Search for Dark Matter at the LHC with the ATLAS and CMS Detectors

Nicolò Trevisani

on behalf of the ATLAS and CMS collaborations

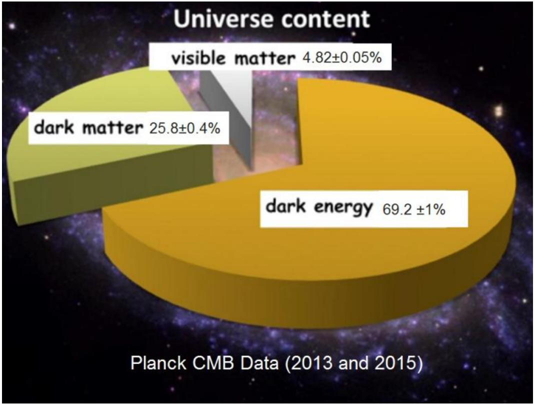
IFCA – Santander

July 9, 2018

Introduction

Dark matter is expected to compose about 25% of our Universe

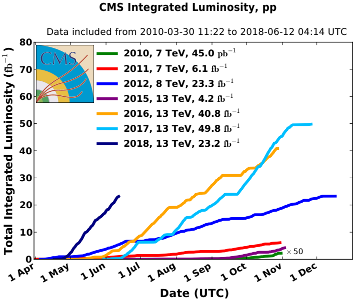
- Its particle nature is unknown and cannot be explained within Standard Model
- At a hadron collider have to assume interaction between Standard Model and Dark Matter candidate particles
- Main candidate: **Weakly Interacting Massive Particle**

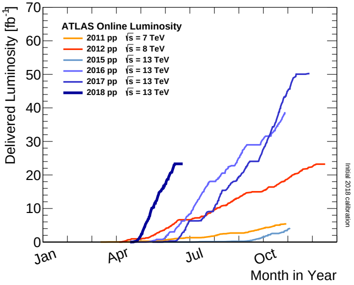


Search for Dark Matter at the LHC

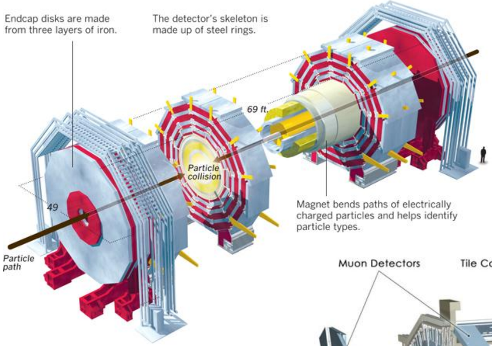
The LHC currently represents the **best machine** to produce high energy physics both for its **energy** and for its **luminosity**

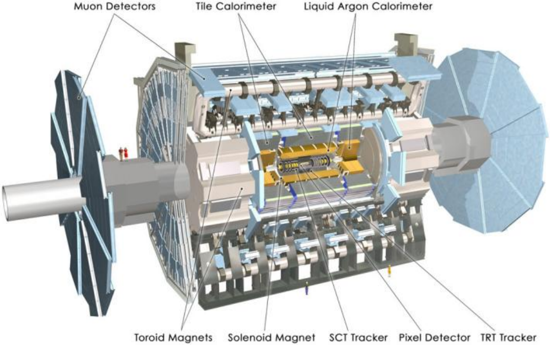
- Possibility to study heavy particles with low production cross sections
- Have to assume at least **weak interaction** between dark matter (DM) and standard model (SM) particles
- Two **multipurpose experiments** to (indirectly) detect dark matter





The ATLAS and CMS Experiments

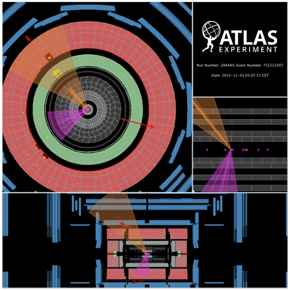


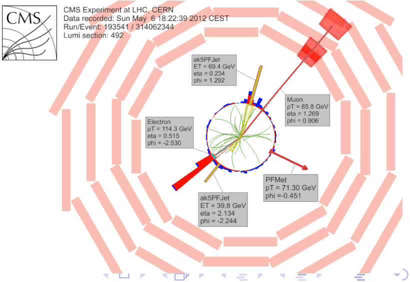


Key Variable: $\mathrm{p_T^{miss}}$

At the LHC the proton beams carry almost no transverse momentum

- The sum of all the final-state particles transverse momentum is expected to be 0
  - $\mathbf{p_T^{miss}} = - |\sum \vec{p}_T| = 0$
- Dark matter particles are not expected to interact with the detectors
  - In final states with dark matter particles, $\mathbf{p_T^{miss}} \neq \mathbf{0}$
- Events with non-null $\mathrm{p_T^{miss}}$ can arise from limited **detector resolution**, presence of **neutrinos** in final state, **non-collisional** background events, ...
  - Fundamental to have **control of the detector** to distinguish SM processes from new physics

