Recent Higgs results in the $\gamma\gamma$ and $Z\gamma$ decay channels from the ATLAS and CMS collaborations

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On behalf of the ATLAS & CMS Collaborations

University of Minnesota

8th annual conference on Large Hadron Collider Physics (online)
25-30 May 2020

**A Zoom/Vidyo/Skype meeting can be setup on request**
**COLLABORATION** | **MEASUREMENT/SEARCH** | **DATASET**
--- | --- | ---
CMS | Higgs mass ** | 2016 (combined with Run 1)
ATLAS, CMS | ttH+tH production and CP studies | FULL Run 2 **NEW**
ATLAS | Search for Higgs boson decays to Zγ | FULL Run 2 **NEW**

**Same measurement also performed by ATLAS earlier in** [Phys. Lett. B 784 (2018) 345]
Overview of the $H \to YY/ZY$ channels

- High resolution channels with a fully reconstructed final state comprising of two photons/two leptons (e or $\mu$) and a photon.
  - $B(H \to \gamma\gamma) \sim 0.23\%$; $B(H \to Z\gamma) \sim 0.15\%$

- Excellent $m_{\gamma\gamma}/m_{ll\gamma}$ resolution of $\sim 1-2\%$ owing to the high precision with which leptons and photons are reconstructed**.
  - A signal appears/would appear as a bump in $m_{\gamma\gamma}/m_{ll\gamma}$ at around 125 GeV

- The signal is modelled from simulation parametrized as a function of $m_H$
  - Requires a precise understanding of the detector with corrections applied to simulated events to accurately represent data.

- Data-driven estimate of the ~smoothly falling background from continuum diphoton/Z$\gamma$ production (+ fakes)

**See Shilpi’s talk for lepton/photon performance in ATLAS and CMS
The Higgs Boson mass: $H \rightarrow \gamma \gamma$

CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-09 17:03:21.065792 GMT
Run / Event / LS: 282734 / 310970836 / 153

m_H in the diphoton channel with the 2016 dataset

• Improved ECAL calibration leading to more stable response with time.

• Dedicated corrections for the photon energy scale using Z→ee events in data and simulation:
  – Five times more granular.
  – Correct nonlinear discrepancies in the photon energy scale with p_T between data and simulation.
  – Precision of the electron energy scale at the level of 0.075%

• The m_W resolution in the most sensitive (weighted sum of all) category is 1.35 (1.68) GeV

m_H = 125.78 ± 0.26 [0.18 (stat.) ± 0.18 (syst.)] GeV
Combined measurement of $m_H$

**ATLAS**

Run 1 + 2016 combined:

$$m_H = 124.97 \pm 0.24 \ [0.16 \text{ (stat.)} \pm 0.18 \text{ (syst.)}] \text{ GeV}$$

See Will's talk for $m_H$ measurements in the $H \rightarrow ZZ \rightarrow 4l$ channel (New ATLAS result with full Run 2).

**CMS**

Run 1 + 2016 combined:

$$m_H = 125.38 \pm 0.14 \ [0.11 \text{ (stat.)} \pm 0.08 \text{ (syst.)}] \text{ GeV}$$

Most precise measurement of $m_H$ till date: $\sim 0.1\%$
ttH + tH production and CP properties of the Higgs boson

Both papers have been submitted to Phys. Rev. Lett.


See Josh’s talk for the current status of ttH measurements in CMS
The t-H coupling: Motivation

- Fermions couple to the Higgs boson via the Yukawa interaction.
  - The coupling is proportional to the fermion mass. Hence largest for the top quark.
- The t-H Yukawa coupling can be constrained indirectly in the production of the Higgs boson via gluon-gluon fusion and in the diphoton decay mode.
  - Requires assumptions on the contribution from BSM particles in the loops.
- ttH and tH production allows for a direct observation and measurement of the t-H Yukawa coupling.
**CP properties of the Higgs boson: Motivation**

- The Higgs boson of the SM is **CP-even** with $J^{CP} = 0^{++}$

- All measurements to date of the CP properties of the Higgs boson via its interactions with gauge bosons are **compatible with the SM**.

- The CP properties of the Higgs boson via fermionic interactions have not been studied so far.
  - Higher sensitivity to the CP-odd contributions which “enter” at the same order as the CP-even terms (No $1/\Lambda^2$ suppression, where $\Lambda$ is the scale for new physics).

