Search for DM particles produced in association with a dark Higgs boson decaying to two W bosons

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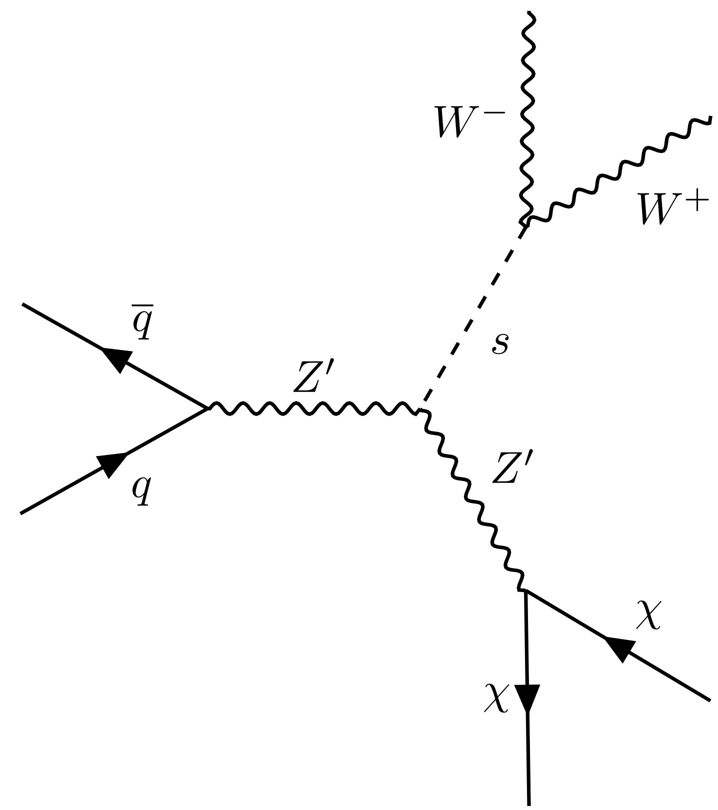
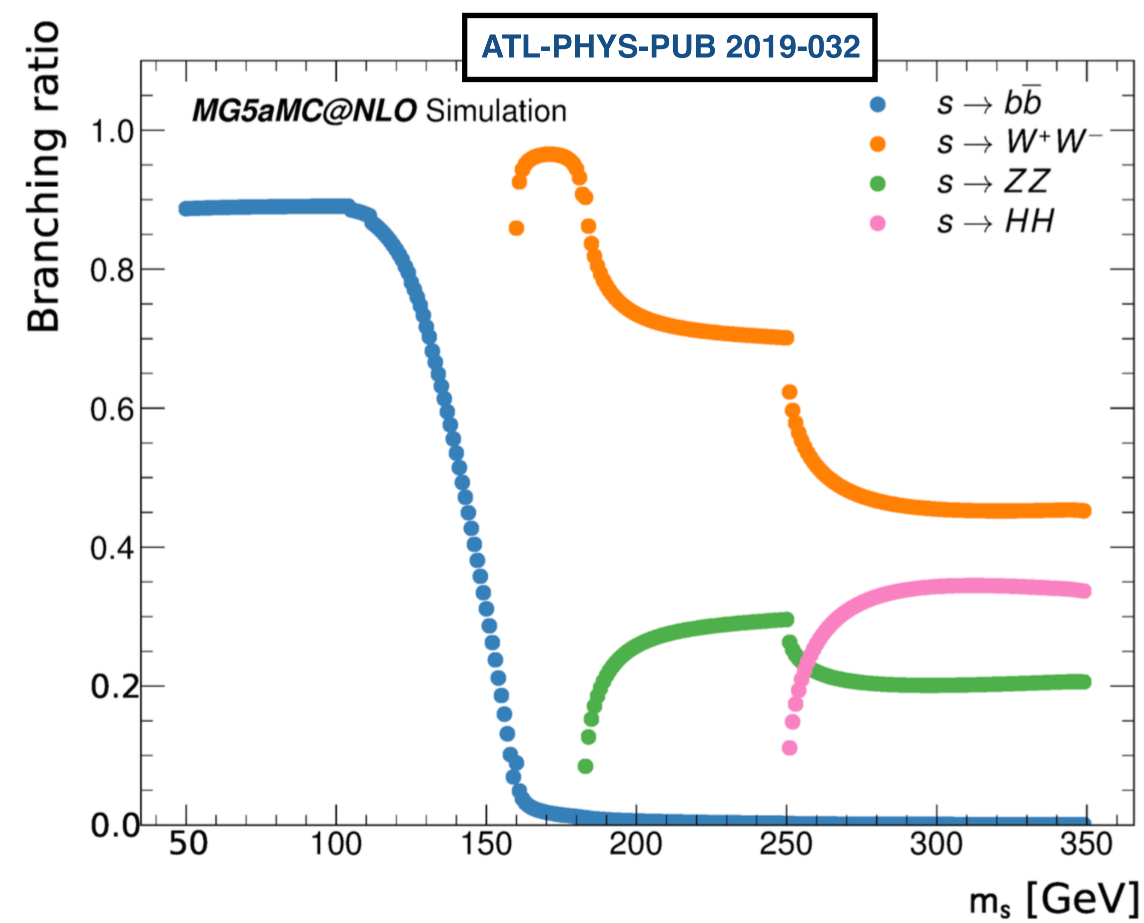
Motivation

