ATLAS and CMS: Higgs Results from the LHC

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

LISHEP 2021
UERJ
International School on High Energy Physics
Rio +Worldwide

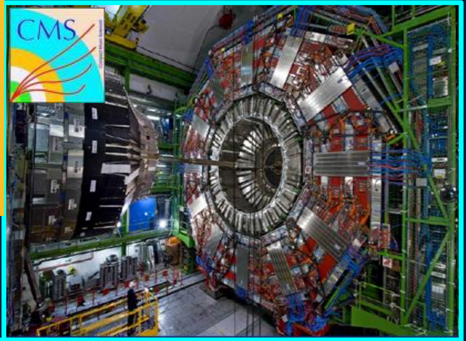
UFBA
LISHEP 2018
International School on High Energy Physics
Salvador

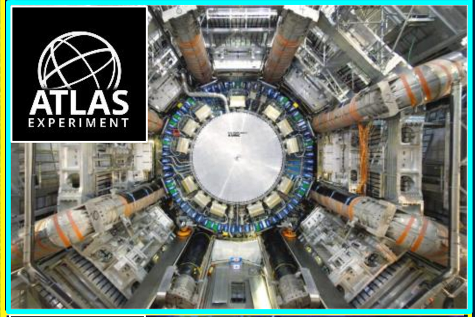
LISHEP 2015
Manaus

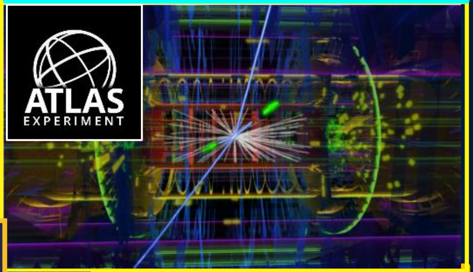
LHC Run2, Run3 and HL LHC

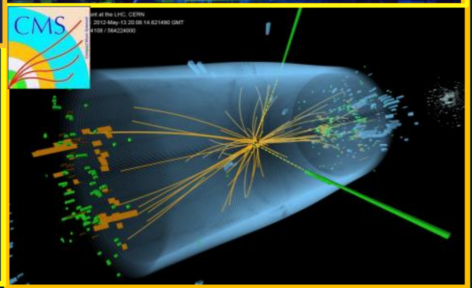
Journey of Discovery

River of Discovery







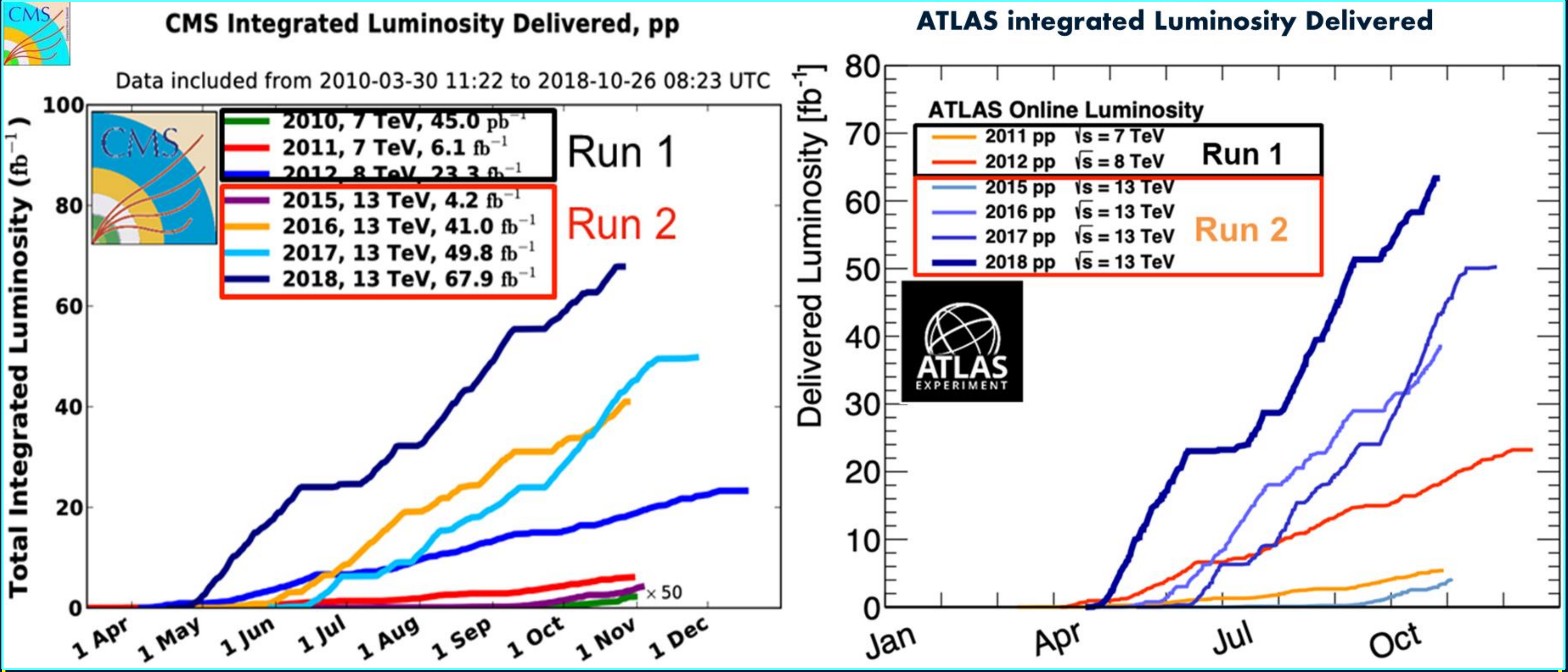


Harvey B Newman

On behalf of the CMS and ATLAS Collaborations

LISHEP 2021 UERJ July 8, 2021

LHC, ATLAS and CMS
Excellent Performance



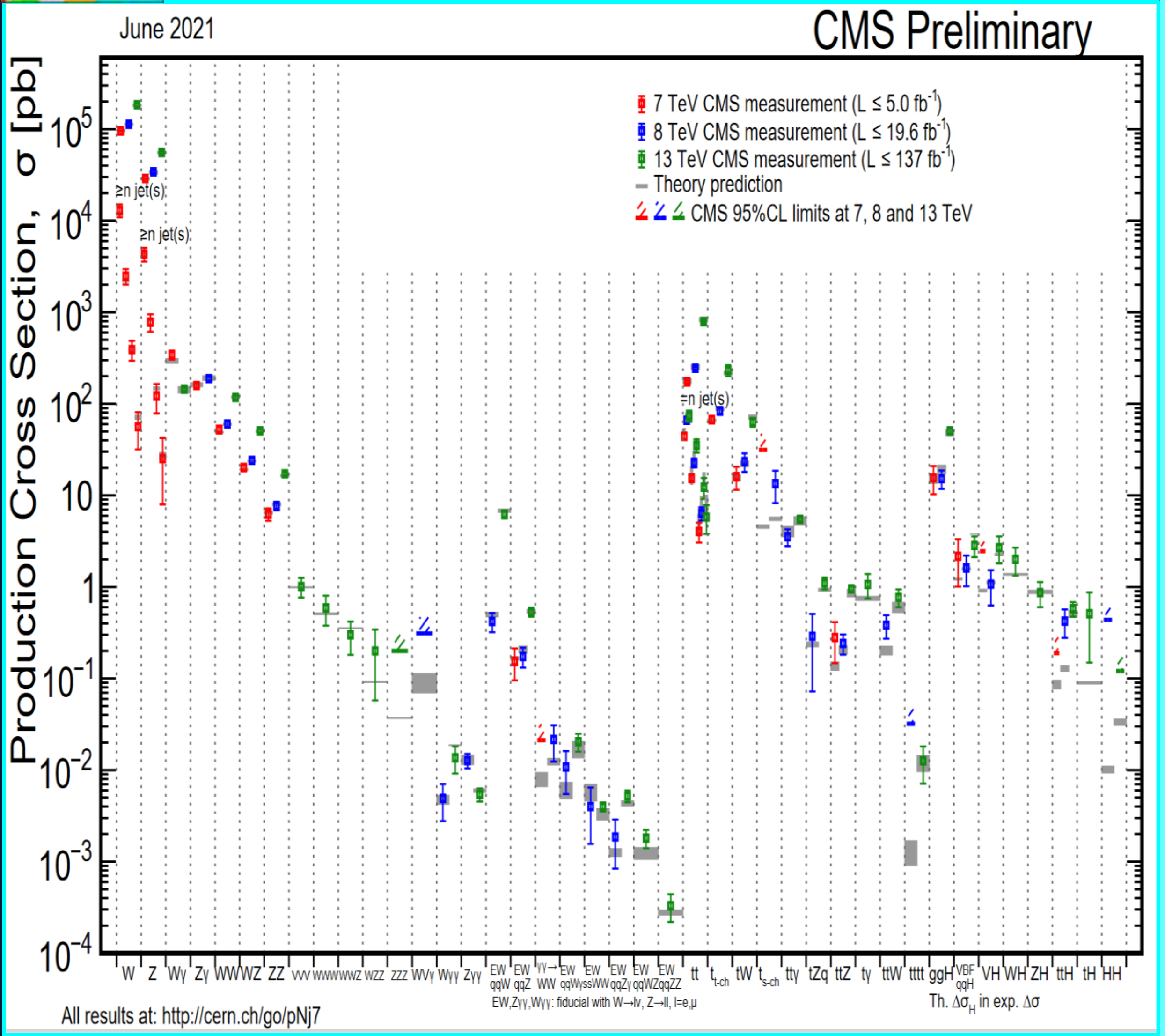
ATLAS and CMS Collected 139 and 137/fb at 13 TeV

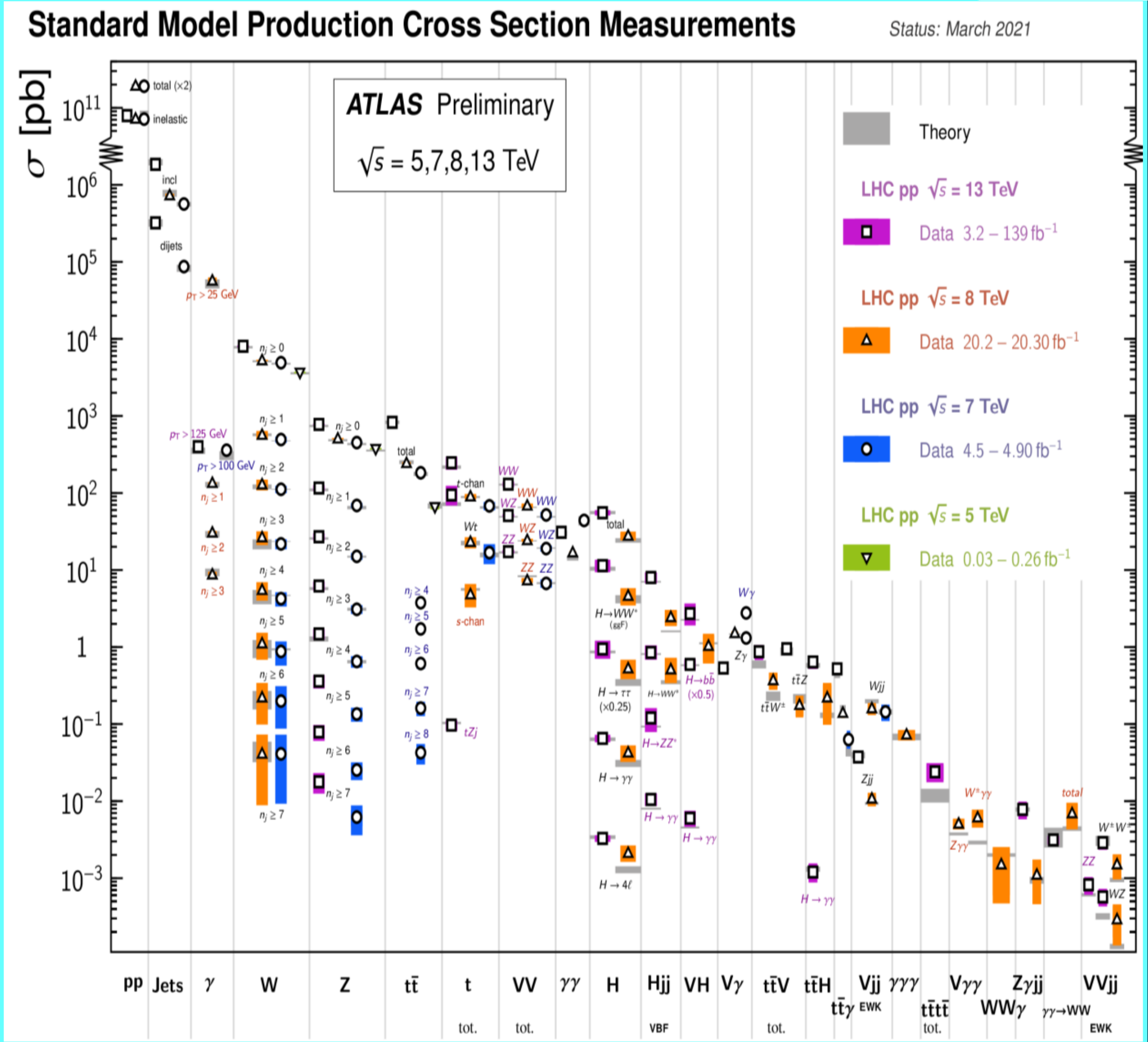
Thanks to the Excellent Performance of the LHC and the Efficient Operation of the Two Detectors

Standard Model Production Cross Sections

Agreement over 14 Orders of Magnitude:

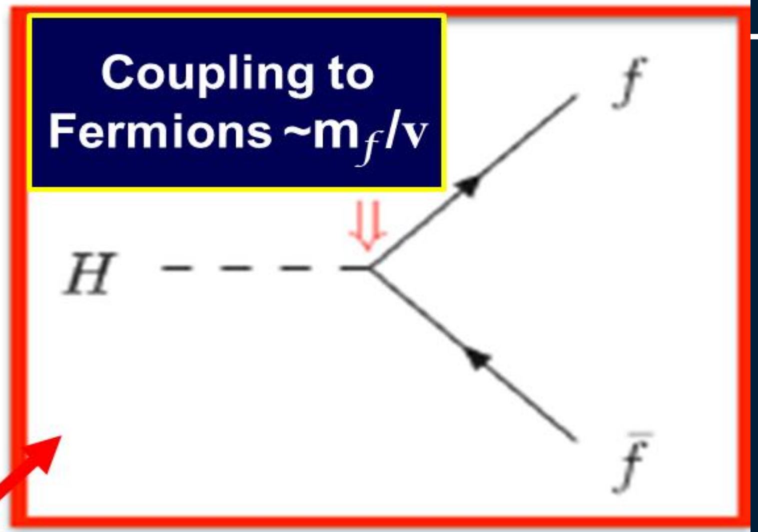
from ~0.1 barn to < 1 femtobarn

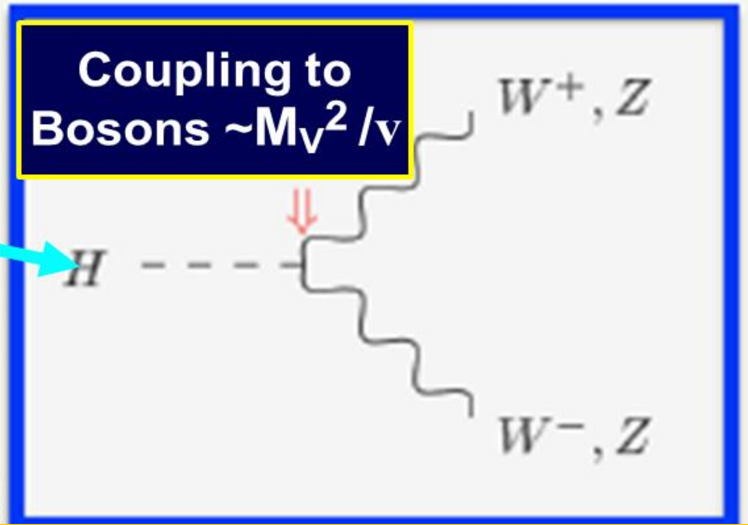




Higgs Boson Discovery: An Achievement of Humanity. Now That Lagrangian is Everywhere

- **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 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



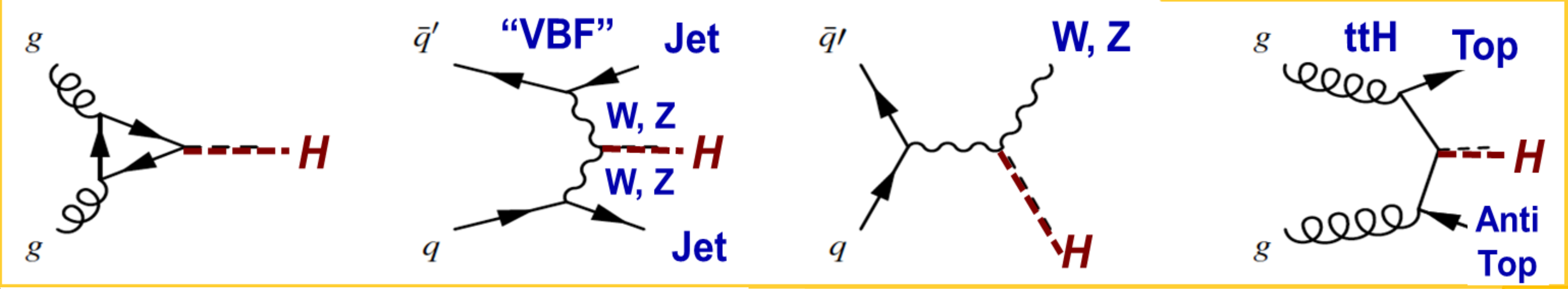


The Higgs Boson Sector:
A New Realm of Exploration Towards Discovery

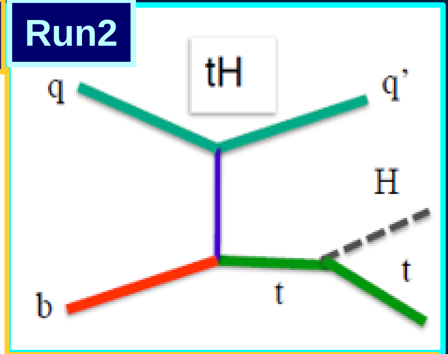
Higgs Production at the LHC

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

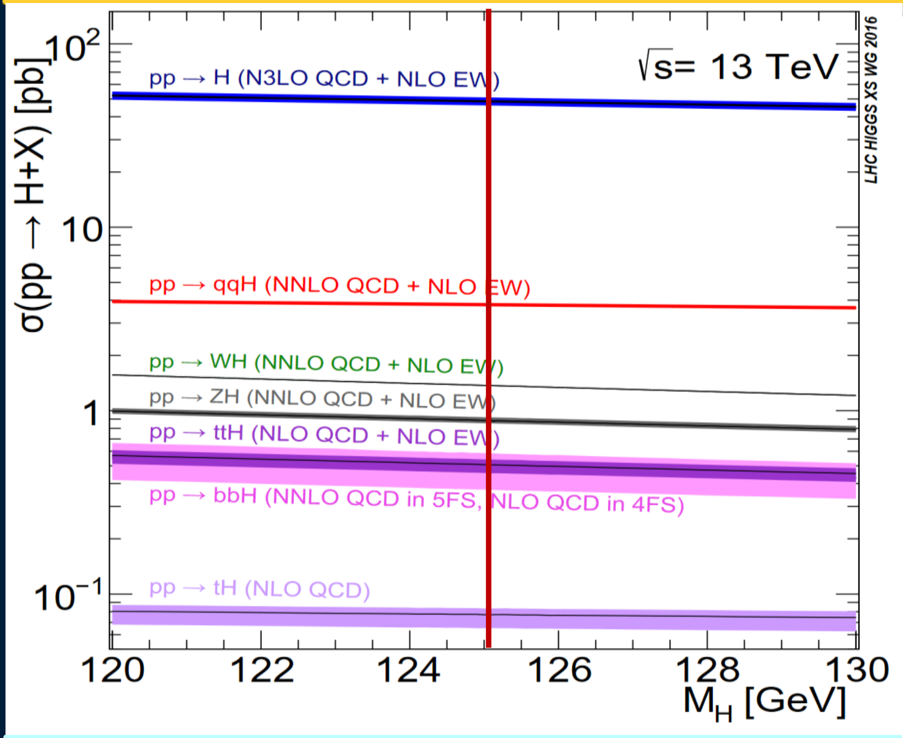
Gluon Fusion gg→ H | **Vector Boson Fusion** | **Associated Production** | **Associated Prod: tt H**

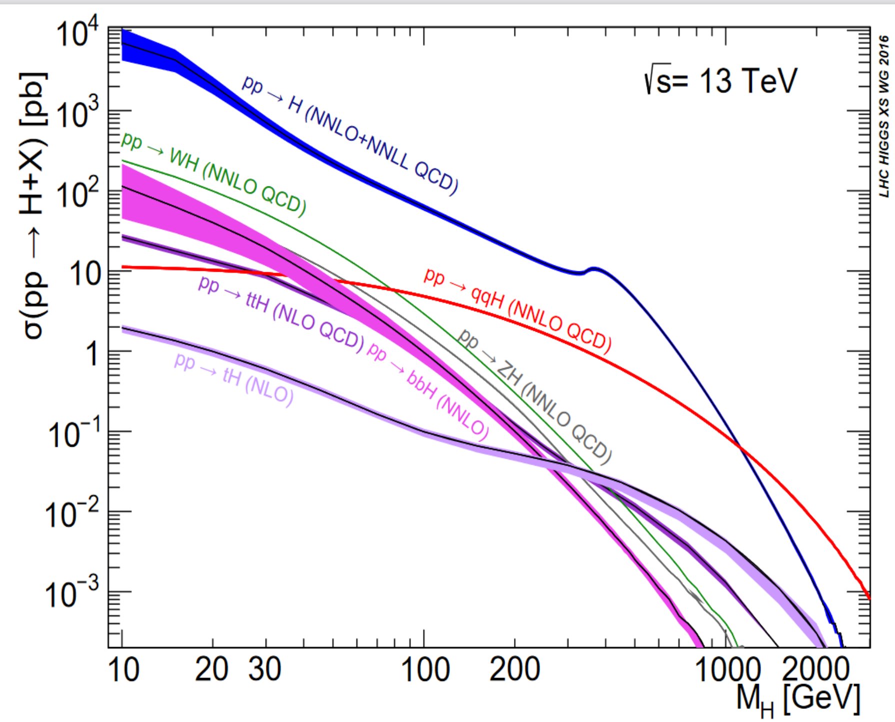


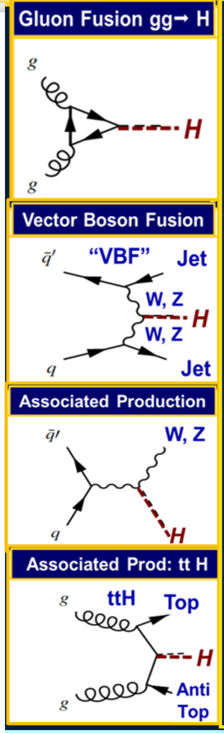
Run2



Single Top: tHq







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

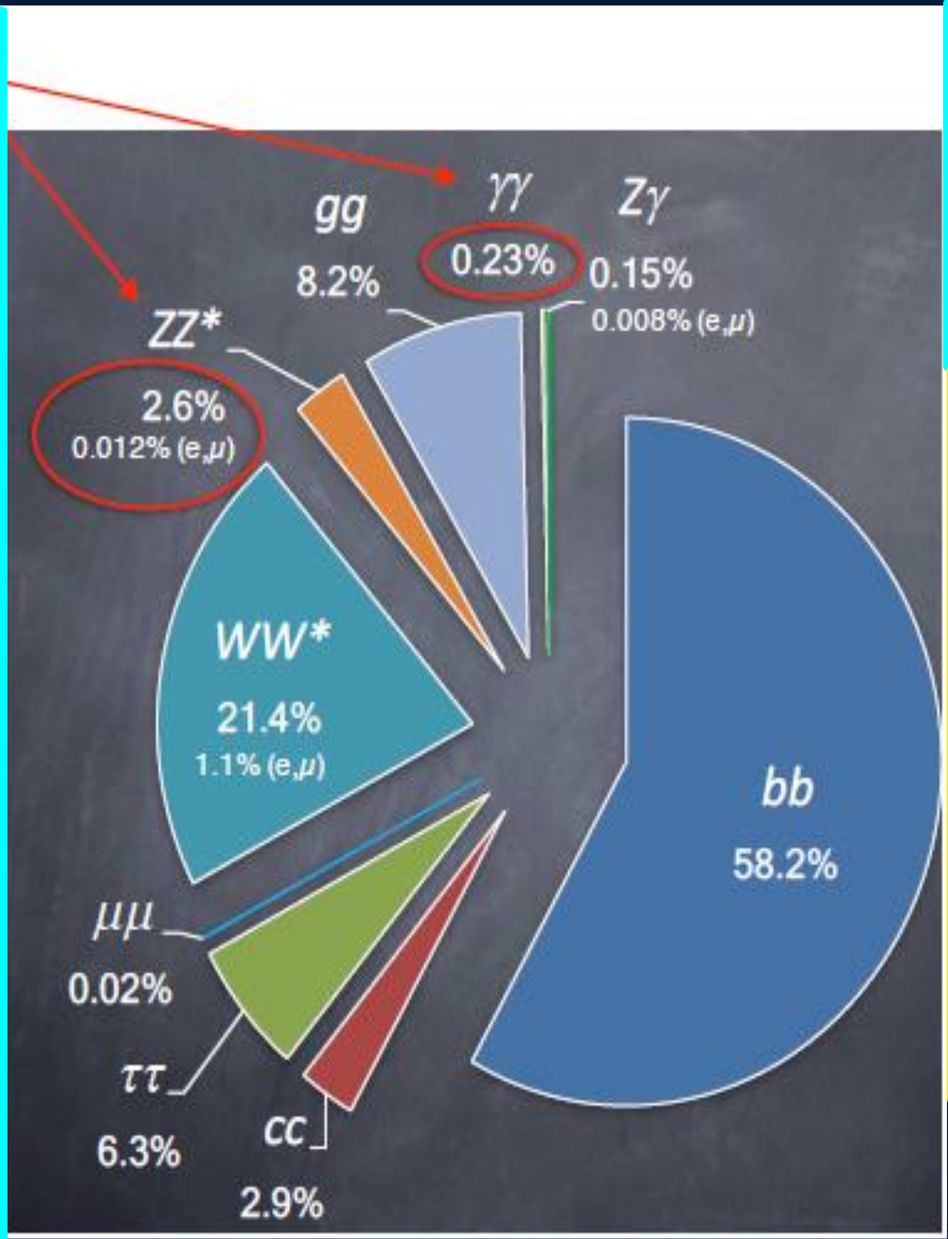
See Handbook on LHC Higgs Cross Sections Vol.4: https://arxiv.org/abs/1610.07922v2 (May 2017)

Higgs Boson Decays

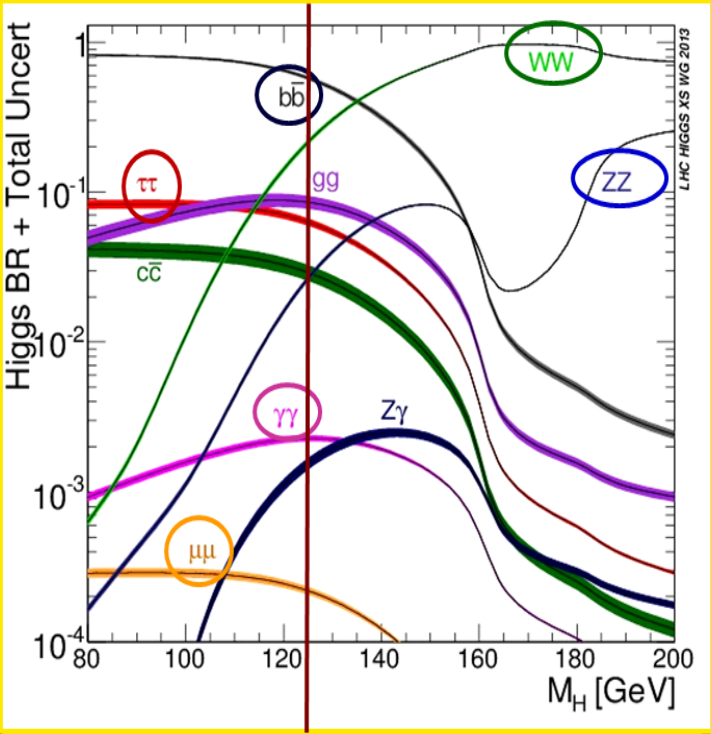
ZZ, γγ: High resolution Channels: Precise Mass and Differential Measurements

WW: High BR but Low Resolution

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



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



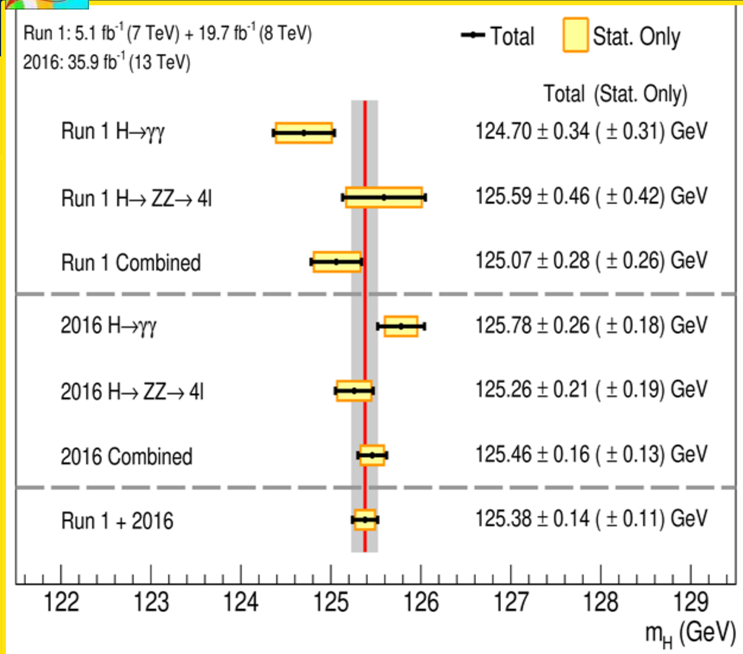
125 GeV – A Spectacular Mass: ~89% of final states studied

Higgs Boson Mass

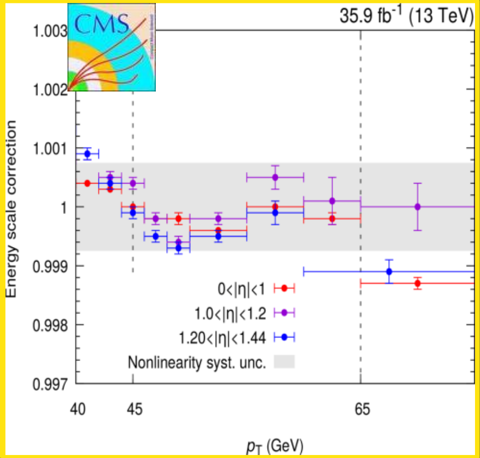
- M_H **in the SM is a free parameter:** Once known, all Higgs boson couplings to SM particles are fixed
- **Most sensitive channels:** $H \to \gamma\gamma$ & $H \to ZZ \to 4l$: fully reconstructed with high resolution
- **CMS+ATLAS Run1 combination** m_H =125.09 ±0.24 GeV
- **ATLAS full Run2 statistics** $H \to ZZ \to 4l$ **channel**
  - m_H = 124.92 ±0.19 (stat) $^{+0.09}_{-0.06}$ (sys) GeV
- **CMS:** $H \to \gamma\gamma$ & $H \to ZZ \to 4l$ *Combined* Run1 + 2016
  - m_H = 125.38 ±0.14 (±0.11 stat. only) GeV

    Most precise to now
- **One of the most precise electroweak measurements** Approaching 0.1%. Impressive for a hadron collider not designed for this level of precision
- **Still statistics limited: More precise measurements expected soon** using the full Run 1 + Run 2 dataset

