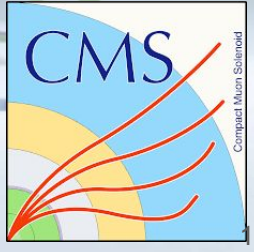
Searches for invisible decays of the Higgs boson at the LHC

Shih-Chieh Hsu 徐士傑
University of Washington
On behalf of the ATLAS and CMS Collaborations

Higgs 2023, Beijing

Nov 30 2023

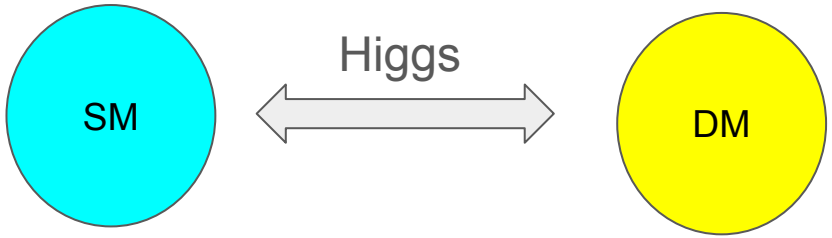


Higgs portal to dark matter

- Significant gravitational anomaly observations in astronomy supporting particle nature of dark matter (DM), a stable weakly interacting massive particle (WIMP)
- If DM corresponding to a singlet scalar, fermion or vector

  ➡ it can substantially couple to SM via SM Higgs boson

- Enhancement of invisible Higgs decay as a probe of DM (H→2DM) at the LHC
  - In the SM, H→ZZ→4ν with SM BR=0.1%

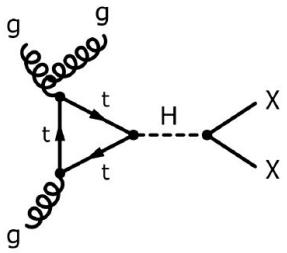


Mass $m_{DM} < m_h/2$

Higgs Portal Models:
- EPJC 73 (2013) 2455
- hep-ph/0605188

Other exotic decay (e.g. long-lived particles) in Hengne Li's talk

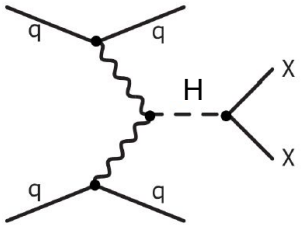
Production modes in H→inv searches



Gluon fusion (ggH)

40pb

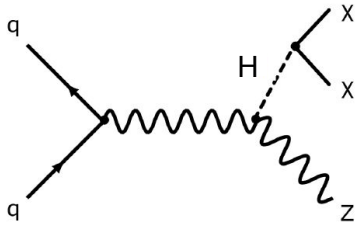
Least sensitive expected limit



Vector-boson fusion (VBF H)

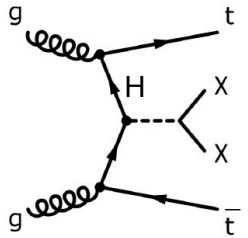
3.8pb

Most sensitive expected limit



Higgs strahlung (VH)

2.3pb

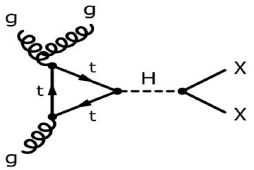


Top-quark associated (ttH)

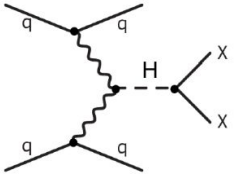
0.5pb

Combine above channels to set the best upper limit on the branching ratio of Higgs to invisible

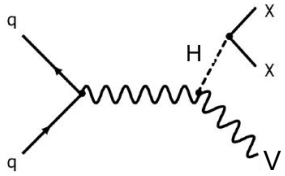
Comprehensive study of $h \to$ inv searches



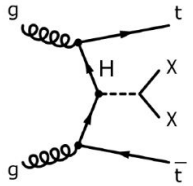
Gluon fusion



Vector-boson fusion (VBF H)



Higgs strahlung (VH)

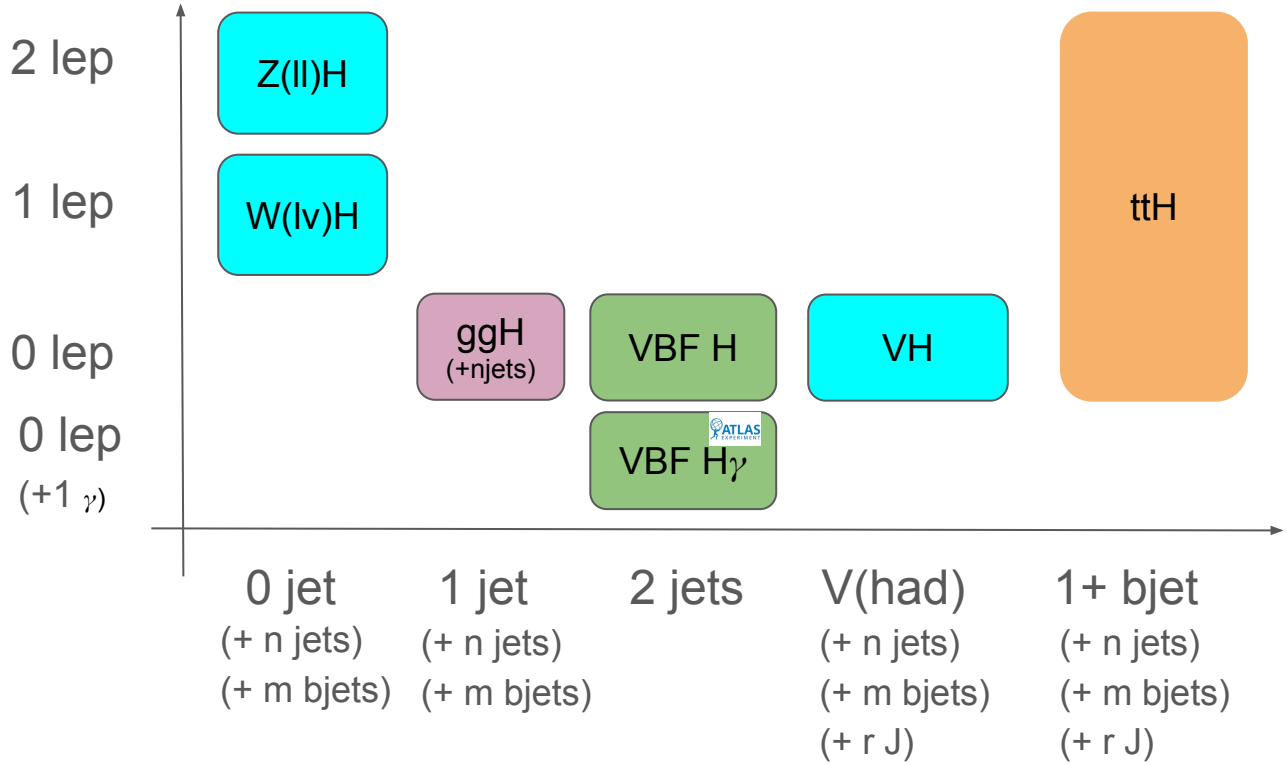


Top-quark associated (ttH)

ATLAS EXPERIMENT PLB 842 (**2023**) 137963	Run1		JHEP 11 (2015) 206	JHEP 11 (2015) 206	
	Run2	PRD 103 (2021) 112006	JHEP 08 (2022) 104 EPJC 82 (2021) 105 (VBF $h\gamma$)	PLB 829 (2021) 137066	EPJC 83 (**2023**) 503
CMS EPJC 83 (**2023**) 933	Run1	EPJC 74 (2014) 2980 JHEP 12 (2016) 083	EPJC 74 (2014) 2980	EPJC 74 (2014) 2980 JHEP 12 (2016) 083	
	Run2	JHEP 02 (2017) 135 JHEP 11 (2021) 153	JHEP 02 (2017) 135 PRD 105 (2022) 092007	JHEP 02 (2017) 135 JHEP 11 (2021) 153 EPJC 83 (**2023**) 933	JHEP 05 (2020) 032 EPJC 81 (2021) 3 EPJC 83 (**2023**) 933

