

Searches for invisibly decaying Higgs bosons

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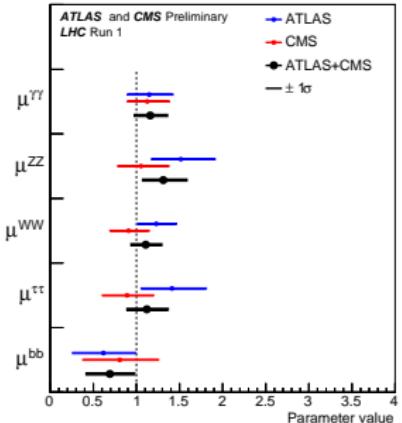
Outline

- ▶ Why search for invisibly decaying Higgs bosons
- ▶ How to search for invisibly decaying Higgs bosons:
 - Direct and indirect searches
 - Focus on most sensitive result: Run 1 VBF channel
- ▶ Results from LHC Runs 1 and 2
- ▶ Interpretations of results
- ▶ Projections of future sensitivity

Why look for invisibly decaying Higgs bosons?

New particle

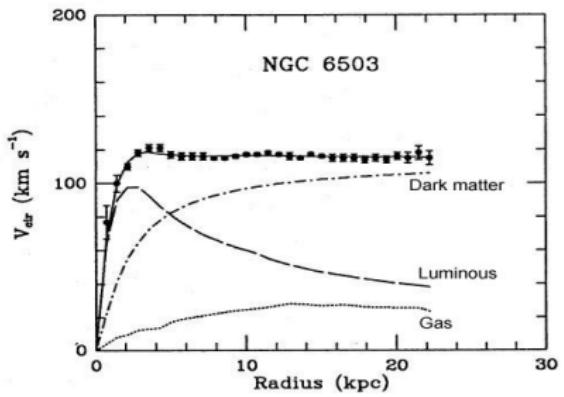
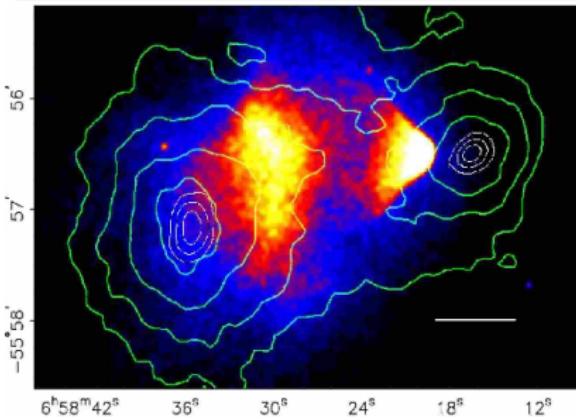
- ▶ Measurements of the Higgs boson made so far are impressive:
 - Mass measured with 0.2% error
- ▶ But a lot of parameters are still relatively unconstrained:
 - Indirect limit on width is $\sim 4\Gamma_{SM}$
- ▶ Plenty of room for Higgs boson couplings to exotic particles



CMS-PAS-HIG-15-002
ATLAS-CONF-2015-044

Why invisible particularly?

- ▶ There is evidence from several sources for “dark matter” (DM)
- ▶ Where does dark matter get its mass from?
- ▶ Amounts of DM and SM matter seem to be of the same order of magnitude so it’s likely they interact



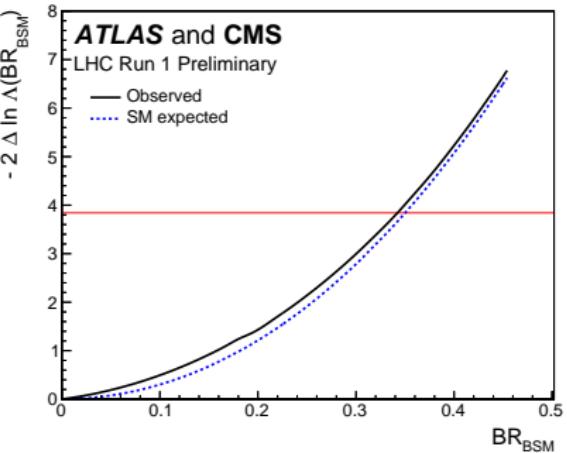
Why look for invisibly decaying Higgs bosons?

- ▶ All massive SM particles get their mass through Higgs field couplings:
 - Fermions: $\bar{\psi}_i y_{ij} \psi_j \phi + \text{hermitian conjugate}$
 - Bosons: $|D_\mu \phi|^2 - V(\phi)$
- ▶ Higgs mechanism is the only known locally gauge invariant way to give mass to particles charged under the SM symmetry groups
- ▶ DM must also get its mass from somewhere motivating interaction with a scalar like the Higgs
- ▶ Some theories of collider DM also have similar production mechanisms to the Higgs

How to search for invisibly decaying Higgs bosons

Indirect searches

- ▶ Compare visible width to total width:
 - $BR_{BSM} = \frac{\Gamma_H - \Gamma_{vis}}{\Gamma_H}$
- ▶ No measurement of Γ_H , need to make an assumption
 - Usually assume SM width
- ▶ ATLAS+CMS combination gives an observed (expected) limit on BR_{BSM} of 0.34 (0.35)

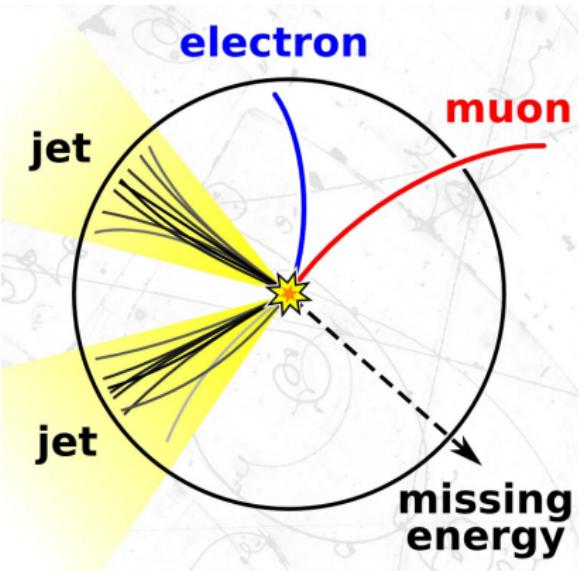


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How to search for invisibly decaying Higgs bosons

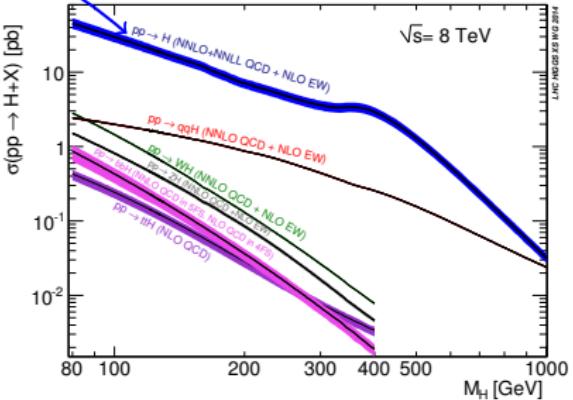
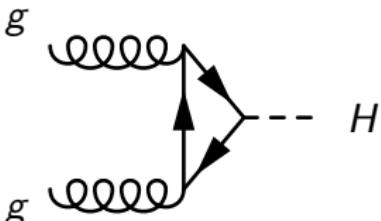
Direct searches

- ▶ No visible products if Higgs boson is created alone
- ▶ Have to use associated Higgs production
- ▶ Tag associated production, then look for momentum imbalance “ E_T^{miss} ”

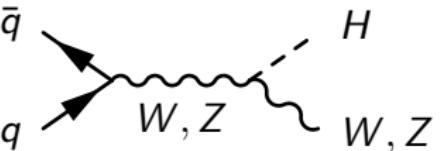


Gluon Fusion: ggH

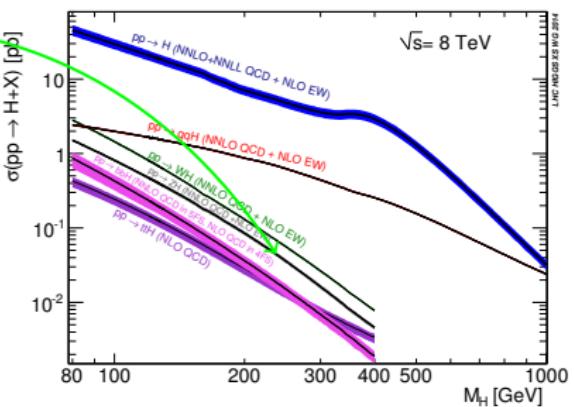
- ▶ Gluon fusion production has the highest rate ✓
- ▶ Normally leaves no visible products ✗
- ▶ Only visible with initial state radiation (ISR)
- ISR is difficult to tag and lowers rate



