

Search for rare processes and lepton-flavor-violating decays of Higgs boson at the ATLAS experiment

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Introduction

- Since the Higgs discovery in 2012 at the LHC, a new era began for testing the Standard Model (SM) and its limits.
- **Rare decays**, such as $H \rightarrow \mu\mu/ee$ and $H \rightarrow Z\gamma$, offer sensitive tests of the Higgs couplings.
- **Lepton-flavor-violating (LFV)** Higgs decays are forbidden in the SM, but suggested by neutrino oscillations and predicted by several **BSM models**.
 - Can these decays **reveal signs of new physics**?
 - What do **precision measurements** tell us about **Yukawa couplings** and **loop-level processes**?



What answers can Higgs decays to 1st and 2nd generation leptons provide?

Can we confirm Standard Model (SM) couplings?

- Higgs decays to muons offer a direct probe of the muon Yukawa coupling
- $\text{BR}(H \rightarrow \mu^+\mu^-) \approx 2.18 \times 10^{-4}$
→ Most promising 2nd-generation decay channel at the LHC
- $\text{BR}(H \rightarrow e^+e^-) \approx 5.0 \times 10^{-9}$ (challenging at current luminosity)
- Couplings to 3rd-generation fermions are established; 2nd-generation Yukawa couplings not yet conclusively measured
- Precise measurement of $H \rightarrow \mu^+\mu^-$ tests SM prediction.

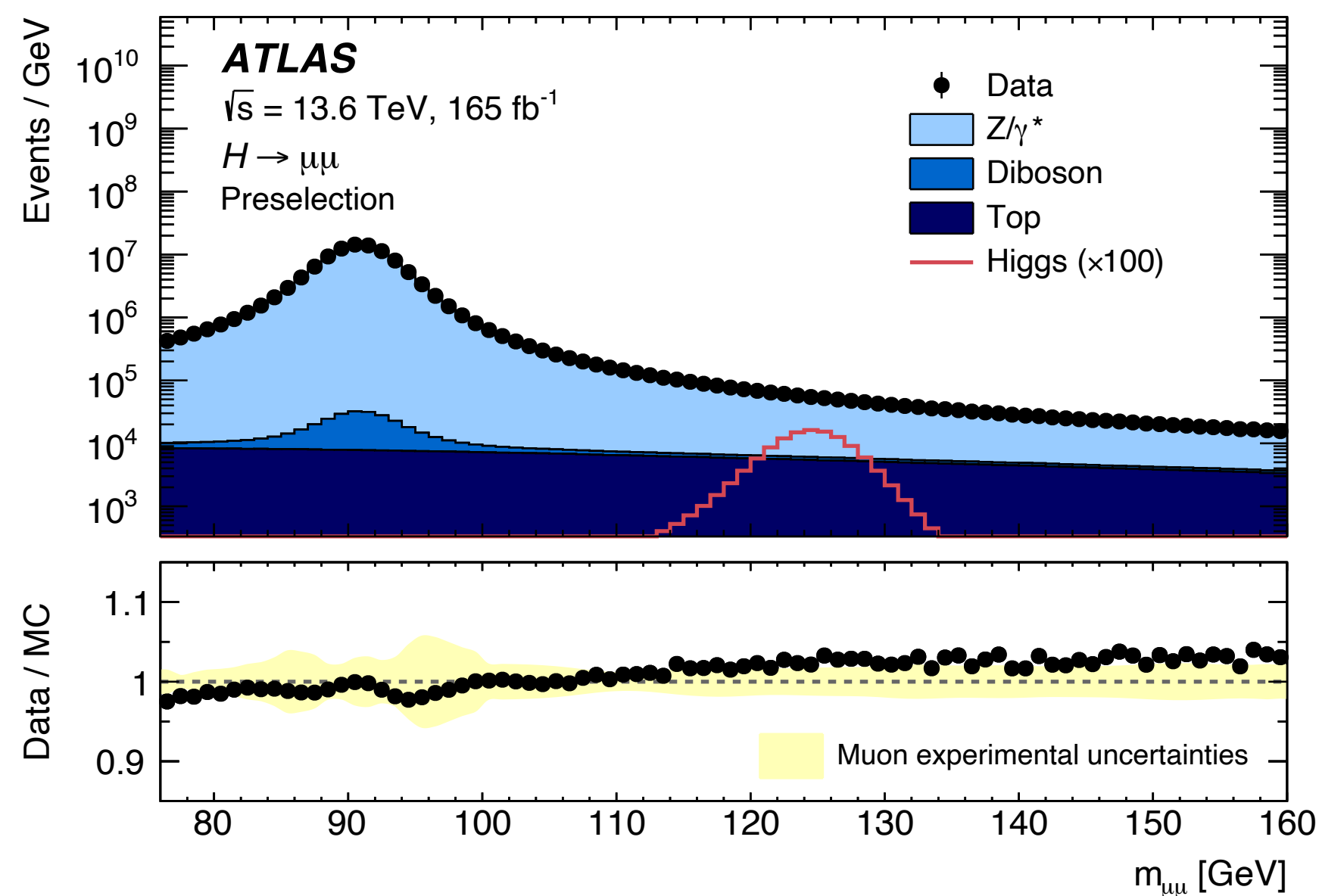
Any indication of Beyond Standard Model (BSM)?

- Are measured rates consistent with SM expectations?
- Enhanced or suppressed $\text{BR}(H \rightarrow \mu\mu)$ can arise from loop-level effects or new particles?
- **Precision measurements** can help constrain BSM parameter space

$H \rightarrow \mu^+\mu^-$: ATLAS Run 2 + Run 3 **NEW!**

Status with Run 2 data for $H \rightarrow \mu^+\mu^-$:

- **ATLAS**: observed (expected) significance **2.0σ** (1.7σ)
- **CMS**: observed (expected) significance **3.0σ** (2.5σ)



Challenge: Rare signal and huge background — signal to background ratio $\sim 0.2\%$

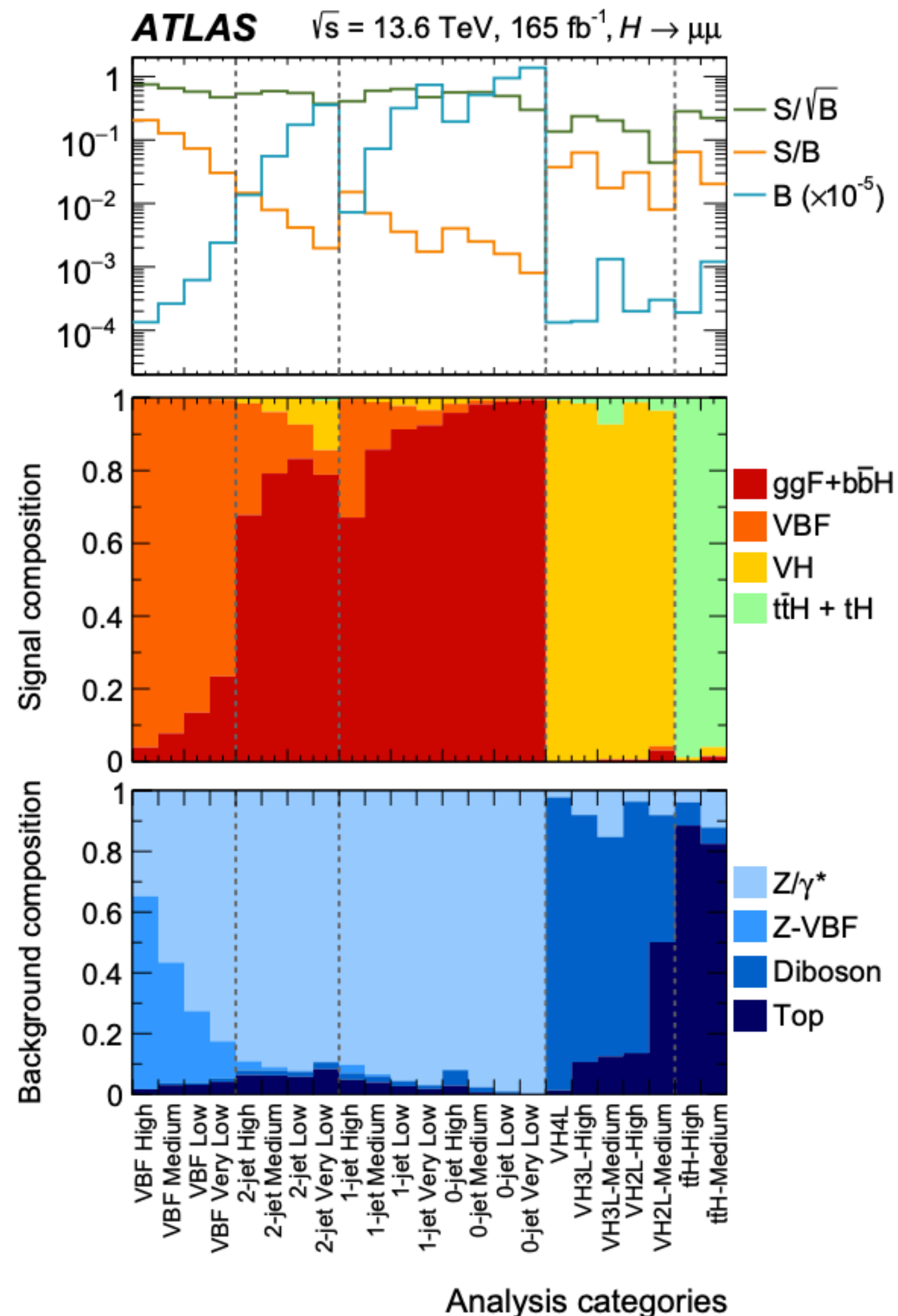
Refined Strategy:

- ✓ Improved muon reconstruction & mass resolution
- ✓ Stronger signal–background separation
- ✓ More robust background modelling: 5B fully simulated events
- ✓ Expanded phase space coverage (including VH- 2ℓ and ttH fully hadronic categories)

Key Enhancements:

- Increased statistics in data
- High-statistics NLO Drell–Yan simulation
- New event categories & better categorization with ML
- Refitting $H \rightarrow \mu^+\mu^-$ primary vertex:
 - More precise d_0 reduces its correlation impact with $m_{\mu\mu}$
 - 1.8% improvement on mass resolution - NEW in Run3
- Including radiation from muons - improvement on mass resolution!

$H \rightarrow \mu^+\mu^-$: ATLAS Run 2 + Run 3 **NEW!**



Event Categorization Strategy

- Events are split into **23 exclusive categories** optimized for different Higgs production modes: **ggF, VBF, VH, $t\bar{t}H$**
- Categorization exploits **topology and kinematics** using ML tools:
 - **BDTs** (XGBoost)
 - **NNs** (Keras/TensorFlow) for $t\bar{t}H$
 - **TMVA** for 4ℓ VH category
- Training uses **final-state kinematics** and object relationships
- Category boundaries optimized for **maximum signal sensitivity**

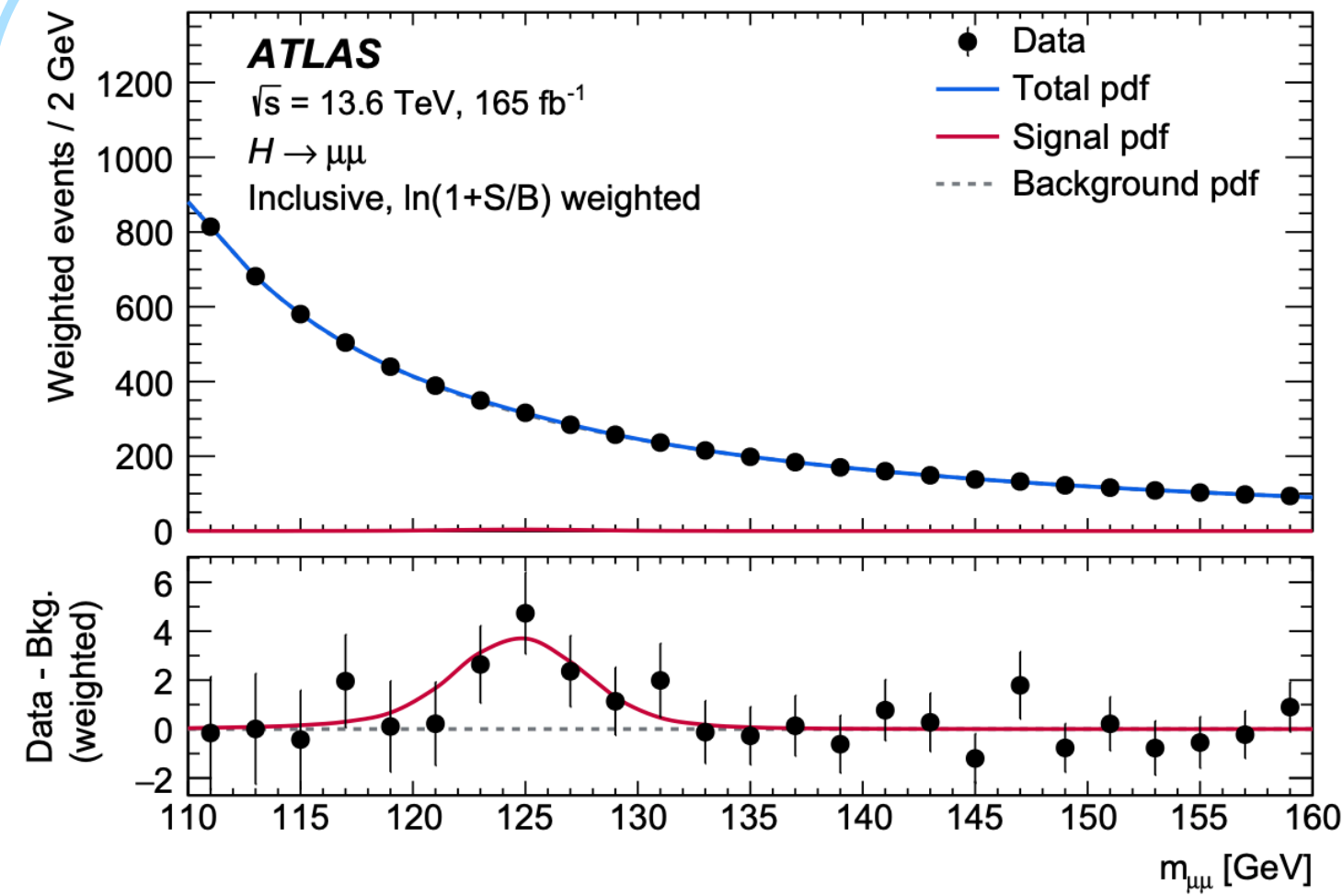
A **simultaneous signal+background fit on the $m_{\mu+\mu-}$ spectrum** with analytic function among all categories:

- Signal:** double-sided Crystal Ball function.
- Background:** Core $\times$ empirical function:
 - Smeared with detector resolution
 - Used full-simulated NLO samples
 - Improved core function with accurate dimuon resolution

H → μ⁺μ⁻: results

NEW!

Run 3



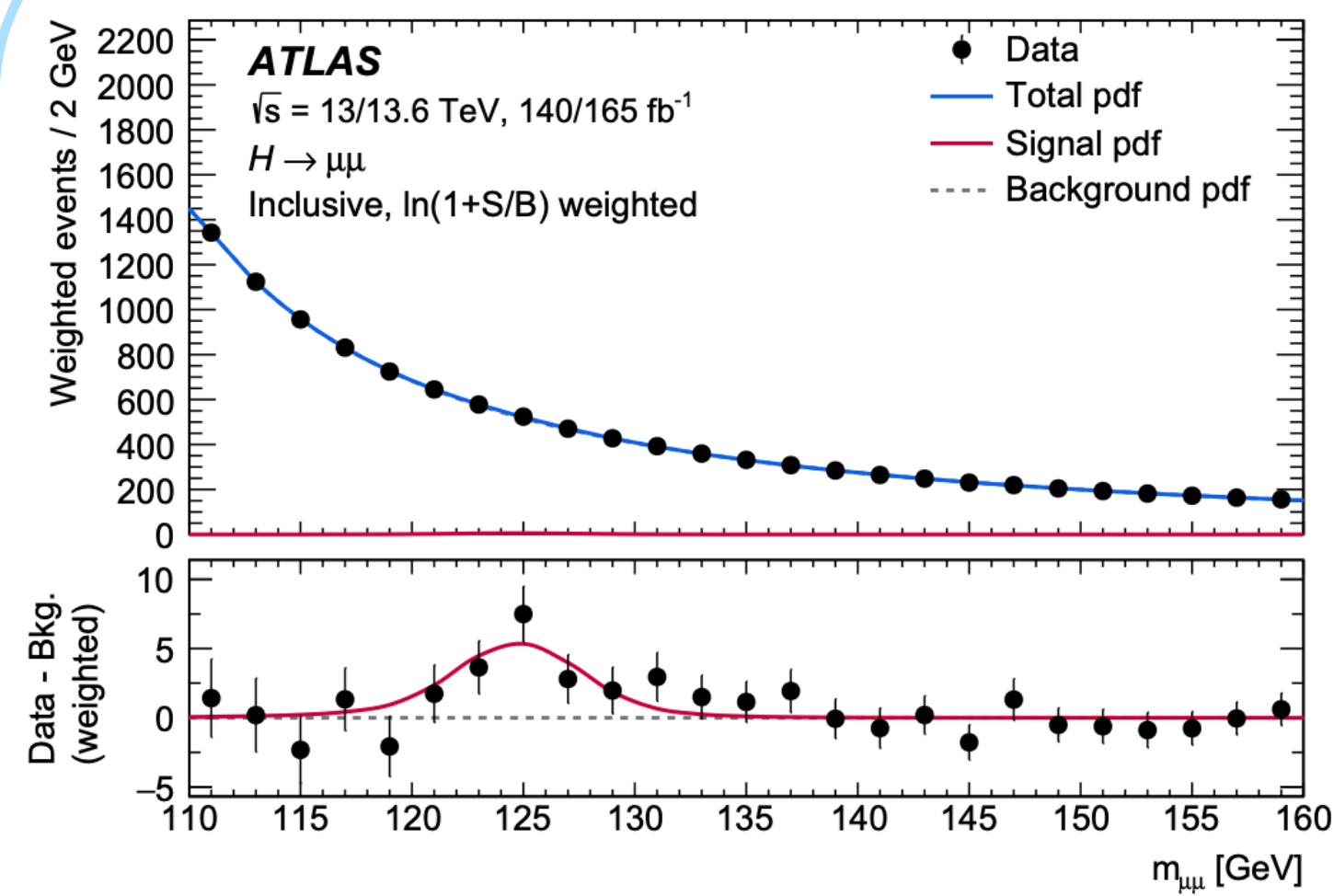
$$\mu = 1.6 \pm 0.6 = 1.6_{-0.5}^{+0.6} \text{ (stat)} \pm 0.2 \text{ (syst)}$$

Observed (expected) **significance 2.8σ (1.8σ)**

Compatibility between Run2 and Run3: 68%

Sensitivity improvement mostly driven by Increased statistics.

Run 2 + Run 3



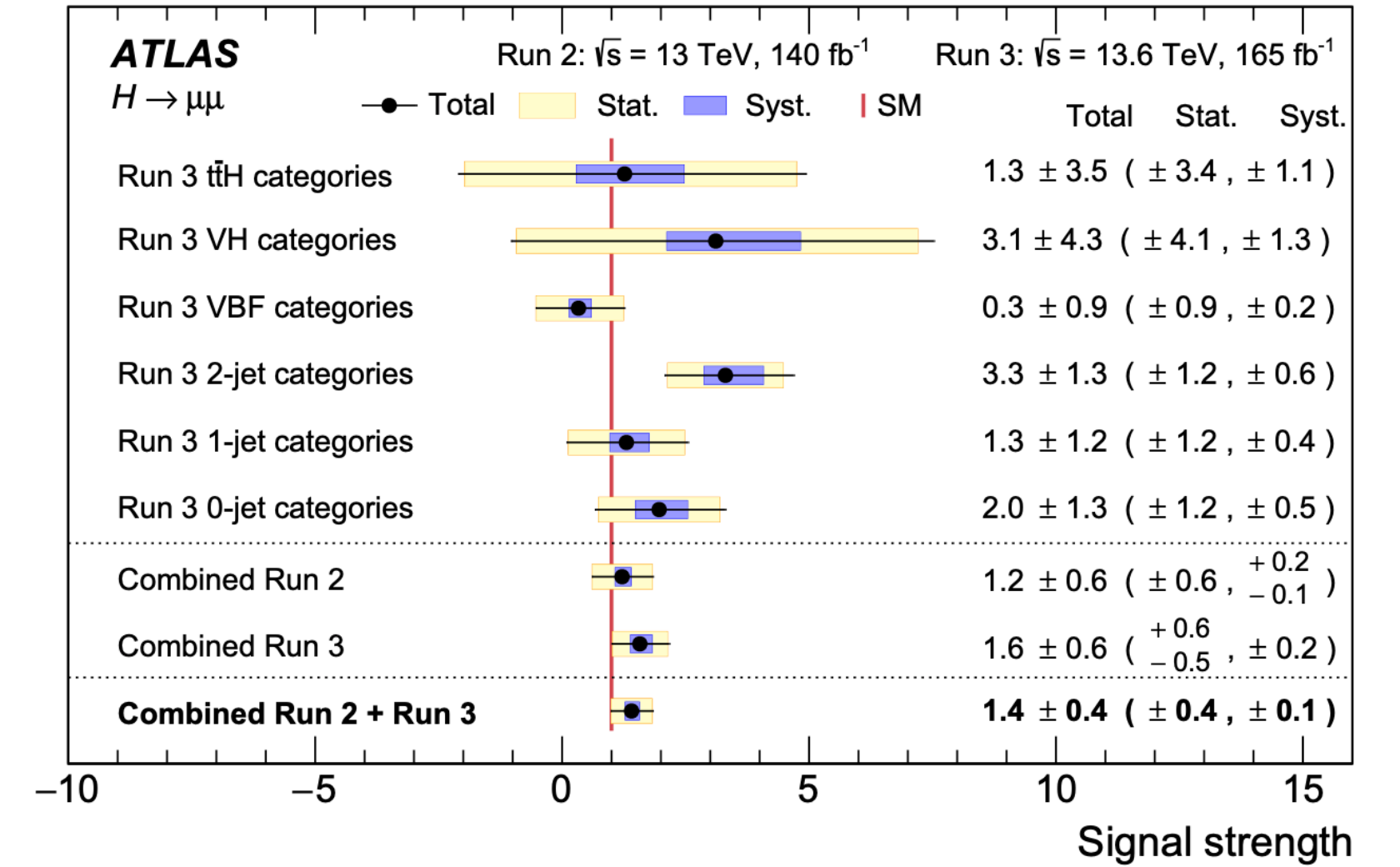
$$\mu = 1.4 \pm 0.4 = 1.4 \pm 0.4 \text{ (stat)} \pm 0.1 \text{ (syst)}$$

Observed (expected) **significance 3.4σ (2.5σ)**

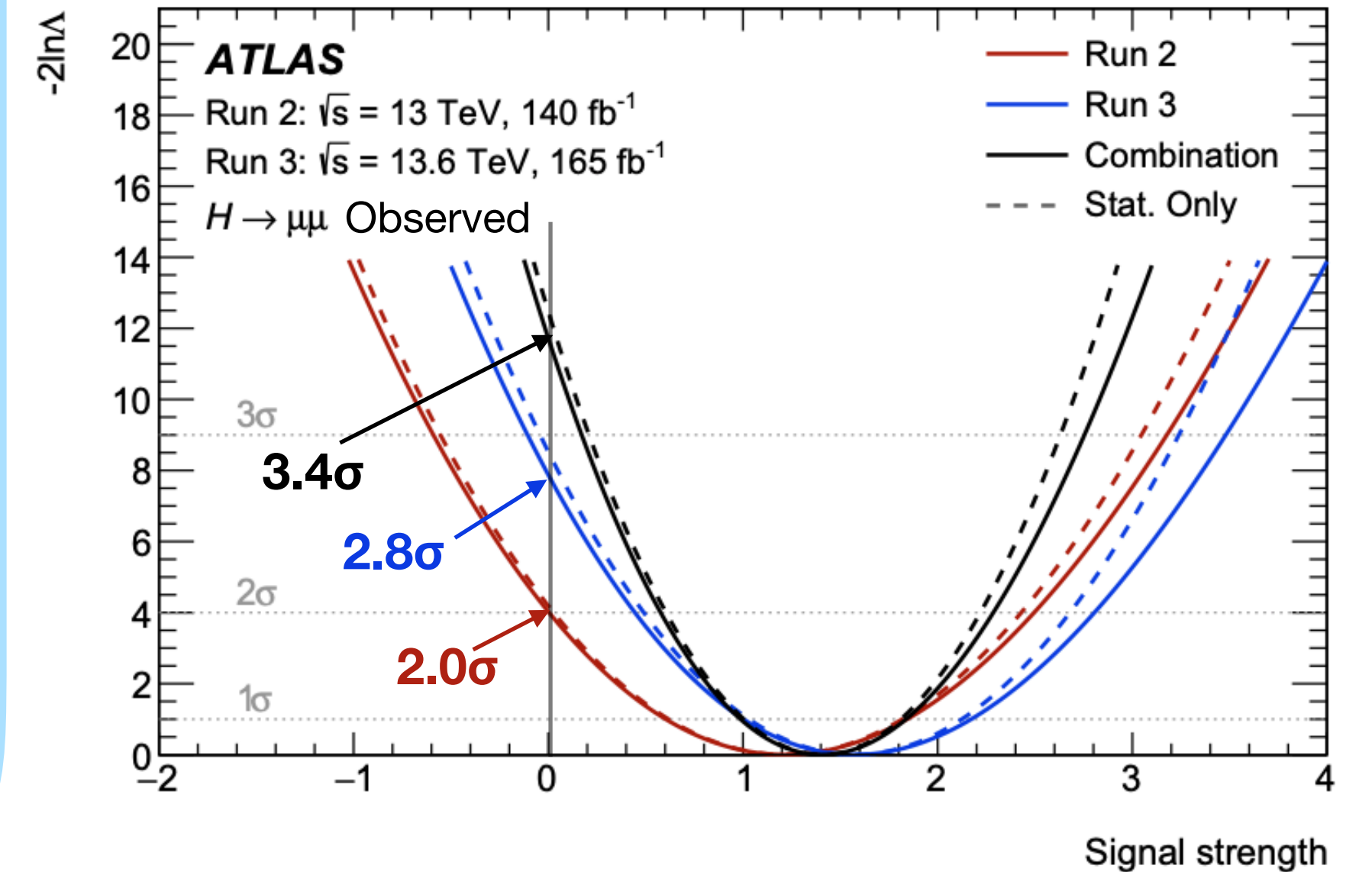
Sensitivity improves by ~50% w.r.t Run 2 results.

Evidence of H → μ⁺μ⁻ decay!

Observed



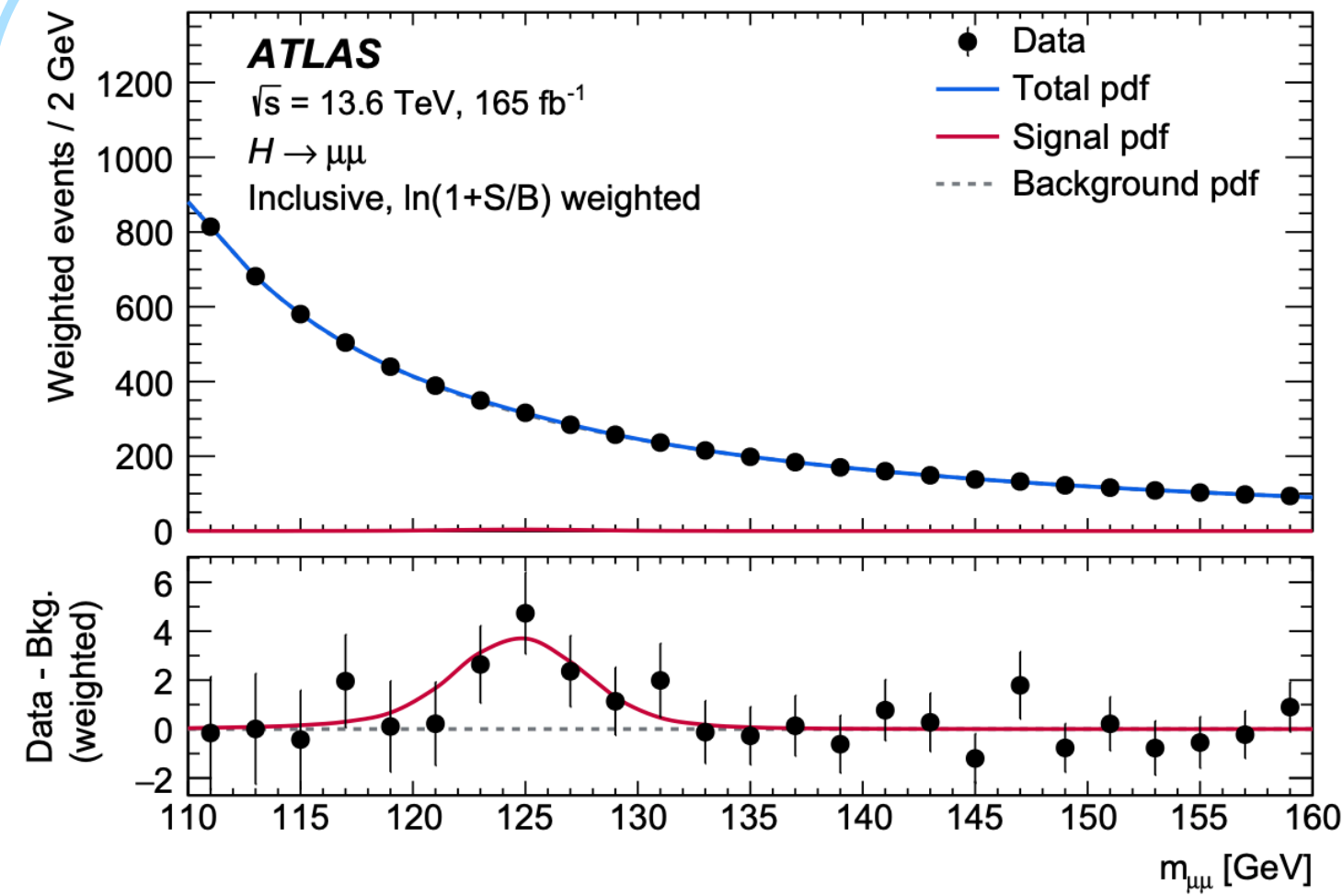
Profile likelihood scan of signal strength



$H \rightarrow \mu^+\mu^-$: results

NEW!

