Search for rare and LFV decays of the Higgs boson with the ATLAS detector

G. Pezzullo

on behalf of the ATLAS collaboration

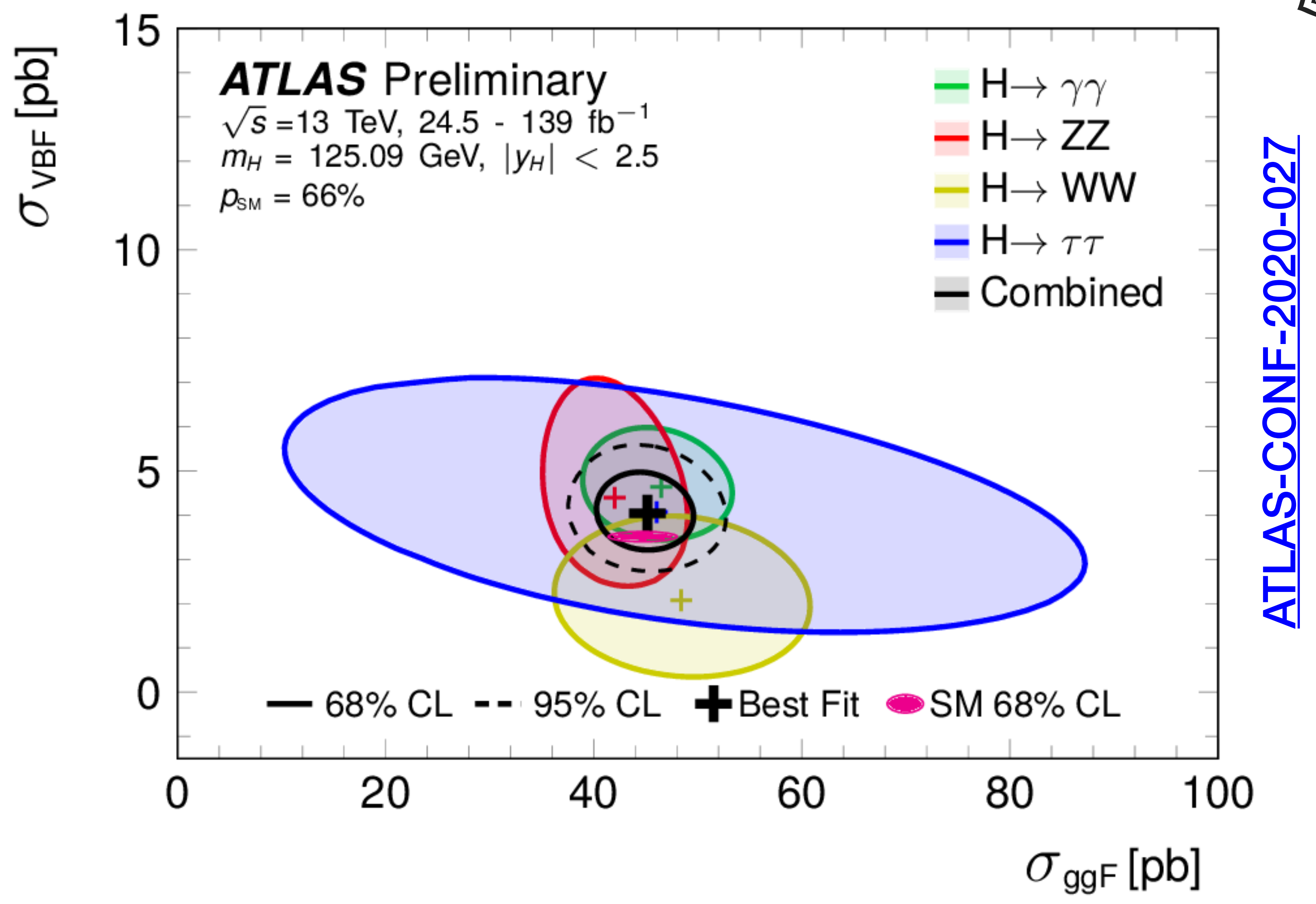
Yale University

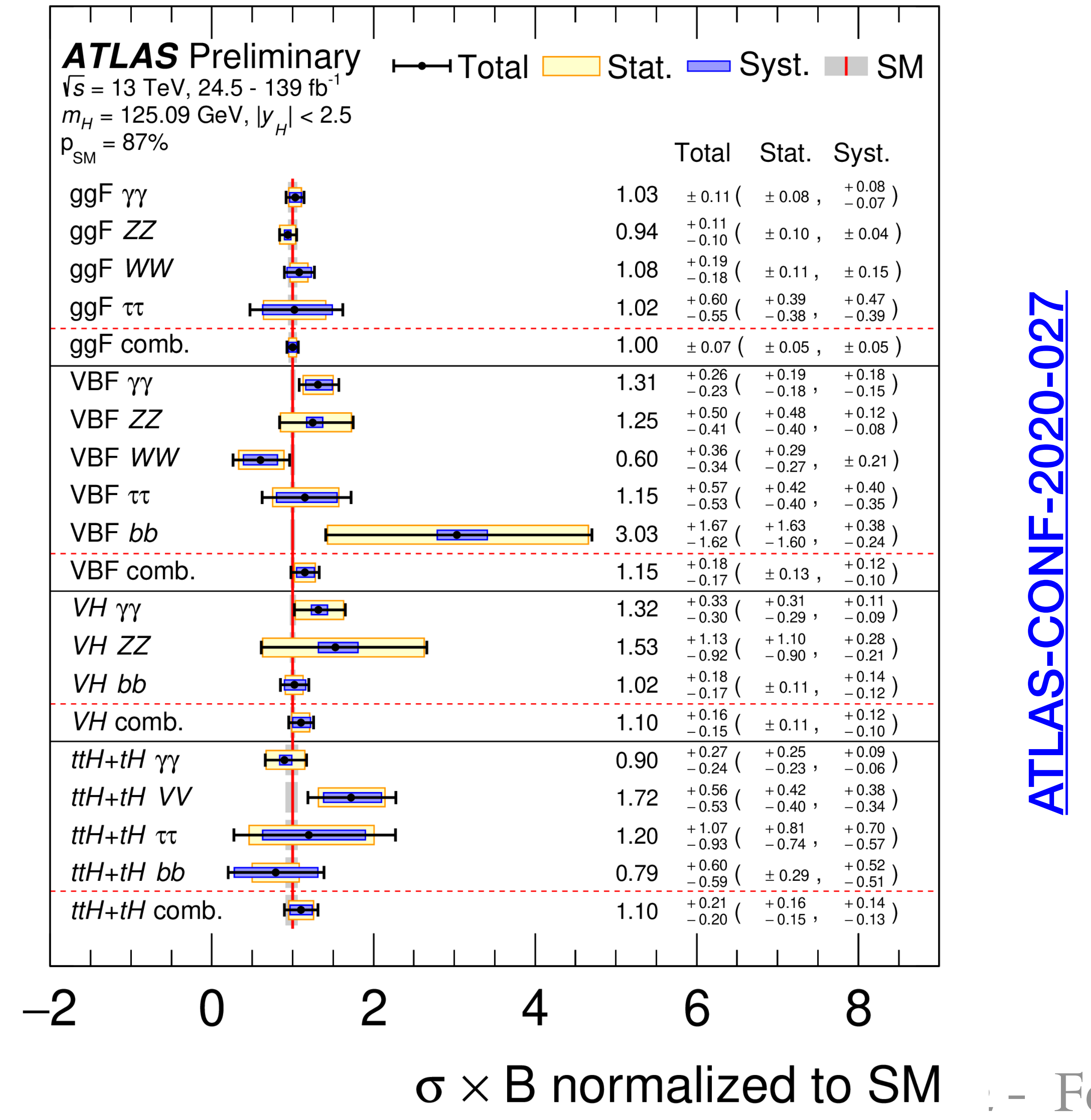
Outline

- Introduction
- Rare and LFV Higgs decays
  - $H \to ll\gamma$
  - $H \to l\tau$
- Summary

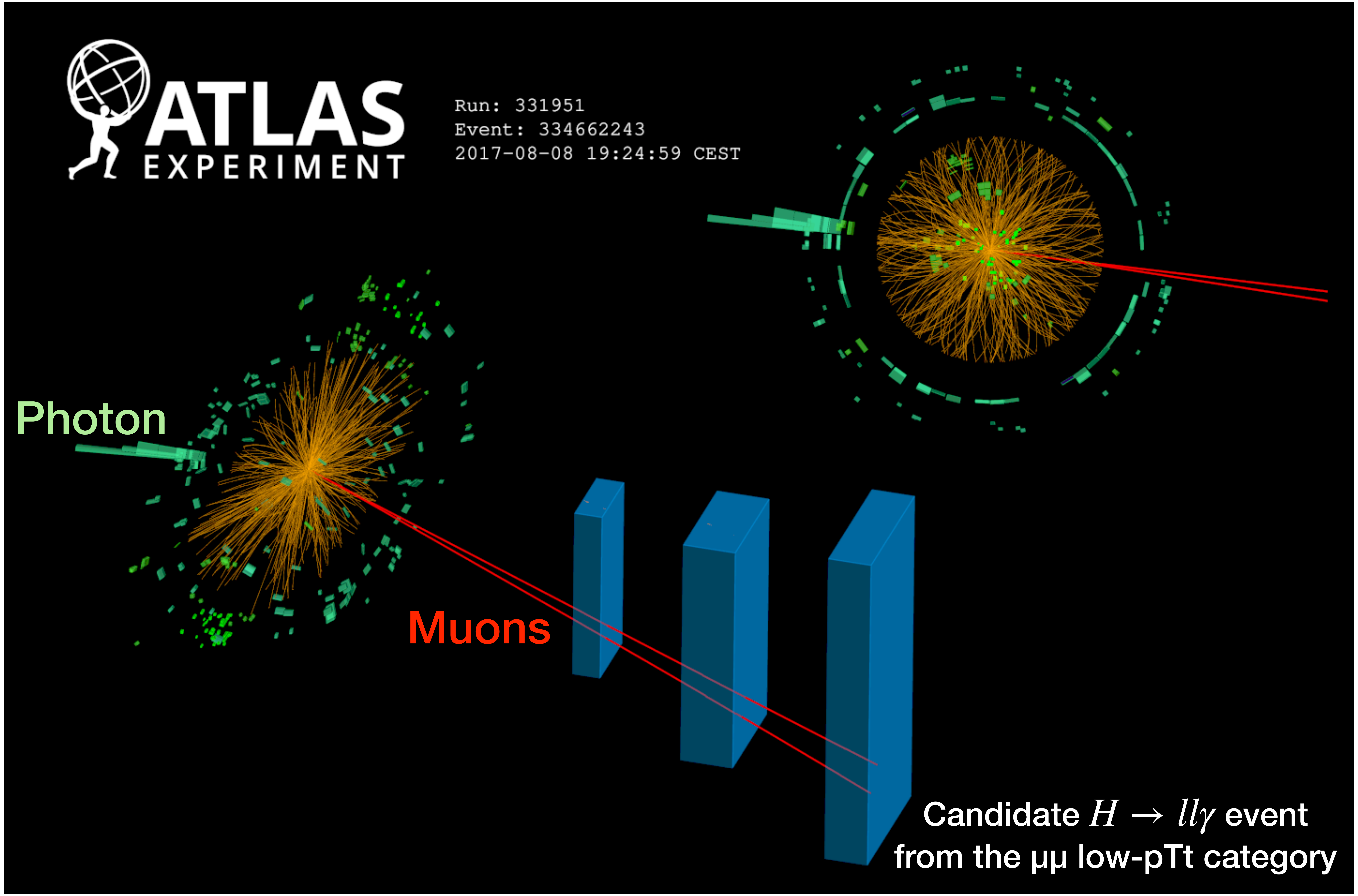
Introduction

- It has been almost 10 years since the discovery of the Higgs boson at the LHC
- ATLAS and CMS have discovered (>5σ) all main production processes and decay channels:
  - Coupling to bosons and 3rd gen. fermions
  - Used in differential measurements (e.g. STXS)
- Searches for decays to 2nd generation fermions and other rare decays already show impressive results
- ATLAS has an extensive program of searches for BSM Higgs decays:
  - Couplings to BSM can increase the decay rate to final states otherwise suppressed in SM
  - Constraint on Br(H→undetected) < 16% (95% CL) from the Higgs combination measurement - lots of 'space' for new physics!