Vector boson associated production: VH

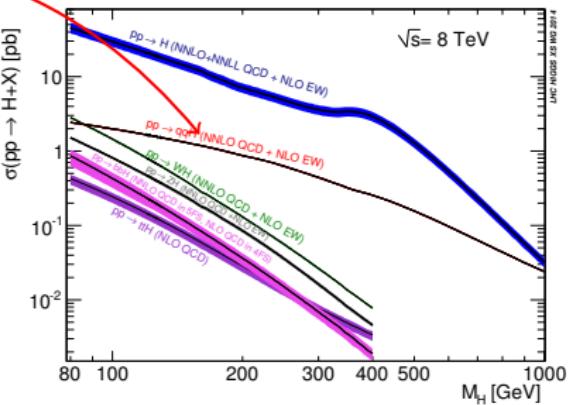
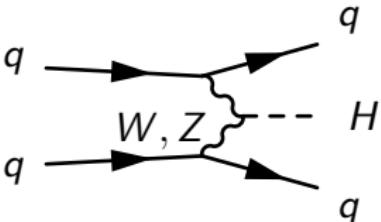


- ▶ VH production has a much lower rate than ggH \times
- ▶ Leptonically decaying vector bosons are easy to tag ✓
- Particularly $Z \rightarrow ll$ which was the first VH channel used

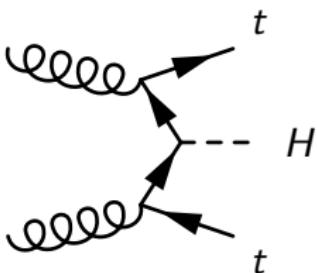


Vector Boson Fusion: VBF

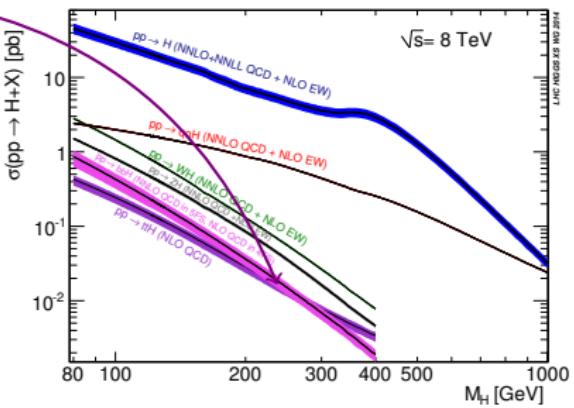
- ▶ VBF has a relatively high production rate ✓
- ▶ Lack of strong force 'colour connection' leaves large polar angle between quarks
 - This allows the resulting jets to be tagged ✓
- ▶ Focus of the rest of the talk



$t\bar{t}H$

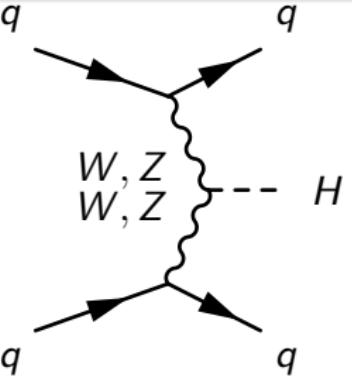


- ▶ $t\bar{t}H$ has a very low rate ✗ ✗
- ▶ Taggable decay products ✓
- ▶ Not sensitive with LHC Run 1 data
 - Starting to become interesting with higher Run 2 energy



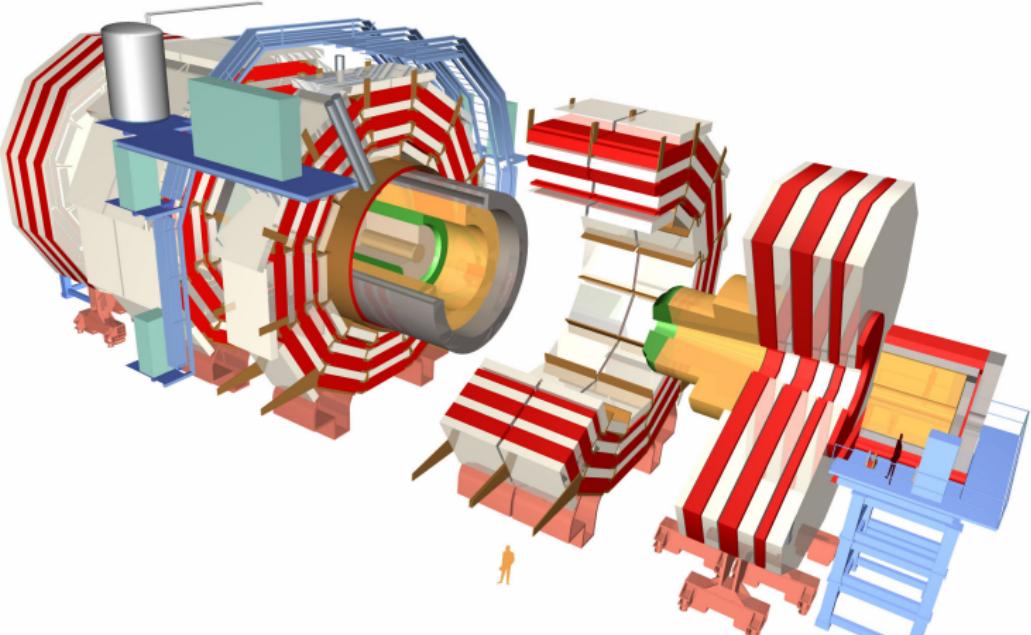
What detector capabilities do we need?

- ▶ VBF jets have a large polar angle separation
 - Calorimetry close to the beamline is important
- ▶ E_T^{miss} measurement accuracy requires a 4π hermitic detector
- ▶ Good energy resolution for all objects is also necessary



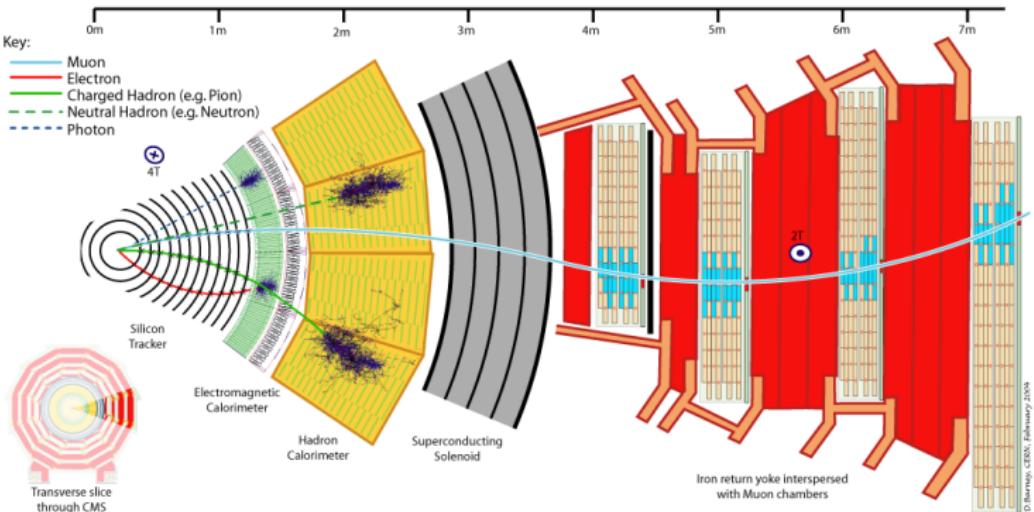
CMS

- Detector covers pseudorapidities up to 5



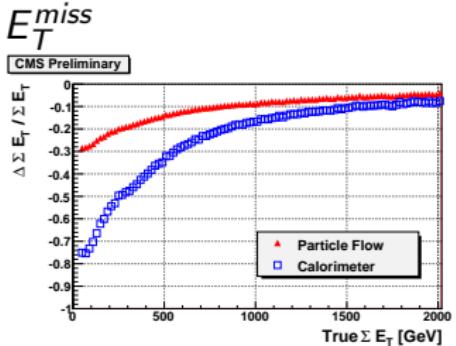
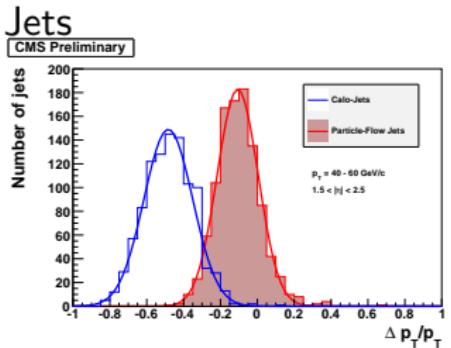
CMS particle flow reconstruction

- ▶ 4T magnet and tracking system give good momentum measurements
- ▶ PbWO₄ crystal ECAL gives good EM energy resolution
- ▶ CMS HCAL is the least precise subdetector
 - What about jet energy resolution?



