Scale factors determination applied to the dark Higgs model

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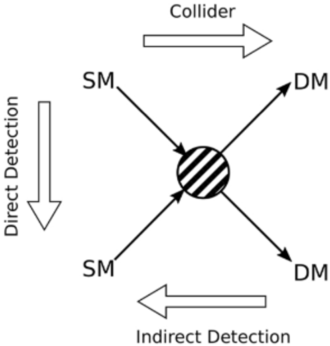
RADPyC2023

June 14th

Dark Matter searches

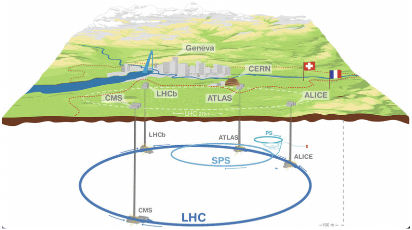


Possible dark matter detection channels (1).

Collider searches:

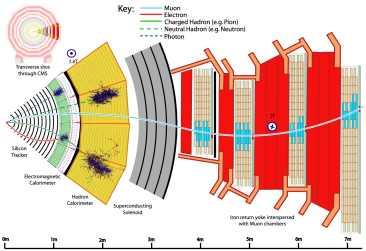
- Interactions between SM and DM
- Discovery of the Higgs boson (new annihilation channels)
- Models proposed for LHC Run-2 searches (2): Simplified models (MET+X)

Large Hadron Collider



The LHC is 27 km long and lies 100 m underground (3).

Compact Muon Solenoid



Sketch of the transverse slice of the CMS detector (4).

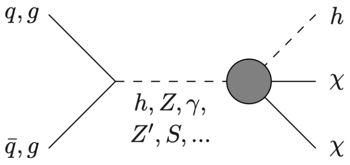
- CMS (Dr. Rogelio REYES ALMANZA)

Mono-dark Higgs searches

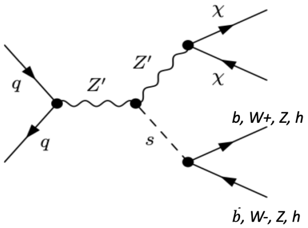
- DM pair production in association with a dark Higgs boson
- $h_s + \chi\chi$ where $h_s \rightarrow b\bar{b}, W^+W^-, ZZ, hh$

Mono-Higgs searches

- DM pair production in association with a Higgs boson
- $h + \chi\chi$ where $h \rightarrow b\bar{b}, \gamma\gamma, ...$



Schematic diagram for mono-Higgs production (5).



Processes leading to a mono-dark-Higgs signal (6).

CMS searches :

Search for dark matter particles produced in association with a dark Higgs boson decaying into W^+W^- in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the CMS detector(CMS PAS EXO-20-013).

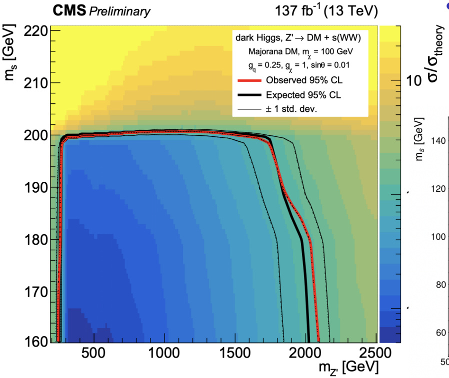


Figure: Combined observed (expected) exclusion regions at 95% CL for the dark Higgs model in the $(m_s, m_{Z'})$ plane, marked by the solid red (black) line.

ATLAS searches :

- RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two b-quarks (ATL-PHYS-PUB-2019-032).
- Active Learning reinterpretation of an ATLAS Dark Matter search constraining a model of a dark Higgs boson decaying to two b-quarks (ATL-PHYS-PUB-2022-045).

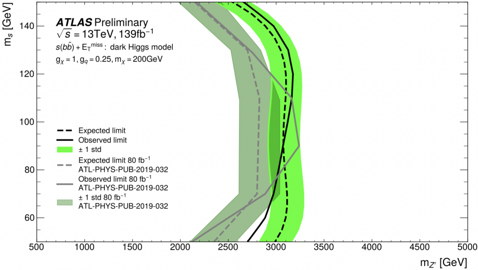


Figure: Exclusion limits on the mediator masses $m_{Z'}$ and m_s.

Dark Higgs Model

Hunting the dark Higgs: arXiv:1701.08780

- Dark Matter Majorana particle
- Dark Higgs in the lightest state
  - h_s mass < 160 GeV
- New Z′ mediator spin 1
  - Couplings g_q= 1, g_χ= 0.25
- Parameters of the model:
  - h_s mass, Z′ mass, χ mass
- Final state: Large MET and bb pair from the dark Higgs

Discriminating variable: Mass of the recoiling large fat jet

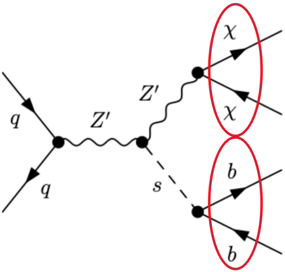
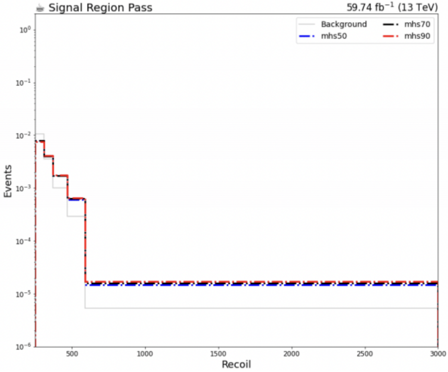
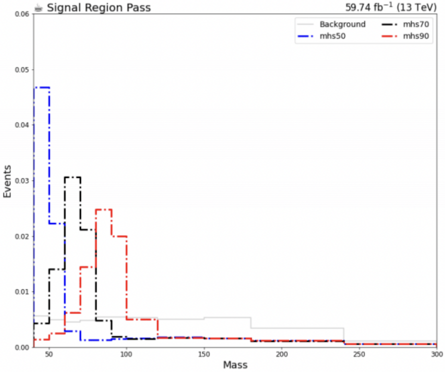


