Higgs boson properties and rare decays in CMS

Michał Bluj
National Centre for Nuclear Research
on behalf of the CMS Collaboration

XXXI Cracow EPIPHANY Conference
13-17 January 2025

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Introduction & overview

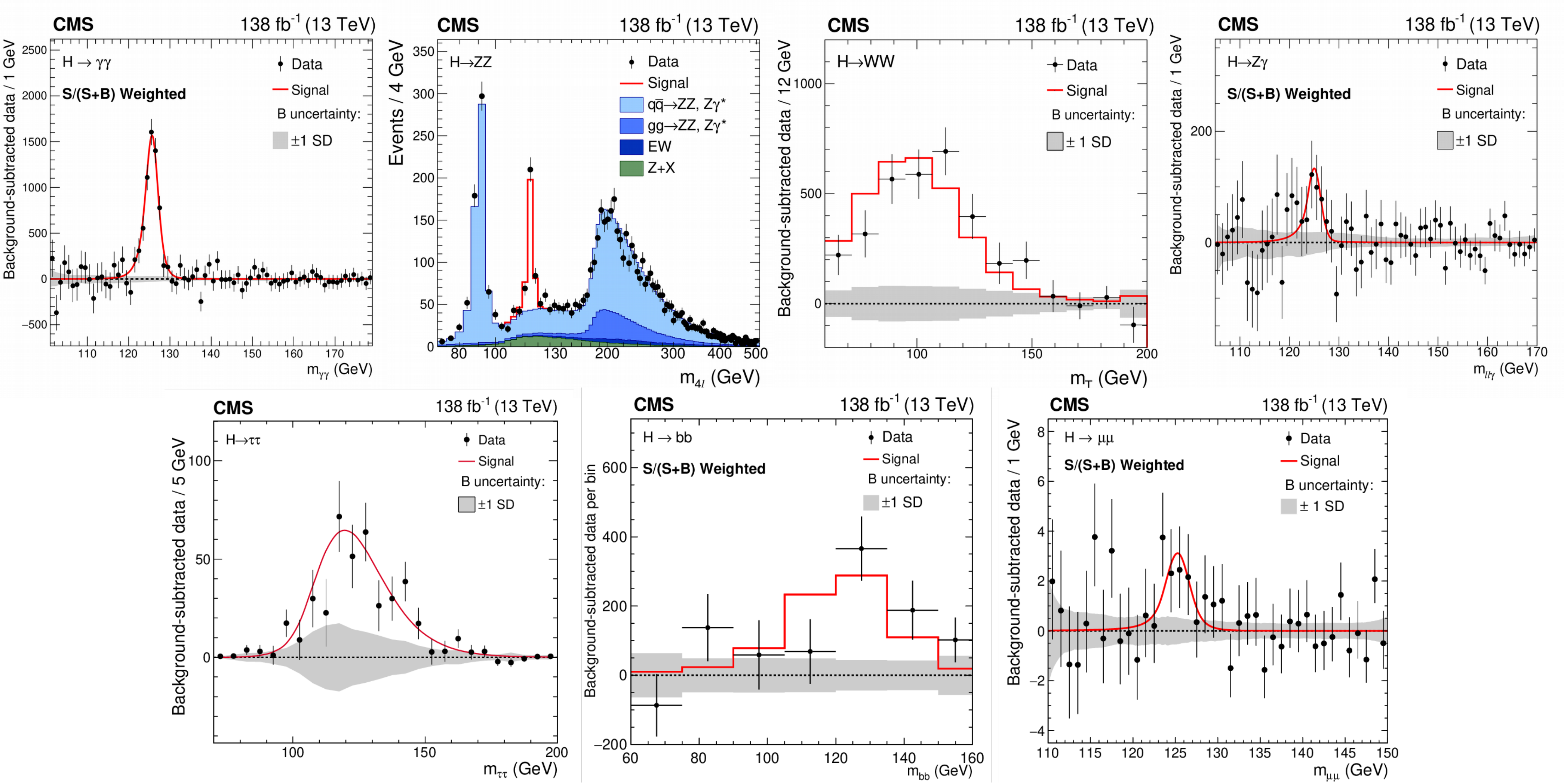
- BEH mechanism(*) one of key features of the Standard Model:

  a scalar field, with a non-zero vacuum expectation, responsible for the masses of particles
  - necessary for both gauge boson and fermion masses
  - predicts relation between gauge boson masses and couplings
    - preserves unitary of VV→VV scattering (through cancellation of diagrams with exchange of V_L and H)
    - essential for renormalisability of the SM
  - predicts existence of (at least one) Higgs boson
- Discovery of the boson confirmed the mechanism and gives insights to its details
- Higgs boson is special
  - The only (fundamental) scalar particle in SM

    (a dynamic explanation of BEH mechanism à la BCS theory will be a breakthrough)
  - Neither matter nor force carrier
  - Couples proportionally to mass

(*) Brout-Englert-Higgs(-Hagen-Guralnik-Kibble) – BEH(HGK) – mechanism

Appetiser: H mass peaks



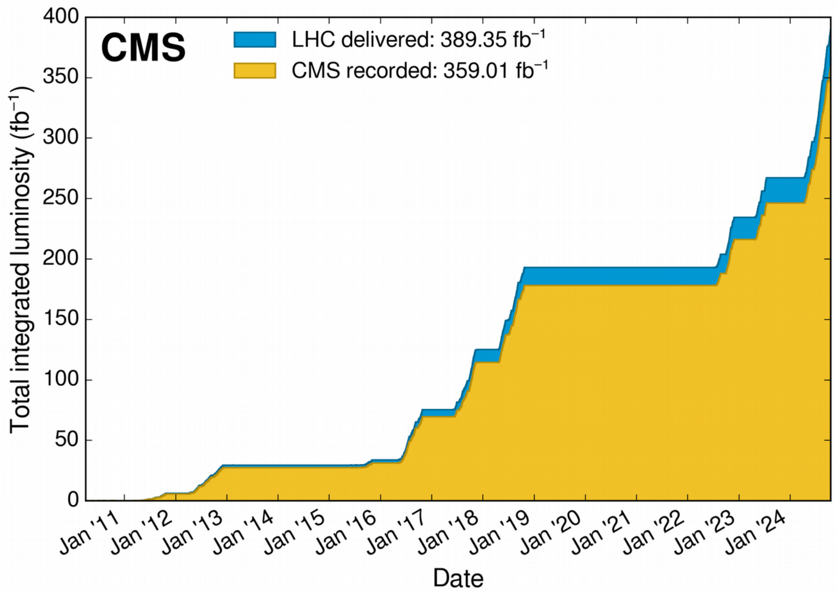
Only the H→ZZ*→4ℓ (ℓ=e,μ) peak visible for „naked eye" w/o bkg. subtraction

Typically S/B << 1 => precise bkg. estimation crucial for Higgs measuremts

- incl. MC generators (DY, Wjets, tt, ...)

Higgs measurements

- Many measurements enabled with large data-sets already collected
  - **Precision measurements:**
    mass & width,
    cross-section & couplings (incl. 3^{rd} generation fermions),
  - **Rare processes:**
    coupling to 2^{nd} generation: $H \to \mu\mu$, $H \to cc$,
    self coupling (HH),
    H->Zγ/γγ* (BSM in loops),
    “Invisible” decays
    rare production processes
  - **BSM searches:**
    additional Higgs bosons,
    exotic decays,
    anomalous couplings



Collected pp data:

- Run-1 at 7&8TeV (2010–12) : ~5+20/fb
- Run-2 at 13 TeV (2015–18): ~140/fb
- Run-3 at 13.6 TeV (2022,23,24...): ~40+30+110/fb
  (early measurements)

=> No. of Higgs bosons at CMS $O(10^8)$

Higgs measurements

- Many measurements enabled with large data-sets already collected
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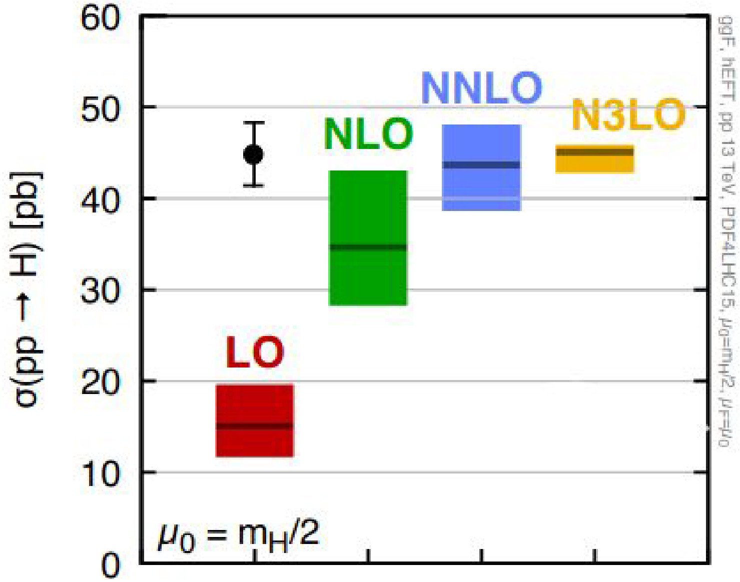


Great results thanks to collective efforts!
- excellent performance of the LHC machine
- extensive understanding of the performance of the CMS experiment
- precision theoretical description of the Higgs boson as well as the backgrounds.
- application of sophisticated analysis techniques incl. machine learning

This talk: *selection from a plethora of very interesting analyses preformed since Higgs boson discovery.*

Mass measurement

m_H is a free parameter of the Standard Model

m_H measured with fully reconstructedm high-resolution final states:

$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$ (ℓ=e,μ)

Mass measurement requires excellent calibration of photon energies ($H \rightarrow \gamma\gamma$)...

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Calibrate reconstructed energy of photons with MC, MC/data with $Z \rightarrow ee$ events with account for differences between e and γ

and lepton momenta ($H \rightarrow ZZ^* \rightarrow 4l$)

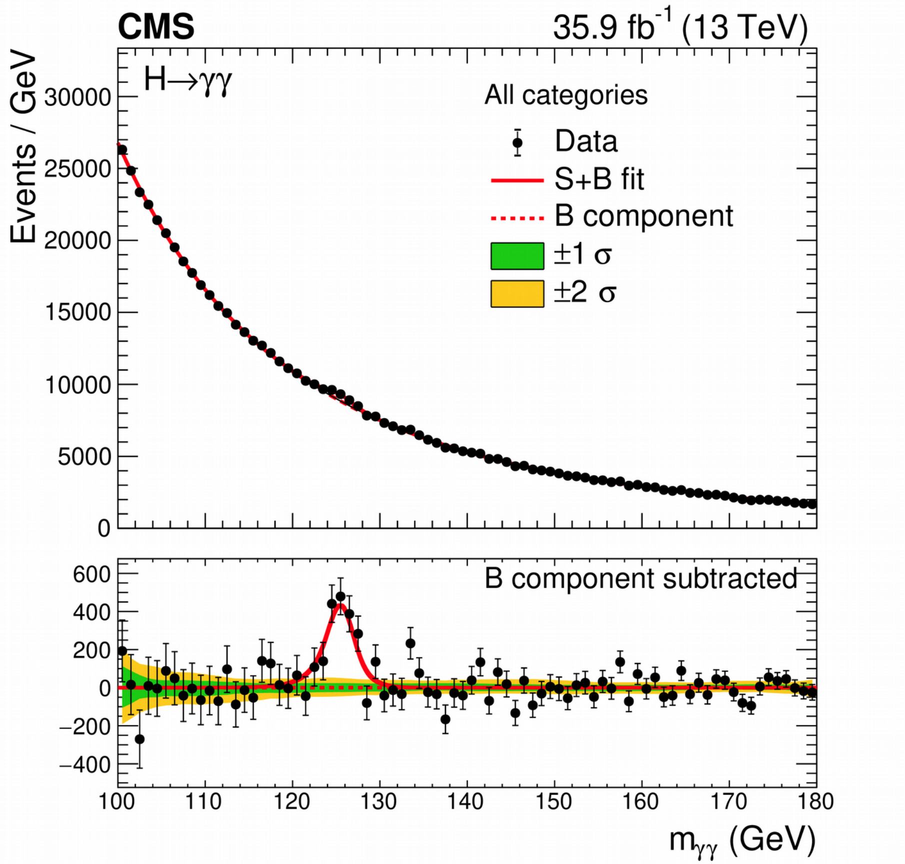
- recover final state radiation photons
- fit lepton momenta with Z_1 mass constraint (usually on-shell Z boson) for each event
- compute m_{4l} with uncertainty at event basis (with refitted lepton momenta)