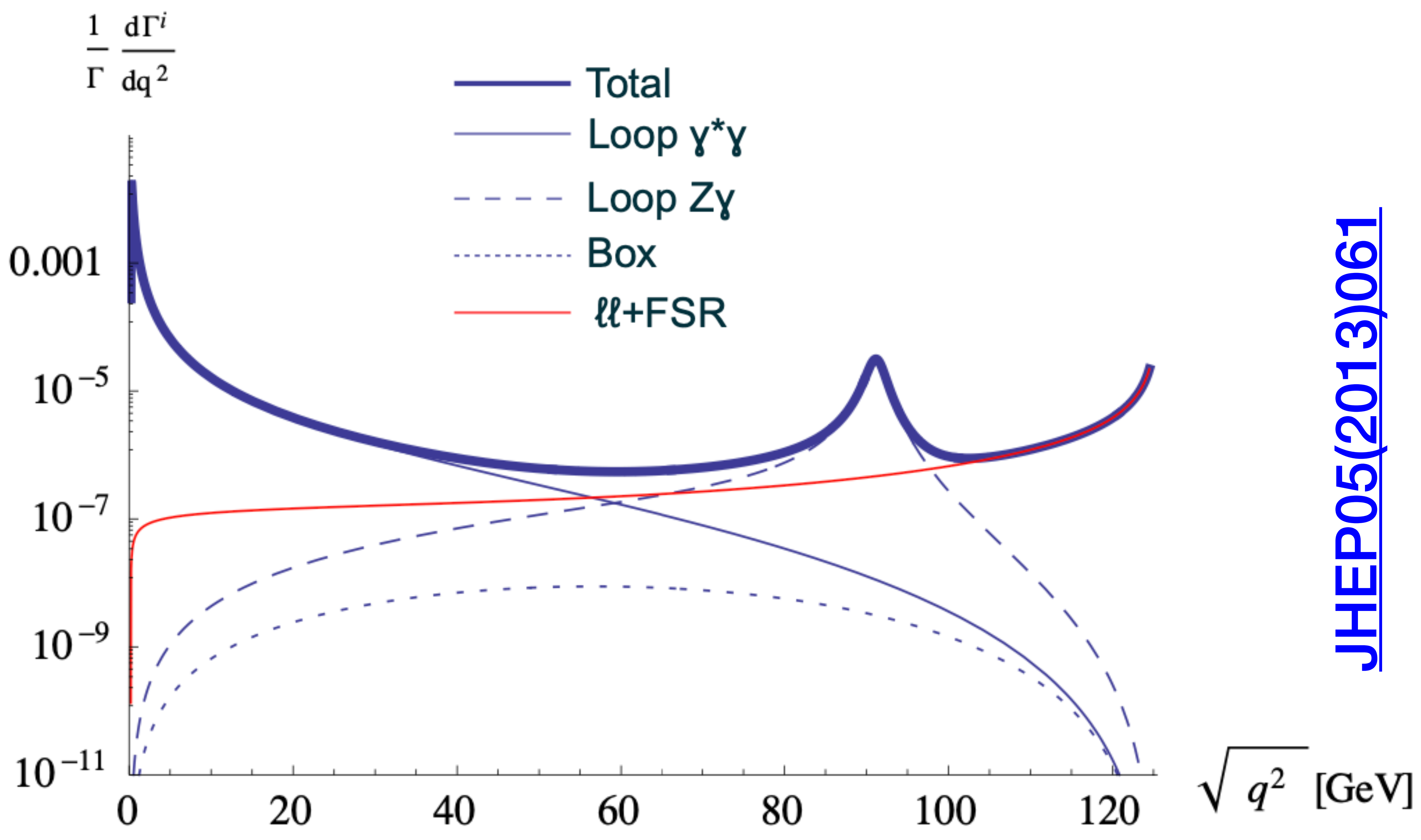
Search for $H \to ll\gamma$ in ATLAS



Phys. Lett. B 819 (2021) 136412

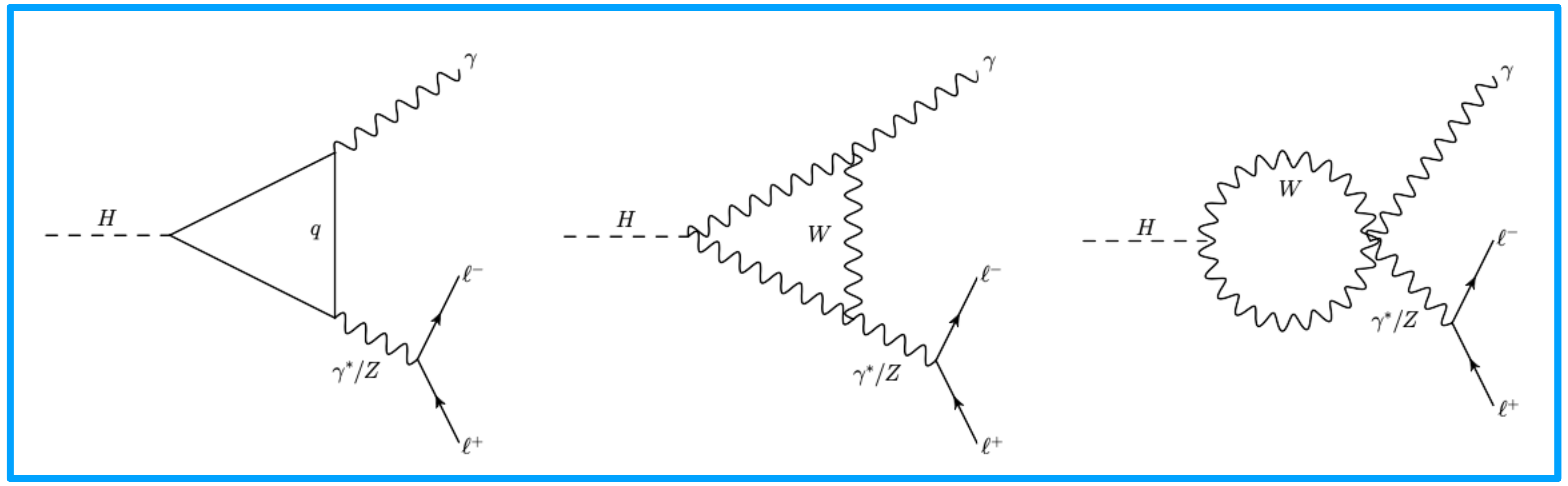
Search for $H \rightarrow ll\gamma$ in ATLAS

- The $H \rightarrow ll\gamma$ ($l = e$ or μ) with m_{ll}< 30 GeV
  - to suppress $H \rightarrow Z\gamma$ contribution
- This region is completely dominated by the decay through γ^*: arXiv:1211.6058
  - The contributions of the other processes and interferences are negligible
- These searches are statistically limited

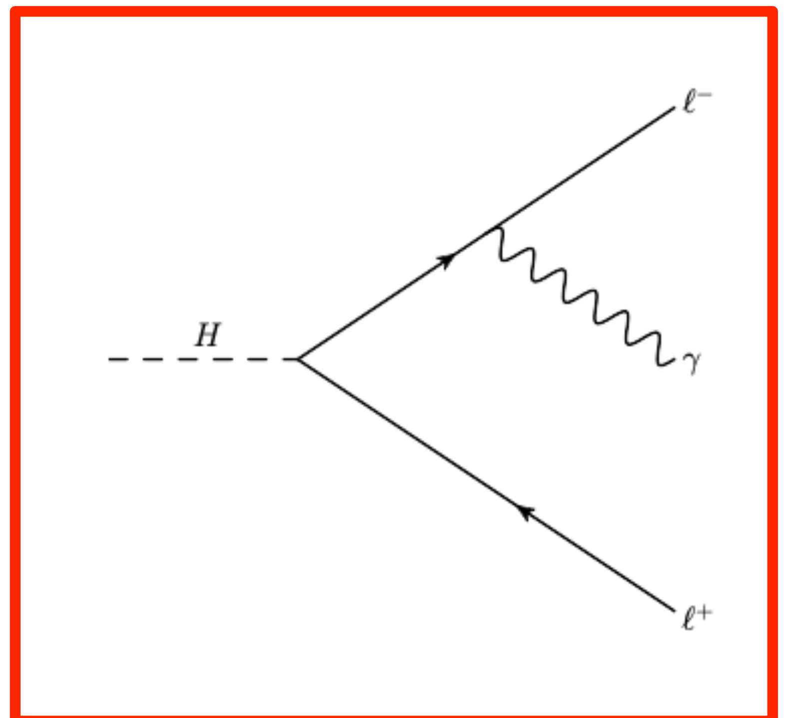


JHEP05(2013)061

Loop induced



ll+FSR

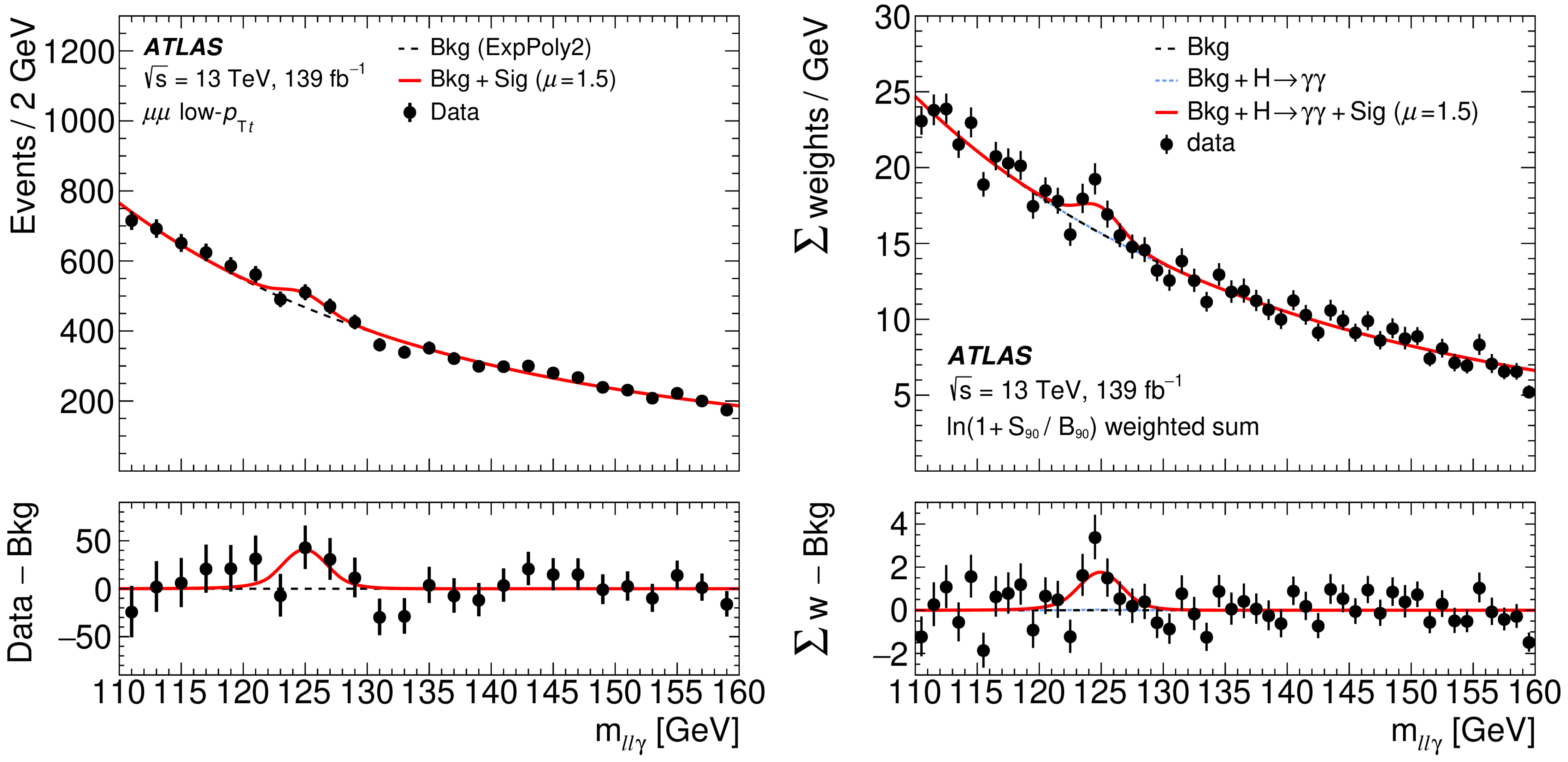


Search for $H \to ll\gamma$ in ATLAS: fit model

- Fit to the invariant mass $m_{ll\gamma}$ in [110, 160] GeV
  - $J/\psi \to ll$ veto: 2.9(2.5)<$m_{\mu\mu(ee)}$<3.3(3.5) GeV
  - $\Upsilon(nS) \to ll$ veto: 9.1(8.0)<$m_{\mu\mu(ee)}$<10.6(11.0) GeV
- Nine categories based on lepton flavor and event kinematics (cluster topology and $p_{\mathrm{T}t}$)

$$p_{\mathrm{T}t} = |\overrightarrow{p}_T^{ll\gamma} \times \hat{t}\,|$$
$$\hat{t} = (\overrightarrow{p}_{\mathrm{T}}^{ll} - \overrightarrow{p}_{\mathrm{T}}^{\gamma})/|\overrightarrow{p}_{\mathrm{T}}^{ll} - \overrightarrow{p}_{\mathrm{T}}^{\gamma}|$$

- The signal is modeled by a double-sided Crystal Ball function
- The background is modeled in each category with a different functional form: exponential, exponential polynomial functions, a power-law functions
- The dominant part of the background originates from non-resonant $ll\gamma$ processes and events with mis-identified photons
  - The template for the non-resonant is built from MC events
  - For events with misidentified objects, they are obtained from background-dominated control regions

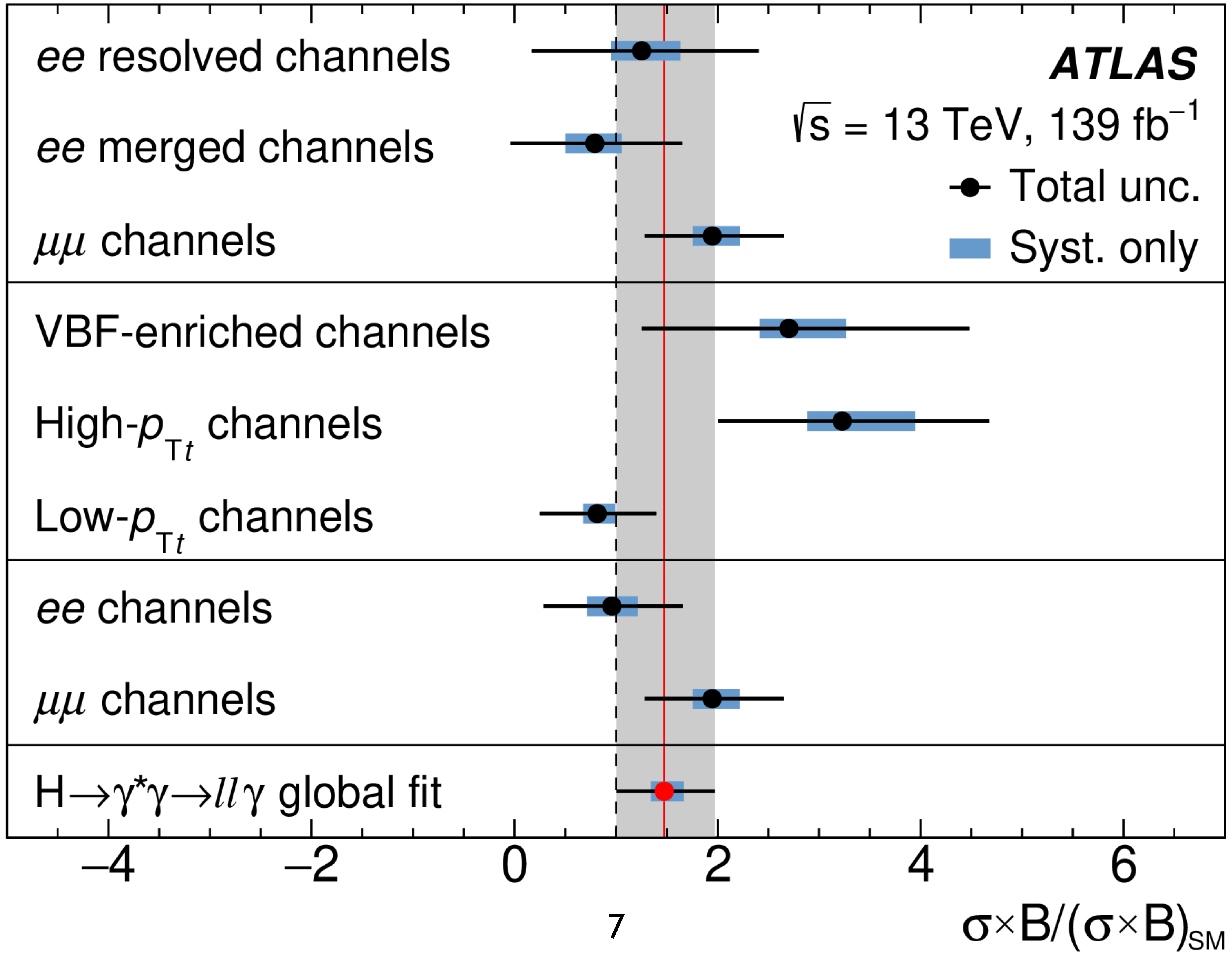


Category	Events	S_{90}	B_{90}^{N}	$B_{H\to\gamma\gamma}$	f_{90} [%]	Z_{90}
ee resolved VBF-enriched	10	0.4	1.6	0.009	20	0.3
ee merged VBF-enriched	15	0.8	2.0	0.07	27	0.5
$\mu\mu$ VBF-enriched	33	1.3	5.9	–	18	0.5
ee resolved high-$p_{\mathrm{T}t}$	86	1.1	12	0.02	9	0.3
ee merged high-$p_{\mathrm{T}t}$	162	2.5	18	0.2	12	0.6
$\mu\mu$ high-$p_{\mathrm{T}t}$	210	4.0	34	–	11	0.7
ee resolved low-$p_{\mathrm{T}t}$	3713	22	729	0.5	2.9	0.8
ee merged low-$p_{\mathrm{T}t}$	5103	29	942	2	3.0	1.0
$\mu\mu$ low-$p_{\mathrm{T}t}$	9813	61	1750	–	3.4	1.4

Phys. Lett. B 819 (2021) 136412

Search for $H \rightarrow ll\gamma$ in ATLAS: results

- Full Run 2 ATLAS result:
  - Observed (expected) significance of **3.2 σ** (2.1 σ expected) with the B-only hypothesis
  - Production cross-section x Br($H \rightarrow ll\gamma$) for m_{ll} < 30 GeV is $8.7^{+2.8}_{-2.7}$ fb



