INVISIBLE HIGGS

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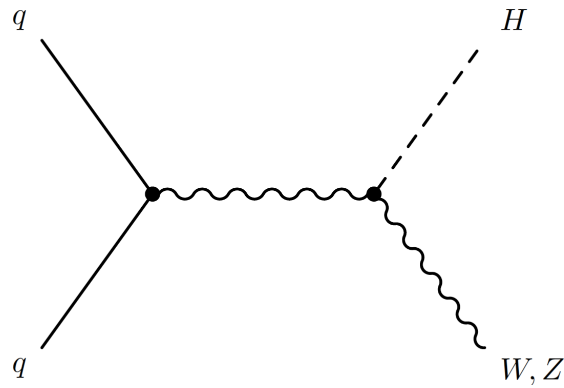
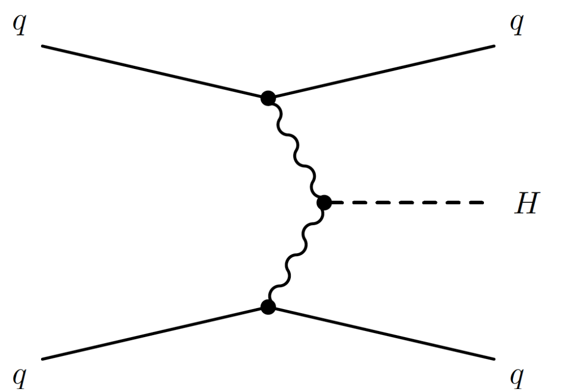
Invisible decay of 125 GeV Higgs

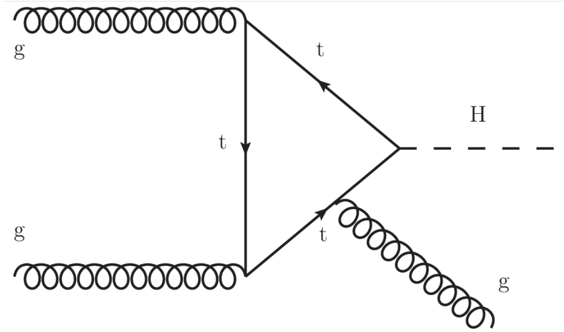
- Concentrate on the 125 GeV Higgs.
  - BSM Higgs is covered by Tongguang Cheng.
  - 2HDM Higgs is covered in mono-H talk by Nicolo Trevisani.
- Physics motivation:
  - 125 GeV H as a part of SUSY: H -> neutralino.
  - Extra dimension: H -> graviscalars.
  - H -> dark matter (DM) particles.
- Indirect constraints from the 125 GeV Higgs measurements:
  - Non-SM decay BF < 0.34 at 95 % CL. (arXiv:1606.02266[hep-ex], ATLAS+CMS, 5 (7 TeV) + 20 (8 TeV) fb^{-1})
  - SM predicts BF(H -> 4v) ~ 0.1 %. Any deviation from it is an indication of new physics.

Higgs production and final states

- 3 major Higgs production modes:
- Associated production (ZH inv (leptonic)) (VH inv (hadronic))
  - Tag on Z -> ll or V(Z or W) -> jet(s)
  - Same final state to mono-Z (lep) and mono-V (had) searches
- Vector Boson Fusion (VBF H inv)
  - Tag on the 2 jets.
  - Same final state to mono-V(jj) searches.
- Gluon Gluon Fusion (ggH inv)
  - Tag on ISR jet.
  - Same final state to mono-jet search.







ZH inv. leptonic mode

- Z decays to 2 leptons (electrons or muons).

	ATLAS	CMS
Data set	13 TeV, 13.3 fb^{-1}	13 TeV, 12.9 fb^{-1}
Document	ATLAS-CONF-2016-056	CMS PAS EXO-16-038
Object selection	Leading lepton p_T > 30 GeV Sub leading lepton p_T > 20 GeV |eta| < 2.5	Leading electron p_T > 25 GeV Leading muon p_T > 20 GeV Sub leading lepton p_T > 20 GeV
Z selection	$\|M(ll) - M(Z)\| < 15$ GeV	-15 GeV < $M(ll) - M(Z)$ < 10 GeV
Event selection	3rd lepton veto B-jet veto Missing E_T > 90 GeV $\Delta R(ll) < 1.8$ $\Delta\varphi(p_T(ll), MET) > 2.7$ $\|\|MET + jet\ p_T\| - p_T(ll)\|/p_T(ll) < 0.2$ $\Delta\varphi(MET, jets) > 0.7$ $p_T(ll)/m_T < 0.9$	3rd lepton veto 0 or 1 jet(s), Tau-jet veto Missing E_T > 100 GeV $p_T(ll)$ > 60 GeV $\Delta\varphi(p_T(ll), MET) > 2.8$ $\|MET - p_T(ll)\|/p_T(ll) < 0.4$ $\Delta\varphi(MET, jet) > 0.5$

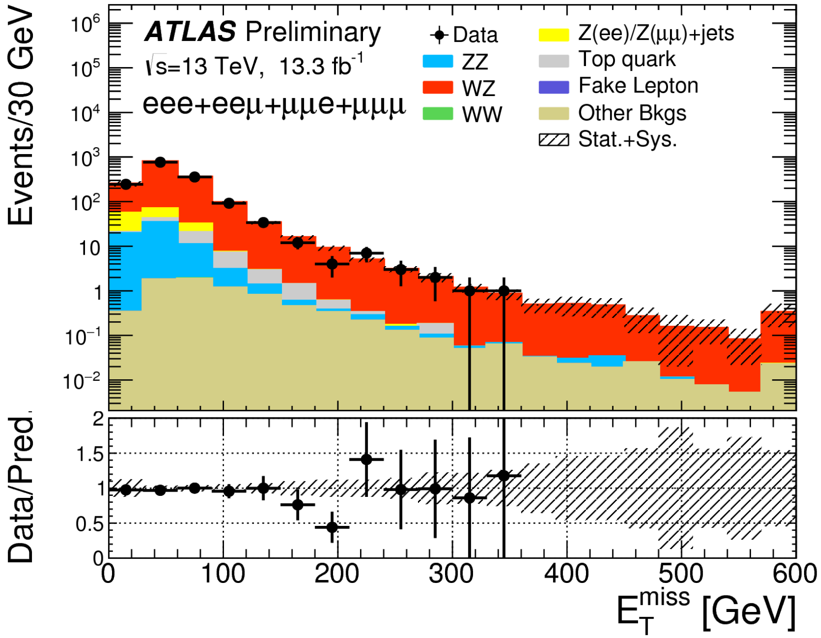
ZH inv. leptonic: Background

- Background estimation

Background	ATLAS	CMS
ZZ	MC simulation	MC simulation
WZ	3 lepton control region	MC simulation
Z + jets	ABCD method	MET sideband
Non-resonant (WW, ttbar, …)	eμ control region	eμ control region

ZH inv. leptonic: WZ Background

- 3-lepton control region: W(lν)Z(ll) dominated.
- Normalization factor data/MC is derived in this region
  - Contributions from other processes are subtracted using MC.
  - Normalization factor:
    1.25 +/- 0.04 (stat) +/- 0.05 (sys)
- Apply it to signal region.

