Search for the dimuon decay of the Higgs boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector NeXT Workshop 2018

Antony Fray
Supervisor - Eram Rizvi

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$H \to \mu\mu$ - Why are we interested?

- One of the most promising ways the LHC can directly measure the couplings between a Standard Model (SM) Higgs boson and second generation fermions.
  - $H \to cc$ and $H \to ss$ have large QCD multi-jet backgrounds.
  - $H \to \mu\mu$ has a very clean final state by comparison.
- H$\to \mu\mu$ is a relatively rare decay (see right).
  - Potential for new physics:
    - Exotic Higgs contributions?
- Obstacle: $\mu\mu$ final state is massively background-dominated by Drell-Yan events.
  - Production cross sections at 13 TeV [2]:
    - Drell-Yan: 1977 pb.
    - Total Signal : 55.69 pb.

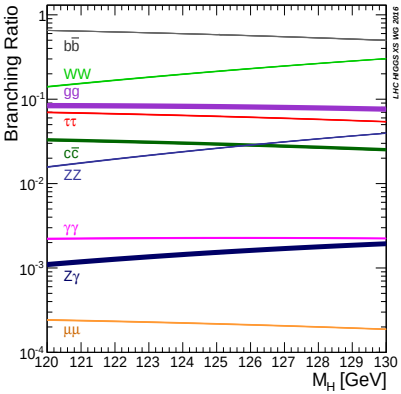

Figure: Higgs boson branching ratios and their uncertainties for the mass range around 125 GeV [1].

Analysis Strategy

- Overarching aim:
  - Maximise sensitivity to find any possible signal so the Higgs - di-muon signal strength can be measured.
  - Utilise the full 2015+2016 pp ATLAS dataset.
- Strategy:
  - Sort data events into several orthogonal signal categories, based on sensitivity to the various Higgs production modes.
    - Two VBF categories (Tight and Loose) are first defined through cutting on a BDT output distribution.
    - Events failing the BDT selection are sorted into one of six ggF categories: Low, medium and high $P_T^{\mu\mu}$, with a further split into central and non-central regions.
    - ttH and VH categories not included as of yet (low event yields).
  - Perform maximum likelihood fit across all categories simultaneously using a combined signal+background fit, from which signal strength μ_s can be extracted.
    - Fully data-driven analysis.

Object Selection

- Muons:
  - $P_T > 15$ GeV
  - $|\eta| < 2.5$
  - Isolated and of sufficient quality
- Jets:
  - Reconstructed using AntiKt4EMTopo algorithm
  - $|\eta| < 4.5$
  - $P_T > 25$ GeV for $|\eta| < 2.4$
  - $P_T > 30$ GeV for $2.4 < |\eta| < 4.5$
  - Isolated and of sufficient quality
  - b-jets:
    - $P_T > 20$ GeV for $|\eta| < 2.5$
    - Satisfy cut on MVA discriminant corresponding to case of 60% b-jet selection efficiency.
- Electrons (used for overlap removal):
  - $P_T > 7$ GeV
  - $|\eta| < 2.47$ excluding crack region between ATLAS barrel and end-caps.
  - Isolated and of sufficient quality

Event Selection

Selection	Requirement
Good Run List	Yes
Event Clean	Yes
Number of Muons	Exactly Two Per Event
Trigger	2015 data - fire isolated $P_T^{\mu} > 20$ GeV trigger OR $P_T^{\mu} > 50$ GeV trigger
	2016 data - fire isolated $P_T^{\mu} > 26$ GeV trigger OR $P_T^{\mu} > 50$ GeV trigger
P_T	$P_T^{\mu,Leading} > 27$ GeV, $P_T^{\mu,Subleading} > 15$ GeV
Opposite Sign	Opposite charge sign for two selected muons
E_T^{Miss}	$E_T^{Miss} < 80$ GeV
B-jet veto	0 B-jets Per Event

Region definitions:

- Z Control Region: 76 GeV $< M^{\mu\mu} <$ 106 GeV.
- Z + Jets Control Region: 76 GeV $< M^{\mu\mu} <$ 106 GeV and NJets ≥ 2.
- Signal Region: 110 $< M^{\mu\mu} <$ 160 GeV.
- Signal + Jets Region: 110 $< M^{\mu\mu} <$ 160 GeV and NJets ≥ 2.

Signal Region

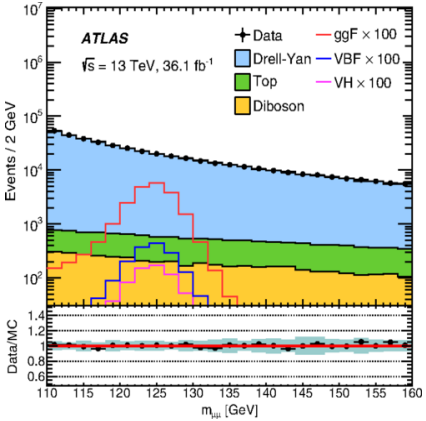

Figure: Observed and simulated $m_{\mu\mu}$ distributions in the inclusive signal region. The expected signals are scaled by a factor of 100. The total background prediction is normalized to the observed data yield, while the relative fractions between the different processes are fixed to the SM predictions. The error band only reflects the statistical and experimental uncertainties in the MC background prediction, while the theoretical uncertainties are not included [3].