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**Probe the CP structure of the t-H interaction**

\[ \mathcal{L} = - \frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t \left[ \cos(\alpha) + i \sin(\alpha)\gamma_5 \right] \psi_t \right\} H \]

- Where $\kappa_t$ is the top Yukawa coupling parameter and $\alpha$ is the CP mixing angle
  - In the SM $\kappa_t = 1$ and $\alpha = 0^\circ$. For CP-odd $\alpha = 90^\circ$
- Params. of interest: $\kappa_t$ and $\alpha$

\[ A(Htt) = - \frac{m_t}{v} \bar{\psi}_t \left( \kappa_t + i \tilde{\kappa}_t \gamma_5 \right) \psi_t \]

- Where $\kappa_t$ and $\tilde{\kappa}_t$ are the CP-even and CP-odd Yukawa couplings. **In the SM $\kappa_t = 1$ and $\tilde{\kappa}_t = 0$**

Param. of interest: $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \sign(\tilde{\kappa}_t/\kappa_t)$
Analysis strategy: ATLAS

**NEW**

- Select events with 2 isolated photons and \( \geq 1 \) b\textbf{tagged jet}. Further divide events depending on the number of reconstructed leptons (e and \( \mu \)).
  - Hadronic region: \#jets \( \geq 3 \) and \#leptons = 0
  - Leptonic region: \#leptons \( \geq 1 \)

- Events categorized into \textbf{12 (8) cats.} using a 2D-partition of 2 1D BDTs for the had. (lep.) regions.
  - “Bkg. rejection BDTs” used to separate the \( \text{ttH} \) process from other SM processes.
  - “CP BDTs” to separate the CP-even from the CP-odd couplings using the \( \text{ttH} \) and \( \text{tH} \) processes.
  - \textbf{The ttH and tH yields are parameterized in terms of} \( k_t \) \textbf{and } \( \alpha \)

- A simultaneous fit is performed to the \( m_{WW} \) distributions in all 20 categories for signal extraction.
• Select events with 2 isolated photons and \( \geq 1 \) jet.
  \( \rightarrow \) Hadronic region : \#jets \( \geq 3 \) (1 b-jet) and \#lep = 0  \( \rightarrow \) Leptonic region : \#lep \( \geq 1 \)

• 1D signal strength analysis : “Bkg. Rej. BDTs” used to define 4*2 categories in the two regions.

• 2D CP analysis : “D_0. BDTs” used to define 12 categories : 3 D_0 * 2 Bkg. Rej. * 2 regions
  – The tH yield is parameterized in terms of \( |f^{Htt}_{CP}| \) and \( \mu_{tH} \)

• A simultaneous fit is performed to the \( m_{\gamma\gamma} \) distributions in all categories for signal extraction.
**Results: ttH + tH signal strength**

- $\mu_{ttH} = 1.4 \pm 0.4 \pm 0.2$ (stat.)\,(syst.)
  - Non ttH Higgs production modes constrained to SM prediction. Assume CP even coupling.
- Obs. (Exp.) sig. = 5.2 $\sigma$ (4.4 $\sigma$)
- $tH$ rate: < 12 x SM xsec at 95% CL
  - Non tH/ttH Higgs production modes constrained to the SM prediction.

- $\mu_{ttH} = 1.38 \pm 0.29^{+0.27}_{-0.21}$\,(stat.)\,$\pm 0.21^{+0.11}_{-0.08}$ (syst.)
  - Non ttH Higgs production modes constrained to SM prediction.
- Obs. (Exp.) sig. = 6.6 $\sigma$ (4.7 $\sigma$)
- $\sigma_{ttH}\cdot B_{WW} = 1.56^{+0.34}_{-0.32}$ fb
  - $= 1.56^{+0.33}_{-0.30}$ (stat.) $\pm 0.09^{+0.08}_{-0.08}$ (syst.) fb
- SM prediction of $(\sigma_{ttH}\cdot B_{WW})_{SM} = 1.13^{+0.08}_{-0.11}$ fb
The Higgs boson coupling modifiers $k_\gamma$ and $k_g$ are constrained to the combination result.

$k_t$ is left free to float in the fit.

- $|\alpha| > 43^\circ (63^\circ)$ obs. (exp) exclusion at 95% CL
- Obs. (Exp.) pure CP-odd coupling excluded at 3.9 $\sigma$ (2.5 $\sigma$)

The Higgs boson couplings to other particles constrained to SM.

- $\mu_{ttH}$ and $|f_{ttH}^{CP}|$ are free to float in the fit.