- Search for DM using the dark Higgs simplified model as benchmark
- Emission of a dark Higgs boson, *S*, that mixes with the SM boson and **would provide mass to the DM (WIMPs) particles**
  - *S* can decay into SM states → can be searched at the LHC.
  - Mass scan [m*S*, mZ', m*χ*]. Fixed couplings
- Since *S* can be lighter than DM particles, it **could relax the DM relic abundance** constraints by introducing a new annihilation channel *χχ* → *SS*
- WW decay mode dominates the dominates the picture for m*S* ≳ 160 GeV (resonance). Ongoing CMS bb analysis is exploring the low mass region m*S* < 160 GeV
- **Analyzed full Run2 CMS data** (2016, 2017, 2018 data periods). Semi- and di-leptonic W^+W^- final states have been studied





Event selection: dileptonic

- The analysis targets the dileptonic + semileptonic decay of the W^+W^- boson pair
- Same event **selection** for the three data periods:

Target signature: two opposite charged isolated leptons, and large transverse missing energy from the neutrinos + χ_s

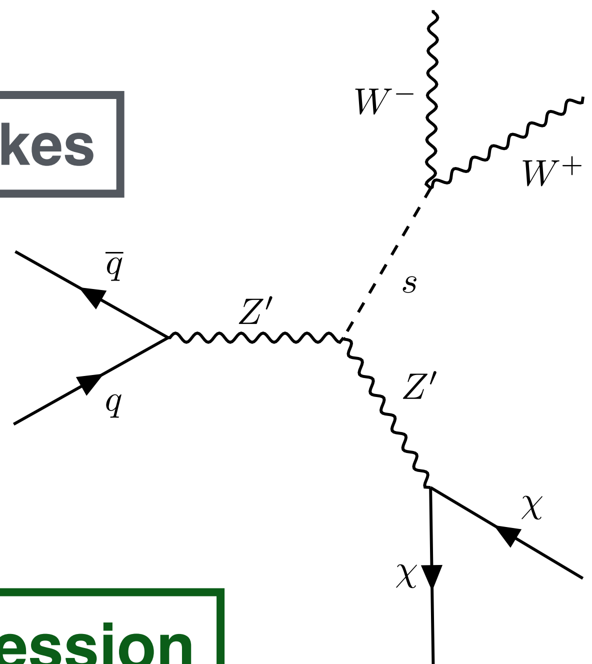
Dilep Selection
2 leptons, Different flavour, opposite signed
$p_{\ell 1T}$ / $p_{\ell 2T}$ > 25 / 20 GeV
Vetoed additional leptons with $p_{\ell 3T}$ > 10 GeV
$p_T^{\ell\ell}$ > 30 GeV
$m_{\ell\ell}$ > 12 GeV
p_T^{miss} > 20 GeV
$m_T(\ell\ell + p_T^{miss})$ > 50 GeV
$\Delta R(\ell\ell)$ < 2.5
Number of b-tagged jets = 0

Reduce Fakes

DY suppression

suppress non-resonant W^+W^-

suppress ttbar



Event selection: semileptonic

- The analysis targets the dileptonic + semileptonic decay of the W^+W^- boson pair
- Same event **selection** for the three data periods:

Target signature: one isolated leptons, two jets, and large transverse missing energy from the neutrinos + χ_s

Semilep Selection
1 isolated lepton, ≥2 jets
$p_{\ell_1 T}$ > trigger thresholds
Vetoed additional leptons with $p_{\ell_2 T} > 10$ GeV
Number of b-tagged jets = 0
$65 < m_{jj} < 105$ GeV
$p_T^{miss} > 60$ GeV
$p_T^{\ell jj} > 60$ GeV
$\Delta\phi(jj,\ell) < 1.8$, $\Delta R(jj,\ell) < 3$
$\Delta\phi(\ell jj, p_T^{miss}) > 2$

suppress ttbar (Number of b-tagged jets = 0)

suppress W+jets ($65 < m_{jj} < 105$ GeV)

target dark Higgs topology (p_T^{miss}, $p_T^{\ell jj}$, $\Delta\phi(jj,\ell)$ / $\Delta R(jj,\ell)$, $\Delta\phi(\ell jj, p_T^{miss})$ cuts)

