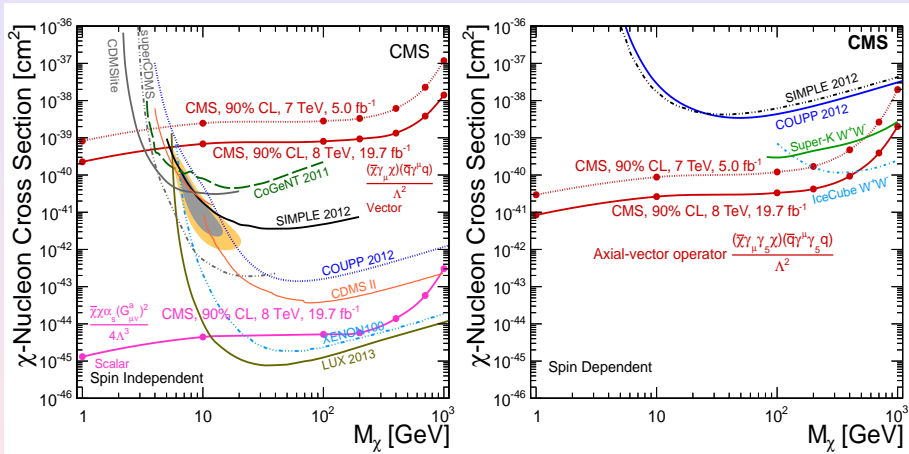
- The main SM backgrounds :  $Z + \text{jets}$ ,  $W + \text{jets}$ ,  $t\bar{t}$
- Basic cuts :  $\cancel{E}_T > 120 \text{ GeV}$ ,  $p_T^j > 80 \text{ GeV}$ ,  $|\eta_j| < 2.6$
- Analysis is performed in 7 regions of  $\cancel{E}_T > 250 - 550 \text{ GeV}$  (in step of 50 GeV),  $p_T^j(j_1) > 110 \text{ GeV}$ ,  $|\eta_j| < 2.4$
- Events with  $N_j > 2$  with  $p_T^j > 30 \text{ GeV}$  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

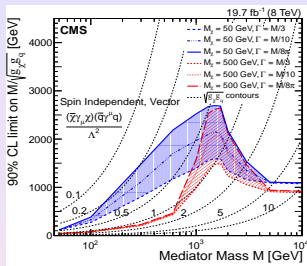


# Lower limits at 90% CL on $\sigma_{\chi-N}^{\text{SI}} - m_\chi$ and $\sigma_{\chi-N}^{\text{SD}} - m_\chi$ plane



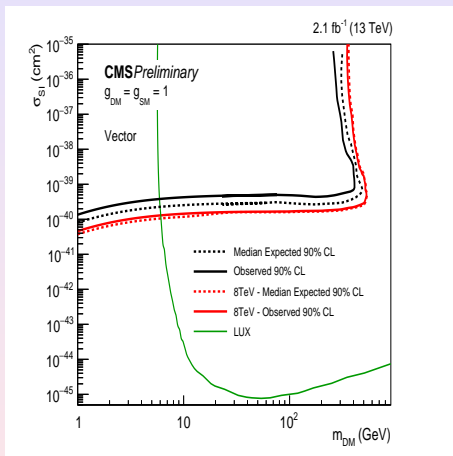
[Ref. V. Khachatryan *et al.*, CMS Collaboration, EPJC 75 (2015), CMS PAS EXO-15-003]

## Lower limits at 90% CL on simplified model parameter space



- $\Lambda \equiv M/\sqrt{g_q g_\chi}$
- Very large  $M (\geq 5 \text{ TeV})$  limits on  $\Lambda \Rightarrow$  EFT frame work
- For  $2m_\chi \ll M \leq 5 \text{ TeV} \Rightarrow$  resonant enhancement leads to a significant improvement in the limit. Mediator is produced on shell
- Strongest enhancement is possible when  $\Gamma$  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  $q\bar{q}$
- For 13 TeV study, simplified model (vector like interactions with  $g_q = g_\chi = 1$ ) considered