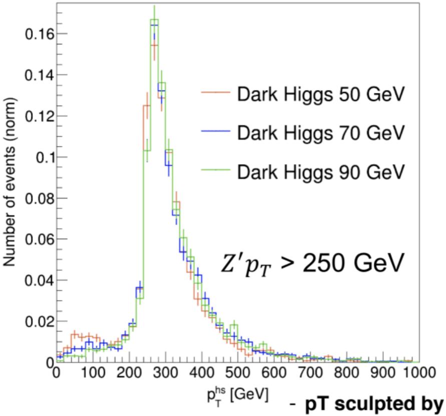
Figure: Processes leading to a mono-dark-Higgs signal(6).

mZ'=500 GeV

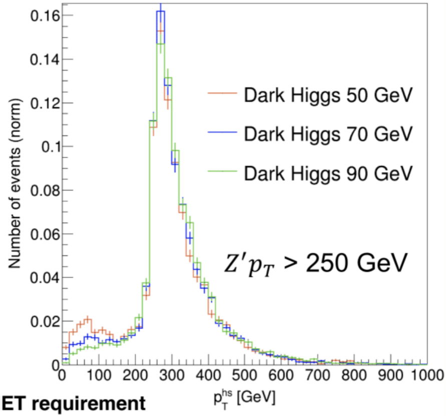

Signal Region Pass
59.74 fb^{-1} (13 TeV)
Background
mhs50
mhs70
mhs90
Events
Recoil
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
500
1000
1500
2000
2500
3000


Signal Region Pass
59.74 fb^{-1} (13 TeV)
Background
mhs50
mhs70
mhs90
Events
Mass
0.06
0.05
0.04
0.03
0.02
0.01
0.00
50
100
150
200
250
300

$M_{Z'} = 195$ GeV, $M_\chi = 100$ GeV



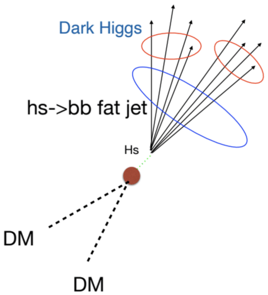
$M_{Z'} = 300$ GeV, $M_\chi = 100$ GeV



- **pT sculpted by the MET requirement**
- **>90% of the signal with pT>160 GeV**

Minimal Event Selection

- Missing energy requirement > 250 GeV
- Minimum fat jet p_T > 160 GeV
  - AK15 jets as dark Higgs candidates



Signal generation: h_s masses: 50, 70, and 90 GeV

Z' mass [GeV]	DM χ mass [GeV]
195	100
200	150
295	150
300	100
495	250
500	150, 500
995	500
1000	150, 1000
1995	1000
2000	500, 1500
2495	1250
2500	750
2995	1500
3000	1000

Signal region

- At least one AK15 jet $p_T >$ 160 GeV
- PFMET > 250 GeV
- τ veto, no e, μ, γ
- Minimum requirement on the DeepAK15 score

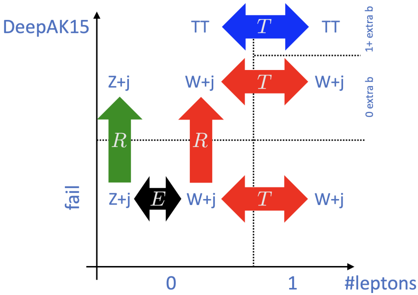
The table represents the expected yields for the different backgrounds. Main contributions: W+jets, Z+jets and $t\bar{t}$.

```
------------------------
------------------------
Category: sr pass
------------------------
------------------------
Hbb 81.2
DY+HF 16.6
DY+LF 21.1
WW 114.7
WZ 221.5
ZZ 253.0
ST 591.7
TT 6456.9
W+HF 1044.3
W+LF 1787.2
Z+HF 3686.2
Z+LF 3201.6
QCD 152.6
------------------------
Total expected: 17628.6
------------------------
------------------------
```

Background estimation: Data Driven

Main background: W/Z + jets, $t\bar{t}$

- Estimation using a data-driven model
- Control regions
- Transfer factors



Rhalphabet: differential alphabet method

- To increase statistics (not data samples with 100% $t\bar{t}, W/Z + jet$)

Predict the $t\bar{t}$, W/Z+jets mass vs recoil distribution using data in control regions

Analysis summary:

Analyze full Run-2 data (137.2 fb^{-1})

- Run2016 B-H datasets 35.9 fb^{-1}
- Run2017 B-F datasets 41.5 fb^{-1}
- Run 2018A-C datasets 59.74 fb^{-1}

Main background W/Z + jets, $t\bar{t}$

- Data-driven

Minimal event selection: MET > 250 GeV and p_T > 160 GeV

Select $b\bar{b}$ events with DeepAK15 tagger as dark Higgs candidates

Files in NanoAOD format. The CMSSW is used as well as COFFEA.

