30th International Symposium on
Lepton Photon interactions at High Energies, online
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Higgs physics: experimental overview

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on behalf of the ATLAS and CMS Collaborations

The Higgs potential

$$\mathscr{L}_{SM} = \cdots + |D_\mu \Phi|^2 + \psi_i y_{ij} \psi_j \Phi - V(\Phi)$$

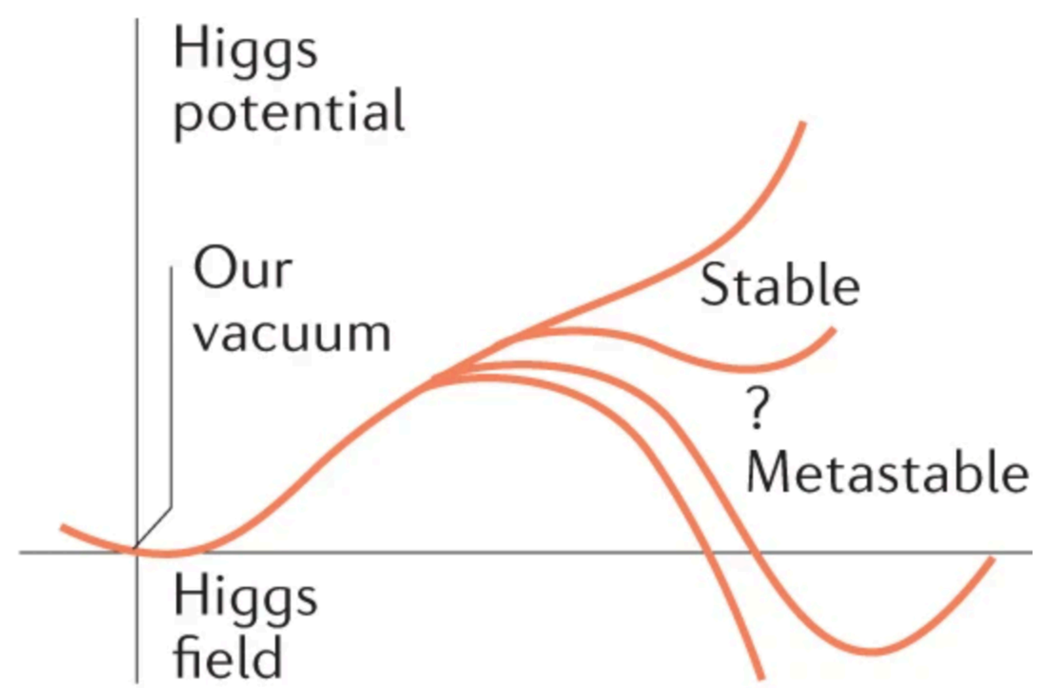
Gauge interactions

Yukawa interactions (fermion masses => proton, neutron masses)

Higgs potential

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

- 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



Higgs mass and width

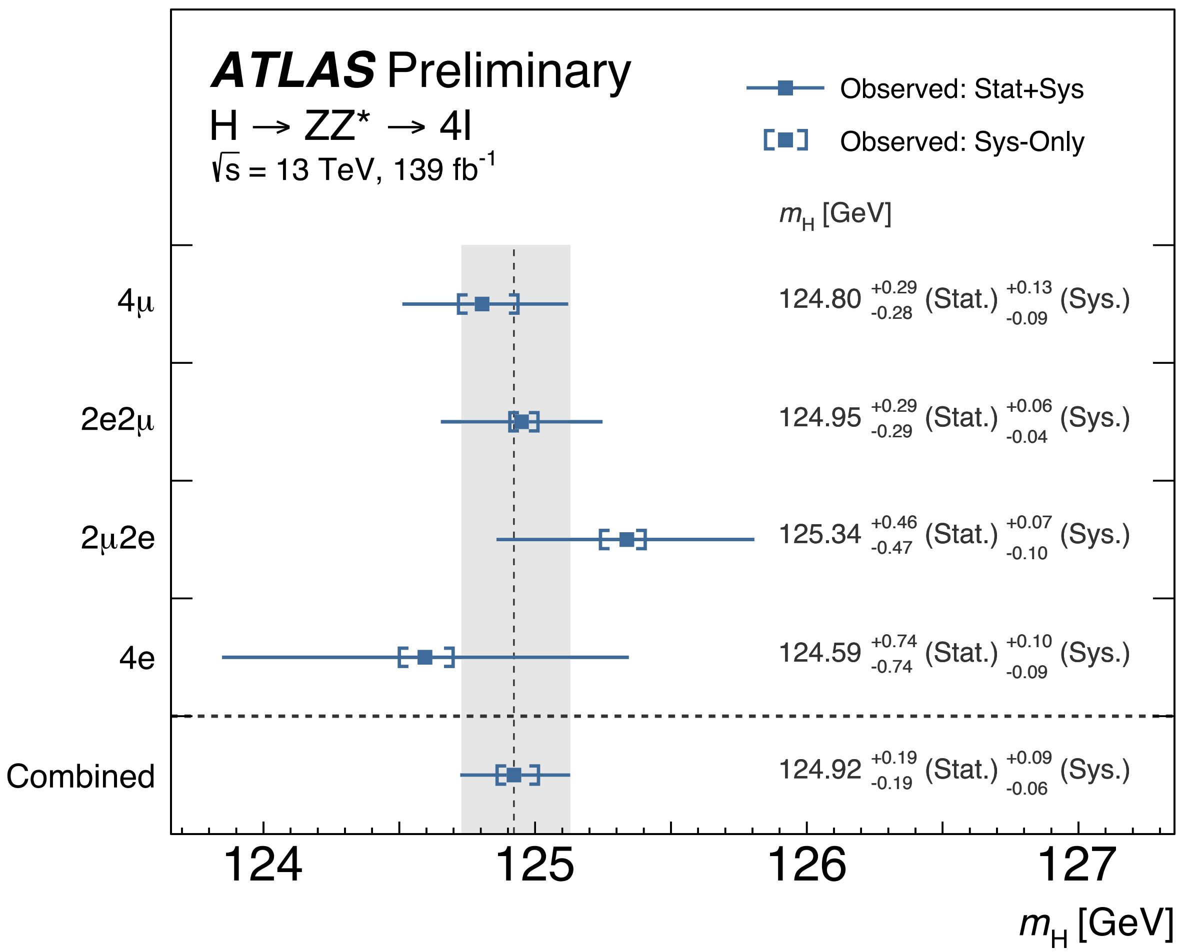
$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

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

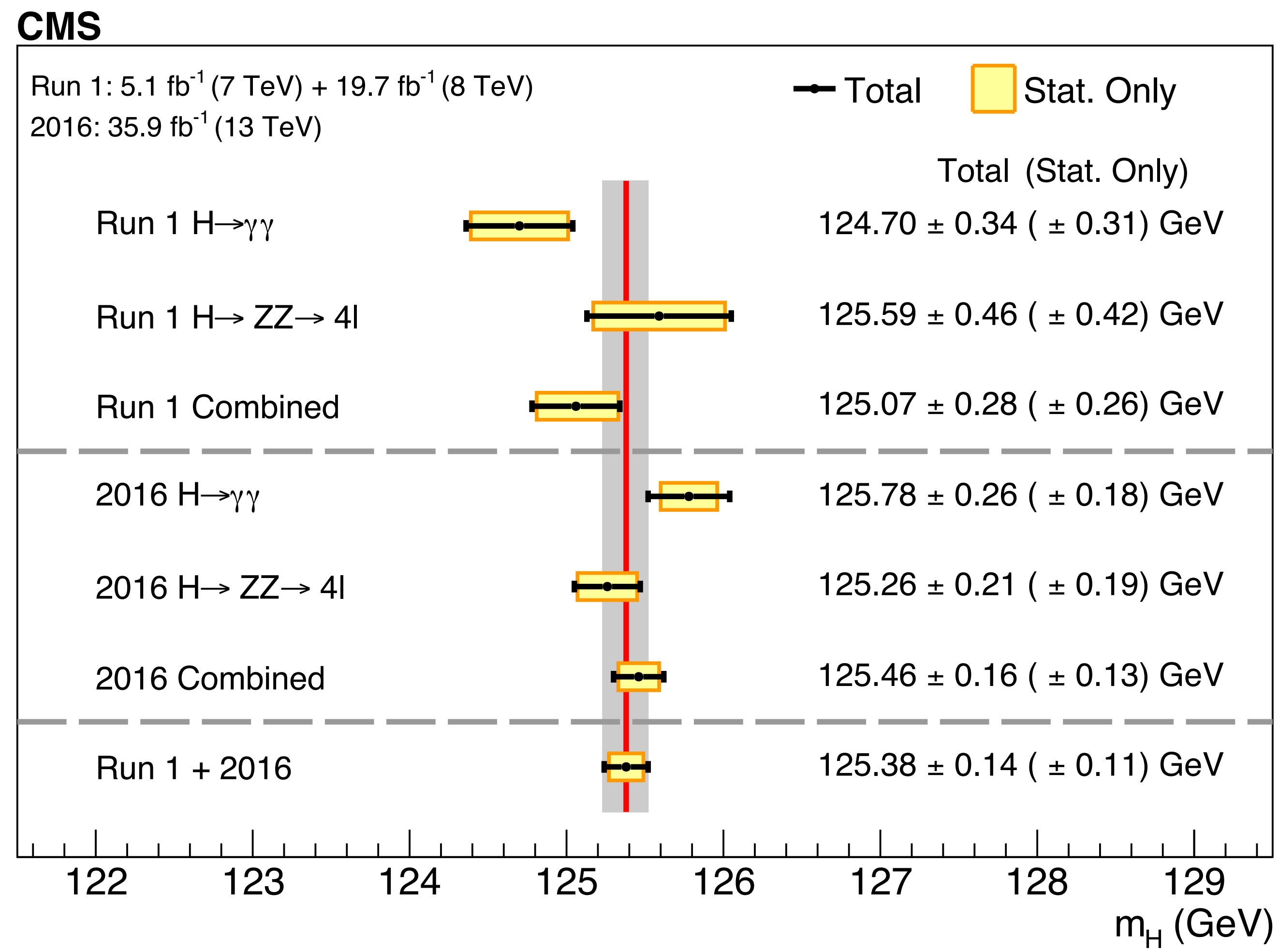
Higgs mass

- Measurement done in $H \to 4\ell$ and $H \to \gamma\gamma$ only
- precision dominated by statistics and experimental systematics

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



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



$$m_H = 124.92 \pm 0.19\ (\text{stat})\ {}^{+0.09}_{-0.06}\ (\text{syst})\ \text{GeV}$$

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

precision on m_H: 140 MeV ≈ 0.1%

Higgs boson width

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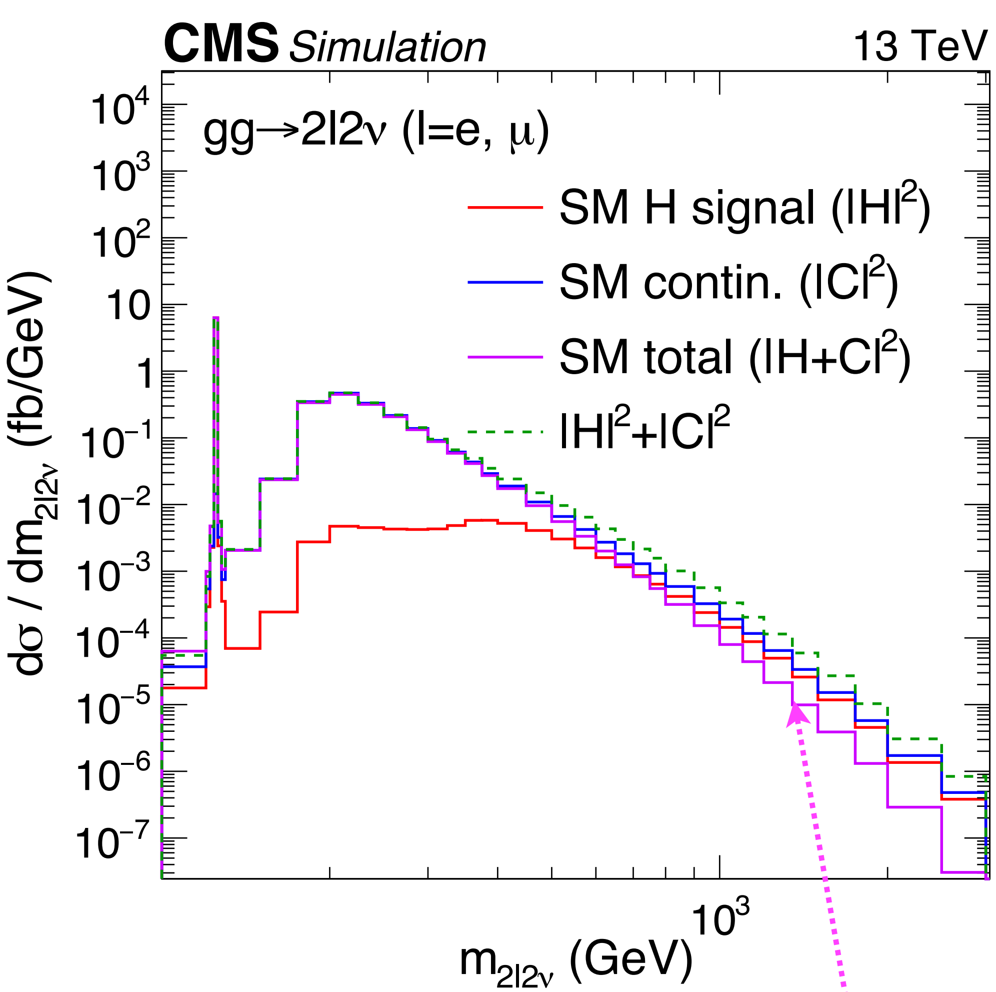
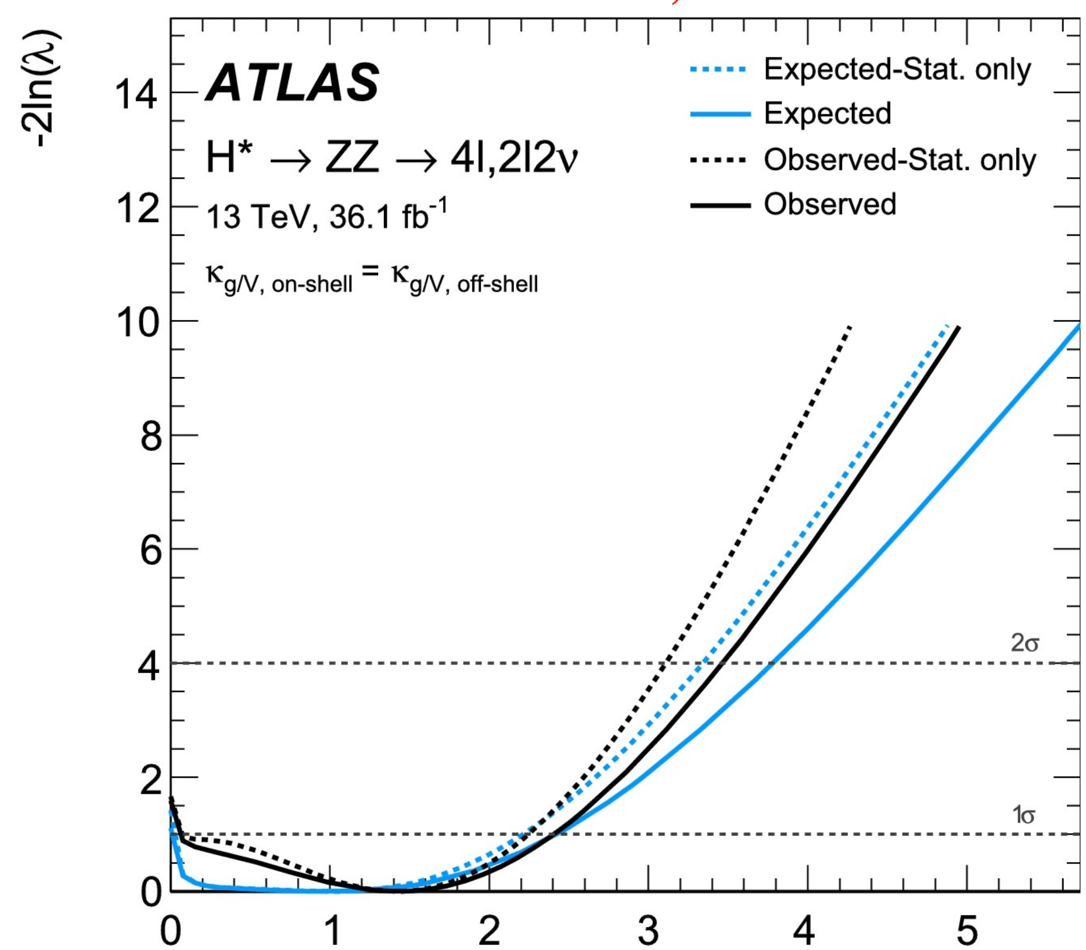
- $\Gamma_H^{SM} = 4.1$ MeV (corresponding to a lifetime $\tau_H \sim 1.6 \times 10^{-22}$s) too small to be measured directly:
  - direct measurement: **Γ_H<1.1 GeV** from on-shell Higgs, limited by detector resolution smearing the Breit-Wigner lineshape
- Higgs width can be extracted from the ratio of on-shell and off-shell yields
  - model assumption: $\mu^H_{\text{off-shell}} \equiv \mu^H_{\text{on-shell}}$

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

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



$H \to ZZ^* \to 4\ell, H \to 2\ell 2\nu$



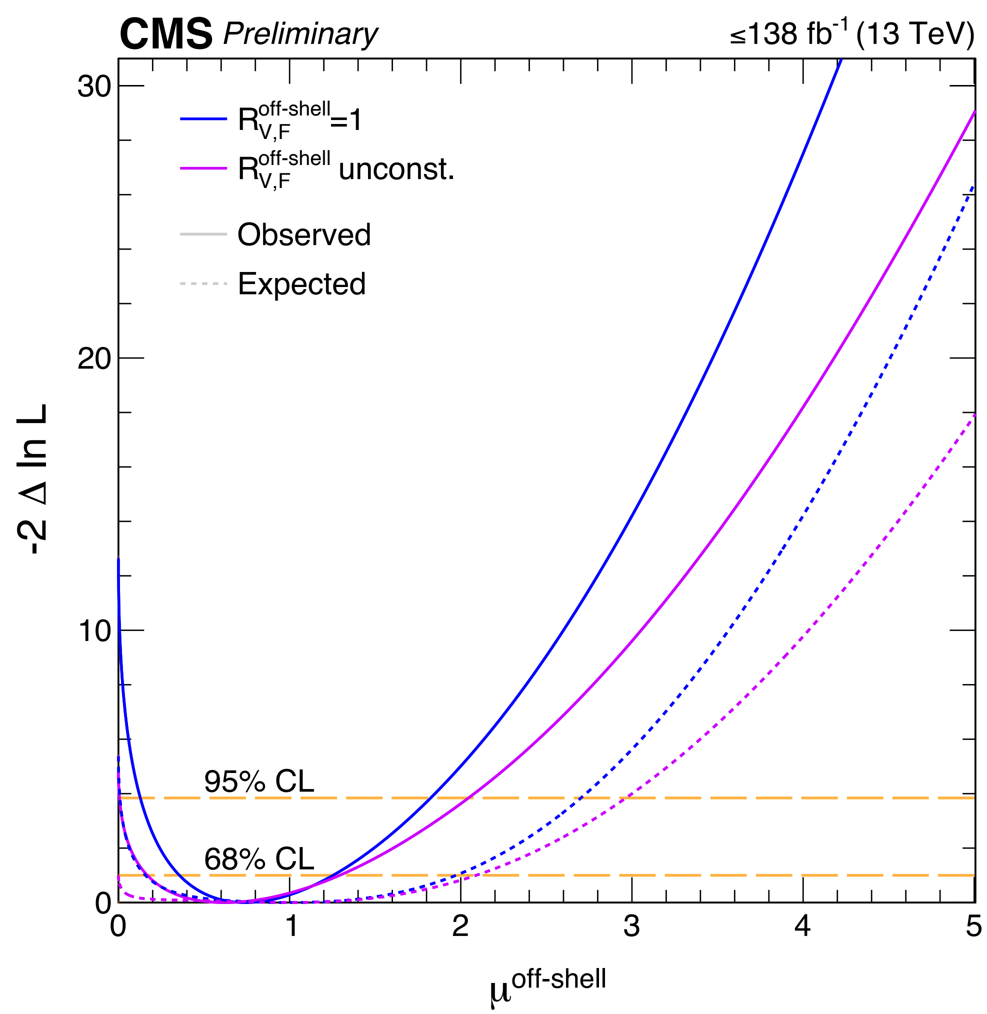
non-resonant ZZ interferes destructively with off-shell H

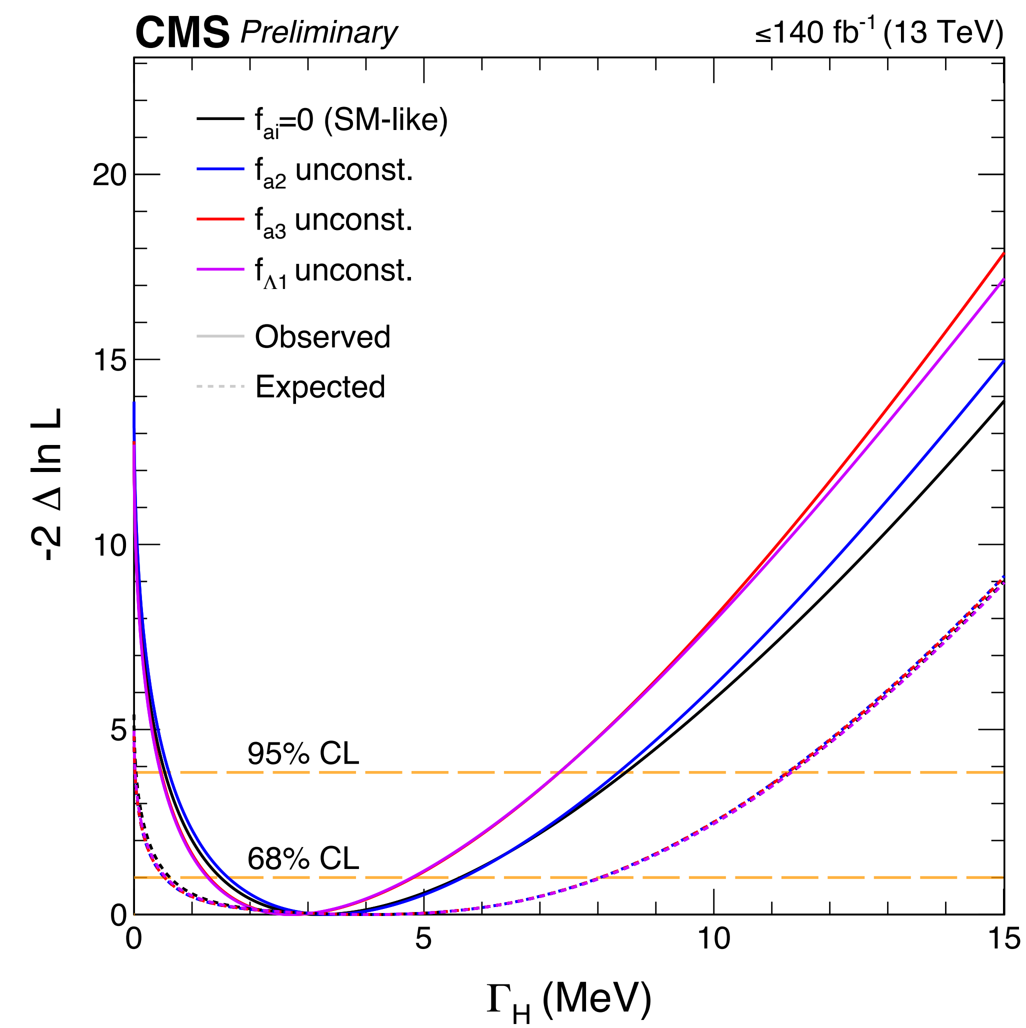
$\Gamma_H < 14.4$ MeV

2015 and 2016 data

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 and categorized in jet multiplicity





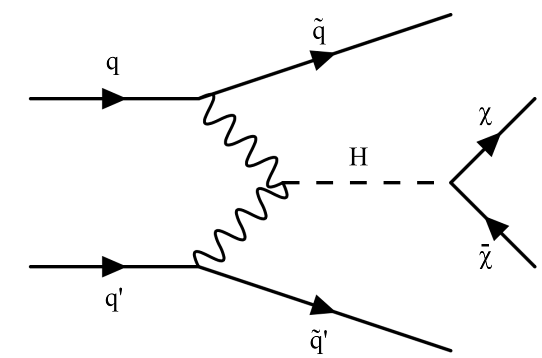
first evidence for off-shell Higgs production at **3.6σ**

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

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

VBF H→ invisible

- Part of Higgs width could be due to decays to not detectable particles: searches can be interpreted within Dark Matter models
- CMS: Search of 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
- ATLAS: VBF combined to VH production
  - $V = Z \to \ell\ell;\ V = (W, Z) \to \text{had}$



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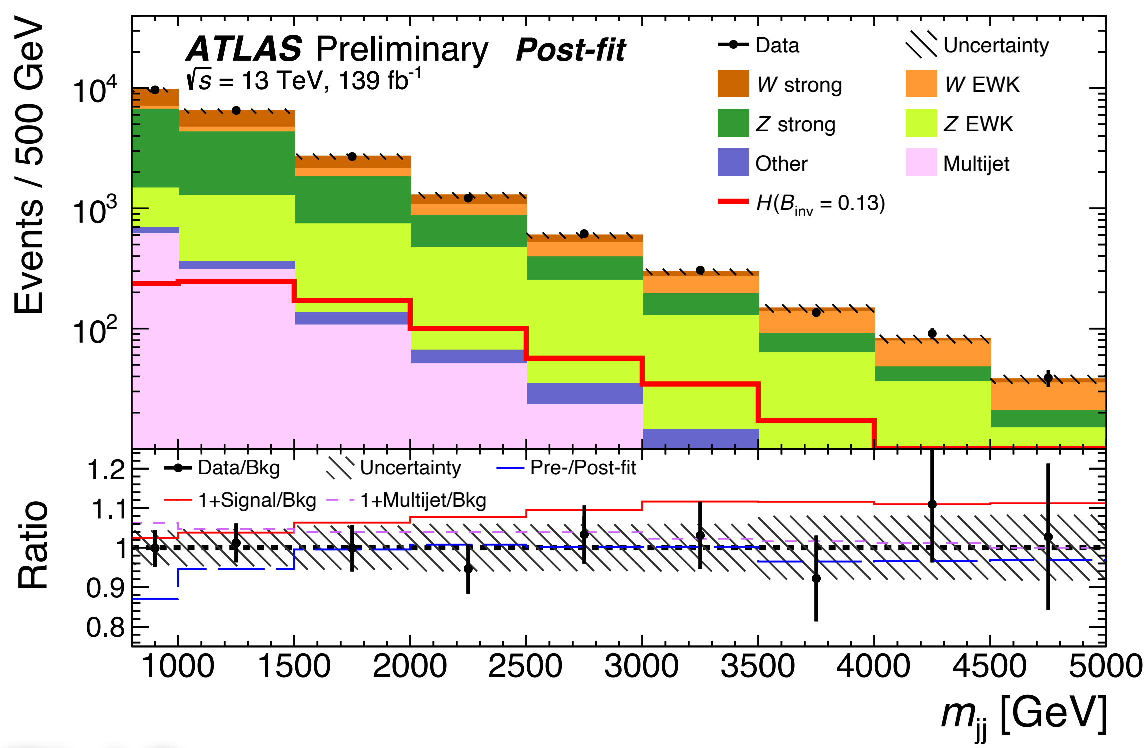
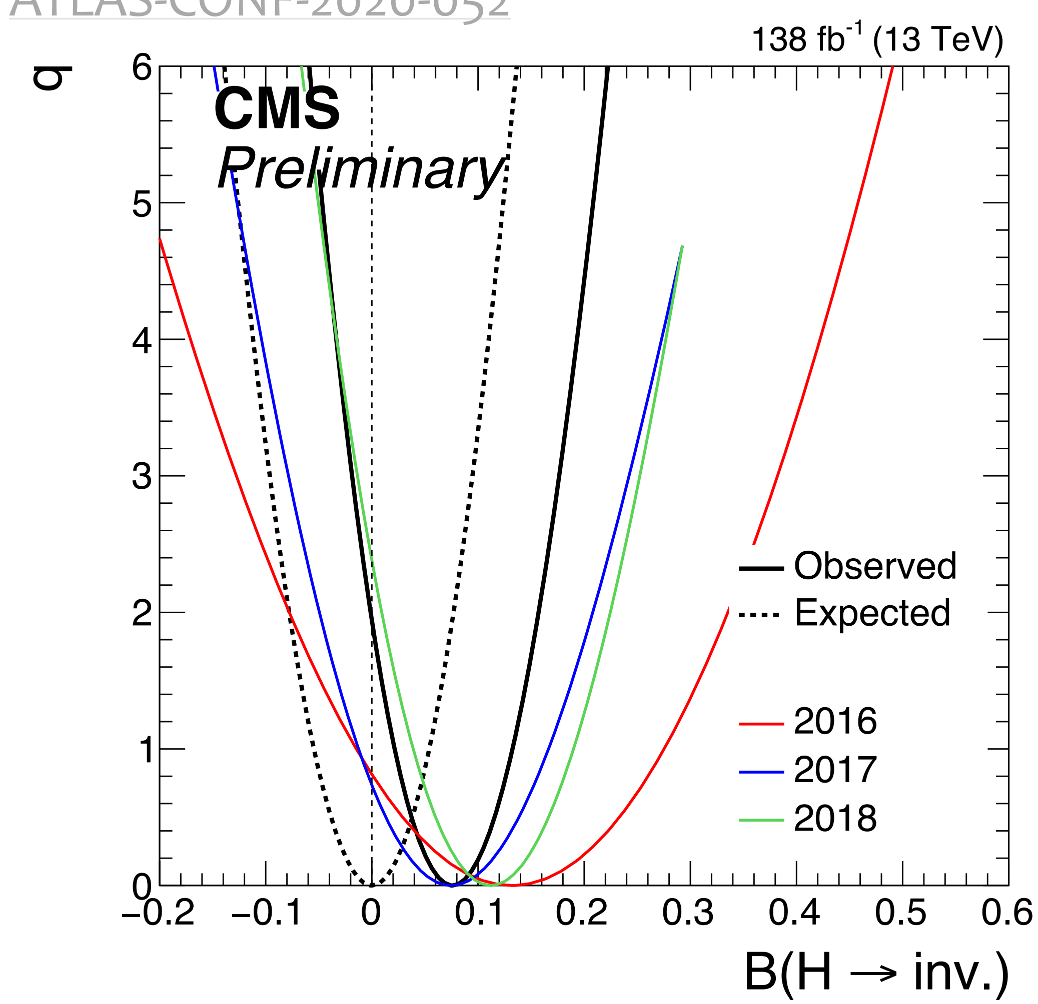
HIGG-2018-26
CMS-PAS-HIG-20-003
ATLAS-CONF-2020-052





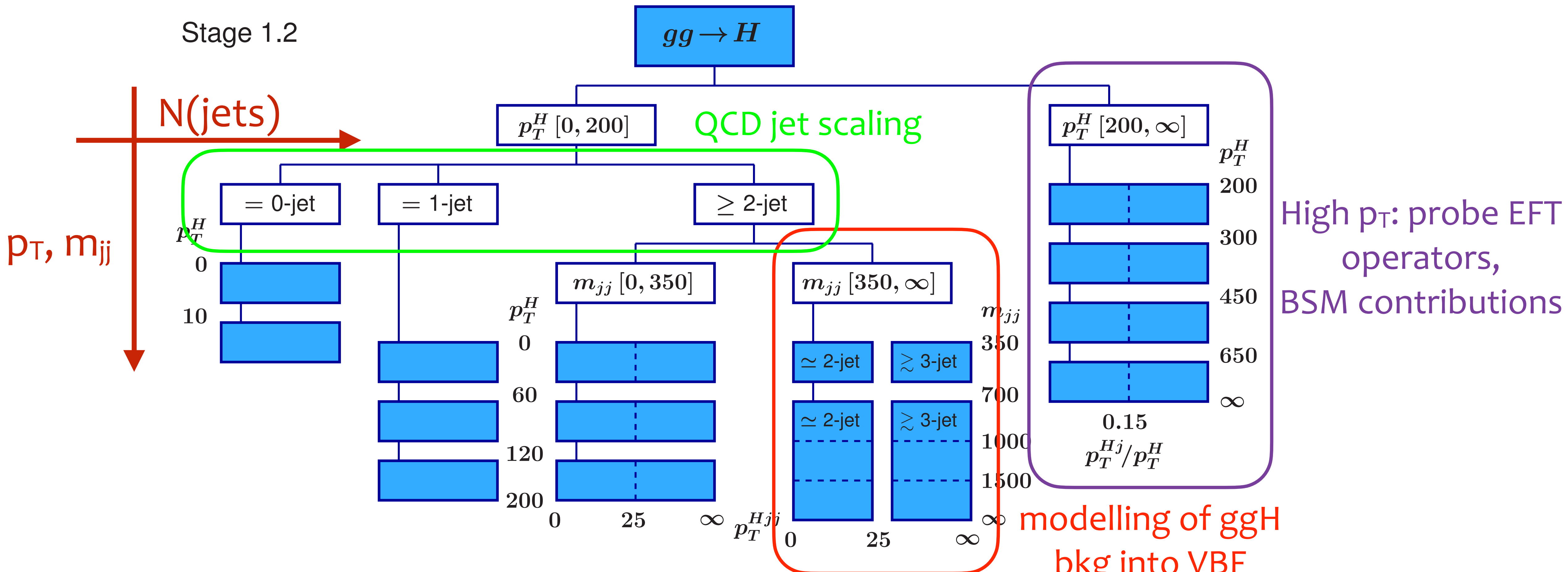
ATLAS: $\mathrm{BR}(H \to \mathrm{inv}) < 0.11$ (exp 0.11)

CMS: $\mathrm{BR}(H \to \mathrm{inv}) < 0.17$ (exp 0.11)

Higgs boson cross sections

STXS measurements overview

- Approach devoted to minimize simultaneously experimental and theoretical uncertainties on Higgs cross section measurements
- Split Higgs 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, used in STXS measurements as proxy for true properties
  - Allow re-interpretation of results in different models
  - Look for BSM in extreme bins of the phase space



STXS in $H \rightarrow \gamma\gamma$

- $H \rightarrow \gamma\gamma$ 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**