Phys. Lett. B 819 (2021) 136412

Search for $H \to Z\gamma$ in ATLAS: result

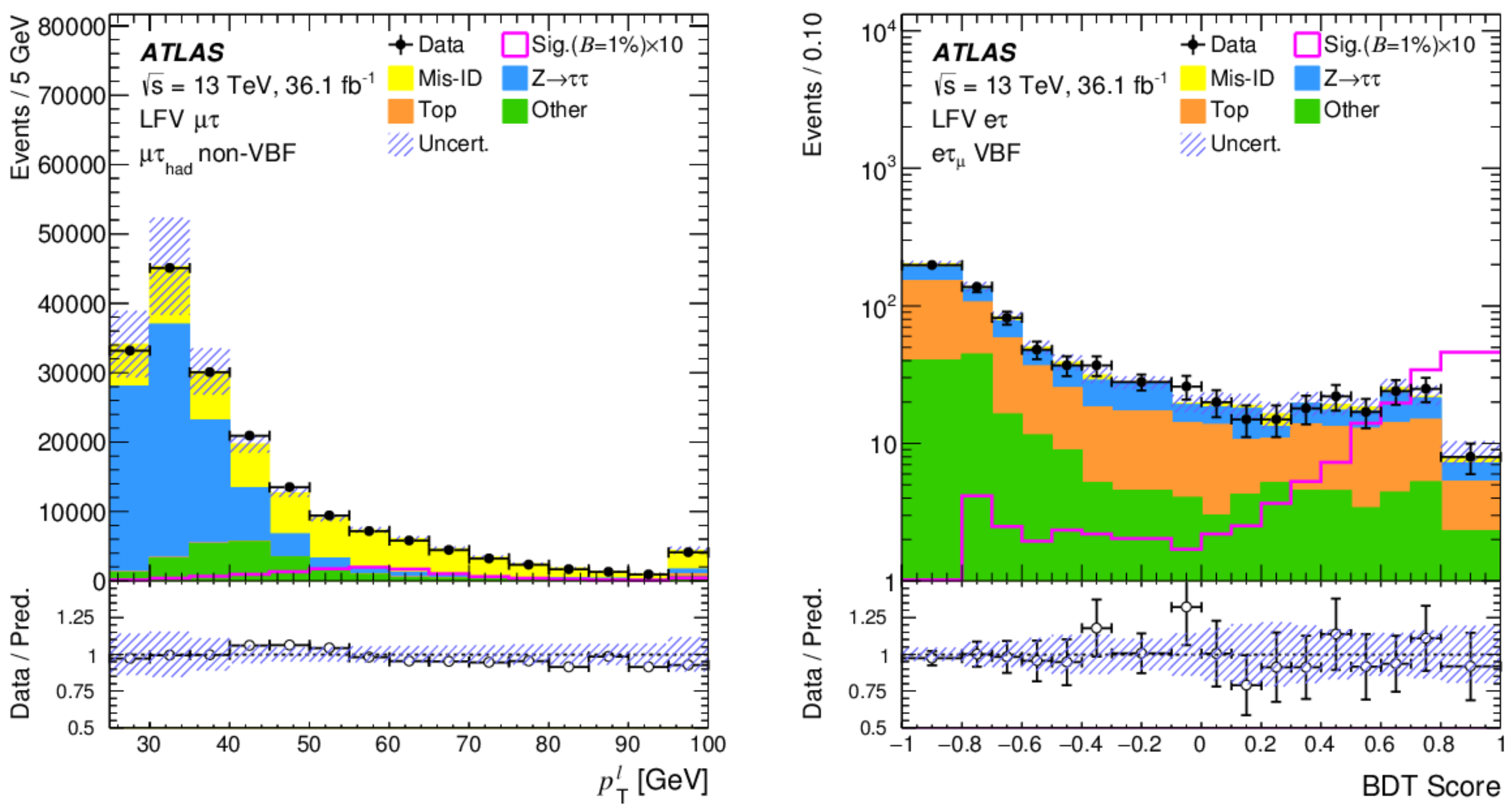
- Full Run 2 ATLAS result:
  - Observed (expected) significance of 2.2 σ (1.2 σ expected) with the B-only hypothesis
  - Best-fit of the $H \to Z\gamma$ (w.r.t. the SM prediction) of $2.0^{+1.0}_{-0.9}$

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_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

Phys. Lett. B 819 (2021) 136412

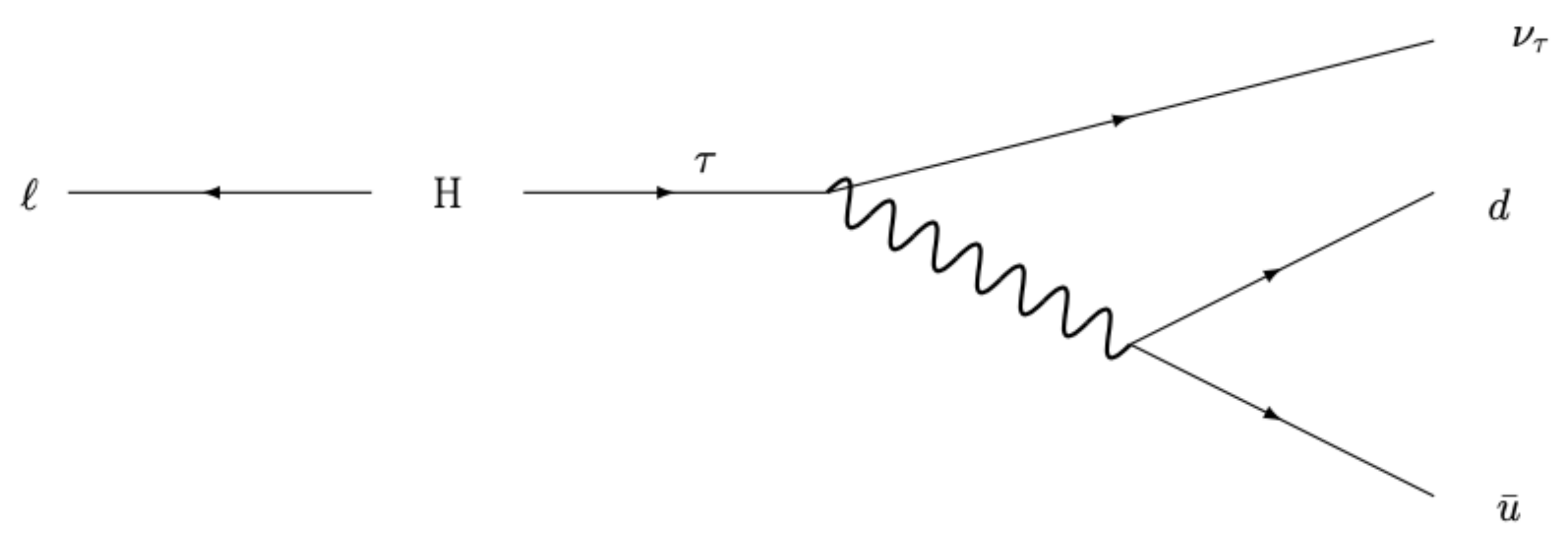
Search for $H \to l\tau$ (l=e or μ) in ATLAS

- Similar final states as in $H \to \tau\tau$
- Two decay modes: $l\tau_{\rm had}$ and $l\tau_{l'}$ ($l \neq l'$)
- The main backgrounds are: $Z \to \tau\tau$, Top processes, W+jets and QCD
- Two categories per decay-mode: VBF and non-VBF
- BDT to discriminate signal from background

