Search for the rare decay H $\rightarrow Z\gamma$ in the ATLAS Experiment

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On behalf of the ATLAS Collaboration

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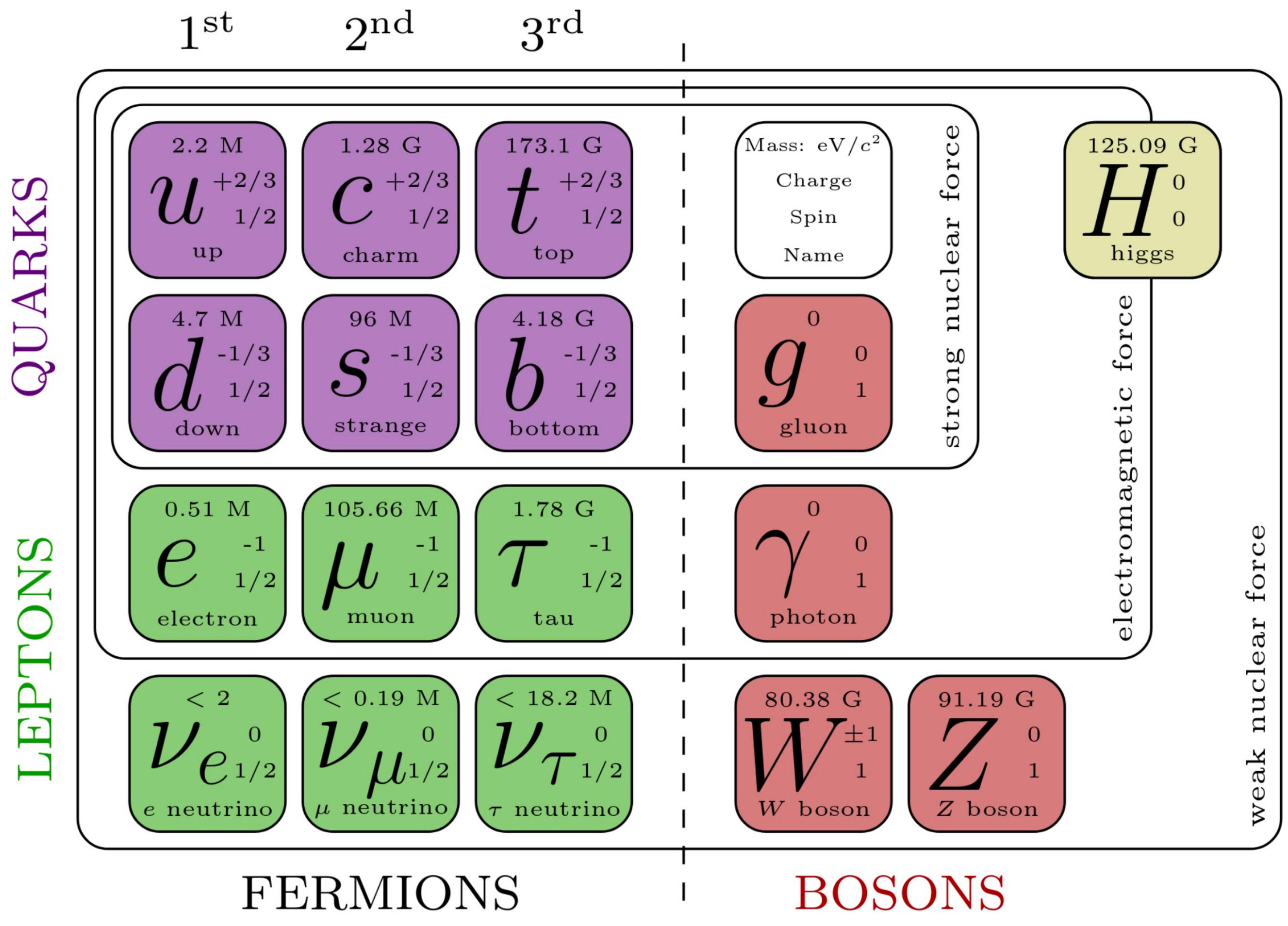
The Standard Model of particle physics



Review of Particle Physics, 2022, 8, 083C01

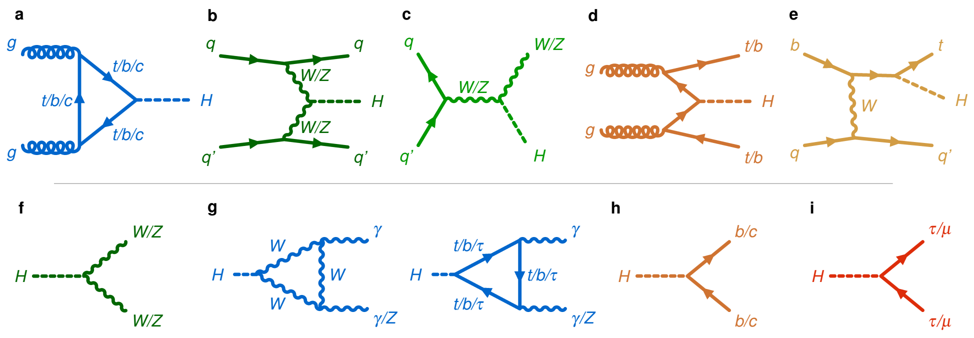
The Standard Model has been extensively validated.

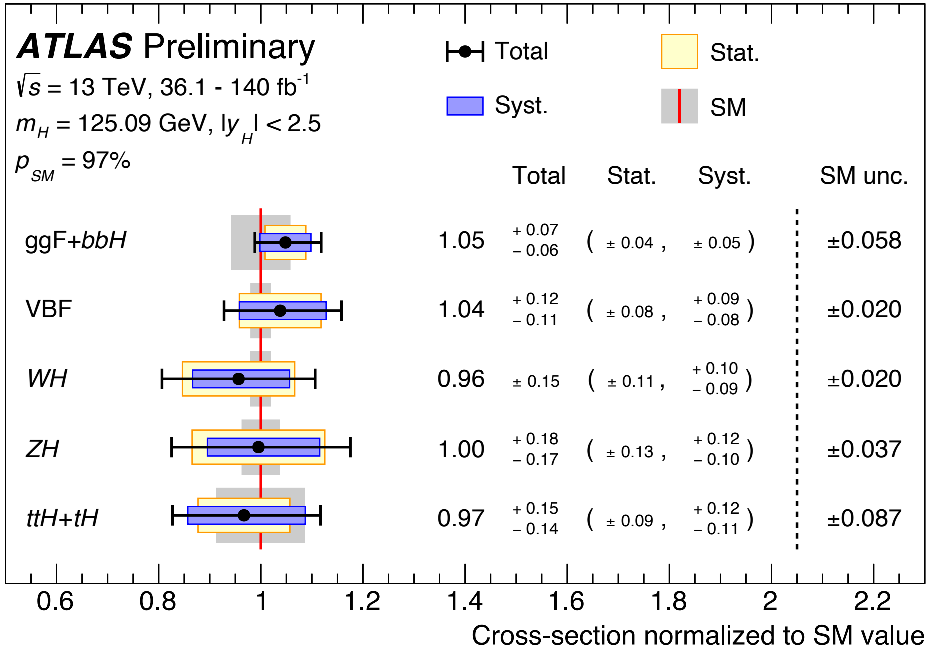
- Fermions constitute matter.
- Bosons mediate interactions.
- The Higgs field endows matter with mass.

The **Higgs boson** was discovered by ATLAS and CMS in 2012.

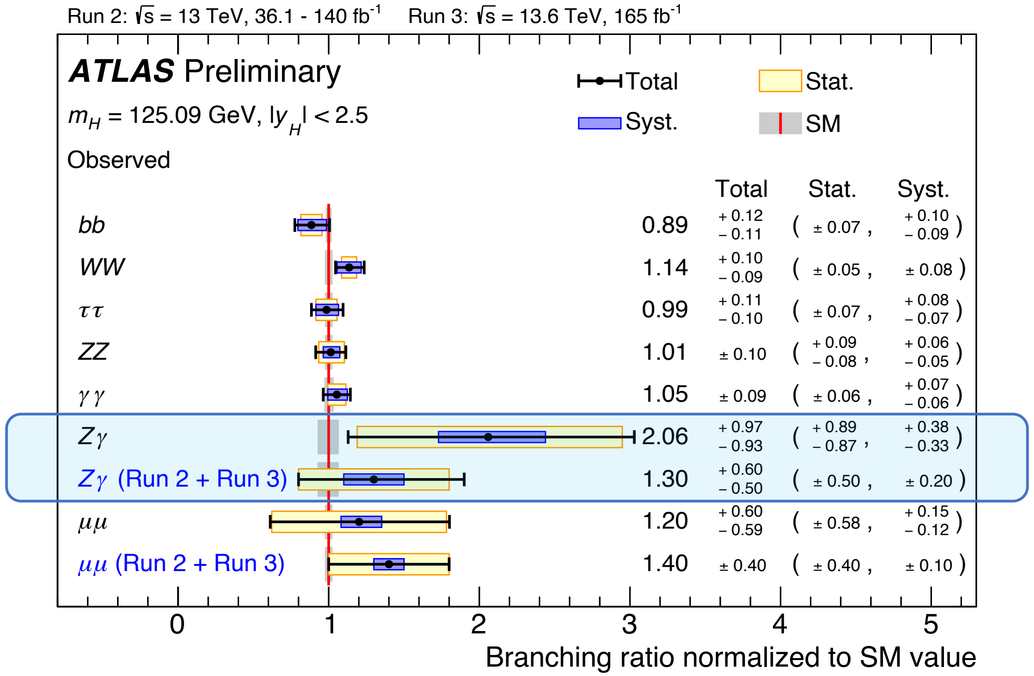
- **Mass**: $125.09 \pm 0.21(stat)$ $\pm\, 0.11(syst)$ GeV
- **Width**: $4.5^{+3.3}_{-2.5}$ MeV (ATLAS)
- **Spin**: 0

