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Bundesministerium
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Physics
Institute III B

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# Search for additional Higgs bosons in WW final states with CMS

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28.11.2017

# Introduction: 2HDM

- The Two Higgs Doublet Model (2HDM) is an extension of the SM, where we have two Higgs doublets
  - 5 Higgs bosons are predicted: h, H, A, $H^{+/-}$

- In 2HDM, two of many free parameters of interest are:
  - α: mixing angle between h and H
  - tanβ: ratio of the two doublets' VEVs: $v_u/v_d$

# Introduction: MSSM



- The MSSM is a type-II 2HDM

  → up-type quarks couple to one doublet;

  down-type quarks and charged leptons couple to the other

- In MSSM, benchmark scenarios are used to set meaningful values to most free parameters

  → 2 free parameters remain

- These two parameters are $m_A$ and tanβ

# MSSM limits from Run 1

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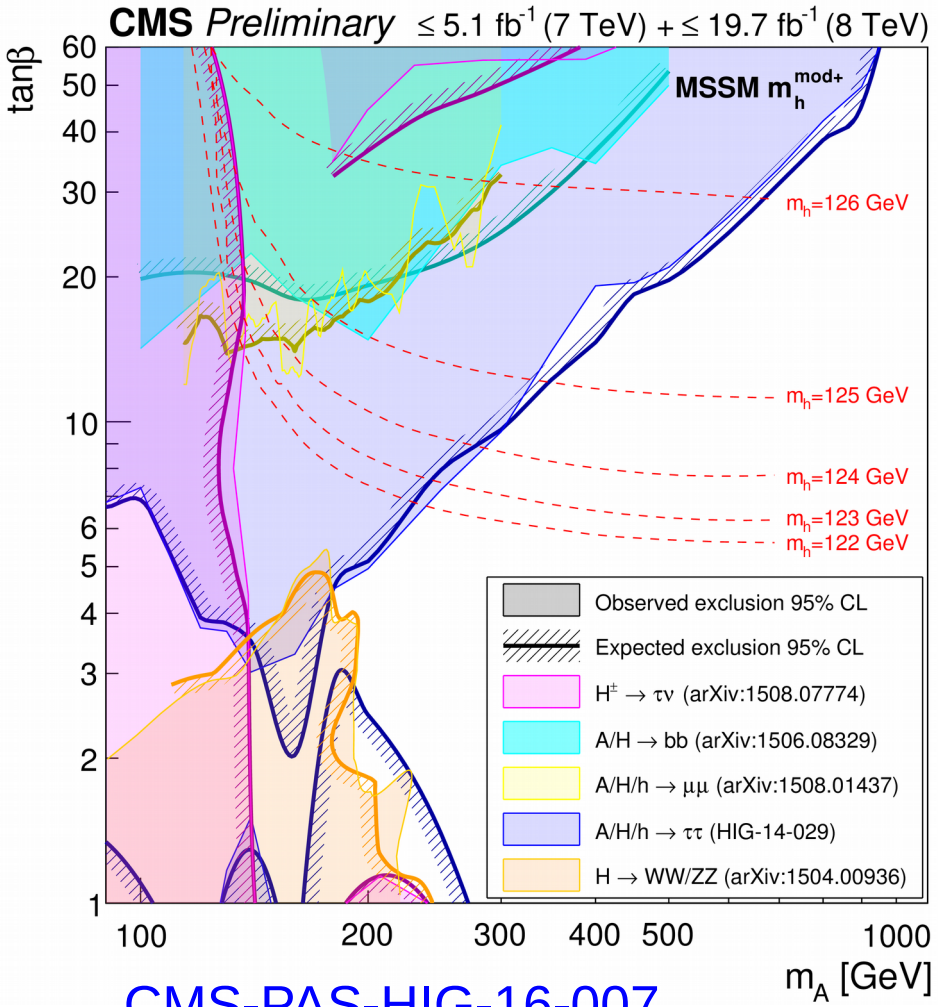
- **H** → WW/ZZ channel (orange) is more sensitive at low $m_A$ and tanβ
- Out of the three neutral MSSM Higgs bosons, only **H** is considered
  - theoretical uncertainty of **h** is too large
  - **A** does not couple to VV