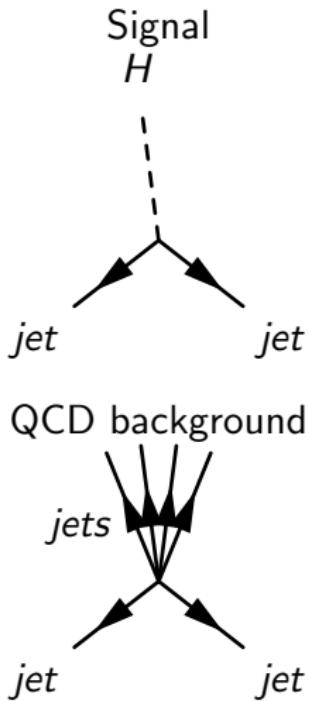
Particle flow

- ▶ Particle flow links information from all subdetectors
- ▶ Jets mostly consist of charged hadrons (60%) and e/γ (30%)
 - Charged hadron deposits in HCAL can be matched to precise tracker measurements
 - e/γ can be measured in the ECAL
- ▶ This leaves only 10% of the jet measured by the HCAL
- ▶ Good resolution of all objects allows accurate E_T^{miss} calculation



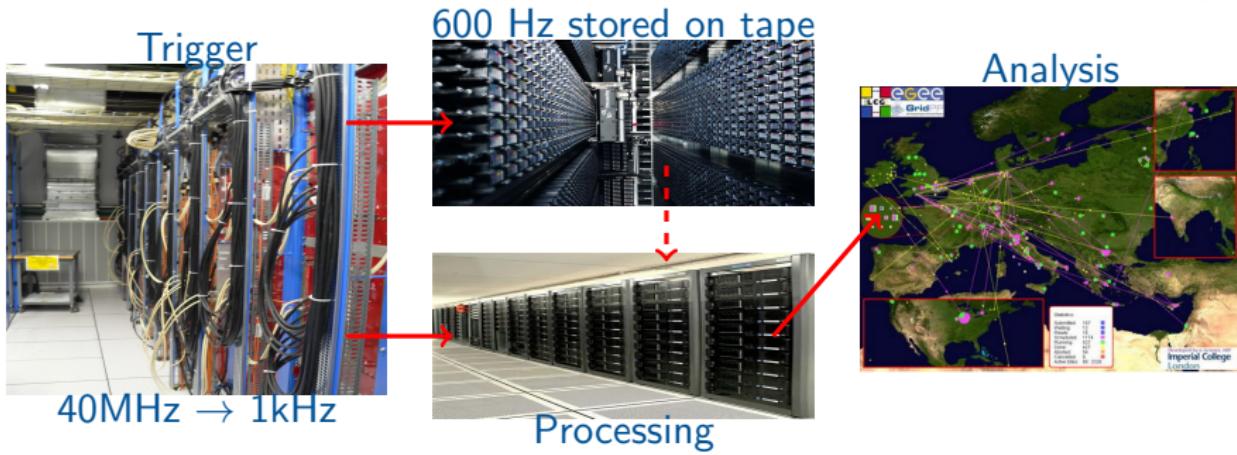
Main challenges for VBF Higgs to invisible

- ▶ QCD multijet production cross-section is much larger than signal cross-section
 - Some of these jets will fake the VBF topology
- ▶ Trigger must be very tight to reduce event rate to an acceptable level
- ▶ Significant remaining QCD background is hard to model



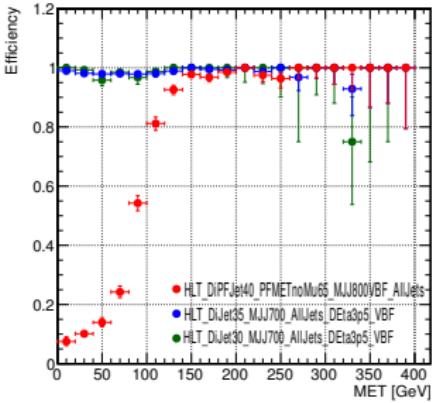
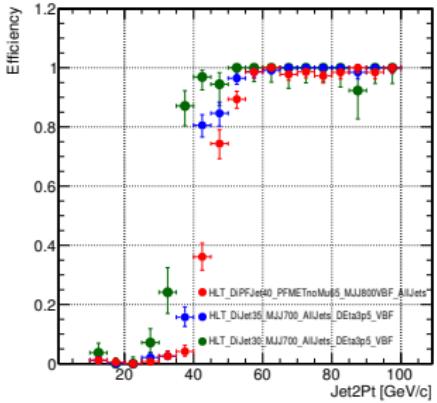
Parked data

- ▶ Limiting factor in CMS event rate found to be processing time, not data output
- ▶ During Run 1 about a third of data was 'promptly' reconstructed
 - Remaining two thirds were 'parked' for reconstruction in the long shutdown
- ▶ This parked data has much looser trigger thresholds
- ▶ Dedicated VBF invisible Higgs triggers were run for both streams



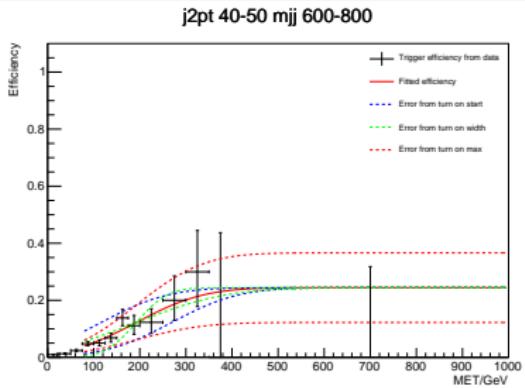
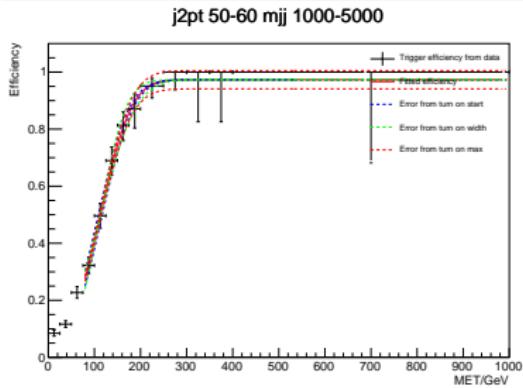
Trigger

- ▶ Require a pair of jets with VBF topology
- ▶ Also require large E_T^{miss}
 - Calculated ignoring muons to enable background estimation
- ▶ Thresholds vary through run periods



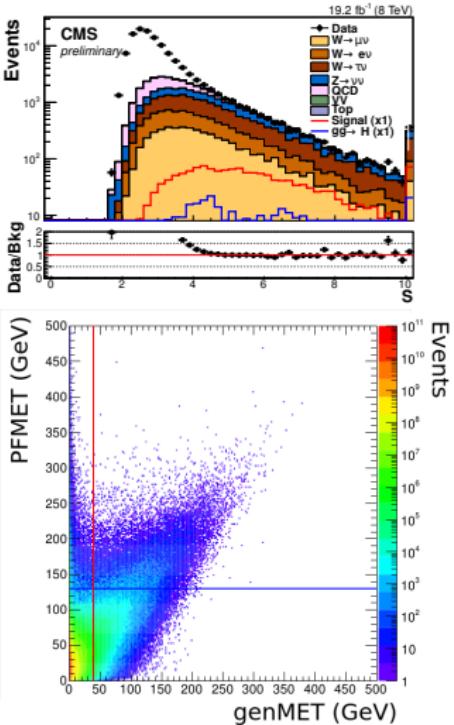
Trigger Efficiency Measurement

- ▶ Trigger thresholds are a limiting factor for the analysis
- ▶ Need to measure accurately so turn on region can be used
 - Variables are highly correlated so measured by fitting as a function of E_T^{miss} in bins of M_{jj} and second jet p_T



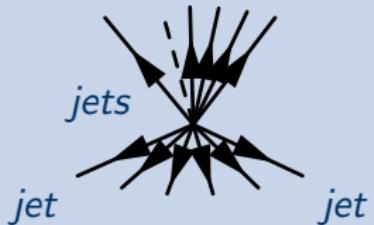
Preselection

- ▶ After setting trigger variables to point of 50% trigger efficiency most data is still QCD
- ▶ Not modelled well by MC
 - Rate is too high to produce a large enough sample
- ▶ Additional tight cuts must be applied before MC driven selection optimisation can be performed



