Run II searches for dark matter at the LHC with the CMS experiment at $\sqrt{s} = 13$ TeV

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Interpreting the LHC Run 2 Data and Beyond

- May 28th, 2019 -

Outline

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- Hunt strategies
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  - Mono-top
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  - Dijet light resonances
  - Dijet angular searches
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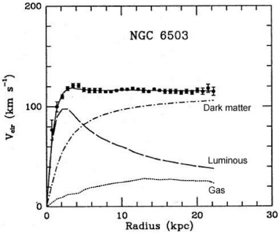
- COmparation of the previous results
- Conclusions

Different **astronomical observations** lead to the birth of the dark matter hypothesis, such as:

- Apparent **gravitational anomalies** and difference between dynamic and luminous mass of the galaxies
- Anisotropies of the **CMB** (DM contributes to the gravitational collapse of matter, but is unaffected by the pressure from photons)
- **Large scale structures** of the Universe



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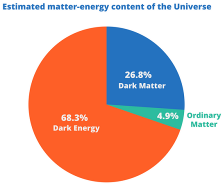
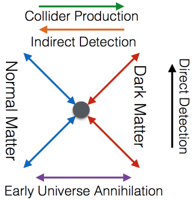


We now know/assume that:

- It accounts for $\sim$**25% of the total content** of the Universe
- Its nature cannot be explained by the Standard Model, **extensions** are needed
- Dark matter candidates are usually cold and only interact **weakly and gravitationally**
- The **WIMPS** (Weakly Interacting Massive Particles) are considered the best dark matter candidate in this talk

DM in particle accelerators

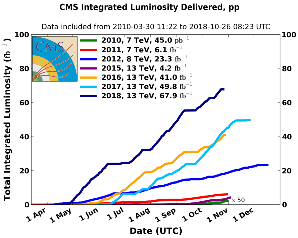


Dark matter can be produced within particle accelerators **if**:

- The dark matter **mass** is low enough
- Its production **cross section** is large enough
- Dark and ordinary matter interact at least weakly with each other

The LHC is able to probe energies higher than ever with huge luminosities:

- Largest dataset to date to analyze at 13 TeV
- Perfect tool to try and detect DM particles
- Able to study a large range of particle **masses and cross-sections**
- The two multipurpose detectors (CMS, ATLAS) are mostly able to search for DM particles

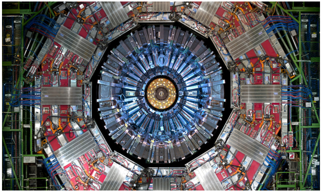


→ However, if producing dark matter particles is theoretically possible, detecting them directly is impossible, as they are **not expected to interact** with our detector.

The CMS detector

The Compact Muon Solenoid is one of the two polyvalent detectors of the LHC, designed to:

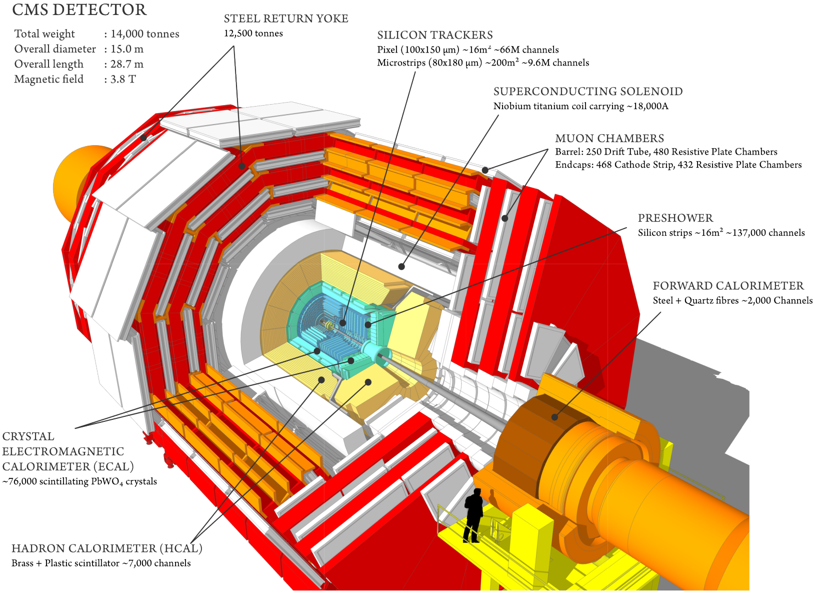
- Make precision measurements
- Search for the Higgs boson
- Search for new exotic processes



CMS in a nutshell

- **Powerful tracker and muon detection system** to measure the properties of the leptons in a large range of energies.
- **Huge solenoid** as central piece able to produce a 3.8T magnetic field, to curve the charged particles and study their properties.
- Made of **different layers** (such as the tracker, the calorimeters and the muon chambers), each having its own purpose, resulting in a **great particle identification** and **precise momentum determination**.
- A **trigger system** is used to select only interesting events out of the 600 million collisions per second produced (current bandwidth $\sim$ 1kHz).

The CMS detector



How to detect DM?

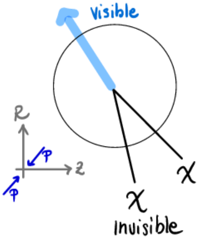
The CMS detector is not able to **directly detect** eventual dark matter particles. However, we can rely on visible particles to detect eventual invisible particles.

