Measurements of the Higgs boson properties with CMS experiment

E. Di Marco(INFN Roma)

seminario INFN (online), 24/01/2022

The Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Precision Electroweak and QCD

$$+|D_\mu\Phi|^2$$

Gauge interactions

$$+V(\Phi)$$

Higgs potential

$$+\psi_i y_{ij} \psi_j \Phi$$

Yukawa interactions (fermion masses => proton, neutron masses), CKM matrix and CP violation

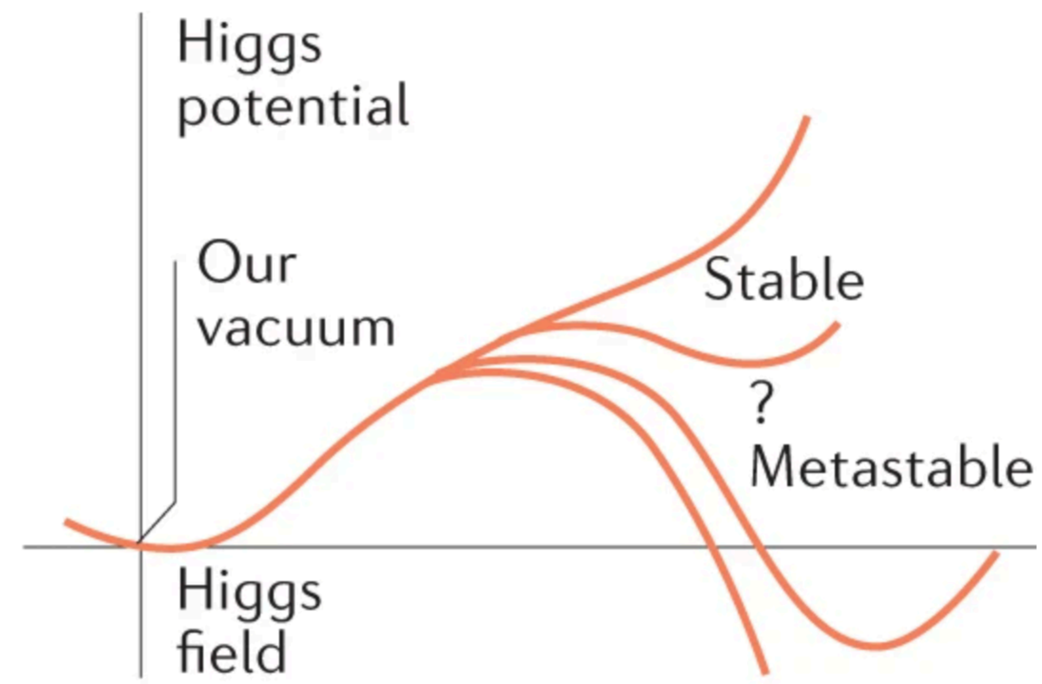
LHC program is to study profoundly the validity of the Higgs and Yukawa sectors of the Standard Model

Look for possible existence of new physics phenomena directly (new particles: $\mathcal{L}_{\text{new}}$), or through breaking of SM predictions in any term of $\mathcal{L}_{SM}$

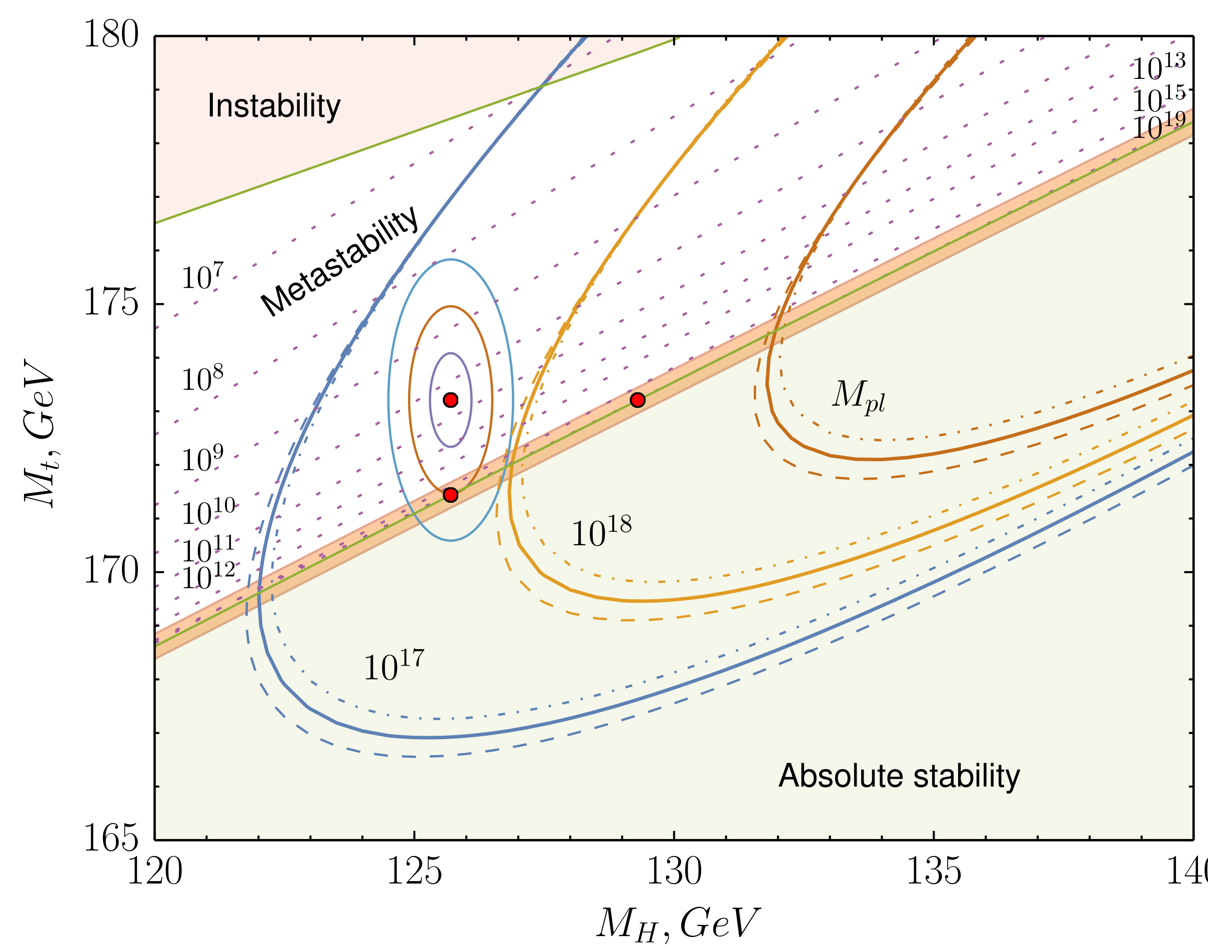
The Higgs potential

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

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

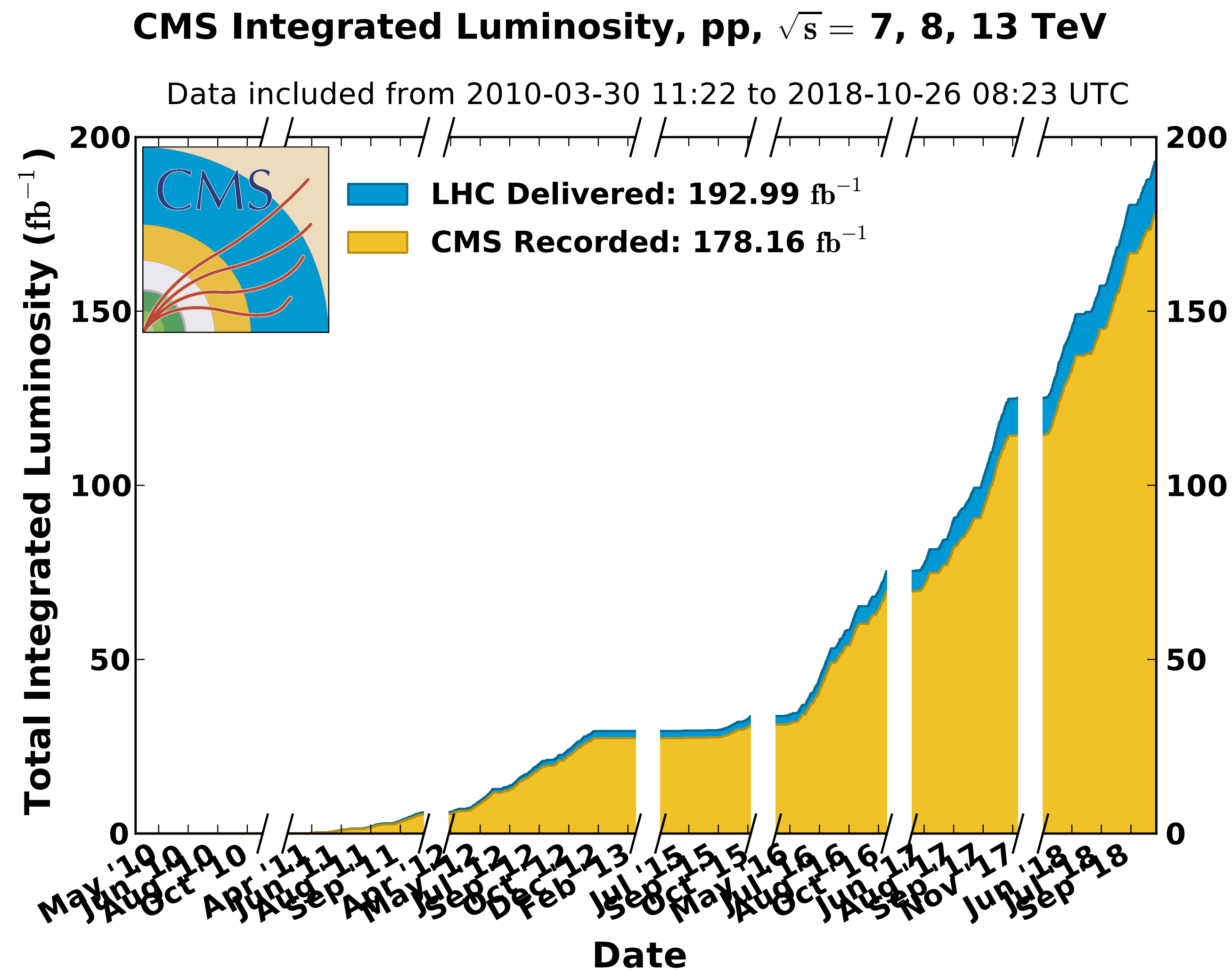


- Responsible of the EWK symmetry breaking and W/Z masses
- Characterizing the Higgs potential means measuring the H boson mass (μ) and the strength of its self coupling (λ)
- $V(\Phi)$ and top mass determine the stability of our vacuum

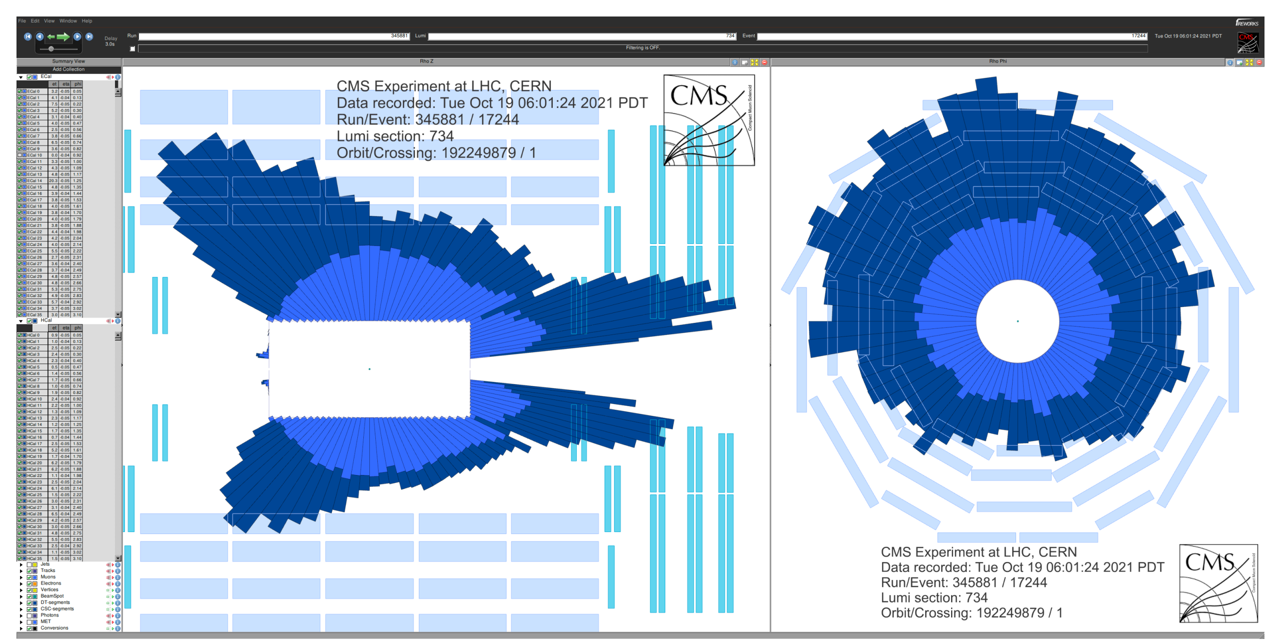


LHC Run-1 and Run-2

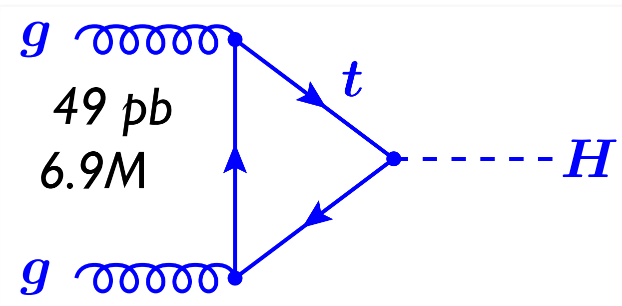
- Excellent performance of the accelerator in Run 1 & 2
- CMS has recorded:
  - **178 fb^{-1}** at 7, 8, 13 TeV data, of which ~90% certified as good for physics analysis
    - Run-1, 7 TeV: 6 fb^{-1}
    - Run-1, 8 TeV: 23 fb^{-1}
    - Run-2, 13 TeV: 151 fb^{-1}



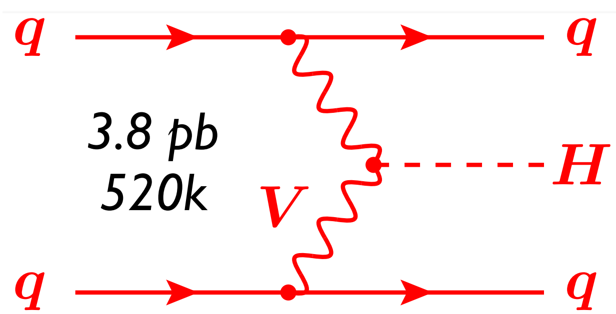
- Pilot Beam Test done in October 2021 brought CMS back to life: **ready for Run-3**



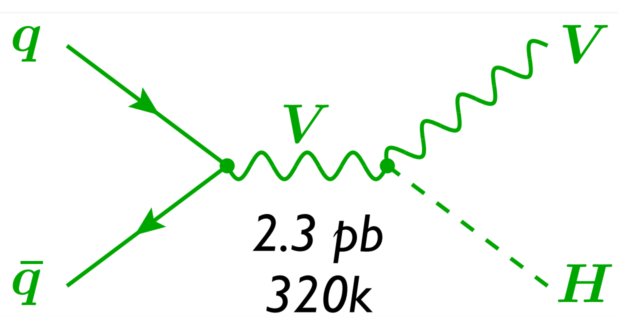
The LHC Higgs factory



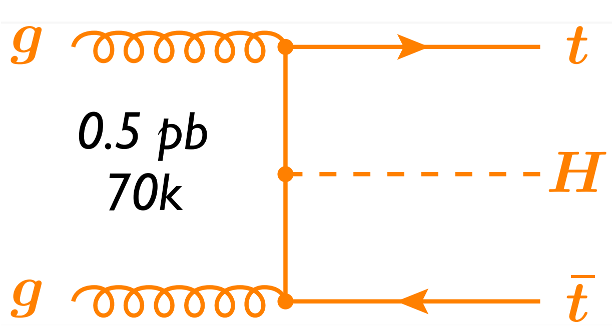
gluon fusion



vector boson fusion (VBF)



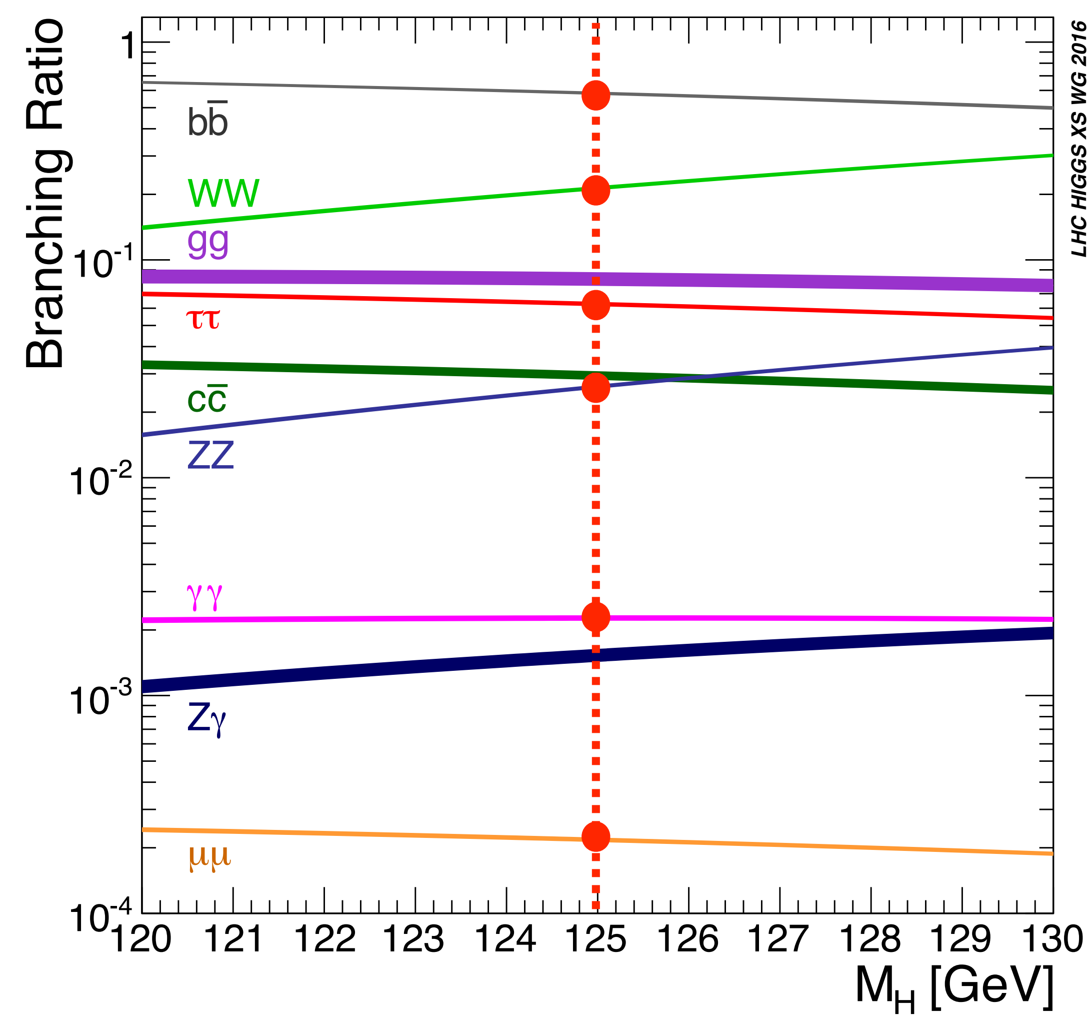
W,Z associated production



$t\bar{t}H$ associated production

σ [pb]
#Higgs produced during Run-2

- About **8 million Higgs bosons** produced by LHC during Run-2
- For $m_H \sim 125\ \text{GeV}$ a wide range of production and decay modes accessible
- Establishing each production mode and studying its properties



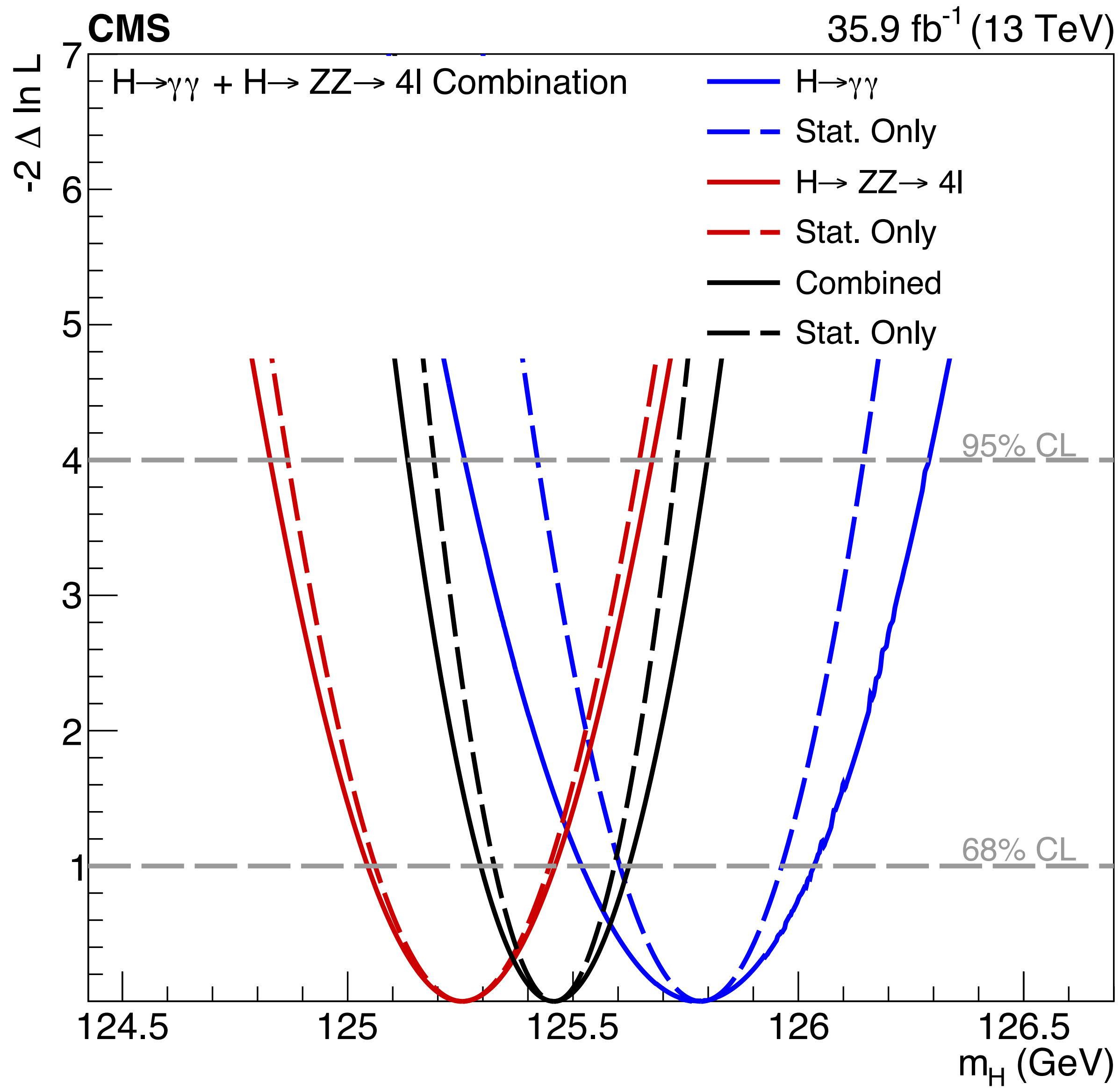
Higgs mass and width

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

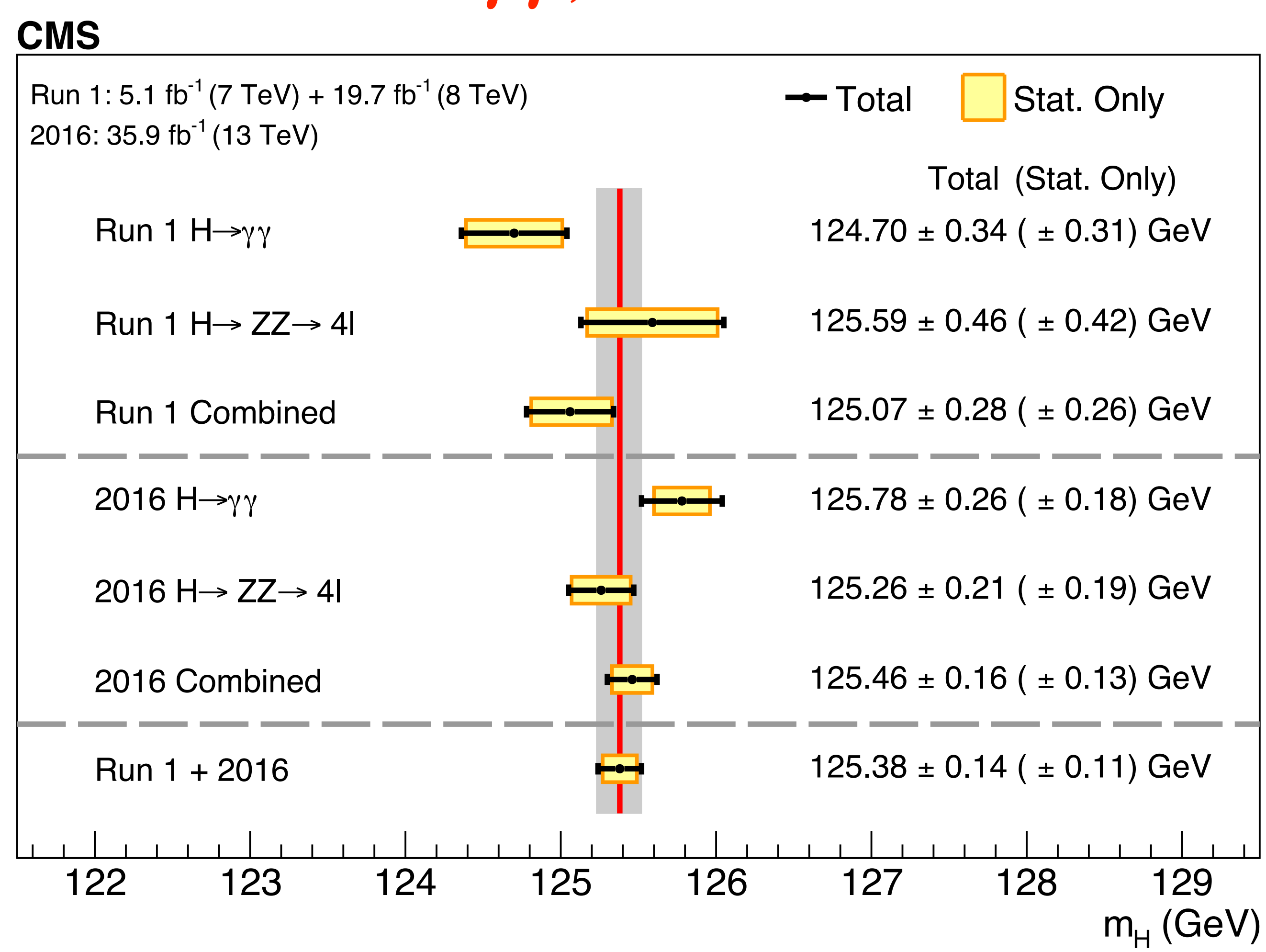
$$= V_0 + \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

Higgs mass

- Measurement done in $H \to 4\ell$ and $H \to \gamma\gamma$ only
- precision dominated by statistics and experimental systematics (e.g. small non-linearities in photon energy response, muon momentum scale)



$H \to \gamma\gamma, ZZ^* \to 4\ell$



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

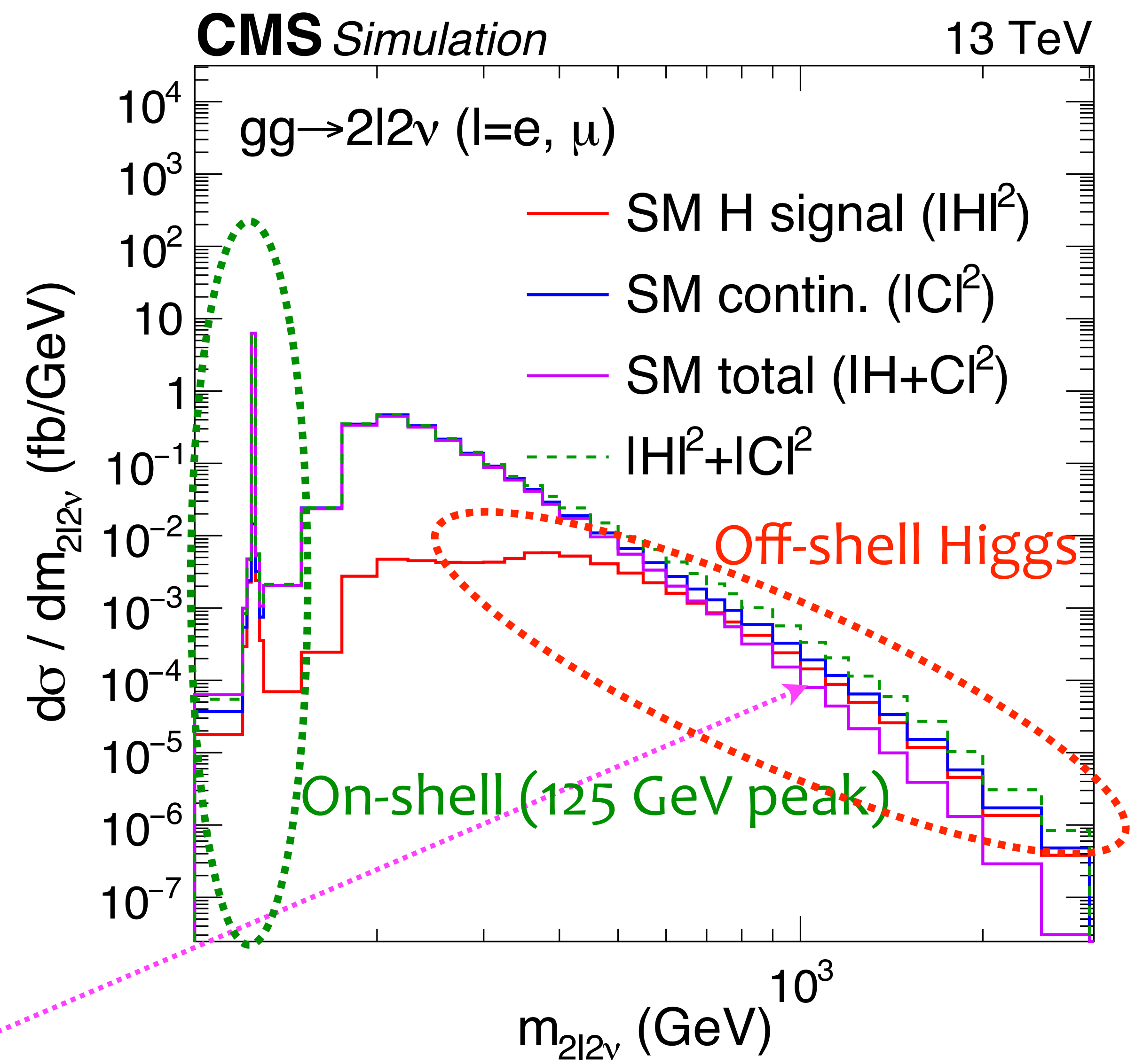
precision on m_H: 140 MeV ≈ 0.1%

- $\Gamma_H^{SM} = 4.1\ \text{MeV}$ (⇔ lifetime $\tau_H \sim 1.6 \times 10^{-22}\text{s}$) too small to be measured directly:
  - **Γ_H<1.1 GeV** from on-shell Higgs, limited by detector resolution
- Textbook use of Heisenberg uncertainty principle:
  - finite particle lifetime => off-shell production must exist
  - Higgs width can be extracted from the ratio of on-shell and off-shell yields
- Interference between amplitudes:

$$pp \rightarrow H \rightarrow ZZ \rightarrow 4\ell$$
$$pp \rightarrow ZZ \rightarrow 4\ell$$

$$\frac{\sigma^{\text{off-shell}}_{vv\rightarrow H\rightarrow 4\ell}}{\sigma^{\text{on-shell}}_{vv\rightarrow H\rightarrow 4\ell}} \propto \Gamma_H$$

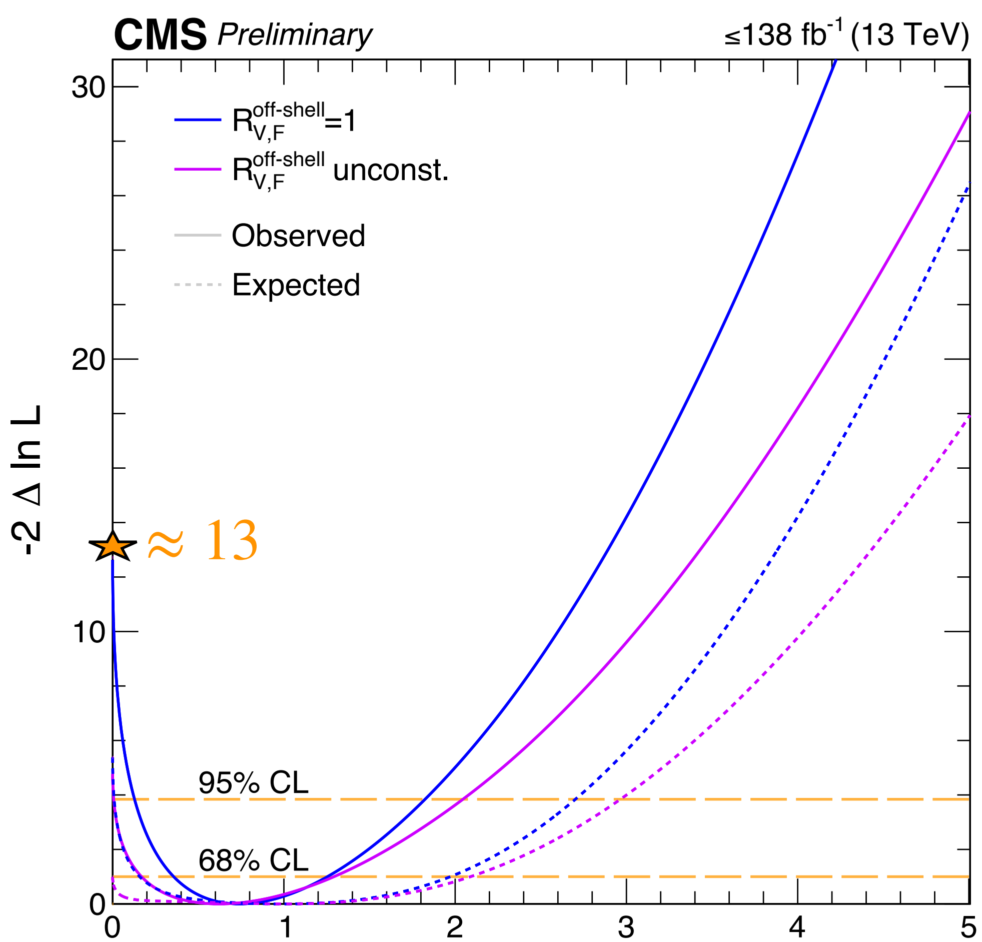
$$vv = gg, WW, ZZ, Z\gamma, \gamma\gamma$$



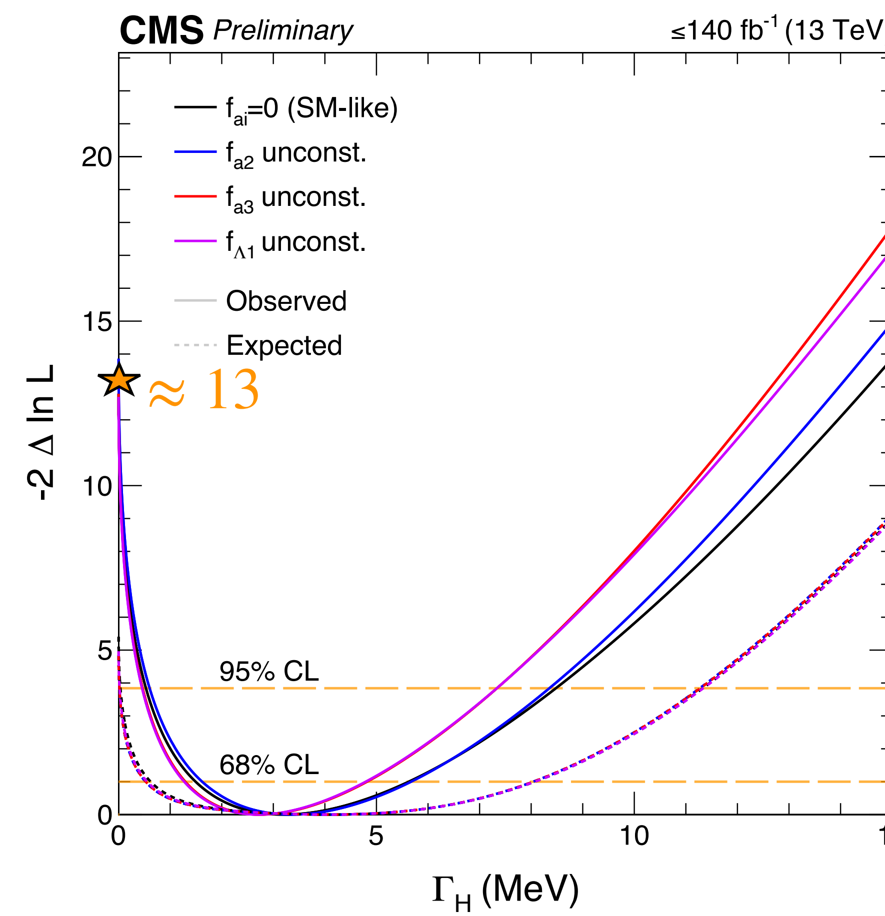
same initial state, same final state => interference between ZZ and off-shell H

Higgs width measurement

- Combination of $H \to 4\ell$, $H \to 2\ell 2\nu$ analysis of full Run2 data CMS-PAS-HIG-21-013
  - $H \to 4\ell$ analysis on full Run2, using on-shell + off-shell events
  - $H \to 2\ell 2\nu$ analysis on full Run2, with $\ell = e, \mu$ final states



$\mu^{\text{off-shell}}$



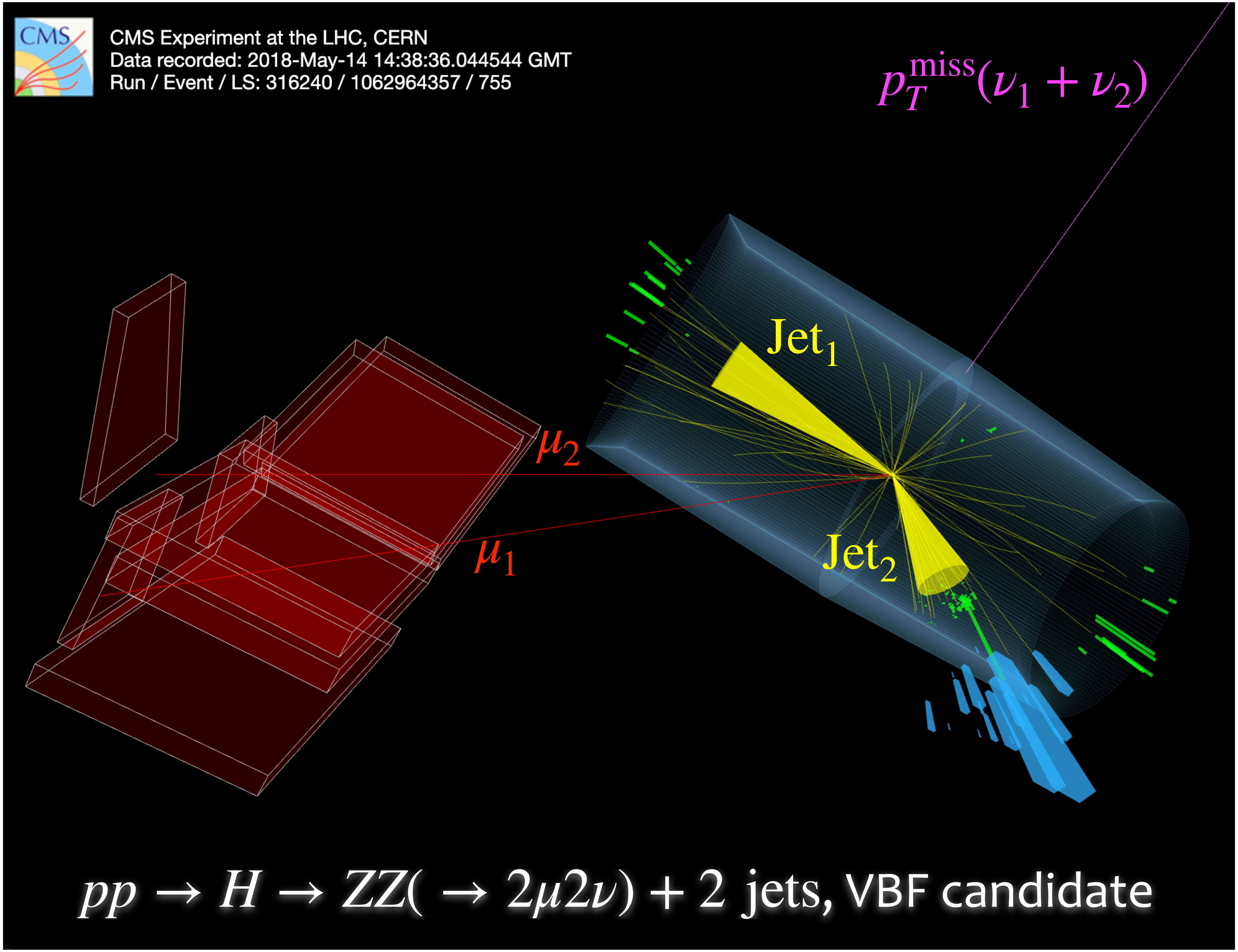
$\Gamma_H = 3.2\,^{+2.4}_{-1.7}$ MeV

$\sigma(\Gamma_H) \sim 50\,\%$: most precise measurement up to now:

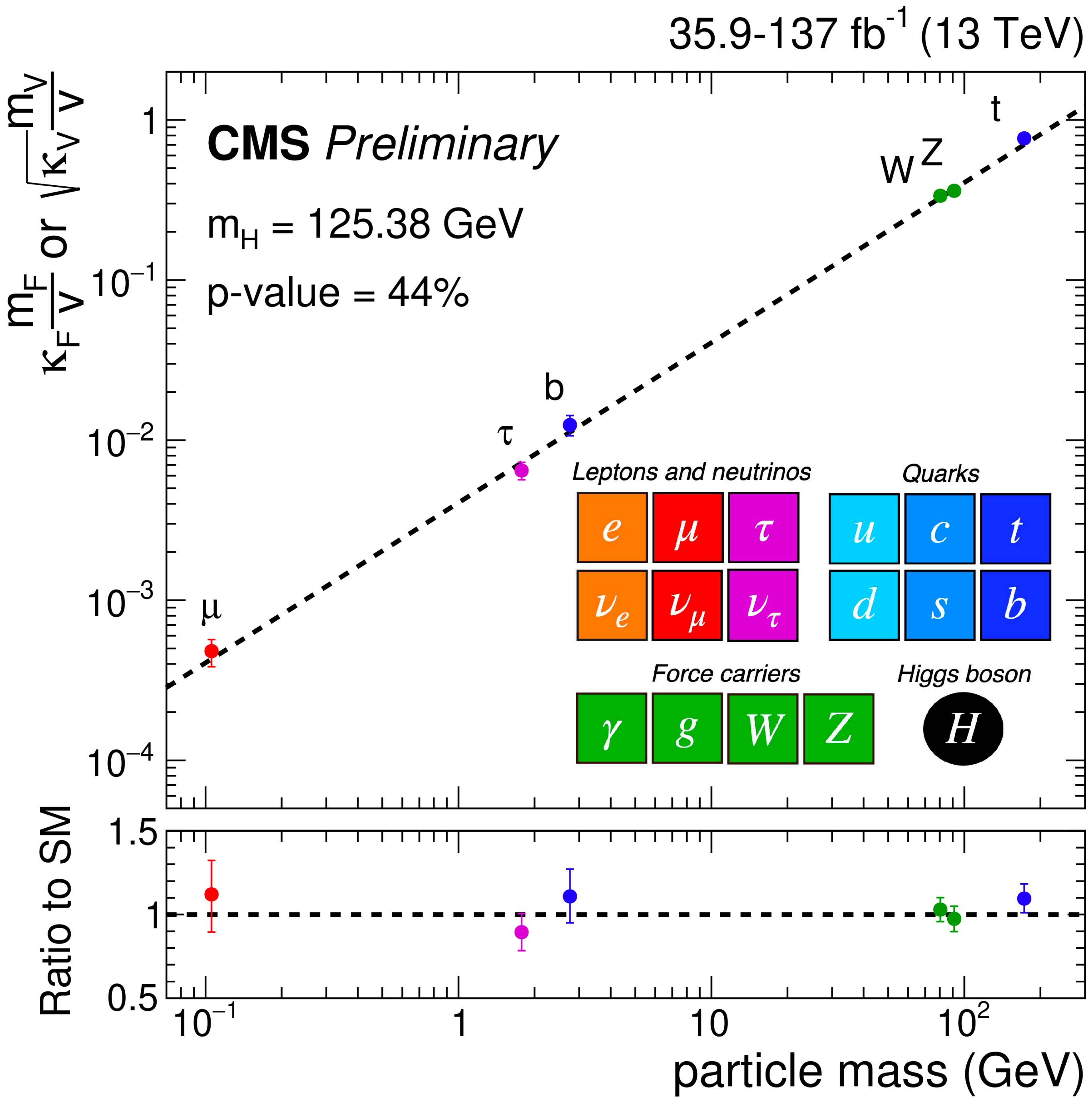
first evidence for off-shell Higgs production at **3.6σ**

