Searches for invisible Higgs at the LHC

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On behalf of the ATLAS and CMS Collaborations

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H→inv decay from combined fits

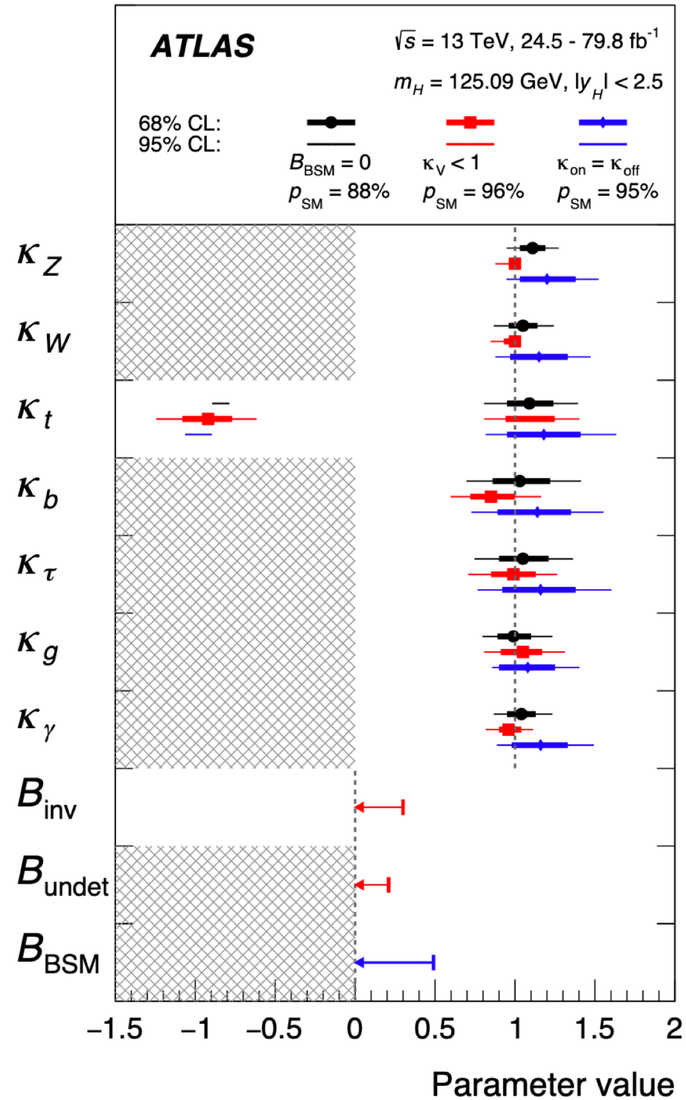
SM predicts that BR(H→ZZ→4ν) is about 0.12%. However, if Higgs also decays to invisible particles, this BR can be significantly enhanced

$B_{BSM}=B_{inv}+B_{undet}$ can be constrained by combined fits including off-shell Higgs:

$$\frac{\Gamma_H(\kappa, B_{BSM})}{\Gamma_H^{SM}} = \frac{\Sigma_j B_f^{SM} \kappa_j^2}{1 - B_{BSM}}$$

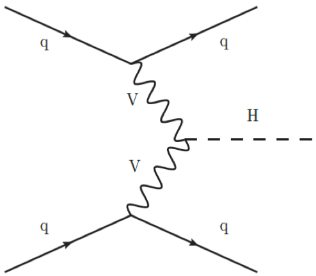
Up to 49% of B_{BSM} can be allowed: coupling strength factors κ can put constraints on B_{BSM} from visible decays and off-shell production of the Higgs

[arXiv:1909.02845]

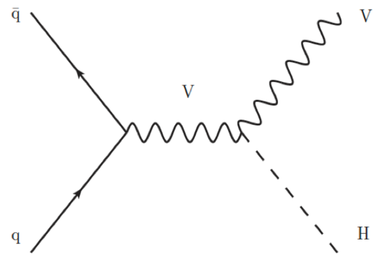


Main search channels

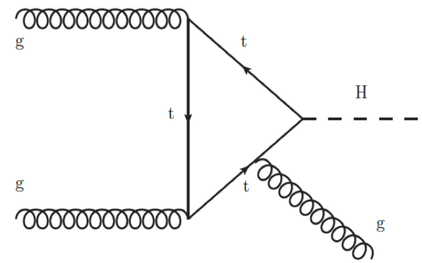
Main Higgs production channels to search for an invisible Higgs:



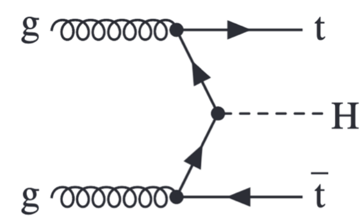
VBF



Associated VH



gg-Fusion + jets

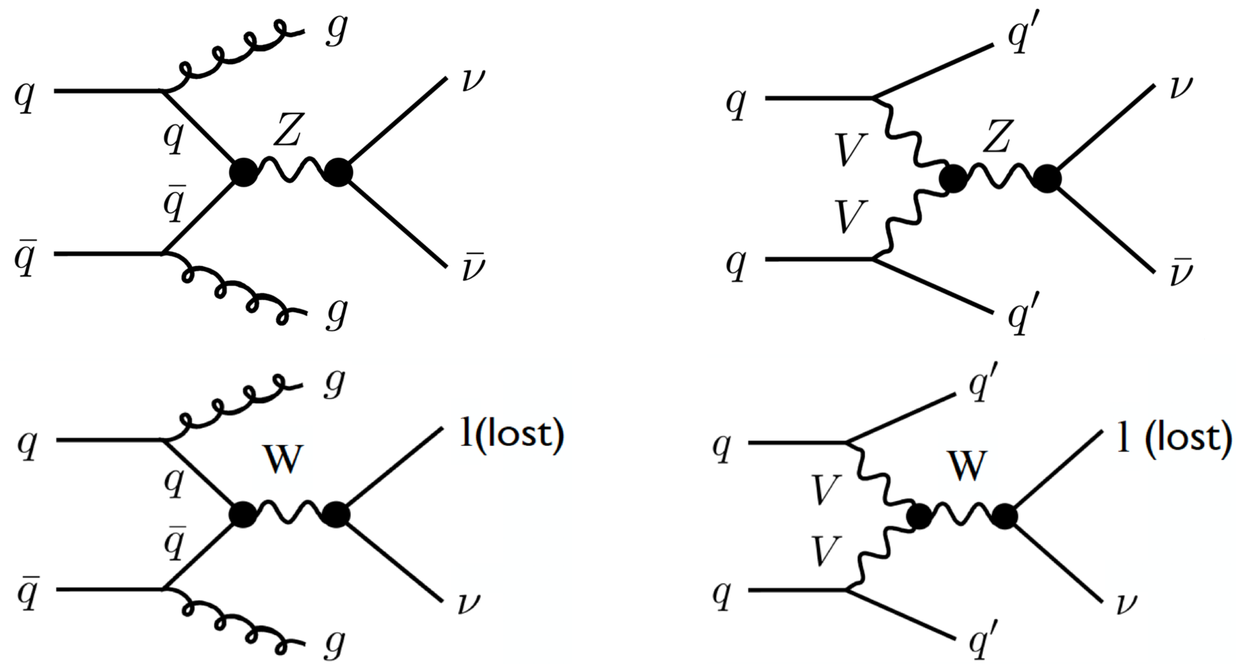


ttH

- Vector Boson Fusion (VBF):
  Largest sensitivity, suppress background with tagging jets kinematics
- Associated VH:
  V decays to dilepton or jets. Lepton or MET triggers. Next sensitive after VBF
- ggF+jet:
  Largest cross section. Use extra jet for trigger. Large QCD background
- ttH:
  Statistically limited. Potentially very important at HL-LHC

Higgs decay to dark matter: assume $m_\chi < \frac{1}{2} m_H$

VBF H→inv background



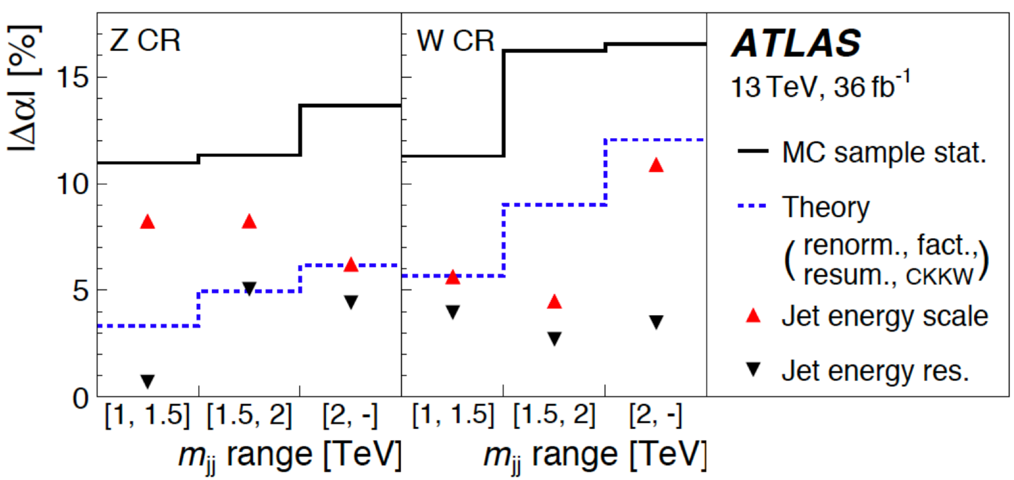
- Main background for VBF H→inv is QCD and EW Z($\nu\nu$)+2j, and W($l\nu$)+2j where the lepton missed reconstruction or ID
- Can constrain them with CRs of Z(ll)+2j and W($l\nu$)+2j where lepton(s) are well reconstructed: other than the leptons, keep the same selection cuts as SR (next slide) and the MET is recalculated by adding the lepton(s) contribution

VBF H→inv (ATLAS)

[Phys. Lett. B793 (2019) 499]

Key analysis SR selections:

- For tagging jets: small $\Delta\phi$ and large $\Delta\eta$ ($|\Delta\phi_{jj}| < 1.8, |\Delta\eta_{jj}| > 4.8$), in opposite hemisphere ($\eta_{j1} \cdot \eta_{j2} < 0$), and large mass $m_{jj} > 1$ TeV
- Require large MET (MET>180 GeV), and MET not aligned with jets ($|\Delta\phi_{j-MET}| > 1$) to reject fake MET events



Divide into 3 m_{jj} bins for number counting in each bin with data-driven Z/W+2j estimation:

