Dark Matter searches at CMS and ATLAS

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On behalf of the ATLAS and CMS collaborations

56th Rencontres de Moriond
Electroweak Interactions & Unified Theories
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What is the nature of dark matter?

- various approaches to answer the question:

  direct/indirect searches

  searches at colliders

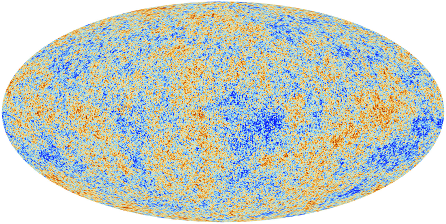
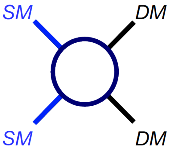
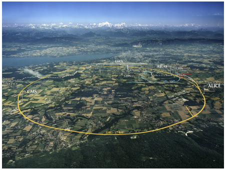


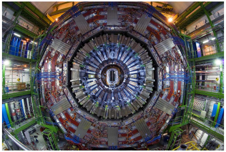
Figure: Planck Collaboration

At the Large Hadron Collider ...

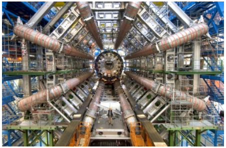




LHC



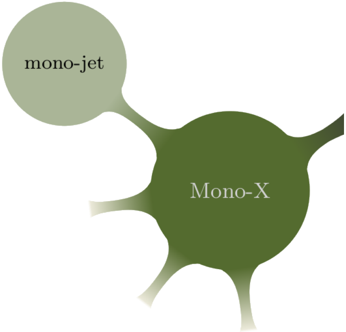
CMS



ATLAS

*A **non-exhaustive** list of typical DM searches at the LHC*

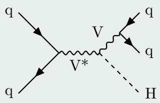
*Covered in **this** talk ...*



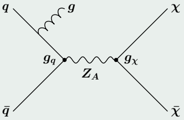
… reducing model dependence by exploiting initial state radiation …

Theoretical Scenarios

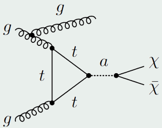
VH production of SM Higgs



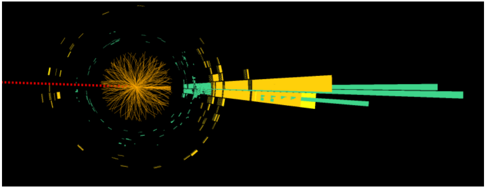
Simpl. model: spin-1 mediator



Complex model: 2HDM+a



Experimental Signature: p_T^{miss} + jet



♦ triggering based on p_T^{miss} ♦

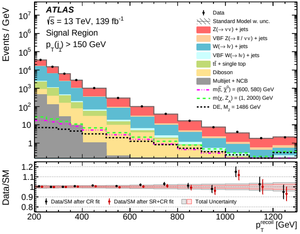
- normally requires high p_T^{miss} thresholds
- removes dominant QCD multi-jet background

♦ offline selection ♦

- targets two types of jets:
  - ⋆ fat jets produced in $V \to qq$ decays
    - collimated hadrons from energetic quarks
    - machine learning used to ‘V-tag’
  - ⋆ standard size jets
- events with μ, e, τ, or γ are vetoed
- large $\Delta\phi(\vec{p}_T^{\,\text{jet}}, \vec{p}_T^{\,\text{miss}})$ to avoid misreconstructed QCD jets

Final Discriminant

♦ p_T^{miss} distribution ♦



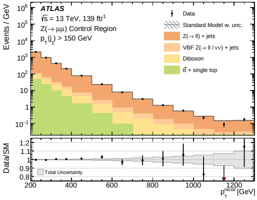
- need to predict p_T^{miss} as precise as possible

