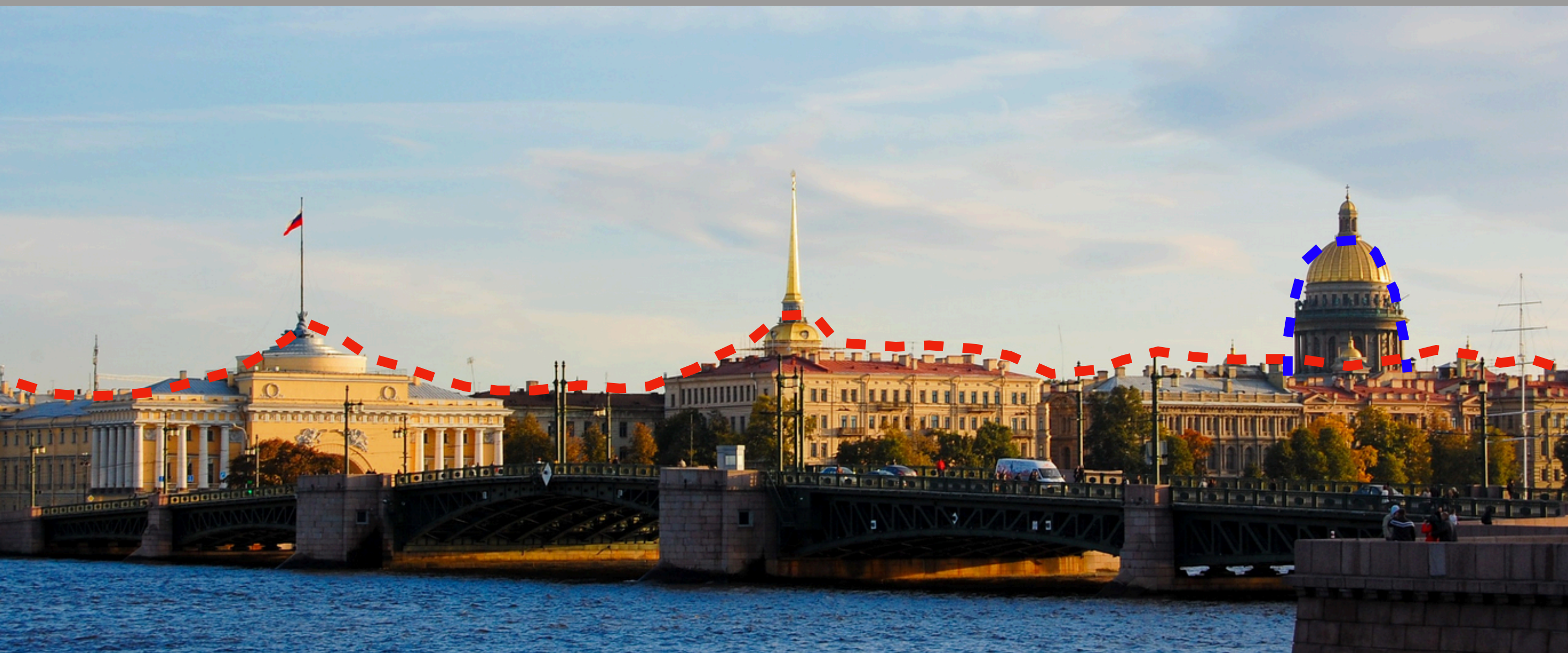


Searches for heavy resonances in the diphoton and ZZ final states with the ATLAS detector



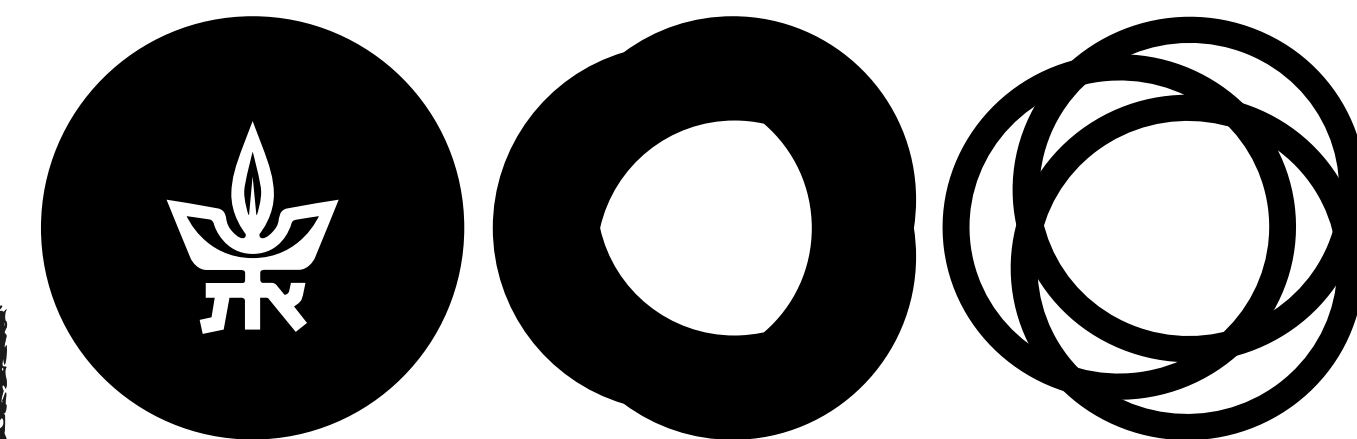
European Research Council
Established by the European Commission

NUCLEUS 2021

St. Petersburg (Online)

23rd September

Luis Pascual Domínguez
On behalf of the ATLAS Collaboration



TEL AVIV אוניברסיטת
UNIVERSITY תל אביב

Introduction

Resonance searches make an excellent probe to explore New Physics scenarios.

- Additional resonances are present in many beyond SM (BSM) theories: 2HDM, extra dimensions...

ATLAS has a broad diboson search program

- Targets as many final states as possible
- Avoid strong assumptions → easier reinterpretation!

This talk:

- Heavy resonance searches with the **diphoton** and **ZZ final states**.
- Full Run 2 dataset (139 fb^{-1} at 13 TeV collected from 2015 to 2018).
- Improvement w.r.t previously published results with partial dataset.

Theoretical motivation

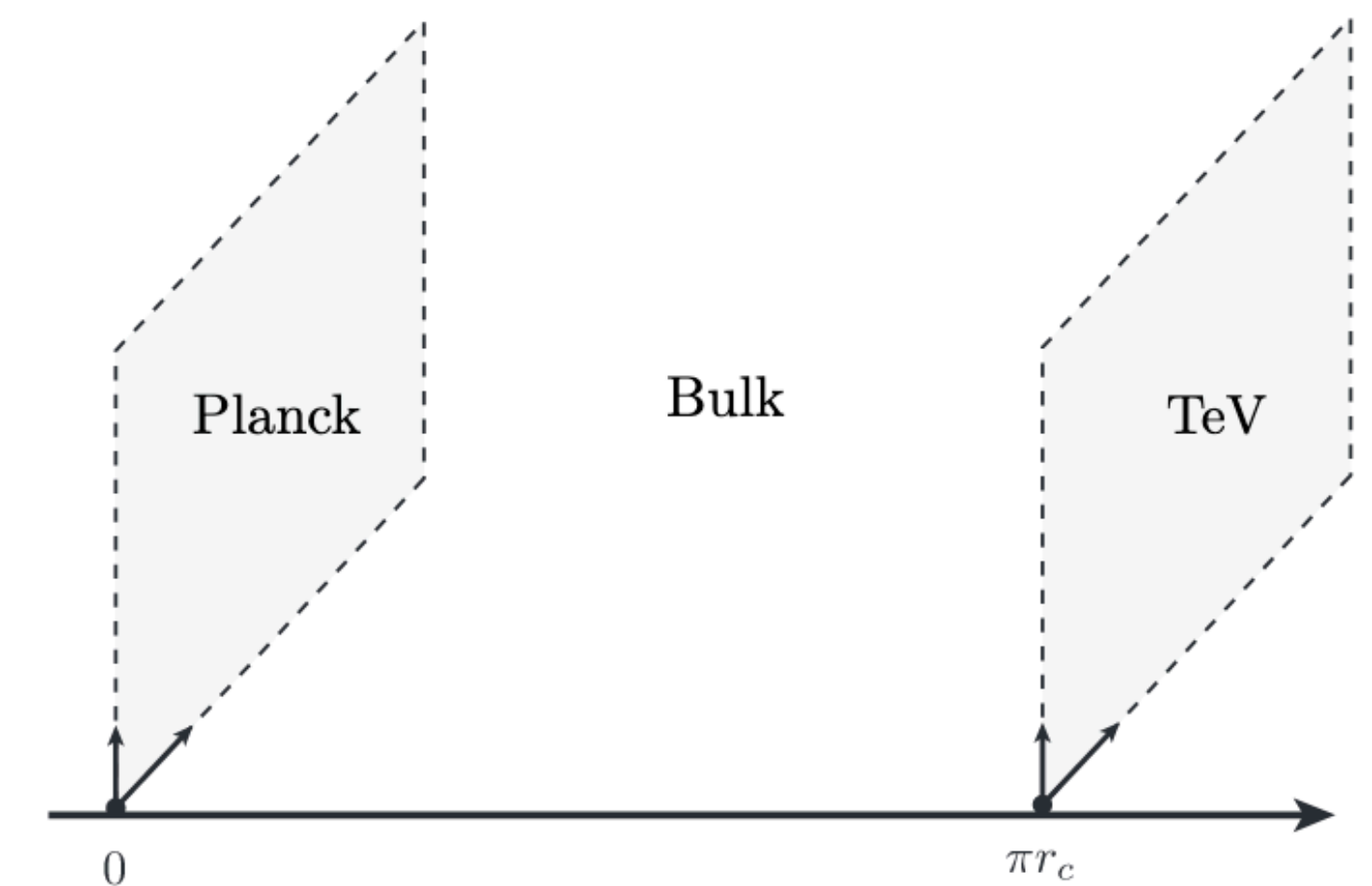
Wide variety of models and theories include additional resonances:

2 Higgs Doublet Model (2HDM)

- Natural BSM extension by adding an additional Higgs doublet.
- Includes **5 additional scalar states**: h , H , A , H^+ , H^- .

