Searches for dark matter produced via scalar resonances in $bbZ + \vec{p}_T^{\,\text{miss}}$ final states for different decay topologies

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Collider Dark Matter Searches:

- guided in the past predominantly by simplified models
- recent turn to more complete scenarios, i.e. 2HDMa
  - many currently being optimized under this benchmark
  - specific topology might be overly restrictive

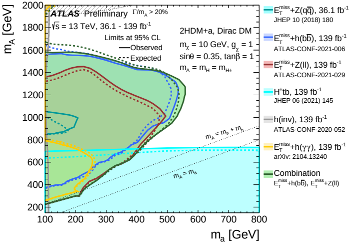

Figure: ATLAS-CONF-2021-036

··· In this study ···

- assessment of sensitivity of current approaches in the context of a wider class of topologies for DM production
  - demonstrate the possibility of re-interpretation of specific searches in a larger variety of BSM models
- exploration of untested production channel: $bbZ + \vec{p}_T^{\,miss}$
  - no dedicated experimental search at the LHC up to now
  - efforts on this channel recently started in CMS (see presentation bbZ+DM@CMS)

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- SM extended by one heavy scalar (Φ), one mediator (M), and one invisible particle (I)
- M and I are *neutral* and can be in three different representations: *scalar*, *fermion*, or *vector*
  - here taken both as scalars for simplicity
- all possible interactions among BSM particles and between SM and BSM particles included
  - e.g. topology *2-vs-1 unbalanced* would reproduce the equivalent one in **2HDMa**

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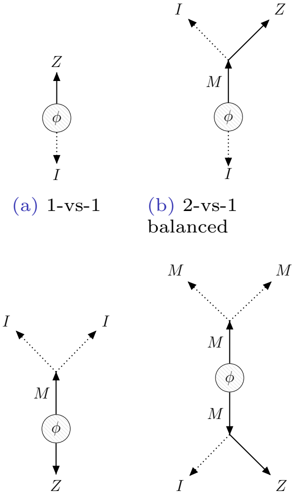
- focus on bottom-associated production of the neutral scalar: $pp \to bb\Phi$
  - decay to a Z boson and different number of invisible particles
  - four topologies illustrated are considered



(a) 1-vs-1

(b) 2-vs-1 balanced

(c) 2-vs-1 unbalanced

(d) 2-vs-2 unbalanced

Figure: Four explored decay topologies; see arXiv:2112.12656 for more details

Event Simulation

- pp collision events at $\sqrt{s} = 13$ TeV simulated under the conditions of the CMS detector
- signal MC samples generated at LO using MadGraph5_aMC@NLO
- main background processes: $Z/\gamma^* \to ll$, top, di-boson; generated using either Powheg (NLO), MadGraph5_aMC@NLO (LO), or Pythia (LO)
- CMS detector simulation performed with Delphes

Analysis Framework

- implemented using combination of MadAnalysis5 and Root
- statistical inference performed within RootStats framework

Signal Parameter Scan

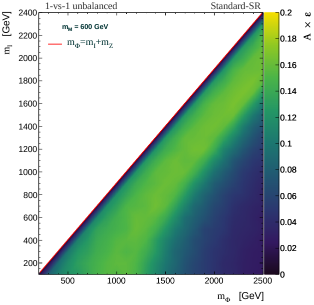
Topology	Mass fixed	Masses varied	Kin. constraints	No. points
1-vs-1 unbalanced	m_M	(m_Φ, m_I)	$m_\Phi \geq m_I + m_Z$	300
2-vs-1 balanced	m_Φ	(m_M, m_I)	$m_\Phi \geq m_I + m_M$ $m_M \geq m_I + m_Z$	80
2-vs-1 unbalanced	m_I	(m_Φ, m_M)	$m_\Phi \geq m_Z + m_M$ $m_M \geq 2m_I$	300
2-vs-2 balanced	m_Φ	(m_M, m_I)	$m_\Phi \geq 2m_M$ $m_M \geq m_I + m_Z$ $m_M \geq 2m_I$	28

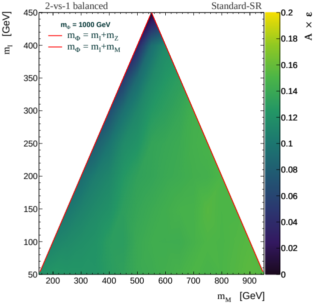
Targets a substantially boosted Z boson accompanied by a pair of relatively forward b-jets