Background Estimation

♦ based on subsidiary measurements in ‘control regions’ ♦

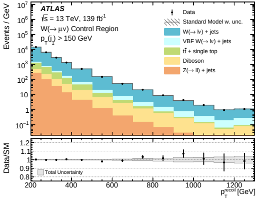
⋆ $Z(\to \nu\bar{\nu})$ + Jets:

- identical topology as signal

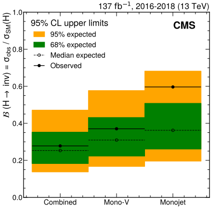


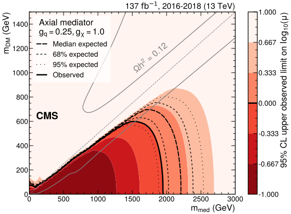
⋆ $W(\to l\bar{\nu}_l)$ + Jets:

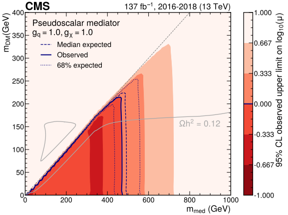
- lepton is not reconstructed

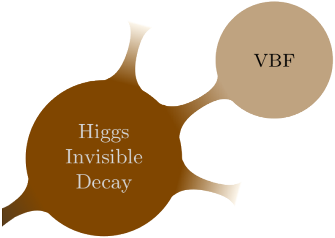


Results







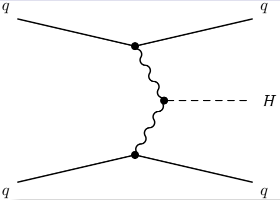


... Higgs not only provides mass, it could also serve as a portal into darkness ...

Simple Scenario: *Additional scalar with mixing*

$$\mathcal{L}(H,\phi,\chi) \supset \lambda(H^\dagger H)^2 + \mu^2(H^\dagger H) + \lambda_\phi \phi^4 + \mu_\phi^2 \phi^2 + \alpha H^\dagger H \phi^2 + y_\chi \bar{\chi}\chi\phi$$

Most sensitive production mode: VBF



- excellent balance between cross-section and signature
- p_T^{miss} and two jets with relatively high separation in η

Selection

♦ combination of p_T^{miss} and VBF-like triggers employed ♦

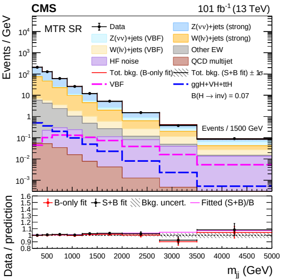
- results in two different categories: moderate p_T^{miss} (VTR) and high p_T^{miss} (MTR)

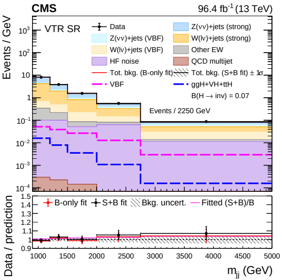
♦ offline selection targets the characteristic VBF kinematics ♦

- two jets in opposite detector hemispheres $\eta_{j_1} \cdot \eta_{j_2} < 0$
- large separation between the jets $|\eta_{jj}| > 1$ and substantial $\Delta\phi(\vec{p}_T^{\text{jets}}, \vec{p}_T^{\text{miss}})$
- events with charged leptons and photons are vetoed

Final Discriminant

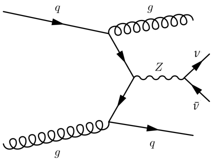
♦ m_{jj} distribution ♦



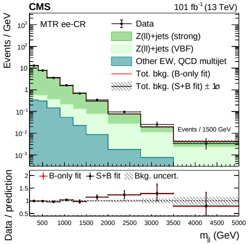


Background Estimation

- dominant SM processes
  - $Z(\to \nu\bar{\nu})$ + Jets
  - $W(\to l\bar{\nu}_l)$ + Jets
- controlled using additional regions



