SEARCHES FOR INVISIBLE DECAYS OF THE HIGGS BOSON

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On behalf of the ATLAS and CMS Collaborations

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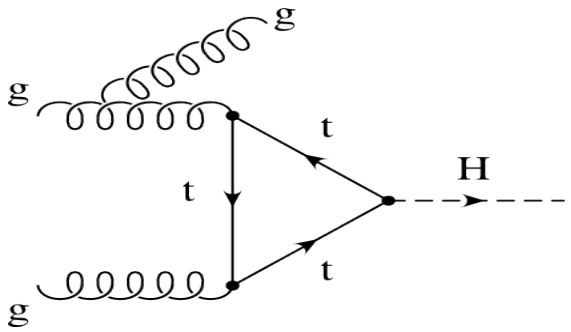
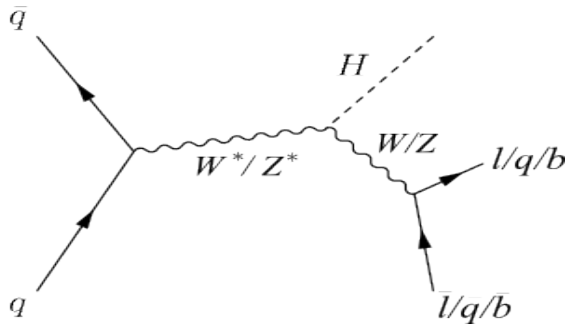
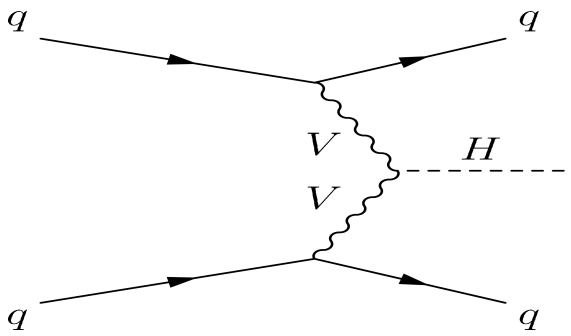
H → invisible searches

- Why investigate Higgs (H) to invisible decays?
  - Probe deviations from Standard Model (SM) H couplings (visible+invisible decays) (→ see talk from G. Carrillo-Montoya)
  - Search for high mass H coupling to invisible
  - Higgs-portal: Higgs-mediated Dark Matter (DM) production
- Which production mode and signatures?
  - Vector Boson Fusion (VBF)
  - Associated ZH and WH production
  - Gluon-gluon (gg) fusion
- Which limits?
  - On σ_{prod}×BR(H → invisible)
  - On BR(H → invisible), assuming SM Higgs
  - 95% confidence level (if not mentioned)

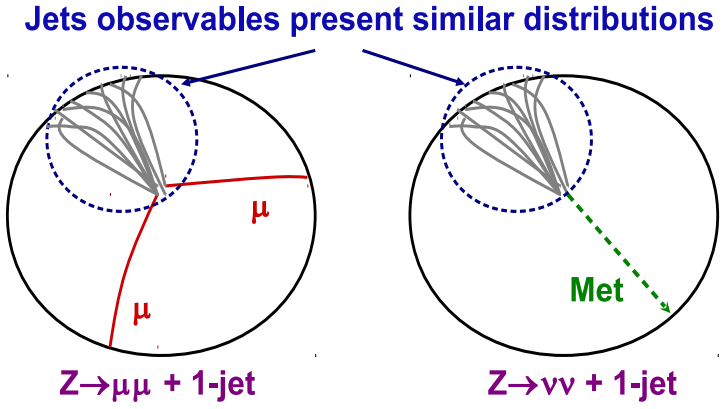






Search in high energy leading jet plus large $\not{E}_T$ final state [ATLAS]

- Published: EPJC 75 (2015) 299
  $\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 20.3\,\mathrm{fb}^{-1}$
- Originally, a DM search scanning various lower missing transverse energy ($\not{E}_T$) thresholds
- Event selection:
  - $\not{E}_T$ trigger, $\not{E}_T > 250\,\mathrm{GeV}$
  - Central leading jet with $p_T > 120\,\mathrm{GeV}$
  - No veto on number of jets
  - Monojet-like topology: $p_T^{jet_1}/\not{E}_T > 0.5$
  - To further suppress QCD multi-jet events: $\Delta\phi(\not{E}_T, jet) > 1$
  - Veto on e and μ
- Main background: $\mathrm{Z} \to \nu\nu$
  - Determination based on 4 W/Z lepton data control regions (CR)
  - E.g.: $\mathrm{Z} \to \mu\mu \;\Rightarrow\; \mathrm{Z} \to \nu\nu$