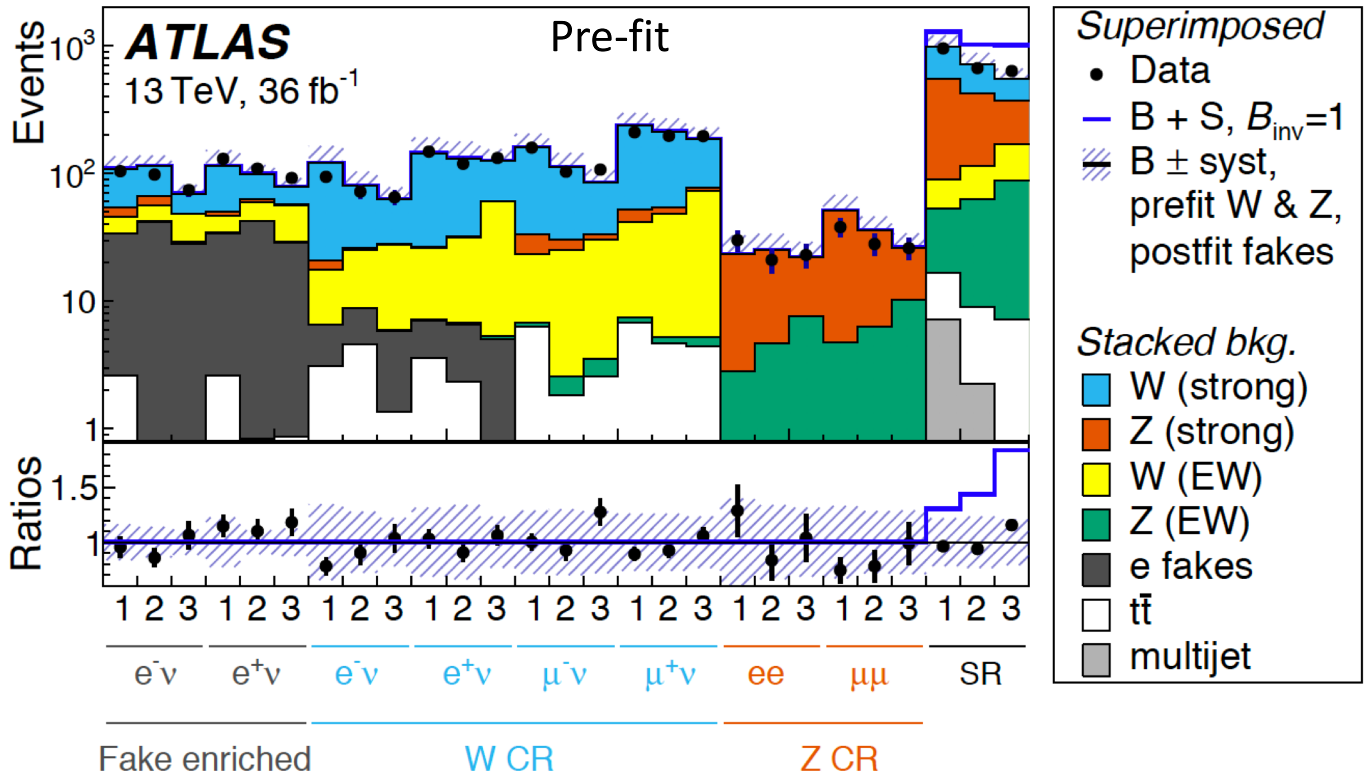
$$\left(B_W^{SR}\right)_{\text{estimate}} = N_W^{CR} \cdot B_W^{SR} / B_W^{CR} = B_W^{SR} \cdot N_W^{CR} / B_W^{CR}$$

$$\left(B_Z^{SR}\right)_{\text{estimate}} = N_Z^{CR} \cdot \underbrace{B_Z^{SR} / B_Z^{CR}}_{\alpha \text{ transfer}} = B_Z^{SR} \cdot \underbrace{N_Z^{CR} / B_Z^{CR}}_{\beta \text{ normalization}}$$

Systematics largely cancel in the transfer factor α

VBF H→inv (ATLAS)

[Phys. Lett. B793 (2019) 499]

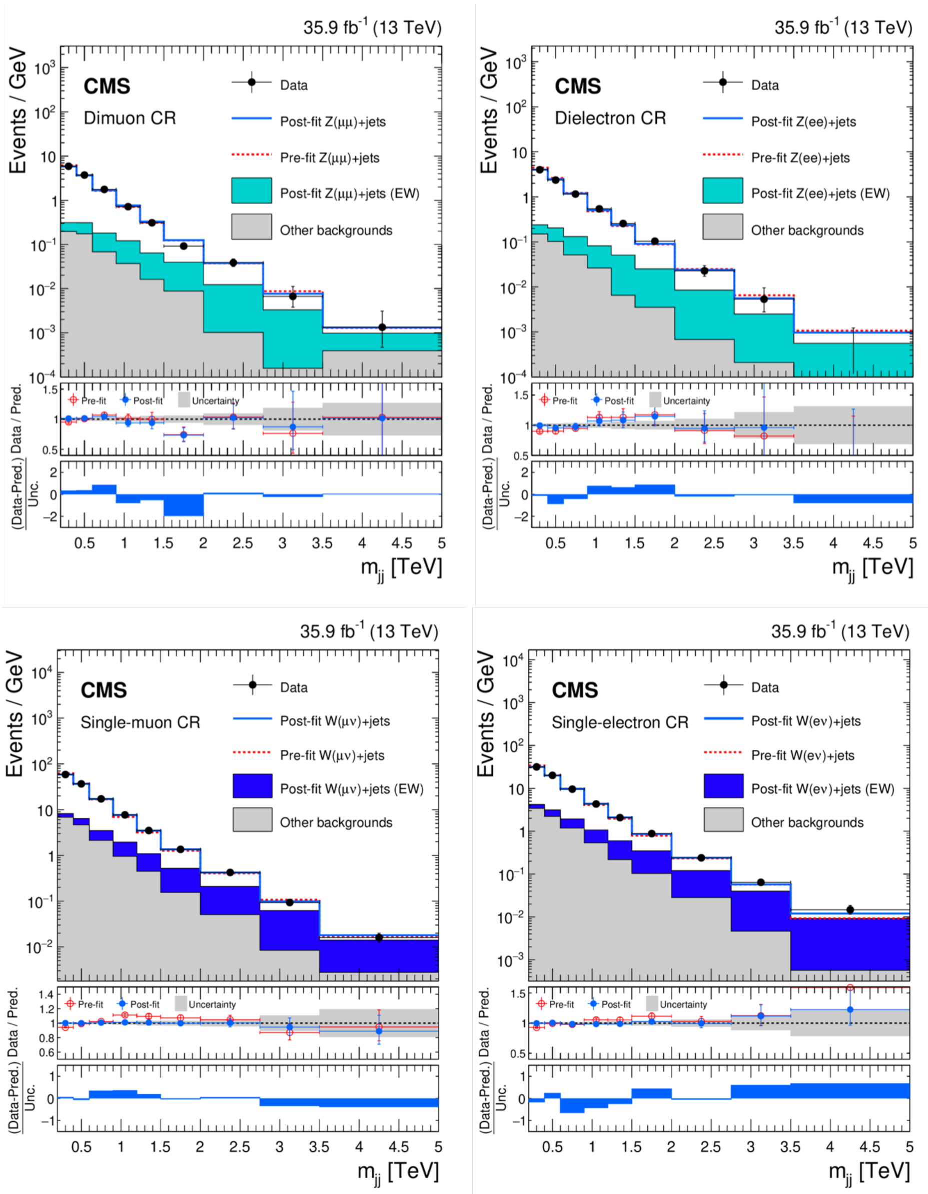


In total 27 mjj bins are defined for the SRs and CRs

The 95% CL upper limit on BR(H→inv) is 0.37 ($0.28^{+0.11}_{-0.08}$) for observed (expected)

VBF H→inv (CMS)

[Phys. Lett. B793 (2019) 520]



CMS define similar transfer factors to estimate V+2j in a simultaneous fit

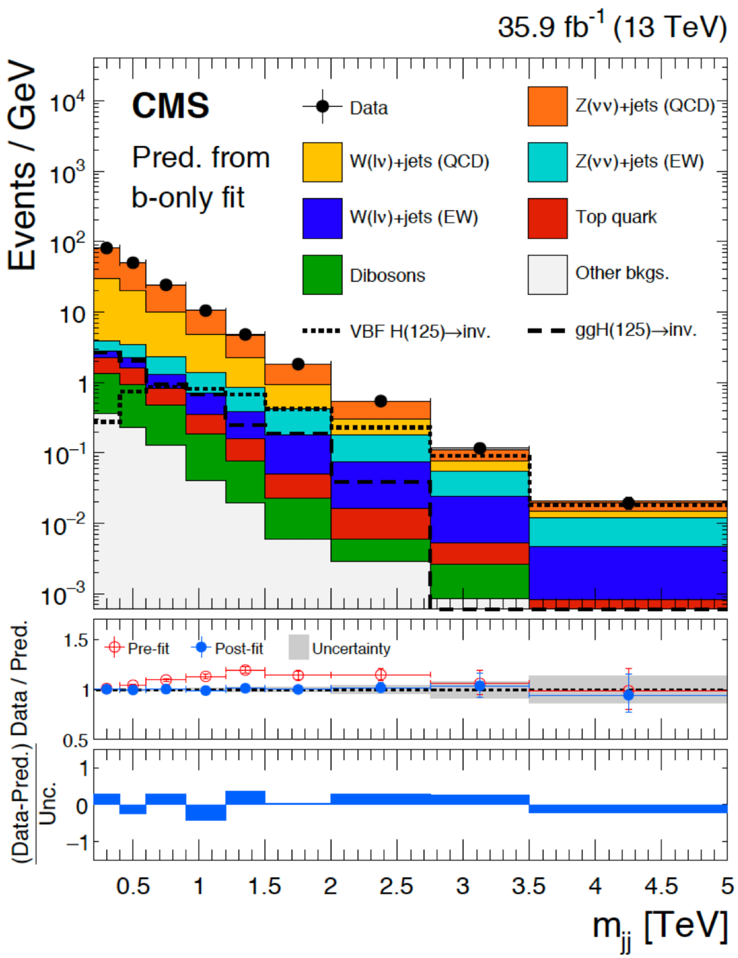
Shape fit to the m_{jj} spectrum, after cutting on other variables (ATLAS has only three m_{jj} bins in SR)

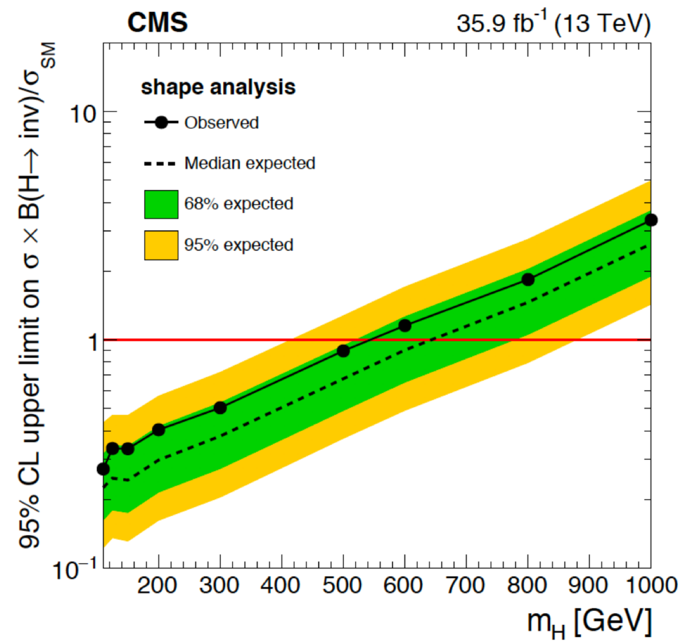
Compared to ATLAS, exploits lower m_{jj} region that are sensitive to ggF (ATLAS starts from 1 TeV for m_{jj})

Cut-and-count analysis also performed to cross check

VBF H→inv (CMS)

[Phys. Lett. B793 (2019) 520]





For 35.9 fb^{-1} data, the 95% CL observed (expected) upper limit on B(H→inv) for m_H=125 GeV is 0.33 (0.25)

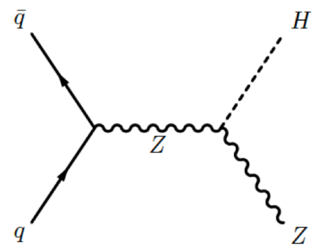
V(*ll*)H(inv) (ATLAS)

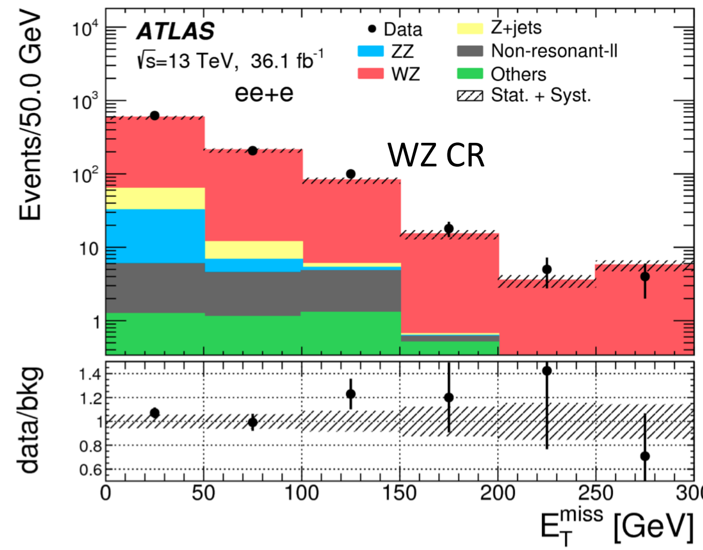
[Phys. Lett. B776 (2017) 318]
[ATLAS HIGG-2016-28 Aux.]

