A search for the $Z\gamma$ decay mode of the Higgs boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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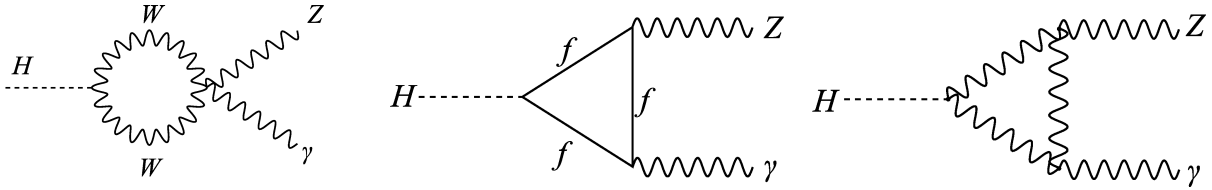
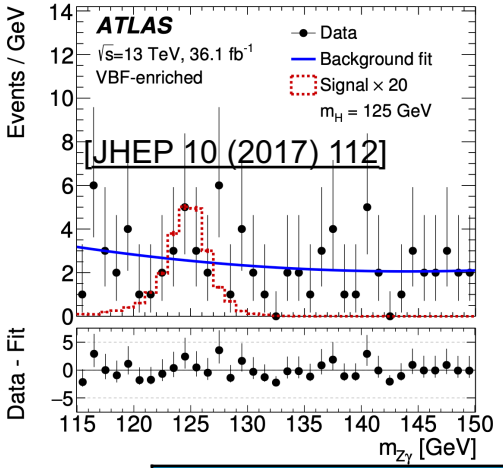
Introduction

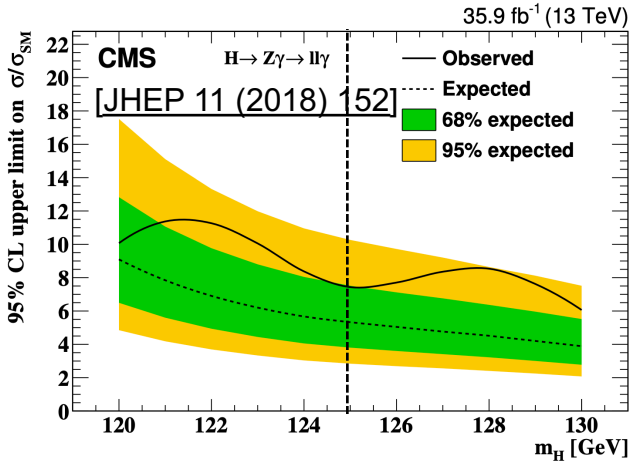
- **SM Higgs** can decay into $Z\gamma$ through **loop** diagrams, with predicted $B(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ at $m_H = 125.09$ GeV; The BR measurements are important for probing the Higgs properties, and for validating SM/BSM theories



- Z to **leptonic decays (e, μ)** can be **efficiently triggered** and **clearly distinguished** from background; In addition, $H \to Z(\to ll)\gamma$ can be reconstructed with **good invariant mass resolution** and relatively **small backgrounds**

- In the previous publications, no significant **excess** of events above the **expected background** is observed



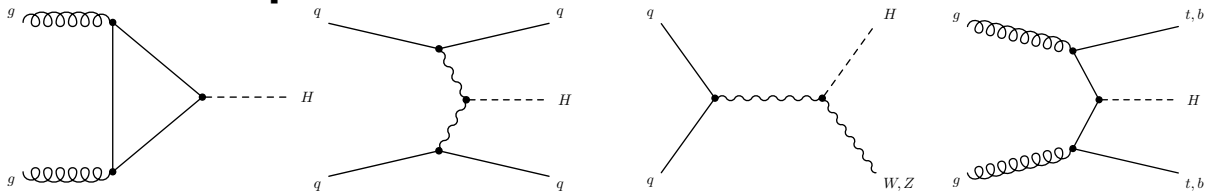


	ATLAS	CMS
Limit of XS x BR at 95% CL	6.6 (5.2) x SM	7.4 (6.0) x SM

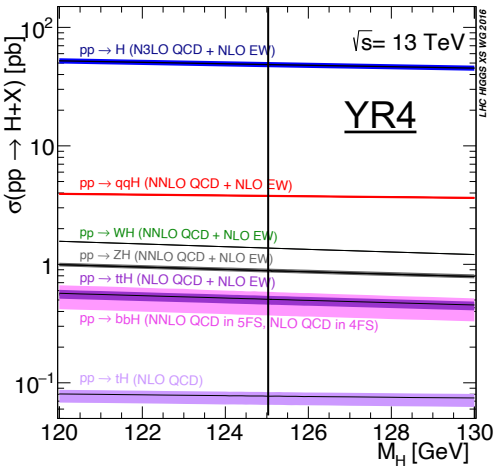
Samples

- An updated search for $H \to Z(\to ll)\gamma$ is presented (Phys. Lett. B 809 (2020) 135754) with **full Run2 data (139 fb^{-1})** at the ATLAS experiment, with important improvements
  - Increase in the **size of dataset**
  - Improved **event categorization**
  - Optimized lepton and photon **ID criteria**

- **MC sample**



- $H \to Z\gamma$ **signal** (PowHeg Pythia8): **ggF, VBF, VH, ttH**
  - **MPIOFF ggF** is used to estimate the **PS** uncertainty
- $H \to \mu\mu$ contamination (QED FSR, ~2%): ggF, VBF, VH, ttH
- **Non-resonant** Sherpa $Z\gamma$
- MG5 **EWK** Zjj (orthogonal to Sherpa $Z\gamma$ at parton level)



Object reconstruction, event selection

- **Trigger** (efficiency: 95.6% for $ee\gamma$; 92.2% for $\mu\mu\gamma$)