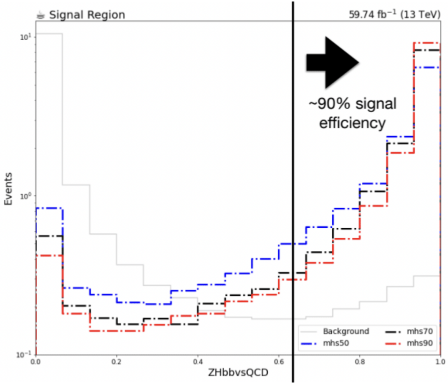
Triggers

- MET Triggers (and filters)
- Electron
- Muon

Corrections and systematics

- Pile-up weights
- MET/single electron trigger efficiencies
- Muon ID, Eletron ID, Photon ID, and scale factors
- Jet Energy Resolution Corrections
- SF for the DeepAK15 efficiency
  - Uncertainty that correct the DeepAK15 tagger signal efficiency (own dark Higgs tagger)

Scale Factors Measurement



SF that corrects the DeepAK15 tagger signal efficiency (MC)

$$\epsilon_{MC}^{W/Z+jets} = \frac{N_{W/Z+\text{jets}}^{\text{pass}}}{N_{W/Z+\text{jets}}} \quad (1)$$

The scores of the DeepAK15 are probabilities

- ZHbbvsQCD: a combination of scores used to discriminate events from QCD
- To increase the efficiency
- > 0.65

Data BtagMu

- Select events with muons associated with jets (BTagMu path)

QCD signal/BKG process:

- sample enriched in b quarks (Soft leptons)
- Difficult pure Z/H $\rightarrow$ bb sample
- bb, b, cc, other

Same event selection

- MET, jet p_T, R

Variable ln(m$_{sv}$, d$_{xy}$ sig max)

- Separation between the bb components from the rest

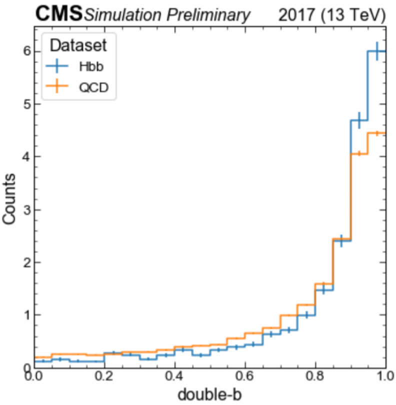
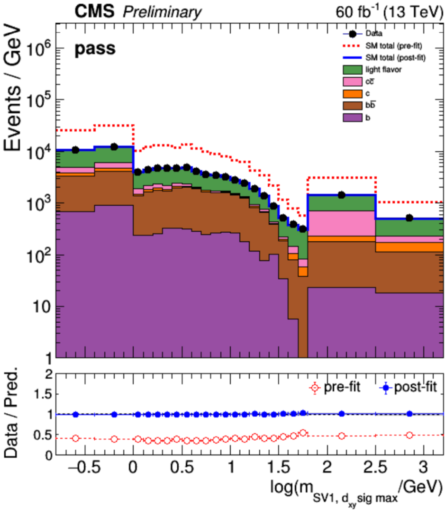


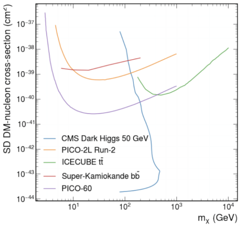
Figure: Proxy for double-b (7)

SF measurement direct from the fit: Higgs Combine Tool

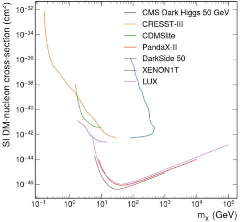


Year	Scale factor
2016	8.5349e-01 ± 1.52e-02
2017	9.3763e-01 ± 5.87e-03
2018	9.8177e-01 ± 1.02e-02

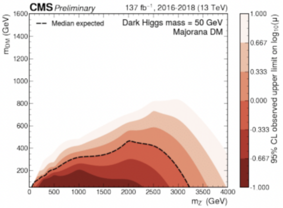
Results



(a) Spin Dependent results



(b) Spin independent results



(c) 2D distribution expected limits

Figure: Fig left and center: Comparison of spin-dependent or independent nucleon cross sections. Fig right expected limits.

Summary

- Obtained scale factors to correct the double b tagger efficiency in Monte Carlo simulations.
- Applied to fat jet analysis in the dark Higgs model.
- Improves accuracy in identifying dark Higgs-associated jets.
- Further studies and validations are ongoing.

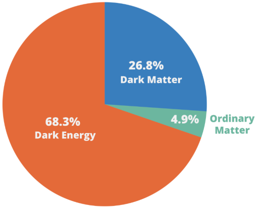
Thank you

Backup

Motivation

Example unsolve SM problems

- Neutrino mass
- Mass hierarchy
- Baryonic asymmetry
- Dark Energy
- Dark Matter



Percentage of ordinary matter, dark matter and dark energy in the universe (8)

Astrophysical observations: Galaxy rotations, Gravitational lensing, etc. Dark Matter features:

- Does not interact with the electromagnetic force
- Weakly interacting
- Stable

Renormalization of the U(1) gauge theory for tensor dark matter: preliminary results (Mr. ARMANDO DE LA CRUZ RANGEL PANTOJA).