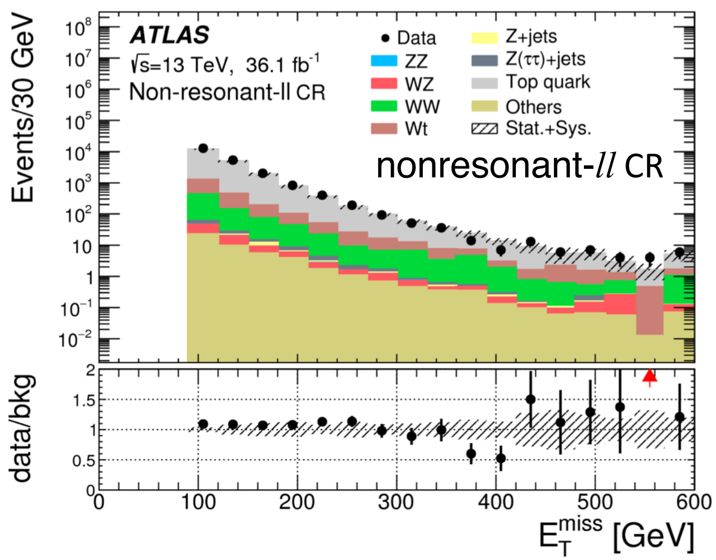
Main SR selection cuts:

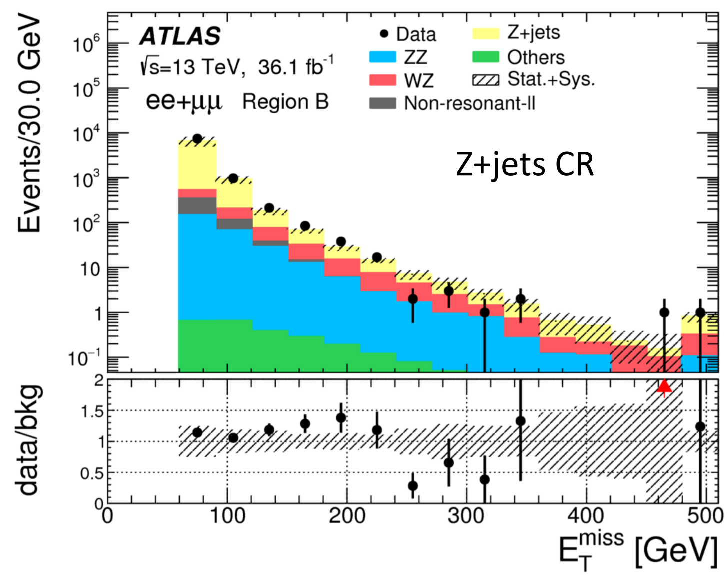
- MET>90 GeV, MET/H_T>0.6
- m_{ll} and $\Delta\phi_{ll}$ cuts
- MET and Z p_T balance
- B-jet veto

Use WZ CR (3lep), nonresonant-ll CR (diff. flav.) and Z+jets CR (ABCD method) to constrain the corresponding bkg.









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[Phys. Lett. B776 (2017) 318]
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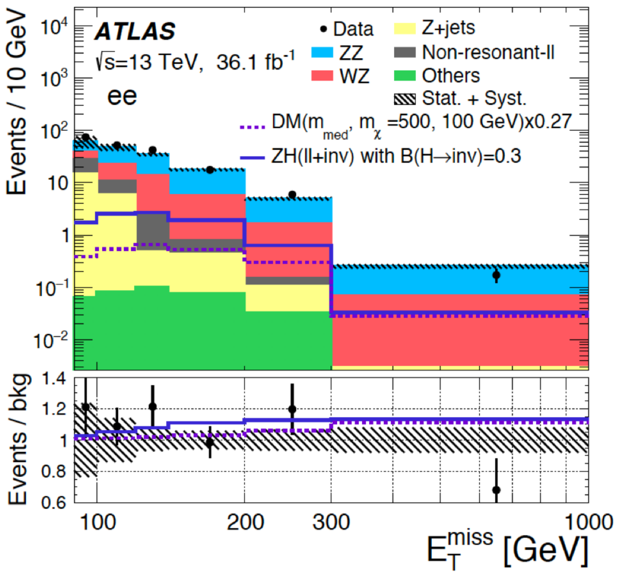
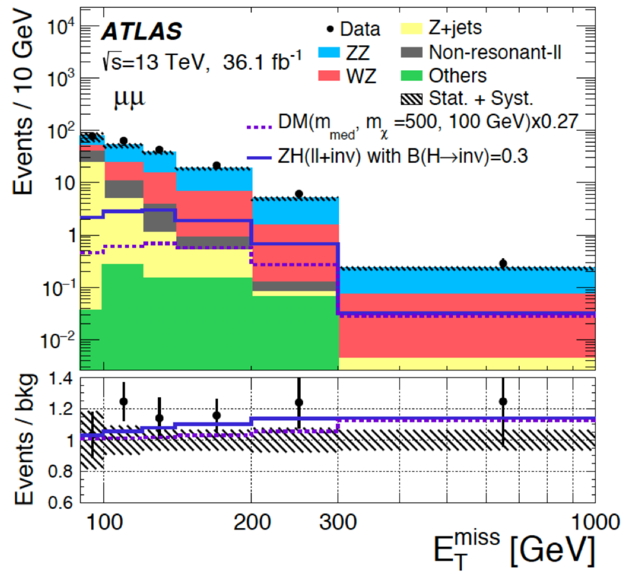
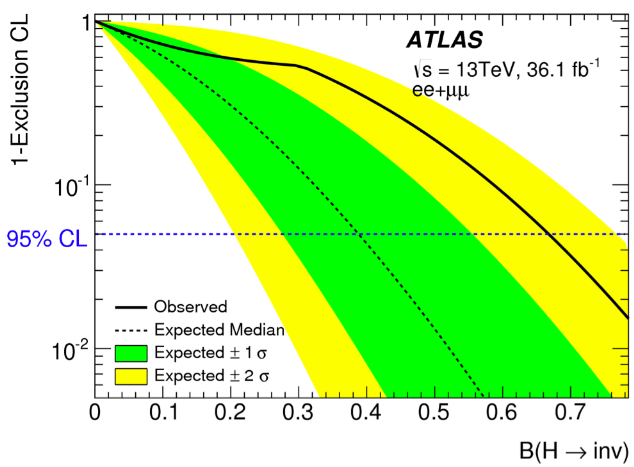






Fit to MET spectrum simultaneously with CR

The 95% CL upper limit on B(H→inv) is 0.67 ($0.39^{+0.17}_{-0.11}$) for observed (expected)

V(ll)H(inv) (CMS)

[Eur. Phys. J. C 78 (2018) 291]

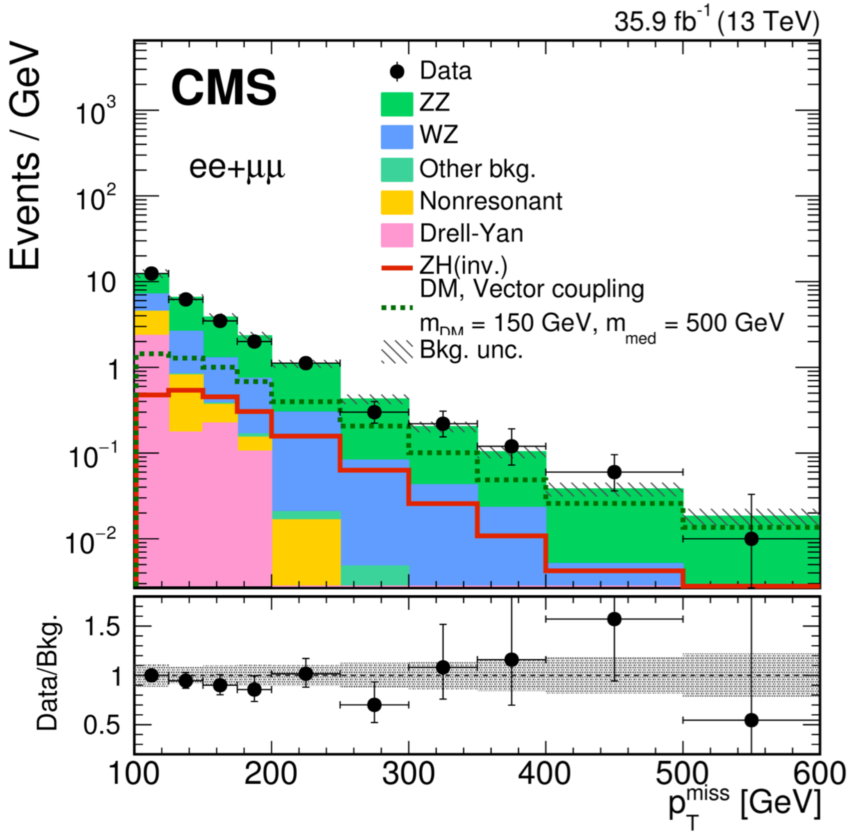
- Two analyses are performed:
  - Fitting the MET spectrum after selection cuts
  - Use multiclass BDT (a BDT for each background and signal, and the final discriminant is the normalized signal likelihood)
- Similar diboson, ttbar and Z+jets CRs as in ATLAS analysis are defined to constrain the backgrounds

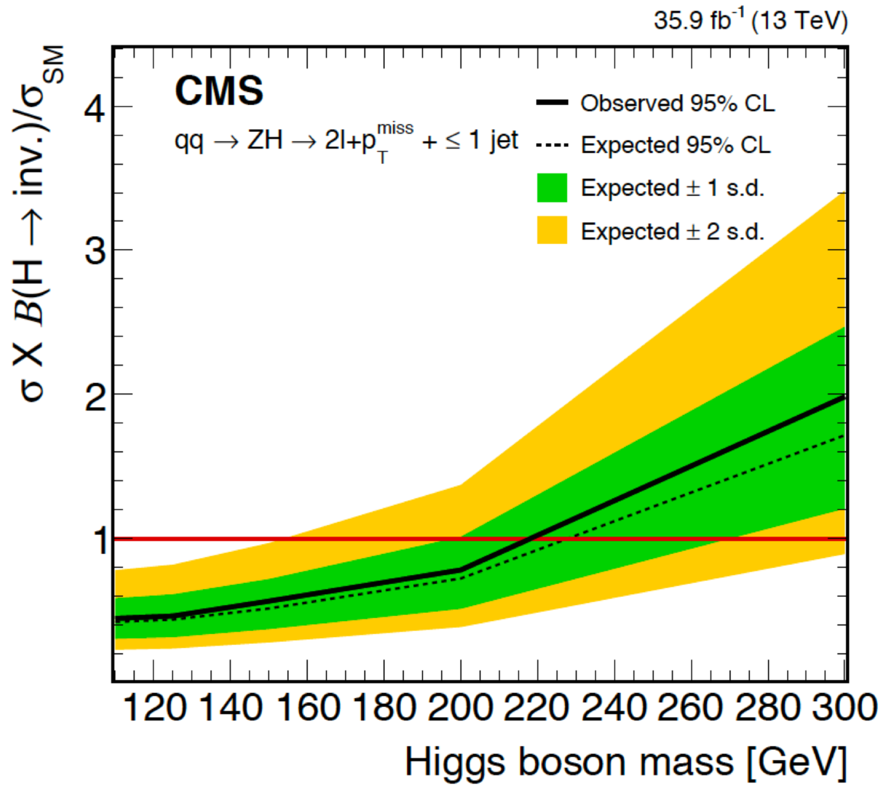
Looser cuts for BDT analysis:

variable	MET fit cuts	BDT cuts
Z mass	$\|m_{ll} - m_z\| < 15$ GeV	$\|m_{ll} - m_z\| < 30$ GeV
jet	≤1 jet (with p_T>30 GeV)	
$p_T(ll)$	>60 GeV	
B-jet and tau	veto	
$\Delta\phi$(jet,MET)	>0.5	
MET	>100 GeV	–
$\Delta\phi$(MET,Z)	>2.6	–
MET balance	$\|MET - p_T^{ll}\|/p_T^{ll}$<0.4	–
ΔR_{ll}	<1.8	–

