# Search for VBF Higgs Production in the H $\rightarrow$ Invisible Channel

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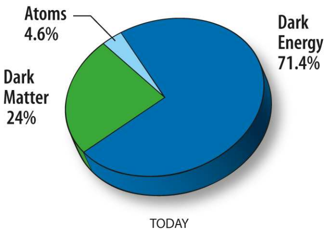
# Motivation

- Solve an astrophysical problem with particle physics
- There is a discrepancy between the mass of astronomical objects from gravitational effects and mass calculated from luminous matter – Dark Matter
- If dark matter interacts weakly then it could couple to the Higgs.
- The Higgs was discovered in 2012 by ATLAS and CMS with a mass of 125GeV
- The branching fraction could be substantial if $m_{DM} < m_H/2$
  - Experimental dark matter evidence indicates low mass DM candidates



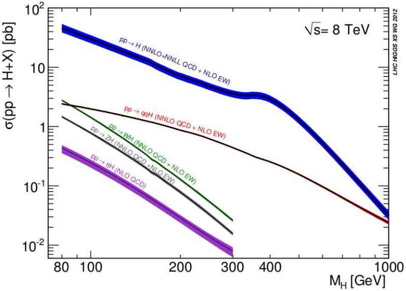
# Dark Matter Candidate – LSP

- Neutralino is the favored possibility
  - In MSSM there are 4 neutralinos that have no charge and are fermions.
  - Mixtures of superpartners of gauge fields (Binos, Winos and Higgsinos)
  - Only stable if R-parity is conserved, otherwise it can decay to charged particles
- Sneutrino is ruled out because it interacts with the Z which hasn't been observed
- Gravitino is also ruled out because the relevant models have a low scale of supersymmetry breaking (100TeV) which makes the the mass too low (order eV) for direct thermal production to be efficient

# Vector Boson Fusion

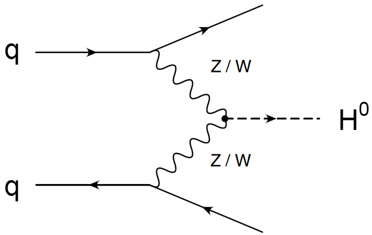
- The Higgs was discovered through the gluon-gluon fusion production mode
- Trigger and background make this mode impossible for H $\rightarrow$ Invisible
- VBF has the next highest cross section and is possible to tag events

- Since the Higgs production cross section will in general not be modified, the constraint will be placed on BR to invisible assuming Standard Model production.



# VBF Signature

- It is kinematically favored for the final state jets to point towards the beamline.
- There is no color flow from the initial quarks (radiation of color singlets)... central jet activity is suppressed.
- Analysis only has sensitity to high MET which is equivalent to a high $p_T$ Higgs.
  - As a result we will use a missing energy trigger (EF_xe80_tclcw_loose) as a baseline



# Event Selection

- Trigger on xe80_tclcw_loose
- MET Ref Final $> 150$GeV
- Lepton veto (currently done by rejecting non-zero MET_RefEle_et, MET_RefMuon_et, MET_MuonBoy_et, MET_RefTau_et)
- Leading jet $p_T > 75$GeV
- Subleading jet $p_T > 50$GeV
- $m_{jj} > 1$TeV
- Leading and subleading jets in opposite hemispheres
- $\Delta\eta(jet0, jet1) > 4.8$
- $\Delta\phi(jet0, jet1) < 2.5$
- $\Delta\phi(MET, anyjet) > 1.6$ (avoids jet mismeasurement)
- No 3rd jet with $p_T > 30$GeV and $\eta < 5$
- No b-tagged jets

# Backgrounds

- $Z$+jets ($Z \rightarrow \nu\nu$): It is rare for the jets to have such a large gap in pseudorapidity.
- $W$+jets ($W \rightarrow l\nu$ with lost lepton): Loose lepton veto helps rejects these events.
- QCD dijet: Gets into the signal region if there is fake MET from mismeasured jets
- $t\bar{t}$ ($t \rightarrow Wb$, $W \rightarrow l\nu$ with lost lepton): B tag veto will help reduce this background
- Electroweak VBF $Z$ ($Z \rightarrow \nu\nu$): Irreducible

Control regions will be needed to estimate the dominant backgrounds to reduce systematics from Monte Carlo.