Trigger case	Electrons	Muons
Single lepton	$p_{\mathrm{T,lead}} > 27$ GeV, $p_{\mathrm{T,sublead}} > 10$ GeV	$p_{\mathrm{T,lead}} > 27$ GeV, $p_{\mathrm{T,sublead}} > 10$ GeV
Dilepton	$p_{\mathrm{T,lead}} > 18$ GeV, $p_{\mathrm{T,sublead}} > 18$ GeV	$p_{\mathrm{T,lead}} > 24$ GeV, $p_{\mathrm{T,sublead}} > 10$ GeV

- GRL, Hardest PV, EQ

- **Object selection** ($\gamma \geq 1$, e or $\mu \geq 2$, OS)

Cut	Electrons	Muons	Photons
p_{T}	> 10 GeV	> 10 GeV	> 10 GeV
$\lvert\eta\rvert$	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.7$	$\lvert\eta\rvert < 2.37$
	exclude $1.37 < \lvert\eta\rvert < 1.52$	-	exclude $1.37 < \lvert\eta\rvert < 1.52$
$\lvert d_0\rvert/\sigma_{d_0}$	< 5	< 3	-
$z_0 \sin\theta$	< 0.5 mm	< 0.5 mm	-
Identification	Loose	Medium	Loose
Isolation	FCLoose	FCLoose	-

Transition region in EM calorimeter

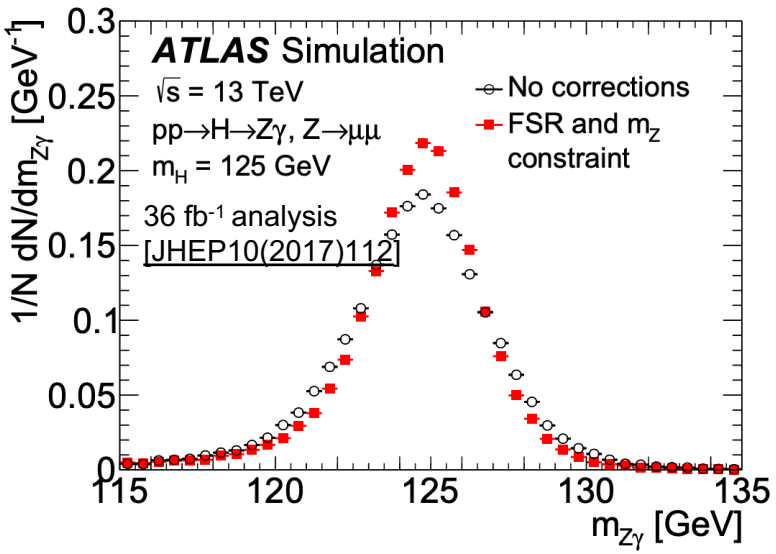
Looser ID cut comparing to the 36 fb^{-1} publication, which was **Medium** $\Longrightarrow$ **higher signal acceptance**

  - **Jet**
    - **EMTopo** clusters using **anti-k_t** algorithm ($\Delta R < 0.4$)
    - $p_T > 25$ GeV, $|\eta| < 4.4$
    - **JVT** cut to suppress **pile-up** effects (efficiency 92%)

- **Overlap removal (selected objects** failing angular cuts ($\Delta\eta$, $\Delta\phi$, ΔR) will be **discarded)**
  - $e - e/\mu$, $\gamma - l$, **jet** $- \gamma/l$

Event selection

- Z candidate**: OS** ee or $\mu\mu$
  - $\mathbf{50 < m_{ll} < 101}$ **GeV before** mass resolution correction
  - **Mass resolution correction** (10 ~ 14%)
    - μ **only**: **FSR** correction
    - **Kinematic fit** correction on m_{ll}
  - $|m_{ll} - m_Z| < \mathbf{10}$ **GeV after** mass resolution correction, $m_Z = 91.2$ GeV; The **closest** di-lepton pair will be selected



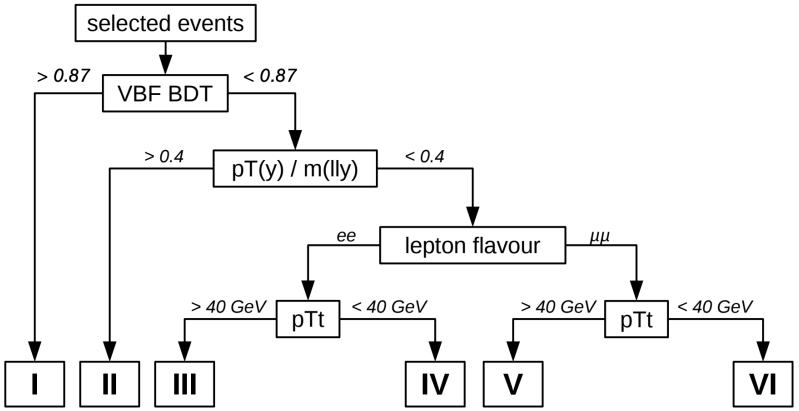
- **Trigger match** on the selected objects

- **Higgs** candidate
  - Z candidate + γ with leading p_T
  - $\mathbf{105 < m_{Z\gamma} < 160}$ **GeV**
  - $\mathbf{p_T^{\gamma}/m_{Z\gamma} > 0.12}$ to suppress background
- SR: **Tight photon ID, FixedCutLoose isolation**

- Total reconstruction/selection **efficiency on signal**: 20.4% $\pm$ 2%

Categorization

- Events are classified into **6 categories** to improve the **sensitivity** of the signal