V(*ll*)H(inv) (CMS)

[Eur. Phys. J. C 78 (2018) 291]
[arXiv:1711.0043]

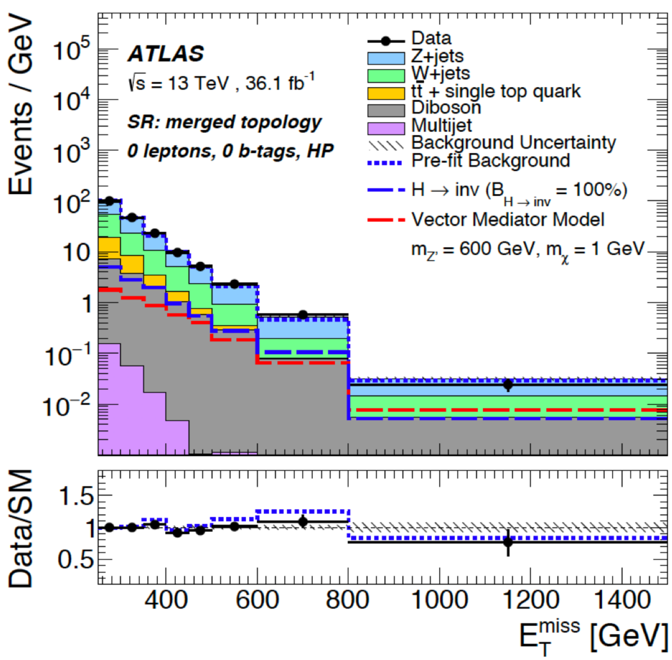


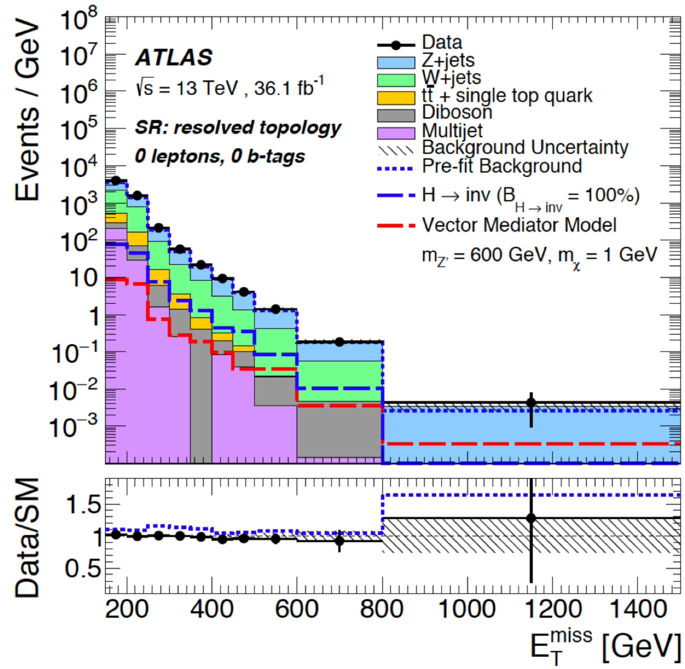


- The 95% CL upper limit on B(H→inv) is 0.45 (0.44) for observed (expected) with m_H=125 GeV and MET fit. The limit is 0.40 (0.42) with BDT
- Caveat in the right figure: only qq→ZH included (gg→ZH not included for show)

V(*qq*)H(inv) (ATLAS)

[JHEP 10 (2018) 180]

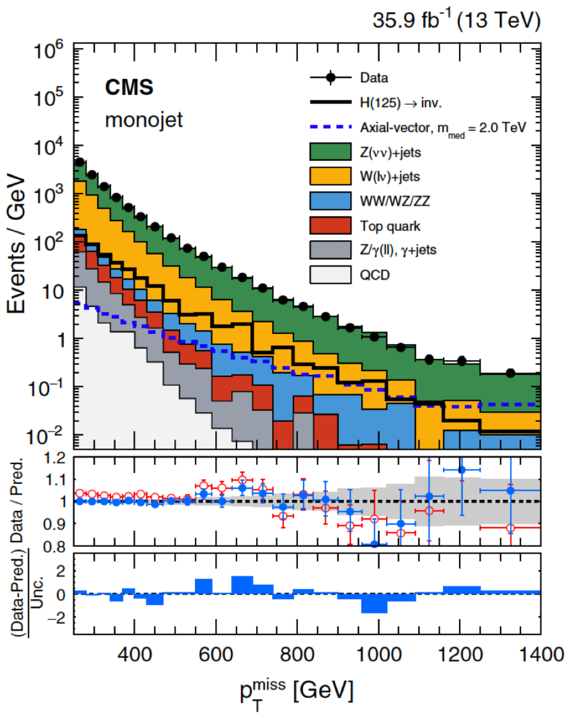


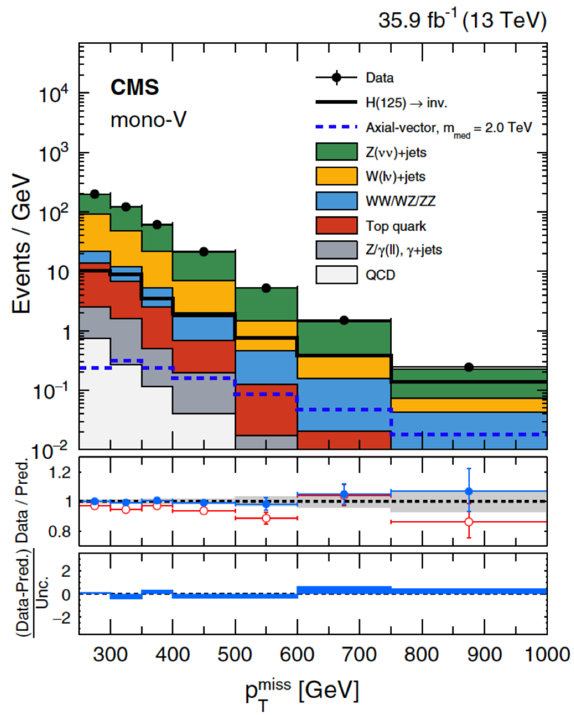


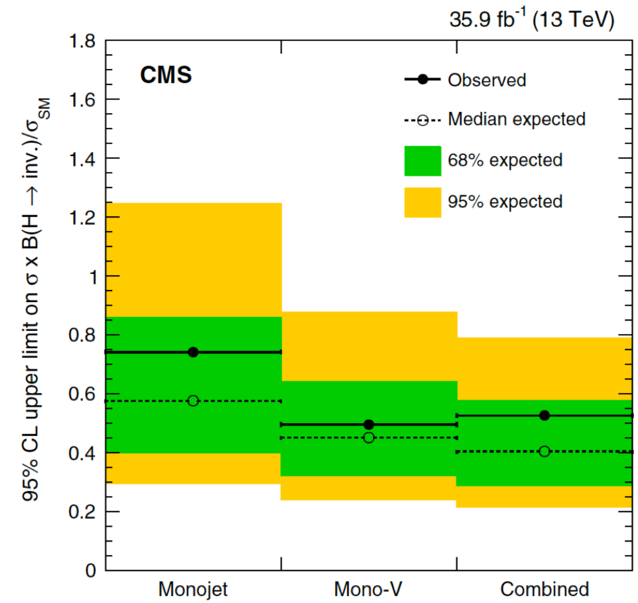
- Backgrounds are dominated by V+jets and ttbar. Require 1 lepton for W+jets and ttbar CR, 2 leptons for Z+jets CR
- Divide into resolved small-R and merged large-R jet categories, and Low and High Purity regions for the latter based on jet substructure (also sensitive to ggF)
- Jet mass consistent with W/Z, e.g., $75<m_J<100$ GeV for merged large-R jet with 2 b-tagged track jets
- MET fit to both SR and CRs. An observed (expected) upper limit of 0.83 (0.58) is obtained at 95% CL on B(H→inv)

V(*qq*)H(inv)+ggH (inv) (CMS)

[Phys. Rev. D97 (2018) 092005]

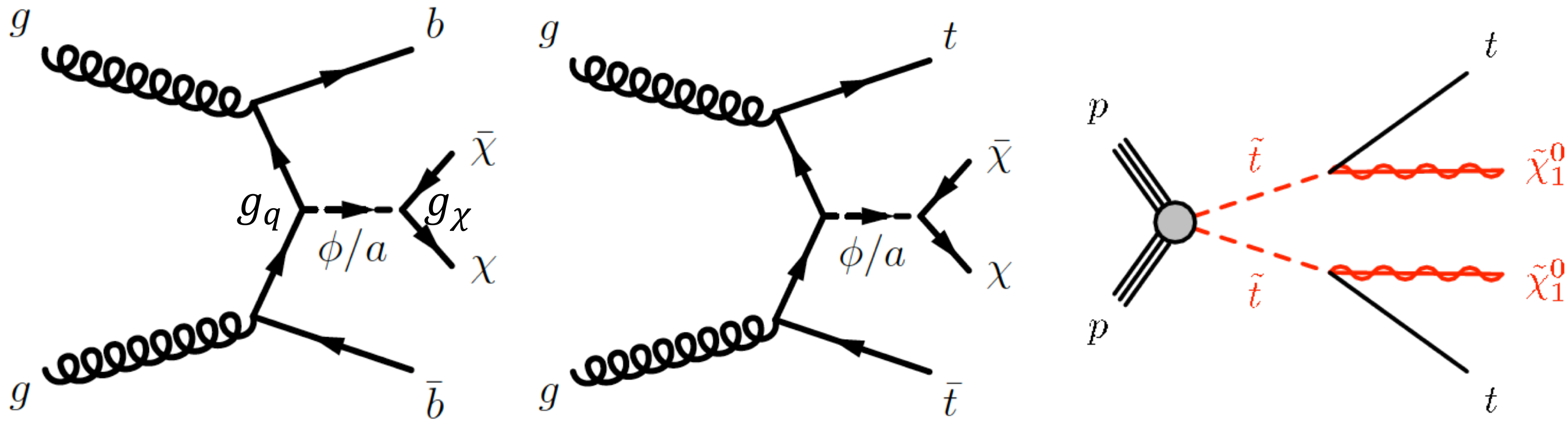






- Compared to ATLAS, also included γ+jets – use hadronic recoil as a proxy for MET modeling (excluding lepton/γ in MET calculation)
- A mono-jet catgegory aiming at jet+DM search, but also covers ggH+1j channel for invisible Higgs search
- The 95% CL observed (expected) upper limit on B(H→ inv) for m_H=125 GeV is 0.53 (0.40)

ttH(inv)+bbH(inv) (ATLAS) [Eur. Phys. J. C78 (2018) 18]