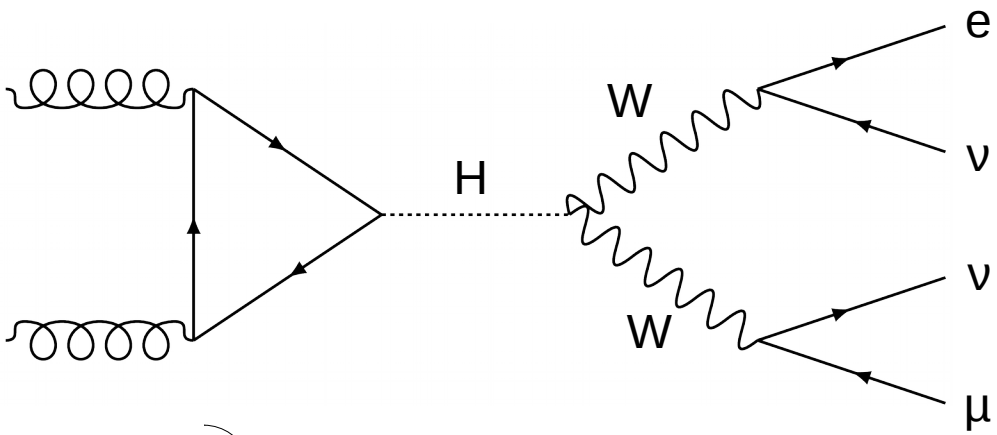



CMS-PAS-HIG-16-007

# Analysis strategy



- Currently, only the ggH → WW → eμ final state is considered



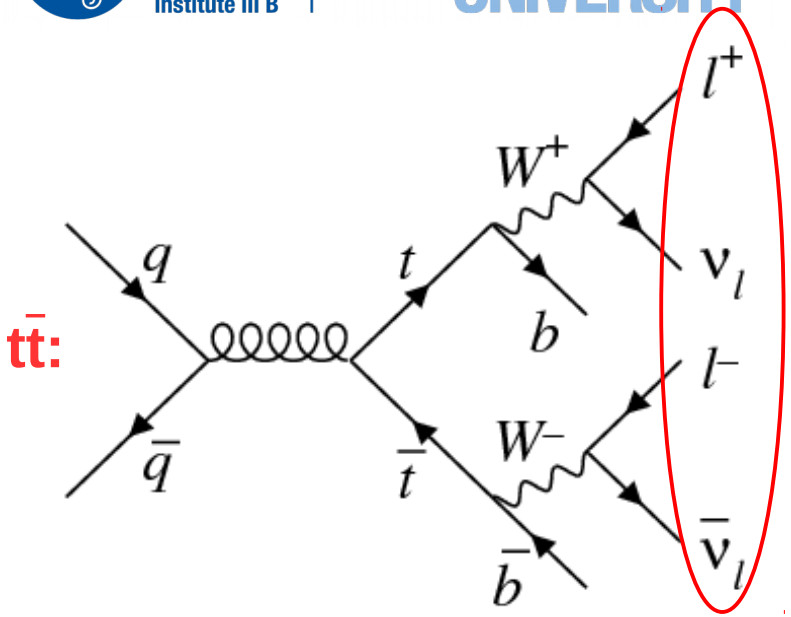

- Categorization:
  - 0 jet
  - 1 jet
  - 2 jet & ($\Delta\eta_{jj} < 3.5$ || $m_{jj} < 500$ GeV)

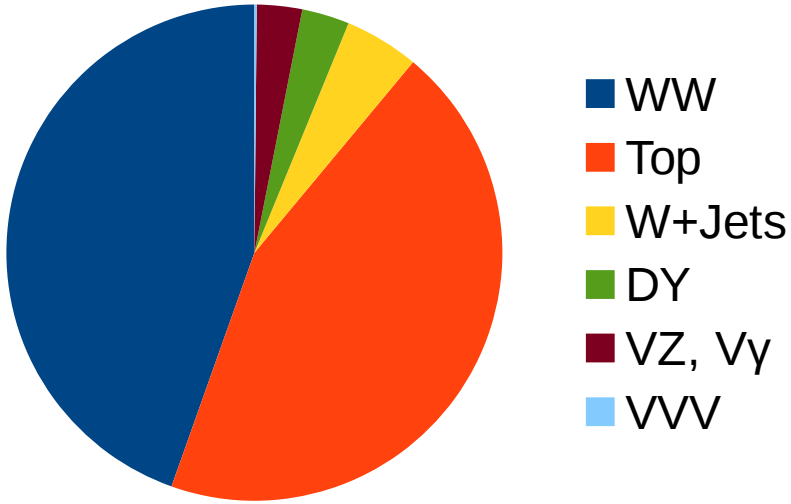
A jet is defined to have $p_T > 30$ GeV

- Addition of VBF production & category is planned
  - 2 jet & ($\Delta\eta_{jj} > 3.5$ & $m_{jj} > 500$ GeV)

# Backgrounds

- Main background processes:
  - WW
  - Top ($t\bar{t}$ & tW)
- Non-dominant backgrounds:
  - W+Jets
  - DrellYan ($Z \rightarrow \tau\tau$)
  - VZ, Vγ
  - VVV

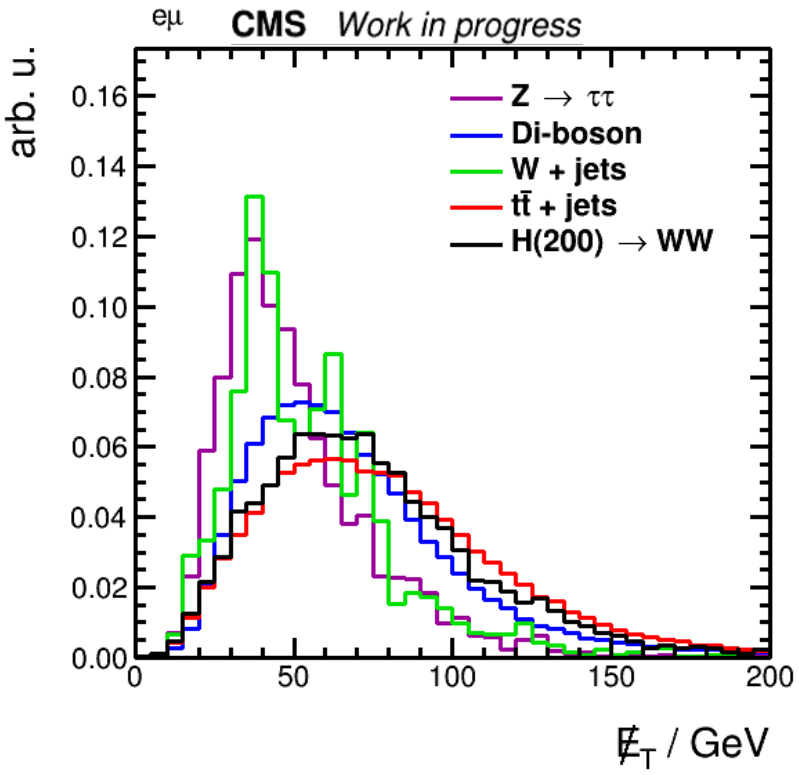


# Selection criteria

- Cuts are applied to reduce background processes
- Most cuts are the same as those used by the H → WW high mass search
  - Stronger cut chosen for $E_T^{miss}$

$E_T^{miss} > 40$ GeV:



