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Searches for invisibly decaying Higgs bosons

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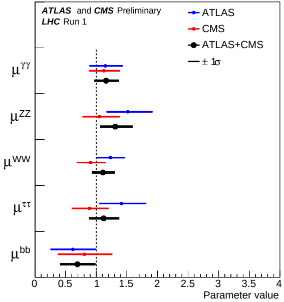
Outline

- 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
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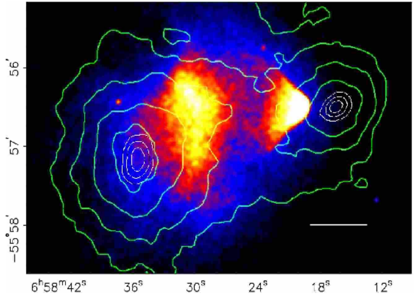
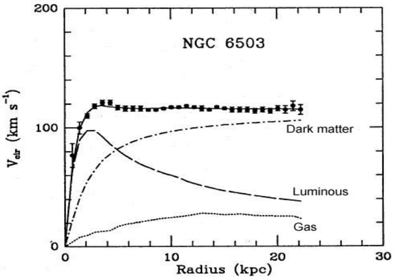
Why invisible particularly?

- 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





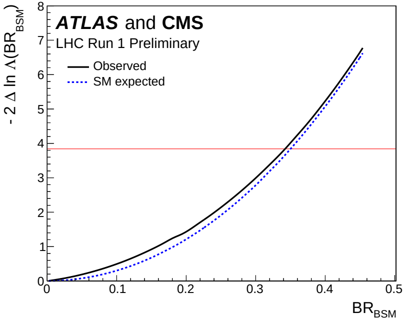
Why look for invisibly decaying Higgs bosons?

- All massive SM particles get their mass through Higgs field couplings:
  - Fermions: $\bar{\psi}_i y_{ij} \psi_j \phi +$ 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:
  - $\mathrm{BR_{BSM}} = \frac{\Gamma_\mathrm{H} - \Gamma_\mathrm{vis}}{\Gamma_\mathrm{H}}$
- No measurement of Γ_H, need to make an assumption
  - Usually assume SM width
- ATLAS+CMS combination gives an observed (expected) limit on $\mathrm{BR_{BSM}}$ of 0.34 (0.35)



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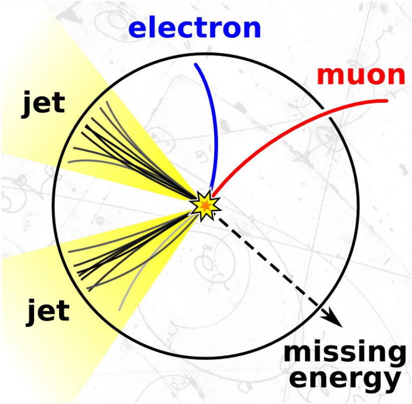
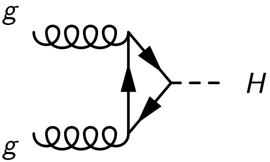
How to search for invisibly decaying Higgs bosons

Direct searches

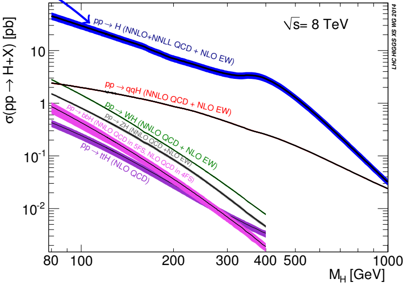
- No visible products if Higgs boson is created alone
- Have to use associated Higgs production
- Tag associated production, then look for momentum imbalance "E_T^{miss}"



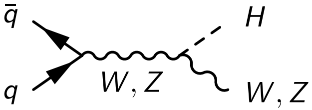
Gluon Fusion: ggH



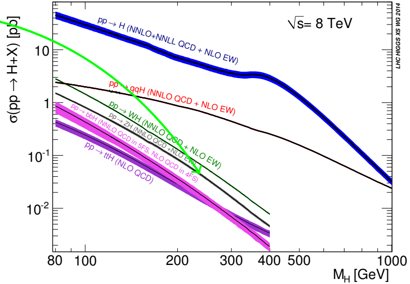
- Gluon fusion production has the highest rate ✓
- Normally leaves no visible products ×
- Only visible with initial state radiation (ISR)
  - ISR is difficult to tag and lowers rate