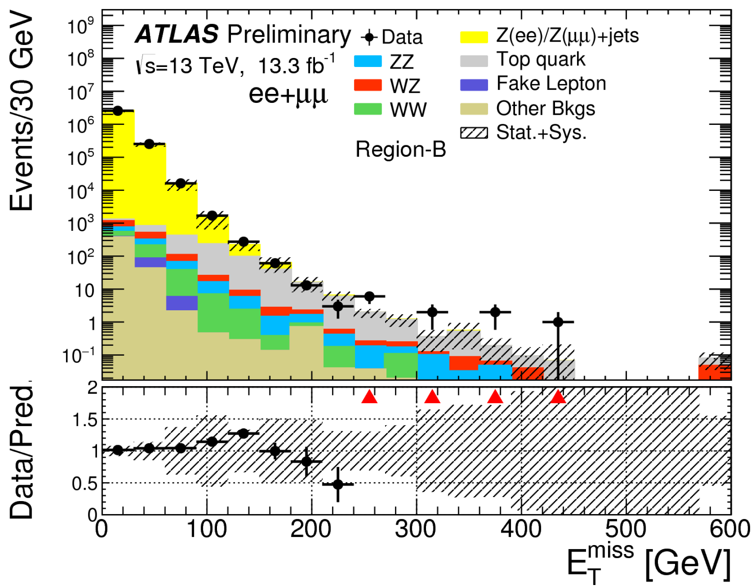


The normalization factor is applied in this plot

ZH inv. leptonic: Z+jets Background

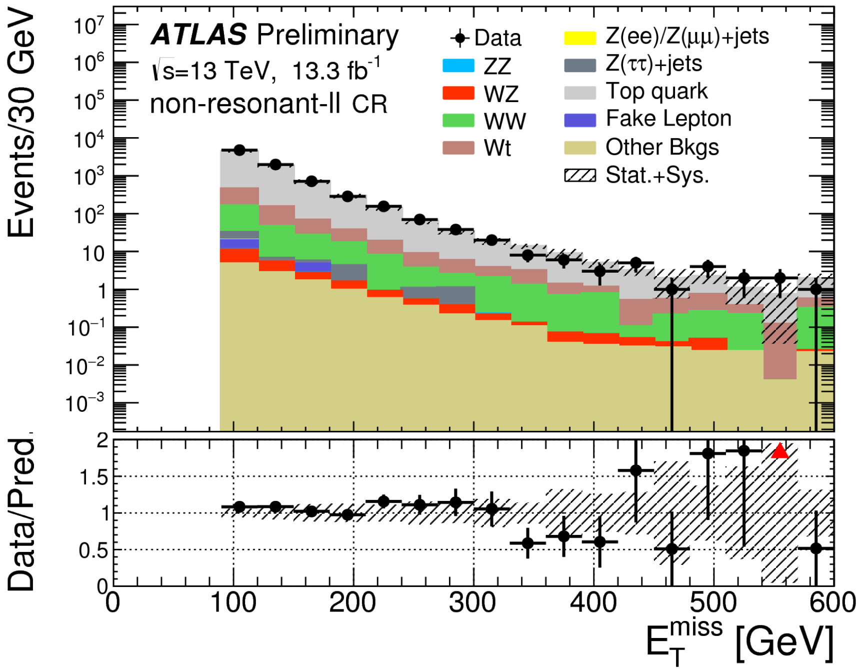
- ABCD method
  - Use two least correlated variables
    - Frac p_T = ||MET + jet p_T| - p_T(ll)|/p_T(ll)
    - $\Delta\varphi$(p_T(ll), MET)
  - A = C*(B/D)
- MET sideband
  - Use MC.
  - Apply scale factor from MET sideband.

Region	Frac p_T	$\Delta\varphi$
A (signal region)	< 0.2	> 2.7
B	> 0.2	> 2.7
C	< 0.2	< 2.7
D	> 0.2	< 2.7