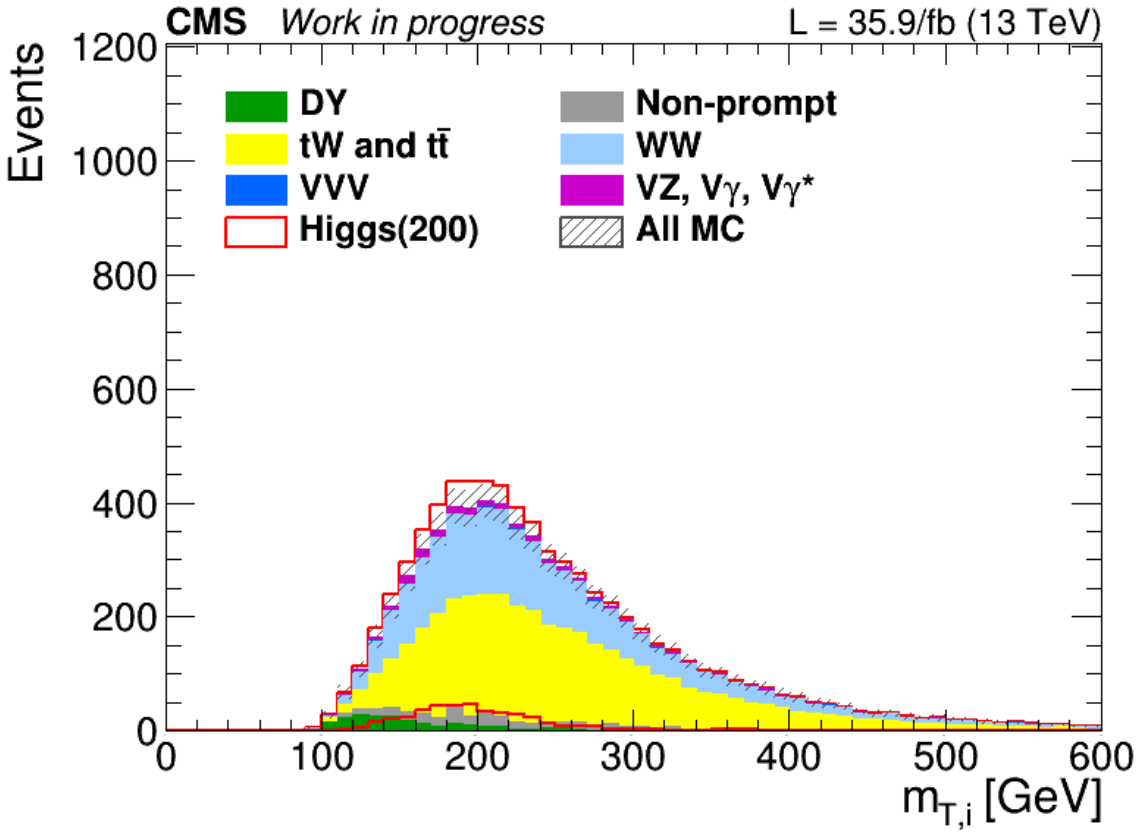
# Discriminant variable



- The final discriminant used in this analysis is a variable $m_{T,i}$

$$m_{\mathrm{T,i}} = \sqrt{(p_{ll} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{ll} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

- Blinded distribution of signal region in the 1 jet category:
  - Red line shows distribution for 200 GeV signal