Vector boson associated production: VH

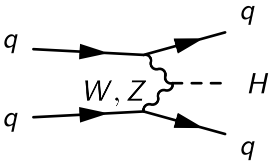


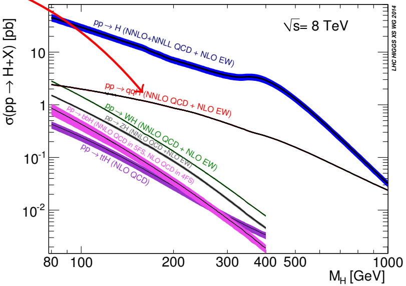
- VH production has a much lower rate than ggH ×
- Leptonically decaying vector bosons are easy to tag ✓
- Particularly $Z \to \ell\ell$ which was the first VH channel used



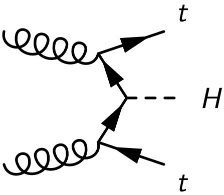
Vector Boson Fusion: VBF

- 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

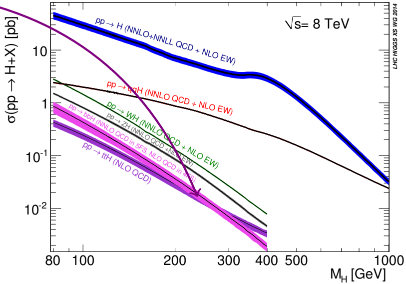




ttH

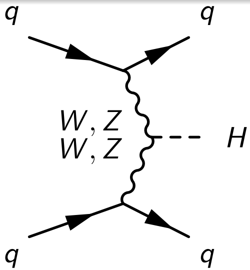


- ttH has a very low rate × ×
- Taggable decay products ✓
- Not sensitive with LHC Run 1 data
  - Starting to become interesting with higher Run 2 energy



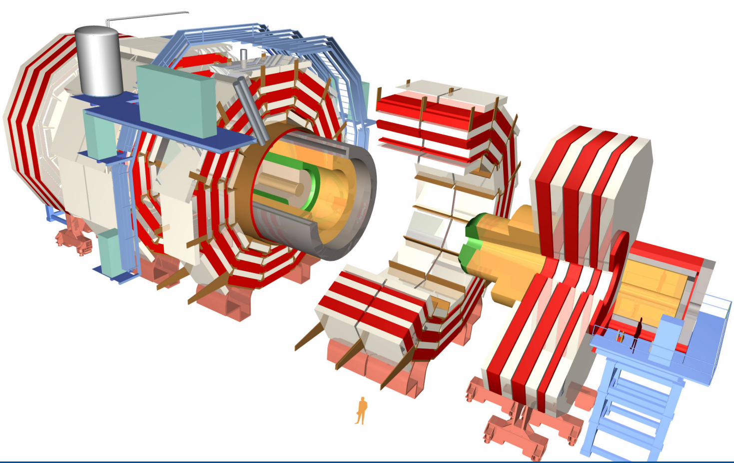
What detector capabilities do we need?

- 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



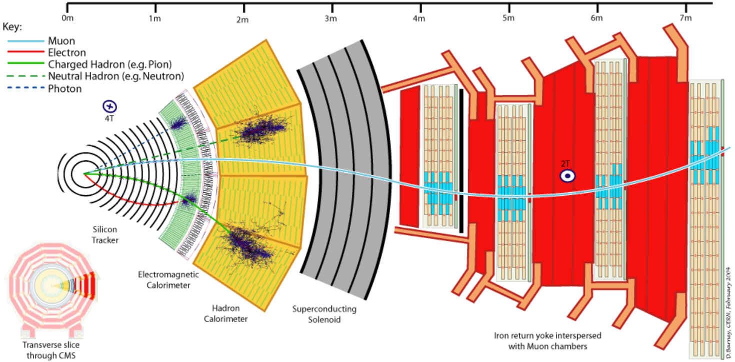
CMS

- Detector covers pseudorapidities up to 5



CMS particle flow reconstruction

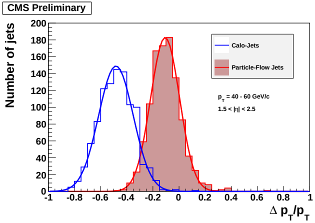
- 4T magnet and tracking system give good momentum measurements
- $PbWO_4$ crystal ECAL gives good EM energy resolution
- CMS HCAL is the least precise subdetector
  - What about jet energy resolution?