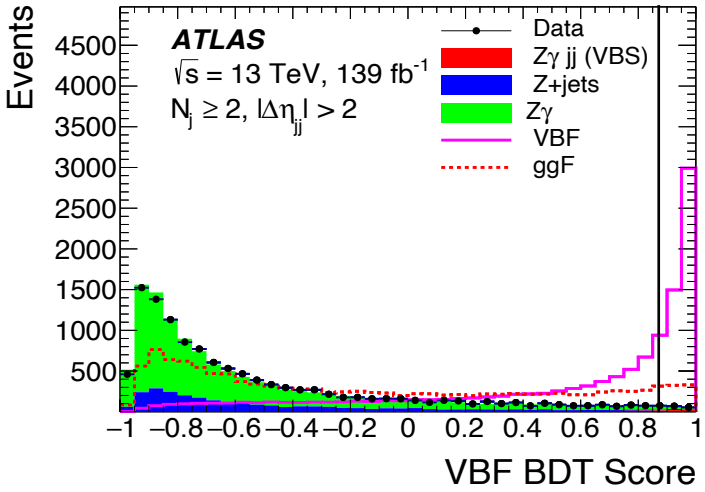
- The **boundaries** of the categories are determined to **maximize the signal significance**

I. VBF-enriched category, trained with **BDT**

- **Precut:** $N_j \geq 2$ (2 **highest** p_T jets are selected), $|\Delta\eta_{jj}| > 2$

Input variable

Variables	Definition
$\Delta\Phi_{Z,\gamma}$	Azimuthal angle between di-lepton system and photon
$\Delta\eta_{jj}$	Pseudo-rapidity separation of dijet
$\Delta R^{min}_{\gamma or Z,j}$	Minimum ΔR between one object of the Zgamma and jets
m_{jj}	Invariant mass of dijet
p_{Tt}	Zgamma p_{T} projected perpendicular to the Zgamma thrust axis
$\eta^{Zeppenfeld}$	$\lvert\eta_{Z\gamma} - 0.5 * (\eta_{j1} + \eta_{j2})\rvert$
$\Delta\Phi_{Z\gamma,jj}$	Azimuthal angle between Zgamma and dijet system



Categorization

- **Signal efficiency ε, fraction f** of each production mode per **category**

	ggF		VBF		WH		ZH		$t\bar{t}H$	
Category	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]
VBF-enriched	0.15	27.5	5.1	71.6	0.11	0.5	0.08	0.2	0.07	0.1
High relative p_{T}	1.1	70.6	2.6	12.9	4.1	7.2	4.1	4.7	7.0	4.6
High $p_{\mathrm{T}t}$ ee	1.7	79.9	2.9	10.8	3.3	4.4	3.4	2.9	3.8	1.9
Low $p_{\mathrm{T}t}$ ee	6.8	93.6	3.5	3.8	3.5	1.3	3.7	0.9	3.1	0.4
High $p_{\mathrm{T}t}$ $\mu\mu$	2.0	79.7	3.6	11.1	4.0	4.4	4.1	2.9	4.3	1.7
Low $p_{\mathrm{T}t}$ $\mu\mu$	8.6	93.6	4.4	3.7	4.5	1.4	4.6	0.9	3.5	0.4
Total efficiency (%)	20.3		22.2		19.5		19.9		21.9	
Expected events	142		12.1		3.8		2.2		1.6	

