The Higgs boson, from the discovery to the most recent measurements

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Outline

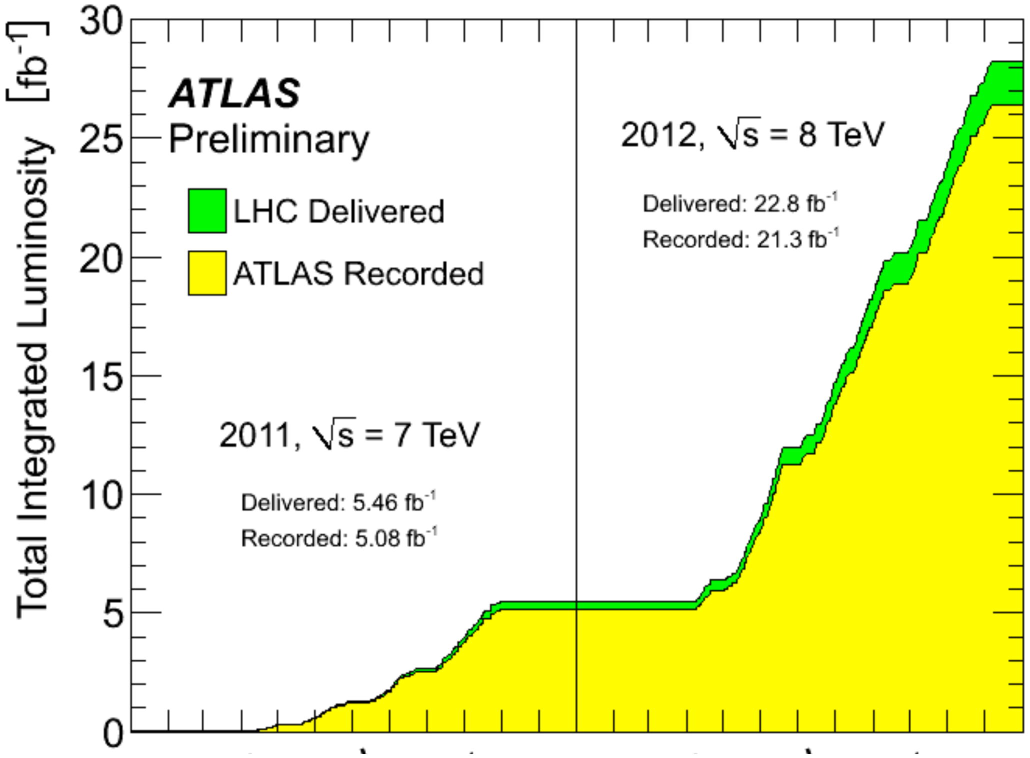
- Introduction, the LHC dataset
- Some relevant channels observed after those that lead to the discovery
- A very quick and incomplete overview of the ongoing properties measurements
    - Mass
    - Width
    - Spin/CP quantum numbers
    - Fiducial and differential cross sections
    - Couplings
    - Simplified template cross sections and couplings
    - BSM couplings in the Effective Field Theory
- Plans for the coming runs of LHC

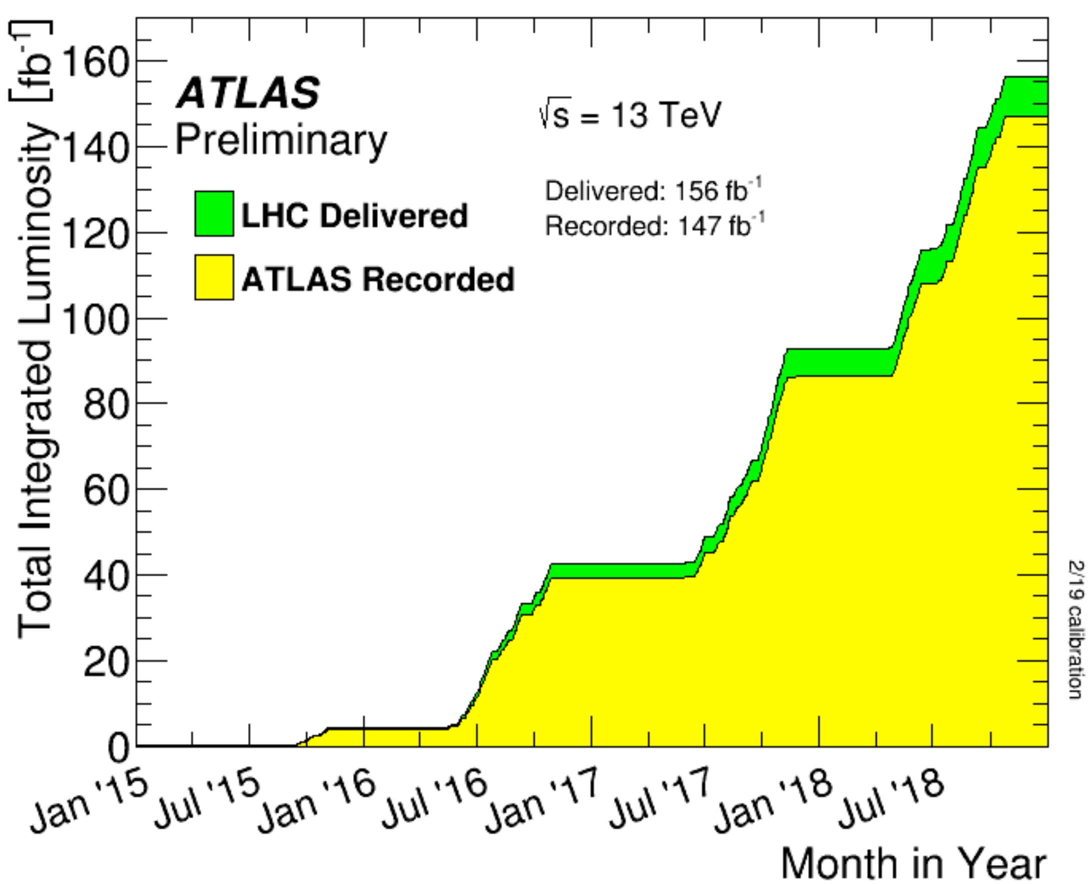
- DISCLAIMER: I am including mostly results from ATLAS just because I am more familiar with them, but of course CMS has a pretty similar set of results
- Link to corresponding publications in each slide

Introduction

The LHC dataset

- All the measurements presented here are based on the run-1 and run-2 LHC datasets
- LHC run-1:
  - From 2010 to 2012, center of mass energy 7 and 8 TeV -> Higgs discovery and first properties measurement
  - Observation of the main decay channels
- LHC run-2
  - From 2015 to 2018, center of mass energy 13 TeV
  - Observation of more channels
    - E.g. decays to fermions
  - Consolidation of properties measurements
  - Search for more SM effects
- LHC run-3 is about to start
  - Center of mass energy 13.6 TeV
  - Various detector improvements for both ATLAS and CMS

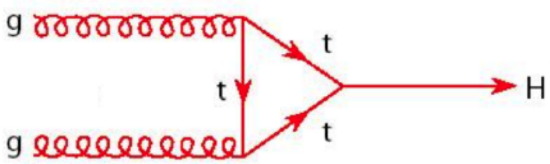




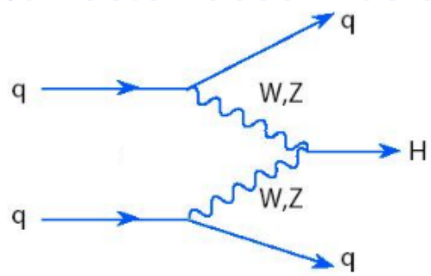
Higgs production at LHC

https://doi.org/10.23731/CYRM-2017-002

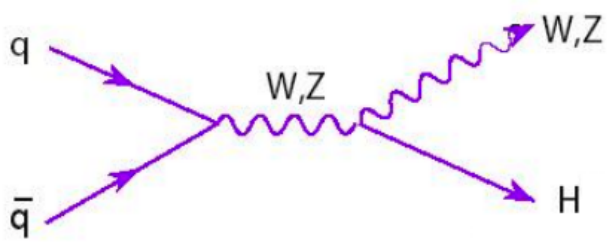
~88% Gluon fusion (ggF)



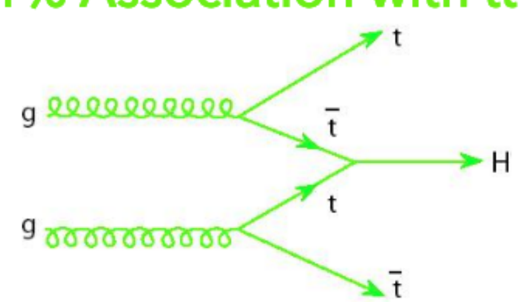
~7% Vector-boson-fusion (VBF)



~4% Higgs-Strahlung (VH)



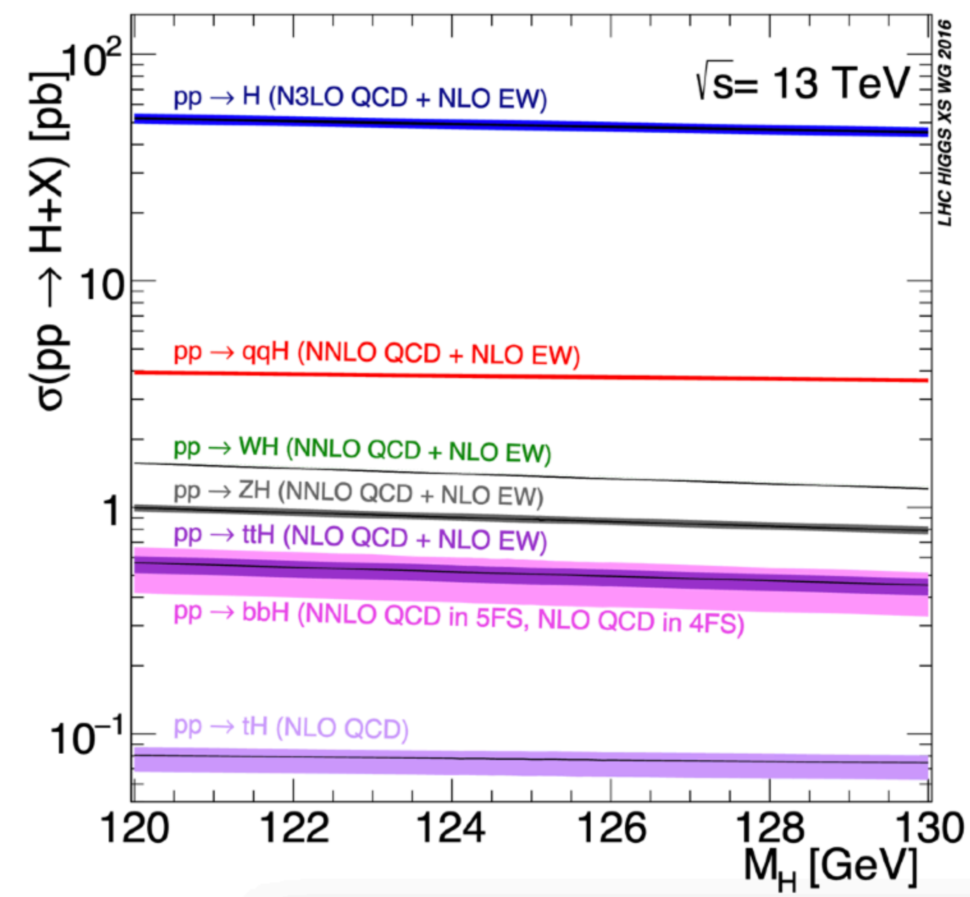
~1% Association with tt̄ (ttH)



- Gluon-gluon fusion (ggF)
  - Highest rate
- Vector Boson Fusion (VBF)
  - Signature: two jets in the forward region, separated in eta
- Associated production with W/Z
  - W/Z decay products associated to the Higgs decays
- ttH production
  - Complex final states and low rate, but important as a check of the Yukawa coupling

While ggF production has the highest rate, the peculiar signatures of VBF and VH can be exploited for background rejection

Signal strength per production mode gives information on the couplings

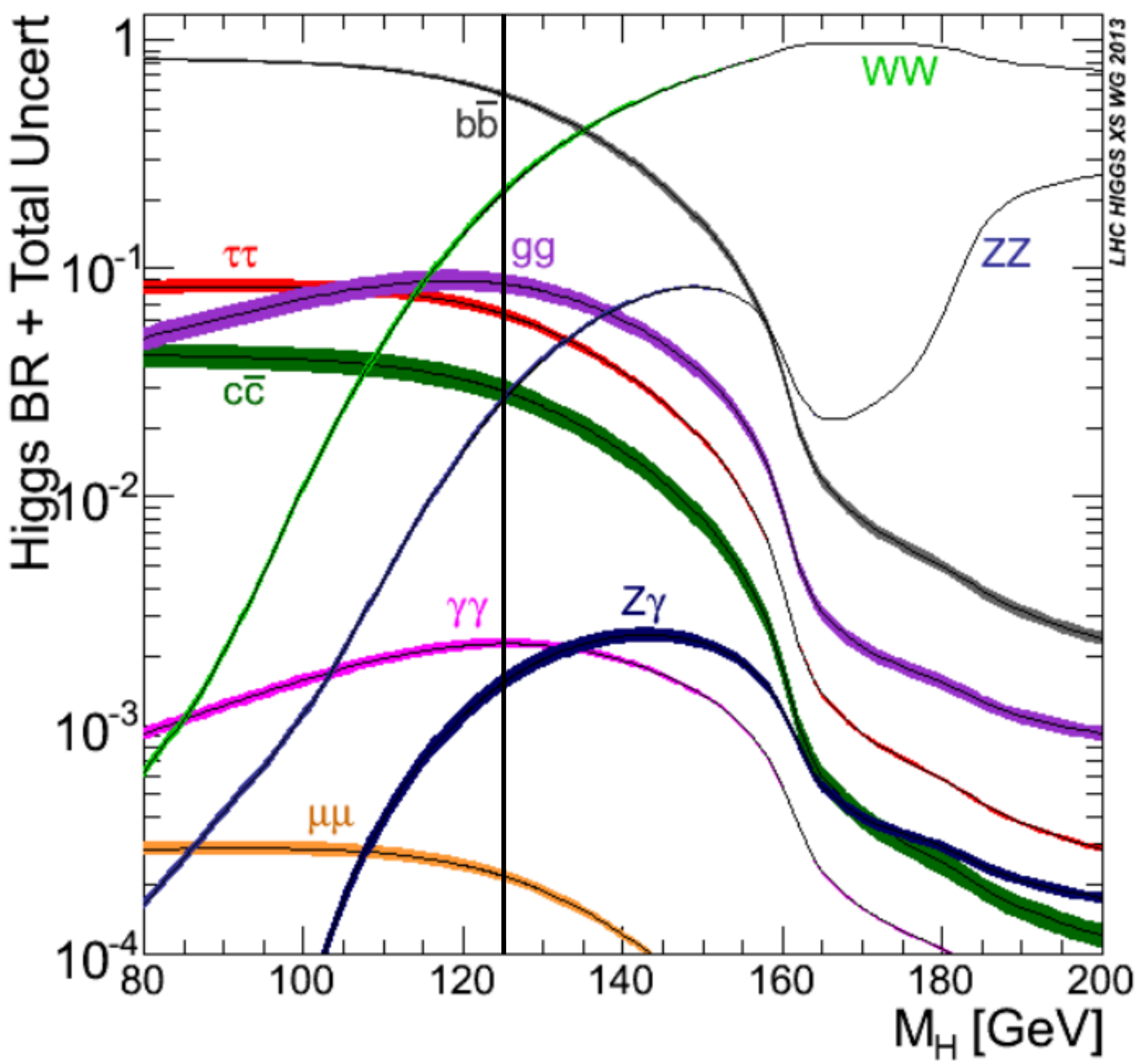


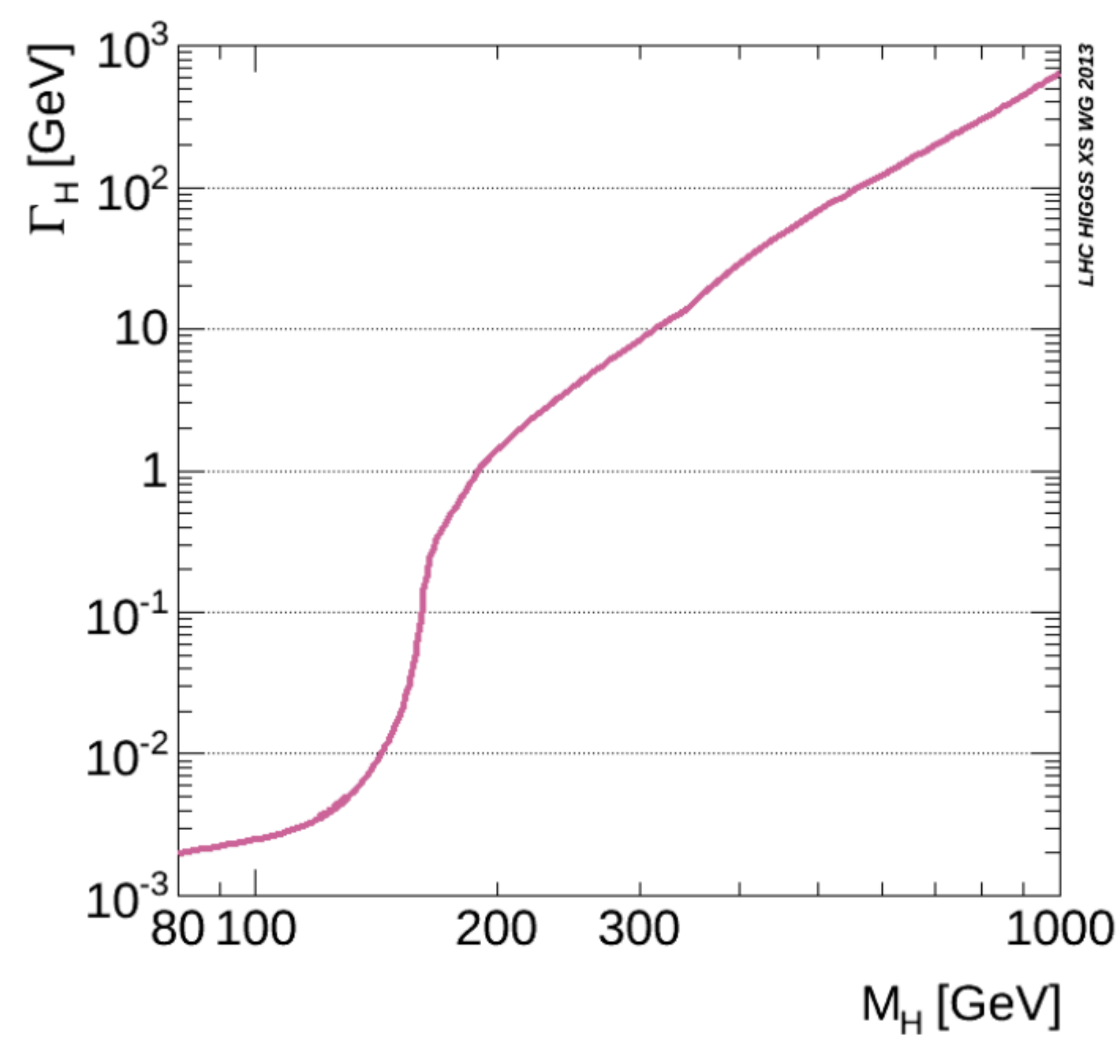
Higgs decay Branching Ratios and width

https://doi.org/10.23731/CYRM-2017-002

- Higgs couplings to the mass
  - ZZ suppressed w.r.t. W+W- due to Bose statistics

Natural width at MH=125 GeV is ~4 MeV
--> reconstructed width depends only on experimental resolution