The key variable to detect DM is the missing transverse energy (MET):

- Defined as the *imbalance in transverse momentum in the plane perpendicular to the beam direction*

$$p_T^{\text{miss}} = -|\sum \overrightarrow{p_T}| = 0$$

- This quantity is $\neq 0$ if something escapes the detector undetected (eg: neutrinos, DM)



Most of the DM searches are therefore dependant on this variable, as they rely on high p_T^{miss} values recoiling against visible objects (such as jets, leptons, photons,...).

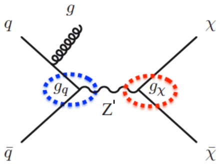
However, a $p_T^{\text{miss}} \neq 0$ does not mean that we discovered new physics, as **common processes** can have the same effect:

- Neutrino production
- Limited detector resolution

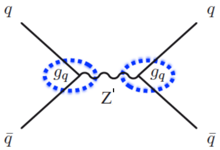
$\rightarrow$ A **good understanding** of the detector is therefore crucial to make a distinction, especially at high p_T^{miss} values!

Different strategies are usually used to search for DM in the LHC:

- **Mono-X/p_T^{miss}+X searches**:
  Search for DM in association with a SM particle, used to **trigger the event** (jet, lepton, photon) and recoiling against the invisible DM system
  - p_T^{miss}+X in the final state
  - $\Delta\phi(DM, X) \simeq \pi$
  - Mono-jet, mono-γ, mono-Z,... analyses
  - Searching for global excesses in the MET spectrum



- **Multi-object/Mediator searches**:
  Initial and final state made out of SM particles, but a DM mediator appeared in the way
  - Can probe the dark interaction even if DM is inaccessible
  - Can look for both invisible and visible decays of the mediator
  - Search for **resonances and bumps** in known spectrum, such as the dijet invariant mass

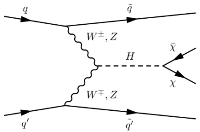


(Main) hunt strategies at the LHC

- **Higgs portal**:

  In this case the DM is produced as a result of the decay of a Higgs boson

  - The SM decay of the Higgs to invisible (4ν) is possible but unlikely ($BR \sim 0.1\%$)
  - Several Higgs production modes can be studied



- **SUSY-like searches**:

  These searches focus mostly on models in which the DM decays to SM particles, but SUSY also provides a DM candidate (such as the lightest supersymmetric particle)

  - This subject will not be covered in this talk either

- **Long-lived searches**:

  Relatelively new searches when one of the particles is able to travel for a short distance before decaying

  - Only makes sense if a SM particle that can be detected is produced in the decay as well
  - The DM can either decay rapidly to SM particles after traveling for some distance, or a long lived partner can be produced with DM
  - This subject will not be covered in this talk either

The ATLAS-CMS Dark Matter Forum for the Run2 searches was held in 2016 and resulted in the publication of a paper in arXiv, **defining the signal models that should be studied** by the analyzers.

Main objectives of this report:

- Channel the efforts of the CMS and ATLAS collaborations
- Define the highest priority analyses that should be conducted
- Define the simplified models and EFTs to be used for the Run2 searches
  - DM is supposed to be a **Dirac fermion** (choice Dirac/Majorana is only expected to produce minor changes in the kinematics)
  - Simulate a set of **prioritized set of operators and parameters** with distinct kinematics for the interpretation of the results, based on the Run1 results

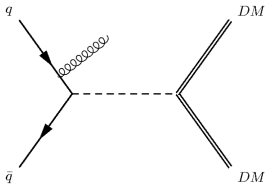
As a result, the mass of the mediator and DM particles along with their spins and couplings g_q and g_χ are defined and usually considered as the **free parameters of all the models considered**, and common for both ATLAS and CMS.

Mono-X searches

Mono-jet/Mono-V (CMS-EXO-16-048)

Results published in 2018 with 35.9 fb^{-1} of data in ▸ Phys. Review D, **several interpretations** considered (simplified DM, fermion portal, non-thermal dark matter models,...)

Simple signature: at least one energetic jet (ISR - monojet - or from a W/Z boson decay -monoV-) **recoiling against an invisible high p_T^{miss} system**:



- Main backgrounds:
  - Z($\nu\nu$)+jets (60%, irreducible)
  - W($l\nu$)+jets (30%)
  - QCD multijet background with mismeasurements of the jet momenta
- Signal extraction performed using the distribution of the p_T imbalance in each event category defined

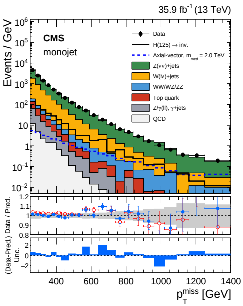
Main improvement since the previous publications: larger dataset, revised theoretical predictions and uncertainties for some processes (γ+jets, Z+jets, W+jets). processes

Mono-jet/Mono-V (CMS-EXO-16-048)

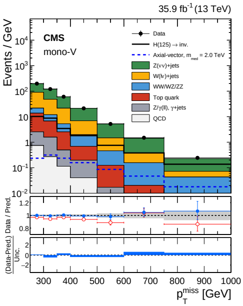
A binned likelihood fit to the data is performed on the p_T^{miss} spectrum in 5 mutually exclusive control regions (dimuon, dielectron, single muon, single electron, γ + jets, and on the signal region. Transfer factors then link the yields from the CR to the SR of different backgrounds.