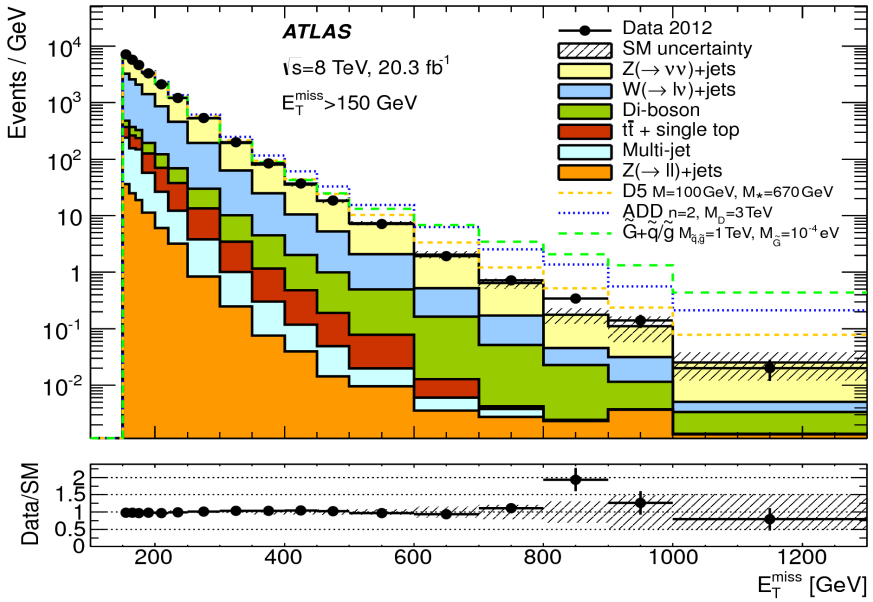


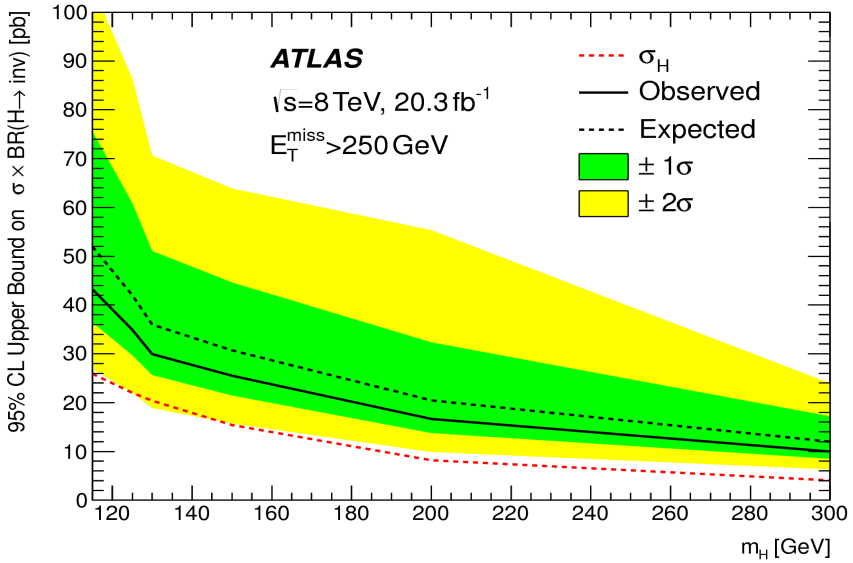
  - Transfer CR to signal region (SR) via ratio of simulated processes
  - Combination of 4 independent $\mathrm{Z} \to \nu\nu$ estimates

Search in high energy leading jet plus large $\not{E}_T$ final state [ATLAS]

- Total uncertainty on $Z \to \nu\nu$:
  - 2.7% for $\not{E}_T > 250\,\mathrm{GeV}$
  - Highly reduced by similar jet topologies in CR and SR
- H → invisible interpretation:
  - Simple counting experiment
  - Considering gg fusion (dominating), VH and VBF Higgs production modes
  - Case $m_H = 125\,\mathrm{GeV}$:

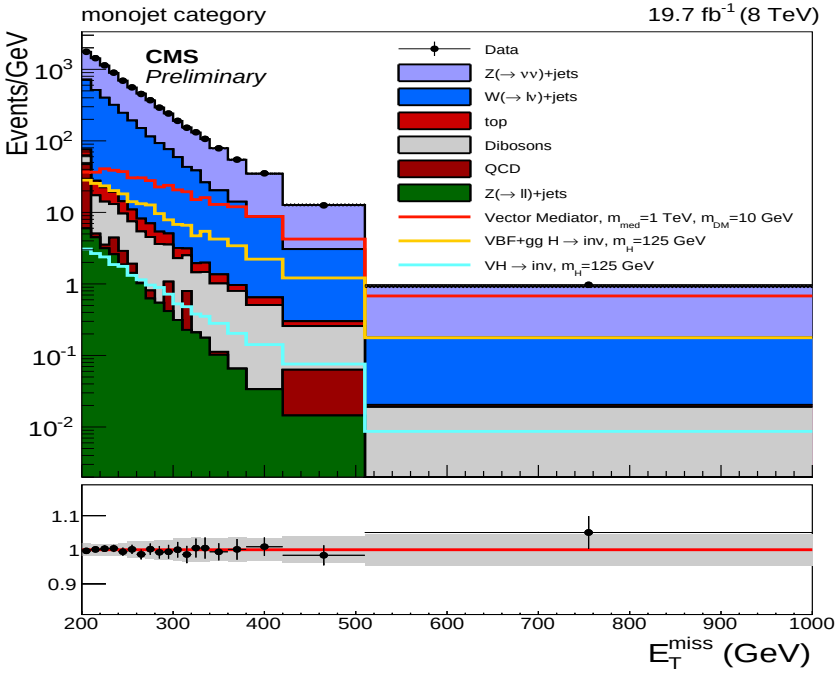
    BR< 1.59 (observed), 1.91 (expected)
  - Sensitivity increases for higher mass Higgs





Search in the V/jet + $\not{E}_T$ final state [CMS]

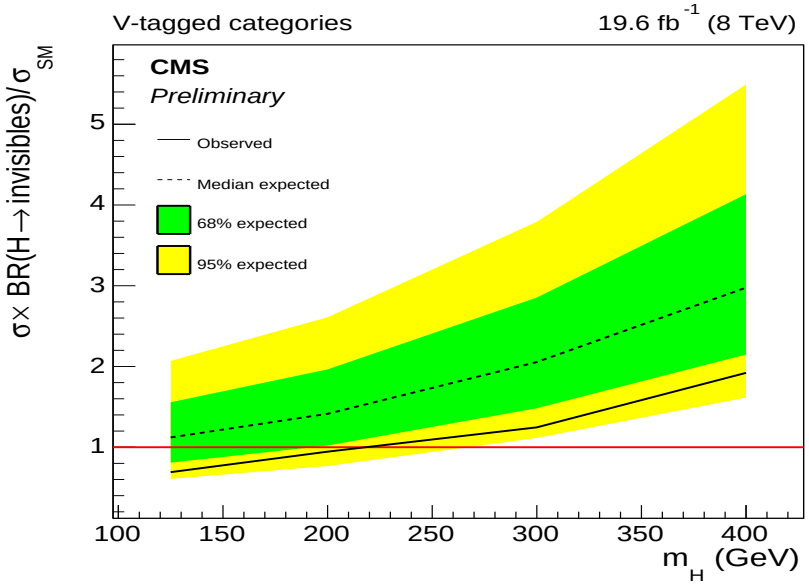
- Preliminary result: CMS-PAS-EXO-12-055 $\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 20.3\,\mathrm{fb}^{-1}$
- V ∈ {W,Z}
- Selection based on large $\not{E}_T$ ($\not{E}_T$+jets triggers), 1 or more jets, no isolated ℓ/γ
- 3 event categories:
  - Unresolved (boosted) V-tag:
    - has a large distance parameter (0.8) high p_T jet, with mass close to V
  - Resolved V-tag:
    - has a pair of smaller distance parameter (0.5) high p_T jets
    - use of multivariate V-tagger
    - b-tag veto
  - Mono-jet:
    - event not V-tagged
    - large lead jet p_T
- Main background: W/Z+jets
  - Use of leptonic W data CR for $\mathrm{W}(\to \mu\nu)$+jets estimate
  - Use of leptonic Z and γ+jets CRs for $\mathrm{Z}(\to \nu\nu)$+jets estimate
  - Likelihood fit in CRs+SR for all 3 events categories