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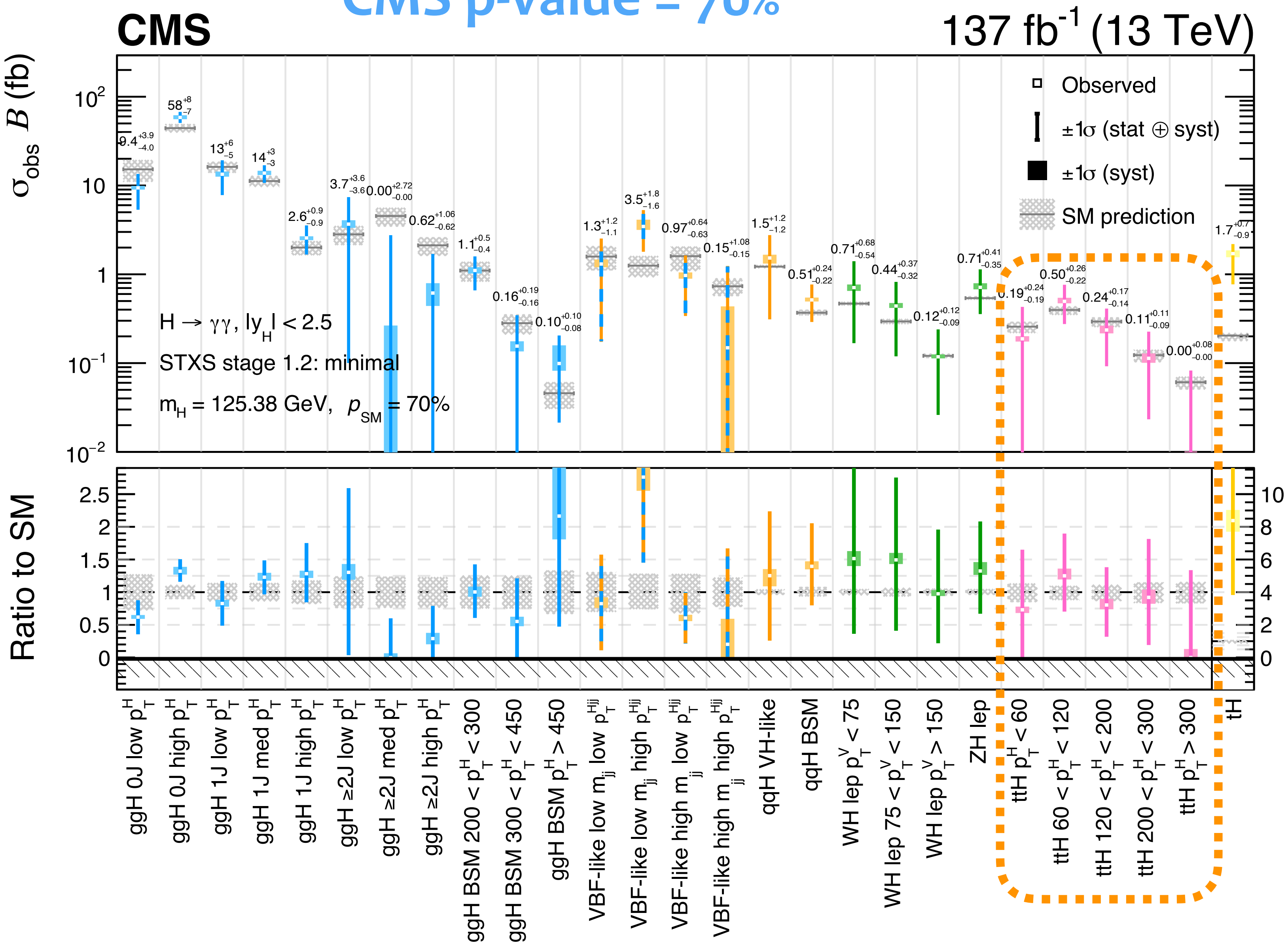
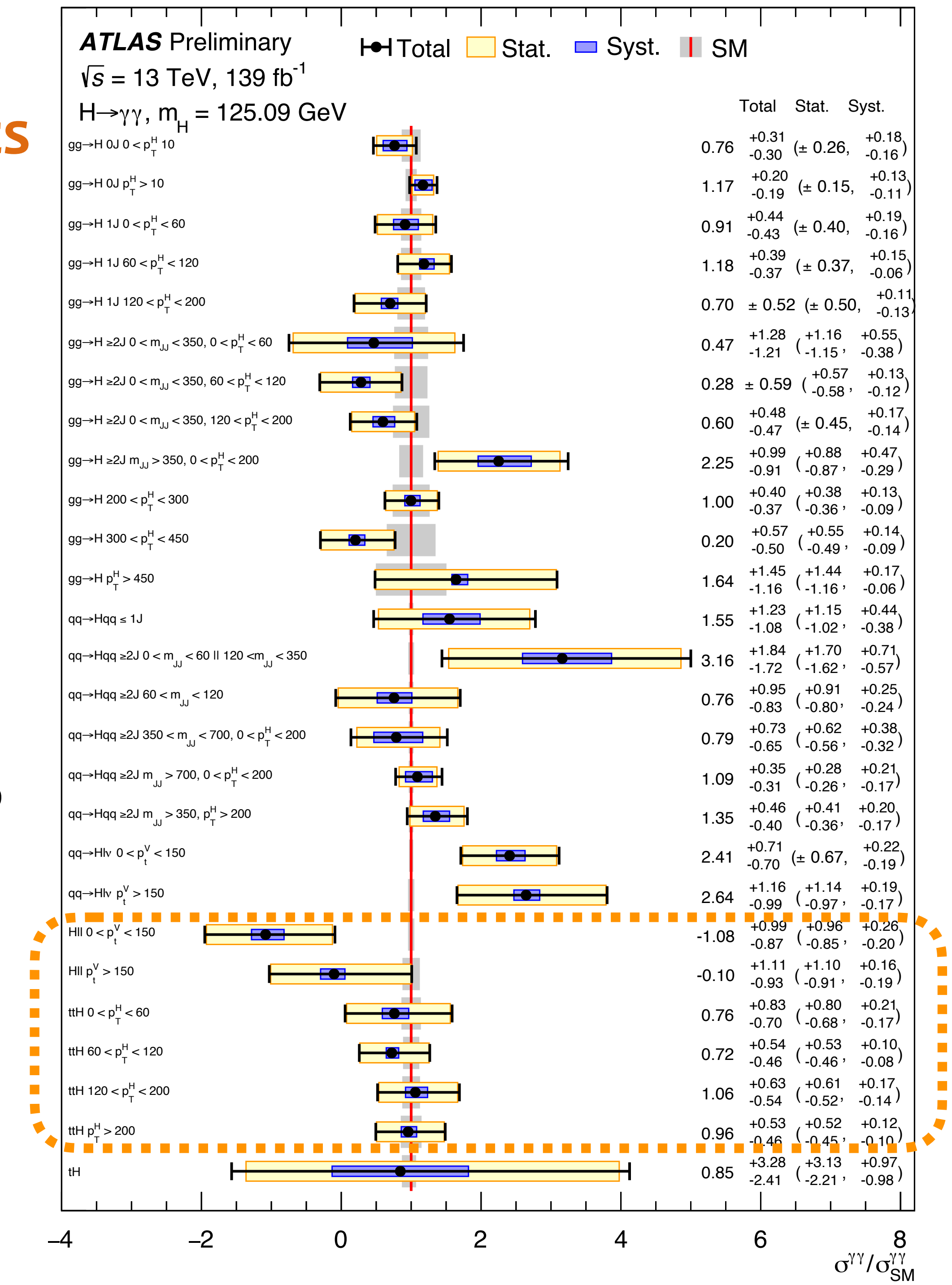
ATLAS-CONF-2020-026

CMS p-value = 70%

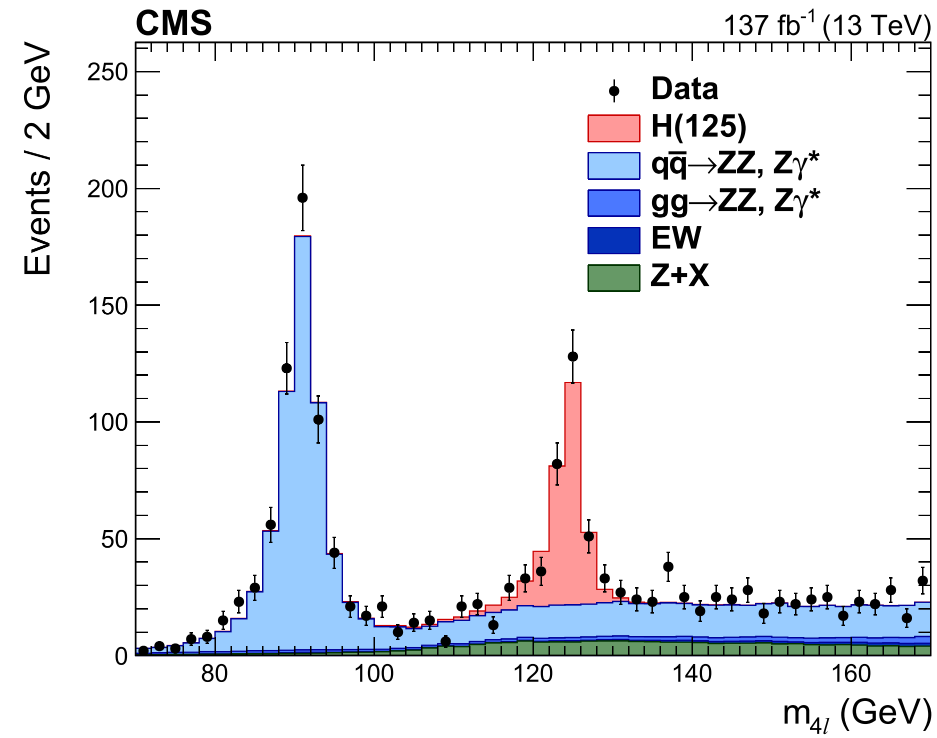


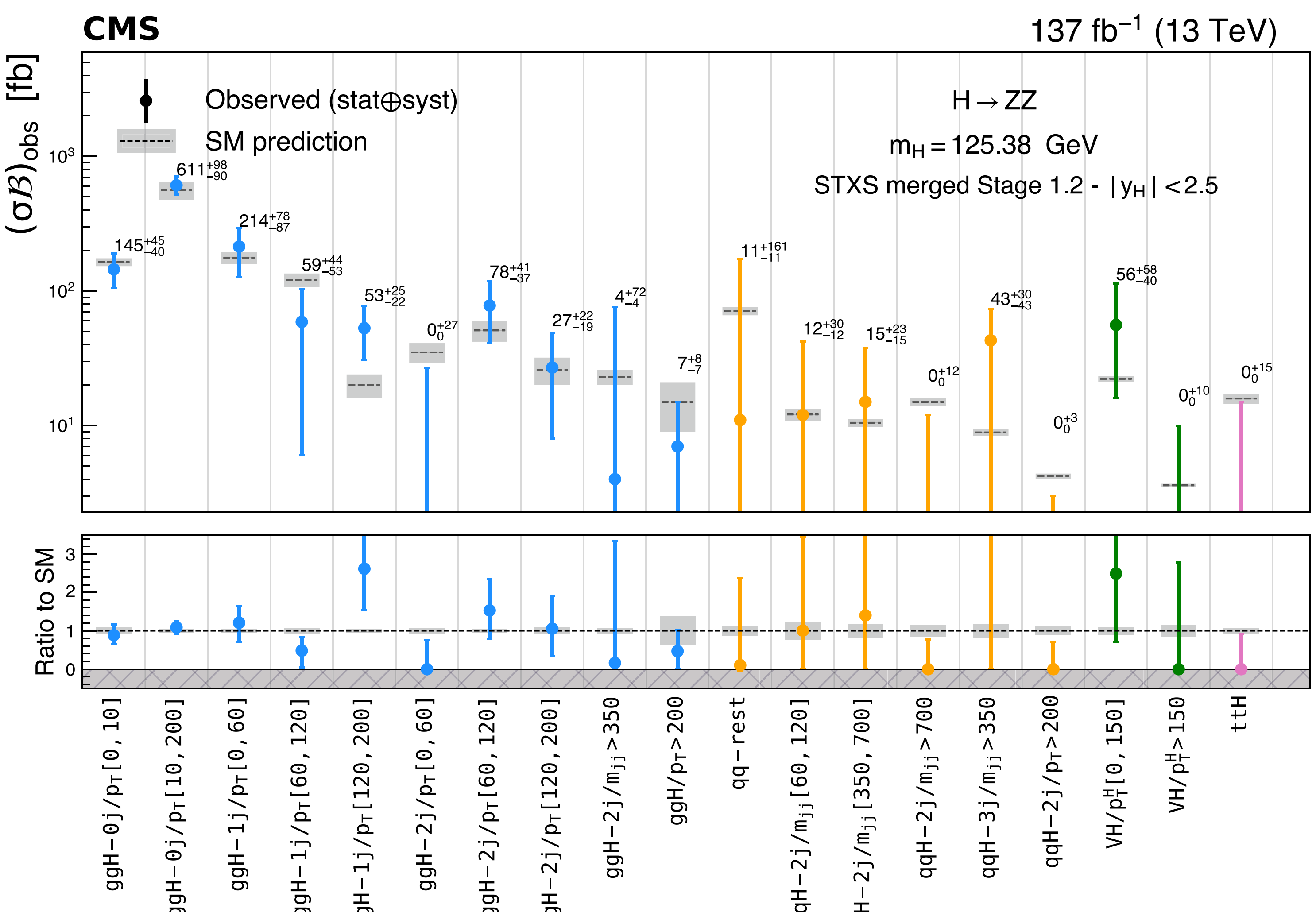
ATLAS p-value = 60%

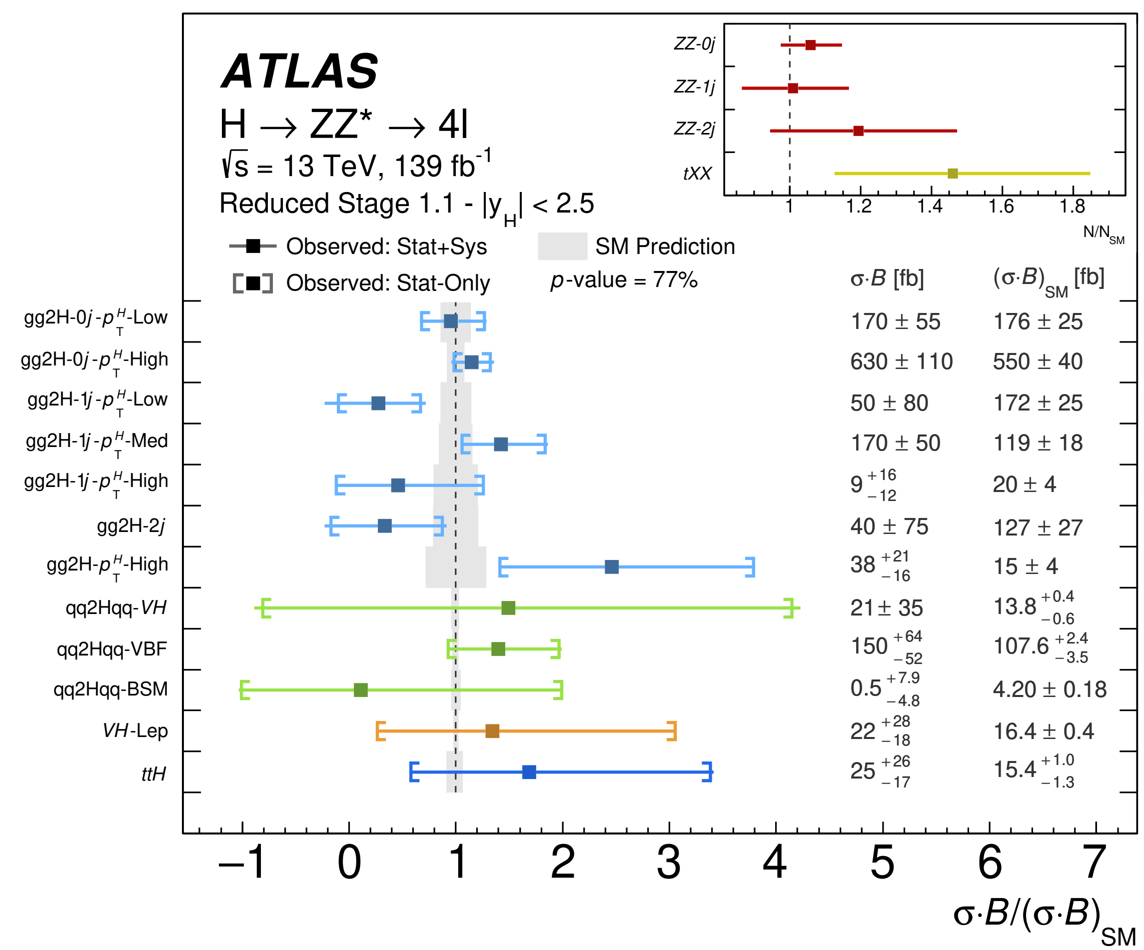


STXS $H \to ZZ^* \to 4\ell$

- 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

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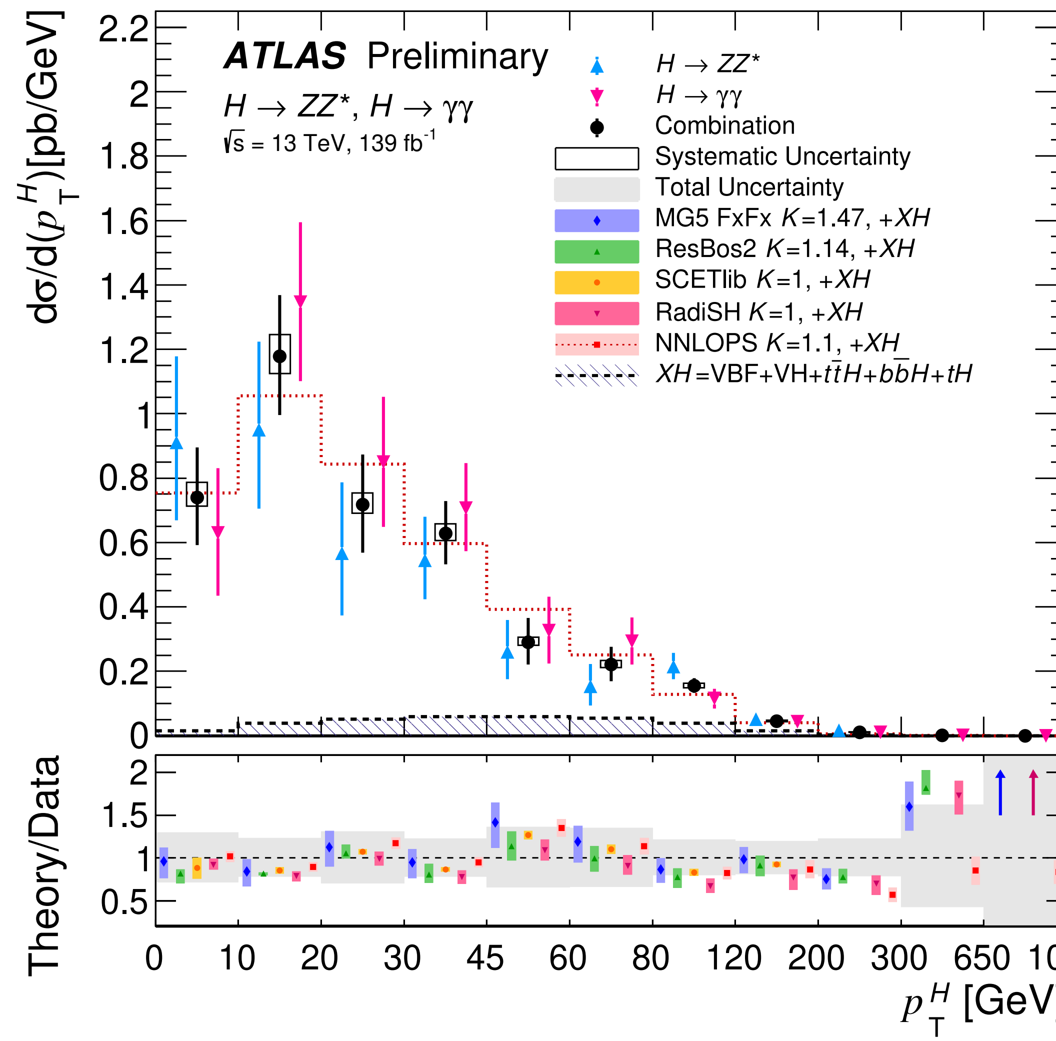
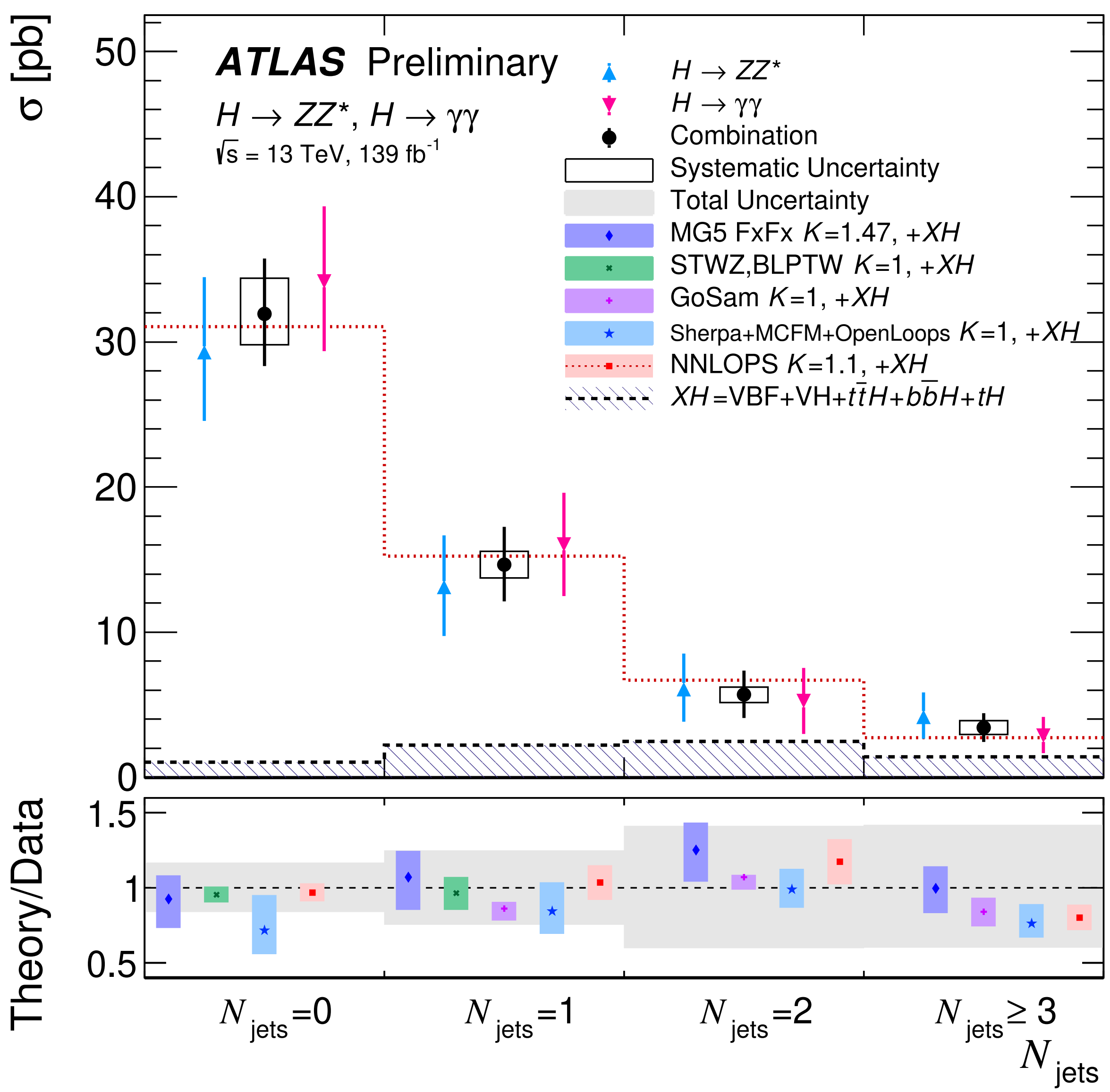
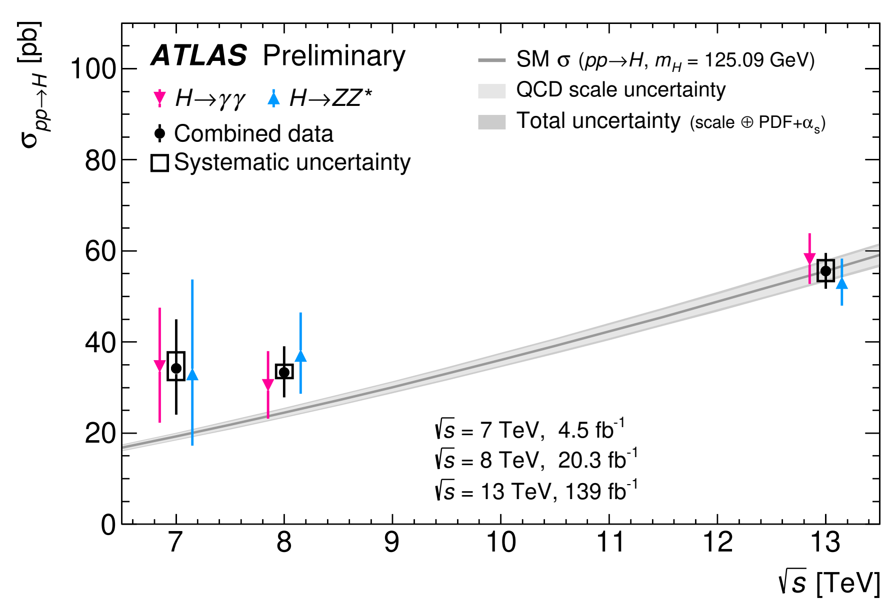
Differential and fiducial σ

- Combination of $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ by ATLAS for differential and inclusive cross-sections with full Run 2





ATLAS-CONF-2022-002



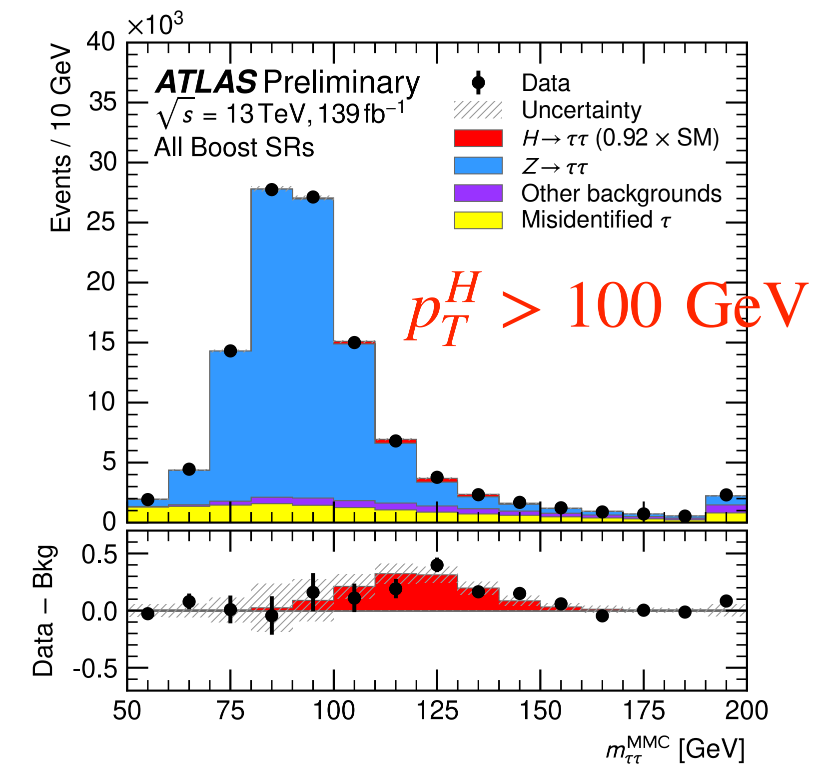
$$\sigma^{\mathrm{meas}}_{13\ \mathrm{TeV}} = 55.5^{+4.0}_{-3.8}\ \mathrm{pb}$$

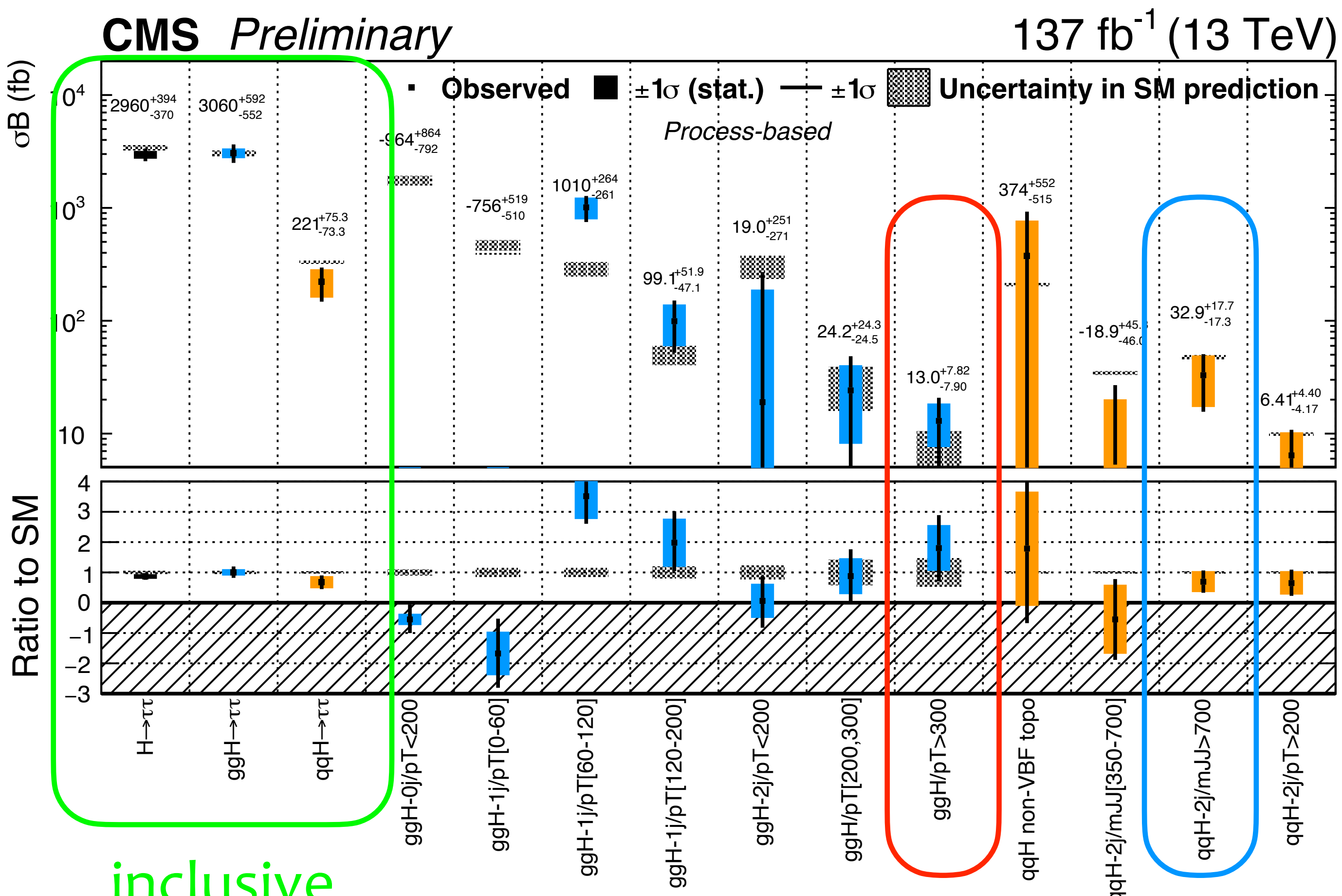
$$\sigma^{\mathrm{SM}}_{13\ \mathrm{TeV}} = 55.6 \pm 2.5\ \mathrm{pb}$$

New for LP21

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

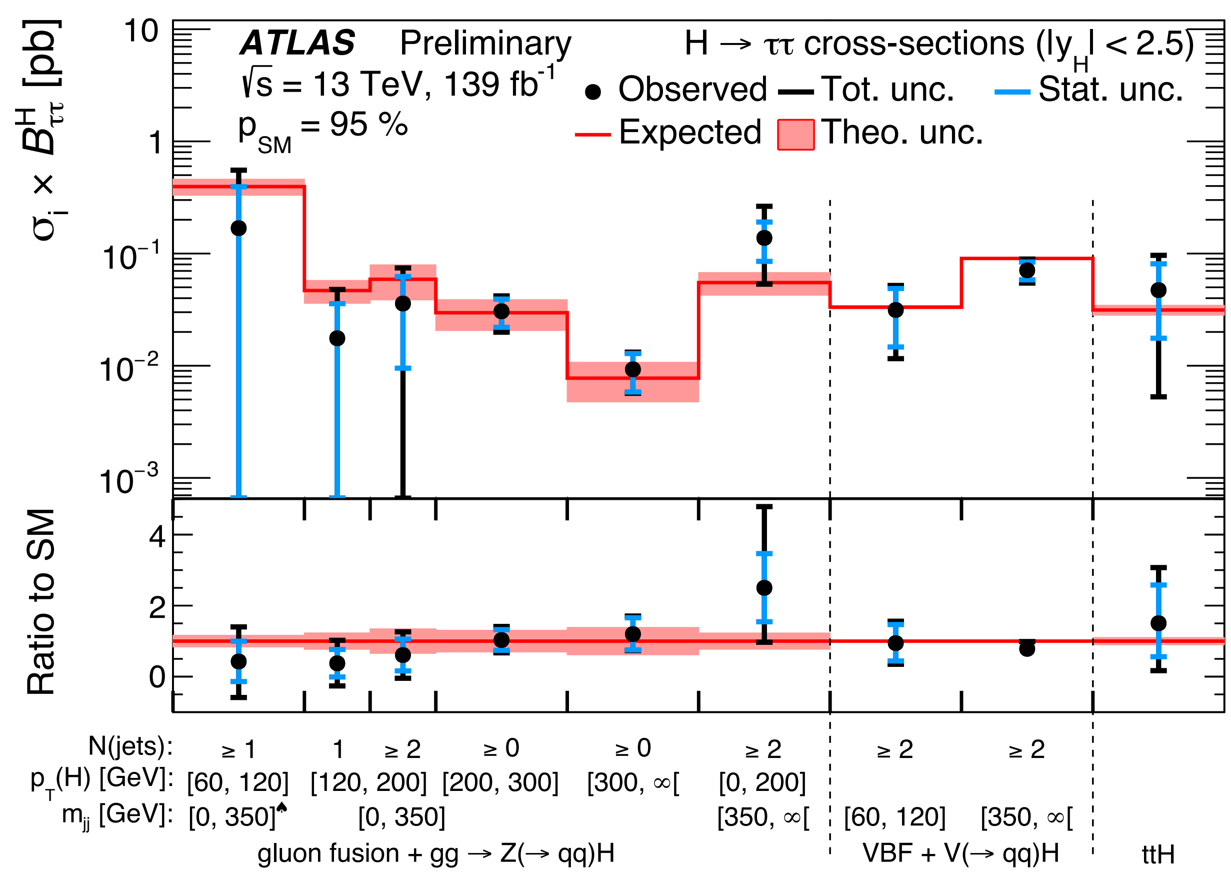




inclusive cross-sections

ggH high p_T

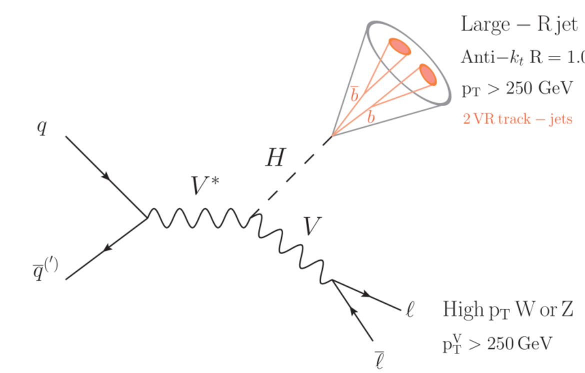
VBF high m_{jj}



ATLAS-CONF-2021-044
CMS-PAS-HIG-19-010

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

- Challenging channel, VH, $H \to b\bar{b}$ can measure highly boosted regime
  - boosted jet analysis targets $p_T(V)$>250 GeV



