CMS: Higgs Results from the LHC

Mass, Couplings, Differential σ, CP, Rare Decays, HH, BSM

LISHEP 2023
International School on High Energy Physics

LISHEP 2021
International School on High Energy Physics

Rio +Worldwide

UFBA
LISHEP 2018
International School on High Energy Physics

Salvador

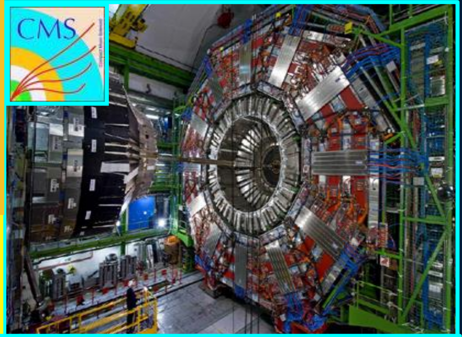
LISHEP 2015

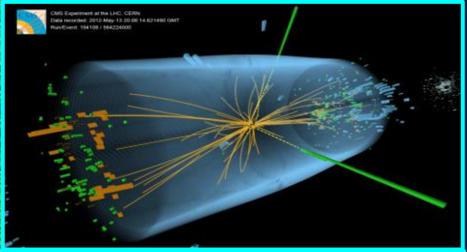
Manaus

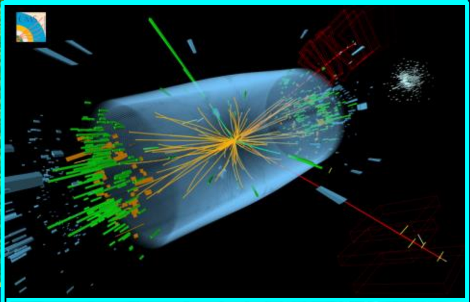
LHC Run2, Run3 and HL LHC

Journey of Discovery

River of Discovery







Harvey B Newman

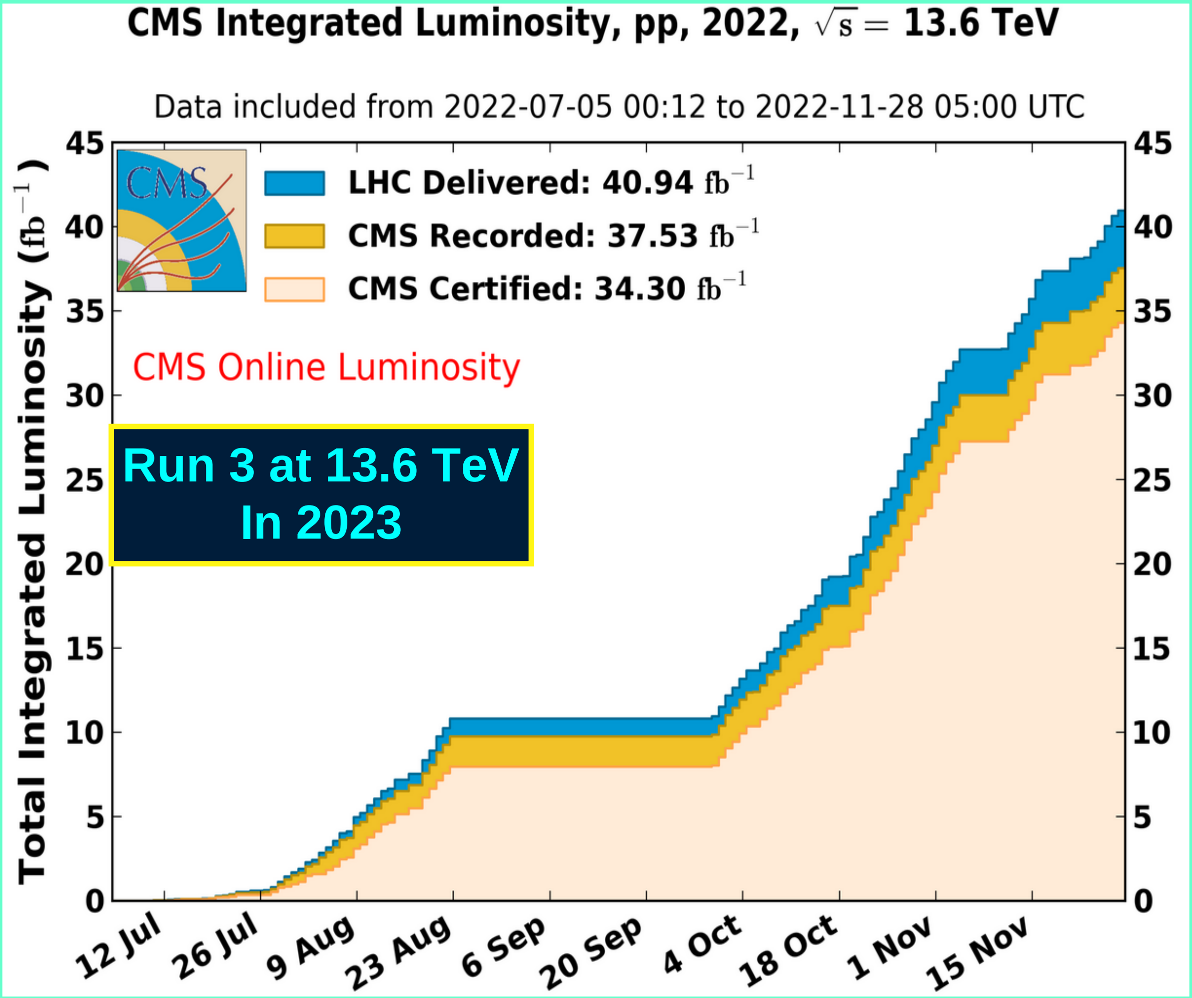
On behalf of the CMS Collaboration

LISHEP 2023 UERJ March 6, 2023

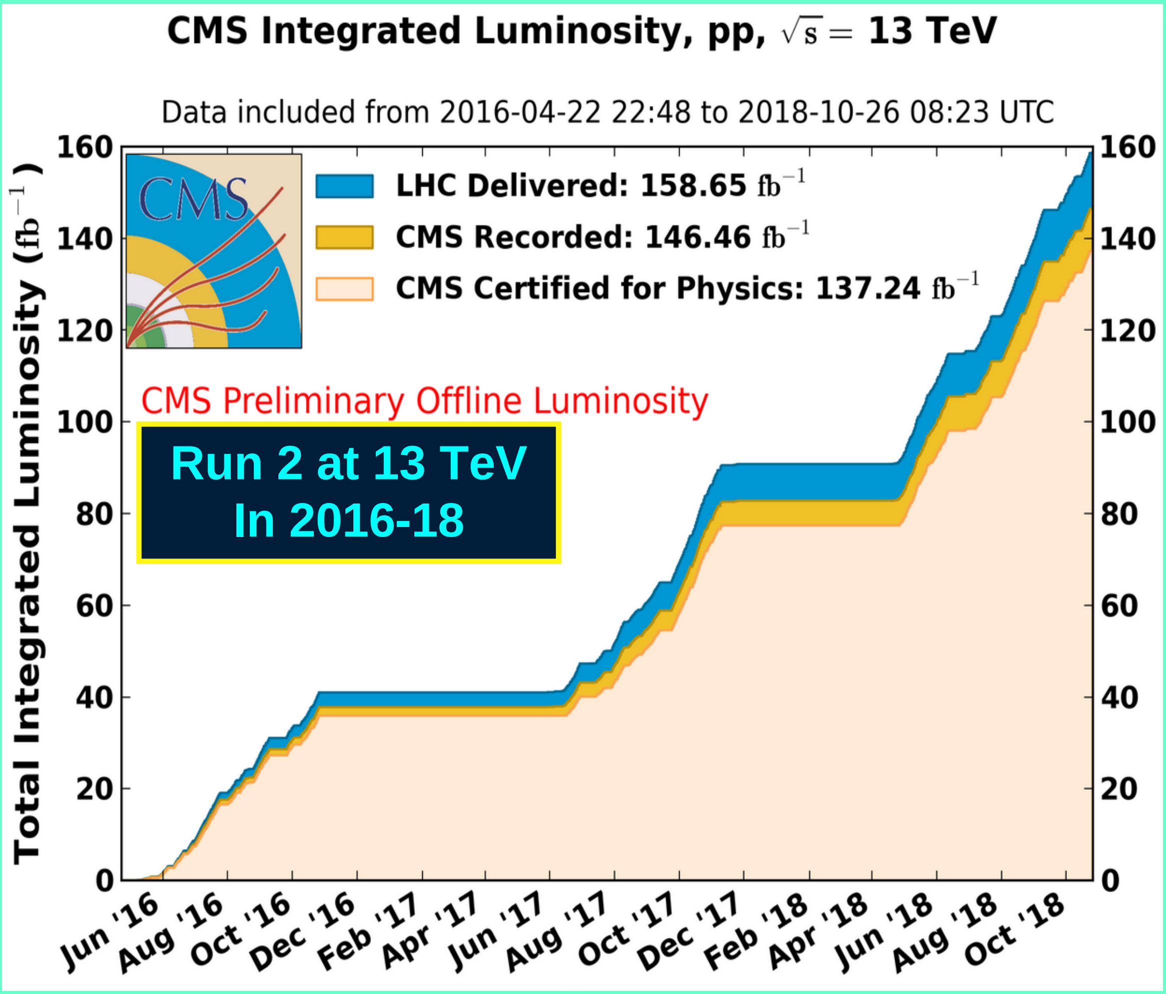
LISHEP: *Return to Rio*

LHC and CMS

Excellent Performance



Run 3 at 13.6 TeV
In 2023

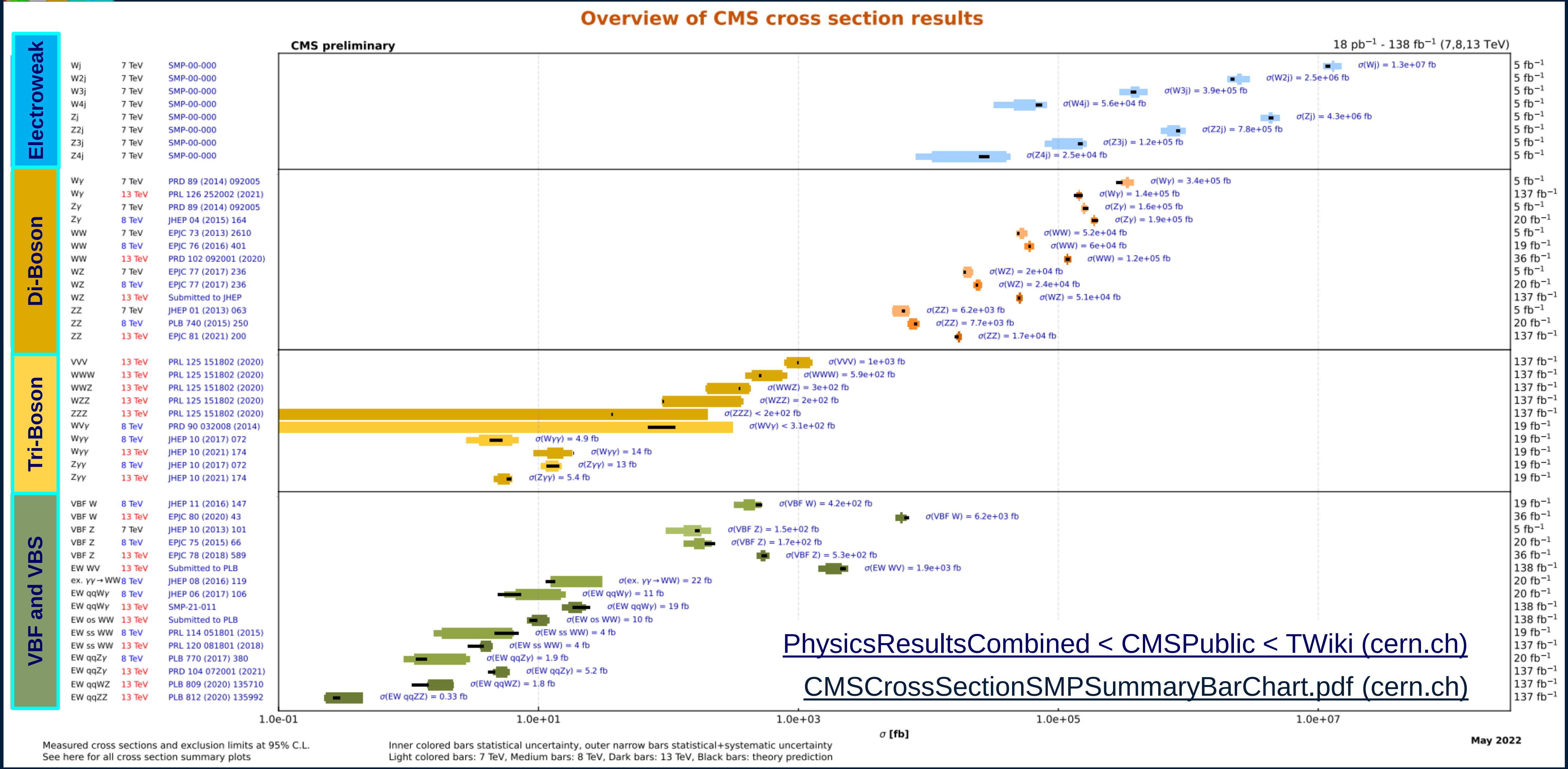


Run 2 at 13 TeV
In 2016-18

CMS Collected 138/fb for Physics at 13 TeV; 91+% Data Taking Efficiency (to 95%) in 2023
Thanks to: Excellent Performance of the LHC & Efficient Operation of Detector Systems
Looking Forward to ~300/fb at 13.6 TeV by the end of Run3

Standard Model Cross Sections 7-13 TeV

Agreement: from ~0.08 barn (pp inelastic) to 0.33 femtobarn (EW qqZZ)

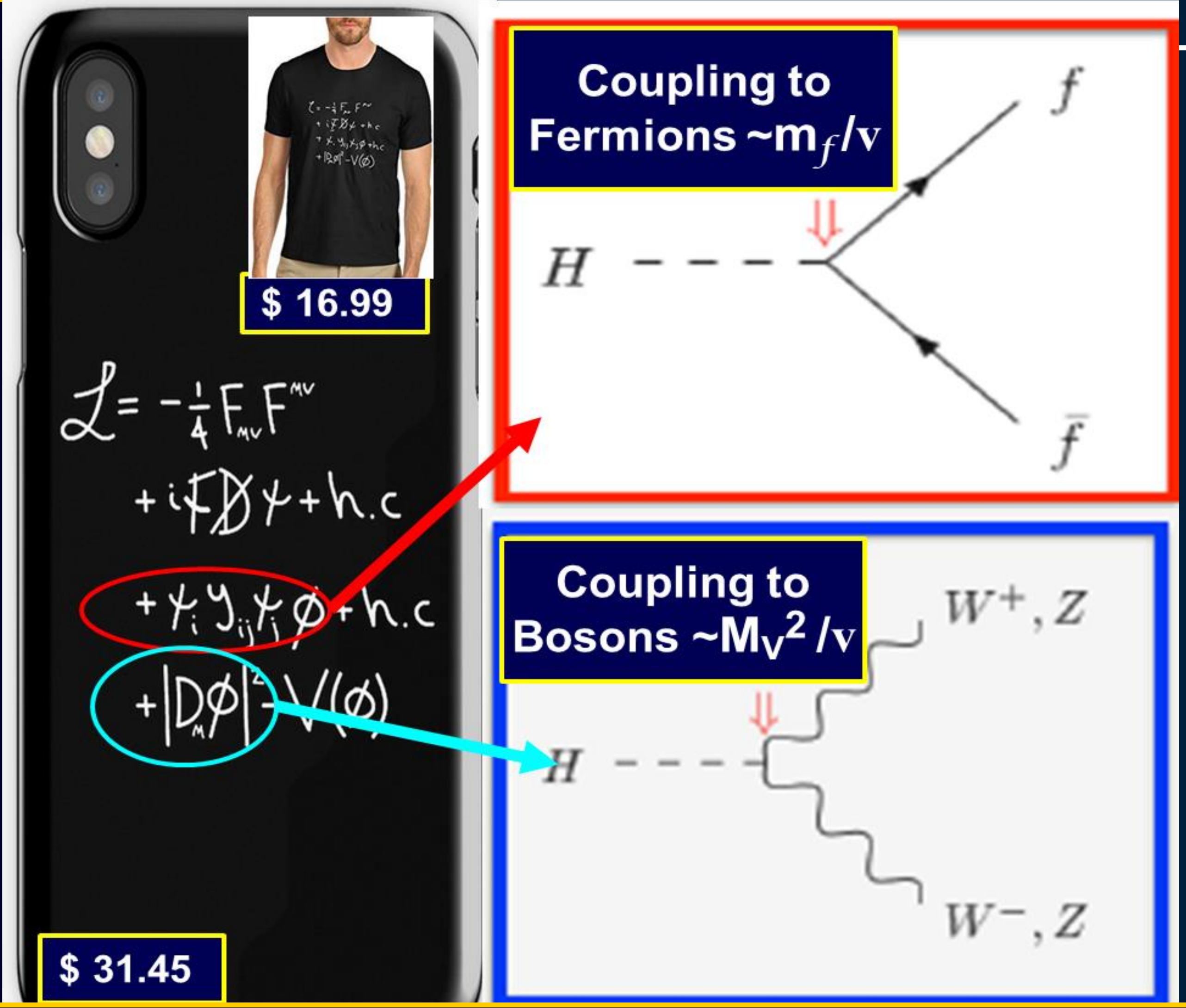


PhysicsResultsCombined < CMSPublic < TWiki (cern.ch)

CMSCrossSectionSMPSummaryBarChart.pdf (cern.ch)

Higgs Boson Discovery: An Achievement of Humanity. Now That Lagrangian is Everywhere

- **Higgs Boson Discovery** Opened a New Window:
  - What Stabilizes the theory
  - What was the physics of the early universe ?
- Are there New Particles (Heavy H, V-prime, graviton, VLQ…)
- **Precise EWSB Exploration**
  - Is it the "perfect" SM Higgs Boson ?
  - Lorentz structure and Symmetries (CP) of the EW + QCD Lagrangian
- Rarer production + decay modes; Kinematics and final state structure
- Milestones: 2nd Gen ff decays, VBS (unitary), HH (self coupling), fiducial and differential σ (STXS)
- BSM Models
- Flavor: LFUV Searches



Coupling to Fermions ~m_f/v

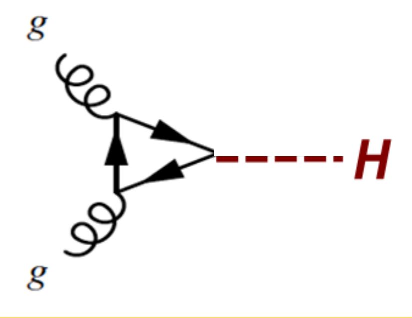
Coupling to Bosons ~M_V^2/v

The Higgs Boson Sector: An Expanding Realm of In-depth Exploration Towards the Next Discovery.

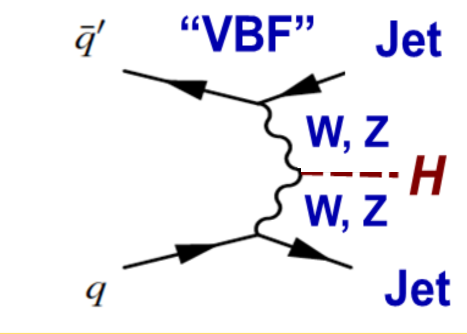
Higgs Production at the LHC

Run 1: 7-8 TeV pp Collisions; Run2 at 13 TeV

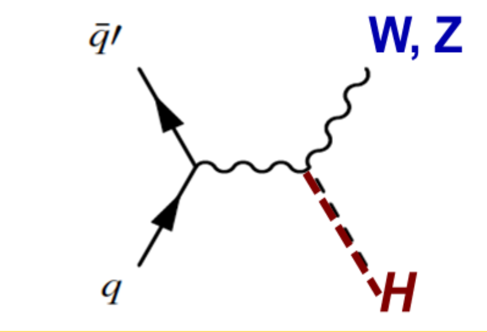
Gluon Fusion gg→ H



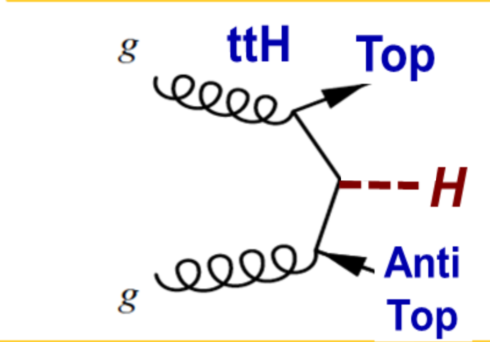
Vector Boson Fusion



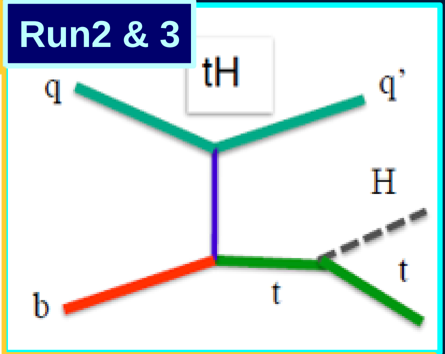
Associated Production



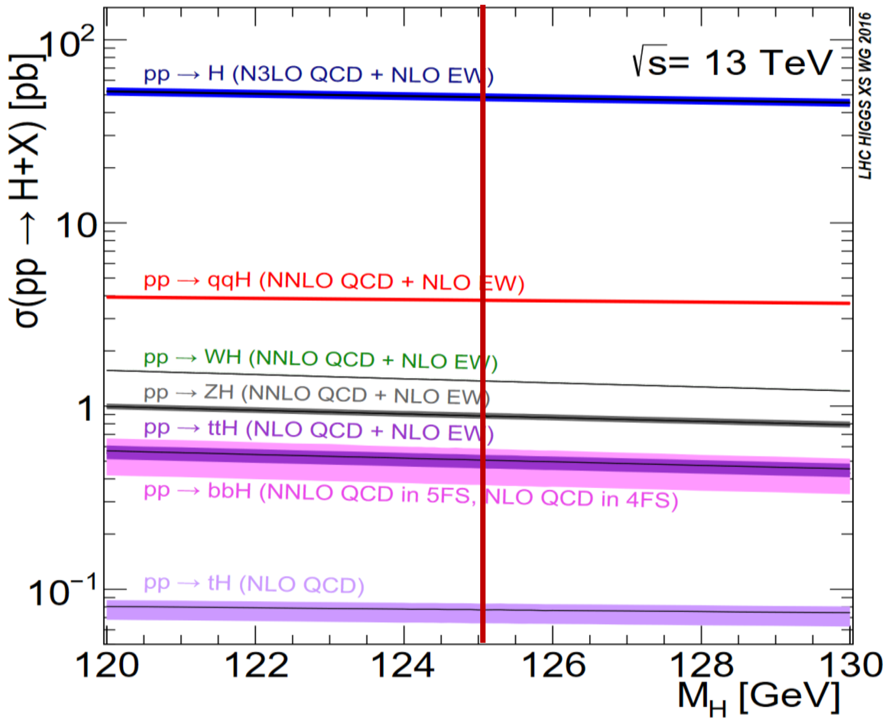
Associated Prod: tt H

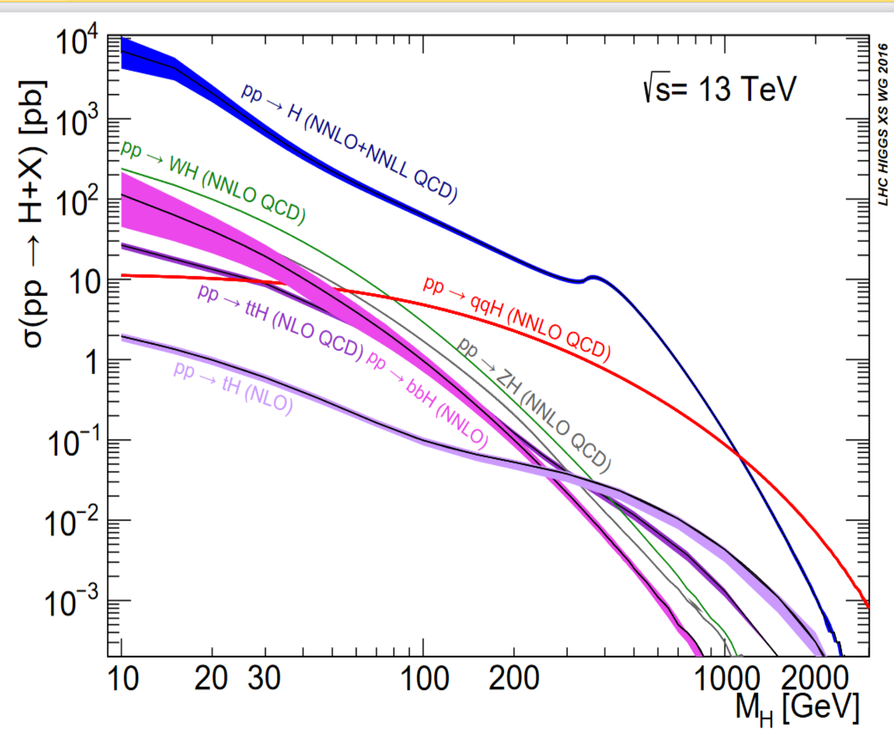


Run2 & 3

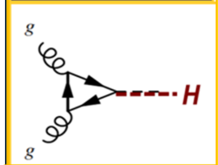


Single Top: tHq

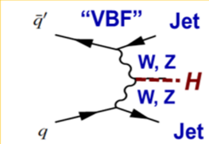




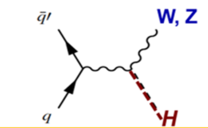
Gluon Fusion gg→ H



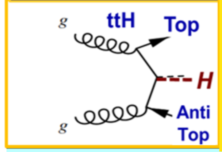
Vector Boson Fusion



Associated Production



Associated Prod: tt H



σ(13 TeV)

ggH: 48.5 pb
N3LO QCD, NLO EW

VBF: 3.78 pb
NNLO QCD, NLO EW

ZH: 0.88 pb
WH: 1.37 pb

NNLO QCD, NLO EW

ttH: 0.51 pb
NLO QCD, NLO EW
tH: 0.074 pb

See Handbook on LHC Higgs Cross Sections Vol.4: https://arxiv.org/abs/1610.07922v2 (May 2017)

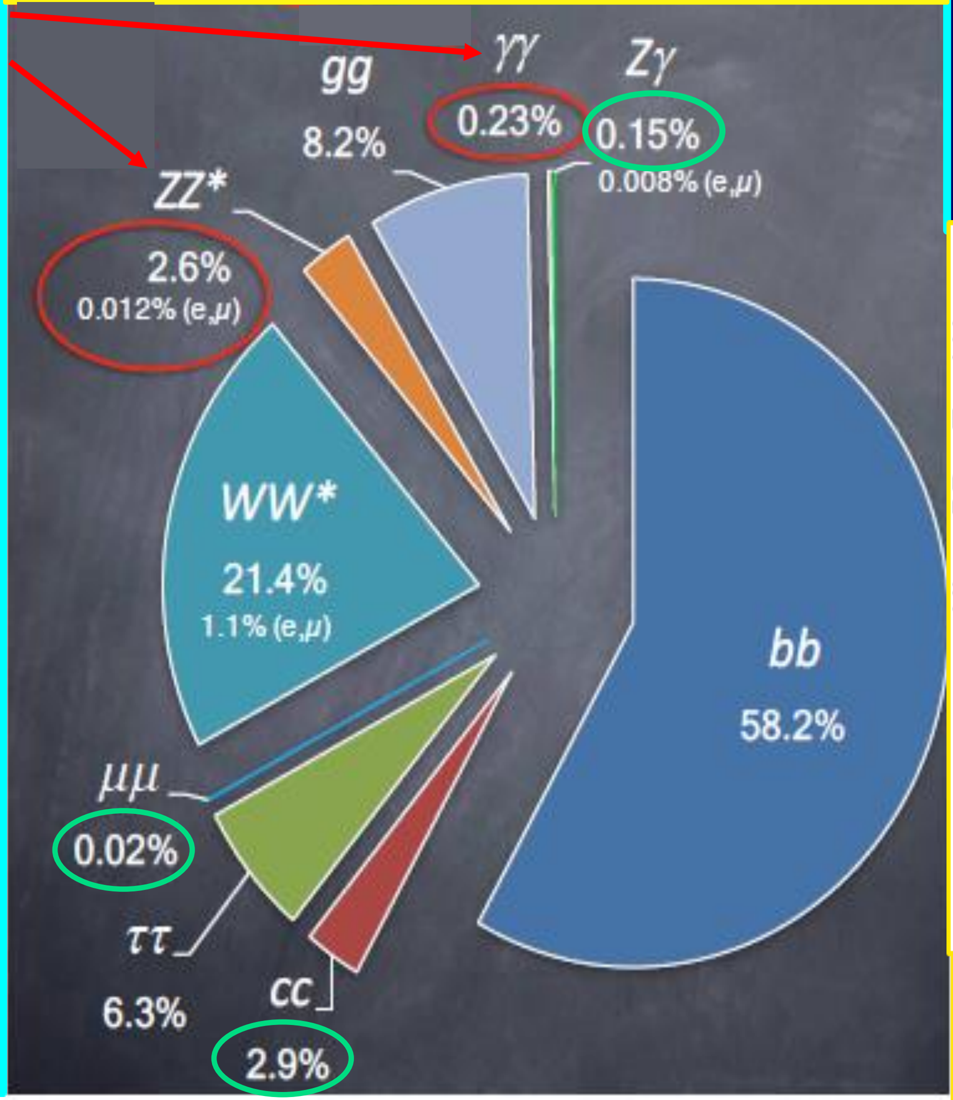
Higgs Boson Decays

ZZ, γγ: High resolution Channels: Precise Mass and Differential Measurements

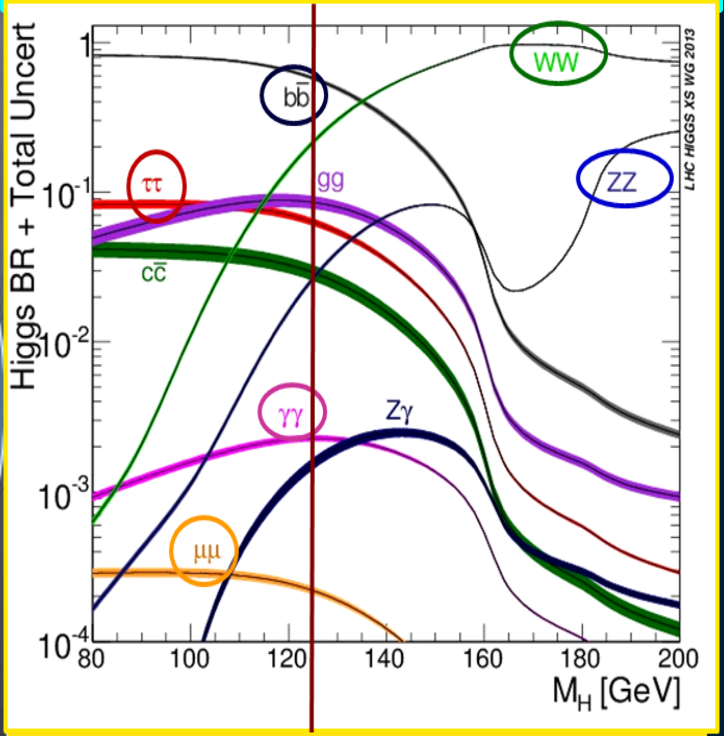
WW: High BR but Low Resolution

μμ: Very small BR but access to Couplings to 2nd Generation Fermions

Renewed focus, progress on rare (μμ, Zγ) and difficult (cc) channels



bb,ττ: High BR but low S/B. Important results: directly probe couplings to fermions



125 GeV – A Spectacular Mass: ~89% of final states studied

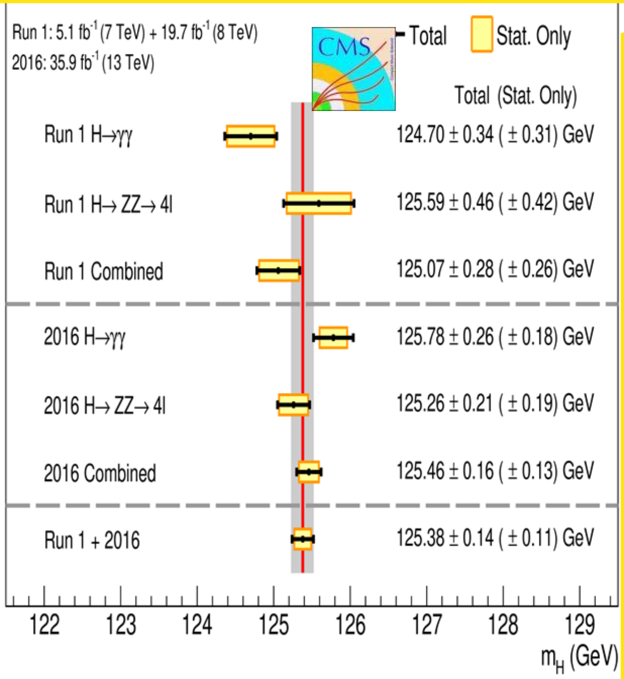
Higgs Boson Mass

- **M_H in the SM is a free parameter:** Once known, all Higgs boson couplings to SM particles are fixed
- **Most sensitive channels: $H \to \gamma\gamma$ & $H \to ZZ \to 4l$:** fully reconstructed with high resolution
- **Statistical power of the two channels similar;** systematics is an emerging challenge in $H \to \gamma\gamma$
- **CMS+ATLAS Run1 combination** m_H =125.09 ±0.24 GeV
- **CMS** $H \to ZZ \to 4l$ channel JHEP11(2017)047
  - m_H =125.26 ±0.20 (stat) ±0.08 (sys) GeV
- **CMS:** $H \to \gamma\gamma$ PLB 805 (2017) 135425
  - m_H =125.78 ±0.18 (stat) ±0.18 (sys) GeV
- **CMS:** $H \to \gamma\gamma$ & $H \to ZZ \to 4l$
  Combined Run1 + 2016: Still the most precise
  - m_H = 125.38 ±0.14 (±0.11 stat. only) GeV
- **Run2:** Results in 2023; to < 100 MeV precision

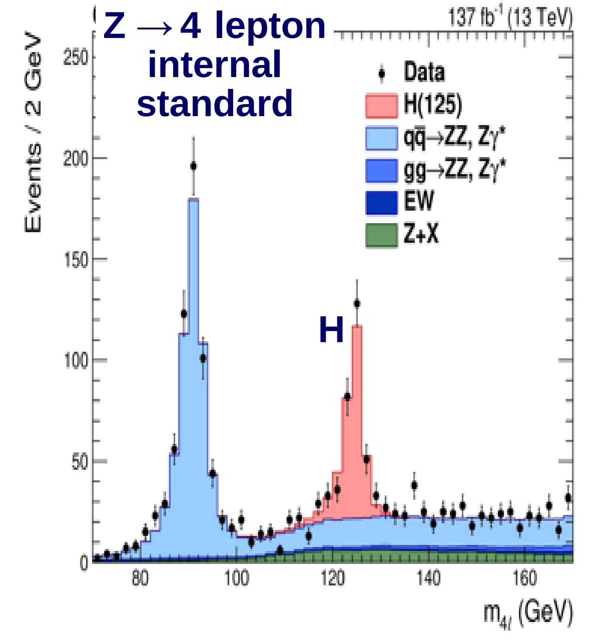
✷ HL-LHC: Expect ~20 MeV precision

CMS PAS FTR-21/007 and 21/008

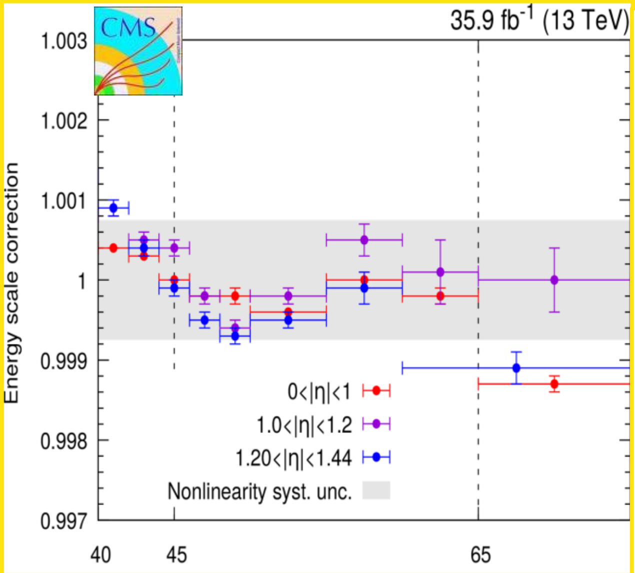
M_H (GeV)



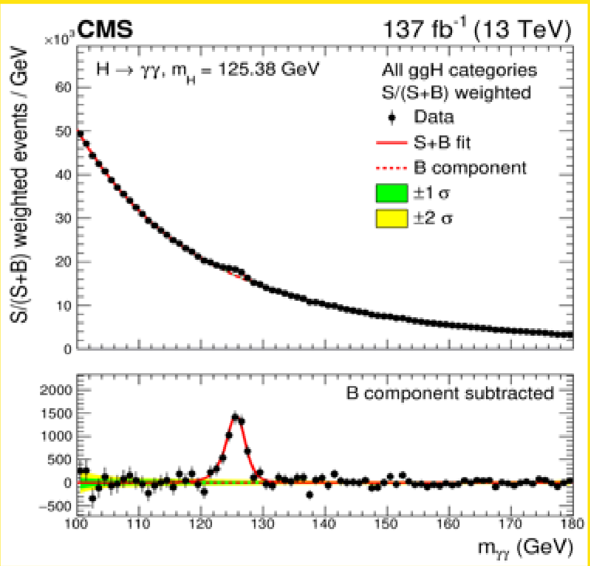
$H \to ZZ \to 4$ lepton (Run 2) Mass distribution



Photon Energy Scale correction vs p_T



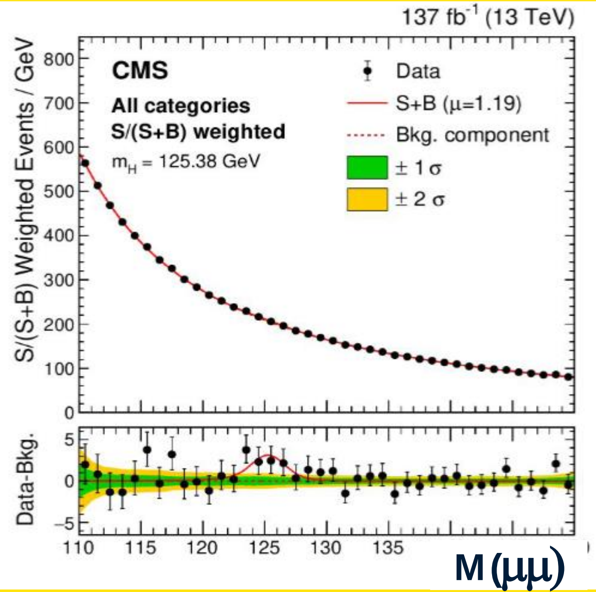
$H \to \gamma\gamma \to 4$ lepton (Run 2) Mass distribution



Decay Coupling Strengths $\mu = \sigma/\sigma_{SM}$ *Long Road to the Combination*

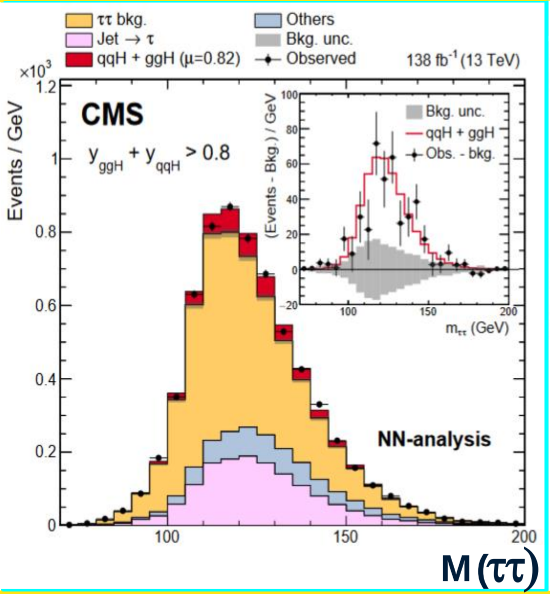
Nature 607 (2022) 60-68

$H \rightarrow \mu\mu$ January 2021



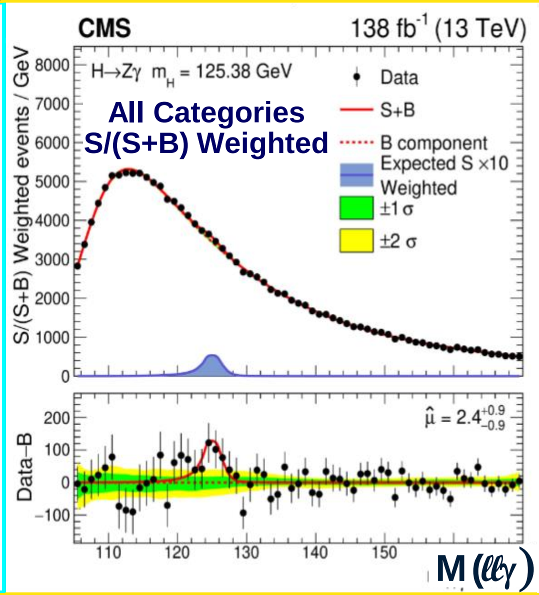
JHEP 01(2021)148

$H \rightarrow \tau\tau$ April 2022



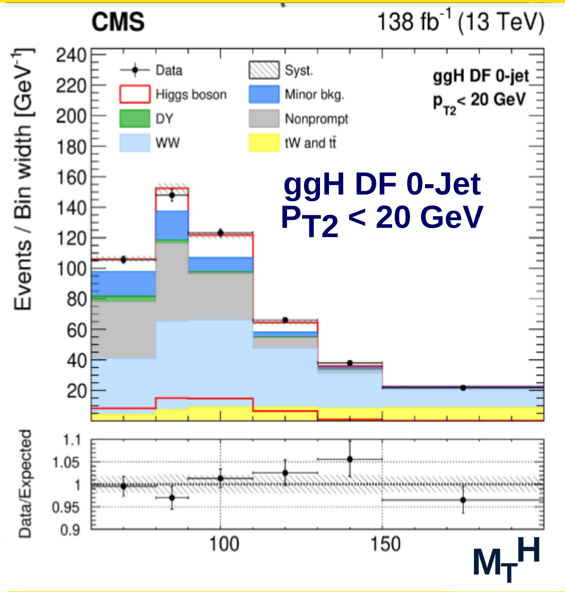
Accepted for Eur. Phys. J. C

$H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ April 2022



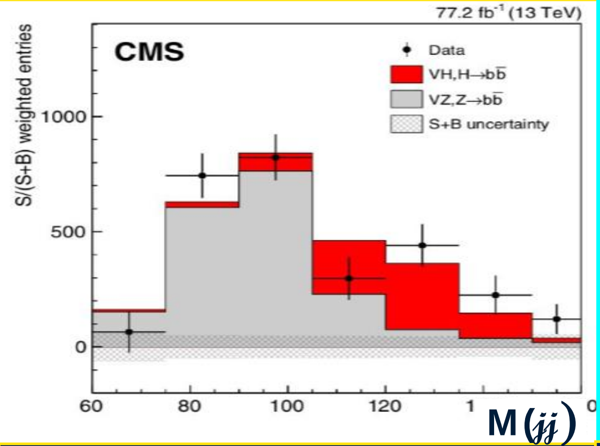
Accepted for JHEP

$H \rightarrow WW$ October 2022



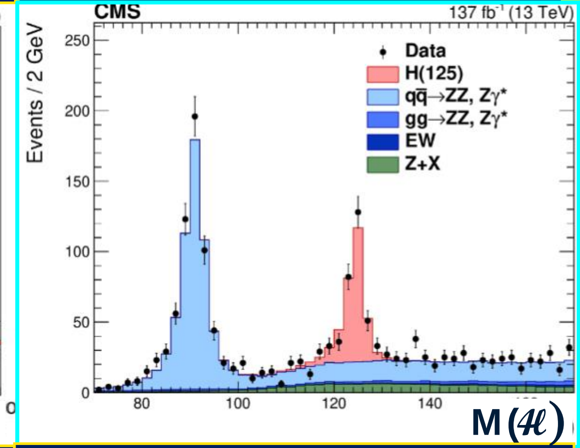
Accepted for Eur. Phys. J. C

$H \rightarrow bb$ 2018



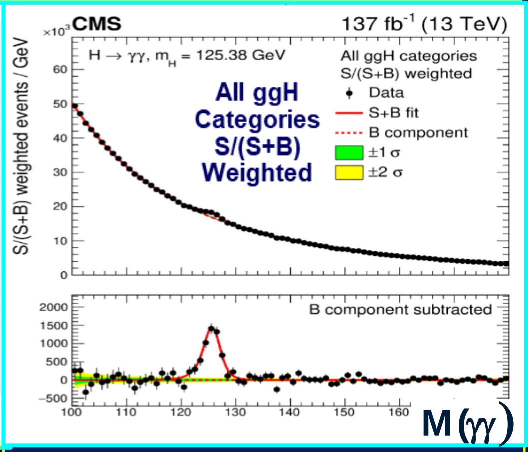
PRL 121, 121801

$H \rightarrow ZZ^* \rightarrow 4\ell$ 2021



Eur. Phys. J. C 81 (2021)

$H \rightarrow \gamma\gamma$ 2021



JHEP 07 (2021) 027

Including Difficult and Rare Decays

See P. Lenzi Talk at Higgs 2022

Recent: $H \rightarrow WW$ Production σ and Couplings

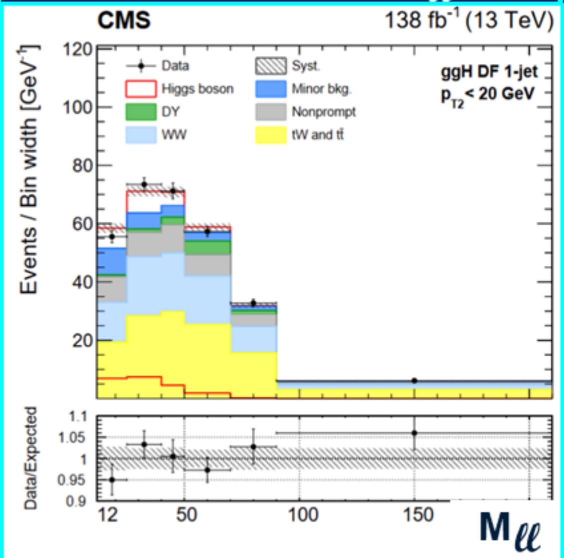
CMS-HIG-20-013 October 2022
Accepted for Eur. Phys.J. C

- **Steady Improvement of Analysis Techniques**
- **Categories overview: Production, leptons, jets;**
  + p_T ranges

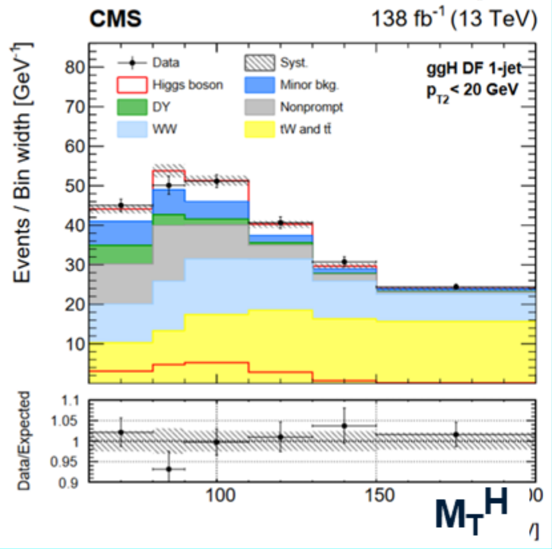
Category	Number of leptons	Number of jets	Subcategorization
ggH	2	—	(DF, SF) × (0 jets, 1 jet, ≥2 jets)
VBF	2	≥2	(DF, SF)
VH2j	2	≥2	(DF, SF)
WHSS	2	≥1	(DF, SF) × (1 jet, 2 jets)
WH3ℓ	3	0	SF lepton pair with opposite or same sign
ZH3ℓ	3	≥1	(1 jet, 2 jets)
ZH4ℓ	4	—	(DF, SF)

- **Main backgrnds: WW, DY; + VV (V = W,Z,γ), tW, $\tau\tau$**
- **Scalar nature of the Higgs leads to lower $m_{\ell\ell}$ relative to WW background**
- **Also need $m_T^H = m_T(m_{\ell\ell}, p_T^{miss})$ to discriminate against low $m_{\ell\ell}$ events from $\tau\tau$, Vγ**
- **b-jet veto against top; multiple control regions to normalize the backgrounds**
- **Final ggH discrimination in the 2D ($m_{\ell\ell}$, m_T^H) plane**
- **DNN Multiclassifier for VBF vs t, WW, ggH**

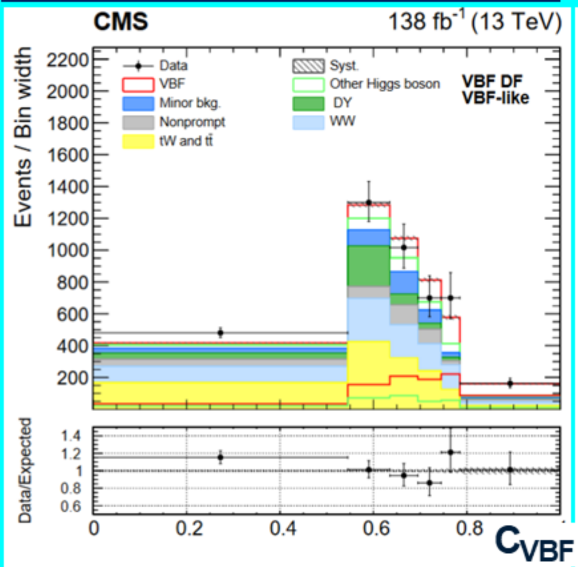
ggH DF 1-Jet $M_{\ell\ell}$



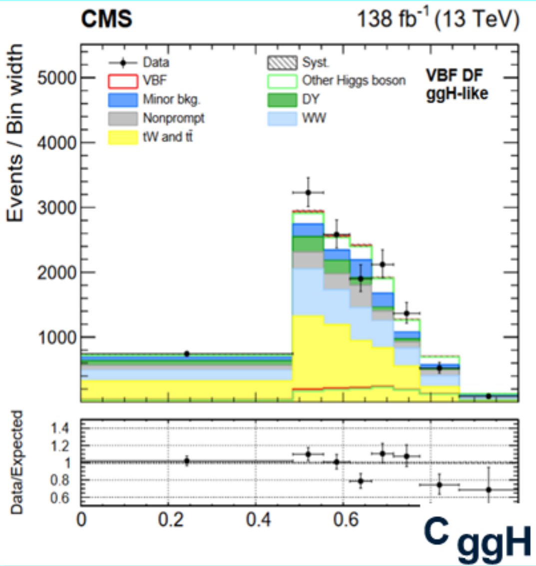
ggH DF 1-Jet M_T^H



C_{VBF} for DF VBF-Like



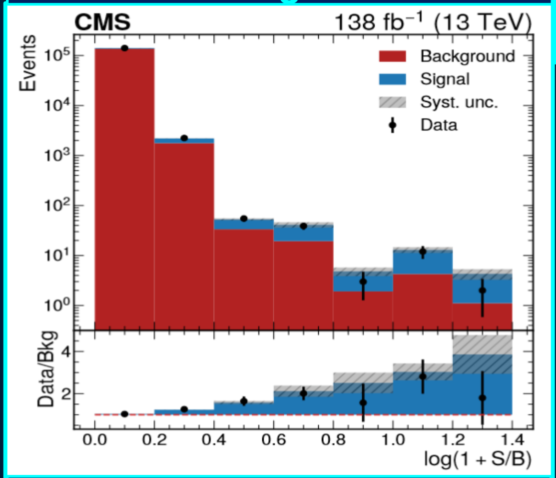
C_{ggH} for DF ggH-Like



H → WW Results

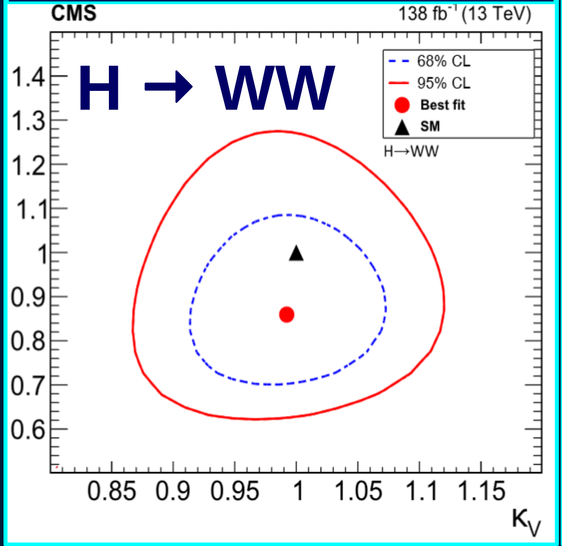
CMS-HIG-20-013 October 2022
Accepted for Eur. Phys.J. C