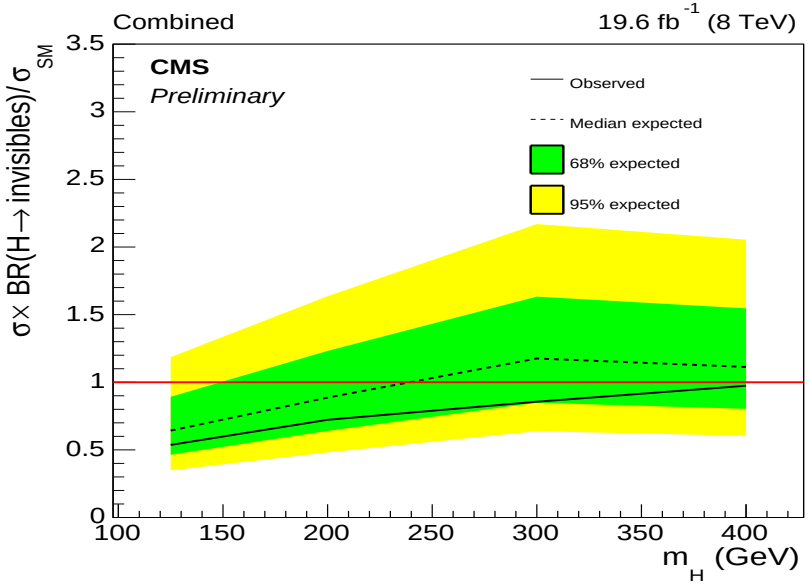


Search in the V/jet + $\not{E}_T$ final state [CMS]

- Uncertainty on likelihood fit:
  - Up to 15% for electroweak corrections when V/γ at TeV scale
- H → invisible interpretation:
  - Shape experiment using $\not{E}_T$
  - Considering gg fusion, VH and VBF Higgs production modes
  - On V-tagged + full combination of 3 categories: mono-jet dominates
  - Kink in fully combined limit due to increase of σ_{gg}
  - Full combination, case $m_H = 125\,\mathrm{GeV}$:

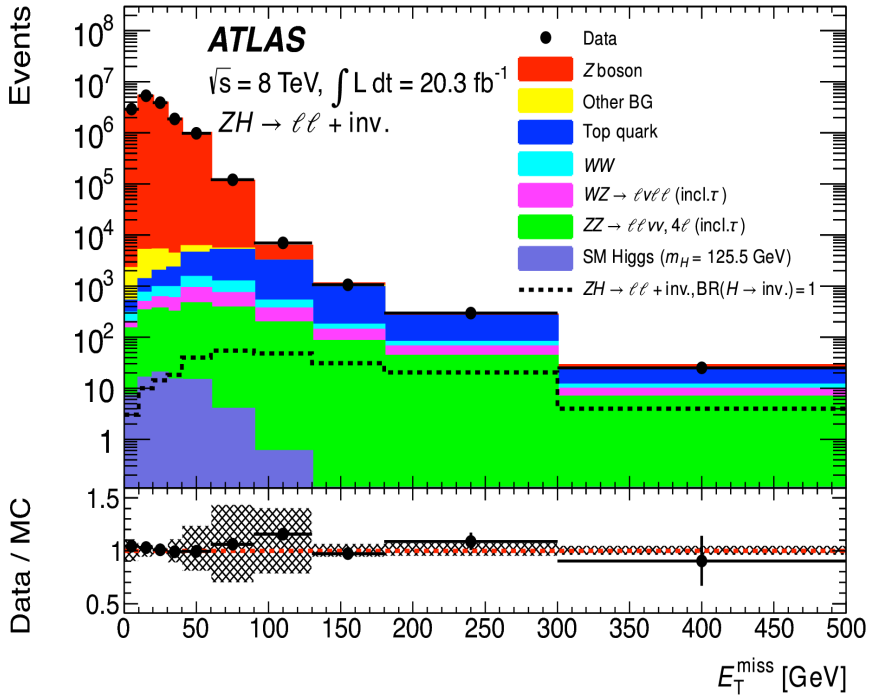
    BR< 0.53 (observed), 0.62 (expected)





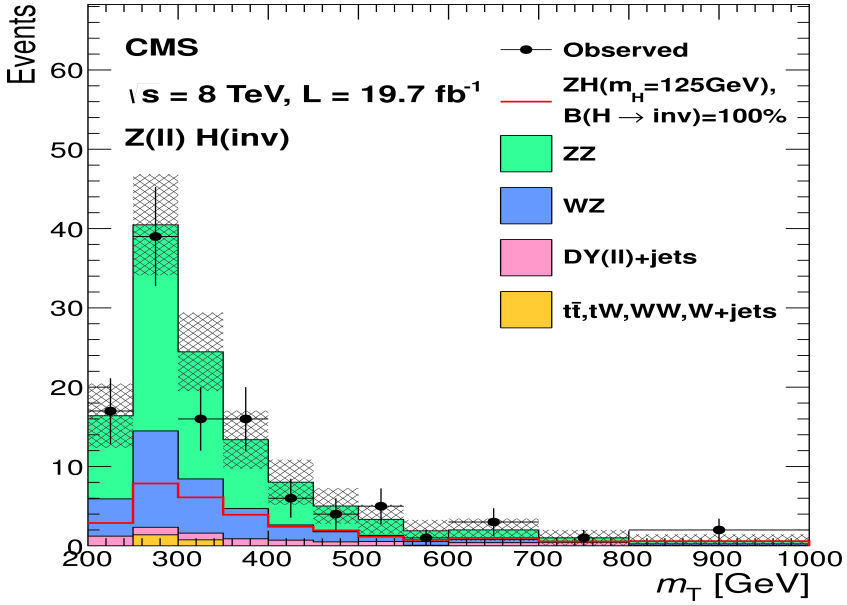
Search in the $\boxed{\mathrm{Z}(\to \ell\ell)\mathrm{H}}$ channel [ATLAS, CMS]