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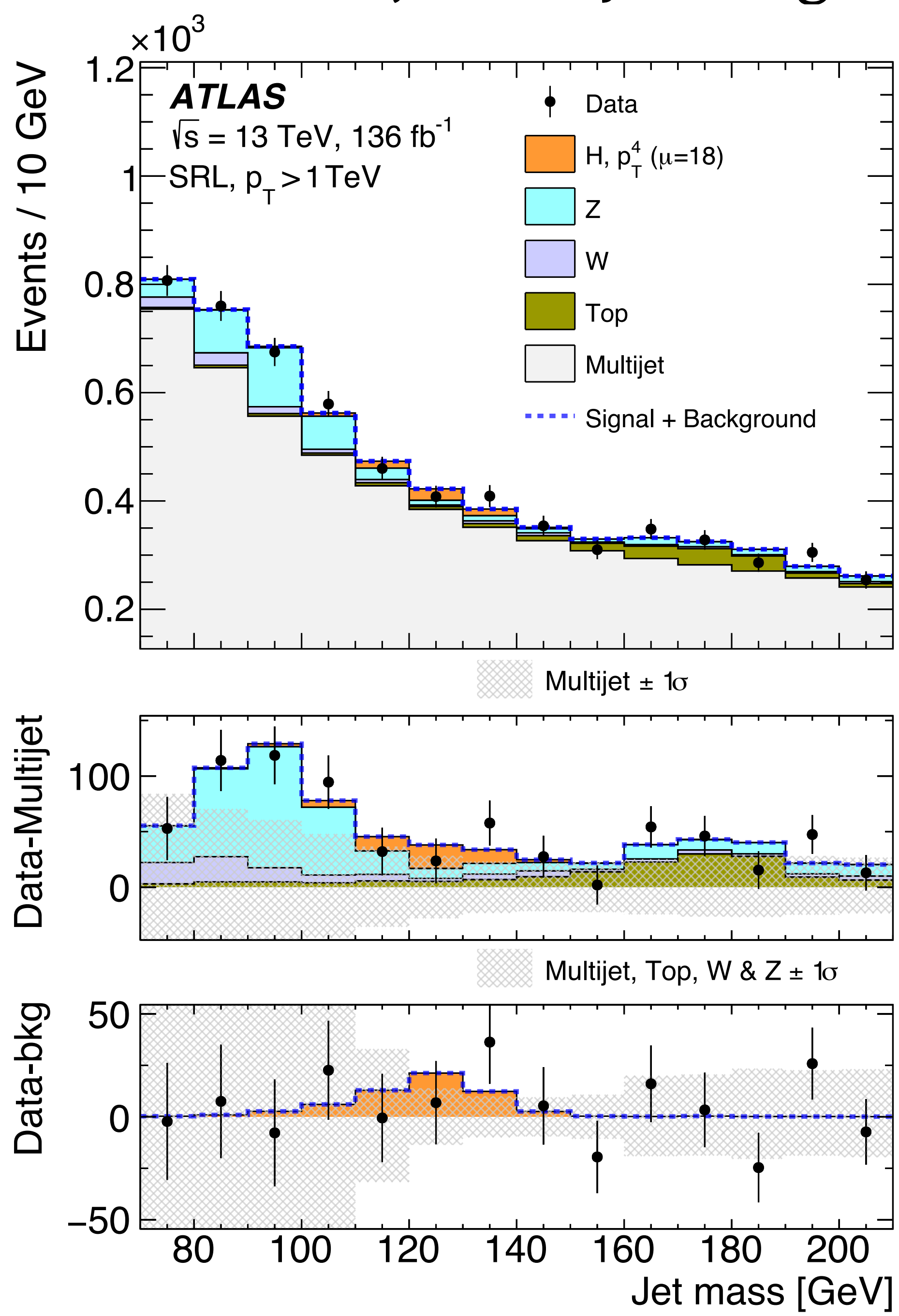
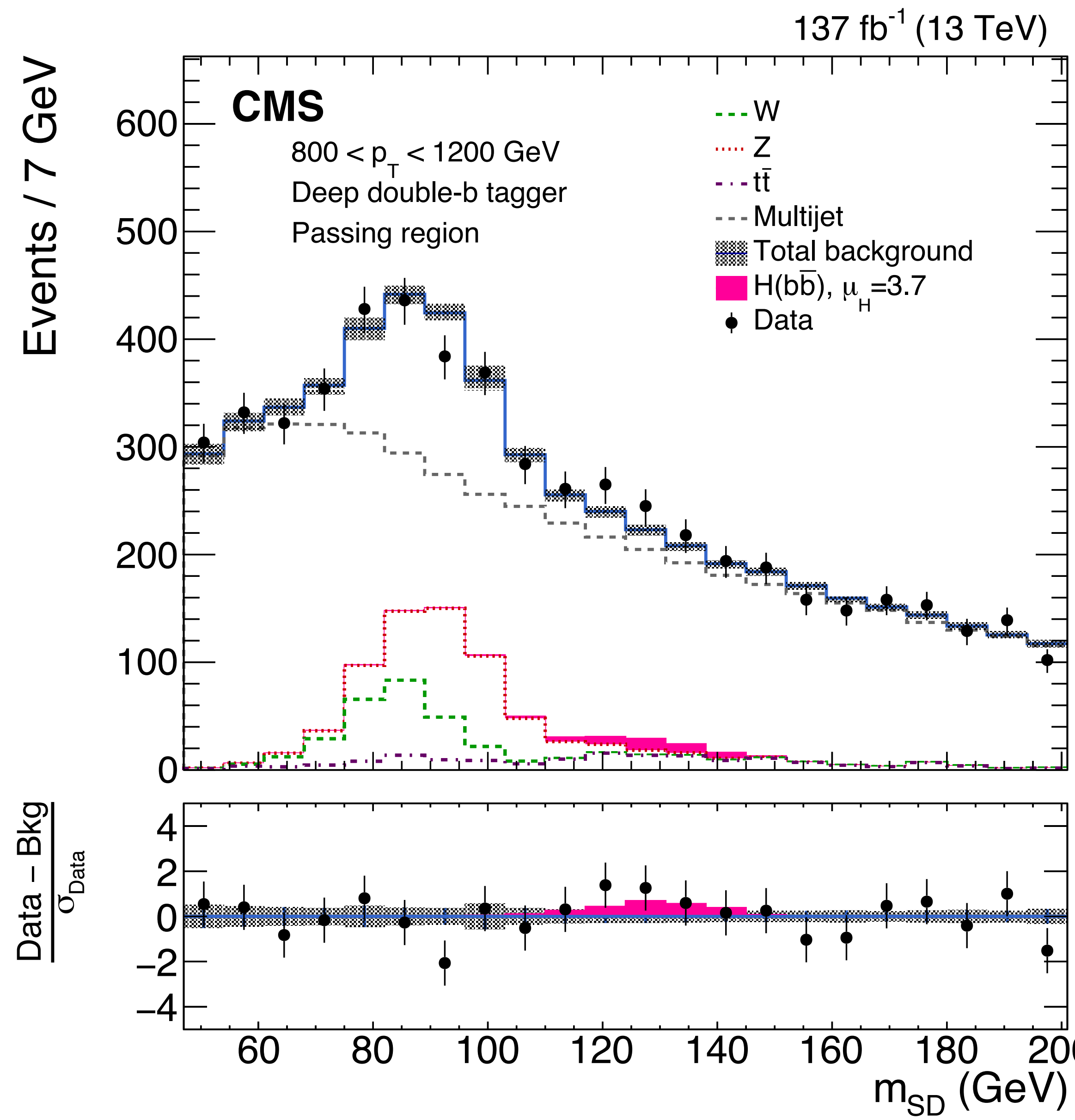


p_T^H > 1 TeV



$0.8 < p_T^H < 1.2$ TeV

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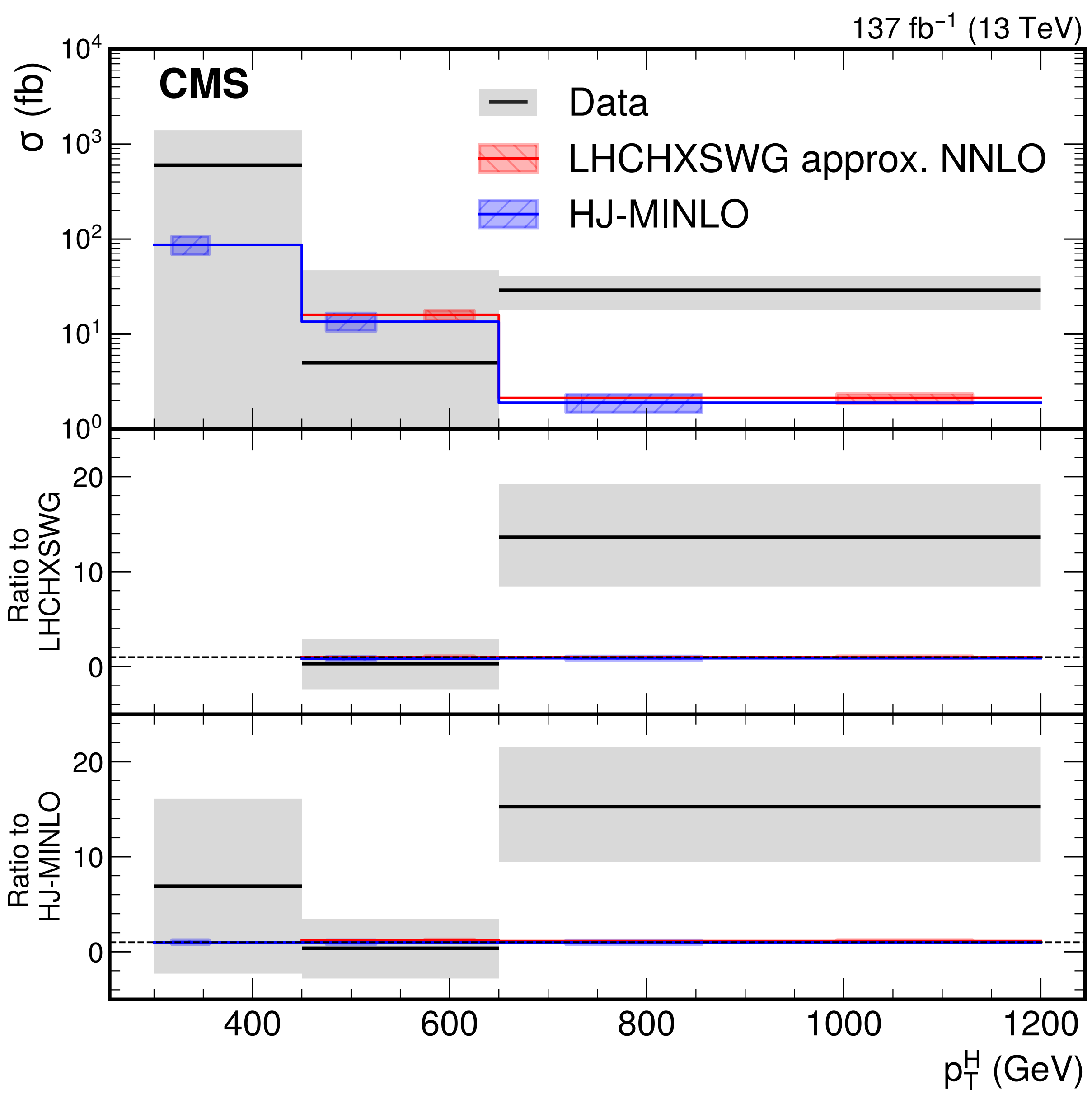
STXS in $H \rightarrow b\bar{b}$

- Observed WH and ZH. Differential cross-sections analysis sensitive to p_T>250 GeV, probing p_T>400 GeV
  - measurements beginning to be **systematically limited**

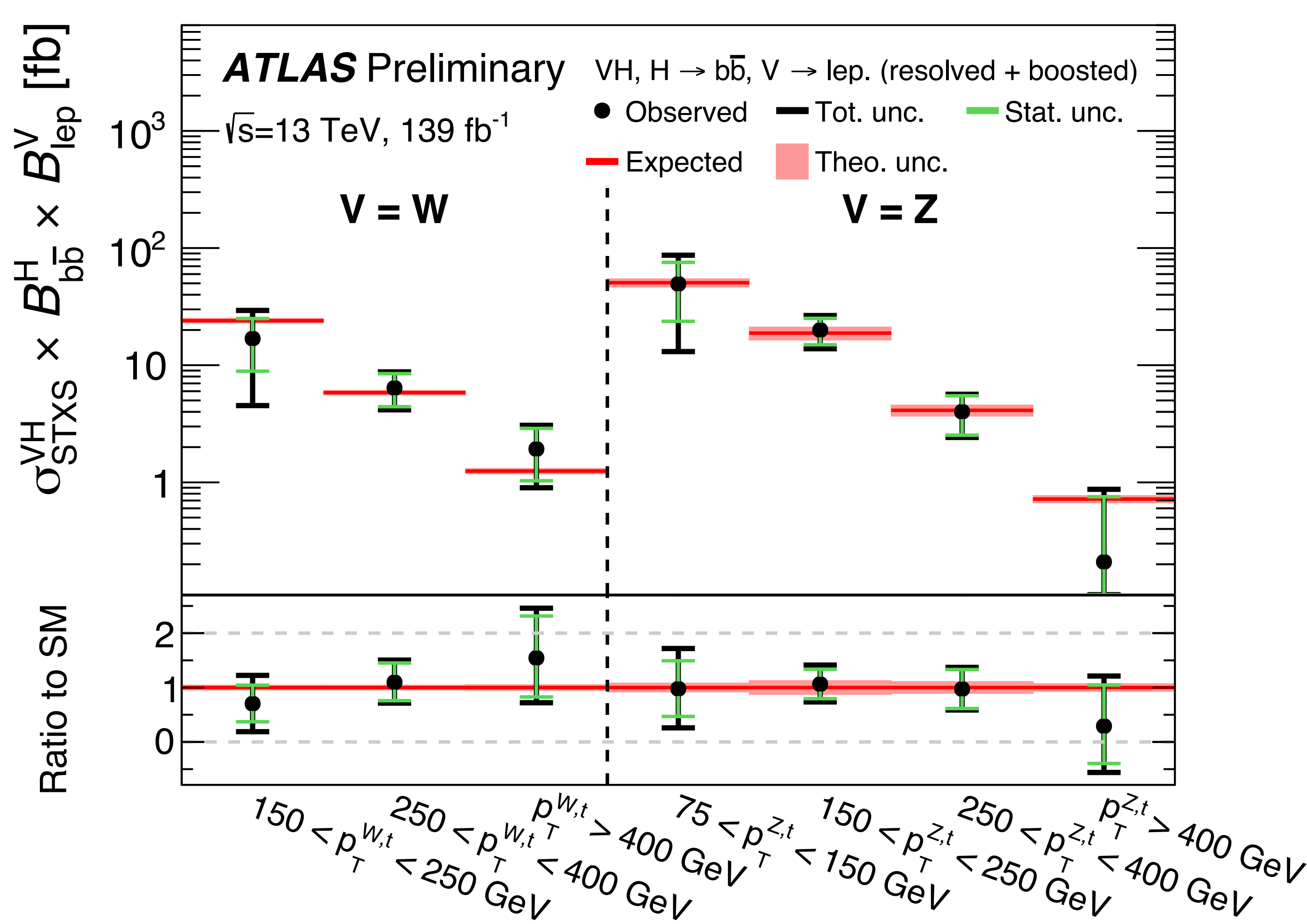


JHEP 12 (2020) 085

resolved+boosted $VH, H \rightarrow b\bar{b}$ combination

$$\mu_{WH}^{b\bar{b}} = 1.03 \pm 0.19\ (\text{stat})\ {}^{+0.21}_{-0.19}\ (\text{syst})$$

$$\mu_{ZH}^{b\bar{b}} = 0.97 \pm 0.17\ (\text{stat})\ {}^{+0.18}_{-0.15}\ (\text{syst})$$



ATLAS-CONF-2021-051

Coupling to 2nd generation

- 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

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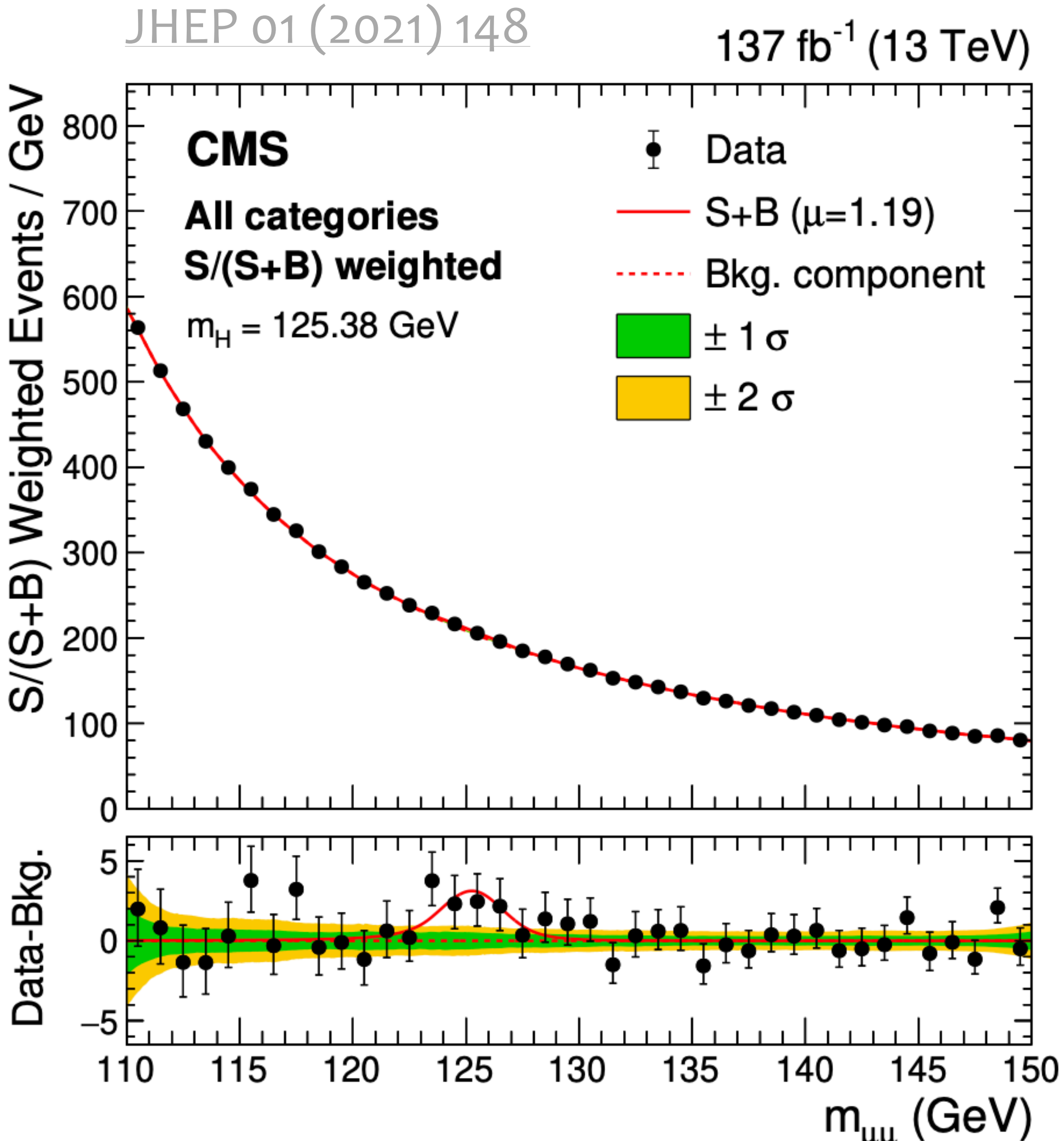
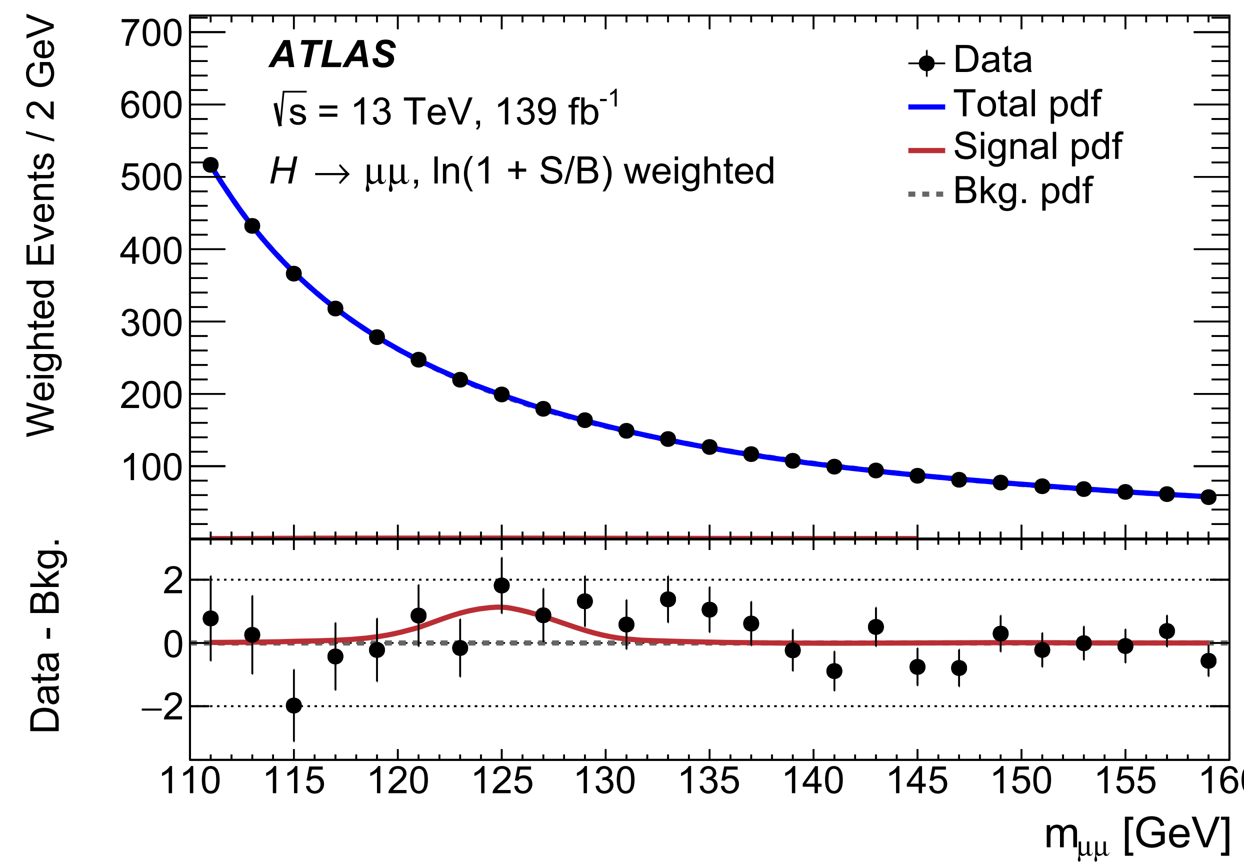


$\mu = 1.2 \pm 0.4$

significance: 3.0σ (2.5σ exp.)

PLB 812(2021) 135980



$\mu = 1.2 \pm 0.6$

significance: 2.0σ (1.7σ exp.)

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

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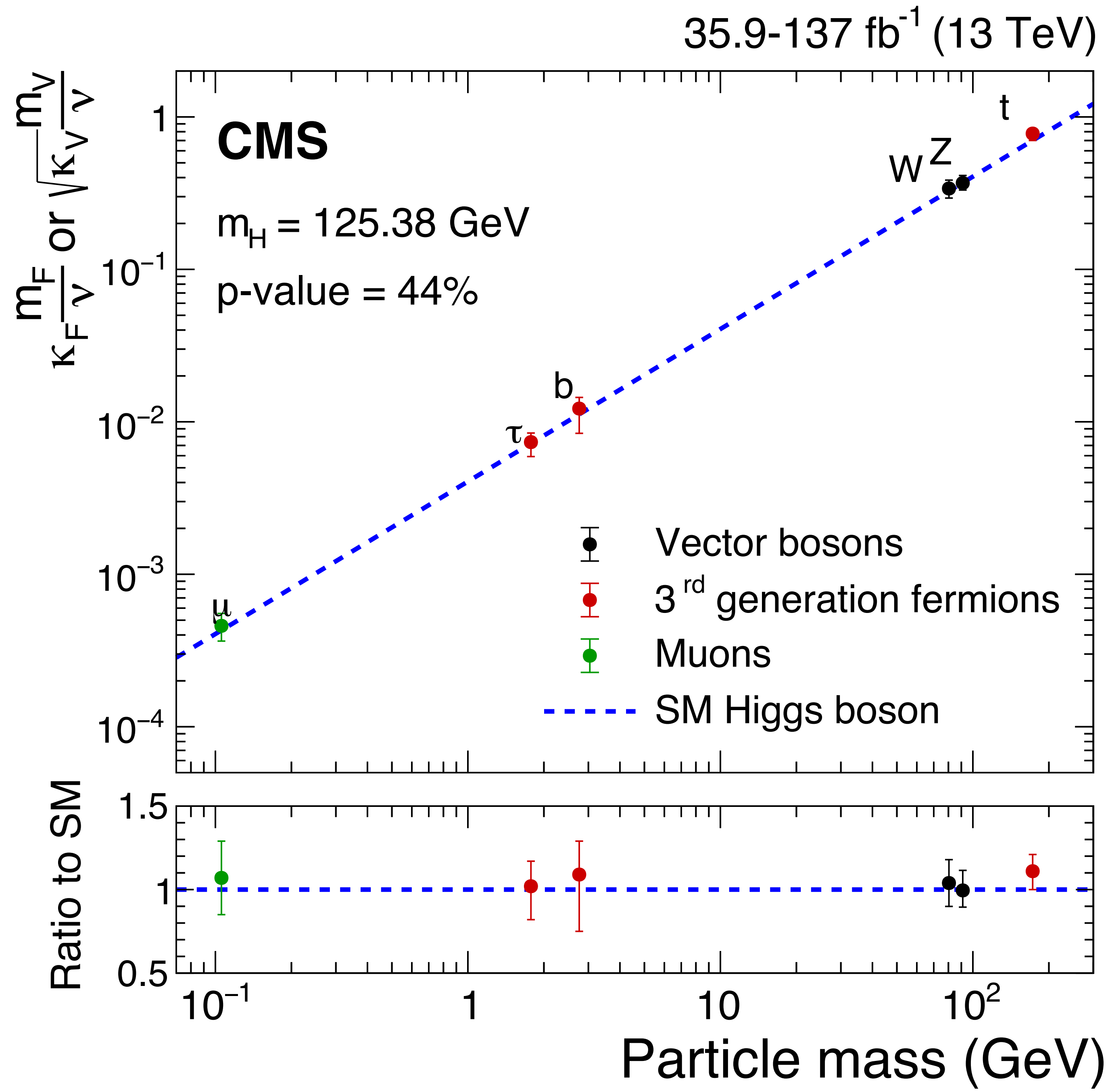

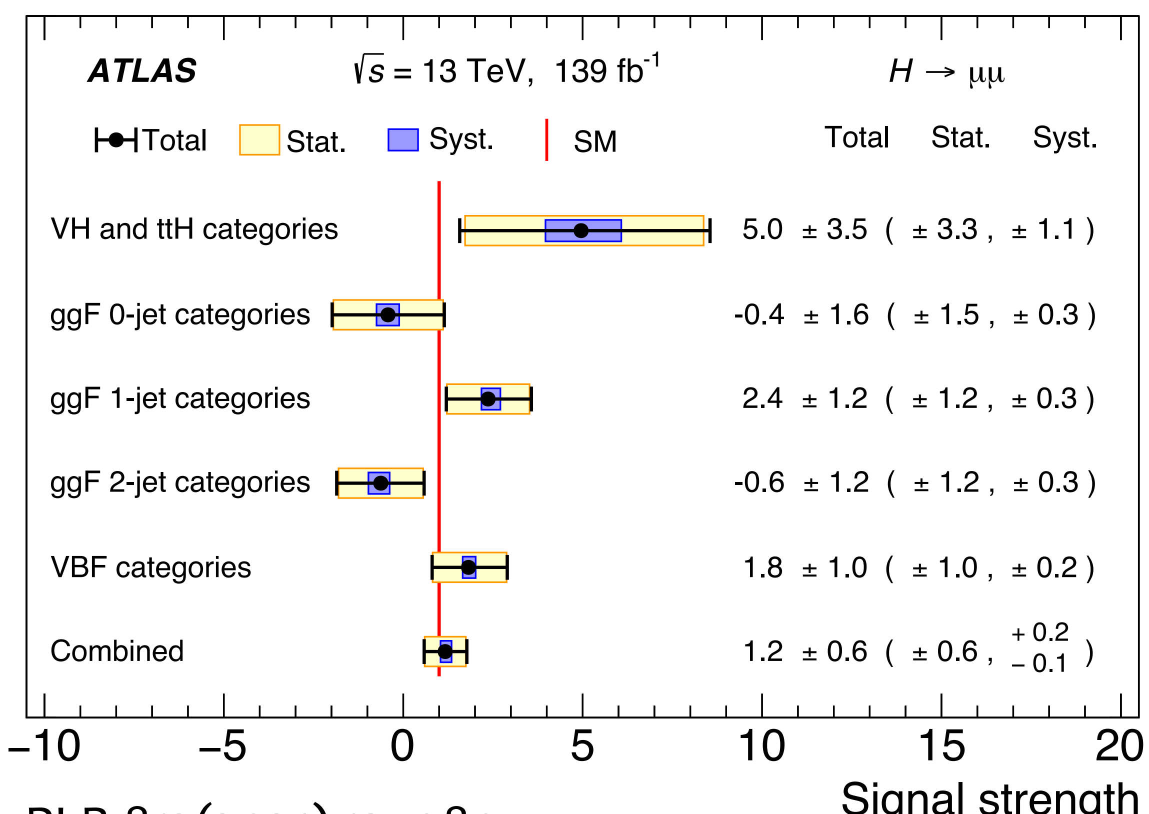

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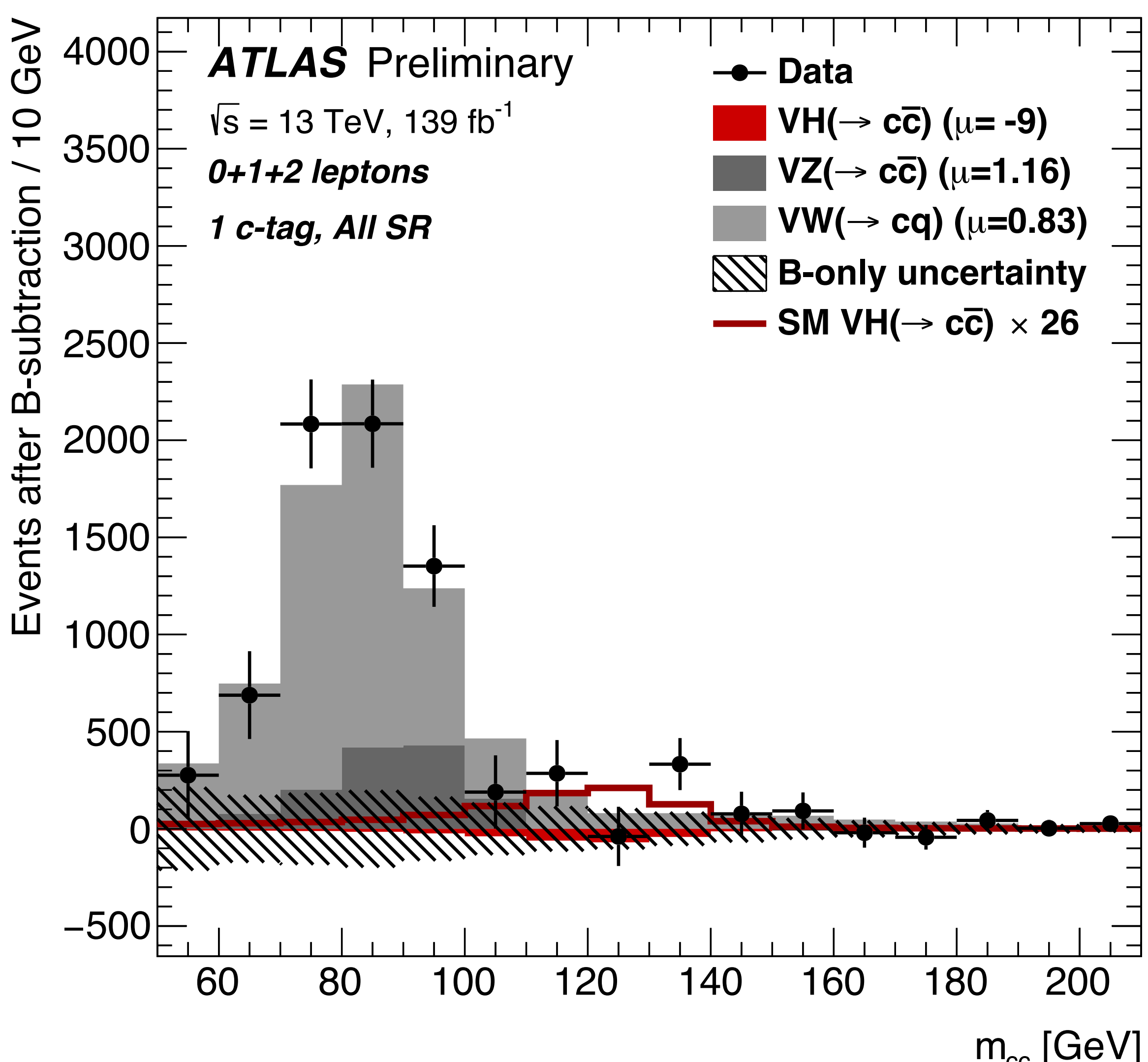
Within target: $H \to c\bar{c}$

- Very challenging channel: large backgrounds from multi-jets
  - c-tagging central to discriminate $H \to b\bar{b}$