Measured with likelihood fit dependent on signal-strength parameter and m_H floating in the fit (+nuisance parameters for systematic uncertenties)

- di-photon mass in $H \rightarrow \gamma\gamma$ channel
- 3D fit in $H \rightarrow ZZ \rightarrow 4l$ with m_{4l}, its resolution and kinematic bkg/sig discriminant

m_H: recent combined results

Combining $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$ with Run 1 (5.1+19.7/fb) + 2016 data (36/fb)



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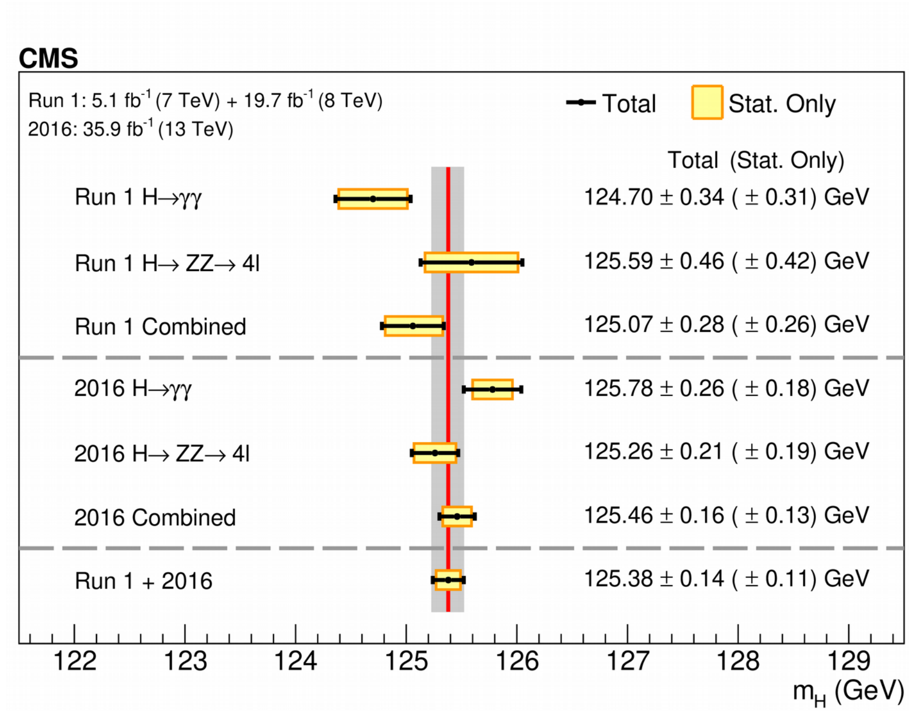


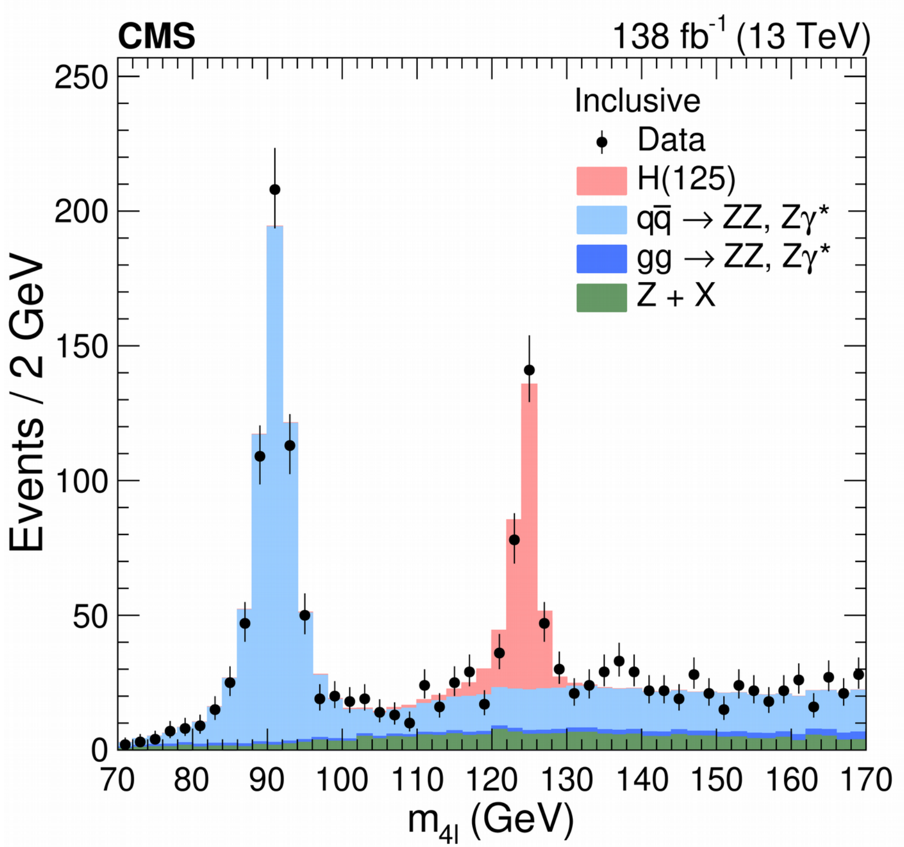
Result: m_H = 125.38 ± 0.11 (stat.) ± 0.09 (sys.) GeV

=> Precision of 140 MeV (0.11%)

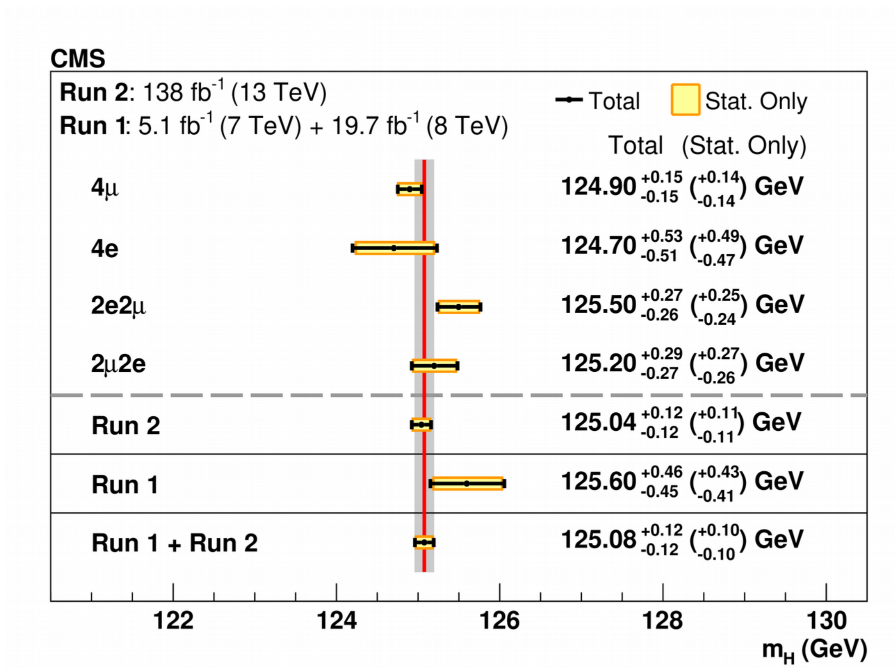
=> Statistical uncertainty bigger than systematic

m_H: H→4ℓ w/ full Run-2 data

H→ZZ*→4ℓ with Run 1 (5.1+19.7/fb) + Run-2 data (138/fb)



CMS-HIG-21-019



Result: m_H = 125.08 ± 0.10 (stat.) ± 0.05 (sys.) GeV

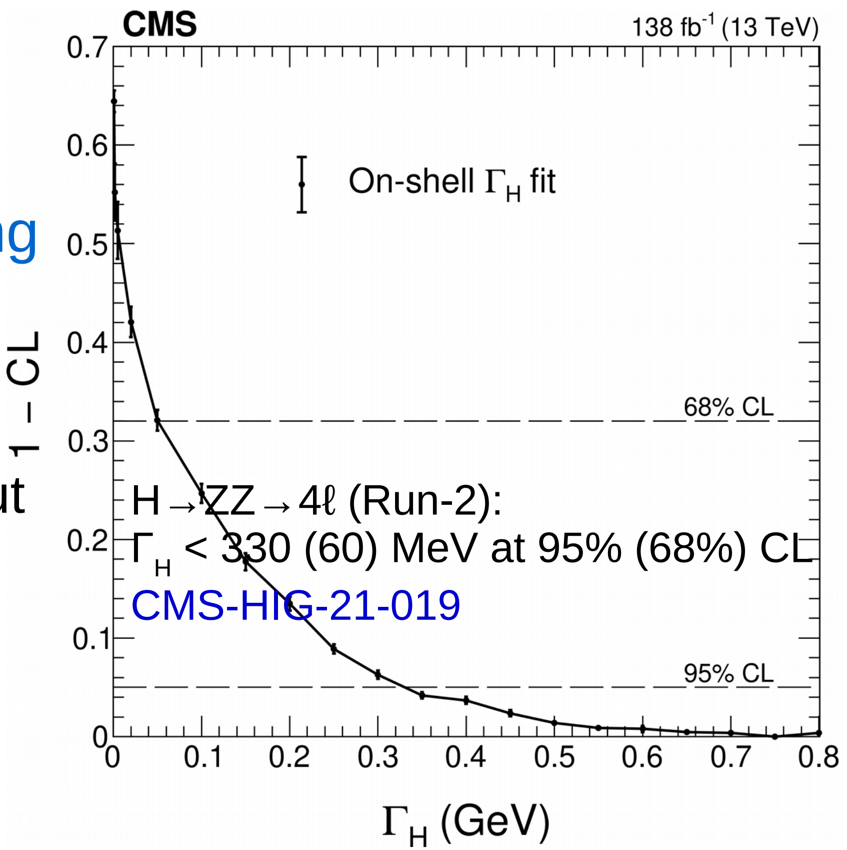
=> Precision of 120 MeV (0.09%)

=> Statistical uncertainty dominates

Measurement with H→γγ using full Run-2 data (and combinaton) ongoing

Total width mesurement

- When m_H is known Γ_H is predicted within Standard Model
  - Γ_H = 4.1 MeV for m_H = 125 GeV
- Deviations from this prediction would mean BSM physics
  - $\Gamma_{H\ inv./undet.}$ < ~10% at 95 CL
- The extraction of H couplings requires making assumption on Γ_H
  - e.g. no BSM decays, and Γ_H computed as a function of all coupling modifiers (κ)
  - or, invisible or undetected decays allowed, but $\kappa_{W,Z} \leq 1$
- Expected Γ_H is much smaller than detector resolution of O(1 GeV) (O(1%))



- Width measurement possible at LHC?
  - Scanning of σ(μμ→H) in function √s with muon collider considered as best method
  - Similarly one can consider σ(ee→H) with e+e- collider, but eeH coupling very small

Γ_H measurement: principles

NCBJ

- Off-shell $H^* \to VV$ (V=W,Z)
  - Competing effects from BW (resonant shape) and $\Gamma_{H\to VV}$
  - ~10% of $gg\to H\to ZZ$ cross section for $m_{zz}>2m_z$
- This feature can be used to measure of the total Higgs width