Complementary final states

Common signatures: large missing transverse energy E_T^{miss}

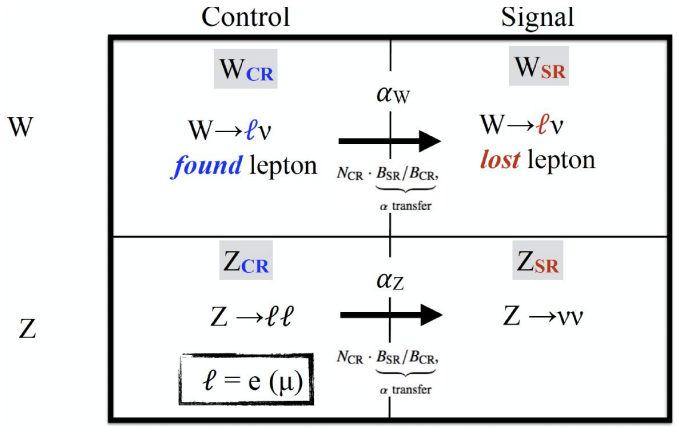


Data-driven background modeling using Control Regions

Simultaneous fit to **signal region** and **control regions** (CR) leads to cancellation of important uncertainties

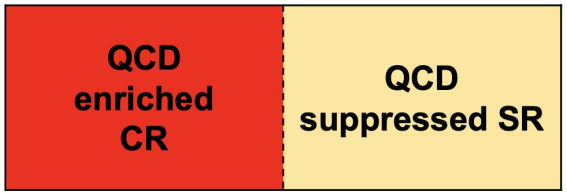
W/Z example:

Attributed to lost lepton or irreducible neutrino decays



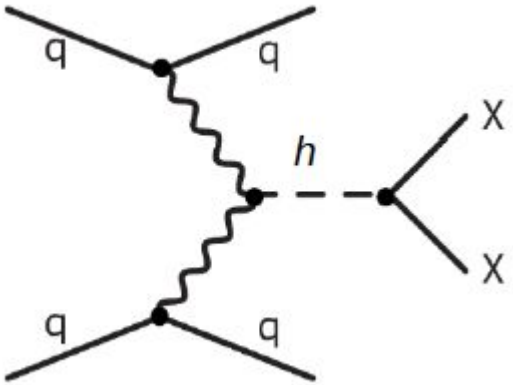
QCD multijets example:

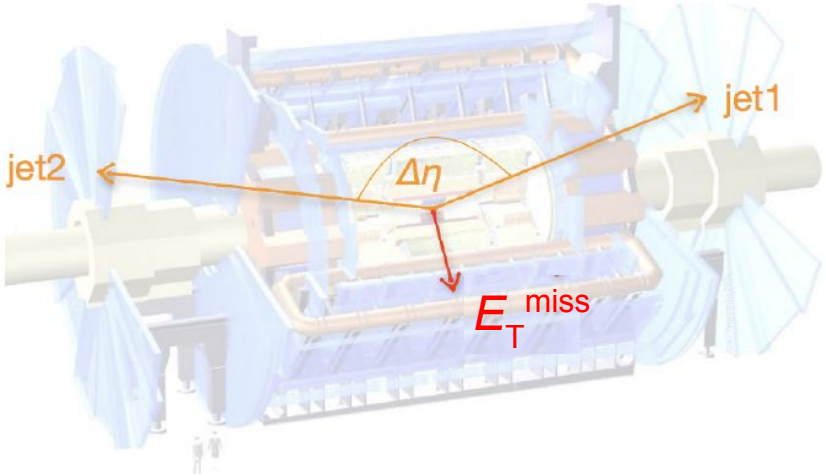
Attributed to jet energy mismeasurement or detector noise



$\Delta\phi_{min}\ (p_{Tj}, p_T^{miss})$

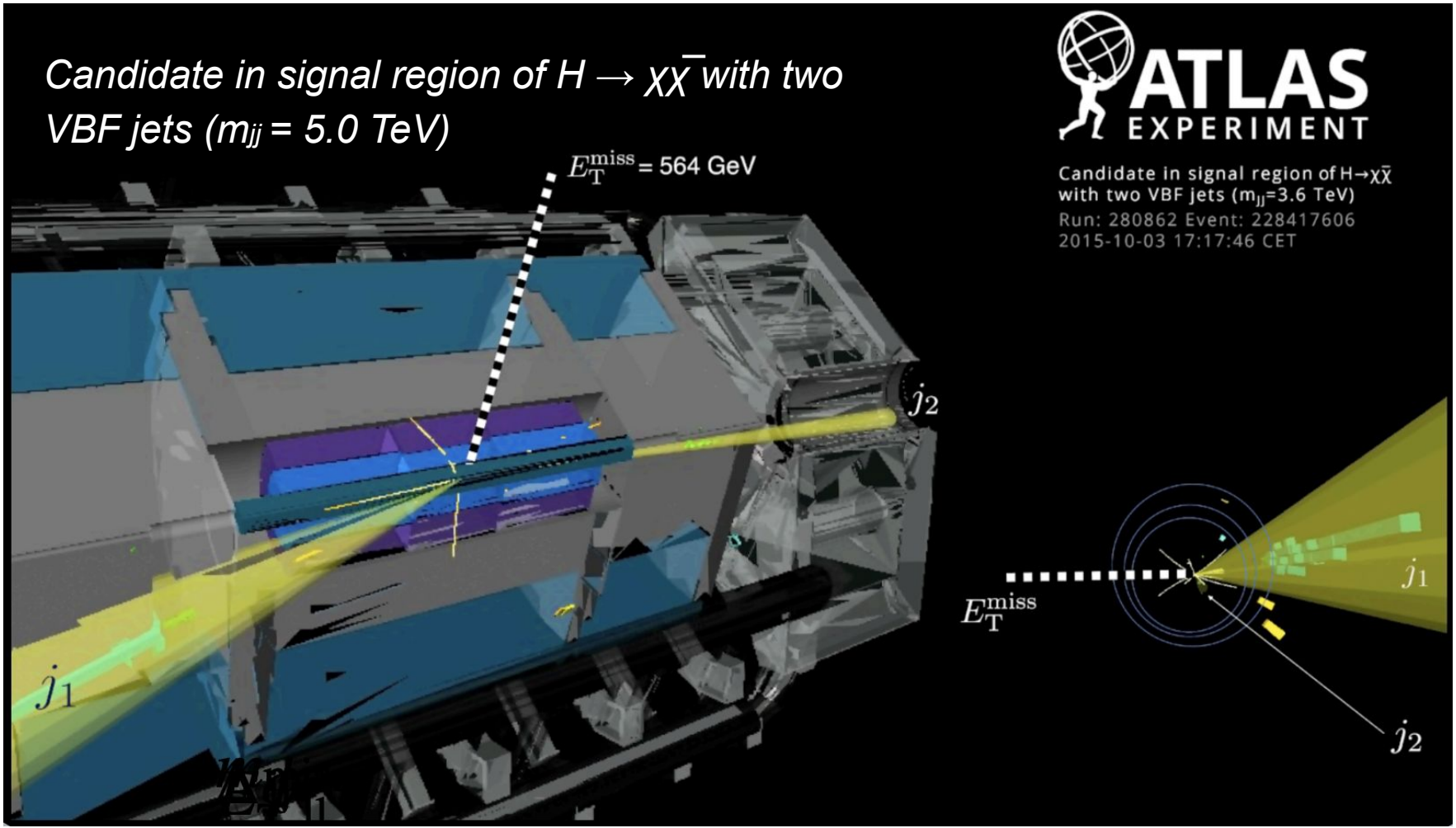
VBF H





- Tag using forward jets with large Δη(jj)
- Main backgrounds are V+jets processes: Z → νν and W → l(lost)ν both QCD and EWK production