Reducing QCD Backgrounds

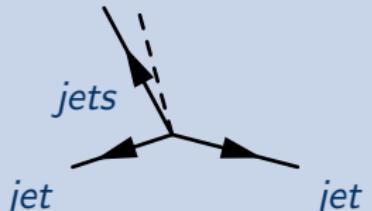
E_T^{miss} significance



VS



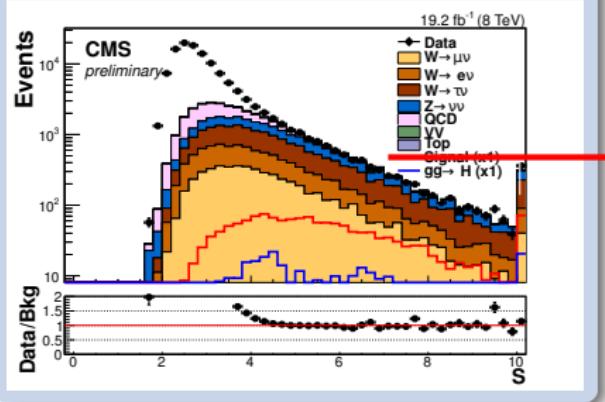
$\min \Delta\phi(j, E_T^{\text{miss}})$



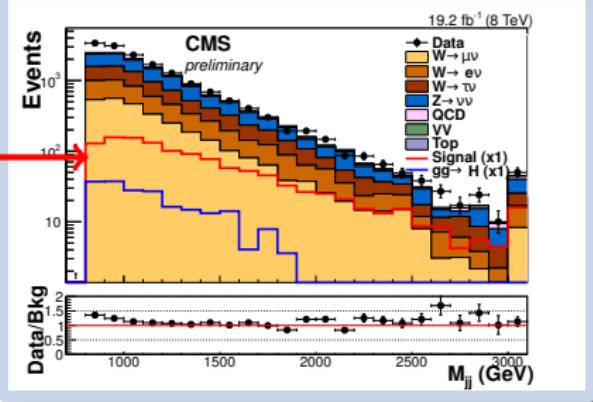
Preselection

- ▶ Require E_T^{miss} significance > 4 , $\min\Delta\phi(j, E_T^{miss}) > 2$ and $M_{jj} > 800$ GeV

Before



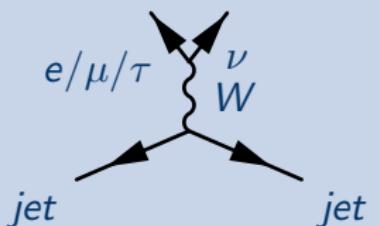
After



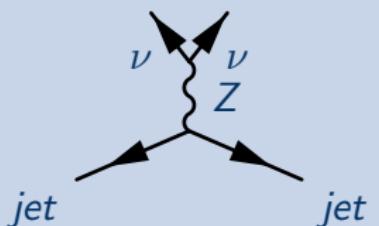
Remaining backgrounds

- ▶ After preselection most backgrounds are from $W/Z + \text{jets}$
- ▶ Veto leptons to reduce leptonic decay contribution
- ▶ Hadronic decays reduced by anti-QCD selection
- ▶ Apply further selection then estimate remainder with data driven techniques
 - Further minor contributions from VV , top and remaining QCD

$W + \text{jets}$



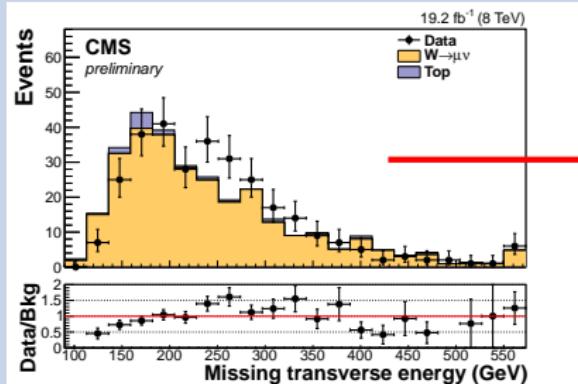
$Z + \text{jets}$



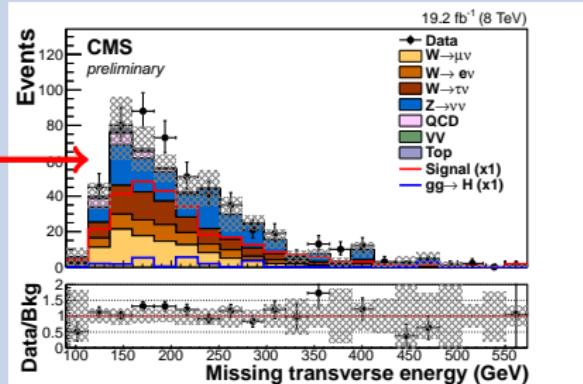
Data driven background estimation

- ▶ Choose control region enriched in background
 - ▶ Use MC signal-control ratio to go to signal region:
- $$N_{Bkg}^{signal} = \frac{(N_{obs}^{control} - N_{otherbkg}^{control})}{N_{MC}^{signal}} \cdot N_{MC}^{control}.$$
- ▶ Ratio referred to as data driven scale factor

Control Region: Single Muon



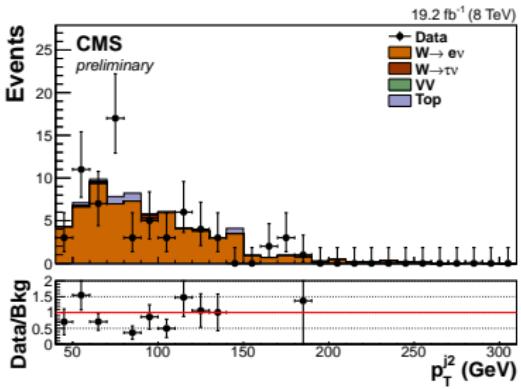
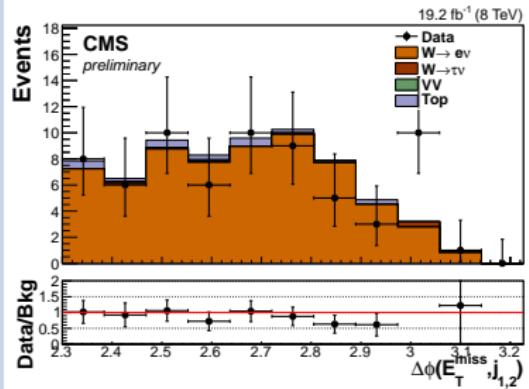
Signal Region: Lepton veto



W control regions

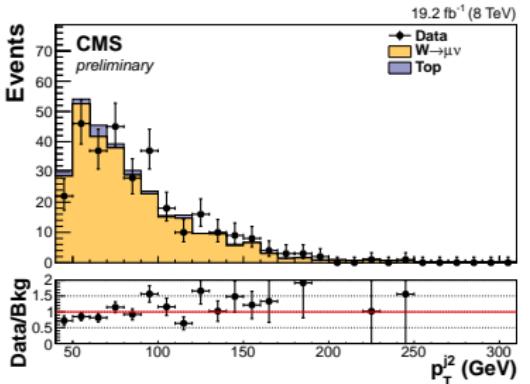
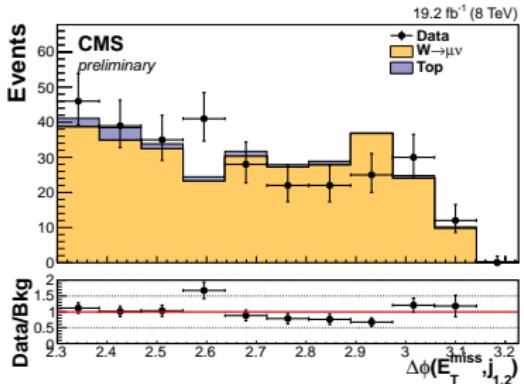
- ▶ For $W \rightarrow \ell\nu + \text{jets}$ background use region with inverted lepton veto
 - Single electron region for $W \rightarrow e\nu$

$W \rightarrow e\nu$



W control regions

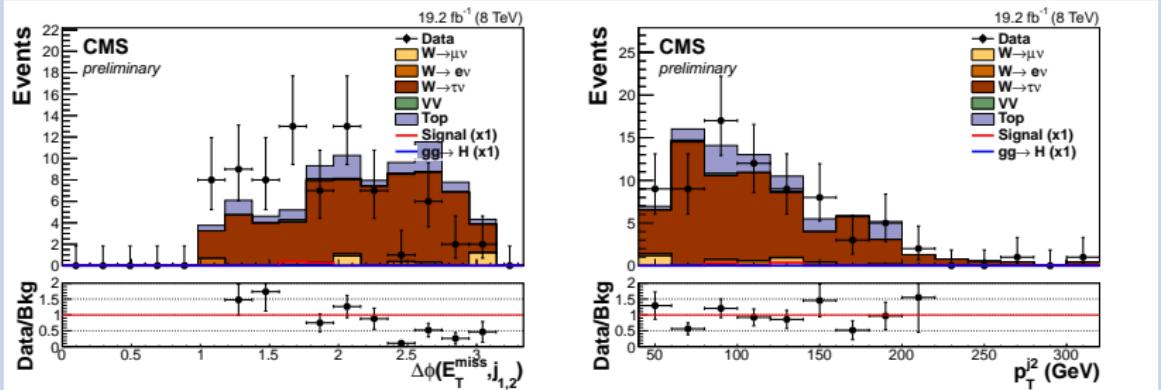
- Single muon region for $W \rightarrow \mu\nu$ with E_T^{miss} recalculated ignoring muon