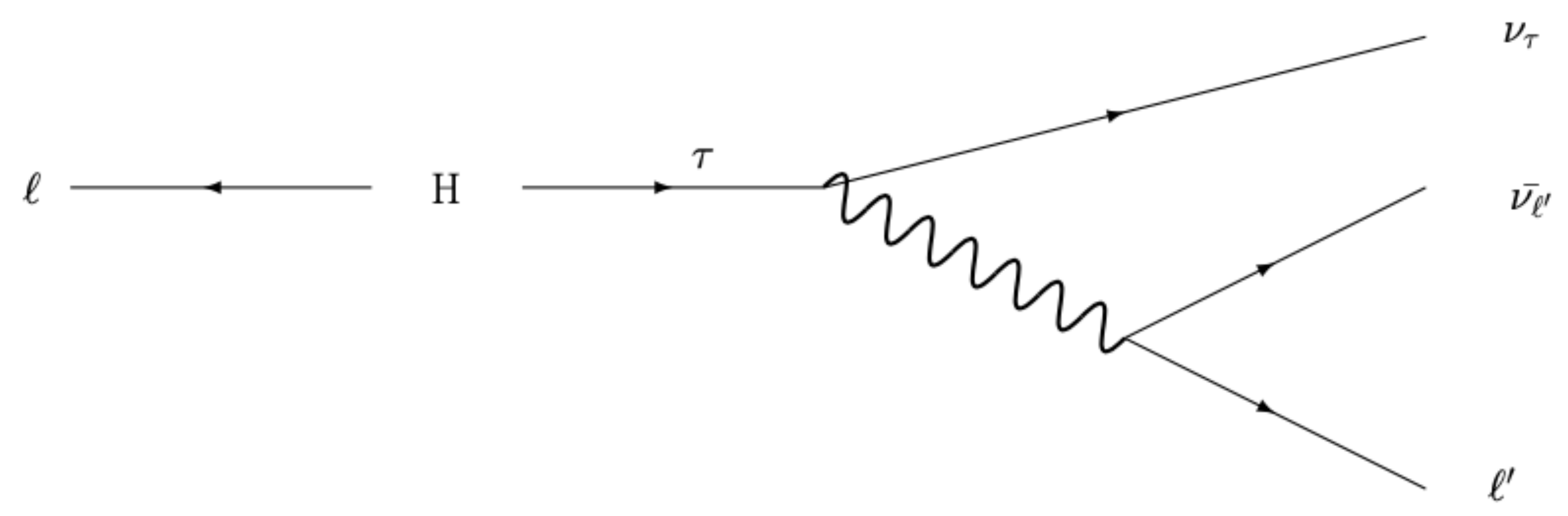


Phys. Lett. B 800 (2020) 135069

$l\tau_{\rm had}$

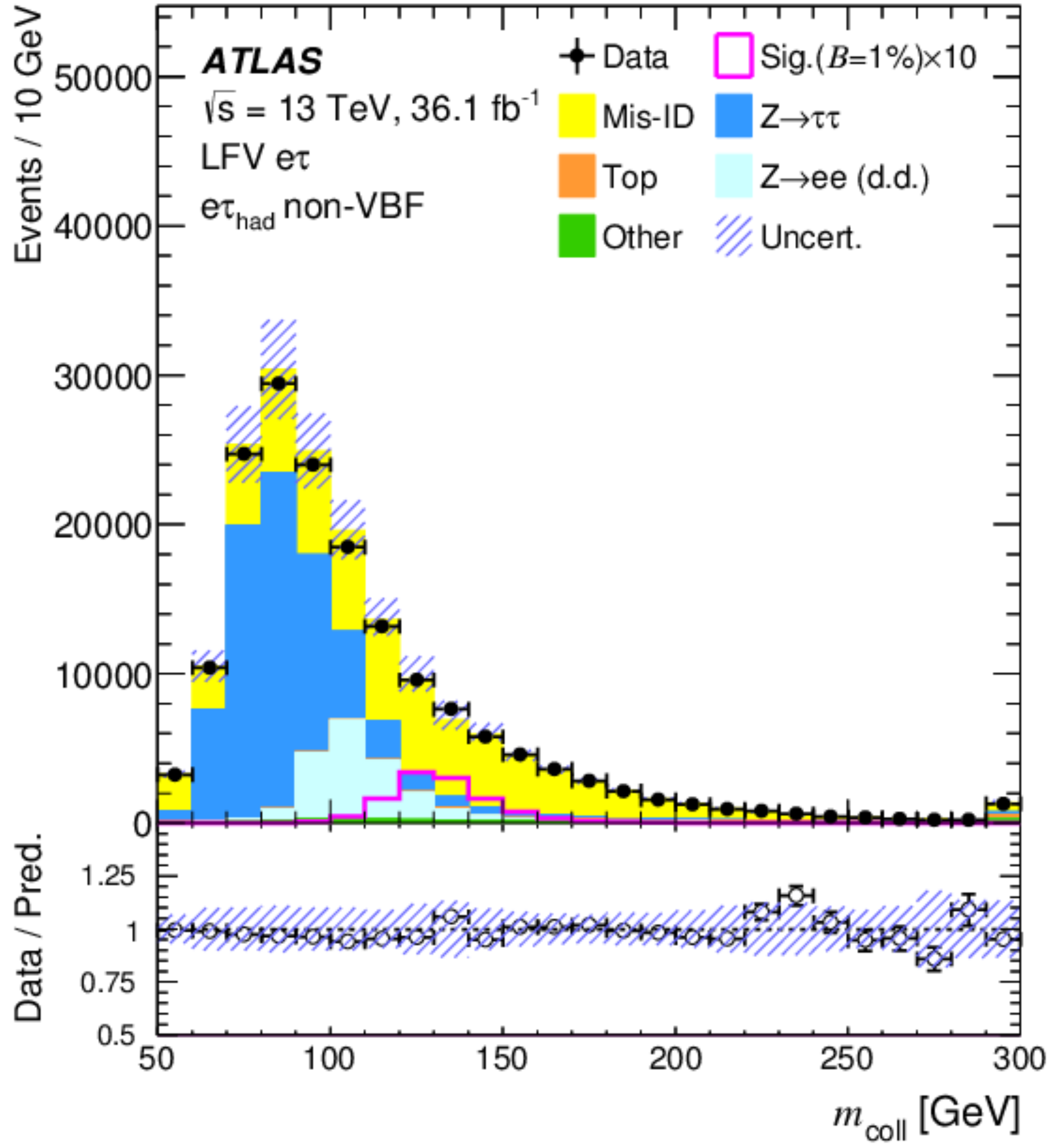


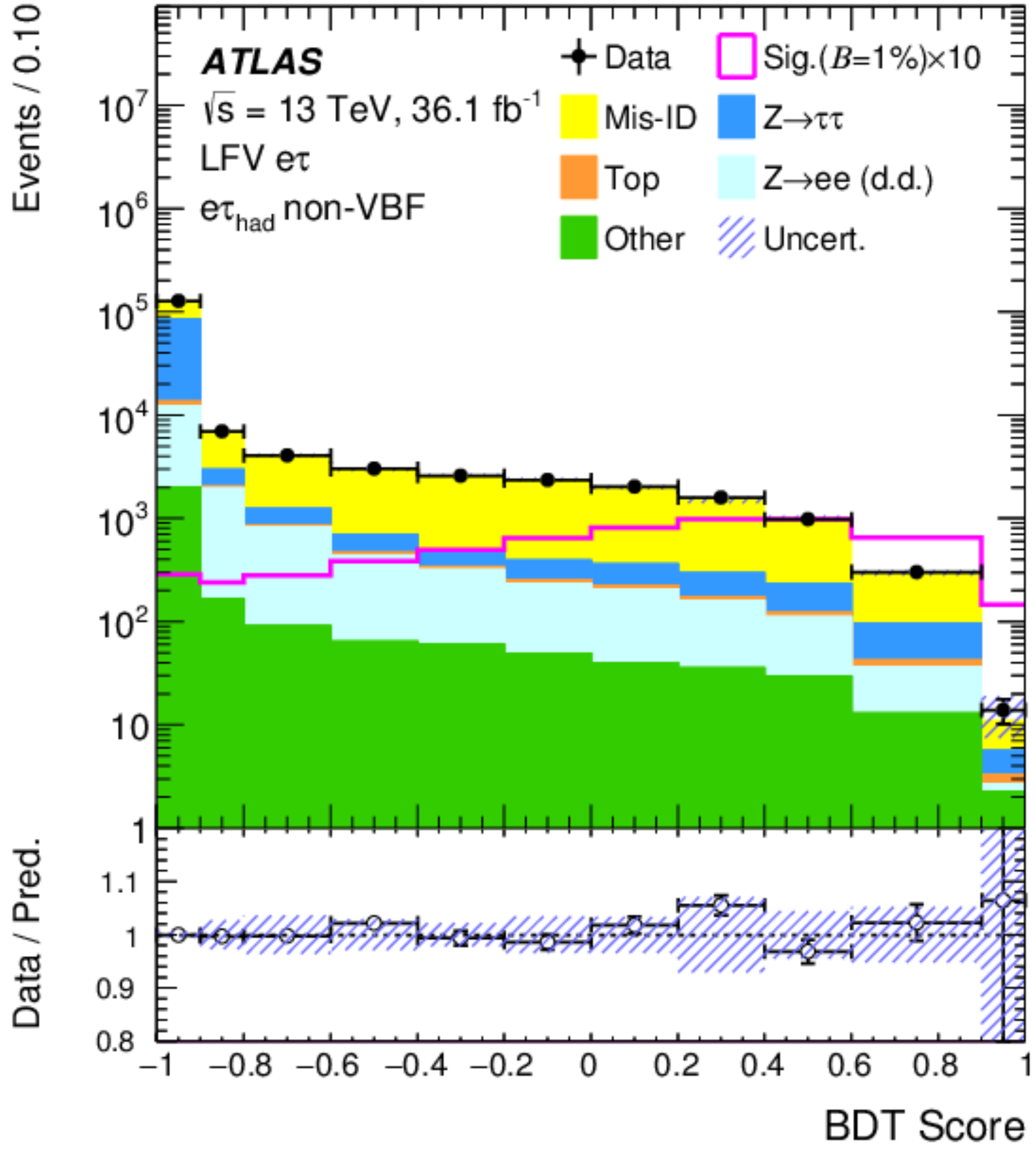
$l\tau_{l'}$



$H \to l\tau$: Zee background in $e\tau_{had}$

- For the $H \to e\tau_{had}$ case, additional $Z \to ee$ background with electron mis-identified as τ_{had}

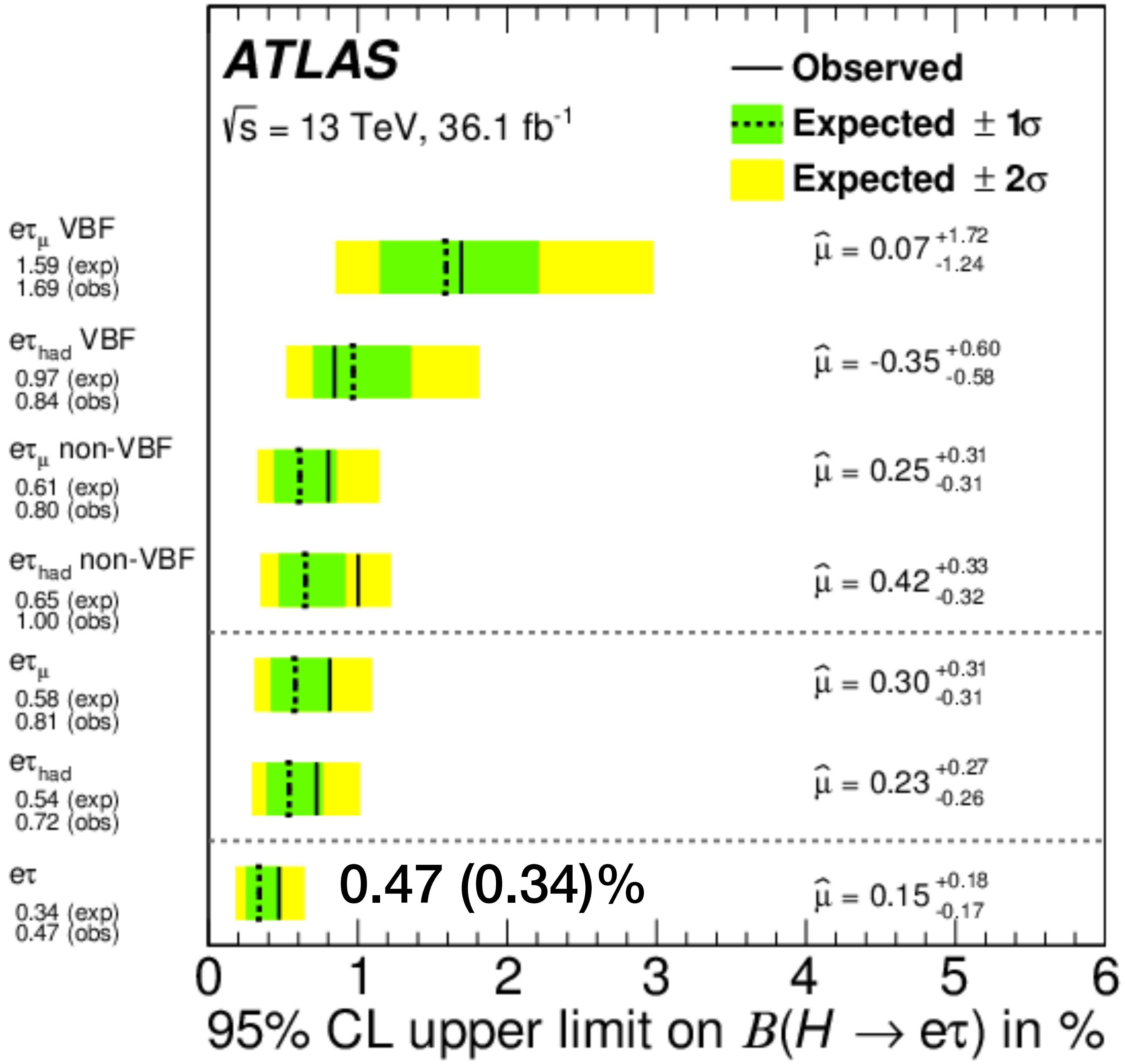


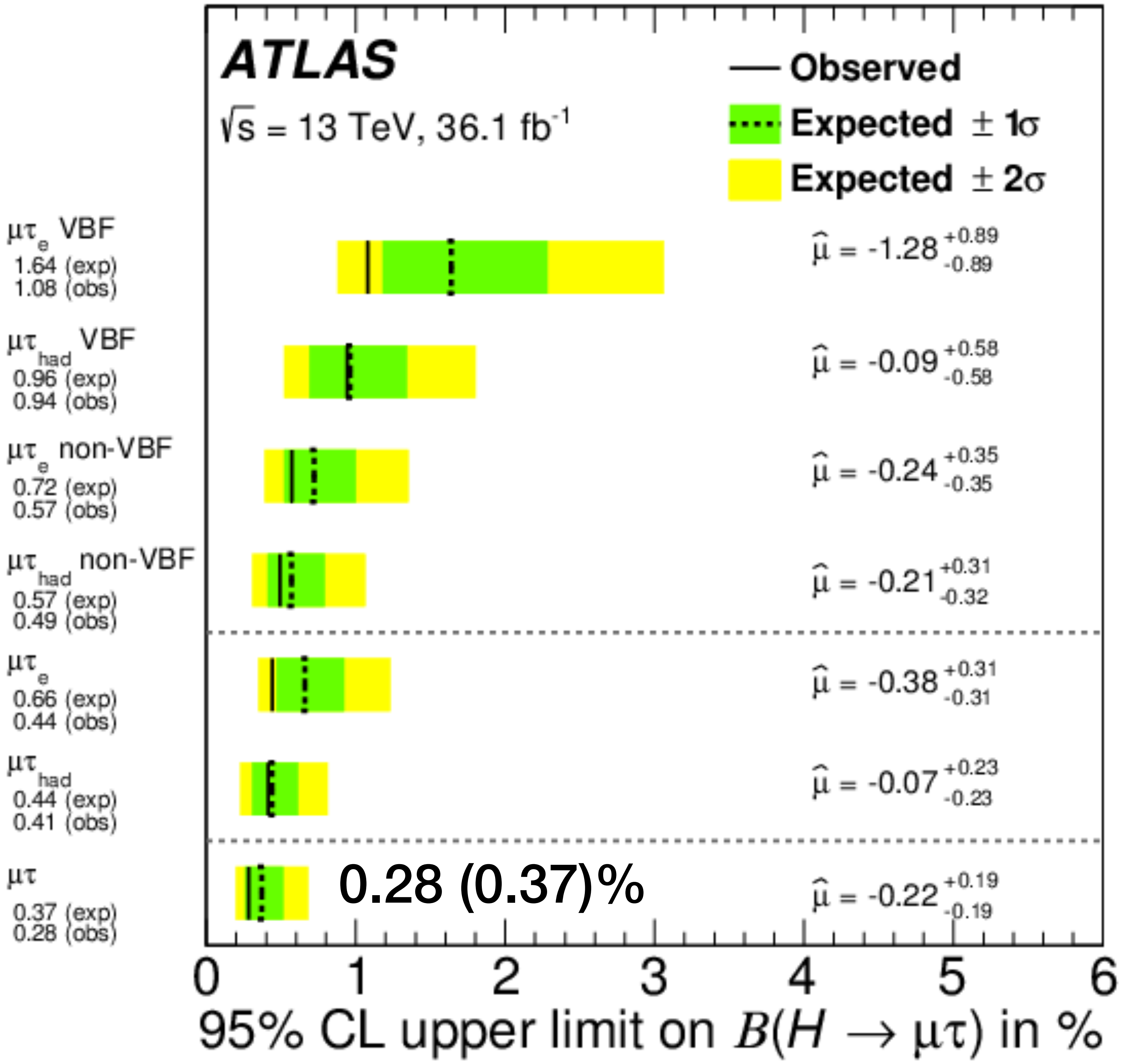


Phys. Lett. B 800 (2020) 135069

Search for $H \to l\tau$ (l=e or μ) in ATLAS: results

- 95% C.L. limits on B($H \to e\tau$) and B($H \to \mu\tau$)
- Best-fit: $(0.15^{+0.18}_{-0.17})$ for $H \to e\tau$, and (-0.22 ± 0.19)% for $H \to \mu\tau$

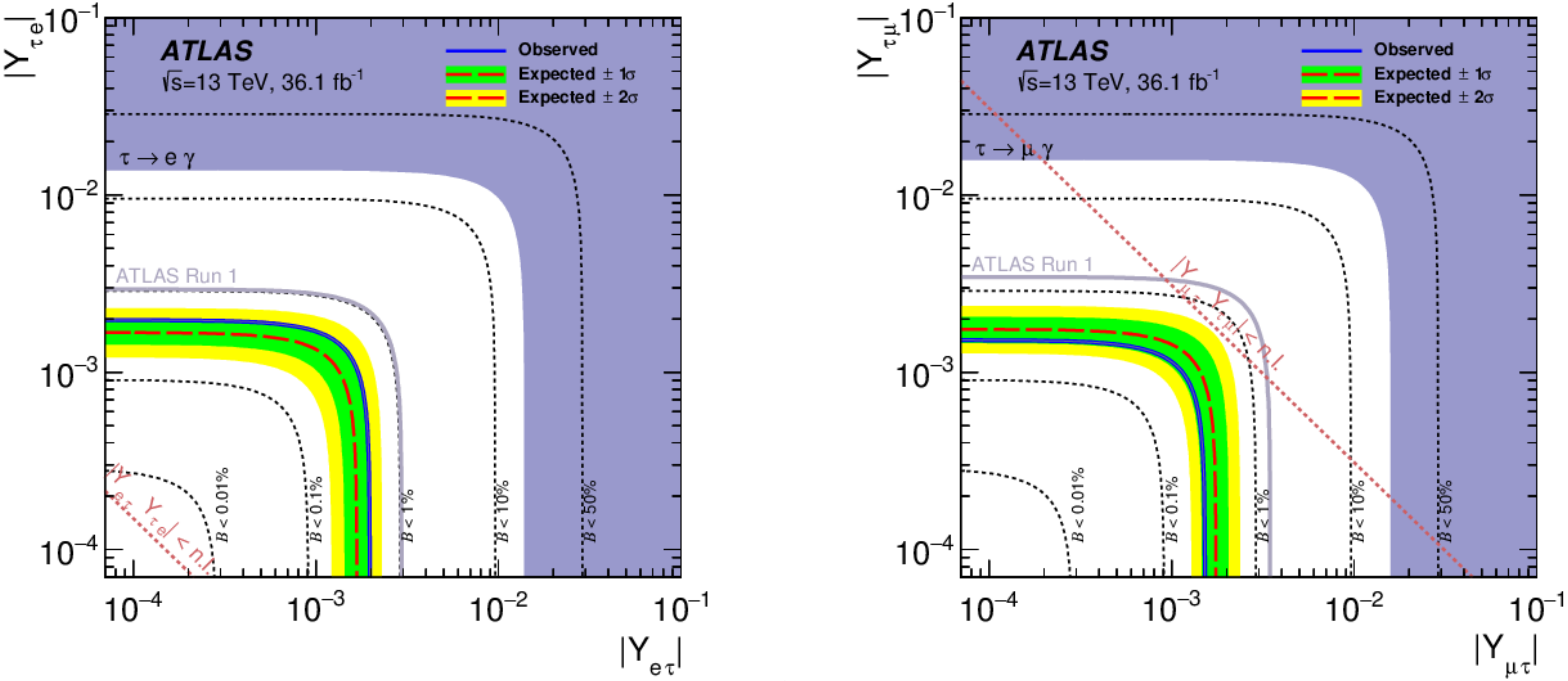




Phys. Lett. B 800 (2020) 135069

Search for $H \to l\tau$ (l=e or μ) in ATLAS: Yukawa couplings

- Constraints on $Y_{l\tau}$ more stringent then indirect searches: $|Y_{l\tau}|^2 + |Y_{\tau l}|^2 = \frac{8\pi}{m_H}\frac{B(H \to l\tau)}{1 - B(H \to l\tau)}\Gamma_H(SM)$