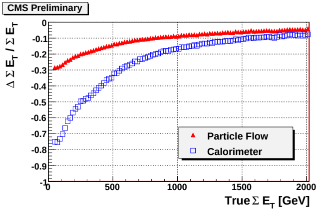
Particle flow

- 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

Jets

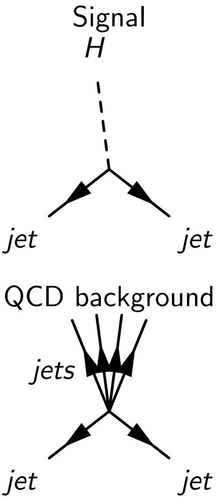


E_T^{miss}



Main challenges for VBF Higgs to invisible

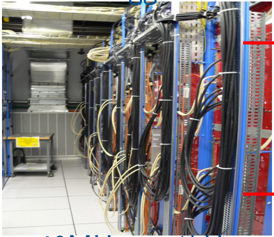
- QCD multijet production cross-section is much larger than signal cross-section
  - Some of these jets will fake the VBF topology
- Trigger must be very tight to reduce event rate to an acceptable level
- Significant remaining QCD background is hard to model



Parked data

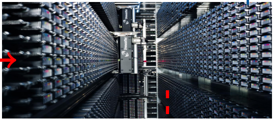
- Limiting factor in CMS event rate found to be processing time, not data output
- During Run 1 about a third of data was 'promptly' reconstructed
  - Remaining two thirds were 'parked' for reconstruction in the long shutdown
- This parked data has much looser trigger thresholds
- Dedicated VBF invisible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

Trigger



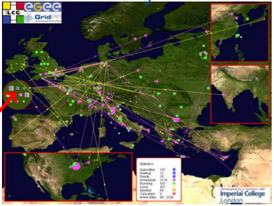
40MHz → 1kHz

600 Hz stored on tape



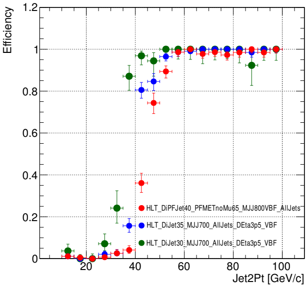
Processing

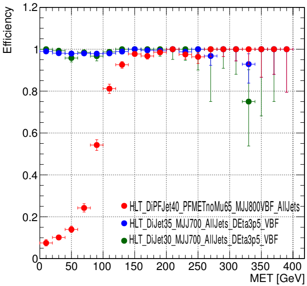
Analysis



Trigger

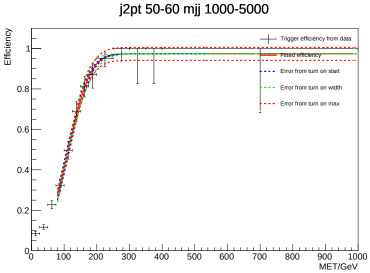
- Require a pair of jets with VBF topology
- Also require large E_T^{miss}
- Calculated ignoring muons to enable background estimation
- Thresholds vary through run periods

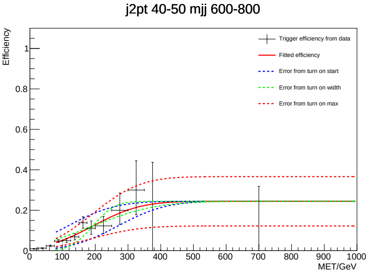




Trigger Efficiency Measurement

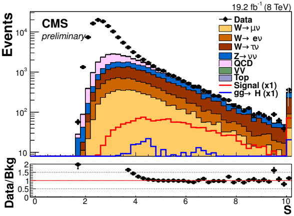
- Trigger thresholds are a limiting factor for the analysis
- Need to measure accurately so turn on region can be used
- Variables are highly correlated so measured by fitting as a function of E_T^{miss} in bins of M_{jj} and second jet p_T

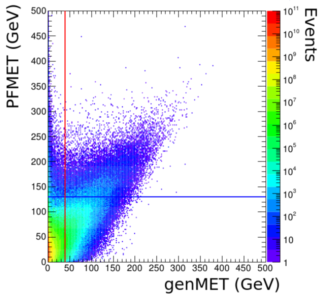




Preselection

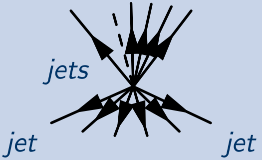
- After setting trigger variables to point of 50% trigger efficiency most data is still QCD
- Not modelled well by MC
- Rate is too high to produce a large enough sample
- Additional tight cuts must be applied before MC driven selection optimisation can be performed



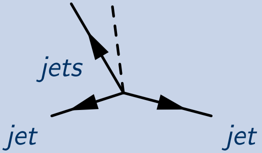


Reducing QCD Backgrounds

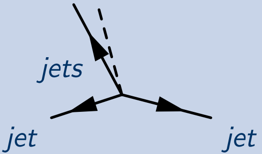
E_T^{miss} significance



VS



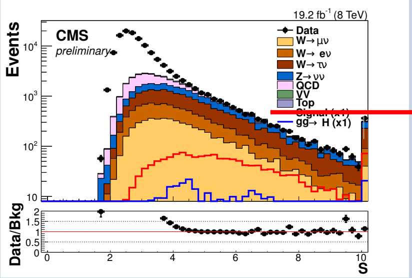
$\min\Delta\phi(\mathrm{j}, E_T^{miss})$