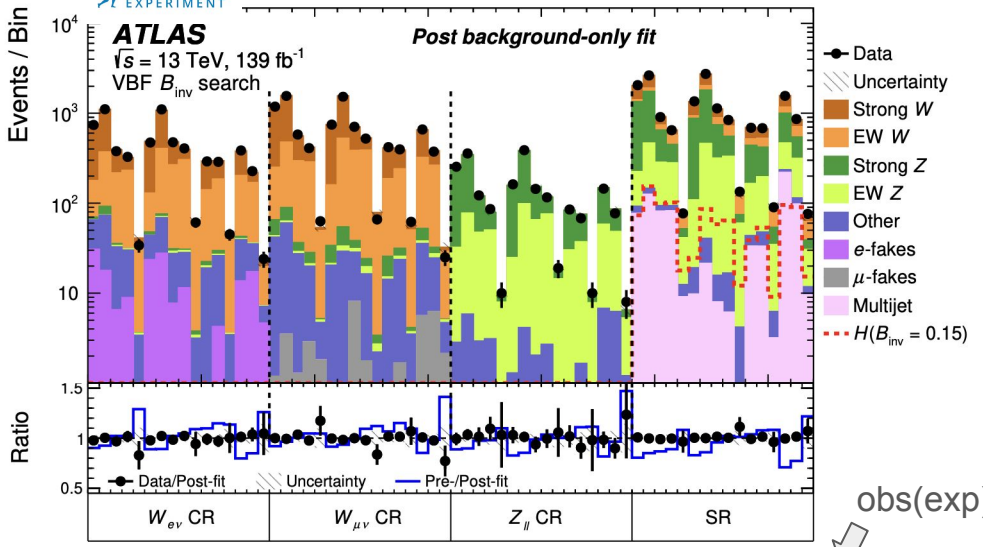
Candidate in signal region of $H \rightarrow \chi\bar{\chi}$ with two VBF jets (m_{jj} = 5.0 TeV)



VBF H Results

- Leading uncertainty : W/Z+jets modelling
- Sub-leading uncertainties : data/MC statistics, leptons/jets measurements, other background modelling

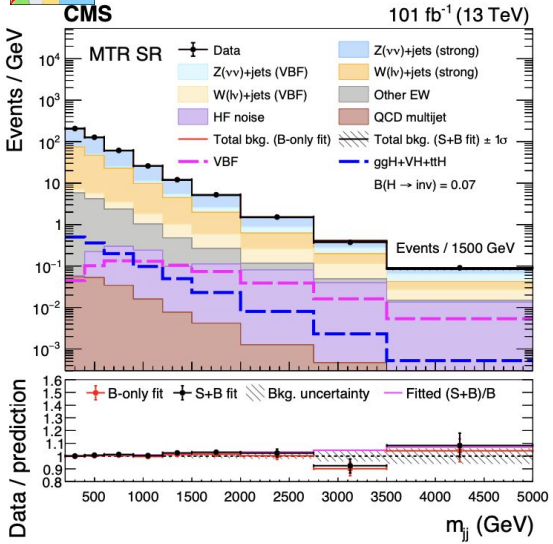
JHEP 08 (2022) 104



obs(exp)

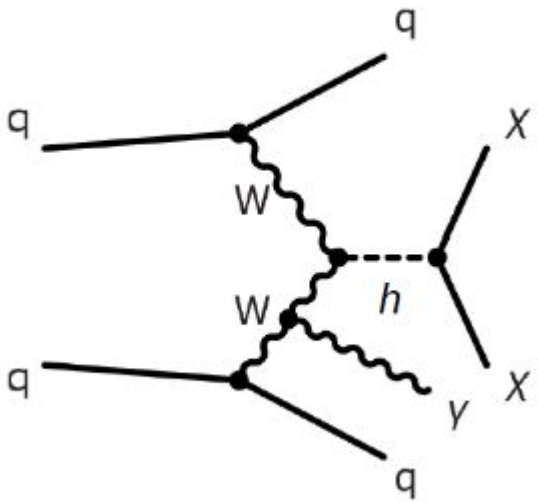
B(H → inv) upper limit @ 95% C.L. = 0.145 (0.103)

PRD 105 (2022) 092007

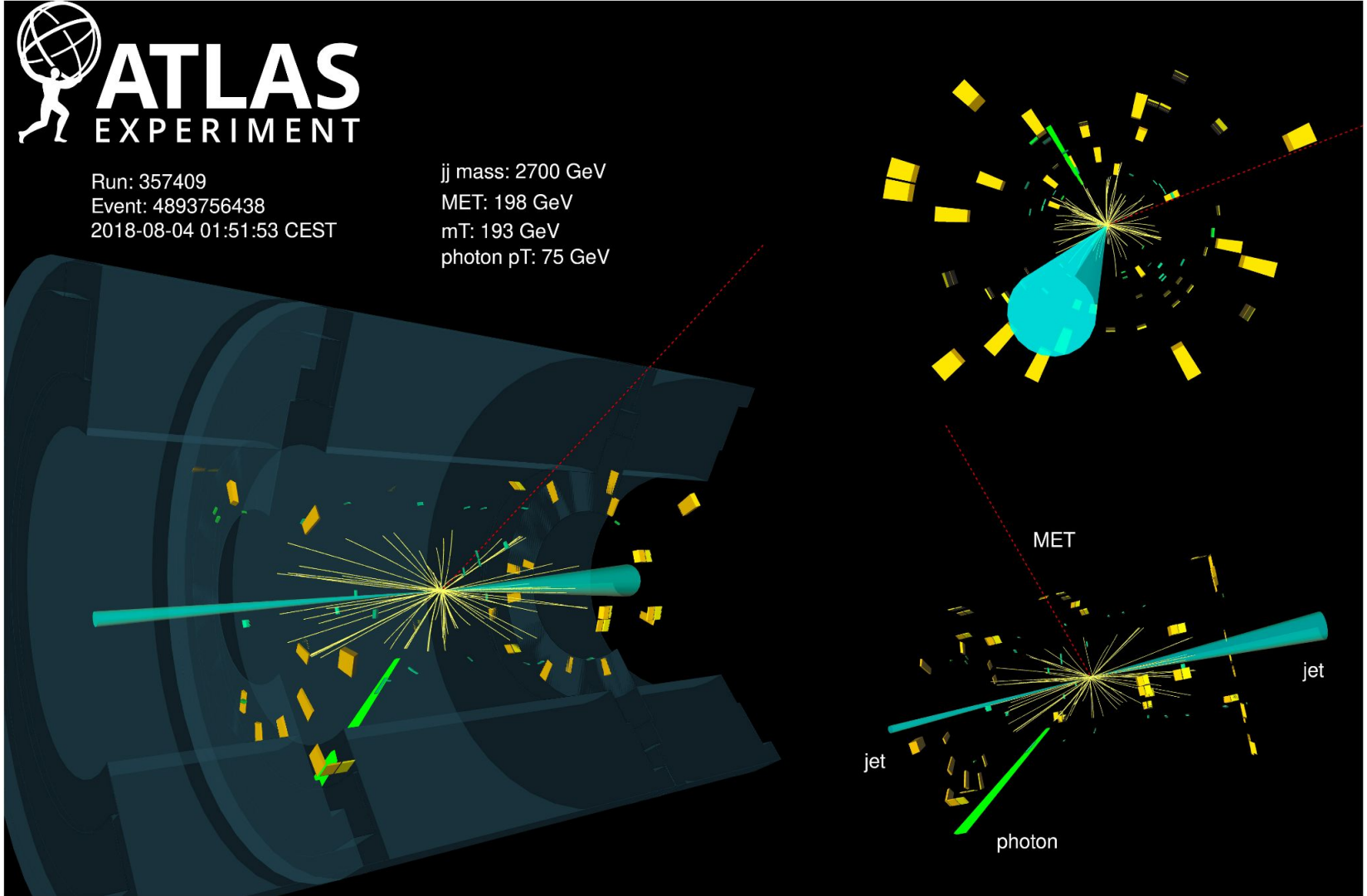


B(H → inv) upper limit @ 95% C.L. = 0.18 (0.12)

VBF H + photon (ATLAS only)



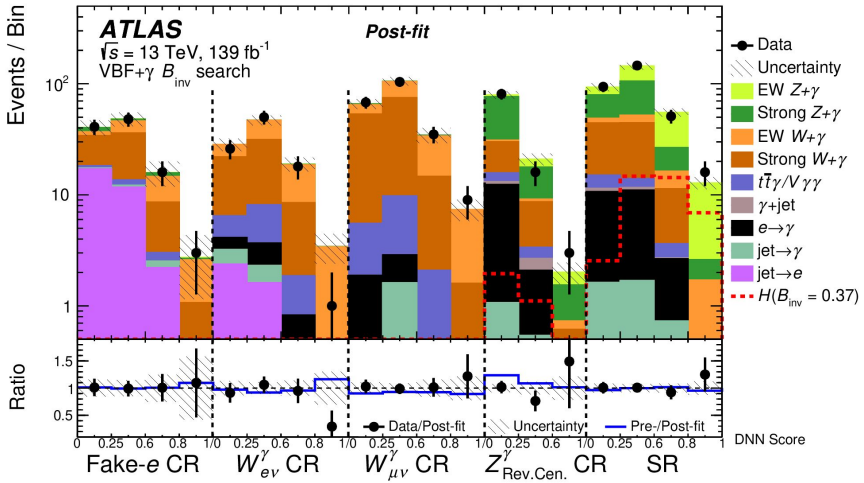
- Signature very similar to the VBF+E_T^{miss} search
  - Except extra photon
- Advantage :
  - Better background rejection
  - Higher signal selection efficiency
- Disadvantage :
  - Smaller production rate
- Background mainly from:
  - $Z(\rightarrow \nu\nu)$ + γ + jets
  - $W(\rightarrow l\nu)$ + γ + jets
- ATLAS only