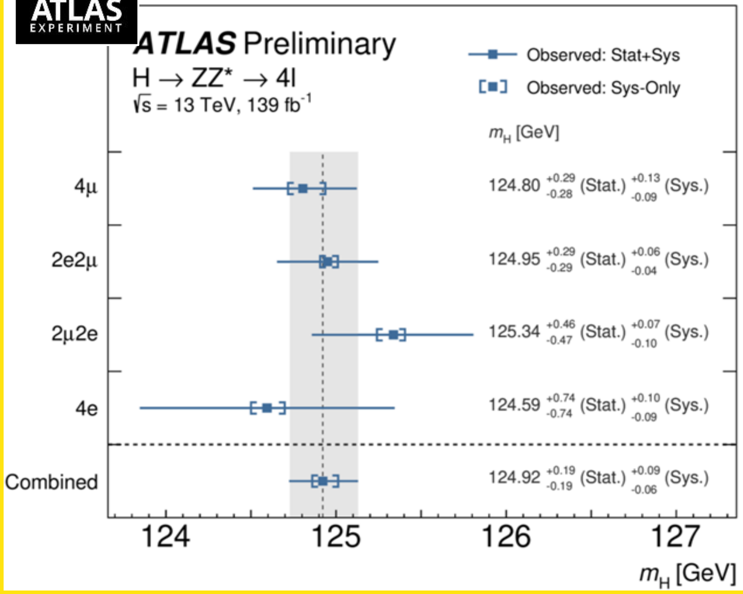
Phys. Lett. B 805 (2020) 135425



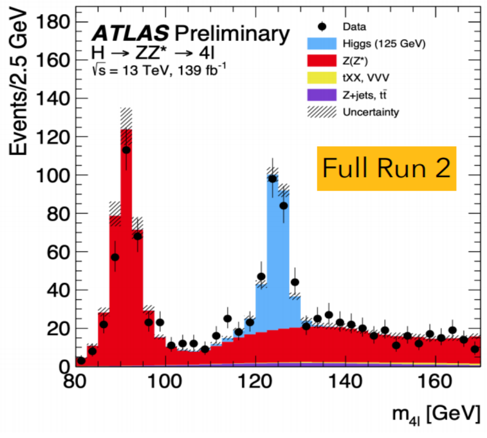
Photon Energy Scale correction vs p_T



ATLAS-CONF-2020-005



$H \to ZZ \to 4$ lepton Mass distribution



H Coupling Modifier Framework:

Characterize possible deviations from SM

κ Factors for Production and Decay

- **Assumptions:** Single resonance, zero width, SM tensor structure
- There are **8 basic parameters** to describe the most relevant decays & production mechanisms:

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

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

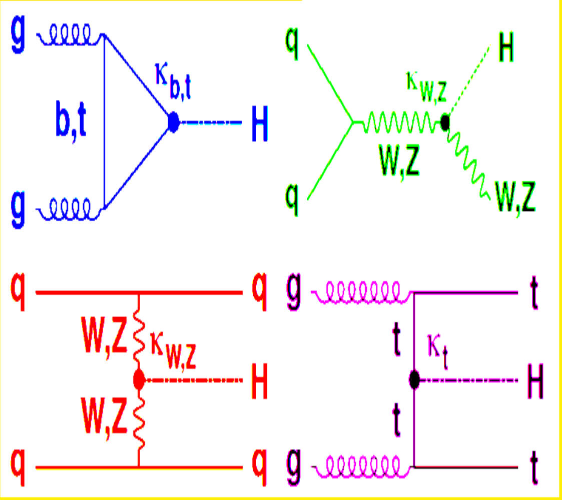
$$\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$$

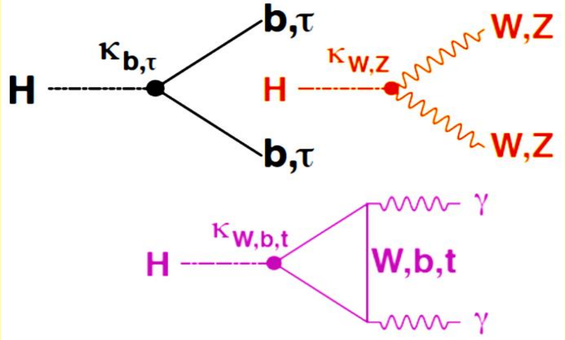
$$\Gamma_i \sim \kappa_i^2 \, \Gamma_i^{SM}$$

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

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

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





- **We cannot extract all 8 parameters at once with the current data.**
- So we do **Coupling Compatibility Tests** using scaling factors κ relative to SM and their ratios λ

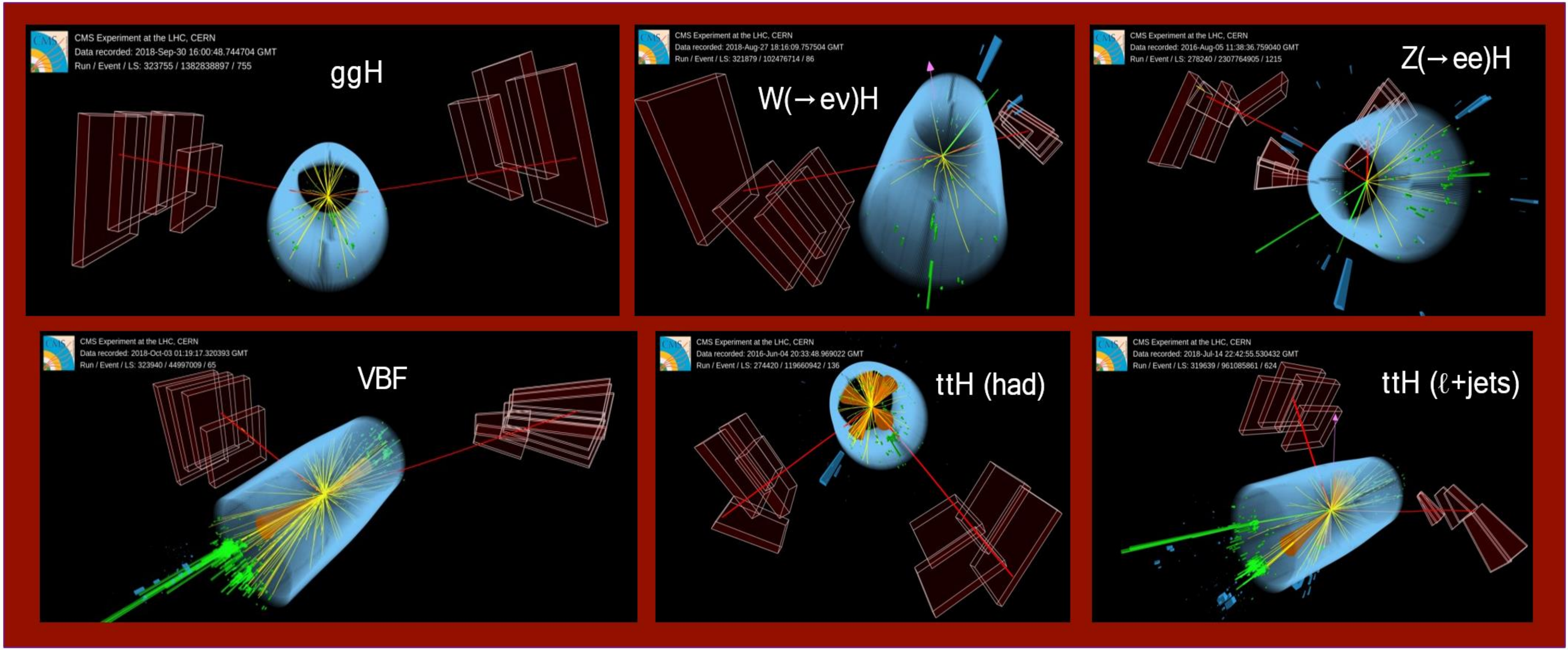
  Example: For the gg → H → γγ process:

$$\sigma \times BR(gg \to H \to \gamma\gamma) \, / \, \sigma_{SM} \times BR(gg \to H \to \gamma\gamma)_{SM} = \kappa_g^2 \kappa_\gamma^2 / \kappa_H^2$$

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

First Evidence for H → μμ

Exclusive categories: ggH, VBF, VH and ttH



1st Evidence for H → μμ

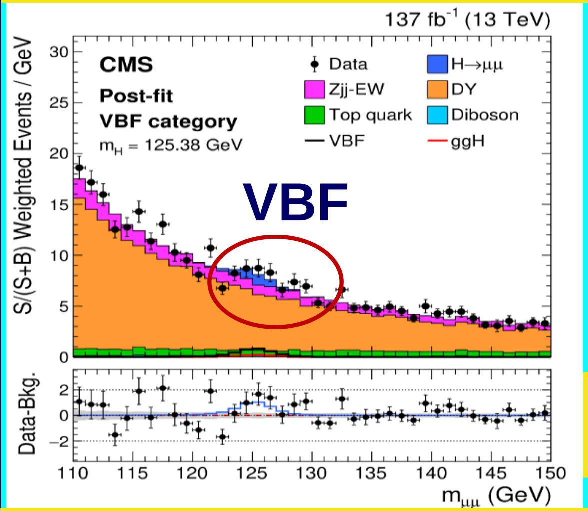
Most Sensitive to 2nd Generation Fermion Coupling

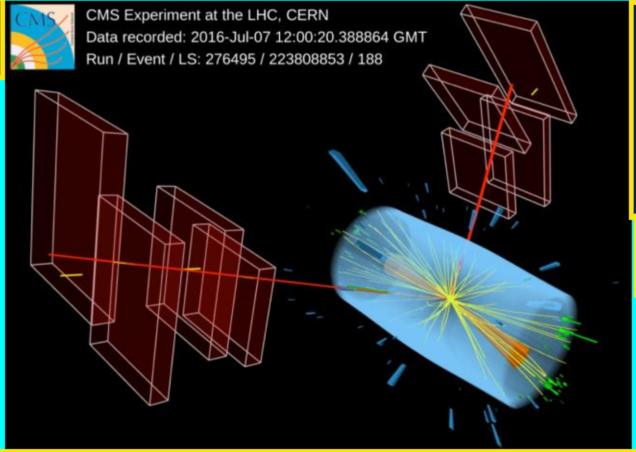
Full Run2 137/fb + Run1

JHEP 01 (2021) 148

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

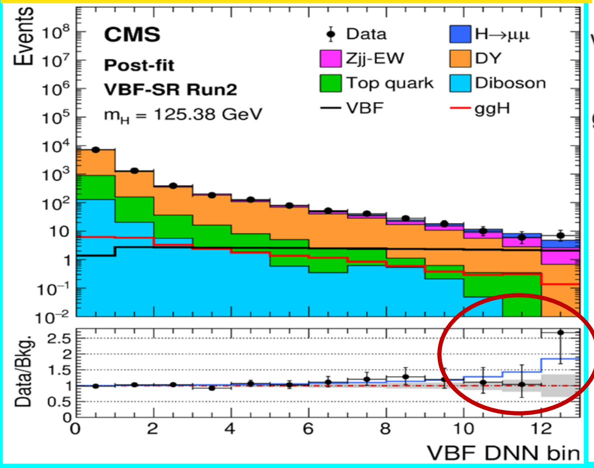
Mμμ distribution

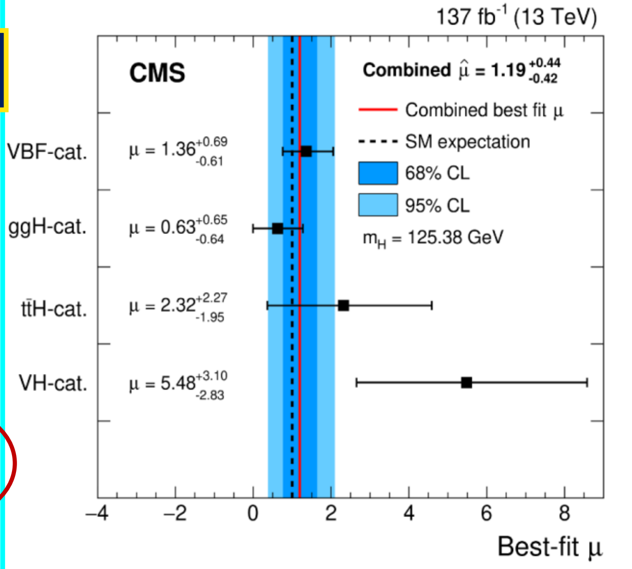




Drell Yan background suppressed by two forward jets

Deep Neural Net Output

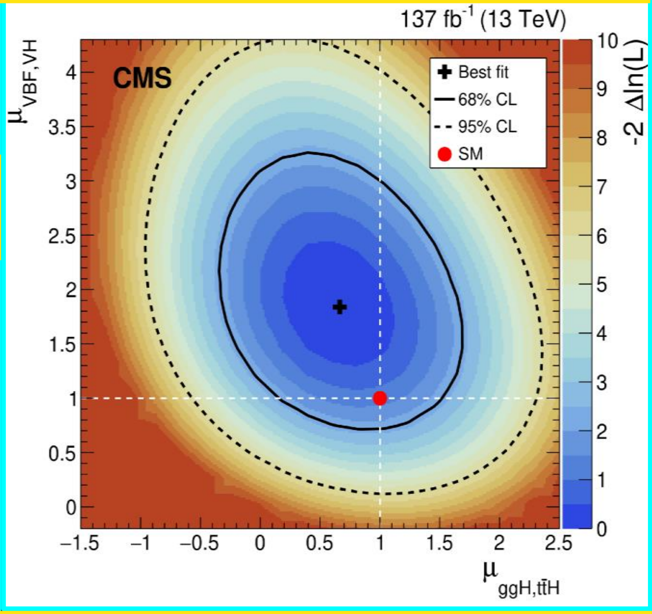




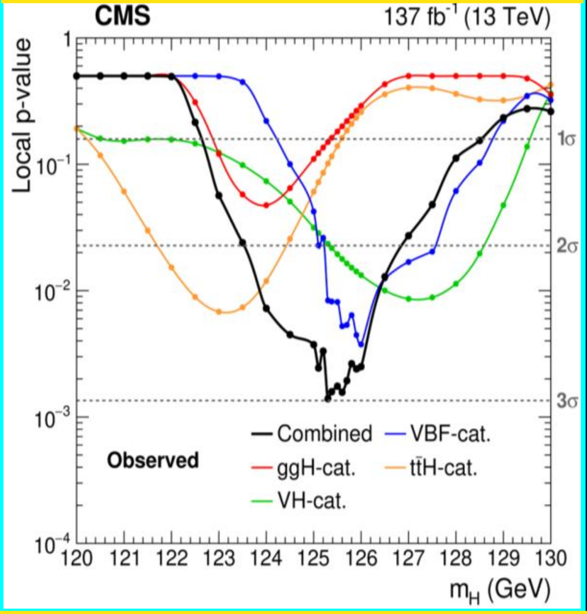
$$\mu(\mu\mu) = 1.19 \; ^{+0.40}_{-0.39} \; (\text{Stat}) \; ^{+0.15}_{-0.14} \; (\text{Sys})$$

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 by Irene Dutta

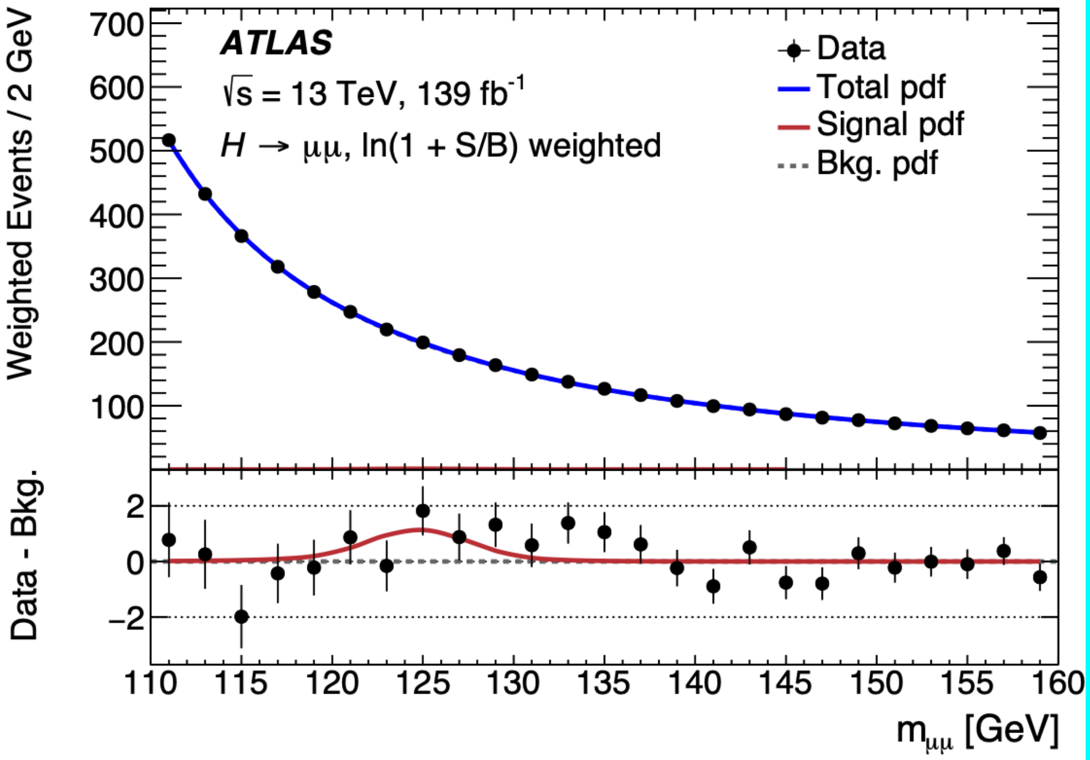
H → μμ

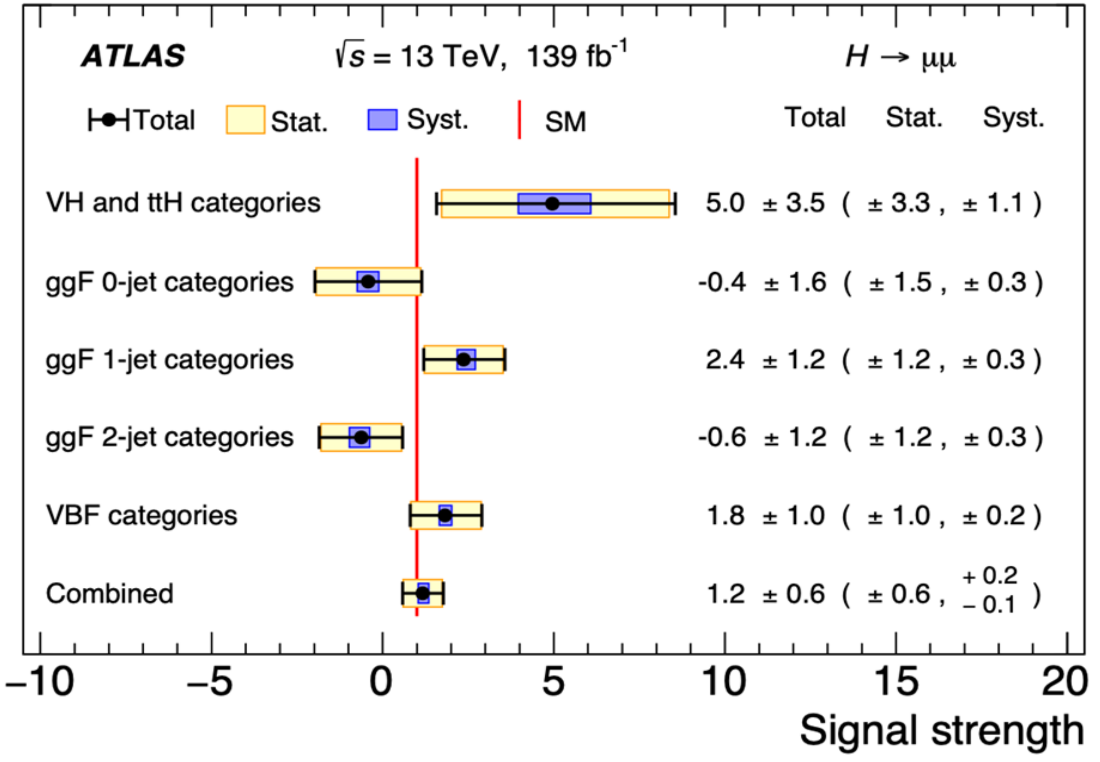
Coupling to second generation leptons

Phys. Lett. B 812 (2021) 135980

Full Run2 139/fb

- Studying Higgs boson to muon coupling has important implication for muon collider
- Challenge: small branching ratio BR(H→μμ): 0.02%, large background S/B: 1~2%





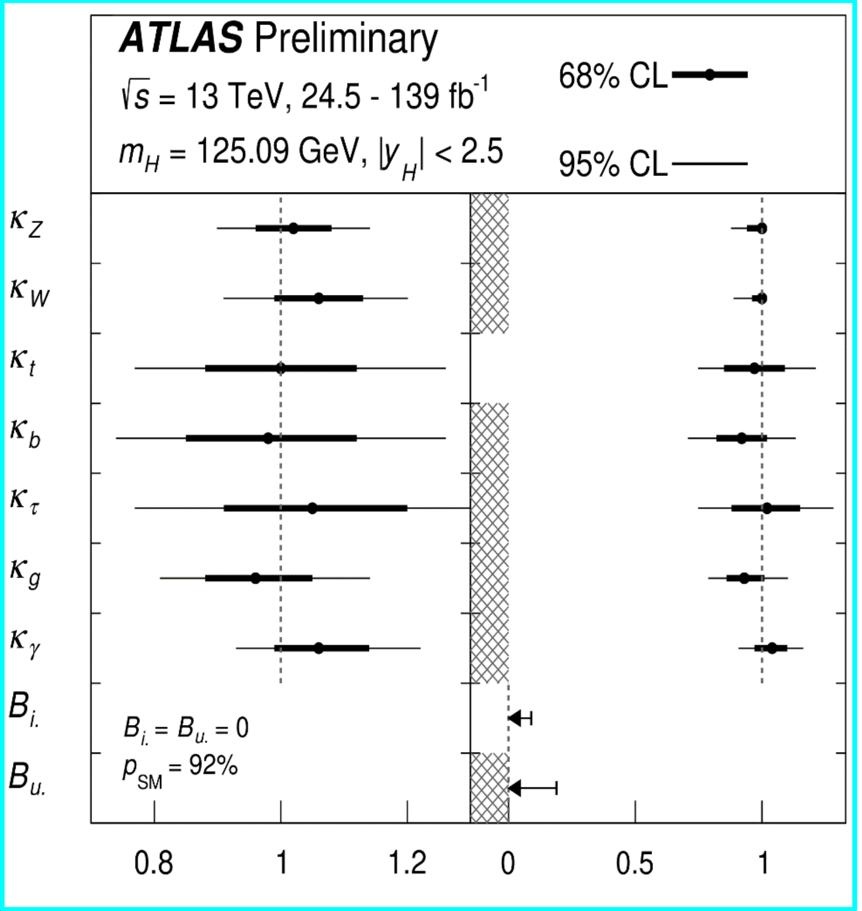
- Significance: 2.0(1.7)σ, obs(exp)
- Signal strength: $\mu = 1.2 \pm 0.58(stats.)^{+0.13}_{-0.08}(theory)^{+0.07}_{-0.03}(exp.) \pm 0.10$ *(Spurious signal)*
- Higgs boson coupling to muon: $\kappa_\mu = 1.12^{+0.26}_{-0.32}$ %68@ CL (ATLAS-CONF-2020-027)

Summary of Higgs Boson Couplings

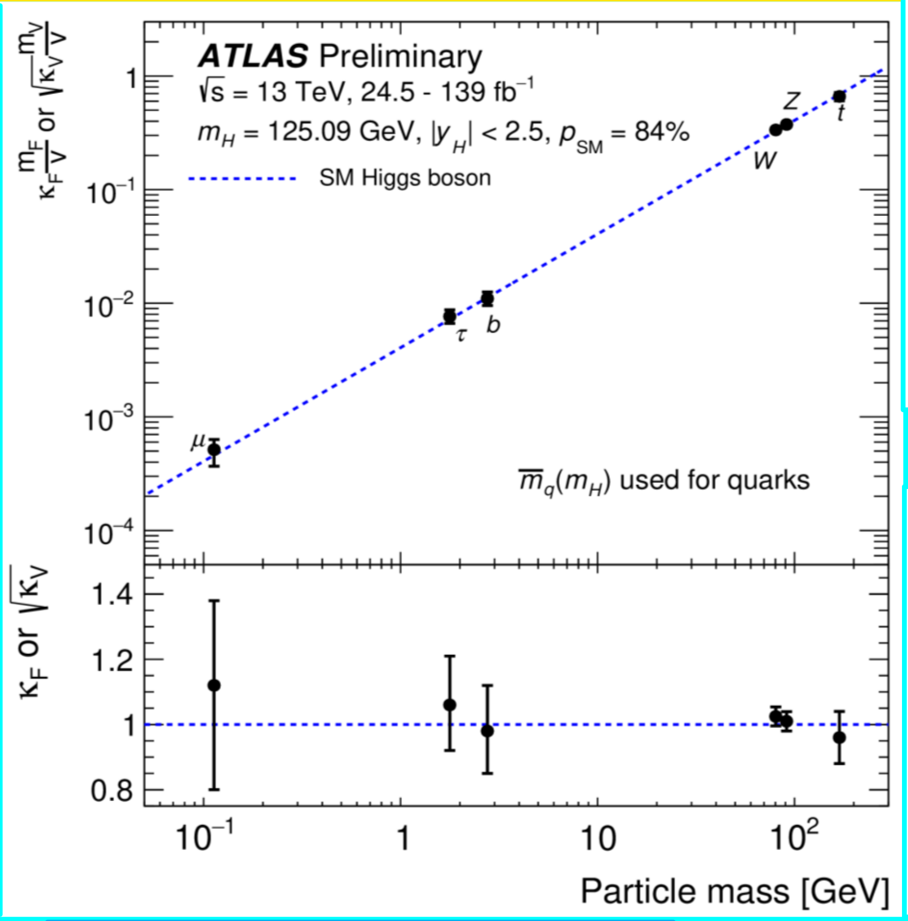
Full Run2 139/fb

Fit for Coupling strength modifiers (κ)

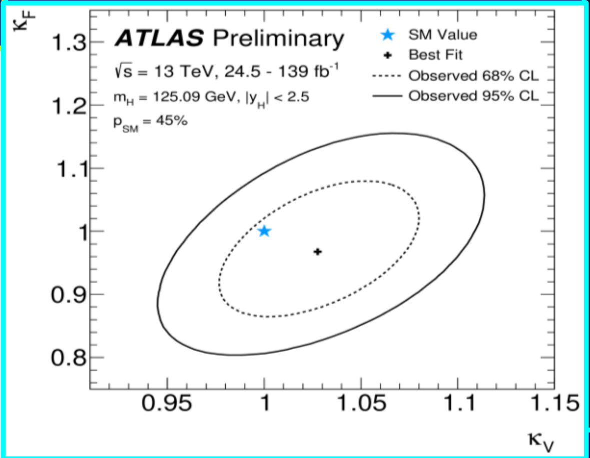
Coupling Strengths to SM Fermions and Bosons



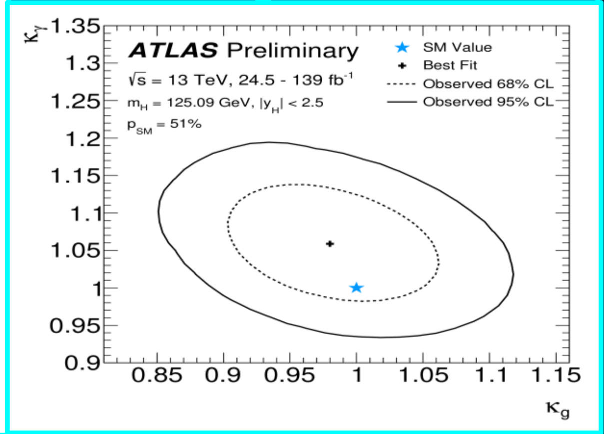
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$ vs Particle Mass



κ_F Vs κ_V p_{SM} = 45%



κ_γ Vs κ_g p_{SM} = 51%



ATLAS-CONF-2020-027

Summary of Higgs Couplings

Full Run2 137/fb

CMS-HIG-19-005, 006

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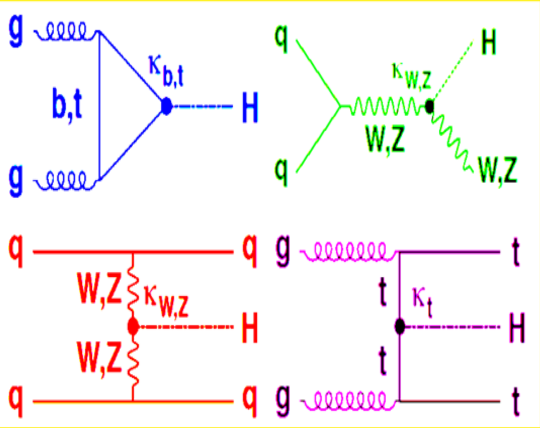
κ Factors for Production and Decay

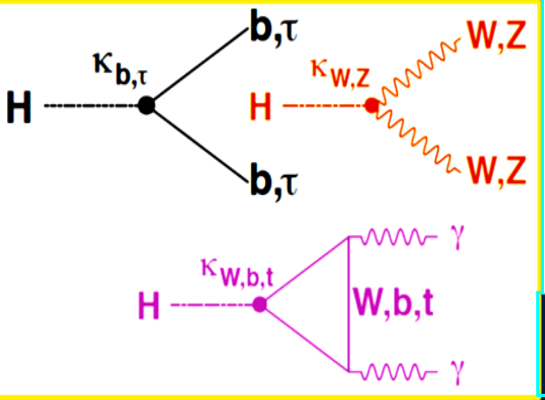
$\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$

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

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

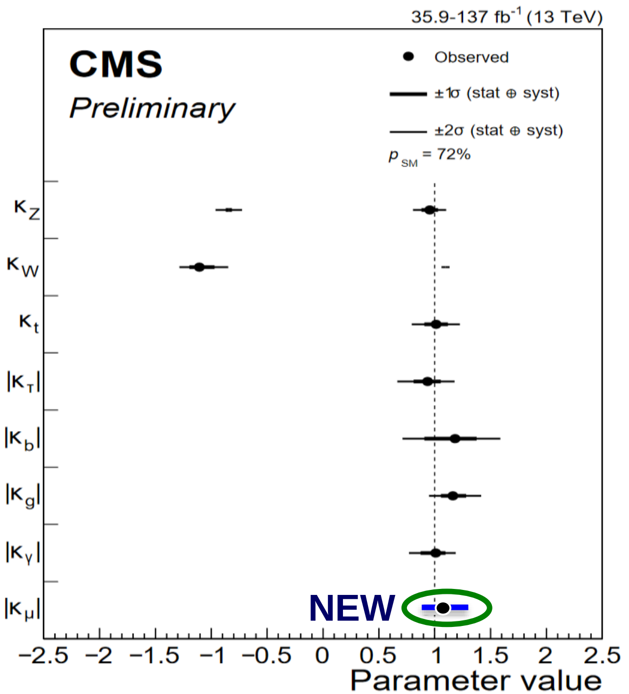
$$N(xx \to H \to yy) \sim \sigma(xx \to H) \cdot B(H \to yy) \sim \frac{\sigma_{xx}\Gamma_{yy}}{\Gamma_H}$$





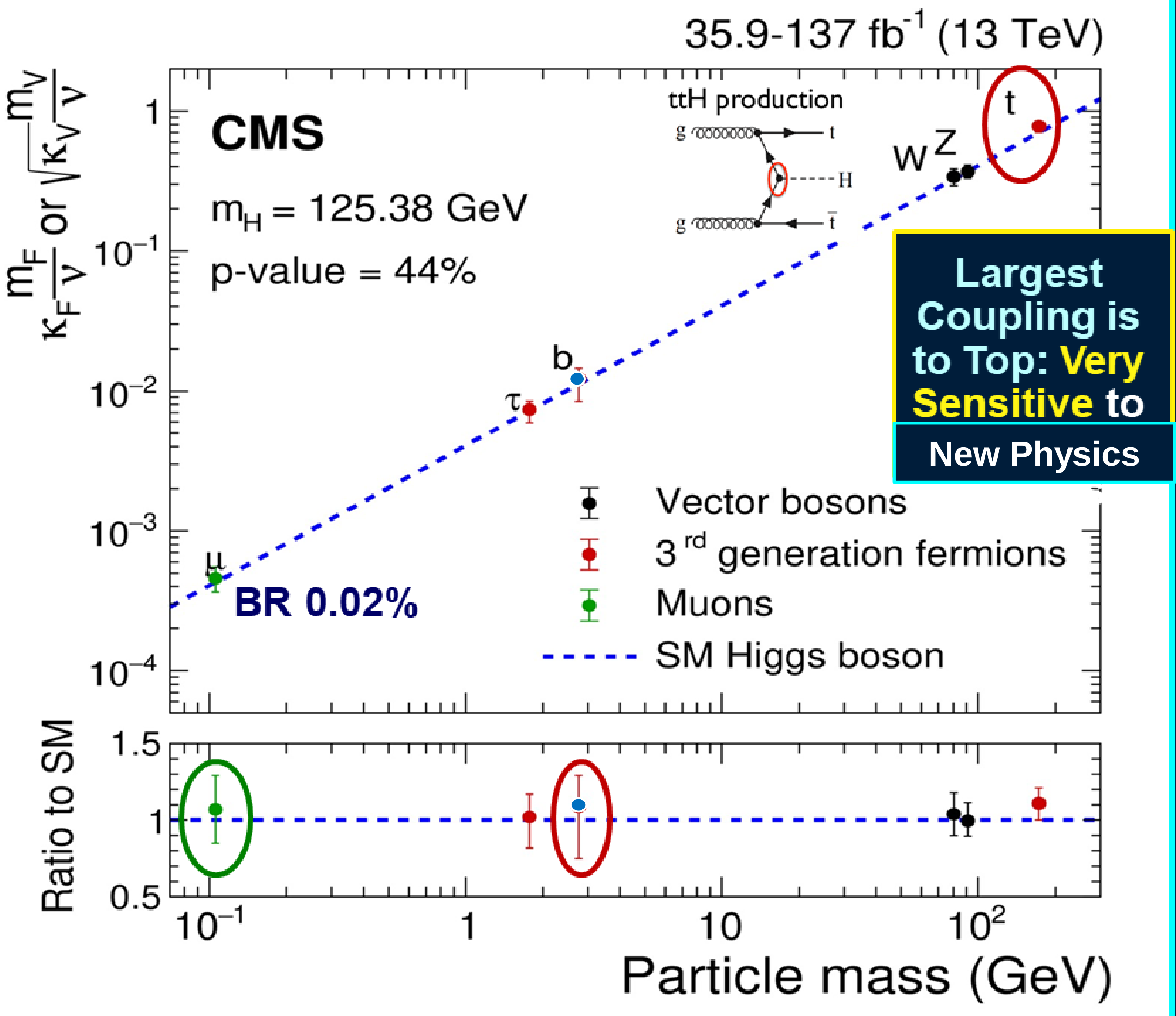
Fit for 8 Coupling strength parameters (κ) for $m_H = 125.38$ GeV