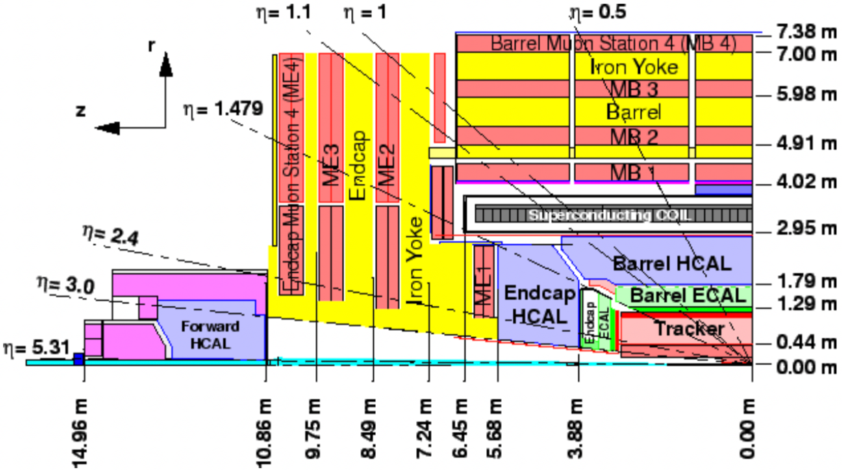
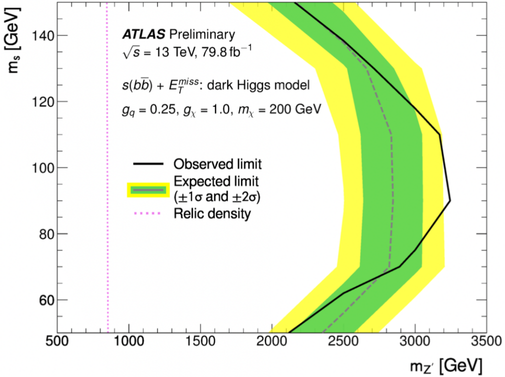


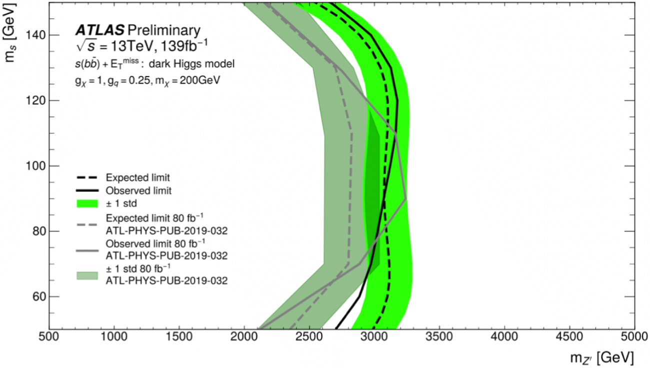
Figure: Longitudinal view of one quadrant of CMS.

RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two b-quarks



Exclusion contour for the dark Higgs model with parameters mχ = 200 GeV, g_q = 0.25, g_χ = 1.0 and different values of m_Z, and m_s[2].

Active Learning reinterpretation of an ATLAS Dark Matter search constraining a model of a dark Higgs boson decaying to two b-quark



Exclusion limits on the mediator masses m_Z and m_s in the plane mχ=200GeV, g_χ=1.0 and g_q=0.25. The exclusion limits of the previous Mono-H(bb) search using a fraction of the Run 2 data are improved by approximately 300 GeV in terms of m_Z[3].

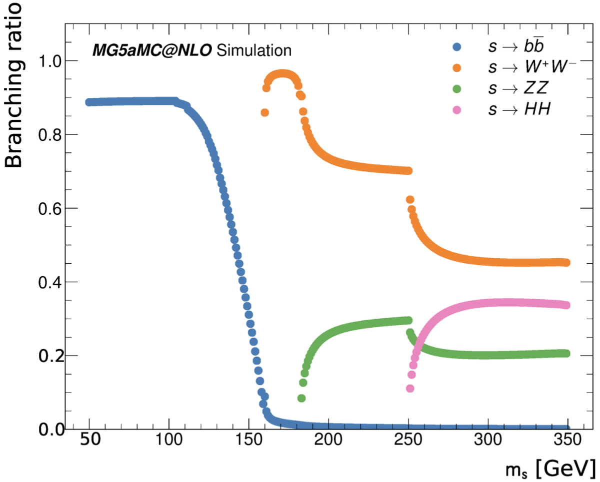
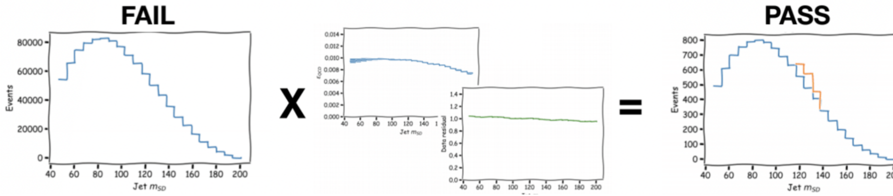


Figure: Branching ratio of the dark Higgs boson (9).

Z + jets background estimation

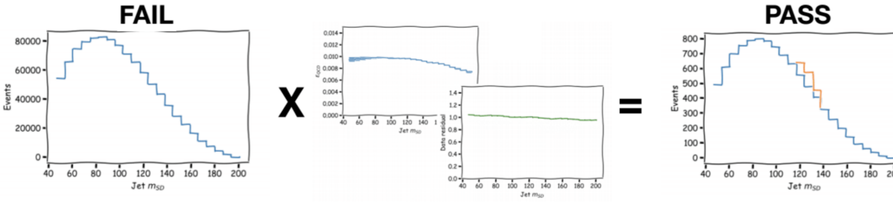
- $$TF_{p/f}^{Z+jets}(msd, P_T^{miss}) = \sum_{k=0}^{n_{msd}} \sum_{l=0}^{n_{P_T^{miss}}} a_{k,l} b_{k,n_{msd}}(msd) b_{l,n_{P_T^{miss}}}(P_T^{miss}) \sum_{k=0}^{m_{msd}} \sum_{l=0}^{m_{P_T^{miss}}} c_{k,l} d_{k,m_{msd}}(msd) d_{l,m_{P_T^{miss}}}(P_T^{miss})$$

$$N_{SR_{pass}}^{Z+jets}(msd, P_T^{miss}) = \mu_{SR_{fail}}^{Z+jets}(msd, P_T^{miss}) TF_{p/f}^{Z+jets}(msd, P_T^{miss})$$