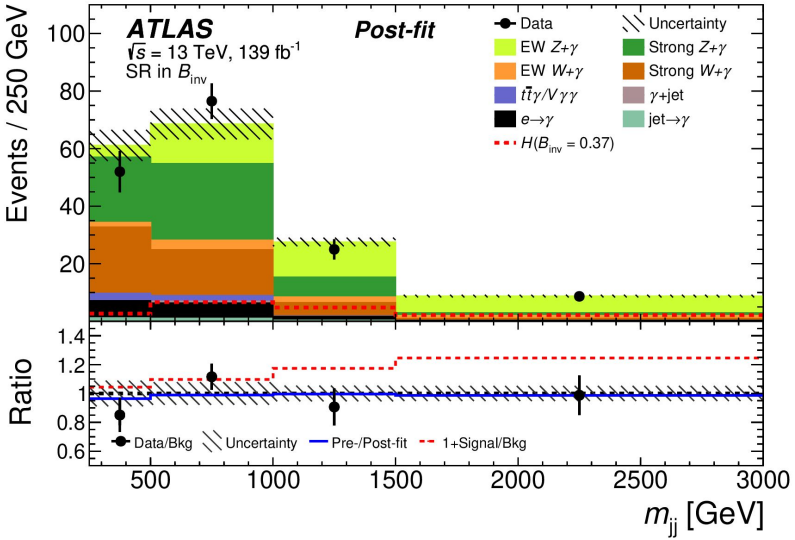

ATLAS
EXPERIMENT
Run: 357409
Event: 4893756438
2018-08-04 01:51:53 CEST
jj mass: 2700 GeV
MET: 198 GeV
mT: 193 GeV
photon pT: 75 GeV
MET
jet
jet
photon

VBF H+photon Results

- Data statistics and V+jet modelling dominant uncertainties

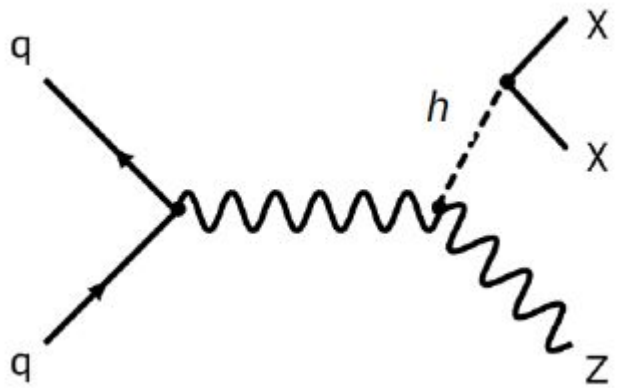
EPJ C 82 (2021) 105

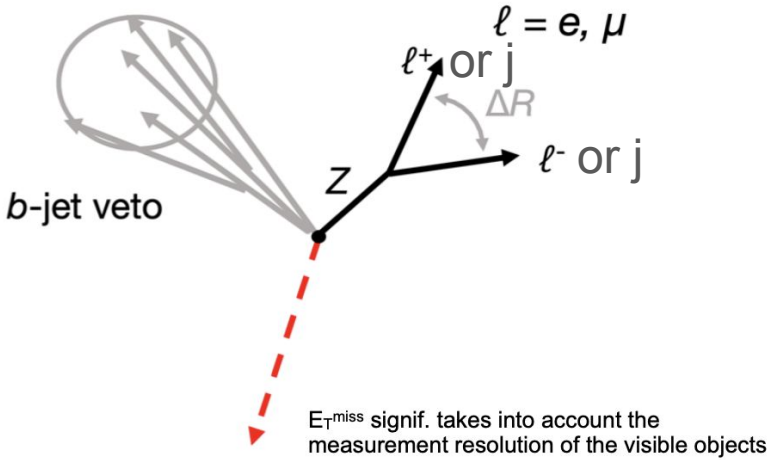




B(H → inv) upper limit @ 95% C.L. = 0.37 (0.34)

Z(ll)H/V(jj)H



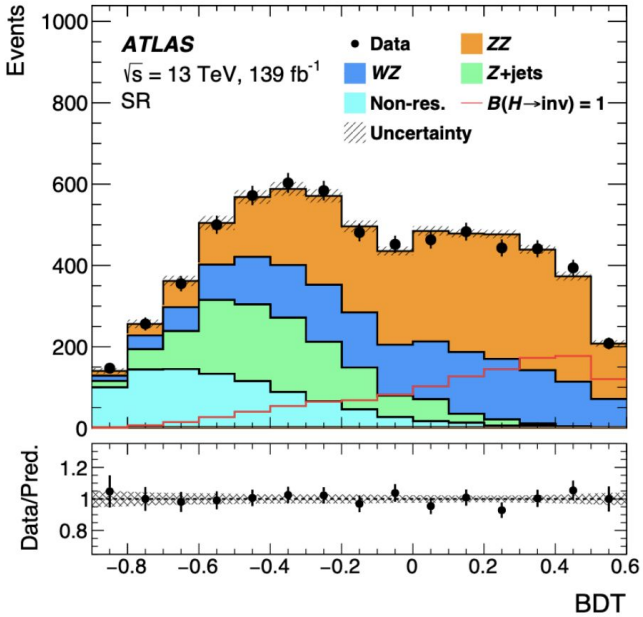


- Tag using Z(ll) or jet from V(jj) by requiring m(ll) or m(jj) being consistent with EWK bosons

Z(ll)H Results

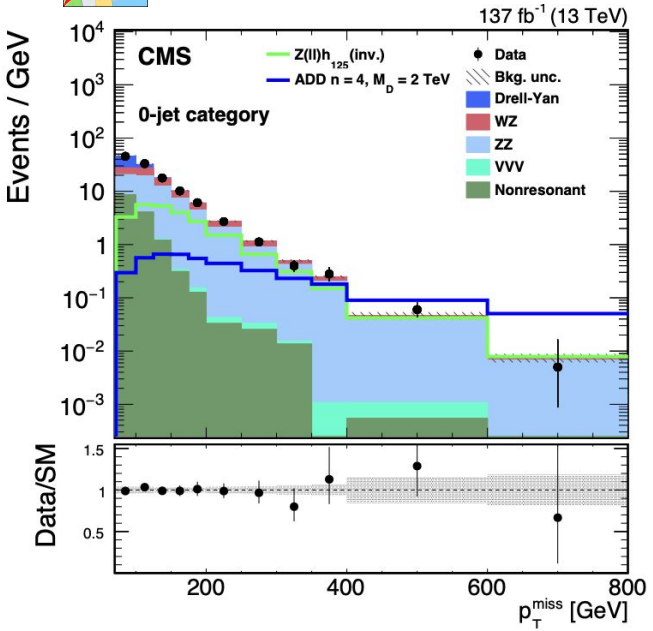
- Main SM background: qq/gg→ZZ
- Dominant uncertainties : Statistical, ZZ modelling, Jet, MET measurement

ATLAS EXPERIMENT PLB 829 (2022) 137066



B(H → inv) limit @ 95% C.L. = 0.19 (0.19)