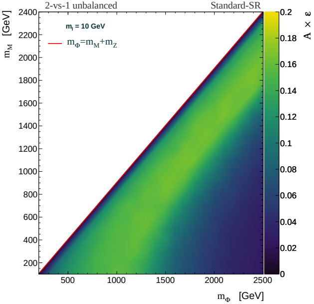
Quantity	Standard-SR	ForwardJets-SR
N_l (opposite-charge, same-flavour)	$= 2$ (with additional lepton veto)	
$p_T(l)$	50/20 GeV leading/trailing	
$m(l^+l^-)$	$86\,\mathrm{GeV} < m(l^+l^-) < 106\,\mathrm{GeV}$	
$p_T(l^+l^-)$	> 50 GeV	
$\Delta R(l^+, l^-)$	< 3	
$\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, l^+l^-)$	> 0.5	
$m_T(\vec{p}_T^{\,\mathrm{miss}}, l^+l^-)$	> 140 GeV	
$N_{\text{b-tag}}$	≥ 1	$= 0$
$\lvert\eta(j_1) - \eta(j_2)\rvert_{\max}$	$-$	> 2.5

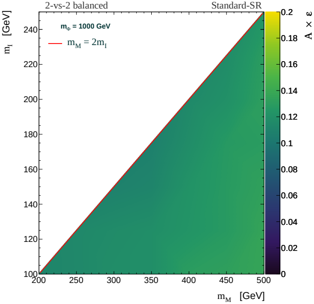
- two signal regions constructed:
  - **Standard-SR**: at least one central b-tagged jet
  - **ForwardJets-SR**: no b-tagged jets and at least two jets with large $\lvert\eta(j_1) - \eta(j_2)\rvert$

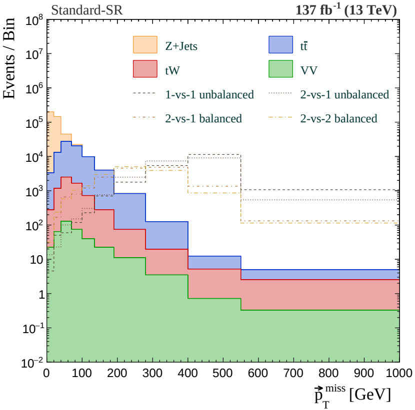
- efficiency in Standard-SR reaches up to 17%
- semi-boosted regime favored
- collimation of leptons makes efficiency drop for very boosted Z bosons
- efficiency in ForwardJets-SR is overall smaller than in Standard-SR and it tends to increase as m_Φ increases (see Backup)
- same kind of topologies (*balanced* or *unbalanced*) seem rather indistinguishable!