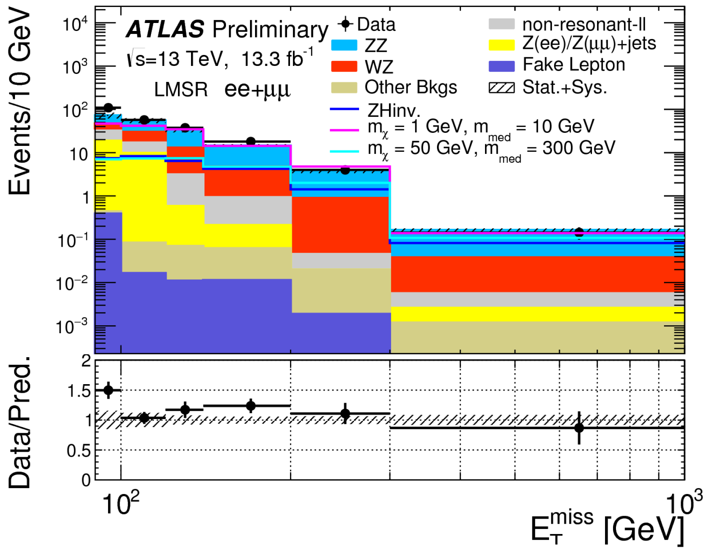
ZH inv: non-resonant Background

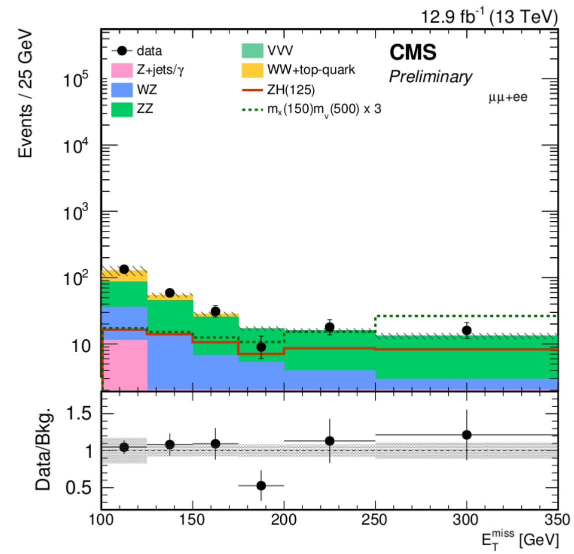
- eμ control region: W(eν)W(μν') and t(eνq)tbar(μν'q') dominated.
- Signal region (ee or μμ) is the half of eμ.
  - Other processes are subtracted using MC.
- Efficiency correction factor between ee and μμ is applied (for the extrapolation to the signal region).



ZH inv. leptonic: Signal region

- Signal region
  - ATLAS: 456 events.
  - CMS: 265 events.
- Main systematic errors:
  - ZZ: MC correction (scale) factors such as lepton energy and resolution, particle ID and trigger efficiency.
  - ZZ: theoretical uncertainties.
  - Z+jets: correlation between ABCD cuts.



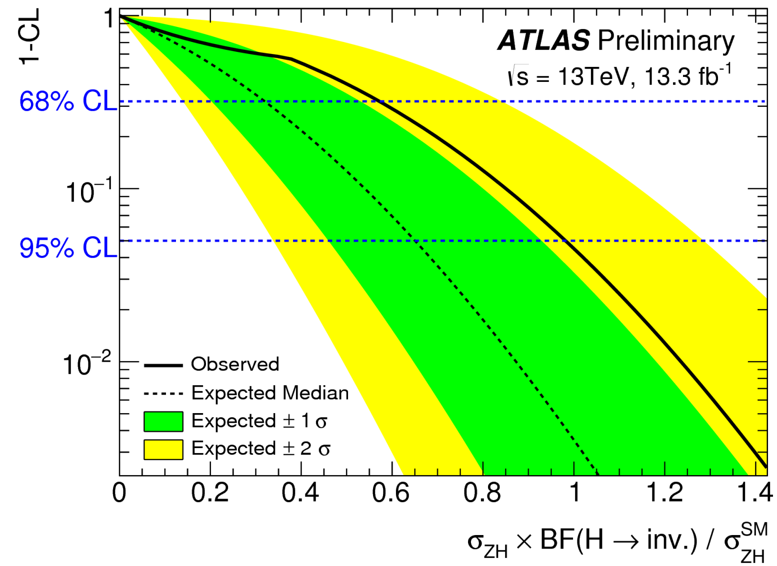


ZH inv. leptonic: Limits

- At 95 % CL
- σ(Z(ll)H)*BF(H->inv) limit

ATLAS

Observed	Expected
88 fb	58 fb



- BF(H -> inv) limit

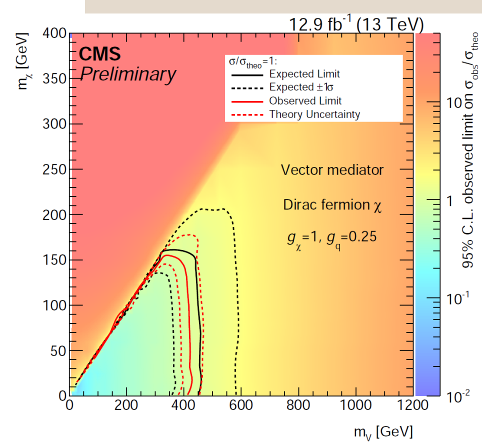
ATLAS

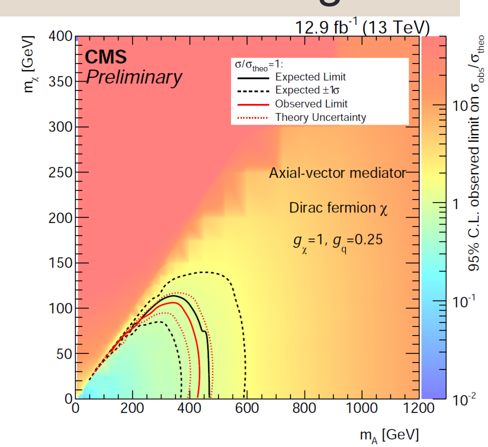
Observed	Expected
0.98	0.65

CMS

Observed	Expected
0.86	0.70

Mono-Z Dark matter limits are also given





VH inv. hadronic mode

- ATLAS, 8 TeV, 20.3 fb-1 (arXiv:1504.04324[hep-ex]).
- W or Z -> 2 jets
  - Accept 3 jets events to improve signal efficiency.
- Event selection:

Item	cut
Missing transverse momentum E_T	MET > 120 GeV
Missing scalar sum of jet p_T	H_T > 120 GeV
Angular cuts	$\Delta\varphi(\mathrm{MET}, p_T^{miss}) < \pi/2$
	$\mathrm{Min}[\Delta\varphi(\mathrm{MET,jets})]>1.5$

p_T^{miss} = track based missing momentum

Backgrounds:

Background	Method
W+jets	W+jets control region
Z+jets	Z+jets control region
ttbar	Ttbar control region
Diboson, top	MC
Mulit-jet	ABCD method

Control region
-> scale factor -> apply to MC

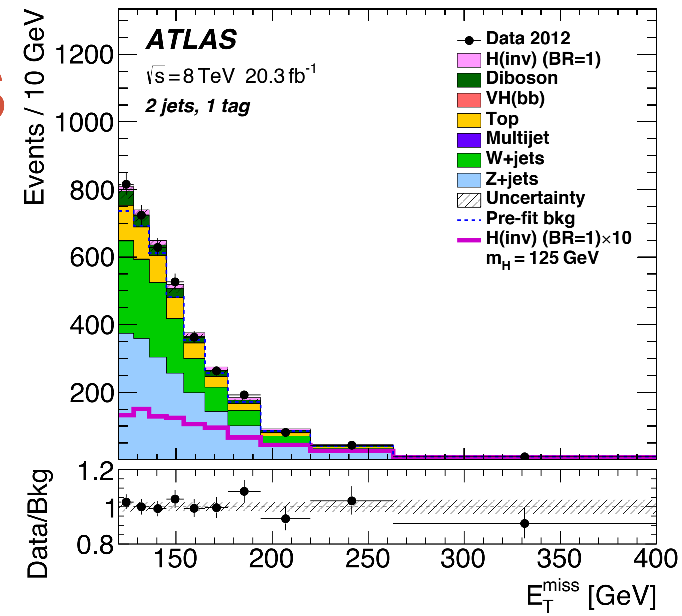
More details covered in mono-V talk by Shuichi Kunori