Run 3



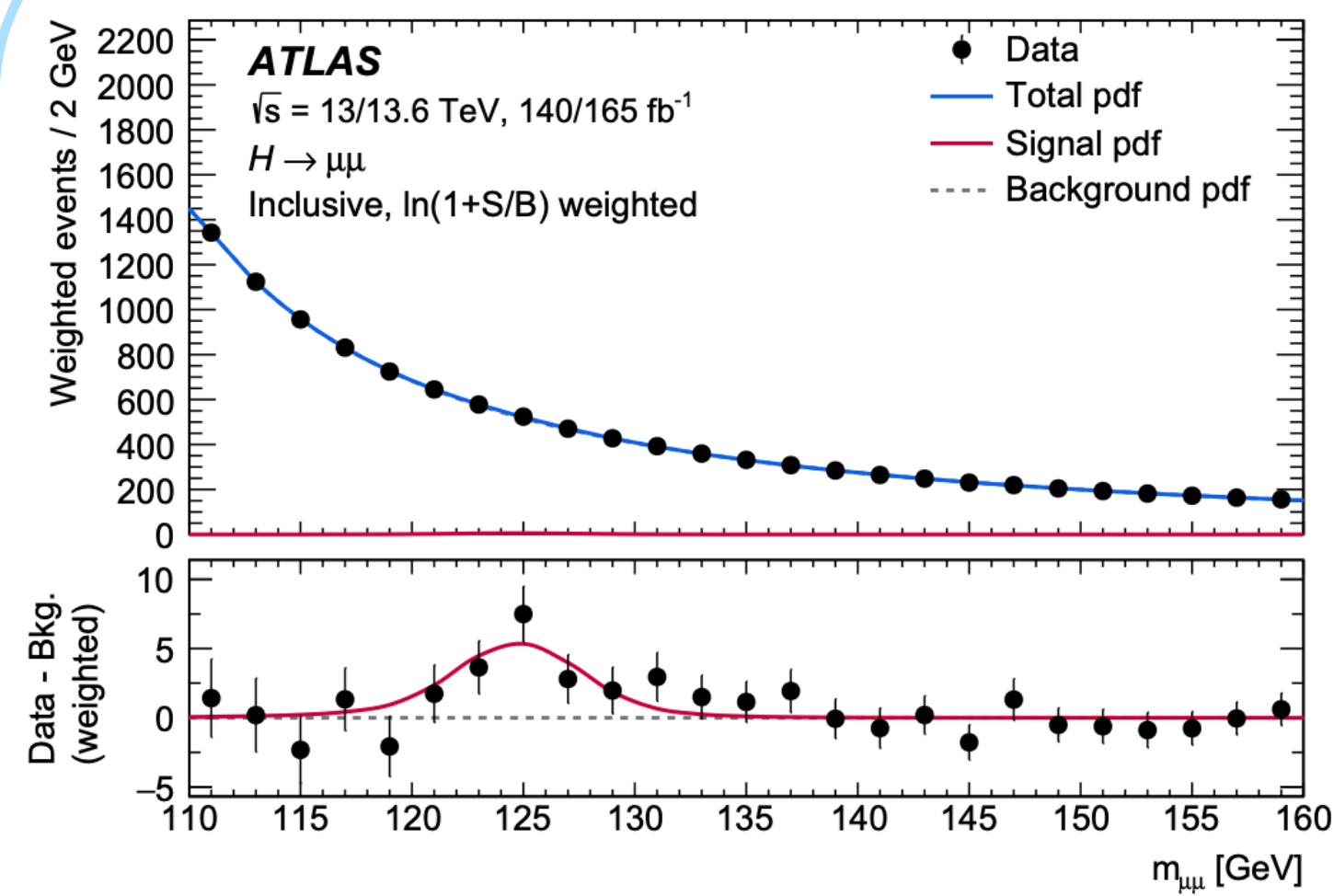
$$\mu = 1.6 \pm 0.6 = 1.6^{+0.6}_{-0.5} \text{ (stat)} \pm 0.2 \text{ (syst)}$$

Observed (expected) **significance 2.8σ (1.8σ)**

Compatibility between Run2 and Run3: 68%

Sensitivity improvement mostly driven by Increased statistics.

Run 2 + Run 3



$$\mu = 1.4 \pm 0.4 = 1.4 \pm 0.4 \text{ (stat)} \pm 0.1 \text{ (syst)}$$

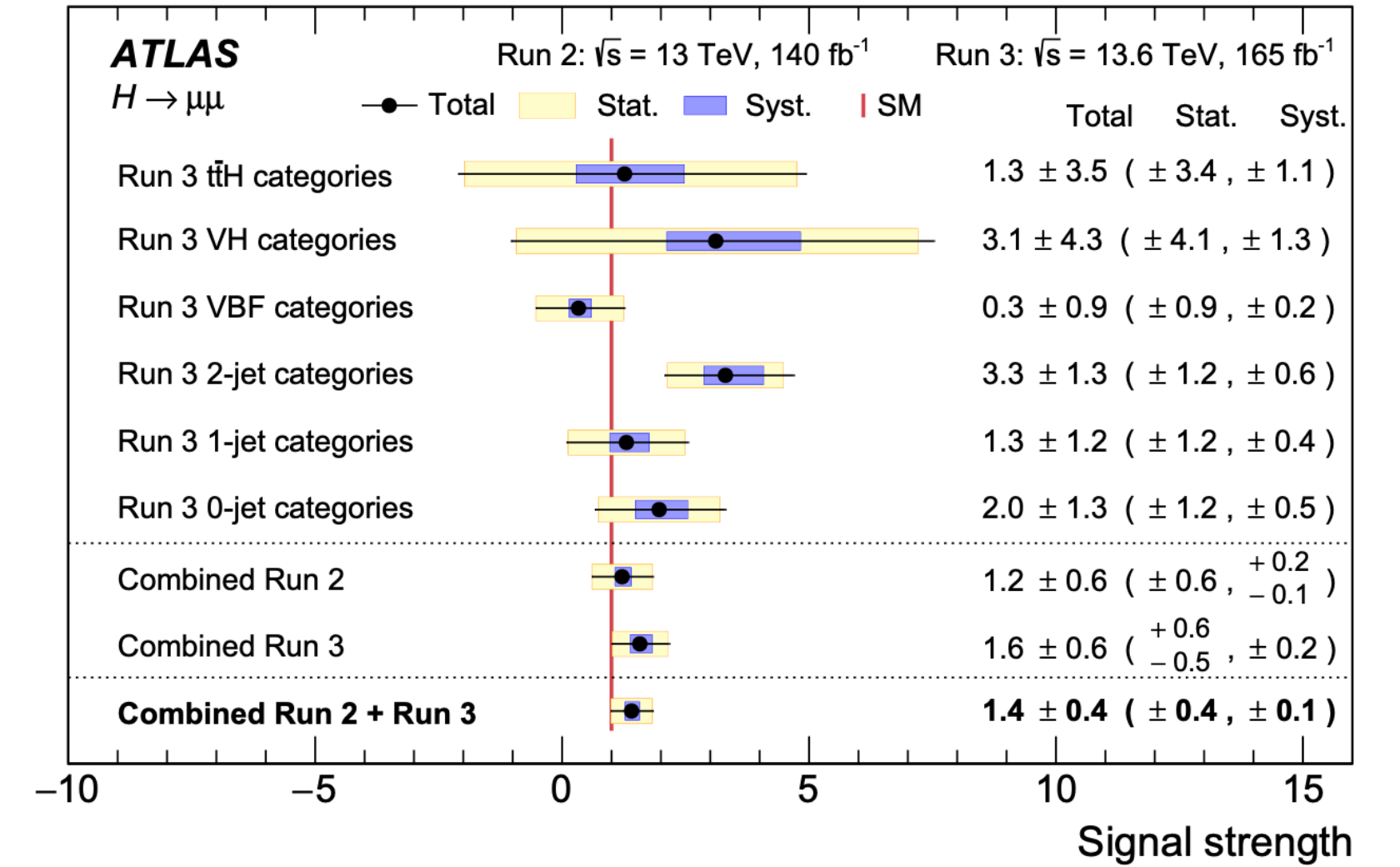
Observed (expected) **significance 3.4σ (2.5σ)**

Sensitivity improves by $\sim 50\%$ w.r.t Run 2 results.

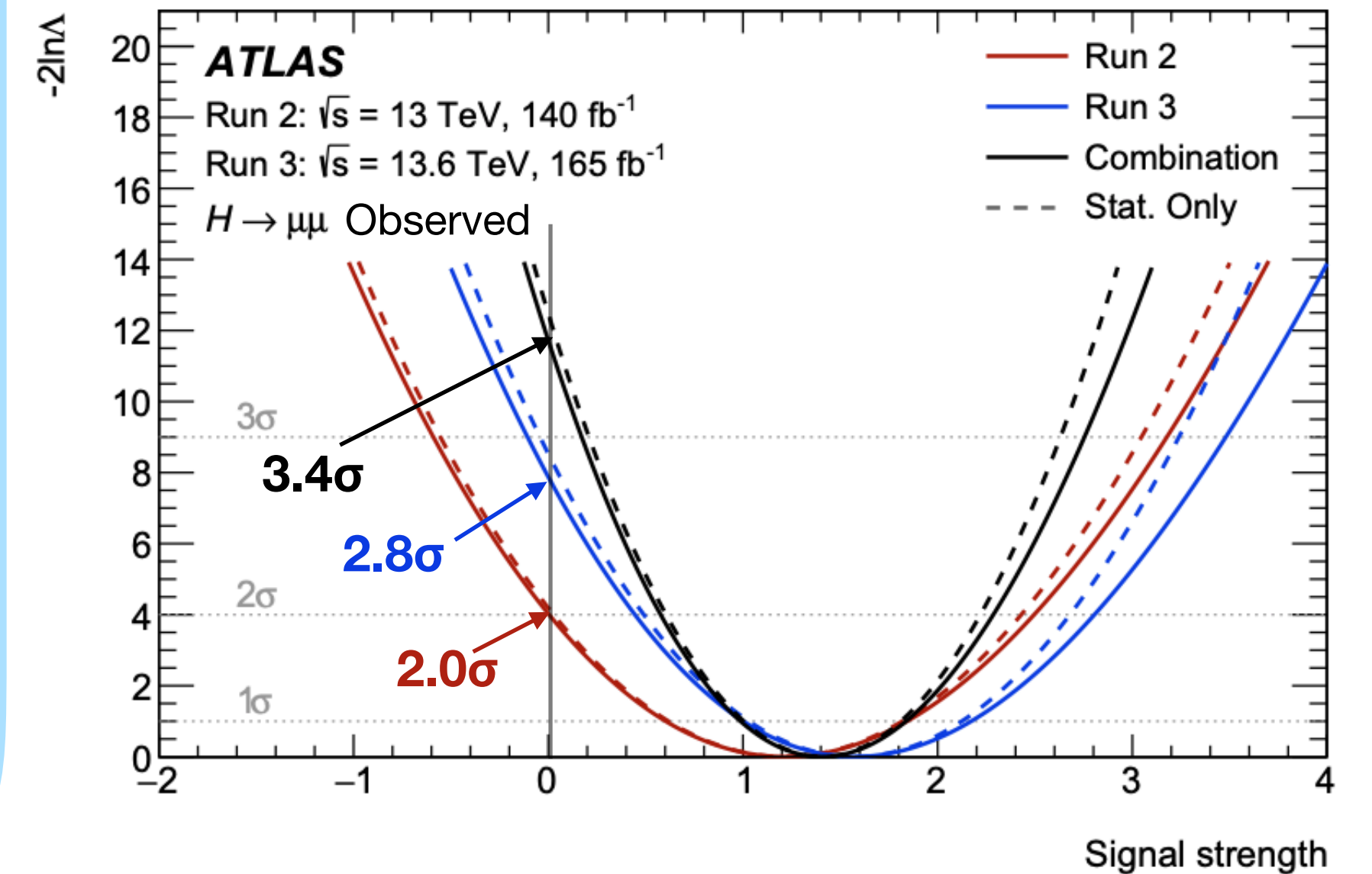
Evidence of $H \rightarrow \mu^+\mu^-$ decay!



Observed



Profile likelihood scan of signal strength



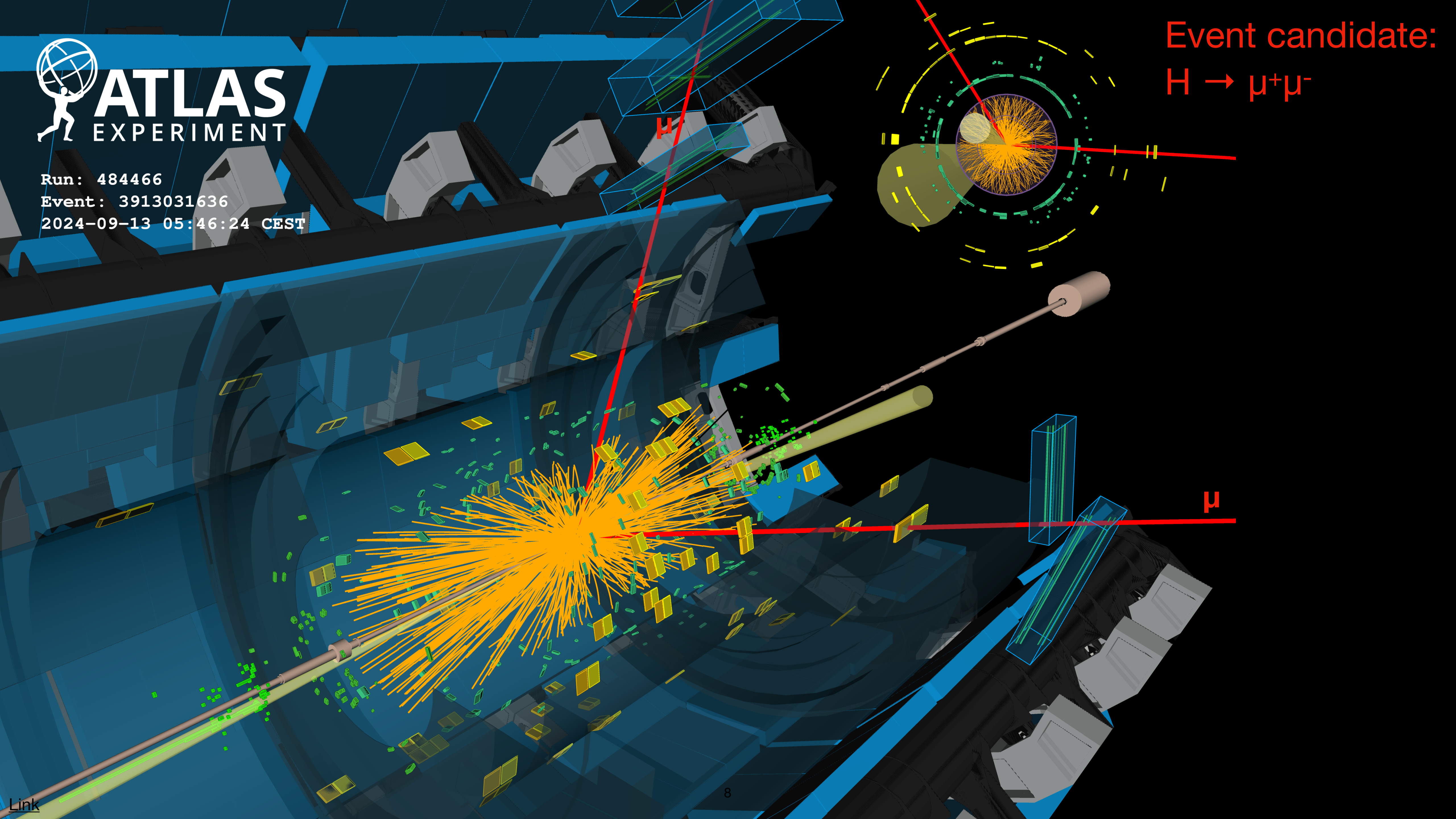


Run: 484466

Event: 3913031636

2024-09-13 05:46:24 CEST

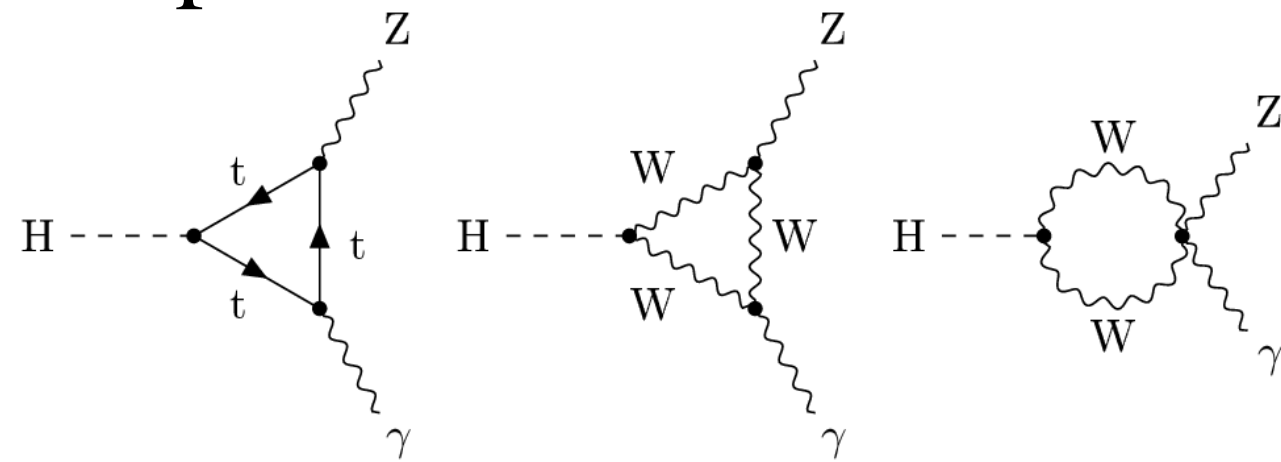
Event candidate:
 $H \rightarrow \mu^+ \mu^-$



What can the rare $H \rightarrow Z\gamma$ decay tell us?

Within the Standard Model:

- Is the observed rate consistent with SM expectations?
- SM predicts $\text{BR}(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$
 - Similar in size to $H \rightarrow \gamma\gamma$ $(2.27 \pm 0.07) \times 10^{-3}$
- Can we observe this rare loop-induced decay and complete the picture of Higgs decays to electroweak bosons ($\gamma\gamma$, ZZ^* , WW^*)?
- How precise can we measure this decay to test the SM loop structure?



Beyond the Standard Model:

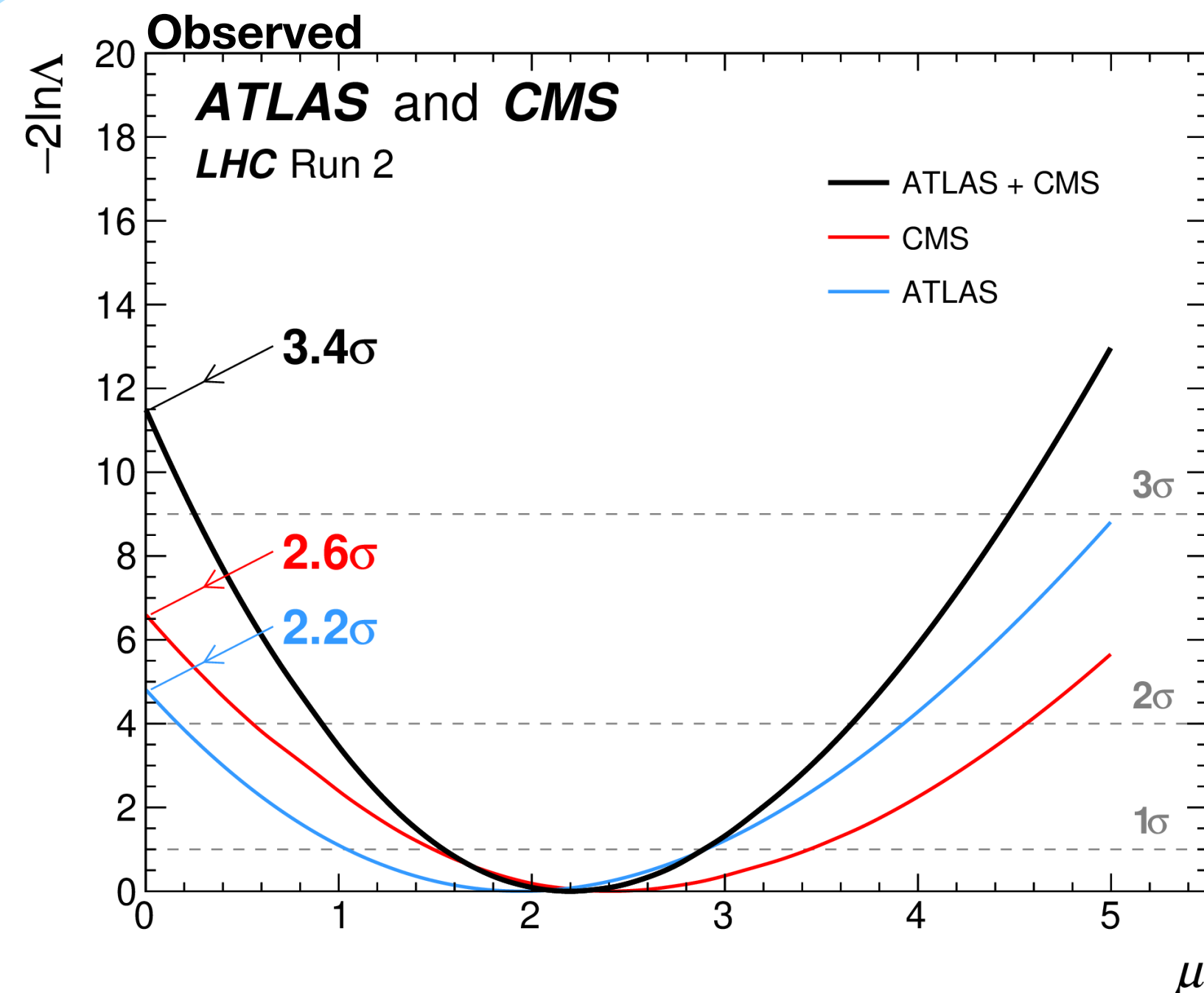
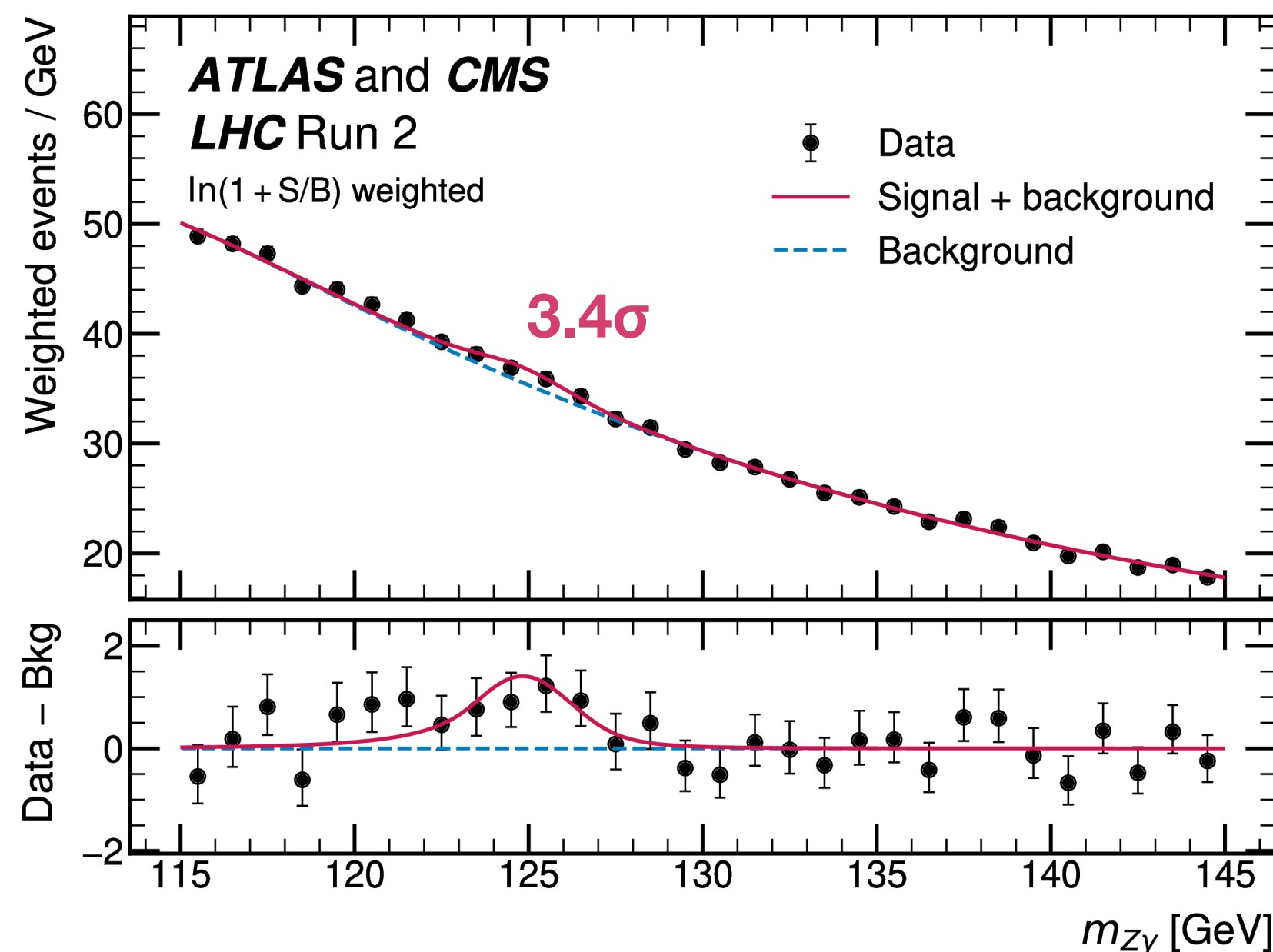
- Are there deviations from the SM prediction in $\text{BR}(H \rightarrow Z\gamma)$?
- Could new particles (charged scalars, fermions, vector bosons) be running in the loop and modifying the decay rate?
- Does the ratio $\text{BR}(H \rightarrow Z\gamma) / \text{BR}(H \rightarrow \gamma\gamma)$ show anomalous behaviour?
- Could this point to composite Higgs scenarios or alternative symmetry-breaking mechanisms?

$H \rightarrow Z\gamma$: ATLAS + CMS - Run 2

Status with Run 2 data for $H \rightarrow Z\gamma$: **Evidence** - combining ATLAS and CMS results!

Event Selection & Categorization:

- Focus on $Z \rightarrow e^+e^-/\mu^+\mu^-$ decays - good mass resolution & background rejection, but small BR (6.7%).
- **ATLAS**: 6 categories, including a VBF-enriched one using a BDT and others split by lepton type & $Z\gamma$ kinematics.
- **CMS**: 8 categories, with BDTs targeting VBF, associated production, and signal-background separation.
- Experimental uncertainties from ATLAS and CMS are treated as uncorrelated; theory (QCD & BR) uncertainties as correlated.



Combined ATLAS and CMS results:

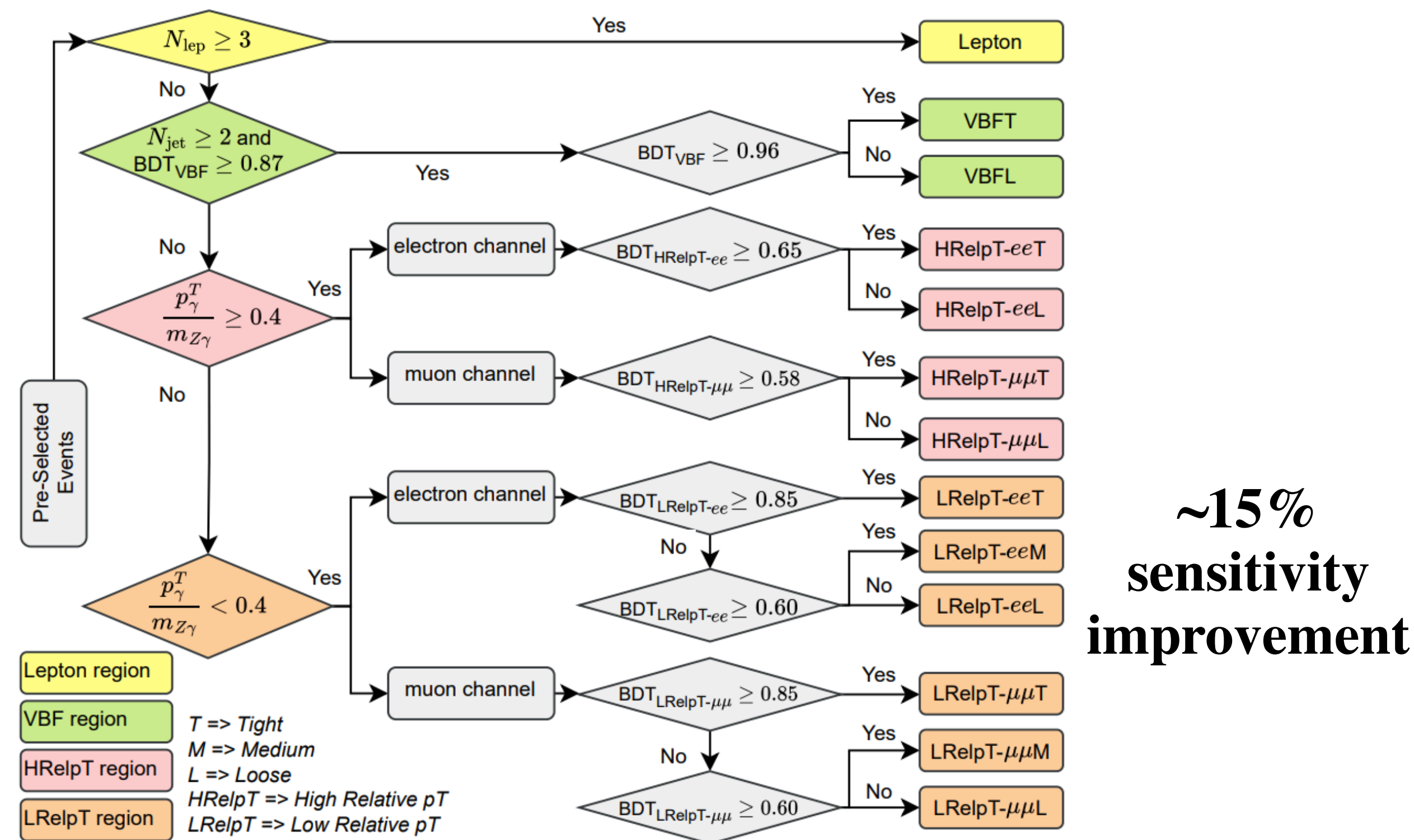
$$\mu = 2.2 \pm 0.7 = 2.2 \pm 0.6 \text{ (stat)}_{-0.2}^{+0.3} \text{ (syst)}$$

Observed (expected) **significance 3.4σ (1.6σ)**

★ **ATLAS** - Observed (expected) significance 2.2σ (1.2σ)

★ **CMS** - Observed (expected) significance 2.6σ (1.1σ)

H $\rightarrow$ Z γ : ATLAS - Run 2 + Run 3 **NEW!**



**~15%
sensitivity
improvement**

Main changes w.r.t. previous ATLAS Run2 search:

- Object threshold **selection optimization** - improve the signal efficiency
- Split into different regions for categorization - targeting all major production modes: ggF, VBF, VH, ttH.
- **Categorization optimization**: new lepton category, VBF re-optimization, MVA optimization with low-relative p_T and high relative p_T separation (in total: 13 categories).
- Including partial ATLAS Run3 data (2022+2023+2024) of 165fb^{-1}

**~30%
sensitivity
improvement**

A **simultaneous signal+background fit on the $l\ell\gamma$ mass spectrum** with analytic function among all categories:

- **Signal**: double-sided Crystal Ball function.
- **Background**: function and fit range chosen to minimize spurious signal.

