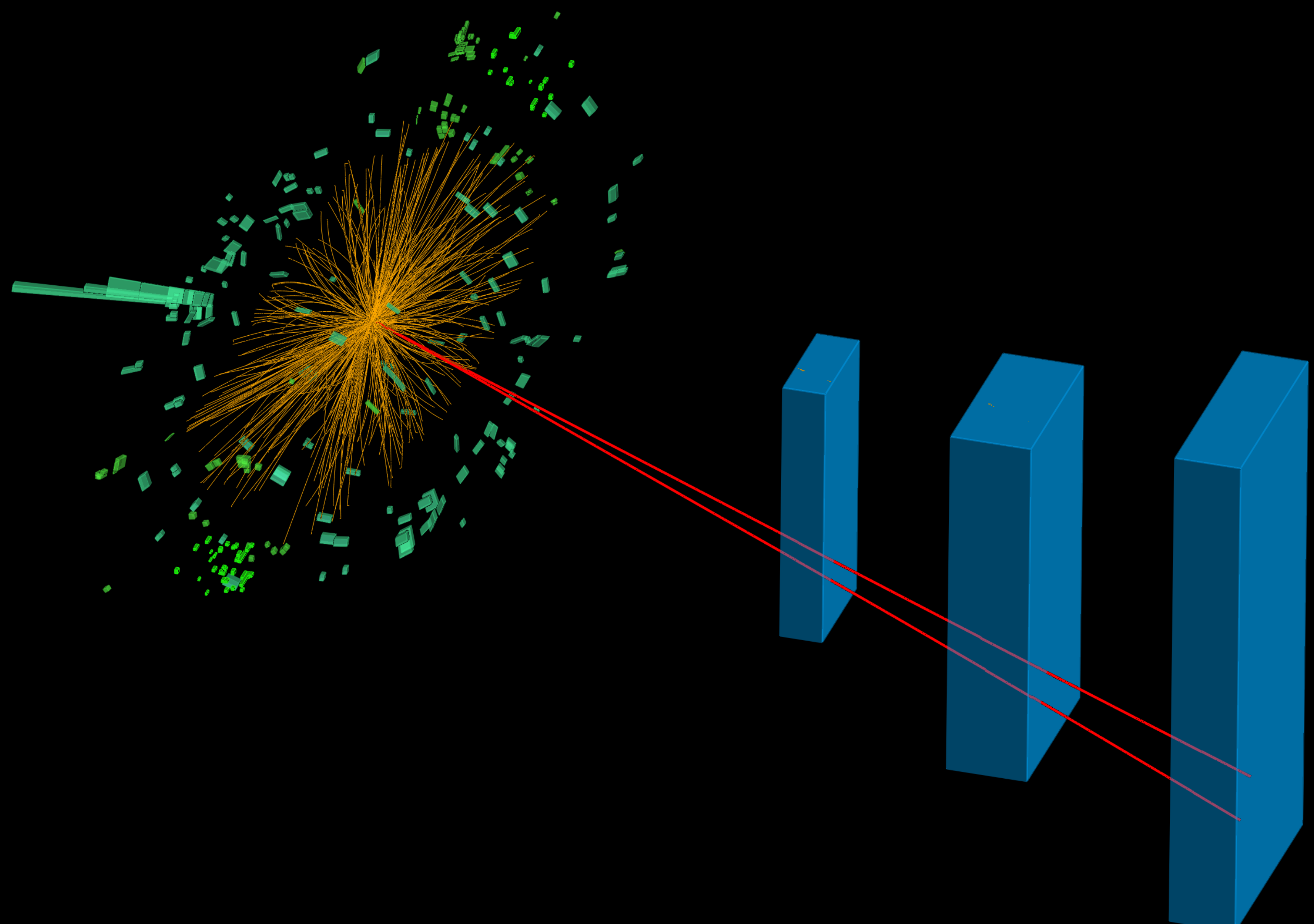
Rare lepton and photon decays of the Higgs boson during Run 2 and 3

Sarah Heim, DESY

PITT PAC Workshop, April 7th, 2021

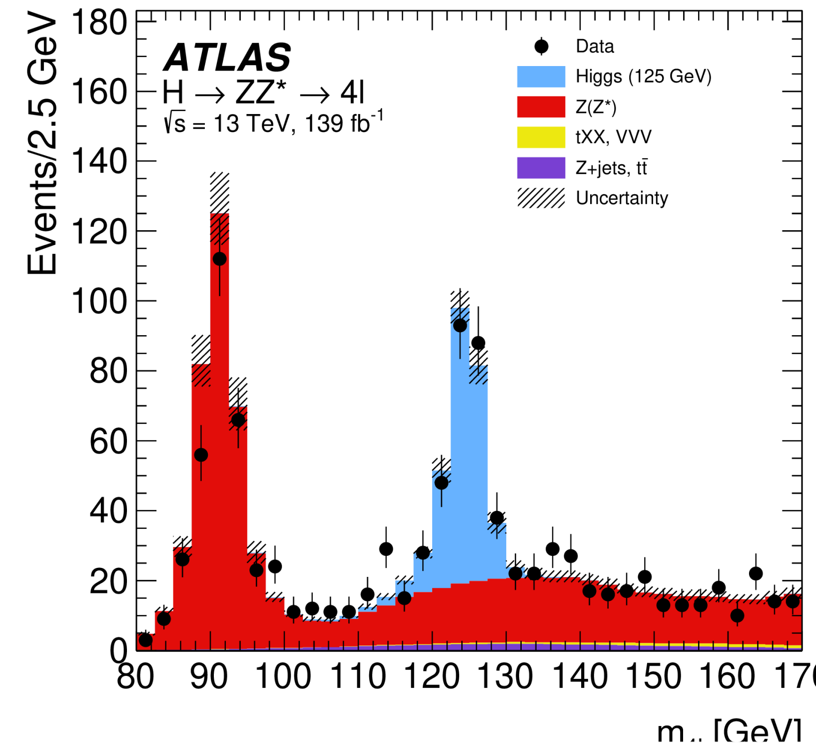


Introduction

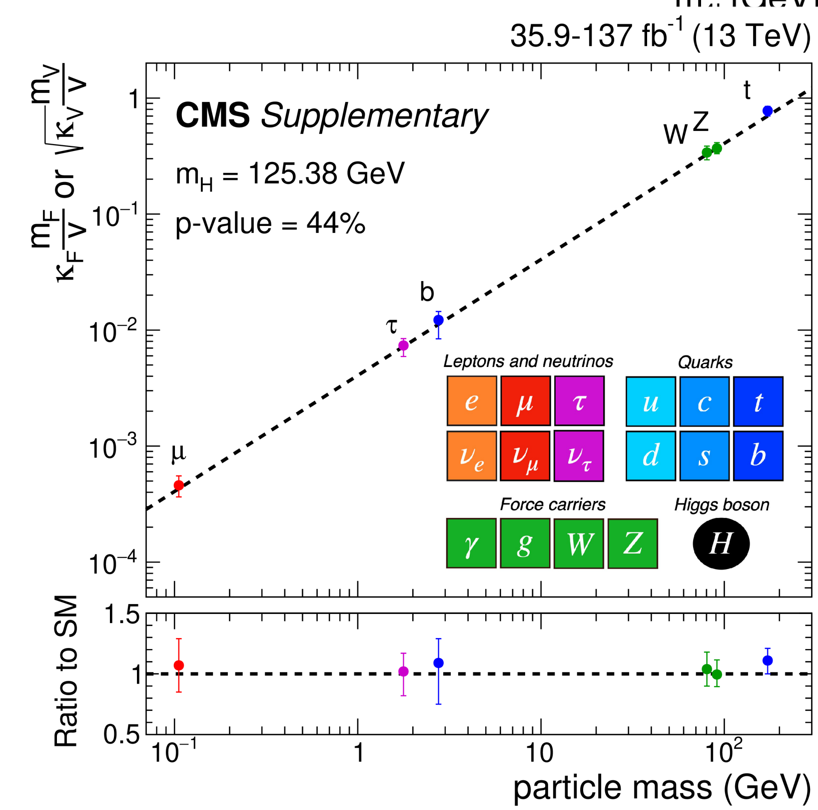
Ever since the discovery of the Higgs boson in 2012: More precise measurements of its properties

- ✔ 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%
- ✔ Higgs couplings
  - assuming SM structure:
    - tested fermion and boson coupling strength
  - pure CP odd couplings to bosons excluded (> 5σ)
  - pure CP odd couplings to fermions excluded (> 3σ)

