Evidence of $H \to \ell\ell\gamma$ decays at ATLAS

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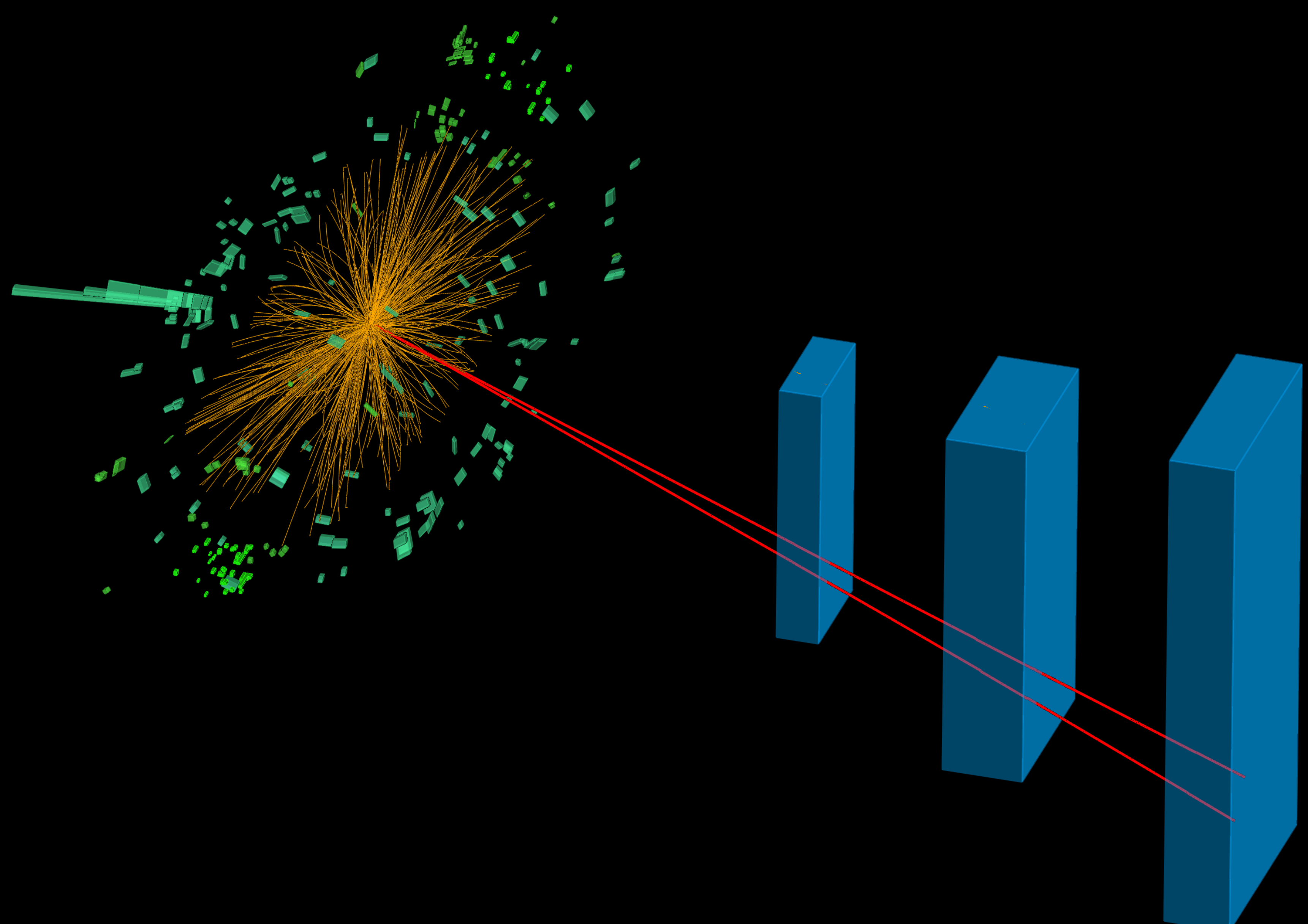
Padova seminar, April 7th, 2021

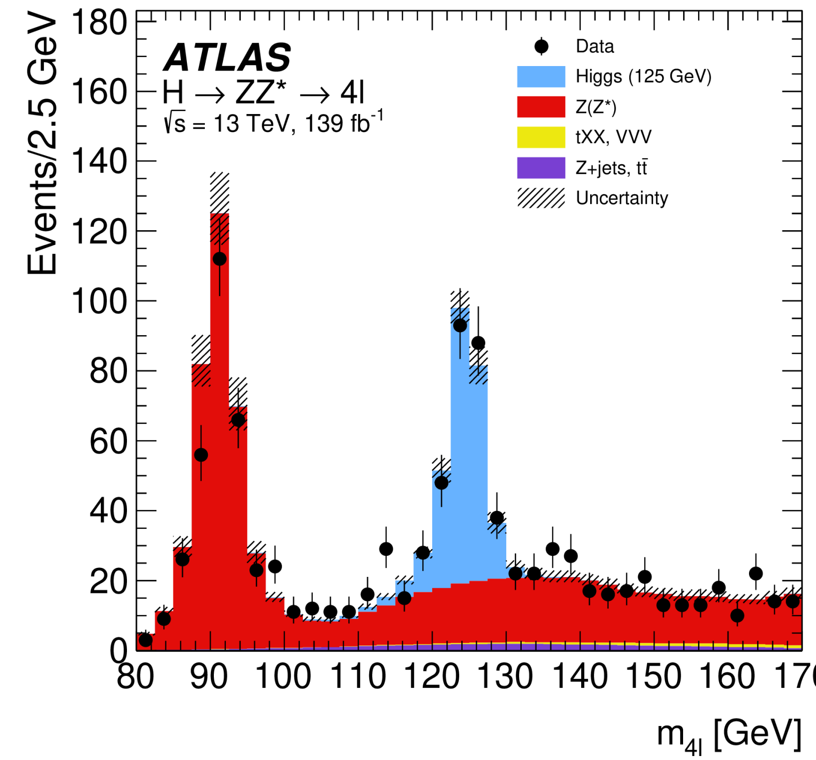


Introduction

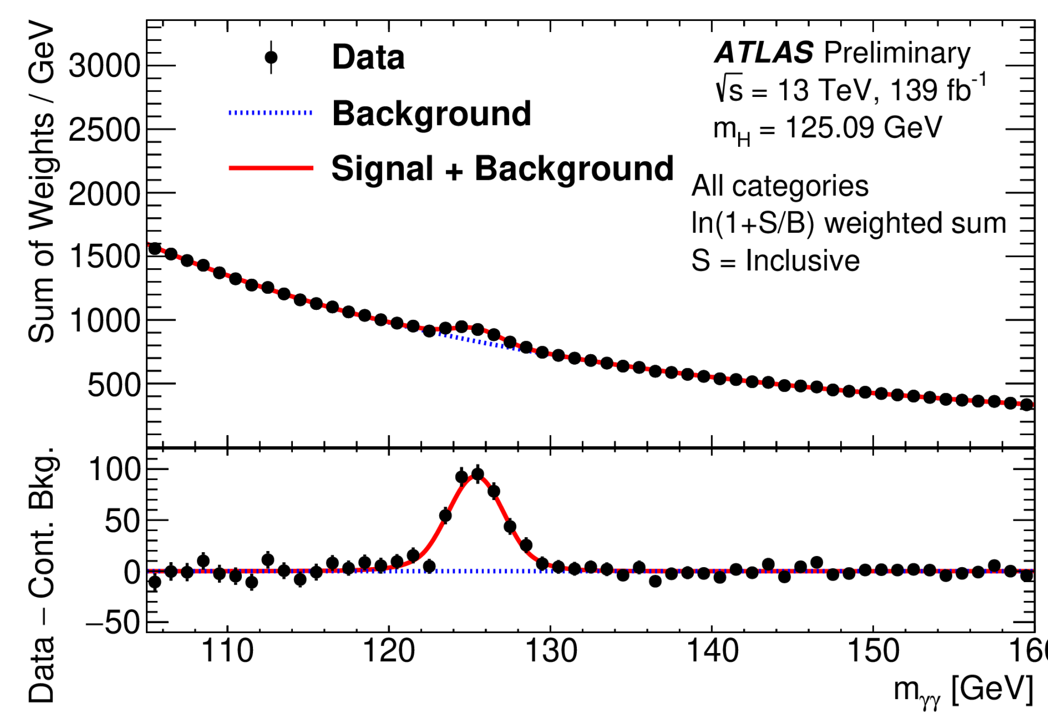
Ever since the discovery of the Higgs boson in 2012: More precise measurements of its properties

- ✔ Higgs mass - 0.1% precision
- ✔ Spin = 0
- ✔ Higgs production
  - all major production modes discovered
- ✔ Higgs decays
  - most major decays discovered
  - now tackling rare decays like H->μμ, H->Zγ, ...
  - H->inv constrained to < 11%