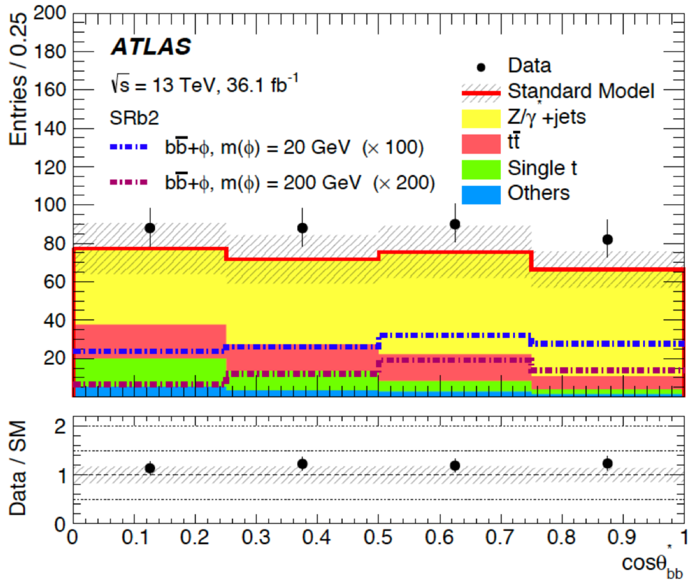
Search for (pseudo-)scalar mediator in association with heavy flavor (b or t). Note: for the ttH production, same final state as the SUSY stop pair production

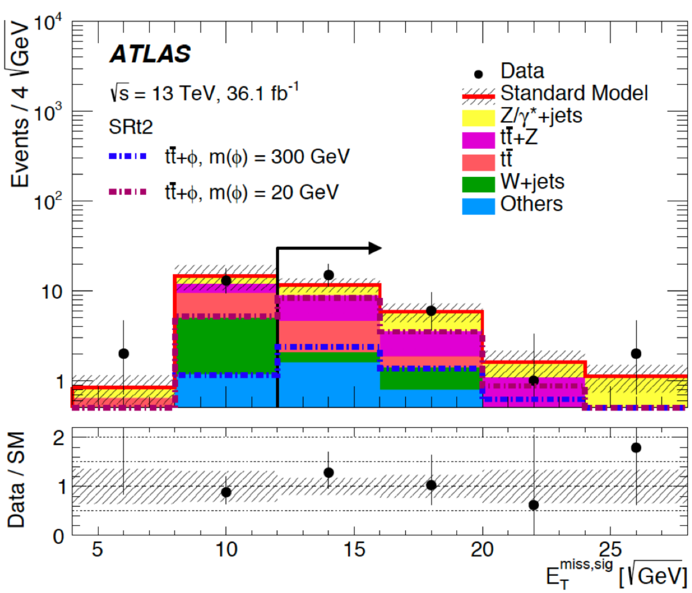
DM is a dirac fermion, Yukawa couplings between mediator and SM fermions ($g_{q,\chi}$)

Five SRs are defined by ATLAS for sensitivity to different signals and regions

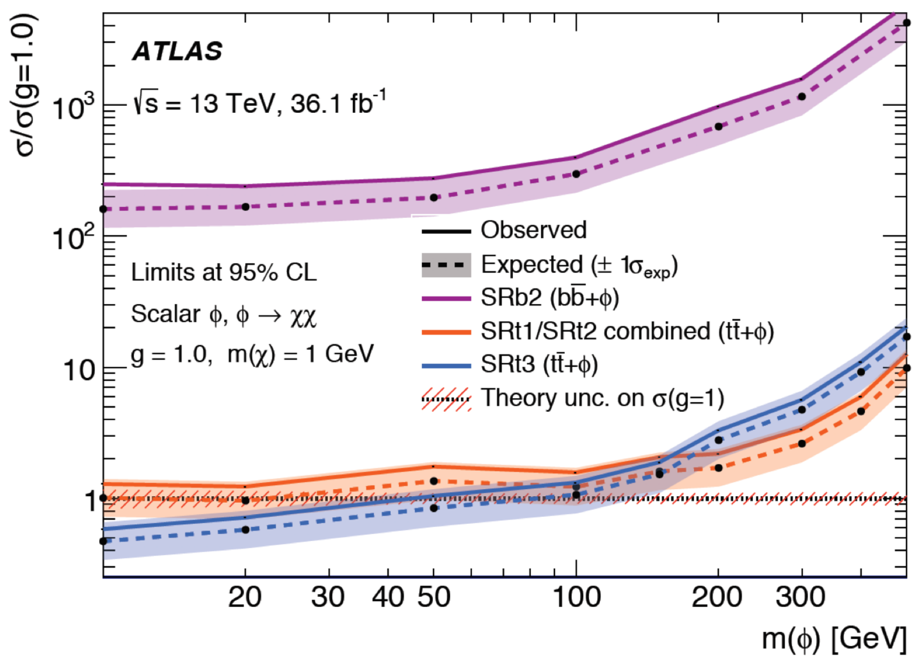
regions	SRb1	SRb2	SRt1	SRt2	SRt3
purpose	1 bjet colored ϕ	2 bjet neutral ϕ	ttbar fully had low ϕ mass	ttbar fully had high ϕ mass	ttbar dileptonic low ϕ mass

ttH(inv)+bbH(inv) (ATLAS) [Eur. Phys. J. C78 (2018) 18]





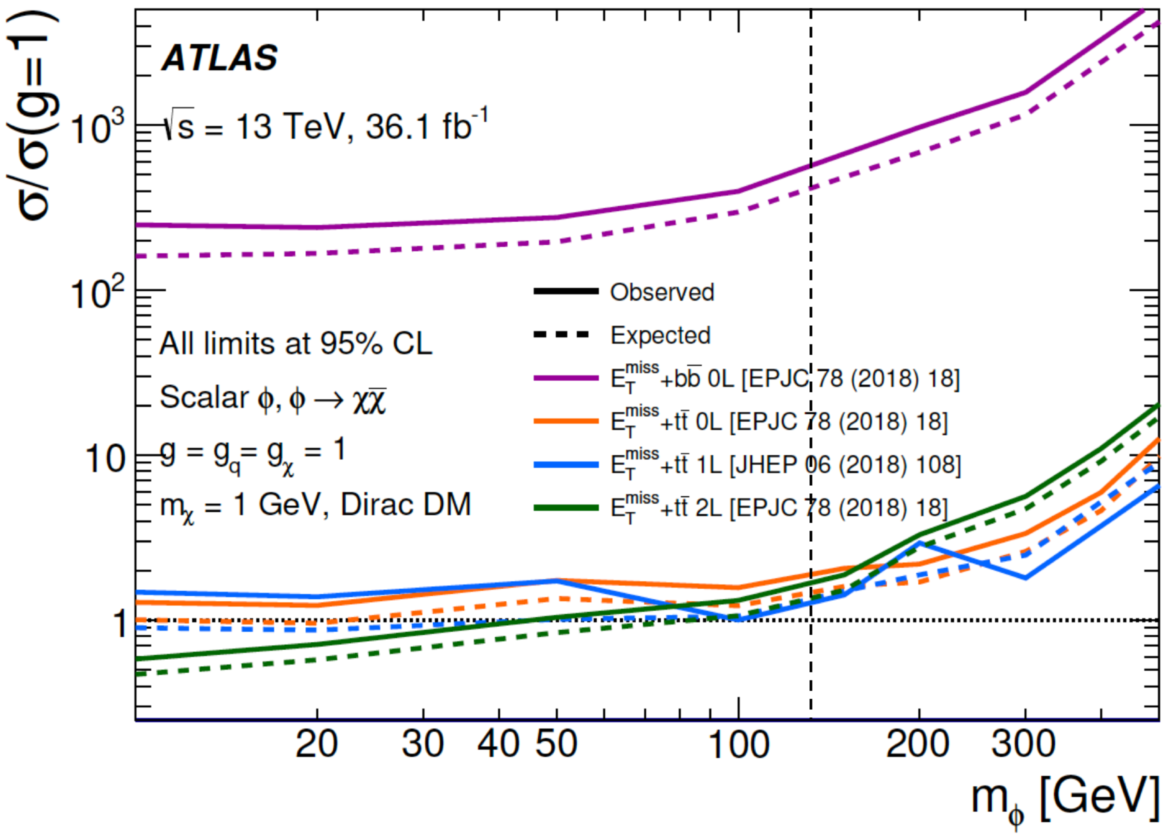
- A number of CRs are defined to constrain the Z+jets, ttbar and ttV backgrounds
- Post-fit prediction of backgrounds in CRs are checked in a number of validation regions
- Upper limit on cross sections of scalars of different masses are obtained with respect to $g = g_q = g_\chi = 1$



ttH(inv) (ATLAS)

[JHEP 05 (2019) 142]

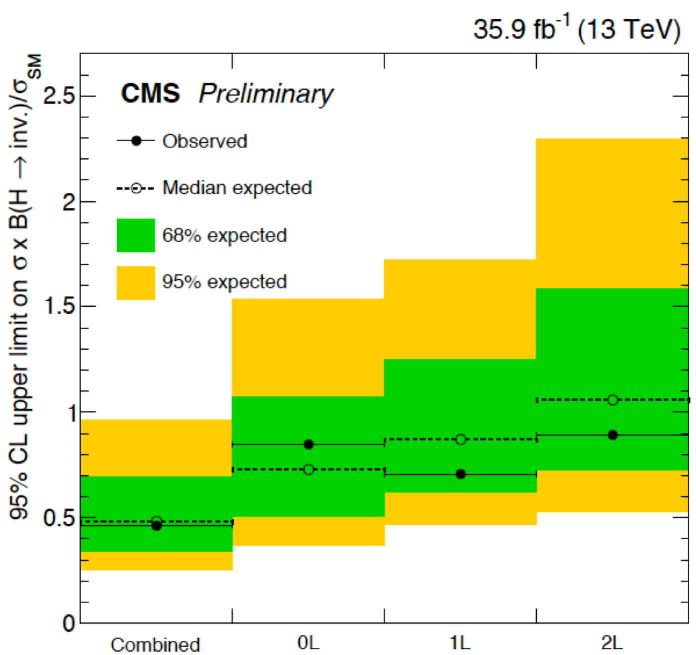
- The 1-lepton decay of ttH(inv) has also been analyzed with similar sensitivity to the 0/2-lepton decay channels
- The ttbar 1-lepton background can be highly suppressed by m_T cut, with ttbar 2-lepton left as the main background

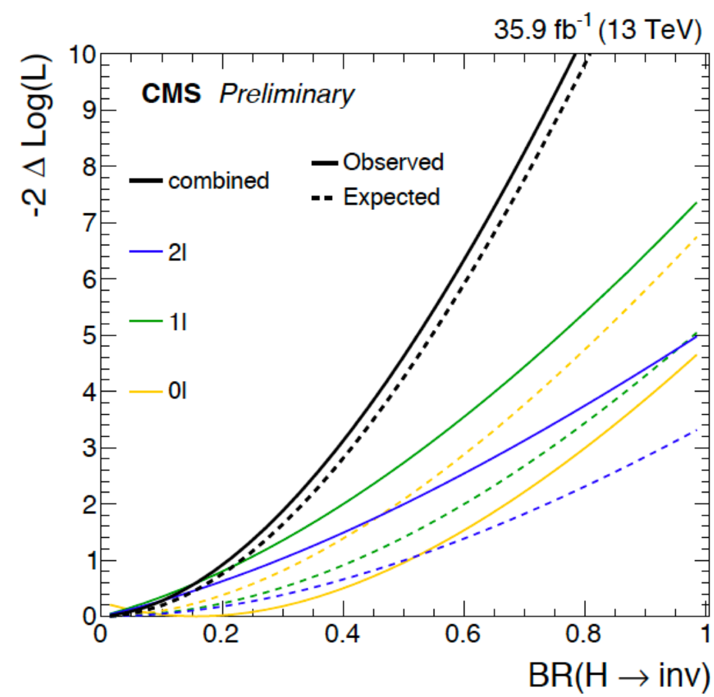


ttH(inv) (CMS)