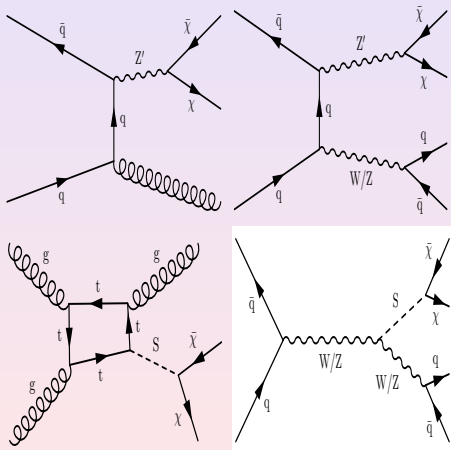
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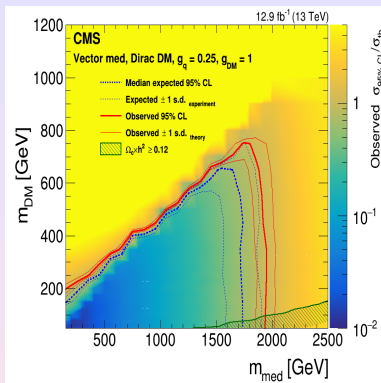
[Ref. V. Khachatryan *et al.*, CMS Collaboration, EPJC 75 (2015), CMS PAS EXO-15-003]

# CMS study of DM with an energetic jet or $W/Z \rightarrow jj$ channel at 13 TeV run

(arXiv:1703.01651v1)

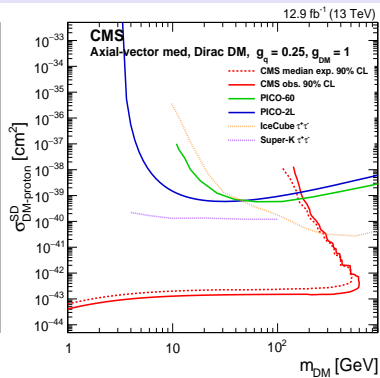
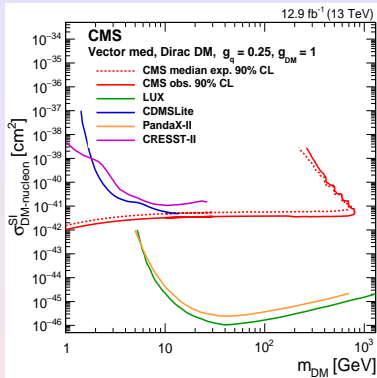


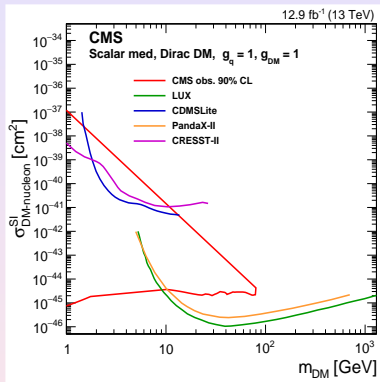
- CMS has studied following two scenarios :
  - DM pair with a ISR jets;
  - DM particles may also be produced in association with  $W/Z$ , the *mono-V* signature
- The data sample correspond to  $12.9 \text{ fb}^{-1}$
- The hadronic decay of a  $W$  or  $Z$  reconstructed as a single large radius jet
- If the  $V$  boson has  $p_T > 250 \text{ GeV}$ , its hadronic decays more likely to be reconstructed as a single fat jet
- Mono-V events are selected with  $E_T^{\text{miss}} > 250 \text{ GeV}$ , leading jet  $p_T > 250 \text{ GeV}$  and  $|\eta| < 2.4$
- $65 < M_{JJ} < 105 \text{ GeV}$
- For DM + ISR jet sample :  $E_T^{\text{miss}} > 200 \text{ GeV}$ , leading jet  $p_T > 100 \text{ GeV}$  and  $|\eta| < 2.5$
- Results are interpreted using simplified DM models; where the interaction between the DM and SM particle is mediated by a spin-1 particle such as a  $Z'$  or a spin -0 particle ( $S$ )



- Exclusion contours in  $m_{\text{med}} - m_{\text{DM}}$  plane for vector mediator
- Mediator masses up to 1.95 TeV and DM masses up to 750 GeV is excluded at 95% CL

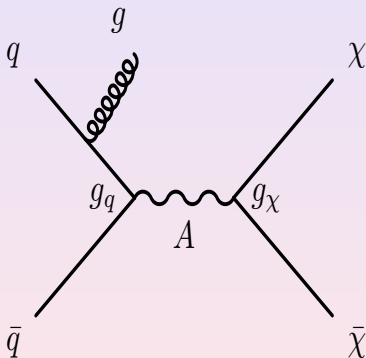






# ATLAS study of the mono-jet signature of DM at 13 TeV run with $3.2 \text{ fb}^{-1}$ data

(arXiv:1604.07773)



[Ref: ATLAS Collaboration, PRD 94, 032005 (2016)]

- Simplified DM model is considered
- $s$ -channel exchange of a spin-1 mediator particle with axial-vector couplings is considered
- spin-1 mediator connects quarks to WIMPs (Dirac type) : leptophobic  $Z'$ -like model
- parameters : WIMP mass  $m_\chi$ , mediator mass  $m_A$ , the coupling of the mediator to WIMPs ( $g_\chi$ ) and the flavour universal couplings to quarks ( $g_q$ )
- Width of the mediator :