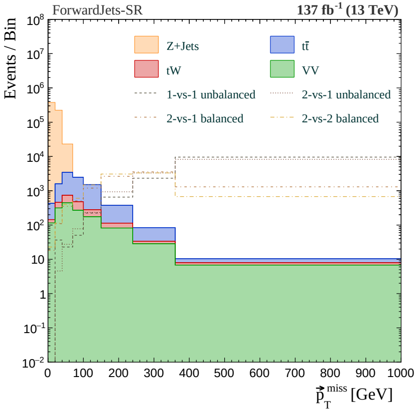




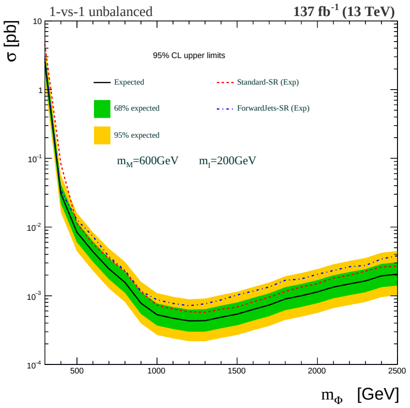


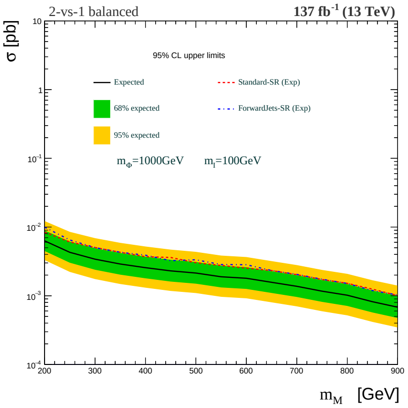






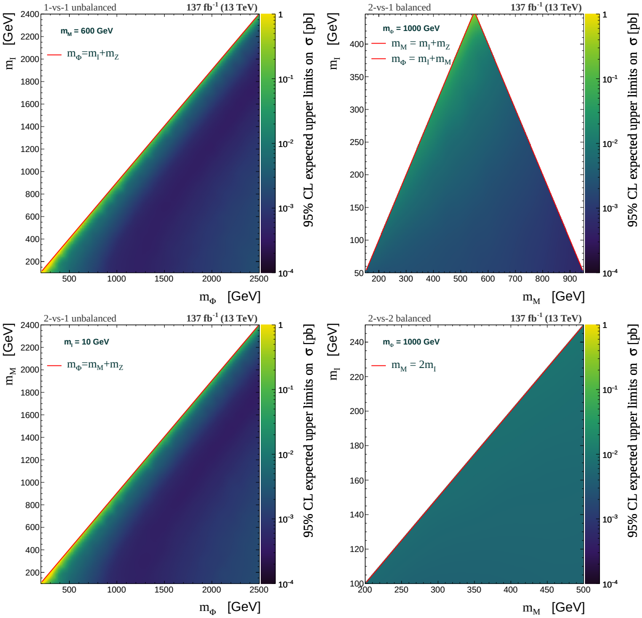
- fit performed using a shape scanning over the binned $\vec{p}_T^{\,miss}$ distribution
  - keeps the analysis as inclusive as possible for the varied kinematics probed
  - possibility to exploit the *shape* discrimination when efficiency becomes lower
  - more realistic scenario in current experimental context compared to cut-and-count

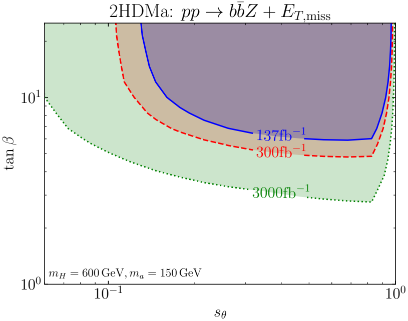


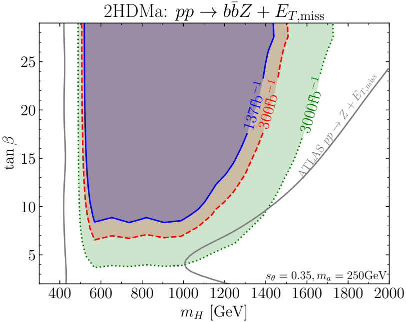


- sensitivity of both signal regions defined is comparable!
  - for some phase-space points ForwardJets-SR even surpasses the Standard-SR
  - in ForwardJets-SR the efficiency is lower but also (substantially) the background contribution

- best upper limits obtained for 1-vs-1 unbalanced and 2-vs-1 unbalanced: $\approx 3.5 \times 10^{-4}$ pb
- close to 5.5×10^{-4} pb and 4.5×10^{-3} pb for the 2-vs-1 balanced and 2-vs-2 balanced topologies
- small shift of the region with the most stringent limits w.r.t. the one with largest efficiency
- clear distinction between unbalanced **vs** balanced scenarios
- 1-vs-1 and 2-vs-1 (unbalanced) remain indistinguishable, whereas 2-vs-1 and 2-vs-2 (balanced) present a mild (almost unnoticeable) difference







- region of $\tan\beta \lesssim 3$ inaccessible even with much more integrated luminosity
- interval $500 \lesssim m_H \lesssim 1600$ GeV can be easily probed for large $\tan\beta$
- ATLAS mono-Z seems to have better sensitivity in 2HDMa compared to this search
  - not fully optimized for unbalanced topology *only*
  - soft p_T spectrum of b-quarks and not fully efficient b-tagging
  - absence of sophisticated analysis techniques in this simple study

- capability of potential new search investigated
  - explored significantly large class of theoretical scenarios
  - use of forward jets seems to add substantial sensitivity to this type of search
- standard analysis approach is sensitive to all topologies
  - further optimization for balanced scenarios should bring additional improvements
  - unbalanced (2HDMa-like) cases might require sophisticated analysis techniques to become competitive
- unbalanced **vs** balanced topologies present noticeable differences in kinematics
  - analyses might benefit from being optimized for each class separately
  - same class of topologies resemble quite each other (individual optimization unnecessary)