Distribution of events vs stat. significance

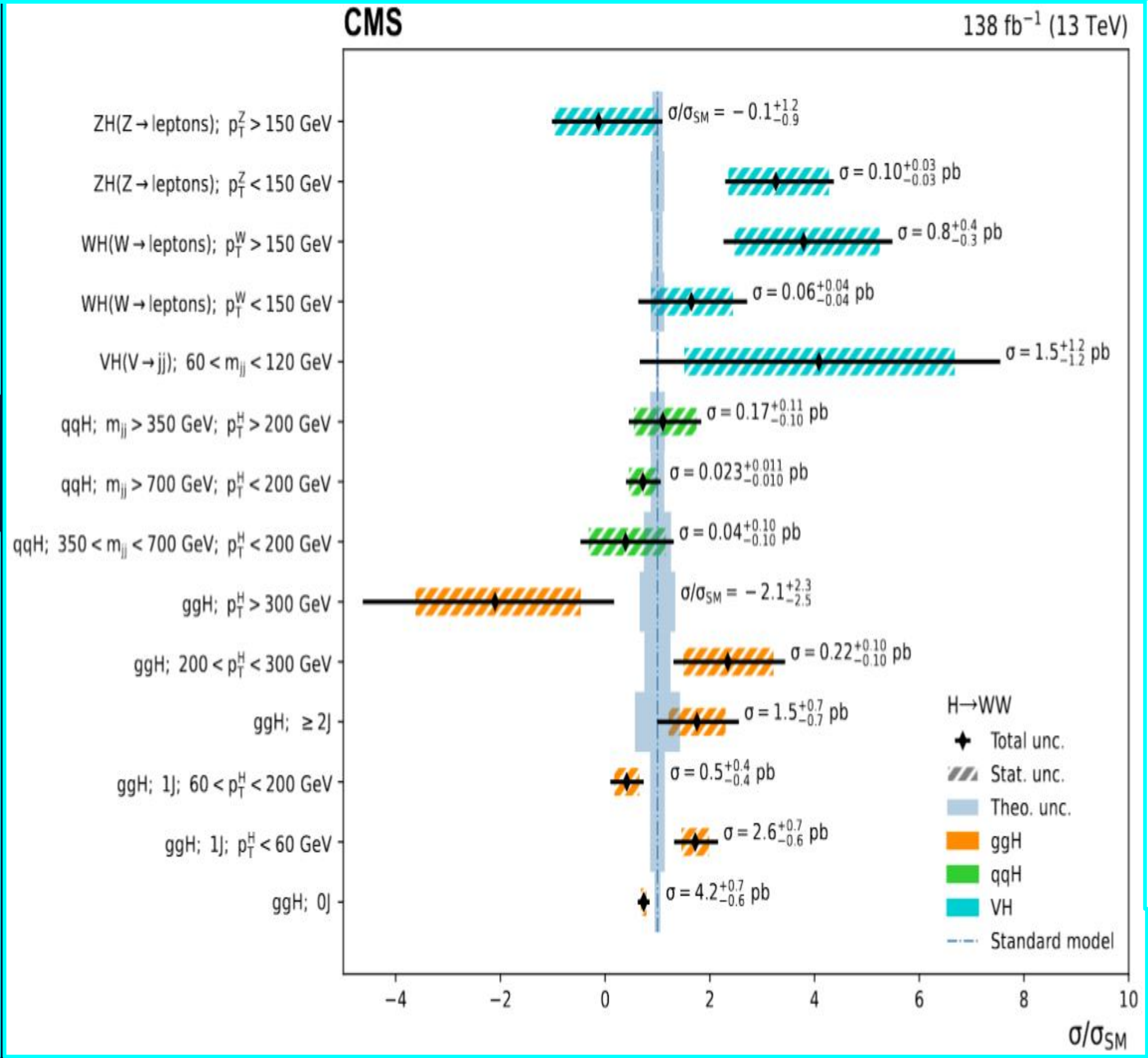


Signal and background contributions after the fit

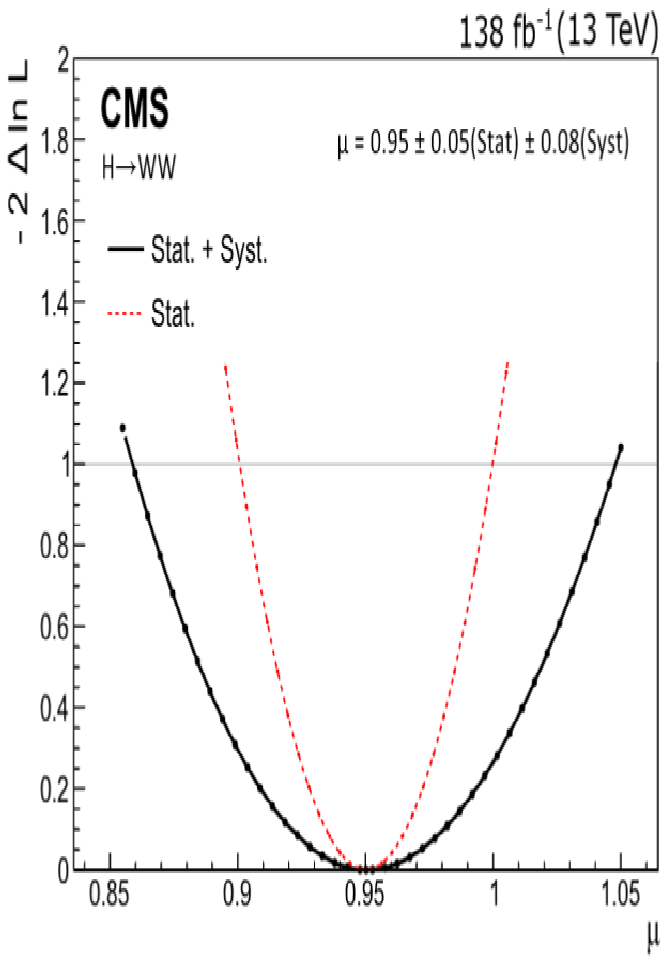
H → WW κ_F vs κ_V



Observed σ/σ_{SM} in each STXS Bin



Global H → WW Strength Modifer μ



$$\mu = 0.95 \pm 0.05\,(\text{stat}) \pm 0.08\,(\text{sys})$$

Inputs to the Combination

Nature 607 (2022) 60-68

The 5 Main Modes: 2022 Combination vs 2016

Channel	stat/syst in 2016 comb	Global μ	Stat	Syst	# STXS bins with unc < 100%
WW	0.10/0.15	0.95	0.05	0.08	~11
ZZ	0.15/0.11	0.94	0.07	0.09	~8
γγ	0.12/0.11	1.12	0.07	0.07	~16
ττ	0.15/0.23	0.82	0.06	0.08	~11
bb	0.31 (stat+sys)	1.04	0.14	0.14	-

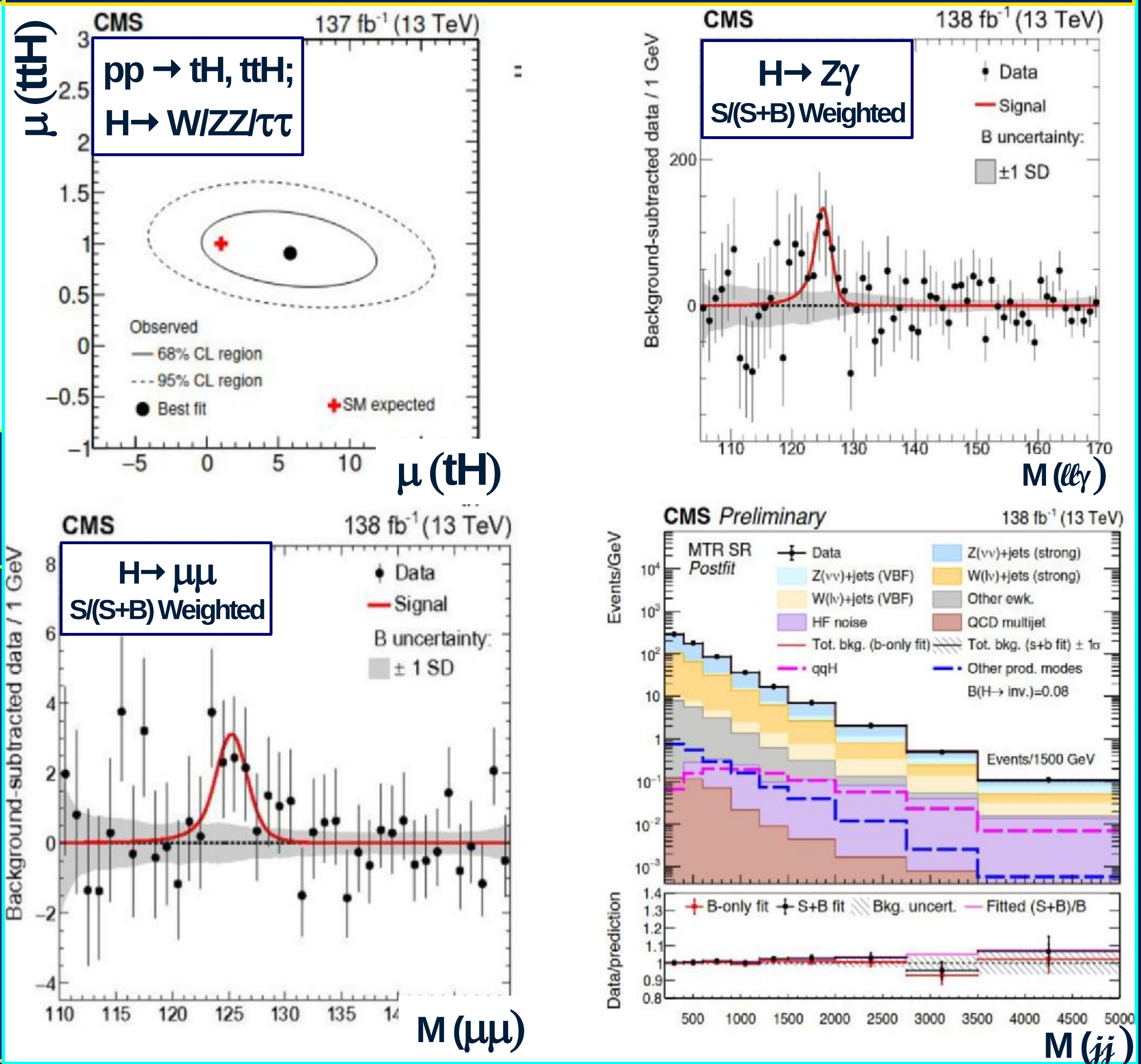
- *Ongoing* improvements in analysis techniques
- Some systematics reduced with increased statistics
- Excellent prospects for Run3

ℛare Processes

- **ttH to multileptons:** New categories, extended ML: Significance 4.7σ (5.2 exp) for ttH; 1.4σ (0.3 exp) for tH
- **H → Zγ: 2.7σ**
- **H → μμ: 3.0 σ**
- **H → Invisible:** Dedicated Triggers in 2017 and 2018 ℬ (H Inv) < 0.18 (0.10 exp); was < 0.22 in 2016

See P. Lenzi Talk at Higgs 2022

ℛare Process Contributions



Coupling Strengths $\mu = \sigma/\sigma_{SM}$

in Production and Decay modes

Nature 607 (2022) 60-68

- **5 well established decay modes with > 5σ:**

  ZZ, γγ, WW, ττ, bb

  Event Rates compatible with the SM

- **Challenge:**

  Experimental statistical uncertainty comparable to systematics and theory

- **Overall Signal strength**

  μ = 1.002 ±0.036 (stat) ±0.029 (exp) ±0.033 (th)

- **Main production modes measured:**

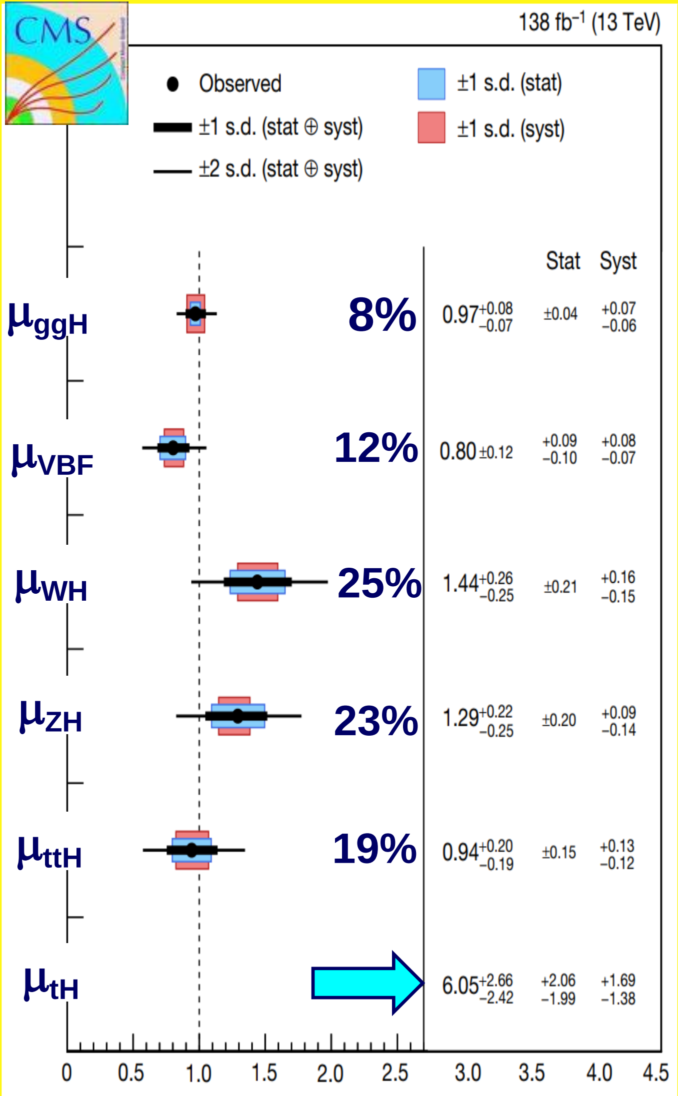
  ggF, VBF, WH, ZH, ttH, tH

- **Difficult (cc) and rare (μμ, Zγ) decay modes: measurements underway**

- ***Hints of excesses* in rare production and decays: to be resolved with Run 3 data**

Production Mode

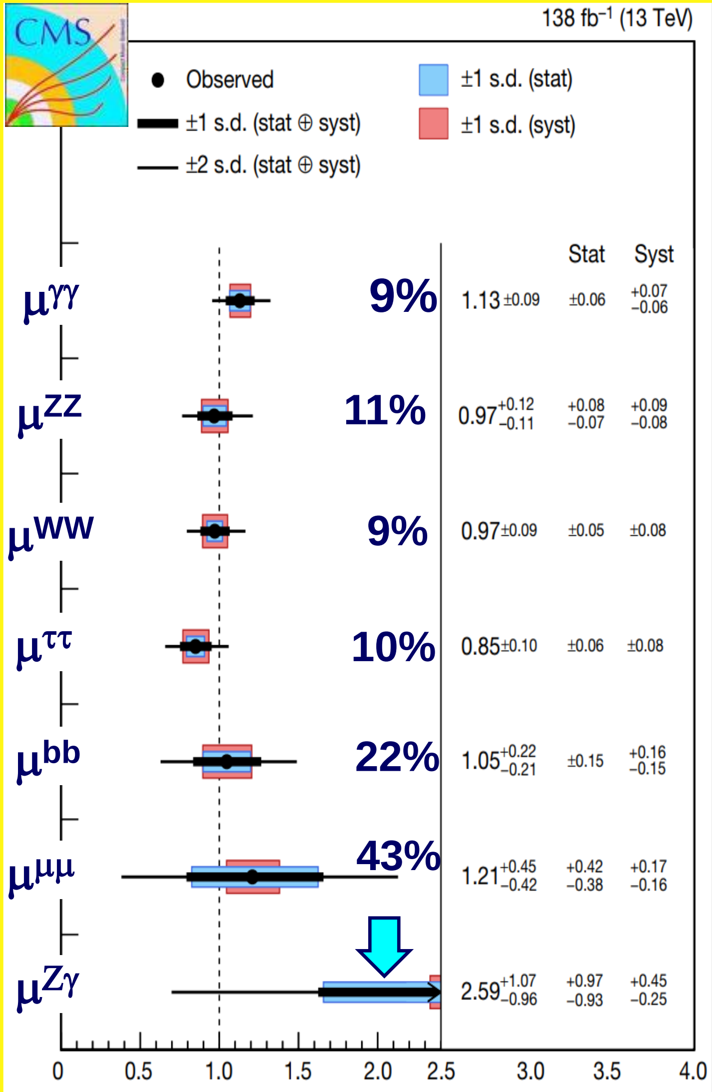
Signal Strengths μ_i



Assuming $\mathcal{B}_f = \mathcal{B}_f(SM)$

Decay Channel

Signal Strengths μ^f



Assuming $\sigma_i = \sigma_i(SM)$

1st Evidence for H → μμ ($\mathcal{BR}$ = 0.02%)

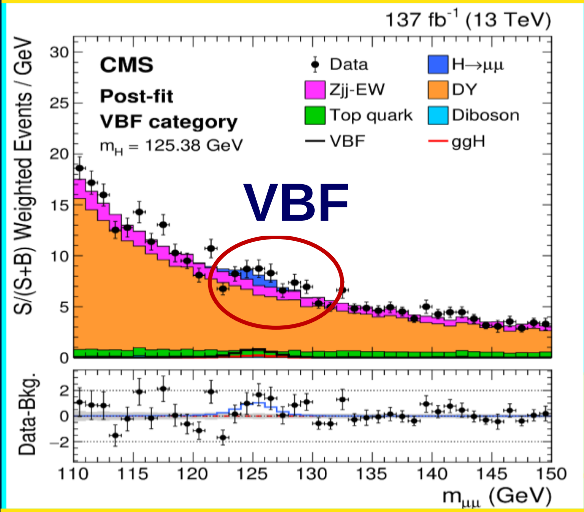
Most Sensitive to 2nd Generation Fermion Coupling

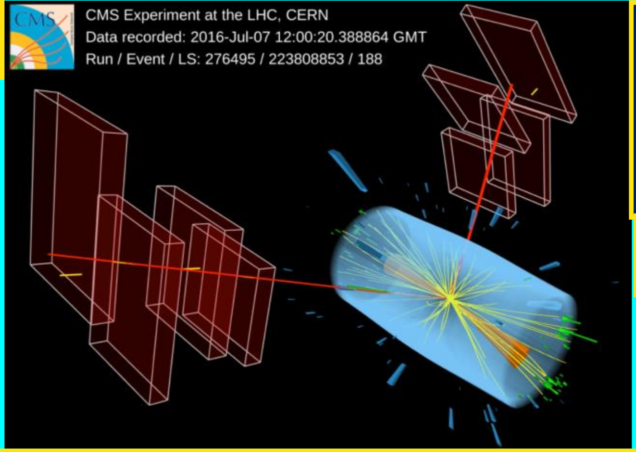
Full Run2 137/fb + Run1

JHEP 01 (2021) 148

VBF: Advanced DNN Machine Learning Techniques Provide similar sensitivity as in ggH

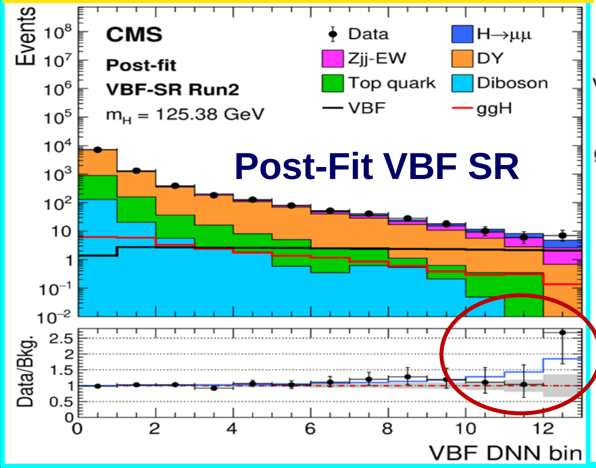
Mμμ distribution



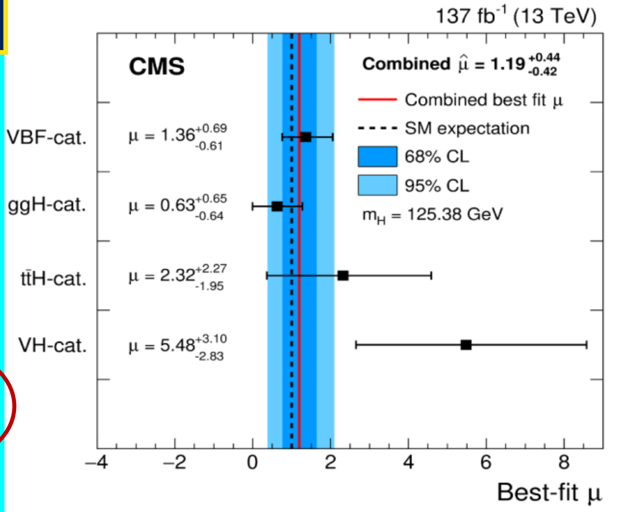


VBF: Drell Yan background suppressed by two forward jets

Deep Neural Net Output



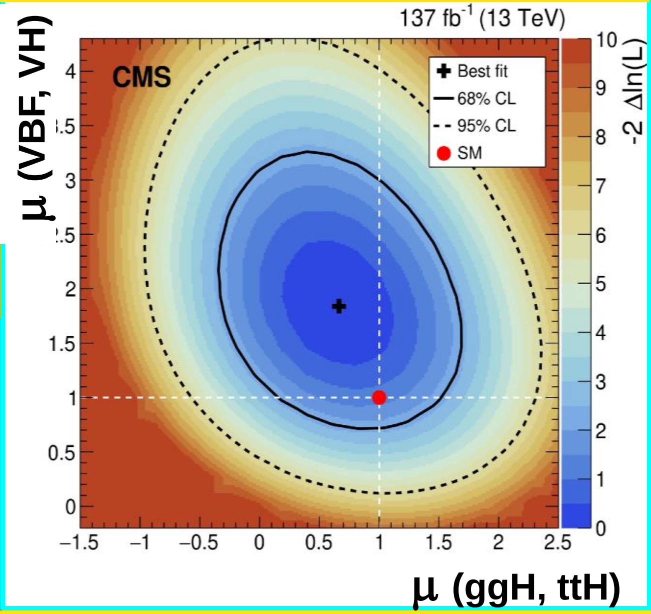
Strengths vs Production Mode



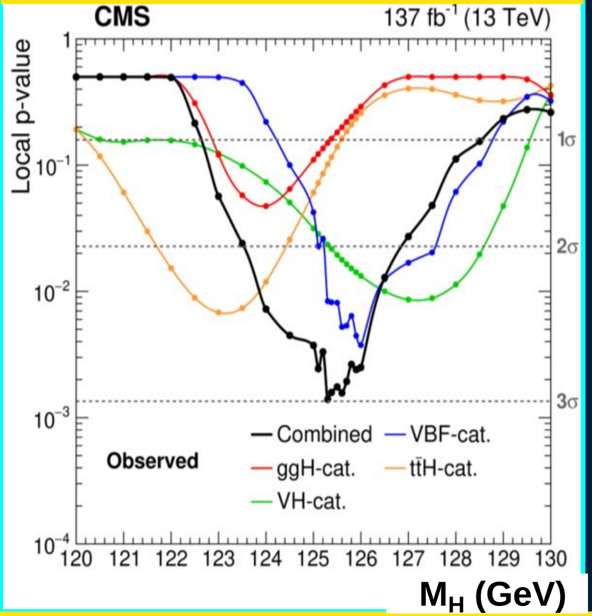
$$\mu(\mu\mu) = 1.19\ ^{+0.40}_{-0.39}\ \text{(Stat)}\ ^{+0.15}_{-0.14}\ \text{(Sys)}$$

Observed (exp) Significance: 3.0σ (2.5σ)

μ (VBF, VH) vs μ(ggH, ttH)



Local p-value vs M_H



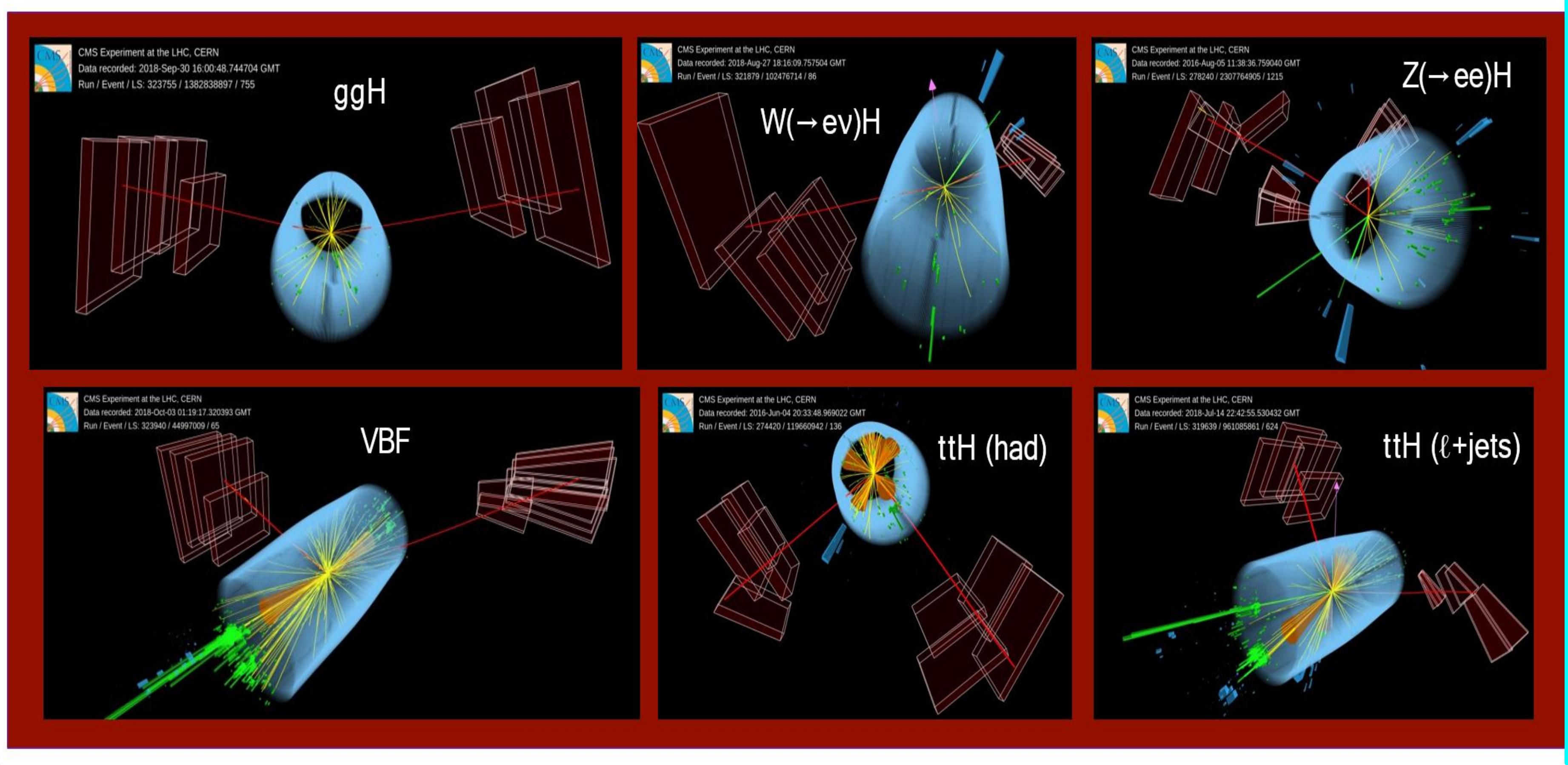
Higgs boson coupling to muons:

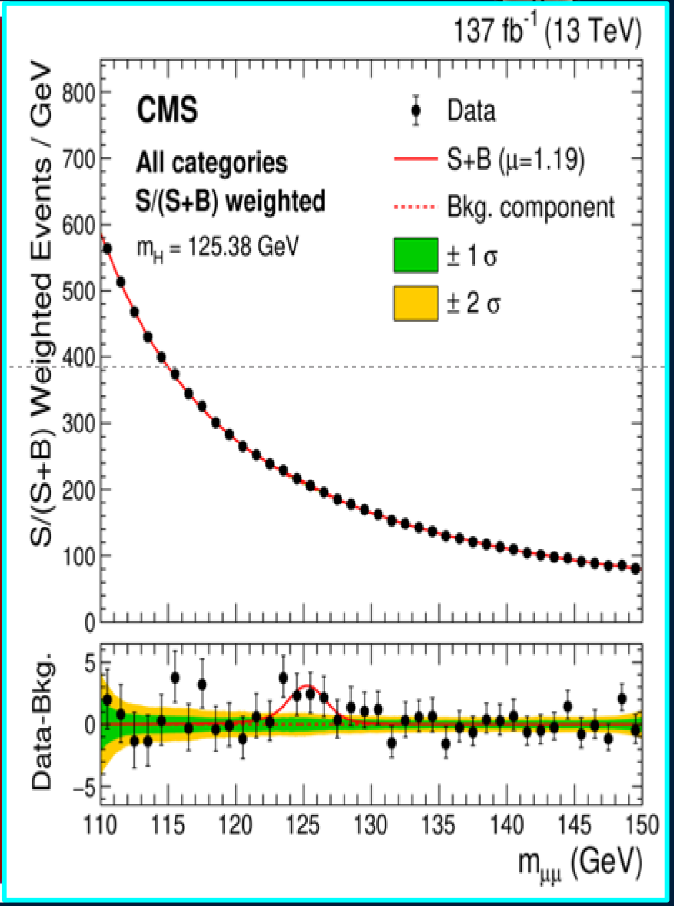
$$\kappa_\mu = 1.07 \pm 0.22$$

See YSF Talk at La Thuile 2021 by Irene Dutta

First Evidence (3.0σ) for H → μμ

Exclusive categories: ggH, VBF, VH and ttH





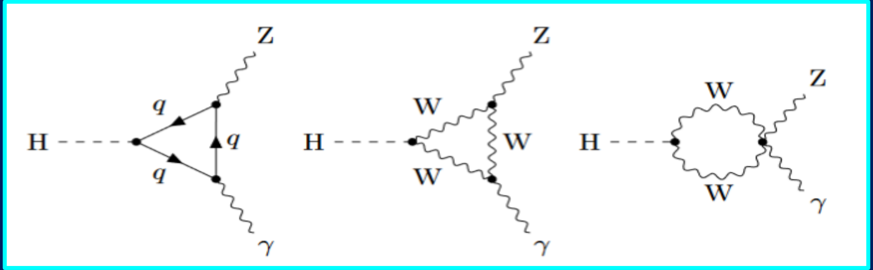
Assuming the SM need ~4 Times the Data for a 5σ Observation

There is some possibility by the end of Run3

Search for H → $Z\gamma$, $Z \to \ell^+\ell^-$ ℓ = (e, μ) CMS PAS HIG-19-014 Accepted by JHEP

- **SM: $\mathcal{B}(H \to Z\gamma)$ / $\mathcal{B}(Z \to ee/\mu\mu) \sim 10^{-4}$**

  Loop Induced: Sensitive to BSM physics



- **Two prompt leptons** with $M_{\ell\ell} \sim M_Z$

  VBF, VH, ttH categories; +ggH with $\mathcal{D}$kin($\ell\ell\gamma$)

  Simultaneous fit to M($\ell\ell\gamma$) in all categories

- **Signal Strength $\mu = \sigma/\sigma_{SM}$**

  for (pp → H) X $\mathcal{B}(H \to Z\gamma)$:

  $\mu = 2.4 \pm 0.9$; Significance 2.7 σ;

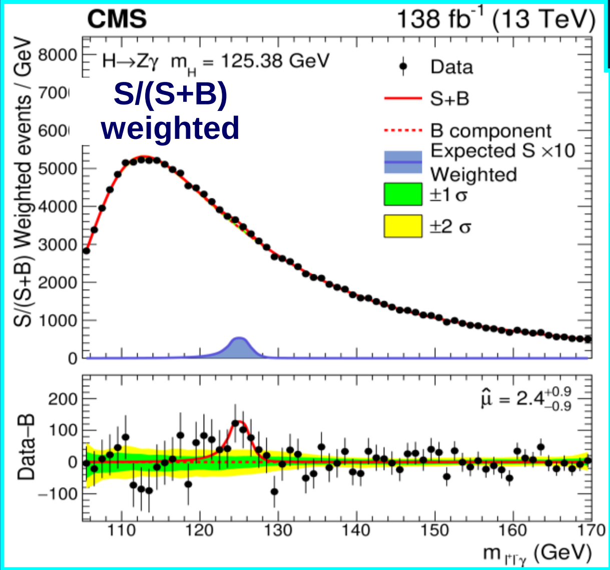
  95% CL Limit: 4.1 observed (1.8 exp)

- **$\mathcal{B}(H \to Z\gamma)$ / $\mathcal{B}(H \to \gamma\gamma)$ = 1.5 +0.7 -0.6**

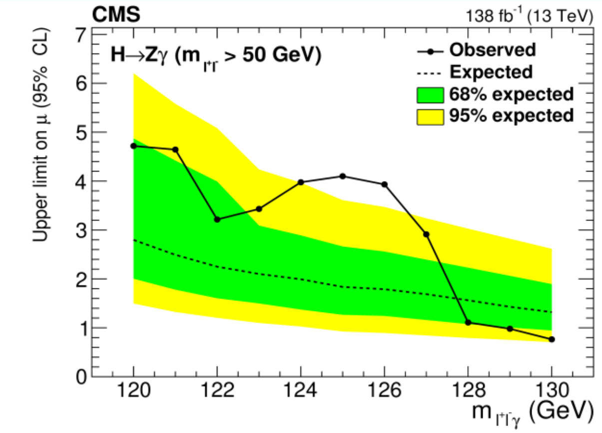
  Compatible with SM ratio

  0.69 ± 0.04 at 1.5σ level

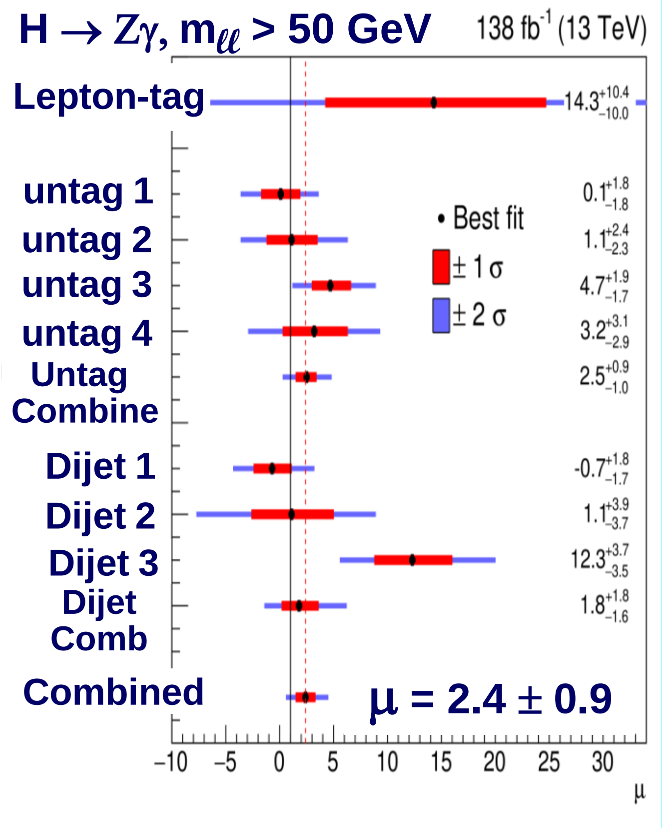
M($\ell\ell\gamma$) distribution All categories



μ: 95% CL Upper Limit Versus M($\ell\ell\gamma$)



μ in each category

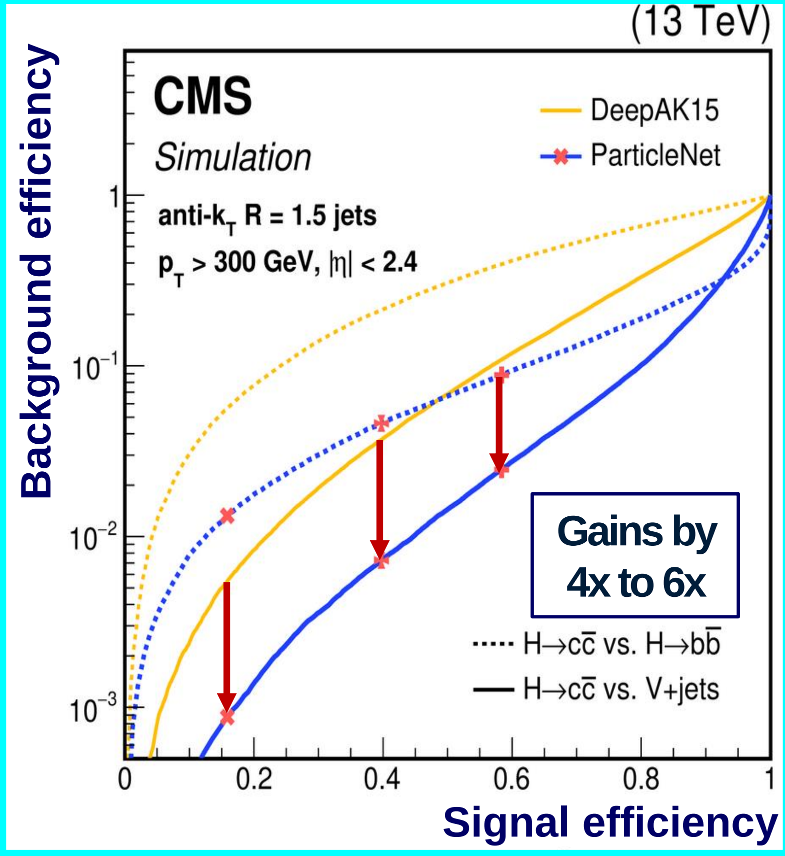


Search for H → c$\bar{c}$ Full Run 2

CMS HIG-21-008
Accepted for PRL(May 2022)

- **Probing Higgs boson Couplings to 2nd Generation Quarks**
- **SM: $\mathscr{B}$(H → c$\bar{c}$) = 2.9%**
- **Using VH (H → c$\bar{c}$) with Z → νν, W → ℓν, Z → ℓℓ (0,1,2 lepton categories)**
- **Challenging backgrounds:**
  - **V + Jets (Enormous cross section)**
  - **VH, H → b$\bar{b}$ (20X the H → c$\bar{c}$ rate)**
  - **Need 3-way discriminator: q/g jet vs c-jet vs b-jet**
- **pp → VZ, Z → c$\bar{c}$ standard candle validates the analysis**
- **ParticleNet GNN discriminator for H → c$\bar{c}$: PF, secondary vtx, wide jets**
  - **p_T > 300 GeV separates boosted Higgs with merged c-quark jets, from resolved category**

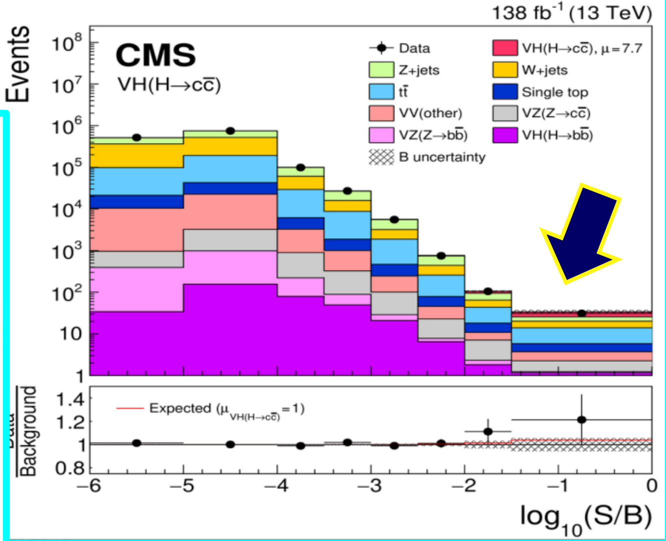
ParticleNet Tagger Efficiency for H → c$\bar{c}$ versus V + Jets and H → bb backgrounds



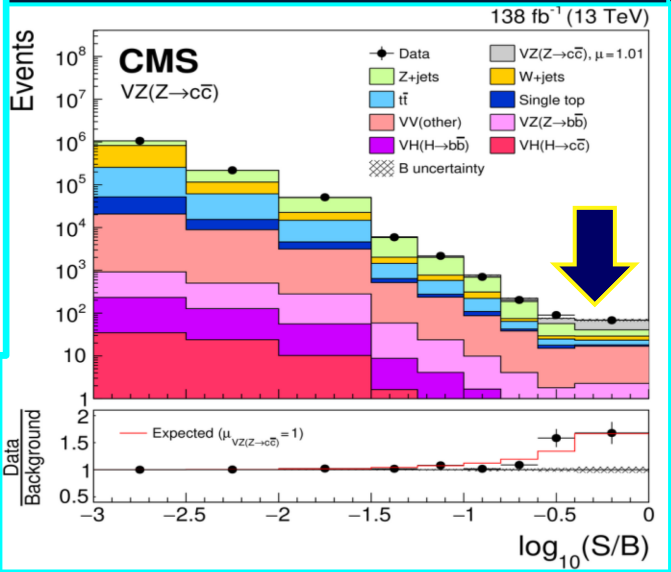
Showing the 3 WPs in the merged jet analysis

Compared to the previous DeepAK15 Tagger

VH (H → c$\bar{c}$) Events vs log (S/B)



VZ (Z → cc) Events vs log (S/B)



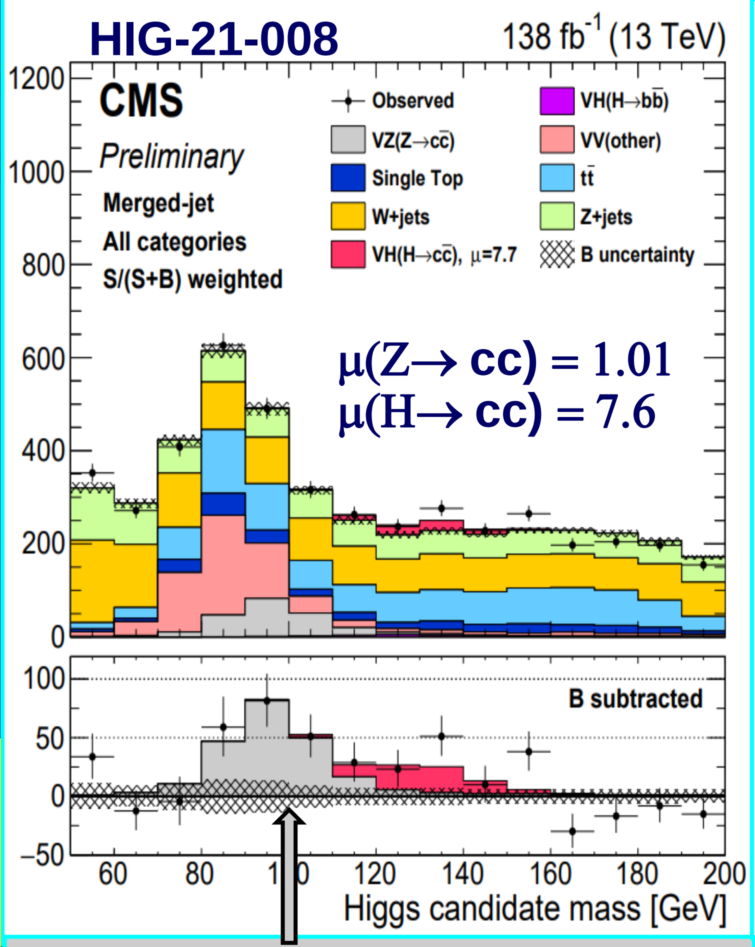
Search for $H \to c\bar{c}$ Full Run 2 $p_T > 450$ Boosted Analysis

CMS PAS HIG-21-008 (February 28, 2022) CMS PAS HIG-21-012 (November 25, 2022)

- Results: HIG-21-008
- Higgs-charm Yukawa coupling modifier $1.1 < |\kappa_c| < 5.5$ Observed
  ($|\kappa_c| < 3.4$ expected)
  - Most stringent limit to date
- Results All Categories:
  $\sigma(VH)\,\mathcal{B}(H \to c\bar{c}) = 0.50\ {+0.22}\ {-0.15}$ pb
  < 0.94 pb at 95% CL
- Signal strength μ (VH, $H \to c\bar{c}$):
  ⇨ $\mu = 7.6\ {+3.4}\ {-2.3}$; $\mu < 14$ at 95% CL
- *Bonus:* VZ, $Z \to c\bar{c}$: 1st observation at a hadron collider: 5.7σ
  $\mu\,(VZ, Z \to c\bar{c}) = 1.01^{+0.23}_{-0.21}$

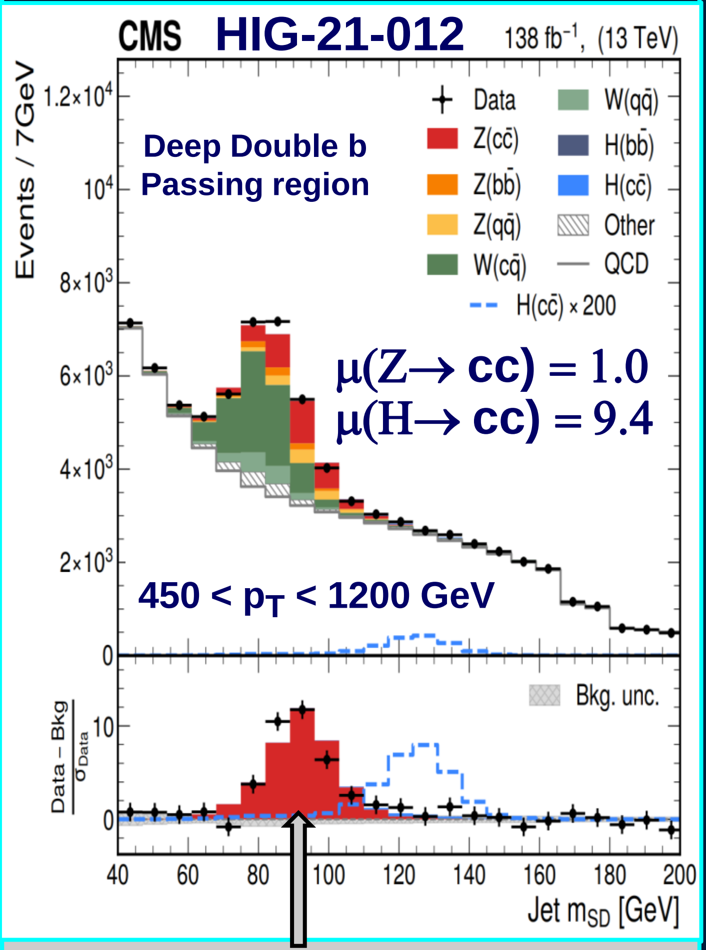
- Results: HIG-21-012 *Boosted:* high p_T
  $\mu < 47$ at 95% CL (39 expected)
- $\mu\,(VZ, Z \to c\bar{c}) = 1.00^{+0.17}_{-0.14} \pm 0.08\ (\text{th}) \pm 0.06\ (\text{stat})$

$M(H_{cand})$ distribution in all categories: merged-jet analysis



Standard Candle: VZ, $Z \to c\bar{c}$ 5.7σ

M_{SD} distribution in high p_T region: merged-jet analysis



Standard Candle: VZ, $Z \to c\bar{c}$

H Coupling Modifier Framework:

Characterize possible deviations from SM

κ Factors for Production and Decay

- There are 8 basic parameters to describe the major decays channels & production mechanisms:

$$\Gamma_{ZZ},\ \Gamma_{WW},\ \Gamma_{\tau\tau},\ \Gamma_{bb},\ \Gamma_{\gamma\gamma},\ \Gamma_{gg},\ \Gamma_{tt} \text{ and } \Gamma_{TOT}$$

$$N(xx \rightarrow \mathrm{H} \rightarrow yy) \sim \sigma(xx \rightarrow \mathrm{H}) \cdot B(\mathrm{H} \rightarrow yy) \sim \frac{\Gamma_{xx}\Gamma_{yy}}{\Gamma_{\mathrm{H}}}$$

- We cannot extract all the parameters at once with current data.
- So we do Coupling Compatibility Tests using scaling factors:

  κ relative to SM and their ratios λ

  Example: For the gg → H → γγ process:

  σ x BR(gg→H→γγ) / σ_{SM}xBR(gg →H→γγ)$_{SM}$= $\kappa_g^2\kappa_\gamma^2 / \kappa_H^2$
- Assumptions: Single narrow resonance, SM tensor structure;
  - No new physics in loops (gg →H, H→γγ)
  - No BSM decays (invisible, not observed)

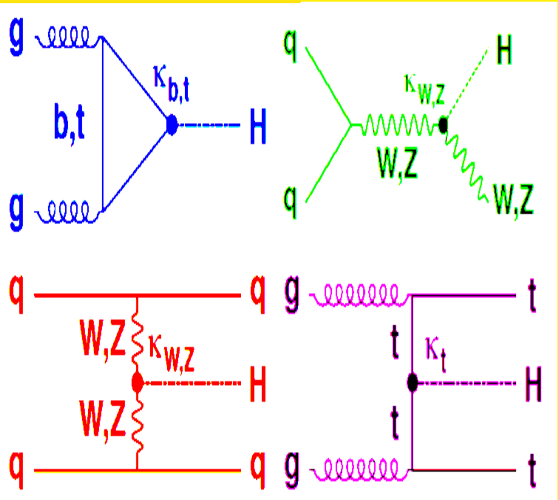
$$\sigma_i \sim \kappa_i^2\, \sigma_i^{SM}$$

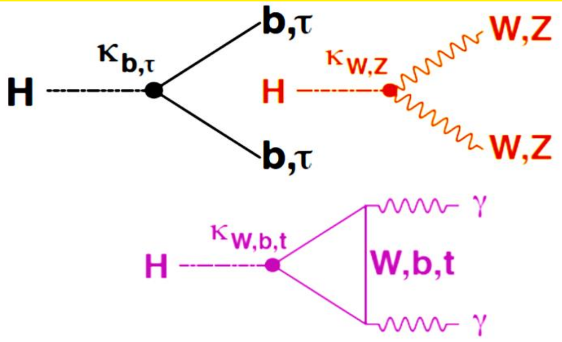
$$\Gamma_i \sim \kappa_i^2\, \Gamma_i^{SM}$$

$$\Gamma_H = \Sigma_i\, \kappa_i^2\, \Gamma_i^{SM}$$

$$g_F = \kappa_F \frac{\sqrt{2}m_F}{v}$$

$$g_V = \kappa_V \frac{2m_V^2}{v}$$





LHC Higgs Cross-Section WG 2013: CERN-2013-004 arXiv:1209.0040. arxiv 1310.4828

H Coupling Modifier Framework:

Characterize possible deviations from SM

κ Factors for Production and Decay

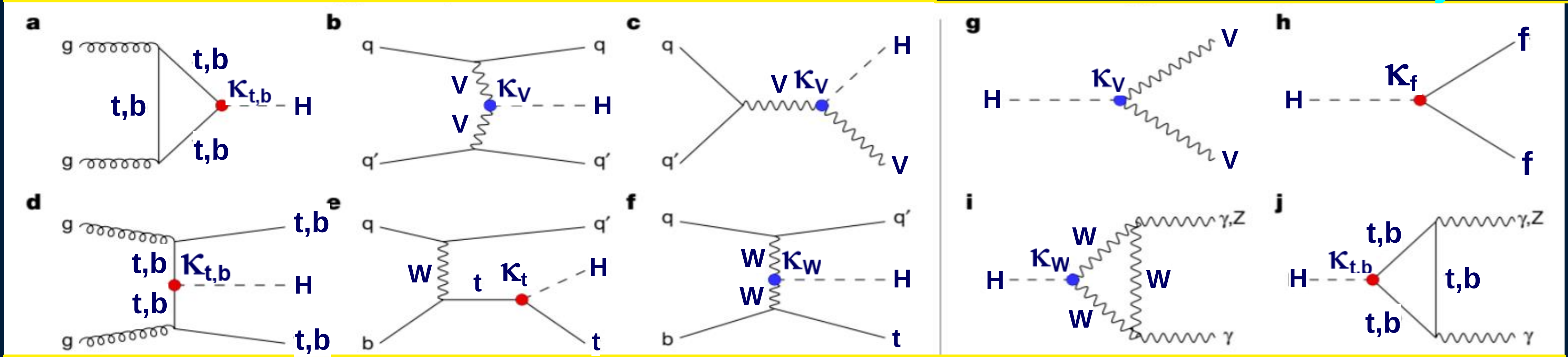
$\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$

$\Gamma_i \sim \kappa_i^2 \, \Gamma_i^{SM}$

$\Gamma_H = \Sigma_i \, \kappa_i^2 \, \Gamma_i^{SM}$

H Boson Production

H Boson Decay



H Pair Production

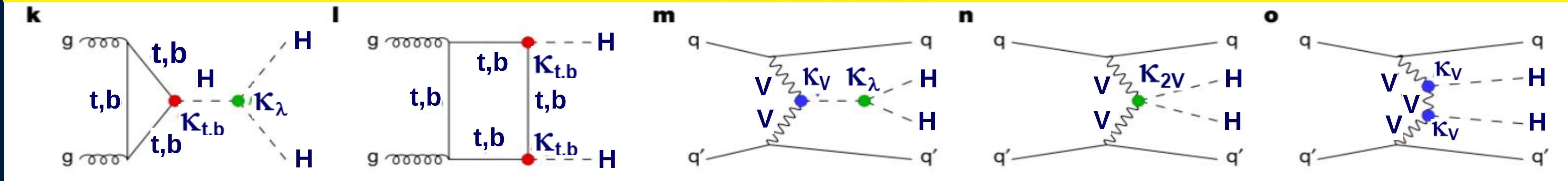


Fig. 1 | Feynman diagrams for the leading Higgs boson interactions. **a**–**f**, Higgs boson production in ggH (**a**) and VBF (**b**), associated production with a W or Z (V) boson (VH; **c**), associated production with a top or bottom quark pair (ttH or bbH; **d**) and associated production with a single top quark (tH; **e**,**f**). **g**–**j**, Higgs boson decays into heavy vector boson pairs (**g**), fermion–antifermion pairs (**h**) and photon pairs or Zγ (**i**,**j**). **k**–**o**, Higgs boson pair production through ggH (**k**,**l**) and through VBF (**m**,**n**,**o**). The different Higgs boson interactions are labelled with the coupling modifiers κ, and highlighted in different colours for Higgs–fermion interactions (red), Higgs–gauge-boson interactions (blue) and multiple Higgs boson interactions (green). The distinction between a particle and its antiparticle is dropped.