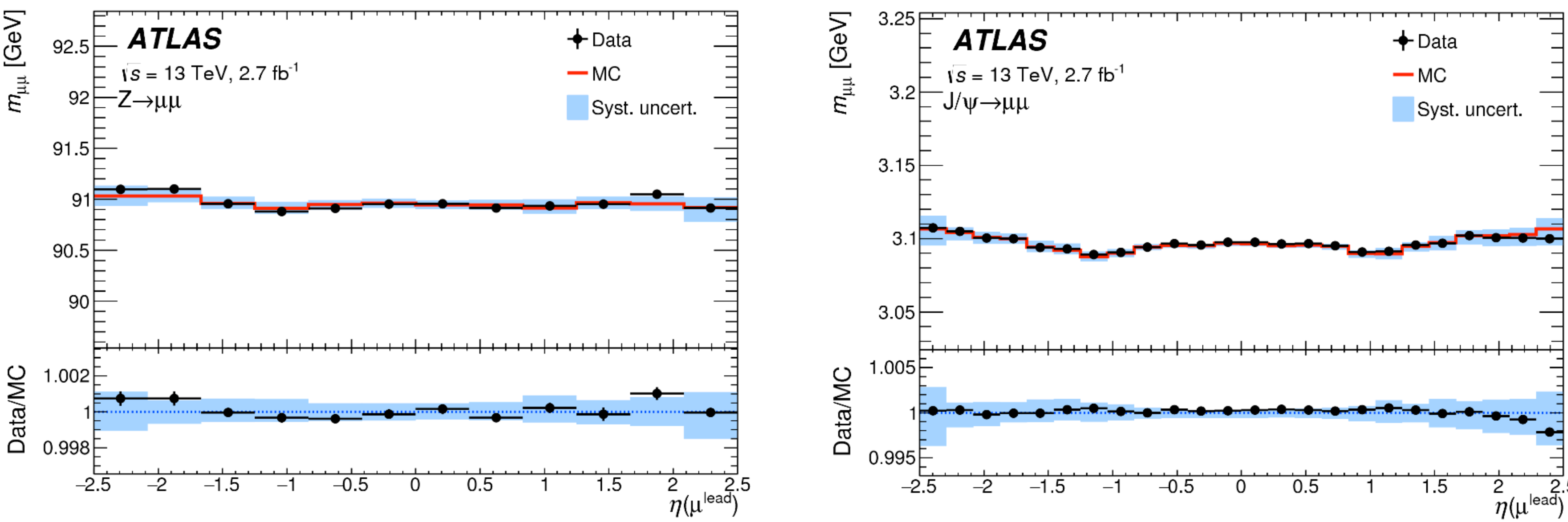


Mass and width

Mass measurements

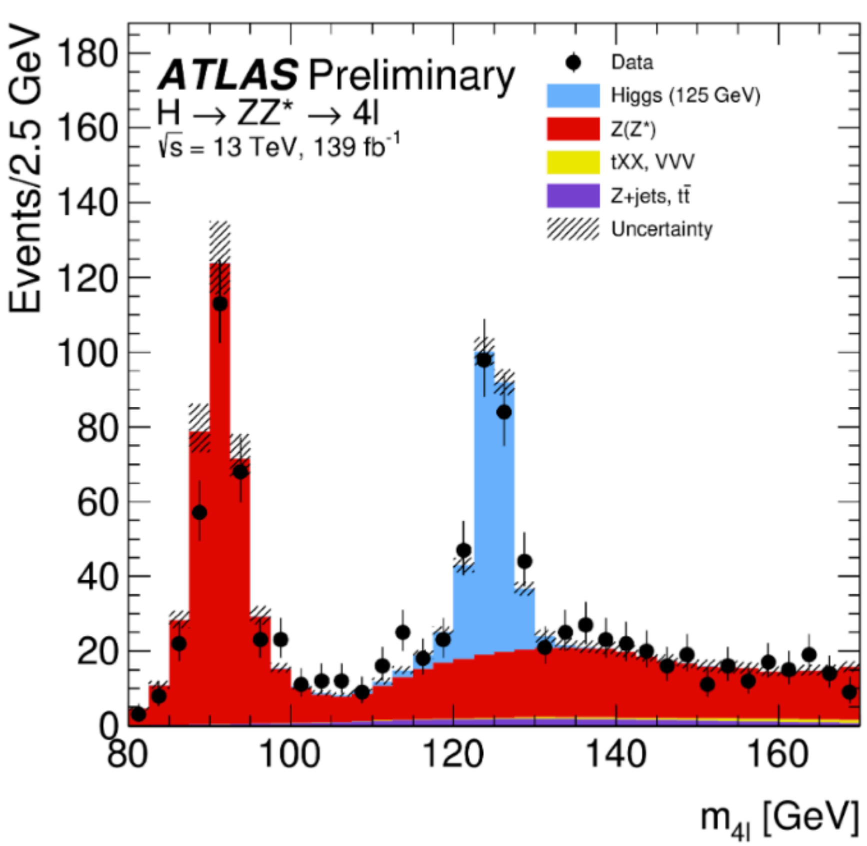
Eur. Phys. J. C 81, 578 (2021)
Phys. Lett. B 805 (2020) 135425
http://cdsweb.cern.ch/record/2714883
JHEP 11 (2017) 047

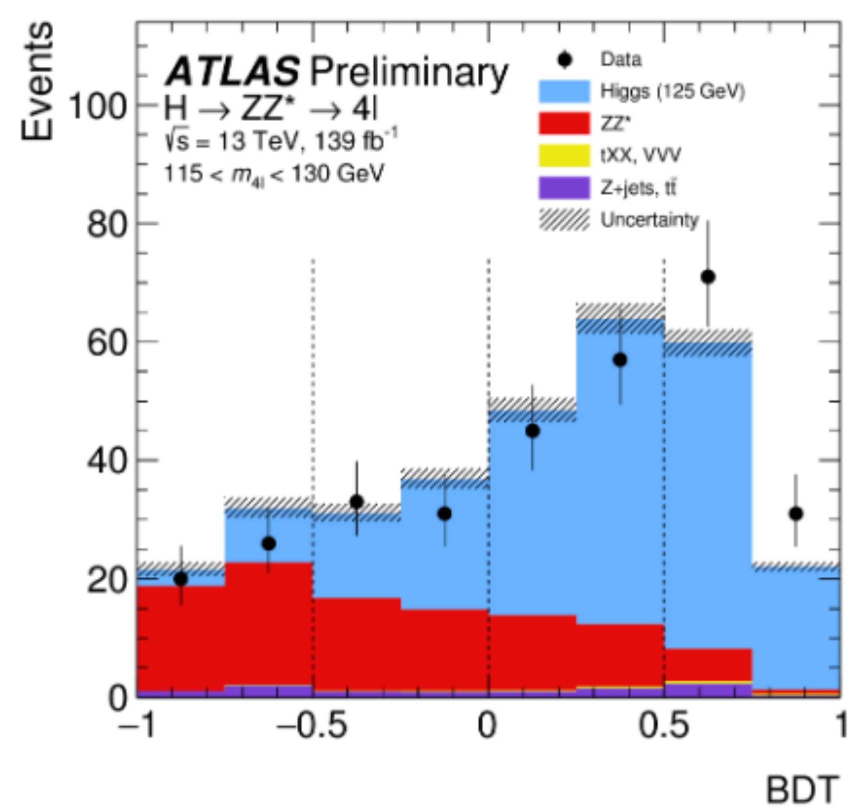
- The H mass can be measured using the channels whose final state can be completely reconstructed
  - H-> 4 leptons and H-> γγ
- Crucial element of the measurement is the calibration of muons, electrons and photons energy scale
- Muon and electrons energy scale can be calibrated using know signatures, i.e. Z-->μμ and Z-->ee
  - It is then possible to strongly reduce systematics in the 4l channel, but with lower signal statistics
- Various methods to calibrate photon energy, but in general with quite larger systematics --> the mass measurement in the γγ channel was already limited by systematics after the first set of run-2 data
  - For example via the reconstruction of Z-->ee+γ

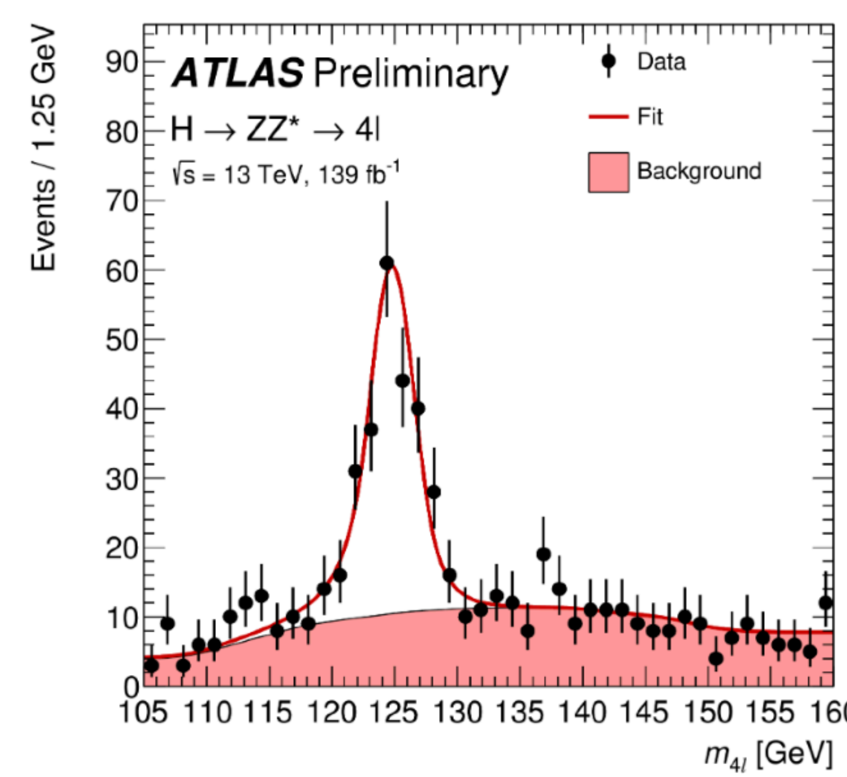


Mass in the H-->ZZ*-->4l channel

- One lepton pair comes from an on-shell Z, so constraining their invariant mass to MZ leads to an improvement on the resolution
  - Likelihood fit constraining the di-lepton mass to the Z lineshape
  - Up to ~17% improvement in the resolution
- Recovering photons from final state radiations leads to a ~1% improvement
- Besides the 4l mass, more variables enter in the fit mass
  - Events categorized based on a BDT designed to separate the signal from the irreducible background
  - Event-by-event uncertainty on the 4l mass

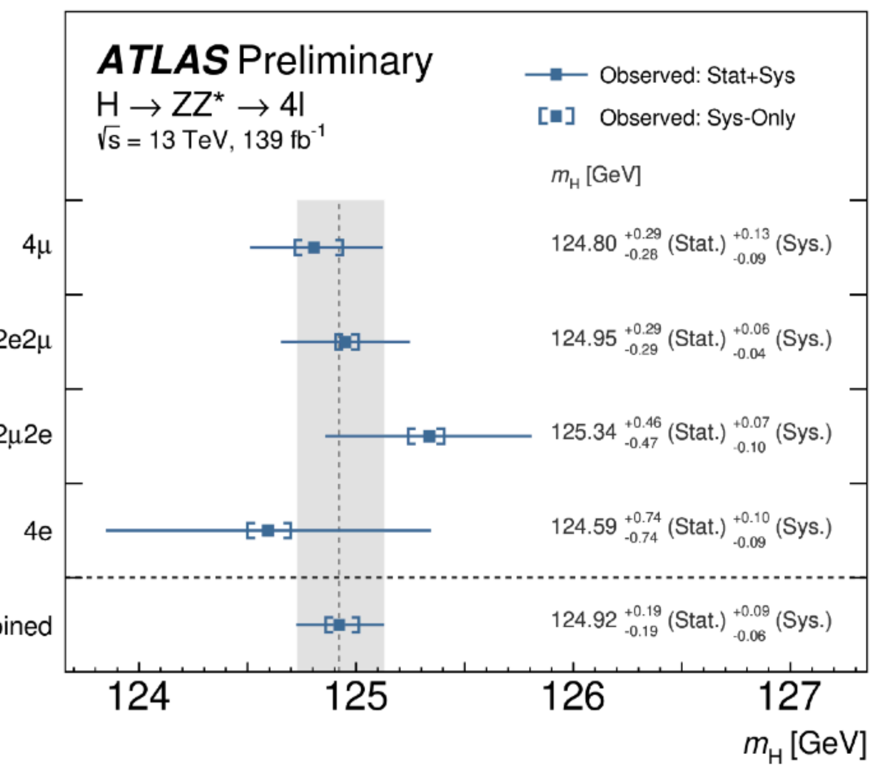


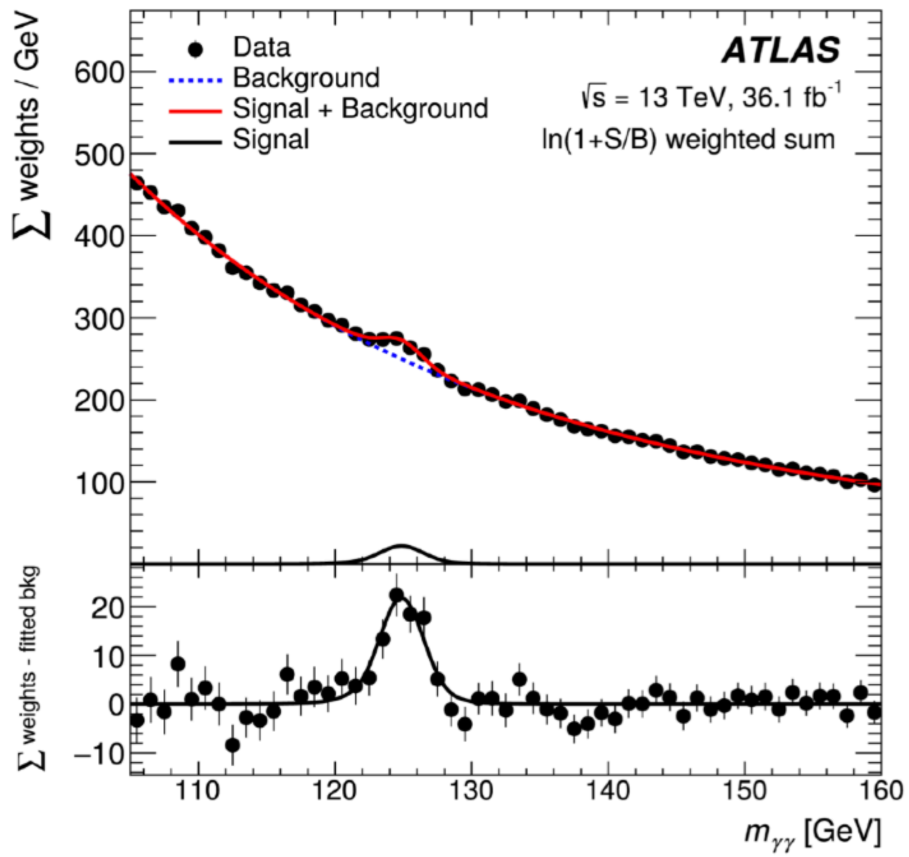


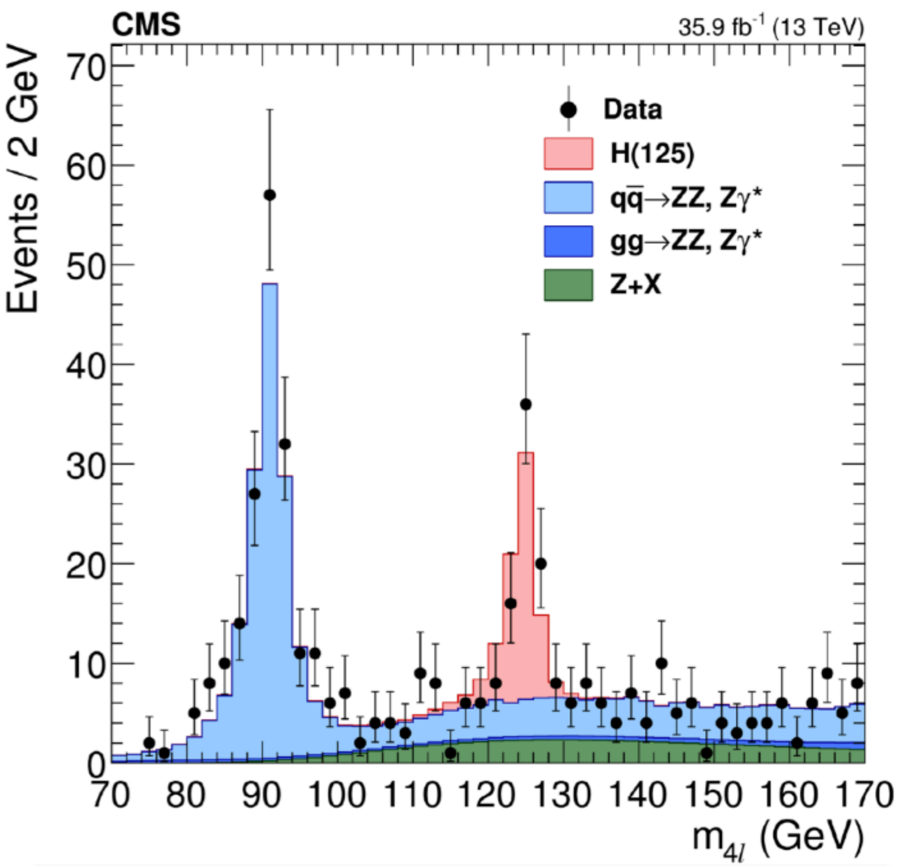


Mass results

- The 4l error is still significantly dominated by the statistical uncertainty







ATLAS 4l with 139 fb-1 at 13 TeV

$$m_H = 124.92 \pm 0.19\,(\text{stat.})\,^{+0.09}_{-0.06}\,(\text{syst.})\ \text{GeV}$$