Lifetime of the Higgs boson: $\tau_H = 2 \times 10^{-22} s$

$H \to ZZ \to 2\mu 2\nu_\mu$ candidate

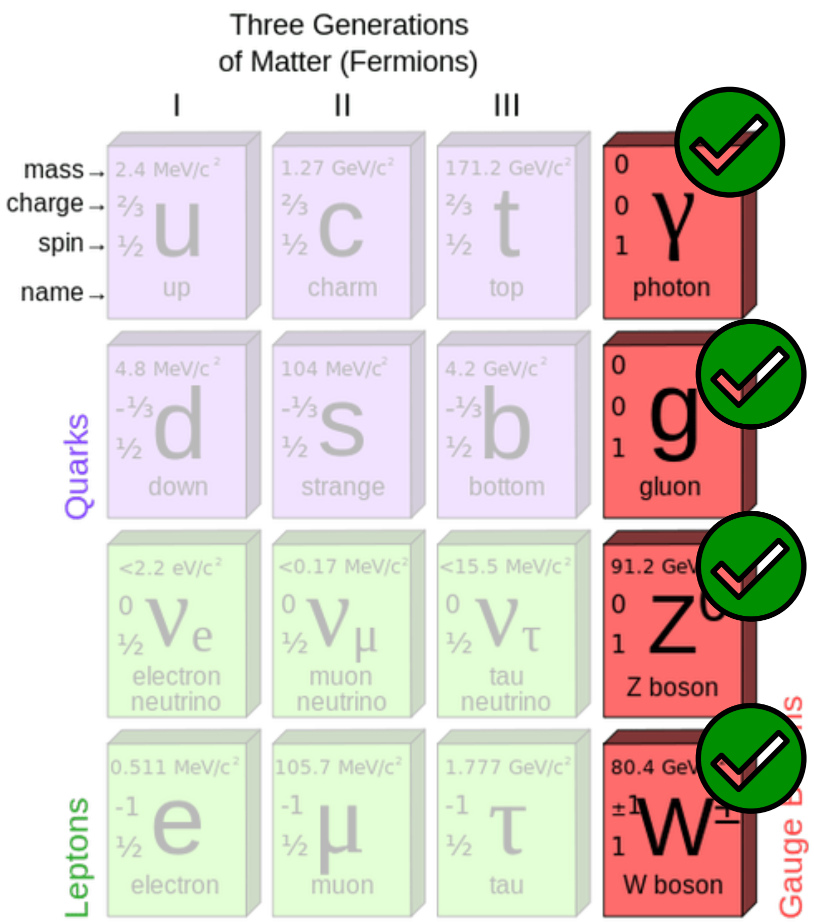


Higgs boson couplings with SM particles

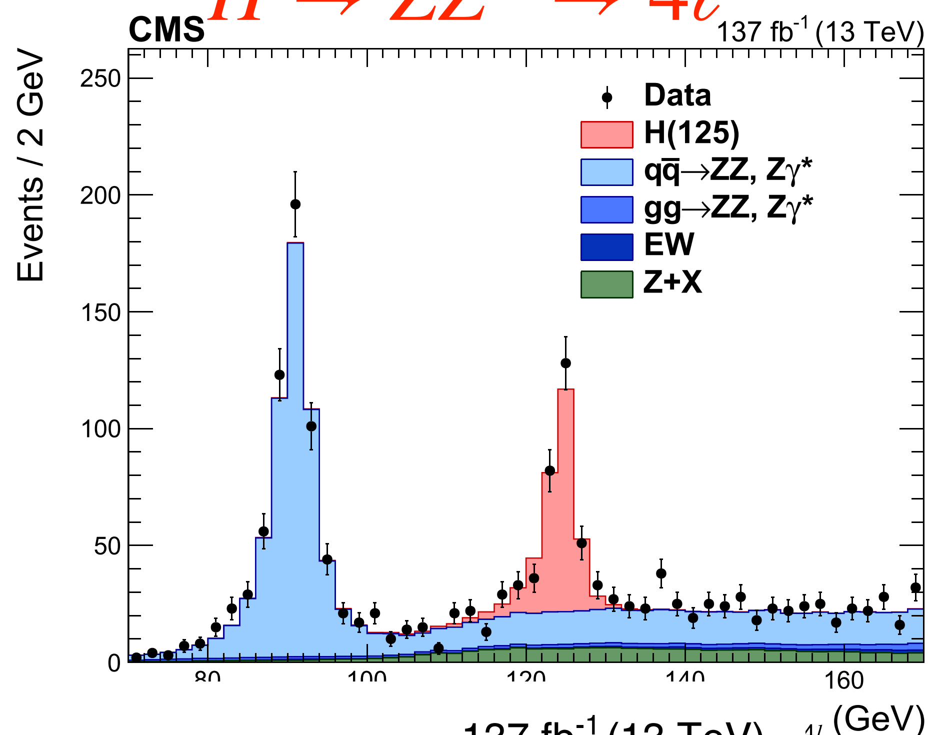


Establishing the scene

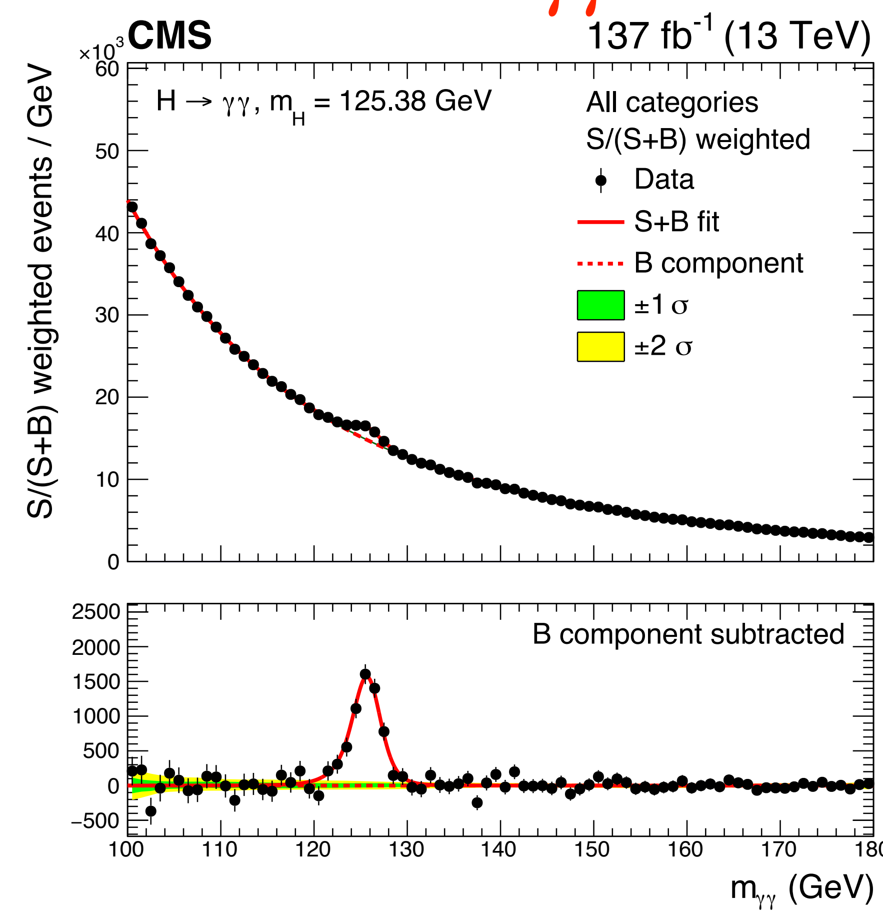
- Couplings to vector bosons in **H→ZZ, H→WW** and indirectly in **H→γγ** well established since Run-1
  - gluon-fusion production measured indirectly (15% uncertainty)
  - VBF production observed at 5.4σ (ATLAS+CMS)



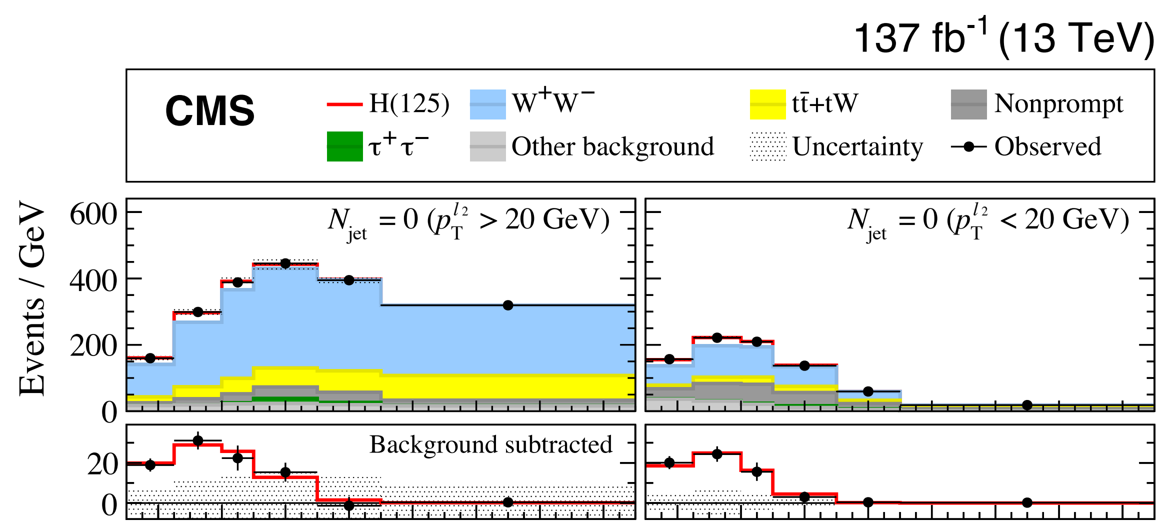
$H \to ZZ^* \to 4\ell$



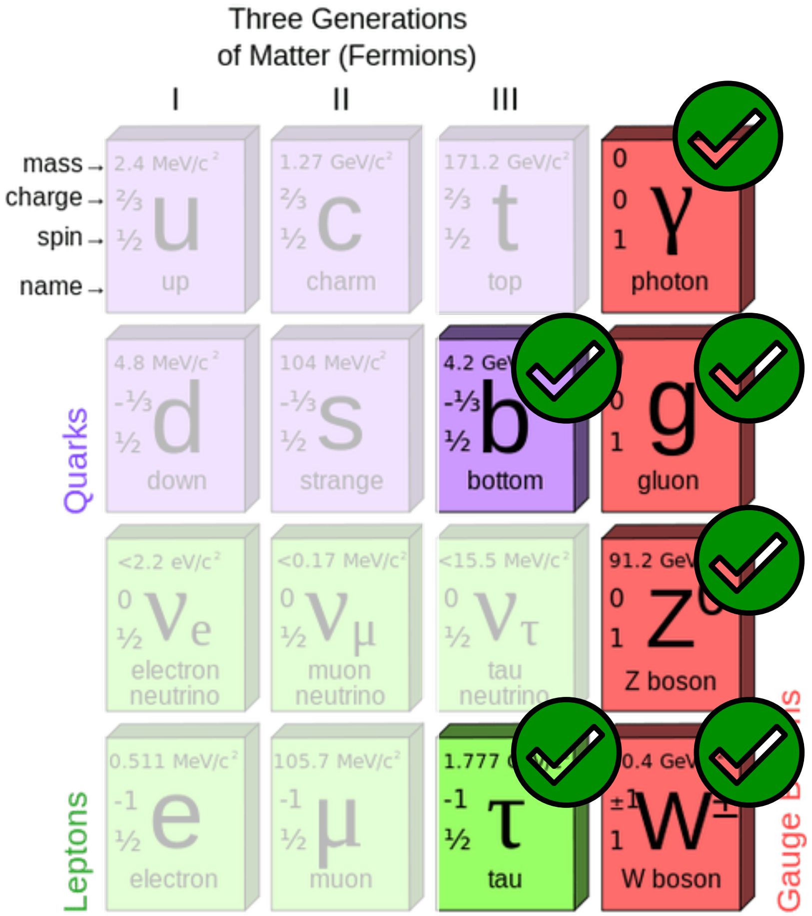
$H \to \gamma\gamma$



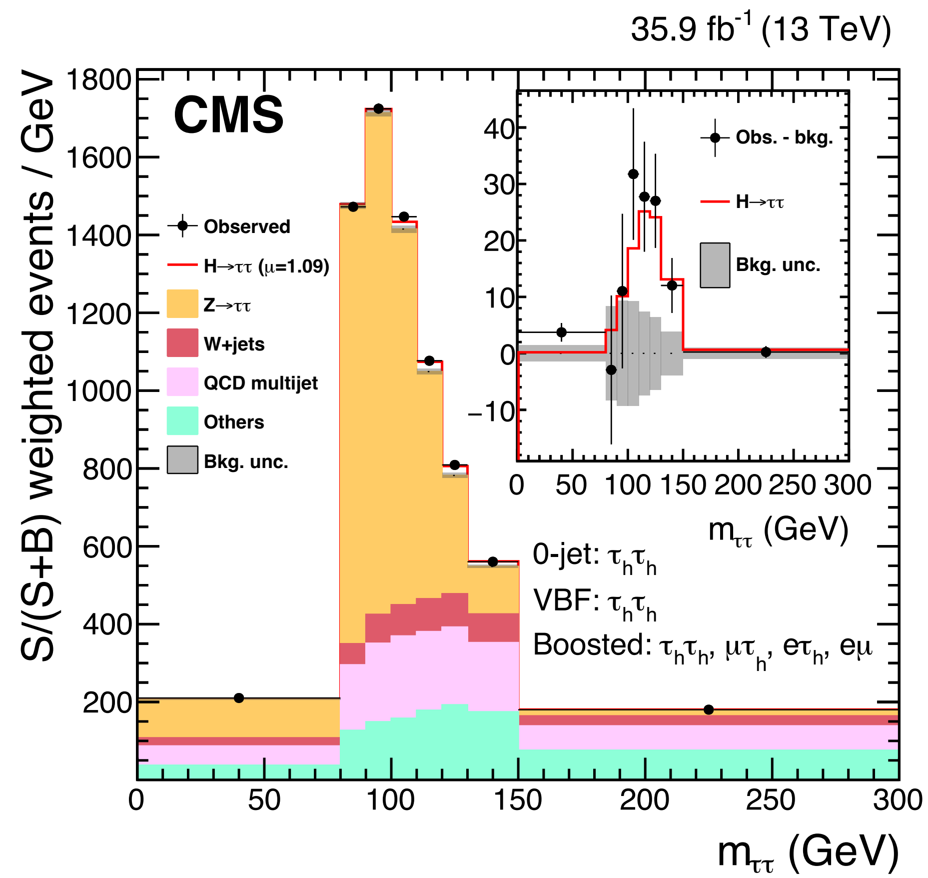
$H \to WW^*$



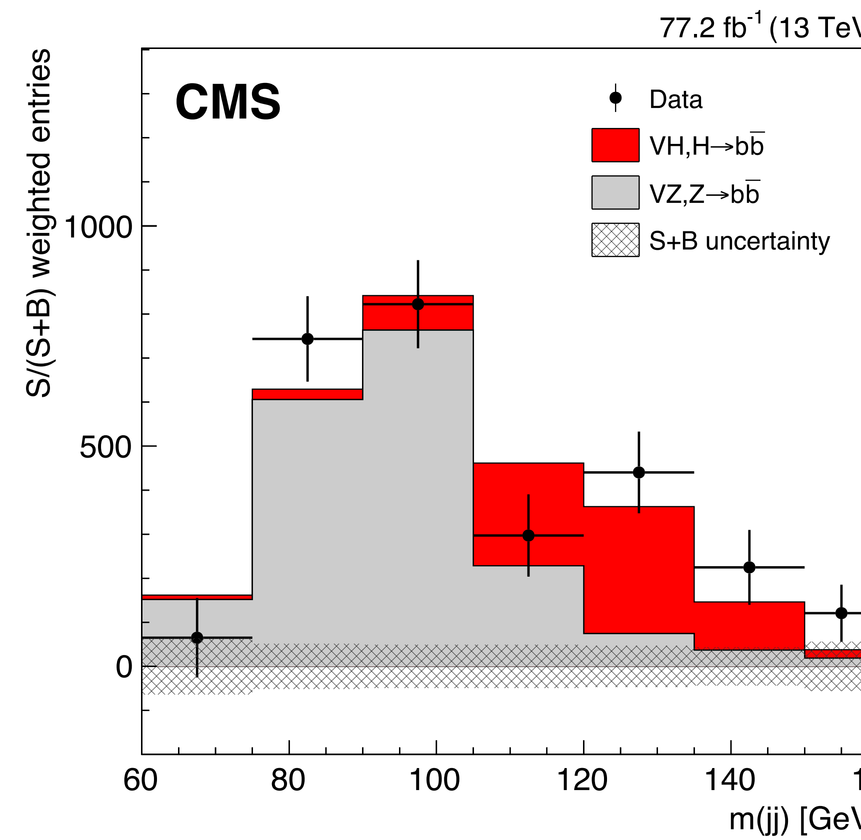
- Couplings to 3rd generation fermions:
  - $H \to \tau\tau$: observed at > 5σ
  - $H \to b\bar{b}$: observed in the associated VH(bb) production at > 5σ



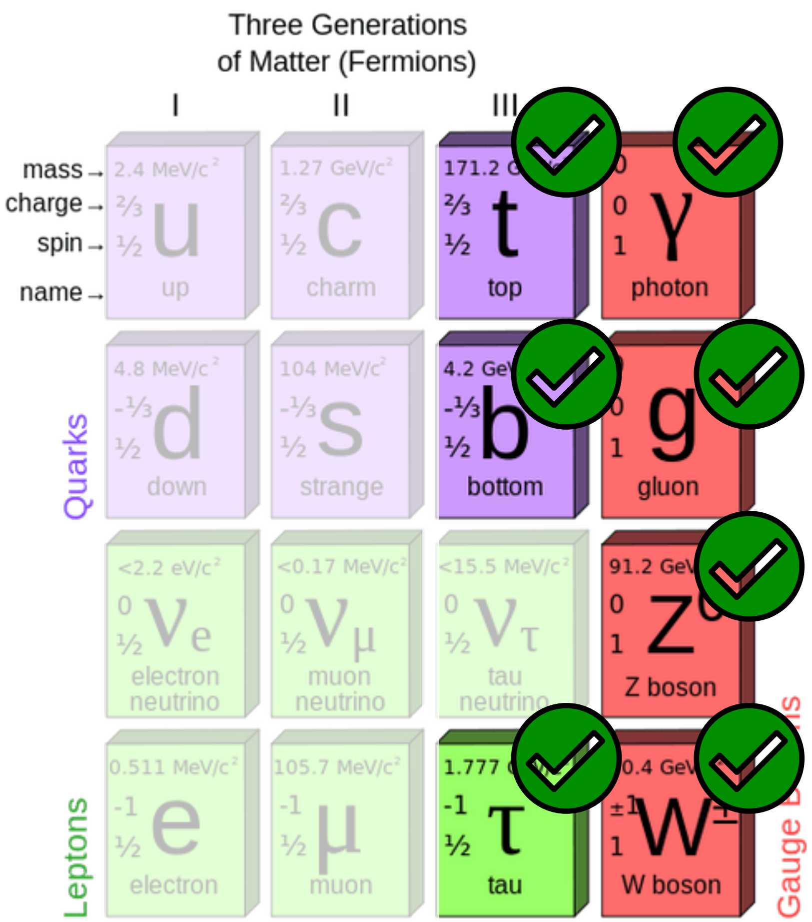
$H \to \tau^+\tau^-$

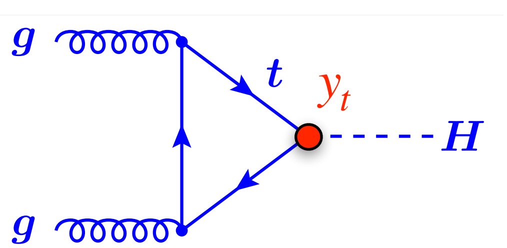


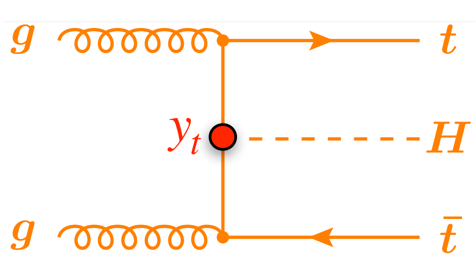
$H \to b\bar{b}$



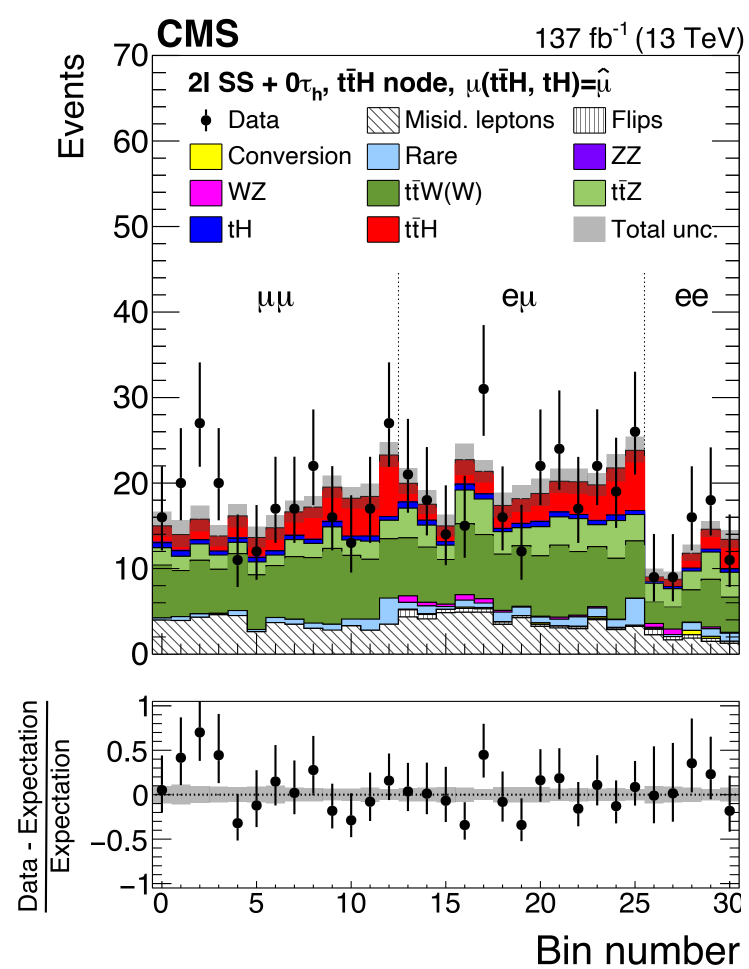
- Top quark Yukawa coupling $y_t \sim 1$:
  - can be inferred indirectly from loops in ggH production and $H \to \gamma\gamma$ decay
  - observed directly in ttH associated production in combination of different channels, and also in a single channel mode ($H \to \gamma\gamma$)



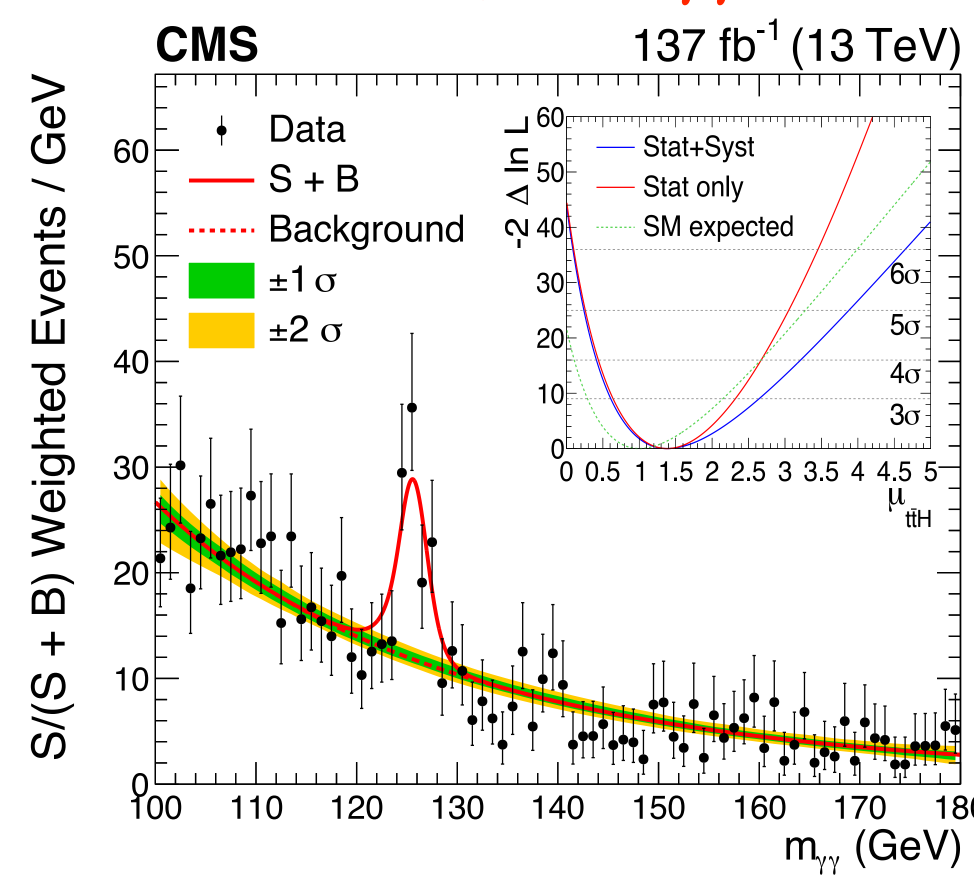




$t\bar{t}H, H \to \mathrm{WW}, \mathrm{ZZ}, \tau\tau$

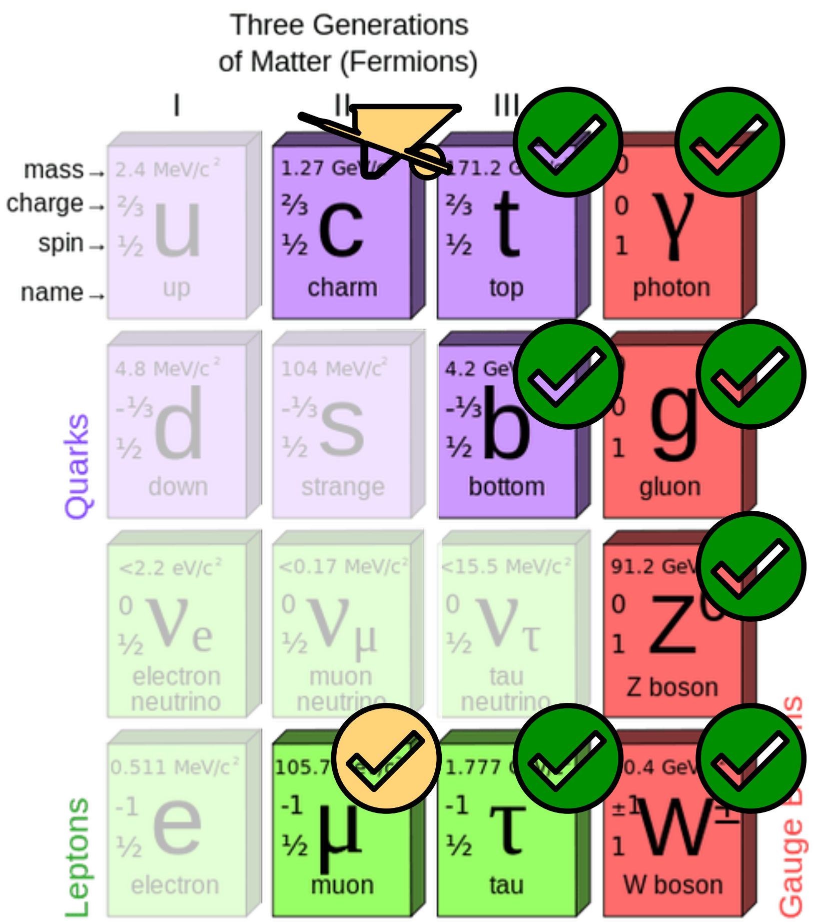


$t\bar{t}H, H \to \gamma\gamma$

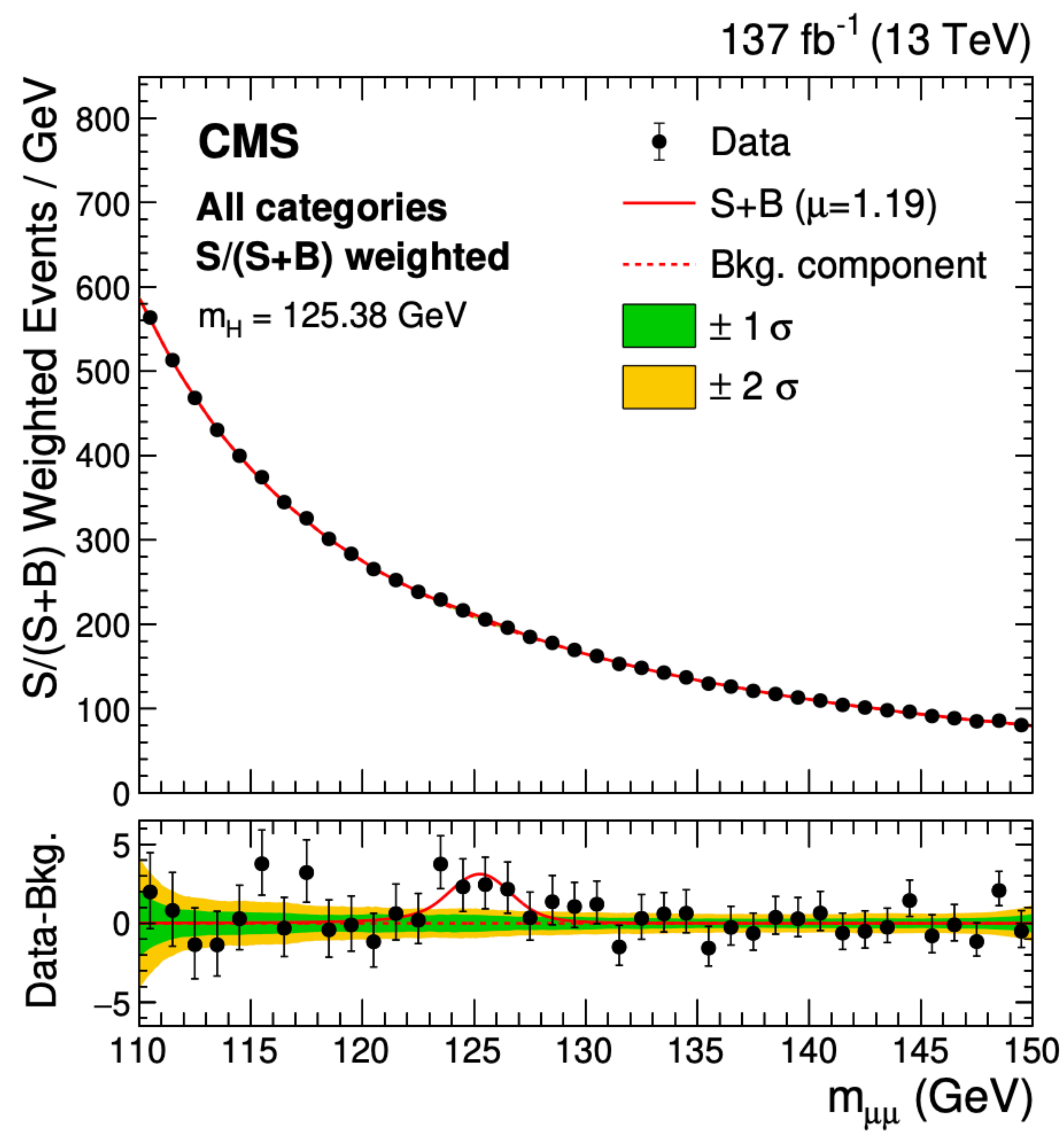


Establishing the scene

- Couplings to 2nd generation (small BRs):
  - Evidence of $H \to \mu\mu$ at 3.0σ, challenging $H \to c\bar{c}$

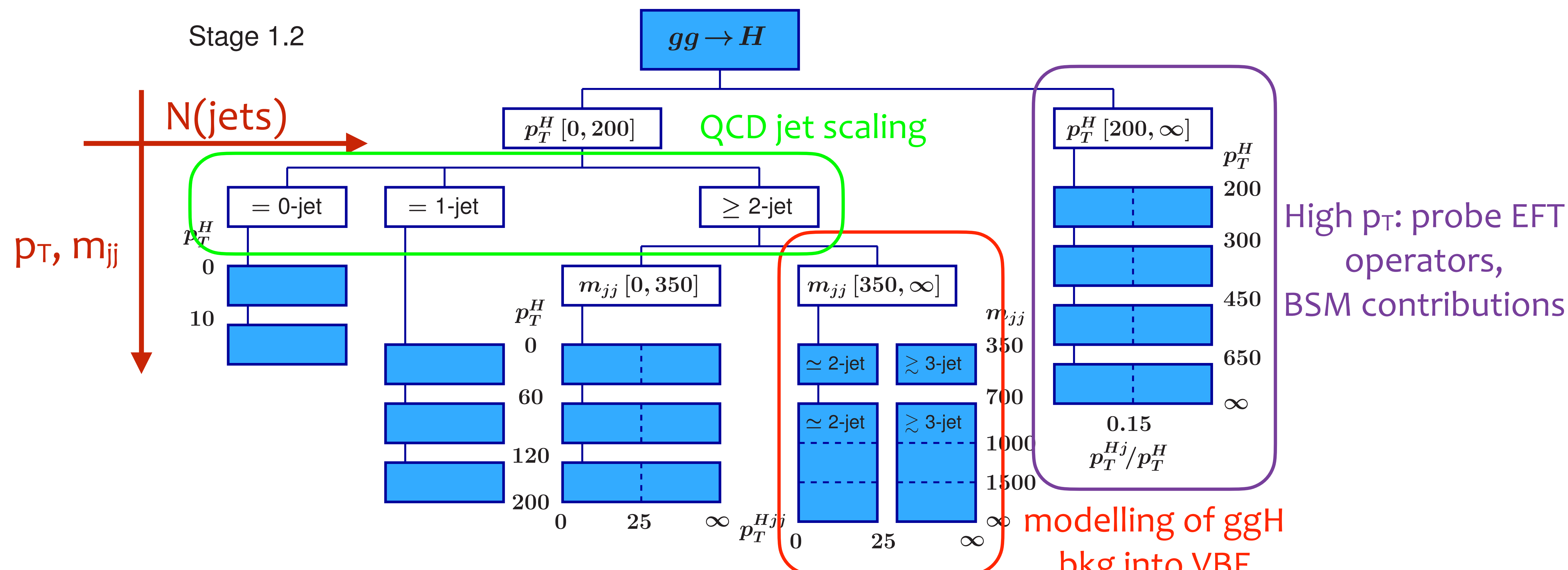


$H \to \mu^+\mu^-$



Going differential: STXS

- Differential production with **Simplified Template Cross Sections (STXS)** approach
  - Minimize simultaneously experimental and theoretical uncertainties on Higgs cross section measurements
  - Split production modes in gen-level bins in p_T, N(jets), m_{jj}
    - Assume within each bin acceptance is only weakly depending on SM kinematics
  - Allow re-interpretation of results in different models
  - Look for BSM in extreme bins of the phase space

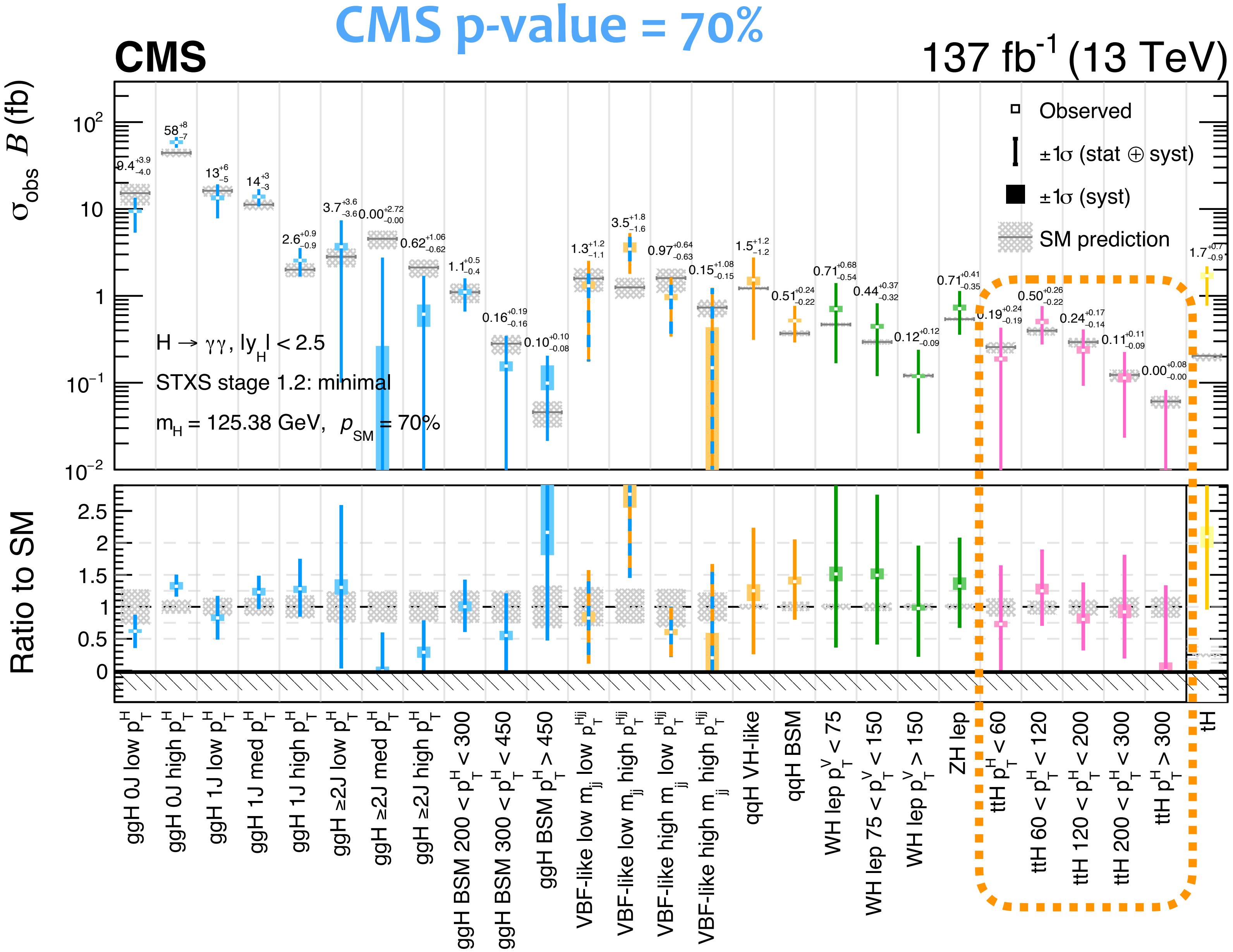


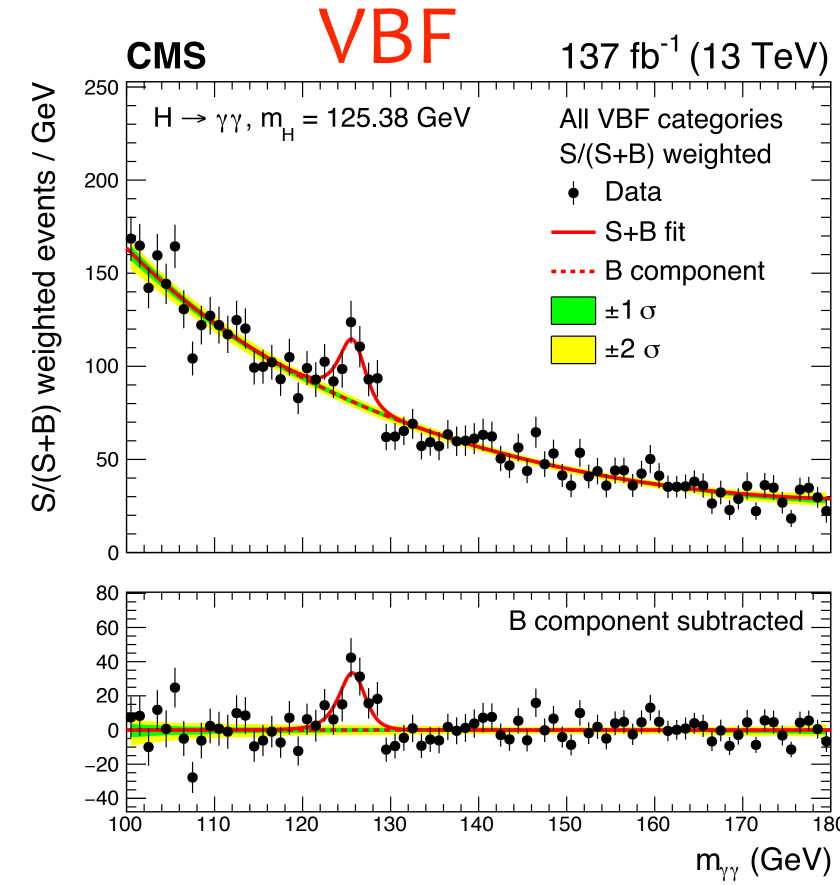
STXS in $H \to \gamma\gamma$

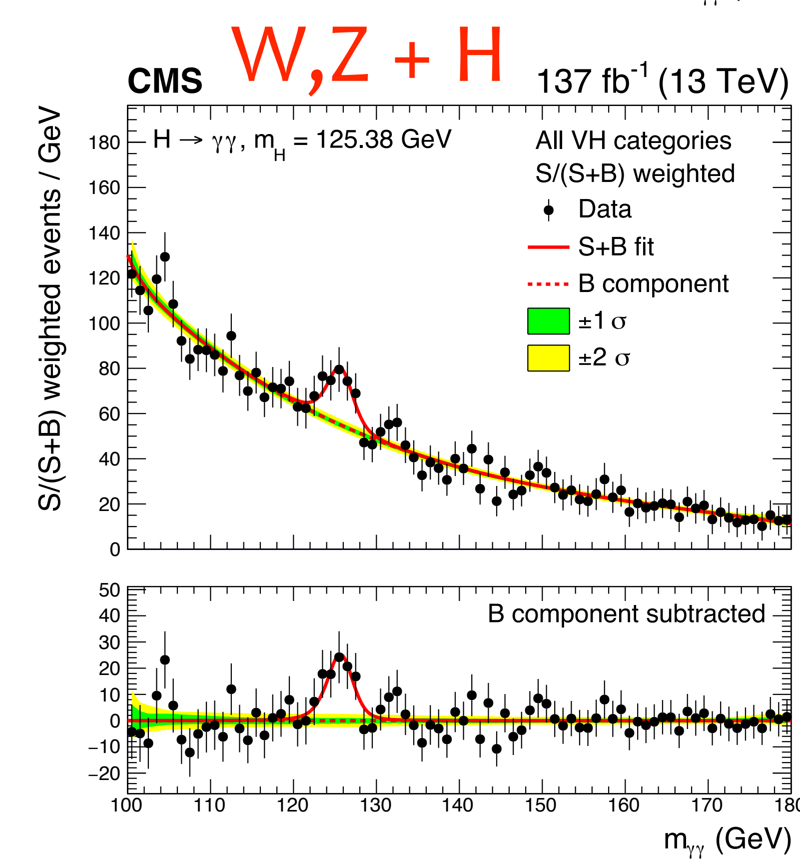
- $H \to \gamma\gamma$ channel well suited for STXS measurement:
  - high yields, efficiency and S/B across whole phase space
  - robust background estimation from m(γγ)
  - **reaching first ttH differential measurements**