Similar for W + jets and ttbar background

- $N^{W+jets}_{SR_{pass}}(msd, P_T^{miss}) = N^{W+jets}_{SR_{fail}}(msd, P_T^{miss})TF^{W+jets}_{p/f}(msd, P_T^{miss})$



- $N^{t\bar{t}}_{WeCR_{pass}}(msd, recoil) = \dfrac{\mu^{t\bar{t}}_{SR_{pass}}(msd, recoil)}{TF^{t\bar{t}}_{WeCR_{pass}}(msd, recoil, \theta)}$

- $TF^{t\bar{t}}_{WeCR_{pass}}(msd, recoil) = \dfrac{{}^{MC}N^{t\bar{t}}_{SR_{pass}}(msd, recoil, \theta)}{{}^{MC}N^{t\bar{t}}_{WeCR_{pass}}(msd, recoil, \theta)}$

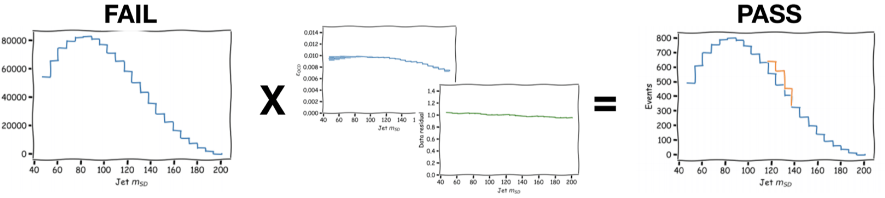
31

Z+jets Background estimation

To increase statistics from data.

Transfer factor (TF) to connect in fail with pass $TF_{p/f}(\text{msd}, p_T^{\text{miss}})$

$$N^{Z+j}_{SR_{\text{pass}}}(\text{msd}, p_T^{\text{miss}}) = N^{Z+j}_{SR_{\text{fail}}}(\text{msd}, p_T^{\text{miss}})\, TF_{p/f}(\text{msd}, p_T^{\text{miss}}). \quad (2)$$



Similar for W+jets and $t\bar{t}$:

$$N^{W+j}_{SR_{\text{pass}}}(\text{msd}, p_T^{\text{miss}}) = N^{W+j}_{SR_{\text{fail}}}(\text{msd}, p_T^{\text{miss}})\, TF_{p/f}(\text{msd}, p_T^{\text{miss}}). \quad (3)$$

$$N^{t\bar{t}}_{t\bar{t}(\mu/e)CR_{\text{pass}}}(\text{msd}, p_T^{\text{miss}}) = \frac{N^{t\bar{t}}_{SR_{\text{pass}}}(\text{msd}, p_T^{\text{miss}})}{\text{TF}^{t\bar{t}}_{t\bar{t}(\mu/e)CR_{\text{pass}}}(\text{msd}, p_T^{\text{miss}}, \theta)}, \quad (4)$$

BtagMu triggers

```
•             self._btagmu_triggers = {
•                 '2016': [
•                     'BTagMu_AK4Jet300_Mu5',
•                     'BTagMu_AK8Jet300_Mu5',
•                     'BTagMu_AK4DiJet170_Mu5'
•                     ],
•                 '2017': [
•                     'BTagMu_AK4Jet300_Mu5',
•                     'BTagMu_AK8Jet300_Mu5',
•                     'BTagMu_AK4DiJet170_Mu5'
•                     ],
•                 '2018': [
•                     'BTagMu_AK4Jet300_Mu5',
•                     'BTagMu_AK8Jet300_Mu5',
•                     'BTagMu_AK4DiJet170_Mu5'
```

Triggers

MET triggers

- HLT PFMETNoMu120 PFMHTNoMu120 IDTight
- HLT PFMETNoMu120 PFMHTNoMu120 HT60

MET filters (induced by the HF detector)

- goodVertices
- globalSuperTightHalo2016Filter
- HBHENoiseFilter
- HBHENoiseIsoFilter
- EcalDeadCellTriggerPrimitiveFilter
- BadPFMuonFilter
- ecalBadCalibFilterV2
- eeBadScFilter (only for data)

Electron triggers

- 2017 HLT_Ele35 WPTight Gsf OR HLT Photon200
- 2018 HLT Ele32 WPTight Gsf OR HLT Photon200

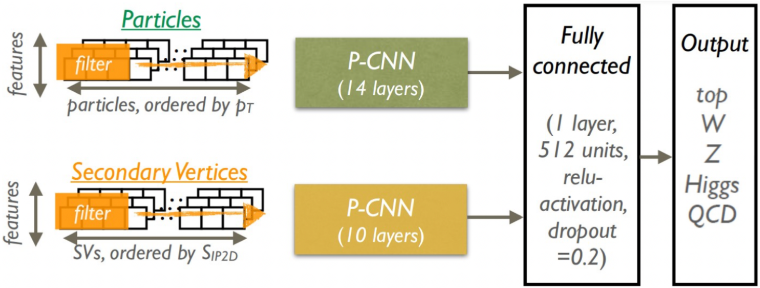
Muon triggers

- 2017 HLT IsoMu27
- 2018 HLT IsoMu24

$$\sigma^0_{\rm SI} = \frac{9\, g^2_{\rm DM}\, g^2_q\, \mu^2_{n\chi}}{\pi M^4_{\rm med}}$$
$$\approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

$$\sigma^0_{\rm SD} = \frac{3\, g^2_{\rm DM}\, g^2_q (\Delta_u + \Delta_d + \Delta_s)^2\, \mu^2_{n\chi}}{\pi M^4_{\rm med}}$$
$$\approx 4.6 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2 ,$$