ATLAS Preliminary
 $\sqrt{s} = 13.6 \text{ TeV}, 165 \text{ fb}^{-1}$
 $H \rightarrow Z\gamma$ all categories
 $\ln(1+S_{68}/B_{68})$ weighted sum

Legend:
 • Data
 — Total pdf
 — Signal pdf
 Background pdf

Top Panel: $\sum \text{weights} / \text{GeV}$ vs $m_{Z\gamma} [\text{GeV}]$

Bottom Panel: $\sum w - \text{Bkg}$ vs $m_{Z\gamma} [\text{GeV}]$

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$
 $\sqrt{s} = 13.6 \text{ TeV}, 165 \text{ fb}^{-1}$
 $H \rightarrow Z\gamma$ all categories
 $\ln(1+S_{68}/B_{68})$ weighted sum

Legend:
 • Data
 — Total pdf
 — Signal pdf
 - - - Background pdf

Top Panel: $\sum w - B_{kg}$ (GeV) vs $m_{Z\gamma}$ [GeV]

Bottom Panel: $\sum w - B_{kg}$ vs $m_{Z\gamma}$ [GeV]



ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}, \sqrt{s} = 13.6 \text{ TeV}, 165 \text{ fb}^{-1}$

	Total	Stat. Syst.
Run3 Lepton	$-6.0^{+6.1}_{-5.8}$	$+6.0$ -1.6
Run3 VBFT	$1.2^{+1.3}_{-1.0}$	$+1.3$ -0.1
Run3 VBFL	$-3.7^{+2.0}_{-1.9}$	$+1.9$ -0.8
Run3 HRRelpT- eeT	$2.5^{+3.1}_{-2.8}$	$+3.0$ -0.9
Run3 HRRelpT- eeL	$1.2^{+3.0}_{-2.8}$	$+2.8$ -0.8
Run3 HRRelpT- $\mu\mu T$	$2.6^{+2.8}_{-2.6}$	$+2.6$ -0.8
Run3 HRRelpT- $\mu\mu L$	$0.6^{+4.6}_{-4.4}$	$+4.1$ -2.1
Run3 LRRelpT- eeT	$0.9^{+2.9}_{-2.8}$	$+2.7$ -1.1
Run3 LRRelpT- eeM	$1.5^{+3.2}_{-3.1}$	$+2.8$ -1.4
Run3 LRRelpT- eeL	$-0.8^{+9.3}_{-9.4}$	$+8.0$ -5.1
Run3 LRRelpT- $\mu\mu T$	$2.3^{+2.9}_{-2.8}$	$+2.8$ -0.3
Run3 LRRelpT- $\mu\mu M$	$3.5^{+2.5}_{-2.4}$	$+2.3$ -0.7
Run3 LRRelpT- $\mu\mu L$	$-11.5^{+5.3}_{-5.7}$	$+4.5$ -3.5
Run2 Comb.	$2.0^{+1.0}_{-0.9}$	$+0.9$ -0.3
Run3 Comb.	$0.9^{+0.7}_{-0.6}$	$+0.7$ -0.1
Run2 + 3 Comb.	$1.3^{+0.6}_{-0.5}$	$+0.5$ -0.2

Signal strength

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$
 $\sqrt{s} = 13.6 \text{ TeV}, 165 \text{ fb}^{-1}$
 $H \rightarrow Z\gamma$, Observed

Run2
Run3
Combination

2.5σ
2.2σ
1.4σ

$\mu_{Z\gamma}$

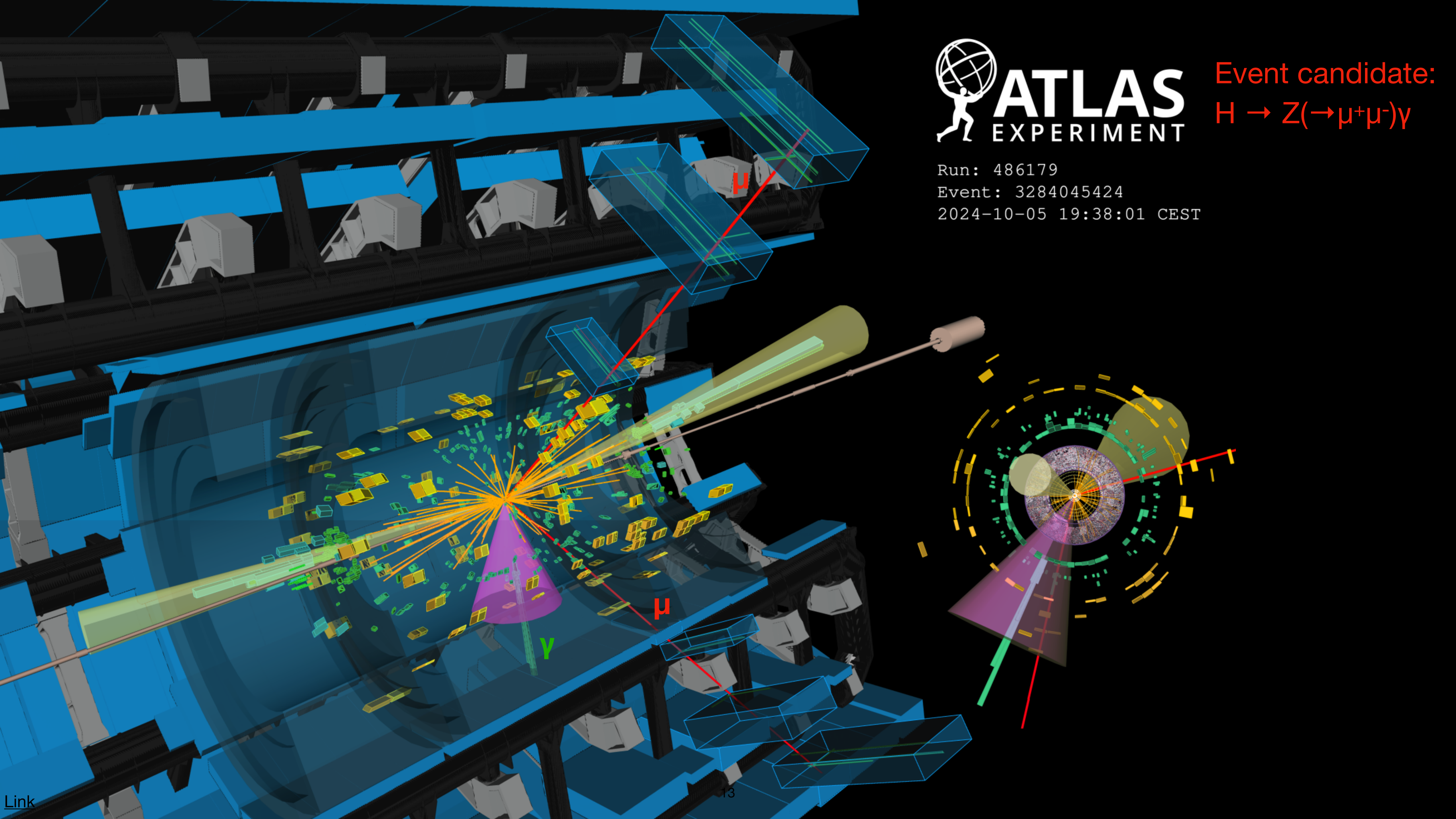


Event candidate:
 $H \rightarrow Z(\rightarrow \mu^+ \mu^-) \gamma$

Run: 486179

Event: 3284045424

2024-10-05 19:38:01 CEST



Lepton Flavour Violation in the Higgs sector?

Not in Standard Model but nature hints otherwise - neutrino oscillations!

What are the possible LFV Higgs decays?

- $H \rightarrow \tau\mu$
- $H \rightarrow \tau e$
- $H \rightarrow e\mu^*$

LFV Higgs decays can probe off-diagonal Yukawa couplings.

Beyond Standard Models predict Higgs LFV decays:

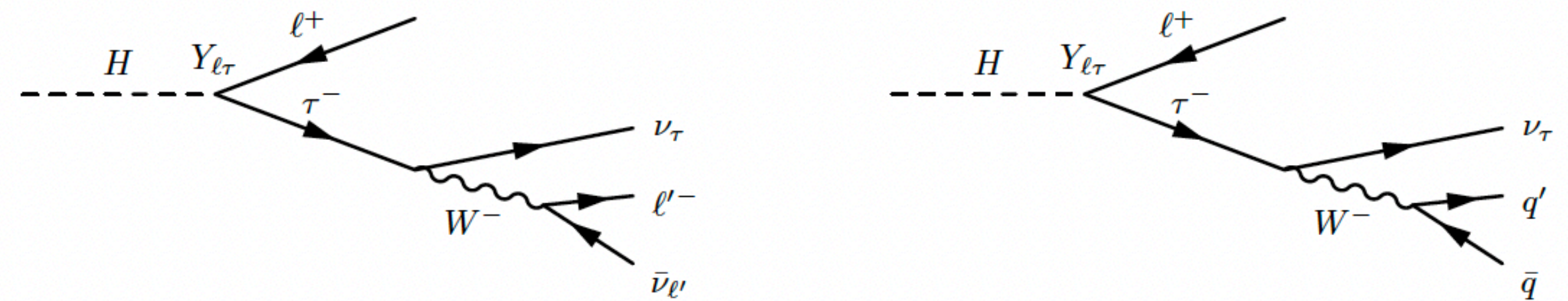
- Supersymmetry (SUSY)
- Two-Higgs-doublet models (2HDM)
- Composite Higgs models
- Randall–Sundrum models
- Other scenarios with extended Higgs sectors

Higgs LFV decay

Status with Run 2 data for Higgs LFV decay

Two independent searches: $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$

Two categories: VBF and Non-VBF

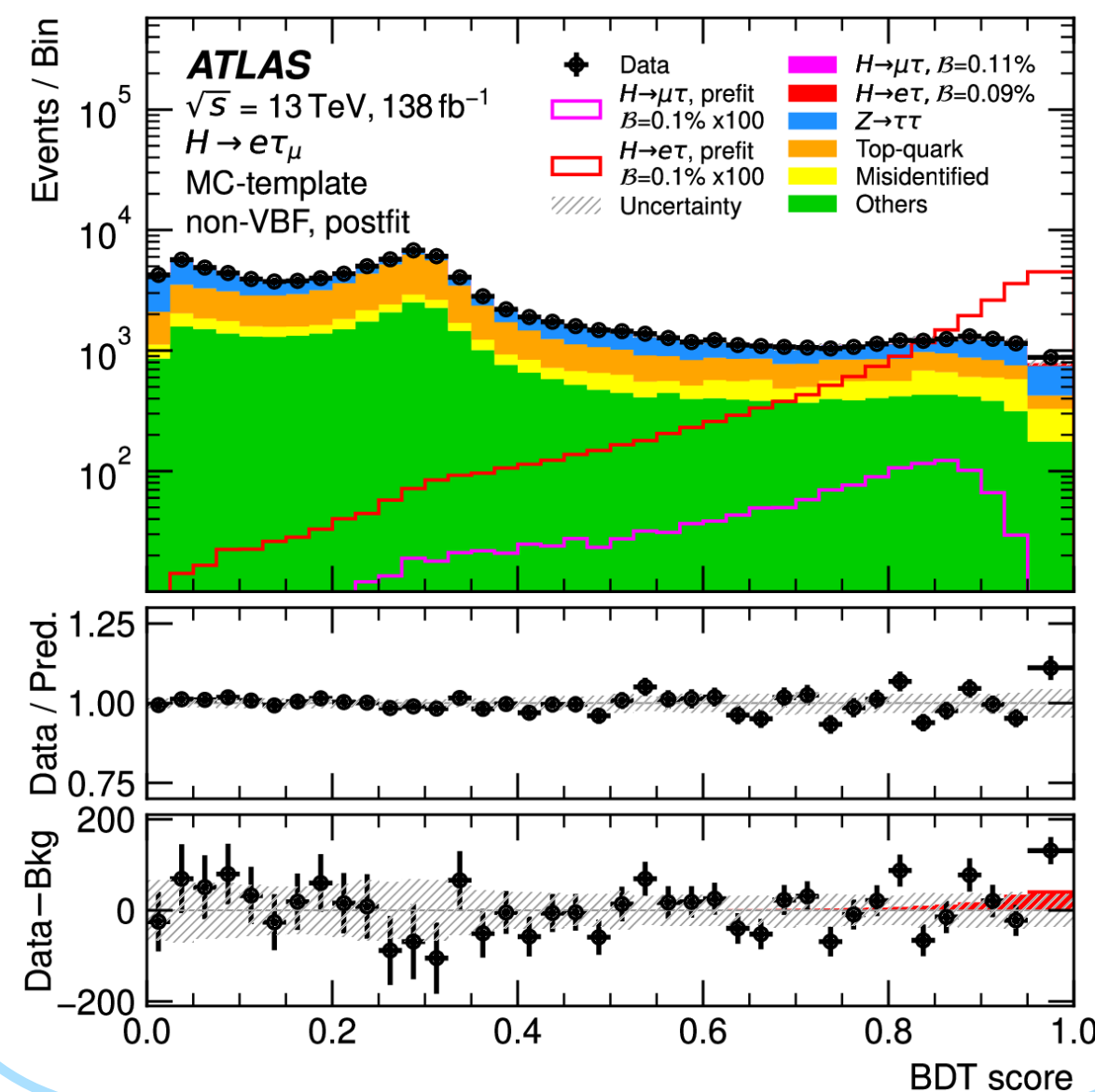


Two independent background methods:

- MC-template (for leptonic and hadronic decays)
- Symmetry method (for leptonic decays)

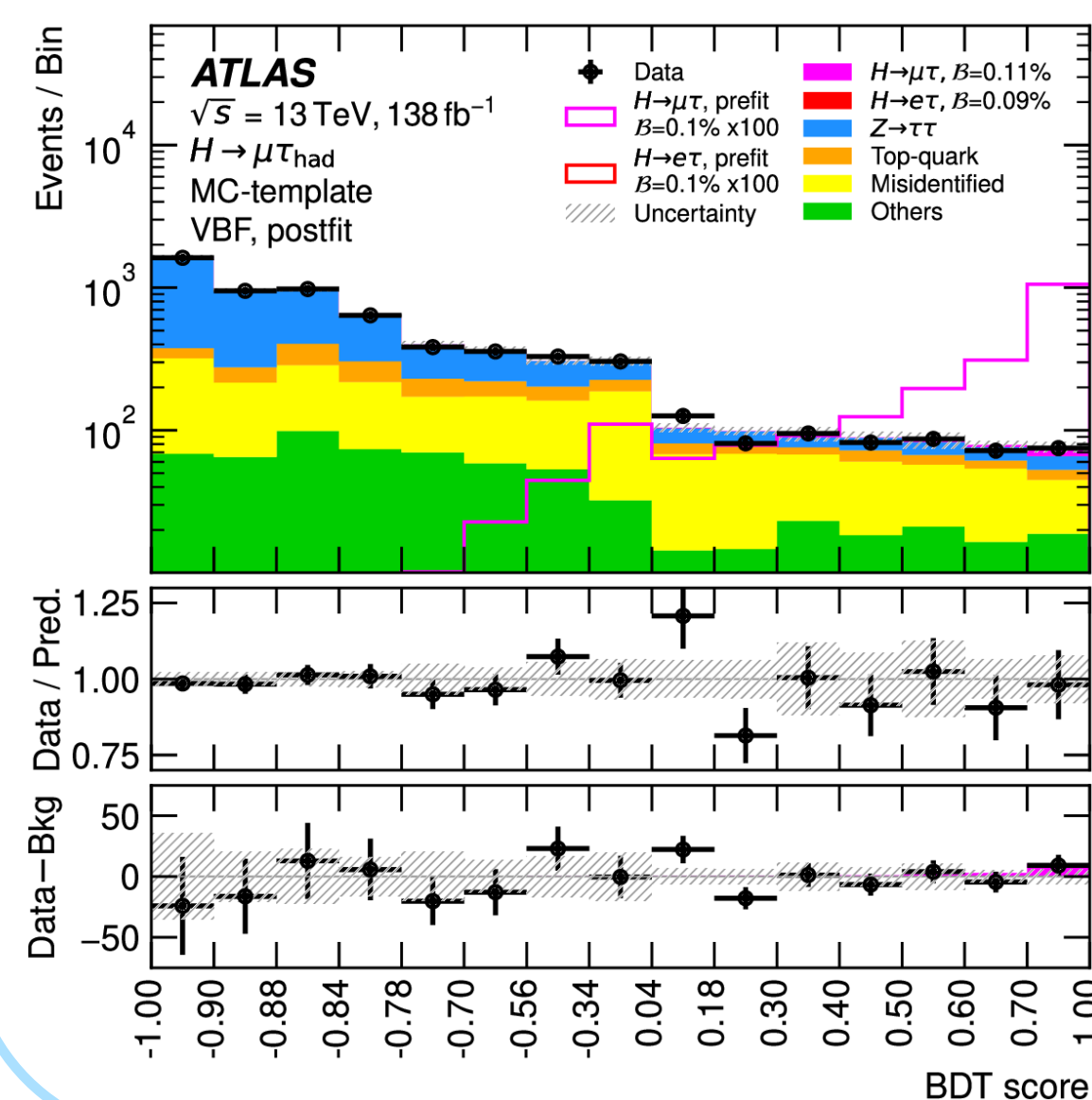
Background estimation:

- Fake background data-driven.
- Other backgrounds — MC templates.



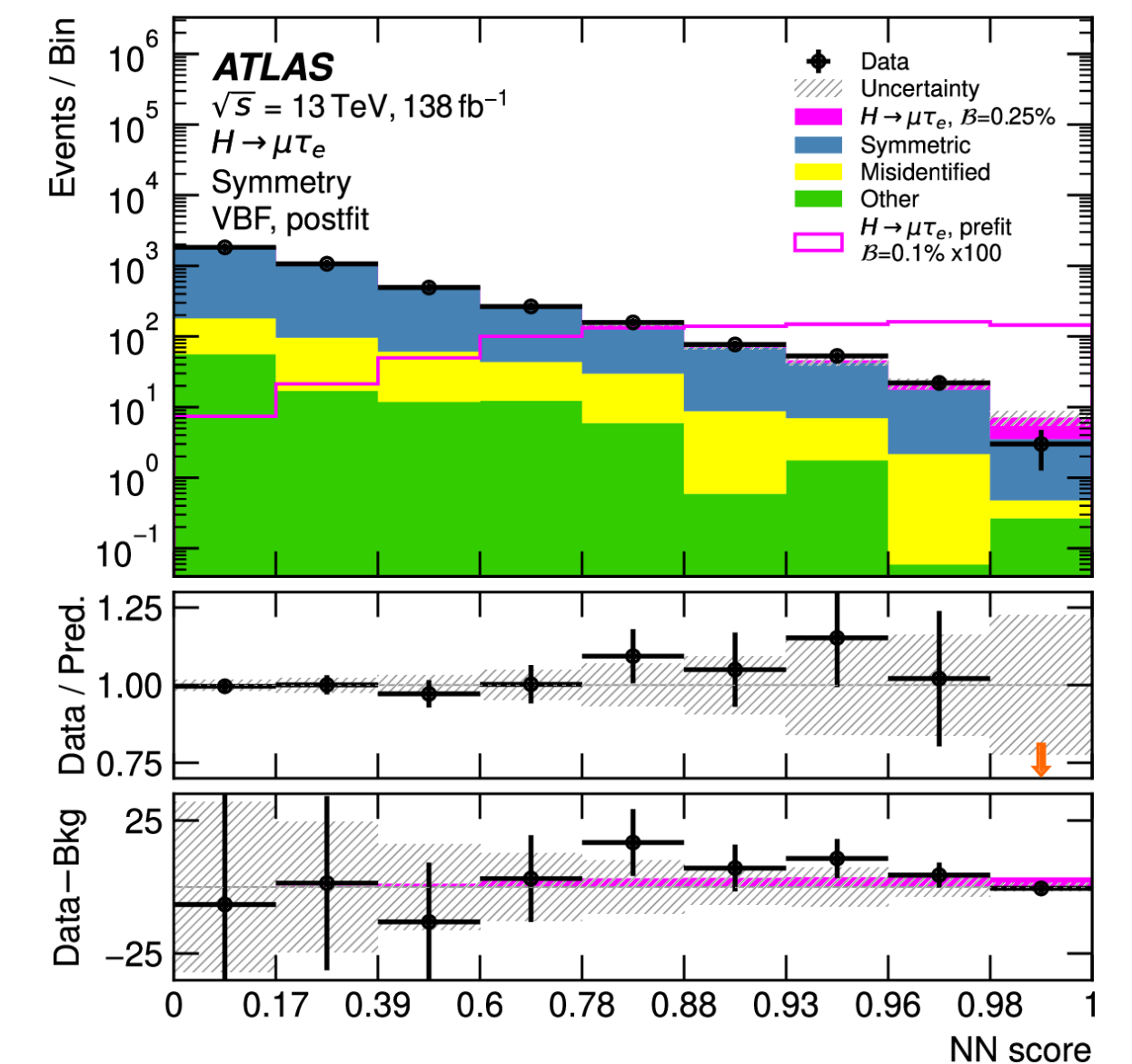
Background estimation:

- Fake background data-driven.
- Other backgrounds — MC templates.



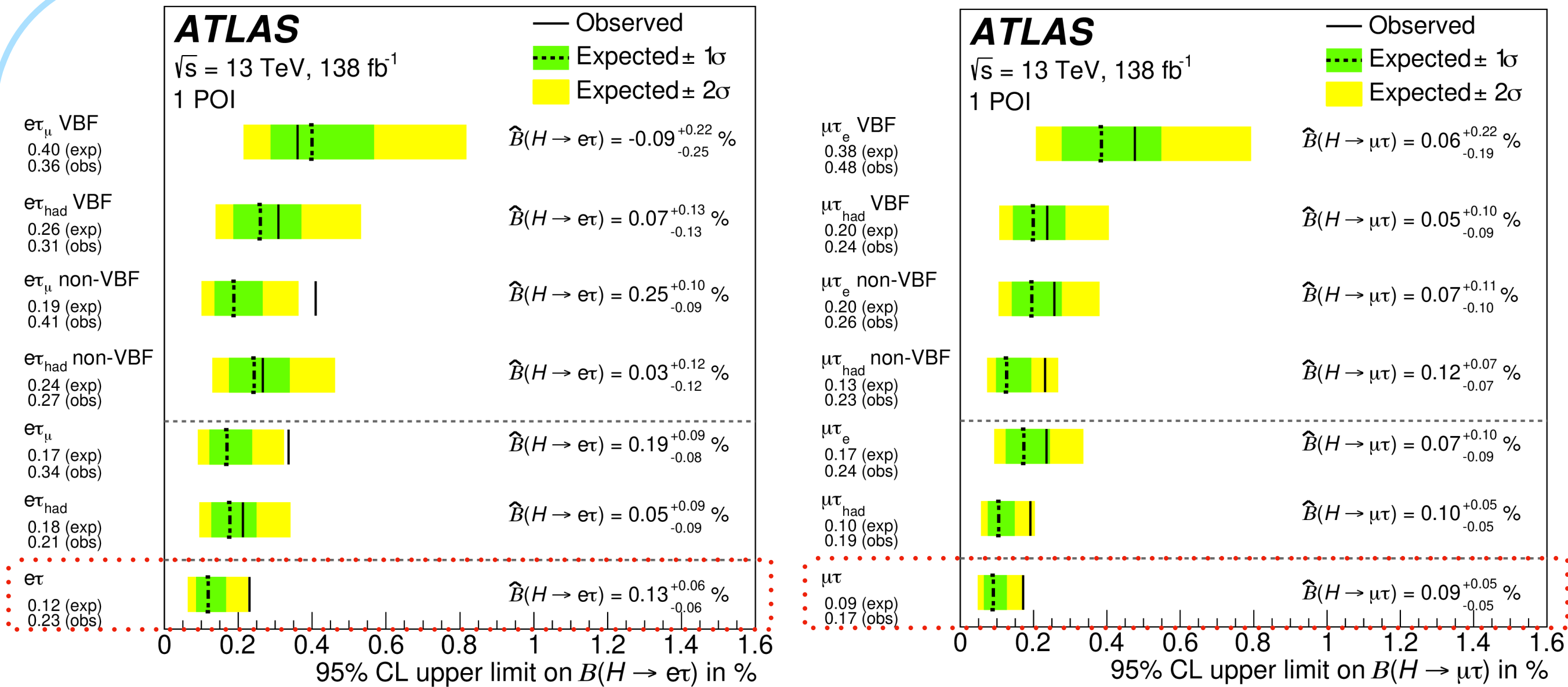
Background estimation:

- Fake background data-driven.
- Other backgrounds — data-driven symmetry method ($e\tau \leftrightarrow \mu\tau$).



Higgs LFV decay: ATLAS Run2 results

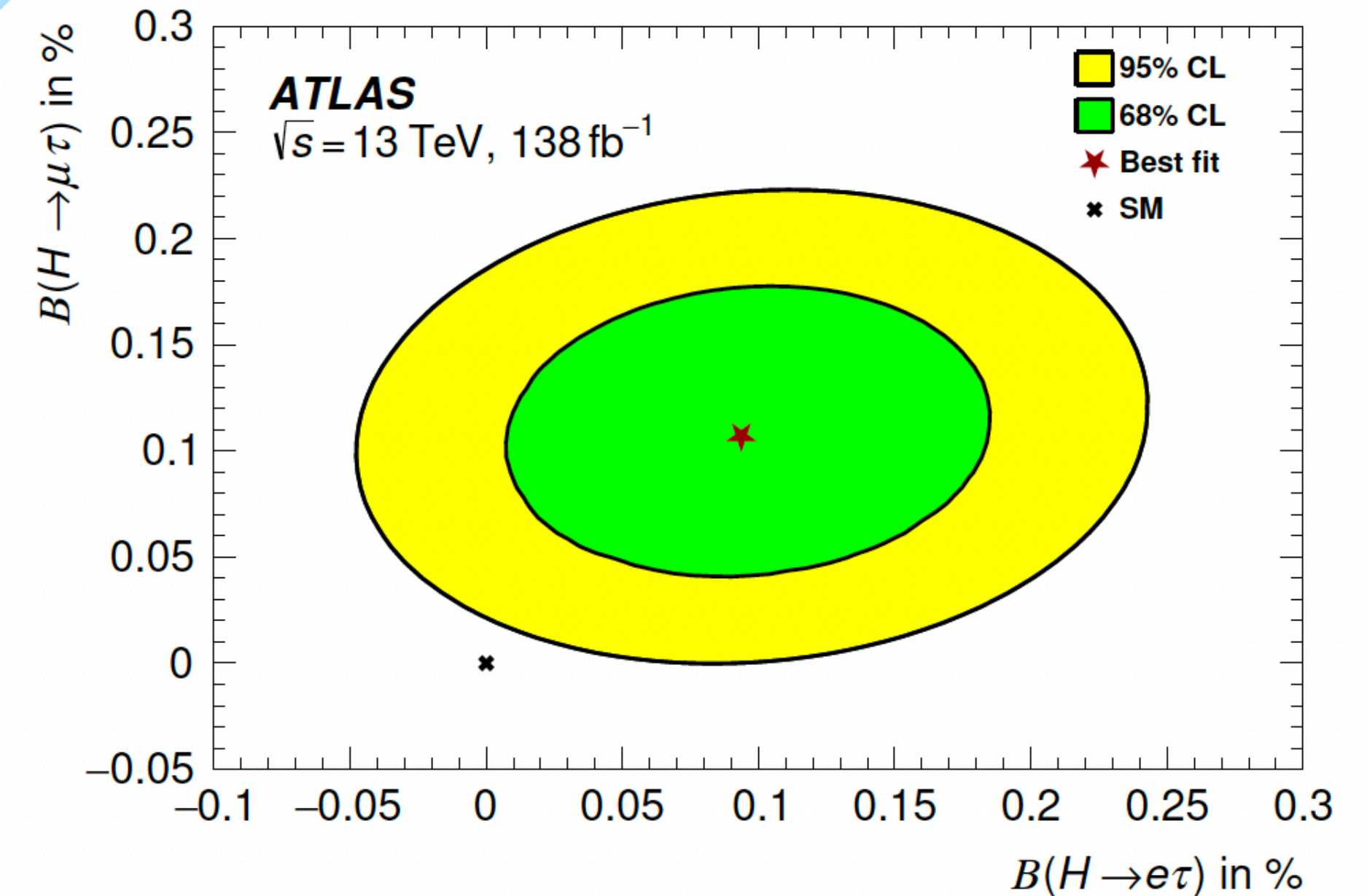
1 POI: Independent fits in $e\tau$ and $\mu\tau$ channels



- Combination of the three analysis approach with a 1 POI fit setup:
 - ▶ Observed limits are above expected ones for both signals.
 - ▶ 2.2σ excess seen for $\mathcal{B}(H \rightarrow e\tau)$ and 1.9σ for $\mathcal{B}(H \rightarrow \mu\tau)$.
- 1 POI setup also used to extract branching ratio difference with Symmetry analysis:

$$\mathcal{B}(H \rightarrow \mu\tau) - \mathcal{B}(H \rightarrow e\tau) = (0.25 \pm 0.10)\%$$

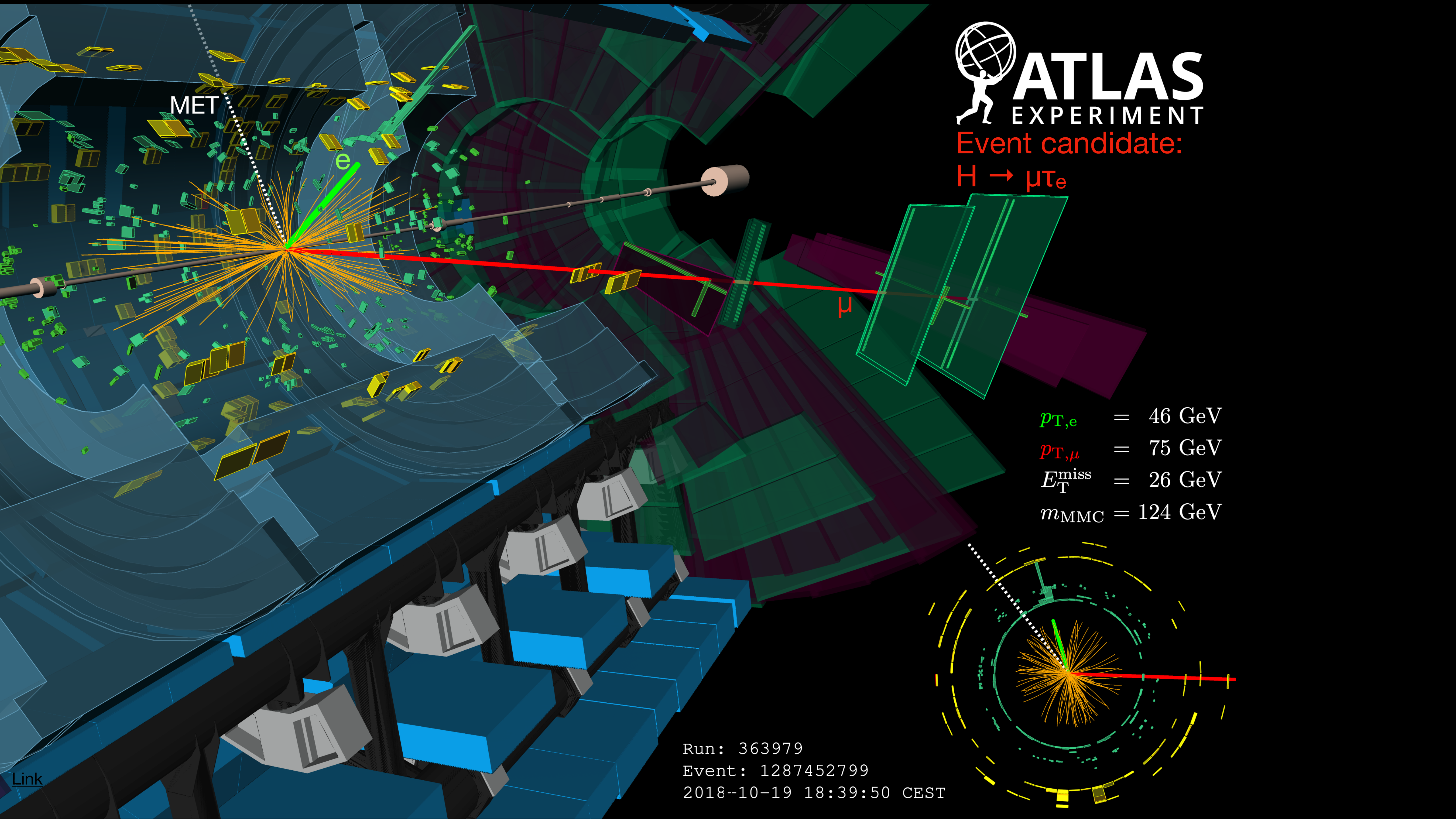
2 POI: Simultaneous fit of $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$



- Observed limits are above expected ones, in line with 1 POI fits.
- 1.6σ excess seen for $\mathcal{B}(H \rightarrow e\tau)$ and 2.4σ for $\mathcal{B}(H \rightarrow \mu\tau)$.
 - A slight upward deviation.
 - Global compatibility with SM within 2.1σ .

Event candidate:

$H \rightarrow \mu\tau_e$



$p_{T,e} = 46 \text{ GeV}$

$p_{T,\mu} = 75 \text{ GeV}$

$E_T^{\text{miss}} = 26 \text{ GeV}$

$m_{\text{MMC}} = 124 \text{ GeV}$

Run: 363979

Event: 1287452799

2018-10-19 18:39:50 CEST

Summary

- ❖ $H \rightarrow \mu\mu$: Evidence at 3.4σ 
- ❖ $H \rightarrow Z\gamma$: Reaching most stringent expected sensitivity to date!
- ❖ $H \rightarrow \tau\mu, \tau e$: Small excesses in Run 2 — consistent with SM within 2.1σ .