- Main selection applied depends on the model
  - Mono-jet: jet $p_T > 100$ GeV
  - Mono-V: jet ($p_T > 250$ GeV) from hadronic decays of Lorentz-boosted W or Z boson
  - But both look for large p_T^{miss}/jet separation and at high p_T^{miss} values (> 250 GeV)
  - A lepton/b-tag veto is applied to reduce the backgrounds

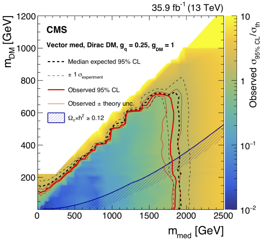
Mono-jet



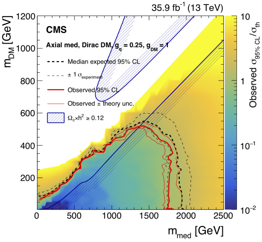
Mono-V



Vector mediator

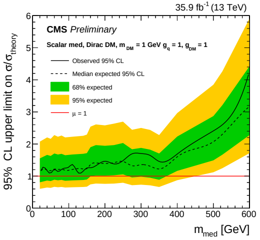


Axial-vector mediator

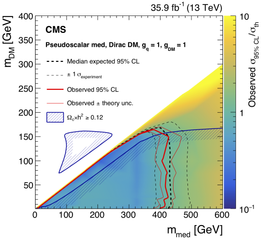


- Upper limits are computed at 95% CL on the ratio of the measured signal cross section to the predicted one
- Vector (axial-vector) mediators excluded up to $\sim$ 1.9 (1.7) TeV
- DM excluded up to $\sim$ 750 (500) GeV

Scalar mediator



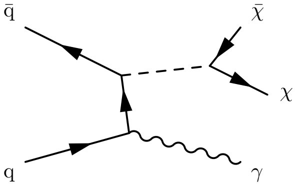
Pseudoscalar mediator



- No exclusion obtained for the scalar case
- Pseudoscalar mediators excluded up to $\sim$ 400 GeV, DM up to $\sim$ 150 GeV

This search is currently one of the most sensitive DM search of CMS, mainly because of its cross-section.

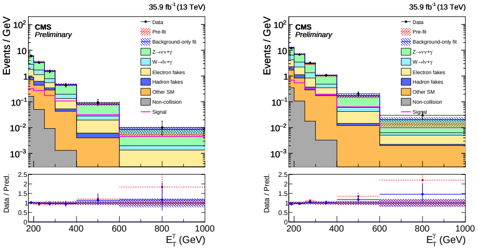
Results published in 2018 with 35.9 fb^{-1} of data in Journal of High Energy Physics



Analysis similar to the mono-jet analysis, with a photon instead of a jet emitted against the DM invisible system:

- Emission less probable, makes the analysis a **bit less sensitive**
- However, high efficiency and purity can be obtained
- Simultaneous fit on the E_T^γ variable on the signal and control regions (instead of a "simple" cut and count)

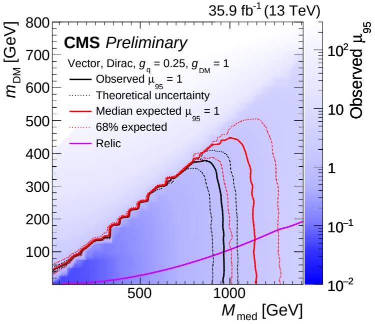
- Typical selection:
  - One photon ($p_T > 165$ GeV)
  - Two DM particles ($p_T^{\text{miss}} > 170$ GeV)
  - Charged leptons are vetoed
- Main backgrounds: $Z(\nu\nu)+\gamma$ (50%), $W(l\nu)(+\gamma)$ (30%)
- Two signal regions to constrain the beam halo normalization



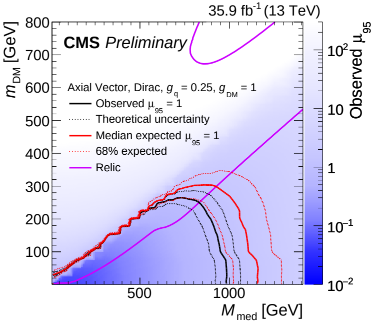
Transfer factors between the four control and signal region are also used to reduce the systematics uncertainty and take advantage of the higher statistics in the single lepton control samples.

The upper limits on the signal production at 95% confidence level have been obtained considering **vector and axial-vector mediators**, in the 2D phase space ($M_{med} - m_{DM}$).

Vector mediator



Axial-vector mediator

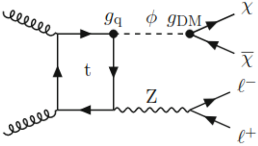


In both cases, mediator masses up to 950 GeV are excluded for $m_\chi < 1$ GeV.

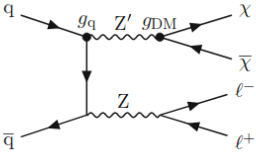
Results published in 2018 with 35.9 fb^{-1} of data in ▸ Journal of High Energy Physics

The results obtained are interpreted in terms of simplified models of DM production with spin 0 or 1 scalar, pseudoscalar, vector or axial-vector mediators:

Spin 0 mediator ϕ



Spin 1 mediator Z'



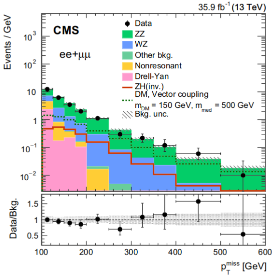
Global selection applied:

- **Exactly two isolated leptons** ($p_T > 25, 20$ GeV)
- Third lepton veto
- Mass close to the Z (15 GeV window)
- **large** p_T^{miss} ($>$ 100 GeV)
- Since little hadrnoic activity is expected, no jet or bjet are expected

Mono-Z($\rightarrow$ ll) (CMS-EXO-16-052)

This channel is competitive thanks to its **small and well-known backgrounds**:

- $ZZ \rightarrow 2l + 2\nu$ (same final state, 60%)
- $WZ \rightarrow 3l + \nu$ (25%)
- $WW \rightarrow 2l + 2\nu$ (5%)



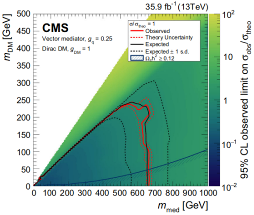
Three variables are used for discrimination and to reduce DY/top backgrounds:

- The missing transverse momentum p_T^{miss}
- Azimuthal angle formed between the dilepton system and the p_T^{miss}
- The $p_T^{\text{miss}} - p_T^{ll}$ balance ratio

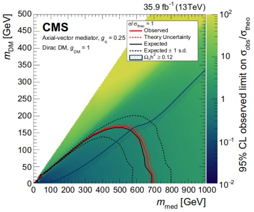
Several improvements since the 2015 results: larger dataset, new techniques to estimate the backgrounds, improvements in the event selection and new BSM models probed.

Mono-Z($\rightarrow$ ll) (CMS-EXO-16-052)

Vector mediator

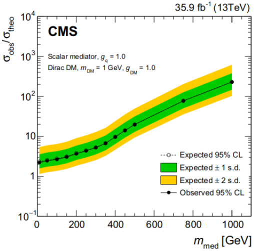


Axial-vector mediator

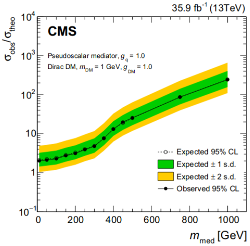


- Vector (axial-vector) mediators excluded up to $\sim$ 680 (700) GeV
- DM excluded up to $\sim$ 240 (160) GeV

Scalar mediator



Pseudoscalar mediator



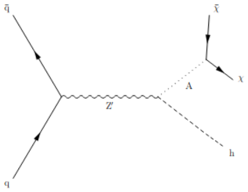
- No exclusion obtained for the scalar or pseudoscalar mediators with this analysis

Results currently targeting publication with 35.9 fb^{-1} of data in the Journal of High Energy Physics.

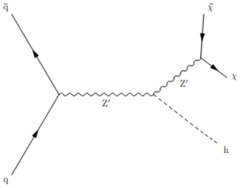
A search for DM with a Higgs boson and high p_T^{miss} is performed:

- Five **orthogonal decay channels** considered: $b\bar{b}$, $\tau\tau$, $\gamma\gamma$, ZZ and, for the first time WW → a combination is then performed to **maximize the sensitivity** of the search (first combination based on 5 Higgs decay channels!)
- The ISR of a Higgs boson is **strongly suppressed** → possible to directly inspect the interaction between DM mediator and Higgs boson
- Two **simplified benchmarks models** considered: the decay of a Z' to a pseudoscalar A (Z'-2HDM) and the radiation of a h when the Z' is the mediator of the DM interaction (Baryonic Z')

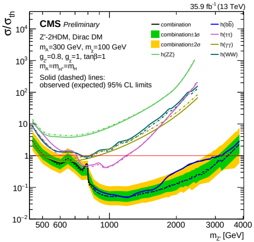
Z'-2HDM



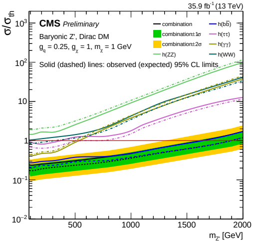
Baryonic Z'



Z'-2HDM

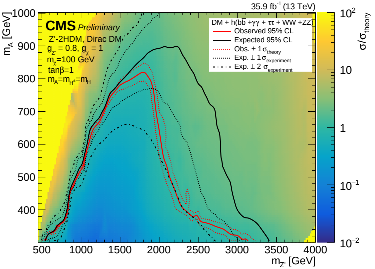


Baryonic Z'

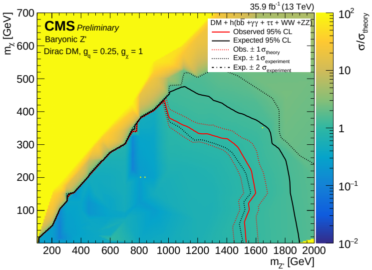


- Limits obtained for the 5 individual decay channels
- The $b\bar{b}$ decay channel gives the best limits because of its high BR

Z'-2HDM



Baryonic Z'

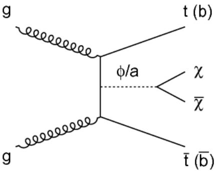


→ Most stringent limits on the parameters of these two models to date.

$t\bar{t}$ + DM (CMS-EXO-16-049)

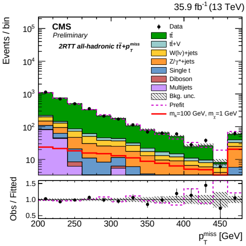
The following model is being considered:

- Spin 1/2 DM χ (1 GeV, Dirac fermion)
- Spin 0 scalar (S)/pseudoscalar (PS) mediator ϕ
- Coupling g_χ between the mediator and the DM set to 1 (same for g_q coupling for all the quarks)
- A signature with top quarks takes advantage from the **large Yukawa coupling** of the mediator

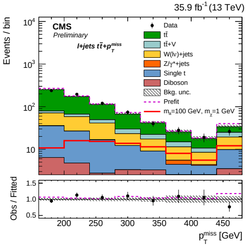


Typical signature includes p_T^{miss}, 2 b-jets from the top decays and a different number of leptons/jets depending on the W decays. Three final states considered:

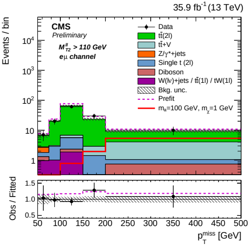
Hadronic channel



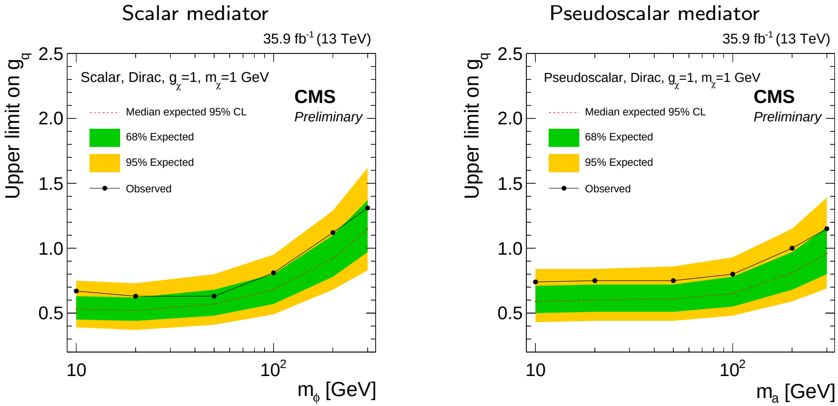
Semi-leptonic channel



Dileptonic channel



$t\bar{t}$ + DM (CMS-EXO-16-049)



This analysis has set the following observed (expected) upper limits on signal production for the model considered, at 95% confidence level:

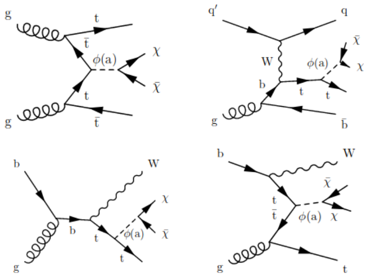
- Up to 160 (240) GeV for scalar mediators
- Up to 220 (320) GeV for pseudoscalar mediators

Results published in 2016 with 35.9 fb^{-1} in ▸ Phys. Rev. Lett. 122

$t/t\bar{t}$ + DM combination (CMS-EXO-18-010)

Analysis published in the ▸ Journal of High Energy Physics with the 2016 data (35.9 fb^{-1}).

Results interpretation: simplified model in which a scalar or pseudoscalar mediator particle couples to a single top quark and decays into DM particles.



Main characteristics of this model:

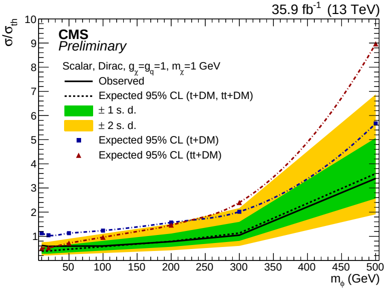
- First search for single top + DM mediated by a neutral spin-0 particle
- Lower production cross-section than the $t\bar{t}$ + DM
- Non-flavour violating single top quark processes kinematically favored
- Takes advantage of the large Yukawa coupling with massive particles

- Additional production of DM in association with a single top quark being studied for the first time
- Search for an excess of data over the SM expectations in the p_T^{miss} spectrum
- Two different signal regions studied (with, without lepton)

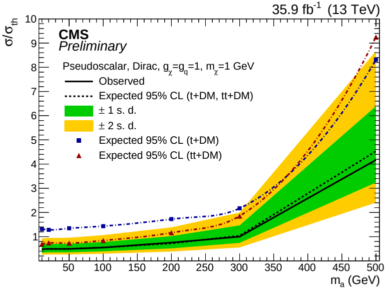
$t/t\bar{t}$ + DM combination (CMS-EXO-18-010)

The results obtained from the single top and $t\bar{t}$ analyses have been combined, improving the limits by a factor 2.

Scalar mediator



Pseudoscalar mediator



The combination of the analyses leads to the exclusion of scalar (pseudoscalar) mediators up to 290 (300) GeV at 95% confidence level.

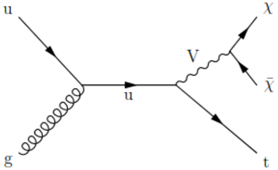
This analysis provides the **most stringent limits** derived at the LHC for these new spin-0 mediator particles.

Mono-top (CMS-EXO-16-051)

Analysis published in the ▸ Journal of High Energy Physics with the 2016 data (35.9 fb^{-1}).

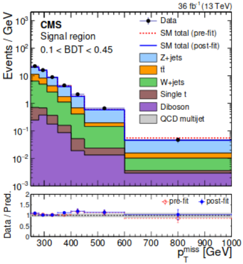
- Search for a similar final state as the previous analysis with a hadronically decaying Lorentz-boosted top quark and DM
- However, no additional jet or W boson is produced in this case

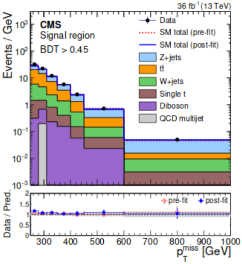
Flavor changing neutral current V



Additional properties of this model:

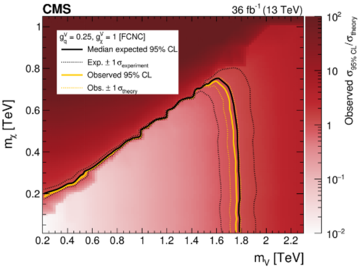
- Consider events with a top quark decaying to a bottom quark and a W, where the W boson decays to two light quarks (large BR $\sim$ 67%, reconstructable) and a high p_T^{miss} ($>$ 250 GeV)
- Production **heavily suppressed** in the standard model (SM) $\rightarrow$ signature used to probe the production of DM particles via a flavor-violating mechanism
- New techniques (BDT) for the reconstruction and identification of the decay products of the highly Lorentz-boosted top quarks used



