Higgs → Invisible at the LHC

June 7th, 2021

Andreas Albert,
on behalf of the ATLAS and CMS collaborations
Why H(inv) at the LHC?

1. The SM has a precise prediction here, and we should test it

- H→ inv. tested ✓
- 2 orders of magnitude for possible surprises
- SM H→ inv. "neutrino floor"

(Visible modes already being tested to better precision)

2. Higgs portal DM could be hard to discover elsewhere

- H(H→ inv) < 0.16
- Details are model dependent
H(125) → invisible searches are driven by production modes

Search strategies are optimized by production mode

Main considerations: Trigger and background
→ Trade-off between production cross section and selection handles
  Note: direct searches assume SM H prod

Results for all channels exist, will focus on full Run-2 (~140fb⁻¹)
VBF
VBF H(inv) basics

Experimental signature for VBF H(inv) is jets + $p_T^{\text{miss}}$

→ Rely on $p_T^{\text{miss}}$-based trigger
$p_T^{\text{miss}} \approx p_T(H)$

Bulk of $p_T$ spectrum not triggered
→ Trigger is limitation for hadronic searches

(exact values depend on data set and experiment)

Main background from $Z(\nu\nu)$, $W(l\nu)\text{jets}$

VBF-like BG production
“EWK”

DY-like BG production
“QCD”

Jet properties allow to separate signal vs QCD BG,
but irreducible BG remains
VBF ATLAS: selection and categorization

Basic selection
- $p_T^{\text{miss}}$ trigger
- $p_T^{\text{miss}} > 200$ GeV

Leading jets:
- $p_{T,1/2} > 80 / 50$ GeV
- $\Delta\phi(j,j) < 2.0$
- $\eta_1 \times \eta_2 < 0$
- $\Delta\eta(jj) > 3.8$
- $m(jj) > 800$ GeV

Veto on extra photons, leptons etc

Final binning in $m_{jj}, \Delta\Phi_{jj}, N_{\text{jet}}$

Percentage = fraction of total signal
Darker color shade = higher S/B
ATLAS VBF fit and result

Maximum-likelihood fit

Signal region
- $Z(\nu\nu)$ yield freely floating per bin

Control regions
- $Z(ee), Z(\mu\mu)$
- $W(e\nu), W(\mu\nu)$

Transfer factors from MC ± unc

Commonly used fit strategy

BG shape and norm. from data, $2 \times N_{\text{bins}}$ unconstrained parameters, shared between DY and VBF production

→ many uncertainties cancel in ratio, especially theory

+ additional control samples for multijets

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VBF + photon (ATLAS)

Sibling to hadronic VBF analysis

Photon radiation off W defines signature, cuts down background significantly

Basic selection looser than hadronic VBF

- $p_T^{\text{miss}}$ trigger
- $p_T^{\text{miss}} > 150$ GeV
- $15 \text{ GeV} < p_T(\gamma) < 110$ GeV
- Photon not aligned with jet

Leading jets:

- $p_T,1/2 > 60 / 50$ GeV
- $\Delta \phi(j,j) < 2.5$
- $\eta_1 \times \eta_2 < 0$
- $\Delta \eta(j,j) > 3.0$
- $m(j,j) > 250$ GeV

Signal discrimination via deep neutral network training method optimizes for $H\rightarrow\text{inv}$ limit, taking into account approximate uncertainty from fit approach

BR($H\rightarrow\text{inv}) < 37\%$ (34% exp)
VH, ggH, ttH
Good Z(II) candidate lepton triggers, $p_T(l) > 25 \/ 20 \text{ GeV}$, $|m(ll) - m_Z| < 15 \text{ GeV}$

Moderate $p_T^{\text{miss}}$ $p_T^{\text{miss}} > 100 \text{ GeV}$

Z and $p_T^{\text{miss}}$ balanced, back to back $|p_T^{\text{miss}} - p_T^{\text{ll}}| / p_T^{\text{ll}} < 0.4$, $\Delta \phi(p_T^{\text{miss}}, p_T^{\text{ll}})$

SR binned in Njets → control DY + fake $p_T^{\text{miss}}$

$\text{BR}(H \rightarrow \text{inv}) < 25 \% (29\% \text{ exp})$

10.1140/epjc/s10052-020-08739-5

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Combined V(qq)H + ggH search (CMS)