=> no disagreements from the SM predictions so far

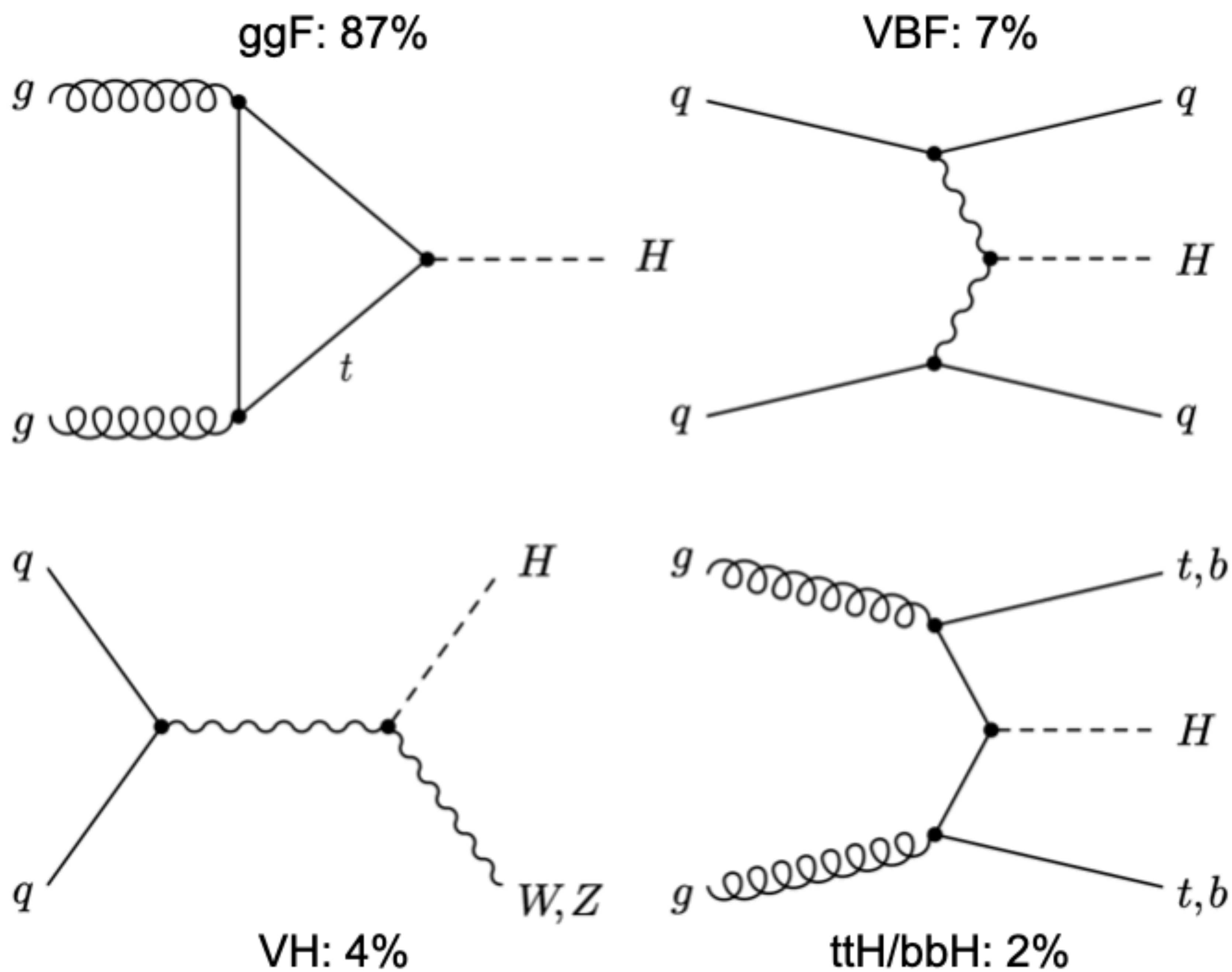


Eur. Phys. J. C 80 (2020) 942



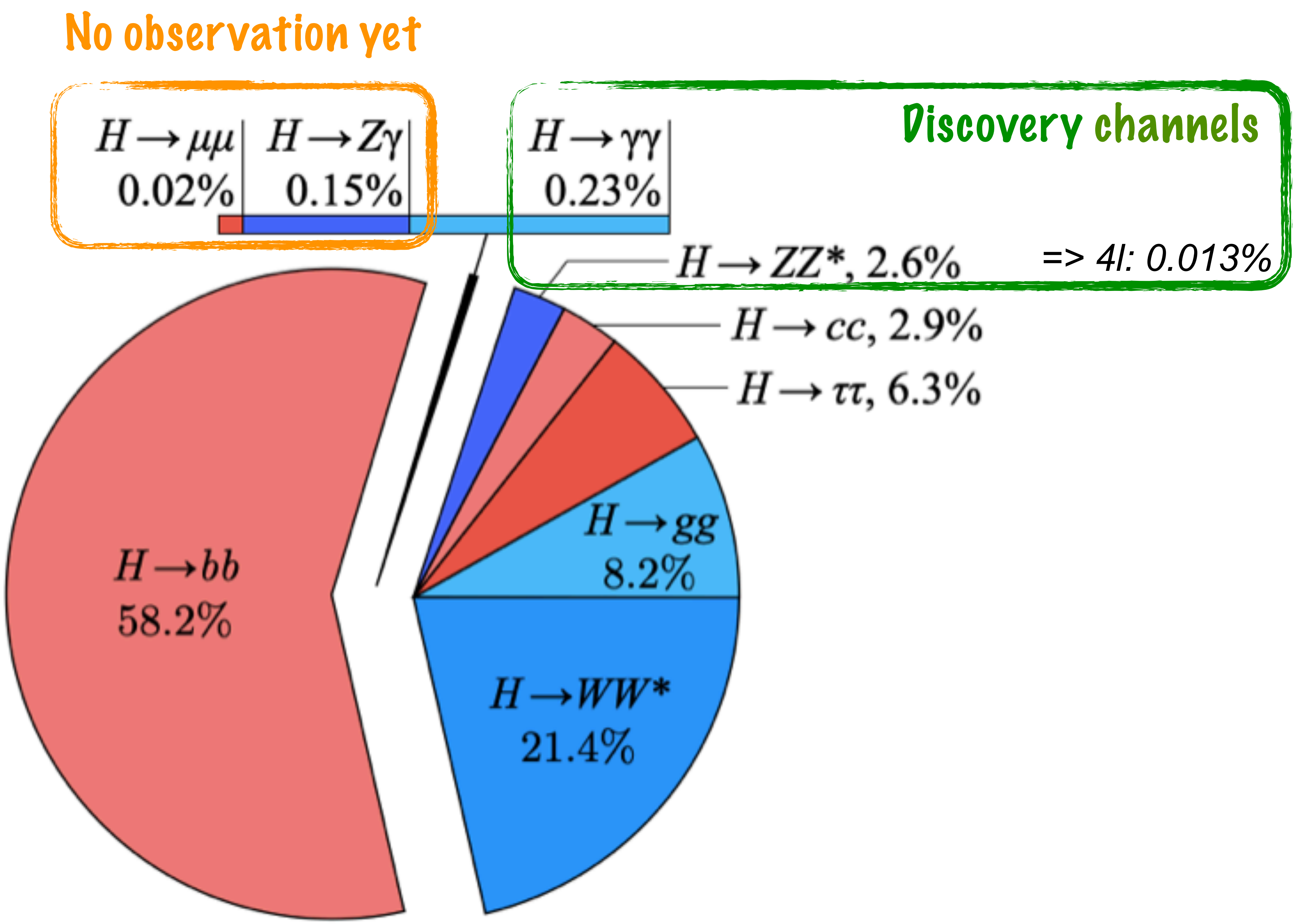
ATLAS-CONF-2020-026

Higgs boson production at the LHC



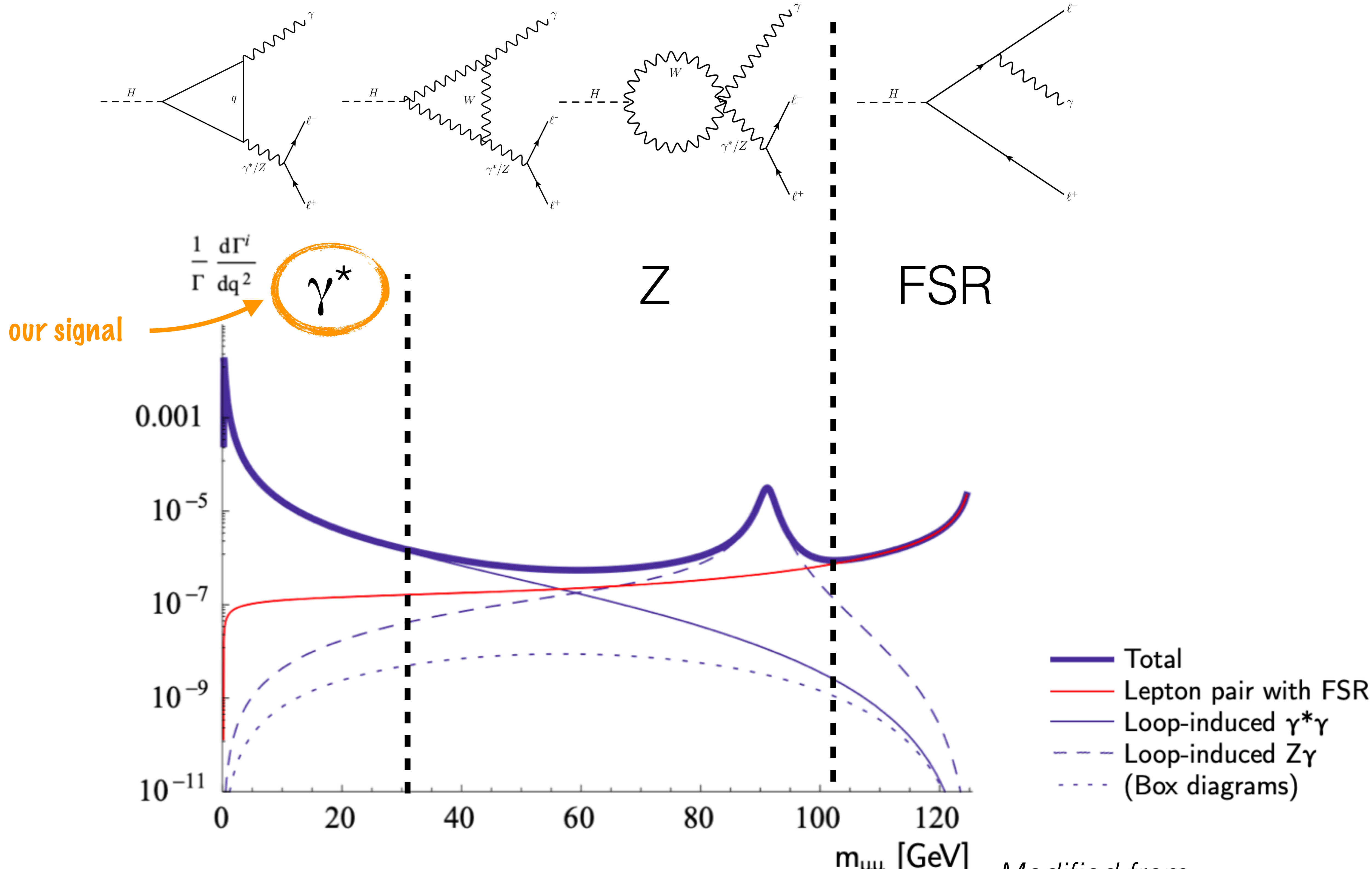
From LHCHWG
m_H = 125 GeV
$\sqrt{s}$ = 13 TeV

Higgs boson decays



From LHCHWG
m_H = 125 GeV

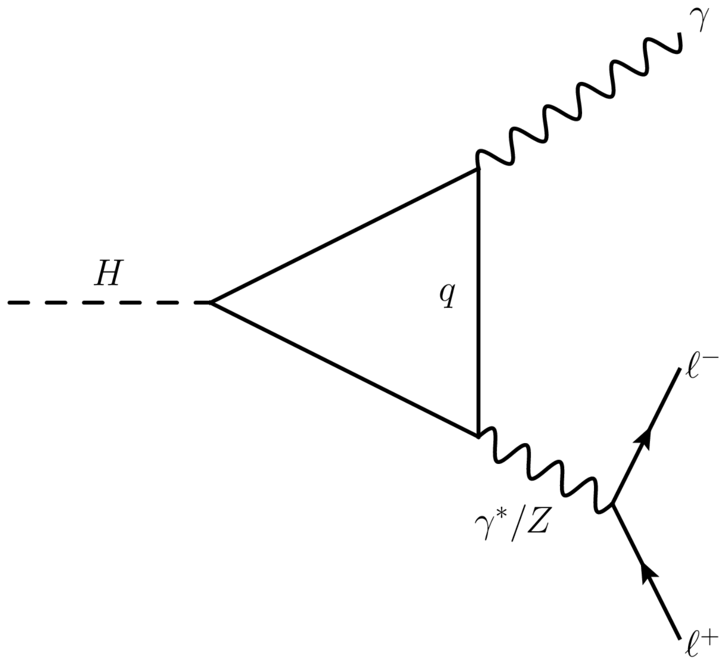
$H \rightarrow \ell\ell\gamma$



Modified from https://arxiv.org/abs/1303.2230

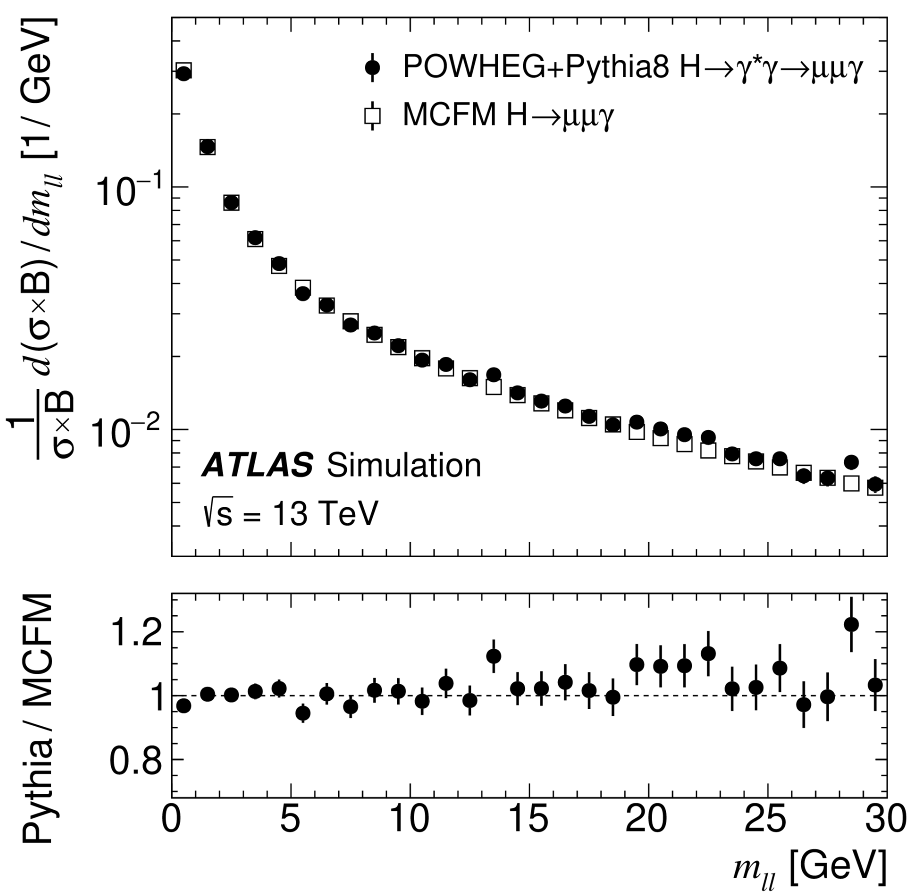
$H \to \ell\ell\gamma$ - motivation

- extremely rare Higgs boson decay (BR for $m_{\ell\ell}$ < 30 GeV ~0.01%)
- loop-induced, tests exotic couplings
- 3 body final state => Higgs CP symmetry tests in the future