Randall-Sundrum (RS) model

- Proposed solution to the hierarchy problem.
- Five dimensional bulk with two branes (called RS1)
- Propagation of the graviton in the bulk:
massive spin-2 excitations (Kaluza-Klein states)



Diphoton resonance searches: Introduction

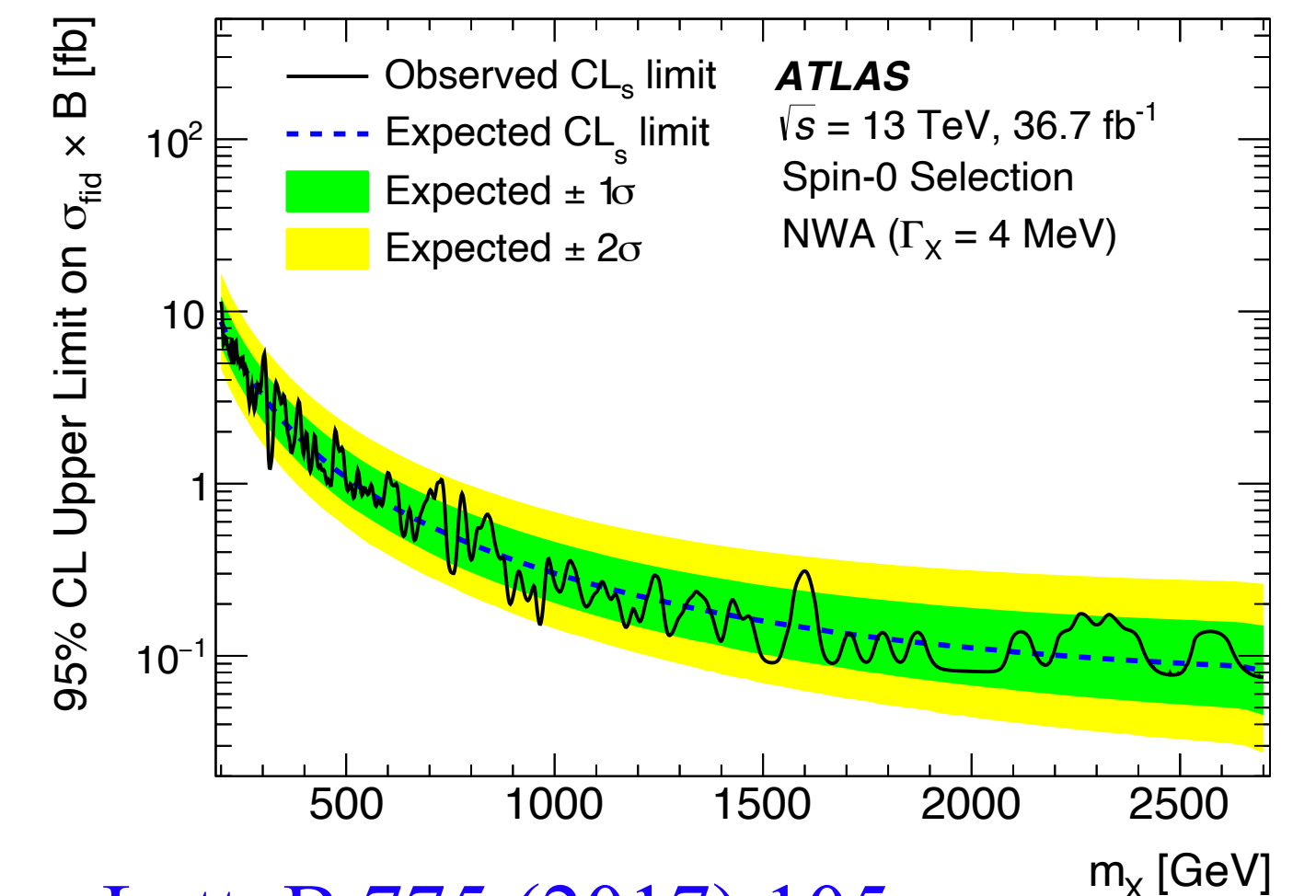
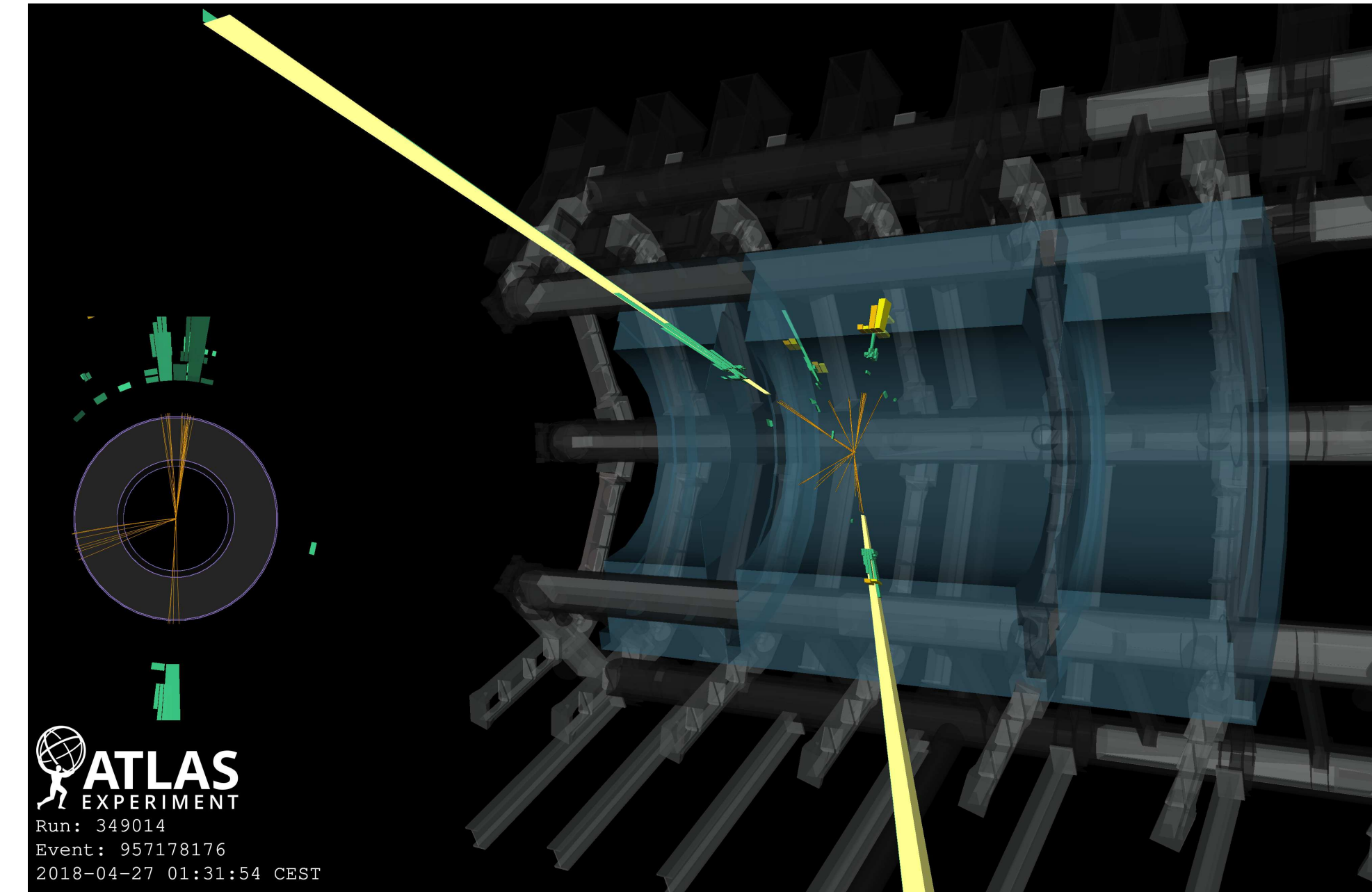
Diphoton analyses **strengths**:

- Excellent mass resolution.
- Very clean signature: 2 isolated photons in the calorimeter.

Results published with partial dataset:

- No significant excesses for diphoton invariant masses above 200 GeV.
- Upper limits expressed in terms of the fiducial cross-section to allow for easier theory interpretations.

Today: new results for the high mass range with $m_{\gamma\gamma} > 160$ GeV with the full Run 2 dataset.



[Phys. Lett. B 775 \(2017\) 105](#)

Strategy:

- Describe with analytical functions both **signal** and **background** components.
- Search for event excesses compatible with the signal shape.

Benchmark models:

- Model independent search of a spin-0 particle.
- Lowest KK graviton in the RS model: a spin-2 resonance.
 - Various widths (couplings) are considered for the spin-0 (2) search.

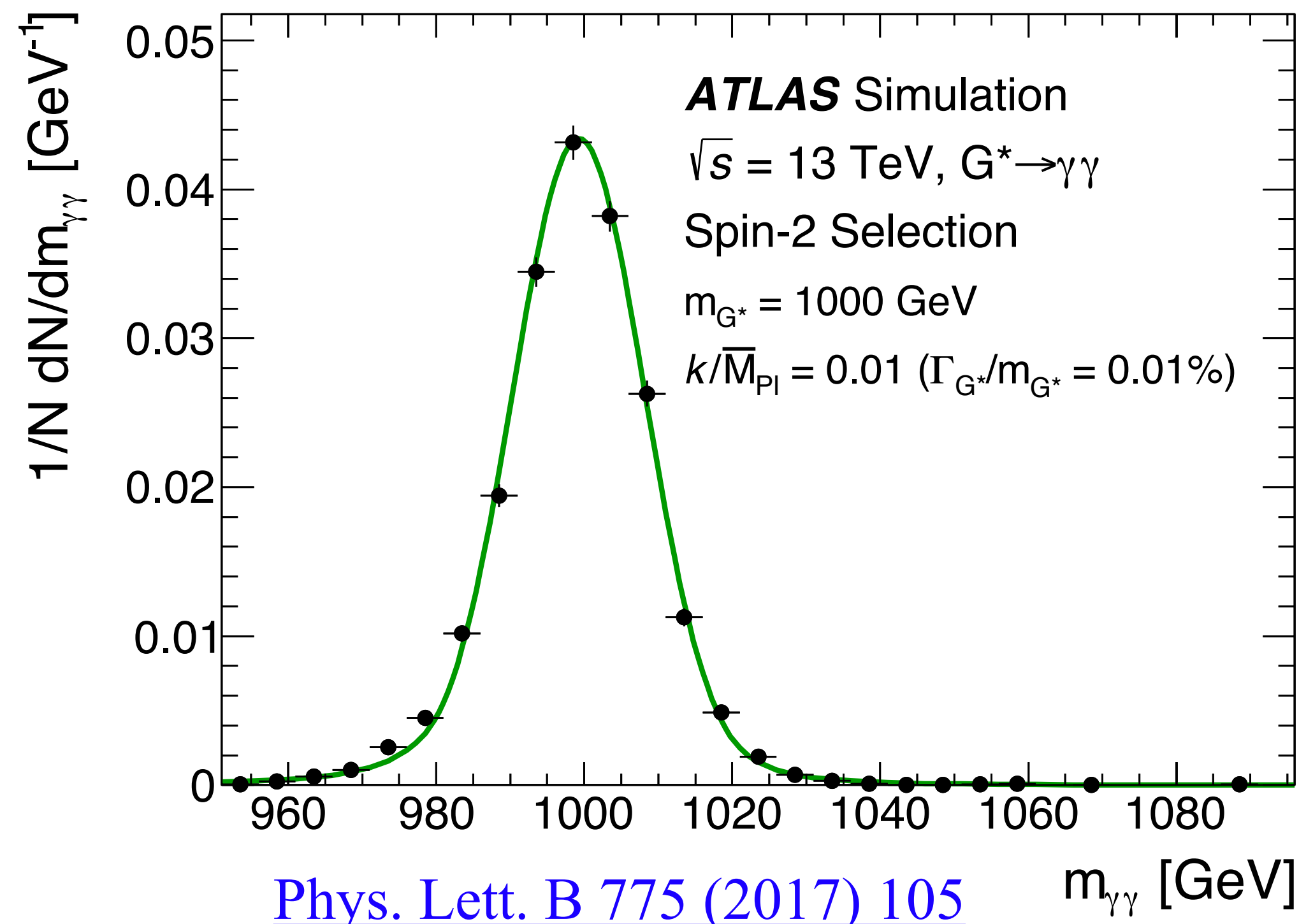
Improvements w.r.t. previous result:

- Optimized event selection common for both interpretations.
- Updated photon reconstruction, identification and calibration
- **Functional decomposition** method to reduce systematic uncertainties ([arxiv:1805.04536](https://arxiv.org/abs/1805.04536)).

Signal shape obtained from simulation.

Analytical function:

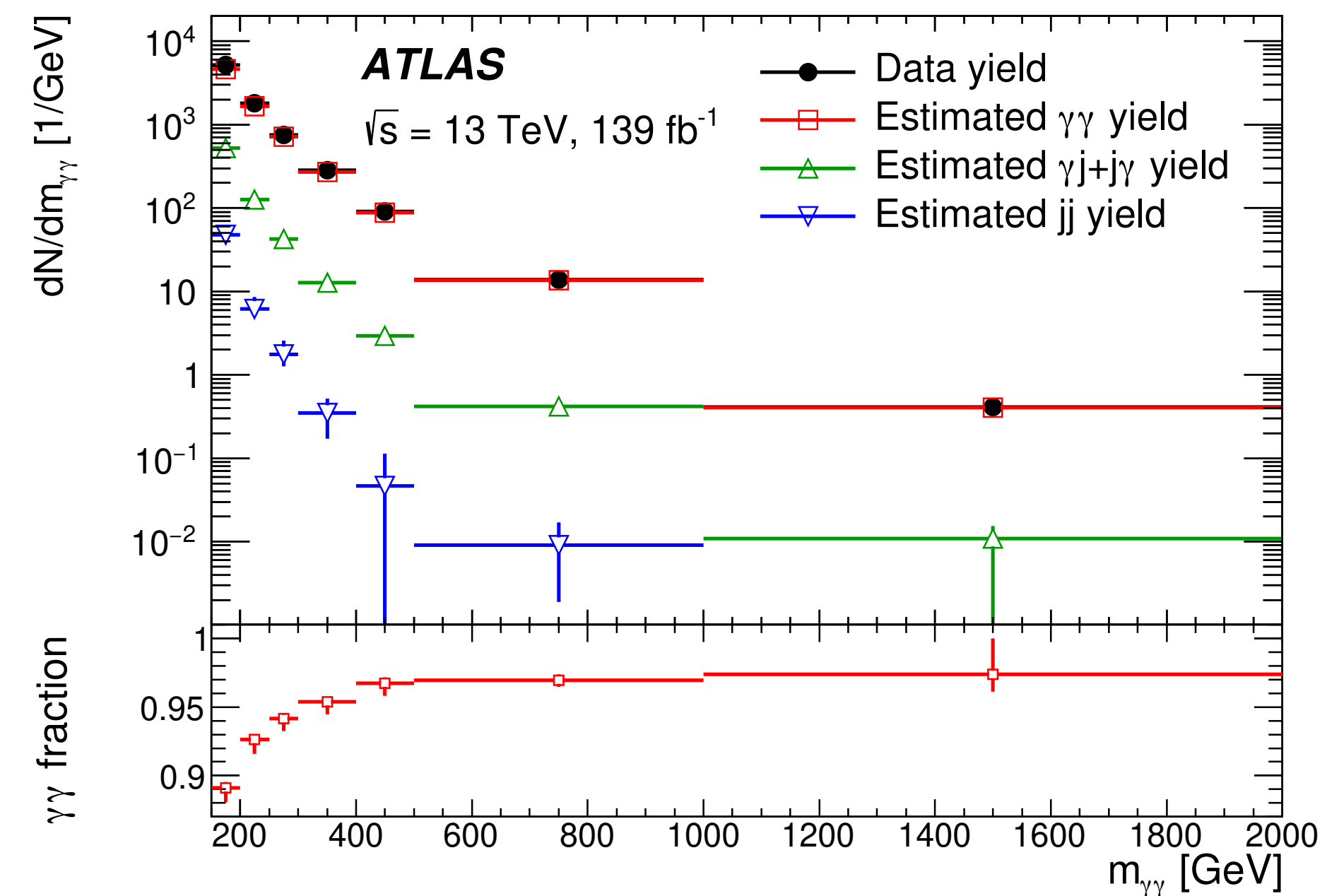
- Double Sided Crystal Ball → detector resolution
- Breit-Wigner → resonance width



Background shape obtained from simulation and data control regions.

Composition:

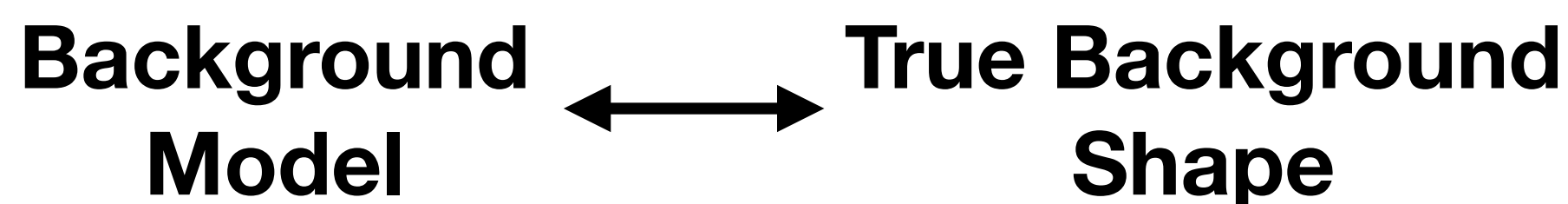
- Non-resonant QCD diphoton pairs ($\gamma\gamma$).
- Misidentified jets as photons ($\gamma j/j\gamma/jj$).