Summary of Higgs Couplings

Full Run2 137/fb

CMS-HIG-22-001

Nature 607 (2022) 60-68

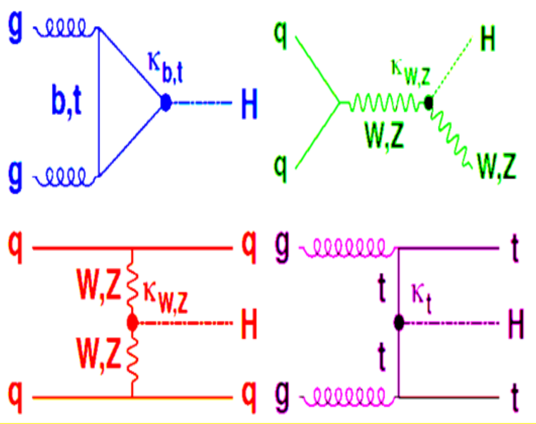
κ Factors for Production and Decay

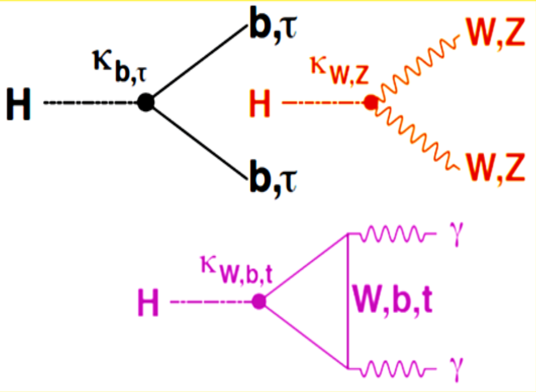
$\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$

$\Gamma_i \sim \kappa_i^2 \, \Gamma_i^{SM}$

$\Gamma_H = \Sigma_i \, \kappa_i^2 \, \Gamma_i^{SM}$

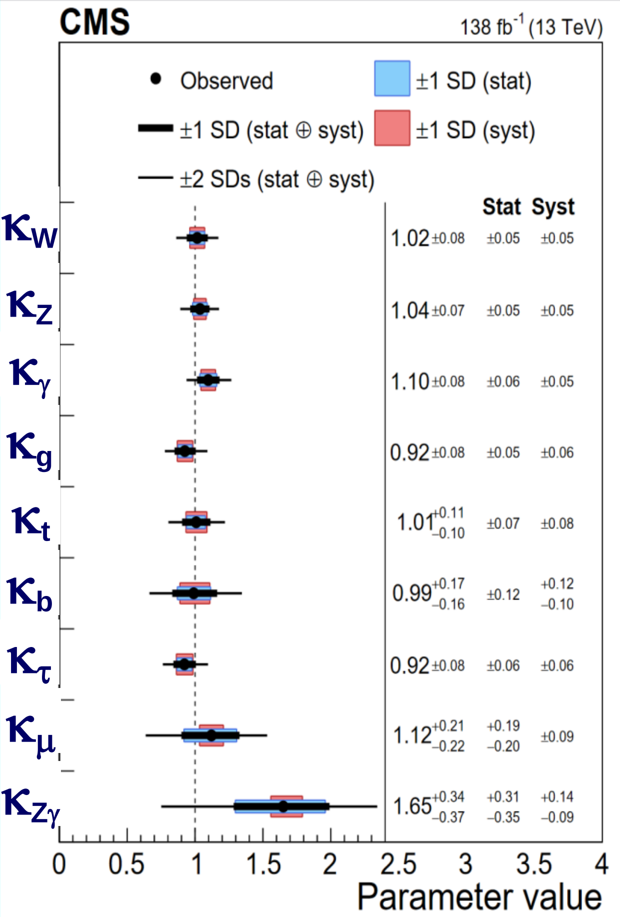
$N(xx \to H \to yy) \sim \sigma(xx \to H) \cdot B(H \to yy) \sim \frac{\sigma_{xx} \Gamma_{yy}}{\Gamma_H}$



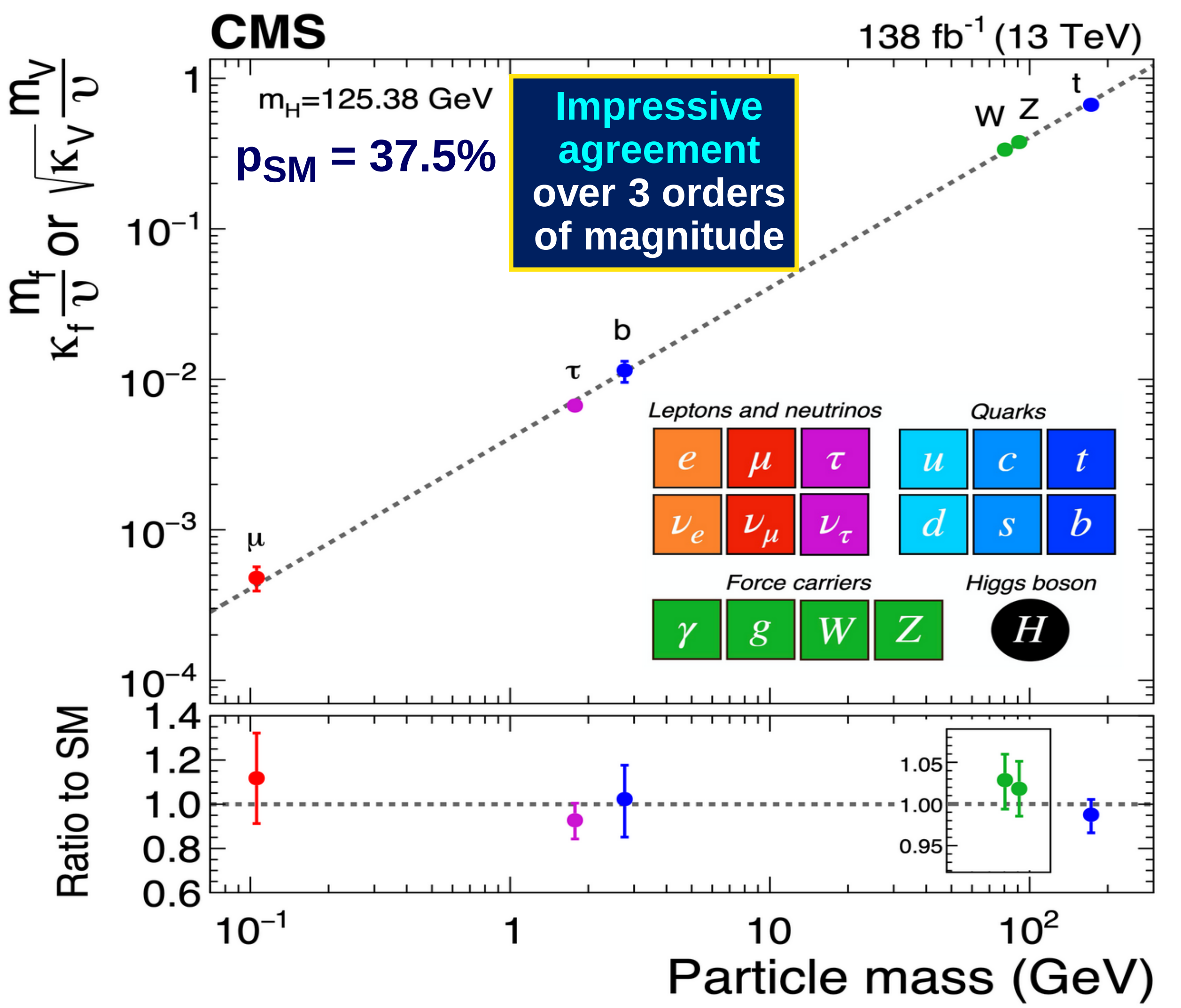


Fit for Coupling strength parameters (κ)

Meaningful 68% and 95% CL intervals for 2nd Generation Fermion (μ,b) and Zγ Couplings



$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$ vs Particle Mass



p_{SM} = 37.5%

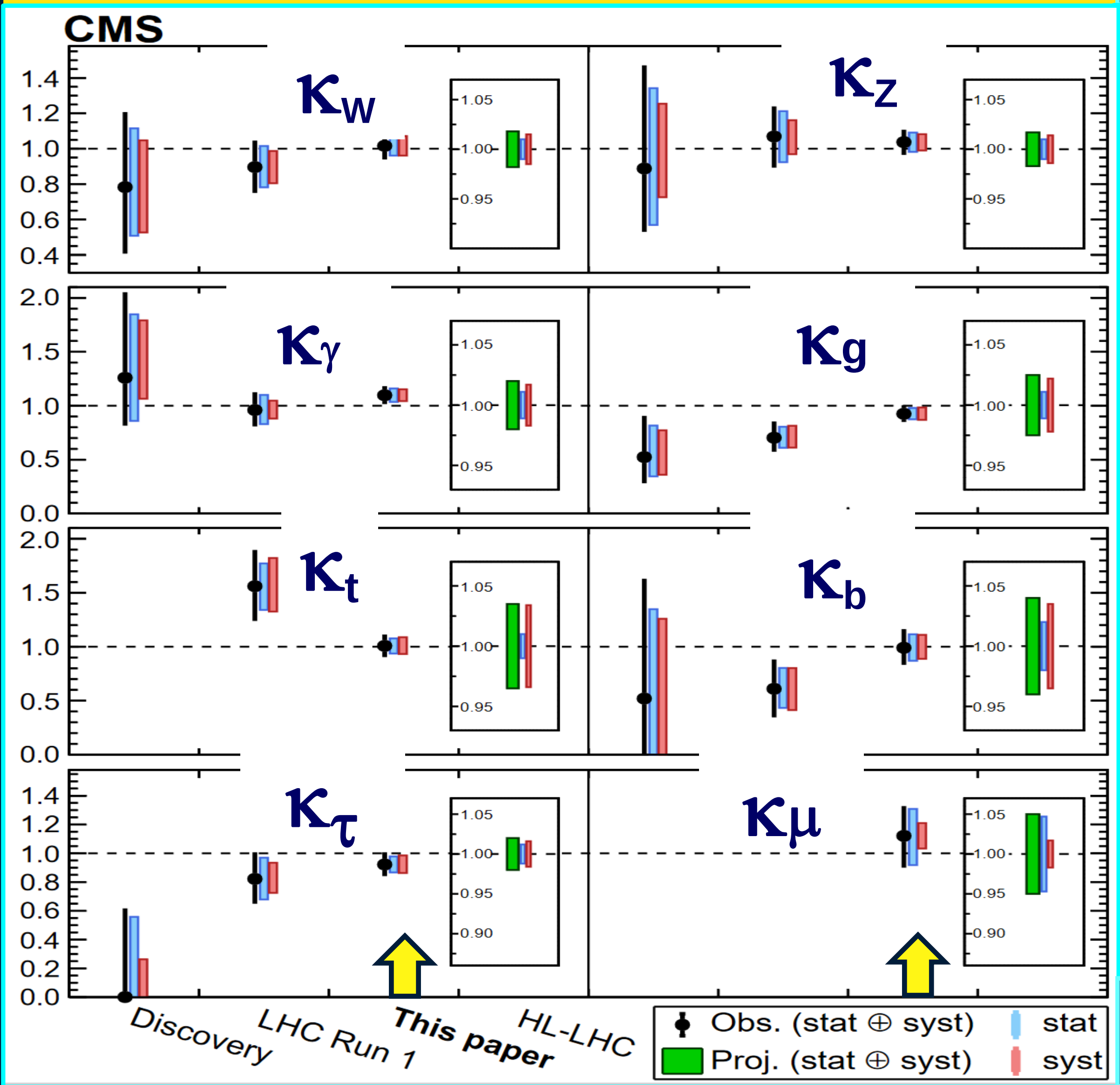
Impressive agreement over 3 orders of magnitude

Higgs Coupling Strength Parameters: The Road to Precision from Discovery to 2023 and Forward to HL LHC

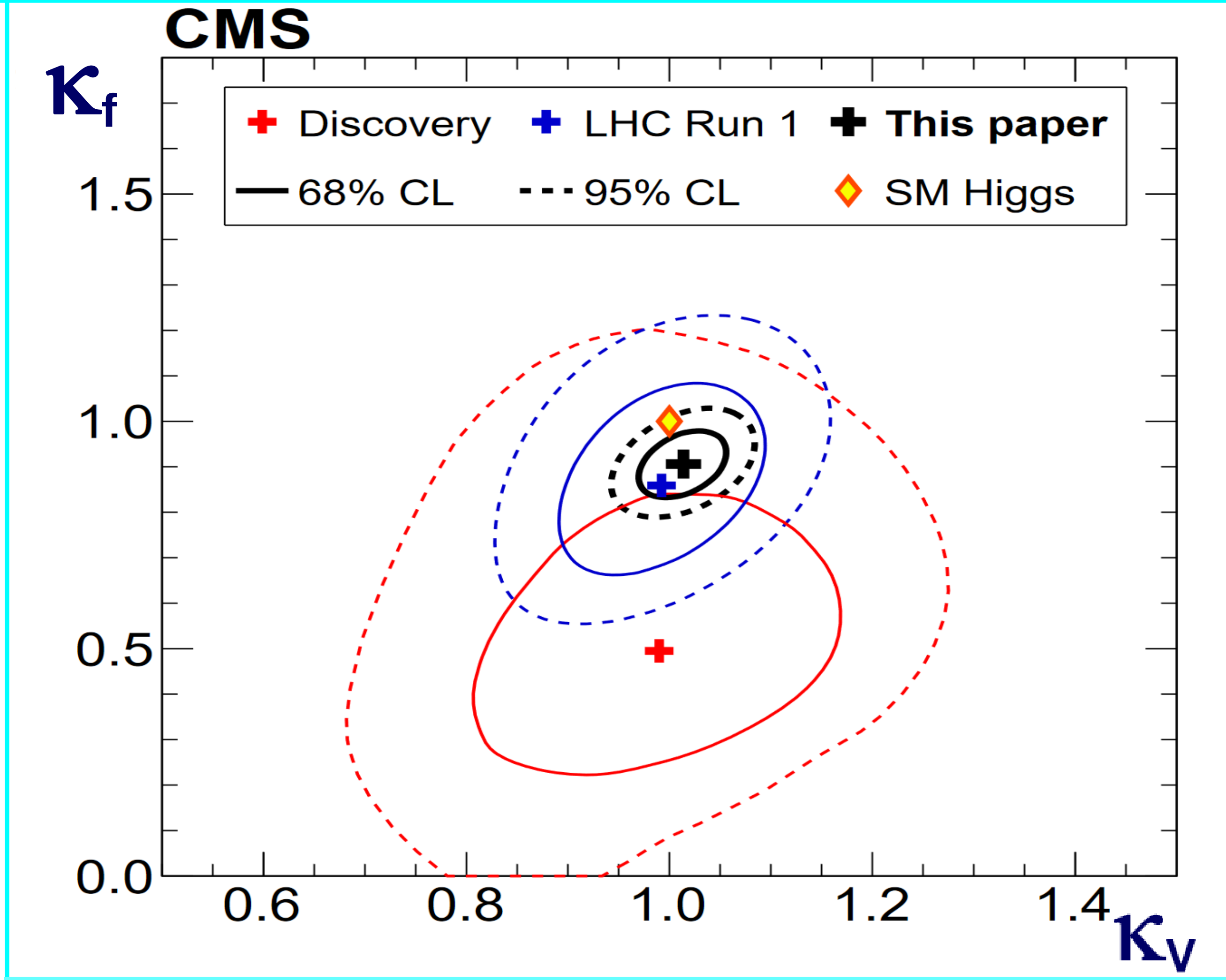
Full Run2 137/fb

Nature 607 (2022) 60-68

Coupling parameters (κ)



κ_f vs κ_V from Discovery to Run1 to Full Run2



Deviations in the couplings can affect **production** as well as **specific decay channels**

Higgs Boson Natural Width and Off-Shell Contributions

$$\sigma^{\text{on-shell}} \propto \frac{g_{\text{p}}^2 g_{\text{d}}^2}{\Gamma_{\text{H}}} \propto \mu_{\text{p}} \Rightarrow \sigma^{\text{off-shell}} \propto g_{\text{p}}^2 g_{\text{d}}^2 \propto \mu_{\text{p}} \Gamma_{\text{H}}$$

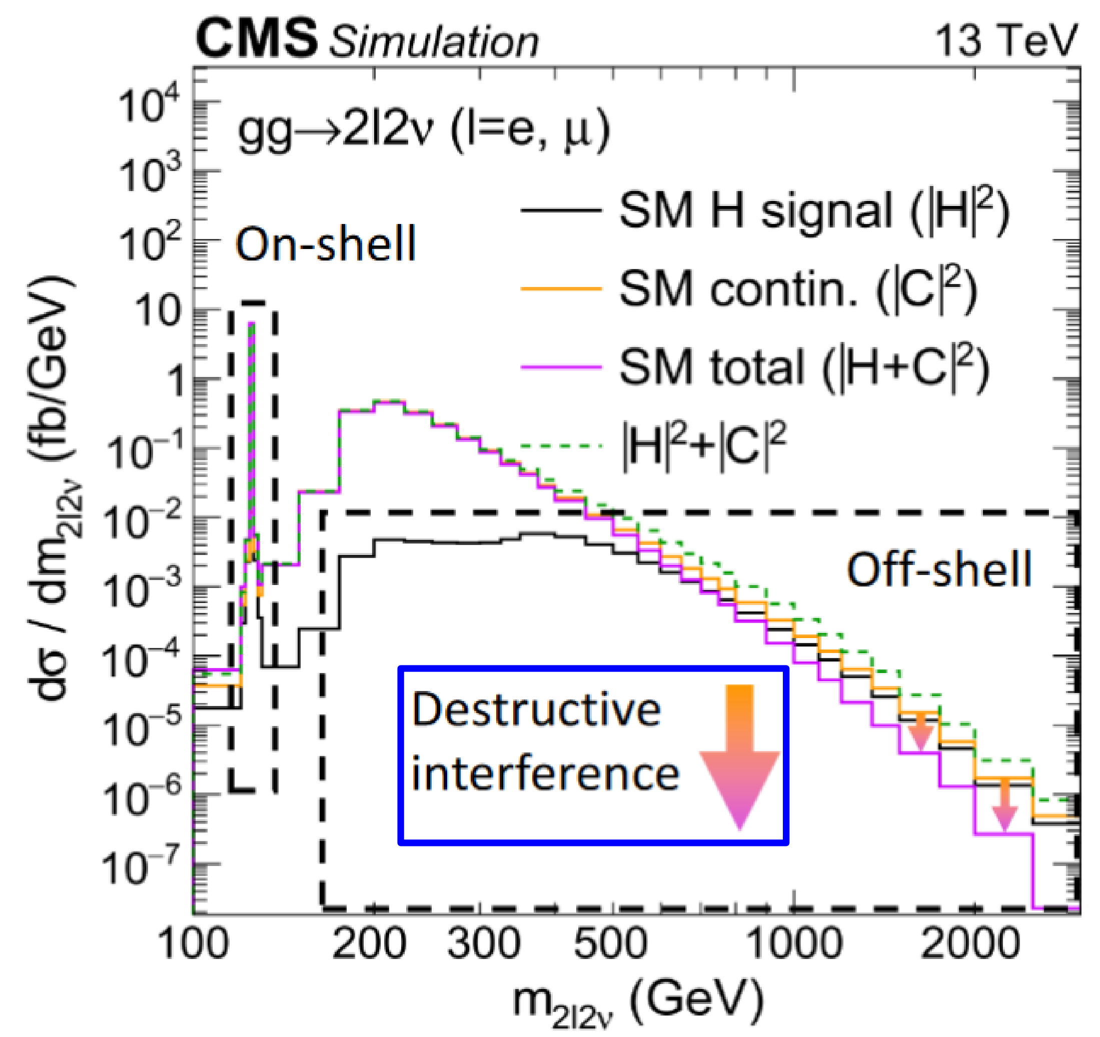
Nature Phys. 18 (2022) 1329

- Measurement ratio of on-shell to off-shell signal strengths for each production mode gives Γ_H

$$\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_H} \propto \mu_{prod} \qquad \sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_H^2)^2} \ldots dm^2 \propto \mu_{prod} \cdot \Gamma_H$$

- Analysis: Need high-mass ZZ events that contain off-shell H contributions
- Can use both 4ℓ (high $m_{4\ell}$) and $2\ell\,2\nu$ (high m_T^{ZZ})
  - Tradeoff: BR ($2\ell\,2\nu$) ~ 6 X BR (4ℓ), But 4ℓ is cleaner: about equal statistical power overall
- Need on-shell H(125) events to extract Γ_H: Only 4ℓ
- Can measure both off-shell μ_F (ggH) and μ_V (VBF, VH)
- Biggest Challenge: Extract off-shell information from the tails, with limited statistics
- Need precise control of both irreducible and reducible backgrounds, and instrumental effects
- Need theory input: NLO EW qq → ZZ, WZ corrections

On Shell and Off Shell gg→$2\ell\,2\nu$



Higgs Boson Natural Width and Off-Shell Contributions

Analysis strategy

Nature Phys. 18 (2022) 1329

- **Off Shell 4ℓ Strategy: CMS-HIG-18-002 (2016-17 Data):**
  $m_{4\ell} > 220$ GeV – All momenta known
  - Use MELA matrix element discriminants for Higgs production, decay or both; or backgrounds

$$\mathcal{D}_{\rm alt}(\Omega) = \frac{\mathcal{P}_{\rm sig}(\Omega)}{\mathcal{P}_{\rm sig}(\Omega) + \mathcal{P}_{\rm alt}(\Omega)}$$

Signal vs alternatives

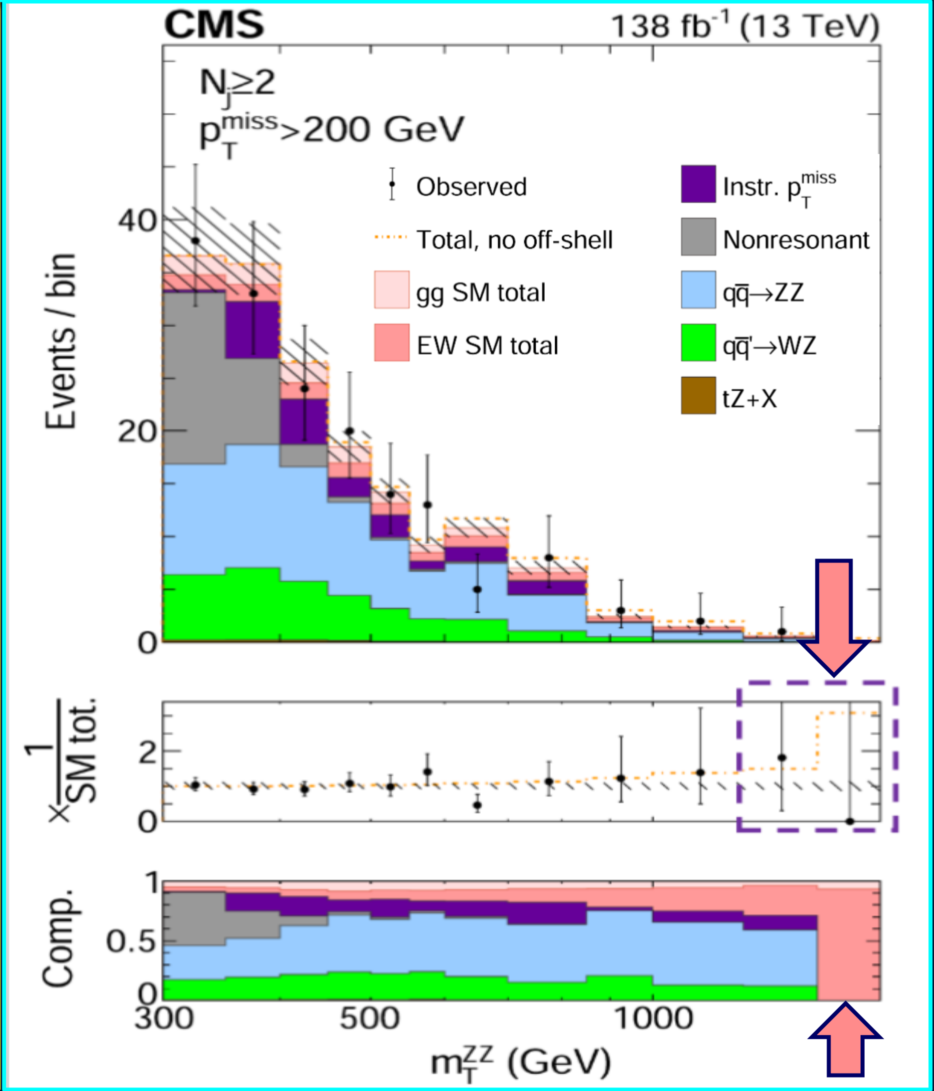
$$\mathcal{D}_{\rm int}(\Omega) = \frac{\mathcal{P}_{\rm int}(\Omega)}{2\sqrt{\mathcal{P}_{\rm sig}(\Omega)\ \mathcal{P}_{\rm alt}(\Omega)}}$$

Signal-alt. interference

- **On Shell 4ℓ Strategy: CMS-HIG-19-009 (2016-18 Data):**
  Finer categorization, more discriminants as observables
  - Provides on-shell μ_F, μ_V and BSM HVV contribution fractions f_{ai} to the off shell 4ℓ analysis
- **Off Shell ZZ → 2ℓ 2ν analysis (2016-2018 data):**
  Main Observable is Transverse mass m_T^{ZZ}
  also p_t^{miss}, N_{jet} categories, MELA discriminants

✷ **No Off Shell ($\Gamma_H = 0$) hypothesis is *inconsistent* with the data: this is visible at high m_T^{ZZ}**

Off Shell 2ℓ 2ν m_T^{ZZ} distribution

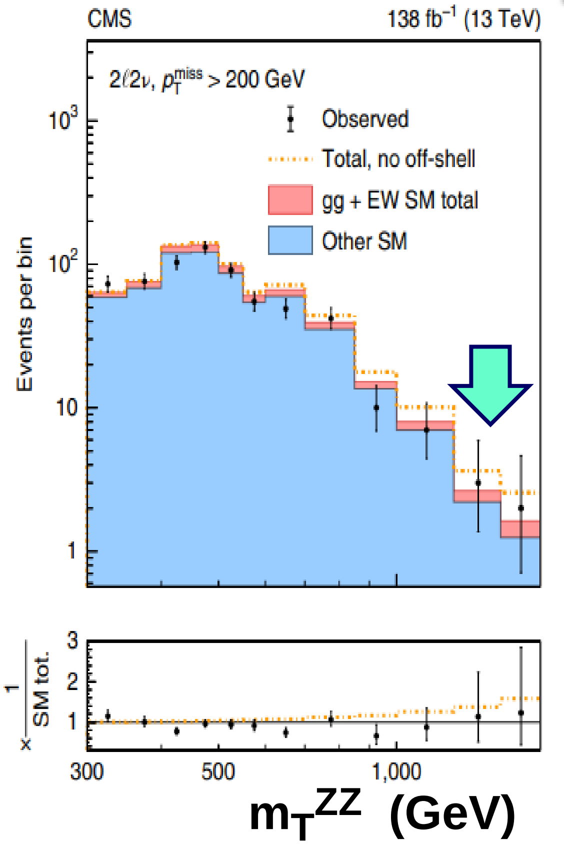


Higgs Boson Natural Width and Off-Shell Contributions

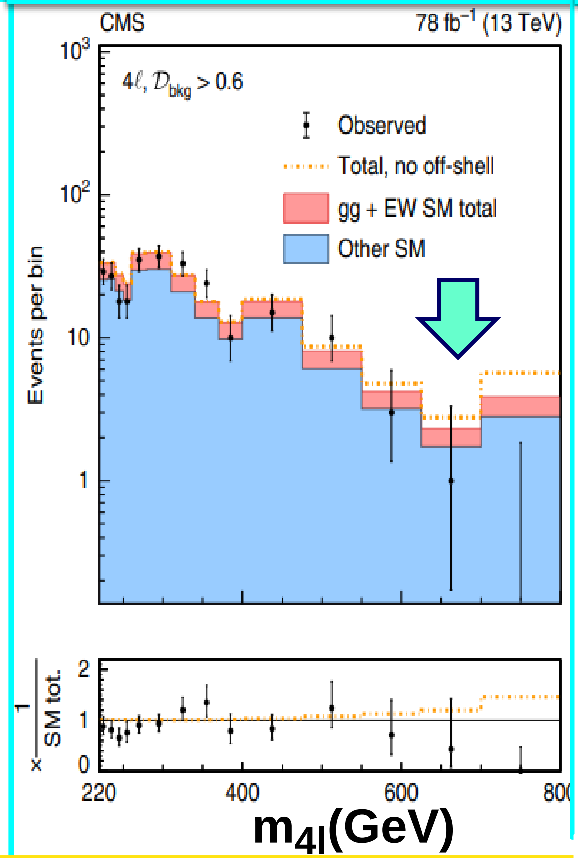
1^{st} Evidence for H off-shell from 4ℓ and $2\ell\,2\nu$

Nature Phys. 18 (2022) 1329

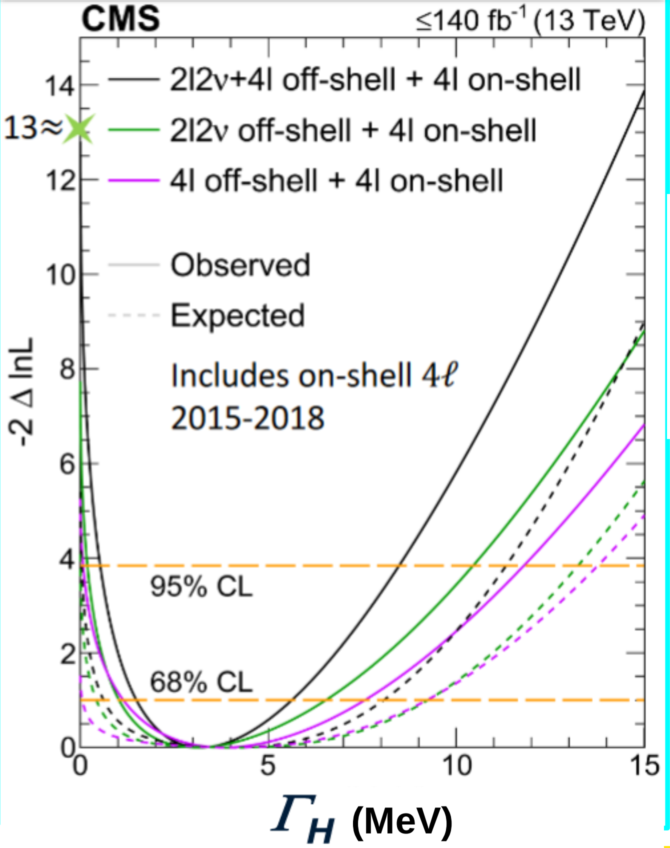
$2\ell\,2\nu$ m_T^{ZZ} distribution



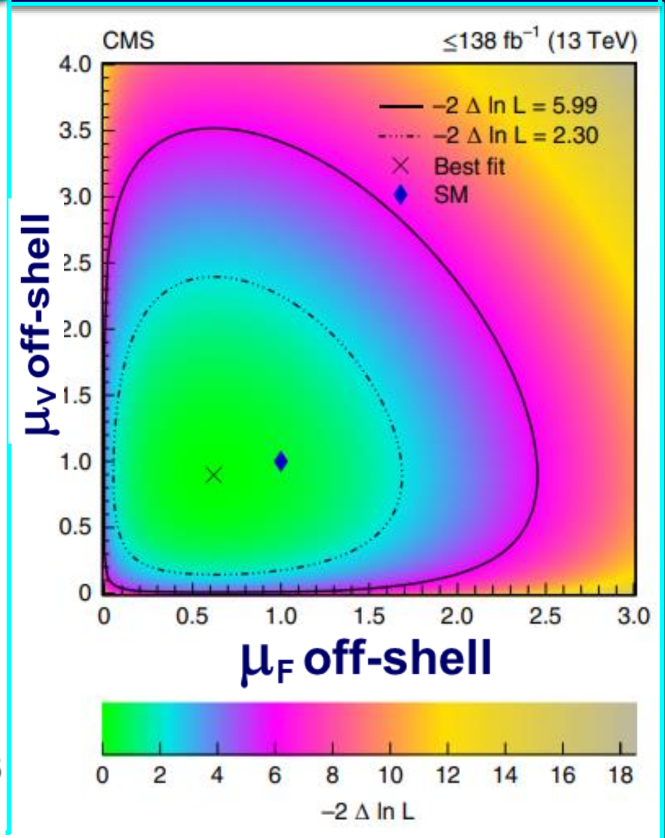
$m_{4\ell}$ distribution



Likelihood Scan: Evidence for off shell



Scan: μ_V vs μ_F Off Shell



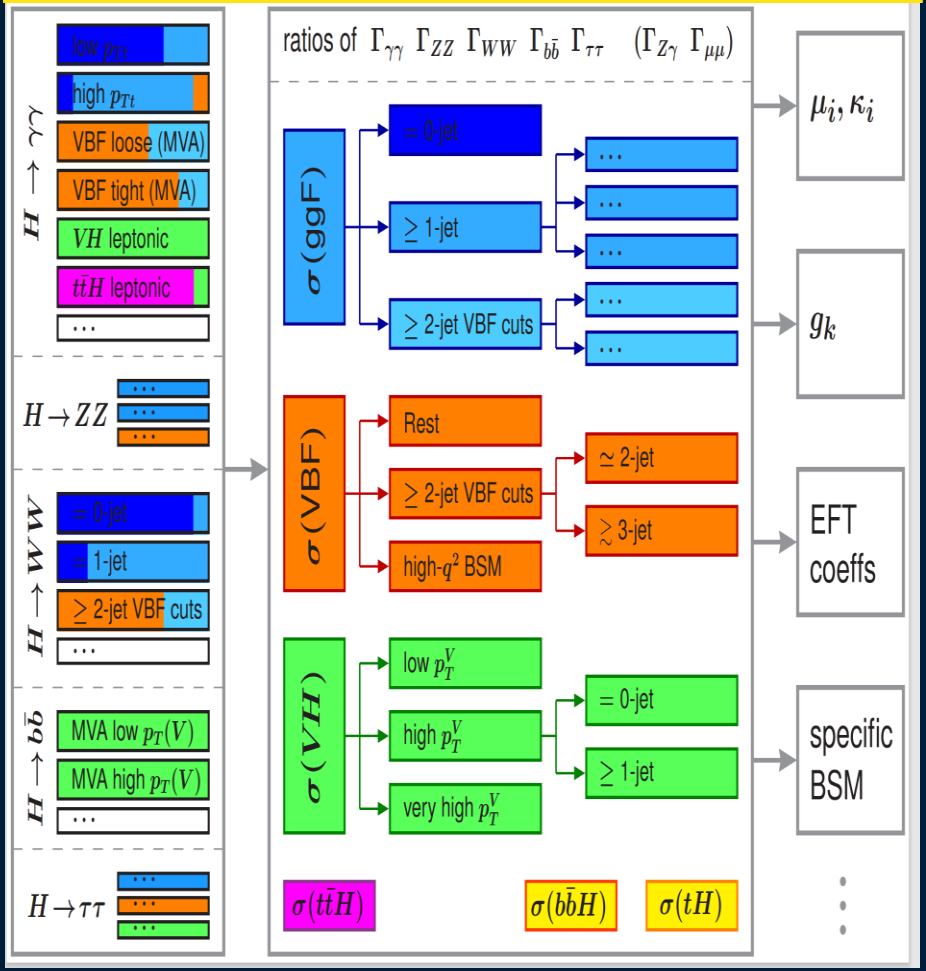
- Results: $\Gamma_H = 3.2$ MeV, in agreement with $\Gamma_H^{SM} = 4.1$ MeV
- Off-Shell / Off-Shell^{SM} 95% CL Limits: (0.0061, 2.0); ***$\Gamma_H = 0$ Excluded at 3.6σ***

Simplified Template Cross Sections (STXS)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGFiducialAndSTXS

- **Extract production mode cross sections in exclusive phase space regions (STXS bins)**
- **Simultaneously maximize the sensitivity of measurements and minimize their theory dependence**
- **Isolate BSM Effects**
- **Minimize the number of bins needed without loss of sensitivity**
- **Significant progress from CMS across many accessible Higgs decays**
- **In many cases the results are statistics limited: excellent prospects for Run3**

Development initiated at Les Houches 2015



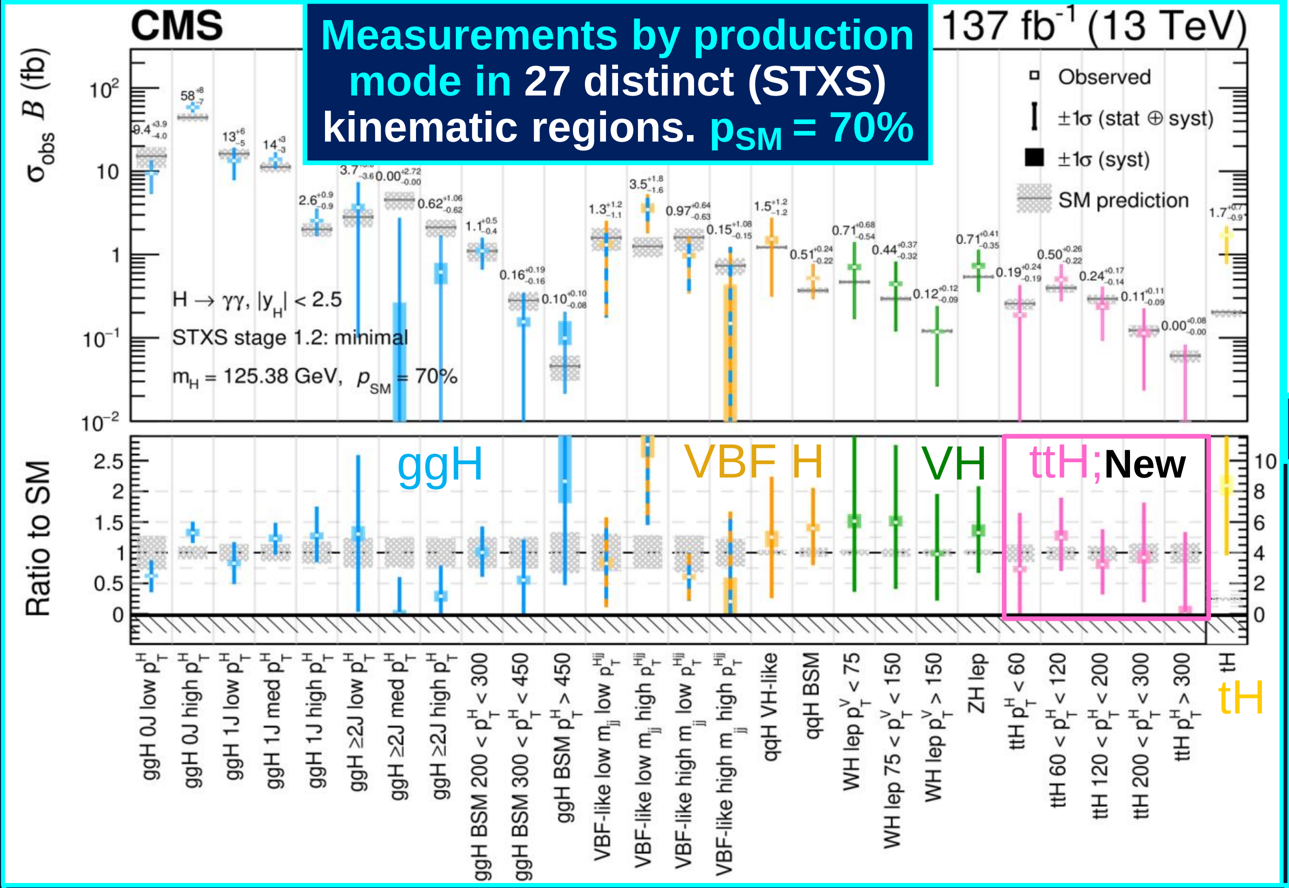
$H \rightarrow \gamma\gamma$ and STXS Stage-1.2

Full Run2 137/fb

CMS-HIG-19-0015

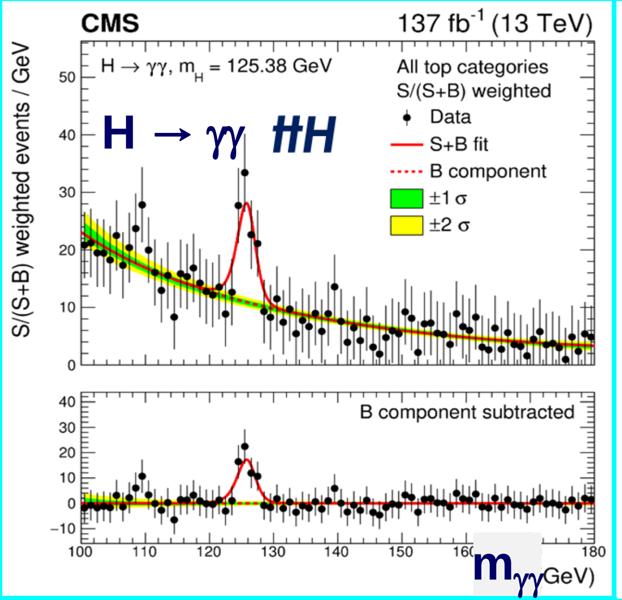
JHEP 07 (2021) 027

Clear $H \rightarrow \gamma\gamma$ signals in all 4 main production modes: ggH, VBF, VH, ttH including 5.2σ in ttH, and strong evidence: 4.7σ in multilepton final states

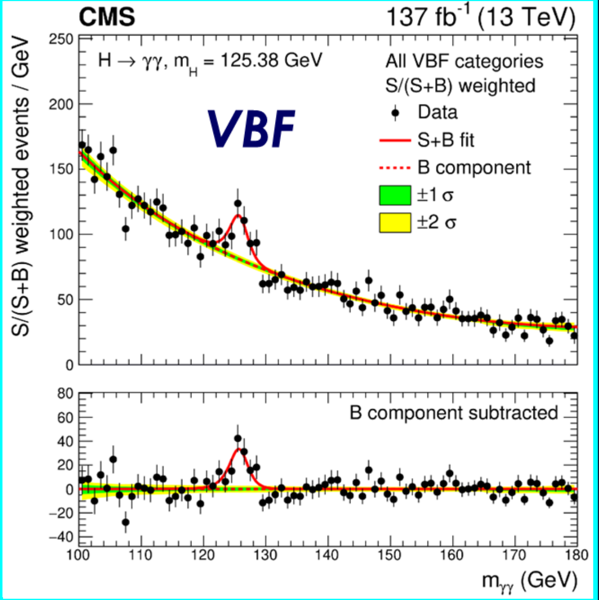

Measurements by production mode in 27 distinct (STXS) kinematic regions. $p_{SM} = 70\%$

$$\mu\,(pp \rightarrow H \rightarrow \gamma\gamma) = 1.12 \pm 0.09$$

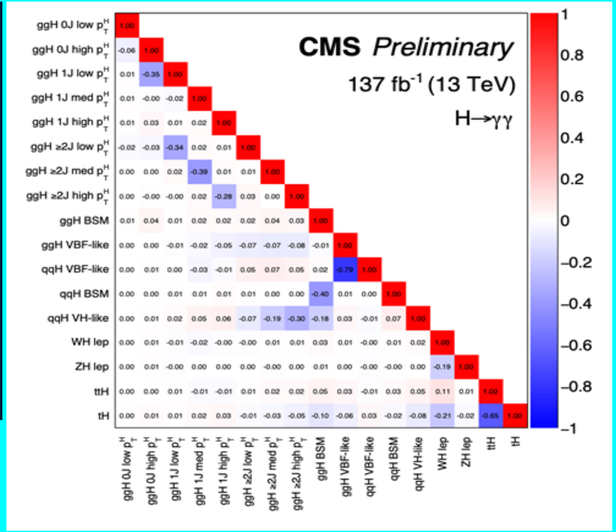
$m_{\gamma\gamma}$ All Top Categories



$m_{\gamma\gamma}$ All VBF Categories



Bins Largely Uncorrelated

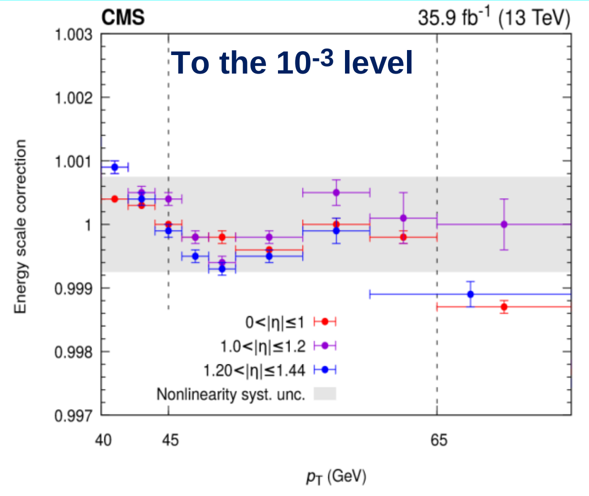

CMS *Preliminary*

137 fb^{-1} (13 TeV)

H→γγ

	ggH 0J low p_T^H	ggH 0J high p_T^H	ggH 1J low p_T^H	ggH 1J med p_T^H	ggH 1J high p_T^H	ggH ≥2J low p_T^H	ggH ≥2J med p_T^H	ggH ≥2J high p_T^H	ggH BSM	ggH VBF-like	qqH VBF-like	qqH BSM	qqH VH-like	WH lep	ZH lep	ttH	tH
ggH 0J low p_T^H	1.00																
ggH 0J high p_T^H	-0.06	1.00															
ggH 1J low p_T^H	0.01	-0.35	1.00														
ggH 1J med p_T^H	0.01	-0.00	-0.02	1.00													
ggH 1J high p_T^H	0.01	0.03	0.01	0.02	1.00												
ggH ≥2J low p_T^H	-0.02	-0.03	-0.34	0.02	0.01	1.00											
ggH ≥2J med p_T^H	0.00	0.00	0.02	-0.39	0.01	0.01	1.00										
ggH ≥2J high p_T^H	0.00	-0.00	-0.00	0.02	-0.28	0.03	0.00	1.00									
ggH BSM	0.01	0.04	0.01	0.02	0.02	0.02	0.04	0.03	1.00								
ggH VBF-like	0.00	0.00	-0.01	-0.02	-0.05	-0.07	-0.07	-0.08	-0.01	1.00							
qqH VBF-like	0.00	0.01	0.00	-0.03	-0.01	0.05	0.07	0.05	0.02	-0.79	1.00						
qqH BSM	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	-0.40	0.01	0.00	1.00					
qqH VH-like	0.00	0.01	0.02	0.05	0.06	-0.07	-0.19	-0.30	-0.18	0.03	-0.01	0.07	1.00				
WH lep	0.00	0.01	-0.01	-0.02	-0.00	-0.00	0.01	0.01	0.03	0.01	-0.00	0.01	0.02	1.00			
ZH lep	0.00	0.01	-0.00	0.00	0.00	0.00	-0.00	0.00	0.01	0.00	-0.00	-0.00	0.00	-0.19	1.00		
ttH	0.00	0.00	0.01	-0.01	-0.01	0.01	0.02	0.02	0.05	0.03	-0.01	0.03	0.05	0.11	0.01	1.00	
tH	0.00	0.01	0.01	0.02	0.03	-0.01	-0.03	-0.05	-0.10	-0.06	0.03	-0.02	-0.08	-0.21	-0.02	-0.65	1.00

Photon Energy Scale Correction vs p_T


To the 10^{-3} level

$H \rightarrow \gamma\gamma$ Full Set of STXS Stage 1.2 Bins

CMS-HIG-19-0015

JHEP 07 (2021) 027

Full Run2 137/fb

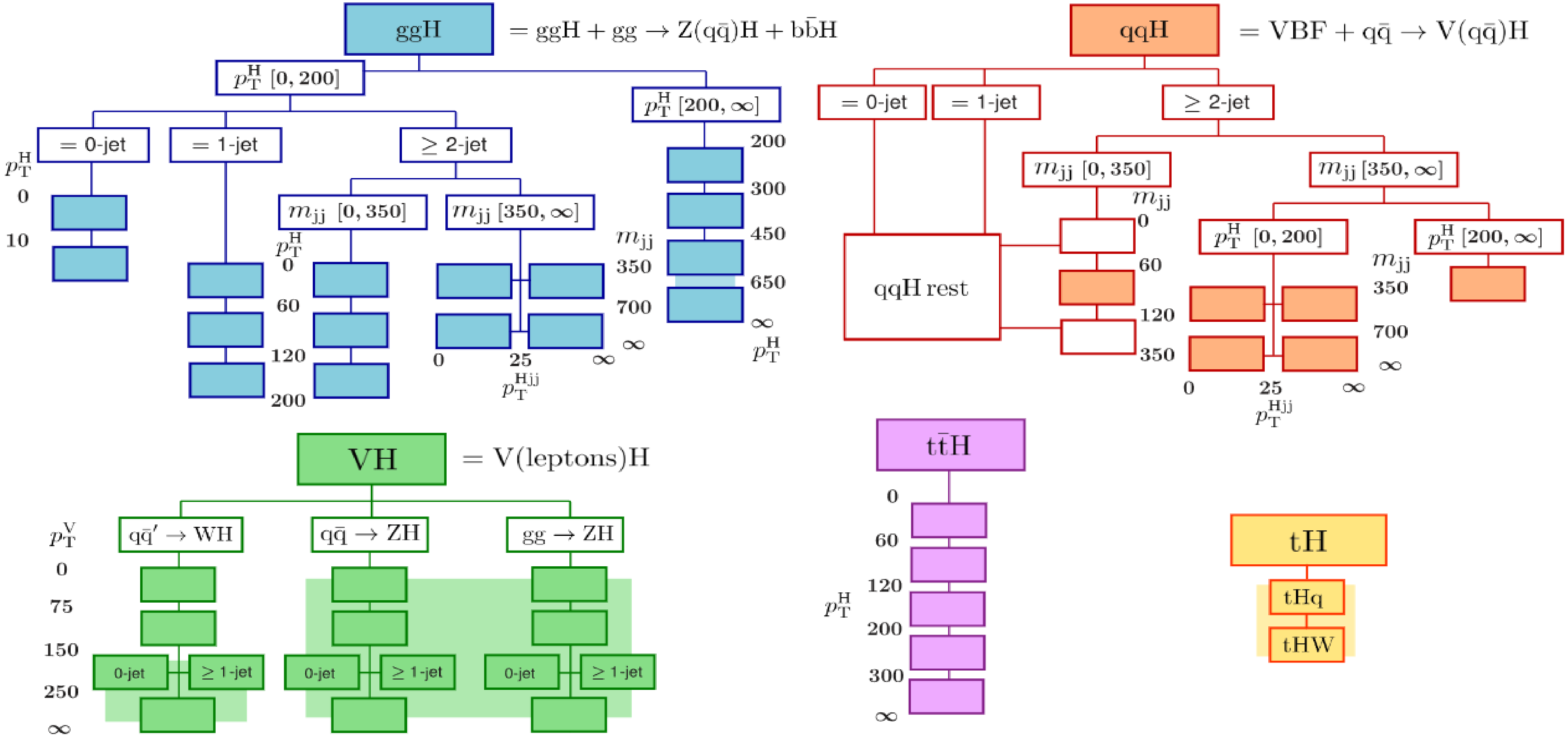
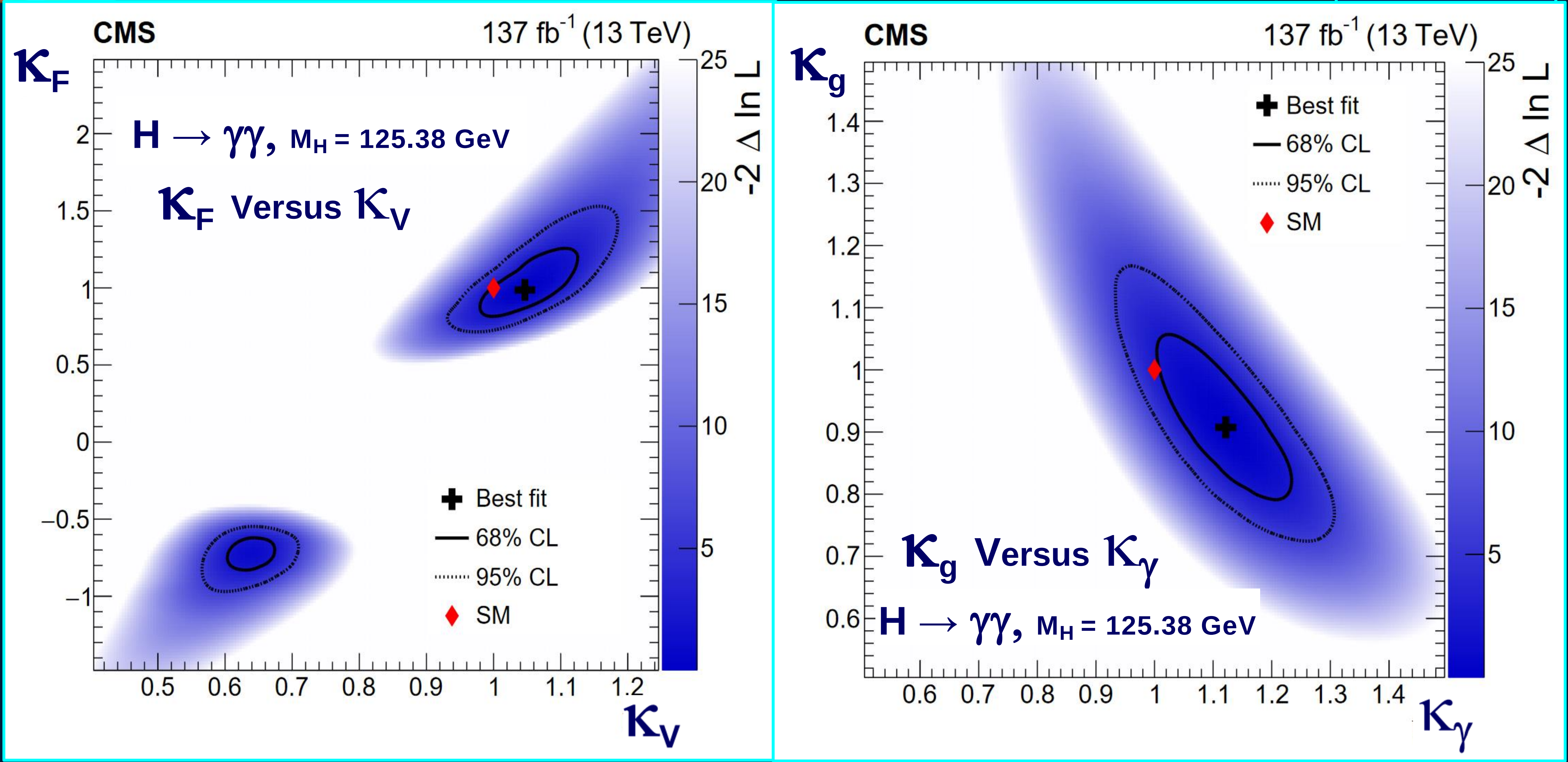


Figure 1: Diagram showing the full set of STXS stage-1.2 bins, adapted from Ref. [10], defined for events with $|y_H| < 2.5$. The solid boxes represent each STXS stage-1.2 bin. The units of p_T^H, m_{jj}, p_T^{Hjj}, and p_T^V are in GeV. The shaded regions indicate the STXS bins that are divided at stage 1.2, but are not measured independently in this analysis.

