Searches for *rare Higgs boson decays*

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Intro to Higgs

- A bit of history 🙂

- The SM expands upon a theory developed in the 19th & 20th centuries that described the EM force
    - Issues arose when trying to combine it with the weak force (originally proposed by Fermi in the 1930's to explain beta decay)
        - Massive weak bosons couldn't be accounted for
    - Mechanism (Higgs!) postulated in the 1960's allowed particles to acquire mass
    - EM and weak forces could be explained together in one single EW theory (Nobel 1979)
    - Strong force (explains e.g. why nuclei stay together despite proton's charge repulsion) was added to the mix, resulting in what we now call the SM

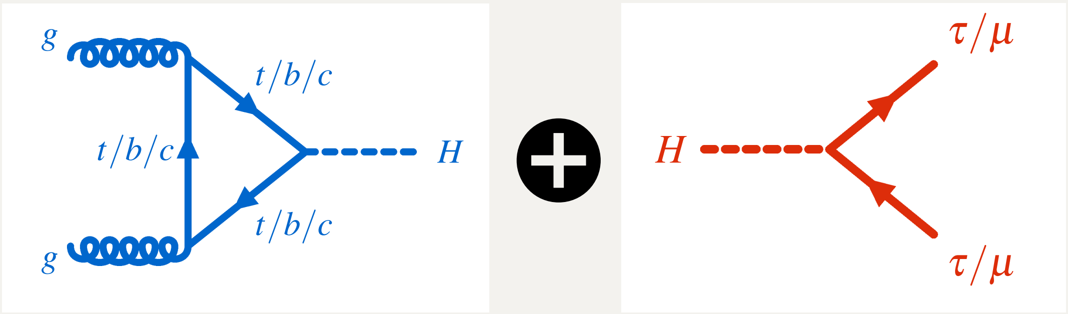
- SM predictions: massive weak bosons (W, Z) and Higgs
    - W boson explained beta decay but Z had never been observed!
    - Z boson discovered at CERN's SPS in the 1980's ➛ seemed like SM was "right"
    - Higgs boson discovered in 2012, half a century after it was postulated

Intro to Higgs

- Higgs mechanism allows particles to gain mass without breaking (symmetries of) the theory
  - Strength of Higgs coupling is proportional to particle's mass
  - Strength of Higgs coupling determines how one can produce a Higgs and how the Higgs can decay

- Experimentally, we have access to two main things:
  - How many Higgs bosons were **produced** (and how) *based on characteristics of production mode*
  - How those Higgs bosons **decayed**

Nature (2022) 607, 52-59



- Production and decay rates contain a lot of information about the Higgs boson (and beyond?)
  - Sensitive to **couplings**
  - Any deviations we find could be signs of BSM!

- Over 30 separate measurements per experiment; rates varying over several orders of magnitude

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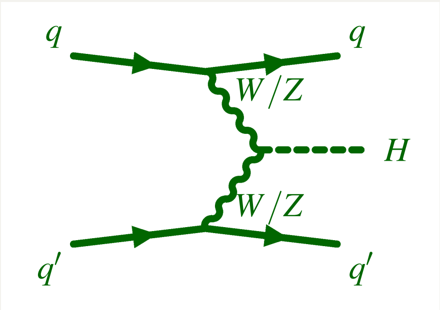