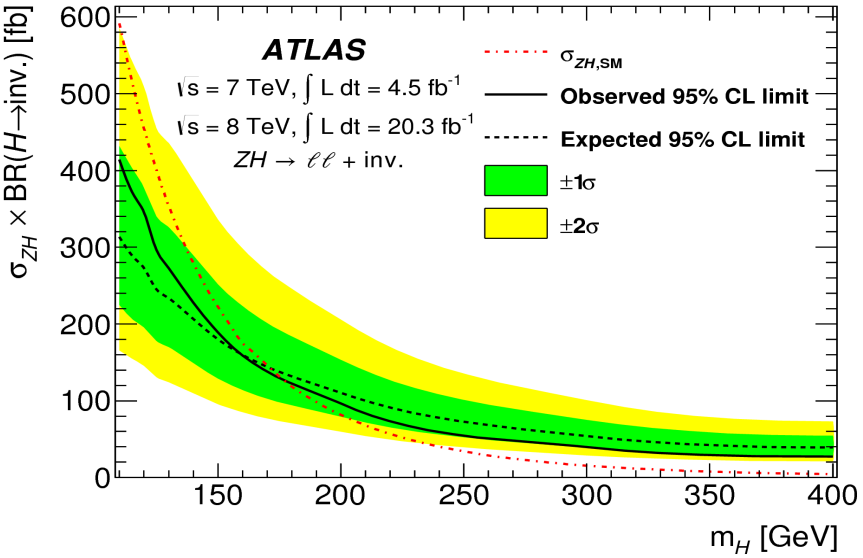
- Published at $7\,\&\,8\,\mathrm{TeV}$ $(5\,\&\,20\,\mathrm{fb}^{-1})$:
  PRL 112, 201802 (2014) [ATLAS]
  EPJC 74 (2014) 2980 [CMS]
- $\ell \in \{e, \mu\}$
- Event selection:
  - Trigger: single or di-lepton
  - $\not{E}_T > 90$ [ATLAS] and $120\,\mathrm{GeV}$ [CMS]
  - 2 ℓ with $m_{\ell\ell}$ within Z mass window
  - Boosted invisible H balanced by Z: use of discriminants $\Delta\Phi(p_T^{\ell\ell}, \not{E}_T)$, $|\not{E}_T - p_T^{\ell\ell}|/p_T^{\ell\ell}$, and $\Delta\Phi(\ell, \ell)$
  - Veto on jets [ATLAS]
    Distinguish 0 and 1-jet cases [CMS]
  - No b-jet [CMS] to kill top
- Main backgrounds:
  - ZZ and WZ, determined by simulation normalized to NLO
  - WW, $t\bar{t}$, Wt, $\mathrm{Z} \to \tau\tau$ estimated from data $e\mu$ CR



Search in the $Z(\to \ell\ell)H$ channel [ATLAS, CMS]

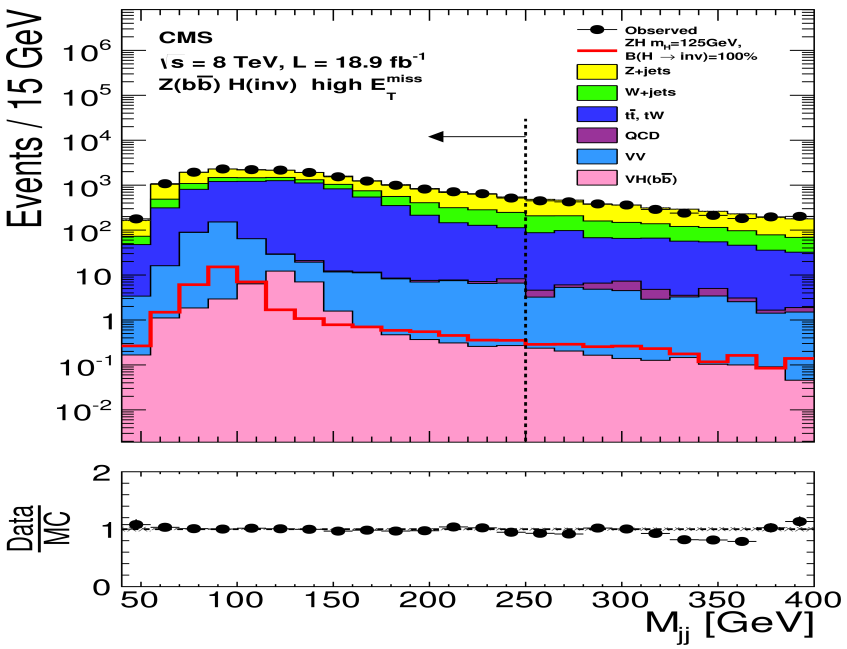
- Main Systematics:
  - Signal theory: 4-6% [ATLAS], 9% [CMS]
  - Background JES: 3-6% [ATLAS], ZZ theory (8%) [ATLAS, CMS]
- Limits:
  - ATLAS: CL_s using maximum likelihood fit to $\not{E}_T$
  - CMS: CL_s using maximum likelihood fit to 2D distribution $\Delta\Phi(\ell,\ell)$ vs m_T transverse mass of dilepton-$\not{E}_T$ system ($8\,\mathrm{TeV}$), or m_T alone ($7\,\mathrm{TeV}$)
  - Upper bounds on BR(H → inv) assuming $m_H = 125\,\mathrm{GeV}$:
    - ATLAS: 75% (62% expected)
    - CMS: 83% (86% expected)