Use neural network tagger to distinguish V(qq) from QCD fat jets
Generic “DeepAK8” tagger 10.1088/1748-0221/15/06/P06005

Fat jets
anti-kt R = 0.8

Fat jets

Inclusive common selection
$p_T^{miss}$ trigger
$p_T^{miss} > 250$ GeV
no leptons, photons

Mono-V: Target V(qq)H
fat jet pt > 250 GeV, $|\eta|<2.4$
jet mass window 65-120 GeV

Monojet:
captures ggH + ISR jet
narrow jet pt > 100, $|\eta| < 2.4$
→ 75% ggH, 20% VBF

one of three categories

(high-purity) 90% VH
(low-purity) 40% VH

(percentages of total signal)
Combined $V(qq)H + ggH$ search (CMS)

Fit strategy with additional $Z/W$ and $Z/\gamma$ transfer

- **Signal region**: $Z(\nu\nu)$
  - yield freely floating per bin
- **Control regions**: $Z(ee), Z(\mu\mu)$
- **Additional regions**: $\gamma$, $W(e\nu), W(\mu\nu)$

→ **Fewer free parameters** (= $1 \times N_{\text{bins}}$)

Cross-process theory uncertainty under control thanks to dedicated theory predictions
→ 10.1140/epjc/s10052-017-5389-1

Main uncs from lepton, photon reco, SR multijet

New analysis of 101 fb$^{-1}$ includes statistical comb. with 2016 result 10.1103/PhysRevD.97.092005

BR($H \rightarrow \text{inv}$) < 28 % (25% exp)
ATLAS ggH, ttH

**ggH from inclusive search in jets + p_T^{miss}**

**BR(H→ inv) < 34 % (39% exp)**

Similar approach to CMS monojet
total BG uncertainty ≈ 1.5 – 4.2 % (!)

**BR(H→ inv) < 40 % (36% exp)**

**ttH(inv) from reinterp. of tt+DM / stop searches**

Main sensitivity from top → leptons
use MT2 to separate ttbar vs ttbar + extra ptmiss

arXiv:2102.10874

June 7th, 2021
Combinations

Combinations are final endgame of H(inv) searches

CMS early Run-2 (2016) + 2015 + Run-1

*BR(H→ inv) < 19 % (15% exp)*

No full Run-2 VBF, ttH, combination, yet

ATLAS full Run-2 VBF + ttH + Run-1

*BR(H→ inv) < 11 % (11% exp)*

No full Run-2 VH, yet. Combination partial.

Significant additions still to come in both experiments

Expect to crack 10% threshold with Run-2 direct searches!

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Indirect constraints from coupling fits

Combination with visible channels can further tighten constraints indirectly

Need assumptions to limit total Higgs width, here $\kappa_W, \kappa_Z \leq 1$

Constraint from VBF already tightened to 9% here

Summary

- **H→ inv searches are well-motivated tests of SM + DM observation option**
- **Pursued in all production modes. Most sensitive: VBF**
  - Best single-channel result to date from ATLAS VBF: BR < 13%
- **Combinations including full Run-2 will probe ≈ 10% threshold**
  - Best partial combination so far from ATLAS: BR < 11%
- **Future sensitivity to be driven by VBF channel**
  - Statistical uncertainty still big → More data will help
  - Improvement fronts:
    - Cross-process transfer factors? → Battle theory uncertainties
    - Better triggers?
    - Ultimate limitations will be experimental:
      - Lepton, photon, QCD multijet estimation precision
- **Indirect constraints can further strengthen exclusion**
  - current best BR < 9%
## Summary of results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channel</th>
<th>Expected</th>
<th>Observed</th>
<th>Full Run-2 included?</th>
<th>Reference</th>
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<tbody>
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<td>ATLAS</td>
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<td>0.13</td>
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<td>✓</td>
<td>arxiv:2102.10874</td>
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<td>V(qq)H</td>
<td>0.58</td>
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<td>10.1007/JHEP10(2018)180</td>
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<td>10.1016/j.physletb.2017.11.049</td>
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<td>0.40</td>
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<td>0.11</td>
<td>0.11</td>
<td>✓</td>
<td>ATLAS-CONF-2020-052</td>
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<td>CMS</td>
<td>VBF</td>
<td>0.25</td>
<td>0.33</td>
<td>2016 only</td>
<td>10.1016/j.physletb.2019.04.025</td>
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<td></td>
<td>ggH + V(qq)H</td>
<td>0.25</td>
<td>0.28</td>
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<td>CMS-PAS-EXO-20-004</td>
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<tr>
<td></td>
<td>Z(II)H</td>
<td>0.25</td>
<td>0.29</td>
<td>✓</td>
<td>10.1140/epjc/s10052-020-08739-5</td>
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<td>Combination</td>
<td>0.15</td>
<td>0.19</td>
<td>up to 2016</td>
<td>10.1016/j.physletb.2019.04.025</td>
</tr>
</tbody>
</table>
Constraints from Higgs property grand combinations