# Background estimation

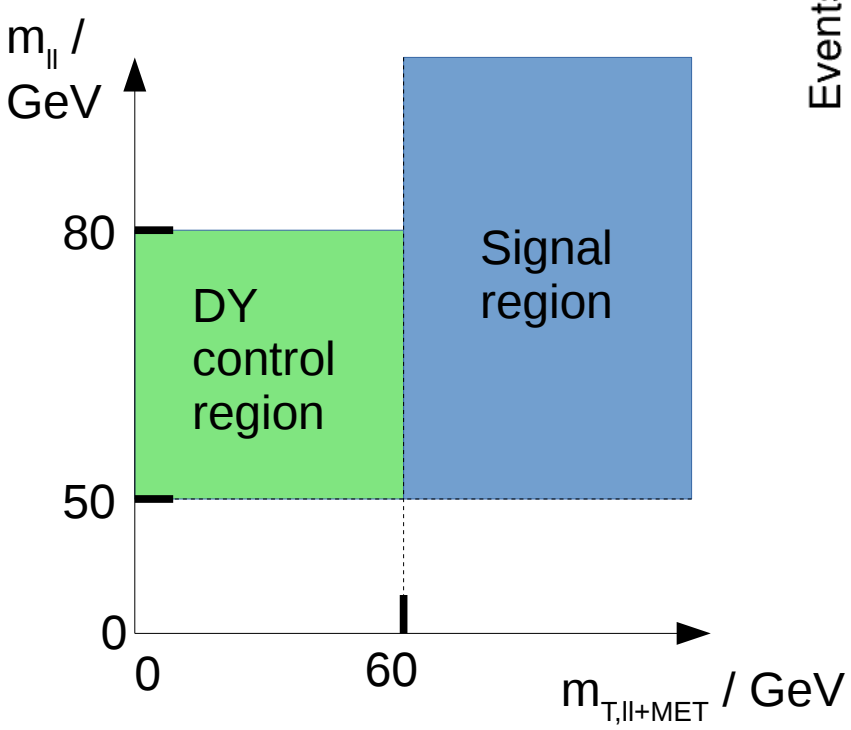


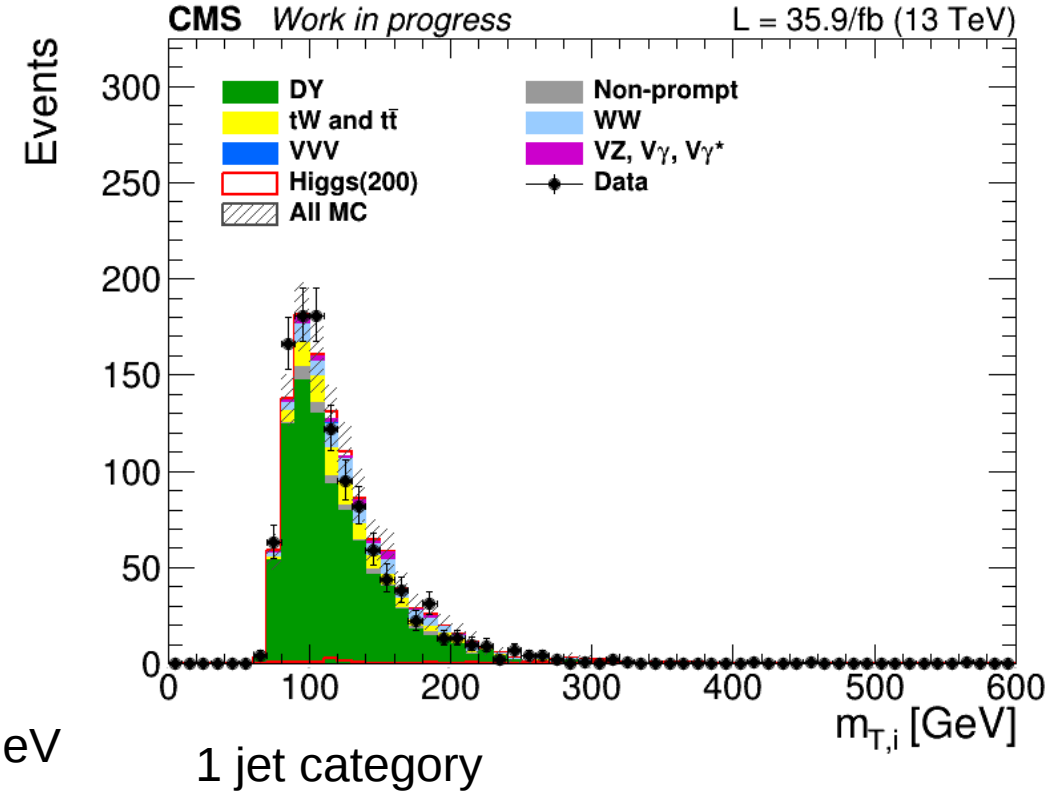
- Data-driven methods are used to estimate the main background processes
  - Top & DY: Control regions are used to extract the normalization from data; Shapes are taken from simulation with applied reweighting corrections

- Currently, the other backgrounds are estimated from simulation

# DY control plots

- Cut on $m_{T,ll+MET}$ is inverted ($m_{T,ll+MET} < 60$ GeV)
- Stronger cut on $m_{ll}$ ($50\ \text{GeV} < m_{ll} < 80\ \text{GeV}$)

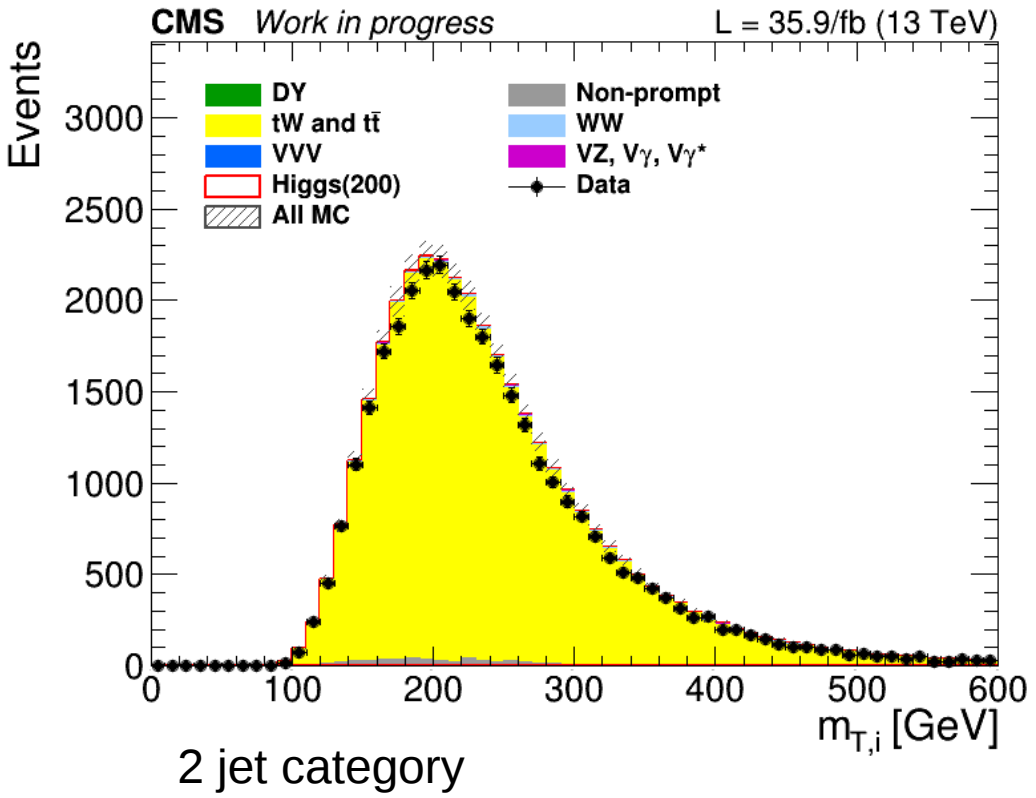



1 jet category

# Top control plots

- Cut on $n_{btag}$ is inverted:
  - 0 jet categ.: $n_{btag} > 0$ ($20\ \text{GeV} < p_T < 30\ \text{GeV}$)
  - 1 jet categ.: $n_{btag} == 1$ ($p_T > 30\ \text{GeV}$)
  - 2 jet categ.: $n_{btag} > 0$