=> no disagreements from the SM predictions so far

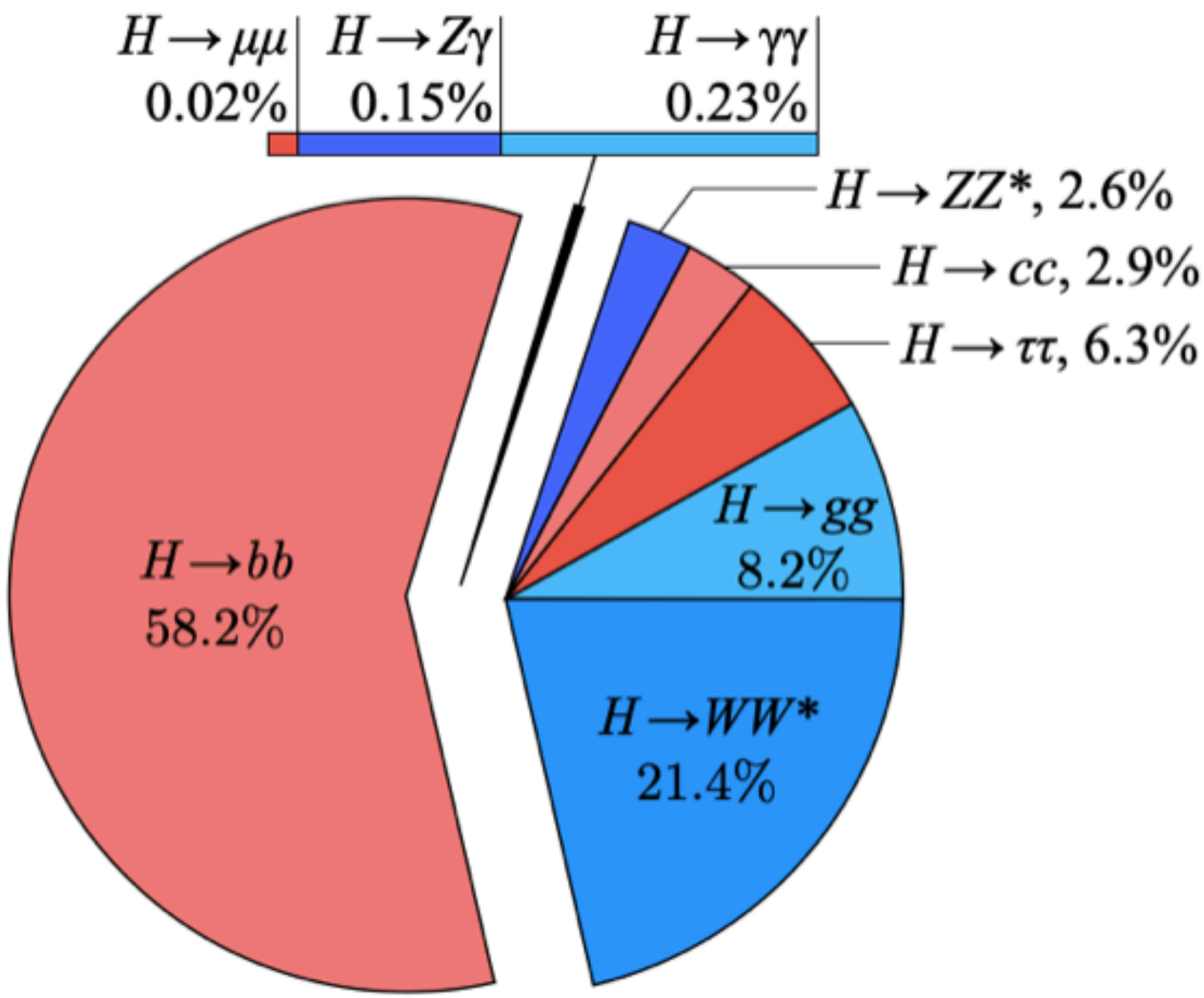


Eur. Phys. J. C 80 (2020) 942



JHEP 01 (2021) 148

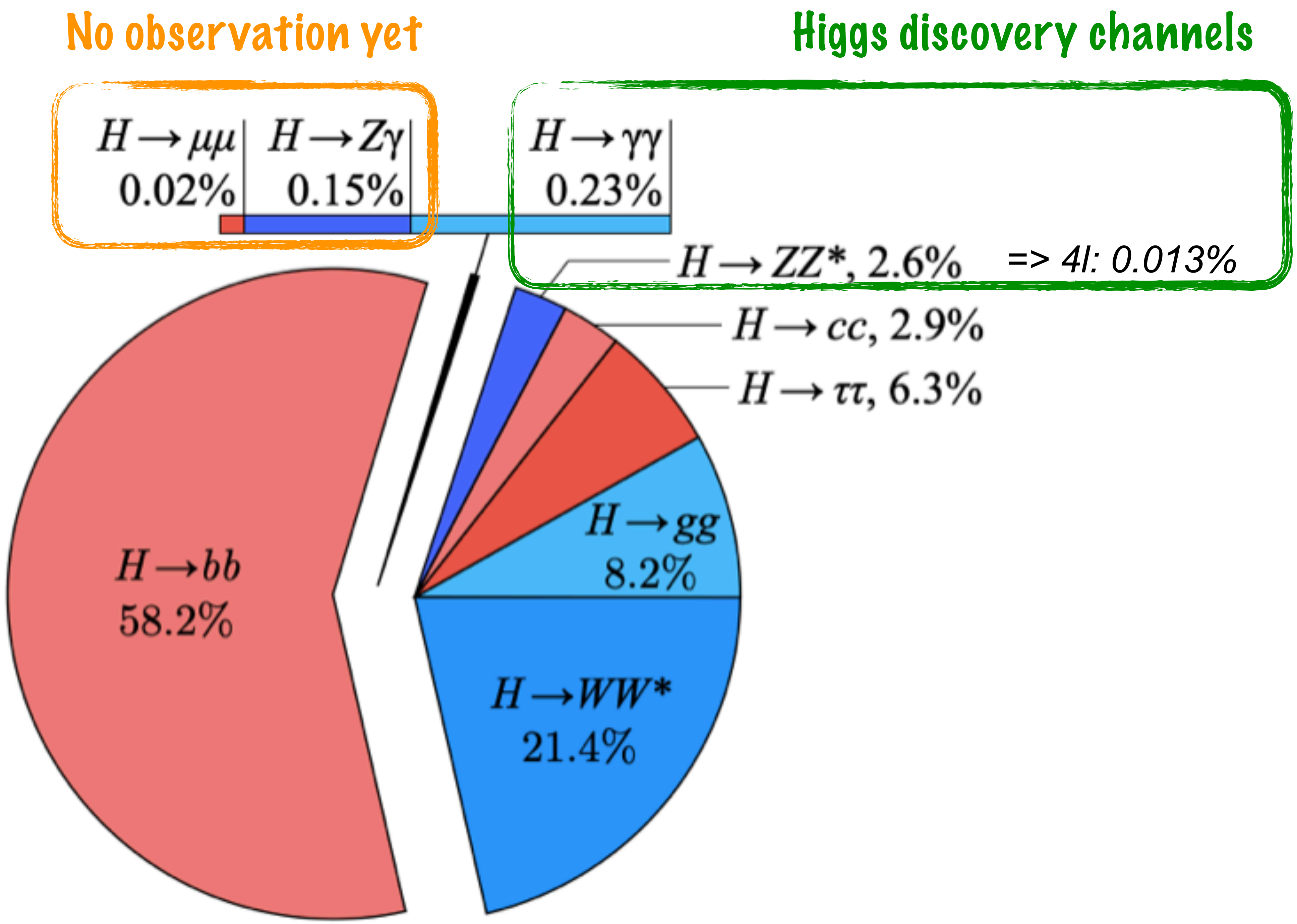
Higgs decays



=> *4l: 0.013%*

From LHCHWG
SM, m_H = 125 GeV

This talk



These final states are not very complicated, are generally easy to trigger on, the backgrounds are well-behaved…but they are rare!

Run-2 highlights - 4ℓ

Mass measurements

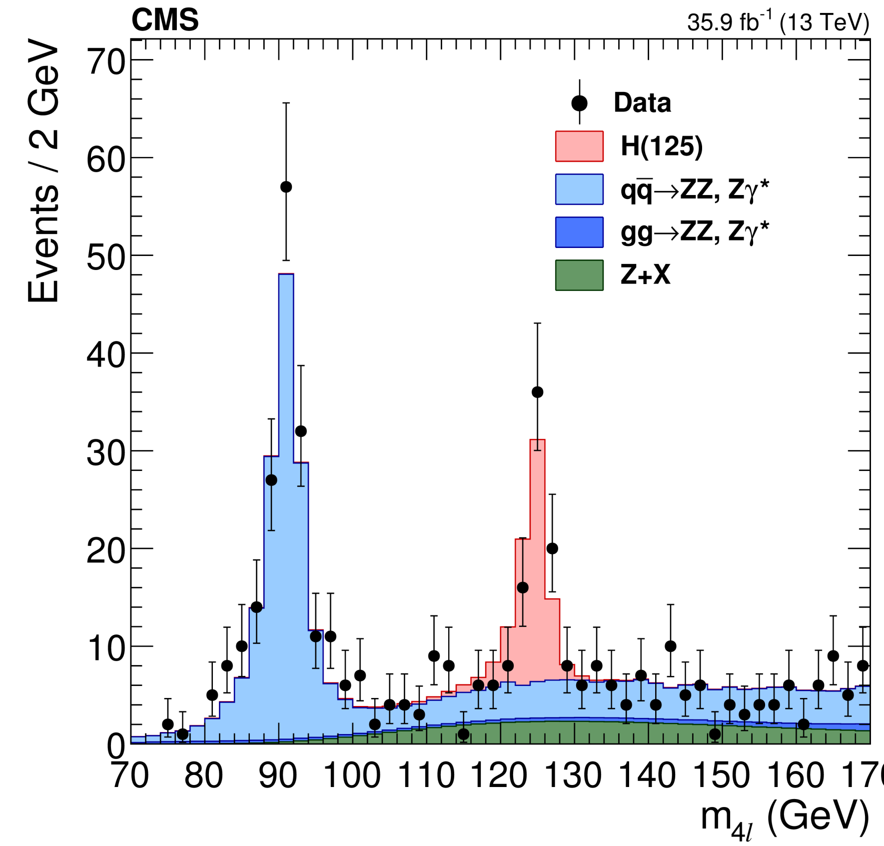
Most precise Higgs mass measurement to date:
CMS, Run-1 + Run-2 4ℓ + γγ, 36 fb^{-1}:

stats only

$$125.38 \pm 0.14\ (\pm 0.11)\ \text{GeV}$$

1 per-mille!