**Grand combinations** of measurements in different Higgs modes are used to set constraints on generic coupling modifiers (See e.g. arxiv:1307.1347 for details on framework)

Most recent result from ATLAS includes VBF H(inv) full Run-2 result to constrain BR(H→ inv)

Without assumption on total H width, cannot further constrain H→ inv here

If one assumes $\kappa_W, \kappa_Z \leq 1$, total H width is limited, and H(inv) constraint tightens to 9% already
Backup: ATLAS VBF analysis
Jet binning

Main analysis focus on 2-jet events. Events with 3-4 jets are in separate bin.
Extra selection requirements aimed to identify whether extra jets are consistent with radiation

$$C_i = \exp \left( -\frac{4}{(\eta^{i1} - \eta^{j2})^2} \left( \eta^i - \frac{\eta^{j1} + \eta^{j2}}{2} \right)^2 \right)$$

$$m_{i\text{rel}} = \frac{\min\{m_{j1,i}, m_{j2,i}\}}{m_{jj}}$$

C small → extra jet is far in $\eta$ from average of leading jets

$m$ small → jet is FSR-like

Require $C_i < 0.6$, $m_{i\text{rel}} < 0.05$ for 3rd, 4th jet if present
(a jet is counted if $p_T > 25$ GeV)
VBF: Electron fakes

Goal: estimate events with fake electrons in W CR

Method: Add additional Fake-e CR to the fit same as regular Weν, but with inverted $p_T^{miss}$ significance $S_{MET} \rightarrow$ enriched in fakes

Transfer factor from low $S_{MET} \rightarrow$ high $S_{MET}$ from sample with inverted ele ID
SR Multijet estimate

Goal: estimate multijet events in SR

Estimation via "rebalance and smear":
- Obtain inclusive multijet sample from single jet triggers
- Rebalance = Vary jet momenta within uncertainties to minimize $p_T^{\text{miss}}$
- Smear = generate toy events by smearing rebalanced jets many times → Apply SR selection on toy events
- Estimate done separately for events with ("Hard scatter + pile-up") and without jets failing vertex assignment ("Hard scatter only")
SR Multijet estimate: Validation + uncertainty

Validate estimate in SR-adjacent validation regions

Average template normalization factor from both regions propagated to SR

Half difference of normalization factors used as non-closure uncertainty, which is dominant effect

<table>
<thead>
<tr>
<th>Period</th>
<th>Event yield</th>
<th>stat.</th>
<th>non-closure $\Delta \phi_{jj} &lt; 1$</th>
<th>non-closure $1 &lt; \Delta \phi_{jj} &lt; 2$</th>
<th>JER core</th>
<th>JER tail</th>
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<tbody>
<tr>
<td>2015+16</td>
<td>85</td>
<td>10%</td>
<td>100%</td>
<td>100%</td>
<td>35%</td>
<td>18%</td>
</tr>
<tr>
<td>2017</td>
<td>231</td>
<td>8%</td>
<td>72%</td>
<td>47%</td>
<td>19%</td>
<td>3%</td>
</tr>
<tr>
<td>2018</td>
<td>289</td>
<td>9%</td>
<td>32%</td>
<td>62%</td>
<td>22%</td>
<td>5%</td>
</tr>
</tbody>
</table>
Likelihood function