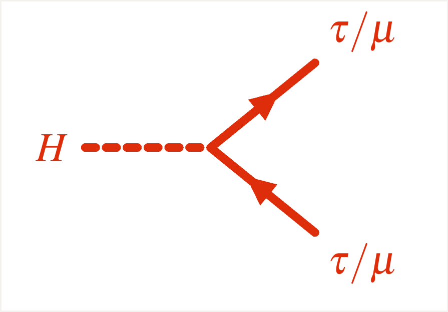

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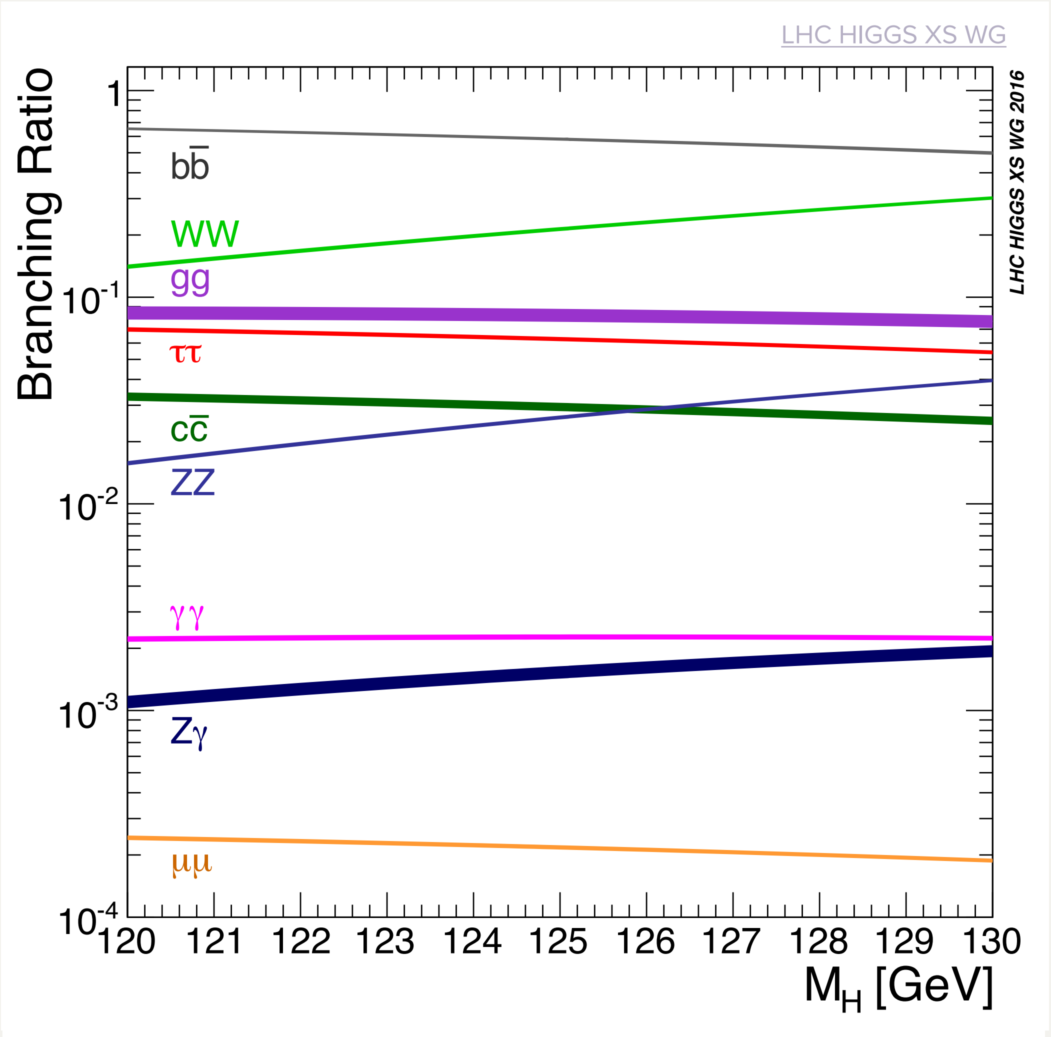
  - In general, at hadron colliders you get a lot of hadrons…so processes like $H \to b\bar{b}$ are hard to distinguish from background
  - $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ are the "golden" channels
    - Relatively low rates
    - Fully-reconstructible final states with good energy/momentum resolution
    - Nice backgrounds: low bkg rate (4ℓ), easy-to-describe ($\gamma\gamma$)
  - This is where Higgs measurements start!