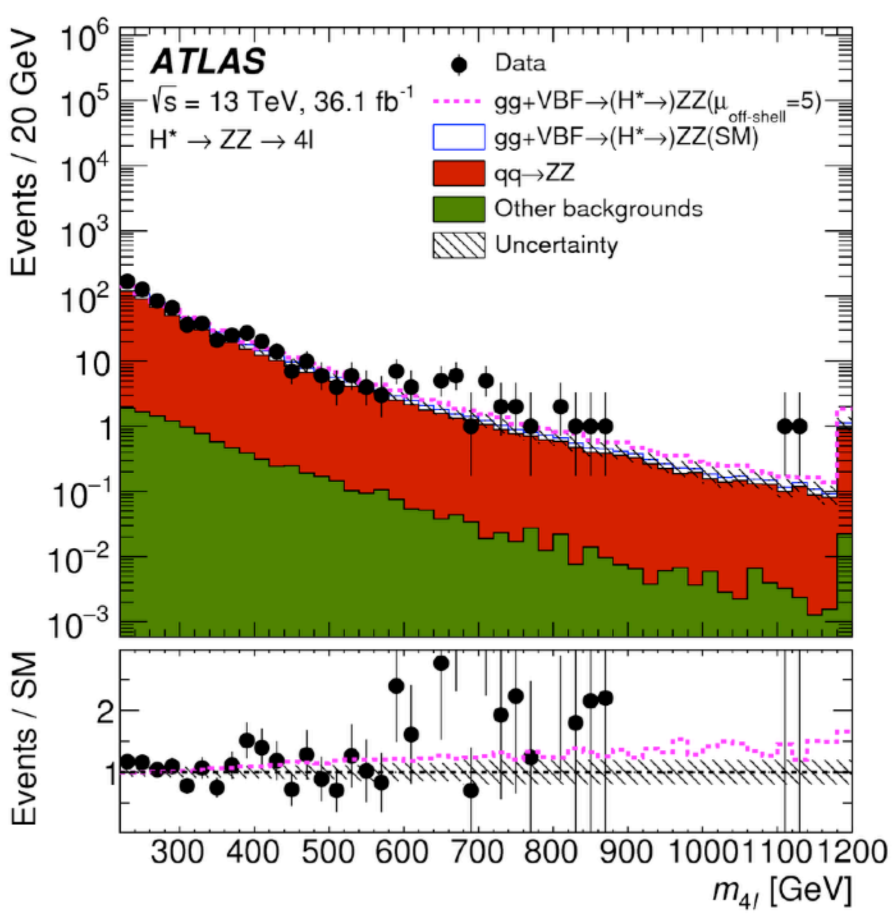
CMS combined 4l and γγ

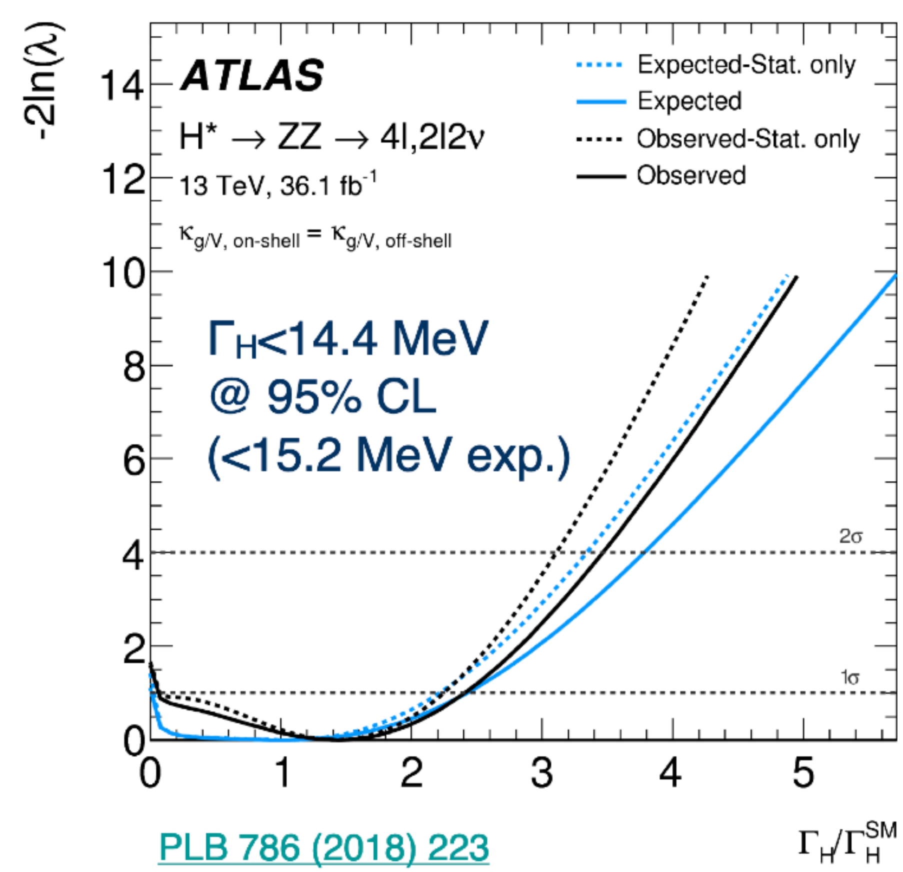
$$m_H = 125.38 \pm 0.11\,(\text{stat.}) \pm 0.08\,(\text{syst.})\ \text{GeV}$$

Width

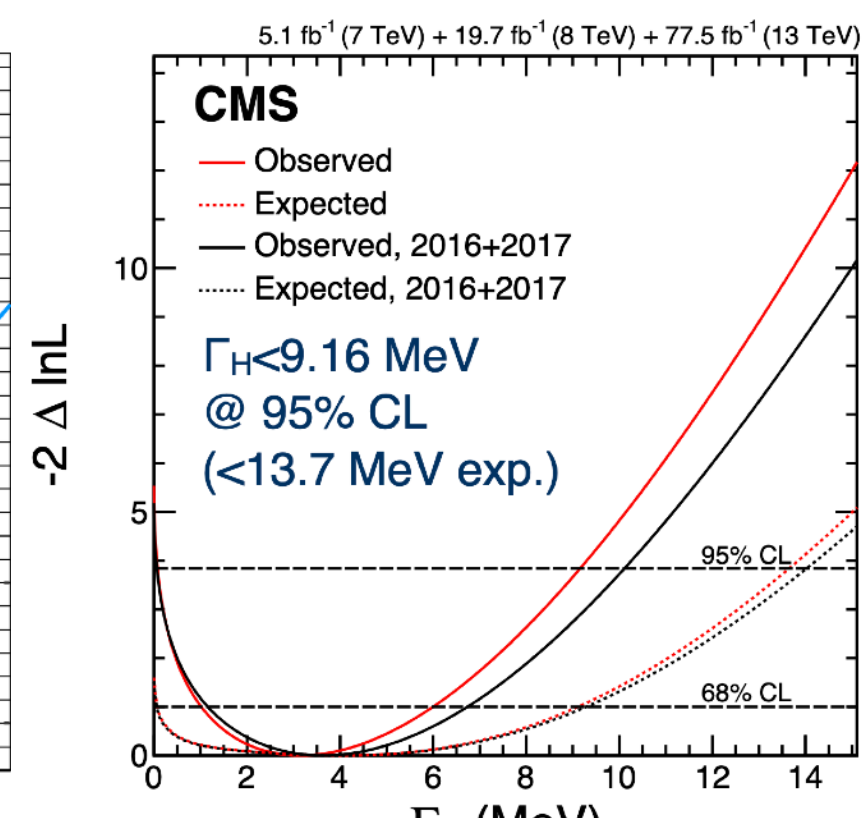
[Phys. Lett. B 786 (2018) 223](#)
[Phys. Rev. D 99 (2019) 112003](#)
[J. High Energy Phys. 09 (2016) 051](#)

- In the SM, the width of the Higgs boson is expected to be ~ 4 MeV
- The reconstructed peak width is thus dominated by the experimental resolution, that is order ~1-2 GeV for the 4l and γγ precision channels
  - A direct measurement of the width is possible, but allows only to se limi
- Better limits on the width can be set using the off-shell signal strength in H-->ZZ-->4l and 2l2v
  - Assuming the same couplings for the on-shell and the off-shell Higgs





PLB 786 (2018) 223



arXiv:1901.00174

Production and decay modes

Observation of production and decay modes

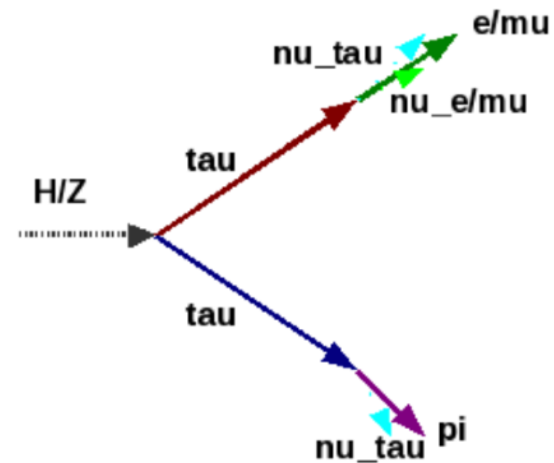
- After the discovery, and the confirm of the scalar nature of the new resonance, the focus has shifted to:
  - Separation of the events based on the production modes
  - And, to the observation of the other decay channels
  - Plus the properties measurement that we'll consider later

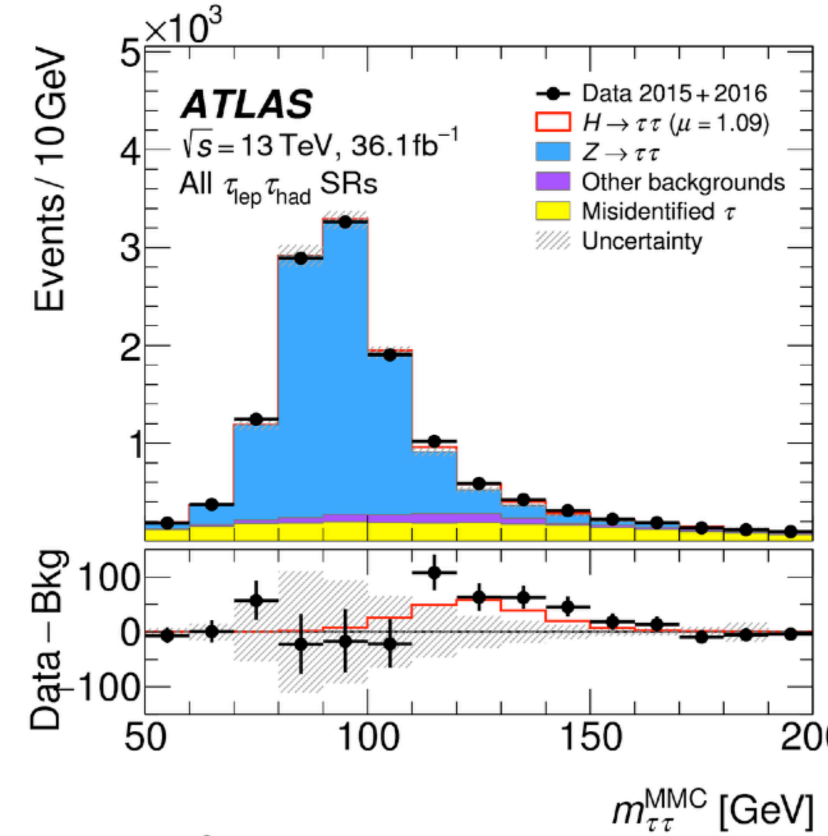
- At the end of run-2, all the production modes have been observed
- Also, all the decay channels that were reachable based on the collected data, have been observed
  - In particular the first decays to fermions, H-->tau tau and H-->bb
- Any deviation from the SM expected rates would imply new physics
  - Check production rate per mechanism and decay channel
  - Study signal differential distributions
- Up to now no significant discrepancy w.r.t. the SM has been observed

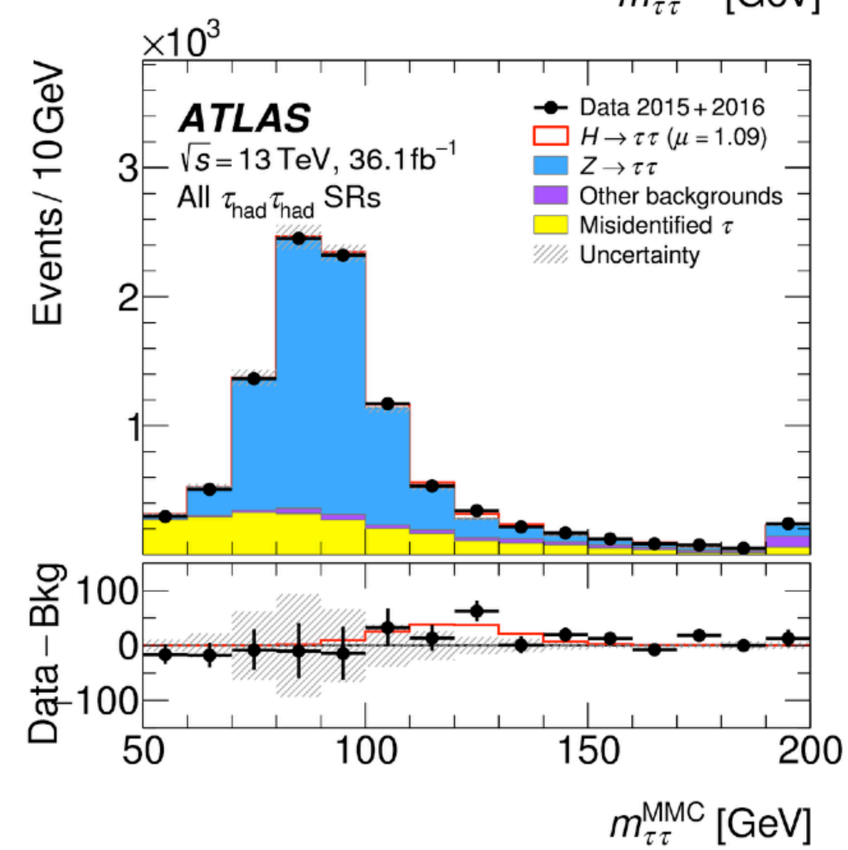
H→ττ

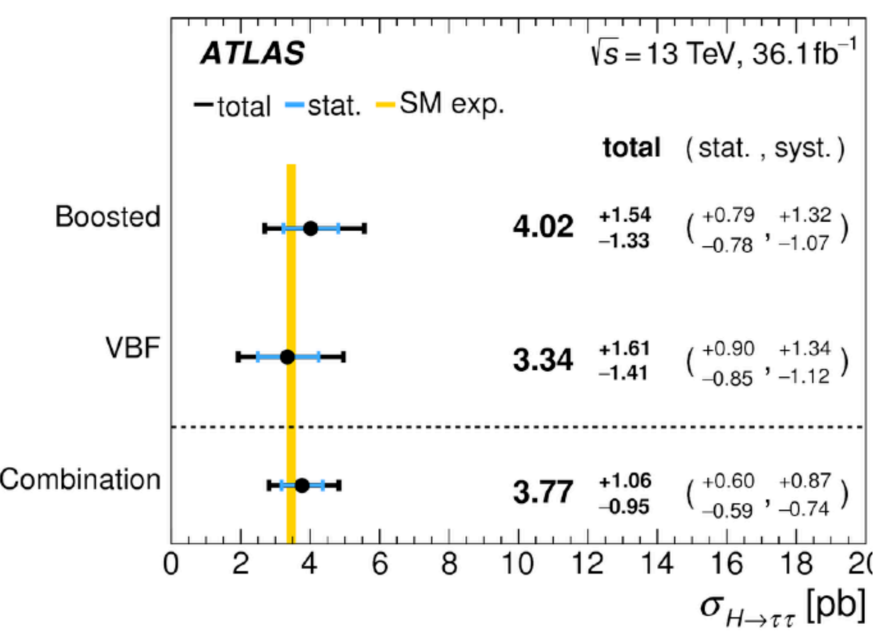
Phys. Rev. D 99 (2019) 072001

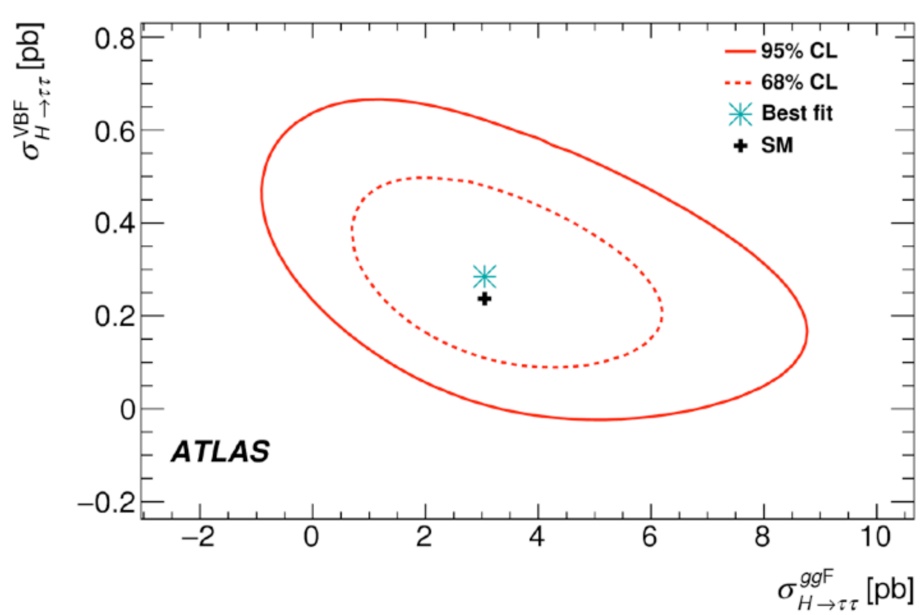
- First direct decay to fermions observed
  - Combining 13, 8 and 7 TeV results
- Select the three combination of decay channels
  - lep-lep, lep-had, had-had
- Reconstruct the invariant mass in the collinear approximation
- Main background is Z-->ττ, mostly determined from data
- Events categorized in VBF-like and "boosted", i.e. with large H pT, due to either ggF+jets or VH production
  - Mainly to remove Z background