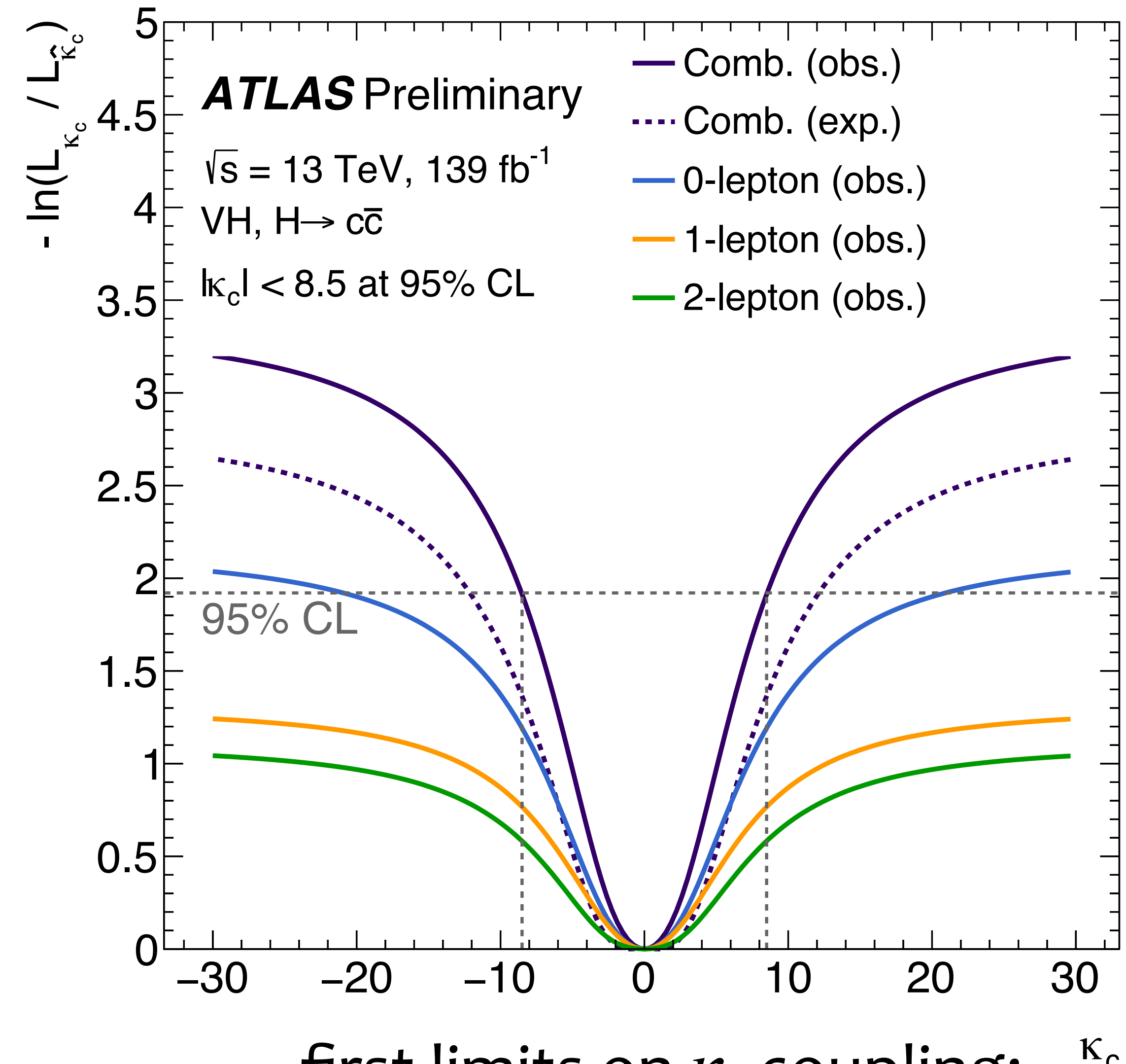
ATLAS-CONF-2021-021

- $(W, Z)H \to c\bar{c}$ associated production categorized in
  - 1, 2, 3 leptons and # c-tagged jets



Data-bkg, including

$WH(\to c\bar{c}), VZ, VW$: 3.8σ for $VW(\to cq)$



first limits on κ_c coupling:

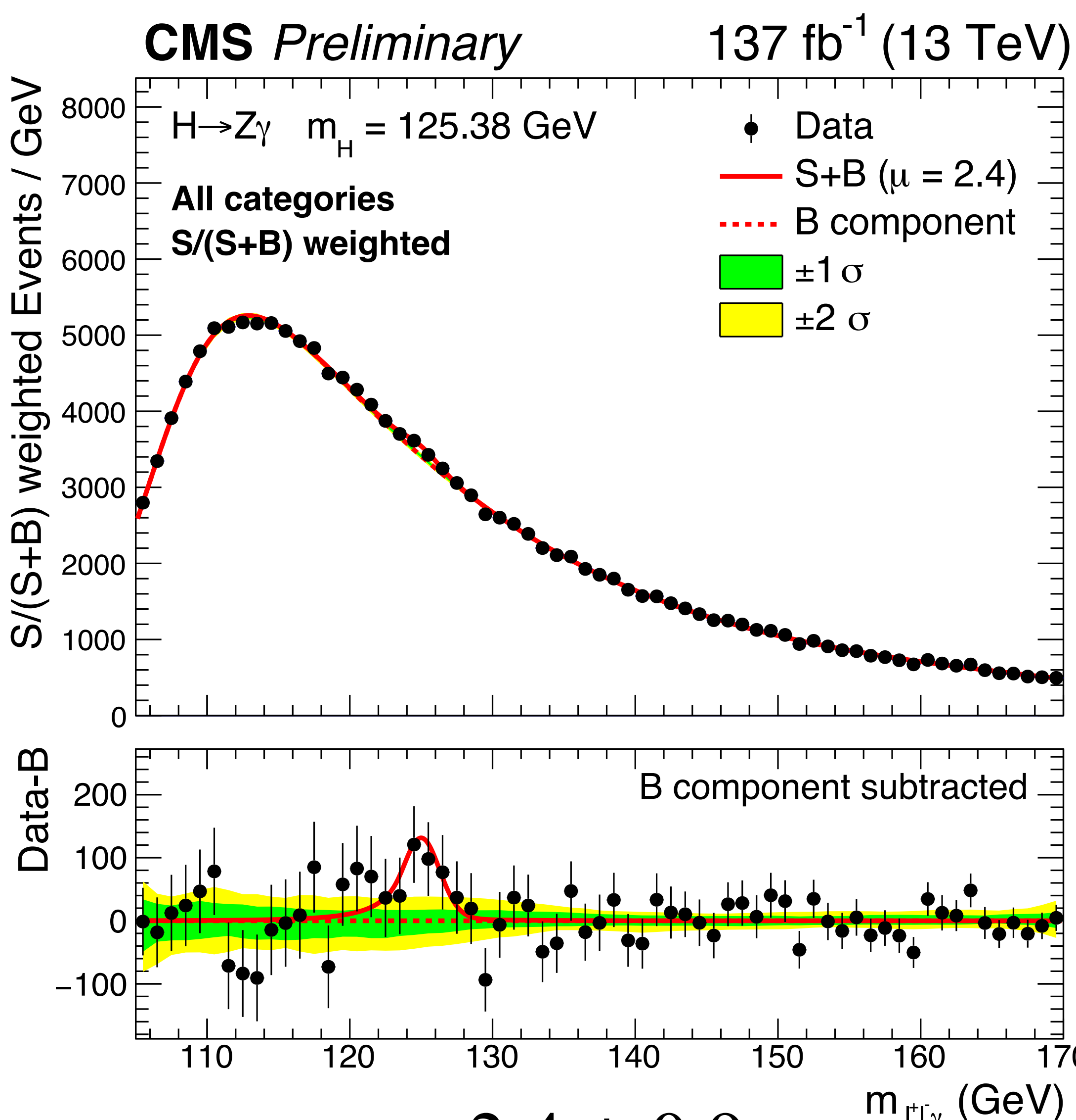
$\sigma/\sigma^{SM} < 26$ (31 exp.)

Search for $H \to Z\gamma$

- $SU(2)_L$ 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) or ggH, VBF (ATLAS)

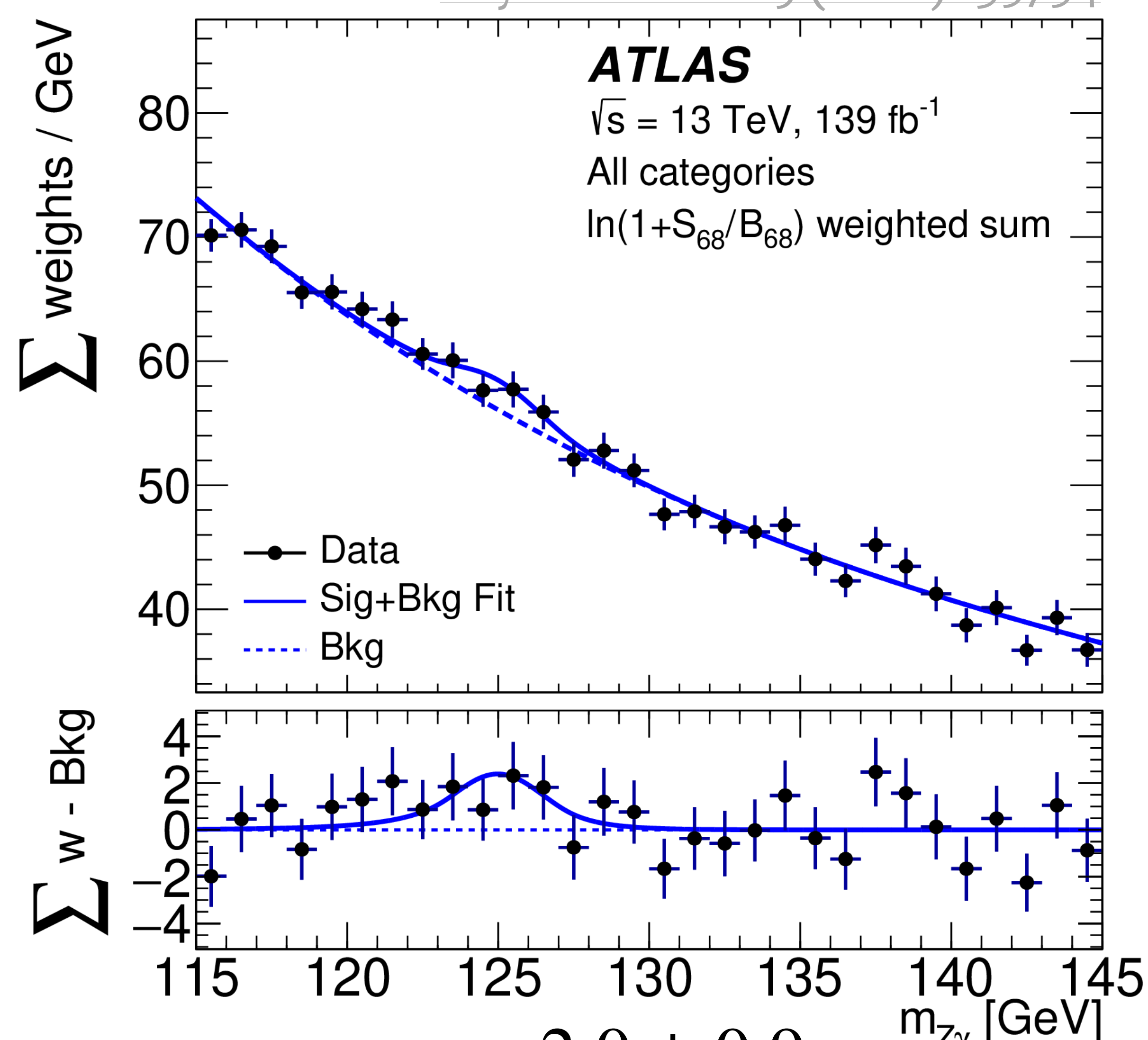
CMS-PAS-HIG-19-014

Phys. Lett. B 809 (2020) 135754



$\mu = 2.4 \pm 0.9$

significance: 2.7σ (1.2σ exp.)



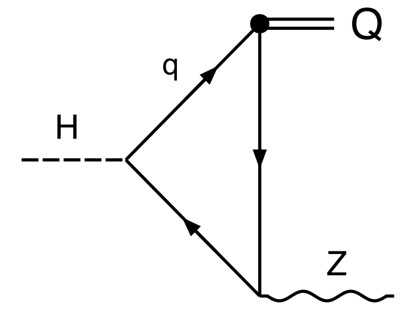
$\mu = 2.0 \pm 0.9$

significance: 2.2σ (1.2σ exp.)

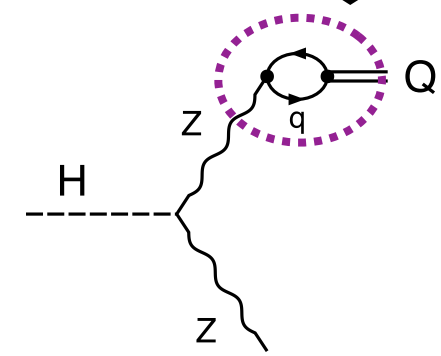
Towards rare decays: quarkonia

New for LP21

- 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, $BR(Z \to QQ) \approx 10^{-12}$



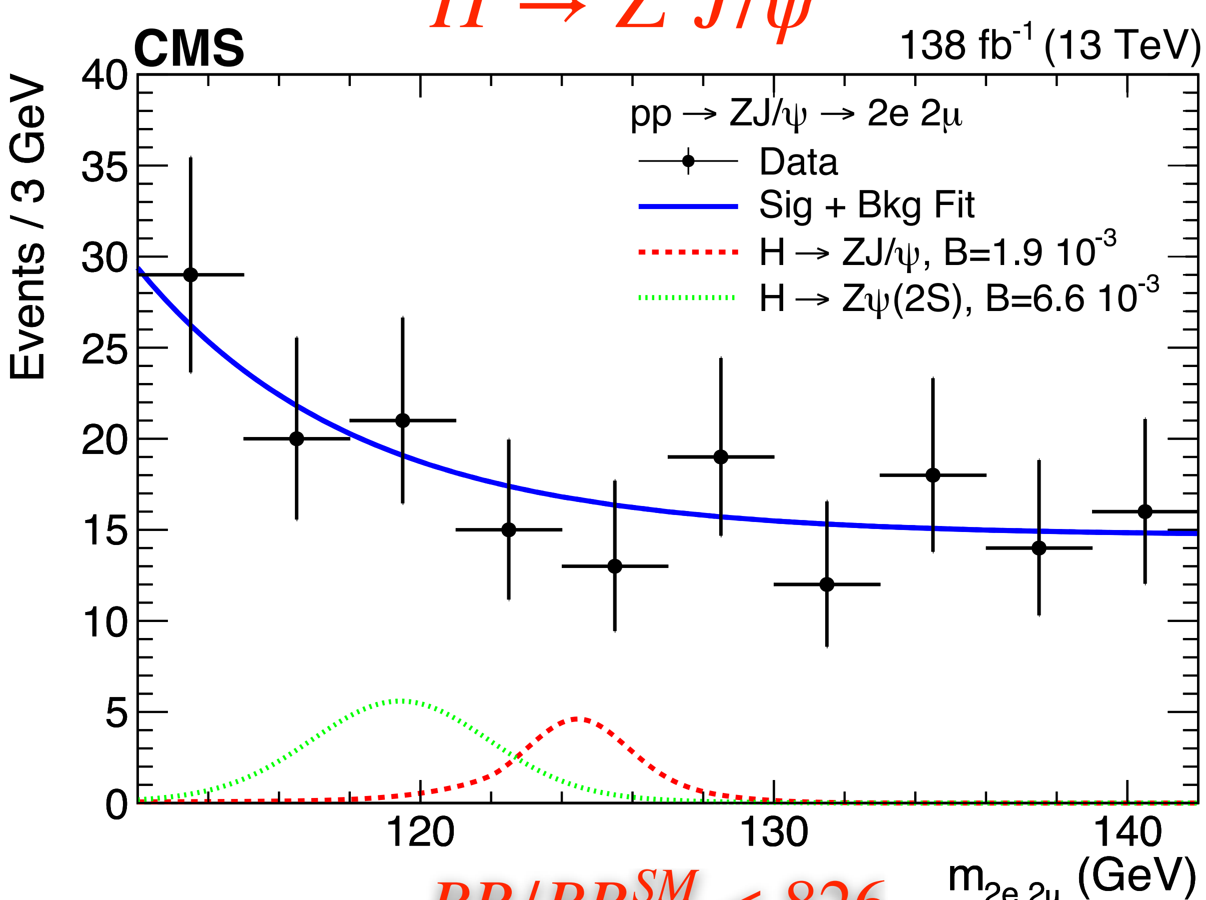
leading order



loop-induced

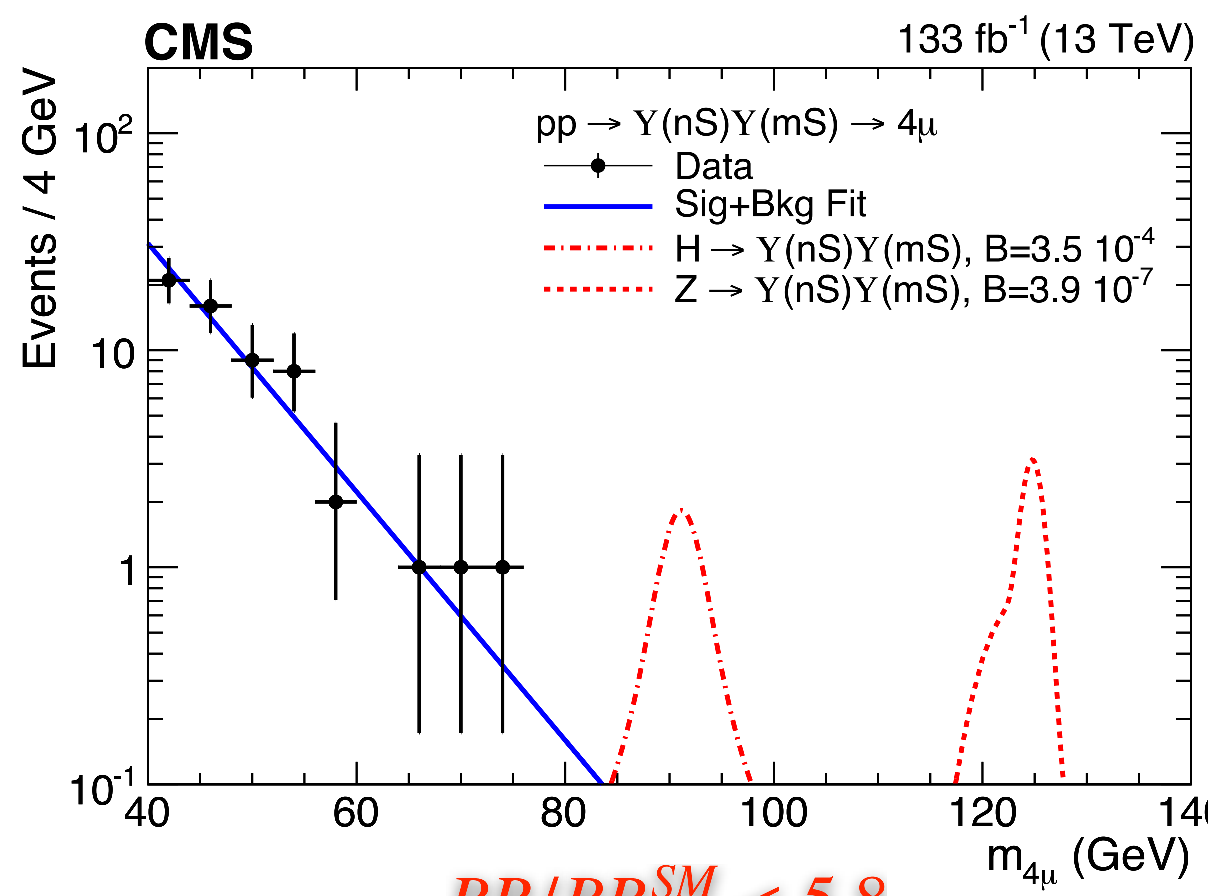
HIG-20-008

$H \to Z\ J/\psi$



$BR/BR^{SM} < 826$

$H \to \Upsilon\ \Upsilon$



$BR/BR^{SM} < 5.8$

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

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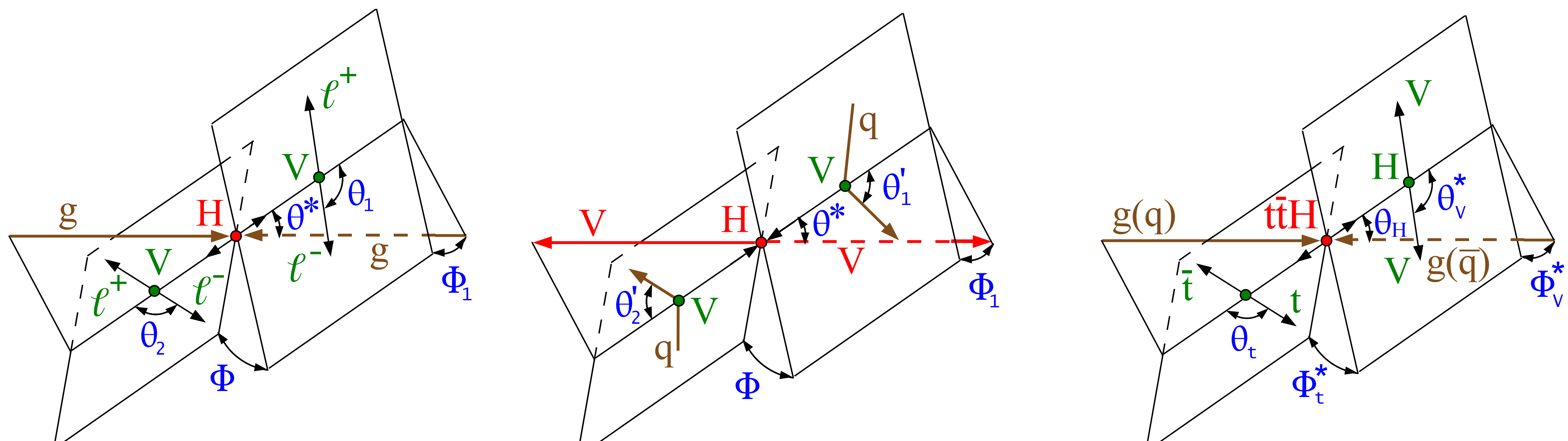


gg→H→VV→4ℓ   qq→VV→H→VV   gg(qq)→ttH→ttVV

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

a_1: SM

a_2: CP even anomalous coupling

a_3: CP odd anomalous coupling

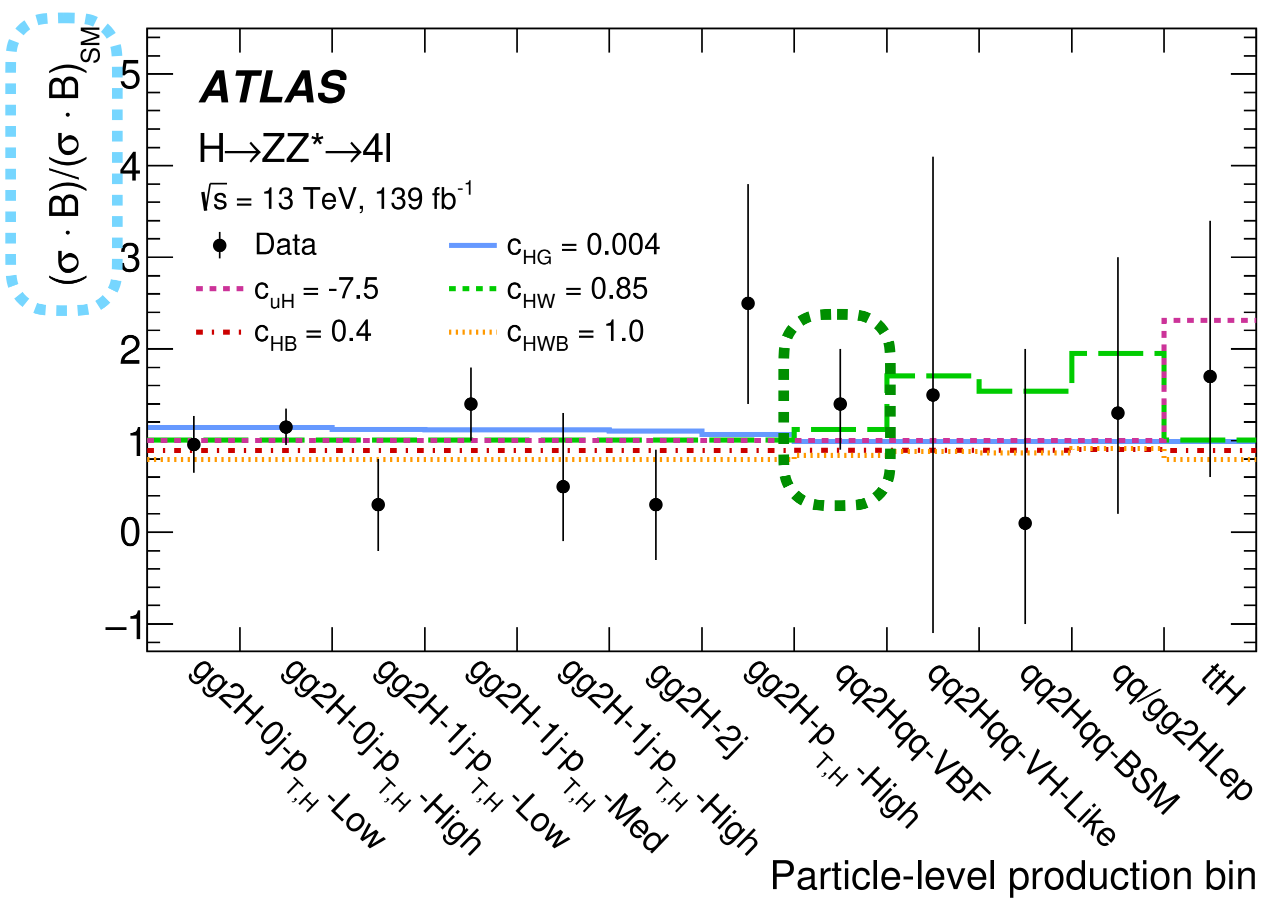
$H \to 4\ell$ AC (ATLAS)

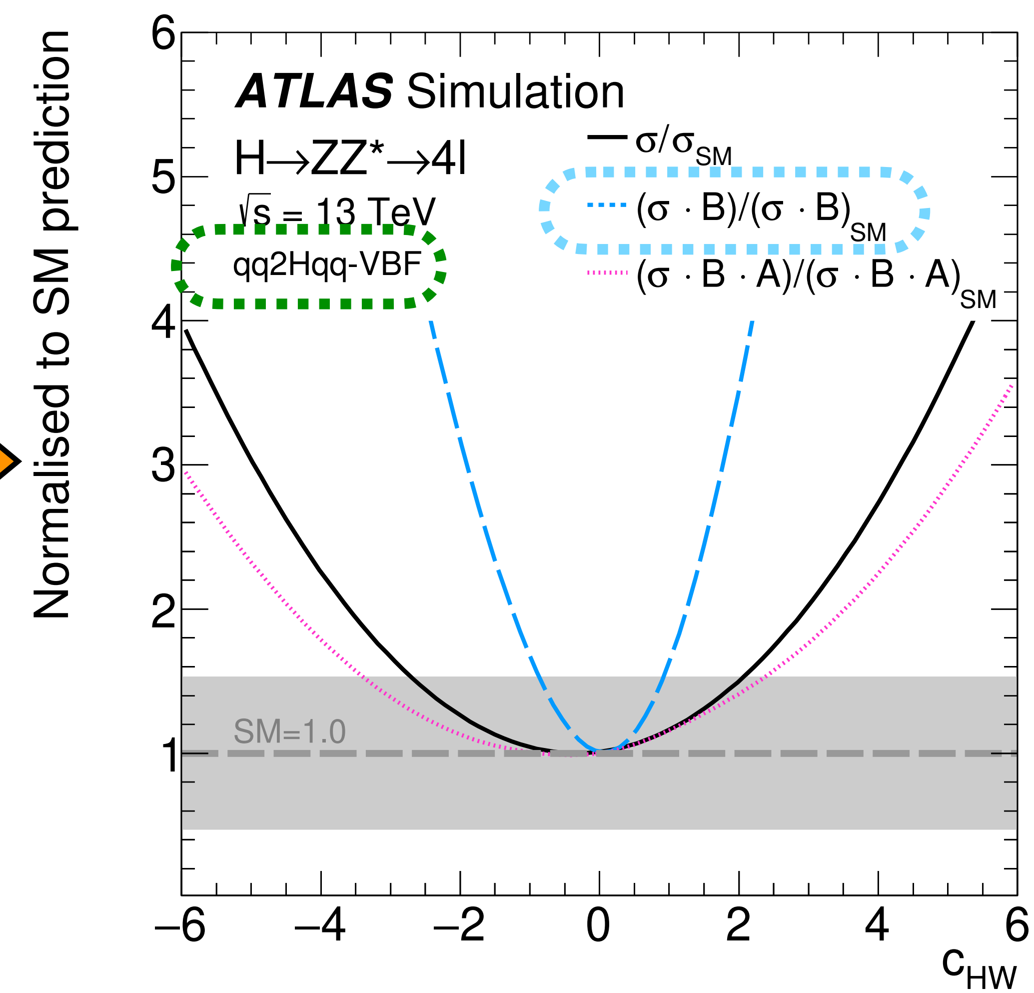
Eur. Phys. J. C 80 (2020) 957

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

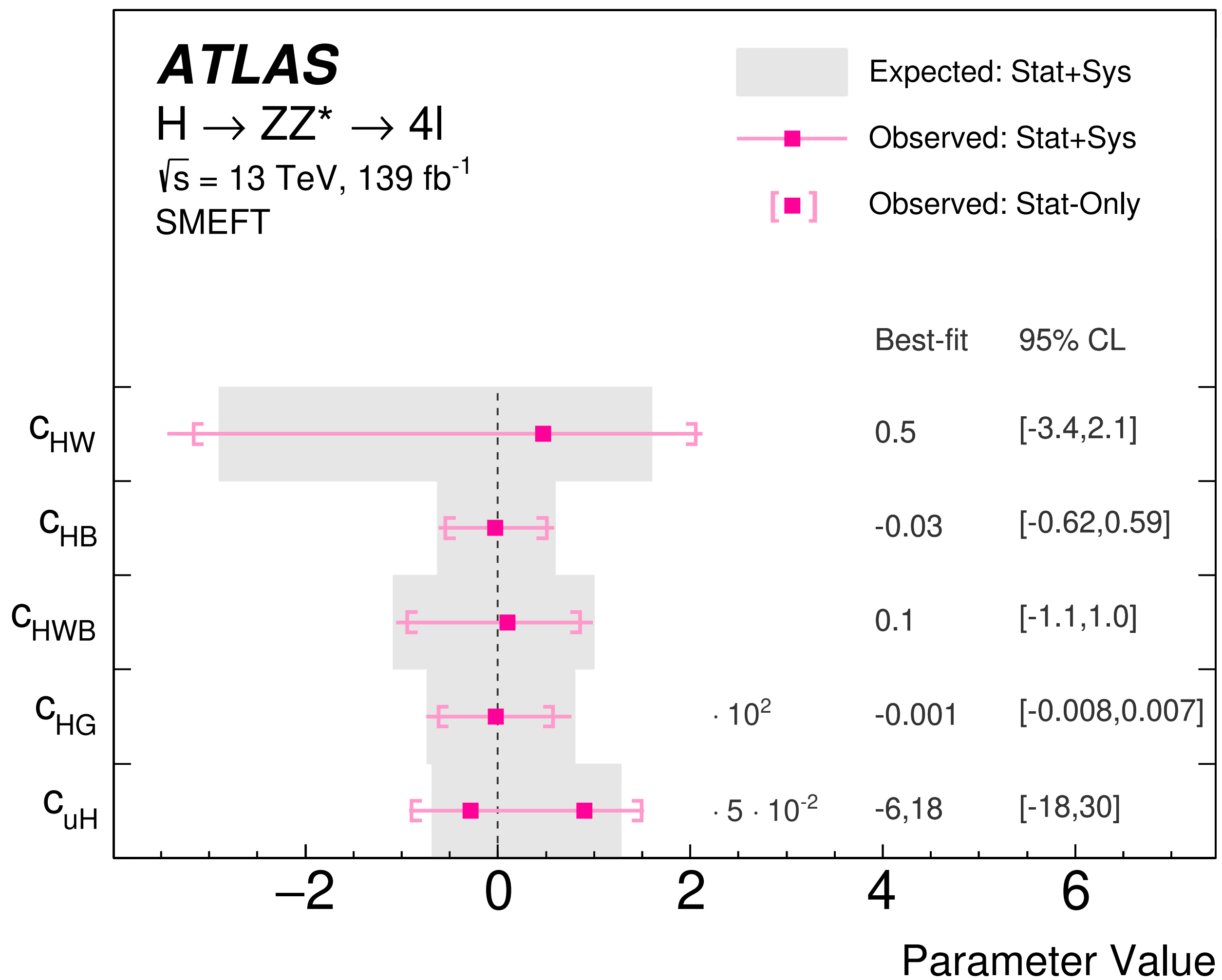
$$\mu_i(c_j) = \frac{\sigma_i^{\text{EFT}}}{\sigma_i^{\text{SM}}}$$

- 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

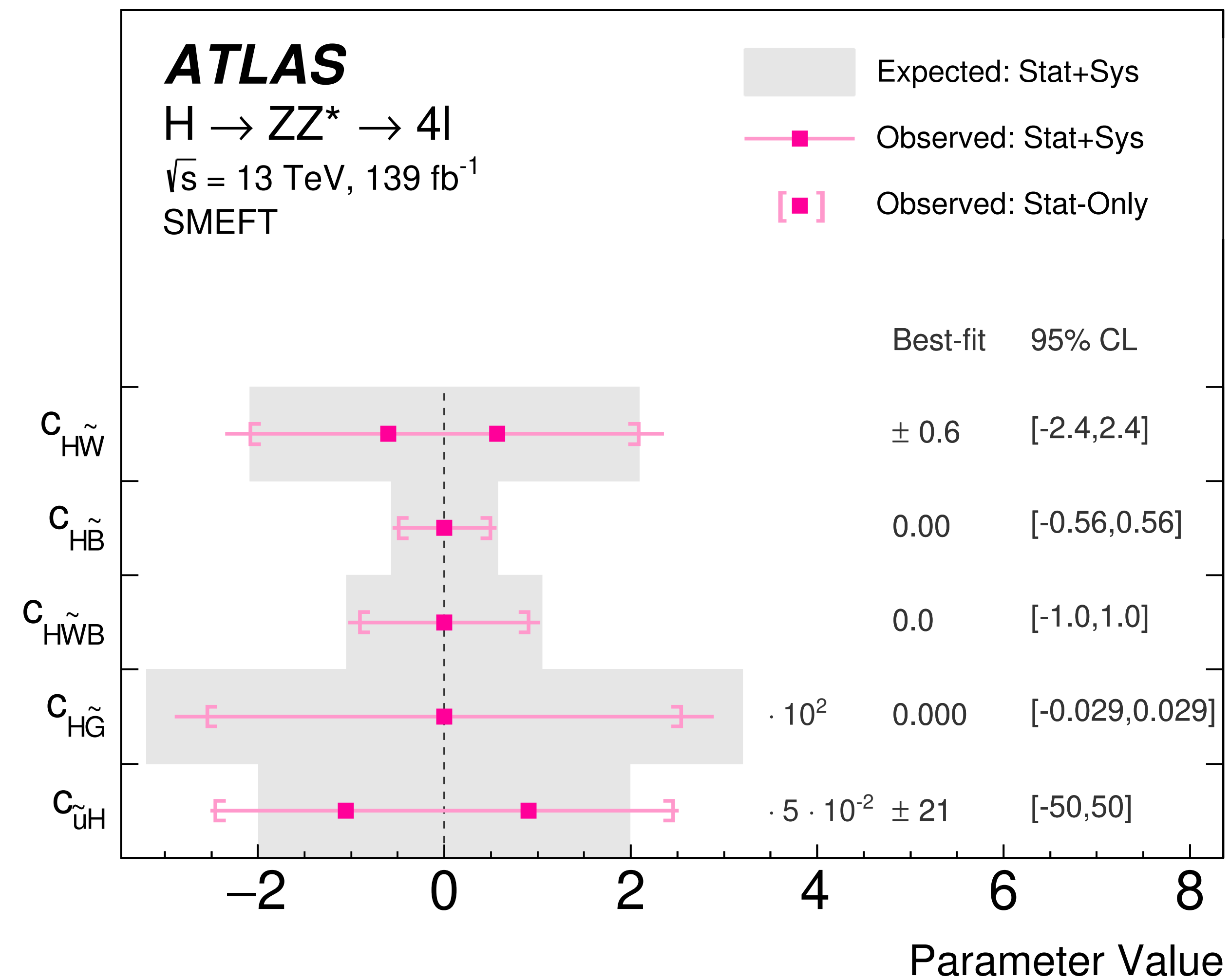




- SMEFT interpretation of the results for CP-conserving parameters: c_{HW}, c_{HB}, c_{HWB} or CP-violating parameters $\tilde{c}_{HW}$, $\tilde{c}_{HB}$, $\tilde{c}_{HWB}$