 $W \rightarrow \mu\nu$ 

W control regions

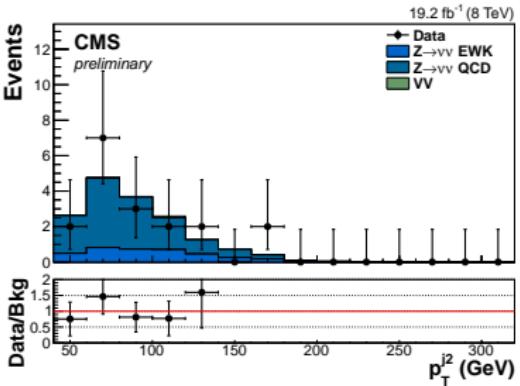
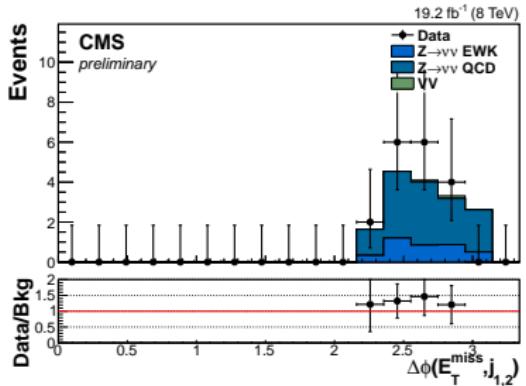
- ▶ Very few events in single tau region after other selections
 - Relaxed $\min\Delta\phi(j, E_T^{\text{miss}})$ requirement to > 1 only considering leading two jets
 - Added lepton- E_T^{miss} $m_T > 20$ GeV requirement to reduce QCD

$W \rightarrow \tau\nu$



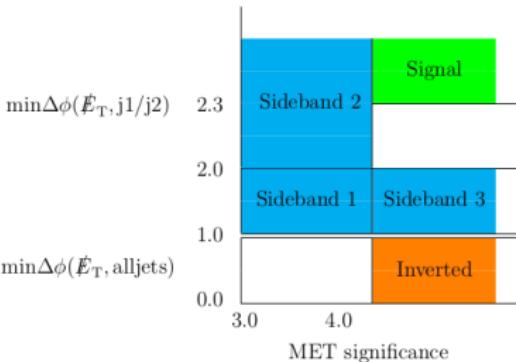
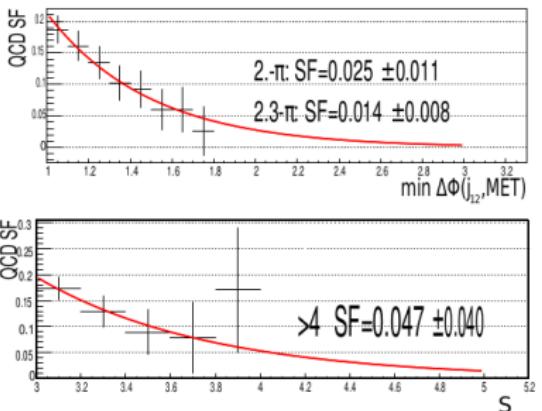
$Z \rightarrow \nu\nu$ control region

- ▶ Remove lepton veto and require a dimuon
 - Statistical uncertainty on event rate in this region is limiting uncertainty on the analysis
- ▶ $Z \rightarrow \nu\nu$ and $Z/\gamma^* \rightarrow \mu\mu$ have different cross-sections
 - Must be corrected for



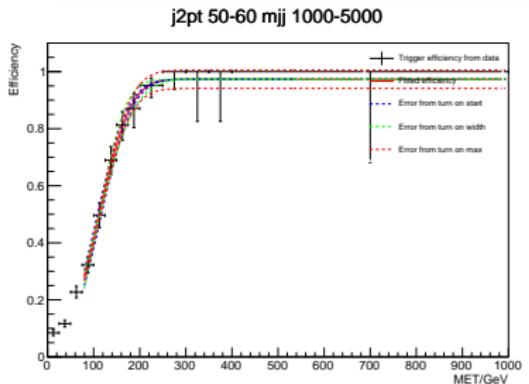
QCD Estimation

- ▶ Small phase space between trigger thresholds and signal region
- ▶ Invert QCD reduction criteria to obtain a shape for QCD background
- ▶ Normalised using fit of scale factor in sideband 1 as QCD reduction criteria are tightened



Selection Optimisation

- ▶ Final selection was determined by tightening preselection requirements to find optimum expected limit
- ▶ Selection driven by the preselection and limited numbers of events in background control regions



Variable	Requirement
$\eta_{j1} + \eta_{j2}$	< 0
jet 1 p_T	> 50 GeV
jet 2 p_T	> 45 GeV
$\Delta\eta_{jj}$	> 3.6
M_{jj}	> 1200 GeV
E_T^{miss}	> 90 GeV
E_T^{miss} significance	> 4 GeV
$\min\Delta\phi(j, E_T^{\text{miss}})$	> 2.3

Systematic uncertainties

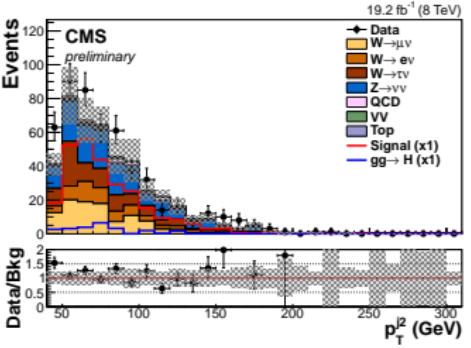
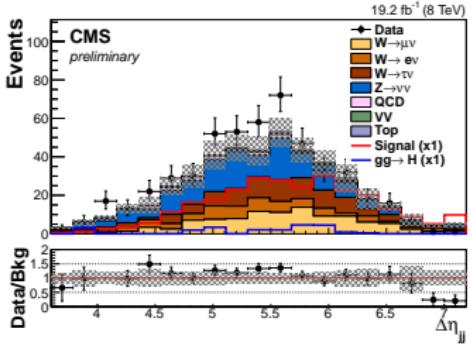
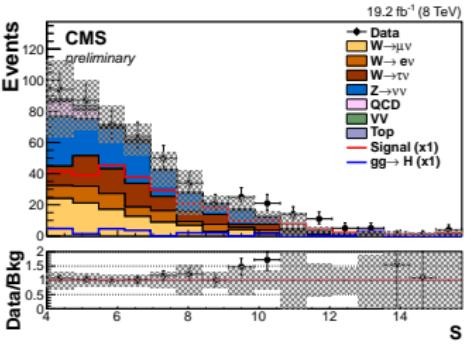
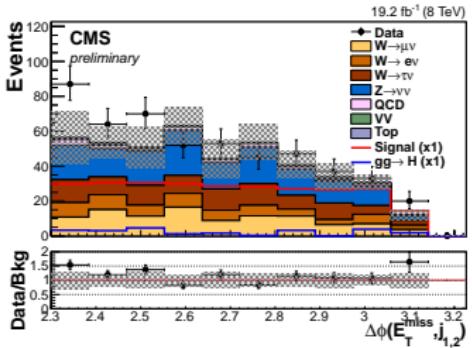
Source	Total background	Signal
Control region statistics	9.3	-
MC statistics	5.4	3.8
JES	4.6	11
$W \rightarrow \tau\nu$ control region extrapolation	4.3	-
QCD background estimation	3.2	-
JER	3.0	1.8
Lepton ID efficiency	2.4	-
UES	1.9	1.6
Pileup weight	1.1	1.5
Top MC scale factor unc.	0.25	-
Luminosity	0.02	2.6
QCD scale, PDF and cross-section uncertainties	0.01	5.2
Total	13.6	13.3

What did we see?