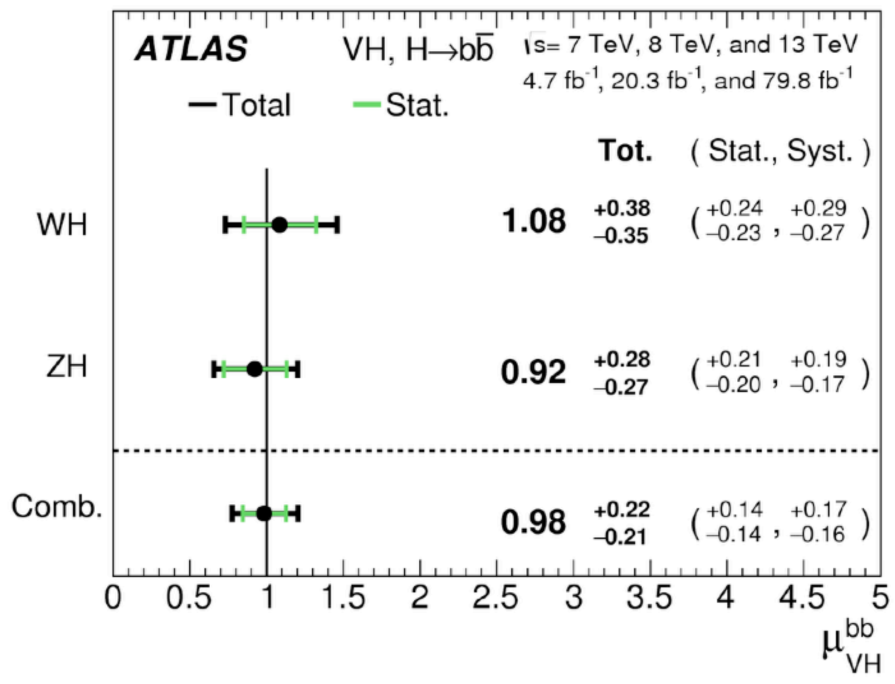


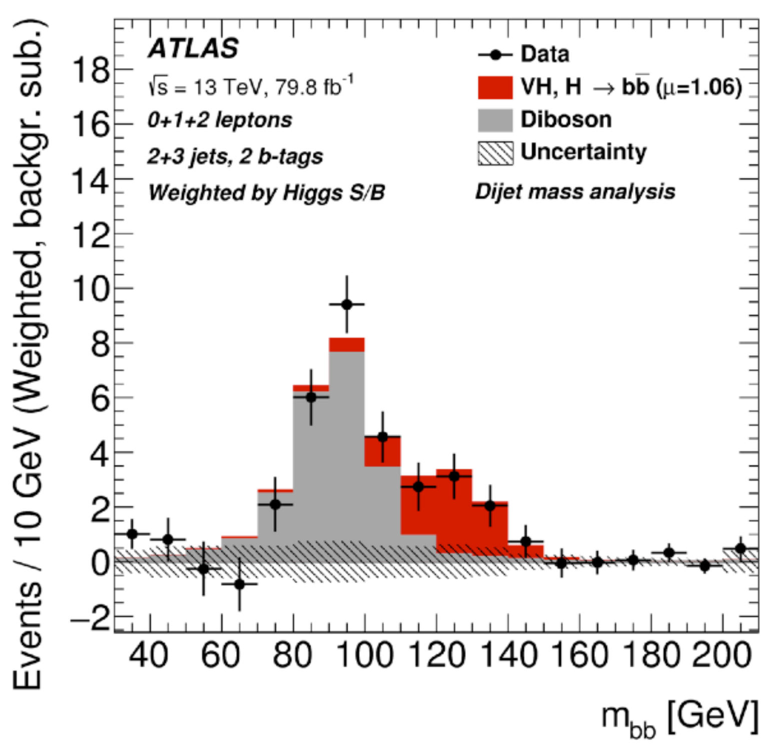


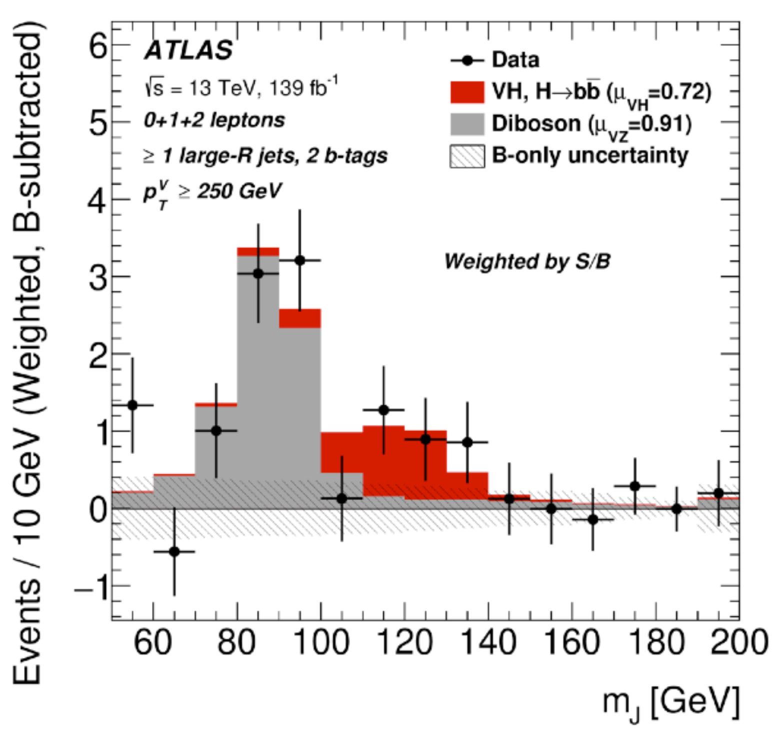
H→bb

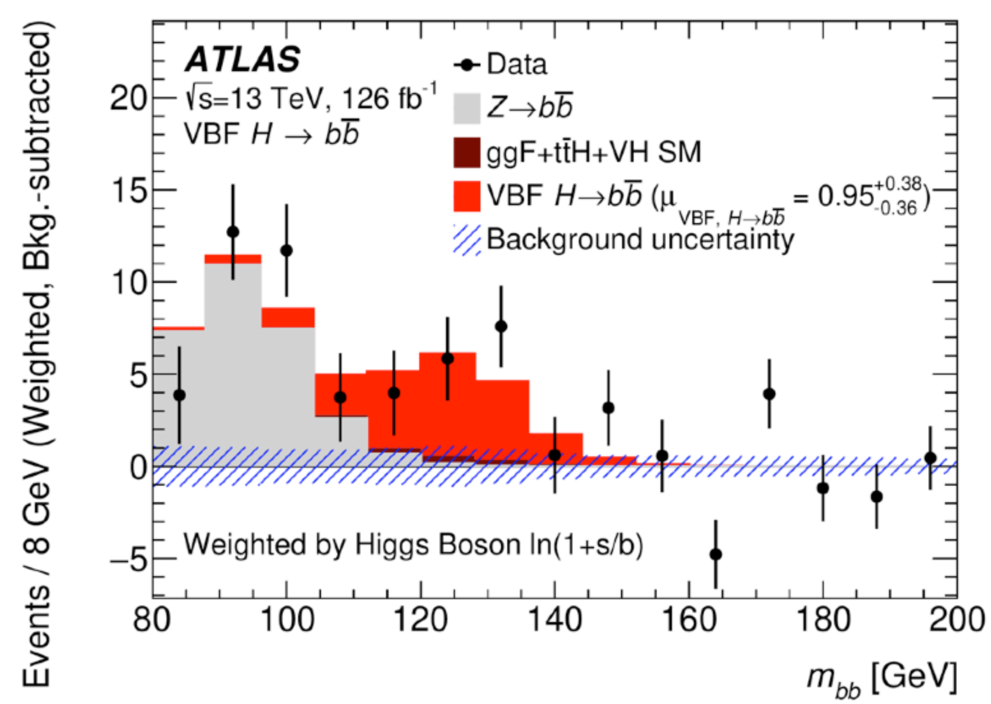
[Eur. Phys. J. C. 81 (2021) 537](#)
[Phys. Lett. B 816 (2021) 136204](#)
[Eur. Phys. J. C 81 (2021) 178](#)

- Channel with the largest BR, but complicated due to the large background at hadron colliders
- Observed exploiting the associated production signature
- Many exclusive channels added later
  - VBF, VH and VH boosted
- Boosted topologies looking for "fat" jets with sub-jet structures (2 b-tagged subjets)





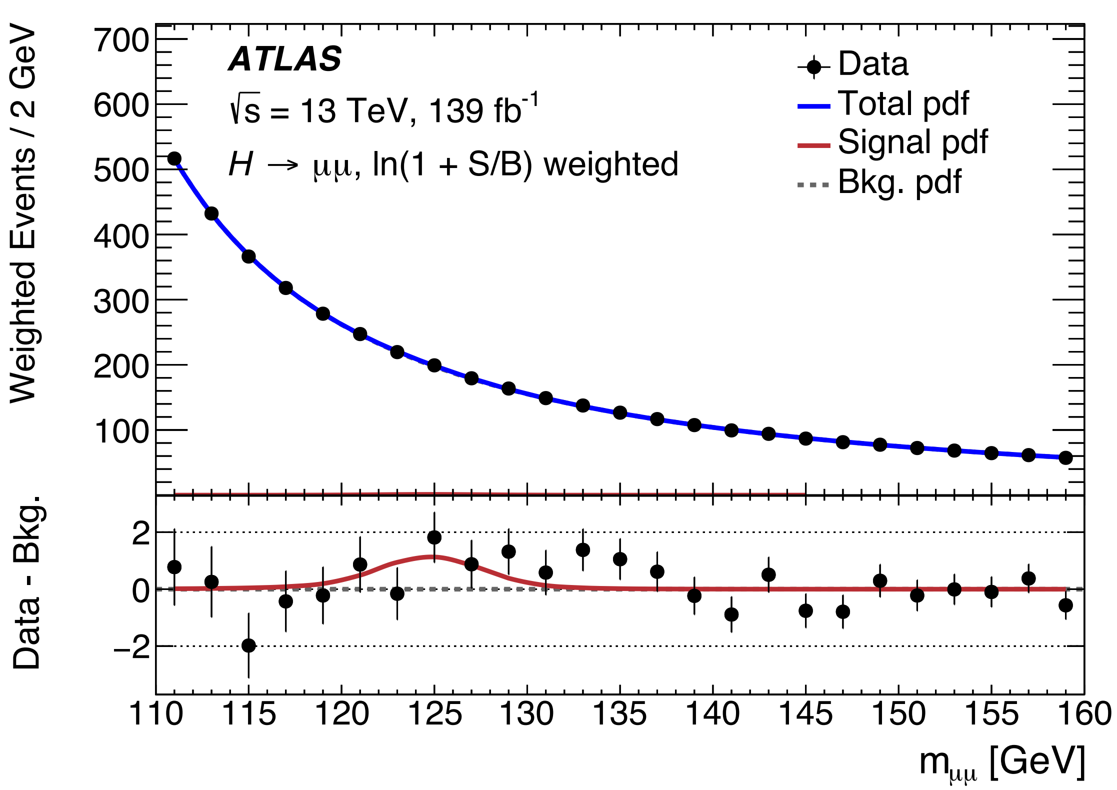


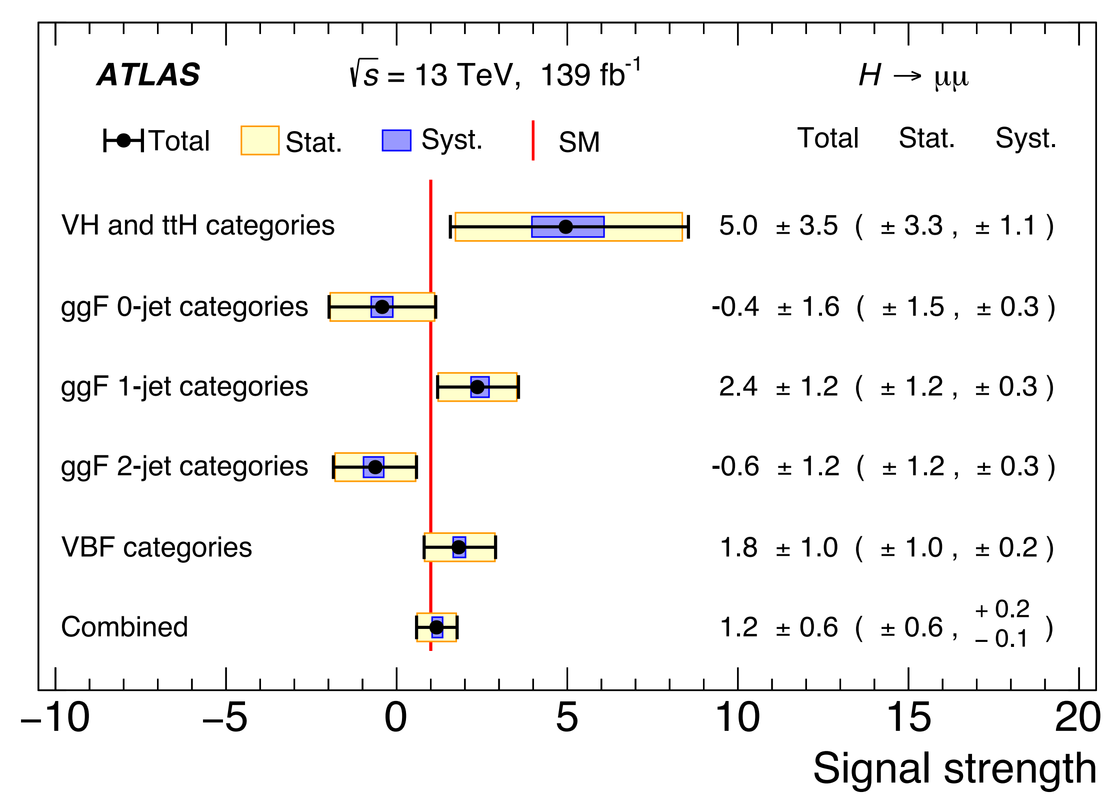


Search for the H→μμ decay

Phys. Lett. B 812 (2021) 135980

- The H→μμ decay offers the best opportunity to measure the Higgs interactions with a second-generation fermion
- Events are categorized in 20 mutually exclusive categories
  - Di-lepton mass fit in the 110-160 GeV region
  - Correct for muon QED FSR
  - Background modeling from core function (LO DY mass shape) convolved with di-lepton mass dependent resolution x empirical functions, category dependent
- Result improve by a factor ~2.5 previous ATLAS result, with a factor ~2 coming from the increased int. luminosity an additional ~25% from analysis improvements
  - Signal strength **μ=1.2±0.6** corresponding to an observed(expected) significance of **2.0σ (1.7σ)**





Couplings and cross sections

Signal strength

- A very important observable in the measurement of the Higgs properties is the Signal Strength (μ)
  - Defined as the ratio between the measured and the SM cross section and BR

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with} \quad \mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}$$

- Thus the number of events per channel can be defined as:

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\mathrm{SM}} \times \mu_f (\mathrm{BR}_f)_{\mathrm{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$

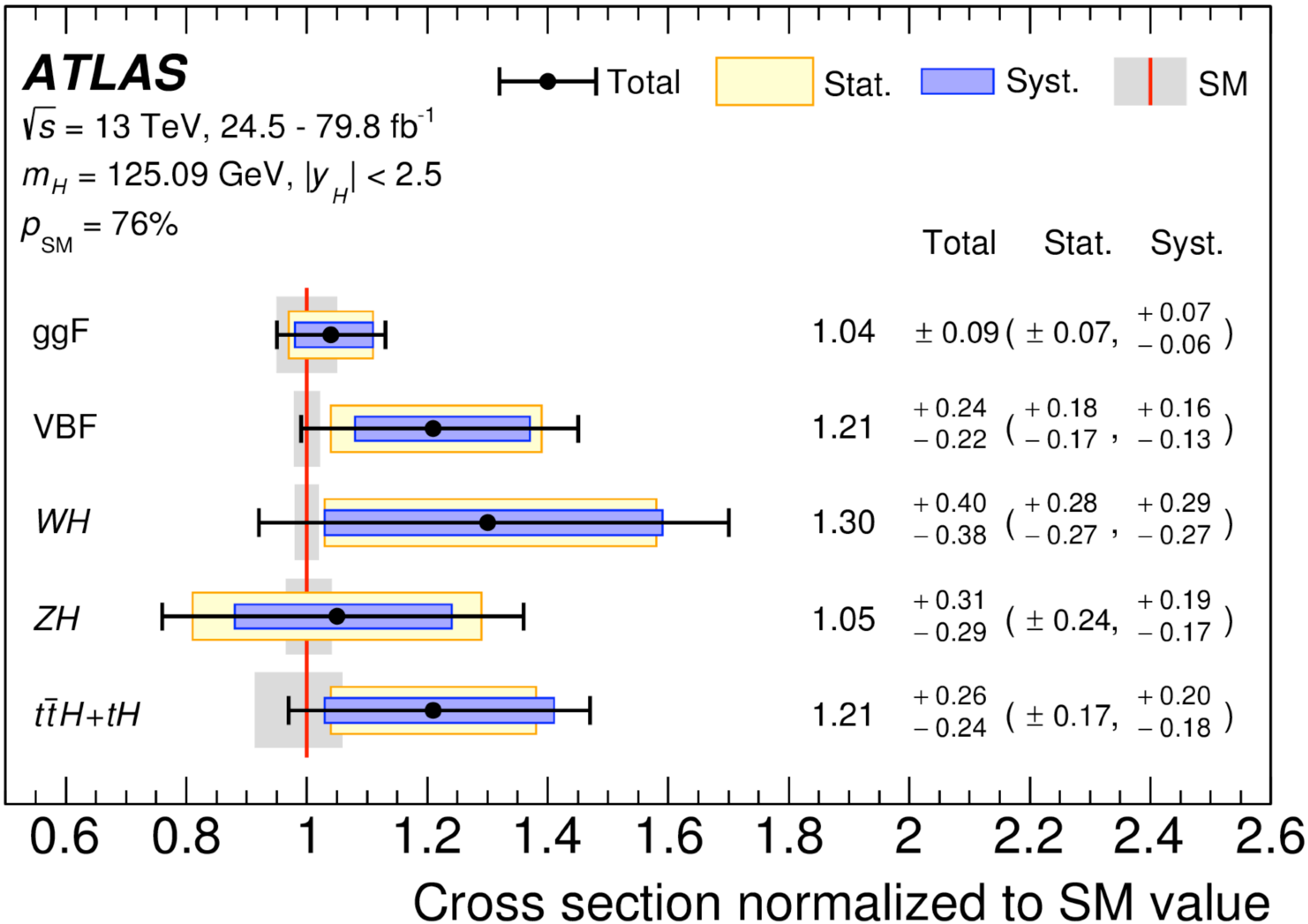
- Measuring the event yields per production mode and channel allows to look for possible deviations from the SM (i.e. μ's different from 1)

Decoupling the production modes

- The final state signature can be used not only to improve background rejection also to decouple the production modes
- In this case, the selection aims at selecting categories in which each production mode is enhanced
- VBF:
  - Two jets in the forward region, with large eta separation
  - Central jet veto and pileup jet veto
- VH:
  - Request Z/W decay products
    - Either l+l- with mll close to the Z mass, or a high momentum lepton and MET
    - Or two jets with mjj close to the Z or W mass (within the larger uncertainty associated to di-jet masses)
- ttH:
  - High multiplicity events
  - b-tagged jets from the top decays
- Aim of the selection is to end up with reconstructed event exclusive categories as clean as possible in terms of the production mode
  - E.g. minimize the ggF "contamination" of the VBF reconstructed category