$H \rightarrow \gamma\gamma$ Two Dimensional Likelihood Scans in the κ Framework

CMS-HIG-19-0015
JHEP 07 (2021) 027

Full Run2 137/fb



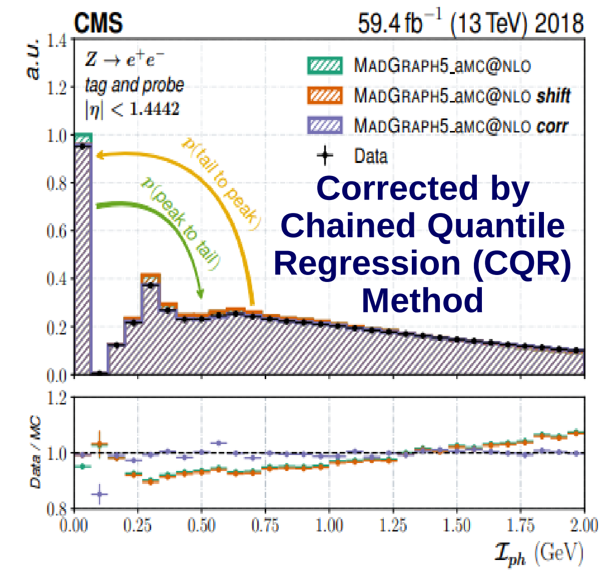
H → γγ Inclusive and differential fiducial cross sections

CMS-HIG-19-0016
Accepted by JHEP

Full Run2 137/fb

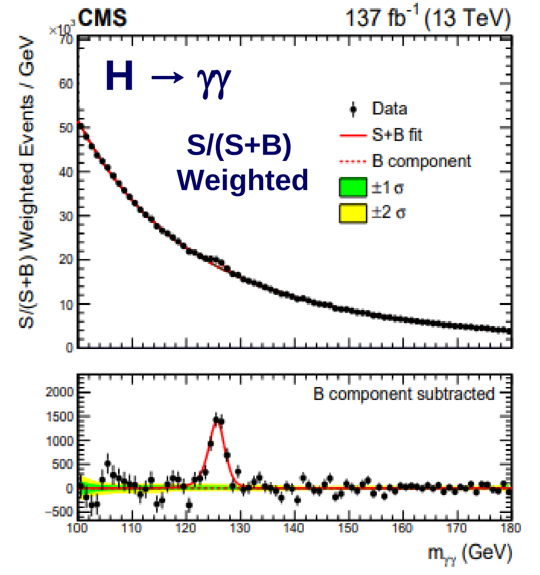
- **Fiducial cross sections:** Probe event kinematics, multiple topologies to reduce model dependence
- **STXS framework** targets ggH, VBF, VH, ttH production modes; covers whole kinematic phase space with mutually exclusive regions to detect BSM effects
- **MVA Analyses:** Photon, diphoton, and photon vertex
- Photon ID MVA: BDT trained on γ+jet events, using kinematics, isolations and shower shape as inputs
  - Corrections on shower shape and isolation variables achieved using quantile morphing method
  - Validated on Z → μμγ and Z → ee(γ) events
- Improves ID output agreement with the data; to ~1% in the barrel; 3% in the endcaps
  - Systematic uncertainty on inclusive fiducial cross section reduced to 1.5%, from previous 5%
- Categorization by diphoton mass resolution σ_m/m; decorrelated wrt m to avoid backgd shape distortions
- Maximum likelihood fit on signal strength per bin includes full unfolding of the detector response matrix

Photon Isolation Sum $\mathcal{I}_{ph}$

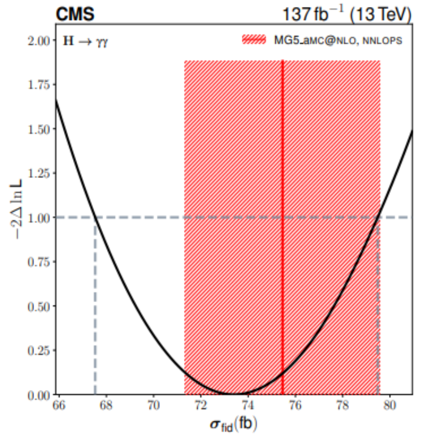


Corrected by Chained Quantile Regression (CQR) Method

$M_{\gamma\gamma}$ All categories



Likelihood Scan
2ΔlnℒvsFiducial σ(fb)



Results:
Fiducial Cross Section

$$\sigma_{fid} = 73.4\ {}^{+5.4}_{-5.3}\,(\text{stat})\ {}^{+2.4}_{-2.2}\,(\text{sys})\ \text{fb}$$

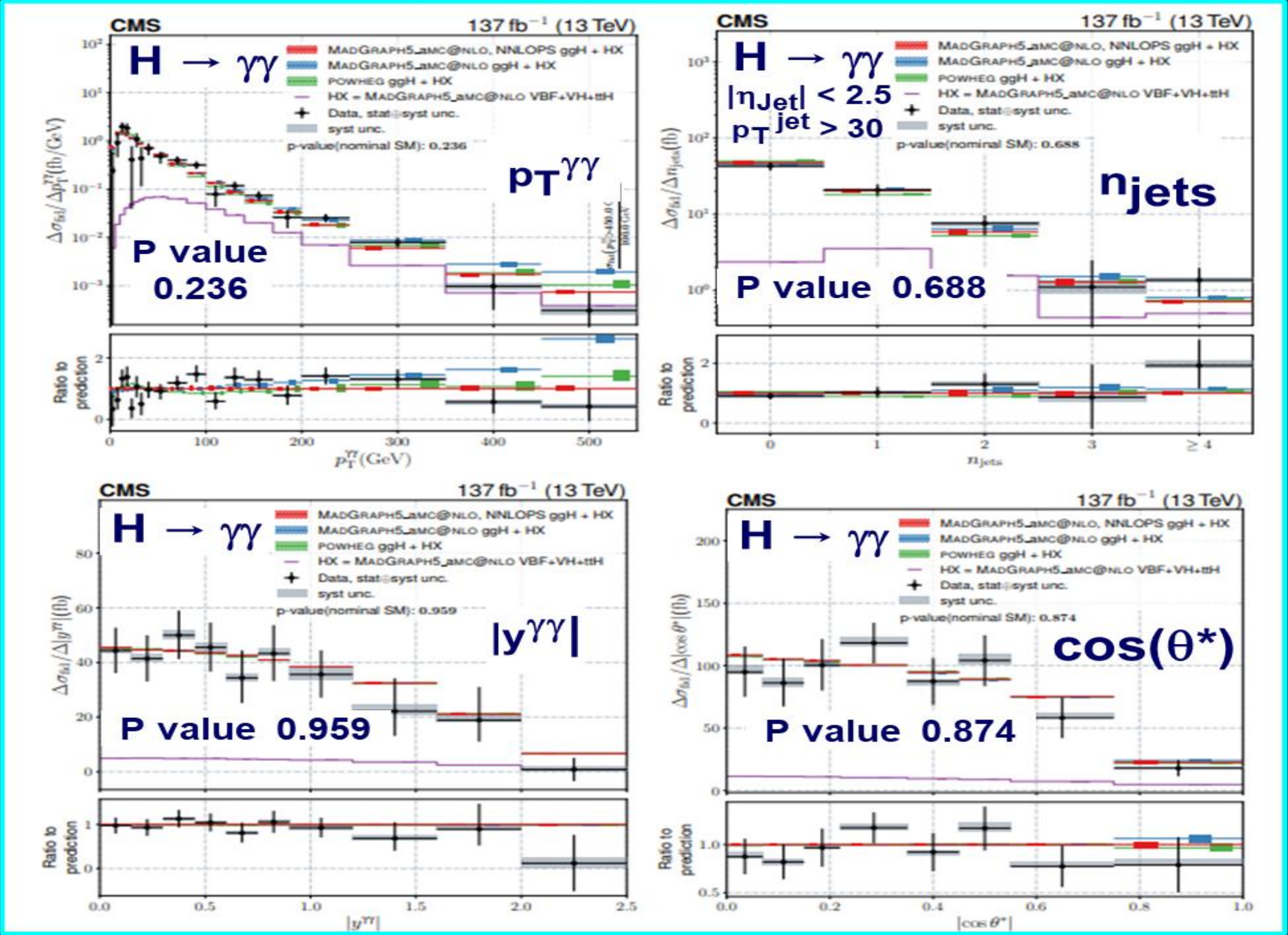
vs SM: 75.4 ± 4.1 fb

H $\rightarrow \gamma\gamma$ Inclusive and differential fiducial cross sections

CMS-HIG-19-0016
Accepted by JHEP

Full Run2 137/fb

Example Observed Differential Distributions: vs $p_T^{\gamma\gamma}$, n_{jets}, $|y^{\gamma\gamma}|$ and $\cos(\theta^*)$



$p_T^{\gamma\gamma}$

P value 0.236

$|\eta_{Jet}| < 2.5$
$p_T^{jet} > 30$

n_{jets}

P value 0.688

$|y^{\gamma\gamma}|$

P value 0.959

$\cos(\theta^*)$

P value 0.874

$H \rightarrow \gamma\gamma$ Inclusive and differential fiducial cross sections

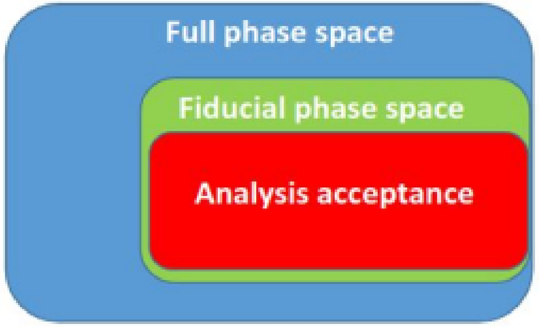
CMS-HIG-19-0016
Accepted by JHEP

Phase space definition for $H \rightarrow \gamma\gamma$ analysis

BR ~ 0.2%
S/B < 0.1

Inclusive fiducial phase space

- $p_T^{\gamma 1} > m_{\gamma\gamma}/3$
- $p_T^{\gamma 2} > m_{\gamma\gamma}/4$
- $|\eta^{\gamma}| < 2.5$
- $\mathrm{Iso}_{gen}^{\gamma} < 10$ GeV



Full phase space

Fiducial phase space

Analysis acceptance

1 jet phase space

- Njet ≥1
- $p_T^{j1} > 30$ GeV
- $|\eta^{j1}| < 2.5$

2 jet phase space

- Njet ≥2
- $p_T^{j1,\,j2} > 30$ GeV,
- $|\eta^{j1.\,j2}| < 4.7$

VBF-like phase space

- Njet = 2
- $|\Delta\eta^{j1.\,j2}| > 3.5$
- $m^{j1.\,j2} > 200$ GeV

Dedicated fiducial xs measurements

ttH-like phase space

- # lepton ≥ 1
- # bjet ≥ 1

VH-like phase space

- # lepton = 1
- $p_T^{miss} < 100$ GeV

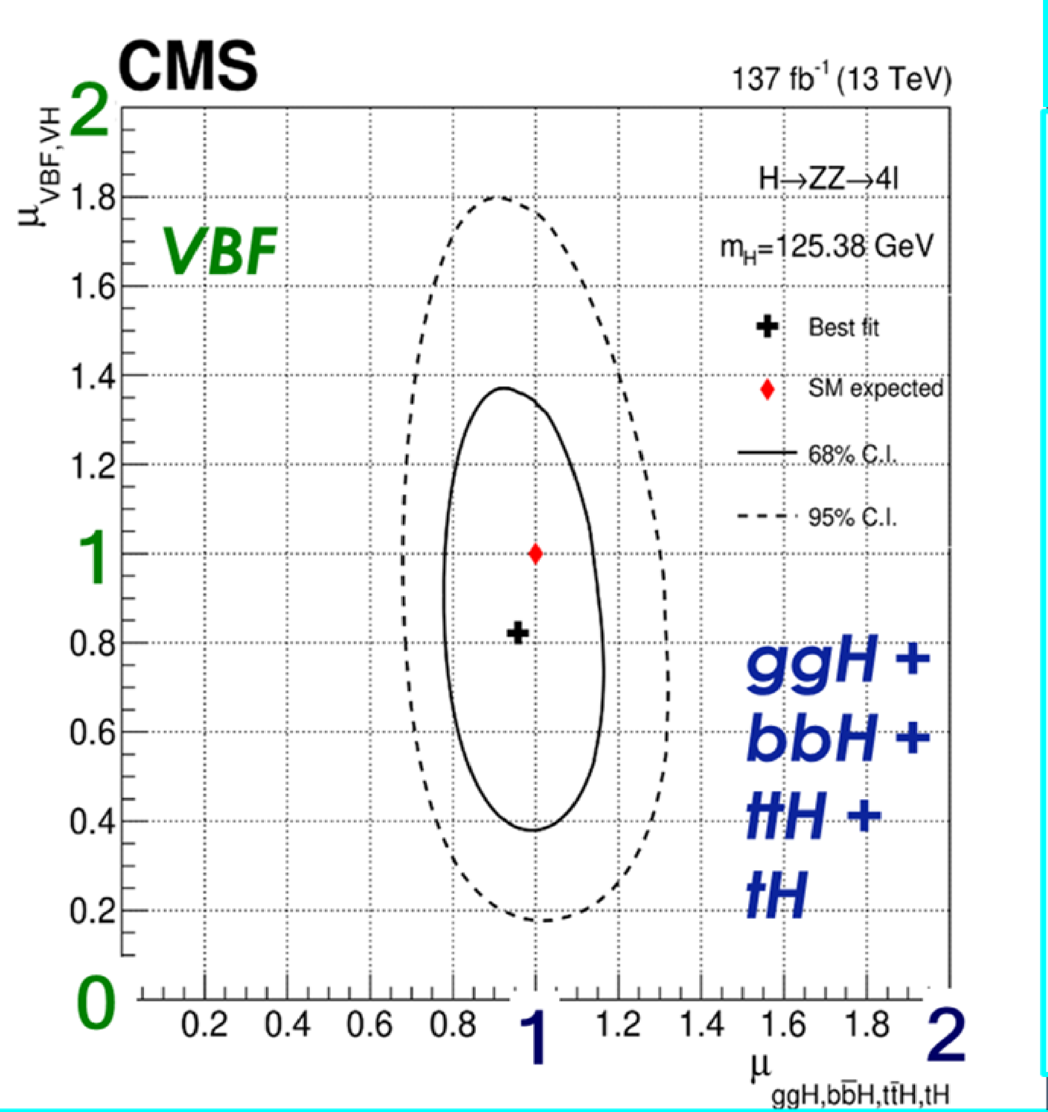
WH-like phase space

- # lepton = 1
- $p_T^{miss} > 100$ GeV

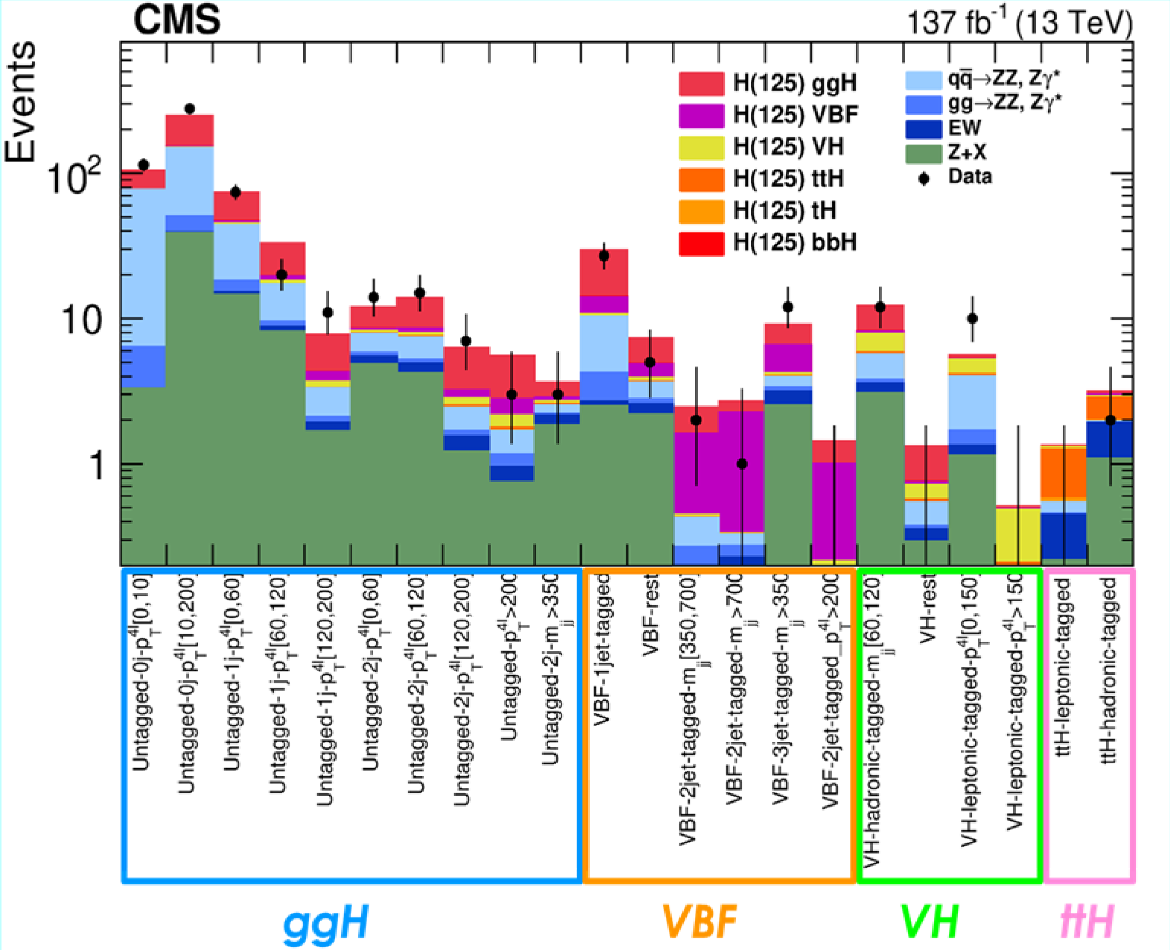
K. Mazumdar at
Higgs 2022 Conference

H → ZZ* → 4ℓ and STXS

Full Run2 137/fb



Measurements by production mode in 17 distinct (STXS) kinematic regions



$$\mu\,(pp \rightarrow H \rightarrow 4\ell) = 0.94 \pm 0.07(\text{stat})\,^{+0.09}_{-0.08}(\text{sys})$$

$$\sigma_{\text{fid}}(4\ell) = 2.84^{+0.23}_{-0.22}(\text{stat})^{+0.26}_{-0.21}(\text{syst})\ \text{fb}$$

SM: 2.84 ±0.15 fb

CMS-HIG-19-001 *Eur. Phys. J. C81(2021) 488*

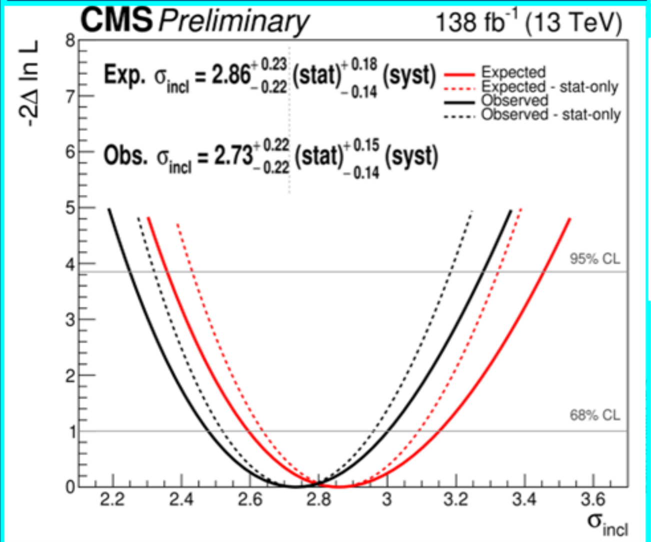
Also see Gritsan et al. Phys. Rev. D 94, 055023

H → ZZ* → 4ℓ Inclusive and Differential Fiducial Cross Sections

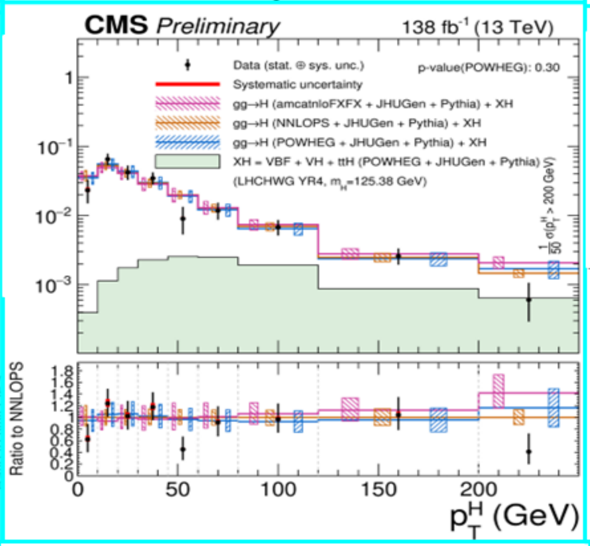
Full Run2 138/fb

CMS-PAS-HIG-21-009

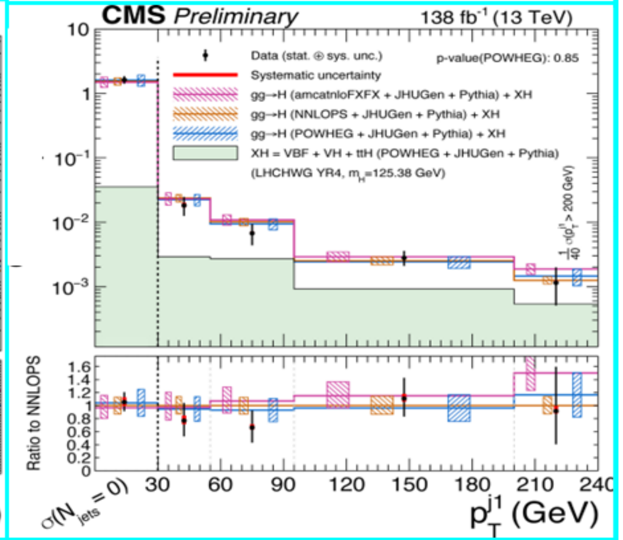
σ_{fid} inclusive likelihood scan



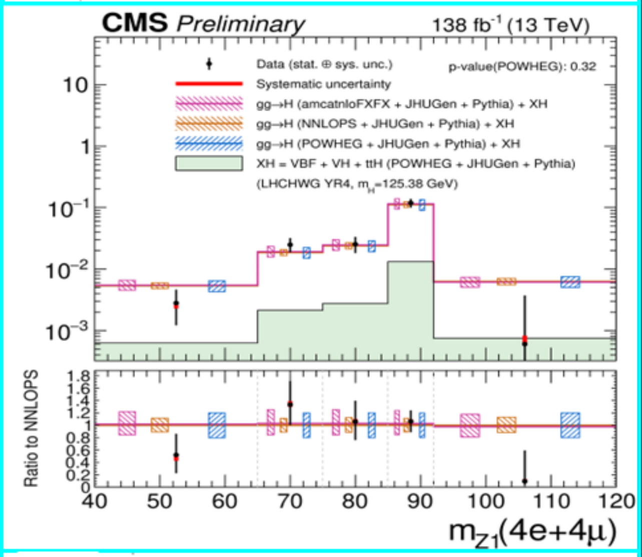
$d\sigma_{fid}/dp_T^H$ (fb/GeV)



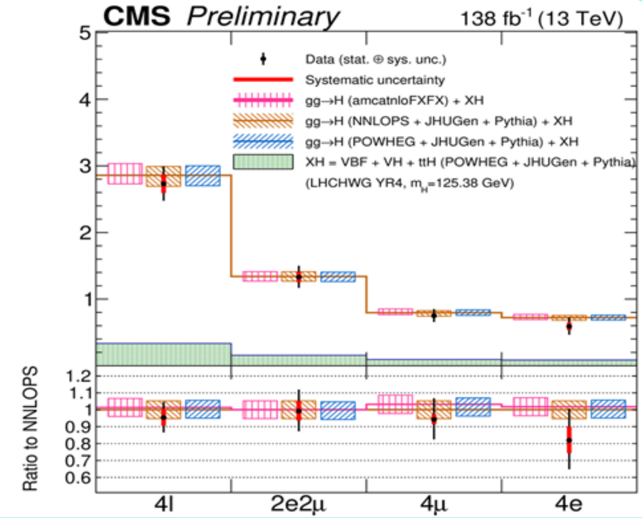
$d\sigma_{fid}/dp_T^{j1}$ (fb/GeV)



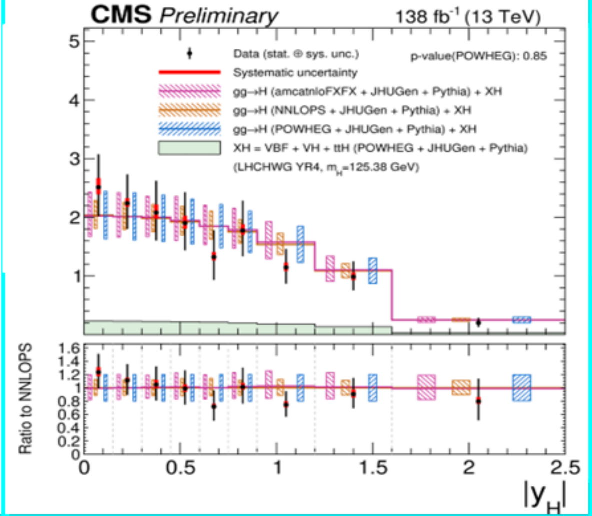
$d\sigma_{fid}/dm_{Z1}$ (fb/GeV)



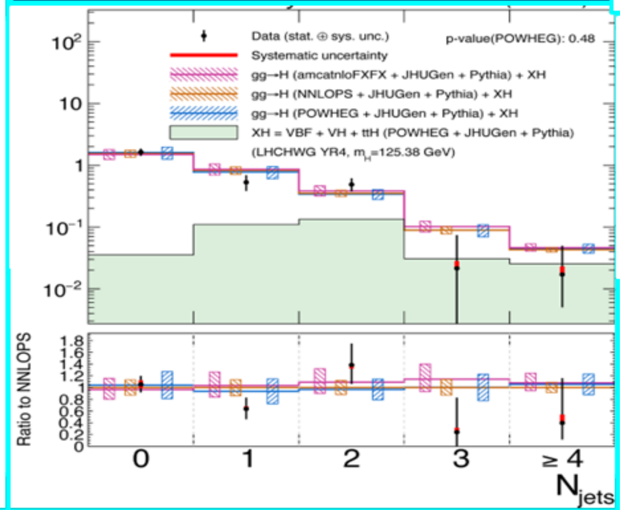
σ_{fid} to 4ℓ, 2e2μ, 4μ, 4e



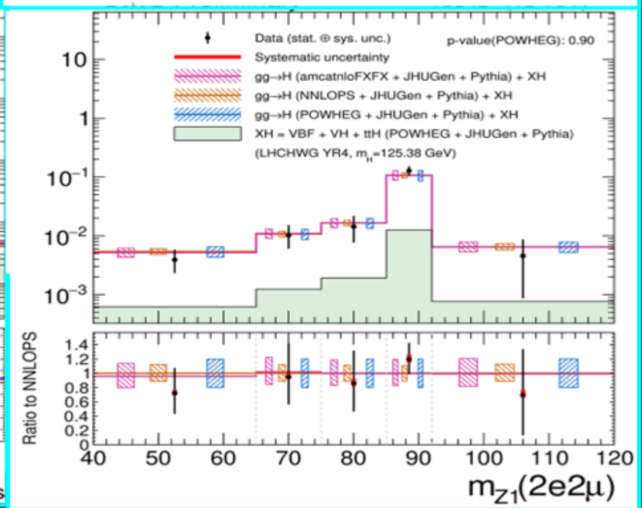
$d\sigma_{fid}/d|y_H|$ (fb)



σ_{fid}(fb) versus N_{Jets}



$d\sigma_{fid}/dm_{Z1}$ (fb/GeV)



H → bb Differential Measurements

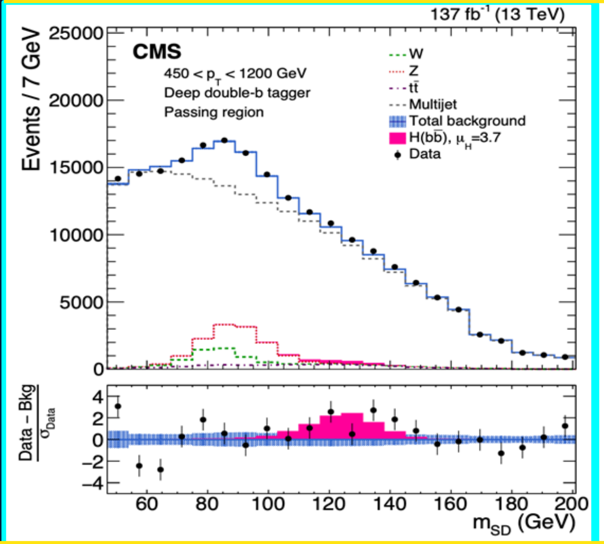
Full Run2 137/fb

JHEP 12 (2020) 085

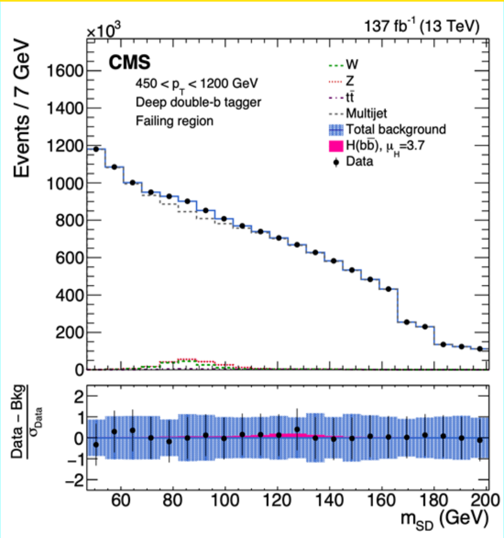
Higgs p_T sensitive to many BSM effects; theory to higher order

- **Highly boosted Higgs (bb example):** a tool to access the very high-p_T regime, **sensitive to BSM physics**
- **Tagging the Higgs with deep-learning methods** based on signature of two b quarks inside a fat jet
- **DDBT tagger** improves bb tagging efficiency at same QCD misidentification rate **by a factor of 1.6**

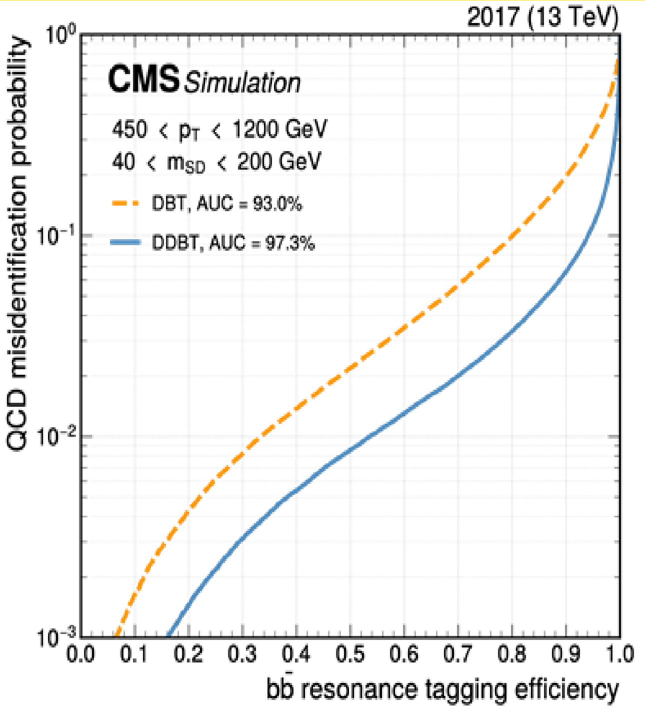
Soft-drop Mass m_{SD}(bb) passing region



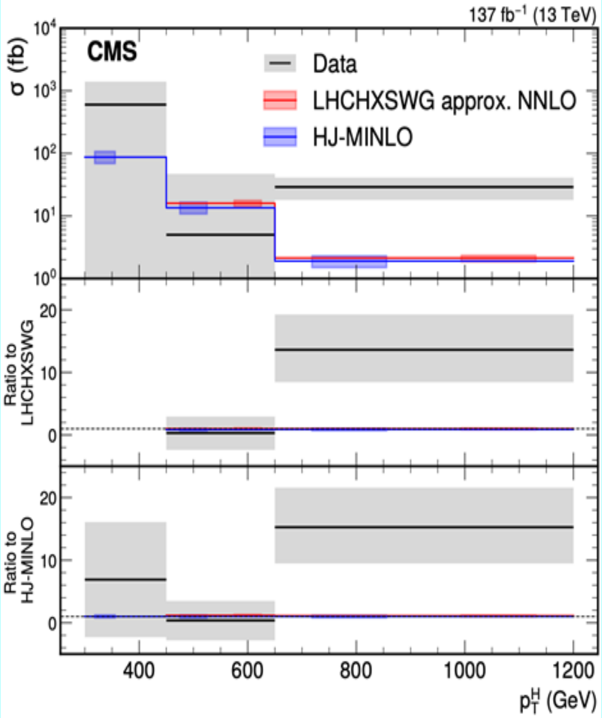
Soft-drop Mass m_{SD}(bb) failing (control) region



Deep double b Tagger misID rate vs efficiency



Unfolded differential cross section in p_T(H)



Observed (exp) **Significance: 2.5σ** (0.7σ)

Signal strength and **local significance** vs SM:

$$\mu_H = 3.7 \pm 1.2\,(\text{stat})\ {}^{+0.8}_{-0.7}\,(\text{syst})\ {}^{+0.8}_{-0.5}\,(\text{theo});$$

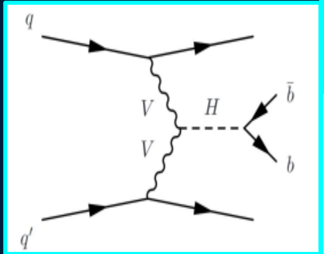
(1.9 expected)

Recall bb Observation: ggF, VBF, ttH, WH, ZH Combination
5.6σ obs (6.5σ exp); μ_H = **1.04 ± 0.20** PRL 121, 121801 (2018)

VBF H → bb

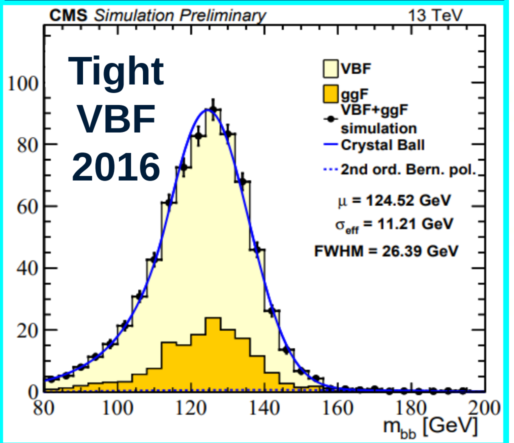
CMS-PAS-HIG-22-009

Analysis Summary

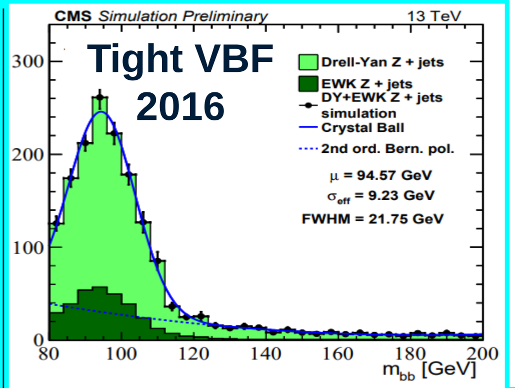


- Inclusive 2016+ 2018 measurement
- Main Backgrounds: QCD, Z+jets
- Dedicated “loose” and “tight” triggers for b-tagged jets plus VBF jets
- Large Δη VBF jets reduce QCD background
- BDTs classify VBF signal, Z+bb, ggH, QCD into regions
- Parametric m(jj) distributions derived from simulation (signal, Z+jets) or sideband data (QCD)
- Z → bb + Jets analysis cross check

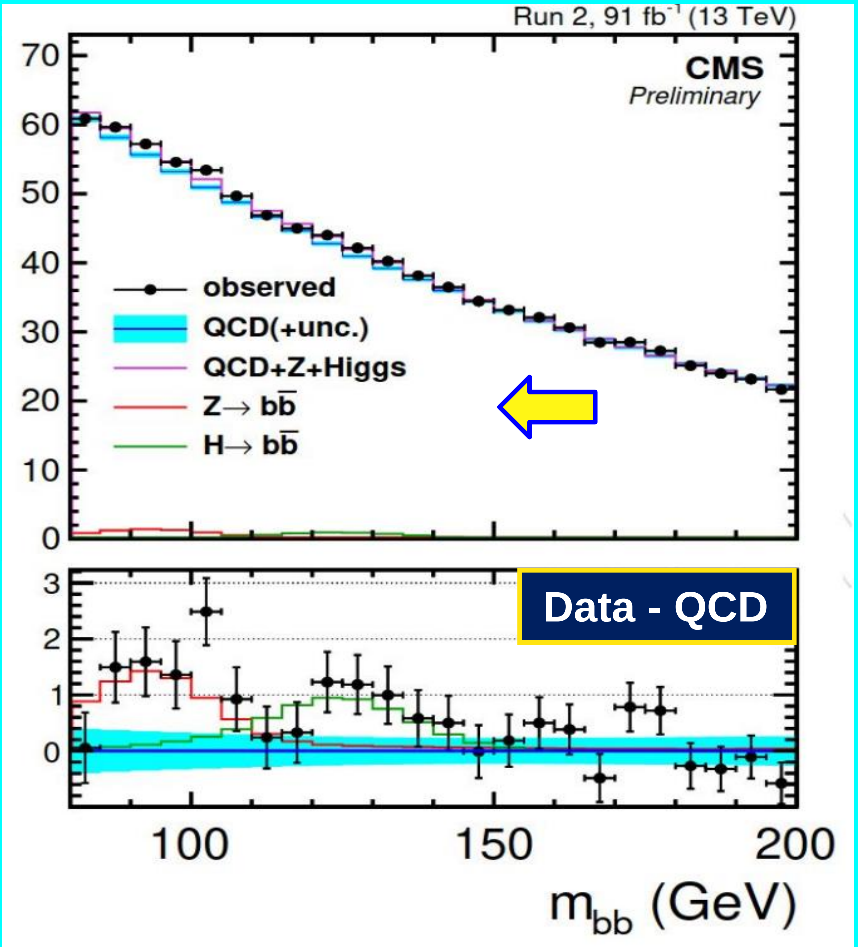
Simulation H→ bb parametric model



Simulation Z→bb parametric model



S/(S+B) weighted m_{bb} distribution



Observed VBF H→bb Significance: 2.4σ (2.7σ exp)

μ_{Hbb} = 0.92 ± 0.32 (stat) $^{+0.31}_{-0.22}$ (syst)

μ_{Zbb} = 0.94 ± 0.20 (stat) ± 0.21 (syst)

$H \rightarrow \tau\tau$ Differential Measurements

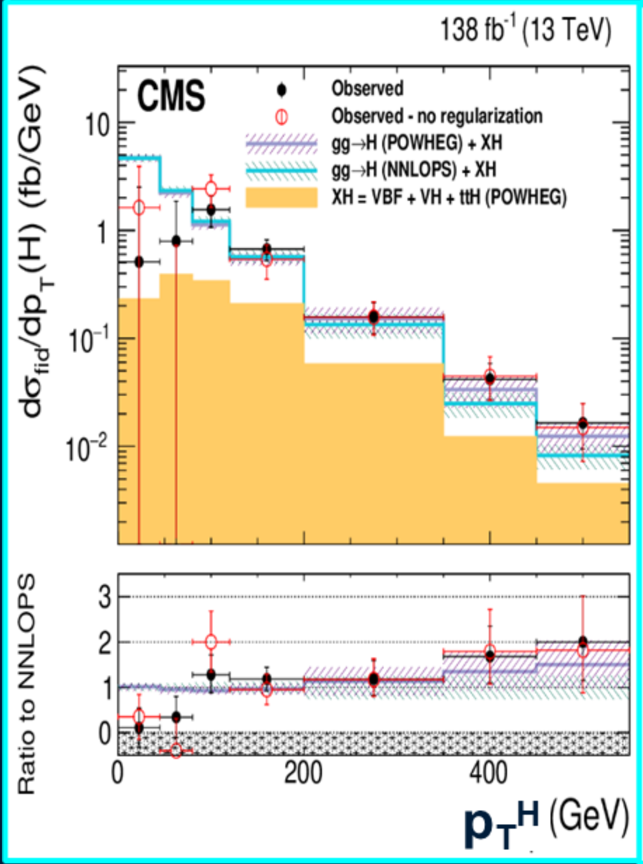
Full Run2

CMS HIG-20-015
Phys. Rev. Lett. 128, 081805

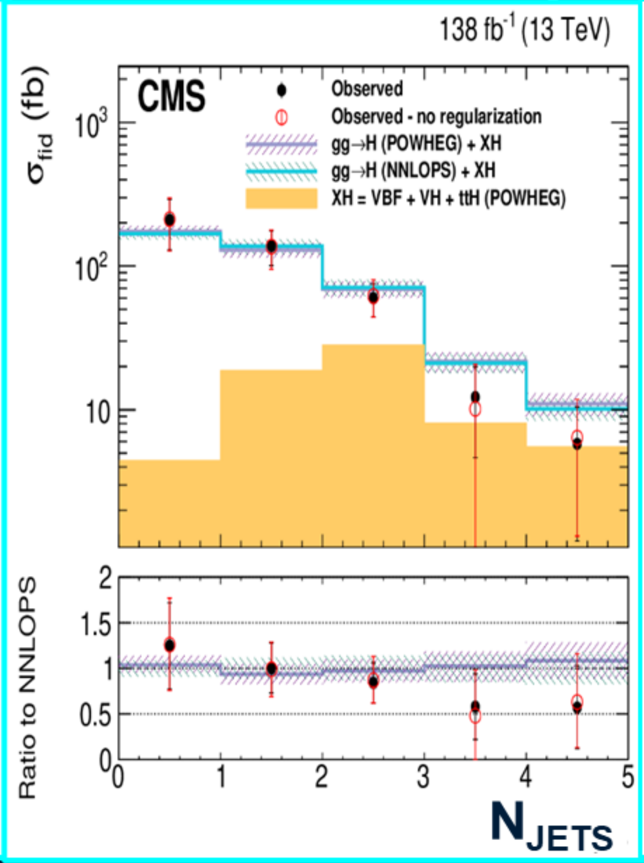
CMS at LHCP 2021: 1st differential measurement in the $H\rightarrow\tau\tau$ channel

Comparing to other final state measurements (4ℓ, $\gamma\gamma$, $\tau\tau$) brings significant improvements:
exploring the phase space of large jet multiplicities and/or Lorentz-boosted Higgs bosons (to NNLO)

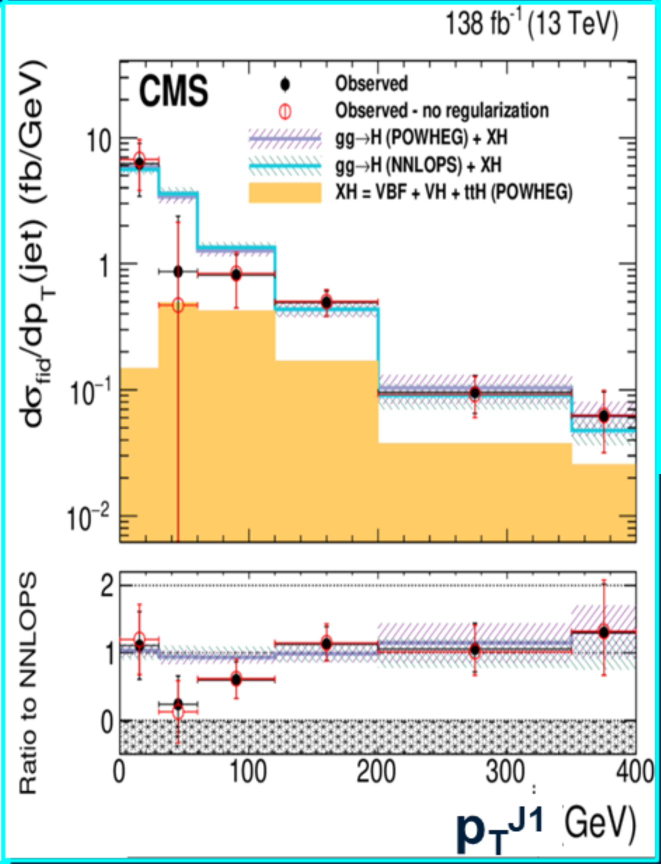
ggF H and XH $d\sigma/dp_T^H$



ggF H and XH $d\sigma/dN_{jets}$



ggF H and XH $d\sigma/dp_T^{J1}$



Overall Agreement with the SM

Observed (SM)

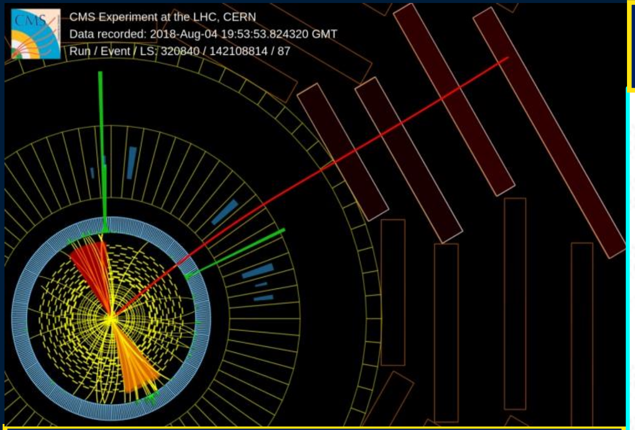
$\sigma_{fid} = 426 \pm 102$ fb
$(402 \pm 27$ fb)

ttH and tH Production

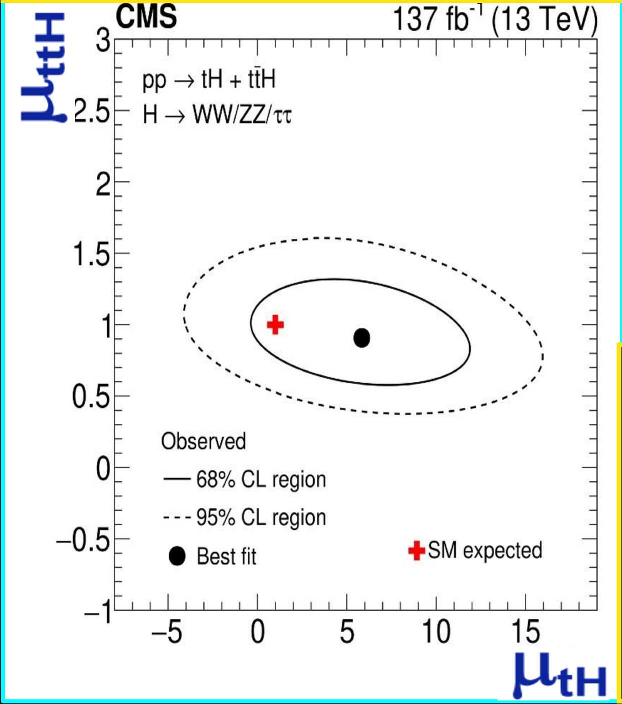
Multilepton Final States (e, μ, τ_h)

Full Run2 137/fb Eur. Phys. J. C 81 (2021) 378

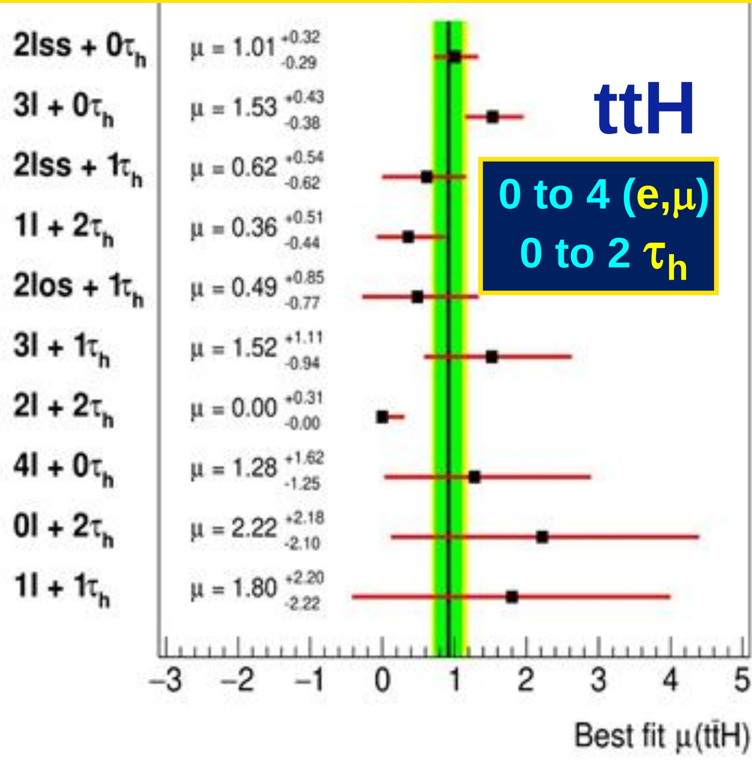
Mostly H → WW, ZZ, ττ



μ (ttH) vs μ(tH)

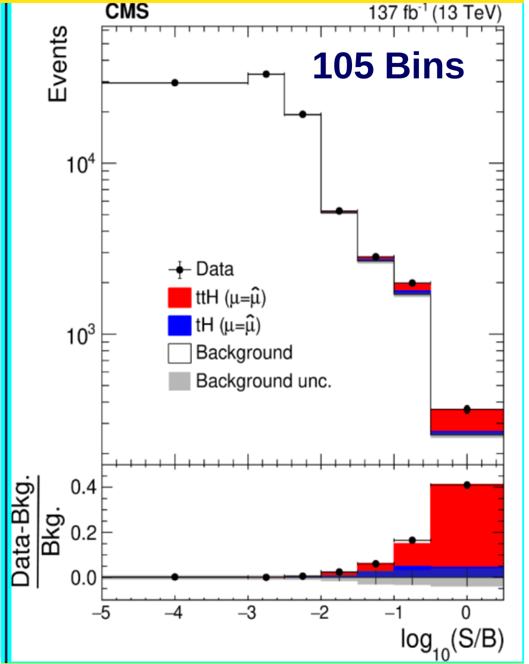


ttH Signal Strengths:10 Categories



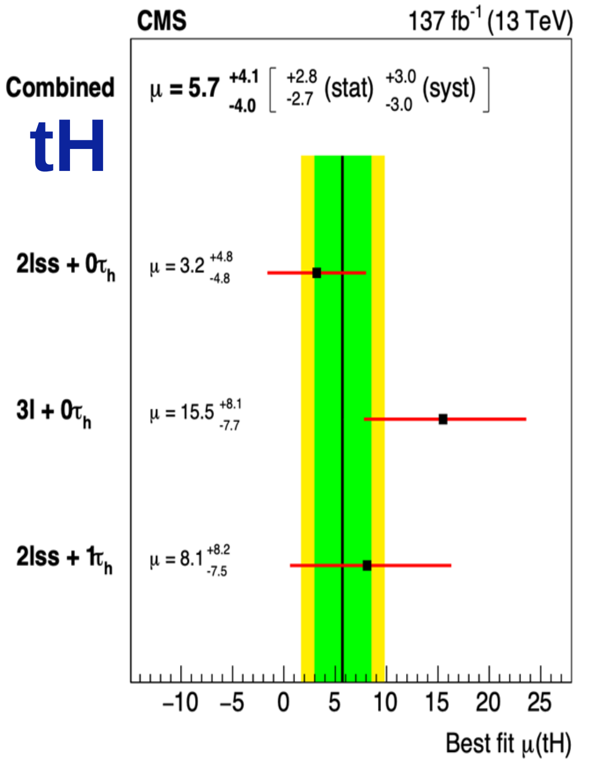
0 to 4 (e,μ)
0 to 2 τ_h

ttH, tH Signals + bkgd



Note: High purity ⮥
subsamples extracted

tH Signal Strengths



Combined μ(ttH) = 0.92 ±0.41 (Stat) $^{+0.19}_{-0.13}$ (Sys)

ttH Observed (exp) Significance: 4.7σ (5.2σ)

μ(tH) = 5.7 ± 2.7 (Stat) ± 3.0 (Sys)

tH Observed (exp) Significance: 1.4σ (0.3σ)

Top Yukawa: $-0.9 < \kappa_t < -0.7$ *or* $0.7 < \kappa_t < 1.1$ at 95% CL

$H \rightarrow \tau\tau$: 1st Direct Measurement of the CP Structure of the Higgs to τ Yukawa Coupling

Full Run2 137/fb

CMS-PAS-HIG-20-006

Parametrize Higgs Fermion Couplings in the mass eigenstate basis

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

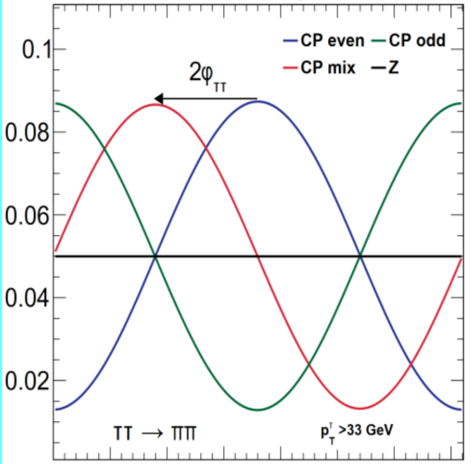
Define mixing angle ϕ where

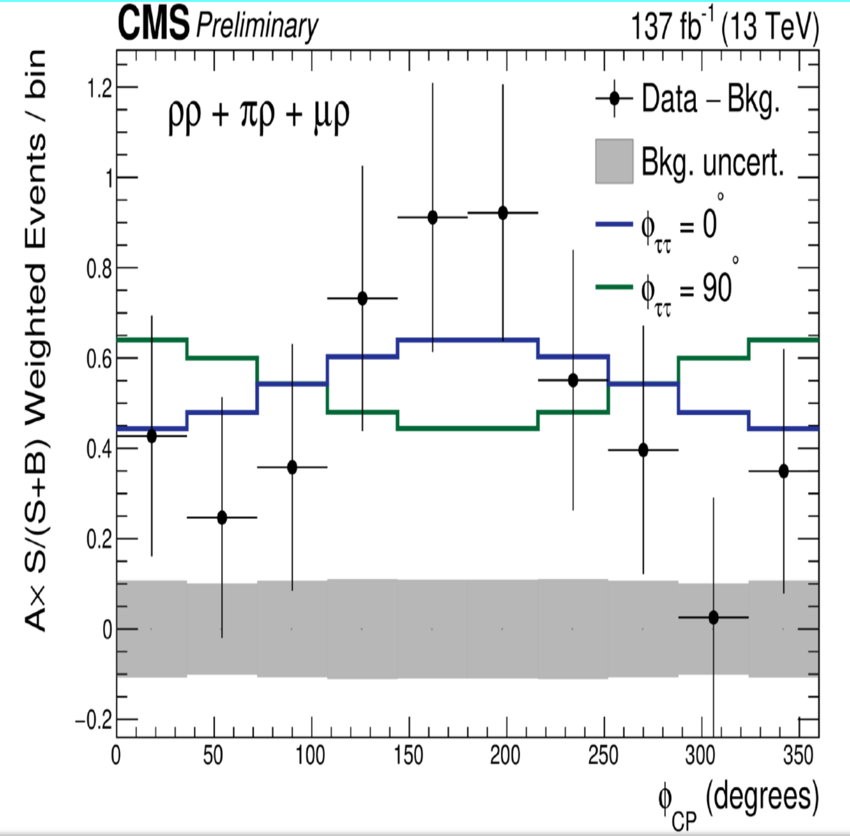
$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau \ \text{CP-odd coupling}}{\kappa_\tau \ \text{CP-even coupling}}$$

