Higgs boson properties in CMS

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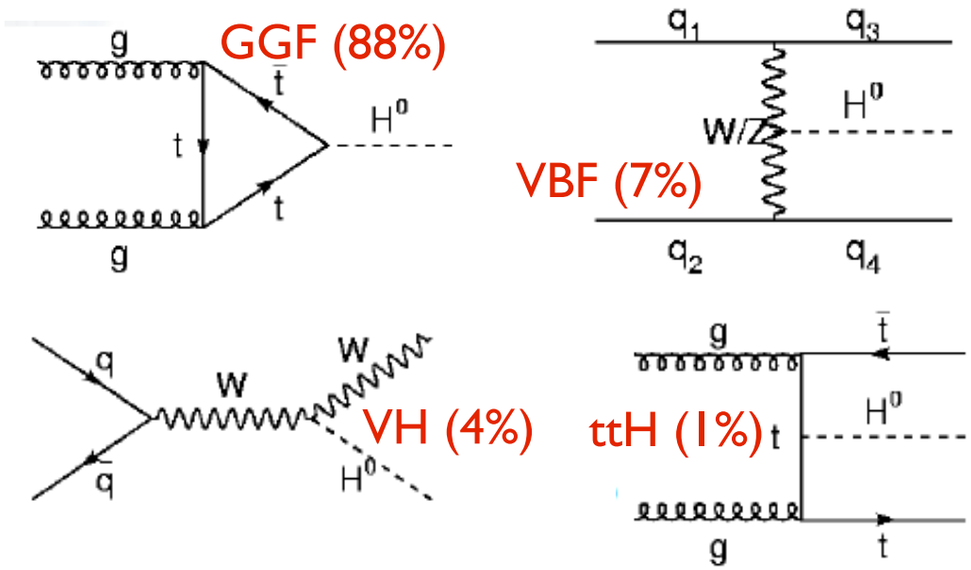
on behalf of the CMS Collaboration

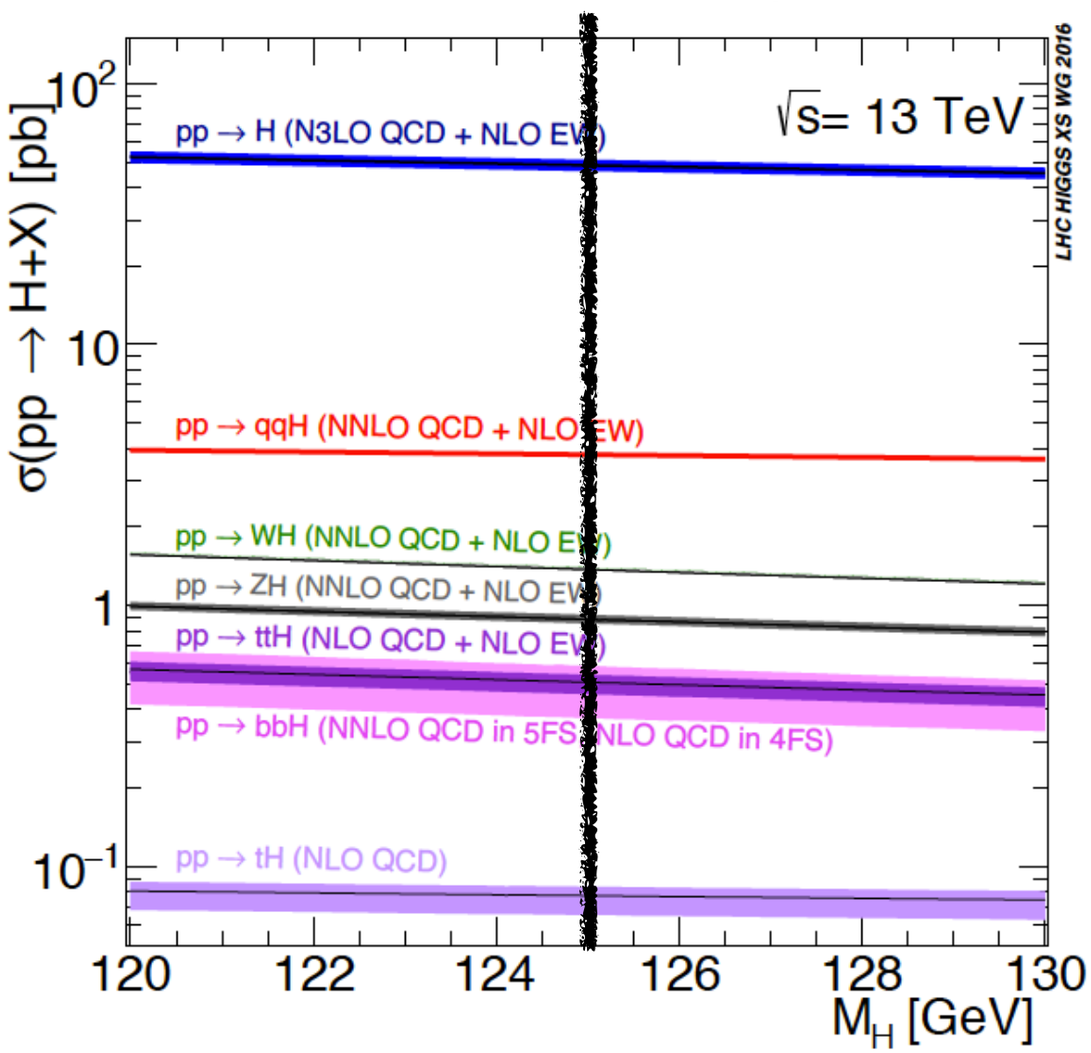
Blois 2019: 31st Rencontres de Blois on "Particle Physics and Cosmology"

Outline of the talk

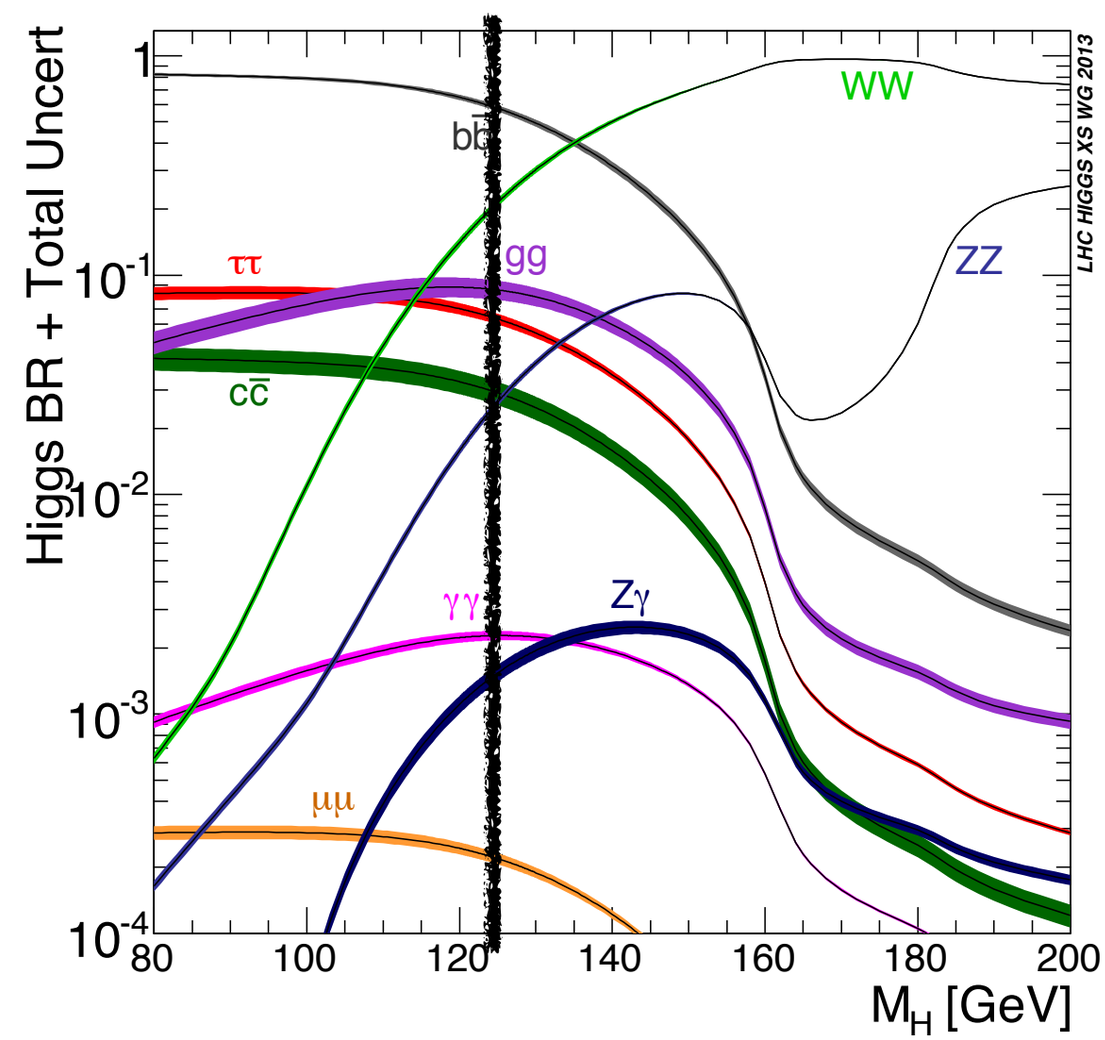
- ✓ Quick overview on Higgs production and decay at the LHC
- ✓ Review of the Higgs boson properties and dedicated highlights on physics analyses
  - Higgs boson mass and spin-parity
  - observation of $H \to bb$ (VH and ttH production mechanisms)
  - rare processes: leptonic modes ($H \to \mu\mu$, $H \to ee$), Higgs self-couplings
  - production cross section, fiducial cross-section, simplified template cross-section
  - Higgs couplings and properties at HL-LHC
- ✓ Wrapping-up and conclusions

Standard Model Higgs production and decay





- Bosonic decays (γγ, ZZ, WW)
  - high sensitivity, and mass resolution (γγ and ZZ)
  - spin-parity properties
- Fermionic decays (bb, ττ, μμ, cc)
  - probing Yukawa couplings to fermions
  - large QCD background



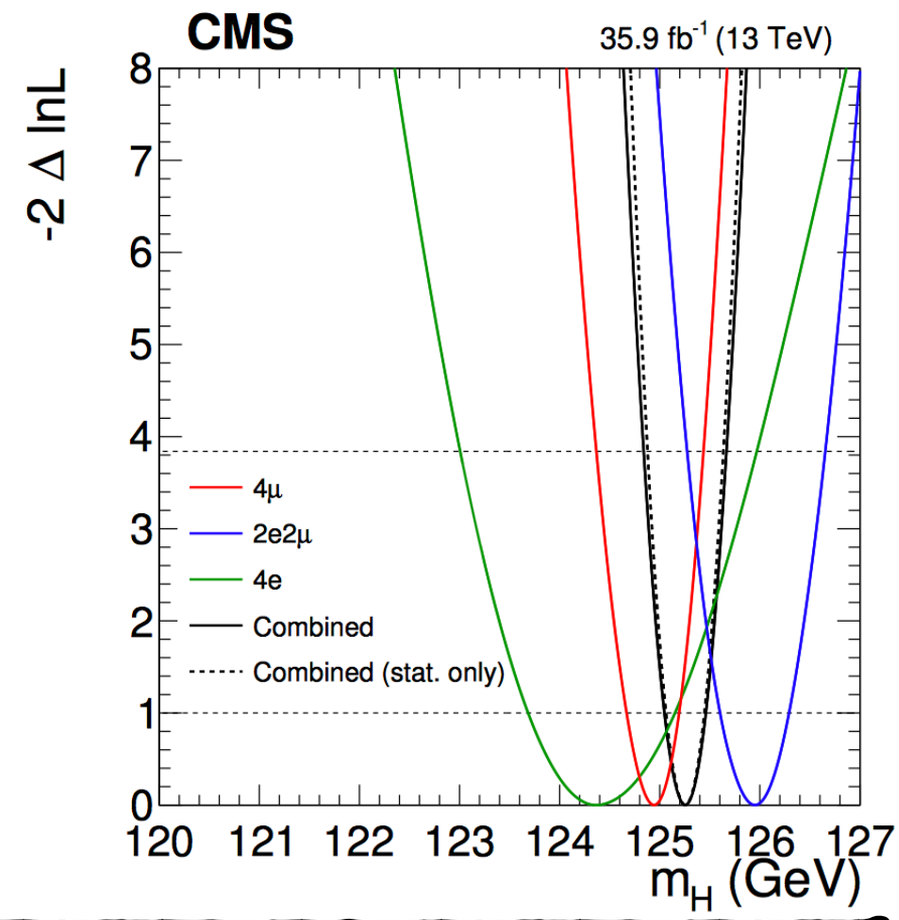
Higgs mass and width measurement

Mass

JHEP 11 (2017) 047

✓ High resolution channels H→γγ and H→ZZ→4l

- strongly rely on excellent detector performance on object identification and reconstruction as well as energy scale determination
- measurements are still dominated by statistical uncertainties
- m_H=125.26±0.21 GeV [±0.20 (stat.) ±0.08 (sys)]