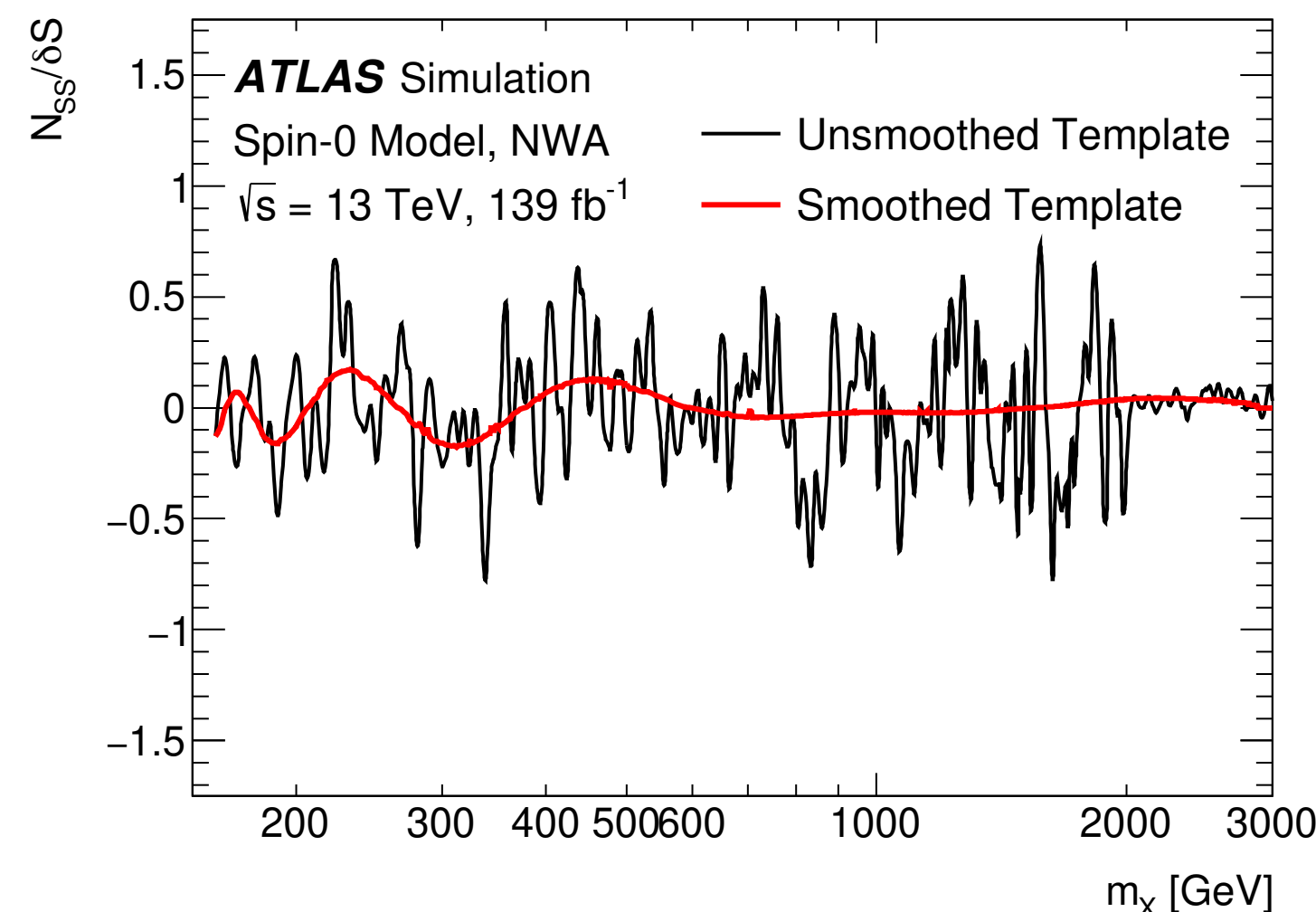
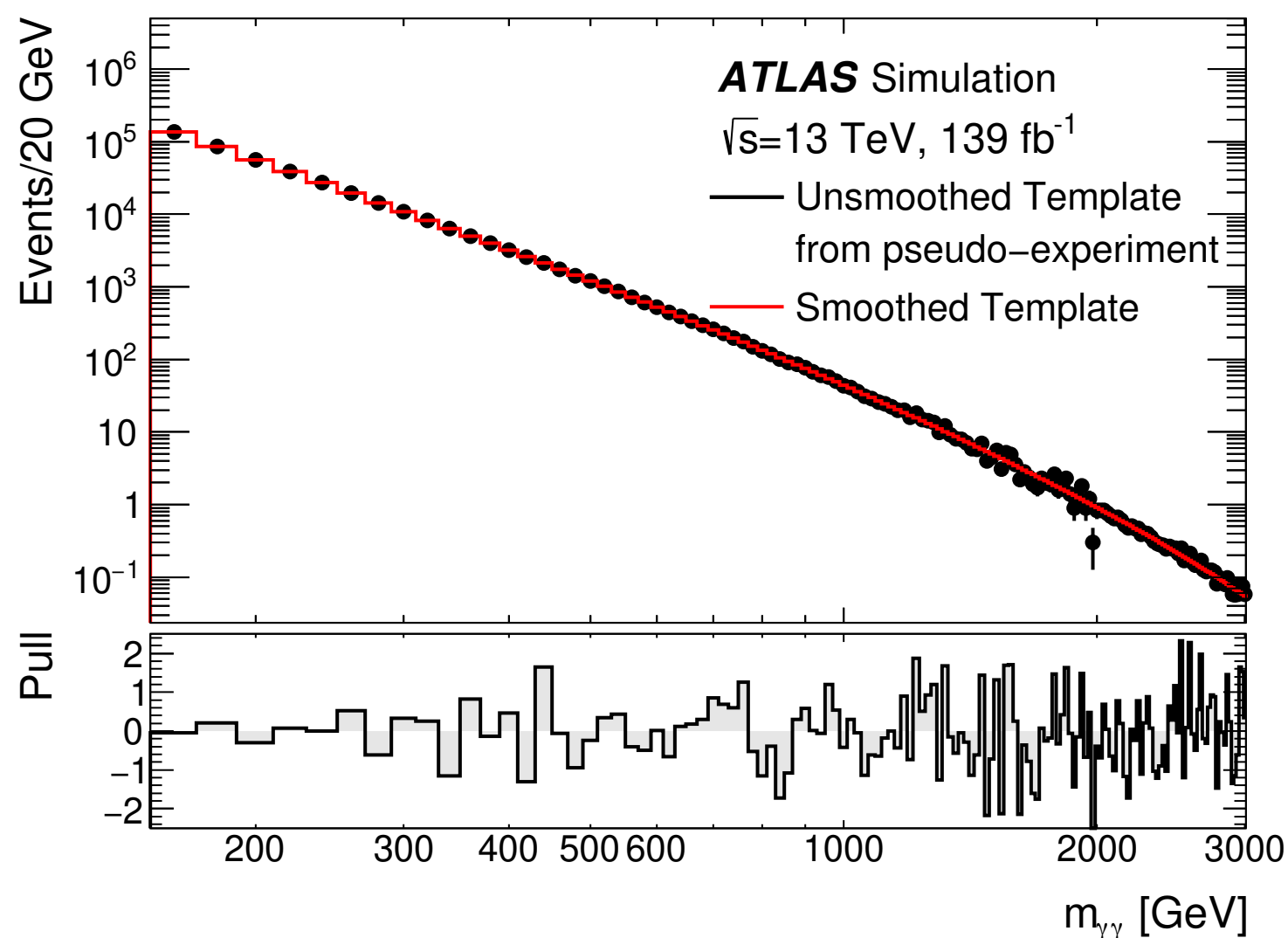
In practice, the analytic description cannot be usually derived from first principles.

- Background model empirically chosen.

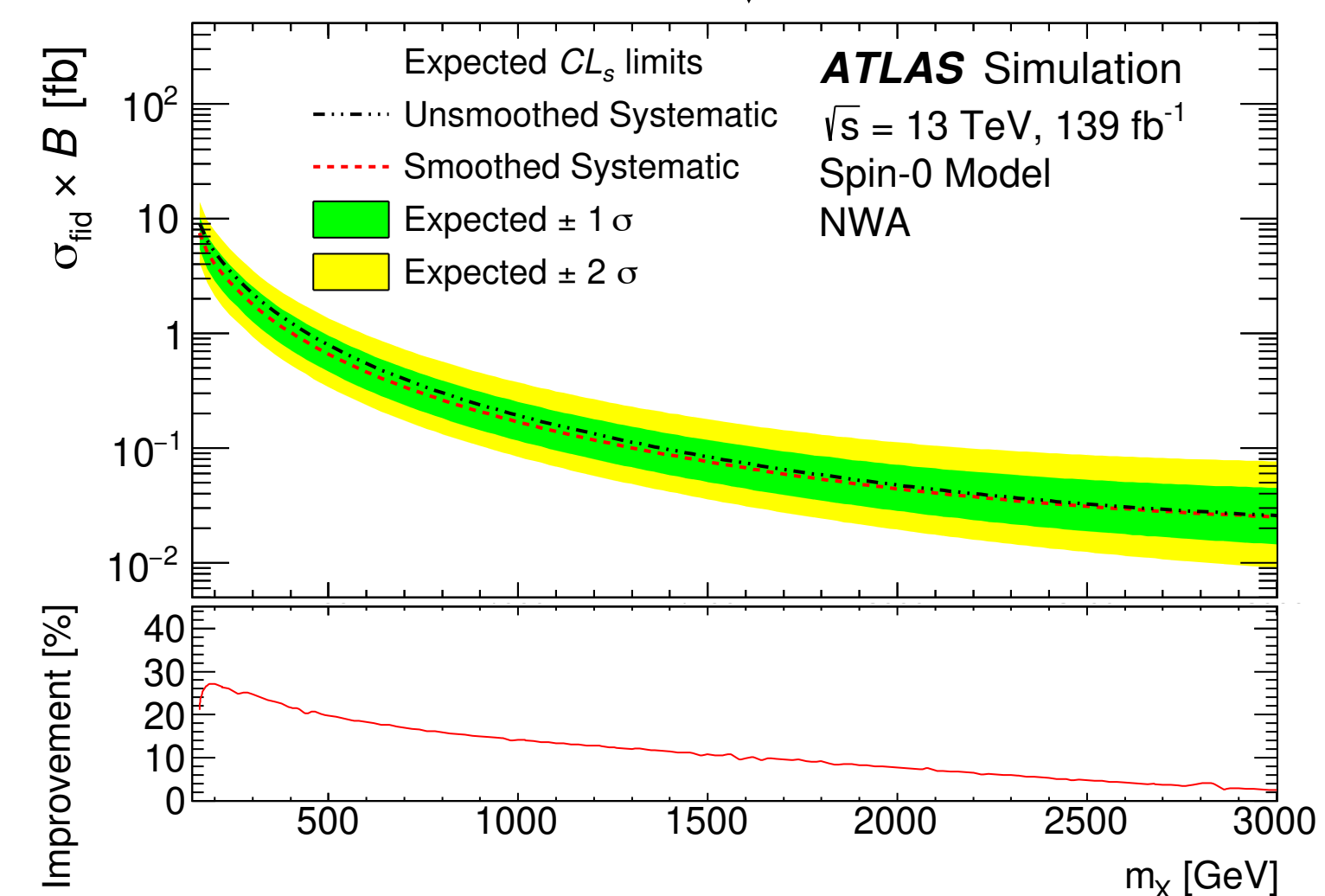
Systematic uncertainties address discrepancies between:



- A large difference could create “spurious signals” .



Improvement of up to 30% on the expected sensitivity!

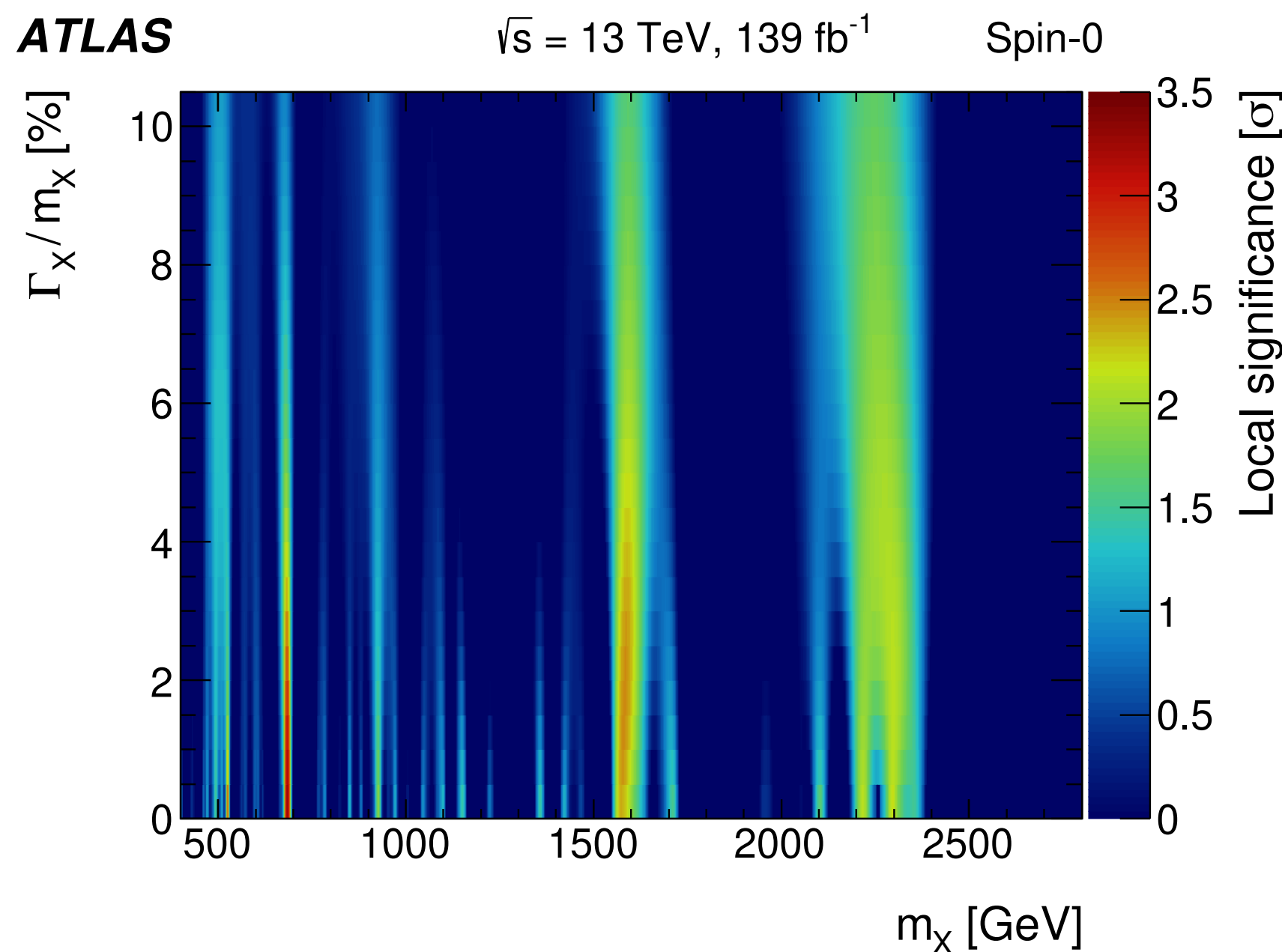


Functional decomposition provides an estimate of the true background shape

Both spin-0 and spin-2 searches in agreement with SM predictions.