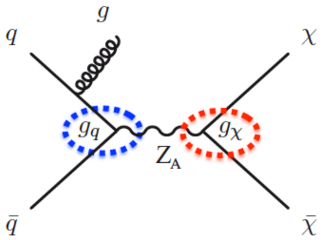




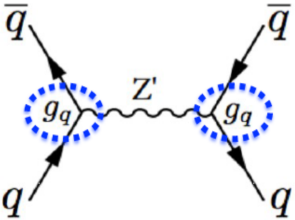
How to Hunt Dark Matter at the LHC

Since dark matter is not expected to interact in the detectors, two indirect approaches are used

- **Mono-X searches**
  - Dark matter particles are produced together with standard model particles
  - Look for an energetic SM particle recoiling against the invisible DM system
  - **p_T^{miss} + X signatures**



- **Mediator searches**
  - Dark matter mediators are produced and decay to pair of SM particles, typically quarks
  - Search for **bumps in the m_{jj} spectrum**

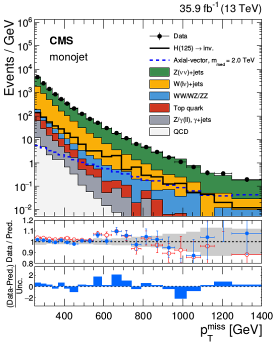


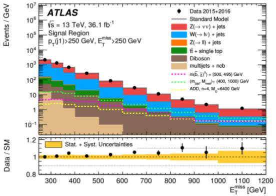
SUSY-like searches in which the DM particles χ can decay to SM particles are not covered in this talk

Mono-Jet

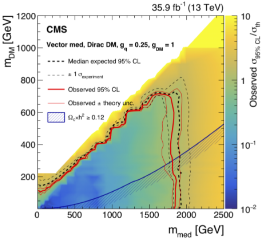
Currently the most sensitive DM search at LHC

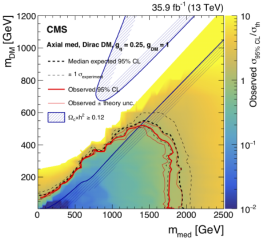
- References
  - CMS: **arXiv:1712.02345**
  - ATLAS: **arXiv:1711.03301**
- **Energetic jet recoiling against invisible system**
  - $p_T^{jet} > 100$ GeV (250 GeV for ATLAS)
  - $p_T^{miss} > 250$ GeV
- Main backgrounds
  - $Z \to \nu\nu$ + jets, $W \to \ell\nu$ + jets
  - Estimated with data in control regions
- Rsults extracted through fit to p_T^{miss} variable
  - Signal region and control regions fitted simultaneously
- Results interpreted in terms of **vector** mediator and **axial-vector** mediator

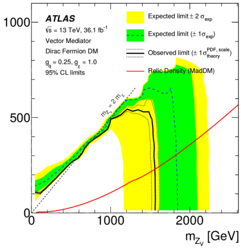


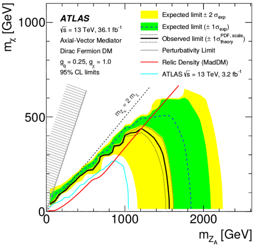


- Vector mediator exclusion (left)
  - m_{med}: 1800 GeV
  - m_{DM}: 700 GeV
- Axial-vector mediator exclusion (right)
  - m_{med}: 1600 GeV
  - m_{DM}: 500 GeV





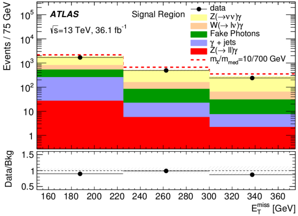


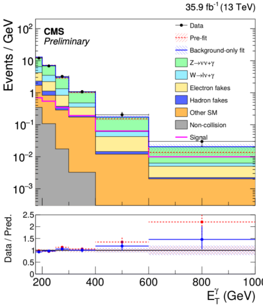


Mono-γ

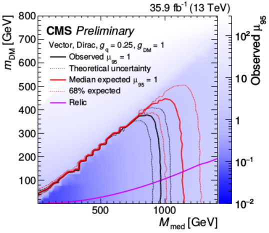
The analysis is similar to the mono-jet one, but the probability of producing a photon from ISR is smaller than the one to produce a gluon, making the analysis less sensitive

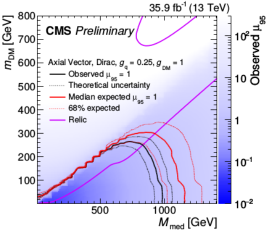
- References
  - CMS: **arXiv:1706.03794v2**
  - ATLAS: **arXiv:1704.03848v2**
- **Energetic photon recoiling against invisible system**
  - $p_T^\gamma > 150$ GeV (175 GeV for CMS)
  - CMS: $p_T^{miss} > 170$ GeV
  - ATLAS: $\frac{p_T^{miss}}{\sqrt{\sum E_T}} > 8.5\ \text{GeV}^{1/2}$
- Main backgrounds
  - $Z \to \nu\nu + \gamma$, $W \to \ell\nu + \gamma$
  - Electrons faking photons in the detectors
- Results interpreted in terms of **vector** mediator and **axial-vector** mediator