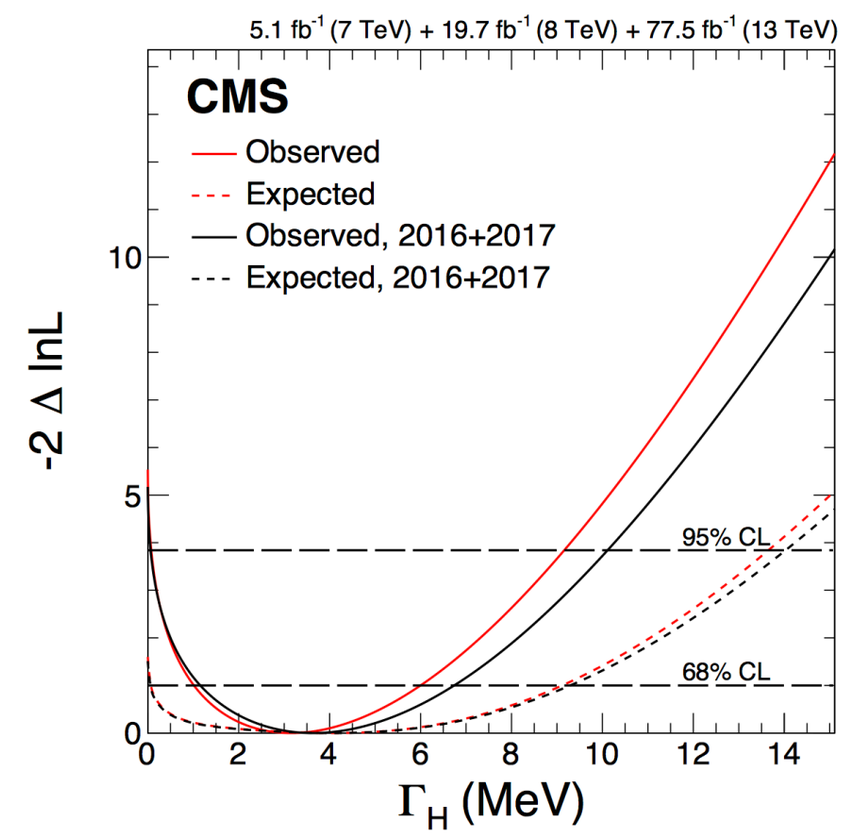


Width

arXiv: 1901:00174

✓ Higgs boson width extracted from combined fit to on-shell and off-shell production in H→ZZ→4l (Run 1+Run 2)

- SM Higgs boson width is 4 MeV - out of reach with direct analysis
- upper bound on Γ_H with model-dependent assumptions on coupling modifiers → Γ_H< 9.16 MeV (13.7 exp.) @ 95% CL

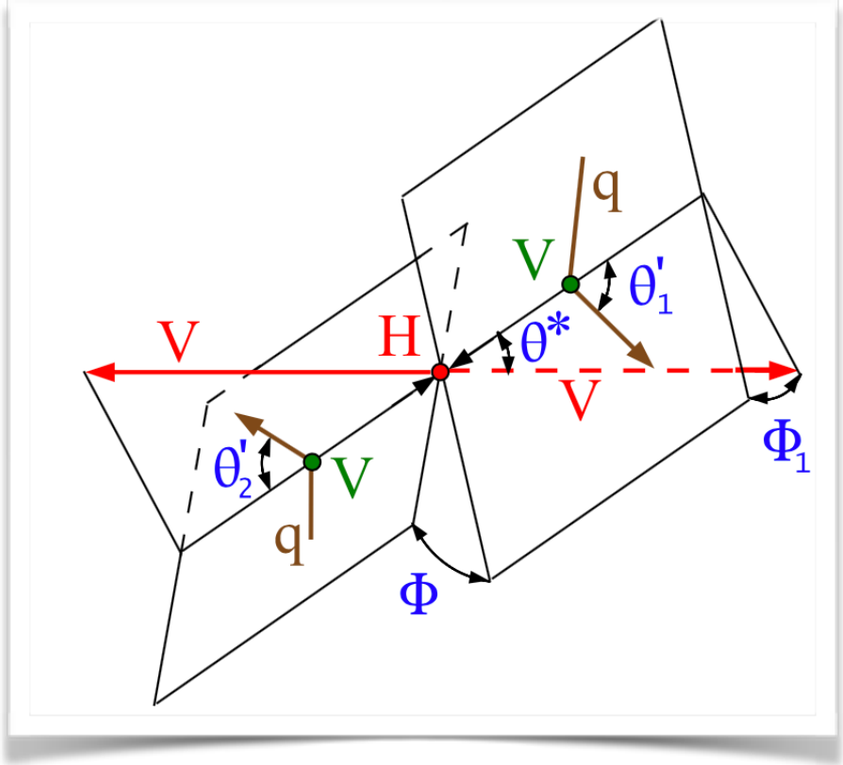


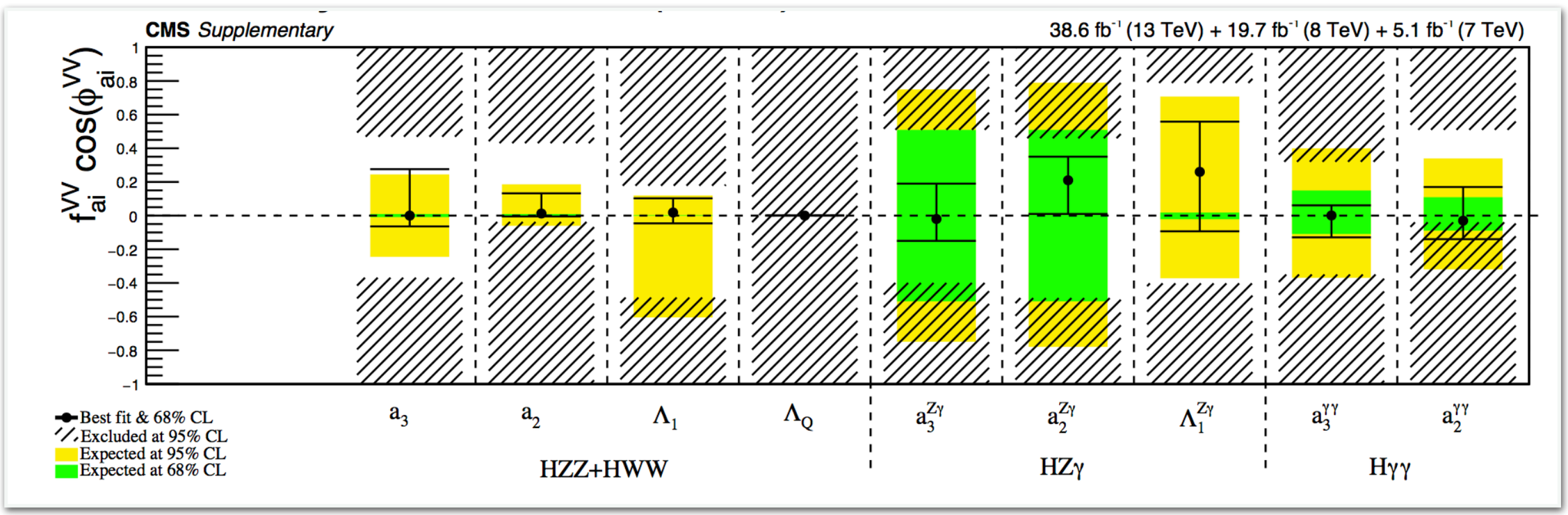
Spin-parity measurements

Spin-CP

Phys. Lett. B775 (2017) 1

- ✓ Analyses exploit angular correlations between the Higgs decay and the objects generated in the final state
  - ✓ Run 1 data ruled out non-SM CP numbers
  - ✓ Run 2 analyses (H→ZZ→4l) improved constraints of the tensor structure of Higgs couplings in HVV vertex
    - no deviations from SM are observed and constraints set on 4 anomalous couplings including CP-violating parameters

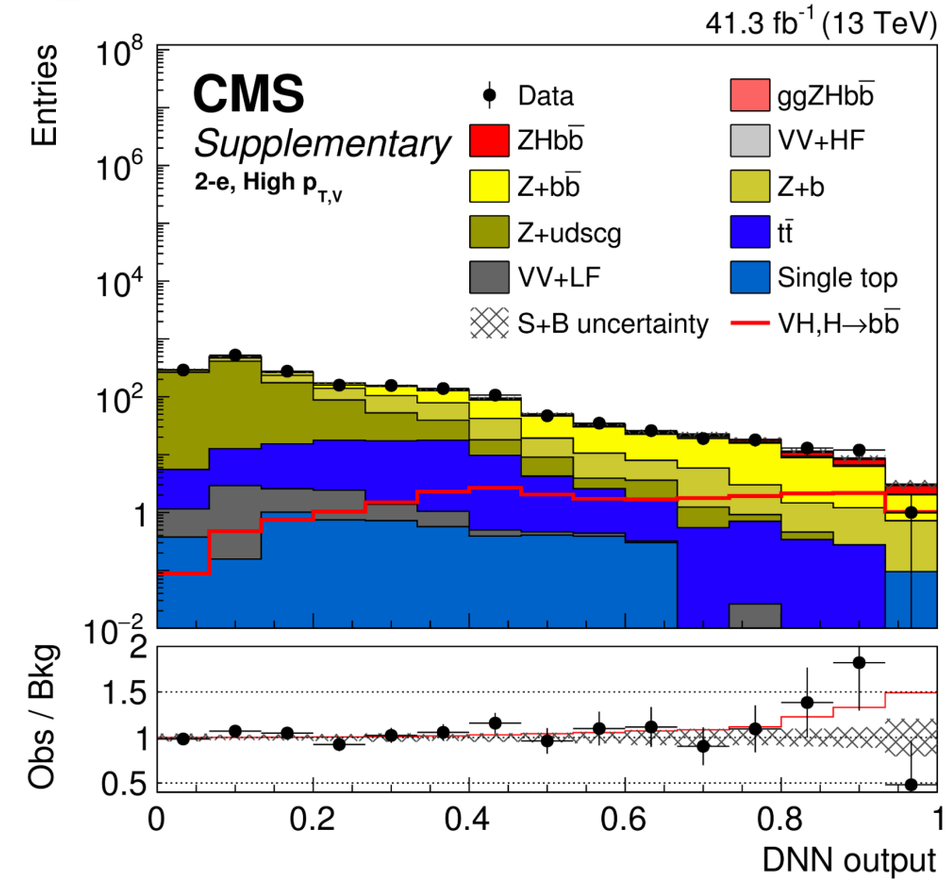




The Hbb observation - analysis overview

✓ Associated production of Higgs with vector boson (W/Z)

- Z→νν, W→lν, Z→ll - lepton multiplicity (0-, 1-, 2-lep) and 2 b-tagged jets
- Signal regions: increase S/B sensitivity with multivariate techniques (DNN) exploiting separation power of final state kinematics (b-tag shape, bb-invariant mass)
- Control regions: abundant in bkg processes (tt, V+jets, V+high-flavour jets) to constrain shape/normalization

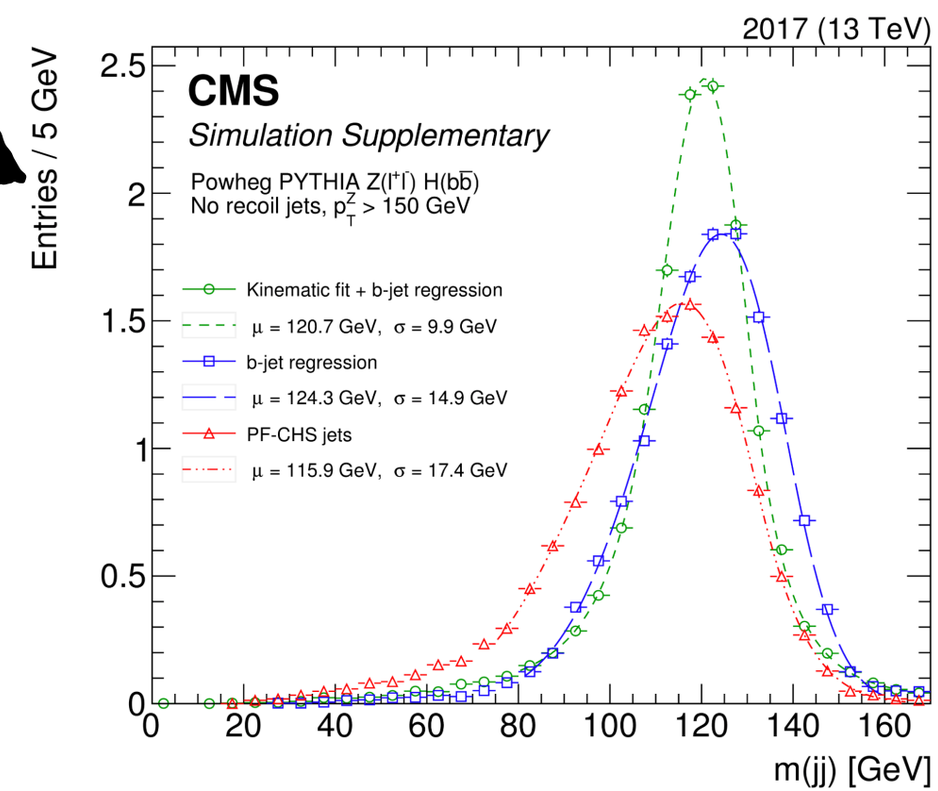


Phys. Rev. LeE. 121 (2018) 121801

✓ Simultaneous fit to signal and control region - VZ analysis carried out as cross-check

✓ Several analysis features included to improve mass resolution and analysis sensitivity

- b-tagging discrimination with NN techniques (DeepCSV)
- b-jet energy regression (+∽20% in m_{bb} resolution)
- kinematic fit in 2lep to constrain Zll (+ ∽20% in m_{bb} resolution)



The Hbb observation – analysis results

H→bb

✓ Fit to di-jet mass performed to visualise the excess

- m(jj) shapes combined and weighted with S/(S+B)
- m(jj) dependency and correlations removed in DNN training
- signal strength extracted compatible with DNN analysis