JHEP 07 (2021) 027

CMS p-value = 70%

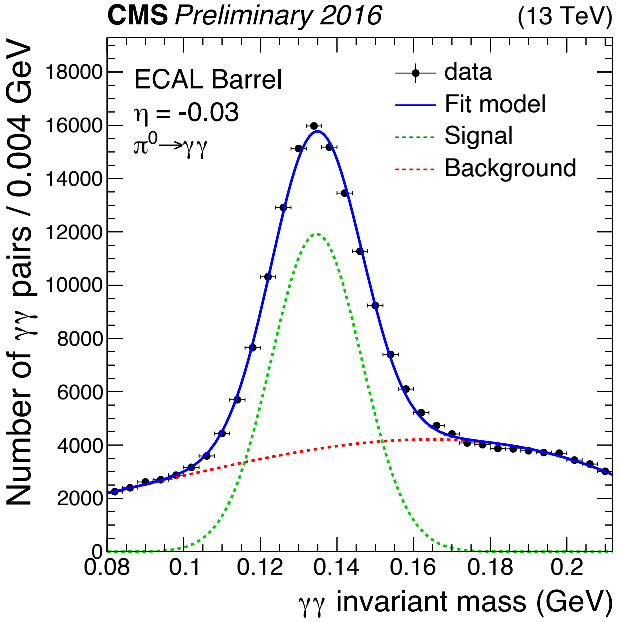




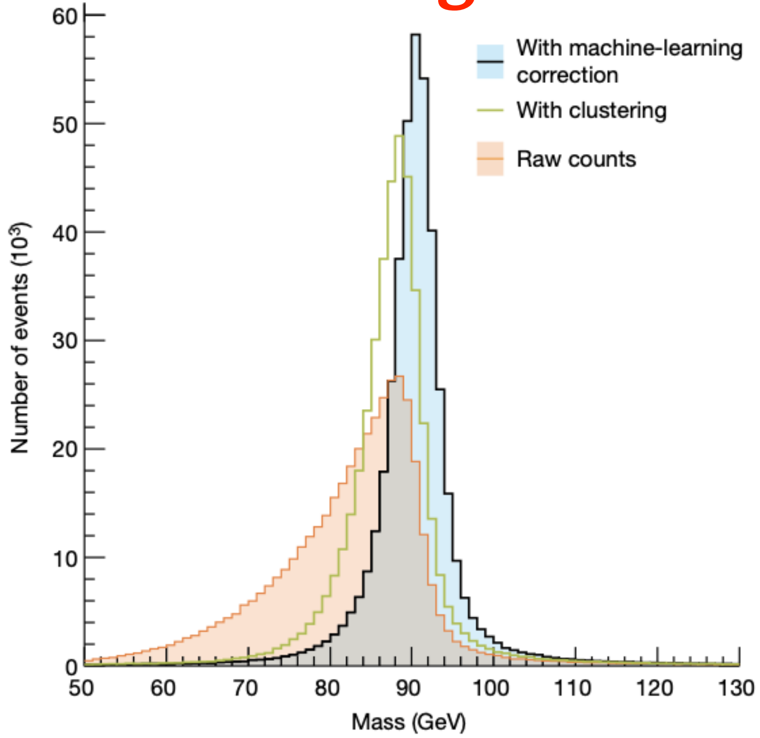


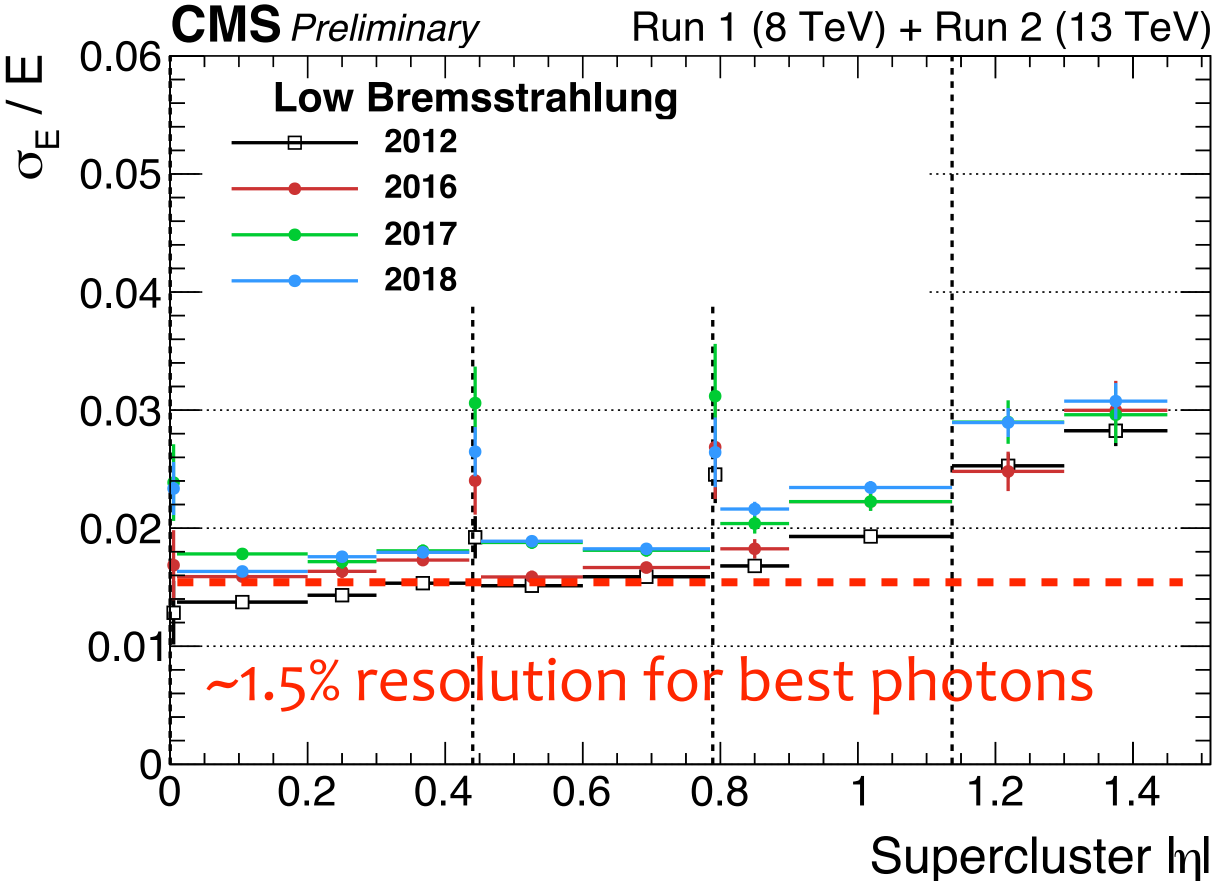
- Seeing tiny signals as $t\bar{t}H(\rightarrow \gamma\gamma)$ depend crucially on the performance of the **ECAL detector**
  - huge work to maintain the excellent performance of Run-1 with **high radiation** and **pileup** of Run-2/3
- Rome group on ECAL since the foundations:
  - construction, commissioning, operations, energy reconstruction, calibration and corrections

$\pi^0 \rightarrow \gamma\gamma$



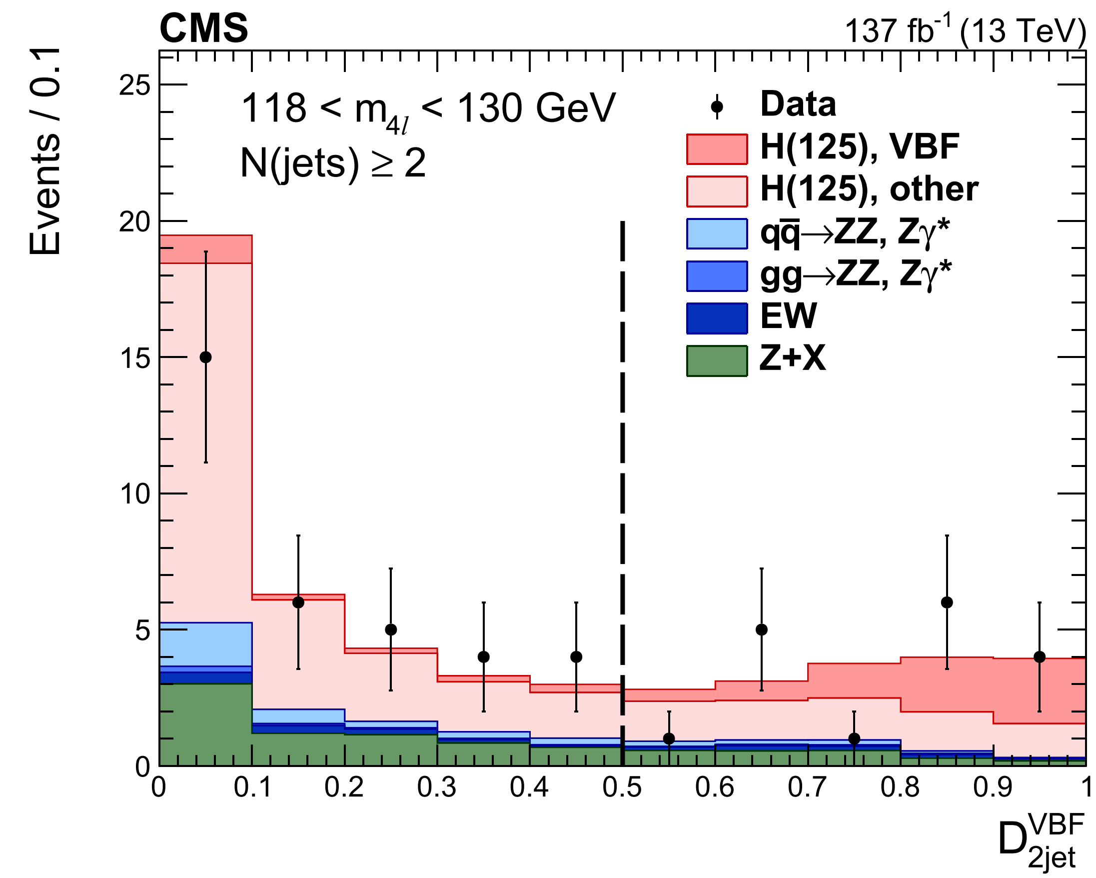
$Z \rightarrow e^+e^-$ with **machine learning corrections**

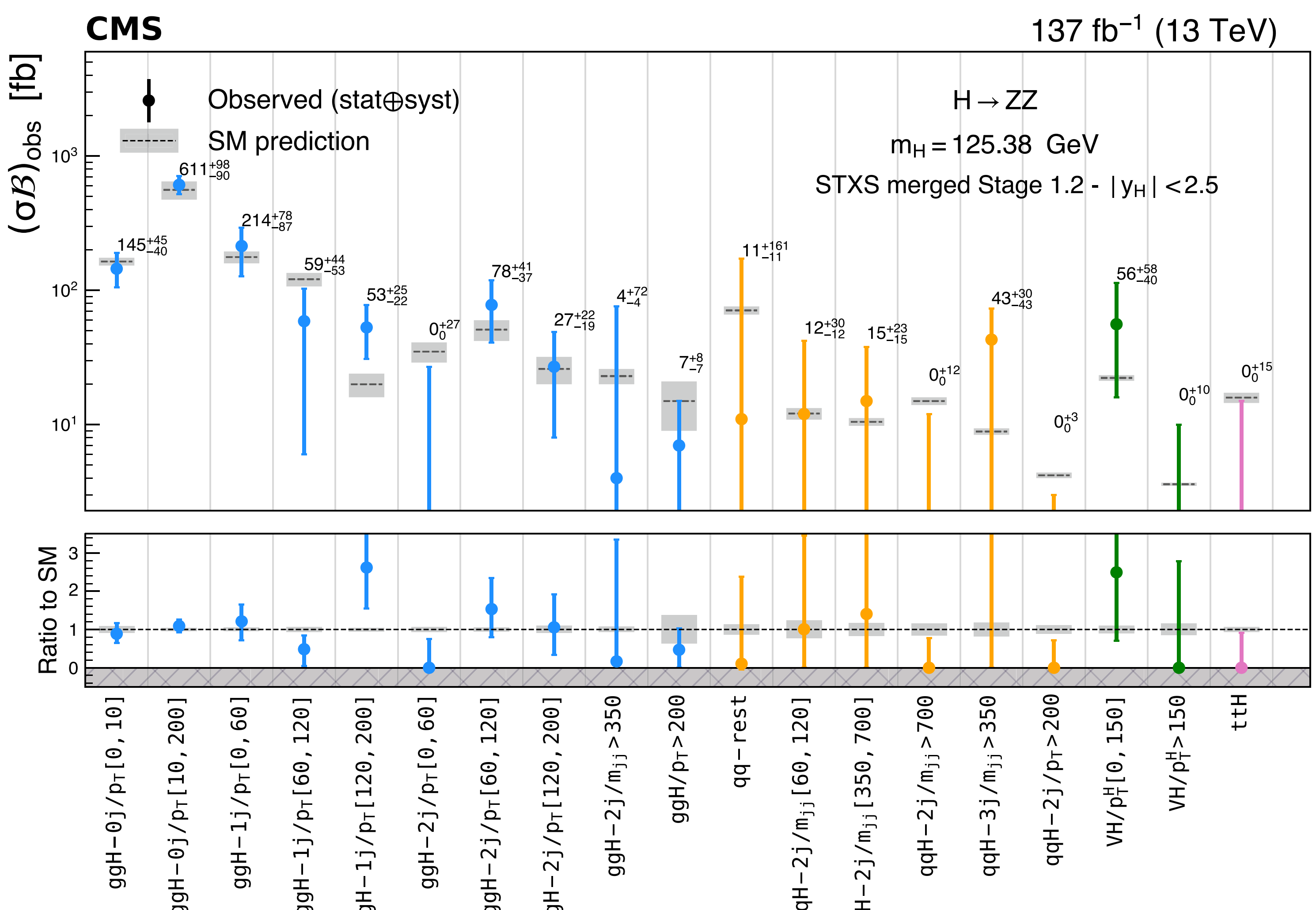


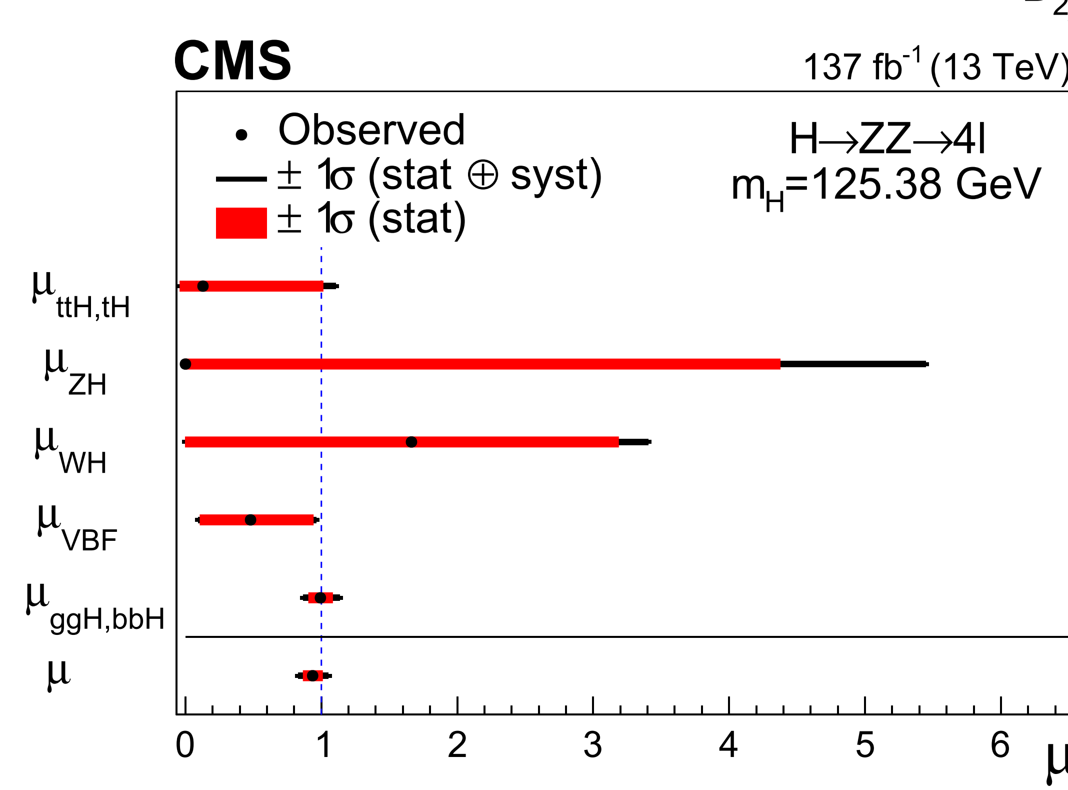


STXS $H \to ZZ^* \to 4\ell$

- Very clean final state, but low event yield:
  - group STXS bins to improve sensitivity, especially VH and ttH processes
  - use DNN (ATLAS) or matrix element (CMS) to define categories







Eur. Phys. J. C 81 (2021) 488
Eur. Phys. J. C 80 (2020) 957

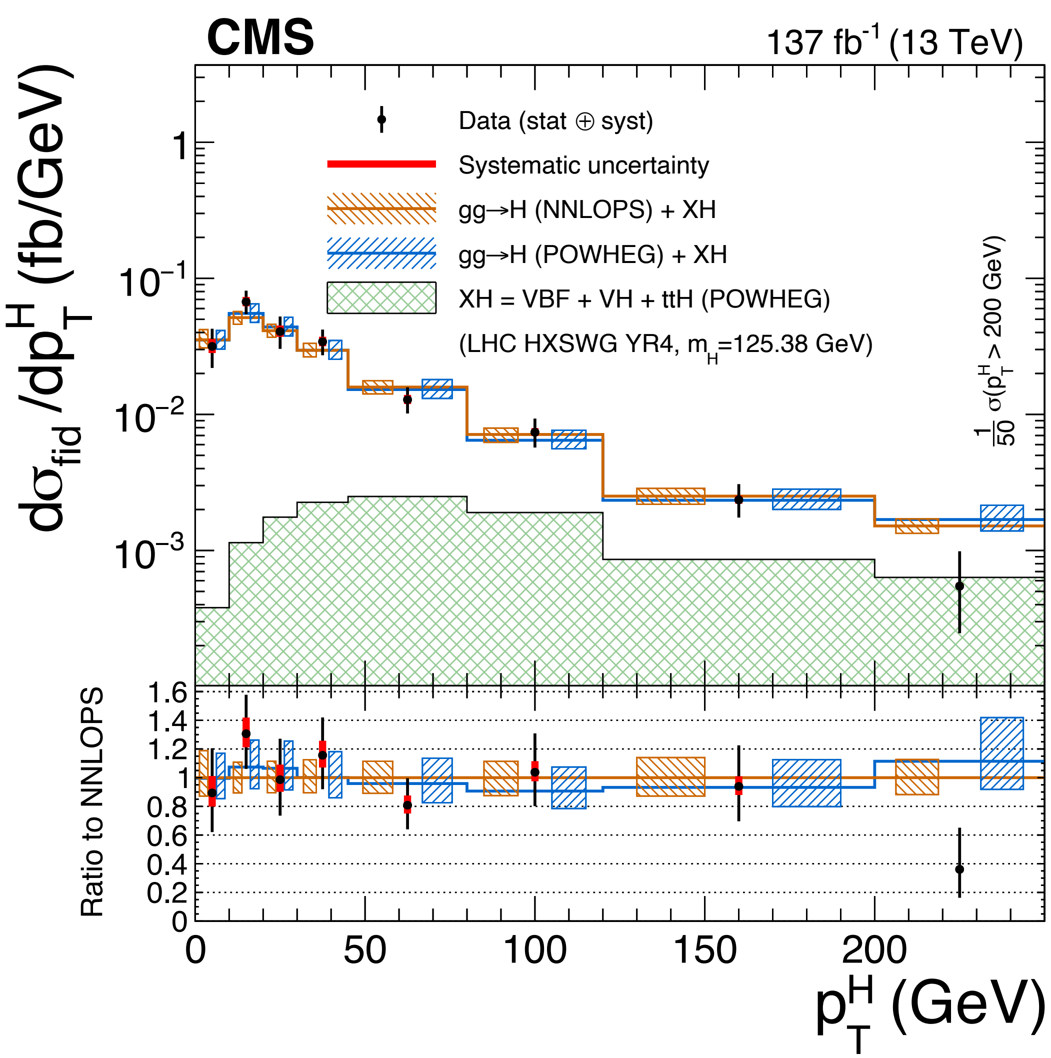
$H \to 4\ell$: differential and fiducial

- single- or doubly-differential distributions measured, consistent with SM
- Fiducial x-sections measured with 10% precision:

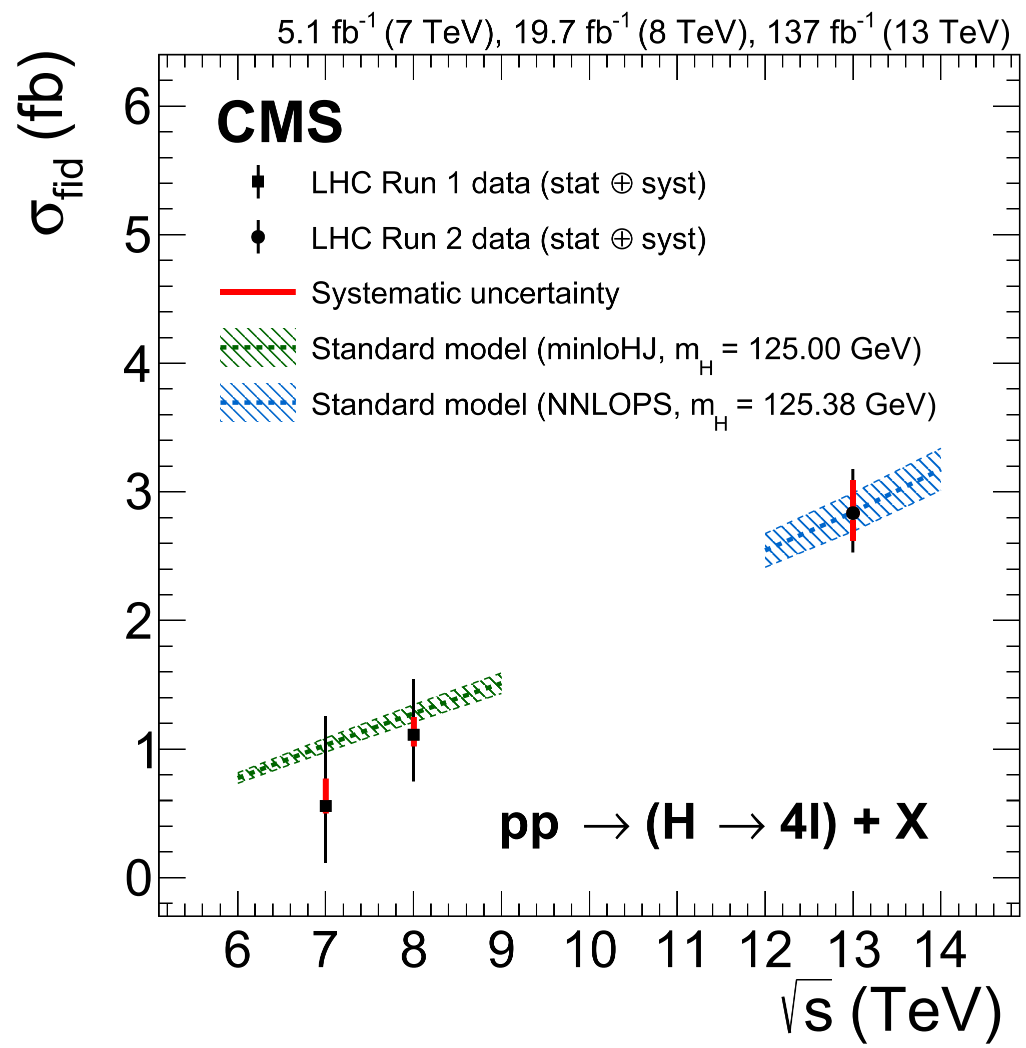
Eur. Phys. J. C 81 (2021) 488

Measured [fb]	SM prediction [fb]
$2.73^{+0.23}_{-0.22}(\text{stat})\ ^{+0.24}_{-0.29}\ (\text{syst})$	2.76 ± 0.14

differential σ vs Higgs p_T

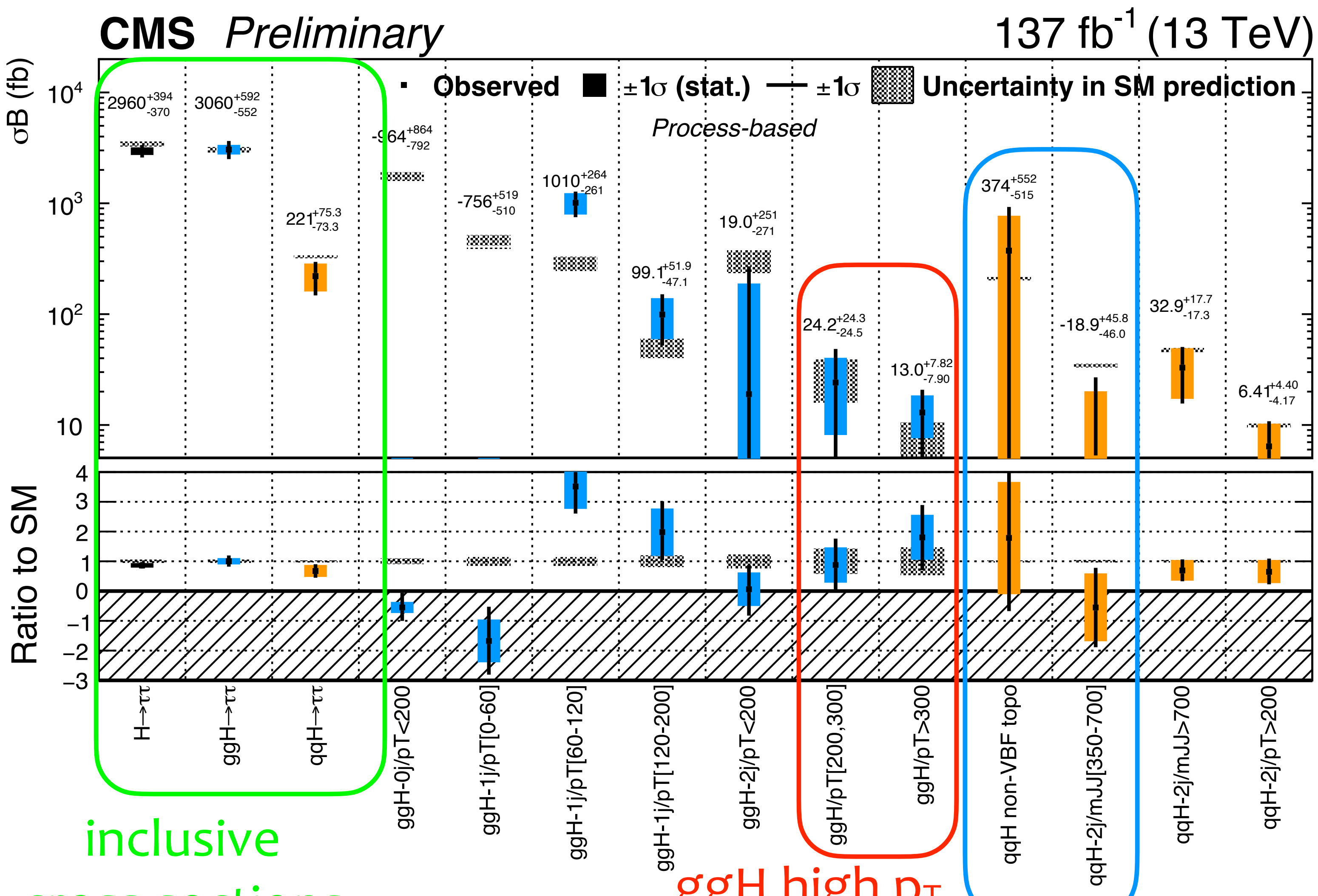


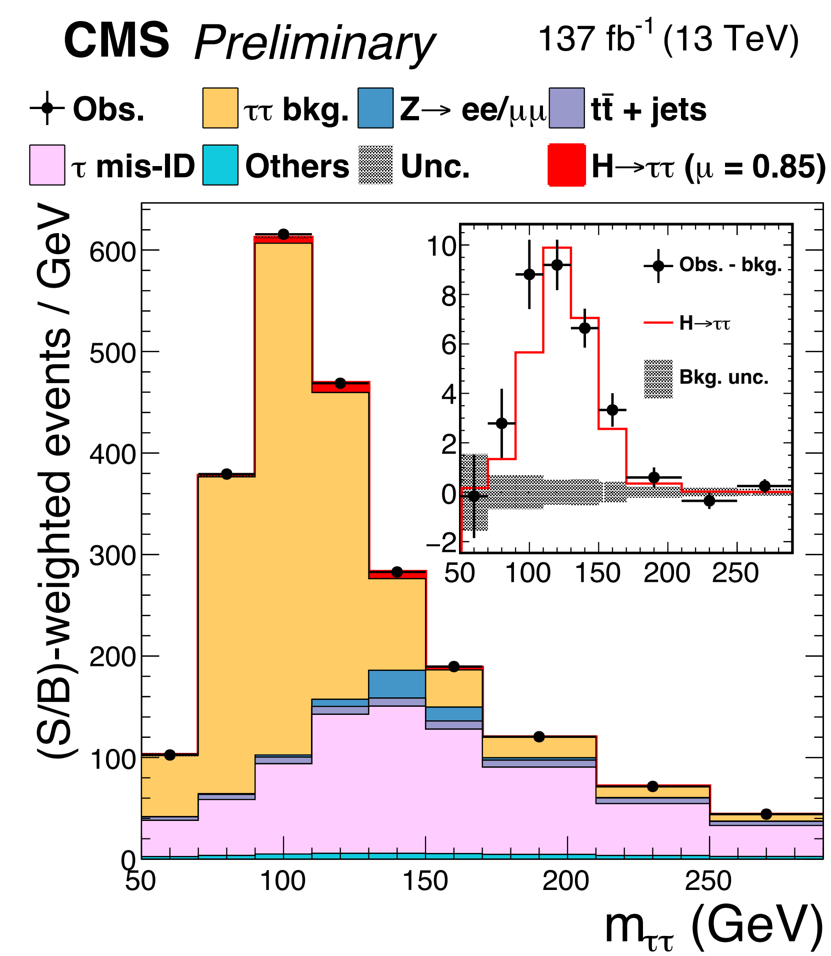
fiducial σ

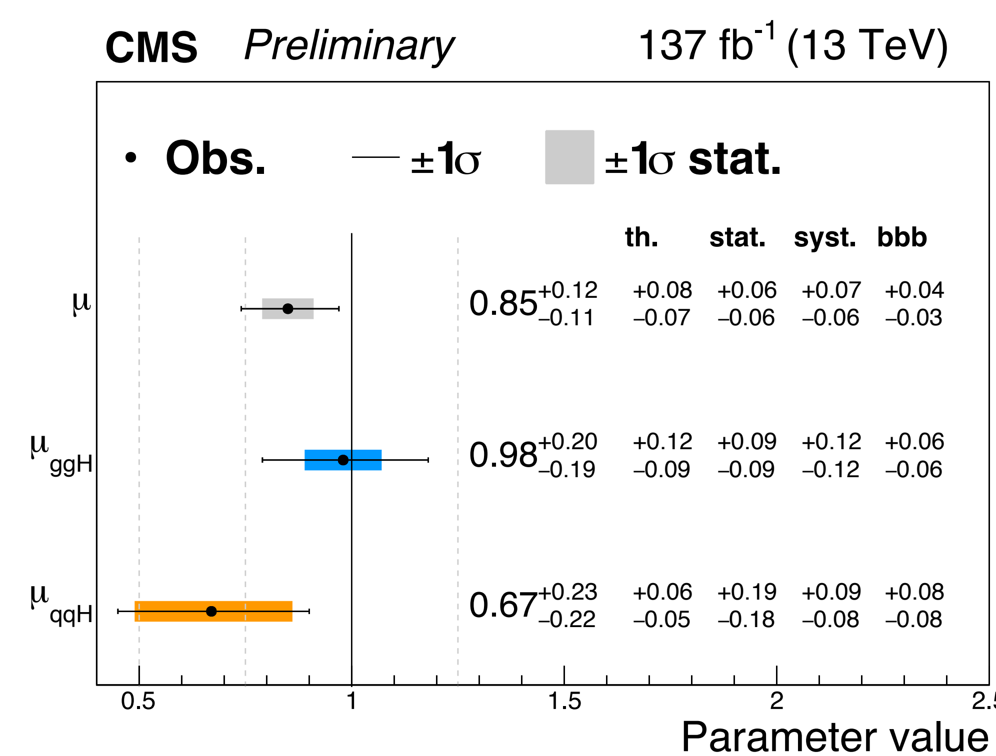


STXS 3rd generation: $H \to \tau\tau$

- Bring sensitivity to region of the phase space less well measured by $H \to \gamma\gamma$ and $H \to 4\ell$, i.e. ggF high pTH and especially VBF:
  - gluon-fusion: Higgs $p_T > 300$ GeV
  - VBF: $m_{jj} > 700$ GeV







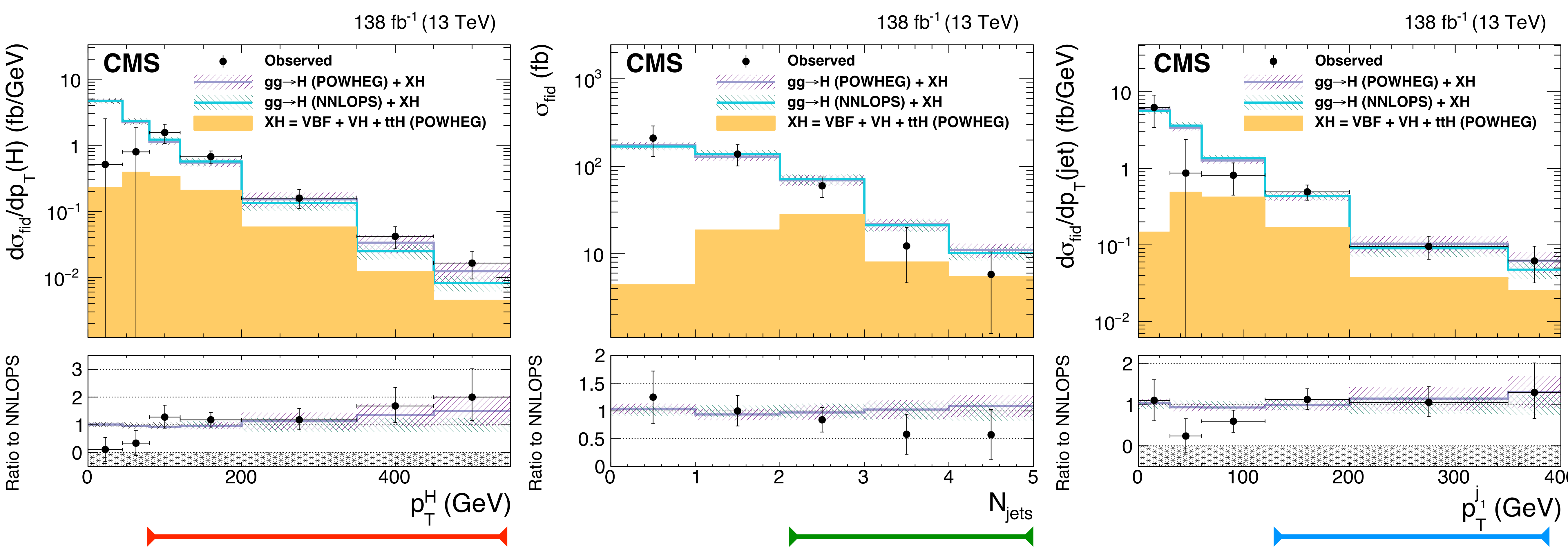
		th.	stat.	syst.	bbb
μ	$0.85^{+0.12}_{-0.11}$	$^{+0.08}_{-0.07}$	$^{+0.06}_{-0.06}$	$^{+0.07}_{-0.06}$	$^{+0.04}_{-0.03}$
μ_{ggH}	$0.98^{+0.20}_{-0.19}$	$^{+0.12}_{-0.09}$	$^{+0.09}_{-0.09}$	$^{+0.12}_{-0.12}$	$^{+0.06}_{-0.06}$
μ_{qqH}	$0.67^{+0.23}_{-0.22}$	$^{+0.06}_{-0.05}$	$^{+0.19}_{-0.18}$	$^{+0.09}_{-0.08}$	$^{+0.08}_{-0.08}$

CMS-PAS-HIG-19-010

$H \to \tau\tau$: differential and fiducial

- Dedicated measurement of differential cross sections complements the ones in $\gamma\gamma, ZZ, b\bar{b}, WW$ channels in the high p_T^H region and high jet multiplicity:
  - $120 < p_T^H < 600$ GeV, N$_{jets}$>2, $p_T^{j_1} > 120$ GeV

CMS-HIG-20-015



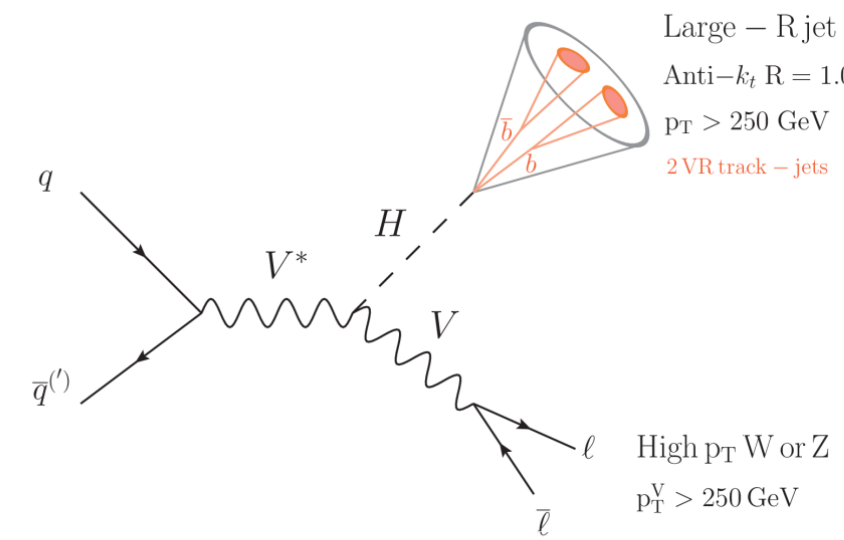
$120 < p_T^H < 600$ GeV

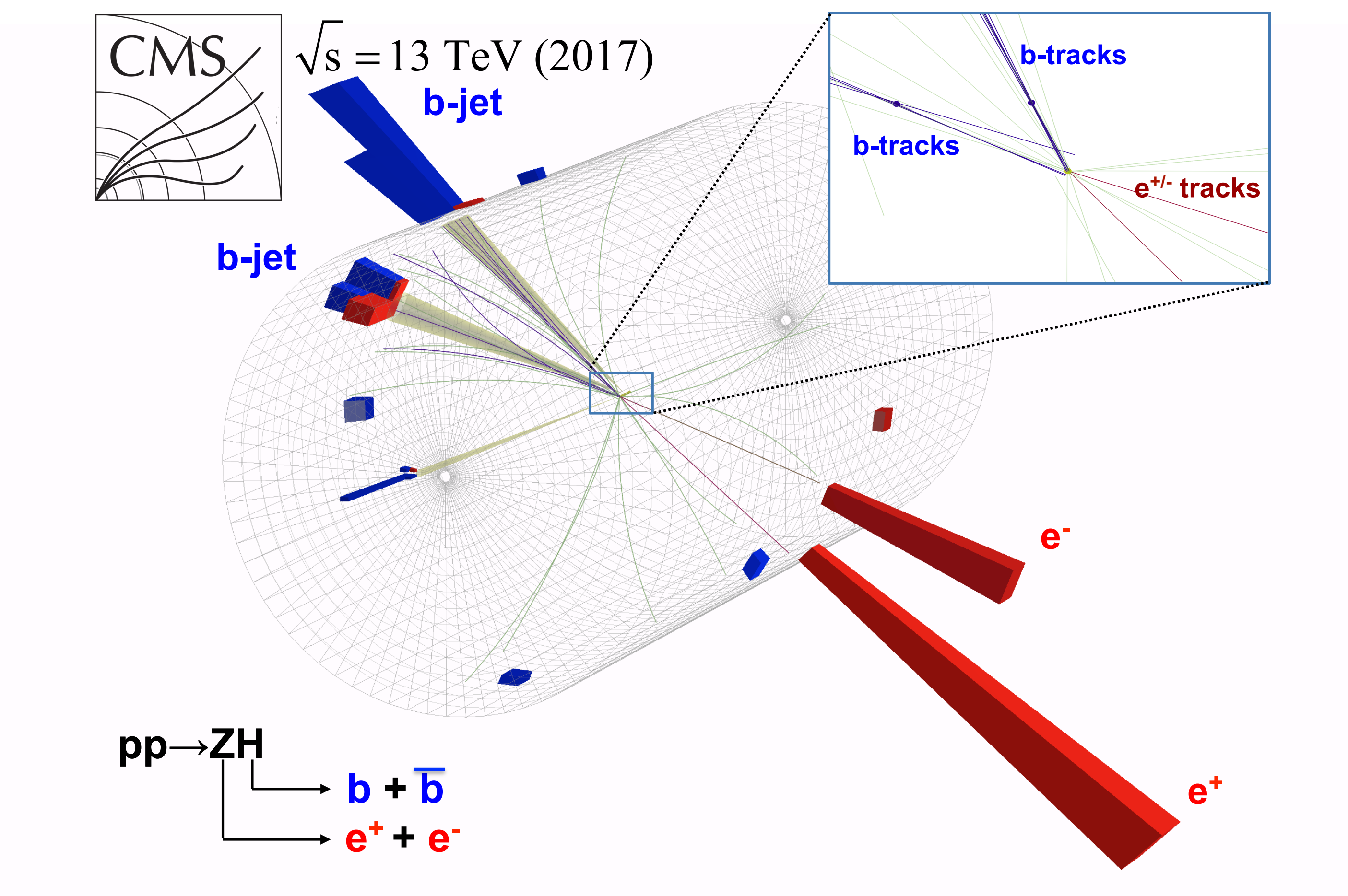
N$_{jets}$>2

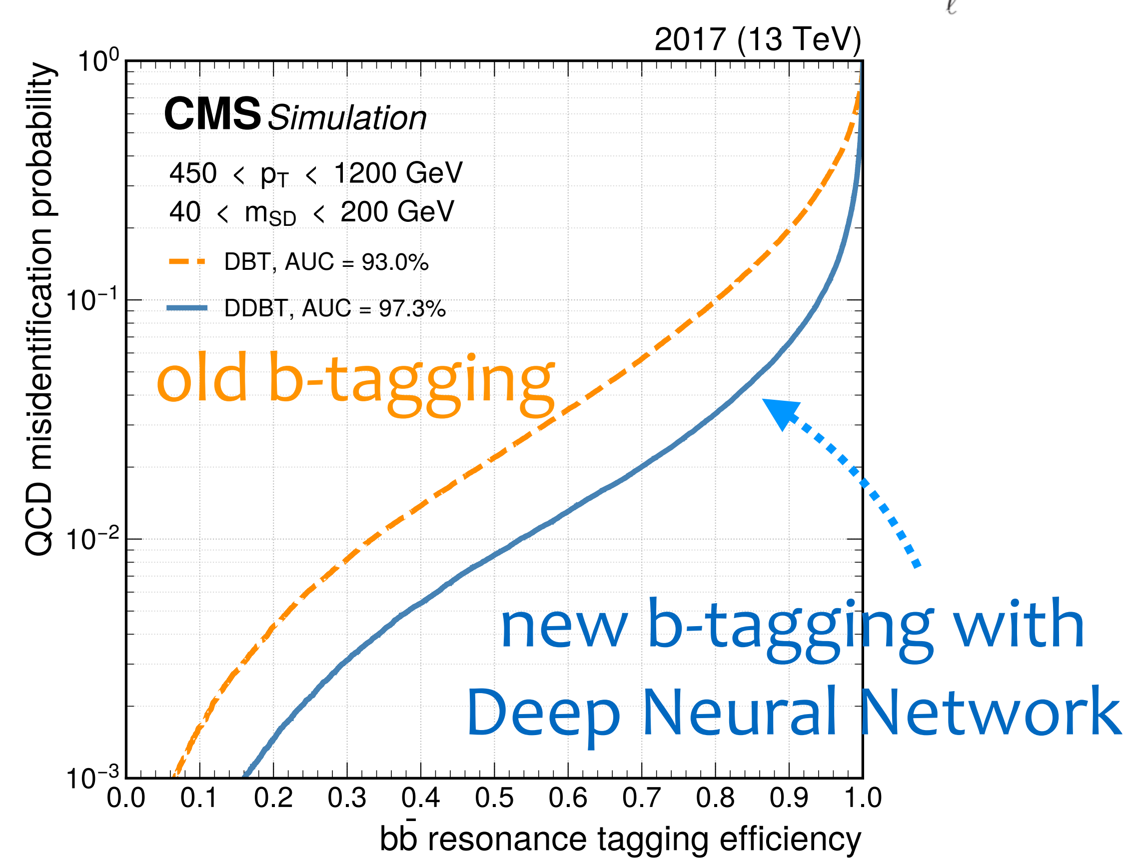
$p_T^{j_1} > 120$ GeV

3rd generation: $H \to b\bar{b}$

- Probes the Yukawa coupling of the Higgs with d-type quark
- Challenging channel because large jets background => associated production VH, $H \to b\bar{b}$ with highly boosted regime very sensitive
  - **crucial b-tagging with DNN Machine Learning tools**
  - boosted jet analysis targets $p_T(V)$>250 GeV





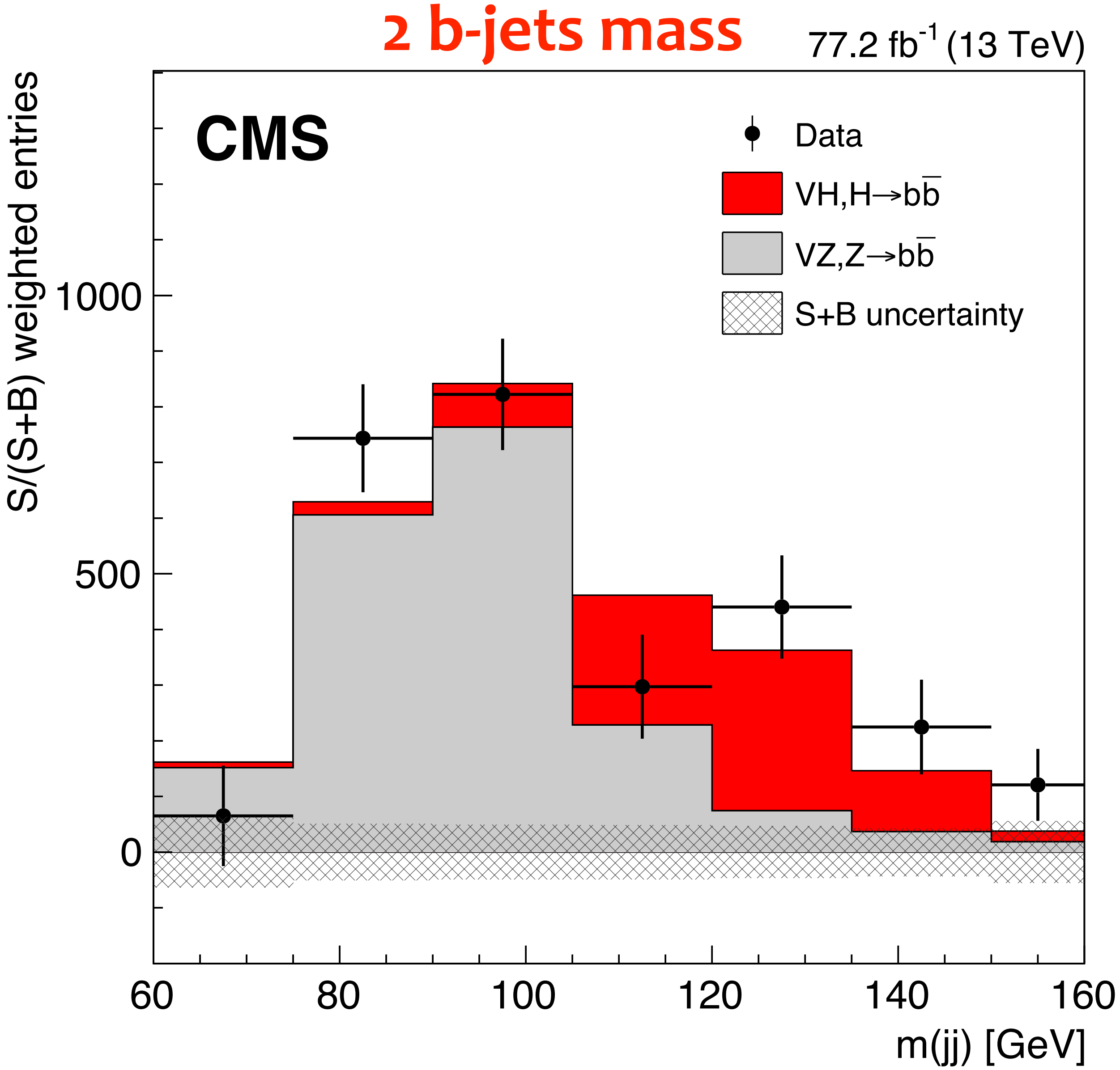


JHEP 12 (2020) 085

STXS in $H \to b\bar{b}$

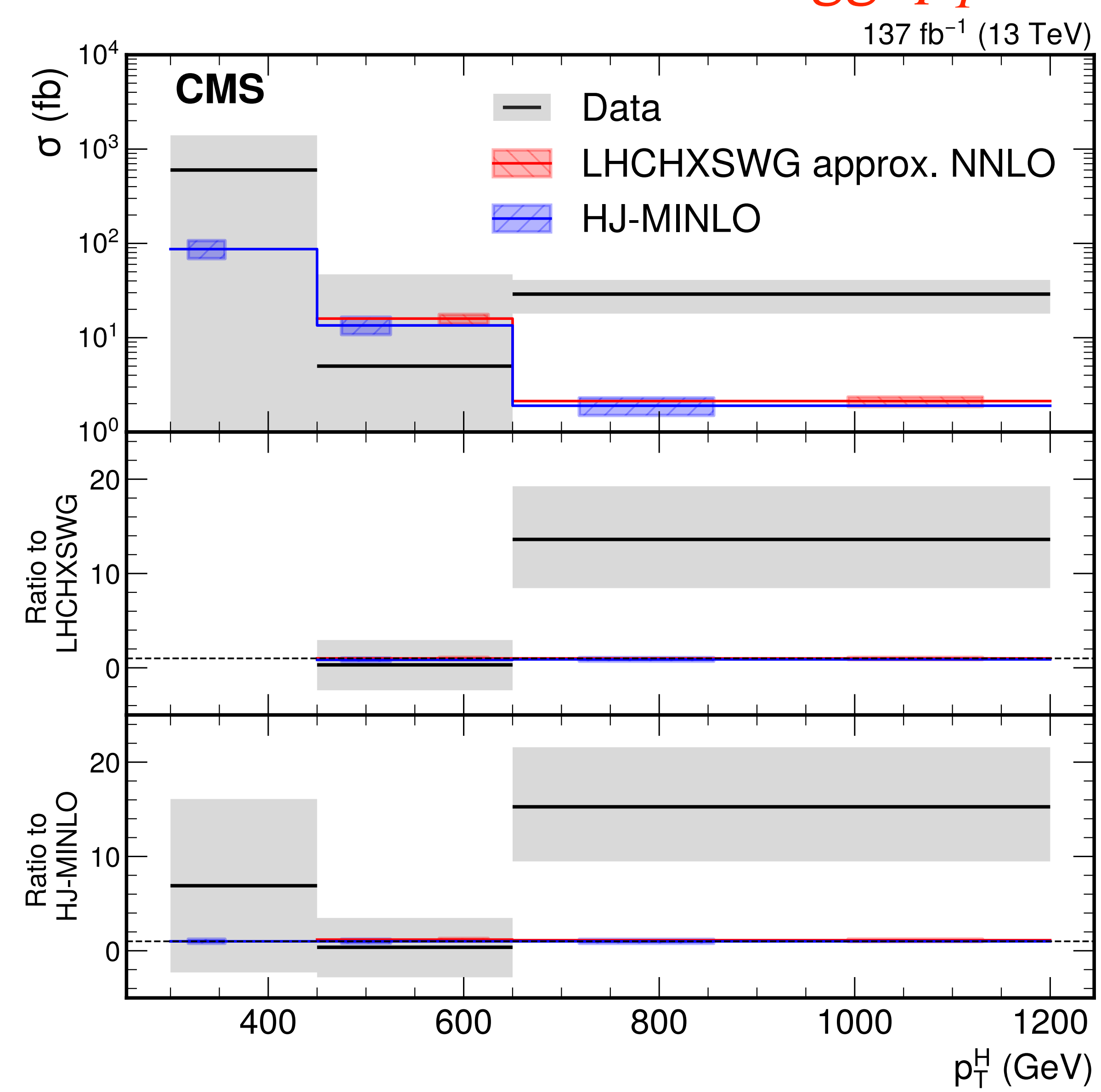
- Observed inclusively WH and ZH at **5.6σ**. Measured $\sigma/\sigma_{SM} = 1.04 \pm 0.20$
  - Differential cross-sections sensitive to p_T>250 GeV, probing p_T>400 GeV
  - measurements beginning to be **systematically limited**