# Model dependent limits

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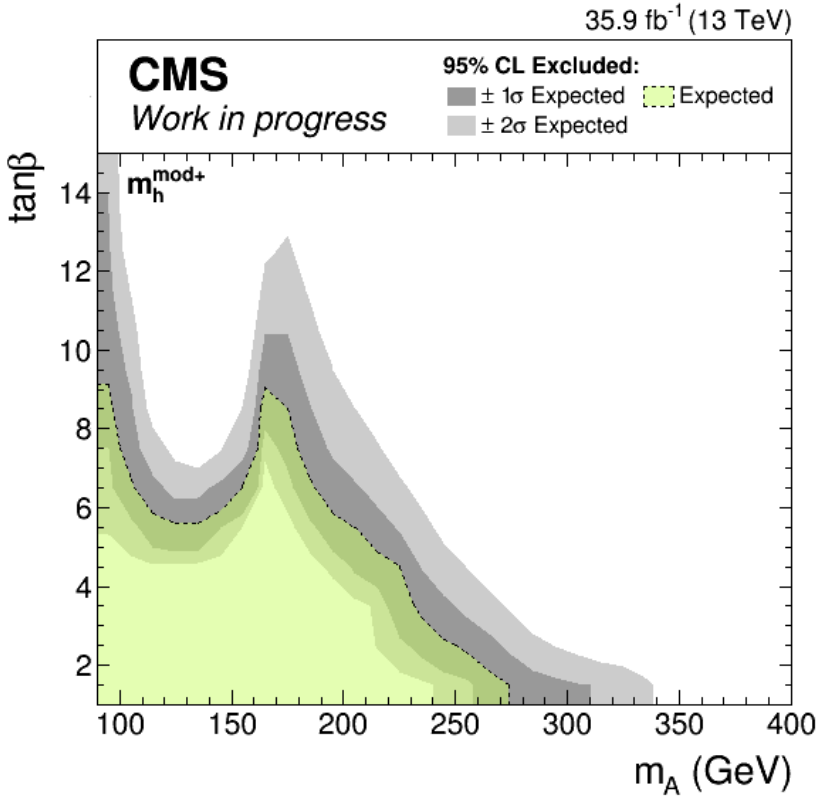
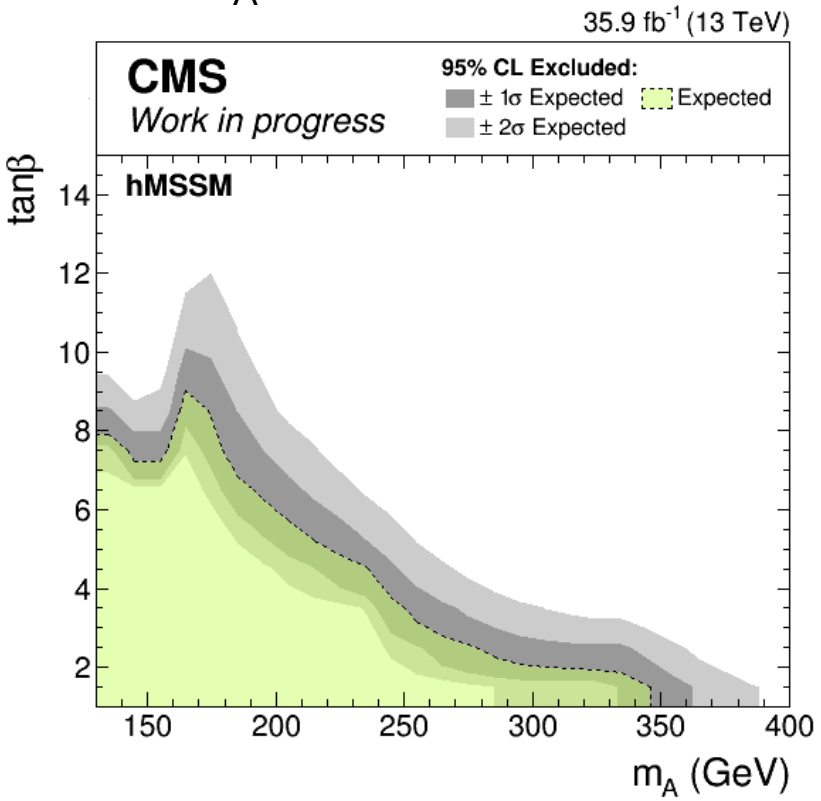
- Preliminary limits using ggH → WW → eμ channel
- $m_h^{mod+}$ and hMSSM scenarios are used
- Expectation excludes area at small $m_A$ and tanβ

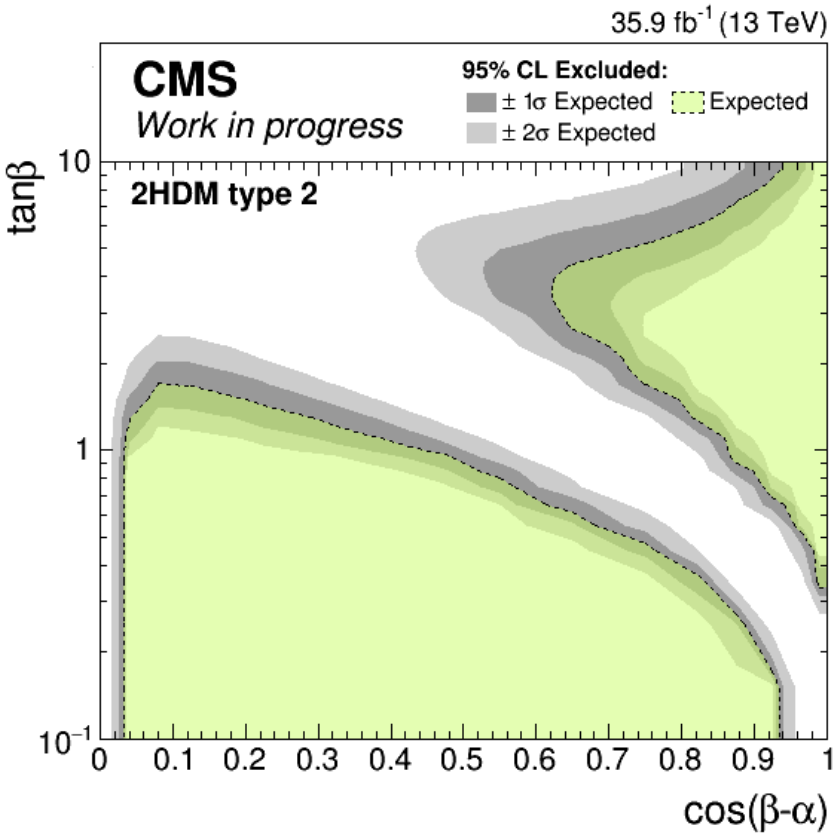


# 2HDM limit

- In a more generalized 2HDM (type 2), limits can be displayed in a cos(β-α)-tanβ plane
  → Coupling of H → WW is proportional to cos(β-α)