- Now, after 10+ years and with much more data, we can move to more difficult/rarer decays

Higgs decays with loops

- Higgs decays with loops are particularly interesting because we only see the objects that "come out" of the loop
  - We don't actually know what is inside the loop (BSM particles?)
  - Can test if the loop contents are consistent with only SM particles, using measured/expected Higgs coupling strengths to SM particles

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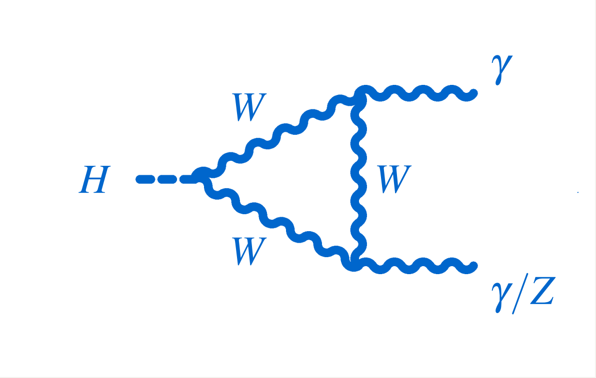
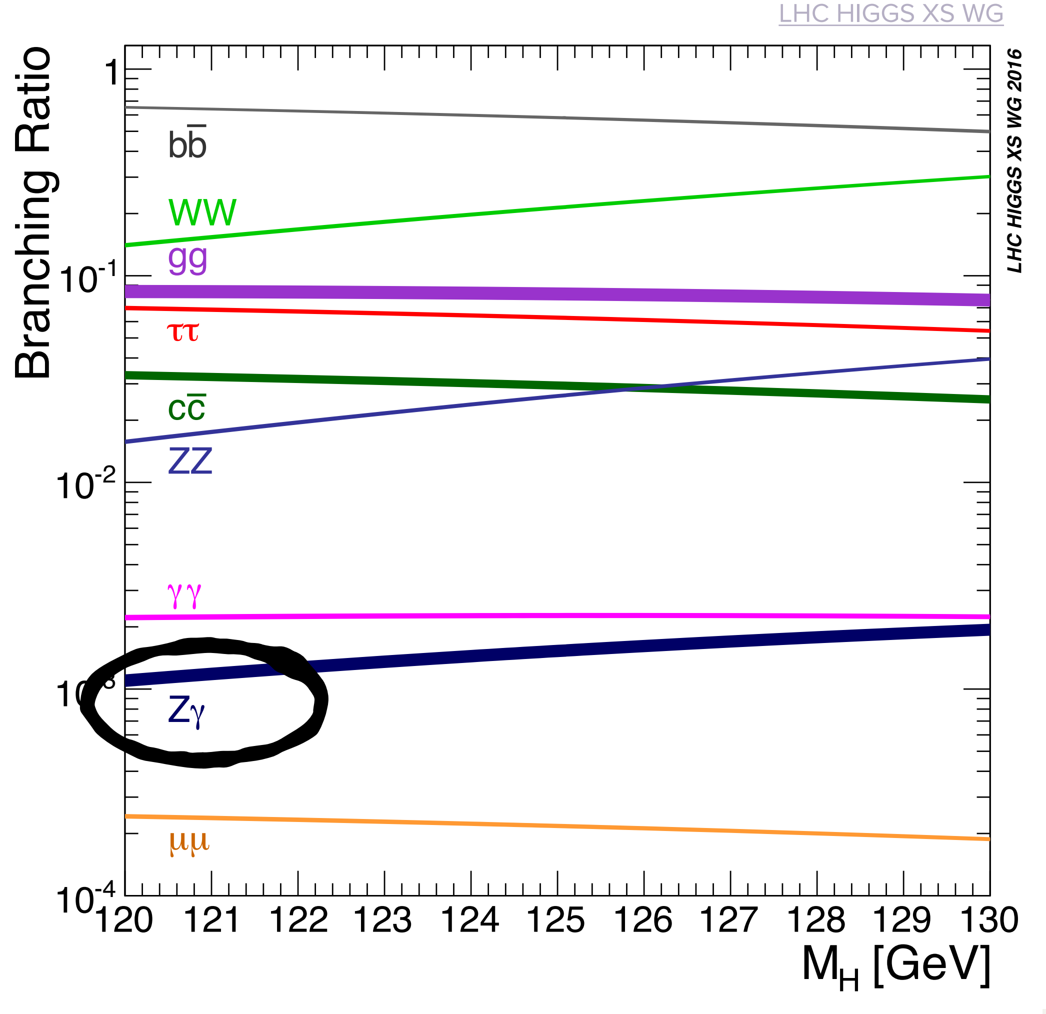