Z production with VBF kinematics

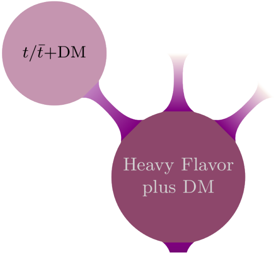


Results

$\mathcal{B}(H \to \text{Inv}) < 0.18$ (0.10 exp) (CMS)
$\mathcal{B}(H \to \text{Inv}) < 0.15$ (0.10 exp) (ATLAS)

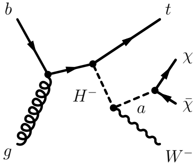
For comparison

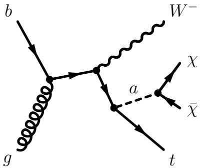
- mono-Jet (CMS): $\mathcal{B}(H \to \text{Inv}) < 0.28$ (0.25 exp)
- mono-Z (ATLAS): $\mathcal{B}(H \to \text{Inv}) < 0.19$ (0.19 exp)



... Yukawa couplings will favor the invisible ones to be accompanied by the heaviest ones ...

Theoretical Scenarios: 2HDM+a





- dominant single top final state when $H^\pm \to W^\pm a$ kinematically allowed
- mainly targets the scenario of a boosted $W^\pm$ boson from $H^\pm \to W^\pm a$ decays

Selection

♦ triggering based on p_T^{miss} ♦

- single-lepton triggers used for auxiliary selections in the estimation of background

♦ offline selection targets two main categories: $0l$ and $1l$ ♦

tW_{0l}

- ▷ high p_T^{miss} in the event
- ▷ no presence of leptons (e or μ)
- ▷ at least 4 standard jets
- ▷ at least 1 b-tagged jet
- ▷ one W-tagged fat jet

tW_{1l}

- ▷ high p_T^{miss} in the event
- ▷ exactly one lepton (e or μ)
- ▷ at least 1 b-tagged jet

$t(\to l\bar{\nu}_l b)W(\to qq')$

- ▷ at least 2 standard jets
- ▷ one W-tagged fat jet

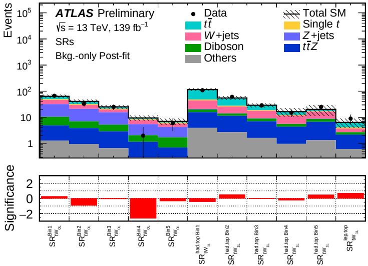
$t(\to qq'b)W(\to l\bar{\nu}_l)$

- ▷ at least 3 standard jets

Final Discriminant

♦ p_T^{miss} distribution ♦

- $0l$ and $1l_{t(\to qq'b)W(\to l\bar{\nu}_l)}$ SRs split in 5 p_T^{miss} bins
- $1l_{t(\to l\bar{\nu}_l b)W(\to qq')}$ SR kept in only 1 p_T^{miss} bin

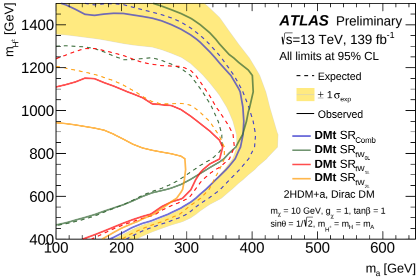


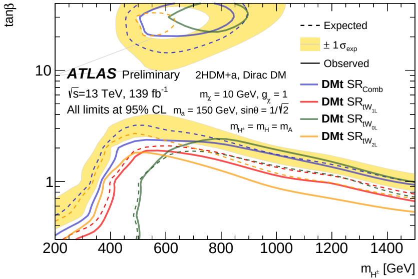
Background Estimation

♦ main sources are $W + Jets$, $t\bar{t}$, $Z + Jets$, and $t\bar{t}Z$ ♦

♦ dedicated control regions targeting normalizations ♦

Results

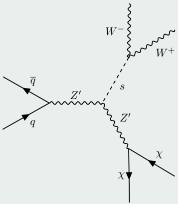




$0l$ and $1l$ channels statistically combined with $2l$ (2011.09308) channel

... not only the visible sector deserves an explanation of how the mass was acquired ...