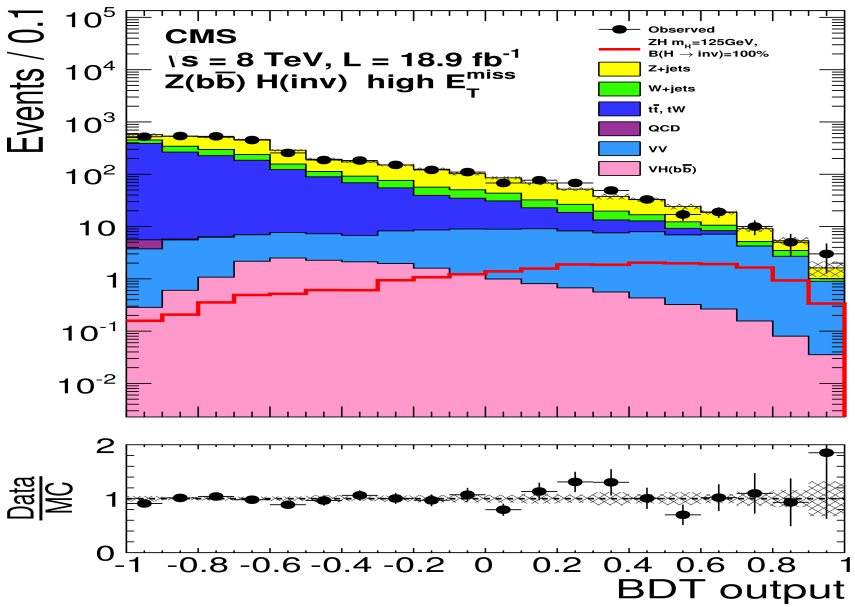
Search in the $\boxed{\mathrm{Z}(\to b\bar{b})\mathrm{H}}$ channel [CMS]

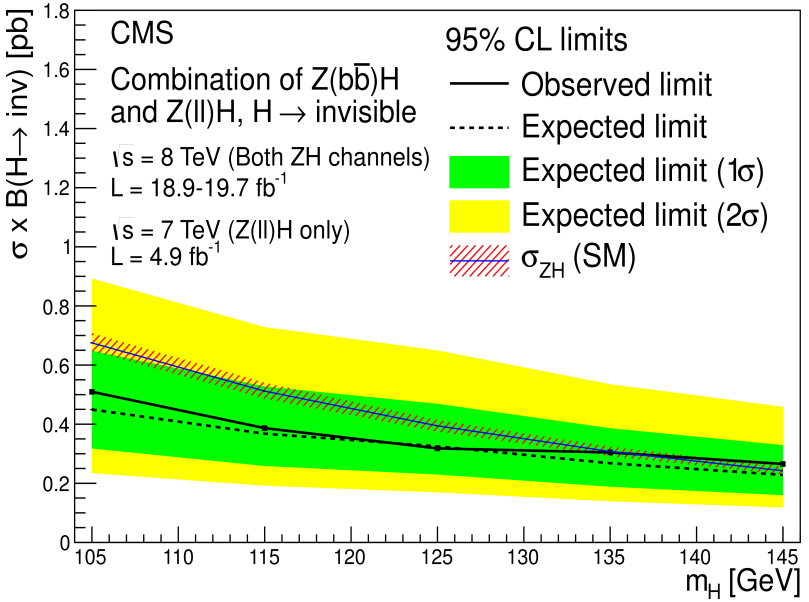
- Published: EPJC 74 (2014) 2980
  $\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 19.7\,\mathrm{fb}^{-1}$
- Event selection:
  - $\not{E}_T$+jets triggers
  - Searching for boosted H:
    - $\Delta\Phi(Z, H) > 2$
    - $\not{E}_T$ SR: 100-130, 130-170, $> 170\,\mathrm{GeV}$
  - Z candidate:
    - 2 high-p_T b-tagged central jets
    - Large p_T^{jj} and veto on m_{jj}
  - Lepton veto (suppress $t\bar{t}$, WZ)
  - To suppress QCD: cuts on $\Delta\Phi(\not{E}_T, jet)$, $\Delta\Phi(\not{E}_T, \not{p}_T^{trk})$, $\not{E}_T$ significance
- Main backgrounds: Z/W+($b\bar{b}$), $t\bar{t}$
  - Estimated by extracting normalization from CRs with inverted lepton veto
  - Normalization depending on number of b-tags for W/Z



Search in the Z(→ $b\bar{b}$)H channel [CMS]

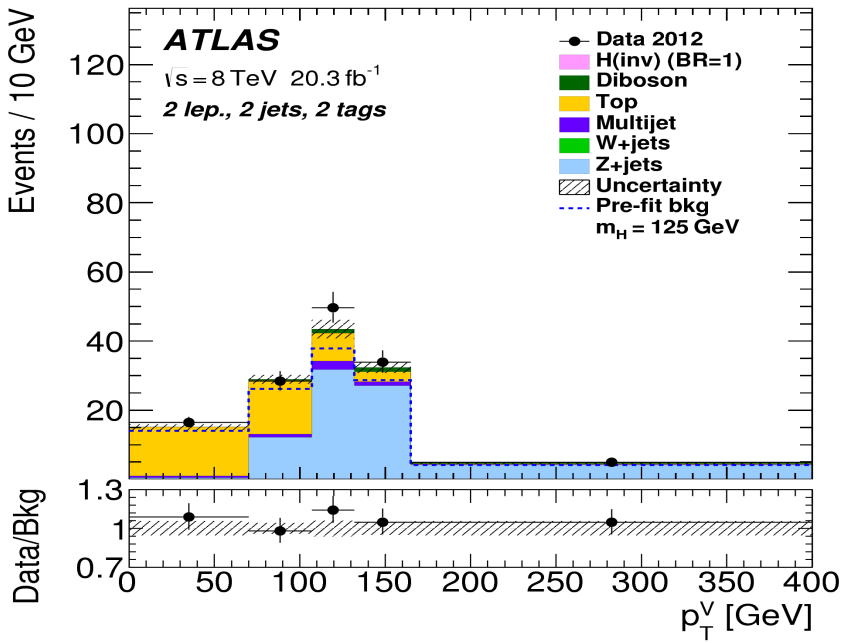
- Final signal/background discriminant via boosted decision trees (BDT)
- Systematics (for most sensitive region):
  - Signal: 11% (mostly b-tag and theory)
  - Background: 12% (mostly b-tag and normalization)
- Limit setting:
  - Signal: ZH production
  - CL_s procedure combining the BDT outputs from the 3 SR
  - Observed (expected) upper BR(H → inv): 1.82 (1.99) (case $m_H = 125\,\mathrm{GeV}$)
  - Combined with Z(→ ℓℓ): 0.81 (0.83)





Search in the V(→ jj)H channel [ATLAS]