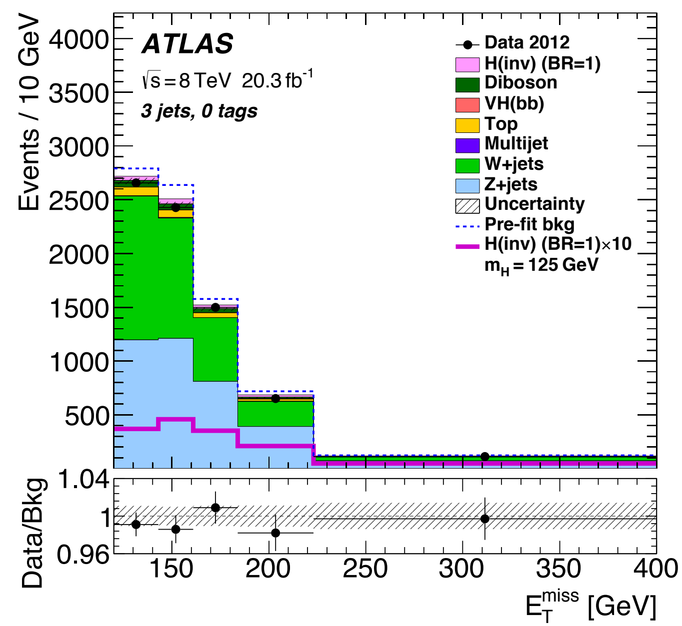
VH inv. hadronic: Results

- Signal Region:

Observed events	2-jets	3-jets
0 b-tag	47,404	18,442
1 b-tag	3,831	1,842
2 b-tag	344	159

- Systematic errors:
  - Jet and missing E_T reconstruction.
  - Diboson: MC modeling uncertainties.
  - Z+jets, W+jets: jet flavor composition, p_T and m(jj) distributions (modelling).





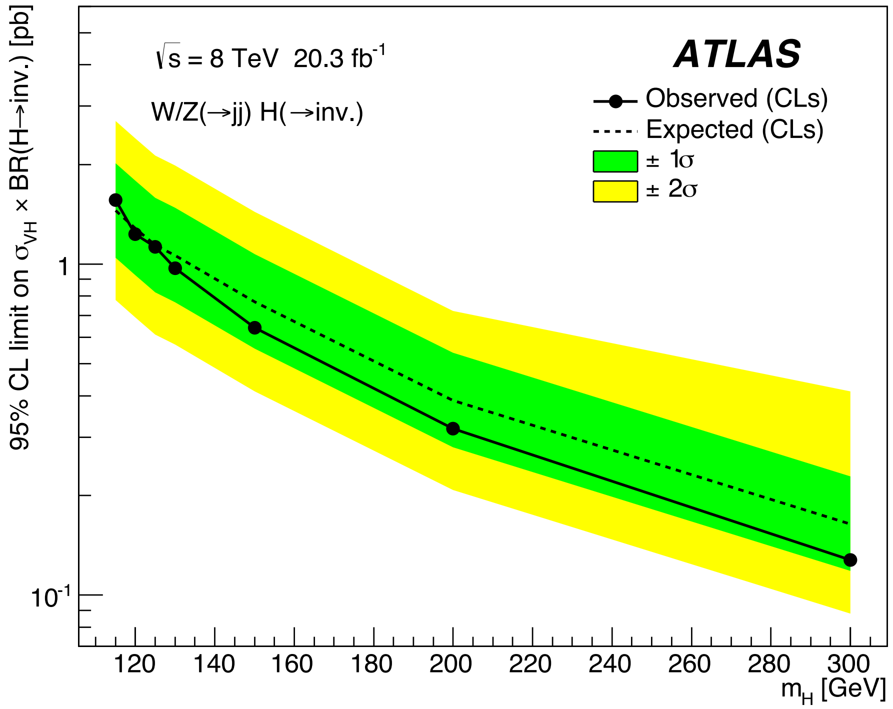
VH inv. hadronic: Limits

- M(H) = 125 GeV at 95 % CL.
- σ(VH)*BF(H->inv) limits:

Observed	Expected
1.1 pb	1.1 pb

- BF(H->inv) limits:

Observed	Expected
0.78	0.86



VBF H inv.

- ATLAS, 8 TeV, 20.3 fb^{-1} (arXiv:1508.07869[hep-ex]).
- Event selection

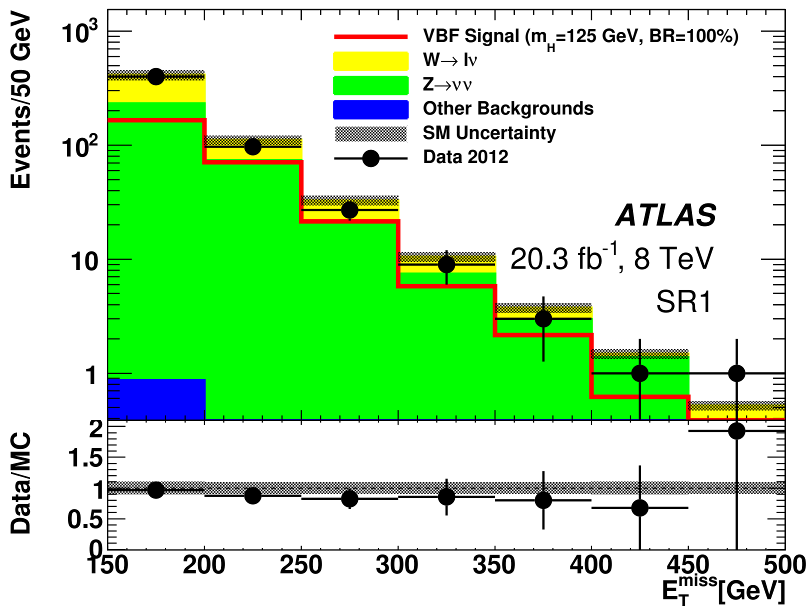
Requirement	SR1	SR2a	SR2b
Leading Jet p_T	>75 GeV	>120 GeV	>120 GeV
Leading Jet Charge Fraction	N/A	>10%	>10%
Second Jet p_T	>50 GeV	>35 GeV	>35 GeV
m_{jj}	>1 TeV	$0.5 < m_{jj} < 1$ TeV	> 1 TeV
$\eta_{j1} \times \eta_{j2}$		<0	
$\lvert\Delta\eta_{jj}\rvert$	>4.8	>3	$3 < \lvert\Delta\eta_{jj}\rvert < 4.8$
$\lvert\Delta\phi_{jj}\rvert$	<2.5	N/A	
Third Jet Veto p_T Threshold	30 GeV		
$\lvert\Delta\phi_{j,E_T^{miss}}\rvert$	>1.6 for j_1, >1 otherwise	>0.5	
E_T^{miss}	>150 GeV	>200 GeV	