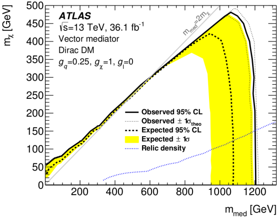


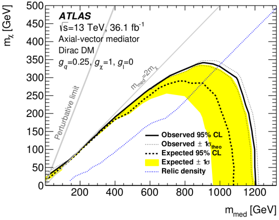


- Vector mediator exclusion (left)
  - m_{med}: 1200 GeV
  - m_{DM}: 500 GeV
- Axial-vector mediator exclusion (right)
  - m_{med}: 1200 GeV
  - m_{DM}: 350 GeV





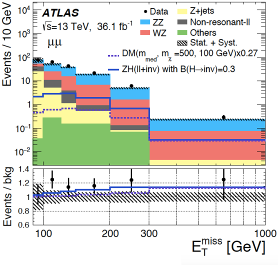


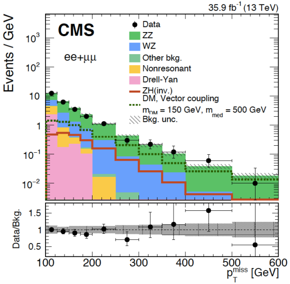


Mono-Z

The production of a Z boson decaying leptonically is easily tagged by **invariant mass** requirings

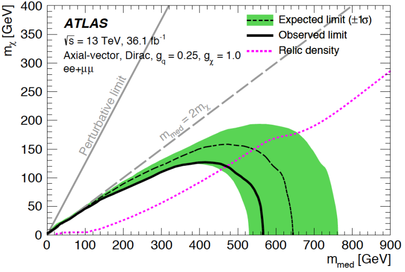
- References
  - CMS: **arXiv:1711.00431v2**
  - ATLAS: **arXiv:1708.09624v2**
- Two same flavour leptons compatible with the decay of a Z boson and large p_T^{miss}
  - 76 GeV $< m_{\ell\ell} <$ 106 GeV
  - $p_T^{miss} > 90$ GeV (100 GeV for CMS)
- Main backgrounds
  - ZZ$\rightarrow \ell\ell\nu\nu$, WZ$\rightarrow \ell\nu\ell\ell$, WW$\rightarrow \ell\nu\ell\nu$, top, Z + jets
- Results interpreted in terms of
  - CMS: **vector** mediator and **axial-vector** mediator
  - ATLAS: **axial-vector** mediator

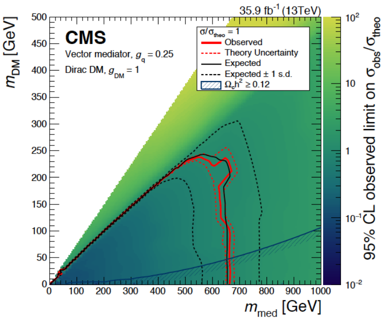


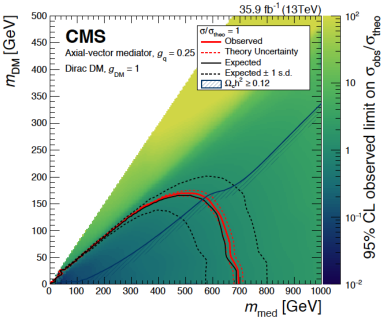


Mono-Z - Interpretations

- Vector mediator exclusion (left, CMS-only)
  - m_{med}: 680 GeV
  - m_{DM}: 250 GeV
- Axial-vector mediator exclusion (right)
  - m_{med}: 700 GeV
  - m_{DM}: 150 GeV



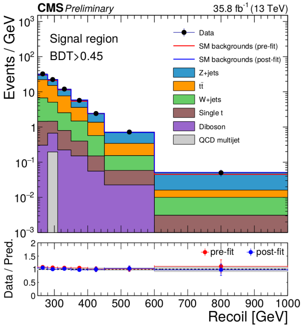


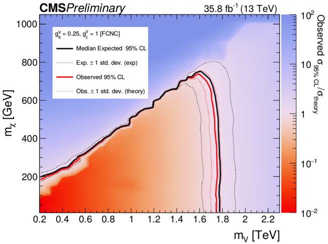


Mono-Top

CMS inspected also the final state with only one top quark and p_T^{miss}

- Only the hadronic decay of the top quark studied
  - CMS: **arXiv:1801.08427**
- Highly boosted top quark recoiling against DM
  - One single jet with $p_T > 250$ GeV and mass compatible with a top quark
  - $p_T^{miss} > 250$ GeV
  - Dedicated BDT to separate top quark from gluons and lighter quarks
- Main backgrounds: Z+jets, W+jets, and ttbar
- Signal extracted with fit to p_T^{miss} variable
- Results interpreted in terms of FCNC vector boson