CMS EPJ C 81 (2021) 13

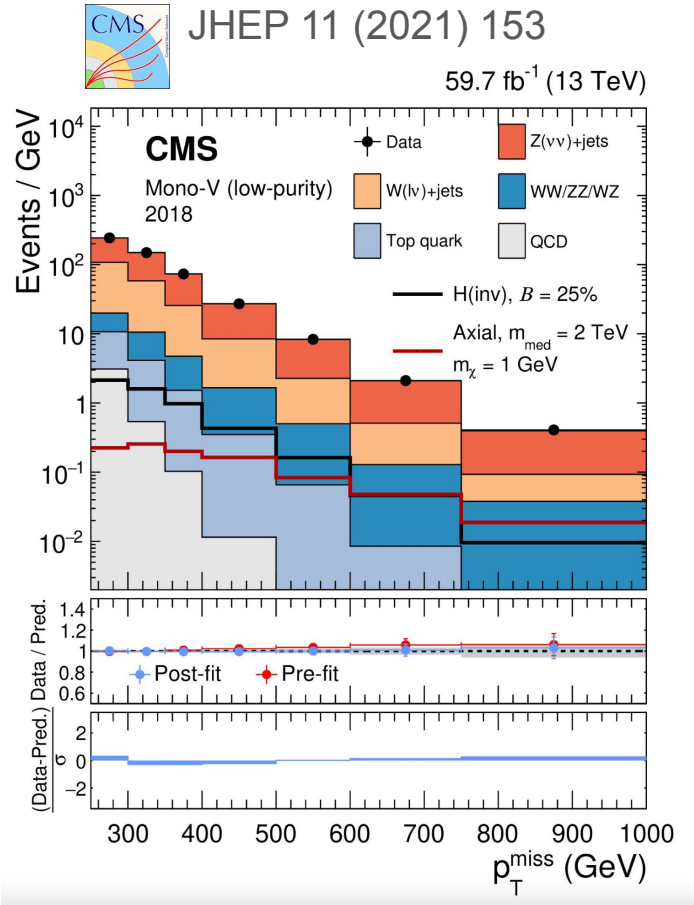


B(H → inv) limit @ 95% C.L. = 0.21 (0.18)

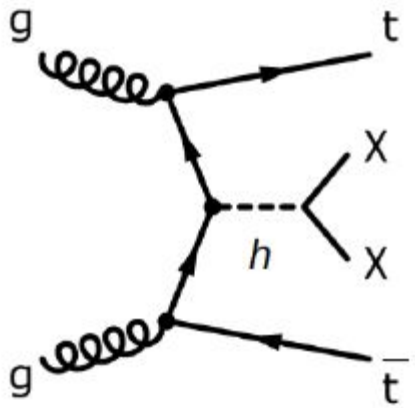
Boosted VH

- Boosted VH pT,boost > 250 GeV
  - Assigned low/high purity according to DeepAK8 score
- Main bkg contribution from V+jets, Main hadronic bkg from QCD multijet
- Dominant systematics: trigger, jet measurements

B(H → inv) limit @ 95% C.L. = 0.28 (0.25)



ttH

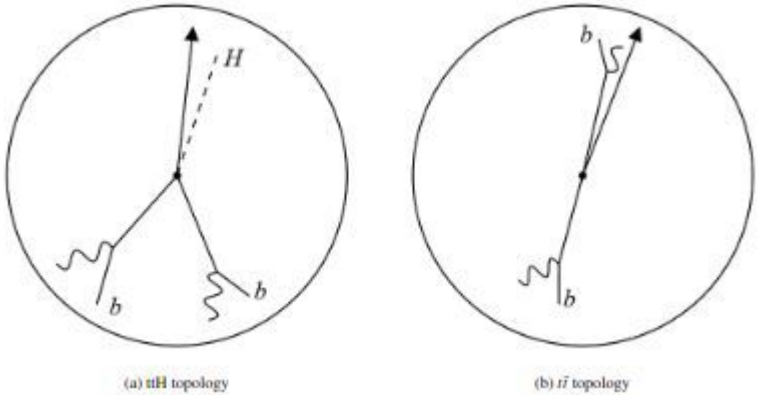


Targeting on top-antitop pair final state

- Defined by lepton, jet, b-jet and boosted object multiplicity

Dominated by ttbar background

- Angle between p_T^{miss} and (b-)jet pT from top decay effective discriminator

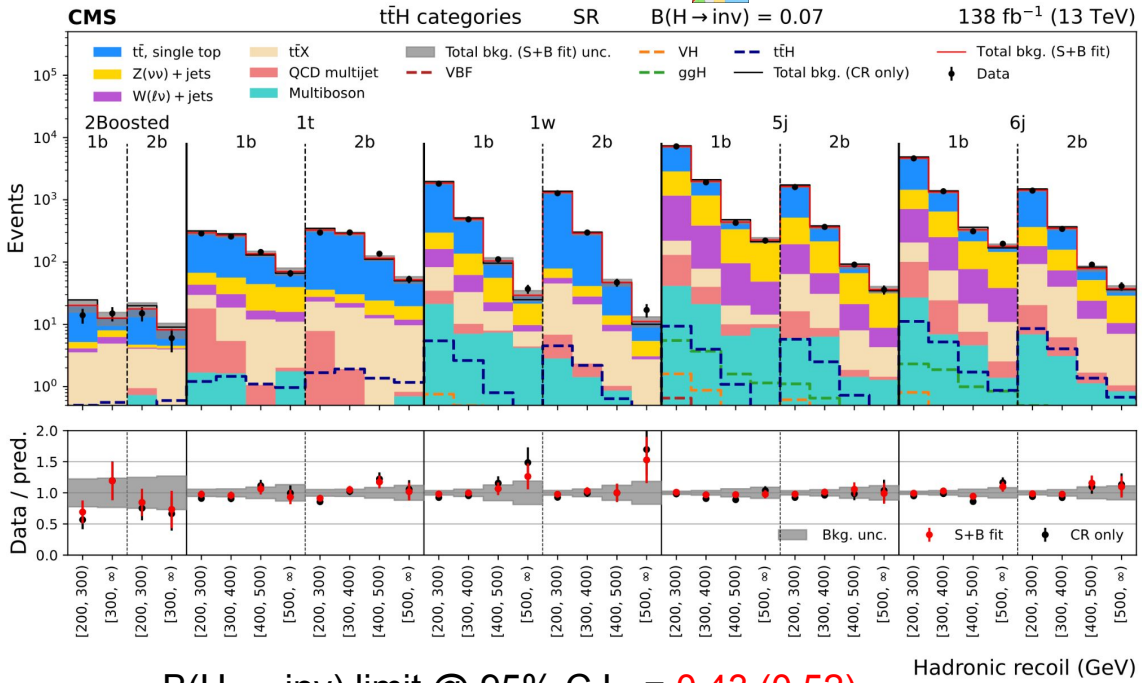


(a) ttH topology (b) $t\bar{t}$ topology

ttH Results: CMS (all hadronic)

Dominant uncertainty: data statistics, jet measurements

Eur. Phys. J. C 83 (2023)

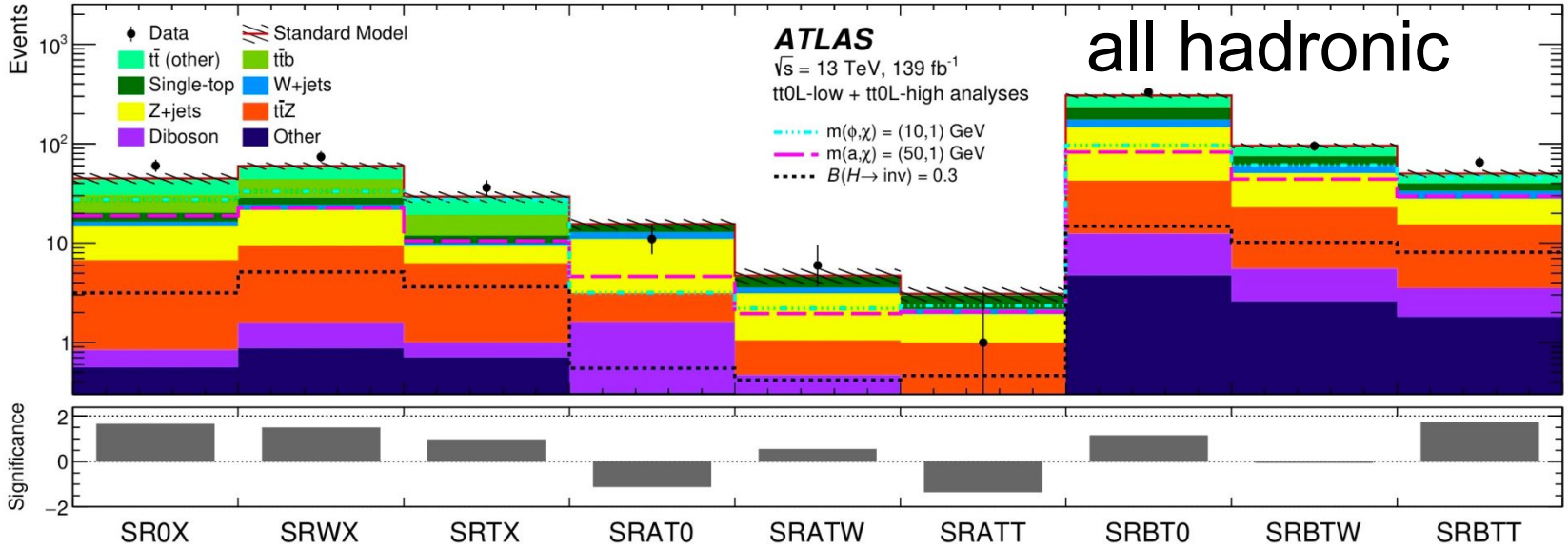


B(H → inv) limit @ 95% C.L. = 0.43 (0.52)