1st Time: Meaningful 68% and 95% CL intervals for Higgs Couplings to 2nd Generation Fermions (μ,b)



Eur. Phys.J.C (2019) 79:421 + CMS-HIG-19-005. Full Run 2 in Progress

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



Largest Coupling is to Top: Very Sensitive to New Physics

New at LHCP: VH → $c\bar{c}$

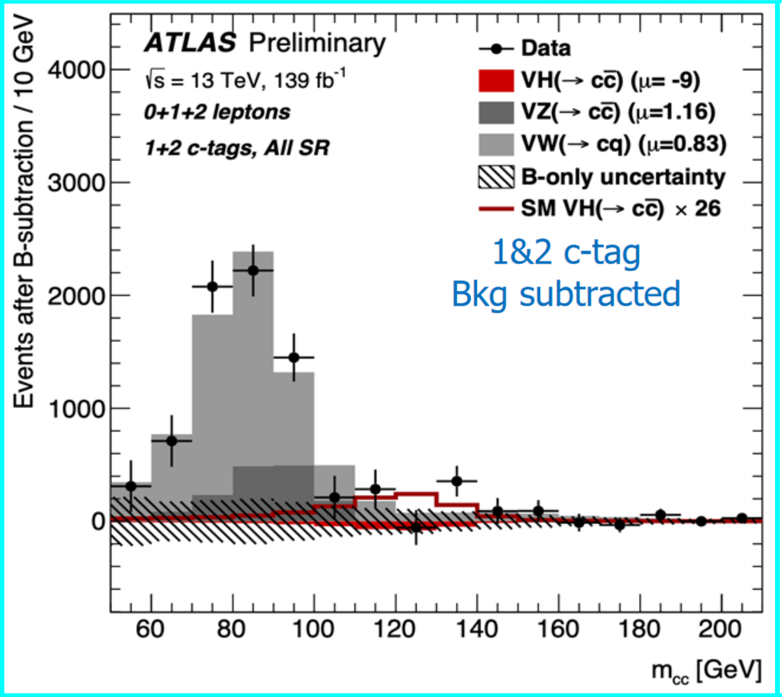
Higgs Boson coupling to 2nd generation quarks

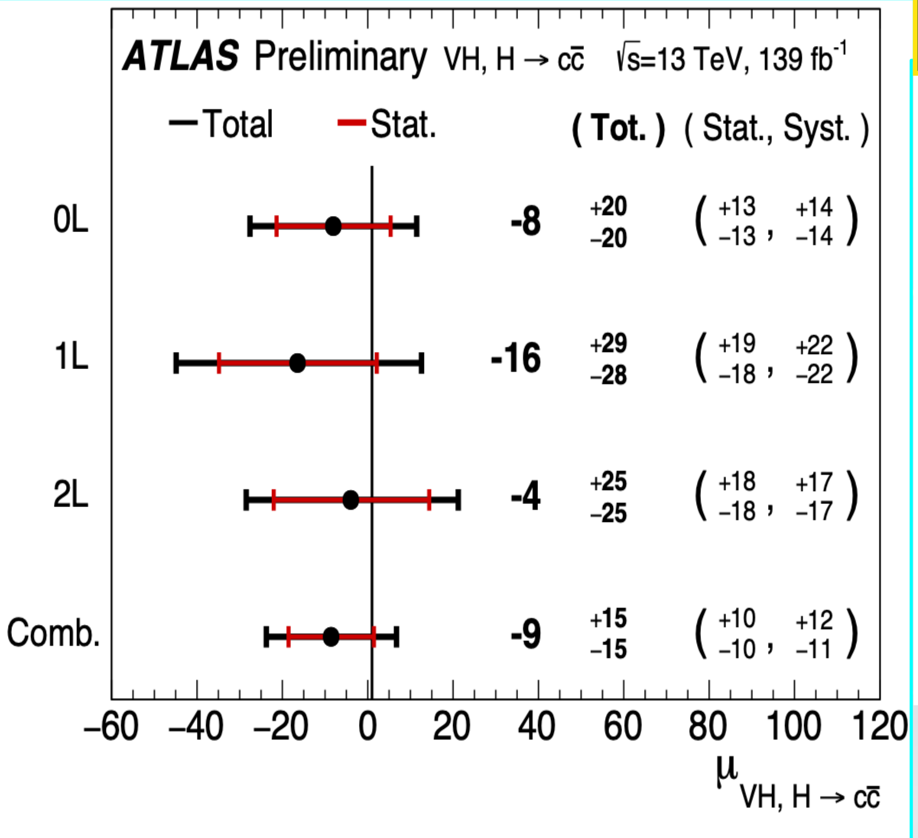
ATLAS-CONF-2021-021

Full Run2 139/fb

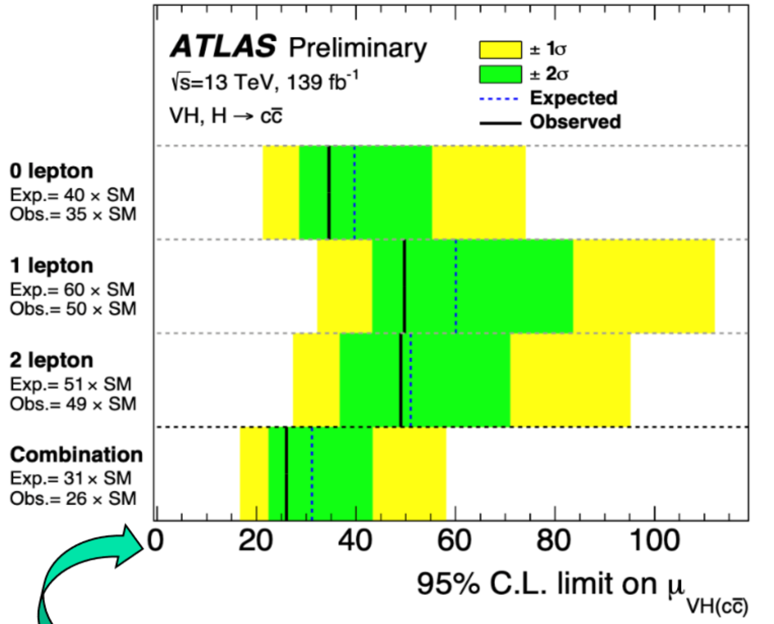
0,1,2ℓ (e,μ)+ c-tagged jets; b-tag veto

$ZH \to \nu\nu c\bar{c}$, $WH \to \ell\nu c\bar{c}$, $ZH \to \ell\ell c\bar{c}$





95% CL Upper Limits on $\mu_{VH}(c\bar{c})$



μ signal strength $\{x\ [\sigma \cdot Br]_{SM}\}$
→26 (31) obs (exp)

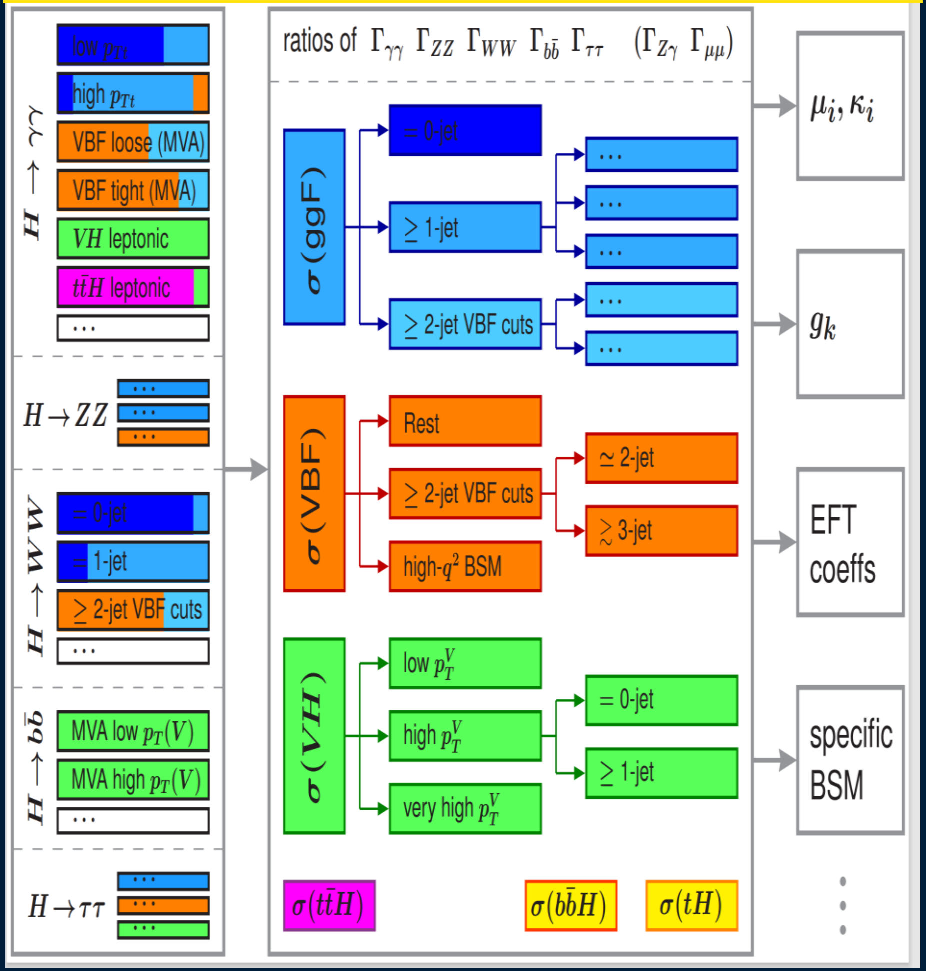
- $\sigma/\sigma(SM) < 26$ (31) obs (exp) @95% CL
- Higgs boson Yukawa coupling to charm quark: $|\kappa_c| < 8.5$ 95% CL
- Most stringent limit to date
- Analysis improvements ongoing

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 without loss of sensitivity**
- **Significant progress from ATLAS and CMS across accessible Higgs decays**

Development initiated at Les Houches 2015

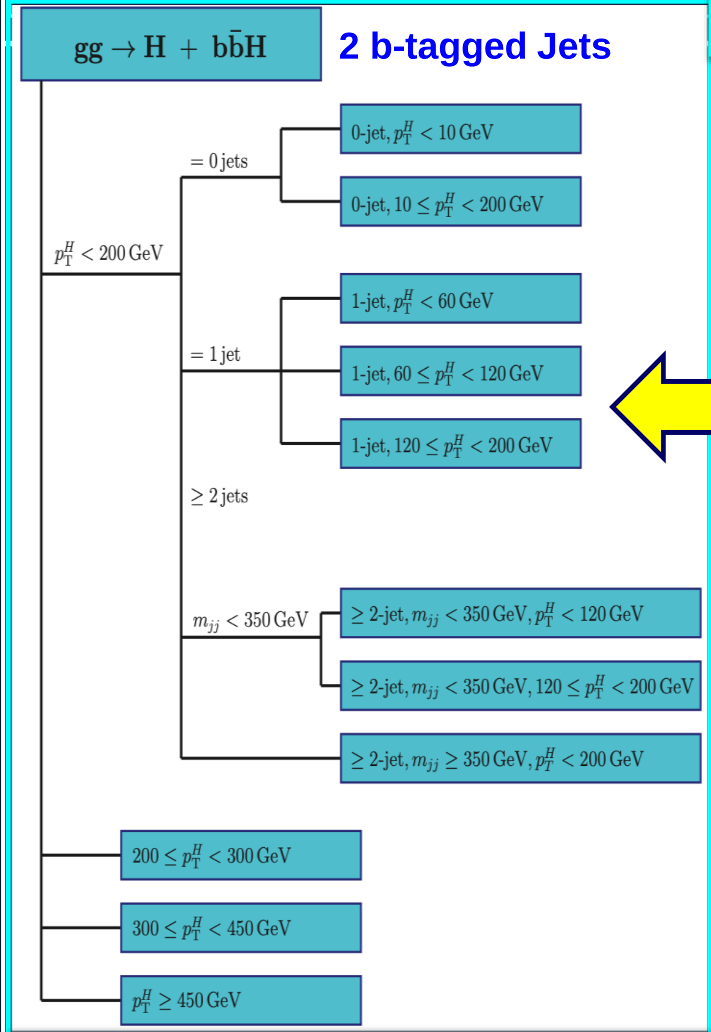


Simplified Template Cross Sections Combination

ATLAS-CONF-2020-027

- Combination of STXS measurements in **H→γγ, H→ZZ*→4l and VH,H→bb**
- Overall good compatibility with SM
- Measurements interpreted using EFT framework and BSM models: ATLAS-CONF-2020-053
- Statistical precision, in particular in most BSM-sensitive regions is still limited: more data will help!

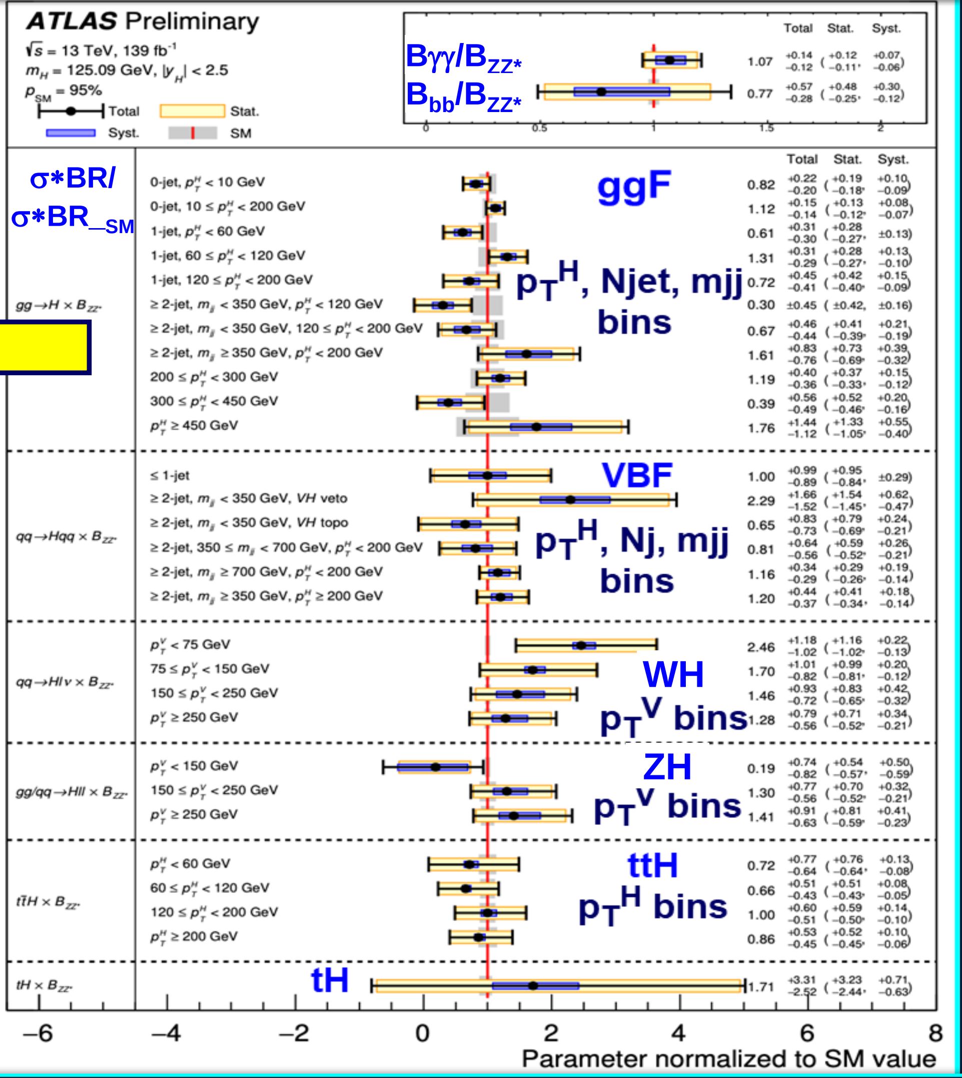
Analysis Flow for ggF→H, bbH



Global Fit: μ_H = 1.06 ± 0.07

WH Observed: 6.3σ (5.2 exp)

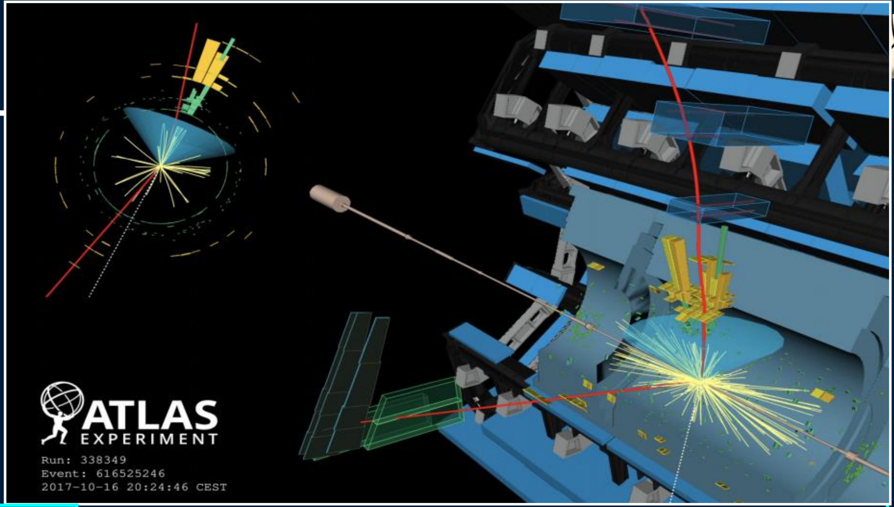
Parsing the data for ggF, VBF, ttH and tH production into p_T, Njet, mjj bins



Overall P-Value 95%

Simplified Template Cross Sections VH → bb Channel

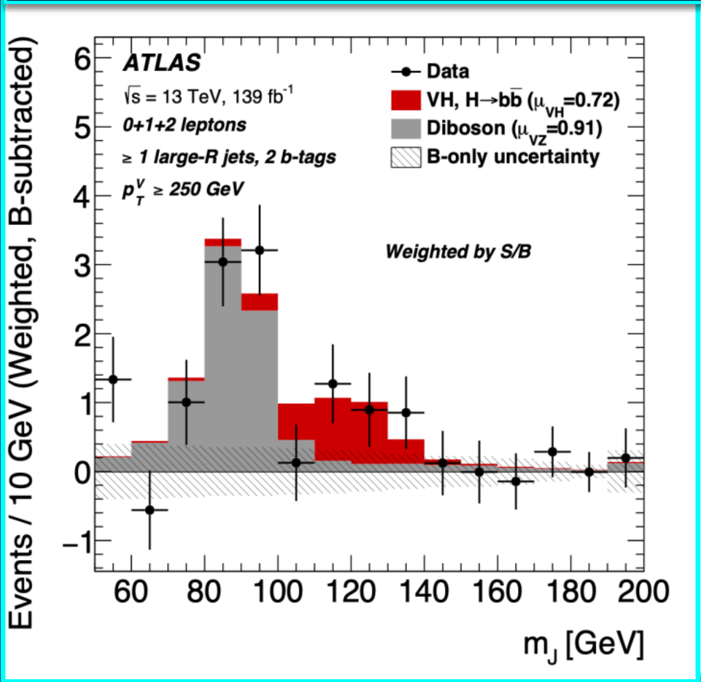
Complementary analyses using small-R jets and boosted Higgs physics objects:

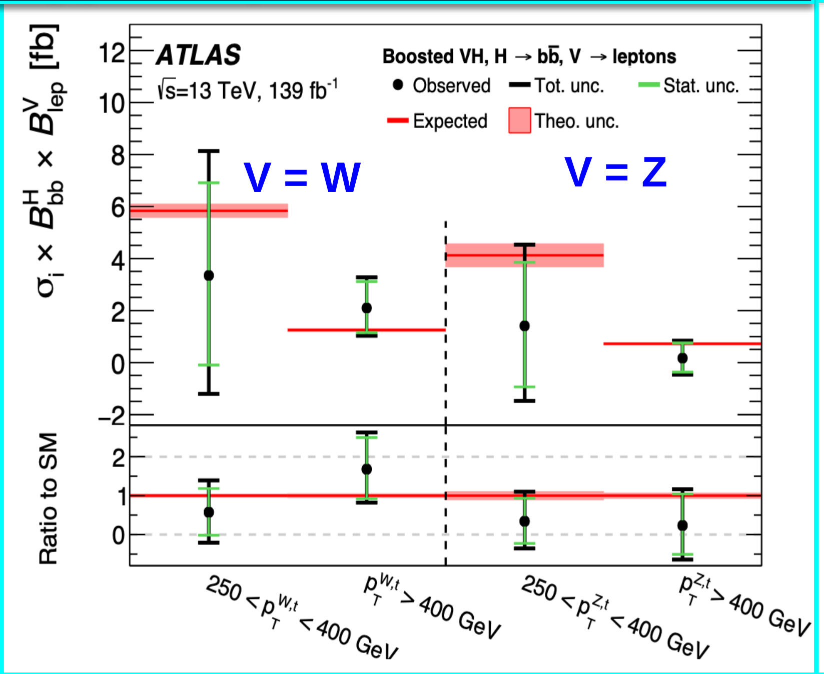


- Strong evidence 4.0σ for WH
  Observation 5.3σ of ZH from small-R jets analysis
- Boosted Higgs analysis: 2.1σ of VH

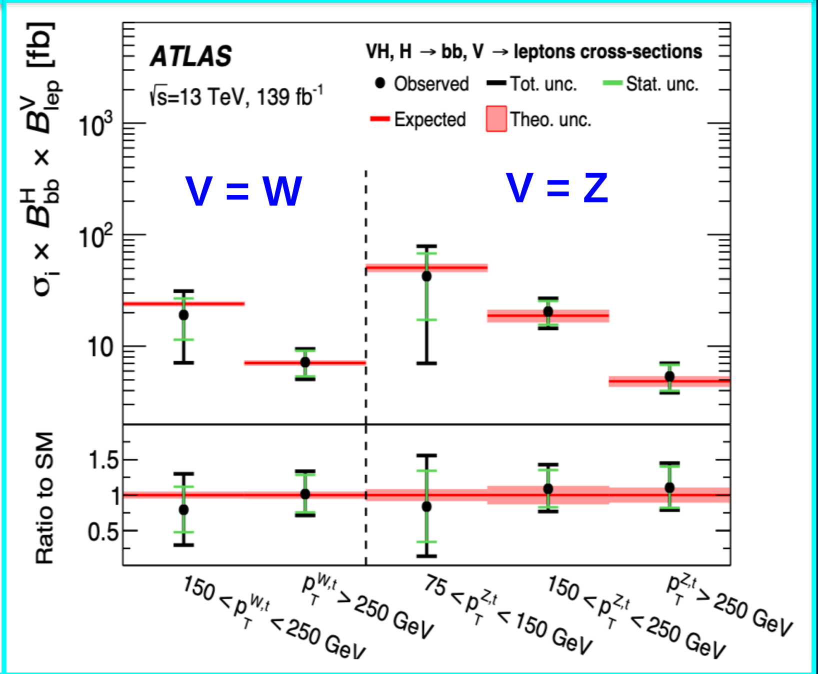
Boosted analysis:
Phys. Lett. B 816 (2021) 136204
small-R jets analysis:
Eur. Phys. J. C 81 (2021) 178

Boosted Higgs analysis





Small-R Jets analysis



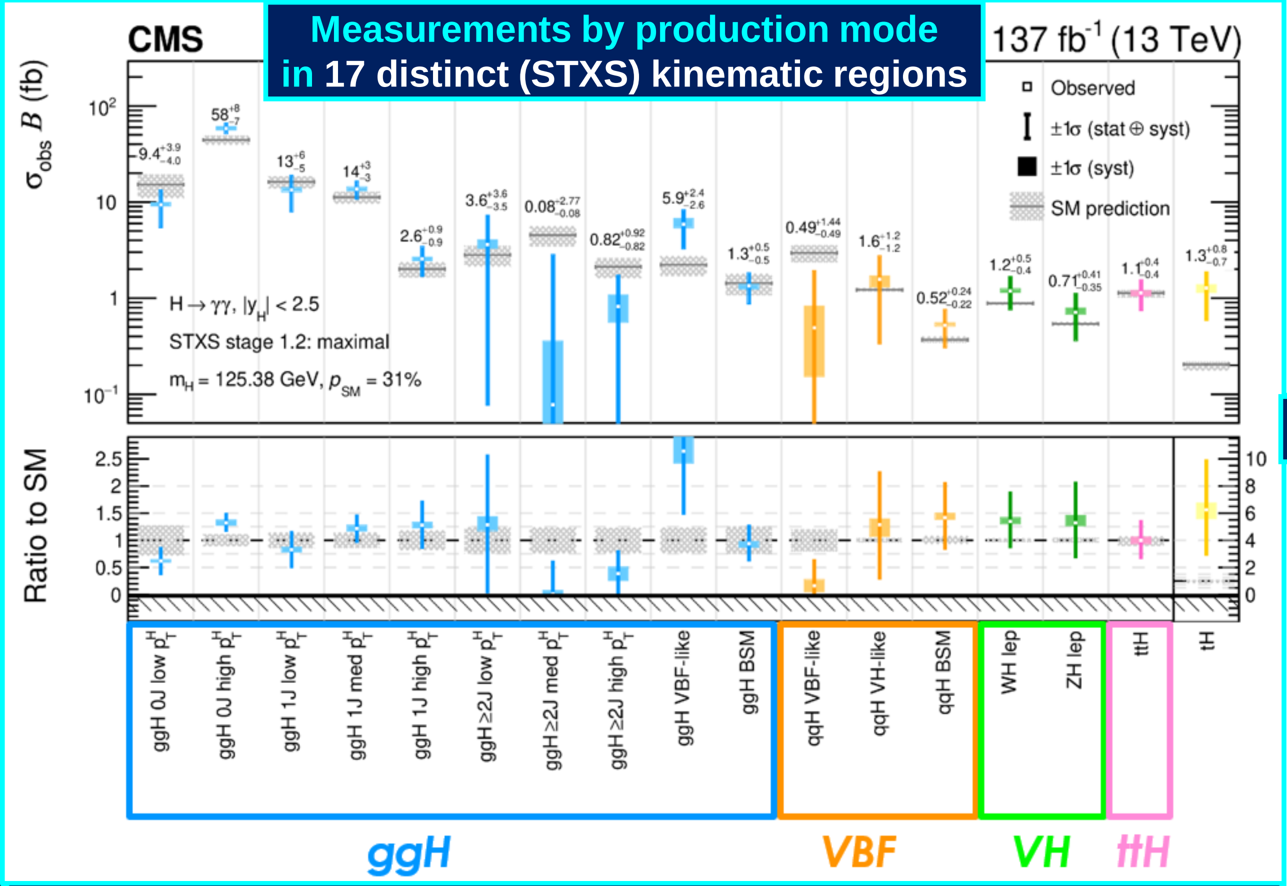
H → γγ and STXS

Full Run2 137/fb

CMS-HIG-19-0015
Submitted to JHEP

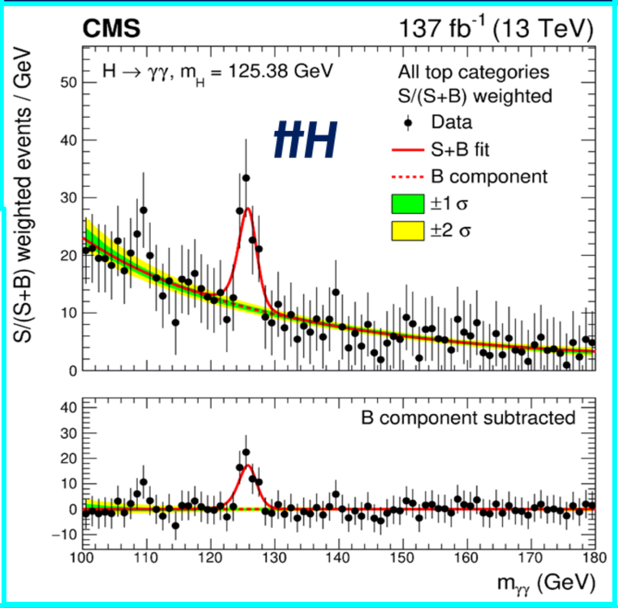
Clear H → γγ signals in all 4 main production modes: ggH, VBF, VH, ttH including 5.2σ in ttH, and strong evidence 4.7σ in multilepton final states

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

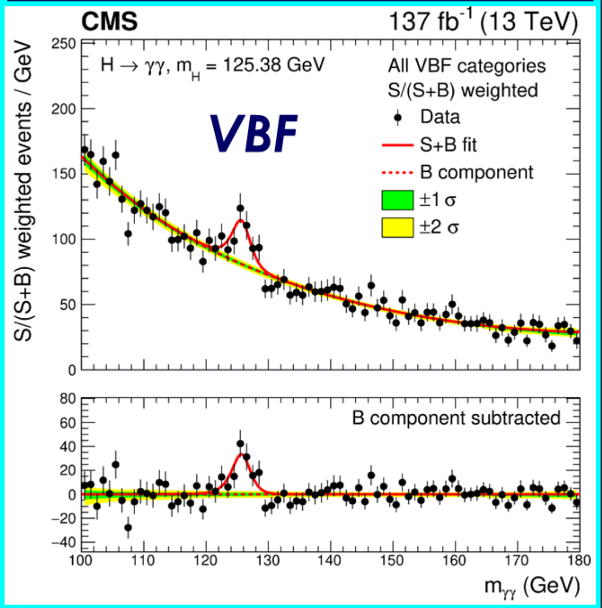


μ (pp→ H → γγ) = 1.12 ± 0.09

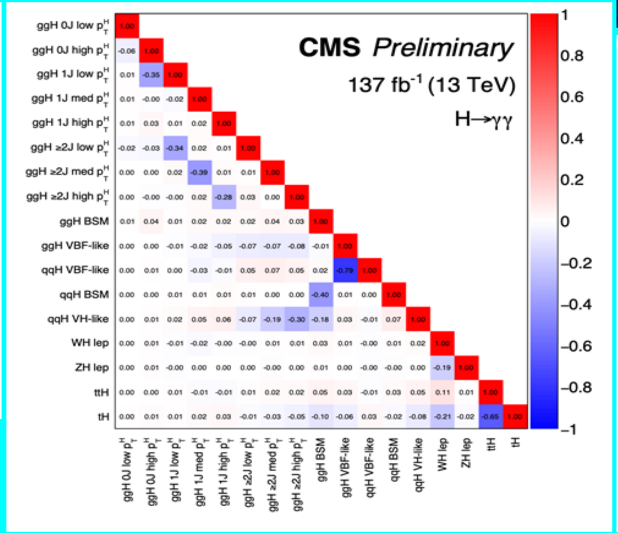
All Top Categories



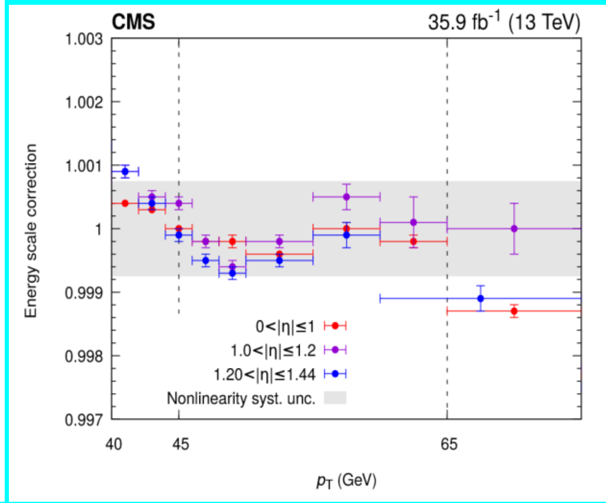
All VBF Categories



Bins Largely Uncorrelated



Photon Energy Scale Correction vs p_T



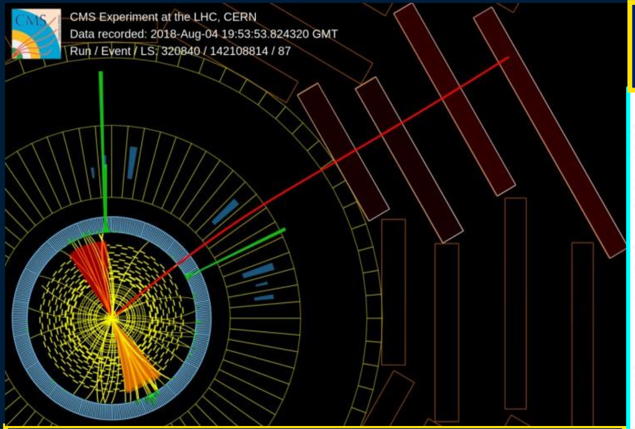
ttH and tH Production

Multilepton Final States (e, μ, τ_h)