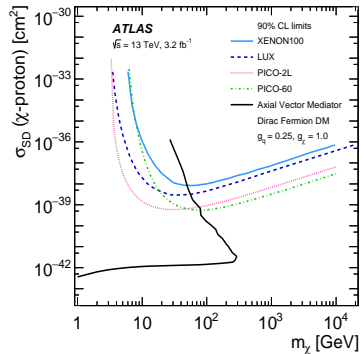
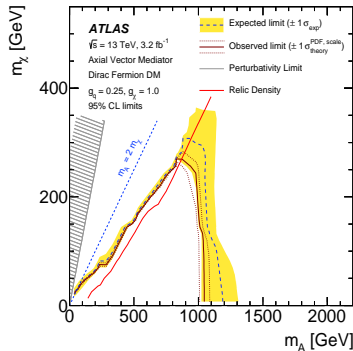
$$\Gamma_{\min} = \frac{g_\chi^2 m_A}{12\pi} \beta_\chi^3 \theta(m_A - 2m_\chi) + \sum_q \frac{3g_q^2 m_A}{12\pi} \beta_q^3 \theta(m_A - 2m_q) \quad (3)$$

- Set  $g_\chi = 1$  and  $g_q = 1/4 \implies$  narrow width  $\Gamma_{\min}/m_A \sim 5\%$
- $m_\chi \sim 1 \text{ GeV} - 1 \text{ TeV}$
- $m_A \sim 10 \text{ GeV} - 2 \text{ TeV}$

Signal events are selected by :

- $E_T^{\text{miss}} > 250 \text{ GeV}$  to  $E_T^{\text{miss}} > 750 \text{ GeV}$
- leading jet  $p_T > 250 \text{ GeV}$  with  $|\eta| < 2.4$
- maximum four jets with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 2.8$  are allowed
- $\Delta\phi(j, p_T^{\text{miss}}) > 0.4$
- events with  $\mu(p_T > 10 \text{ GeV})$  and  $e(p_T > 20 \text{ GeV})$  are rejected

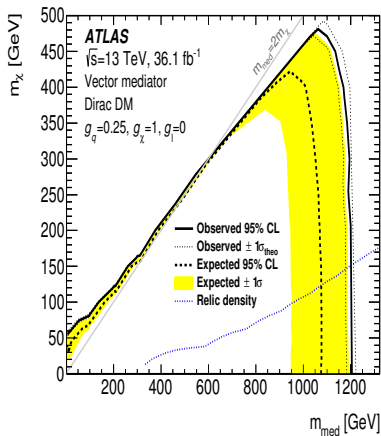
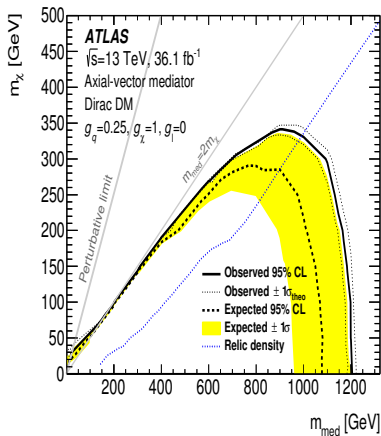
# Lower limits at 90% CL on $\sigma_{\chi-N}^{\text{SI}}$ and $\sigma_{\chi-N}^{\text{SD}}$ as a function of WIMP mass ( $m_\chi$ )



## ATLAS study of $\gamma + \cancel{E}_T$ channel at $\sqrt{s} = 13$ TeV

- $\gamma + \cancel{E}_T$  process studied using  $36.1\text{fb}^{-1}$  data
- Events are selected based on
  - 1  $\cancel{E}_T > 150 - 300$  GeV
  - 2  $p_T^\gamma > 150$  GeV
  - 3  $|\eta| < 1.37$
  - 4  $\Delta\phi(\gamma, \cancel{E}_T) > 0.4$
  - 5 Events with more than one jet or with a jet with  $\Delta\phi(\text{jet}, \cancel{E}_T) < 0.4$  are rejected
- Two scenarios are considered to interpret the results in the context of DM:
  - 1 Dirac DM produced via  $s$ -channel mediator with vector (V1) or axial-vector (A1) interactions
  - 2 **Four parameters** :  $m_\chi, m_{\text{med}}, g_q, g_\chi$
  - 3 for both model scenarios :  $g_q = 0.25, g_\chi = 1$