- $f_{ttH}^{CP} = 0.00 \pm 0.33$ at 68% CL
- Limit at 95% CL: $|f_{ttH}^{CP}| < 0.67$
- Obs. (Exp.) pure CP-odd coupling excluded at 3.2 $\sigma$ (2.6 $\sigma$)
A search for Higgs boson decays to $Z\gamma$

Submitted to Phys. Lett. B

**NEW**
Higgs boson decays to $Z\gamma$ : Introduction

- The SM Higgs boson can decay into $Z\gamma$ via loop diagrams with a branching ratio of $\sim 0.15\%$ @ $m_H = 125.09$ GeV.
  - The branching ratio can differ from the above value in BSM scenarios where the Higgs is a neutral scalar of non-SM origin or for a composite Higgs.
  - The branching ratio can also differ if there exist additional non-SM particles that couple to the SM Higgs boson via loop corrections.

- First result with the full 139 fb$^{-1}$ Run 2 dataset.

- Search performed in $Z(\rightarrow ll)$ final states where $l = e$ or $\mu$.
  - $Z$ boson branching ratio $\sim 7\%$ in these final states

- One of the signal-bkg. discriminating variables $p_{Tt}$ is used to suppress background an in categorization.
  - $p_{Tt} = (2*p_{TZ}*p_{Ty}*\sin \Delta \Phi_{Z\gamma})/p_{Z\gamma T}$
Event selection and categorization

Event Selection:
- Select events with an opposite sign same flavour lepton pair (ee + \(\mu\mu\)) and a photon
- Muon energy is corrected for FSR
  - 3% improvement \(m_{Z\gamma}\) resolution
- Constrained kinematic fit with the Z-boson lineshape is used to recompute the dilepton 4-vector
  - 14% improvement \(m_{Z\gamma}\) resolution
- \(m_{ll}\) within 10 GeV of nominal Z mass.

Event Categorization:
- To optimize the S/B of the measurement events are picked up in one of six mutually exclusive categories:
  - A VBF enriched category using a dedicated BDT
  - Remaining categories based on cut based selections on \(p_T/m_{Z\gamma}\) and \(p_{Tt}\).
• The observed data are consistent with the background only hypothesis with a significance of 2.2 $\sigma$ 
  – The expected significance is 1.2 $\sigma$ under the hypothesis of the presence of a SM Higgs boson.

• The best fit signal strength $\mu_{Z\gamma}$:
  – Observed $\mu_{Z\gamma} = 2.00^{+1.0}_{-0.9}$
    
    $\quad = 2.00 \pm 0.9$ (stat) $^{+0.4}_{-0.3}$ (syst)
  
  with the signal yield normalized to the SM prediction.

• Observed 95% CL upper limit on $\mu_{Z\gamma} = 3.6$ x SM prediction
  – Expected limit assuming no (SM) Higgs boson decay into $Z\gamma$ is 1.7 (2.6) times the SM prediction.

• The observed upper limit on $\sigma_{pp \rightarrow H \cdot B_{H \rightarrow Z\gamma}}$ is 305 fb at 95% CL

• The upper limit at 95% CL on the $H \rightarrow Z\gamma$ branching ratio is 0.55% (assuming SM Higgs boson production cross-section).

Dominant uncertainty:
• Statistics
• The dominant systematic uncertainty, amounting to 28%, on $\mu_{Z\gamma}$ arises out of the “spurious-signal” uncertainties.
Summary

We have entered a precision era with LHC Run 2.

• **The m\(_H\) has been measured to a precision of 0.1 % by the CMS collaboration.**
  – The same measurement has also been performed by the ATLAS collaboration.

• **First single channel observation of Higgs boson production in association with a top quark pair by both experiments.**
  – The CP structure of the H-t coupling has been studied for the first time with the pure CP-odd hypothesis excluded at > 3\(\sigma\) by both experiments.
  – Most stringent limit on tH production of < 12 times the SM xsec. at 95% CL from ATLAS

• The search for Higgs boson decays to Z\(\gamma\) has been updated with the full Run 2 dataset by the ATLAS collaboration.

• **Exciting times are ahead with analyses being updated with the full Run 2 dataset.**
  – From these individual measurements along with their combination a coherent global picture will emerge.