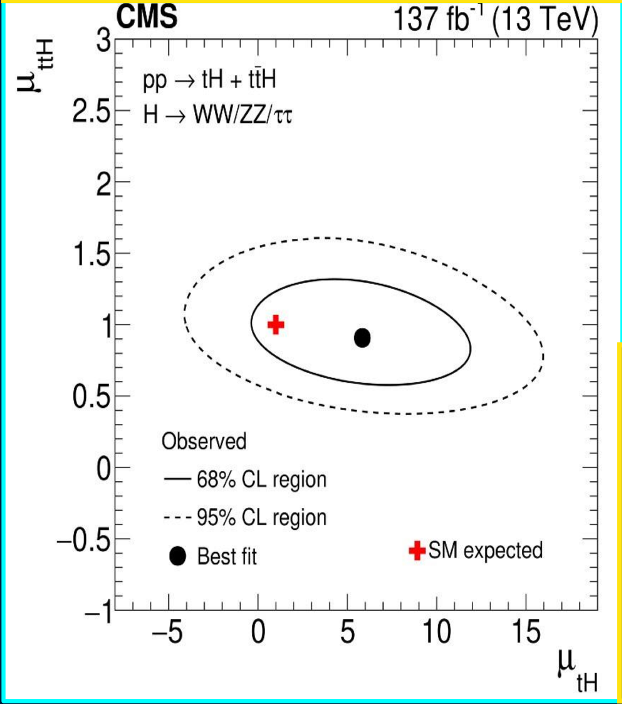
Full Run2 137/fb

Eur. Phys. J. C 81 (2021) 378

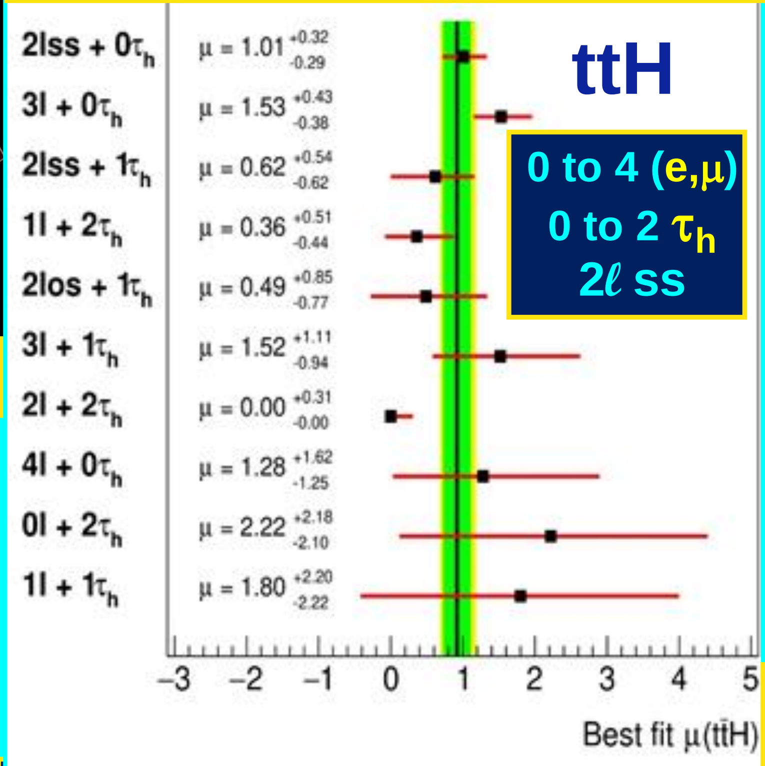
Mostly H → WW, ZZ, ττ



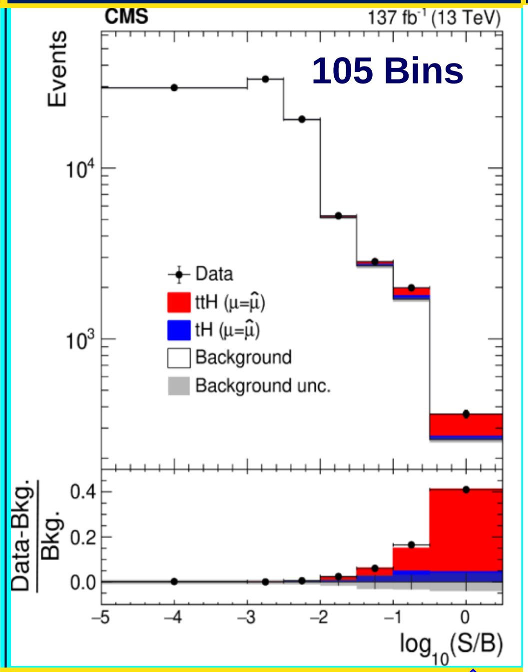
μ (ttH) vs μ(tH)



ttH Signal Strengths: 10 Categories

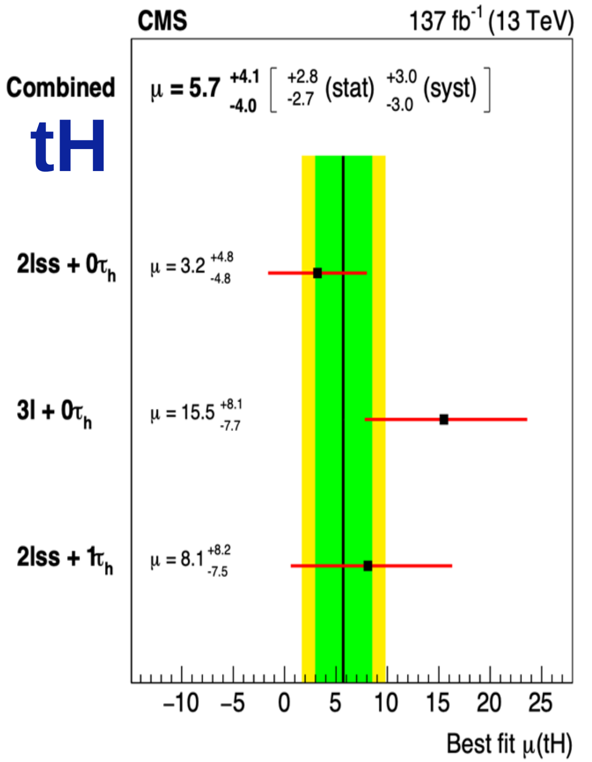


ttH, tH Signals + bkgd



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)

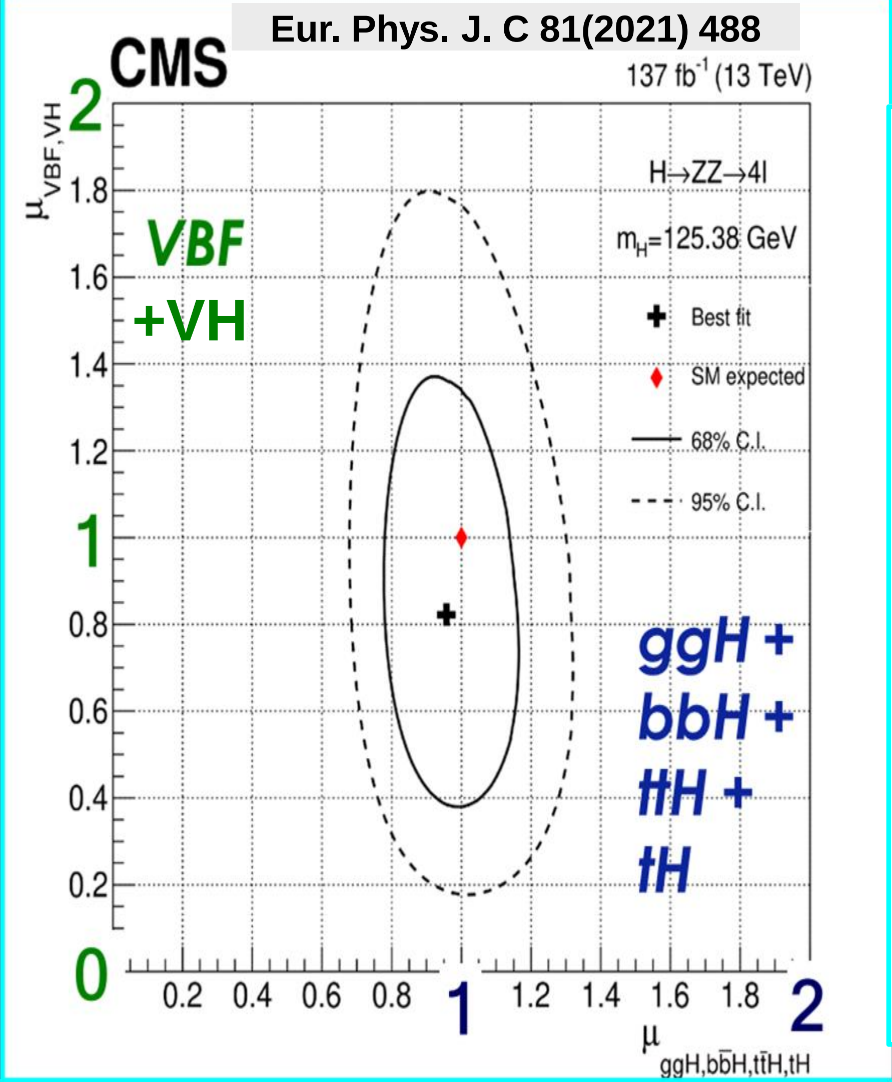
tH Measured (exp) Significance: 1.4σ (0.3σ)

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

H → ZZ* → 4ℓ and STXS

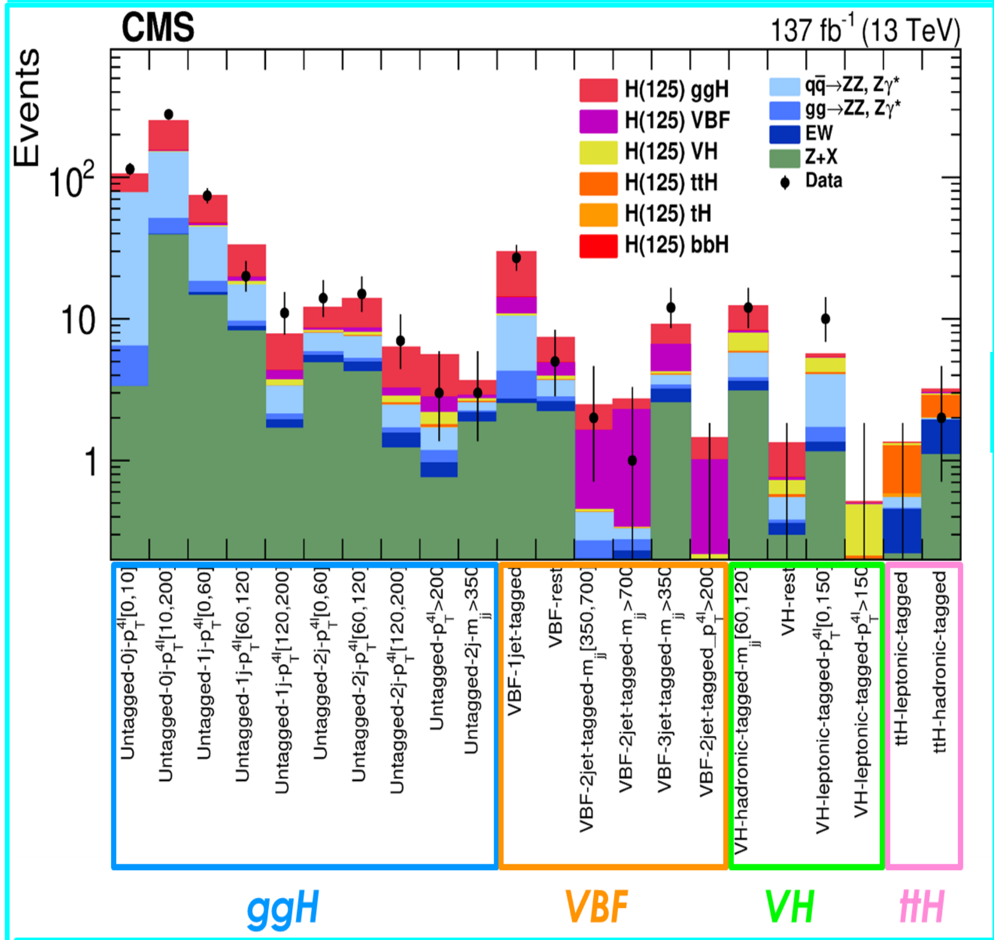
Full Run2 137/fb

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



μ (pp→ H → 4ℓ) = 0.94 ±0.07(stat) $^{+0.09}_{-0.08}$(sys)

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

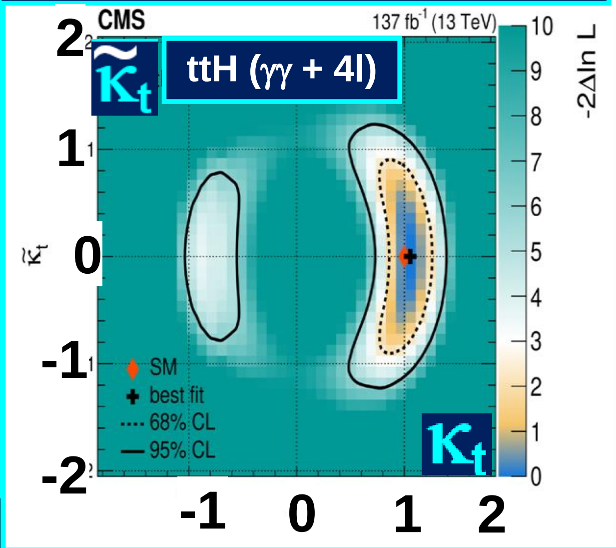


$$\sigma_{fid}(4\ell) = 2.84^{+0.23}_{-0.22}(\text{stat})^{+0.26}_{-0.21}(\text{syst})\ \text{fb}$$

SM: 2.84 ±0.15 fb

+ Comprehensive Study of ttH CP structure and anomalous CP couplings Combining H→ 4ℓ & H → γγ

$\tilde{\kappa}_t$ vs κ_t



CMS-HIG-19-009

Submitted to PRD

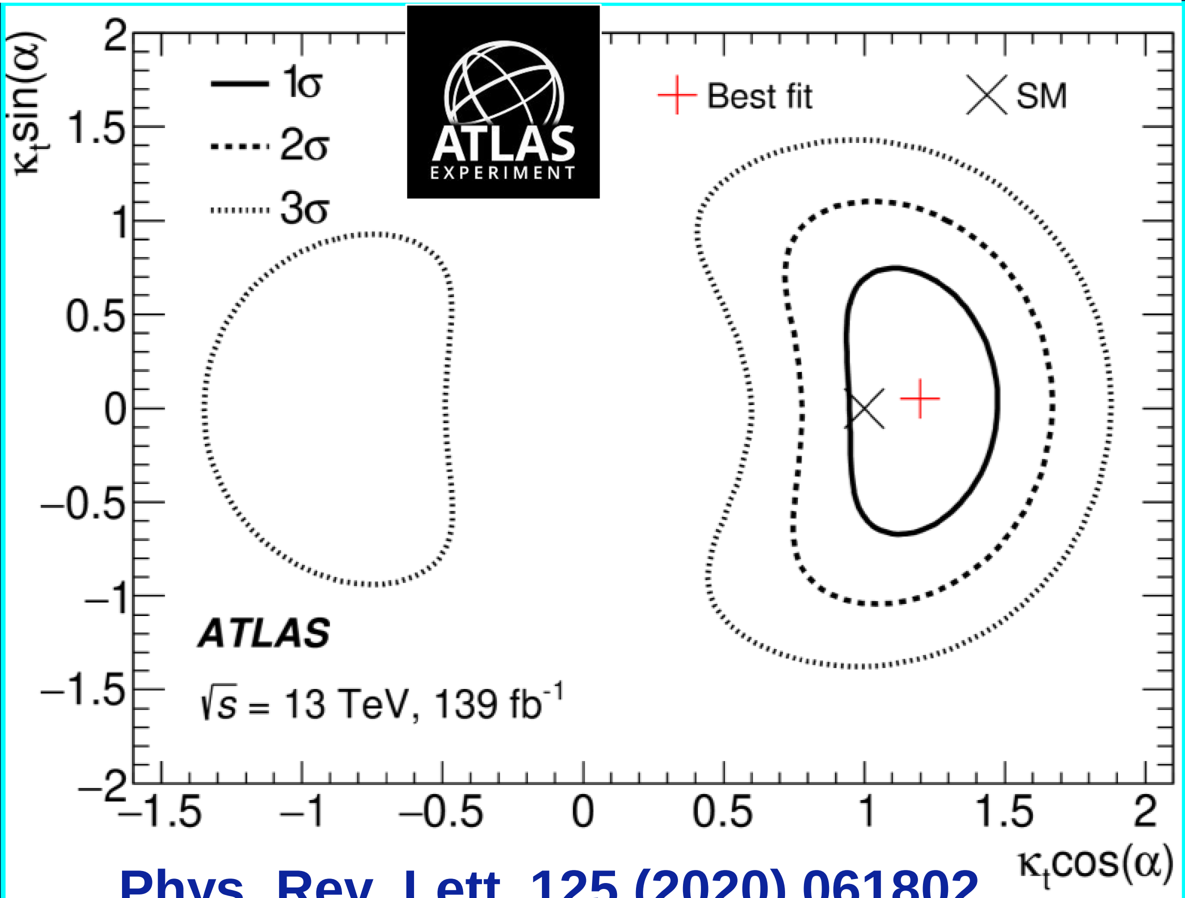
Also see Gritsan et al. Phys. Rev. D 94, 055023

Higgs Boson CP Studies

CP Structure of the Higgs to τ Yukawa Coupling

- In the SM, the Higgs boson has quantum numbers $J^{CP} = 0^{++}$
- Run 1: spin-0 nature established, CP structure explored in Higgs-boson couplings
- Recent Run 2 results on CP structure:
  - Higgs-fermion couplings probed in First direct measurement
    (1) $H \to \tau\tau$ decay and
    (2) ttH production using the $H \to \gamma\gamma$ decay channel
  - CP structure in Higgs-boson couplings probed in $H \to ZZ^* \to 4l$ channel

CP Properties in ttH and tH, $H \to \gamma\gamma$



Phys. Rev. Lett. 125 (2020) 061802

ggF and $H \to \gamma\gamma$ constrained by the Higgs boson coupling combination

CP-mixing angle $|\alpha| < 43°$ @95% CL
pure CP-odd excluded at 3.9σ

$H \to \tau\tau$: 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

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

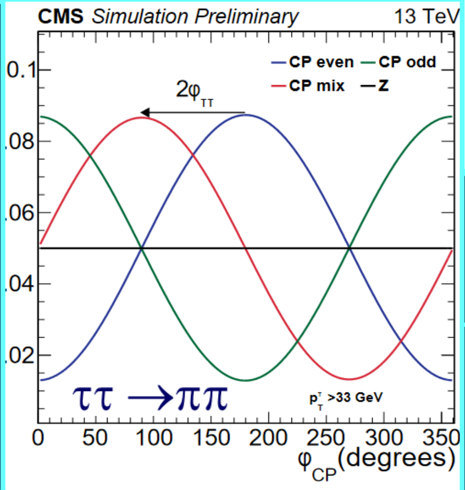
Define mixing angle ϕ where

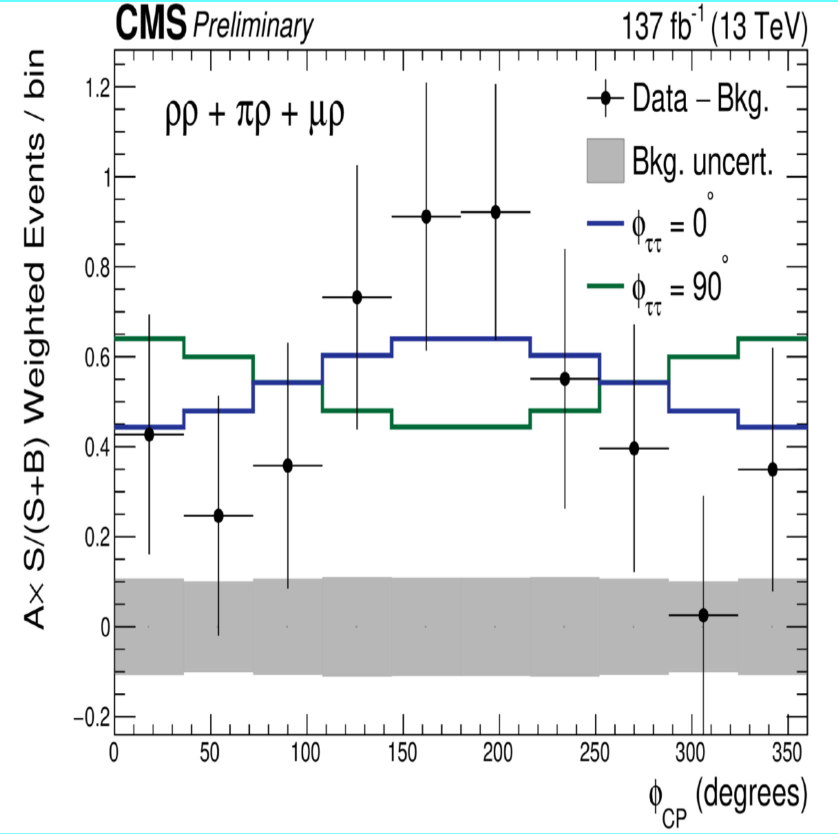
$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau \ \text{CP-odd coupling}}{\kappa_\tau \ \text{CP-even coupling}}$$

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 or π^0 vectors in the Higgs rest frame

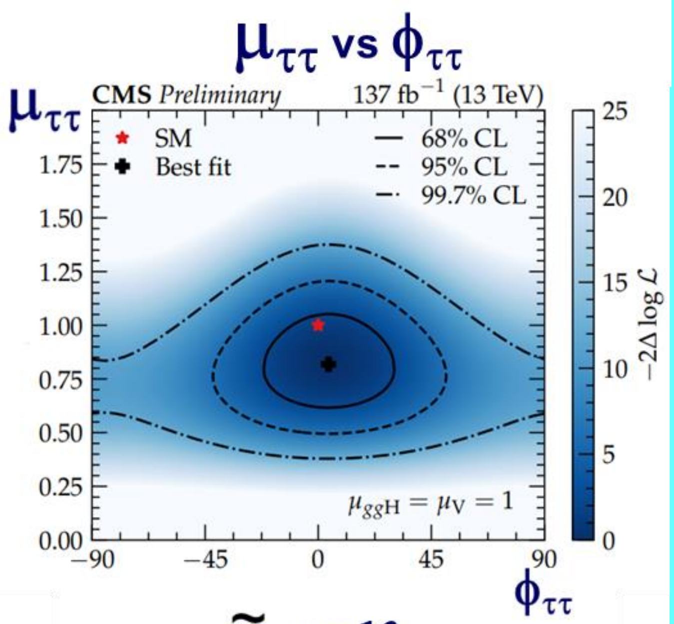


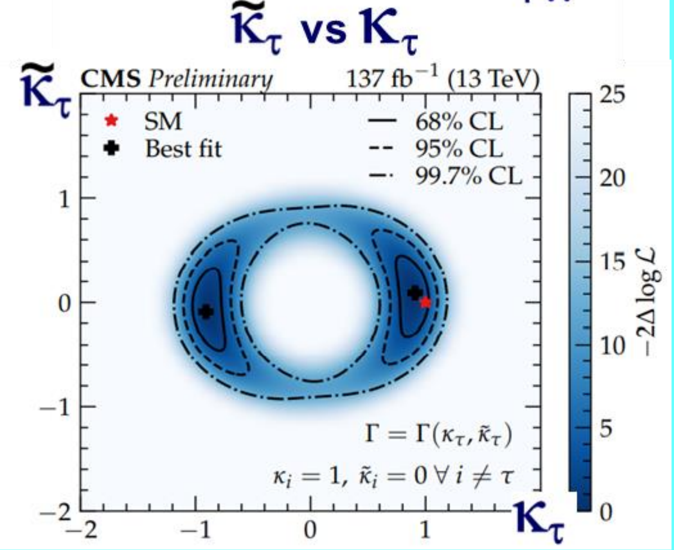


CP-mixing angle

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

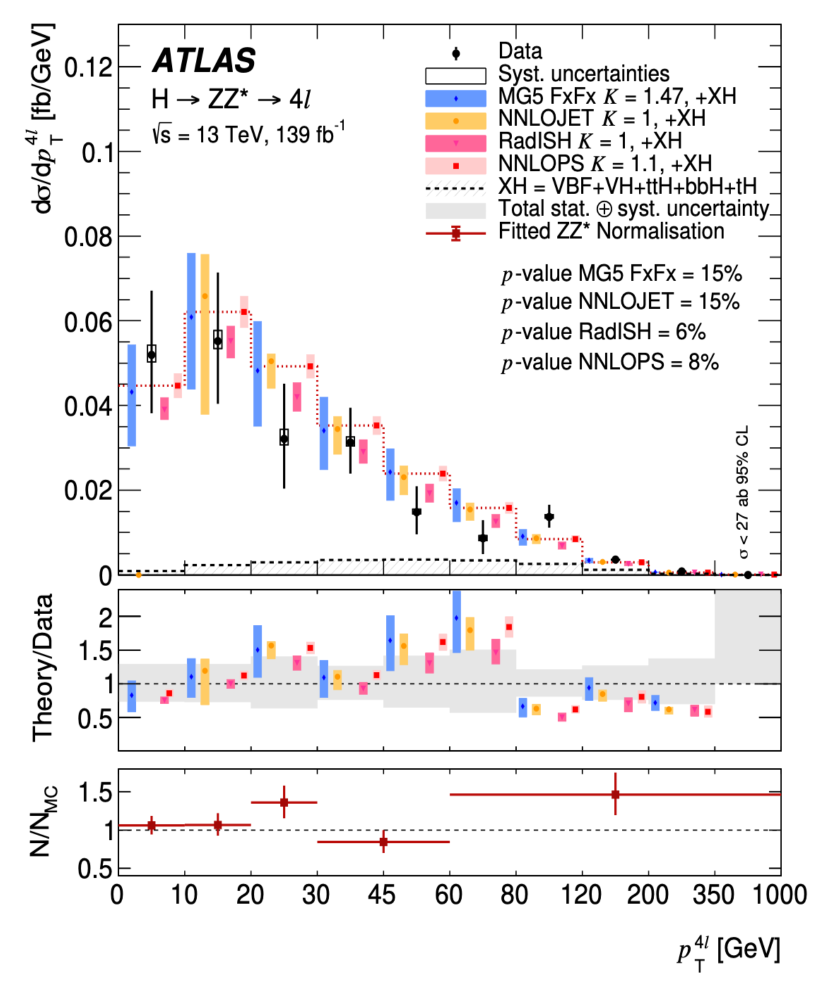
3.2σ exclusion of pure CP odd





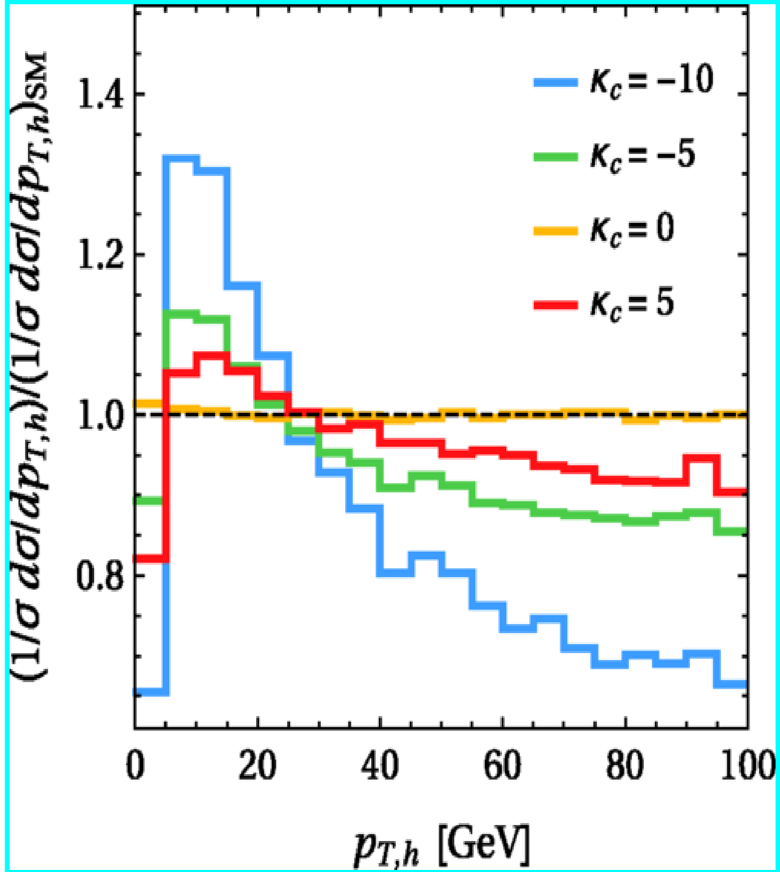
Higgs Boson Differential Measurements H → ZZ* → 4ℓ

Higgs p_T sensitive to many BSM effects: physics in the ggH loops, perturbative QCD calculations, Higgs couplings to charm and bottom quarks, …



Eur. Phys. J. C 80 (2020) 942

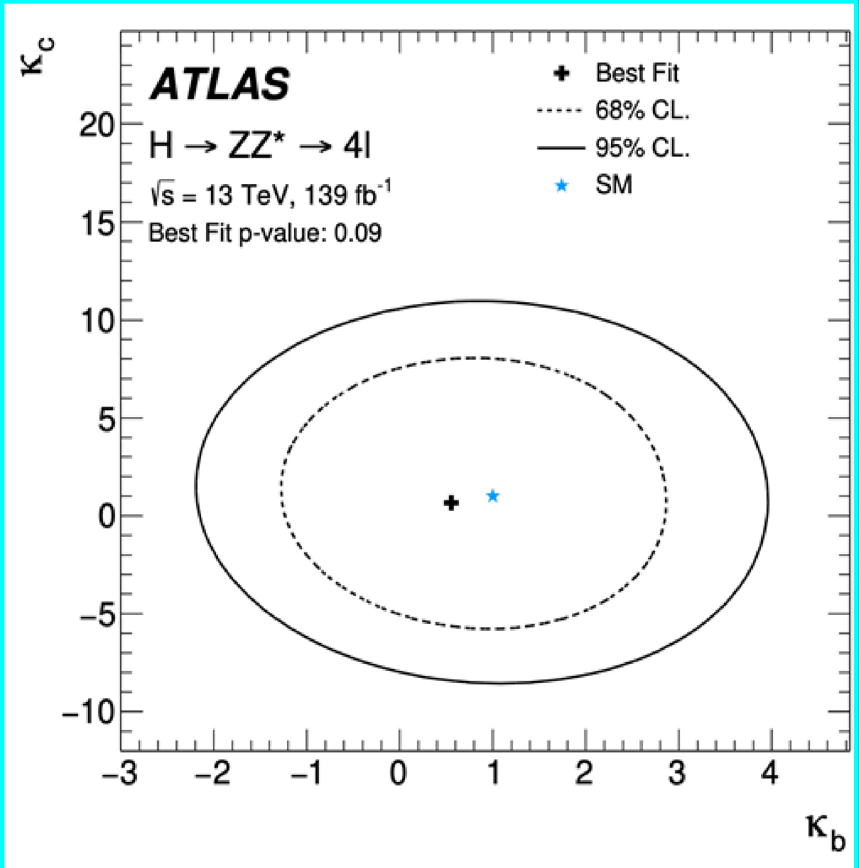
Variations in p_T(H) with charm quark coupling strength κ_c