- $m_H = m_A = 300$ GeV
- sin(β-α) > 0

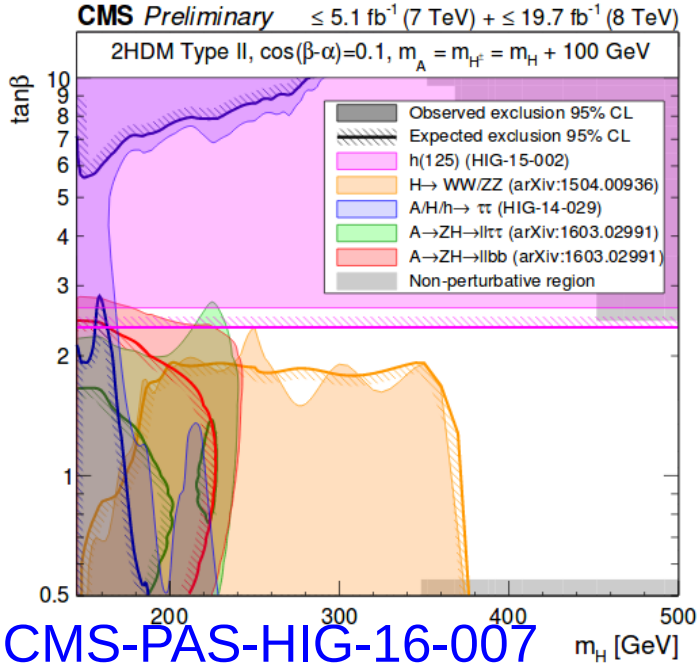


# 2HDM limit



- Limit in the $m_H$-tanβ plane to compare with Run 1:

  $m_H = m_A$, $\cos(\beta-\alpha) = 0.1$, $\sin(\beta-\alpha) > 0$

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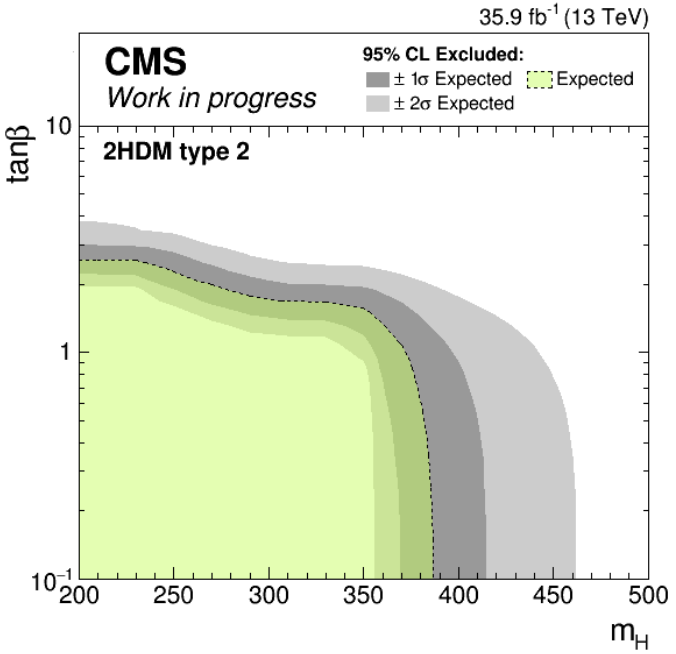
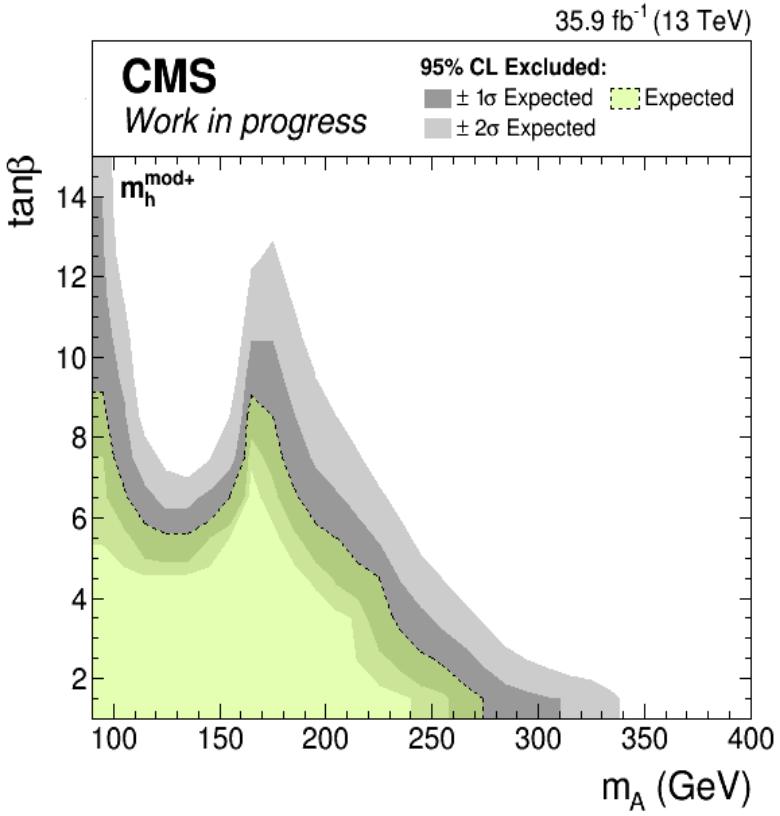