Improved sensitivity achieved through:

- Enhanced **event reconstruction & categorization**
- **Machine Learning techniques** (BDTs, NNs)
- Larger datasets and **Run 3 inclusion**

Outlook: Great potential to observe rare Higgs boson decay modes to probe new physics with:

- Improved analysis techniques
- Increased integrated luminosity in Run 3
- And not in very far future: High Luminosity LHC

Stay tuned!

Thank you!

Backup

Background Modelling

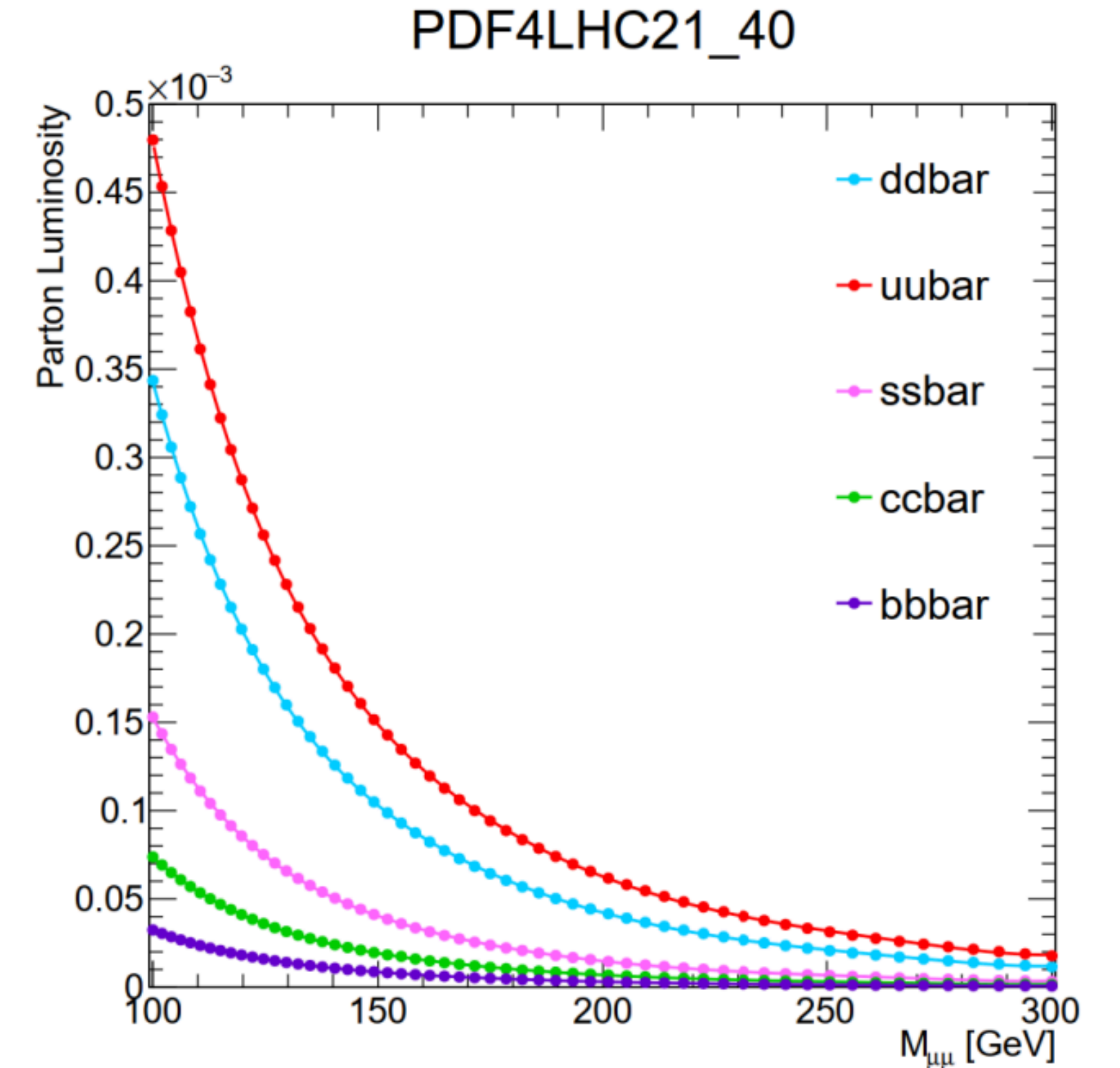
$$H \rightarrow \mu^+ \mu^-$$

- Analytic function used for background modelling:
 - Core $\times$ empirical function

$$F(m_{\mu\mu}, a_i)^{\text{cat}} = \text{Core}(m_{\mu\mu}) \times \text{Empirical}(m_{\mu\mu}, a_i)^{\text{cat}}$$

- **Core:** Same DY lineshape for all categorize
 - Rigid function without DOF
 - Calculated with parton luminosity and LO DY cross section
 - **New $c\bar{c}$ and $b\bar{b}$ contribution in Run3**
 - Smeared with detector resolution from FullSim samples

$$DY_{LS}(m_{\mu\mu}) = \sum_q \mathcal{L}_{q\bar{q}} \cdot \sigma_{q\bar{q}} \cdot m_{\mu\mu}, \quad q = u, s, d, c, b$$



Selection of Empirical Function

$$H \rightarrow \mu^+ \mu^-$$

- Empirical function used to account for the remaining bias
 - Determined by **spurious signal test**
- S+B fit on B-only template (from FullSim MC)
- $S \pm 1\sigma / \delta S < 20\%$
 - 1σ : the MC statistical uncertainty on the fitted signal
 - δS : statistical uncertainty assuming 165/fb error
- X^2 probability of b-only fit better than 1%
- If multiple functions pass selection:
 - Choose the one with smallest NDOF
 - Then, least spurious signal
- The final spurious signal will be taken as additional systematic for bkg bias

List of functions for testing

Function	Expression	nPar
Epoly1	$\exp(a_1 m_{\mu\mu})$	1
Epoly2	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2)$	2
Epoly3	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + a_3 m_{\mu\mu}^3)$	3
Epoly4	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + a_3 m_{\mu\mu}^3 + a_4 m_{\mu\mu}^4)$	4
Power0	$\text{pow}(m_{\mu\mu}, a_0)$	1
Power1	$\text{pow}(m_{\mu\mu}, a_0 + a_1 m_{\mu\mu})$	2
Power2	$\text{pow}(m_{\mu\mu}, a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2)$	3
Power3	$\text{pow}(m_{\mu\mu}, a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + a_3 m_{\mu\mu}^3)$	4

Run3 Categorization

$$H \rightarrow \mu^+ \mu^-$$

Category	$ggF + b\bar{b}H$	VBF	WH	ZH	$t\bar{t}H + tH$
$t\bar{t}H$ -High	0.1%	0.0%	0.5%	0.5%	98.9%
$t\bar{t}H$ -Medium	1.4%	0.1%	1.2%	1.3%	96.0%
VH4L	0.0%	0.0%	0.0%	99.3%	0.7%
VH3L-High	0.1%	0.0%	95.1%	3.3%	1.5%
VH3L-Medium	0.5%	0.2%	83.7%	8.3%	7.3%
VH2L-High	0.4%	0.1%	26.1%	72.0%	1.3%
VH2L-Medium	3.1%	1.1%	29.7%	62.5%	3.5%
VBF High	3.9%	96.1%	0.0%	0.0%	0.0%
VBF Medium	7.7%	92.2%	0.0%	0.0%	0.0%
VBF Low	13.4%	86.4%	0.0%	0.1%	0.1%
VBF Very Low	23.4%	76.2%	0.1%	0.1%	0.2%
2-jet High	67.8%	30.7%	0.7%	0.6%	0.2%
2-jet Medium	79.2%	16.9%	2.2%	1.5%	0.2%
2-jet Low	83.2%	9.4%	4.4%	2.7%	0.3%
2-jet Very Low	78.9%	6.7%	8.4%	5.2%	0.8%
1-jet High	67.1%	32.5%	0.2%	0.2%	0.0%
1-jet Medium	85.8%	13.0%	0.7%	0.5%	0.0%
1-jet Low	91.3%	6.5%	1.4%	0.8%	0.0%
1-jet Very Low	92.4%	4.2%	2.2%	1.1%	0.0%
0-jet High	95.9%	2.5%	0.7%	0.9%	0.0%
0-jet Medium	98.3%	1.1%	0.3%	0.3%	0.0%
0-jet Low	98.8%	0.7%	0.2%	0.3%	0.0%
0-jet Very Low	99.5%	0.3%	0.1%	0.1%	0.0%

Signal composition per category

Category	Data	S	B	$S/\sqrt{B}$	S/B [%]
$t\bar{t}H$ -High	12	1.9 ± 0.7	15.5 ± 2.3	0.49	12.5
$t\bar{t}H$ -Medium	117	3.9 ± 1.4	115 ± 7	0.36	3.4
VH4L	11	0.78 ± 0.29	12.2 ± 1.8	0.22	6.4
VH3L-High	25	1.4 ± 0.5	17.4 ± 2.9	0.33	8.0
VH3L-Medium	143	3.7 ± 1.4	136 ± 10	0.31	2.7
VH2L-High	19	1.0 ± 0.4	18.3 ± 2.9	0.23	5.3
VH2L-Medium	30	0.38 ± 0.14	31.7 ± 3.1	0.07	1.2
VBF High	9	4.3 ± 1.6	10.5 ± 1.8	1.34	41.2
VBF Medium	28	5.3 ± 2.0	25.8 ± 2.7	1.04	20.5
VBF Low	69	7.2 ± 2.7	62 ± 4	0.91	11.6
VBF Very Low	217	11 ± 4	225 ± 8	0.76	5.1
2-jet High	1 399	31 ± 12	$1 367 \pm 25$	0.84	2.3
2-jet Medium	5 657	69 ± 26	$5 560 \pm 50$	0.92	1.2
2-jet Low	17 684	110 ± 40	$17 300 \pm 70$	0.87	0.7
2-jet Very Low	35 147	110 ± 40	$35 160 \pm 140$	0.59	0.3
1-jet High	708	17 ± 6	710 ± 16	0.65	2.4
1-jet Medium	7 166	80 ± 30	$7 140 \pm 70$	0.95	1.1
1-jet Low	31 761	180 ± 70	$31 510 \pm 120$	1.00	0.6
1-jet Very Low	73 578	200 ± 80	$73 330 \pm 200$	0.75	0.3
0-jet High	19 445	120 ± 50	$19 260 \pm 90$	0.89	0.6
0-jet Medium	50 742	200 ± 80	$50 830 \pm 190$	0.90	0.4
0-jet Low	94 032	240 ± 90	$93 770 \pm 210$	0.78	0.3
0-jet Very Low	136 762	170 ± 60	$136 510 \pm 290$	0.47	0.1

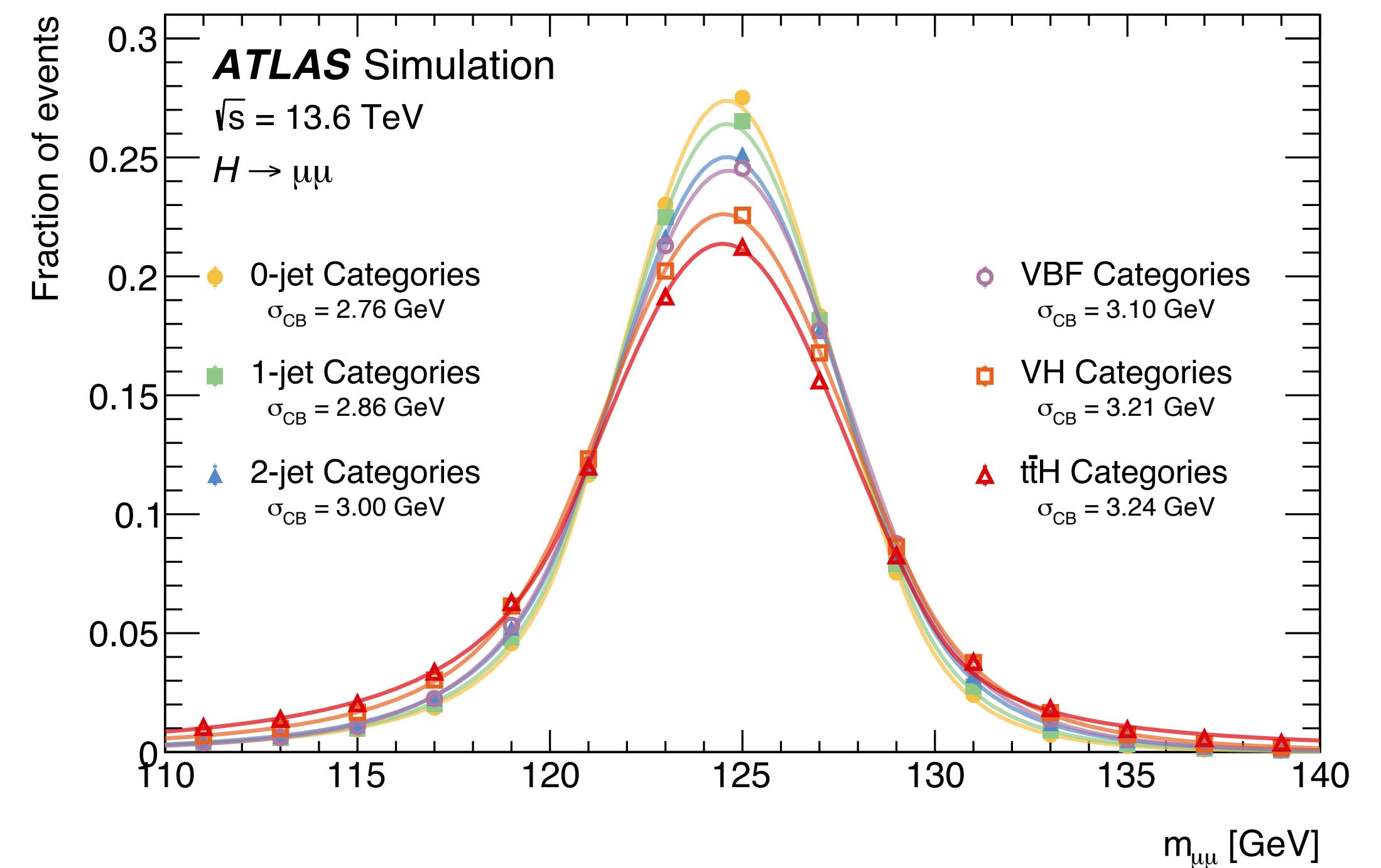
The number of observed events and the fitted number of signal (S) and background (B) events from the combined fit to 165 fb⁻¹ of Run-3 data

Signal Modelling

$$H \rightarrow \mu^+ \mu^-$$

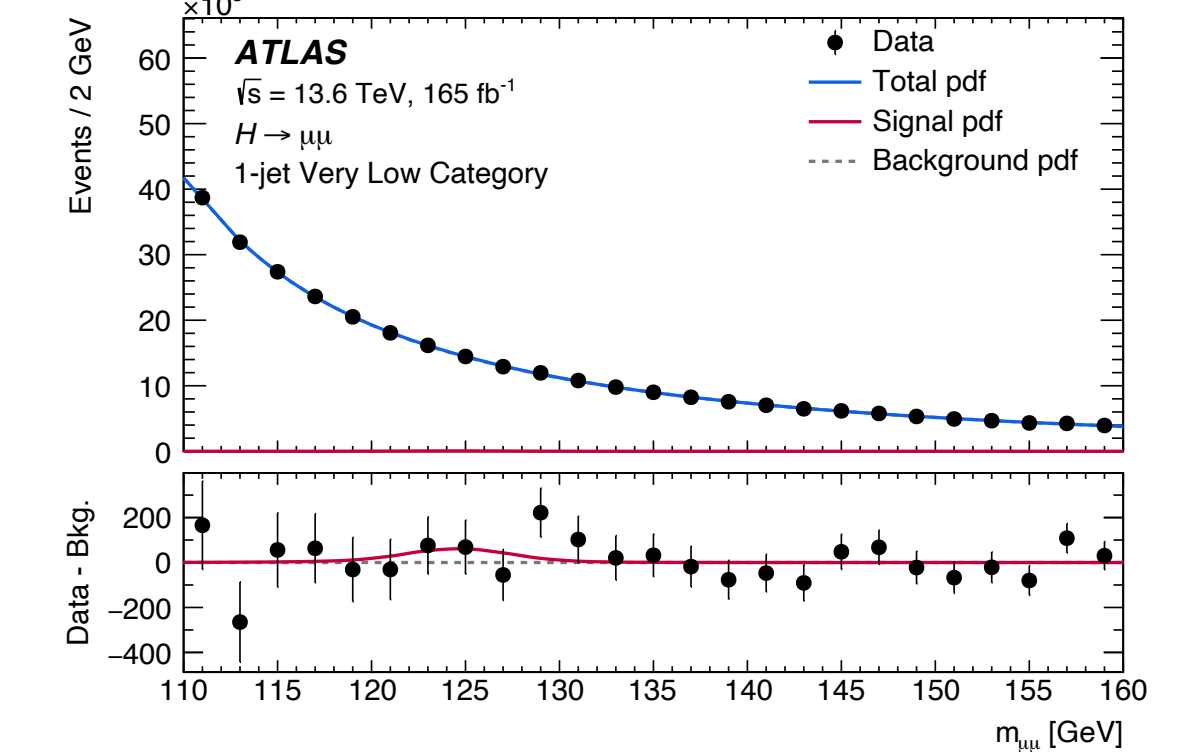
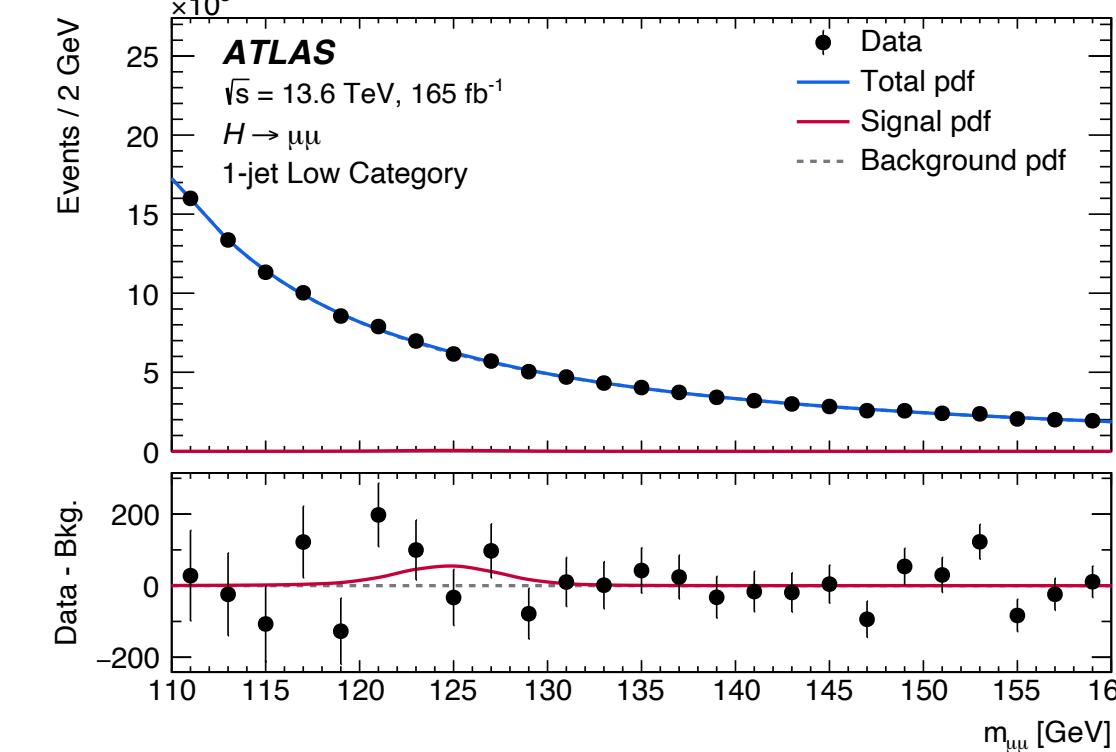
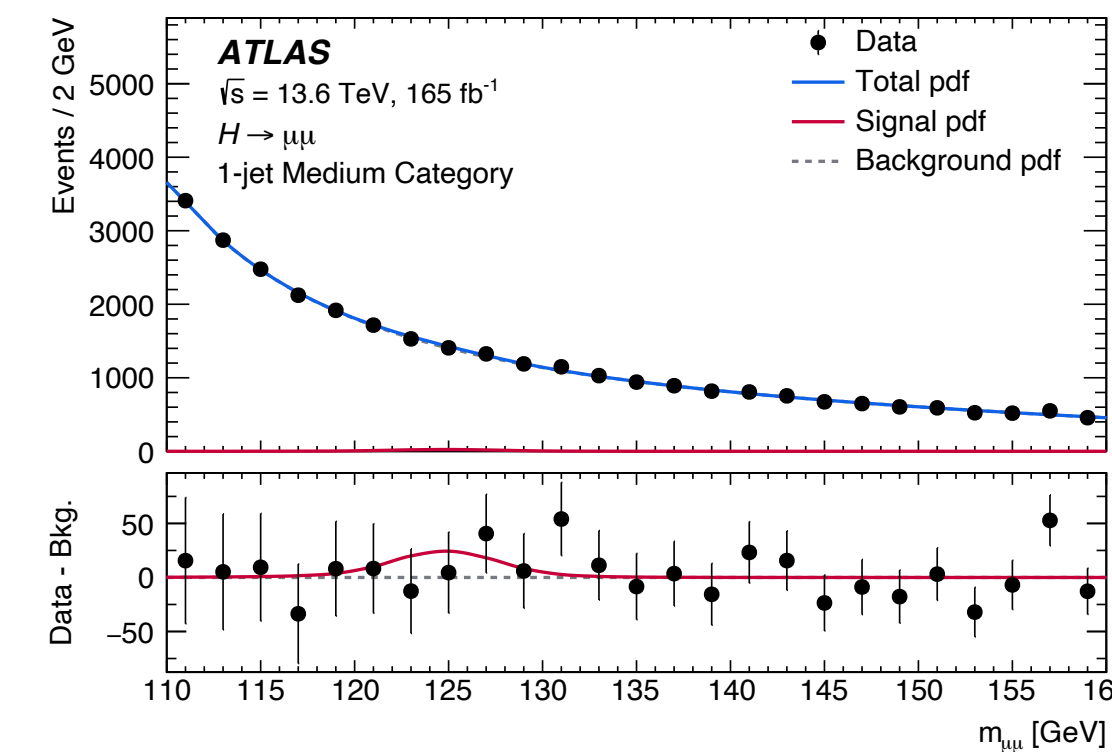
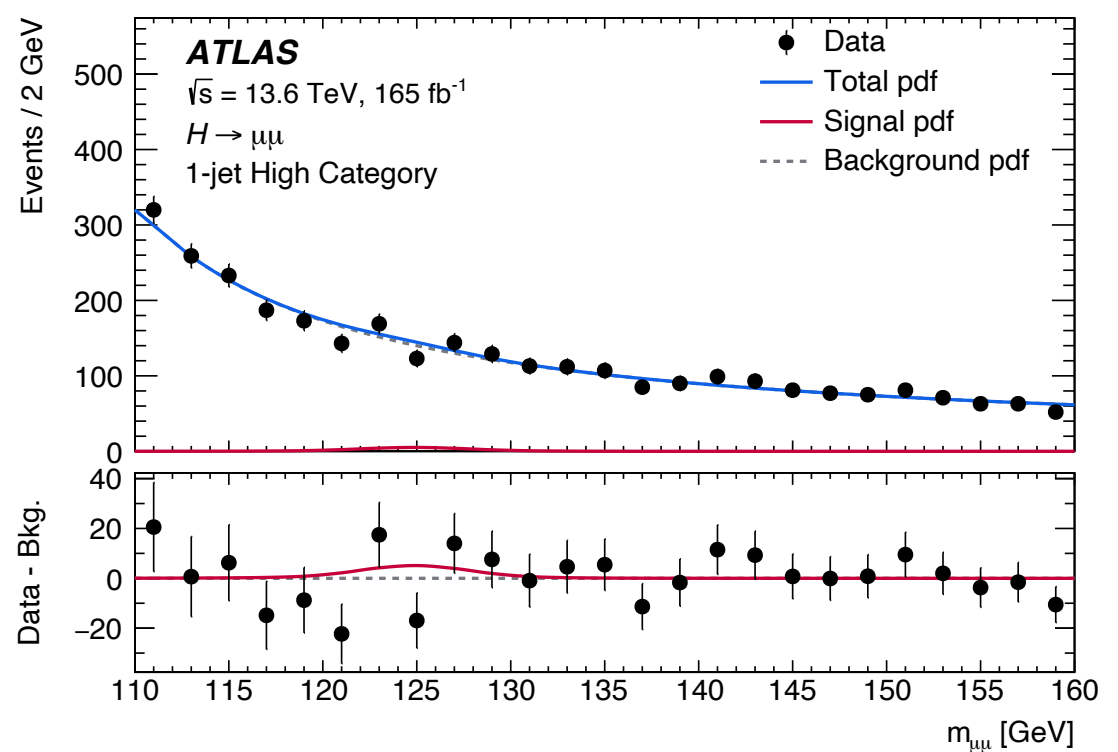
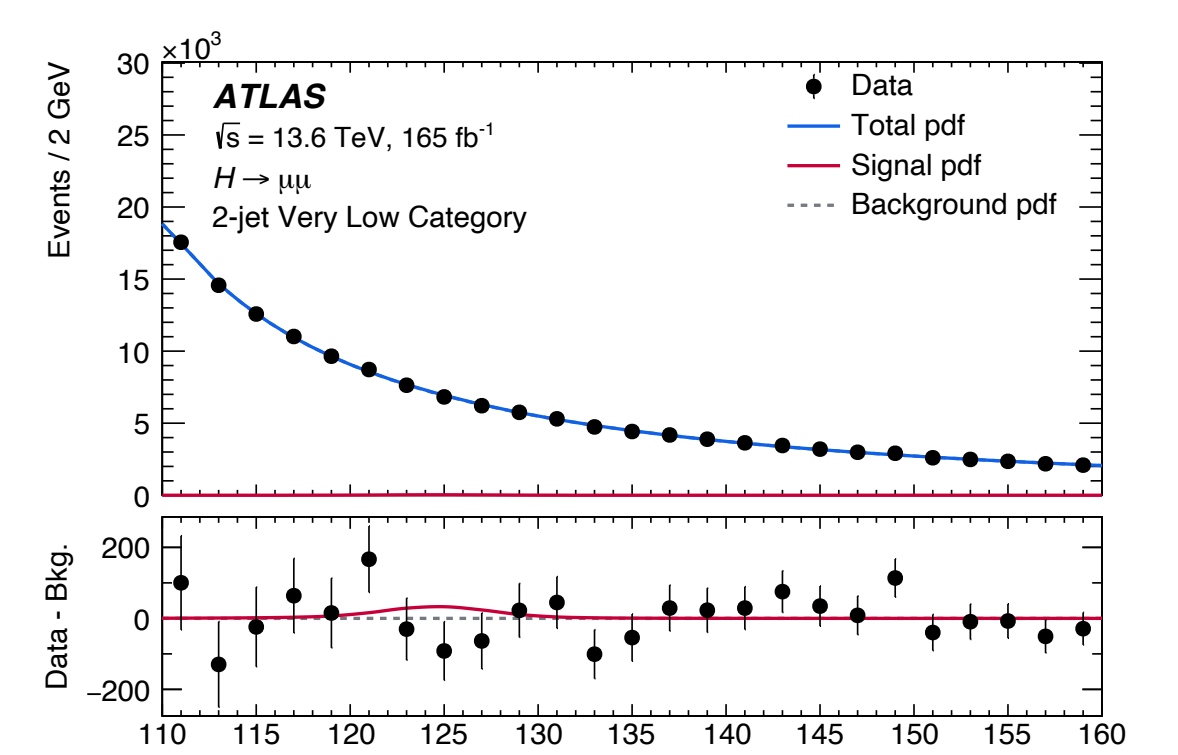
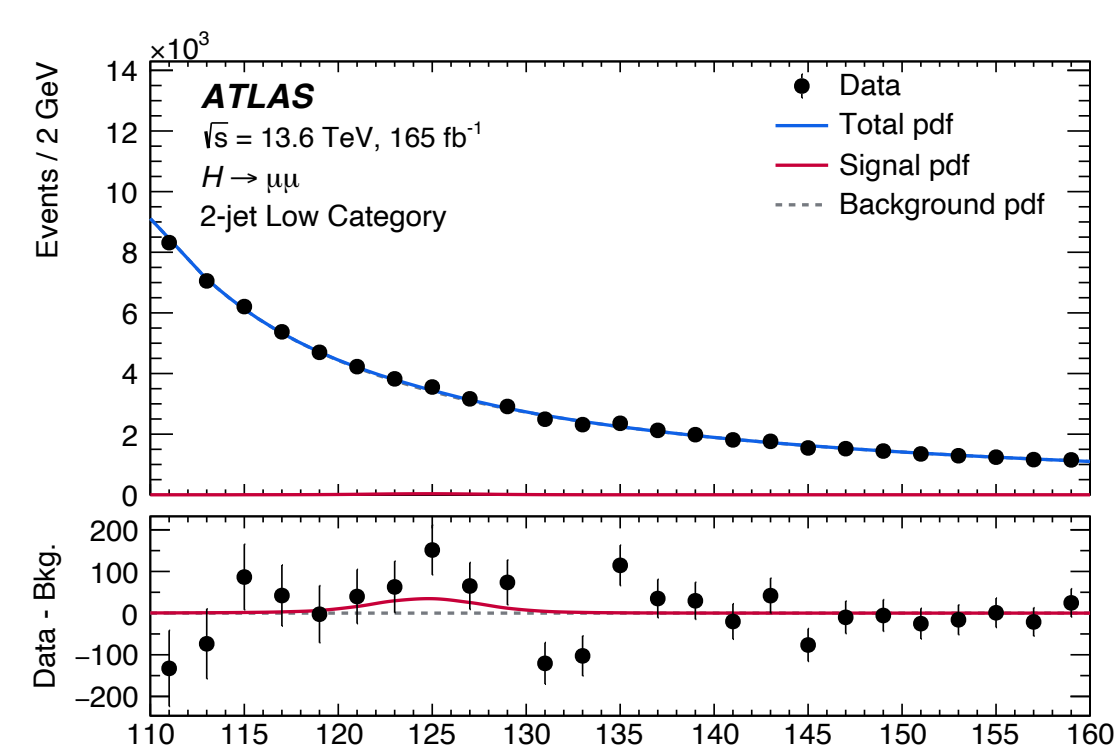
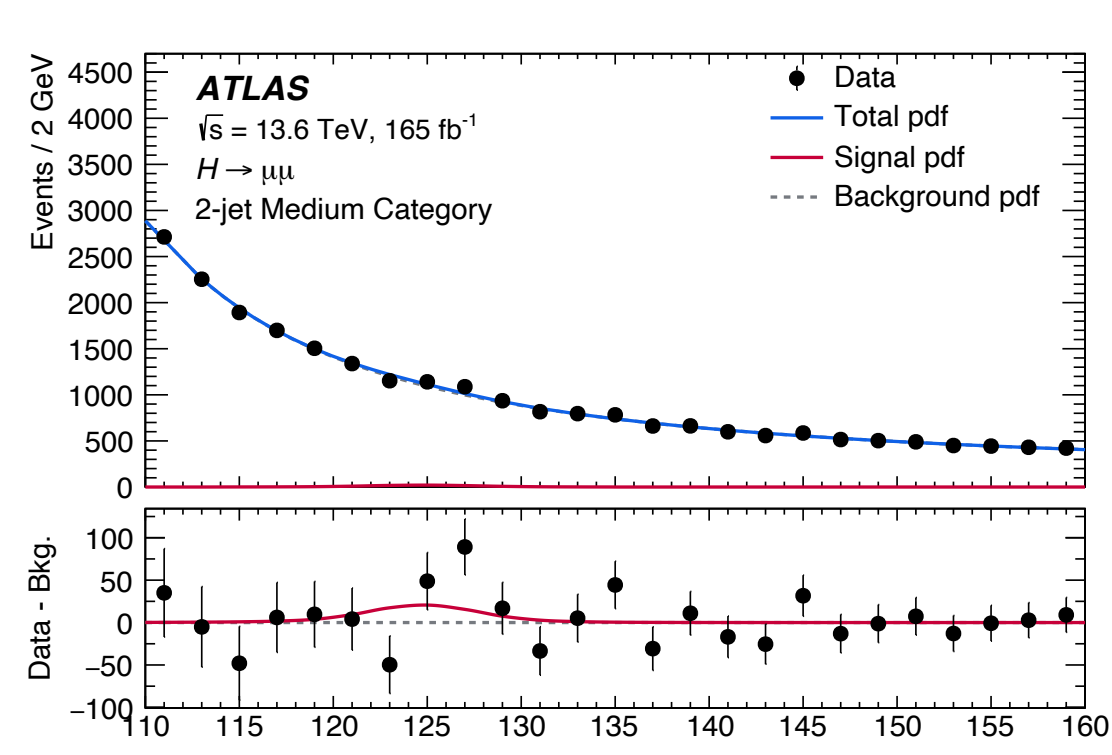
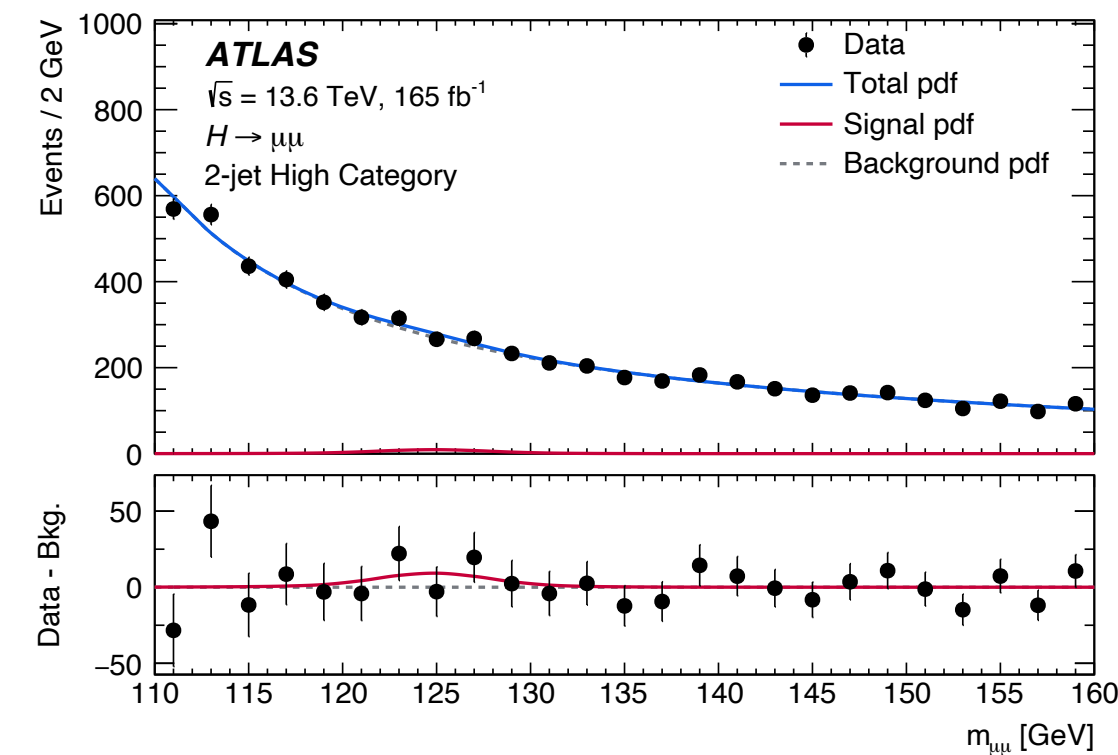
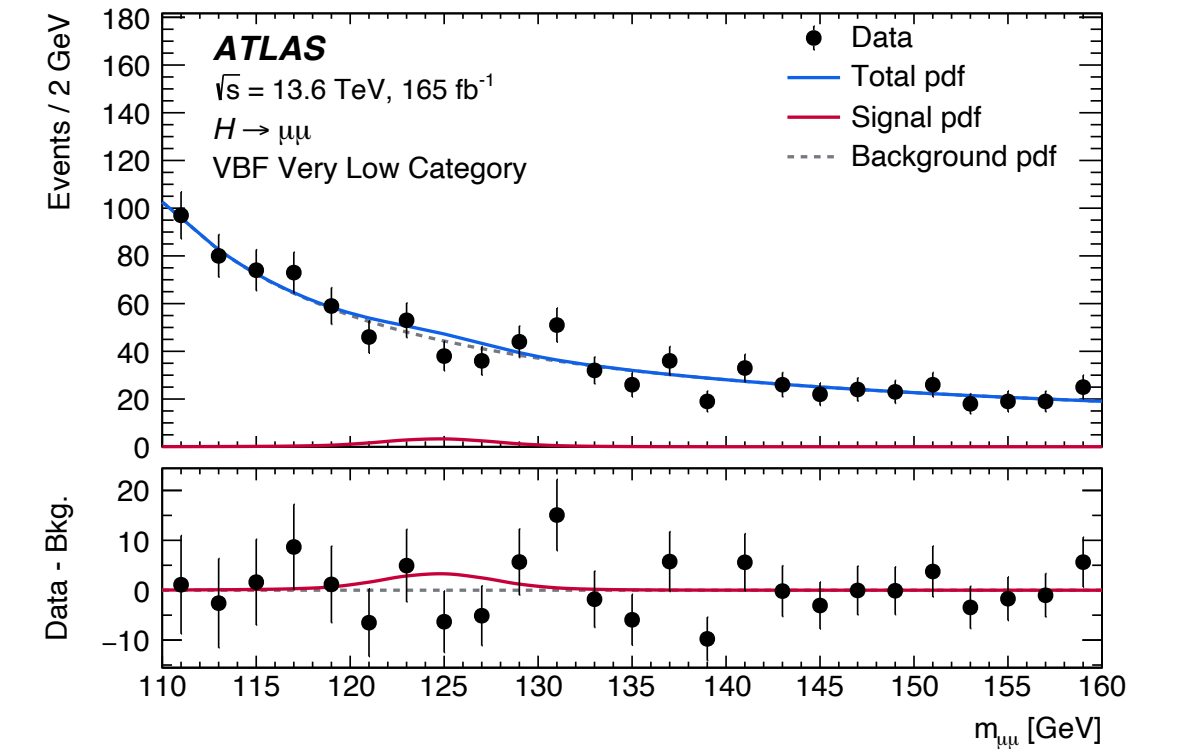
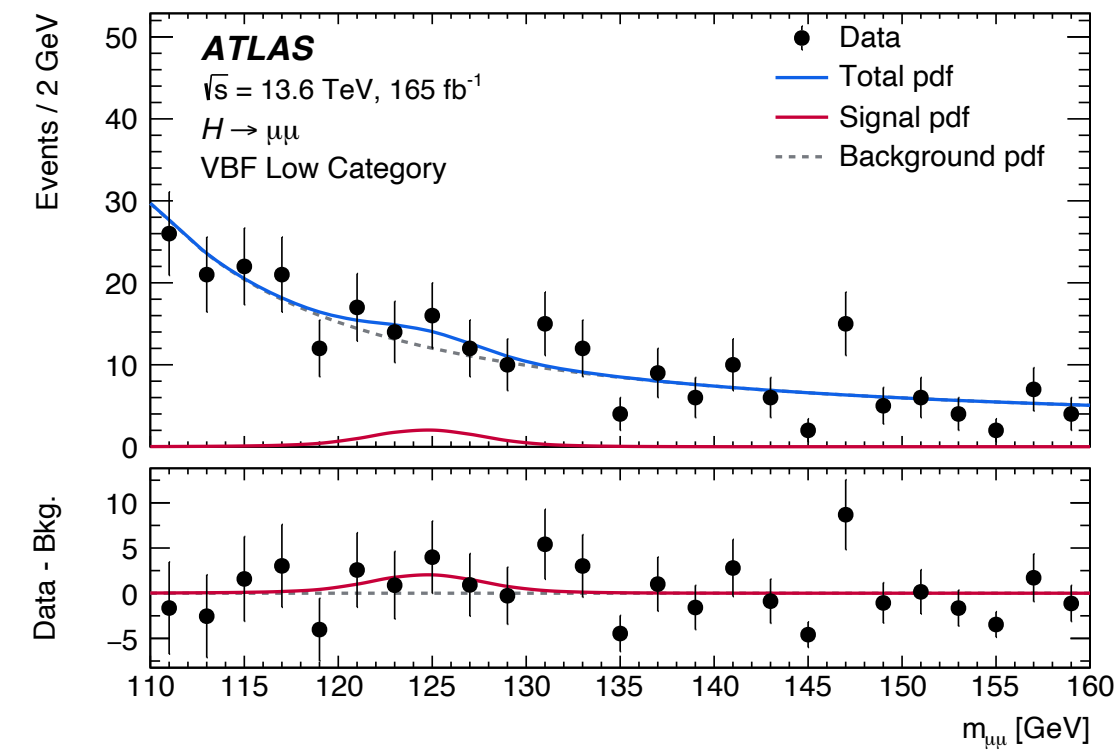
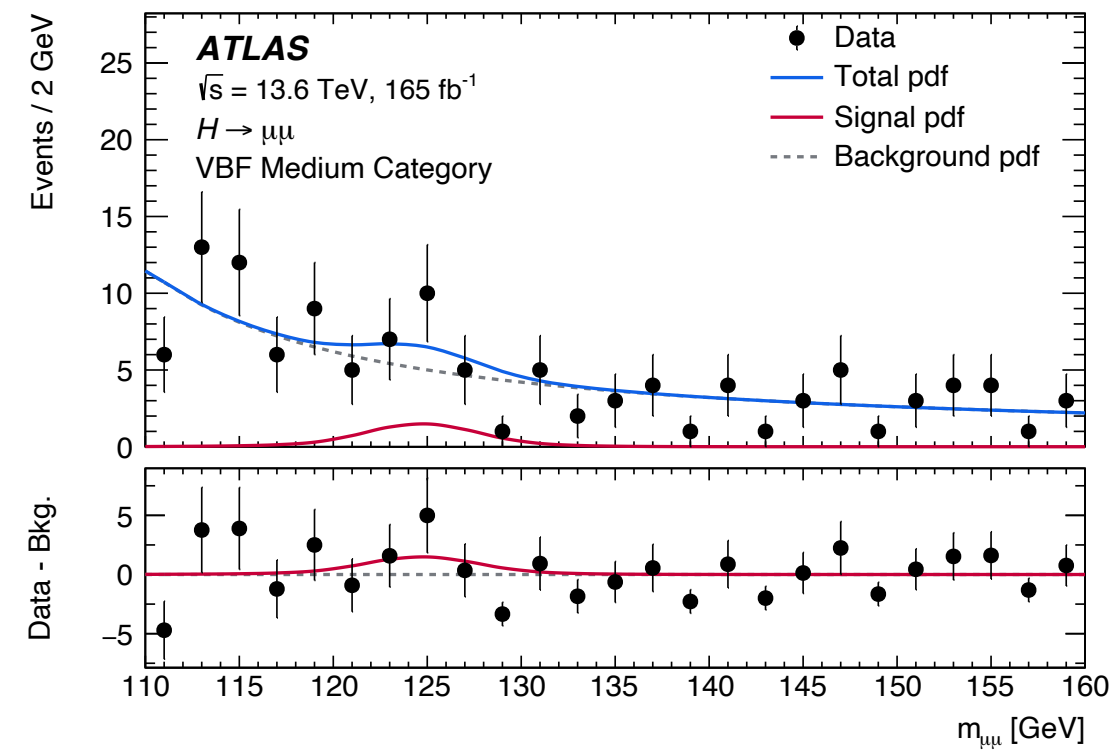
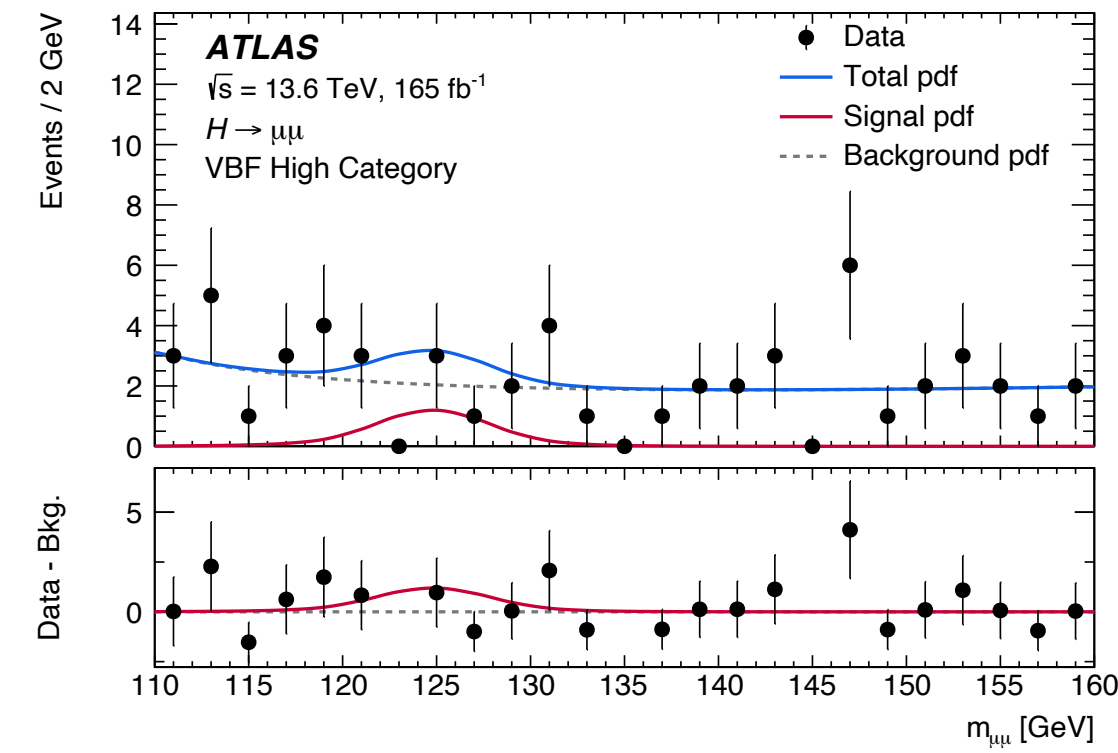
- Parametrise Higgs peak with **Double-Sided Crystal Ball** function
 - 2% improvement on resolution mc23a/d
 - Benefit from reprocessed data
 - New MS alignment
 - Similar to Run2 after including mc23e
- **Resolution: 2.6GeV to 3.5GeV**