Phys. Rev. Lett. 118 (2017) 121801

κ_c vs κ_b

Constraint from p_T(H) shape



Full Run2 139/fb

H → bb Differential Measurements

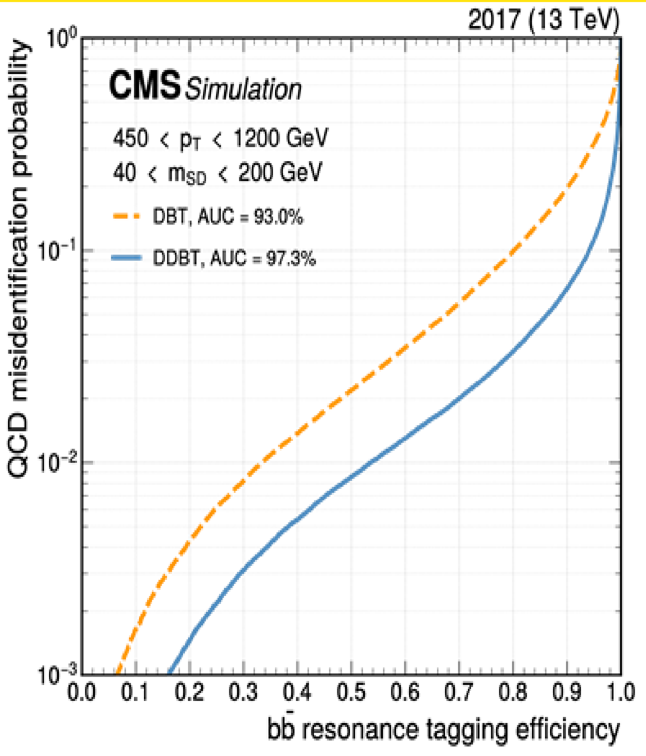
Full Run2 137/fb

JHEP 12 (2020) 085

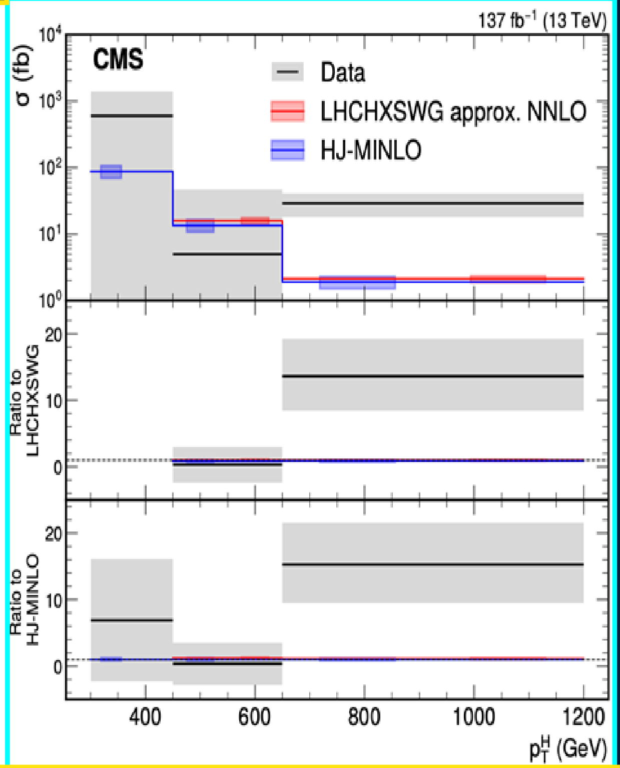
Higgs p_T sensitive to many BSM effects; theory to higher order

- **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**

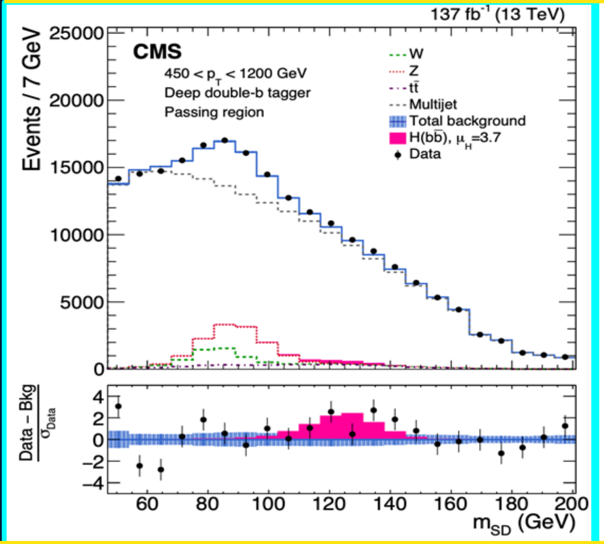
Deep double b Tagger
misID rate vs efficiency



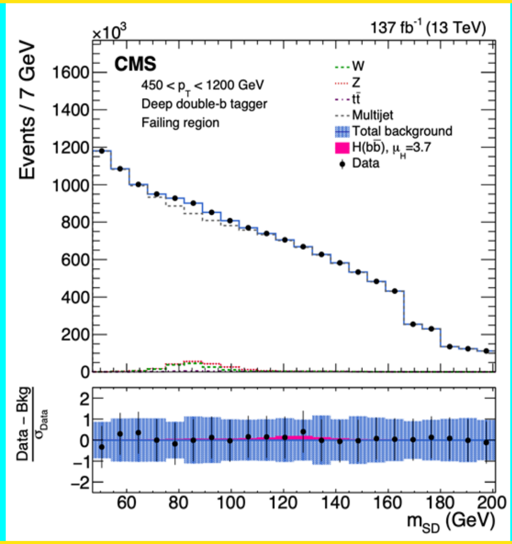
Unfolded differential cross section in $p_T(H)$



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



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



Observed (exp) Significance: 2.5σ (0.7σ)
Signal strength and local significance vs SM:

$$\mu_H = 3.7 \pm 1.2\,(\text{stat})\ ^{+0.8}_{-0.7}\,(\text{syst})\ ^{+0.8}_{-0.5}\,(\text{theo});\ 1.9\sigma$$

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)

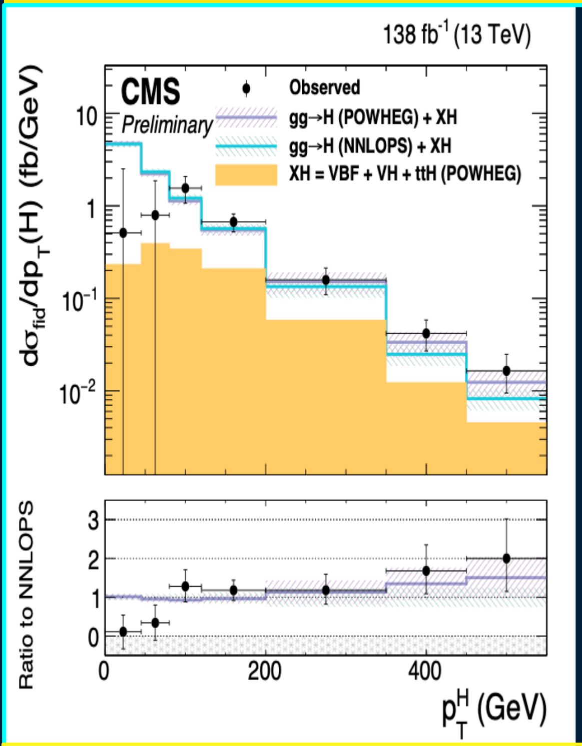
Higgs Boson Differential Measurements

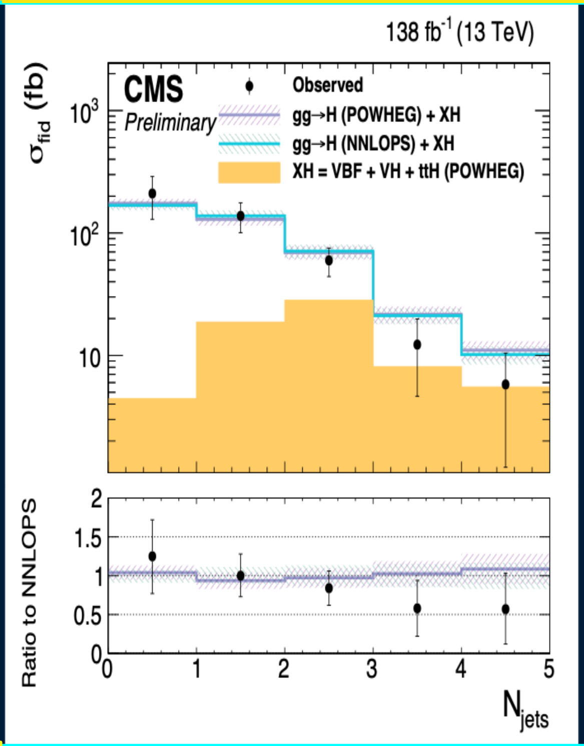
Full Run2

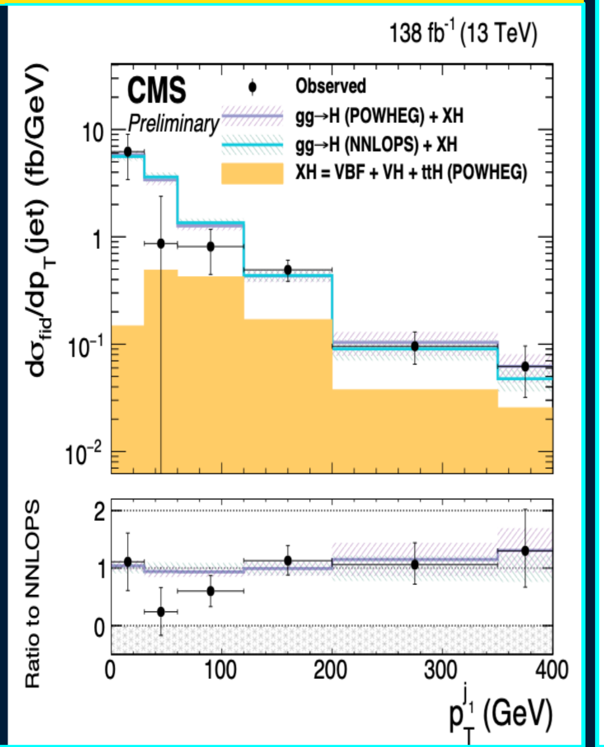
Comparing to other final state measurements (4ℓ, $\gamma\gamma$, $\tau\tau$) brings significant improvements:
exploring the phase space of large jet multiplicities and/or Lorentz-boosted Higgs bosons (to NNLO)

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

ggF H and XH $d\sigma/dp_T$	ggF H and XH $d\sigma/dN_{jets}$	ggF H and XH $d\sigma/dp_T^{j1}$





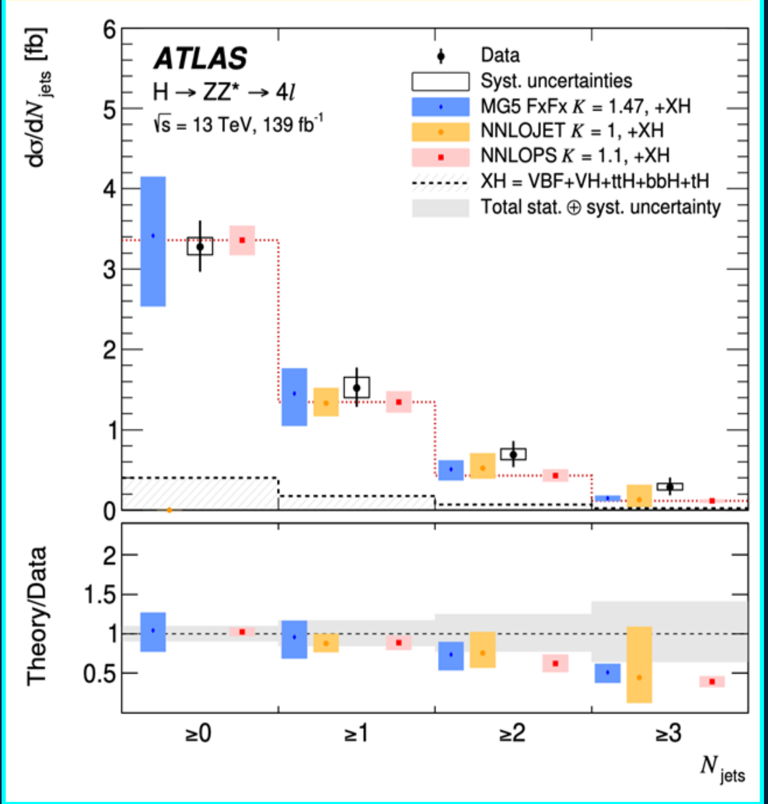


XH = VBF + VH + ttH

CMS-PAS-HIG-20-015

ATLAS: $H\rightarrow ZZ\rightarrow 4\ell$

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



Eur. Phys. J. C (2020) 80:942

High P_T Higgs Production with $H \rightarrow bb$:

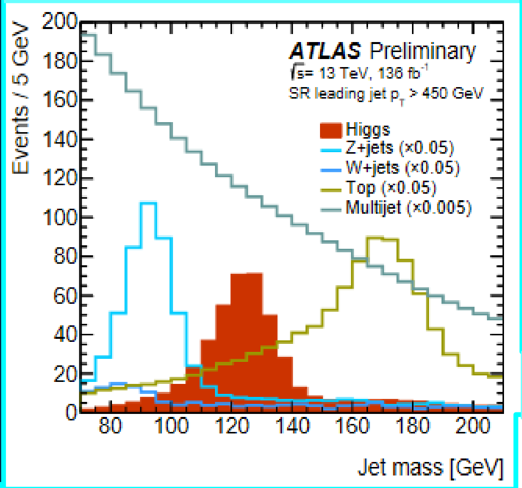
Leading and Subleading double tagged jets

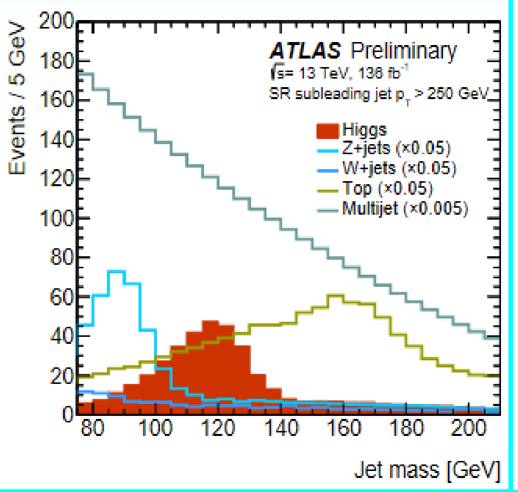
Full Run2 139/fb

ATLAS CONF-2021-010

NB: With TeV scale p_T, the ggF, VBF and VH contributions to H production are comparable

Leading & subleading jet mass for H, Z, t, QCD

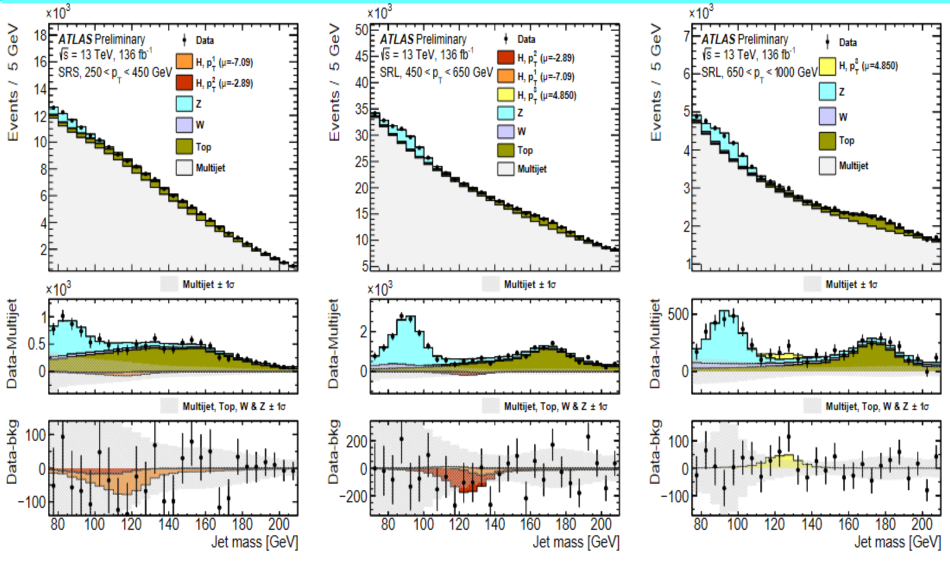




Inclusive, Fiducial and Differential Signal Regions

Region	Jet p_T [GeV] SRL	Jet p_T [GeV] SRS	p_T^H [GeV] SRL	p_T^H [GeV] SRS	$\lvert\eta_H\rvert$ SRL/SRS
Inclusive	>450	>250	–	–	–
Fiducial	>450 >1000	>450 –	>450 >1000	>450 –	< 2 < 2
Differential	450–650, 650–1000	250–450, 450–650, 650–1000	450–650, >650	300–450, 450–650, >650	< 2

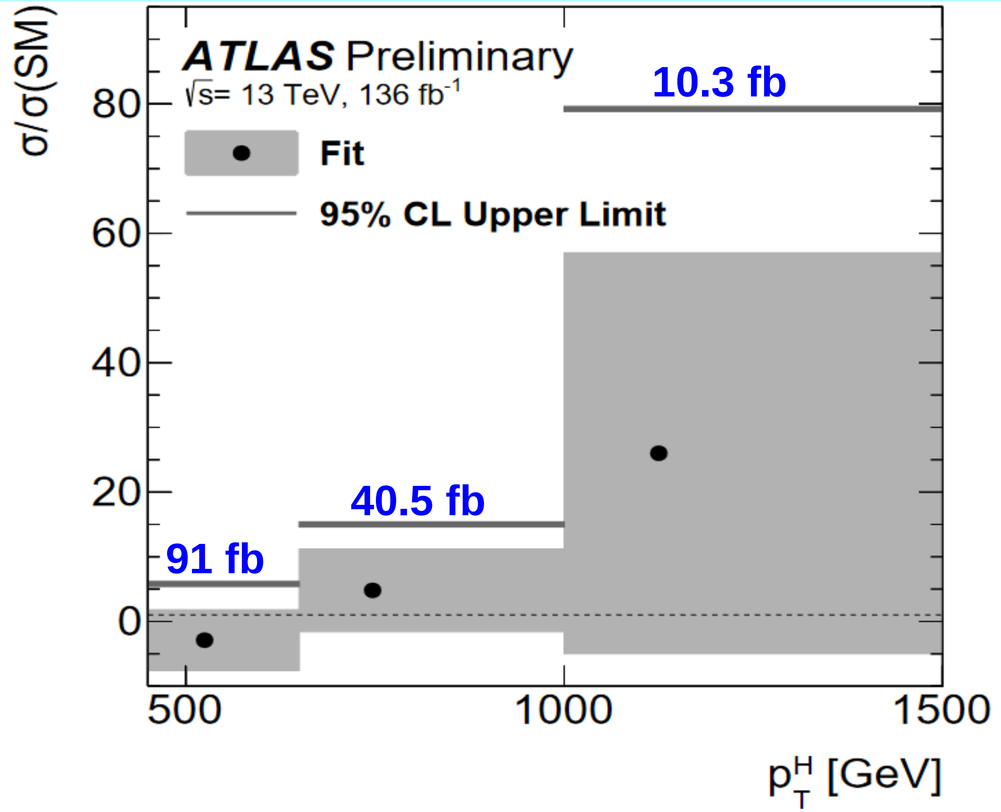
Post Fit Multijet, t, W and Z Jet Mass Distributions



Fitted σ_H Values in 3 P_T Bins

$$\sigma_H(p_T^H > 450\ \text{GeV}) = 13 \pm 57\ (\text{stat.}) \pm 22\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb},$$
$$\sigma_H(p_T^H > 650\ \text{GeV}) = 13 \pm 16\ (\text{stat.}) \pm 7\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb},$$
$$\sigma_H(p_T^H > 1\ \text{TeV}) = 3.4 \pm 3.9\ (\text{stat.}) \pm 1.0\ (\text{syst.}) \pm 0.8\ (\text{theory})\ \text{fb}.$$

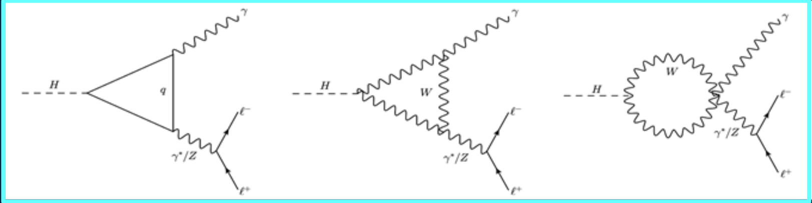
Fitted σ/σ_{SM} Values & 95% CL Upper Limits in 3 P_T Bins



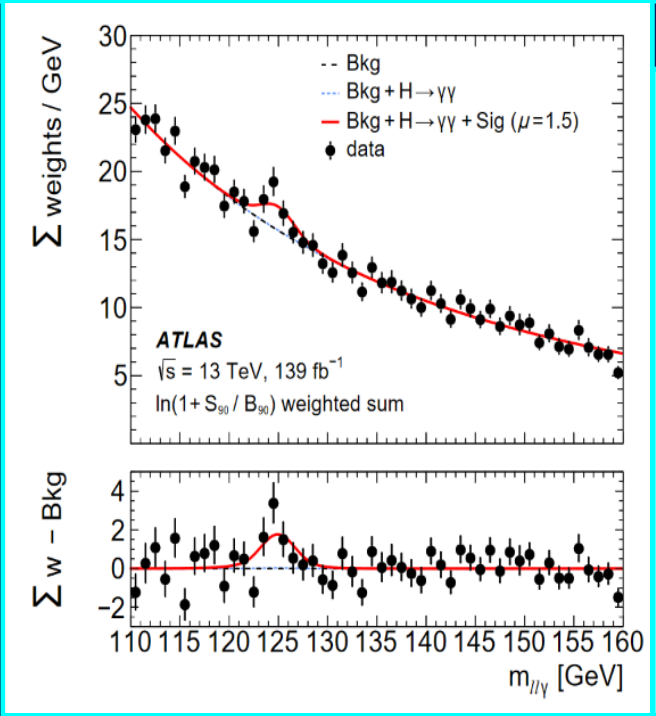
Evidence for Rare Decay H → $\ell\ell\gamma$

Phys. Lett. B 819 (2021) 136412

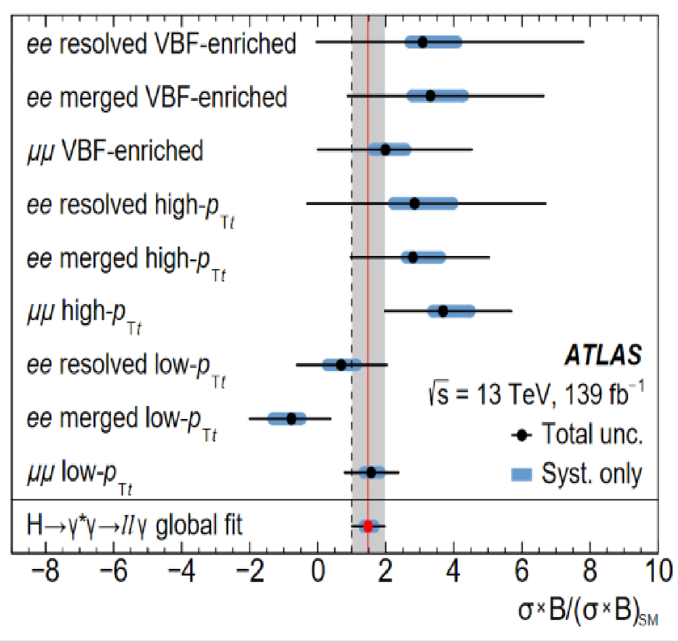
- Rare decay process **H → $\ell\ell\gamma$** ($m_{\ell\ell}$ < 30 GeV) probes exotic couplings and CP-violation in the Higgs sector



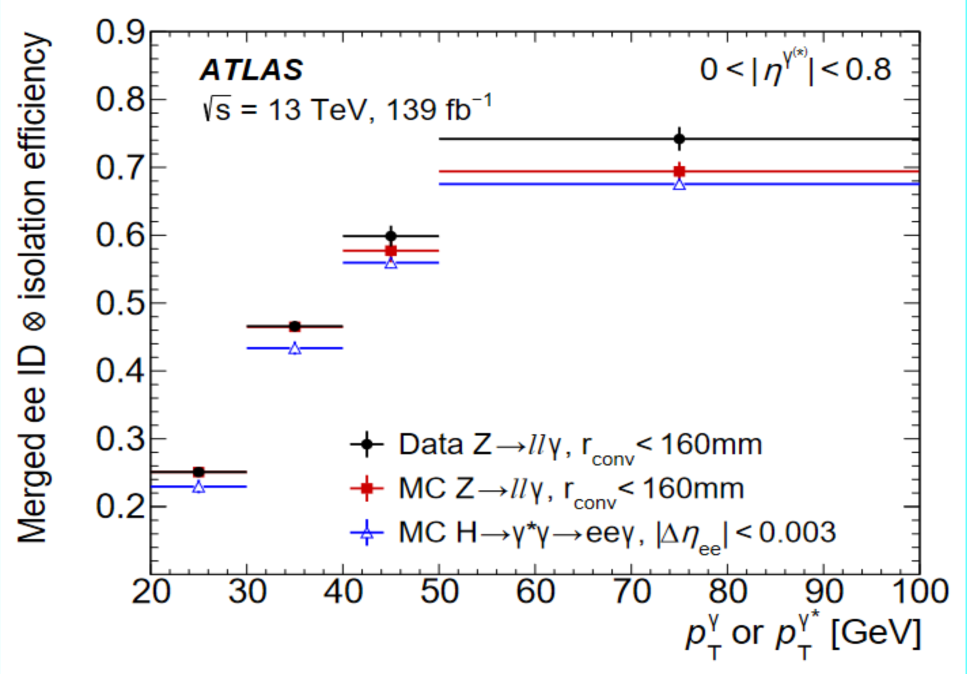
- Lepton pair is often very collimated: developed methods to reconstruct merged-ee objects
- Signal significance **3.2σ (2.1σ)** obs (exp)

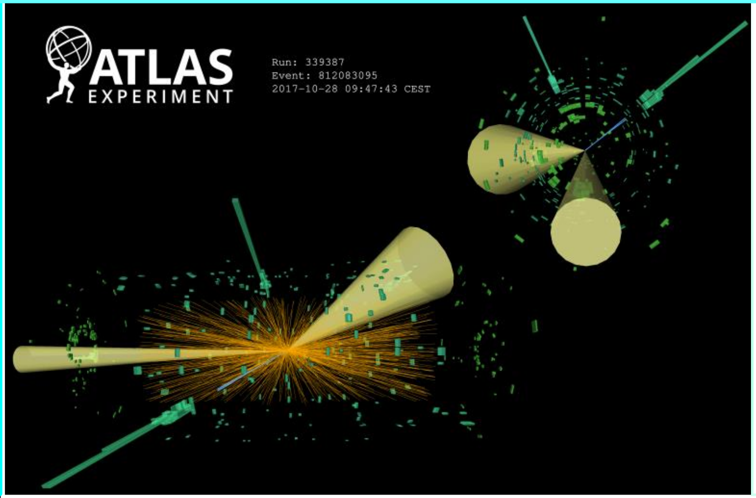


Signal strength μ = 1.5 ± 0.5



Merged ee ID X efficiency vs p_T^{γ}





Event display of a candidate H → eeγ event from ee-merged VBF-enriched category

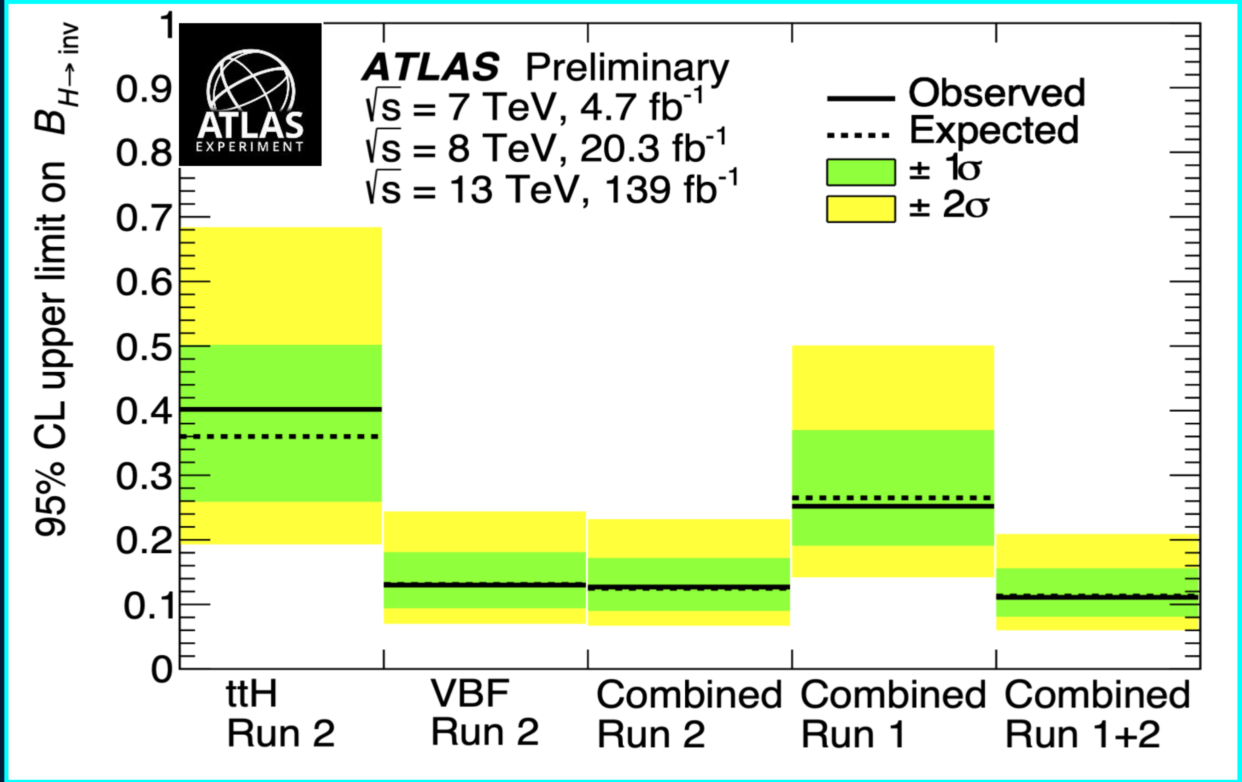
BSM Higgs: H → Invisible

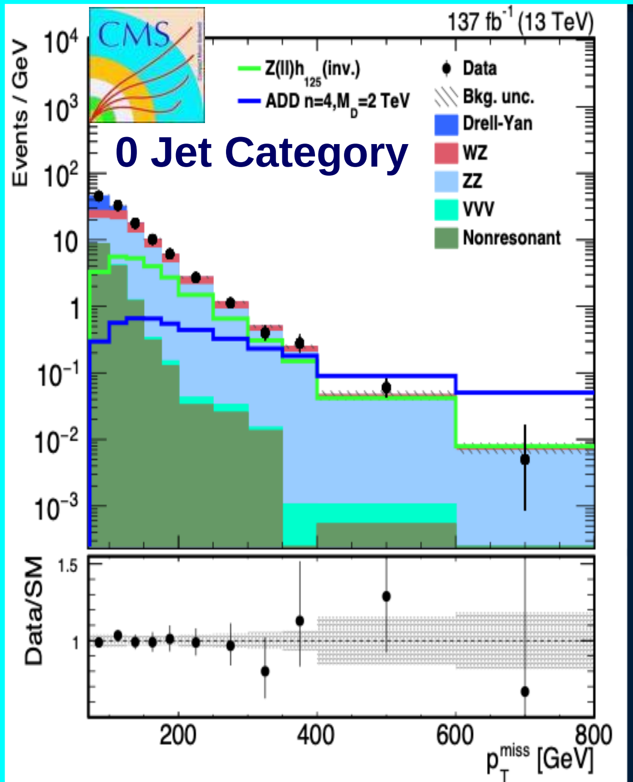
ATLAS Run 1, 2 combination: ATLAS-CONF-2020-052

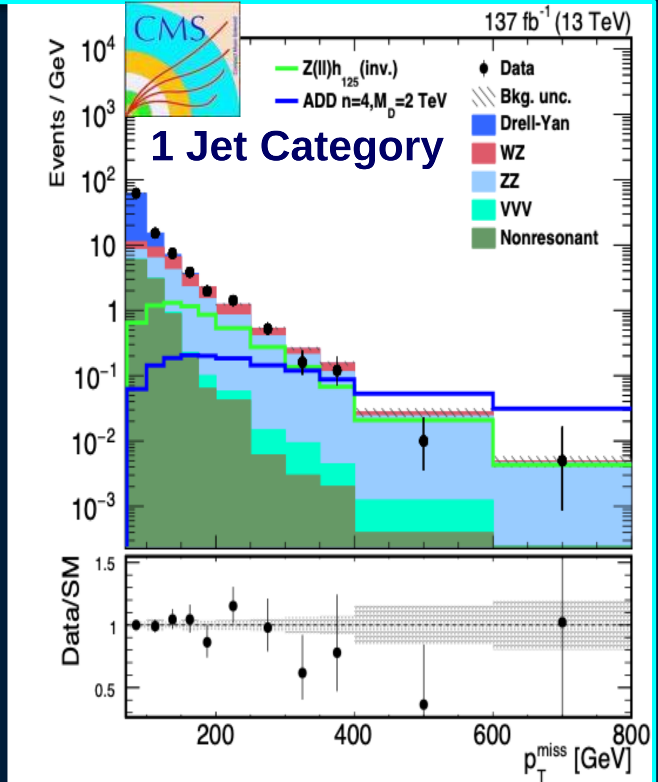
CMS Z(ℓℓ) H, full Run 2 result: Eur. Phys. J. C 81 (2021) 13

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

- **Higgs portal to dark matter and invisible particles in BSM models**
- **SM prediction: BR(H→invisible) = 1×10^{-3} from H→ZZ*→4ν decays**







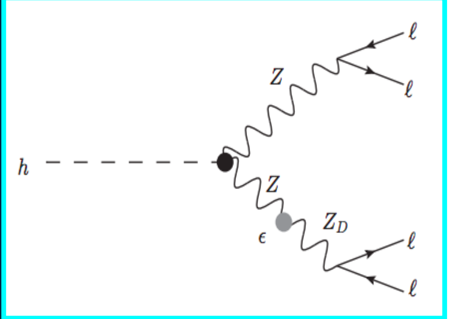
Observed upper limit from combination of VBF and ttH, H→invisible: BR(H→invisible) < 11% @95% CL