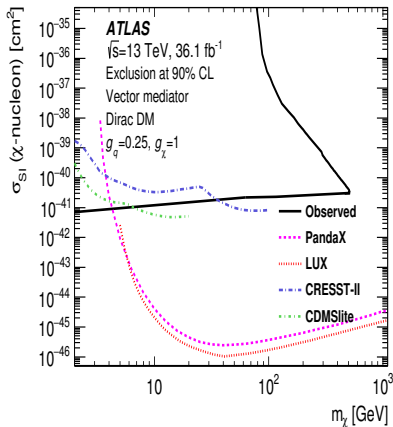
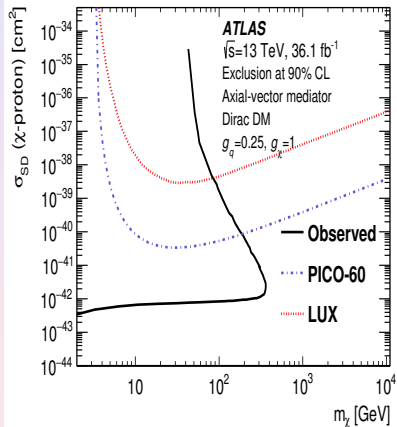
[Ref: ATLAS Collaboration, arXiv: 1704.03848]



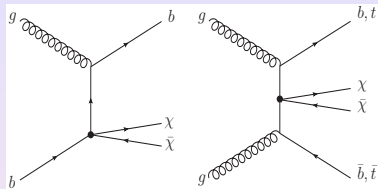
- for both A1 & V1 , 95% CL limit on  $m_{\text{med}}$  is 1200 GeV for low  $m_\chi$
- 95% CL limit on  $m_\chi$  is 340 (480) GeV for A1(V1)



# ATLAS lower limits at 90% CL on $\sigma_{\text{SI}}$ and $\sigma_{\text{SD}}$ as a function of WIMP mass ( $m_\chi$ ) ( $\gamma + \cancel{E}_T$ )



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



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

$$\mathcal{O}_S^Q = \frac{m_Q}{M_*^3} (\bar{\chi}\chi) \bar{Q}Q; \quad \mathcal{O}_P^Q = \frac{m_Q}{M_*^3} (\bar{\chi}\gamma_5\chi) \bar{Q}\gamma_5Q; \quad (Q = t, b)$$

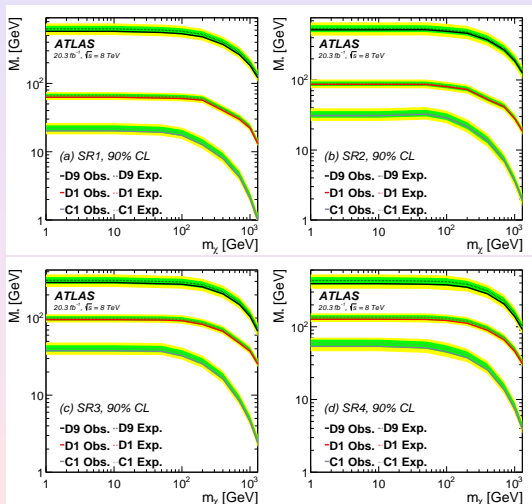
- ATLAS collaboration has looked into this channel. They have also considered Tensor operator in addition to  $\mathcal{O}_S, \mathcal{O}_P$ .  $\mathcal{O}_T = \frac{1}{M_*^2} \bar{\chi}\sigma^{\mu\nu}\chi \bar{Q}\sigma_{\mu\nu}Q$

[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), Bhattacharjee *et al.*, arXiv:1212.5013]

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

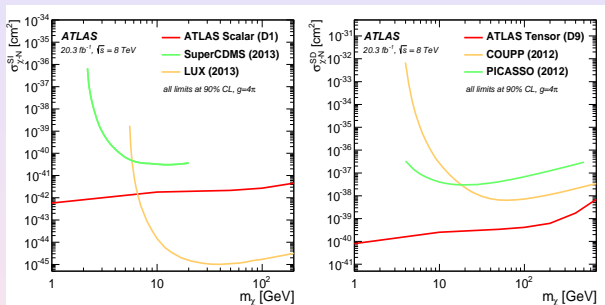
- Two types of signals are studied :
  - $pp \rightarrow \bar{\chi}\chi + \bar{b}b$ ; **SR1** & **SR2**
  - $pp \rightarrow \bar{\chi}\chi + t\bar{t}$ ; **SR3** & **SR4**
- **SR1** : DM produced in association with one  $b$ -quark in the final state
- **SR2**: DM produced in association with two  $b$ -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 $m_\chi$ 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 $\sigma_{\chi-N}^{\text{SI}}$ and $\sigma_{\chi-N}^{\text{SD}}$ as function of $m_\chi$ for D1 and D9 operators (arXiv:1410.4031)

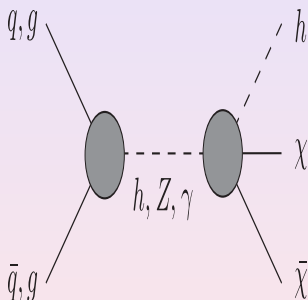


- Limits are strong for low mass region
- The couplings is assumed to be  $g_q g_\chi = g = 4\pi$
- The sensitivity for D1 operator is approximately  $\sigma_{\chi-N}^{\text{SI}} = 10^{-42} \text{cm}^2$  for  $m_\chi = 10 \text{ GeV}$ .