Higgs boson production and decay



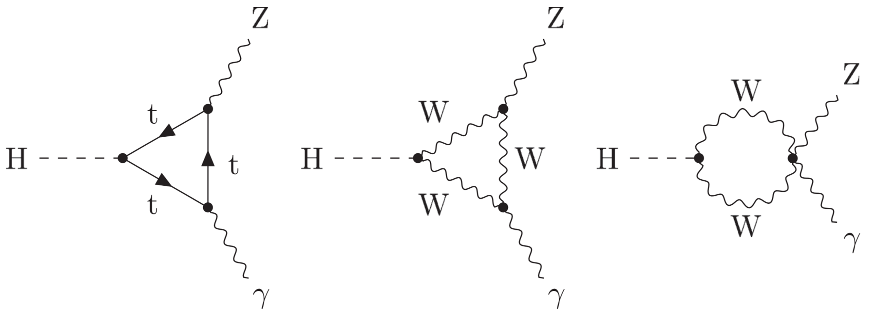


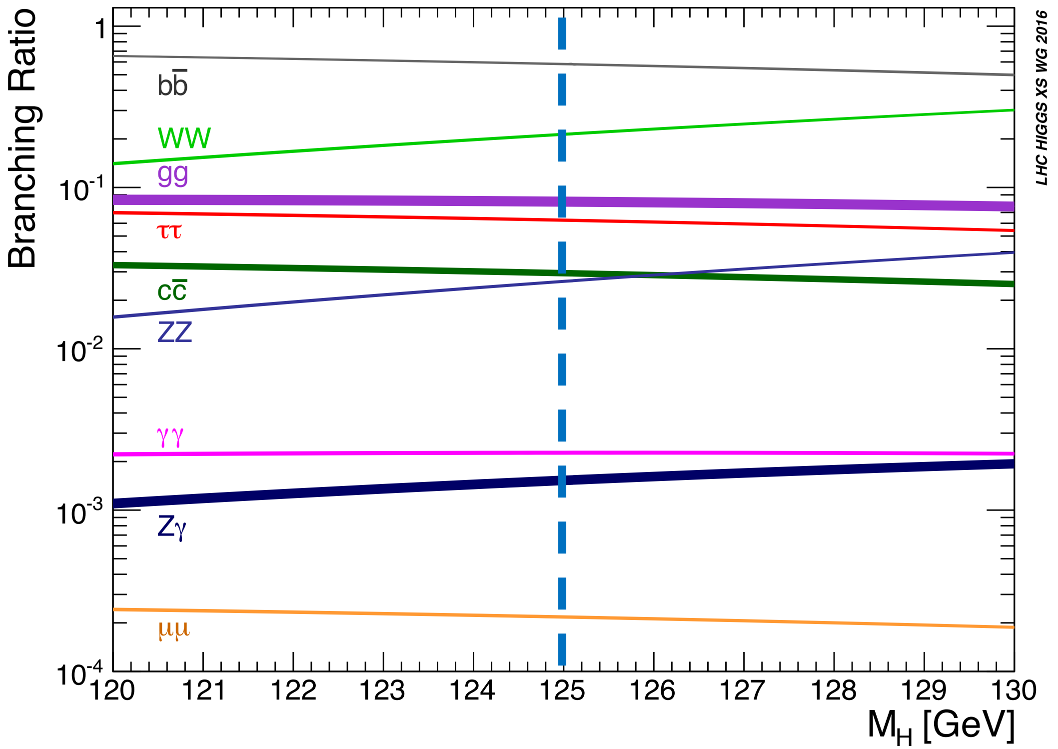
ATLAS-CONF-2025-006



- Higgs **production cross section** agrees with SM.
- Measured **branching ratios** match SM.
- The ***H* → *Zγ* decay** has not yet been observed.

Motivation for the H→Zγ search





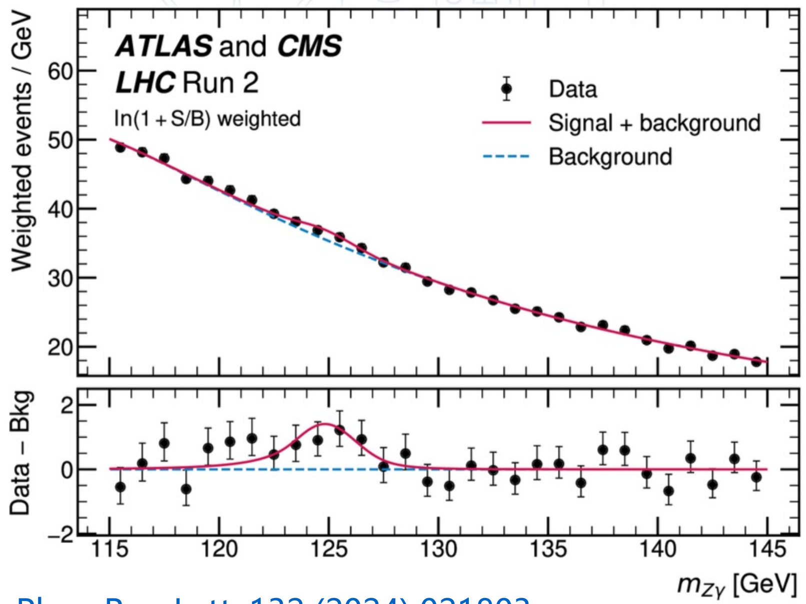
- The H → Zγ decay is a potential channel to explore physics **Beyond the Standard Model**.
- H → Zγ is a rare decay, $\mathrm{Br_{SM}}(\mathrm{H} \to \mathrm{Z}\gamma) = 1.5\times10^{-3}$.
- H → Zγ proceeds only via loop diagrams in the SM.

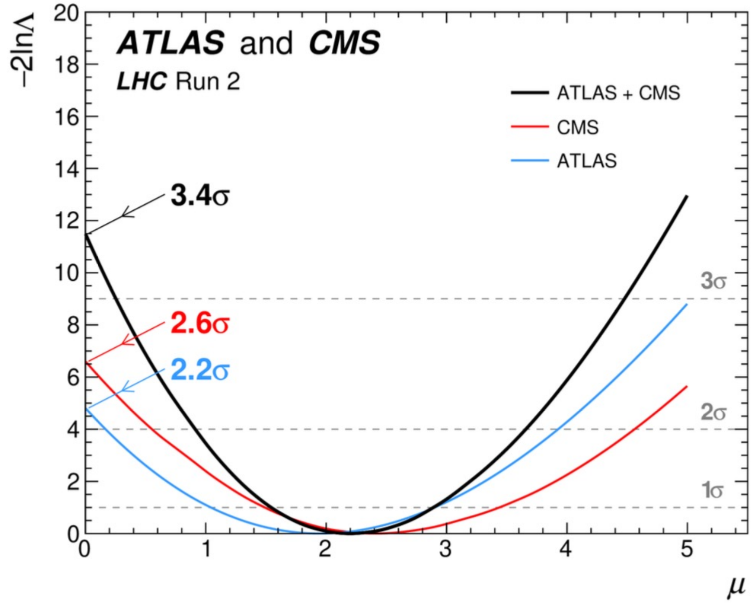
Examples of BSM:

- **Minimal fermion extension model** (vector-like fermions: two singlets and one doublet) [JHEP 10 (2024) 135].
- **Light axionlike particle** via $H \to Za,\ a \to \gamma\gamma$ [Phys. Rev. D 110, 055016 (2024)] .

$H \to Z\gamma$ decay search status

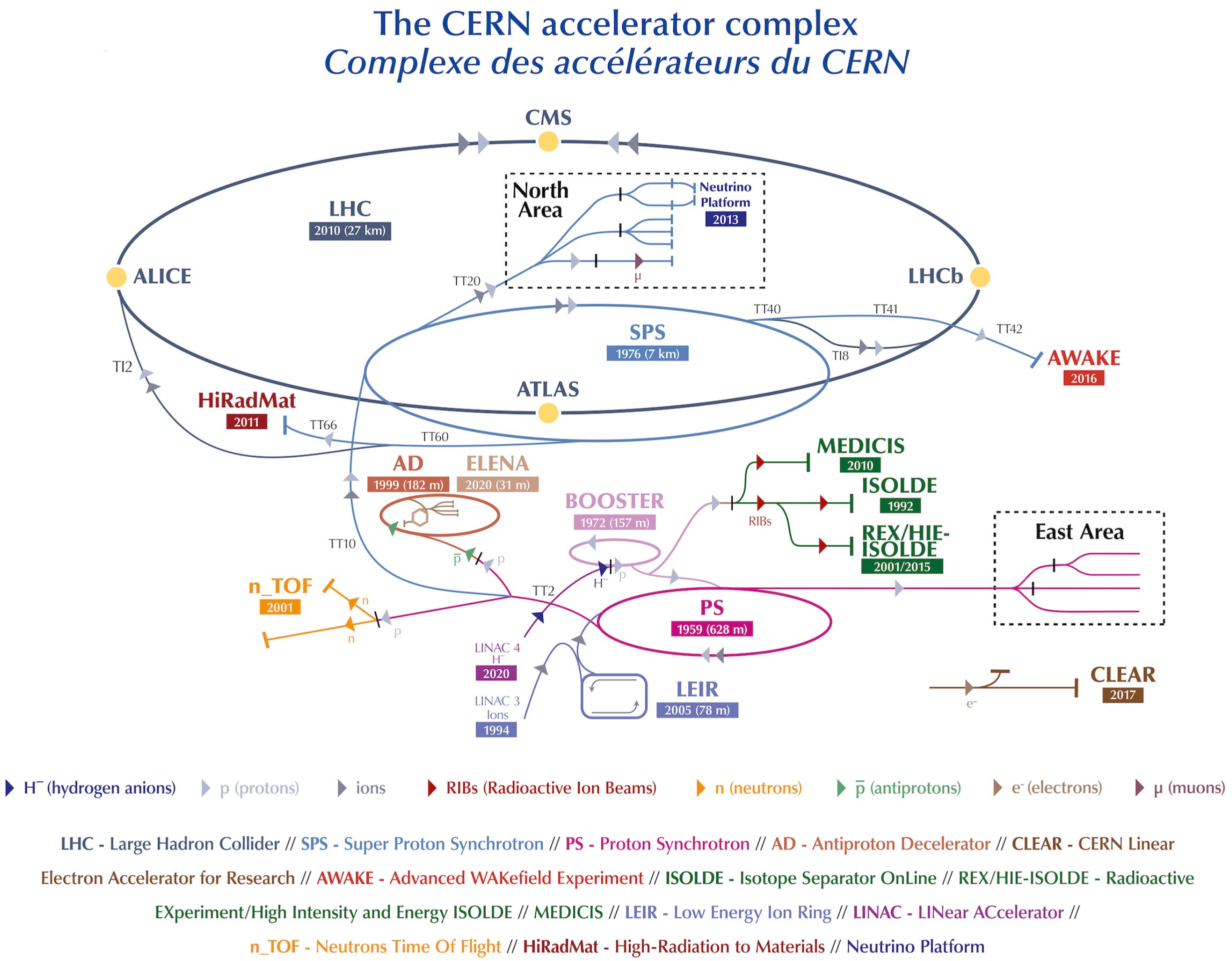
- Neither the ATLAS nor the CMS experiment has independently observation.
- Evidence for $H \to Z\gamma$ in combination of ATLAS and CMS results
  - Run2 ATLAS-only (Physics Letters B 809 (2020) 135754): Obs.(Exp.) Significance of $2.2\sigma(1.2\sigma)$
  - Run2 ATLAS+CMS(Phys. Rev. Lett. 132 (2024) 021803): Obs.(Exp.) Significance of $3.4\sigma(1.6\sigma)$
  - The excess of Obs. over the Exp. need further explore.