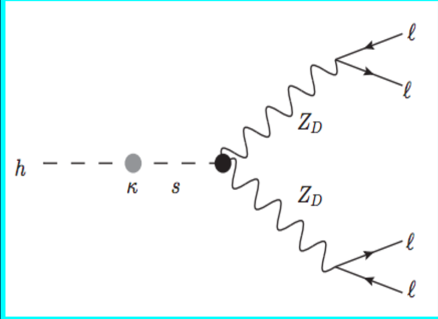
Observed upper limit from Z (ℓℓ) H, H→invisible: BR(H→invisible) < 29% @95% CL

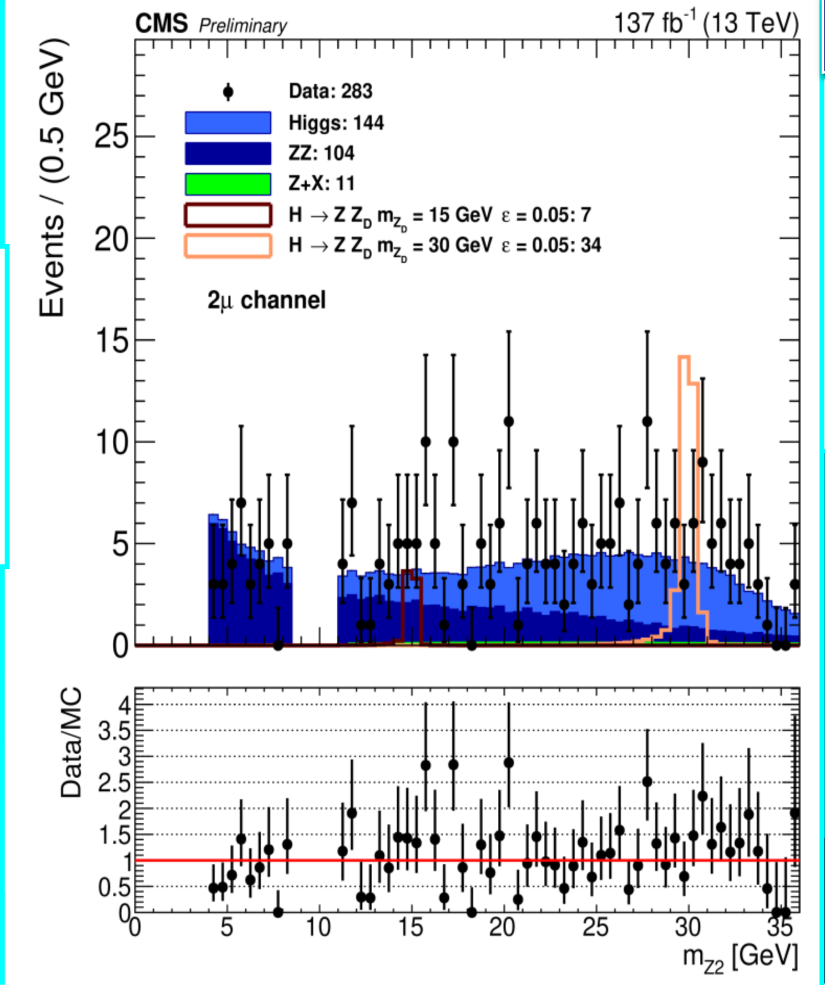
Recent BSM Higgs Search Results

Search for a Dark Photon and an Axion-like particle $H \to ZZ \to ZZ_D$, $H \to S \to Z_D Z_D$

Search for $H \to ZZ_D, Z_D Z_D$ in the four lepton channel



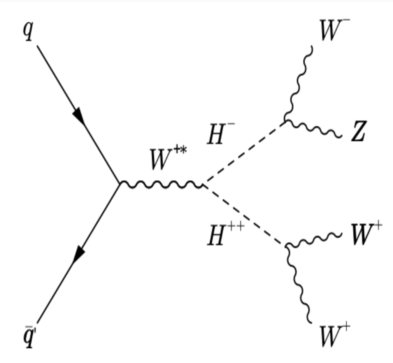


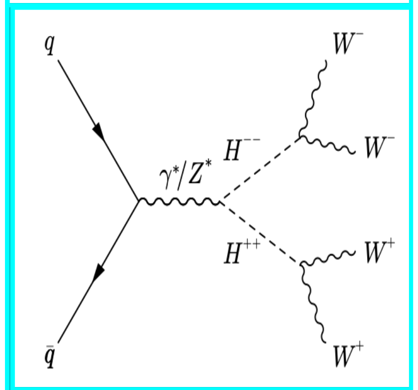


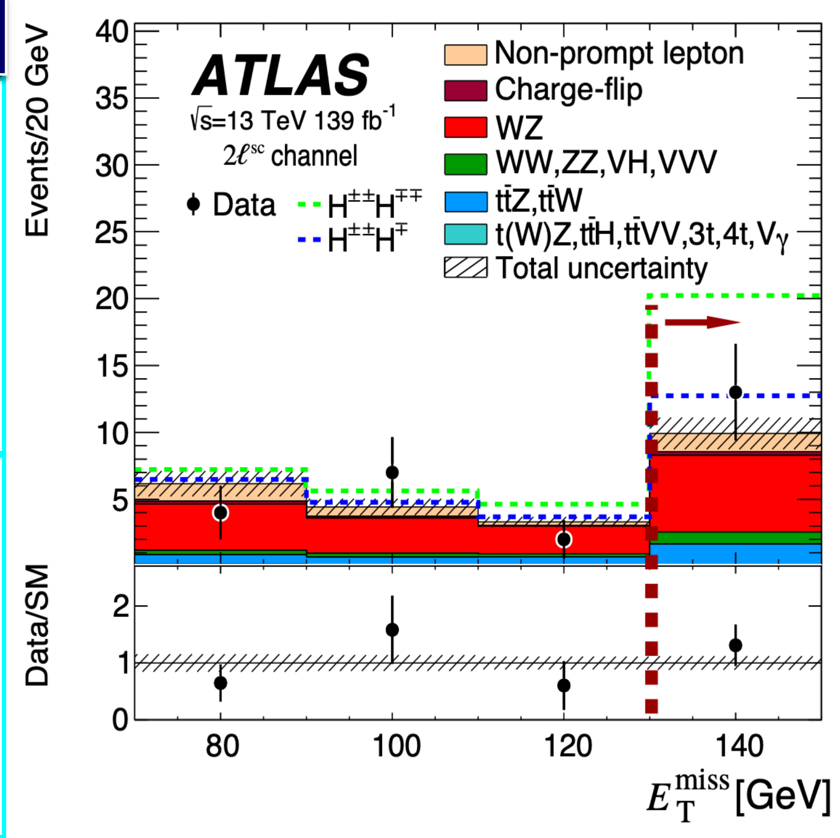
CMS-PAS-HIG-19-007

Search for Doubly Charged Higgs H^{++}, H^{--}

In $W^{\pm}W^{\pm}$ + W V







m($H^{\pm\pm}$) excluded up to 350 and 230 GeV at 95% CL
for the pair and associated production modes

arXiv:2101.11961

Higgs Boson Self-Coupling: HH Searches

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

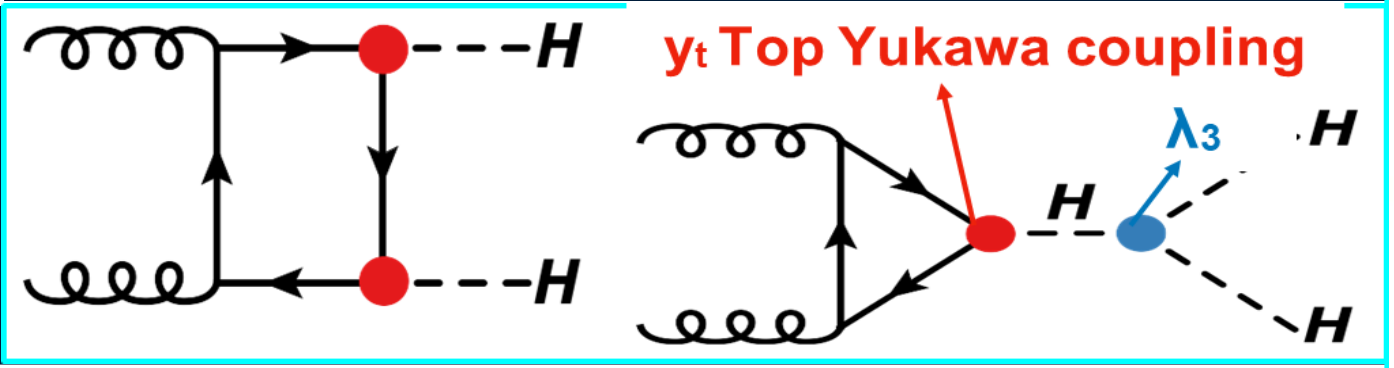
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

λ_3: Trilinear Higgs self-coupling

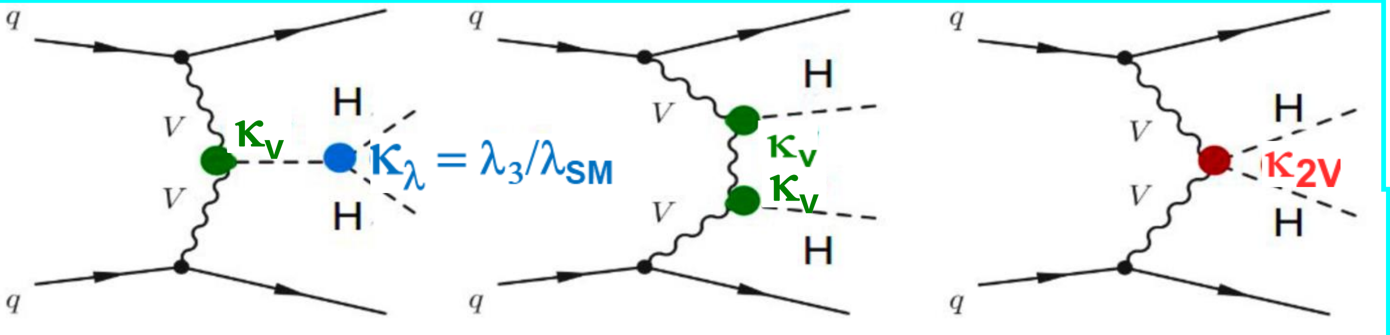
- λ_3 can be probed via HH production:
  extremely challenging at LHC, accessible at HL-LHC

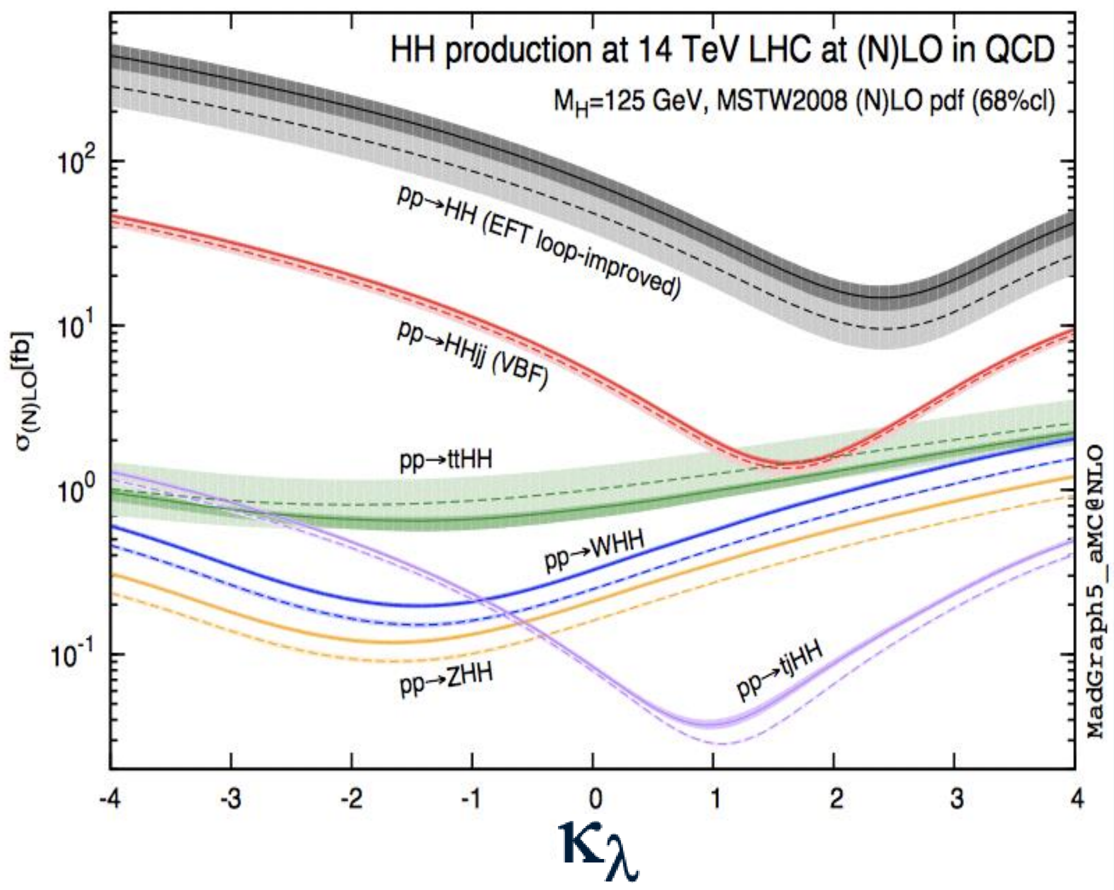
Data	λ_3/λ_{SM} 95%CL	$\sigma_{HH}/\sigma_{SM\,HH}$
ATLAS 2015+16	[-5.0, 12.0]	< 6.9
CMS 2016 data	[-11.8, 18.8]	< 22.2

Main production mode ggF ~31.05 fb @13 TeV NNLO$_{FTapprox}$



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



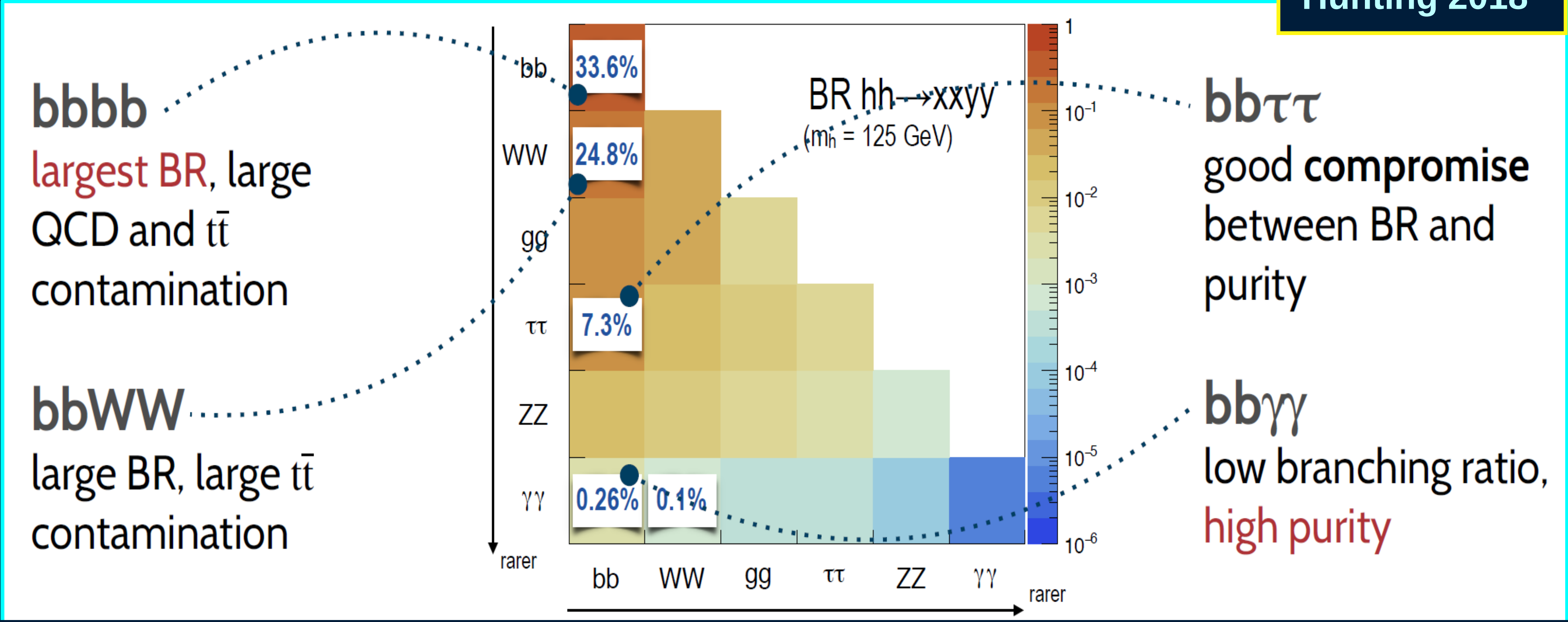


R.Frederix et al: Phys.Lett. B732 (2014) 142-149

HH Combination

- 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***

C. Amendola at Higgs Hunting 2018*



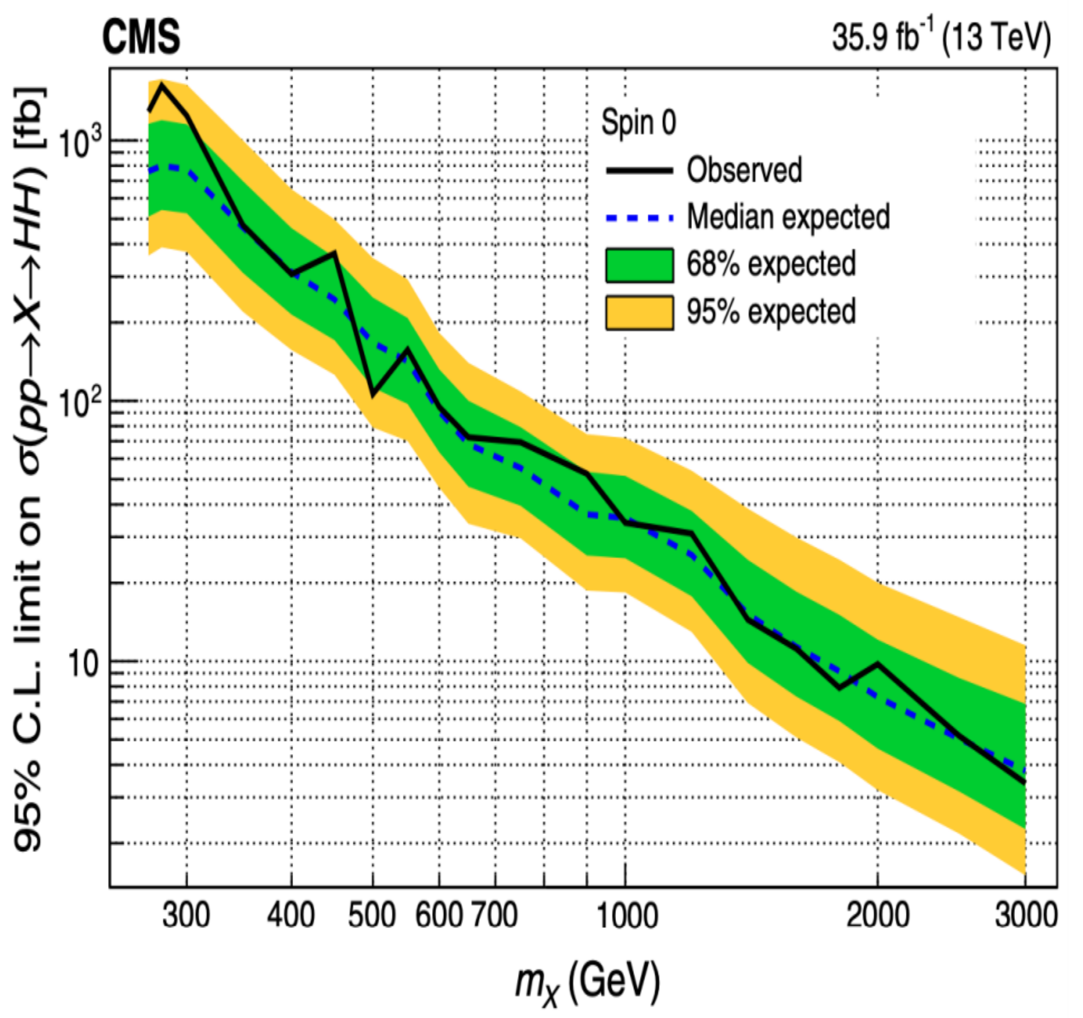
* https://indico.ijclab.in2p3.fr/event/4754/contributions/15561/subcontributions/1386/attachments/13213/15822/Amendola_HiggsHunting2018.pdf

Complementary roles of the dominant ggF and subdominant VBF production modes

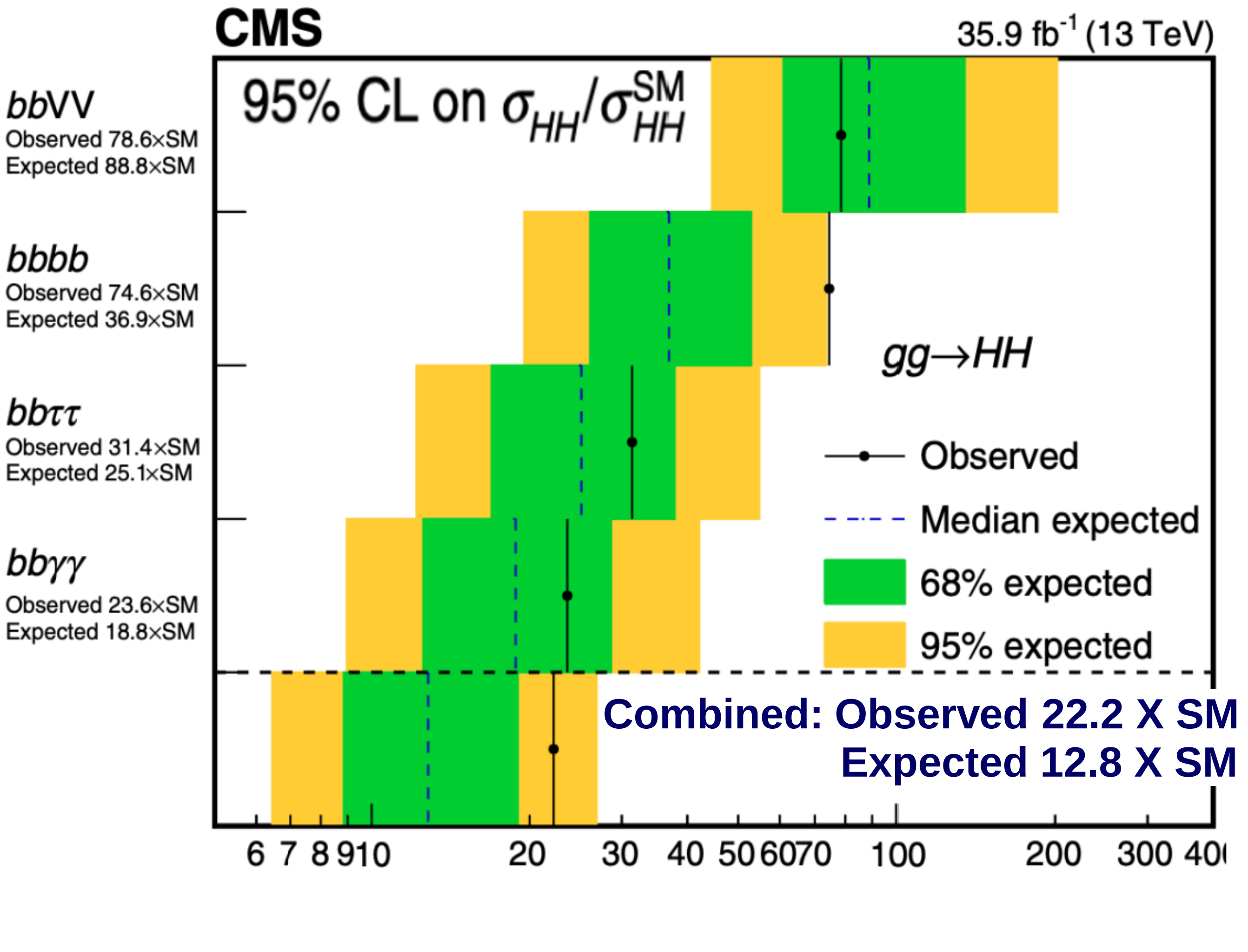
Inclusive HH Searches

PRL 122 (2019) 121803

Resonant Search
σ (pp → X → HH) vs m_X



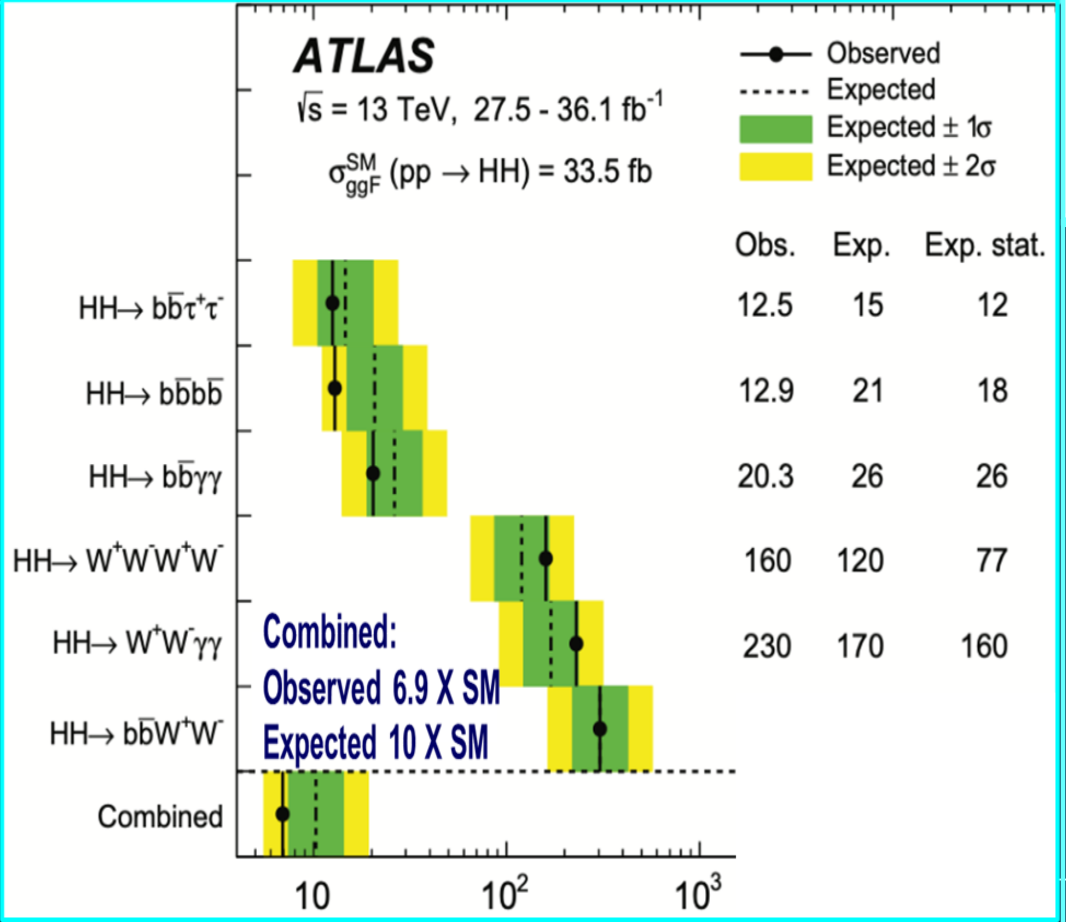
Nonresonant HH → bbVV, bbbb, bbττ, bbγγ, + Combination



Inclusive HH Searches

Phys. Lett. B 800 (2020) 135103

ggF: HH → bbWW, WWWW, WWγγ, bbbb, bbττ, bbγγ, + Combination
95% CL Upper Limit on σ(HH)/σ(HH_{SM})



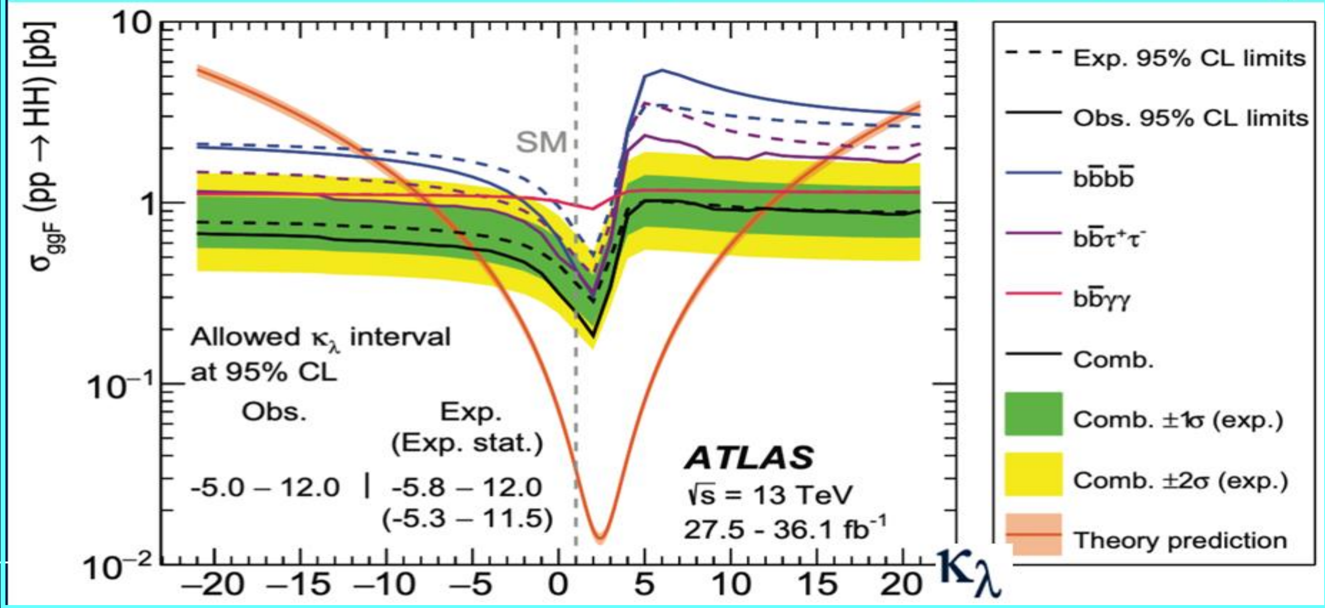
Resonant Searches X → HH Searches

	$b\bar{b}b\bar{b}$	$b\bar{b}W^+W^-$	$b\bar{b}\tau^+\tau^-$	$W^+W^-W^+W^-$	$b\bar{b}\gamma\gamma$	$W^+W^-\gamma\gamma$
$\mathcal{B}(HH \to x\bar{x}y\bar{y})$	0.34	0.25	0.073	0.046	$2.6 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$\mathcal{L}_{int}$ [fb^{-1}]	27.5 [36.1]	36.1	36.1	36.1	36.1	36.1
Categories	2 [2–5]	1 [1]	3 [2–3]	9 [9]	2 [2]	1 [1]
Discriminant	m_{HH} [m_{HH}]	c.e. [m_{HH}]	BDT [BDT]	c.e. [c.e.]	$m_{\gamma\gamma}$ [m_{HH}]	$m_{\gamma\gamma}$ [$m_{\gamma\gamma}$]
Model	NR [S/G]	NR [S/G]	NR [S/G]	NR [S]	NR [S]	NR [S]
$m_{S/G}$ [TeV]	[0.26–3.00]	[0.50–3.00]	[0.26–1.00]	[0.26–0.50]	[0.26–1.00]	[0.26–0.50]

c.e = counting events
NR = SM HH(non-resonant)
S/G = Scalar/Graviton

Allowed Mass Interval (TeV)

95% CL UL on σ(pp → HH) (pb) vs κ_λ



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

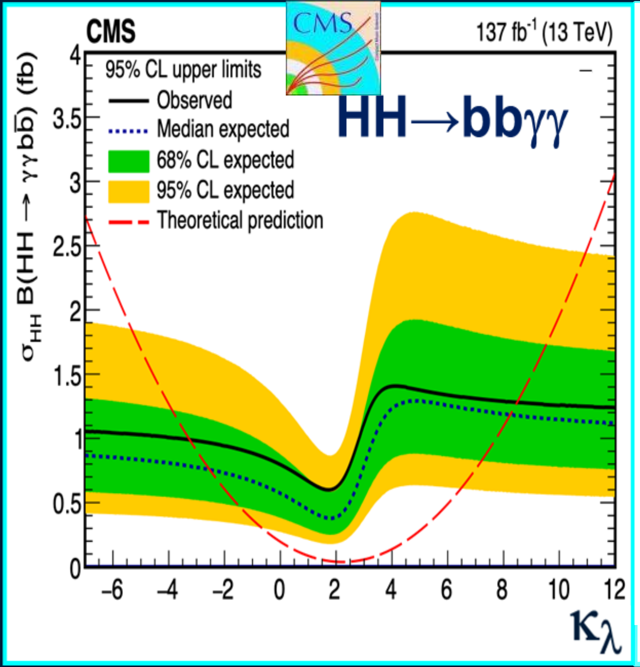
CMS HH→bbγγ (JHEP 03 (2021) 257):