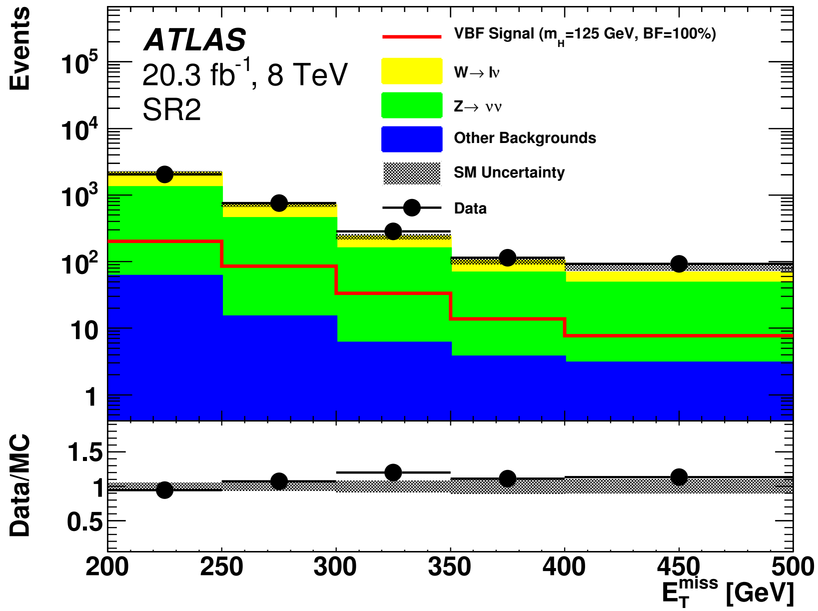
- Background
  - W+jets: W+jets control region (Only one lepton)
  - Z+jes: Z+jets control region (|m(ll) – m(Z)| < 25 GeV)
  - Multi-jets: jet smearing method (→ see the reference)

CMS analysis is give in combined analysis

VBF H inv: Results and Limits

- Results: SR1 (539 events) SR2 (3,290 events)





- BF(H->inv) limits:

Observed	Expected
0.28	0.31

Dominant systematic errors:
- Jet energy scale and resolution
- Parton shower modeling

CMS limit is give in combined analysis

ggH inv:

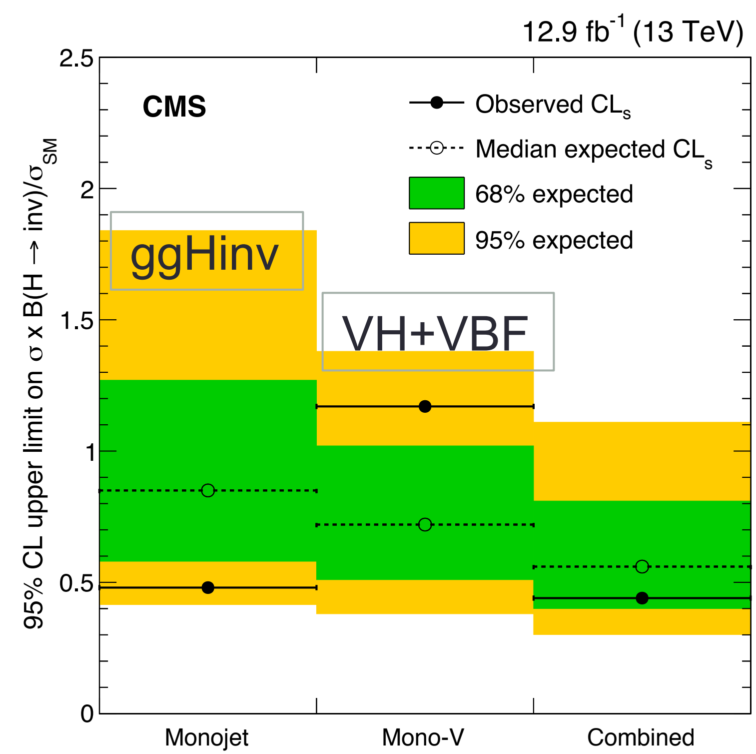
- CMS, 13 TeV, 12.9 fb^{-1} (arXiV:1703.01651[hep-ex])
- Re-interpretation of mono-jet and mono-V(hadronic) dark matter search.
- Details covered in mono-jet talk by Osamu Jinnouchi.
- BF(H->inv) combined limits:

Observed	Expected
0.44	0.56

Combination of
- ggH_{inv} (mono-jet)
- $V(had)H_{inv}$ + VBF H_{inv} (mono-V)

- ggH inv only limits:

Observed	Expected
0.48	0.85

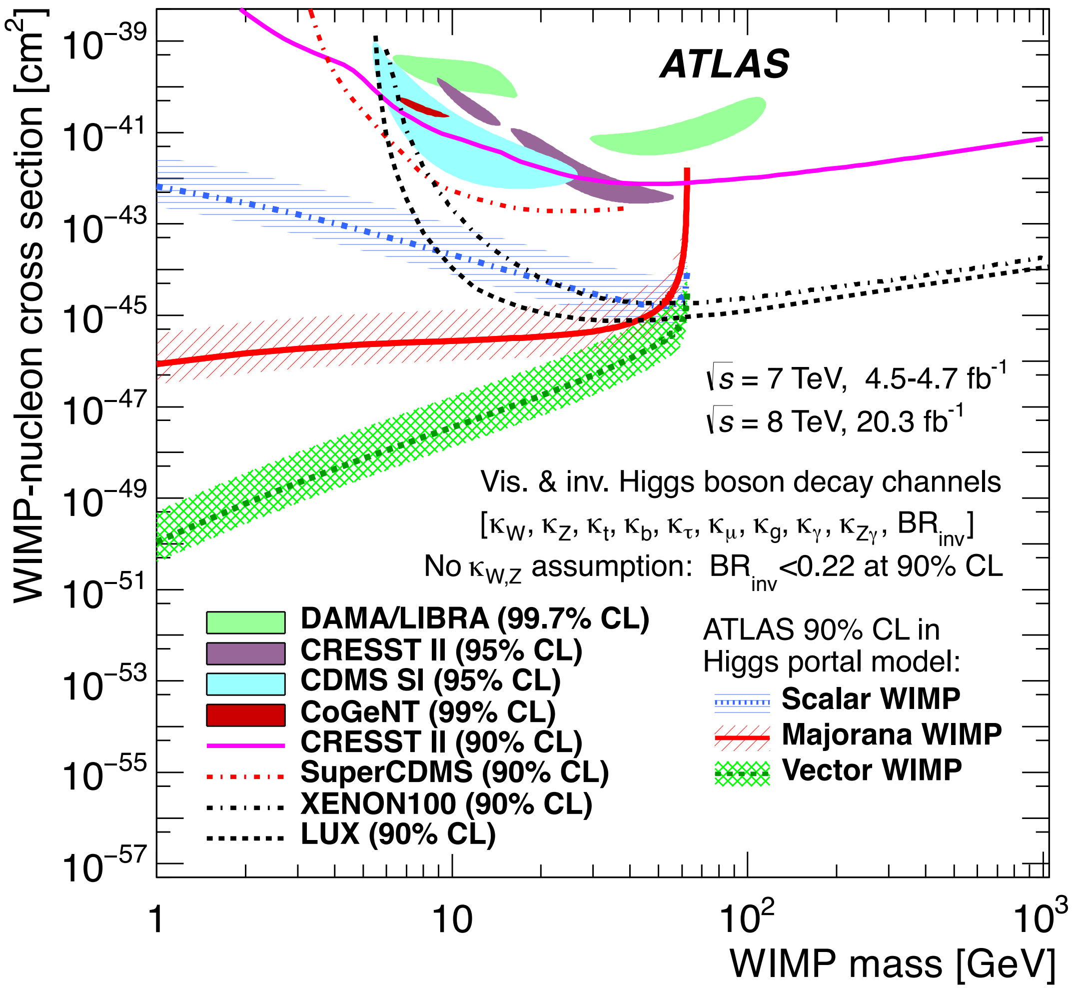


ATLAS combined analysis

- ATLAS, 4.7 (7 TeV) + 20.3 (8 TeV) fb^{-1} (arXiv: 1509.00672[hep-ex])
- Combination of 3 modes:
  - VBF Hinv (shown above)
  - ZHinv leptonic (arXiv:1402.3244[hep-ex]).
  - ZHinv hadronic (shown above)
- BF(H->inv) limit = 0.25
- Further combining with visible decay modes:
  - BF(H->inv) limit = 0.23

ATLAS combined: DM Limits

- Higgs-portal dark matter (H→WIMP pair) limits



CMS combined analysis

- CMS, 5.1 (7 TeV) + 19.7 (8 TeV) + 2.3 (13 TeV) fb^{-1} (arXiv: 1610.09218[hep-ex])
- Combination of 4 modes:
  - VBFH$_{inv}$, ZH$_{inv}$ leptonic, ZH$_{inv}$ bbbar (arXiv:1404.1344[hep-ex])
  - VH$_{inv}$ dijet, ggH$_{inv}$ mono-jet (arXiv:1607.05764[hep-ex])
  - Plus 13 TeV data.
- Event selection and background estimation for each mode are similar to other analysis:

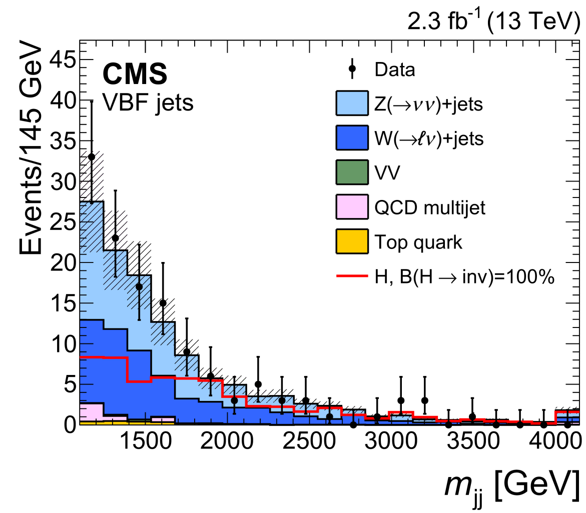
	8 TeV		13 TeV	
	V(jj)	Monojet	V(jj)	Monojet
p_T^j	>200 GeV	>150 GeV	>250 GeV	>100 GeV
$\|\eta\|^j$	<2		<2.4	<2.5
E_T^{miss}	>250 GeV	>200 GeV	>250 GeV	>200 GeV
τ_2/τ_1	<0.5	—	<0.6	—
m_{prune}	60–110 GeV	—	65–105 GeV	—
$\min \Delta\phi(\vec{p}_T^{miss}, j)$	>2 rad		>0.5 rad	
N_j	$=1$		—	