Background estimation overview

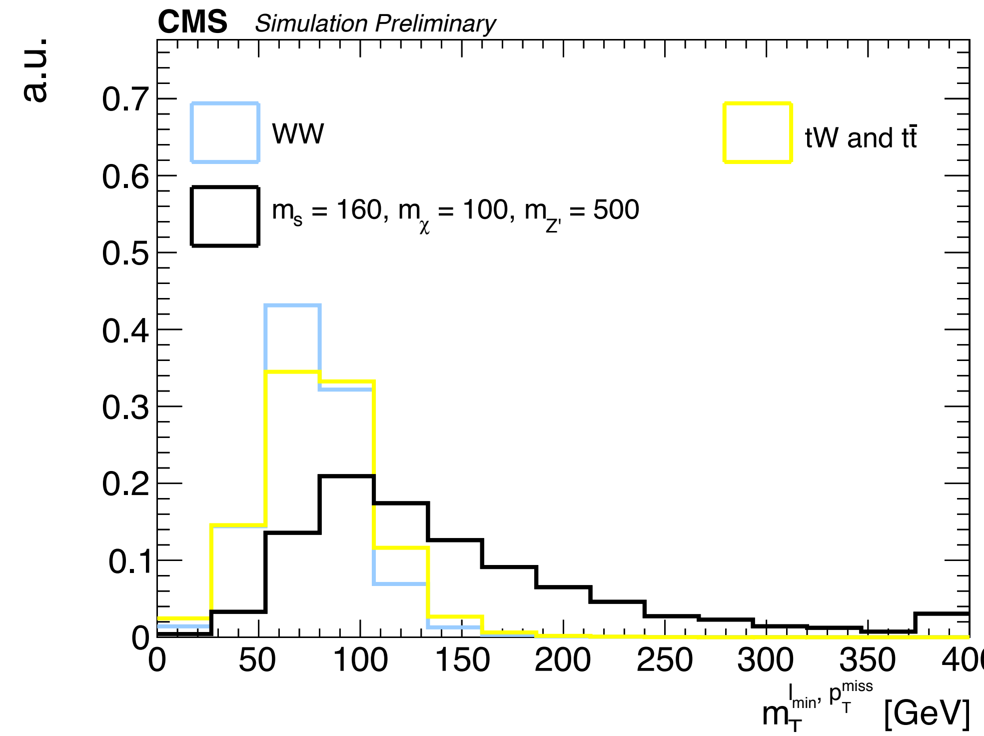
- **Dileptonic:**
  - **Non-prompt** leptons: estimated with a fully data-driven method, and validated in same-signed validation region
  - **Top-quark:** the normalization is measured using top-tagged events in data control region
  - **Non-resonant WW**: the normalization is measured using events with large angular distance between the two leptons in data control region
  - **$Z/\gamma^* \rightarrow \tau^+\tau^-$**: the normalization is measured using low mT(ℓℓ+MET) events in data control region
- **Semileptonic:**
  - **Non-prompt:** same strategy as for dileptonic
  - **Top-quark:** same strategy as for dileptonic
  - **W+Jets:** the normalization is measured using events with mjj side band in data control region
- All other (small) processes are estimated directly from simulation: HWW, Vϒ/Vϒ*, VZ, VVV

Orthogonal selection:
Same lepton charges
Number of b-tagged jets > 0
ΔR(ℓℓ) > 2.5
m_T(ℓℓ+MET) < 50 GeV
mT(l + MET) < 30 GeV && MET < 30 GeV
Number of b-tagged jets > 0
m_{jj} <65 or m_{jj} > 105 GeV

(keeping the other preselection requirements in each case)

Analysis strategy: dileptonic

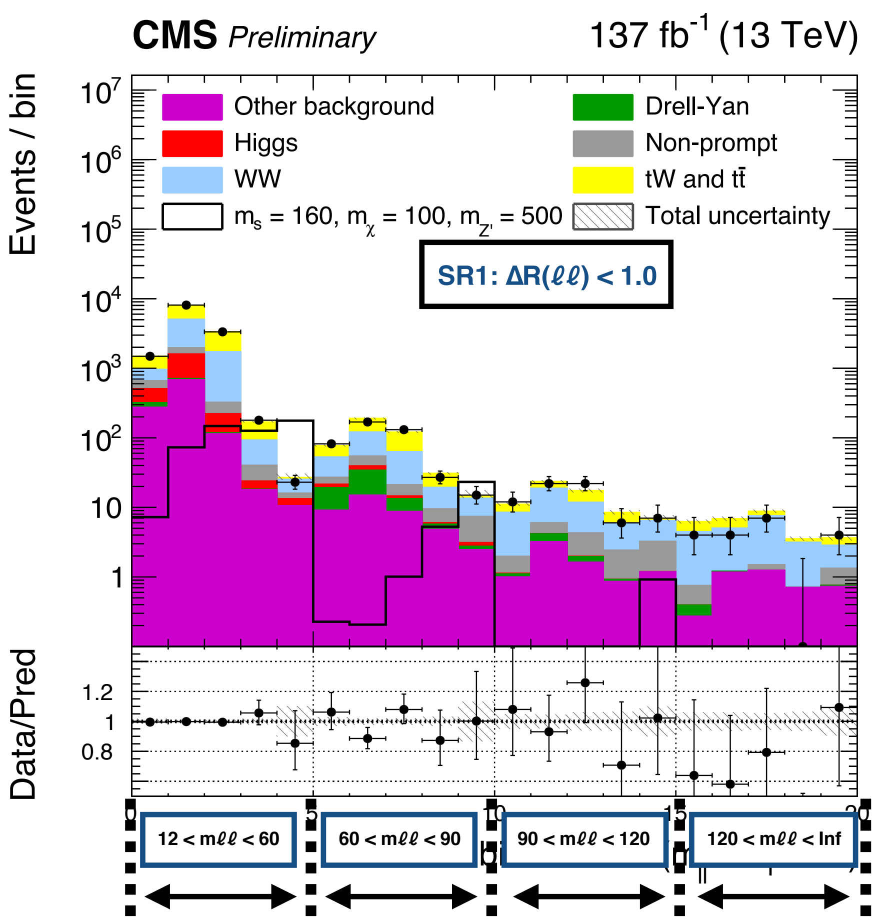
- **Dileptonic signal extraction:** 3D ML fit to ΔR(ℓℓ) - mℓℓ - mT(ℓmin + p_T^{mis})
- More sensitive to the dark Higgs signal prediction than other quantities based on lepton kinematics and/or p_T^{miss}
- **Optimized procedure:** strong kinematic dependence on m_S
    - Three signal regions are defined in ΔR(ℓℓ), based on the S/sqrt(S+B) curves vs ΔR(ℓℓ) for each dark Higgs mass
        - **SR1:** ΔR(ℓℓ) < 1.0, **SR2:** 1.0 < ΔR(ℓℓ) < 1.5, **SR3:** 1.5 < ΔR(ℓℓ) < 2.5