CP-even
Wilson coefficients



CP-odd
Wilson coefficients

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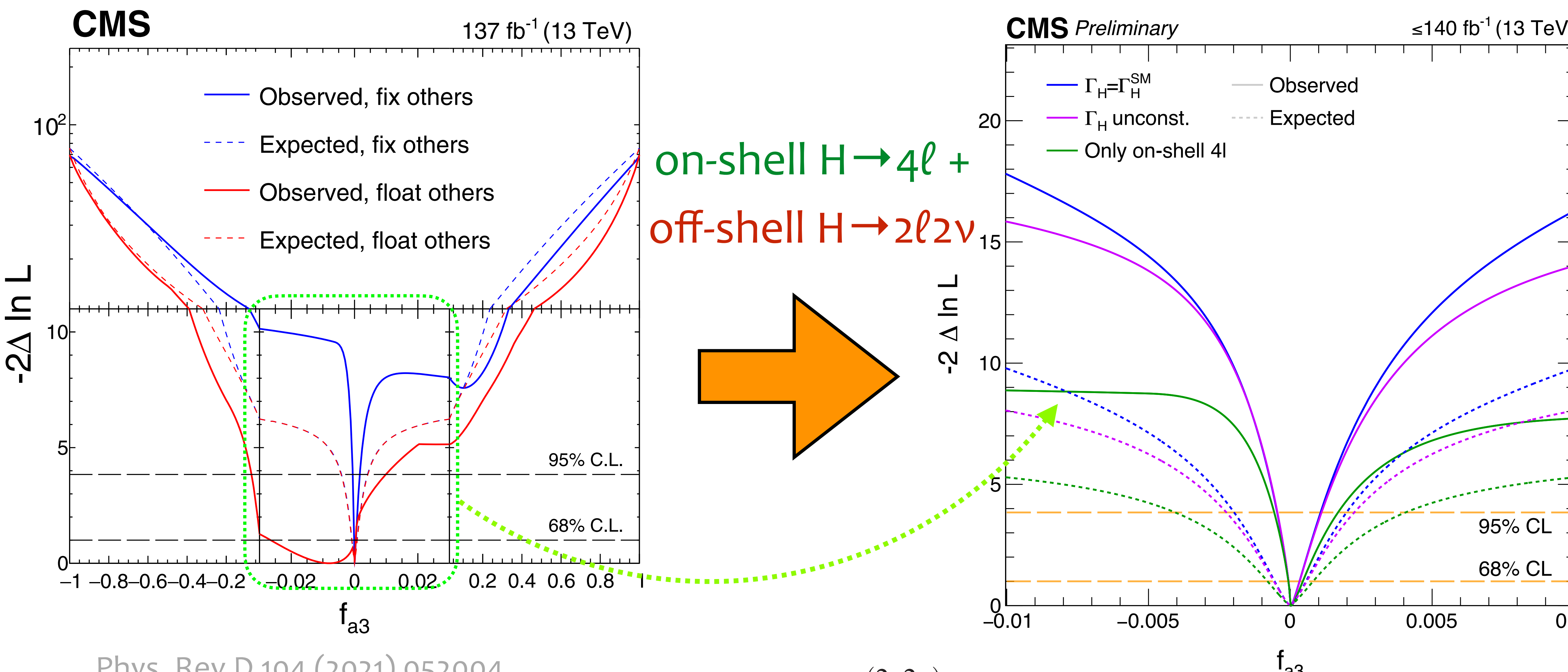
$H \to 4\ell$ AC (CMS)

- Dedicated analysis for anomalous couplings to probe 3 independent HVV and Hff+Hgg 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}

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

Yukawa $t\bar{t}H$ couplings

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

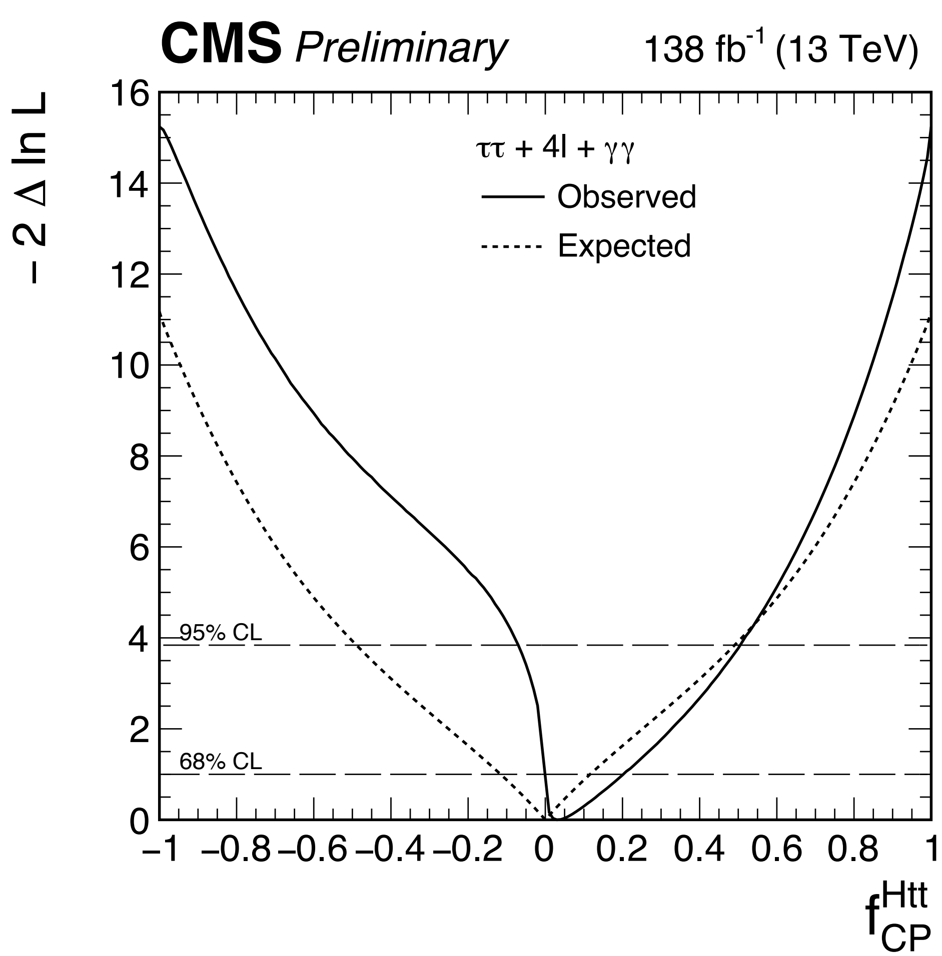
$$A(Hff) = -\frac{m_f}{v}\bar{\psi}_f(\kappa_f + i\tilde{\kappa}_f\gamma_5)\psi_f$$

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

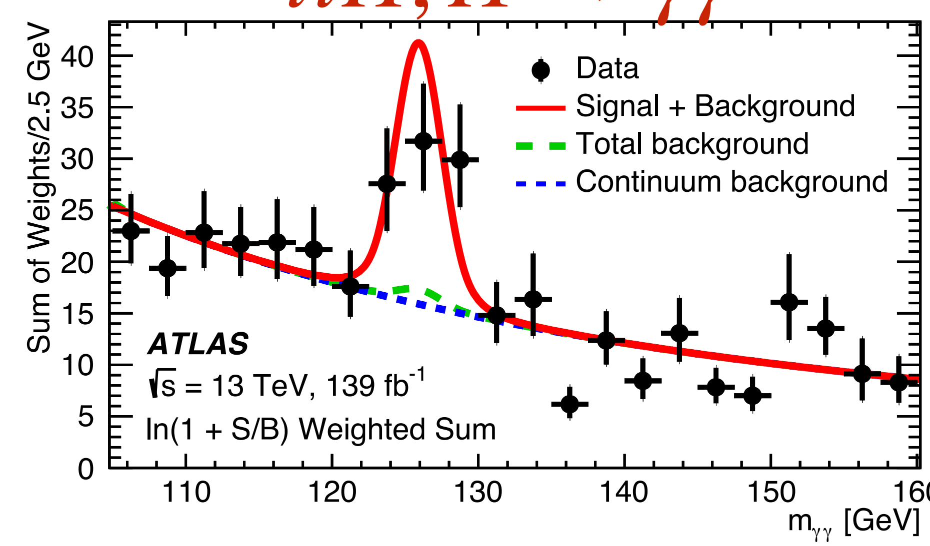
Phys. Rev. Lett. 125 (2020) 061802

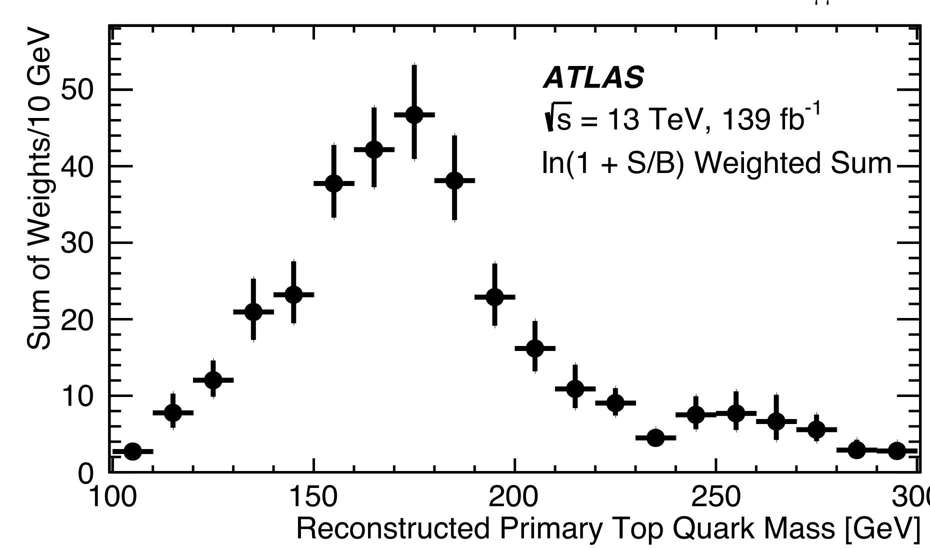
- BDT dedicated to ttH, tH CP with top-diphoton kinematics (ATLAS) or ttH CP MVA (CMS) in multiple categories
  - CMS combined ttH $H \to \gamma\gamma$, $H \to 4\ell$ and $H \to \tau\tau$

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



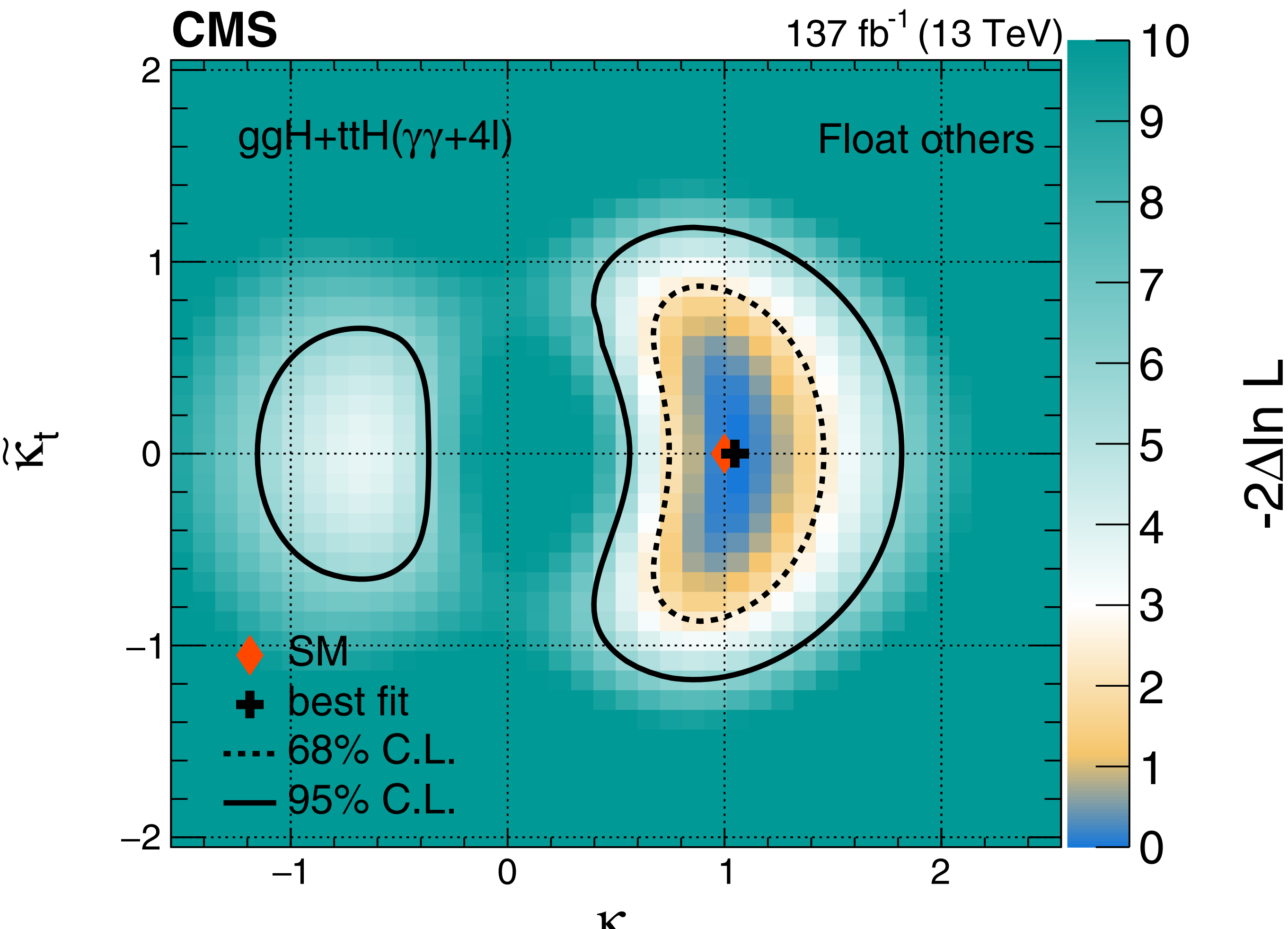
$t\bar{t}H, H \to \gamma\gamma$





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 $\tilde{\kappa}_t$



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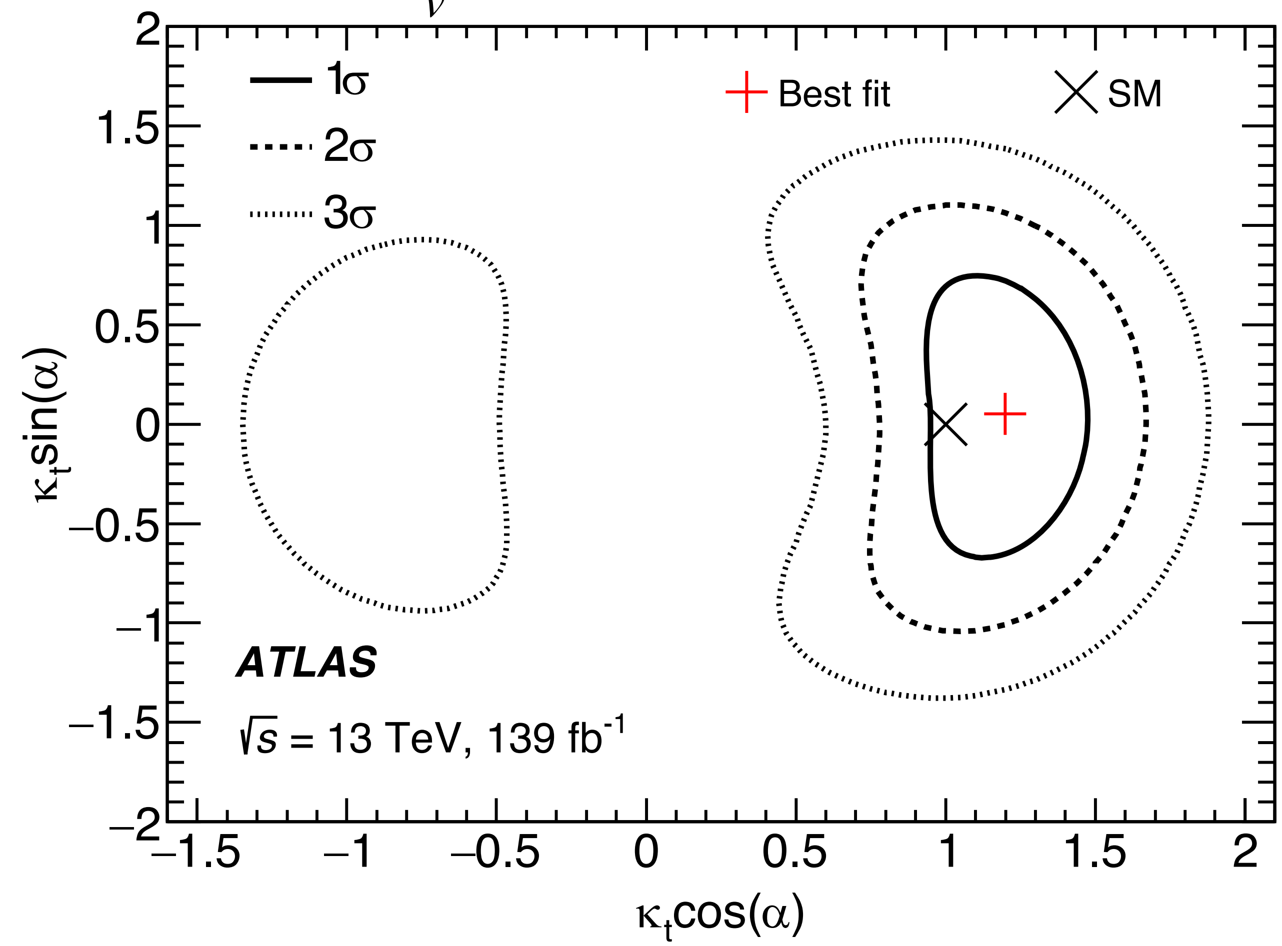
N.B. : sligtly different notation:

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$



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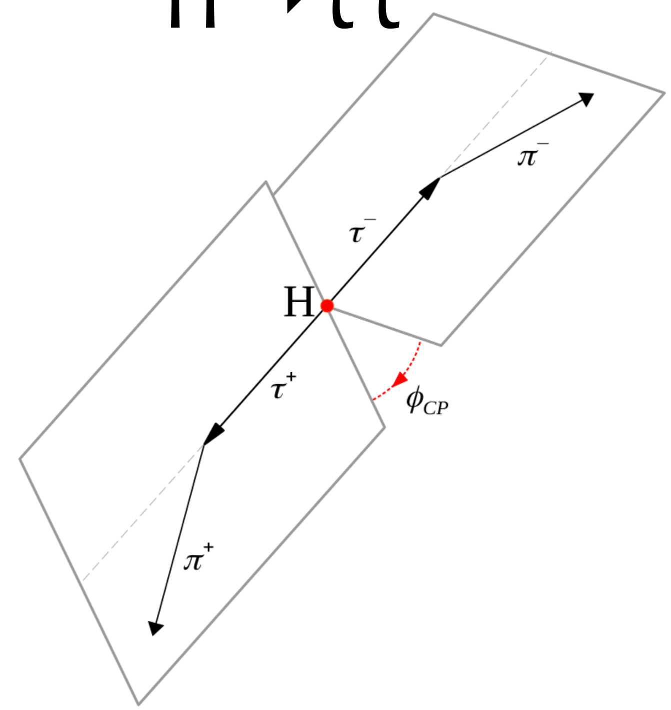
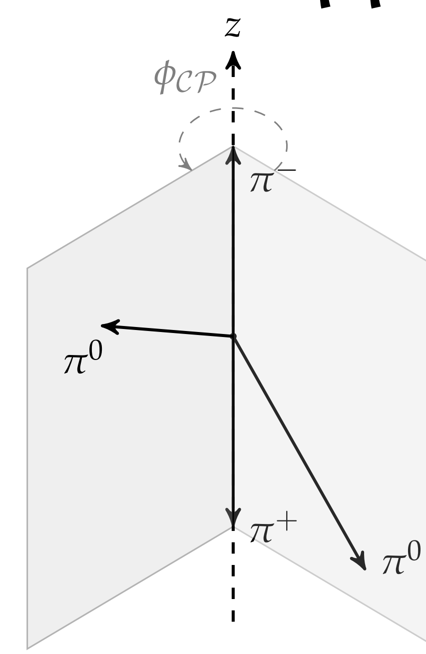
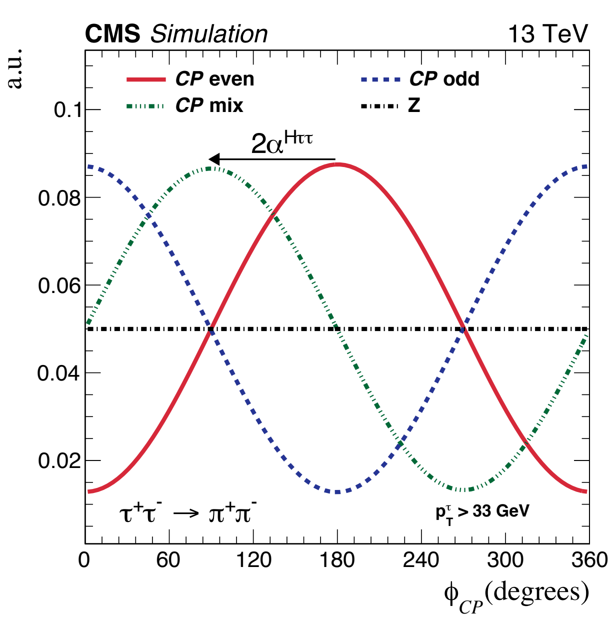
gluon fusion pointlike couplings $c_{gg}, \tilde{c}_{gg}$ profiled

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

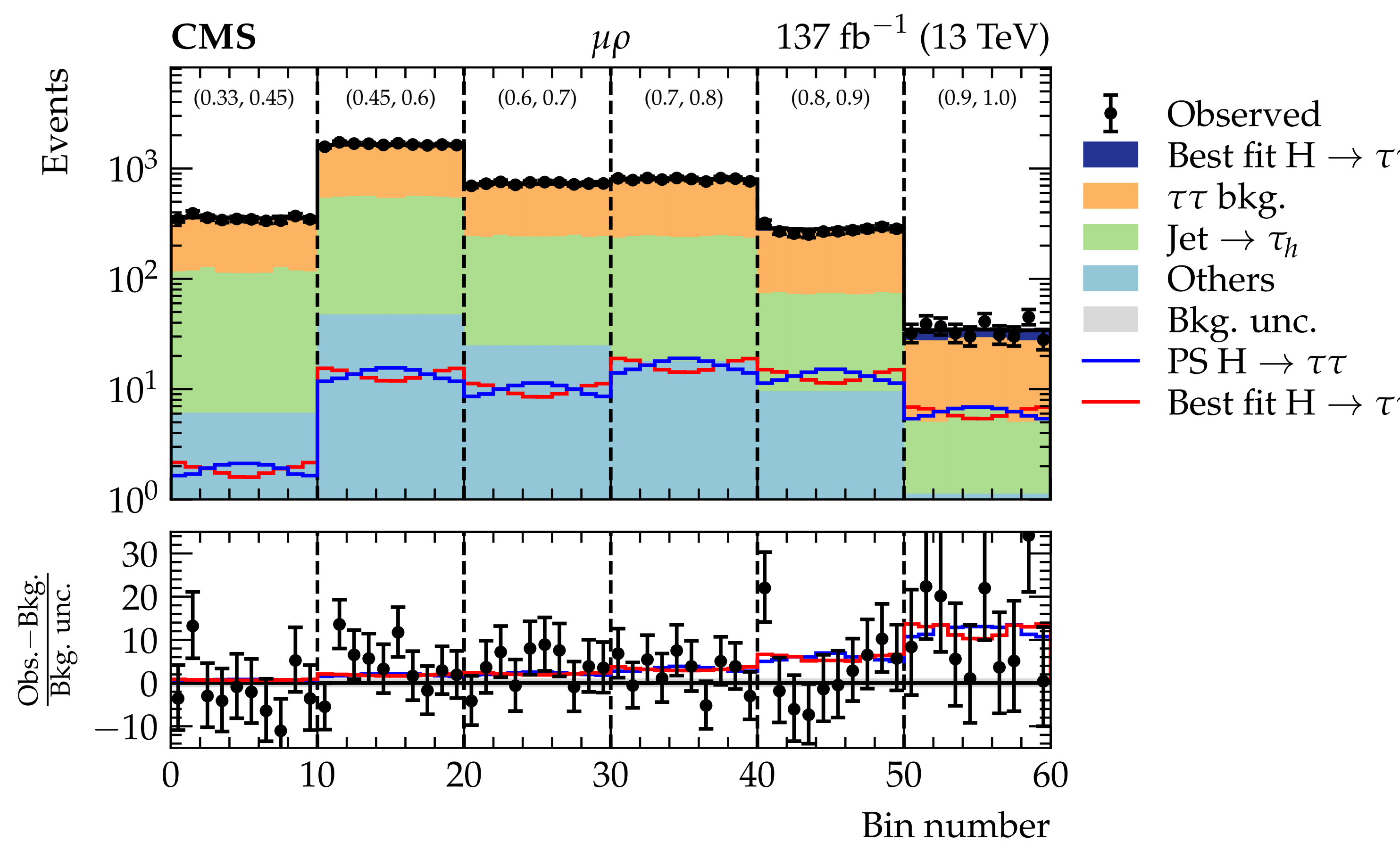
- Full Run2 analysis to measure CP odd/even mixing in $H \to \tau\tau$
  - **Use ~70% of the τ BR:** $H \to \tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$ with τ_h decays to $\pi^\pm$, $\rho^\pm(\pi^\pm\pi^0)$, $a1^\pm(\pi^\pm\pi^0\pi^0)$, $a_1^\pm(\pi^\pm\pi^+\pi^-)$
  - estimate the τ plane from multiple 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





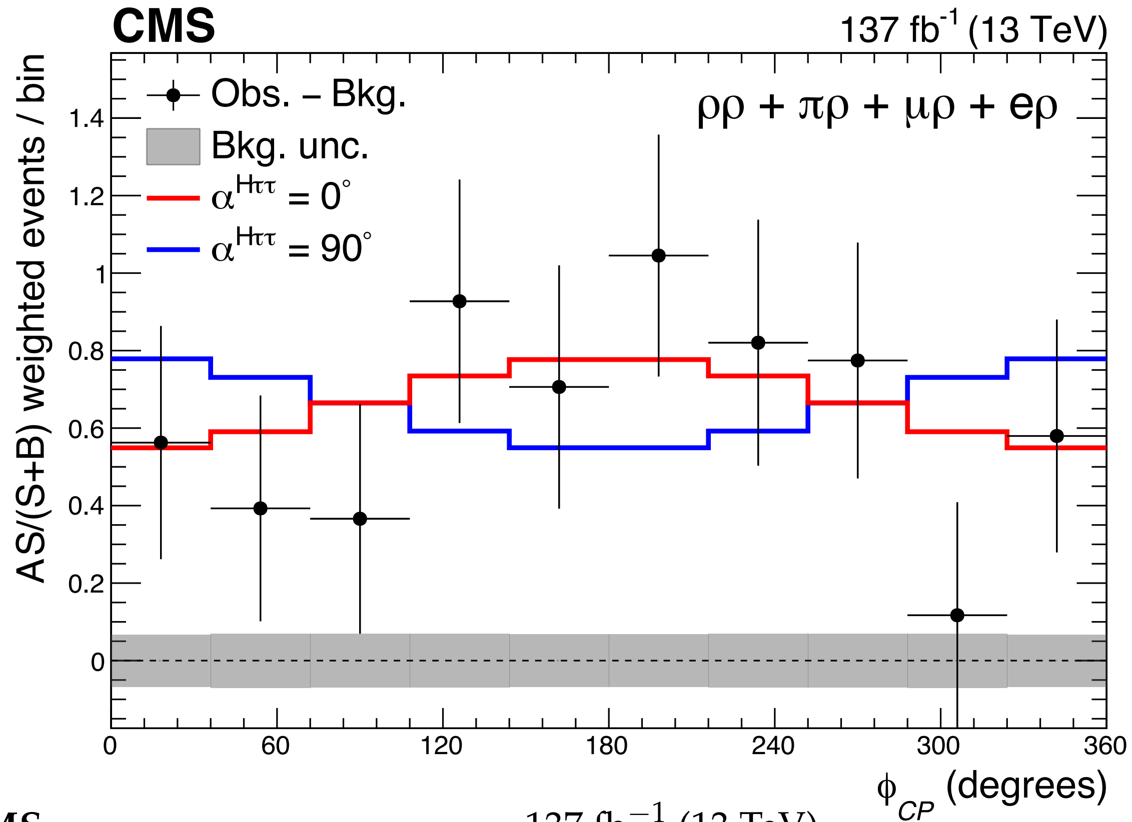


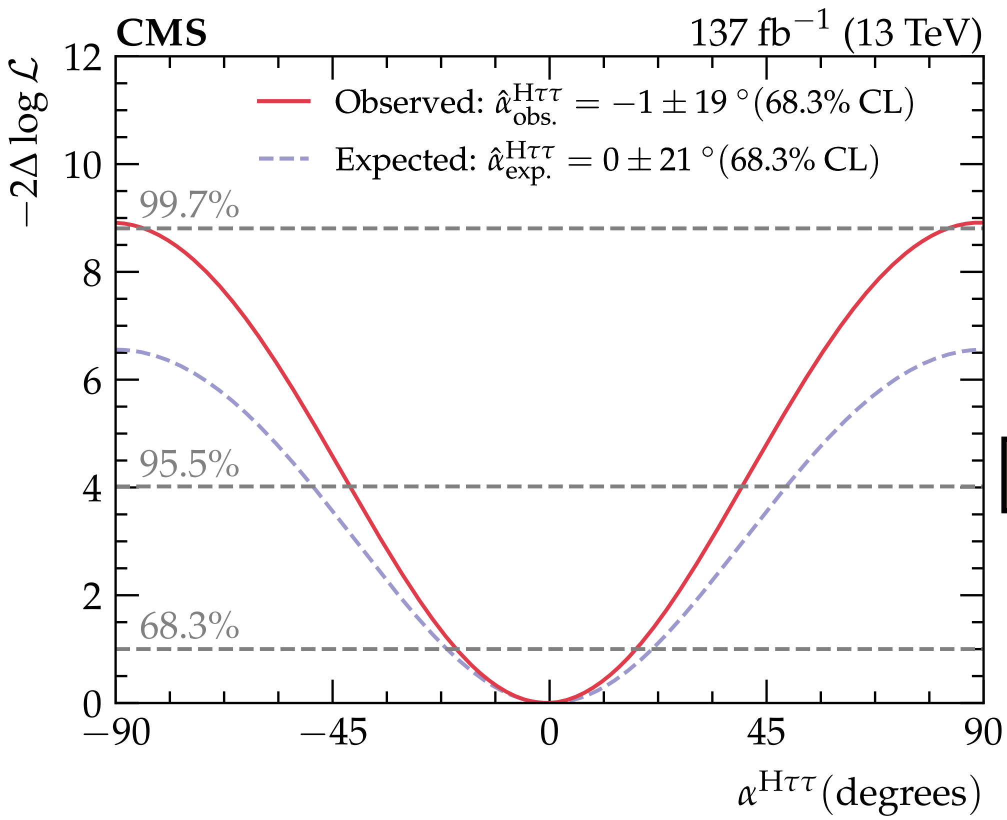
φ_{CP} binned in slices of MVA signal score for each decay mode



$H \to \tau\tau$ CP results

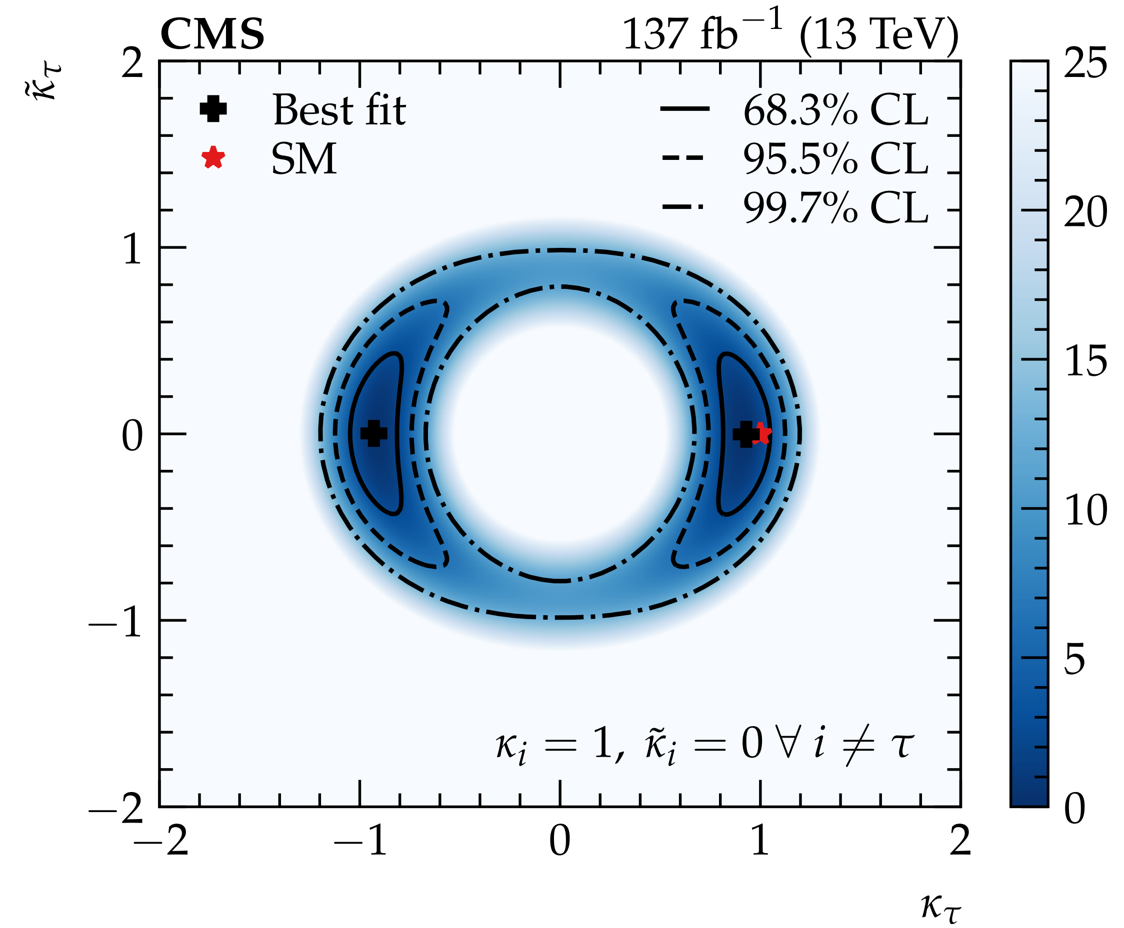
- Most sensitive final states: μρ, ρρ, πρ