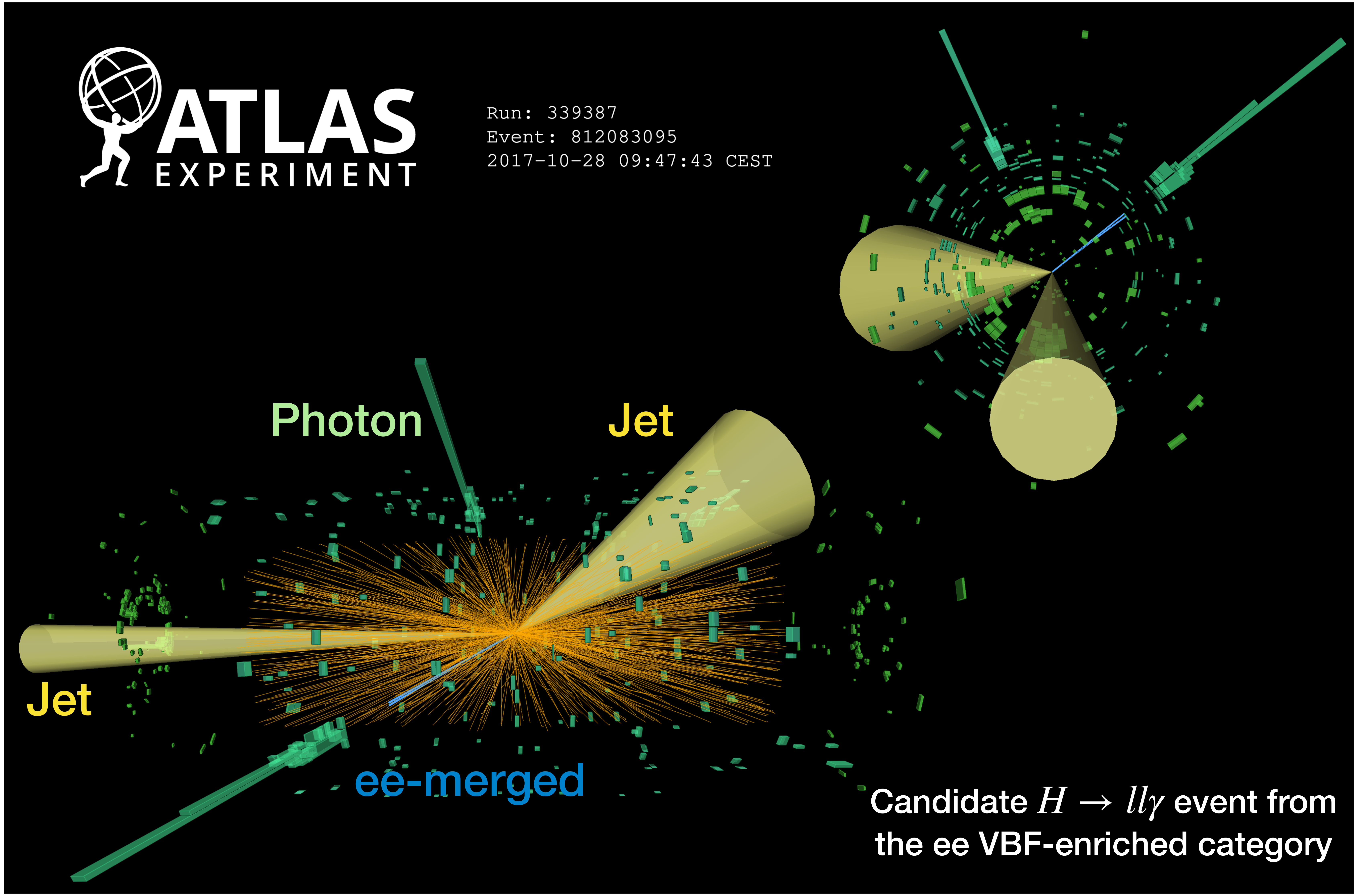
[Phys. Lett. B 800 (2020) 135069](https://doi.org/10.1016/j.physletb.2019.135069)

Summary

- Rare and LFV Higgs decay searches with the ATLAS detector were presented
  - Powerful tests to search for BSM
- First evidence (**3.2 σ**) of $H \rightarrow ll\gamma$ for m_{ll}< 30 GeV was reported
  - High-mass $H \rightarrow Z\gamma$ at 2.2 σ
- LFV search for $H \rightarrow l\tau$ (*l*=e or μ) using 36.1 fb^{-1} was also presented
  - Tighter constraints to $Y_{l\tau}$ compared to indirect searches
- Searches for the rare/LFV $H \rightarrow ee/e\mu$ decays are also performed with no significant deviations from the SM found

Backup slides

Search for $H \rightarrow ll\gamma$ in ATLAS

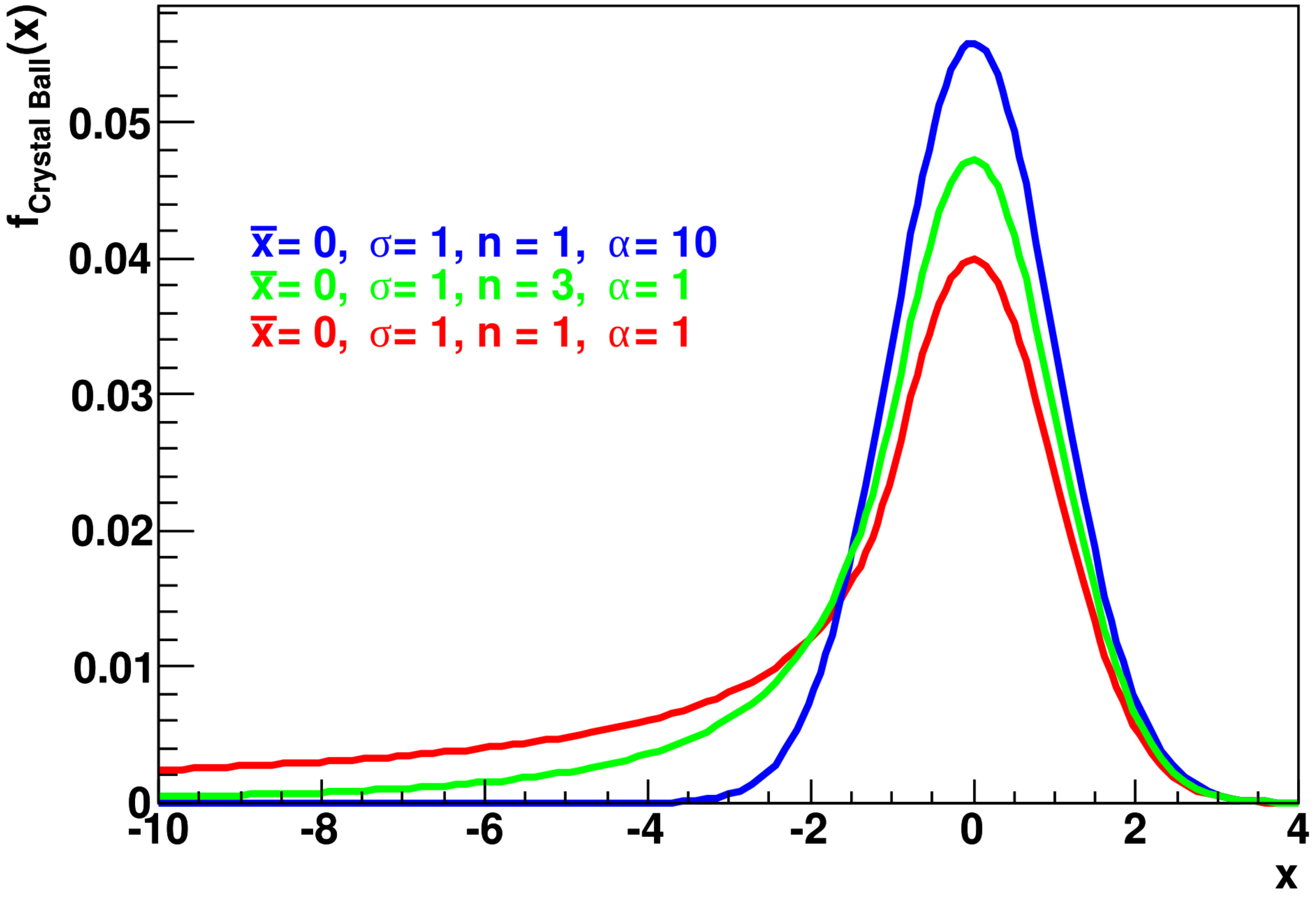


Phys. Lett. B 819 (2021) 136412

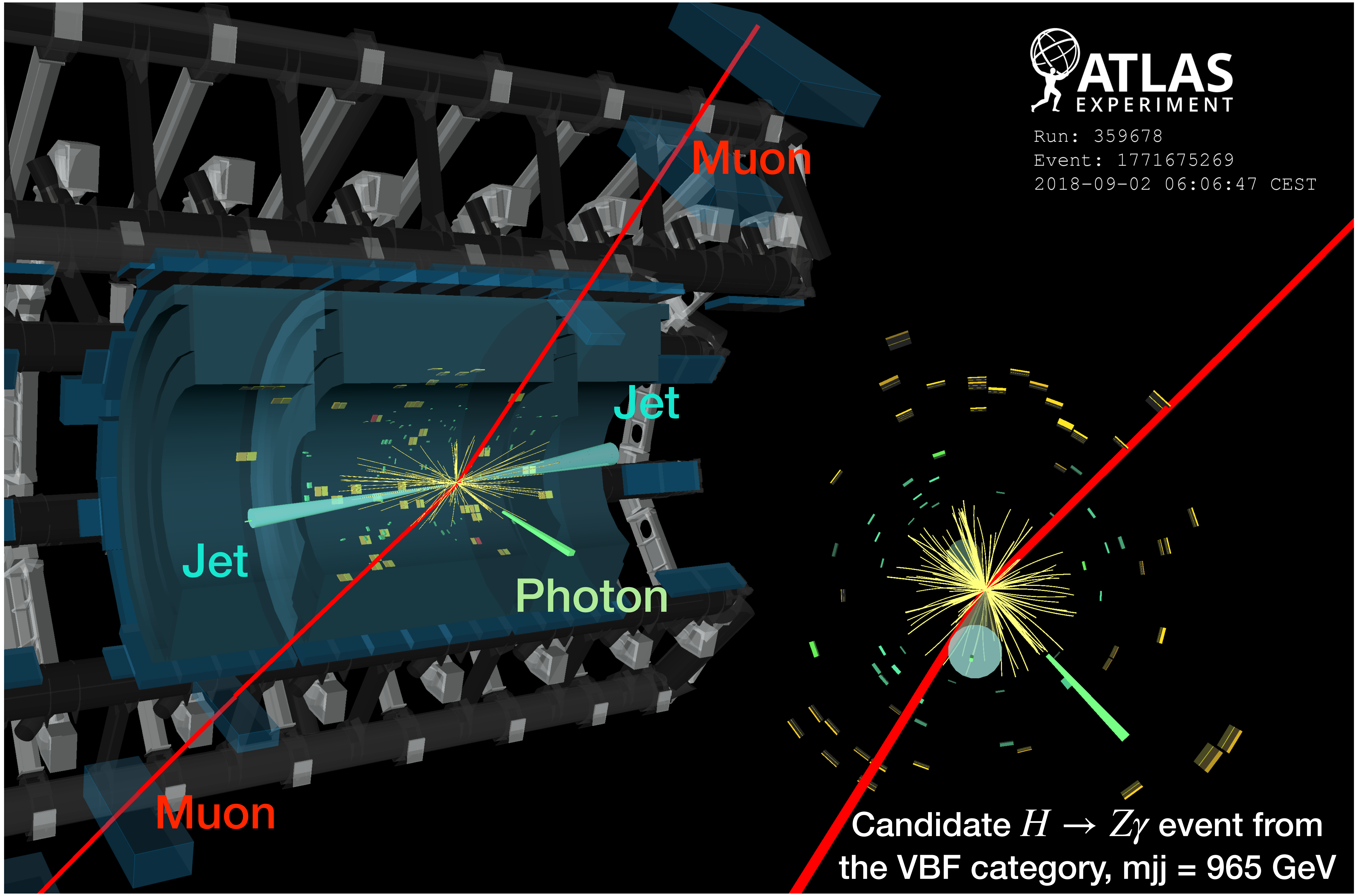
Crystal Ball function

- Probability density function consisting of a Gaussian core and a power-law tail(s)

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

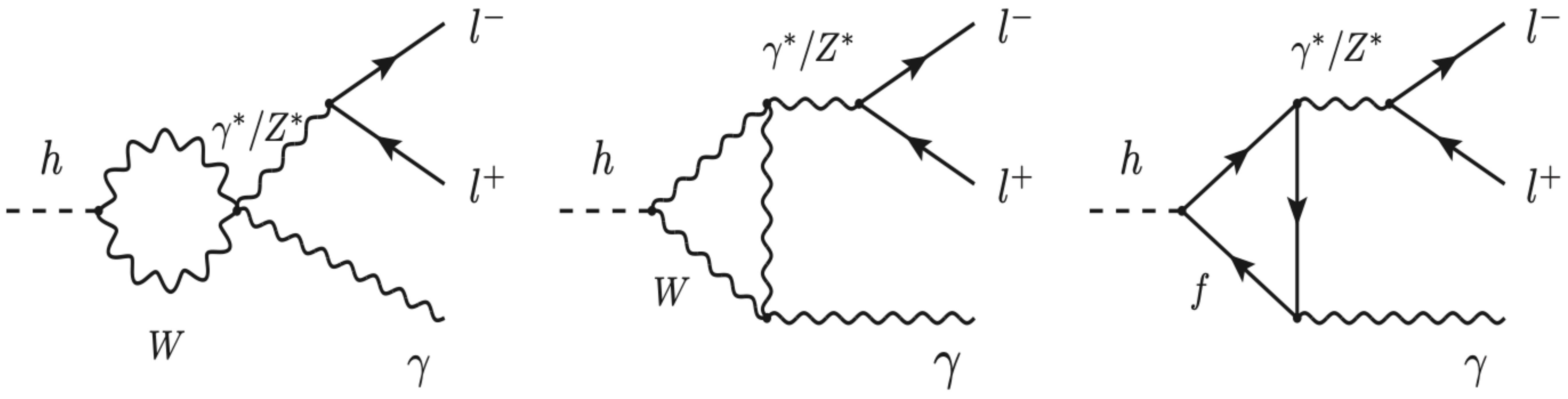


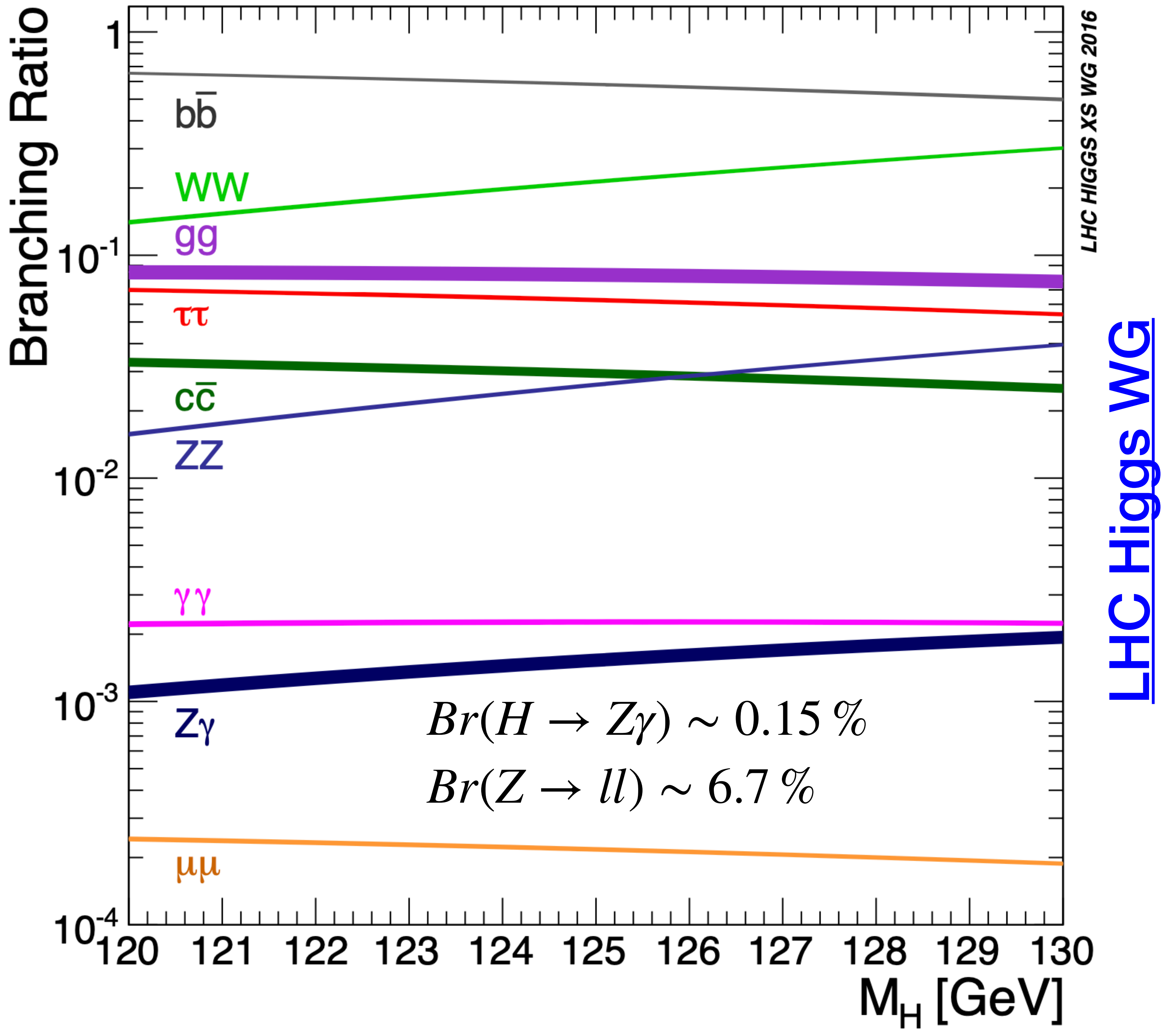
Search for $H \to Z\gamma$ in ATLAS



Search for $H \to Z\gamma$ in ATLAS

- SM $H \to Z\gamma$ decay through loop diagrams
  - $Br(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$
- $H \to Z\gamma, Z \to l^+l^-$ signature is more difficult to produce than $H \to \gamma\gamma$, but it almost no QCD background
- Sensitive to BSM contributions:
  - Composite-Higgs: arXiv:1308.2676
  - Singlet scalars: arXiv:1105.4587