Theoretical Model



- *additional* $U(1)'$ local gauge symmetry
- $U(1)'$ *broken* by introducing complex scalar ($s \leftrightarrow Z$ interaction)
- SM particles interact with s through $s \leftrightarrow H$ *mixing*
- specify how mediator and DM get their *mass* (as opposed to Simpl.)

Signature for dileptonic W^+W^- decay: $l\bar{l} + p_T^{\text{miss}}$

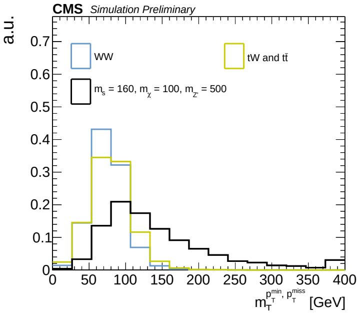
♦ single-lepton and di-lepton triggers used ♦

- boosting in leptons for some mass configurations

♦ offline selection uses leptons and p_T^{miss} ♦

- 2 opposite-charge leptons with different flavor (reduces $Z + Jets$)
- events with b-tagged jet are vetoed (reduces $t\bar{t}$ & tW)
- key variable is the transverse mass $m_T^{l_{min}, p_T^{\text{miss}}}$

$$m_T^{l_{min}, p_T^{\text{miss}}} = \sqrt{2 p_T^{l_{min}} p_T^{\text{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,l_{min}}, \vec{p}_T^{\,\text{miss}})\right]}$$

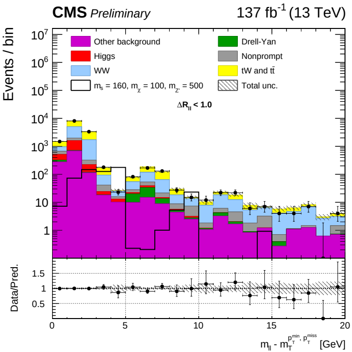


Final Discriminant

♦ 2D m_{ll} **vs** $m_T^{l_{min},p_T^{\mathrm{miss}}}$ distribution ♦

- signal region further categorized according $\Delta R(\bar{l}, l)$
- accounts for different signal boosting regimes

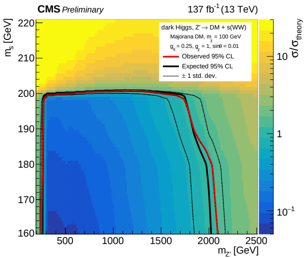
unrolled 2D distribution ⇒

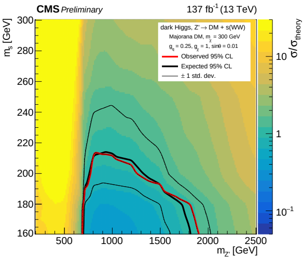


Background Estimation

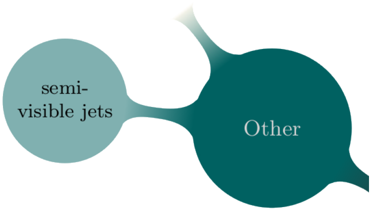
♦ mainly from simulation, normalizations in CRs ♦

Results





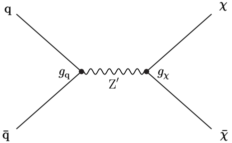
- *can probe Z' masses up to 2TeV*
- *most stringent limits for $m_\chi \sim 150$ GeV*
- *sensitivity weakens for $m_s > 2m_\chi$ as $s \rightarrow \bar{\chi}\chi$ starts to dominate*

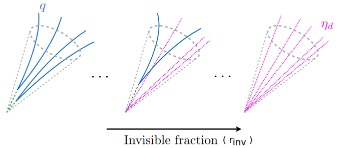


... hidden intricate dynamics can produce truly distinctive signatures ...