- Largest excess at $m_X \sim 684$ GeV with 3.29σ (1.30σ) of local (global) significance.

Limits are provided in a 2D plane of width (coupling) vs mass for spin-0 (spin-2) models.

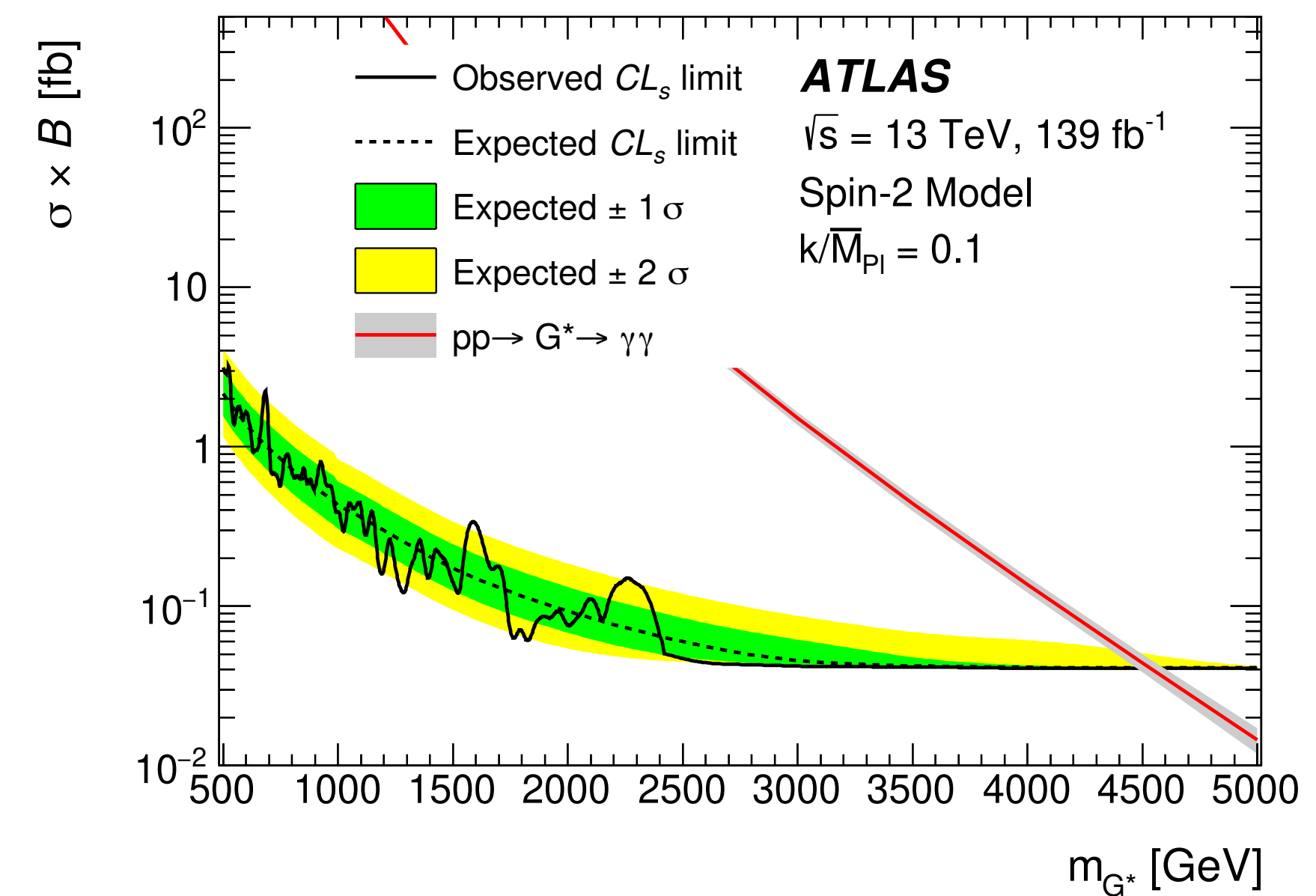
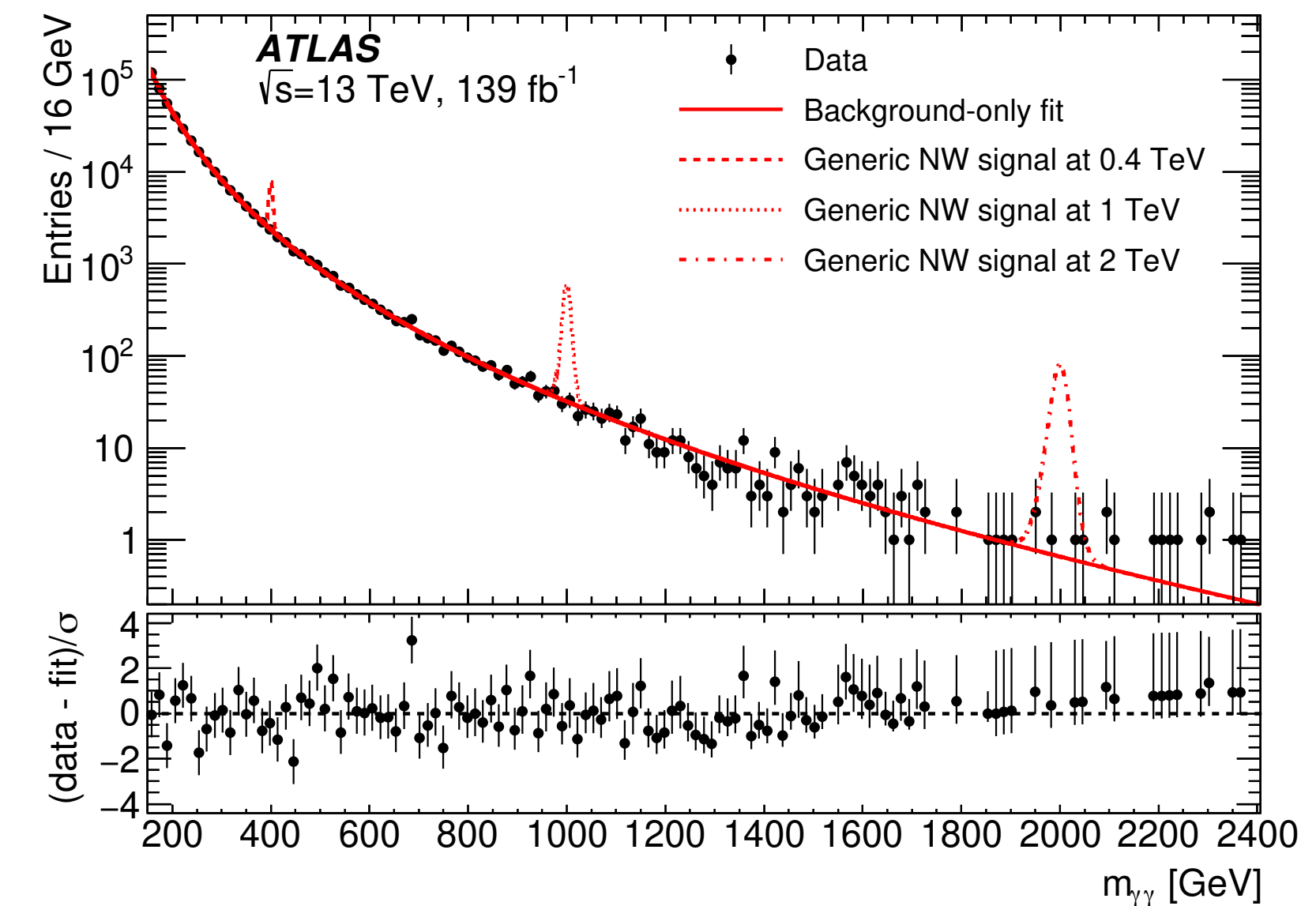


RS1 model excluded for graviton masses

$$m_{G^*} < 2.2, 3.9, 4.5 \text{ TeV}$$

with couplings

$$k/\overline{M}_{Pl} = 0.01, 0.05, 0.1 \text{ respectively.}$$



ZZ resonance searches: Introduction

Focus today on **leptonic final states**: 2 searches

- $ZZ \rightarrow 4l$: good mass resolution.
- $ZZ \rightarrow ll\nu\nu$: large branching ratio