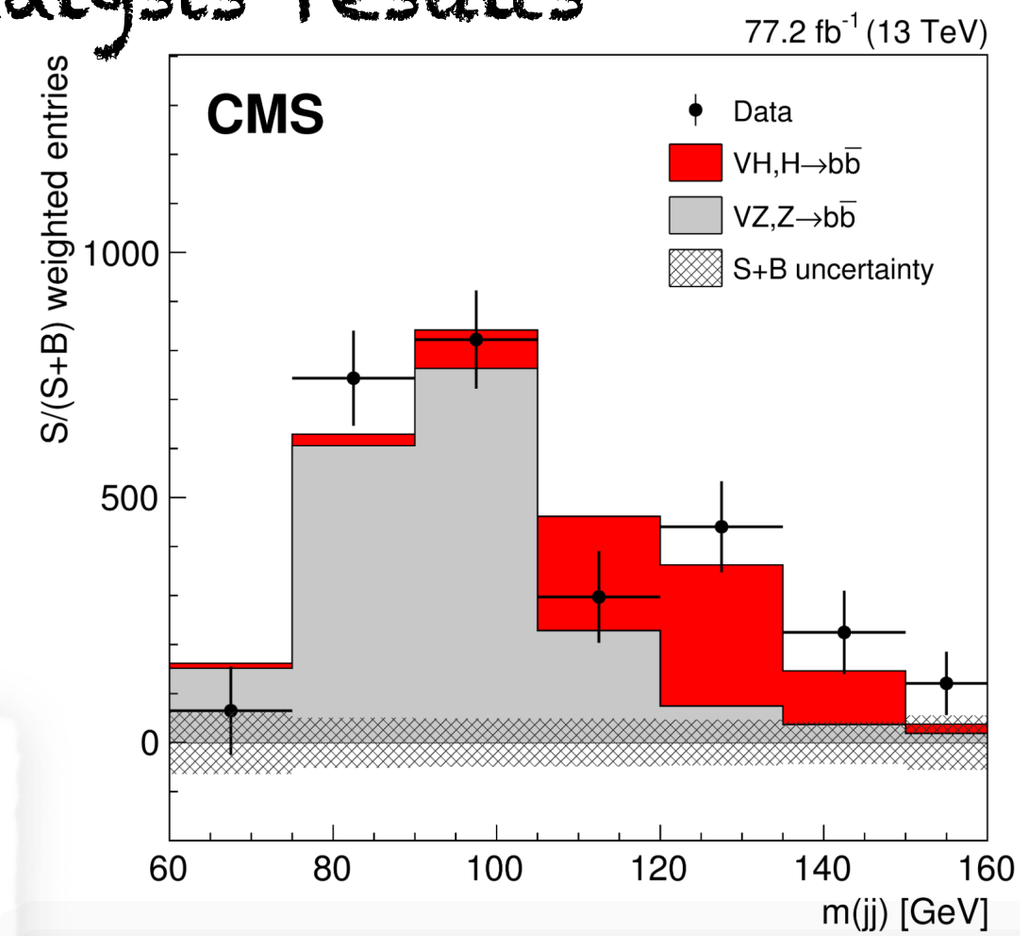
➡ Evidence for the VH production mode

- using Run 1 + Run 2 combined results based on VH production→4.8(4.9)σ obs(exp) significance
- signal strength compatible with SM

➡ Observation of H→bb with Run 1+Run 2 combined dataset

- all production modes included→ 5.6(5.5)σ obs(exp) significance

✓ Systematic uncertainties dominated by MC size, b-tagging and background modelling



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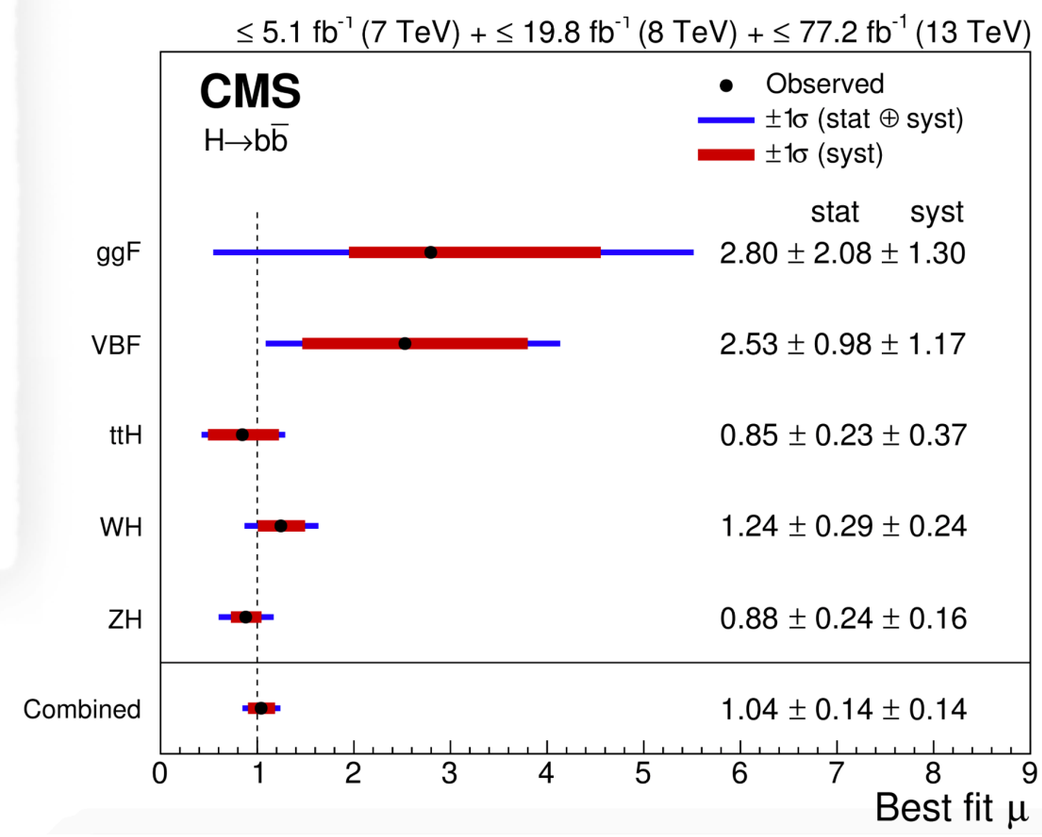


The ttH observation

Phys. Rev. LeE. (2018) 231801

➡ Observation of ttH using Run 1 + partial Run 2 dataset in ttH multilepton, ttH→bb, ttH→γγ modes

- since then results have been updated with more data and improved analysis methods [talks by M. Wassmer, R. Polifka]

✓ ttH→bb

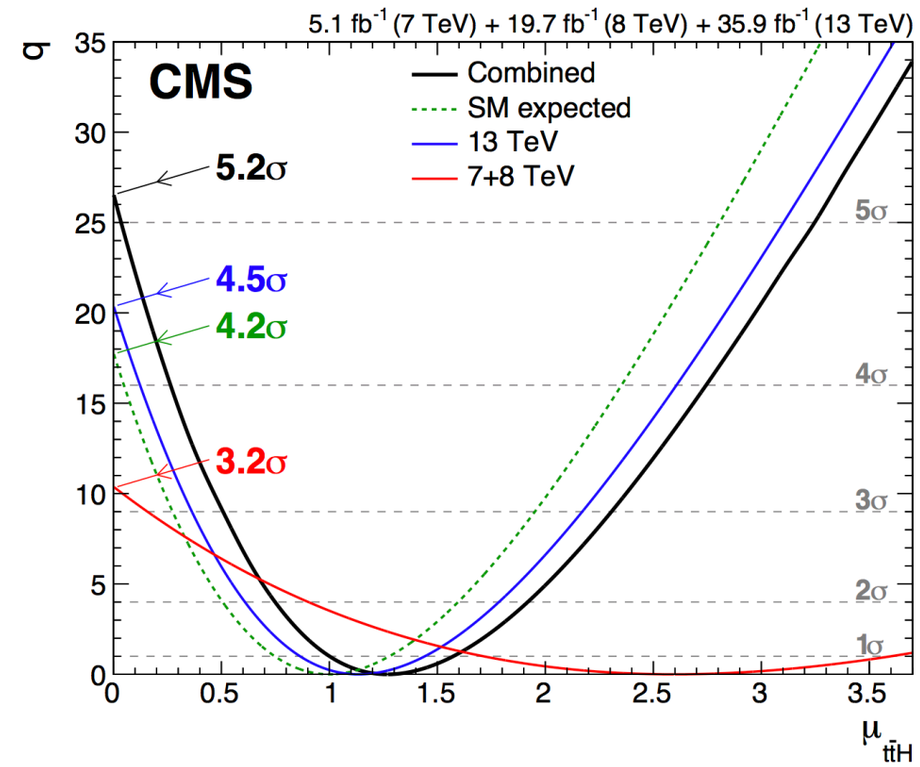
- characterised by large uncertainty on tt+bb - modelling of tt+jets process in MC simulation, signal extraction: matrix-element-method and MVA approaches (BDT, NN). Fully-hadronic final states also included

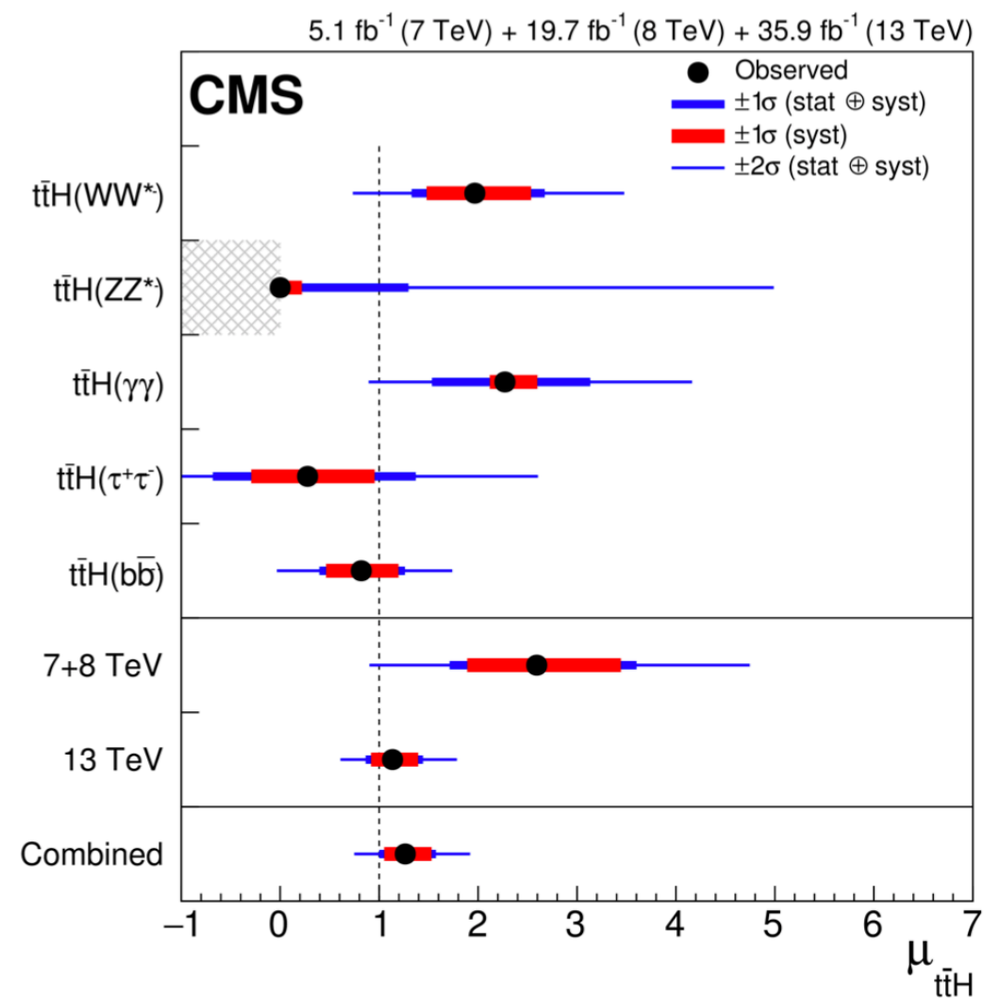
✓ ttH→ZZ*/WW*/ττ

- combination of simple yield, BDT and MEM according to the final state - main uncertainty: tt+V modeling

✓ ttH→γγ

- clean decay channels but very rare process - benefits from full Run 2 statistics





Rare processes: H→μμ & H->ee

PRL 122 (2019), 021801

- ✓ Clean final state with isolated muons but small BR - analysis strategy based on peak search on smooth background - parametric shape of background extracted from data control regions
- ✓ Background is dominated by Drell-Yan and leptonic ttbar
  - analysis strategy based on exploitation of dimuon mass resolution and MVA approaches to categorise regions enriched in VBF and gluon-fusion