- includes MELA discriminant against background

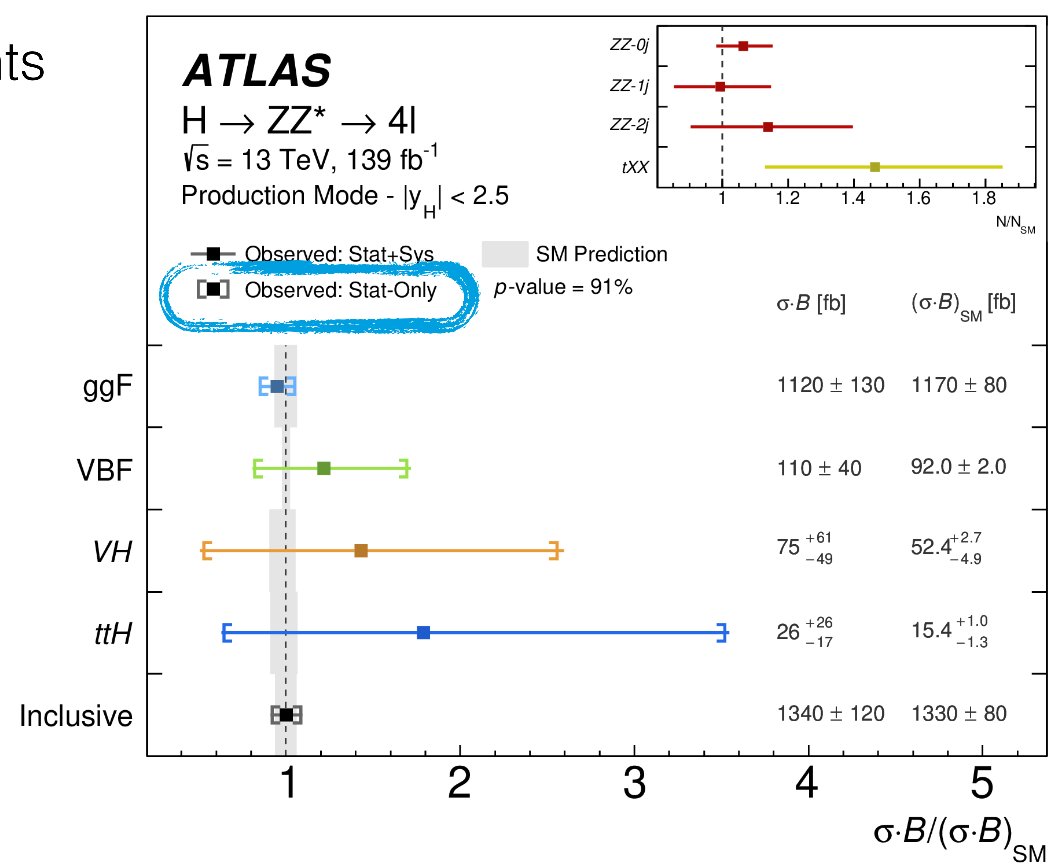


JHEP 11 (2017) 047

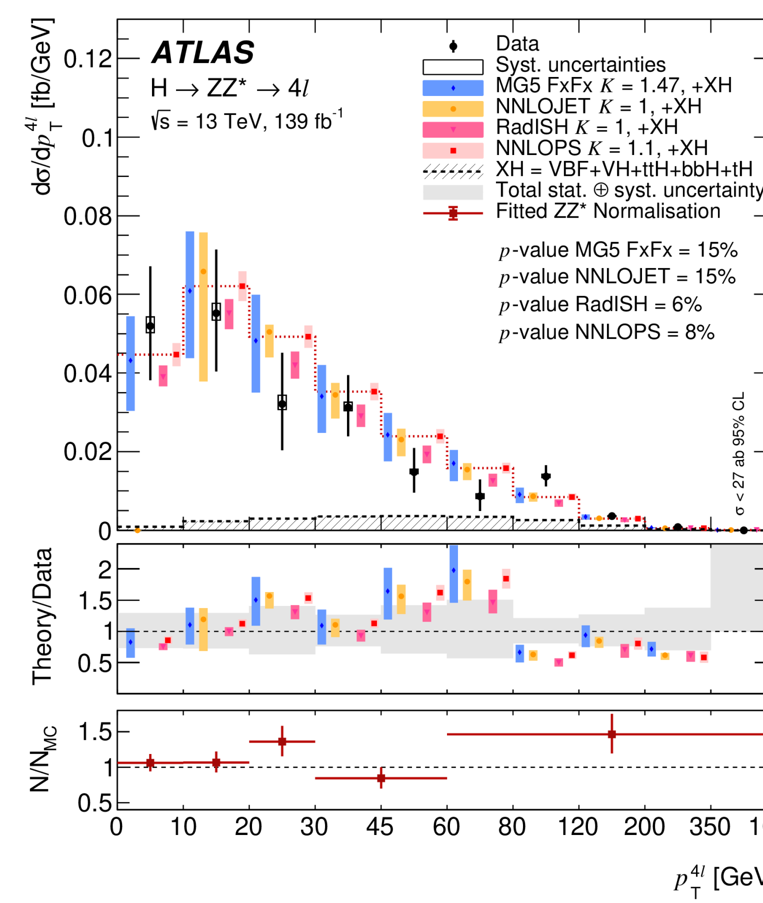
Cross section measurements

Neural net discriminants are used to separate

- ZZ backgrounds
- production modes



Eur. Phys. J. C 80 (2020) 957



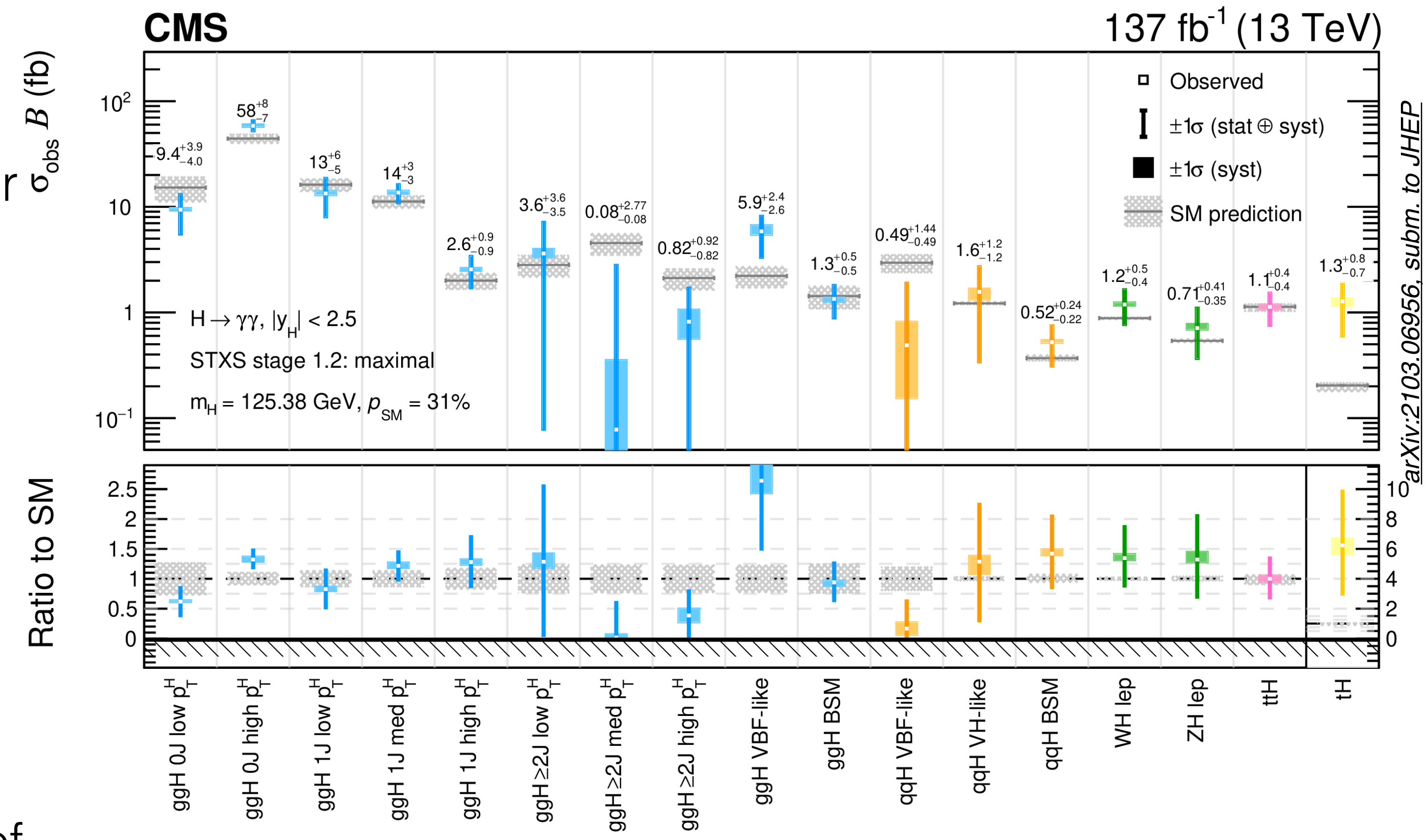
Eur. Phys. J. C 80 (2020) 942

Run-2 highlights - γγ

Cross section measurements

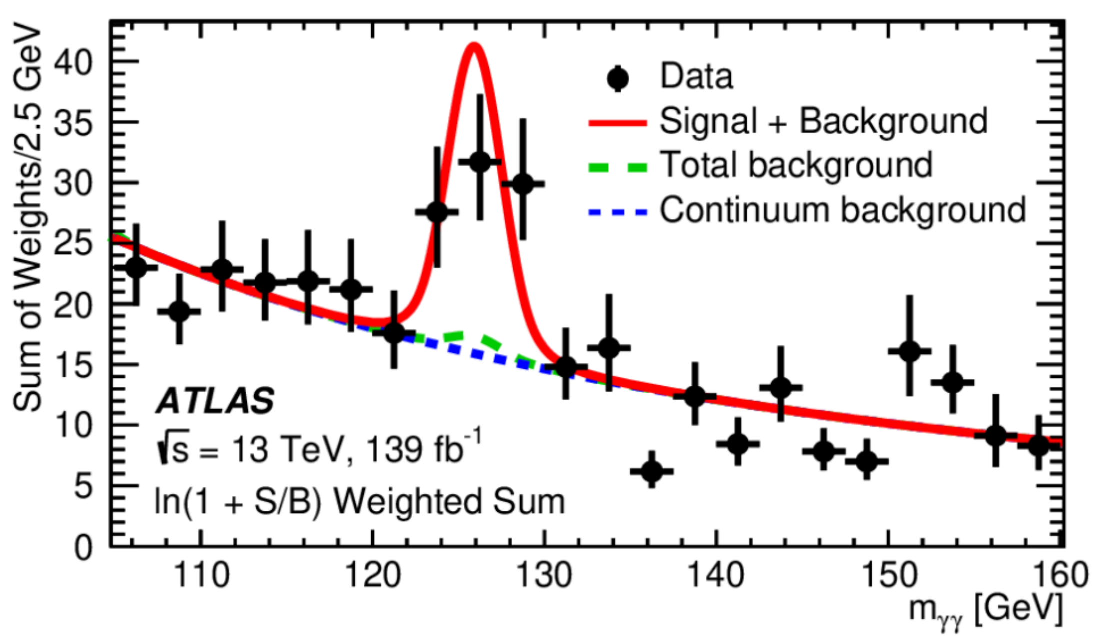
Simplified template cross sections: Binned per production mode and additional criteria

- various ML techniques used for event classification and to reduce data-MC differences