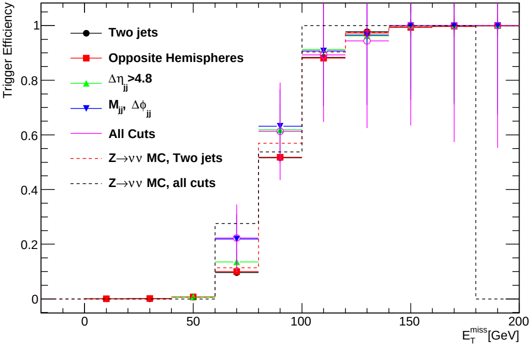
# Control and Validation Regions

- Leptons
  - $Z \to ll$
    - Used to estimate $Z \to \nu\nu$
  - $W \to l\nu$
    - Used to estimate case where lepton is lost
- Multijet
  - QCD Control region: Central jet veto reversed, $\Delta\phi$(MET, any jet) $< 1$, 4th jet veto
    - This is especially important since we don't have enough Monte Carlo statistics!
  - Small $\Delta\eta$: $\Delta\eta < 3.8$
    - Validation region for W and Z background normalization

# Z+jets Control Region Definition

- Single lepton trigger
  - electron: EF_e24vhi_medium1 or EF_e60_medium1
  - muon: EF_mu24i_tight or EF_mu36_tight
  - Trigger matching required
- Exactly 2 electrons or muons with $p_T > 20$GeV
- Opposite sign and leading lepton with $p_T > 30$GeV
- Emulated MET $> 150$GeV
  - Add lepton $p_T$ values to trigger MET.
- Leading jet $p_T > 75$GeV, subleading jet $p_T > 50$GeV
- $m_{jj} > 1$TeV
- Jets in opposite hemispheres
- $\Delta\eta(jet0, jet1) > 4.8$
- $\Delta\phi(jet0, jet1) < 2.5$
- $\Delta\phi(MET, anyjet) > 1.6$
- Central jet veto for jets with $p_T > 30$GeV and $\eta < 5.0$
- Veto b-jets

# Trigger Efficiency with Emulation




- Solid lines are different points in the cutflow for $Z \to ee$ emulating $Z \to \nu\nu$

# Alternative Z+jets Estimate using $\gamma$+jets

- Look at events that trigger EF_g20_loose, EF_g40_loose, EF_g60_loose, EF_g80_loose, EF_g100_loose, EF_g120_loose
- Find corresponding trigger and weight according to trigger prescale: The event rate is too high for the trigger to keep all events passing the photon triggers, so each one is scaled to keep a certain fraction of the events.
- Subtract Monte Carlo photon backgrounds
- Reweight $p_T$ distribution to the Z $p_T$
- Add photon $p_T$ to MET to create an "emulated MET"
- Apply signal region cuts

# W+jets Control Region Definition

- Single lepton trigger
  - electron: EF_e24vhi_medium1 or EF_e60_medium1
  - muon: EF_mu24i_tight or EF_mu36_tight
  - Trigger matching required
- Exactly 1 electron or muon with $p_T > 20$GeV
- Emulated MET $> 150$GeV
  - Add lepton $p_T$ value to trigger MET.
- $m_T > 40$GeV
- Leading jet $p_T > 75$GeV, subleading jet $p_T > 50$GeV
- $m_{jj} > 1$TeV
- Jets in opposite hemispheres
- $\Delta\eta(jet0, jet1) > 4.8$
- $\Delta\phi(jet0, jet1) < 2.5$
- $\Delta\phi(MET, anyjet) > 1.6$
- Central jet veto for jets with $p_T > 30$GeV and $\eta < 5.0$
- Veto b-jets

# Using the W+jets Control Region

There are a couple of complications with using the W+jets control region in the same way as the Z+jets.

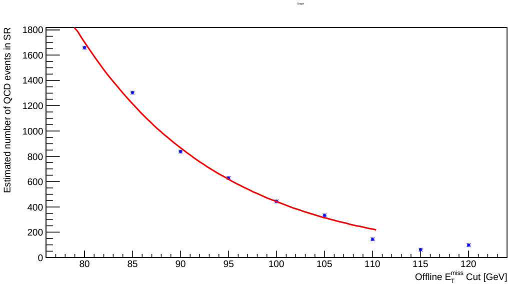
- After all cuts there will be a contamination by QCD events with a jet misidentified as a lepton.
  - An anti-isolated W$\rightarrow l\nu$ is used to determine the shape
- The lepton veto preferentially rejects where the W has large $p_T$ which sculpts the MET
- The lepton requirement for the W+jets control region favors a W with large $p_T$
- In order to solve this there is a boosting procedure:
  - The z component of the neutrino is solved assuming the W mass (lower value taken)
  - In the W rest frame the decay products are replaced by a randomly generated W decay assuming a uniform angular distribution of lepton/neutrino (doesn't account for W spin)
  - Decay products are then boosted back to the lab frame