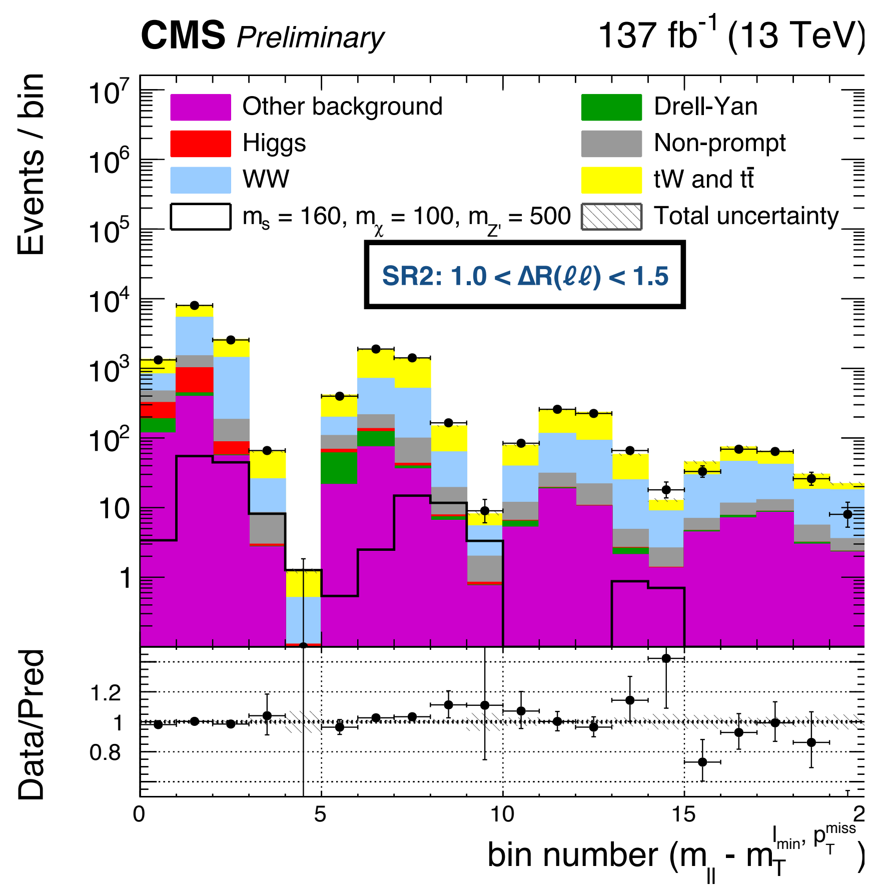


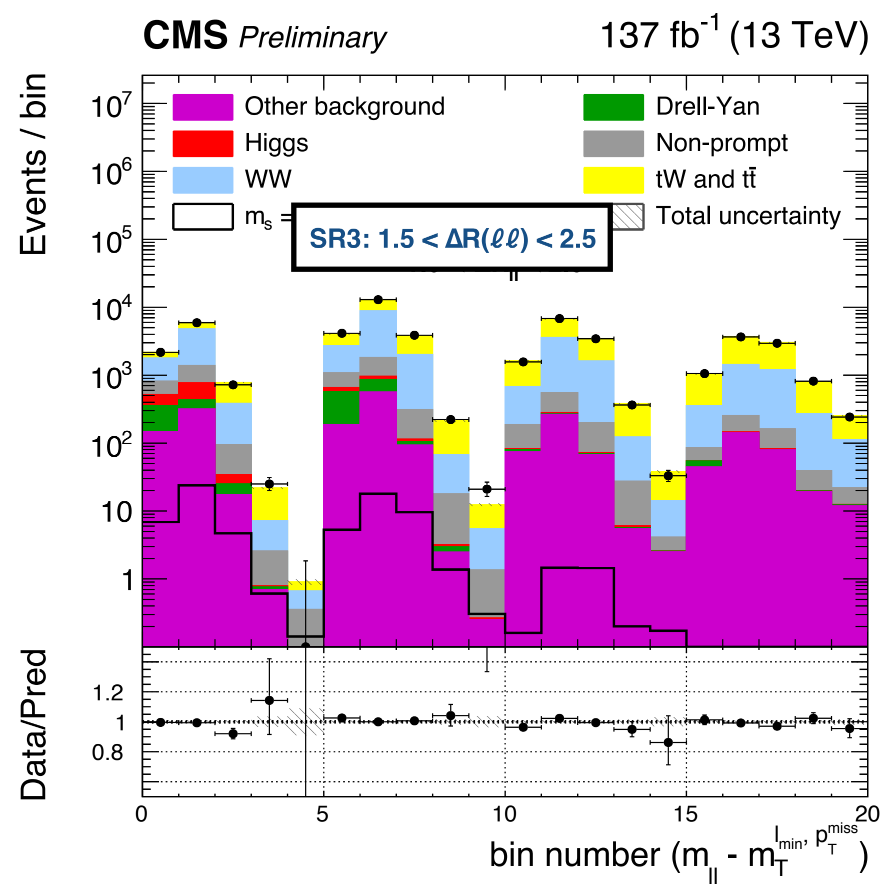
- For each SR, a 2D template of **mℓℓ - mT(ℓmin + p_T^{mis})** is defined:
    - The mℓℓ binning is set from significance S/sqrt(S+B) curves vs mℓℓ for each dark Higgs mass
    - The mT(ℓmin + pTmiss) binning is set by squeezing the sensitivity for each data period
- Allow the different signal mass points to **freely populate the 3D phase space** while using the same background modeling procedure