Process	Event yields
$Z \rightarrow \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
$W \rightarrow e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \rightarrow \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \rightarrow \tau\nu$	$94.6 \pm 13.1 \pm 23.8$
top	5.5 ± 1.8
Minor backgrounds	3.9 ± 0.7
QCD multijet	17 ± 14
Total background	$439.4 \pm 40.7 \pm 43.5$
Signal(VBF)	273.1 ± 31.2
Signal(ggH)	23.1 ± 15.9
Observed data	508

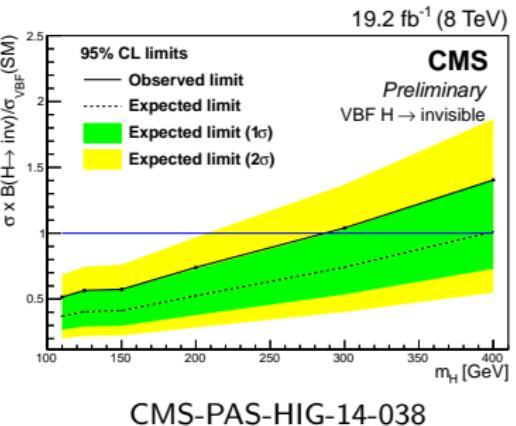
- ▶ Small 1σ excess seen

Control plots



Limits from Run 1 VBF search

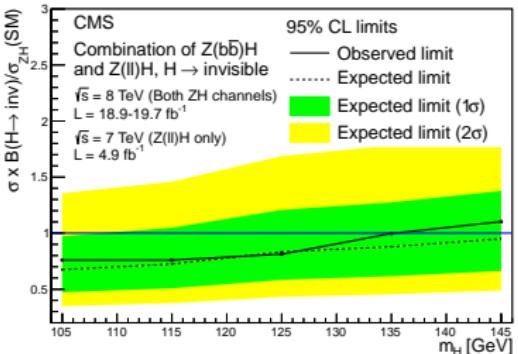
- ▶ Perform a single bin counting experiment using LHC CL_s formalism
- ▶ 95% CL Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125$ GeV is 57 (40)%
- ▶ All V+jets normalisations were allowed to float separately
 - If all V+jets normalisations had same uncertainty as $W \rightarrow \mu\nu$ expected limit would be 33%



Other Run 1 analyses

Run 1 CMS direct searches - ZH

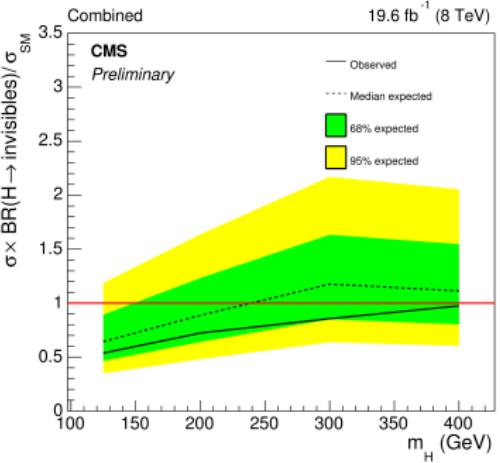
- ▶ Searches in $Z \rightarrow ll$ and $Z \rightarrow b\bar{b}$ channels
- ▶ $Z(ll)H$ search is a 2D shape analysis with data driven backgrounds
- ▶ $Z(b\bar{b})H$ search is a BDT shape analysis with data driven backgrounds
- ▶ Combined ZH searches observed (expected) limit on $\mathcal{B}(H \rightarrow inv.)$ for $m_H = 125$ GeV is 81 (83)%



Eur. Phys. J. C 74 (2014) 2980

Run 1 CMS direct searches - Monojet+V(had)H

- ▶ Search has categories targeting $V(\text{had})H$ and ggH production modes
- ▶ E_T^{miss} shape analysis with data driven background estimation
- ▶ Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125$ GeV is 53 (62)%



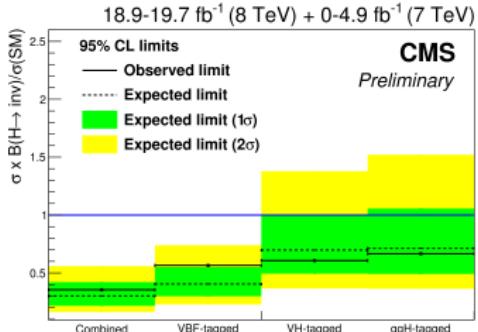
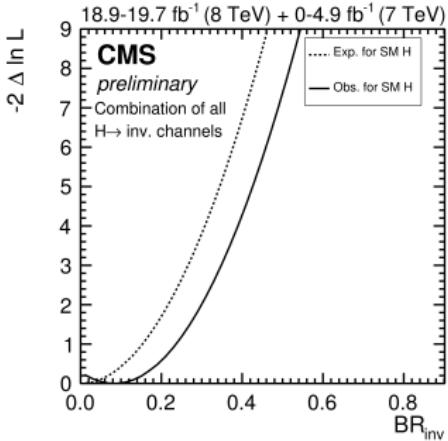
CMS-PAS-EXO-12-055

Combining

- ▶ Best result can be obtained by combining all available searches
- ▶ Must properly account for correlations between channels
 - CMS framework only allows for 100% or 0% correlation of a parameter
- ▶ Most energy resolutions and reconstruction efficiencies are centrally calculated so the uncertainties on these are correlated
- ▶ Exceptions are jet uncertainties in monojet analysis which are not correlated due to very different kinematics from other analyses
- ▶ Some cross-section uncertainties are also correlated between channels

Run 1 CMS direct searches - Combination

- ▶ Combine by production mode as well as full combination
 - ggH-tagged is monojet, VH-tagged is $Z(\ell\ell)H+Z(bb)H+V(\text{had})H$, VBF-tagged is VBF
- ▶ Obs. (exp.) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ at $m_H = 125$ GeV was 36 (30)%



CMS-PAS-HIG-15-012

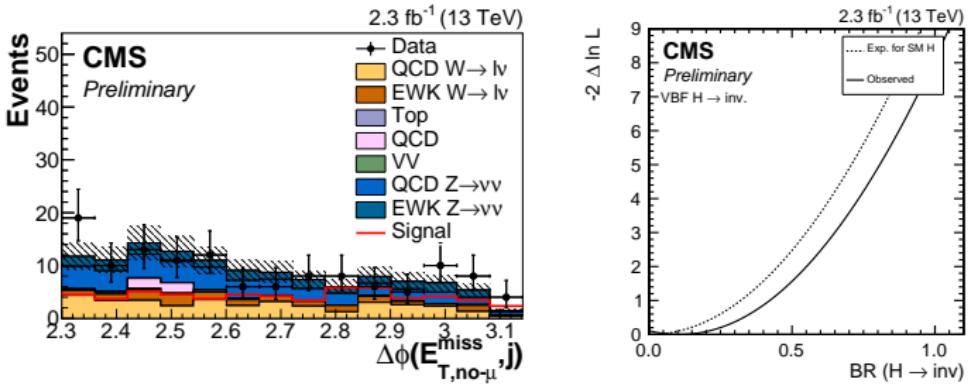
Run 2

Run 2 CMS direct searches - VBF improvements

- ▶ Dominant uncertainty in Run 1 was control region statistics
- ▶ In order to improve this all $W+jets$ processes now assumed to share the same scale factor
 - True in the absence of mismodelling of lepton identification efficiency
 - Previous results show compatible scale factors within statistical errors
- ▶ $W+jets$ and $Z+jets$ normalisations are also tied together
 - 30% systematic uncertainty calculated using NLO MC placed on their ratio

Run 2 CMS direct searches - VBF

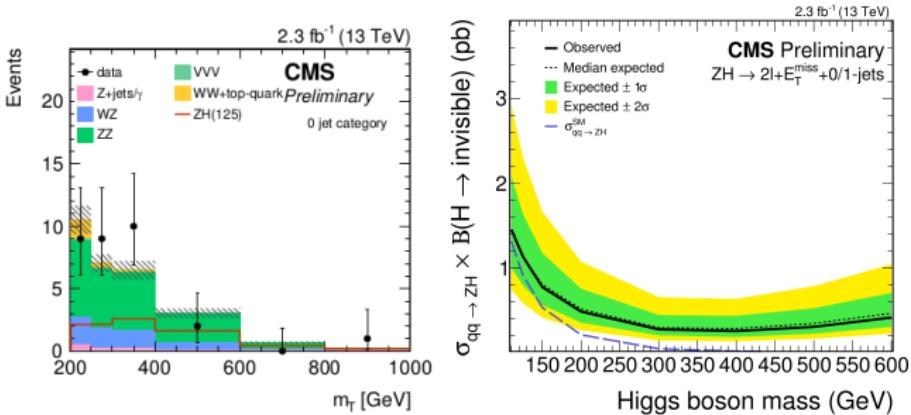
- ▶ Dedicated trigger used again with tighter thresholds due to increased pileup and higher energy beam
- ▶ Control regions and signal region are all considered as single bins in a simultaneous fit
- ▶ Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125$ GeV is 69 (62)%



CMS-PAS-HIG-16-009

Run 2 CMS direct searches - ZH

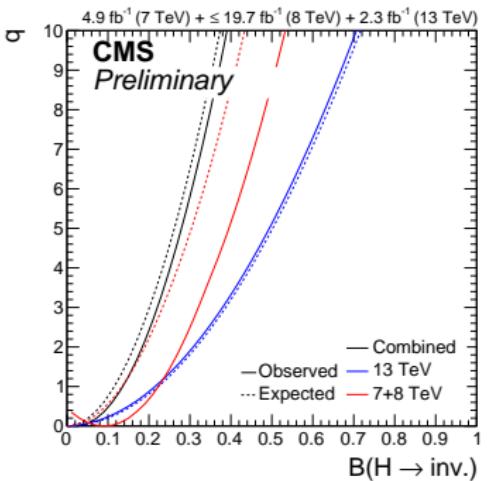
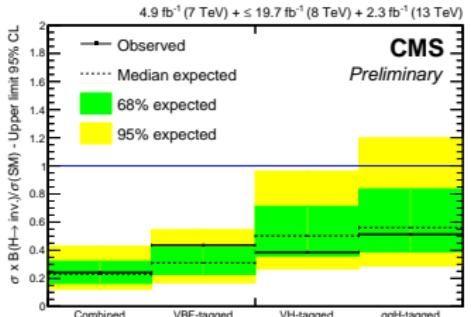
- ▶ Targets $Z \rightarrow \ell\ell$ final state
- ▶ 2D shape analysis with leading backgrounds estimated using MC
- ▶ Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125$ GeV is 124 (124)%