Dominant

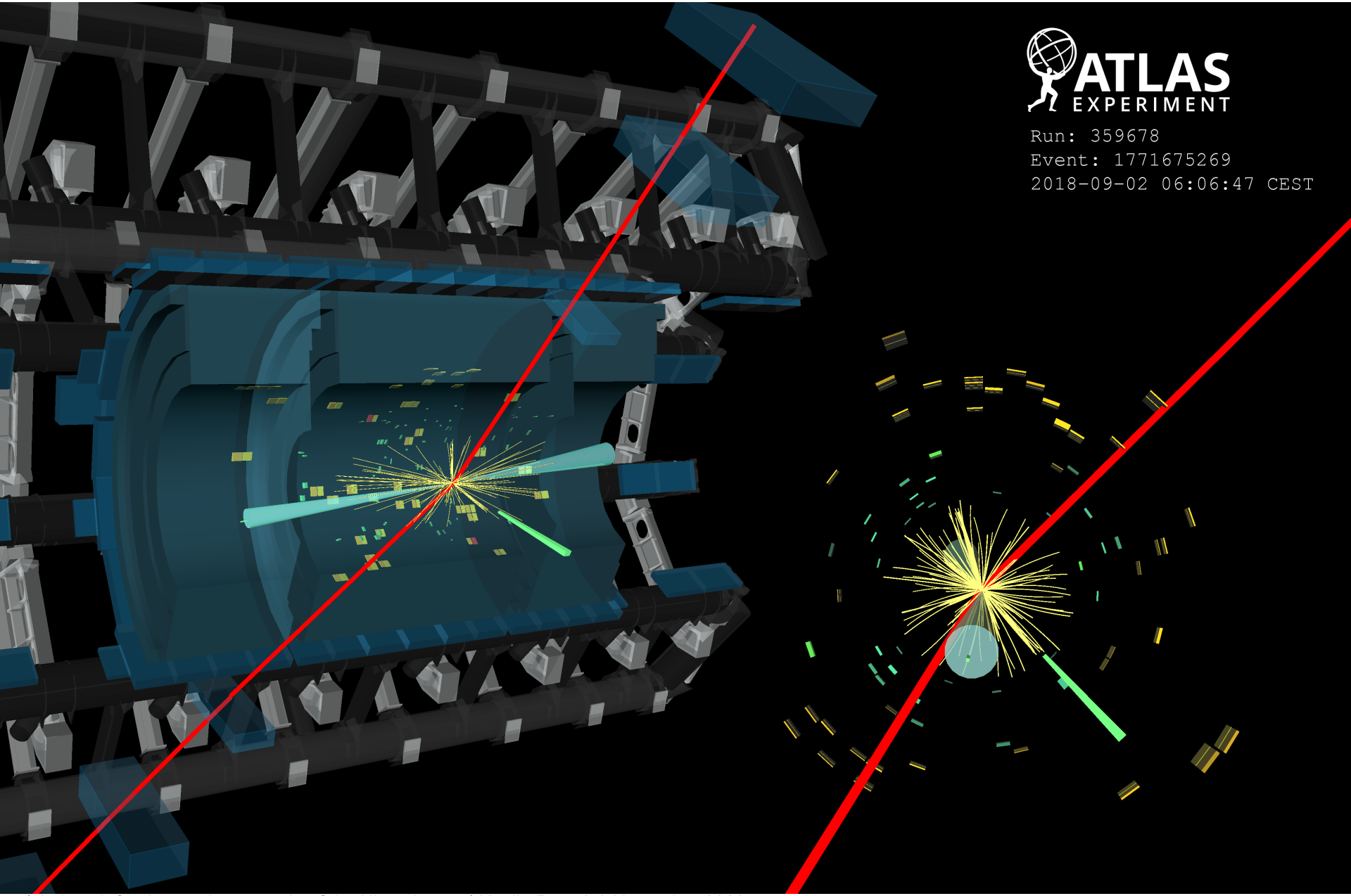
- Expected **signal significance**

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

$$\sqrt{\sum Z_i^2} = 1.3$$

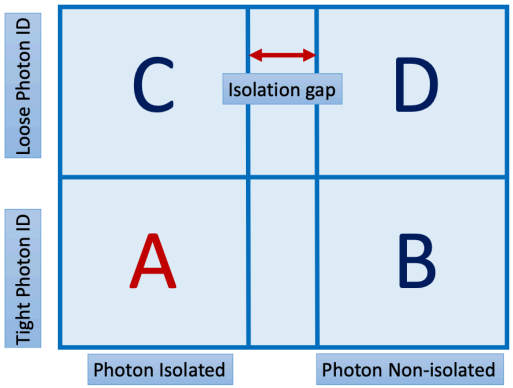
- **Continuum $Z\gamma$** background has on average **lower p_T** of candidate than the signal $\Longrightarrow$ **higher signal significance** in the VBF-enriched, high relative p_T, high p_{Tt} categories
- The **categorization** improves the **sensitivity** by ~50% than the inclusive case

Event display of a VBF-enriched candidate



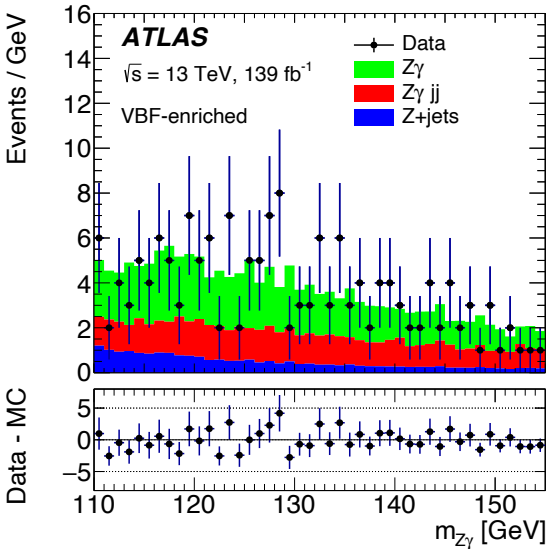
Background composition

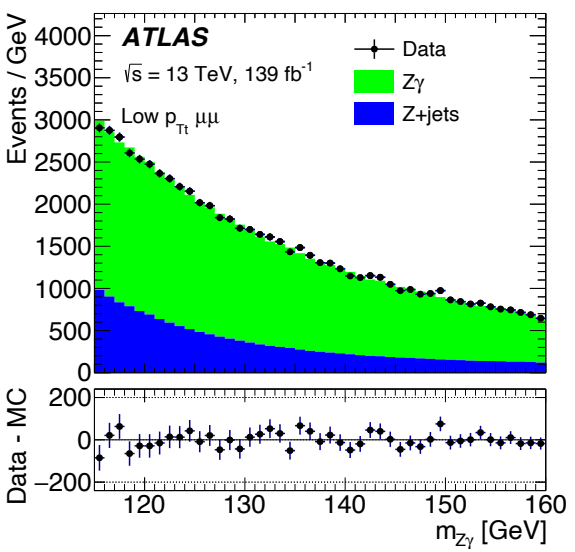
- **Background components: dominant $Z\gamma$**, secondary $Z + j$ where jet is misidentified at photon
- **2D sideband** method is applied to estimate **fractions of background components** based on **photon ID/ISO** performances



- $N_A^{Z\gamma} = N_A^{data} - (N_B^{data} - \boldsymbol{c_B} N_A^{Z\gamma}) \frac{(N_C^{data} - \boldsymbol{c_C} N_A^{Z\gamma})}{(N_D^{data} - \boldsymbol{c_D} N_A^{Z\gamma})} \boldsymbol{R^{Zj}}$
- $\boldsymbol{c_K} \equiv N_K^{Z\gamma} / N_A^{Z\gamma}$, $Z\gamma$ leakage fractions extracted from $\boldsymbol{Z\gamma}$ **MC**
- $\boldsymbol{R^{Zj}} \equiv \frac{N_A^{Zj} N_D^{Zj}}{N_B^{Zj} N_C^{Zj}}$, jet correlation factor between photon **ID/ISO** regions; Obtained from **"prime" region data** (fail photon ISO)
- The fraction of $\boldsymbol{Z\gamma}$ **background** in **inclusive** case is $0.78^{+0.04}_{-0.09}$