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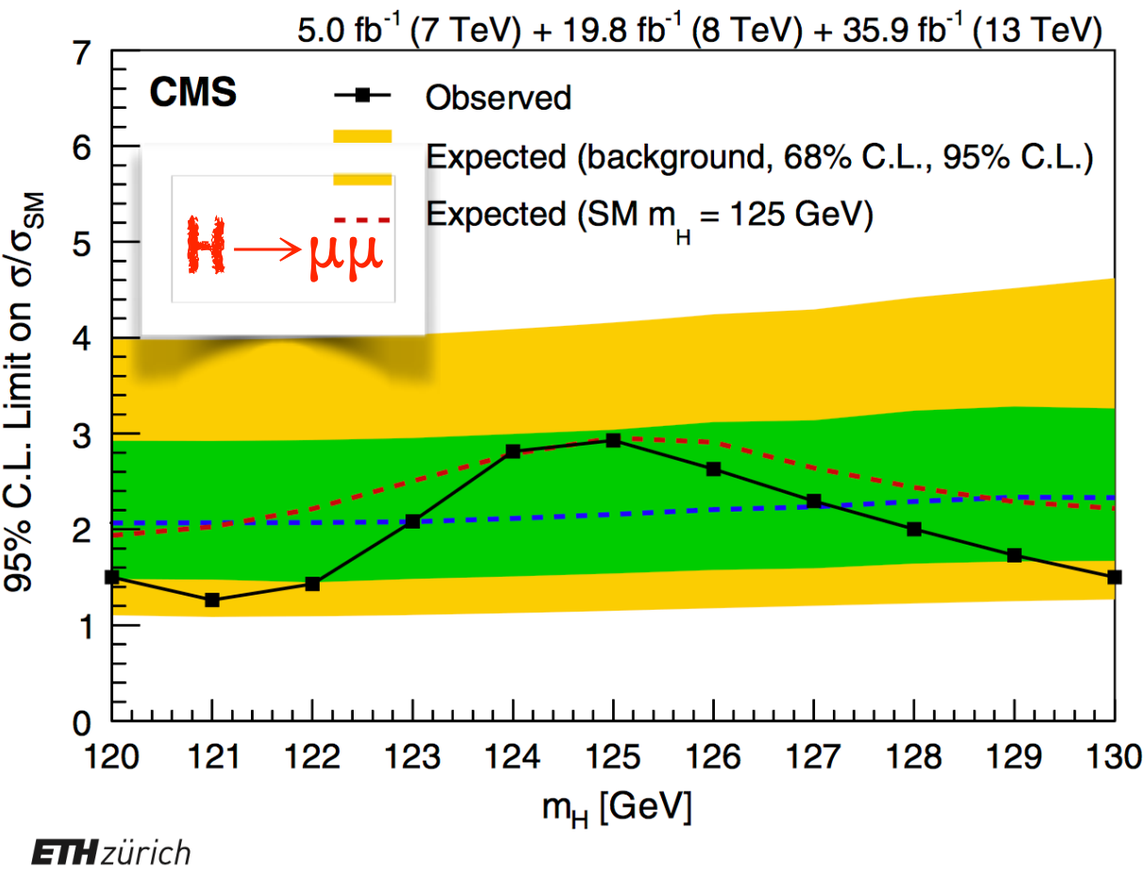
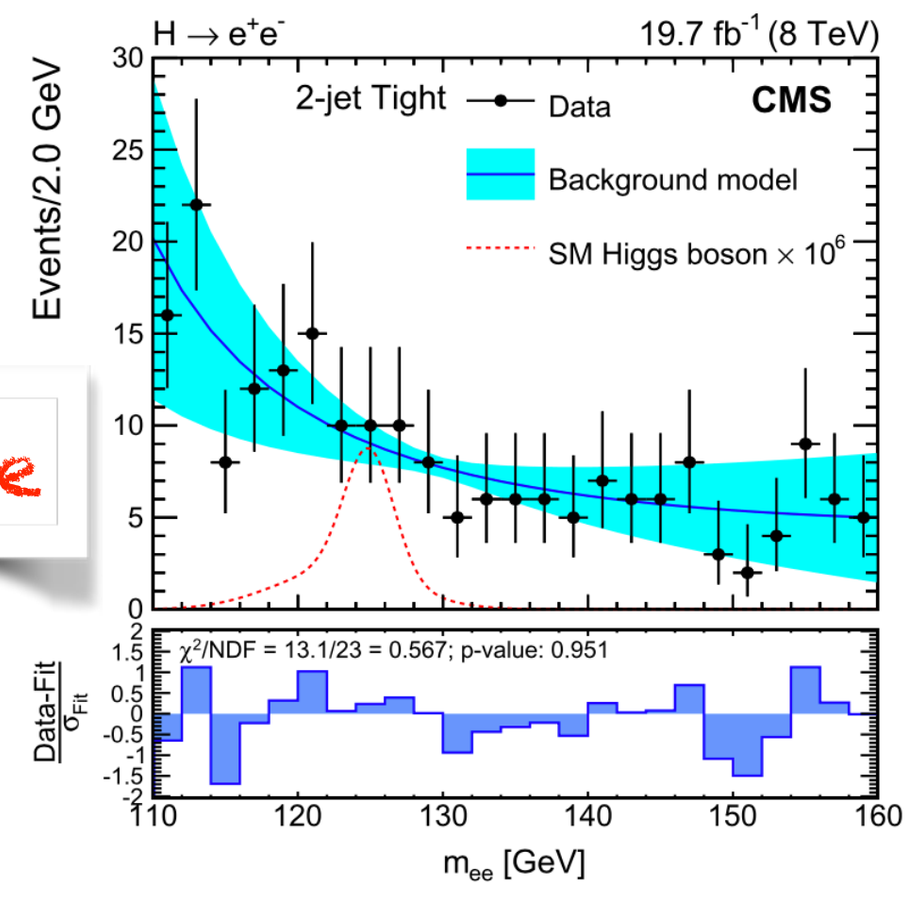
➡ Upper limits on Run1+Run (24.8+35.9 /fb): <2.9 (2.2)*SM predictions

- ✓ Very small BR in electron final state ($5*10^{-9}$) - Run 1 analysis based on search for narrow peak in di-electron invariant mass using additional jet categories - limits on BR in electrons at $3.7*10^{-5}$ @ 95% CL



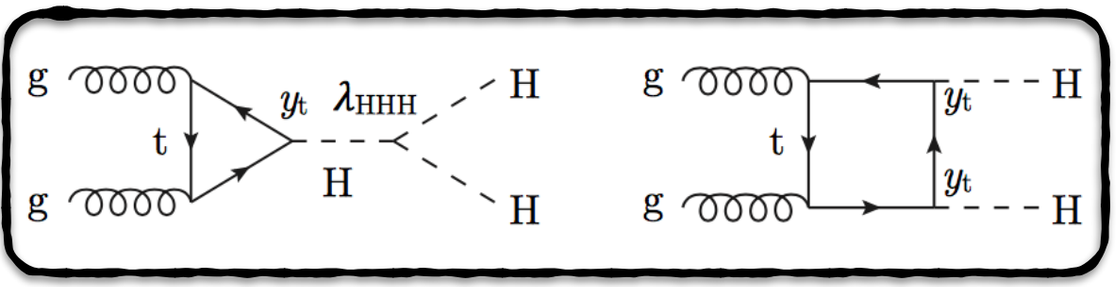
H→ee



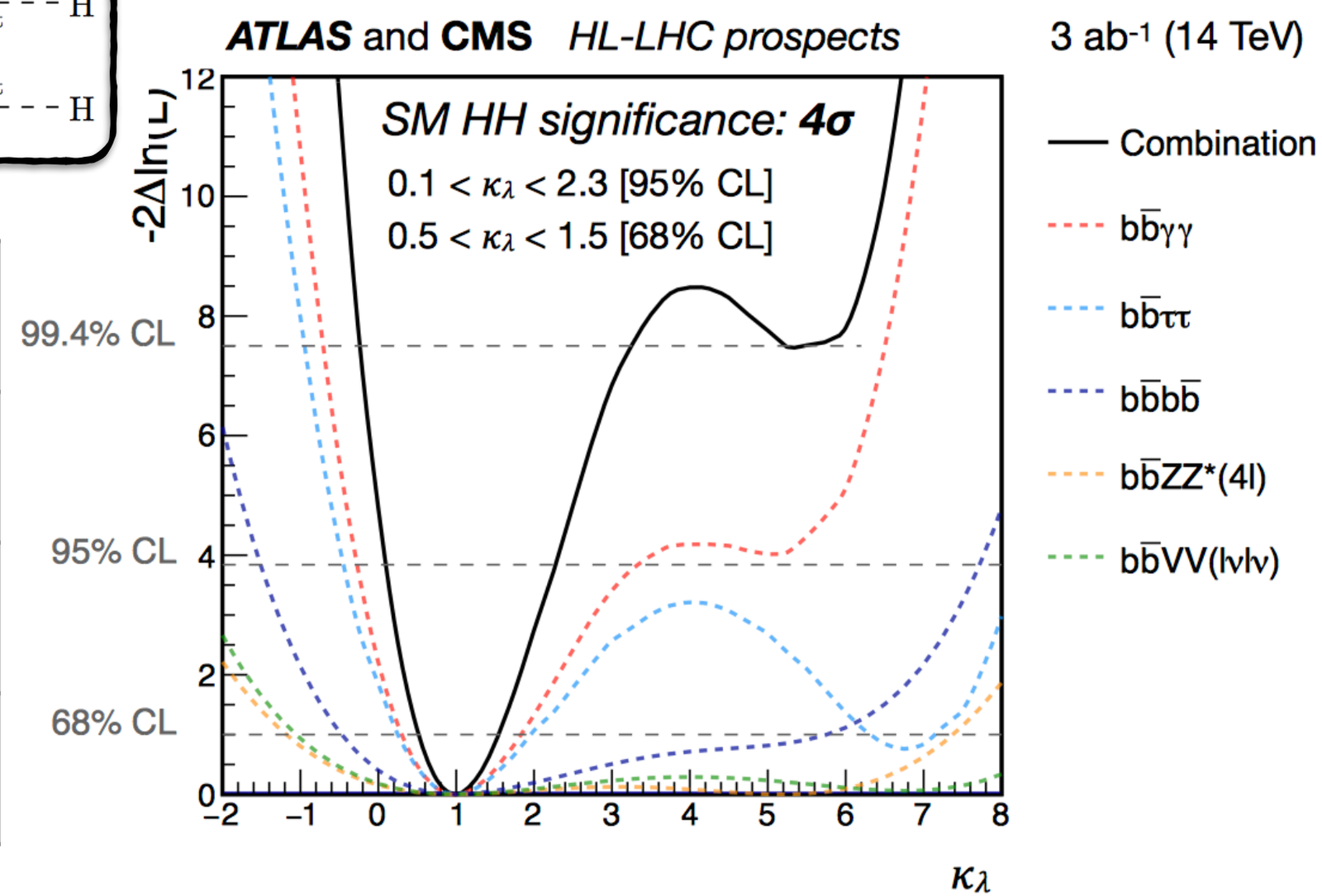
Rare processes: Higgs boson self-couplings

arXiv: 1902.00134

- ✓ Crucial measurements to explore EWSB mechanism and to probe NLO effects on λ(hhh)
- ✓ Not sensitive to SM HH self-coupling production before HL-LHC
  - useful tool for exclusion of BSM models for Higgs self coupling
  - most sensitive channel for HH self-coupling measurement in Run 2 is HH→bbbb (observed 95% UL on signal strength at 13 TeV)



