Search for the $Z\gamma$ decay mode of the Higgs boson and for new high-mass resonances in pp collisions at 13TeV with the ATLAS detector

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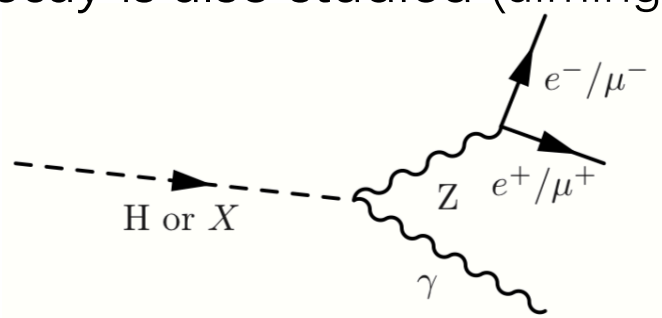
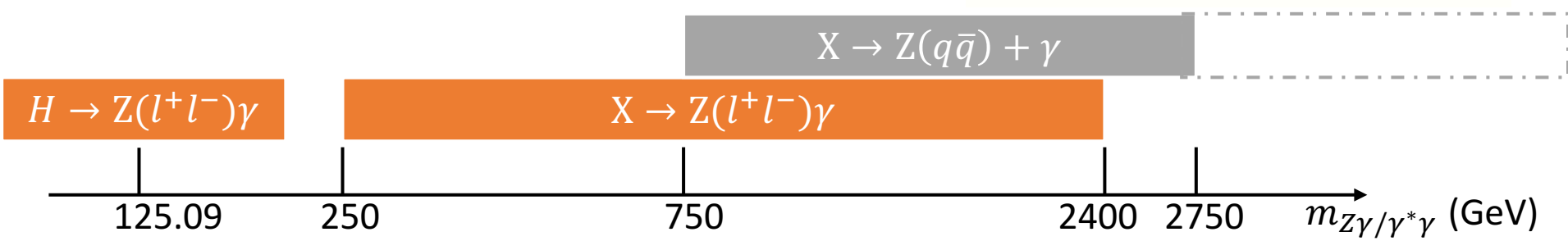
Introduction

- **Searches in $Z\gamma$ channel**
  - **$\mathbf{H} \rightarrow Z\gamma$ decay** which is rare decay of SM Higgs boson
  - **High-mass resonance search** based on many theoretical models introducing a new BSM boson
- For both searches, Z lepton-decay modes ($\mathbf{Z} \rightarrow e^+e^-/\mu^+\mu^-$) are studied due to less background contamination
  - >99% background events are non-resonance $Z+\gamma, Z+jet$
  - In extra-high-mass region, Z hadronic decay is also studied (aiming for new paper, details in backup)





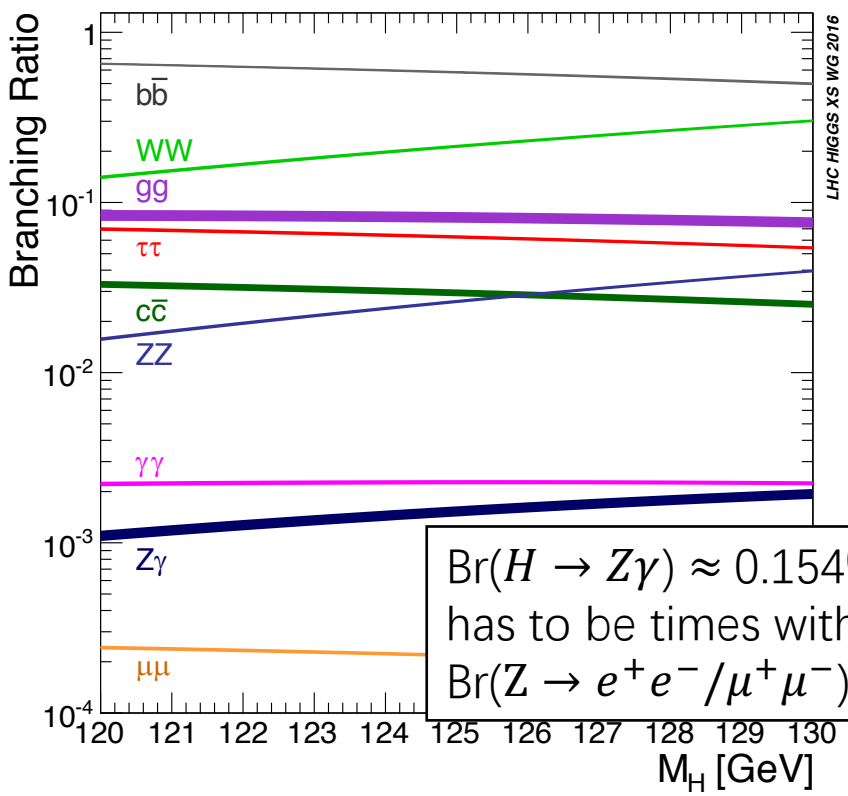
Higgs search: Introduction

$H \to Z(e^+e^-/\mu^+\mu^-)\gamma$

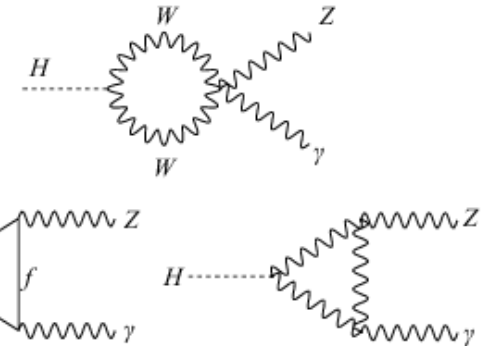
$m_{Z\gamma/\gamma^*\gamma}$ (GeV)

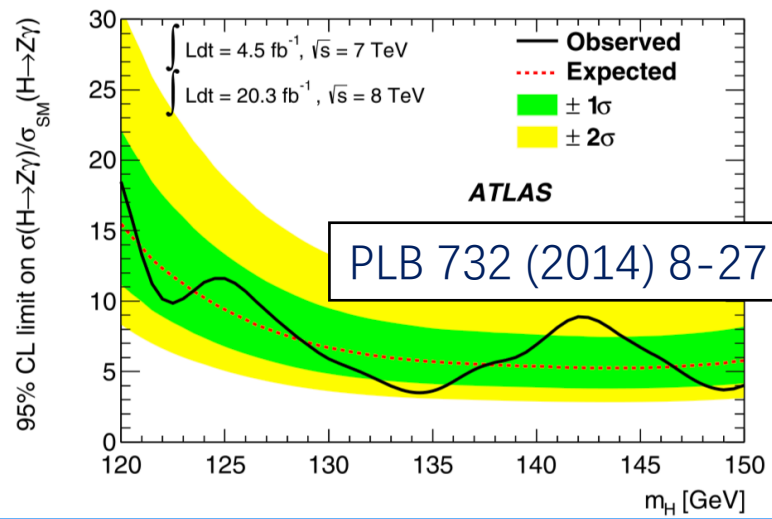
125.09

- **Higgs search:**
- SM search @ 125.09GeV, the branching ratio in this channel is expected to be modified in some BSM theories
- **Run1 7+8TeV:** Set limit at 95% CL on $\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$ at 120-150GeV