Results: dileptonic

- The signal strength is extracted by fitting the predicted yields to the observed events
- **ML fit:** 3 Signal Regions, 1 Top Control Region, 1 DY Control Region, 1 WW Control Region for each data period
  - Signal regions information entering in the fit: 2D histograms of $m_{\ell\ell}$ - $m_T(\ell_{min} + p_T^{mis})$ from SR1, SR2 and SR3
  - Control regions information entering in the fit: 1-bin distributions. Top, WW, and DY normalization freely float within the global fit







- No significant excess over the SM prediction

Binning

2016. $m_{\ell\ell}$: [12,60,90,120,inf], $m_T(\ell_{min} + p_T^{mis})$: [0,50,90,130,160,inf]
2017. $m_{\ell\ell}$: [12,60,90,120,inf], $m_T(\ell_{min} + p_T^{mis})$: [0,50,90,130,170,inf]
2018. $m_{\ell\ell}$: [12,60,90,120,inf], $m_T(\ell_{min} + p_T^{mis})$: [0,50,90,130,180,inf]

Analysis strategy: semileptonic

- **Semileptonic signal extraction:** fit to the shape of BDT output score
- BDT trained with set of variables that showed most separation power between signal and background, based on final state objects (lepton, 2 jets, MET)

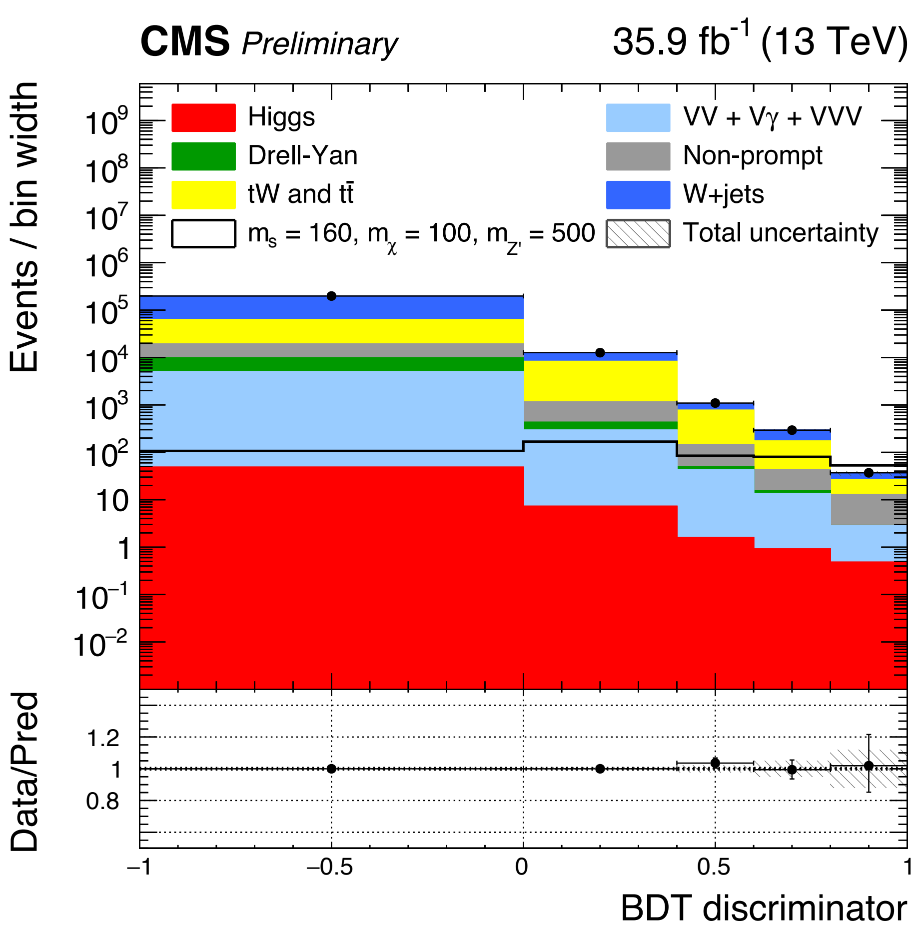
Variable	Definition
$p_{\mathrm{T}}^{\mathrm{jj}}$	p_{T} of the vectorial sum of the W candidate jets
$p_{\mathrm{T}}^{\ell \mathrm{jj}}$	p_{T} of the vectorial sum of the visible particles
$p_{\mathrm{T}}^{\mathrm{miss}}$	Size of the missing transverse momentum vector
$\Delta\eta_{\ell,\mathrm{jj}}$ and $\Delta\phi_{\ell,\mathrm{jj}}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and the di-jet system
$\Delta\eta_{\mathrm{j,j}}$ and $\Delta\phi_{\mathrm{j,j}}$	$\Delta\eta$ and $\Delta\phi$ between the W candidate jets
$\Delta\eta_{\ell,p_{\mathrm{T}}^{\mathrm{miss}}}$ and $\Delta\phi_{\ell,p_{\mathrm{T}}^{\mathrm{miss}}}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
$\Delta\phi_{\ell \mathrm{jj},p_{\mathrm{T}}^{\mathrm{miss}}}$	$\Delta\phi$ between the vectorial sum of the visible particles and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
$min(p_{\mathrm{T}}^{\ell}, p_{\mathrm{T}}^{\mathrm{j}_2})/p_{\mathrm{T}}^{\mathrm{miss}}$	Minimum of the lepton p_{T} and the trailing jet p_{T}, divided by $p_{\mathrm{T}}^{\mathrm{miss}}$
$max(p_{\mathrm{T}}^{\ell}, p_{\mathrm{T}}^{\mathrm{j}_2})/p_{\mathrm{T}}^{\mathrm{miss}}$	Maximum of the lepton p_{T} and the leading jet p_{T}, divided by $p_{\mathrm{T}}^{\mathrm{miss}}$
$max(p_{\mathrm{T}}^{\ell}, p_{\mathrm{T}}^{\mathrm{j}_1})/m_{\ell \mathrm{jj} p_{\mathrm{T}}^{\mathrm{miss}}}$	Maximum of the lepton p_{T} and the leading jet p_{T}, divided by the invariant mass of the vectorial sum of the visible particles and the $p_{\mathrm{T}}^{\mathrm{miss}}$ where the missing energy is considered to be massless