[CMS-PAS-HIG-18-008]

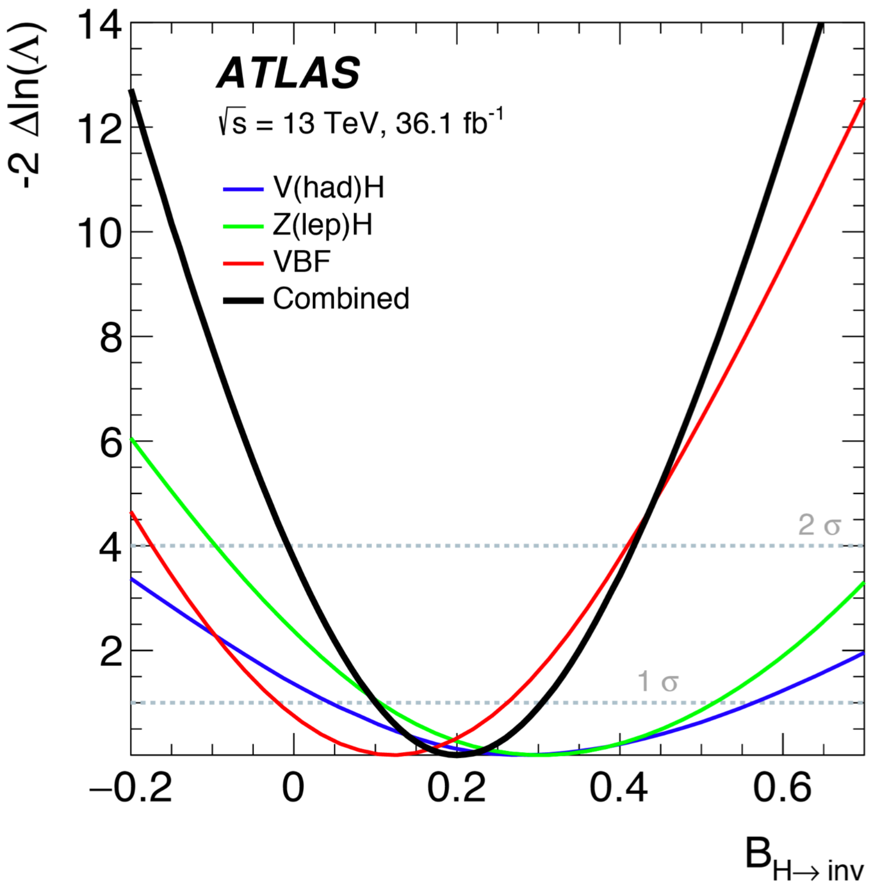
- CMS also includes the 0/1/2-lepton decay channels of the ttbar decay of ttH production
- CRs are used to constrain the top, V+jets and ttV background – reuse the SUSY stop pair analysis results

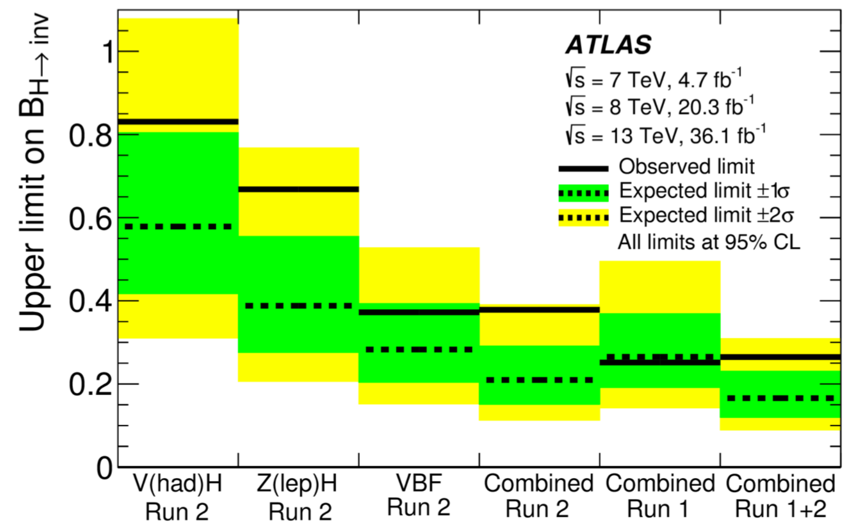




The 95% CL observed (expected) combined upper limit on B(H→inv) for m_H=125 GeV with the ttH production is 0.46 (0.48)

ATLAS Combination [Phys. Rev. Lett. 122 (2019) 231801]

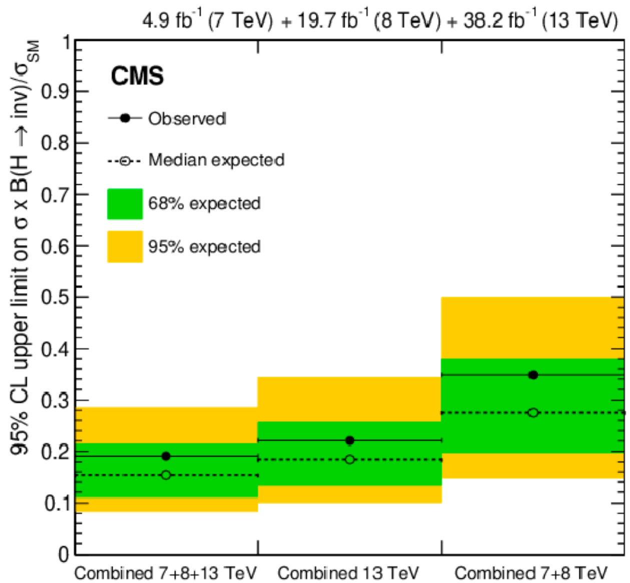


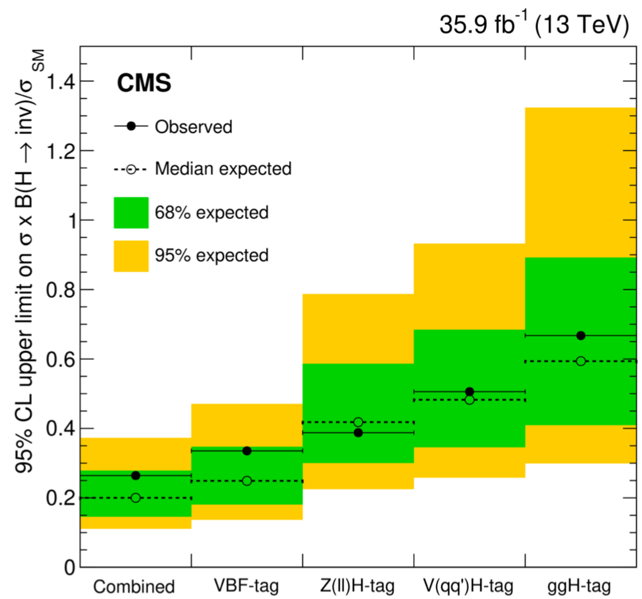


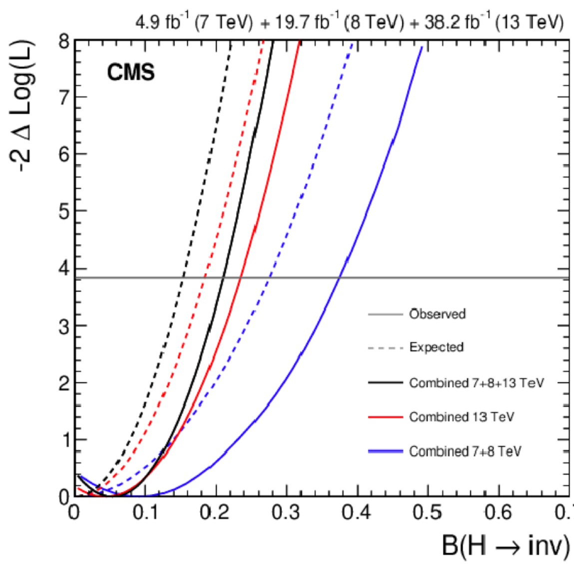
The exclusion limit on B(H→inv) is 0.26 ($0.17^{+0.07}_{-0.05}$) at 95% CL for observed (expected), combining Run 1 and Run 2 data and all Higgs production modes

CMS Combination

[Phys. Lett. B793 (2019) 520]

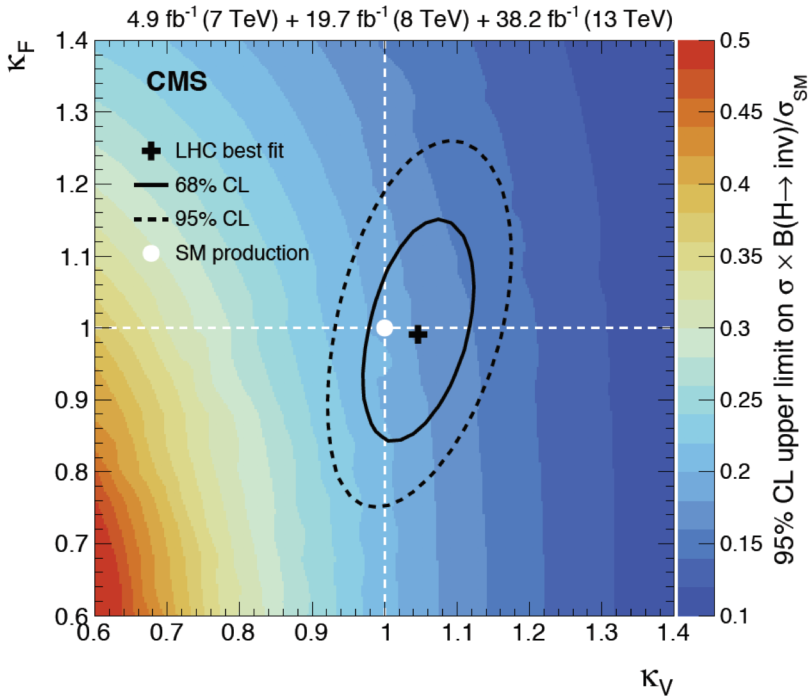






For CMS, an observed (expected) upper limit of 0.19 (0.15) at 95% CL is set on B(H→inv), combining Run 1 and Run 2 data and all Higgs production modes

CMS Combination

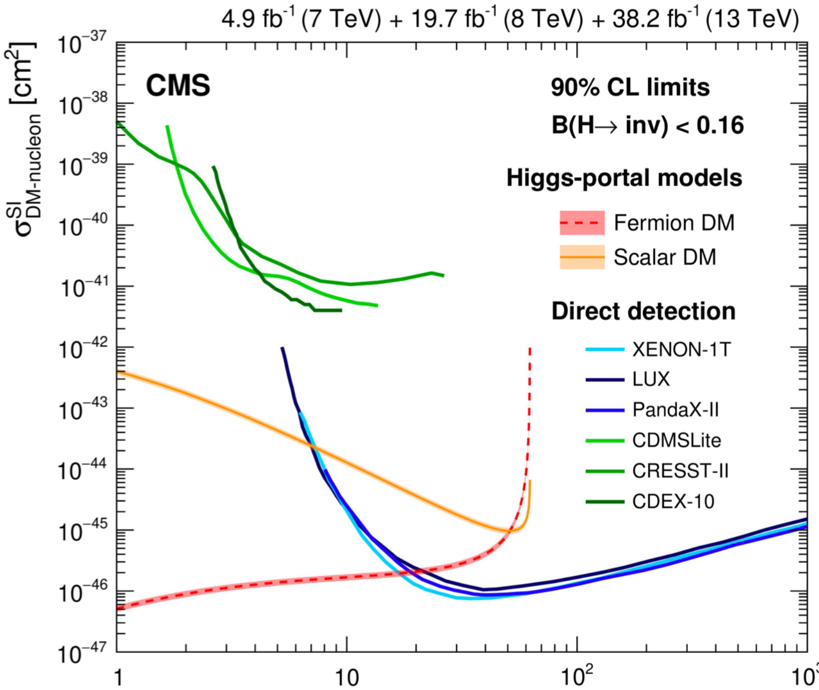


[Phys. Lett. B793 (2019) 520]