$Br(H \to Z\gamma) \approx 0.154\%$, but it has to be times with the $Br(Z \to e^+e^-/\mu^+\mu^-) \approx 6.6\%$





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Higgs search : event selection

- **Data : 3.2 fb^{-1}** 2015 data **+ 32.9 fb^{-1}** 2016 data
- **Resonance search strategy:**

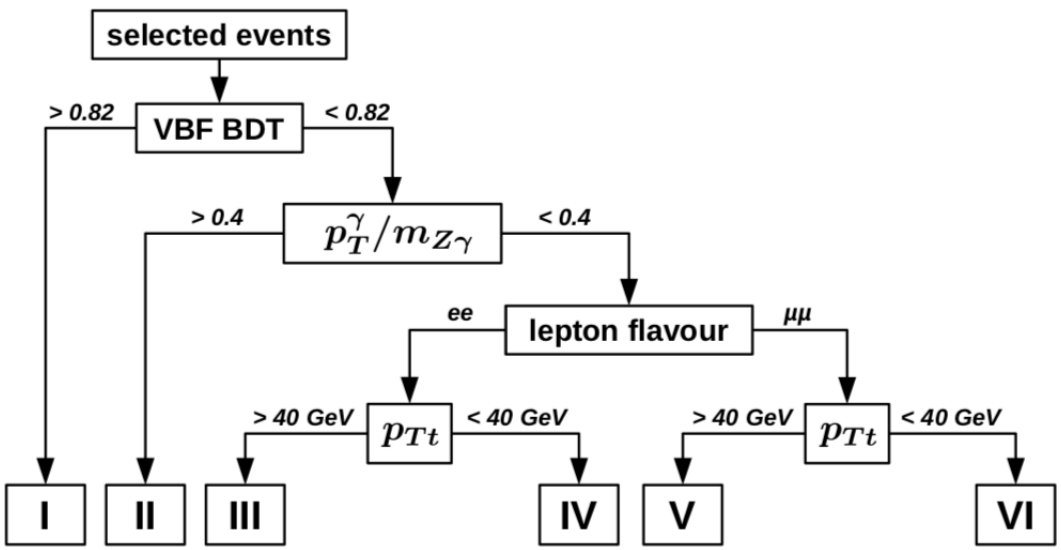
$$\sigma_{pp\to H}\times Br_{H\to Z\gamma} = \frac{N_{obs}}{Lumi.\times\varepsilon_H\times Br_{Z\to e^+e^-/\mu^+\mu^-}}$$

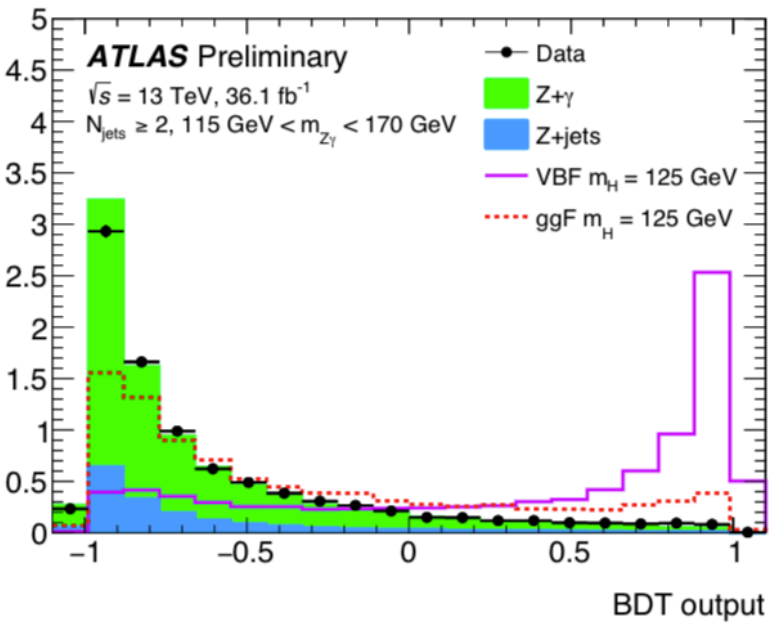
$$\mu = \frac{\sigma\times Br}{(\sigma\times Br)_{SM}}$$

- **Event selection:**
  - **Photon:** p_T > 15GeV, tight-ID, isolated
  - **Single e/μ:** $|d0/\delta_{d0}|, |\eta|$ cuts, p_T >10GeV, medium ID, isolated
  - **$e^+e^-/\mu^+\mu^-$ pair :** single/di-lepton triggers, opposite sign, Z mass window
  - **Jet (for VBF category):** p_T > 25GeV, $|\eta|$<4.4, JVT
  - **Overlap removal:**
    - **Muon in muon:** ΔR<0.02 **Electron in electron**: Δη < 0.075 ; Δφ < 0.125;
    - **Electron in muon:** ΔR < 0.02 **photon in electron/muon:** ΔR < 0.3
    - **Jet in photon/electron/muon:** ΔR < 0.3

Higgs search : categorization

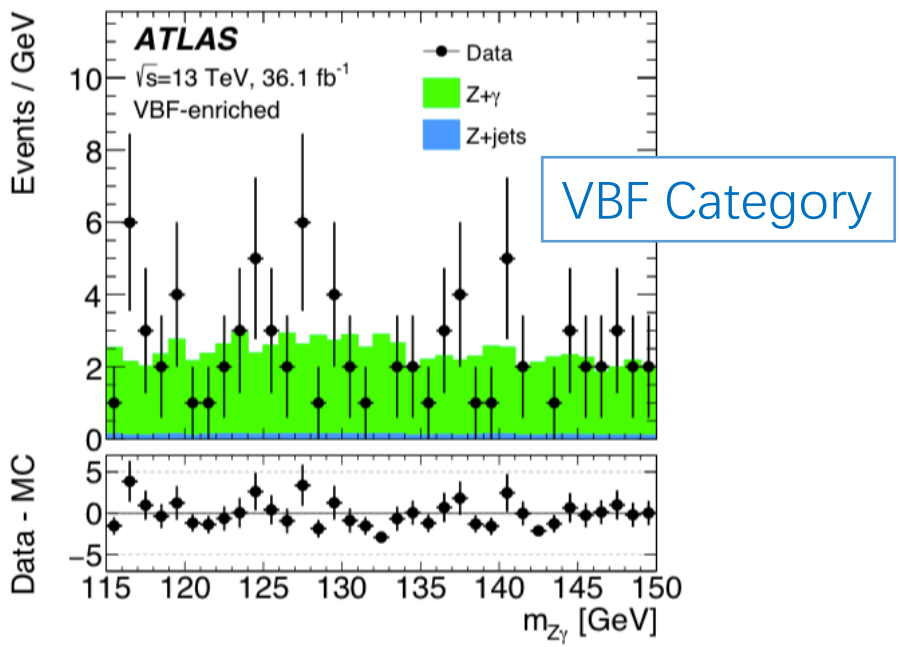
- **6 Categories:**
  - Five cut-based optimized categories based on $p_{Tt}^{Z\gamma}$ and $\frac{p_T^{\gamma}}{m_{Z\gamma}}$
  - One VBF enriched category based on the boosted decision tree (BDT) response
    - 6 jet kinematic variables $(m_{jj}, \Delta\phi_{Z\gamma,jj} \ldots)$ used in BDT method