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

τ Yukawa coupling



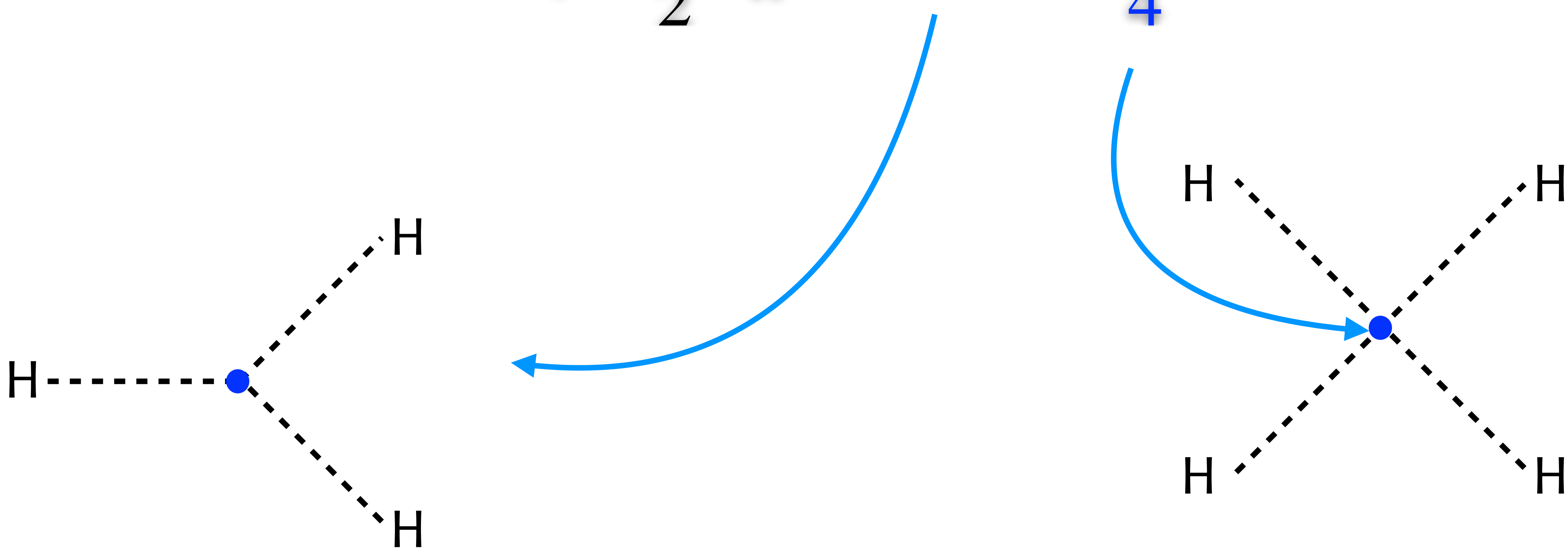
Pseudoscalar hypothesis ($\alpha^{H\tau\tau} = \pm 90°$) excluded at 3.0σ vs scalar ($\alpha^{H\tau\tau} = 0°$)

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

Higgs self-coupling

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

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

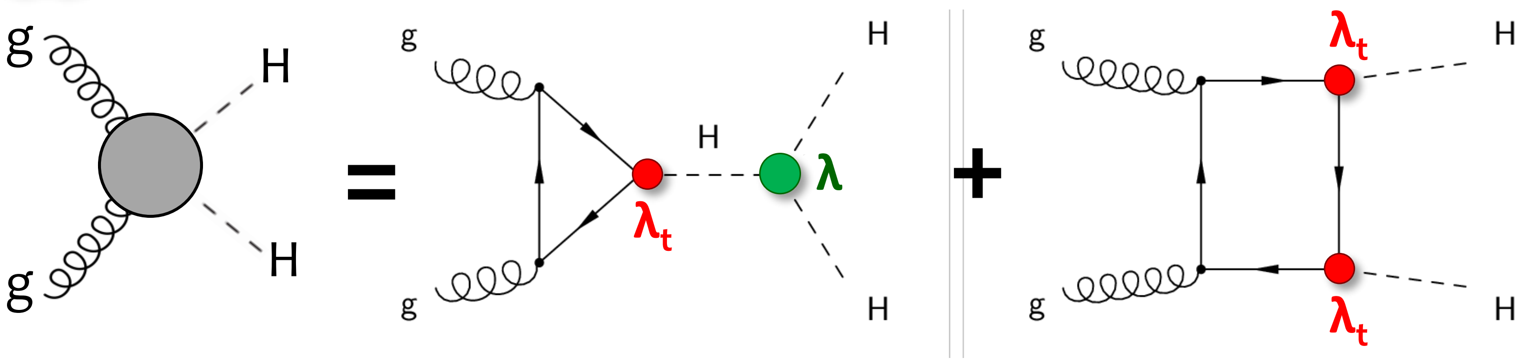


HH production

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

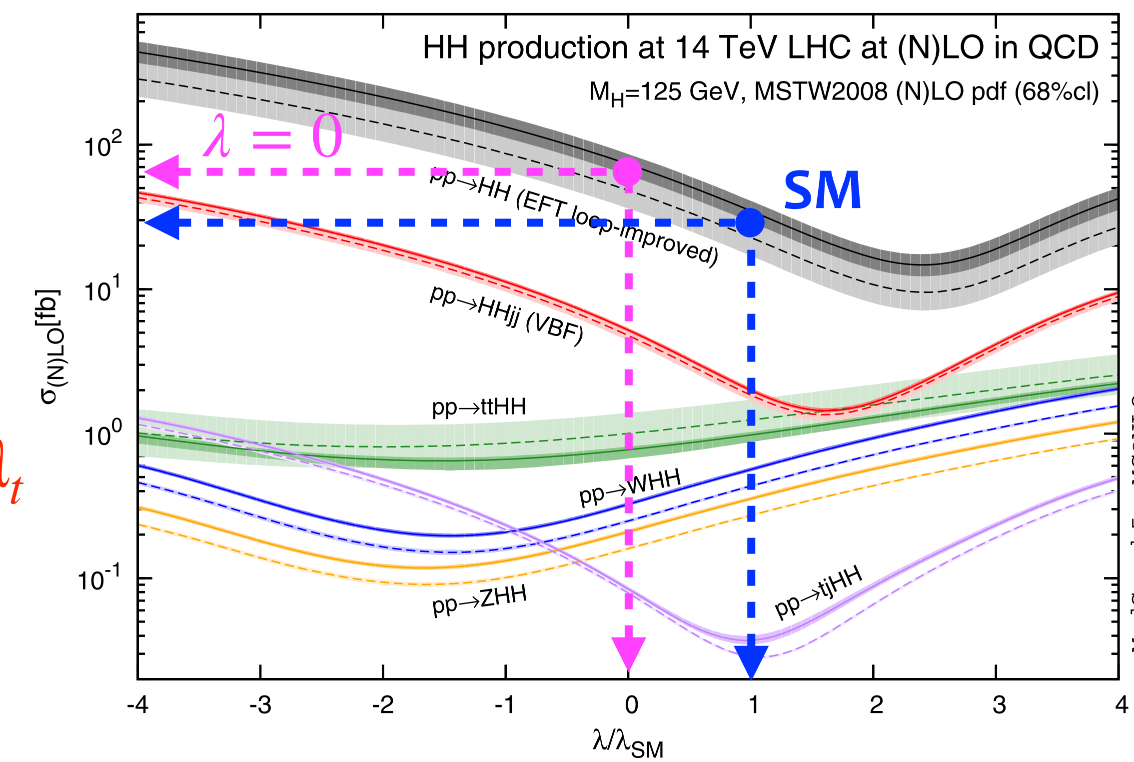
PLB 732 (2014) 142-149

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

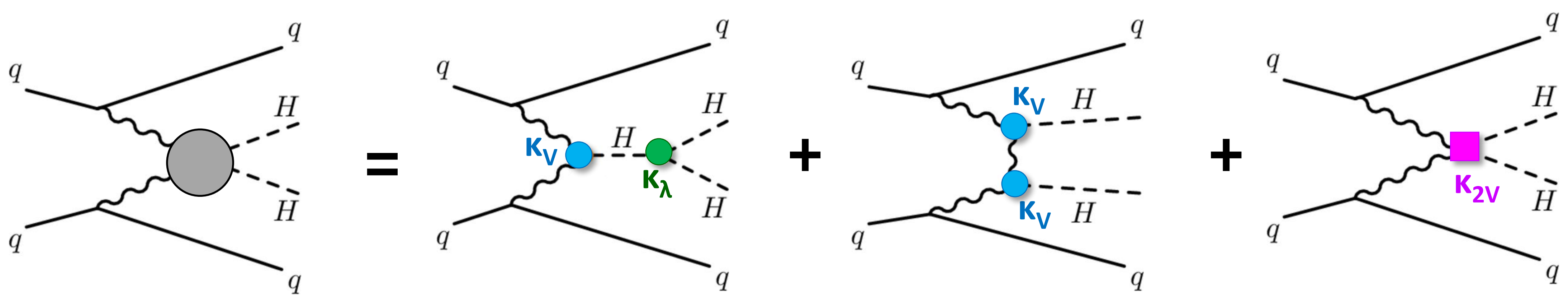


self-coupling λ Higgs-top coupling λ_t

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



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

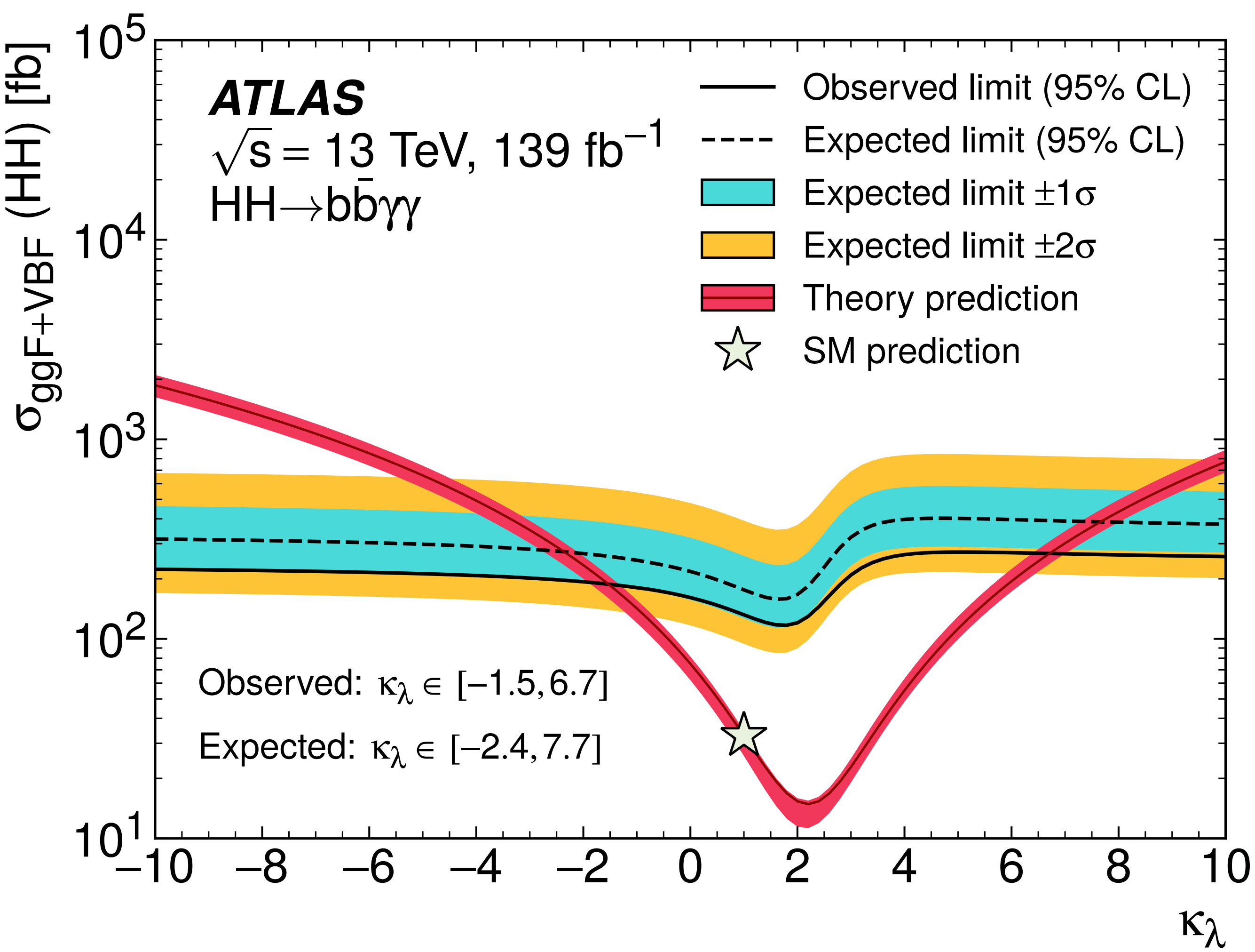


self-coupling λ HHH and HVV single H coupling κ_λ

HHVV quartic coupling
only in VBF production

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

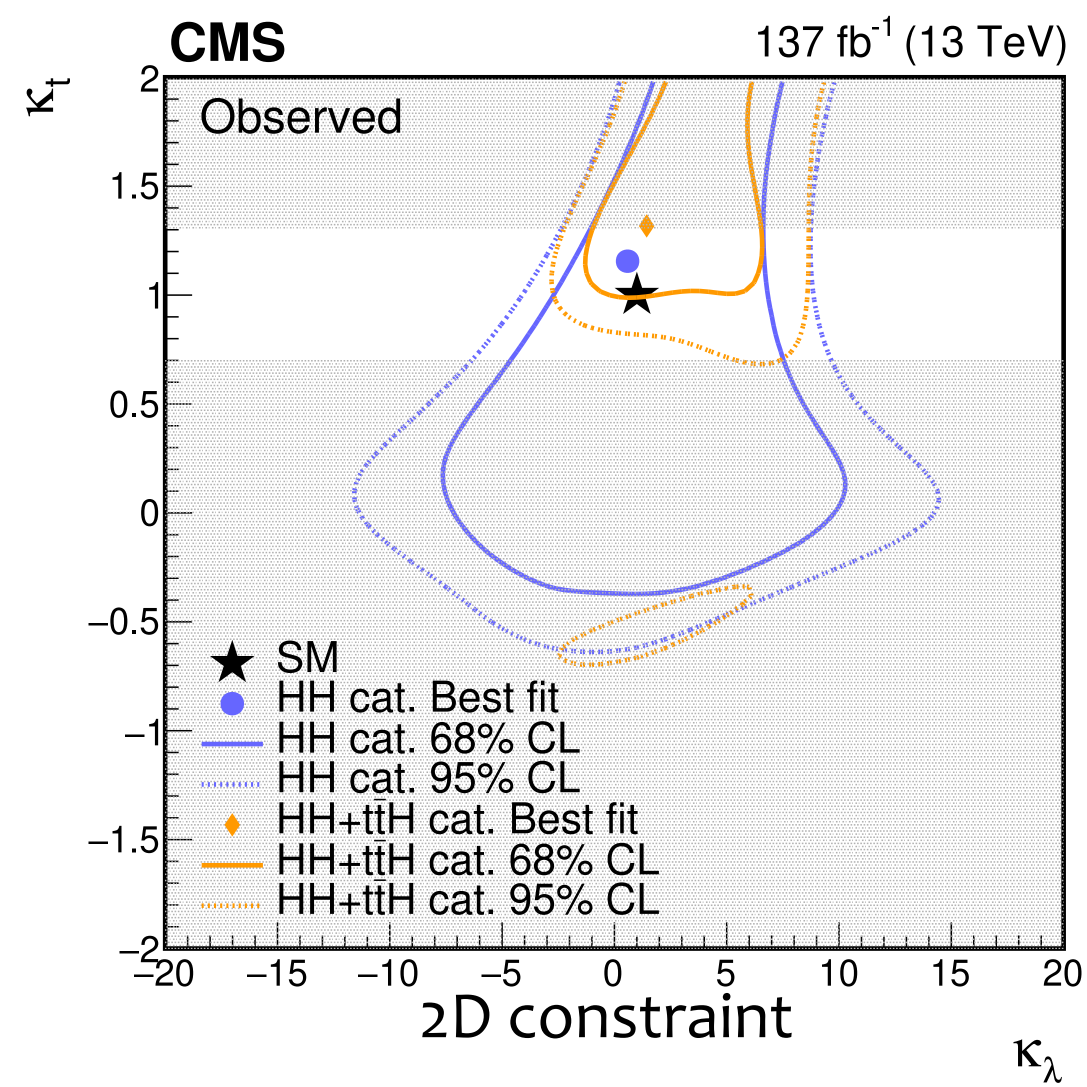
- Phase space of 2 photons and 2 b-tagged jets, with $m_{\gamma\gamma}$ around 125 GeV
  - both CMS and ATLAS also look for a resonant $X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$
  - bkgs: $\gamma\gamma + jets$ from data sidebands and single Higgs from MC fullsim
- ATLAS limit: 4.2 (5.7 exp) $\times\, \sigma_{SM}^{HH}$
- CMS limit: 7.7 (5.2 exp) $\times\, \sigma_{SM}^{HH}$



Constraint on trilinear coupling at 95% CL:

-1.5 < κ_λ <6.7

arXiv:2112.11876



2D constraint

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

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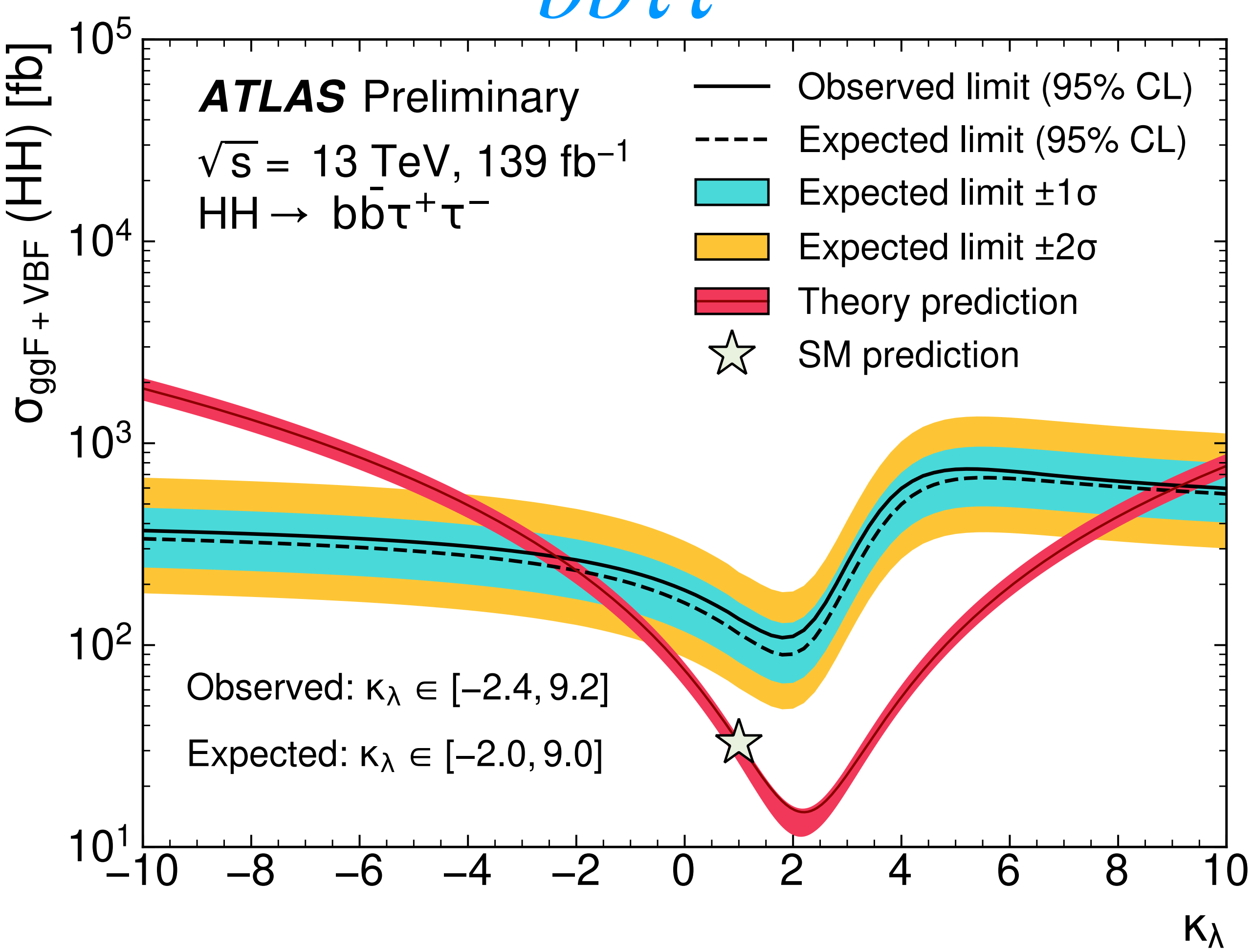
$HH \to b\bar{b}\tau^+\tau^-$

ATLAS-CONF-2021-030

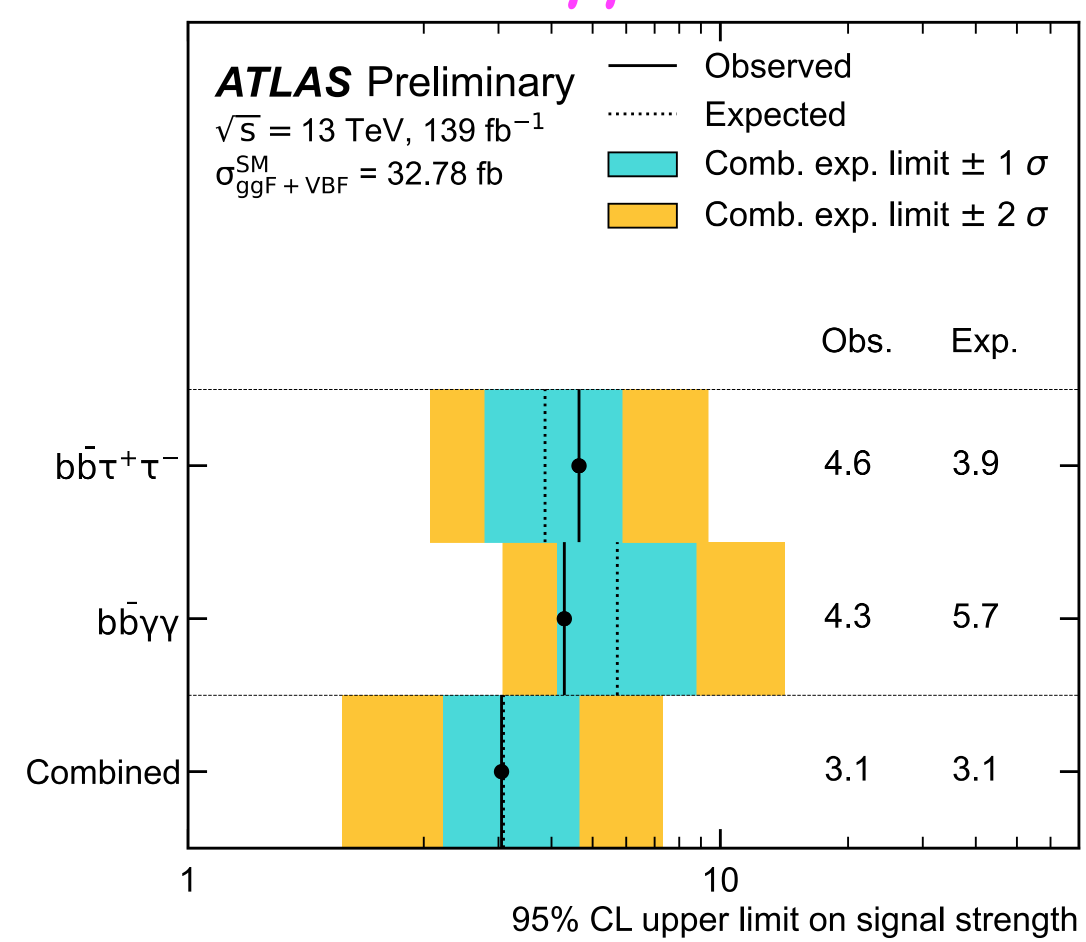
- ATLAS searches for $HH \to b\bar{b}\tau\tau$ using $\tau_h\tau_h$, $\tau_h\tau_e$, $\tau_h\tau_\mu$
  - 2 b-tagged jets categorized in di-τ system decay mode
    - bkgs from $t\bar{t}$ and Z+heavy flavor jets from fullsim MC
    - jets faking τ_h in $t\bar{t}$ and QCD estimated from data

$b\bar{b}\tau\tau$



$\sigma_{HH}/\sigma_{HH}^{SM} < 4.6$ (obs), 3.9 (exp)

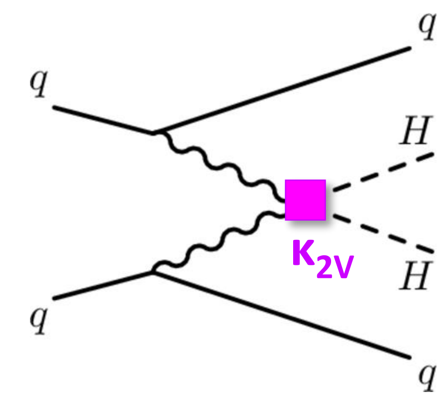
$b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ combination

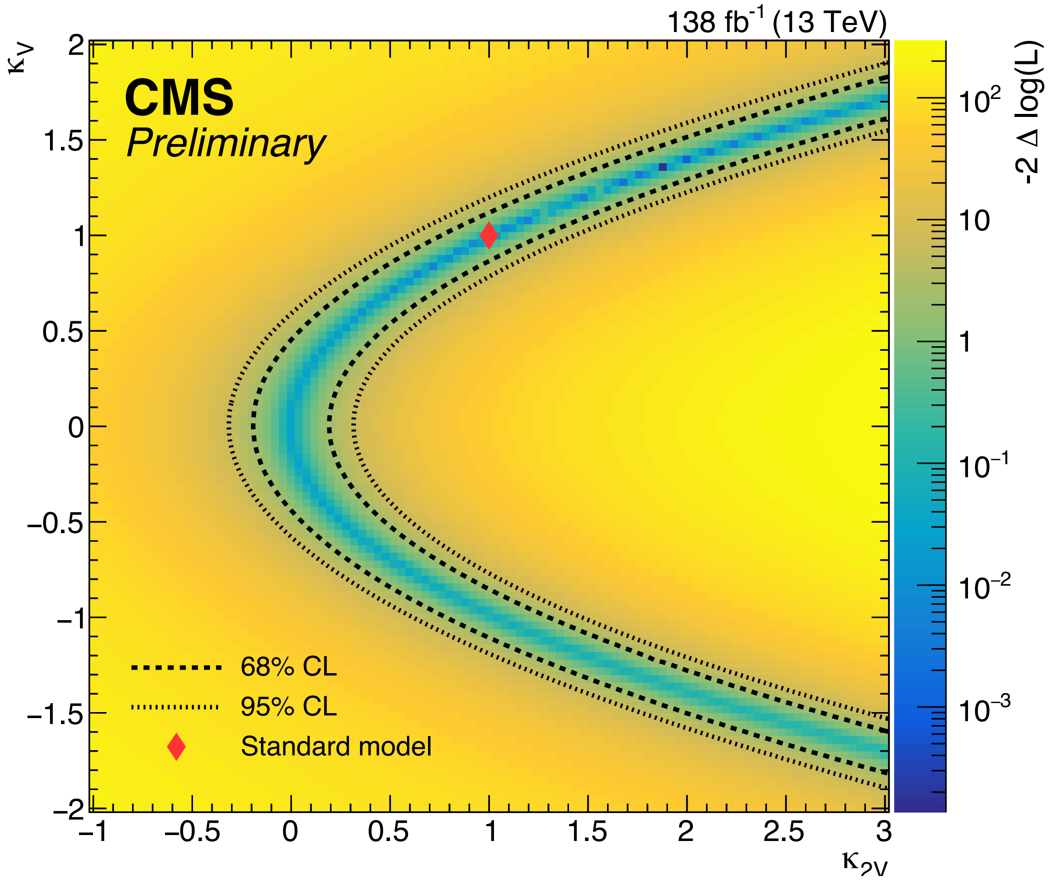


$\sigma_{HH}/\sigma_{HH}^{SM} < 3.1$ (obs), 3.1 (exp)

$HH \to 4b$

- 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:
  - SM sensitivities $\sigma^{HH}/\sigma^{HH}_{SM} < 6.9$ (ATLAS), 7.3 (CMS)
- **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





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

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

CMS-PAS-HIG-20-005

CMS-PAS-B2G-21-001

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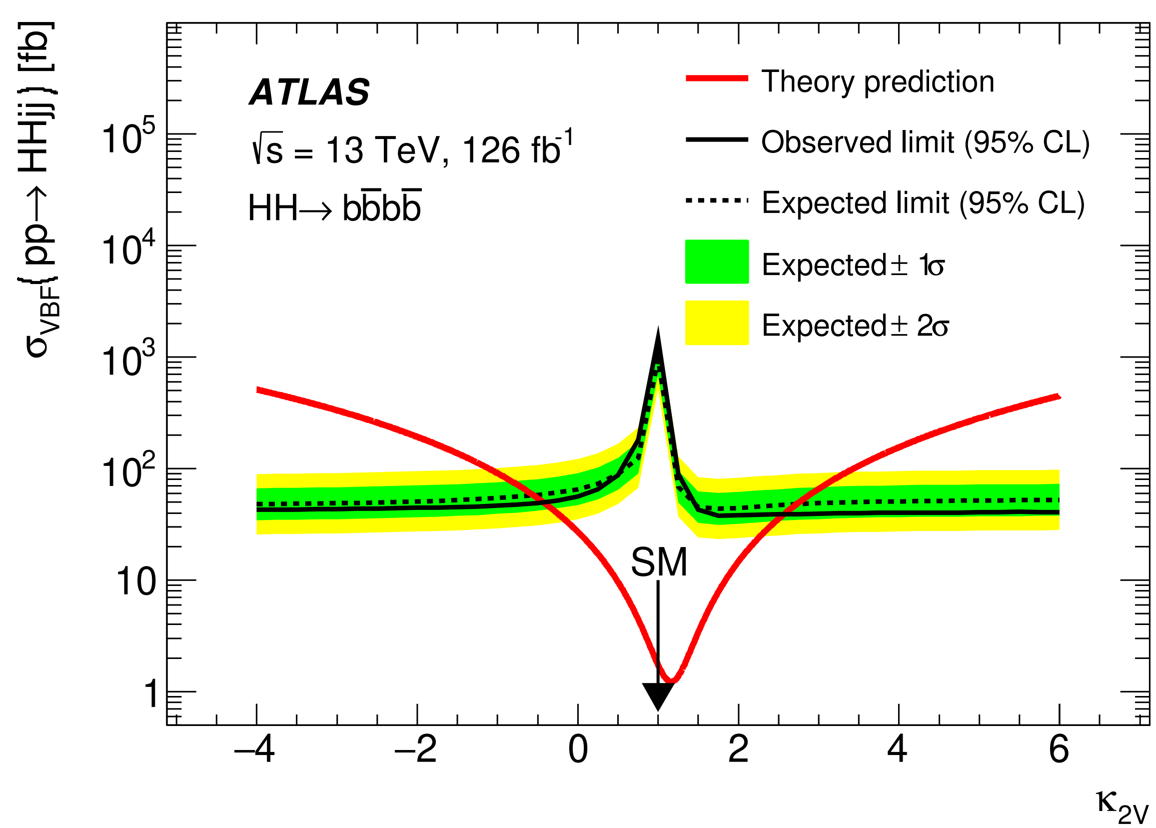
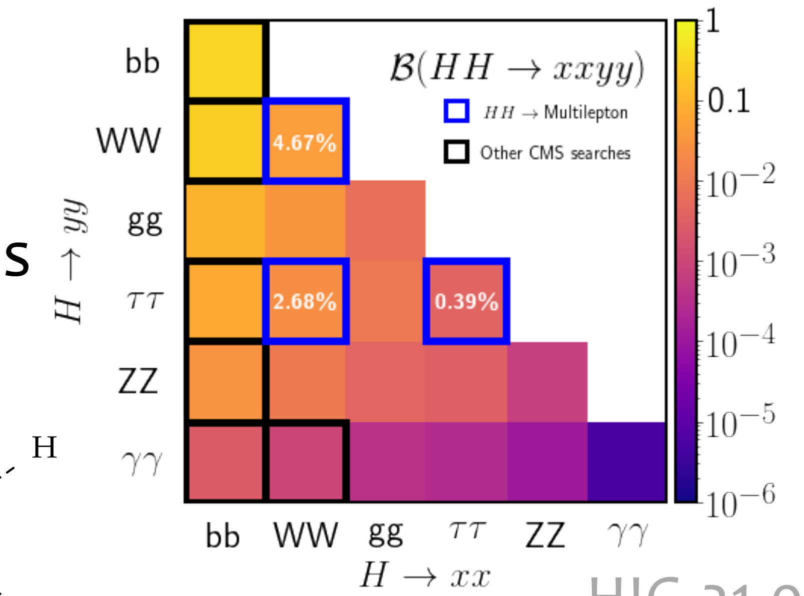
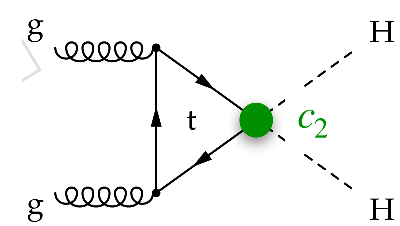