Branching ratio calculations for low-$m_{\ell\ell}$ process

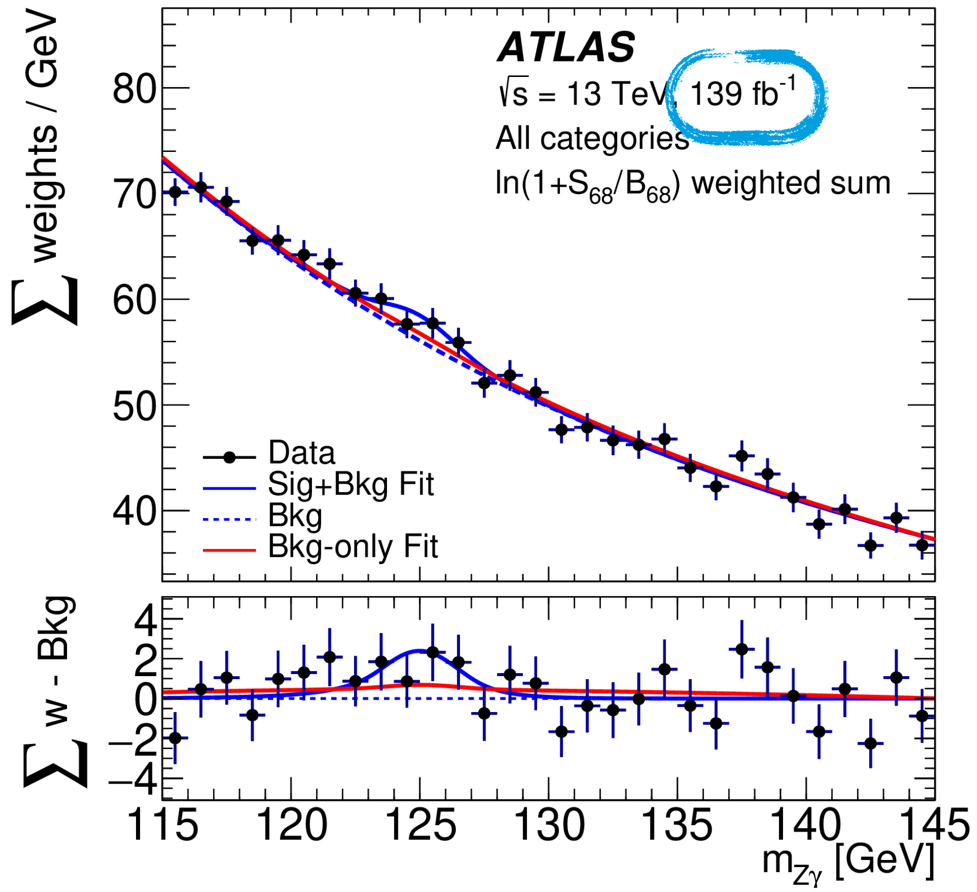
- different calculations for low-$m_{\ell\ell}$ process available, not all in agreement
- they come without uncertainty
- in this analysis: modelled with Pythia as a fraction of $\gamma\gamma$, for $m_{\ell\ell}$ < 30 GeV
  - in ~3% agreement with calculations in
    - Firan, Stroynowski (Phys. Rev. D 76, 057301)
    - Dicus, Repko (Phys. Rev. D 87, 077301)
- assumed BR uncertainty to be the same as $Z\gamma$ (5.8%)

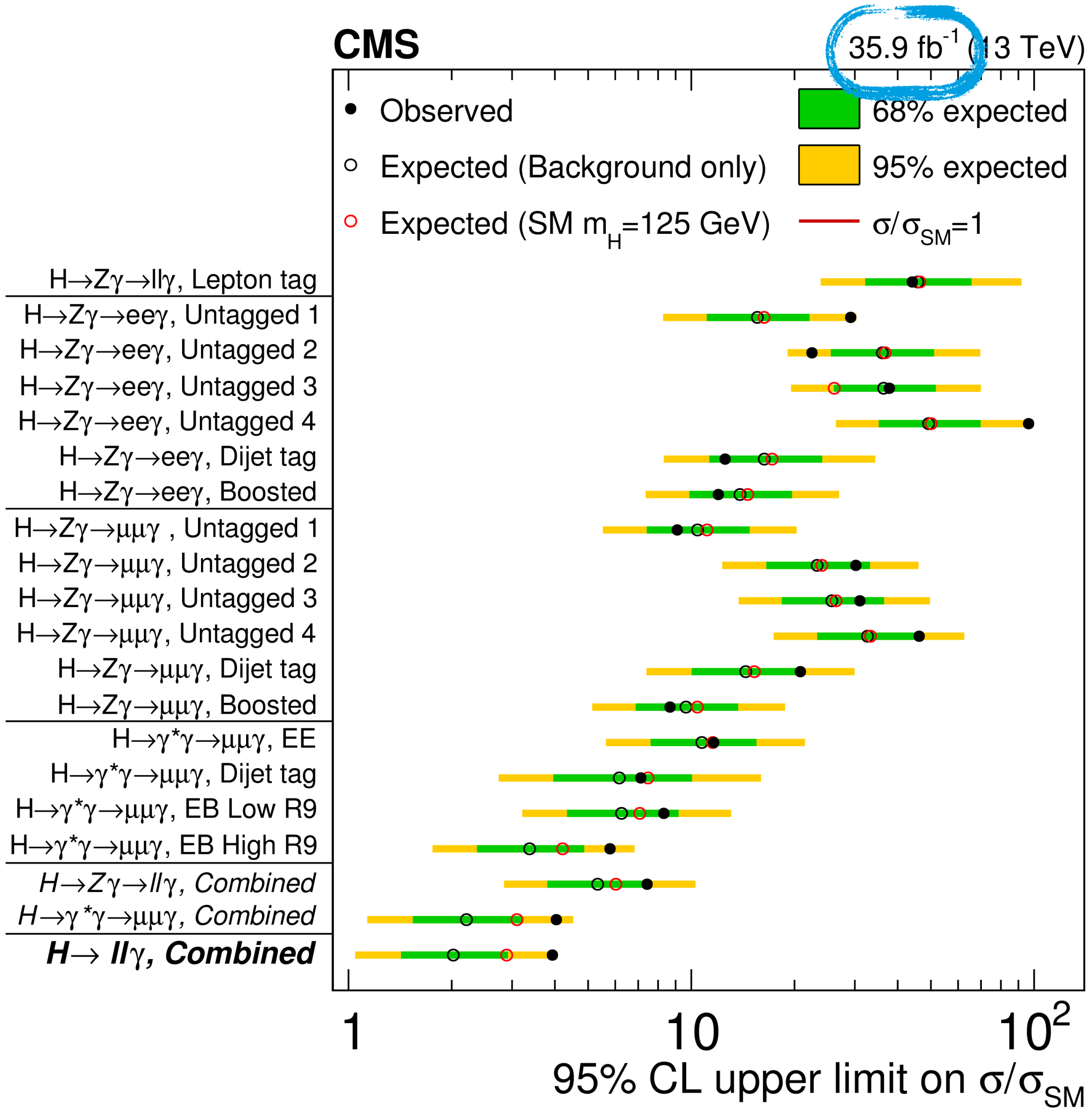


H → ℓℓγ - previous measurements

Zγ (ATLAS, Phys. Lett. B 809 (2020) 135754)

- $m_{\ell\ell}$: Z boson mass +/-10 GeV
- significance: 2.2 σ (expected w/ Higgs: 1.2 σ)
- upper limit: 3.6 * SM (expected w/ Higgs: 2.6 * SM)





ℓℓγ (CMS, JHEP 11 (2018) 152)

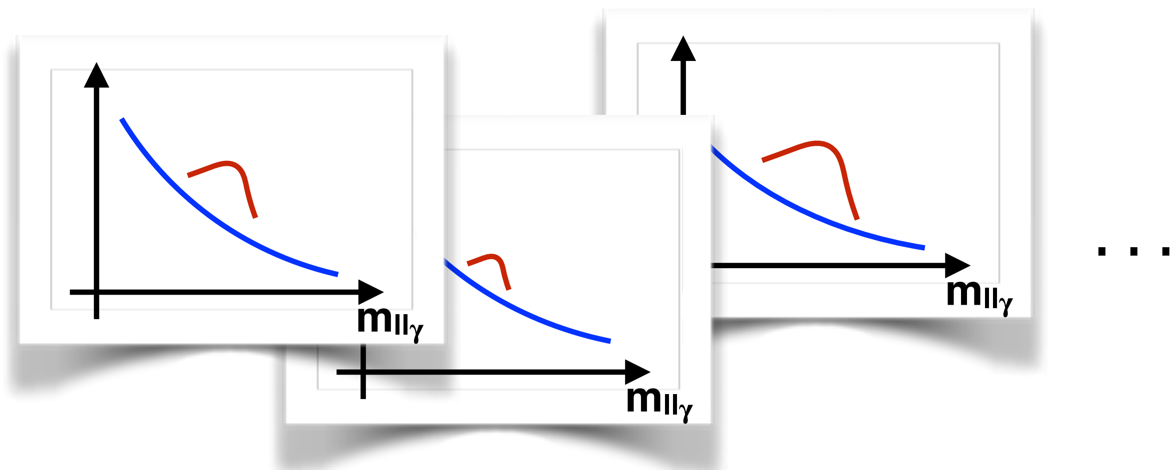
Upper limit Zγ: 7.5 * SM
(expected w/ Higgs: 6 * SM)

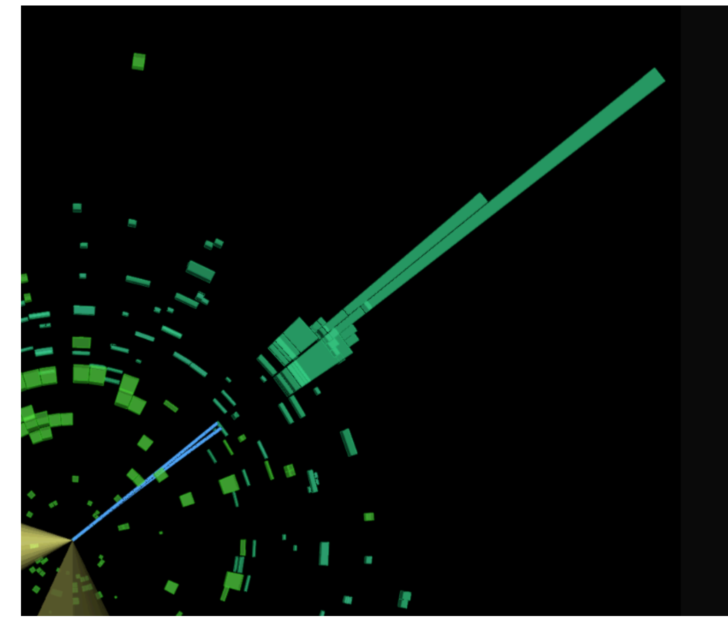
Upper limit γ*γ (μμ): 4 * SM
(expected w/Higgs: 3 * SM)

Analysis overview and challenges

Resonance search using $\ell\ell\gamma$ invariant mass spectrum

- 9 categories to enhance the sensitivity
- functional parameterization of signal and background



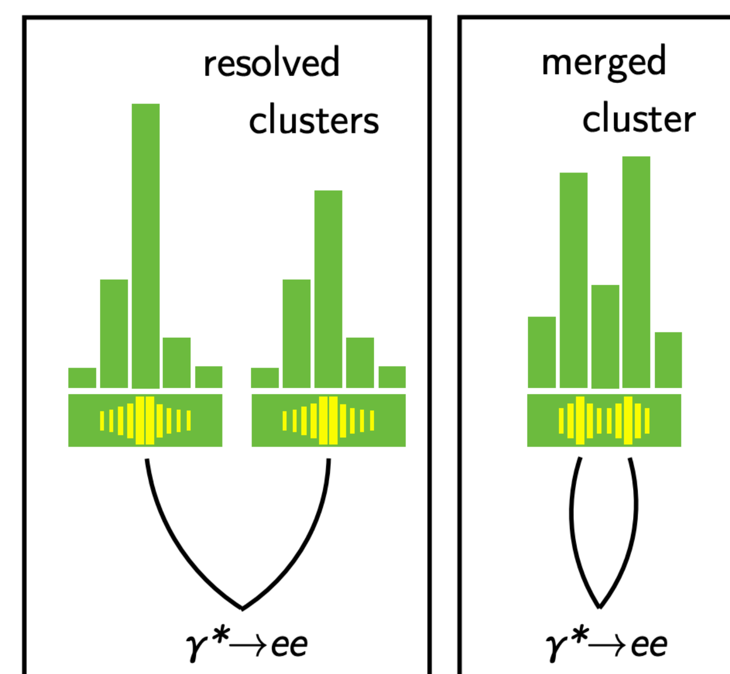


Biggest challenge:

- collimated leptons due to low invariant mass of γ^*
- especially problematic for electrons => overlapping EM clusters

=> two categories of electron pairs in this analysis:
 resolved and merged (close-by)