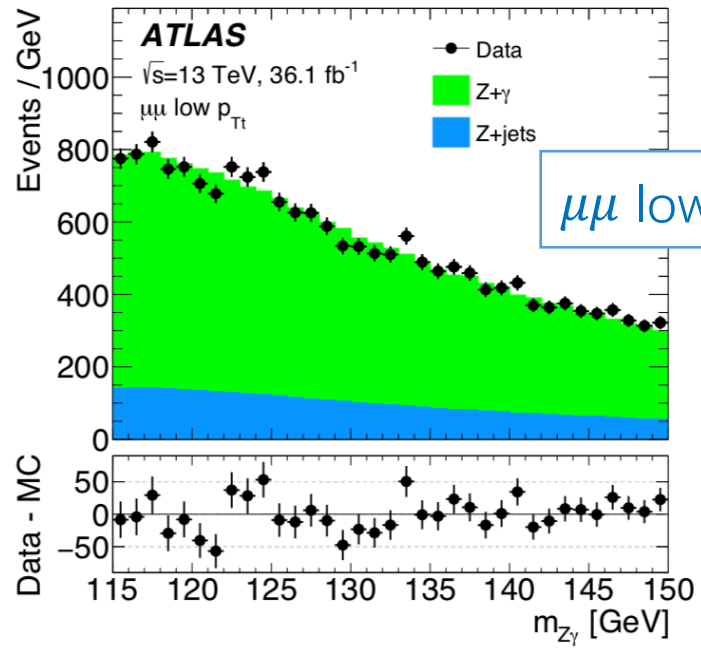


Higgs search : backgrounds

- **Main background:** $Z+\gamma, Z+jet$
  - **Z+γ description:** High-stat MC
  - **Z+jet description:** Data-driven shape from the control region of photon selection
  - **Decomposition (inclusive):** Z+γ (84%), Z+jet (16%)



VBF Category



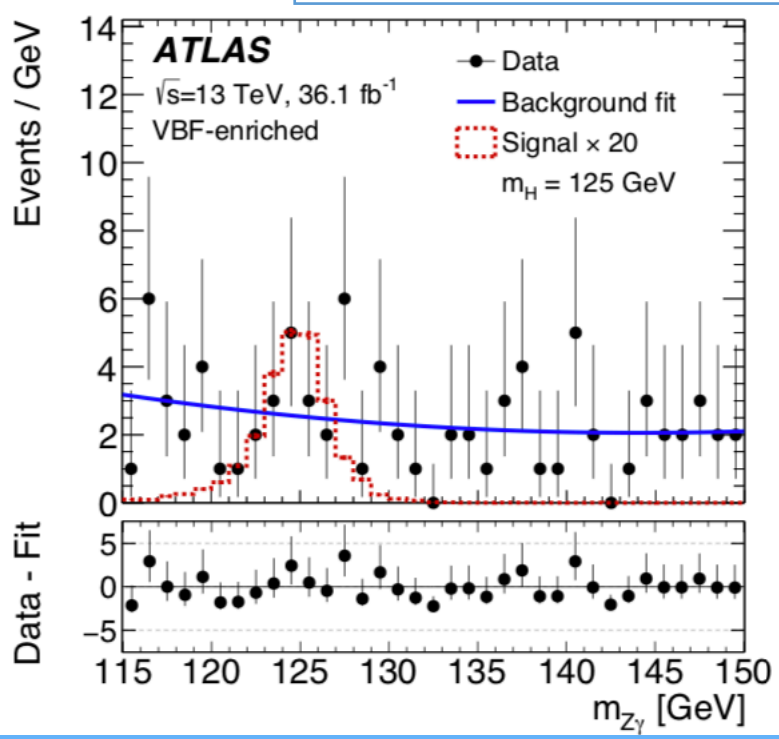
$\mu\mu$ low $p_{Tt}^{Z\gamma}$

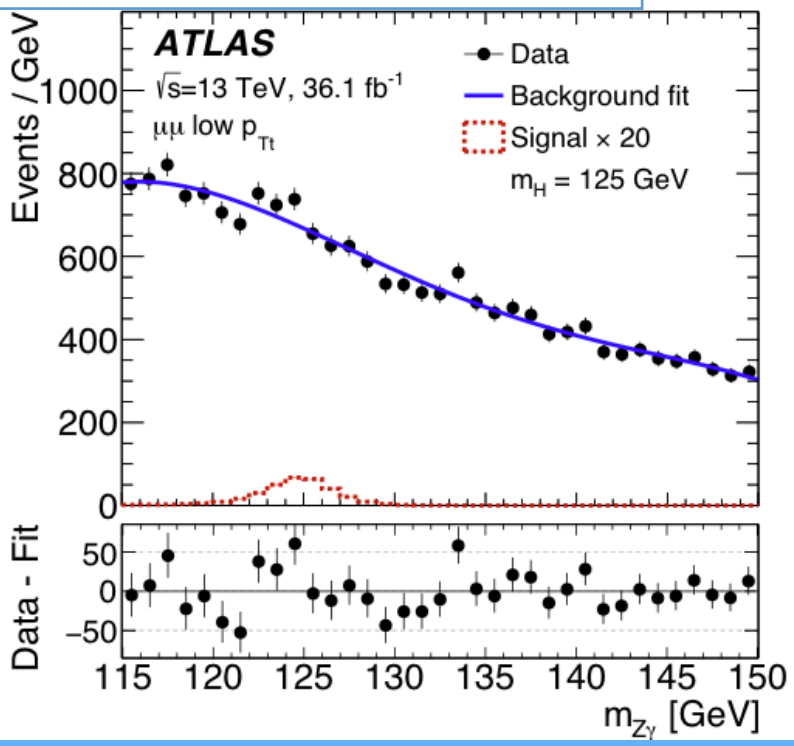
Higgs search : S+B fit

S+B fit on $Z\gamma$ mass with SM Higgs (ggH, VBF, VH)