	mc23a/d	mc23e	Run3 inclusive	Run2 inclusive
M_{CB} [GeV]	124.60	124.58	124.58	124.64
σ_{CB} [GeV]	2.71	2.80	2.77	2.74



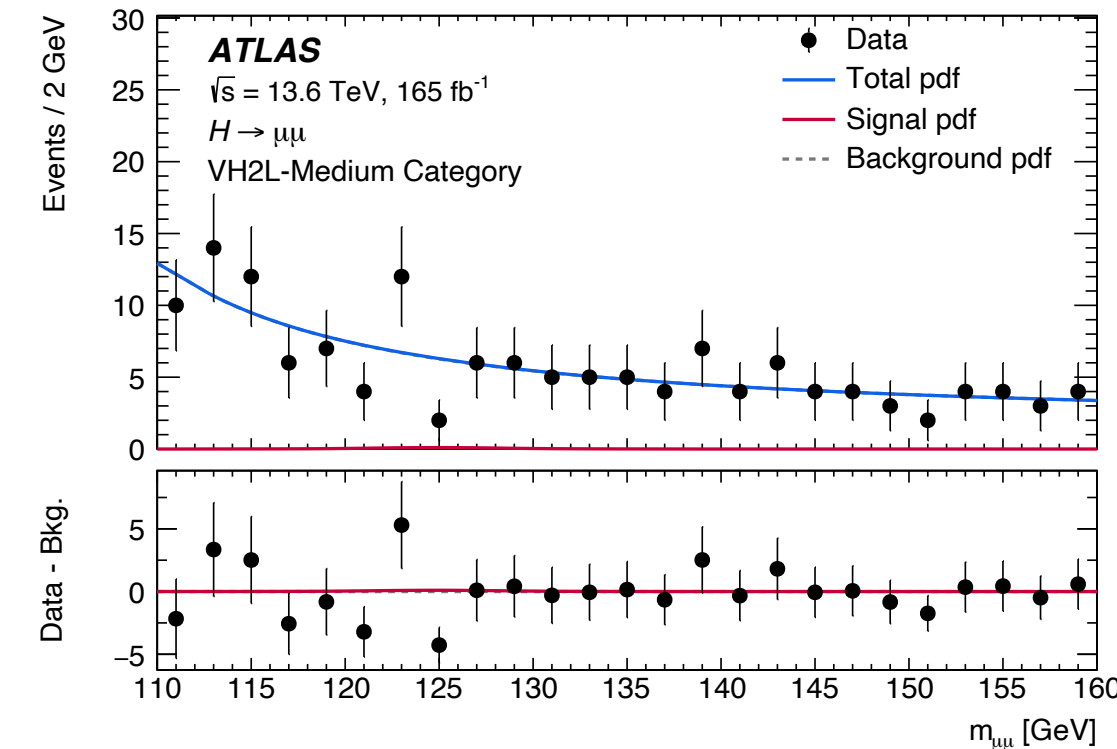
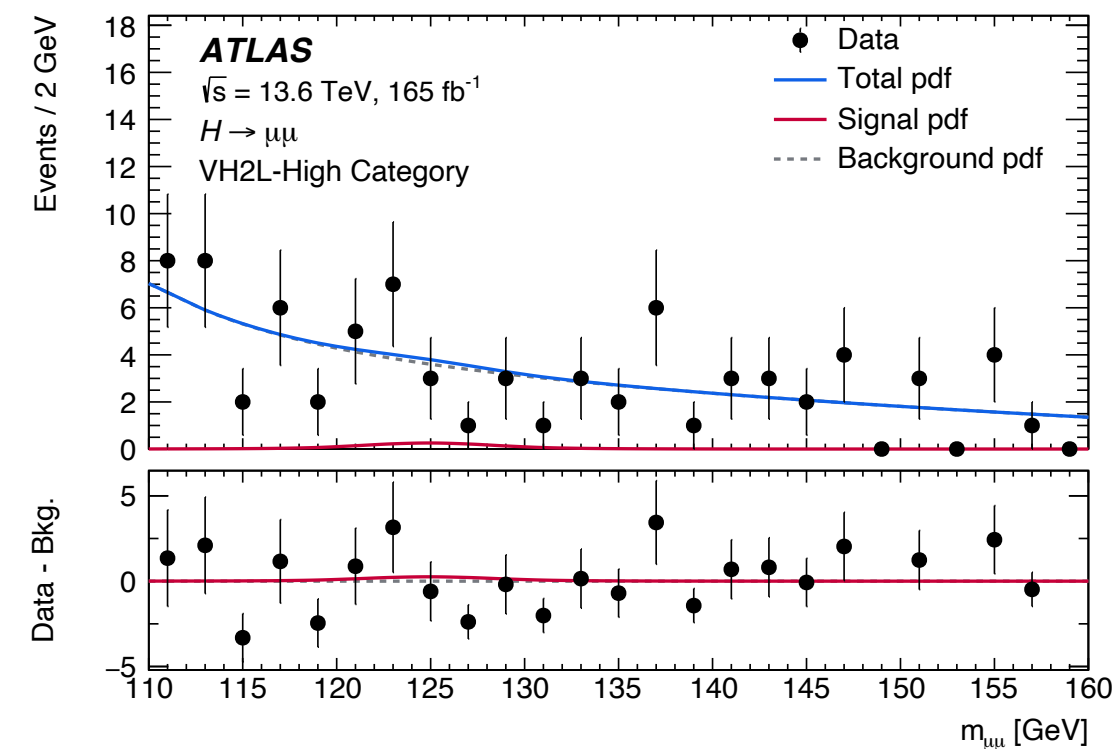
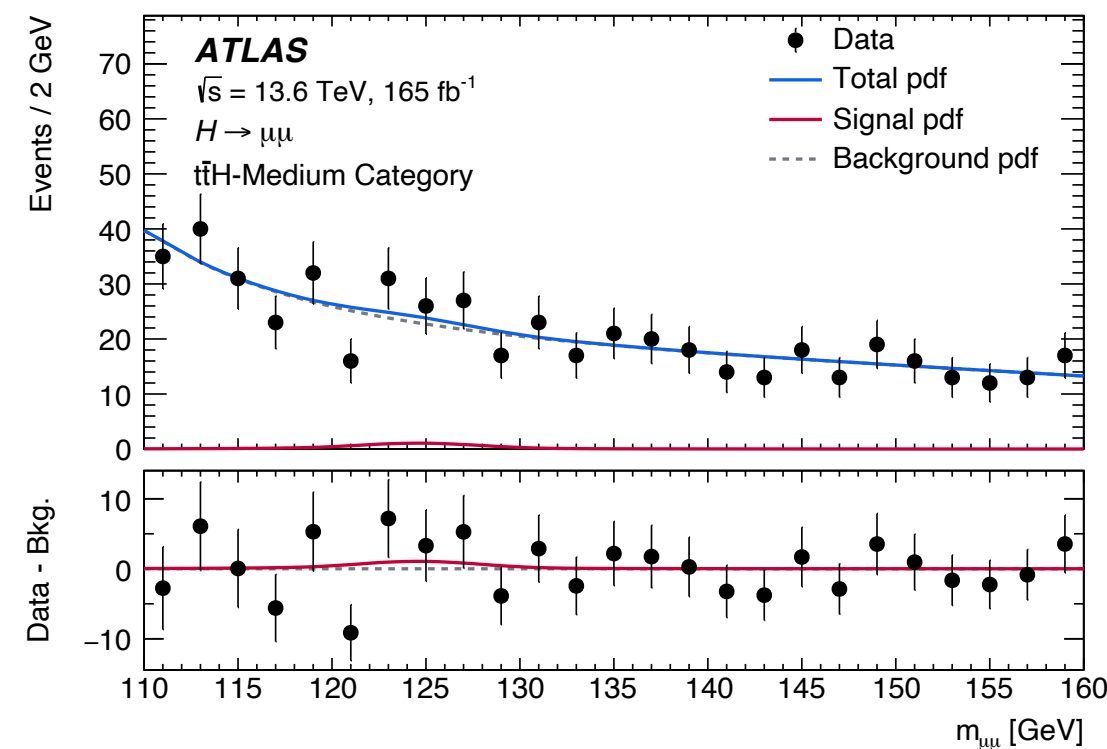
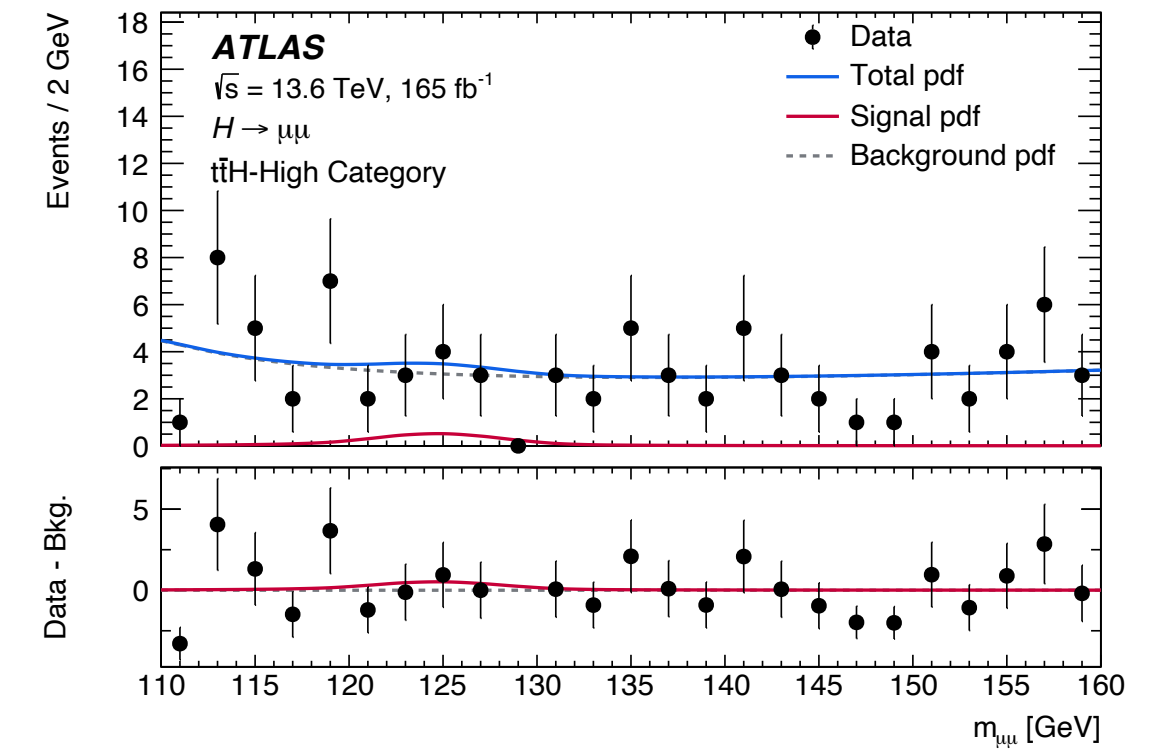
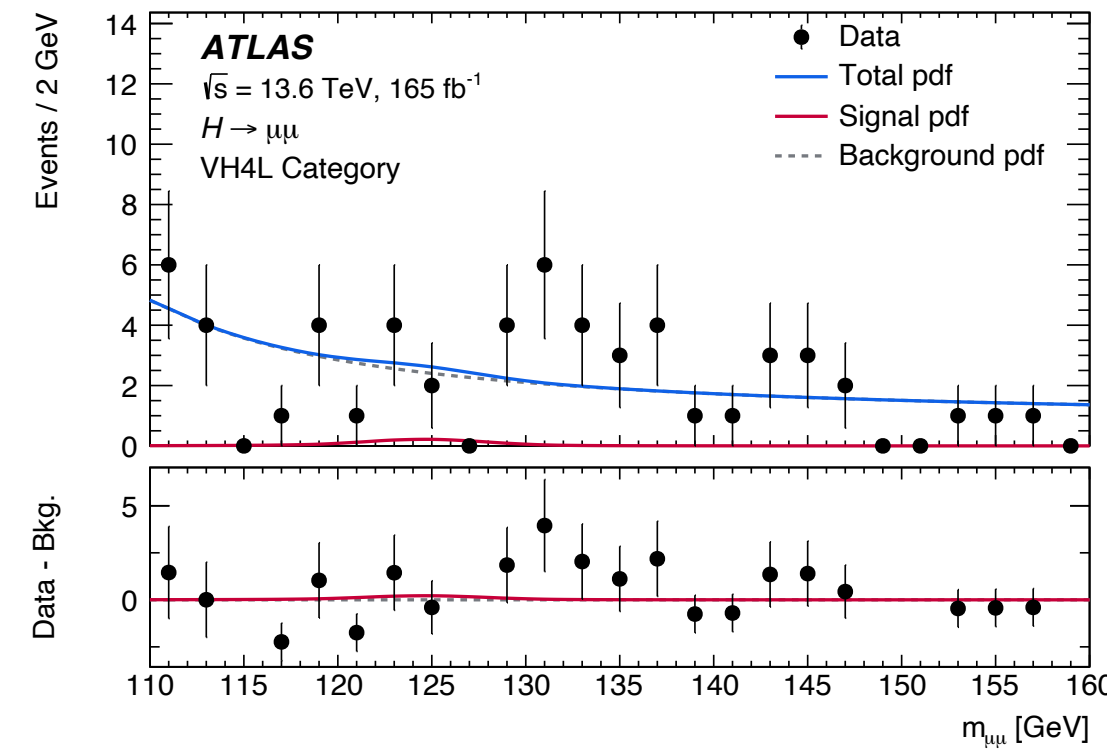
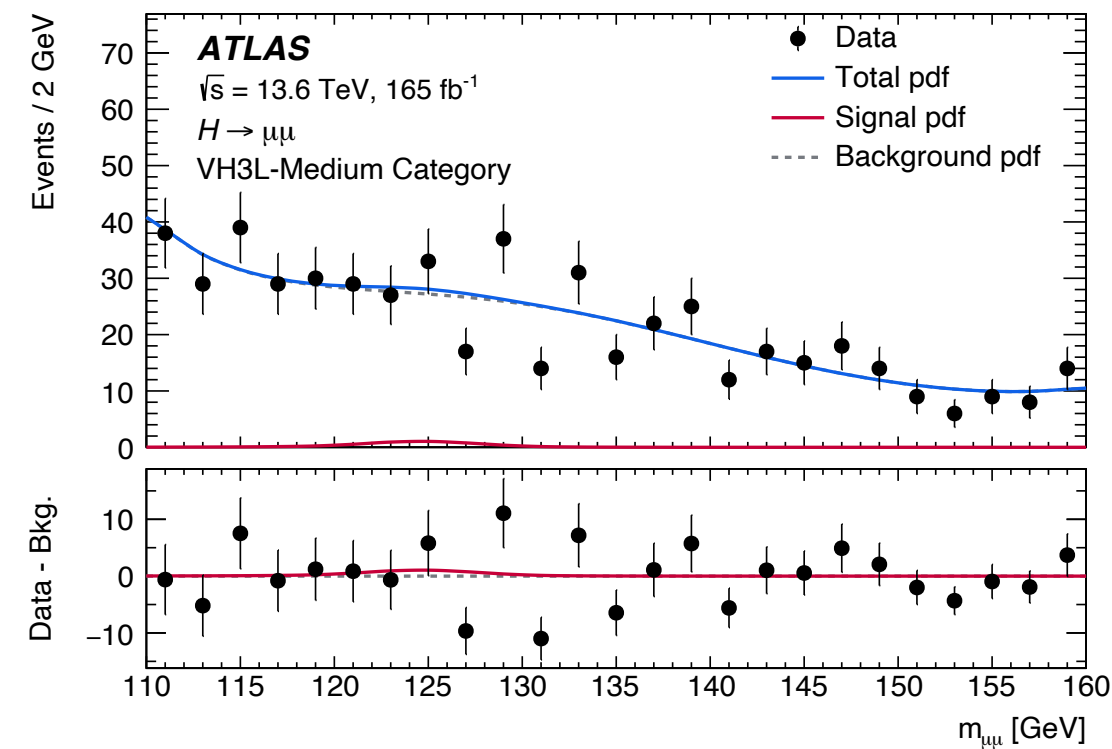
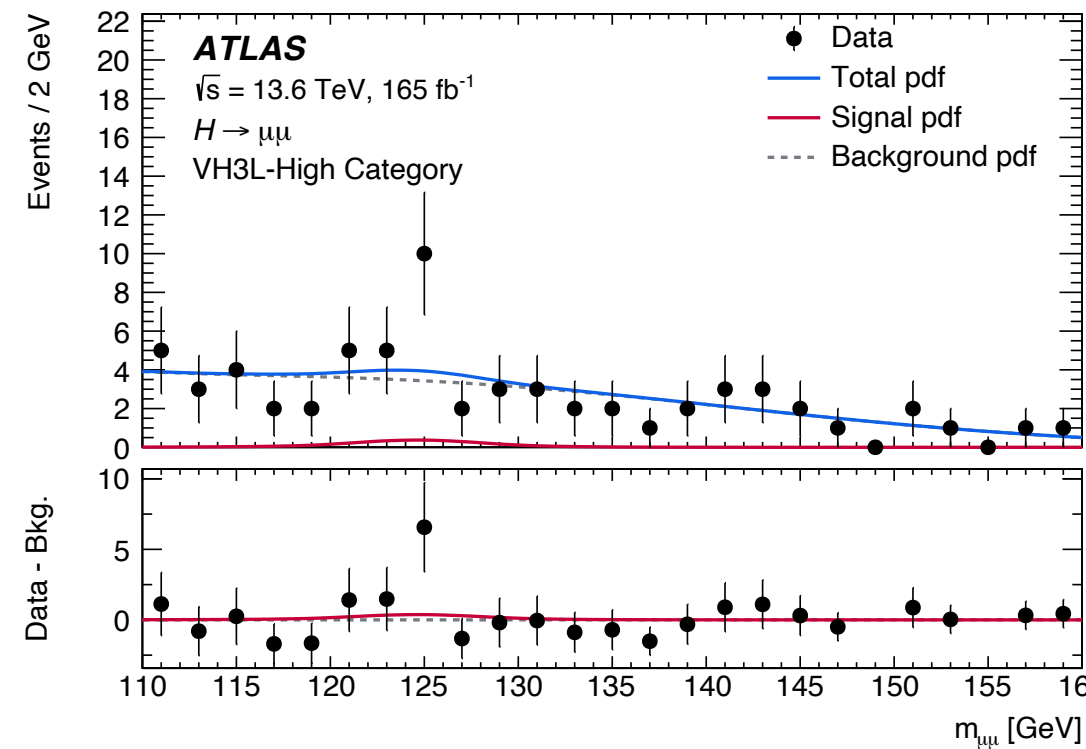
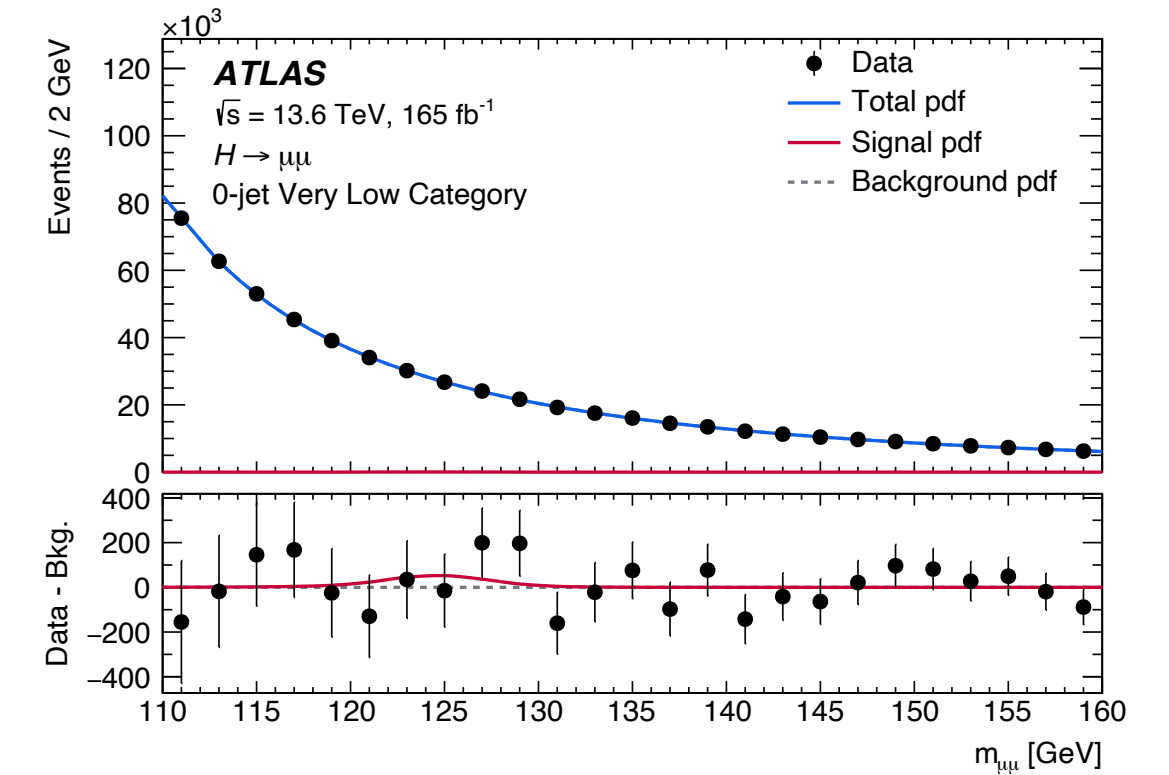
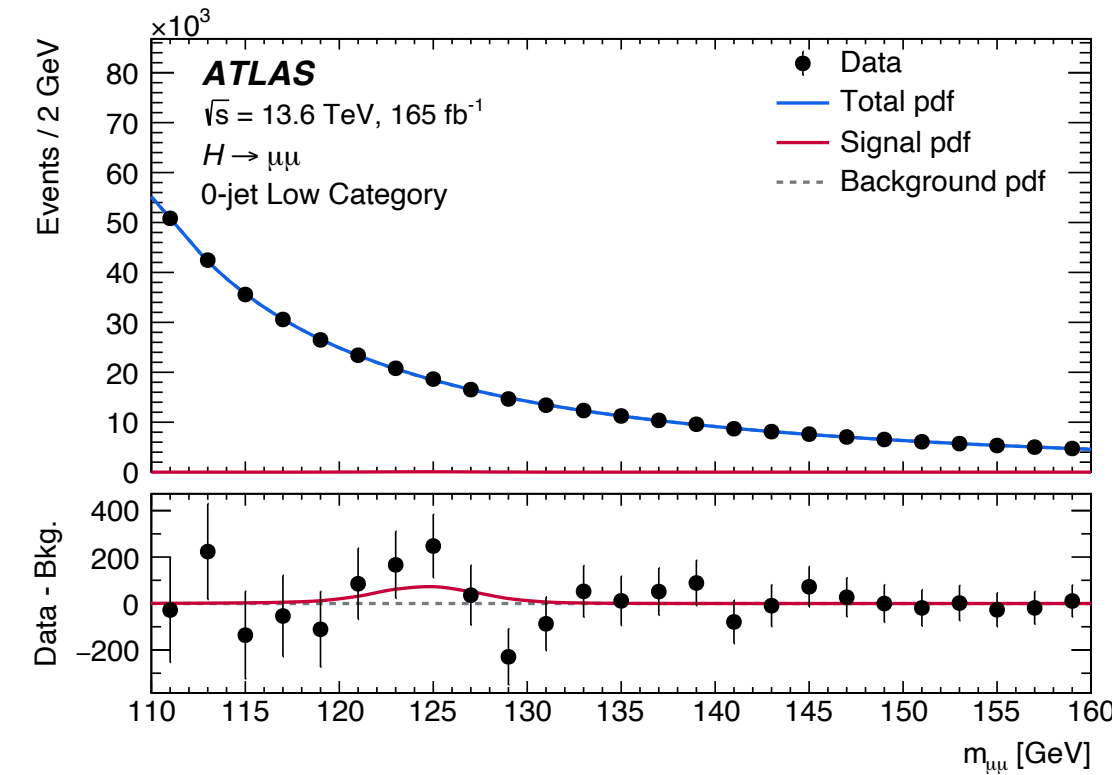
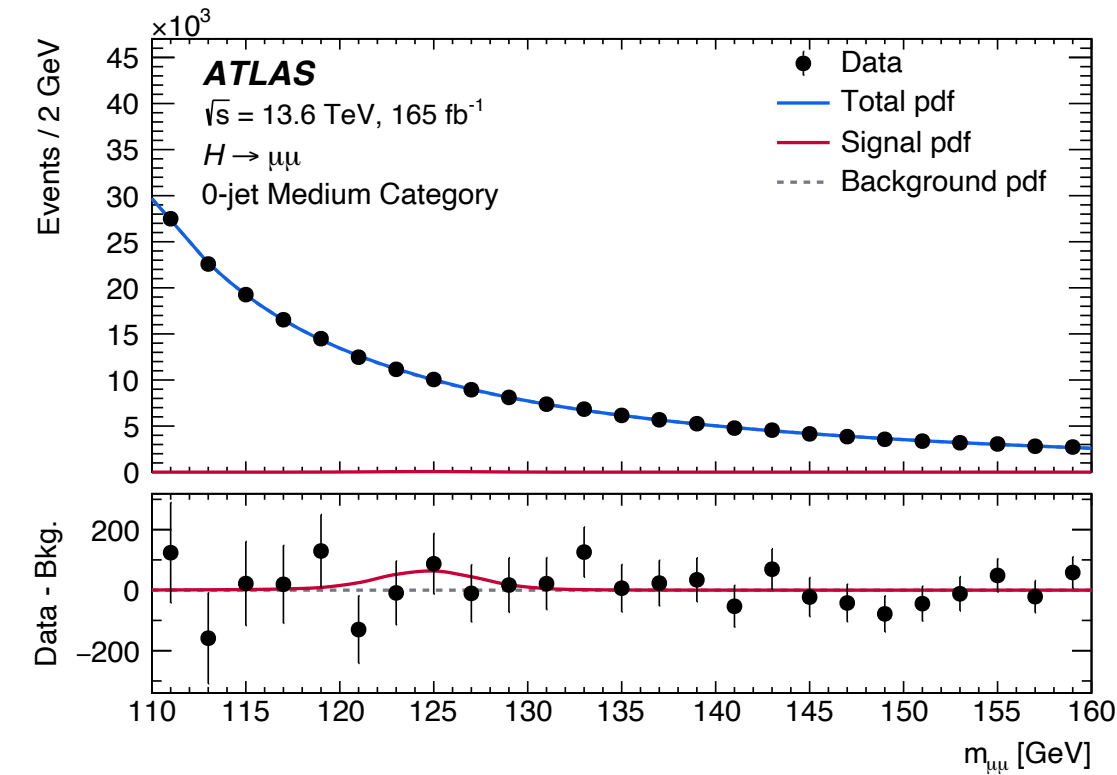
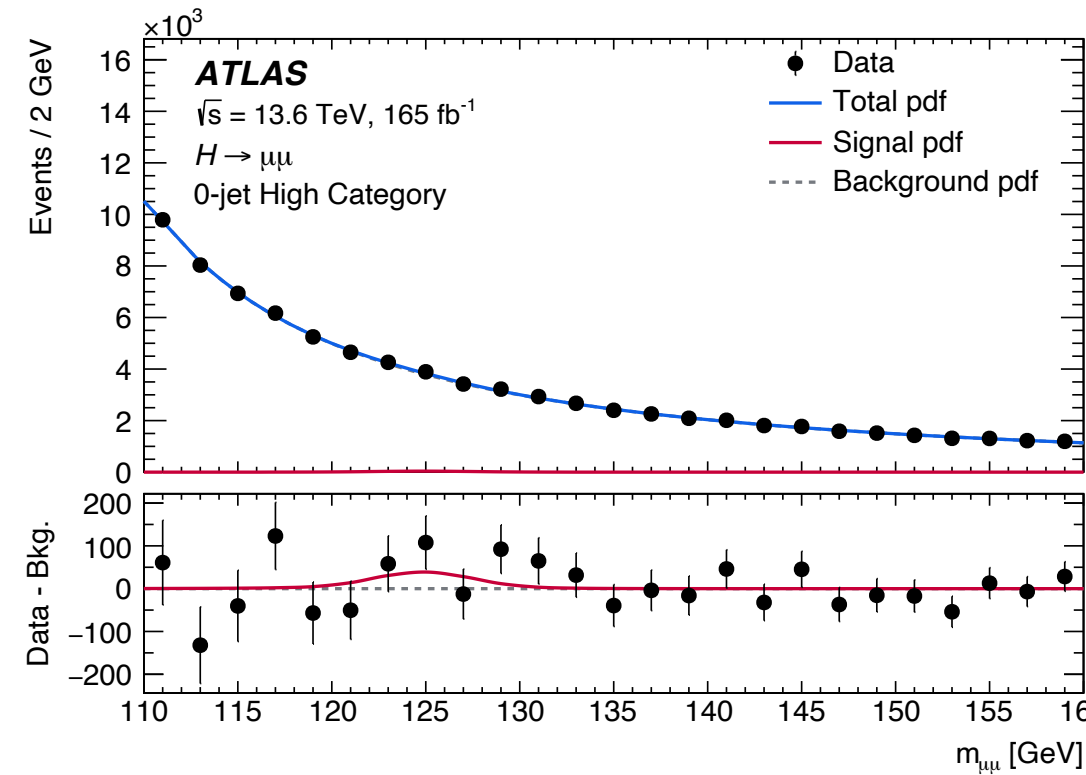
Individual categories in the $H \rightarrow \mu^+\mu^-$ analyses