Freely floating scaling factors $\beta$ are common for given process in all regions → Ratio of $Z(SR)/Z(CR)$ is as predicted from MC, modulo constrained uncertainties same for $W$

$$\mathcal{L}(\mu, \tilde{\beta}_Z, \tilde{\beta}_W, \tilde{n}_{\text{fake}}, \tilde{\theta}) = \prod_i \mathcal{P}
\left( N_{Z_i}^{SR} \mid \beta_{Z_i} \cdot B_{Z_i}^{SR,MC} + \beta_{W_i} \cdot B_{W_i}^{SR,MC} + B_{SR,\text{MJ},i} + B_{SR,\text{other},i} + \mu \cdot S_i^{SR,MC} \right)
\prod_i \mathcal{P}
\left( N_{Z_i}^{CR} \mid \beta_{Z_i} \cdot B_{Z_i}^{Z,C,R,MC} + B_{Z_i}^{Z,C,R,\text{non-Z},i} \right)
\prod_i \mathcal{P}
\left( N_{W_i}^{\mu\nu CR} \mid \beta_{W_i} \cdot B_{W_i}^{W,\mu\nu CR,MC} + B_{W_i}^{W,\mu\nu CR,\text{non-W},i} \right)
\prod_i \mathcal{P}
\left( N_{W_i}^{\text{We},\nu CR} \mid \beta_{W_i} \cdot B_{W_i}^{\text{We},\nu CR,MC} + B_{W_i}^{\text{We},\nu CR,\text{non-W},i} + R_{S,i} \cdot n_{\text{fake},i} \right)
\prod_i \mathcal{P}
\left( N_{\text{fake-e} CR} \mid \beta_{W_i} \cdot B_{W_i}^{\text{fake-e} CR,\text{MC}} + B_{W_i}^{\text{fake-e} CR,\text{MC},\text{non-W},i} + n_{\text{fake},i} \right)
\prod_j \mathcal{G}(0|\theta_j),$$

Ratio of $Z/W$ freely determined from data
### Simulation samples

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>ME Order</th>
<th>PDF</th>
<th>Parton Shower</th>
<th>Tune</th>
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</thead>
<tbody>
<tr>
<td>Strong V+jets</td>
<td>SHERPA v2.2.1, SHERPA v2.2.7 (m_{jj}-filtered)</td>
<td>NLO (up to 2-jets), LO (up to 4-jets)</td>
<td>NNPDF3.0nnlo</td>
<td>SHERPA</td>
<td>MEPS@NLO</td>
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<tr>
<td>Electroweak V+jets</td>
<td>SHERPA v2.2.1 reweighted by HERWIG 7 in m_{jj}</td>
<td>LO (up to 4-jets), NLO (reweighting)</td>
<td>NNPDF3.0nnlo</td>
<td>SHERPA</td>
<td>MEPS@LO</td>
</tr>
<tr>
<td>VV+jets (including gg → VV+jets)</td>
<td>SHERPA v2.2.1 or SHERPA v2.2.2</td>
<td>NLO (up to 1-jet), LO (up to 3-jets)</td>
<td>NNPDF3.0nnlo</td>
<td>SHERPA</td>
<td>MEPS@NLO</td>
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<tr>
<td>Electroweak VV+jets</td>
<td>SHERPA v2.2.1 or SHERPA v2.2.2</td>
<td>LO</td>
<td>NNPDF3.0nnlo</td>
<td>SHERPA</td>
<td>MEPS@LO</td>
</tr>
<tr>
<td>V+jets $\alpha_{ew}^3$ interference</td>
<td>MadGraph5_aMC@NLO</td>
<td>LO</td>
<td>PDF4LHC15</td>
<td>PYTHIA8</td>
<td></td>
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<tr>
<td>tt</td>
<td>POWHEGBox v2</td>
<td>NLO</td>
<td>NNPDF3.0nnlo</td>
<td>PYTHIA8</td>
<td>A14</td>
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<td>QCD multijet</td>
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<td>LO</td>
<td>NNPDF2.31o</td>
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<td>ggF Higgs</td>
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<td>VBF Higgs</td>
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<td>VH Higgs</td>
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<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA8</td>
<td>AZNLO</td>
</tr>
</tbody>
</table>
Direct detection comparison

$B_{\text{inv}} < 0.11$

All limits at 90% CL

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

Higgs Portal
Scalar WIMP
Majorana WIMP
Other experiments
DarkSide-50
LUX
PandaX-II
Xenon1T

$\sigma_{\text{WIMP-nucleon}}$ [cm$^2$]