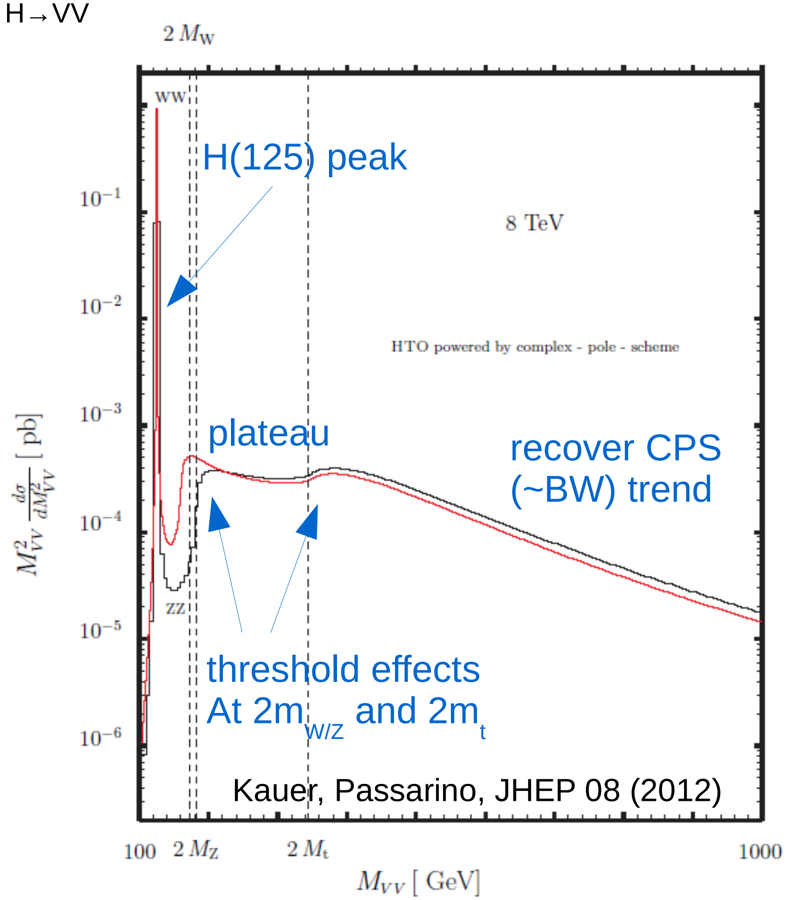
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2 + m^2_H \Gamma^2_H}$$

Integrated around m_H

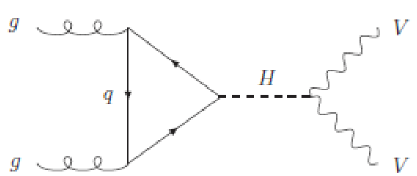
Integrated for $m_{zz} > 2m_z$ where $(m_{zz}-m_H) >> \Gamma_H$

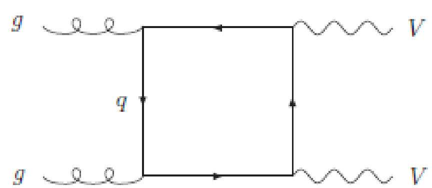
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

=> combined on-shell and off-shell measurements allow to constrain width



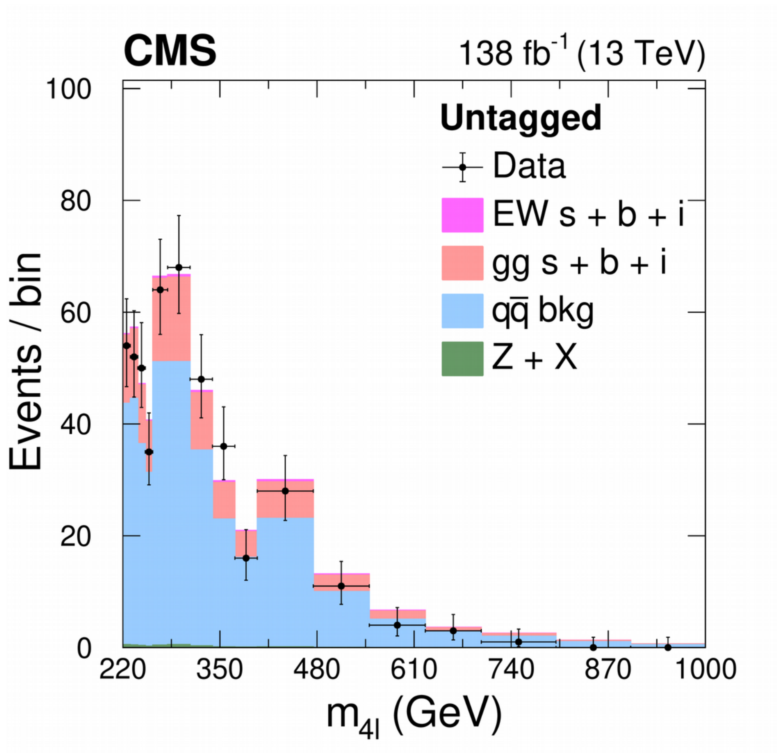
- Significant (destructive) interference with $gg\to VV$ continuum should be accounted for

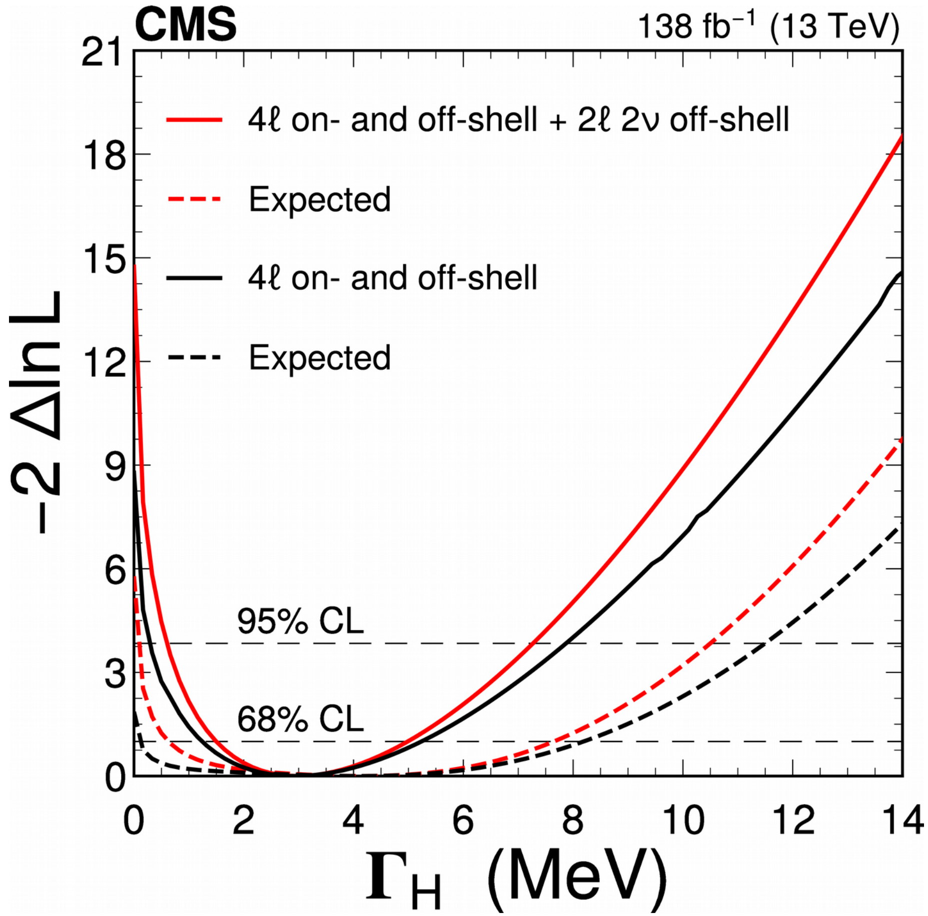




Higgs total width: results

CMS-HIG-21-019





$\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV (in agreement with the SM expectation of 4.1 MeV)

Lack of off-shell production excluded at 3.8 standard deviations

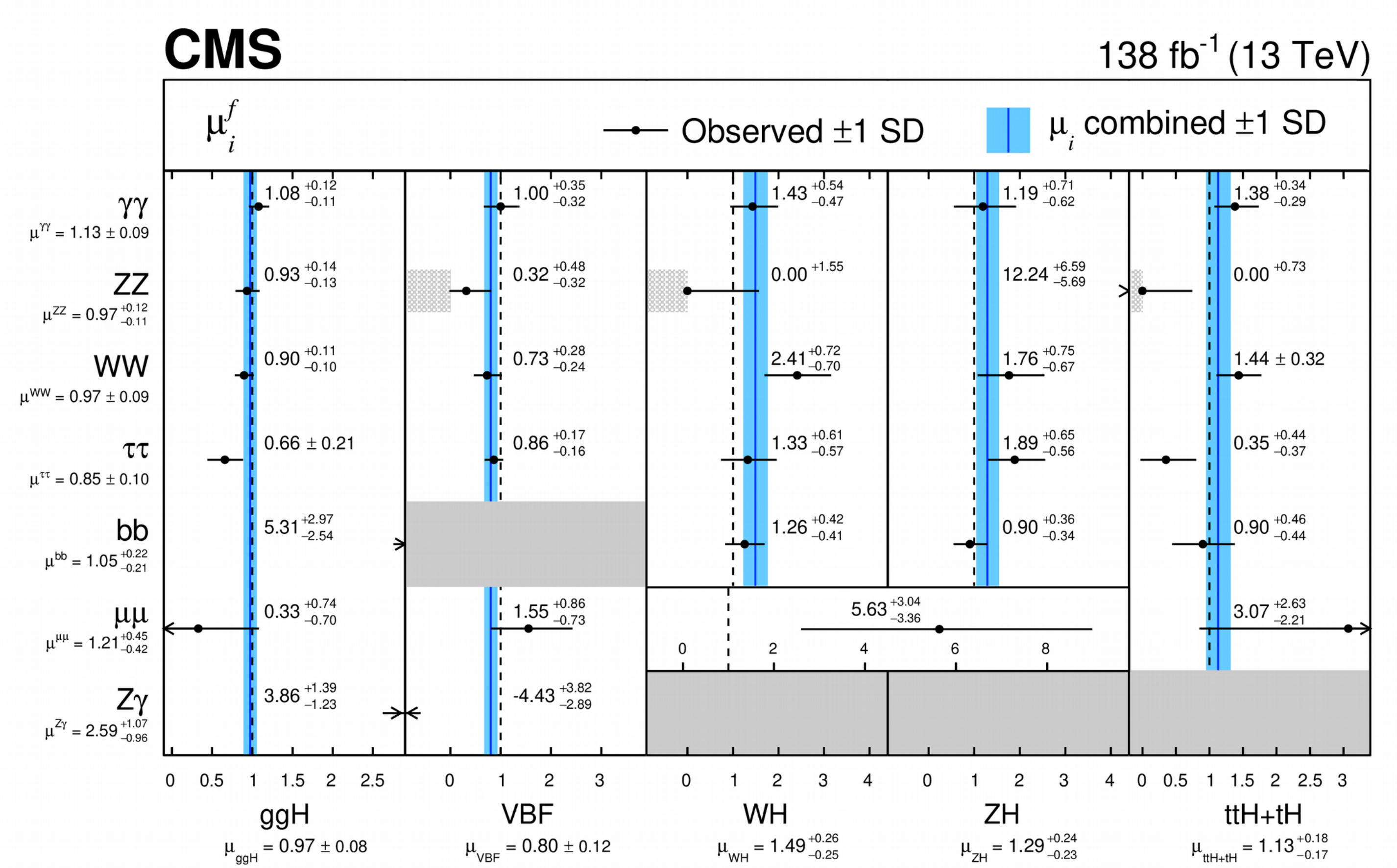
Perspectives on Γ_H measurement

- Off-shell production with ZZ decays provide a way to measure Γ_H at LHC!
  - involves a few (weak) assumptions
- Precision is still small (~50-70%)
  - still plenty room for new physics
- Systematic uncertainties can still improve, e.g. on ZZ background
- Statistical uncertainties on off-shell yields are still large
  - these will improve for sure

Nature 607 (2022), 60

Production and decays

- Production and decay signal strengths (μ) obtained by combination of individual measurements



Signal strength (μ) scales cross sections and branching fractions relative to SM:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}^f_{SM}} \qquad \mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{SM}} = \mu_i \times \mu^f$$

Production and decays

- Production and decay signal strengths (μ) obtained by combination of individual measurements