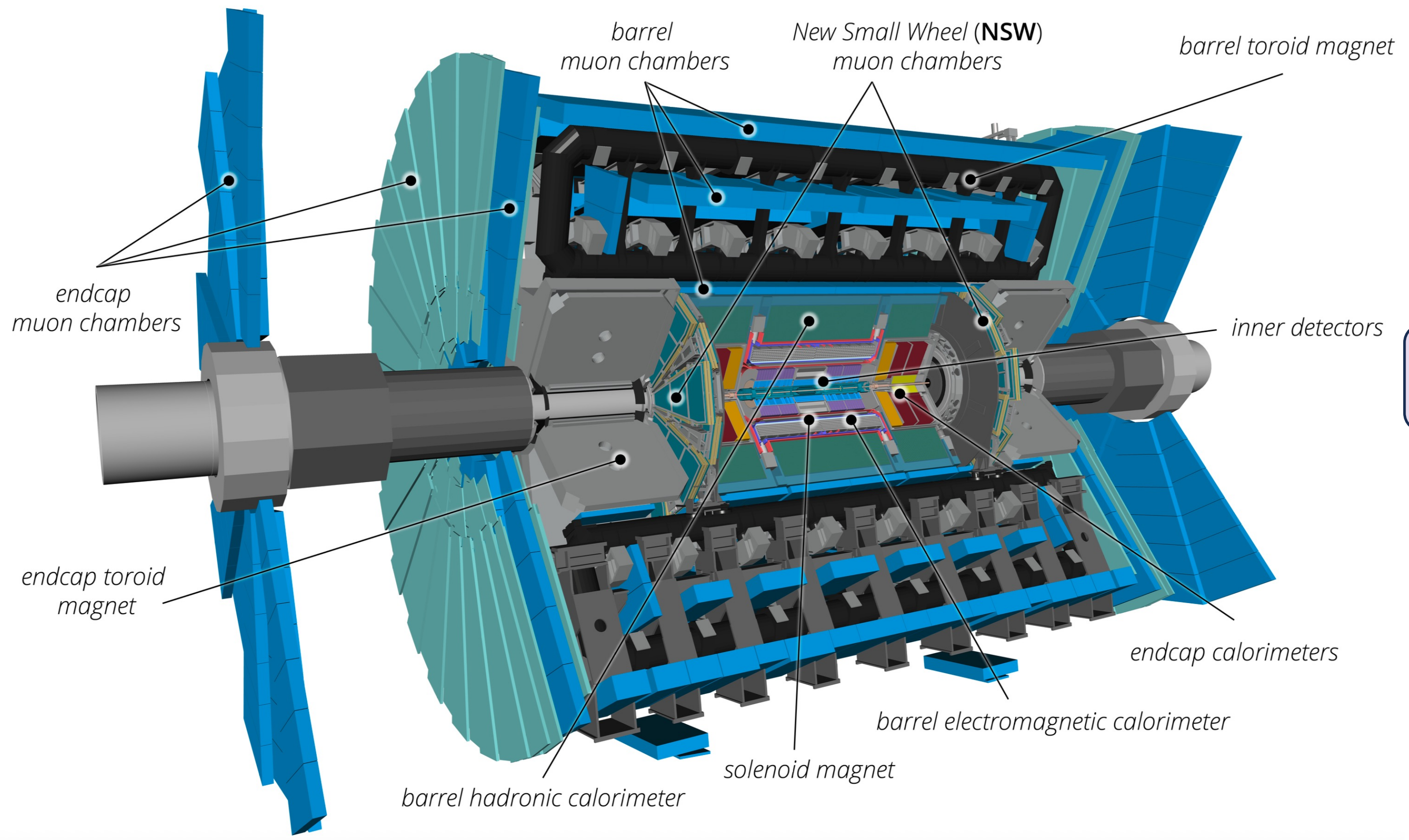
Phys. Rev. Lett. 132 (2024) 021803

The Large Hadron Collider (LHC)



The LHC is the world's largest and most powerful particle collider, collision $\sqrt{s} = 13.6$ TeV.

The ATLAS Detector



ATLAS is one of the two large general-purpose particle physics detectors.

Inner Detector

- charged-particle tracks.
- $\frac{\sigma_{p_T}}{p_T} = 0.05\% p_T(GeV) \oplus 1\%$

Electromagnetic Calorimeter

- electrons and photons energy.
- $\frac{\sigma_E}{E} = 10\%/\sqrt{E(GeV)} \oplus 0.7\%$

Hadronic Calorimeter

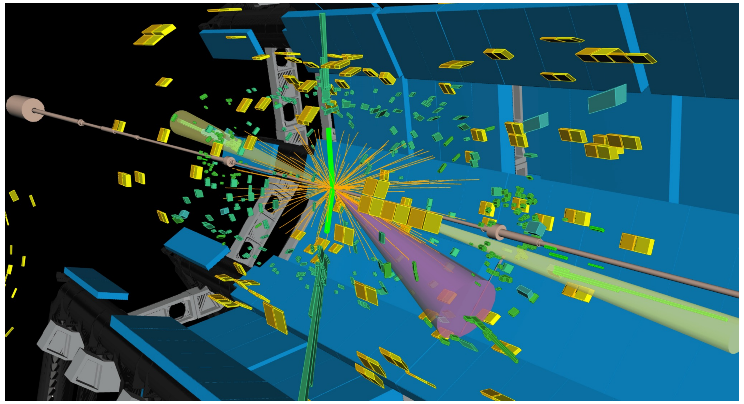
- Hadrons (π, kaons, jets) energy.
- $\frac{\sigma_E}{E} = 50\%/\sqrt{E(GeV)} \oplus 3\%$(Barrel & Cap)
- $\frac{\sigma_E}{E} = 100\%/\sqrt{E(GeV)} \oplus 10\%$(Forward)

Muon Spectrometer

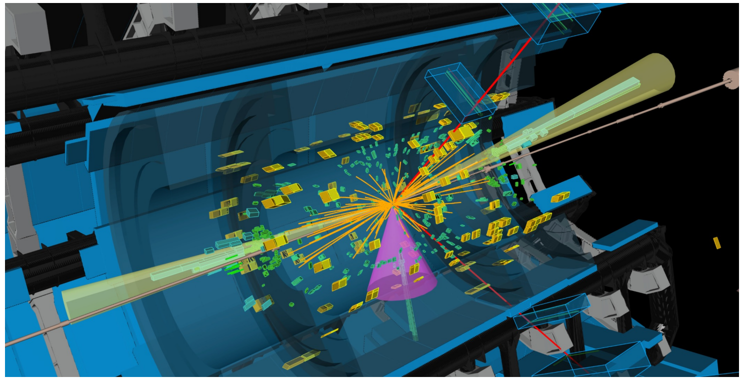
- Muons momentum.
- $\frac{\sigma_{p_T}}{p_T} = 10\%\ at\ p_T = 1TeV$

Strategy of $H \to Z\gamma$ analysis

- **Using $H \to Z\gamma, Z \to ll\gamma$ ($l = e$ or μ) final state.**
  - Strong **background rejection,** Excellent invariant **mass resolution**.
  - Full kinematic reconstruction.
  - **Efficient triggering** through a logical OR of electron and muon triggers.
- **Using event-by-event likelihood with signal and background modeling.**
  - $H \to Z\gamma$ is a rare process, signal yield is quite low. → Need parametric signal PDF
  - Large background with a smooth continuum distribution. → Describe by analytic PDFs to separate weak signals.
- **Benefit from ATLAS Run3 dataset.**
  - $\sqrt{s}$: 13TeV → 13.6 TeV, **~7.7%** higher Higgs Boson production σ.
  - Higher statistics: Integrated luminosity 165 fb^{-1} (2022-2024).
  - Large simulated background samples, corresponding to about 81 times the data.