- Good levels of data/MC agreement seen.

Event Yields

	S	B	$\frac{S}{\sqrt{B}}$	FWHM	Data
Central low $p_T\mu\mu$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T\mu\mu$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T\mu\mu$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T\mu\mu$	66	31000	0.37	7.1 GeV	31291
Central high $p_T\mu\mu$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T\mu\mu$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

Table: Event yields for the expected signal (S) and background (B) processes, and numbers of the observed data events in different categories. The full widths at half maximum (FWHM) of the signal $m_{\mu\mu}$ distributions are also shown. In each category, the event yields are counted within an $m_{\mu\mu}$ interval, which is centered at the simulated signal peak and contains 90% of the expected signal events. The expected signal event yields are normalized to 36.1 fb^{-1}. The background in each category is normalized to the observed data yield, while the relative fractions between the different processes are fixed to the SM predictions [3].

- Most sensitive categories are VBF Tight, Non-Central High $P_T^{\mu\mu}$ and Non-Central Medium $P_T^{\mu\mu}$.

Signal and Background Fits

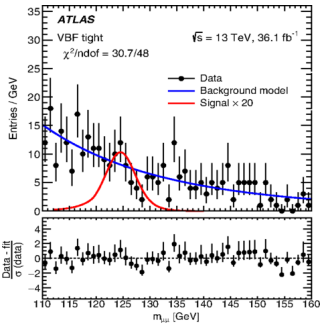

Figure: Background-only fit to the observed $m_{\mu\mu}$ distribution in the VBF tight category. Only the statistical uncertainties are shown for the data points. The expected signal is scaled by a factor of 20 [3].

- Our signal model is a combined Crystal Ball + Gaussian distribution:
- Our background model consists of four components:
  - A Breit-Wigner (BW) function is used to model the resonant $Z/\gamma*$ process.
  - The BW is convolved with a Gaussian to account for detector resolution effects.
  - An $\frac{e^x}{x^3}$ term accounts for di-boson and $t\bar{t}$ contributions.
- Signal fits are performed on ggF and VBF MC.
- Background fits (see left) are performed on data (we are data driven).
- See reasonable chi2/ndof values across all categories for both fits.
- Final results are determined by performing signal+background fit to data in all categories simultaneously.

Experimental and Theoretical Systematics

- Dominating uncertainty on the signal strength is the **statistical uncertainty of the data**.
- The standard experimental systematic uncertainties have been applied:
  - Total experimental uncertainty on predicted signal yield in ggF categories is 4-6%.
    - Dominated by luminosity, muon, jet and pileup contributions.
  - Uncertainty increases to 15% in VBF categories due to larger contributions from jet energy scale and resolution uncertainties.
- Treatment of theoretical systematics follow the standard prescriptions and recommendations.
  - Theoretical uncertainty of ggF signal prediction ranges from 15-25%, dominated by uncertainties due to omitted high-order effects.
  - Theoretical uncertainty of VBF signal yield is around 5% (in each category).
- Largest systematic contributions come from spurious signal systematics.
  - Measure of the bias in our background fit which can lead to "spurious" signal events.
  - Uncertainty varies from 8% to 50% of the statistical uncertainty of the background, depending on the category.
  - Systematic has a 2% effect on the expected upper limit on the signal strength.

Results

- Measured signal strength $\mu_s = -0.1^{+1.5}_{-1.5}$.
- No significant excess is observed in the data, so we set upper limits on the signal strength μ_s at the 95% Confidence Level (CL).
- Observed (expected) upper limits on μ_s at 95% CL found to be 3.0 (3.1).
- When combined with Run-1 data, observed (expected) upper limits on μ_s at 95% CL found to be 2.8 (2.9).
  - Corresponds to a measured signal strength of $\mu_s = -0.1^{+1.4}_{-1.4}$.

Conclusion and Future Developments

- $H\rightarrow \mu\mu$ is a promising channel through which we can try to measure Higgs couplings to second generation fermions.
- Control plots with 36.1 fb^{-1} of data show good data-MC agreement in general.
- Signal and background fits perform well.
- Dominating uncertainty remains to be the statistical uncertainty of the data.
- No excess is observed in the data.
- In combination with Run-1, observed (expected) upper limit on μ_s at 95% C.L. set at 2.8 (2.9).

- Future work being considered:
  - Addition of dedicated VH and ttH categories.
  - Further optimisation of BDT.
  - Reduce impact of spurious signal systematics.

Backup

Data and MC Samples

- Using HIGG3D1 derivations for all samples.
- Data:
  - Full 2015 (3.2 fb^{-1}) + 2016 (33.0 fb^{-1}) datasets used.
- MC:
  - Z+Jets: Madgraph+Pythia8 Ht Sliced.
  - Top: Powheg+Pythia8.
  - Di-boson: Sherpa.
  - ggF, VBF and VH Signals: Powheg+Pythia8.
  - ttH Signal: aMC@NLO+Pythia8.