ttH Results: ATLAS

Dominant uncertainty: data statistics, jet measurements

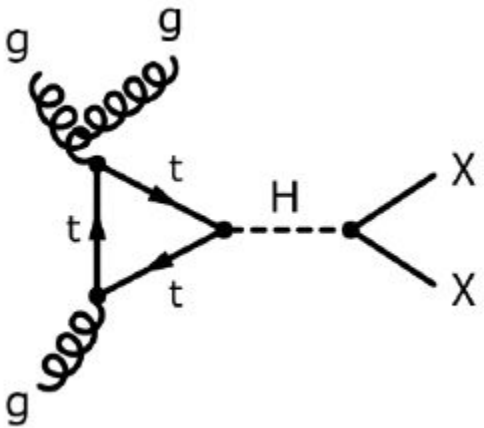
EPJ C 83 (2023) 503



ATLAS B(H → inv) limit @ 95% C.L. = 0.38 (0.30) (all channels)

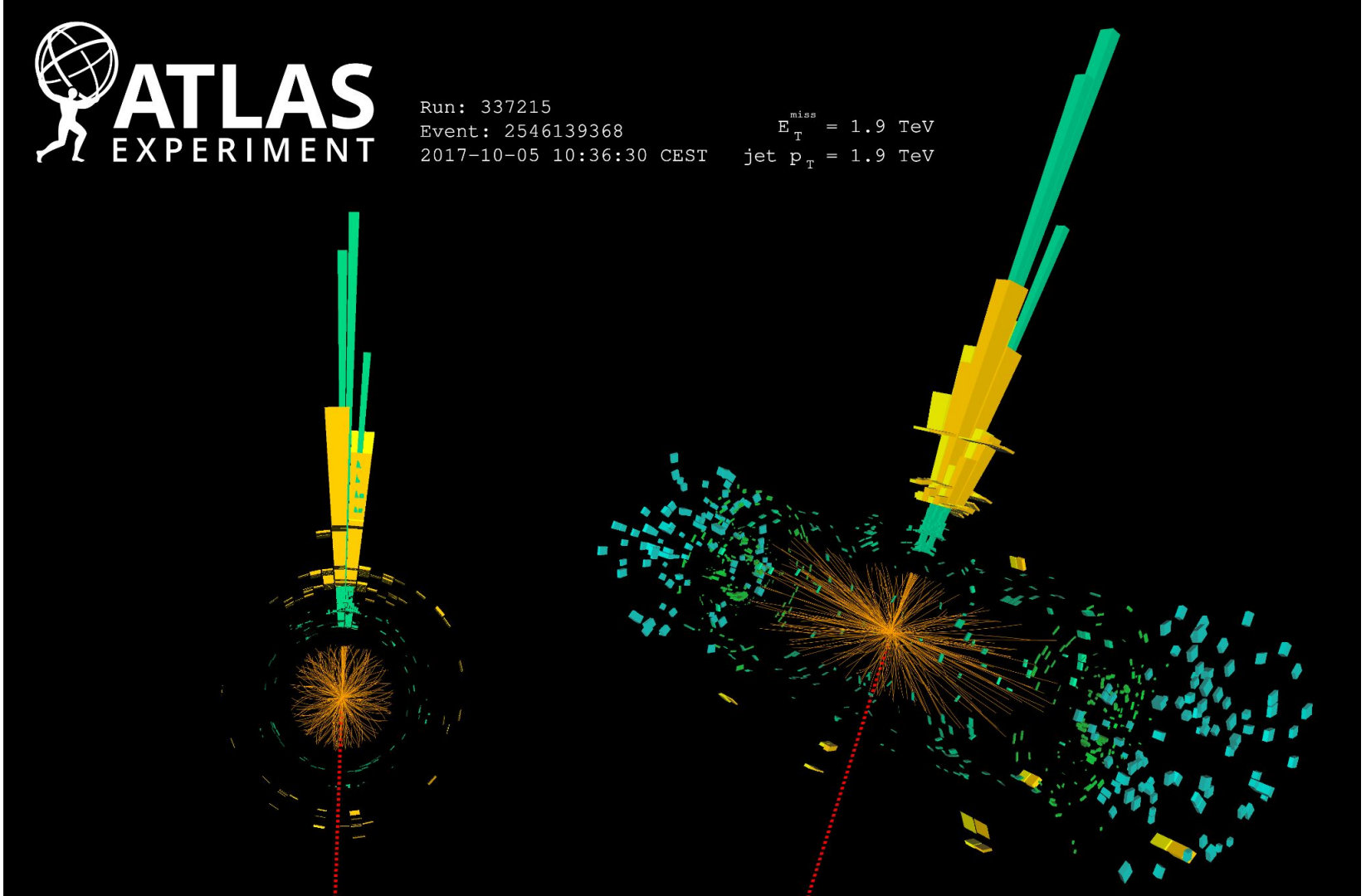
CMS B(H → inv) limit @ 95% C.L. = 0.43 (0.52) (all hadronic)

ggH



- Event selection
  - At least one jet and large missing transverse momentum
  - Trigger selection based on the presence of ETmiss
  - Events vetoed if any charged lepton or photon is reconstructed.

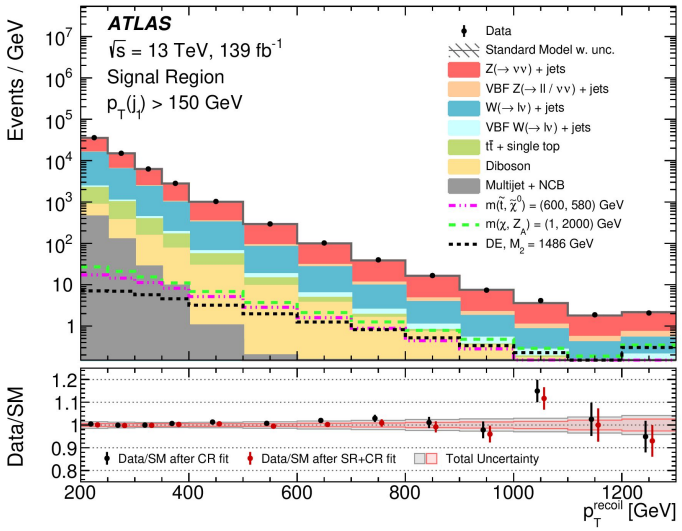
- Use an ISR jet for triggering
- Main background: Z→ $\nu\nu$, EWK → lost leptons


ATLAS
EXPERIMENT
Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST
E_T^{miss} = 1.9 TeV
jet p_T = 1.9 TeV