Event display of $H \to Z\gamma \to ee\gamma$



Event display of $H \to Z\gamma \to \mu\mu\gamma$

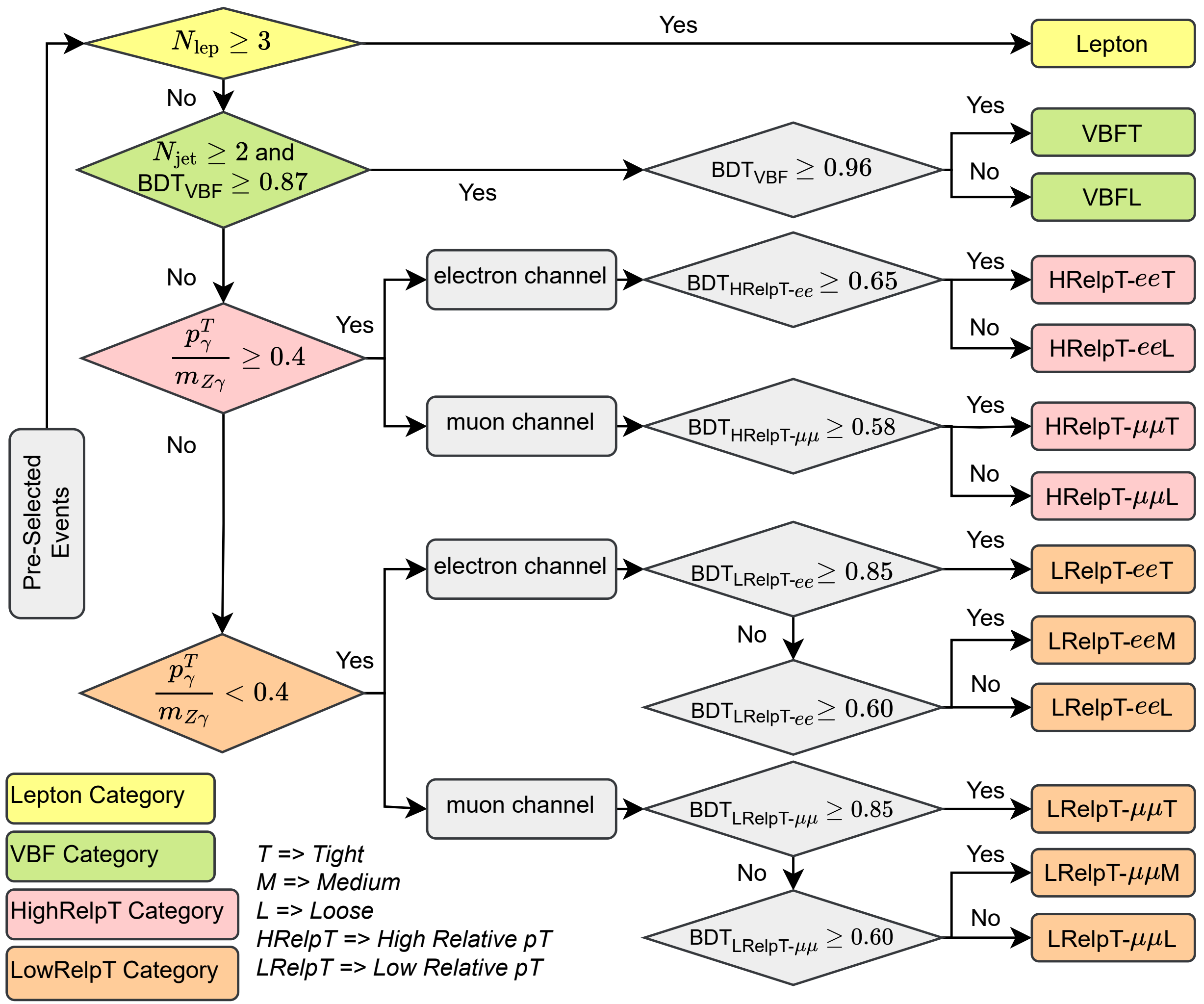
Objects and Event selection

- **Signal objects**: $H \rightarrow Z\gamma,\ Z \rightarrow \ell\ell\boldsymbol{\gamma},\ (\ell = \boldsymbol{e}\ or\ \boldsymbol{\mu})$
- **Background objects**: **Jets** misidentified as photons.

Cut	Electrons	Photons	Mouns	Jets
$\boldsymbol{p_T}$	>10 GeV	>10 GeV	>5 GeV	> 25 GeV
$\lvert\boldsymbol{\eta}\rvert$	<2.47(exclude [1.37,1.52])	<2.37(exclude [1.37,1.52])	<2.5	<4.4
Identification	Loose	Tight	Medium	Loose
Isolation	Loose	FixedCutLoose	Loose	FixedEffPt

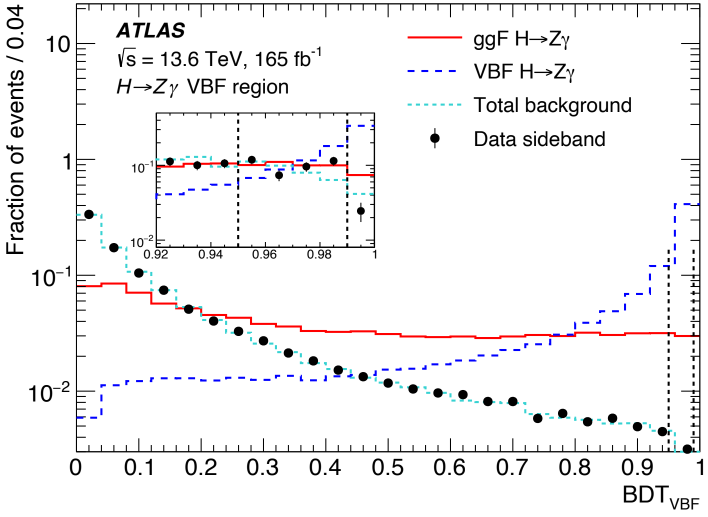
- **Event selection**
  - At least two leptons (same-flavor, opposite-charge) to select Z candidate.
  - Z mass requirement: $|m_{ll} - m_Z| < 10\ GeV$.
  - Z candidate plus one photon with high p_T to built Higgs candidate.
  - Overlap removal is applied between leptons, photons and jets.
  - Photon relative p_T requirement: $p_\gamma^T/m_{Z\gamma} > 0.09$.

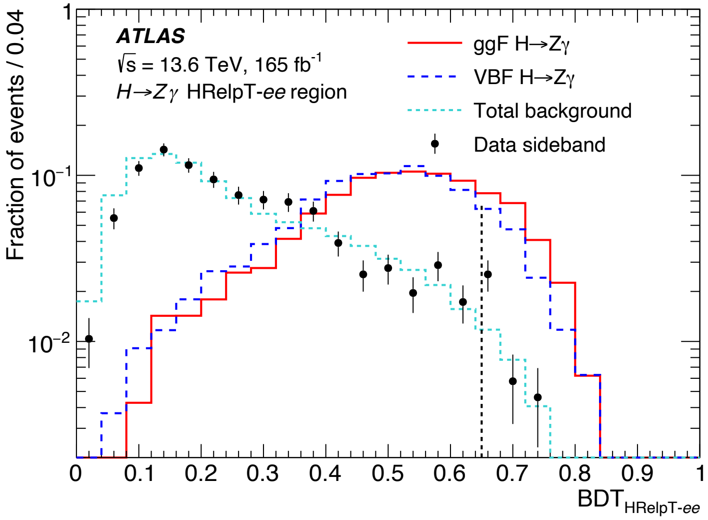
Event categorization



- ➢ Events are classified into **13 categories**.
- ➢ BDT classifications for VBF, HRelpT and LRelpT categories.
- ➢ **Lepton category:**
  - Additional leptons
- ➢ **VBF category:**
  - Train the events and categorize to two region: Tight and Loose
- ➢ **High Relative p_T category:**
  - Train the events, split them by channel, and categorize to **Tight** and **Loose** for each channel
- ➢ **Low Relative p_T category:**
  - Train the events, split by channel, categorize to **Tight**, **Medium** and **Loose** for each channel.

Boosted Decision Tree training





Input variable	VBF	relative photon p_T
N_{jet}	✓	✓
$p_T^{j_1}, \eta_{j_1}$	✓	✓
m_{j_1}	✓	
ϕ_{j_1}		✓
$m_{j_2}, p_T^{j_2}, \eta_{j_2}$	✓	
$m_{j_1 j_2}, p_T^{j_1 j_2}, \Delta\eta_{j_1 j_2}$	✓	
η_γ	✓	✓
p_T^γ	✓	
$p_T^{\ell\ell}$	✓	
$\eta_{\ell\ell}, \eta_{\ell\ell\gamma}$	✓	✓
$p_T^{\ell\ell\gamma}$	✓	
$p_T^{\ell\ell\gamma}/m_{\ell\ell\gamma}, p_T^\gamma/m_{\ell\ell\gamma}$		✓
$p_T^{\ell\ell}/m_{\ell\ell\gamma}$		✓
p_T^t	✓	✓
$\Delta\phi_{\ell\ell,\gamma}$	✓	✓
$\Delta\phi_{\ell\ell\gamma,j_1}$	✓	✓
$\Delta\phi_{\ell\ell\gamma,j_1 j_2}$	✓	
$\Delta\eta_{\ell\ell,\gamma}$	✓	✓
$\Delta R^{\text{min}}_{\gamma \text{ or } \ell\ell, j}$	✓	✓
$\cos\theta^*(\ell^+)$	✓	✓
$\cos\theta(\ell\ell)$ in $\ell\ell\gamma$	✓	✓
$\eta^{\text{Zeppenfeld}}$	✓	

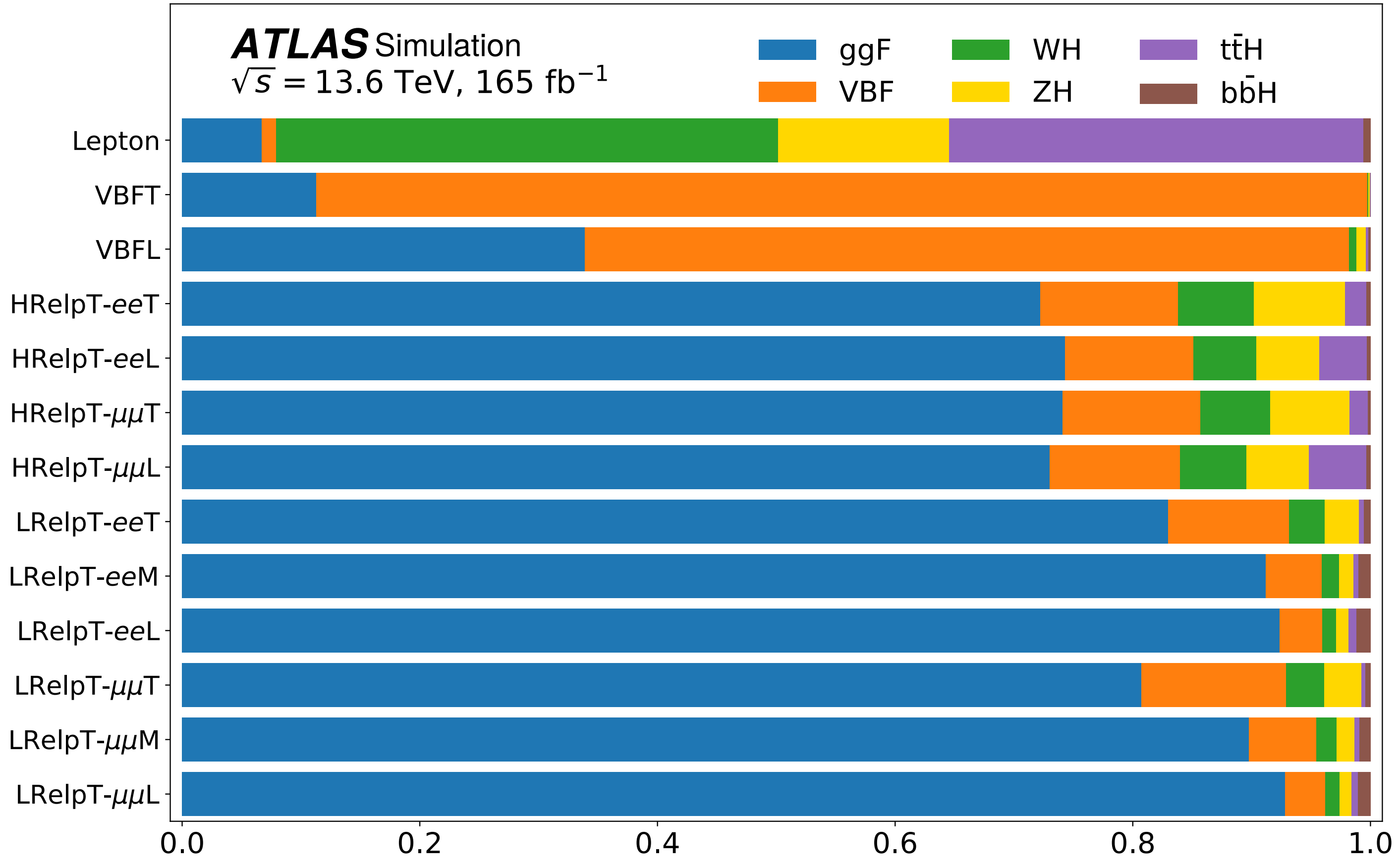
- Boosted decision trees are used to maximize the combined significance in the mass window of [120, 130] GeV.
- BDT inputs are selected to minimize correlation with $m_{\ell\ell\gamma}$.
- At least two background events in the signal region [120, 130] GeV.