- $H \to Z\gamma$ is similar to $H \to \gamma\gamma$
  - Branching ratio is quite low (10^{-3})
  - Can be enhanced in BSM scenarios (e.g. additional colourless bosons)
  - $H \to Z\gamma \to \ell\ell\gamma$ is quite nice
    - Leptons + photons: good mass resolution
    - Can pick out a nice Higgs boson "bump"
  - Analysis strategy is similar to $H \to \gamma\gamma$
    - Use lessons learned in $H \to \gamma\gamma$
    - Share software, tools, techniques, …

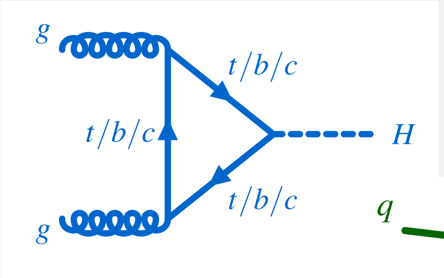
LHC HIGGS XS WG



How does the analysis work?

1. Select events that are consistent with $H \to Z\gamma \to \ell\ell\gamma$ decays
    - Two light leptons and a photon: not too strict (low stats signal), but not too loose (don't want bkg)
    - Invariant mass near m_H
    - Can ask the invariant mass of the two leptons to be near m_Z (or not, for $H \to \gamma^*\gamma \to \ell\ell\gamma$)

2. Select events that target specific Higgs boson production modes
    - Typically allows better signal/background separation by focusing on specific kinematics



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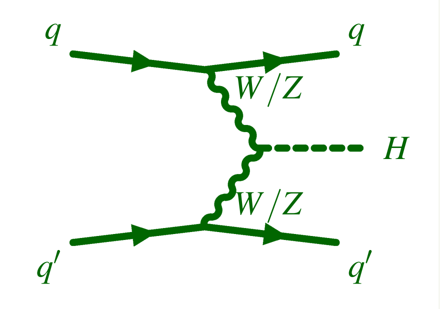
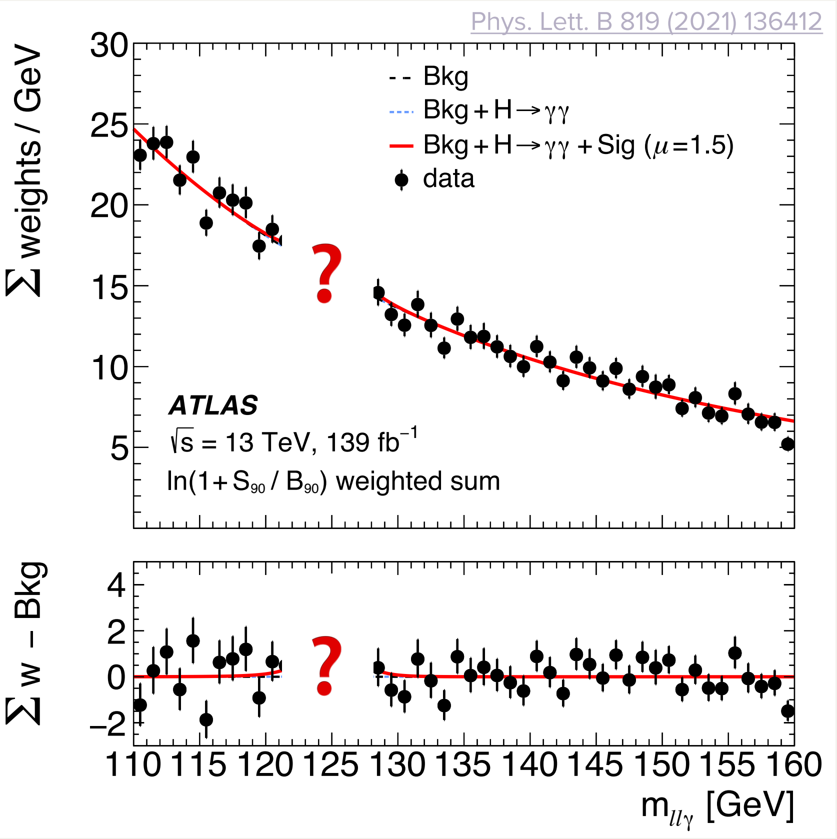