- Binning optimized based on S/sqrt(S+B) curves for the three data periods

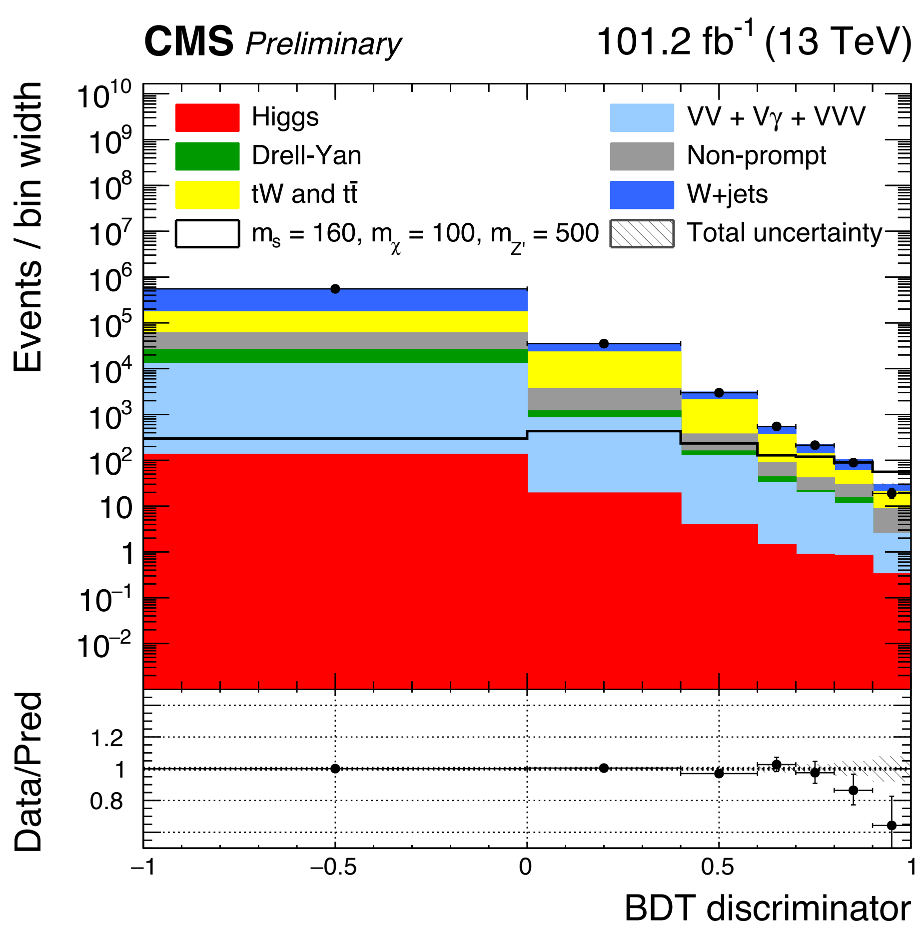
Results: semileptonic

- **ML fit:** 1 Signal Regions, 1 Top Control Regions, 1 DY Control Region, 1 WW Control Region for each data period
  - Signal regions information entering in the fit: 1D histograms of BDT output score
  - Control regions information entering in the fit: 1-bin distributions. Top and W+Jets normalization freely float within the global fit