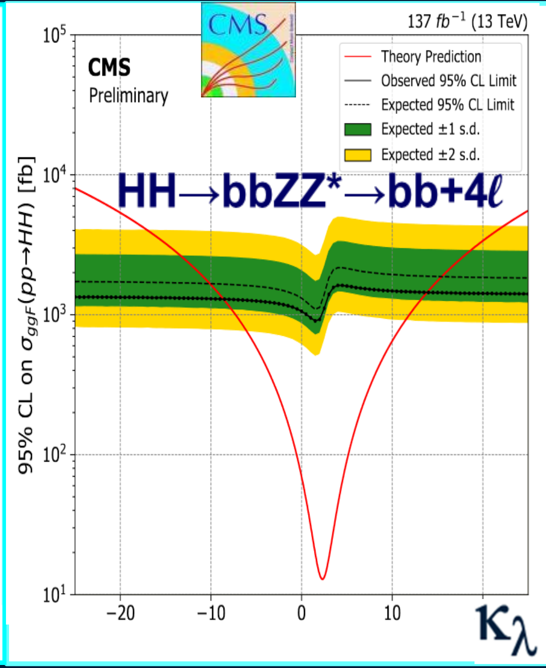
- $-3.3 < \kappa_\lambda < 8.5$ obs @95% CL
- $\sigma(HH)/\sigma(HH_{SM}) < 7.7$ (5.2) obs(exp) @95% CL

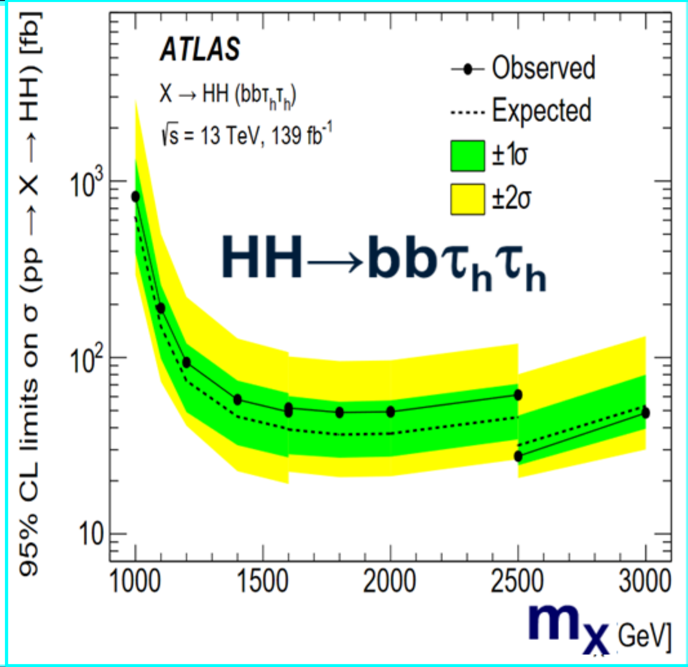
CMS HH→bbZZ*→bb+4ℓ (CMS-PAS-HIG-20-004):

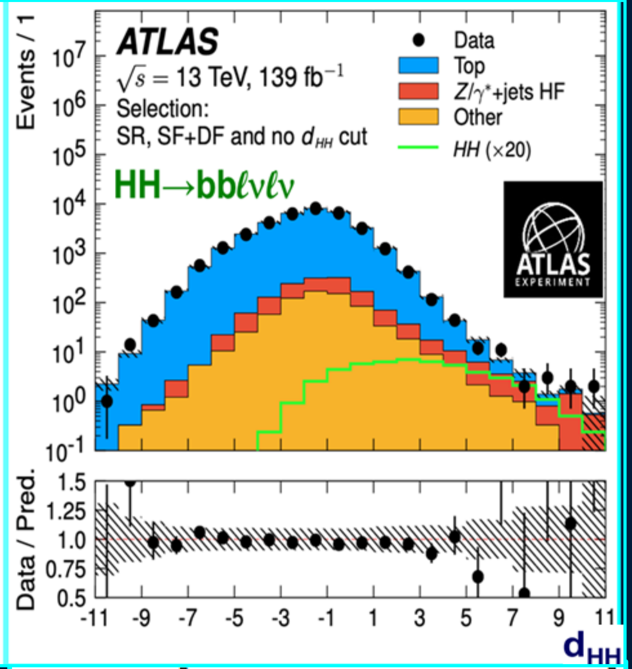
- $-9 < \kappa_\lambda < 14$ obs @95% CL
- $\sigma(HH)/\sigma(HH_{SM}) < 30$ (37) obs(exp) @95% CL

- **ATLAS search for resonant HH production to boosted bb pair and boosted ττ pair JHEP 11 (2020) 163**
- **ATLAS HH→bb ℓνℓν (Phys. Lett. B 801 (2020) 135145)**
  - $\sigma(HH)/\sigma(HH_{SM}) < 40$ (29) obs(exp) @95% CL









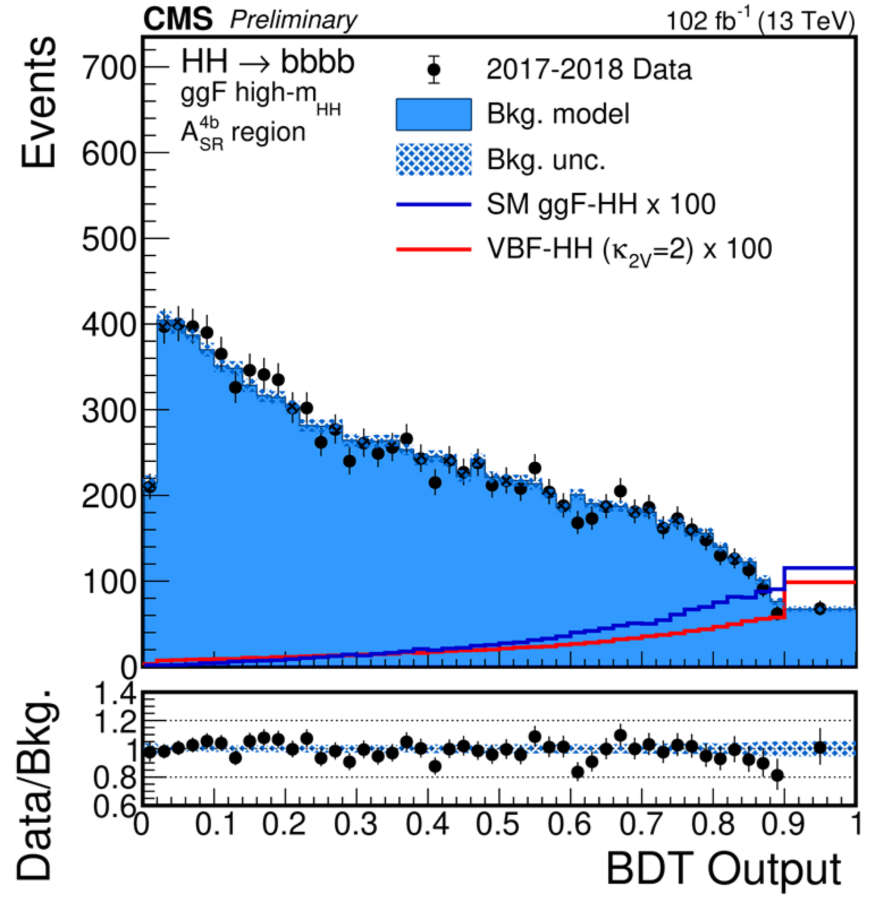
$$d_{HH} = \ln\left[p_{HH}/\left(p_{\mathrm{Top}} + p_{Z\text{-}\ell\ell} + p_{Z\text{-}\tau\tau}\right)\right]$$

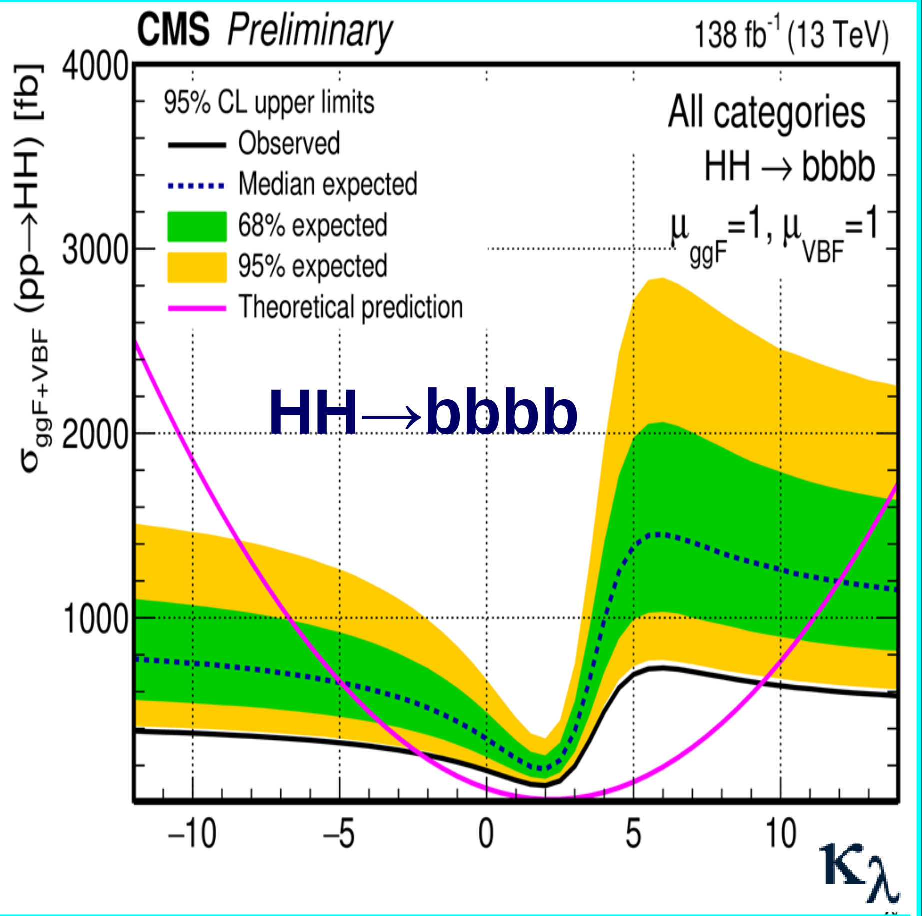
Recent Higgs Boson Self-Coupling Results with Full Run2 Data

New at LHCP: Resolved analysis HH→bbbb currently provides the most stringent limit on HH production

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

CMS-PAS-HIG-20-005





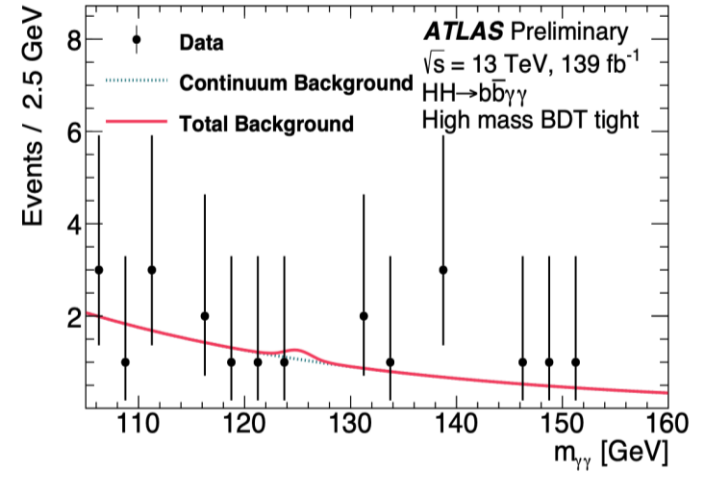
$\sigma(HH)/\sigma(HH_{SM}) < 3.6$ (7.3) obs (exp)

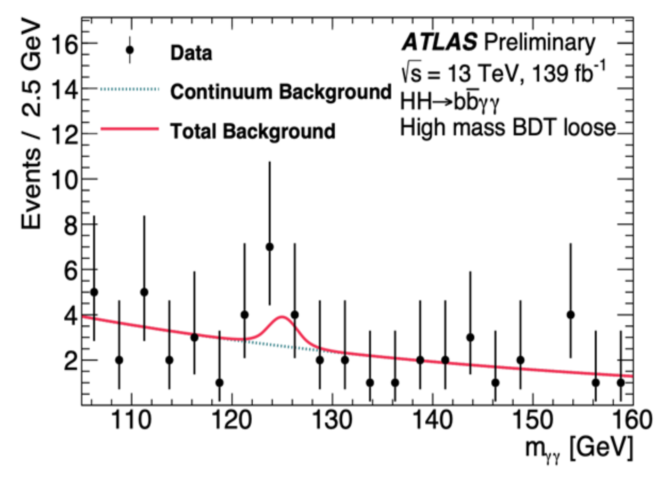
$-2.3 < \kappa_\lambda < 9.4$ obs @95% CL

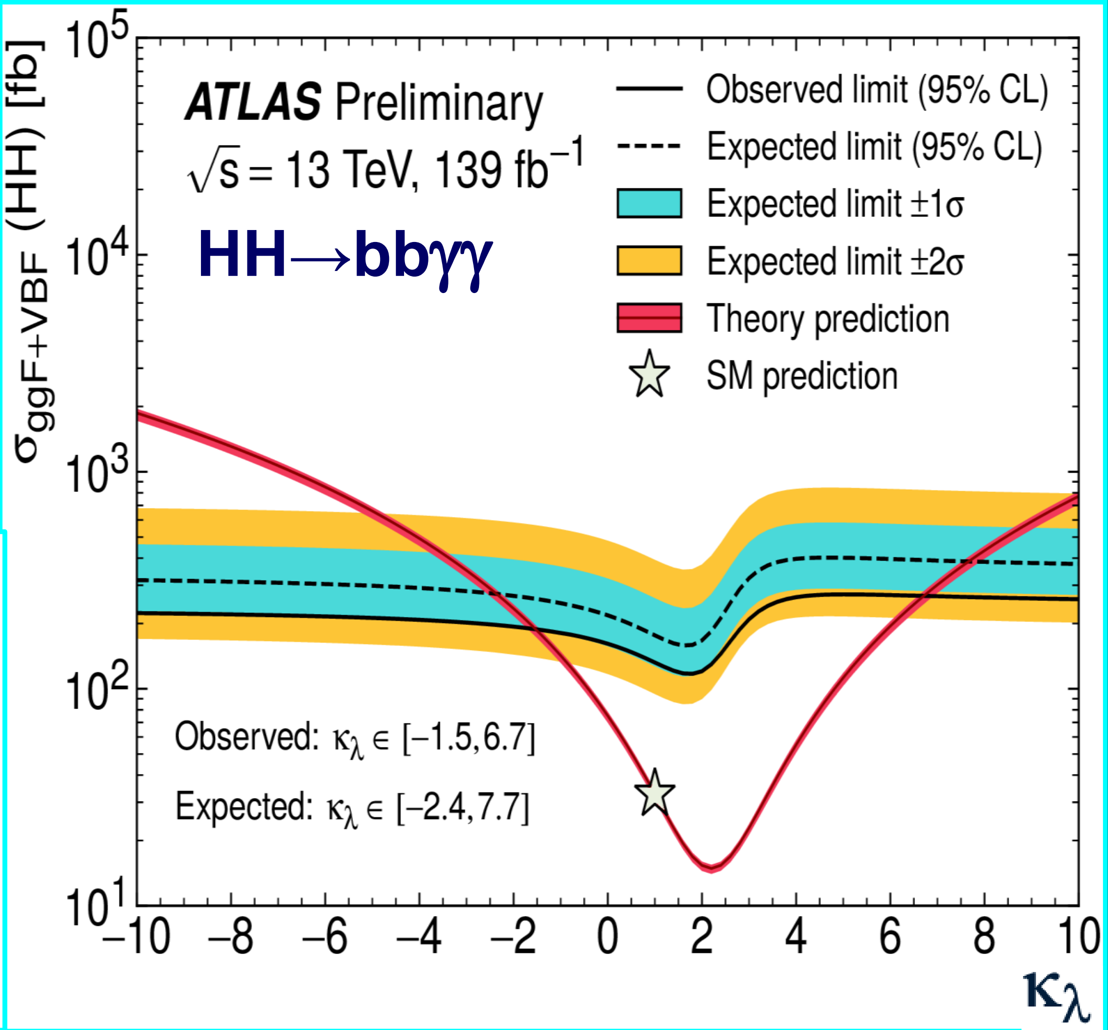
Recent Higgs Boson Self-Coupling Results with Full Run2 Data Moriond 2021: ATLAS HH→bbγγ

ATLAS-CONF-2021-016

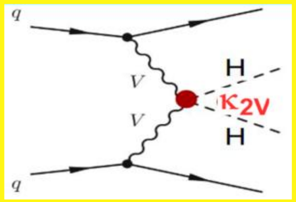
	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	4.9 ± 1.1	9.5 ± 1.5	3.7 ± 1.0	24.9 ± 2.5
Single Higgs boson background	0.670 ± 0.032	1.57 ± 0.04	0.220 ± 0.016	1.39 ± 0.04
ggF	0.261 ± 0.028	0.44 ± 0.04	0.063 ± 0.014	0.274 ± 0.030
$t\bar{t}H$	0.1929 ± 0.0045	0.491 ± 0.007	0.1074 ± 0.0033	0.742 ± 0.009
ZH	0.142 ± 0.005	0.486 ± 0.010	0.04019 ± 0.0027	0.269 ± 0.007
Rest	0.074 ± 0.012	0.155 ± 0.020	0.008 ± 0.006	0.109 ± 0.016
SM HH signal	0.8753 ± 0.0032	0.3680 ± 0.0020	$(49.4 \pm 0.7) \cdot 10^{-3}$	$(78.7 \pm 0.9) \cdot 10^{-3}$
ggF	0.8626 ± 0.0032	0.3518 ± 0.0020	$(46.1 \pm 0.7) \cdot 10^{-3}$	$(71.8 \pm 0.9) \cdot 10^{-3}$
VBF	0.01266 ± 0.00016	0.01618 ± 0.00018	$(3.22 \pm 0.08) \cdot 10^{-3}$	$(6.923 \pm 0.011) \cdot 10^{-3}$
Alternative $HH(\kappa_\lambda = 10)$ signal	6.36 ± 0.05	3.691 ± 0.038	4.65 ± 0.04	8.64 ± 0.06
Data	2	17	5	14







- $\sigma(HH)/\sigma(HH_{SM}) < 4.1$ (5.5) obs (expected) $-5.1 < \kappa_\lambda < 6.7$ obs @95% CL



VBF HH: Probing the HHVV Coupling κ_{2V}

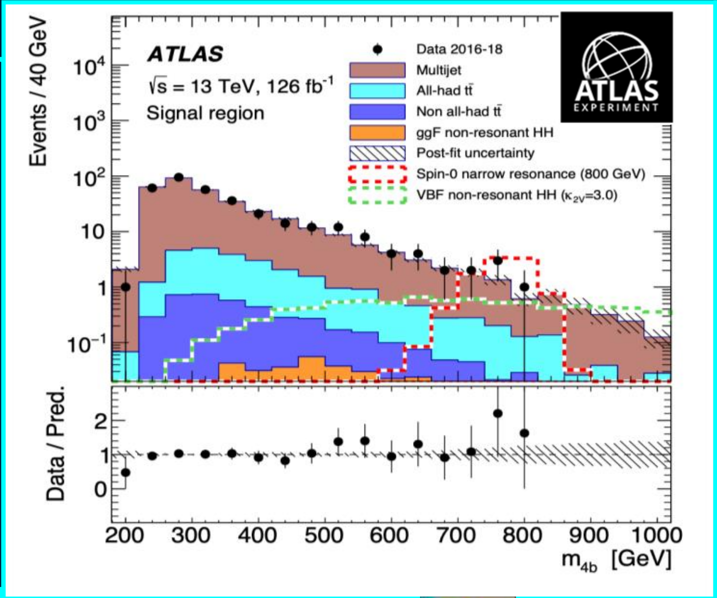
ATLAS VBF HH→bbbb Run 2

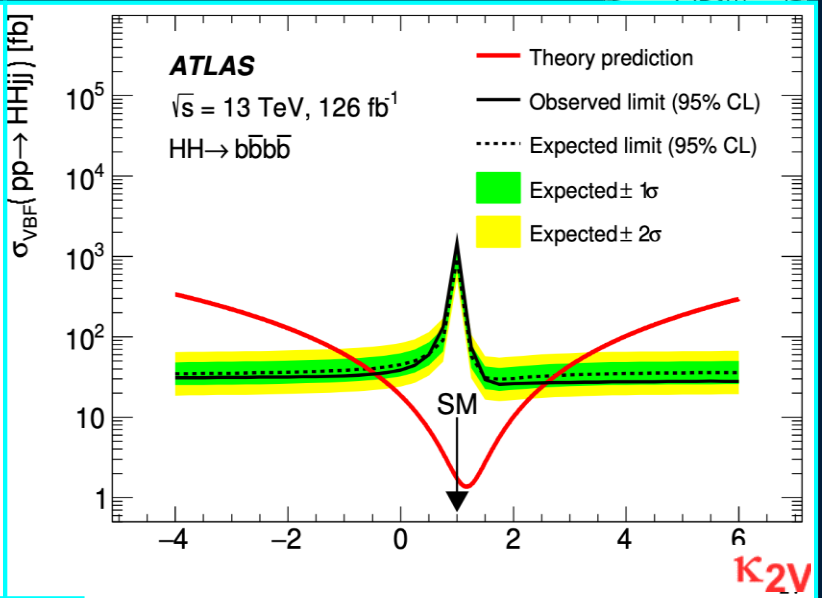
Four b-jets; two VBF jets
with m_{jj} >1 TeV and $|\Delta\eta_{jj}| > 5.0$

Final Discriminant m_{4b}

$-0.43 < \kappa_{2V} < 2.56$ @95% CL

JHEP 07 (2020) 108 [Erratum]





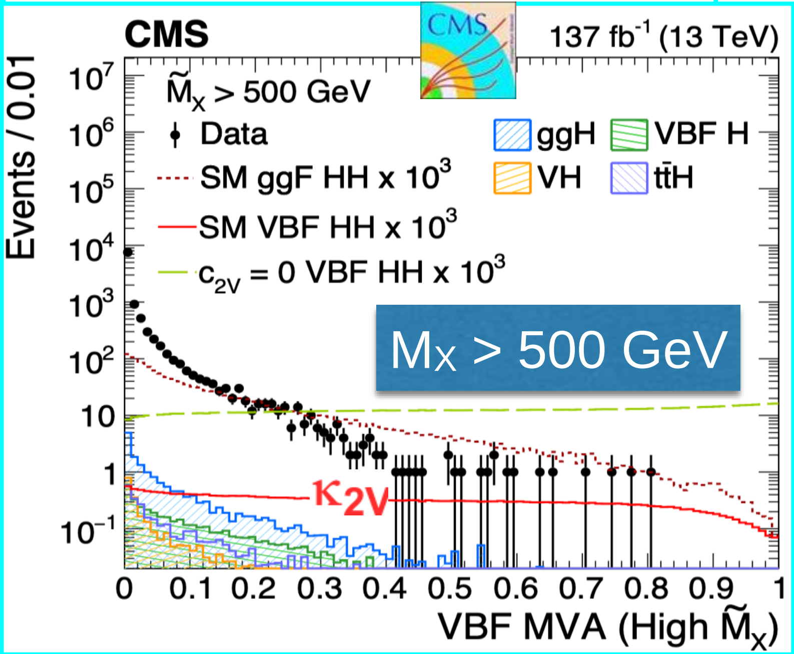
CMS VBF HH→bb γγ Run 2

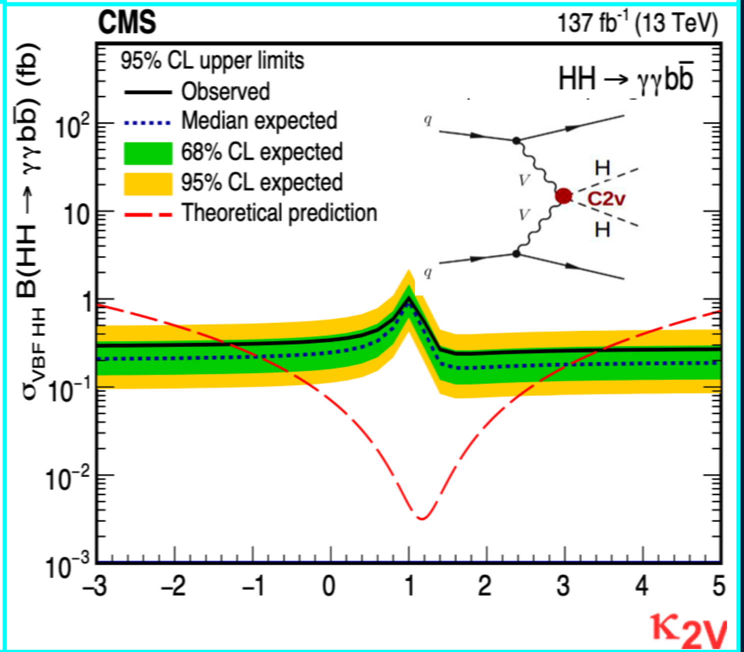
$$\tilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

Category	MVA	$\tilde{M}_X$ (GeV)
VBF CAT 0	0.52-1.00	>500
VBF CAT 1	0.86-1.00	250-500

$-1.3 < \kappa_{2V} < 3.5$ @95% CL

arXiv:2011.12373

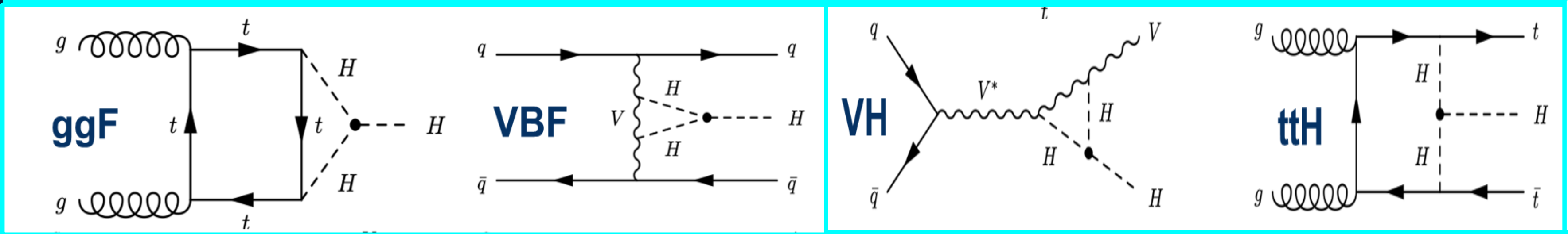


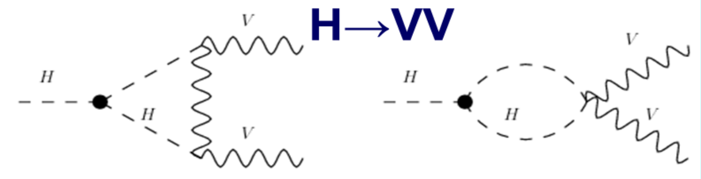


Higgs Boson Self-Coupling: H and HH Combination

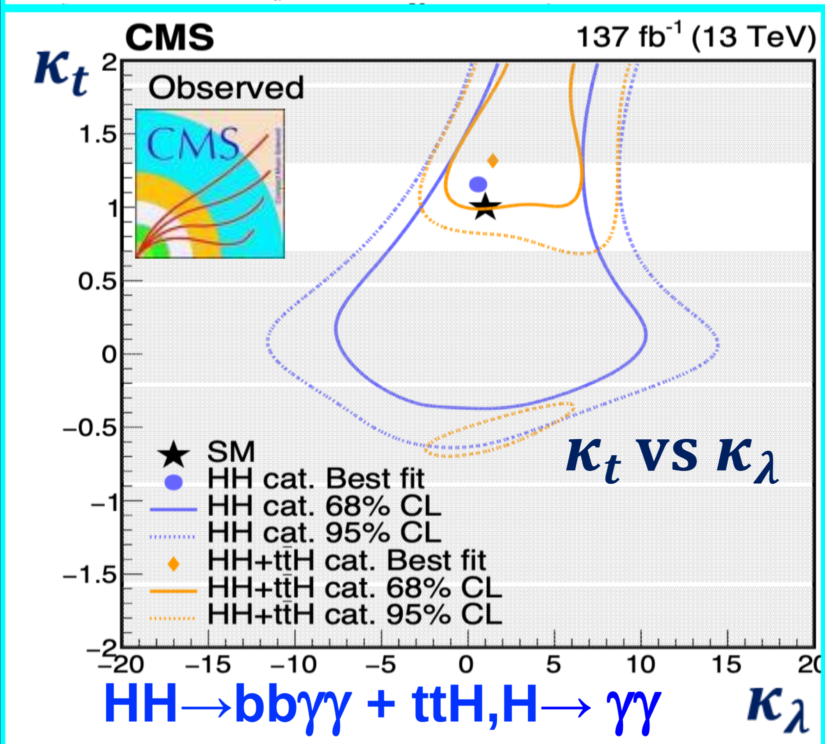
Single Higgs boson production & decay rates, kinematics, are sensitive to Higgs self-coupling through Electroweak Corrections

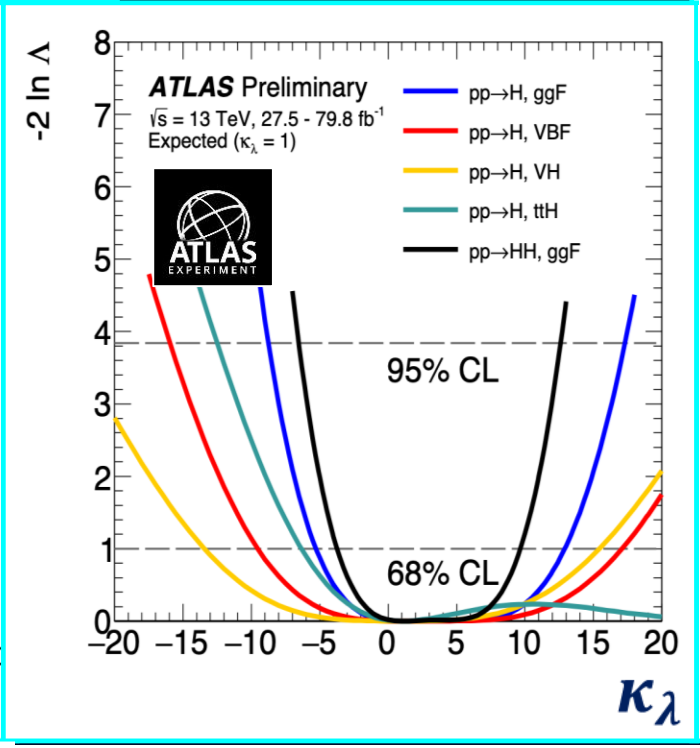
➡ indirectly constrain κ_λ ,assuming no other BSM effects

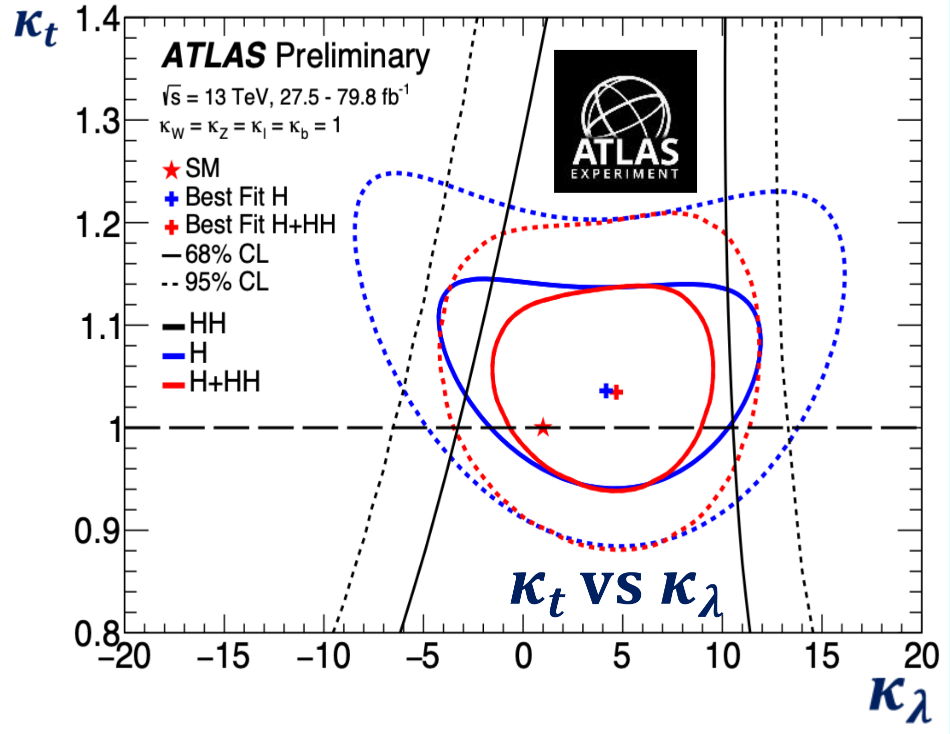




G. DeGrassi et al, JHEP 12 (2016) 080
F. Maltoni et al, EPJC 77 (2017) 887







JHEP 03 (2020) 257

ATLAS-CONF-2019-049

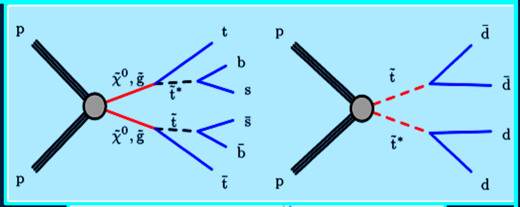
Searches for Long Lived Particles (LLPs)

