Higgs and Boson

- Experimental Progress at the LHC

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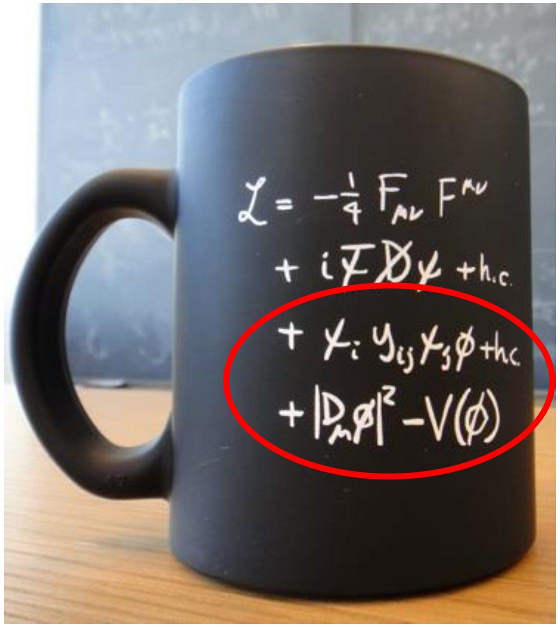
CLHCP2020, Nov. 6-9, 2020, Virtual World

Caution: with personal selection of materials and biases

Higgs boson

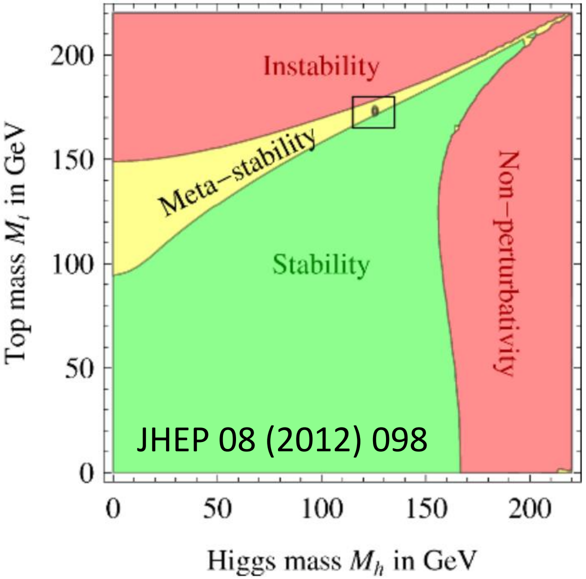
Central place in the SM:

Generation of masses
for elementary particles



Lastly observed
SM particles

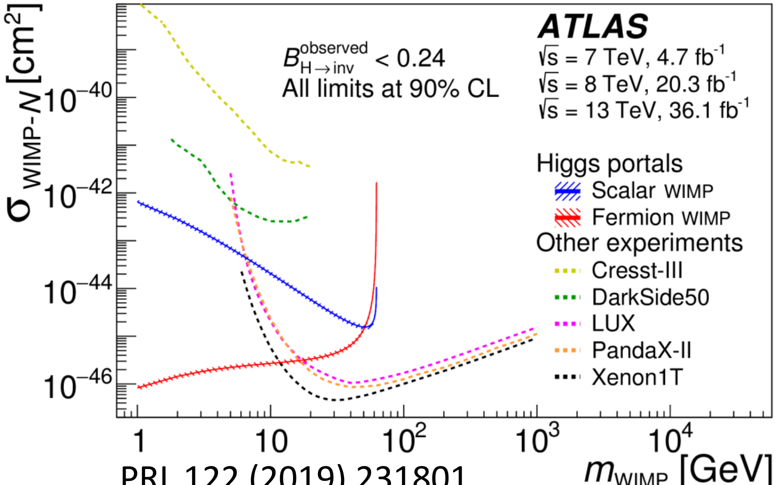
Remain
mysterious



JHEP 08 (2012) 098

Vacuum and
Universe?

Portal to new physics?

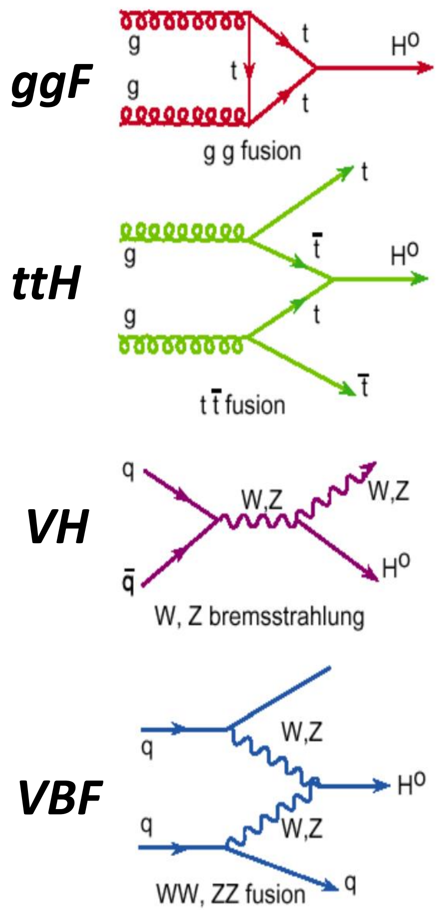


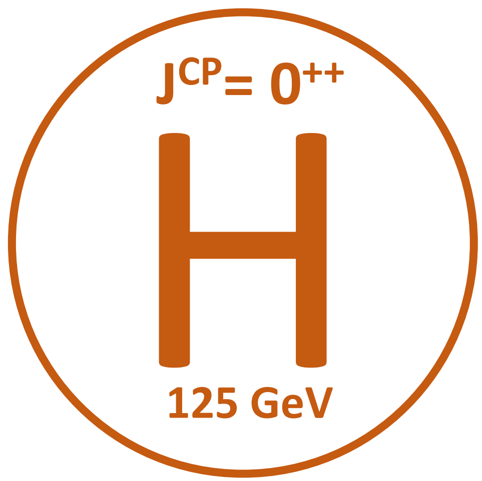
PRL 122 (2019) 231801

Higgs boson

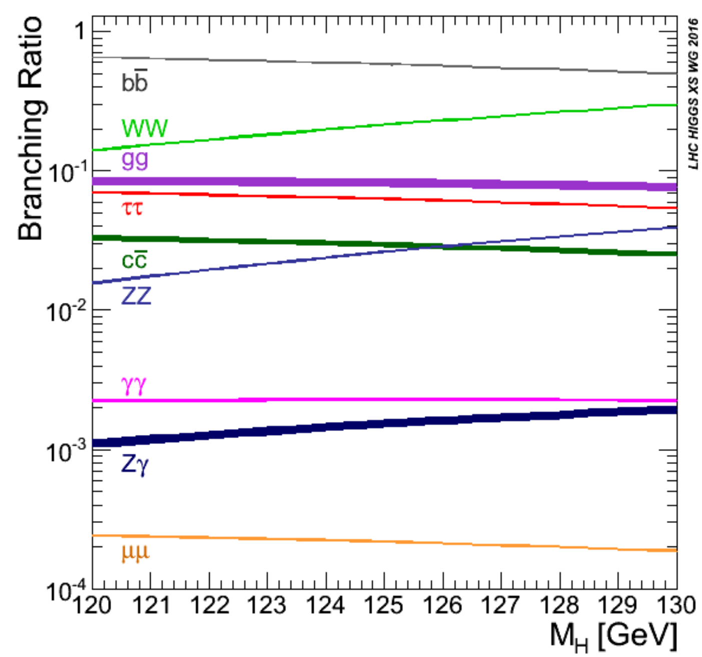
Key answers lie in **property measurements** of the observed new particle **H**

Production





Decay



Properties: mass, J^{CP}, total width, couplings

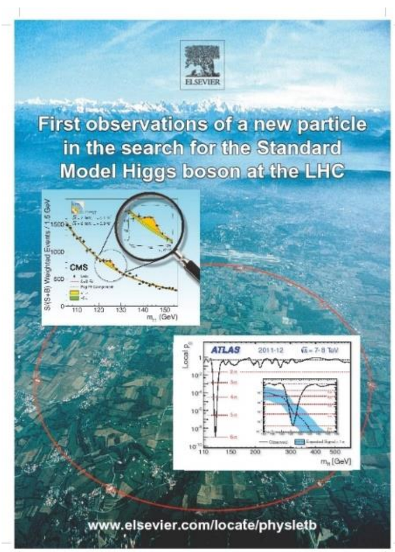
→ being studied via all possible H production and decay channels