$H \rightarrow \mu^+\mu^-$



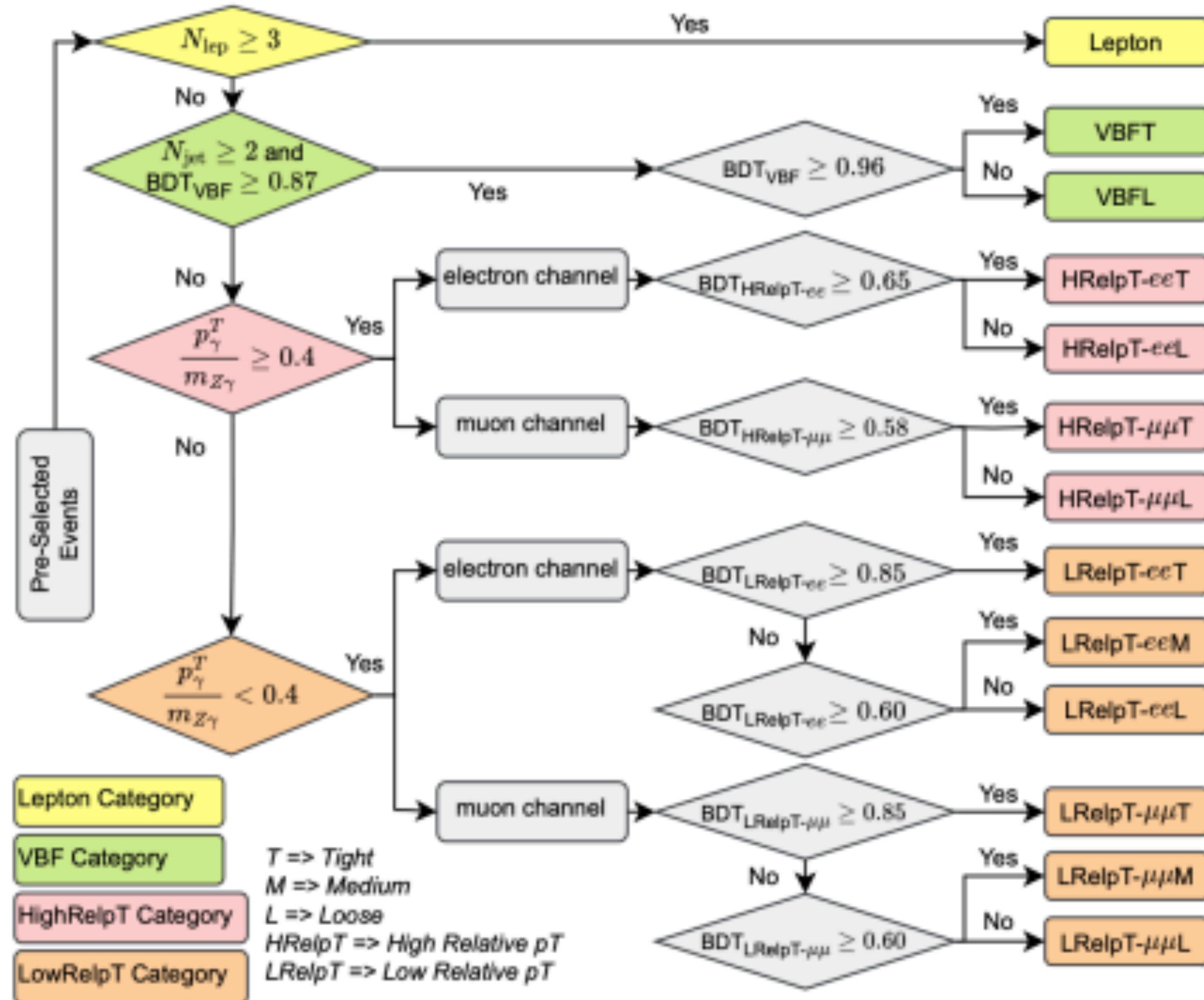
Individual categories in the $H \rightarrow \mu^+\mu^-$ analyses

$$H \rightarrow \mu^+\mu^-$$



Categorization

$$H \rightarrow Z\gamma$$



➤ Events after preselection are classified into 13 categories

• BDT classifications for VBF, HRelpT and LRelpT categories.

➤ **Lepton category**

• Additional lepton ($N_{lepton} \geq 3$)

➤ **VBF category:**

• Train the events with $N_{jet} \geq 2$ and categorize to two region: Tight and Loose

➤ **High Relative pT category**

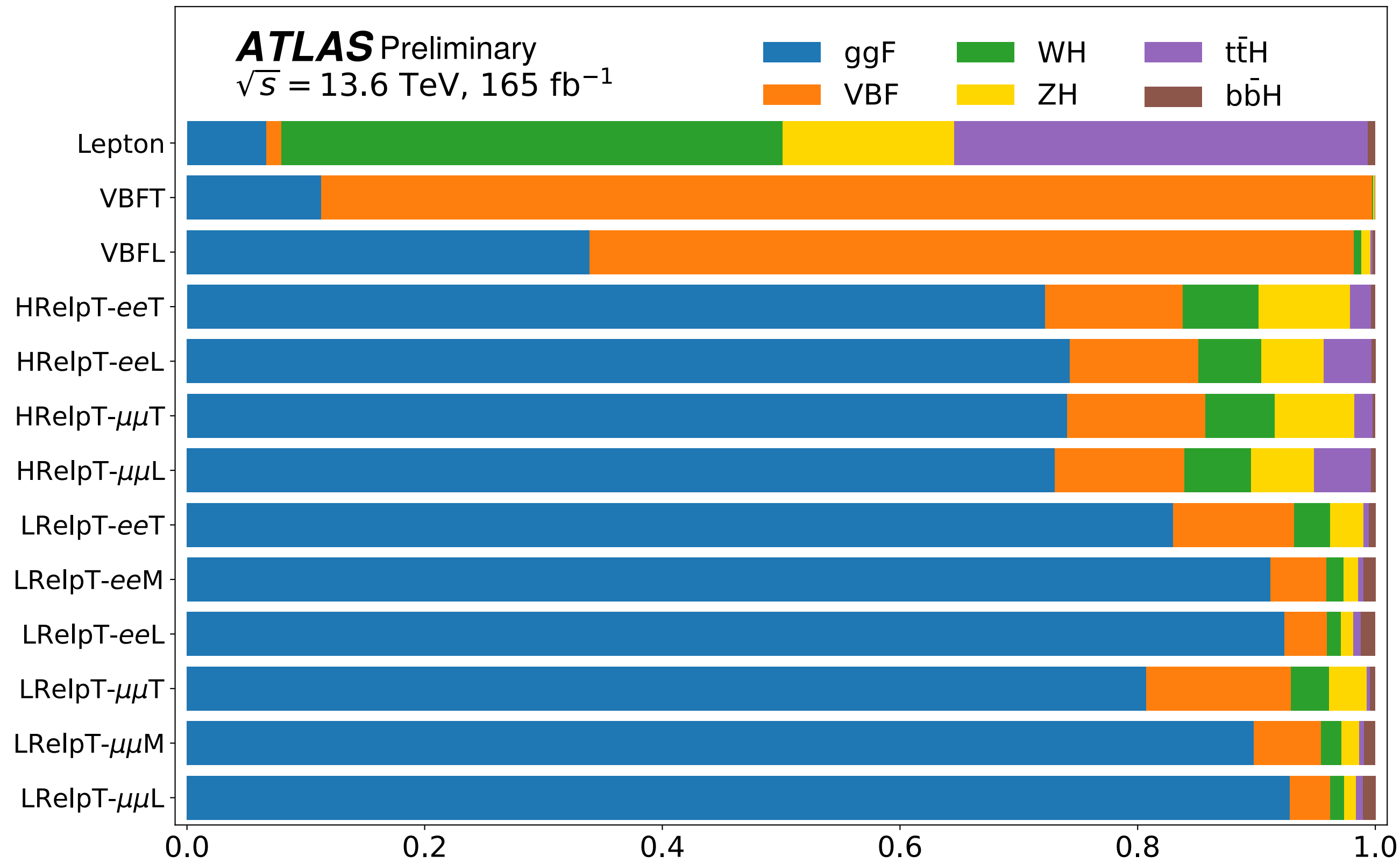
• Train the events with $pT_{\gamma}/m_{l\bar{l}\gamma} \geq 0.4$, split them by channel, and categorize to Tight and Loose for each channel

➤ **Low Relative pT category**

• Train the events with $pT_{\gamma}/m_{l\bar{l}\gamma} < 0.4$, split by channel, categorize to Tight, Medium and Loose for each channel

Signal decomposition in each category

$$H \rightarrow Z\gamma$$



➤ Lepton category: VH and ttH dominant

- VH 56% and ttH 35%

➤ VBF category:

- 89% VBF and 11% ggH in VBF tight
- 64% VBF and 34% ggH in VBF Loose

➤ HRelpT category:

- ~73% ggH and ~11% VBF

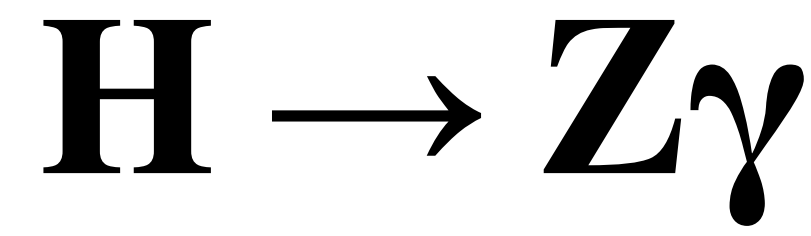
➤ LRelpT category

- ~92% ggH and ~6% VBF

● Signal modeling

- The three-body invariant mass distribution is fitted independently in each category using the Double-Sided Crystal Ball (DSCB) function.

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



$$t = \Delta m_H / \sigma_{CB}$$

$$\Delta m_H = m_{ll\gamma} - \mu_{CB}$$

N : normalization parameter

μ_{CB} : the peak of the Gaussian distribution

Mean and resolution in each category

Category	Mean [GeV]	Resolution [GeV]
Lepton	125.009	1.617
VBFT	125.021	1.422
VBFL	125.020	1.566
HRelpT- ee T	125.138	1.136
HRelpT- ee L	125.243	1.452
HRelpT- $\mu\mu$ T	124.907	1.456
HRelpT- $\mu\mu$ L	125.055	1.584
LRelpT- ee T	125.137	1.566
LRelpT- ee M	125.163	1.637
LRelpT- ee L	124.941	1.889
LRelpT- $\mu\mu$ T	124.883	1.628
LRelpT- $\mu\mu$ M	124.940	1.713
LRelpT- $\mu\mu$ L	124.827	1.828

$$H \rightarrow Z\gamma$$

● Run2 & Run3 combination correlation scheme

➤ Experimental uncertainty correlation

- **Trigger uncertainties: decorrelation** between Run2 and Run3. In addition, in Run3 decorrelation between 2022 and 2023/2024 due to the new L1 trigger change.
- **Luminosity: decorrelated** between Run2 and Run3
- **EGamma: decorrelated** between Run2 and Run3
- **JET: correlate** everything between Run2 and Run3 except for **InSitu NonClosure PreRec** components.
- **Muon uncertainties: correlate** everything between Run2 and Run3.
- **Spurious signal uncertainties: de-correlated** between Run2 and Run3 since categorization change