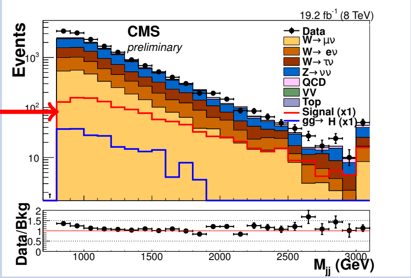
Preselection

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

Before



After

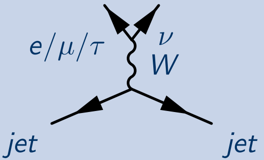


Remaining backgrounds

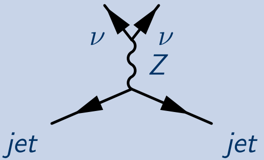
- After preselection most backgrounds are from W/Z+jets
- Veto leptons to reduce leptonic decay contribution
- Hadronic decays reduced by anti-QCD selection
- Apply further selection then estimate remainder with data driven techniques

\- Further minor contributions from VV, top and remaining QCD

W+jets



Z+jets



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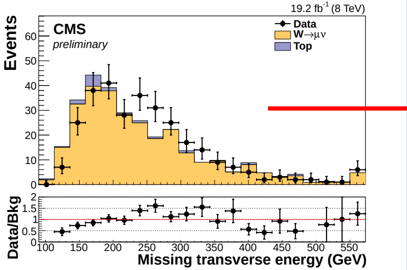
Data driven background estimation

- Choose control region enriched in background
- Use MC signal-control ratio to go to signal region:

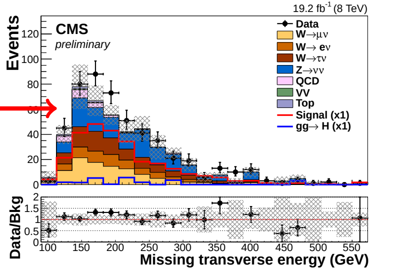
$$N^{signal}_{Bkg} = \frac{(N^{control}_{obs} - N^{control}_{otherbkgs})}{N^{control}_{MC}} \cdot N^{signal}_{MC}.$$

- Ratio referred to as data driven scale factor

Control Region: Single Muon



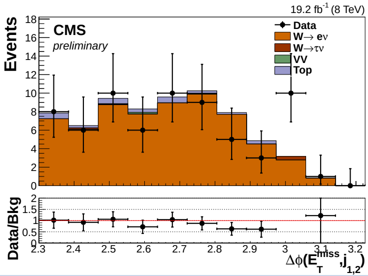
Signal Region: Lepton veto

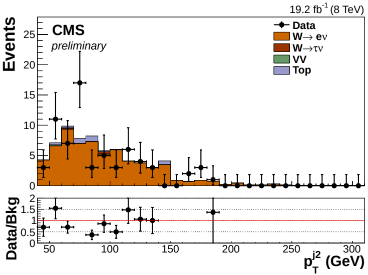


W control regions

- For $W \to \ell\nu$+jets background use region with inverted lepton veto
  - Single electron region for $W \to e\nu$

$W \to e\nu$





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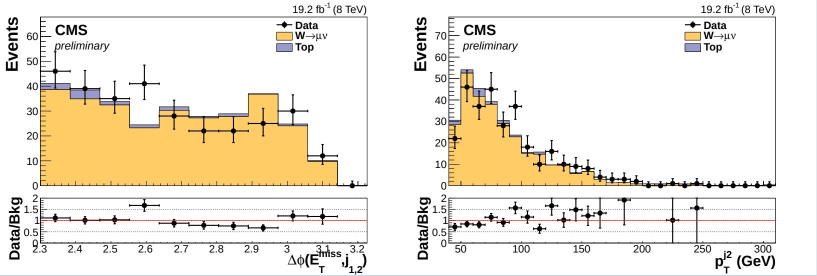
W control regions