Higgs to VV decays

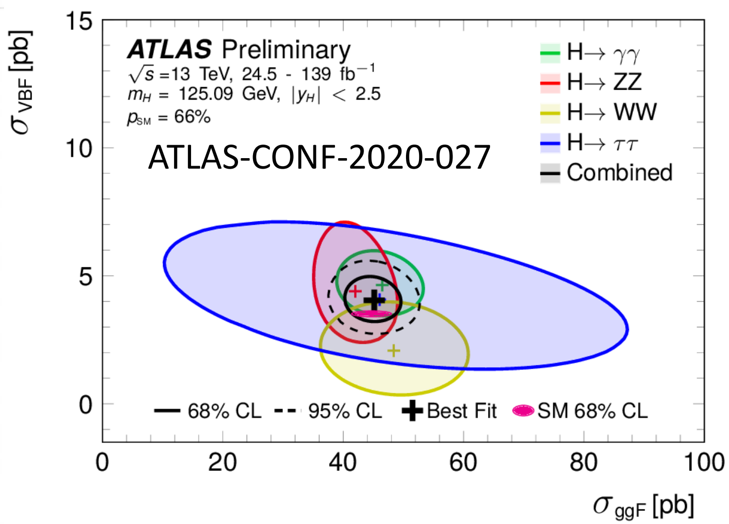
V – vector boson

Often referred to as **precision Higgs channels**

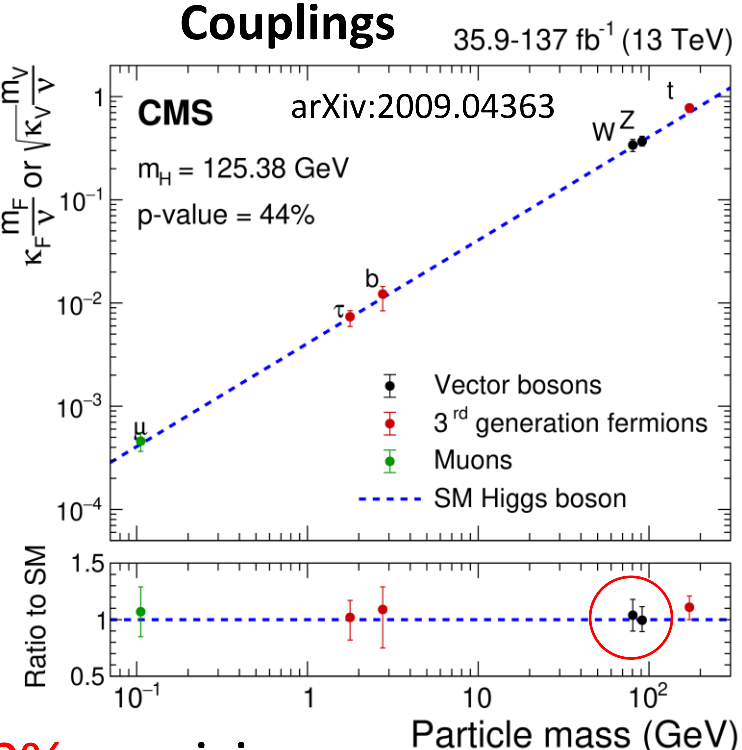
2012 **2020**



Cross-section



Couplings

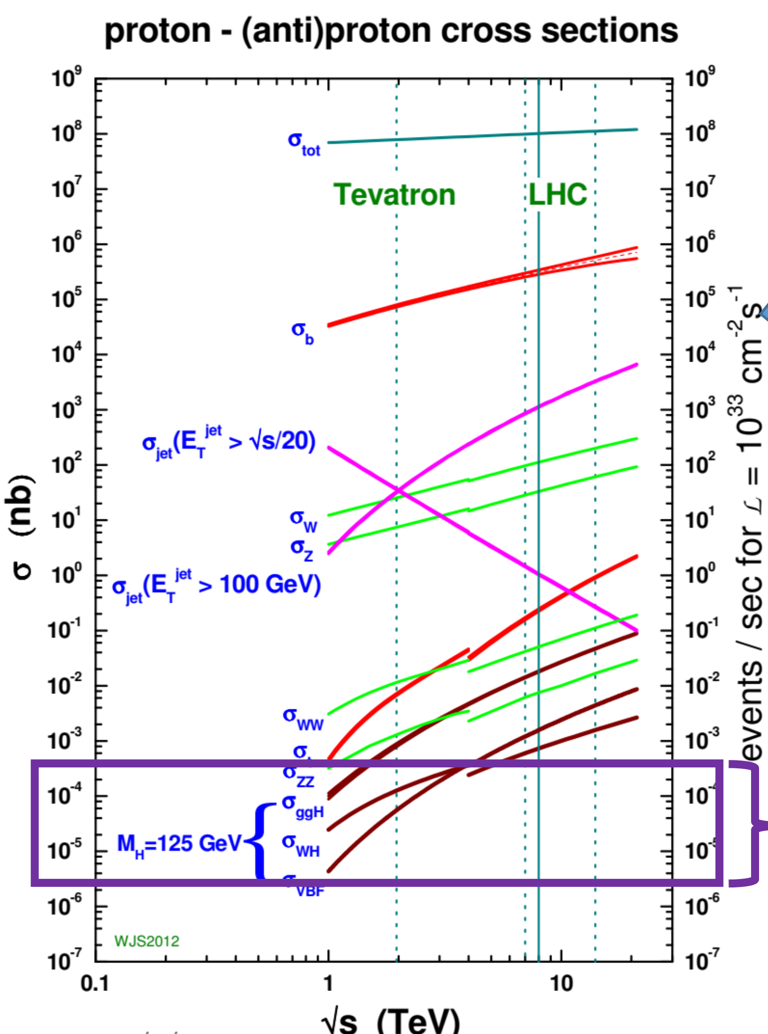


H→WW, H→ZZ, H→$\gamma\gamma$ were three channels for Higgs discovery

Reached 10% precision for VV channels

The measurement channels

Production cross-sections



Enormous QCD backgrounds by many orders

Signal is "a drop in the sea"

$H \rightarrow \gamma\gamma$

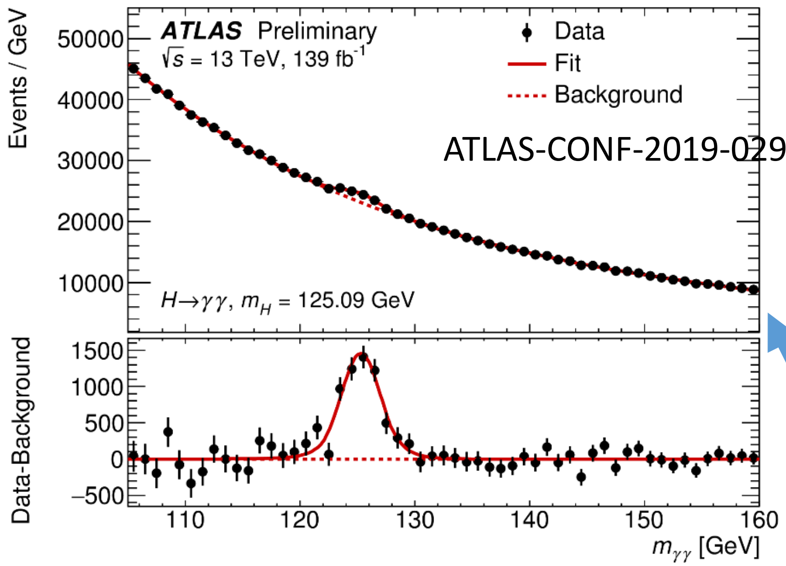
$H \rightarrow WW \rightarrow l\nu l\nu$

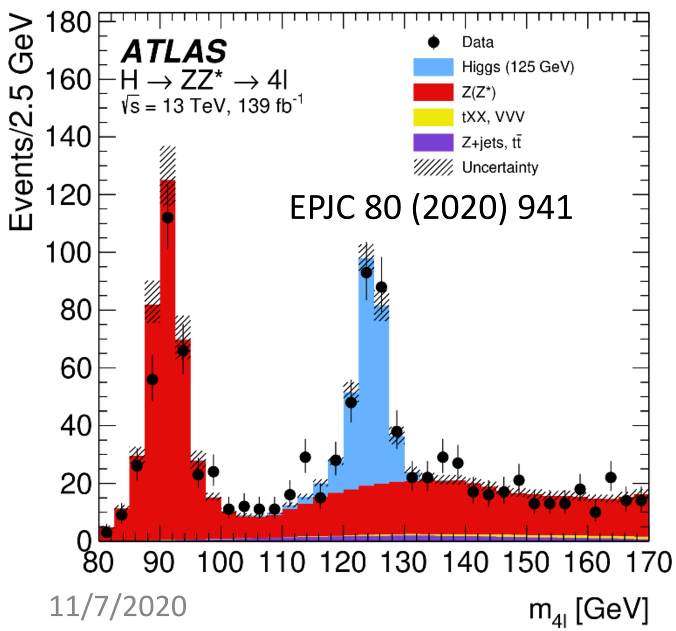
$H \rightarrow ZZ \rightarrow l^+ l^- l'^+ l'^-$

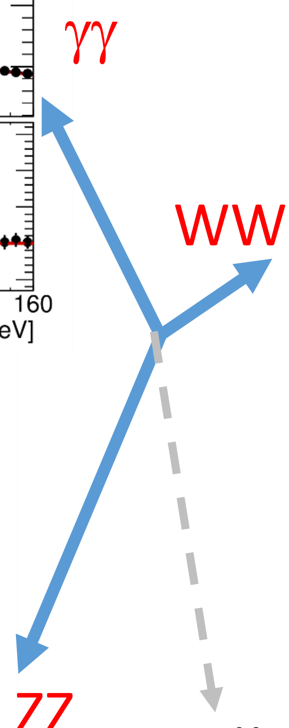
$Br = 10^{-2} – 10^{-4}$

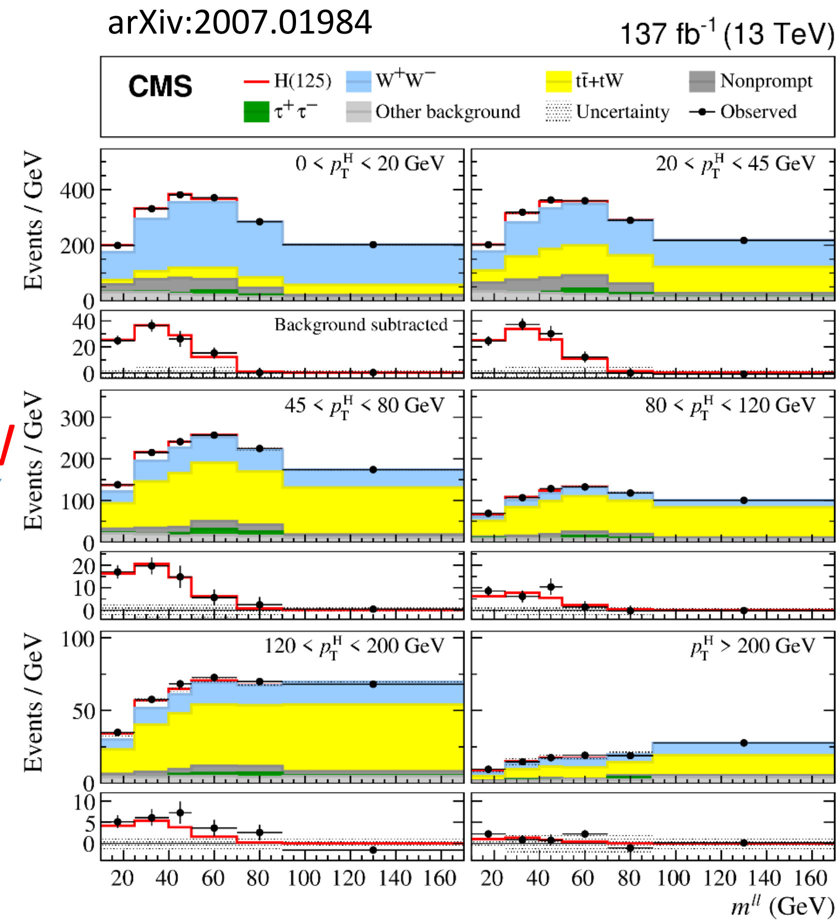
$O(10^2 – 10^4)$ Higgs bosons in these channels for O(100) fb^{-1} at 13 TeV

The measurement channels



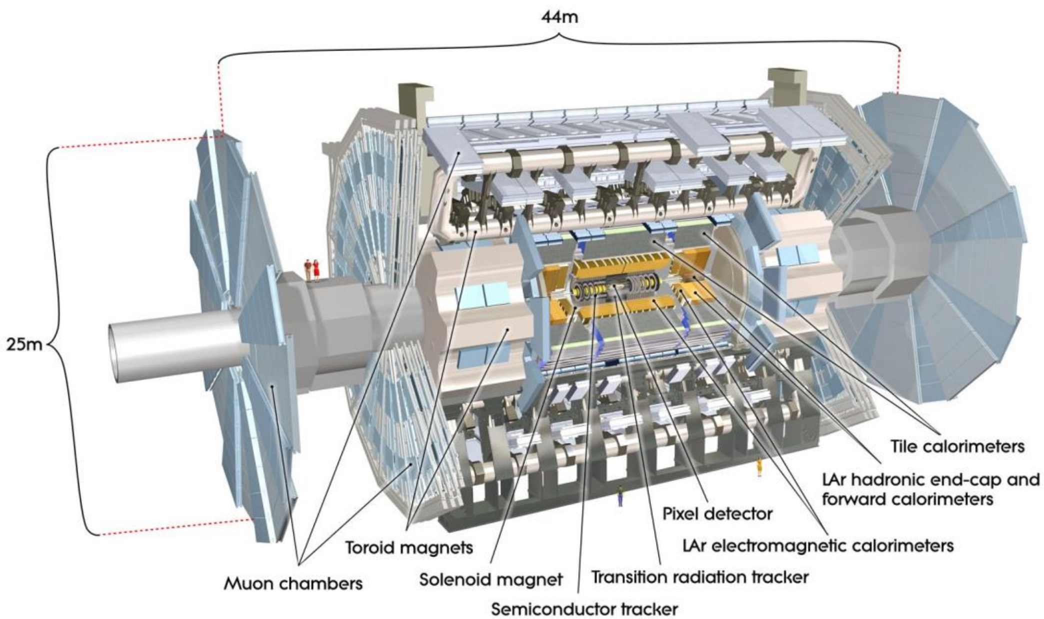


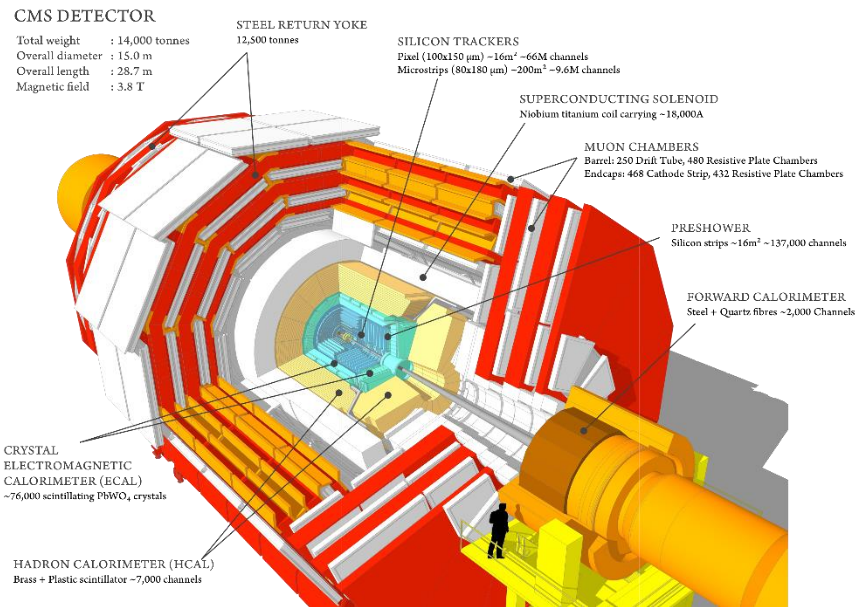




Keys towards success: precise determination of physics objects (e, μ, jets, missing-ET)