3. Describe the signal
    - Usually a Double-Sided Crystal Ball (DSCB) function is used
        - Same as for $H \to \gamma\gamma$ analysis
        - Roughly: mean maps to the Higgs boson mass, width maps to the resolution

4. Understand the backgrounds
    - Mainly two types: $Z + \gamma$ events (not from a Higgs decay) and $Z +$ jets where a jet gets mis-identified as a photon
    - Neither peaks around m_H

Background estimates

- Background is a smoothly-falling spectrum
  - Shape of this spectrum under Higgs peak very important
  - If we predict this wrong under the Higgs peak, the rate measurement will be off



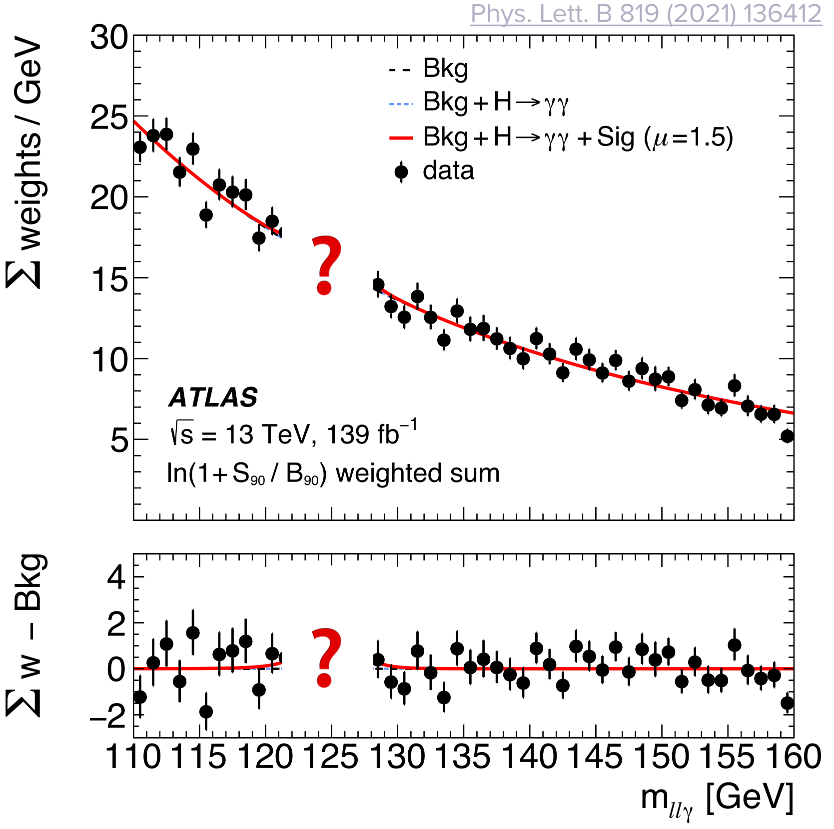
- Simulated $\ell\ell + \gamma$ events used to estimate "shape" of this contribution
  - This is the largest background, especially at low $m_{\ell\ell}$
  - Very large samples are created to have minimal statistical fluctuations that could distort the shape
  - Typically done using fast simulation