- **VBF category BDT**
  - Requirement: at least 2 jets.
  - Signal: VBF $H \to Z\gamma$.
  - Bkg.: ggF, non-resonant $Z\gamma$, EW $Z\gamma + jj$.

- **High/Low Rel-p_T category BDT**
  - Separation between $ee\gamma/\mu\mu\gamma$ final states.
  - Signal: ggF $H \to Z\gamma$.
  - Bkg.: non-resonant $Z\gamma$, $Z + jets$.

Event decomposition and expected yields

- Signal composition in each category includes contributions from ggF, VBF, VH, $t\bar{t}H$, and $b\bar{b}H$.
- The lepton category is dominant by **VH** and $\boldsymbol{t\bar{t}H}$.
- The VBF and High/Low Rel-p_T categories are dominated by **ggF** and **VBF**.



Signal modeling

- Low signal yield → need a differentiable peak-shape PDF for precise modeling.
- The three-body invariant mass distribution is fitted independently in each category using the **Double-Sided Crystal Ball (DSCB)** function.
- The $\ell\ell\gamma$ mass resolution is improved by 17% (11%) in the electron (muon) channel:
  - **Z-mass constraint**: kinematic fit applied to correct lepton four-momentum.
  - **FSR photon correction** ($\Delta R<0.15$) applied to the corresponding muons.

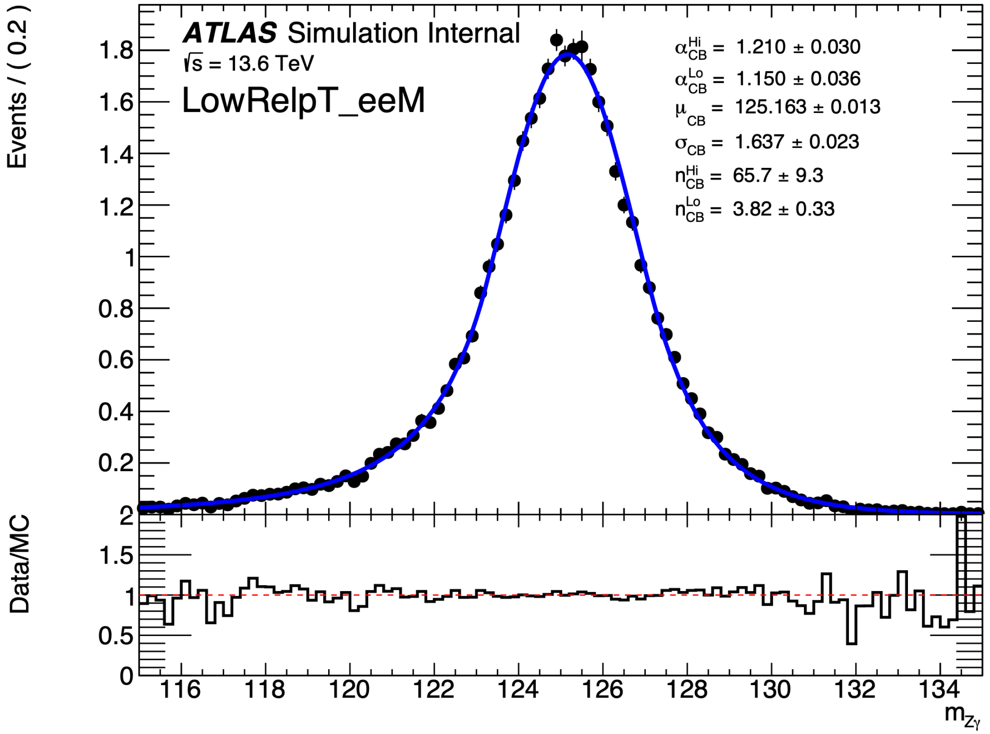
$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\mathrm{Lo}} \leq t \leq \alpha_{\mathrm{Hi}} \\ \dfrac{e^{-0.5\alpha_{\mathrm{Lo}}^2}}{\left[\frac{\alpha_{\mathrm{Lo}}}{n_{\mathrm{Lo}}}\left(\frac{n_{\mathrm{Lo}}}{\alpha_{\mathrm{Lo}}}-\alpha_{\mathrm{Lo}}-t\right)\right]^{n_{\mathrm{Lo}}}}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