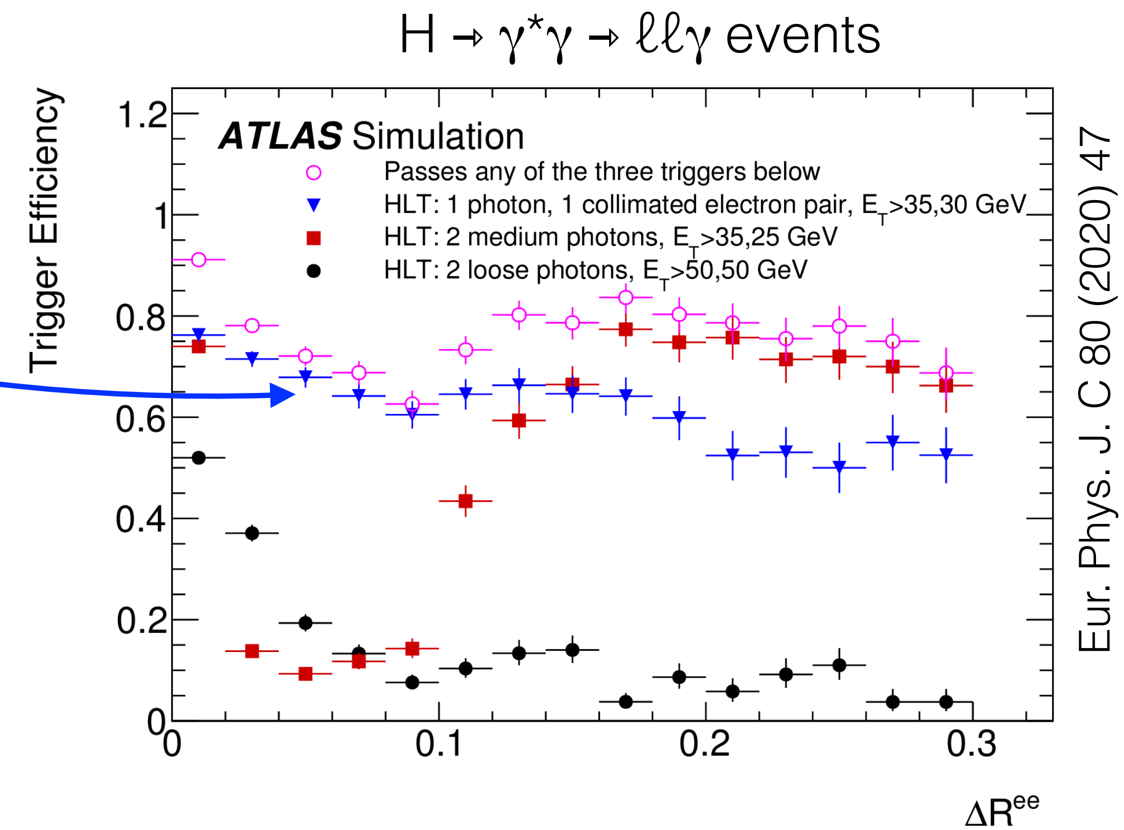
- important for muons and resolved electrons:
    - remove energy deposit of nearby lepton from isolation cone calculation



Close-by electrons - trigger/reco/ID

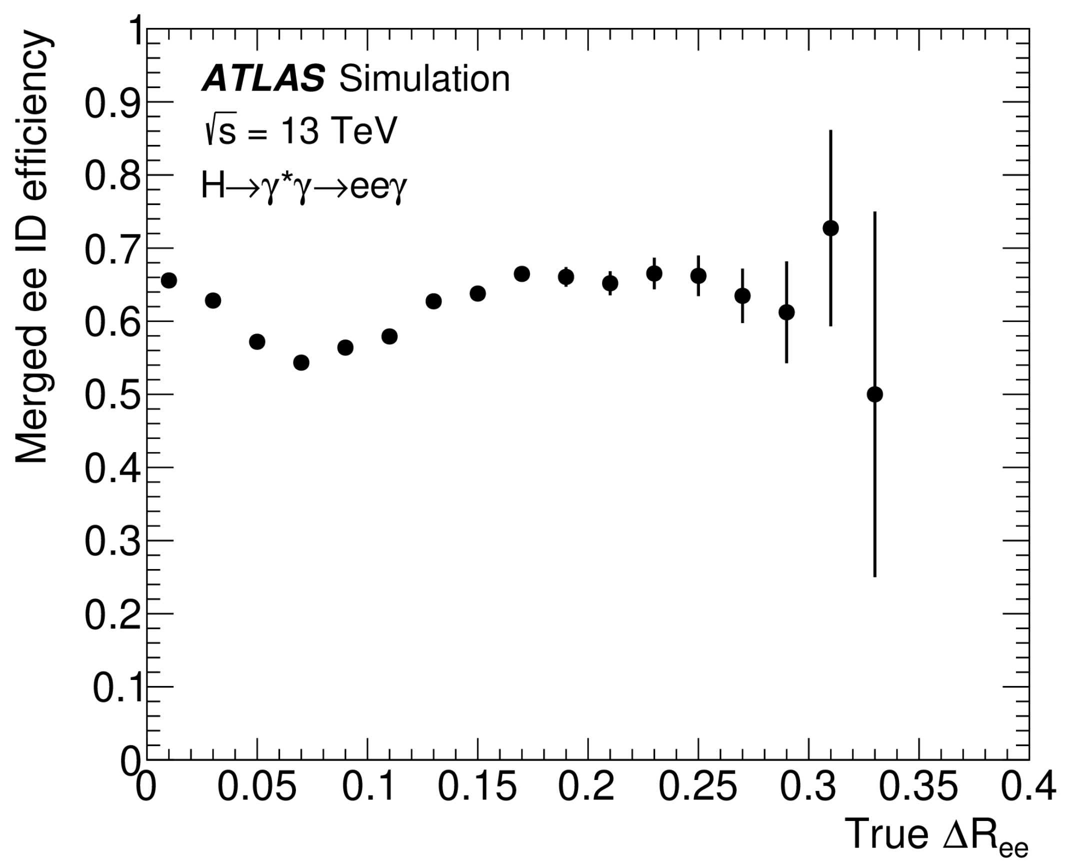
Trigger

- starting 2017: 1 photon + 1 EM cluster without shower width requirements (matched to track)



Reconstruction

- 1 EM cluster, matched to two tracks
- tracks: opposite charged, hits in innermost Pixel layer, no match to conversion vertex with R > 20 mm
- 4-vector: calibrated energy from cluster, direction from two-track vertex

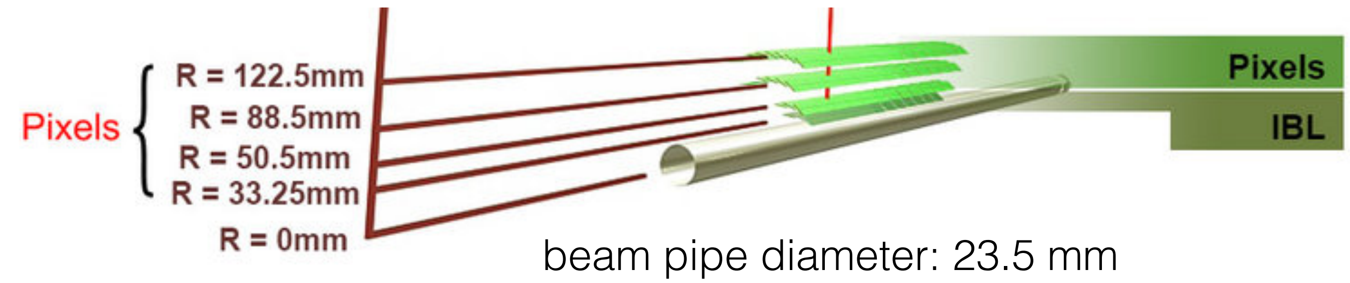


Identification of merged electrons

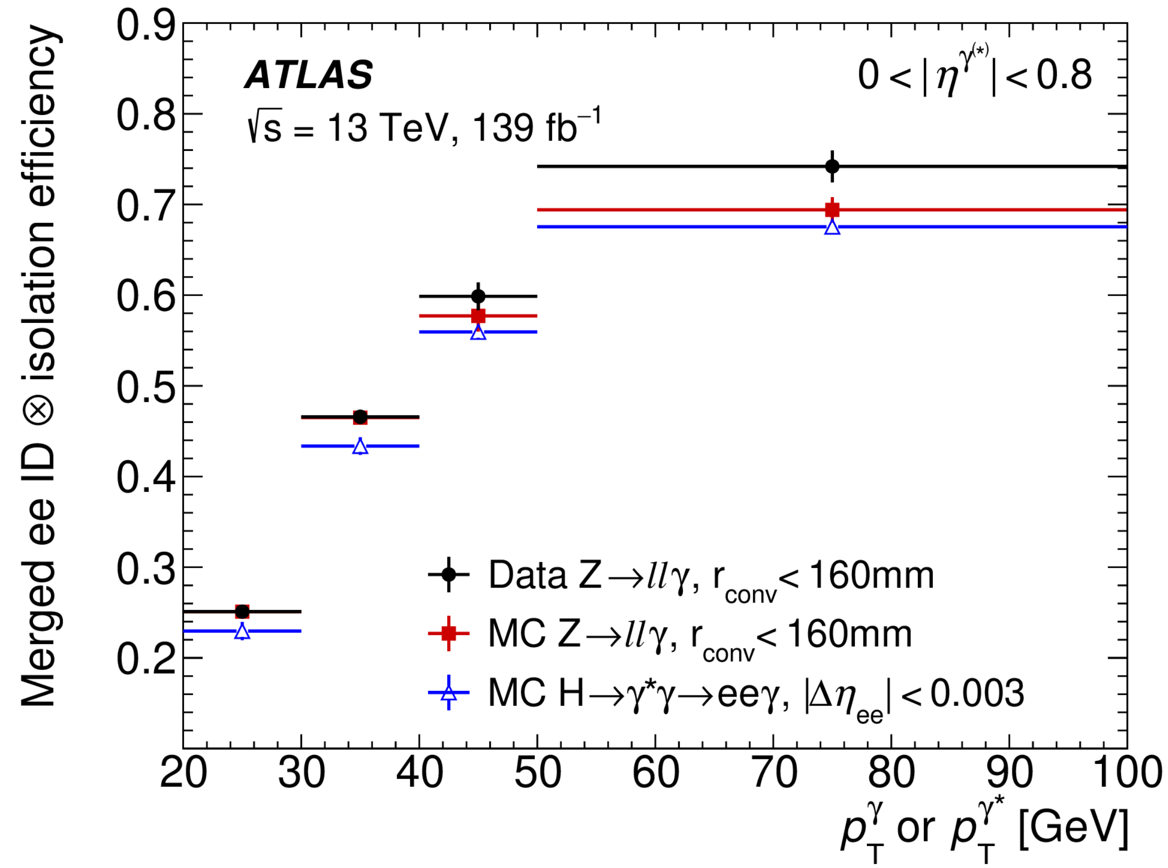
- custom cut-based ID
  - shower shape and tracking variables
    - including cluster-vertex/track matching
  - backgrounds: hadronic jets, single electrons

Close-by electrons - efficiency measurements

- **Need objects with a signature similar to γ*:**
  - photons converting to e+e- pair close to the interaction point
  - (γ*: larger opening angle due to mass)



- **Use Z(ℓℓ) production + FSR γ**
  - require photon conversions within R < 160 mm
  - measure identification and isolation efficiencies in data with T&P method ($m_{\ell\ell\gamma}$ mass as discriminating variable)
  - compare data and simulation to derive correction factors