- **Fit 115-150GeV, signal search @ 125.09GeV**
- **Signal Function:** Double-sided crystal ball (DSCB)
- **Background:** analytic parameterization from MC/pseudo-data

31233 events in total between 115-150GeV





Higgs search : Results

- **No significant excess found**
- Set limit at 95% CL on μ *and* $\sigma_{pp\to H}\times Br_{\mathrm{H}\to Z\gamma}$ @ 125.09GeV
- **Main uncertainties on limit:**
- Background bias (2%-25% on signal yield), underlying event (3%-25% on signal yield)

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	Limit on μ	Limit on $\sigma(\mathrm{H}\to Z\gamma)$	Local significance
Observed	6.6	547fb	-
SM expected	5.2	-	0.5 σ
Bkg-only expected	4.4	-	1.0 σ

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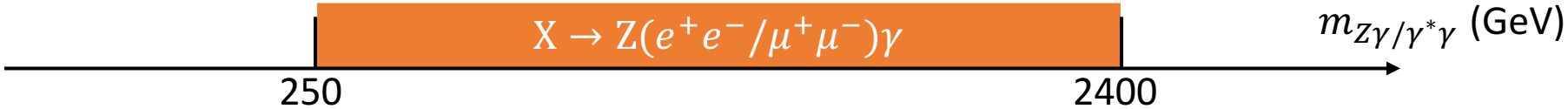
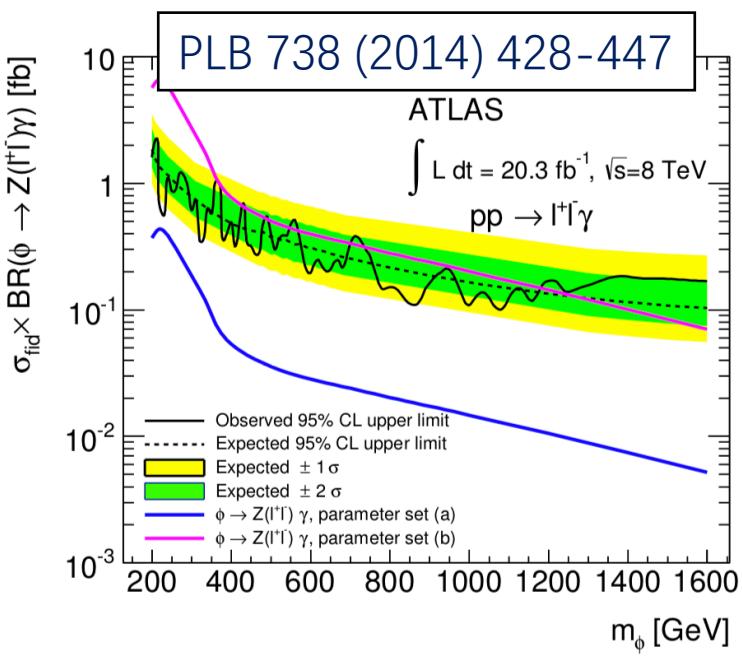
	Limit on μ
Run1 Bkg-only expected	9

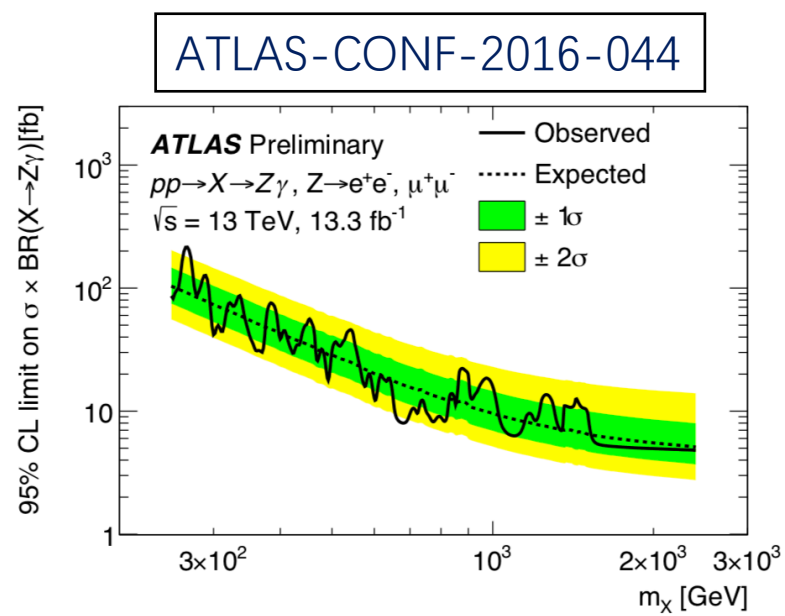
55% gain in exclusion sensitivity
20% gain taking into higher lumi and Xs of Run2

High-mass search: Introduction



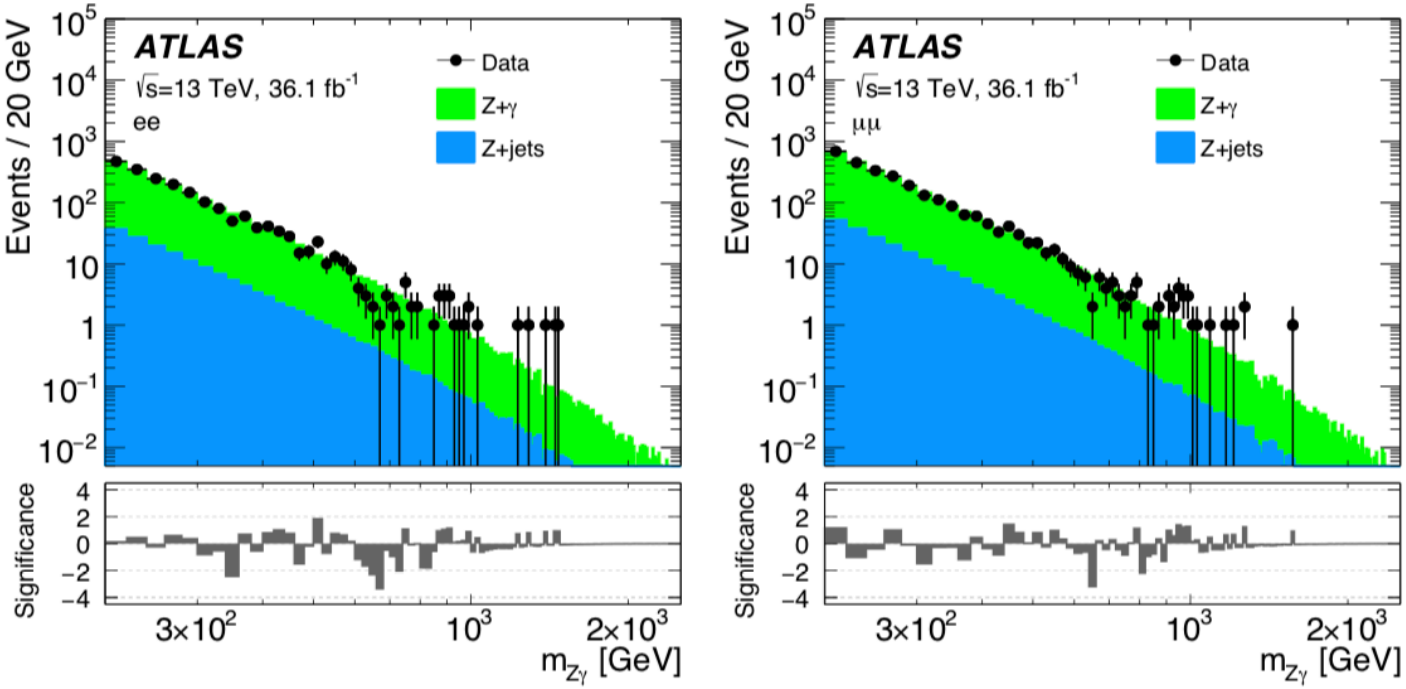
- **High-mass search** for a new BSM boson in 250-2400GeV, this search is model-independent search, but optimized with either an extension of Higgs sector or additional gauge fields
- **Run1 8TeV:** set limit at 95% CL on $\sigma_{fid} \times Br_{\phi \to Z\gamma}$, between 200-1600GeV
- **Run2 13TeV 13.3fb^{-1}:** set limit at 95% CL on $\sigma_{pp \to X} \times Br_{X \to Z\gamma}$, between 250-2400GeV