- DeepAK15 tagger



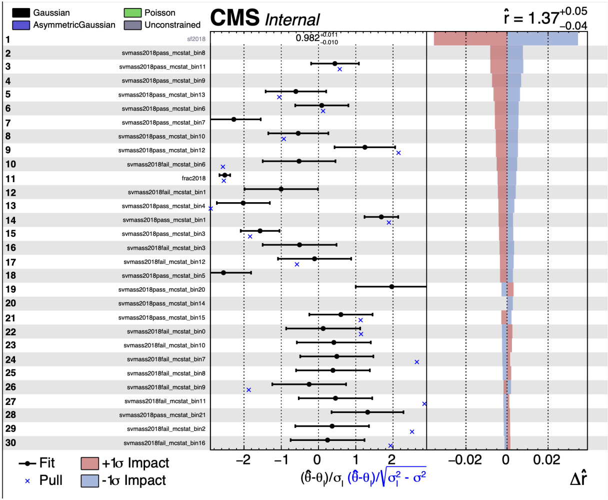
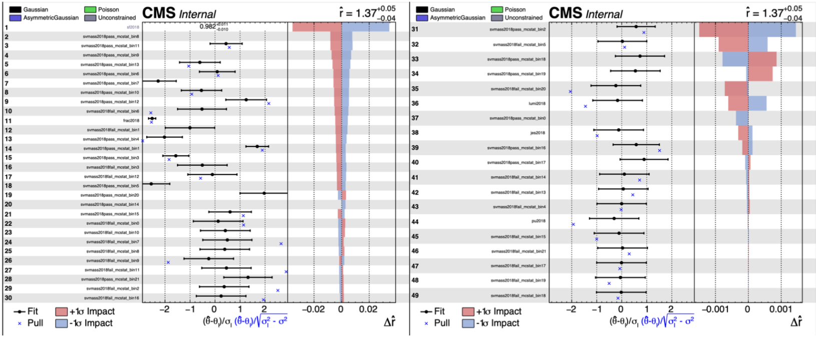


Figure: Impacts of the nuisance parameters (NP) on the parameter of interest for 2018

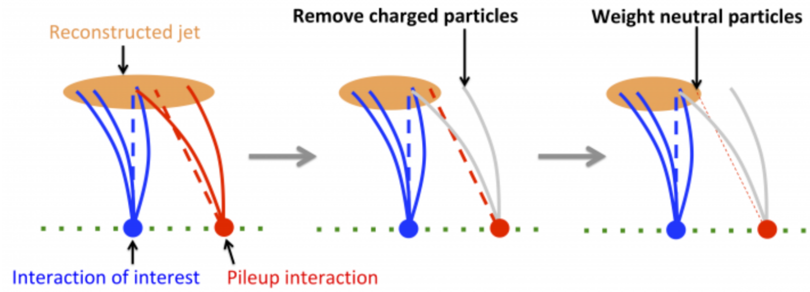


Impacts of the nuisance parameters (NP) on the parameter of interest for 2018

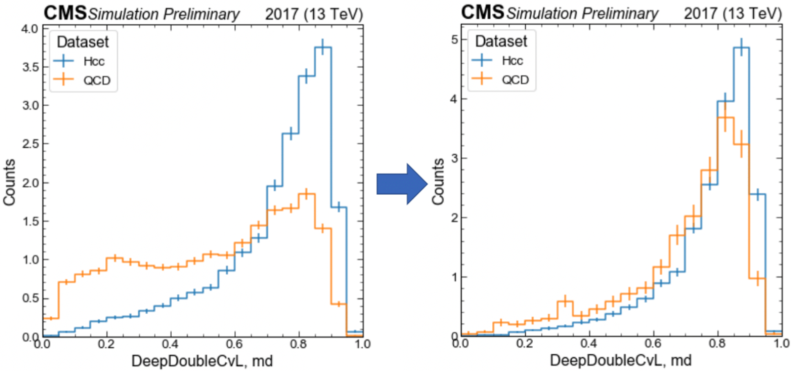
- AK4:
  - CHS, latest AK4 JEC applied
  - Tight jet ID, pT>30 & abs(eta)<2.4 & nhf<0.8 & chf>0.1
  - Loose PU ID for pT<50
  - DeepFlavor loose WP>0.0494
- AK15:
  - PUPPI, latest AK8 JEC applied
  - Tight jet ID, pT>160 & abs(eta)<2.4
  - Soft-drop mass corrected
  - DeepAK15 for dark Higgs taggin

- Muons
  - Loose: loose ID, pt>15 & abs(eta)<2.4 & pfRelIso04_all<0.25
  - Tight: tight ID, pt>30 & abs(eta)<2.4 & pfRelIso04_all<0.15
- Electrons
  - Loose: cut-based veto ID, pt>10 & abs(eta)<2.5
  - Tight: cut-based tight ID, pt>40 & abs(eta)<2.5
  - abs(eta)<1.4442 (barrel): abs(dxy)<0.05 & abs(dz)<0.1
  - abs(eta)>1.5660 (endcap): abs(dxy)<0.1 & abs(dz)<0.2
  - dR(electrons, loose muons)>0.3
- Taus
  - MVAoldDM2017v2 very loose ID, pt>18 & abs(eta)<2.3
  - Decay mode flag activated
  - dR(electrons, loose electrons/muons)>0.4
- Photons
  - Loose: cut-based loose ID, pt>15 & abs(eta)<2.5 & !(1.4442<abs(eta)<1.5660)