Pure CP-even state → $\phi_{\tau\tau} = 0^o$

Pure CP-odd state → $\phi_{\tau\tau} = 90^o$

$\phi_{\tau\tau}$: angle between the τ decay planes determined by the impact parameter and charged particle vectors in the Higgs rest frame



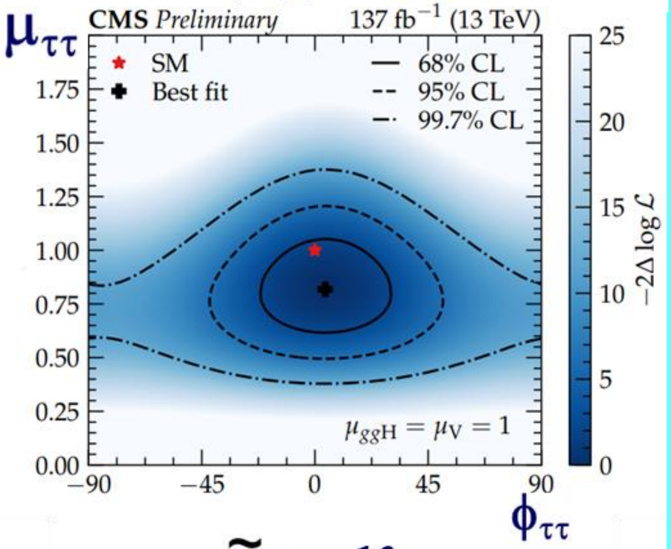


CP-mixing angle

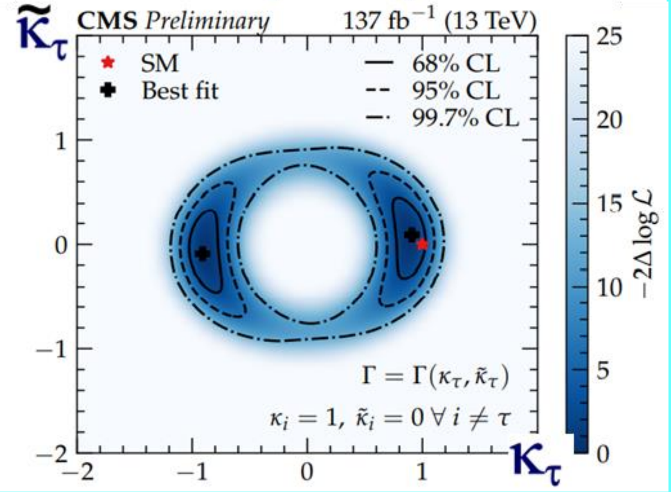
$\phi_{\tau\tau}$ = (4 ± 17)° @68% CL

3.2σ exclusion of pure CP odd

$\mu_{\tau\tau}$ vs $\phi_{\tau\tau}$



$\tilde{\kappa}_\tau$ vs κ_τ



First observation of ttH and H → $\gamma\gamma$ Decay and CP Structure of the Htt Yukawa Interaction

Full Run2 137/fb

PRL 125 061801 (2020)

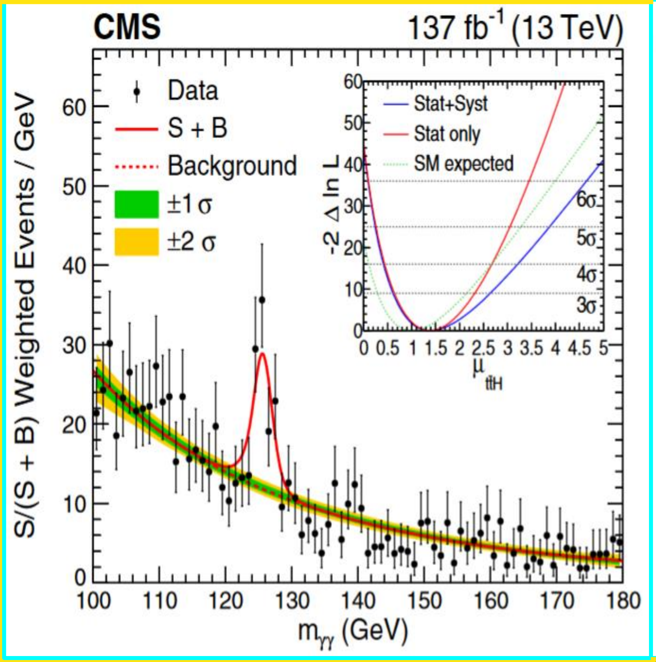
- **Studies of Htt coupling provide an alternate and independent path for CP Tests in the Higgs sector**
- **Main backgrounds $\gamma\gamma$ + jets, tt + $\gamma\gamma$, $\gamma\gamma$ + jets**
- **Hadronic and leptonic categories; BDT and DNN discriminants**
- **CP structure of the Htt amplitude:**

$$\mathcal{A}(Htt) = -\frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\tilde{\kappa}_t\gamma_5)\psi_t$$

- **Measure the CP Odd fraction with:**
-

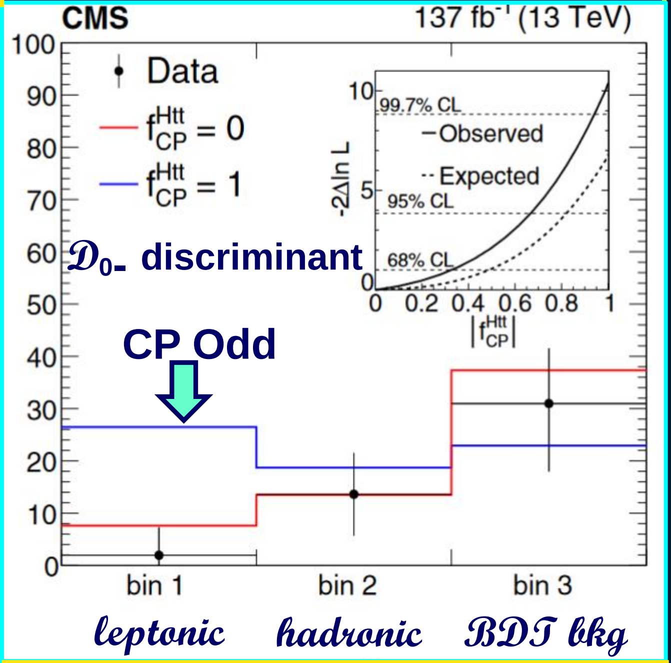
$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

ttH signal and background vs $m_{\gamma\gamma}$ S/(S+B) weighted



Inset: μ(ttH) likelihood scan with m_H profiled

$\mathcal{D}_{0-}$ discriminant leptonic, hadronic and BDT bkg bins



Inset: $|f(Htt)^{CP}|$ fraction likelihood scan

μ(ttH, H → $\gamma\gamma$) = 1.38 $^{+0.36}_{-0.29}$

Observed Significance: 6.6σ

σ(ttH) $\mathcal{B}(\gamma\gamma)$ = 1.56 $^{+0.34}_{-0.32}$ fb

CP structure of Higgs coupling to fermions:

$f(Htt)^{CP}$ = 0.00 ± 0.33; $|f(Htt)^{CP}|$ < 0.67 at 95% CL

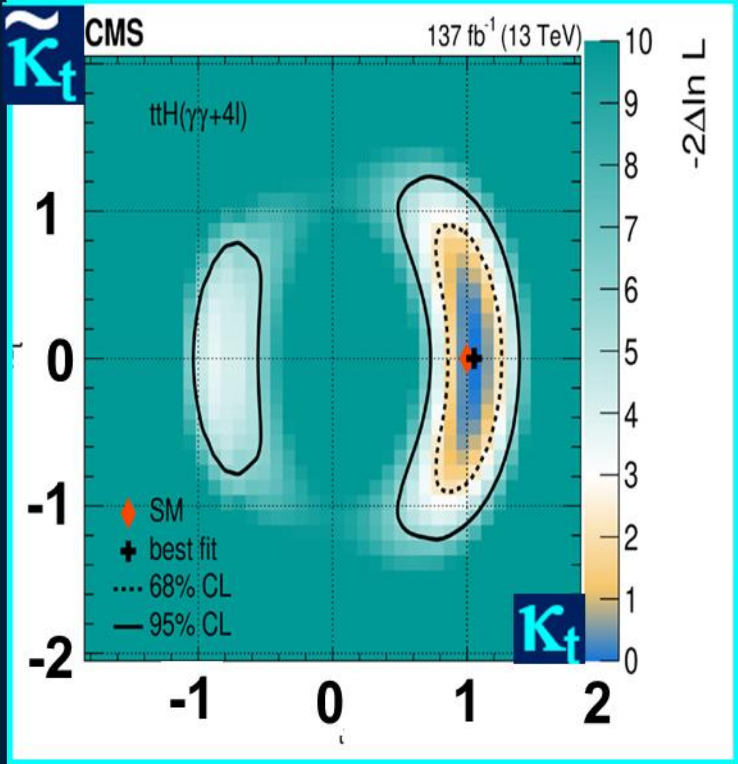
Pure CP Odd ($f(Htt)^{CP}$ =1) Excluded at 3.2σ

Combined Htt Yukawa CP Structure Studies

- CP Structure of Higgs fermion couplings explored in multiple Higgs-boson final states:
  - H →ττ, or ttH, tH with H →ττ
  - ttH, tH with H → γγ decays
- CP structure in Higgs-boson vector couplings probed in
  - H→ZZ*→4ℓ channel
  - New: Multilepton final states in ttH, tH with H→WW, t → Wb
- Results: No significant CP odd contributions observed
- Combined results: Best fit $|f(Htt)^{CP}| = 0.28$; < 0.55 at 68% CL
- Compatible with SM CP Even: $|f(Htt)^{CP}| = 0$

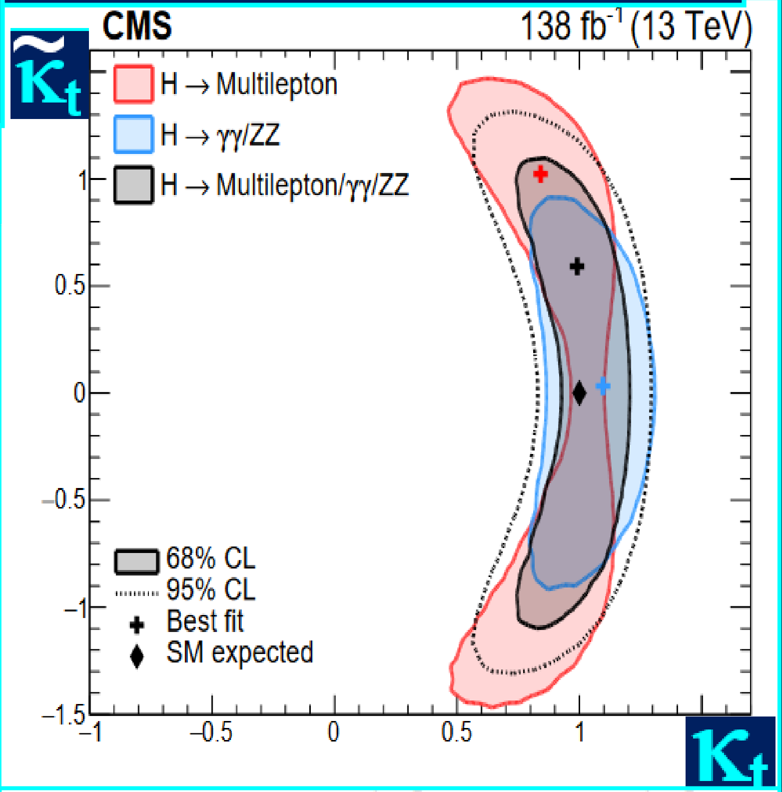
Comprehensive Study of ttH CP structure and anomalous CP couplings

$\tilde{\kappa}_t$ vs κ_t ttH ($\gamma\gamma + 4\ell$)



Phys. Rev. D 104 (2021) 052004

$\tilde{\kappa}_t$ vs κ_t Combined

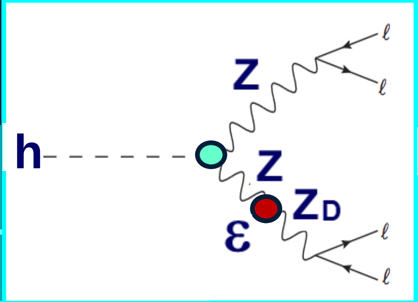


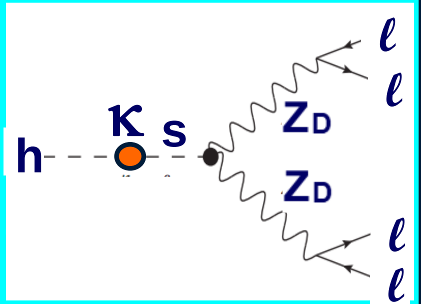
Parameter	68% CL	95% CL
κ_t	(0.96, 1.16)	(0.86, 1.26)
$\tilde{\kappa}_t$	(-0.86, 0.85)	(-1.07, 1.07)

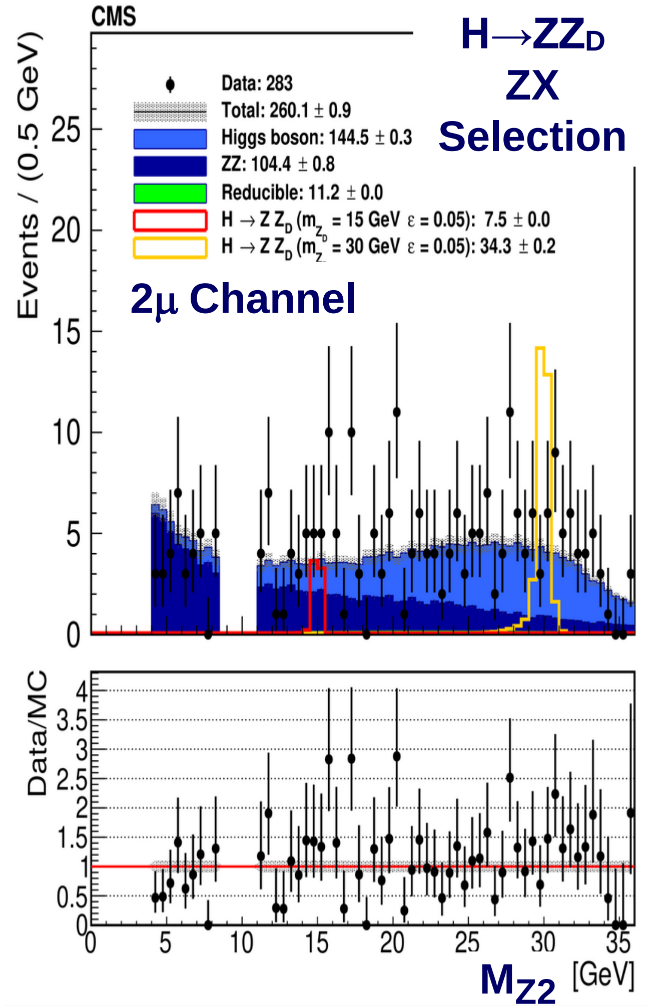
CMS-HIG-21-006 (August 2022)

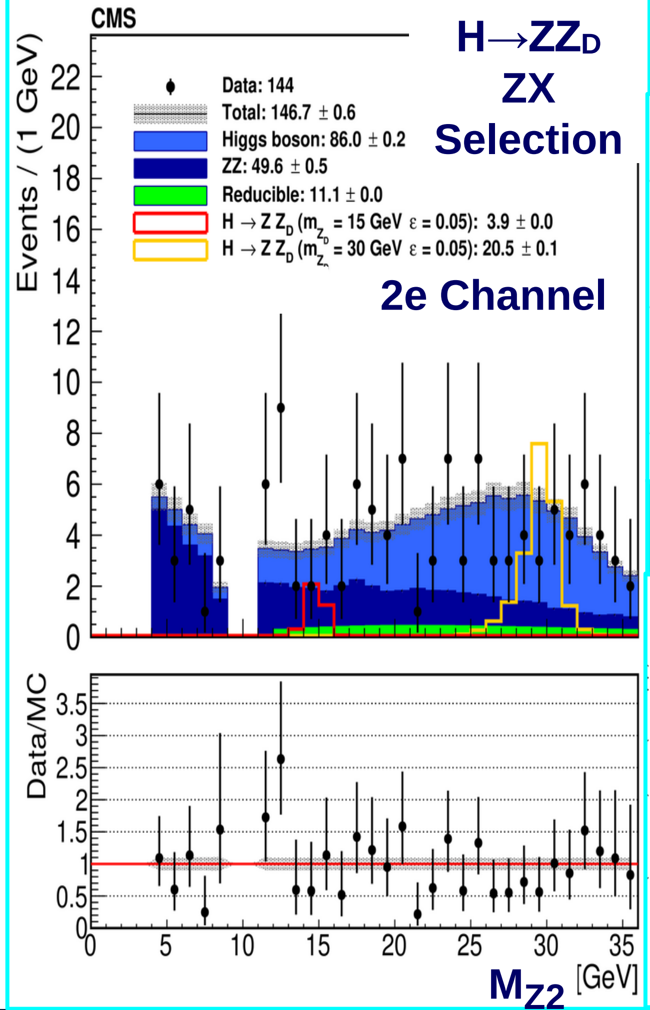
Recent BSM Higgs Search Results

Search for a Dark Photon and an Axion-like particle
$H \to ZZ \to ZZ_D$, $H \to S \to Z_DZ_D$ in 4 Lepton Channels

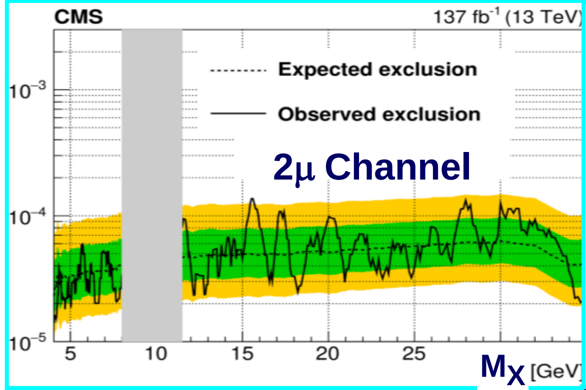




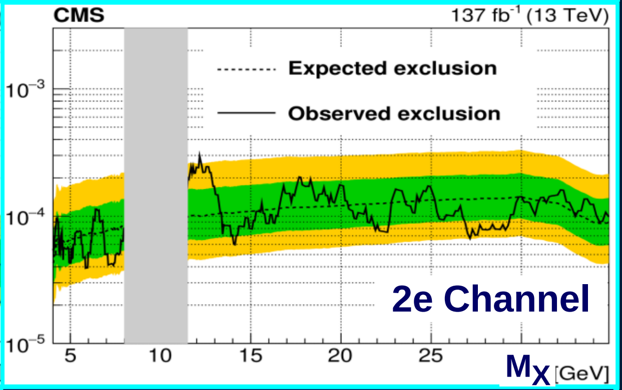




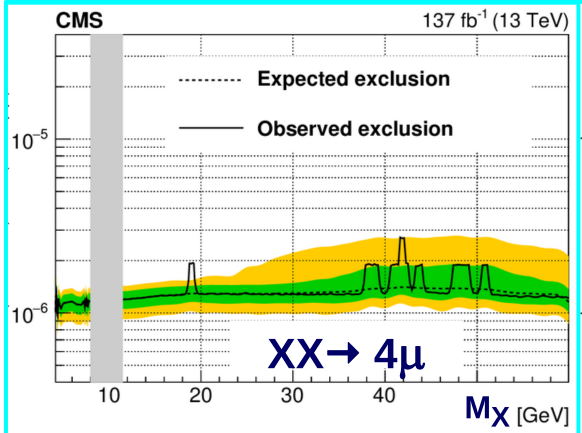
95% CL Limit on $\mathcal{B}(H \to ZX)\,\mathcal{B}(X \to \mu\mu)$



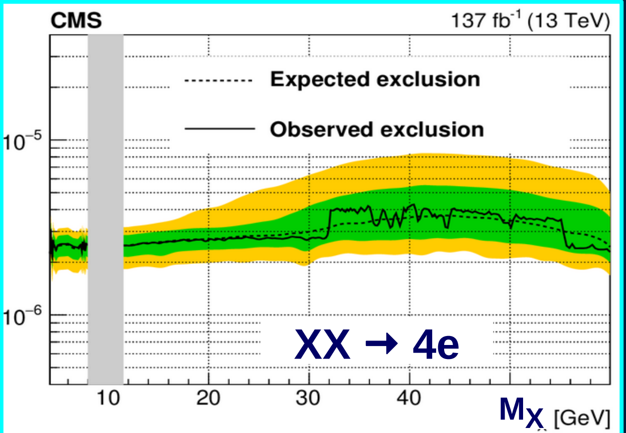
95% CL Limit on $\mathcal{B}(H \to ZX)\,\mathcal{B}(X \to ee)$



95% CL Limit on $\mathcal{B}(H \to XX)\,\mathcal{B}(X \to \mu\mu)^2$



95% CL Limit on $\mathcal{B}(H \to XX)\,\mathcal{B}(X \to ee)^2$



Eur. Phys. J. C 82 (2022) 290   CMS HIG-19-007

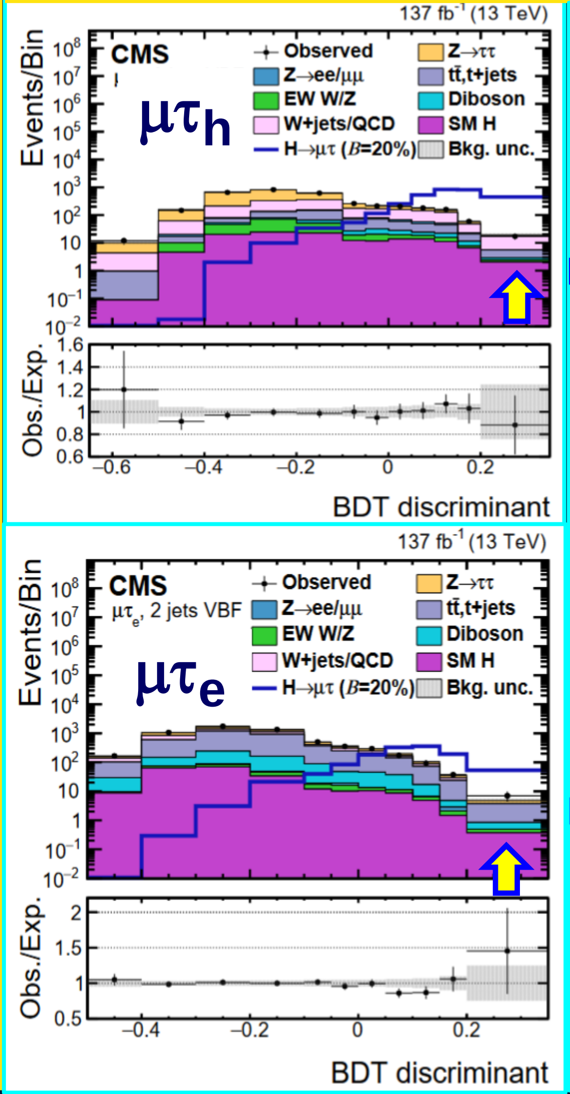
Search for Lepton Flavor Violating Decays in $H \to \mu\tau, e\tau$

Full Run2 ; Direct Search

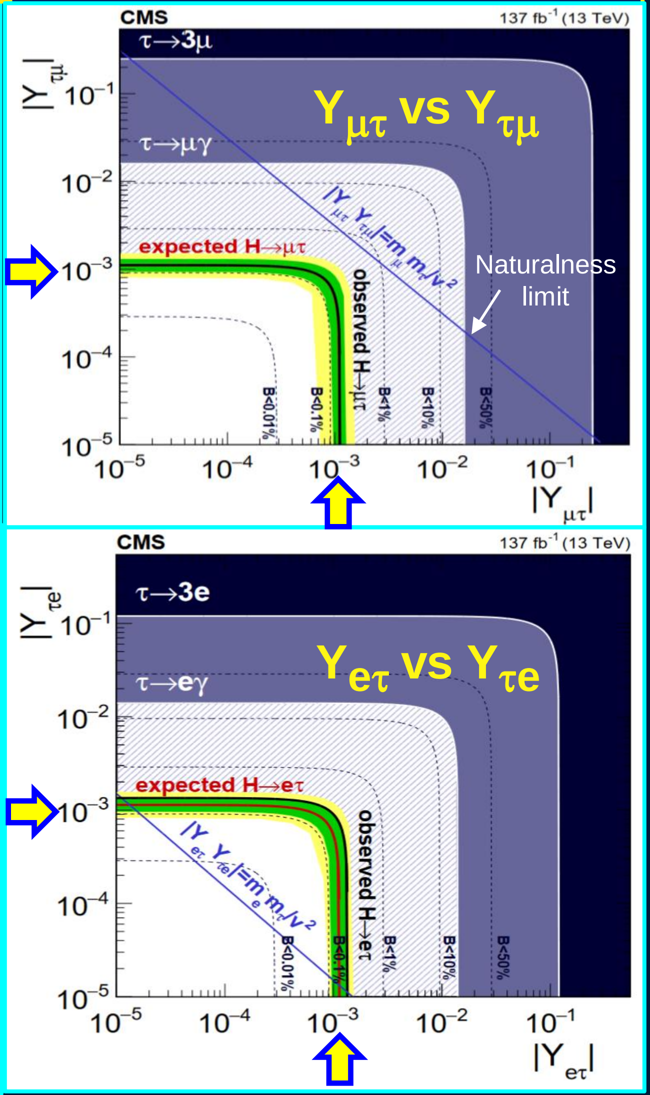
PRD 104 (2021) 032013

- **Arise in many BSM Models:** 2HDM, composite H, exotic resonances, extra dimensions, etc.
- **Constraints:** $\mu \to e\gamma$ limits $\to \mathcal{B}(H \to e\mu) < 10^{-8}$ $\tau \to e\gamma$, $\tau \to \mu\gamma$, $(g-2)_e$, $(g-2)_\mu \to \mathcal{B}(H \to \mu\tau, e\tau) \lesssim 10\%$
- **Search Channels:** $\mu\tau_h$ $\mu\tau_e$, $e\tau_h$, $e\tau_e$
- **BF constraints translated to limits on** LFV Yukawas $Y_{e\tau}$, $Y_{\mu\tau}$
- **$\mu\tau$ analysis somewhat similar to $H \to \tau\tau$,** except muons are prompt, tend to have higher momenta
- **0,1,2 jet, ggF, VBF categories;**
- **BDTs to separate signals** from non-Higgs and $H \to \tau\tau$ backgrounds
- Results; 95% CL Upper Limits
  - $\mathcal{B}(H \to \mu\tau) < 0.15\%$ (0.15% expected)
  - $\mathcal{B}(H \to e\tau) < 0.22\%$ (0.16% expected)

BDTs in most sensitive channels: VBF 2 Jet



Limits on Off-diagonal Yukawa Couplings + BRs

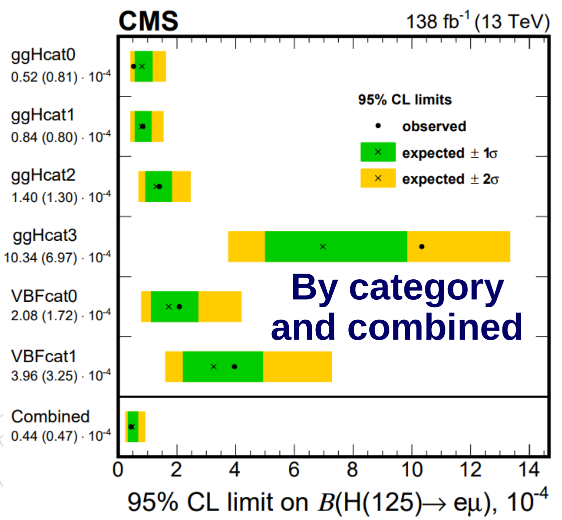


Search for Lepton Flavor Violating H → eμ Decays

Full Run2
CMS-HIG-22-002

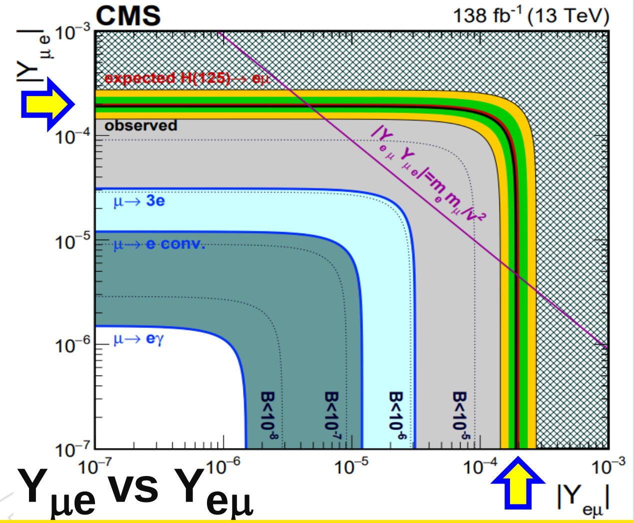
- Constraints: μ → eγ limits → $\mathcal{B}(H \to e\mu) < 10^{-8}$
- Search for LFV OS decay to μe of an SM-like or BSM Higgs with $110 < m_X < 160$ GeV
- Signature: m_X or m_H peak on a smooth background: Mainly tt, WW leptonic decays
- Categories: for ggF, VBF production; and S/B bins from BDTs trained to extract the signal
- Simultaneous fit of S and B models to extract an upper limit on either $\mathcal{B}(H\,(125) \to e\mu)$ or
  $\sigma(pp \to X \to e\mu)$ for a BSM Higgs
- Results: Observed (exp) 95% CL upper limit on
  $\mathcal{B}(H\,(125) \to e\mu) = 4.4 \times 10^{-5}$ (4.7×10^{-5})
- $\mathcal{B}(H\,(125) \to e\mu)$ is translated to an upper limit on the LFV Yukawas $Y_{e\mu}$, $Y_{\mu e}$
- An excess of events over background observed around 146 GeV:
  Global (local) significance = 2.8σ (3.8σ)

95% CL Observed (exp) limits on $\mathcal{B}(H\,(125) \to e\mu)$



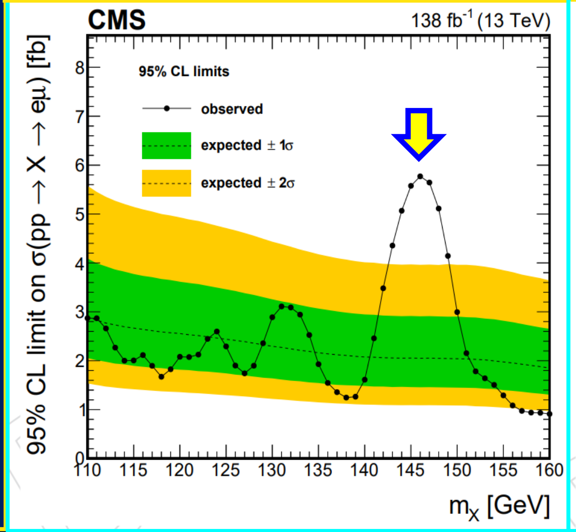
By category and combined

Limits on Off-diagonal Yukawa Couplings

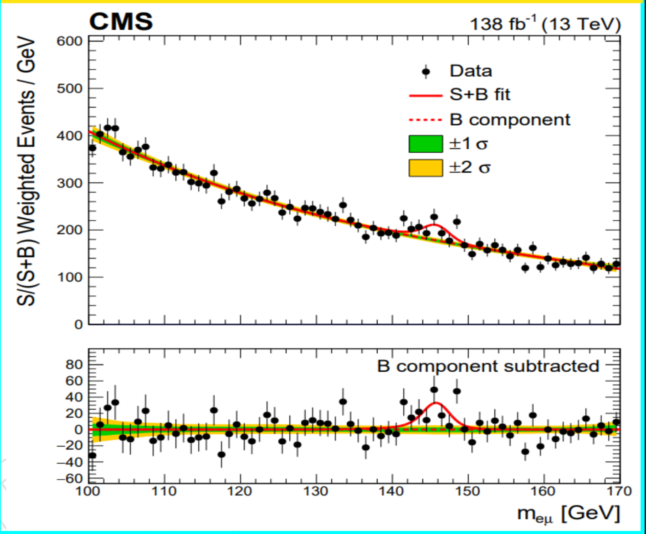


$Y_{\mu e}$ vs $Y_{e\mu}$

95% CL Observed (exp) $\sigma(pp \to X \to e\mu)$ limit



$m_{e\mu}$ Distribution with S+B Fit at 146 GeV



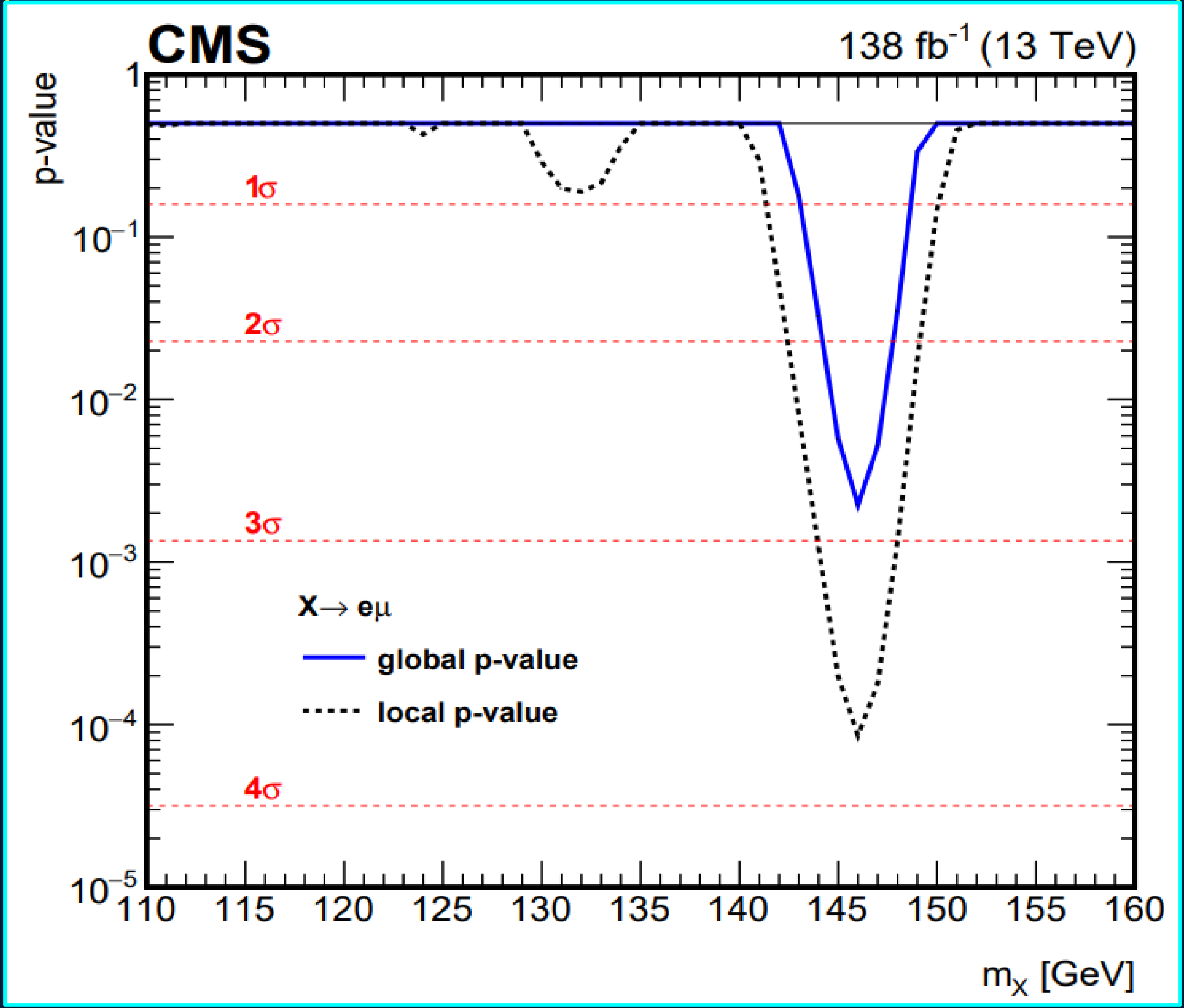
Search for Lepton Flavor Violating H → eμ Decays

Full Run2

CMS-HIG-22-002

Observed Global and local p-values

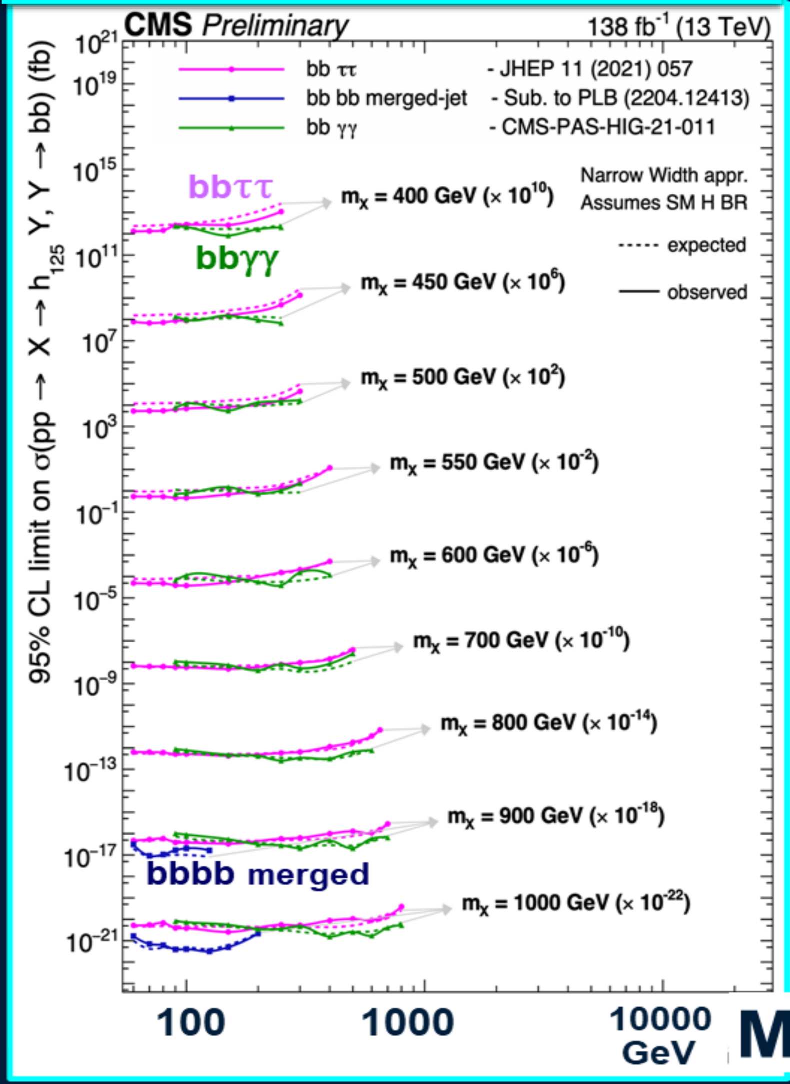
versus the hypothesized BSM Higgs mass m_X



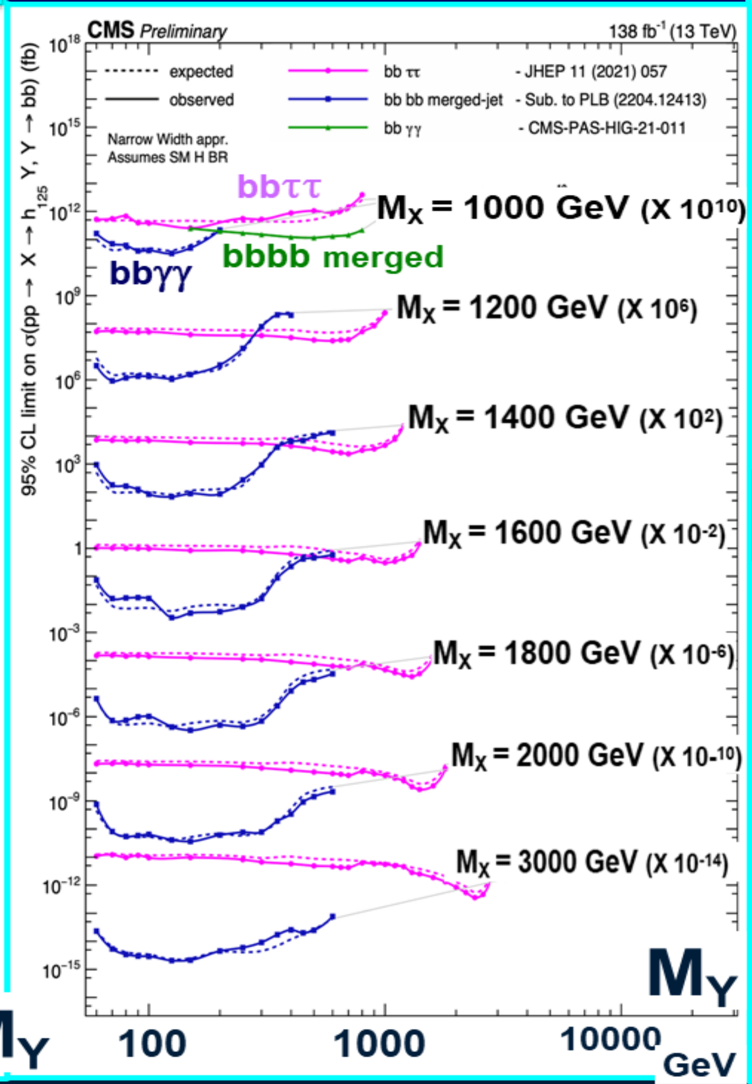
Higgs Portal: Wide Ranging Searches for Exotic Resonances

95% CL Limits at 13 TeV (June 2022) Full Run2

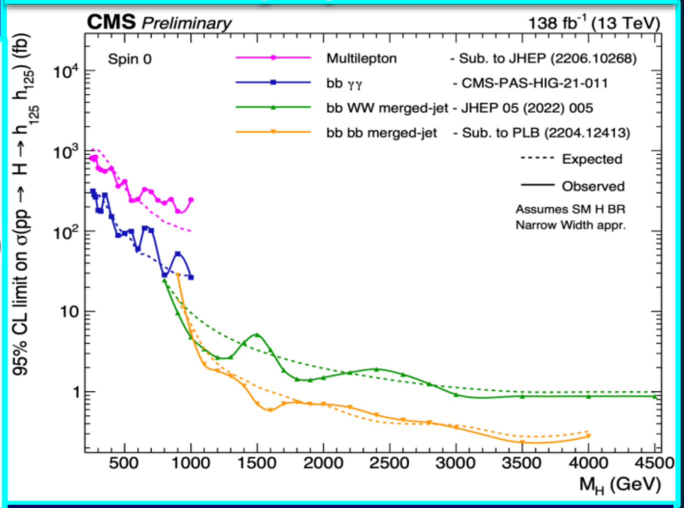
$\sigma(gg \to X)\,\mathcal{B}(X \to h_{125}Y)$
Limit vs M_Y (M_X to 1 TeV)



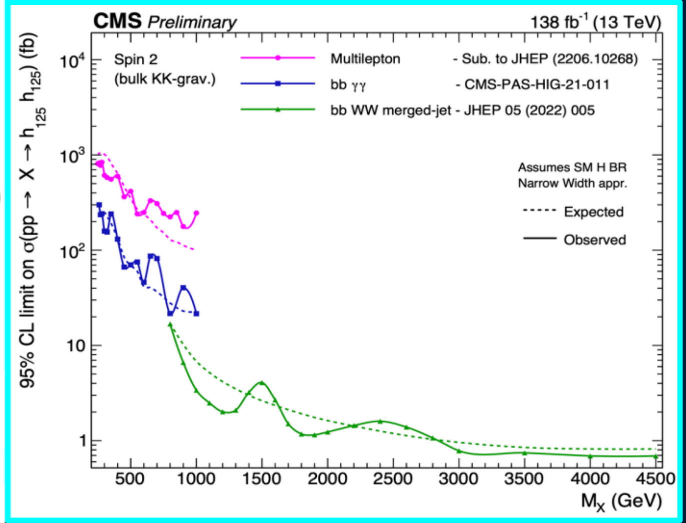
$\sigma(gg \to X \to h_{125}Y)\,\mathcal{B}(Y \to bb)$
Limit vs M_Y (M_X 1 to 3 TeV)



$\sigma(gg \to H)\,\mathcal{B}(H \to h_{125}\,h_{125})$
H heavy Spin 0 Scalar



$\sigma(gg \to H)\,\mathcal{B}(H \to h_{125}\,h_{125})$
H Spin 2 KK Bulk Graviton

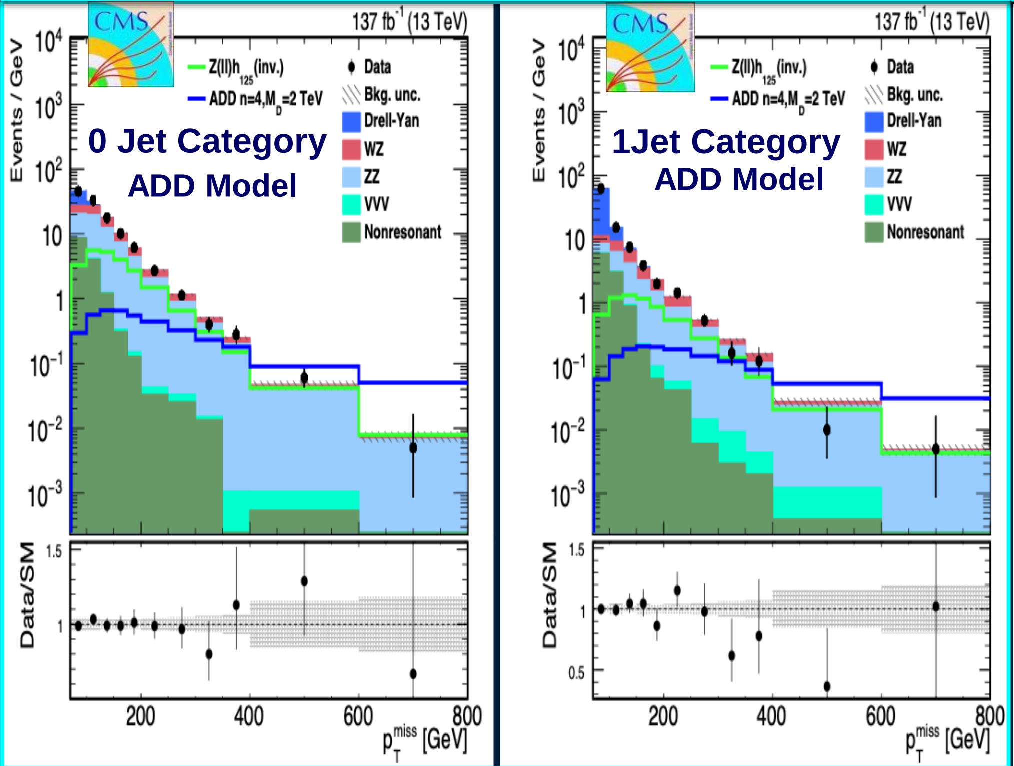


BSM Higgs searches: A Broad Program: Additional Higgses, invisible decays, lepton-flavour-violating decay and 2HDM+scalar models with h→aa, Charged Higgses,…

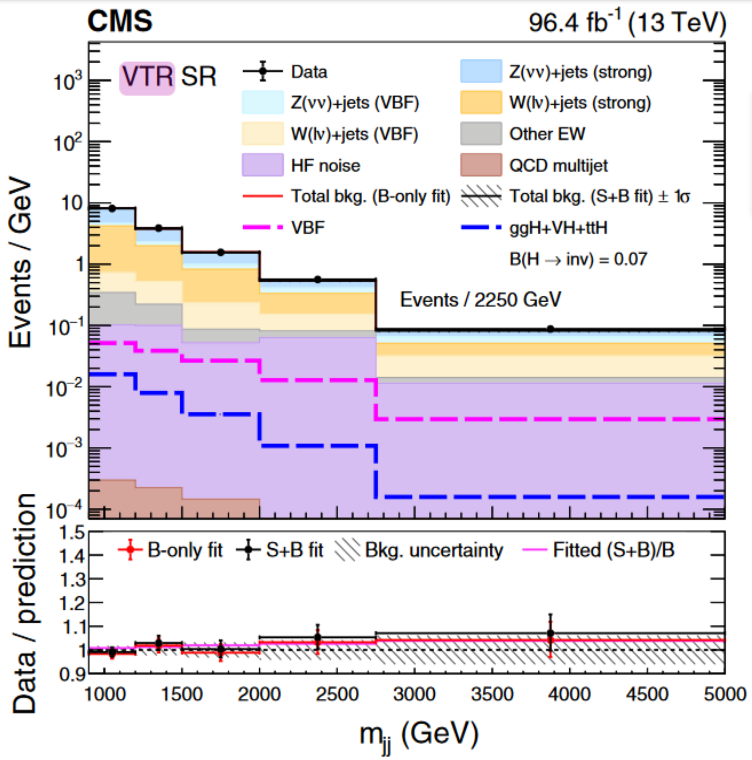
H → Invisible Examples: Z(ℓℓ) H(χχ), VBF H(χχ)

Signatures: MET. + Dileptons or VBF Jets
Main Backgrounds: $Z(\ell\ell, \nu\nu)$ or $W(\ell\nu)$ + Jets

SM prediction: BR(H→invisible)
$\sim 1 \times 10^{-3}$ from H→ZZ*→4ν



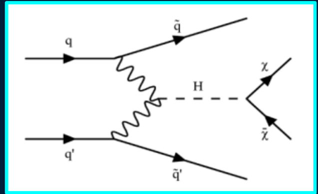
95% CL limit from Z (ℓℓ) H, H → Invisible:
BR(H→invisible) < 29%; Combined limit < 19%
Eur. Phys. J. C 81 (2021) 13

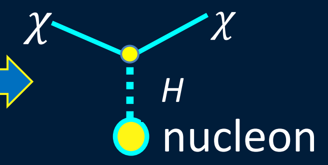


95% CL limit from VBF Jets + H → Inv:
BR(H→inv) < 18% Combined
Phys. Rev. D 105 (2022) 092007

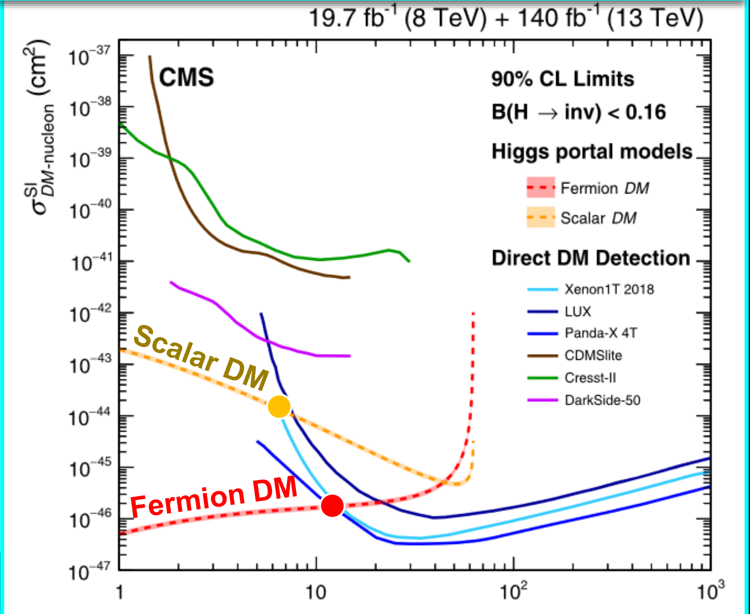
REINTEPRETATION

B(H → χχ) ⇒ χN scattering cross section





90% CL σ^{SI} (DM-nucleon) Limits
Compared to Direct DM experiments



Phys. Rev. D 105 (2022) 092007

Complementary for M_{DM} < 12 (6) GeV

BSM Heavy Resonances: $X \to VV, VH \to (jj)(jj)$

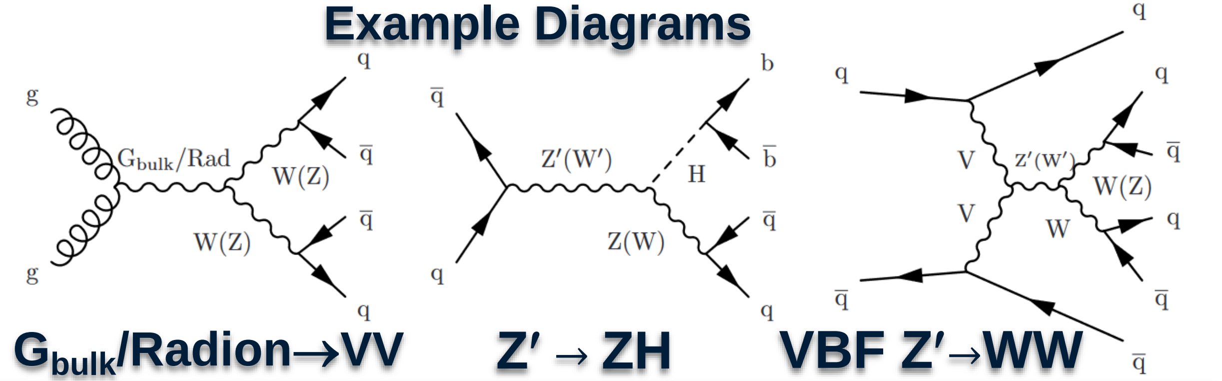
Highly Boosted: Two large merged jets (R = 0.8)

CMS B2G-20-009
Submitted to Phys. Lett. B

- Heavy Resonance Examples: X = Graviton (J=2), W′/Z′ Triplet (J=1), Radion, Heavy H (J=0)
- Signature:
  - SM bosons (W, Z, H) each decay to qq jet pairs
  - For $m_X > 1.3$ TeV, expect two wide jets (R=0.8)
  - Relatively narrow resonance: assume $\Gamma_X \ll m_{JJ}$
  - Explore both VBF as well as ggF production
- Deep Learning Taggers; HPHP... LPLP Categories; Final 3D discriminant using (m_{JJ}, m_{J1}, m_{J2})
- Mass Limit Examples:

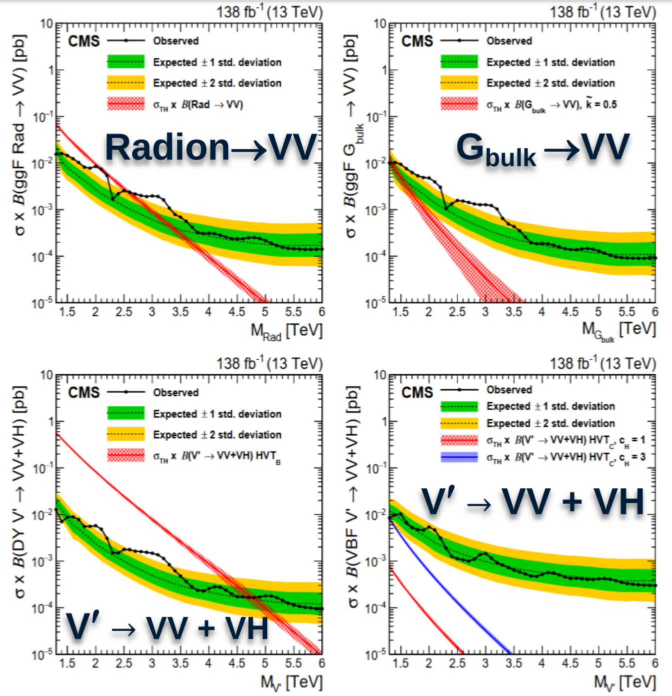
  $V' \to VV+VH$: $m_{V'} > 4.8$ TeV
  Radion $\to$ VV: $m_{V'} > 2.7$ TeV
  Graviton $\to$ VV: $m_{V'} > 1.4$ TeV
- In bulk graviton model, exclude:
  Spin 2 Gravitons with M < 1.4 TeV
  Spin 0 Radions with M < 2.7 TeV
- Maximum Excesses observed at 2.1 and 2.9 TeV:
  Significance: 3.6σ local, 2.3σ global

Example Diagrams

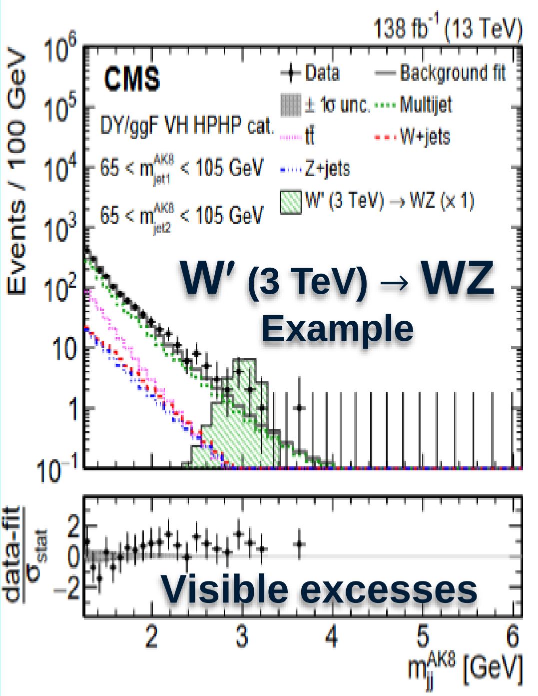


G_{bulk}/Radion→VV
Z′ → ZH
VBF Z′→WW

95% CL Limits vs M_X (TeV)



DY/ggF VH HPHP Category



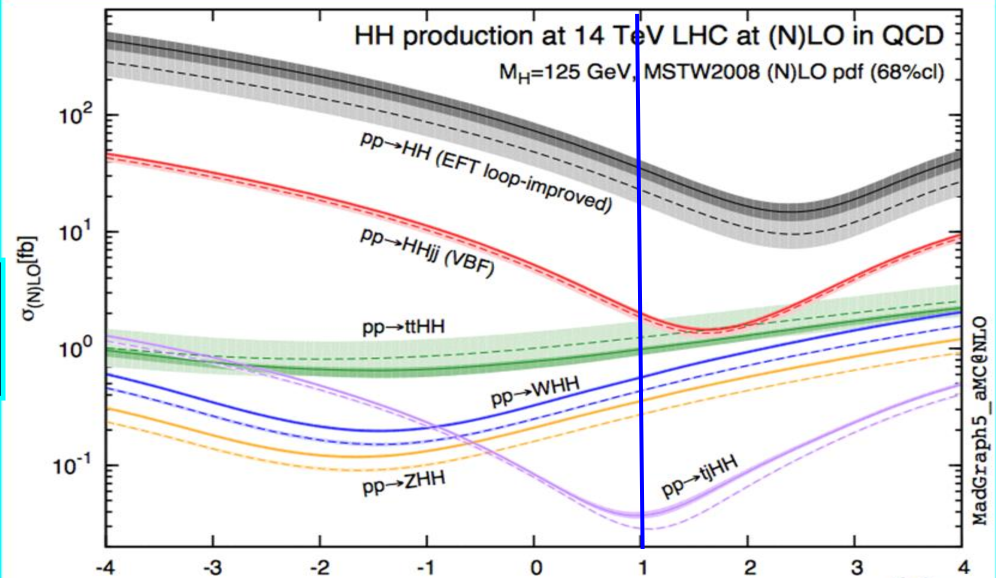
Higgs Boson Self-Coupling: HH Searches

- Higgs self-coupling probes the nature of the Higgs potential:

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

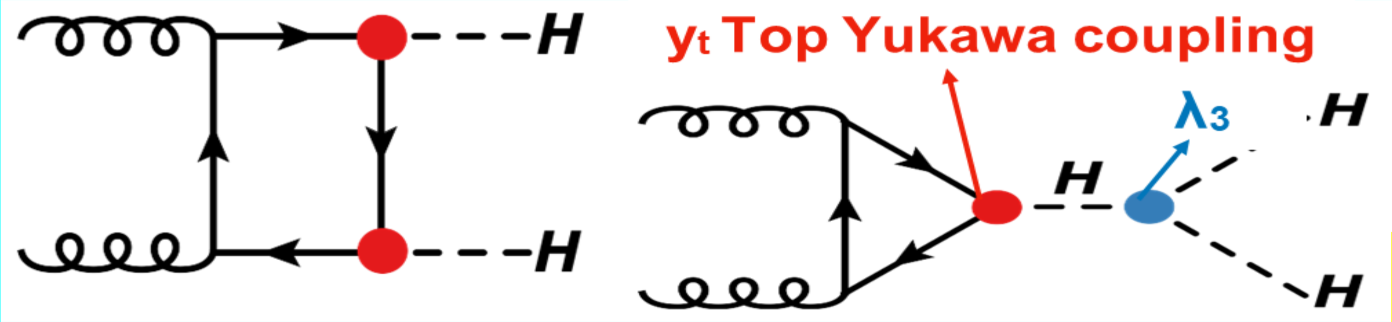
λ_3: Trilinear Higgs self-coupling

- λ_3 can be probed via HH production: extremely challenging at LHC, accessible at HL-LHC

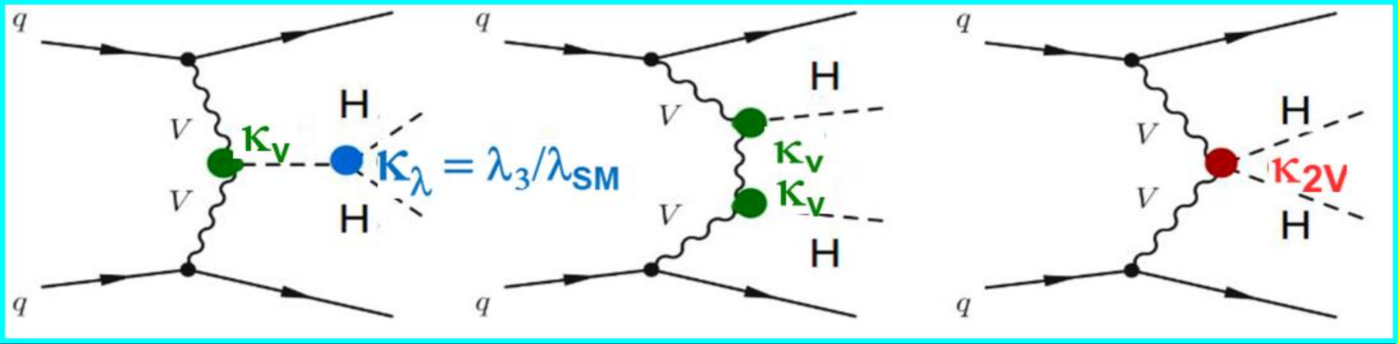


R.Frederix et al: Phys.Lett. B732 (2014) 142-149

Main production mode ggF ~31.05 fb @NNLO
Destructive Interference in the SM

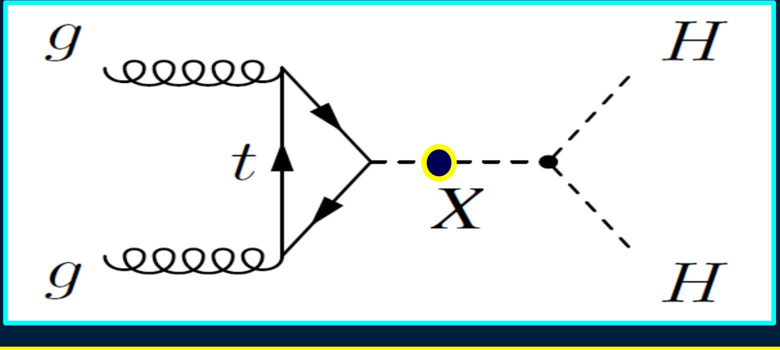


Sub-leading VBF ~1.73 fb @13 TeV N^{3}LO QCD
VBF channel provides access to the HVV (κ_V), triple HHH (κ_λ), and HHVV (κ_{2V}) quartic couplings



Resonant Searches: X →HH

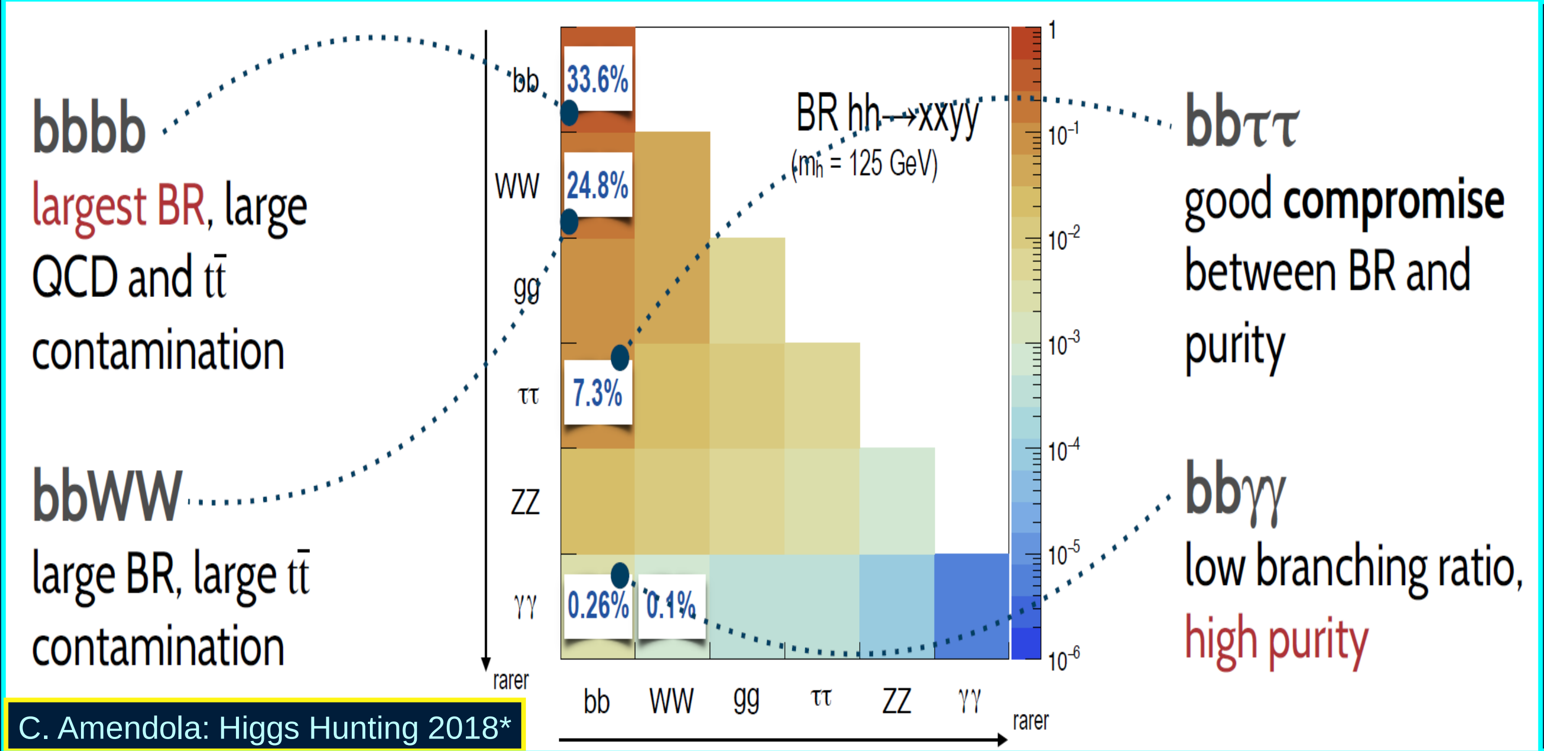
Predictedi BSM Extensions:
MSSM, other 2HDMs, Extra Singlets, Warped Extra Dimensions, CP-Even Spin 0 or Spin 2



HH Combination

- **Production Modes** (Tags): **ggF, VBF**
- Main decay channels are Complementary: **HH → bbγγ, bbWW, bbττ, bbbb**
  - **Tradeoff** between **BR1*BR2** and **relative purity**
  - Cover **different phase space regions;** Most sensitive **in different mass ranges**

➡ **A lot gained by *combining***



bbbb
largest BR, large QCD and $t\bar{t}$ contamination

bbWW
large BR, large $t\bar{t}$ contamination

bbττ
good **compromise** between BR and purity

bbγγ
low branching ratio, high purity

C. Amendola: Higgs Hunting 2018*

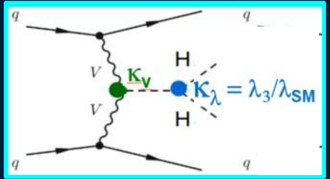
Results (95% CL Limits)

- HH **production signal strength**

$$\mu < 2.6$$

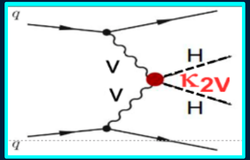
- HHH **Coupling Modifier**

$$-1.2 < \kappa_\lambda < 6.5$$



- VVHH **Quartic Coupling**

$$-0.7 < \kappa_{2V} < 1.4$$

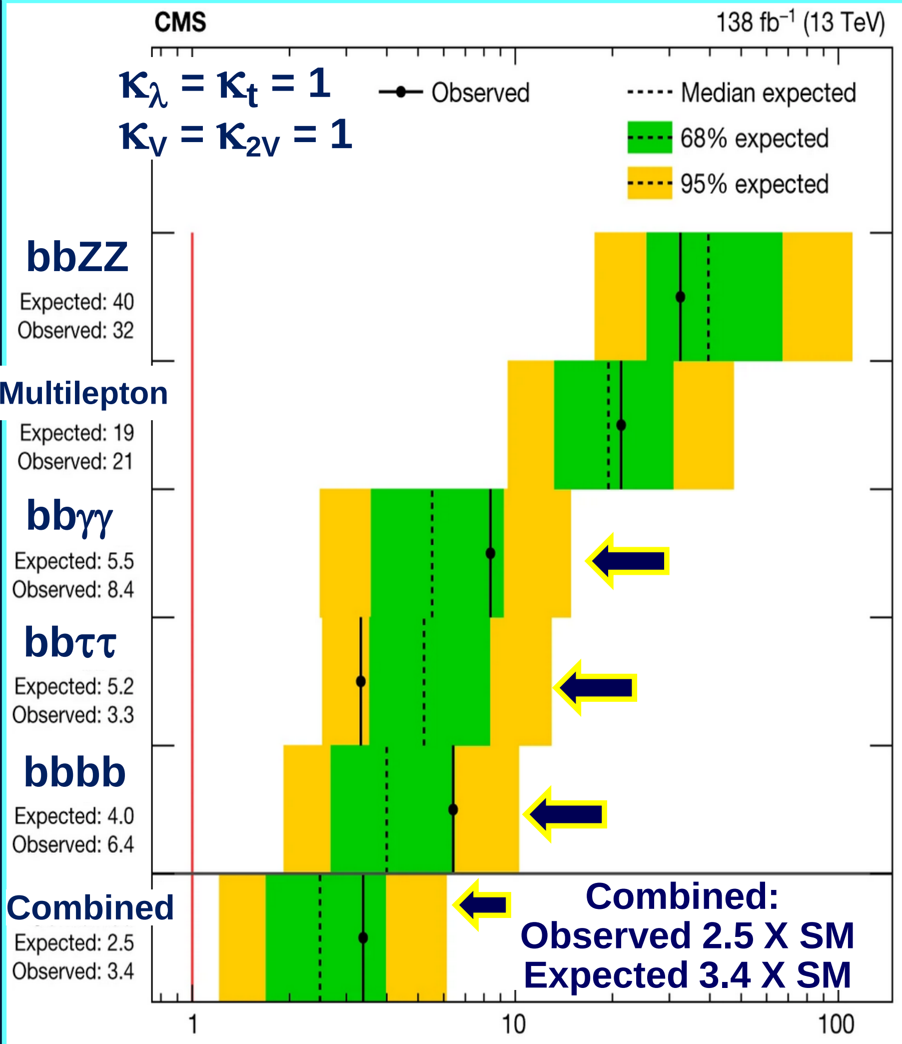


Complementary roles of the **dominant ggF** and **subdominant VBF** production modes

Inclusive HH Searches

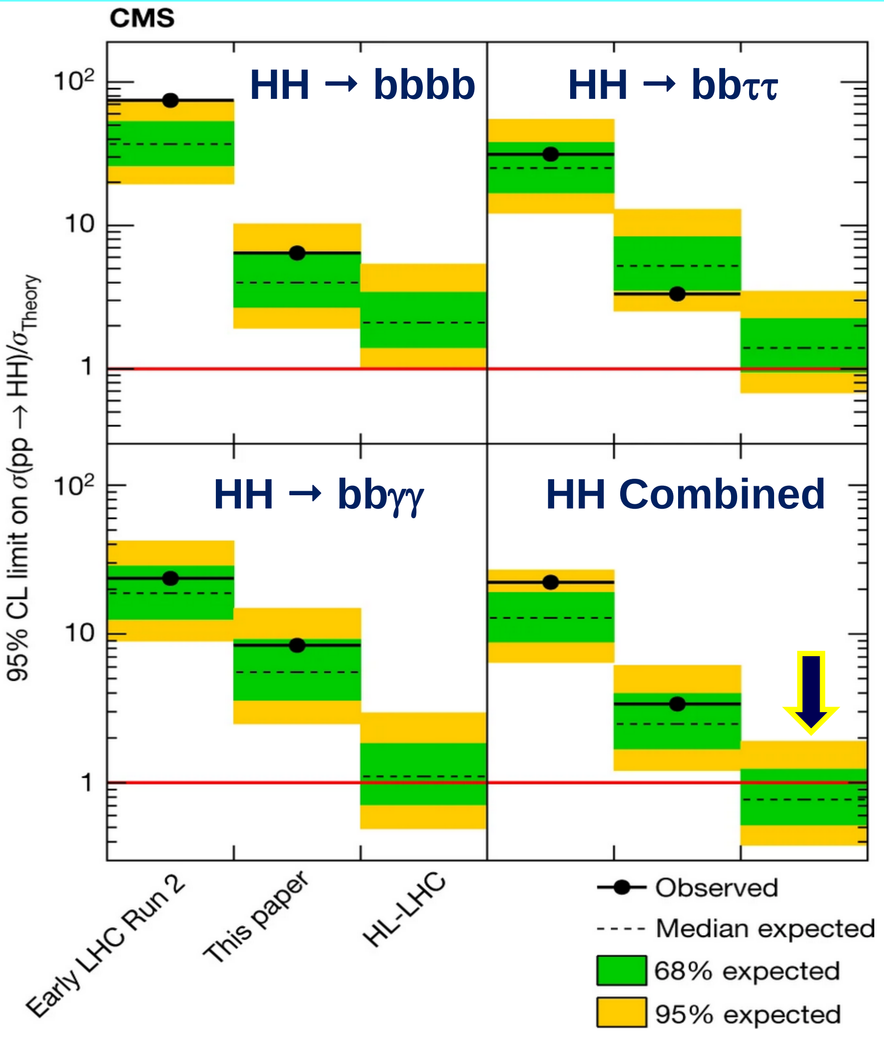
Nature **607**, 60–68 (2022)

σ/σ_{SM} 95% CL Limit Nonresonant HH → bbVV, bbbb, bbττ, bbγγ + Combined

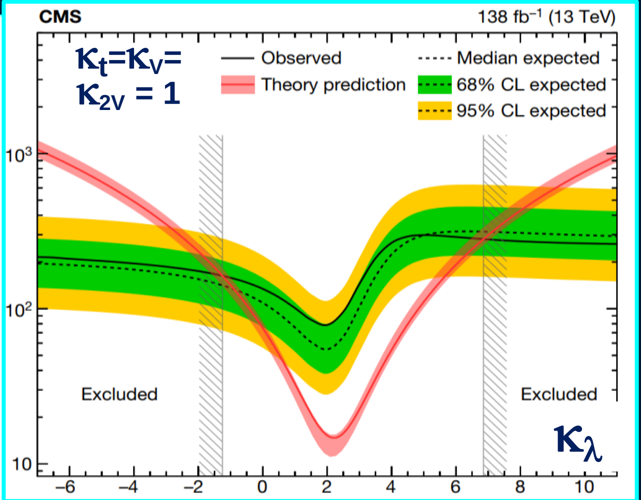


Combined:
Observed 2.5 X SM
Expected 3.4 X SM

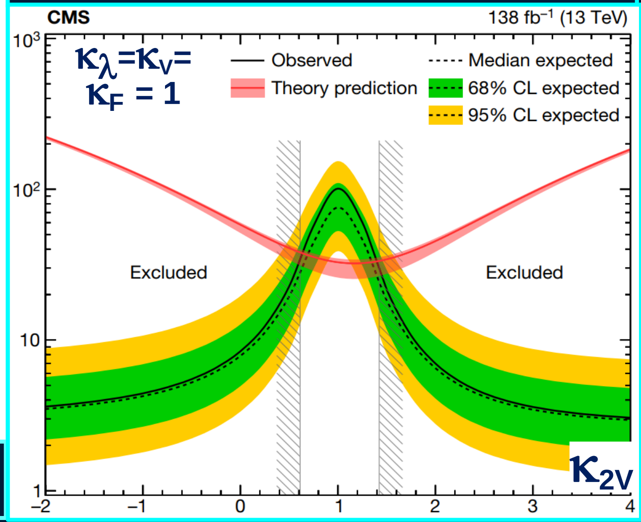
Evolution: Early Run2 to Now to HL LHC HH → bbbb, bbττ, bbγγ + Combined



95% CL Limit on σ(HH) (fb) vs self-coupling κ_λ



95% CL Limit on σ(HH) (fb) vs quartic coupling κ_{2V}



HH Observation Coming Into Reach at HL LHC

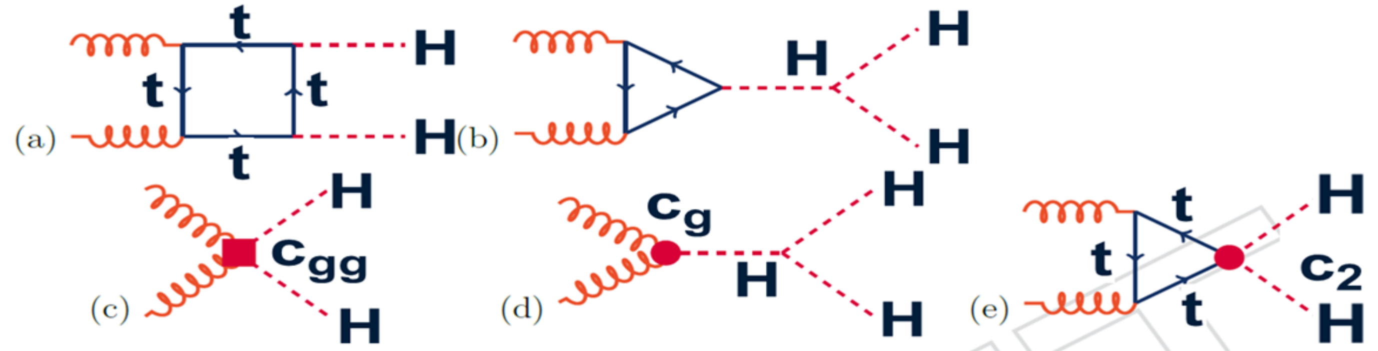
SM and Search for BSM in HH → bbγγ at 13 TeV

Higgs Self Coupling; Top Coupling; BSM Couplings

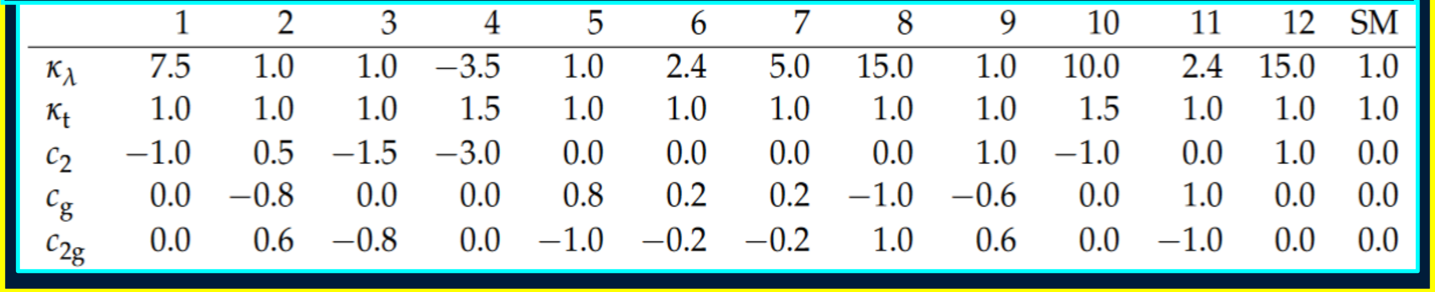
- *Self coupling and Yukawa coupling modifiers:*
- $\kappa_\lambda \equiv \lambda_{\mathrm{HHH}}/\lambda^{\mathrm{SM}}_{\mathrm{HHH}}$ *where* $\lambda^{\mathrm{SM}}_{\mathrm{HHH}} \equiv m^2_{\mathrm{H}}/(2v^2) = 0.129$
- *and* $\kappa_t \equiv y_t/y^{\mathrm{SM}}_t$ *where* $y^{\mathrm{SM}}_t = m_t/v \approx 0.7$

+ BSM Couplings from Dim. 6 Operators: c_2, c_g, c_{gg}

$$\mathcal{L}_{\mathrm{HH}} = \kappa_\lambda \lambda^{\mathrm{SM}}_{\mathrm{HHH}} v \mathrm{H}^3 - \frac{m_t}{v}\left(\kappa_t \mathrm{H} + \frac{c_2}{v}\mathrm{H}^2\right)\left(\bar{t}_L t_R + \mathrm{h.c.}\right) + \frac{1}{4}\frac{\alpha_S}{3\pi v}\left(c_g \mathrm{H} - \frac{c_{2g}}{2v}\mathrm{H}^2\right) G^{\mu\nu}G_{\mu\nu}$$

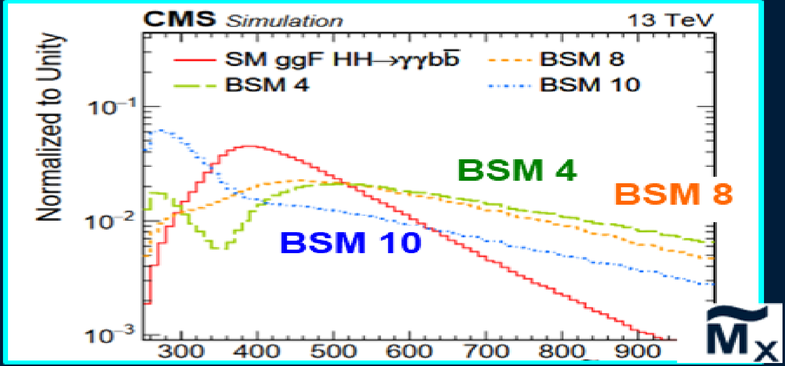


12 BSM Benchmark Hypotheses

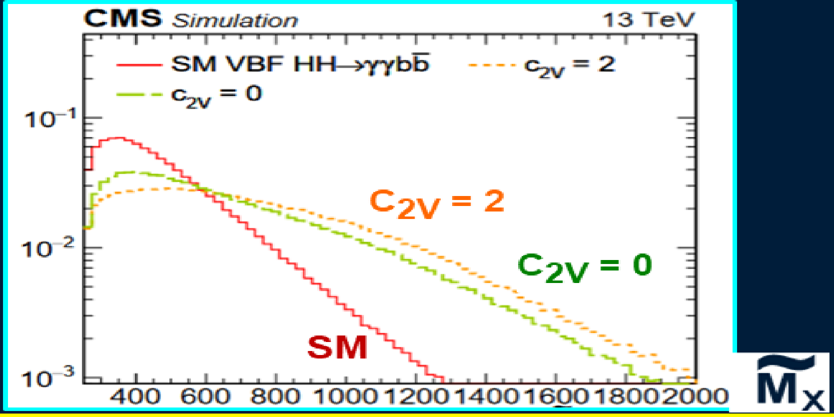


	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

- $\mathrm{M_X}$ $\widetilde{M}_{\mathrm{X}} = m_{\gamma\gamma\mathrm{jj}} - (m_{\mathrm{jj}} - m_{\mathrm{H}}) - (m_{\gamma\gamma} - m_{\mathrm{H}})$
  is particularly sensitive to the different BSM benchmark parameter choices;
  less sensitive to dijet, diphoton resolution
- SM ggF HH signal compared to
  BSM benchmark points 4, 8, 10:



- VBF HH signal compared to
  two anomalous C_{2V} values: 0 and 2



Recent Higgs Boson Self-Coupling Results with Full Run2 Data

- New HH decay channels and significantly improved analysis strategies
- Explore VBF production mode and HHVV coupling

$HH\to bb\gamma\gamma$ Inclusive: *JHEP 03 (2021) 257*

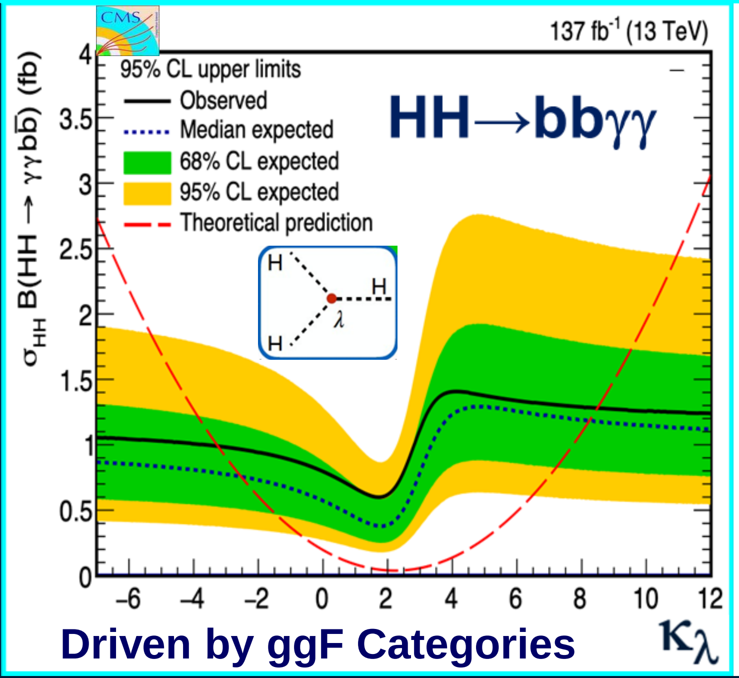
- **$-3.3 < \kappa_\lambda < 8.5$ obs @95% CL**
- **$\sigma(HH)\ /\ \sigma(HH_{SM}) < 7.7\ (5.2)$ obs(exp) @95% CL**
- **$HH\to bb\gamma\gamma$ VBF Categories**
- **$\sigma(HH)\ /\ \sigma(HH_{SM}) < 225\ (208)$ obs(exp) @95% CL**

$HH\to bbZZ^*\to bb+4\ell$ (CMS-PAS-HIG-20-004):

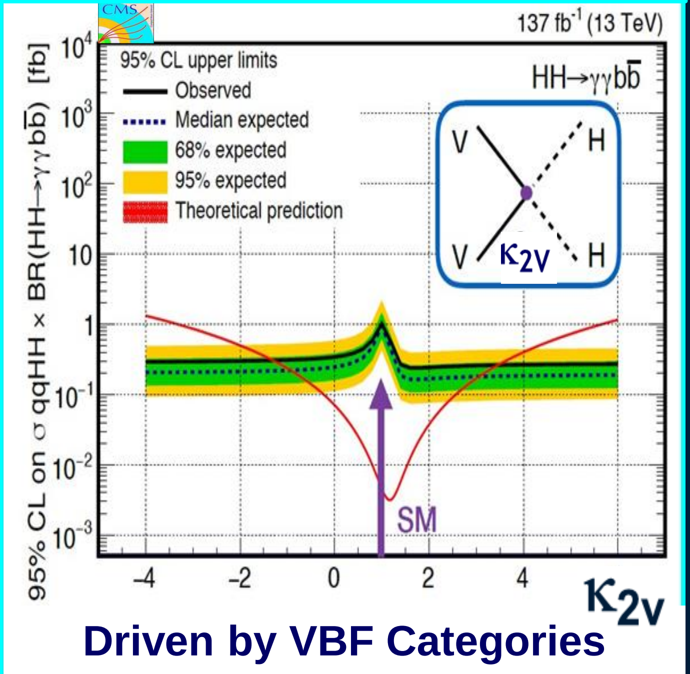
- **$-8.8 < \kappa_\lambda < 13.4$ obs @95% CL**
- **$\sigma(HH)\ /\ \sigma(HH_{SM}) < 32.4\ (39.6)$ obs(exp) @95% CL**

95% CL Upper Limit on $\sigma(HH) \times \mathcal{B}(HH \to bb\gamma\gamma)$ (fb)

Versus κ_λ **Versus κ_{2V}**



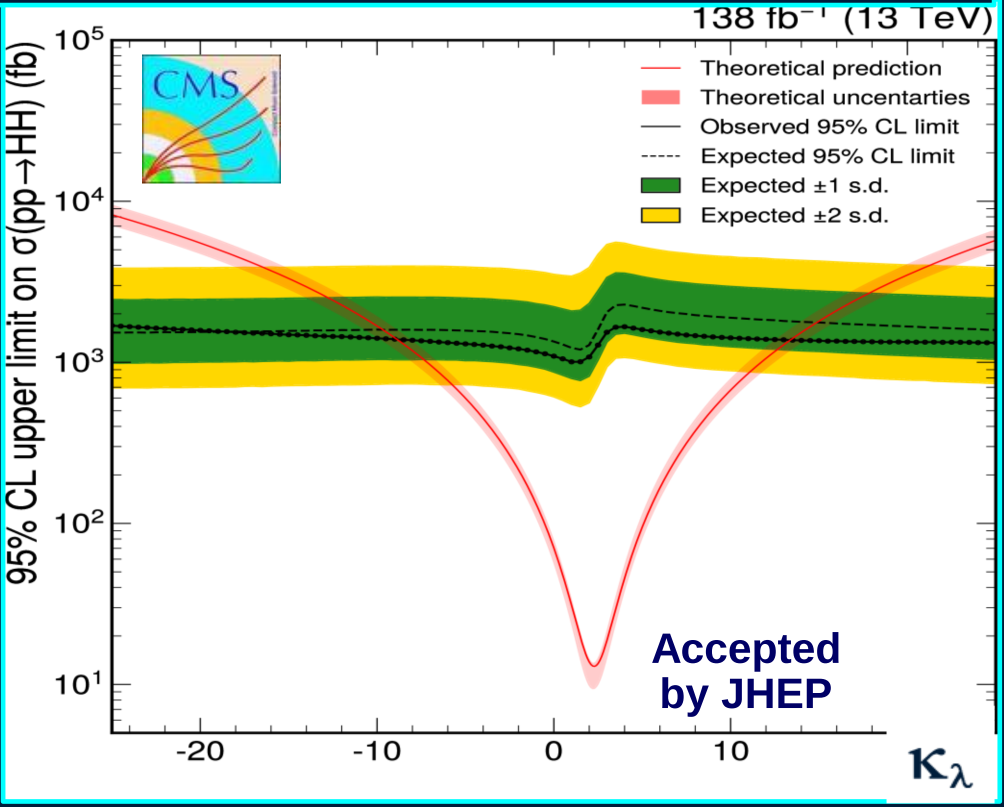
Driven by ggF Categories



Driven by VBF Categories

95% CL Limit on $\sigma(HH) \times \mathcal{B}(H \to bbZZ^* \to bb+4\ell)$

Versus κ_λ



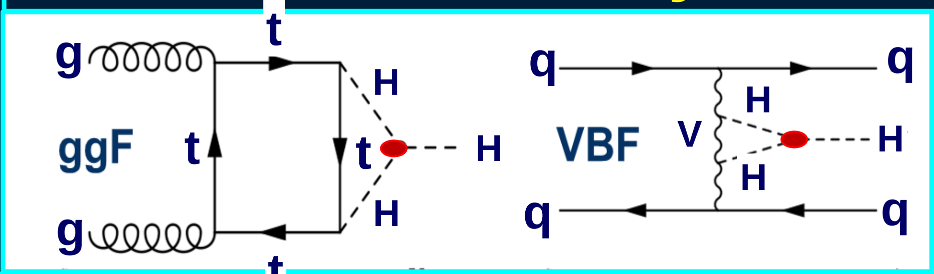
Accepted by JHEP

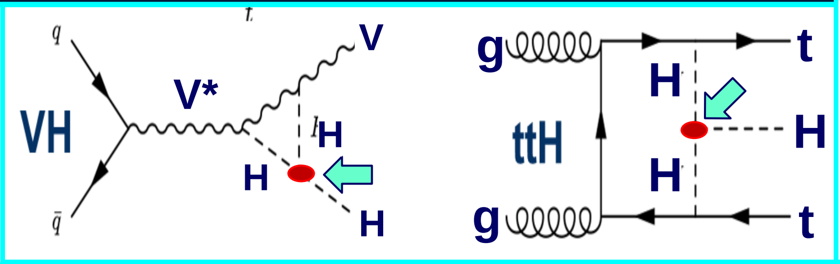
Self- and tH Couplings: HH→bbγγ + ttH,H→ γγ

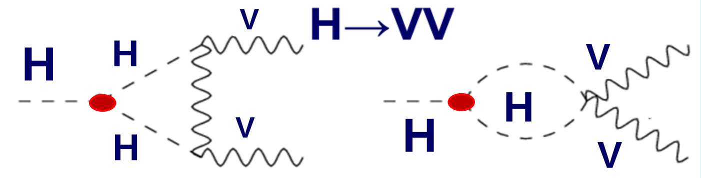
JHEP 03 (2021) 257

Single Higgs boson production & decay rates, kinematics, are sensitive to Higgs self-coupling through Electroweak Corrections

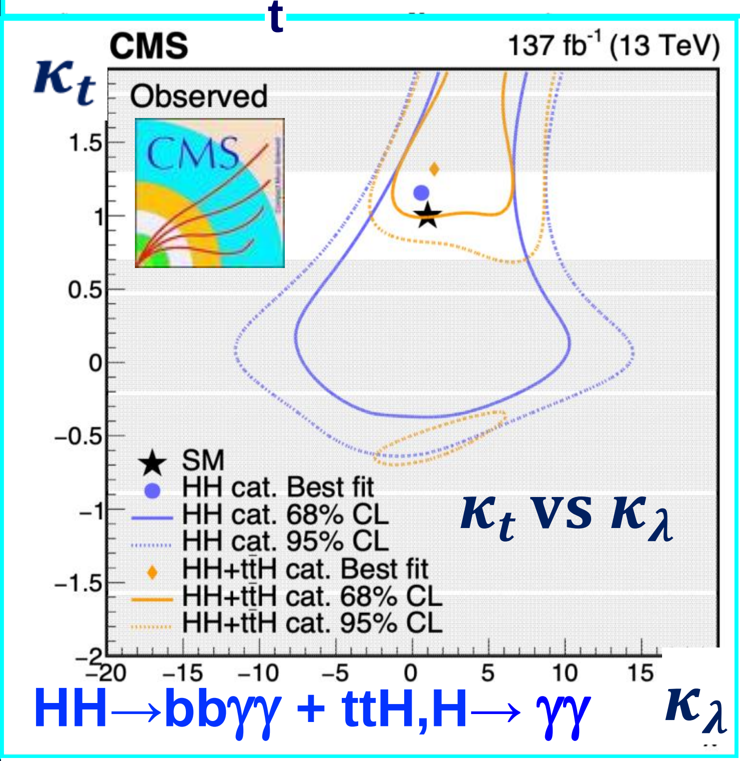
➡ indirectly constrain κ_λ ,assuming no other BSM effects





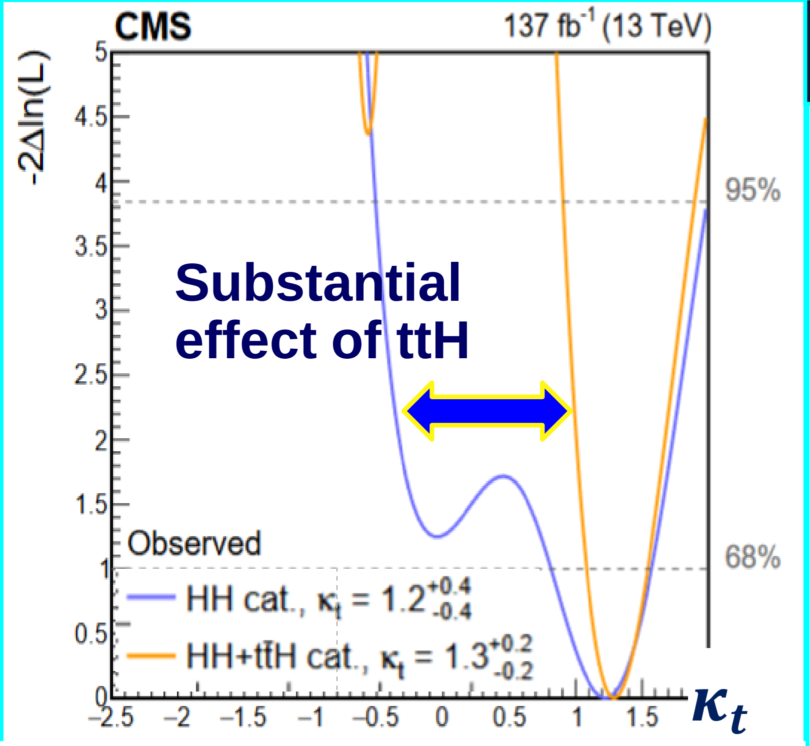


G. DeGrassi et al, JHEP 12 (2016) 080
F. Maltoni et al, EPJC 77 (2017) 887



κ_t vs κ_λ

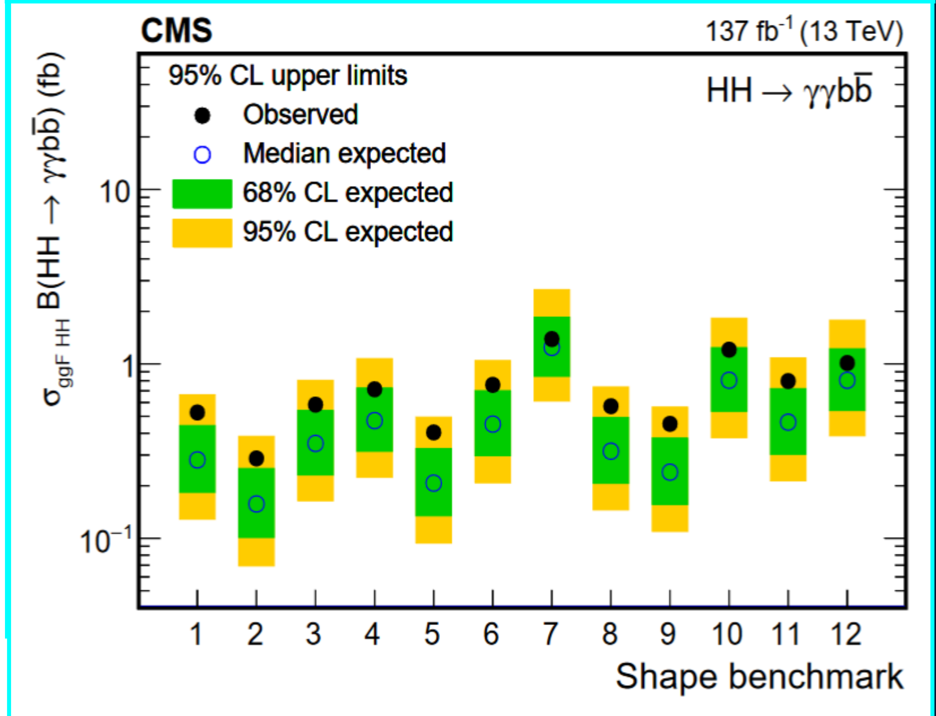
HH→bbγγ + ttH,H→ γγ



Substantial effect of ttH

JHEP 03 (2021) 257

σ(ggF → HH → bbγγ) 95% CL Upper Limits for 12 Shape Benchmark Points



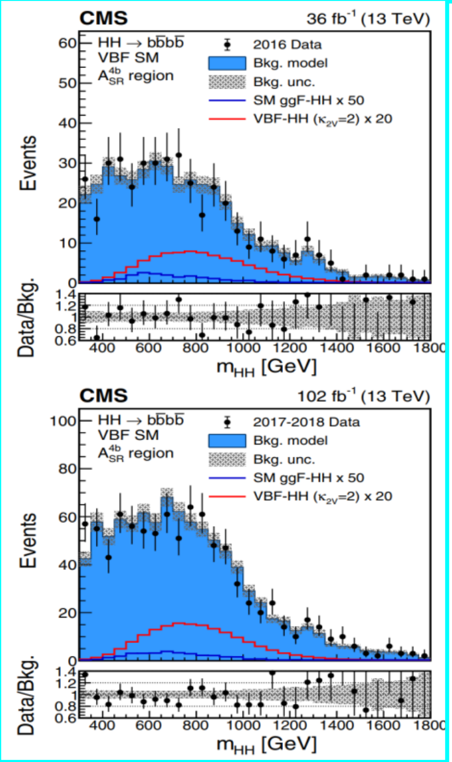
Recent Higgs Self- and Quartic Coupling Results with Full Run2 Data

Resolved analysis $HH \to b\bar{b}b\bar{b}$ currently provides the most stringent limit on HH production from an individual decay channel PRL 129, 081802 (2022)

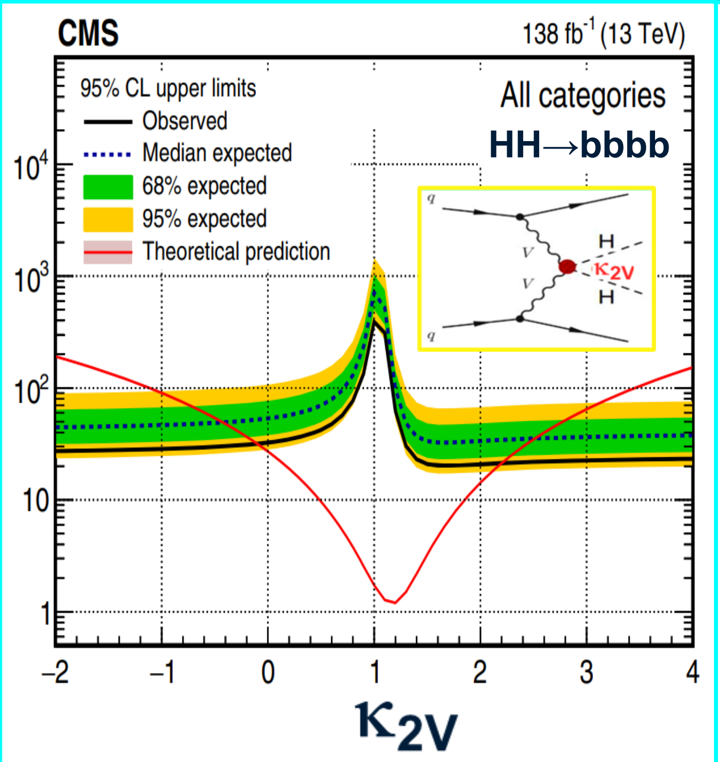
- **Targets both ggF and VBF Production**
- **Dedicated triggers: on 3-4 b-jets**
- **New analysis: Multivariate with Background estimated from multiple control regions**
- **DeepFlavour b-tagger**

- **Largest Uncertainty Sources**
  - Total integrated luminosity
  - Jet energy scale & resol'n
  - Trigger efficiency
  - b-tagging selection

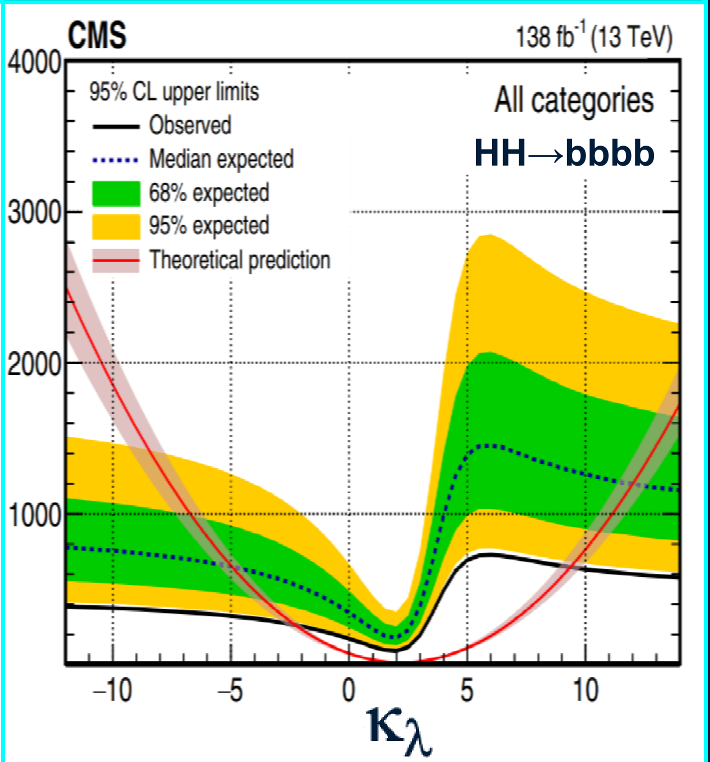
M_{HH} distribution VBF SM Like Region



$\sigma_{VBF}(pp \longrightarrow HH)$(fb) vs κ_{2V}



$\sigma_{VBF}(pp \longrightarrow HH)$(fb) vs κ_{λ}



$\sigma(HH)/\sigma(HH_{SM}) < 3.9$ (7.8) obs (exp)

$-2.3 < \kappa_{\lambda} < 9.4$ obs @95% CL

-0.1 (-0.4) $< \kappa_{2V} < 2.2$ (2.5) observed (exp) @95% CL

New: Higgs Boson Self- and Quartic Couplings κ_λ, κ_{2V} with Full Run2 Data

Highly Boosted HH → bbbb analysis with ParticleNet GNN H → bb tagger: Most stringent limit on Quartic HHVV Couplings

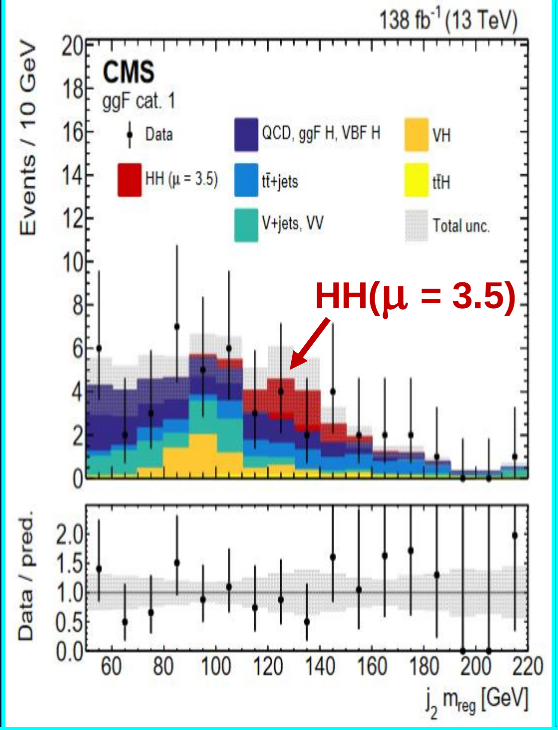
CMS-B2G-22-003
Accepted by PRL

- Targets both ggF and VBF Production; 30X κ_{2V} Sensitivity
- State of the art ParticleNet GNN discriminant $\mathcal{D}_{bb}$ selects large radius jets from H → bb rejecting QCD jet and tt pairs
- $\mathcal{D}_{bb}$ score → 3 Working points Tight, Medium, Loose:

Efficiencies	60, 80, 90%
QCD + tt Backgd	0.3, 1, 2%

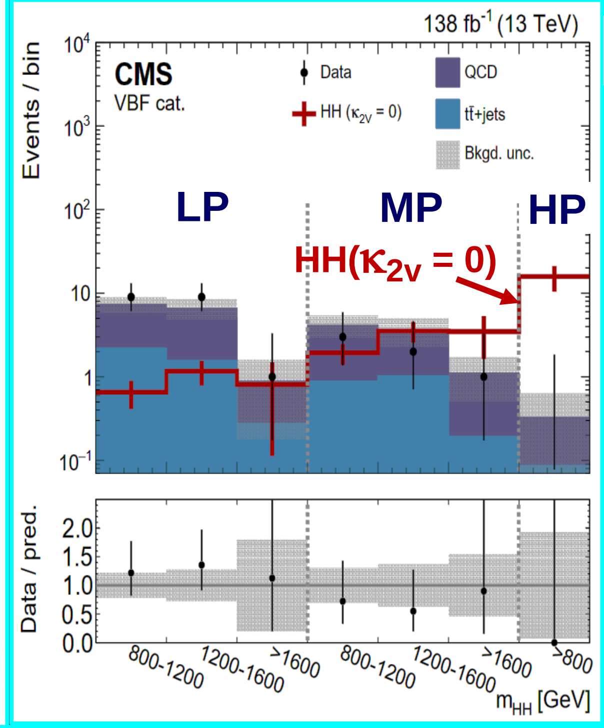
- BDT score uses jet p_T & mass, p_T, η kinematics, and $\mathcal{D}_{bb}$ → tight, medium and loose WPs with 1, 2, and 12% misID rates
- High, medium and low signal purity categories based on the $\mathcal{D}_{bb}$ and BDT scores
- High Purity VBF Category requires 2 tight $\mathcal{D}_{bb}$ large jets