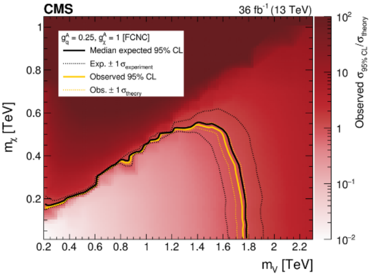


- Major backgrounds: Z+jets, W+jets, $t\bar{t}$, constrained from CR and transfer factors
- BDT defined as discriminator based on the jet substructure, to distinguish between top quarks and gluons/lighter quarks

Vector mediator



Axial mediator



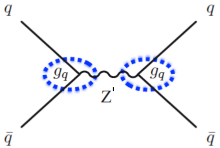
→ Vector and axial mediators have been excluded up to ∼ 1.8 TeV.

Mediator searches

Mediator searches (introduction)

As explained, many of the BSM models require new particles that couple to quarks/gluons and decay to dijets:

- The dijet invariant mass spectrum is usually studied
- An eventual signal is expected to appear as a bump instead of a global excess in the spectrum
- The **width of the resonances** increase with the coupling, and can vary from narrow to broad



Usual issue with these analyses: the trigger limitation, due to the high dijet production cross-section:

- We either have to go at high p_T to select events
- Find ways to speed up the reconstruction at the trigger level
- Or try to recover inefficiencies due to this issue

$\rightarrow$ This will be the main the focus of the following analyses.

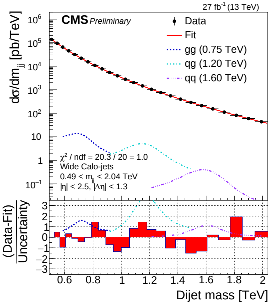
This search for narrow resonances decaying to two jets has been published last year in the ▸ Journal of High Energy Physics with the 2016 data.

The **global strategy is quite simple**:

- Select events with two reconstructed jets
- Fit a smooth function to the m_{jj} spectrum
- Search for eventual excesses/bumps due to new resonances

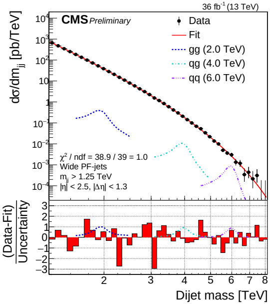
Low mass search (0.6 to 1.6 TeV, 27 fb^{-1})

Dijets from calorimeter information



High mass search (From 1.6 TeV, 36 fb^{-1})

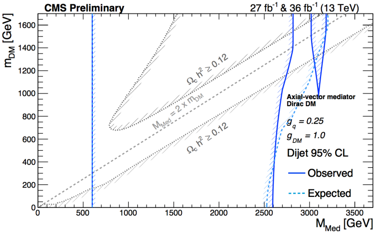
Dijets reconstructed from PF algorithm



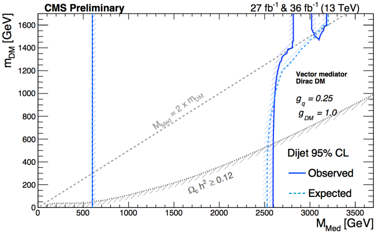
Limits on the production of new particles decaying to parton pairs are set using the dijet mass spectrum:

- Approach **sensitive to high mass mediators** (≥ 1 TeV), since the sensitivity to low mass mediators is **limited by the trigger bandwidth**
- Both **narrow and wide resonances** are considered, as resonances containing gluons (emiting more QCD radiation than the quarks) are wider
- Vector and axial-vector mediators have been considered, in simplified model of DM interactions
- The dijet searches allow to put limits to the couplings g_q between quarks and mediators

Vector-axial mediator



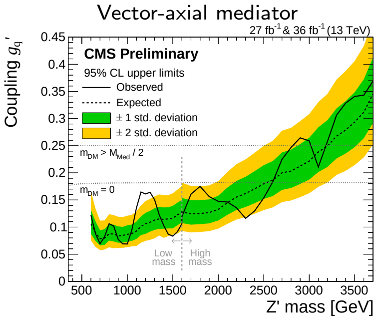
Vector mediator



$\rightarrow$ Dark matter mediators between 600 GeV and 2.6 TeV are excluded with this analysis.

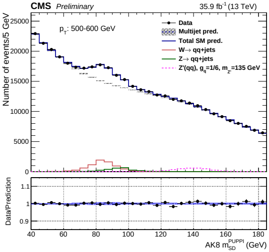
The dijet searches also allow to put limits to the couplings g_q between quarks and mediators since at a fixed resonance mass, we can exclude models with smaller couplings when the sensitivity increases.

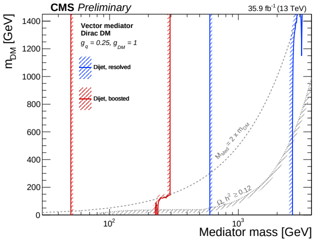
The 95% CL upper limits on the universal quark coupling g_q' as a function of resonance mass for a Z' resonance have been calculated.