Production mode strengths

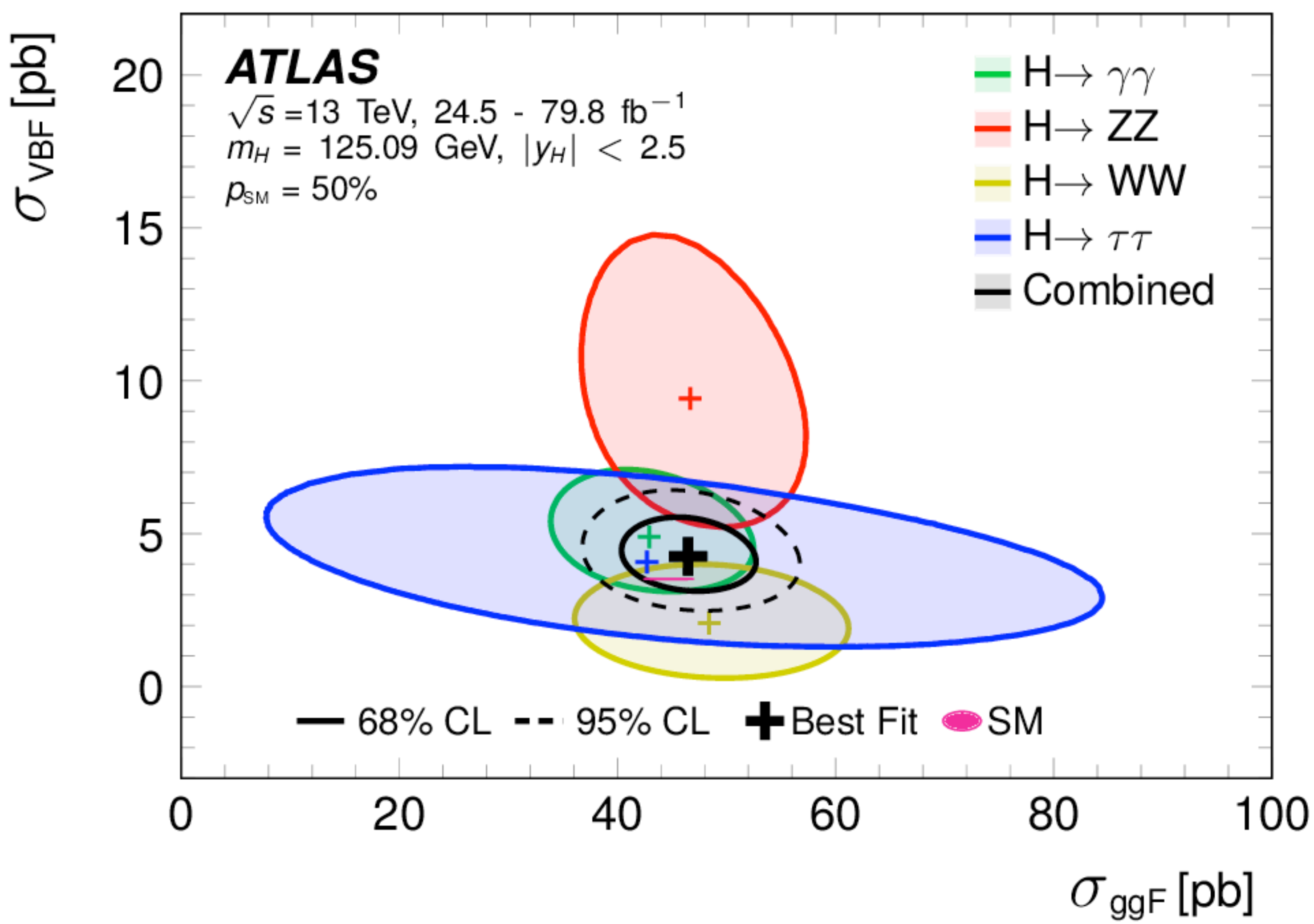
Phys. Rev. D 101 (2020) 012002

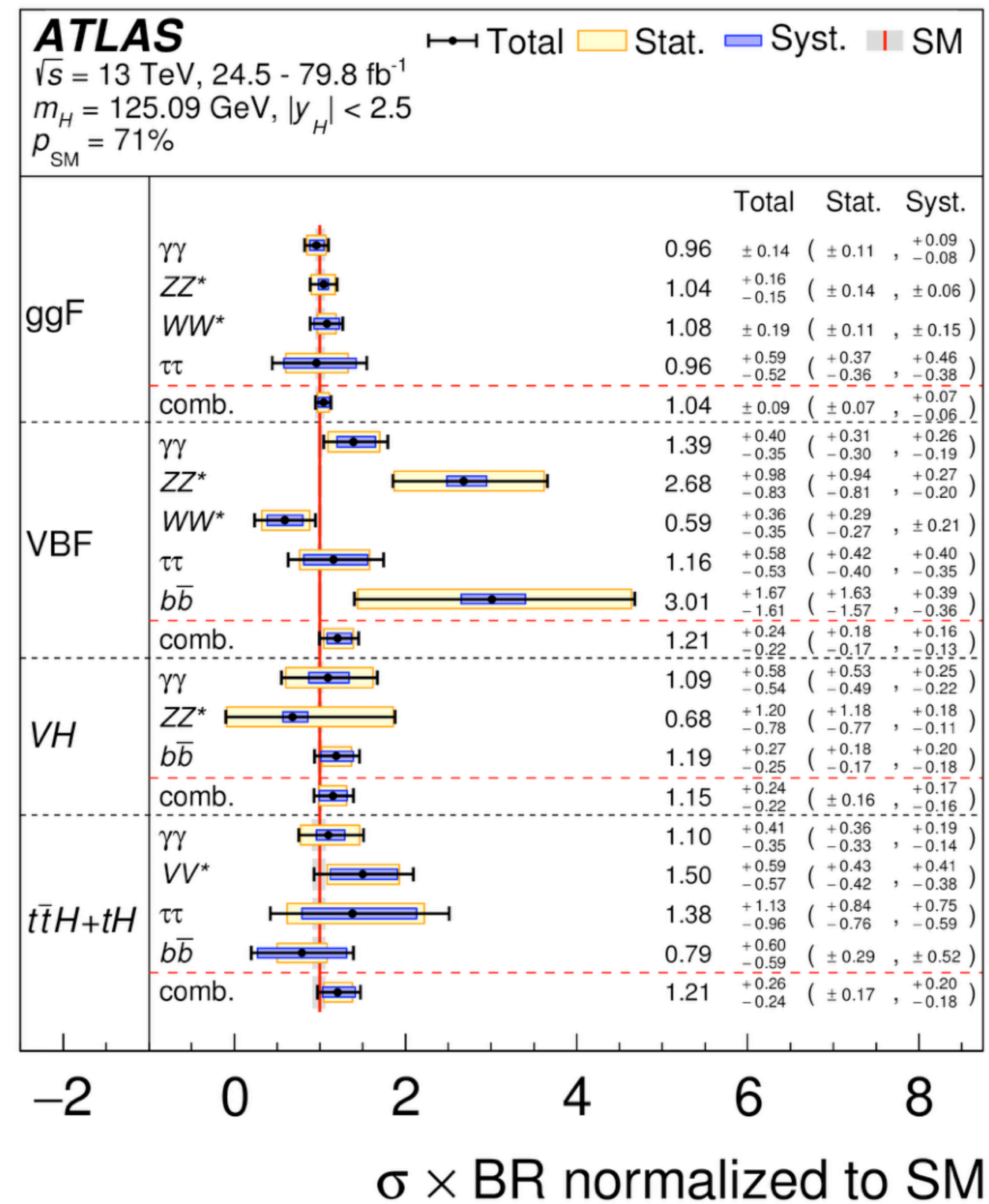


Cross section per production mode

Phys. Rev. D 101 (2020) 012002

- The best sensitivity is obtained from all available channels combination



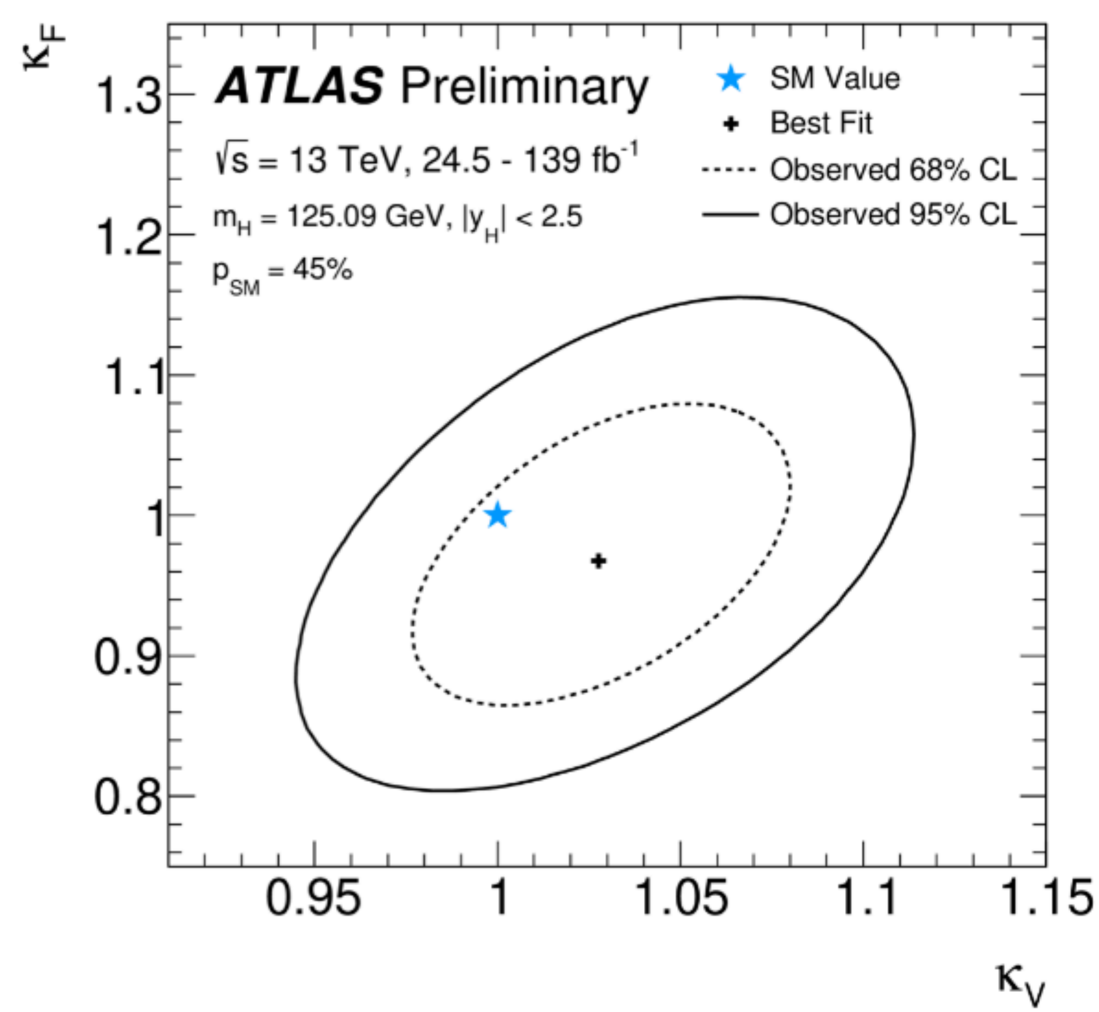


Couplings in the κ-framework

ATLAS-CONF-2020-027

- To quantify deviations from the SM it is possible to include couplings modifiers, the so called κ factors
- This is done assuming the SM structure of the couplings
  - So this framework can only account for deviations in the event rates
- Either define a factor for each coupling or two factors $\kappa_f \kappa_V$, common to all fermions and V-bosons

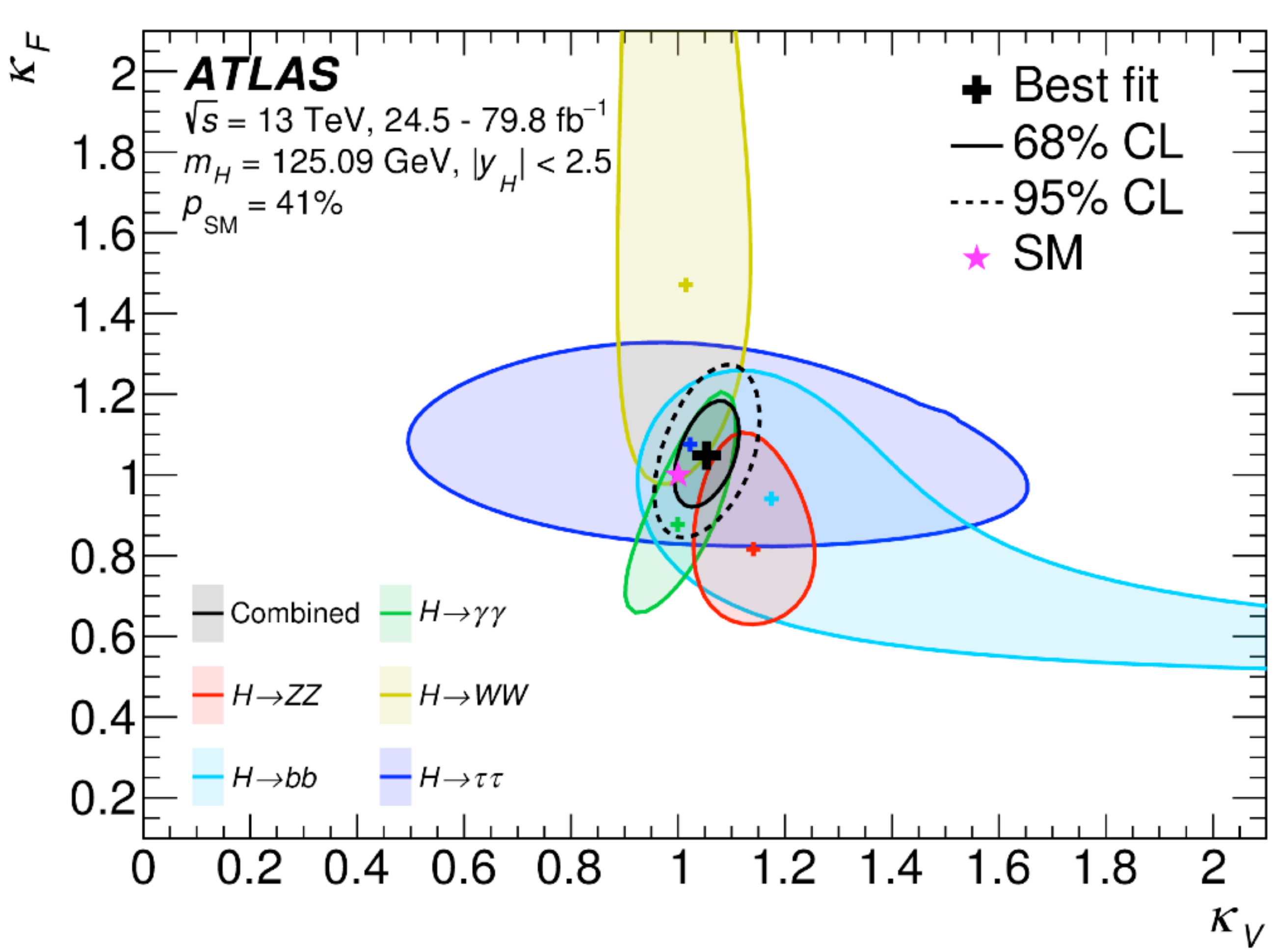
$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

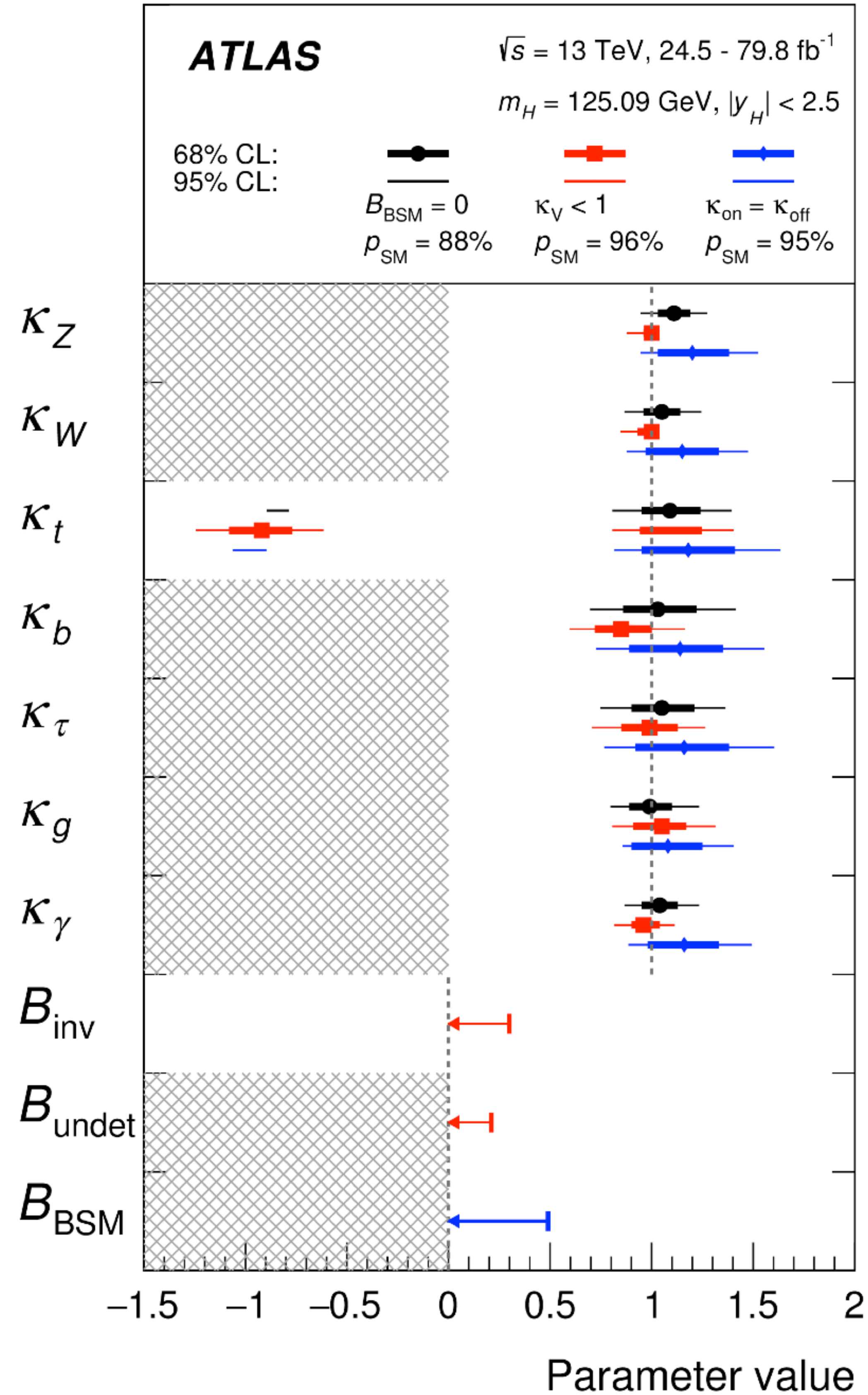


κ-framework results

Phys. Rev. D 101 (2020) 012002

- Results per channel and combined
- Assume only SM contributions, or invisible / undetected decays
  - In this case it is possible to set corresponding limits

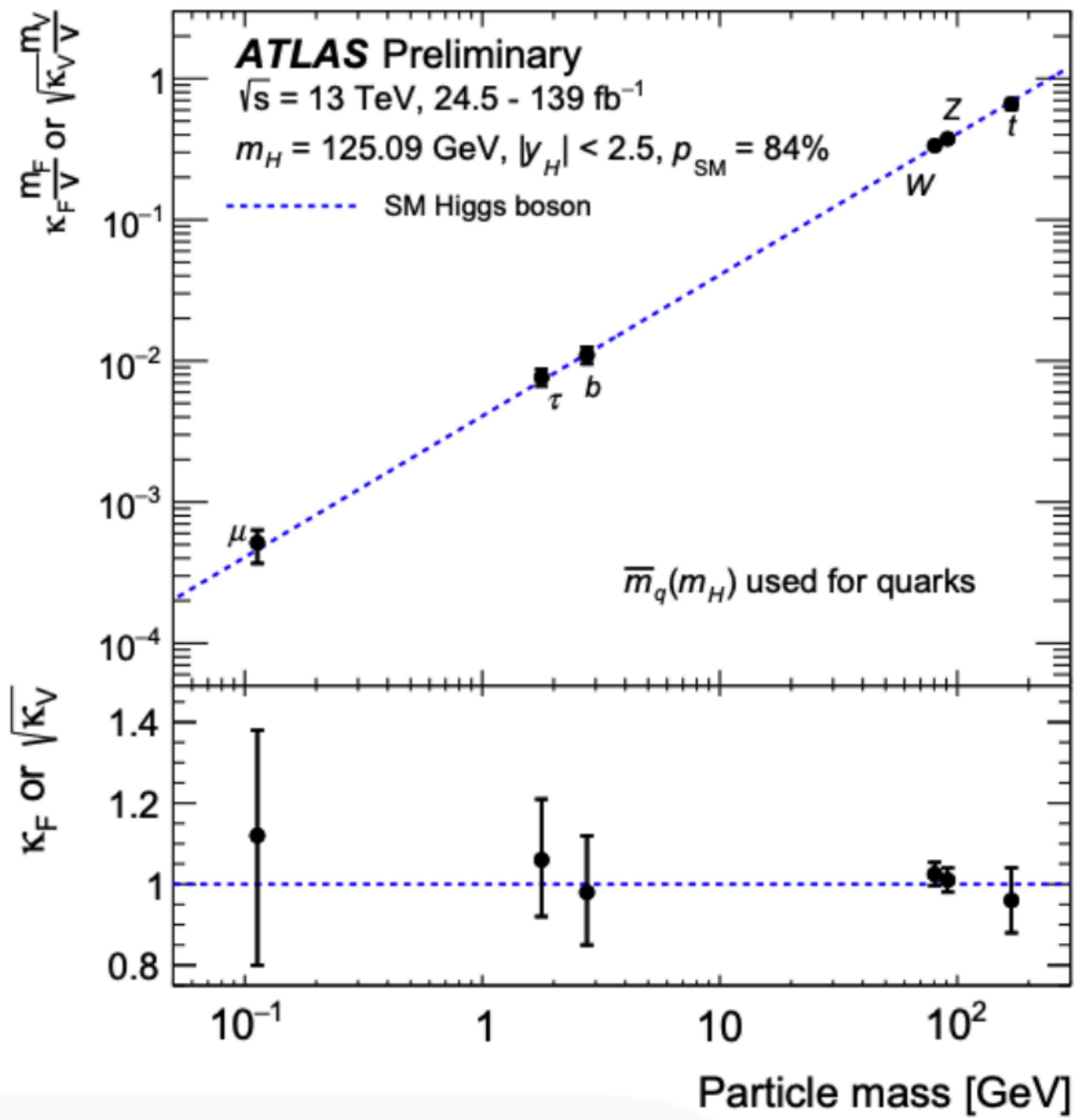




κ-factors summary

ATLAS-CONF-2020-027

- No deviation from the SM observed up to now



Fiducial and differential cross sections

- Total Fiducial cross sections:
  - Define a volume in the phase space, close to the detector + selection acceptance
  - Measure the cross section in that region
  - This allows to keep the A ~1 and limit the theory systematics connected to the acceptance correction

$$\sigma = \frac{N_{\text{reco}}}{(A \times \epsilon)\, L}$$

- Differential fiducial
  - Perform the fiducial cross section measurement in bis of a given variable
  - Subtract the backgrounds and unfold to truth-level quantities (correct for detector effects)

- Pros of the fiducial measurements are:
  - The model dependence is minimal
    - SM assumptions enter only in the extrapolation to the fiducial volume and in the unfolding
    - The results can be re-interpreted in different models as long as A doesn't change significantly
- Main Cons are:
  - The definition of the fiducial volume is final state dependent
    - Difficult to combine all decay channels
  - Difficult definition of the fiducial volume in case of complex selections
  - Possible to unfold only 1- or 2- dimensions