- Limits on (σ/σ_{SM})B(H→inv) for a Higgs boson with a mass of 125.09 GeV, whose production cross section varies as a function of the coupling modifiers κ_V and κ_F
- All available data and Higgs production modes are used. Within the 95% CL region, the observed (expected) upper limit on B(H→inv) varies between 0.14 (0.11) and 0.24 (0.19)

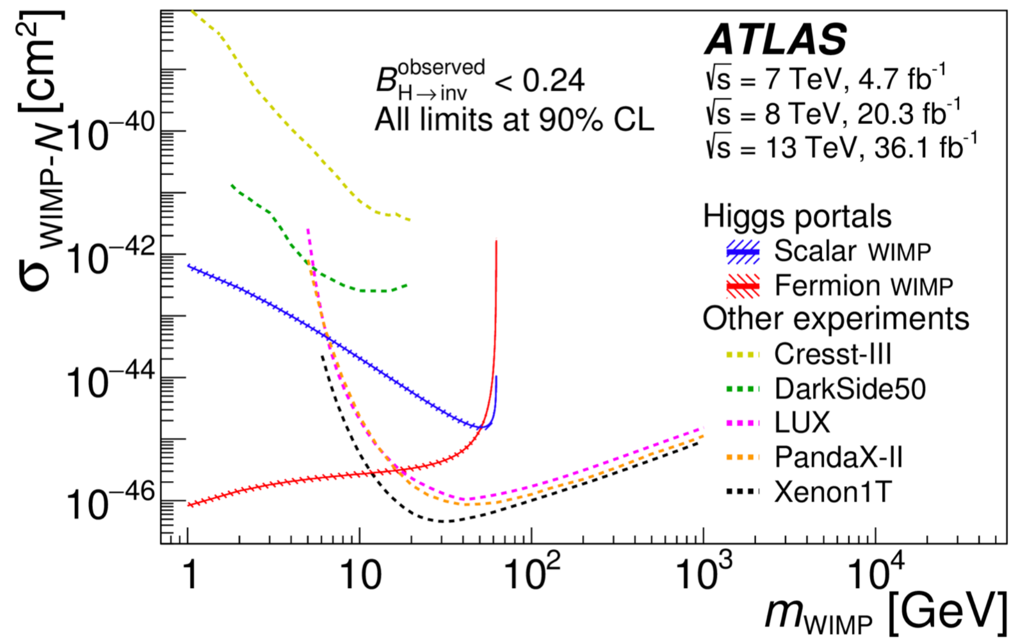
Constraints on DM search

The exclusion limit on the production cross-section of color-neutral scalar mediator particles can be converted into a limit on the spin-independent DM-nucleon scattering cross-section, and be compared with the results from direct-detection experiments



[Phys. Lett. B793 (2019) 520]

[Phys. Rev. Lett. 122 (2019) 231801]



Caveat: there may exist a strong model dependence in the collider interpretation (e.g. require a specific Higgs portal model, c.f. backup), while direct detection has a much lower model dependence (e.g. only relies on assuming a DM velocity with an average given by velocity of sun moving around galaxy center)

Summary

- Higgs can be a portal particle to DM. Searches for invisible Higgs decay are carried out in all Higgs production modes at ATLAS and CMS

- ATLAS and CMS have combined the run-1 and 2015-2016 run-2 data in the 125 GeV $H \rightarrow inv$ direct searches
  - ATLAS: BR($H \rightarrow inv$) < 0.26 (0.17) for observed (expected) @95% CL
  - CMS: BR($H \rightarrow inv$) < 0.19 (0.15) for observed (expected) @95% CL

- DM searches with a scalar of a mass different from 125 GeV, and with pseudo-scalar and vector mediator, are also being carried out at LHC on a broader scale

- It may happen that not all results are covered in this talk. Stay tuned for the full run-2 search results!

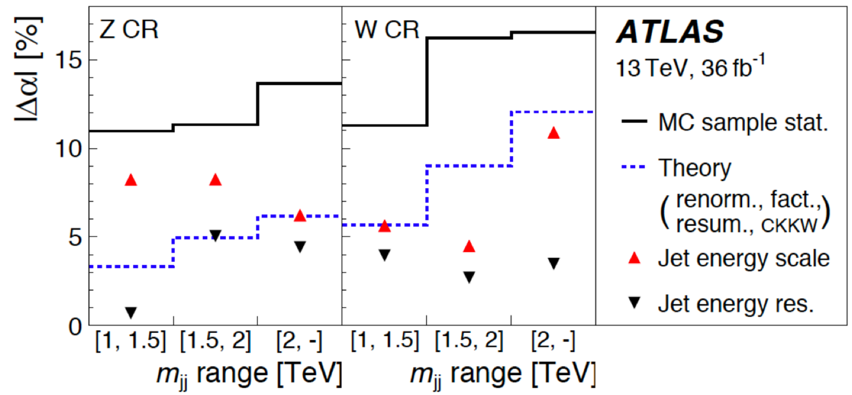
Backup Slides

VBF H→inv (ATLAS)

[Phys. Lett. B793 (2019) 499]

Analysis SR selection:

- no isolated electron or muon,
- a leading jet with $p_T > 80\,\text{GeV}$,
- a subleading jet with $p_T > 50\,\text{GeV}$,
- no additional jets with $p_T > 25\,\text{GeV}$,
- $E_T^{miss} > 180\,\text{GeV}$,
- $H_T^{miss} > 150\,\text{GeV}$.
- not be aligned with $\vec{E}_T^{miss}$, $|\Delta\phi_{j\text{-MET}}| > 1$,
- not be back-to-back, $|\Delta\phi_{jj}| < 1.8$,
- be well separated in η, $|\Delta\eta_{jj}| > 4.8$,
- be in opposite η hemispheres, $\eta_{j_1} \cdot \eta_{j_2} < 0$,
- $m_{jj} > 1$ TeV.



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Systematics largely cancel in the transfer factor α

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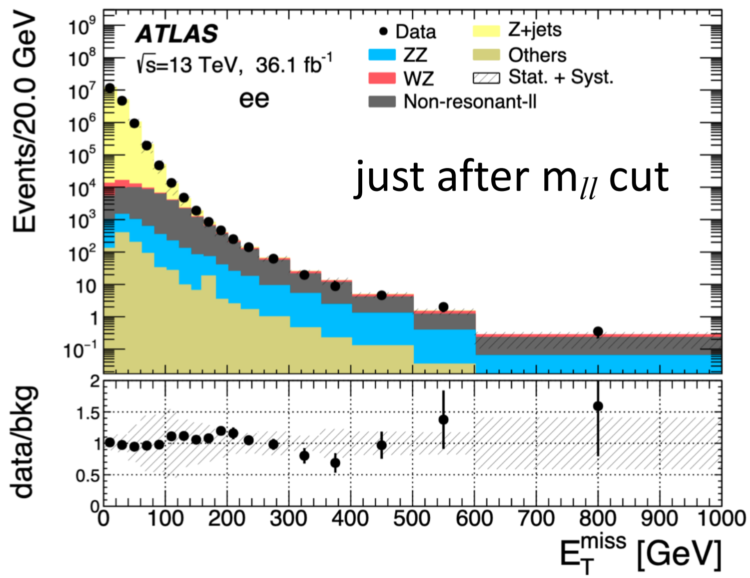
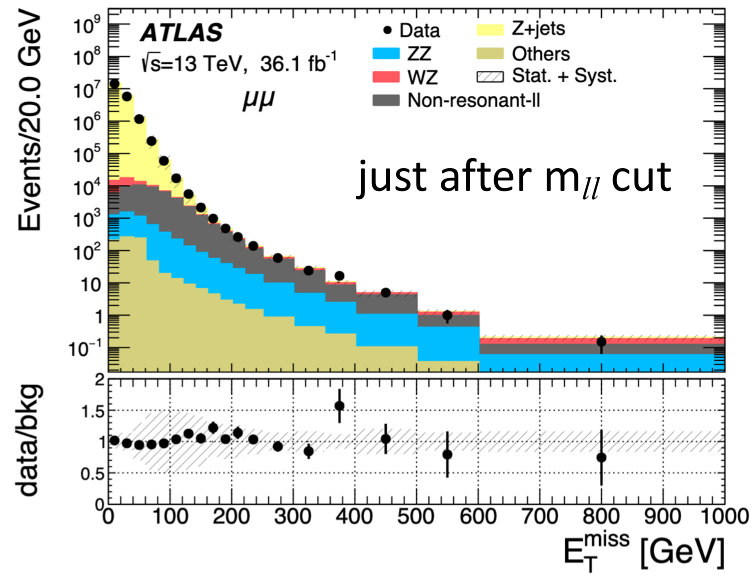
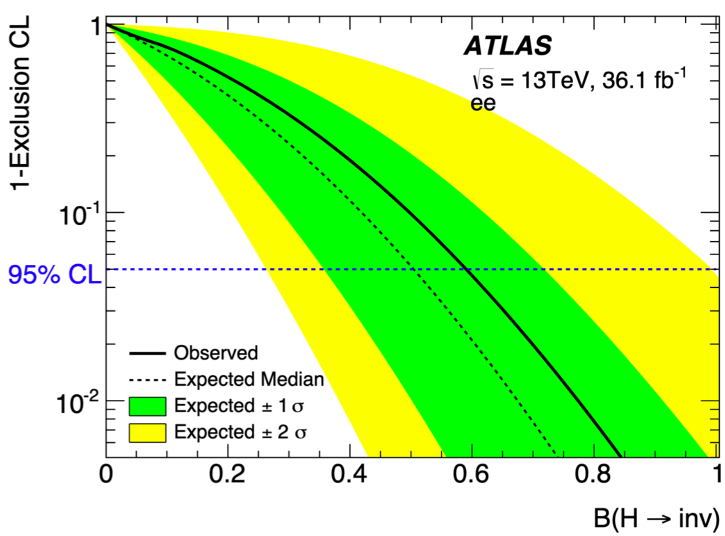
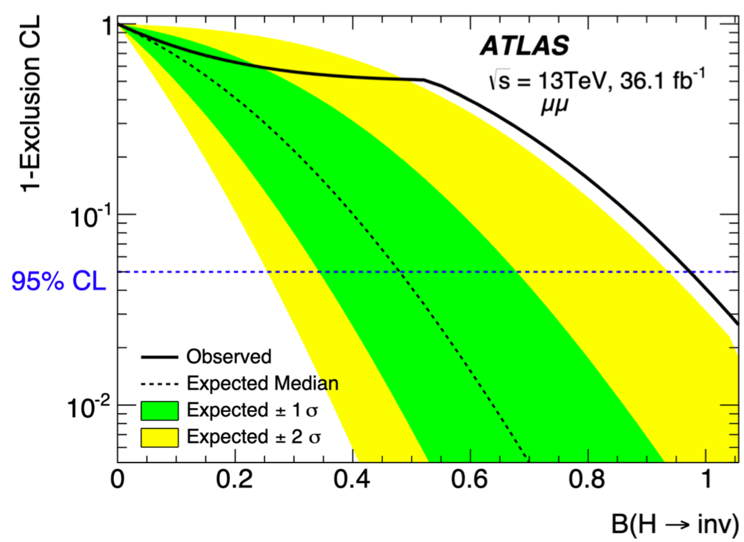