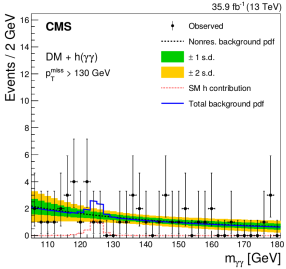




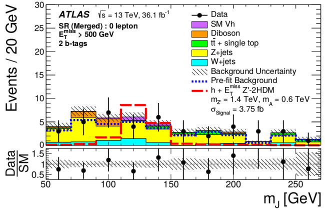
The ISR of a Higgs boson is strongly suppressed $\rightarrow$ possible to directly inspect the interaction between DM mediator and Higgs boson

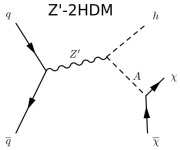
- Different Higgs decay channel studied
  - CMS: $\mathbf{h} \rightarrow \mathbf{bb}$, $\mathbf{h} \rightarrow \tau\tau$ + $\mathbf{h} \rightarrow \gamma\gamma$
  - ATLAS: $\mathbf{h} \rightarrow \mathbf{bb}$, $\mathbf{h} \rightarrow \gamma\gamma$
- Typical analysis strategy
  - **Tag the Higgs boson** through invariant mass requirements
  - Ask for **considerable $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$**
- Results interpreted in terms of
  - h$\rightarrow$ bb: **Z'-2HDM** model (for CMS also **Z'-Baryonic**)
  - h$\rightarrow \tau\tau$, h$\rightarrow \gamma\gamma$: **Z'-2HDM** model and **Z'-Baryonic** model

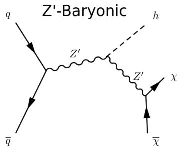
[arXiv:1806.04771]



[arXiv:1707.01302]





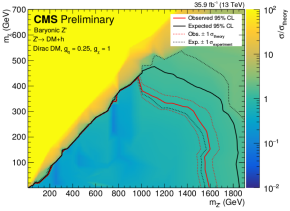


Mono-Higgs - Interpretations

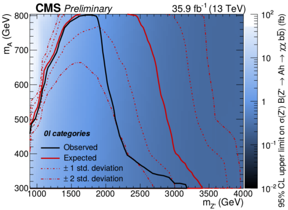
For Z'-Baryonic model slightly different value of quarks-mediator coupling (ATLAS $g_q = 1/3$, CMS $g_q = 0.25$)

- Z'-Baryonic Model exclusion (left)
  - m_{med}: 1600 GeV
  - m_{DM}: 400 GeV
- Z'-2HDM Model exclusion (right)
  - m_{med}: 3200 GeV
  - m_{DM}: 800 GeV

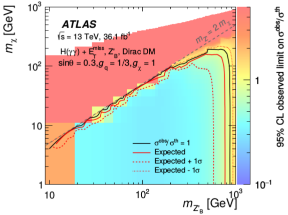
[CMS-PAS-EXO-16-050]



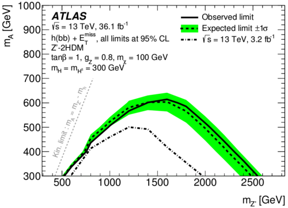
[CMS-B2G-17-004]



[arXiv:1706.03948]



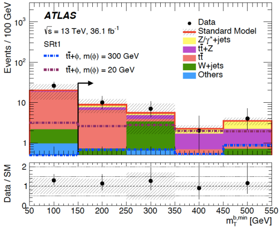
[arXiv:1707.0102]

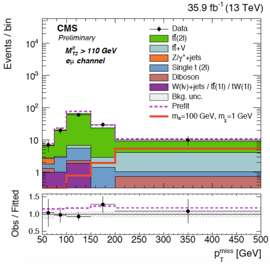


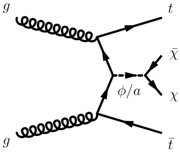
ttbar + DM

This search assumes a Yukawa coupling between a scalar or pseudoscalar DM mediator and SM particles
$\rightarrow$ a signature with top quarks takes advantage from the **large coupling**

- Final states with 0, 1 or 2 leptons studied
  - ATLAS: **arXiv:1710.11412v2, arXiv:1711.115120**
  - CMS: **inspireHep:1665757**
- Typical analysis strategy
  - Require the presence of **b-jets** or **top-tagged** events
  - Ask for **considerable p_T^{miss}**
- Main background: SM ttbar production