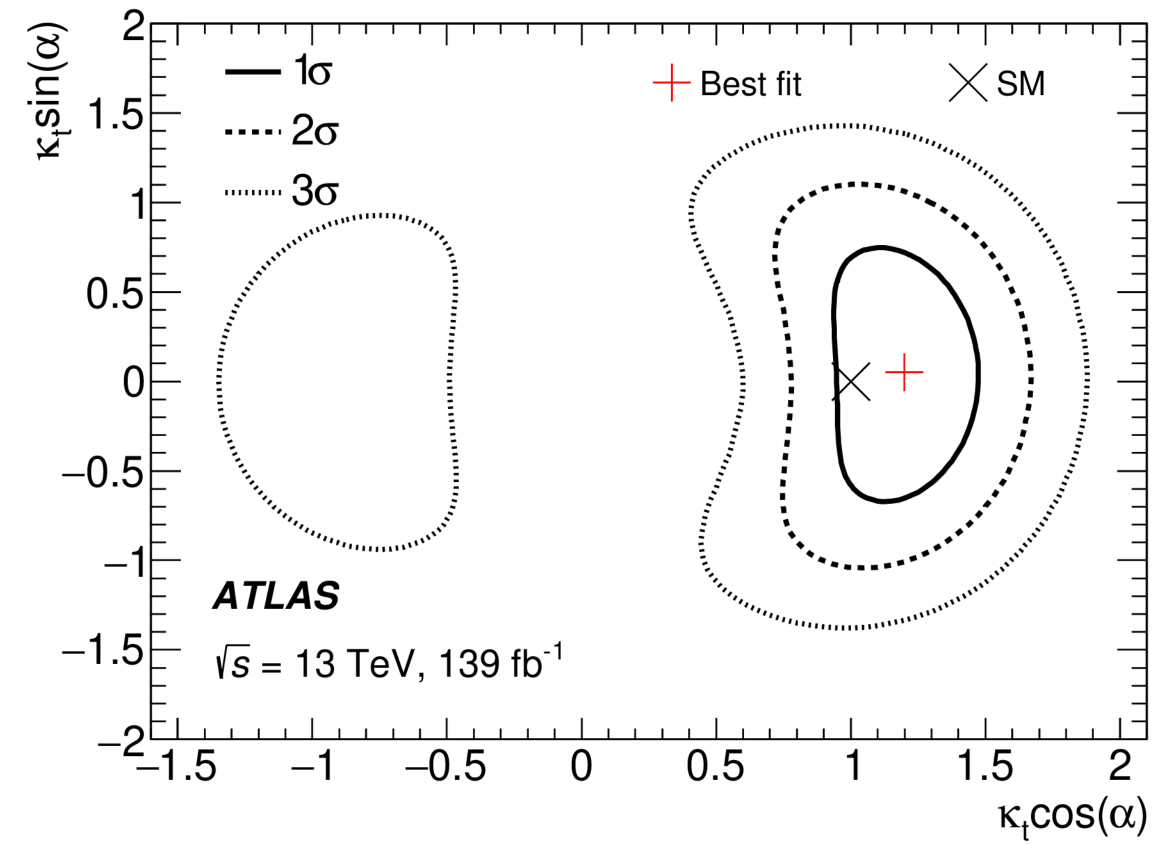


ttH production

- γγ important discovery channel for ttH
- CP studies:
  - excluded complete CP-odd coupling of Higgs boson to top quarks with 3.9 σ
  - Use of BDTs for top reconstruction, bkg rejection and CP discrimination



Phys. Rev. Lett. 125 (2020) 061802



Run-2 highlights - H → μμ

CMS, 139 fb^{-1}:

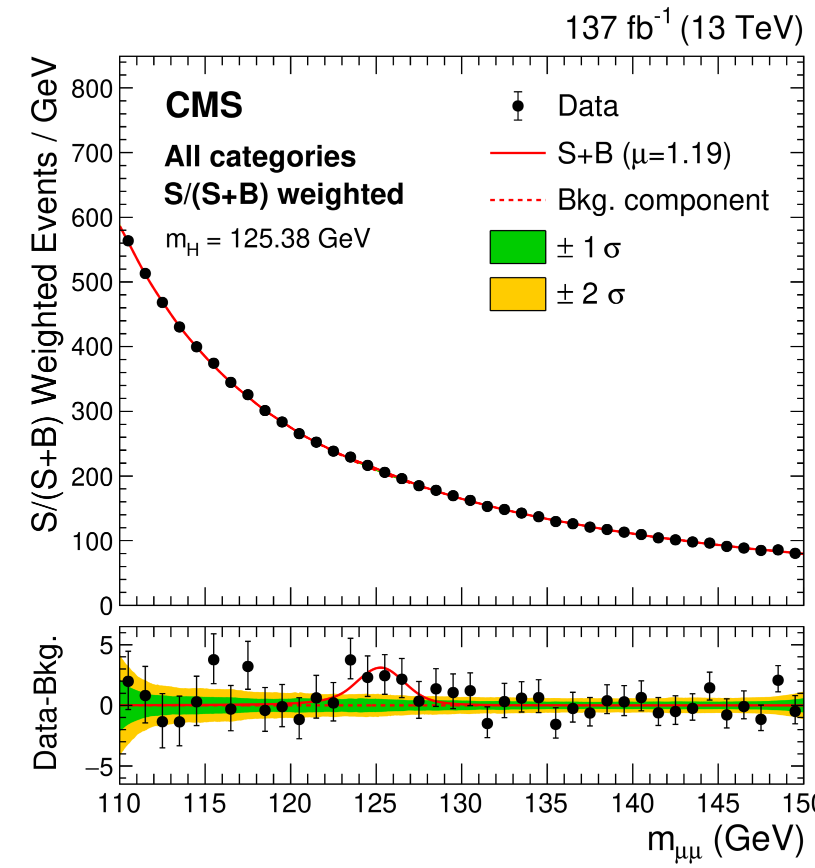
Evidence: 3.0 σ (expected w/ Higgs 2.5 σ)

Best fit signal strength

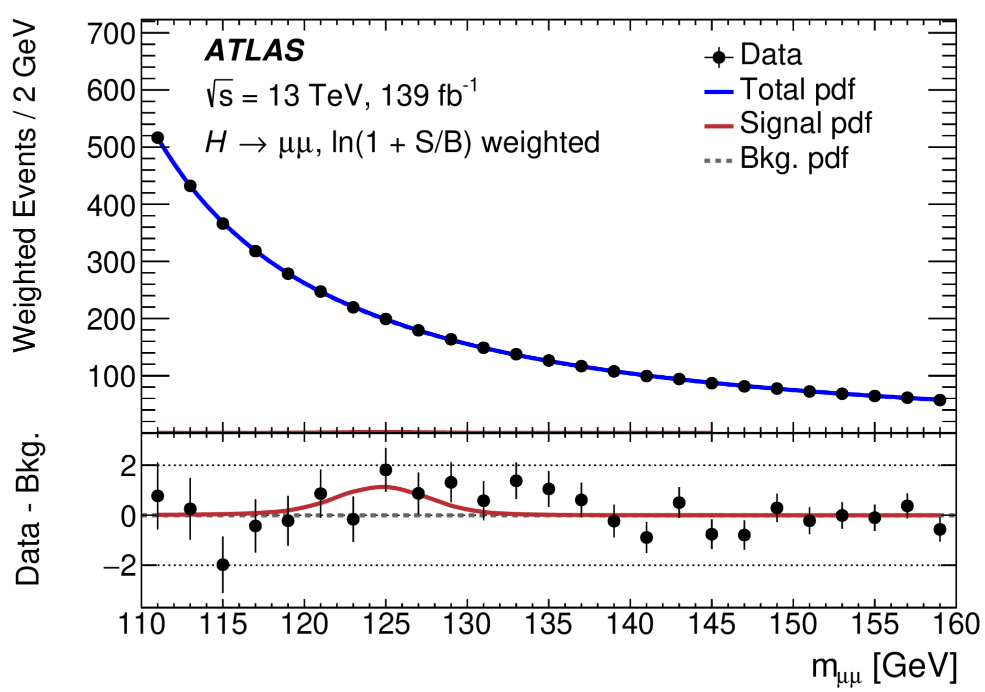
$$\mu = 1.19^{+0.40}_{-0.39}\ (\mathrm{stat.})\ ^{+0.15}_{-0.14}(\mathrm{syst.}) = 1.19^{+0.44}_{-0.42}$$