$m_{\text{WIMP}}$ [GeV]
Backup: ATLAS VBF + photon analysis
Selection

Photon centrality requirement favors photons close to average $\eta$ of jets

$$C_Y = \exp\left(-\frac{4}{(\eta_1 - \eta_2)^2} (\eta_Y - \frac{\eta_1 + \eta_2}{2})^2\right).$$

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR</th>
<th>$W^\gamma_{\mu\nu}$ CR</th>
<th>$W^\gamma_{e\nu}$ CR</th>
<th>$Z^\gamma_{\text{Rev.Cen.}}$ CR</th>
<th>Fake$-e$ CR</th>
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<tr>
<td>$p_T$ ($j_1$) [GeV]</td>
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<td>$N_{\text{jet}}$</td>
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<tr>
<td>$\Delta\phi_{jj}$</td>
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<td>$</td>
<td>\Delta\eta_{jj}</td>
<td>$</td>
<td></td>
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<tr>
<td>$\eta(j_1) \times \eta(j_2)$</td>
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<td>$C_3$</td>
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<td>$m_{jj}$ [TeV]</td>
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<td>$E^\text{miss,lep-rm}_{T}$ [GeV]</td>
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<td>&gt; 150</td>
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<tr>
<td>$E^\text{jets,no-jvt}_{T}$ [GeV]</td>
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<td>&gt; 15, &lt; 15, &lt;max(110, 0.733 x m_T)</td>
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<td>$\Delta\phi(\gamma, E^\text{miss,lep-rm}_{T})$</td>
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<td>$p_T$ ($\ell$) [GeV]</td>
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<td></td>
<td></td>
<td></td>
<td>&gt; 30</td>
</tr>
</tbody>
</table>

June 7th, 2021

A. Albert - H(inv) @ ATLAS, CMS
Neural network

Three hidden layers + input feature pass through
ReLU → ReLU → ReLU → Sigmoid
training with dropout + batch norm.

Train in epochs with standard binary cross-entropy loss on loosened phase space

After every epoch, evaluate approximate signal significance measure
keep epoch weight effect only if significance increases

\[ \mathcal{E}^{-1} = \sqrt{\sum_{i \in \text{bins}} \mathcal{E}_i^{-2}}, \quad \mathcal{E}_i = 2 \sqrt{b_i + \left( b_i^{V\gamma} \cdot \frac{\sqrt{d_i(CR) + \sum_{j \in \text{ev}} w_{i,j}(CR)}}{b_i^{V\gamma(CR)}} \right)^2 + \sum_{j \in \text{ev}} w_{i,j}^2} \]

b = background
d = data
s = signal
w = MC weights
Fake estimate

jet → γ fake

e → γ fake

ABCD in photon ID/iso plane:

\[ A = B \times C / D \]

+ correlation corr from MC

fake rate determined in \( Z \rightarrow ee \) events (tag & probe)

fake rate from 1.5 – 9% (depends on \(|\eta|, p_T\))

applied to events from CR in which photon replaced by electron

total uncertainty is 30% at low \( p_T \), 15% at high \( p_T \)
Backup: CMS $V(qq)H + ggH$
Categorization

Categorization is two-dimensional

Events failing mono-V selection
go to monojet category
(also if no fat jet found in event)
Backup: ATLAS ttH
ATLAS ttH dileptonic

\[ m_{T2}(p_{T,1}, p_{T,2}, p_{T}^{\text{miss}}) = \min_{q_{T,1} + q_{T,2} = p_{T}^{\text{miss}}} \left\{ \max \left[ m_T(p_{T,1}, q_{T,1}), m_T(p_{T,2}, q_{T,2}) \right] \right\} \]

\( p_{T,i} \) are known charged lepton momenta
\( q_{T,i} \) are unknown neutrino momenta

SM background with W decays has kinematic endpoint at \( m_W \) (washed out here)

High-MT2 populated by processes with additional \( p_T^{\text{miss}} \), such as ttZ or ttH(inv)

BG shape from MC, norm from tt and ttZ CRs
ATLAS monojet

**Signal Region**

\[ p_T(j) > 150 \text{ GeV} \]

**Control regions**

- **Z(\nu\nu)** overall norm. freely floating
- **W(l\nu)**
- **Z(\ell\ell)** same as for **W → e\nu**
- **W(e\nu)**, **W(\mu\nu)** same as for **W → e\nu**
- **top**
- **top(1l) + b**