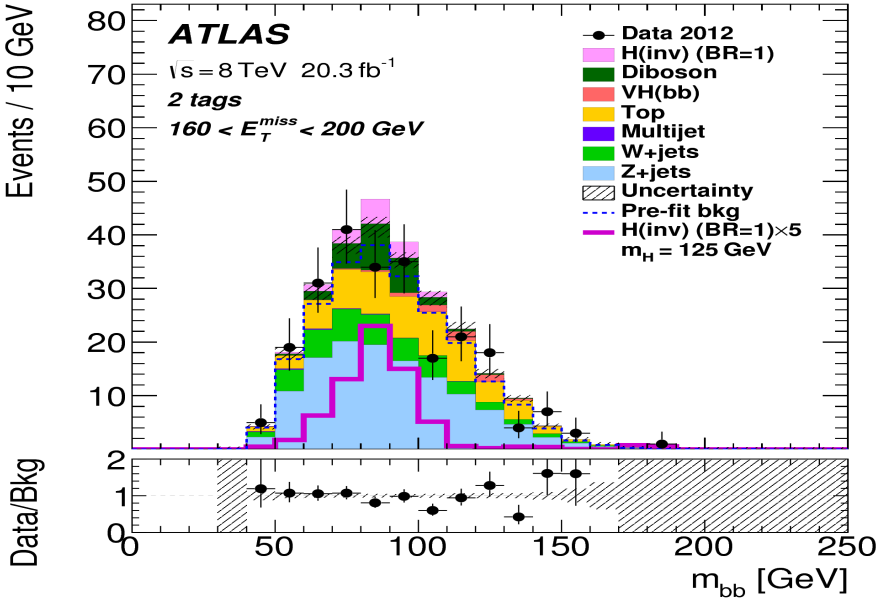
- Accepted by EPJC, arXiv:1504.04324
  $\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 20.3\,\mathrm{fb}^{-1}$
- V ∈ {W,Z}
- Event selection:
  - $\not{E}_T$ trigger
  - V candidate: low ΔR_{jj}, m_{jj} within V mass window, separated from $\not{E}_T$
  - 6 SR, so that:
    - 2 or 3 jets
    - 0, 1, or 2 b-tags
  - Cuts Optimised in 4 $\not{E}_T$ ranges
  - Lepton veto
  - To suppress QCD: cuts on $\Delta\Phi(\not{E}_T, jet)$, $\Delta\Phi(\not{E}_T, \not{p}_T^{trk})$, $\not{E}_T$ significance
- Main backgrounds: V+jets and $t\bar{t}$
  - Normalization estimated by likelihood fit to $\not{E}_T$ distribution in SR+sideband, and $p_T^{W/Z/e+\mu}$ in enriched W/Z/$t\bar{t}$ regions
  - Sideband: events failing m_{jj} cut

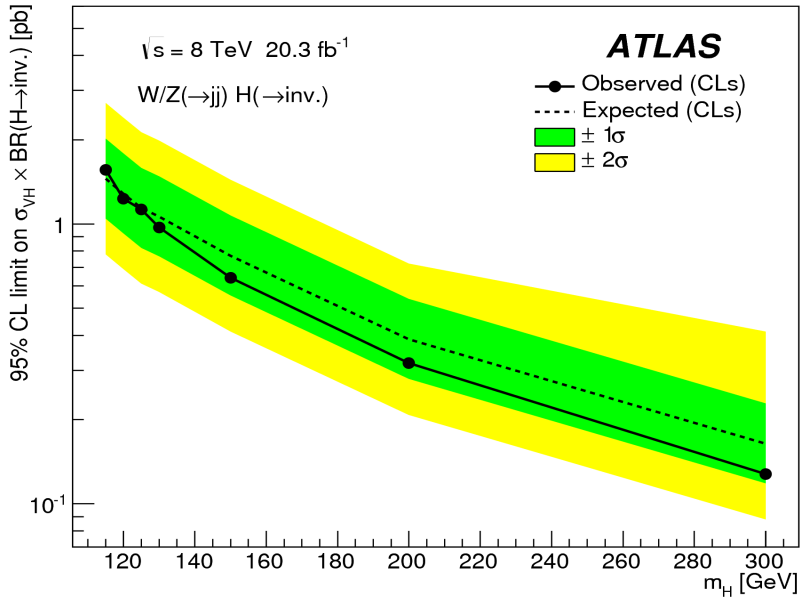


Search in the $\boxed{\mathbf{V}(\to jj)\mathbf{H}}$ channel [ATLAS]

- Main systematics:
  - Signal: parton shower modeling up to 8% (VH), renormalization/factorization scale up to 15% (gg fusion)
  - Background: JER (5-20%), b-tagging (2-8%)

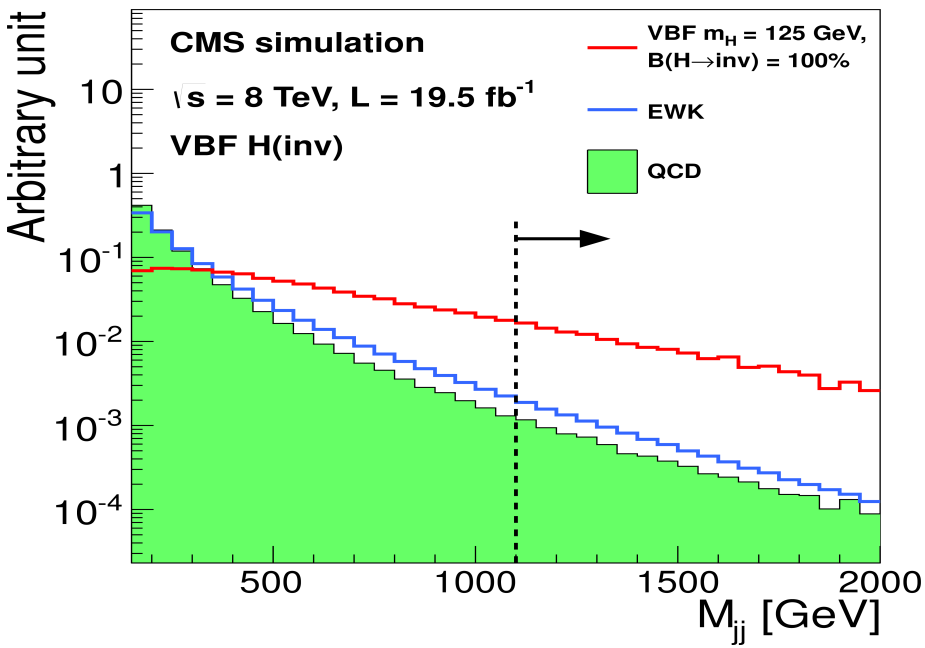
- Limit setting:
  - Signal: VH production and gg fusion (latter contributes with ∼29% to expected sensitivity)
  - Limit extracted from combined likelihood fit in SR+sidebands+CRs
  - Observed (expected) upper bound on BR(H → inv): 78% (86%) (case $m_H = 125\,\mathrm{GeV}$)