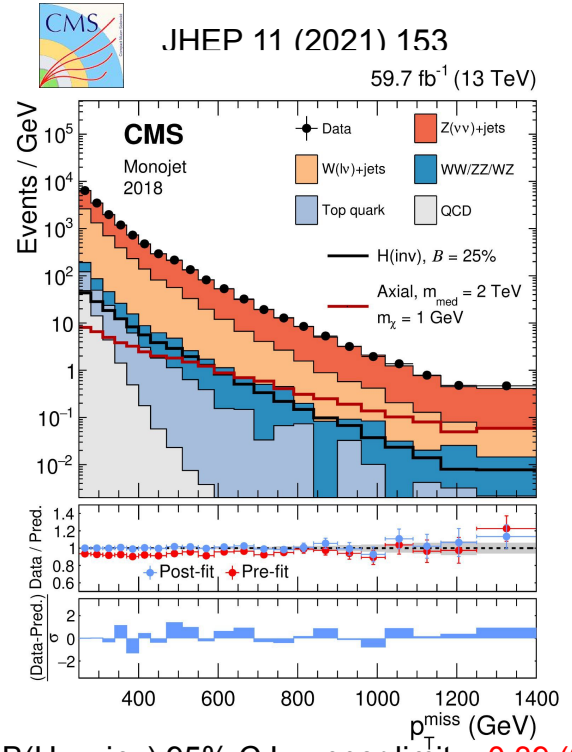
ggH Results

Dominant sys. uncertainty: trigger, jet measurements

ATLAS EXPERIMENT PRD 103 (2021) 112006



B(H → inv) 95% C.L. upper limit = 0.329 (0.383)

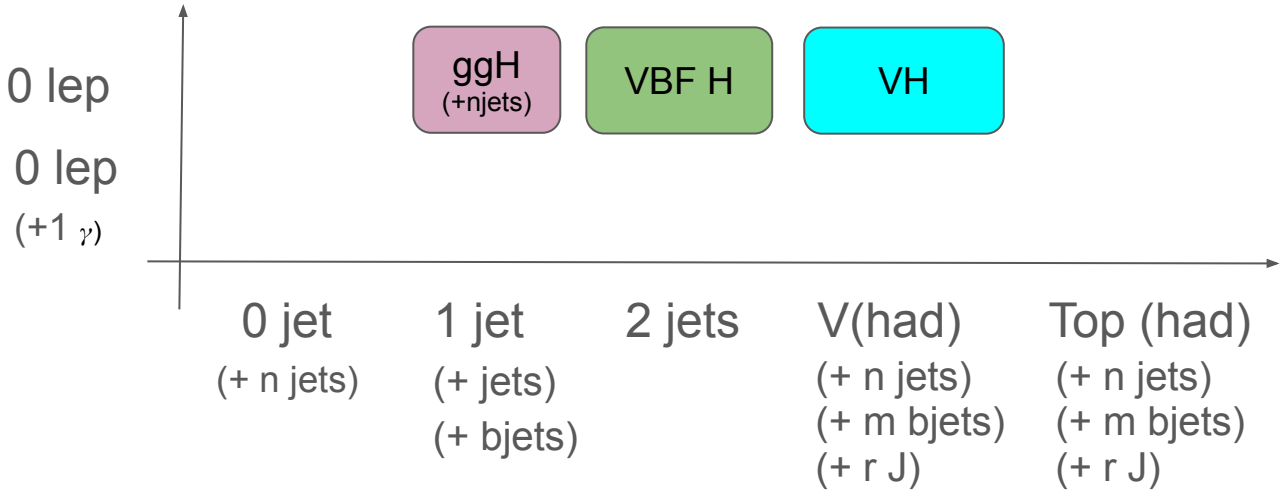


B(H → inv) 95% C.L. upper limit = 0.39 (0.32)

Combination synthesis: phase space overlap

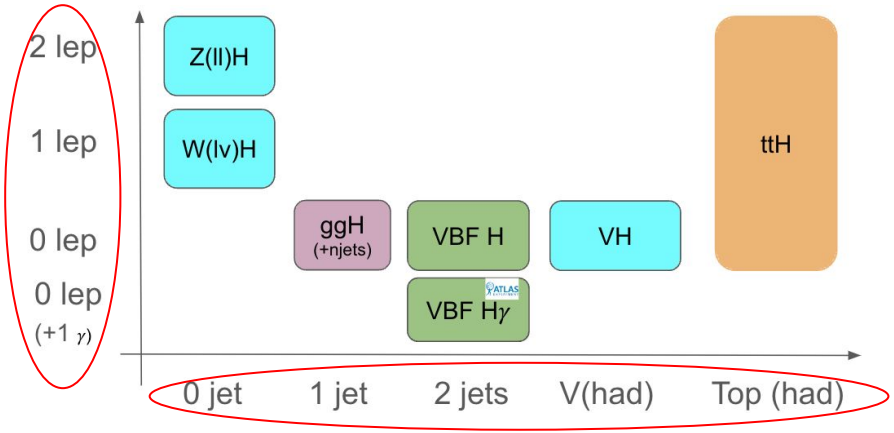
Phase space overlap between analyses mitigated through cuts and vetoes

- Overlap events less than 0.2% (1.5%) for data (MC) in ATLAS
- Similar in CMS



Combination synthesis: systematics correlation

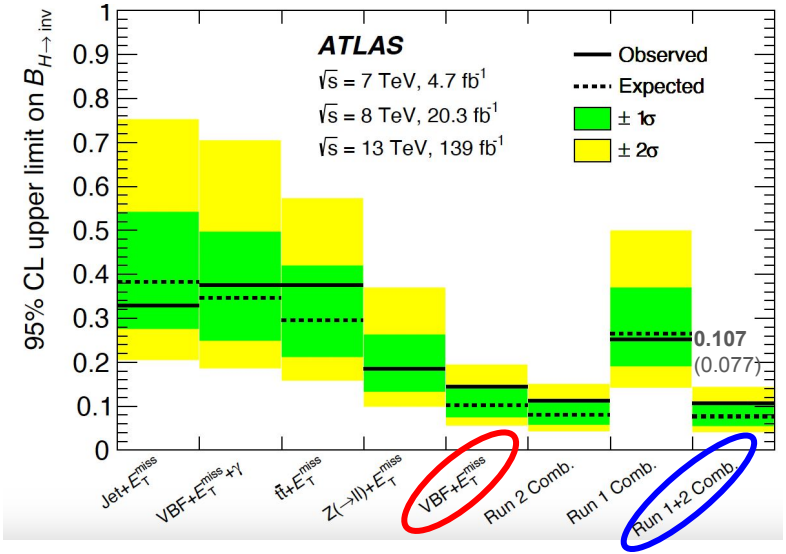
- **Correlate systematic** uncertainties with similar reconstruction techniques
  - Theoretical signal systematics, lumi, trigger, lepton efficiencies, JER/JES all correlated if same paths/phase space/values
- **Non-correlated systematics** include object identification, isolation and reconstruction, and W/Z/γ/VV bkg theories



Combination

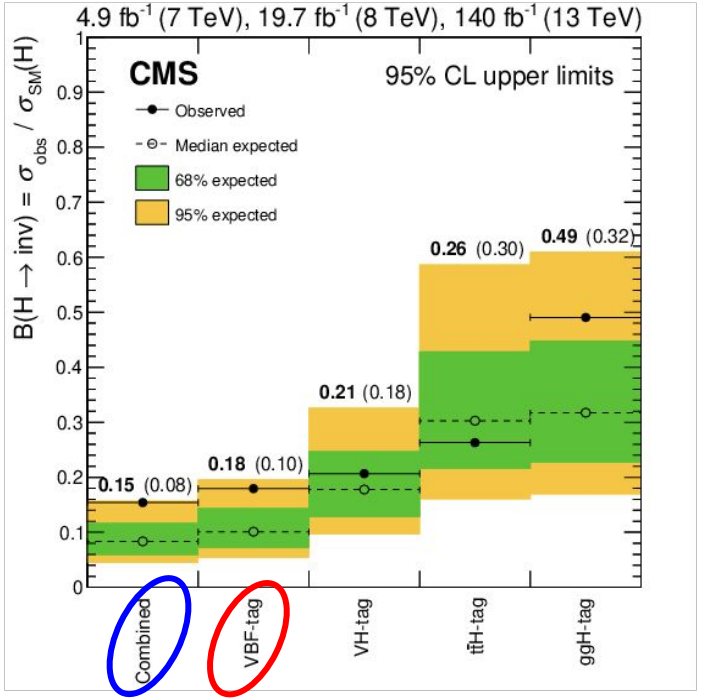
- Sensitivity dominant by VBF+E_T^{miss} with additional improvement
  - ~20% by adding other channels
  - ~4% by including Run 1

ATLAS EXPERIMENT PLB 842 (**2023**) 137963



- ATLAS B(H → inv) 95% limit : 10.7% (7.7%)
- CMS B(H → inv) 95% limit : 15% (8%)