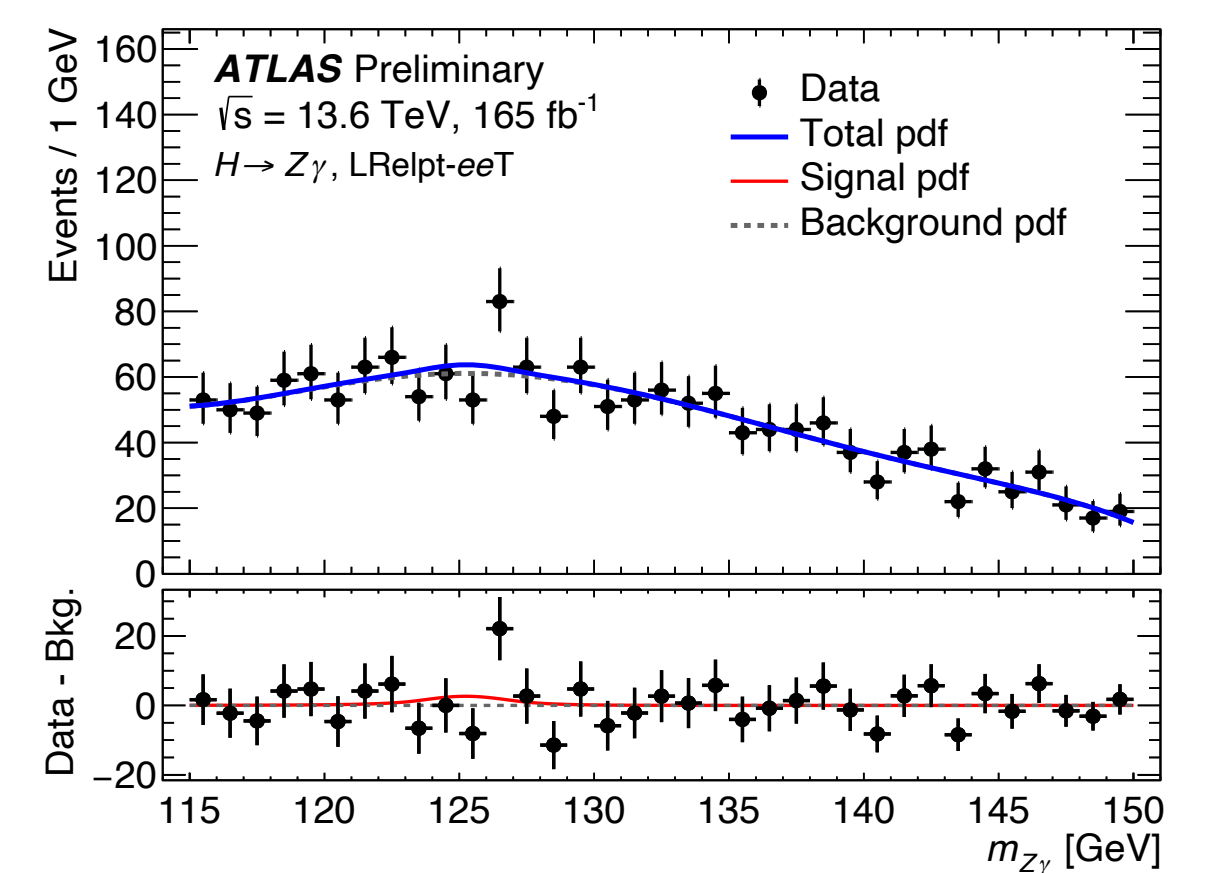
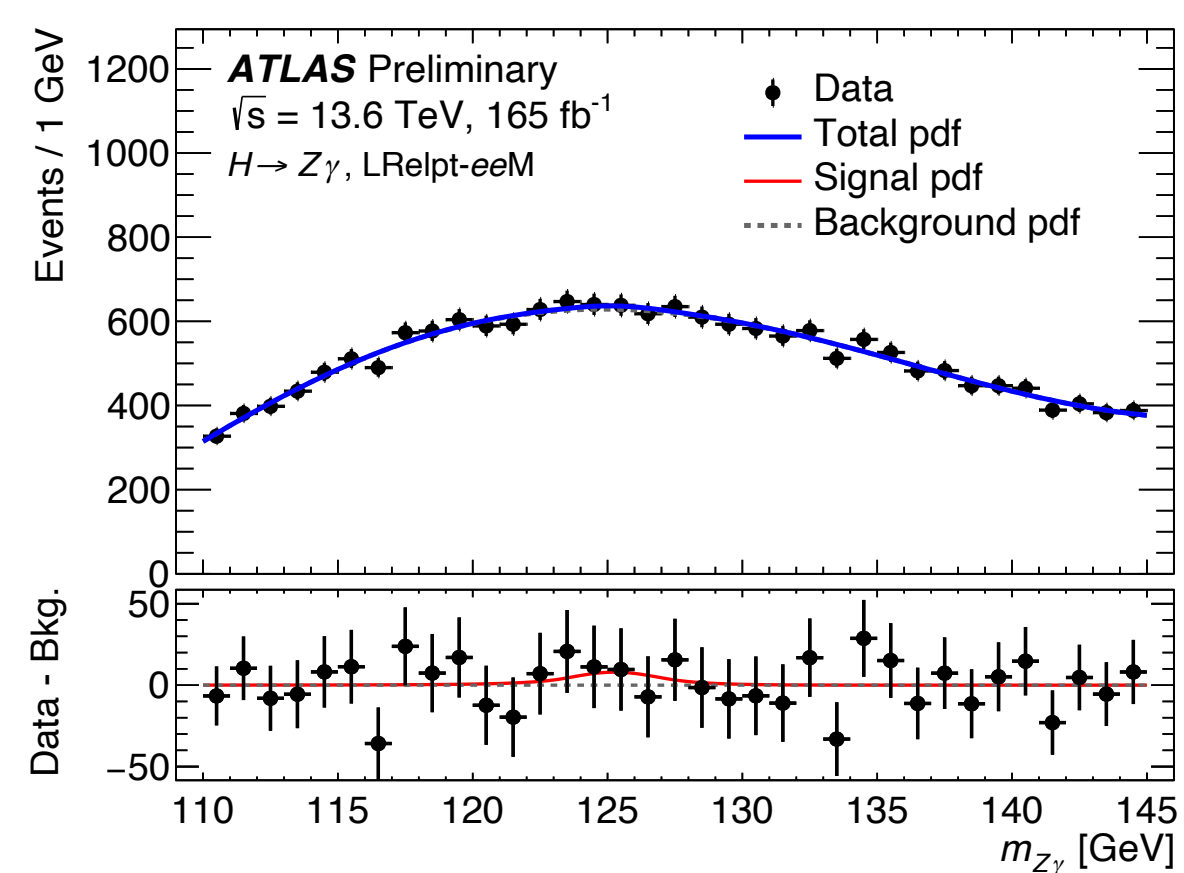
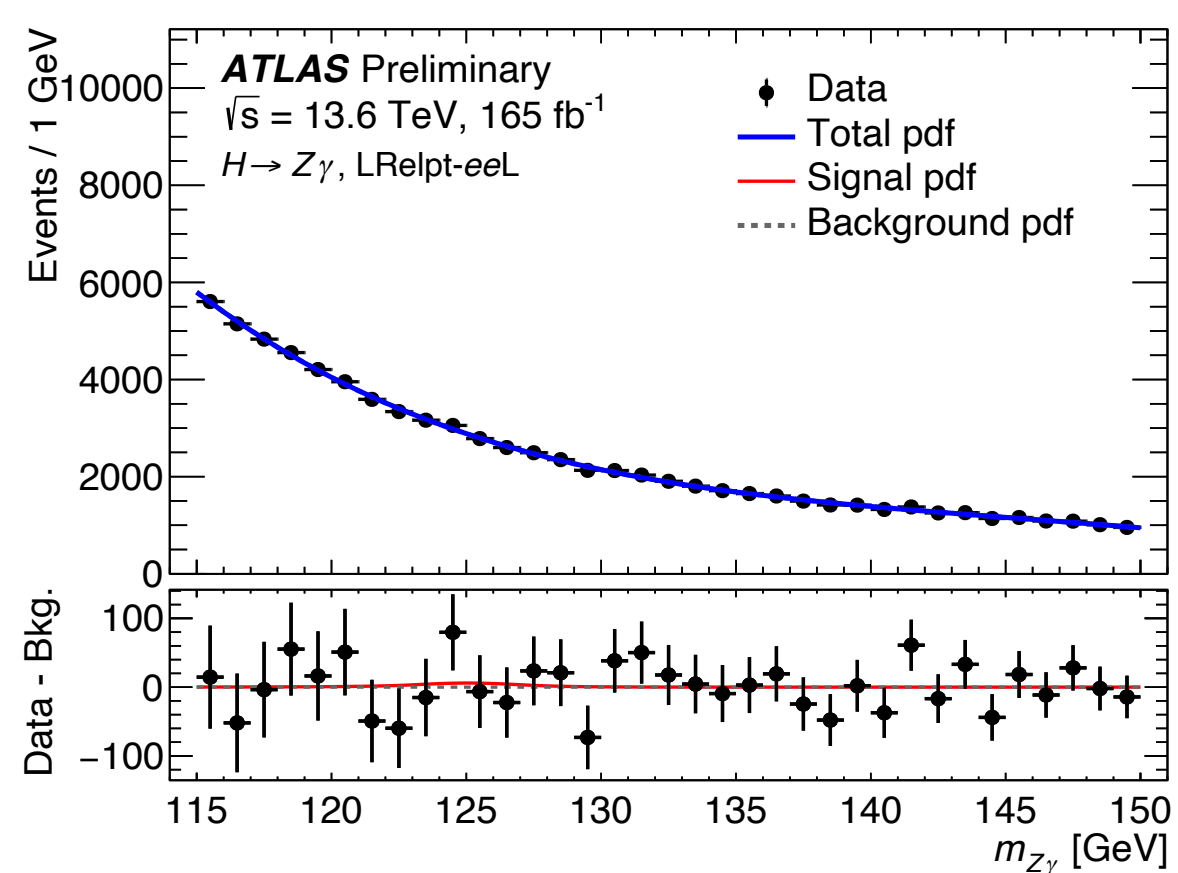
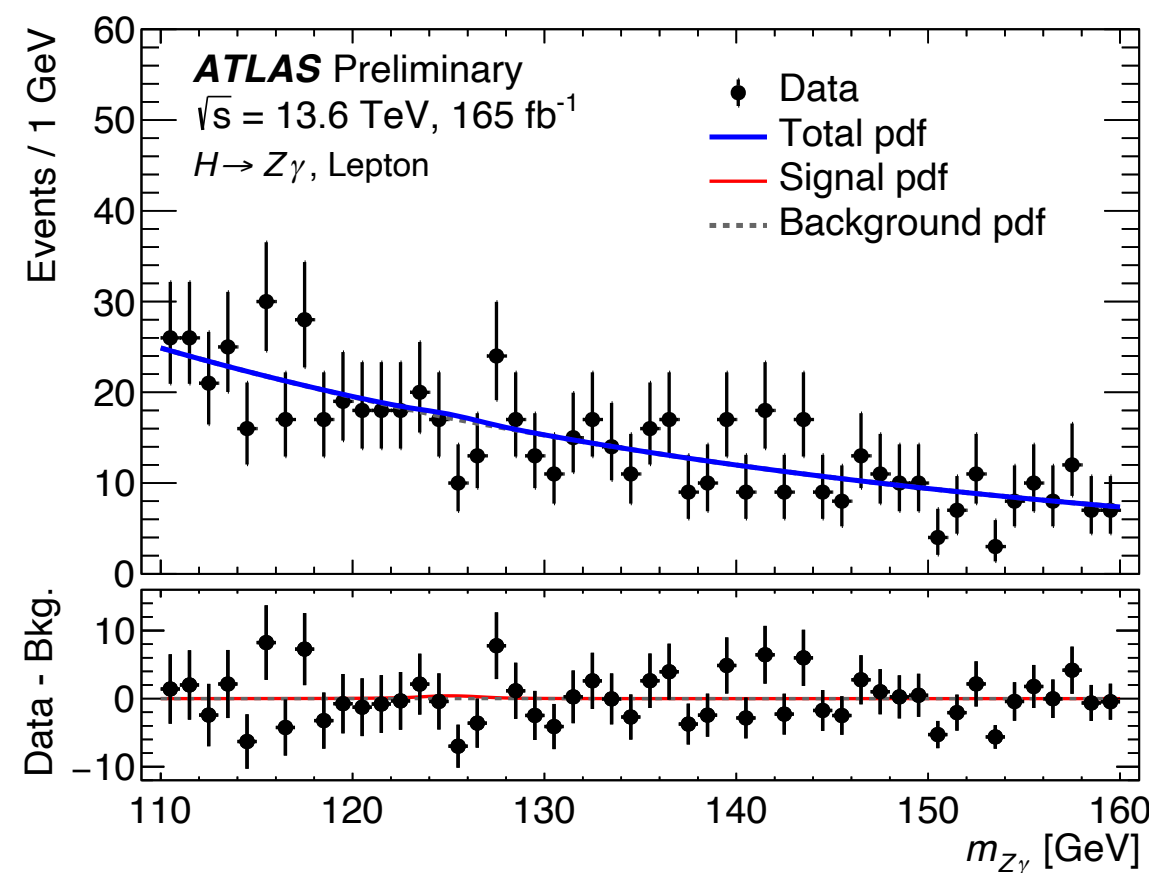
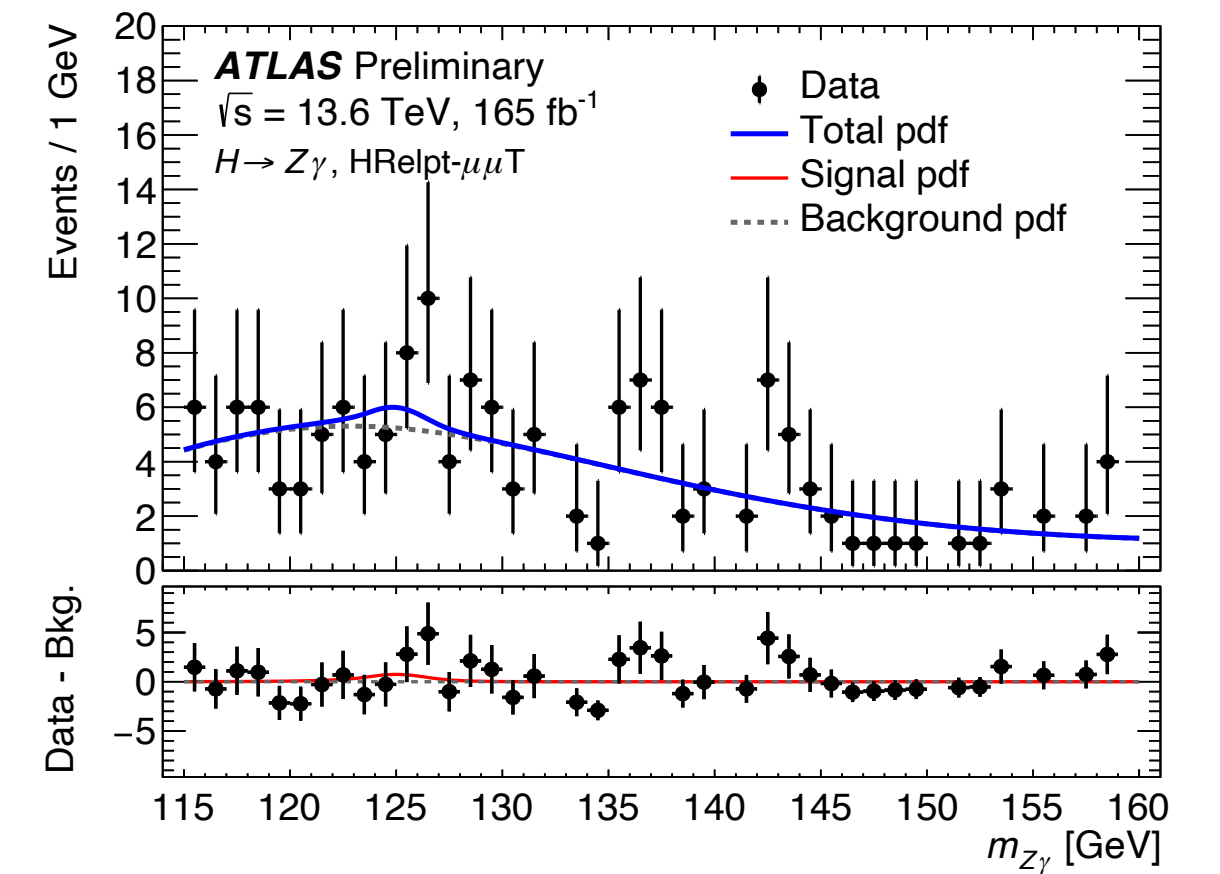
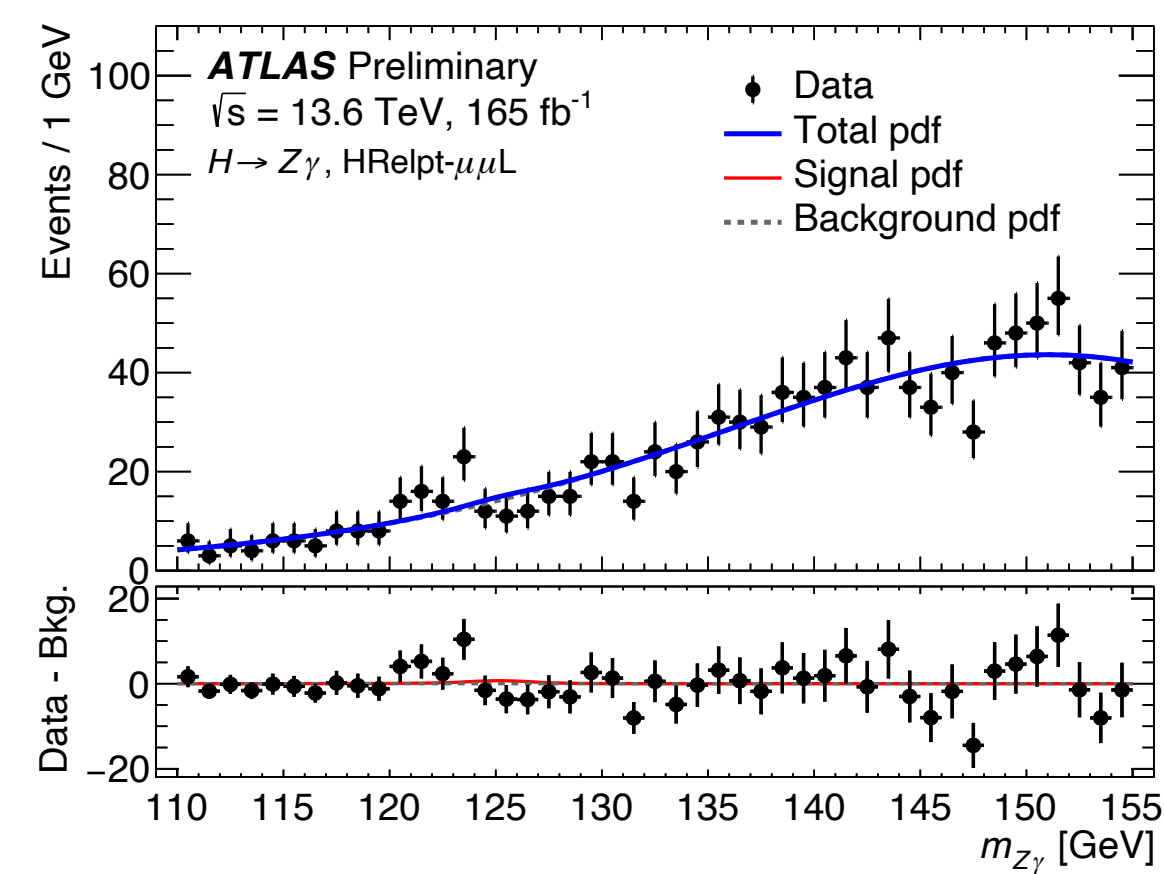
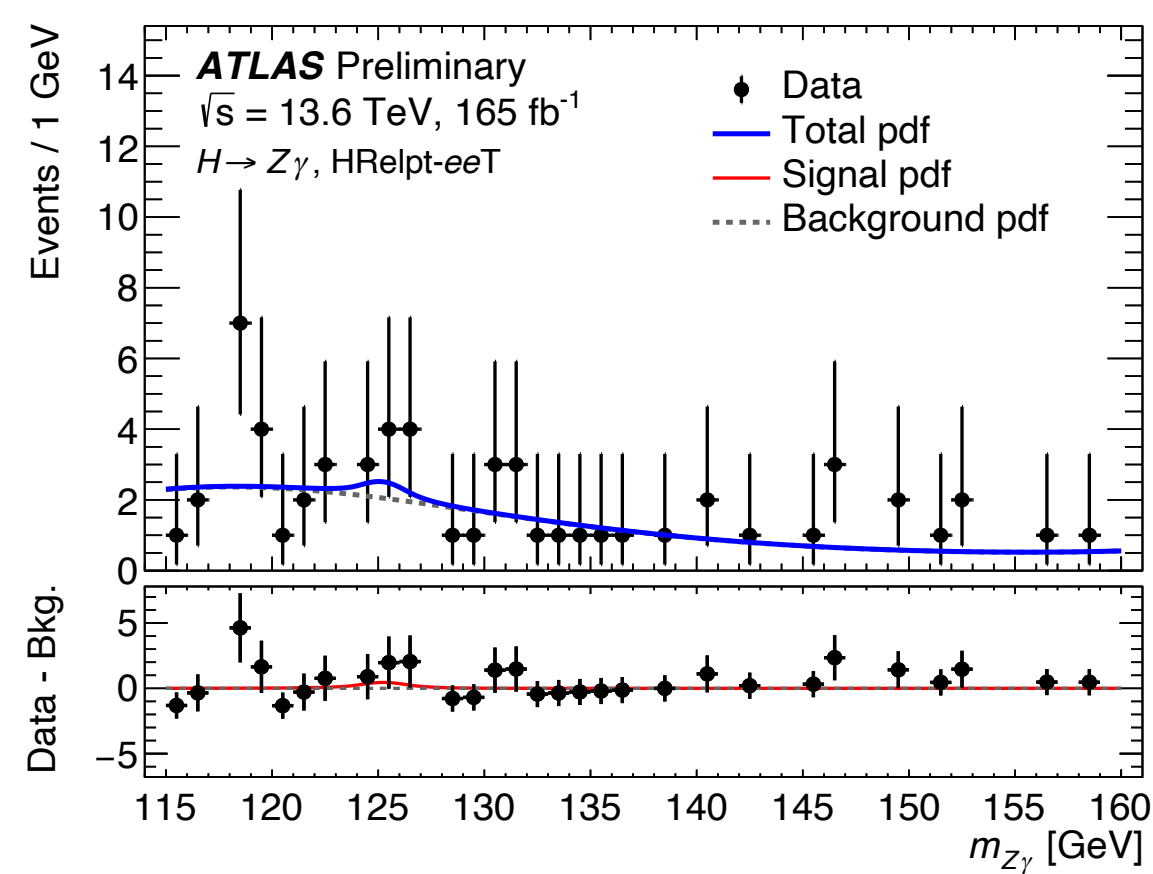
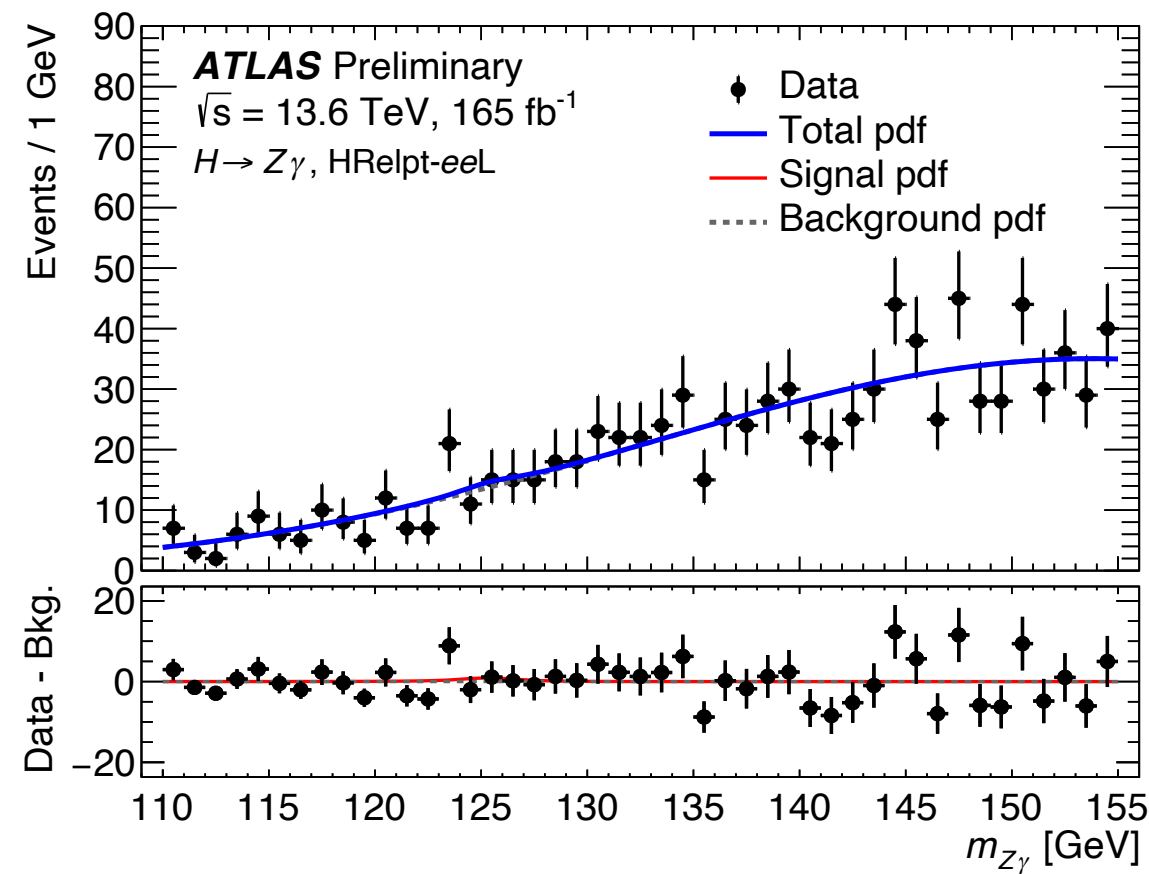
➤ Theoretical uncertainties

- **Branch ratio** uncertainty are correlated
- **QCD, PDF and alphas** are correlated

➤ Negligible impact from correlation!

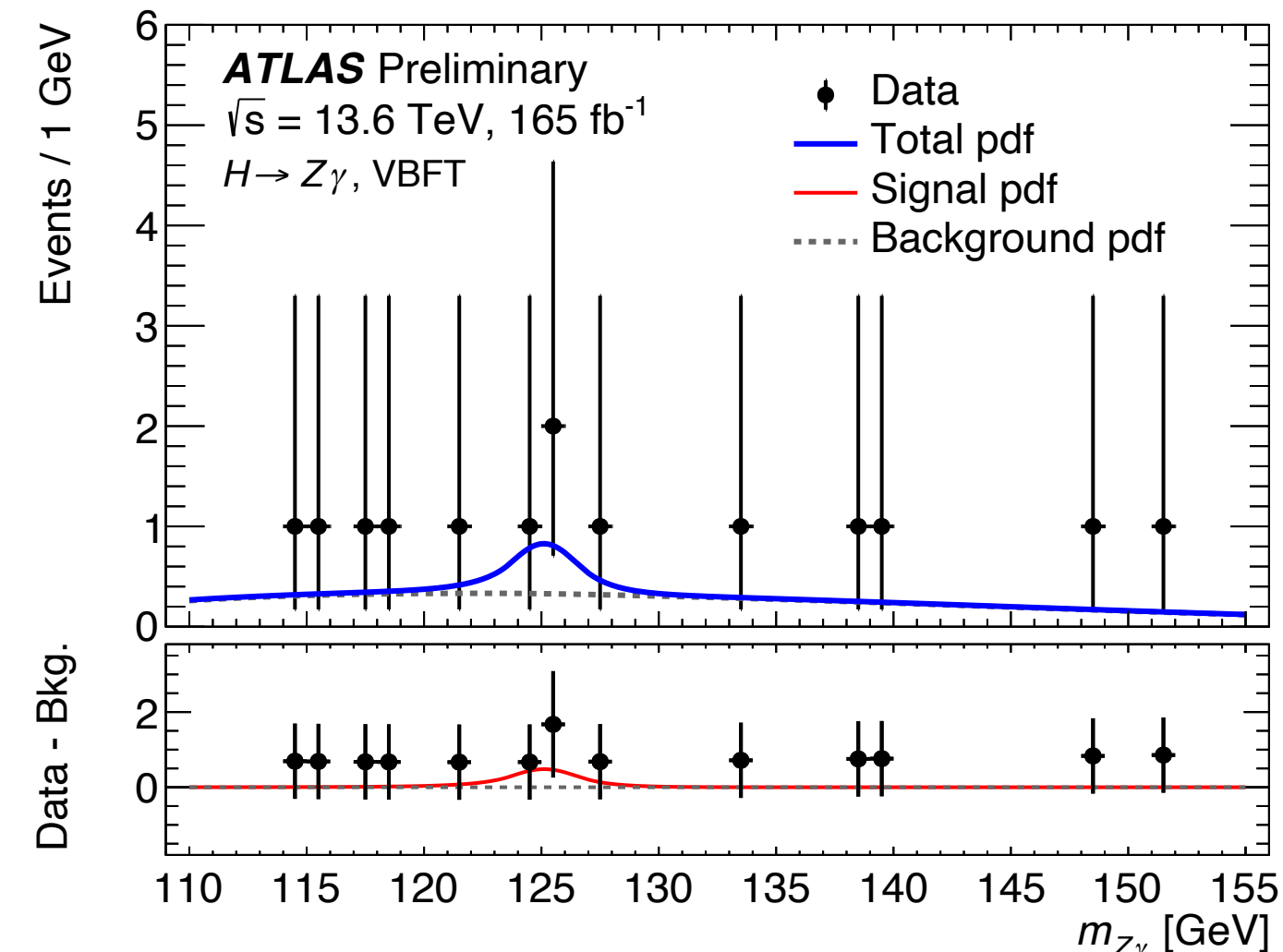
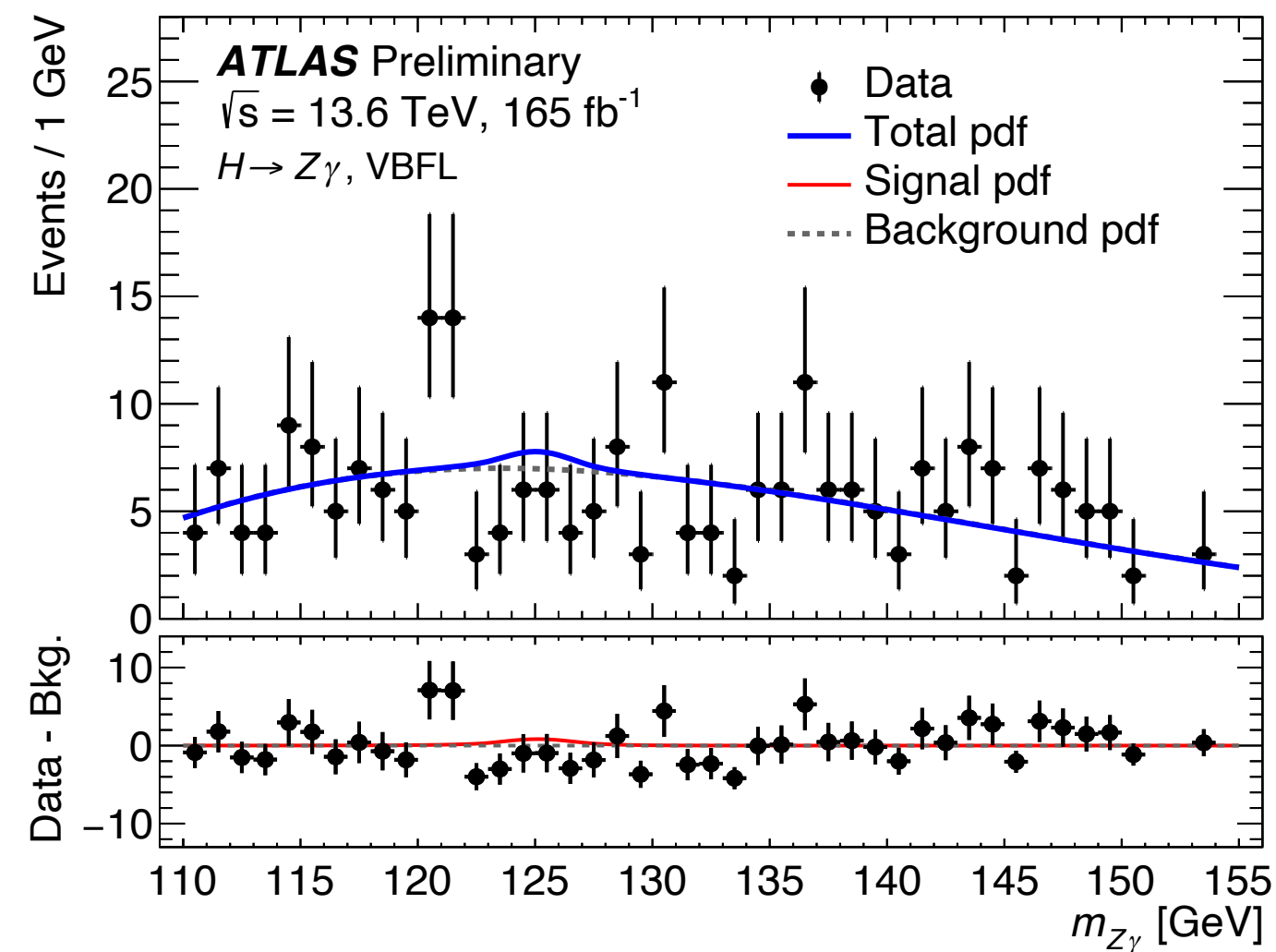
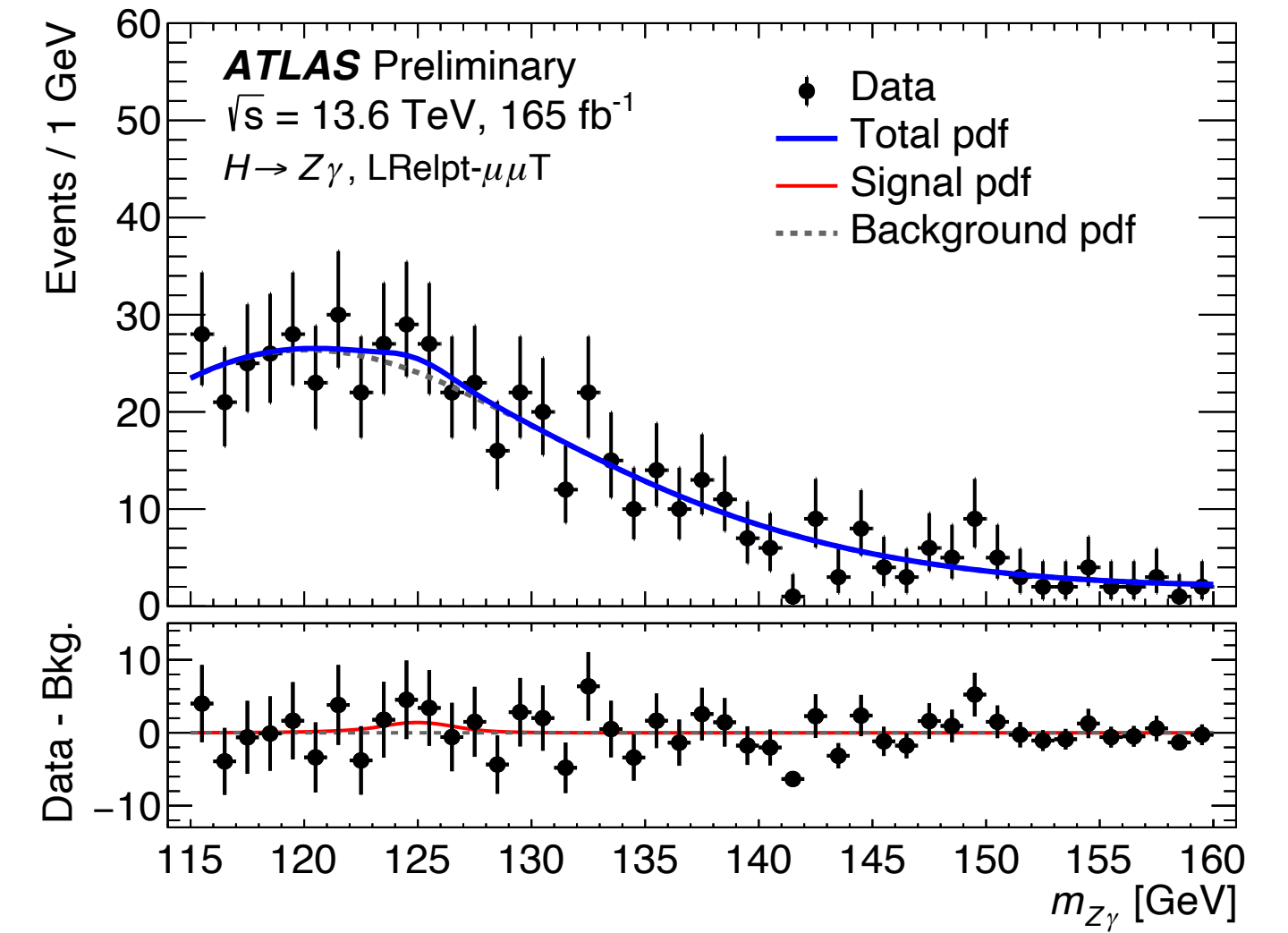
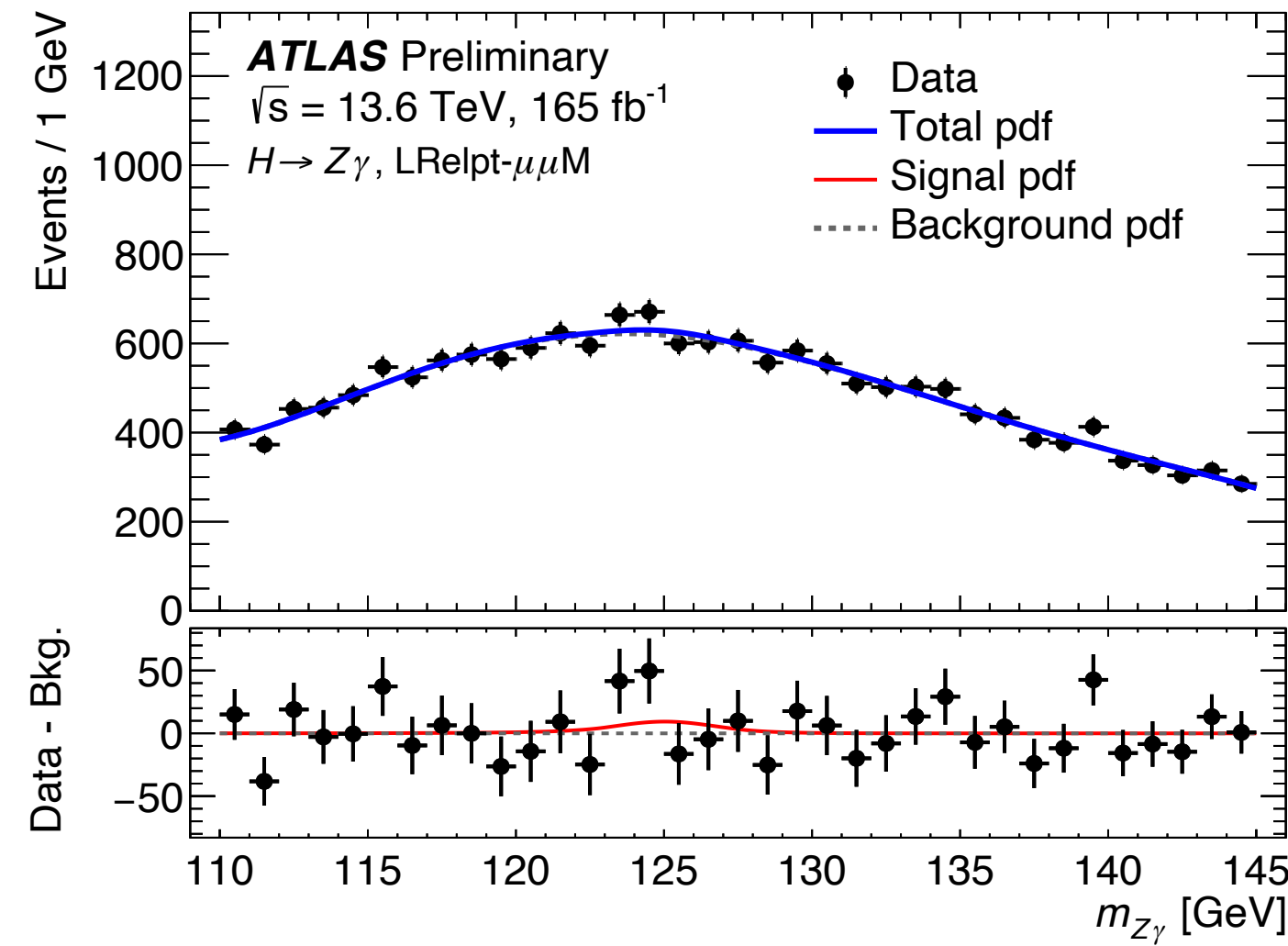
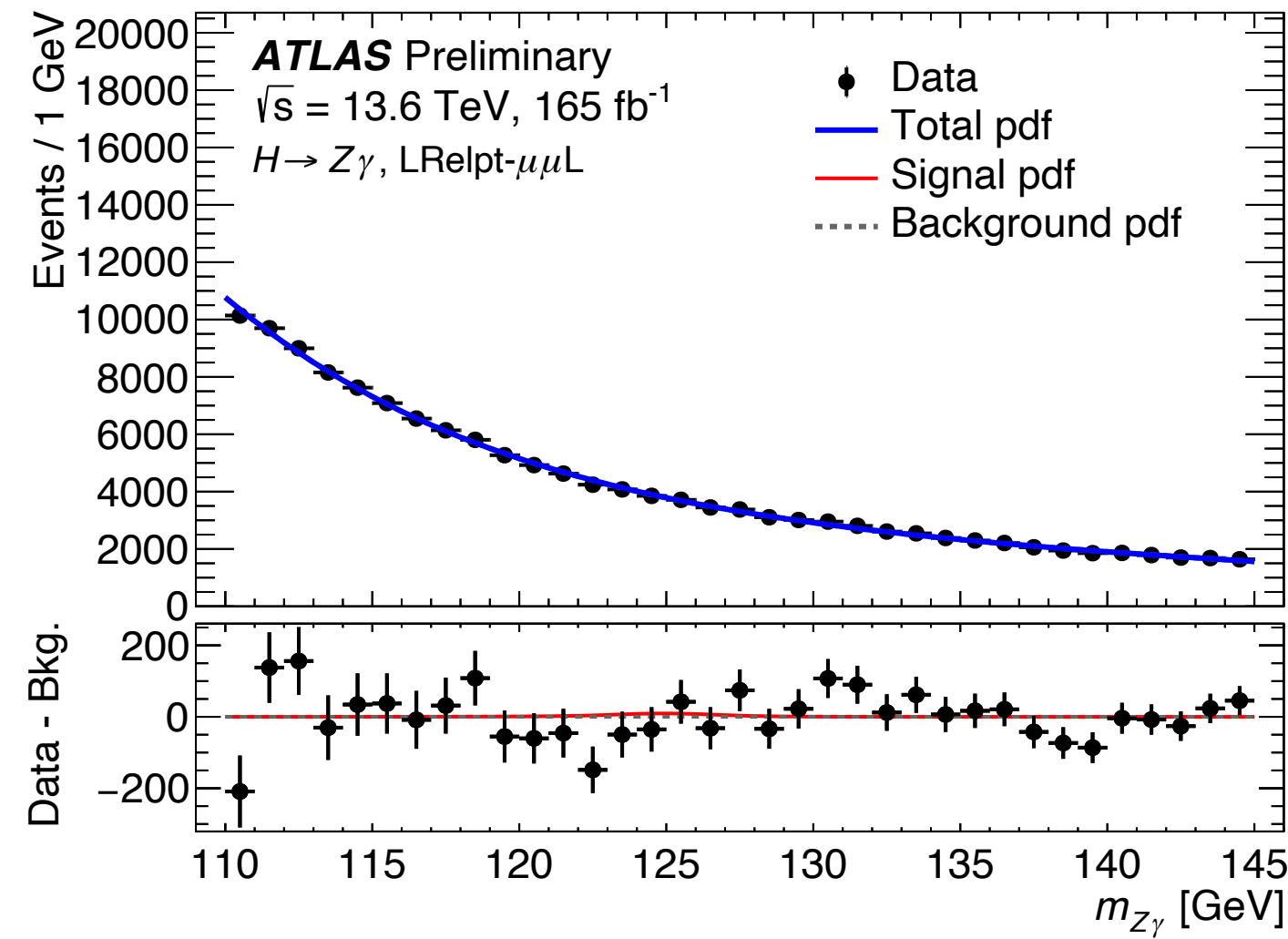
Individual categories in the $H \rightarrow Z\gamma$ analyses