$-0.56 < \kappa_{2V} < 2.89$ @ 95% CL

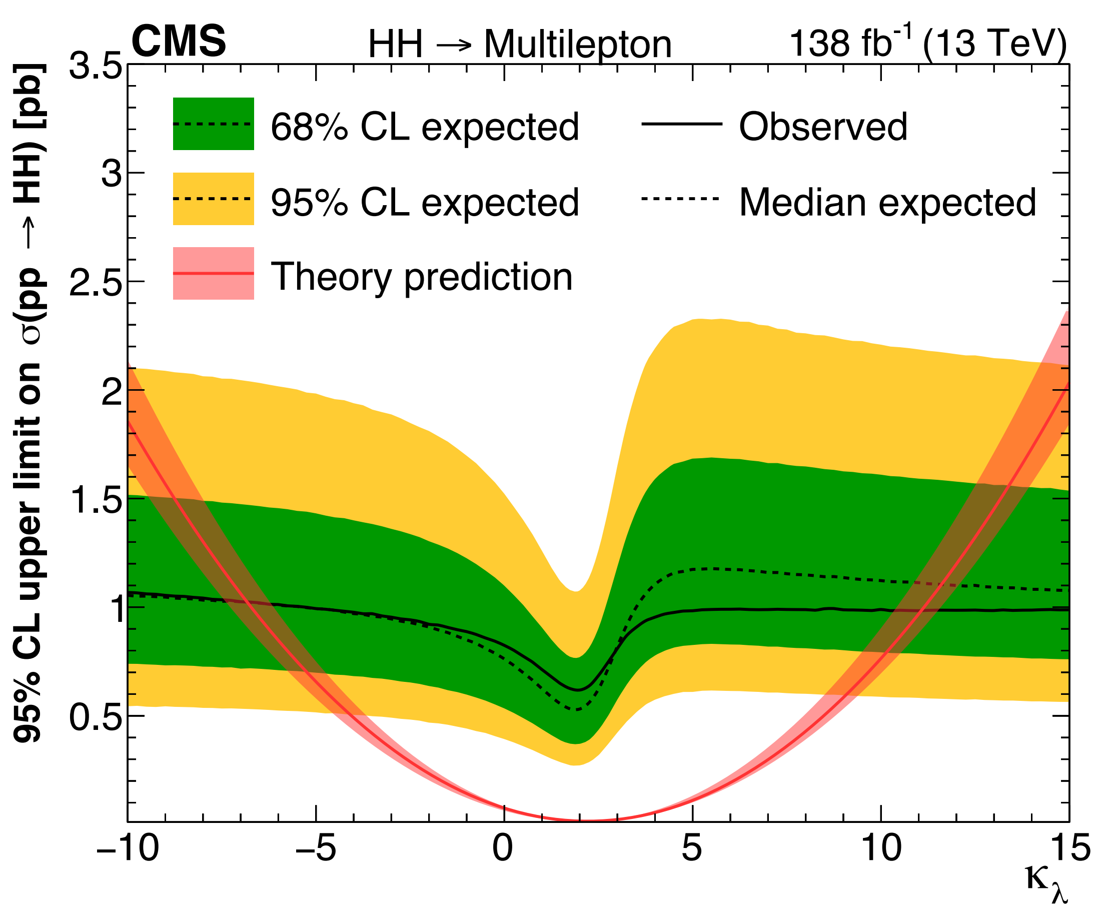
Multilepton HH search

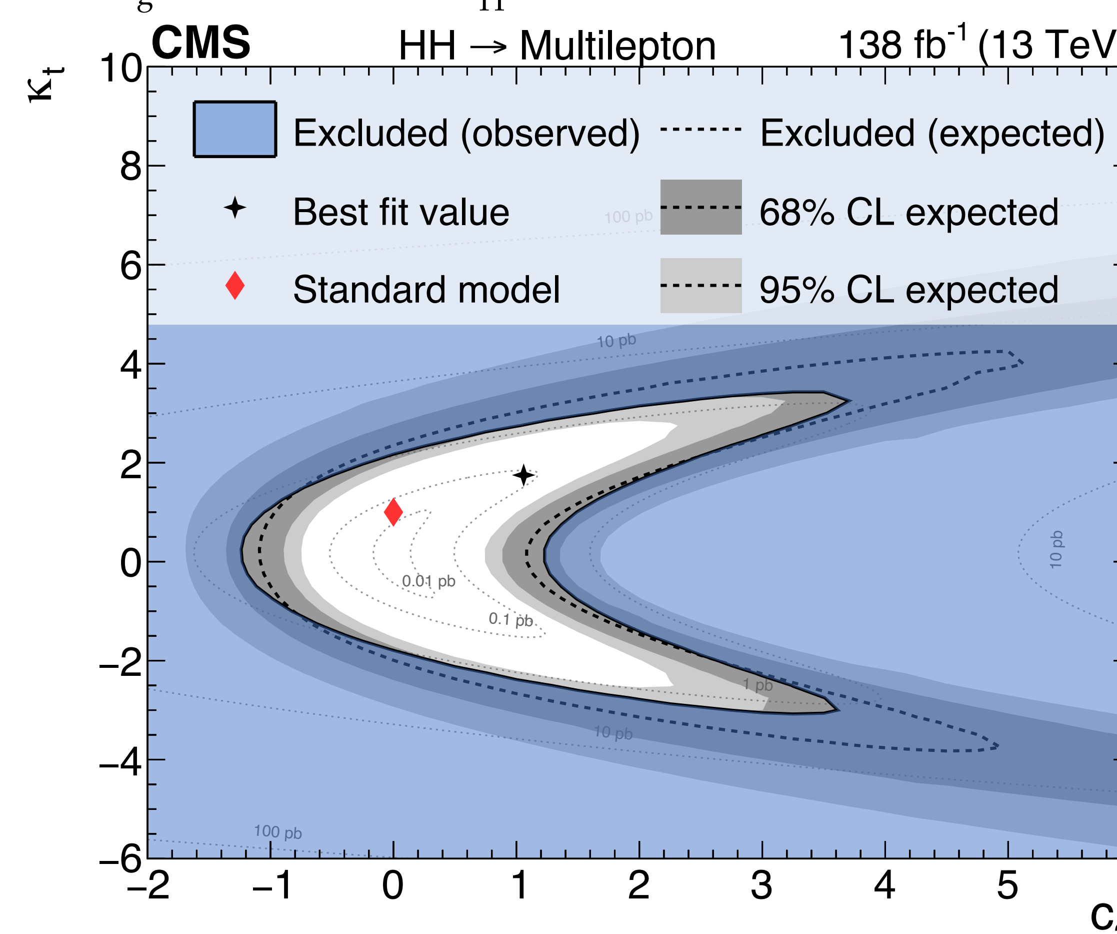
- Double H decays into 4W, 4τ, $2W2\tau$ in final states with $\ell = e, \mu$ and an hadronically decaying τ_h cover ~7.7% of the HH decays
  - dedicated categories for 7 channels and 2 CRs
  - background estimates from data as ttH multileptons
- Sensitivity $\approx 20 \times \sigma_{SM}^{HH}$





HIG-21-002





Constraint on trilinear coupling at 95% CL:

New for LP21

$-7 < \kappa_\lambda < 11$

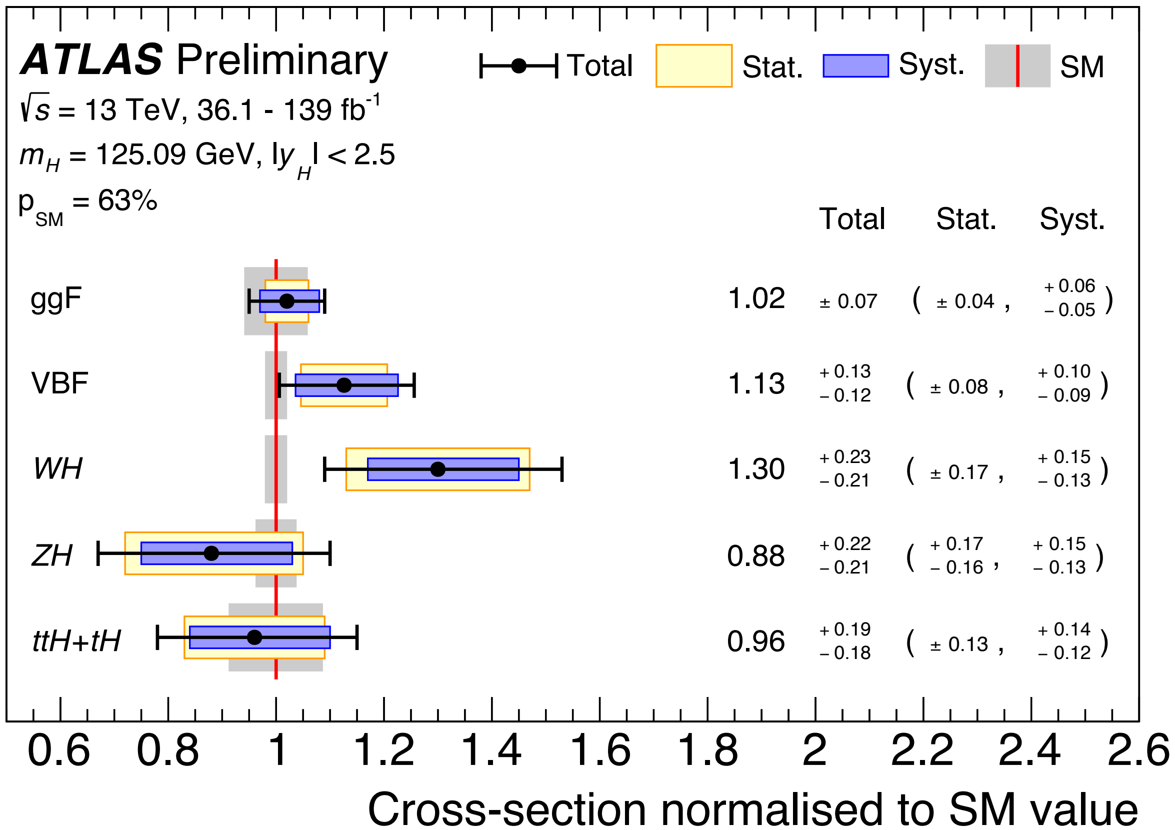
2t-2H coupling c_2 vs H-t coupling κ_t

Combination

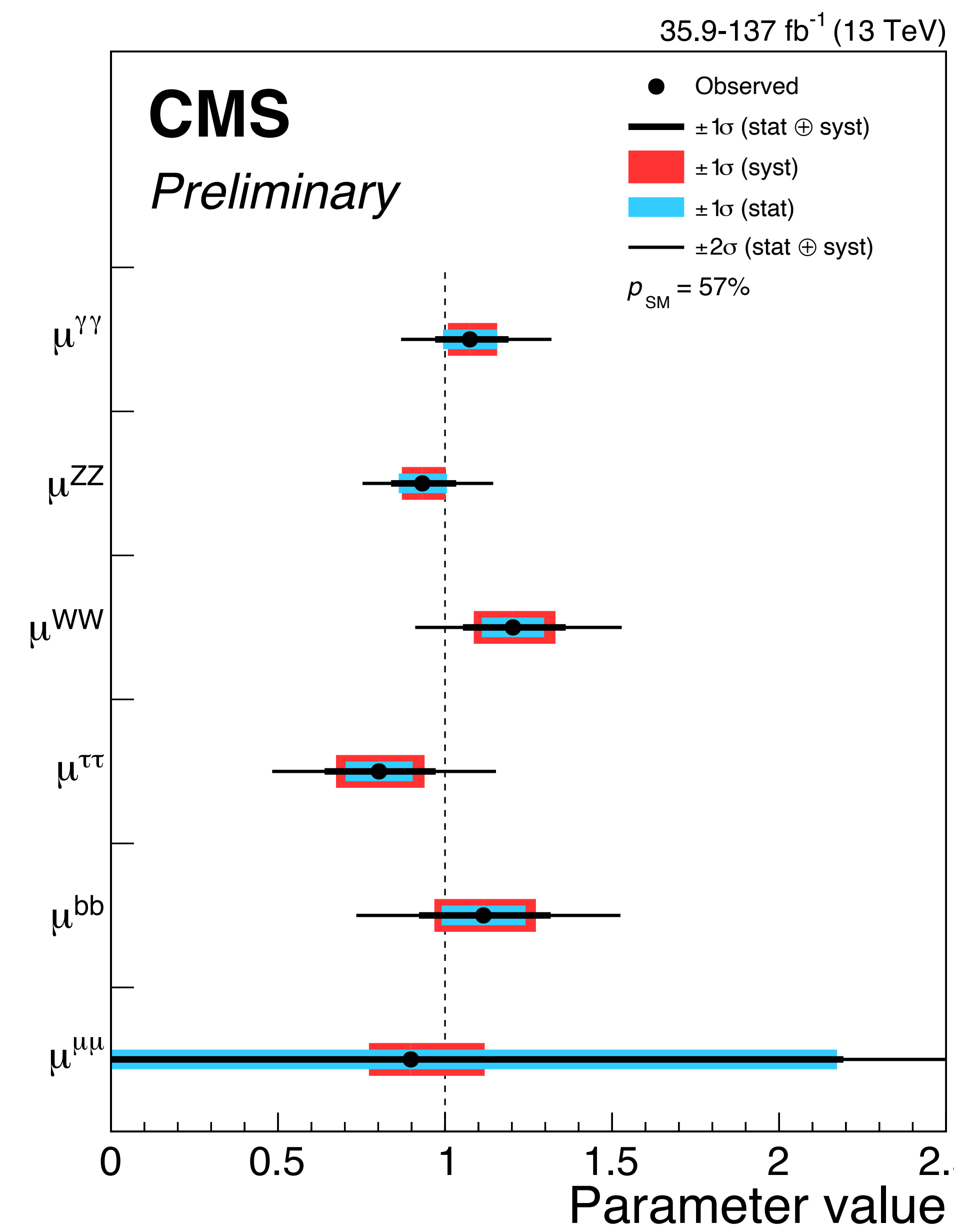
Run 2 combination: μ

- Higgs physics in the **era of precision (6% on μ)**:
  - **ATLAS**: $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$
  - **CMS**: $\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat.}) \pm 0.04(\text{exp.}) \pm (\text{th.})$

ATLAS-CONF-2021-053
CMS-PAS-HIG-19-005



σ^H/σ^H_{SM} in production



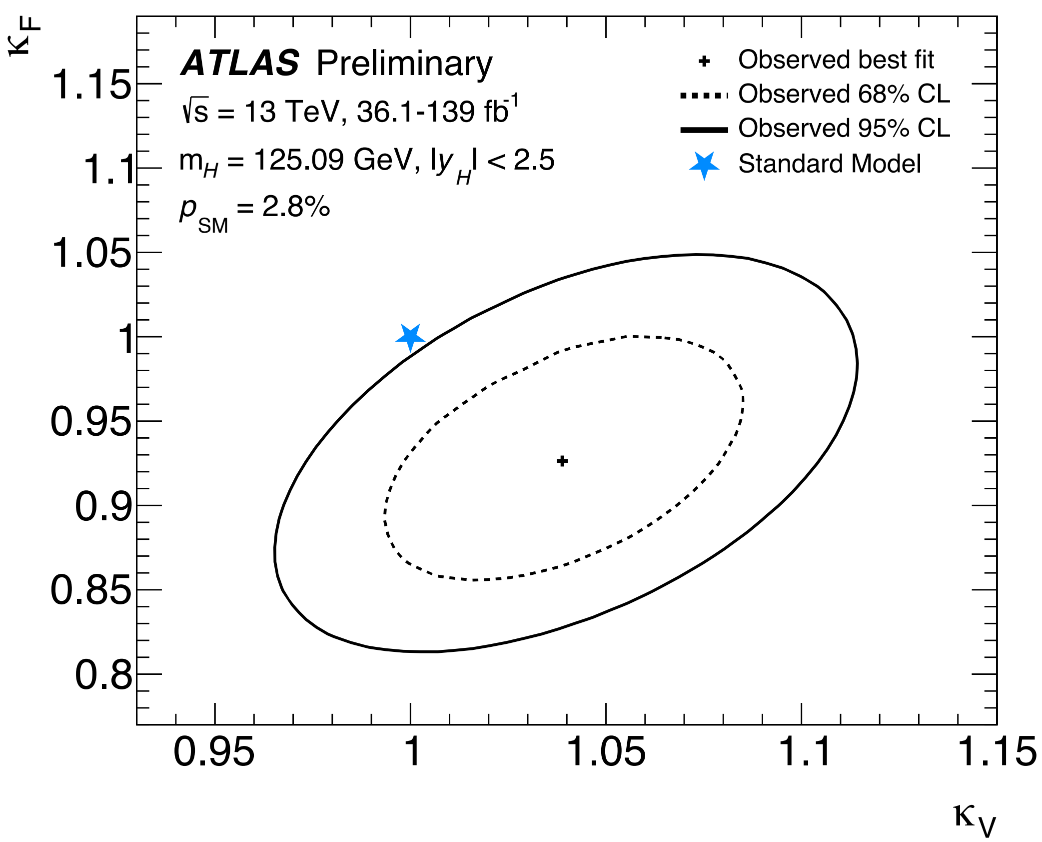
σ^H/σ^H_{SM} in decay

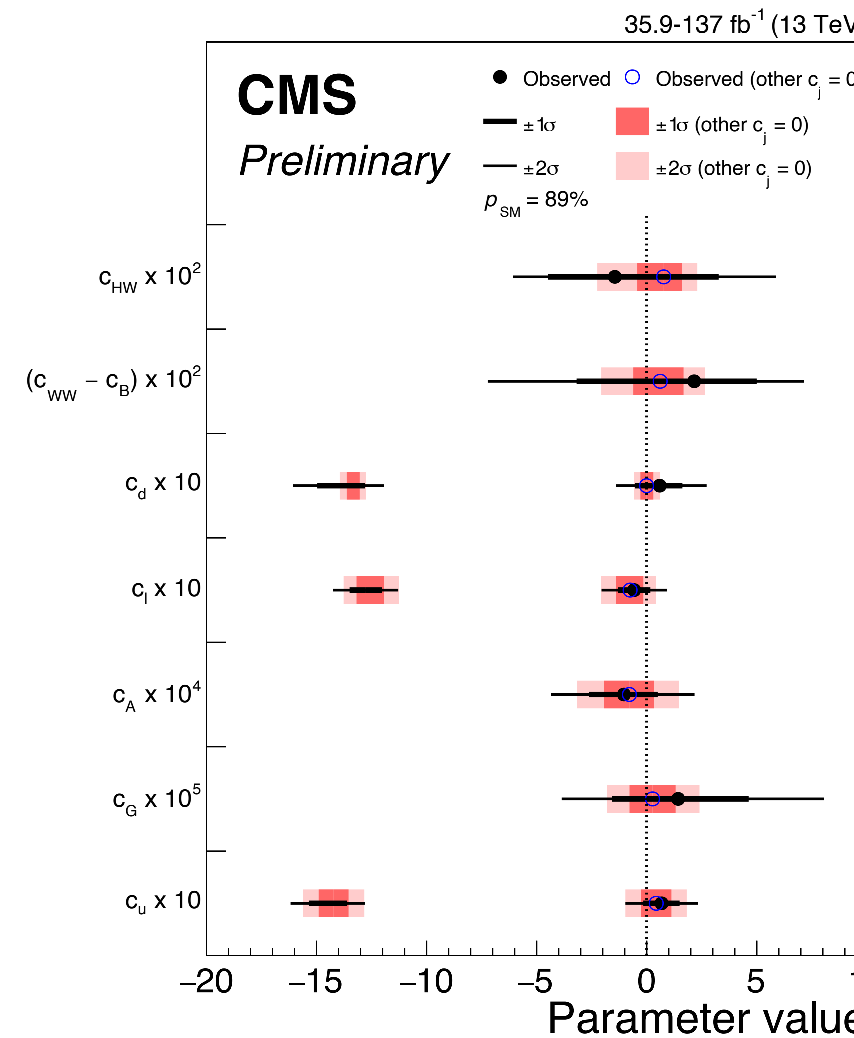
Run 2 combination: κ and EFT

- Combination also for in the **κ-framework** for the coupling modifiers
  - assuming decays to SM-only particles

$$\kappa_j^2 = \Gamma_j / \Gamma_J^{SM}$$

  - e.g. universal vector-boson couplings $\kappa_V = \kappa_W = \kappa_Z$ and universal fermion couplings $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$





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

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

ATLAS-CONF-2021-053
CMS-PAS-HIG-19-005

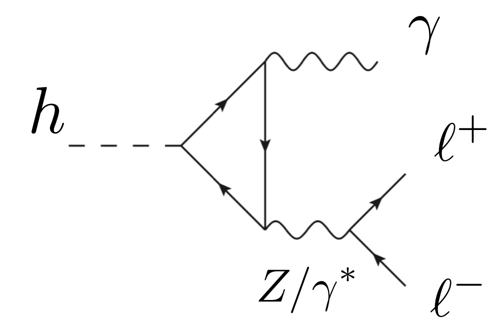
Conclusions

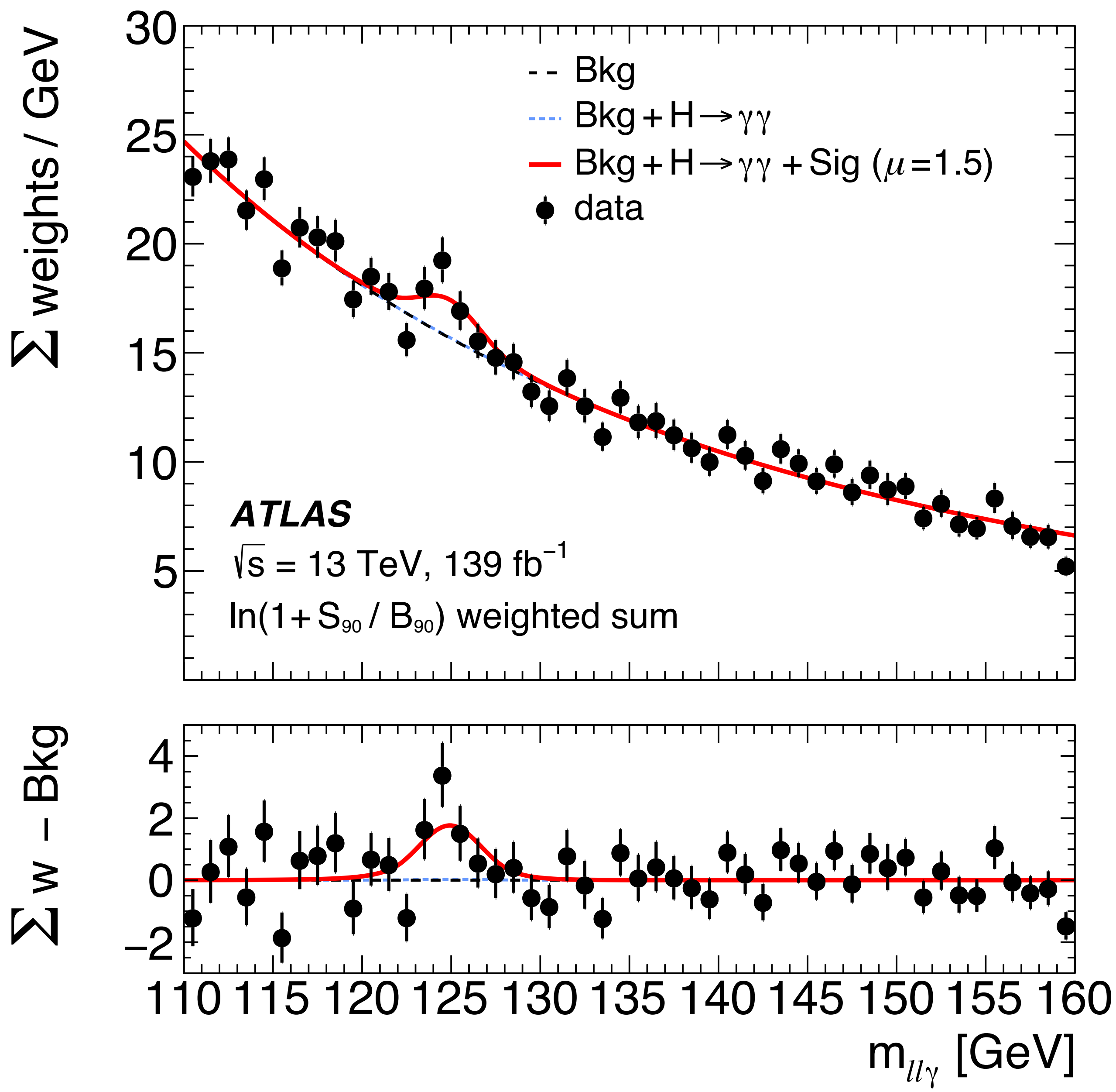
- The LHC Run2 provided data for a lot of results from ATLAS and CMS characterizing the Higgs boson
  - mass measured with 0.1% precision, and width measured for the first time with 50% precision
  - the production cross section are now measured differentially in many STXS bins, in several production 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 **500 fb^{-1} is expected per experiment in Run3**
  - a unique opportunity to continue characterizing the Higgs potential: entering the precision era for the Higgs field

extras

Evidence for $H \to \gamma\ell^+\ell^-$

- Rare three body decay of the Higgs: $BR(H \to \mu\mu[ee]\gamma) \approx 3.4[7.2] \times 10^{-5}$ for $m_{\ell\ell}$<30 GeV
  - LFV affecting B-meson R_{K^*} ratio could also affect the ℓℓγ rate
  - can be used to probe CP-violation in the Higgs sector





- 3 productions (ggH low pT, ggH high pT and VBF) x 3 final states (ee-resolved, ee-merged, μμ)
- required new experimental technique for merged electrons in the e.m. calorimeter

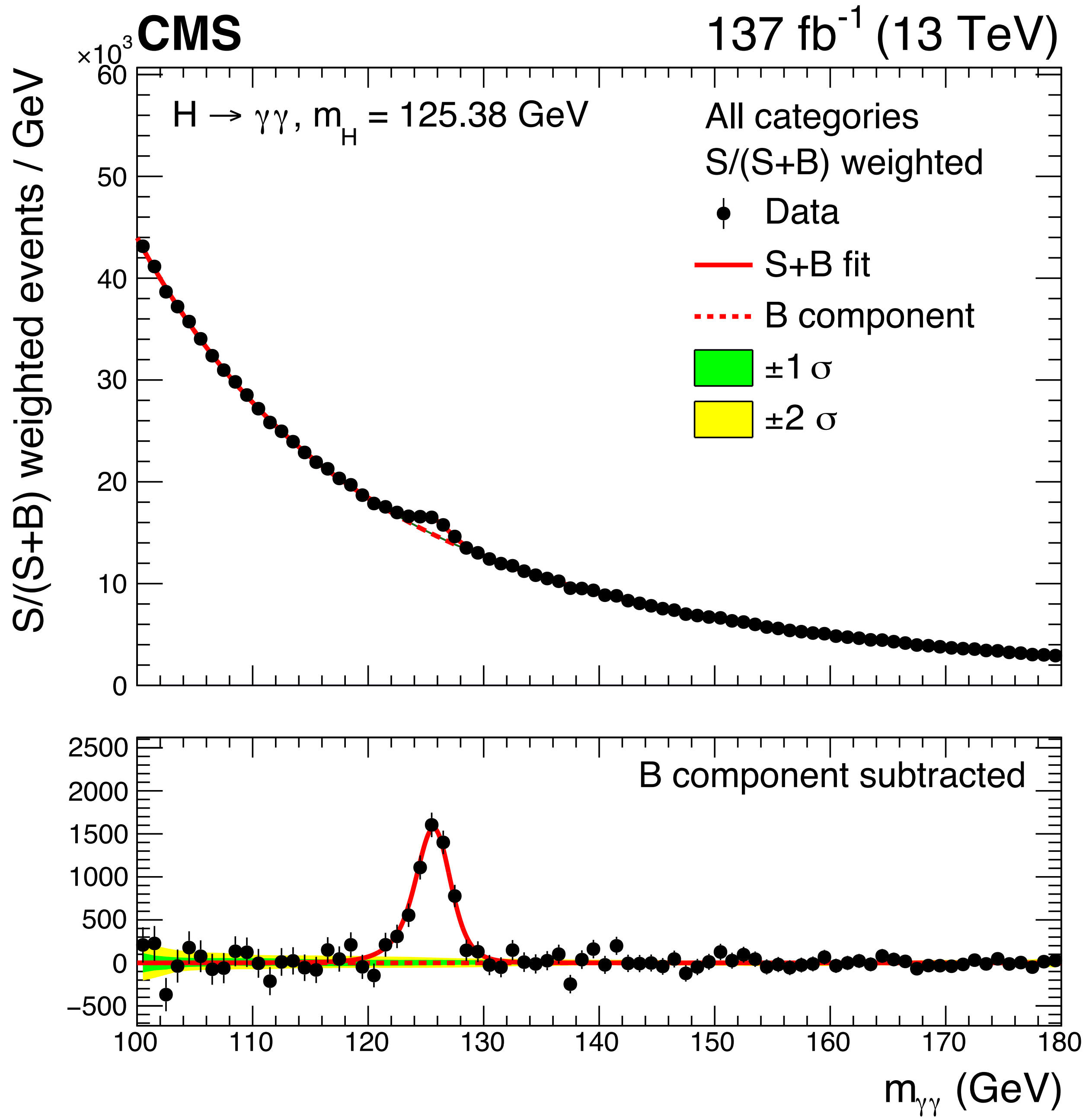
$$\mu = 1.5 \pm 0.5\ (\text{stat})^{+0.2}_{-0.1}\ (\text{syst})$$

significance: 3.2σ (2.1σ exp.)

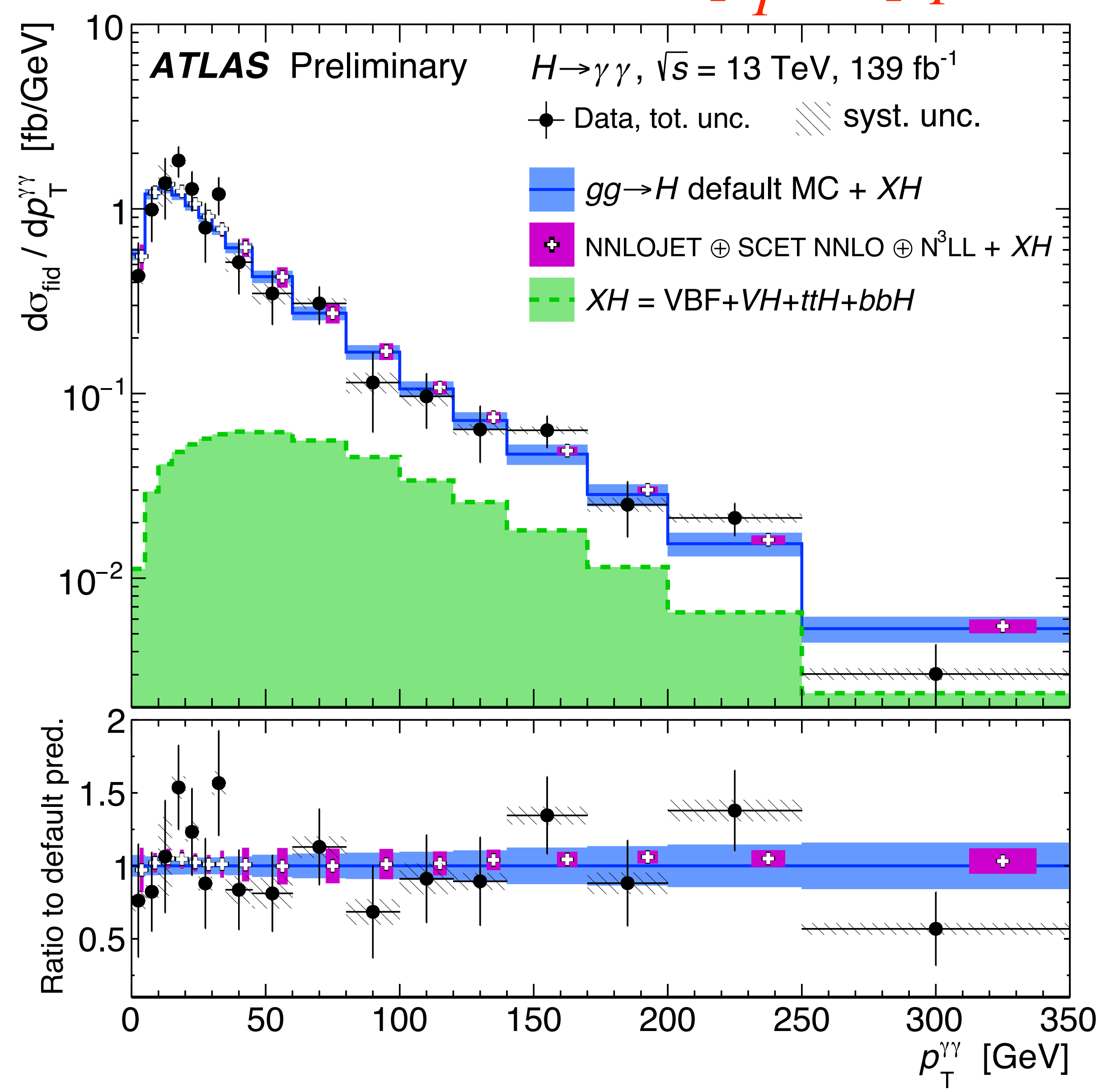
Phys. Lett. B 819 (2021) 136412

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

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



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



Unfolding key variables:

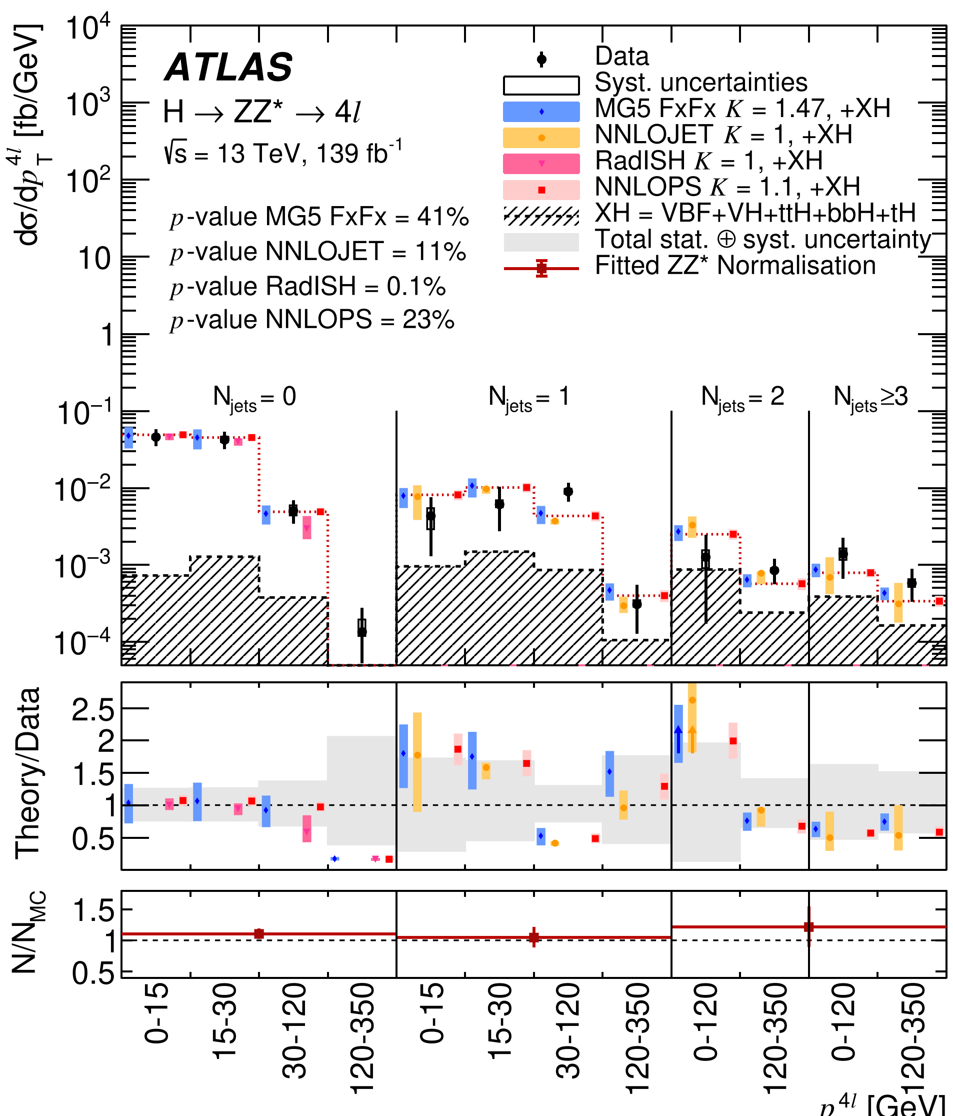
$p_T(H), y(H), N(\text{jets}), p_T(j_1), m_{jj}, \Delta\phi_{jj}$