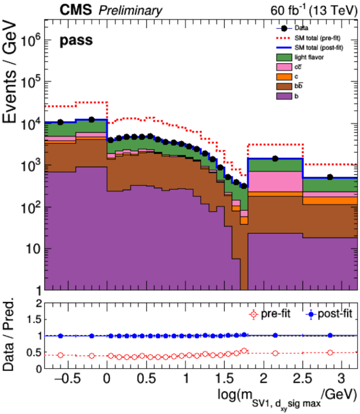
CMS pileup

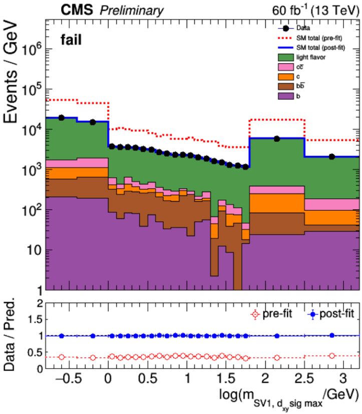

Reconstructed jet
Remove charged particles
Weight neutral particles
Interaction of interest
Pileup interaction

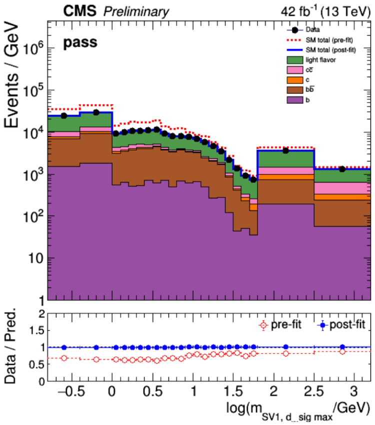
DeepDoubleBvL Proxy

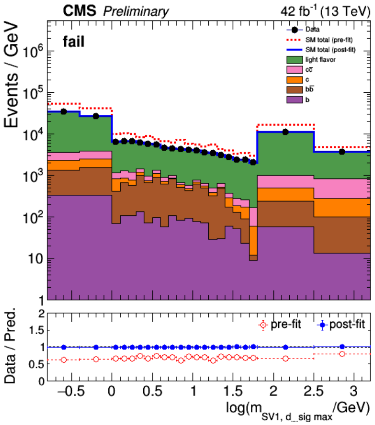


Default Selection **Modified Selection**


CMS Preliminary
60 fb^{-1} (13 TeV)
pass
Data
SM total (pre-fit)
SM total (post-fit)
light flavor
$c\bar{c}$
c
$b\bar{b}$
b
Events / GeV
Data / Pred.
pre-fit
post-fit
log($m_{SV1,\, d_{xy} sig\, max}$/GeV)


CMS Preliminary
60 fb^{-1} (13 TeV)
fail
Data
SM total (pre-fit)
SM total (post-fit)
light flavor
$c\bar{c}$
c
$b\bar{b}$
b
Events / GeV
Data / Pred.
pre-fit
post-fit
log($m_{SV1,\, d_{xy} sig\, max}$/GeV)


CMS Preliminary
42 fb^{-1} (13 TeV)
pass
Data
SM total (pre-fit)
SM total (post-fit)
light flavor
$c\bar{c}$
c
$b\bar{b}$
b
Events / GeV
Data / Pred.
pre-fit
post-fit
log(m$_{SV1, d_sig max}$/GeV)


CMS Preliminary
42 fb^{-1} (13 TeV)
fail
Data
SM total (pre-fit)
SM total (post-fit)
light flavor
$c\bar{c}$
c
$b\bar{b}$
b
Events / GeV
Data / Pred.
pre-fit
post-fit
log(m$_{SV1, d_sig max}$/GeV)

Selection requirements

- Muons
  - Loose: loose ID, p_T >15 & abs(eta)<2.4 & pfRelIso04_all<0.25
  - Tight: tight ID, p_T >30 & abs(eta)<2.4 & pfRelIso04_all<0.
- Electrons
  - Loose: cut-based veto ID, p_T >10 & abs(eta)<2.5
  - Tight: cut-based tight ID, p_T >40 & abs(eta)<2.5
  - abs(eta)<1.4442 (barrel): abs(dxy)<0.05 & abs(dz)<0.1
  - abs(eta)>1.5660 (endcap): abs(dxy)<0.1 & abs(dz)<0.2
  - dR(electrons, loose muons)>0.
- Tau
  - Loose ID, p_T >18 & abs(eta)<2
  - dR(electrons, loose electrons/muons)>0.4
- Photons
  - Loose: cut-based loose ID, p_T >15 & abs(eta)<2.5 & !(1.4442<abs(eta)<1.5660)
  - Tight: cut-based medium ID, p_T >230 and supercluster eta within barrel acceptance
  - pass electron veto, dR(photons, loose electrons/muons)>0.

- Scale factors for W/Z + jets

$$N^{\text{total}}_{W/Z+jets} = N^{\text{pass}}_{W/Z+jets} + N^{\text{fail}}_{W/Z+jets} \qquad (12)$$

considering

$$N^{\text{pass}}_{W/Z+jets} = \boxed{\epsilon^{\text{W/Z+jets mis-tag}}_{\text{data}}} \times N^{\text{total}}_{W/Z+jets} = \boxed{SF^{\text{W/Z+jets mis-tag}}_{pass} \times \epsilon^{\text{W/Z+jets mis-tag}}_{\text{MC}}} \times N^{\text{total}}_{W/Z+je} \qquad (13)$$

and deriving $N^{\text{fail}}_{W/Z+jets}$ as

$$N^{\text{fail}}_{W/Z+jets} = N^{\text{total}}_{W/Z+jets} \times (1 - SF^{\text{W/Z+jets mis-tag}}_{pass} \times \epsilon^{\text{W/Z+jets mis-tag}}_{\text{MC}}) \qquad (14)$$