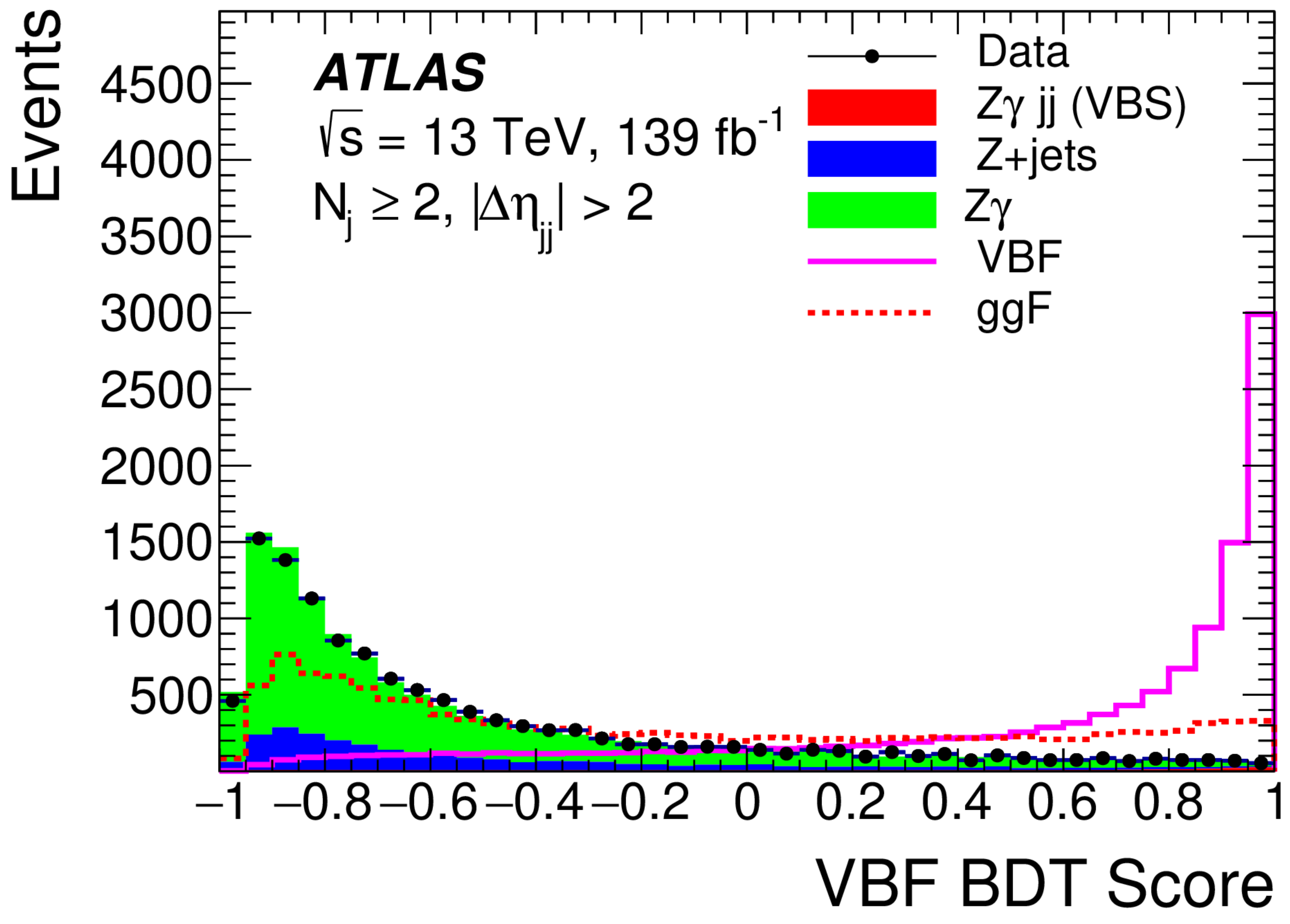




Search for $H \rightarrow Z\gamma$ in ATLAS: analysis

- $H \rightarrow Z(\rightarrow ll)\gamma$ ($l = e$ or μ) advantages
  - Efficiently triggered
  - Good invariant mass resolution
  - Relatively small background
- Six categories orthogonal to each other based on lepton flavor and event kinematics (using $p_{\mathrm{T}t}$)
- A BDT is trained to separate the VBF signal from other production modes and backgrounds

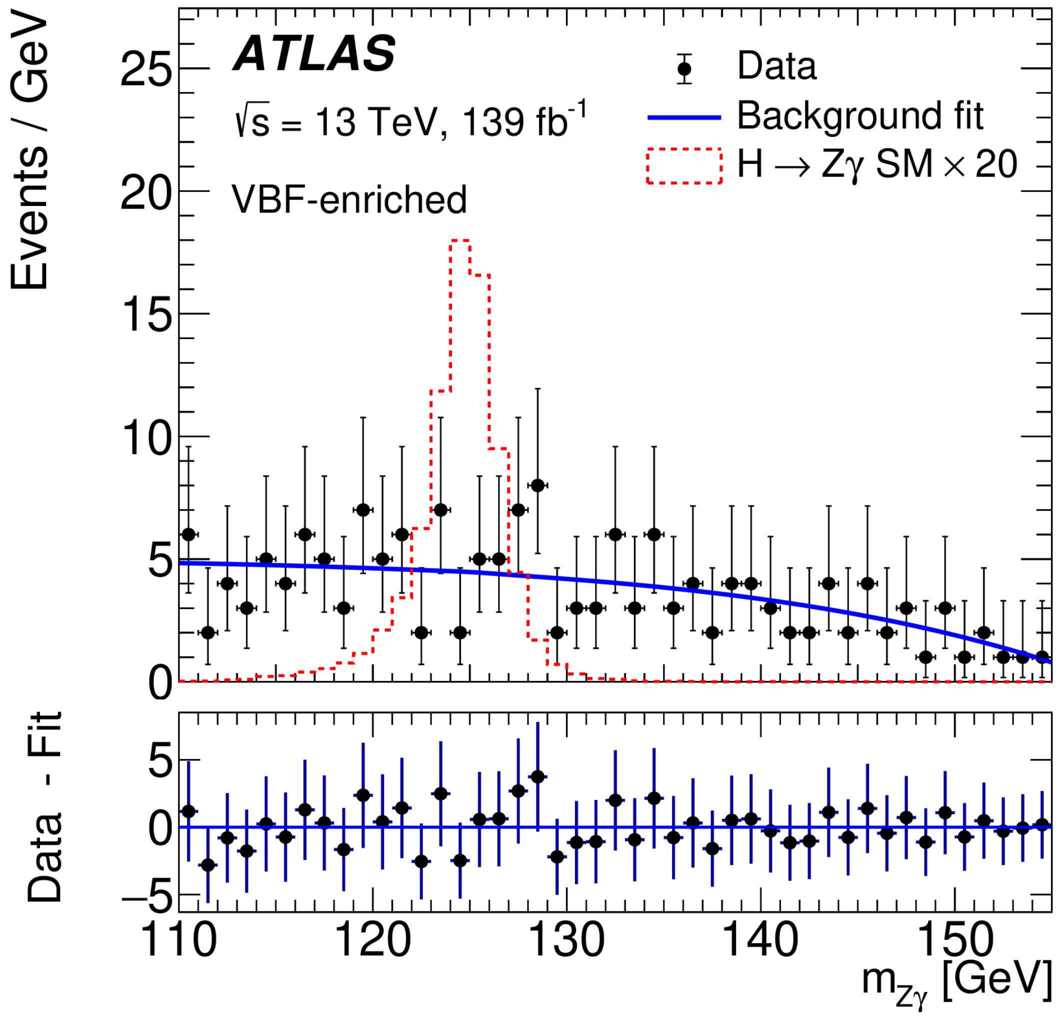
$$p_{\mathrm{T}t} = |\vec{p}_T^{ll\gamma} \times \hat{t}|$$
$$\hat{t} = (\vec{p}_{\mathrm{T}}^{ll} - \vec{p}_{\mathrm{T}}^{\gamma})/|\vec{p}_{\mathrm{T}}^{ll} - \vec{p}_{\mathrm{T}}^{\gamma}|$$

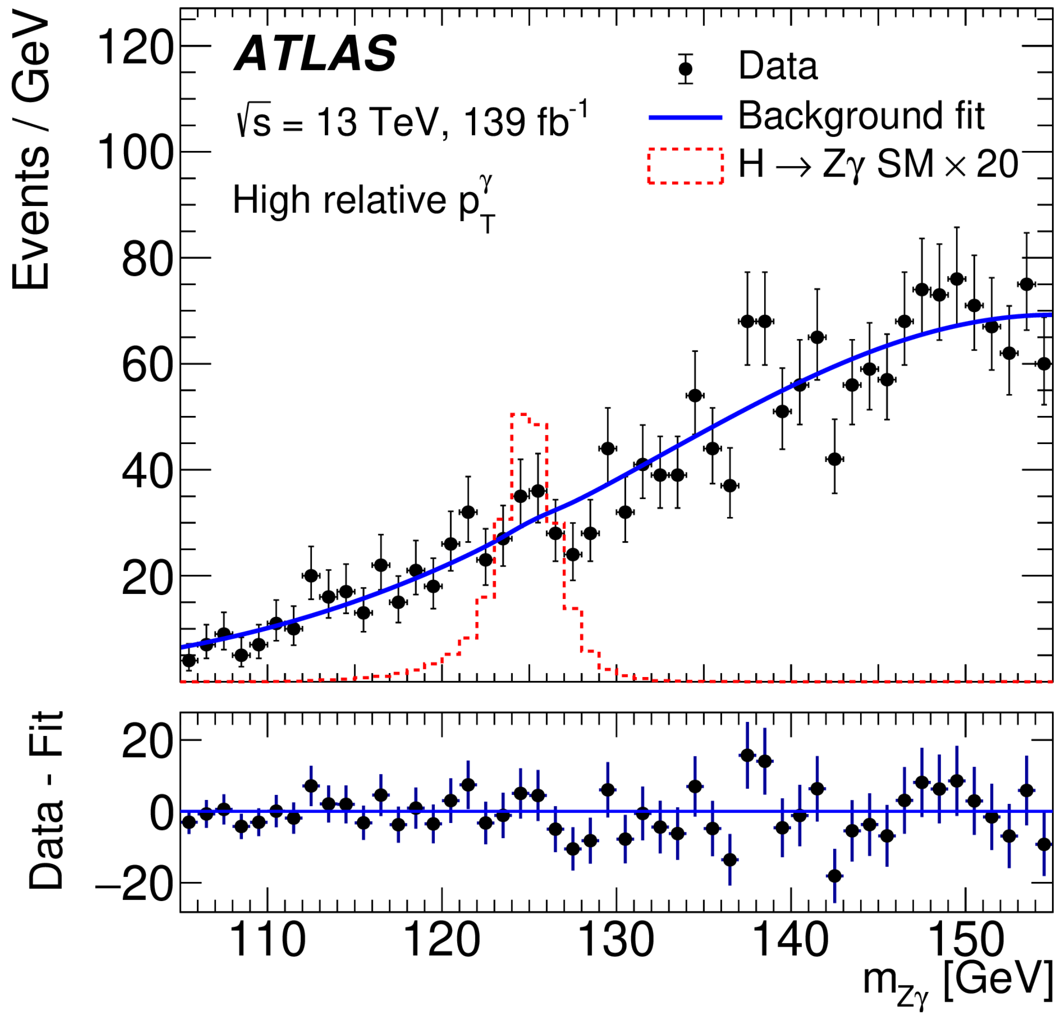


Phys. Lett. B 809 (2020) 135754

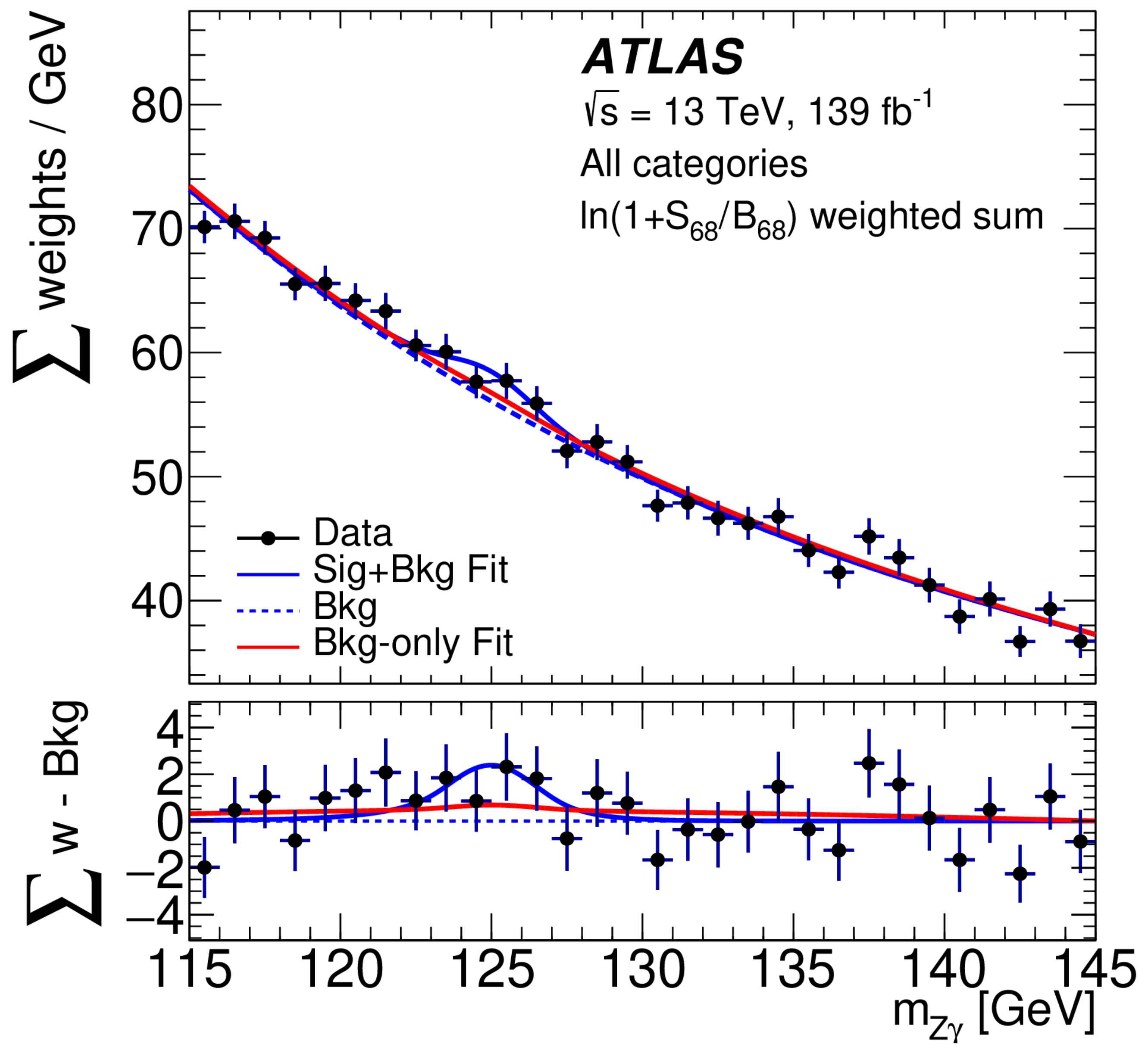
Search for $H \rightarrow Z\gamma$ in ATLAS: fit model