Detectors



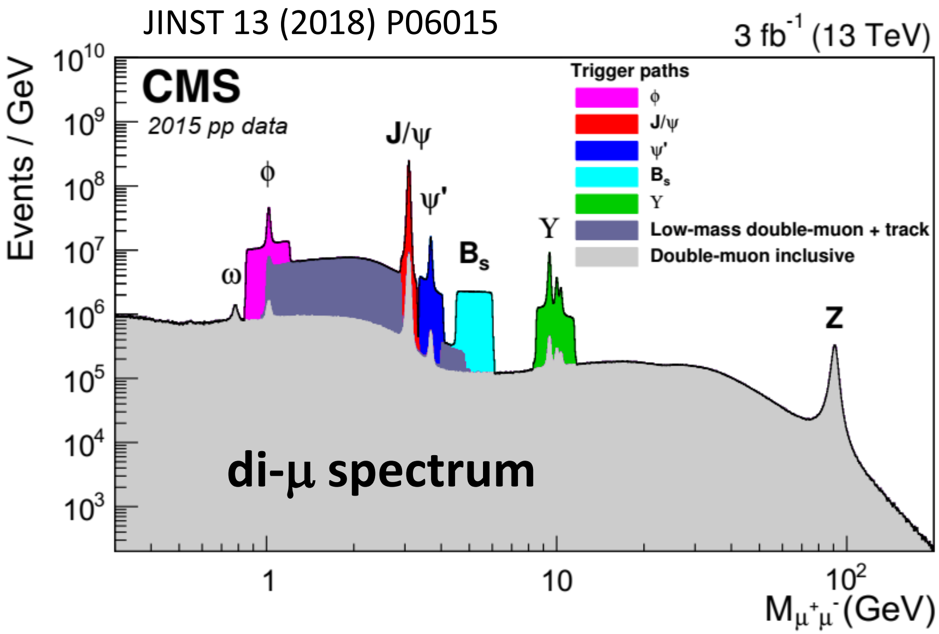


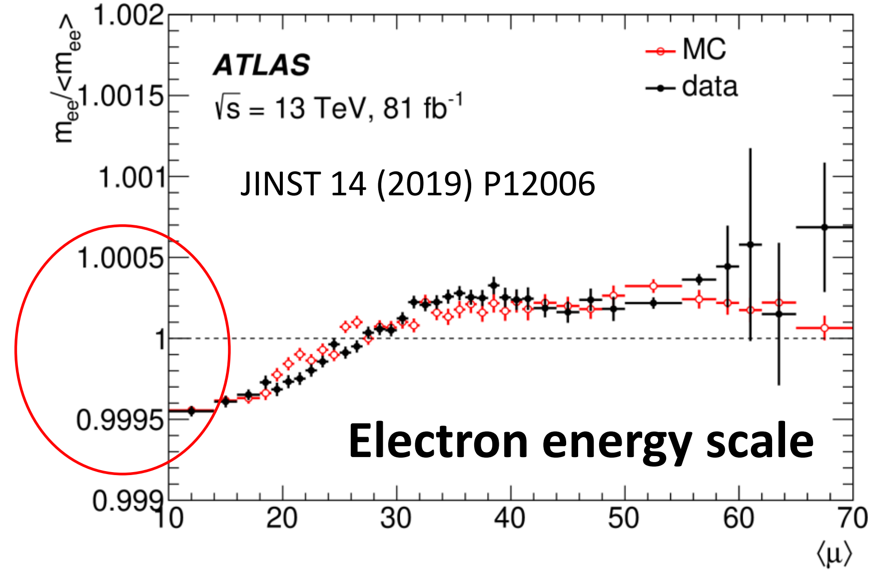
Optimized for Higgs studies at EW scale and searches at TeV

Path to success required dedication in

detector design, construction, operation, reconstruction, and calibration

Performance (Selected)





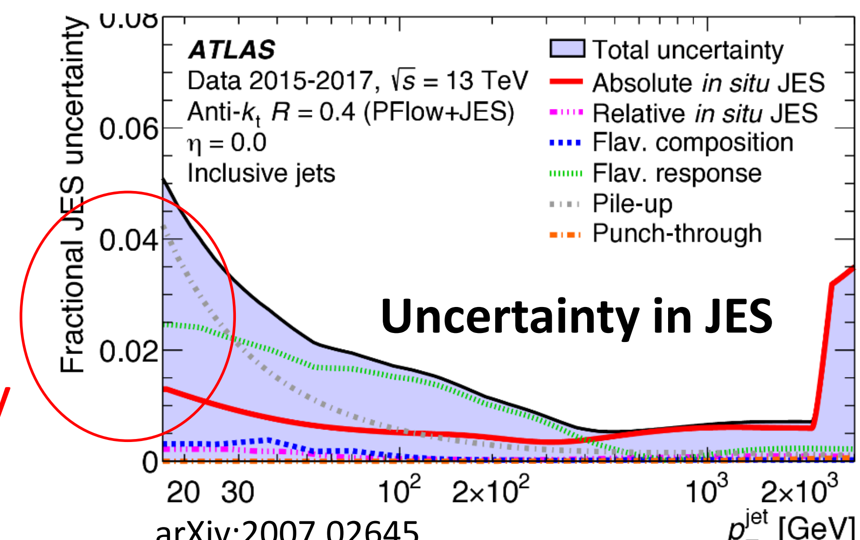
Typical precision at EW scale:

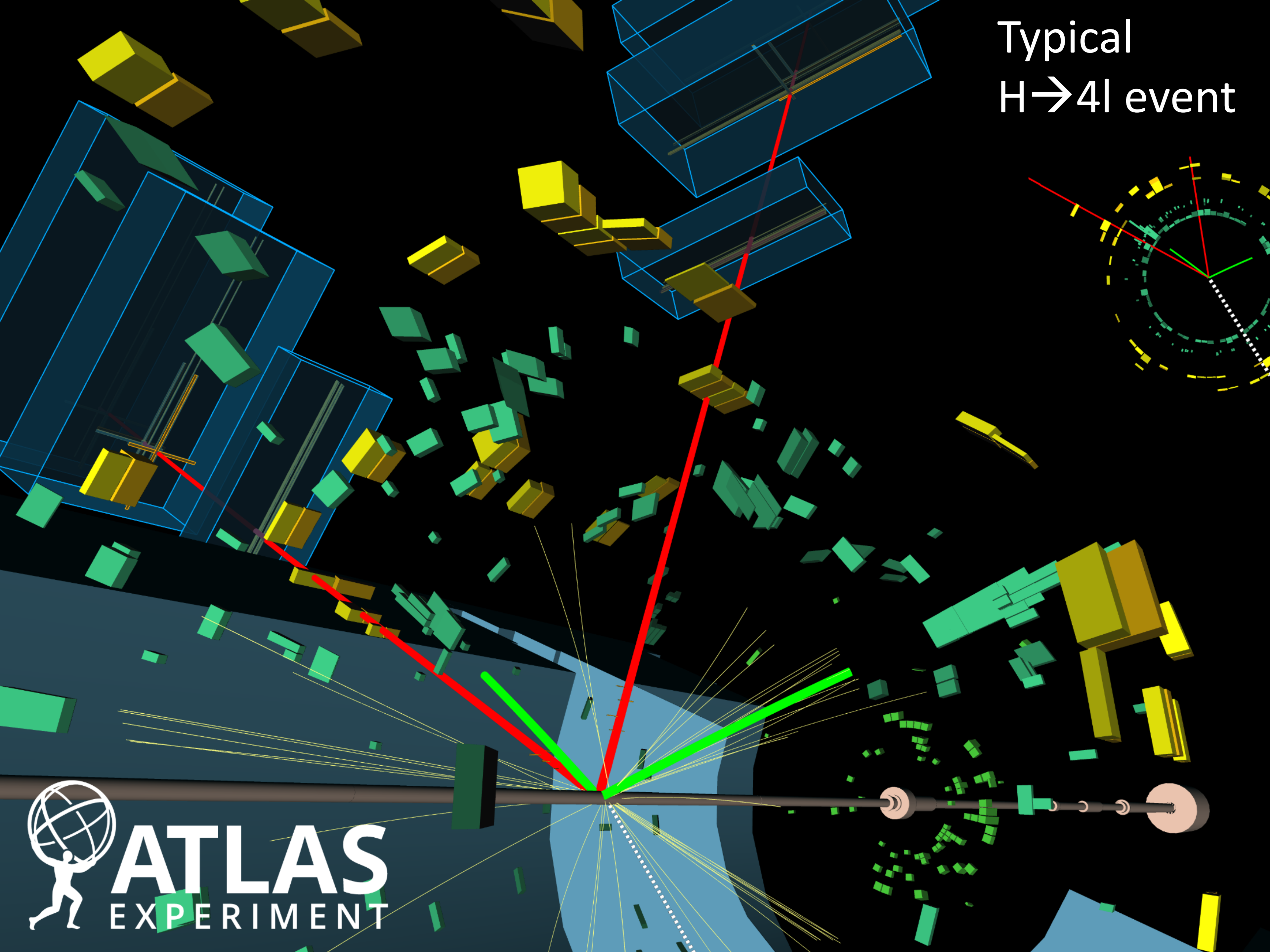
1% p_T resolution

0.1% p_T scale

1% uncertainty in lepton efficiency

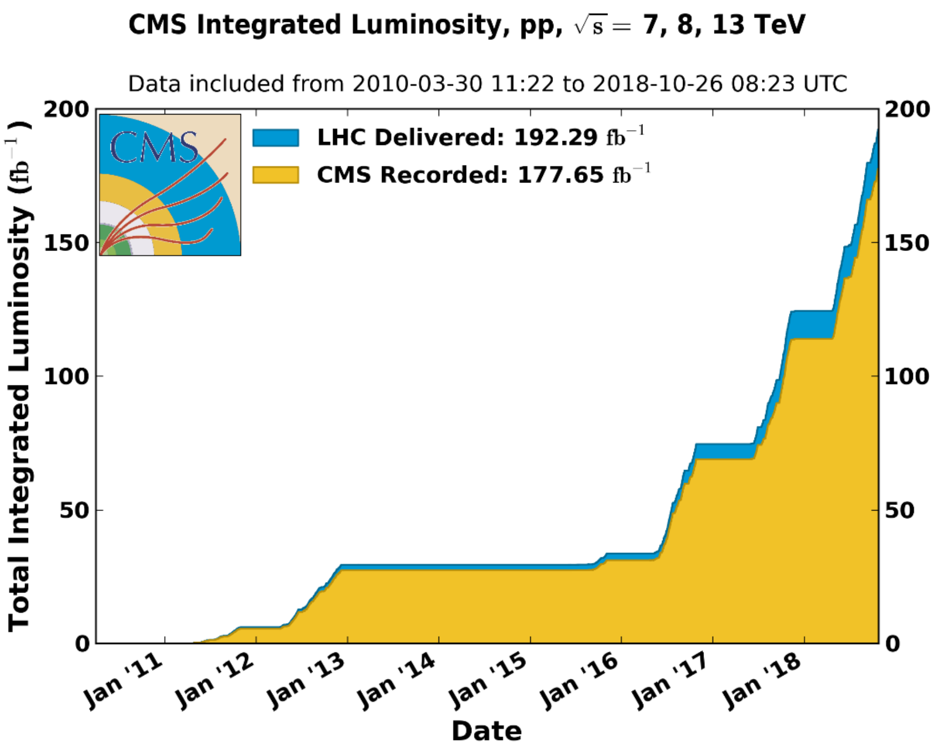
and more… …




Typical
H→4l event
ATLAS
EXPERIMENT

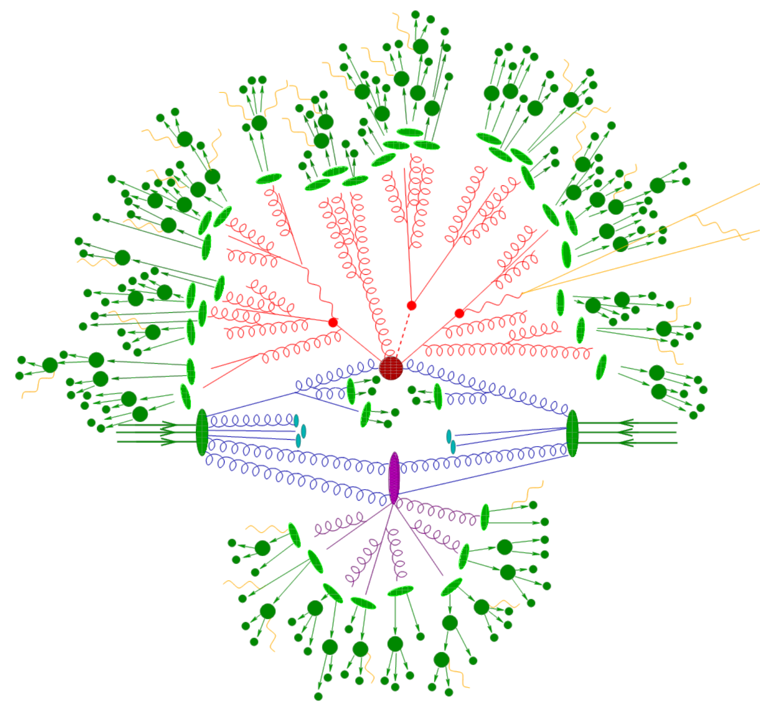
Data and Modelling

Both ATLAS and CMS accumulated about 150 fb^{-1} 13 TeV data



With high data-taking quality

State of art modelling used for signal and backgrounds



QCD: NLO→NNNLO+ PS, multi-leg
EW: NLO correction often applied

The Flow

Measurement of the processes

Differential or exclusive measurements

New physics sensitive, Effective Field Theory, Modelling of signal

Property measurements: couplings, mass, total width, J^P

Stringent test of the SM

ggF
VBF
VH
ttH
…

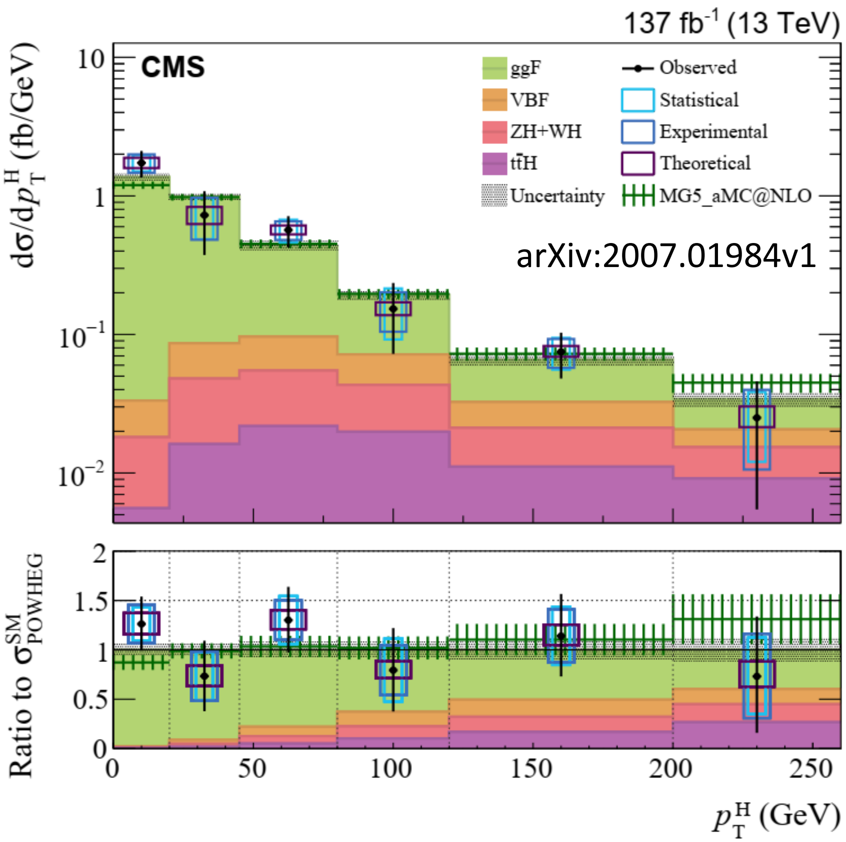
$\times$

H→$\gamma\gamma$
H→WW→$l\nu l\nu$
H→ZZ→ $l^+l^-l'^+l'^-$

Measurements: WW

Focused on eμ events

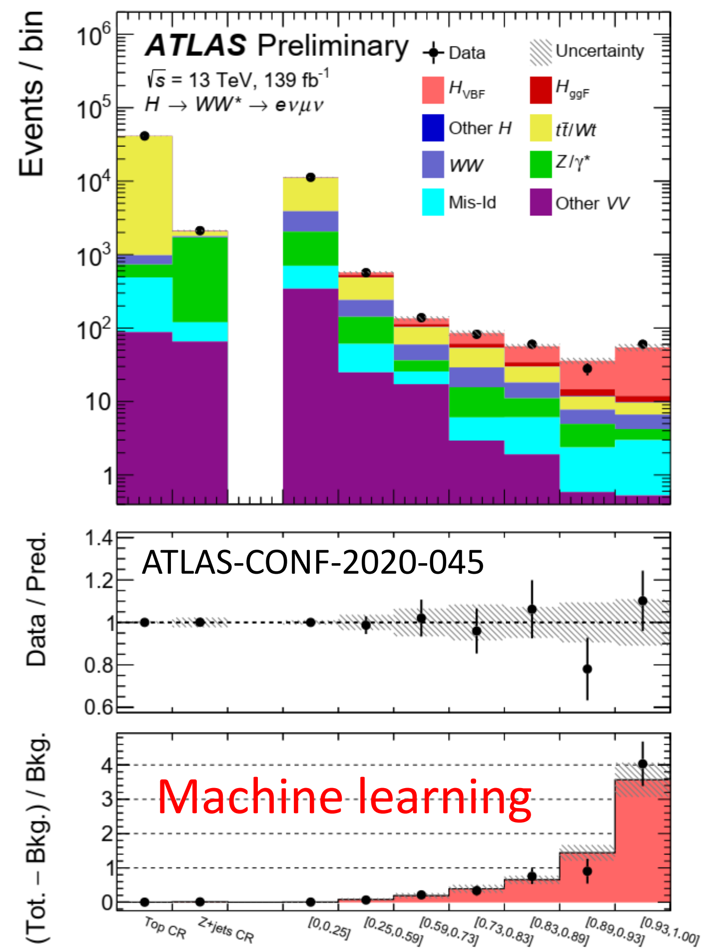
Differential measurements of inclusive events for critical variables, such as p_T^H



Reasonable precision achieved (down to 20% per bin)

Observation of VBF H→WW

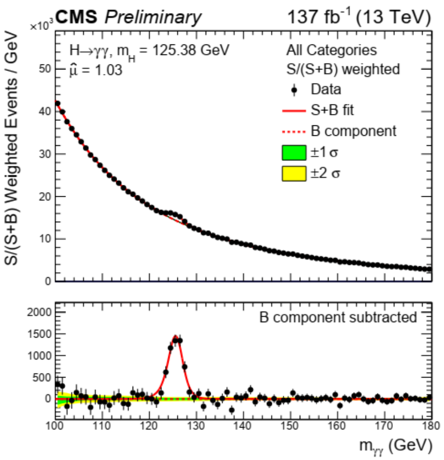
$\sigma_{meas}/\sigma_{pred} = 0.9 \pm 0.2$



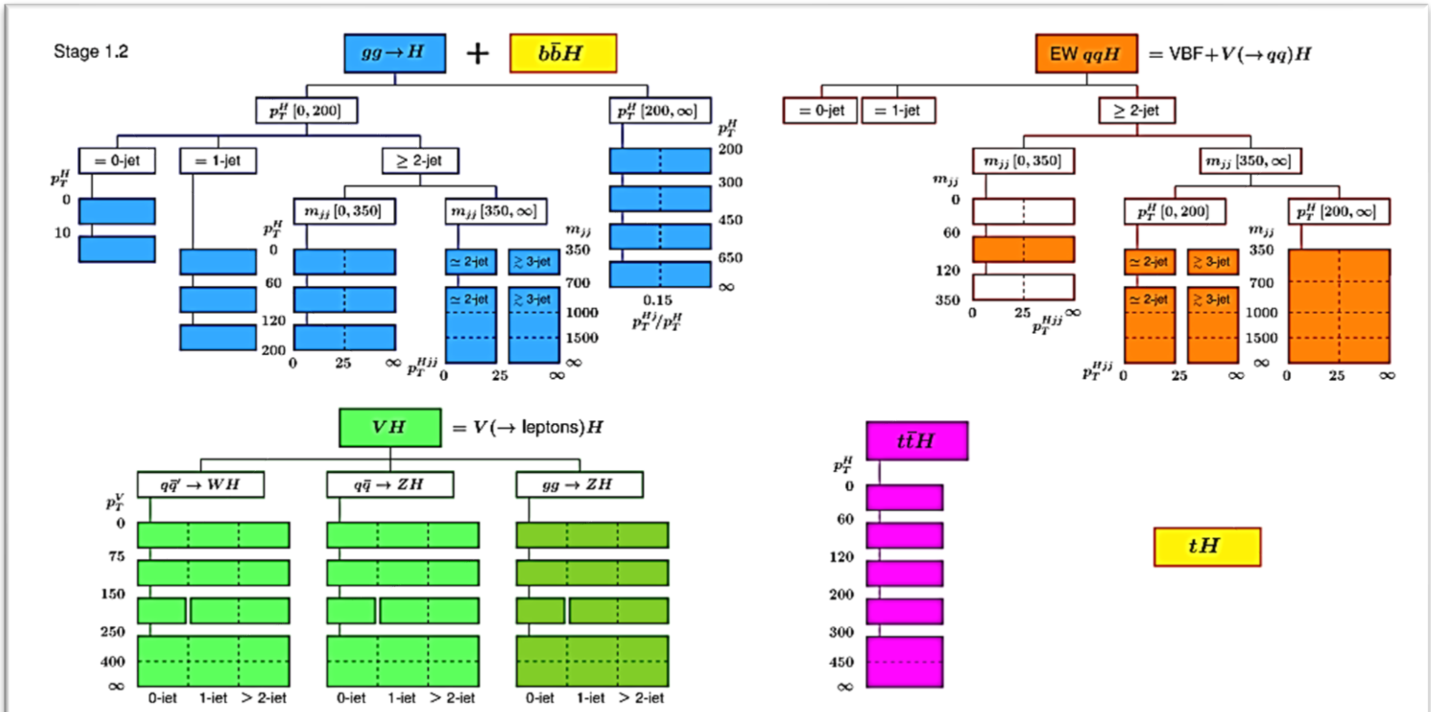
CRs DNN output in SR

Measurements: γγ

CMS-PAS-HIG-19-015



With sufficient statistics, more refined phase space categorization (*STXS framework*) to increase the physics precision/potentials