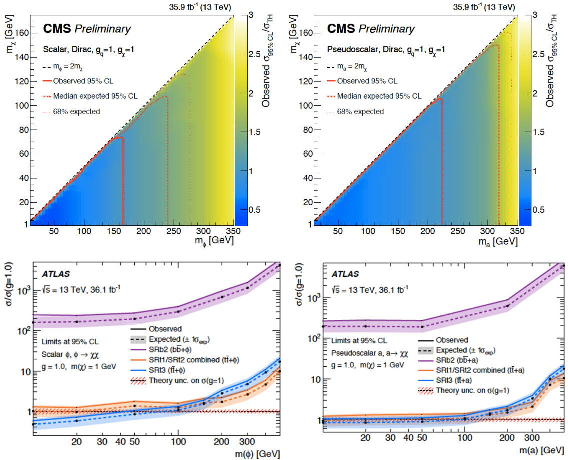




ttbar + DM - Interpretations

ATLAS results shown here do not include semi-leptonic top decay channel. ATLAS Fully hadronic and dileptonic channels are not shown combined together.

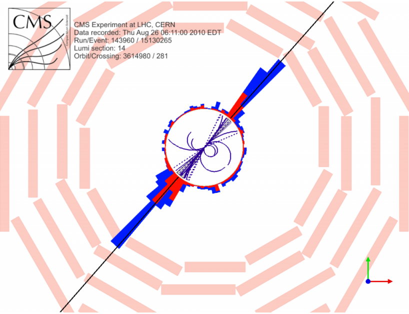
- Scalar mediator exclusion (left)
  - m_{med}: 165 GeV
  - m_{DM}: 75 GeV
- Pseudo-scalar exclusion (right)
  - m_{med}: 220 GeV
  - m_{DM}: 105 GeV

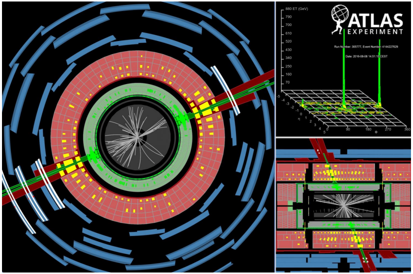


Di-Jet Searches

The LHC is also an excellent machine to look for dark matter resonances decaying to **pairs of quarks**

- Abundant production of events with two jets in the final state at LHC
- QCD predicts monotonically falling spectrum for m_{jj}
  - **Look for bumps** due to new resonances
- In SM jets are preferentially produced in the forward direction
  - Look for more **isotropic signatures**

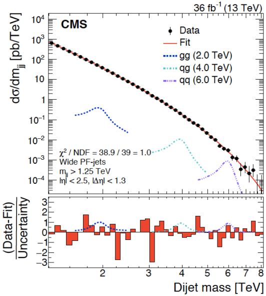


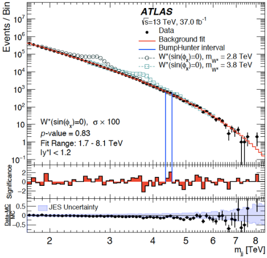


Di-Jet

The search of heavy resonances decaying to a pair of quarks is the most straightforward way to look for dark matter in this final state

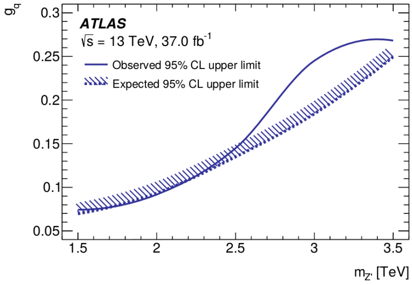
- References
  - ATLAS: **arXiv:1703.09127v1**
  - CMS: **arXiv:1806.00843v1**
- Typical analysis strategy
  - Select event with two reconstructed jets
  - Fit the m_{jj} distribution with a smooth function
  - Look for excesses in the distribution
- This approach is sensitive to very heavy mediators
  - $m_{med} > 1$ TeV
- Sensitivity to **low-mass mediators limited** by trigger bandwidth
  - Need to require high p_T^{jet} thresholds

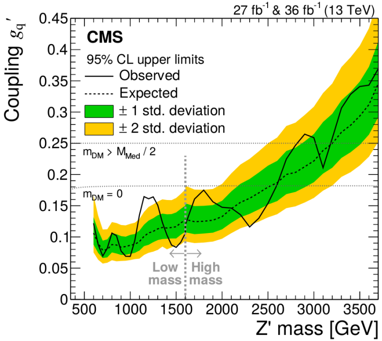




The results are **interpreted** in terms of **coupling** between the dark matter mediator and the SM quarks

- ATLAS: For mediator mass of 1.5 TeV couplings larger than 0.08 are excluded
- CMS: For mediator masses of 1.6 TeV couplings larger than 0.12 are excluded