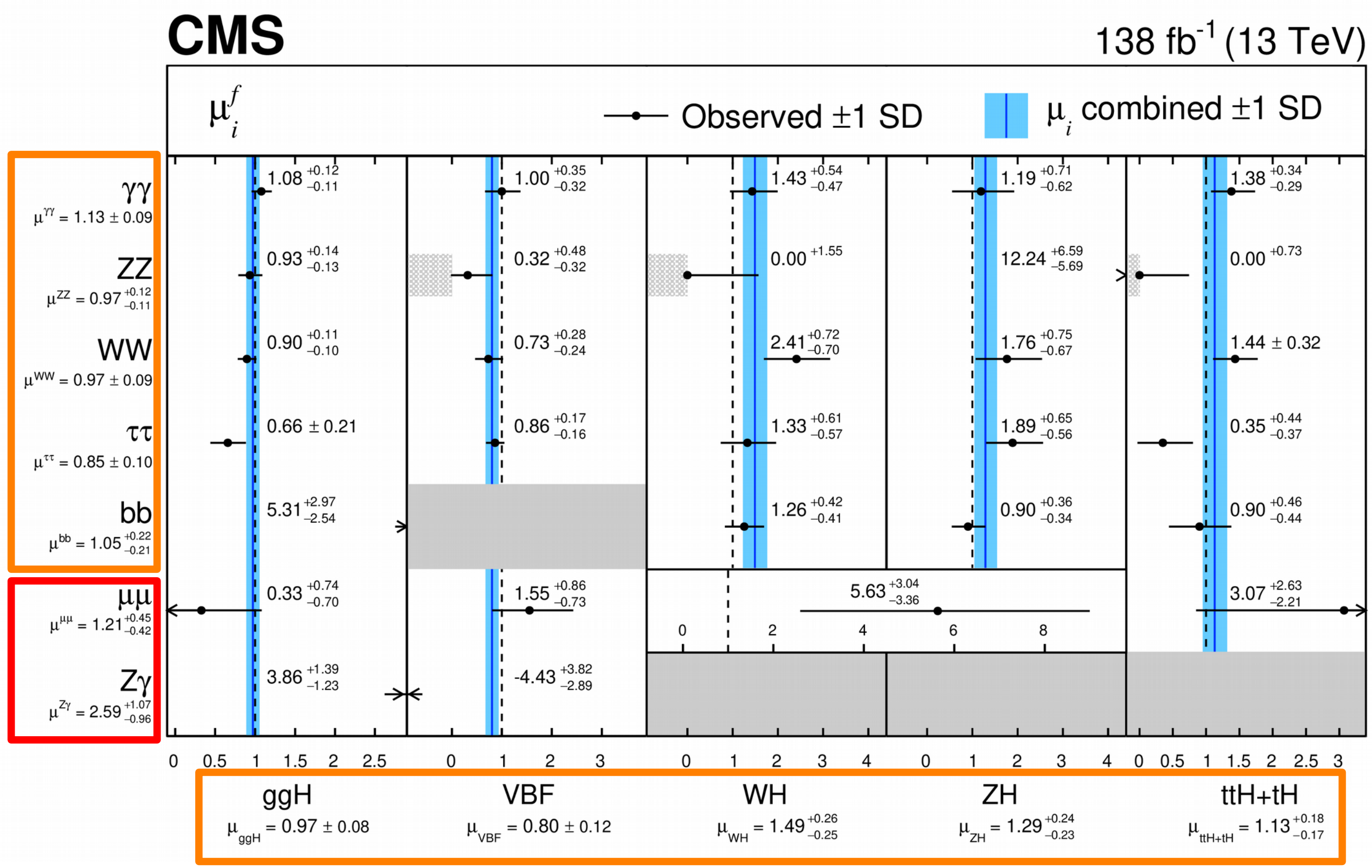
  => **5 main production** and **5 main decay** channels observed (>5σ)

  => great agreement with SM

$H \to VV$ &
$H \to \tau\tau$ ~10%

$H \to bb$ ~20%

Uncertainties on $H \to \mu\mu$, $Z\gamma$ still sizeable



gluon-gluon fusion precision <10%!
10-20% precision on other main production processes

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H → μμ decay

Experimentally easiest access to a coupling to 2^{nd} generation

Search for narrow peak on falling background

Excellent muon resolution, but

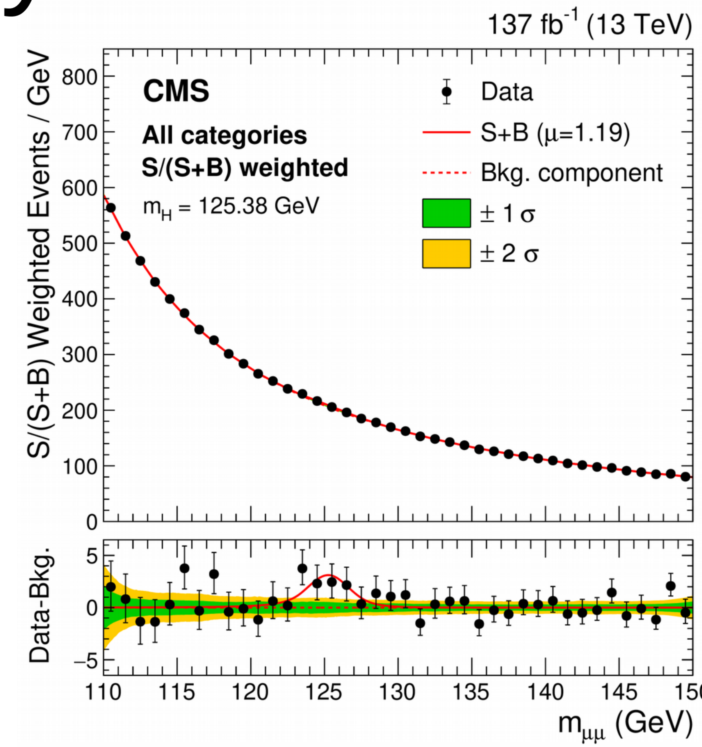
- low Br~$2.2 \cdot 10^{-4}$
- high bkg. from no-resonant μμ production (Drell-Yan)

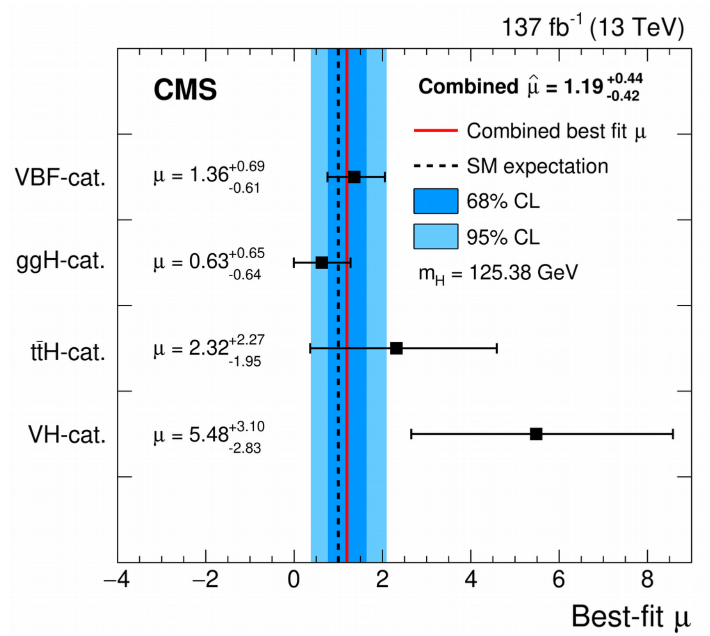
Categories based on production processes and dedicated ML discriminants to increase sensitivity

- Independent on m(μμ)

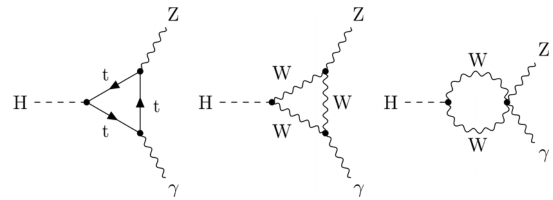
Results:

- μ = 1.19± 0.41 (stat.) ± 0.17 (sys.)
- Significance 3.0σ (exp. 2.5σ) **=> Evidence**





H → Zγ decay

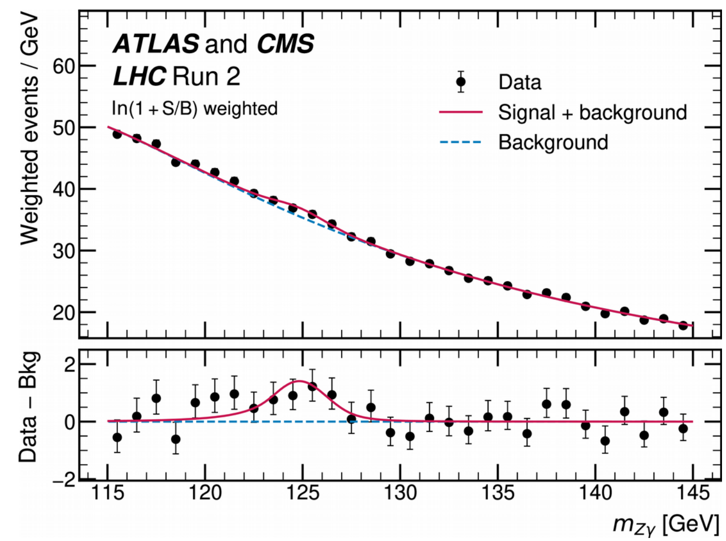


Rare H → Zγ via loops:

- Br ~1.5·10^{-3}
  - further lowered by requirement of Z → ℓℓ
- Sensitive to BSM contributions

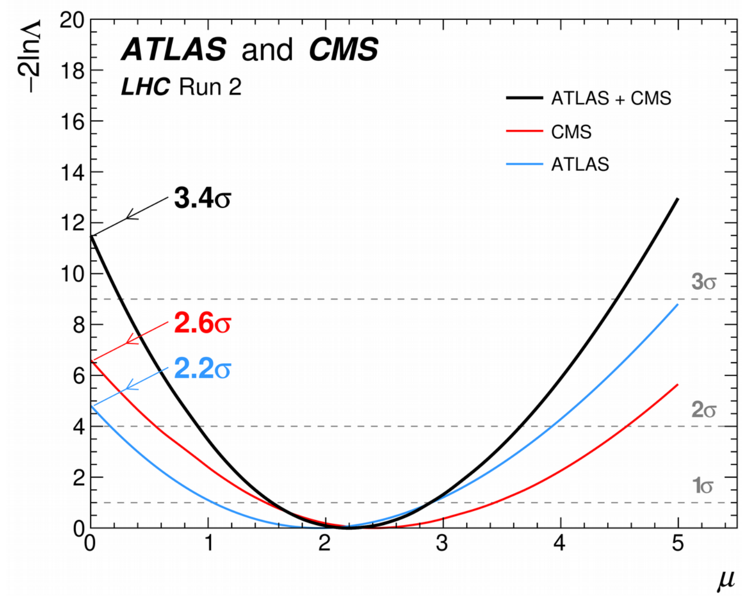
Search for narrow peak in m(ℓℓγ) on falling background

- Excellent resolution
- High bkg. Drell-Yan + ISR/jet



Categories based on production processes and dedicated ML discriminants to increase sensitivity

Combined ATLAS & CMS searches



Results:

- μ = 2.2± 0.6 (stat.) ± 0.3 (sys.)
- Significance 3.4σ (exp. 1.6σ) **=> Evidence**
- Agrees with SM within 1.9σ