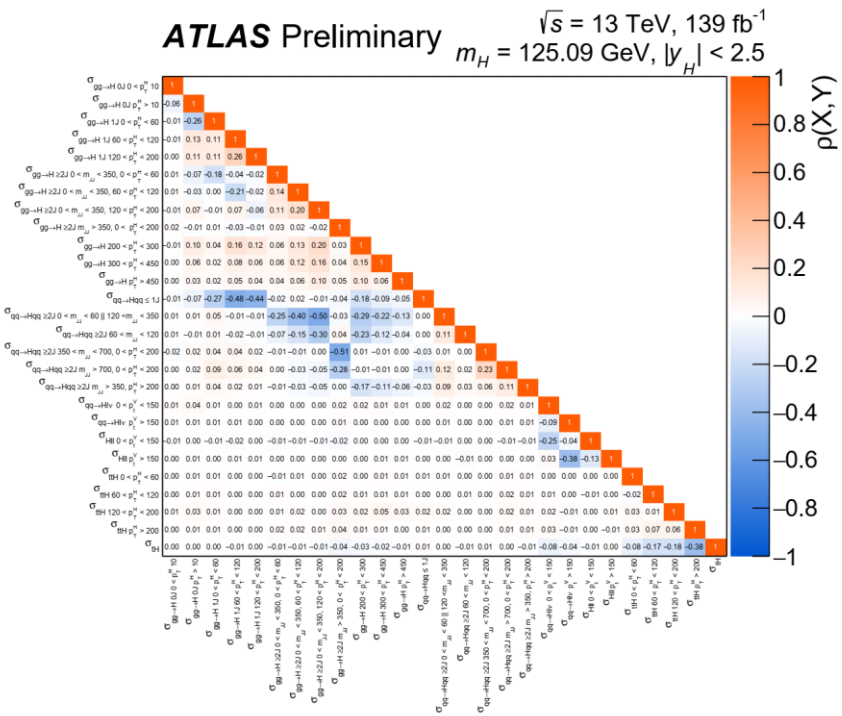


Machine learning for purity and S/B separation

Can be combined for coupling measurements or interpretation

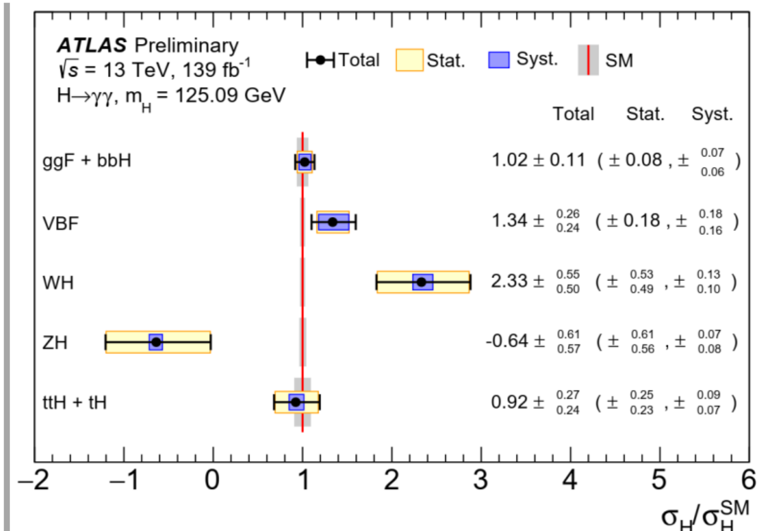
Measurements: $\gamma\gamma$

STXS Phase space measurement correlation matrix



Complex methodology successful

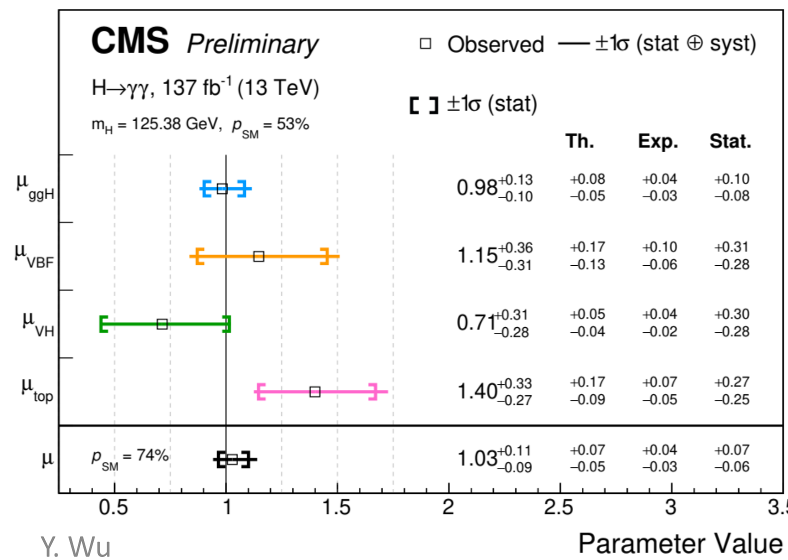
ATLAS-CONF-2020-026



$\sigma_{meas}/\sigma_{pred}$

1 ± 0.1

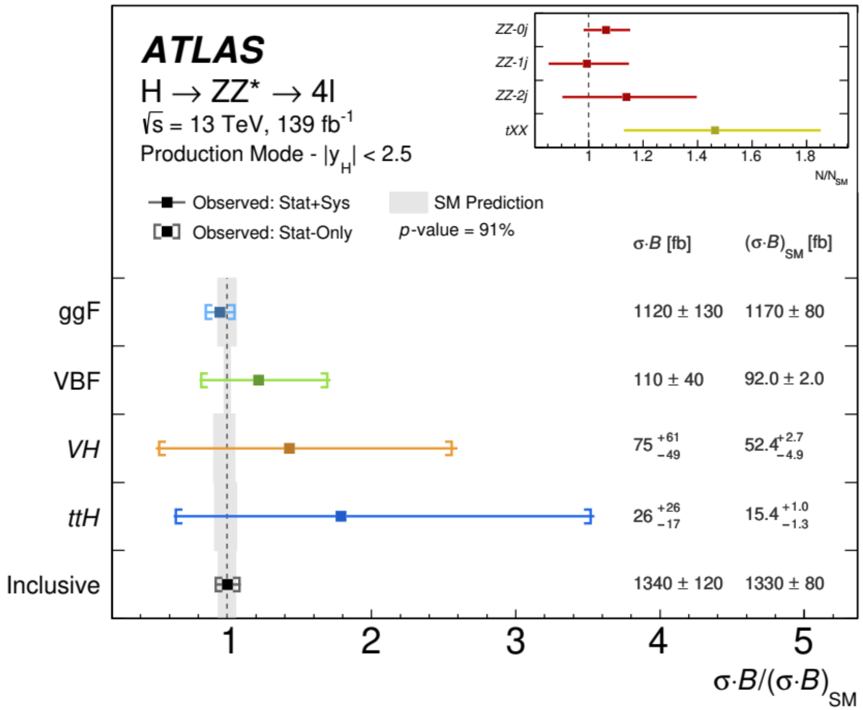
CMS-PAS-HIG-19-015



Measurements: ZZ

STXS approach

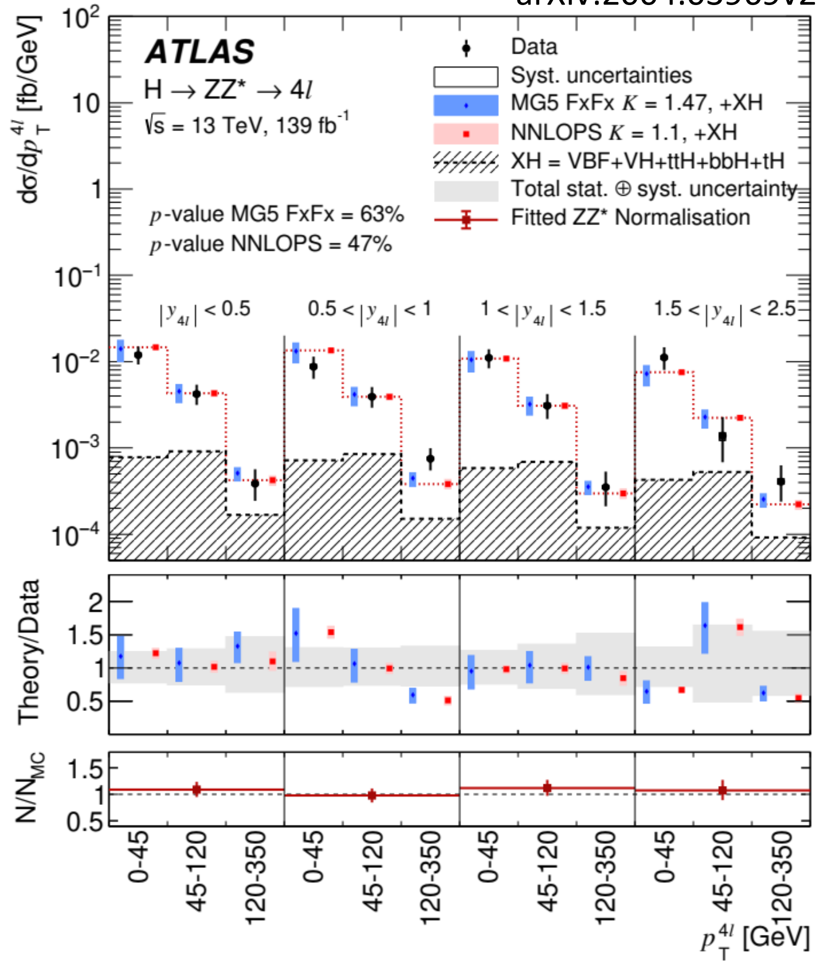
arXiv:2004.03447v1



With about 200 signal events and clean 4-lepton final state, inclusive **measurement unc. < 10%**