2 b-jets mass



Phys. Rev. Lett. 121 (2018) 121801

differential $H \to b\bar{b}$ in Higgs p_T



JHEP 12 (2020) 085

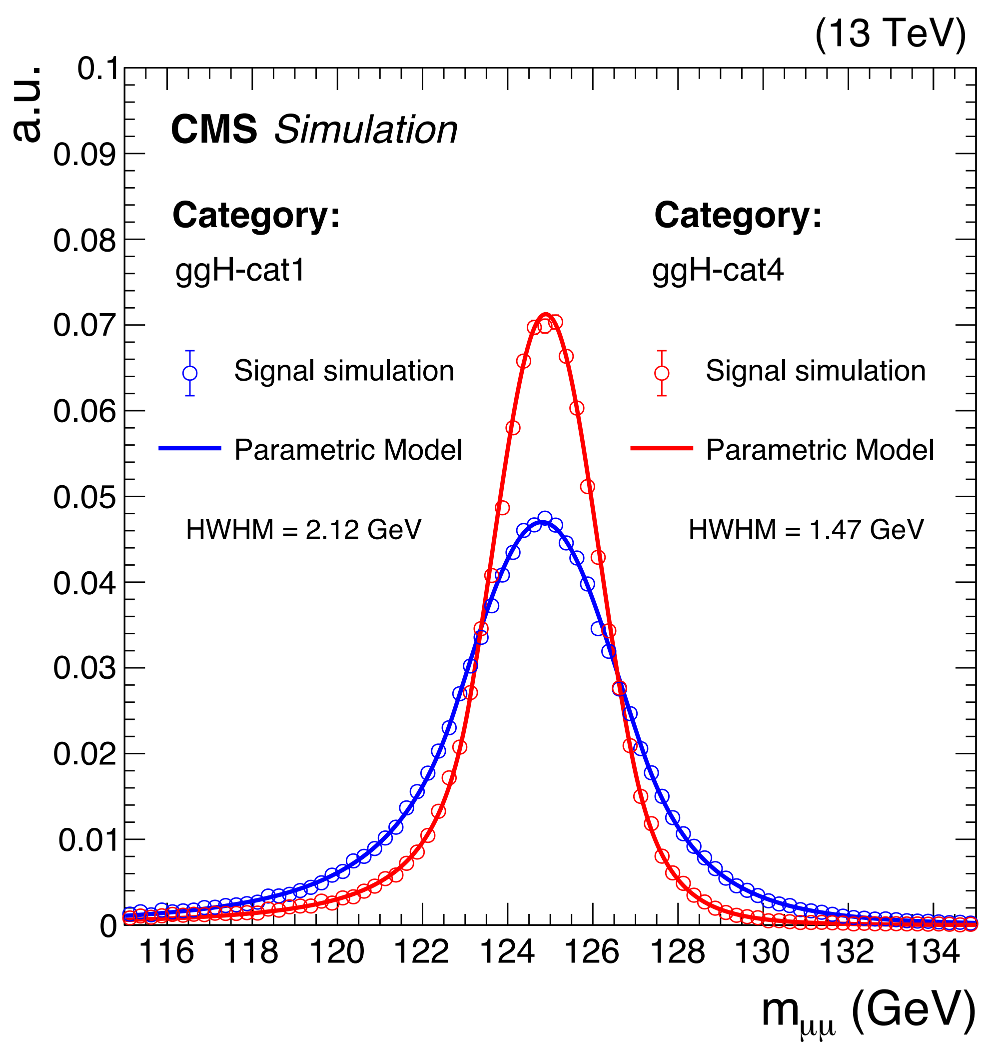
Coupling to 2nd generation

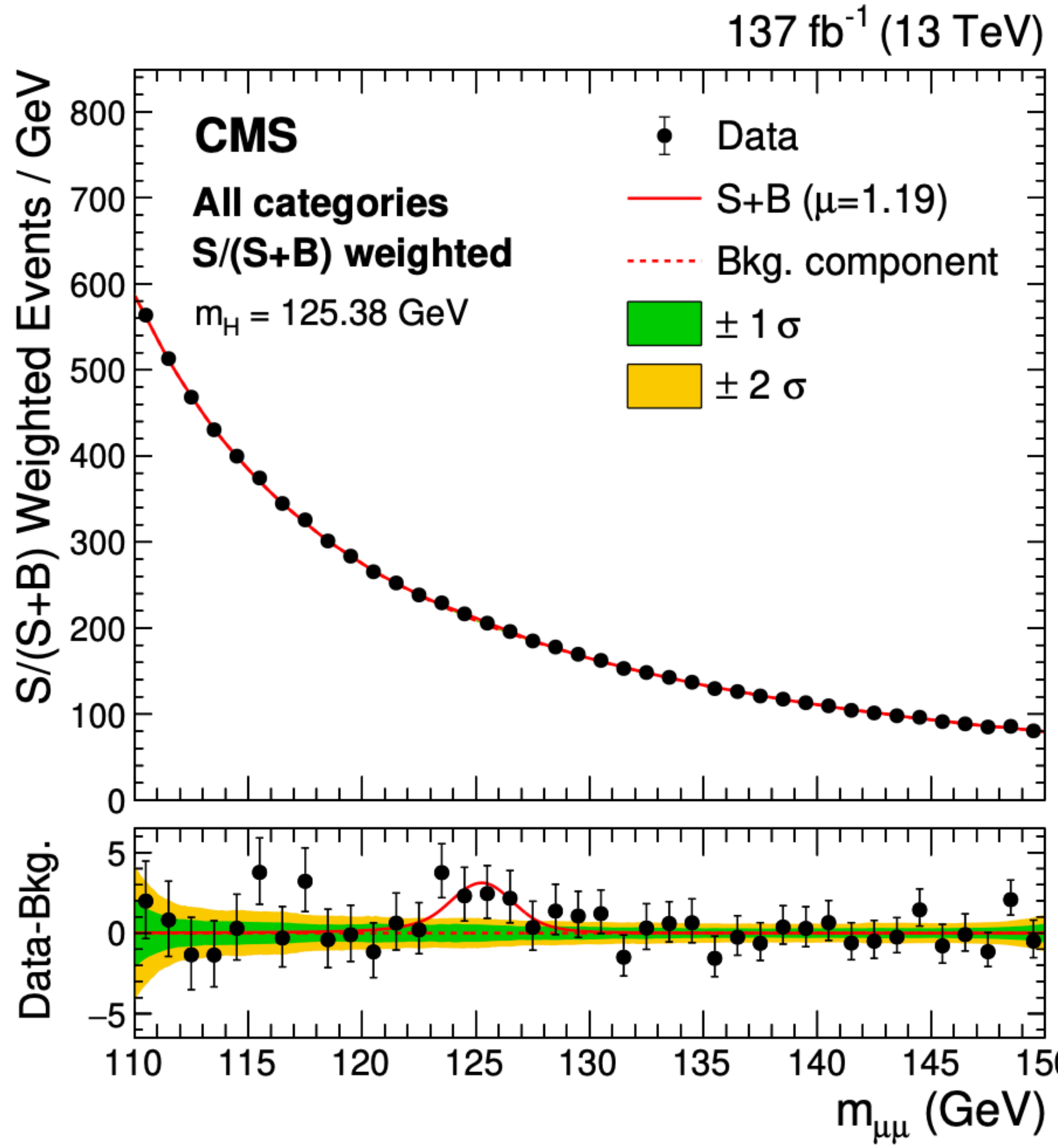
JHEP 01 (2021) 148

- Rare decay: $BR(H \to \mu\mu) \approx 2 \times 10^{-4}$, with large non-resonant background from $DY \to \mu\mu$
  - all production modes used: ggF, VBF, VH, ttH, categorized to improve sensitivity
  - **di-μ mass resolution: [1.5-2.1] GeV**

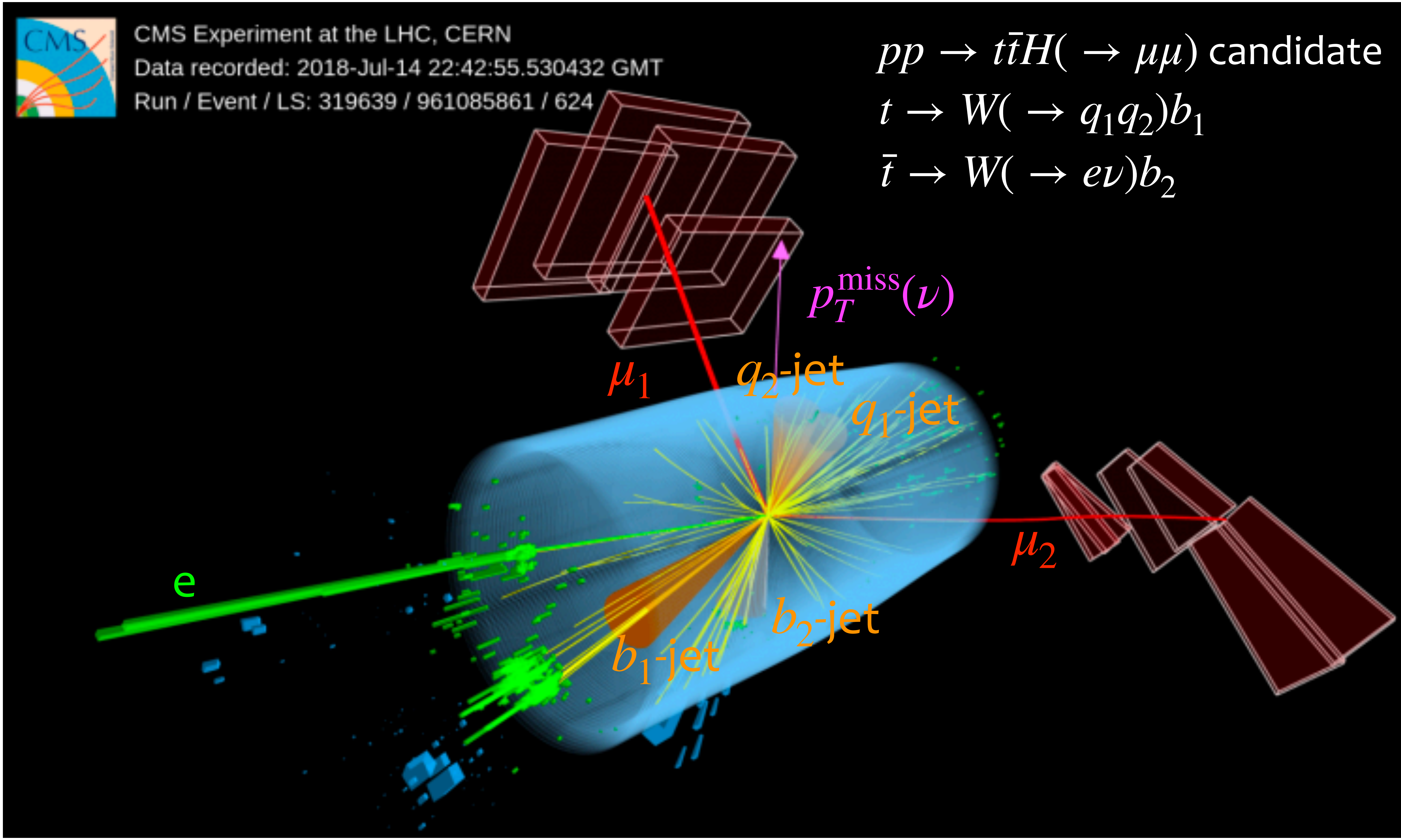
$\mu = 1.2 \pm 0.4$

significance: 3.0σ (2.5σ exp.)





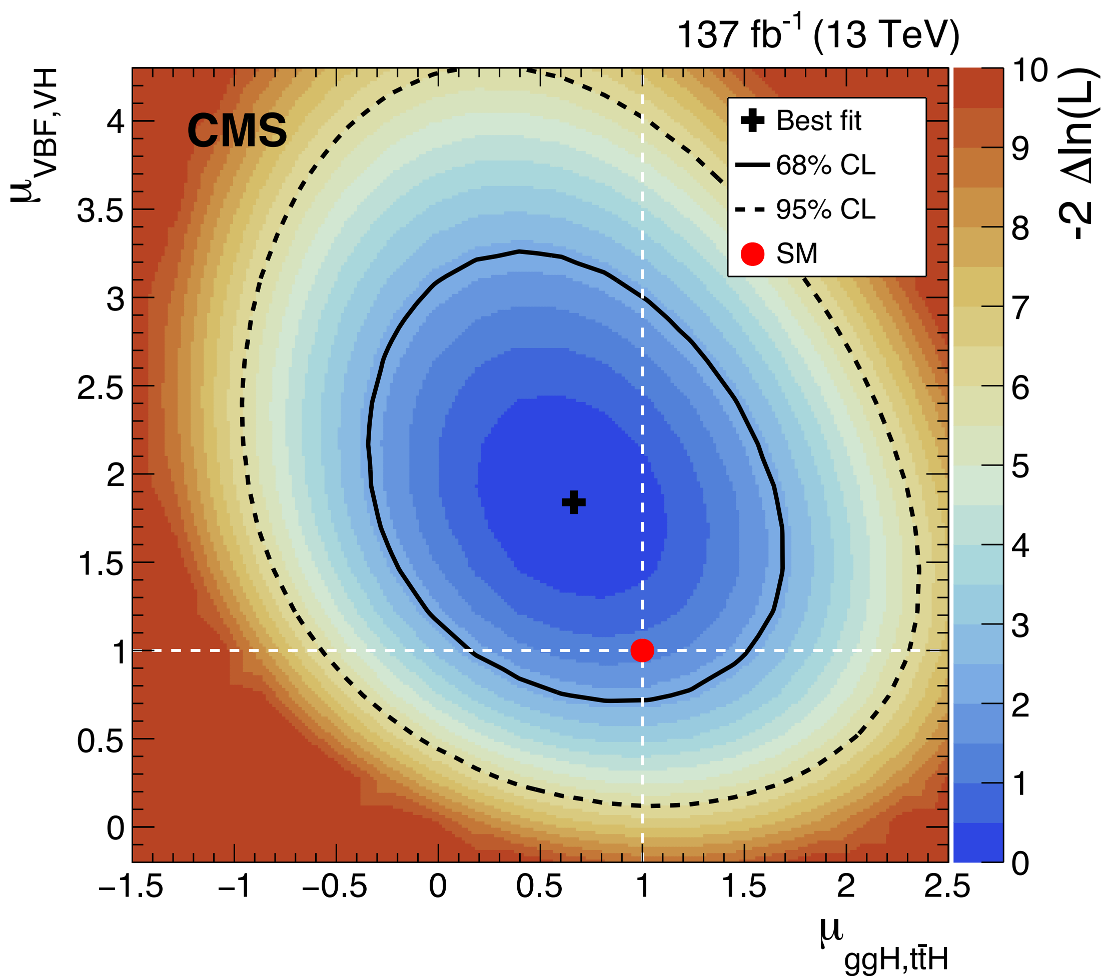
$H \to \mu\mu$ candidate

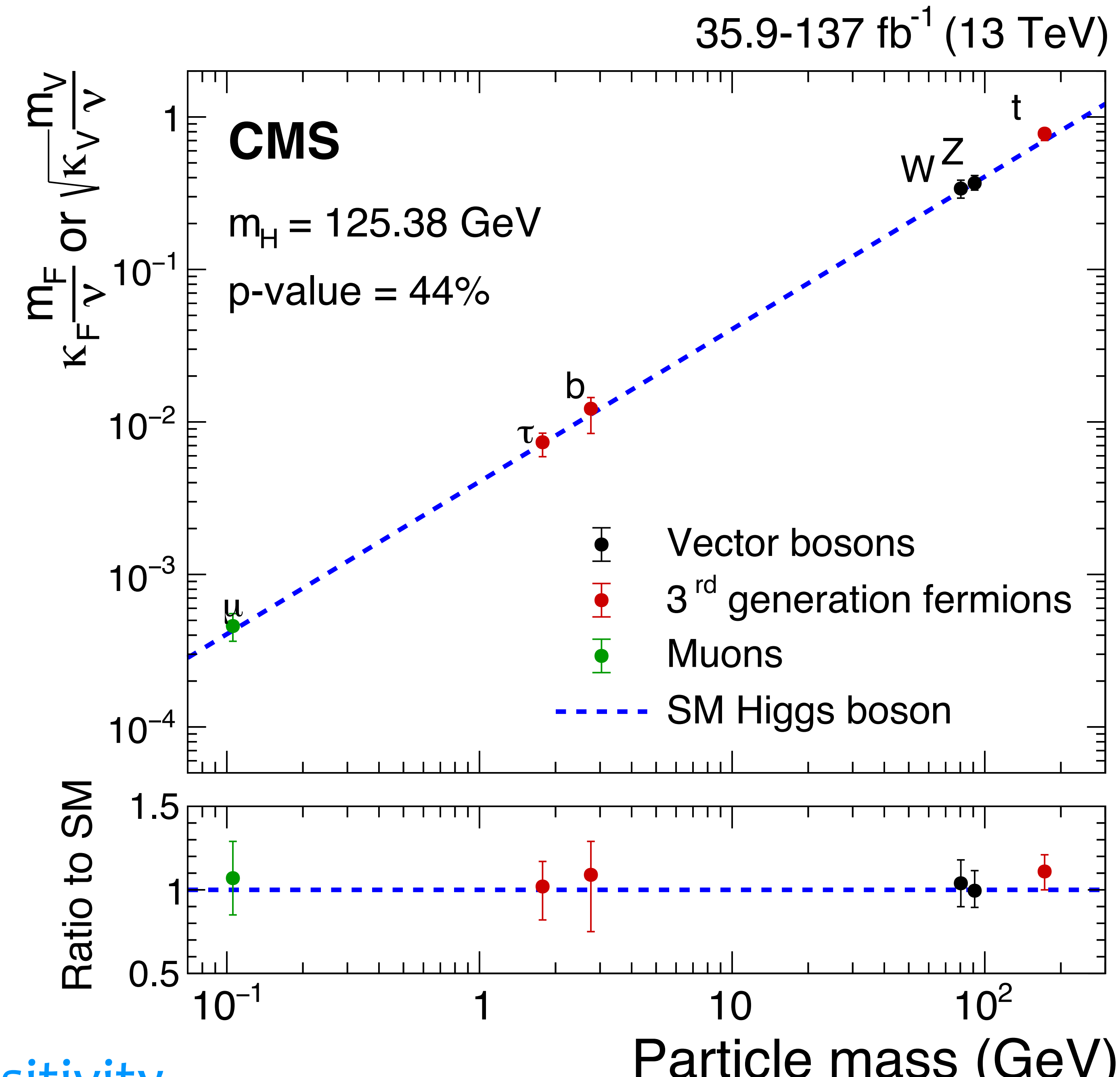


$H \rightarrow \mu^+\mu^-$ challenges

- S/B ~ 0.1% for inclusive events at 125 GeV
- Strategies to increase sensitivity:
  - improve $\sigma(m_{\mu\mu})$ with FSR recovery, constrain tracks to beam line
  - use dedicated DNN/BDT in each category
  - very accurate DY bkg modelling

JHEP 01 (2021) 148

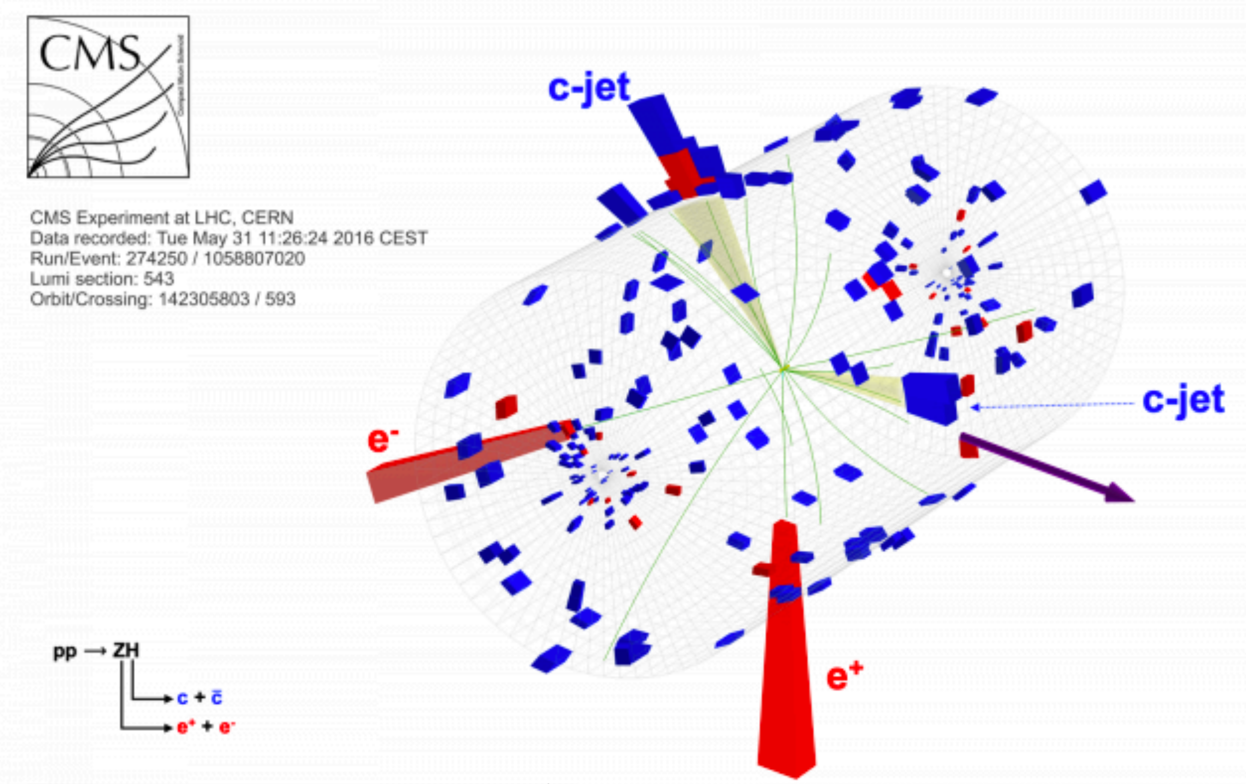


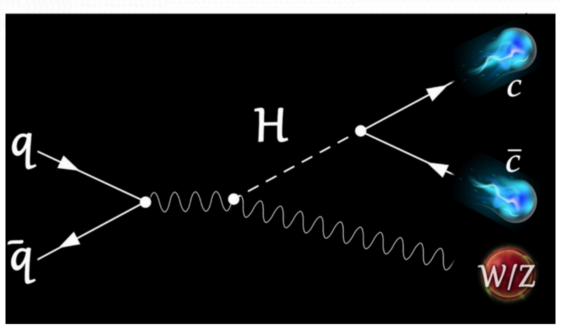


gluon-fusion and VBF with similar sensitivity

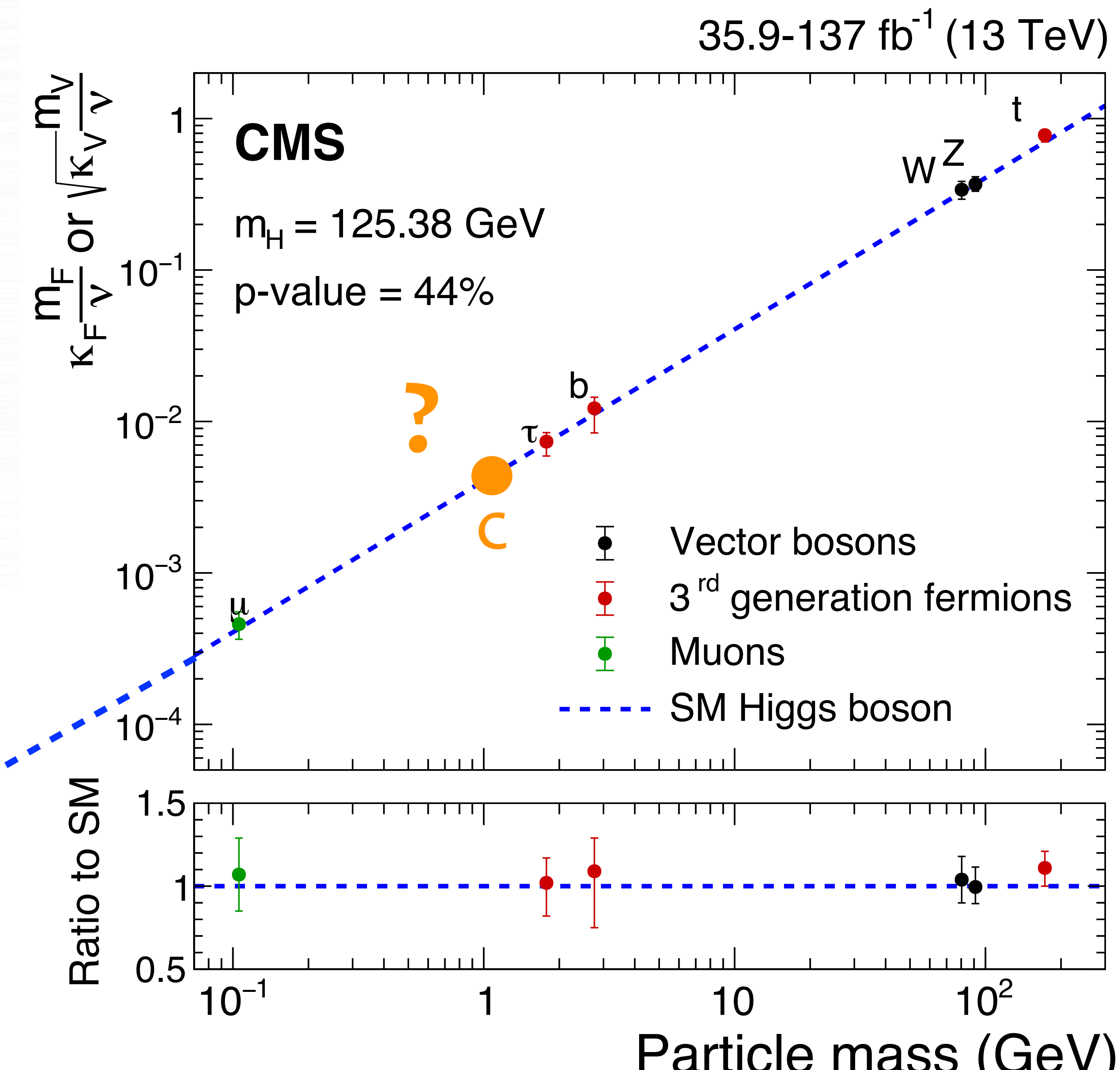
Within target: $H \to c\bar{c}$

- $H \to e^+e^-$ far from LHC reach.
- What about 2nd generation Higgs c-quark couplings?



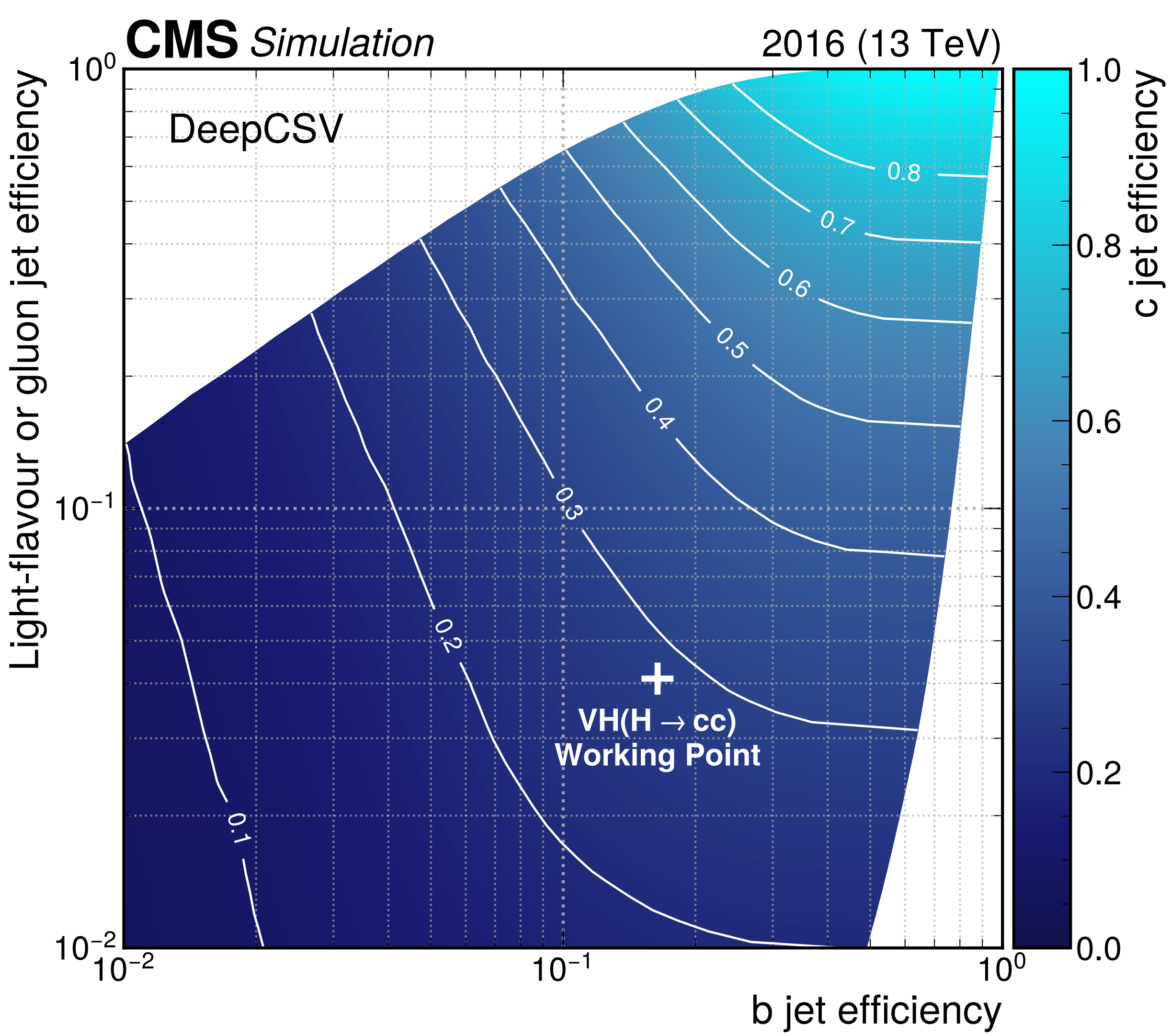


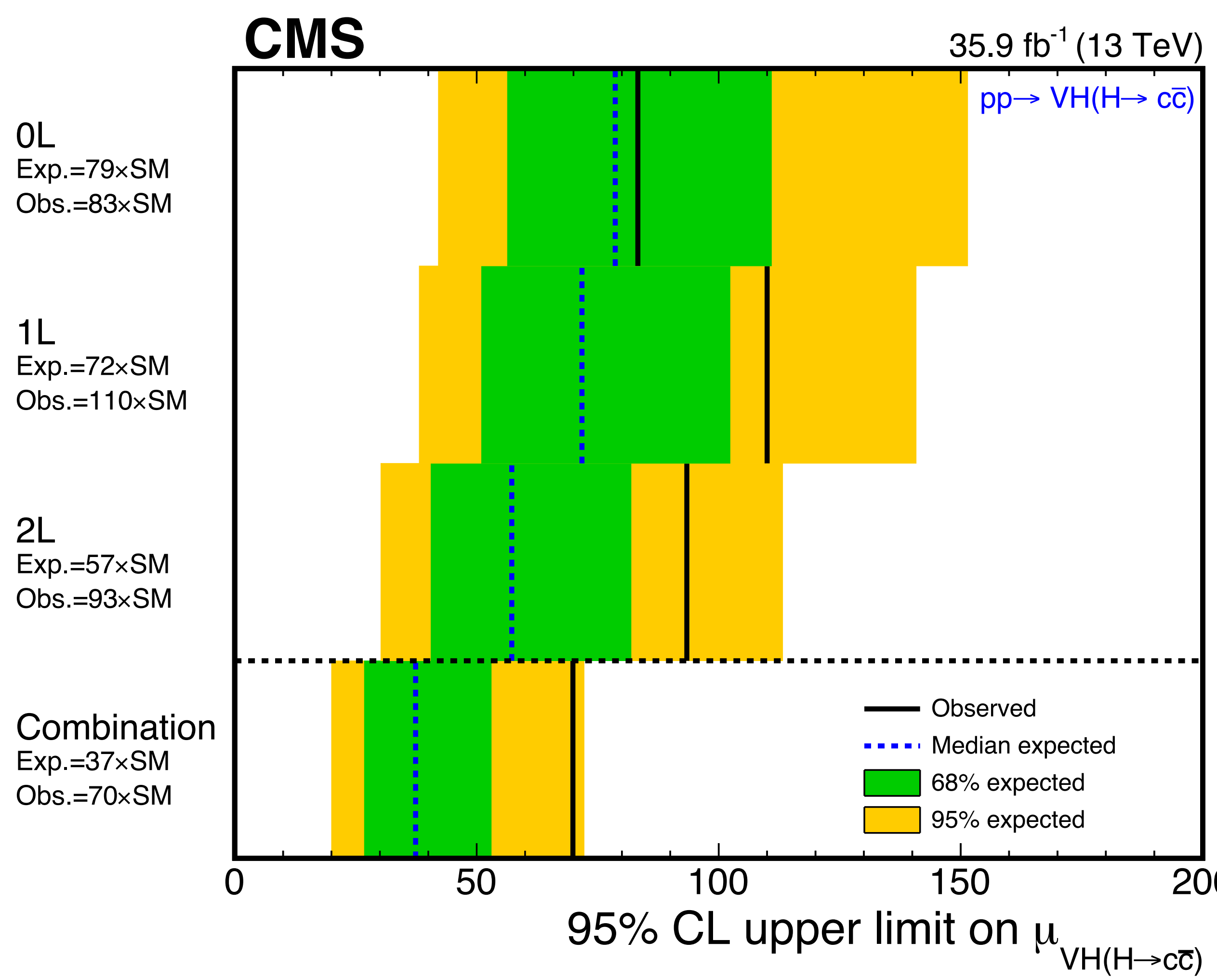
electrons



JHEP 03 (2020) 131

- Very challenging channel: large backgrounds from multi-jets
  - c-tagging central to discriminate $H \to b\bar{b}$: **Deep NN algorithms play crucial role**
- $(W, Z)H \to c\bar{c}$ associated production categorized in
  - 1, 2, 3 leptons and # c-tagged jets





b-jet and light-jet misID at fixed c-jet efficiencies

sensitivity still far away:

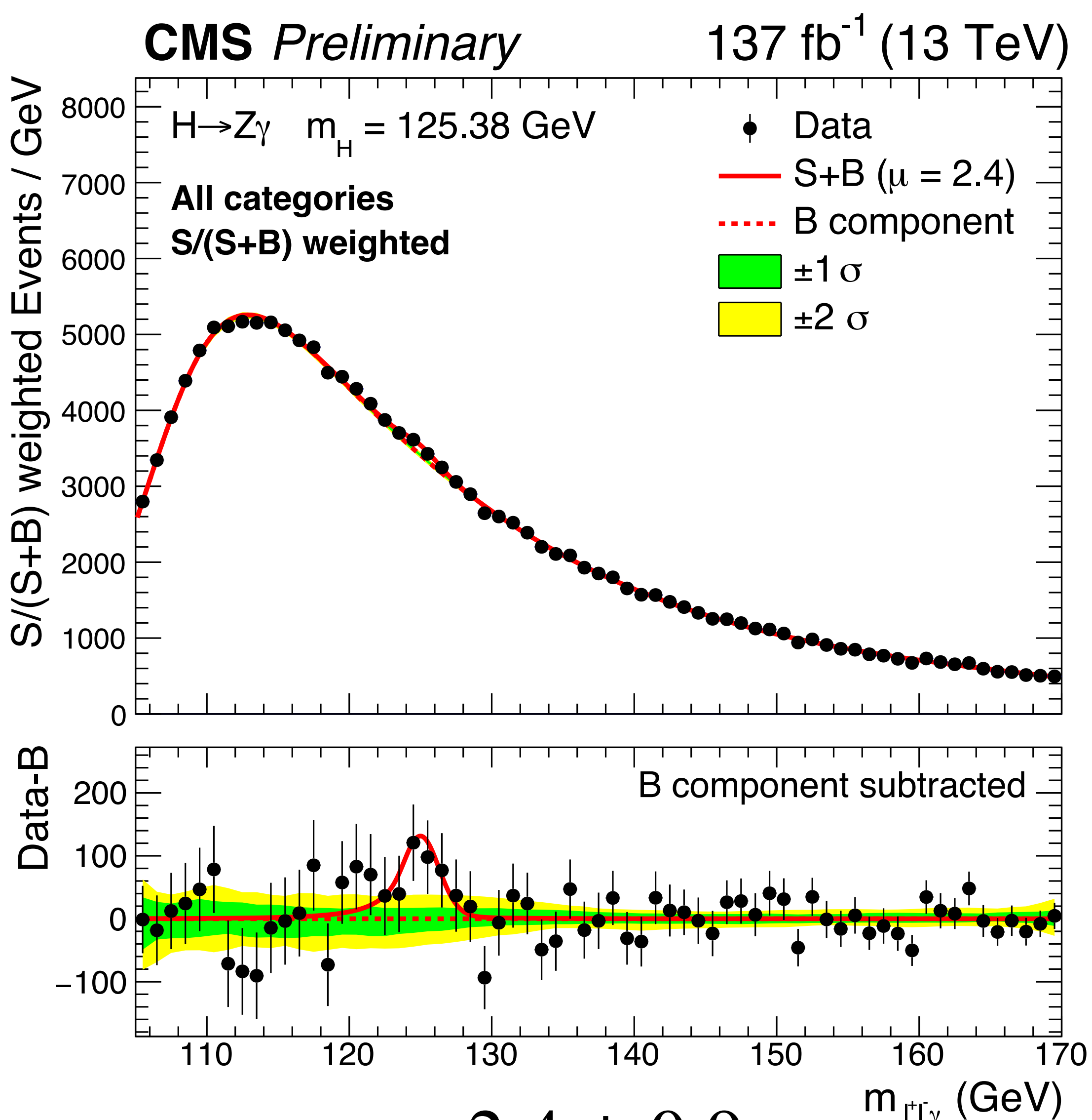
$\sigma/\sigma^{SM} < 70$ (37 exp.)

Search for $H \rightarrow Z\gamma$

- $SU(2)_L$ symmetry relates the HWW, HZZ, Hγγ, HZγ interactions
  - if heavy new physics respects $SU(2)_L$, correlated effects across the four
- Categorizing by production mode: ggH,VBF,VH and ttH

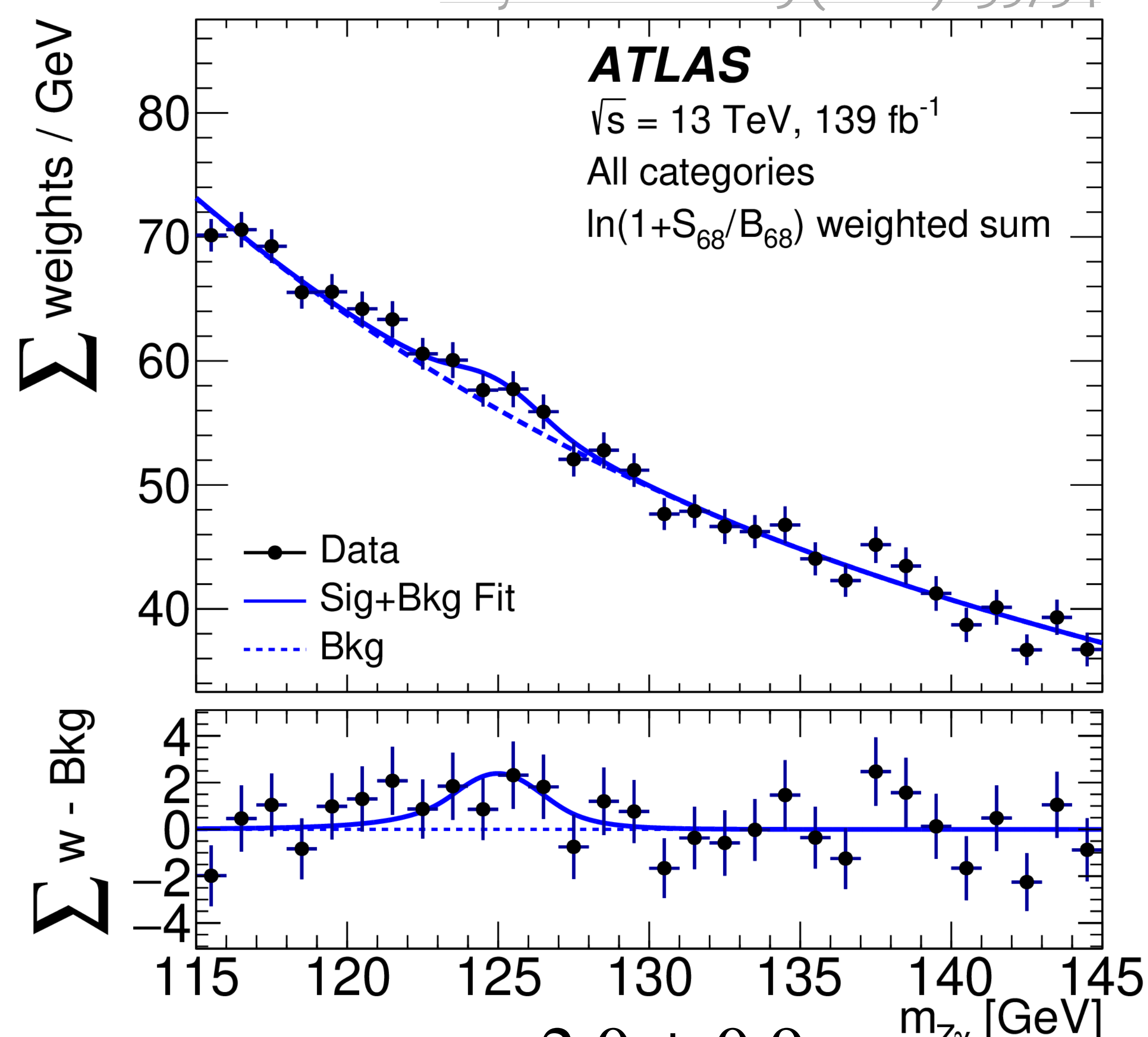
CMS-PAS-HIG-19-014

Phys. Lett. B 809 (2020) 135754



$\mu = 2.4 \pm 0.9$

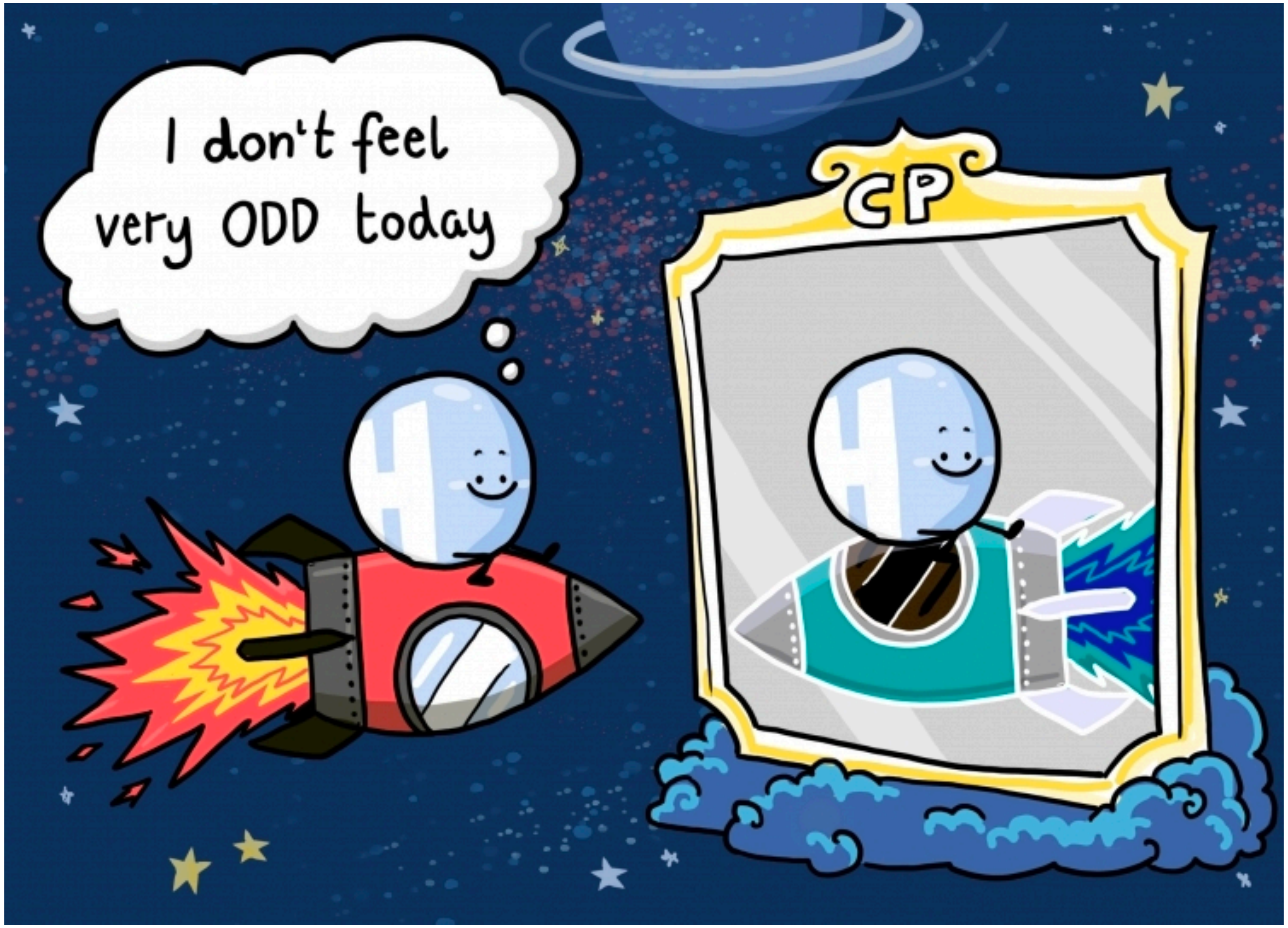
significance: 2.7σ (1.2σ exp.)