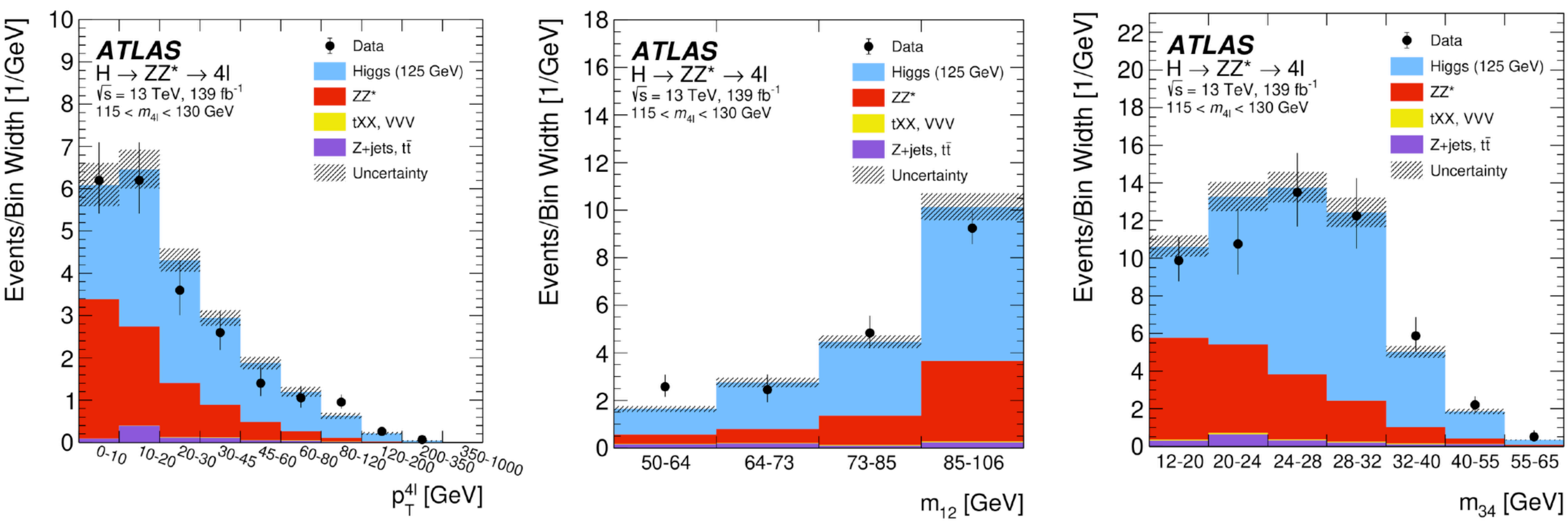
Differential cross sections

- The variables to differentiate the cross section are chosen based on:
  - Sensitivity to New Physics
    - Choose those on which the largest impact is foreseen in various models
  - Obvious experimental considerations related to each decay channel
    - Can that variable be computed for a given final state ?
    - Is the detector resolution good enough to be able to correct for it without introducing too large systematics ?
- Typical variable considered are:
  - pT of the Higgs
  - Decay angles in the final state (similar to those considered for spin-CP measurements)
  - Variables related to jets
    - Number of jets
    - pT of the leading and sub-leading jet
  - Invariant masses of pair of production decays (the masses of the two Z's in the case of H-->ZZ)

Differential cross sections in H-->ZZ*-->4l

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

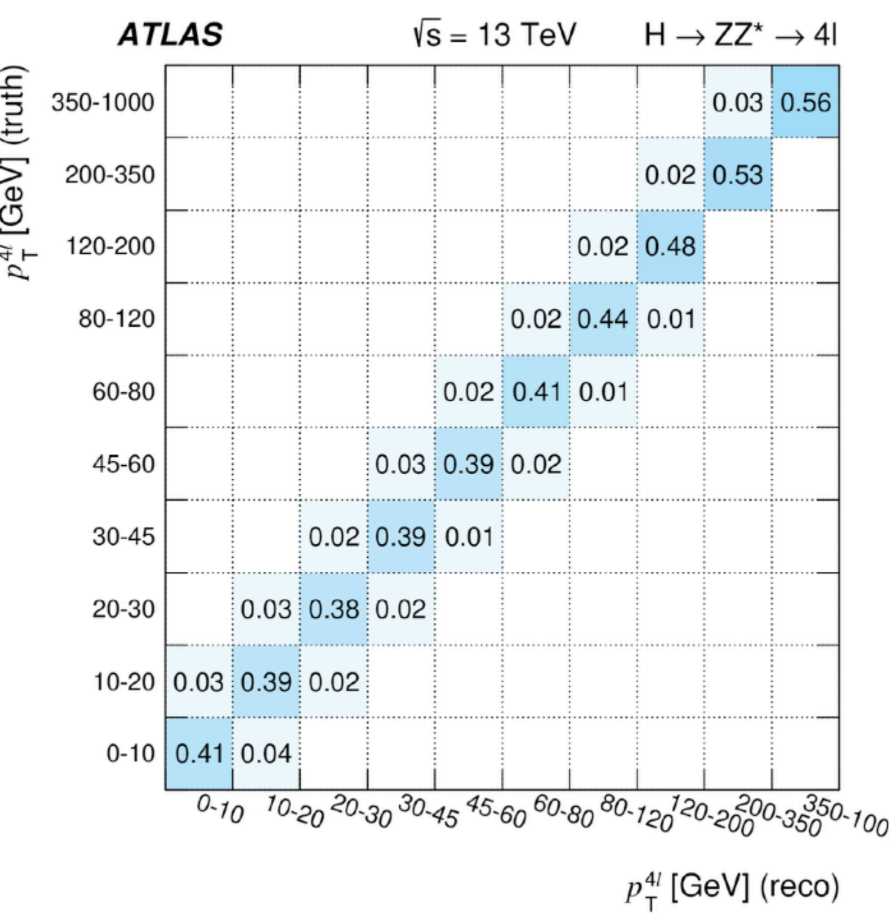
- Clean channel, with the best resolution in many reconstructed variables
- The masses of the 2 Z's (m12, m34) and their correlation
- General method to extract the cross section:
  - Consider the signal region (via e.g. a 4l mass window)
  - Subtract the background, unfold to truth level quantities

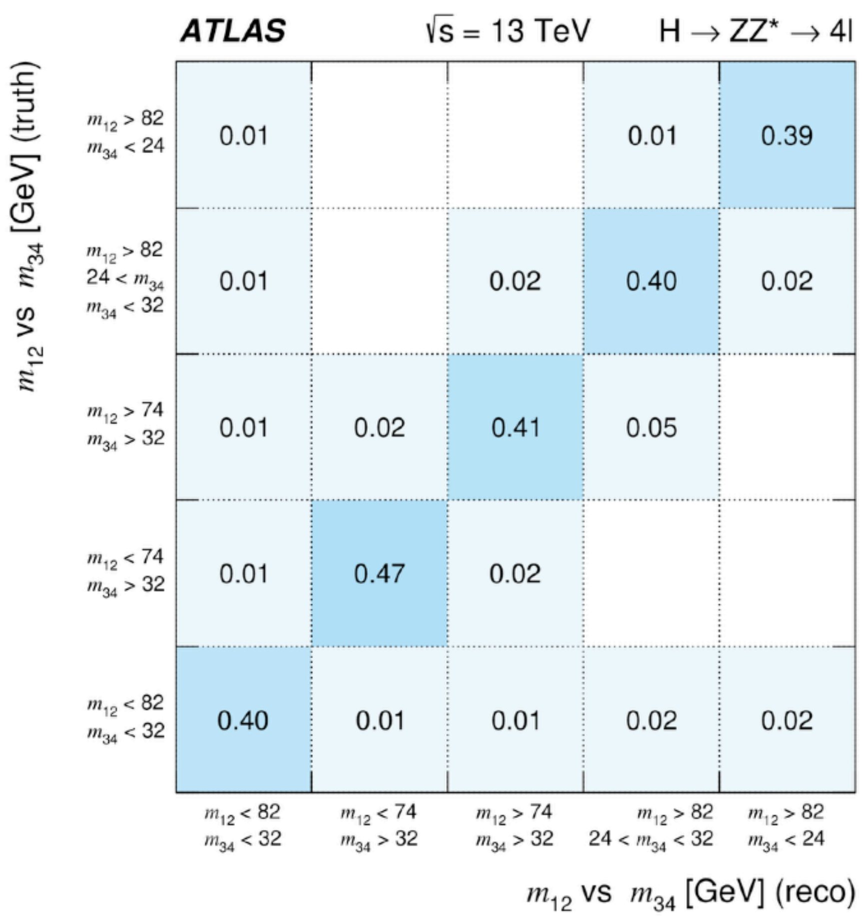


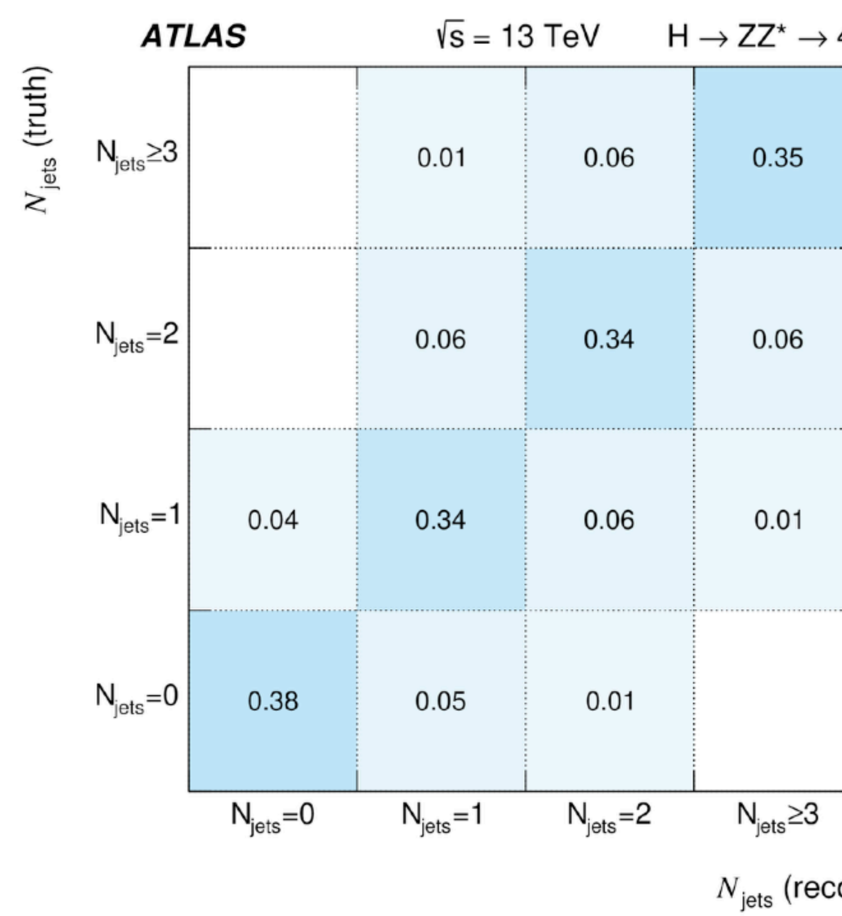
Unfolding

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

- Some example variables, pT Higgs, m12 vs m34, and Njets
- The migration matrix is channel dependent



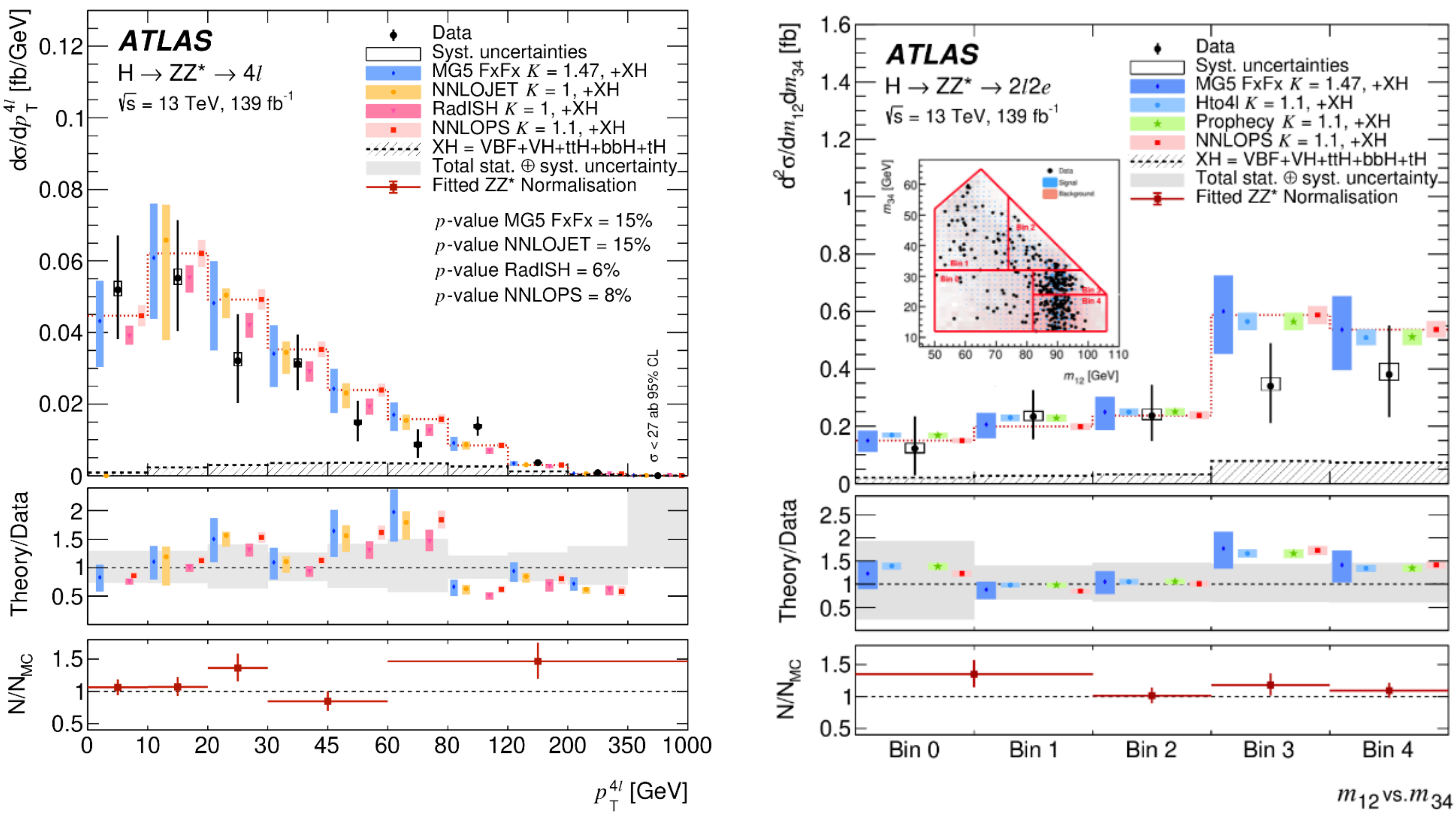




Differential fiducial cross sections in 4l

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

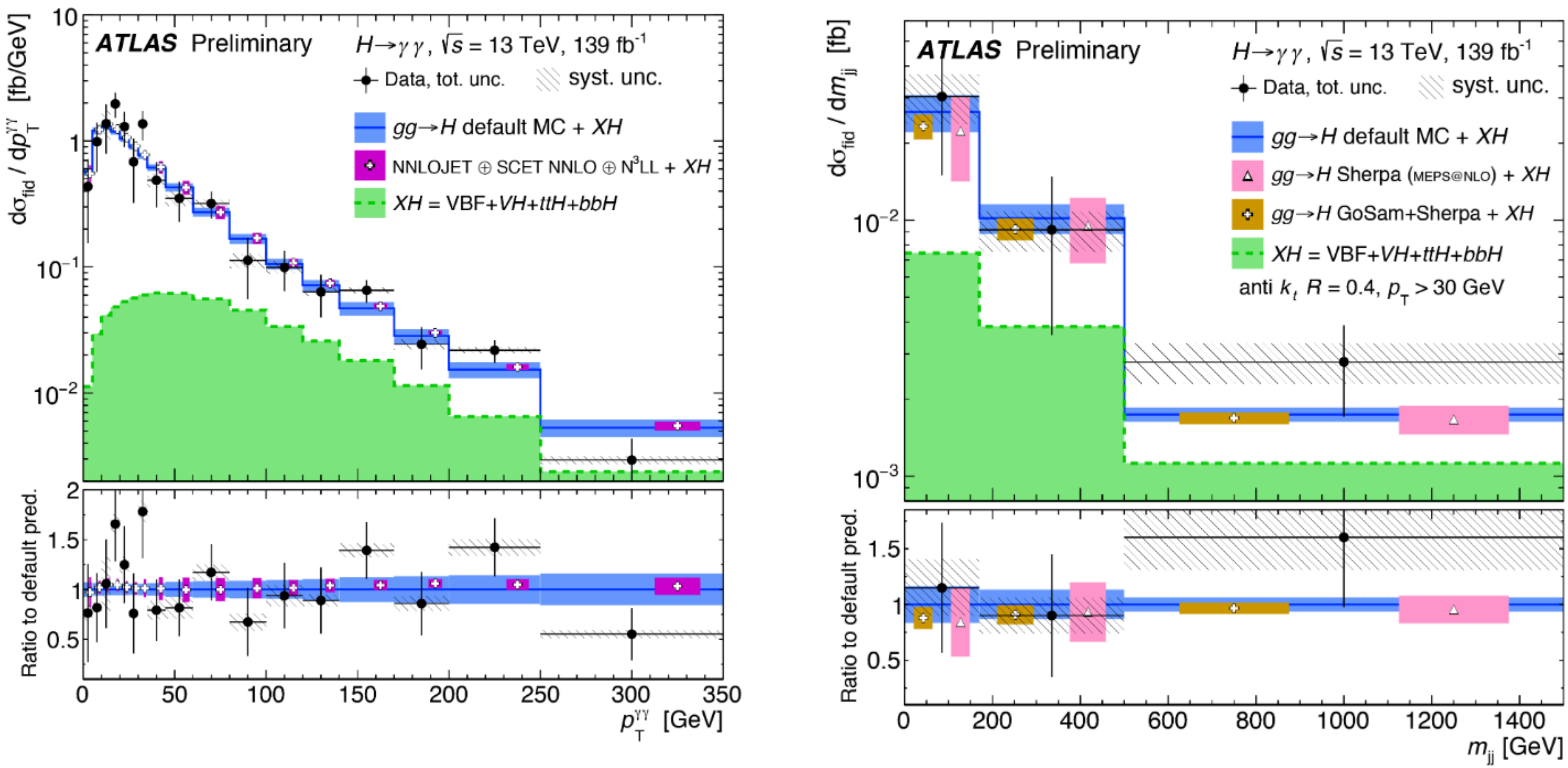
- Some results and comparison to models / generators