ATLAS, 139 fb^{-1}:

Significance: 2.0 σ (expected w/ Higgs 1.7 σ)

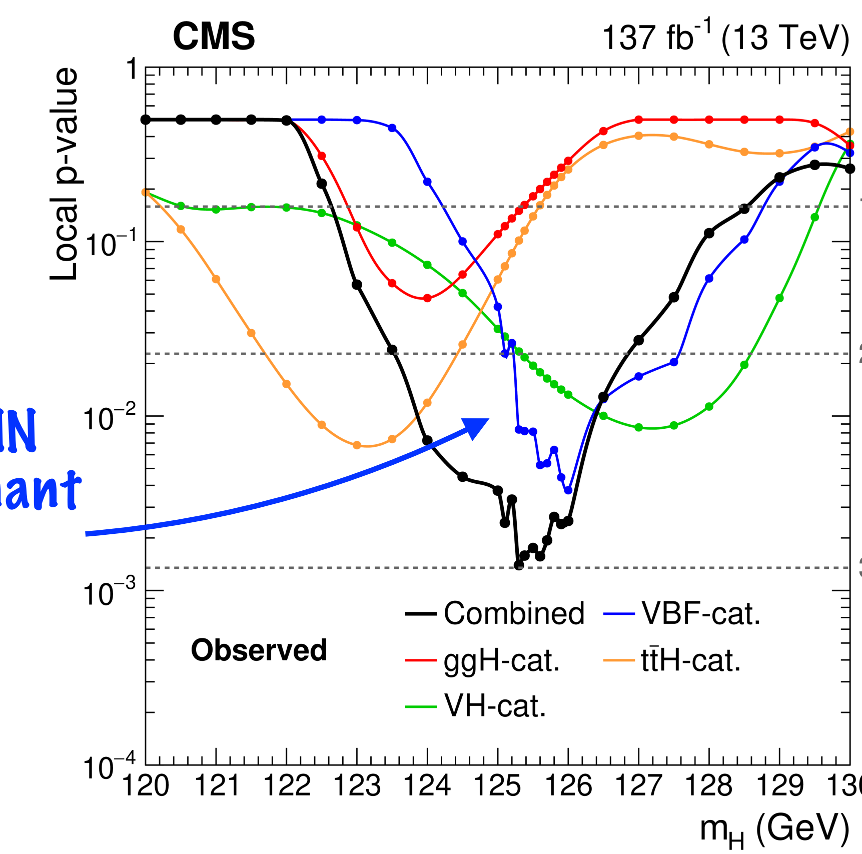


JHEP 01 (2021) 148

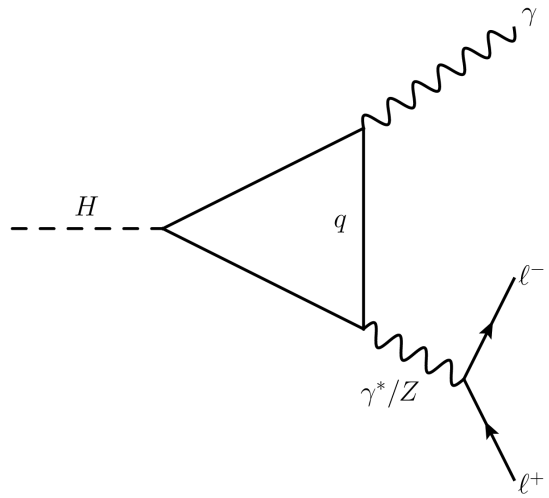


Phys. Lett. B 812 (2021) 135980

Fitted DNN discriminant for VBF



Run-2 highlights - H → ℓℓγ



Zγ ($m_{\ell\ell}$ around the Z mass peak), ATLAS 139 fb^{-1}

Significance: 2.2 σ (expected w/ Higgs: 1.2 σ)

Upper limit: 3.6 * SM (expected w/ Higgs: 2.6 * SM)

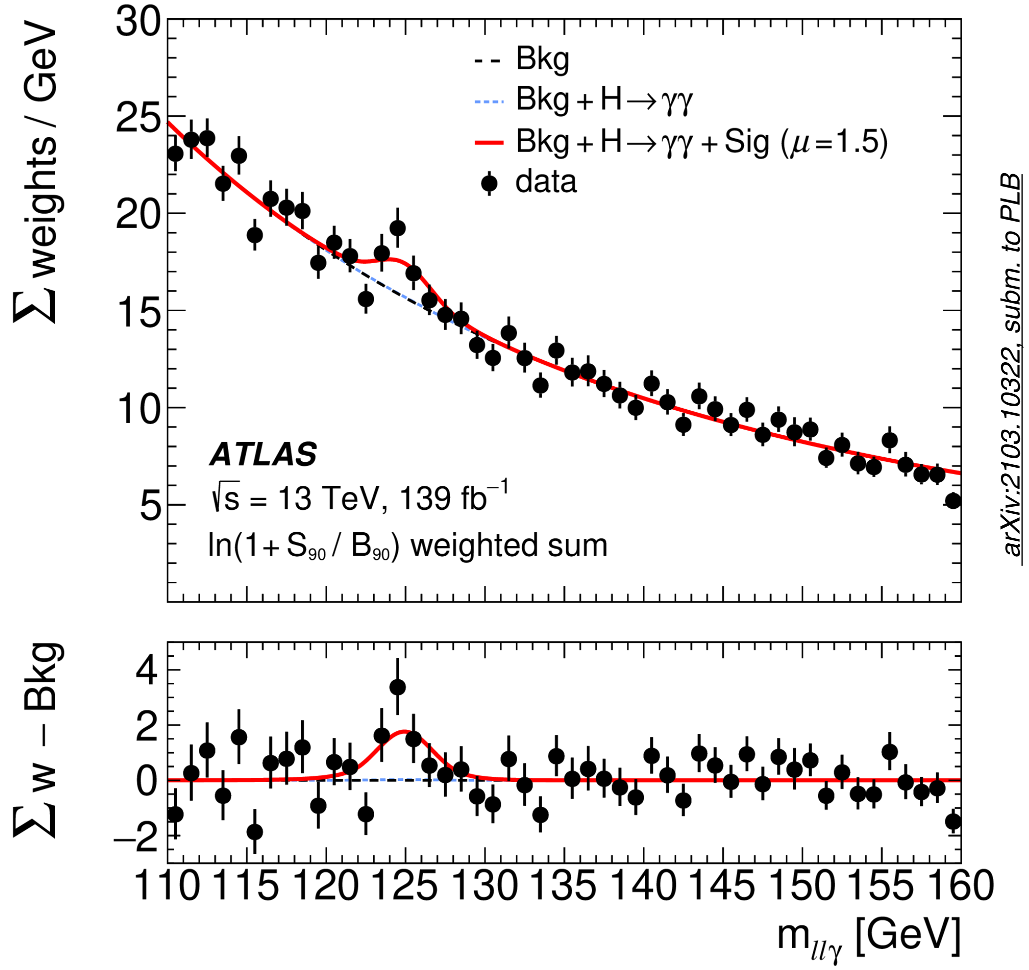
Low-mass ℓℓγ ($m_{\ell\ell}$ < 30 GeV), ATLAS 139 fb^{-1}

Evidence: 3.2 σ (expected w/Higgs: 2.1 σ)

Best fit signal strength:

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

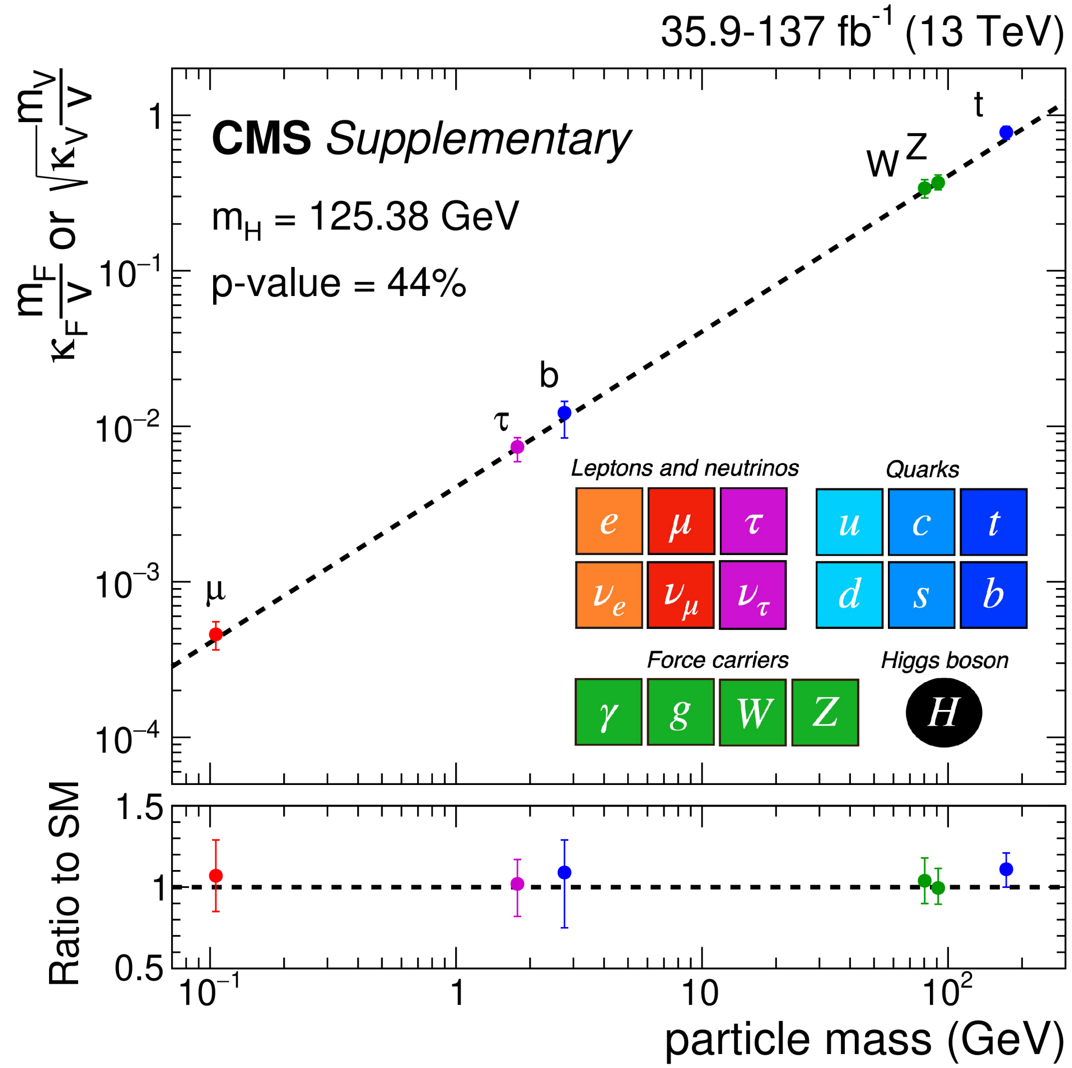
Main challenge: close-by electrons, special trigger was introduced in 2017, also special identification



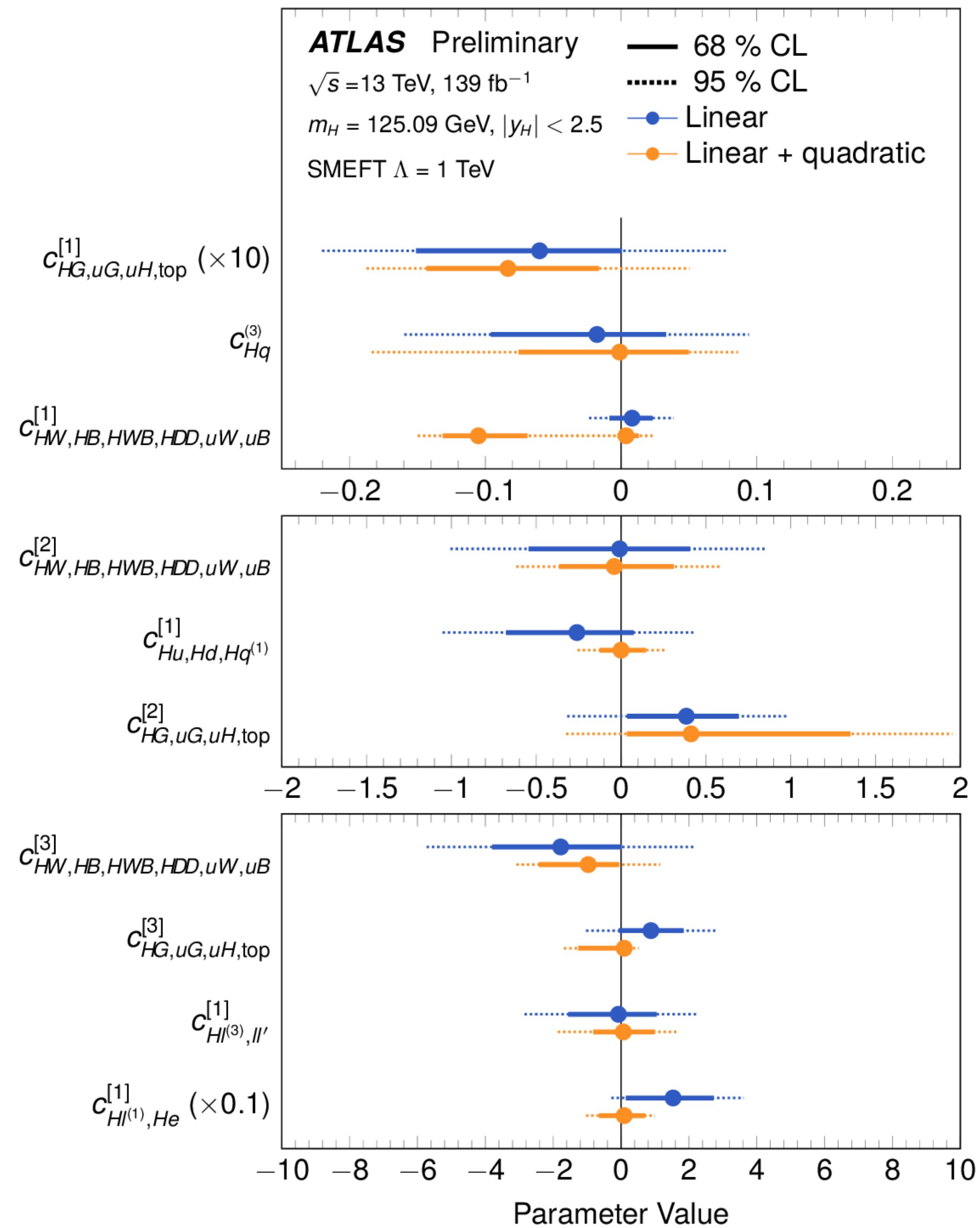
Run-2 highlights - Higgs combinations

….and interpretations (including all available decay channels)

- kappa framework, Higgs self-coupling, Effective Field Theory, MSSM



JHEP 01 (2021) 148



ATLAS-CONF-2020-053

(ATLAS - CMS combinations under discussions)

Run-2 limitations and Run-3

Almost all measurements above are limited by **statistical uncertainties**

What can help?

- more data => Run-3
- narrower peaks
  - object calibration improvements
- acceptance increases
  - trigger efficiencies (typically not the limiting factor for analyses with leptons/photons)
  - object efficiencies
  - increase probed phase spaces

Other improvements

- improvements in categorization (ML)
- smart use of the data - Optimal Observables, ML-inference like MadMiner
- reducing theory systematics (UEPS!) - through improved estimates, possible control regions, etc.
- improvements in background estimates

Run 3 - objects

Objects are the center-piece of most analyses

For the discussed analyses, mainly:

>> electrons, muons, photons for Higgs boson reconstruction
>> also jets and MET for associated productions, categorization

1) Calibration
- Photon calibration improvements through direct use of $Z\gamma$ events?
- Muon calibration

2) Photon/lepton identification/efficiencies and uncertainties
- More advanced ML for identification
- Improve precision of efficiency measurements especially for electrons at low transverse momentum
    - ATLAS uses J/Psi and FSR Z events, but challenging/stats limited

3) Also with an eye on HL-LHC
- improve pileup robustness

H → 4ℓ for Run 3 - acceptance increase

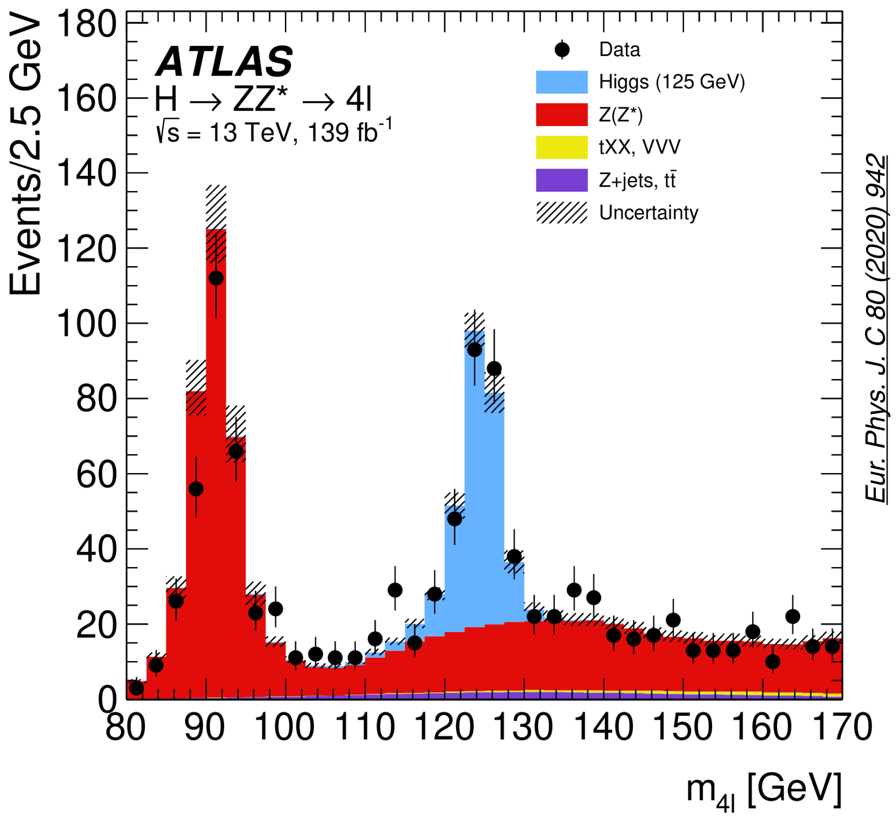
Total number of expected signal events in ATLAS Run-2 4l analysis is **200 => stats unc: ~7%**

Analysis selections are already very loose.