- **Data VS background template** with background fraction applied





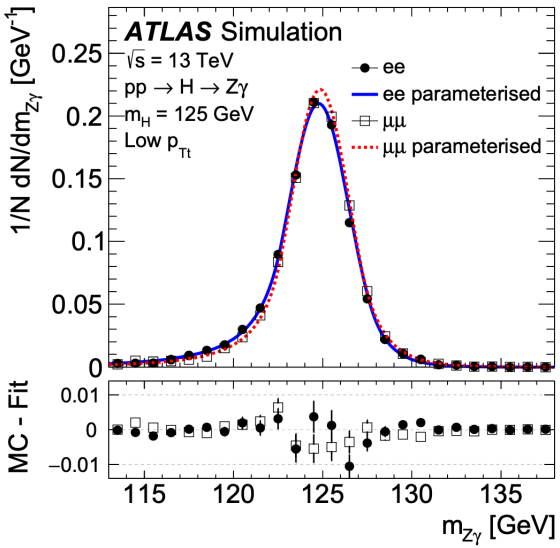
Signal modelling

- The signal and background will be extracted from $m_{Z\gamma}$ **fit in data,** assuming **parametric models** for signal and background
- **Signal**
  - **Acceptance** and **parameters** of the shape are obtained from **MC**
  - Well modeled by **DSCB** function

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\mathrm{Lo}} \le t \le \alpha_{\mathrm{Hi}} \\ \dfrac{e^{-0.5\alpha_{\mathrm{Lo}}^2}}{\left[\frac{\alpha_{\mathrm{Lo}}}{n_{\mathrm{Lo}}}\left(\frac{n_{\mathrm{Lo}}}{\alpha_{\mathrm{Lo}}} - \alpha_{\mathrm{Lo}} - t\right)\right]^{n_{\mathrm{Lo}}}} & \text{if } t < -\alpha_{\mathrm{Lo}} \\ \dfrac{e^{-0.5\alpha_{\mathrm{Hi}}^2}}{\left[\frac{\alpha_{\mathrm{Hi}}}{n_{\mathrm{Hi}}}\left(\frac{n_{\mathrm{Hi}}}{\alpha_{\mathrm{Hi}}} - \alpha_{\mathrm{Hi}} + t\right)\right]^{n_{\mathrm{Hi}}}} & \text{if } t > \alpha_{\mathrm{Hi}}, \end{cases}$$

$$\Delta m_H = m_{Z\gamma} - \mu_{CB}$$
$$t = \Delta m_H / \sigma_{CB}$$

36 fb^{-1} analysis
[JHEP10(2017)112]



Background modelling

- **Background models** are chosen using **template**, **value of parameters** are determined by fitting $m_{Z\gamma}$ in **data**
- **Template: MC $Z\gamma + Z\gamma jj$, data-driven $Z + j$** (data CR failing photon tight ID), normalized to data with background fractions respectively
- The choice of **analytical model** and **$m_{Z\gamma}$ fit range** are optimized with **spurious signal (SP)** method
  - Perform **S+B** fit to $m_{Z\gamma}$ **background-only** distribution, scan "signal" in [123, 127] GeV
  - The **maximum** number of "signal" is taken as **SP uncertainty**
  - **Criteria** when selecting background function: $N_{SP} < 50\% \cdot \delta S$ (statistical signal uncertainty); Background only fit $P(\chi^2) > 1\%$
  - The optimal **fit range** and **function** are selected to achieve the **highest signal significance** while fitting the expected **S+B** $m_{Z\gamma}$ distribution, including the **SP uncertainty**

Category	Function Type	Fit range [GeV]
VBF-enriched	Second-order power function	110–155
High relative p_{T}	Second-order exponential polynomial	105–155
ee high $p_{\mathrm{T}t}$	Second-order Bernstein polynomial	115–145
ee low $p_{\mathrm{T}t}$	Second-order exponential polynomial	115–160
$\mu\mu$ high $p_{\mathrm{T}t}$	Third-order Bernstein polynomial	115–160
$\mu\mu$ low $p_{\mathrm{T}t}$	Third-order Bernstein polynomial	115–160

Systematic uncertainties

Experimental

Sources	$H \to Z\gamma$	
Luminosity [%]		
Luminosity	1.7	
Signal efficiency [%]		
Modelling of pile-up interactions	0.0–0.2	
Photon identification efficiency	0.8–1.8	< 2.6%
Photon isolation efficiency	0.7–1.9	
Electron identification efficiency	0.0–2.3	< 2.4%
Electron isolation efficiency	0.0–0.1	
Electron reconstruction efficiency	0.0–0.5	
Electron trigger efficiency	0.0–0.1	
Muon selection efficiency	0.0–0.6	< 1.6%
Muon trigger efficiency	0.0–1.6	
Jet energy scale	0.0–3.5	
Jet resolution	0.0–15	
Jet pile-up	0.0–7.5	
Jet flavor	0.0–11	
Signal modelling on σ_{CB} [%]		
Electron and photon energy resolution	0.5–3.4	
Muon – Inner detector resolution	0.0–1.2	< 3.6%
Muon – Muon spectrometer resolution	0.0–3.4	
Signal modelling on μ_{CB} [%]		
Electron and photon energy scale	0.09–0.15	
Muon momentum scale	0.0–0.03	
Higgs boson mass measurement	0.19	
Background modelling [number of spurious signal events]		
Spurious signal	1.5–39	**Dominant:** 28%

Theoretical

Sources	
Total cross-section and efficiency [%]	
ggF Underlying event	1.3
perturbative order	4.7–9.6
PDF and α_s	1.8–2.8
$B(H \to Z\gamma)$	5.7
Total (total cross-section and efficiency)	7.5–11
Category acceptance [%]	
ggF Underlying event	0.1–11
ggF H p_T perturbative order	0.3–0.4
ggF in VBF-enriched category	37
ggF in high relative p_T category	21
ggF in other categories	10–15
Other production modes	1.0–15
PDF and α_s	0.4–3.5
Total (category acceptance)	11–37