A dedicated low mass search has been performed in order to recover the ineficiencies due to the trigger bandwith of the previous analysis. Narrow vector resonances decaying to a quark-antiquark pair are searched for:

- Looking at events with an **energetic ISR jet** and **highly boosted jets** to reduce the backgrounds
- In this case, the decay products of the resonance are merged in a **single massive jet**
- The soft drop jet mass is studied:
  - Soft and wide-angle radiation inside the jet removed (from parton shower, PU interactions or underlying event)





- The 95% CL limits have been obtained for the vector mediator case
- The 50-(240)300 GeV mediator masses range has been excluded

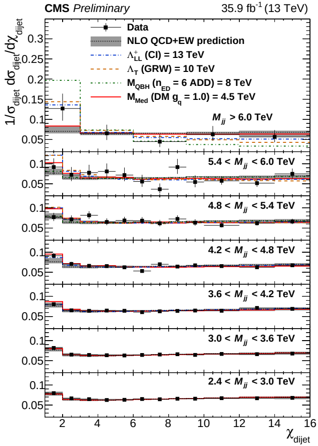
An additional search for DM in the dijet final state using the angular distribution of the jets has been published in the ▸ European Physical Journal C

The angular distribution:

- Is **particularly effective** in the case of wide resonances or non-resonant searches
- Is expressed as

$$\chi_{\text{dijet}} = e^{|y_1 - y_2|}$$

  where y_1 and y_2 are the rapidities of the two highest p_T jets of the event
- Is divided into several M_{jj} categories to **increase the sensitivity**

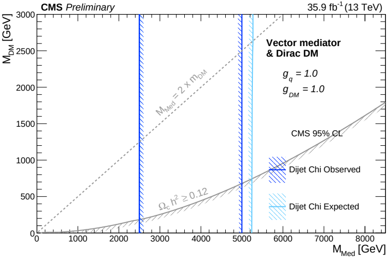


The angular searches are interesting mainly to recover sensitivity when the mediator has a high decay width or when the BSM production mechanism is non-resonant → classical bump searches inefficient in this case

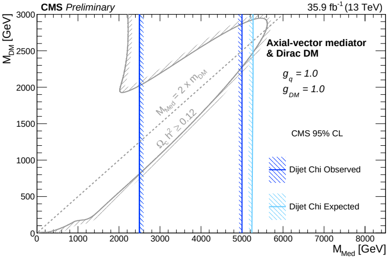
The eventual presence of new physics is expected to show up as an excess of events at low χ values.

Since **no significative excess has been found**, the limits have been obtained considering both spin-1 vector and axial-vector mediators in the plane of dark matter vs mediator mass.

Vector mediator



Axial-vector mediator



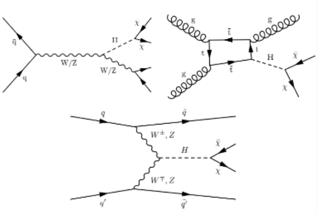
$\rightarrow$ This search is able to exclude dark matter mediator with masses between 2.5 and 5 TeV for both the vector and axial-vector mediators, for the couplings considered.

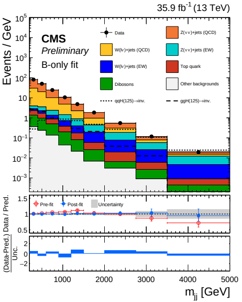
Higgs portal

To be published in Physics Letter B (35.9 fb^{-1}), currently available in arXiv

Several Higgs production modes studied:

- qqH (VBF): two jets, with a large m_{jj} and a large η/small $|\Delta\phi_{jj}|$ separation $\rightarrow$ most sensitive channel
- Z($\rightarrow$ ll), Z/W($\rightarrow$ qq) as main backgrounds estimated in CR from data
- gg $\rightarrow$ H + high p_T jet
- Search for a high p_T^{miss} ($>$ 250 GeV)

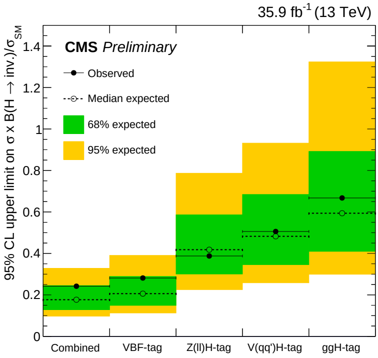




- The Higgs to invisible process exists in the SM, but is rare ($H \rightarrow ZZ \rightarrow \nu\nu$, BR $\sim 0.1\%$)
- A shape analysis of the m_{jj} distribution is performed instead of a counting experiment previously
- Dominant background is V+jets ($\sim 95\%$), estimated from four mutually exclusive control regions:
  - V+jets (EW): jets from W/Z, kinematically close to VBF signal events and more important at high m_{jj}
  - V+jets (QCD), with QCD jets

The signal is expected to show up as an excess of events at large values of m_{jj}.

Since the data is in agreement with the SM expectations, upper limits on the signal production cross-section have been set at the 95% confidence level, considering different Higgs production mechanisms and their combination:



The combination gives an observed (expected) upper limit of 0.19 (0.15) on the branching ratio of the Higgs to invisible process.

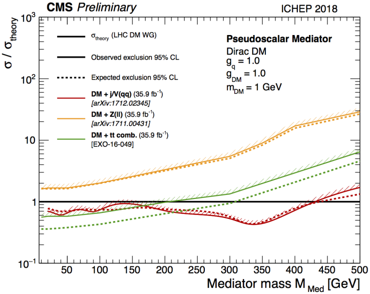
The results have also been interpreted in terms of **DM candidate through Higgs portal models**, providing the strongest constraints on the fermion (scalar) DM particles up to 18 (7) GeV.