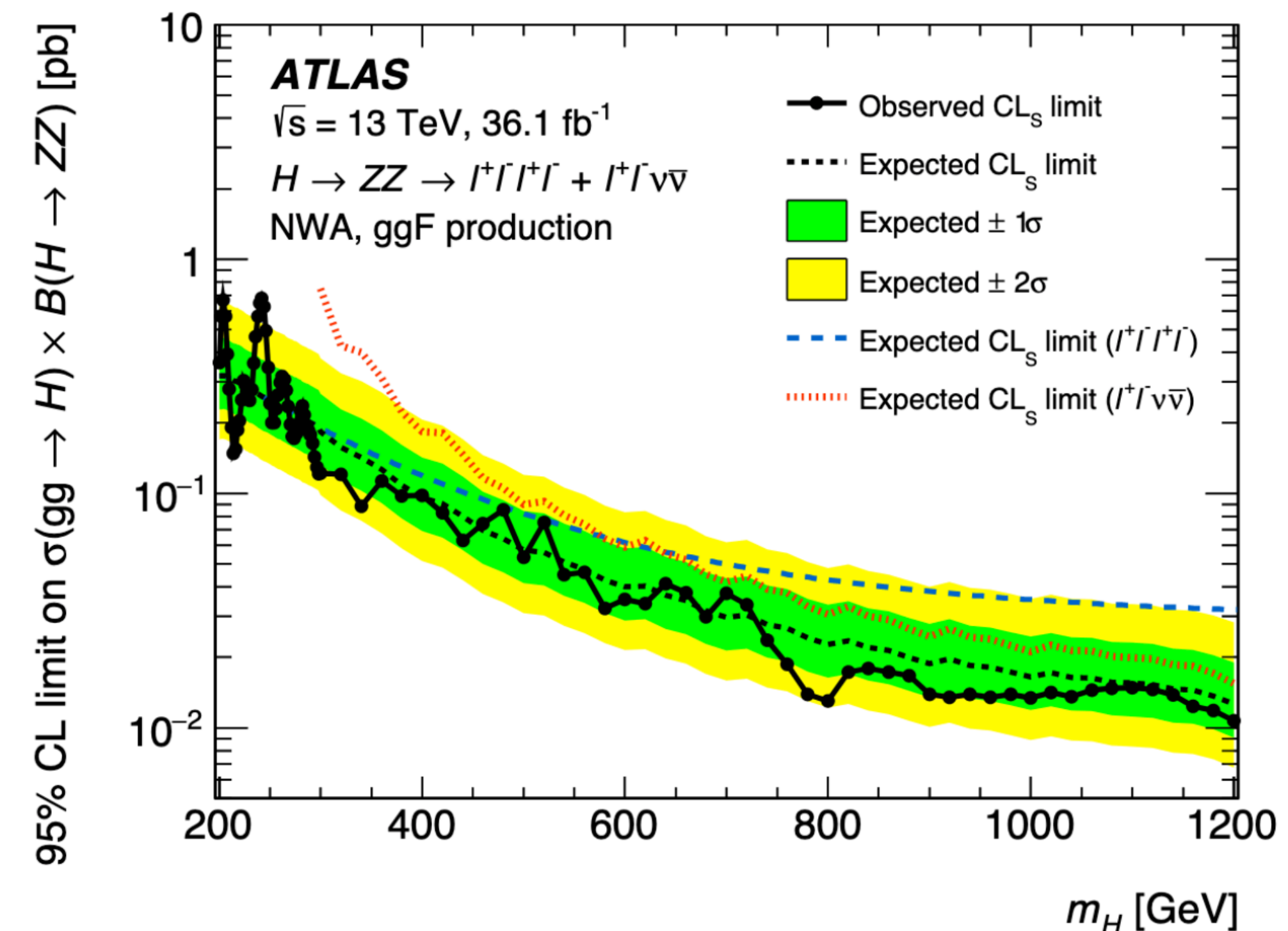
Complementary searches!

Results published with partial dataset:

- No significant excesses for masses in the $m_H : [200, 1200]$ range.
- Upper limits computed for gluon fusion (ggF) and vector boson fusion (VBF) production for both channels.

Today: new results for masses in the $m_H : [200, 2000]$ GeV range with the full Run 2 dataset.

[Eur. Phys. J. C 78 \(2018\) 293](#)



Strategy for $ZZ \rightarrow 4l$: event excess over the m_{4l} distribution.

Strategy for $ZZ \rightarrow ll\nu\nu$: event excess over the m_T distribution (neutrinos escape!)

Benchmark models:

- Model independent search of a spin-0 particle.
- Spin-2 particle from bulk RS model (extends the low mass $\gamma\gamma$ limit)
- Resonances present in the 2HDM
 - Various widths are considered for the spin-0 search.

Improvements w.r.t. previous result:

- Improved lepton and jet reconstruction
- Use of data-driven estimates for the dominant background: SM ZZ
- $ZZ \rightarrow 4l$: machine learning event classification
- Extended range up to 2 TeV.

Selection and categorization

Event selection relies on the reconstruction of the Z boson final state objects:

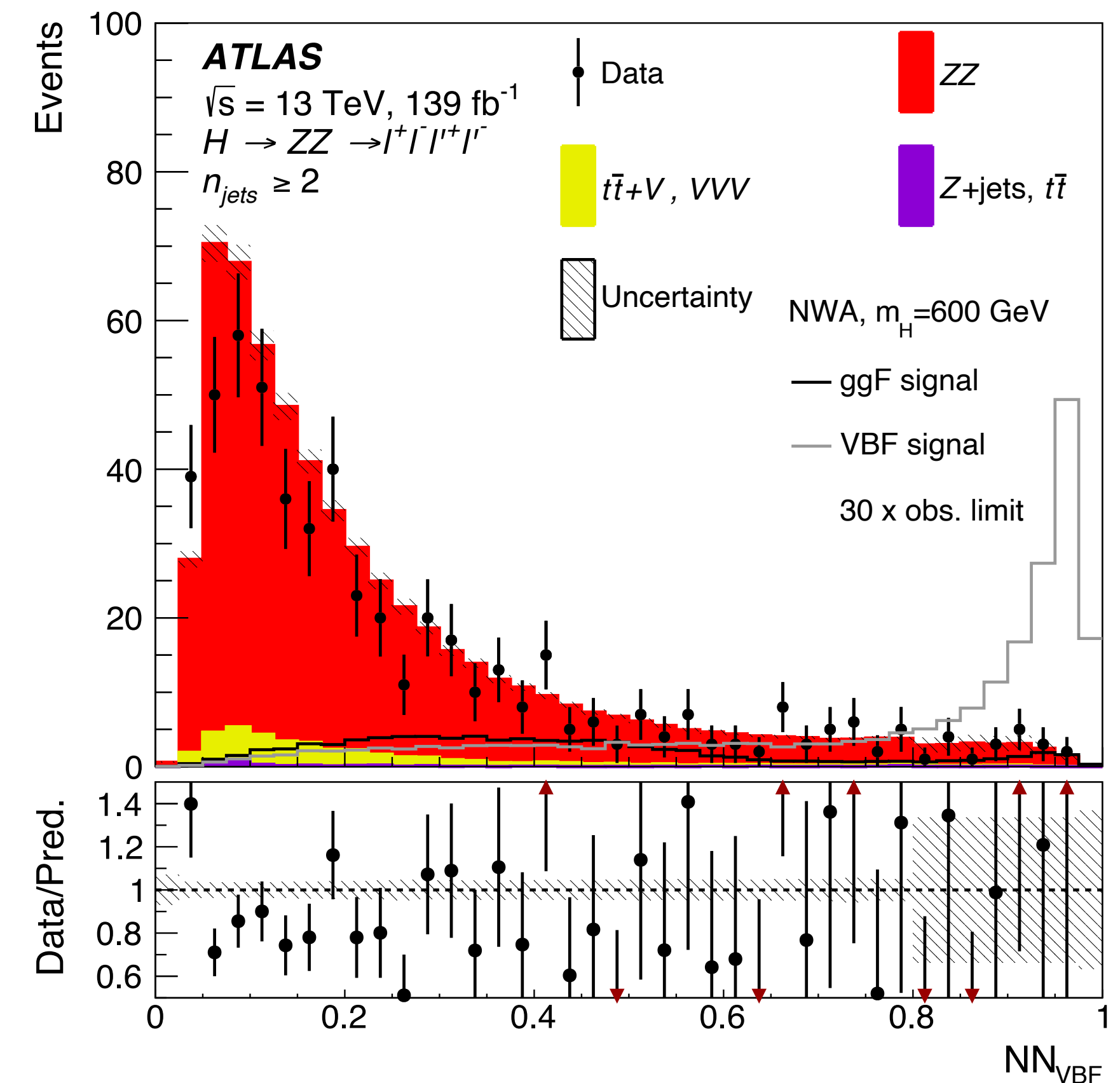
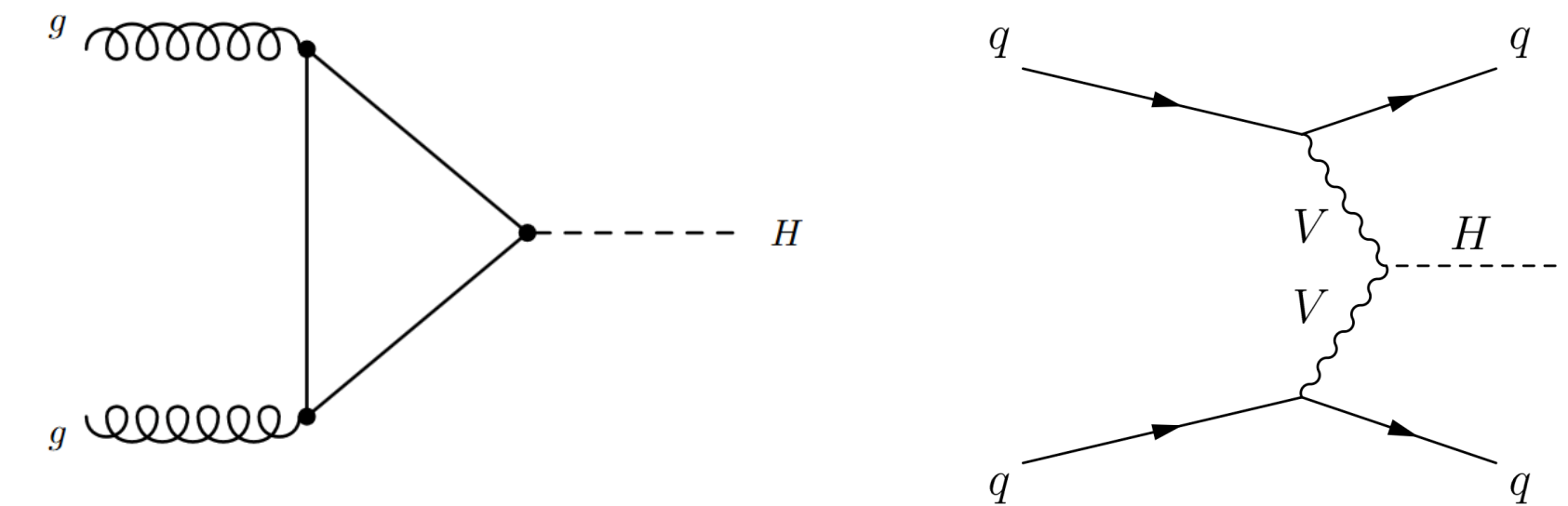
- $ZZ \rightarrow 4l$: Two pairs of $l^\pm \bar{l}^\mp$ with m_{2l} close to m_z
- $ZZ \rightarrow ll\nu\nu$: One pair of $l^\pm \bar{l}^\mp$ with m_{2l} close to m_z and large missing transverse momentum

Cut-based classification in the $ZZ \rightarrow ll\nu\nu$ analysis:

- Massive dijet (>550 GeV) requirement to enrich the VBF category.
- Classified as ggF otherwise.