Theoretical Models

- hidden sectors with strong dynamics (analogous to QCD)
- possibility of compositeness with stable (DM candidate) and unstable 'dark hadrons'
- unstable dark hadrons can decay to visible hadrons through the portal coupling





$$r_{\text{Inv}} = \frac{N_{\text{stable}}}{N_{\text{stable}} + N_{\text{unstable}}}$$

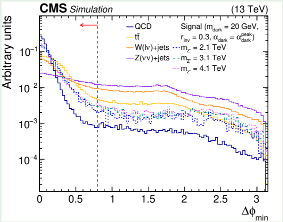
Signature: *two highly energetic jets*

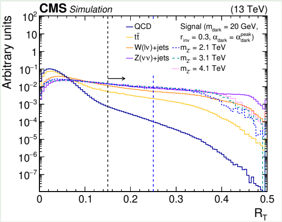
♦ triggering based on jets ♦

♦ offline selection ♦

- low $\Delta\phi_{\min} = \min[\Delta\phi(\vec{p}_{j_1,j_2}, \vec{p}_T^{\,\text{miss}})]$ **(previous searches imposed an inverted cut to avoid fake p_T^{miss}!)**
- high $R_T = p_T^{\text{miss}}/m_T$ **(used to uncorrelate $p_T^{\text{miss}} \leftrightarrow m_T$)**
- key distribution:

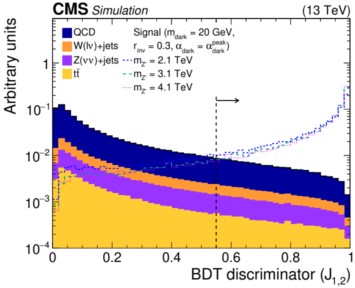
$$m_T^2 = m_{jj}^2 + 2p_T^{\text{miss}}\left[E_{T_{jj}} - p_{T_{jj}}\cos(\phi)\right]$$





Identification of semivisible jets

- designed to reduce even further the background
- targets differences between semivisible jets and SM jets
- *15* input variables are combined in a BDT
  - exploit quantities related to jet-substructure
  - accounts for variations in signal (r_{Inv}, $m_{Z'}$, m_{dark})
  - chosen WP (0.55) rejects (accept) around 85% (87%)



Final Discriminant

♦ dijet transverse mass m_T ♦

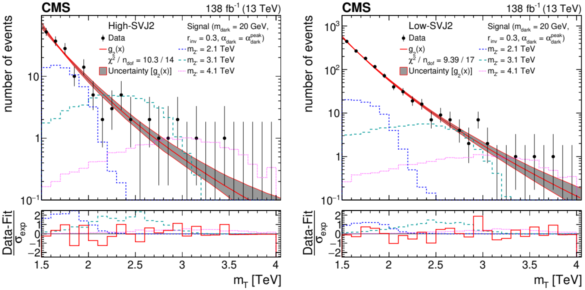
- selection categorized according to R_T (*low* and *high*)

Background Estimation

♦ analytic smoothly falling function ♦

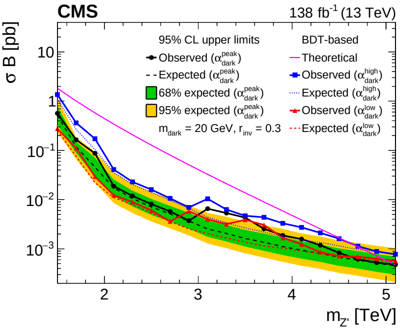
$$g(x) = e^{p_1 x} x^{p_2 [1 + p_3 \ln(x)]}$$

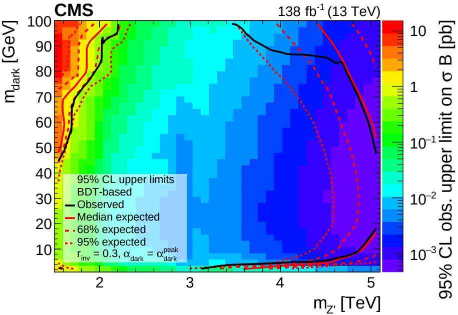
- parameters (p_i) and normalization freely floating in the final fit