## ATLAS study of DM in association with a Higgs ( $\rightarrow b\bar{b}$ ) (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  $20.3 \text{ fb}^{-1}$  data
- Signal :  $b\bar{b} + \cancel{E}_T$
- 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 :  $2\text{HDM} + Z'$

## Set of EFT operators studied by ATLAS:



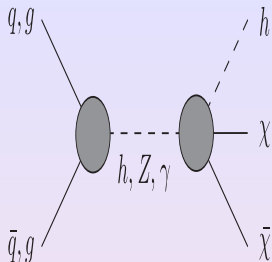
$$\lambda |\chi|^2 |H|^2 \quad (S, D = 4)$$

$$\frac{1}{M_*} \bar{\chi} i \gamma_5 \chi |H|^2 \quad (F, D = 5)$$

$$\frac{1}{M_*^2} \chi^\dagger \partial^\mu \chi H^\dagger D_\mu H \quad (S, D = 6)$$

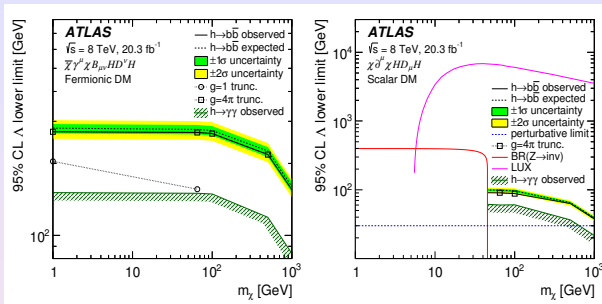
$$\frac{1}{M_*^4} \bar{\chi} \gamma^\mu \chi B_{\mu\nu} H^\dagger D^\nu H \quad (F, D = 8)$$

- $\chi$  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  $m_\chi$ , the coupling  $\lambda$  and the suppression scale  $M_*$



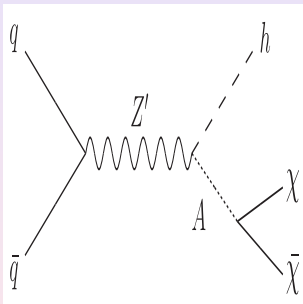
- $\chi$  is the DM,  $h$  is the 125 GeV observed Higgs boson
- the left dark circle denotes the coupling from  $q\bar{q}$  or  $gg$  to  $h, Z, \gamma$  that mediates the  $DM + h$  production
- the right dark circle represents the contact interaction in EFT framework between DM, the Higgs and the mediator
- Mediator can be a spin 1 heavy gauge boson
- signal :  $b\bar{b} + \cancel{E}_T$
- 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 :  $h(\rightarrow b\bar{b}) + \cancel{E}_T$  : regions below the line is excluded
- The solid green line with hash marks indicates regions excluded by collider searches for  $h(\rightarrow \gamma\gamma) + \cancel{E}_T$
- On right figure, the regions below the dashed blue line fails the perturbativity requirement
- red line indicates regions excluded by the limits on the  $\text{Br}(Z \rightarrow \nu\bar{\nu})$
- the magenta line indicates regions excluded by the LUX Collaboration

## Simplified model ( $Z'$ – 2HDM) interpretation

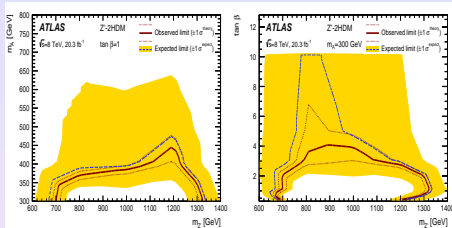


- $Z'$  gauge boson with 2HDM where the DM particle is coupled to the heavy pseudoscalar Higgs boson  $A$
- the  $Z'$  is produced resonantly
- $Z' \rightarrow h + A$  in a Type 2 two-Higgs-doublet model
- $h$  is the observed Higgs boson, and  $A$  has a large BR to DM pair
- $Z' \rightarrow Z + h$  also possible, followed by  $Z \rightarrow \nu\nu \implies$  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  $\rho_0$  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  $\sigma$  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  $b \rightarrow s\gamma$  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  $A \rightarrow \bar{\chi}\chi$ ,  $m_{Z'} = 700 - 1300$  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) ( $\chi$ )
- 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]]