CMS-PAS-HIG-16-008

Run 2 CMS direct searches - Combination

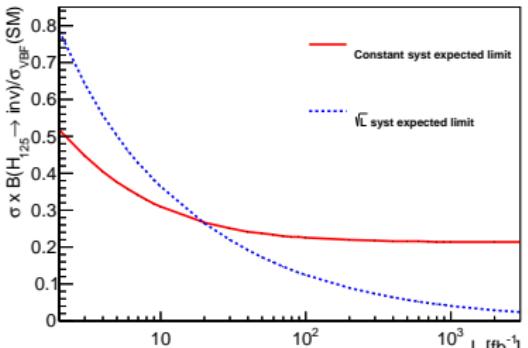
- ▶ All of the above analyses plus a 13 TeV update of Monojet+V(had)H search were combined
- ▶ 8 TeV VBF analysis redone with simultaneous fit and joint V+jets normalisation
- ▶ Observed (expected) $\mathcal{B}(H \rightarrow \text{inv.})$ limit for $m_H = 125$ GeV is 24 (23)%



CMS-PAS-HIG-16-016

VBF analysis projections

- ▶ CMS VBF analysis projected to increased luminosity at 13 TeV
- ▶ If systematics scale as $\sqrt{\mathcal{L}}$ can exclude $\mathcal{B}(H \rightarrow \text{inv.}) = 5\%$ with full LHC dataset



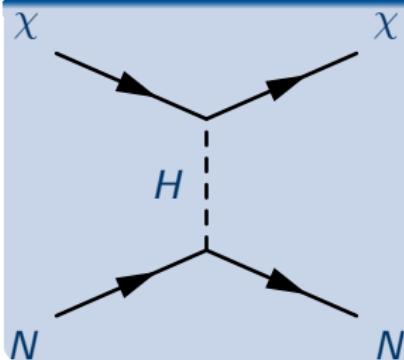
arXiv:1603.07739

Dark matter interpretations

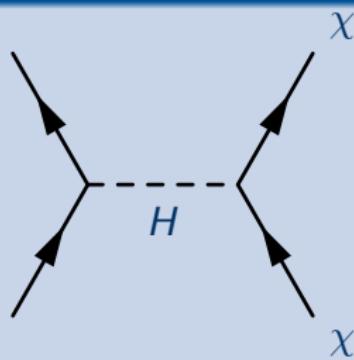
What does this mean for dark matter?

- If DM couples to the Higgs the following diagrams are possible

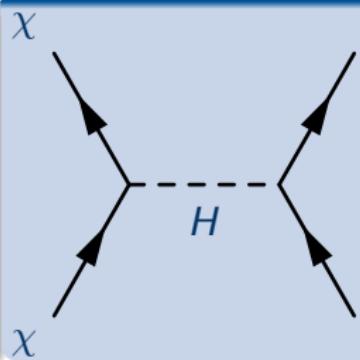
Direct Detection - e.g. LUX



Invisible Higgs - LHC



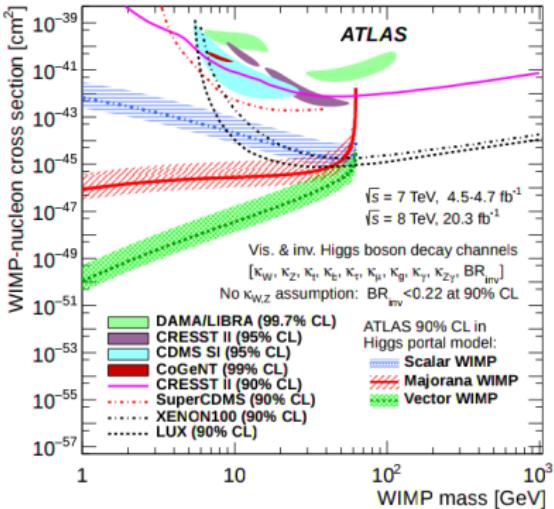
Annihilation - e.g. WMAP



- Limits on $\mathcal{B}(H \rightarrow \text{inv})$ therefore constrain Higgs Portal DM models
- These constraints are directly comparable to those from other experiments
 - Only valid within the assumptions of the model used so caution needed

Which model to use? - Run 1 results

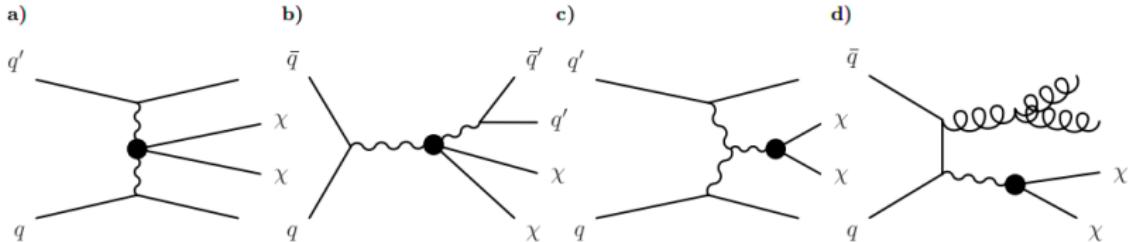
- ▶ Several models for interpreting invisible Higgs limits
- ▶ “Higgs portal” has been quite commonly used
 - Assume 125 GeV Higgs acts as mediator between visible and dark matter sectors
 - Assume scalar, fermion or vector dark matter
- ▶ Scalar dark matter would mix with Higgs boson
 - mixing angle must be small
- ▶ Vector dark matter width goes to infinity as mass decreases



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Dark matter interpretations - Projections

- ▶ EFT models with electroweak couplings studied: favour VBF channel
- ▶ VBF topology allows looser E_T^{miss} selection than QCD driven searches making EFTs valid
- ▶ Also studied ‘implied’ models with a scalar/pseudoscalar mediator
- ▶ Projections of CMS VBF channel sensitivity at several luminosities

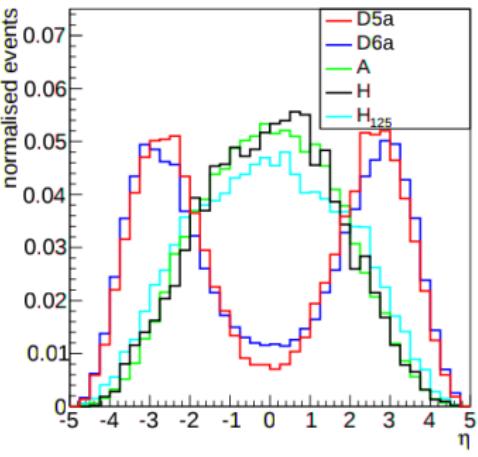
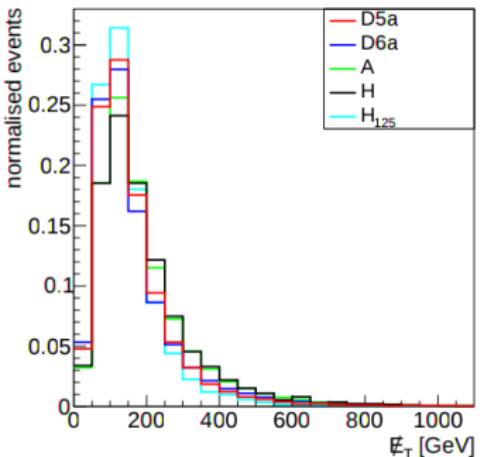