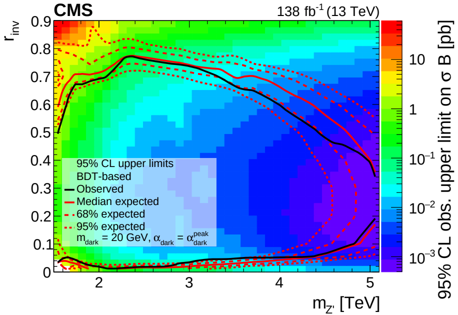


Results

- *large improvement **vs** analysis without BDT identification of semivisible jets*
- *excluding* $1.5 \lesssim m_{Z'} \lesssim 5$ *TeV for* $r_{Inv} = 0.3$
- *excluding* $0.01 \lesssim r_{Inv} \lesssim 0.77$ *for* $m_{dark} = 20$ *GeV*
- *small excess around* $m_{Z'} = 3.5$ *TeV with no real significance* ($\sim 2\sigma$ *local*)

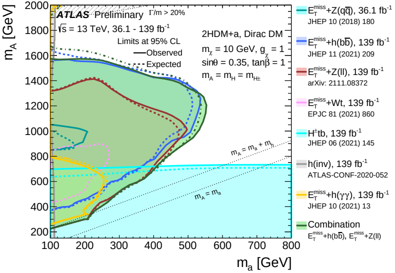






- large variety of interesting signatures being covered by ATLAS and CMS
  - dedicated analyses for specific final states
  - optimized for a wide range of model types
- experimental techniques evolving to more sophisticated approaches
  - use of machine learning is consolidating bringing substantial improvements
  - increase on importance of having good control of systematic uncertainties
- still more searches to be ready in the near future with full RunII data
  - improvements expected also from adding channels previously not considered
- no signal observed yet, but many new searches planned

For more results: CMS/ATLAS



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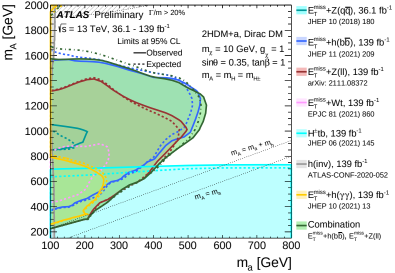


Thanks for your attention!