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

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{\lambda_v}{4}(V_\mu V^\mu)^2 + \frac{\lambda_{hVV}}{4}V_\mu V^\mu |H|^2 \quad (5)$$

$$\Delta\mathcal{L}_F = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{\lambda_{hff}}{4\Lambda} |H|^2 \bar{\chi}\chi \quad (6)$$

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

$$M_s^2 = m_s^2 + \frac{1}{2}\lambda_{hss}v^2 \quad (7)$$

$$M_V^2 = m_v^2 + \frac{1}{2}\lambda_{hVV}v^2 \quad (8)$$

$$M_F = m_f + \frac{1}{2\Lambda}\lambda_{hff}v^2 \quad (9)$$

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

$$\Gamma(H \rightarrow ss) = \frac{\lambda_{hss}^2 v^2 \beta_s}{128\pi M_H} \quad (10)$$

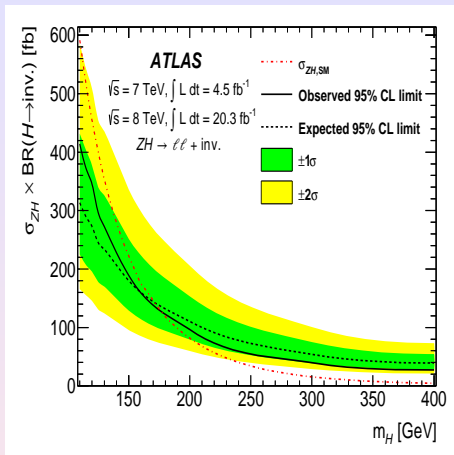
$$\Gamma(H \rightarrow \bar{\chi}\chi) = \frac{\lambda_{hff}^2 v^2 \beta_f^3 M_H}{\Lambda^2 64\pi} \quad (11)$$

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

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

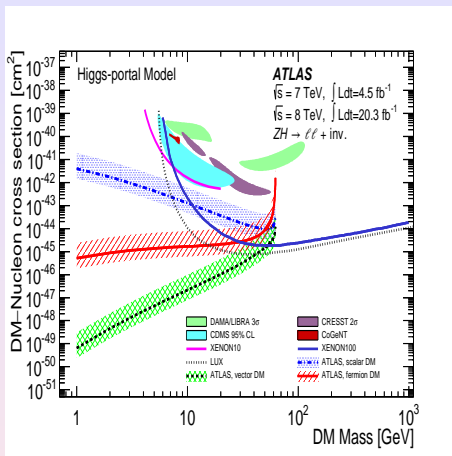
- AT colliders this would lead to invisible decay of the SM Higgs boson. Both ATLAS & CMS have studied this channel. For  $M_s \leq 10$  GeV, the collider limits are stronger than the SI results.

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



- $pp \rightarrow ZH$  with  $H \rightarrow ss$  give rise  $\ell\ell + \cancel{E}_T$  signal
- 95% CL upper limits on  $\sigma_{ZH} \times \text{BR}(H \rightarrow \text{inv.})$  in the mass range  $110 < M_H < 400 \text{ GeV}$  for the combined 7 & 8 TeV data





- $$\sigma_{S-N}^{SI} = \frac{\lambda_{hss}^2}{16\pi M_H^4} \frac{M_N^4 f_N^2}{(M_s + M_N)^2}$$

- Limits on the DM-nucleon scattering cross section at 90% CL

## Summary

- Different astrophysical observations  $\implies$  DM exists
- WIMPs are good candidate for the cold dark matter
- WIMPs require physics beyond the SM
- The existence of WIMPs can be tested in direct detection, indirect detection experiments
- WIMPs can also leave its footprint at colliders as large  $\cancel{E}_T$  signature, but it is very difficult to confirm
- jets +  $\cancel{E}_T$  and  $\gamma + \cancel{E}_T$  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  $E \ll M_{\text{med}}$
- 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 ( $m_\chi \leq 10 \text{ GeV}$ ) collider limits are stronger than direct detection limits

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 ( $\text{cm}^2$ ):

$$\sigma^{D1} = 1.60 \times 10^{-37} \left( \frac{\mu_\chi}{1\text{GeV}} \right) \left( \frac{20\text{GeV}}{M_*} \right)^6 \quad (13)$$

$$\sigma^{D5,C3} = 1.38 \times 10^{-37} \left( \frac{\mu_\chi}{1\text{GeV}} \right) \left( \frac{300\text{GeV}}{M_*} \right)^4 \quad (14)$$

$$\sigma^{D8,D9} = 9.18 \times 10^{-40} \left( \frac{\mu_\chi}{1\text{GeV}} \right) \left( \frac{300\text{GeV}}{M_*} \right)^4 \quad (15)$$