Differential fiducial cross sections in γγ

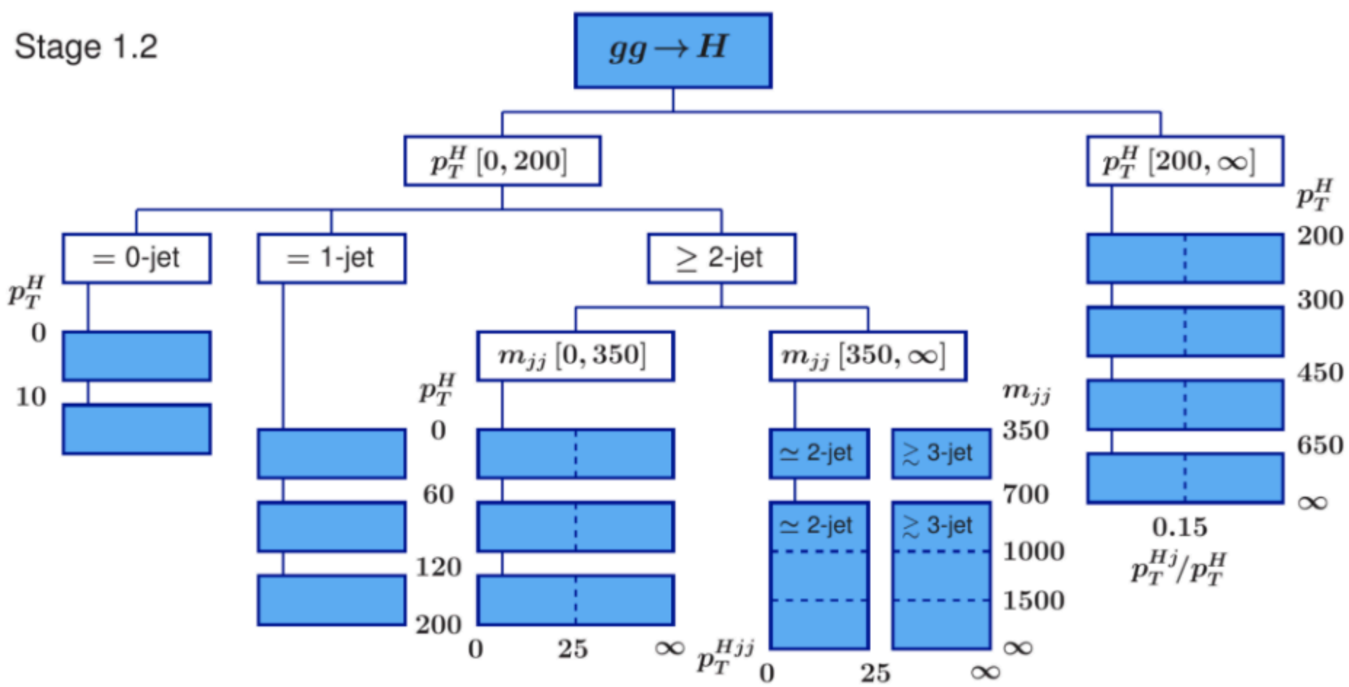
ATLAS-CONF-2019-029

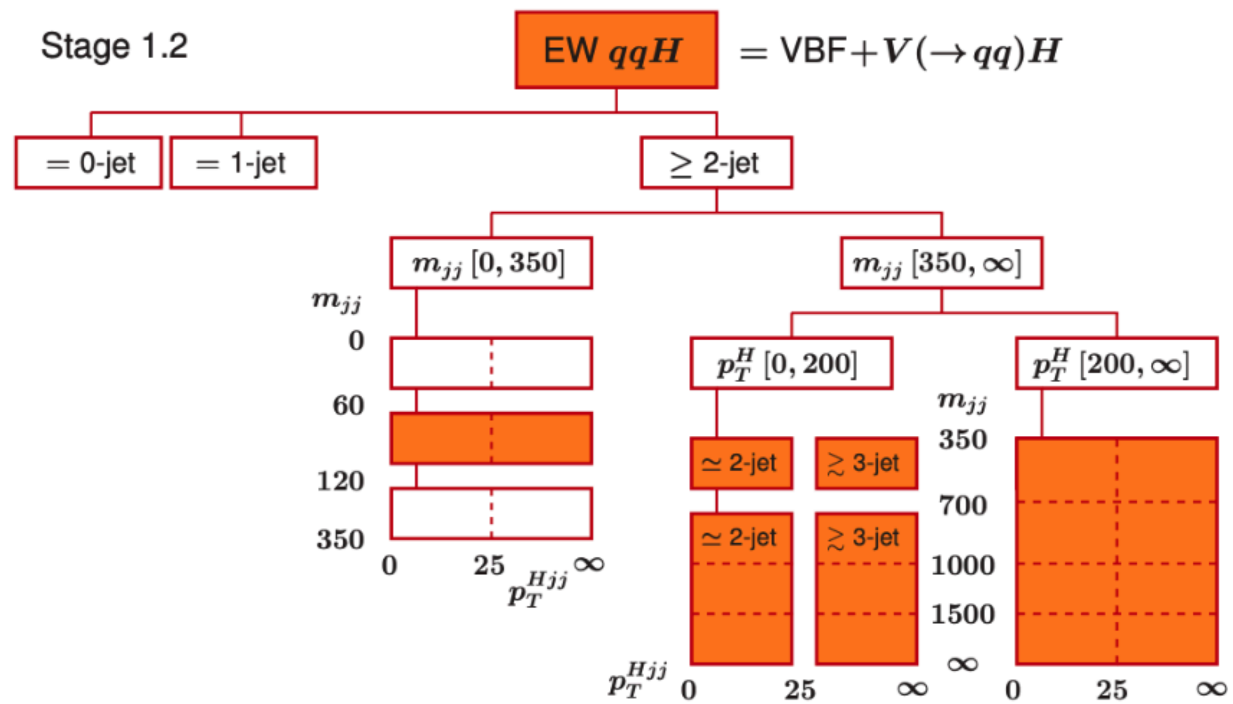
- Other high-resolution channel that allows to reconstruct many variables

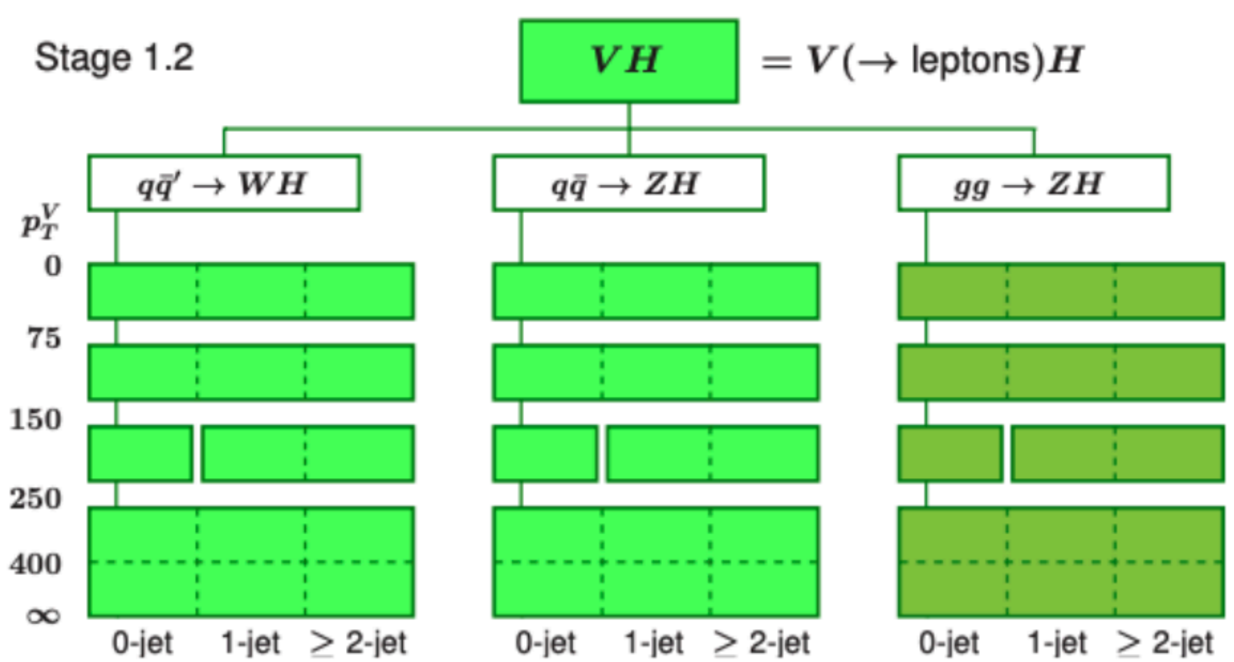


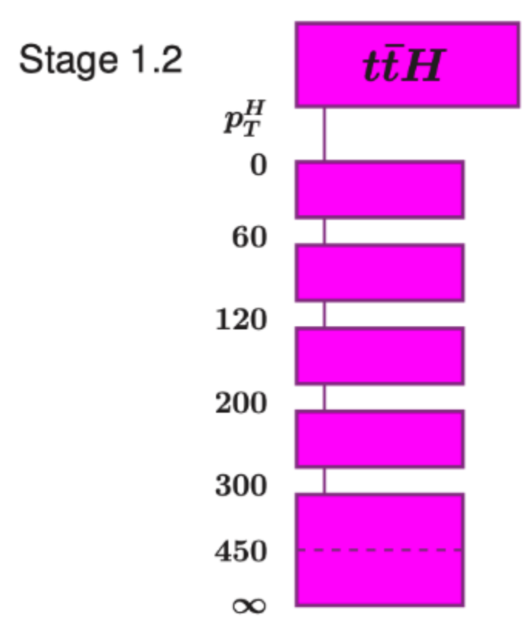
Simplified template cross sections (STXS)

- Measure the signal strength separated per production mode, in bins of (truth) quantities









The analyses are designed trying to match the bins of truth quantities

Different granularity --> can be chosen depending on the channel's statistics

STXS

- A way to break up each production mode in bins
  - General acceptance cut of $|y_H|<2.5$
- Within each bin, the SM behaviour (i.e. kinematics) is assumed
  - This implies model dependence, however it also makes easier to develop analyses and event selection (check impact of cuts, develop MVA etc.)
- Same bins definition for all decay modes simplifies a lot the combination
  - So increasing the sensitivity on the measurement of the signal strength per production mode
- Also a common binning will include information from multiple variables/ selection

- However assuming SM behaviour within each bin implies model dependence,
  - But, it also makes easier to develop analyses and event selection (directly check impact of cuts, develop MVA etc.)

STXS in H-->ZZ*-->4l

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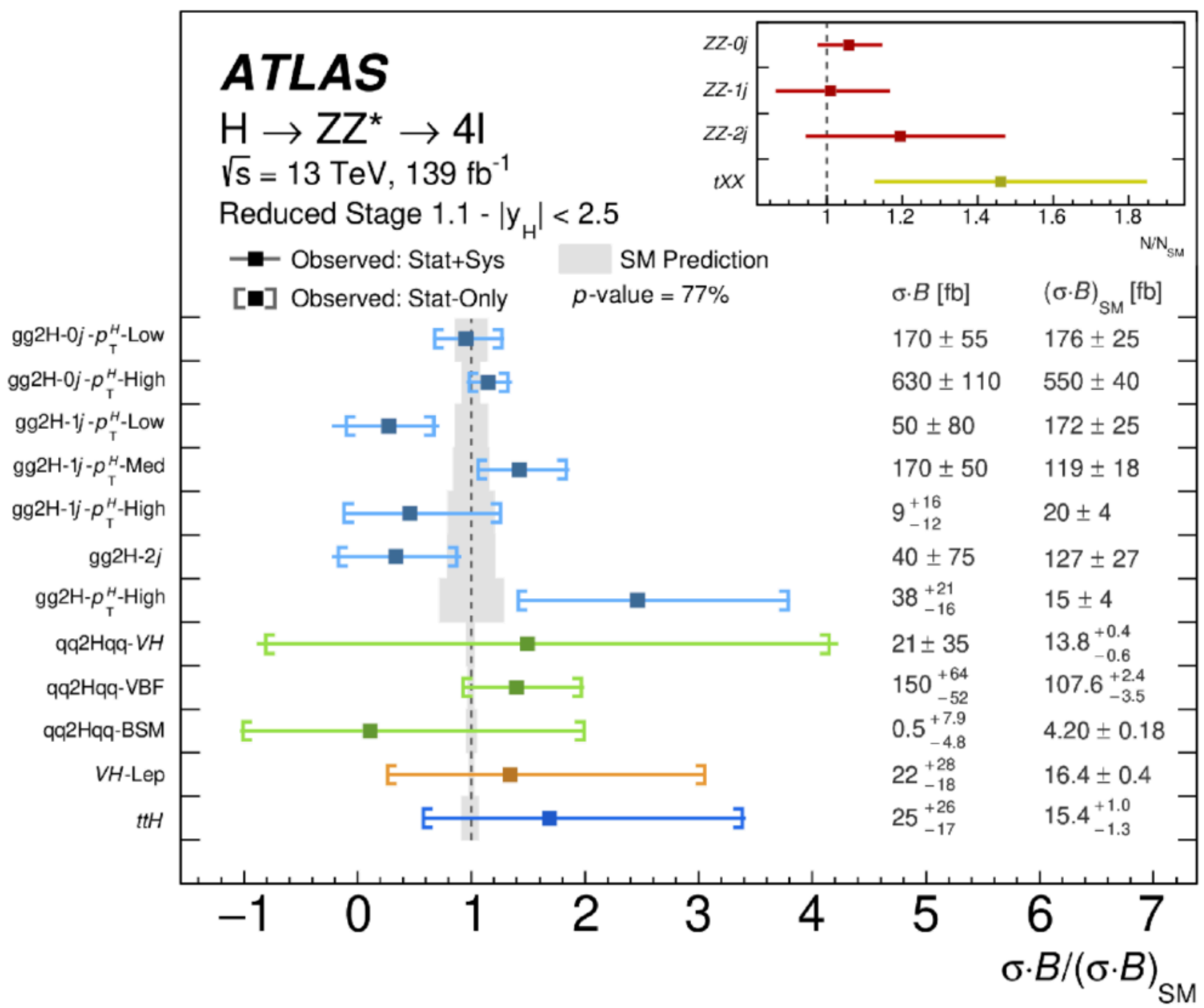
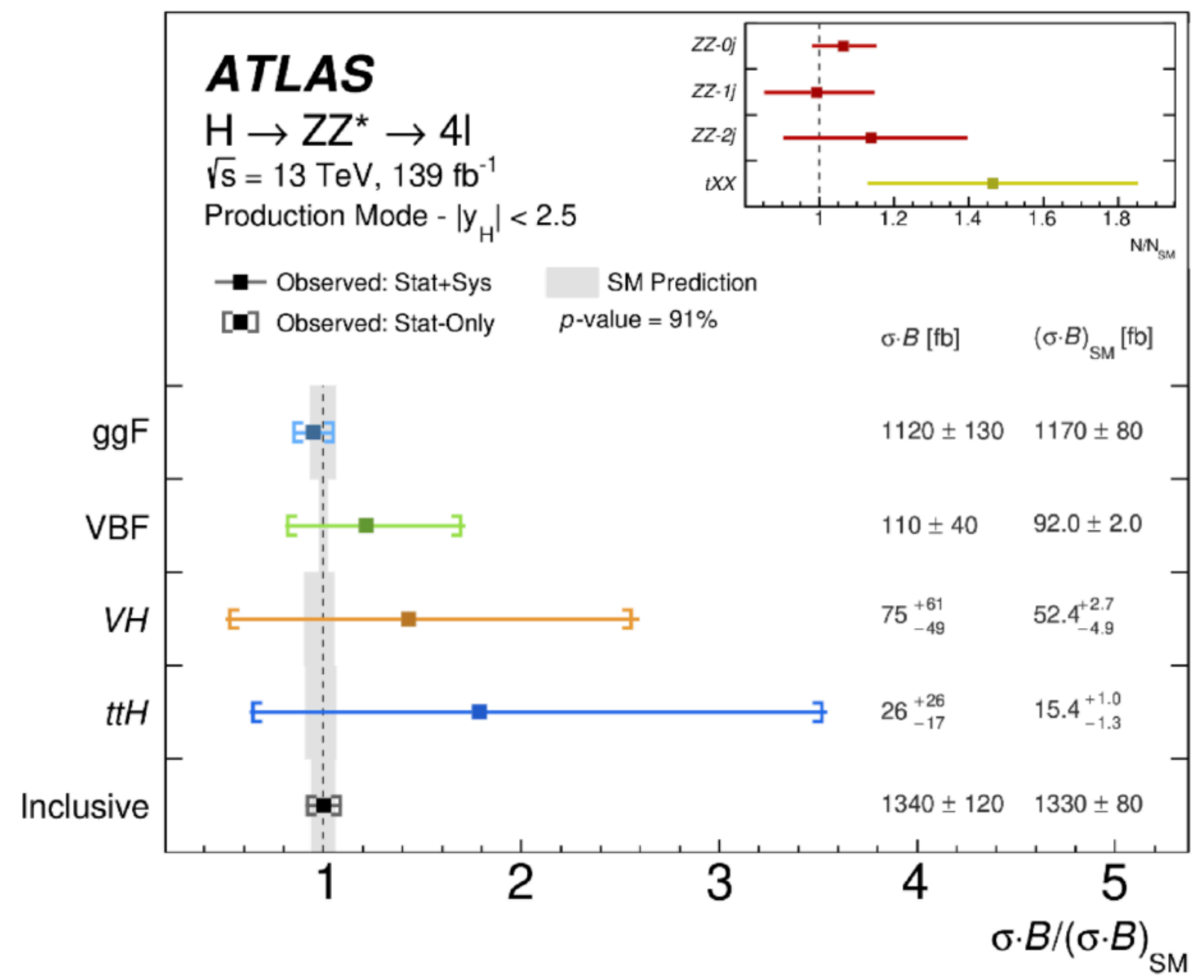
- Low-statistics channel
  - Use stage 1.1 bins





STXS combination

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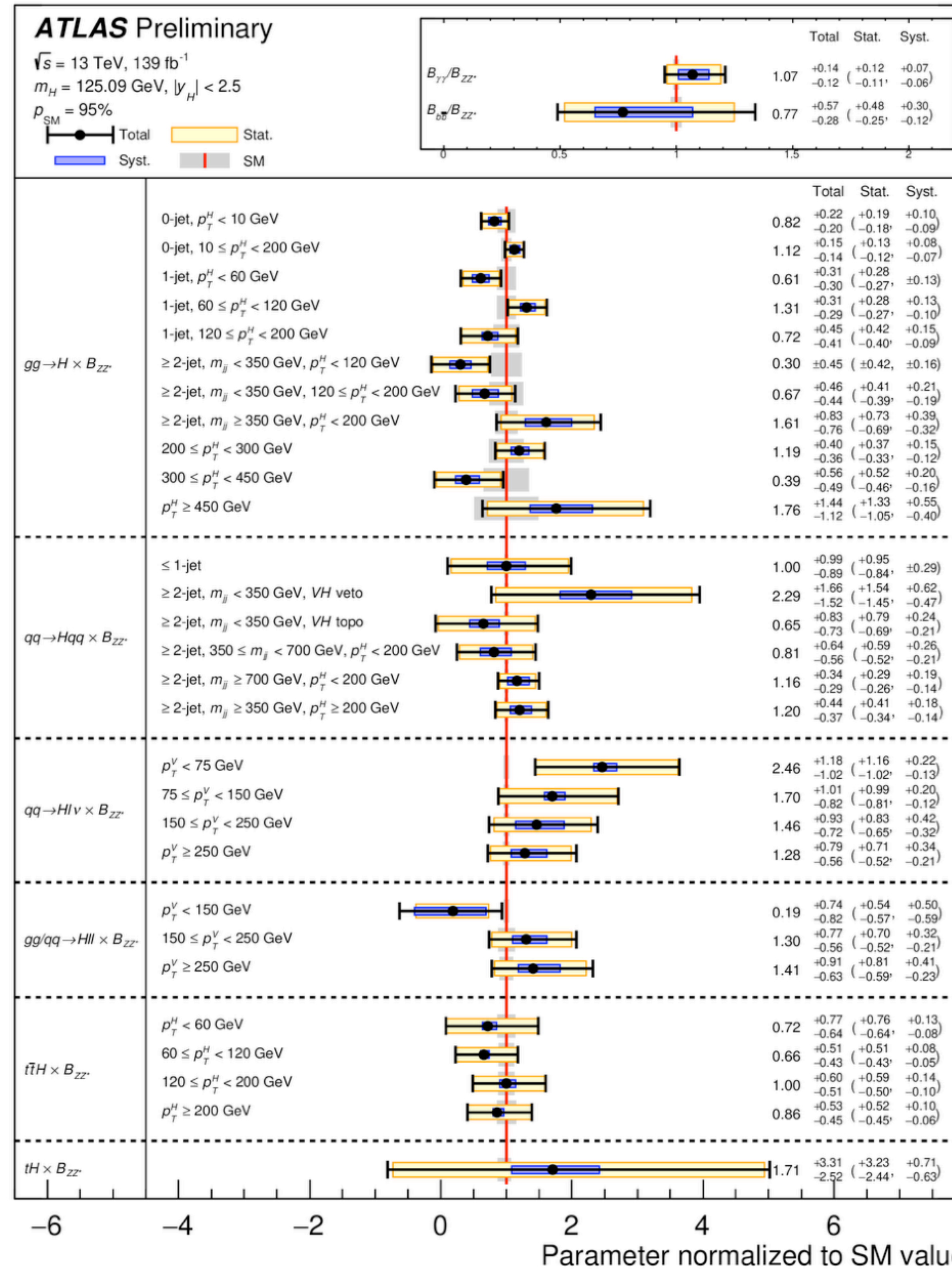
- Best precision from the combination of all production and decay channels
  - Actually this combination includes H-->ZZ, H-->γγ, VH(bb), more to be included
- Limiting the measurement to the 29 bins for which enough sensitivity can be reached
- All measurements are still limited by statistics
- Very good agreement with the SM
  - p-value 95%



Effective Field Theory

- Effective Field Theory is a tool to study possible effects beyond the SM (BSM), whose direct observation (e.g. via a resonance) would be possible only at scales higher than those actually reachable

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

Fixing Λ=TeV

- Limiting to O(6) operators, the total matrix element can be expressed as:

$$\mathcal{M}_{\mathrm{SMEFT}} = \left| \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i \right|^2$$