**No evidence available yet of any deviation from SM predictions**
The Higgs boson: a particle like no other

The Higgs mass is a free parameter of the SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \gamma^\mu D_\mu \psi + h.c. \]

\[ + \mu^2 |\phi|^2 + 0.5 \lambda |\phi|^4 \]

\[ \rightarrow \text{Higgs self coupling} \]

Yukawa interaction

\[ \rightarrow \text{Coupling to fermions} \]

Gauge interaction

\[ \rightarrow \text{Coupling to bosons} \]
Higgs production at the LHC in Run 2

- In Run 2 we have > 11 times increase in Higgs production w.r.t Run 1
  - Much higher sensitivity in the measurement of the properties of the Higgs boson.
- Gluon fusion is the dominant production mode.
  - Sensitivity to given production modes depend on the decay channel being considered.

\(\text{ggF} \sim 87\%\)
\(\text{VBF} \sim 7\%\)
\(\text{VH} \sim 4\%\)
\(\text{ttH} \sim 1\%\)

- The decay modes presented today are \(\gamma\gamma\) and \(Z\gamma\)
  - \(B(H\rightarrow\gamma\gamma) \sim 0.23\%\)
  - \(B(H\rightarrow Z\gamma) \sim 0.15\%\)
What do we wish to do with all this data

Cross-sections

Signal-strengths
- Inclusive
  - Used for discovery
  - Now syst. limited
- Per prod. mode
  - Some modes are stat. limited.

Couplings
- Using $\kappa$-framework
  - Reduced model dependence and shape information.
  - Heavily stat. limited.

STXS framework
- Reduced model dependence and shape information.
- Heavily stat. limited.

Total and differential

Mass
- Using the high resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ channels only.
- Requires a deep understanding of the detector to correctly estimate the systematic uncertainties.
$m_H$ in the diphoton channel with the 2016 dataset ATLAS

- Diphoptron vertex selected using a dedicated DNN
- Events selected in a total of 31 exclusive cats. based on the photon kinematics and other objects.
- The $M_{\gamma\gamma}$ resolution varies between $1.59 - 2.10$ GeV

$m_H = 124.93 \pm 0.40 [0.21 \text{ (stat.)} \pm 0.34 \text{ (syst.)}]$ GeV

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty on $m_{\gamma\gamma}^H$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimeter cell non-linearity</td>
<td>$\pm 180$</td>
</tr>
<tr>
<td>EM calorimeter layer calibration</td>
<td>$\pm 170$</td>
</tr>
<tr>
<td>Non-ID material</td>
<td>$\pm 120$</td>
</tr>
<tr>
<td>ID material</td>
<td>$\pm 110$</td>
</tr>
<tr>
<td>Lateral shower shape</td>
<td>$\pm 110$</td>
</tr>
<tr>
<td>$Z \to ee$ calibration</td>
<td>$\pm 80$</td>
</tr>
<tr>
<td>Conversion reconstruction</td>
<td>$\pm 50$</td>
</tr>
<tr>
<td>Background model</td>
<td>$\pm 50$</td>
</tr>
<tr>
<td>Selection of the diphoton production vertex</td>
<td>$\pm 40$</td>
</tr>
<tr>
<td>Resolution</td>
<td>$\pm 20$</td>
</tr>
<tr>
<td>Signal model</td>
<td>$\pm 20$</td>
</tr>
</tbody>
</table>

Combined measurement of the Higgs mass ATLAS

-2\ln(\Lambda)

\begin{align*}
\text{ATLAS} \\
\text{H} & \rightarrow \text{ZZ}^* + \text{H} \rightarrow \gamma\gamma \text{ Combination} \\
\text{Run 2: } & \sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1}
\end{align*}

\begin{align*}
\text{m}_H & \text{ [GeV]} \\
\text{Run 1: } & \sqrt{s} = 7.8 \text{ TeV, 25 fb}^{-1} \\
\text{Run 2: } & \sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1}
\end{align*}

The main sources of uncertainty are those related to the photon energy scale:

- The electron energy scale uncertainties are propagated directly to the photon energy scale.
- Additional uncertainties on the photon energy scale account for the differences in between electron and photon interactions.
  - Modelling of upstream material
  - **Non-uniformity in light collection in ECAL crystals due to radiation damage**
    - New light collection efficiency models that account for radiation damage.
$m_H$ in $H \rightarrow \gamma \gamma$: Systematic uncertainties CMS (2)
\( m_H \) in the diphoton decay channel with the 2016 dataset CMS

The signal model is obtained from simulation using a sum of up to 4 Gaussians.

The background model is obtained directly from data using the discrete profiling method.

Two signal strength parameters \( \mu^{GGH+TTH} \), \( \mu^{VBF+VH} \) are free to vary in the fit.

