SM HIGGS AT THE LHC

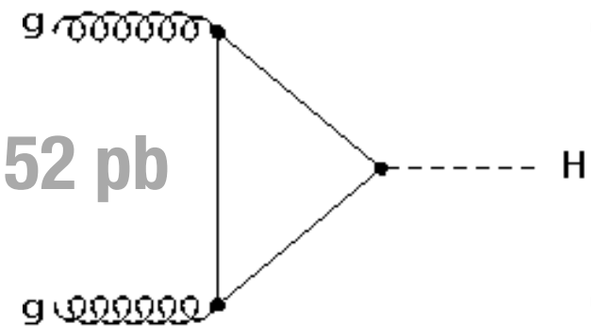
MARÍA CEPEDA (CERN)
ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

25th Anniversary of the Rencontres du Vietnam, Qui Nhon, August 2018

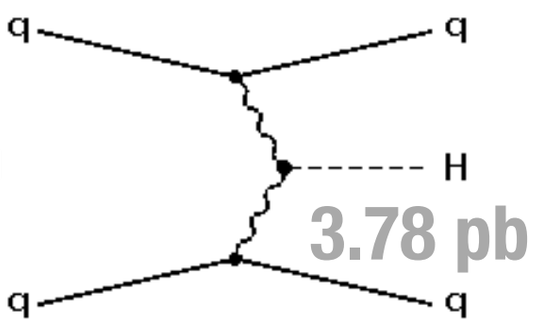
Higgs Physics at the LHC

- We have come a long way since the Higgs discovery in 2012
- The available LHC Run1 (7,8 TeV~25fb^{-1}) & Run2 (13 TeV ~80fb^{-1}) datasets have pushed Higgs physics from search mode to measurement mode, probing the nature of the boson and its agreement with the SM
- All the main production and decay modes under scrutiny by ATLAS and CMS

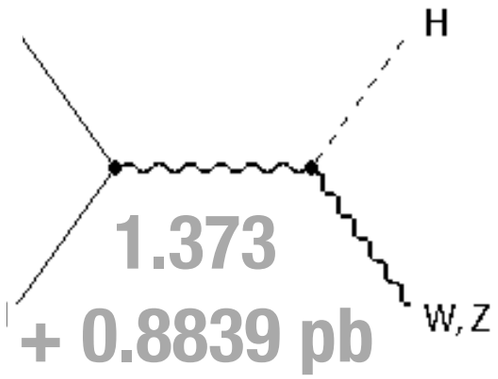
proton-proton → 



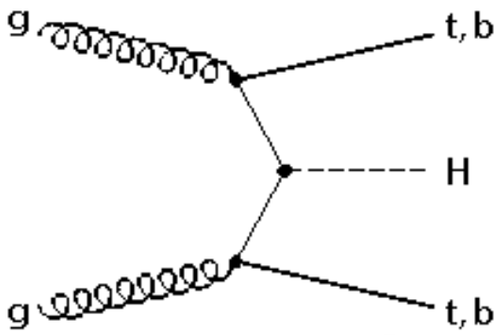
48.52 pb



3.78 pb

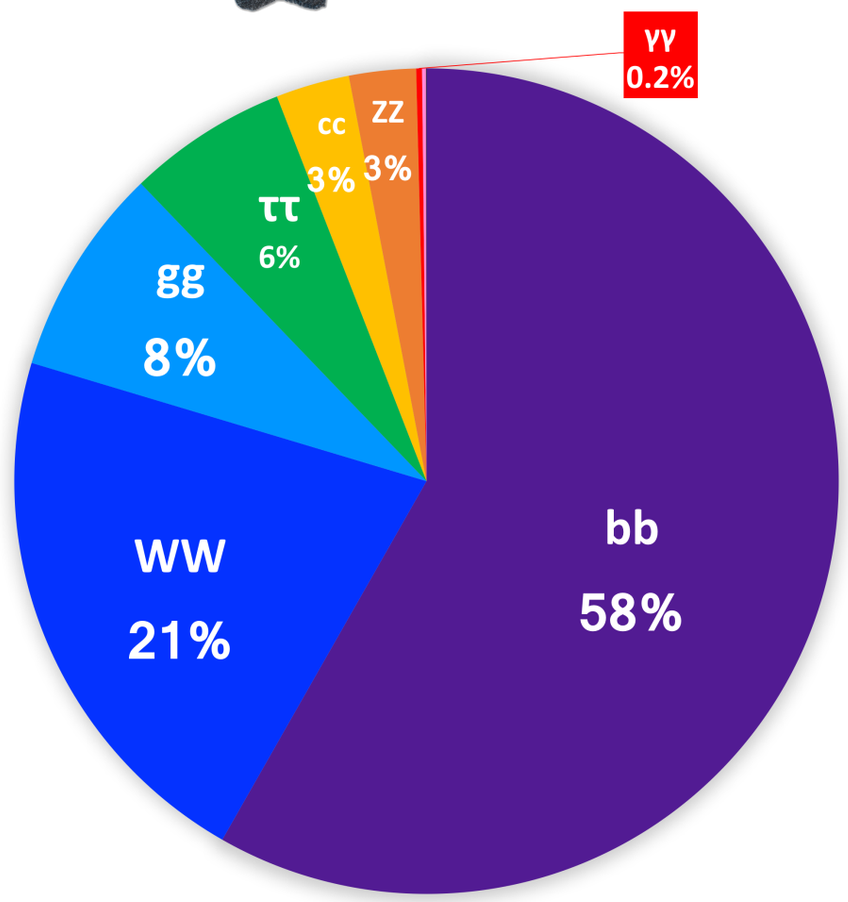


1.373
+ 0.8839 pb



0.5071 pb

 → **SM**



What to ask?

Not covering theoretical aspects of Higgs physics in this talk, lets focus on the experimental study of the boson:

- Is its production rate, where we measure it, at the correct SM level?
- How do we caracterize it? (mass, width, spin)
- Does it couple to SM particles at the appropriate level?
- How well can we model its behaviour?
- Does it couple to itself?
- Does it decay unusually?
- Are there more Higgses?
- Higgs as a tool for discovery

Larger datasets → rarer / more complex production and decay modes become accessible
Precise differential measurements possible

Outline

- **Couplings to Bosons**
- **Couplings to Fermions**
- **Combination of Measurements**
- **DiHiggs Production**

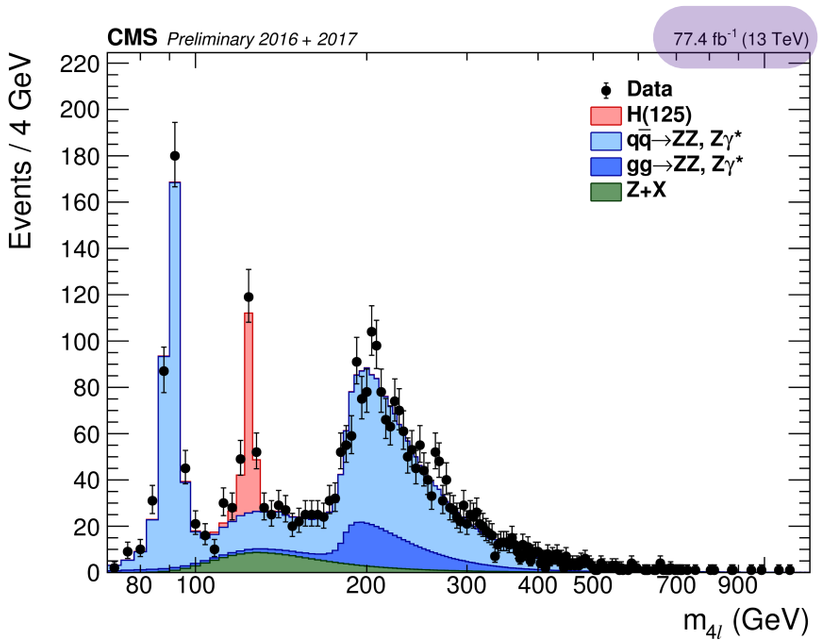
We've been busy! impossible to cover all aspects in detail in 30'…
Highlighting recent results. For more:

All Higgs Results in CMS **All Higgs Results in ATLAS**

- **Couplings to Bosons**
- Couplings to Fermions
- Combination of Measurements
- DiHiggs Production

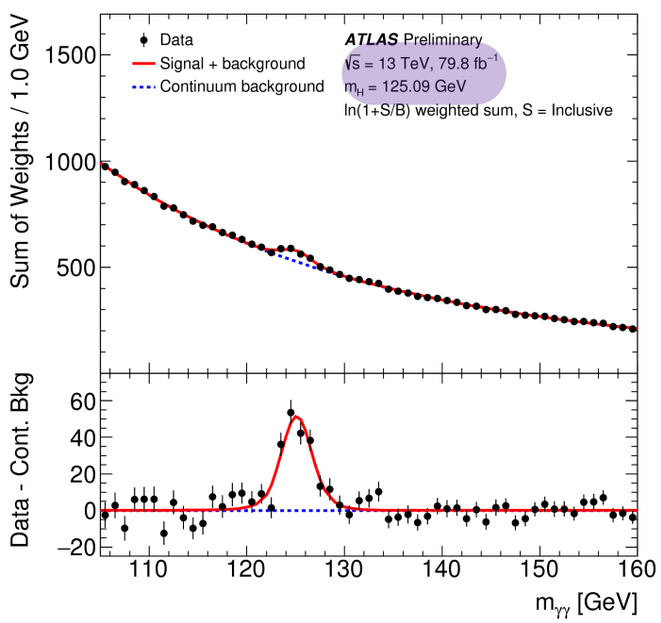
Couplings to Bosons

- Well beyond search mode —> Higgs **measurements**
  - **ZZ and γγ:** Low branching ratio but clean signatures and full system reconstruction
    - **ZZ** (2.6%): clean & narrow peak, very low flat background
    - **γγ** (0.2%) : narrow peak over smooth background
  - **WW** (21.5%) : large branching ratio, but missing final state information (neutrinos)



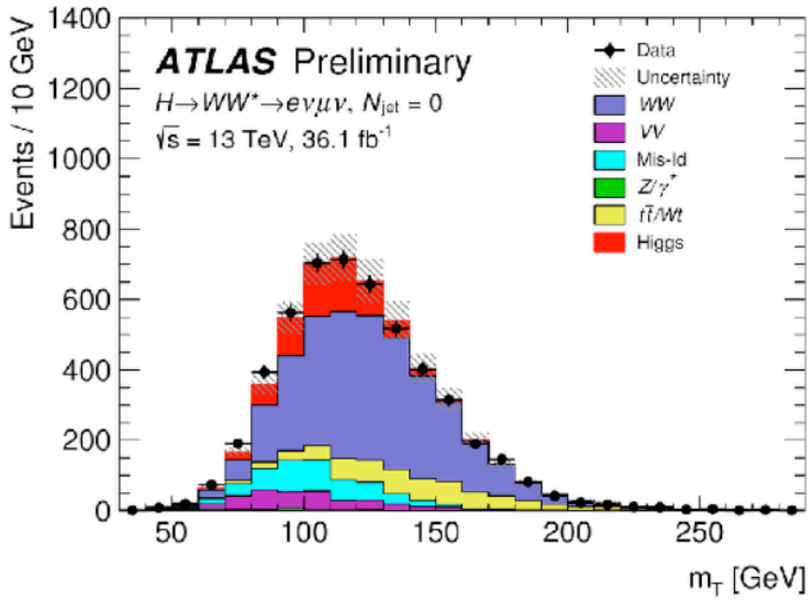
ATLAS CONF 2018-018

CMS PAS HIG-18-001



ATLAS CONF 2018-028

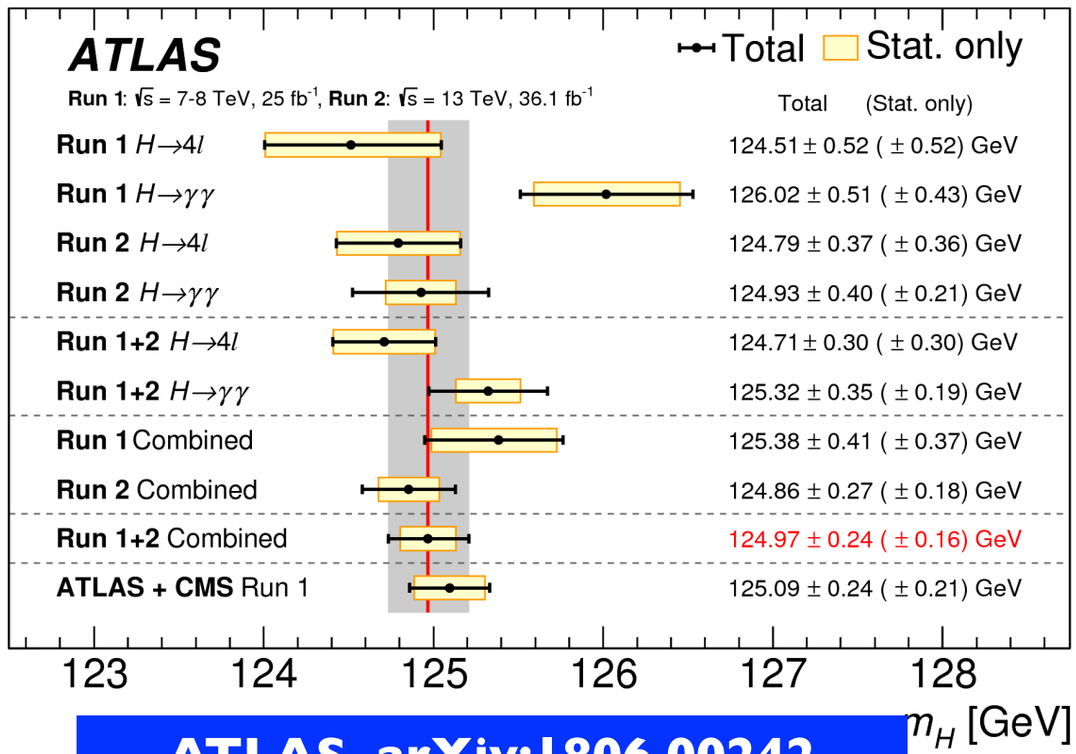
CMS arXiv:1807.03825



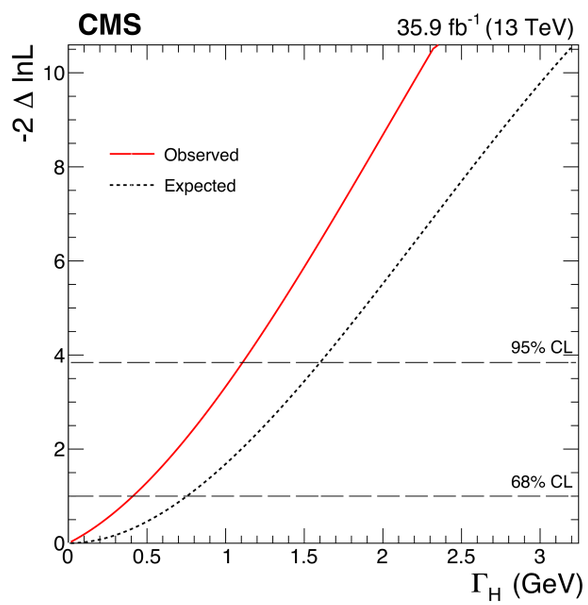
ATLAS CONF 2018-004

CMS PAS HIG-16-042

Property Measurements



ATLAS arXiv:1806.00242

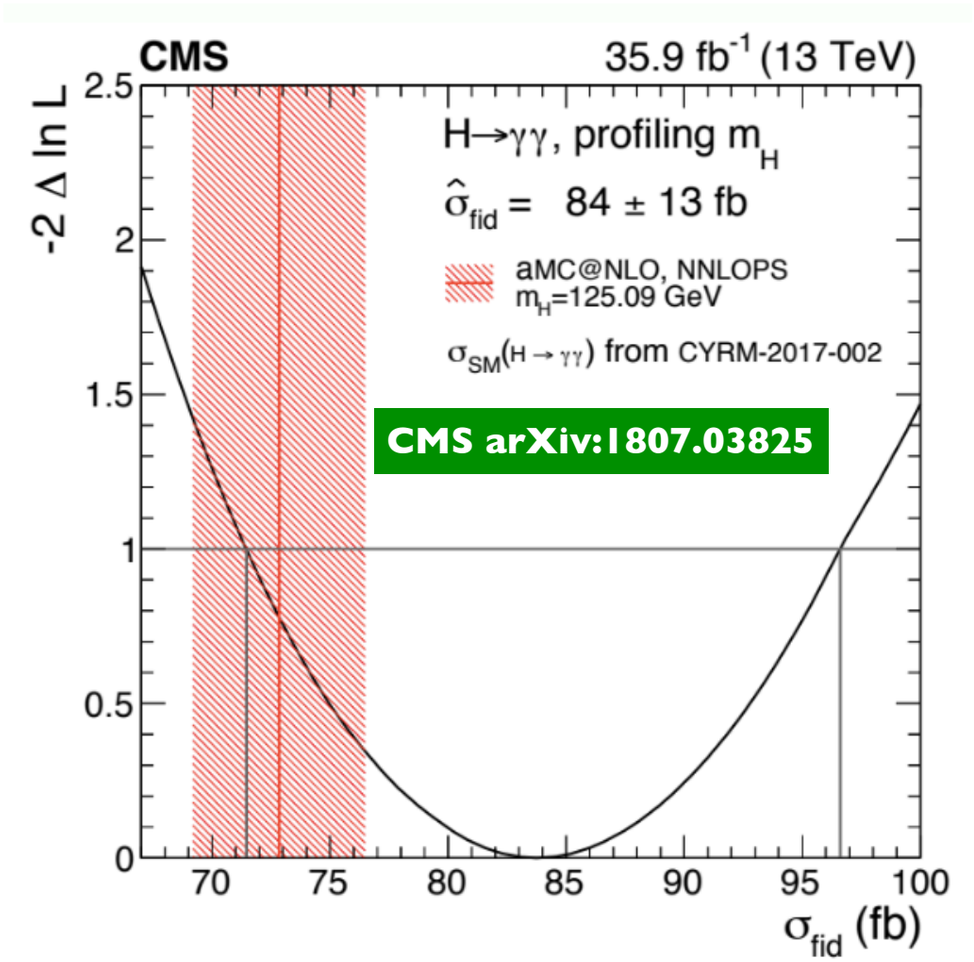


CMS JHEP 11 (2017) 047

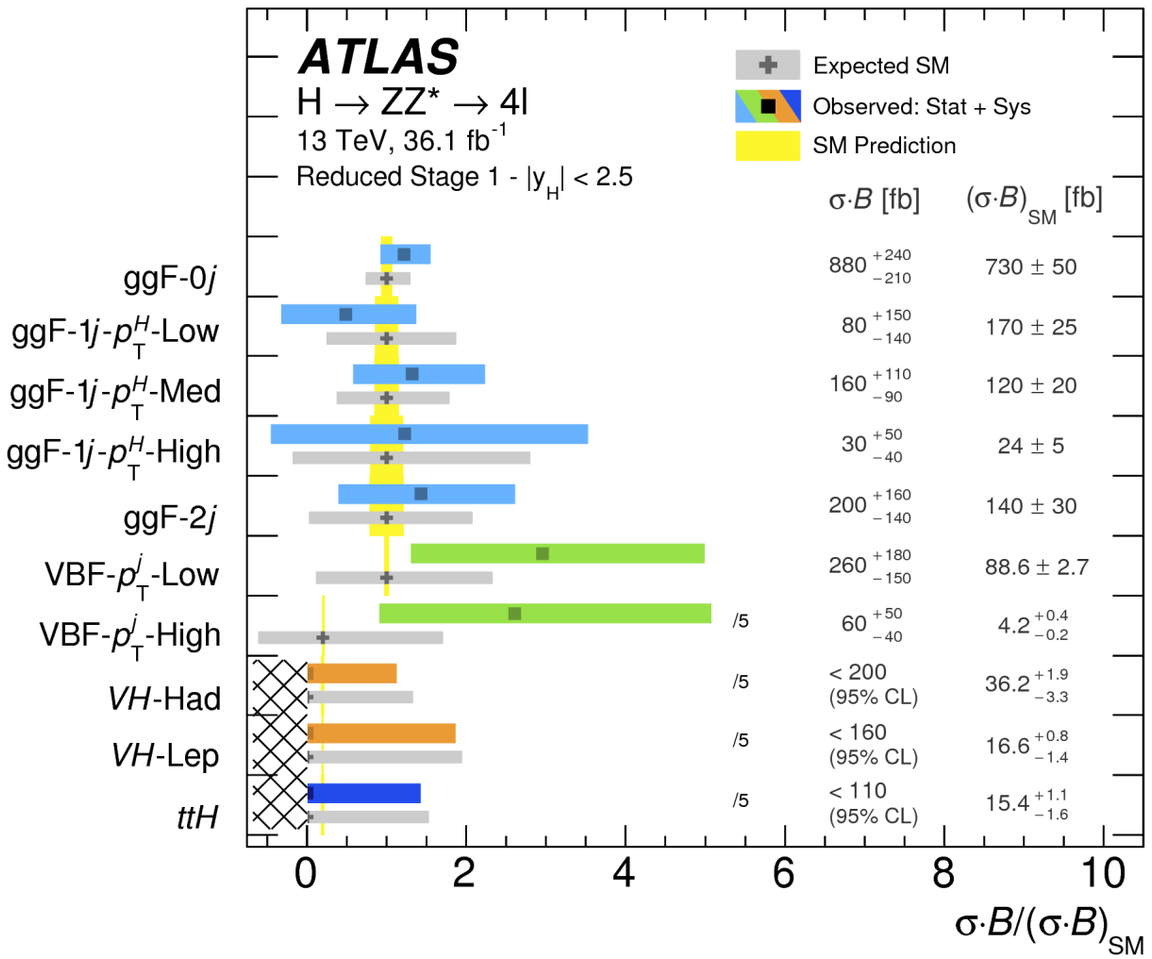
- **Mass (γγ and ZZ):**
  - Run 1 CMS+ATLAS combination: 125.09 ± 0.21 (stat) ±0.11 (syst) GeV
  - Run1+Run2 ATLAS (most recent): 124.97 ± 0.19 (stat) ±0.13 (syst) GeV
  - Run2 CMS (most precise): 125.26 ± 0.20 (stat) ±0.08 (syst) GeV
- **Width (ZZ, Run2)**
  - Direct Measurement: <1.1 GeV (95% CL) (CMS)
  - Onshell/Offshell ratio: <14.4 MeV (expected 15.2 MeV) (ATLAS, ICHEP18)
- **Spin-CP measurements: 0+**
  - Large bibliography (Run1+early Run2). Latest results Phys. Lett. B 775 (2017) 1 and Eur. Phys. J. C76 (2016) 658

Not comprehensive list, recent results highlighted

Cross Section Measurements: I



- Going beyond signal strength and SM agreement statements
- **Fiducial cross sections:** reduced dependence on theoretical uncertainty

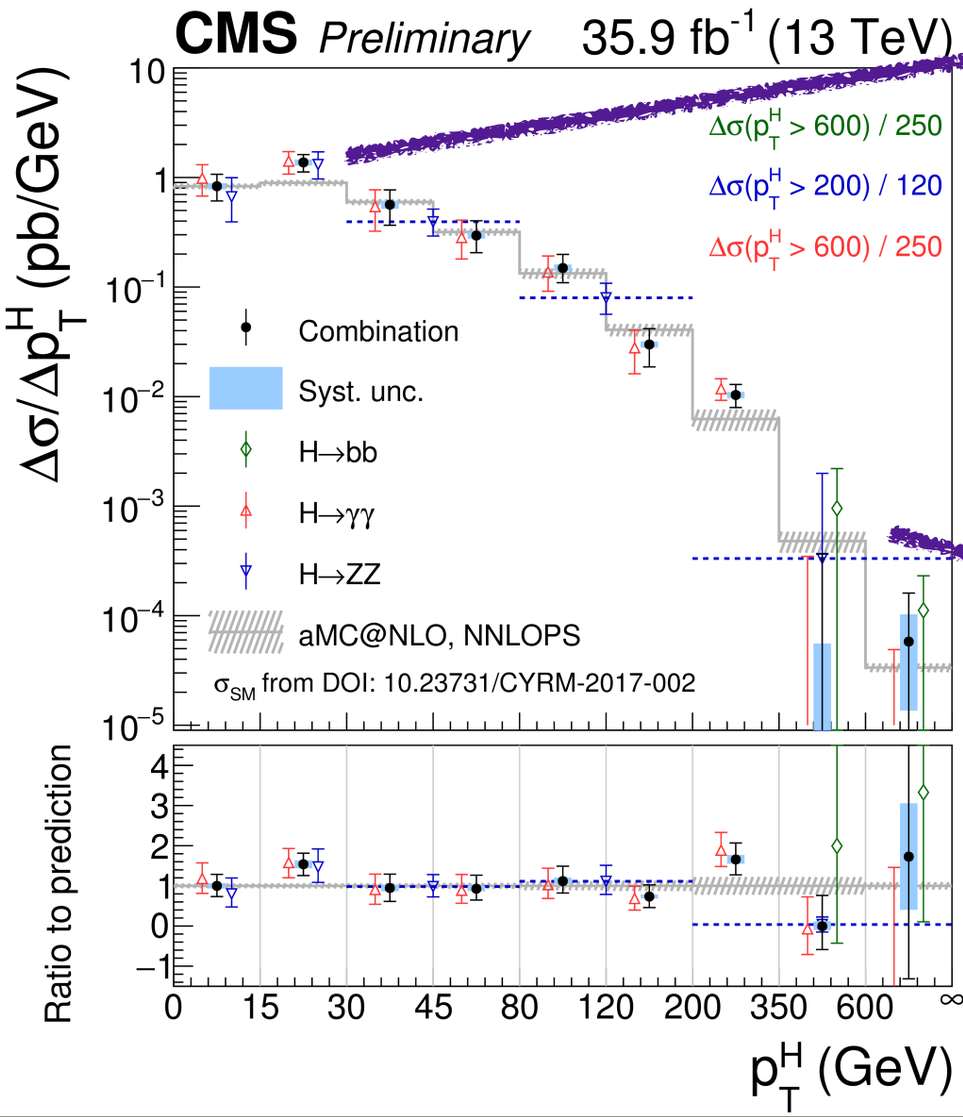


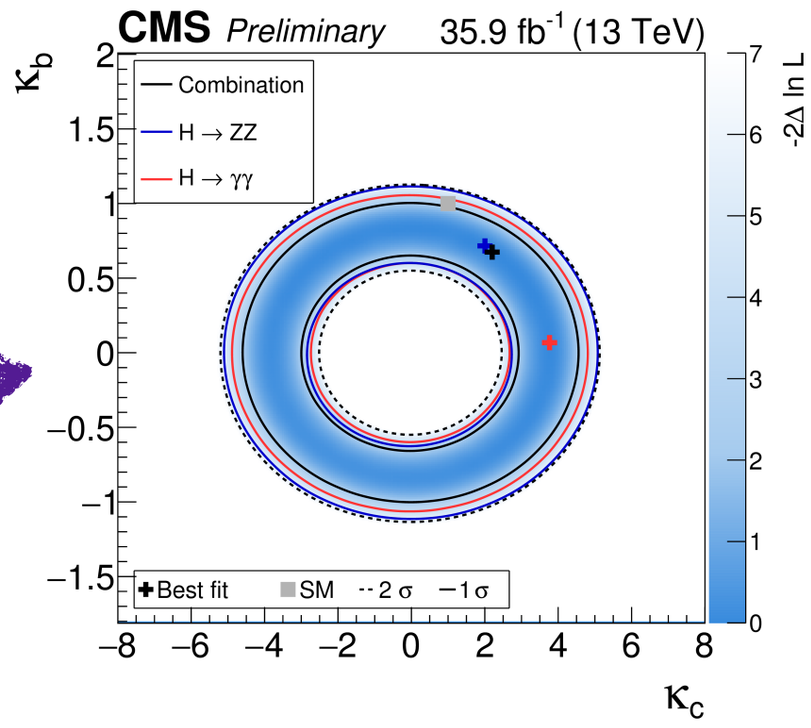
ATLAS JHEP 03 (2018) 095

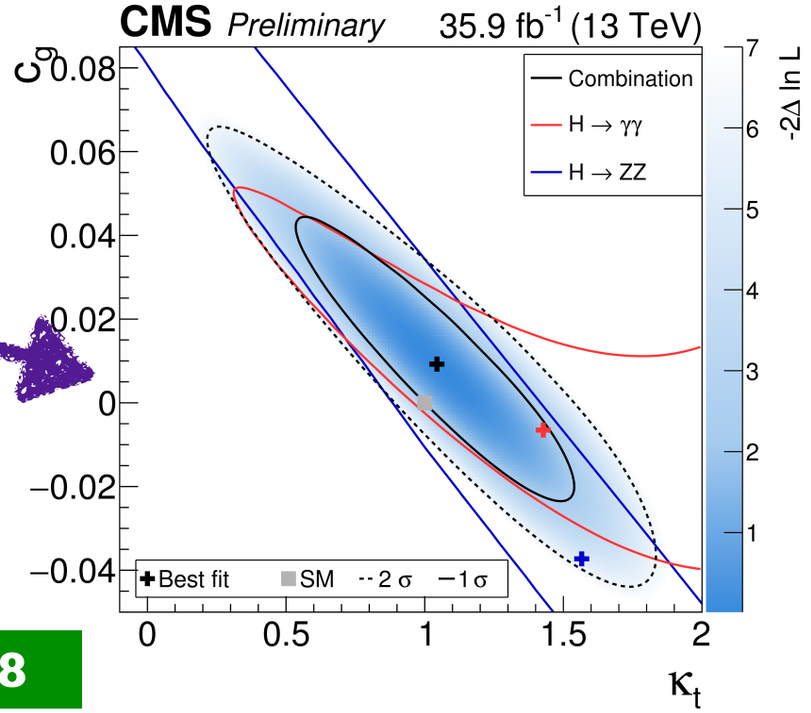
- **Simplified Template Cross Section (STXS):**
  - LHC-wide agreement phase-space and object definition (theory community+ATLAS+CMS)
  - Cross Sections split by production mode and region of phase space

Cross Section Measurements: II

- **Differential Cross Sections**
  - Dominated by statistical uncertainty
  - Allow for a EFT interpretation of Higgs differential distributions —> coupling constraints. Sensitive to k_b/k_c (low p_T). k_t/BSM (high p_T)







CMS PAS HIG-17-028

- Couplings to Bosons
- **Couplings to Fermions**
- Combination of Measurements
- DiHiggs Production

Couplings to Fermions

- Yukawa Couplings in the SM proportional to the fermion mass

- **Observation of Higgs coupling to third generation fermions**

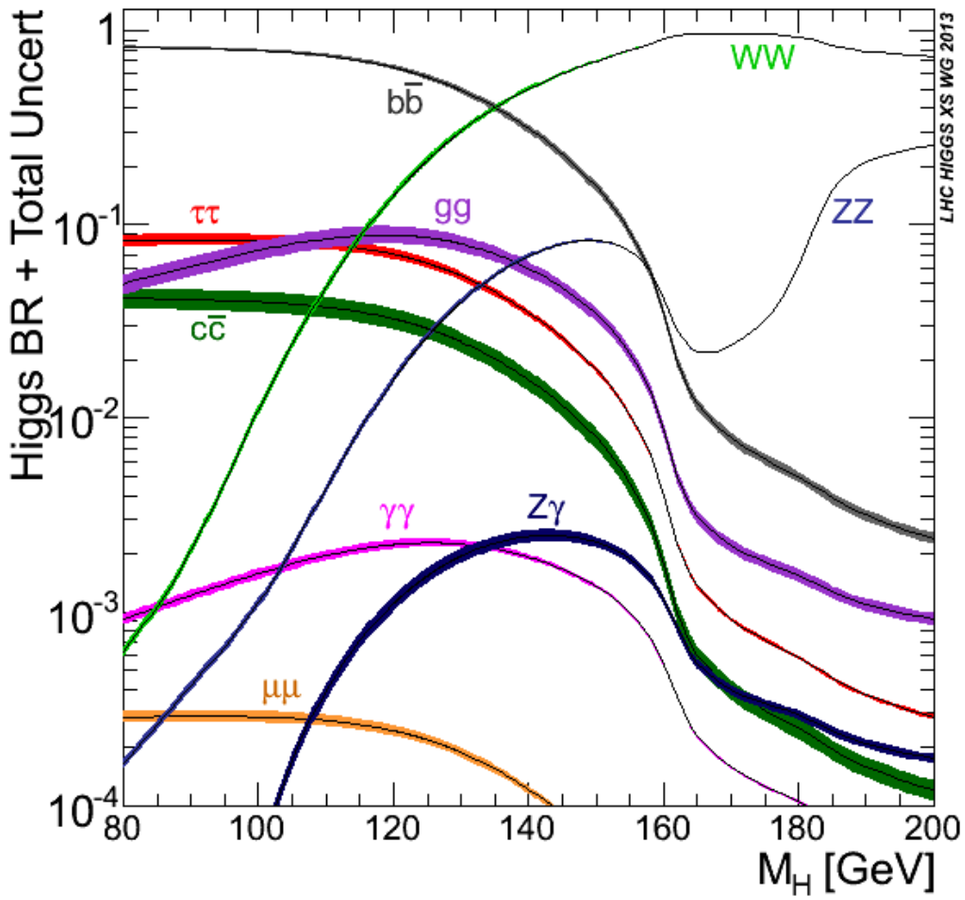
  - Run2 data reaches observation level per channel with the data of each experiment alone

  - **Hbb**: largest branching ratio (%), extremely challenging background, state of the art tagging techniques, focus on associated production to identify events

  - **Hττ**: challenging reconstruction of hadronic decays of tau hadrons

  - **ttH / tH** -> explore the top Yukawa

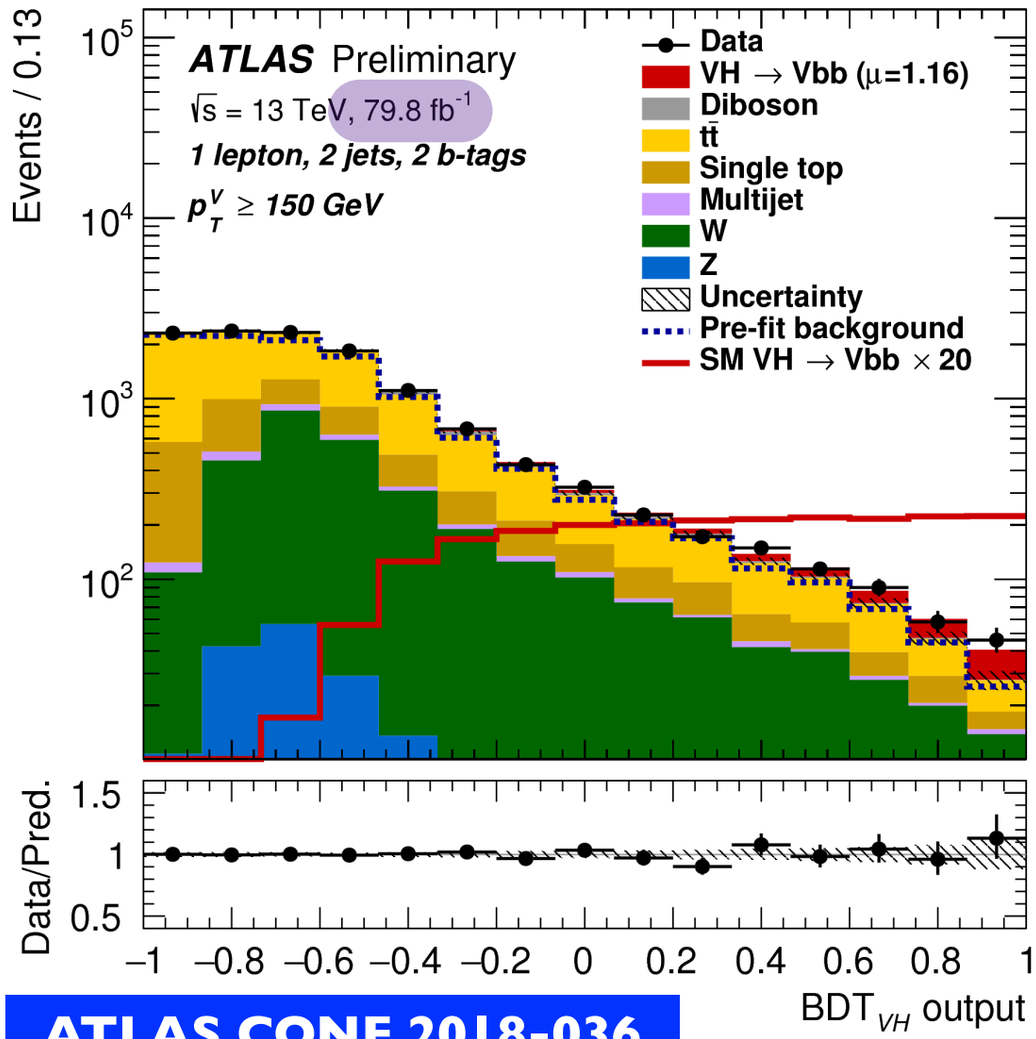
- Coupling to second generation? (μμ, cc)



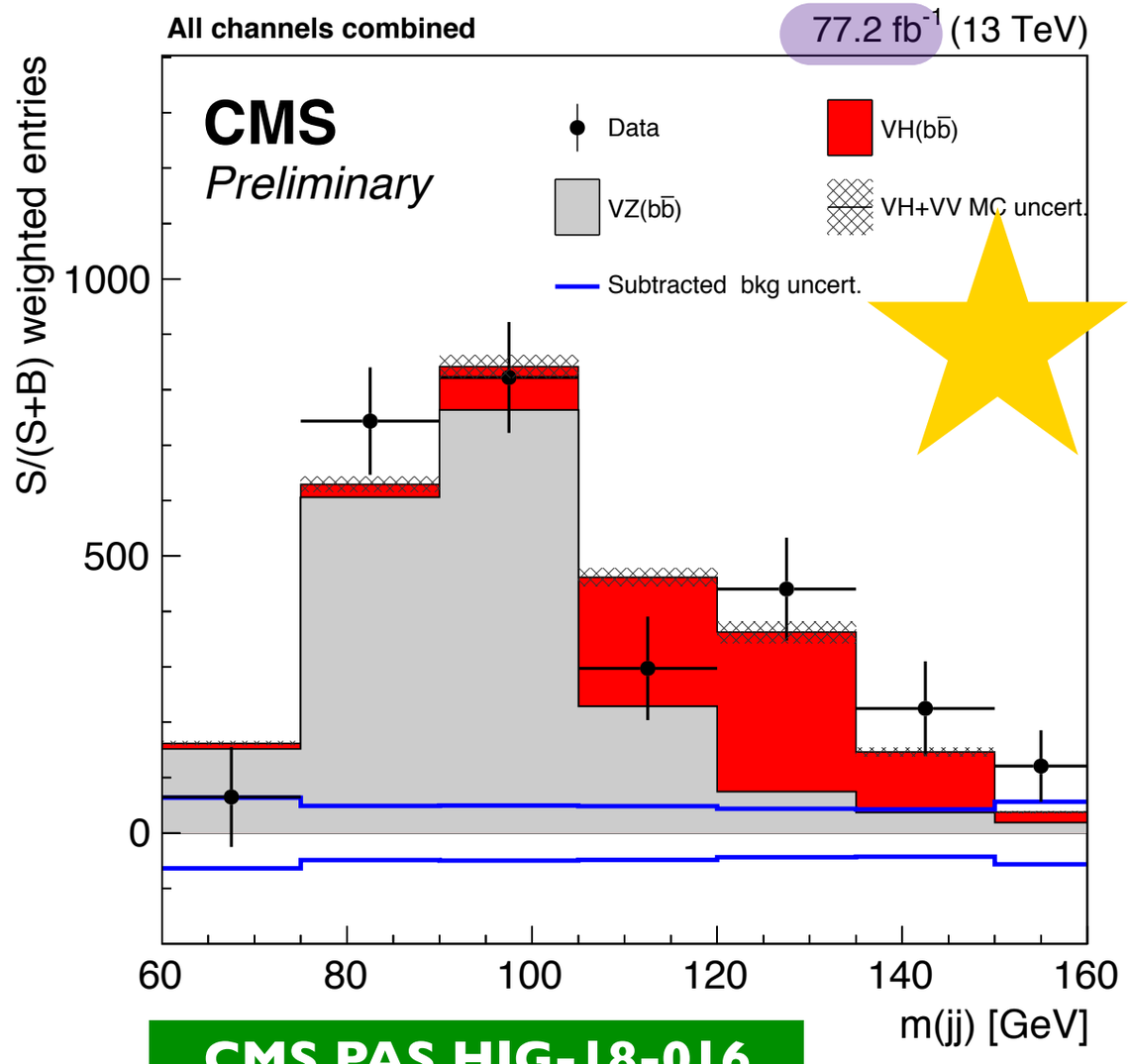
+ Parallel talk by S. Lai

VH, Hbb

- **Event identification through VH topology (reduced QCD background)**
  - Categories based on the number of leptons (0,1,2 x mu, ele) and number of jets
  - Identification of the Higgs decay through the b-jet pair
  - Further background reduction through high pt selection
- **BDT techniques** to optimise S/B : driven by $p_T(V)$, btag, and b-pair topology (m(bb), ΔR(bb))



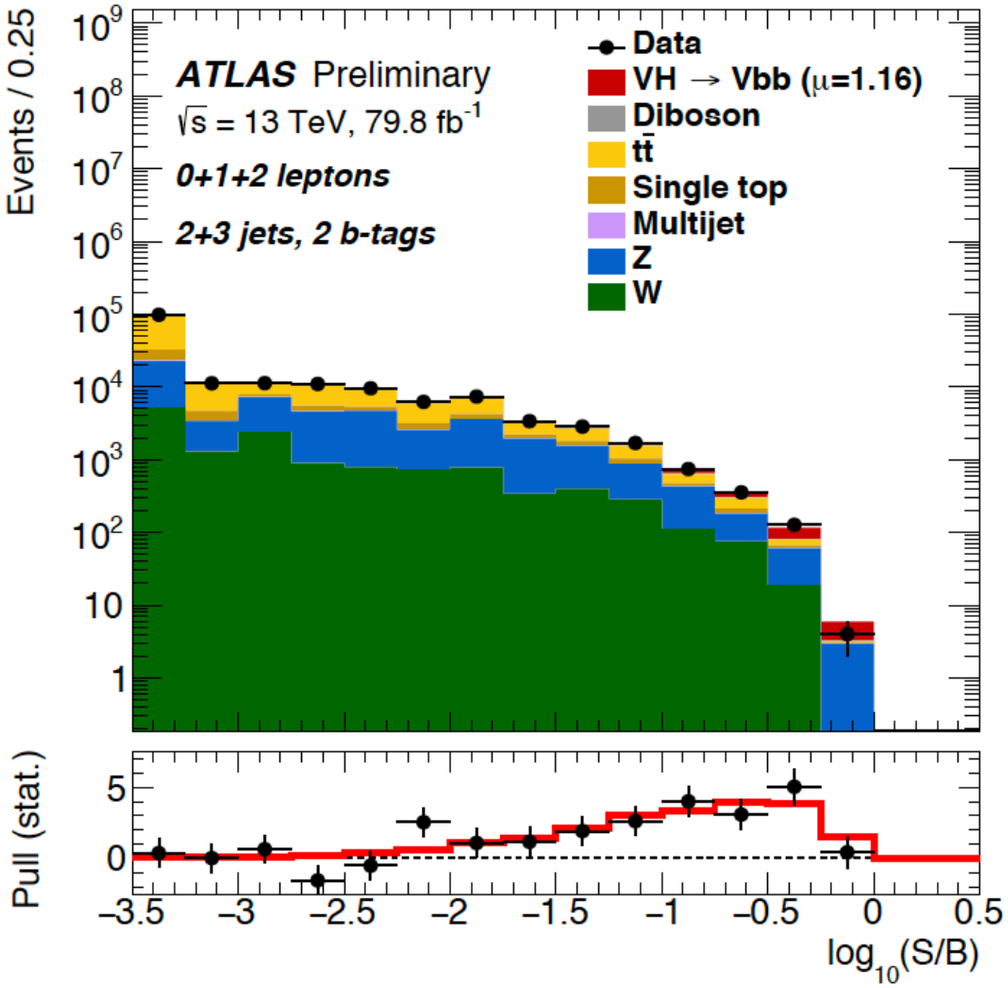
ATLAS CONF 2018-036

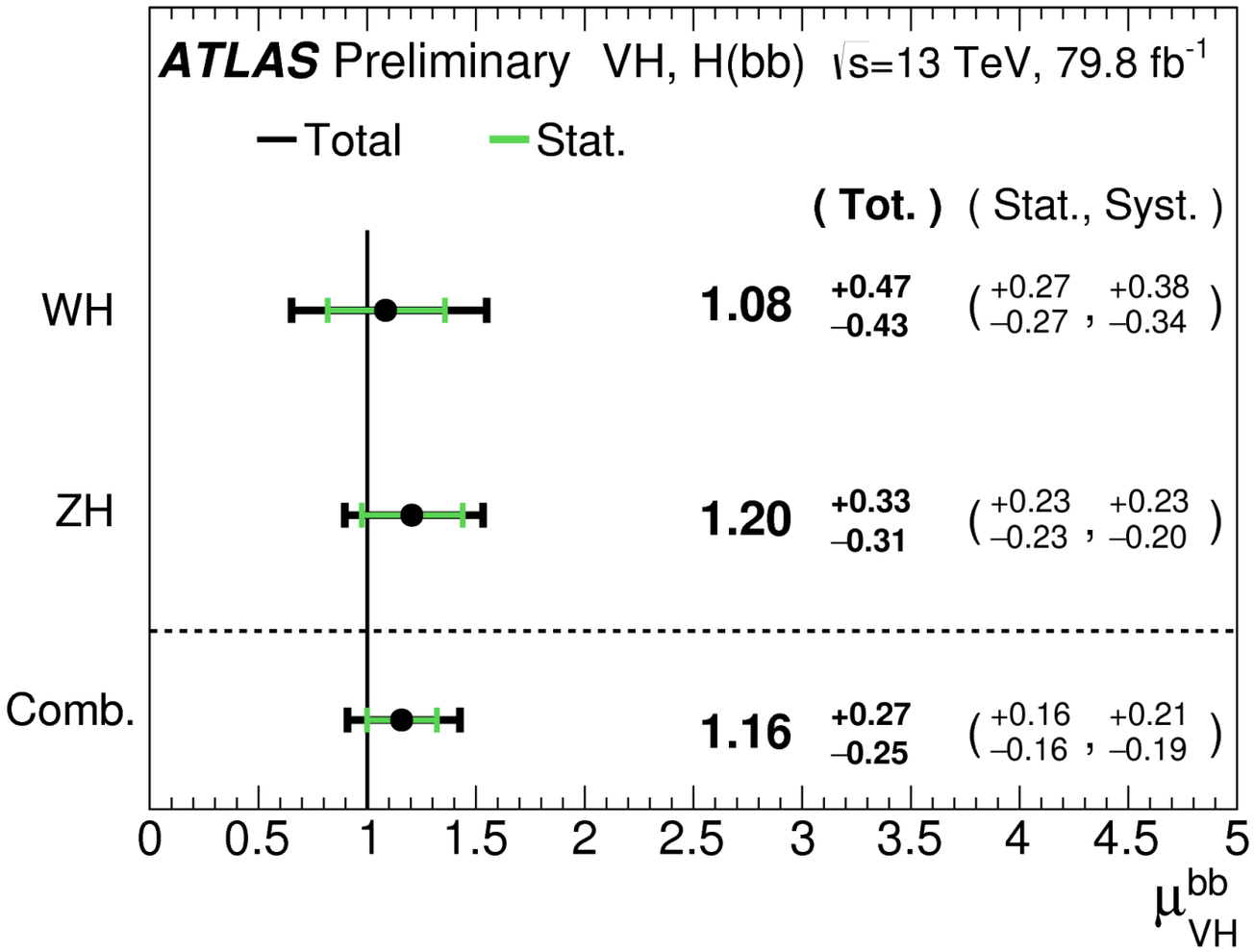


CMS PAS HIG-18-016

Observation of VH Hbb

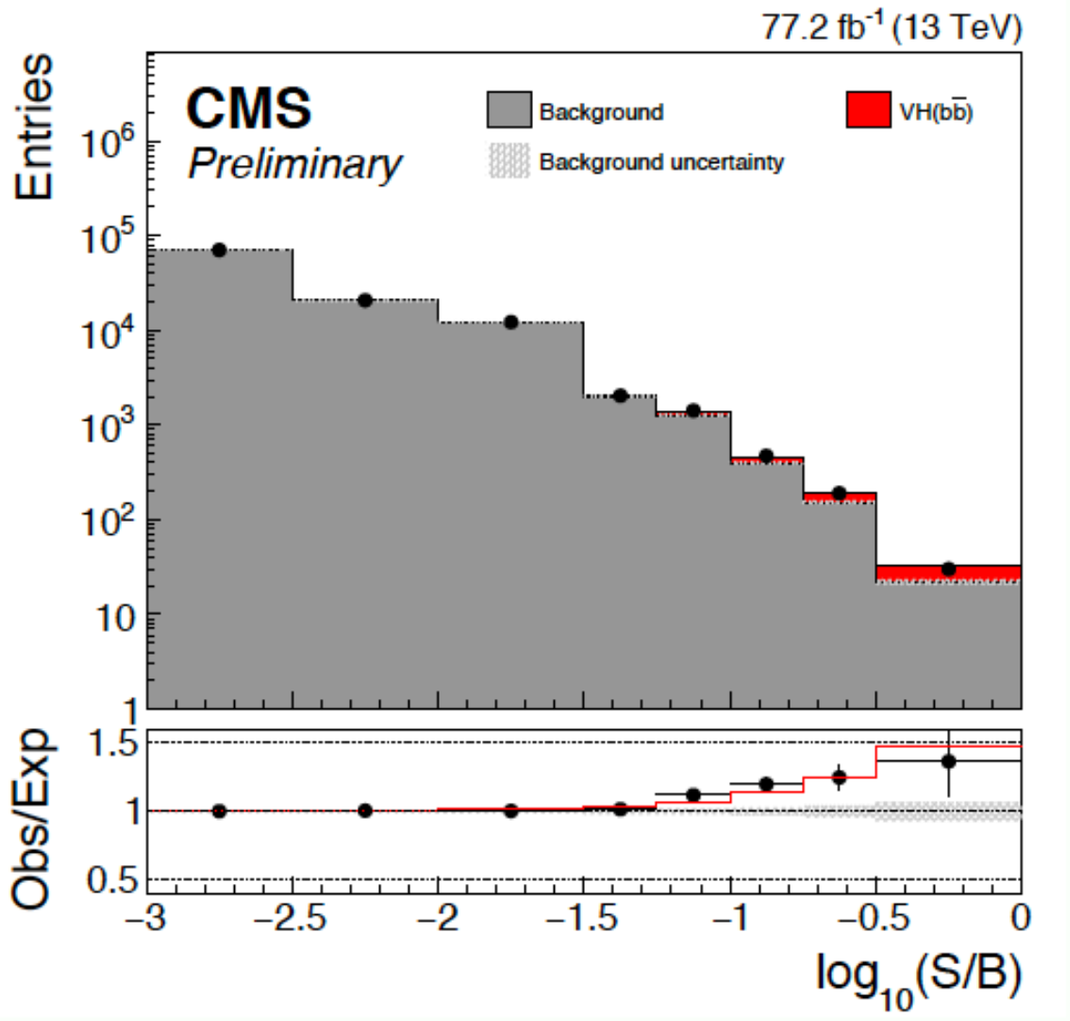
ATLAS VH Hbb (Run2): 4.9 σ (4.3 σ exp.)
Run1+Run2: 4.9 σ (5.1 σ exp.)

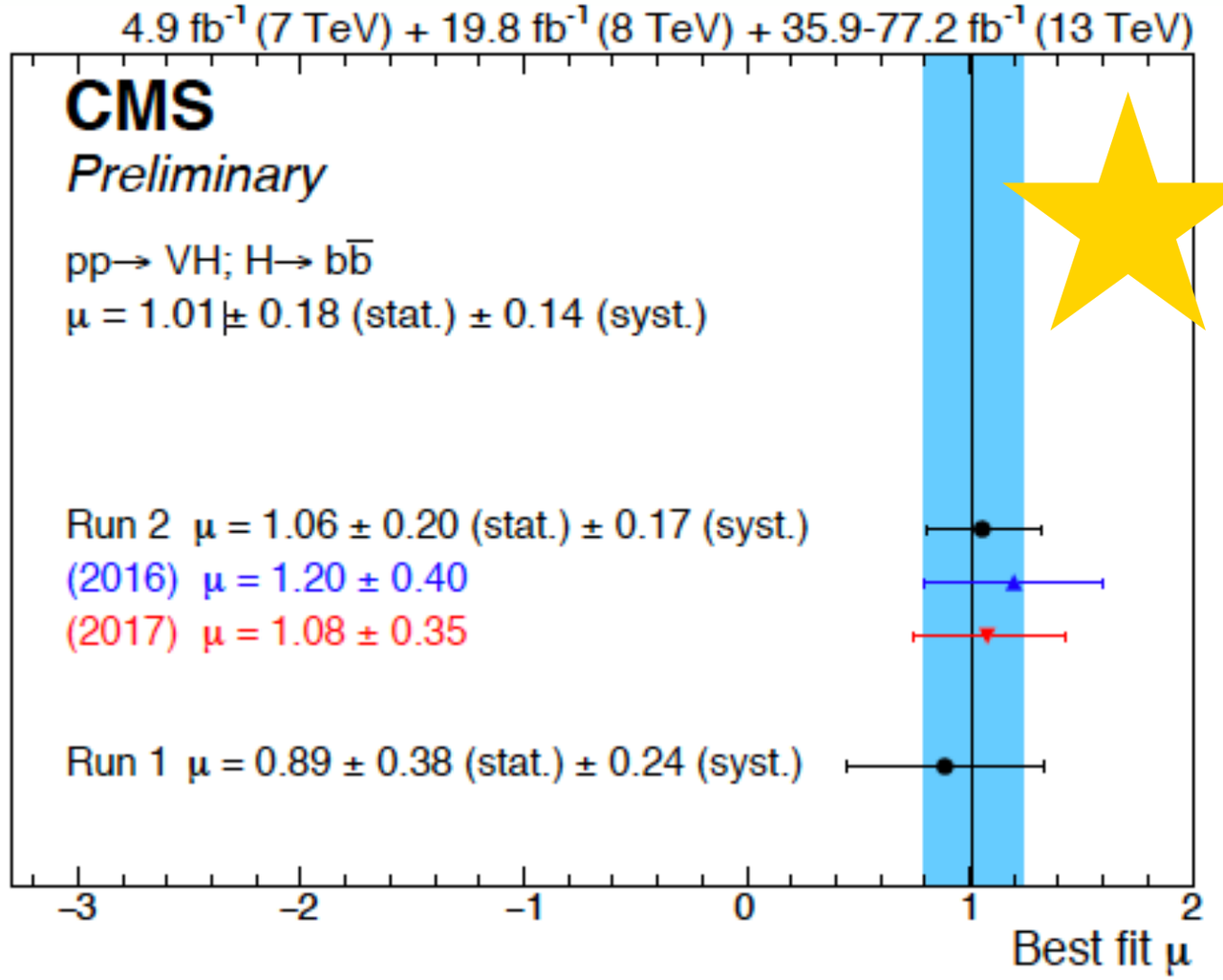




Observation of VH Hbb

CMS VH Hbb (Run2): 4.4 σ (4.2 σ exp.)
Run1+Run2: 4.8 σ (4.9 σ exp.)

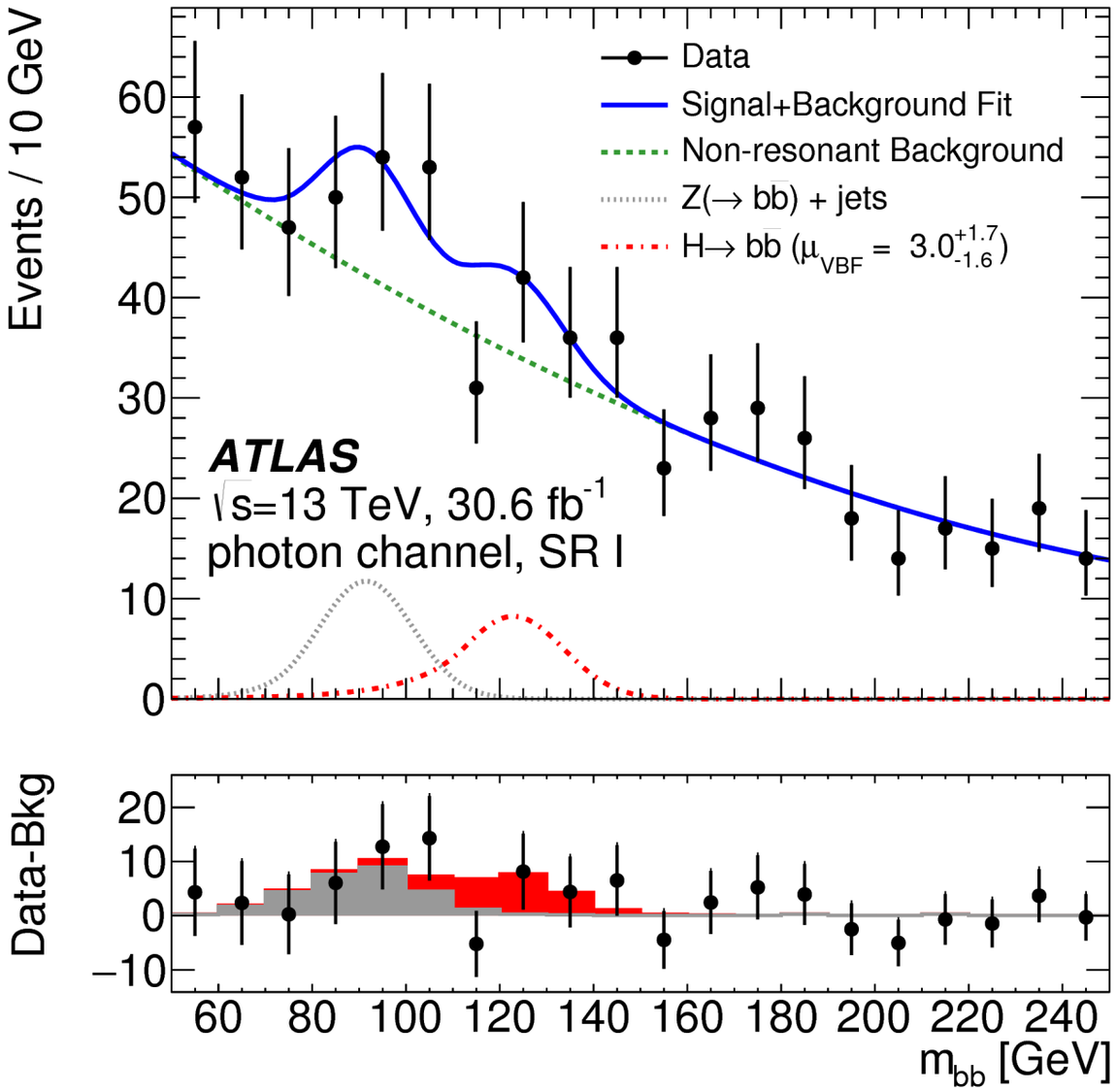




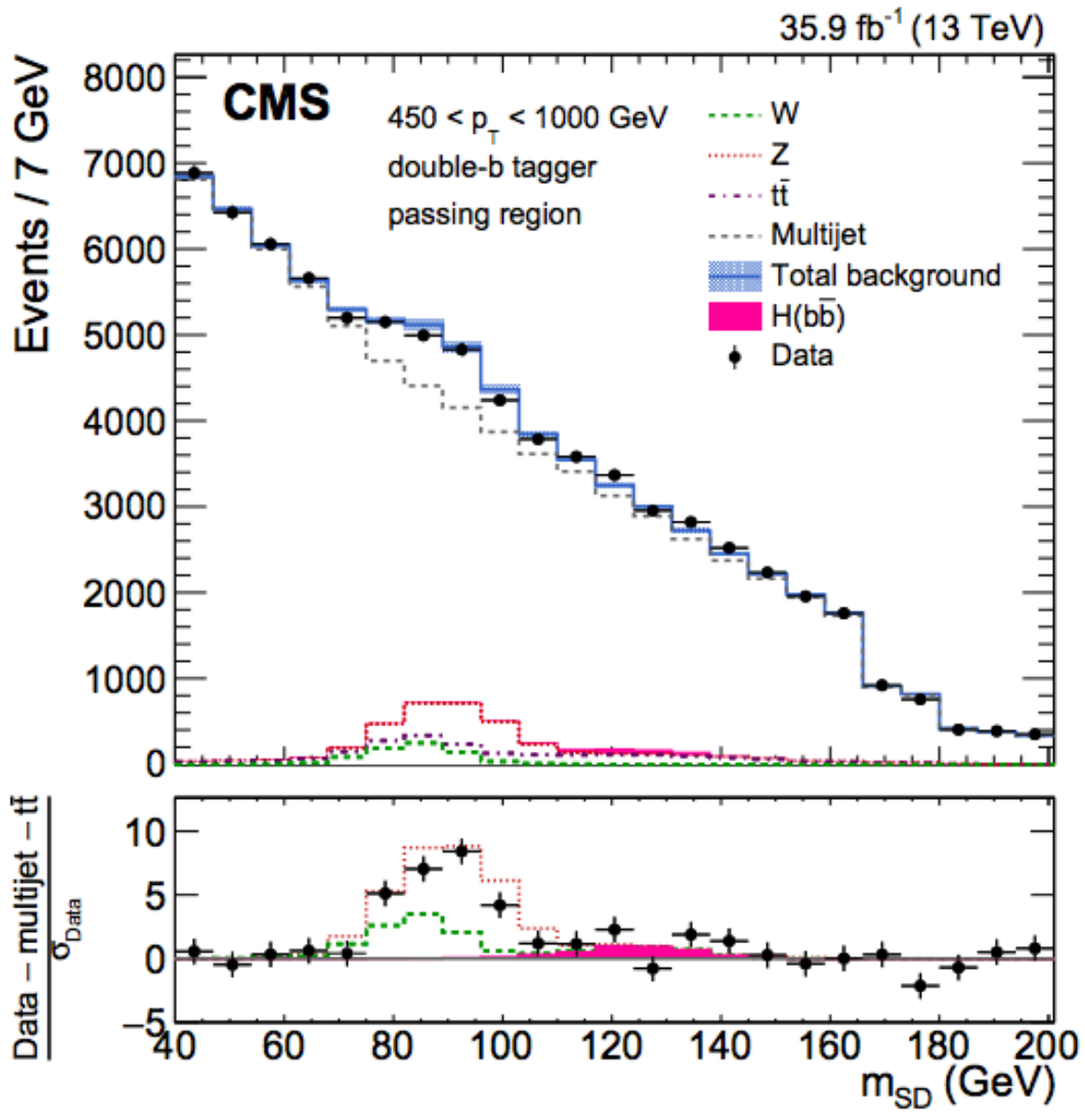
Beyond VH: VBF, ttH and Boosted GGF

- BDT and/or jet substructure techniques employed to move beyond VH tagging: tag the topology or the Higgs decay
- Probe unique phase spaces

ATLAS arXiv:1807.08639



CMS Phys. Rev. Lett. 120 (2018) 071802

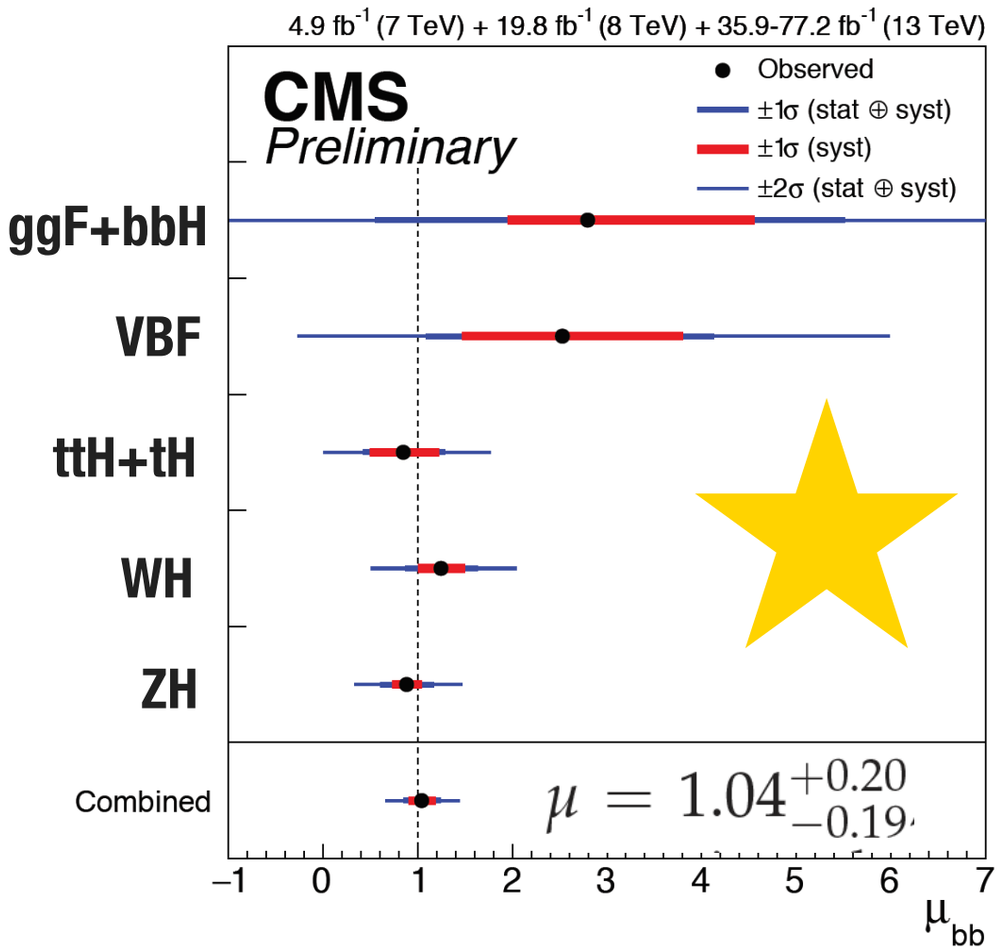


Observation of Hbb

- Combination of Hbb production modes:

ATLAS Hbb (Run1+Run2): 5.4 σ (5.5 σ exp.)

CMS Hbb (Run1+Run2): 5.6 σ (5.5 σ exp.)



Higgs Decay to Tau Pairs

- Strong Coupling to the Higgs
- Large background (dominated by Zττ), but smaller than for Hbb

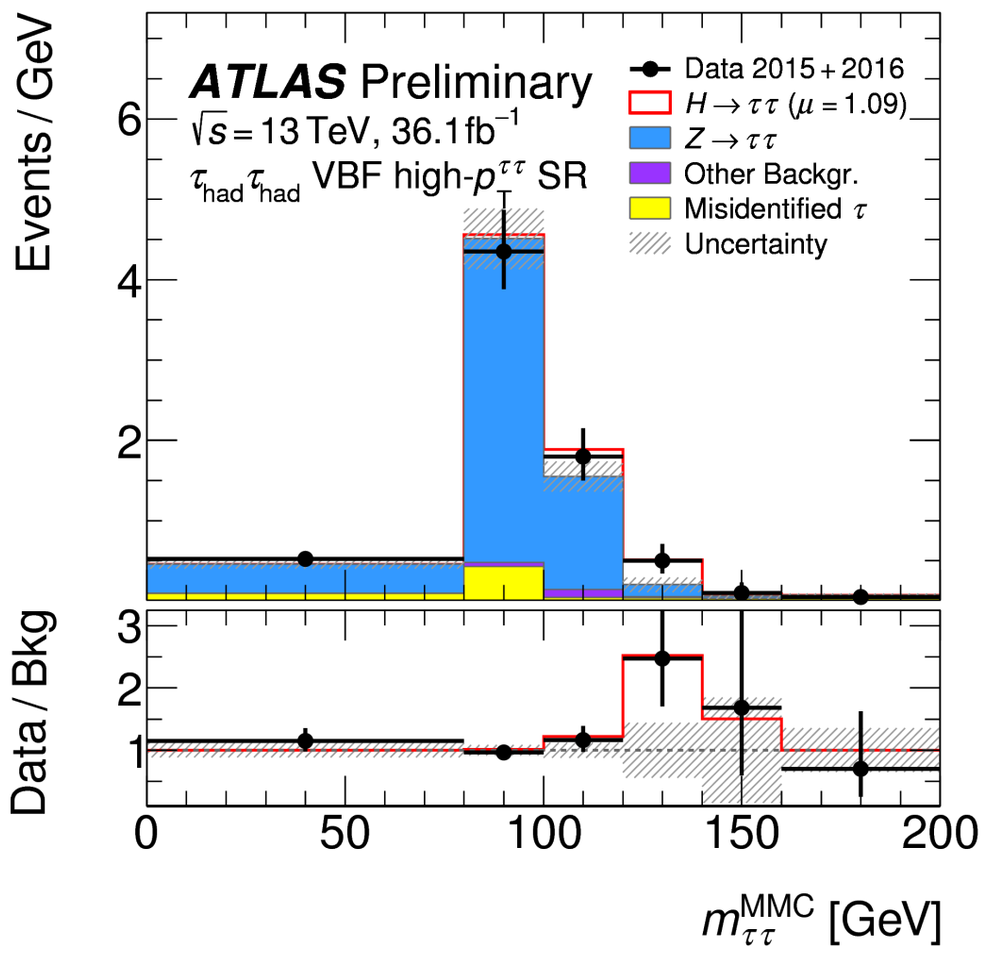
Exploit division in categories to enhance significance:

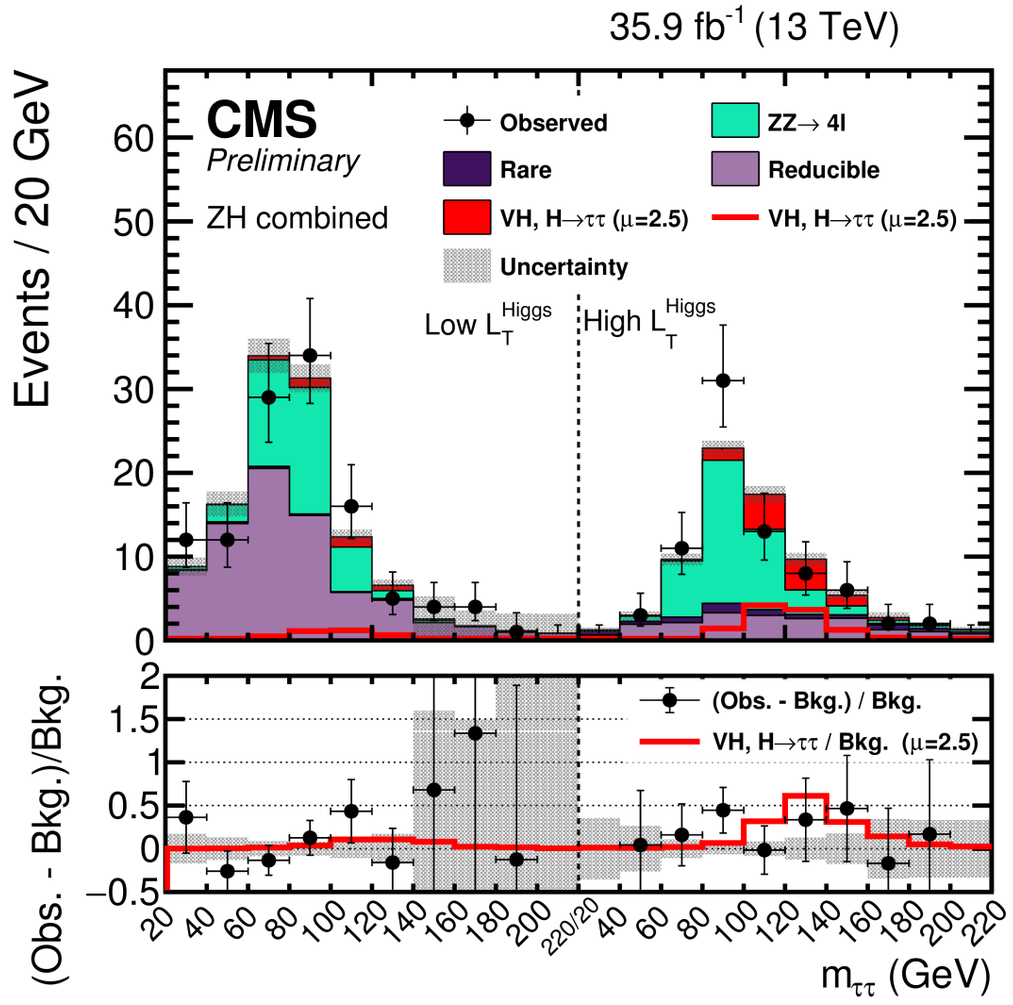
- VBF+GGF: (2,1,0 Jets) × (eμ, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)
- VH categories (CMS): ll×(eτ_h,μτ_h,$\tau_h\tau_h$,eμ), l×(μτ_h,$\tau_h\tau_h$)

CMS PLB 779 (2018) 283

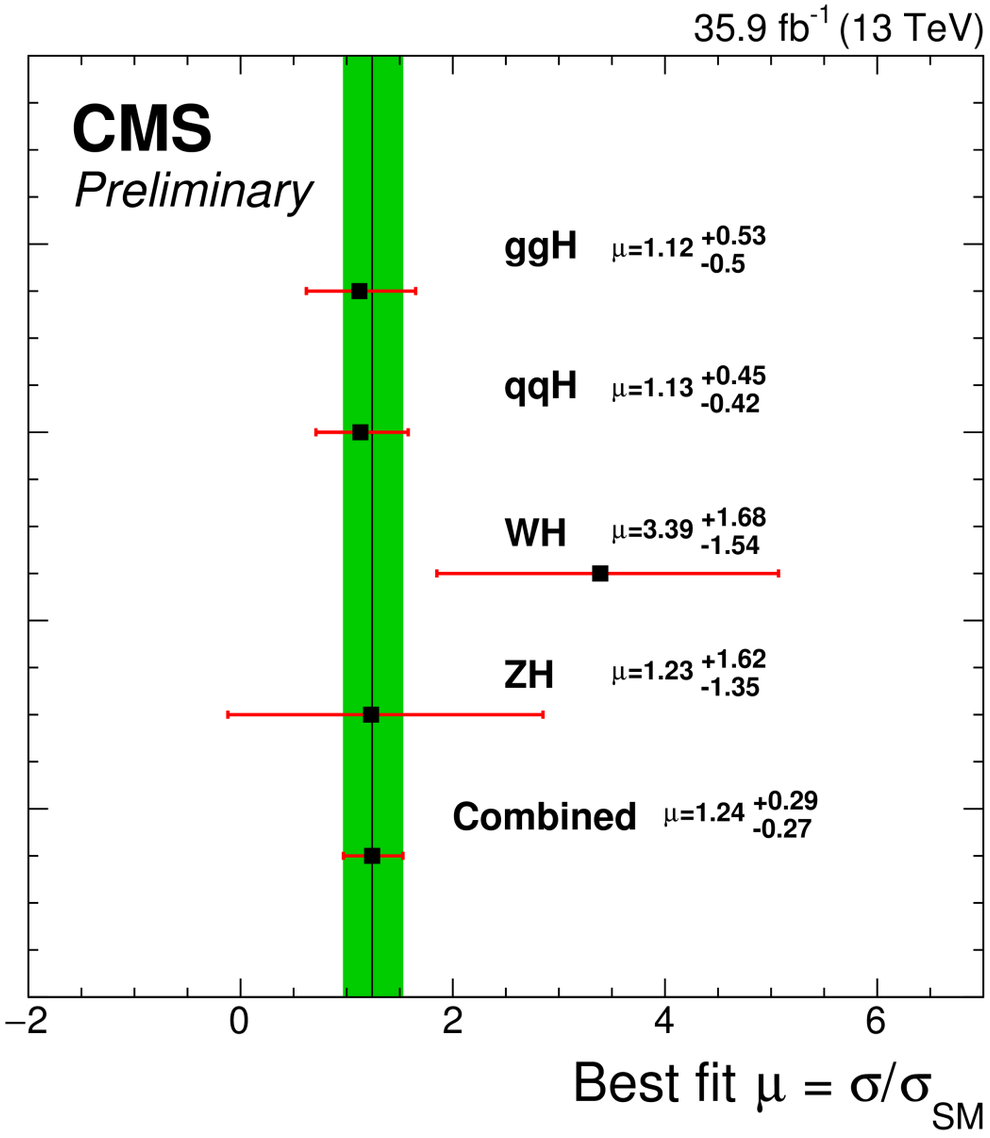
ATLAS CONF 2018-021

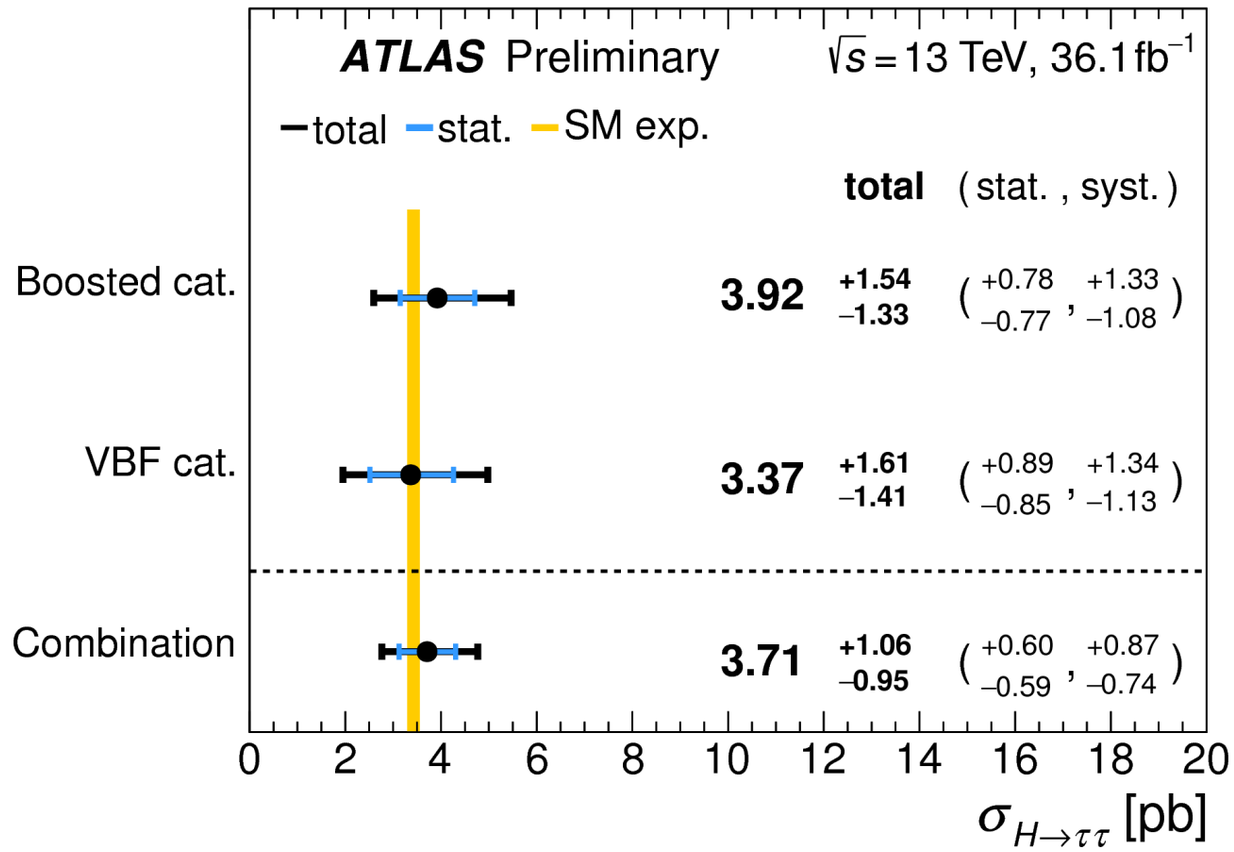
CMS PAS HIG-18-007





Observation of Hττ





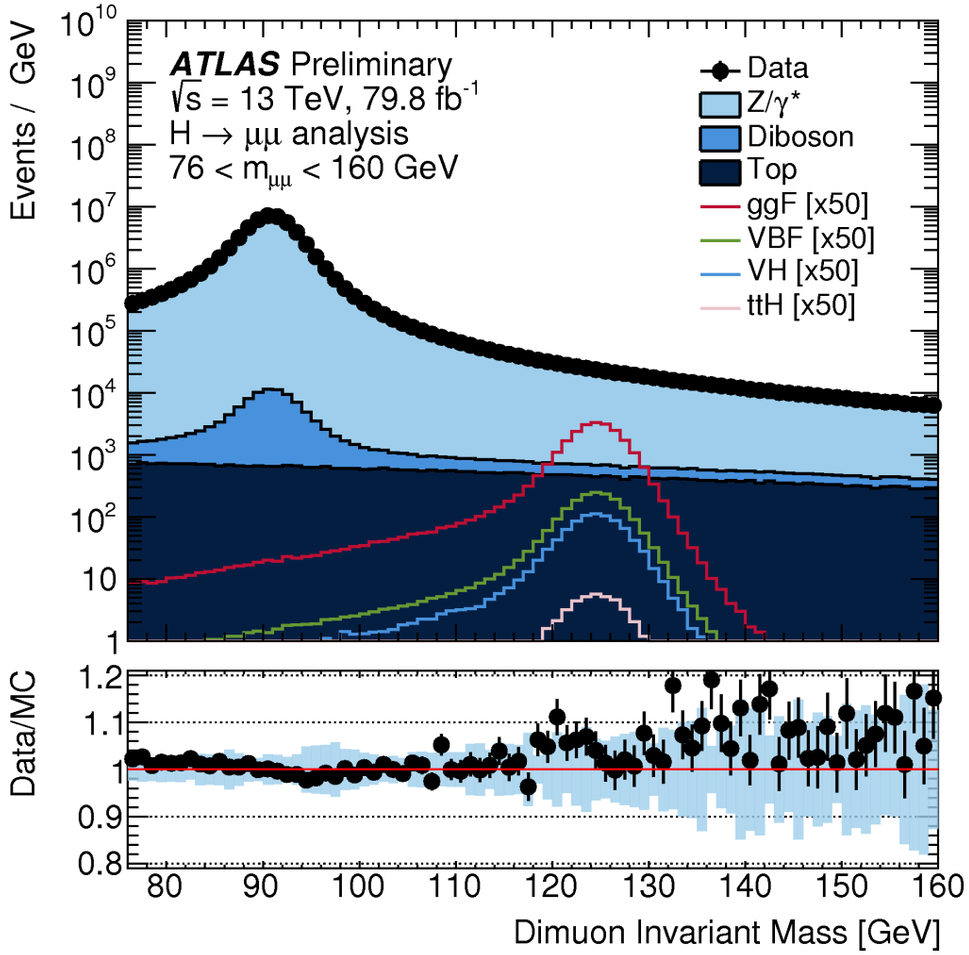
CMS GF+VBF: 4.9 σ (3.7 σ exp.) (+Run1 5.9)
CMS VH (Run2): 2.3 σ (1.0 σ exp.)
CMS full combination (Run2): 5.5 σ (4.8 σ exp.)

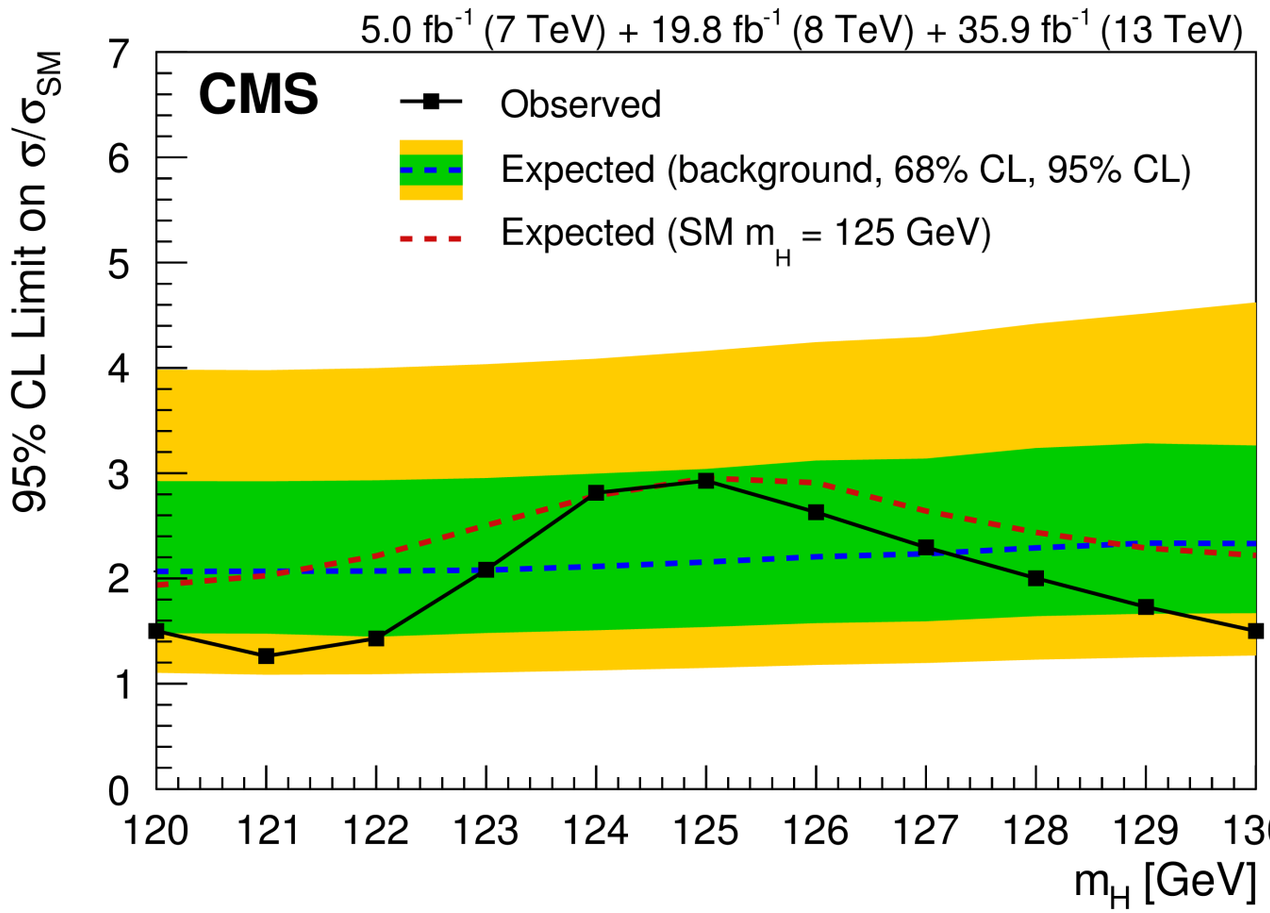
ATLAS (Run1+Run2): 6.4 σ (5.4 σ exp.)

2nd Generation: Hμμ

- Small and narrow signal over a large but smooth DY background
- Still inaccessible with the current statistics (deviations from SM?), but getting close

CMS (61fb^{-1}, Run1+Run2): μ < 2.92 (exp 2.16) at 95%CL
ATLAS (80fb^{-1}, Run2): μ < 2.1 (exp 2.0) at 95%CL





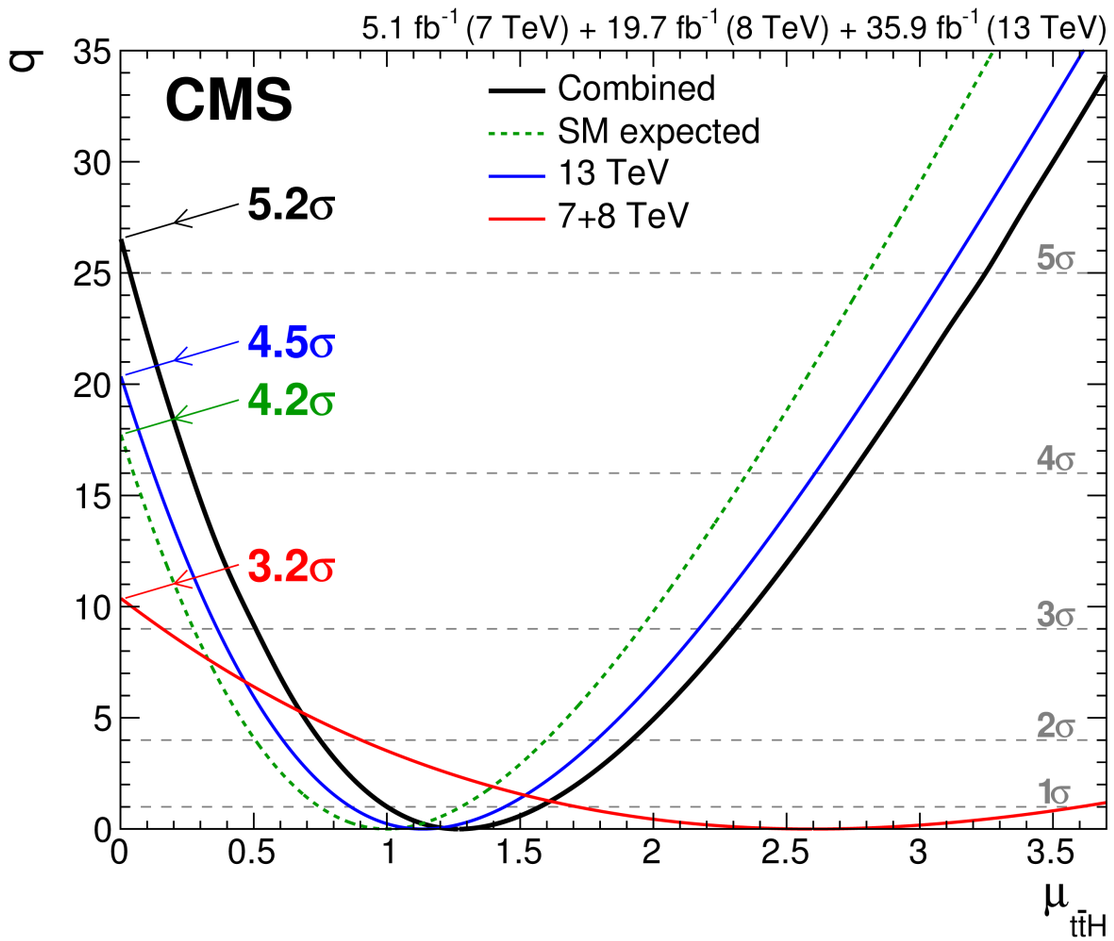
ATLAS CONF 2018-026

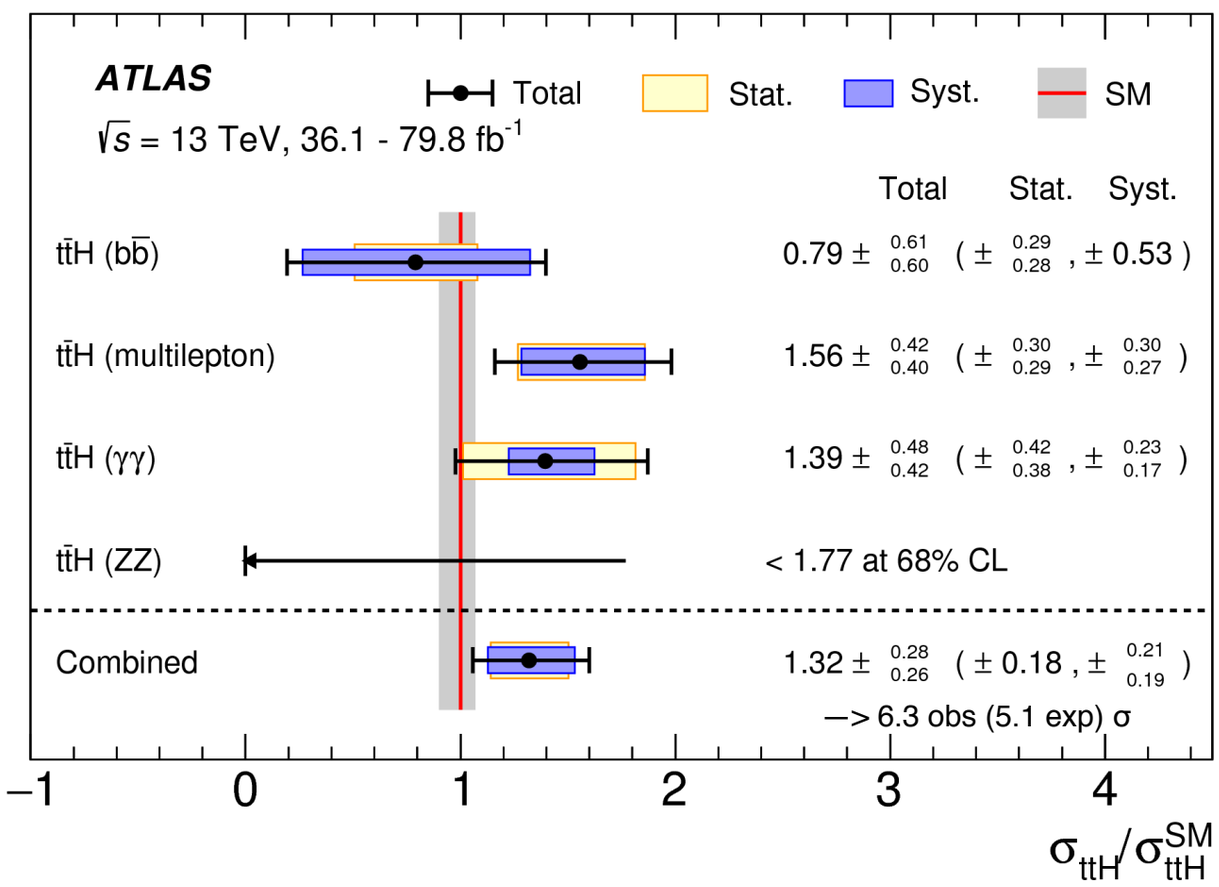
CMS arXiv:1807.06325

Coupling to top quarks: ttH

- Observation of ttH production independently in both experiments through the combination of γγ, 4l, multilepton (WW, ττ, ZZ*), and bb final states

+ Parallel talks by F. Blekman and J. Raine





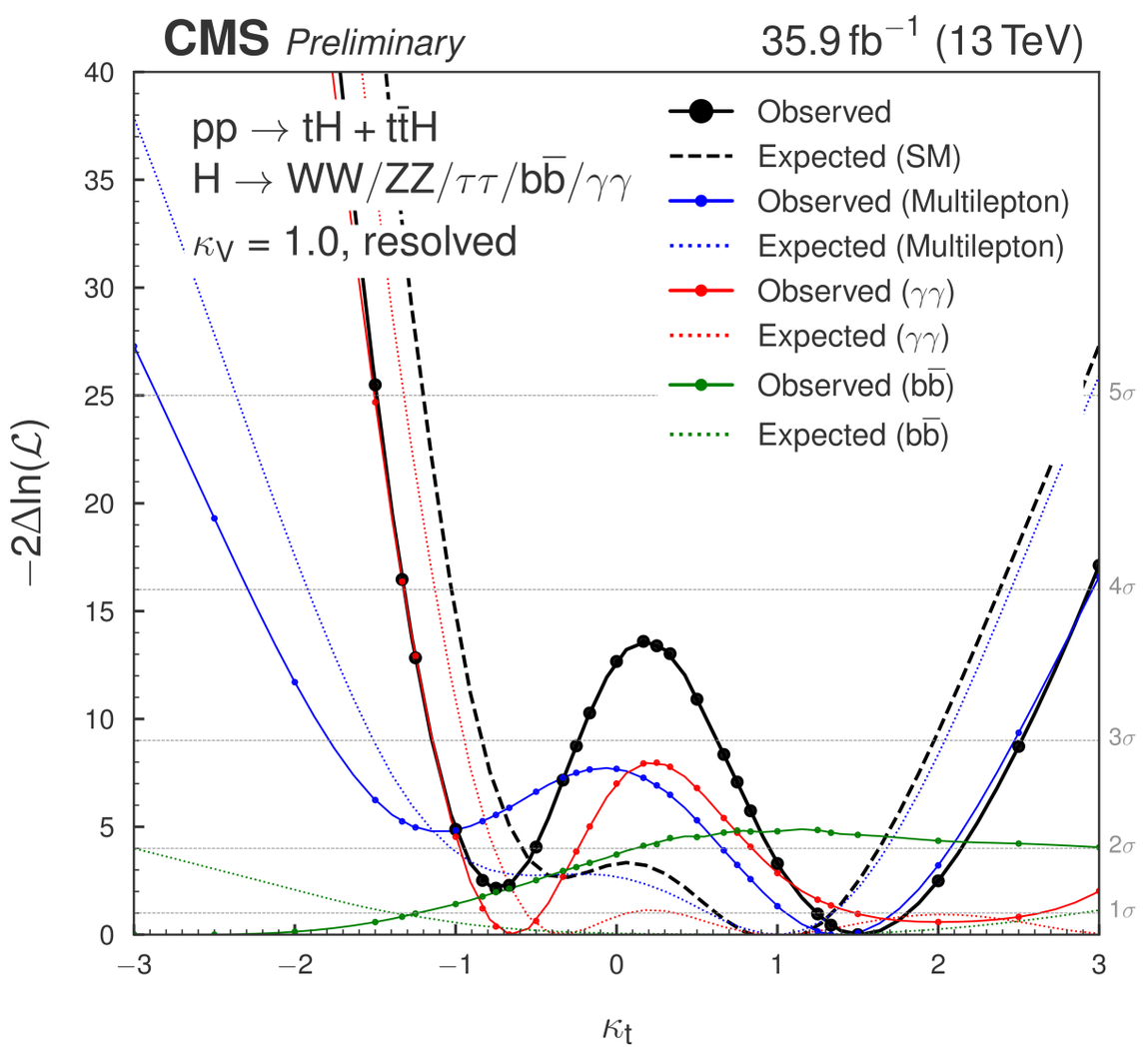
CMS Phys. Rev. Lett. 120 (2018) 231801

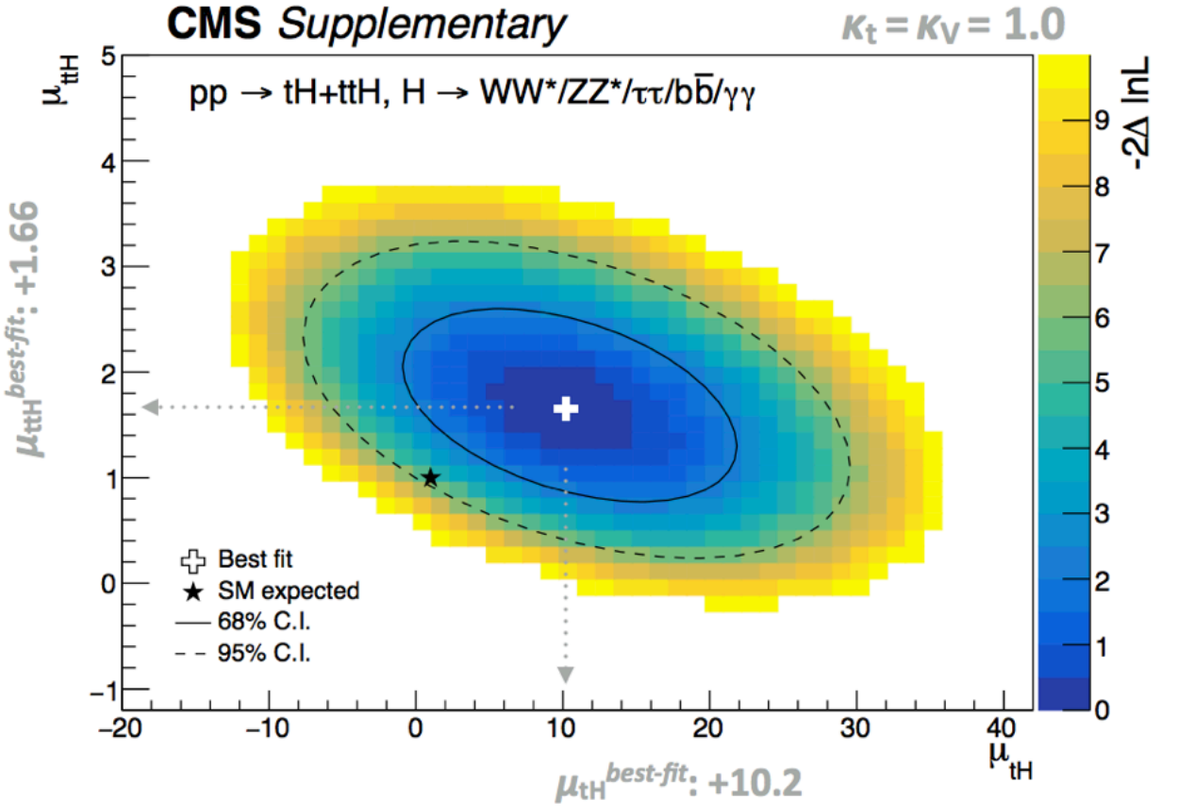
ATLAS arXiv:1806.00425

Single Top + Higgs

- Probe the sign of the top Yukawa coupling
- Small cross section, ttH as background

+ Parallel talk by F. Blekman





CMS PAS HIG-18-009

- Couplings to Bosons
- Couplings to Fermions
- **Combination of Measurements**
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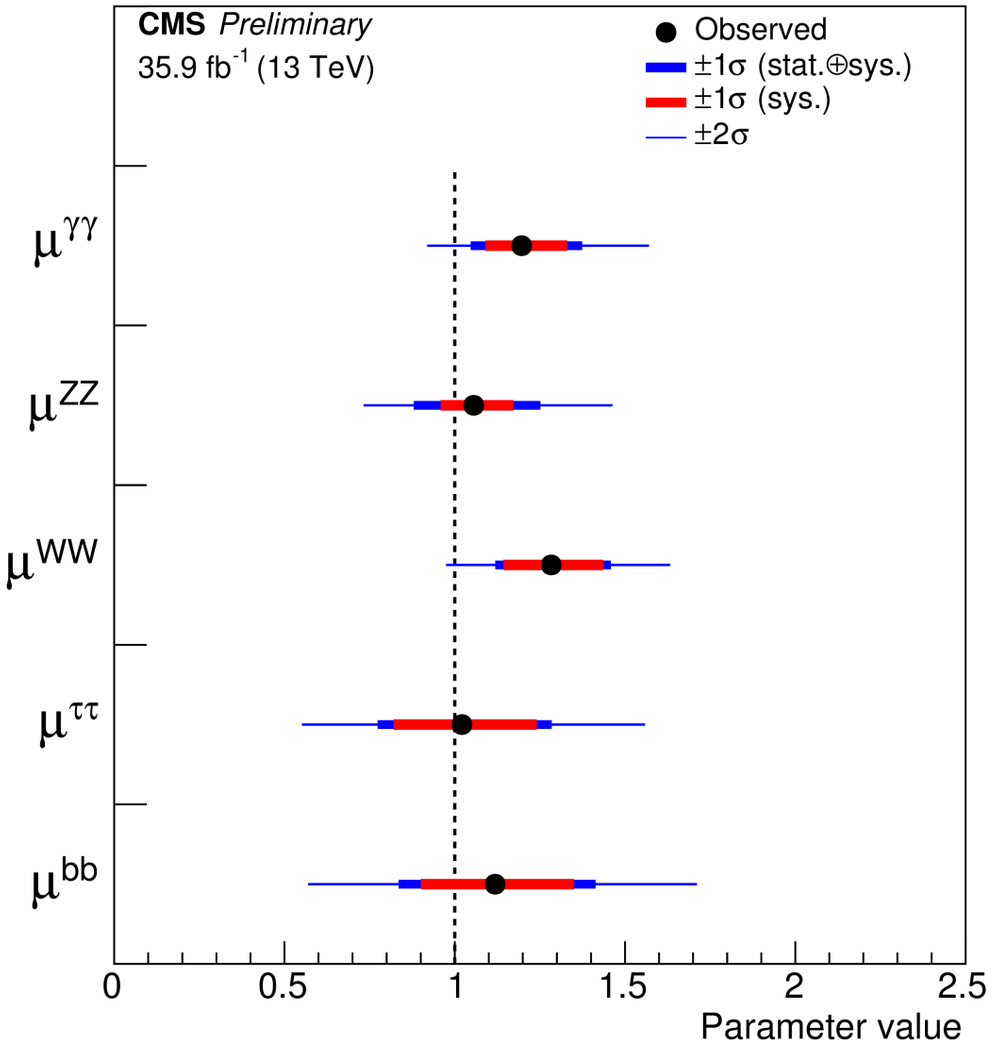
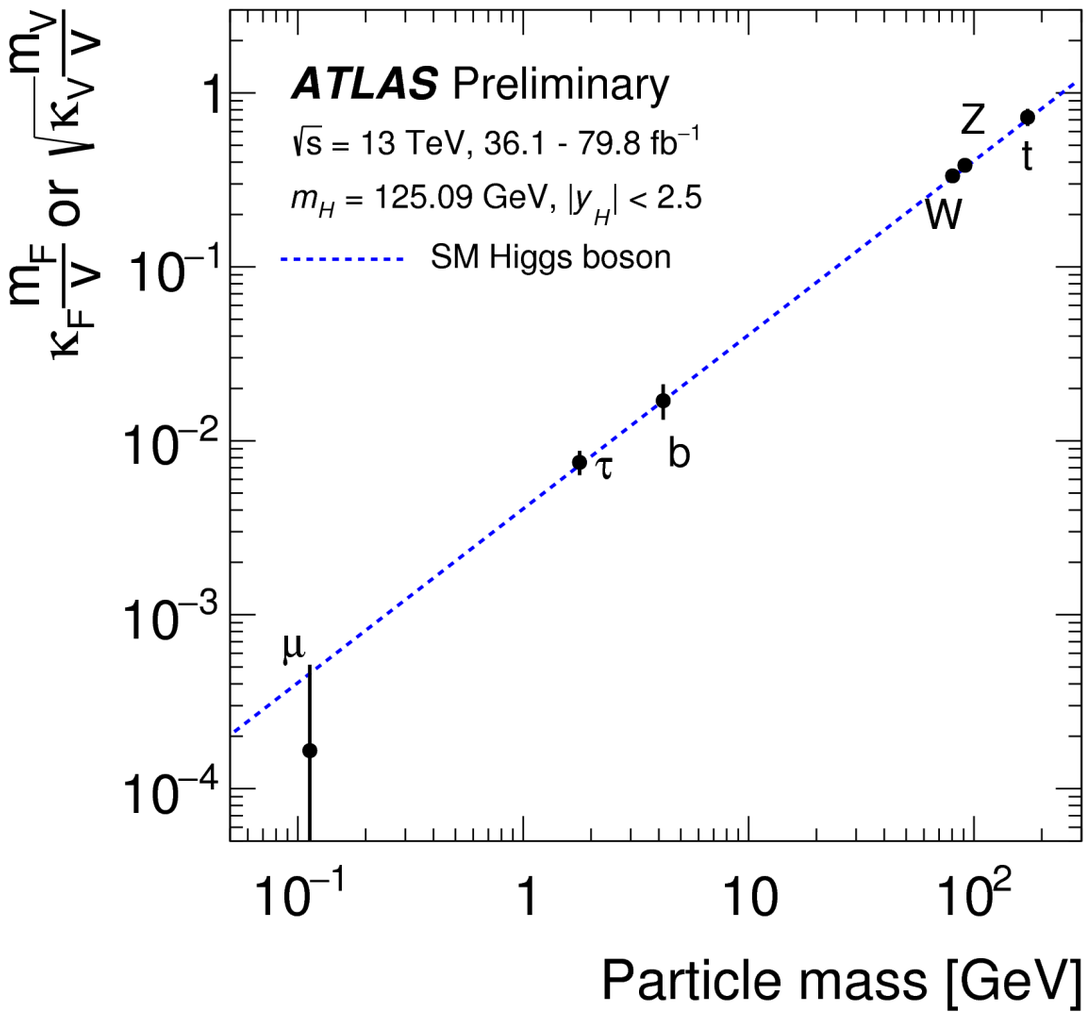
Higgs Decay

- Combining the information from the main decay channels presented until now we can obtain a detailed view of the Higgs agreement with the SM predictions
- Single experiment results more sensitive than Run1 ATLAS+CMS combination



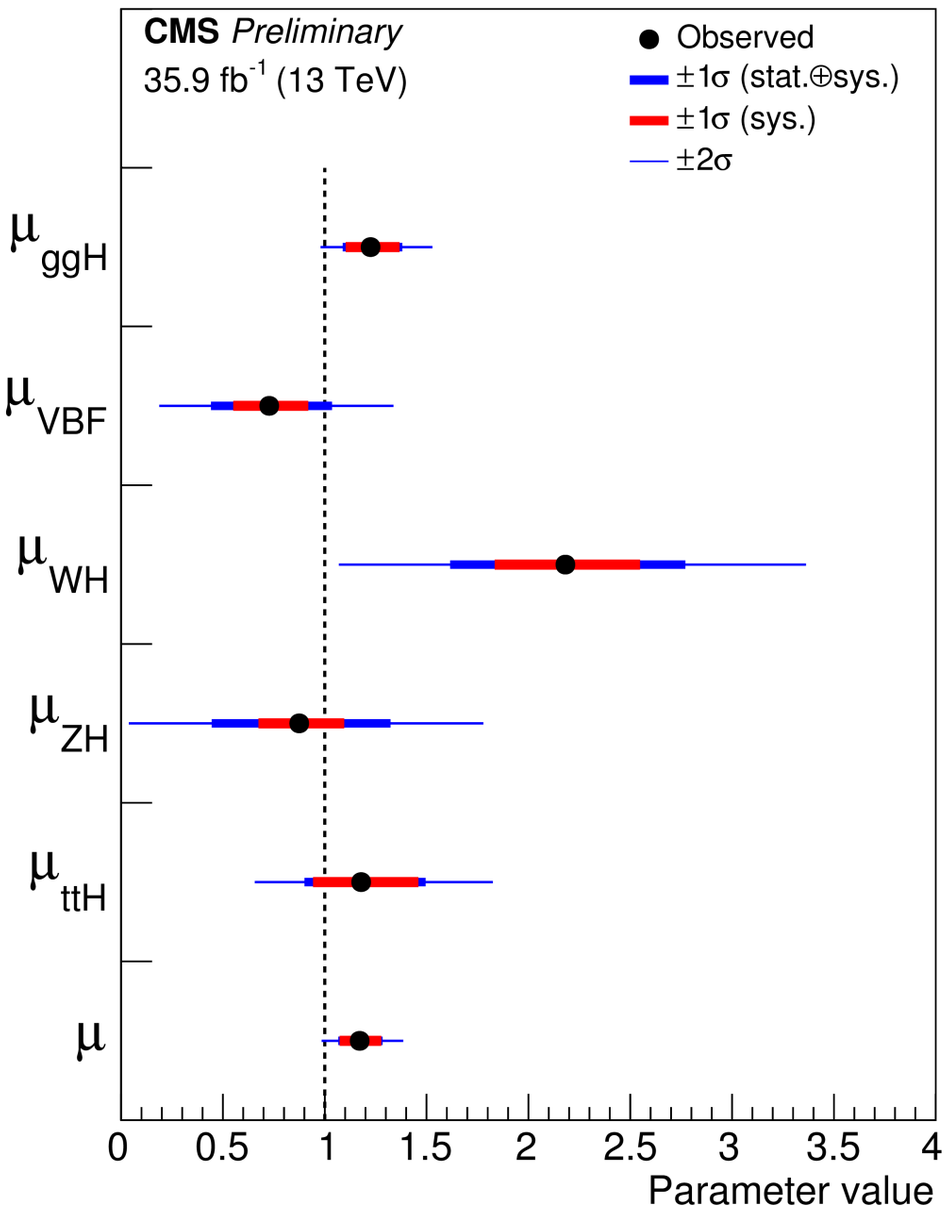
CMS PAS HIG-17-031

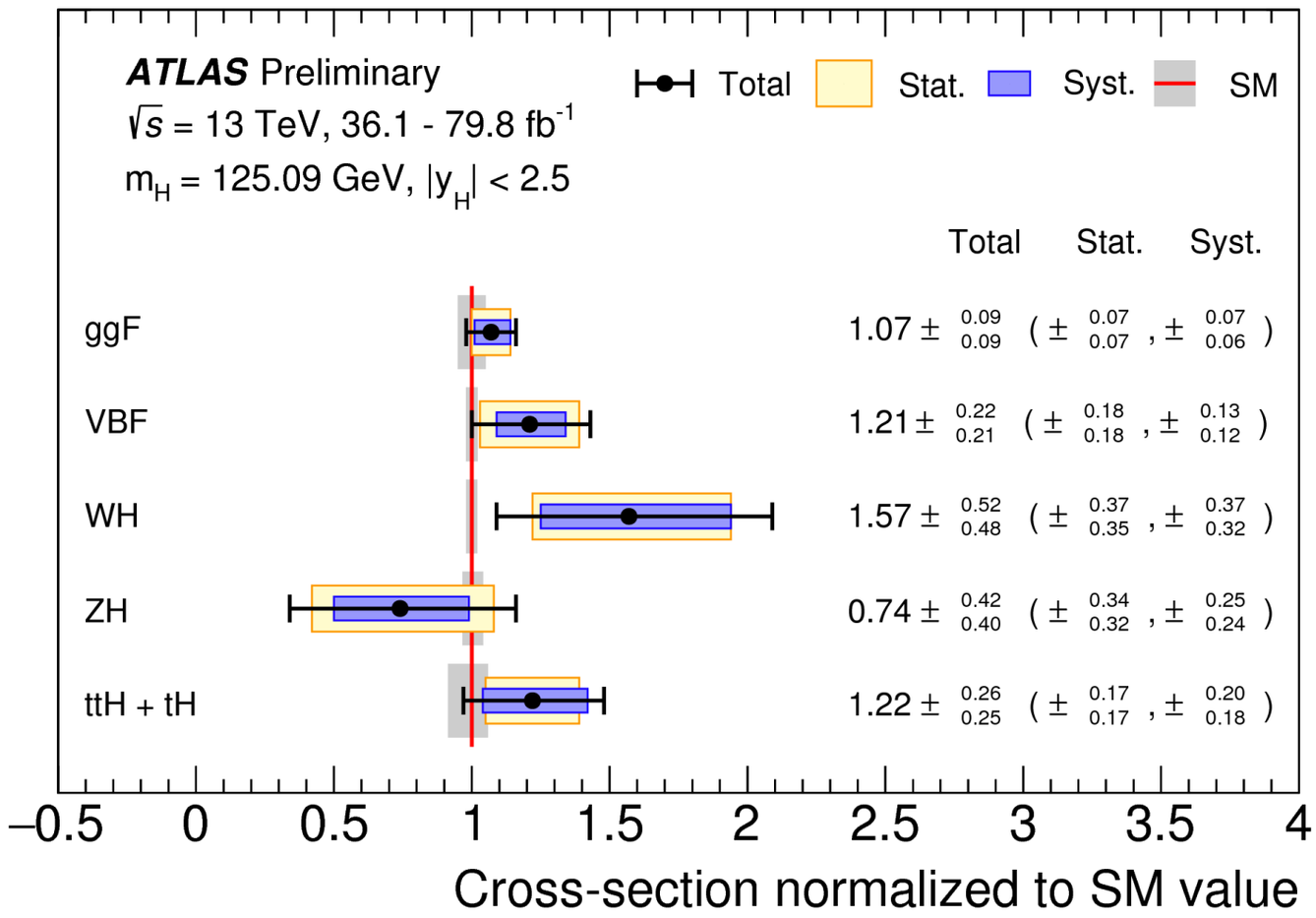


ATLAS CONF 2018-031

Higgs Production

- **Main production modes observed (GF, VBF, VH, ttH)**



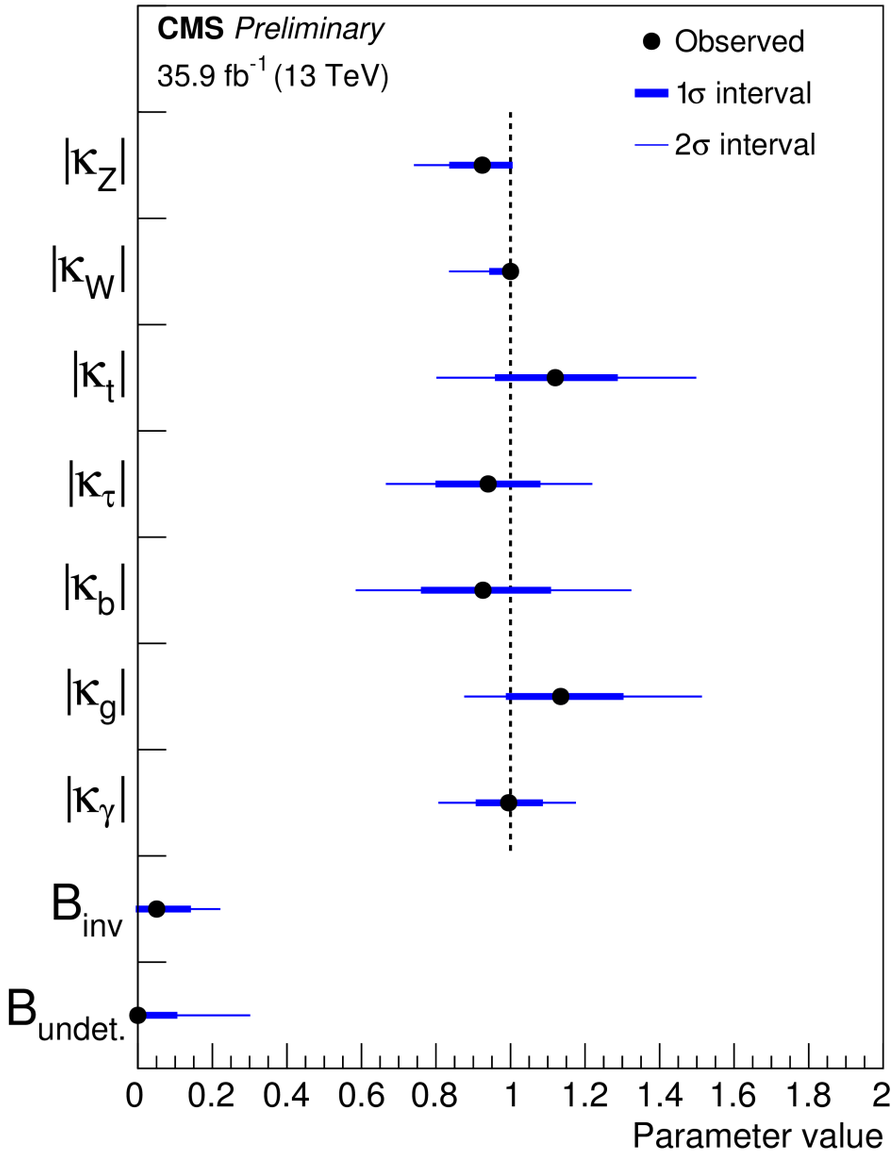


CMS PAS HIG-17-031

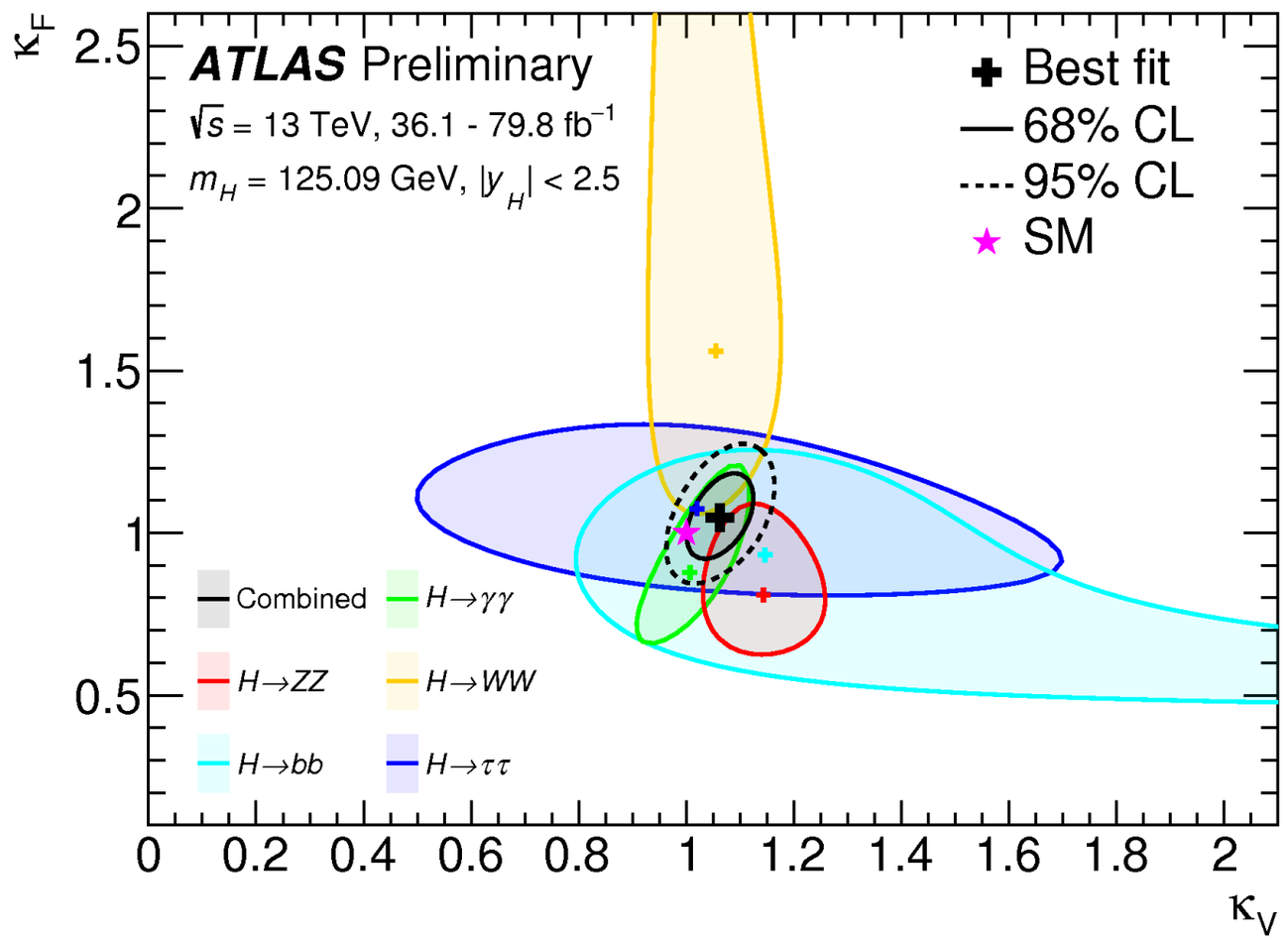
ATLAS CONF 2018-031

Kappa Model

- Benchmark model fits: kappa framework and further test for deviations from SM expectations
- Coupling modifiers known to the 10-20% level (Run2, 1 experiment)