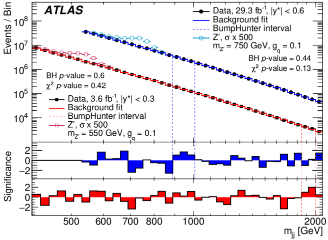


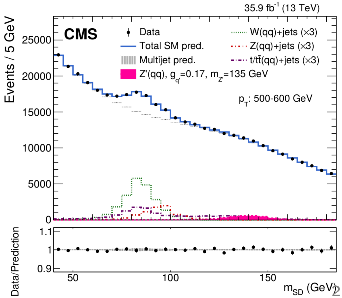


Low-Mass Di-Jet

To recover the inefficiencies at low mediator masses mainly due to trigger different approaches have been implemented

- **Use only limited** relevant **information at trigger level** to enhance the rate of data acquisition
  - ATLAS: **arXiv:1804.03496v1**
  - CMS: **arXiv:1806.00843v1**
- Require the **jets pair to recoil** against an ISR jet
  - The jets pair is highly boosted and events with lower m_{jj} can pass the trigger thresholds
  - CMS: **arXiv:1710.00159v2**
- Sensitivity recovered to low-mass resonances
  - Trigger level analysis: $m_{jj} > 450$ GeV
  - ISR-recoil analysis: $50 \text{ GeV} < m_{jj} < 300 \text{ GeV}$

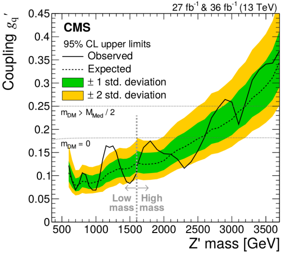


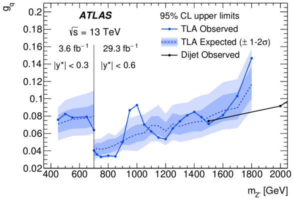


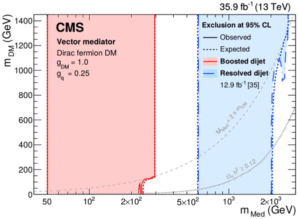
Low-Mass Di-Jet - Interpretations

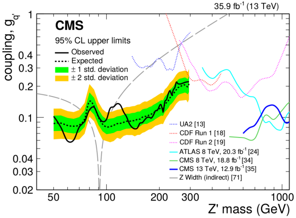
The results are interpreted in terms of coupling between the dark matter mediator and the SM quarks or resonances invariant mass

- ATLAS: Couplings down to 0.03 excluded for $m_{med} = 800$ GeV
- CMS: Couplings down to 0.06 excluded for $m_{med} = 60$ GeV
- CMS: Resonances with masses between 50 GeV and 300 GeV excluded





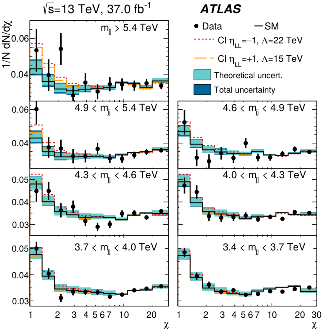


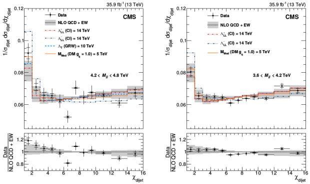


Di-Jet χ Searches

An alternative search for dark matter in the di-jet channel exploits the angular distribution of the quarks in the final state

- Particularly effective in case of **wide resonances** or non-resonant searches
  - ATLAS: **arXiv:1703.09127v1**
  - CMS: **arXiv:1803.08030v1**
- Named after the χ angular distribution
  - $\chi = e^{|y_1 - y_2|}$
- χ distribution categorized in $m_{\ell\ell}$ bins to enhance sensitivity
- Presence of new physiscs would show up as an **excess** of events at **low** χ values

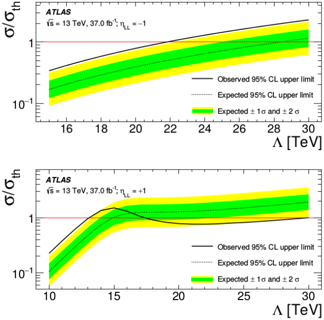


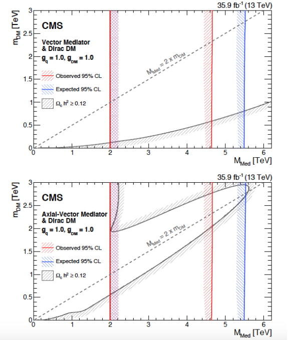


Di-Jet χ - Interpretations

The results are **interpreted** in different frameworks by the two experiments

- CMS: Limits are put on the **invariant mass** of vector or axial-vector DM mediators considering a coupling with quarks $g_q = 1$
  - Resonances with mass between 2 TeV and 4.6 TeV are ruled out
- ATLAS: **Contact interactions** characterized by a single energy scale Λ are considered
  - Values of Λ up to 21 TeV in case of constructive interference with QCD, and up to 13 TeV in case of destructive interference with QCD are excluded