Uncertainty on the photon energy scale arising out of the \( Z \rightarrow ee \) based energy scale corrections are of the same order as those arising out of differences in e-\( \gamma \) interaction.
Combined measurement of the Higgs mass CMS

Simplified Template cross-sections (STXS)

- The STXS framework, a logical evolution of the per process signal strength measurements, aims to maximize the sensitivity of measurements and minimize their theory dependence.
  - Developed collectively by ATLAS, CMS and theorists.

- Certain exclusive regions of phase space, “bins”, are defined specific to the different production modes in stages with increasing granularity:
  - minimizing the number of bins without loss of experimental sensitivity.
  - Allowing for combinations across decay channels and experiments.
  - Isolating possible BSM effects.

STAGE 0: The standard SM Higgs production modes

STAGE 1: further splitting based on $p_T(H)$, #Jets, $p_T(jet1)$, etc
H→γγ recast in STXS stage 1 bins

CMS: PAS-HIG-18-029
Simplified Template cross-sections (STXS)

STAGE 0

- Cross-sections in a fiducial region, in exclusive phase space regions ("bins") for the different production modes
  - Evolution of per-process signal strengths.
  - Reducing theory dependence.
  - Allows for combinations across decay channels and experiments.
  - Isolate possible BSM effects.

STAGE 1
H→γγ in STXS stage-1 bins: Grouping 1 results

- The stage-1 bins are defined using “cuts” on the corresponding “RECO” level quantities.
  - 9 STXS bins in all.
  - Total of 27 categories in these bins with a mix of cut based and BDT selection.

**Analysis performed targeting the ggH and VBF bins.**

- The stage-1 bins are defined using “cuts” on the corresponding “RECO” level quantities.
  - Dedicated BDTs used to reject backgrounds.
  - Two sets of results with 7 and 13 STXS bins respectively.
H→γγ in STXS stage-1 bins: Grouping 2 results

ttH + tH production and CP properties of the Higgs boson

ATLAS: arxiv:2004.04545
CMS: arxiv:2003.10866
Both papers have been submitted to Phys. Rev. Lett.
BDT input features: ATLAS

ttH Bkg. Rejection BDT

• Leptonic channel input features:
  – Photons: $p_T^\gamma/m_\gamma, \eta, \Phi$ of each photon
  – Leptons: 4 vectors of up to 2 leading in $p_T$ leptons
  – Jets: 4 vectors of up to 4 leading in $p_T$ jets
  – MET: magnitude and $\Phi$

• Hadronic channel input features
  – Photons: $p_T^\gamma/m_\gamma, \eta, \Phi$ of each photon
  – Jets: 4 vectors, b-tag of up to 6 leading in $p_T$ jets
  – MET: magnitude

CP BDT

• Total of up to 20 input features:
  – Photons: $p_T$ and $\eta$ of the diphoton system
  – Top quarks: $p_T, \eta, t$-BDT scores of up to 2 reco. top quarks, $\Phi_{YY,t1}, \Phi_{YY,t2}, \Delta\eta_{t1t2}, \Delta\Phi_{t1t2}, m_{YY,t1}, m_{t1,t2}$
  – Jets and MET: #jets, #b-tagged jets, $H_T$, MET/$\sqrt{H_T}$, lowest and second lowest $\Delta\eta_{vj}$
BDT input features: CMS

**ttH Bkg. Rejection BDT**

- **Hadronic channel with up to 35 input features**
  - Photons: $p_T^\gamma/m_{\gamma\gamma}$, $\eta$, PSV of each photon; Max and Min $\gamma$ ID MVA
  - Diphoton system: $p_T^{\gamma\gamma}/m_{\gamma\gamma}$, $\gamma_y$, $\Delta R_{\gamma\gamma}$, $\cos(\Delta \Phi)_{\gamma\gamma}$, $|\cos(\text{Helicity angle})|$
  - Jets and MET: 4 vectors, b-tag of up to 4 leading in $p_T$ jets; Highest and 2nd Highest b-tag score; #jets, $H_T$, MET
  - Dedicated variables: DNN to suppress diphoton background, top-tagger BDT

- **Leptonic channel with up to 32 input features**:
  - Photons: Same
  - Diphoton system: Same
  - Leptons: #leptons, $p_T$, $\eta$ of lead lepton
  - Jets and MET: Same [up to 3 lead jets]
  - Dedicated variables: DNN to suppress tt+γγ background