# QCD Control Region Definition

- Trigger on xe80_tclcw_loose
- MET Ref Final $> 150$GeV
- Lepton veto (currently done by rejecting non-zero MET_RefEle_et, MET_RefMuon_et, MET_MuonBoy_et, MET_RefTau_et)
- Leading jet $p_T > 75$GeV
- Subleading jet $p_T > 50$GeV
- $m_{jj} > 1$TeV
- Leading and subleading jets in opposite hemispheres
- $\Delta\eta(jet0, jet1) > 4.8$
- $\Delta\phi(jet0, jet1) < 2.5$
- Require 3rd jet with $p_T > 30$GeV
- $\Delta\phi(MET, anyjet) < 1.0$
- Veto events with 4th jet
- No b-tagged jets

# Using the QCD Control Region

- Previous plan: Use the QCD control region to extrapolate to jet $p_T < 30\text{GeV}$
  - Statistics were limited after MET cut, but using the $p_T$ distribution before MET cuts depends on shape being the same. Results in $\approx 12$ events.
- New plan: The QCD control region yield is used with varying MET cuts to extrapolate to the signal region requirement (150GeV). Results in $\approx 14$ events.



# Other Backgrounds

- Monte Carlo will be used for the top production since it is expected to be small
- Same for electroweak VBF Z production since it is irreducible
  - However, when the $\gamma$+jet method is implemented this will accounted (relative strength of WW$\gamma$ and WWZ will have to be considered)

# Example Cutflow

| Cut | Signal ($m_H = 125$ GeV) | $Z \rightarrow \nu\nu$+jets | $W$+jets | Dijets | Other BGs |
|---|---|---|---|---|---|
| $p_T^{j1,j2}$ | 5358 $\pm$ 163 | 254339 $\pm$ 1970 | 250136 $\pm$ 1189 | 8251337 $\pm$ 676723 | 3749 $\pm$ 42.6 |
| Opp. Hemispheres | 3417 $\pm$ 116 | 110306 $\pm$ 1268 | 93944 $\pm$ 668 | 3747722 $\pm$ 465895 | 1191 $\pm$ 24.8 |
| $\Delta\eta_{jj} > 4.8$ | 625 $\pm$ 34.1 | 2459 $\pm$ 227 | 2511 $\pm$ 138 | 186420 $\pm$ 115811 | 32.3 $\pm$ 4.68 |
| $m_{jj}$ >1 TeV | 556 $\pm$ 32.9 | 1756 $\pm$ 182 | 2124 $\pm$ 125 | 86998 $\pm$ 72528 | 27.4 $\pm$ 4.49 |
| $\Delta\phi_{jj} < 2.5$ | 506 $\pm$ 31.5 | 1344 $\pm$ 163 | 1552 $\pm$ 109 | 4633 $\pm$ 3678 | 17.2 $\pm$ 2.60 |
| Jet Veto | 430 $\pm$ 26.0 | 926 $\pm$ 194 | 743 $\pm$ 78.8 | - | 1.25 $\pm$ 0.66 |
| $\Delta\phi_{j,MET} > 1$ | 425 $\pm$ 25.9 | 903 $\pm$ 189 | 730 $\pm$ 78.4 | - | 1.25 $\pm$ 0.66 |
| $E_T^{miss} > 150$ GeV | 217 $\pm$ 21.0 | 327 $\pm$ 112 | 153 $\pm$ 31.7 | - | 0.52 $\pm$ 0.50 |

# Plans

- All of the cuts used in the signal region are preliminary and have not been optimized, many of them are too tight
  - Having both an $m_{jj}$ requirement and opposite hemispheres is redundant
- Many steps of the analysis still need refinement
- Using W charge asymmetry for an additional handle on W+jets background
- Investigate various aspects of Monte Carlo modeling
  - Generator dependencies, PDFs, etc
- $\gamma + jet$ Method
- QCD smearing
- Detector systematics
  - Jet energy scale, MET, electron resolution, muon scale, etc.