Additional ideas that show up regularly, but need to be studied for feasibility, S/B, significance gain:

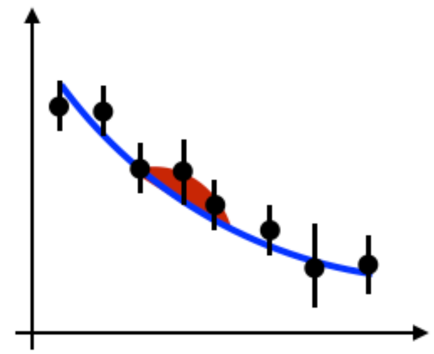
- include forward electrons
    - no tracking information available
- include taus
- include hadronic decays of one of the Z bosons

=> possibly promising for specific areas of phase space (off-shell, high p_T, …)?



H → γγ/ℓℓγ/μμ - background estimates

Challenge: Find a function that can describe the falling background spectra, and assign uncertainties on this function choice



ATLAS: Spurious signal

1. Build background-only template
- from MC and/or CR
- challenge: MC statistics

2. Fit different background functions + signal function to this template
- determine fake (spurious) signal
- only allow functions which fulfil certain criteria on the spurious signal, the fit quality etc.
- pick function with lowest number of degrees of freedom and smallest spurious signal

3. Propagated uncertainty: fake signal
(depending on category among largest systematic uncertainties)

CMS: discrete function fitting

1. Done directly on data

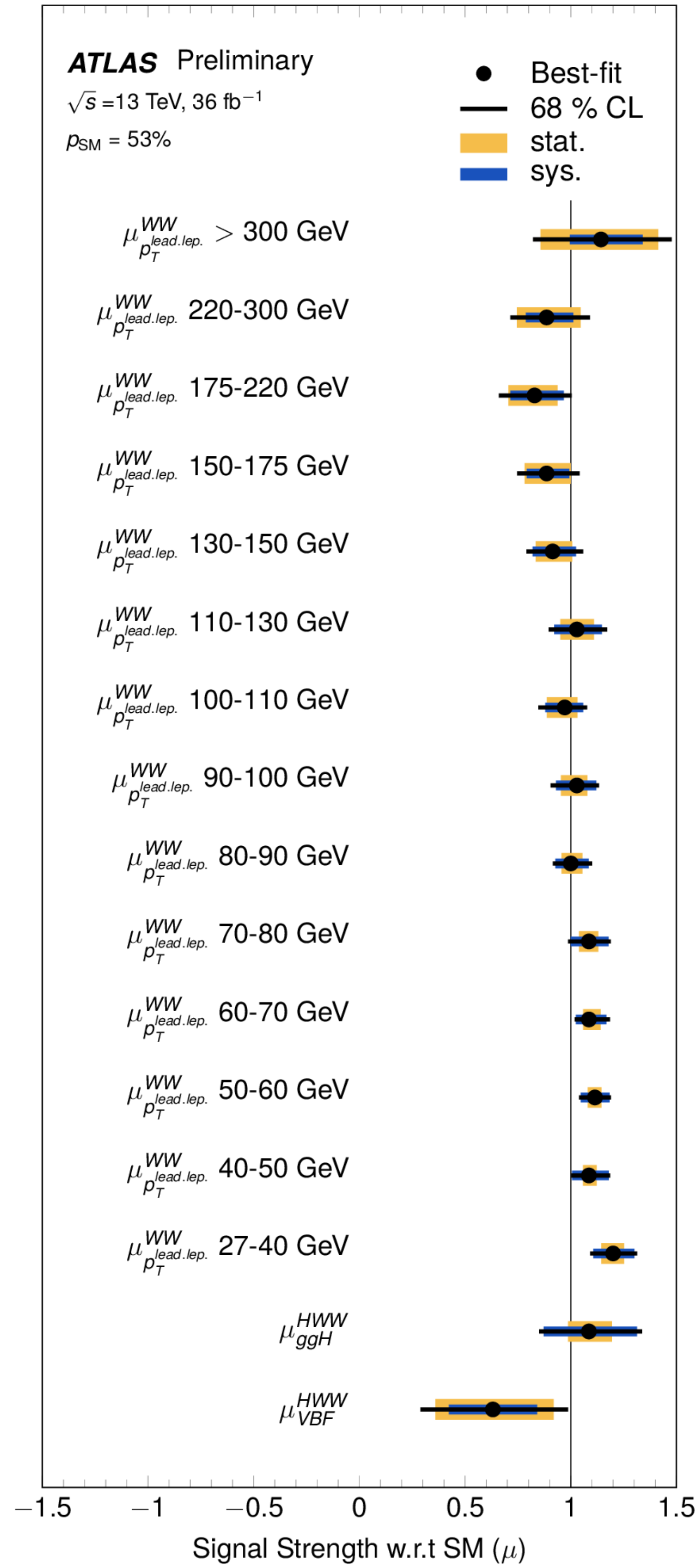
2. F-tests and chi2 tests to determine needed numbers of degrees of freedom per tested function family

3. likelihood picks best-fitting function, punishment for higher number of degrees of freedom

4. uncertainty assigned by likelihood fit on function choice, bias considered negligible

Run-3 possible analysis directions

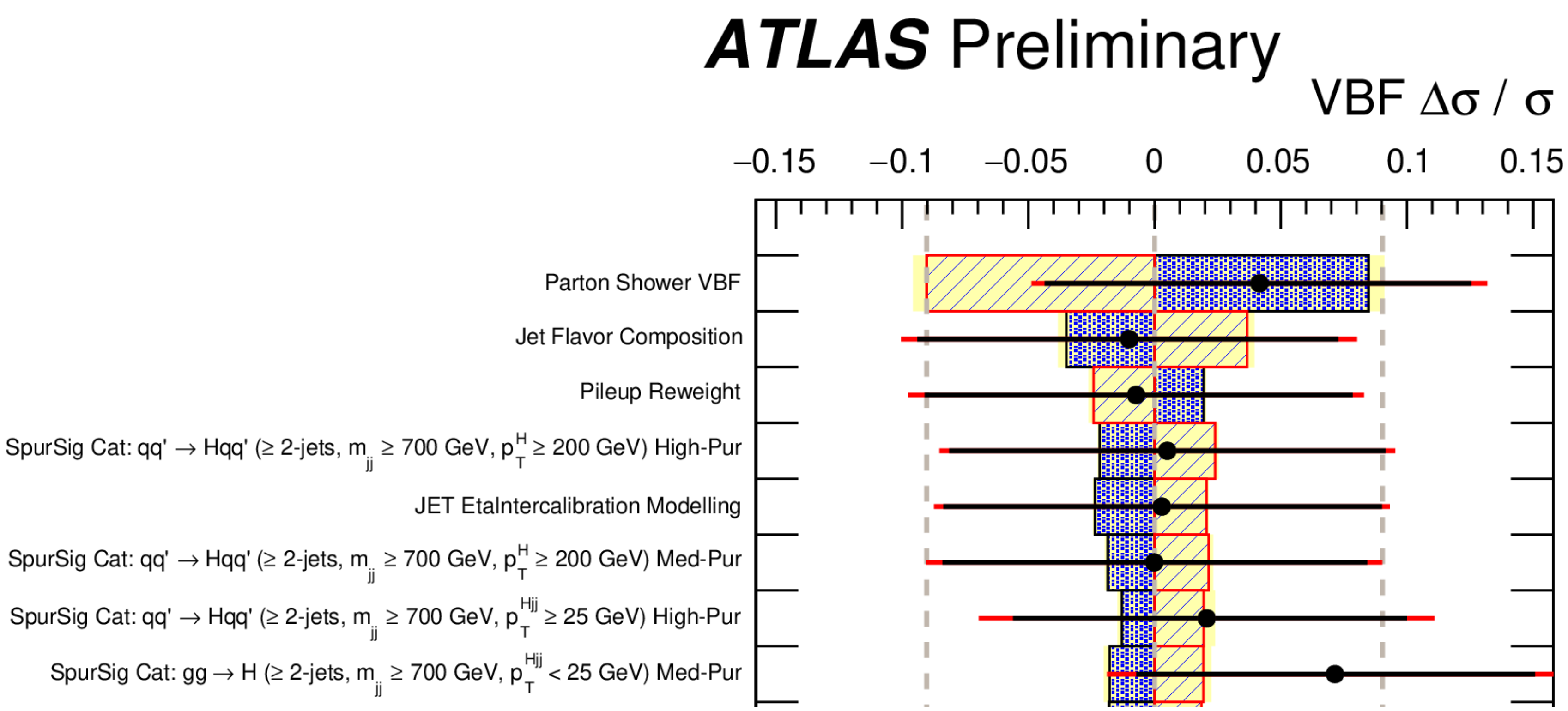
- evidence for H → Zγ? How far can we push H → μμ?
- single top + Higgs production in H → γγ channel
  - can we reach evidence in Run-3?
- expect to see more EFT analyses
  - combinations of Higgs and measurements of other SM processes
  - see example PubNote WW →
  - offshell analyses
- Other (related) hot topics: CP studies, polarization studies
- simplified template cross sections:
  - possibility to extend to decay bins?