- Uncertainty from $\boldsymbol{H \to \mu\mu}$ contamination: 2.1%
- All **systematics** have secondary contributions on the **total uncertainty** due to **large statistical error (80%)**

Statistical procedures

- A **profile-likelihood-ratio** test statistic is used to search for a signal excess above the background by fitting on $\boldsymbol{m_{Z\gamma}}$

$$\mathcal{L}\left((\mu,\boldsymbol{\theta})\middle|\{m^i_{Z\gamma}\}_{i=1..n}\right) = \underbrace{\frac{e^{-N(\mu,\boldsymbol{\theta})}N^n(\mu,\boldsymbol{\theta})}{n!}}_{\text{Poisson term}}\underbrace{\left(\prod_{i=1}^{n} f_{\text{tot}}(m^i_{Z\gamma},\mu,\boldsymbol{\theta})\right)}_{\text{PDF of } m_{Z\gamma} \text{ distribution}} \times \boxed{G(\boldsymbol{\theta}) \text{ Constraint term of NP}}$$

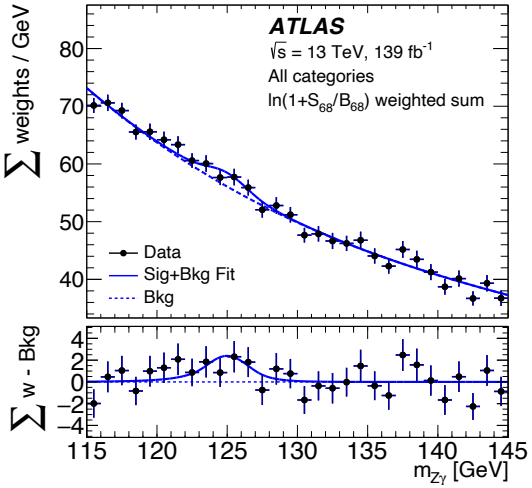
$$f_{\text{tot}}(m^i_{Z\gamma},\mu,\boldsymbol{\theta}) = \frac{1}{N}\sum_c \Big\{\Big[N^{(c)}_{\text{sig}}(m_X,\mu,\boldsymbol{\theta}_{\text{sig}}) + N^{(c)}_{\text{spur}}(m_X,\theta_{\text{spur}})\Big] \times f^{(c)}_{\text{sig}}(m^i_{Z\gamma},\boldsymbol{\theta}_{\text{sig}}) + N^{(c)}_{H\mu\mu}(m_X,\theta_{H\mu\mu}) \times f^{(c)}_{H\mu\mu}(m^i_{ll\gamma}) + N^{(c)}_{\text{bkg}} \times f^{(c)}_{\text{bkg}}(m^i_{Z\gamma},\boldsymbol{\theta}_{\text{bkg}})\Big\}$$

- **Upper limits** are set on $\sigma(pp \to H)\times B(H \to Z\gamma)$ at **95% CL** using asymptotic approximation

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \text{for } \mu \geq \hat{\mu} \\ 0 & \text{for } \mu < \hat{\mu} \end{cases} \quad \text{with} \quad \tilde{\lambda}(\mu) = \begin{cases} \ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & \text{for } \hat{\mu} \geq 0 \\ \ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\theta}(0))} & \text{for } \hat{\mu} < 0 \end{cases}$$

Result

- **Weighted sum plot** of all categories with fitted S+B model



Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_{T}	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High $p_{\mathrm{T}t}$ ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low $p_{\mathrm{T}t}$ ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High $p_{\mathrm{T}t}$ $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low $p_{\mathrm{T}t}$ $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

Signal strength compatibility amongst all categories: ***p*-value 77%**

- $\mu = \frac{\sigma \times B}{(\sigma \times B)^{SM}} = 2.0 \pm 0.9(stat.)^{+0.4}_{-0.3}(syst.) = 2.0^{+1.0}_{-0.9}(tot.)$
- Expected $\mu = 1.0 \pm 0.8(stat.) \pm 0.3(syst.)$

- **95% CL limit on μ**: 3.6 (2.6) × SM, assuming **SM Higgs decays to $Z\gamma$** in the expected results
- **95% CL limit on $\sigma(pp \to H) \times B(H \to Z\gamma)$**: 305 fb
- **95% CL limit on $B(H \to Z\gamma)$***:* 0.55%, assuming SM Higgs production XS

- Total uncertainty is dominated by **statistical error**
- Dominant **systematics: SP uncertainty**

- Besides the increase in size of the dataset, there're **extra 20% improvement** in **expected sensitivity** compared with the 36 fb^{-1} publication due to **improved analysis strategy** (optimal object recommendation, improved categorization, …)

Summary

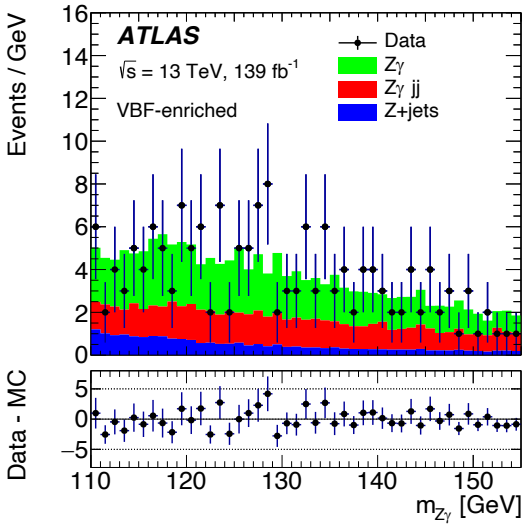
- A search for **SM $H \to Z\gamma$** decay with 139 fb^{-1} dataset recorded by the ATLAS detector is presented in Phys. Lett. B 809 (2020) 135754