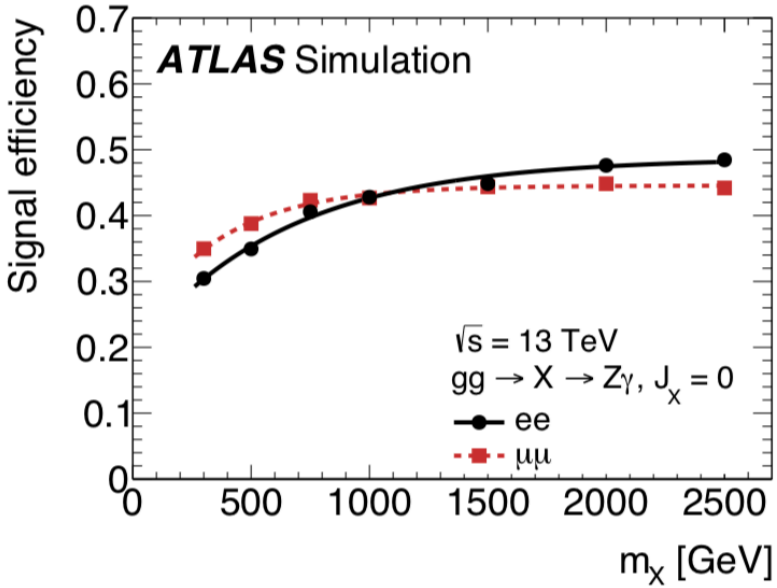
High-mass: selection/categorization

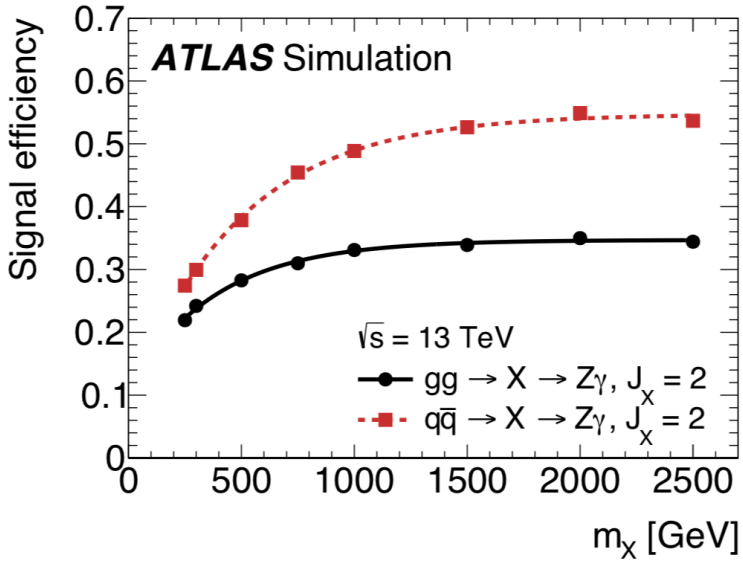
- Data (36.1fb^{-1})
- **Resonance search strategy:** $\sigma_{pp\to X}\times Br_{X\to Z\gamma} = \frac{N_{obs}}{Lumi.\times\varepsilon_X\times Br_{Z\to e^+e^-/\mu^+\mu^-}}$
- **Event selection:**
  - **Photon:** $p_T > 0.3*m_{Z\gamma}$ **Other selections:** same as Higgs search
- **Categorization:** $\mathrm{Z}\to e^+e^-$ *and* $\mathrm{Z}\to\mu^+\mu^-$
- Main background ($Z+\gamma, Z+jet$)



High-mass: Sig-parameterization

- **The search is model independent, while signal efficiencies are parameterization based on the following models**
- **Signal models:**
  - Narrow-width spin-0 boson via gluons fusion
  - Narrow-width spin-2 boson via gluons fusion
  - Narrow-width spin-2 boson from $q\bar{q}$ initial state
- The result (limit setting) will be studied for both the 3 models