$\mu = 2.0 \pm 0.9$

significance: 2.2σ (1.2σ exp.)

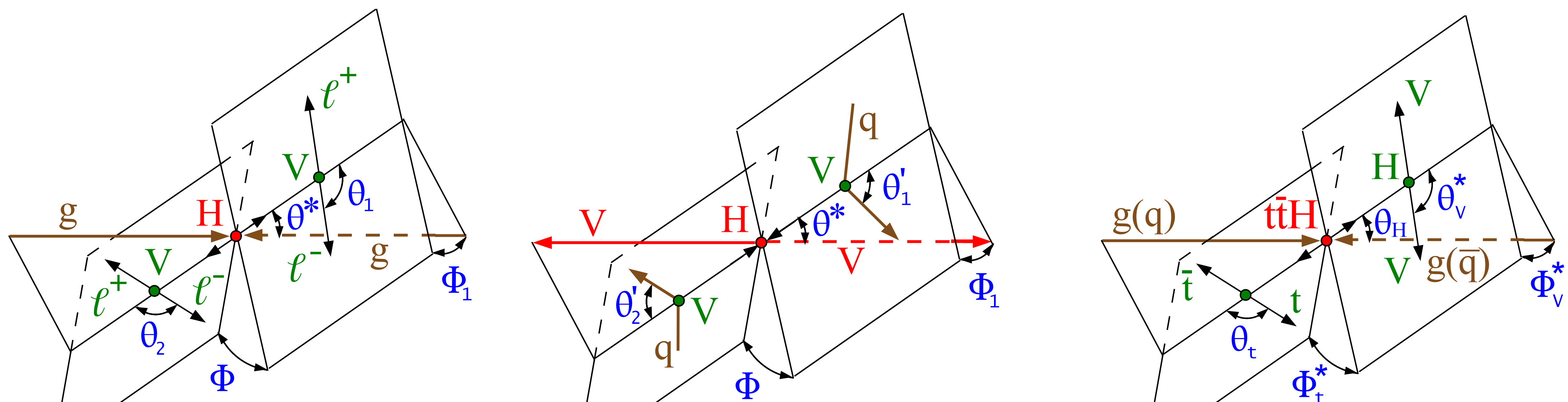
CP and anomalous couplings (AC)



HVV in H->ZZ (4ℓ and 2ℓ2ν)

- After Run1 excluded spin-1 and spin-2 hypotheses, analyses with full Run2 investigate CP structure in a vast program of measurements
- HVV couplings tested with H→4ℓ using production and decay
  - production categories: untagged, boosted, VBF 1/2 jets, VH H hadronic/leptonic

Phys. Rev D 104 (2021) 052004



gg→H→VV→4ℓ qq→VV→H→VV gg(qq)→ttH→ttVV

$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

a_1: SM

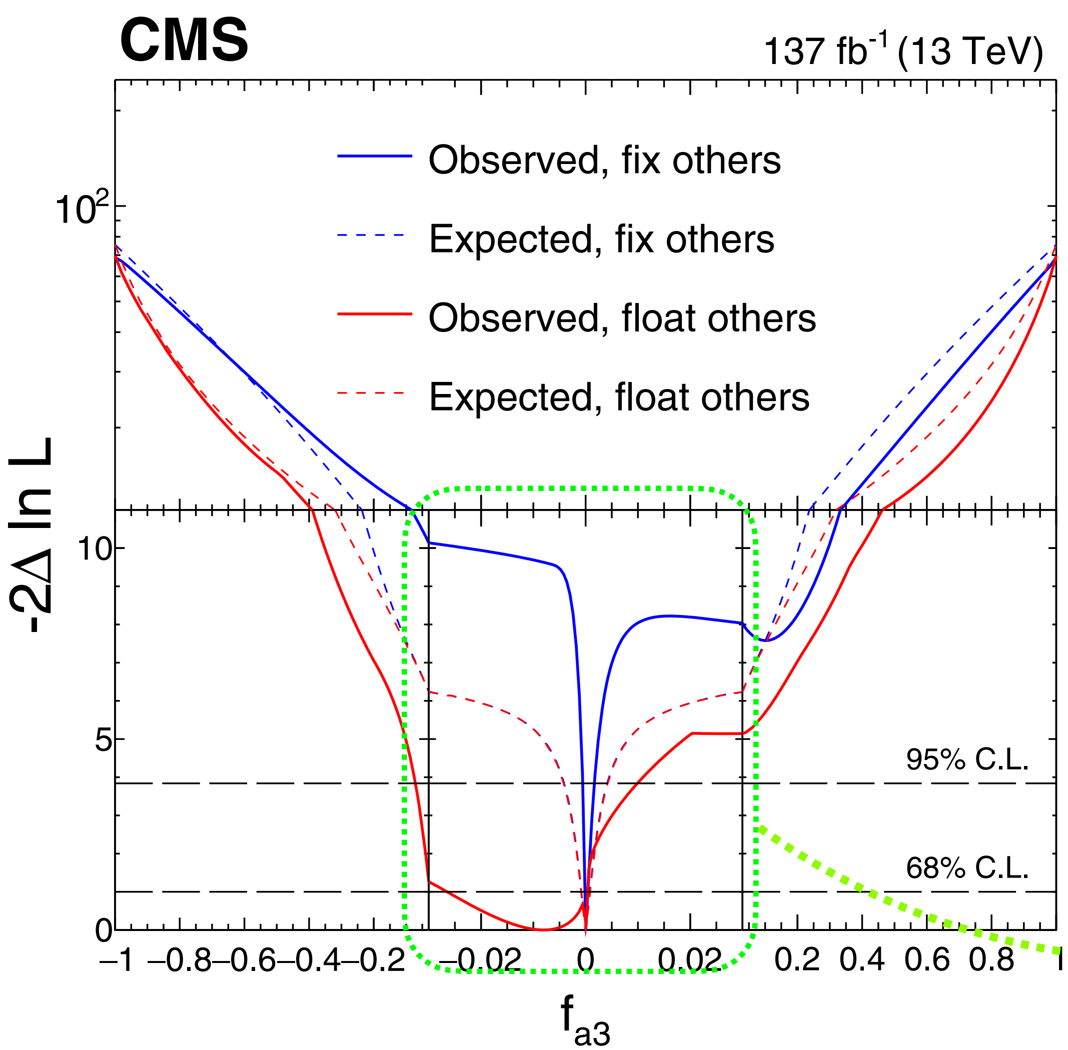
New Physics at a scale $\Lambda \gg \Lambda_{EWK}$

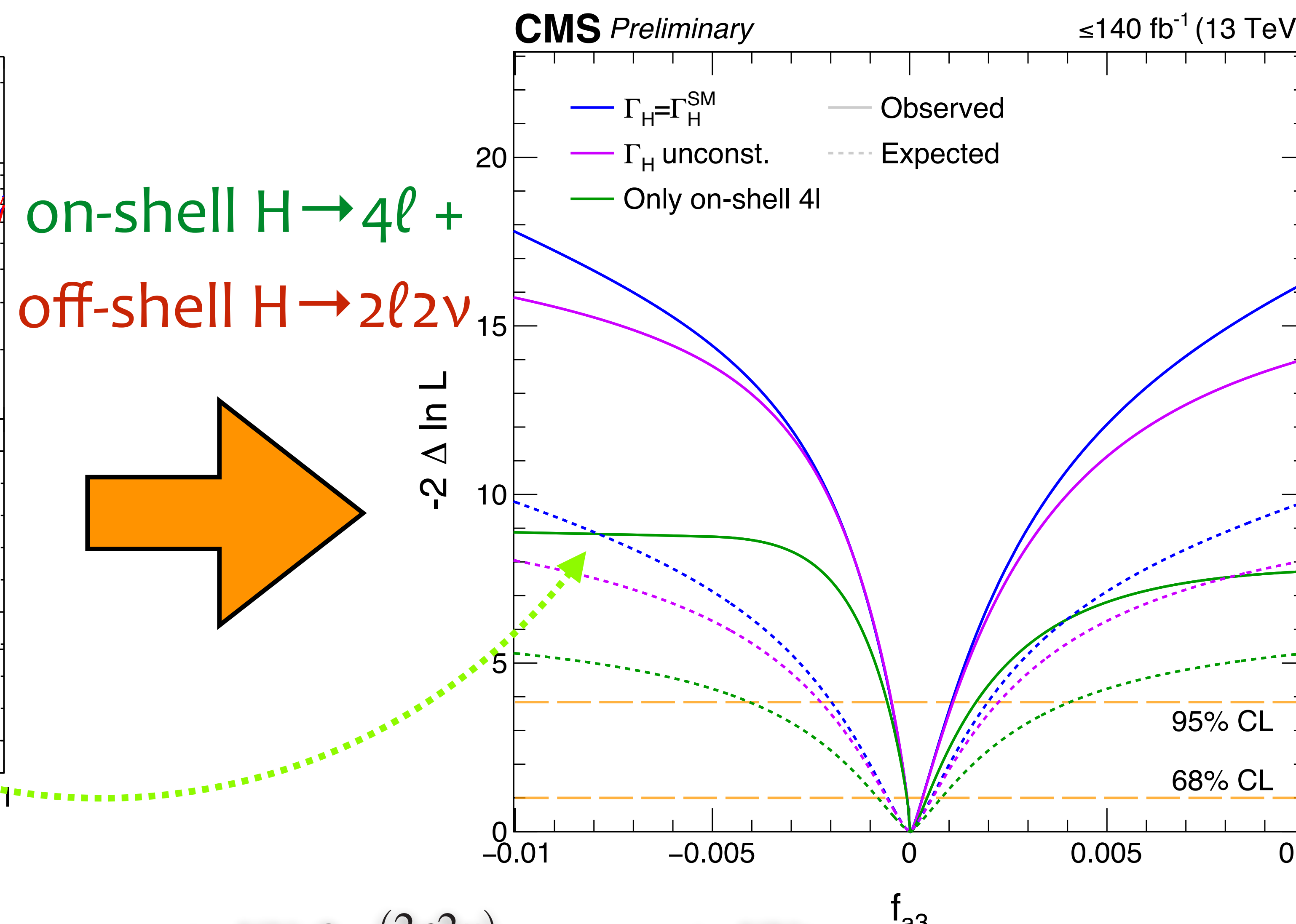
a_2: CP even anomalous coupling

a_3: CP odd anomalous coupling

$H \to 4\ell$ anomalous couplings

- Dedicated analysis for anomalous couplings to probe **3 independent HVV** and Hff couplings
  - includes SMEFT interpretation in the Higgs basis
  - constraints sensitivity dominated by production information





Phys. Rev D 104 (2021) 052004

CMS-PAS-HIG-21-013

Example: **fractional effective CP-odd cross-section f_{a3}**

$$f_{ai}^{VV} = \frac{|a_i^{VV}|^2 \alpha_{ii}^{(2e2\mu)}}{\sum_j |a_j^{VV}|^2 \alpha_{jj}^{(2e2\mu)}} \,\mathrm{sign}\left(\frac{a_i^{VV}}{a_1}\right)$$

- Lagrangian with CP-odd component $\tilde{\kappa}$ can be tested also in Higgs-fermion couplings via ttH and $\tau\tau$:

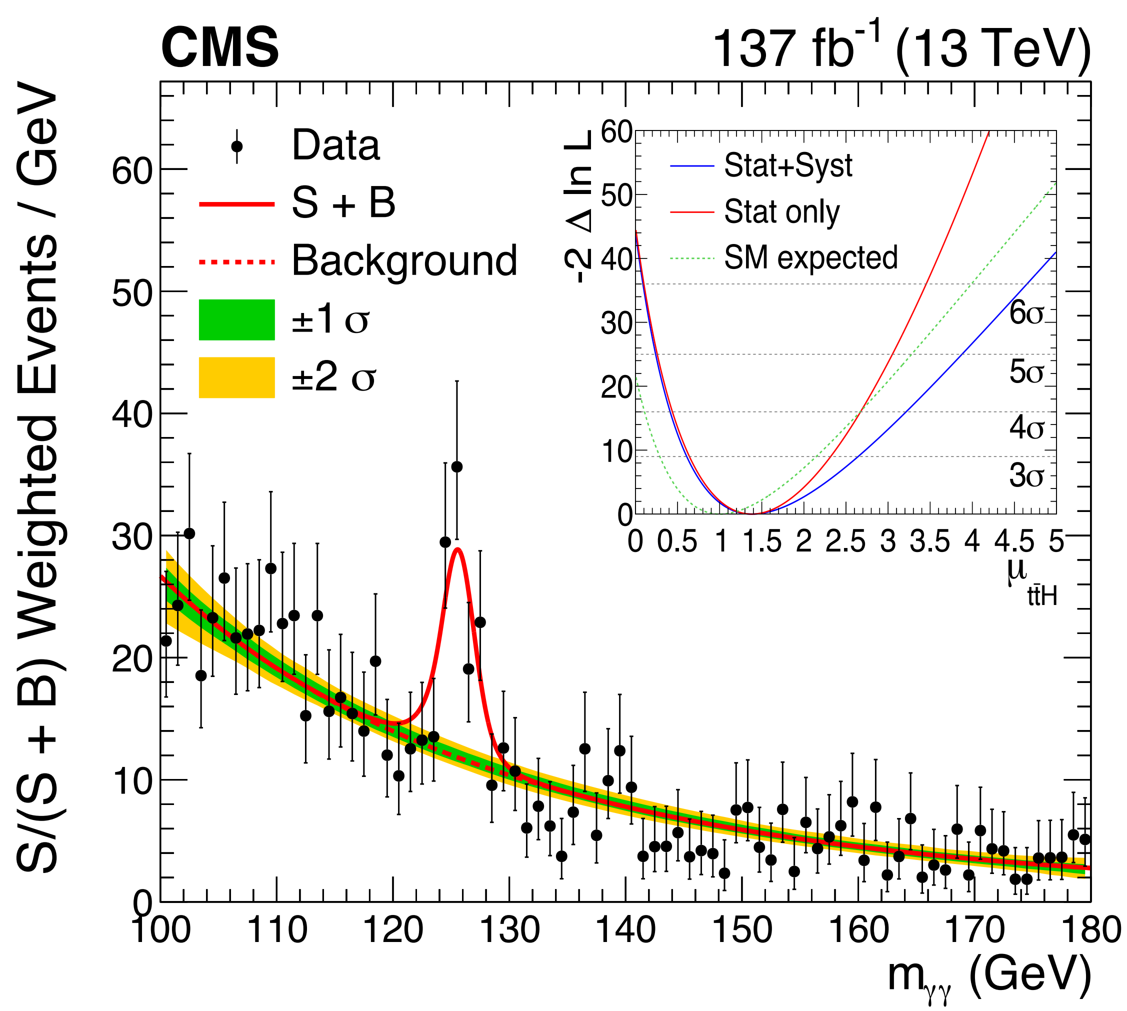
$$A(H\mathrm{ff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}(\kappa_\mathrm{f} + \mathrm{i}\tilde{\kappa}_\mathrm{f}\gamma_5)\psi_\mathrm{f}$$

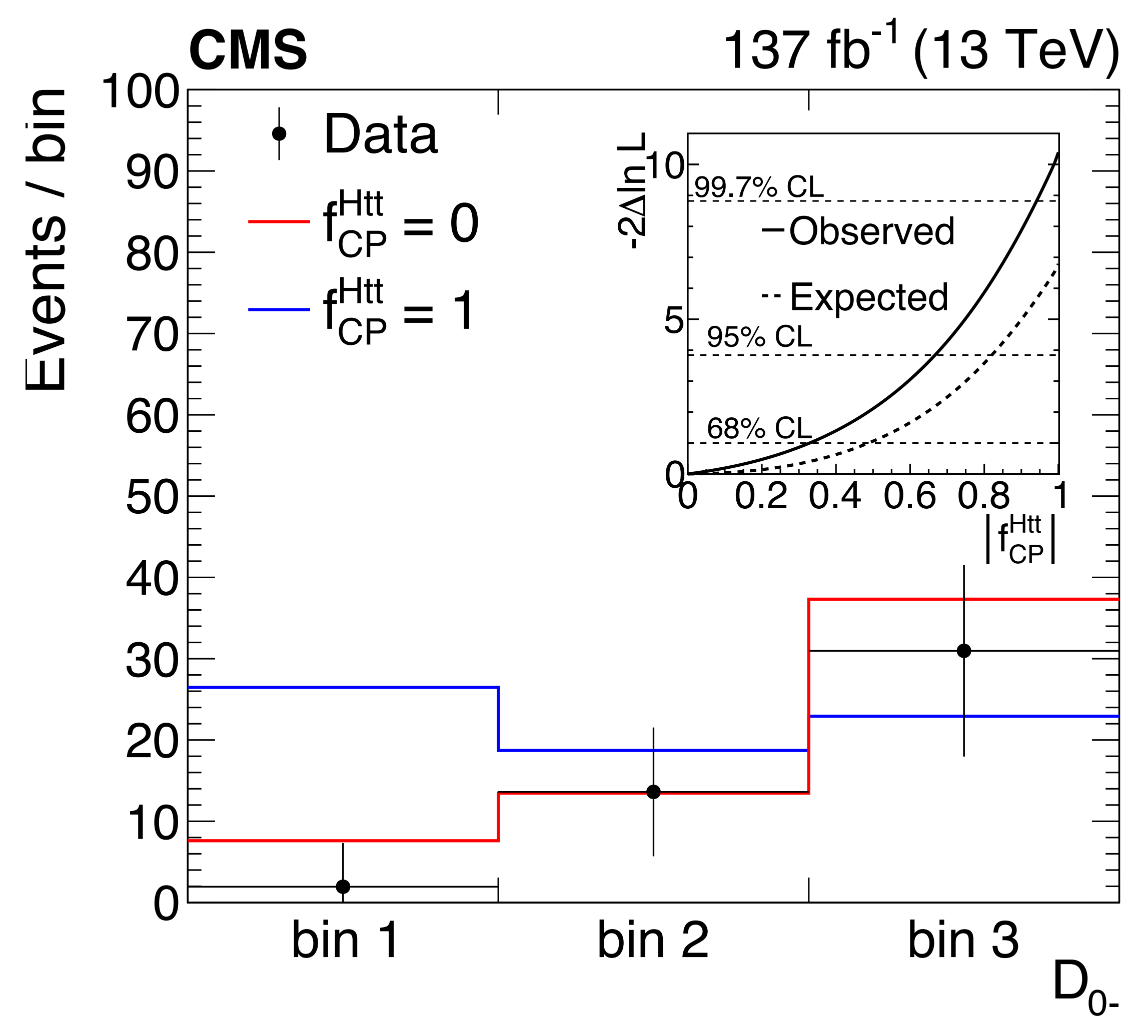
  - CP mixing angle $\Phi_{CP} = \arg(\kappa_f/\tilde{\kappa}_f)$

Phys. Rev. Lett. 125 (2020) 061802

- ttH CP MVA in multiple categories, using Matrix Element as input: D_{0-}
  - Combined multiple channels: ttH $H \to \gamma\gamma$, $H \to 4\ell$ and $H \to \tau\tau$

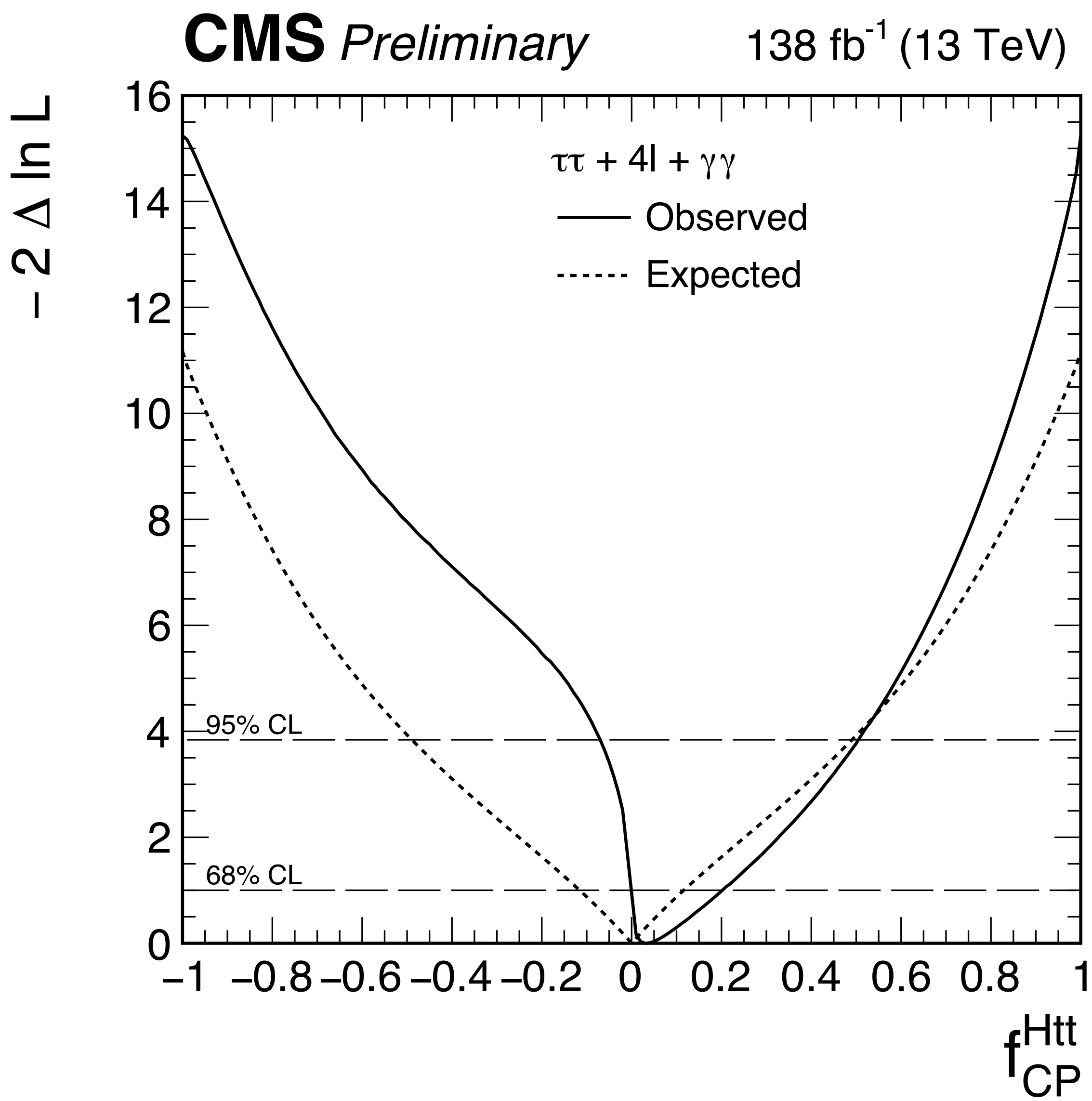
Phys. Rev. Lett. 125 (2020) 061801
Phys. Rev. D 104 (2021) 052004
CMS-PAS-HIG-20-007



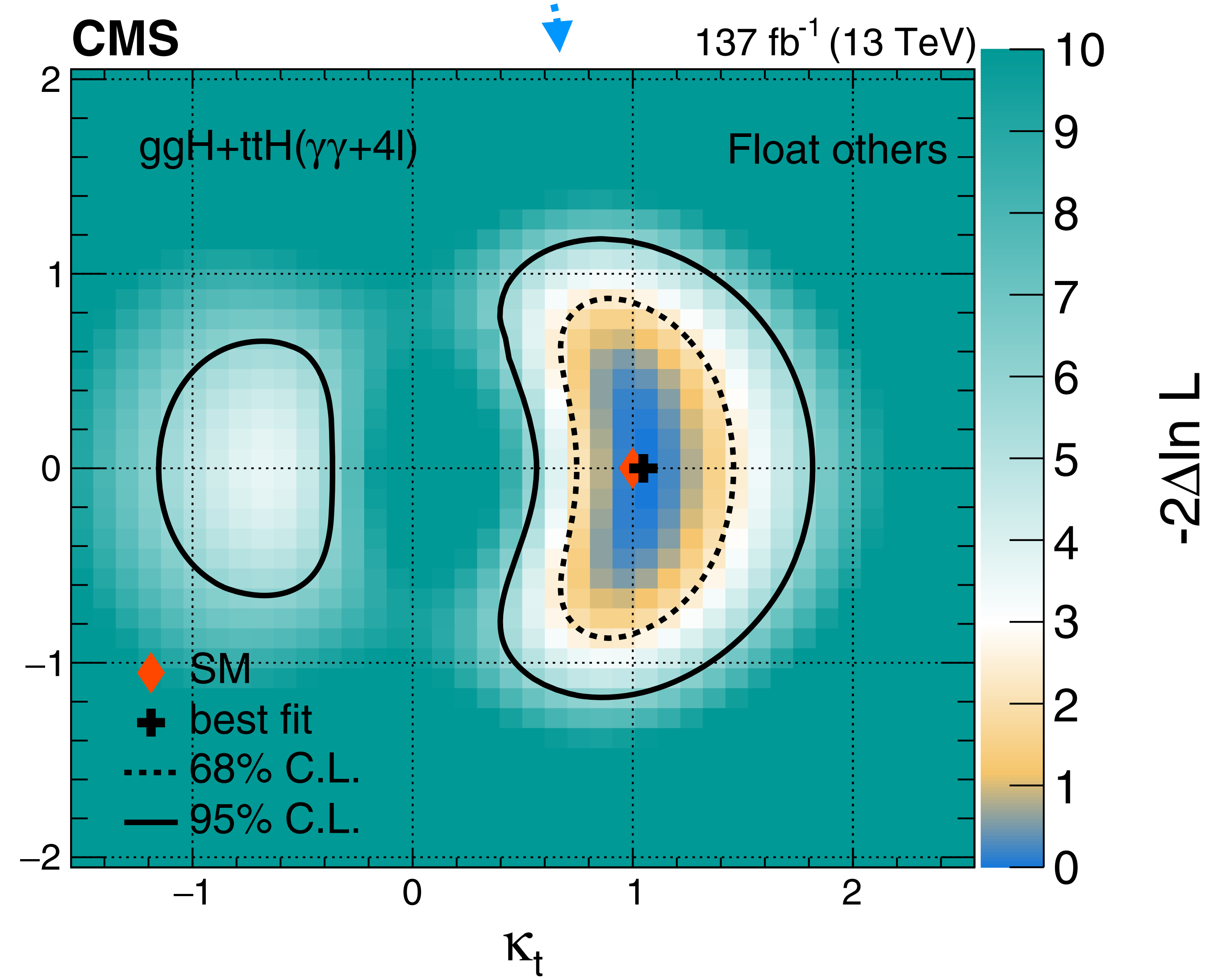


Yukawa top couplings

- Combine ttH in $H \to \gamma\gamma$ and $H \to 4\ell$ with uncorrelated signal strengths and interpret them as top couplings κ_t and $\tilde{\kappa}_t$



CP-odd fraction in the top-Higgs coupling using $H \to \tau\tau, 4\ell, \gamma\gamma$

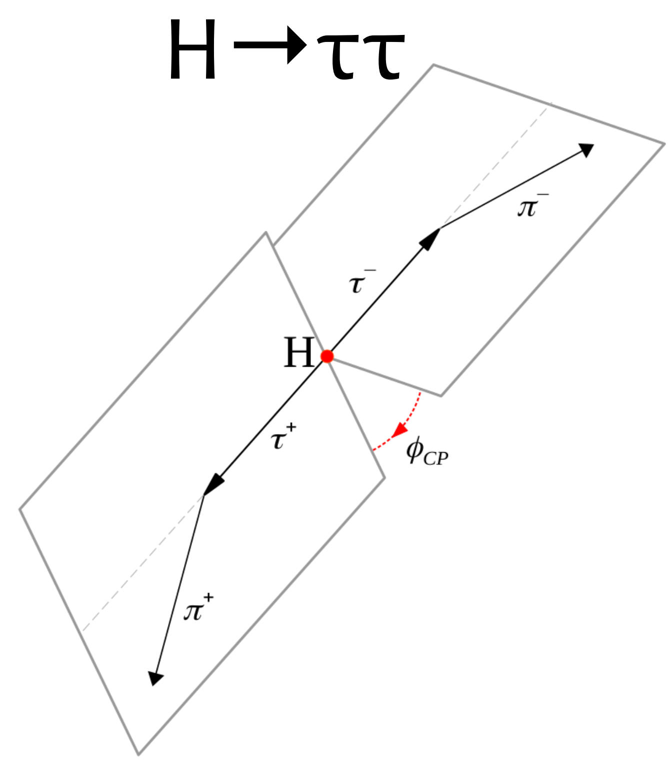


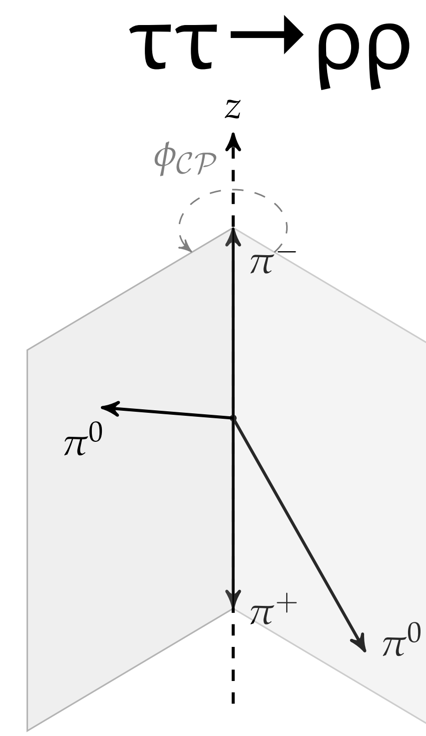
Phys. Rev. D 104 (2021) 052004

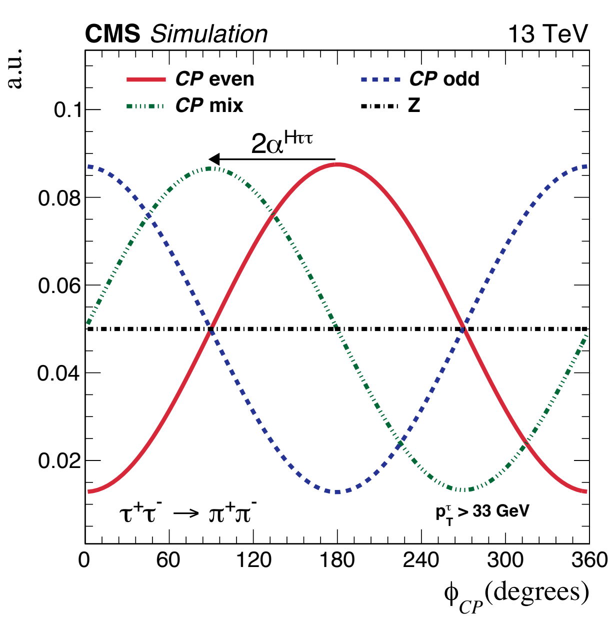
gluon fusion pointlike couplings $c_{gg}, \tilde{c}_{gg}$ profiled

CP from Yukawa $H \to \tau\tau$

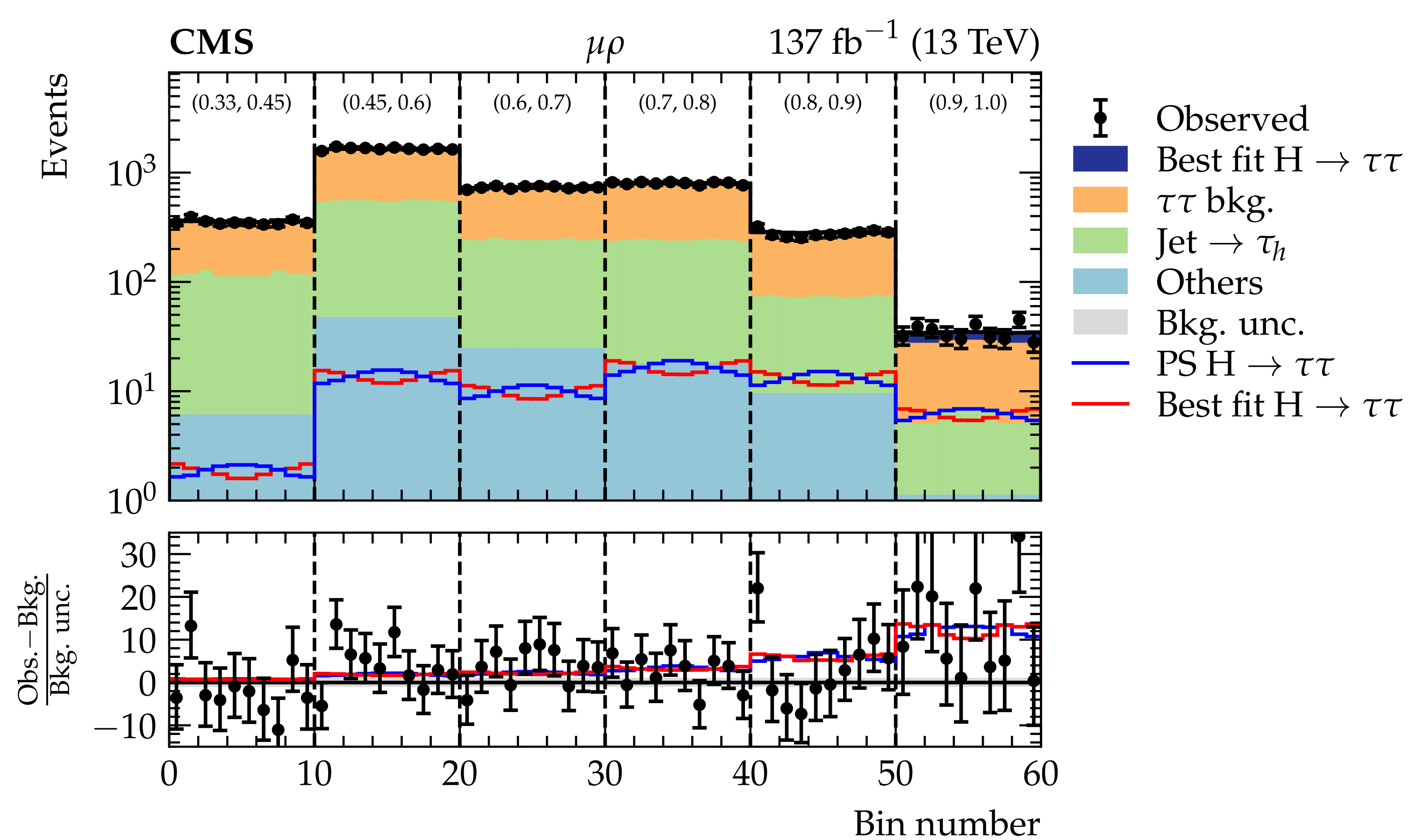
- Full Run2 analysis to measure CP odd/even mixing in $H \to \tau\tau$
  - **Use ~70% of the τ BR:** $H \to \tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$ with τ_h decays to $\pi^\pm$, $\rho^\pm(\pi^\pm\pi^0)$, $a1^\pm(\pi^\pm\pi^0\pi^0)$, $a_1^\pm(\pi^\pm\pi^+\pi^-)$
  - estimate the τ plane from multiple tracks or from the the track impact parameter vector and momentum for 1-track decays
  - Use the distribution of the angle between the two τ decay planes



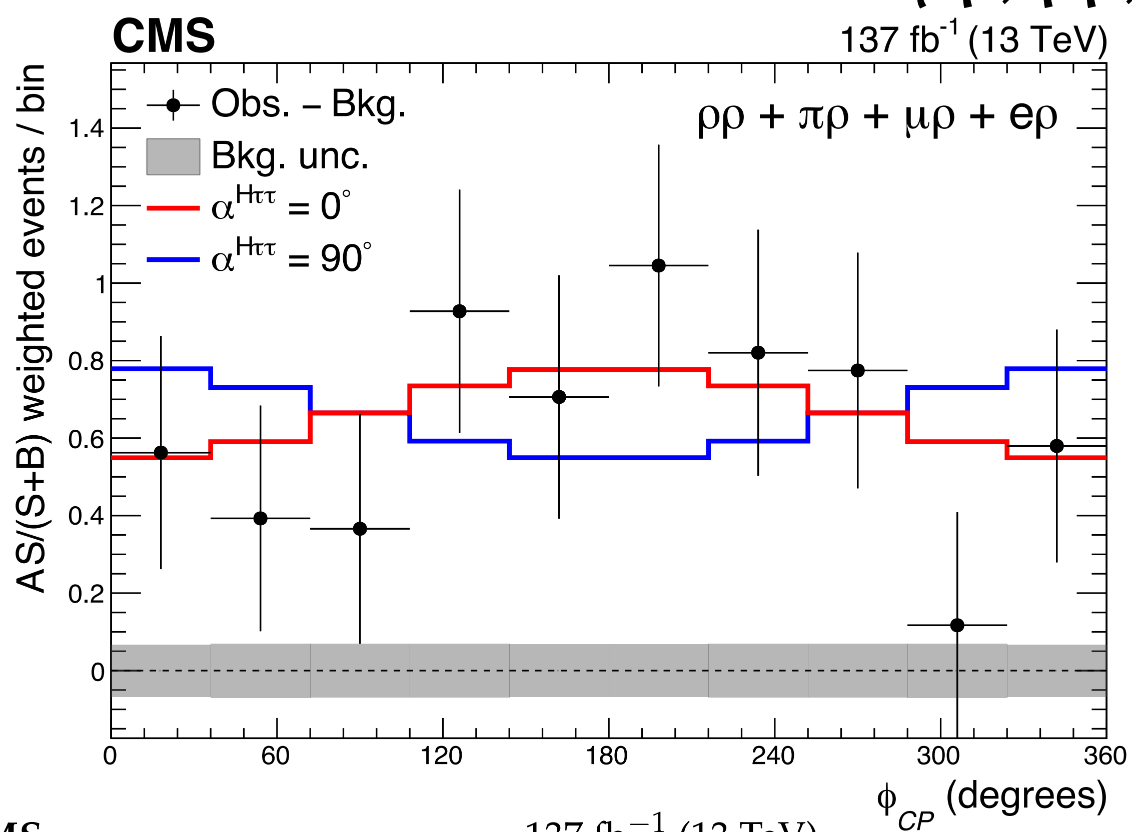




φ_{CP} binned in slices of MVA signal score for each decay mode

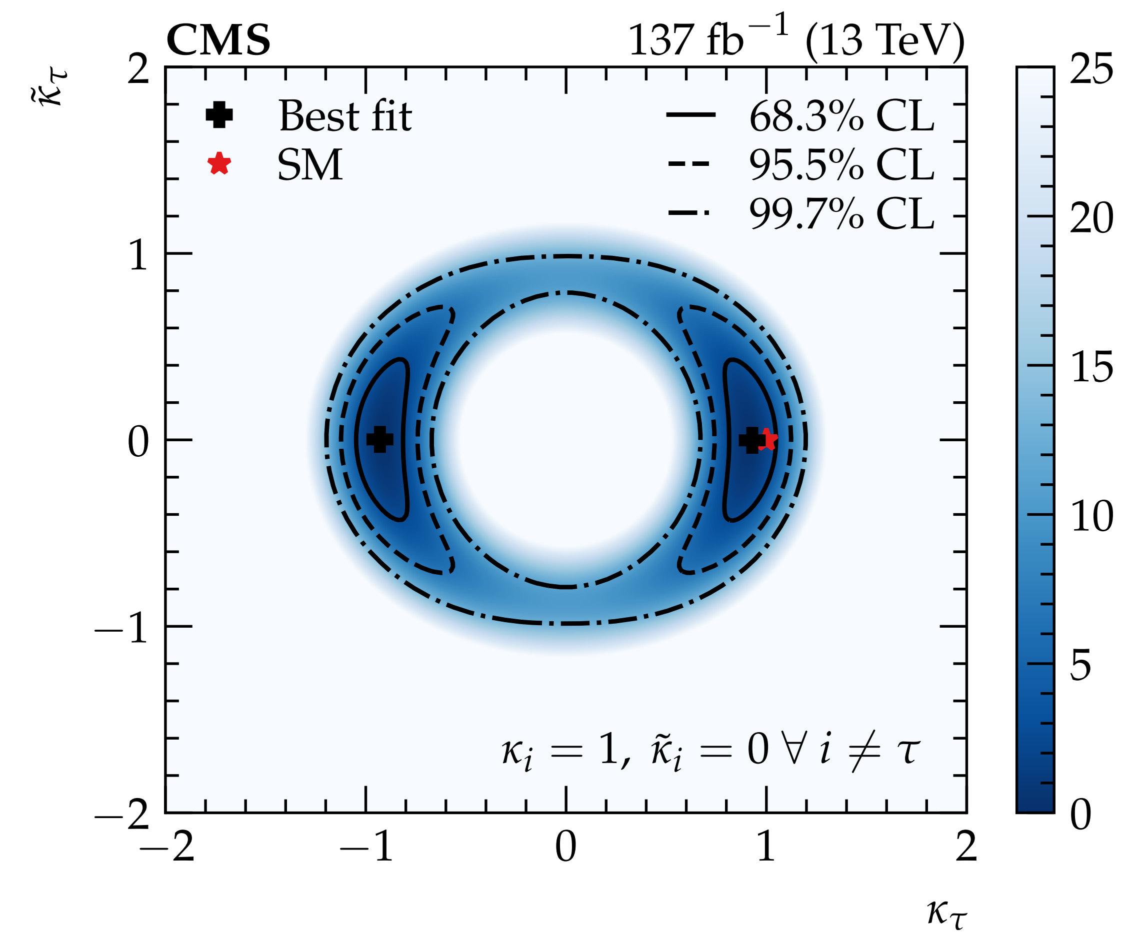


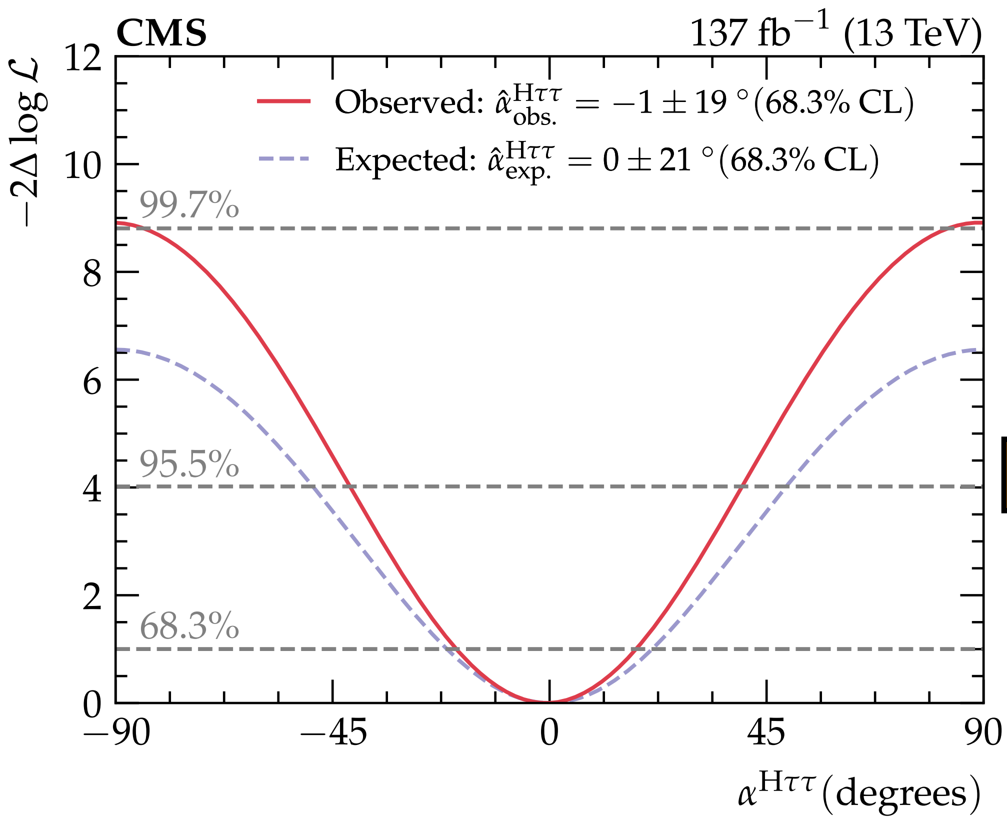
- Most sensitive final states: μρ, ρρ, πρ