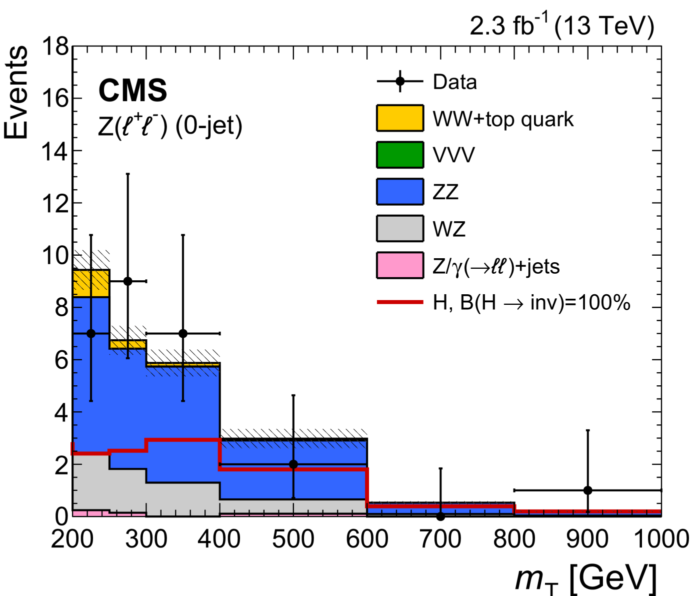
VBF selection	8 TeV	13 TeV
$p_T^{j_1}$	>50 GeV	>80 GeV
$p_T^{j_2}$	>45 GeV	>70 GeV
m_{jj}	>1200 GeV	>1100 GeV
E_T^{miss}	>90 GeV	>200 GeV
$S(E_T^{miss})$	$>4\sqrt{\text{GeV}}$	—
$\min \Delta\phi(\vec{p}_T^{miss}, j)$	>2.3	
$\Delta\eta(j_1, j_2)$	>3.6	

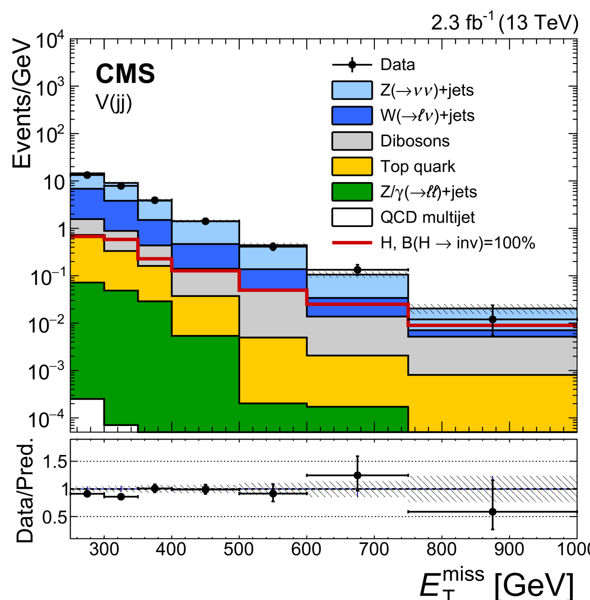
CMS combined: 13 TeV Results

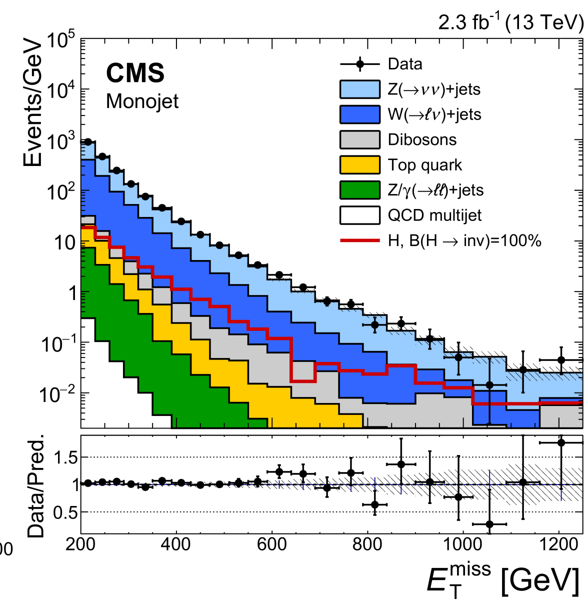
- 13 TeV, 2.3 fb^{-1} results:

Mode	Observed events
VBF	126
Z(ll) 0-jet	26
Z(ll) 1-jet	6
V(jj)	~30?
Monojet	~2000?