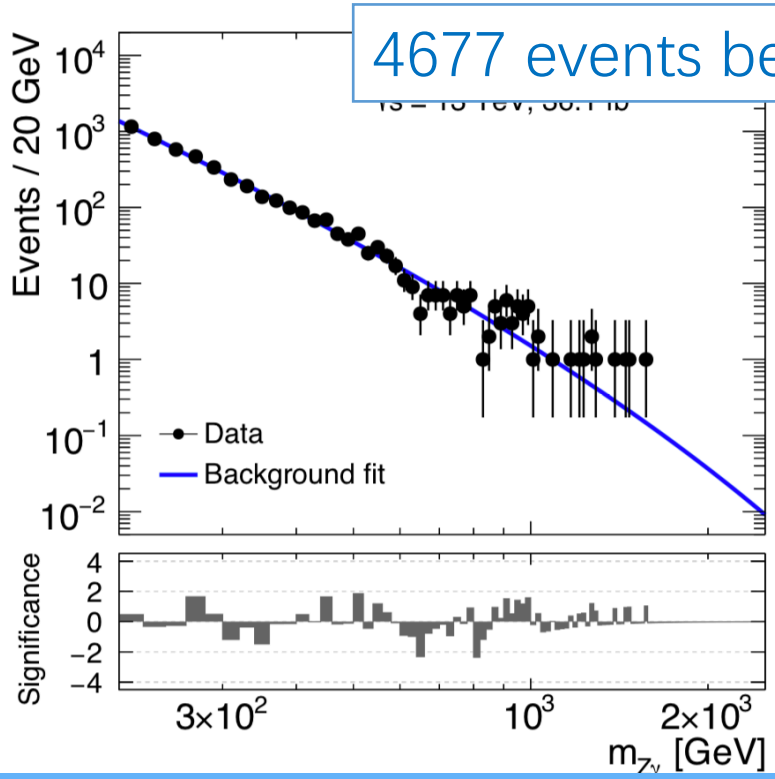


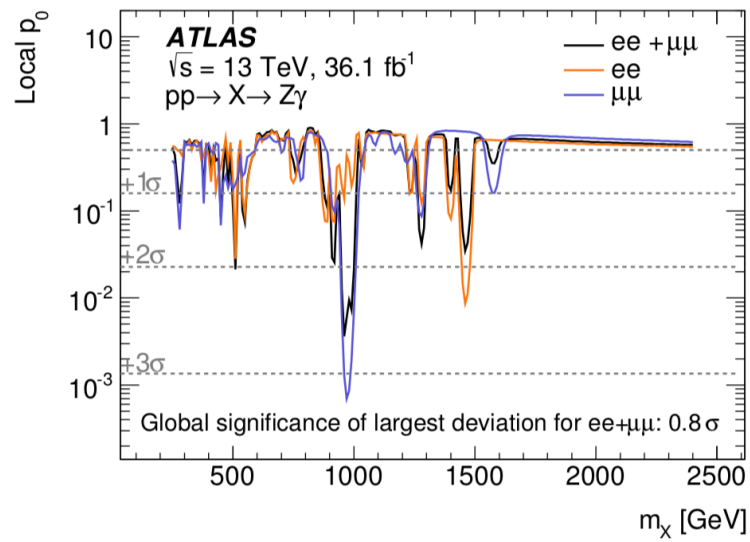
High-mass: S+B fit

S+B fit on $Z\gamma$ mass with X boson (narrow-width, spin-0/spin-2)

- **Fit 200-2500GeV, search 250-2400GeV**
- **Signal Function:** DSCB parametrized with mass
- **Background:** analytic parameterization
- **Largest local significance:** ~2.7σ @ 960GeV

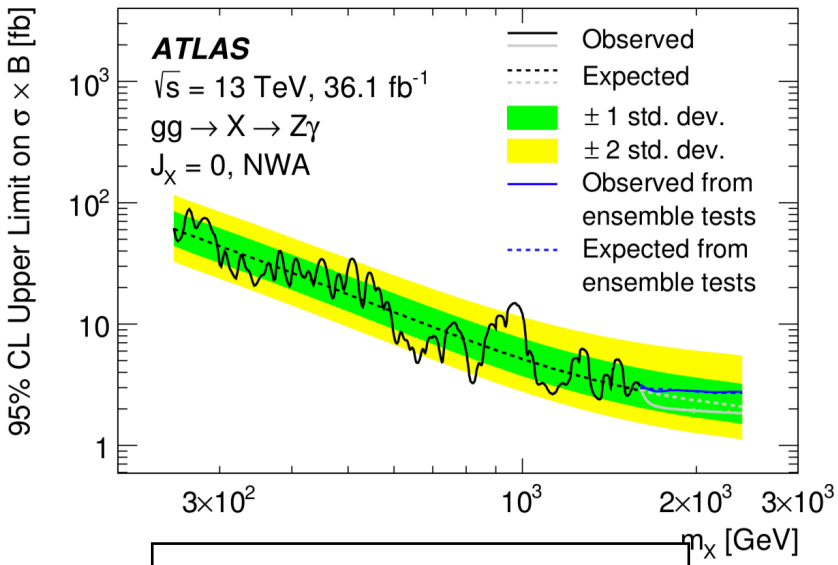
4677 events between 200-2500GeV





High-mass search: Results

- **No significant excess found**
- Set limit at 95% CL on $\sigma_{pp\to X}\times Br_{X\to Z\gamma}$ in 250-2400GeV, with 3 signal models (ggX spin0, ggX spin2, qqX spin2)
- **Main uncertainties on limit:**
- e/gamma resolution (4-30% on signal width), background bias (0-6% on signal yield)



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Upper 95% CL limits on $\sigma_{pp\to H}\times Br_{H\to Z\gamma}$			
	$gg \to X$ **spin-0**	$gg \to X$ **spin-2**	$qq \to X$ **spin-2**
Exp. high	61 fb	82 fb	66 fb
Exp. low	2.1 fb	2.7 fb	1.7 fb
Obs. high	88 fb	117 fb	94 fb
Obs. low	1.8 fb	2.4 fb	1.5 fb

Summary

- **With Run-II 13TeV, 36.1fb^{-1} DATA:**

- **Search for SM Higgs** decaying into Z boson ($\mathrm{Z} \rightarrow e^+e^-/\mu^+\mu^-$) and γ @ 125.09GeV
  - No excess found, set limit on μ *and* $\sigma_{pp\rightarrow H} \times Br_{\mathrm{H}\rightarrow Z\gamma}$
  - **Next:** update to full Run-II data, re-optimize selection/categorization (e.g. matrix element method), combination with Run-I/CMS

- **Search for heavy resonance** decaying into Z boson ($\mathrm{Z} \rightarrow e^+e^-/\mu^+\mu^-$) and γ in 250-2400GeV
  - No excess found, set limit on $\sigma_{pp\rightarrow X} \times Br_{\mathrm{X}\rightarrow Z\gamma}$
  - **Next:** update to full Run-II data, extend the search region beyond 2.4TeV by dealing with the boosted effect on di-lepton, combination with Z-hadronic channel/CMS/Run-I

Thank you!

References

- Run1 Higgs search: https://arxiv.org/abs/1402.3051
- Run2 Higgs search: https://arxiv.org/abs/1708.00212

- Run1 High-mass search: https://arxiv.org/abs/1407.8150
- Run2 High-mass search: (2015 data): https://arxiv.org/abs/1607.06363
- Run2 High-mass search (ICHEP): https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-044/
- Run2 High-mass search (2015+2016): https://arxiv.org/abs/1708.00212
- Run2 High-mass Z hadron decay search (2015+2016): https://cds.cern.ch/record/2286912

Hadronic channel: high-mass search

- 2015+2016 data:
  - Paper draft : https://cds.cern.ch/record/2286912
  - Search region 1-6.8TeV, for both spin-0 and spin-2 resonance
  - ATLAS open presentation is done, comments due by 15 Jan. 2018
  - EXOT-2016-30, to be submitted to PRD

- 2015 data:
  - PLB 764 (2017) 11-30 : https://arxiv.org/pdf/1607.06363.pdf
  - Search region 0.75-2.5TeV