CP-even (κ_τ) vs CP-odd ($\tilde{\kappa}_\tau$)

τ Yukawa coupling





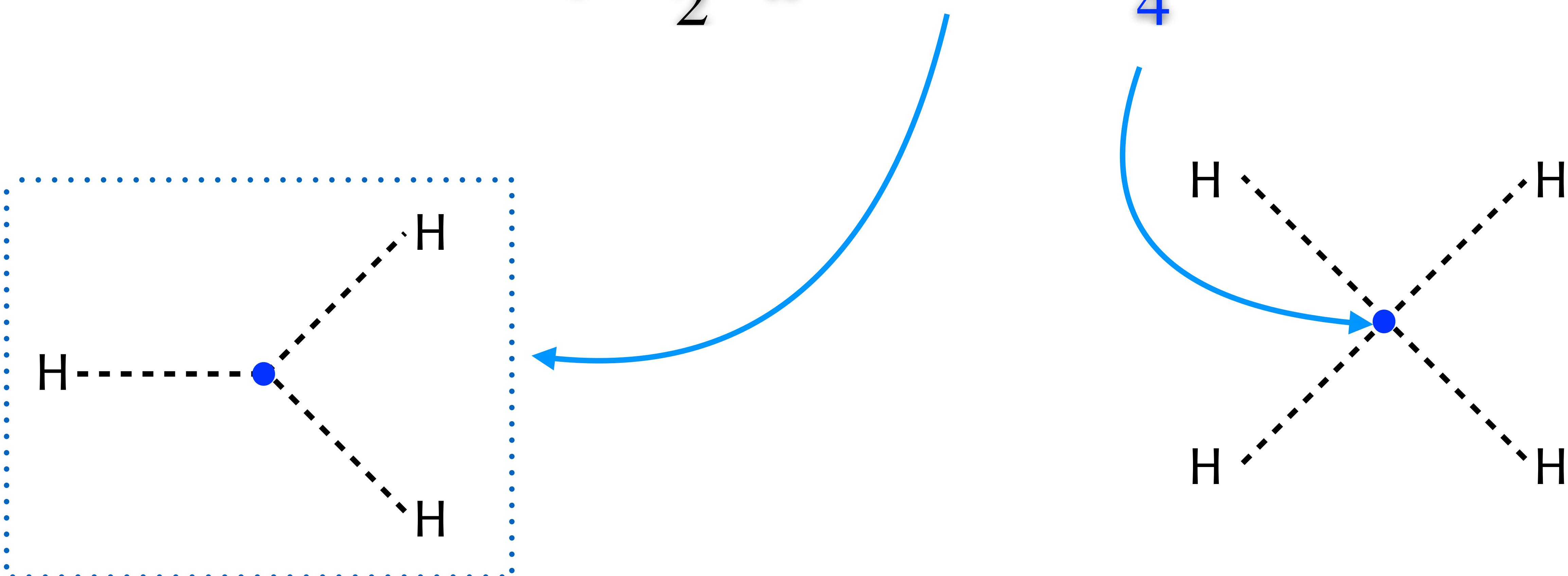
Pseudoscalar hypothesis ($\alpha^{H\tau\tau} = \pm 90°$) excluded at 3.0σ vs scalar ($\alpha^{H\tau\tau} = 0°$)

- 95% CL limit is $|\alpha^{H\tau\tau}| < 41°$

Higgs self-coupling

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

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

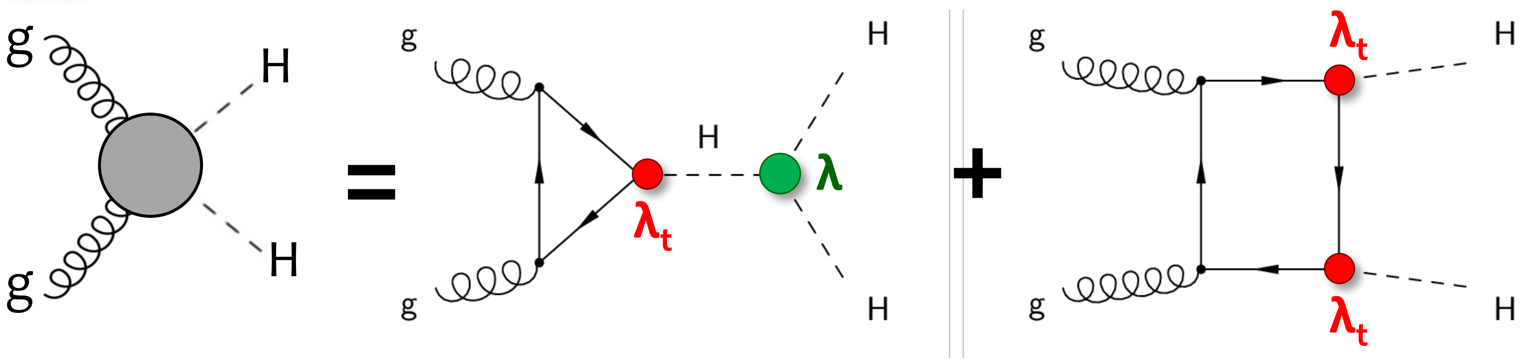


HH production

- Di-Higgs production at the LHC is dominated by the gluon-fusion process, followed (1/20) by VBF production

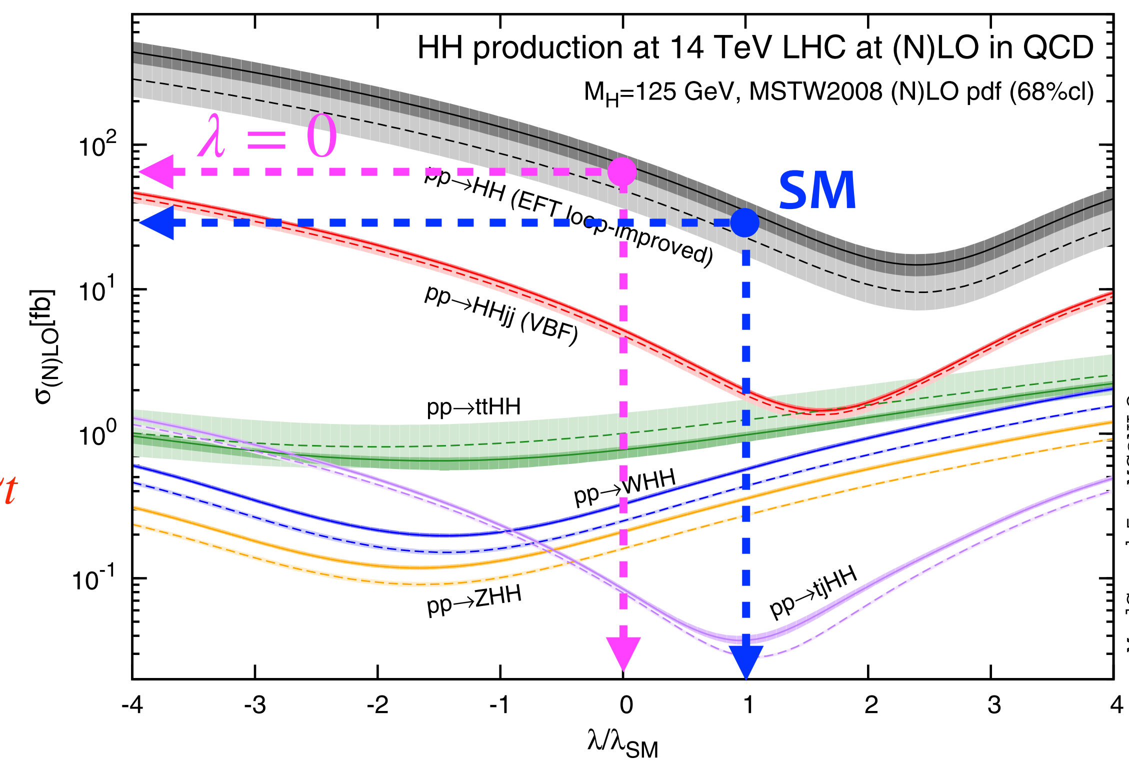
PLB 732 (2014) 142-149

ggF: $\sigma(ggHH) = 31 \text{ fb} \approx 1/1500 \times \sigma(ggH)$

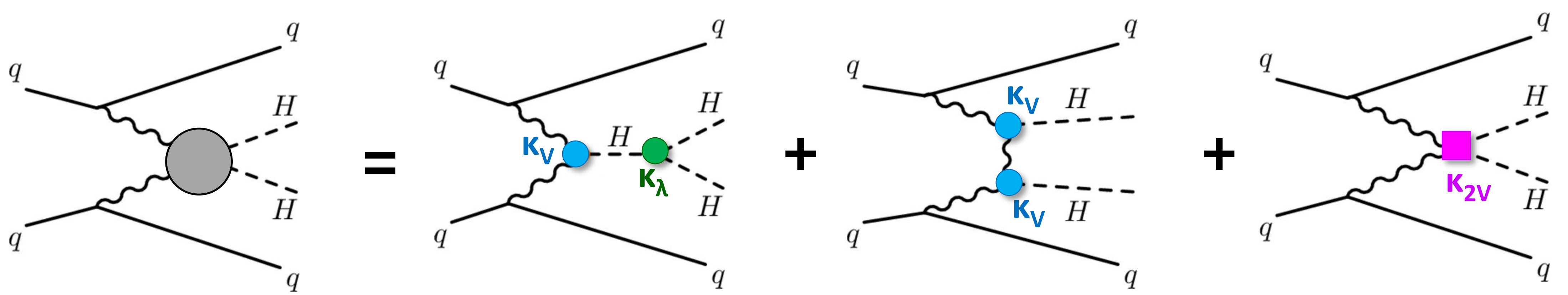


self-coupling λ Higgs-top coupling λ_t

destructive interference makes $\sigma^{\lambda=0} > \sigma^{SM}$



VBF: $\sigma = 1.72 \text{ fb} \approx 1/1500 \times \sigma(ggH)$

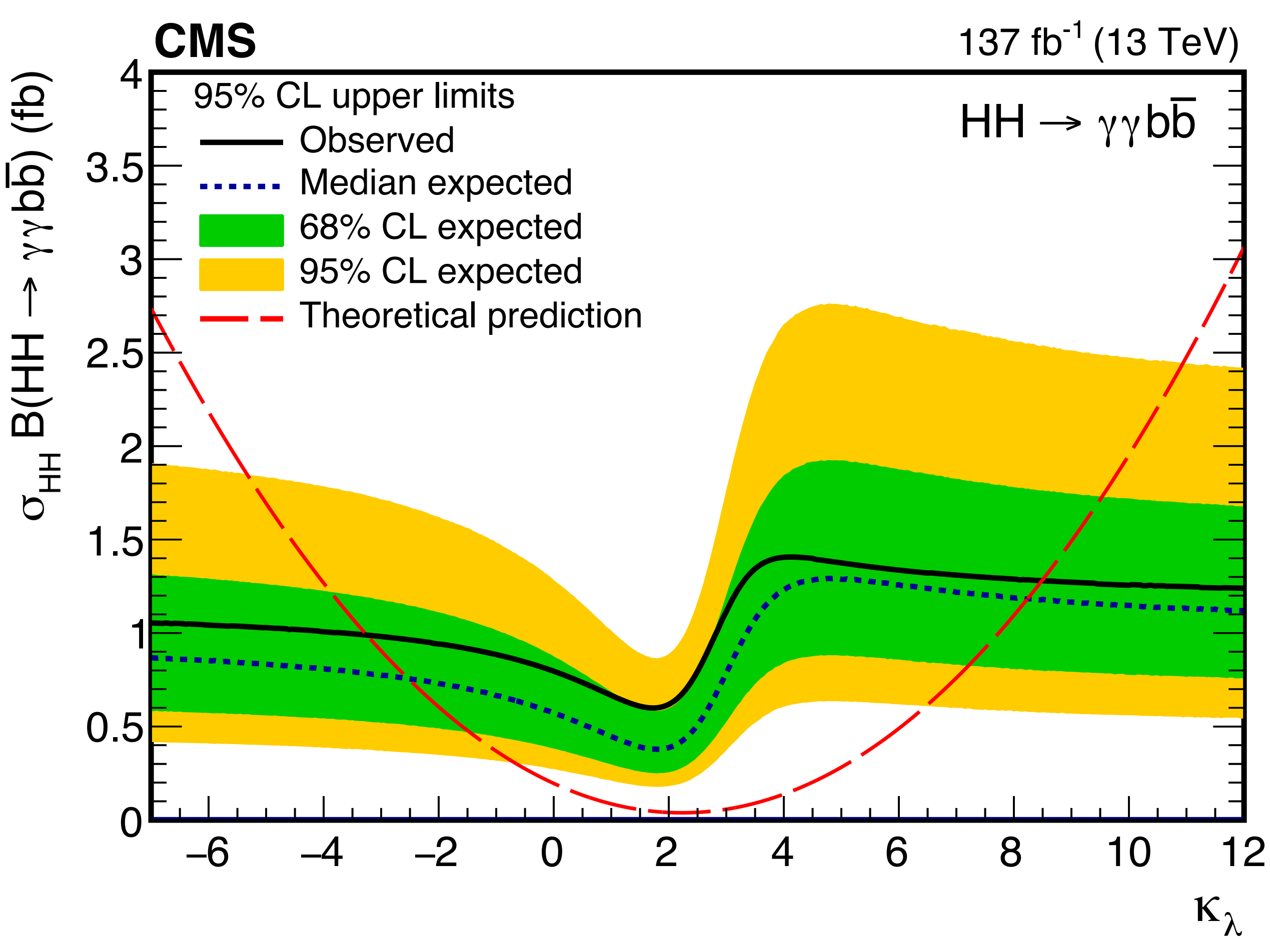


self-coupling λ HHH and HVV single H coupling κ_λ

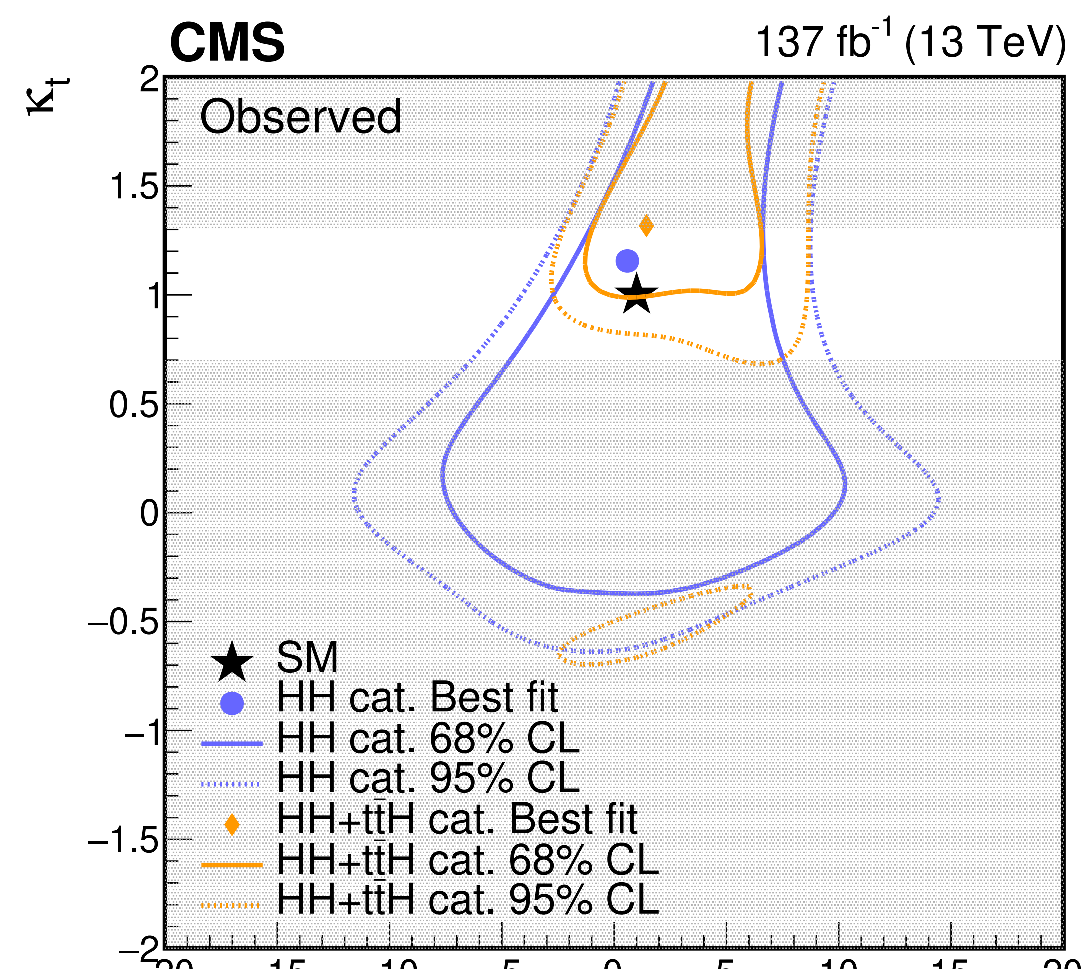
HHVV quartic coupling only in VBF production

$HH \to b\bar{b}\gamma\gamma$

- Phase space of 2 photons and 2 b-tagged jets, with $m_{\gamma\gamma}$ around 125 GeV
  - both CMS and ATLAS also look for a resonant $X \to HH \to b\bar{b}\gamma\gamma$
  - bkgs: $\gamma\gamma + jets$ from data sidebands and single Higgs from MC fullsim
- cross section upper limit = 7.7 (5.2 exp) $\times\, \sigma_{SM}^{HH}$



Constraint on trilinear coupling at 95% CL:
$-3.3 < \kappa_\lambda < 8.5$



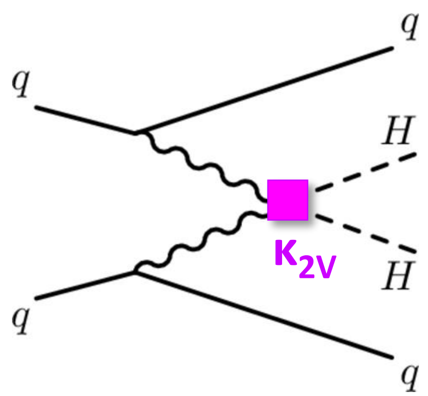
2D constraint

self-coupling κ_λ vs **Higgs-top coupling κ_t**

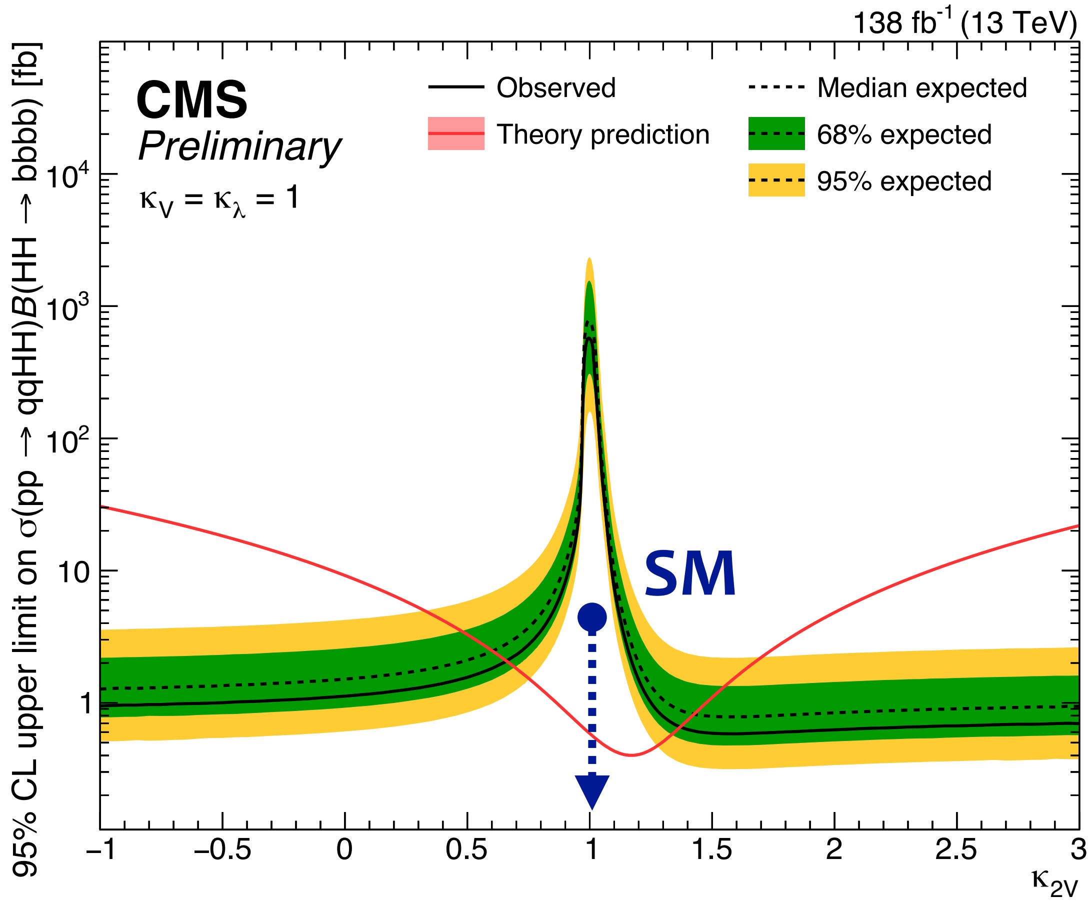
JHEP 03 (2021) 257

$HH \to 4b$

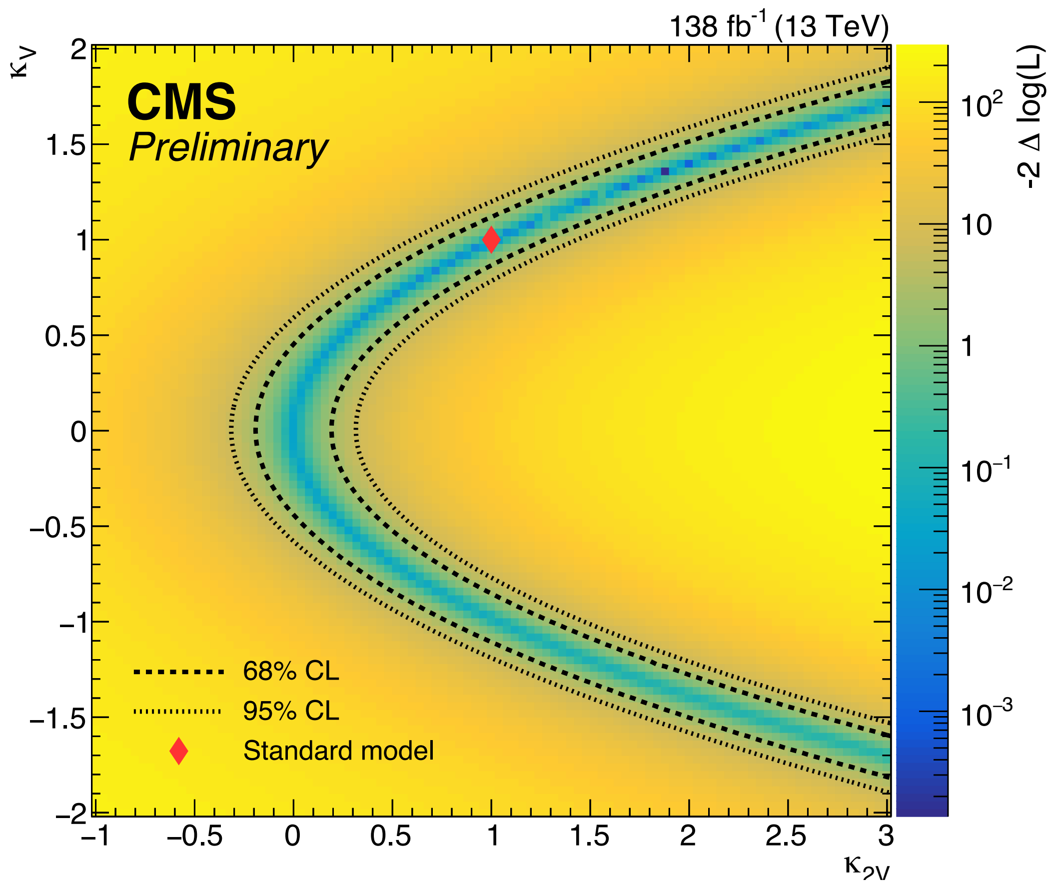
- Early Run 2 results focused on ggF production in the context of EFT using the three most sensitive channels: $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$ with non-boosted topology:
  - Still far to be sensitive to SM process: $\sigma^{HH}/\sigma^{HH}_{SM} < 7.3$ (10 exp.)
- **VBF** $HH \to 4b$ also targets the extreme kinematic of **$\kappa_{2V} \neq 1$**
  - Two boosted $H \to b\bar{b}$ candidates (two large-R jets)
  - VBF topology, $t\bar{t}$ and QCD bkg discriminated with convolutional NNs



CMS-PAS-HIG-20-005
CMS-PAS-B2G-21-001



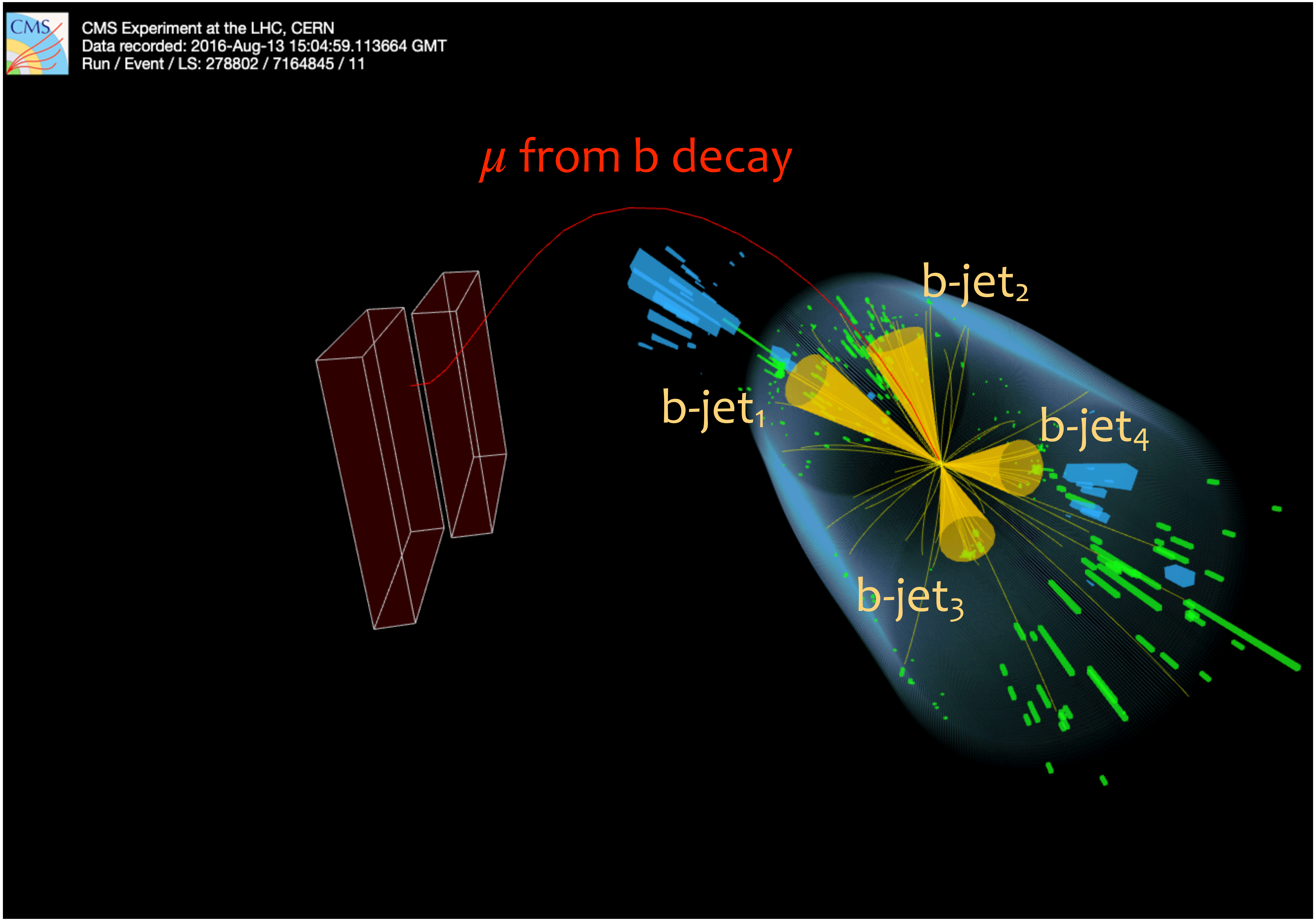
$-0.6 < \kappa_{2V} < 1.4$ @ 95% CL



$\kappa_{2V} \neq 0$ excluded @ >99.99% for k_V=1

$0.6 < \kappa_{2V} < 1.4$ @ 95% CL

$HH \rightarrow 4b$ candidate



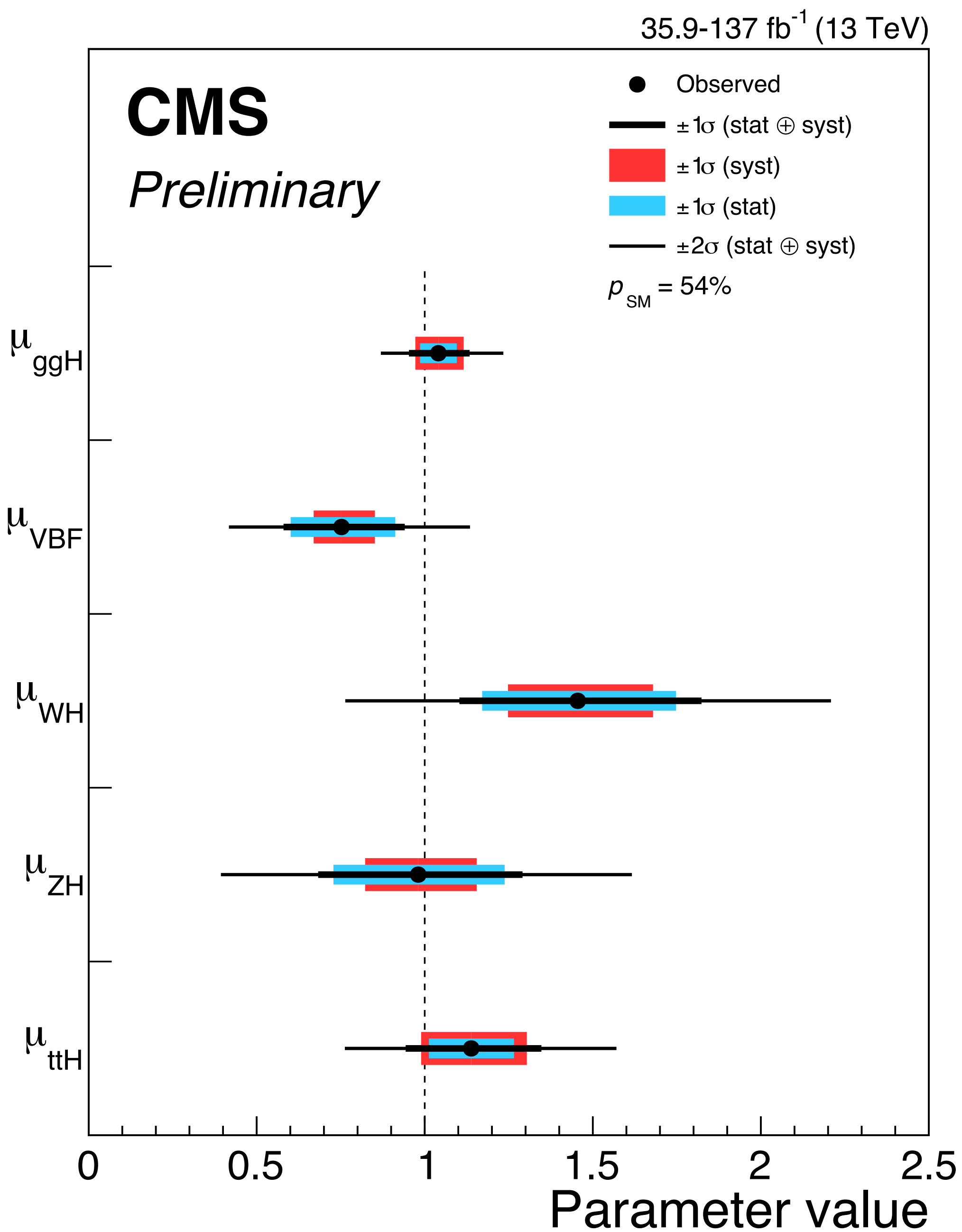
Combination

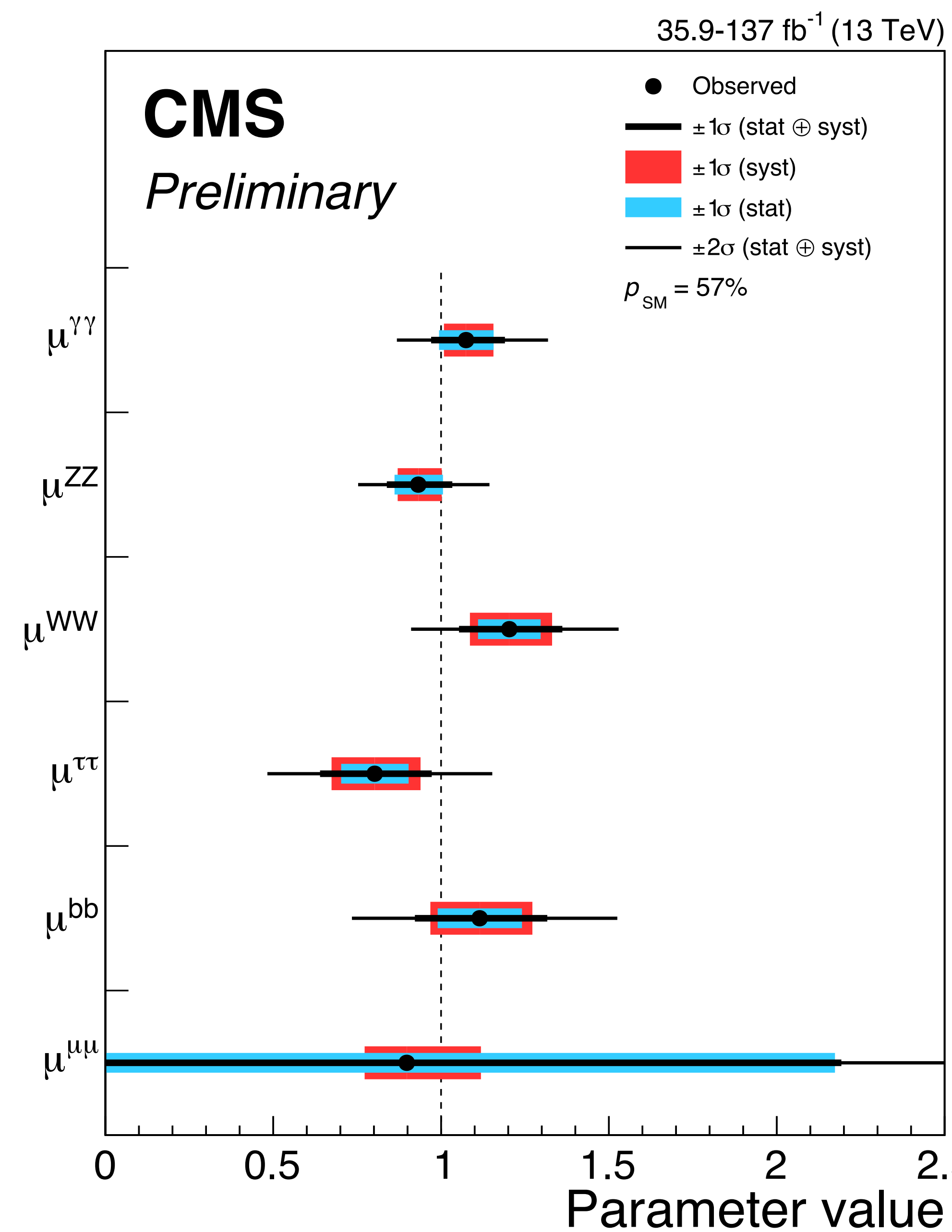
Run 2 combination: signal strength μ

- Higgs physics in the **era of precision (6% on μ)**:

CMS-PAS-HIG-19-005

  - **CMS:** $\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat.}) \pm 0.04(\text{exp.}) \pm (\text{th.})$





σ^H/σ^H_{SM} by production mode

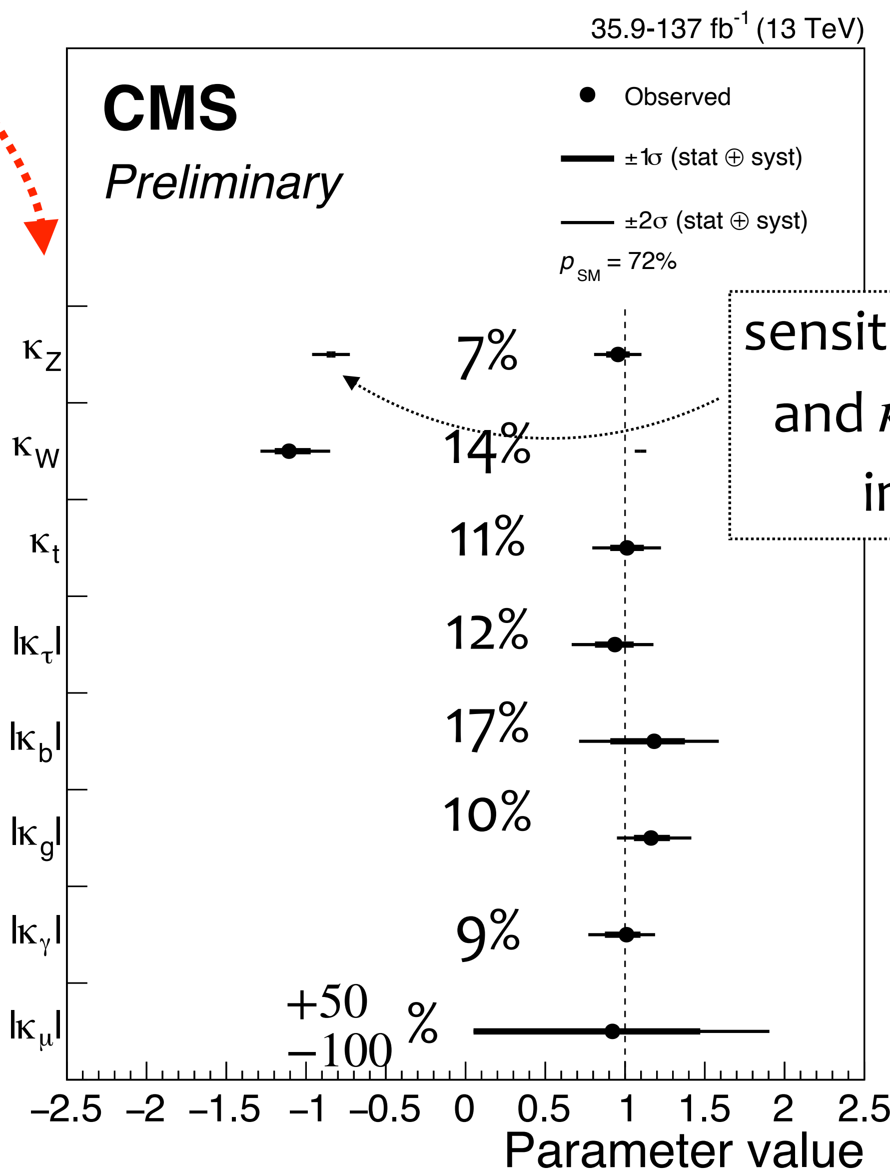
σ^H/σ^H_{SM} by decay mode

Run 2 combination: κ and EFT

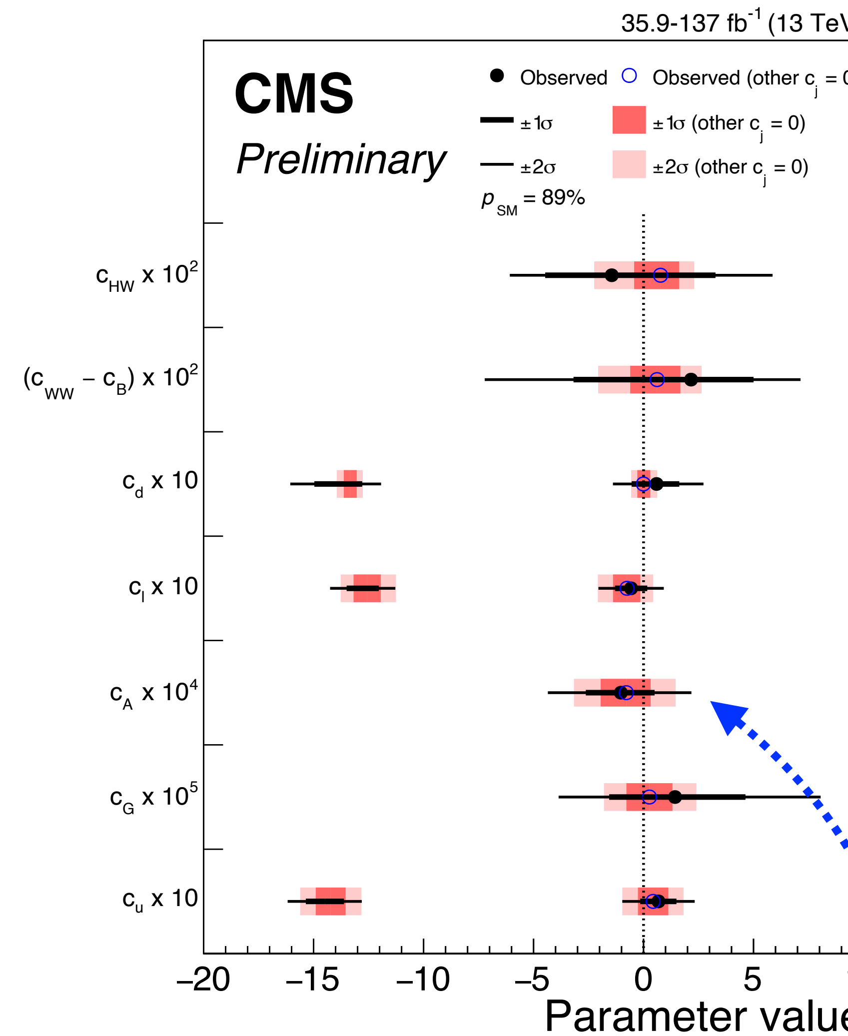
- Combination in the **κ-framework** for the coupling modifiers
  - assuming decays to SM-only particles, the same κ parameter scales cross section and partial width

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM}, \quad \kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$$

  - difference from μ: accounts for interference



sensitive to relative κ_Z and κ_t sign via ggZH interference



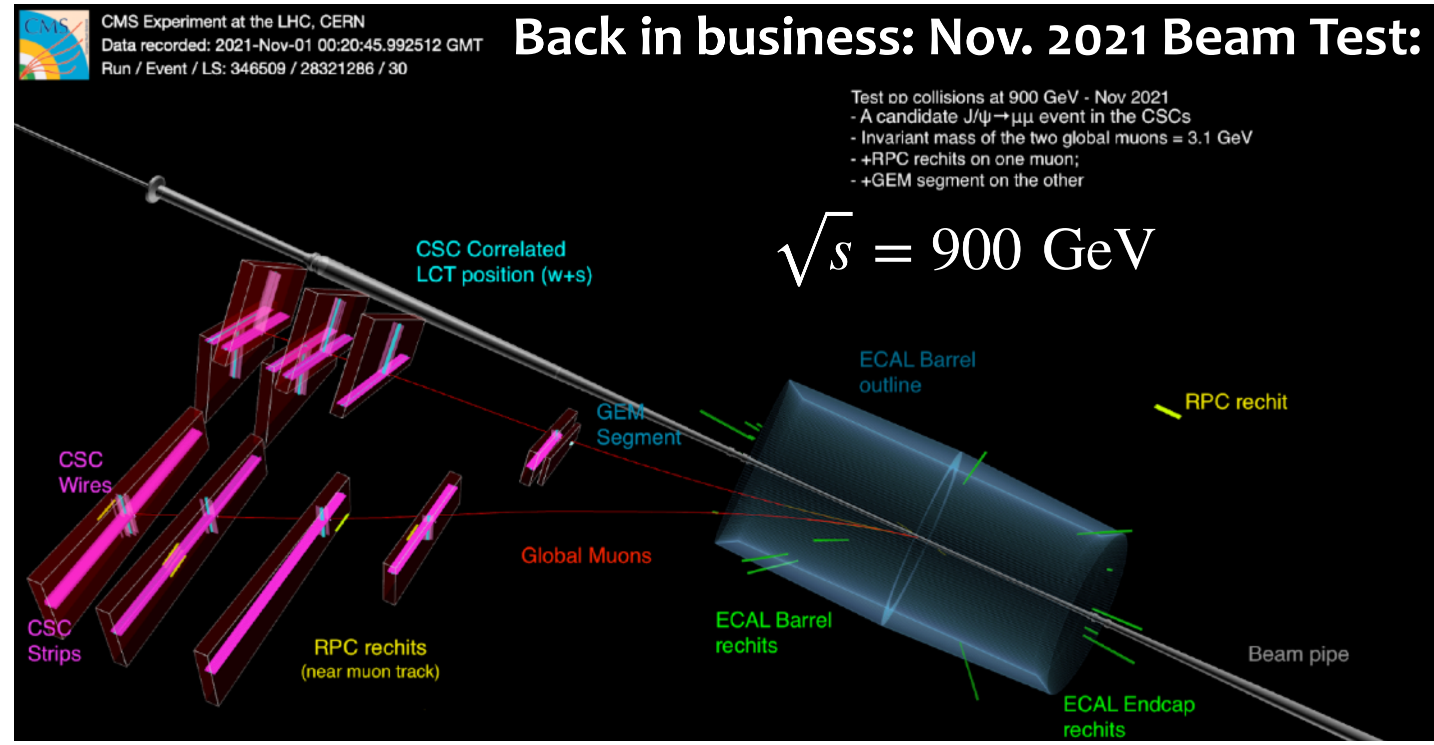
- **Or EFT for BSM at a scale $\Lambda \gg \mathrm{VEV}^H$**: constraints of Wilson coefficients of the higher-order operators derived from STXS signal strengths μ_i in each bin-i:

$$\mu_i(c_j) = \frac{\sigma_i^{\mathrm{EFT}}}{\sigma_i^{\mathrm{SM}}}$$

CMS-PAS-HIG-19-005

Run-3 @ LHC and beyond

- Even if HL-LHC is so far in time, **we are entering Run-3**.
  - $\sqrt{s} = 13.6$ TeV
  - high instantaneous luminosity with levelling: $\mathscr{L} = 2 \times 10^{34} cm^{-2} s^{-1}$
  - pileup: **50-60** collisions / crossing