2016 BDT output



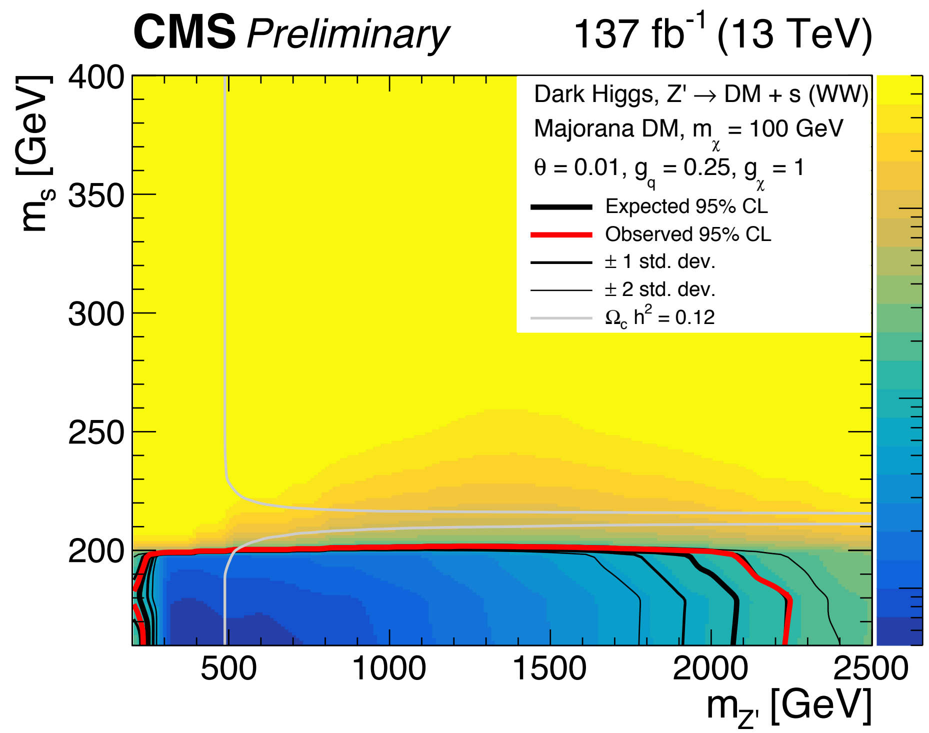
2017+2018 BDT output



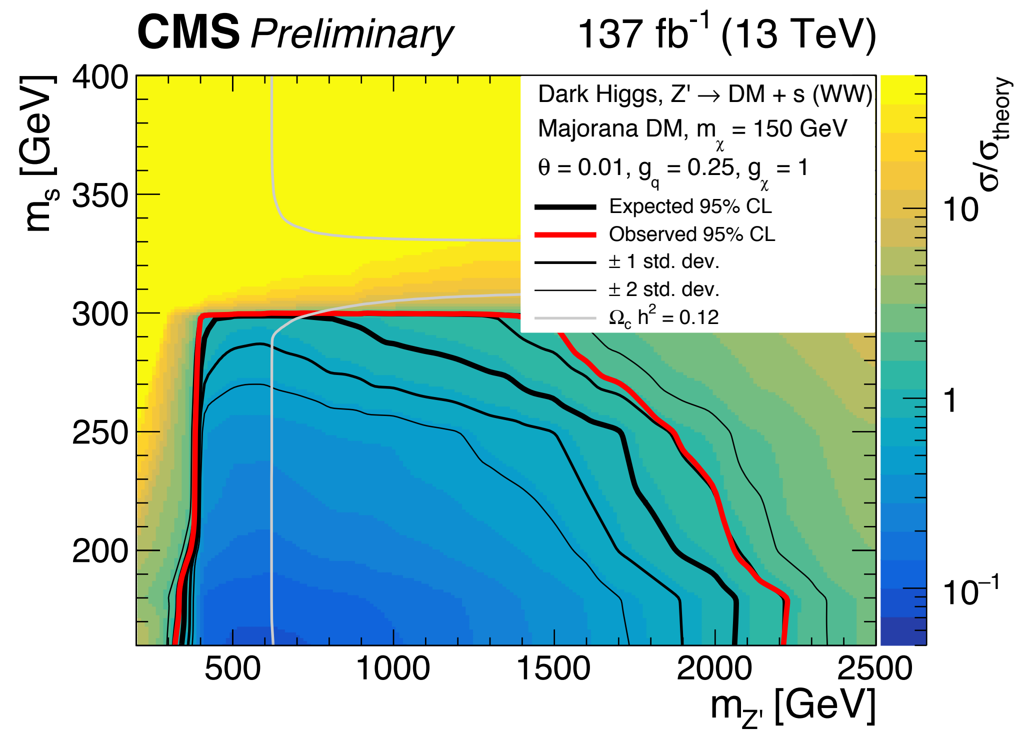
- Finer binning in 2017-2018 to squeeze the sensitivity