13 TeV results	95% UL on μ
HH→bbττ	<30 (25 expected)
HH→bbWW	<79 (89 expected)
HH→bbγγ	<24 (19 expected)

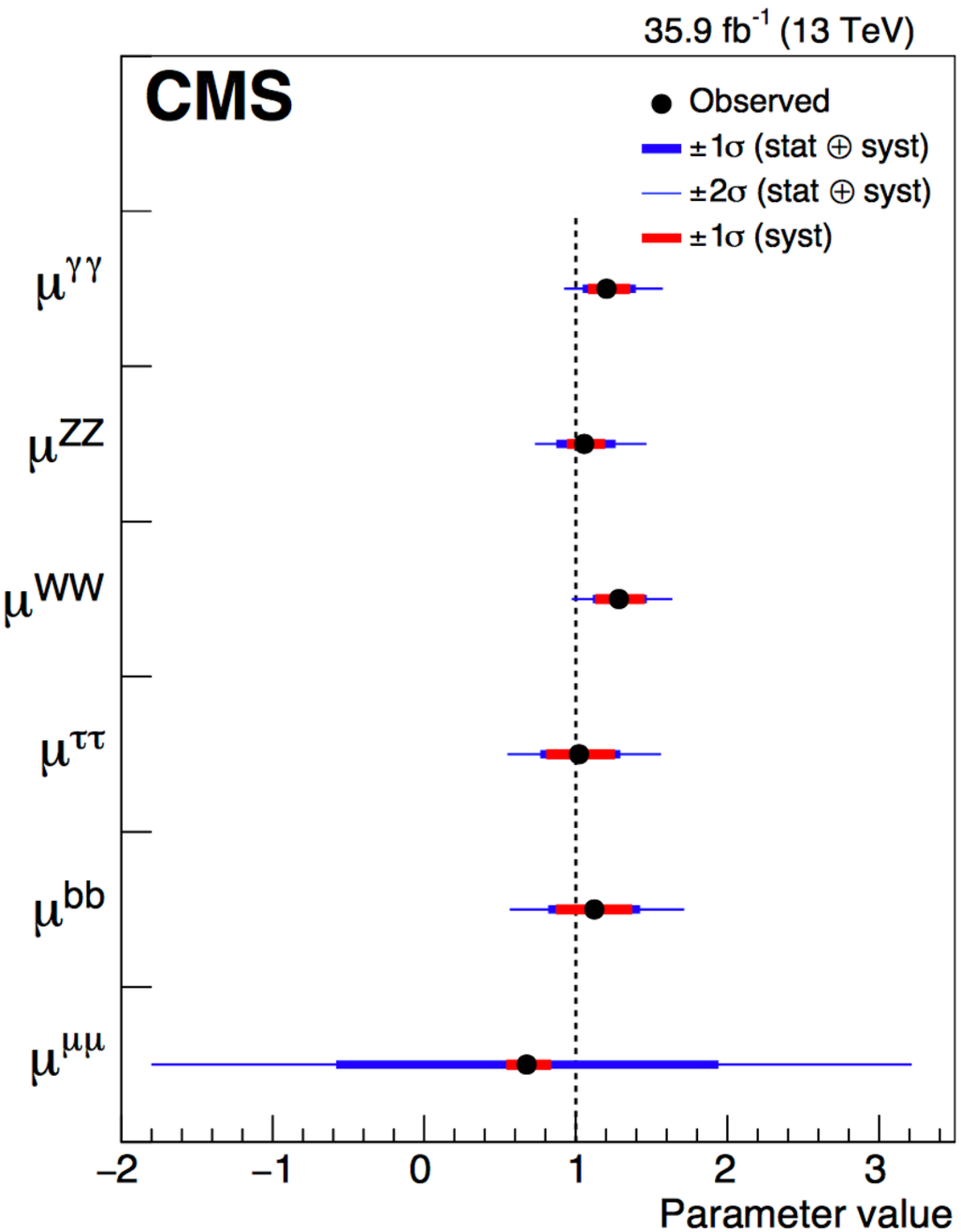


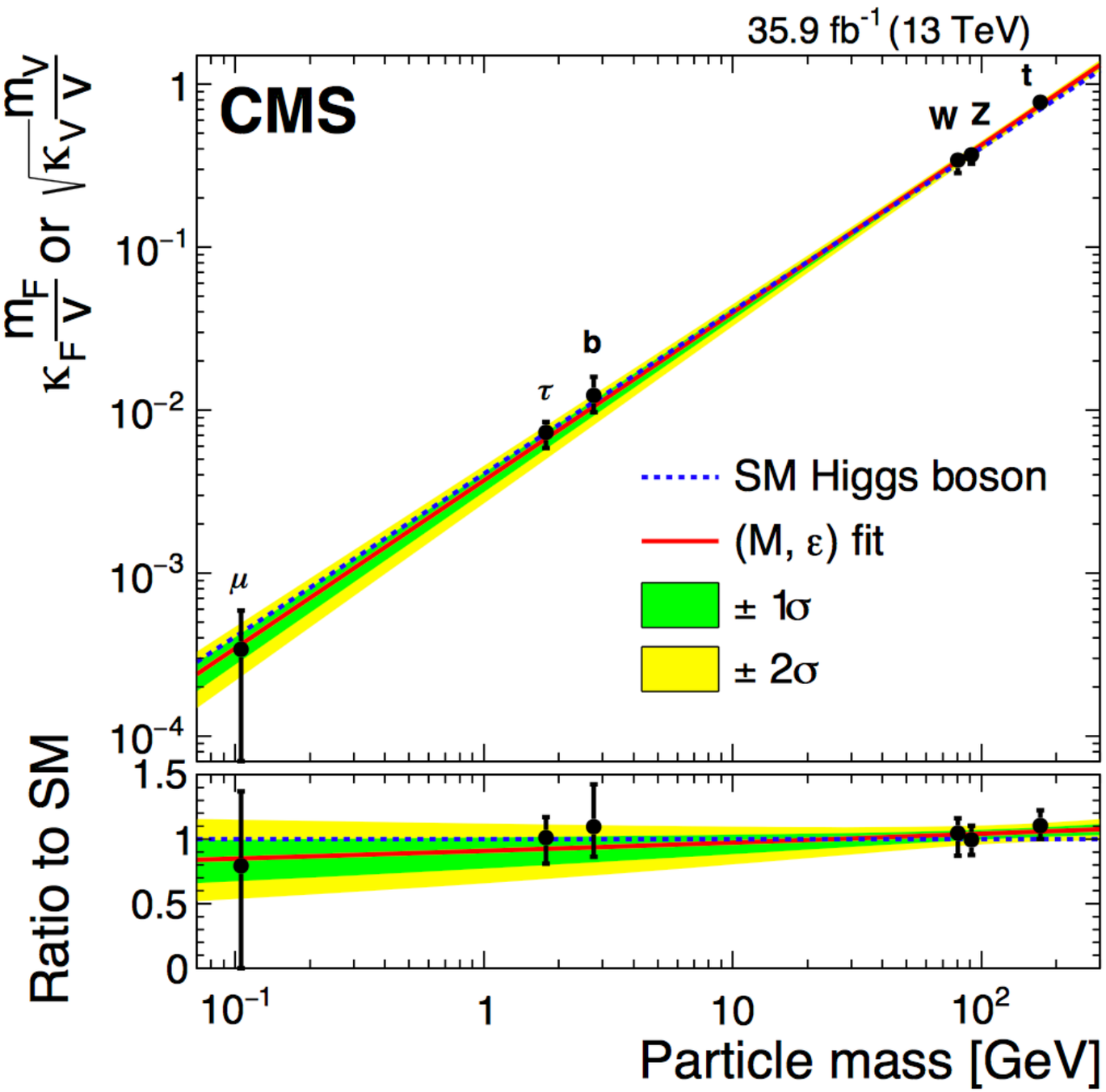
Production+decay mode & couplings

arXiv: 1809.10733

✓ Signal strengths of production modes in agreement with SM within uncertainties

- Assuming no BSM particles in the loop, coupling strength fitted as a function of the particle mass - results also used to constrain the BSM parameter space





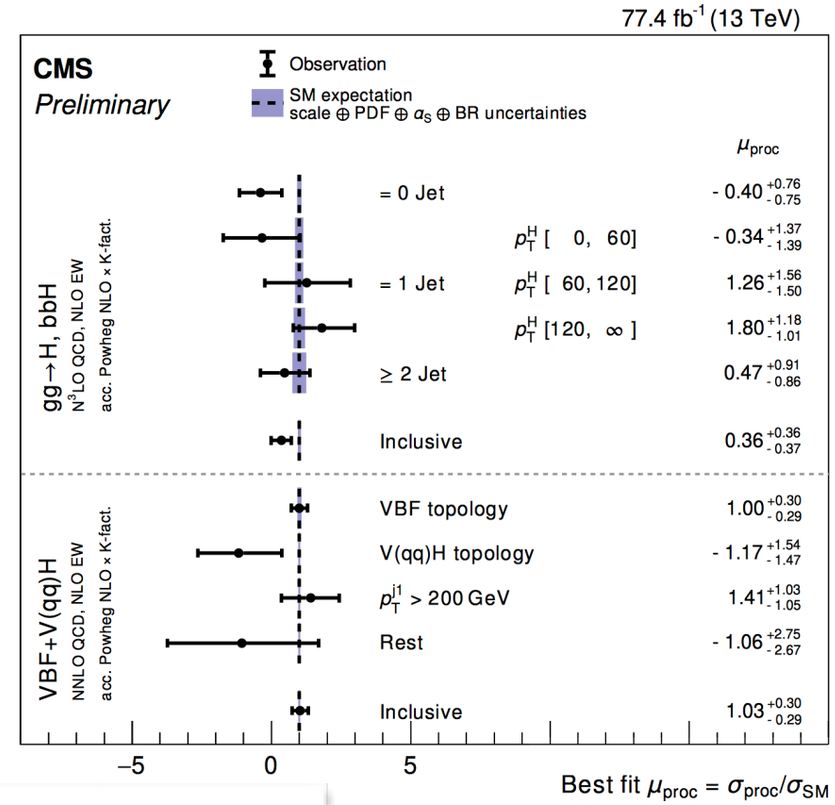
Simplified template cross section

✓ STXS - compromise between fiducial cross-section measurements and signal strength fits

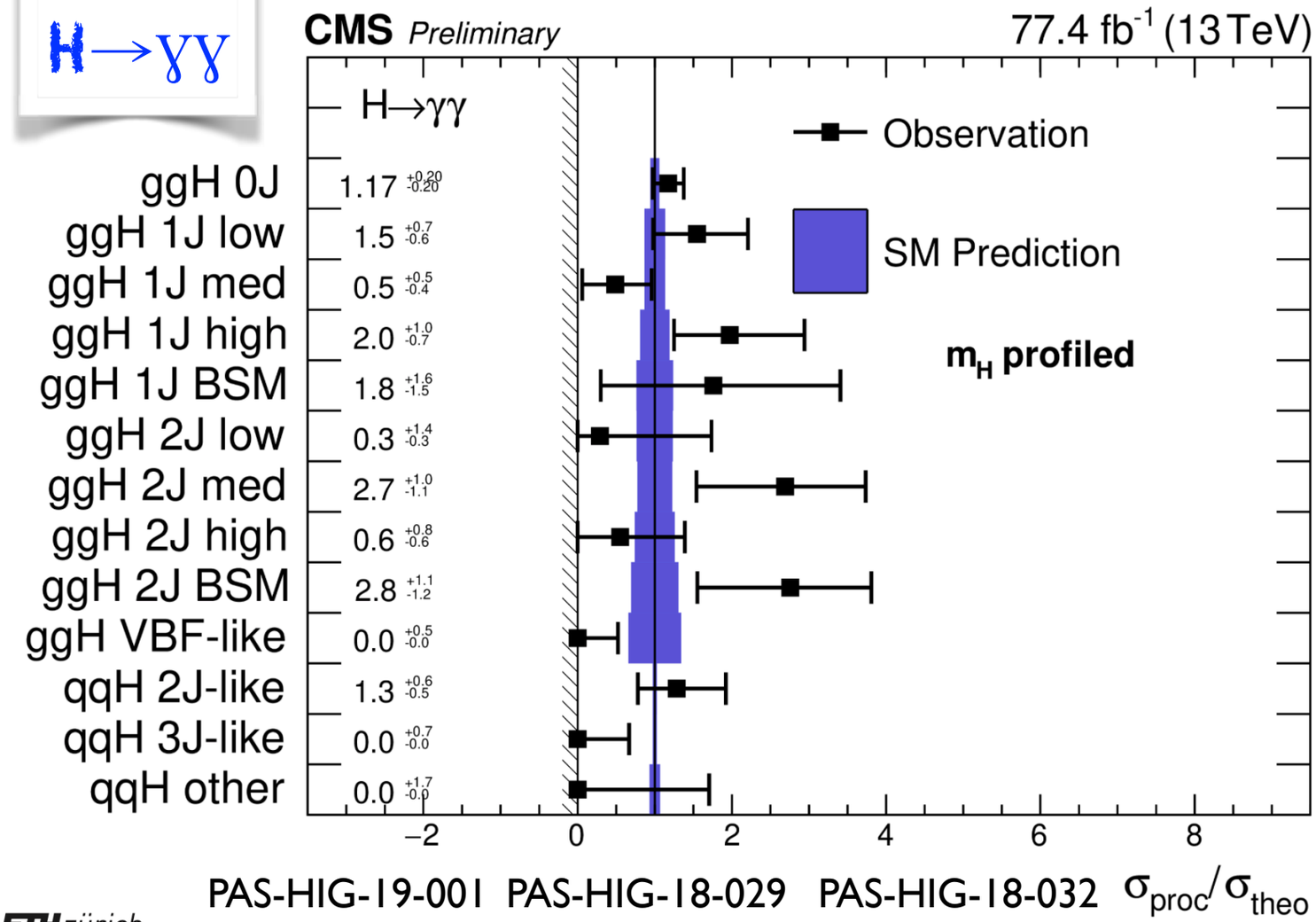
- theory dependency reduced through division of phase-space in categories based on generator level bins in transverse momentum/jet multiplicity

$H \to \tau\tau$

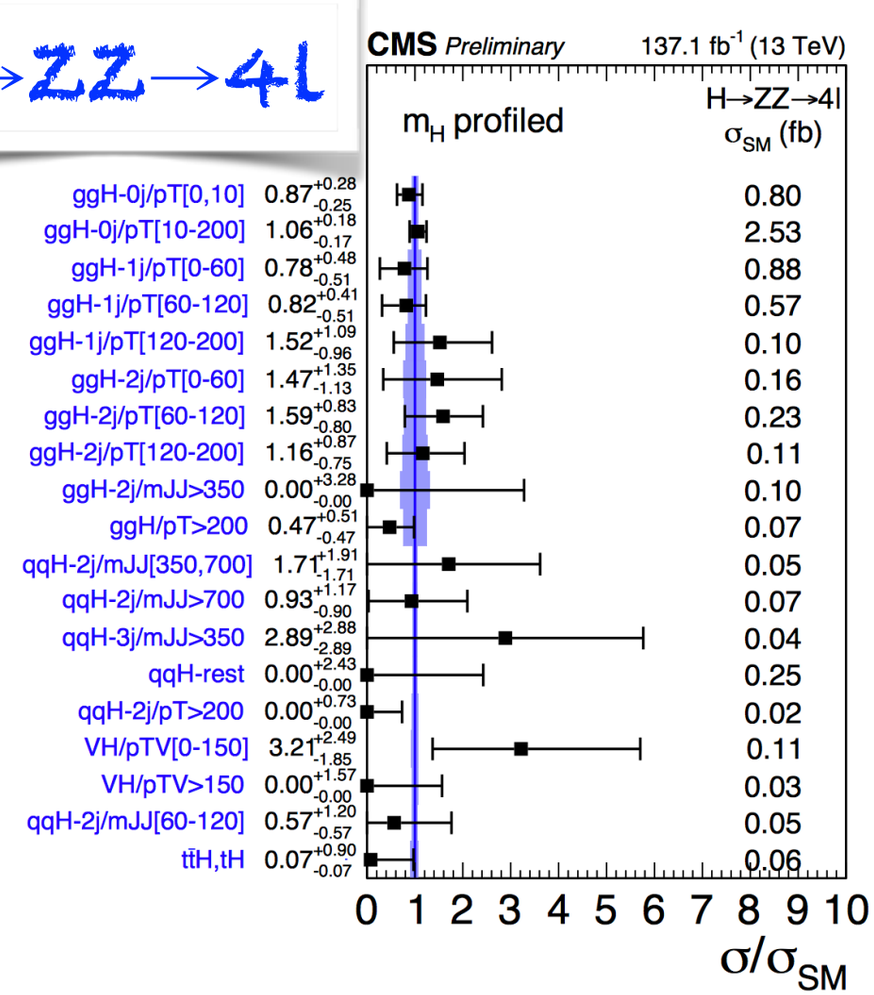
- signal strength is parameter of interest extracted for analysis categories - splitting regions strongly depends on channel topology - $H \to \tau\tau$, $H \to \gamma\gamma$, $H \to ZZ \to 4l$



$H \to \gamma\gamma$



$H \to ZZ \to 4l$

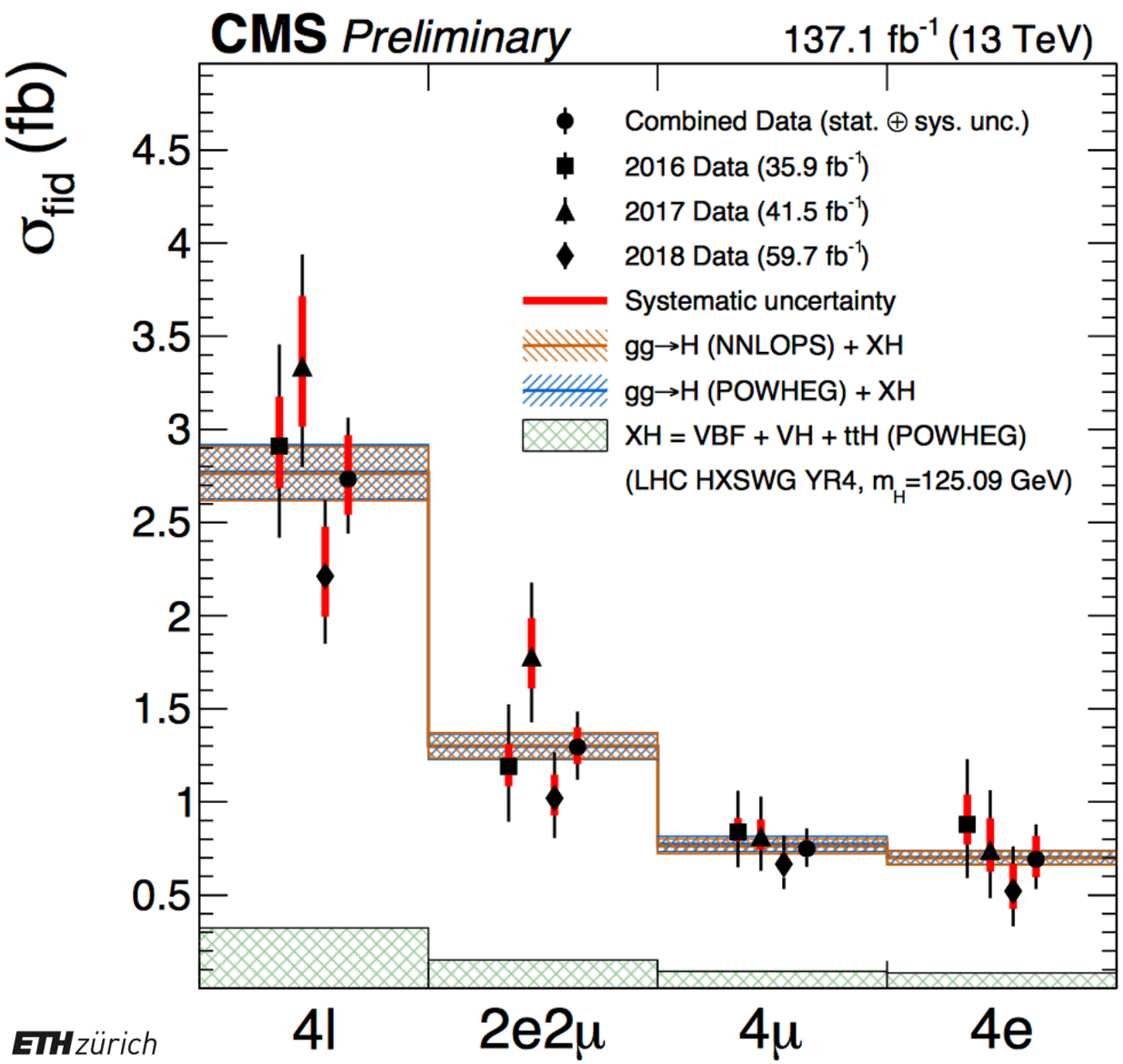


Fiducial and differential cross section

H->ZZ->4l

✓ Fiducial and differential cross-section measurements also performed

- full Run 2 dataset in H→ZZ→4l channel - data in agreement with gg→H,VBF/VH/ttH→H SM expectations
- fine granularity measurements in kinematic observables (Higgs momentum, rapidity, jet multiplicity) allow to probe SM validity and constrain contribution from possible BSM Higgs couplings



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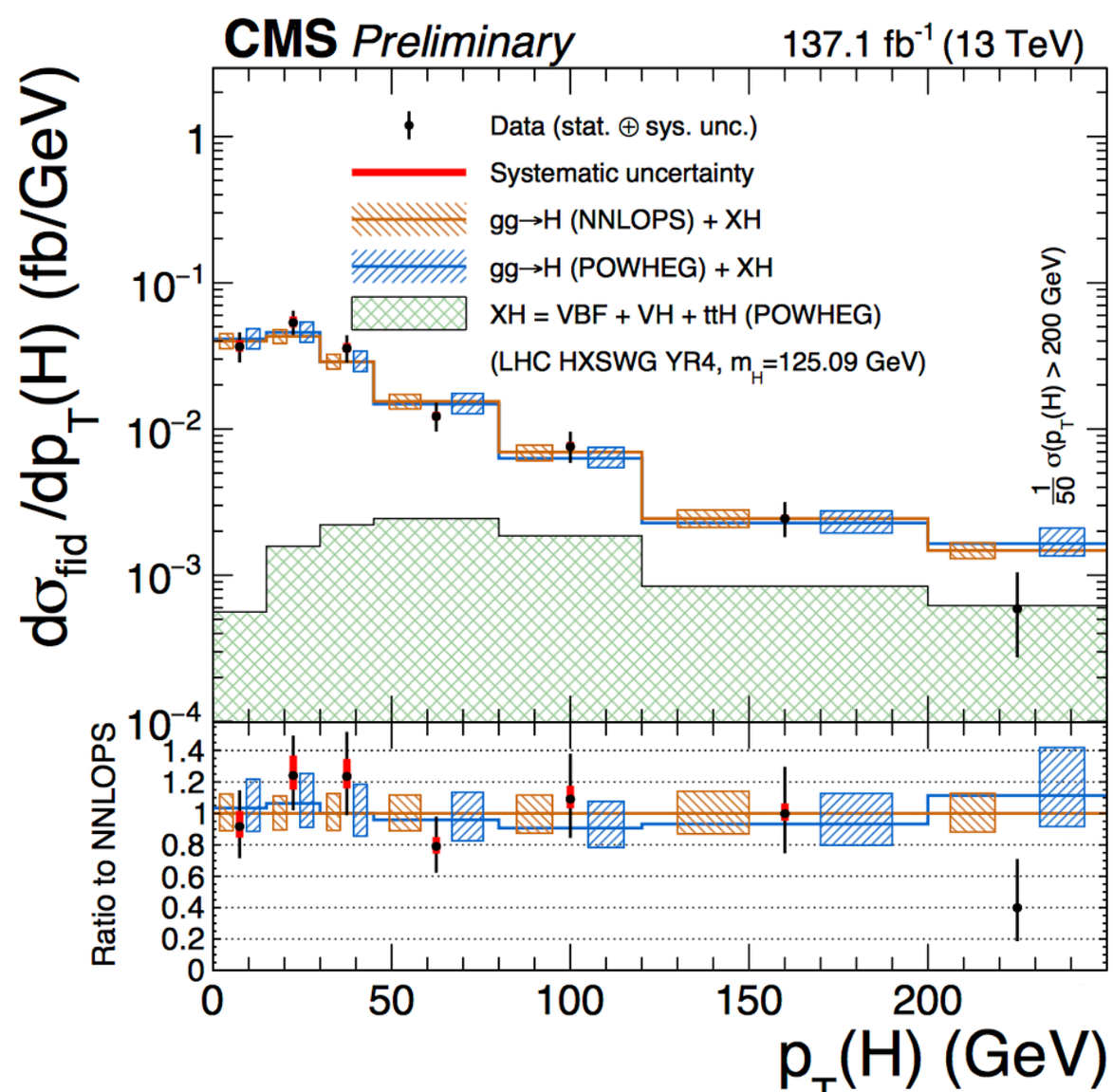
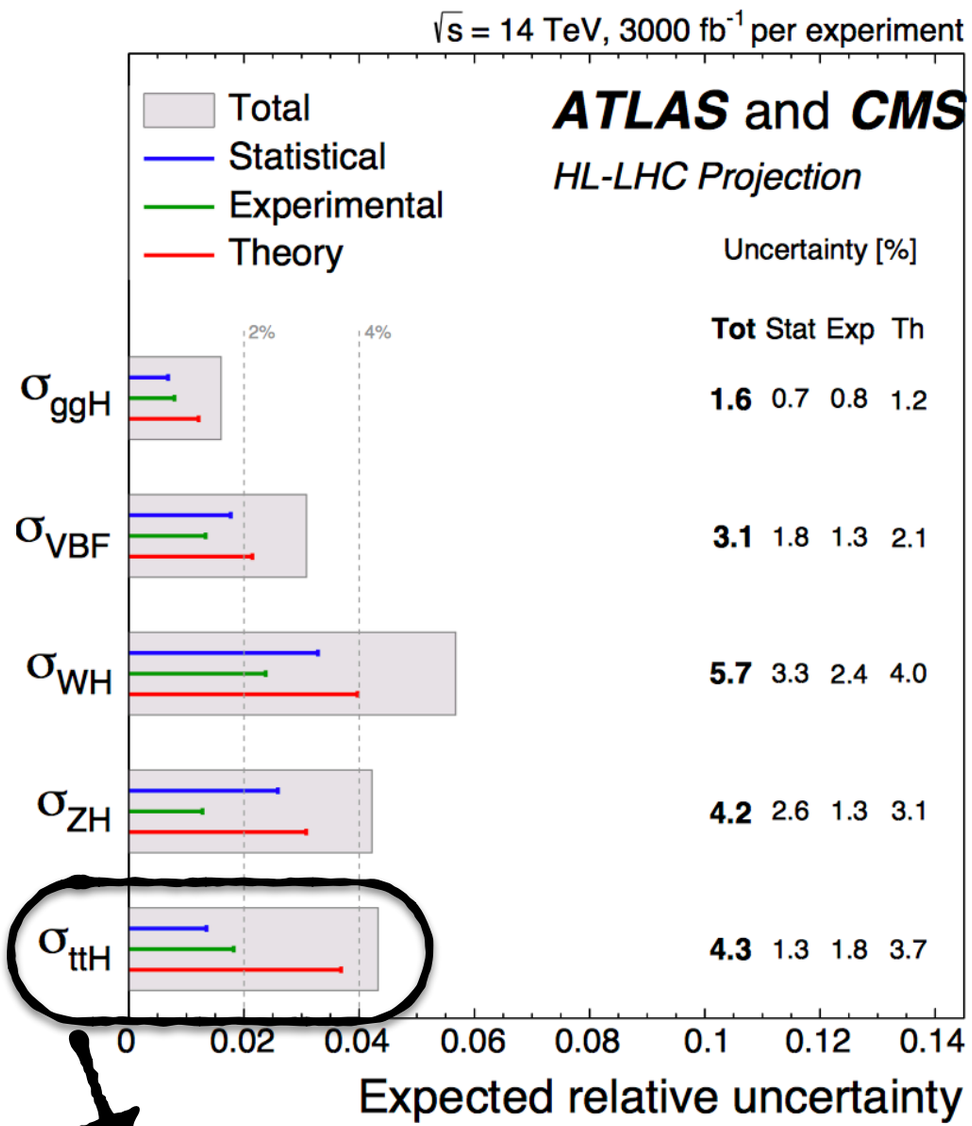


Higgs couplings at HL-LHC

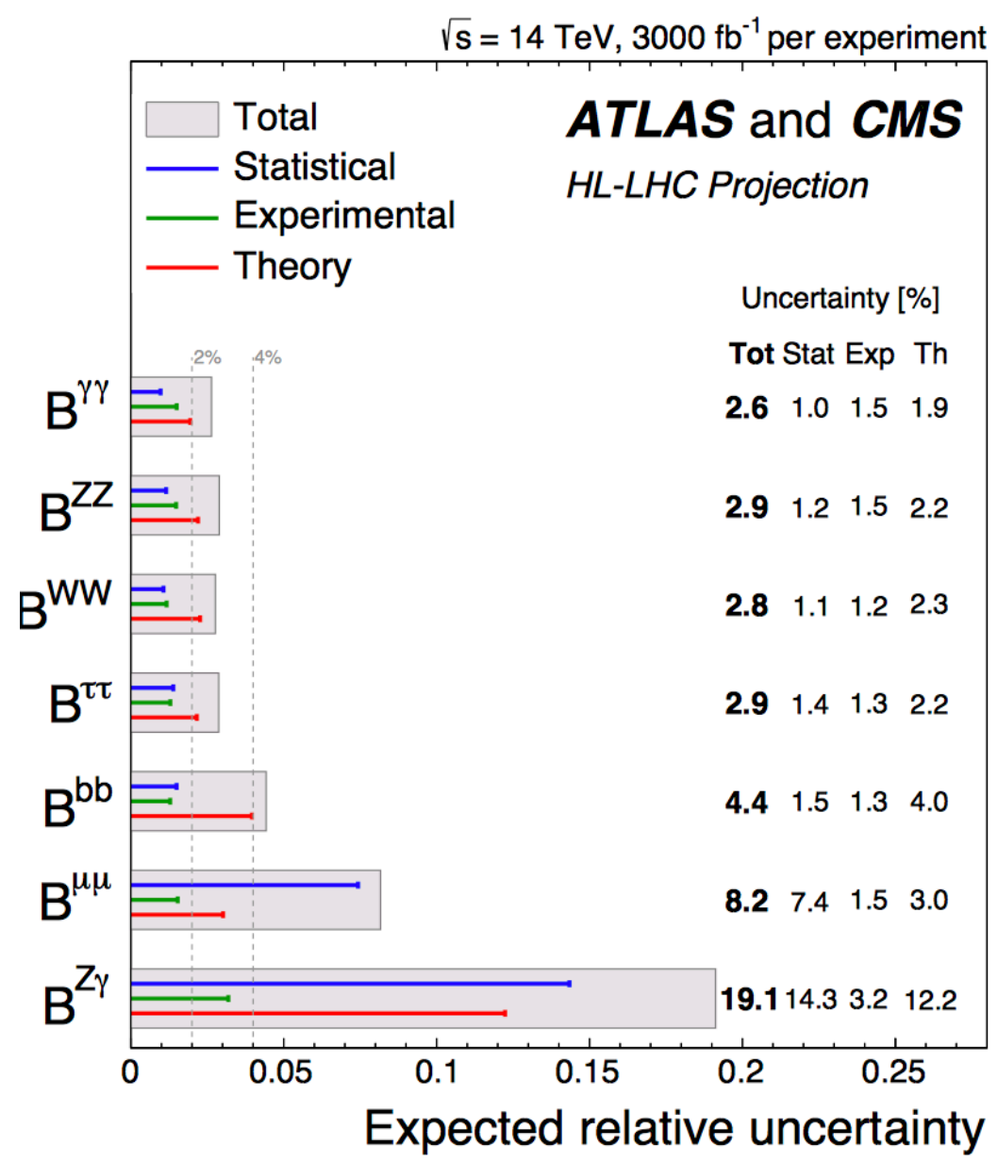
arXiv: 1902.00134

✓ Extrapolation studies for Higgs coupling combination at 3000 /fb HL-LHC

- dedicated scenarios for the treatment of systematics uncertainties (Run 2 scenario, systematics uncertainties down by 2, experimental uncertainties by sqrt(L))
- expected relative uncertainty on inclusive production cross-section, per-channel cross-section and branching ratios for all main production and decay modes



Theory dominating uncertainties at HL-LHC



Wrapping-up and conclusions

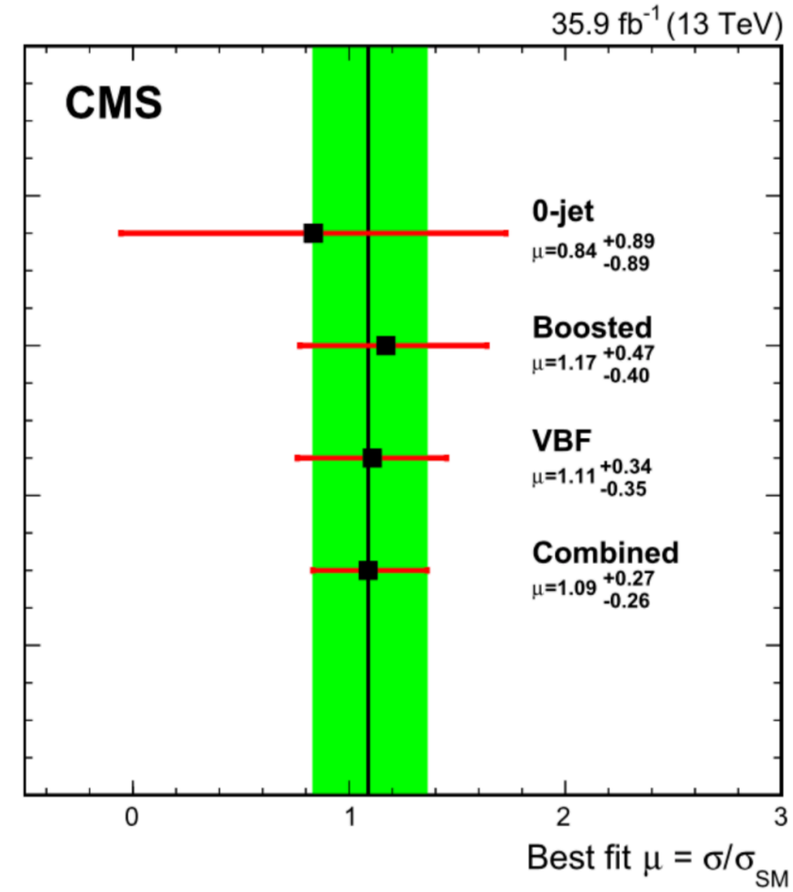
- ✓ The observation of the Higgs boson in 2012 opened a new exciting path of research in high-energy physics - characterisation of the properties of the Higgs particle essential to explore the validity of the Standard Model electroweak symmetry breaking mechanism
- ✓ Mass and spin-parity measurements making use of high precision Higgs decays in bosons ($H \to \gamma\gamma$, $H \to ZZ$)
- ✓ CMS and ATLAS have reached observation of Higgs boson decays into bb, $\tau\tau$ and in the ttH production mode
  - Standard Model assumption on Yukawa coupling to fermions confirmed within O(20%) uncertainty
- ✓ New approaches beyond inclusive and differential measurements, e.g. simplified template cross-section results available for $H \to \gamma\gamma$, $H \to ZZ$, $H \to \tau\tau$
- ✓ Looking for rare processes ($H \to \mu\mu$, $H \to ee$, double Higgs production) and started towards improving measurement precision of Higgs boson couplings at HL-LHC

Additional slides

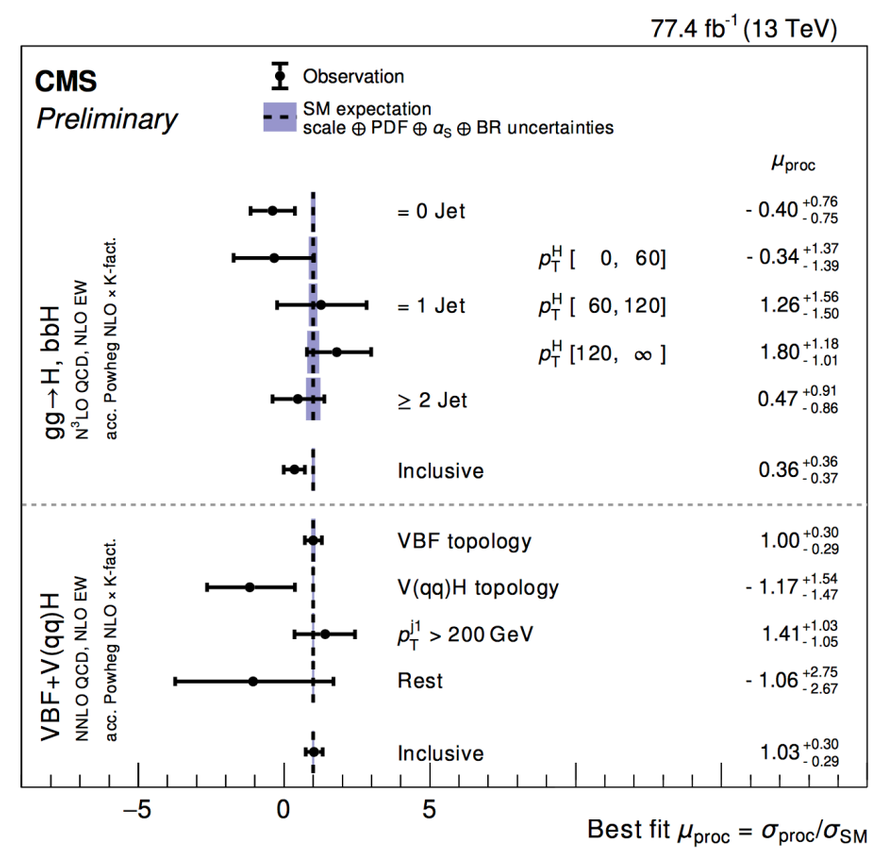
Observation of H→ττ and inclusive cross-section / STXS

PLB 779 (2018) 283
CMS-PAS-HIG-18-032

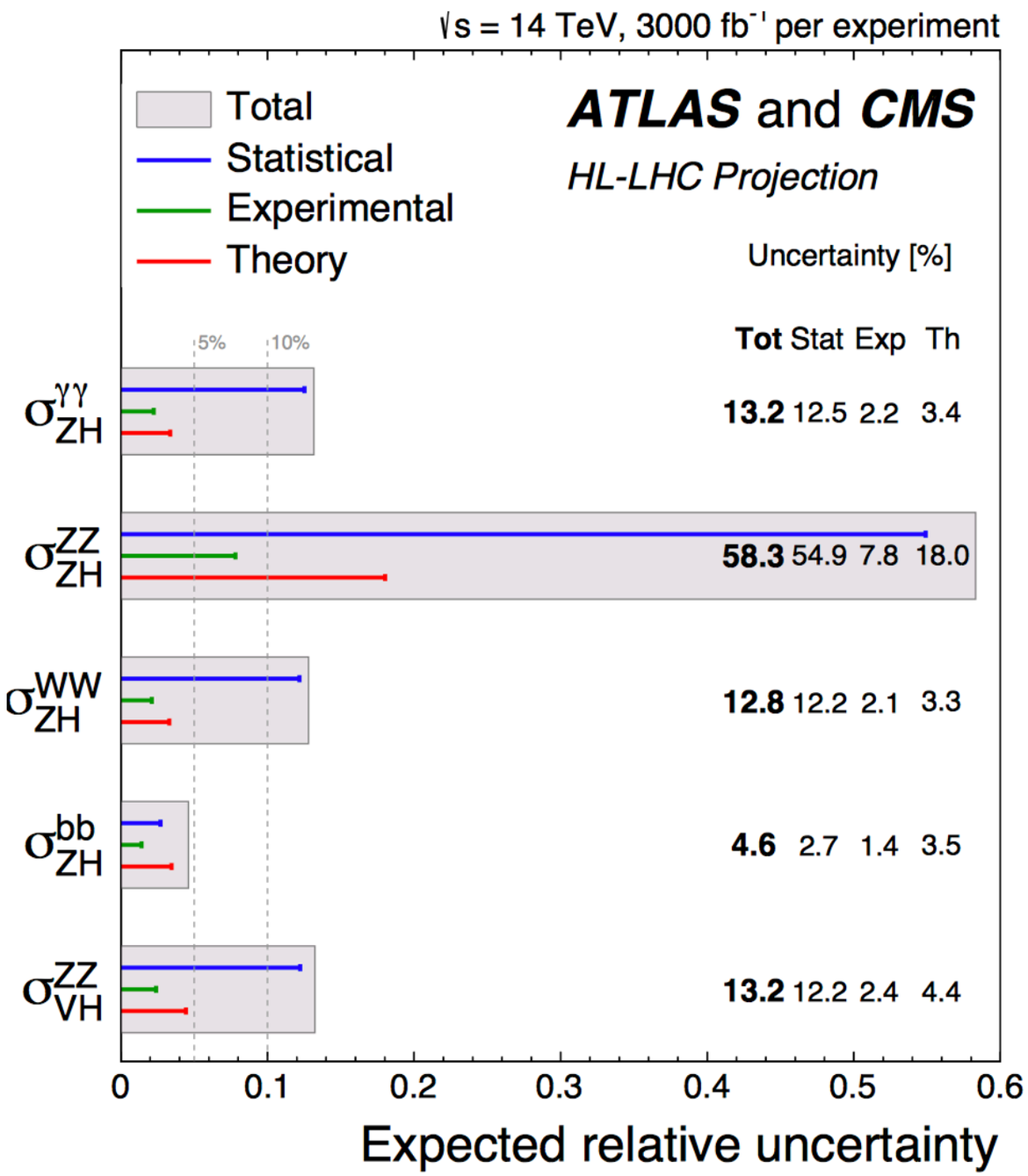
- ✓ Analysis strategy based on 3 categories: 0-jet, VBF and boosted - signal extraction using likelihood fit; main backgrounds are diboson and fake-τ
  - observed (expected) significance: 5.9 (5.5)σ using Run 1+Run 2 data - extracted signal strength compatible with SM

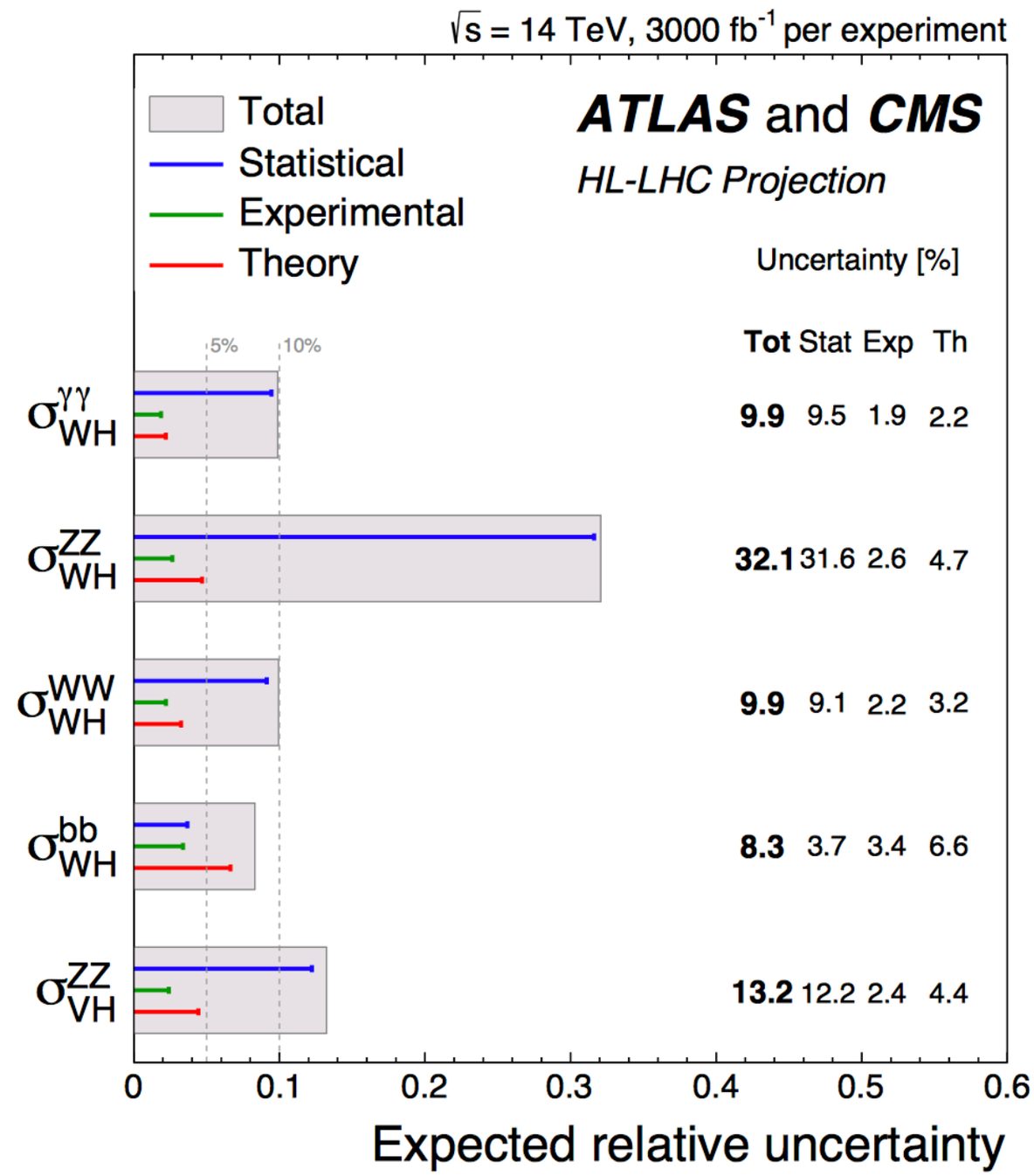


- ✓ H→ττ inclusive production cross-section also extracted in GGF and VBF production modes using Run 2 data (2016+2017)
  - excellent signal-to-background discrimination achieved by using NN multi-classifier selecting regions enriched in ggH, VBF and background (background is estimated in data using τ-embedding technique)
  - σ•BR (H→ττ)=2.56±0.48(stat)±0.34(sys) pb
  - stage 1 STXS using ggH and VBF categorisation
    - signal strength extracted in analysis bins