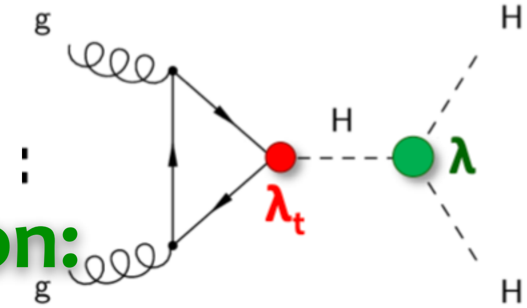
- Expected integrated luminosity:
  - 30 fb^{-1} in 2022, and 80 fb^{-1} / year in 2023-2025
  - total Run-3: **L = 270 fb^{-1}**
- LHC commissioning ~ April 2022

- HL-LHC beyond 2029 foresees a big jump: **3000 fb^{-1} by 2041**
- One of the goals for the experiments important for Higgs physics is reducing the **luminosity uncertainty down to 1% level (now ~1.6%)**

arXiv:1902.00134

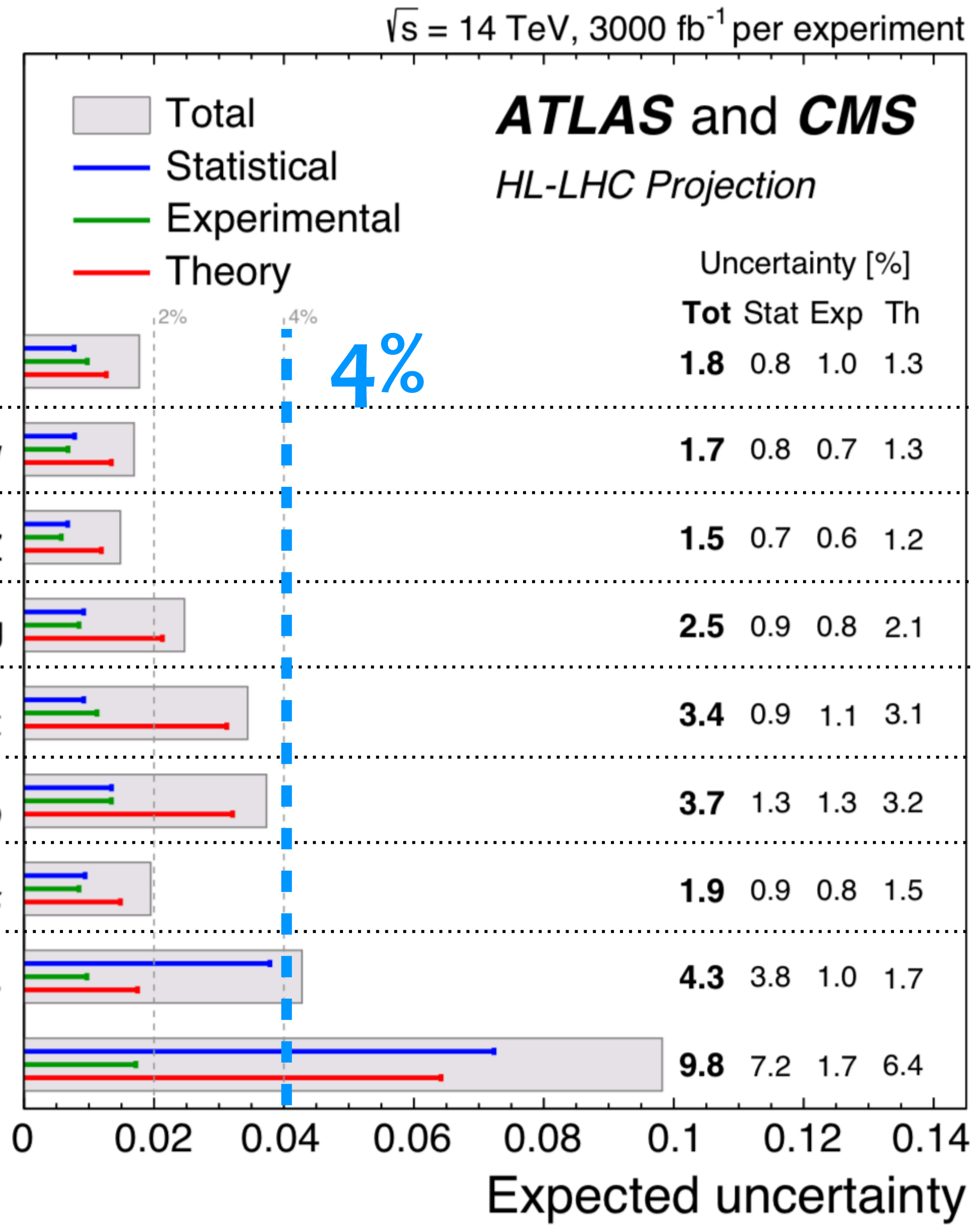
Single H couplings: precision to few %

Self-coupling λ : from HH production:

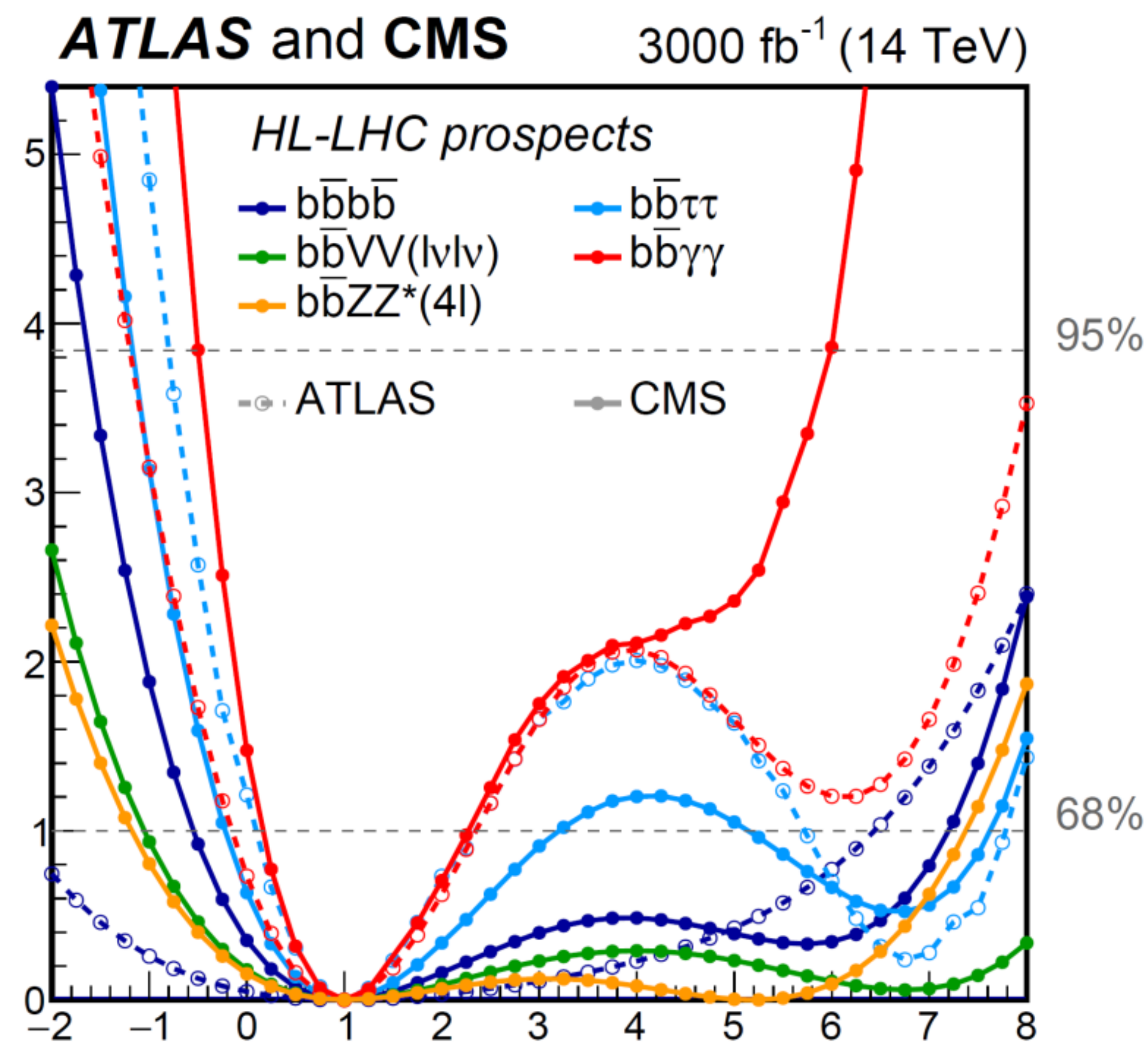


Current precision

6%	κ_γ
6%	κ_W
6%	κ_Z
7%	κ_g
11%	κ_t
11%	κ_b
8%	κ_τ
	κ_μ
	$\kappa_{Z\gamma}$



Year: 2041?



Current estimate:

- **4σ observation**
- measure κ_λ with 50% uncertainty

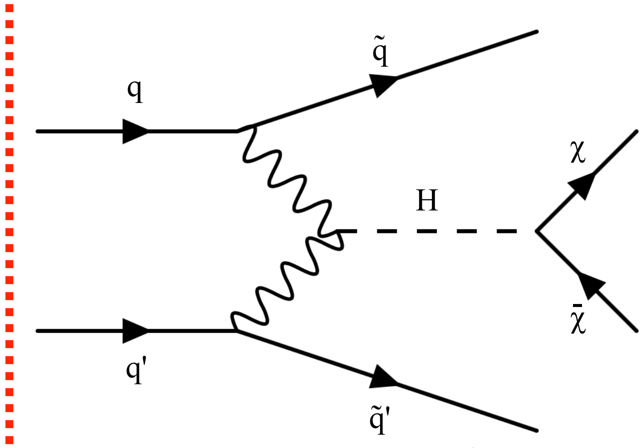
Conclusions

- The LHC Run2 provided data for a lot of results from CMS characterizing the Higgs boson
  - mass measured with 0.1% precision, and width measured for the first time with 50% precision
  - the production cross section are now measured differentially in many STXS bins, in several production modes
  - fiducial cross sections and coupling modifiers measured at 10% level, allowing interesting EFT interpretations
  - couplings to 2nd generation established with $H \to \mu^+\mu^-$, next challenge is $H \to c\bar{c}$
  - CP violation studied in many channels, including rare ttH
  - searches for HH production for H self-couplings impressive
- **The LHC is going to have new collisions in Spring 2022** with $\sqrt{s}$=13.6 TeV and **450 fb^{-1} are expected per experiment for Run1+2+3**
  - a unique opportunity to continue characterizing the Higgs potential: entering the precision era for the Higgs field!

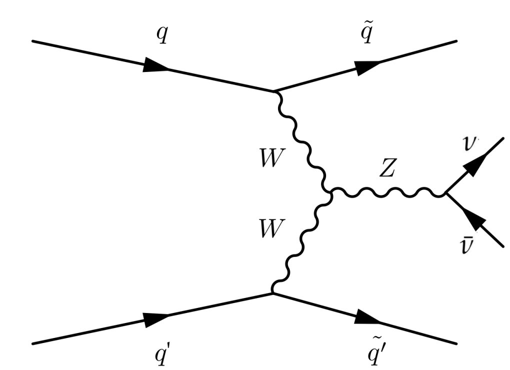
extras

VBF $H \to$ invisible

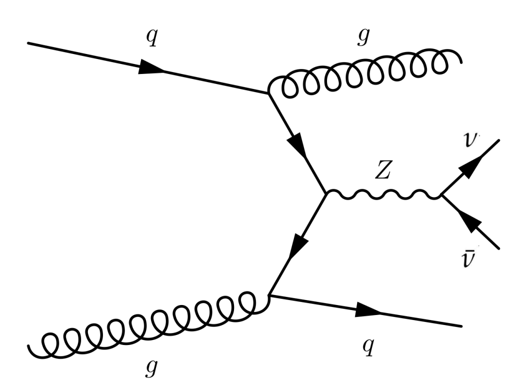
- Part of Higgs width could be due to decays to not detectable particles: searches can be interpreted within Dark Matter models
- 2 forward jets with high M_{jj} and high $|\Delta\eta_{jj}|$ + MET
  - Dominant backgrounds: $W \to \ell\nu$ and $Z \to \nu\nu$ +jets
  - systematically dominated by V+jets modelling



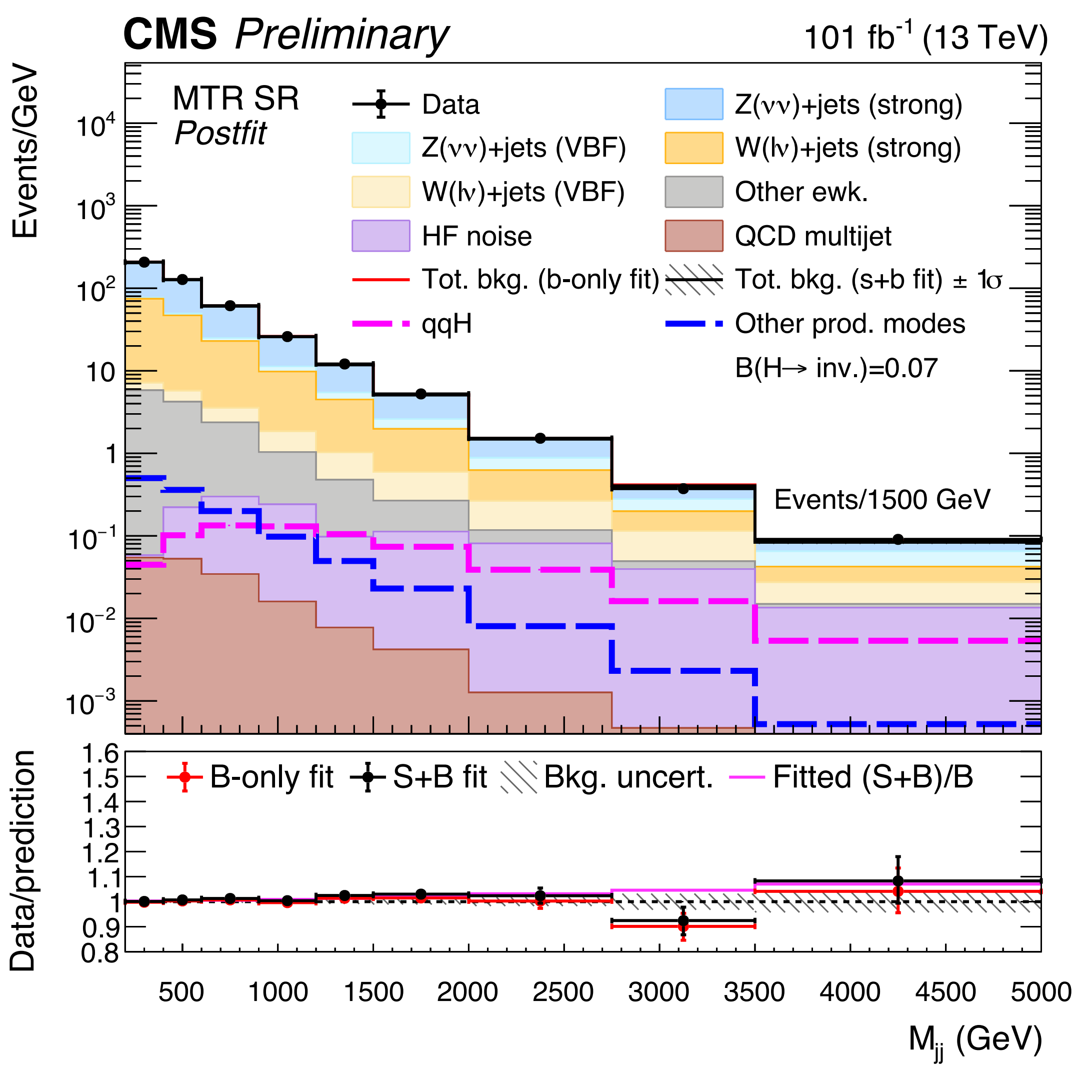
signal $H \to$ inv



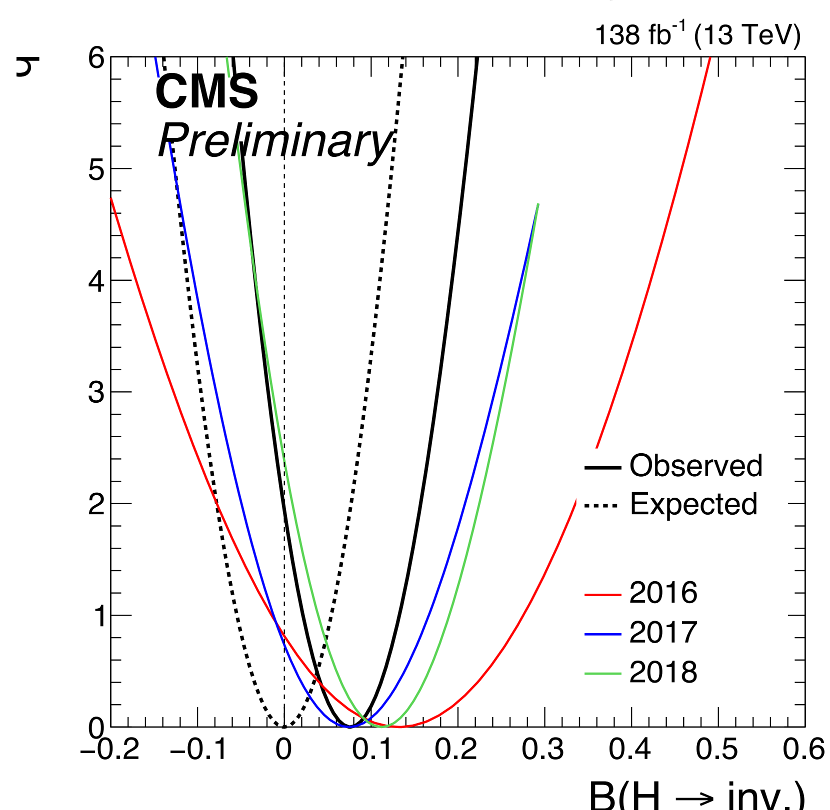
bkg: VBF $Z \to \nu\bar{\nu}$



bkg: QCD $Z \to \nu\bar{\nu}$



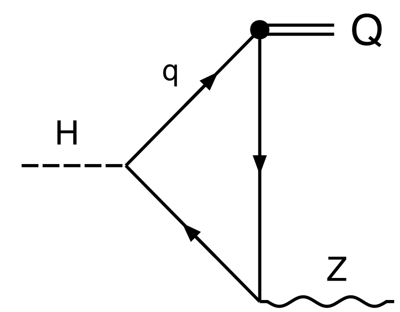
CMS-PAS-HIG-20-003



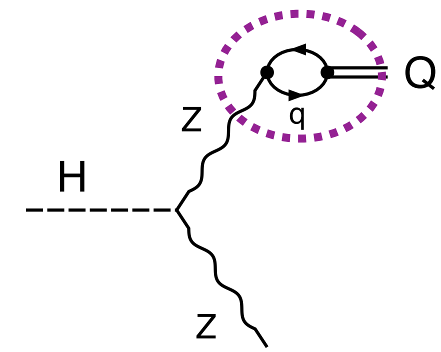
$BR(H \to \text{inv}) < 0.17$ (exp 0.11)

Towards rare decays: quarkonia

- Rare decays predicted by the SM: $H \to Z\ J/\psi,\ J/\psi J/\psi,\ \Upsilon\Upsilon$
  - in the SM: $BR(H \to ZJ/\psi, Z\psi(2S) \approx 10^{-6}$,
  - even smaller $BR(H \to QQ)$
  - new physics in loops can increase this
- Same search also for Z decays to QQ:
  - in the SM, $BR(Z \to QQ) \approx 10^{-12}$



leading order

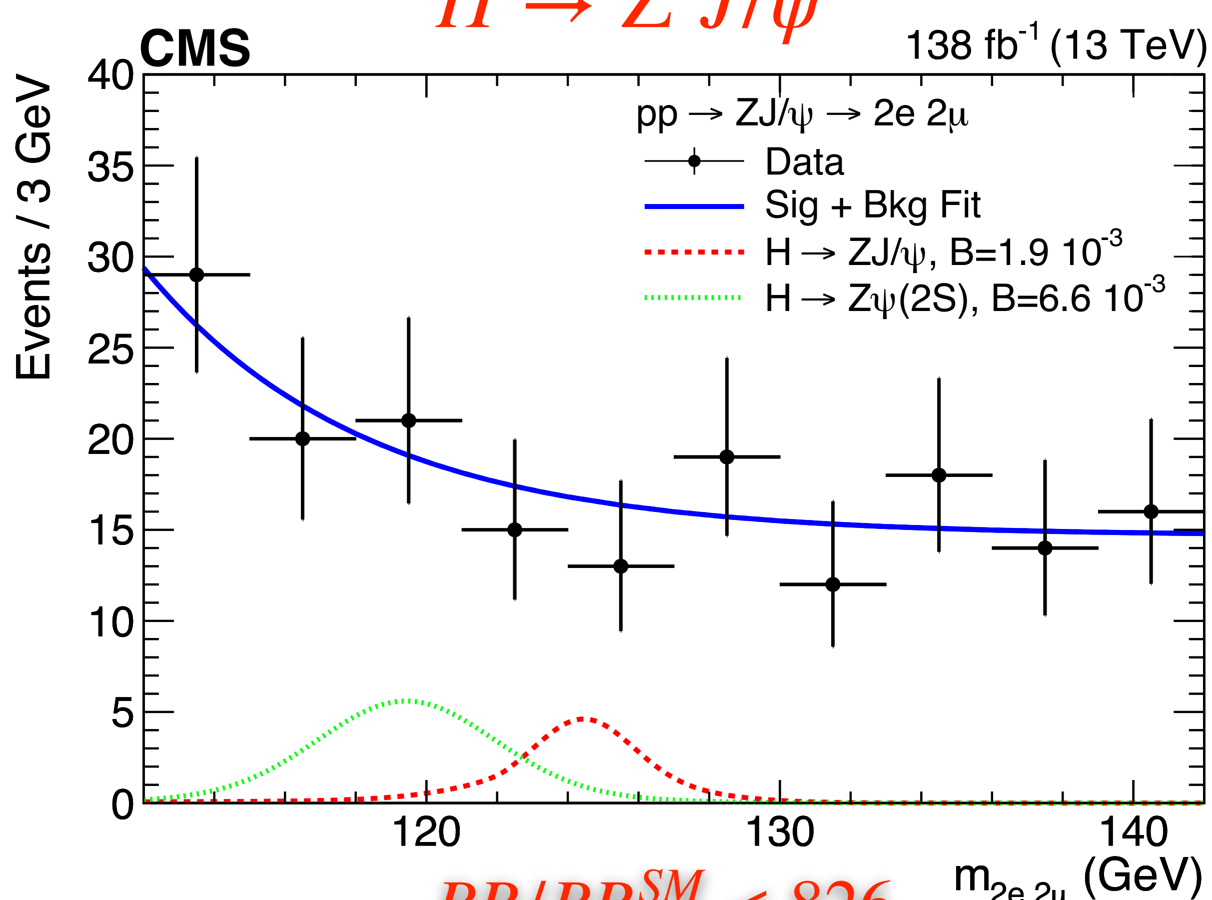


loop-induced

New result Jan. 2022

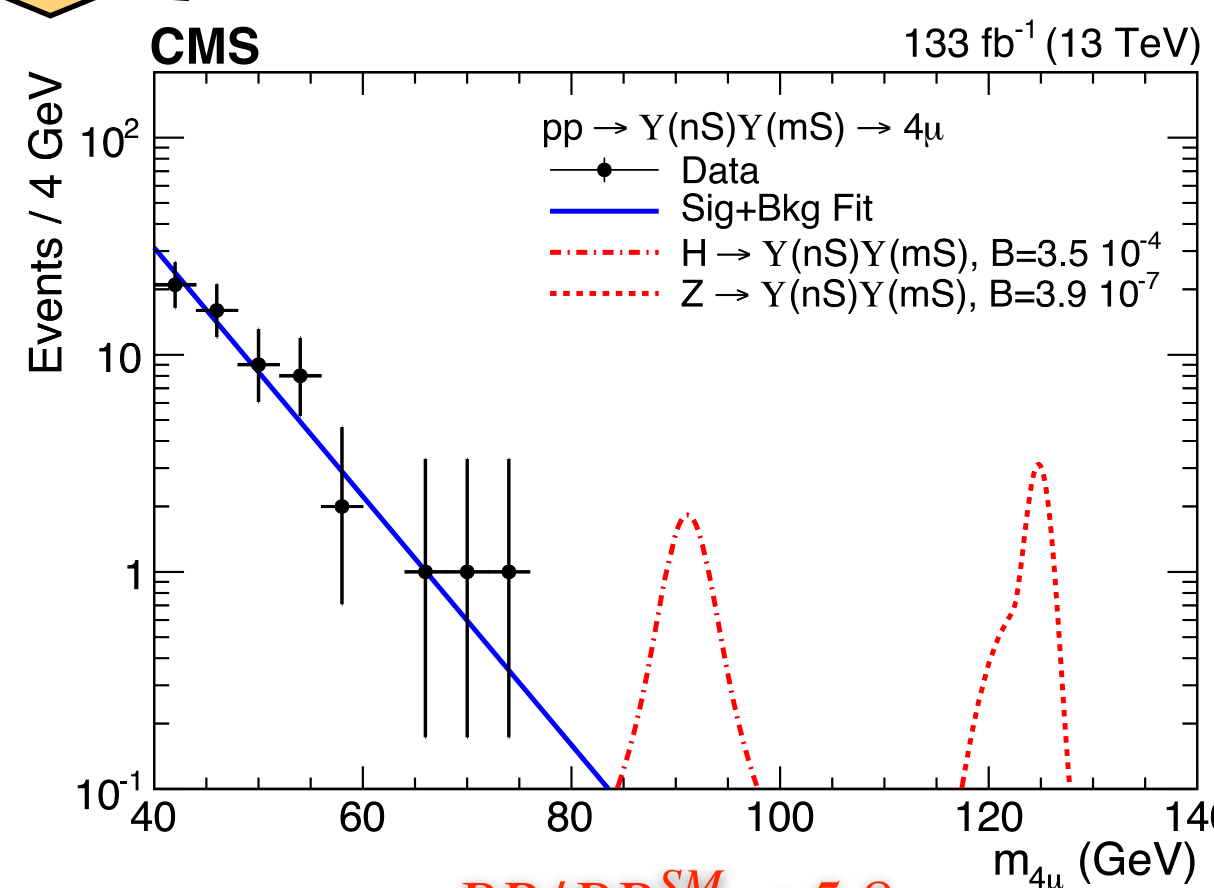
HIG-20-008

$H \to Z\ J/\psi$



$BR/BR^{SM} < 826$

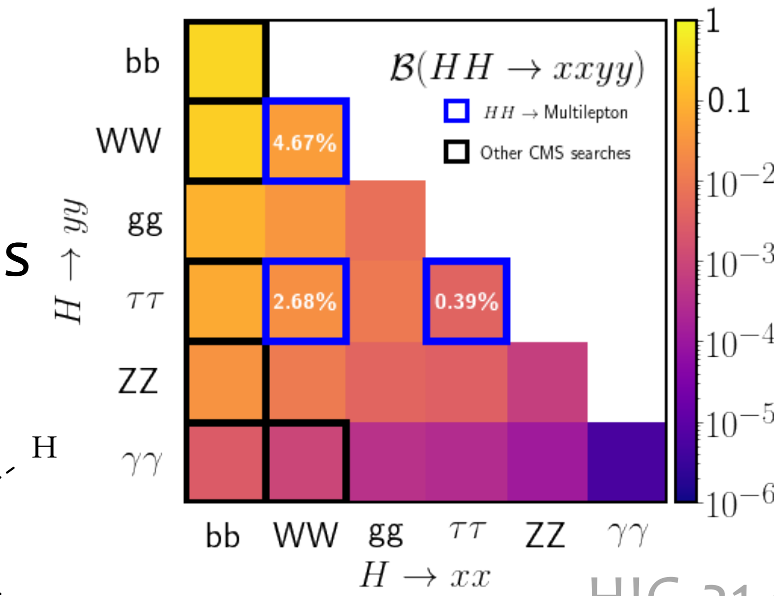
$H \to \Upsilon\ \Upsilon$



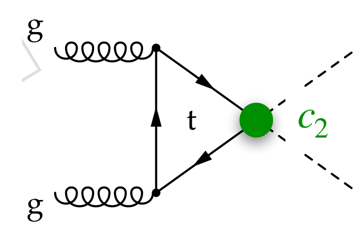
$BR/BR^{SM} < 5.8$

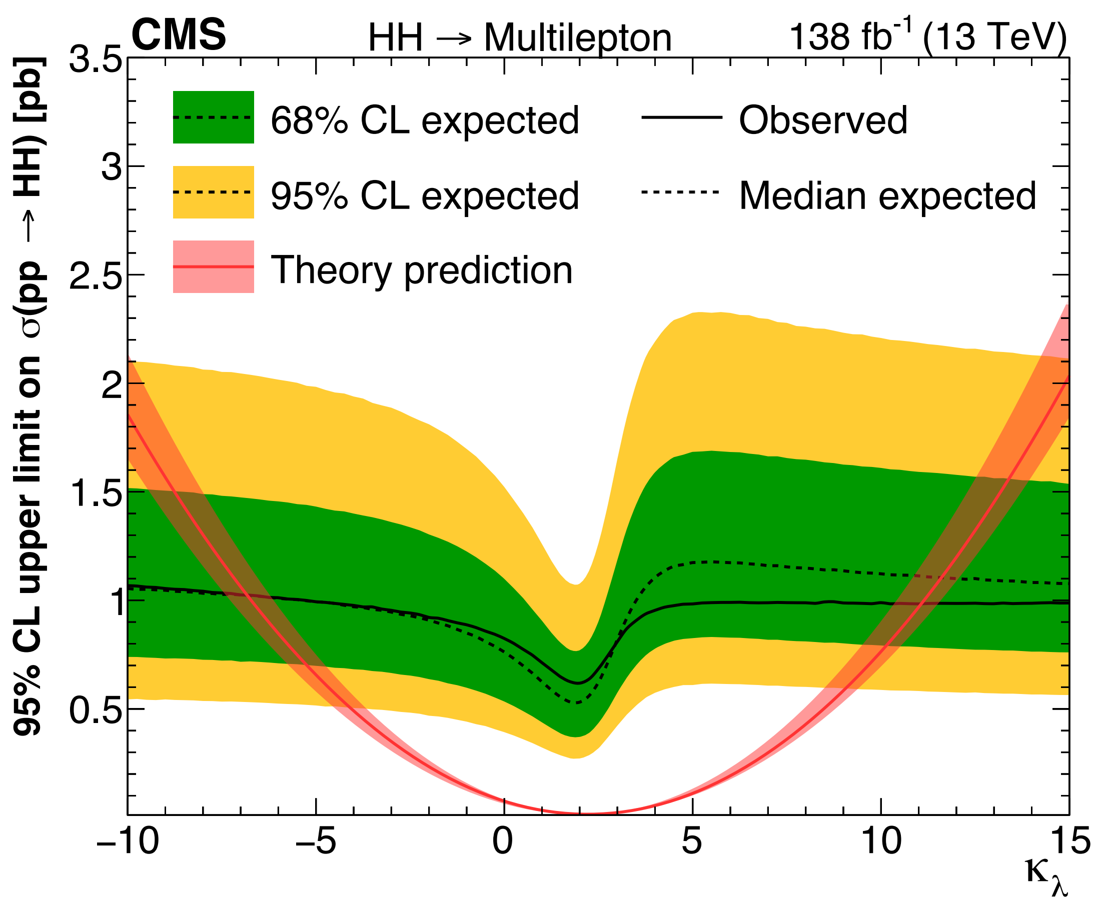
Multilepton HH search

- Double H decays into 4W, 4τ, $2W2\tau$ in final states with $\ell = e, \mu$ and an hadronically decaying τ_h cover ~7.7% of the HH decays
  - dedicated categories for 7 channels and 2 CRs
  - background estimates from data as ttH multileptons
- Sensitivity $\approx 20 \times \sigma_{SM}^{HH}$



HIG-21-002

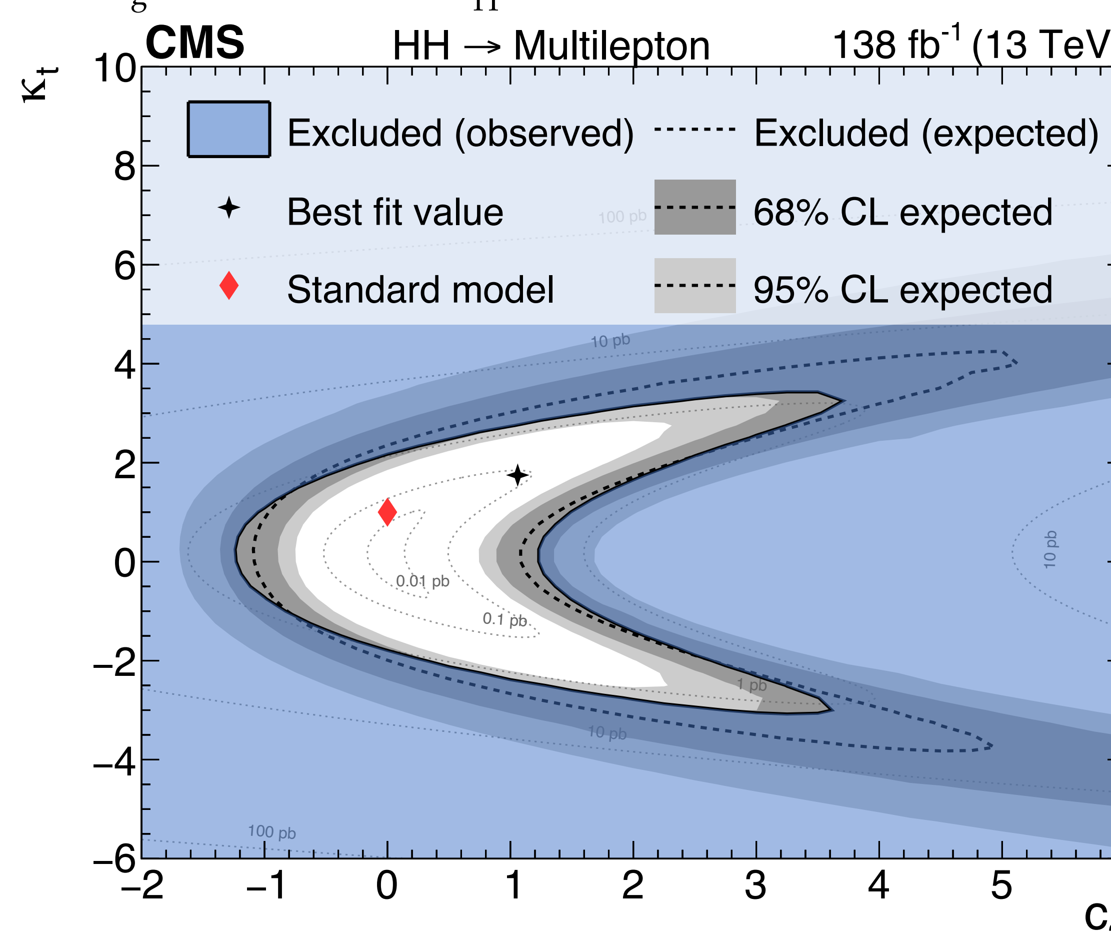




Constraint on trilinear coupling at 95% CL:

New result Jan. 2022

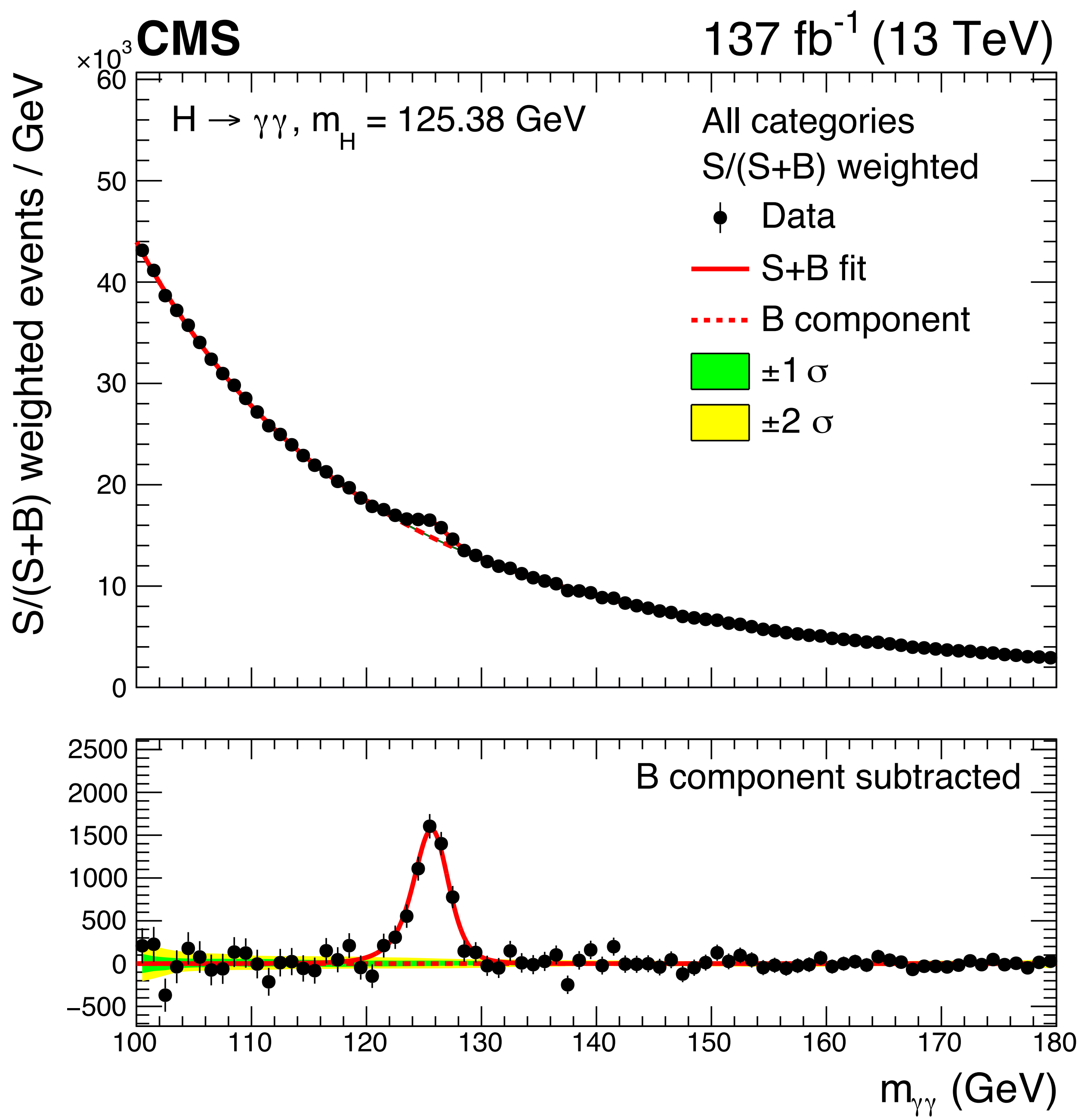
-7 < κ_λ < 11



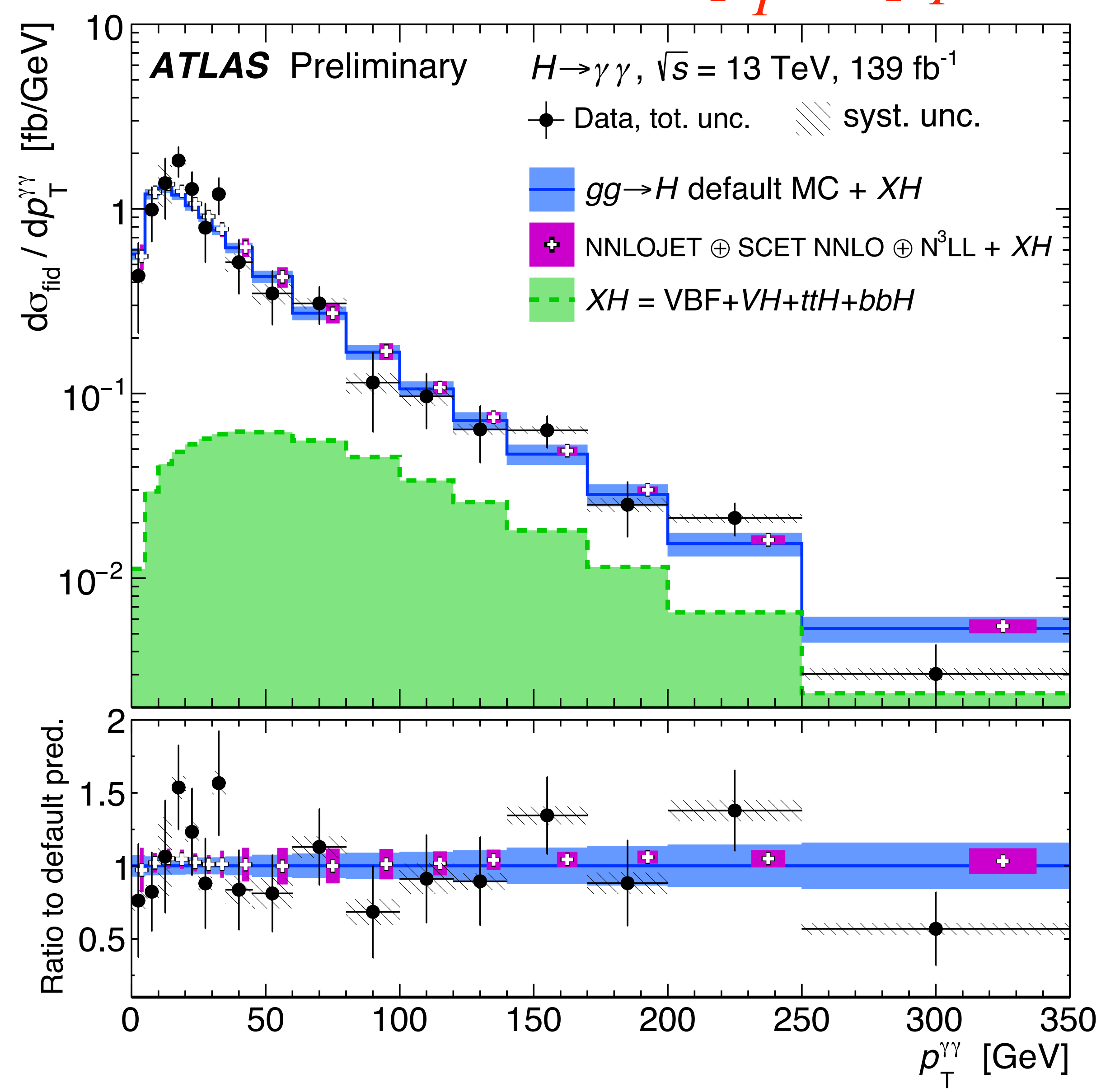
2t-2H coupling c_2 vs H-t coupling κ_t

$H \rightarrow \gamma\gamma$: differential and fiducial

- Inclusive fiducial cross section measurement has precision of 10%:
  - $\sigma_{fid} = 65.2 \pm 4.5(\text{stat}) \pm 5.6(\text{syst}) \pm 0.3(\text{th})$ fb (ATLAS)
  - $\sigma_{SM} = 63.6 \pm 3.3$ fb



$p_T^{\gamma\gamma} = p_T(H)$



Unfolding key variables:

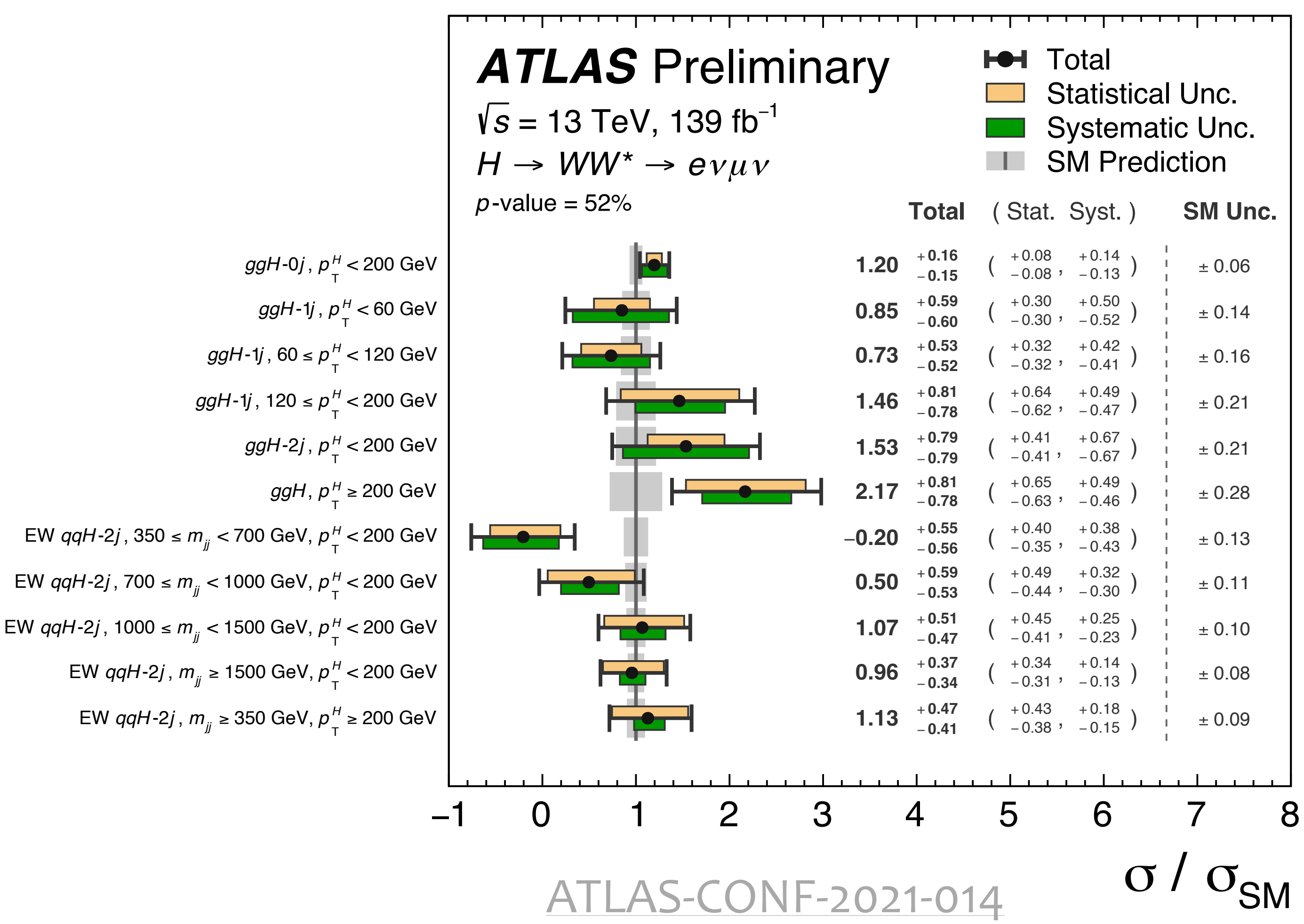
$p_T(H), y(H), N(\text{jets}), p_T(j_1), m_{jj}, \Delta\phi_{jj}$