Comparison results

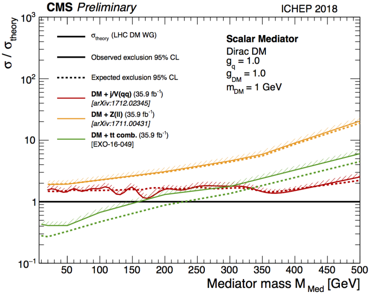
Spin-0 comparison

The same combination can be performed considered spin-0 mediators as well (pseudoscalar, scalar mediators):

Pseudoscalar mediator



Scalar mediator



In this case, considering a Dirac DM of 1 GeV with couplings $g_{DM} = 1.0$ and $g_q = 1.0$, the exclusion is mainly driven by:

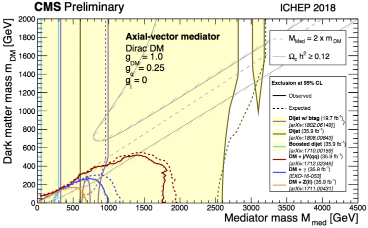
- The $t/\bar{t}$+DM analysis at low mediator masses
- The Mono-jet/Mono-V analysis at higher masses

Pseudoscalar mediators have been excluded up to $\sim$ 400 GeV, and scalar mediators up to $\sim$ 150 GeV.

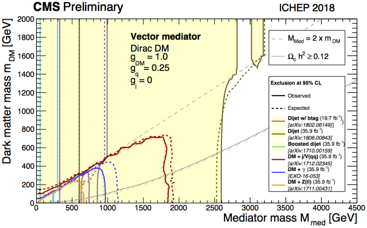
Spin-1 comparison

All the previous results can be combined together, first for the spin-1 mediators (axial-vector, vector mediators):

Axial-vector mediator



Vector mediator

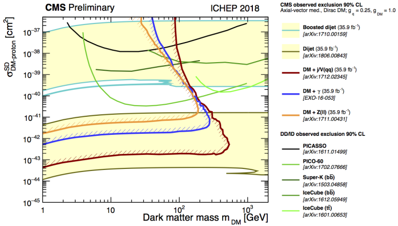


In this case, considering a Dirac DM with couplings $g_{DM} = 1.0$, $g_q = 0.25$ and $g_l = 0$, the exclusion is mainly driven by the dijet analysis, exluding mediator masses up to $\sim$ 2.5 TeV for both axial-vector and vector mediators.

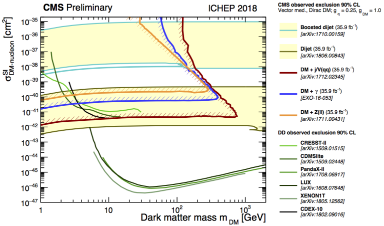
The previous results can be further reinterpreted in terms of DM-nucleon scattering, to compare the results with the ones obtained by the direct detection experiments, as explained in this ▸ publication.

This is done both for the spin-dependant (SD) and spin-independant (SI) interactions.

SD interaction



SI interaction



For this reinterpretation, Dirac DM candidates are considered, with the usual couplings $g_{DM} = 1.0$, $g_q = 0.25$ and $g_l = 0$.

Conclusions

The main searches for DM production with the CMS detector have been presented.

Different signatures have been studied, such as the:

- Production of dark matter in association with SM particles
- Production of SM particles from the decay of dark matter mediators
- Production of dark matter through the Higgs portal

No significant discrepancies with the SM expectaction have been observed. The results have then been interpreted by setting limits on the mass and couplings of the DM interaction mediators considering **simplified DM models**.

These results are then reinterpreted in terms of DM-nuclei interaction to compare them with direct detection experiments.

Most of the analyses presented here are using the 2016 dataset:

- Most of them will be updated and improved by taking advantage of the complete Run2 dataset (2016, 2017, 2018)
- Four times more data waiting to be analyzed (~ 150 fb^{-1} of data instead of ~ 36 fb^{-1})
- Stay tuned for more exciting news in the next few months!

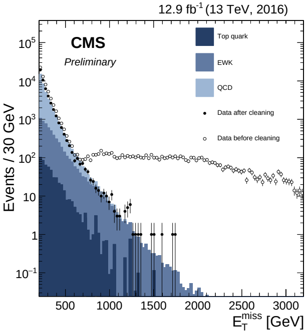
Thank you!

Data cleaning

Additional (smaller) instrumental effects can also lead to anomalous p_T^{miss} values, such as:

- ECAL mismeasurements from beam halo or eventual dead cells
- HCAL mismeasurements from electronic noise and direct particle interactions with the light guides and photomultiplier tubes of the forward calorimeter

These effects can be estimated and substracted, leading to a nice agreement even in the p_T^{miss} distribution tail. More details in CMS-PAS-JME-16-004



Each of the decay channel has its own strategy and advantages:

- $h \to b\bar{b}$ has the highest BR and uses a simultaneous CR/SR fit for the baryonic Z' and parametric fits for the Z'-2HDM.
- $h \to \gamma\gamma$ exhibits a good reconstruction of the Higgs invariant mass and uses a fit to the diphoton invariant mass in two p_T^{miss} categories.
- $h \to \tau\tau$ has lower backgrounds and considers the 3 leptonic decays of the τ with the highest BR (simultaneous fit on the Higgs reconstructed mass)
- $h \to WW$ considers the fully leptonic decay of the Ws and the $e\mu$ channel to reduce the backgrounds
- $h \to ZZ$ also consideres the fully leptonic decay of the Z.

The $h \to \tau\tau$, $h \to WW$ and $h \to ZZ$ benefits from lower backgrounds and can be competitive for signals with soft p_T^{miss} spectrum.