- Fit to the invariant mass $m_{Z\gamma}$ in [105, 160] GeV
- The signal mass distribution is modeled by a double-sided Crystal Ball function
- The background is modeled using a template that is constructed from the simulated $Z\gamma$ and electroweak $Z\gamma jj$ events, and a Z+jets contribution derived from data
  - Each category uses a different functional form: Bernstein polynomials, exponential polynomial functions, a sum of power functions





Phys. Lett. B 809 (2020) 135754



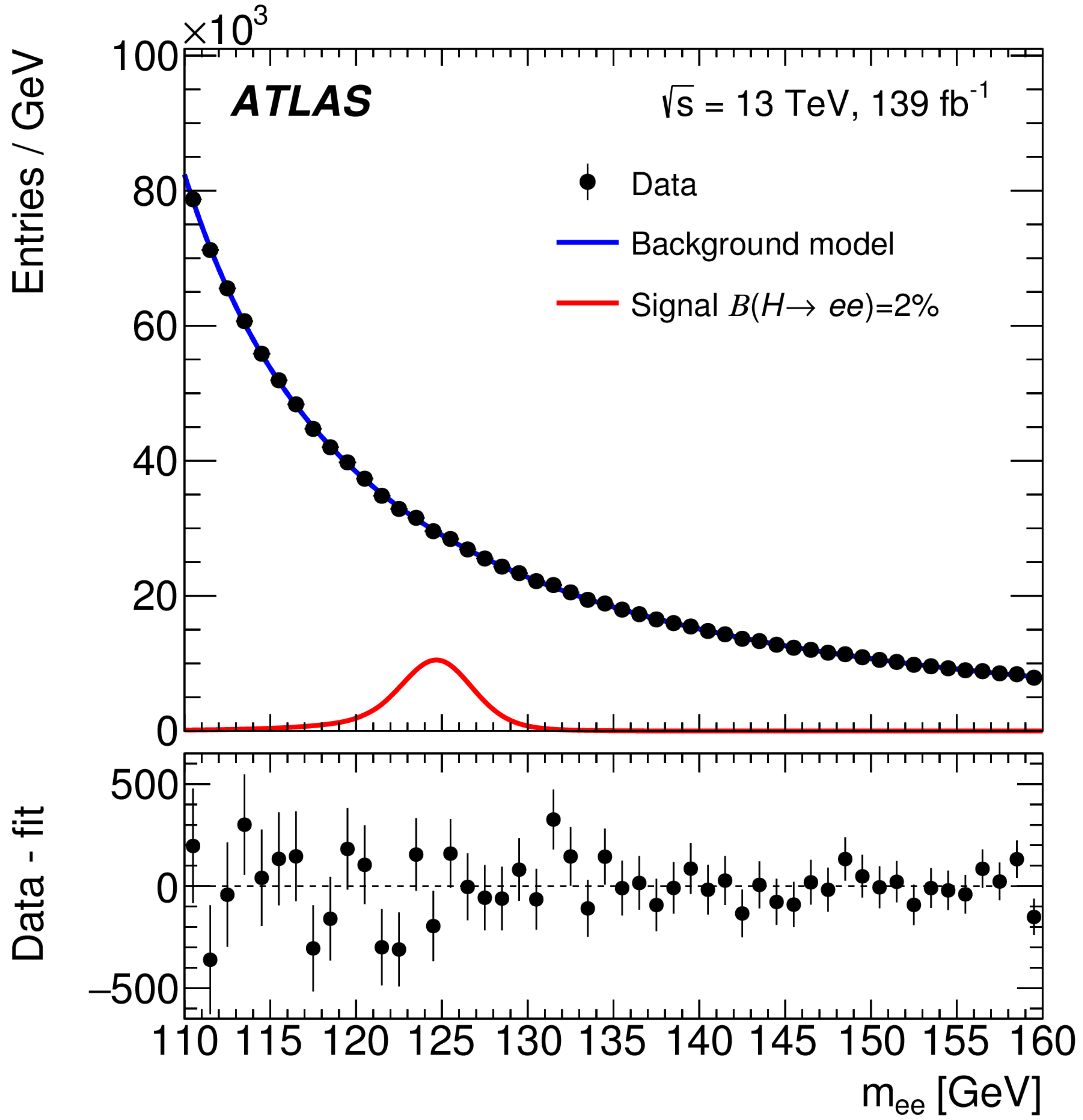
Phys. Lett. B 809 (2020) 135754

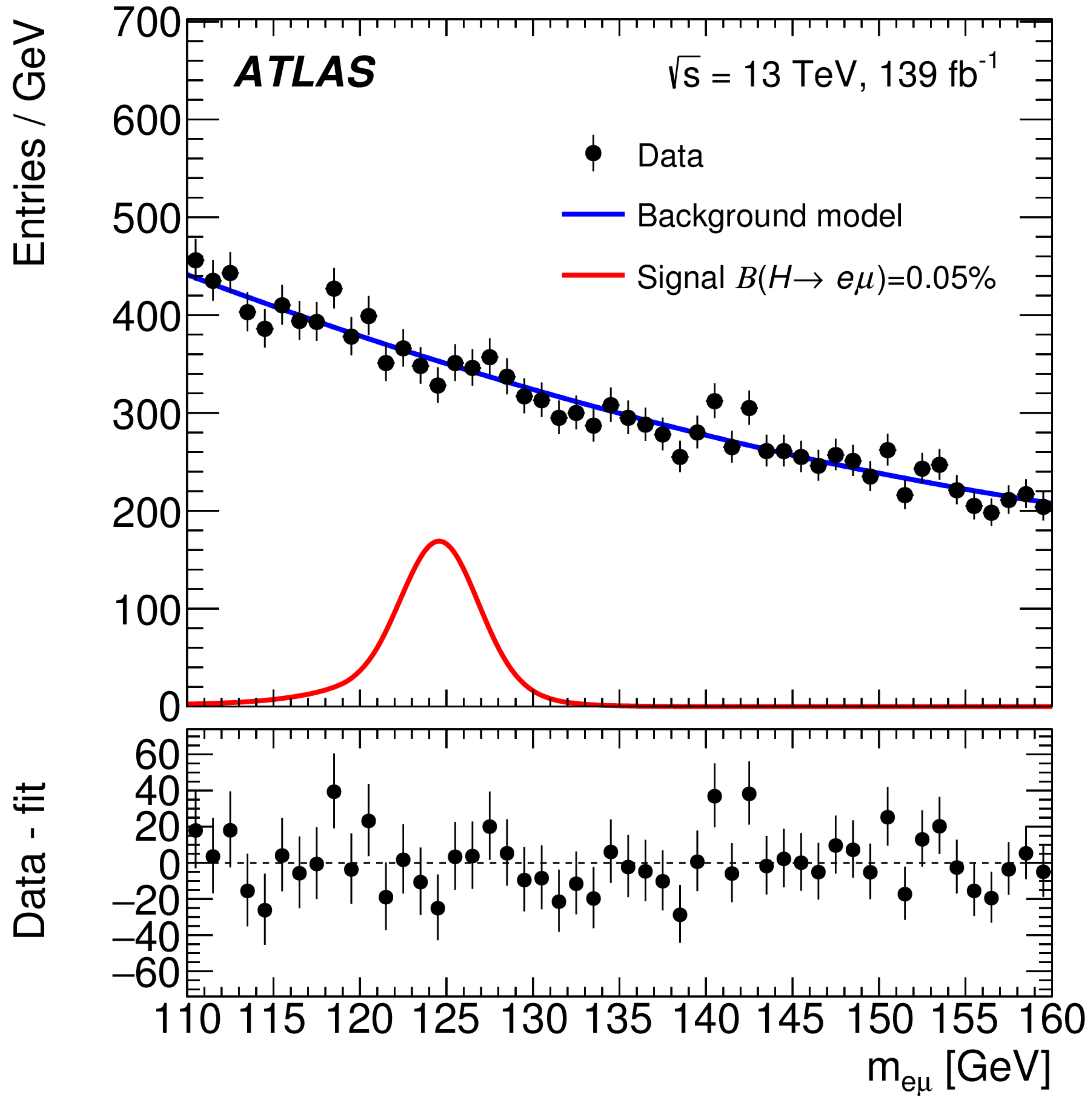
Search for $H \to ee/e\mu$ in ATLAS

- $Br(H \to ee) = G_F m_H m_e^2/(4\sqrt{2}\pi\Gamma_H) \approx 5 \times 10^{-9}$
  - Far below the sensitivity of the LHC
- The LFV $H \to e\mu$ decay is heavily constrained by indirect search ($\mu \to e\gamma$)
  - BUT indirect constraints assume SM values for the Y_{ee} and $Y_{\mu\mu}$
- The $H \to e\mu$ search allows to constrain $Y_{e\mu}$ directly
- The signal is separated from the background by identifying a peak in the distribution of m_{ll}
- Backgrounds:
  - For $H \to ee$, the main contributions come from DYee, $t\bar{t}$ and Diboson
  - For $H \to e\mu$, the main contribution comes from $Z/\gamma* \to \tau_l\tau_l$

Search for $H \to ee/e\mu$ in ATLAS: fit model

- Fit to the invariant mass m_{ll} in [110, 160] GeV
- The dataset is split in 7(8) categories for the ee (eμ) channel
- Signal modeled by the sum of a Crystal Ball and a Gaussian distribution
- Background modeled by a Bernstein polynomial of degree two with category-dependent parameters