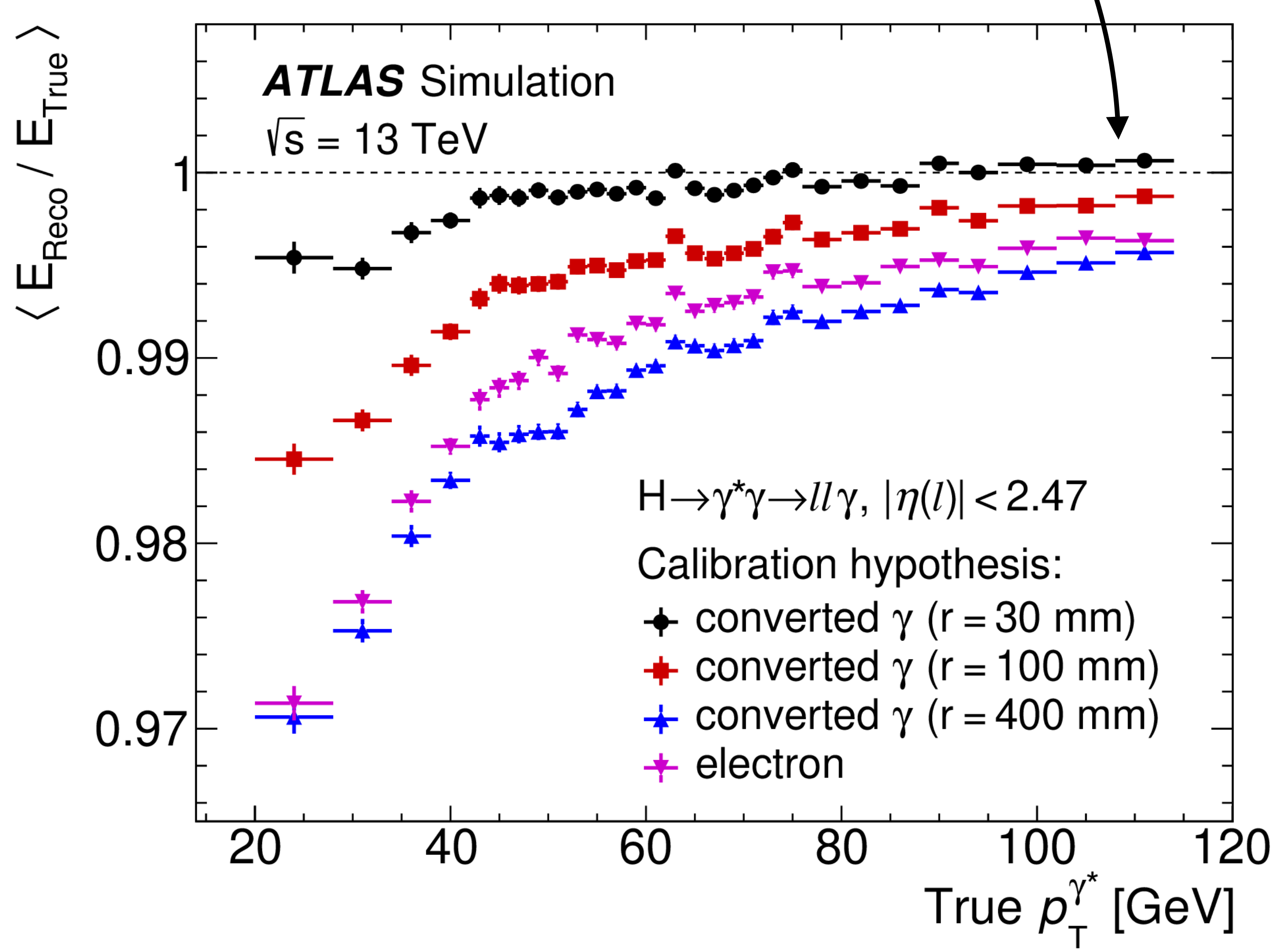
Close-by electrons - energy calibration

Single-electron calibration hypothesis leads to underestimate of energy

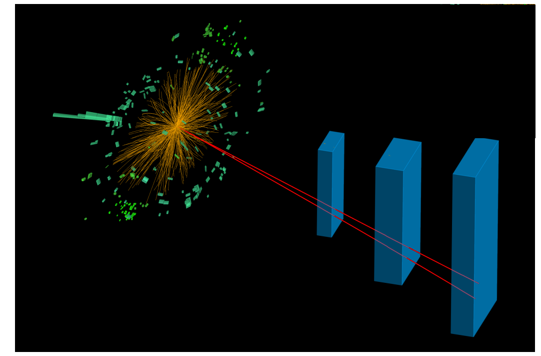
>> calibrate merged electrons like **converted photons with a conversion radius of 30 mm**

Resolution

- additional uncertainty assigned based on resolution differences between converted photons and merged electrons



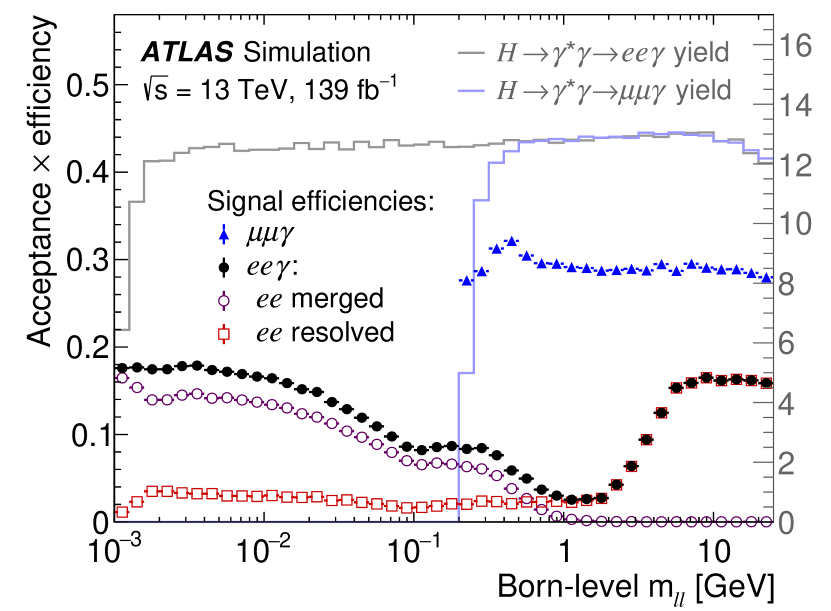
Event selection and categorization



Event selection

- mix of triggers
  - single-ℓ, 2ℓ, γ–ℓ, γγ, γ–2ℓ (total efficiency 97%)
- 2 leptons + 1 photon
  - priority: muon pairs
  - $p_T(\mu) > 11$ GeV, $p_T(e) > 13$ GeV, p_T(merged-ee) > 20 GeV
- relative p_T cuts: $p_T(\ell\ell)/m_{\ell\ell\gamma} > 0.3$, $p_T(\gamma)/m_{\ell\ell\gamma} > 0.3$
- $m_{\ell\ell} < 30$ GeV, outside J/ψ and Υ(ns) windows

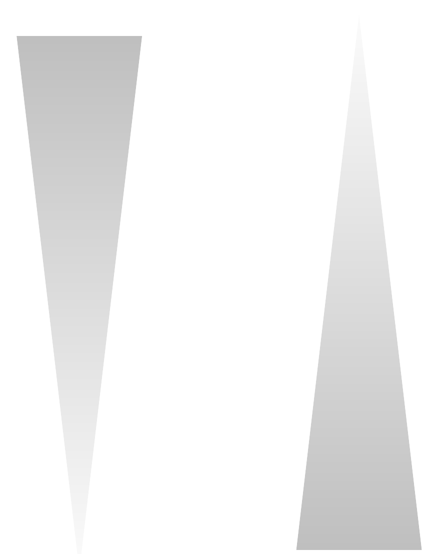
Removed J/ψ, Υ(ns) criteria for this plot



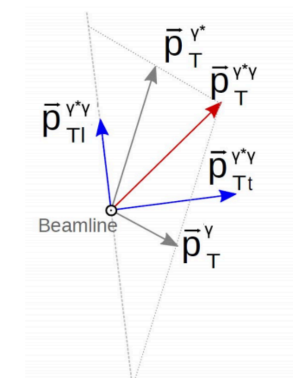
Categorization

- VBF-like (2 jets, high m_{jj}, well separated, …)
- High p_{Tt} (!VBF, ~high Higgs transverse momentum)
- Low p_{Tt} (rest)

S/B statistics



=> 9 categories: (μμ, ee, merged-ee) x (VBF, high p_{Tt}, low p_{Tt})



p_T "thrust":

In the plane transverse to the beam, projection of the $\mathbf{p}_T^{\gamma^*\gamma}$ perpendicular to $\mathbf{p}_T^{\gamma^*} - \mathbf{p}_T^{\gamma}$

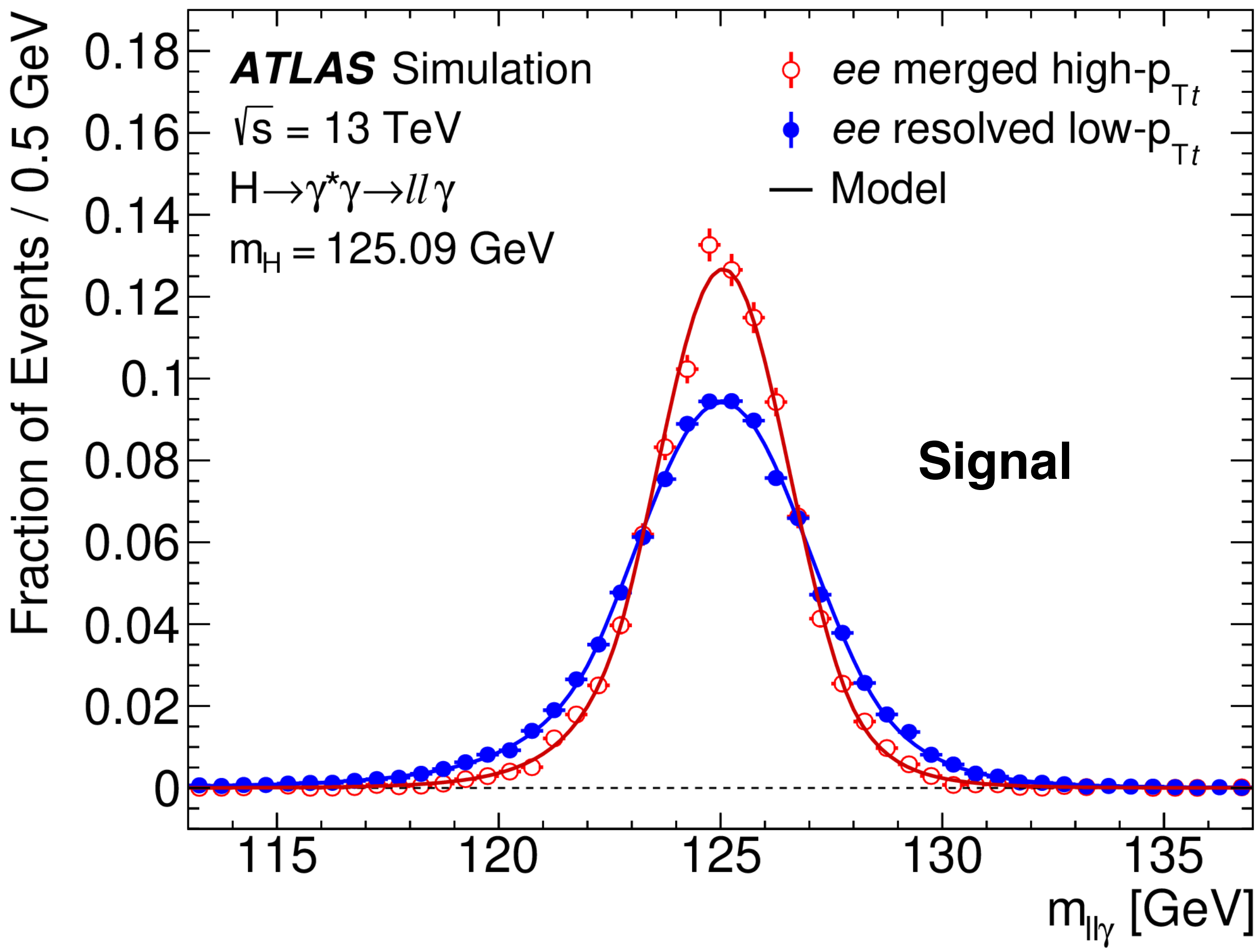
highly correlated with $\mathbf{p}_T^{\gamma^*\gamma}$ but with better experimental resolution

Signal and H → $\gamma\gamma$ background modelling

- discriminating variable: $m_{\ell\ell\gamma}$

- Double-sided Crystal-Ball function fit to simulated Higgs H → $\gamma^*\gamma$ → $\ell\ell\gamma$ events to obtain parameters
  - use best available Higgs MC samples and cross sections
    - p.ex. Powheg NNLOPS for ggF, scaled to N^3LO
  - assumed Higgs mass: 125.09 GeV

- same parameterization used for (small) resonant H → $\gamma\gamma$ background (from converted photons), scaled to expected cross section

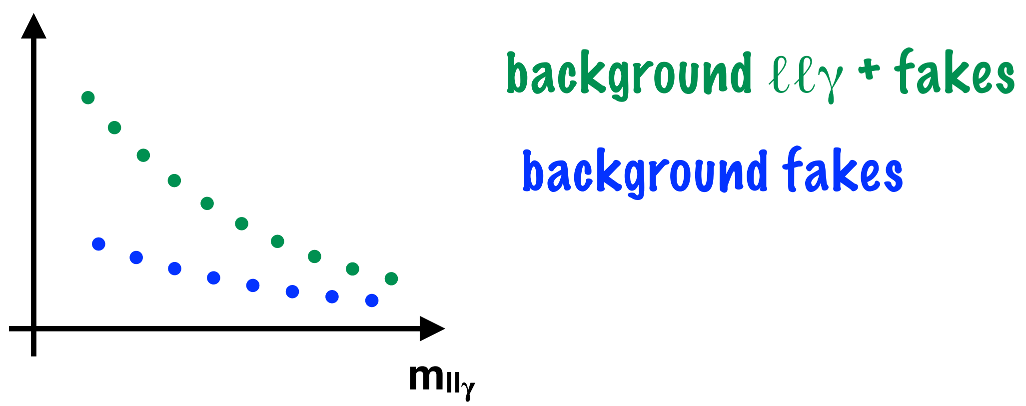


σ = 1.6 GeV
σ = 2.2 GeV

Background estimates - overview

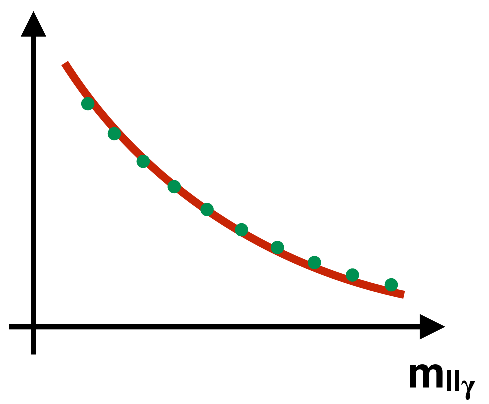
1) Build a background template

- create templates and determine relative normalization for the different components
- add up



2) Find a parameterization

- find a functional form that can describe the background-only template (parameters are later extracted in the fit to data)