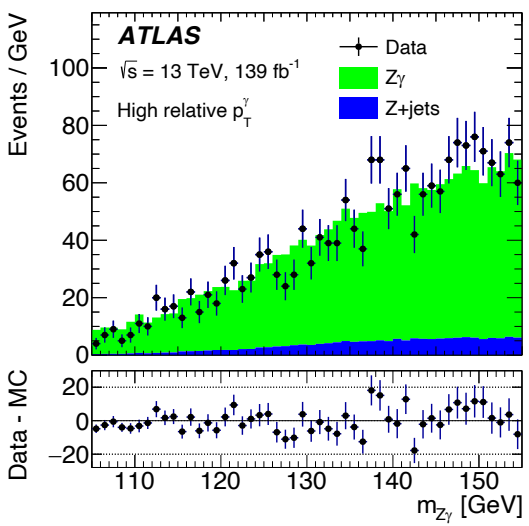
- $\mu = \frac{\sigma \times B}{(\sigma \times B)^{SM}} = 2.0^{+1.0}_{-0.9}(tot.)$, where the **statistical uncertainty** is dominant
- The **observed** data are consistent with the expected **background** with a p-value of 1.3% (**significance:** 2.2σ); The **expected p-value** is 12.3% (**significance:** 1.2σ)
- The **observed 95% CL upper limit** on the $\sigma(pp \to H) \cdot B(H \to Z\gamma)$ is 3.6 × SM for $m_H = 125.09$ GeV; **The expected limit** assuming **SM $H \to Z\gamma$ decay** is 2.6 × SM

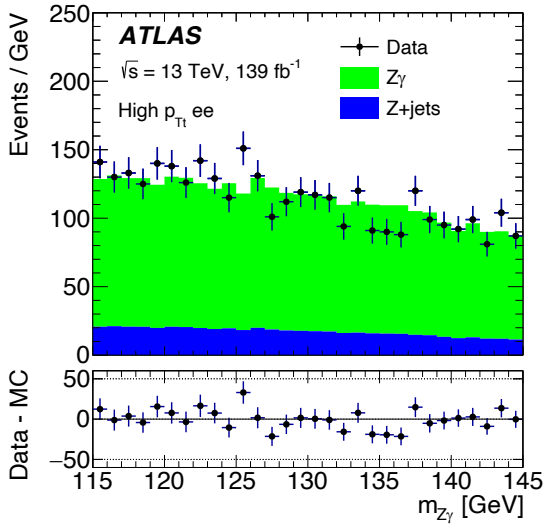
- There're **extra 20% improvement** in **expected sensitivity** compared with the 36 fb^{-1} publication just from **the optimized analysis strategy**