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

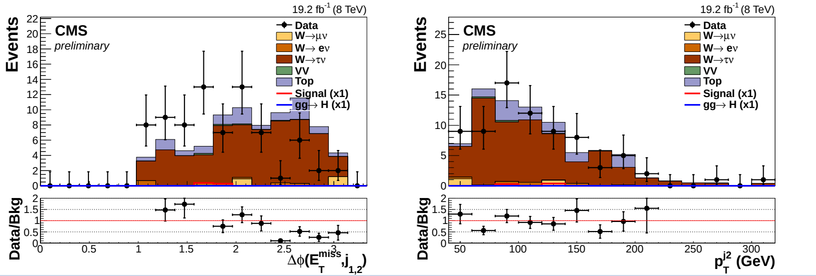
$W \to \mu\nu$



W control regions

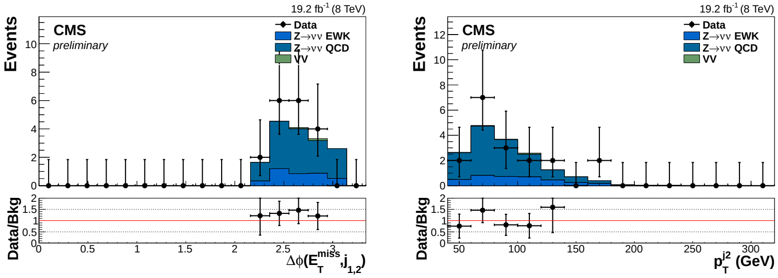
- Very few events in single tau region after other selections
  - Relaxed min$\Delta\phi(\mathrm{j}, E_T^{miss})$ requirement to > 1 only considering leading two jets
  - Added lepton-E_T^{miss} $m_T > 20$ GeV requirement to reduce QCD

$W \to \tau\nu$



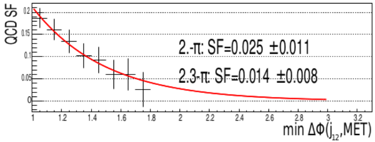
$Z \rightarrow \nu\nu$ control region

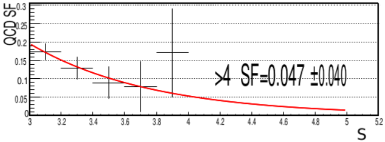
- Remove lepton veto and require a dimuon
  - Statistical uncertainty on event rate in this region is limiting uncertainty on the analysis
- $Z \rightarrow \nu\nu$ and $Z/\gamma^* \rightarrow \mu\mu$ have different cross-sections
  - Must be corrected for

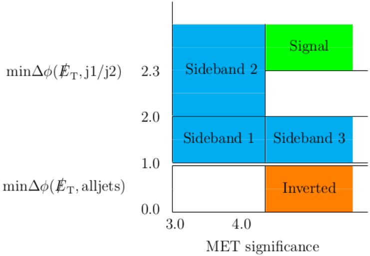


QCD Estimation

- 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

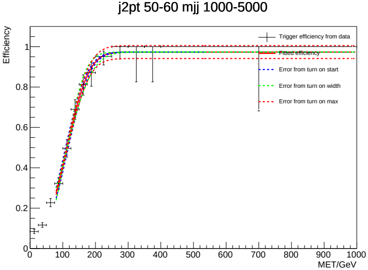






Selection Optimisation

- 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^{miss})	> 2.3

Systematic uncertainties

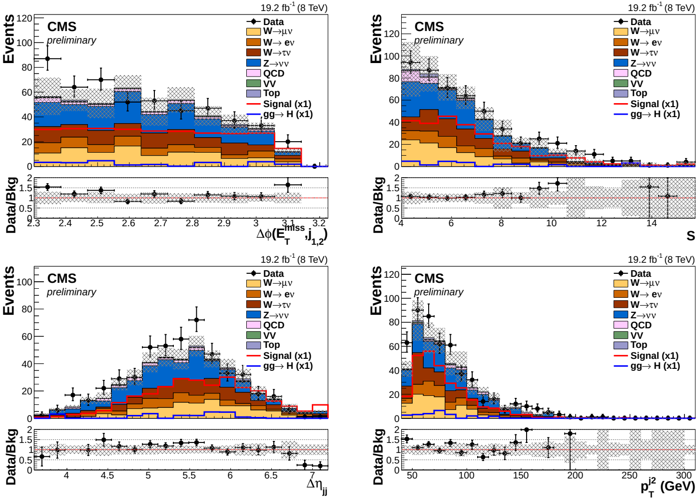
Source	Total background	Signal
Control region statistics	9.3	-
MC statistics	5.4	3.8
JES	4.6	11
$W \rightarrow \tau\nu$ control region extrapolation	4.3	-
QCD background estimation	3.2	-
JER	3.0	1.8
Lepton ID efficiency	2.4	-
UES	1.9	1.6
Pileup weight	1.1	1.5
Top MC scale factor unc.	0.25	-
Luminosity	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
$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
$W \to e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \to \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \to \tau\nu$	$94.6 \pm 13.1 \pm 23.8$
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