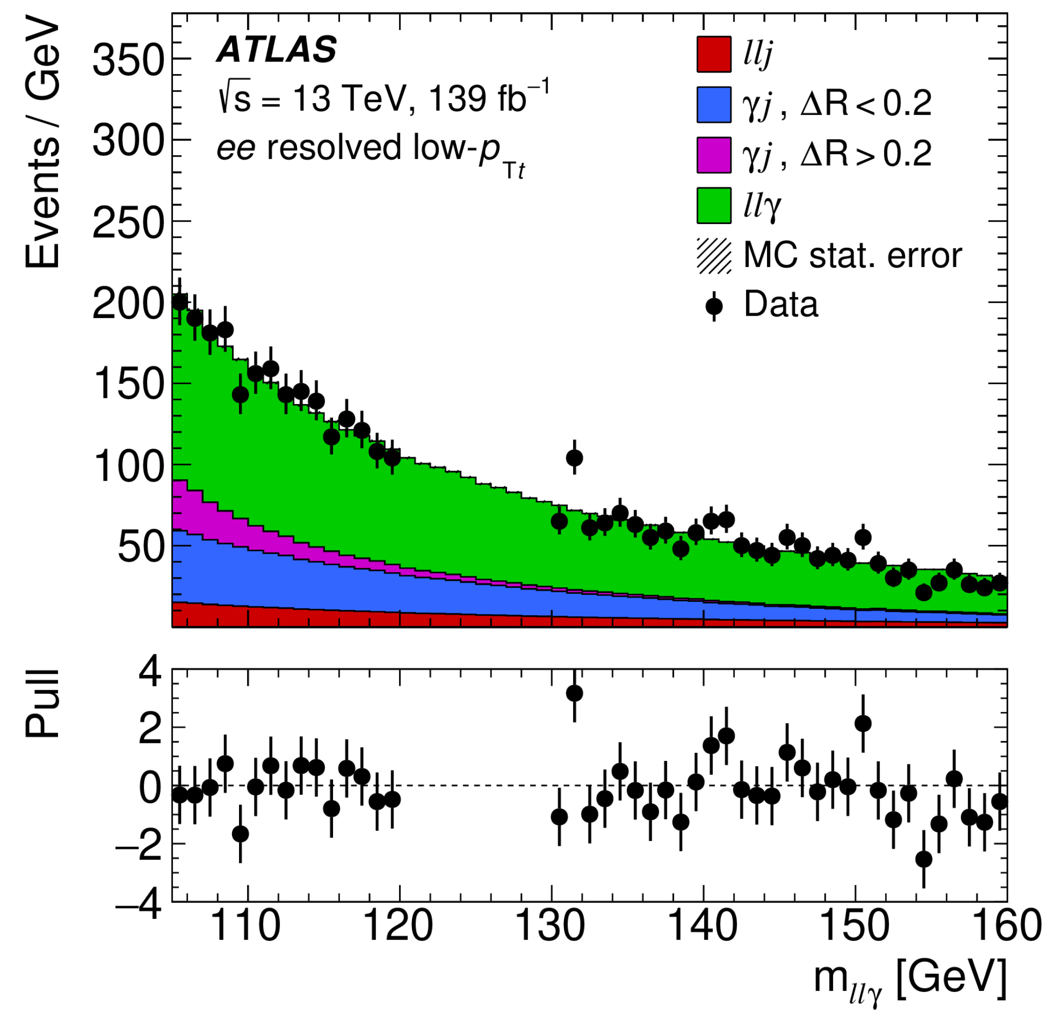


Background estimates - template building

1) Build a background template

Non-resonant $\ell\ell\gamma$ background:

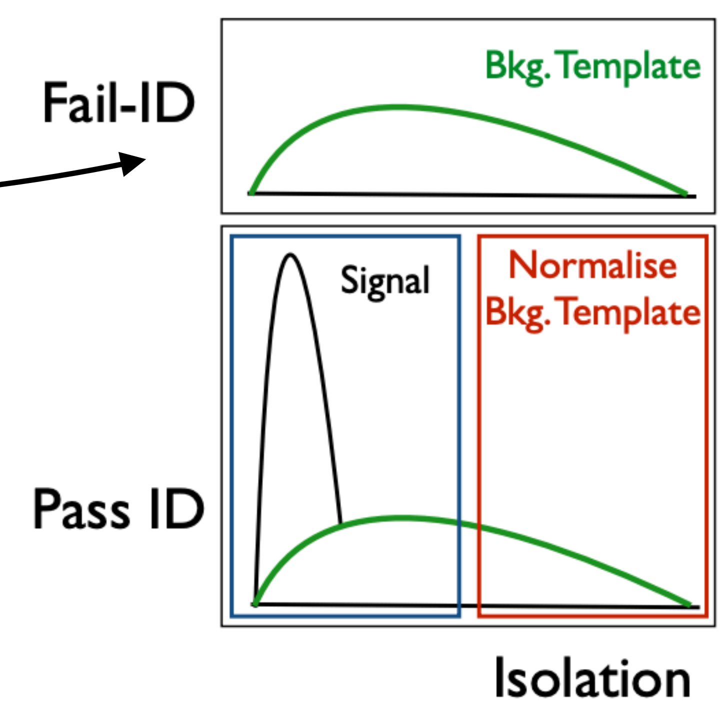
- generator-level samples with parameterized object efficiencies
- generator: leading order Sherpa for 0, 1, 2, 3 jets



Reducible backgrounds:

Events with fake photons or fake leptons

- to obtain composition: sideband method
  - isolation distribution as discriminating observable
  - inverted ID to create background template
  - **fraction of events with fake photon ~10%**
  - **fake leptons: category-dependent - 2-30%**
- to obtain $m_{\ell\ell\gamma}$ shape: control region



Background estimates - function choice

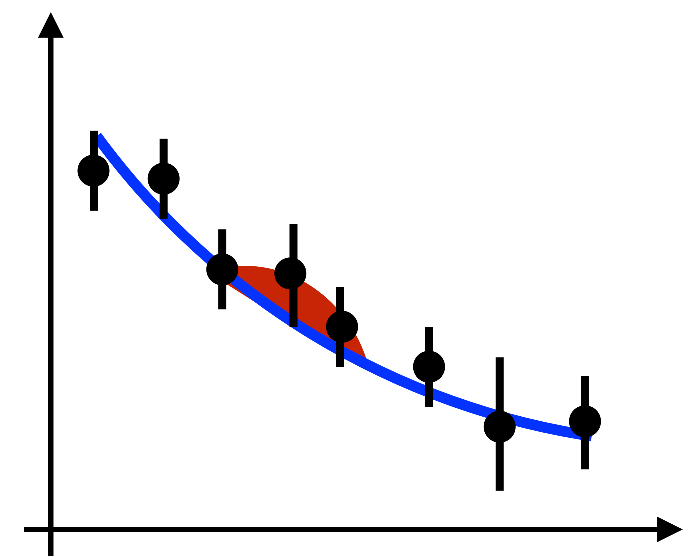
Similar procedure used for all ATLAS H->γγ and H->ℓℓγ analyses

2) Choose the function with fewest degrees of freedom and smallest "fake"/spurious signal when fitted to the background-only template

- test signal hypothesis between 121 GeV and 129 GeV, take absolute maximum bias as spurious signal

Spurious signal must be

- less than 10% of expected $H \to \gamma^*\gamma \to \ell\ell\gamma$
  - OR less than 20% of its statistical uncertainty (due to expected number of background events)
  - criteria is relaxed by the statistical uncertainty due to the template (MC stats)
- in background-only fit of template, function must pass a χ^2 test with P > 1%.
- F-test on data sideband also a function of the same family with more degrees of freedom to check which one is preferred



Remaining bias: systematic uncertainties

Chosen background functions:

- Power-law ($m_{\ell\ell\gamma}^{\alpha}$) for all categories
  - except for three categories: $\exp(\alpha^* m_{\ell\ell\gamma})$, $\exp(\alpha^* m_{\ell\ell\gamma}+\beta^* m_{\ell\ell\gamma}^2)$

Systematic uncertainties

Analysis is dominated by statistical uncertainties, systematic uncertainties ~35% of the total uncertainty

Dominant systematic uncertainties

- Background estimate
  - spurious signal
- Branching ratio
  - from $Z\gamma$ calculations
- QCD scale
  - differential in categories, p.ex. ggF contribution in VBF category
- Lepton and photon ID and calibration
  - in particular for the merged electrons

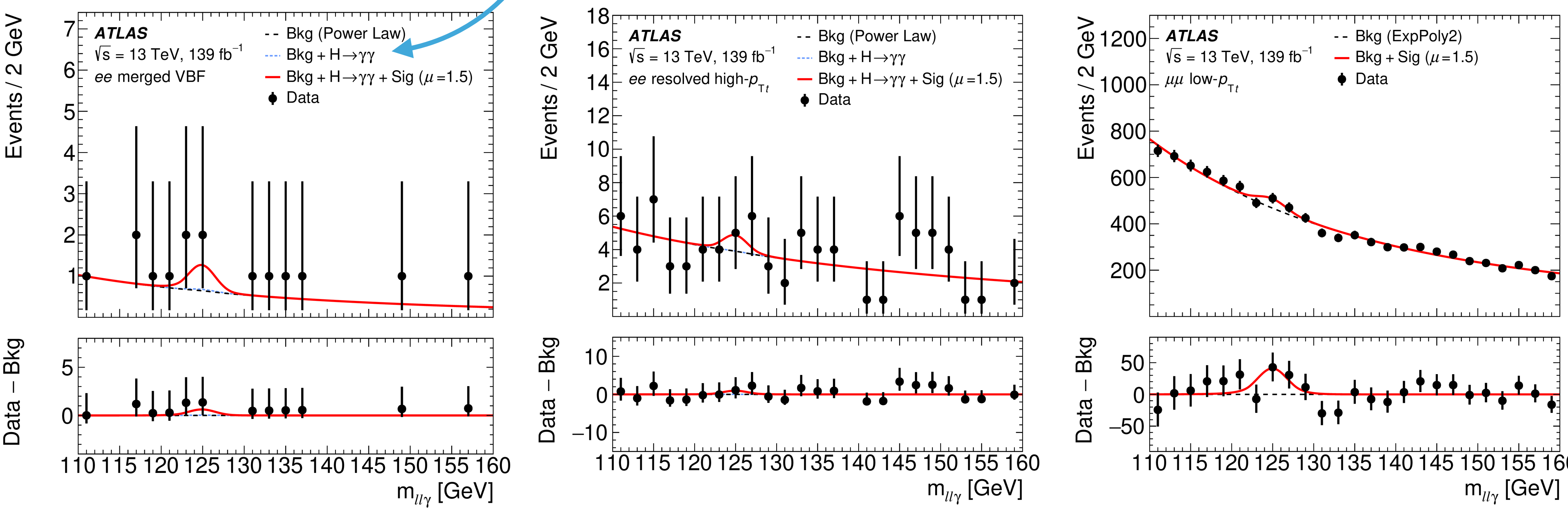
Uncertainty source	μ	$\sigma \times \mathcal{B}$
Spurious Signal	6.1	
$\mathcal{B}(H \to \ell\ell\gamma)$	5.8	–
QCD scale	4.7	1.1
ℓ, γ, jets	4.0	
PDF	2.3	0.9
Luminosity	1.7	
Pile-up	1.7	
Minor prod. modes	0.8	
$H \to \gamma\gamma$ background	0.7	
Parton Shower	0.3	
Total systematic	11	7.9
Statistical	31	
Total	33	32

Fit and results (individual categories)

Simultaneous signal + background likelihood fit in all categories (110 GeV < $m_{\ell\ell\gamma}$ <160 GeV)

3 of the 9 categories

at most few %



ee merged VBF | **ee resolved high-p_{Tt}** | **μμ low-p_{Tt}**

Results

Observed significance: 3.2 σ

Expected: 2.1 σ

Measured signal strength:

$$\mu = 1.5 \pm 0.5$$
$$= 1.5 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$$