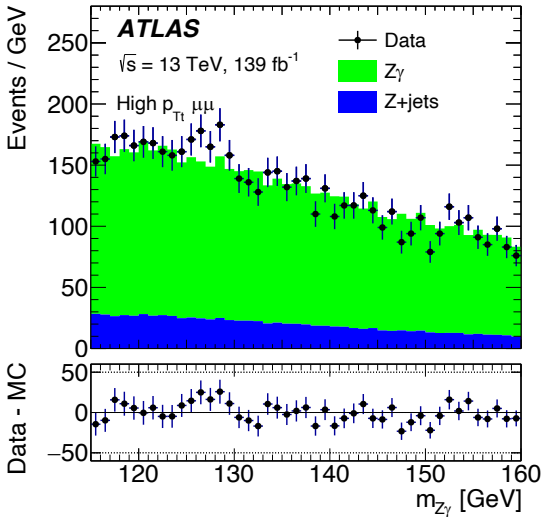
Backup

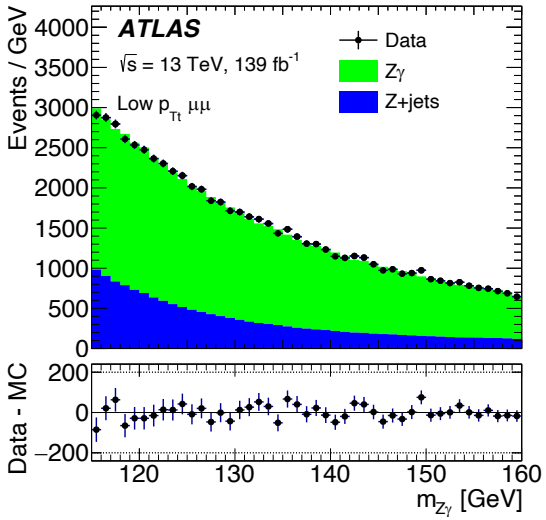
Data VS background template

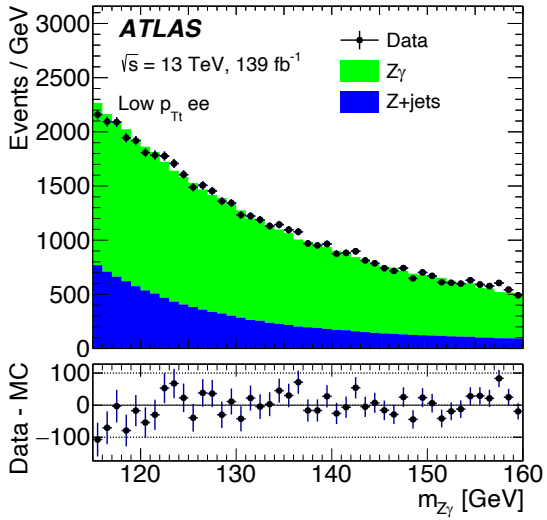




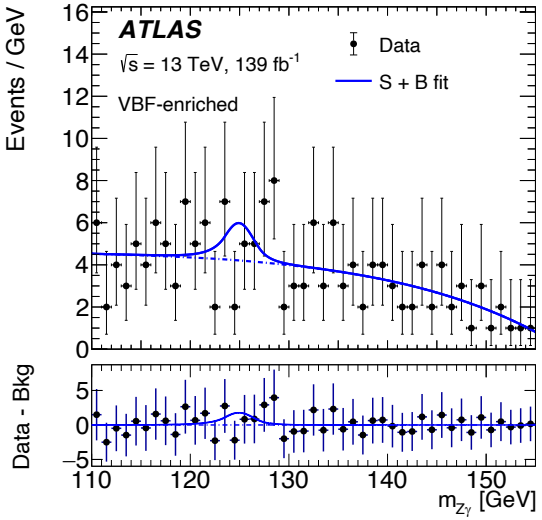


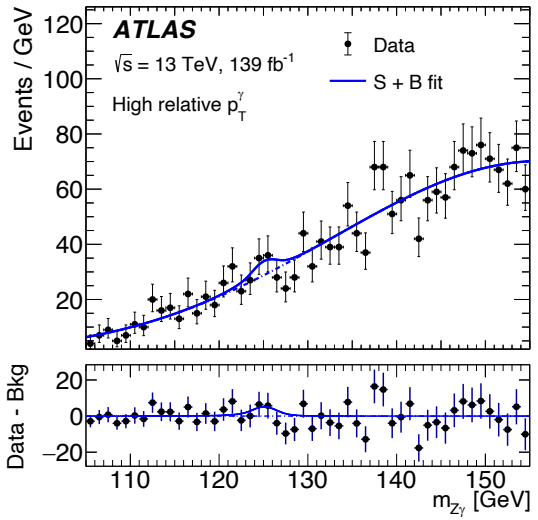


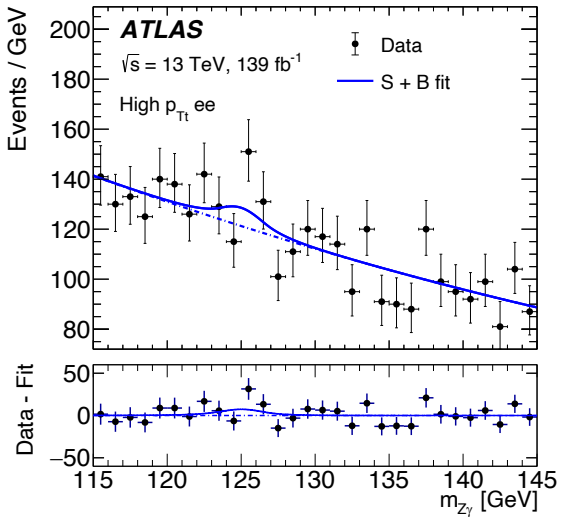


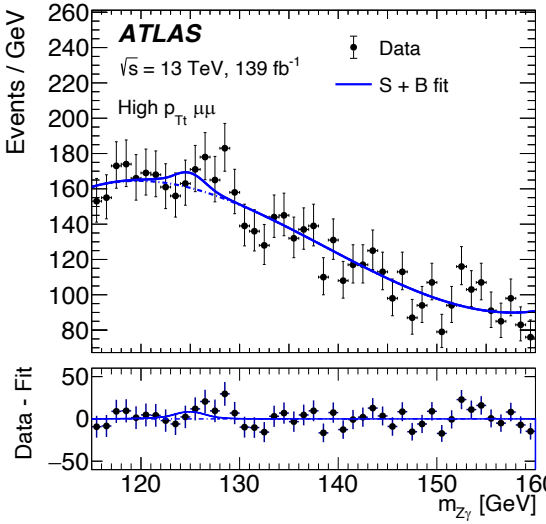


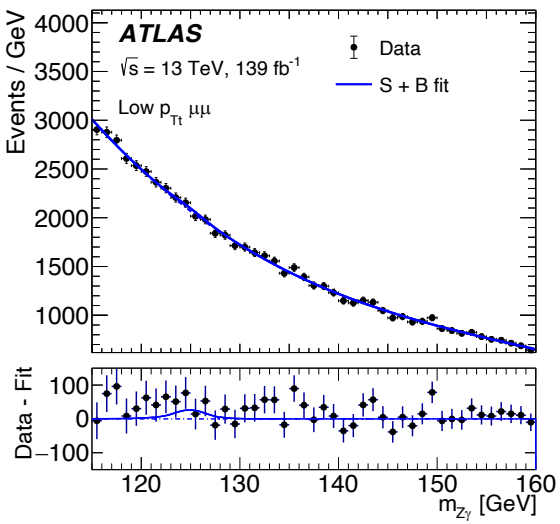
S+B fit in data

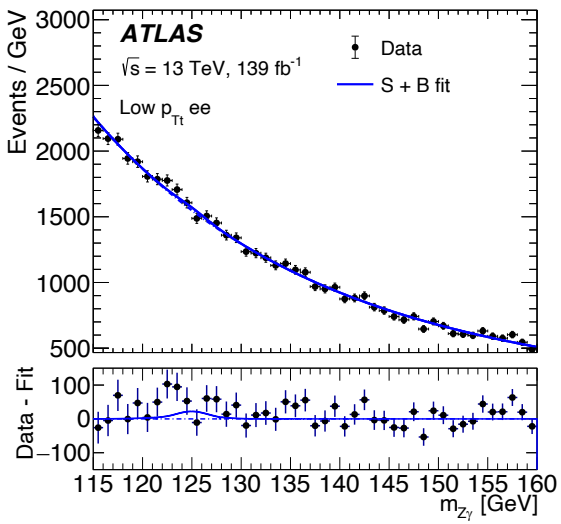












HL-LHC projection