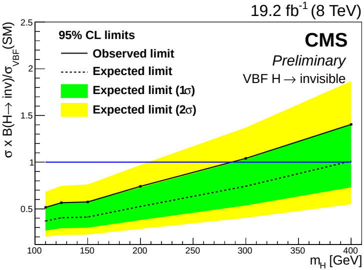
- Small 1 σ excess seen

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 $\mathcal{B}(H \rightarrow inv.)$ 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%

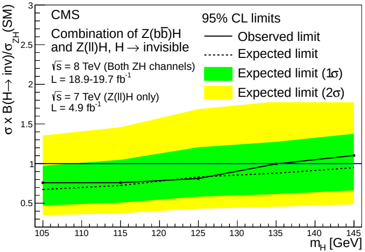


CMS-PAS-HIG-14-038

Other Run 1 analyses

Run 1 CMS direct searches - ZH

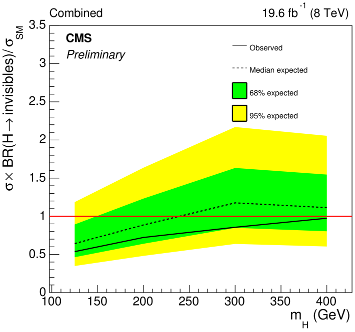
- Searches in $Z \to \ell\ell$ and $Z \to b\bar{b}$ channels
- $Z(\ell\ell)H$ search is a 2D shape analysis with data driven backgrounds
- $Z(b\bar{b})H$ search is a BDT shape analysis with data driven backgrounds
- Combined ZH searches observed (expected) limit on $\mathcal{B}(H \to inv.)$ for m_H =125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



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

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

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



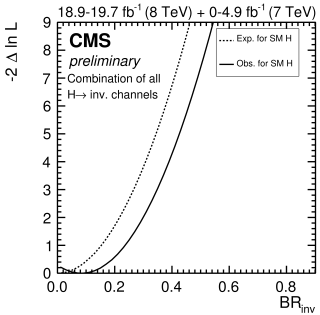
CMS-PAS-EXO-12-055

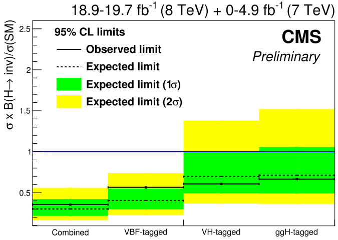
Combining

- 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 $Z(\ell\ell)H+Z(bb)H+V(had)H$, VBF-tagged is VBF
- Obs. (exp.) limit on $\mathcal{B}(H \to inv.)$ at m_H =125 GeV was 36 (30)%





CMS-PAS-HIG-15-012

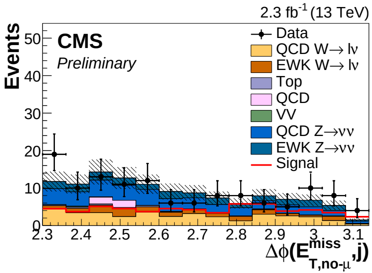
Run 2

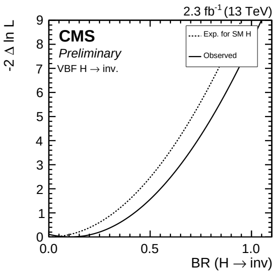
Run 2 CMS direct searches - VBF improvements

- 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 $\mathcal{B}(H \to inv.)$ for m_H =125 GeV is 69 (62)%

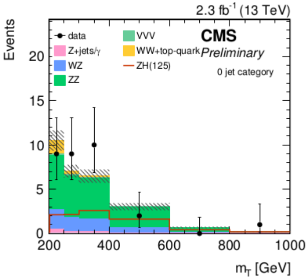


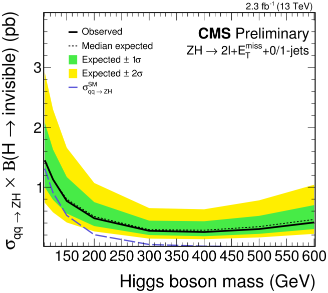


CMS-PAS-HIG-16-009

Run 2 CMS direct searches - ZH

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

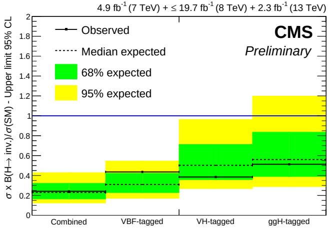


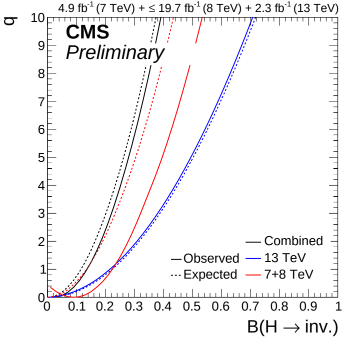


CMS-PAS-HIG-16-008

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) $\mathcal{B}(H \rightarrow inv.)$ limit for m_H =125 GeV is 24 (23)%