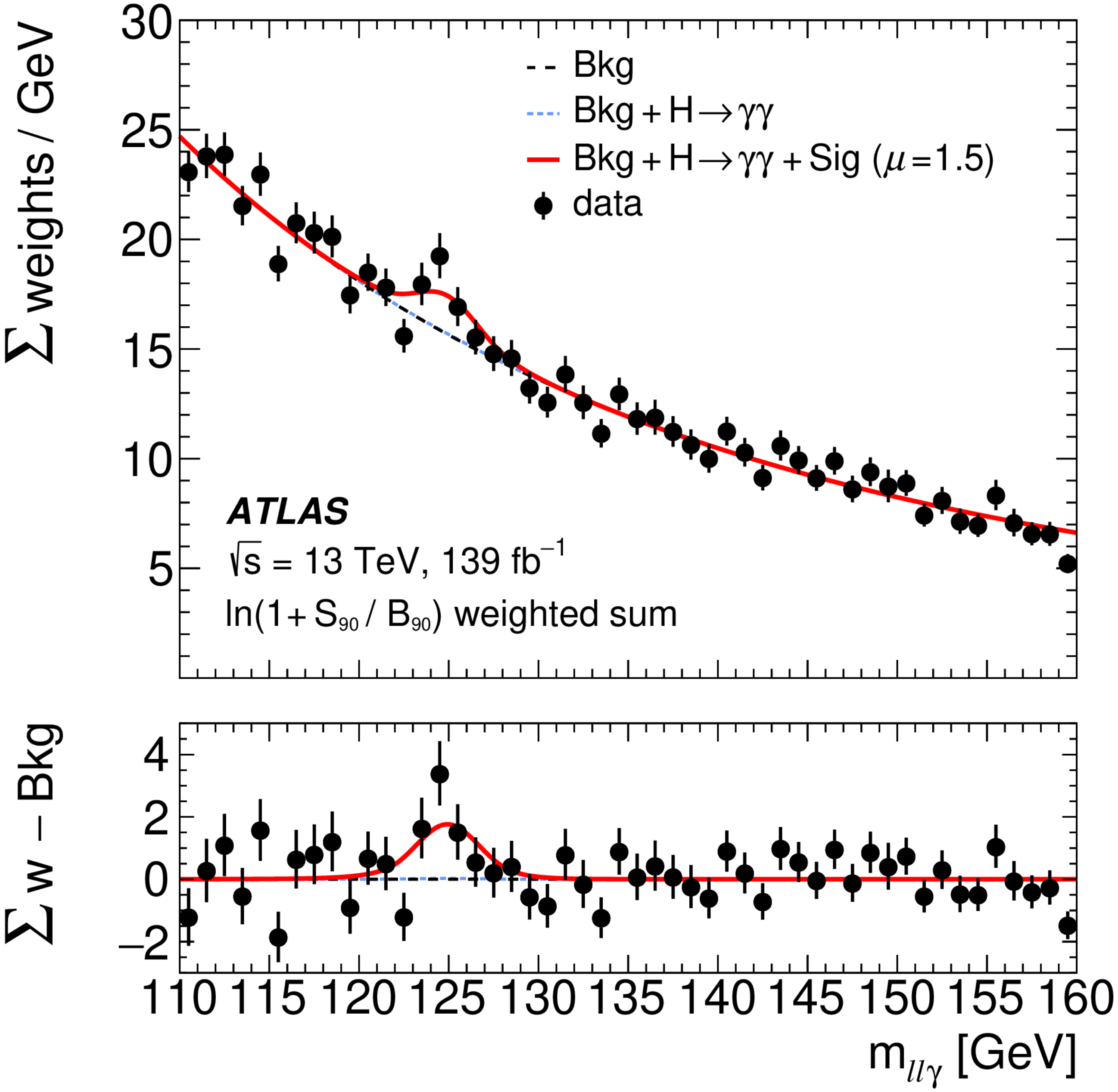
Measured XS * BR ($m_{\ell\ell}$ < 30 GeV):

$$\sigma \times \mathcal{B} = 8.7\ ^{+2.8}_{-2.7}\ \text{fb}$$
$$= 8.7 \pm 2.7\ (\text{stat.})\ ^{+0.7}_{-0.6}\ (\text{syst.})\ \text{fb}$$

First evidence of the H → $\ell\ell\gamma$ decays!

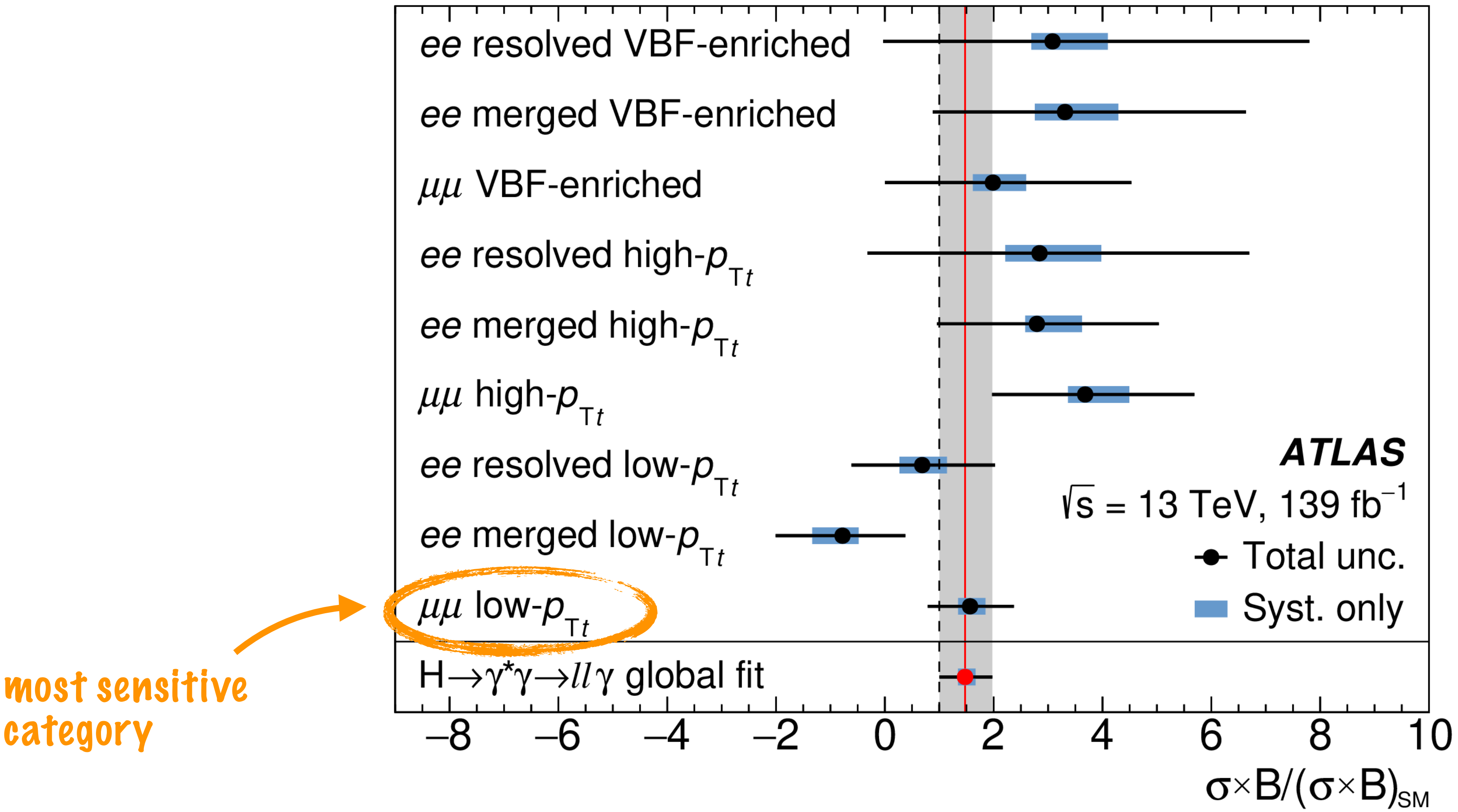
arXiv: 2103.10322

submitted to PLB



Results (consistency checks)

Fit with 9 parameters of interest

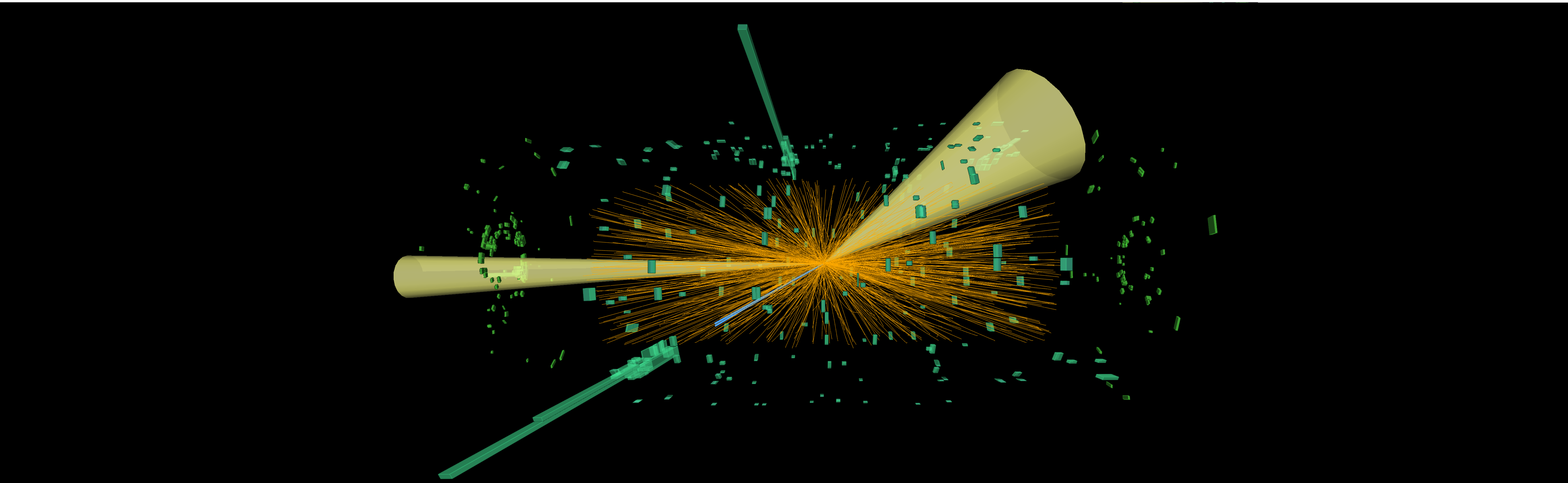


Conclusion & outlook

- Found evidence of a very rare Higgs boson decay
  - first low-mass $\ell\ell\gamma$ search with full Run-2 data, still statistically limited
  - possible analysis improvements for Run 3: use of ML for ID, categorization

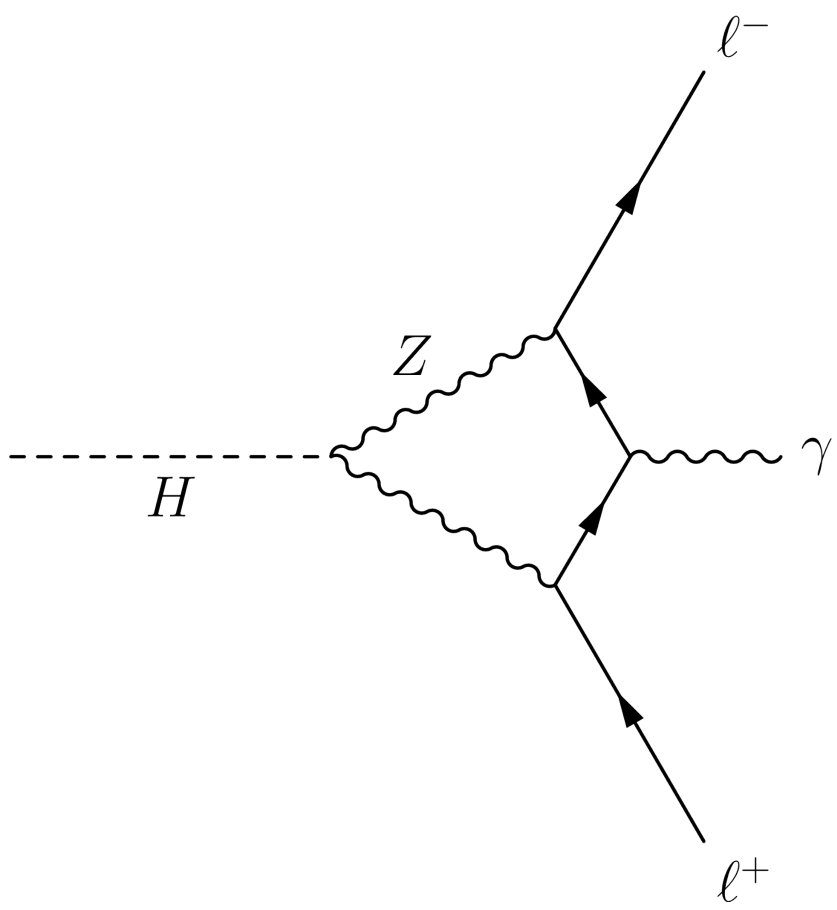
- Looking forward to first $Z\gamma$ evidence (in Run 3?)
  - HL-LHC projection ATLAS: 4.9 σ for $Z\gamma$ with 3000 fb^{-1} (can hopefully be beaten)