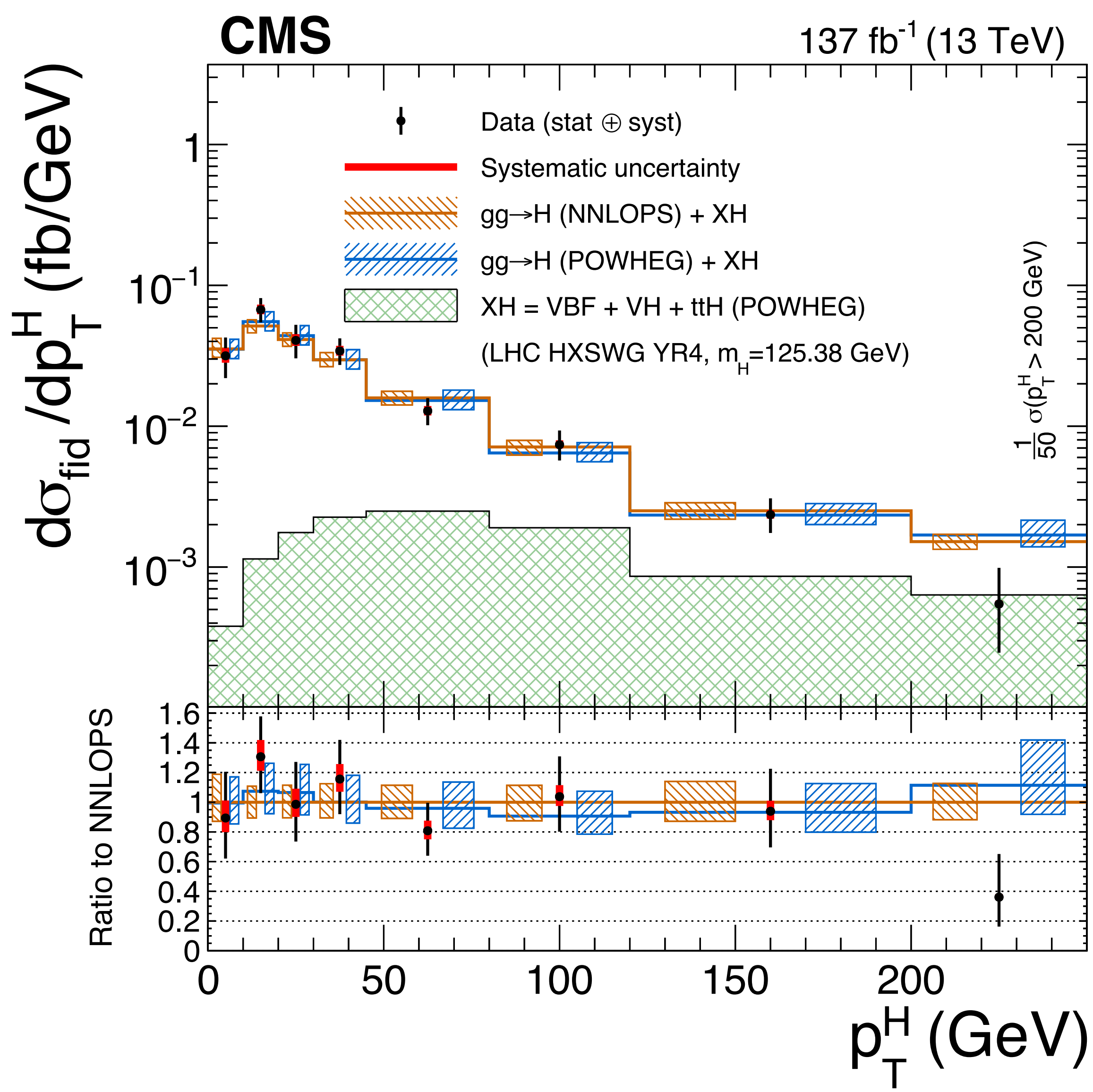
$H \rightarrow 4\ell$: differential and fiducial

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

Eur. Phys. J. C 80 (2020) 942
Eur. Phys. J. C 81 (2021) 488

	Measured [fb]	SM prediction [fb]
ATLAS	3.18 ± 0.31 (stat) ± 0.11 (syst)	3.41 ± 0.18
CMS	$2.73^{+0.23}_{-0.22}$ (stat) $^{+0.24}_{-0.29}$ (syst)	2.76 ± 0.14

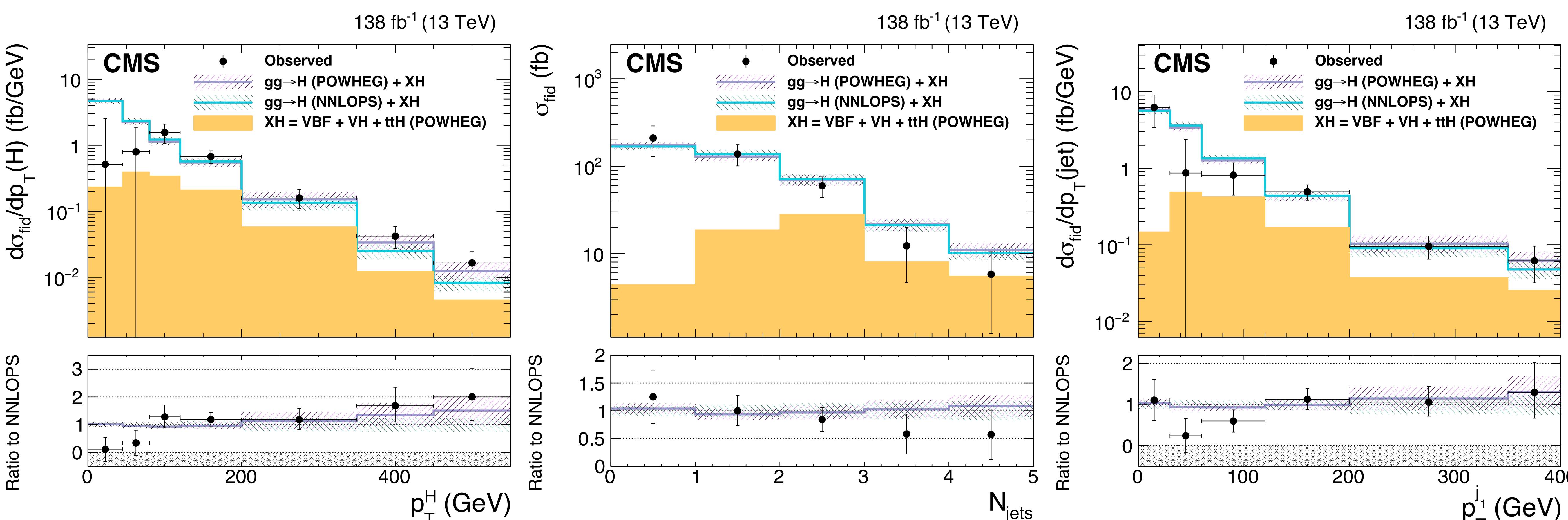




$H \to \tau\tau$: differential and fiducial

- 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

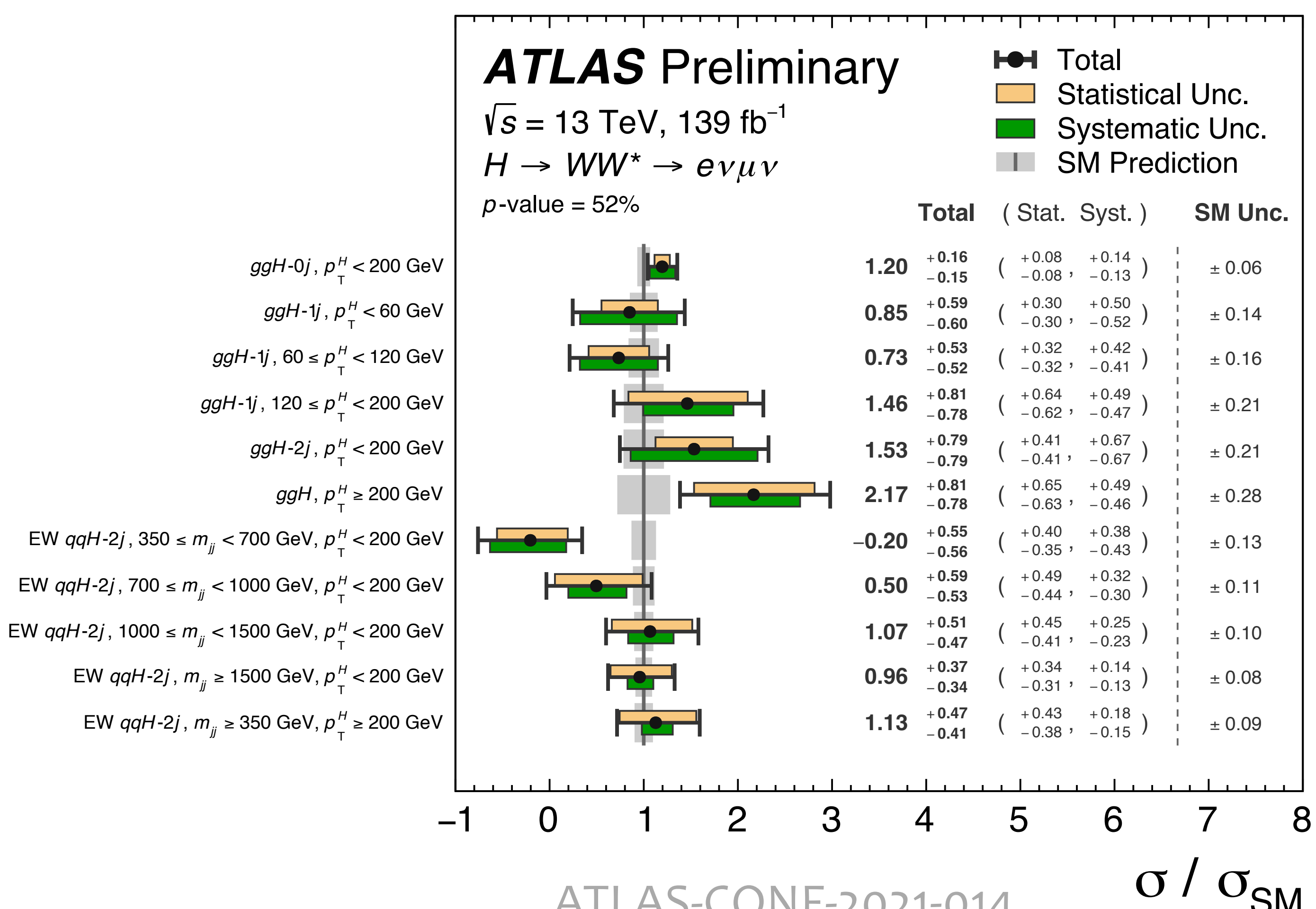
$N_{jets}>2$

$p_T^{j_1} > 120$ GeV

STXS in $H \rightarrow WW^*$

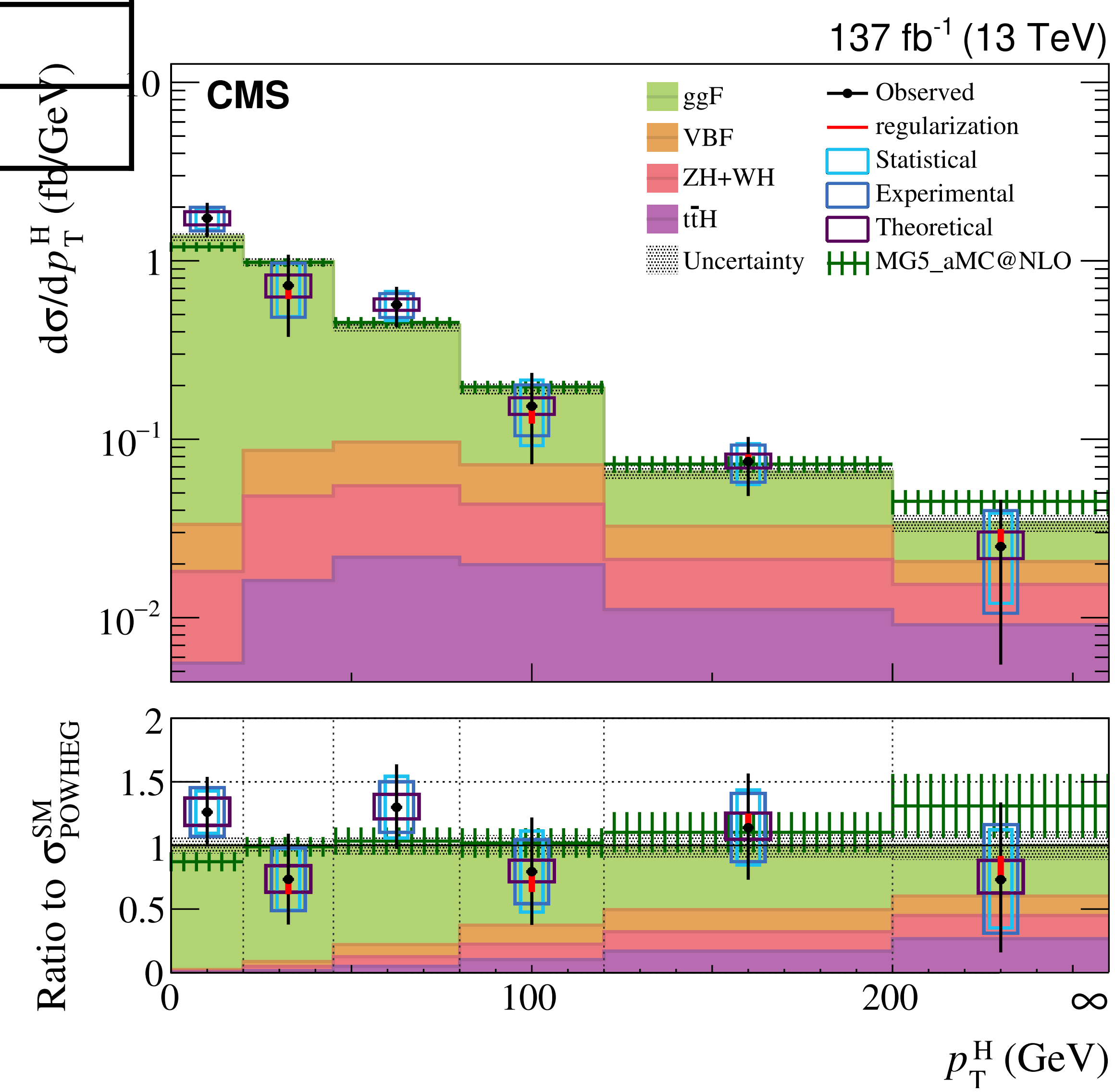
- $H \rightarrow 2\ell 2\nu$ challenging channel where backgrounds needs to be modelled with data accurately
- Large signal yield allows granular binning for differential cross sections

	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

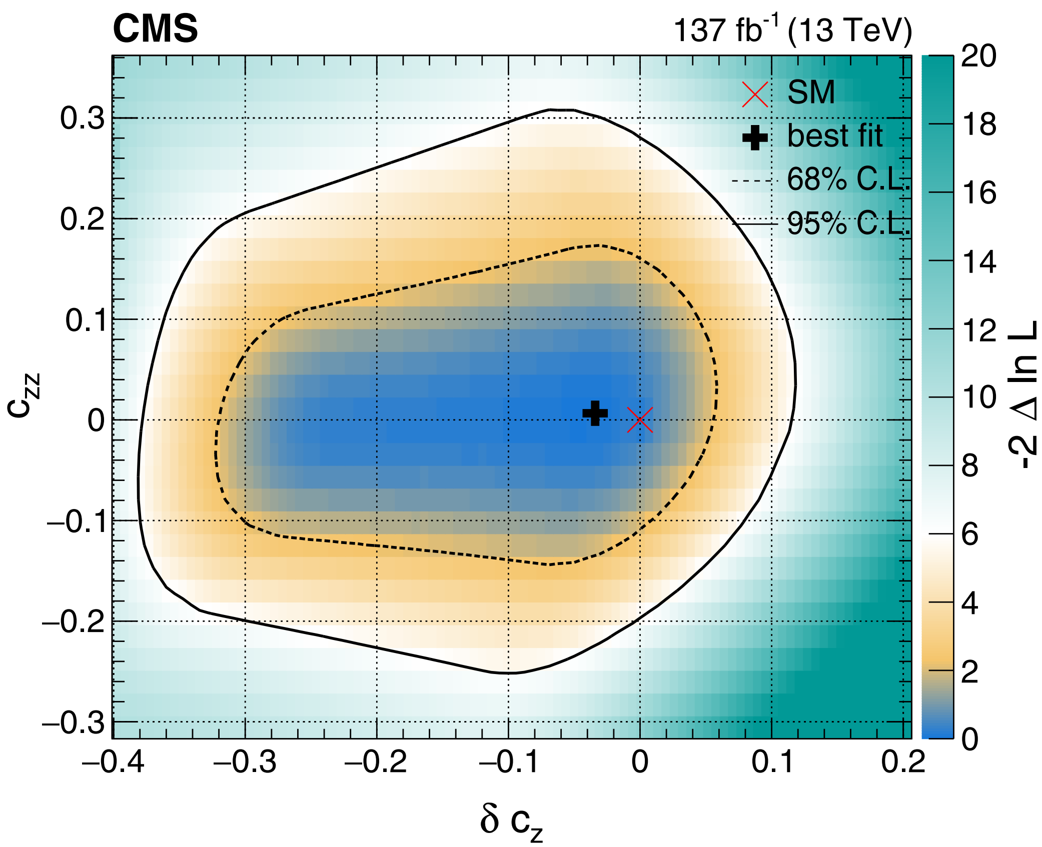


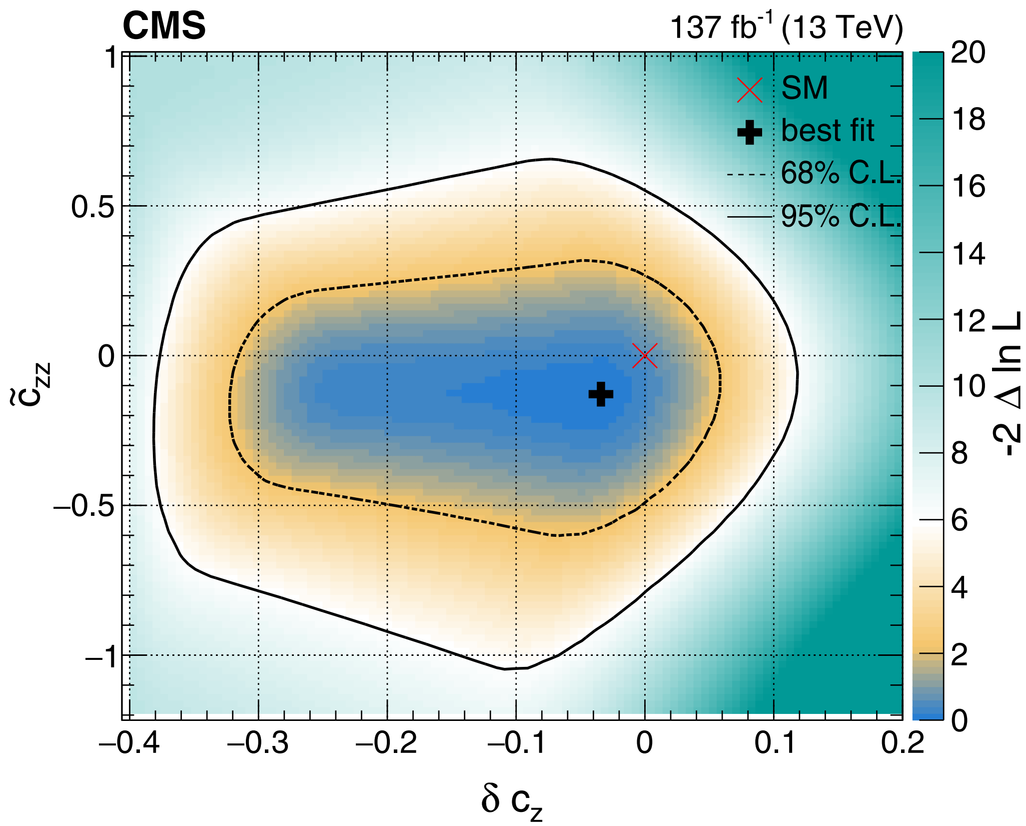
ATLAS-CONF-2021-014

JHEP03(2021)003



- 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(γγ), BR(Zγ)





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

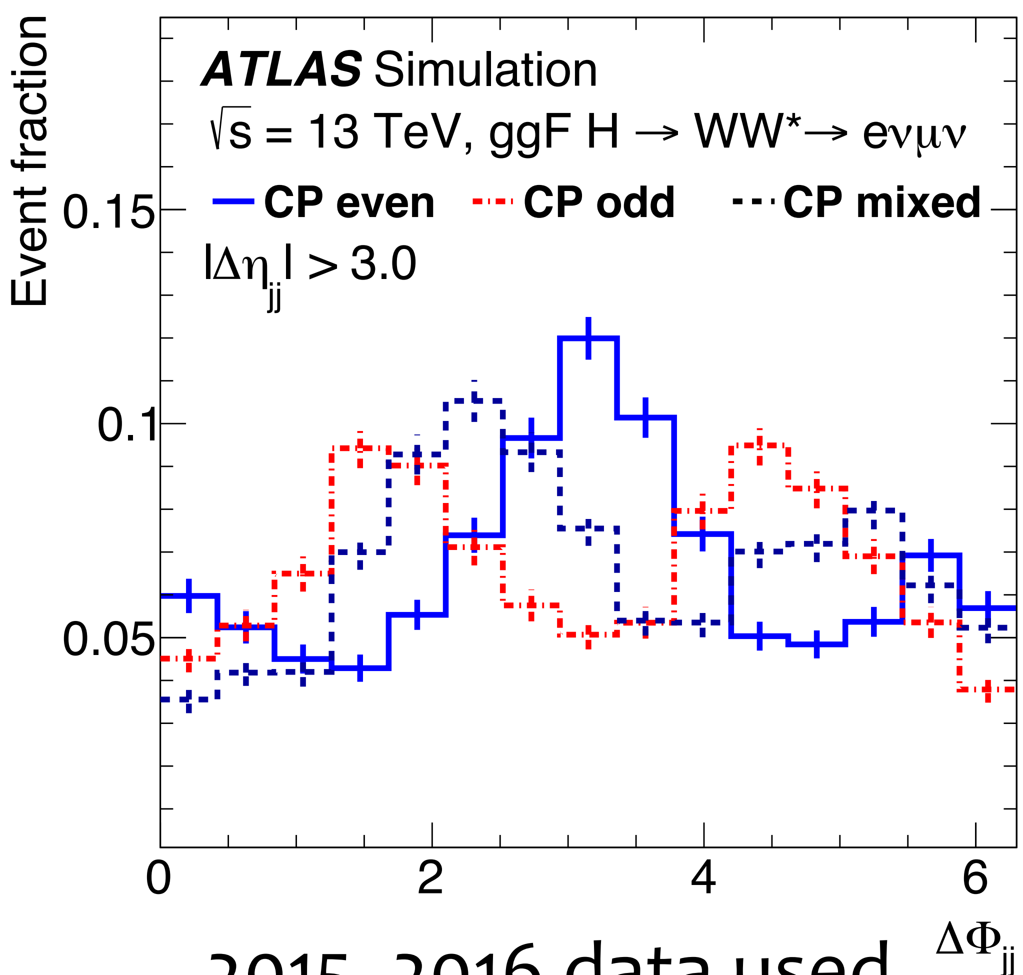
Hgg from $H \to WW \to e\nu_e\mu\nu_\mu$

- Effective Higgs-gluon interaction: arXiv:2109.13808

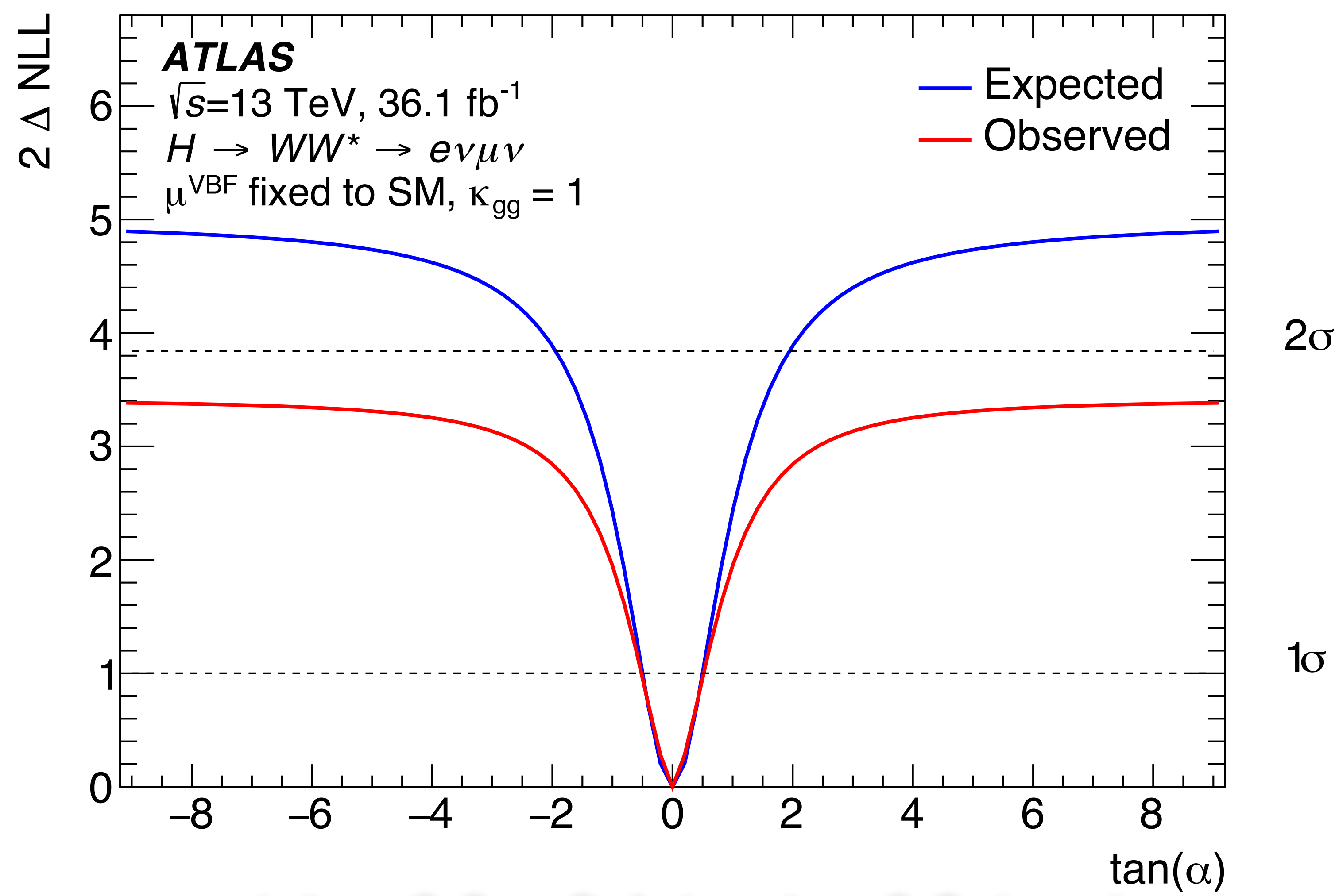
$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

κ_{gg}: coupling modifier α: CP-mixing angle

- Use production information of $e\nu\mu\nu jj$ events in kinematics/MVA categories
  - CP odd/even separation from $\Delta\Phi_{jj}$ distribution in high $|\Delta\eta_{jj}|$ regions



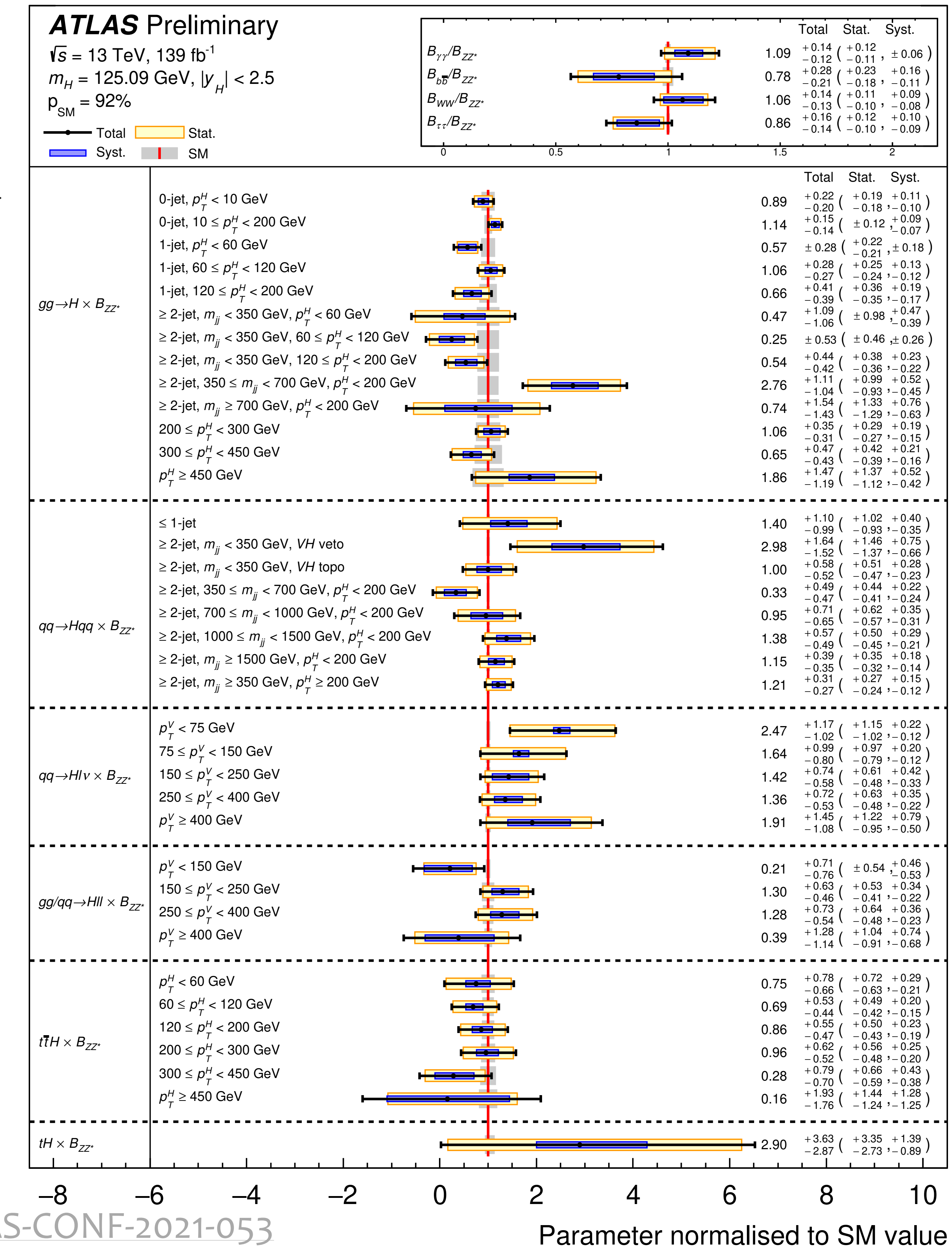
2015, 2016 data used

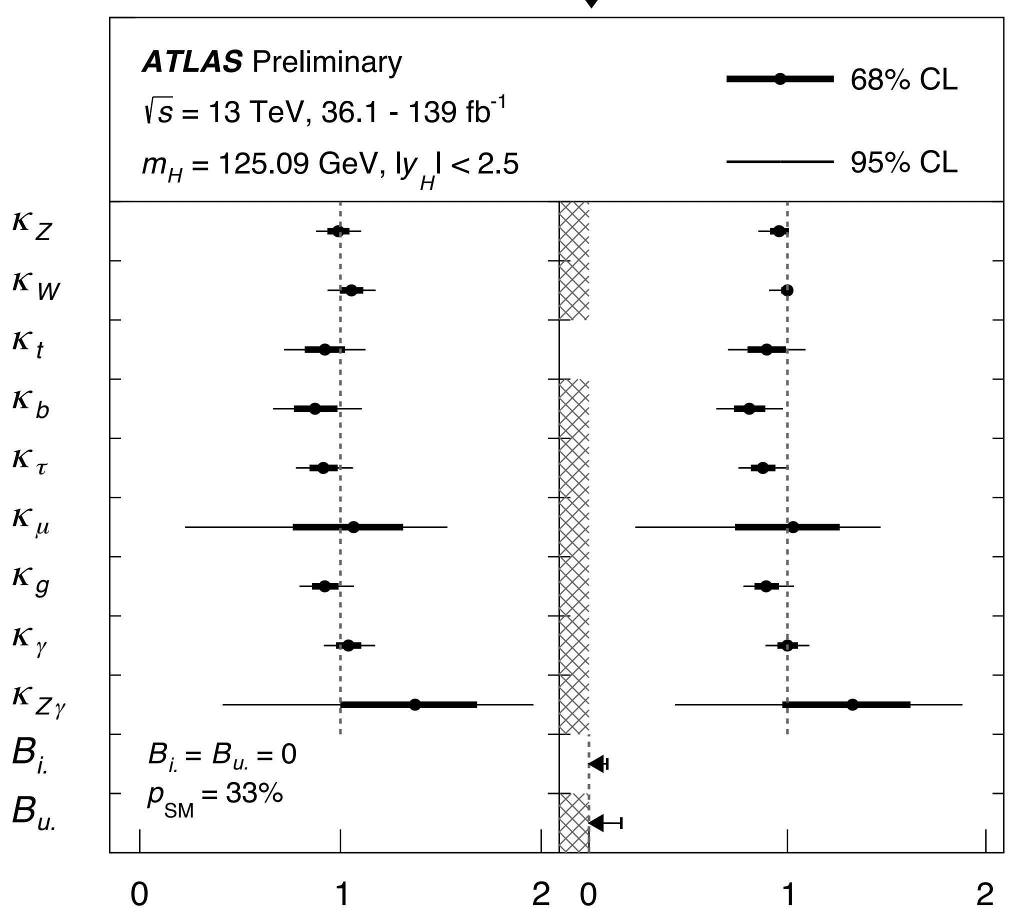


$\tan(\alpha) = 0.0 \pm 0.4\ (\text{stat}) \pm 0.3\ (\text{syst})$

STXS combination

- Precision era:
  - Combination of several channels for the STXS measurements
    - unc within 13%-100% apart tH and few extreme bins
  - coupling modifier per particle type





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