- Orange Run 1 result (left) uses also VBF, more final states, and H → ZZ channel

# Outlook

- Insight was given into the BSM H → WW analysis
  - This channel is sensitive for low values of $m_A$ and tanβ in MSSM scenarios
- Next steps:
  - Include VBF
  - Include same flavor final states (ee and μμ)
  - Look at 2016 data
  - Perform analysis on 2017 data



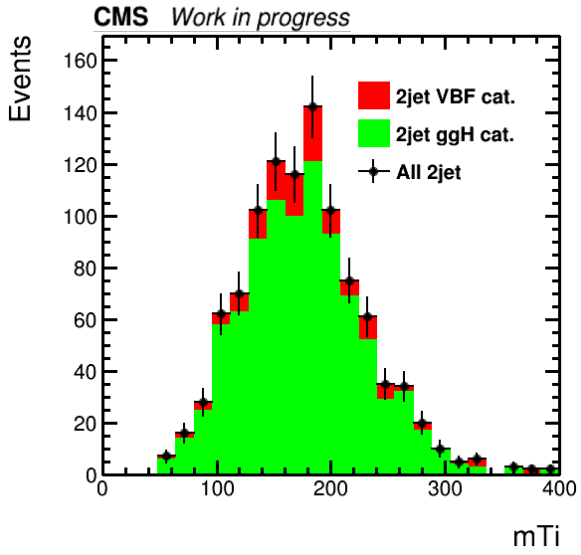
# Backup

# Effect of VBF category

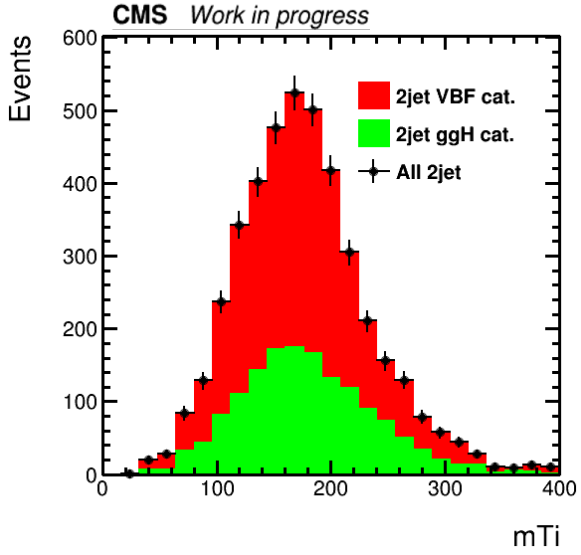


- 2jet („ggH“) category: $\Delta\eta_{jj} < 3.5 \,||\, m_{jj} < 500$ GeV
- 2jet VBF category: $\Delta\eta_{jj} > 3.5 \,\&\, m_{jj} > 500$ GeV

- Effect on (200GeV) ggH signal sample:




- Effect on (200GeV) VBF signal sample:



# Selection criteria

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- Applied cuts:
  - $p_{T,1} > 25$ GeV
  - $p_{T,2} > 20$ GeV

  } Leptons are also well identified and isolated

  - $p_{T,3} < 10$ GeV → Reduces VZ, Vγ, VVV
  - $E_T^{miss} > 40$ GeV → Neutrinos in end state
  - $p_{T,vis} > 30$ GeV → Reduces DY
  - $m_{T,ll+MET} > 60$ GeV → Reduces DY

  } Removes QCD

  - $m_{ll} > 50$ GeV → Reduces W+jets
  - $n_{btag}(p_T > 20\ \text{GeV}) == 0$ → Reduces Top

# Backgrounds by category

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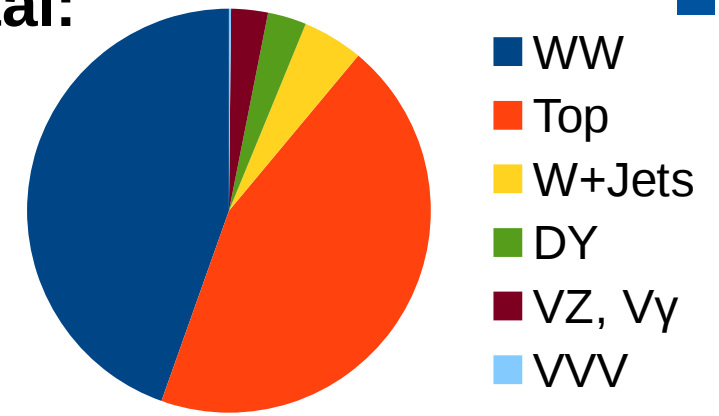
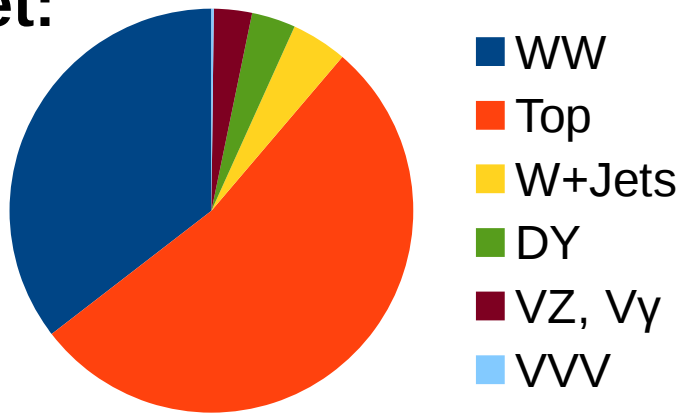
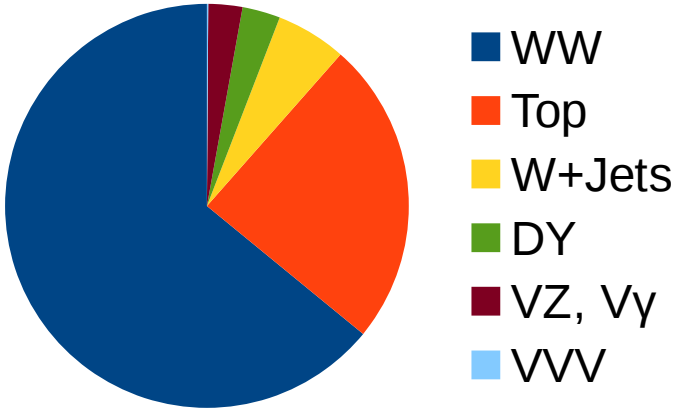
- **Total:**