Nature 607 (2022), 60

Couplings

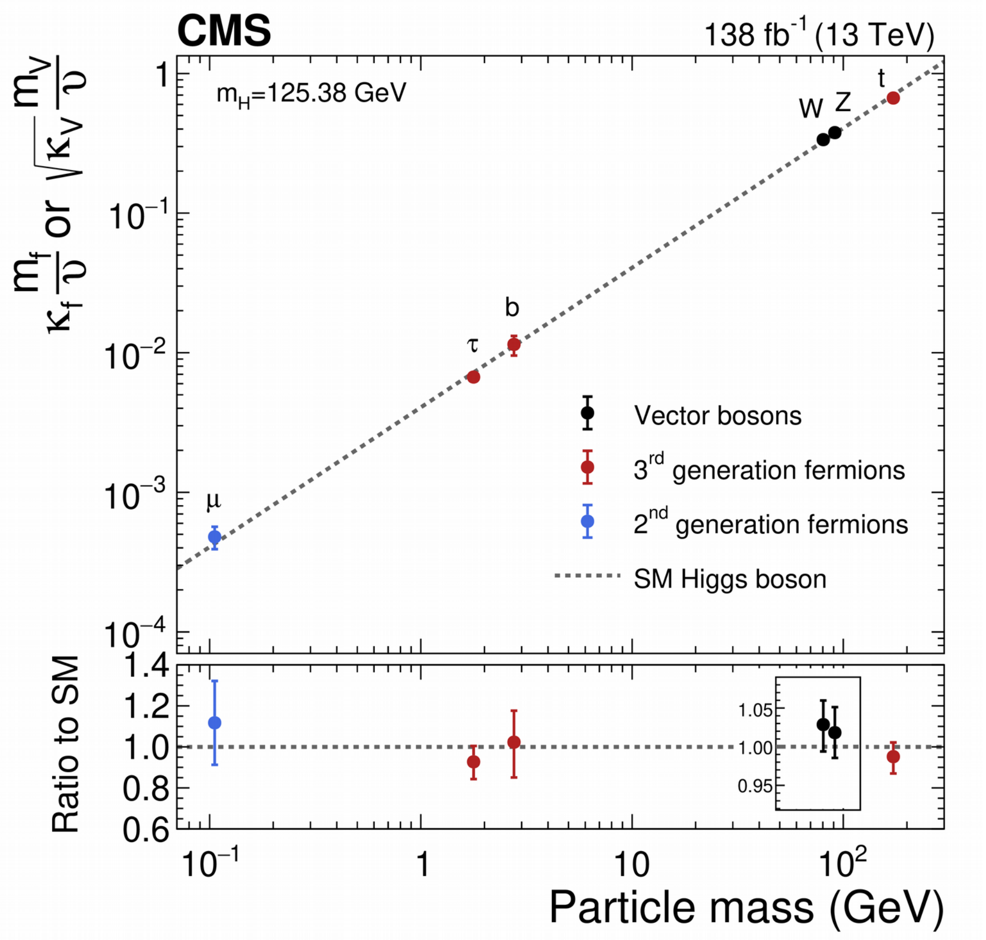
Couplings follow expectation of the BEH mechanism

=> agreement with SM over 3 orders of magnitude

=> κ_V with ~5% precision

=> Observation of couplings with 3rd generation

=> Evidence (>3σ) of coupling with muons



Coupling modifier (κ = g/g$_{SM}$): parametrisation of inclusive production and decay rates $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$ $\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$

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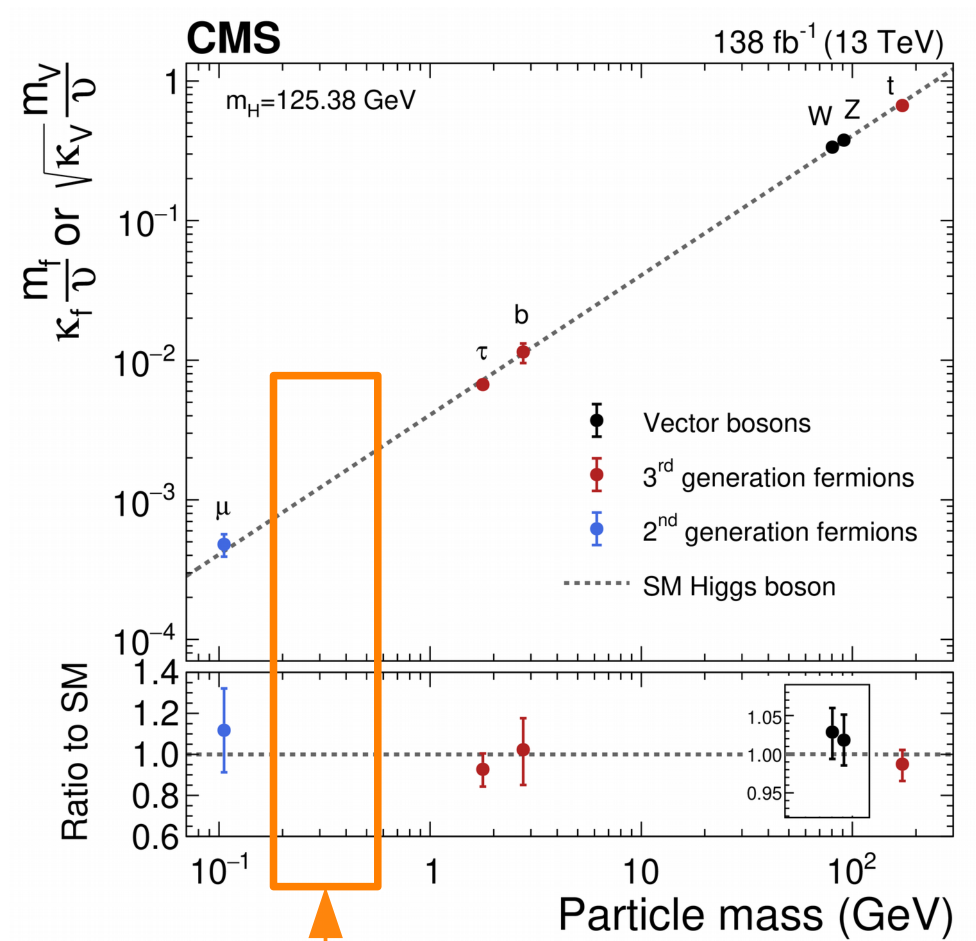


What about coupling to charm?

H → cc decay

Golden channel to probe Higgs-charm coupling (Br~2.8%)

Use VH production to cope with overwhelming bkg.

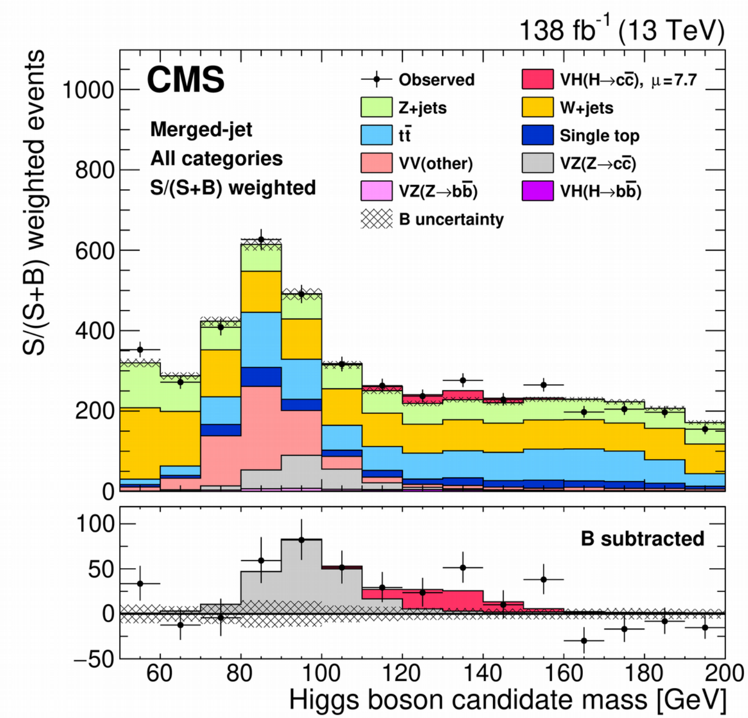
Learn from history of VH(bb) measurements:

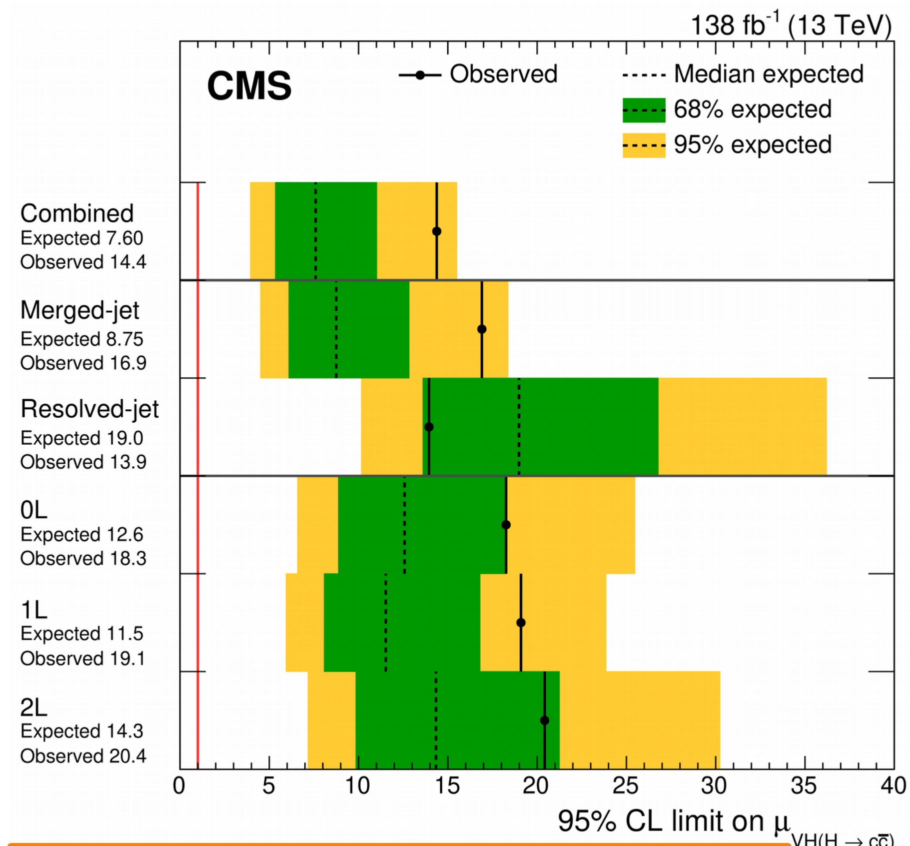
=> Tag leptonically decaying W/Z (with high-p_T)

=> Combine „resolved” and „merged” topologies

=> Exploit Z → cc “standard candle”

Novel GraphNN (ParticleNet) for c-tagging (both topologies) and mass of merged jet



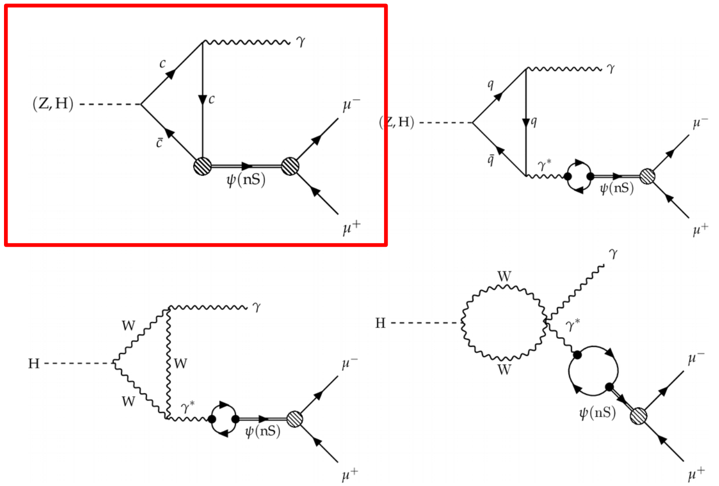


Results:

- μ < 14.4 (exp. 7.6)
- **1.1 < |κ_c| < 5.5 (exp. <3.4)**
- Z → cc with 5.7σ

Rare decays: H → J/Ψγ & Ψ(2S)γ

Higgs decay via c-loop to photon and charmonia



Background from indirect processes

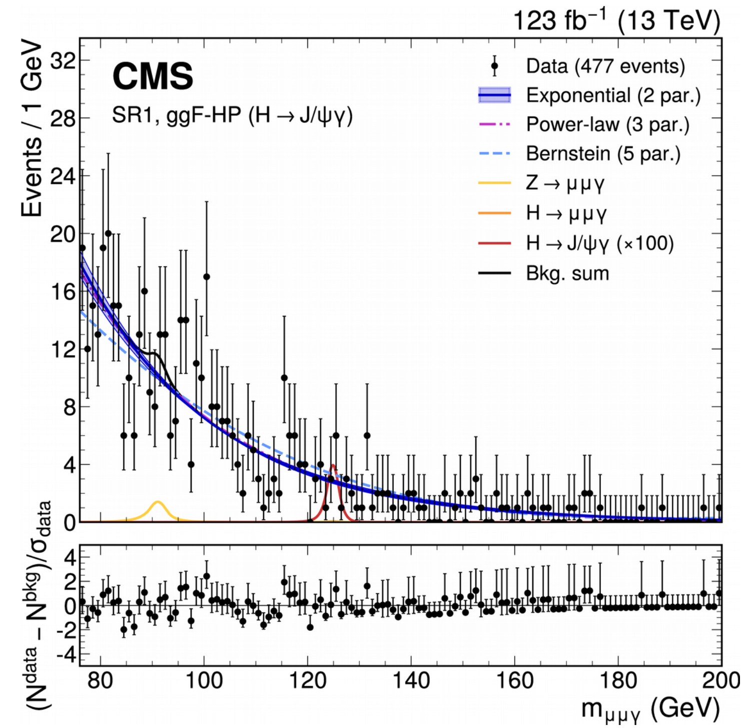
Exploit excellent muon reconstruction

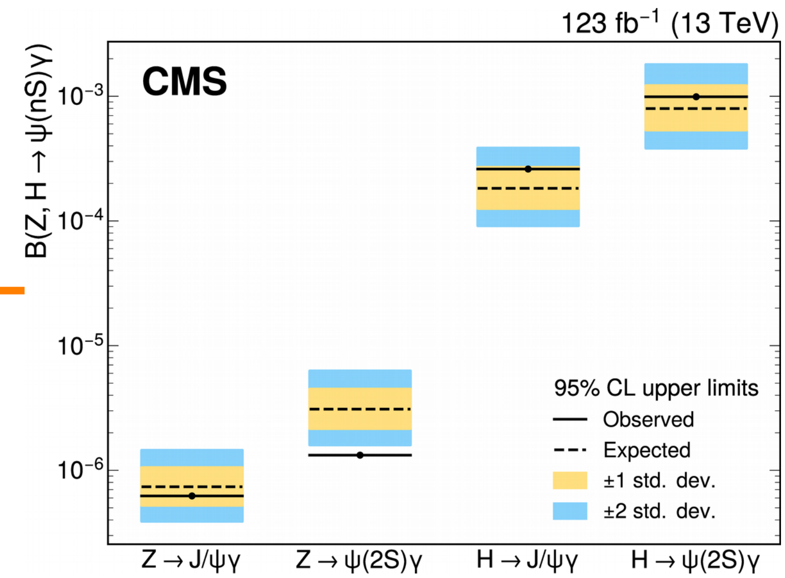
- di-muon + gamma final state

Br < 10^{-6}

Z-boson equivalent ~100 more frequent

$-166 < \kappa_c < 208$



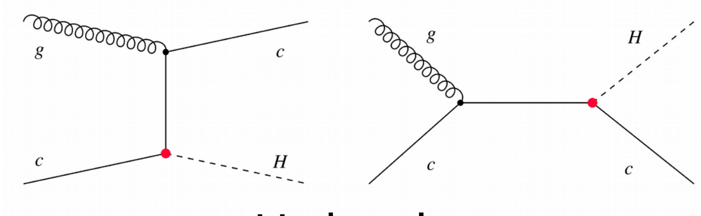


NB: Similar idea used to hunt light-quark couplings with H → ρ/φ/K^{*0} + γ: CMS-HIG-23-005

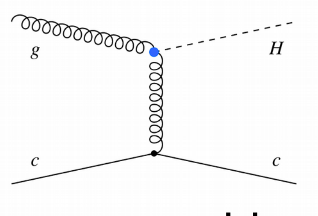
H+c production

Signal „sensitive" cross section ~90 fb

Difficult bkg: ggH and „insensitive" H+c production



cH signal

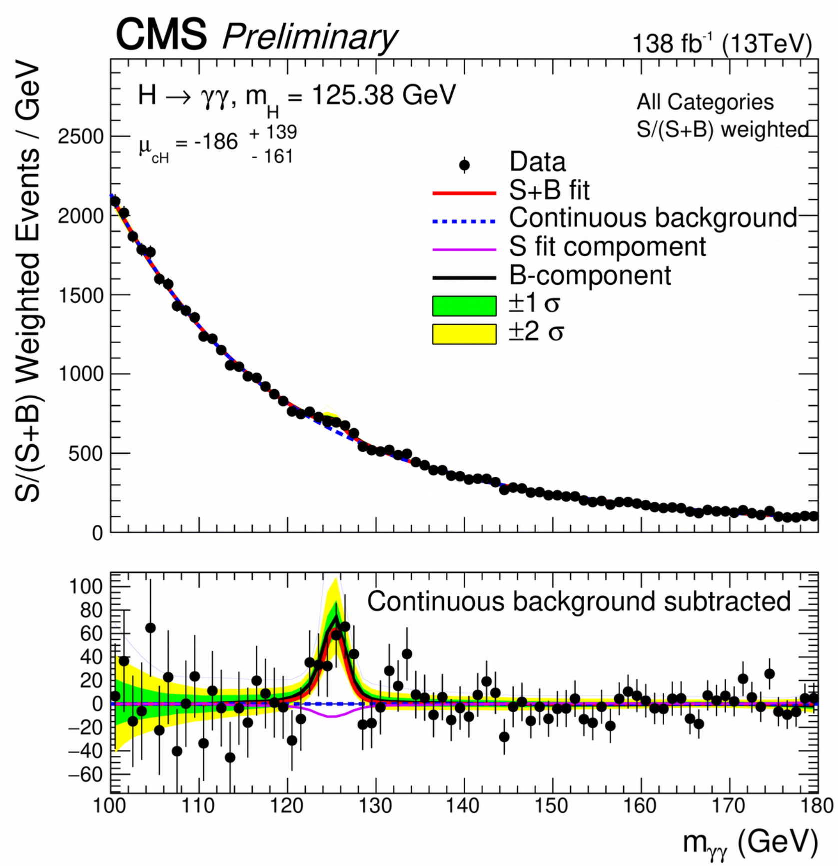


resonant bkg.

Use $H \to \gamma\gamma$ channel

- Well understood
- 0.06 signal events expected (22.5k bkg.)!
- Charm-tagging is crucial

Theoretical uncertainties on cH signal	38%
Theoretical uncertainties on resonant background	59%
Experimental uncertainties on yields	27%
Experimental uncertainties on mass shapes	negligible
Luminosity uncertainties	negligible



Result: $|\kappa_c| < 38.1$ (exp. < 72.5)

Probe of y_c via Higgs kinematics

CMS-PAS-HIG-23-013

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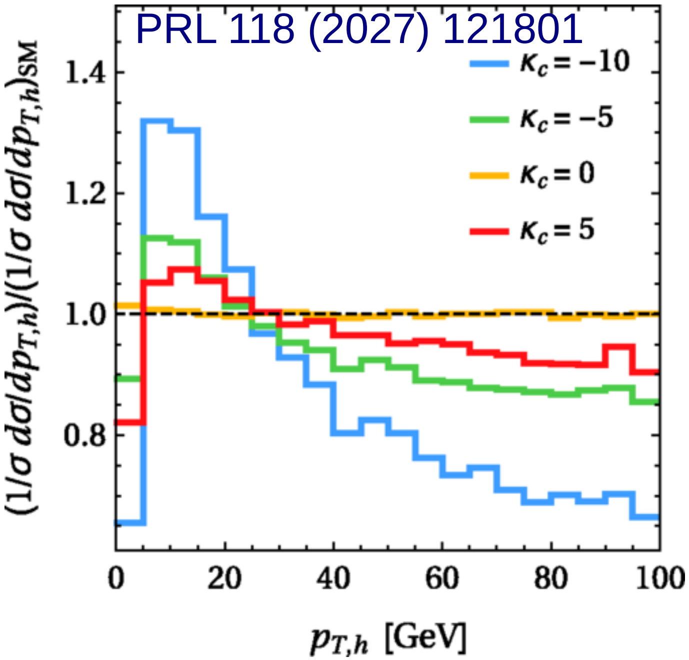
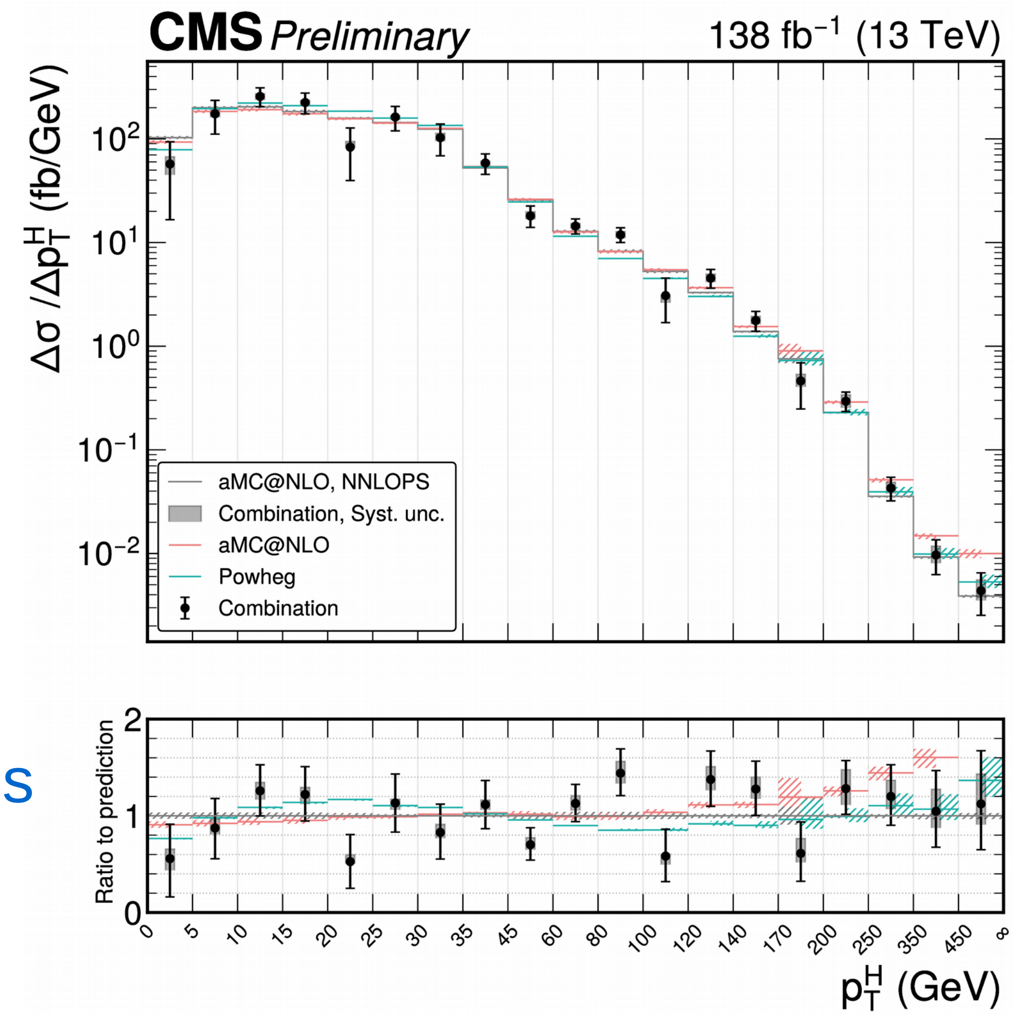
Higgs production sensitive to y_c (p_T, |y|, n_{jets})

=> able to separate b/c contributions





Precise ggH differential cross sections from combinations of $H\to\gamma\gamma$, $H\to 4\ell$, $H\to\tau\tau$, $H\to 2\ell 2\nu$ measurements