$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}.$$



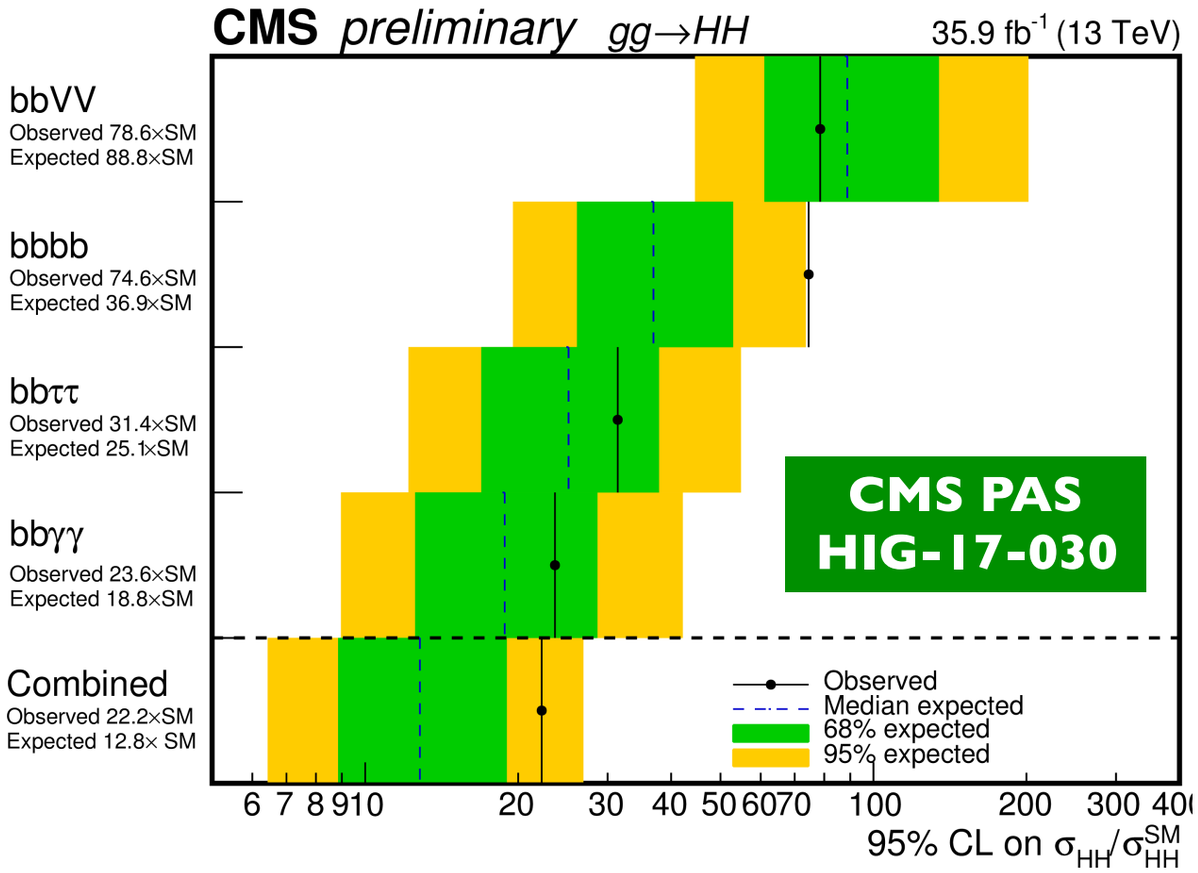
CMS PAS HIG-17-031

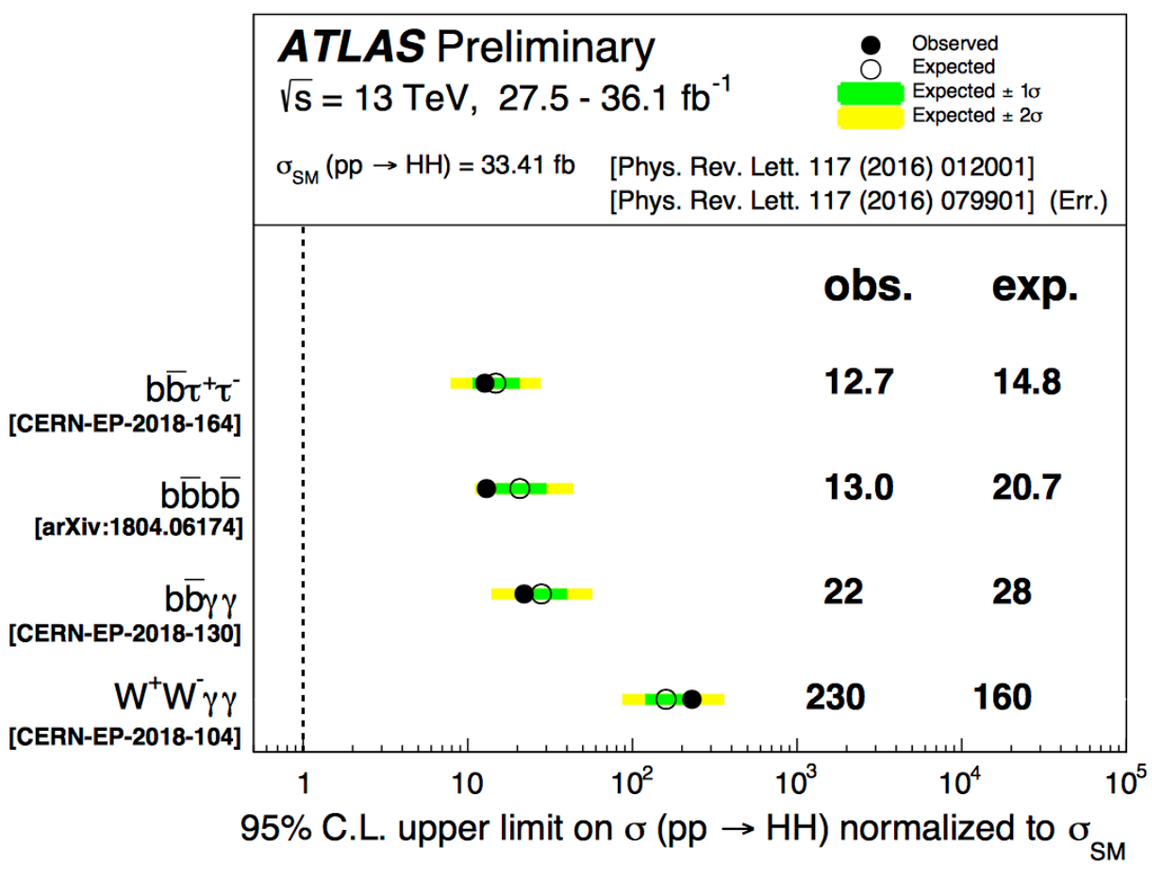
ATLAS CONF 2018-031

- Couplings to Bosons
- Couplings to Fermions
- Combination of Measurements
- DiHiggs Production

SM DiHiggs Production

- Beyond Single Higgs studies: can we see SM HH production at the LHC?
  - Low cross section (31.05 fb @ 13 TeV): destructive interference
  - SM cross section not accessible with Run2 data (HL-LHC benchmark)
  - Expanding list of final states in both experiments





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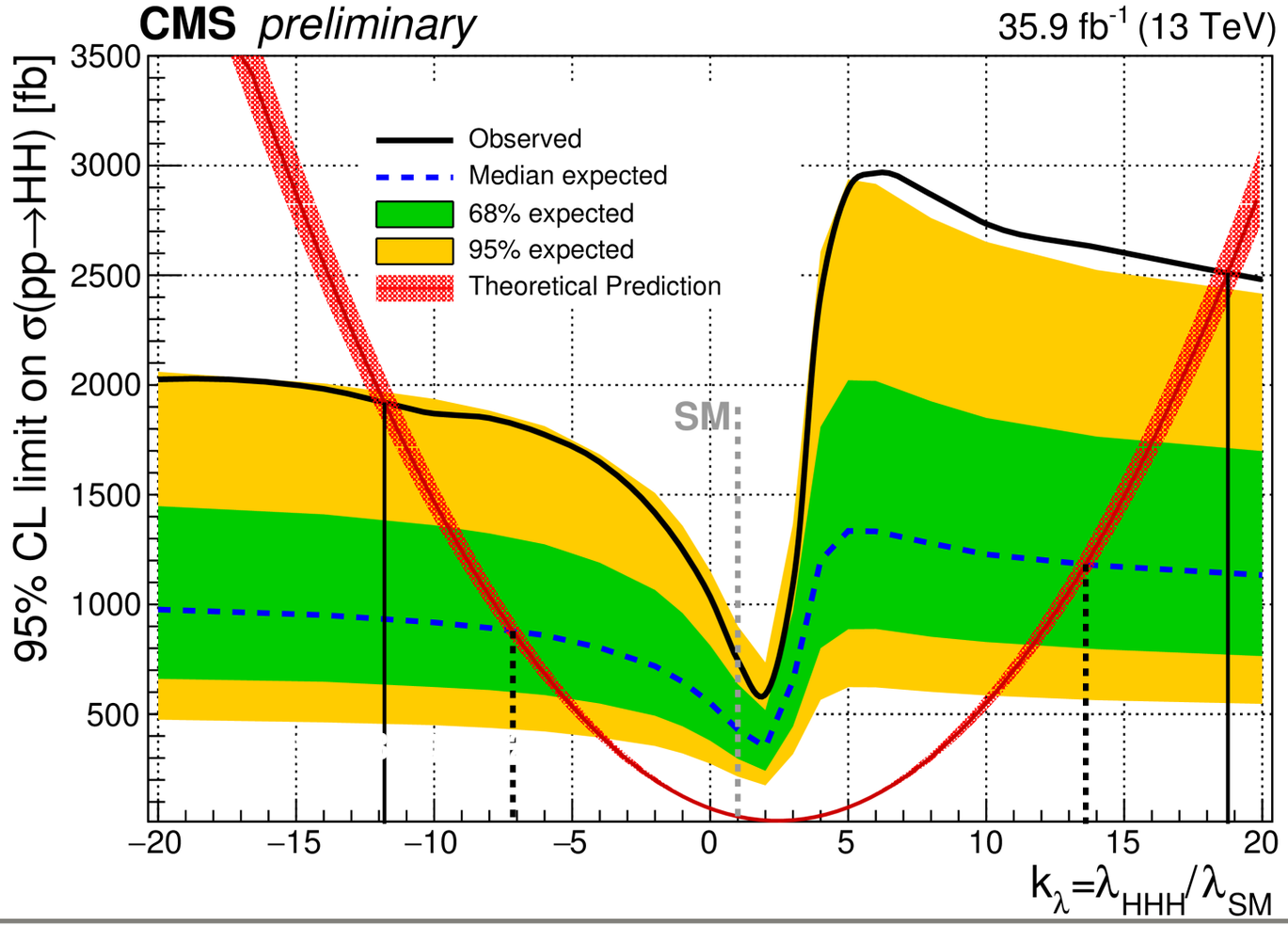
  - SM cross section not accessible with Run2 data (HL-LHC benchmark)
  - Expanding list of final states in both experiments



- Going beyond limits —> combined constraint on the self coupling

SM Higgs @ HL-LHC

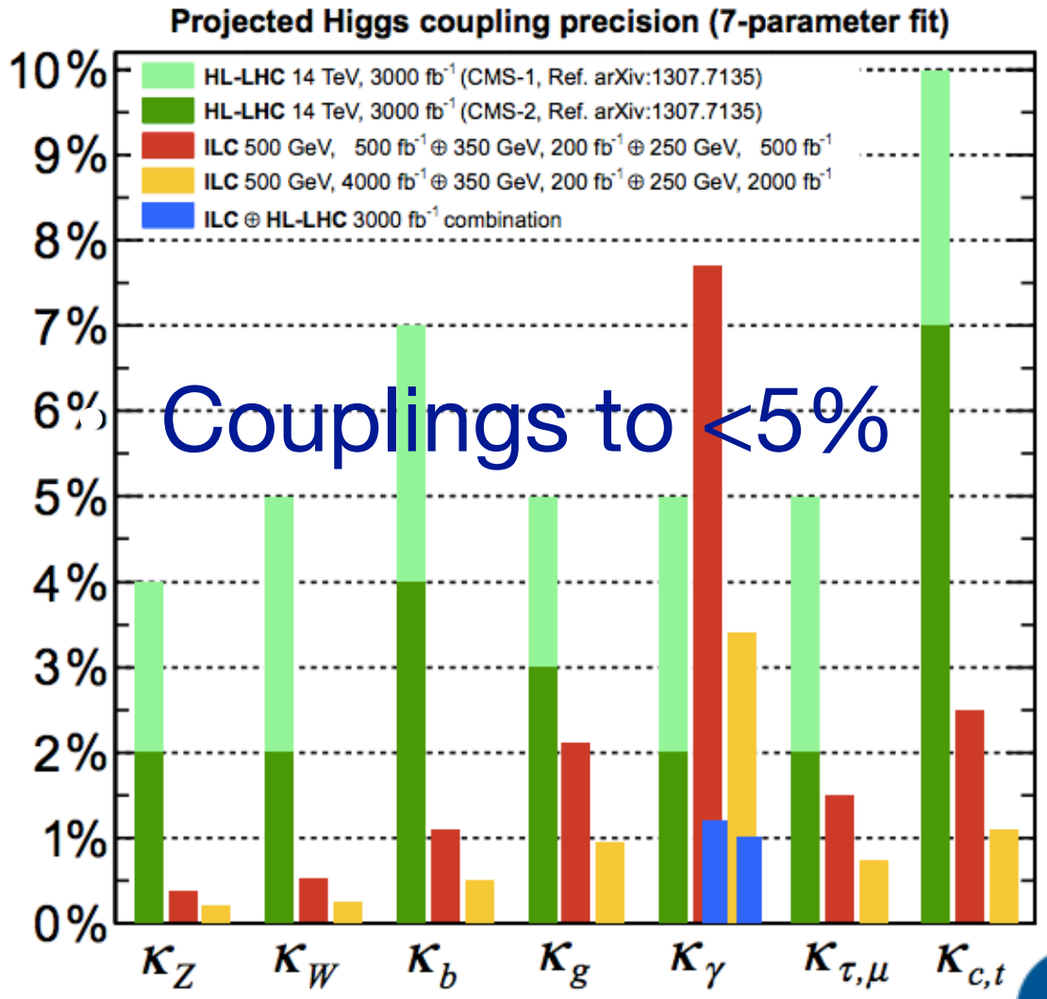
What can we do with 3000fb^{-1}?

- **Precision Measurements** (Rates to ~10%, Couplings to ~5%, Differential Distributions, Width, assessment of the top Yukawa…)
- **Rare decays** (observation of Hmumu, probe of Hcc, quarkonia…)
- **Di-Higgs production ➜** self coupling

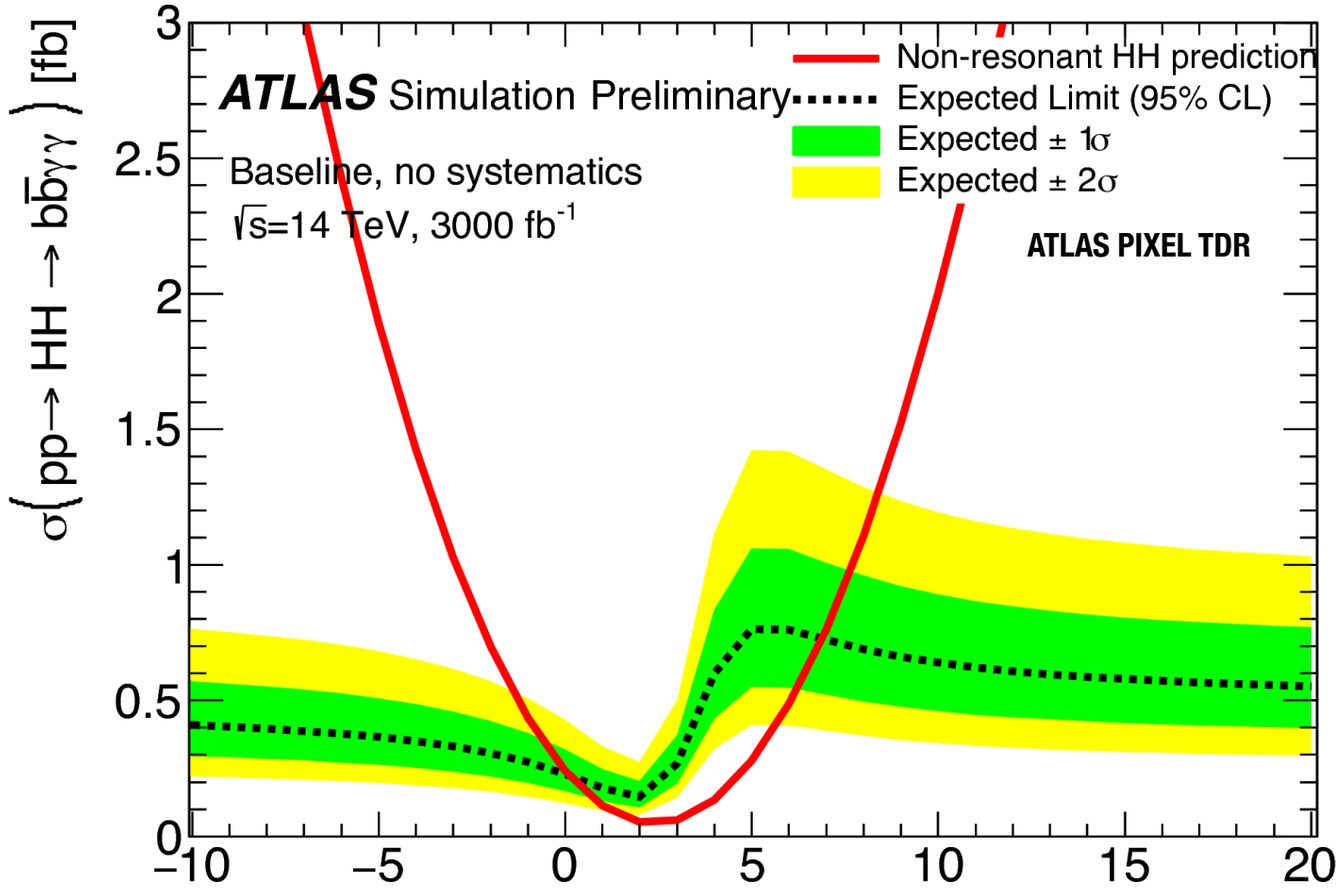
+ expansion of BSM phase space probe

Couplings @ HL-LHC

- Existing studies: comprehensive, but mostly based on extrapolations of Run1/ early Run2 results, plus specific analyses with parametrised full simulation
- Overall update of the Higgs prospects at HL-LHC ongoing this year to take in consideration the latest analysis improvements and revisit the uncertainty scenarios —> Yellow Report end 2018



arXiv:1506.05992



+ more on Higgs@ILC in the parallel by S. Kawada

+ more on Physics@HL-LLC in the talk by I. Ojalvo

2018 so far…

- Exciting year for Higgs physics:
  - Observation of ttH (all main Higgs production modes observed!)
  - Observation of Hbb (all main Higgs decay modes observed!)
  - 13TeV update of combined Higgs couplings fits (~10-20% precision)
  - Differential distributions probing unique phase spaces
  - New HH results, including combination of final states
- Only started to exploit the Run2 dataset: much more to come!
- Beyond the LHC: Comprehensive review of the future prospects of Higgs physics at HL-LHC and beyond ongoing (Yellow Report 2018)

Back to the beginning…

- Is its production rate, where we measure it, at the correct SM level?
- How do we caracterize it? (mass, width, spin)
- Does it couple to SM particles at the appropriate level?
- How well can we model its behaviour?
- Does it couple to itself?
- Does it decay unusually?
- Are there more Higgses?
- Higgs as a tool for discovery

} **see next!**

Cảm ơn nhiều!