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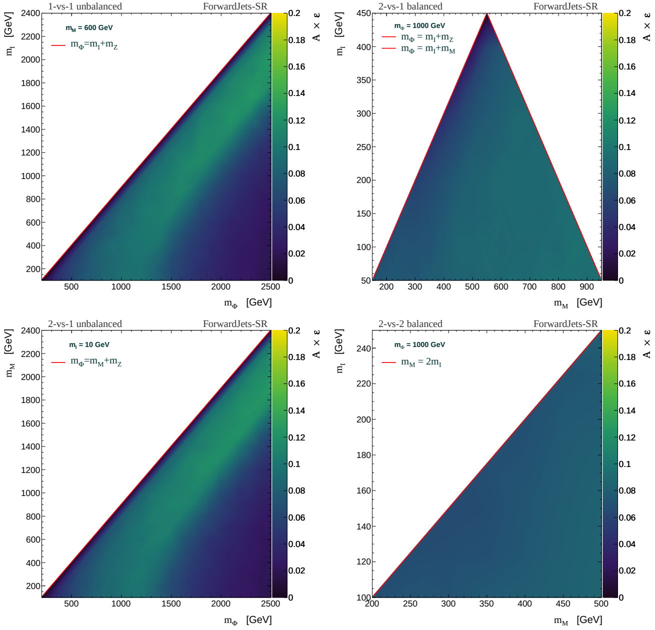
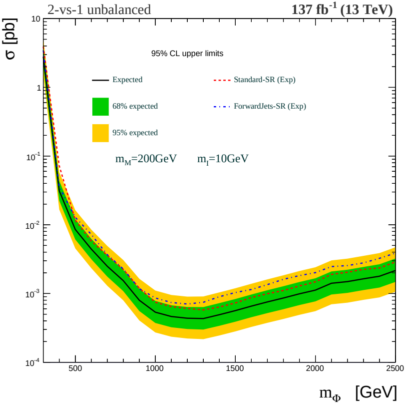
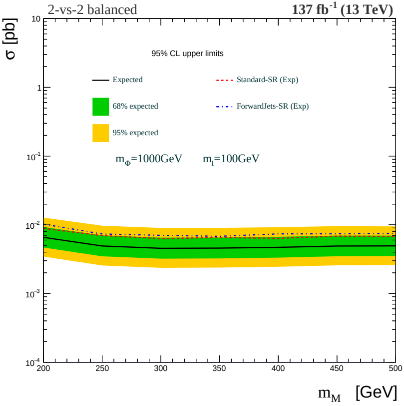
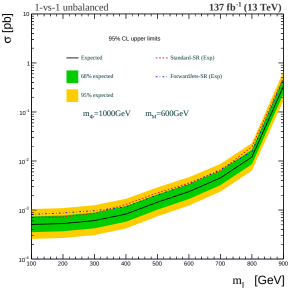
Thanks for your attention!

Backup


1-vs-1 unbalanced
ForwardJets-SR
m_M = 600 GeV
$m_\Phi = m_I + m_Z$
m_I [GeV]
m_Φ [GeV]
$A \times \epsilon$
2-vs-1 balanced
ForwardJets-SR
m_Φ = 1000 GeV
$m_\Phi = m_I + m_Z$
$m_\Phi = m_I + m_M$
m_I [GeV]
m_M [GeV]
$A \times \epsilon$
2-vs-1 unbalanced
ForwardJets-SR
m_I = 10 GeV
$m_\Phi = m_M + m_Z$
m_M [GeV]
m_Φ [GeV]
$A \times \epsilon$
2-vs-2 balanced
ForwardJets-SR
m_Φ = 1000 GeV
$m_M = 2m_I$
m_I [GeV]
m_M [GeV]
$A \times \epsilon$


2-vs-1 unbalanced
137 fb^{-1} (13 TeV)
95% CL upper limits
Expected
Standard-SR (Exp)
68% expected
ForwardJets-SR (Exp)
95% expected
m_M=200GeV
m_I=10GeV
σ [pb]
m_Φ [GeV]


2-vs-2 balanced
137 fb^{-1} (13 TeV)
95% CL upper limits
Expected
Standard-SR (Exp)
68% expected
ForwardJets-SR (Exp)
95% expected
m_Φ=1000GeV
m_I=100GeV
σ [pb]
m_M [GeV]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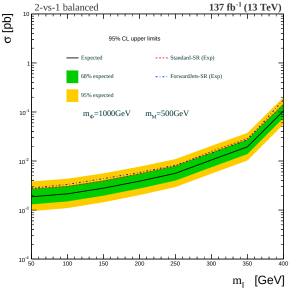
68% expected
ForwardJets-SR (Exp)
95% expected
m_Φ=1000GeV
m_M=600GeV
σ [pb]
m_I [GeV]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m_Φ=1000GeV
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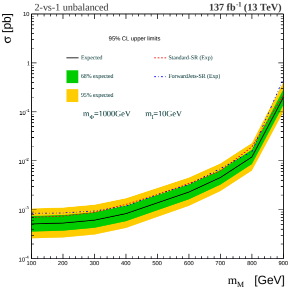
σ [pb]
m_I [GeV]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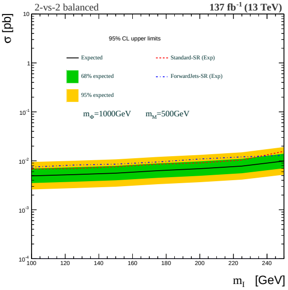
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m_I [GeV]