Backup

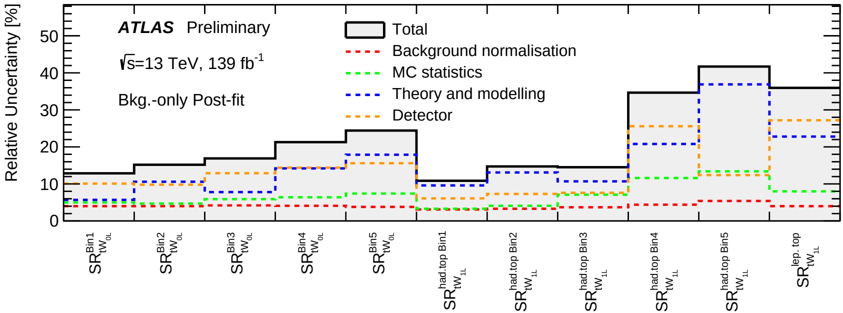
Requirement	SR	$W \to \mu\nu$	$Z \to \mu\mu$	$W \to e\nu$	$Z \to ee$	Top
Primary vertex	at least one with ≥ 2 associated tracks with $p_{\mathrm{T}} > 500$ MeV					
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$			single-electron		$E_{\mathrm{T}}^{\mathrm{miss}}$, single-electron
$p_{\mathrm{T}}^{\mathrm{recoil}}$ cut	$E_{\mathrm{T}}^{\mathrm{miss}} >$ 200 GeV	$\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}(\mu)\rvert >$ 200 GeV	$\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}(\mu\mu)\rvert >$ 200 GeV	$\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}(e)\rvert >$ 200 GeV	$\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}(ee)\rvert >$ 200 GeV	$\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}(\mu)\rvert >$ 200 GeV or $\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}(e)\rvert >$ 200 GeV
Jets	up to 4 with $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.8$					
$\lvert\Delta\phi(\text{jets},\mathbf{p}_{\mathrm{T}}^{\mathrm{recoil}})\rvert$	> 0.4 (> 0.6 if 200 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} \leq 250$ GeV)					
Leading jet	$p_{\mathrm{T}} > 150$ GeV, $\lvert\eta\rvert < 2.4$, $f_{\mathrm{ch}}/f_{\mathrm{max}} > 0.1$					
b-jets	any	none	any	none	any	at least one
Electrons or muons	none	exactly one muon, with $p_{\mathrm{T}} >$ 10 GeV, $30 < m_{\mathrm{T}} <$ 100 GeV; no electron	exactly two muons, with $p_{\mathrm{T}} >$ 10 GeV, $66 < m_{\mu\mu} <$ 116 GeV; no electron	exactly one electron, tight, with $p_{\mathrm{T}} >$ 30 GeV, $\lvert\eta\rvert \notin (1.37, 1.52)$, tight isolation, $30 < m_{\mathrm{T}} <$ 100 GeV; no muon	exactly two electrons, with $p_{\mathrm{T}} >$ 30 GeV, $66 < m_{ee} <$ 116 GeV; no muon	same as for $W \to \mu\nu$ or same as for $W \to e\nu$
τ-leptons	none					
Photons	none					

Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ-lepton identification efficiency	0.1 – 0.07
Jet energy scale	0.17 – 1.0	Luminosity	0.01 – 0.05
Jet energy resolution	0.15 – 1.3	Noncollision background	0.2 – 0.0
Jet JVT efficiency	0.01 – 0.03	Multijet background	1.0 – 0.0
Pileup reweighting	0.4 – 0.24	Diboson theory	0.01 – 0.22
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	0.34 – 0.04	Single-top theory	0.13 – 0.28
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	0.5 – 0.25	$t\bar{t}$ theory	0.06 – 0.7
Electron and photon energy resolution	0.01 – 0.08	V+jets τ-lepton definition	0.04 – 0.16
Electron and photon energy scale	0.3 – 0.7	V+jets pure QCD corrections	0.24 – 1.1
Electron identification efficiency	0.5 – 1.0	V+jets pure EW corrections	0.17 – 2.2
Electron reconstruction efficiency	0.15 – 0.2	V+jets mixed QCD–EW corrections	0.02 – 0.7
Electron isolation efficiency	0.04 – 0.19	V+jets PDF	0.01 – 0.7
Muon identification efficiency	0.03 – 0.9	VBF EW V+jets backgrounds	0.02 – 1.1
Muon reconstruction efficiency	0.4 – 1.5	Limited MC statistics	0.05 – 1.9
Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%			

	CMS	ATLAS
p_T^{miss}	> 250 GeV	> 200 GeV
number of p_T^{miss} bins	22	13
categories	mono-jet, mono-V	mono-jet
control regions	5 ($2 \times W$, $2 \times Z$, $1 \times \gamma$)	5 ($2 \times W$, $2 \times Z$, $1 \times t$)
$\mathcal{B}(h \to \text{Inv})$	< 0.28 (0.25 exp)	< 0.34 (0.39 exp)

Group of systematic uncertainties	Impact on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$	
	Observed	Expected
Theory	$^{+0.026}_{-0.025}$	± 0.024
Simulated event count	± 0.022	$^{+0.021}_{-0.022}$
Triggers	$^{+0.018}_{-0.019}$	± 0.018
Jet calibration	$^{+0.014}_{-0.012}$	± 0.011
QCD multijet mismodelling	± 0.012	± 0.013
Leptons/photons/b-tagged jets	$^{+0.011}_{-0.010}$	$^{+0.009}_{-0.010}$
Integrated luminosity/pileup	± 0.004	± 0.004
Other systematic uncertainties	$^{+0.013}_{-0.009}$	± 0.009
Statistical uncertainty	± 0.028	± 0.028