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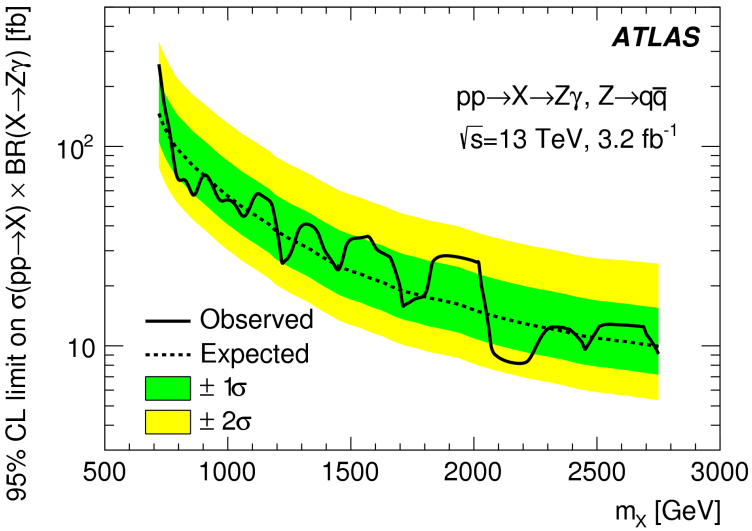
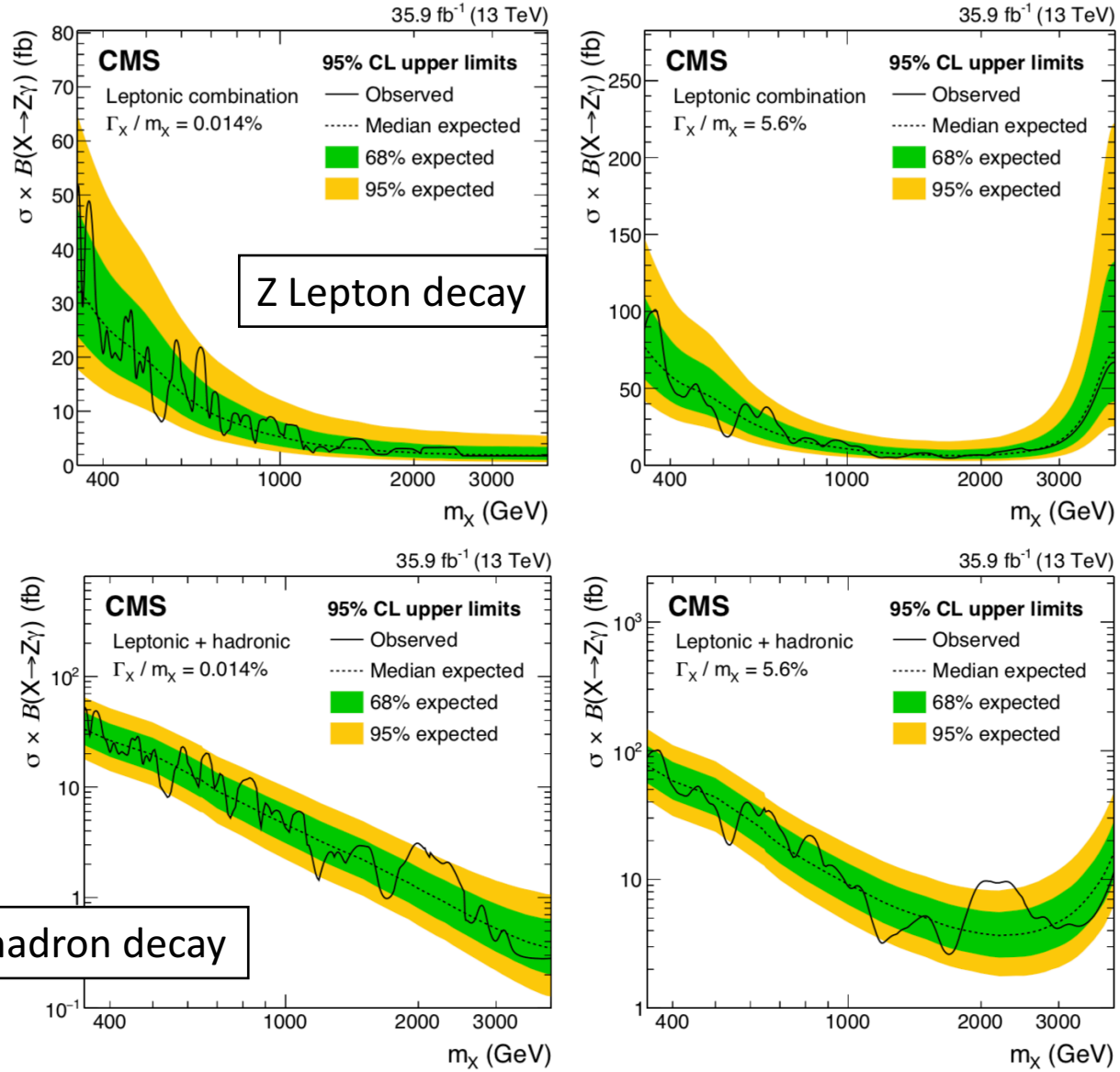


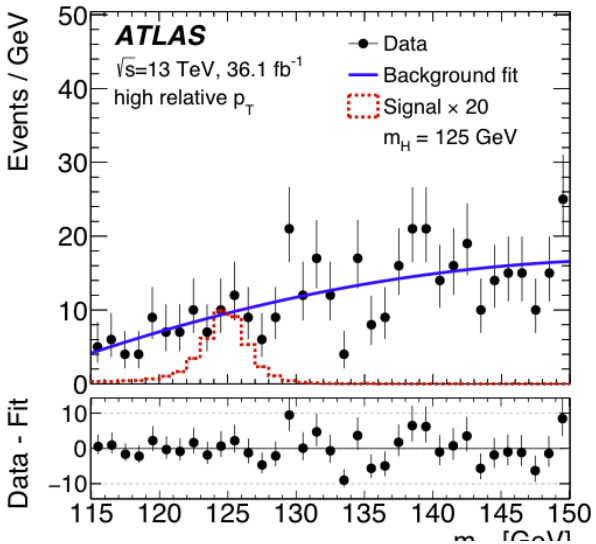
CMS: high-mass search

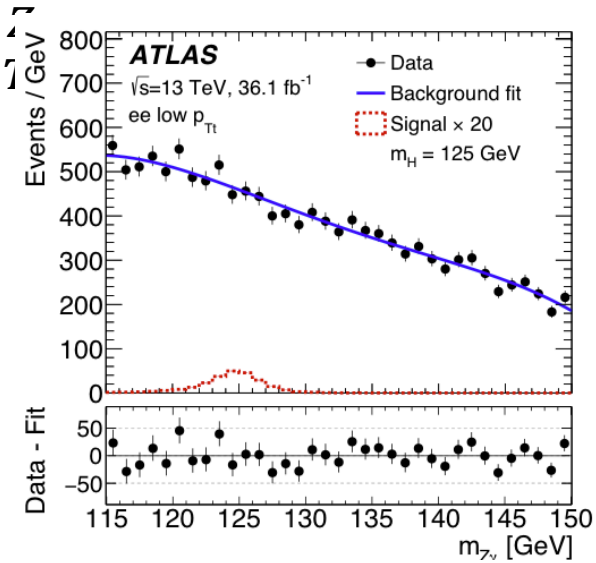
- Paper submitted to JHEP, plots are public
  - https://arxiv.org/pdf/1712.03143.pdf
- Signal:
  - Spin-0, narrow width or 5.6% width
- Z lepton decay: 0.35-4TeV
- Z hadron decay: 0.65-4TeV