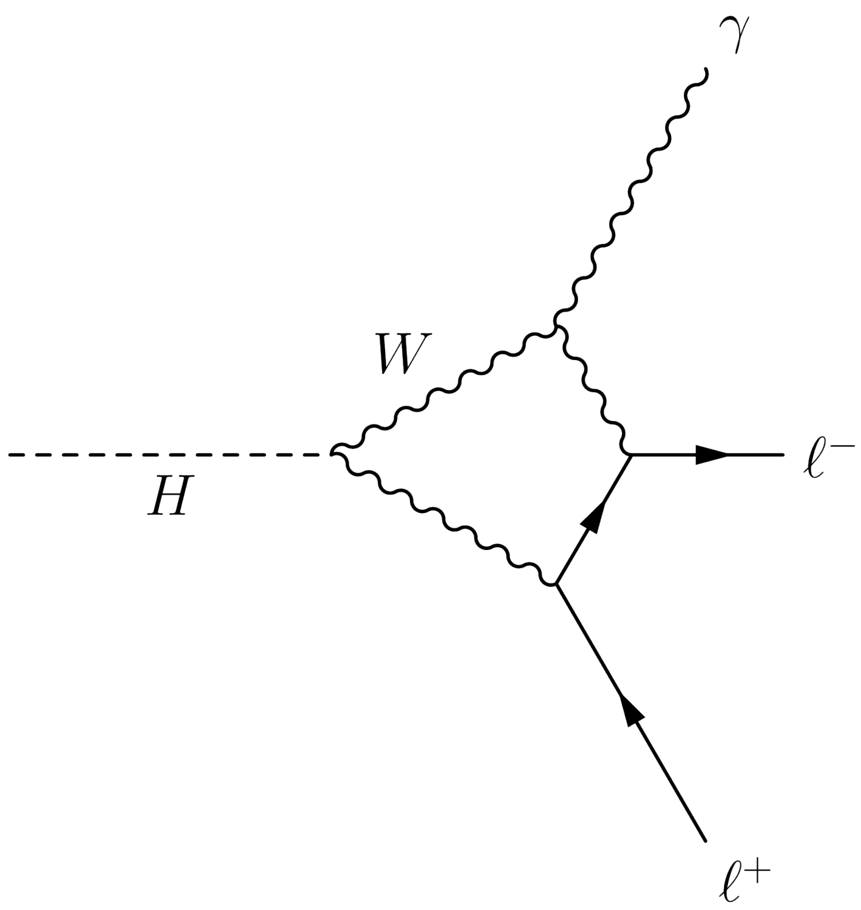
- Further future:
  - Measure $m_{\ell\ell}$ spectrum to search for exotic light vector-like bosons
  - CP studies



BACKUP

Backup - box diagrams



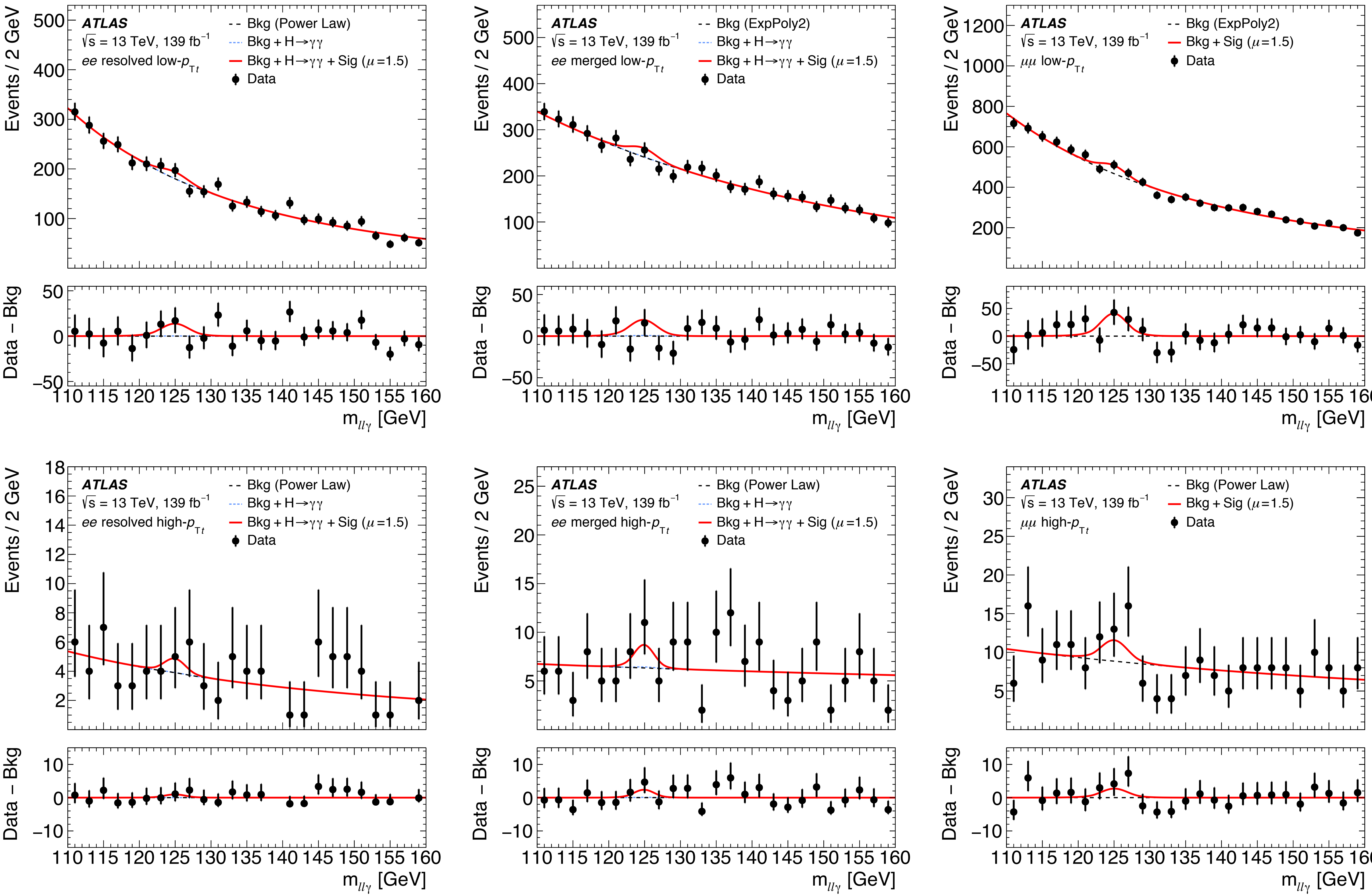


Backup - table with S/B numbers

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

Number of data events selected in each analysis category in the $m_{\ell\ell\gamma}$ mass range of 110–160 GeV. In addition, the following numbers are given: number of $H\to\gamma^*\gamma\to\ell\ell\gamma$ events in the smallest $m_{\ell\ell\gamma}$ window containing 90 of the expected signal (S90), the non-resonant background in the same interval (B90N) as estimated from fits to the data sidebands using the background models described in Section 6, the resonant background in the same interval ($B_{H\to\gamma\gamma}$), the expected signal purity f90 = S90/(S90+B90), and the expected significance estimate defined as Z90 = √[2((S90+B90) ln(1+S90/B90) - S90)] where B90 = B90N + $B_{H\to\gamma\gamma}$. $B_{H\to\gamma\gamma}$ is only relevant for the electron categories and is marked as "–" otherwise.

Backup - more fit plots



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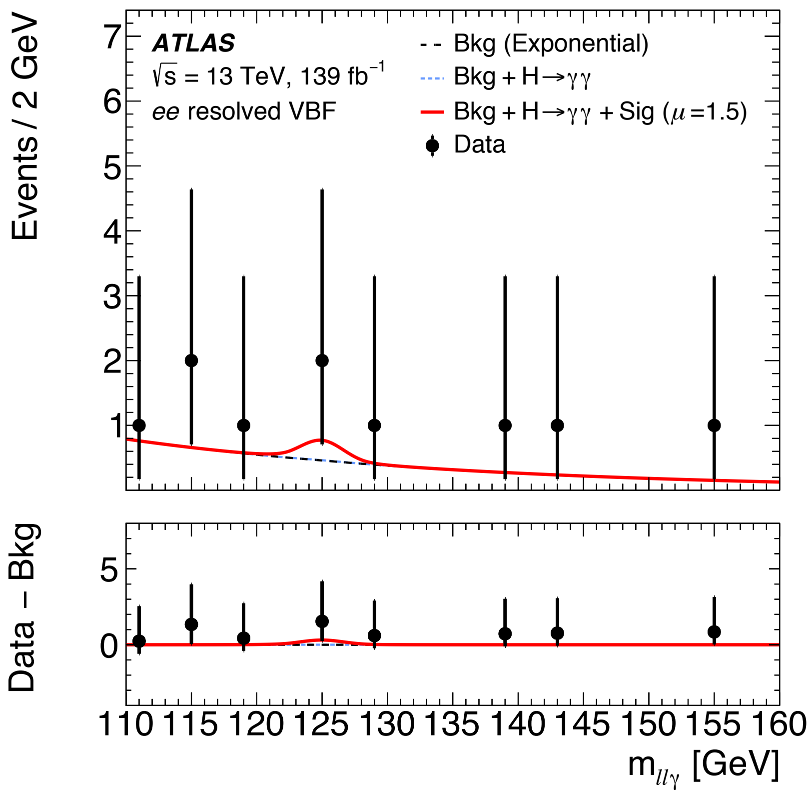

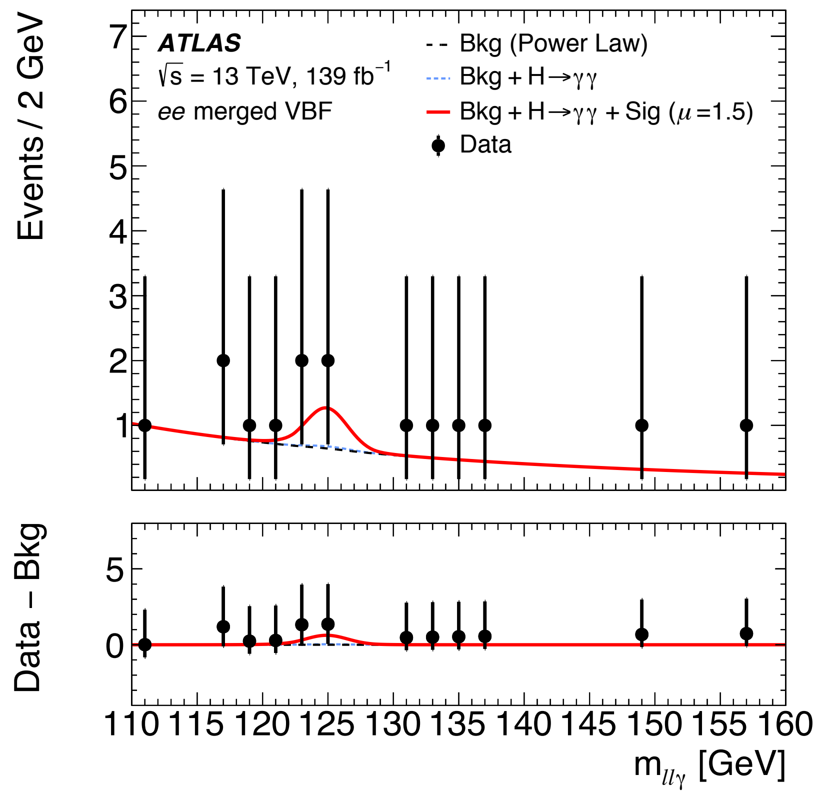

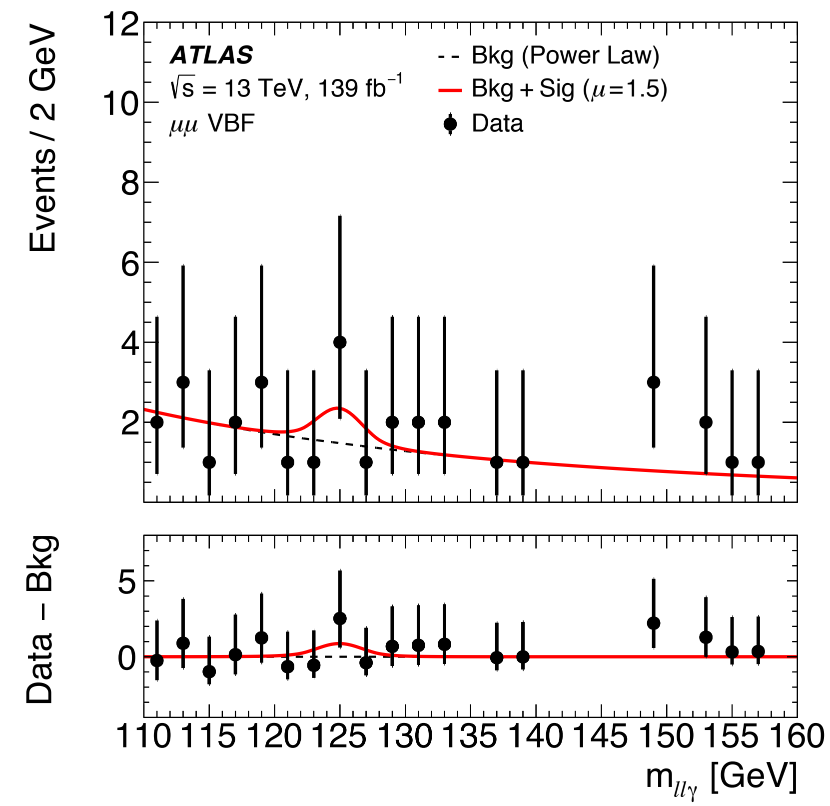

Backup - different fits