Classification in the $ZZ \rightarrow 4l$ analysis:

- NN classifier to enrich ggF and VBF categories.
- Cut based classification retained for more model-independent results.



Signal shape obtained from simulation and described with analytical functions.

Background estimation differs between the two analyses:

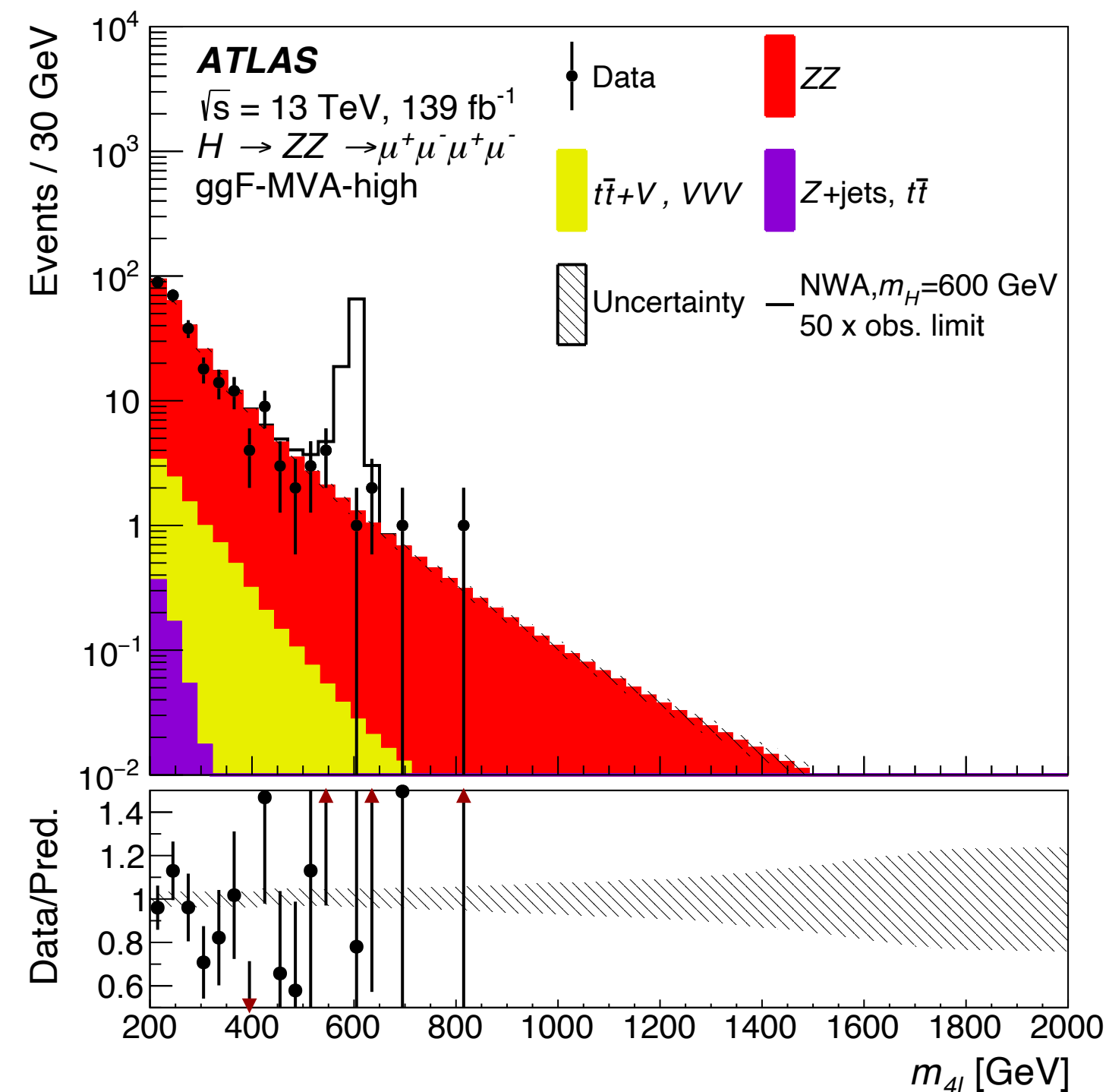
ZZ → 4l:

- Simulated samples and data from control regions.
- Yields normalized from data.
- Dominant contribution (SM ZZ production) described with an analytic function.

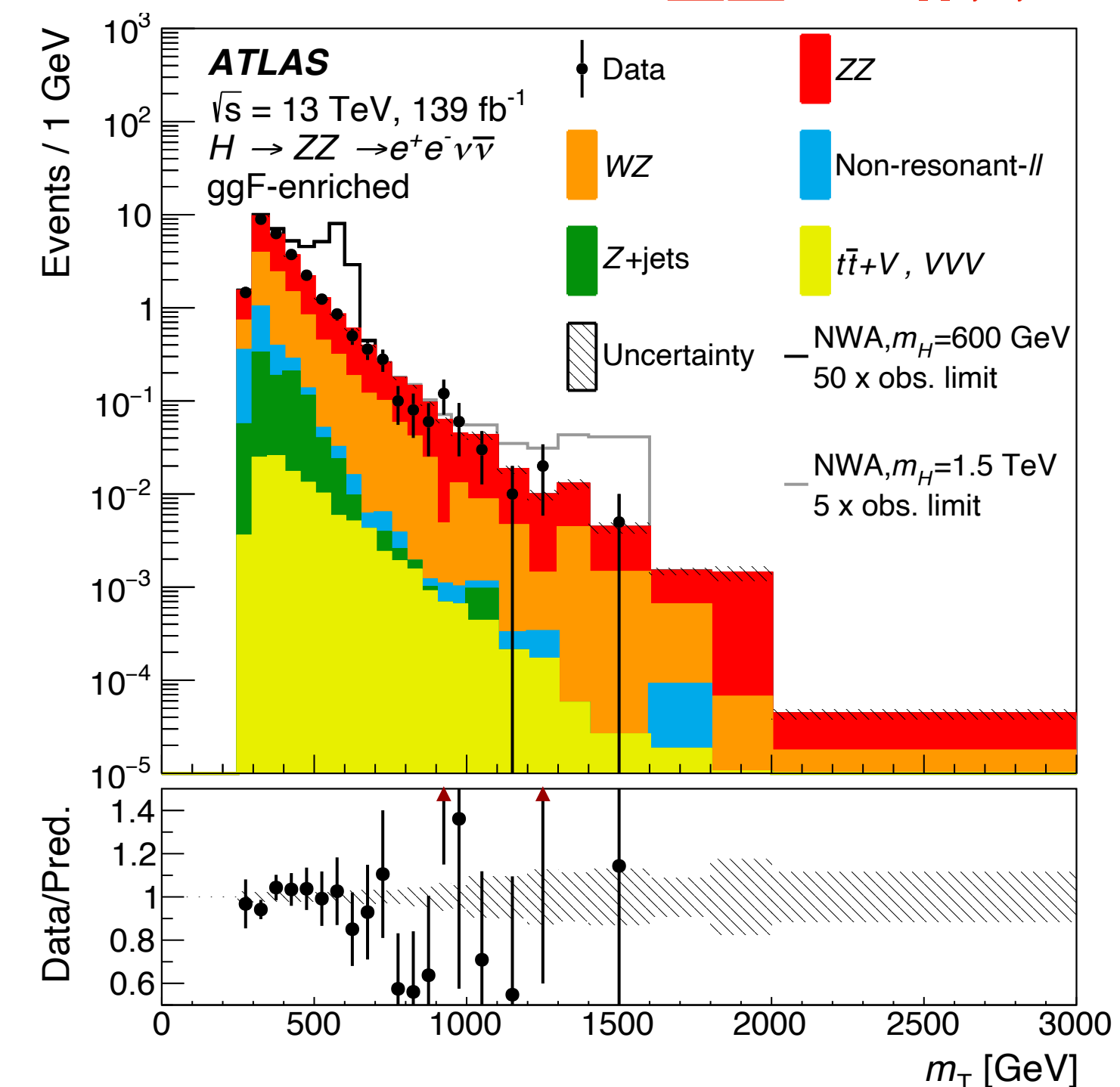
ZZ → llνν:

- Simulated samples with yields normalized from data.