**D_0- BDT to separate the CP-even and CP-odd couplings using the ttH/tH processes**

- **input features**:
  - Diphoton system: kinematic variables (not including $m_{\gamma\gamma}$)
  - Leptons (lepton channel only): #leptons, kinematic variables of the lead lepton
  - jets: kinematic variables, b-tag scores of up to 6 leading jets
A search for Higgs boson decays to $Z\gamma$ (ATLAS)

arxiv:2005.05382
Event categorization

Selected events

- VBF BDT
  - $p_T^\gamma / m_{Z\gamma} > 0.4$
  - $p_T^\gamma / m_{Z\gamma} < 0.4$
  - $p_T^t > 40$ GeV
  - $p_T^t < 40$ GeV

Lepton flavour
- ee
- $\mu \mu$

Categories:
- I
- II
- III
- IV
- V
- VI

VBF like

GGH like
Signal and background modelling

- A parametric signal model is obtained from fits to the $m_{Z\gamma}$ distributions in simulation for all 6 categories.
  - Used a double-sided crystal ball function.
- A parametric background model is used to describe the $m_{Z\gamma}$ distribution using a template of simulated $Z\gamma$ and EW $Z\gamma_{jj}$ events along with the $Z$+jets from data.
  - Family of functions: exponential, Bernstein and power law.
  - The choice of the analytical model of the background and the $m_{Z\gamma}$ fit range optimized in each category using the templates.
    - The “spurious signal” is require to be less than 50% of the exp. stat. unc. on the signal yield. A S+B fit to the $m_{Z\gamma}$ background-only distribution with $m_H$ varied in the range 123-127 GeV: The max. number of signal events obtained from these fits constitute the spurious signal systematic unc.
    - The optimal fit range is by varying the bound of 105-115 GeV and 140-160 GeV in 5 GeV steps in order to achieve the highest signal significance.

<table>
<thead>
<tr>
<th>Category</th>
<th>Function Type</th>
<th>Fit range [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF-enriched</td>
<td>Second-order power function</td>
<td>110–155</td>
</tr>
<tr>
<td>High relative $p_T$</td>
<td>Second-order exponential polynomial</td>
<td>105–155</td>
</tr>
<tr>
<td>ee high $p_{Tt}$</td>
<td>Second-order Bernstein polynomial</td>
<td>115–145</td>
</tr>
<tr>
<td>ee low $p_{Tt}$</td>
<td>Second-order exponential polynomial</td>
<td>115–160</td>
</tr>
<tr>
<td>$\mu\mu$ high $p_{Tt}$</td>
<td>Third-order Bernstein polynomial</td>
<td>115–160</td>
</tr>
<tr>
<td>$\mu\mu$ low $p_{Tt}$</td>
<td>Third-order Bernstein polynomial</td>
<td>115–160</td>
</tr>
</tbody>
</table>
### S+B fits and significance

![Graphs showing data and fits for ATLAS experiments.](image)

### Table: Category Analysis

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
<th>$S_{68}$</th>
<th>$B_{68}$</th>
<th>$w_{68}$ [GeV]</th>
<th>$\frac{S_{68}}{B_{68}} [10^{-2}]$</th>
<th>$\frac{S_{68}}{\sqrt{S_{68} + B_{68}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF-enriched</td>
<td>194</td>
<td>2.7</td>
<td>18.7</td>
<td>3.7</td>
<td>14.3</td>
<td>0.58</td>
</tr>
<tr>
<td>High relative $p_T$</td>
<td>2276</td>
<td>7.6</td>
<td>112.8</td>
<td>3.7</td>
<td>6.7</td>
<td>0.69</td>
</tr>
<tr>
<td>High $p_T$, ee</td>
<td>5567</td>
<td>9.9</td>
<td>444.0</td>
<td>3.8</td>
<td>2.2</td>
<td>0.46</td>
</tr>
<tr>
<td>Low $p_T$, ee</td>
<td>76,679</td>
<td>34.5</td>
<td>6654.1</td>
<td>4.1</td>
<td>0.5</td>
<td>0.42</td>
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<tr>
<td>High $p_T$, $\mu\mu$</td>
<td>6979</td>
<td>12.0</td>
<td>610.8</td>
<td>3.9</td>
<td>2.0</td>
<td>0.48</td>
</tr>
<tr>
<td>Low $p_T$, $\mu\mu$</td>
<td>100,876</td>
<td>43.5</td>
<td>8861.5</td>
<td>4.0</td>
<td>0.5</td>
<td>0.46</td>
</tr>
<tr>
<td>Inclusive</td>
<td>192,571</td>
<td>110.2</td>
<td>16,701.9</td>
<td>4.0</td>
<td>0.7</td>
<td>0.85</td>
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