ATL-PHYS-PUB-2021-010

Wishlist for theorists from the above channels

- recommendations for parton shower uncertainties
  - different strategies: difference between models (Pythia vs Herwig), Pythia variations
  - In some cases dominant (systematic) uncertainty
- electroweak+QCD higher order corrections for VBF offshell production
- full electroweak+QCD higher order corrections for diboson backgrounds
- Would be nice to get a llγ BR prediction for low mass, including uncertainties



H → γγ XS measurements

ATLAS-CONF-2020-026

Conclusion

- Higgs decays with leptons and photons are powerful tools for precision studies of the Higgs boson

- they include extremely rare processes that we still need to establish

- most analyses are limited by small event numbers

- increasing acceptances and efficiencies might be the key for going beyond sqrt(L) improvements
  - performance work is extremely important
  - also smarter categorizations and improved background estimates can help

- opportunities for Run-3:
  - establish evidence for $H \to Z\gamma$, push $H \to \mu\mu$ further? Also Higgs+single top…
  - EFT fits, together with other LHC measurements
  - establish techniques, analyses also with an eye on HL-LHC (proof-of-principle)

BACKUP

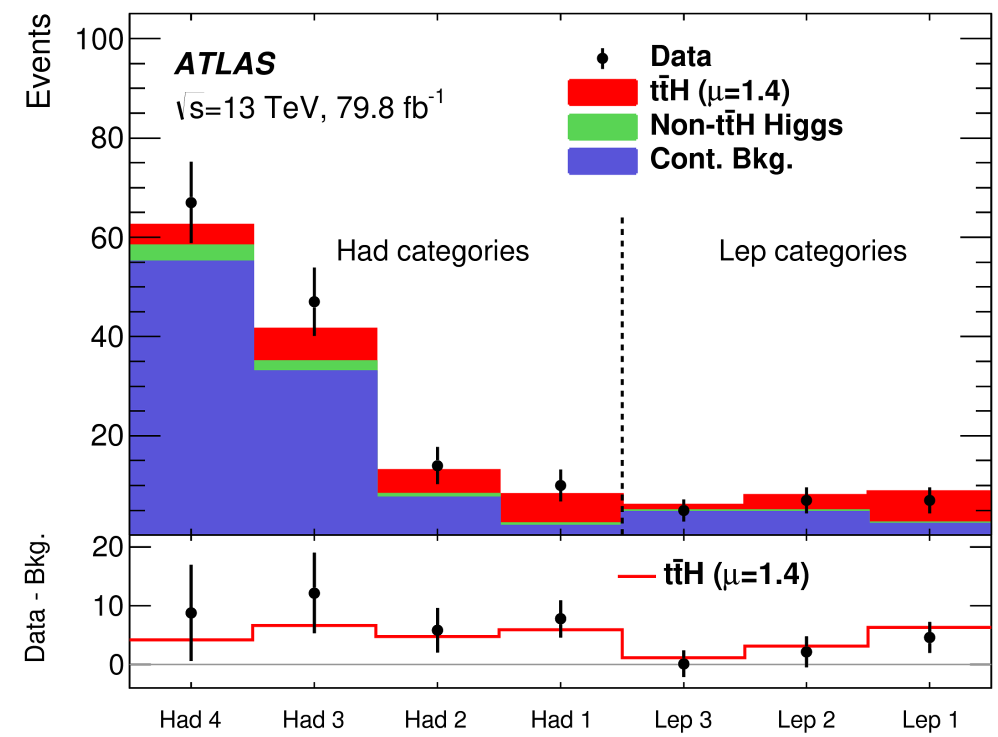
H → γγ, μμ, ℓℓγ

Baseline analysis strategies are very similar

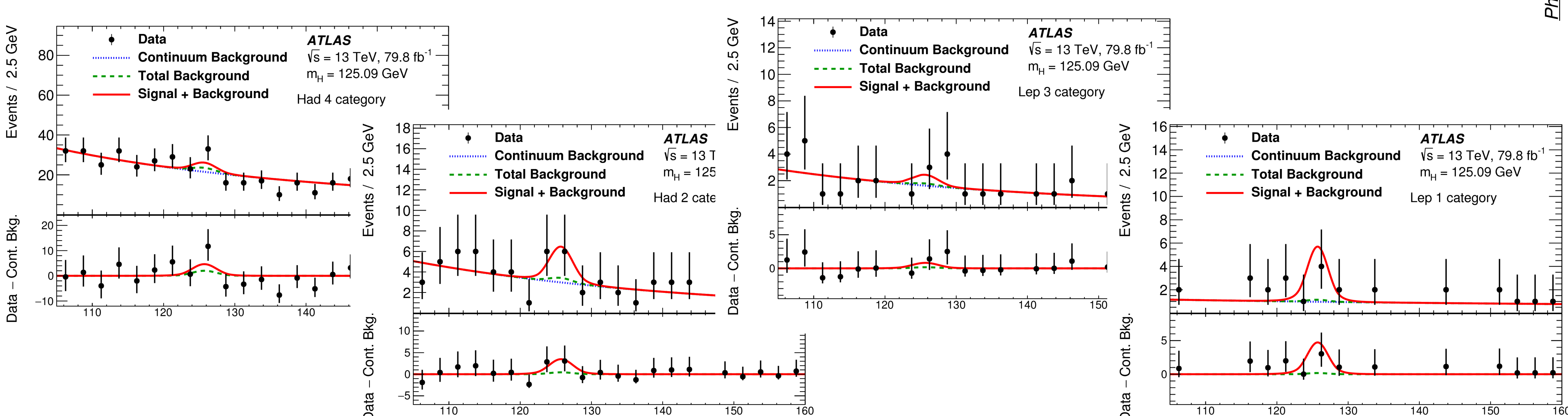
1. **Select events**
2. **Categorize with cuts or ML (p.ex. bins of a BDT)**
3. **In each category, fit the falling invariant mass spectrum with functional form and a signal peak**

- variation: fit the discriminant variable directly, use simulation as background estimate

Example $t\bar{t}H$ discovery, γγ-events
BDT bins, background from data-fits



Phys. Lett. B 784 (2018) 173



Likelihood thoughts - Run 3

- Likelihood sharing for Higgs analyses (age-old discussion, still requested regularly by theorists)
  - likelihoods can be complicated
  - a lot of thought needed what make sense here, is usable, etc.
  - experience in other physics groups with Pyhf, but problems with unbinned fits and other more complicated workspace features (like multiple POIs)
  - at the very least should make sure necessary correlation matrices etc. are shared

Massimo Corradi

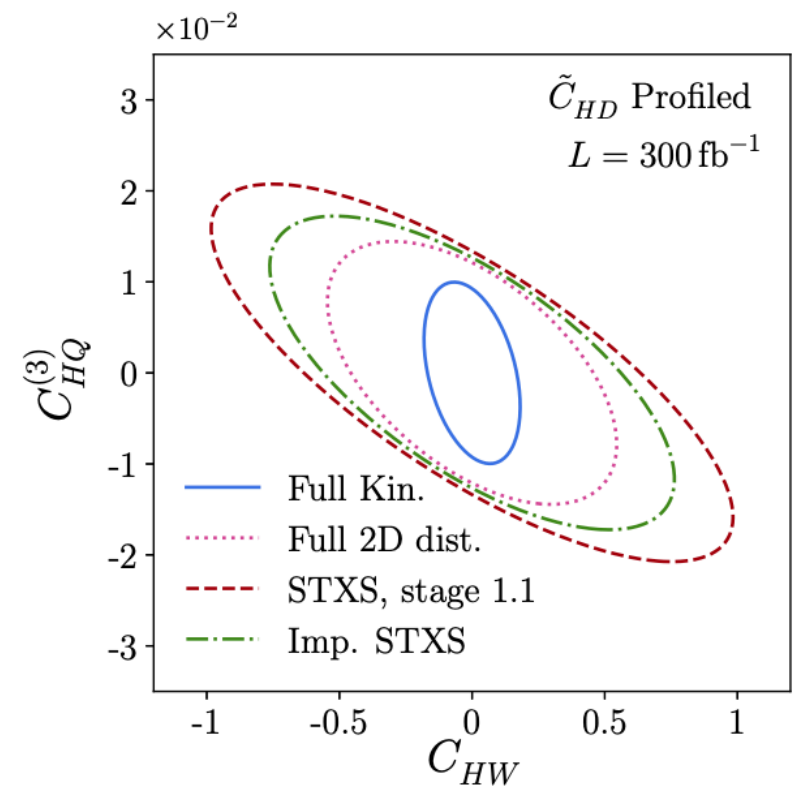
It seems to me that there is a general consensus that what is really meaningful for an experiment is *likelihood*, and almost everybody would agree on the prescription that experiments should give their likelihood function for these kinds of results. Does everybody agree on this statement, to publish likelihoods?

Louis Lyons

Any disagreement ? Carried unanimously. That's actually quite an achievement for this Workshop.

(1st Workshop on Confidence Limits, CERN, 2000)

- How to make best use of the data for constraining multi-dimensional parameter space (p.ex. EFT)
  - Optimal Observable already used often: matrix element information
  - combine ML and matrix-element methods to learn approximate likelihoods from simulated samples
    - MadMiner package *[arXiv:1907.10621]*, simulation-based inference for particle physics (neural network)



arXiv:1908.06980

Backup: $\ell\ell\gamma$ trigger