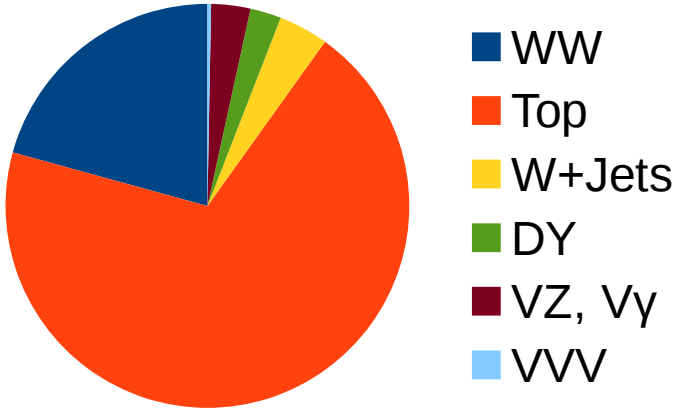

- **1 jet:**




- **0 jet:**




- **2 jet:**

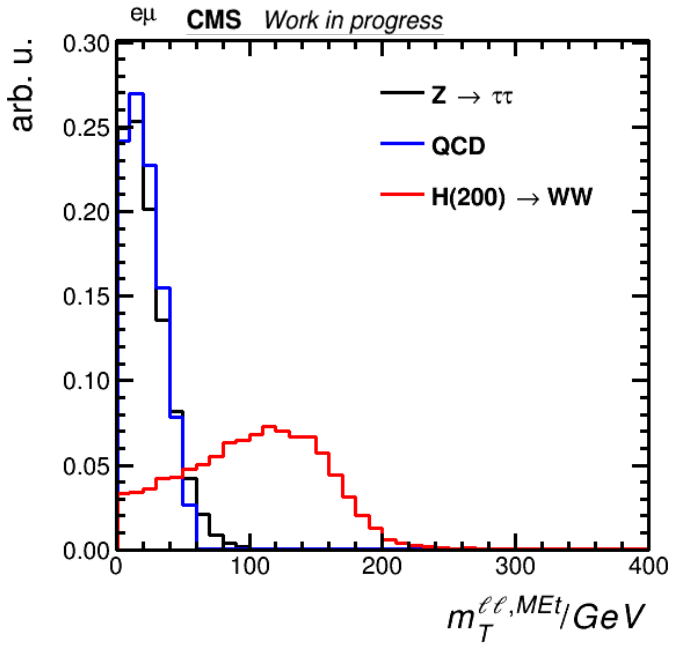


# Selection criteria

- Cuts are applied to reduce background processes
- Examples:

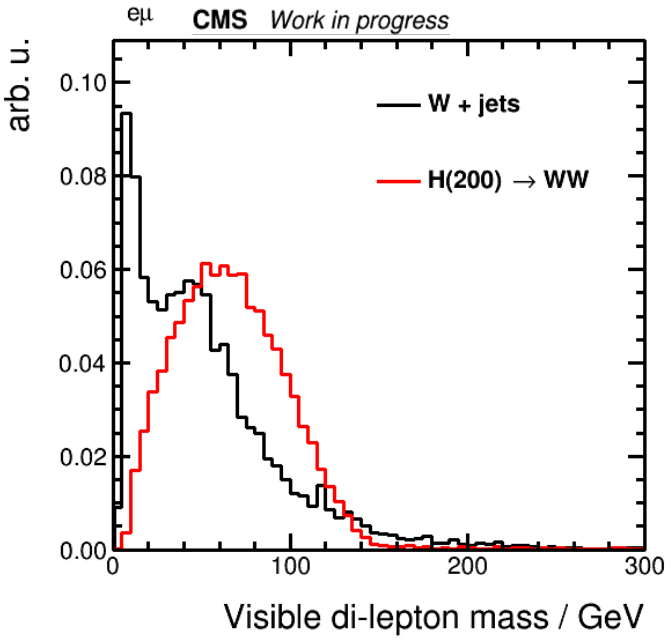
$m_{T,ll+MET} > 60$ GeV

→ Reduces DY and QCD




$m_{ll} > 50$ GeV

→ Reduces W+jets



# Uncertainties

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- The nuisances are the same as those used in the H → WW high mass search analysis
- Experimental:
  - Luminosity
  - Jet energy scale
  - Lepton $p_T$ scale and resolution
  - $E_T^{miss}$ modeling
  - B-tag scale factor uncertainty
  - MC statistics
- Theoretical:
  - PDF and QCD scale
  - Jet bin migration
  - gg → WW normalization
  - tt and tW relative fraction uncertainty
  - PDF and QCD scale on selection efficiency
  - NNLO+NNLL reweighting for qq → WW
  - UE: different Pythia8 tunes
  - PS: Pythia8 vs Herwig

# Branching ratio H → WW



- BR decreases for higher tanβ because coupling is instead enhanced for down-type quarks and charged leptons
- BR decreases for higher $m_A$ because coupling proportional to cos(β-α) → 0 (decoupling limit)

| $\Phi$ | $g_{\Phi\bar{u}u}$ | $g_{\Phi\bar{d}d}$ | $g_{\Phi VV}$ |
|---|---|---|---|
| $h$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\sin(\beta-\alpha)$ |
| $H$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\cos(\beta-\alpha)$ |
| $A$ | $1/\tan\beta$ | $\tan\beta$ | $0$ |