D_{bb} subleading jet Mass m_{reg}



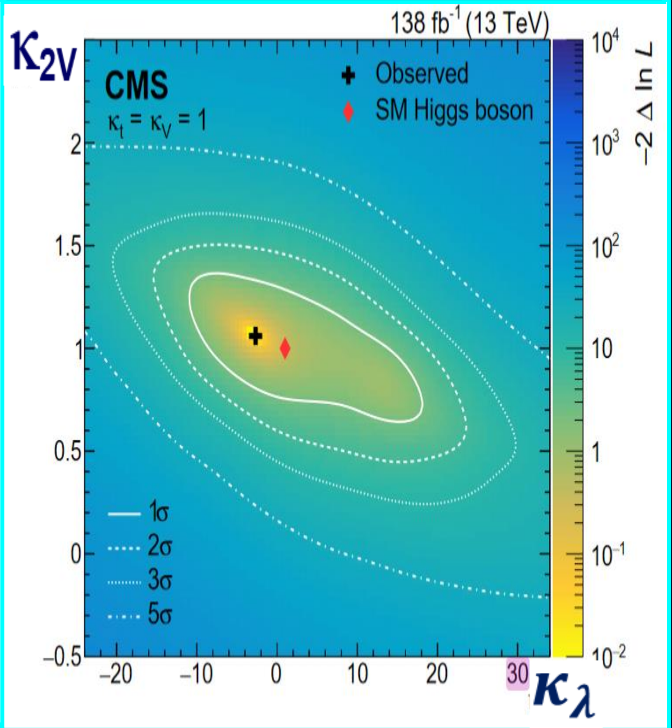
ggF BDT Category 1

M_{HH} for $\kappa_{2V} = 0$ $\kappa_\lambda = \kappa_V = 1$



VBF LP, MP, HP Categories

κ_{2V} vs κ_λ 2D profiles $\kappa_t = \kappa_V = 1$



Showing the 1,2,3,5σ CL regions

κ_{2V} = 0 excluded for the first time, at 6.3σ

0.62 (0.66) < κ_{2V} < 1.41 (1.37) observed (exp) @95% CL

−9.9 (-5.1) < κ_λ < 16.9 (12.2) observed (exp) @95% CL

http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-22-003

Conclusions

- Measurements of Higgs boson properties agree with SM expectations, hints for new physics could emerge as data taking progresses and analyses advance
  - Major production and decay channels reaching ~10% level precision. Improved sensitivity to rare process e.g. evidence of H→μμ and H→ℓℓγ

  - Substantial progress in fiducial/differential and STXS measurements, and new machine learning methods: deepening the search
  - Higgs boson coupling CP-structure studied in both Higgs-fermion and Higgs-boson couplings, no sign of CP-mixing so far
- Good progress in HH searches with new channels and improvements in analysis:

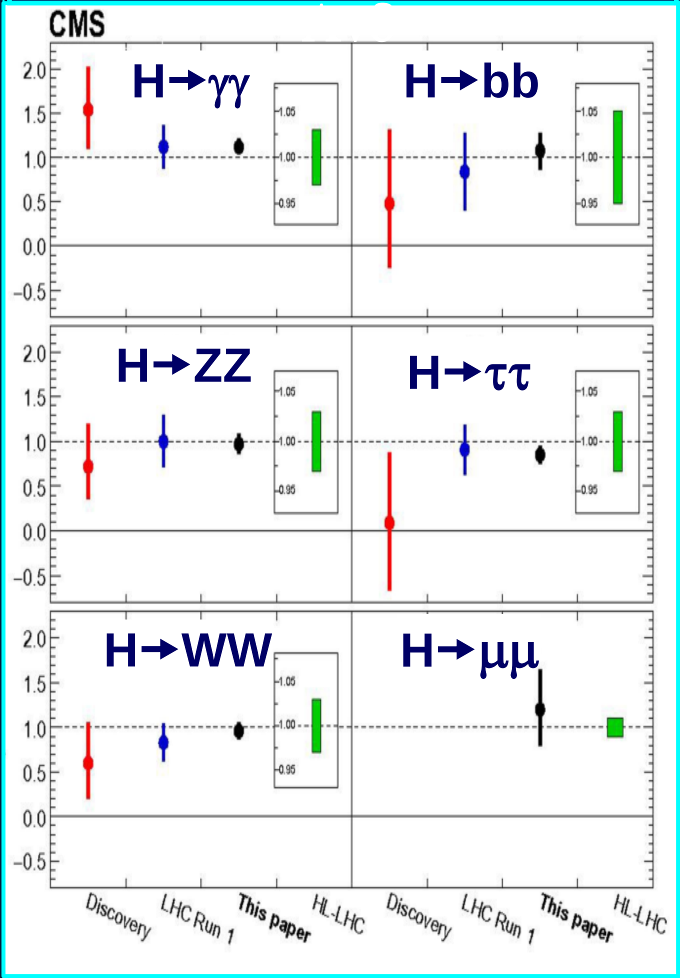
  Upper limit on $\sigma(HH)/\sigma_{SM}$ down to 2.5

  Prospect of 5σ at HL-LHC
- The search for BSM physics is expanding on many fronts: in the Higgs sector & beyond

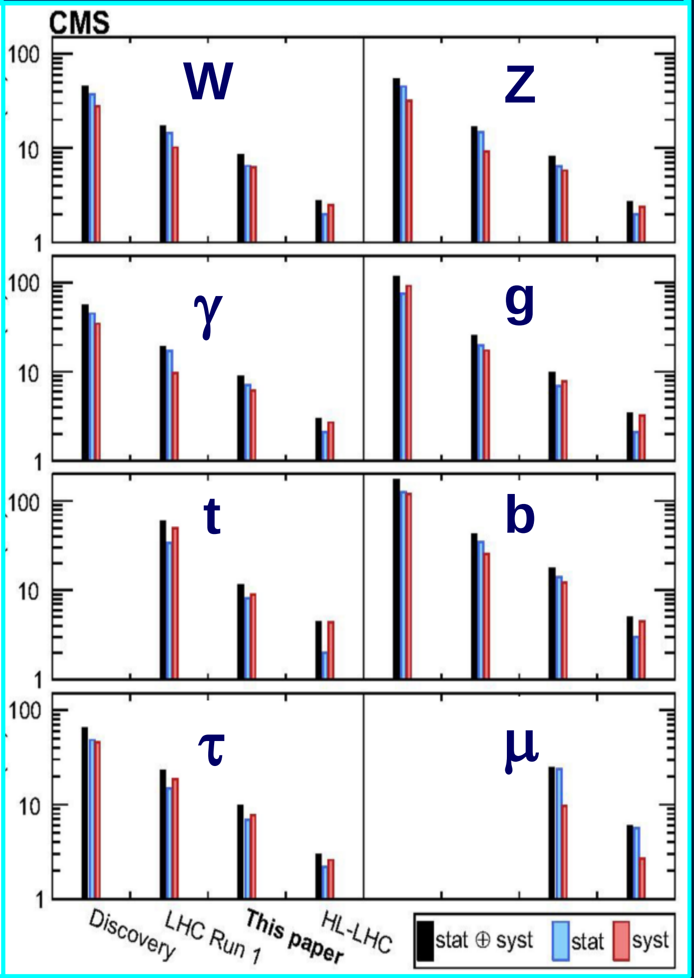
Time Evolution: From Discovery to HL-LHC

Nature 607 60-68

Signal Strengths μ and Precision



Couplings Precision Δκ/κ (%)



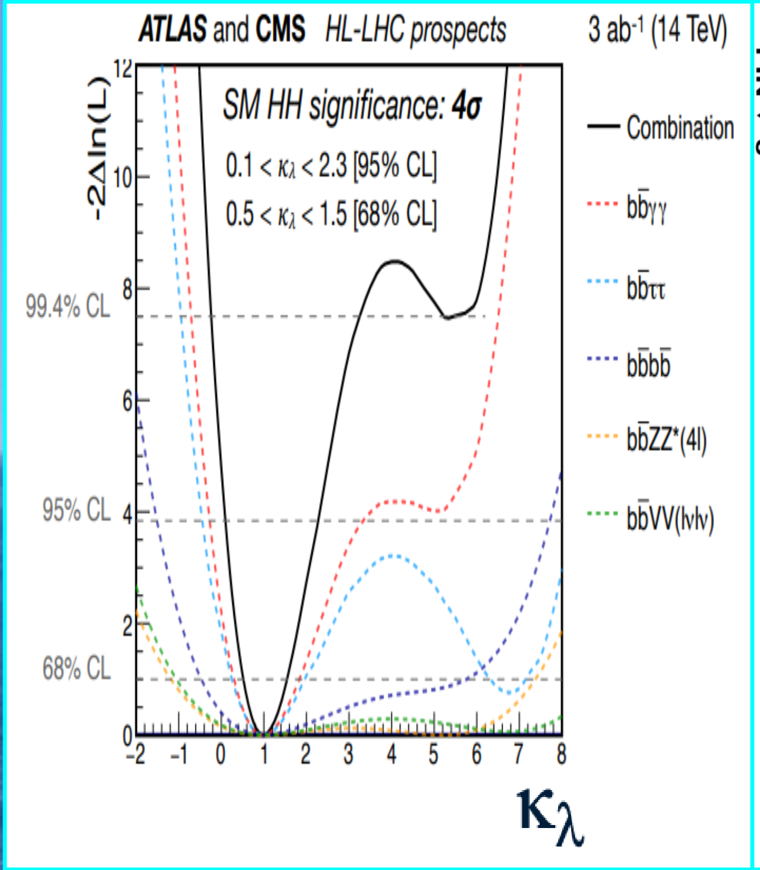
The expected LHC + HL LHC dataset is 20X the current dataset

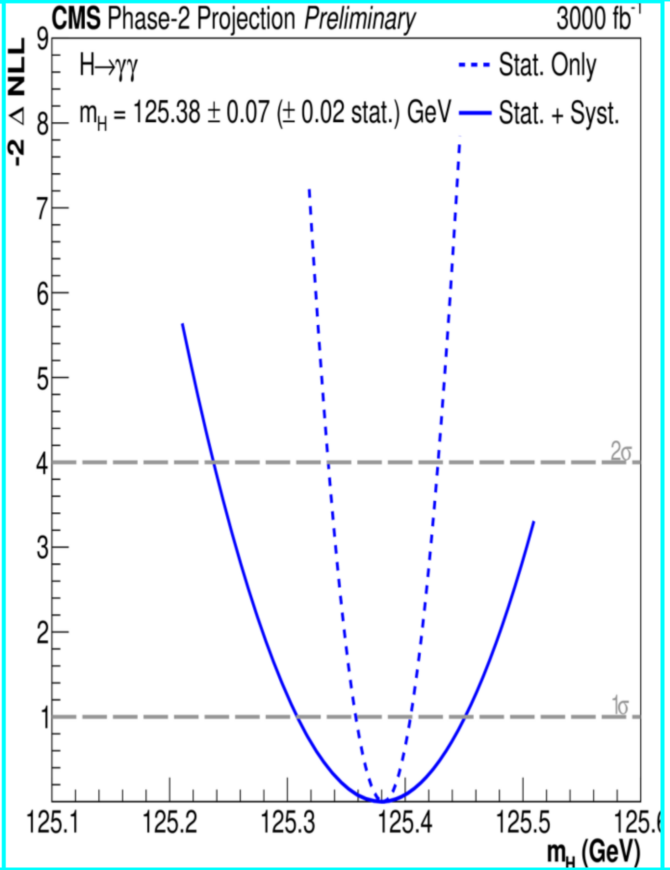
LHC Run3 and Beyond

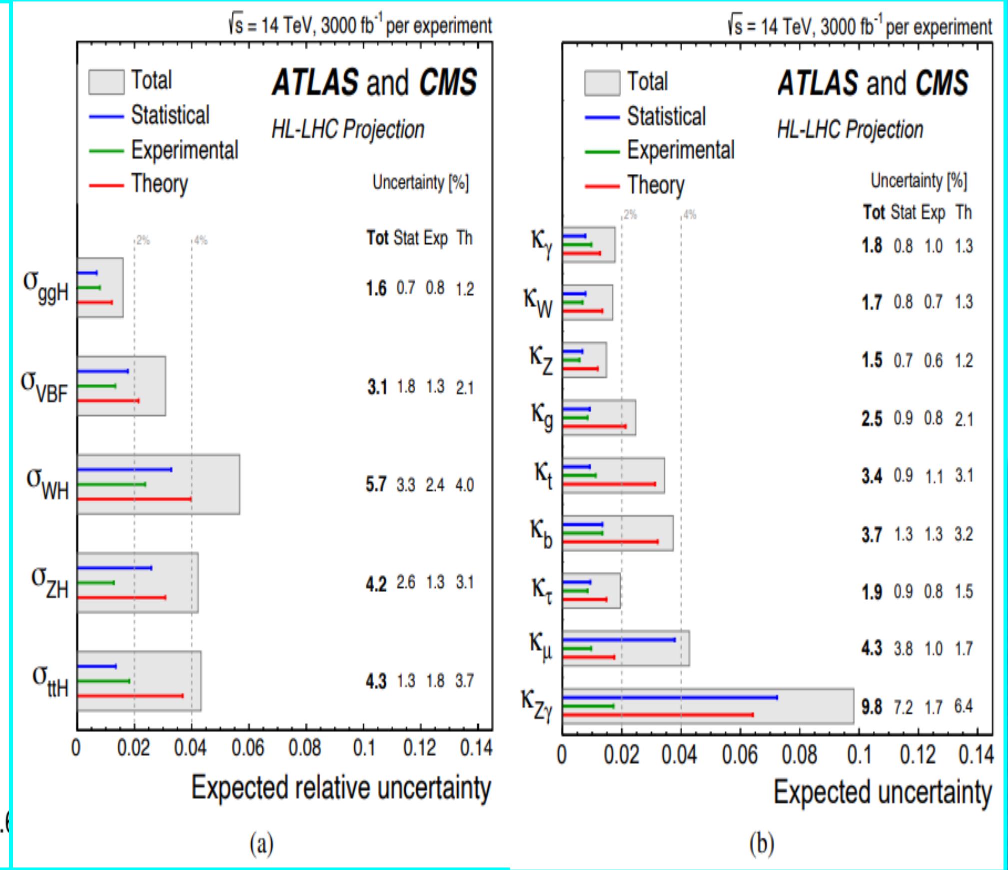
We have launched on an *Ocean of Discovery*

Brazilian Morning

Bright Prospects for the HL LHC







Outlook: $M_{\mathcal{H}} = 125.38 \pm 0.03$ *GeV;* $\Gamma_{\mathcal{H}} < 0.18$ *GeV at 95% CL*

Above All: A Voyage from Precision to Discovery

Brazilian Morning

Many More Higgs and Other Physics Results

https://cms-results.web.cern.ch/cms-results/public-results/publications/

https://cms.cern/tags/physics-briefing

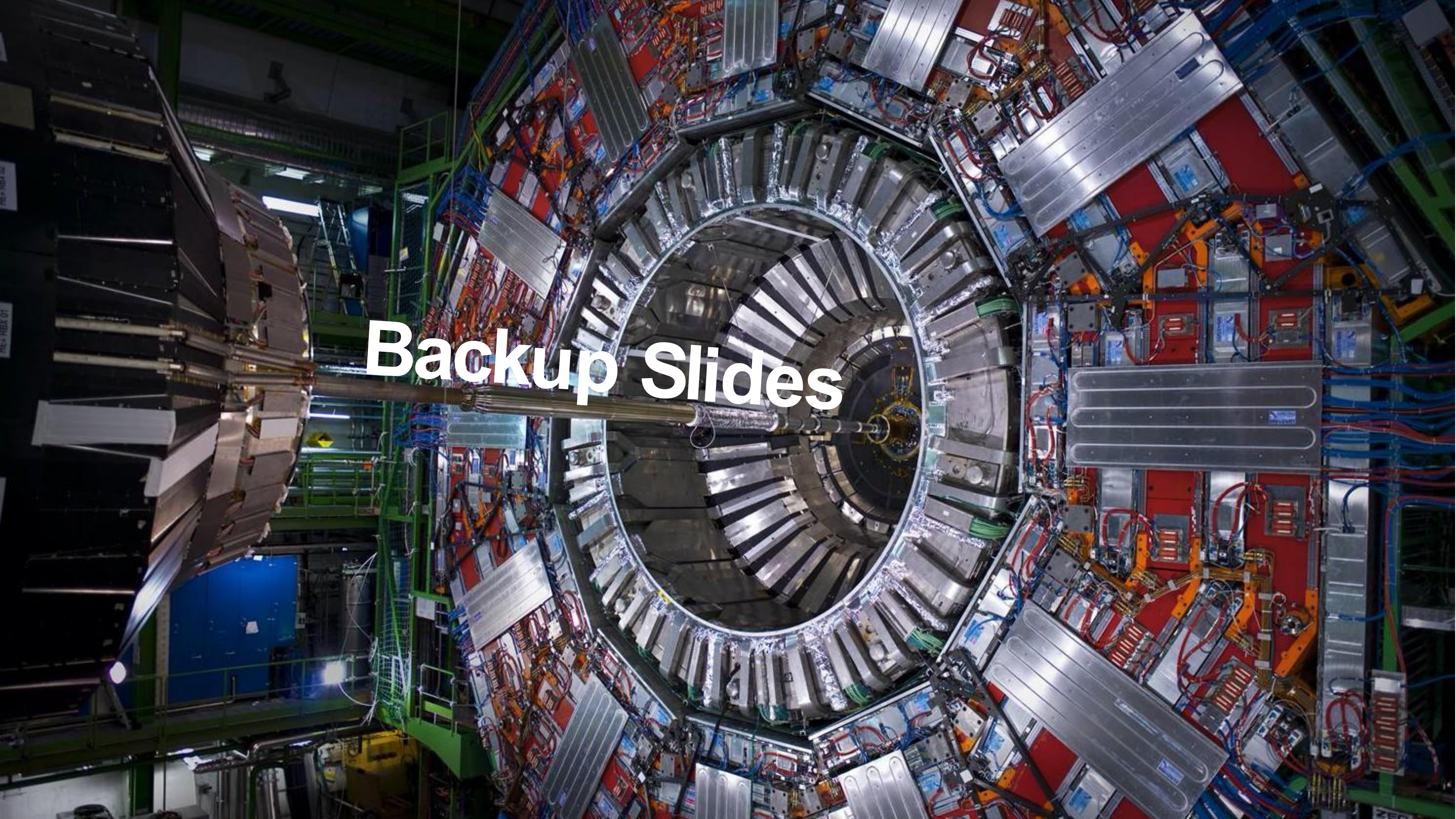
The Higgs 2022 Conference (November 2022):

https://indico.cern.ch/event/1086716/timetable/#all.detailed

57th Rencontres de Moriond (March 2023)

https://moriond.in2p3.fr/2023/ Ongoing

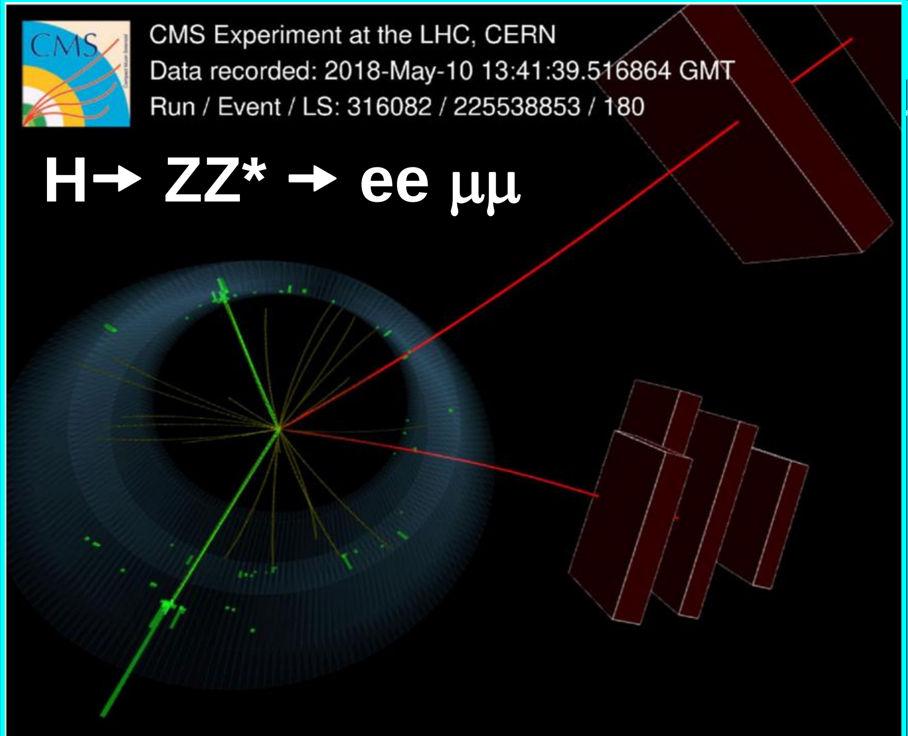
Backup Slides



LISHEP 2018 *Salvador, Bahia*

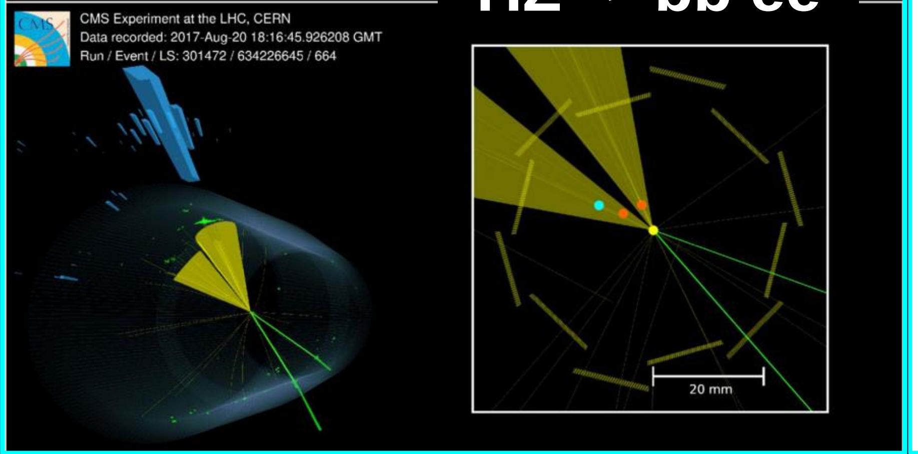
Candidate Events

Mass Peaks



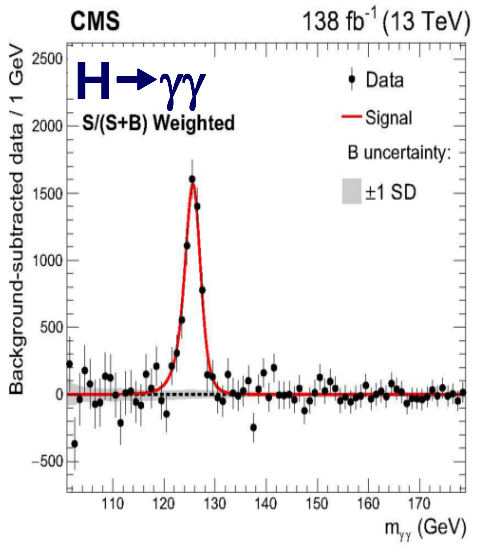
H→ ZZ* → ee μμ

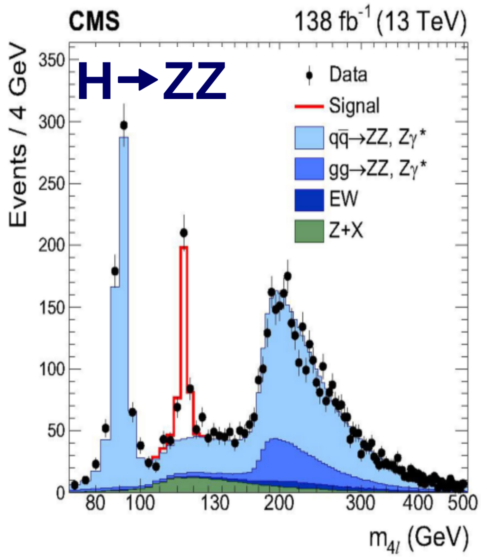
HZ → bb ee

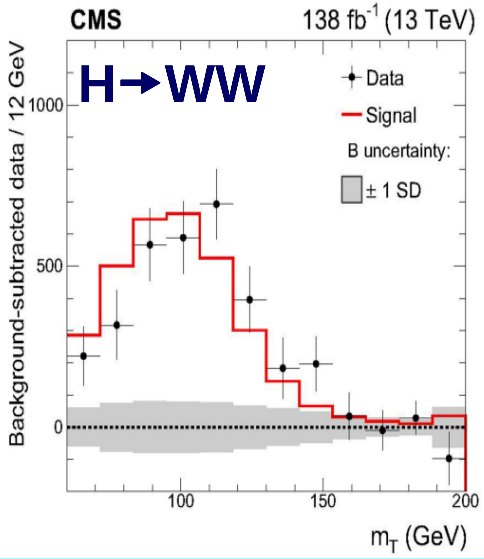


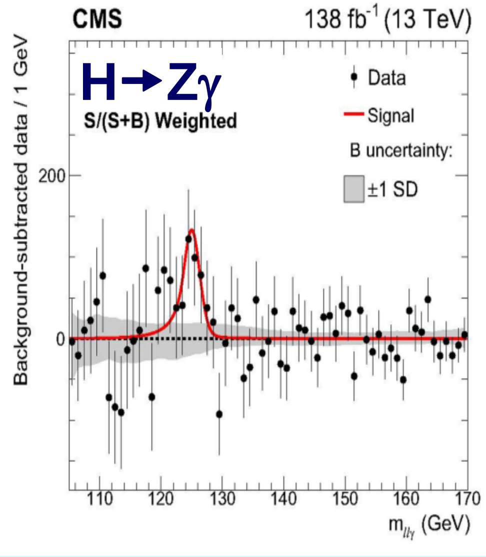
H → Bosons

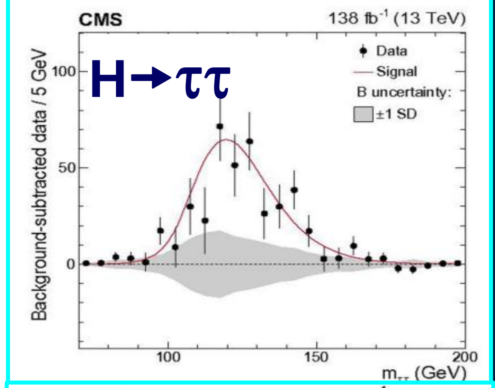
H → Fermions

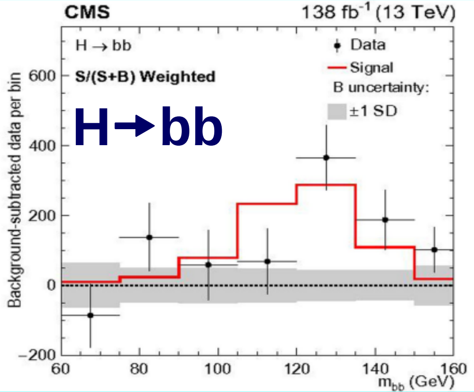


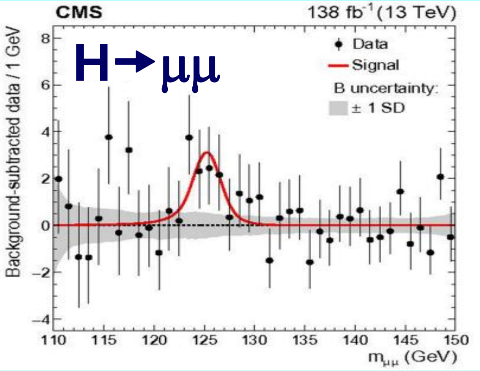












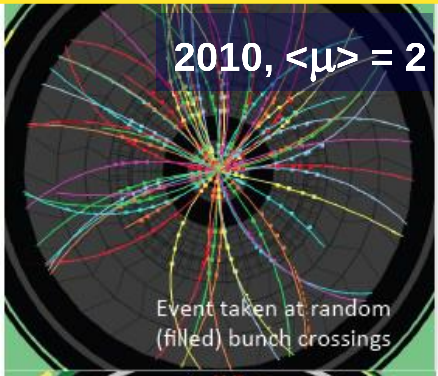
The LHC: Spectacular Performance

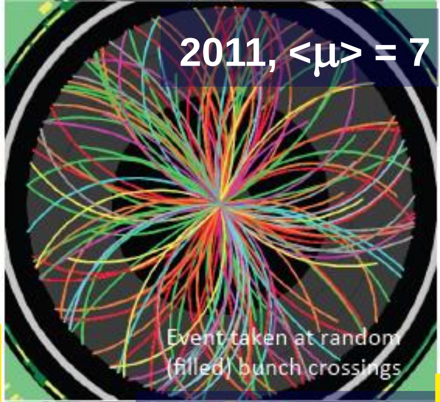
A new era of opportunity; a new era of challenges

Data Complexity: The Challenge of Pileup

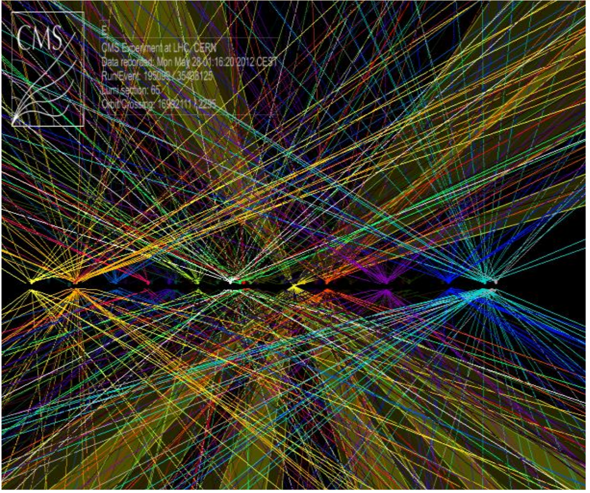
Run3 and Beyond will bring:

- Higher energy and intensity
- Greater science opportunity
- Greater data volume & complexity
- A new Realm of Challenges





~3.5 X 10^{15} pp Collisions ~5M Higgs Bosons produced in CMS in Run 2



~50 Vertices, 14 Jets, 2 TeV

Average Pileup

Run 1 21

Run 2 40

Run 3 ~54-65

HL LHC 140-200

The Outlook

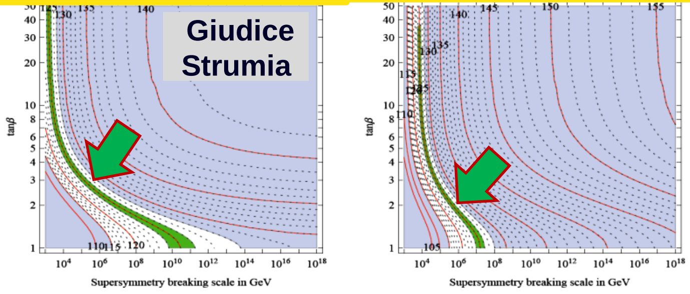
- SM or not: the 125 GeV Higgs boson has taken us to the threshold of an era of new physics, with a host of questions
- Natural, Split or High Scale SUSY ?:
  - A nearby 3rd generation at <~2 TeV ?
  - Another nearby scale at ~5-100 TeV ?
- *OR: new singlets, doublets, triplets; new scalars, vectors, composites, extra dim. ?…*
- Vacuum (meta)stability ➡ Another new scale at ~$10^{10\text{-}12}$ GeV ?
- Neutrino masses (via seesaws or RH ν): A “similar” intermediate scale ?
- *The Discovery has Expanded our Vision*

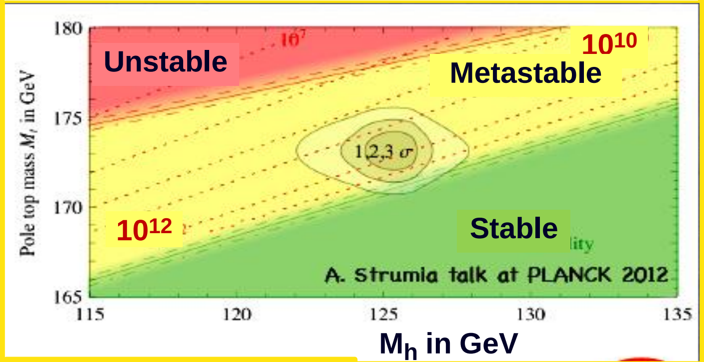
➡ Run3+ : a new horizon to explore and test our ideas: on EWSB and beyond

Apologies for all I could not cover

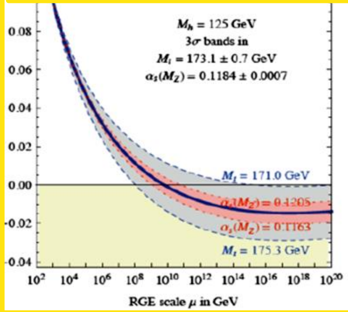
$$M_h^2 \overset{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1-\frac{X_t^2}{12 M_S^2}\right)\right]$$

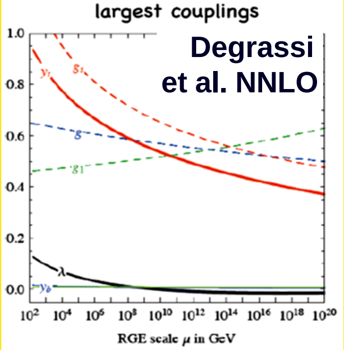
High Scale SUSY **Split SUSY**





λ at High Scales

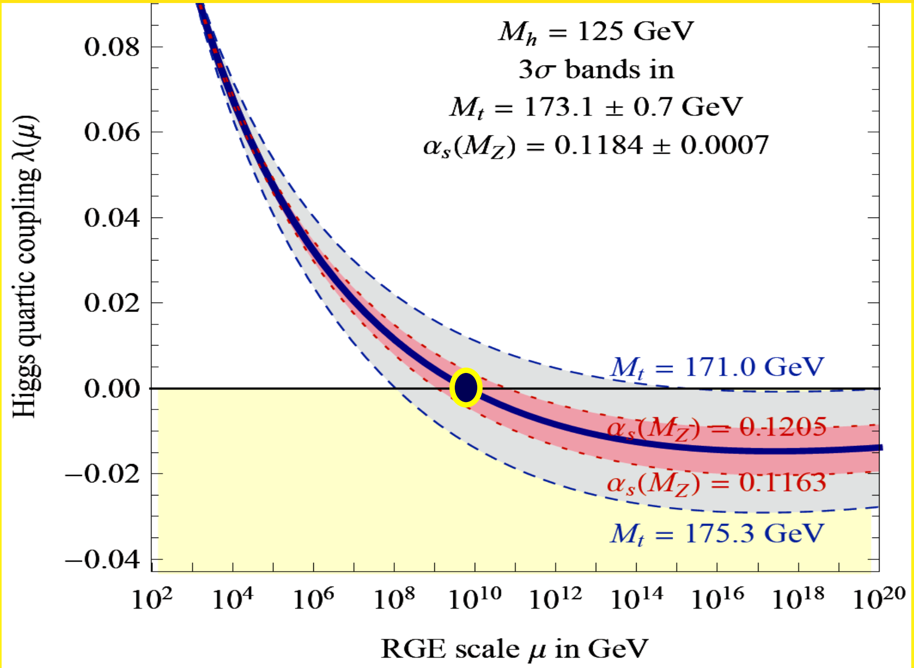




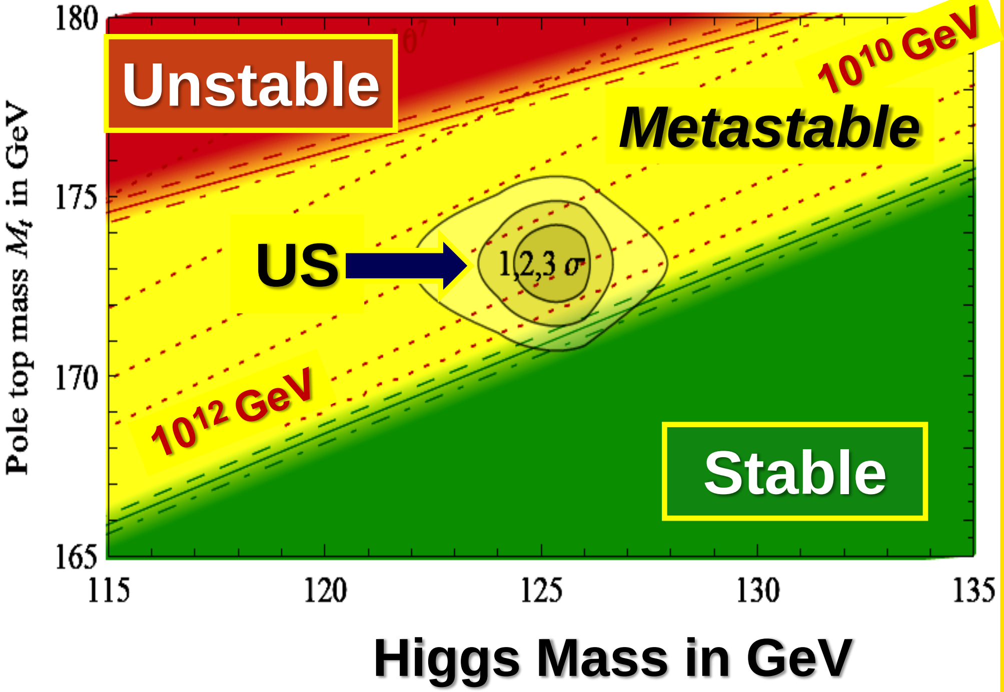
The 125 GeV Higgs Mass

Are we just on the wrong side of the Vacuum Stability Bound ?

NNLO Evolution of the Higgs Self-coupling λ(μ)



Precise Knowledge of the Top Mass as well as the Higgs Mass is Important



- For a Higgs mass of ~125 GeV

➡ λ goes negative ➡ Vacuum we are in is *metastable… ??*

➡ *OR:* New physics at an intermediate energy scale ~10^{10-12} GeV

- *What lies between us and the Big Bang ?*

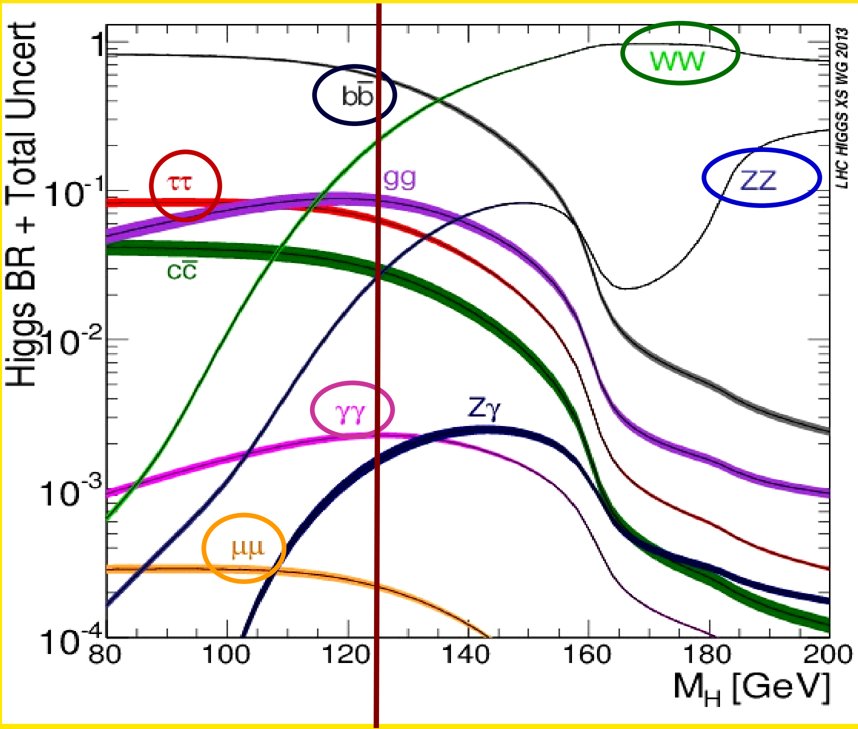
Higgs Boson Decays

Many Modes Contribute near 125 GeV

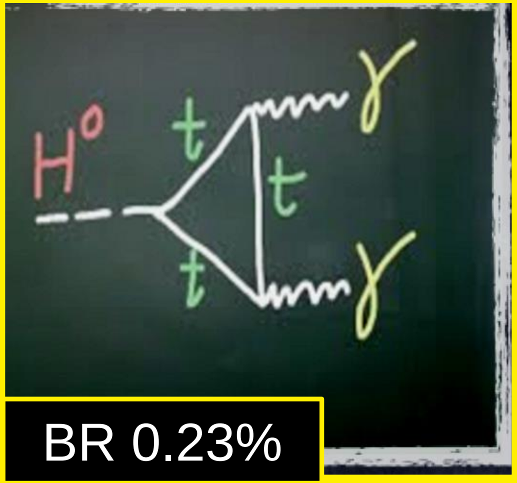
ZZ,,γγ, WW,,ττ, bb [the big 5✸]

Rare High Mass Resolution Channels Have a Special Role:

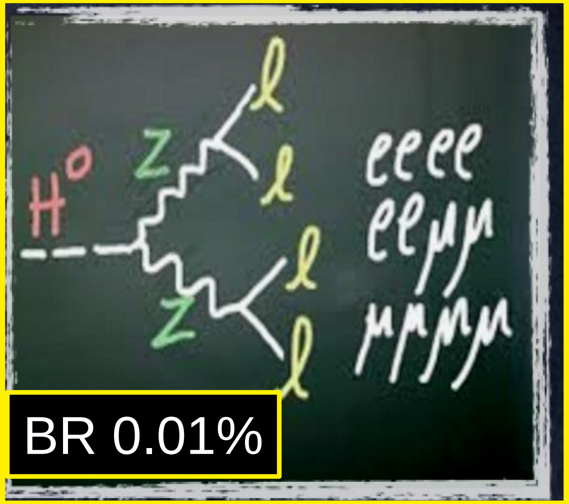
H→γγ and H→ ZZ → 4 Leptons



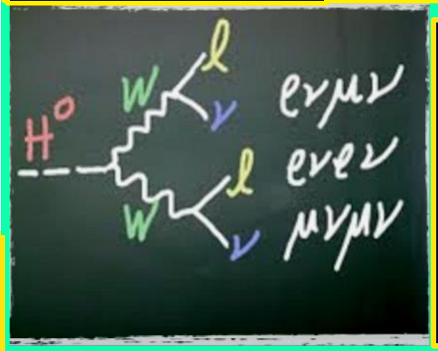
125 GeV – A Spectacular Mass:
~89% of final states studied



BR 0.23%



BR 0.01%



✸+ *Low Mass: W/Z + H → (WW) → 3l 3ν; H → Zγ;* WH + ZH → qq′ 2l 2ν

✸+ *High Mass Search ZZ → 2l* 2ν; ZZ → qq′ 2l; WW → qq′ lν; *H → ZZ →2l2τ*

HH Production Measurements at CMS in HH → $b\bar{b}\gamma\gamma$, $b\bar{b}\ell\nu\ell\nu$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$

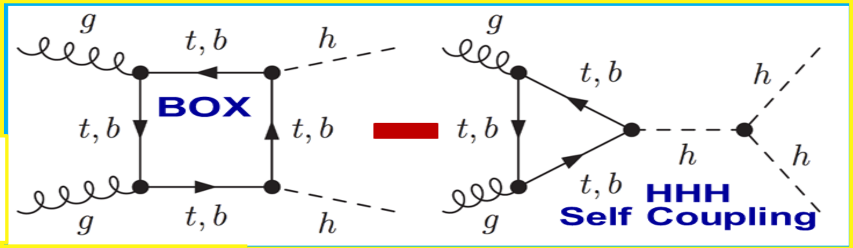
- A Unique Probe of the Higgs Mechanism
  - Allows a measurement of the Higgs self-coupling λ
  - Provides information on the shape of the Higgs potential, and on the stability of the electroweak vacuum

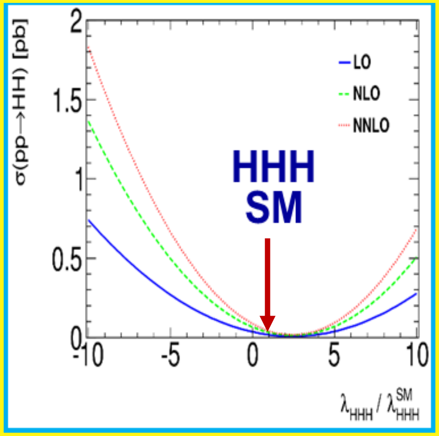
Talks by C. Amendolia at Higgs Hunting and D. Majumdar at ICHEP2018

$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

- SM: $\lambda_3 = \lambda_4 = \lambda = \frac{m_H^2}{2v^2} \approx 0.13$

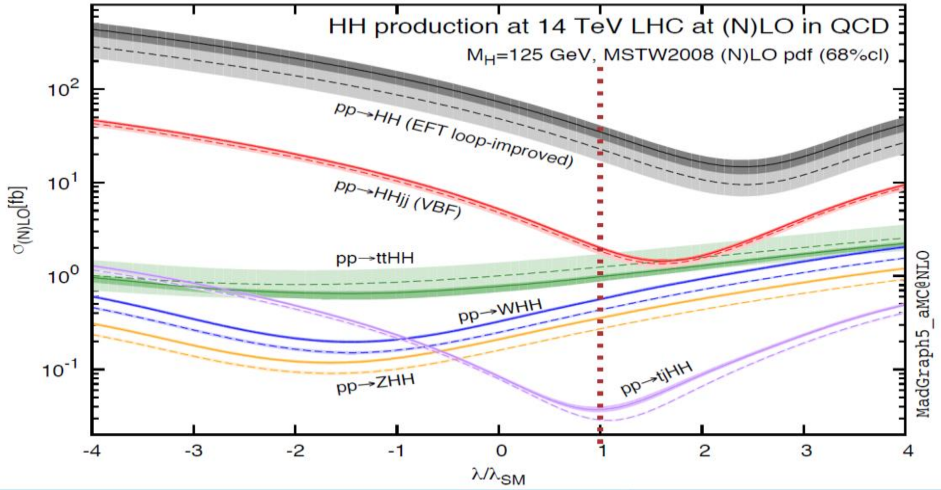
Destructive Interference: $\sigma_{HH}/\sigma_{ggf} < 10^{-3}$





Non-Resonant Searches

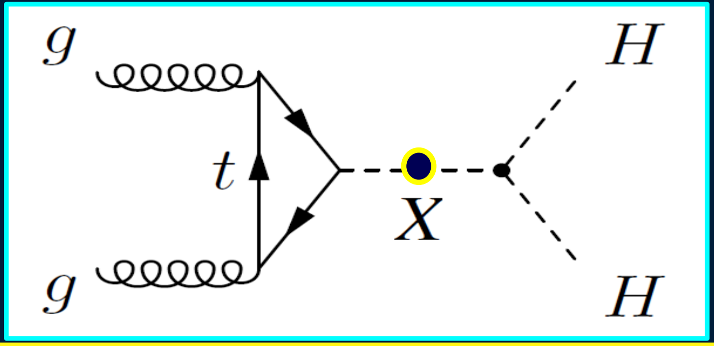
- BSM anomalous couplings could lead to (largely) enhanced cross sections



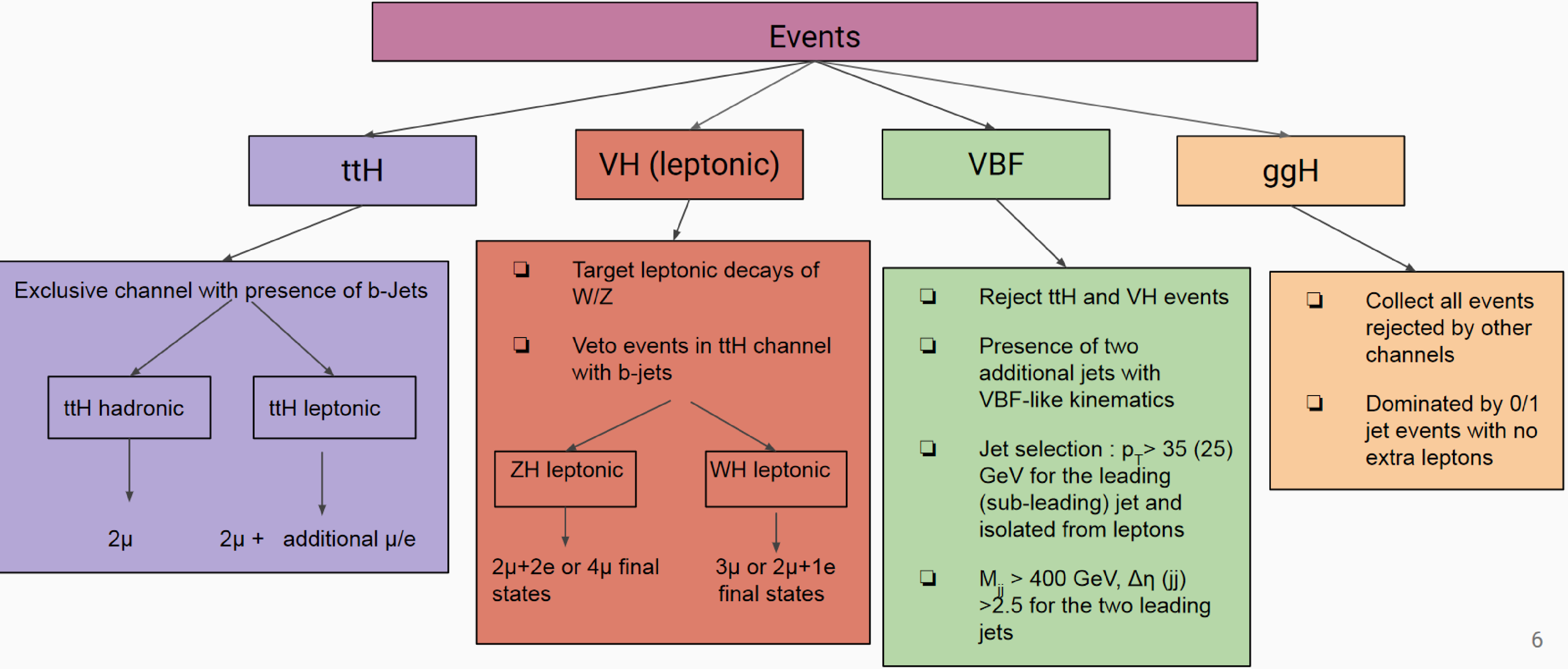
Resonant Searches: X →HH

Predicted by many Extensions of the SM:

MSSM, other 2HDMs, Extra Singlets, Warped Extra Dimensions, CP-Even Spin 0 or Spin 2



Event separation



Events

ttH

Exclusive channel with presence of b-Jets

- ttH hadronic → 2μ
- ttH leptonic → 2μ + additional μ/e

VH (leptonic)

- ❑ Target leptonic decays of W/Z
- ❑ Veto events in ttH channel with b-jets

- ZH leptonic → 2μ+2e or 4μ final states
- WH leptonic → 3μ or 2μ+1e final states

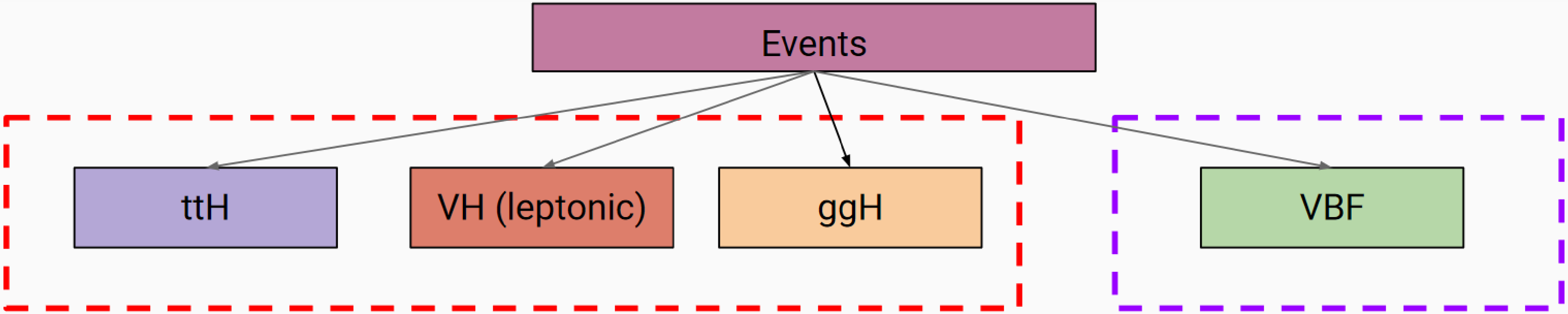
VBF

- ❑ Reject ttH and VH events
- ❑ Presence of two additional jets with VBF-like kinematics
- ❑ Jet selection : $p_T > 35\ (25)$ GeV for the leading (sub-leading) jet and isolated from leptons
- ❑ $M_{jj} > 400$ GeV, $\Delta\eta\ (jj) > 2.5$ for the two leading jets

ggH

- ❑ Collect all events rejected by other channels
- ❑ Dominated by 0/1 jet events with no extra leptons

Event separation



Events

ttH

VH (leptonic)

ggH

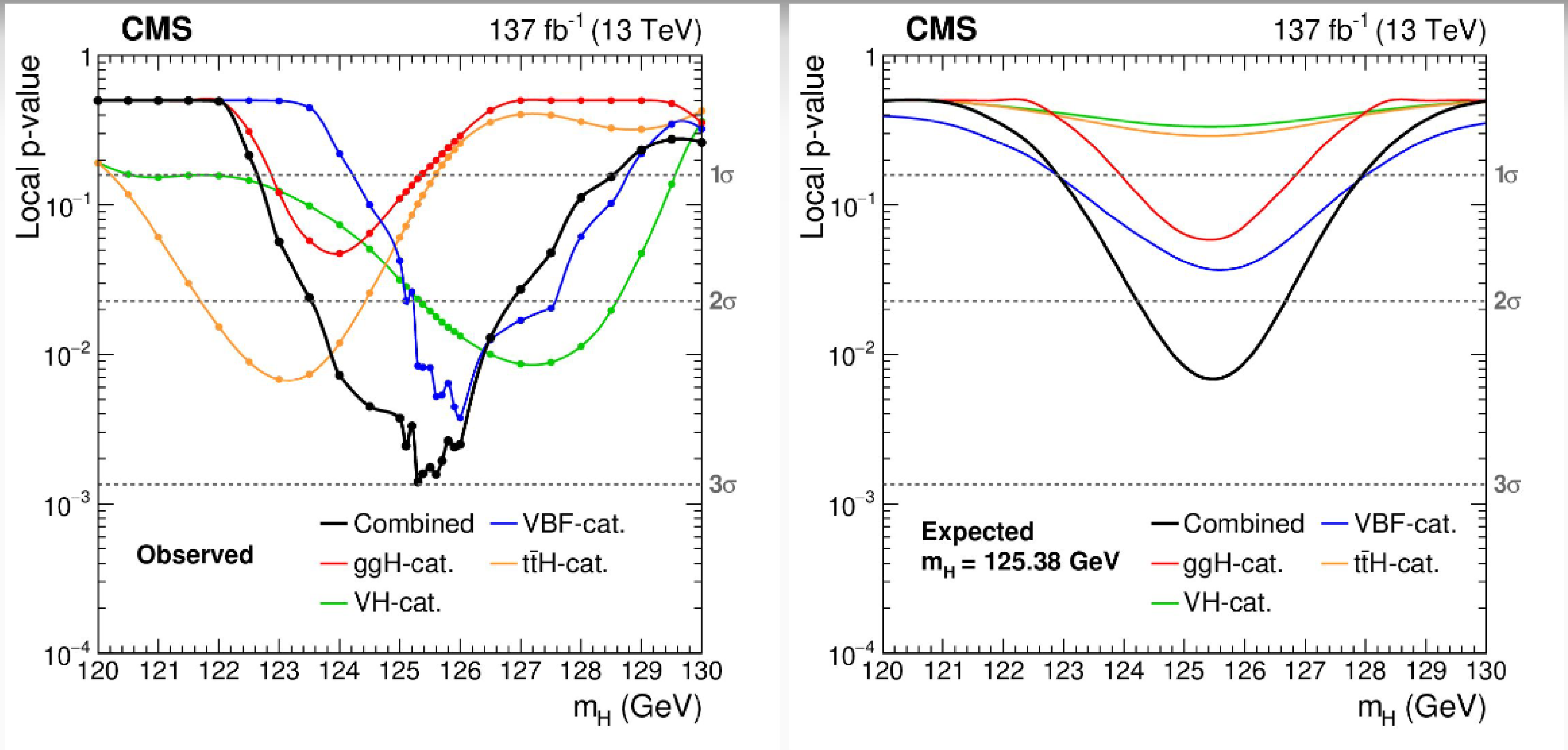
VBF

- Train independent BDTs for each region
- Background modelled with discrete likelihood profile of physics inspired and empirical functions.
- Signal peak modelled with a Gaussian function with power-law tails on both sides
- Perform a parametric fit to $M_{\mu\mu}$ spectrum

- Train a deep neural network
- Perform a simulation based template fit to DNN score output

Evidence of H→μμ

Irene Dutta: H → μμ Evidence:Talk at La Thuile



- For ggH, VH, and ttH channels - interpolate signal shape parameters analytically from m_H = 120, 125, and 130 GeV signal samples.
- For VBF channel, re-evaluate DNN for each mass point with the mass input fixed to that value and perform a new fit
- Observed jitter in VBF due to shuffling of data events in high score DNN bins as mass changes (binned fit).