- For events with $m_{\ell\ell} \approx m_Z$, there is an important contribution from $Z + \text{jets}$
  - Difficult to simulate enough jets that look photon-like (most jets are <u>not</u> photon-like)
  - Solution: take $\ell\ell + \text{jets}$ events from data
  - Select events with a jet that is *somewhat* photon-like (e.g. passes "loose" identification selection)
    - Use this to estimate the shape of $\ell\ell + \text{jets}$ events with jets that are more photon-like
    - Ends up being quite similar to $\ell\ell + \gamma$, can just take $\ell\ell + \gamma$ and correct it a bit

Background estimates

- Now that we know what the two shapes look like, we need their relative contributions, especially under the Higgs peak
- Don't do this check in our measurement region
- Instead:
  - Look at events in data where the third object is more/less photon-like and more/less isolated
  - Learn how the fraction changes, so you can predict what the faction will be in the measurement region

Phys. Lett. B 819 (2021) 136412



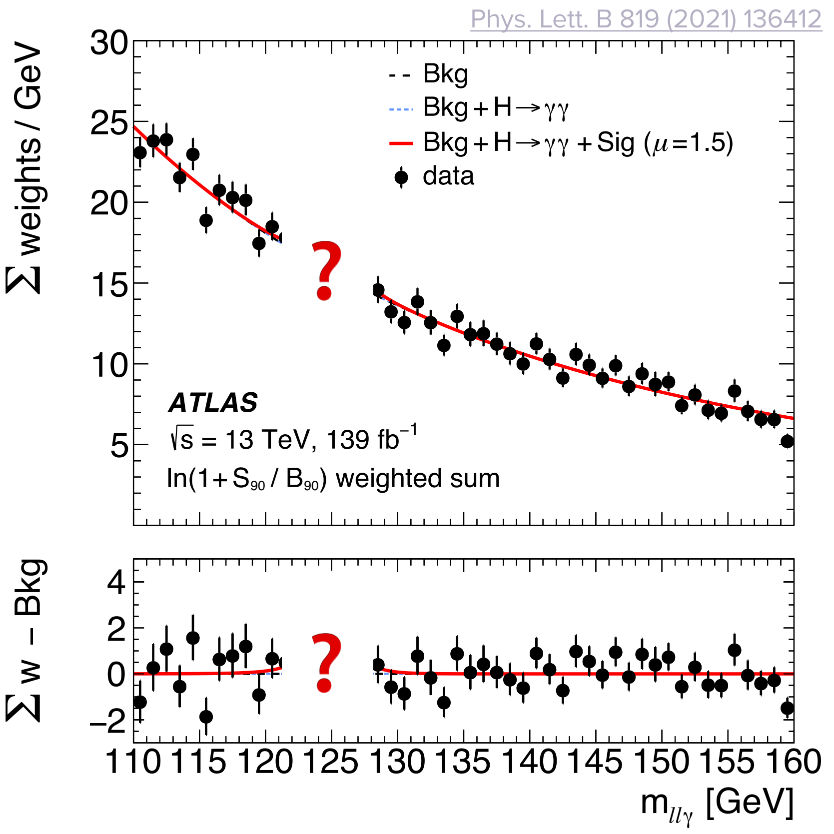
	More isolated	Less isolated
More photon-like	A	B
Less photon-like	C	D

How does the rate of $\ell\ell + \gamma$ vs $\ell\ell + \text{jets}$ change if you ask the object to be more photon-like?

How does the rate of $\ell\ell + \gamma$ vs $\ell\ell + \text{jets}$ change if you ask the object to be more isolated?