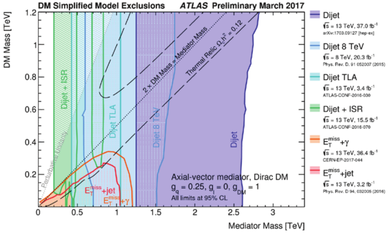


Putting Everything Together

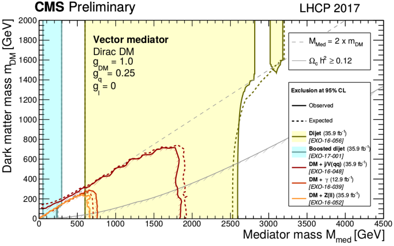
Putting all the **results** of the different searches **together**

- Exclusion mainly **driven by di-jet** analyses
  - Sensitivity recovered by dedicated low-mass searches
- Coupling of the mediator with leptons (g_ℓ) set to 0
- References:
  - ATLAS: **ATL-PHYS-PROC-2017-133**
  - CMS: **DM Summary Plots 2017**

ATLAS - Axial-vector mediator



CMS - Vector mediator

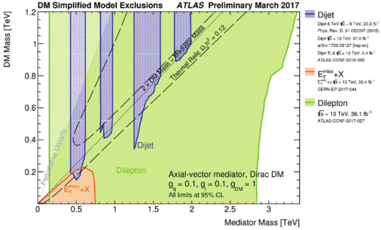


Putting Everything Together - Introducing Lepton Coupling

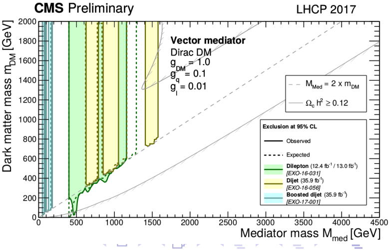
Introducing a non-zero coupling of the DM mediator with leptons the di-jet searches loose importance in favour of **di-lepton analyses**

- In this case different values of g_ℓ for ATLAS and CMS
  - ATLAS: $g_\ell = 0.1$
  - CMS: $g_\ell = 0.01$
- Quark-mediator coupling g_q lowered from 0.25 to 0.1
- References:
  - ATLAS: **ATL-PHYS-PROC-2017-133**
  - CMS: **DM Summary Plots 2017**

ATLAS - Axial-vector mediator



CMS - Vector mediator

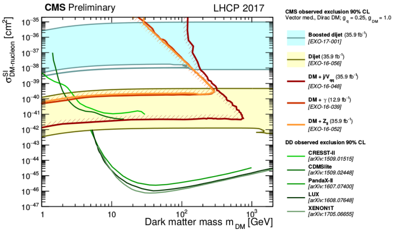


Direct Detection Reinterpretation

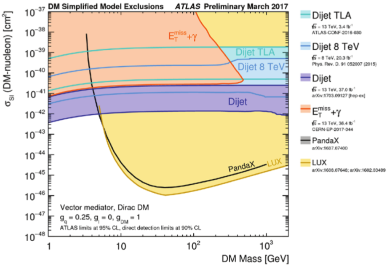
The results are further re-interpreted in terms of DM-nucleon scattering

- Allows comparison with direct detection experiments
- Separated results present for spin-dependent (σ^{SD}) and spin-independent interaction (σ^{SI})
- Need to fix couplings
  - $g_q = 0.25$, $g_{\mathrm{DM}} = 1.0$, $g_\ell = 0$

CMS - σ^{SI} Results



ATLAS - σ^{SI} Results

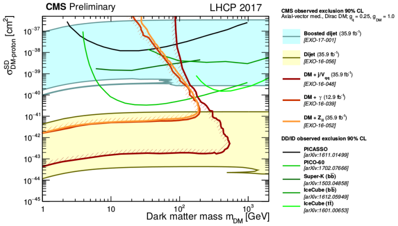


Direct Detection Reinterpretation (2)

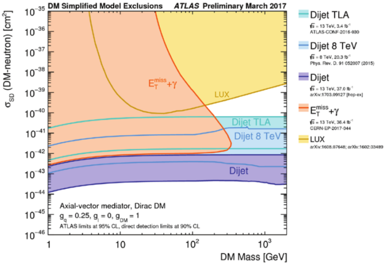
The results are further re-interpreted in terms of DM-nucleon scattering

- Allows comparison with direct detection experiments
- Separated results present for spin-dependent (σ^{SD}) and spin-independent interaction (σ^{SI})
- Need to fix couplings
  - $\mathrm{g_q} = 0.25$, $\mathrm{g_{DM}} = 1.0$, $\mathrm{g_\ell} = 0$

CMS - σ^{SD} Results



ATLAS - σ^{SD} Results



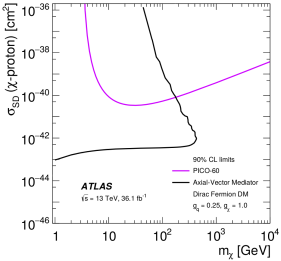
Conclusions

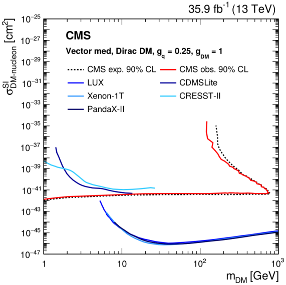
The searches for **dark matter** performed with the **ATLAS and CMS** detectors have been presented