## Implications for direct detection

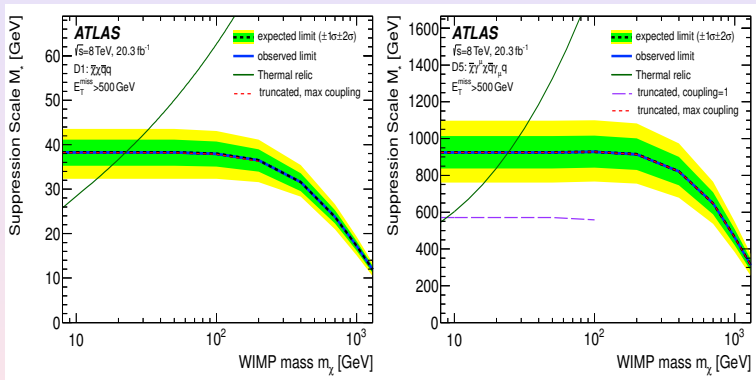
$$\sigma^{D11} = 3.83 \times 10^{-41} \left( \frac{\mu_\chi}{1\text{GeV}} \right) \left( \frac{100\text{GeV}}{M_*} \right)^6 \quad (16)$$

$$\sigma^{C1,R1} = 2.56 \times 10^{-36} \left( \frac{\mu_\chi}{1\text{GeV}} \right) \left( \frac{10\text{GeV}}{M_*} \right)^4 \left( \frac{10\text{GeV}}{m_\chi} \right)^2 \quad (17)$$

$$\sigma^{C5,R3} = 7.40 \times 10^{-39} \left( \frac{\mu_\chi}{1\text{GeV}} \right) \left( \frac{60\text{GeV}}{M_*} \right)^4 \left( \frac{10\text{GeV}}{m_\chi} \right)^2 \quad (18)$$

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

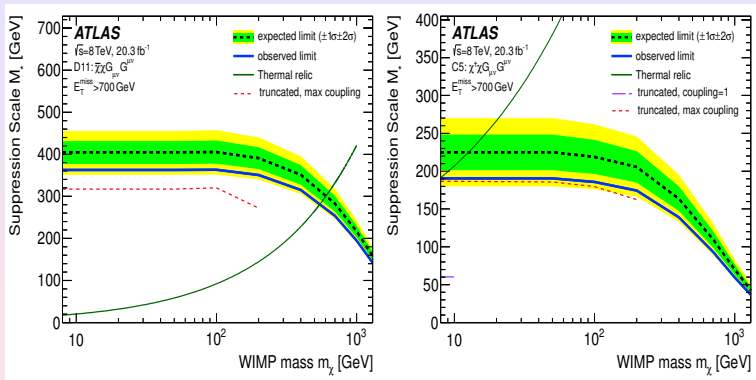
# Lower limits at 95% CL on $M_*$ as function of the WIMP mass $m_\chi$ for $D1$ & $D5$



[Ref: ATLAS Collaboration, arXiv:1502.01518 ]

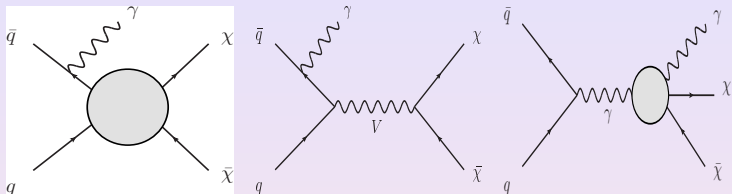


# Lower limits at 95% CL on $M_*$ as function of the WIMP mass $m_\chi$ for D11 & C5



[Ref: ATLAS Collaboration, arXiv:1502.01518 ]

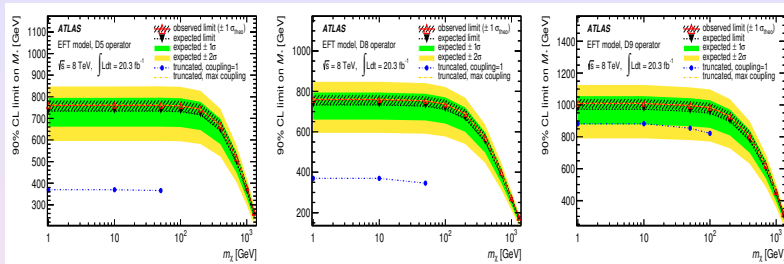
# ATLAS study of the mono-photon signature of DM (arXiv:1411.1559) at $\sqrt{s} = 8 \text{ TeV}$