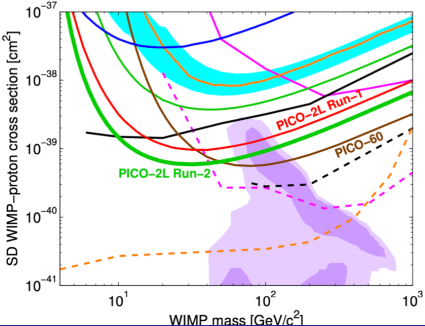
so that $SF^{\text{W/Z+jets mis-tag}}_{fail}$ can be expressed in terms of $SF^{\text{W/Z+jets mis-tag}}_{pass}$ as

$$SF^{\text{W/Z+jets mis-tag}}_{fail} = \frac{1 - SF^{\text{W/Z+jets mis-tag}}_{pass} \times \epsilon^{\text{W/Z+jets mis-tag}}_{\text{MC}}}{1 - \epsilon^{\text{W/Z+jets mis-tag}}_{\text{MC}}} \qquad (15)$$

$$\boxed{SF_f = \varepsilon^{\text{data}}_f(p_{\text{T}}, \eta) / \varepsilon^{\text{MC}}_f(p_{\text{T}}, \eta)}$$

PICO-2L Run2

- The 90 % C.L. limit on the SD WIMP-proton cross section from Run-2 (Run-1 [8]) of PICO-2L is plotted in green (red), along with limits from PICO-60 (brown), COUPP-4 (light blue region), PICASSO (dark blue), SIMPLE (thin green), XENON100 (orange), IceCube (dashed and solid pink), SuperK (dashed and solid black) and CMS (dashed orange) [9, 10, 12, 13, 25–29]. For the IceCube and SuperK results, the dashed lines assume annihilation to W pairs while the solid lines assume annihilation to b quarks. Comparable limits assuming these and other annihilation channels are set by the ANTARES, Baikal and Baksan neutrino telescopes [30–32]. The CMS limit is from a monojet search and assumes an effective field theory, valid only for a heavy mediator [33, 34]. Comparable limits are set by ATLAS [35, 36]. The purple region represents the parameter space of the constrained minimal supersymmetric standard model of Ref. [37].



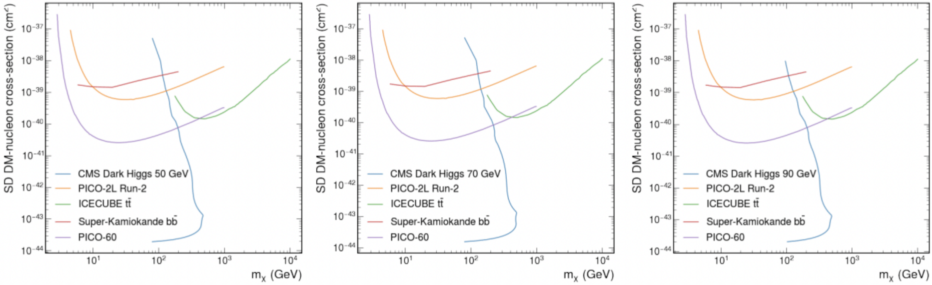


Figure: Spin dependent results

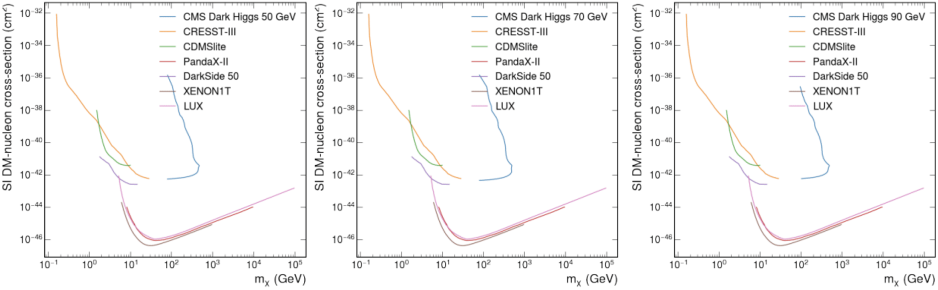


Figure: Spin independent results

- S. Giagu, ``Wimp dark matter searches with the atlas detector at the lhc,'' *Front. in Phys.*, vol. 7, p. 75, 2019.
- D. A. *et al.*, ``Dark matter benchmark models for early lhc run-2 searches: Report of the atlas/cms dark matter forum,'' *Physics of the Dark Universe*, vol. 27, p. 100371, Jan 2020.
- I. P. Enginnering, ``The lhc is 27 km long and lies 100 m underground,'' 2021.
  (The LHC is 27 km long and lies 100 m underground).
- A. M. Sirunyan *et al.*, ``Particle-flow reconstruction and global event description with the cms detector,'' *Journal of Instrumentation*, vol. 12, pp. P10003--P10003, Oct 2017.
- L. Carpenter, A. DiFranzo, M. Mulhearn, C. Shimmin, S. Tulin, and D. Whiteson, ``Mono-higgs-boson: A new collider probe of dark matter,'' *Phys. Rev. D*, vol. 89, p. 075017, Apr 2014.

- M. Duerr, A. Grohsjean, F. Kahlhoefer, B. Penning, K. Schmidt-Hoberg, and C. Schwanenberger, ``Hunting the dark higgs,'' *Journal of High Energy Physics*, vol. 2017, apr 2017.
- A. Novak, ``Better proxy is better.'' Presentation at the BTV Meeting, July 2019.
- E. Ward, ``Estimated matter-energy content of the universe,'' 2019.
  (Estimated matter-energy content of the Universe).
- ``RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two b-quarks,'' tech. rep., CERN, Geneva, 2019.

All figures including auxiliary figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-032.