Extrapolated to full phase-space

Probe of y_c via Higgs kinematics

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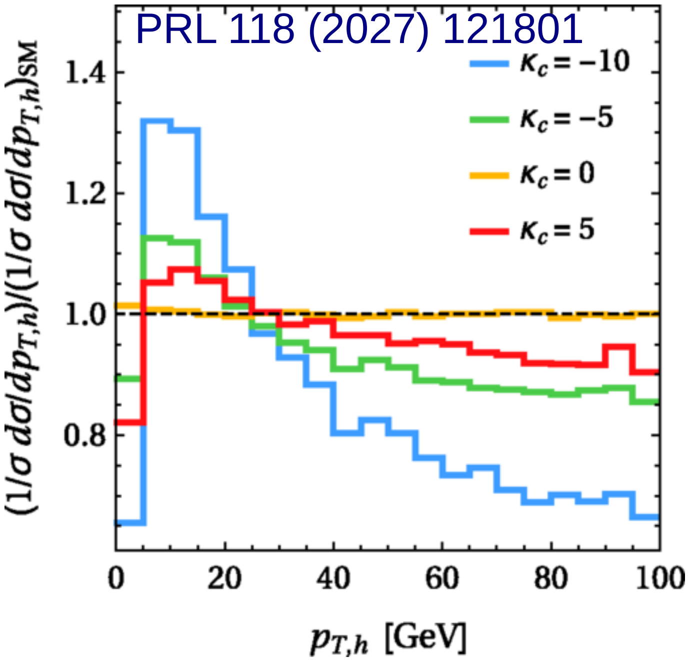
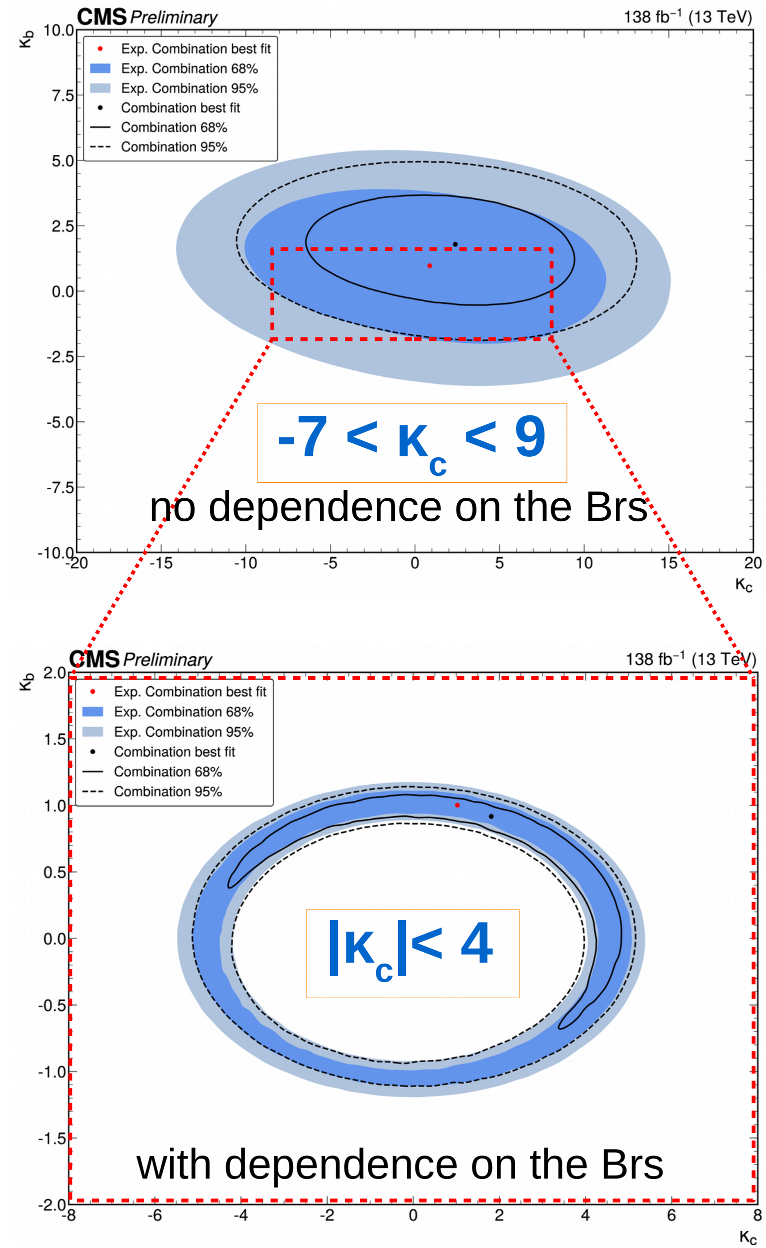




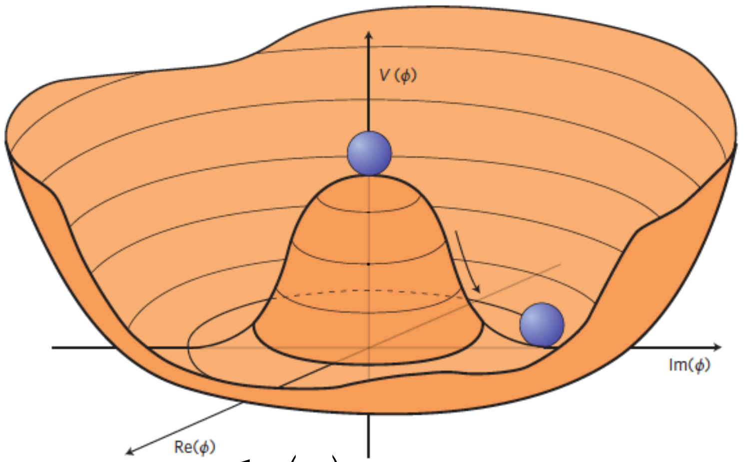
Precise ggH differential cross sections from combinations of $H \to \gamma\gamma$, $H \to 4\ell$, $H \to \tau\tau$, $H \to 2\ell 2\nu$ measurements

Extrapolated to full phase-space

Higgs self-coupling

Determining the Higgs potential, are H self-couplings as predicted by SM?

- Higgs boson self-couplings defined by m_H in SM



$$\langle \Phi_0 \rangle = \frac{1}{2}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{\mu^2/\lambda}$$

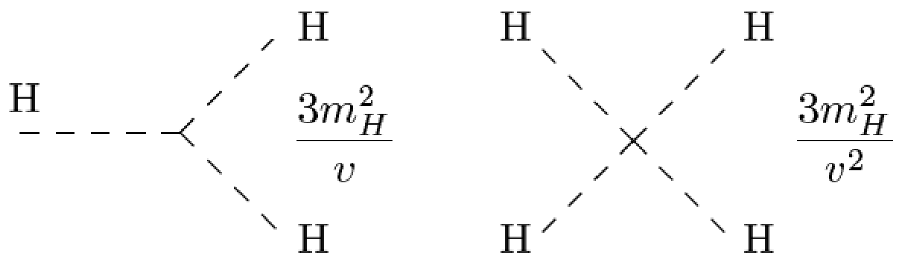
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi \rightarrow v + H$$

$$V = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$

Mass term

Self- and quadratic couplings
Proportional to m_H in SM



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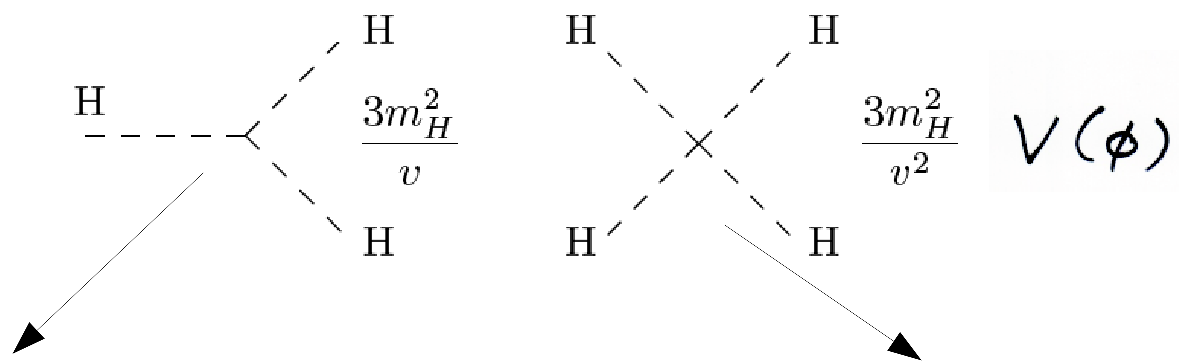
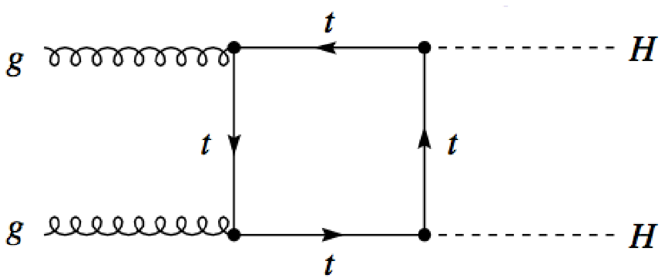
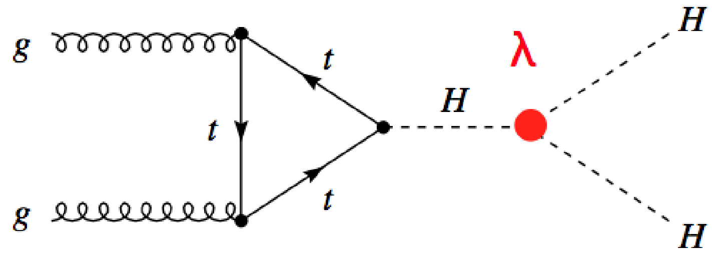


Very difficult due to the “direct” double H production, which interferes with the signal

Probably hopeless in any planned experiment





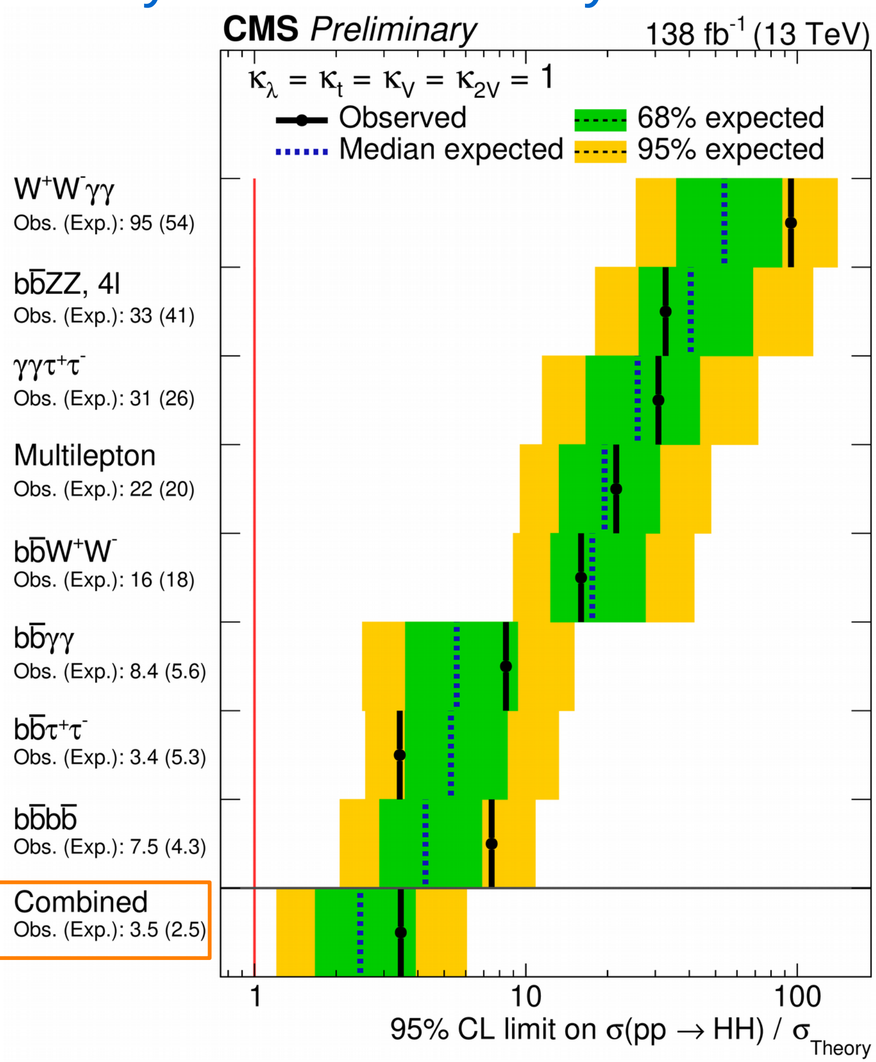
HH events from the self-interaction diagrams are soft