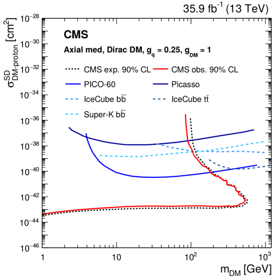
- **Signatures** inspected
  - Production of dark matter **in association** with SM particles
  - Production of SM particles from decay of dark matter **mediators**
- **No** significant **discrepancies with SM** predictions observed
- Results are **interpreted**
  - As limits on DM mediators or stable particles **masses**
  - As limits on simplified models **parameters**
  - As limits on DM-nuclei interaction **cross sections**
- Large part of the results exploits 2016 dataset ($\sim 36\ \mathrm{fb}^{-1}$)
  - Much **higher statistics** from 2017 and 2018 data taking

The results are further re-interpreted to produce comparisons with direct detection experiments results

- Spin-independent scattering (left)
  - From vector results
  - Cross-sections larger than 10^{-42} cm^2 excluded
- Spin-dependent scattering (right)
  - From axial-vector results
  - Cross-sections larger than 10^{-43} cm^2 excluded



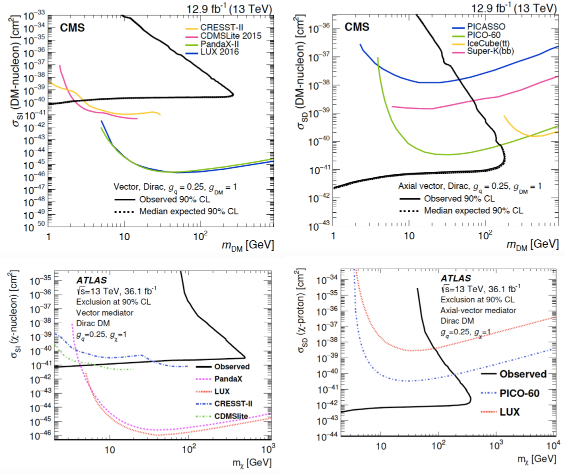




Mono-γ - Direct Detection Re-Interpretation

The results are further re-interpreted to produce comparisons with direct detection experiments results

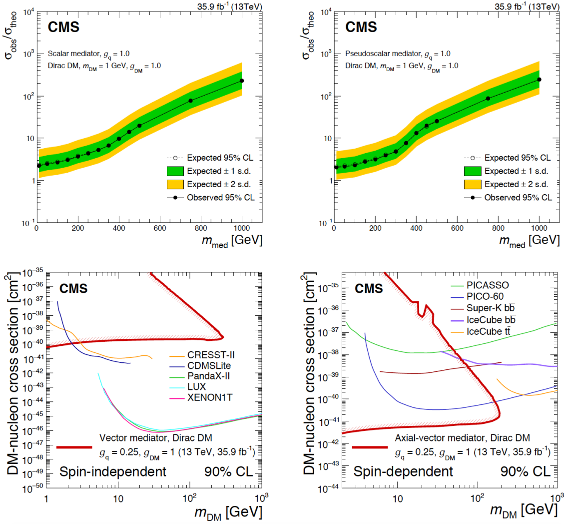
- Spin-independent scattering (left)
  - From vector results
  - Cross-sections larger than 10^{-41} cm^2 excluded
- Spin-dependent scattering (right)
  - From axial-vector results
  - Cross-sections larger than 10^{-43} cm^2 excluded



Mono-Z - Additional Interpretations from CMS

CMS interpreted the results also in terms of scalar or pseudo-scalar mediators, and in terms of DM-necleus scattering cross-section

- No sensitivity to scalr or pseudo-scalar mediators (top)
- Spin-independent scattering (bottom-left)
  - σ^{SI} larger than 10^{-40} cm^2 excluded
- Spin-dependent scattering (bottom-right)
  - σ^{SI} larger than 10^{-41} cm^2 excluded

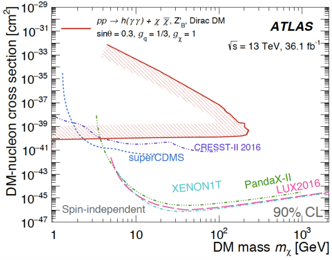


Mono-Higgs - Direct Detection Re-Interpretations

For Z'-Baryonic model, the $\gamma\gamma$ and $\tau\tau$ results have been re-interpreted in the framework of direct-detection experiments

- Spin-independent interactions with nuclei are considered
  - Cross-sections larger than 10^{-41} cm^2 are excluded

[arXiv.1706.03948]



arXiv:1806.04771]