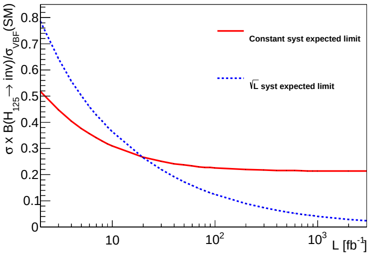




CMS-PAS-HIG-16-016

VBF analysis projections

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



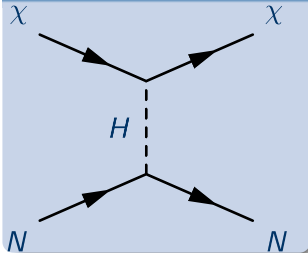
arXiv:1603.07739

Dark matter interpretations

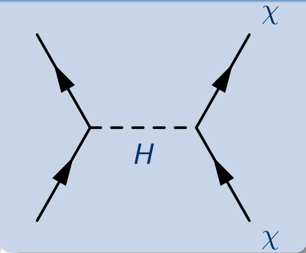
What does this mean for dark matter?

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

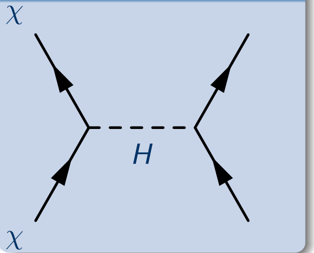
Direct Detection - e.g. LUX



Invisible Higgs - LHC



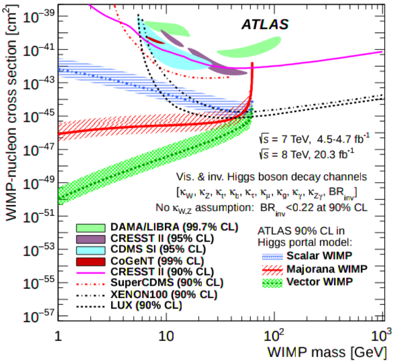
Annihilation - e.g. WMAP



- Limits on $\mathcal{B}(\mathrm{H}\to\mathrm{inv})$ 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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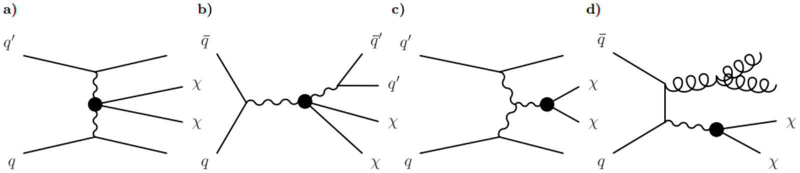
Dark matter interpretations - Projections

- 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 ‘simplified’ models with a scalar/pseudoscalar mediator
- Projections of CMS VBF channel sensitivity at several luminosities



arXiv:1603.07739

$$\mathcal{L}_{\mathrm{D5a}} \supseteq \frac{1}{\Lambda}[\bar{\chi}\chi]\left[\frac{Z_\mu Z^\mu}{2} + W^+_\mu W^{-\mu}\right],$$

$$\mathcal{L}_{\mathrm{D5b}} \supseteq \frac{1}{\Lambda}[\bar{\chi}\gamma^5\chi]\left[\frac{Z_\mu Z^\mu}{2} + W^+_\mu W^{-\mu}\right],$$

$$\mathcal{L}_{\mathrm{D5c}} \supseteq \frac{g}{\Lambda}[\bar{\chi}\sigma^{\mu\nu}\chi]\left[\frac{\partial_\mu Z_\nu - \partial_\nu Z_\mu}{\cos\theta_W} - ig\left(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu\right)\right],$$

$$\mathcal{L}_{\mathrm{D5d}} \supseteq \frac{g}{\Lambda}[\bar{\chi}\sigma_{\mu\nu}\chi]\,\epsilon^{\mu\nu\sigma\rho}\left[\frac{\partial_\sigma Z_\rho - \partial_\rho Z_\sigma}{\cos\theta_W} - ig\left(W^+_\sigma W^-_\rho - W^+_\rho W^-_\sigma\right)\right],$$

$$\mathcal{L}_{\mathrm{D6a}} \supseteq \frac{g}{\Lambda^2}\partial^\nu[\bar{\chi}\gamma^\mu\chi]\left[\frac{\partial_\mu Z_\nu - \partial_\nu Z_\mu}{\cos\theta_W} - ig\left(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu\right)\right],$$

$$\mathcal{L}_{\mathrm{D6b}} \supseteq \frac{g}{\Lambda^2}\partial_\nu[\bar{\chi}\gamma_\mu\chi]\,\epsilon^{\mu\nu\rho\sigma}\left[\frac{\partial_\sigma Z_\rho - \partial_\rho Z_\sigma}{\cos\theta_W} - ig\left(W^+_\sigma W^-_\rho - W^+_\rho W^-_\sigma\right)\right],$$

$$\mathcal{L}_{\mathrm{D7a}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\chi]\,W^{i,\mu\nu}W^i_{\mu\nu},$$