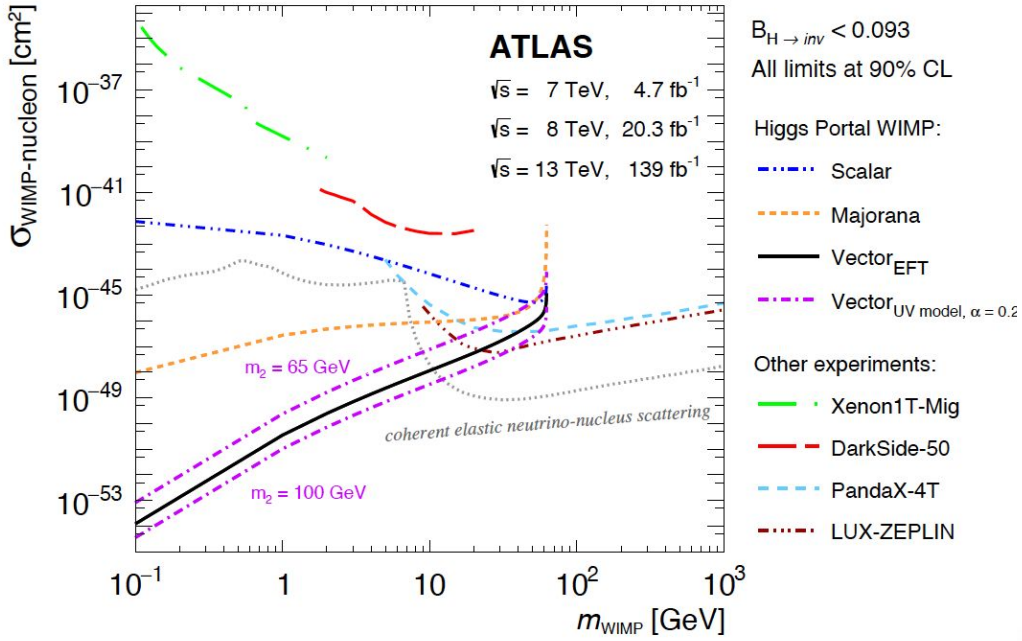
CMS EPJC 83 (**2023**) 933



Interpretation: Higgs Portal Models

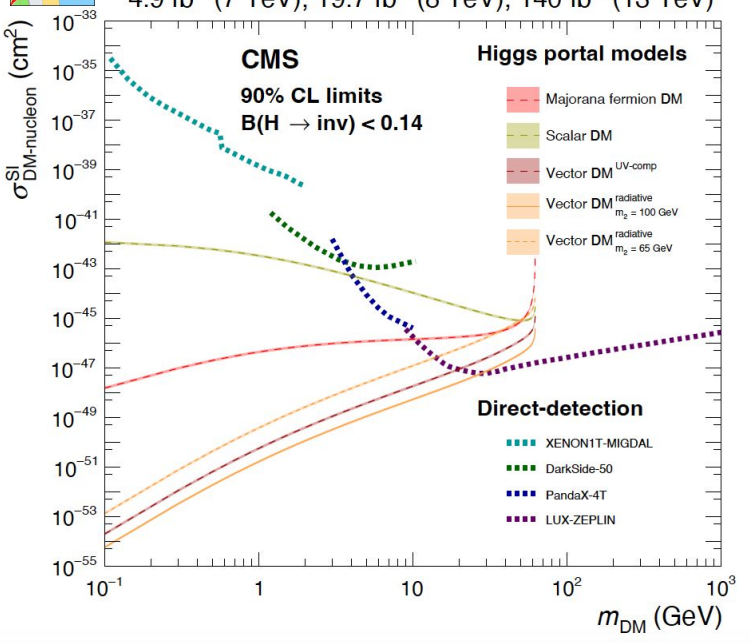
Convert the BR(H→inv) limit to the limit on spin independent scattering cross section
→ complement to direct search for dark matter in **low mass region**

ATLAS EXPERIMENT PLB 842 (**2023**) 137963



CMS EPJC 83 (**2023**) 933

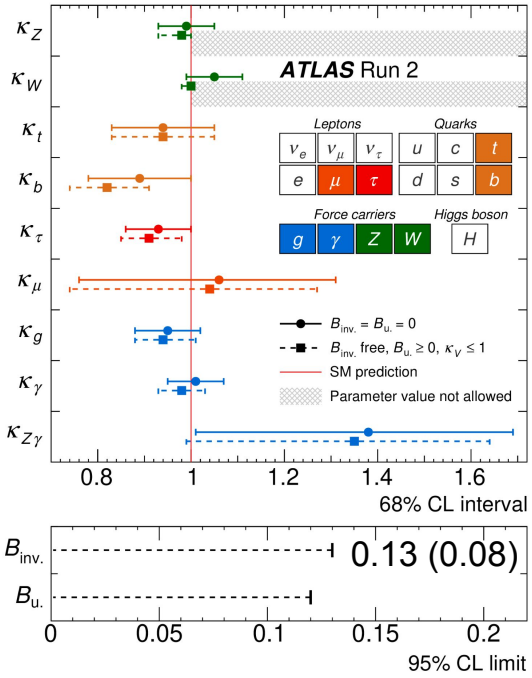
4.9 fb-1 (7 TeV), 19.7 fb-1 (8 TeV), 140 fb-1 (13 TeV)



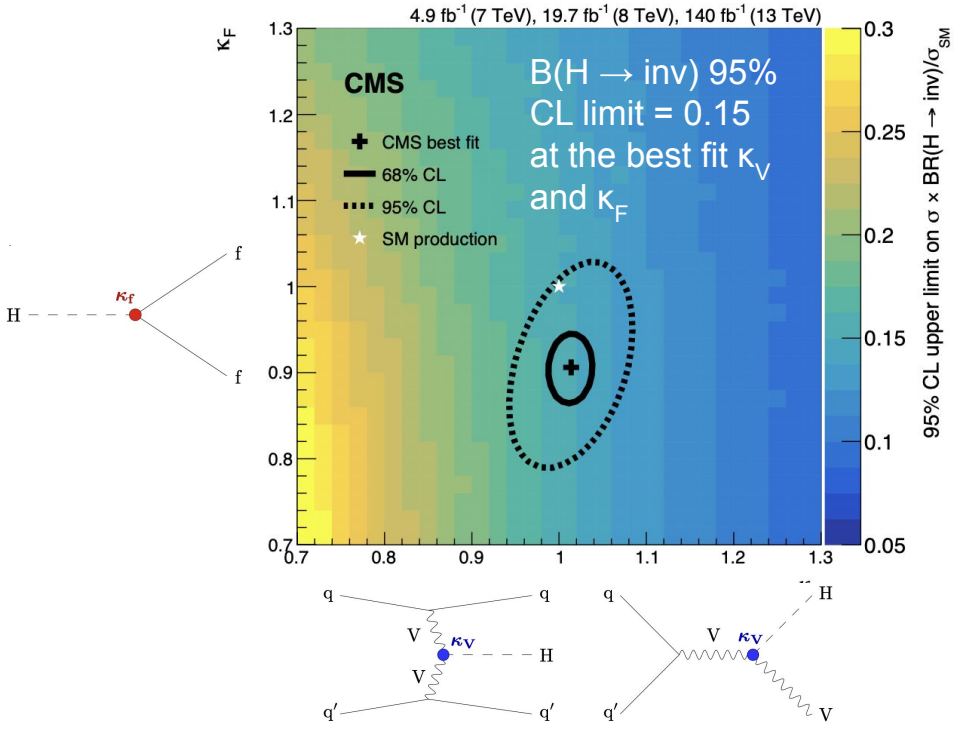
Indirect constraint on B(H → inv) from coupling strength modifier

- Two channels VBF+VH being directly scaled by coupling strength modifiers κ_V and κ_F to investigate BSM scenarios

ATLAS EXPERIMENT Nature 607, 52 (2022)



CMS EPJC 83 (**2023**) 933



Summary

- Searches for invisible Higgs boson decay sensitive to new physics and dark matter
- Full Run2+Run1 combined limits on BR(H→inv) compatible in 2 experiments
  - ATLAS: 10.7% obs. (7.7% expt.)
  - CMS : 15% obs. (8% expt.)
- Interpretation in context of Higgs portal model complement to direct detection of dark matter limits at low masses
- LHC combination to be discussed in http://cern.ch/lhcdm24
  - Expect sensitivity improvement in Run 3 due to statistics limitation in all analyses
  - Precise prediction of V+jets is highly desired in order to reduce major theory uncertainties