MC Corrections

- $P_T^{\mu\mu}$ and m^{jj} re-weightings are applied to all Z+Jets MC.
  - Polynomial functions fitted to data/MC ratio in order to correct Z+Jets MC to data.
    - $P_T^{\mu\mu}$ - 6th order polynomial.
    - m^{jj} - 3rd order polynomial.
  - All Z+Jets MC samples used in this analysis have these corrections applied by default.

Details of BDT

- VBF categories are defined by cutting on the BDT output distribution.
  - VBF Loose: $0.7 <$ BDTResponse < 0.9
  - VBF Tight: BDTResponse > 0.9
- Signal samples used for training: VBF
- Background samples used for training: Z (with $P_T^{\mu\mu}$ and m^{jj} re-weighting applied), di-boson and top.
- 14 Variables used for training: $P_T^{\mu\mu}$, $\Delta\eta^{jj}$, M^{jj}, ΔR^{jj}, H_T, $\mathrm{Centrality}$, E_T^{miss}, $P_T^{jj\mu\mu}$, P_T^{jj}, $P_T^{j_1\mu\mu}$, $P_T^{j_2\mu\mu}$, $\Delta y^{jj\mu\mu}$, $\Delta y^{j_1\mu\mu}$, $\Delta y^{j_2\mu\mu}$
- Configuration:
  - NTrees=200
  - MaxDepth=4
  - nCuts=20
  - UseBaggedBoost=True
  - Shrinkage=0.1
  - BoostType=Grad
  - GradBaggingFraction=0.5

Experimental Systematics List

- MUON_SCALE
- MUON_ID
- MUON_MS
- MUON_EFF_RECO_STAT
- MUON_EFF_RECO_SYS
- MUON_EFF_ISO_STAT
- MUON_EFF_ISO_SYS
- JET_JER_SINGLE_NP
- JET_EtaIntercalibration_NonClosure
- JET_GroupedNP_1
- JET_GroupedNP_2
- JET_GroupedNP_3
- JET_JvtEfficiency
- JET_fJvtEfficiency
- MET_SoftTrk_ResoPara
- MET_SoftTrk_ResoPerp
- MET_SofTrk_Scale
- PRW_DATASF
- FT_EFF_B_systematics
- FT_EFF_C_systematics
- FT_EFF_Light_systematics
- FT_EFF_extrapolation
- FT_EFF_extrapolation_from_charm
- M^{ij} reweighting uncertainty

Spurious Signal Systematic - Methodology

- Concept: fit signal+background model to a smooth, background-only distribution to test for any fitting biases which may result in 'spurious' signal events.
- Strategy:
  - Generate a high-statistic truth MC $Z \to \mu\mu$ sample with Powheg+Pythia8.
    - For previous paper, an 870 million event sample was privately generated (5000 fb^{-1}).
  - Process the reco- and truth-level information from official $Z \to \mu\mu$ sample.
  - Fit $\frac{\text{truth-reco}}{\text{truth}} P_T^\mu$ distributions from official sample in bins of P_T^μ and η^μ to derive smearing functions and reconstruction efficiencies.
  - Smear high-statistic truth sample to reco-level using derived functions.
  - Compare official and 'private' distributions (validation).
  - Fit smeared MC with signal+background model in each category to derive spurious signal strength.

Fit Model Details

- Signal Fit:

$$f_{sig}(x, f, M, \sigma_C, \alpha, n, \sigma_G) = (1-f) \cdot CB(x, M_C, \sigma_C, \alpha, n) + f \cdot Gaus(x, M_G, \sigma_G)\Big) \quad (1)$$

- f - fraction of Gaussian contribution - $0 < f < 0.4$.
- M_C - mean of Crystal Ball - floating.
- σ_C - width of Crystal Ball - floating.
- α - $1 < \alpha < 2$.
- n - fixed to 1.
- M_G - mean of Gaussian - floating.
- σ_G - width of Gaussian - floating.

- Background Fit:

$$f_B(x, M_{BW}, \Gamma_{BW}, \sigma_{GS}, f, B) = f \cdot (BW(x, M_{BW}, \Gamma_{BW}) * GS(\sigma_{GS}))(x) + (1-f) \cdot (e^{B \cdot x})/x^3 \quad (2)$$

- M_{BW} - mean of BW - fixed to 91.2 GeV (PDG value).
- Γ_{BW} - width of BW - fixed to 2.49 GeV (PDG value).
- f - fraction of Gaussian+BW contribution - $0 < f < 1$.
- σ_{GS} - width of Gaussian - obtained from fits to $m_{\mu\mu}^{truth} - m_{\mu\mu}^{reco}$ in each category.
- B - $-1 < B < 1$.

Bibliography

1 Chin.Phys. C40 (2016) no.10, 100001

2 LHCHXSWG-DRAFT-INT-2016-008

3 Phys. Rev. Lett. 119, 051802 (2017)