arXiv:1603.07739

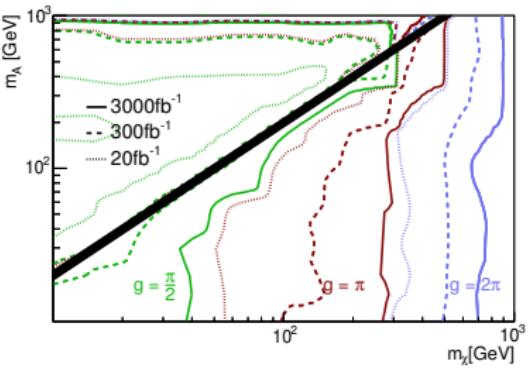
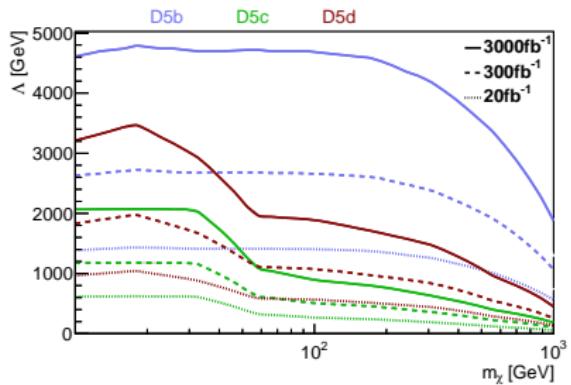
$$\begin{aligned}
 \mathcal{L}_{\text{D5a}} &\supseteq \frac{1}{\Lambda} [\bar{\chi}\chi] \left[\frac{Z_\mu Z^\mu}{2} + W_\mu^+ W^{-\mu} \right], \\
 \mathcal{L}_{\text{D5b}} &\supseteq \frac{1}{\Lambda} [\bar{\chi}\gamma^5\chi] \left[\frac{Z_\mu Z^\mu}{2} + W_\mu^+ W^{-\mu} \right], \\
 \mathcal{L}_{\text{D5c}} &\supseteq \frac{g}{\Lambda} [\bar{\chi}\sigma^{\mu\nu}\chi] \left[\frac{\partial_\mu Z_\nu - \partial_\nu Z_\mu}{\cos \theta_W} - ig (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) \right], \\
 \mathcal{L}_{\text{D5d}} &\supseteq \frac{g}{\Lambda} [\bar{\chi}\sigma_{\mu\nu}\chi] \epsilon^{\mu\nu\rho\sigma} \left[\frac{\partial_\sigma Z_\rho - \partial_\rho Z_\sigma}{\cos \theta_W} - ig (W_\sigma^+ W_\rho^- - W_\rho^+ W_\sigma^-) \right], \\
 \mathcal{L}_{\text{D6a}} &\supseteq \frac{g}{\Lambda^2} \partial^\nu [\bar{\chi}\gamma^\mu\chi] \left[\frac{\partial_\mu Z_\nu - \partial_\nu Z_\mu}{\cos \theta_W} - ig (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) \right], \\
 \mathcal{L}_{\text{D6b}} &\supseteq \frac{g}{\Lambda^2} \partial_\nu [\bar{\chi}\gamma_\mu\chi] \epsilon^{\mu\nu\rho\sigma} \left[\frac{\partial_\sigma Z_\rho - \partial_\rho Z_\sigma}{\cos \theta_W} - ig (W_\sigma^+ W_\rho^- - W_\rho^+ W_\sigma^-) \right], \\
 \mathcal{L}_{\text{D7a}} &\supseteq \frac{1}{\Lambda^3} [\bar{\chi}\chi] W^{i,\mu\nu} W_{\mu\nu}^i, \\
 \mathcal{L}_{\text{D7b}} &\supseteq \frac{1}{\Lambda^3} [\bar{\chi}\gamma^5\chi] W^{i,\mu\nu} W_{\mu\nu}^i, \\
 \mathcal{L}_{\text{D7c}} &\supseteq \frac{1}{\Lambda^3} [\bar{\chi}\chi] \epsilon^{\mu\nu\rho\sigma} W_{\mu\nu}^i W_{\rho\sigma}^i, \\
 \mathcal{L}_{\text{D7d}} &\supseteq \frac{1}{\Lambda^3} [\bar{\chi}\gamma^5\chi] \epsilon^{\mu\nu\rho\sigma} W_{\mu\nu}^i W_{\rho\sigma}^i.
 \end{aligned}$$

Simulation framework

- Events simulated with MadGraph and run through Delphes fast detector simulation
- Simulation validated by comparing VBF produced SM Higgs to invisible events with yields from CMS central sample



► Exclusion possible to several TeV for some models

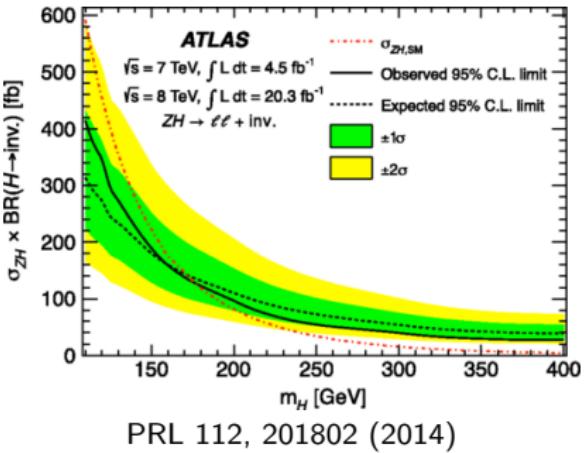


Summary

- ▶ CMS has produced a wide range of invisibly decaying Higgs boson searches in LHC Runs 1 and 2
- ▶ Current 95% CL upper observed (expected) limit on invisible branching fraction from direct searches is 24 (23)% comparable with ATLAS: 25 (27) %
 - Combination of channels allow sensitivity to be greatly improved
- ▶ Projected limit on $\mathcal{B}(H \rightarrow \text{inv.}) \sim 10\text{-}20\%$ from VBF alone by the end of LHC Run 2 and 5% by end of LHC running assuming systematics scale as $\sqrt{\mathcal{L}}$
- ▶ Several dark matter interpretations are being investigated
 - Starting to move beyond simple Higgs portal models

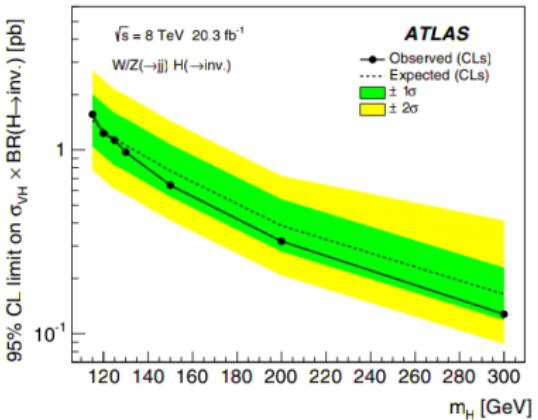
Run 1 ATLAS direct searches - $Z(\ell\ell)H$

- ▶ Selects two leptons opposite large E_T^{miss}
- ▶ E_T^{miss} shape analysis with data driven backgrounds
- ▶ Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125.5$ GeV is 75 (62)%



Run 1 ATLAS direct searches - V(had)H

- ▶ Targets $W/Z \rightarrow qq$ final state
- ▶ E_T^{miss} and dijet p_T shape analysis with data driven backgrounds
- ▶ Observed (expected) limit on $\mathcal{B}(H \rightarrow inv.)$ for $m_H = 125$ GeV is 78 (86)%



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Run 1 ATLAS direct searches - VBF

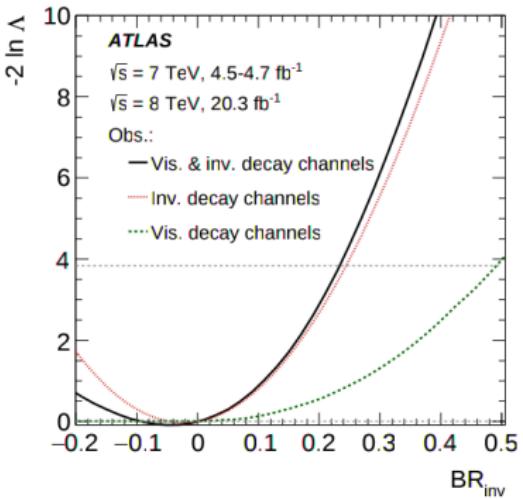
- ▶ Select two jets with large $\Delta\eta$ opposite large E_T^{miss}
- ▶ Counting experiment with data driven background estimation
- $W \rightarrow e\nu$, $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$ and $Z \rightarrow \nu\nu$
normalisation tied together
- ▶ Observed (expected) limit on $\mathcal{B}(H \rightarrow inv.)$ for $m_H = 125$ GeV is 28 (31)%

Signal region Process	SR1	SR2a	SR2b
ggF signal	20 ± 15	58 ± 22	19 ± 8
VBF signal	286 ± 57	182 ± 19	105 ± 15
$Z(\rightarrow \nu\nu) + \text{jets}$	339 ± 37	1580 ± 90	335 ± 23
$W(\rightarrow \ell\nu) + \text{jets}$	235 ± 42	1010 ± 50	225 ± 16
Multijet	2 ± 2	20 ± 20	4 ± 4
Other backgrounds	1 ± 0.4	64 ± 9	19 ± 6
Total background	577 ± 62	2680 ± 130	583 ± 34
Data	539	2654	636

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Run 1 ATLAS direct searches - Combination

- ▶ Combining searches significantly improves limits
- ▶ Direct searches provide most sensitivity
 - Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125$ GeV is 25 (27)%
- ▶ Adding indirect results adds assumption on Higgs total width
 - Observed (expected) limit on $\mathcal{B}(H \rightarrow \text{inv.})$ for $m_H = 125$ GeV is 23 (24)%



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