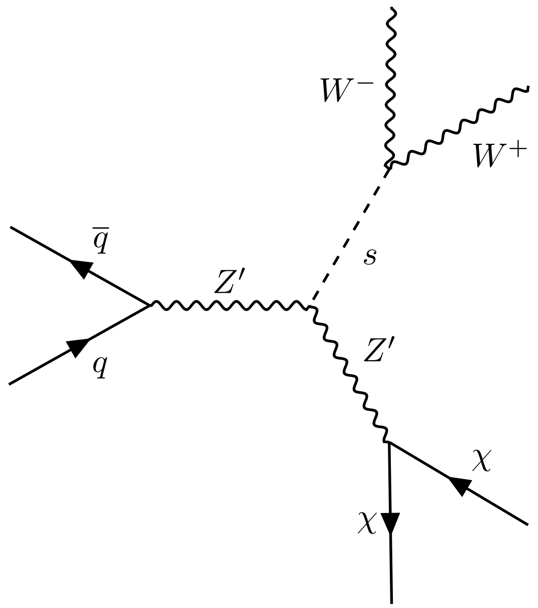
Results: combination

mχ = 100 GeV

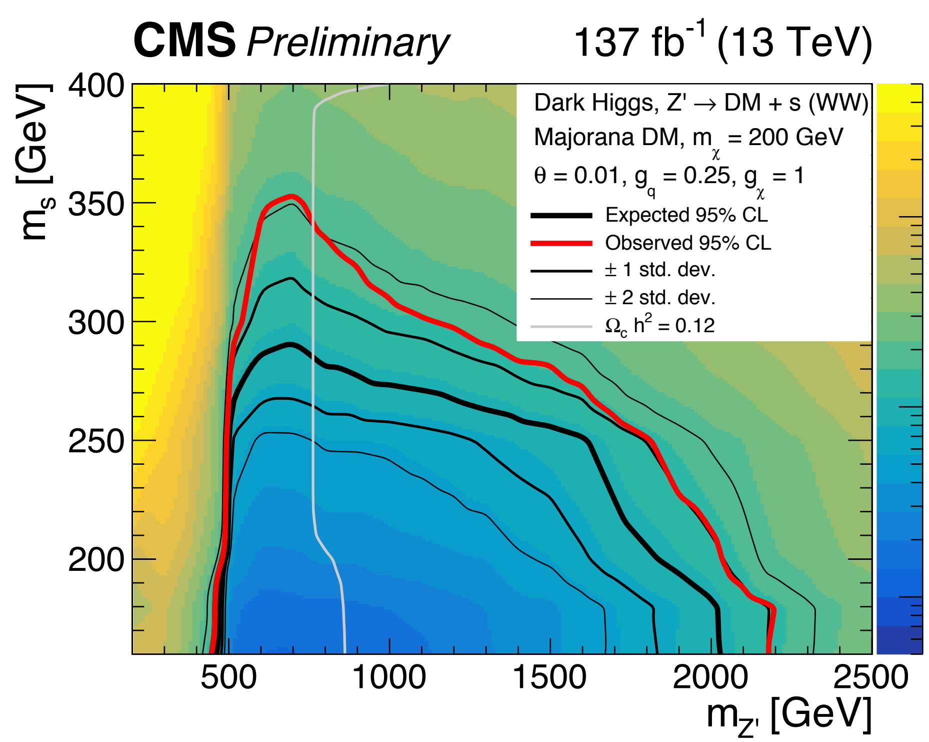


mχ = 150 GeV

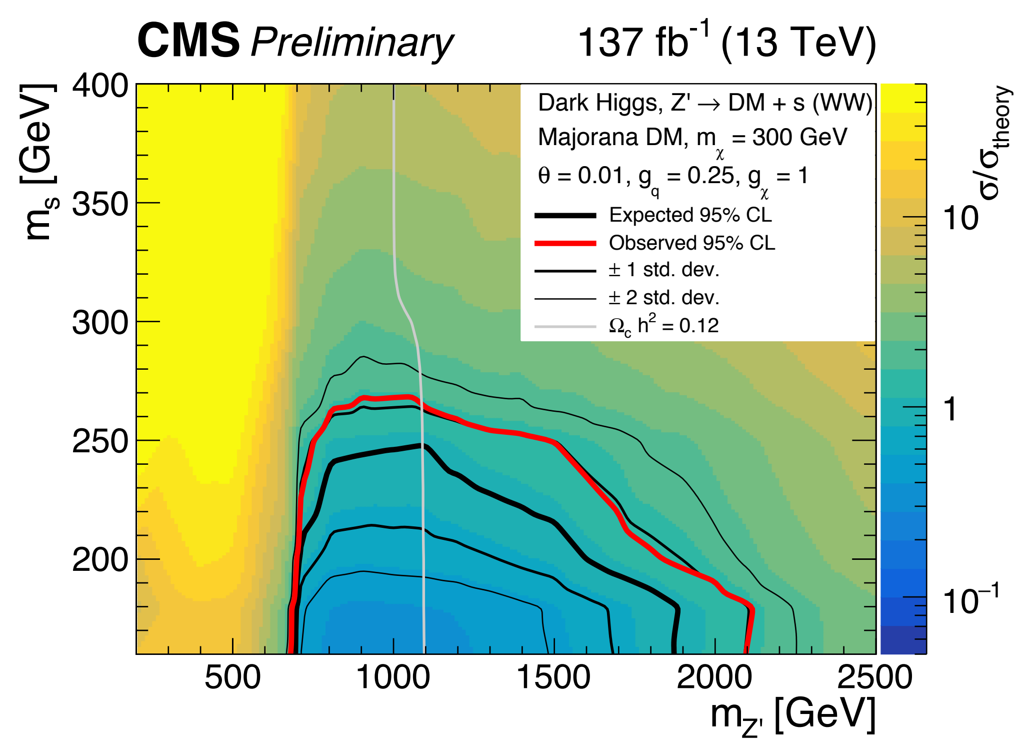




mχ = 200 GeV



mχ = 300 GeV



- Dominant $S \to \chi\chi$ decay mode (invisible) for m$S \geq 2$mχ
- Observed limit is better than the expected due to slight data deficit in some of the sensitive bins

Summary

- A search for dark matter particles produced in association with a dark Higgs boson has been presented, using the full Run2 CMS dataset
    - **First measurement at CMS.**
    - The decay modes of the dark Higgs boson to WW→2ℓ,2nu and WW→1ℓ,1nu,2j have been explored
    - No significant deviation from the Standard Model predictions is observed. Upper limits are set on the dark Higgs model parameters
    - Comparable sensitivity with latest ATLAS result (talk by A. García-Bellido on Friday)