Search with the VBF signature [ATLAS, CMS]

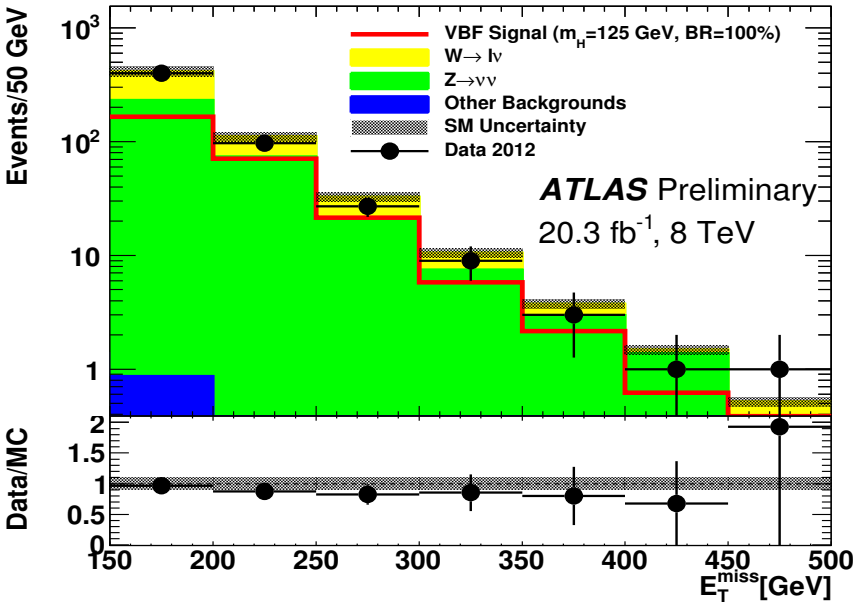
- Preliminary results, $8\,\mathrm{TeV}$ & $20\,\mathrm{fb}^{-1}$:
  CMS-PAS-HIG-14-038
  ATLAS-CONF-2015-004 (updated)
- Event selection:
  - Trigger: $\not{E}_T$ [ATLAS] or $\not{E}_T$+jet [CMS]
  - $\not{E}_T > 90$ [CMS], $150\text{-}200\,\mathrm{GeV}$ [ATLAS]
  - VBF topology:
    - exactly 2 high-p_T jets in opposite hemispheres ($> 45\text{-}75\,\mathrm{GeV}$)
    - CMS: $\Delta\eta_{jj} > 4.2$ and $m_{jj} > 1.2\,\mathrm{TeV}$
    - ATLAS: $\Delta\eta_{jj} > 4.8$ and $m_{jj} > 1\,\mathrm{TeV}$ combined to lower purity region (down to $m_{jj} > 500\,\mathrm{GeV}$ and $\Delta\eta_{jj} > 3$)
  - To further suppress multi-jet events: cuts on $\Delta\phi(\not{E}_T, jet)$ and $\not{E}_T$ significance
  - Veto on e, μ [ATLAS, CMS], τ [ATLAS]
- Main background: $\mathrm{Z} \to \nu\nu$
  - Estimate from leptonic data W/Z CR [ATLAS] or Z only [CMS]
  - Combined likelihood fit of $\not{E}_T$ in CR and SR [ATLAS]

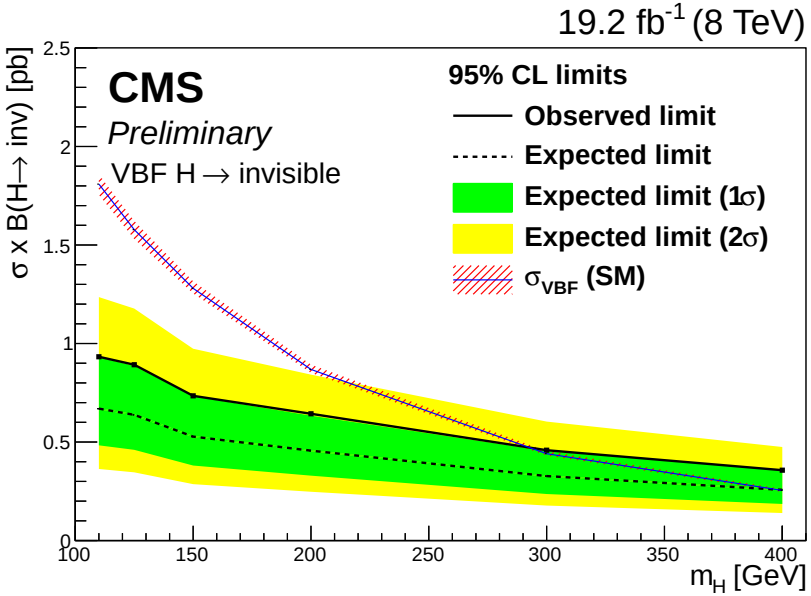


Search with the VBF signature [ATLAS, CMS]

- Total uncertainties on $Z \to \nu\nu$:
  - CMS: 27%, with 23.5% stat.
  - ATLAS: 11%, with $< 6.4\%$ stat.