	CMS	**ATLAS**
final discriminant	m_{jj} (2 cat.: MTR & VTR)	3D binning (16) in $[n_j,\ m_{jj},\ \Delta\phi(j,j)]$
p_T^{miss}	> 160 GeV	> 160 GeV
$\lvert\Delta\eta_{jj}\rvert$	> 1	> 3.8
$\Delta\phi_{jj}$	$< 1.5(1.8)$	< 2
control regions	V+Jets, QCD	V+Jets, QCD
$\mathcal{B}(h \to \text{Inv})$	< 0.18 (0.10 exp)	< 0.15 (0.10 exp)

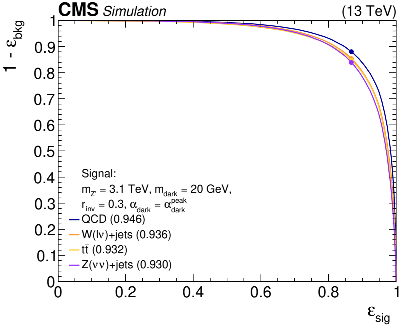


Binning: $p_T^{\mathrm{miss}} = [250, 330, 400, 500, 600, \mathrm{inf}]$ GeV

Quantity	Selection
Number of leptons	2
Lepton flavors	eμ, μe
Lepton charges	Opposite
Additional leptons	0
$p_{\mathrm{T}}^{\ell\,\mathrm{max}}$	> 25
$p_{\mathrm{T}}^{\ell\,\mathrm{min}}$	> 20
$m_{\ell\ell}$	> 12
$p_{\mathrm{T}}^{\ell\ell}$	> 30
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 20
$p_{\mathrm{T,proj}}^{\mathrm{miss}}$	> 20
$m_{\mathrm{T}}^{ll,p_{\mathrm{T}}^{\mathrm{miss}}}$	> 50
$\Delta R_{\ell\ell}$	< 2.5
Number of b-tagged jets	0

Binning: $m_T^{l_{min},p_T^{\mathrm{miss}}} = [0, 50, 90, 130, 160, \inf]$ GeV **vs** $m_{ll} = [12, 60, 90, 120, \inf]$ GeV

⋆ comparable impact between statistical and systematic uncertainties



Background	Acc.	AUC	$1/\varepsilon_{bkg}$ ($\varepsilon_{sig} = 0.3$)
QCD	0.883	0.946	636.8
$t\bar{t}$	0.883	0.932	290.0
W+jets	0.883	0.936	477.1
Z+jets	0.883	0.930	455.4

Scan	$m_{Z'}$ [TeV]	m_{dark} [GeV]	r_{inv}	α_{dark}
1	1.5–5.1	1–100	0.3	α_{dark}^{peak}
2	1.5–5.1	20	0–1	α_{dark}^{peak}
3	1.5–5.1	20	0.3	α_{dark}^{low}–α_{dark}^{high}

Uncertainty	Yield effect [%]
Integrated luminosity	1.6
Jet energy corrections	0.05–12
Jet energy resolution	0.02–2.3
Jet energy scale	0.29–21
PDF	0.0–5.3
Parton shower FSR	0.07–9.4
Parton shower ISR	0.0–2.9
Pileup reweighting	0.0–1.3
Renormalization and factorization scales	0.0–0.12
Statistical	1.2–4.9
Trigger control region	0.24–0.40
Trigger efficiency	2.0
Total	3.3–22

Figure: Signal uncertainties

- ⋆ impacts dominated by fit function parameter uncertainties
    - largest one is from background normalization (unconstrained pre-fit)