Differential measurement

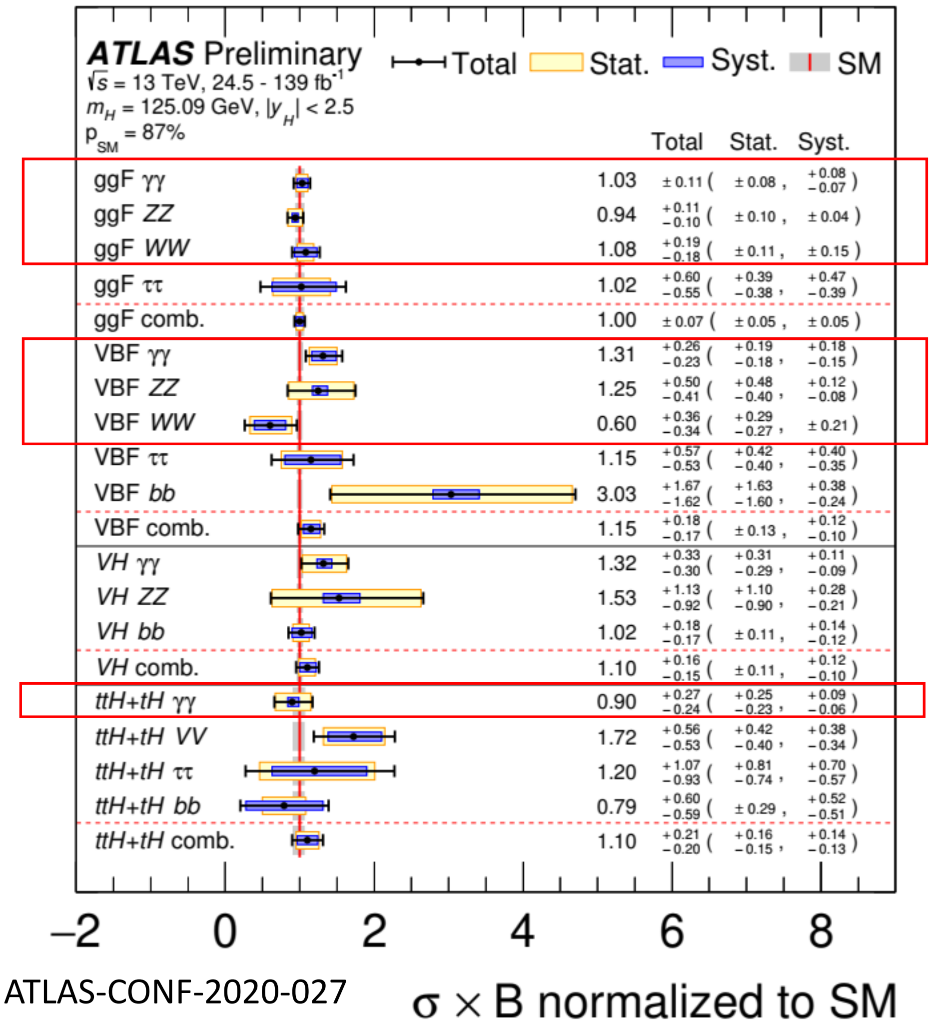
arXiv:2004.03969v2



Combined

CMS results at CMS PAS HIG-19-005; less full dataset channels

VV channels key for ggF and VBF modes



ATLAS-CONF-2020-027

Attempt to measure Higgs couplings: simplified κ-framework

$$\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

Coupling modifiers

Cross-section of each measured phase space can be parametrized as functions of κ

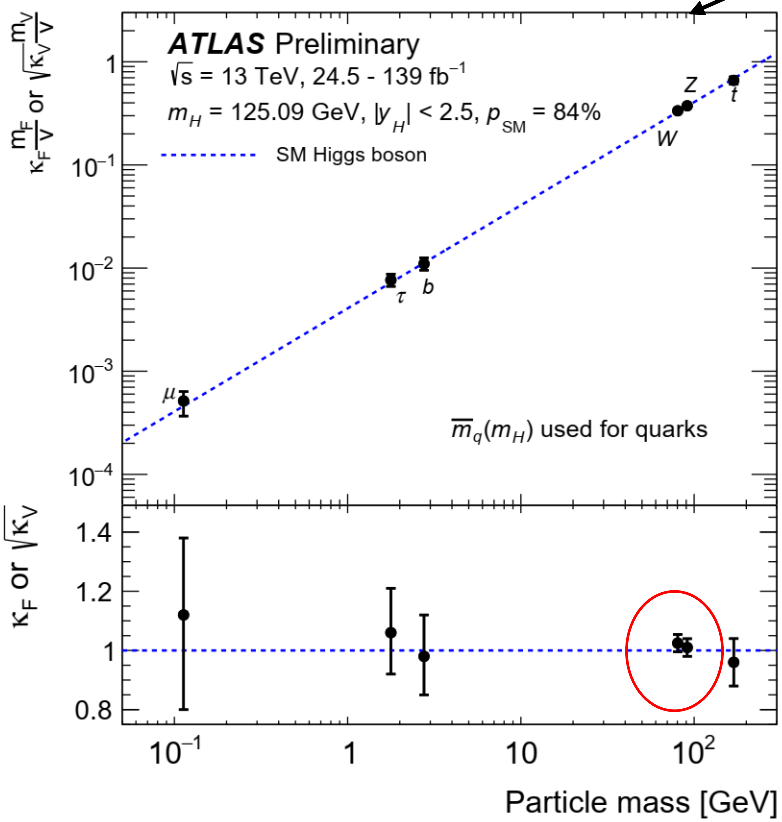
κ measurements

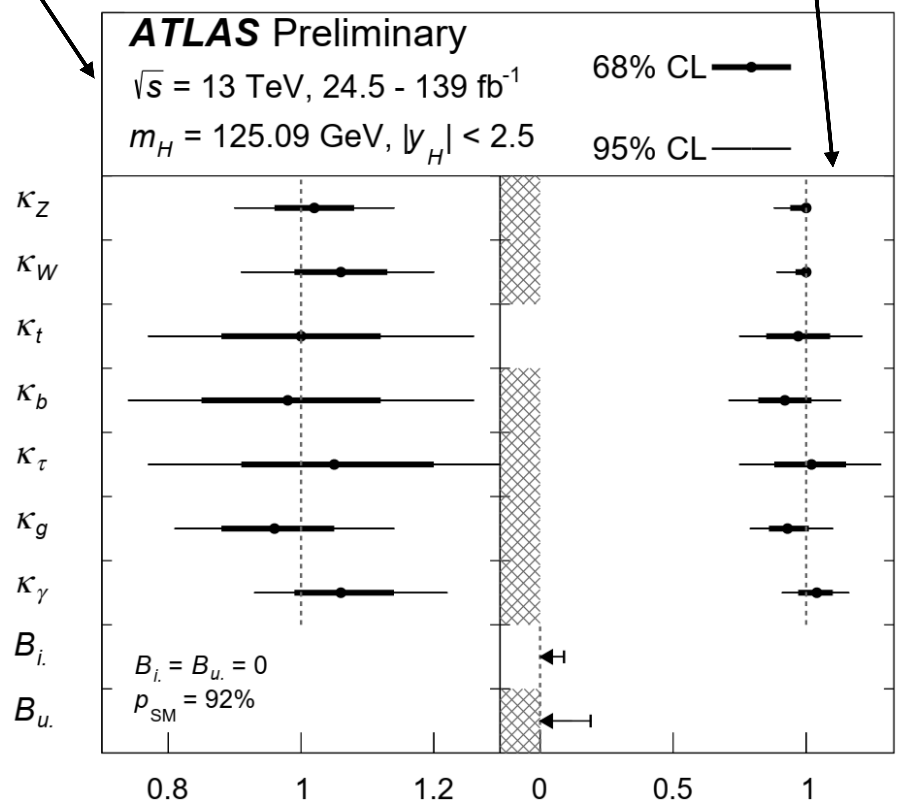
Couplings

ATLAS-CONF-2020-027

Higgs total width is uncertain (provided there might be unknown channels)

Assuming no unknown **Floating unknown**





VV couplings known to great precision

Total width via off-shell

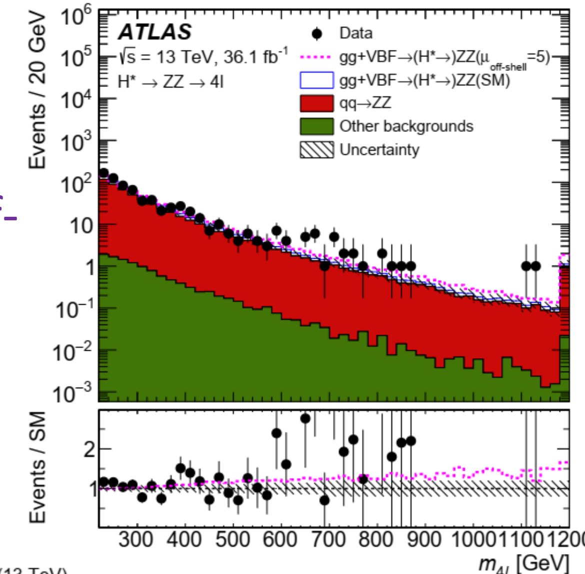
Γ_H is crucial: BSM sensitivity, coupling determination

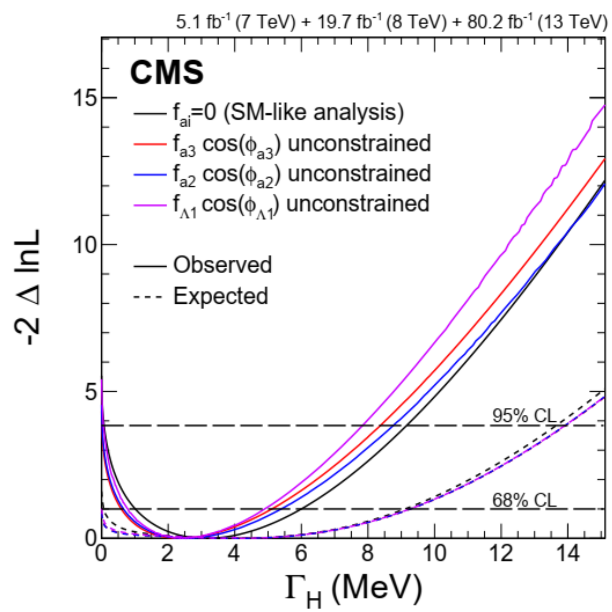
Predicted at 4 MeV, but direct probe (detector H mass) has much larger resolution

With assumptions, ratio of off-shell and on-shell Higgs production provides Γ_H measurement

PLB 786 (2018) 223

Demonstration of off-shell Higgs regions





ZZ→4l

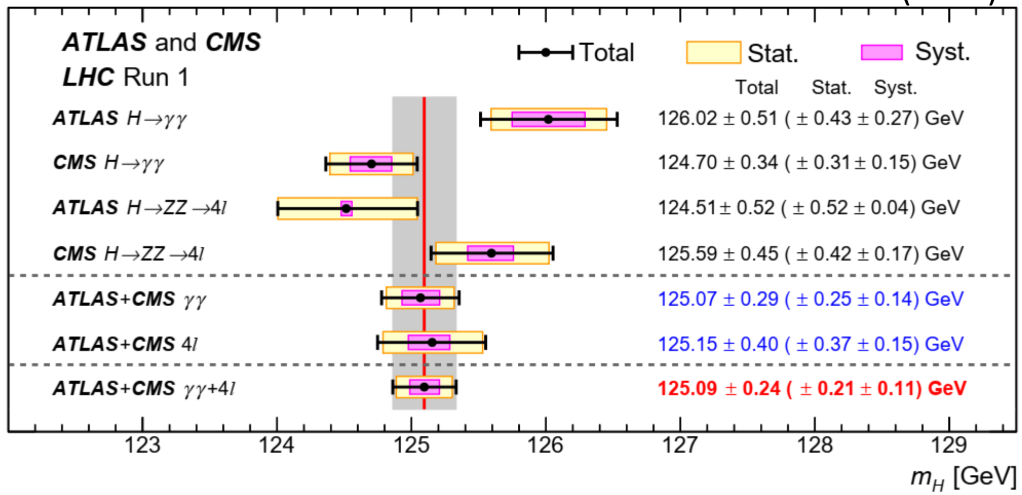
$\Gamma_H = 3 \pm 3$ MeV

PRD 99 (2019) 112003

Higgs boson mass

Full exploitation of detector for a precise determination of H mass

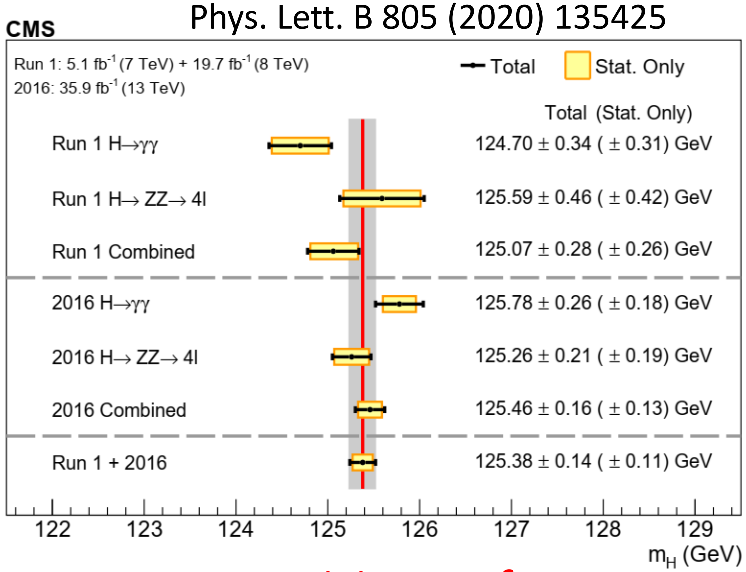
PRL 114 (2015) 191803



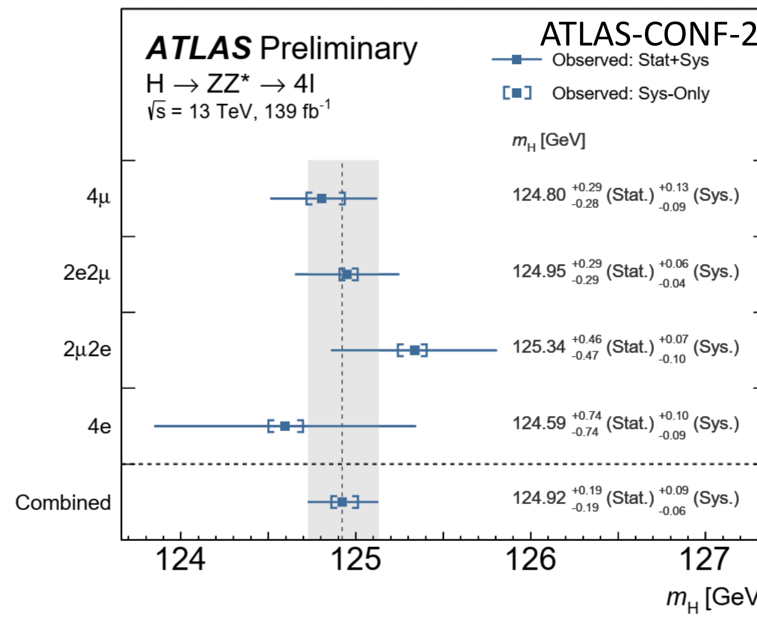
Run-I data:

With 13 TeV data

Phys. Lett. B 805 (2020) 135425



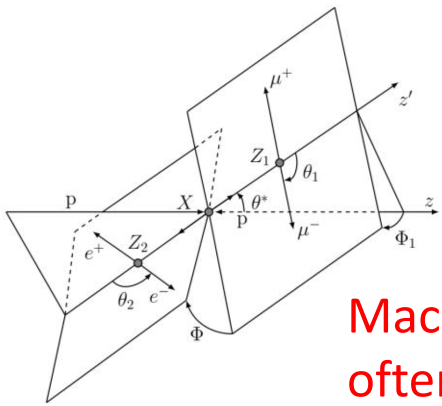
ATLAS-CONF-2020-005



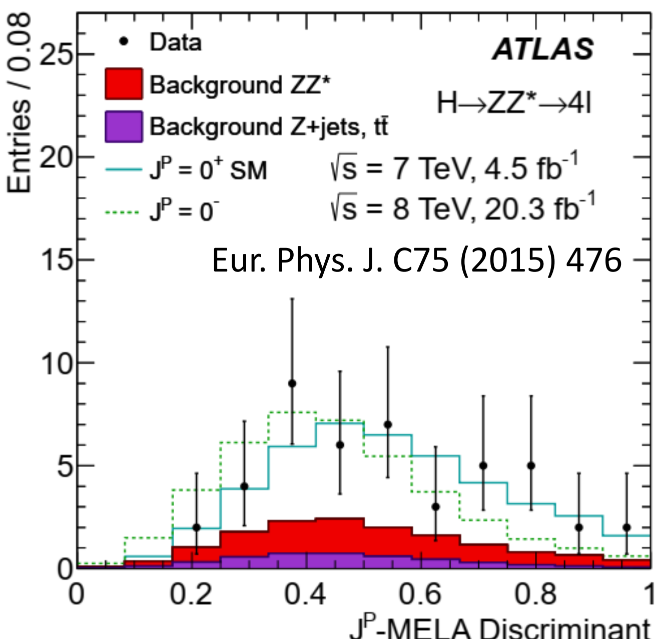
Best precision so far

Spin/CP

Examined the decay properties
infer the intrinsic characteristics

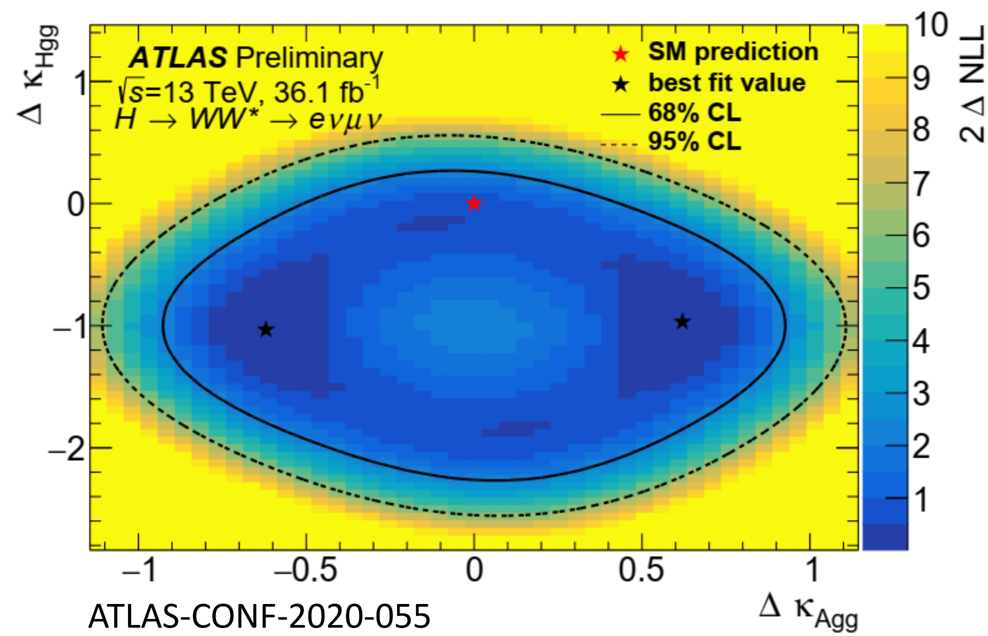


Machine learning
often deployed



Alternative spin, CP hypotheses rejected
long ago

Further efforts to study CP structures (mixing, violation)



ATLAS-CONF-2020-055

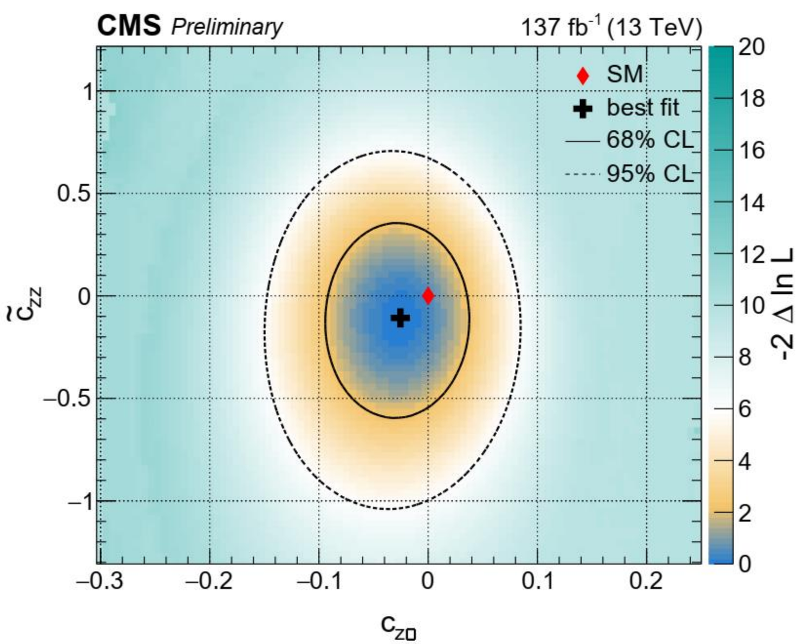
Interesting attempt with VBF
WW for effective H-g coupling

Effective Field Theories

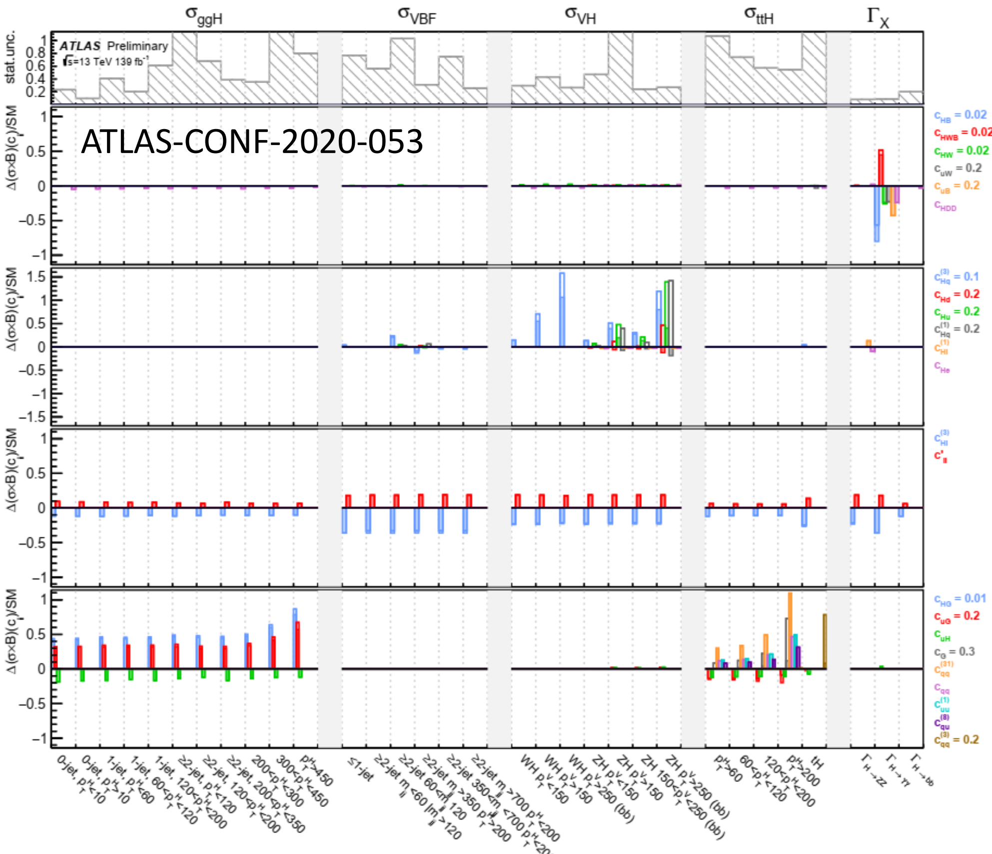
EFTs have their virtues in consistently describing modifications to properties