Multitude of HH channels, no golden one => Complex analyses (ML usage)

Search for HH process

NCBJ

8 decay channels annalysed



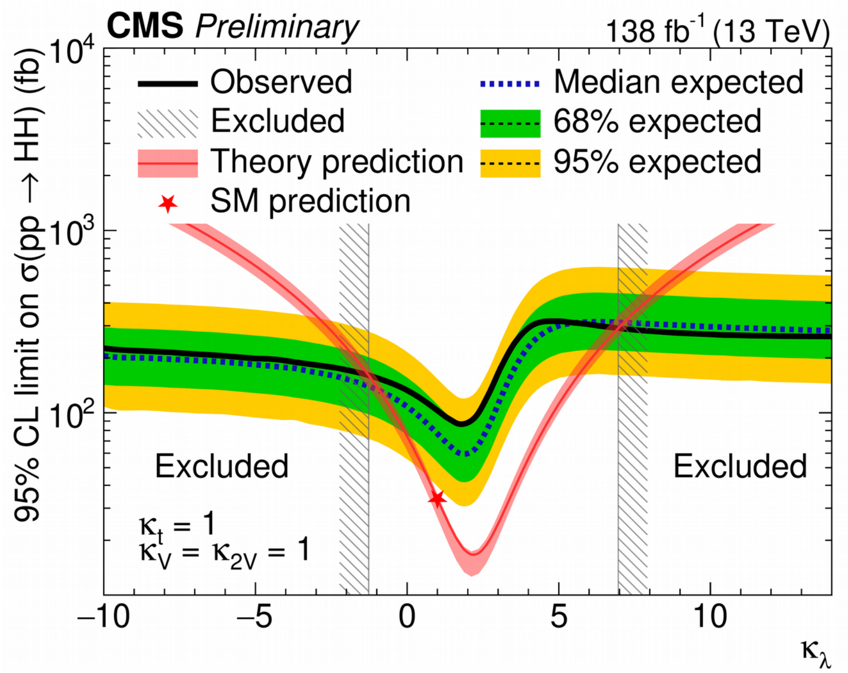
WRT Nature 607

NEW

NEW

NEW

Revised overlap removal



$\kappa_\lambda = \lambda_{HHH}/\lambda_{SMHHH}$ at 95% CL:

- $-1.39 < \kappa_\lambda < 7.02$ (obs)
- $-1.02 < \kappa_\lambda < 7.19$ (exp)

Current (Run-2) sensitivity for HH with ~3×SM cross section
=> need 3/ab of HL-LHC data

Summary

- Only a small sample Higgs measuremnts at CMS presented today
- We have learned much about the Higgs boson since its discovery
  - Its mass is known with ~0.1% precision
  - First measurements of its total witdth (with off-shell decays) performed
  - Cross-section known with up to ~10% precision
  - Couplings to other particles probed
- Still need to establish couplings to 2nd generation fermions
  - Coupling to muons on the reach of HL-LHC (3 s.d. already),
  - Big effort to probe coupling to charm

  and Higgs self coupling
  - HH pair production should be observed in HL-LHC

=> Results in agreement with the Standard Model

- Data-taking continues:
  - Annalysing of Run-3 data (~180/fb collected, >300/fb expected)
  - HL-LHC, with upgraded CMS detector, improved theory calculations and analysis techniques will enable even more precise measurements

BACKUP

Run-3 measurements

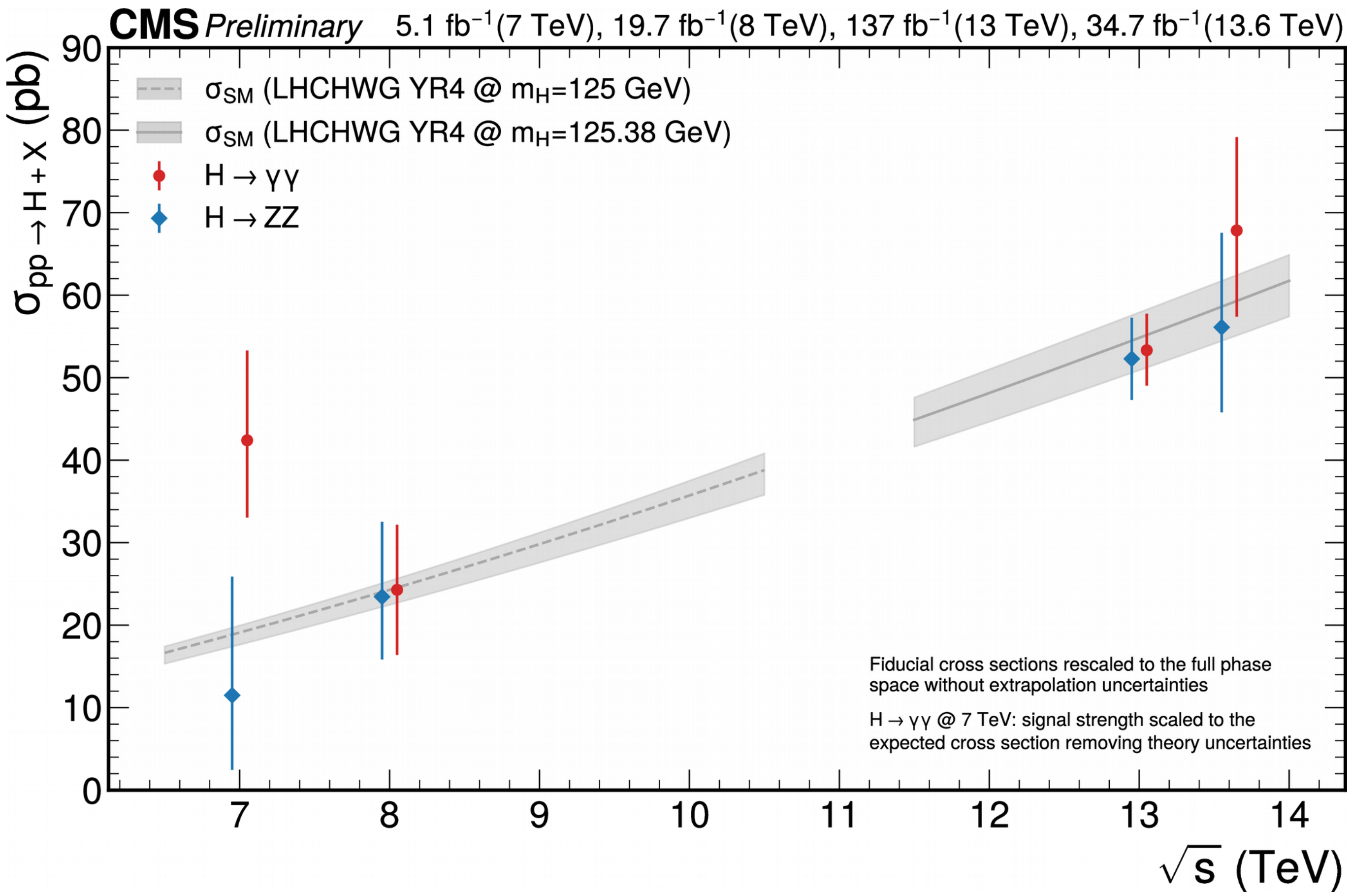
Measurements with 2022 data at 13.6TeV, 34.7/fb

$H \to \gamma\gamma$ (CMS-PAS-HIG-23-014)

$H \to 4\ell$ (CMS-PAS-HIG-24-013)

Cross section at different √s

CMS-PAS-HIG-23-014

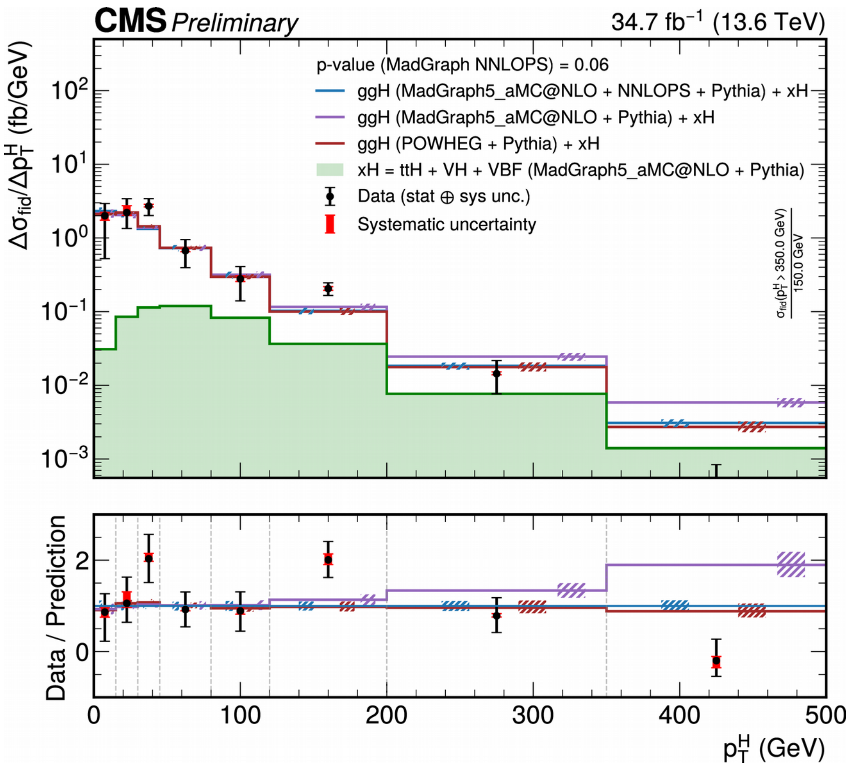


Good agreement with SM

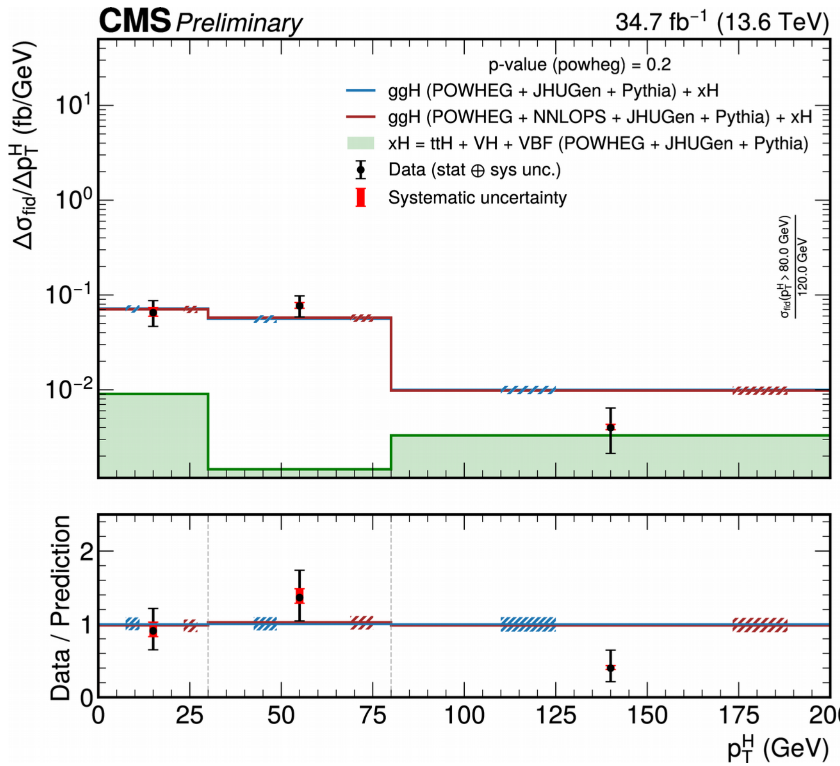
Run-3 measurements

Measurements with 2022 data at 13.6TeV, 34.7/fb

H → γγ (CMS-PAS-HIG-23-014)



H → 4ℓ (CMS-PAS-HIG-24-013)



Good agreement with SM