- Observed (expected) upper limits on BR(H→inv) assuming $m_H = 125\,\mathrm{GeV}$:
  - ATLAS: 28% (31%)
  - CMS: 57% (40%)
  - Expected CMS bound is 33% if Z CR had as much stat as a W→ $\mu\nu$ CR
  - VBF is most sensitive channel



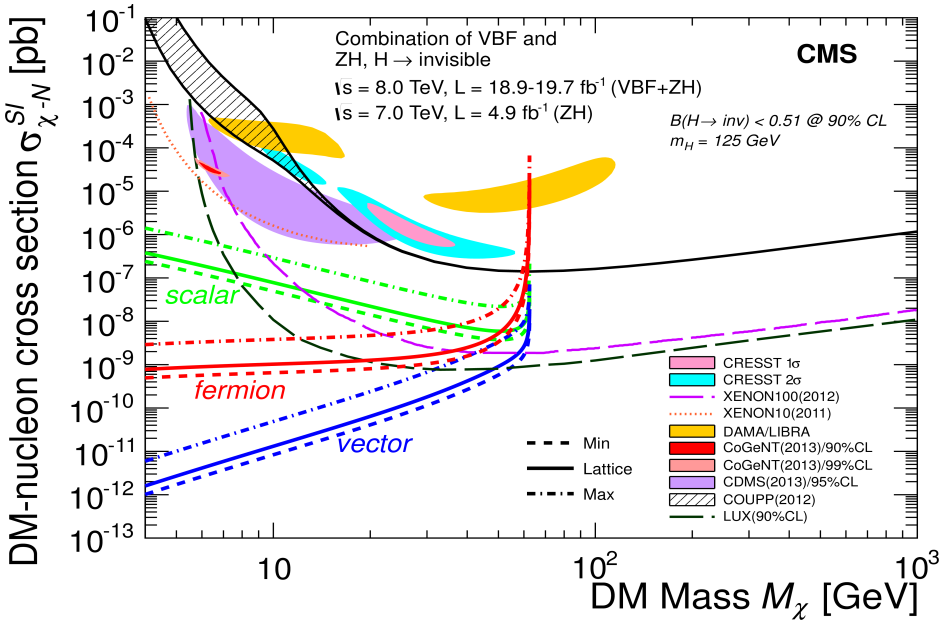


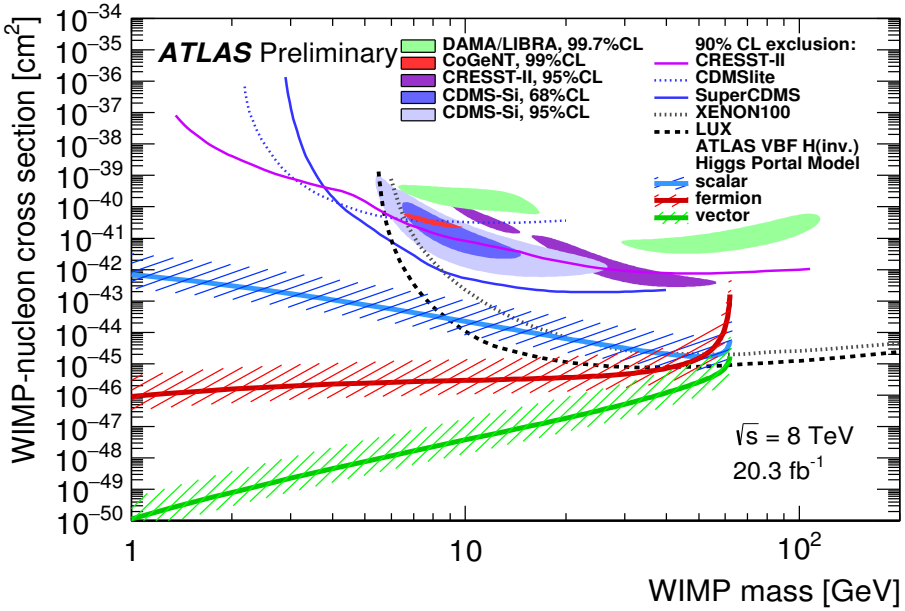
Dark Portal [ATLAS, CMS]

- Higgs-portal: renormalizable coupling between hidden sector and SM via Higgs boson
- Limits from collider experiment can be reinterpreted into upper bounds on the spin-independent DM-Nucleon scattering cross section

  ⇒ Comparison to astroparticle direct searches

- Scalar, vector, and fermionic interactions are probed
- No sensitivity if m_{DM} exceeds $m_H/2$
- Colliders particularly sensitive a low DM mass





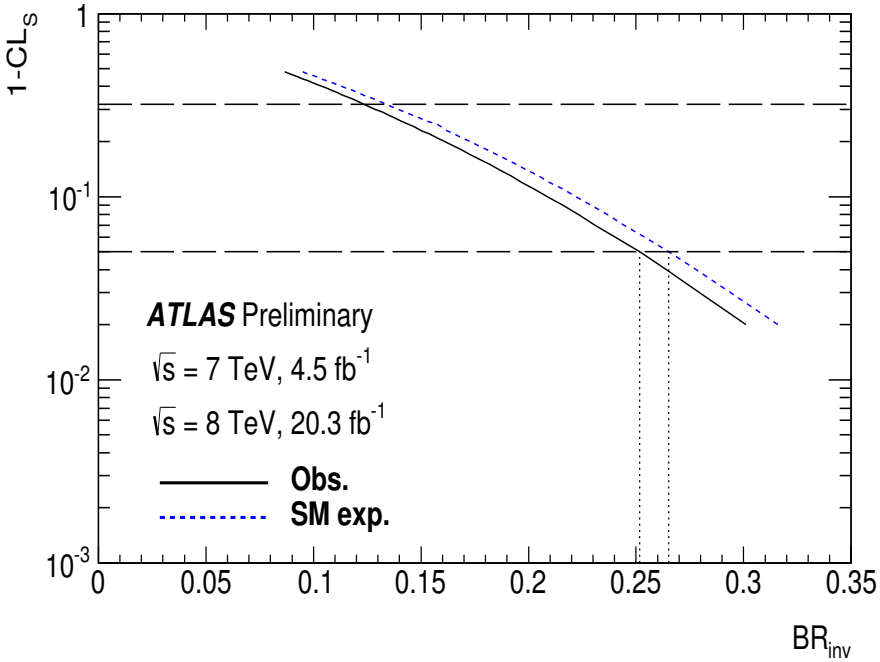
Conclusion

- No evidence of new physics has been observed. Limits on the invisible branching ratio of the Higgs boson have been set as function of the assumed boson mass.
- Summary at $M_H = 125\,\mathrm{GeV}$:
  - Combination from CMS (VBF+ZH): BR< 0.47 (0.35 expected)
  - Combination from ATLAS (VBF+VH) BR< 0.25 (0.27 expected)
- New window on DM search via Higgs-Portal. Colliders sensitive at low DM mass, and complementary to astroparticle experiments.
- For more information:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

BACKUP

Full combination of invisible Higgs decay channels

ATLAS (VBF+VH)



CMS (VBF+ZH) [not latest VBF results]