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

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

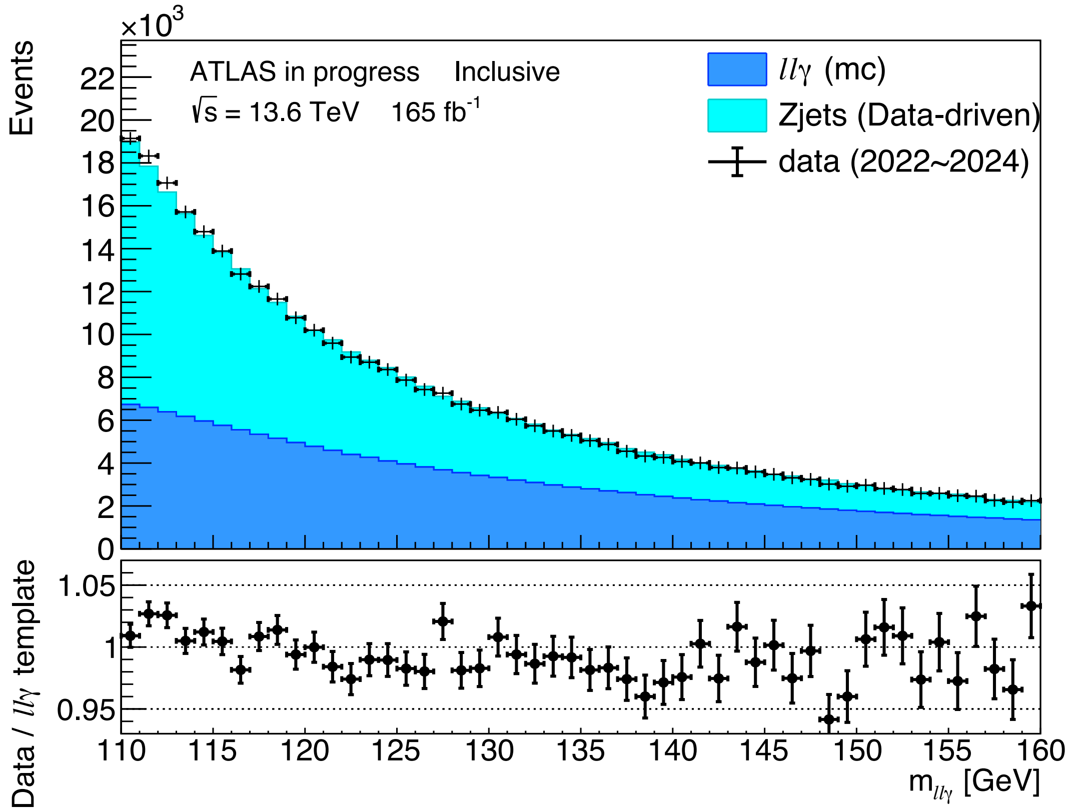
N: normalization parameter

μ_{CB}: the peak of the Gaussian distribution

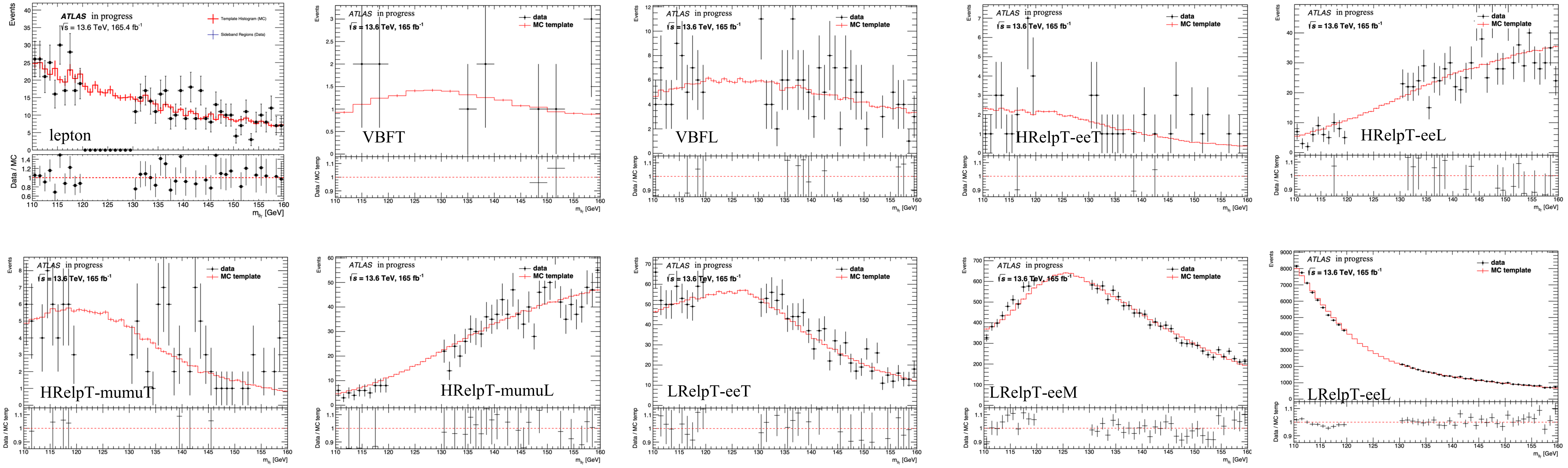


Background template study

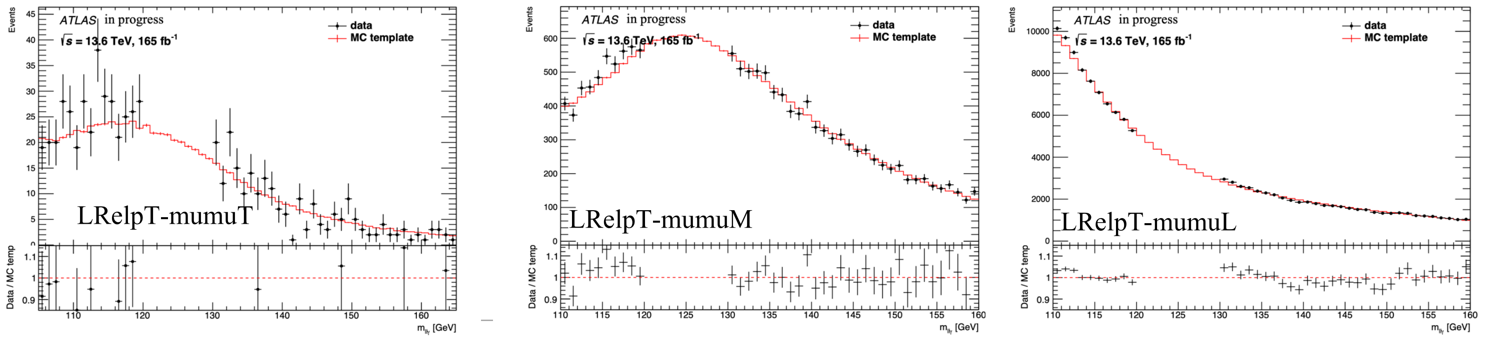
- The **dominant background** components:
  - Non-resonant $\boldsymbol{Z\gamma}$, irreducible
  - **Z +jets**, reducible
  - **Di-boson process**, 35% in lepton category, 0.2% inclusively
- $Z\gamma$ fraction is $0.49^{+0.05}_{-0.10}$ in mass window [110, 160] GeV, central value from ABCD method.
- Low-statistics **data-driven Zjets** → large error bars.
- **High Rel-$\mathbf{p_T}$ category**: scale $Z\gamma$ sample to the data yield.
- **Low Rel-$\mathbf{p_T}$ category**: reweight $Z\gamma$ sample to match $Z\gamma$ + Zjets yield.
- **Lepton category**: normalized $Z\gamma$ and di-boson by cross-section and scaled to data.
- **VBF categories**: reweight VBS to match $Z\gamma$ +VBS.



Background template in each category

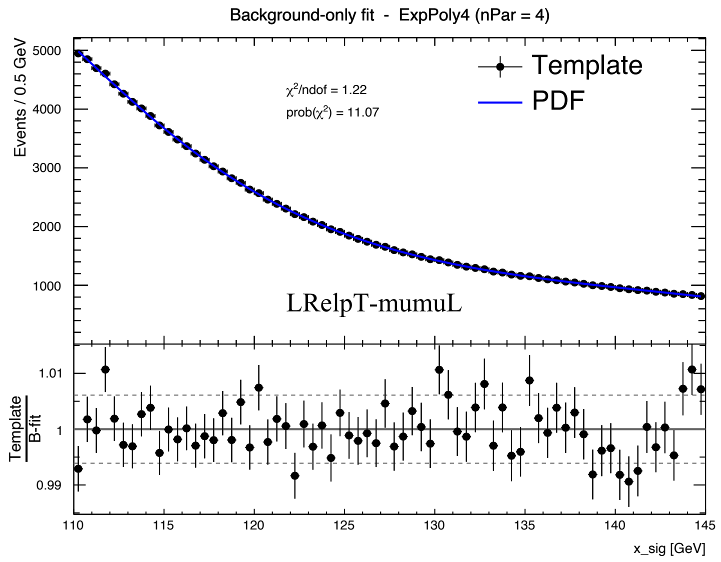


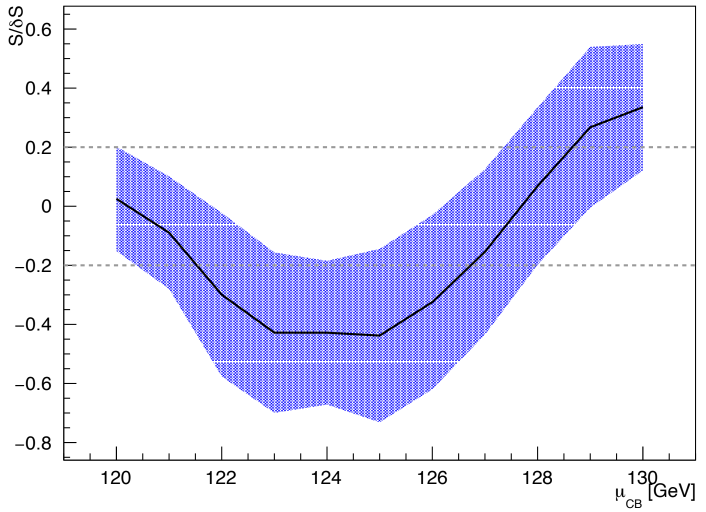
Background templates are used for modeling, show good agreement with the data sidebands.



Background modeling and Spurious signal study

- **Background functions:**
  - ***Exponential***: $f = e^{a_0 x}$, ***ExpPoly2~4***: $e^{x} f_{Poly}(a_0, a_1, a_2, a_3)$, ***Fk0~2***, ***Bern2~6***, ***Power***, ***Pow2***: $x^{a_0} + a_1 x^{a_2}$
- **Selection criteria:** $\boldsymbol{S/\Delta S < 20\%}$**,** $\boldsymbol{P_{(\chi^2)} > 0.01}$**,** $\boldsymbol{S \pm 1\zeta/\Delta S < 20\%}$
- **Fit range optimization:**
  - Tested in the mass range 110–160 GeV, with mass window ≥ 35 GeV.
  - Selection priority: lowest DOF → lowest spurious signal (for same DOF).
- **Reduce spurious signal uncertainties by GPR smoothing:**
  - Sufficient statistics for the background template.
  - No change in the background function choice, but the **spurious signal** is reduced.

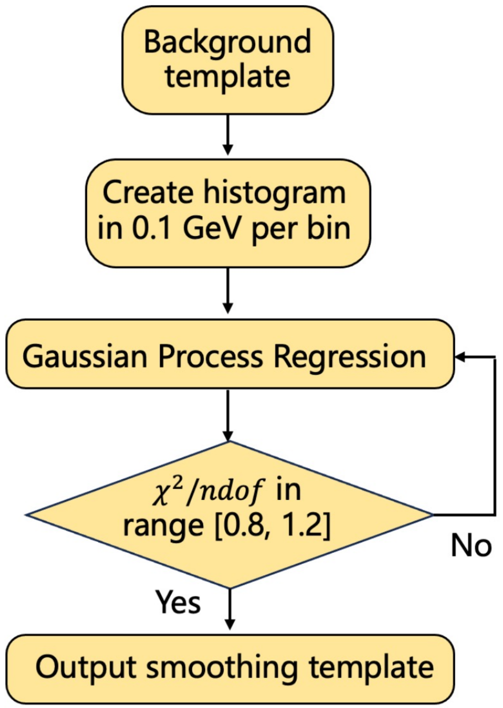




Gaussian Process Regression smoothing

- Spurious signal may arise solely from statistical fluctuations in the background template.
- Mitigated with GPR smoothing (scikit-learn, Gibbs kernel).

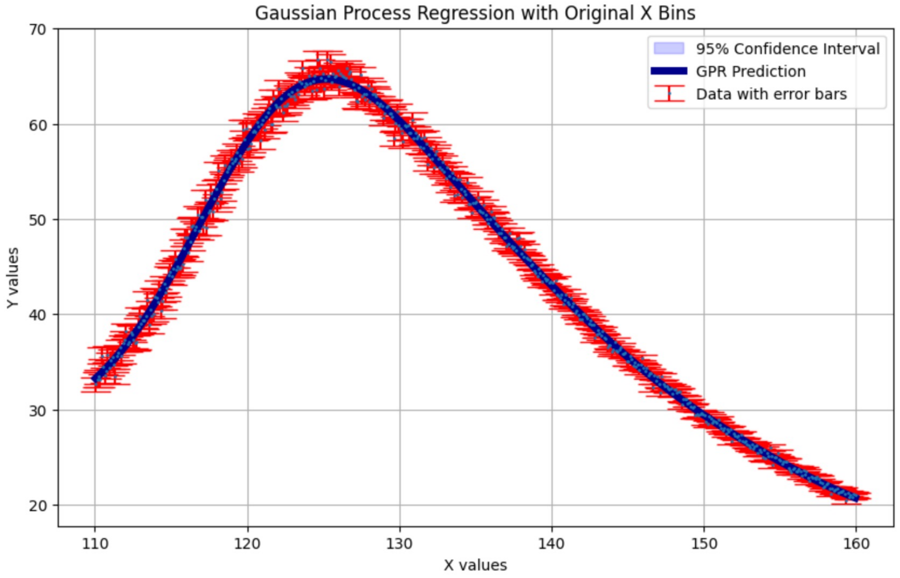
$$K(x,x') = \sqrt{\frac{2l(x)l(x')}{l(x)^2 + l(x')^2}} \exp\left(-\frac{(x-x')^2}{l(x)^2 + l(x')^2}\right) \qquad l(x) = b_\lambda x + \lambda$$