  - Where ci is the Wilson coefficient of the operator Oi

- So a cross section will be given by:

$$\begin{aligned}\sigma \propto |\mathcal{M}_{\mathrm{SMEFT}}|^2 &= \left| \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{M}_i \right|^2 \\ &= |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i 2Re\left(\mathcal{M}_{\mathrm{SM}}^* \mathcal{M}_i\right) \frac{C_i}{\Lambda^2} \\ &\quad + \sum_{ij} 2Re\left(\mathcal{M}_i^* \mathcal{M}_j\right) \frac{C_i C_j}{\Lambda^4},\end{aligned}$$

$$\rightarrow \quad \frac{\sigma^p(\vec{c})}{\sigma^p_{\mathrm{SM}}} = 1 + \sum_i A_i^p c_i + \sum_{ij} B_{ij}^p c_i c_j,$$

- Interference term can have only CP-even operators, while the fully BSM ones can also contain CP-odd terms

EFT couplings fit in H-->ZZ*-->4l

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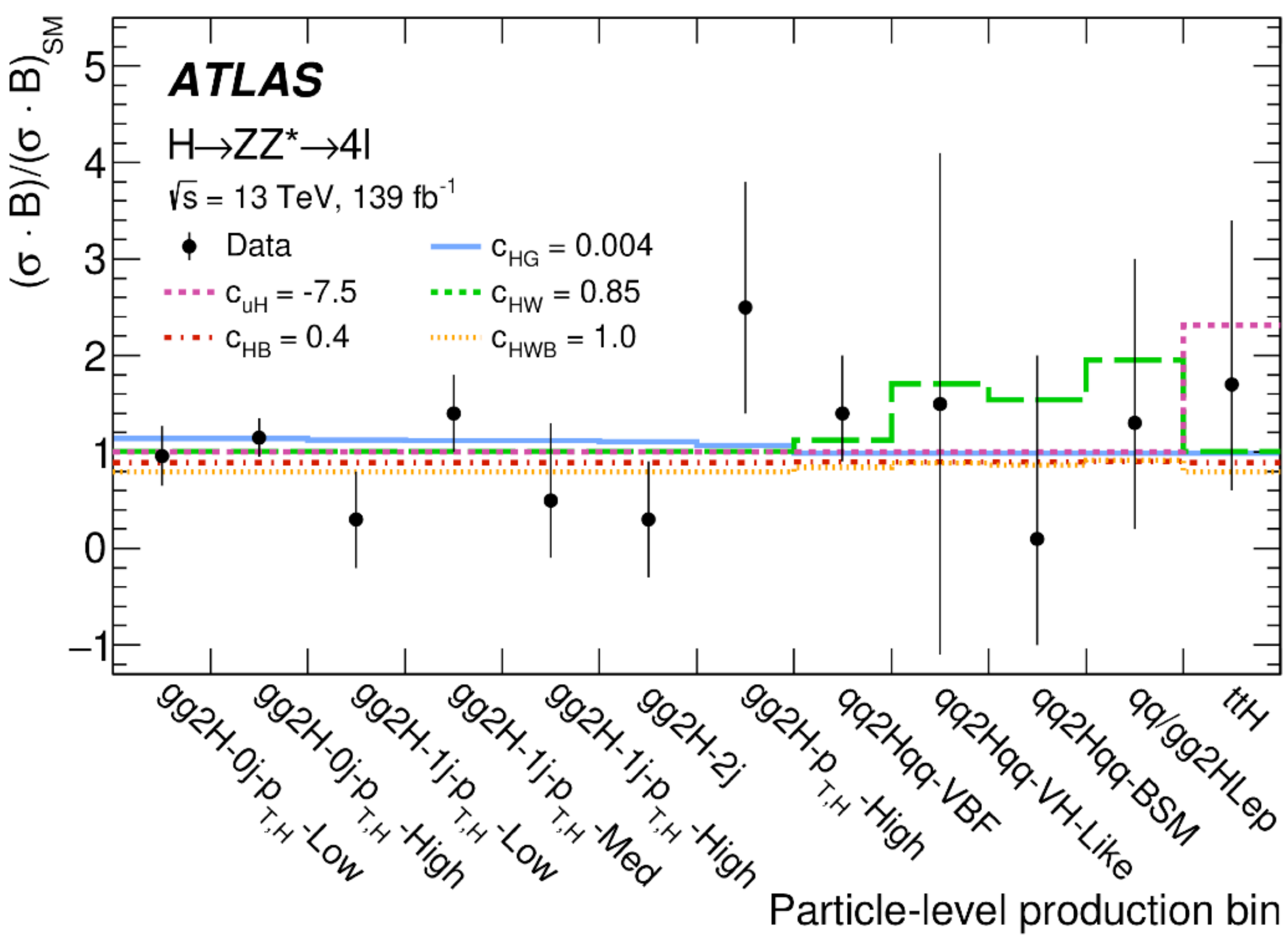
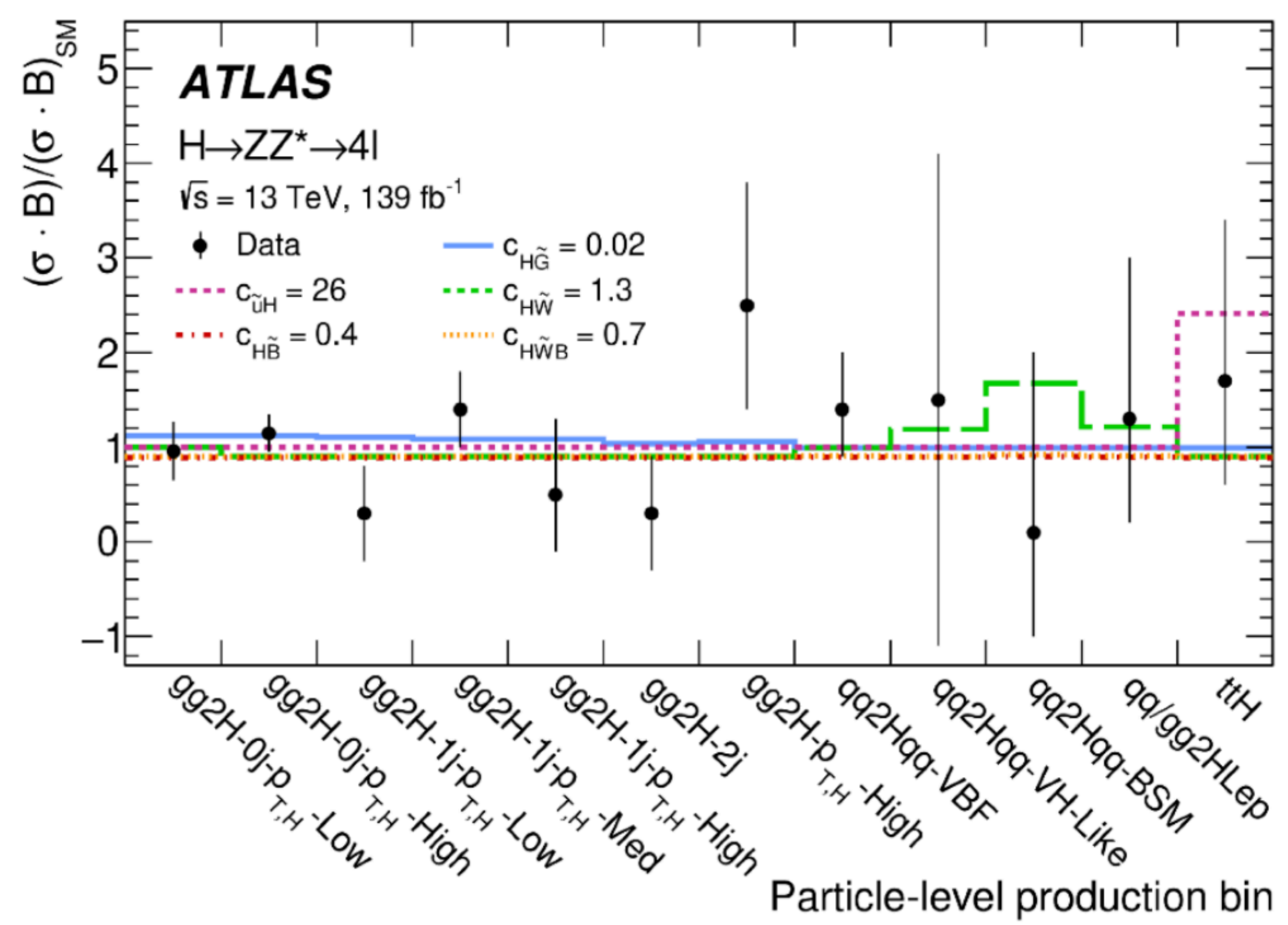
- Each channel is sensitive to a different set of coupling, so for example in the case of H-->ZZ*-->4l:

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes





EFT couplings fit

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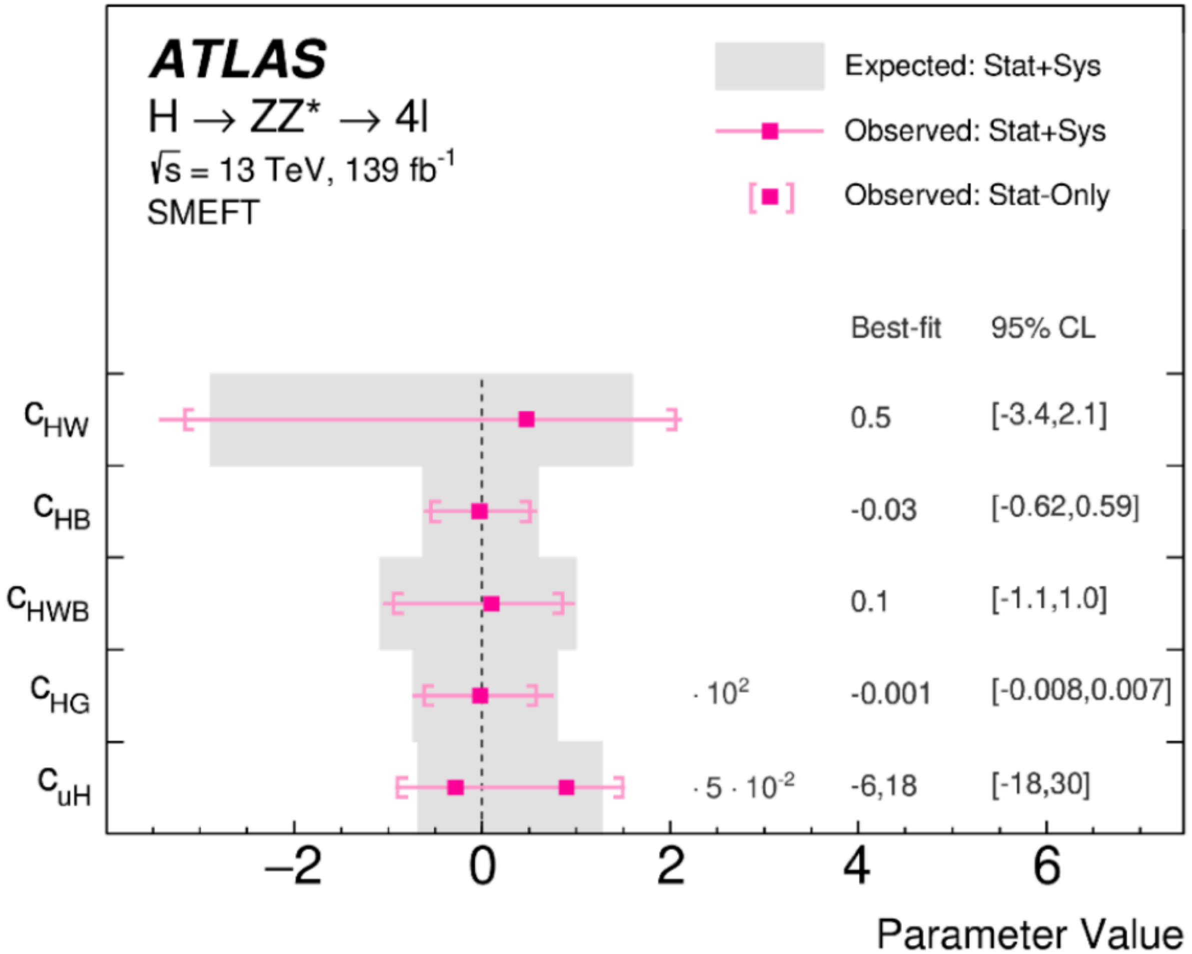
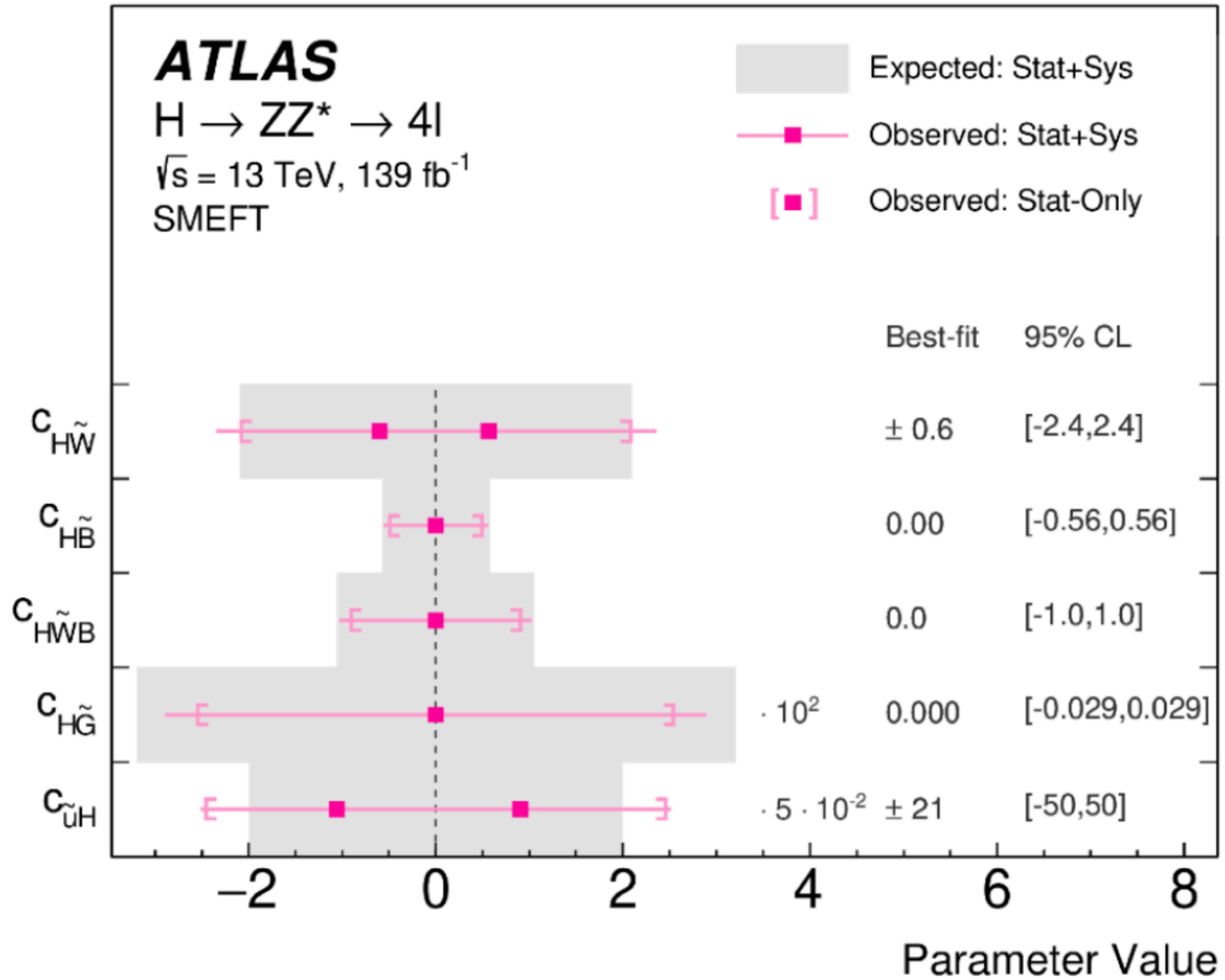
- Results, fitting only one parameter at the time, with the others fixed at zero





Combined SM EFT interpretation

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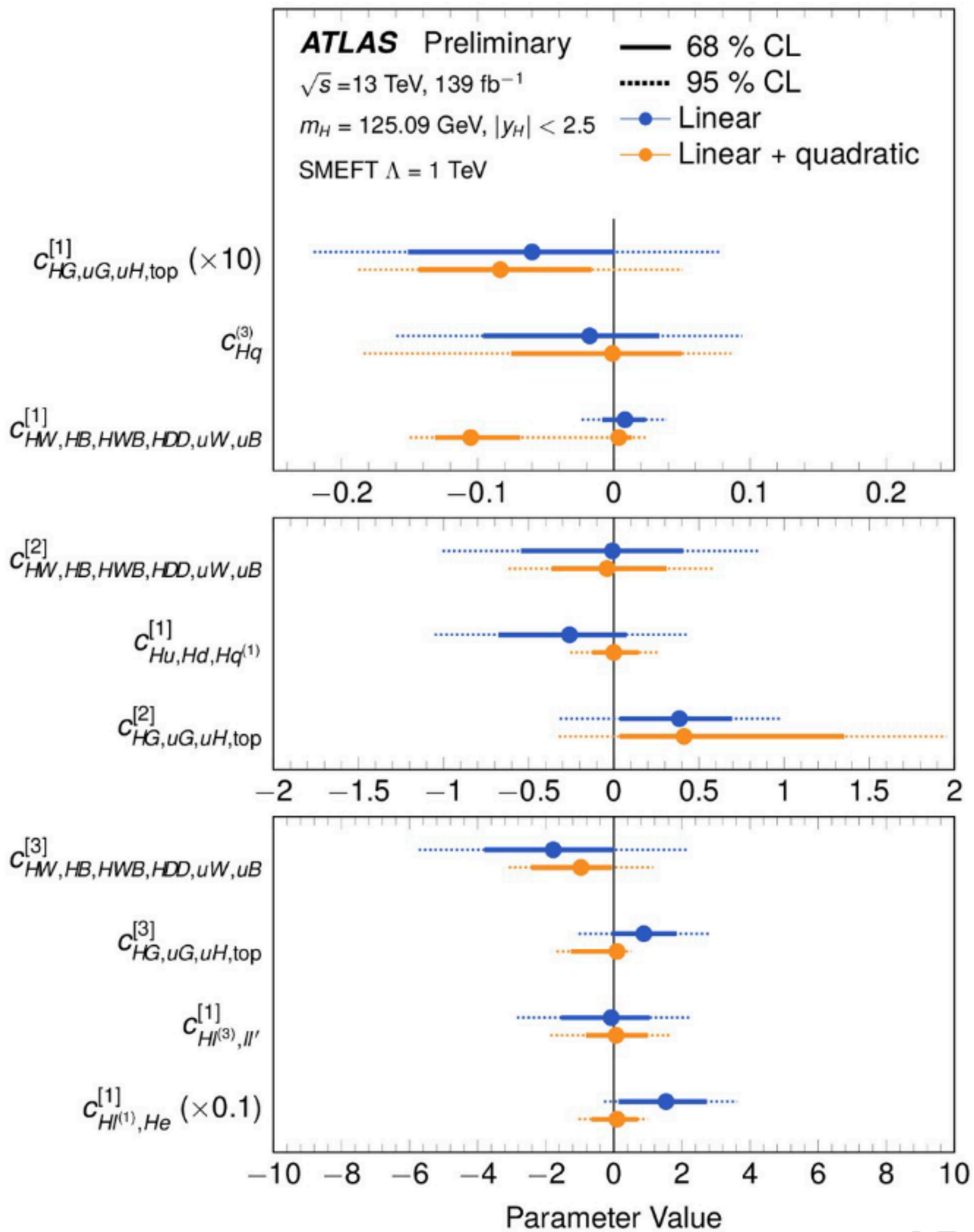

Conclusions

- After the discovery, and the confirmation of the scalar hypothesis, the focus of Higgs analyses
- The analyses have now a dataset including ~139 fb-1 at 13 TeV
- No deviation from the SM observed up to now
- Most measurements are still limited by statistics, so the next runs of LHC will allow to increase significantly the precision and the sensitivities