Background estimates

- Not done yet!
- Really need to reduce statistical fluctuations
    - Smoothest thing you can get: a functional form
    - Function options (from $H \to \gamma\gamma$: power law, Bernstein polynomials or exponential of polynomials)

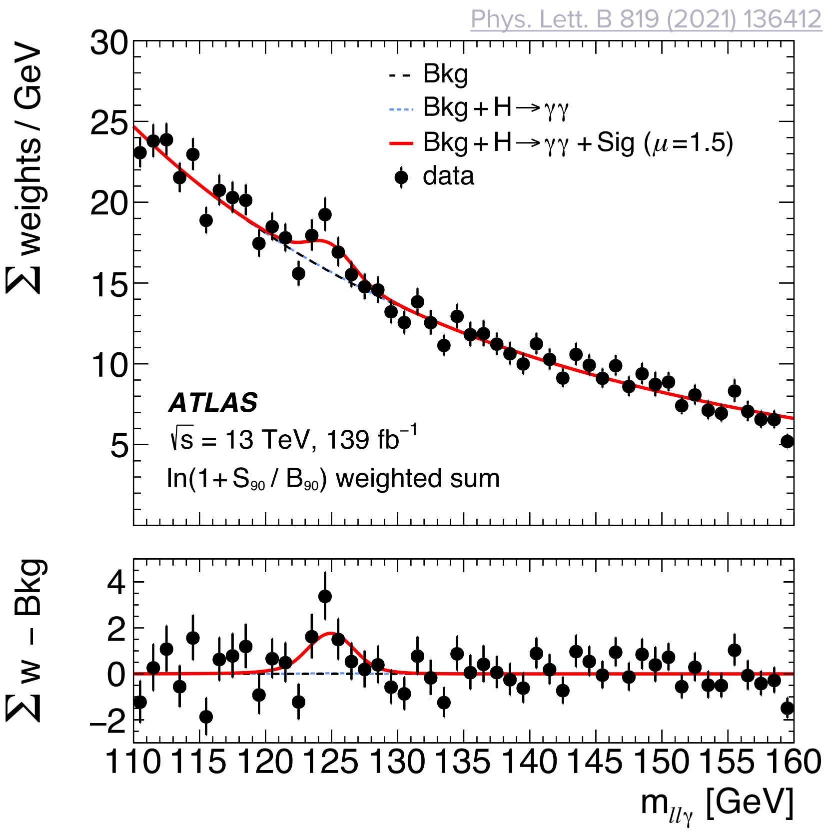


- Fit the $\ell\ell + \gamma$ vs $\ell\ell + \text{jets}$ distribution we created
    - See what function works best
    - Criteria:
        1. Describes data in side-band
        2. Minimises the possibility of finding a signal where there isn't any (spurious signal, i.e. S+B fit to B-only MC)

- Different functions are needed in different regions (e.g. VBF vs ggF)

- Spurious signal is the largest source of systematic uncertainty in this measurement

Results + conclusion



- This kind of analysis was done by ATLAS and CMS
- $H \to \gamma\gamma^*$ and $H \to Z\gamma$ at 3σ "evidence" in Run 2:
  - $H \to \gamma\gamma^*$:
    - 3.2σ observed (2.1σ expected) in ATLAS Phys. Lett. B 819 (2021) 136412
    - 95% CL of ~4.0 x SM for $H \to \gamma\gamma^* \to \mu\mu\gamma$ in CMS JHEP 11 (2018) 152
  - $H \to Z\gamma$:
    - 2.2σ observed (1.2σ expected) in ATLAS Phys. Lett. B 809 (2020) 135754
    - 2.6σ observed (1.2σ expected) in CMS JHEP 05 (2023) 233
    - Combined 3.4σ observed (1.6σ expected) PRL 132 (2024) 021803
- Results are above SM expectation near m_Z and way from it, and in ATLAS and CMS
  - Not very statistically significant, but interesting 🙂
- Stat-limited analyses that greatly benefit from the Run 3 dataset + analysis improvements
  - Stay tuned for Run 3 publications!