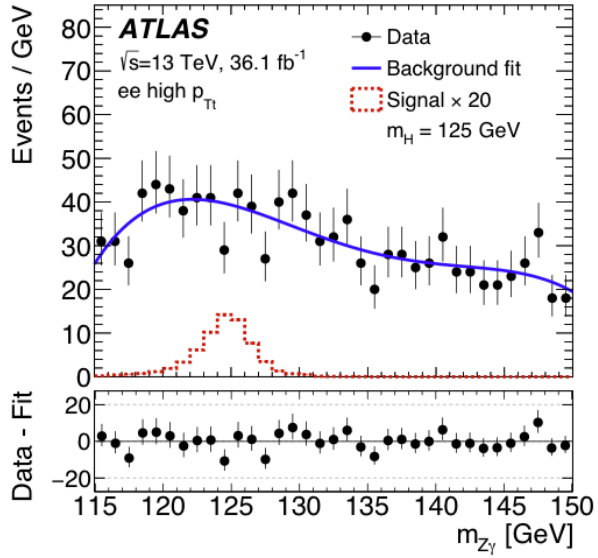


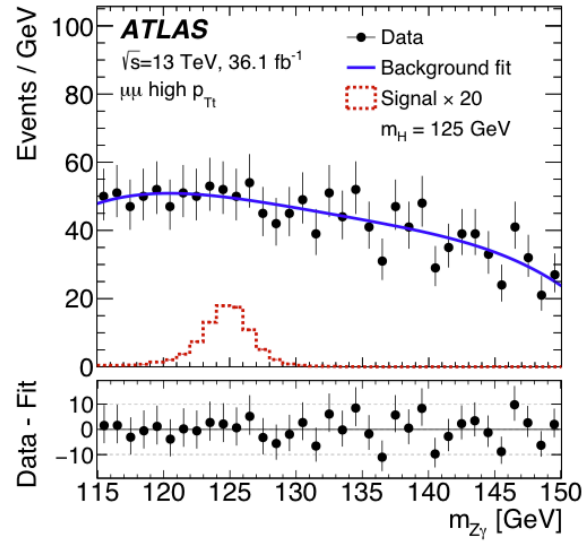
Higgs search : Strategy

- **Background only fits**
- $(m_{jj}, R_{Z/\gamma\_j}$ and p_T^Z









Samples

- **Data**
  - **3.2 fb-1** 2015 data **+ 32.9 fb-1** 2016 data
- **Signal MC**
  - NNLO ggH VBF qqZH WmH WpH 125GeV
  - NWA (Γ=4MeV) spin-0 ggF mass points: 200, 300, 500, 700, 750, 800, 1000, 1500, 2000, 2500 GeV
  - NWA spin-2 ggF/qqX mass points: 200-2500GeV
- **Background MC**
  - **Z+γ** Sherpa **full-sim** in photon pt slices
  - **Z+γ** Sherpa **fast-sim (high-stat)** in $M_{Z\gamma}$ slices (only ICHEP 2016)
  - **Z+jet** Sherpa 2.2 **full-sim** with Pt slices and Jet flavor slices
- **Derivation (HIGG1D2):**
  - at least one photon and two leptons

Selection Criteria

- **Signal/di-lepton trigger** (dividing 2015 and 2016 data)

candidates	channel	single/di-lepton	trigger name
2015 data	$Z(\rightarrow ee)\gamma$	single electron	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium, HLT_e120_lhloose
2015 data	$Z(\rightarrow ee)\gamma$	di-electron	HLT_2e12_lhloose_L12EM10VH
2016 data	$Z(\rightarrow ee)\gamma$	single electron	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
2016 data	$Z(\rightarrow ee)\gamma$	di-electron	HLT_2e17_lhvloose_nod0
2015 data	$Z(\rightarrow \mu\mu)\gamma$	single muon	HLT_mu26_imedium, HLT_mu50
2015 data	$Z(\rightarrow \mu\mu)\gamma$	di-muon	HLT_mu22_mu8noL1
2016 data	$Z(\rightarrow \mu\mu)\gamma$	single muon	HLT_mu26_ivarmedium, HLT_mu50
2016 data	$Z(\rightarrow \mu\mu)\gamma$	di-muon	HLT_mu22_mu8noL1

- **Pre-selection :**
  - Harmonized 2015 and 2016 data
  - **2015 Paper lepton isolation:** Loose+GraidentLoose (blocking > 1.5TeV events)
  - **2016 IHCEP lepton Isolation:** LooseTrackOnly (for higher search region)

Lepton and Photon Preselection (before overlap removal)			
Cut	Electrons	Muons	Photons
p_T	> 10 GeV	> 10 GeV	> 10 GeV
$\|\eta\|$	$\|\eta\| < 2.47$	$\|\eta\| < 2.7$	$\|\eta\| < 2.37$
	exclude $1.37 < \|\eta\| < 1.52$	-	exclude $1.37 < \|\eta\| < 1.52$
$\|d_0\|/\sigma_{d_0}$	< 5	< 3	-
$z_0 \sin\theta$	< 0.5 mm	< 0.5 mm	-
Identification	Medium	Medium	Loose
Isolation	LooseTrackOnly	LooseTrackOnly	-

Signal modeling and parameterization

- **Signal:** **Narrow width scalar via gluons fusion**
- **Mass range:** **200-2500 GeV** considering the drop of Zγ→eeγ efficiency
- **Signal Parameterization:** **Double-sided crystal ball**
- **Signal efficiency:** **a+b*exp(cx)**

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

Parameter	Fitted function
μ_{CB}	$a_\mu + b_\mu \times x + c_\mu \times x^2 + m_X$
σ_{CB}	$a_\sigma + b_\sigma \times x$
α_{Lo}	$a_{\alpha_{\mathrm{Lo}}} + b_{\alpha_{\mathrm{Lo}}}/(x + c_{\alpha_{\mathrm{Lo}}})$
α_{Hi}	$a_{\alpha_{\mathrm{Hi}}} + b_{\alpha_{\mathrm{Hi}}}/(x + c_{\alpha_{\mathrm{Hi}}})$
x	$(m_X - 100\mathrm{GeV})/100\ \mathrm{GeV}$