ZZ → 4l



ZZ → llνν



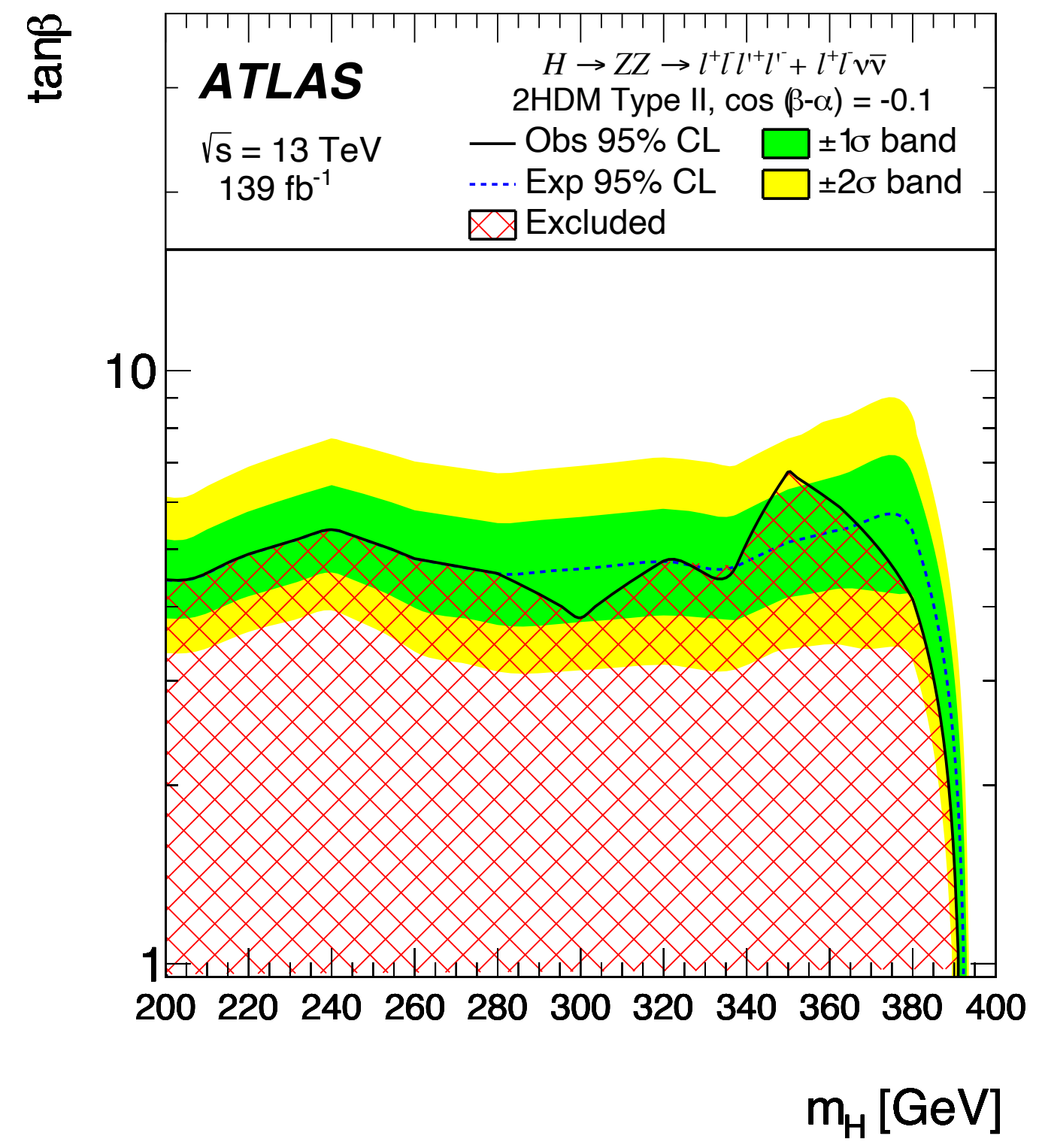
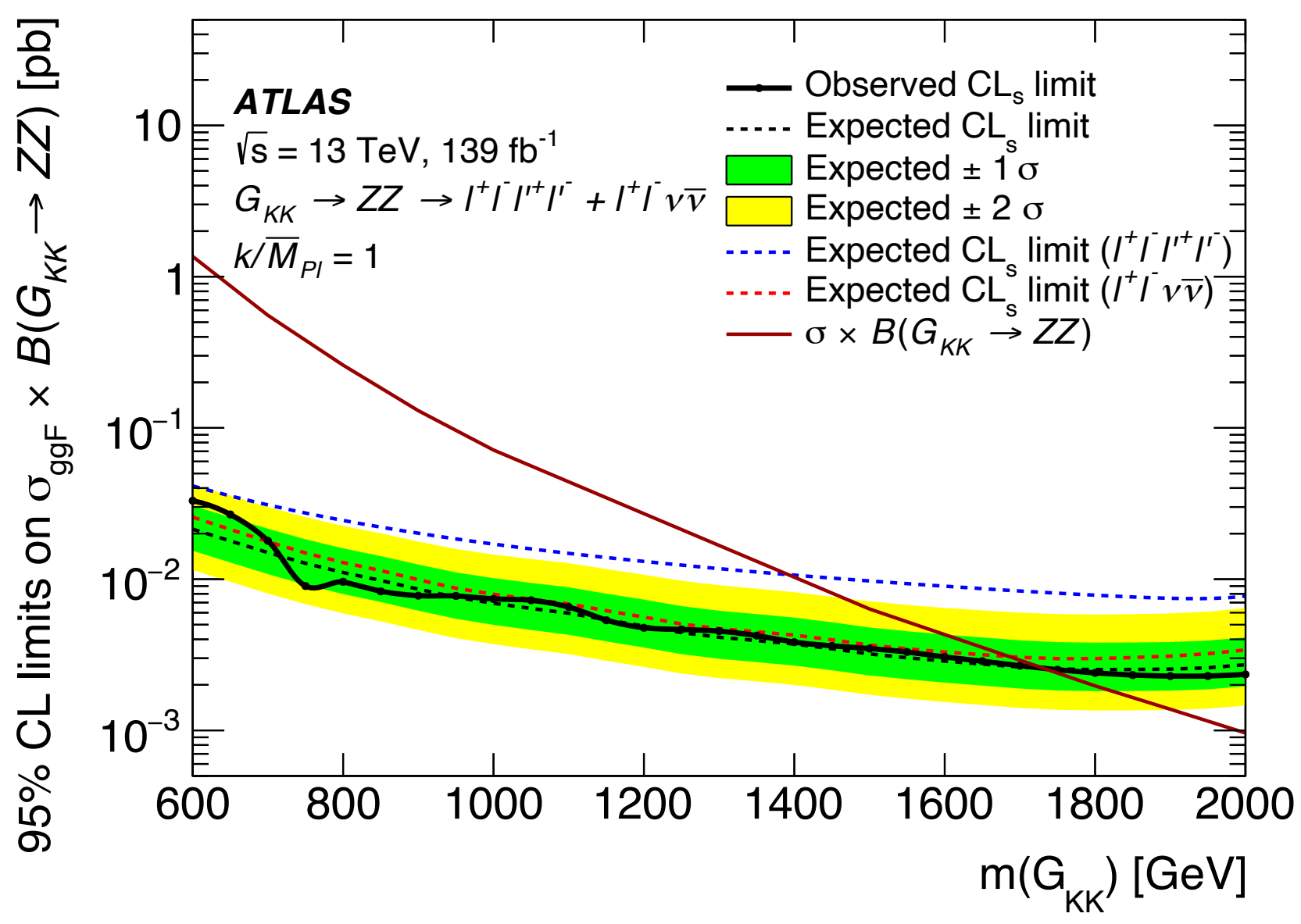
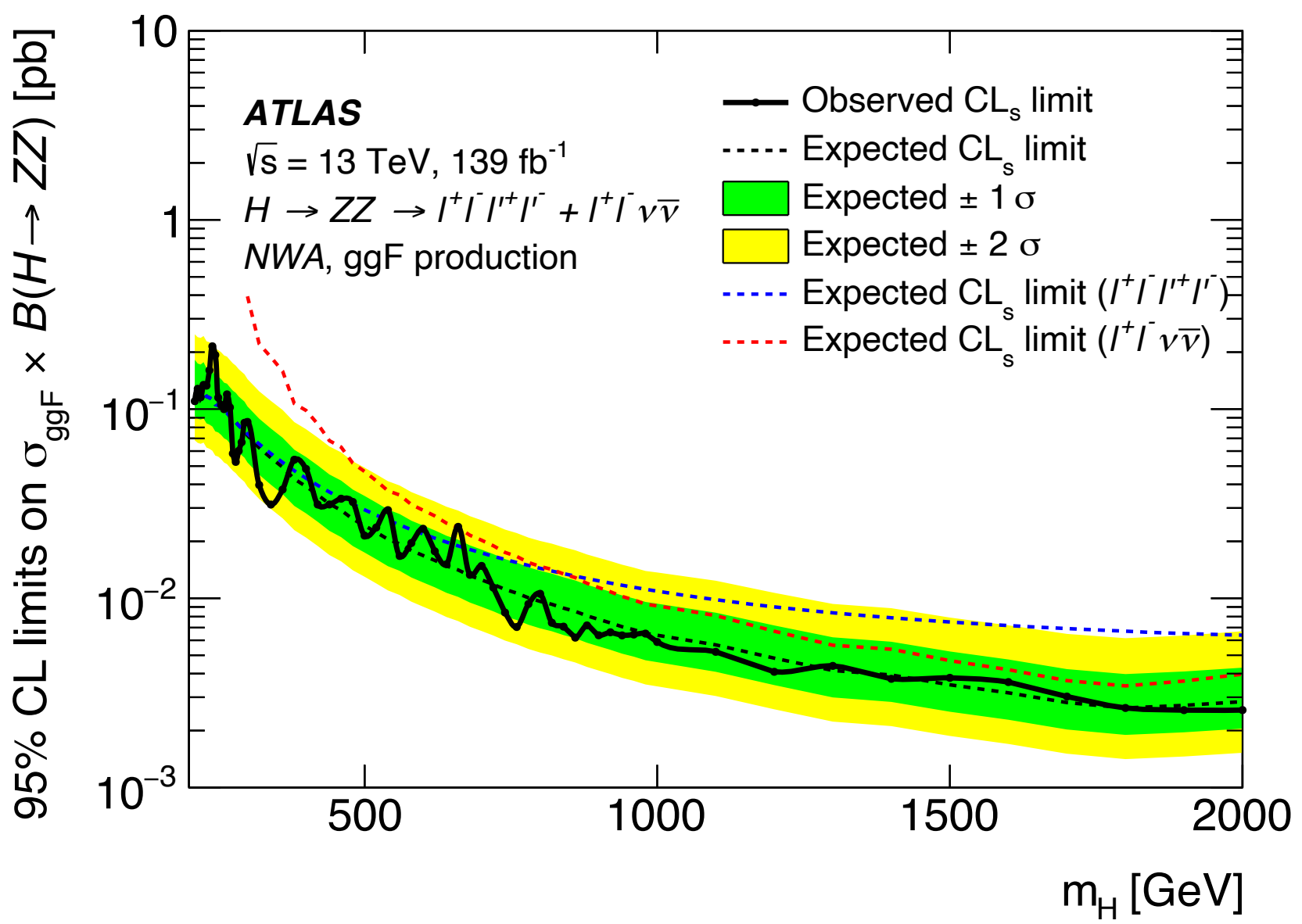
Simulated signals overlaid on both distributions

Combination of both ZZ searches

All searches in agreement with SM predictions.

Upper limits are set on various signal hypothesis and production mechanisms.

- Combined ggF and VBF for the 2HDM (known relative fraction)
- ggF: spin-0, spin-2 for narrow and large width resonances.
- VBF: spin-0 narrow width resonance.



Conclusions and future perspectives

Analysis updates on resonances decaying into boson pairs using 139 fb^{-1} at 13 TeV collected in 2015-2018.

- Only leptonic and diphoton final states described.

Diphoton searches

- Updated reconstruction, identification and calibration.
- Reduced systematic uncertainties: up to 30% improved sensitivity.

$X \rightarrow ZZ$

- Data-driven estimation of the background normalization.
- Event classification optimized with machine learning techniques.
- The search is extended up to 2000 GeV.

Both searches are compatible with background-only processes.

ATLAS covers a much wider landscape of final states!

- A non-extensive selection can be found in: [Summary of diboson searches](#)

Promising future ahead with novel techniques and improved detectors: stay tuned!

Backup

Multivariate analysis classification

Motivation: use deep neural networks to improve the sensitivity of Higgs-like signals in the VBF and ggF production modes.

- VBF classifier: 2 recurrent NN and 1 multilayer perceptron (MLP)
- ggF classifier: 1 recurrent NN and 1 MLP

Both classifiers trained separately on signal events according to their production mode.

- Background events are weighted to the luminosity.

Signal acceptance found to be between 30% (15%) and 46% (22%) for the ggF (VBF)-enriched category the ggF(VBF) production mode.