STXS in $H \to WW^*$

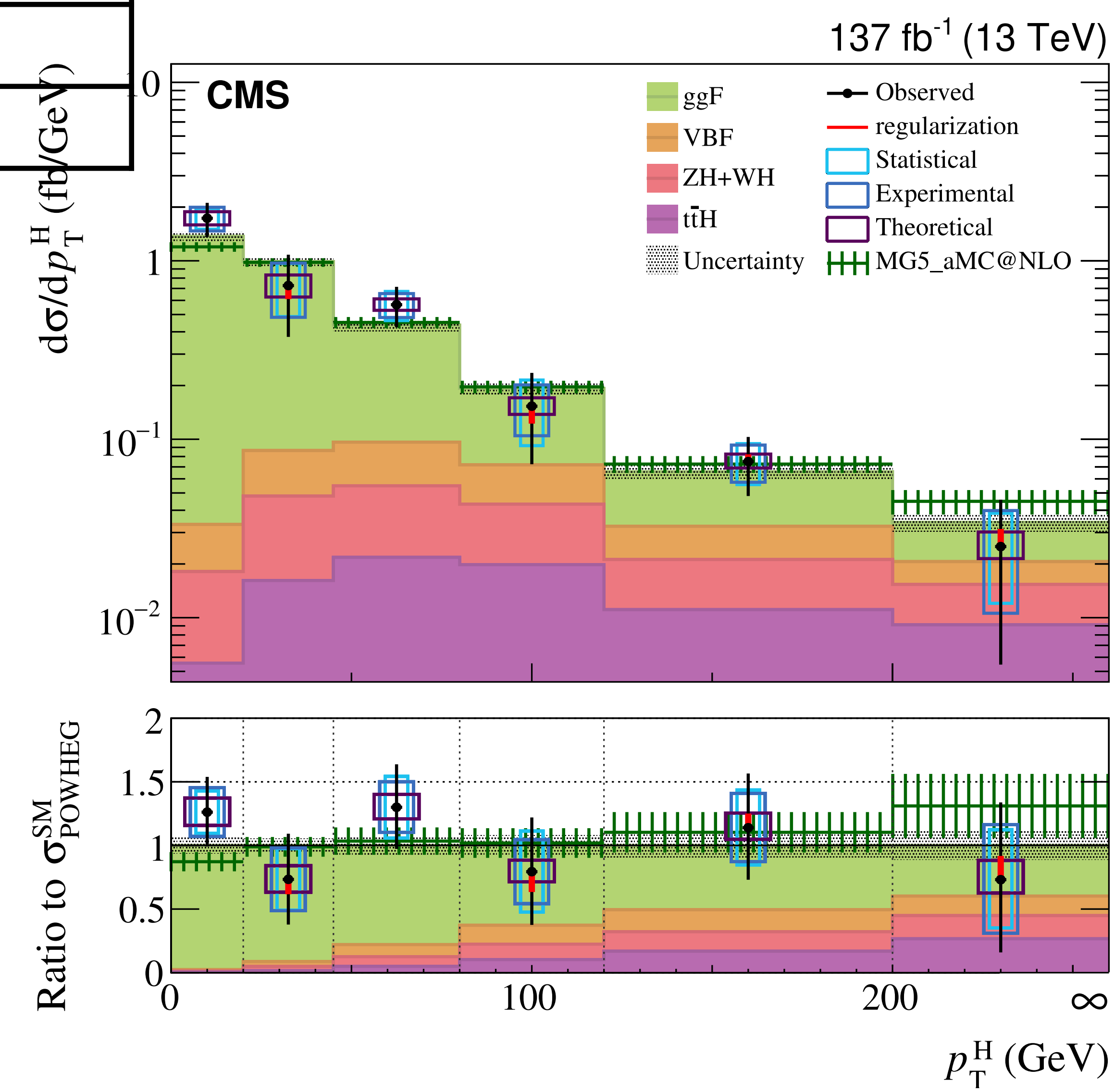
- $H \to 2\ell 2\nu$ challenging channel where backgrounds needs to be modelled with data accurately
- Large signal yield allows granular binning for differential cross sections

	Measured [fb]	SM prediction [fb]
ATLAS ggH	12.4 ± 1.5	10.4 ± 0.6
ATLAS VBF	$0.79^{+0.19}_{-0.16}$	0.81 ± 0.02
CMS fiducial	86.5 ± 9.5	82.5 ± 4.2

JHEP03(2021)003

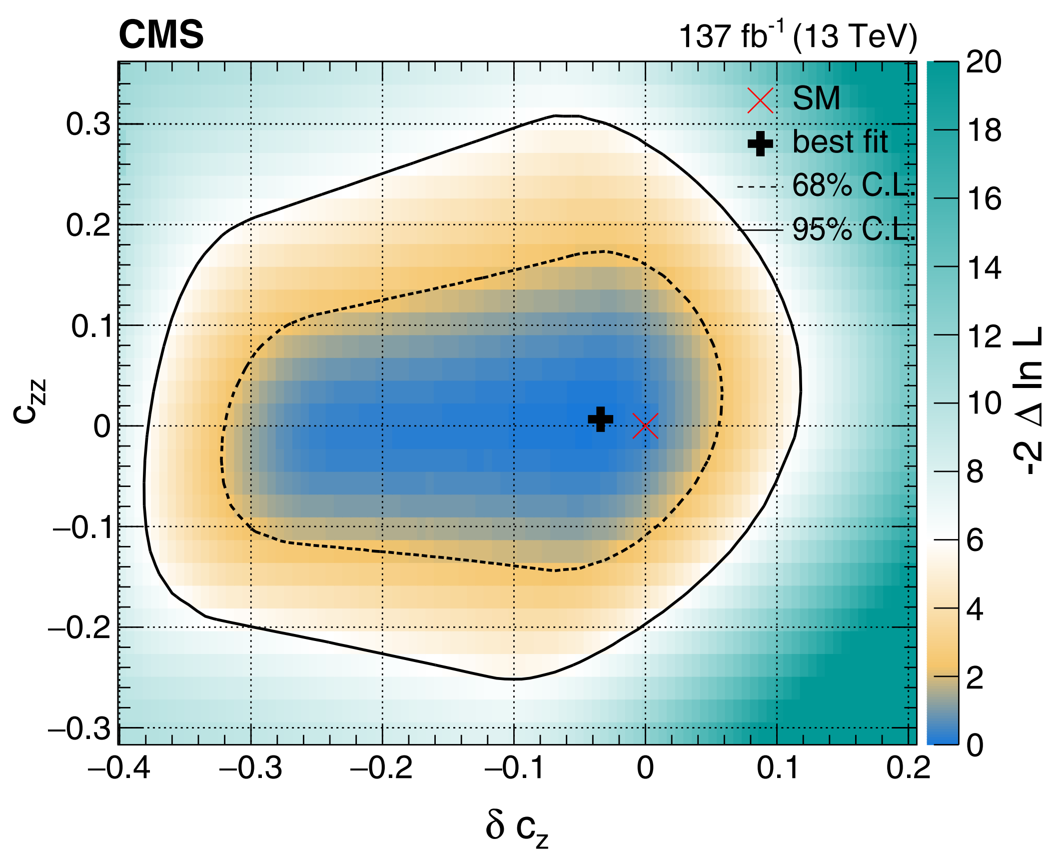


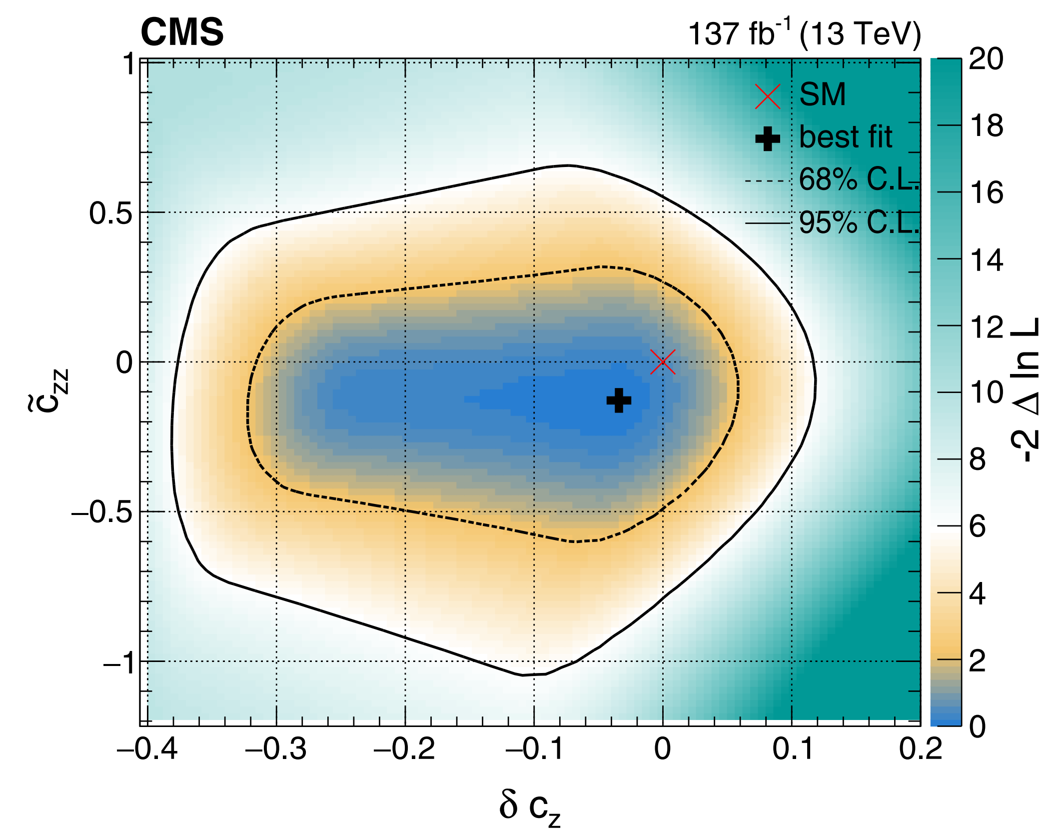
ATLAS-CONF-2021-014



$H \to 4\ell$ SMEFT (CMS)

- Same analysis framework for anomalous couplings fits also SMEFT parameters
  - fits up to 4 parameters simultaneously, in the Higgs basis
    - c_{gg} and $\tilde{c}_{gg}$ included and profiled away
    - $c_{\gamma\gamma}$ and $c_{Z\gamma}$ set to zero, assuming tightly constrained by BR($\gamma\gamma$), BR($Z\gamma$)





δc_z	$-0.03^{+0.06}_{-0.25}$	$0.00^{+0.07}_{-0.27}$
c_{zz}	$0.01^{+0.11}_{-0.10}$	$0.00^{+0.22}_{-0.16}$
$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$
$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$

results in Higgs basis can be translated in Warsaw basis

Coupling modifiers model

- Use the LO coupling modifier ("κ-framework") to probe deviations from the SM
  - assuming decays to SM-only particles, the same κ parameter scales cross section and partial width

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM}, \quad \kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$$

  - => $\sigma_i \cdot BR^f = \dfrac{\sigma_i(\vec{\kappa})}{\Gamma_H}$, with:
    - the total width Γ_H given by $\dfrac{\Gamma_H}{\Gamma_H^{SM}} = \dfrac{\kappa_H^2}{1-(BR_{\text{undet.}} + BR_{\text{inv.}})}$
    - and $\kappa_H^2 = \sum_j BR_{SM}^j \kappa_j^2$

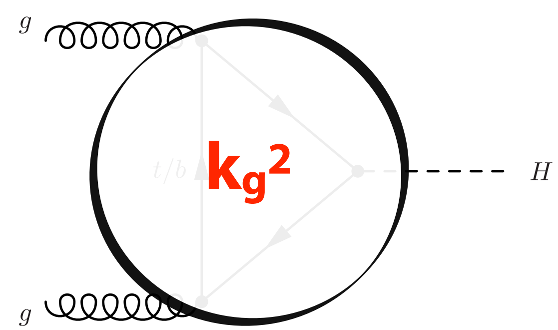
- BR_{inv} = signal BR to invisible particles from direct H→invisible searches
- $BR_{undet.}$ = BR into any final state not directly detected by analyses

Coupling modifiers model

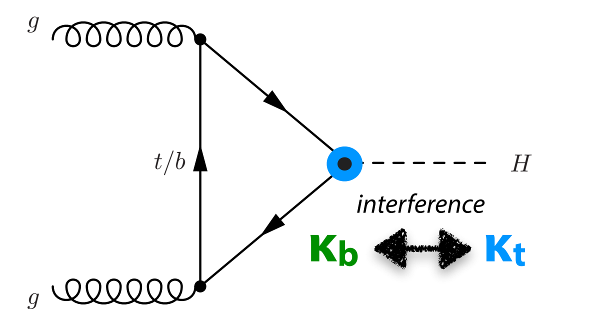
- Contrary to signal strength model have interference effects in some production and decay processes.
  - example: κ_g and κ_γ effective couplings vs resolved κ's after interference

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\mathrm{ggH})$	✓	$\mathrm{b-t}$	κ_g^2	$1.04 \cdot \kappa_\mathrm{t}^2 + 0.002 \cdot \kappa_\mathrm{b}^2 - 0.038 \cdot \kappa_\mathrm{t}\kappa_\mathrm{b}$

Gluon fusion production can be scaled by an independent effective coupling parameter: allows for contribution of BSM particles in the loop



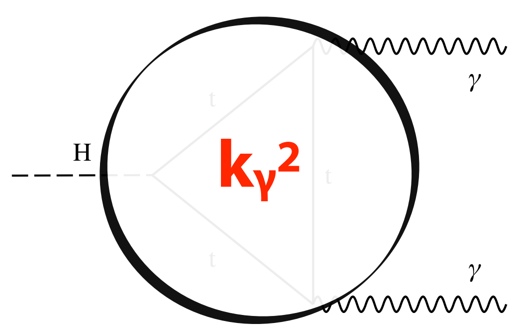
Effective coupling



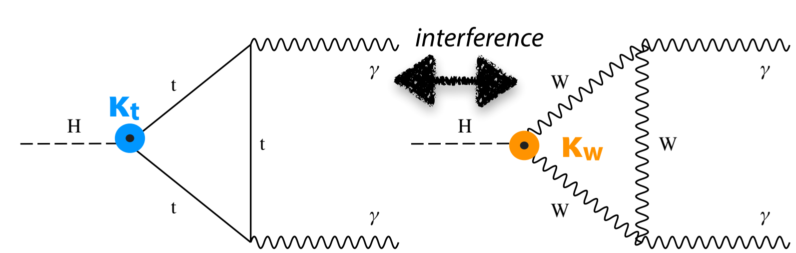
Resolved in terms of t and b couplings

Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$\mathrm{W-t}$	κ_γ^2	$1.59 \cdot \kappa_\mathrm{W}^2 + 0.07 \cdot \kappa_\mathrm{t}^2 - 0.67 \cdot \kappa_\mathrm{W}\kappa_\mathrm{t}$

Similar for $H\rightarrow\gamma\gamma$. When resolved into scaling by κ_t and κ_W we are sensitive to the relative sign: $\mathbf{\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}^{SM} = 2.3}$ when $\kappa_W \cdot \kappa_t = -1$



Effective coupling



Resolved in terms of t and W couplings

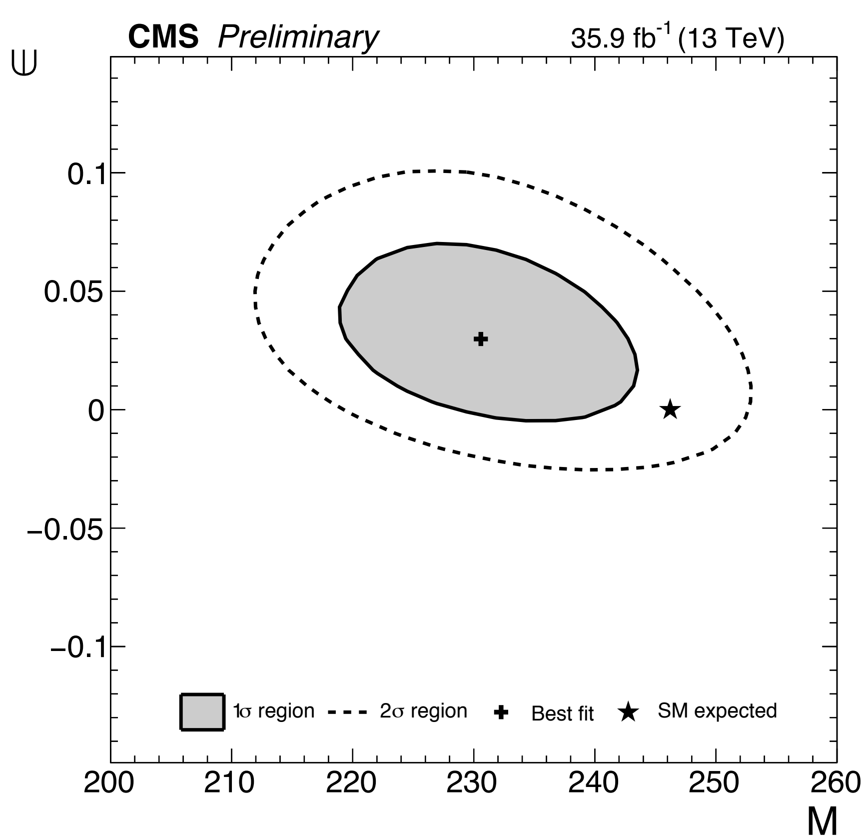
Single particle coupling

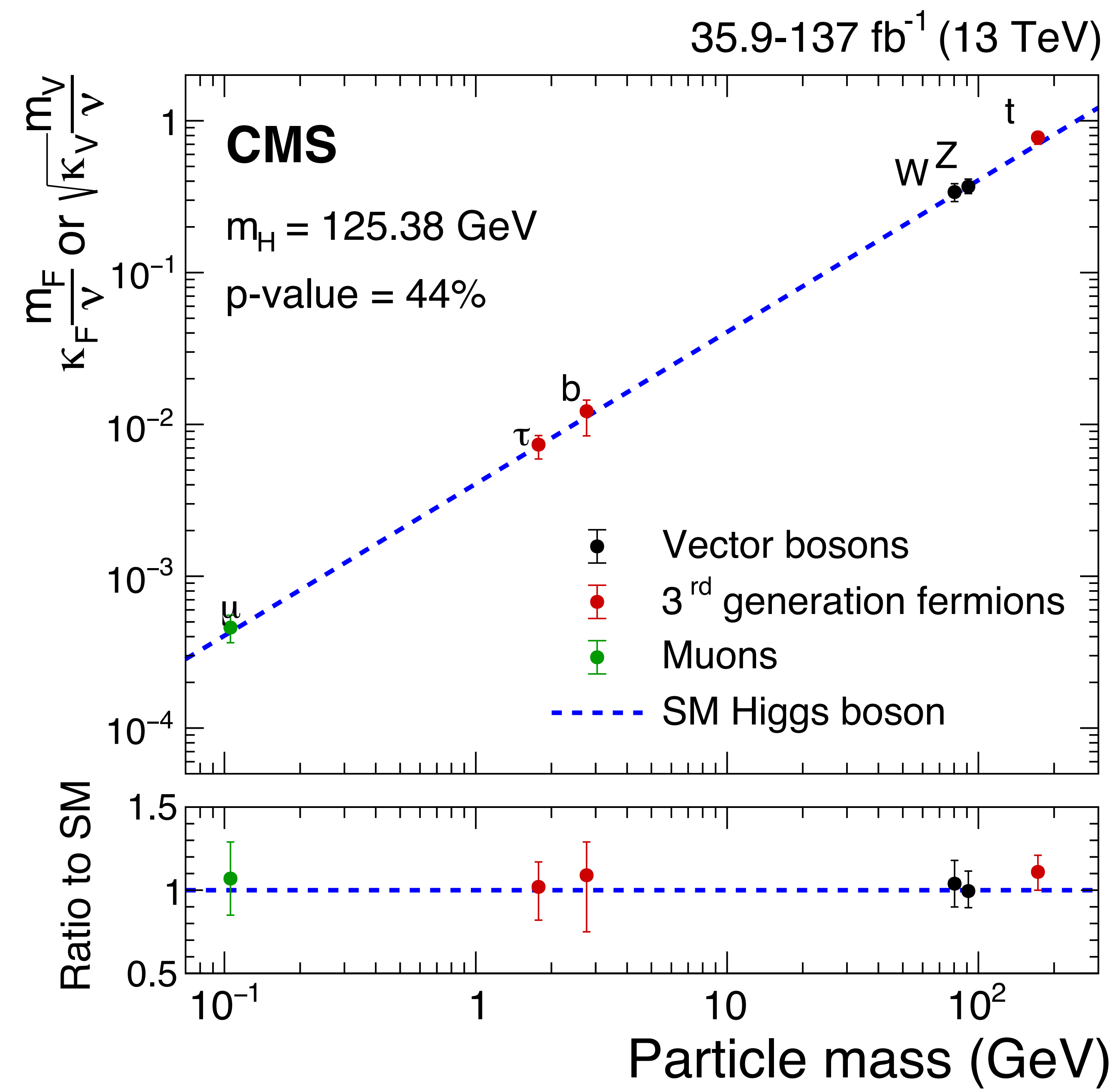
- Fit done in terms of 2 parameters (M,ε):

$$\kappa_{F,i} = v\frac{m_{F,i}^{\varepsilon}}{M^{1+\varepsilon}} \qquad \kappa_{V,i} = v\frac{m_{V,i}^{2\varepsilon}}{M^{1+2\varepsilon}}$$

  - where the SM value is: $\epsilon = 0,\ M = 246\ \text{GeV}$

- Result visualized in the plane (M, ε) or as coupling modifier κ vs particle mass (m_F or m_V)

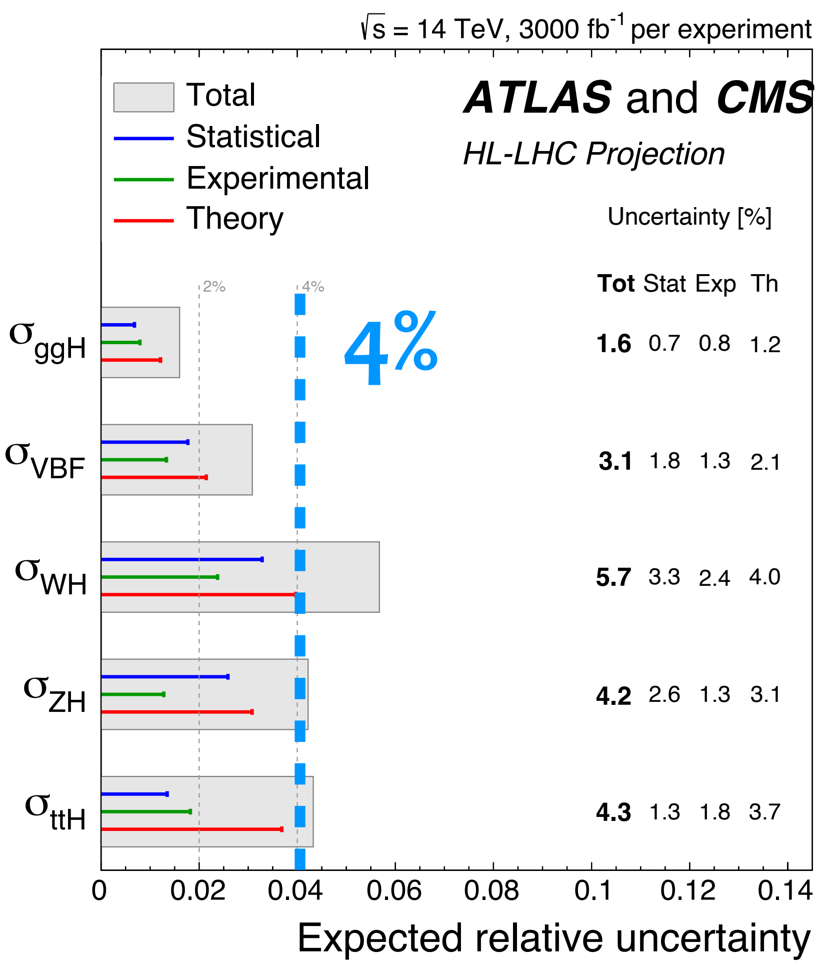




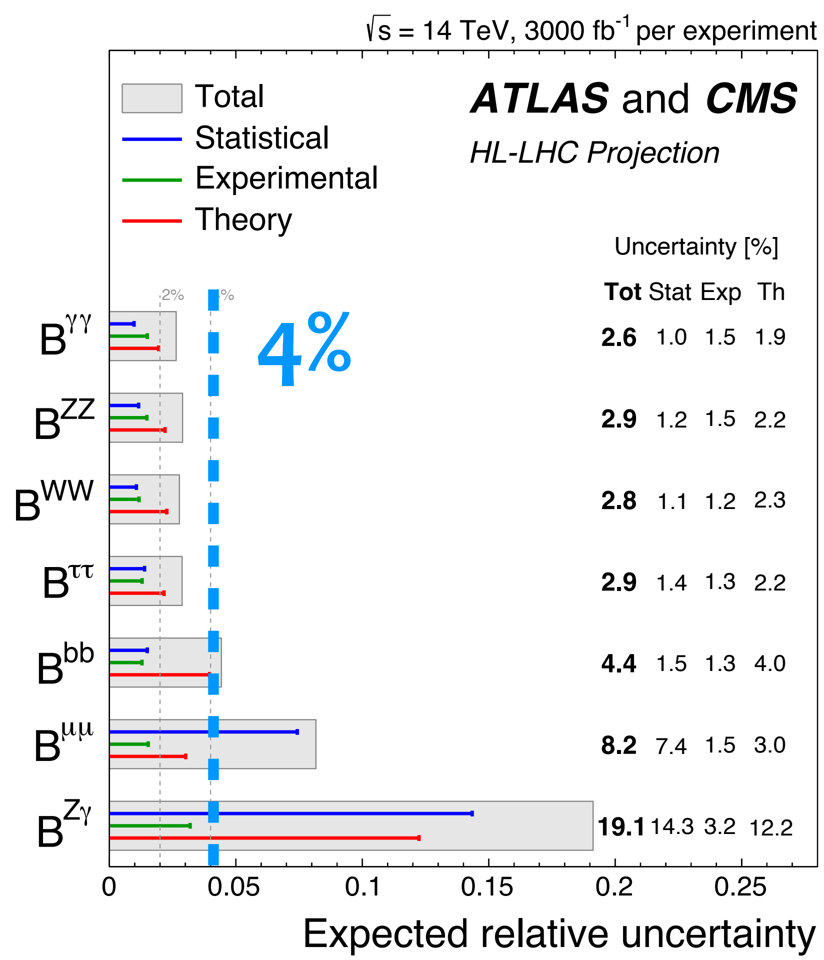
Higgs @ HL-LHC projections

- Sensitivity for Higgs boson physics at HL-LHC evaluated back in 2018 in the context of the European Strategy update
  - Mostly based on knowledge from early LHC run 2 analyses (2016 data)

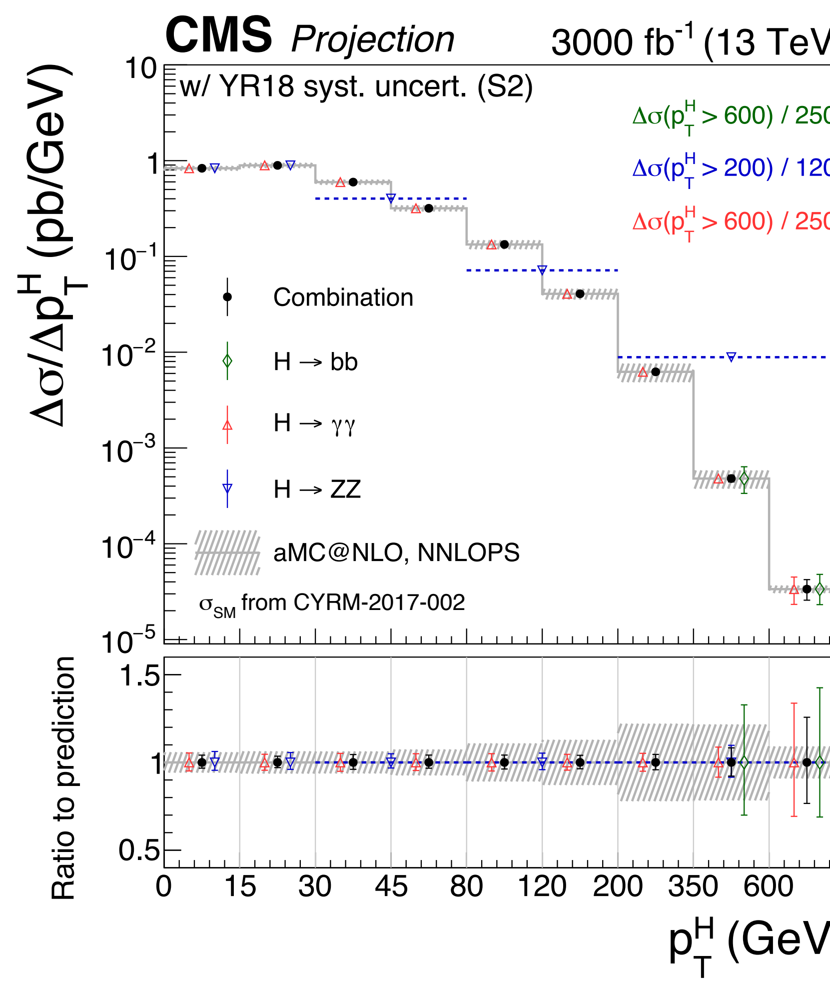
Cross section



Branching ratio



Differential $d\sigma/dp_T(H)$



arXiv:1902.00134

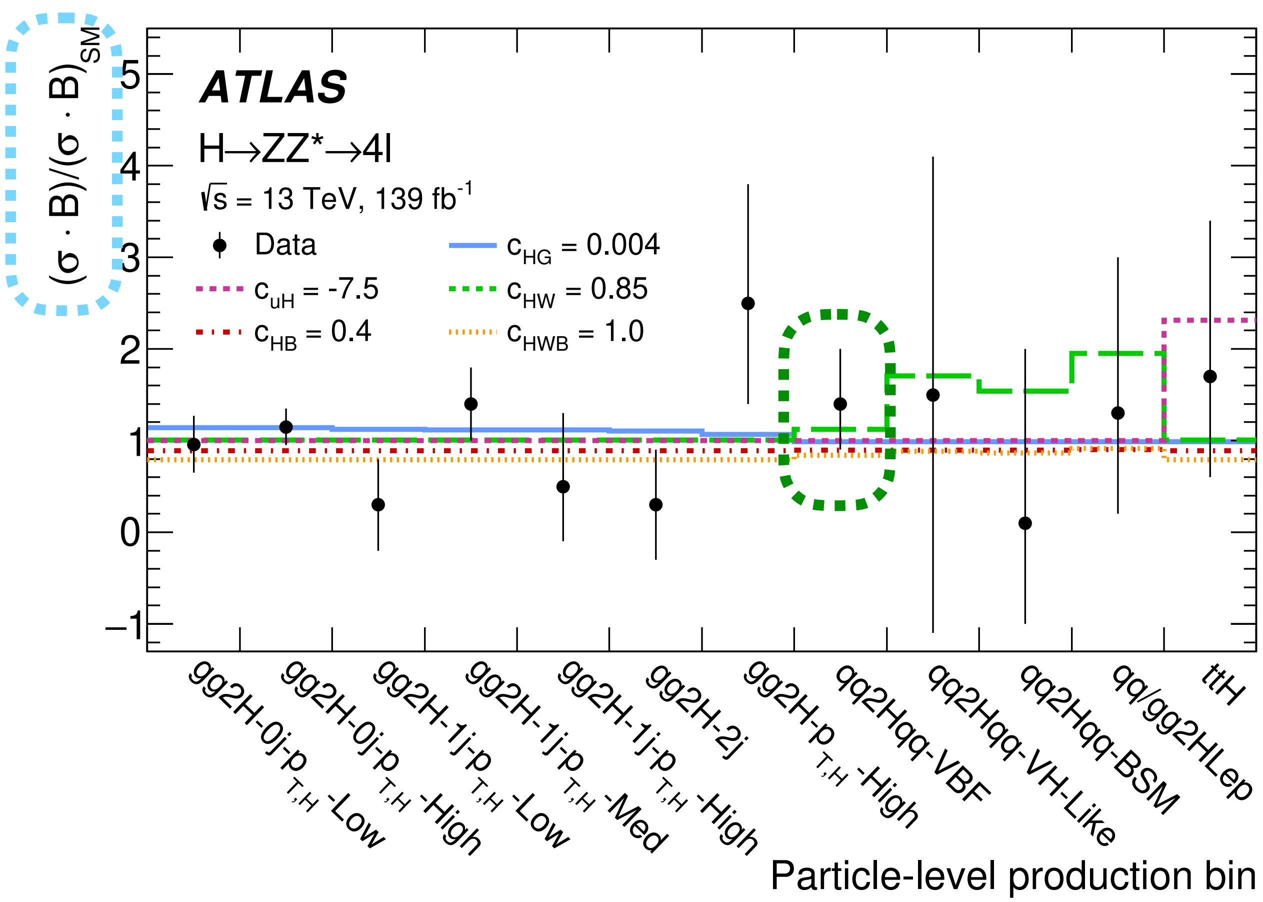
$H \to 4\ell$ AC (ATLAS)

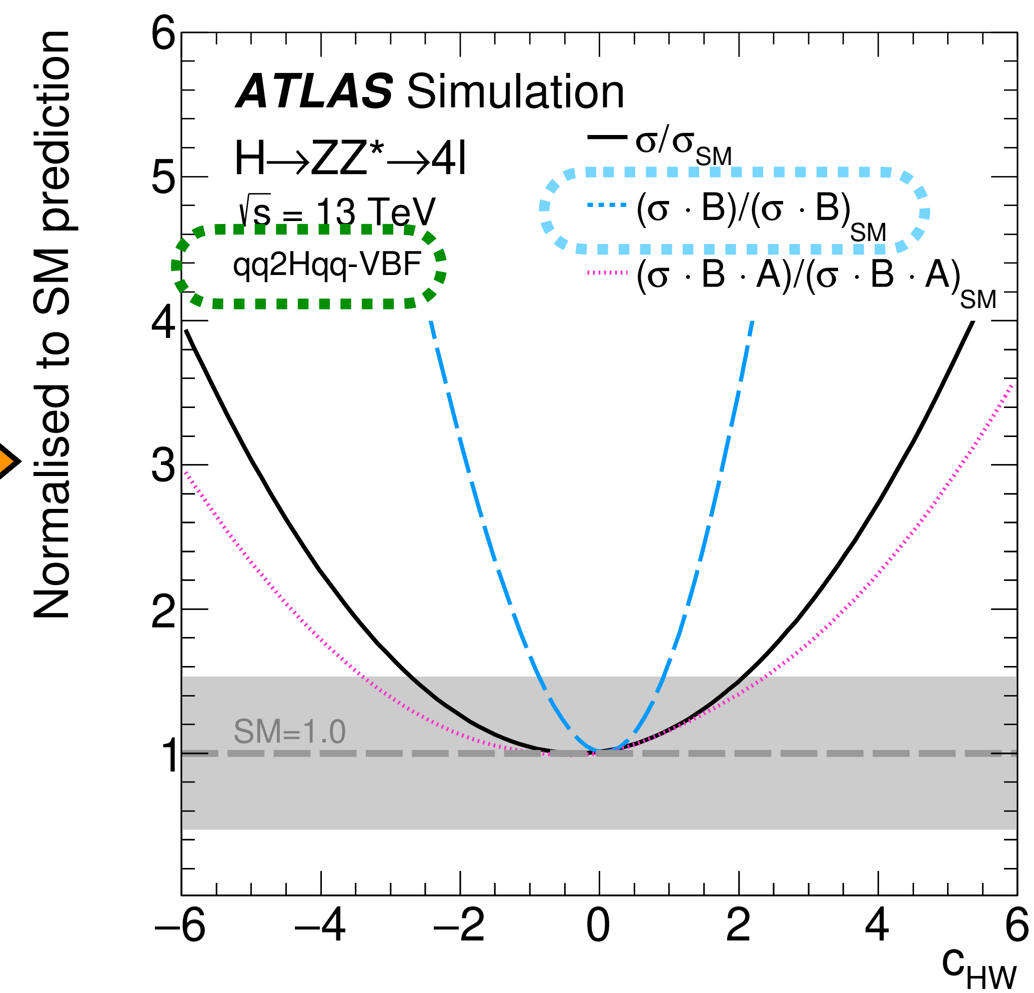
Eur. Phys. J. C 80 (2020) 957

- **EFT interpretations**: BSM contributions at a high scale appear at low scale as deviations of Wilson coefficients c_j of the higher orders operators

$$\mu_i(c_j) = \frac{\sigma_i^{\mathrm{EFT}}}{\sigma_i^{\mathrm{SM}}}$$

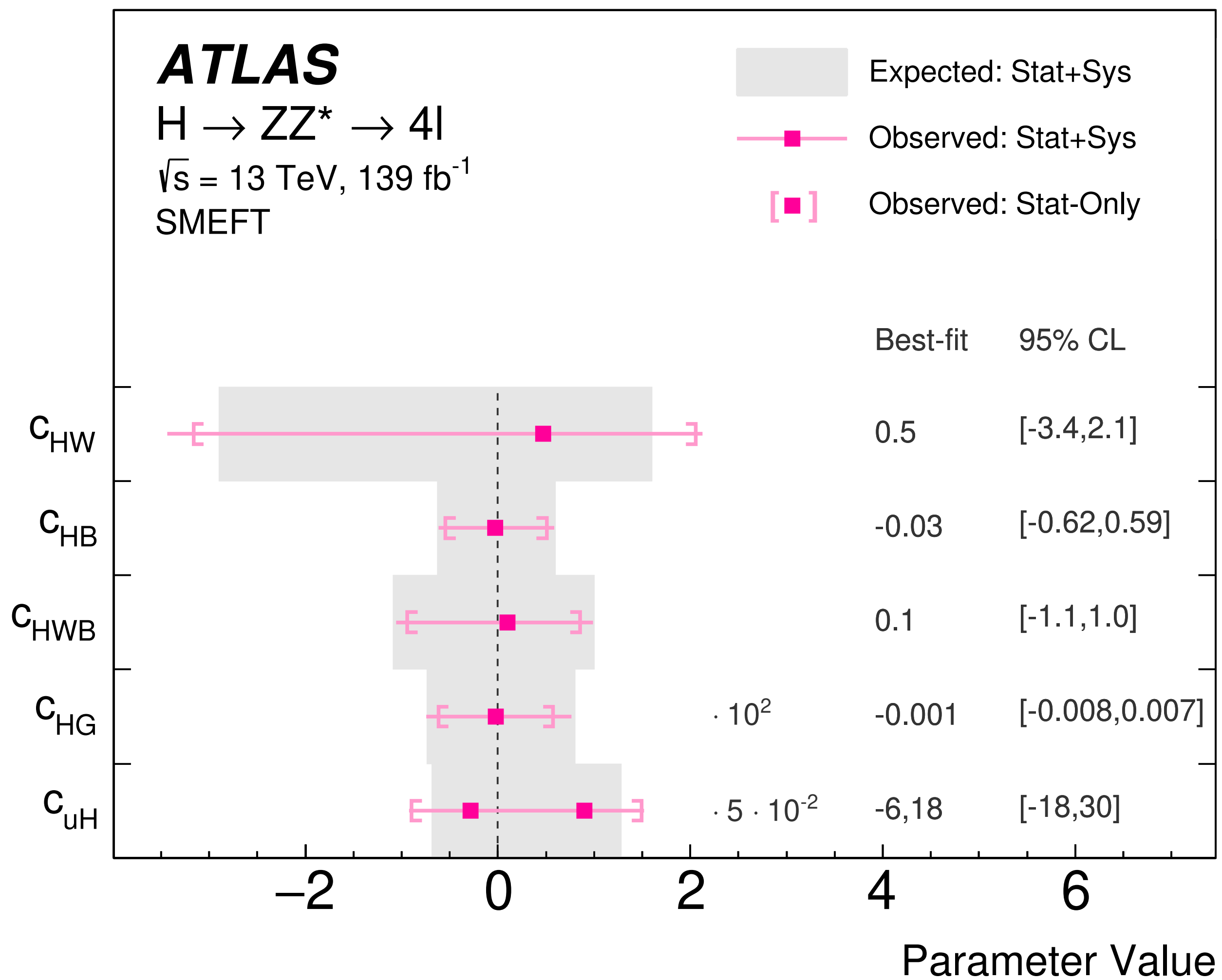
- Signal strength for STXS bin μ_i parameterised at LO in Warsaw basis
  - fit HVV couplings in production (VBF, VH, ggH, ttH)
  - acceptance effects estimated from signal full simulation and parameterized as a function of anomalous couplings



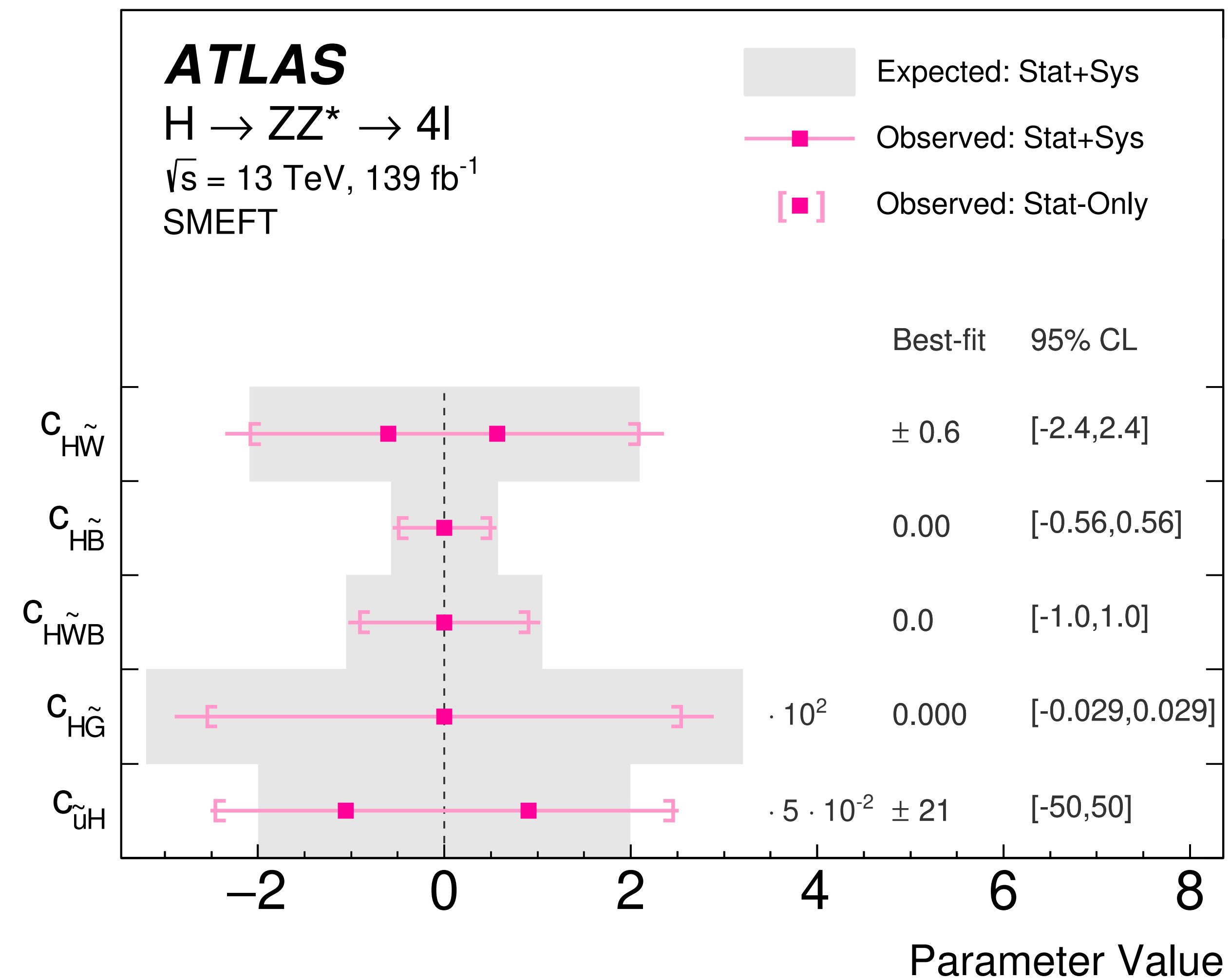


$H \rightarrow 4\ell$ SMEFT (ATLAS)

- SMEFT interpretation of the results for CP-conserving parameters: c_{HW}, c_{HB}, c_{HWB} or CP-violating parameters $\tilde{c}_{HW}$, $\tilde{c}_{HB}$, $\tilde{c}_{HWB}$



CP-even
Wilson coefficients



CP-odd
Wilson coefficients

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