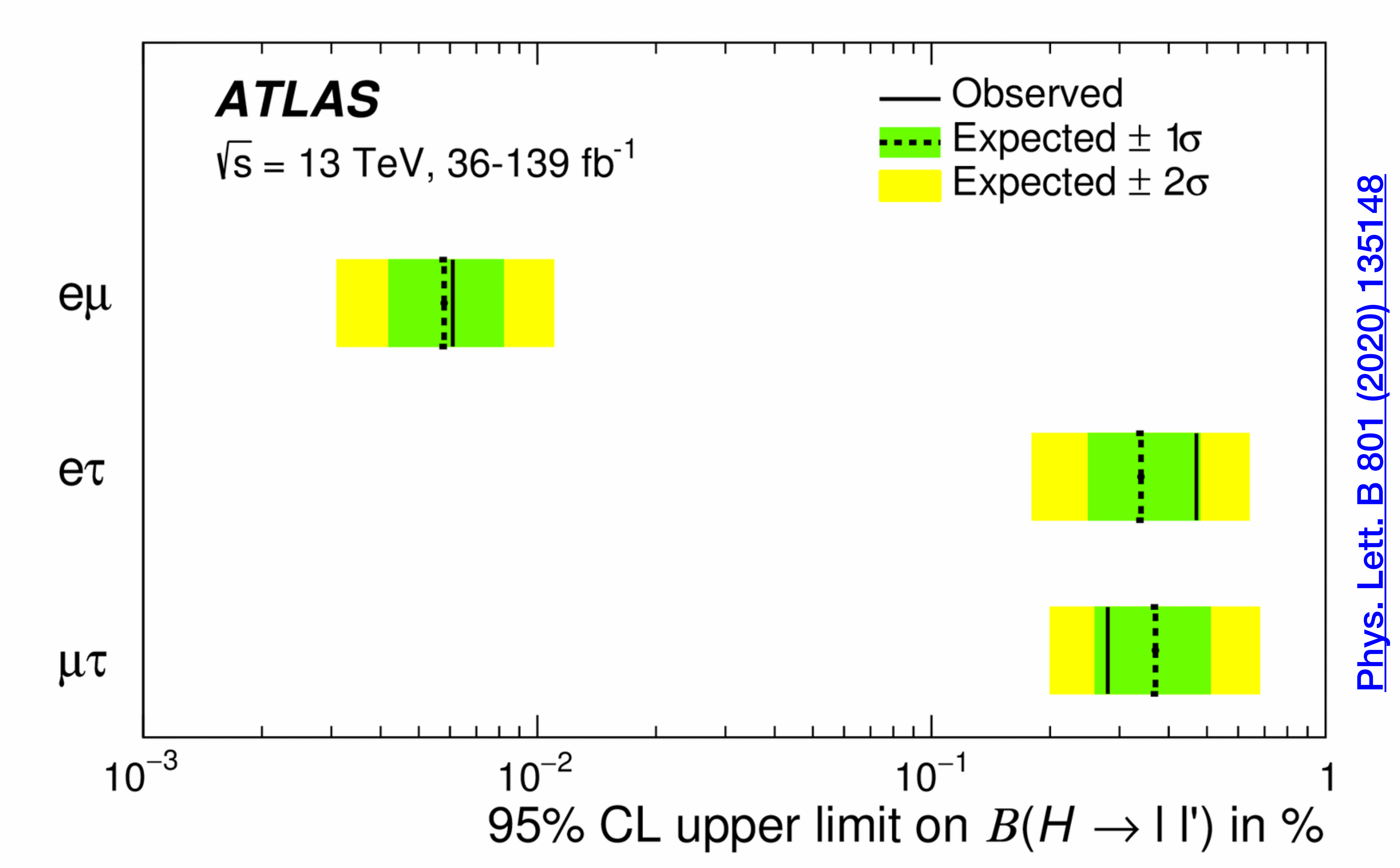


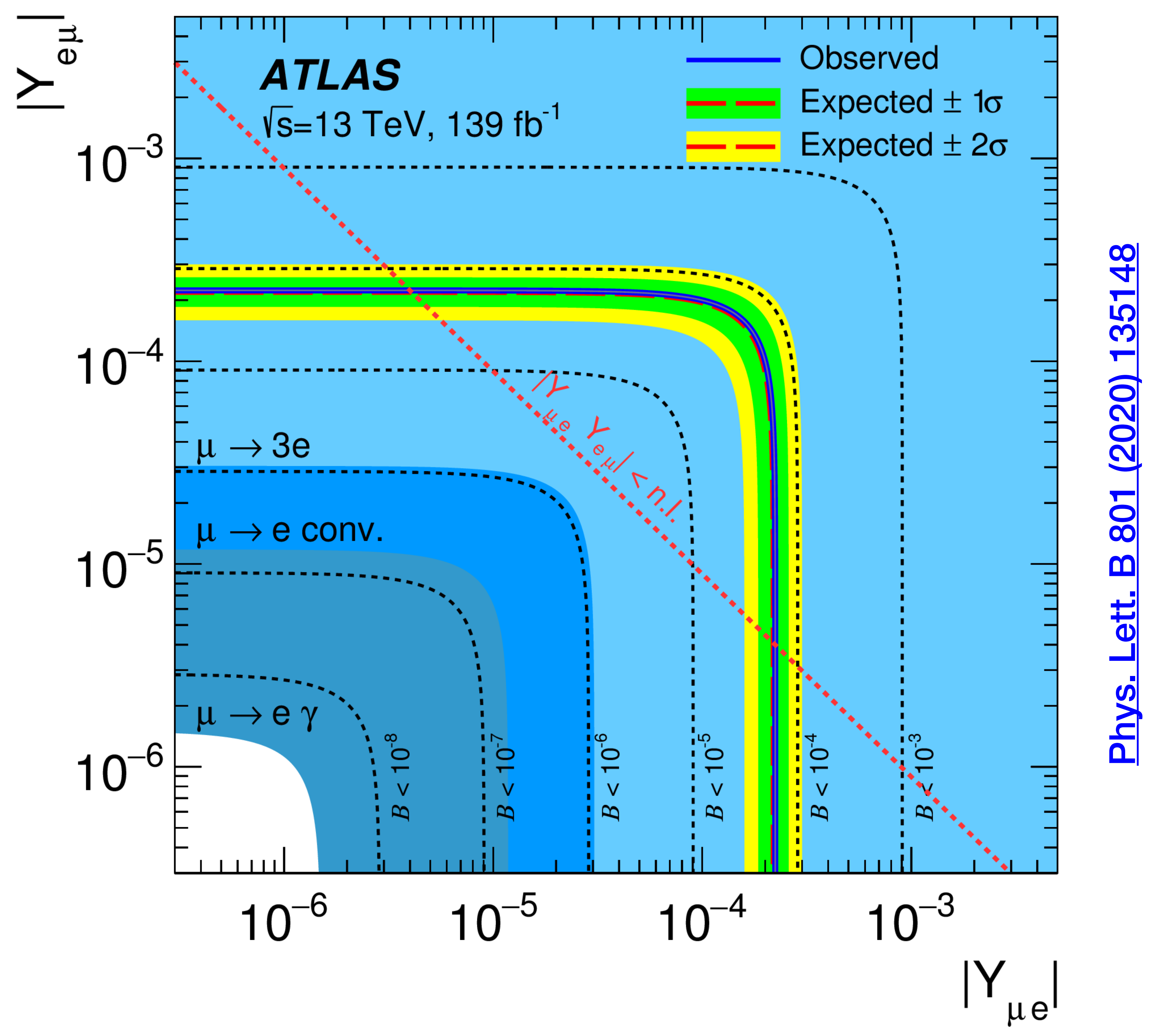
Phys. Lett. B 801 (2020) 135148

Search for $H \to ee/e\mu$ in ATLAS: results

- No evidence of the $H \to ee$ decay is observed
  - Best-fit: Br($H \to ee$) = (0.0±1.7(stat)±0.6(syst))x10^{-4}
- No excess observed for $H \to e\mu$, 95% CL limit is Br($H \to e\mu$)<6.1×10^{-5} (5.8×10^{-5} expected)

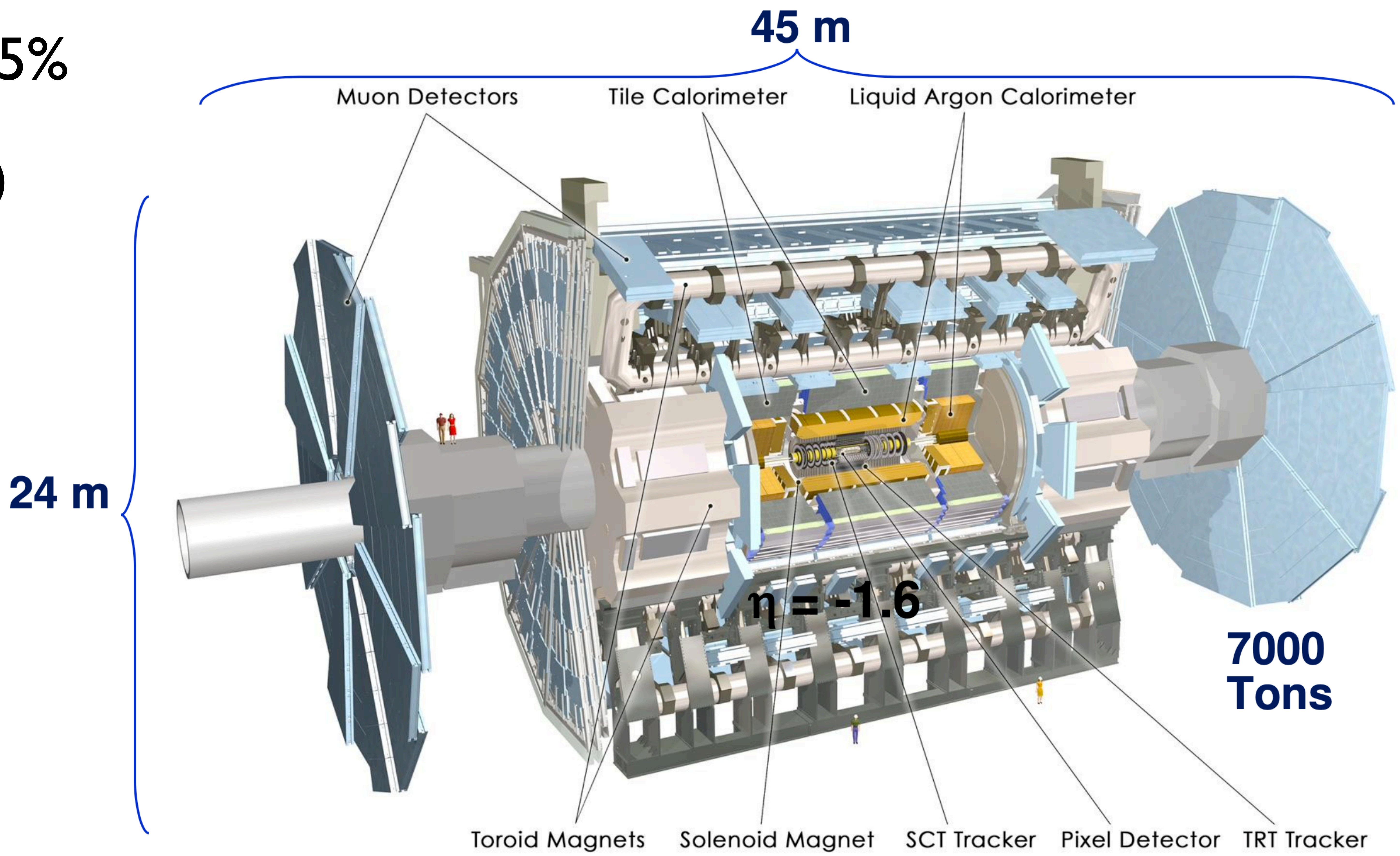
$$|Y_{e\mu}|^2 + |Y_{\mu e}|^2 = \frac{8\pi}{m_H} \frac{B(H \to e\mu)}{1 - B(H \to e\mu)} \Gamma_H(SM)$$





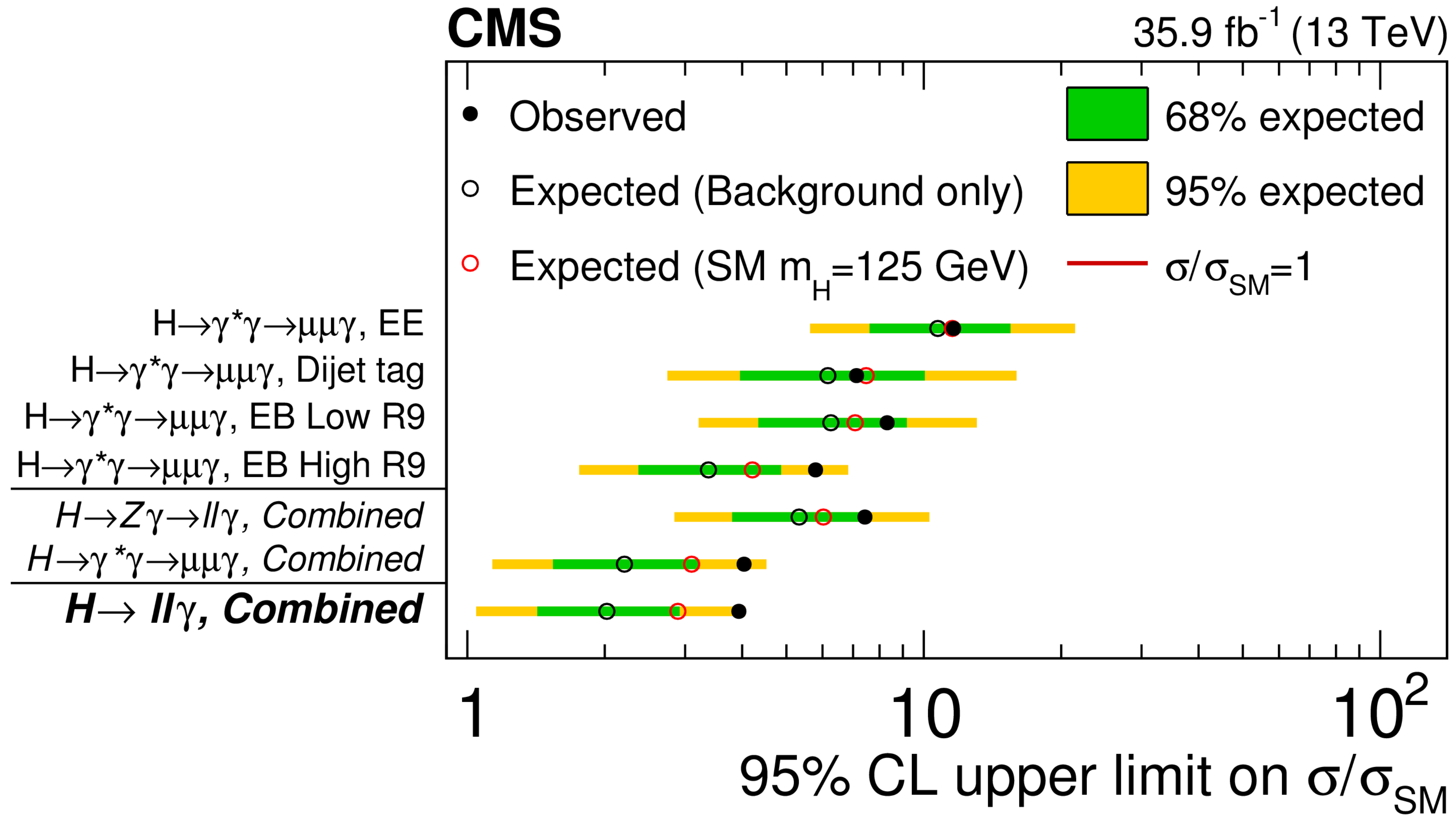
ATLAS experiment

- 2 magnet systems (central 2T solenoid and large toroids in muon spectrometer)
- Electron scale uncertainty ~0.7% in central region
- Muon momentum scale uncert 0.05%
- τ energy scale uncertainty 2% (3%) for 1- (3-) prong τ-lepton

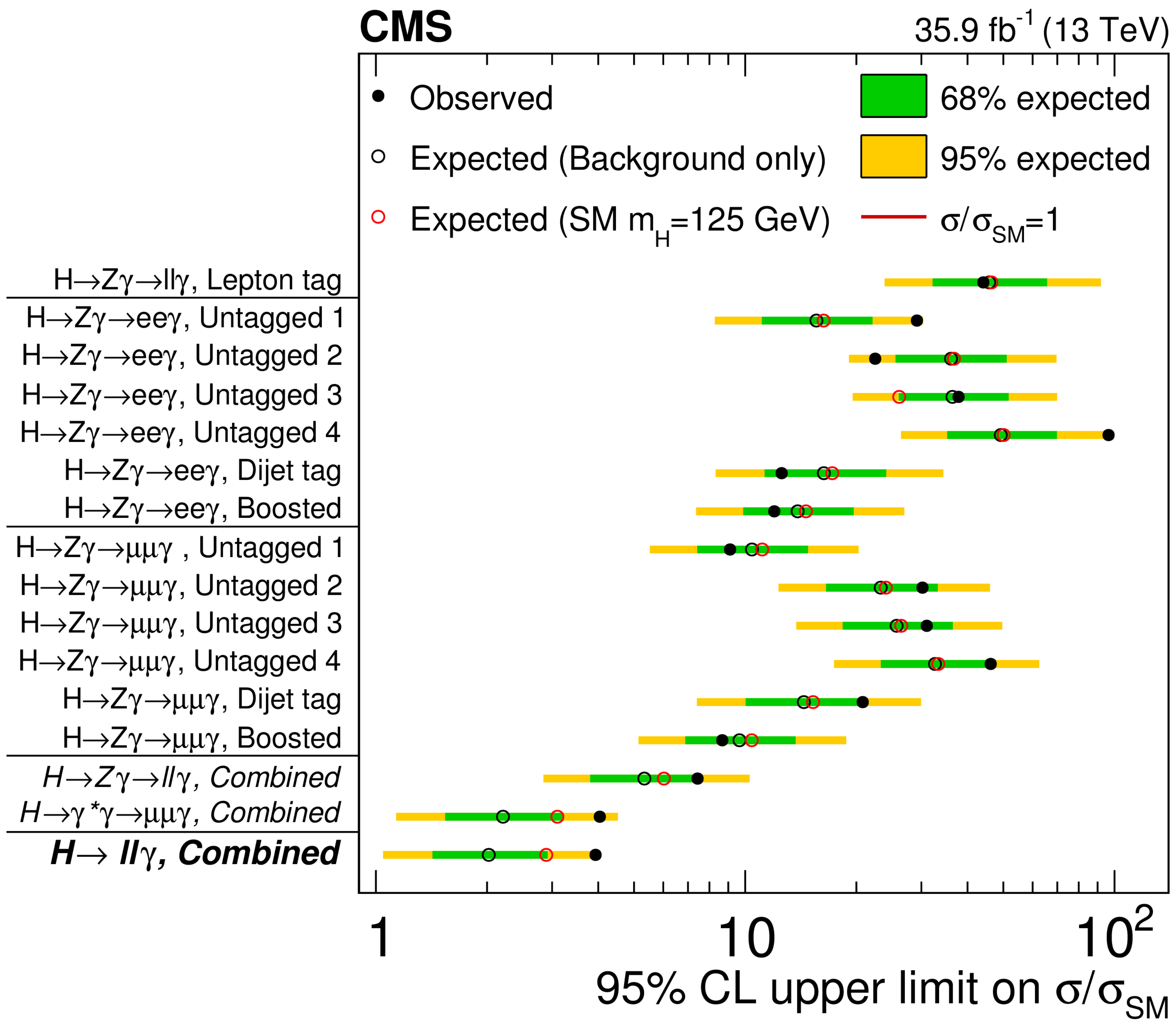


CMS: $H \to Z\gamma$ and $H \to ll\gamma$

- CMS measurement with 36 fb-1:
  - 3.9 × SM (2.0 × SM expected) for combined low + high mass



JHEP 11 (2018) 152



JHEP 11 (2018) 152

$H \to l\tau$ @ CMS (Full Run 2)

- CMS results: [Phys. Rev. D 104 (2021) 032013]