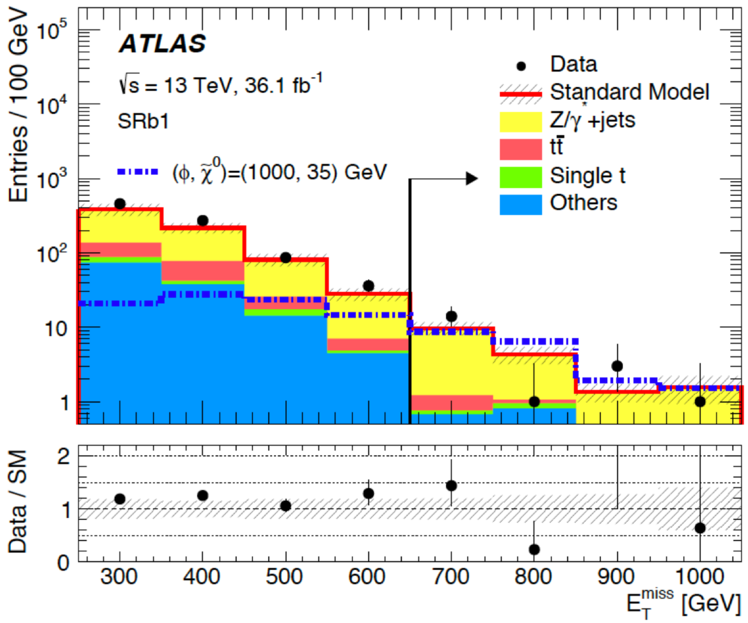


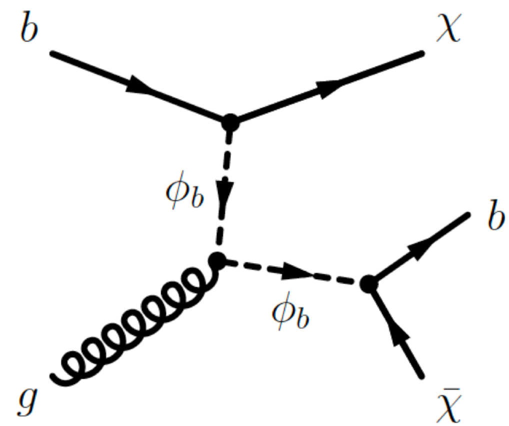


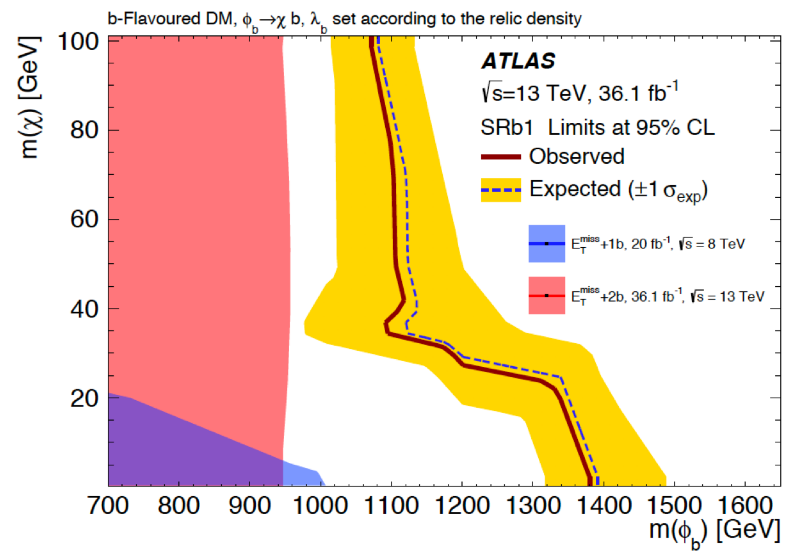


bbH(inv) (ATLAS)

[Eur. Phys. J. C78 (2018) 18]







- The scalar mediator can be color-charged that lead to decay $\phi \rightarrow b\chi$
- Setting the coupling λ_b to fulfil the relic density, a ϕ mass up to ~1.4 TeV can be excluded

H→Dark Matter

The Higgs decay width (and WIMP-Nucleon cross section) to WIMP depends on whether the WIMP particle is a scalar, fermion (Majorana), or vector

[A. Djouadi et al., arXiv:1112.3299]

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \ ,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu ,$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi \ .$$

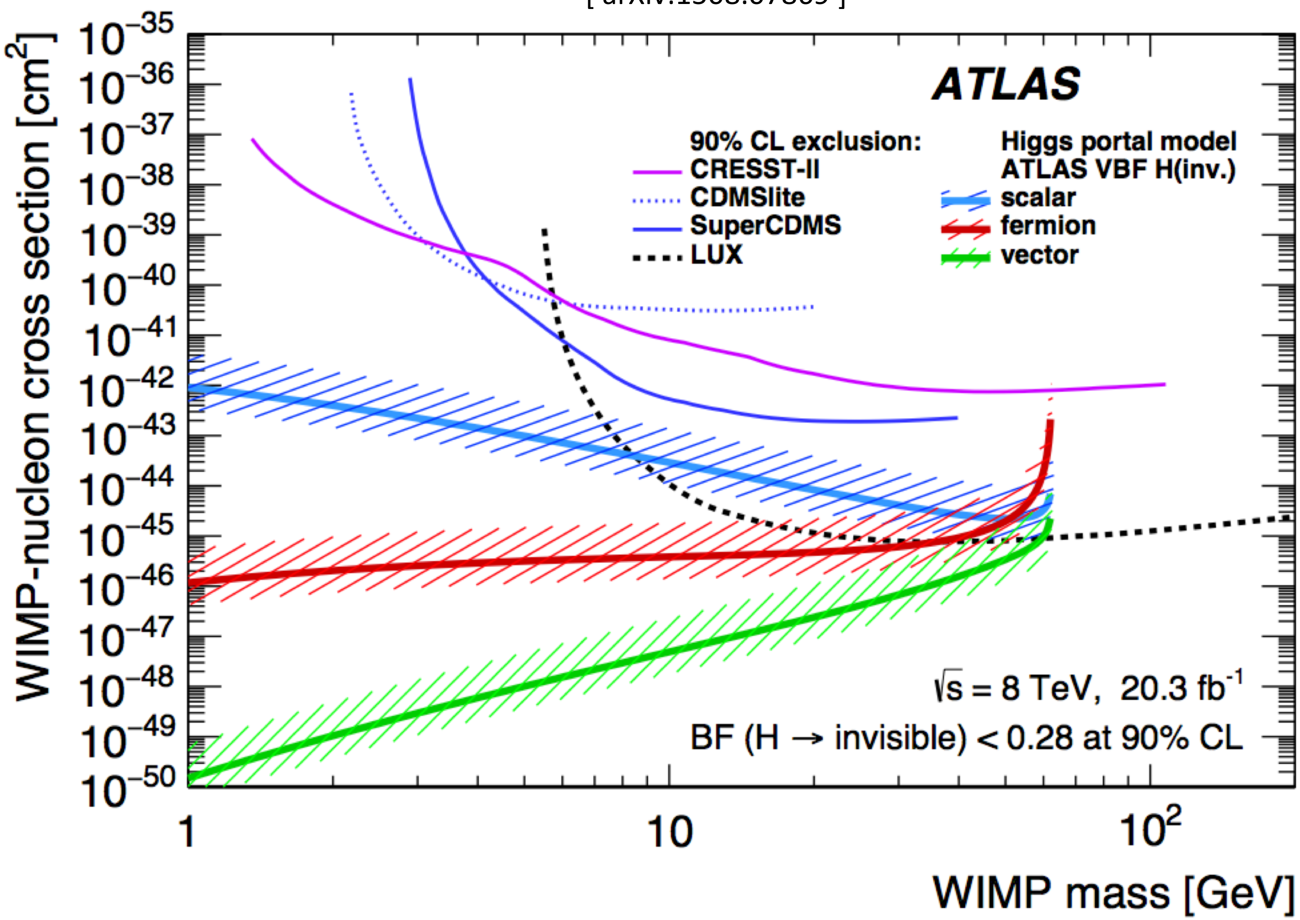
$$\sigma^{SI}_{S-N} = \frac{\lambda_{hSS}^2}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S + m_N)^2} \ , \qquad \Gamma^{\rm inv}_{h\to SS} = \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h} \ ,$$

$$\sigma^{SI}_{V-N} = \frac{\lambda_{hVV}^2}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_V + m_N)^2} \ , \qquad \Gamma^{\rm inv}_{h\to VV} = \frac{\lambda_{hVV}^2 v^2 m_h^3 \beta_V}{256\pi M_V^4}\left(1 - 4\frac{M_V^2}{m_h^2} + 12\frac{M_V^4}{m_h^4}\right) ,$$

$$\sigma^{SI}_{f-N} = \frac{\lambda_{hff}^2}{4\pi \Lambda^2 m_h^4}\frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2} \ , \qquad \Gamma^{\rm inv}_{h\to \chi\chi} = \frac{\lambda_{hff}^2 v^2 m_h \beta_f^3}{32\pi \Lambda^2} \ ,$$

H→Dark Matter

[arXiv:1508.07869]

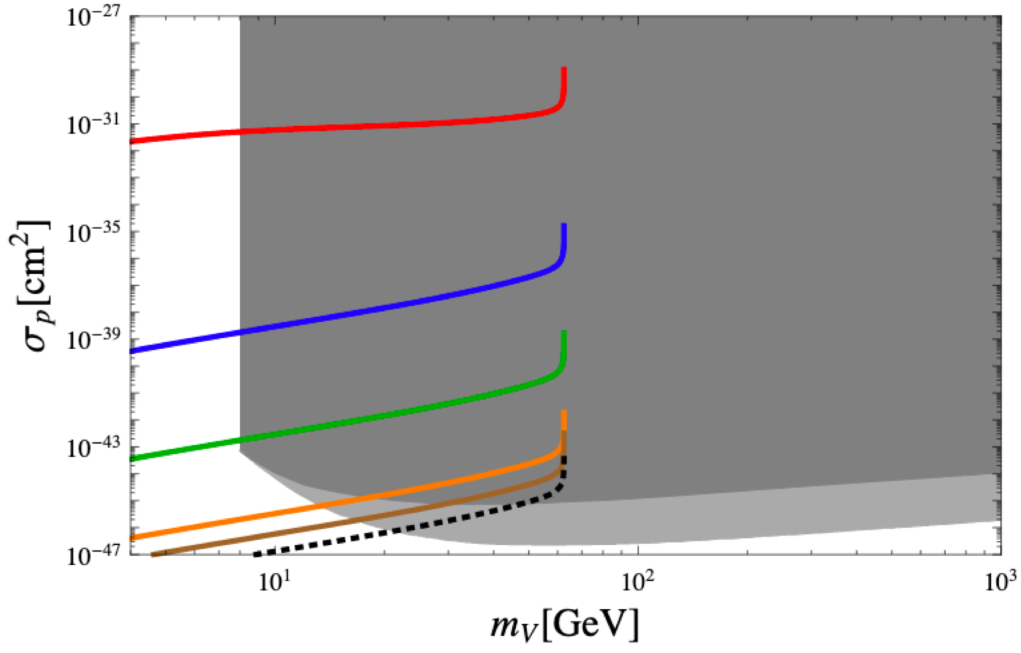


H→Dark Matter

- However, it was pointed out that the fermion Higgs portal is EFT (only valid for energy less than ~1 TeV), and vector Higgs portal is not renormalizable due to missing dark Higgs
- The renormalizable vector case (with a 2nd scalar Φ – dark Higgs):

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$

[arXiv:1405.3530]



For small m_2, limits can be weaker than EFT