Production category	Observed (expected) Signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
tt̄H	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13\,\text{TeV}$	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7,\ 8,\ 13\,\text{TeV}$	2.98 (2.48)	1.93 (0.81)

M_H = 125.38 GeV

Prospects for Run3 and Beyond

"There's Plenty of Room at the Bottom"

An Invitation to Enter a New Field of Physics
(Feynman Lecture at Caltech, December 29, 1959)

There is So Much Room

We have only just begun

CMS [Scenario S1; Being Updated Now]

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
300	7%	6%	6%	8%	13%	15%	8%	41%	23%	28%
3000	5%	5%	4%	5%	7%	10%	5%	12%	8%	17%

ATLAS [Scenario S1]

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
300	9%	9%	8%	14%	23%	22%	14%	24%	21%	22%
3000	5%	5%	4%	9%	12%	11%	10%	14%	8%	14%

And If We Both Improve [S2; 3000/fb]

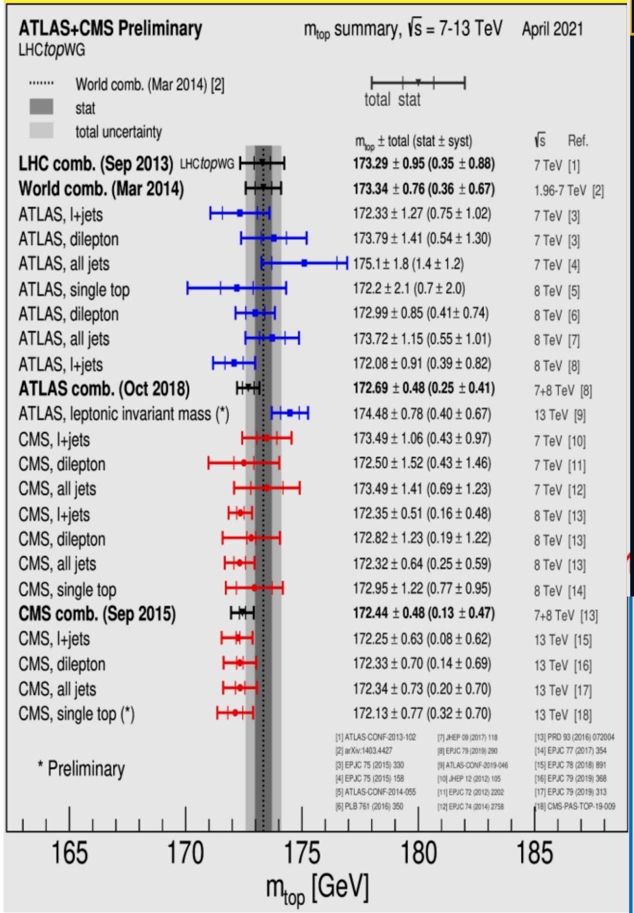
→ Reduce Theory Systematics by 50%

→ Reduce Exp Syst by √Lumi

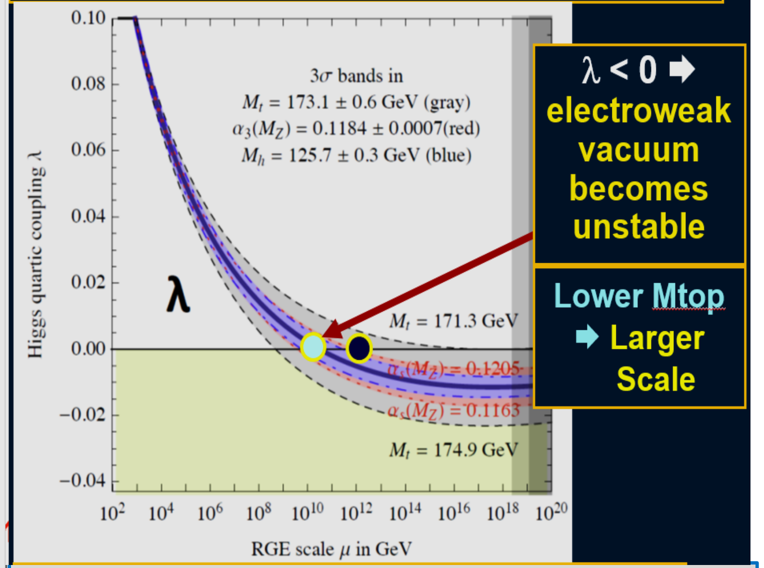
	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
ATLAS	5→4	5→5	4→4	9→7	12→11	11→9	10→9	14→14	8→7	14→11
CMS	5→2	5→2	4→2	5→3	7→4	10→7	5→2	12→10	8→8	6→3

Now that Higgs Boson Mass is precisely known: importance of precise M_{Top} (and M_W) measurements

LHC Top WG April 2021



Precision top mass may reveal fate of our universe, or hint at new physics



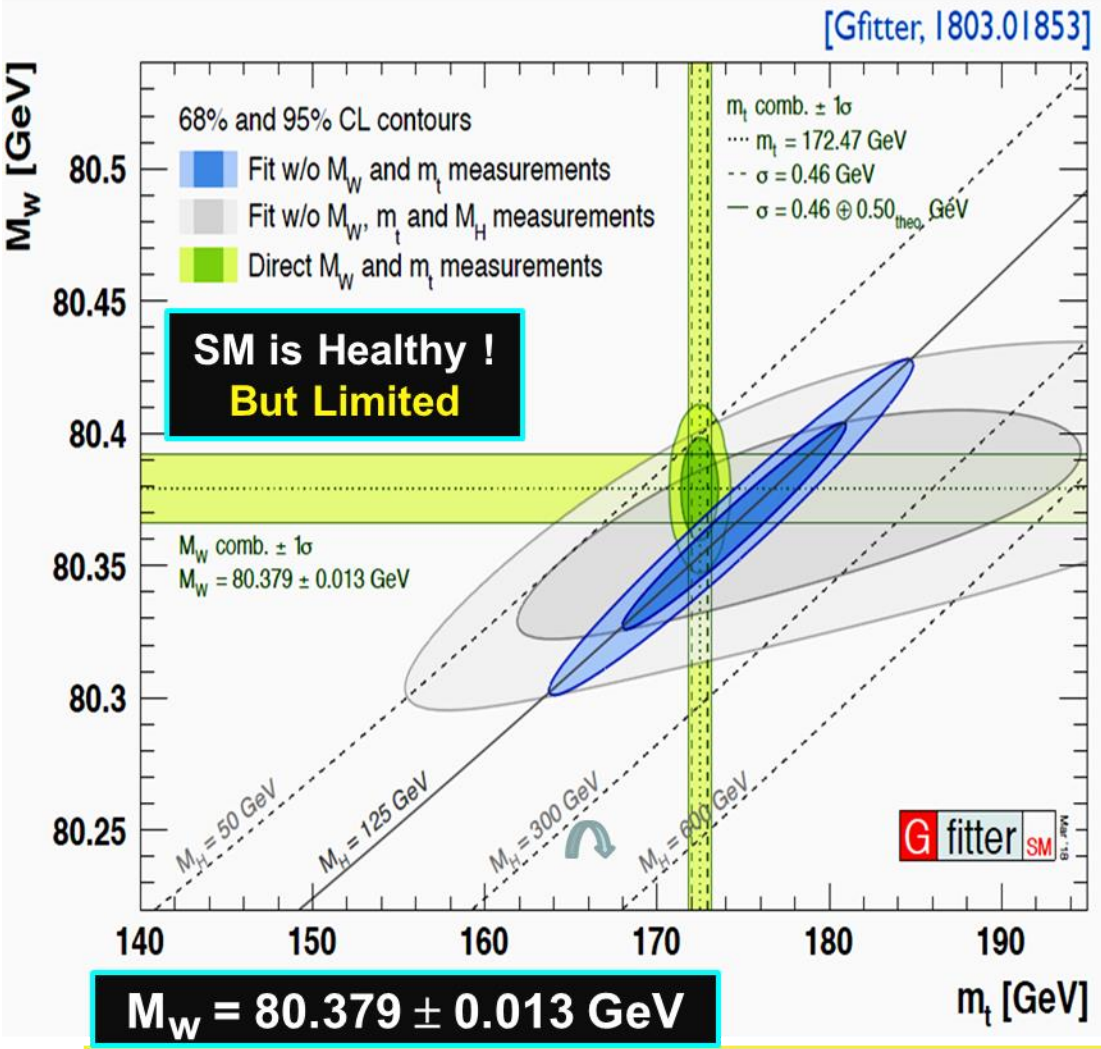
λ < 0 ➡ electroweak vacuum becomes unstable

Lower Mtop ➡ Larger Scale

- ► Main systematic uncertainties
  - ► hadronization ∼ 0.35 GeV
  - ► jet energy corrections ∼ 0.15 GeV
  - ► hard-process scattering ∼ 0.15 GeV

↪ correlated between channels, methods, and experiments

↪ total uncertainty < 0.3%



SM is Healthy ! But Limited

M_W = 80.379 ± 0.013 GeV

Update of Gfitter Precision Elwk Fit: R. Kogler, Moriond EW 2018

Higgs Coupling Constraints in the κ framework

BSM: Allowing for BR (Undetected) and BR (Invisible)

To Study BSM contributions to Higgs width in loop processes

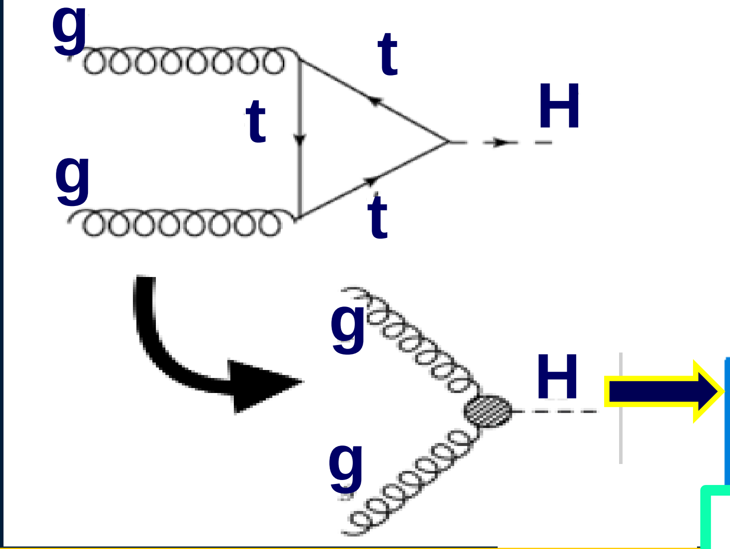
- Use *Effective* coupling modifiers κ_γ , κ_g

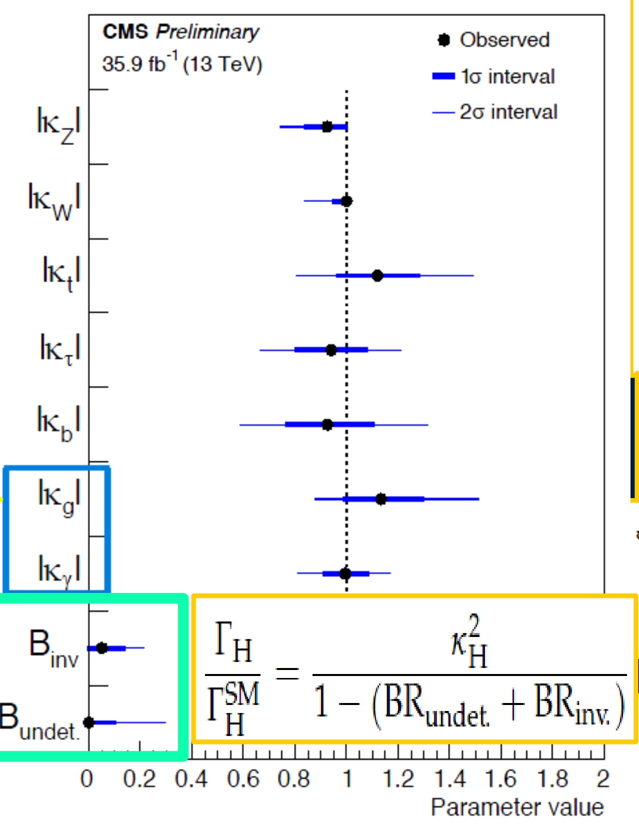
Assume $\kappa_Z, \kappa_W > 0$; $|\kappa_Z|, |\kappa_W|$ <= 1; BR_{undet} and BR_{inv} >0, free parameters

,

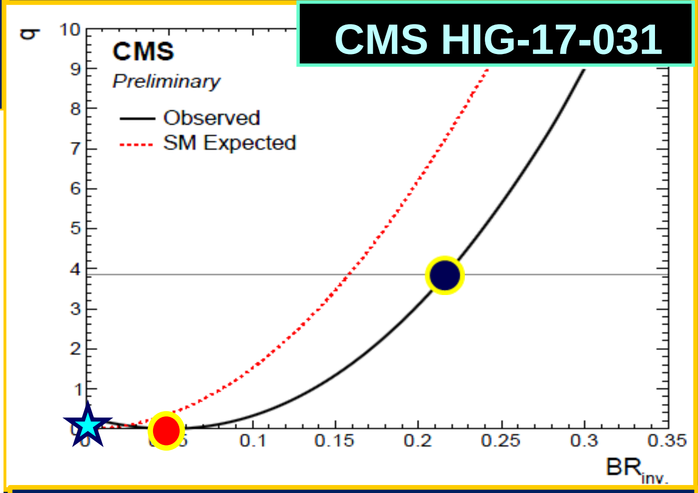
Likelihood ratio scan
$BR_{INVISIBLE} < 0.22$ at 95% CL

CMS HIG-17-031

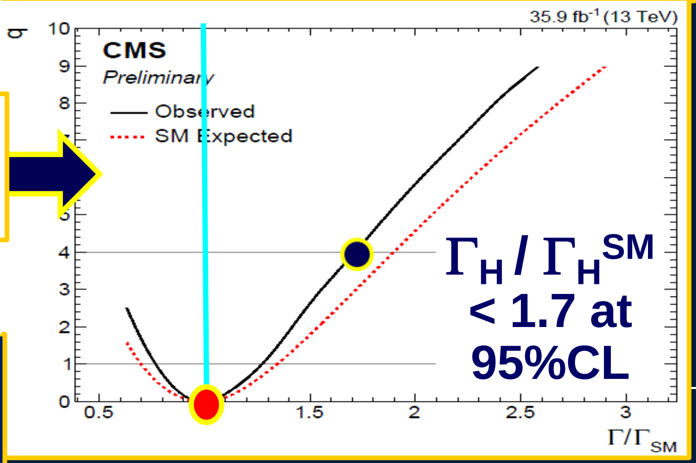




$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{1-(BR_{undet.}+BR_{inv.})}$$



Likelihood ratio scan
Higgs Width Γ_H / Γ_H^{SM}



Γ_H / Γ_H^{SM} < 1.7 at 95%CL

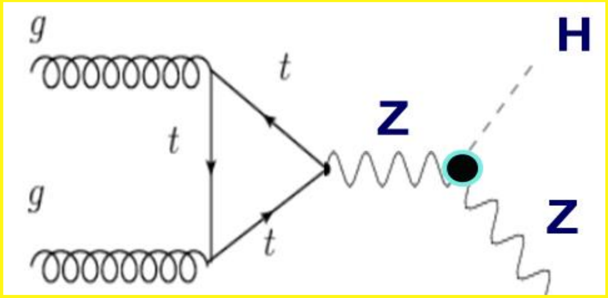
And: BSM Decay Modes
H → Invisible (e.g. $\chi\chi$).
p_T^{Miss} + X Searches
Constrain BR (H → inv)
Talk by R. Garosa at ICHEP

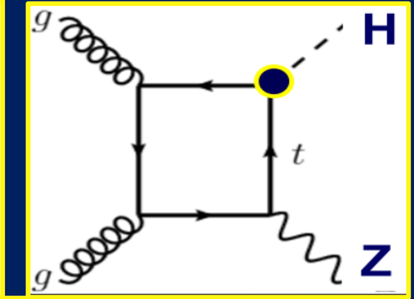
κ_t uncertainty 40% lower than Run1: σ, categories

H Coupling Constraints (I)

κ Factors
for Production and Decay

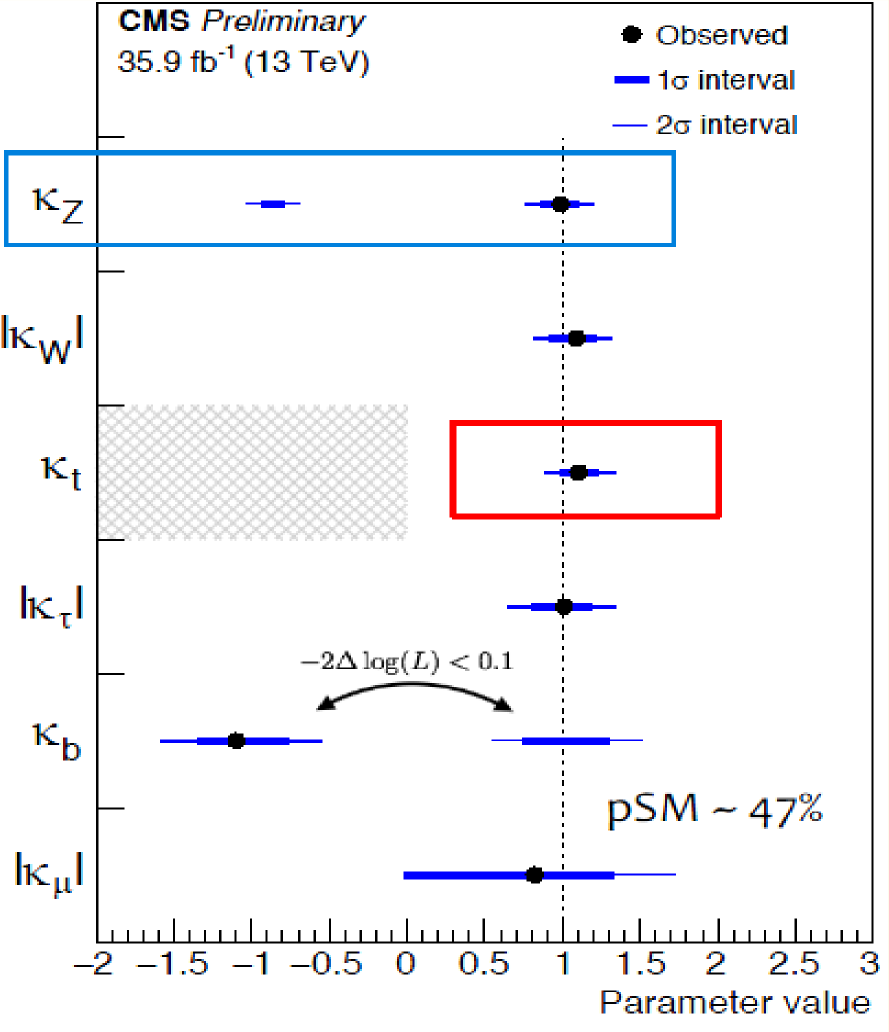
- NOTE: Leading order κ framework correlates production and decay rates
- Interferences among diagrams constrain and may resolve degeneracies, such as positive vs negative κ values.
- gg → ZH production can break the κ_Z, and ggF H production (t-b loop interference) can break the κ_b degeneracy





$$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \, \boxed{\kappa_Z \kappa_t}$$

$$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \, \boxed{\kappa_t \kappa_b}$$



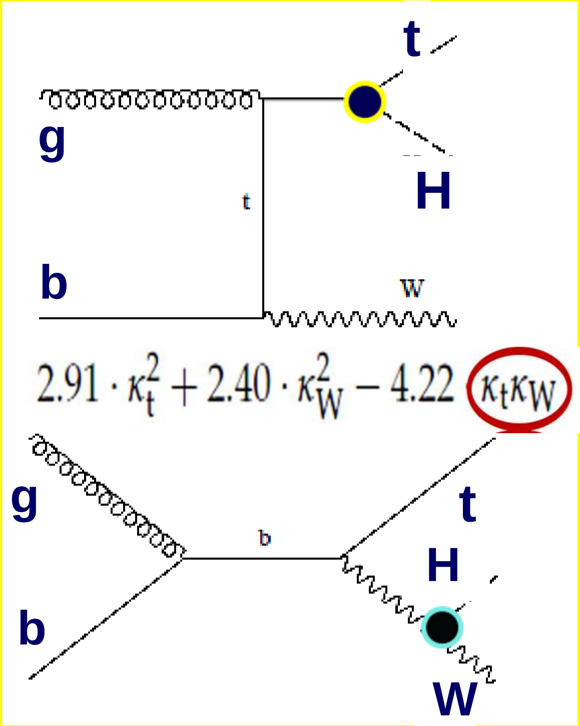
Negative sign for κ_b *slightly* preferred due to small ggF production excess over SM expectations

LHC Higgs Cross-Section WG 2013: CERN-2013-004 arXiv:1209.0040. arxiv 1310.4828

H Coupling Constraints (II)

κ Factors for Production and Decay

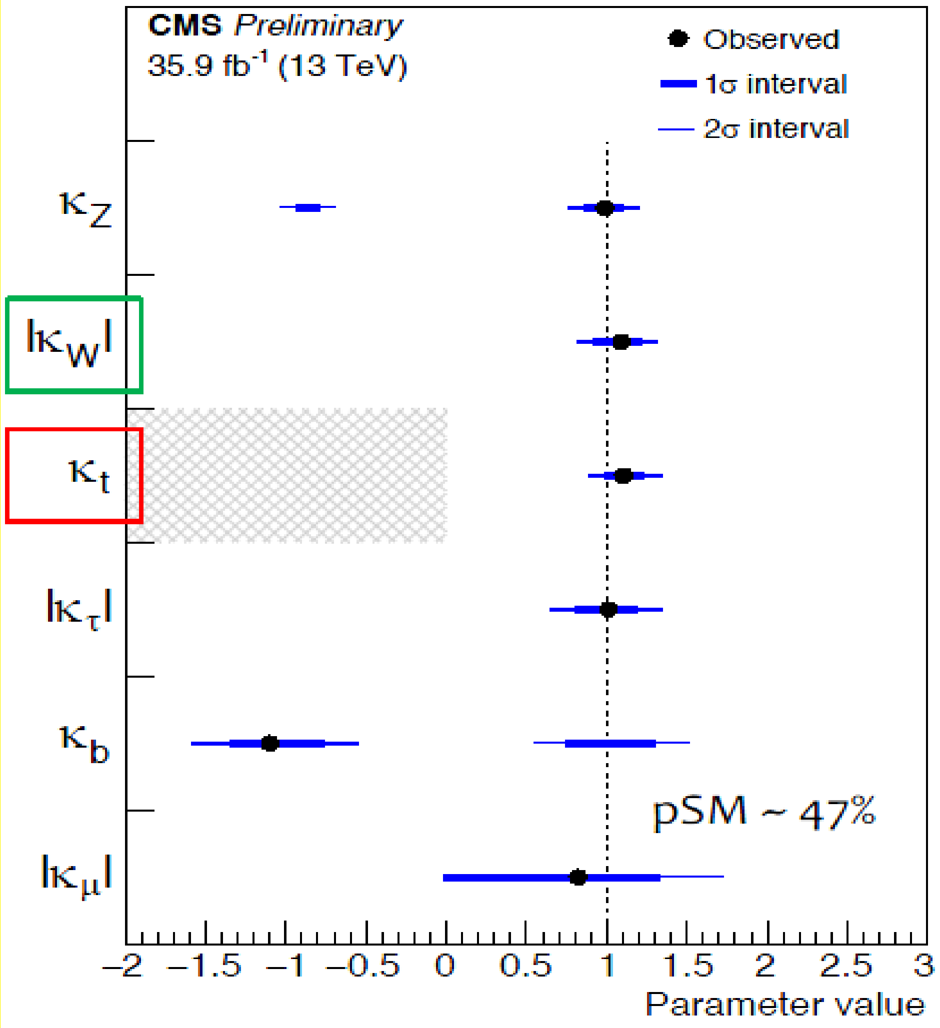
- There is an overall sign degeneracy: So fix $\kappa_t > 0$ and only consider the cases where $\kappa_t \times \kappa_W > 0$
- Single top production, for example tHq, probes the relative sign [*]



$$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \boxed{\kappa_t \kappa_W}$$

[*] NOTE: Large changes in the tH cross section and kinematic distributions are possible in BSM scenarios, including when $\kappa_t \times \kappa_W < 0$

➡ BSM tree level contributions to ttH, VVH vertices expected to be highly suppressed

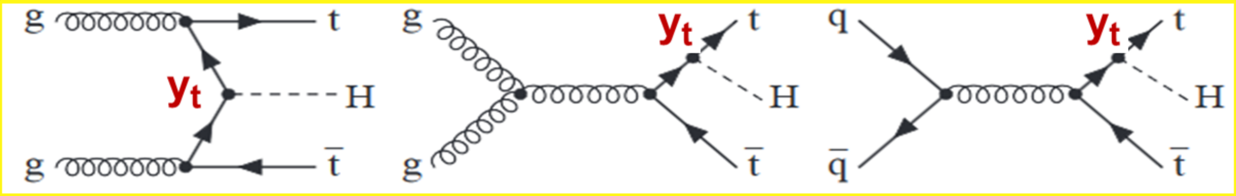


Assumes no new particles in loops: $BR_{BSM} = 0$; κ_γ, κ_g resolved in terms of the others: κ_W κ_Z κ_t κ_τ and κ_b

Observation of $t\bar{t}H$ Production !

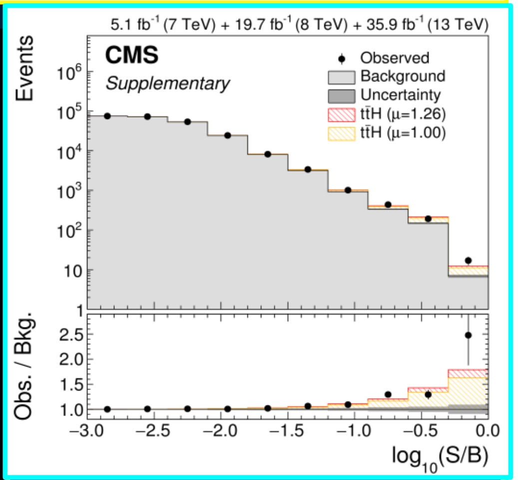
Direct Top Yukawa Measurement

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

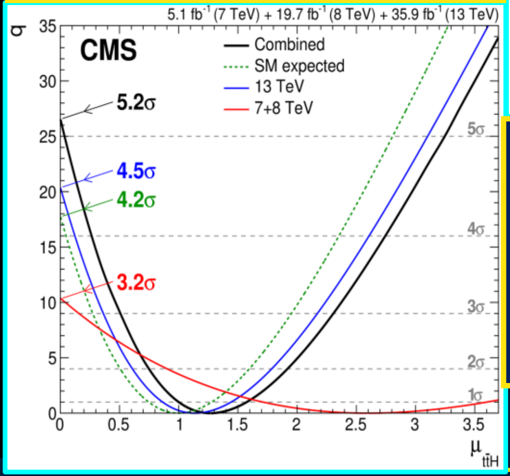


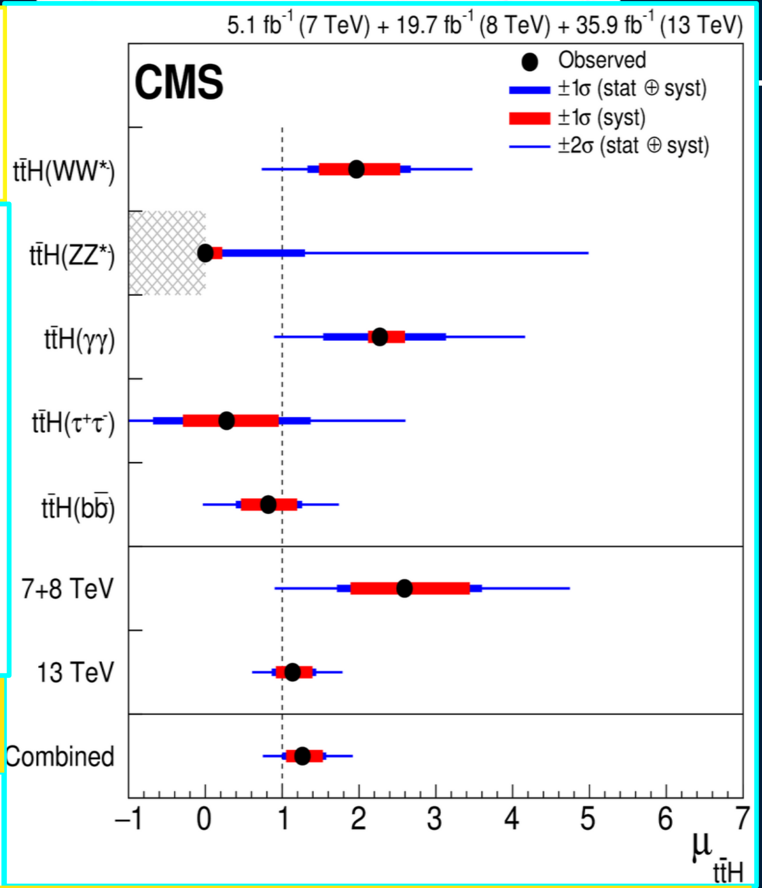
- **SM Top Yukawa (~1)** already probed through gluon fusion production and H→γγ decay
- But **direct observation yields more information**: e.g. **disentangle possible BSM loop contributions**
- **ttH cross section at 13 TeV: 0.51 pb** (**4X Larger than 8 TeV**)
- Small x-section but good S/B; Combine many channels:

  H→ hadrons (bb,ττ,WW), Leptons (WW,ZZ,ττ), Photons (γγ)
- **Main background: t-tbar** (measured), **ttW, ttZ** (from theory (MC))



μ_{tth} Signal Strength





Best Fit $\mu(ttH) = \sigma/\sigma_{SM}$

1.26 +0.31 -0.26

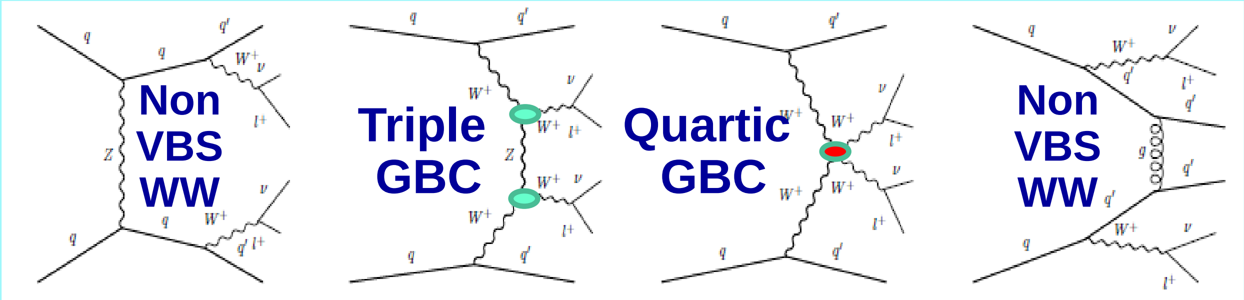
Significance 5.2σ

(4.2σ expected)

Talk by Davide di Croce at LISHEP 2018

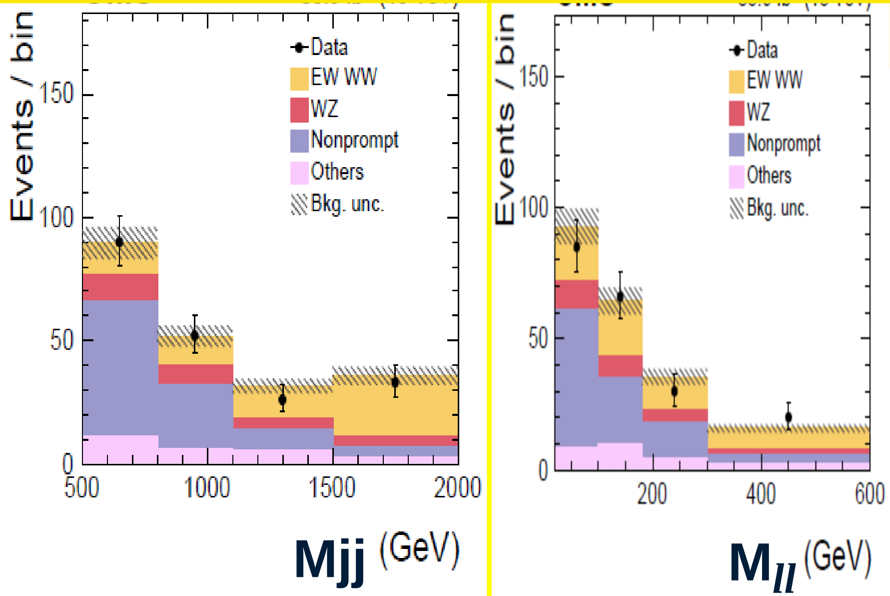
1^{st} Observation of Vector Boson Scattering (VBS) in Same Sign W Boson Pairs [Fall 2017; 2016 Data]

- Final States: Same sign dilepton, 2 Jet, MET
- Excess over SM possible from anomalous Quartic couplings or new resonance

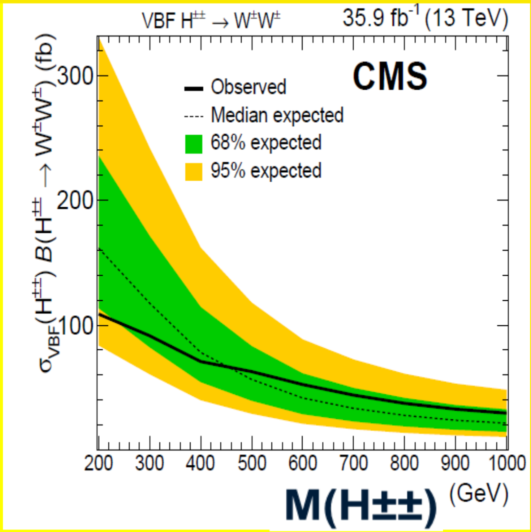


- Exactly 2 SS Leptons, veto 3^{rd} with $p_T > 10$ GeV, $m_{ll} > 20$ GeV, M_Z veto; for e+e-: $p_T^{miss} > 40$ GeV
- 2 Jets, $m_{jj} > 500$GeV, $|\Delta\eta| > 2.5$
- Suppress backgrds: WZ, DY, top, nonprompt events

Extracting the VBS Signal



BSM Search for VBF → H±±



Results

1^{st} Observation of VBS: 5.5σ

(5.7σ expected)

$\mu = 0.90 \pm 0.22$

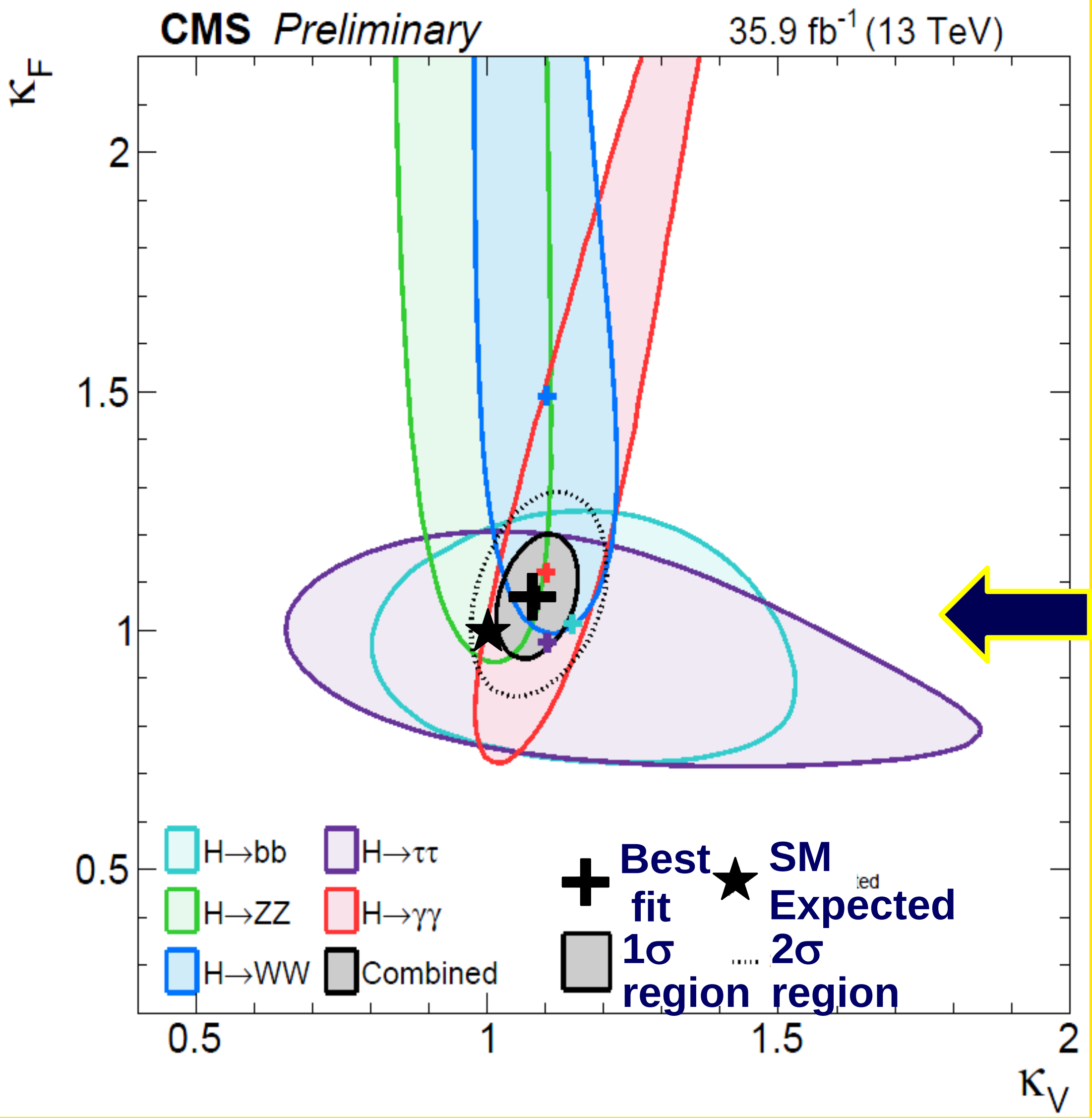
Improved bounds on Structure of Quartic VB gauge interactions

By a factor of 6

Phys. Rev. Lett. 120 (2018) 081801; CMS SMP-17-004

Extras from LISHEP2018

Higgs Couplings to Fermions and Bosons: Set all fermion scale factors to κ_F, W & Z scale factors to κ_V



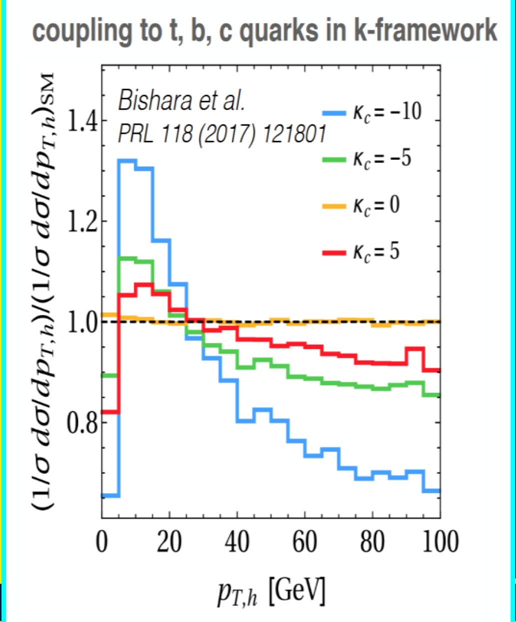
- **Constrained Fit: Assume**
  - Custodial symmetry
  - Fermion universality
  - No BSM particles
  - All loops resolved
- **Relative Sign Constraints:**
  - γγ decay loop & single top interference constrain $\kappa_t\kappa_W$
  - gg → ZH interference constrains $\kappa_t\kappa_W$
  - ggH loop interference constrains $\kappa_t\kappa_b$

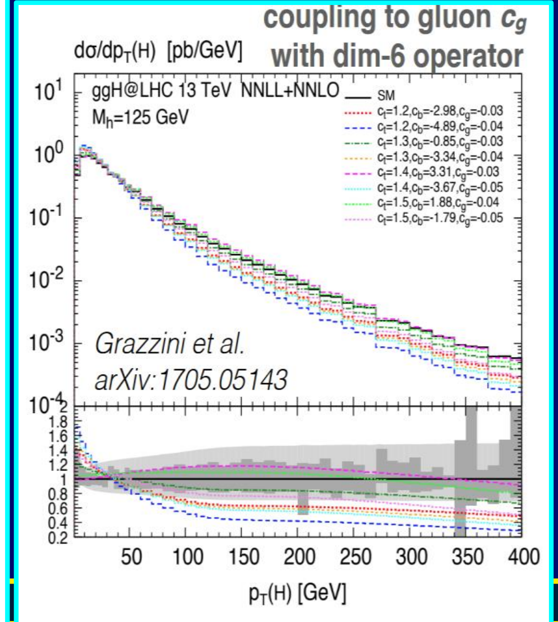
Data closely consistent with SM: $\kappa_V = 1$; $\kappa_F = 1$; *Exclude non-SM relative sign at ≥5 σ*

Differential Measurements of Higgs Inclusive Production

Combine & Adapt H→ $\gamma\gamma$, ZZ, **Boosted** bb: σ_{fid} + Differential Analyses

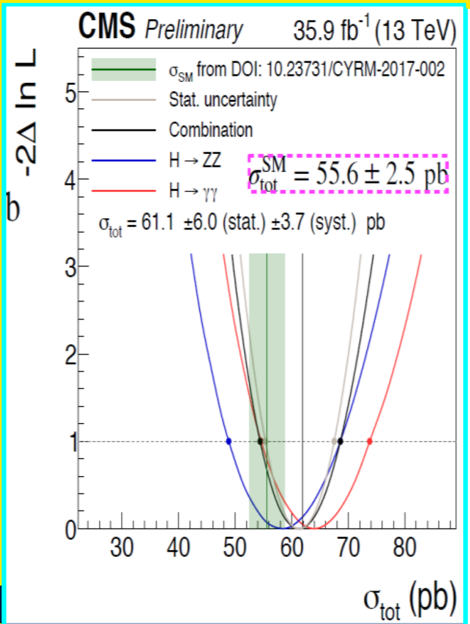
- **Fair fermion constraints** already from inclusive cross sections:
  evident in couplings κ_b, κ_t
- **But access additional information** through shapes: P_T^H, $|y_H|$, N_{jets}, $p_T(J1)$
- **Including on lighter quark coupling κ_c**
- Variations in the κs distort the shape



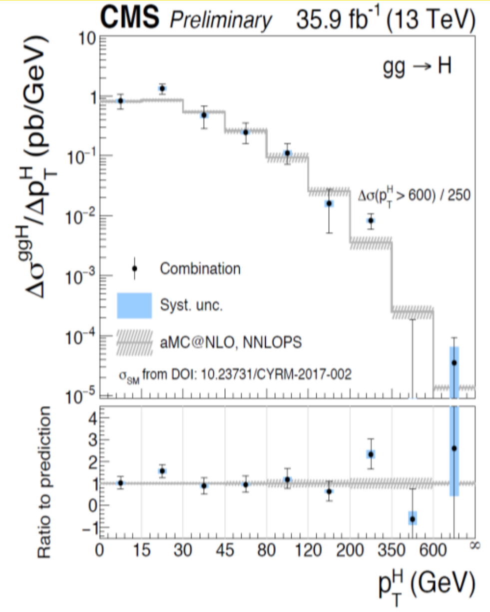


- Combination analysis *adapts the* analyses of $\sigma_{fiducial}$ + distributions in the H→ $\gamma\gamma$, ZZ, bb channels individually
  - Match bin boundaries; bb important at high P_T^H
- Combined σ_{TOT} matches SM to 11%

σ(TOT) scan



dσ(ggf)/dP$_T^H$



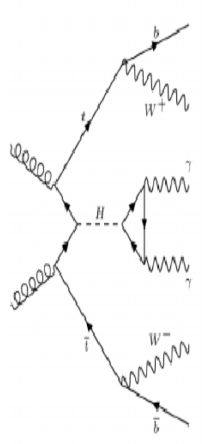
Talk by R.V. Tavalaro at ICHEP; CMS HIG-17-028

- Agree with SM; *Still statistics limited*

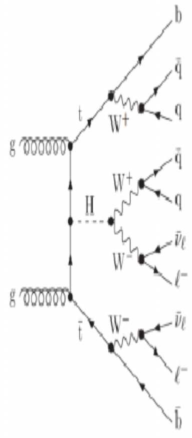
$t\bar{t}H$ Observation: Welcome to the Family

with 78/fb: including full 2017 dataset

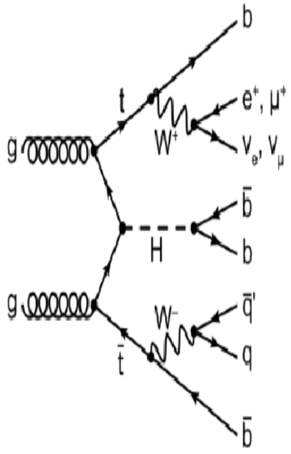
$t\bar{t}H$ Production Measurements



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

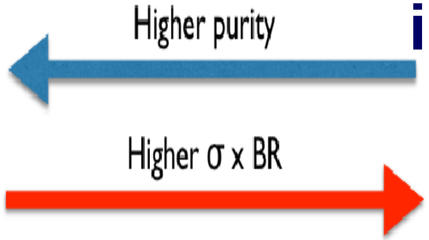


$H \to WW^* \to \ell\nu\ell\nu$
$H \to \tau\tau$
(multi-leptons)



$H \to b\bar{b}$

+ All Hadronic in CMS



Higher purity

Higher σ x BR

Analysis Outline

- Very clean final state, but tiny branching fraction
- Dedicated $t\bar{t}H$ channel part of the global H→ ZZ^* analysis
- $t\bar{t}$ hadronic and leptonic channels
    - ≥ 4 jets, ≥ 1 b-tagged jet and additional 0/1 leptons
- Combined fit (relying on $m_{4\ell}$ and a kinematic discriminant) with analysis of 2016 data (doi:10.1007/JHEP11(2017)047)

Phys. Rev. Lett. 120, 231801 (2018); HIG-18-001

See Talk by Carmen Diez Pardos at ICHEP

Higgs→ $b\bar{b}$ Observation !

Coupling to 2nd Gen Fermions, Down Type Quarks

77/fb, Including 41/fb of 2017 Data

- Largest BR (58%) but very large Background

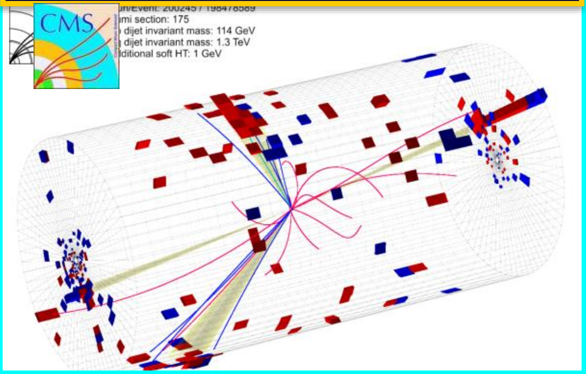
➡ Use WH, ZH: Greater S/B; Direct probe of Yukawa Coupling

5 VH Channels Z(ℓℓ)+H(bb), Z(νν)+H(bb), W(ℓν)+H(bb)

Signatures: two b-jets; Leptons and/or E_T^{Miss}

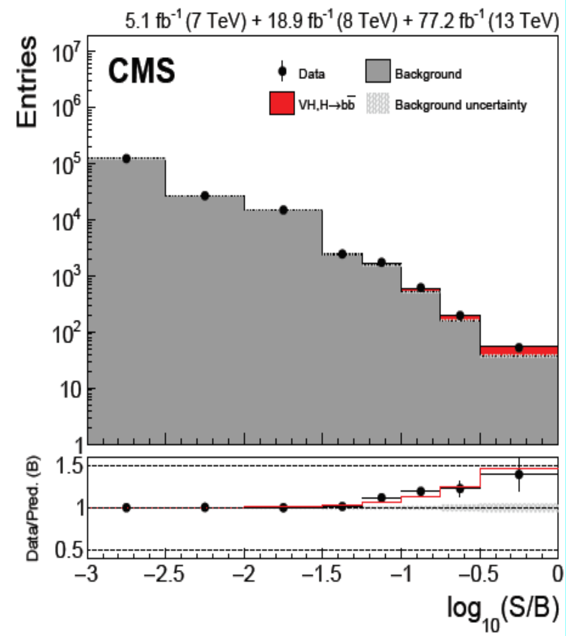
  - Three Channels: 0,1,2 Leptons from V decay
- Validated with VZ, where Z → bb (5-15X VH cross section)
- Improvements: DNN for b-jet ID, regression improves mass resolution, MVA techniques for better S/B separation

H →bb Candidate

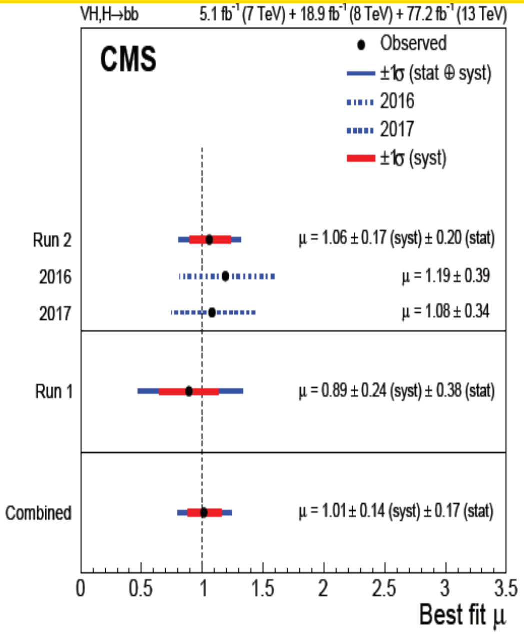


Backgrounds: V+Jets, VV,Top, QCD

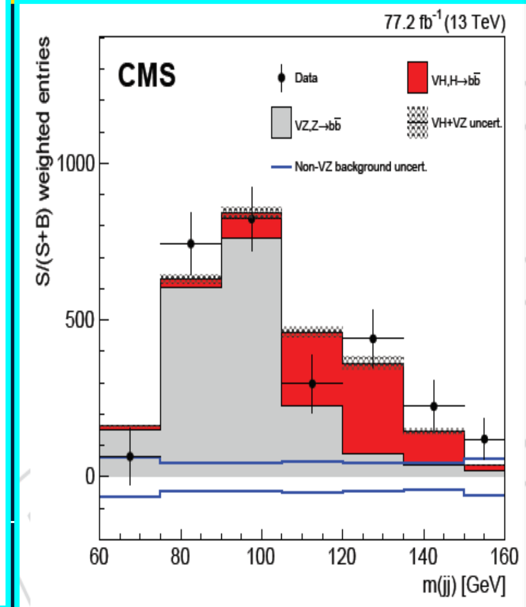
Events vs Log (S/B)



μ = 1.01 ±0.17±0.14



Mjj weighted by Higgs S/(S+B)



Significance All Data

5.6σ Observed

5.5σ Expected

μ = 1.04 ±0.20