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

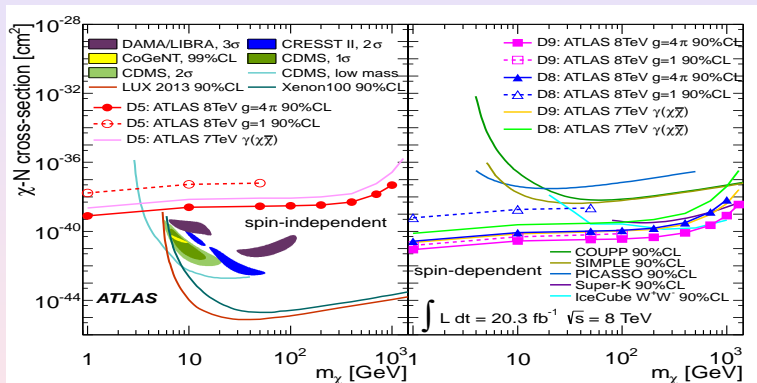
- $\gamma + \cancel{E}_T$  signal at  $\sqrt{s} = 8$  TeV with an integrated luminosity of  $20.3 \text{ fb}^{-1}$
- $Z(\rightarrow \nu\bar{\nu}) + \text{ISR } \gamma$  : the main SM background
- Secondary background come from  $W\gamma$  and  $Z\gamma$  with unidentified leptons,  $WZ$  production where leptons or a jet is misidentified as a photon
- Signal events are selected with these set of cuts:
  - $\cancel{E}_T > 150 \text{ GeV}$
  - $p_T^\gamma > 125 \text{ GeV}$
  - $|\eta| < 1.37$
  - $\Delta\phi(\gamma, \cancel{E}_T) > 0.4$
  - Events with more than one jet or with a jet with  $\Delta\phi(\text{jet}, \cancel{E}_T) < 0.4$  are rejected

## 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  $m_\chi$
- For unit coupling truncated case : For *D5* & *D8* : sample generated up to  $m_\chi = 50 \text{ GeV}$ , for *D9* : up to  $m_\chi = 100 \text{ GeV}$
- Lower limits on  $M_*$  now translated into upper limits on  $\sigma_{\chi-N}$  as a function of  $m_\chi$

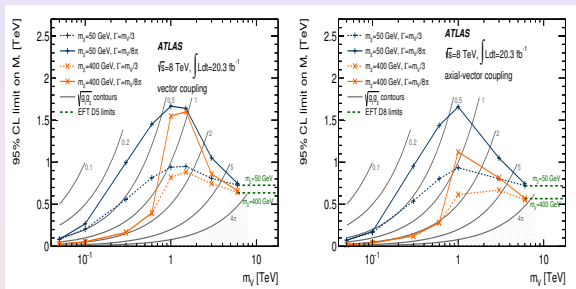
# Lower limits at 90% CL on $\sigma_{SI}$ and $\sigma_{SD}$ as a function of WIMP mass ( $m_\chi$ ) ( $\gamma + \cancel{E}_T$ )



[Ref: ATLAS Collaboration, arXiv:1411.1559]

## Result interpretation using simplified model

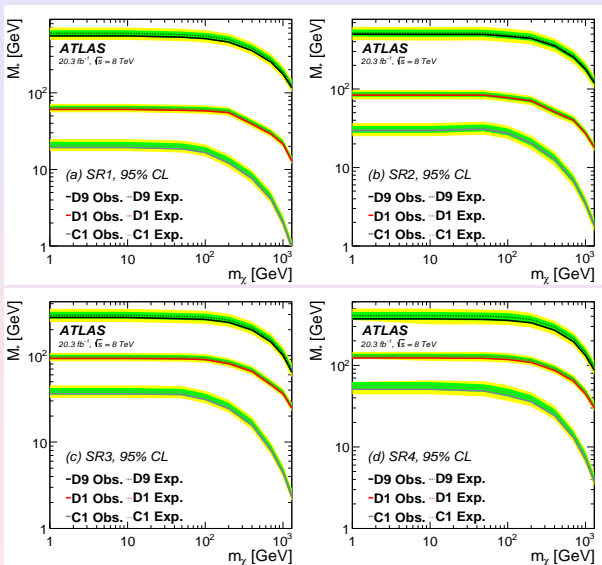
- For the simplified model :  $Z'$  model with vector & axial-vector interactions are considered



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

[Ref: ATLAS Collaboration, arXiv:1411.1559]

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



# Lower limits at 95% CL on $\sigma_{\chi N}$ as function of $m_\chi$ for $D1$ and $D9$ operators

arXiv:1410.4031