Scale $mc_{z\gamma} * purity$ +
Scale $Zjets * (1 - purity)$

RBF Kernel Function

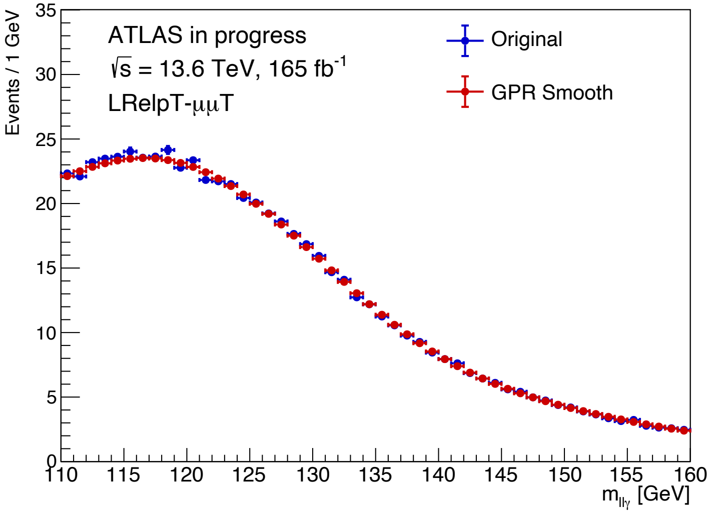
```
Optimized kernel parameters:
27.7**2 * RBF(length_scale=11)
Chi-squared: 515.05
Degrees of freedom: 498
Chi-squared per degree of freedom: 1.03
Original yield: 21948.59
GPR yield: 21943.96
```

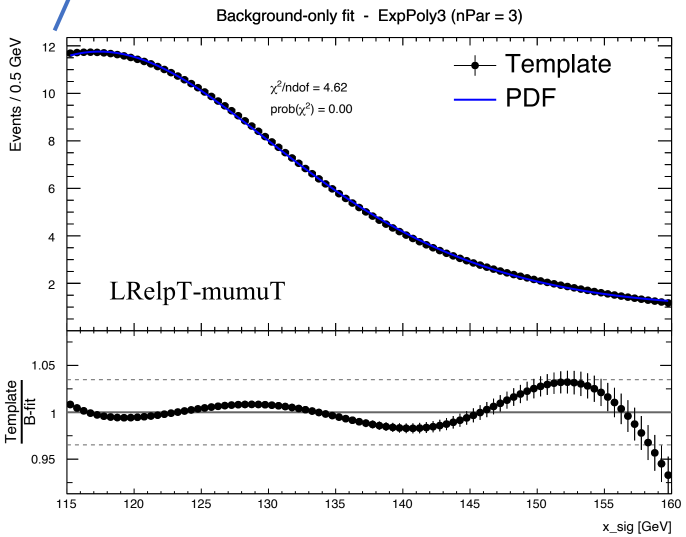


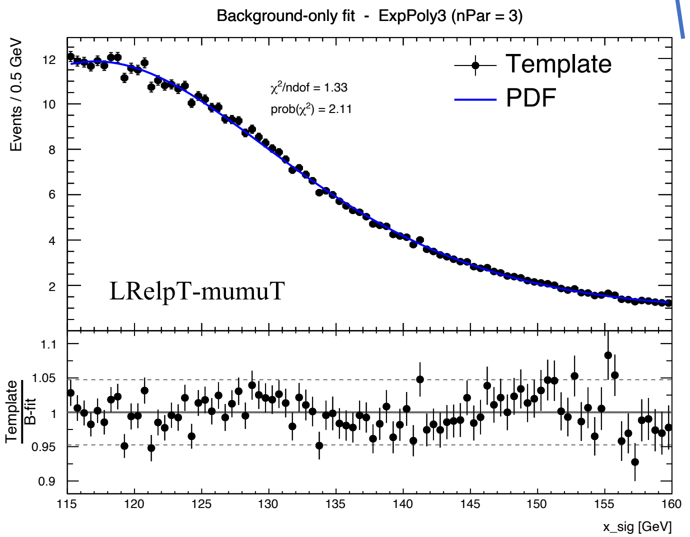
Gaussian Process Regression smoothing

- The background template becomes **smoother** and shows good agreement with the original template.
- The spurious signal is significantly reduced after GPR smoothing.
- Does not change the selected function.

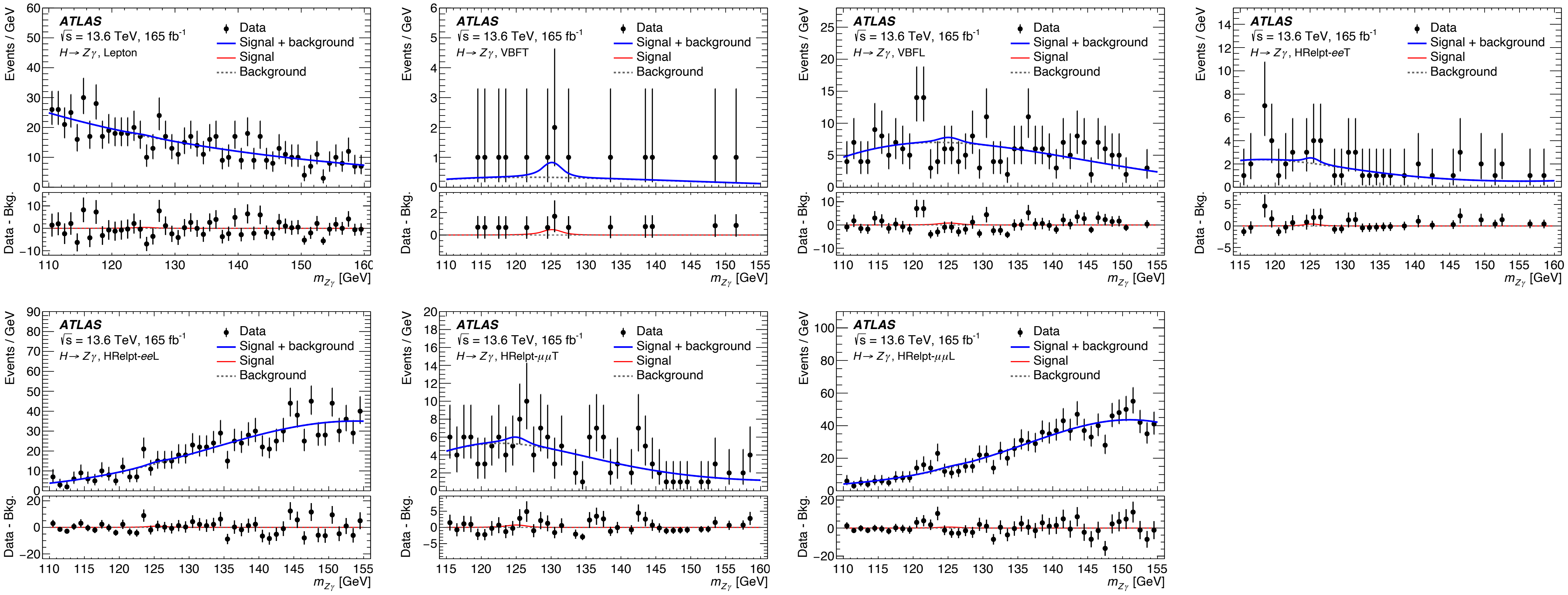
Category	fit range / GeV	PDF	SS value	$S/\Delta S$	SS value (GPR)	$S/\Delta S$ (GPR)
Lepton	110-160	Exponential	3.25	-24.1%	2.16	15.4%
VBFT	110-155	FK0	0.070	3.4%	-0.0123	-0.651%
VBFL	110-155	FK0	0.813	10.1%	0.255	3.16%
HRelpT-eeT	115-160	ExpPoly3	0.412	9.3%	-0.068	-1.58%
HRelpT-eeL	110-155	ExpPoly2 (Wald test)	0.98	7.48%	2.18	17.6%
HRelpT-$\mu\mu$T	115-160	ExpPoly3	1.07	14.3%	-0.392	-4.88%
HRelpT-$\mu\mu$L	110-155	ExpPoly3	-1.85	-13.6%	-0.356	-3.13%
LRelpT-eeT	115-150	Bern5	6.82	20.1%	-1.18	-3.5%
LRelpT-eeM	110-145	Bern5	78.8	68.9%	48.4	41.7%
LRelpT-eeL	115-150	Bern4 (Wald test)	-216	-77.8%	154	-53.8%
LRelpT-$\mu\mu$T	115-160	ExpPoly3	3.66	24.0%	1.71	10.8%
LRelpT-$\mu\mu$M	110-145	Bern5	31	27.2%	30.6	26.9%
LRelpT-$\mu\mu$L	110-145	ExpPoly4	-112	-43.8%	-117	-36.1%