CMS combined: Limits

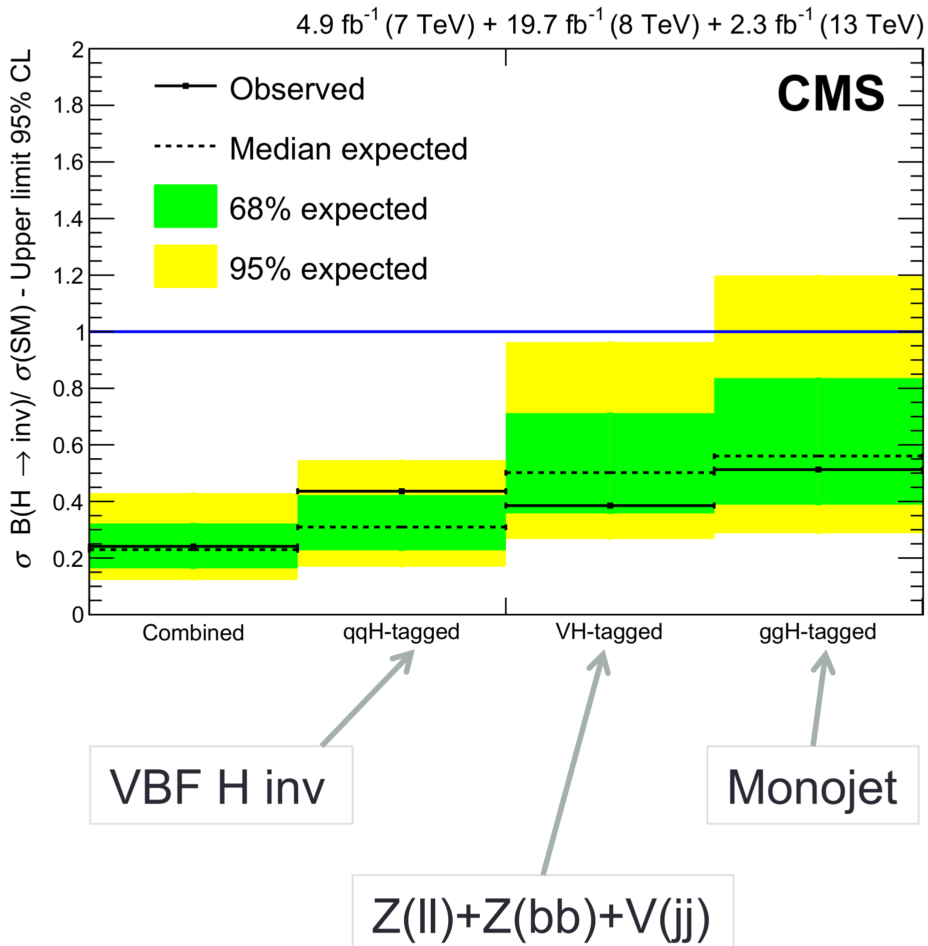
- BF(H->inv) combined limit

Observed	Expected
0.24	0.23

- VBF H inv limit can be read out from the plot

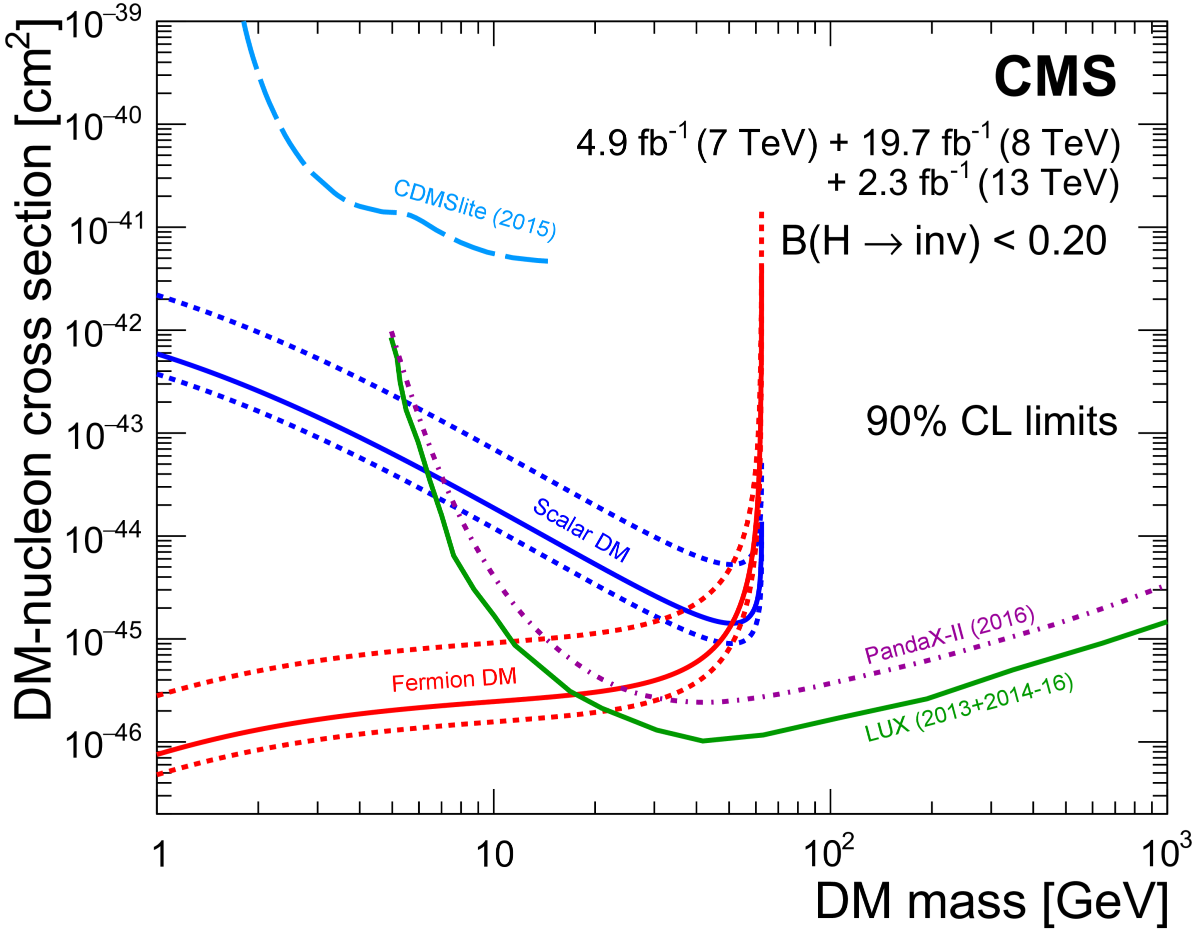
Observed	Expected
0.44	0.32

- Dominant systematic uncertainties:
  - Lepton efficiency
  - W+jets/Z+jets ratio, theory



CMS combined: DM limits

- Higgs-portal dark matter limits:



Conclusion

- This table summarize current constraints on BF(H->inv) from each channel and combined.

Mode	ATLAS		CMS	
ZH inv leptonic	0.98	13.3 (13 TeV) fb^{-1}	0.86	12.9 (13 TeV) fb^{-1}
VH inv hadronic	0.78	20.3 (8 TeV) fb^{-1}	n/a	
ggH inv	n/a		0.48	12.9 (13 TeV) fb-1
VBF H inv	0.28	20.3 (8 TeV) fb^{-1}	0.44	5.1 (7 TeV) + 19.7 (8 TeV) + 2.3 (13 TeV) fb^{-1}
Combined	0.23	4.7 (7 TeV) + 20.3 (8 TeV) fb^{-1}	0.24	5.1 (7 TeV) + 19.7 (8 TeV) + 2.3 (13 TeV) fb^{-1}

- Analysis with full 2016 dataset is on-going.

Paper references

- arXiv:1606.02266[hep-ex] JHEP08(2016)045
- arXiv:1504.04324[hep-ex] Eur. Phys. J. C (2015) 75:337
- arXiv:1508.07869[hep-ex] JHEP 01 (2016) 172
- arXiV:1703.01651[hep-ex] Submitted to JHEP
- arXiv:1509.00672[hep-ex] JHEP11(2015)206
- arXiv:1402.3244[hep-ex] Phys. Rev. Lett. 112, 201802 (2014)
- arXiv:1610.09218[hep-ex] JHEP 02 (2017) 135
- arXiv:1404.1344[hep-ex] Eur. Phys. J. C 74 (2014) 2980
- arXiv:1607.05764[hep-ex] JHEP 12 (2016) 083

Backup: VBF H inv: Z(W)+jets background

- Scale factors (signal region)/(control region) are derived by MC.
- (Signal region) = (scale factor)*(control region)
- Z+jets control region: W+jets control region: