Motivation

- Why the invisible final state?
- What are the main production modes?
- Main challenges?

CMS results

- Two new results, first out of two experiments
- Full Run 2 summary for VBF and ttH
- What are the latest conclusions?

ATLAS results

Future prospects

Conclusion

- Where are we now?
- Where can we be in a few years?
- What do we need to do to advance there?

Summary of the approach

- Run 1 + 2016 data
- Full Run 2 result for Z(II)H(inv.)

What about the HL-LHC?

Example using upgraded CMS detector
Motivation

- The “crown jewel” of the experimental particle physics:

  - Higgs boson was discovered by ATLAS and CMS experiments at CERN in 2012
  - All of the following measurements of its properties have shown a complete agreement with the Standard Model (SM)

- Large uncertainties of these measurements can allow for physics beyond the SM

- Why the interest in the invisible final state?

  - According to the SM, the probability of a Higgs decaying to something invisible to our detectors:
  - \( B(H \rightarrow 4\nu) \sim 0.1\% \):
  - Can represent a good way of testing for new physics at the LHC!
Motivation

- Invisible decays of the Higgs boson, as part of the “Higgs portal model” scenarios, are a good way of searching for new physics.
- Higgs boson could be a mediator between SM particles and ones that belong to the DM sector.
- Detection requires for the Higgs boson to recoil against a visible system:
  - $qqH$: Higgs boson is produced in a vector boson fusion topology (VBF).
  - $VH$: Higgs boson production with a vector boson ($V = Z$ or $W$).
  - $ggH$: Higgs boson produced via gluon fusion.
Motivation – VBF production mode

- Channel with the largest sensitivity

- Main characteristics of this category:
  - **Two jets** separated by a large $\eta$
  - **Large** dijet invariant mass ($m_{jj}$)

- Main SM backgrounds mimicking the signal:
  - **V+jets:** $W(l\nu)+$jets and $Z(\nu\nu)+$jets
  - Where the charged lepton is unidentified

- **V+Jets:** Dedicated **control regions** (CR) in data
  - Z or W boson associated with the same dijet topology
  - Resulting in four CRs separated by lepton flavor ($e/\mu$)
Motivation – VH production mode

- **monoV channel:**
  - Main characteristics:
    - Energetic jets due to V(qq)
    - An imbalance in MET due to undetected particles

- **monoJet channel:**
  - A jet originating from ISR
  - Interpreted as ggH production associated with one jet

- **Z(ll)H channel**
  - Main characteristics of this category:
    - The production of a pair of leptons
    - Originating from a Z boson, together with large MET
Motivation – VH production mode

- **monoV channel:**
  - Main characteristics:
    - Energetic jets due to $V(qq)$
    - An imbalance in MET due to undetected particles

- **monoJet channel:**
  - A jet originating from ISR
  - Interpreted as $ggH$ production associated with one jet

- **Z(ll)H channel**
  - Main characteristics of this category:
    - The production of a pair of leptons
    - Originating from a Z boson, together with large MET
CMS Results

- Latest results published using dataset collected in 2016 containing ~36fb-1 of data
- Includes the combination with Run 1 measurements!

Physics Letters B 793 2019
- 90% CL upper limits on the spin-independent DM-nucleon scattering cross section in Higgs portal models, assuming a scalar or fermion DM candidate.

Physics Letters B 793 2019
CMS Results

- Brand new result! Full Run 2 Z(\(l\)l)H(inv.)
- PAS is going to be available on CDS soon!

- Signature:
  - \(Z (l^+l^-), \) where \(l = e \) or \(\mu\)
  - Large MET

The observed (expected) 95% CL upper limit at \(m_H = 125\) GeV on \(B(H \to \text{invisible})\) is 29% (25%).
ATLAS Results

- Newly presented result – VBF full Run 2 result! – ATLAS-CONF-2020-008
- Improved categorization: 11 (new) vs 3 (old) bins
  - Optimized to select 50% more signal events

- Significant improvements to MC generation filtering
  - Bringing 3x as many events for a given CPU time
  - Reducing the MC statistical uncertainty

<table>
<thead>
<tr>
<th>Observed</th>
<th>Expected</th>
<th>+1σ</th>
<th>−1σ</th>
<th>+2σ</th>
<th>−2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.132</td>
<td>0.132</td>
<td>0.183</td>
<td>0.095</td>
<td>0.248</td>
<td>0.071</td>
</tr>
</tbody>
</table>

Vukašin Milošević (Imperial College London)  
DM@LHC 2020, 2.6.2020.
Upper limit on cross section times branching ratio to invisible particles for heavy scalar mediator particle as a function of its mass.

Upper limits on the spin-independent WIMP–nucleon cross section using Higgs portal interpretations of $B(\text{Hinv})$ at 90% CL vs. $m(\text{WIMP})$ (scalar or majorana).
Previous publications used the similar strategy as CMS when combining datasets

~36fb-1 of Run 2 data + Run 1

Comparison with CMS results: (Physics Letters B 793 2019)

ATLAS VBF Full Run 2
ATLAS Results

- New result – $ttH(\text{inv.})$ - ATLAS-CONF-2020-003
- BSM searches with top quark pairs in final state

- Exactly one isolated charged lepton ($e/\mu$)
  - Per decay of W boson,

- High-$p_T$ jets, and a large MET
  - Requiring existence of at least 2 b-jets
Future prospects

- VBF production mode presents the best sensitivity
  - Chosen to investigate the sensitivity of the search with the HL-LHC
- A high mj category was used for this study
  - Cut-and count approach
- The threshold on MET is varied from 130 to 400 GeV
  - Likewise, the lower threshold on Mjj is varied from 1000 to 4000 GeV
- Upper limits on the $B(H_{inv})$ are placed at the 95% CL using the CLs criterion
- Similar study by ATLAS for the VH mode:
  - $BR \sim 8\%$ (ATL-PHYS-PUB-2013-014)
Conclusion

- Interesting time for H->Inv. analyses
  - Both experiments are preparing the full Run 2 legacy results
  - Near future will bring even greater levels of sensitivity!

- Complementarity with other experiments, contributing to a clearer look at the “bigger” picture

- Preparations for the upcoming phases are well underway!
  - Exciting new possibilities for the analysis specific trigger algorithms
Thank you for your time!
Backup
Motivation – VBF production mode

- Channel with the largest sensitivity

- Main characteristics of this category:
  - Two jets separated by a large $\eta$
  - Large dijet invariant mass ($m_{jj}$)

- Main SM backgrounds mimicking the signal:
  - V+jets: $W(l\nu)+$jets and $Z(\nu\nu)+$jets
  - Where the charged lepton is unidentified

- Contribution from QCD multijet processes
- Diboson and top quark processes
  - Estimated from simulation

- V+Jets: Dedicated control regions (CR) in data
  - Z or W boson associated with the same dijet topology
  - Resulting in four CRs separated by lepton flavor ($e/\mu$)
- Fit performed in bins of the dijet mass
  - Taking the advantage of low mjj bins as well (more dominated with ggH signal)

- Connecting the CRs to the SR using the Transfer Factor approach

- $Z(\nu\nu)$ and $W(l\nu)$ normalization is estimated from a simultaneous CR+SR fit

- Dedicated CR region for QCD multijet estimation
Post-fit results of all SR and CR bins

- Using the Transfer Factor approach:
  \[ B_{W,i}^{SR} = B_{W,i}^{SR,MC} \cdot \frac{N_i^{W,CR} - B_{non-W,i}^{W,CR}}{B_{W,i}^{W,CR, MC}} \]
  \[ B_{Z,i}^{SR} = B_{Z,i}^{SR,MC} \cdot \frac{N_i^{Z,CR} - B_{non-Z,i}^{Z,CR}}{B_{Z,i}^{Z,CR, MC}} \cdot \beta_{Z,i} \]

- Simultaneous fit on the CRs and SR

- Correlation between systematics for SR and CRs (for each bin) leading to the cancellation of a number of them
Final VBF result using the full Run 2 dataset: **ATLAS-CONF-2020-008**

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Expected</th>
<th>(+1\sigma)</th>
<th>(-1\sigma)</th>
<th>(+2\sigma)</th>
<th>(-2\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.132</td>
<td>0.132</td>
<td>0.183</td>
<td>0.095</td>
<td>0.248</td>
<td>0.071</td>
</tr>
</tbody>
</table>
Fig. 4 Distribution of the $p_T^{\text{miss}}$ in the combination of the $ee$ and $\mu\mu$ channels after the full selection. The last bin also includes any events with $p_T^{\text{miss}} > 600\ GeV$. The uncertainty band includes both statistical and systematic components. The ZH(inv.) signal normalization assumes SM production rates and the branching fraction $B(H \rightarrow \text{inv.}) = 1$.
Table 3: The 95% CL upper limits on $B_{H \rightarrow \text{inv}}$ for $m_H = 125$ GeV from the $ee$, $\mu\mu$, and combined $ee + \mu\mu$ channels. Both the observed and expected limits are given, and the 1$\sigma$ and 2$\sigma$ uncertainties on the expected limits are also presented.

<table>
<thead>
<tr>
<th></th>
<th>Obs. $B_{H \rightarrow \text{inv}}$ Limit</th>
<th>Exp. $B_{H \rightarrow \text{inv}}$ Limit ±1$\sigma$ ±2$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>59%</td>
<td>(51$^{+21}<em>{-15}$ $^{+49}</em>{-24}$) %</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>97%</td>
<td>(48$^{+20}<em>{-14}$ $^{+46}</em>{-22}$) %</td>
</tr>
<tr>
<td>$ee + \mu\mu$</td>
<td>67%</td>
<td>(39$^{+17}<em>{-11}$ $^{+38}</em>{-18}$) %</td>
</tr>
</tbody>
</table>
CMS Results

PHYSICAL REVIEW D 97, 092005 (2018)
CMS PAS HIG-18-008

CMS Results

Vukašin Milošević (Imperial College London)

DM@LHC 2020, 2.6.2020.
New result – \( ttH(\text{inv.}) \) - ATLAS-CONF-2020-003

Study focused on BSM searches with top quark pairs in final state

- Requiring existence of at least 2 b-jets

\[ Z = \sqrt{2(n \ln \left[ \frac{n(b+\sigma^2)}{b^2+n\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[ 1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)} \right] )} \] when \( n \geq b \), or

\[ Z = -\sqrt{2(n \ln \left[ \frac{n(b+\sigma^2)}{b^2+n\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[ 1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)} \right] )} \] when \( n < b \).
Future prospects

- For the best case scenario: $B(H_{\text{inv}}) = 3.8\%$
- Goal - inclusion of ML based algorithms prepared for testing in Run 3
  - Production mode targeting triggers

CERN-LPCC-2018-04
Future prospects

- Predictions of the HL-LHC (right figure) limits from Hinv. searches with limits from DM direct detection experiments on the spin-independent DM-nucleon scattering cross section as a function of the DM mass.