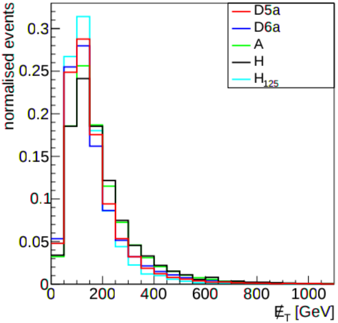
$$\mathcal{L}_{\mathrm{D7b}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\gamma^5\chi]\,W^{i,\mu\nu}W^i_{\mu\nu},$$

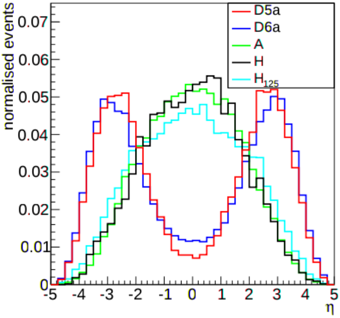
$$\mathcal{L}_{\mathrm{D7c}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\chi]\,\epsilon^{\mu\nu\rho\sigma}W^i_{\mu\nu}W^i_{\rho\sigma},$$

$$\mathcal{L}_{\mathrm{D7d}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\gamma^5\chi]\,\epsilon^{\mu\nu\rho\sigma}W^i_{\mu\nu}W^i_{\rho\sigma}.$$

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





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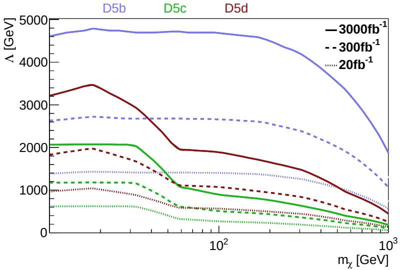
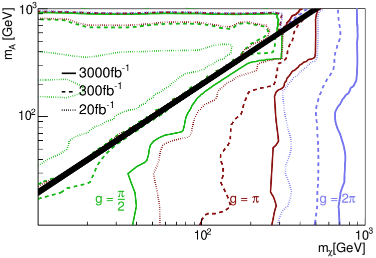
- Exclusion possible to several TeV for some models



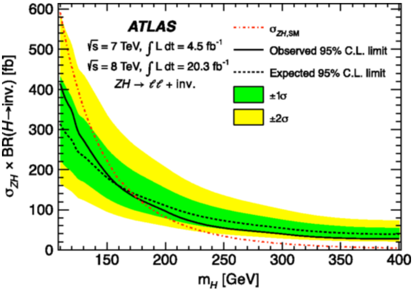


Summary

- 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 $\mathcal{B}(H \to inv.)$ ~10-20% 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

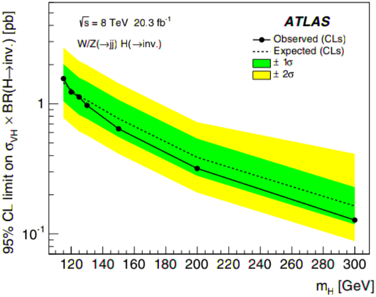
- Selects two leptons opposite large E_T^{miss}
- E_T^{miss} shape analysis with data driven backgrounds
- Observed (expected) limit on $\mathcal{B}(H \to inv.)$ for m_H =125.5 GeV is 75 (62)%



PRL 112, 201802 (2014)

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
$Z(\rightarrow \nu\nu)$+jets	339± 37	1580± 90	335±23
$W(\rightarrow \ell\nu)$+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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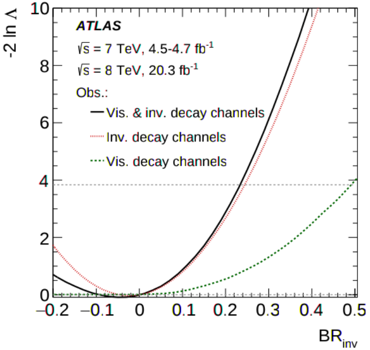
Run 1 ATLAS direct searches - Combination

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



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