Limited precision in EFT interpretation; no obvious deviation so far

CMS PAS HIG-19-009



ATLAS-CONF-2020-053

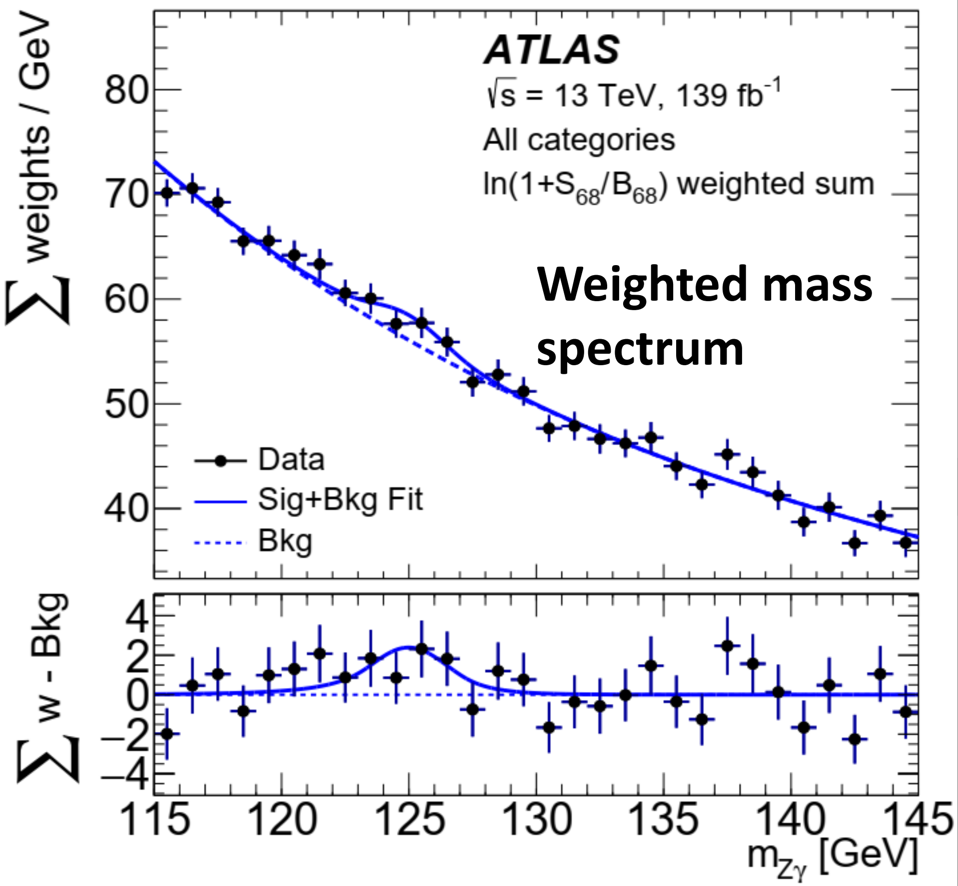


Constraining EFT operators relating to CP and loop BSM through H→4l events

Demonstration:
EFT coefficients ⇔ Measurements

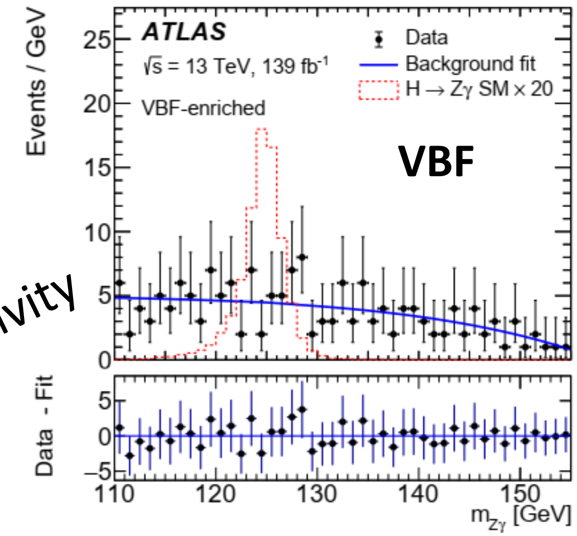
Rare Processes

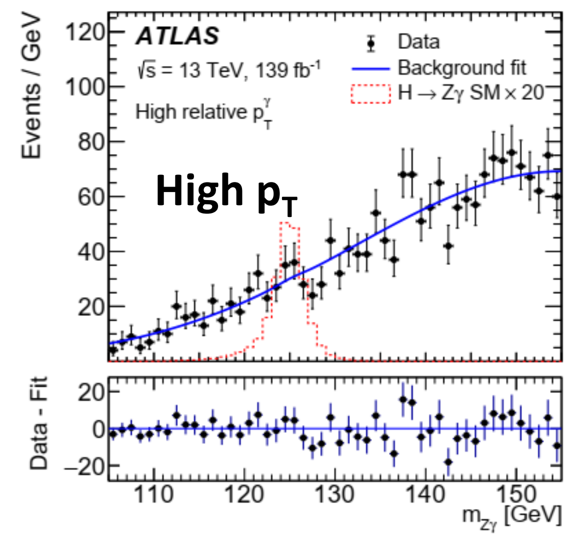
Search for H→Zγ decay (B~10^{-3})



Measured signal strength 2 ± 1, marching towards measurement sensitivity

Examples of high sensitivity channels

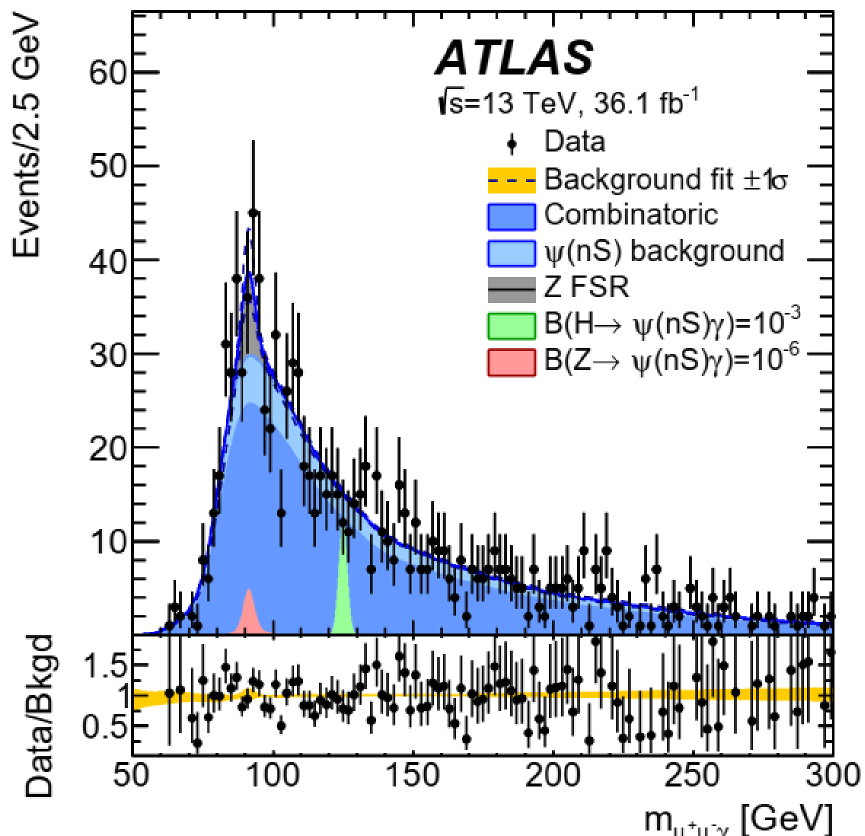




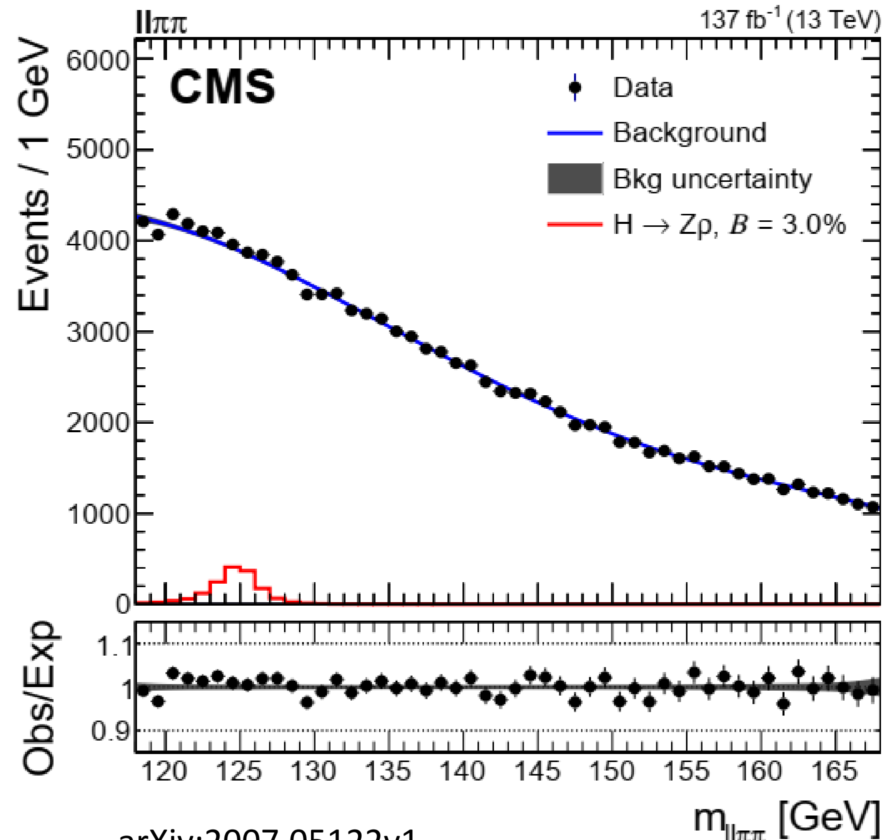
Rare Processes

H→ Jpsi/Upsilon + γ **H→ Z + rho/phi**

Complementary, but far away from sensitivity measurements



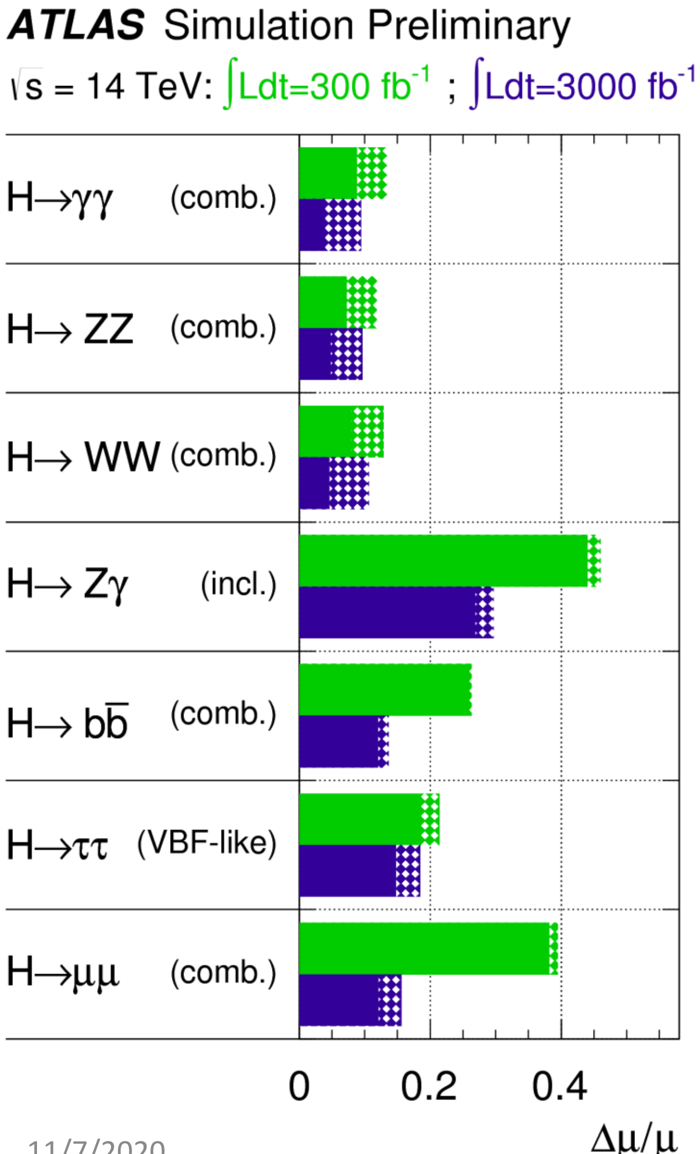
PLB 786 (2018) 134



arXiv:2007.05122v1

Prospect

ATL-PHYS-PUB-2014-016



Relative conservative projection

Real precision regime expected for H→VV channels:

- Potentials with upgraded detectors (larger coverage, better resolution, more exclusive triggering, timing, …)
- More precise theory predictions desired

Summary

Bosonic channels serve for precision measurements, already entering 10% regime

Thorough investigation of Higgs boson properties have been conducted, often further insights being established

No beyond-the-SM effects observed so far : - (

Quest is to increase the precision, not only via increasing luminosities, but also requiring further insights in **physics**, **detector**, and **analysis techniques**


Thank you for your attention