$$H \rightarrow Z\gamma$$

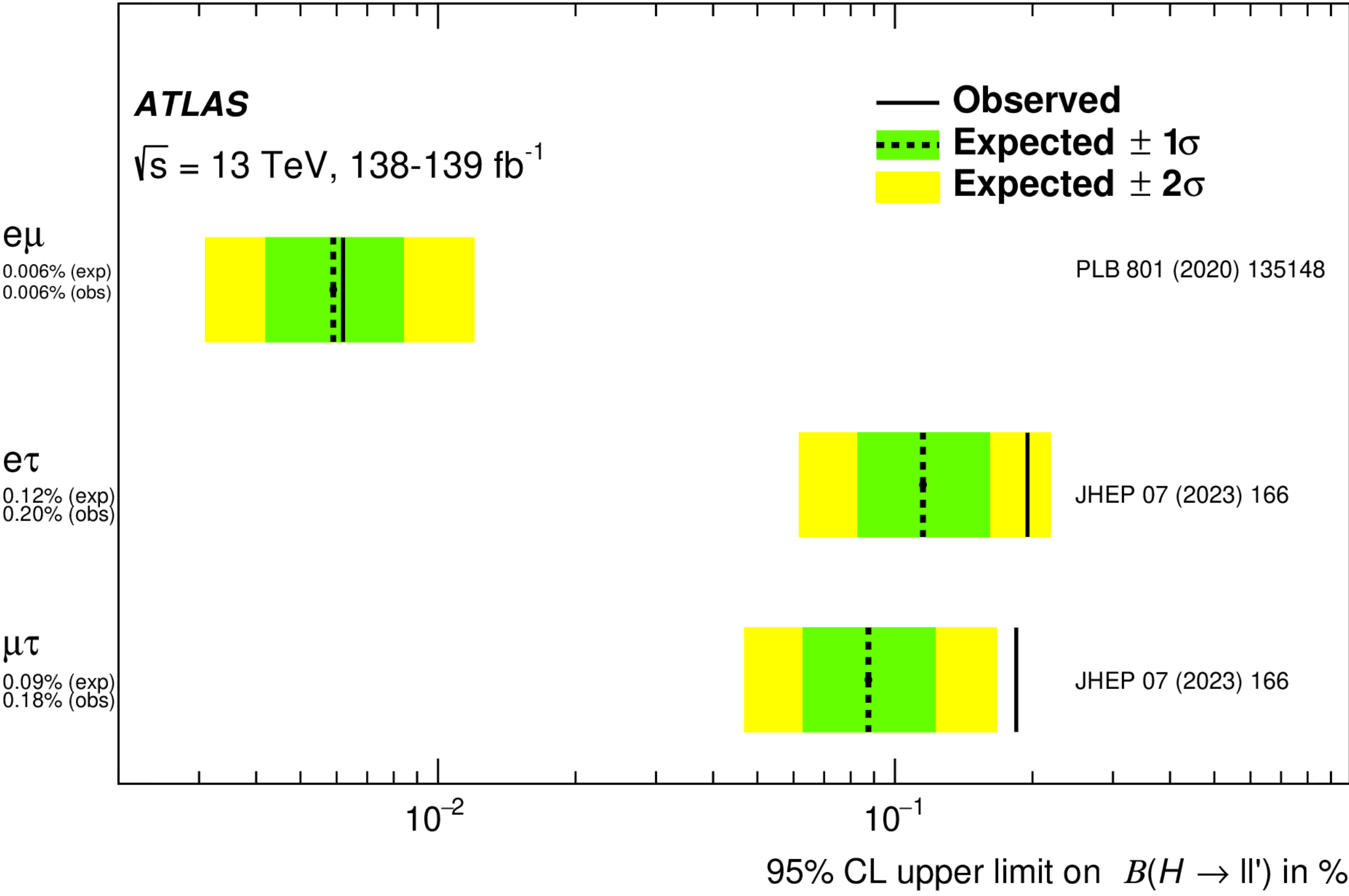


Individual categories in the $H \rightarrow Z\gamma$ analyses

$$H \rightarrow Z\gamma$$

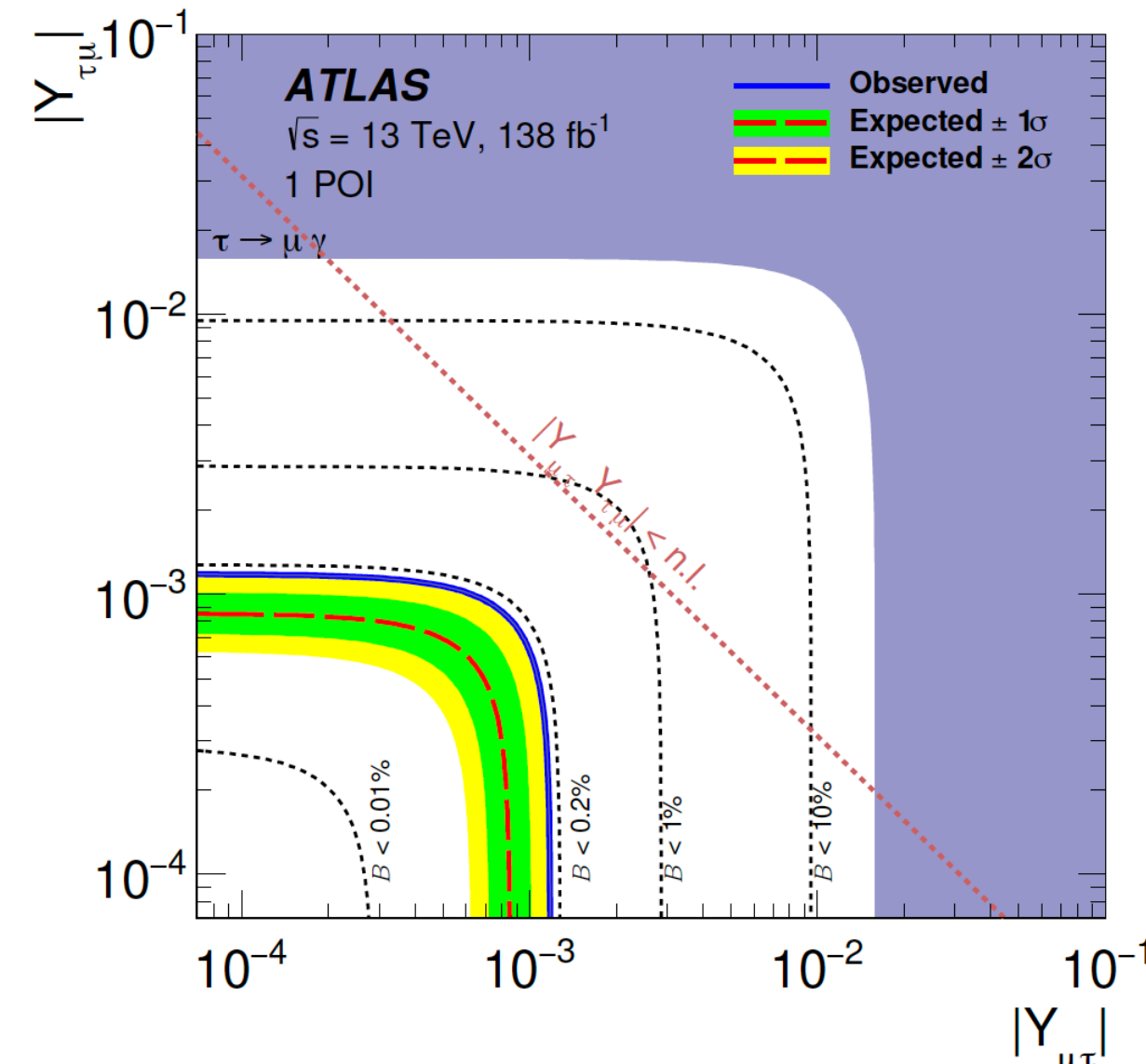
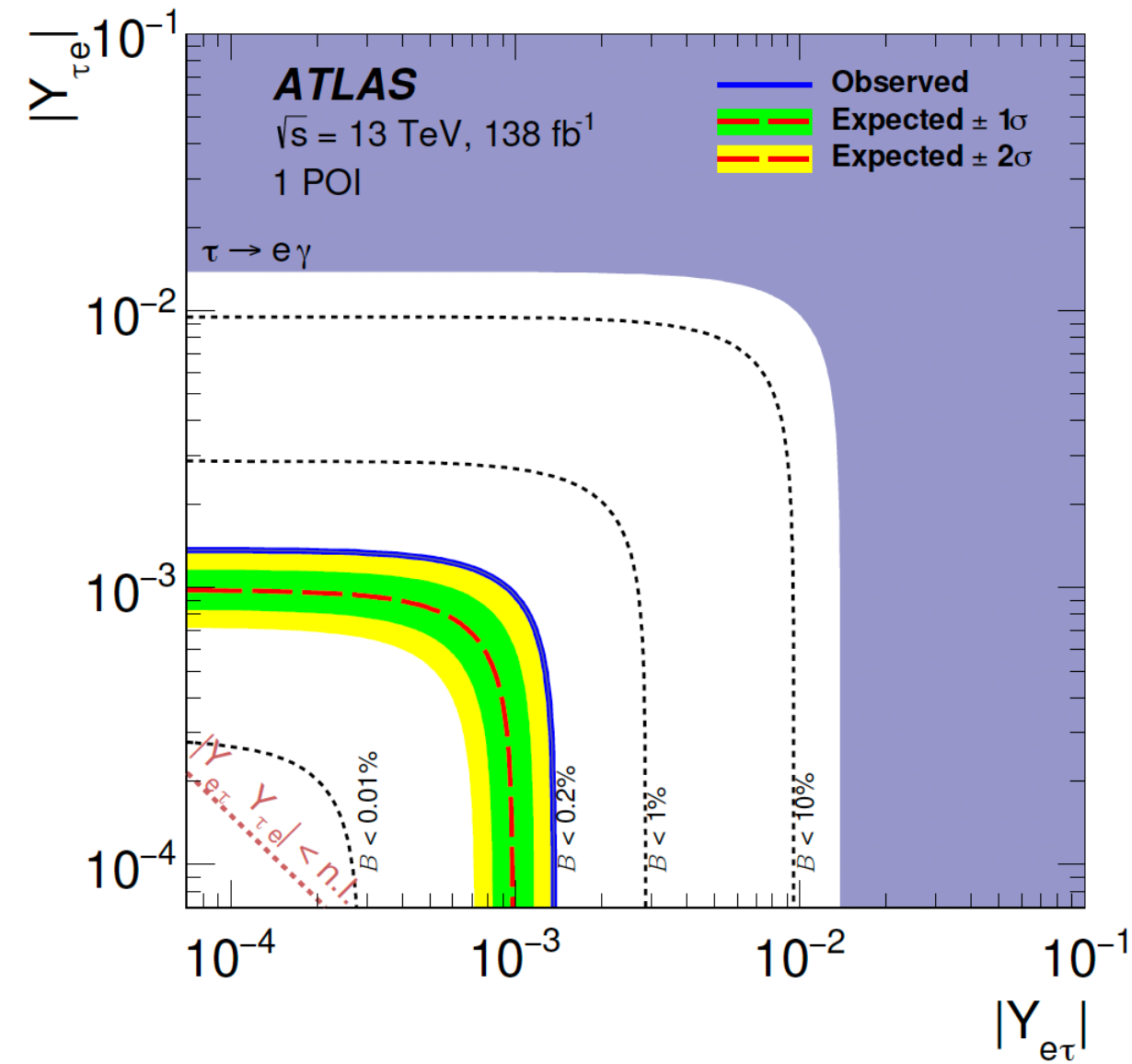


LFV Higgs searches



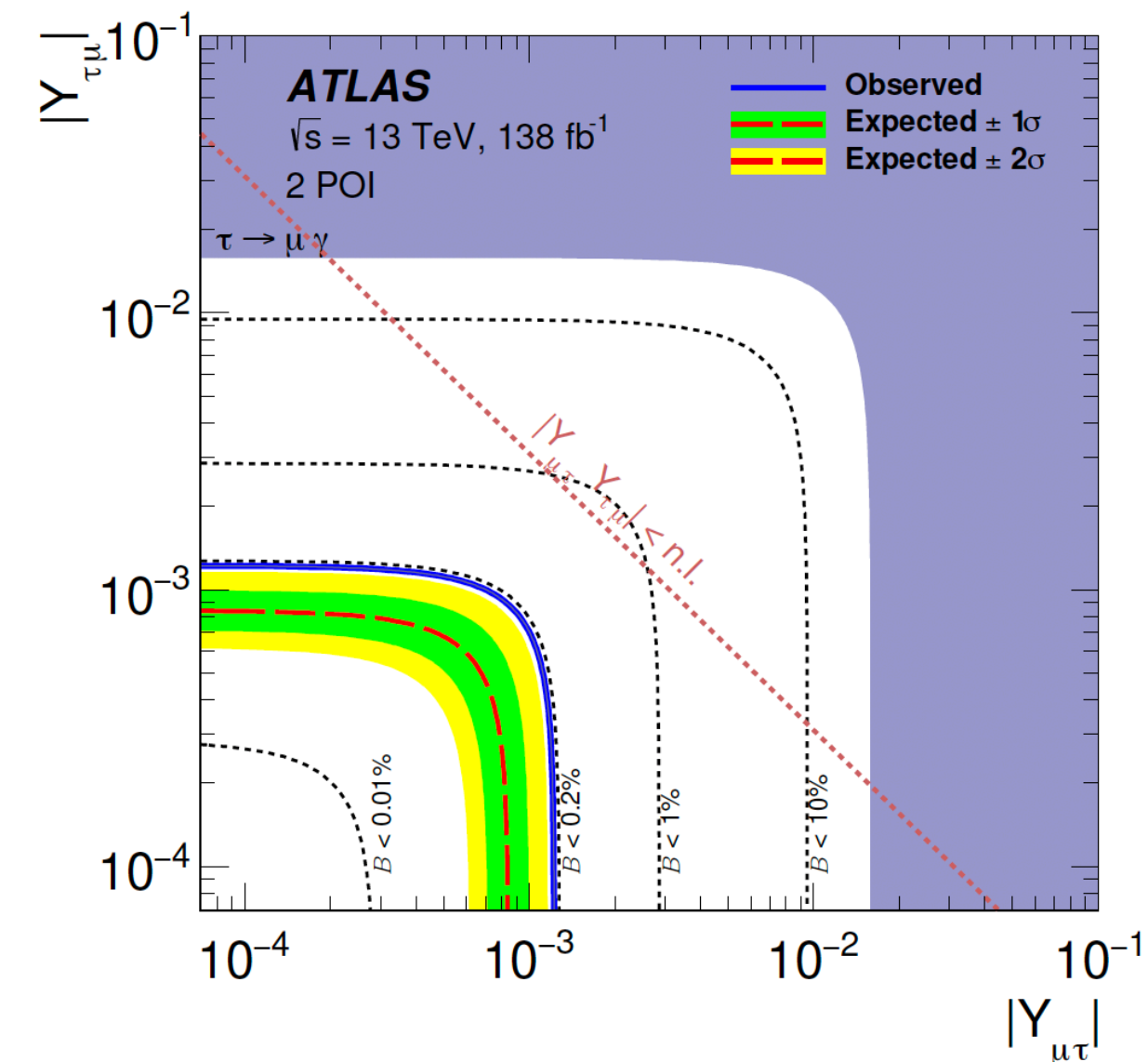
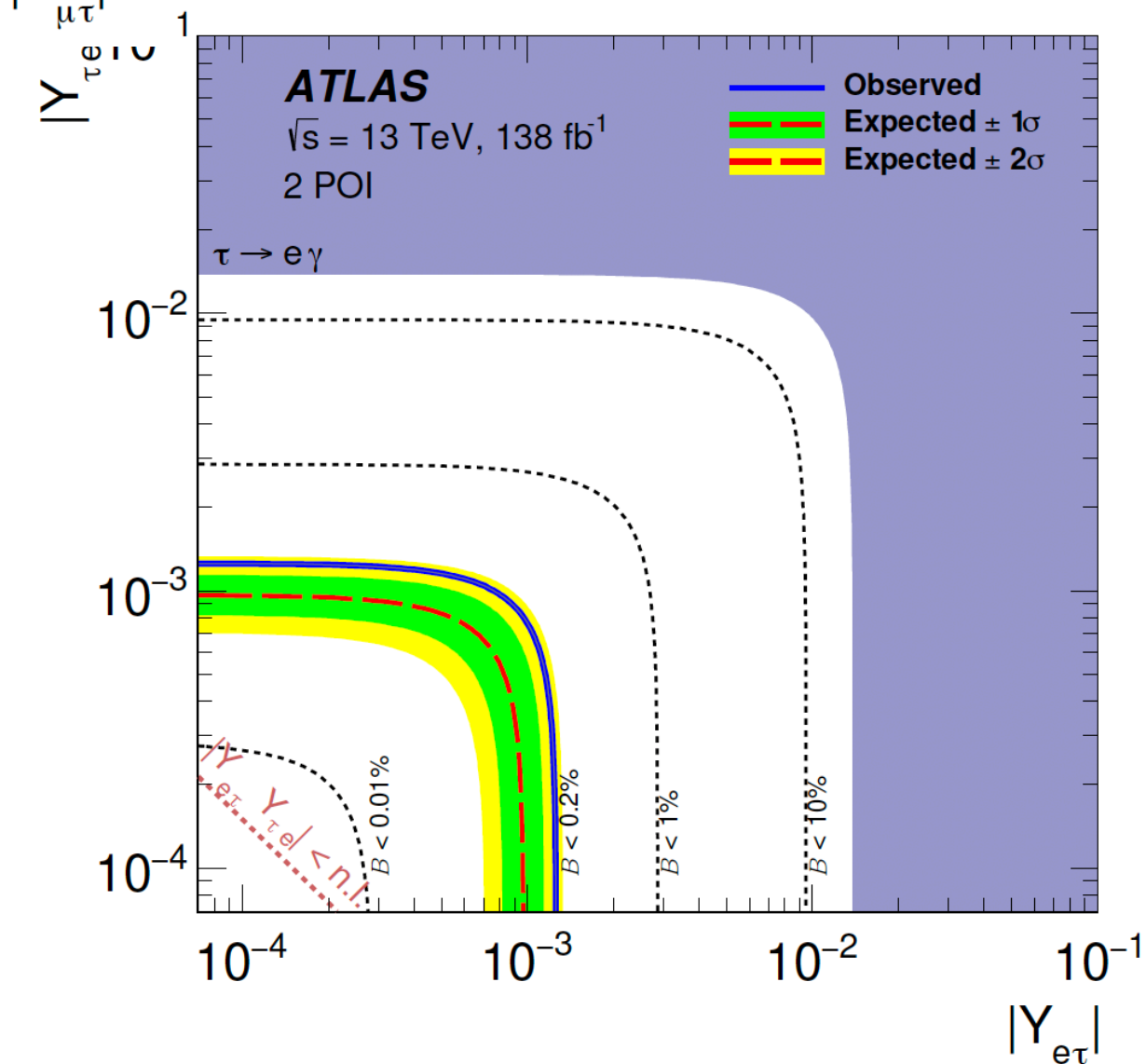
LFV decay	Direct searches	
	Upper limit	Reference
$H \rightarrow e\mu$	0.061%	ATLAS 139 fb ⁻¹ [1909.10235]
$H \rightarrow e\tau$	0.22% 0.20%	CMS 137 fb ⁻¹ [2105.03007] ATLAS 138 fb ⁻¹ [2302.05225]
$H \rightarrow \mu\tau$	0.15% 0.18%	CMS 137 fb ⁻¹ [2105.03007] ATLAS 138 fb ⁻¹ [2302.05225]

LFV Higgs: Yukawa couplings

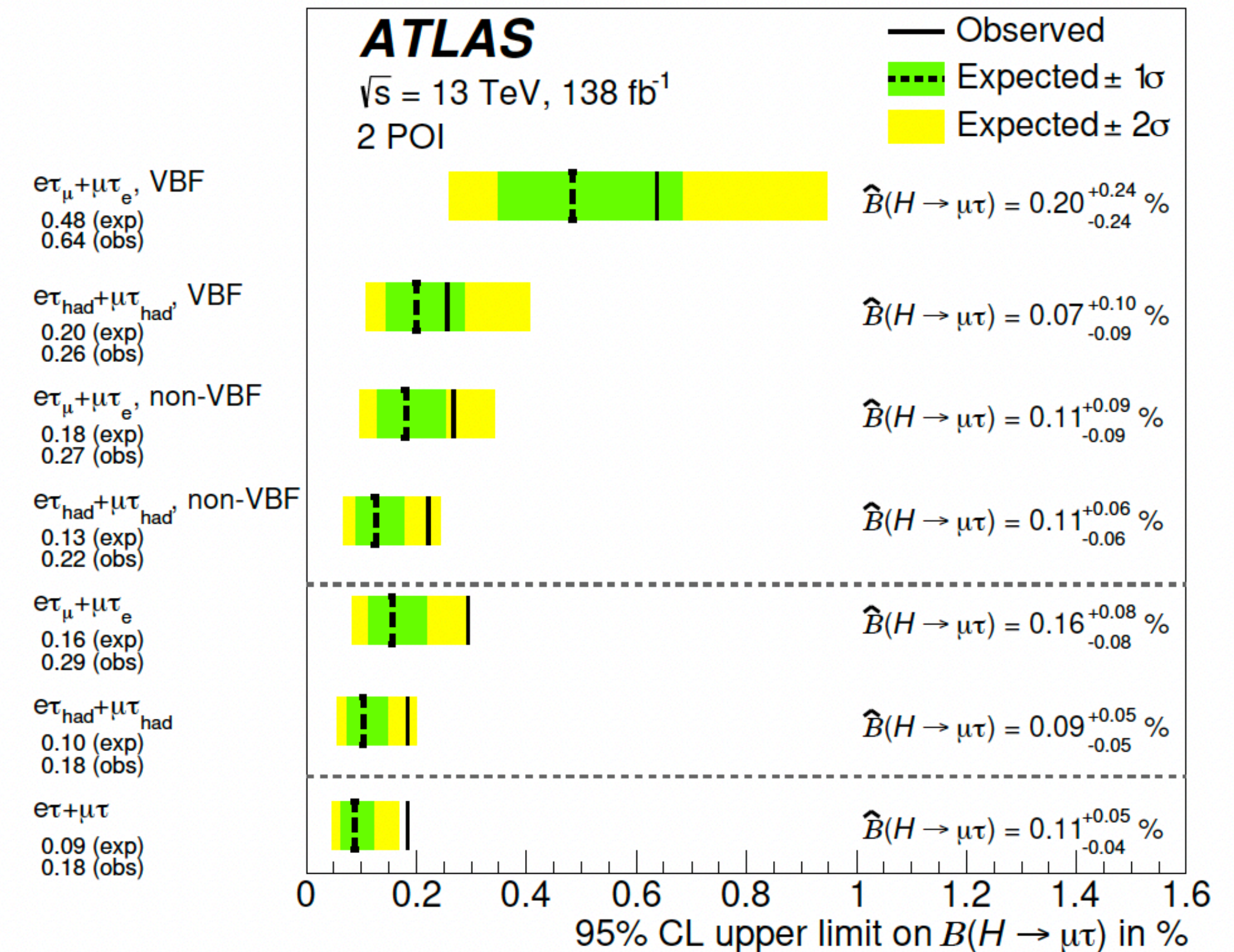
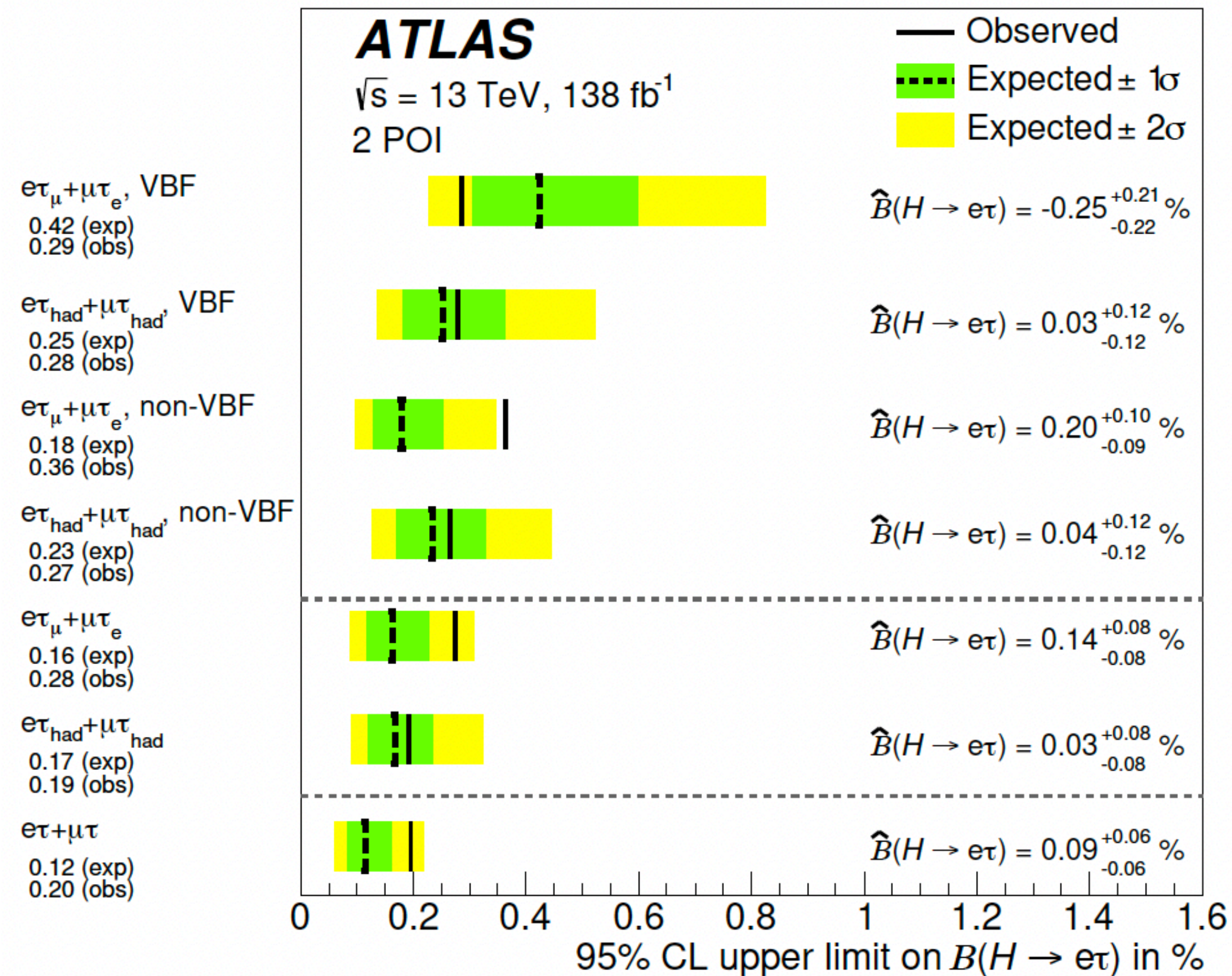


The short-dashed lines represent limits corresponding to different branching ratios (0.01%, 0.2%, 1% and 10%), while the dotted line indicates the naturalness limit (denoted by n.l.).

Expected (red long-dashed line) and observed (solid blue line) 95% CL upper limits from the simultaneous fit (1/2 POI) of the two searches on the absolute value of the couplings $Y_{\tau\mu}$ and $Y_{\mu\tau}$ together with the most stringent indirect limits from tau to gamma searches (dark purple region) for (a) $l = e$ or (b) $l = \mu$.



LFV Higgs: 2 POI



For the $H \rightarrow \tau\mu$ ($H \rightarrow \tau e$) signal, a 2.4 (1.6) excess is observed. In the case of the $H \rightarrow \tau e$ signal, this is driven mainly by the non-VBF category of the lelep final state based on the MC-template method. In the case of the $H \rightarrow \tau\mu$ signal, it is driven by the non-VBF category of the lephad final state.