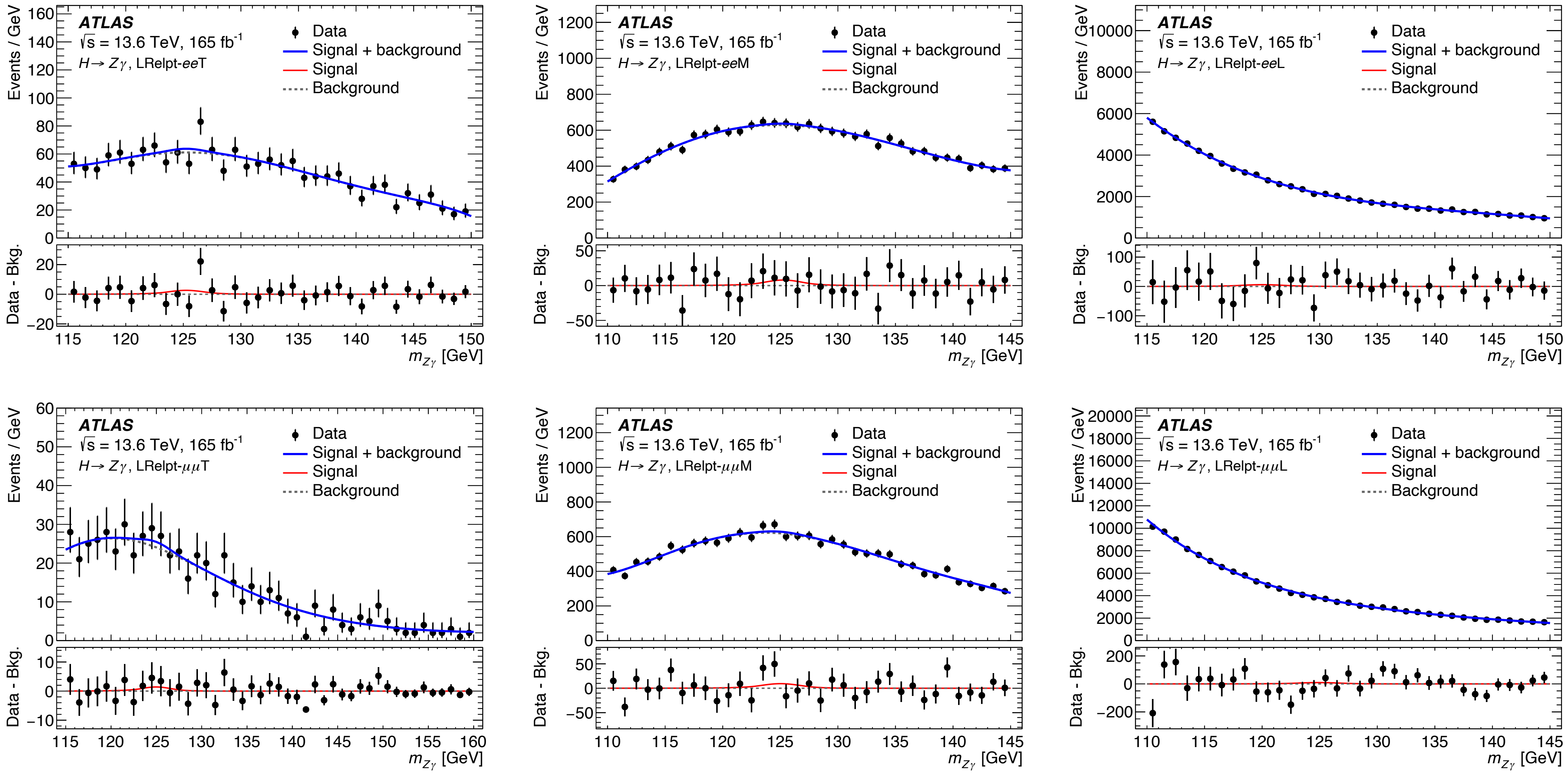




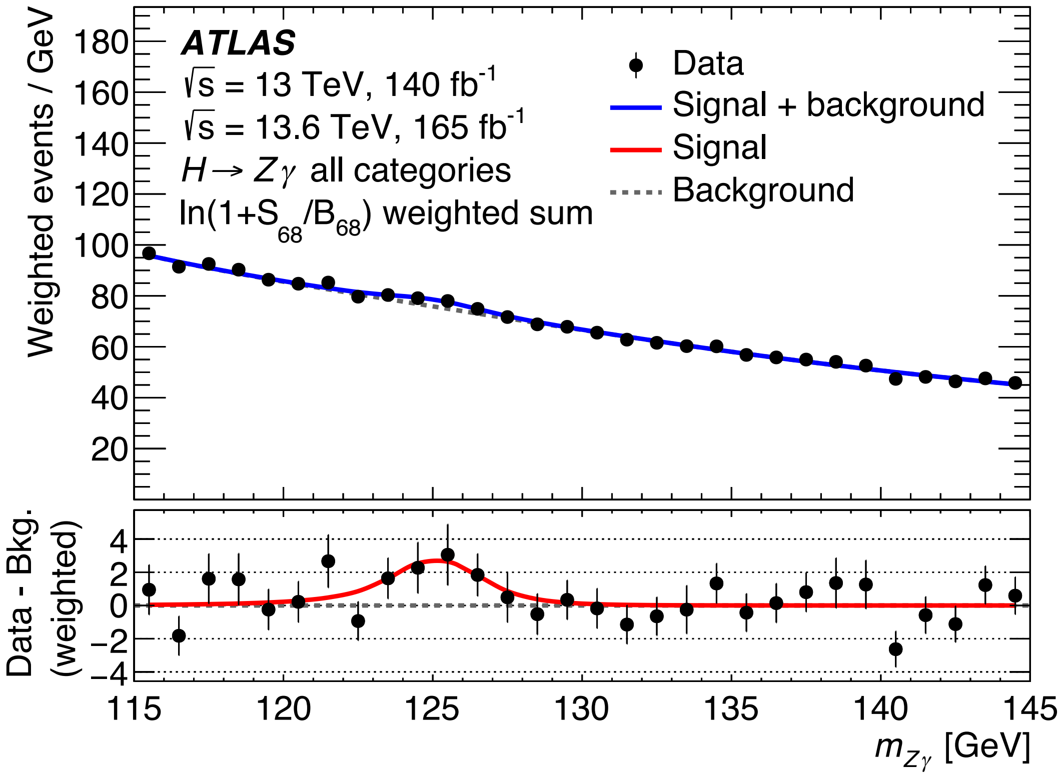
Invariant mass distribution for low stats categories

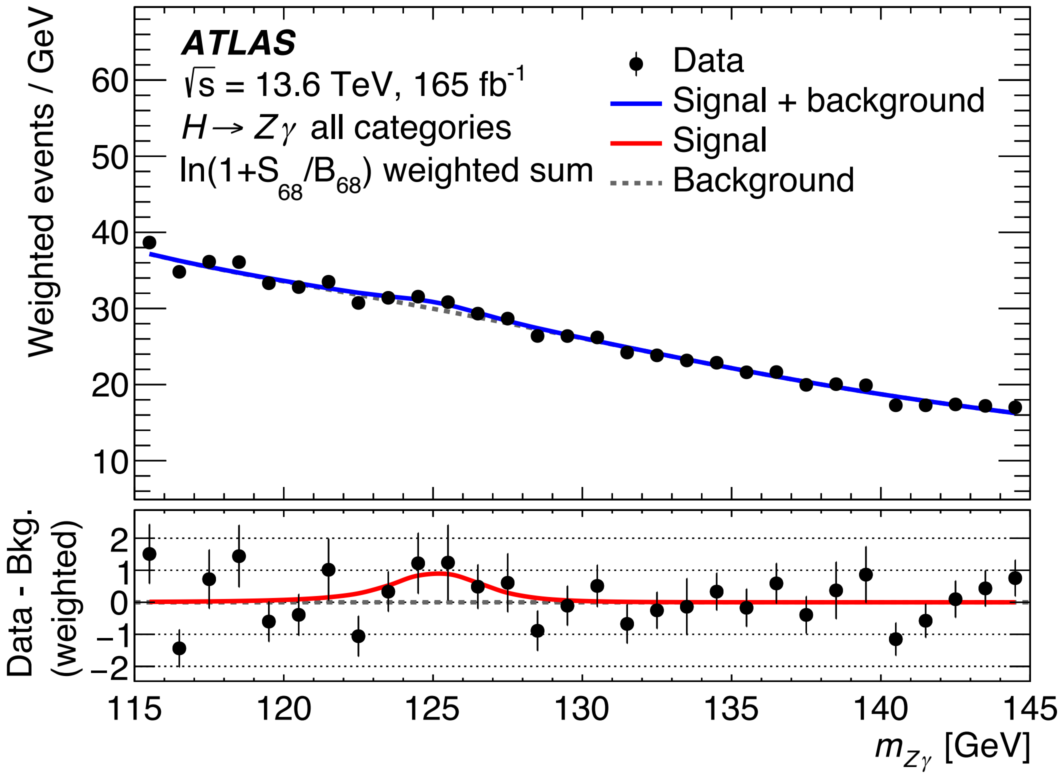


Invariant mass distribution for high stats categories



Invariant mass distribution for $H \to Z\gamma \to \ell\ell\gamma$





- Statistical results from the un-binned likelihood fit:
  - Run 3 observed (expected) significance with respect to the background-only hypothesis: 1.4σ (1.5σ).
  - Run 2 + Run 3 combined observed (expected) significance: 2.5σ (1.9σ).

Combination of Run 2 and Run 3 results

- **Run 3 results**:

  measured signal strength $\mu = 0.9^{+0.7}_{-0.6}(stat)^{+0.2}_{-0.1}(syst)$

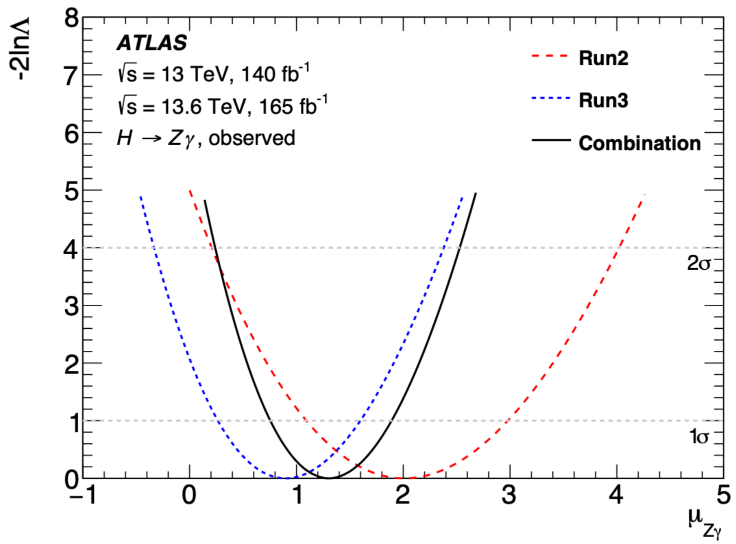
- **Run 2 + Run 3 combination**:

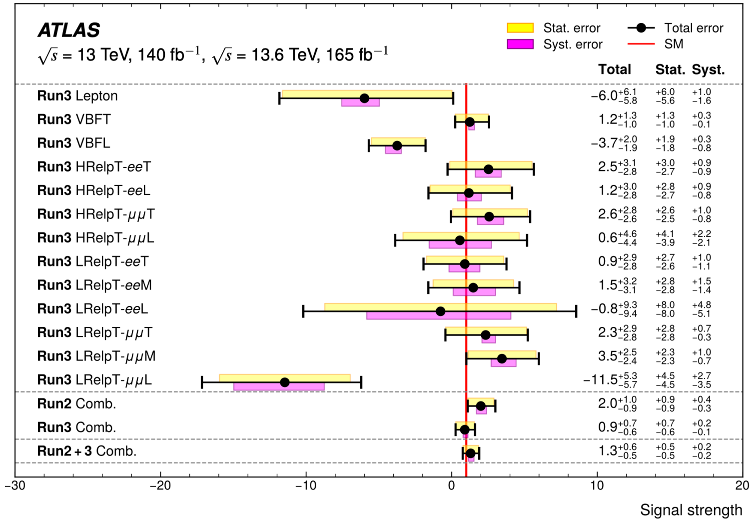
  signal strength $\mu = 1.3 \pm 0.5(stat.) \pm 0.2(sys.)$

- Compatibility between Run 2 and Run 3 results: *p-value* = 0.33

- Overall sensitivity improvement of 61% with respect to the ATLAS Run-2 analysis. Driven by:
  - Increased statistics in Run 3, 165 fb^{-1}
  - Lower photon p_T threshold → +8% signal efficiency
  - Event selection and categorization → +15% performance

- 19% improvement with respect to the ATLAS+CMS Run-2 combination.





Thanks