Higgs couplings at HL-LHC





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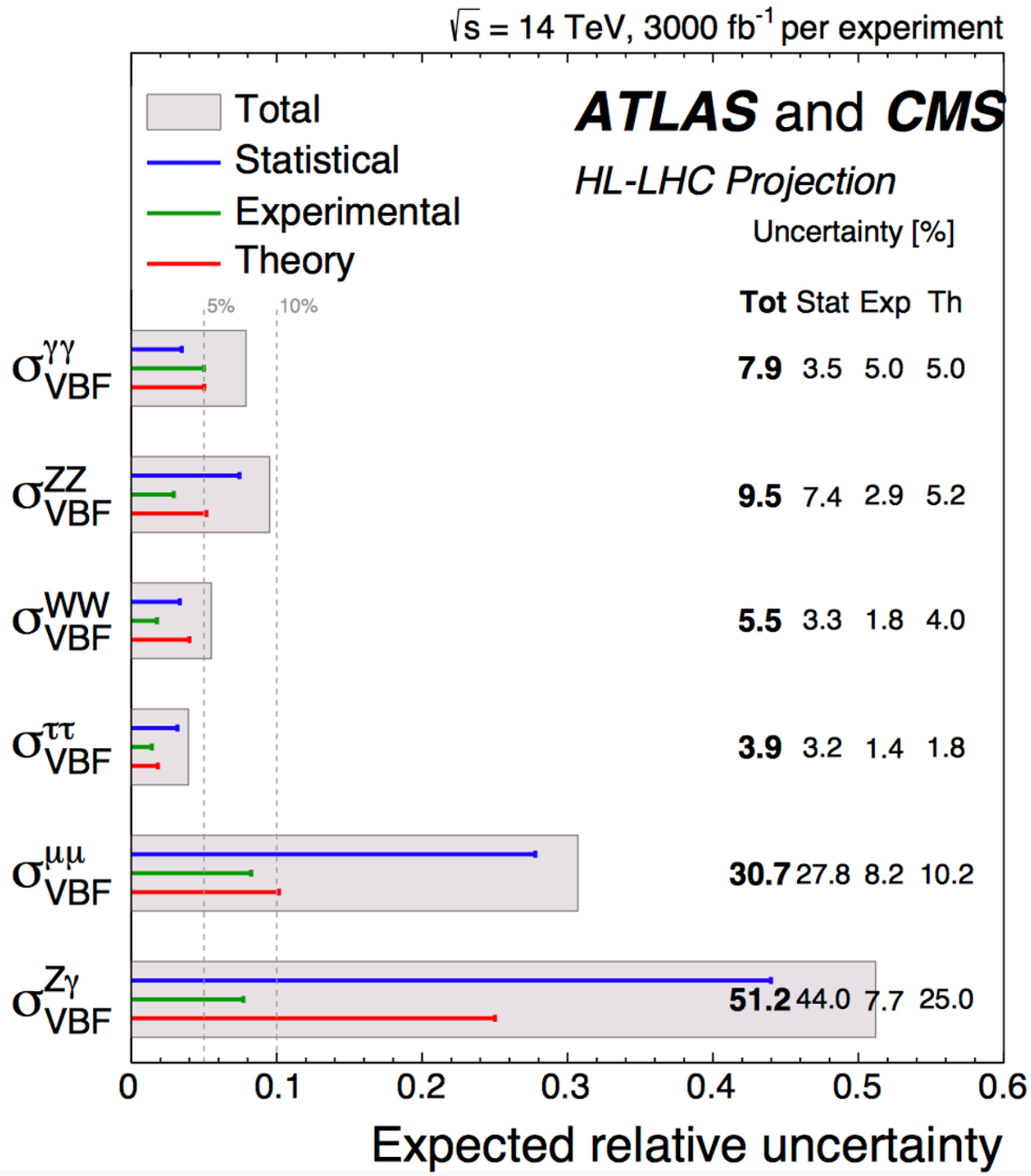
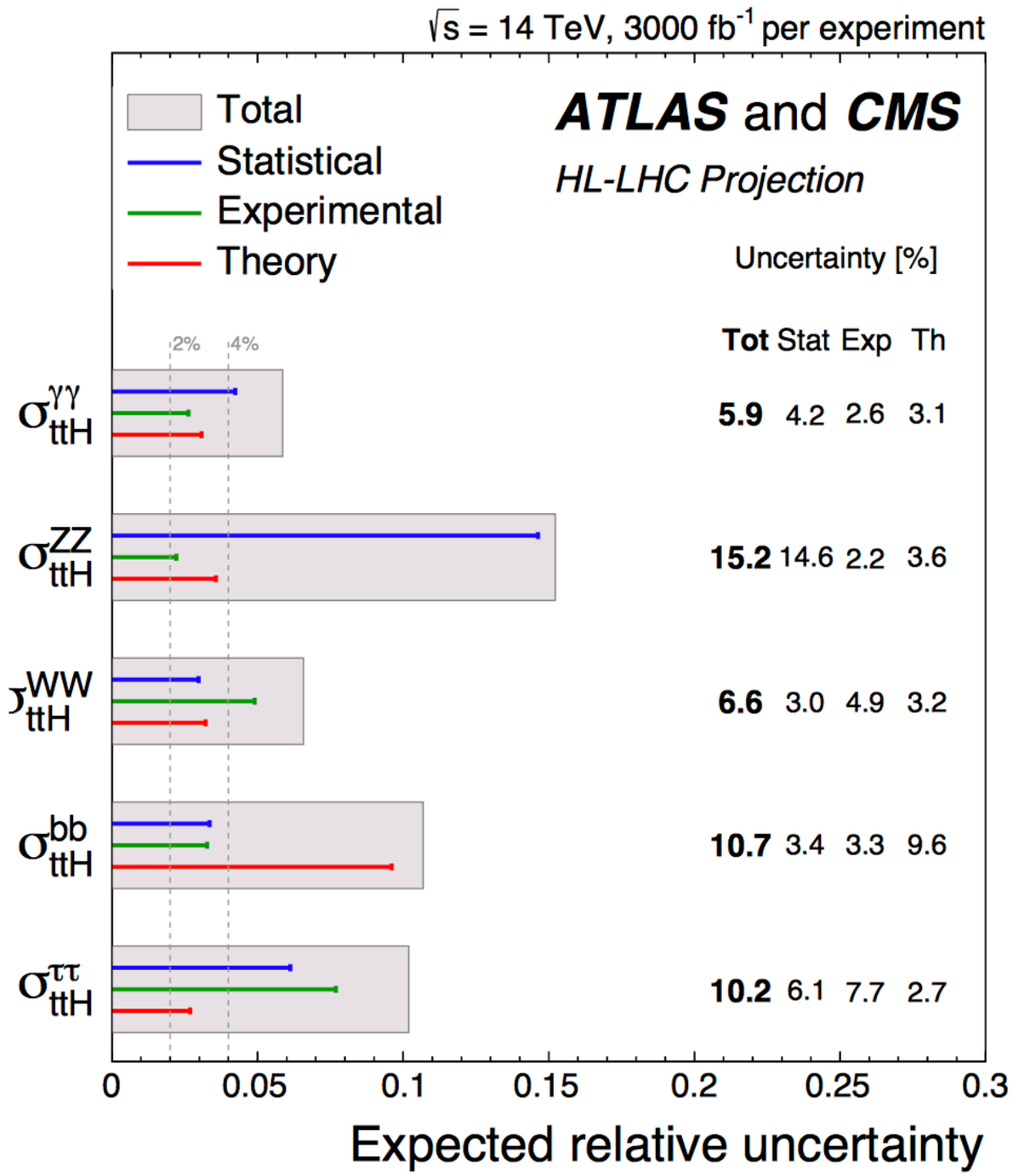
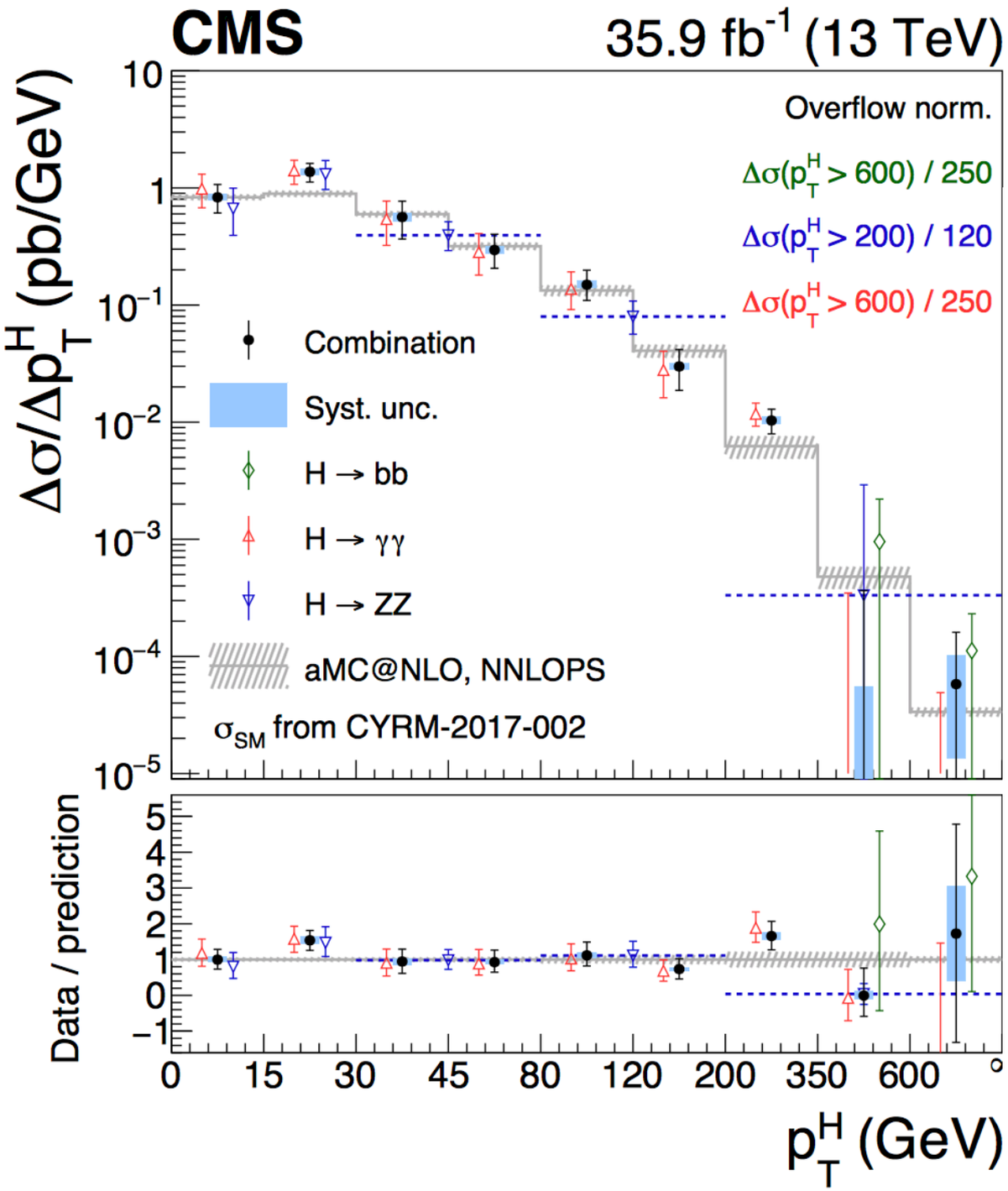
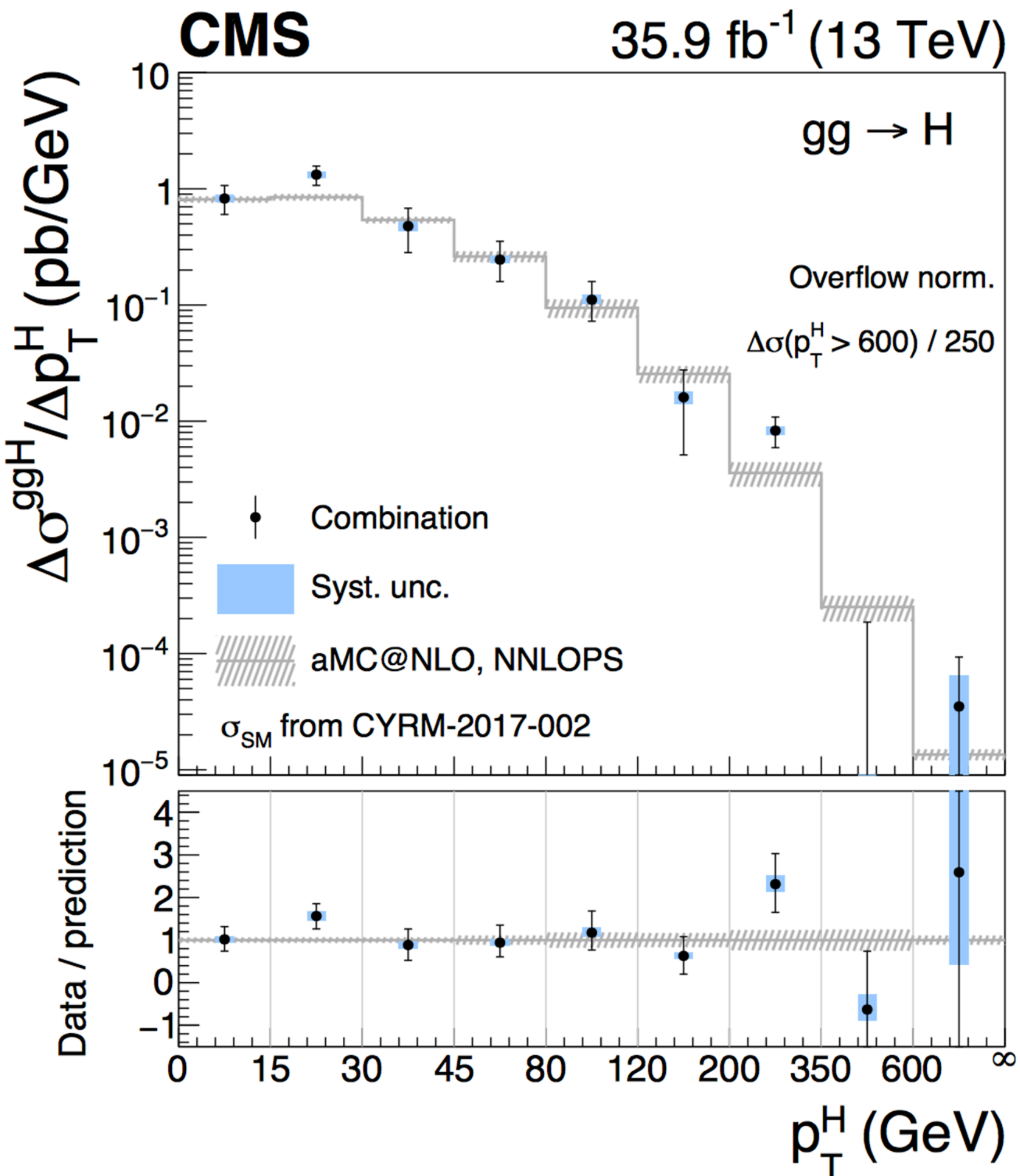




Higgs boson differential cross-section





Higgs boson differential cross-section (2)