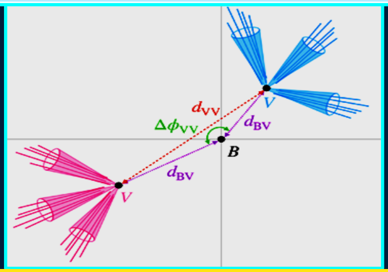
Full Run2 140/fb

Search for pair-produced LLPs

- With mean decay length 0.1 - 100 mm (i.e. within the beam pipe)
- Each decaying to two or more quark - jets

CMS-EXO-19-013
Submitted to PRD

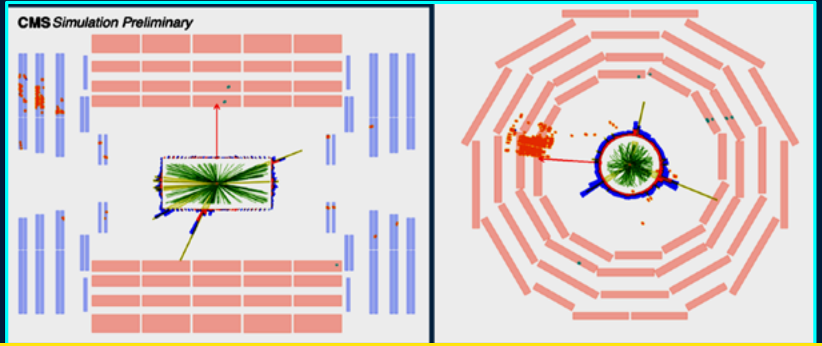




Search for Higgs decays to long-lived scalars $h \to SS$

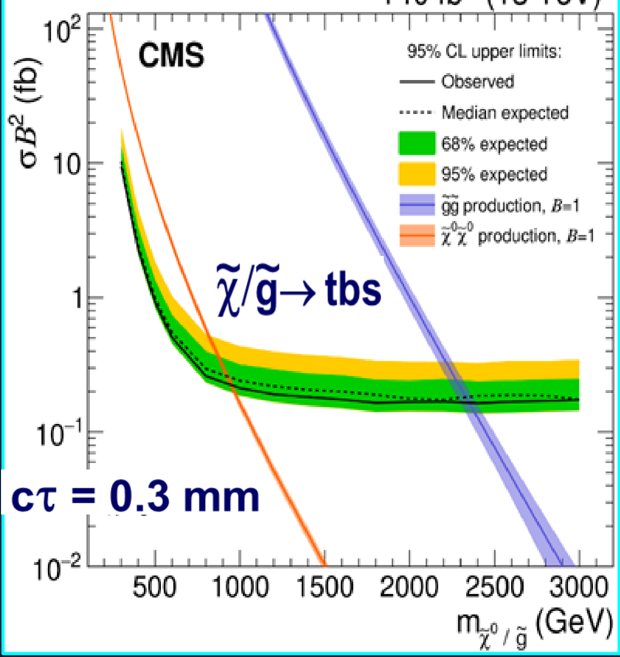
- Each decaying to a pair of quarks or tau leptons: hadronic clusters in the forward muon chambers

CMS-PAS-EXO-20-015



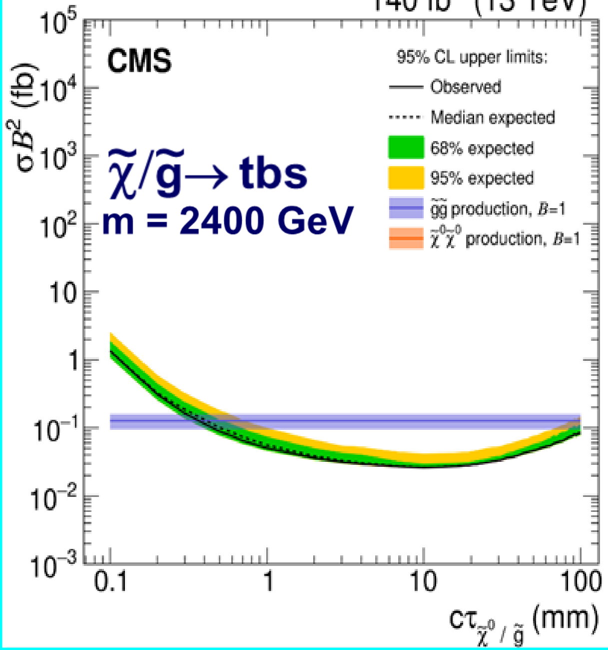
σ*BR1*BR2 vs m($\tilde{\chi}^0$ or $\tilde{g}$)

95% CL upper limits

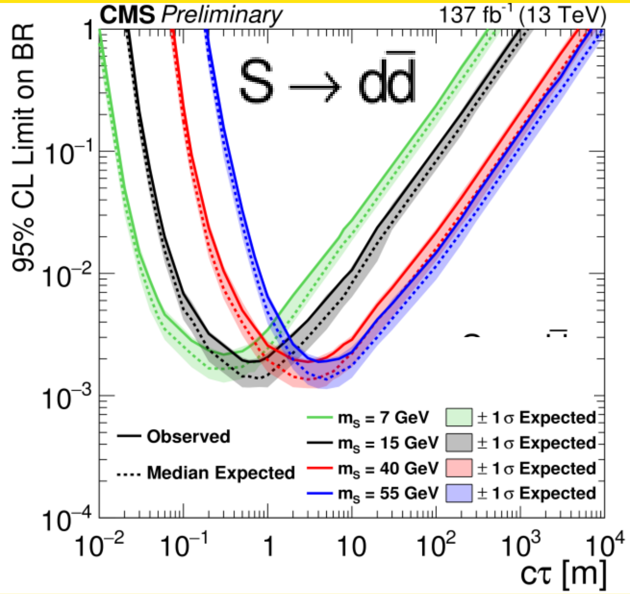


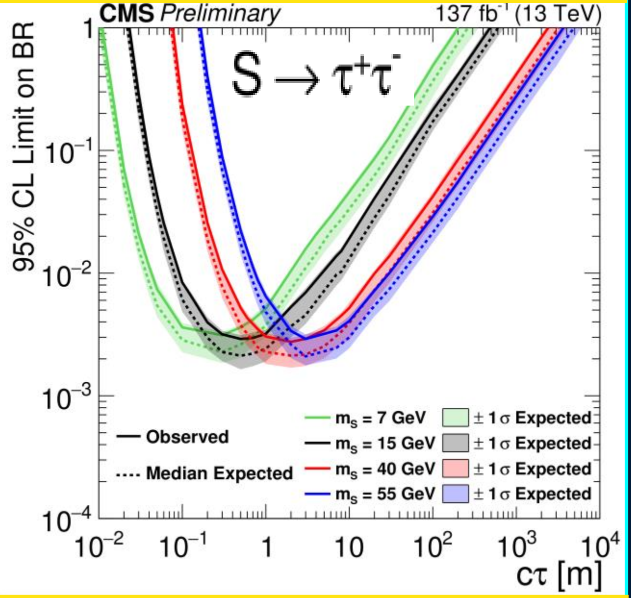
σ*BR1*BR2 vs cτ($\tilde{\chi}^0$ or $\tilde{g}$)

95% CL upper limits



$\mathcal{B}(h^0 \to SS)$ 95% CL upper limits vs cτ





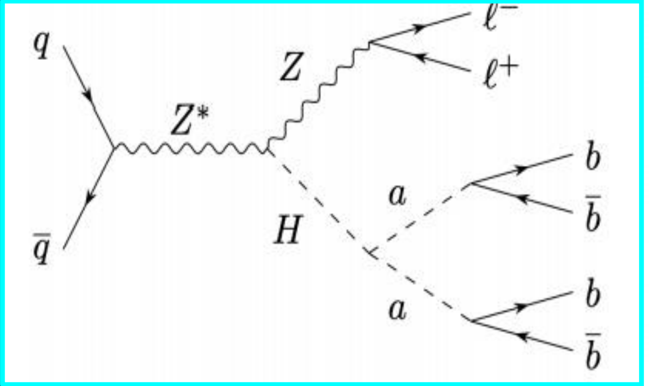
Four mass hypotheses: 7 (green), 15 (black), 40 (red), and 55 (blue) GeV

Best sensitivity for LLP cτ > a few meters

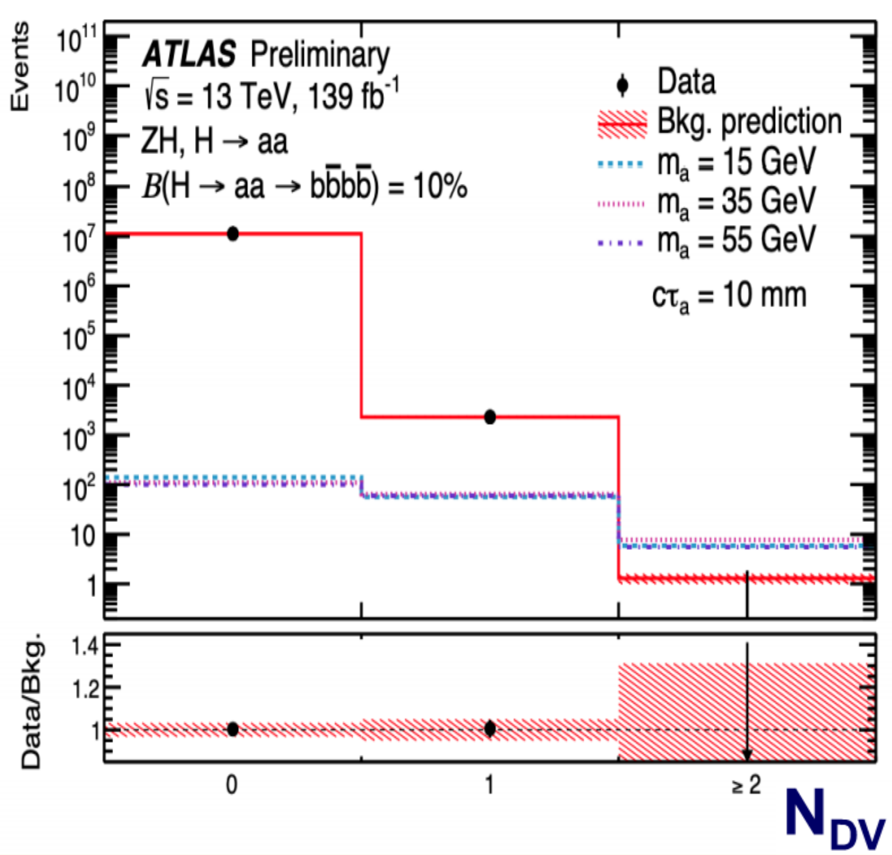
A factor of 2-6 improvement for cτ above 100 m

Search for LLPs $H \to ZH \to aa\, l^+l^- \to bbbb\, l^+l^-$

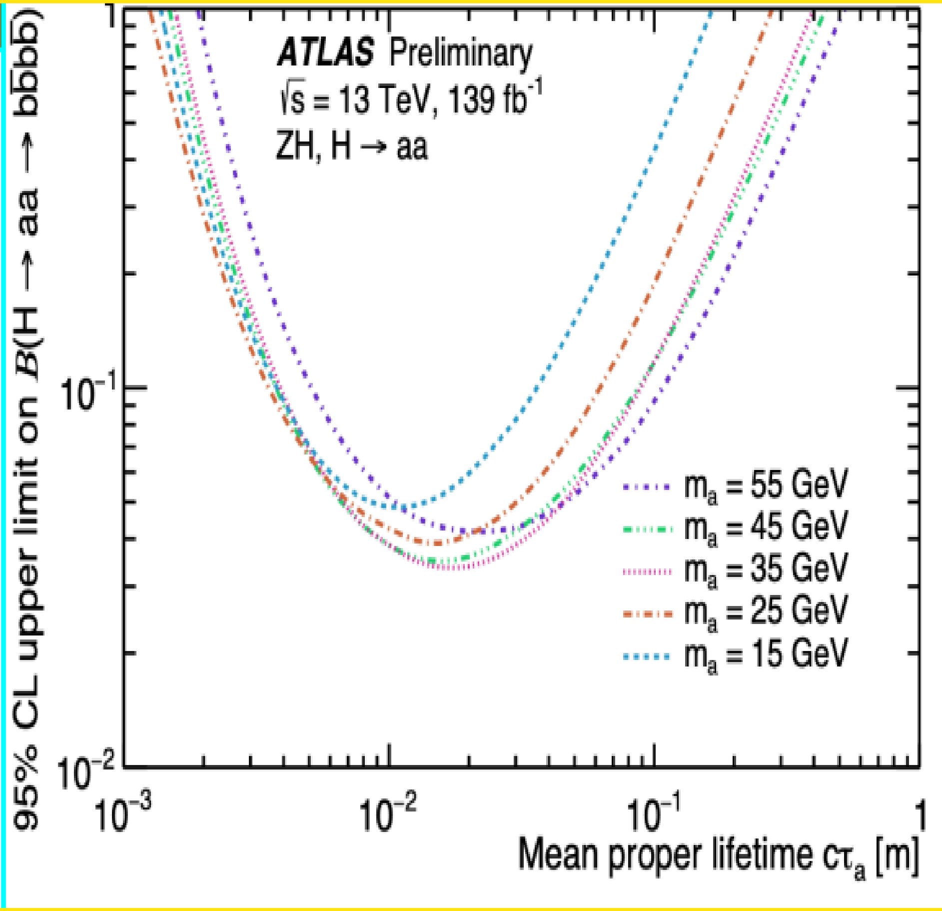
- Benchmark Model:
- Pseudoscalar a that decays exclusively to bb
- Parameters: $c\tau_a$, m_a



Search with displaced vertices
Example: BR($H \to aa \to bbbb$) = 10%
$c\tau_a$ = 10 mm



95% CL Upper Limit on BR($H \to aa \to bbbb$) vs $c\tau_a$

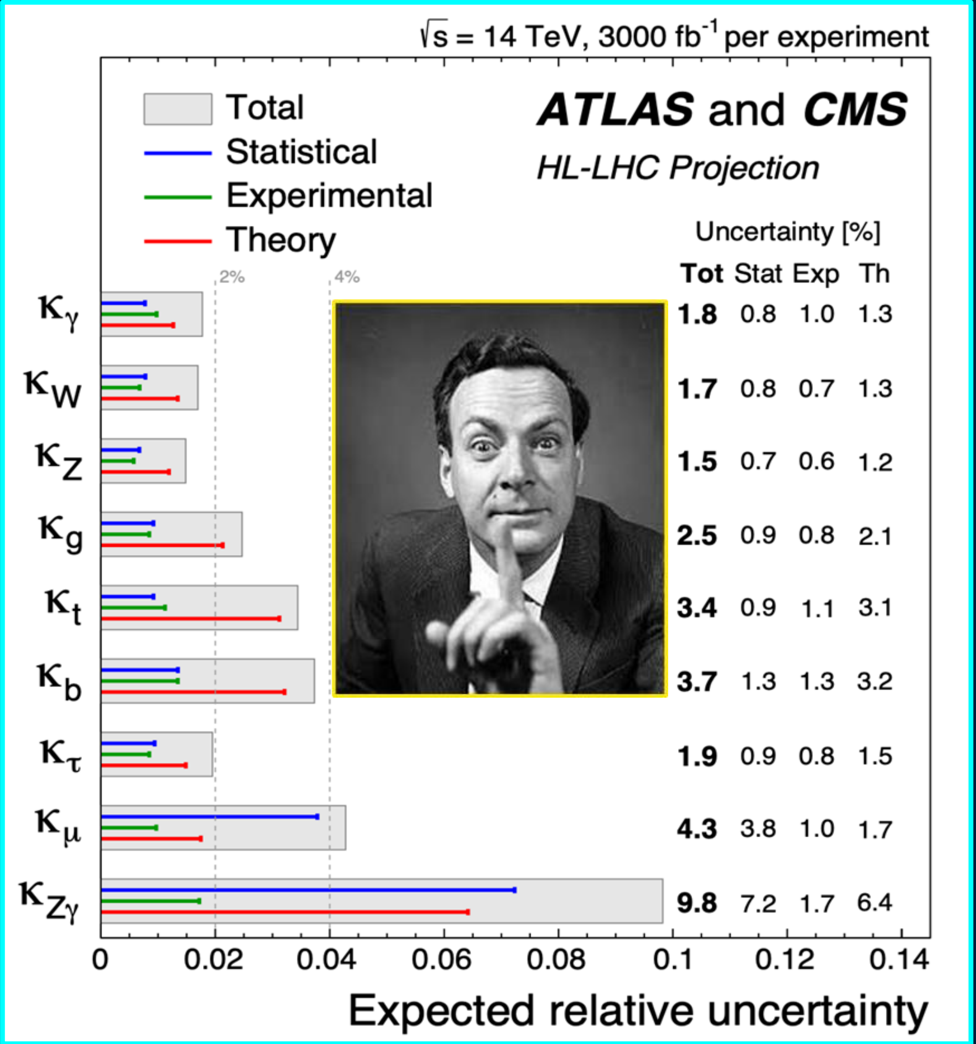


Mass hypotheses: m_a= 15 to 55 GeV

Conclusions

- Measurements of Higgs boson properties agree with SM expectations, hints for new physics could be uncovered as data taking progresses and analyses advance
  - Major production and decay channels now reaching ~10% level precision. Improved sensitivity to rare process e.g. evidence of H→μμ and H→$\ell\ell\gamma$
  - Significant progress in fiducial/differential and STXS measurements: 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 techniques: upper limit on σ(HH) down to 3.6 × SM
- A broad program searching for BSM physics in the Higgs sector is expanding

Projections for HL-LHC
arXiv:1902.00134



The expected LHC + HL LHC dataset is 20X the current dataset
Prospects for sub-percent precision at next generation colliders

LHC: to Run3 and Beyond

We have launched on an *Ocean of Discovery*

Brazilian Morning

The Outlook

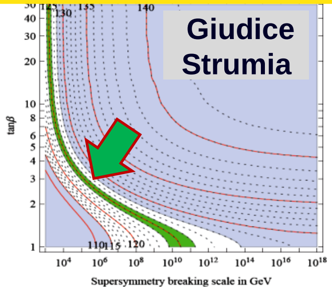
- **SM or not:** the **125 GeV Higgs boson** has taken us to the **threshold of an era of new physics**, with a host of questions
- **Natural, Split or High Scale SUSY ?:**
  - A nearby 3rd generation at <~2 TeV ?
  - Another nearby scale at ~5-100 TeV ?
- *OR: new singlets, doublets, triplets; new scalars,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

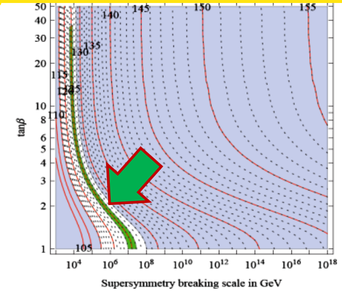
Apologies for all I could not cover

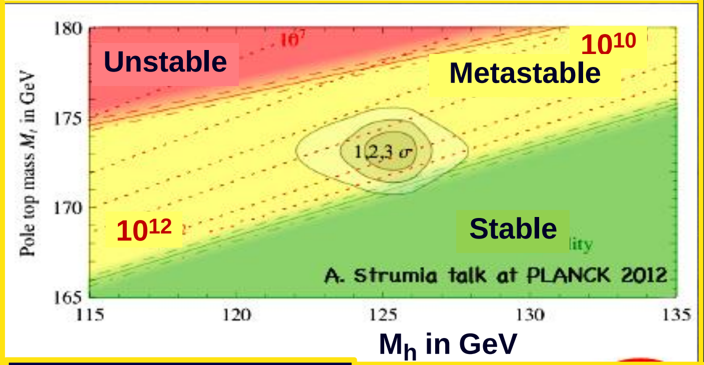
$$M_h^2 \overset{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

High Scale SUSY

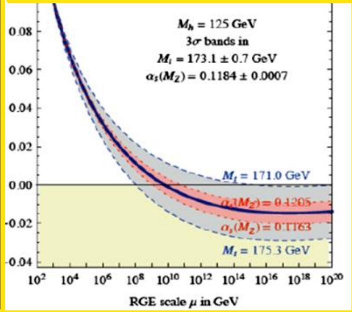


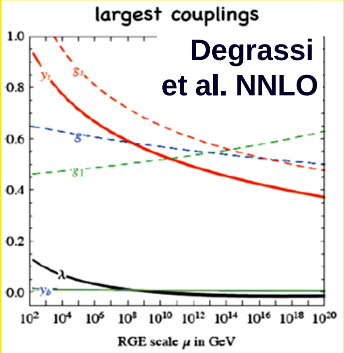
Split SUSY





λ at High Scales





Many More Higgs and Other Physics Results

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

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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Papers_Conference_notes_Public_n

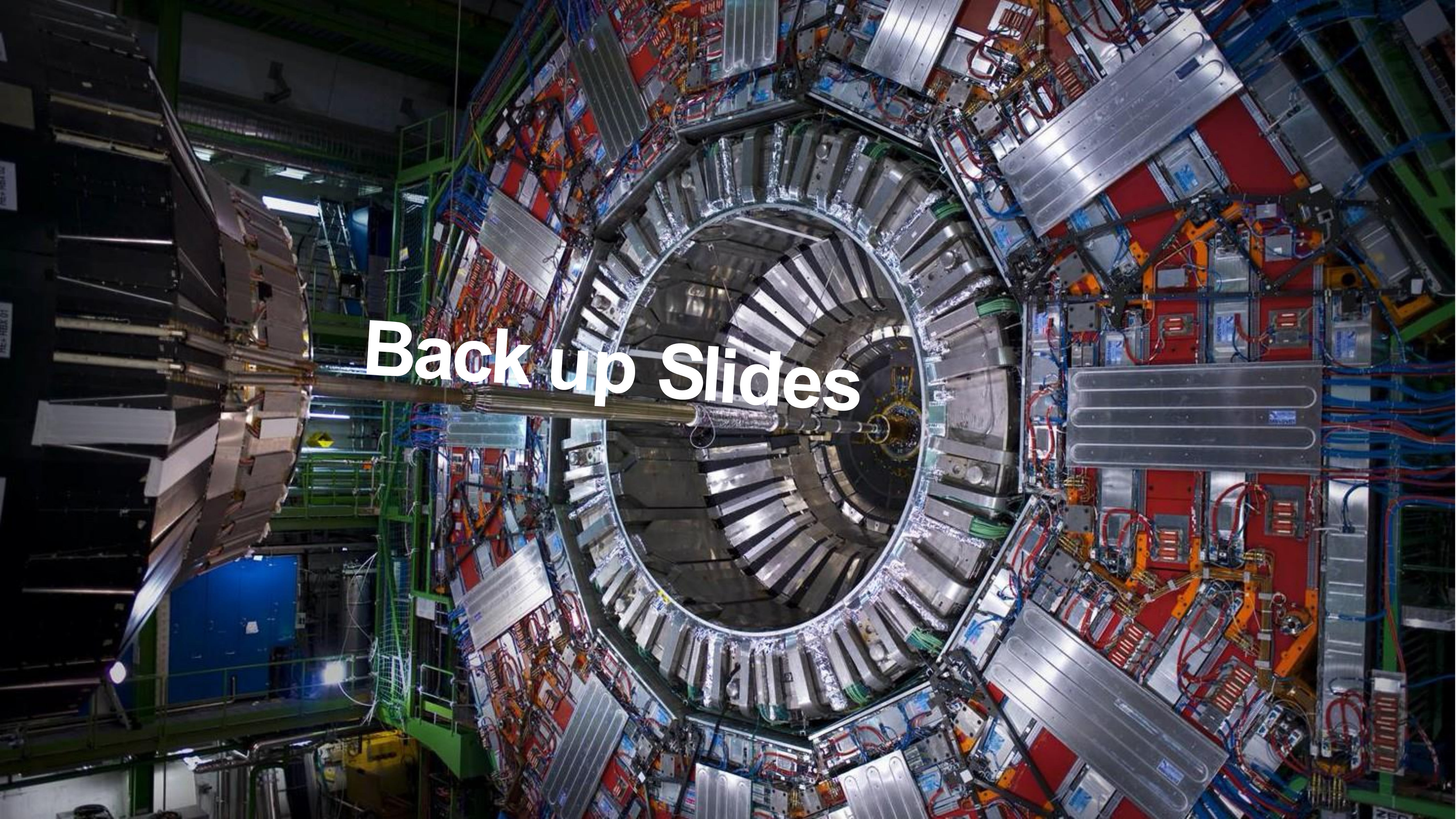
https://atlas.cern/tags/physics-results

The LHCP Conference (June 2021):

https://indico.cern.ch/event/905399/timetable/?view=standard

LISHEP: *Return to Rio*

Back up Slides

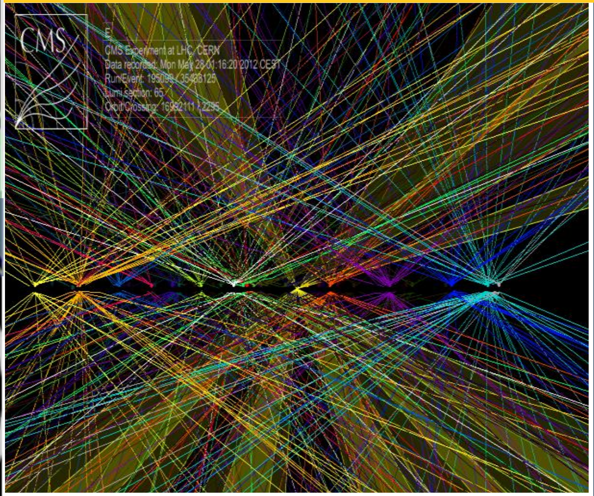


LISHEP 2018 *Salvador, Bahia*

The LHC: Spectacular Performance
A new era of opportunity; a new era of challenges

Data Complexity: The Challenge of Pileup

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



~50 Vertices, 14 Jets, 2 TeV

Run2 and Beyond will bring:

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

Average Pileup

Run 1 21

Run 2 40

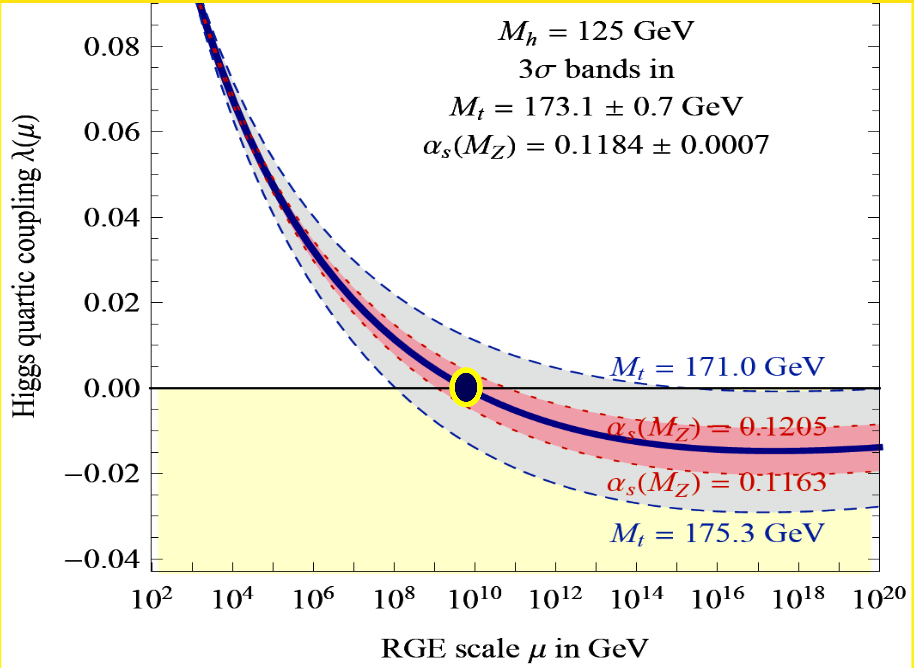
Run 3 ~53

HL LHC 140-200

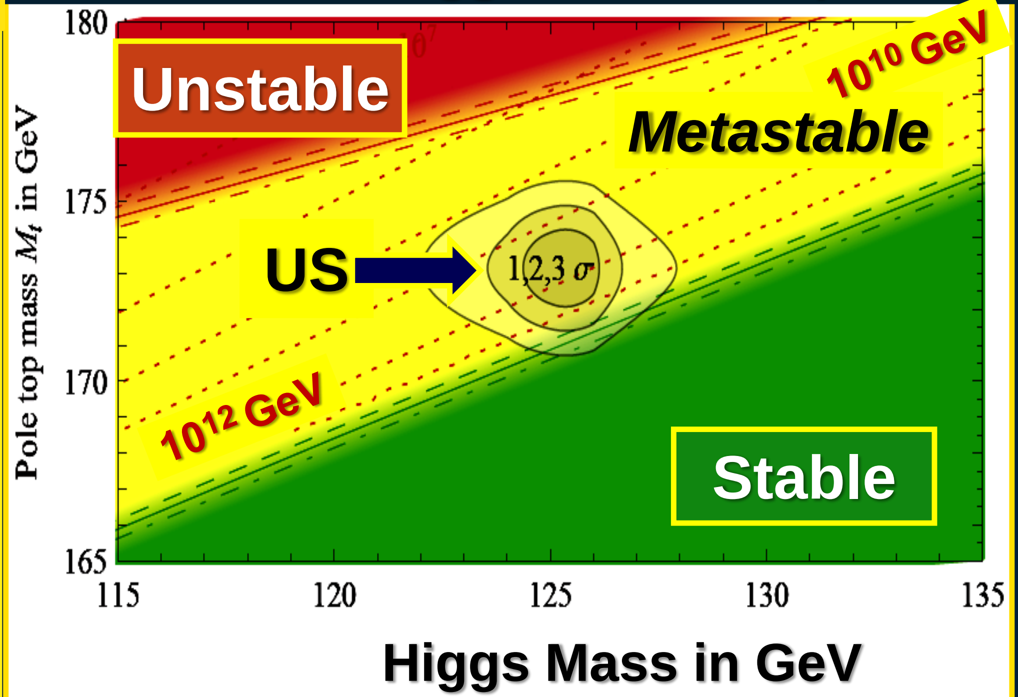
The 125 GeV Higgs Mass

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

NNLO Evolution of the Higgs Self-coupling $\lambda(\mu)$



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 ?***

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

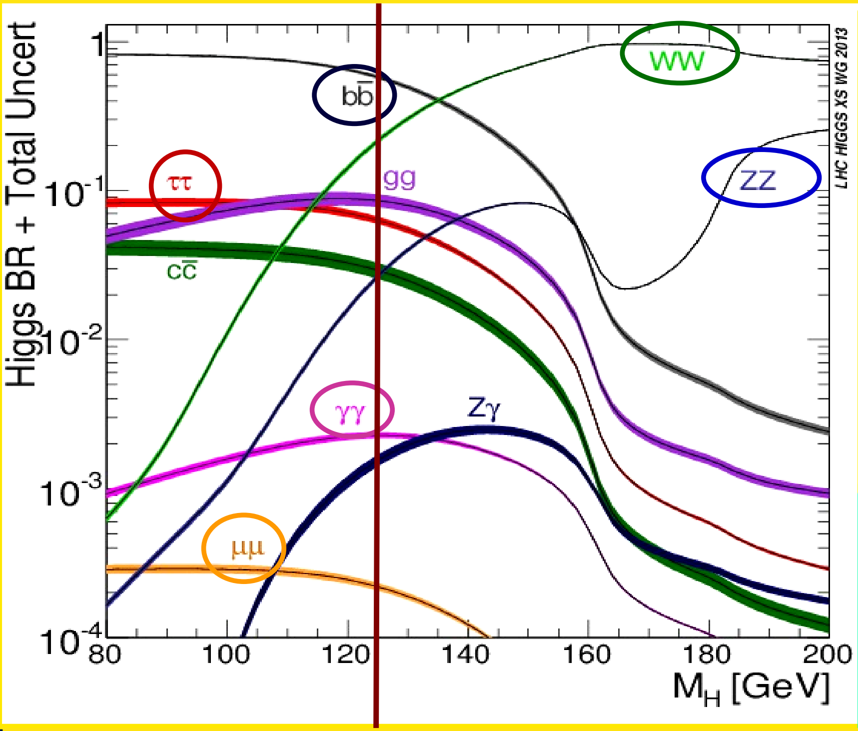
	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
ATLAS	5→4	5→5	4→4	9→7	12→11	11→9	10→9	14→14	8→7	14→11
CMS	5→2	5→2	4→2	5→3	7→4	10→7	5→2	12→10	8→8	6→3

Higgs Boson Decays

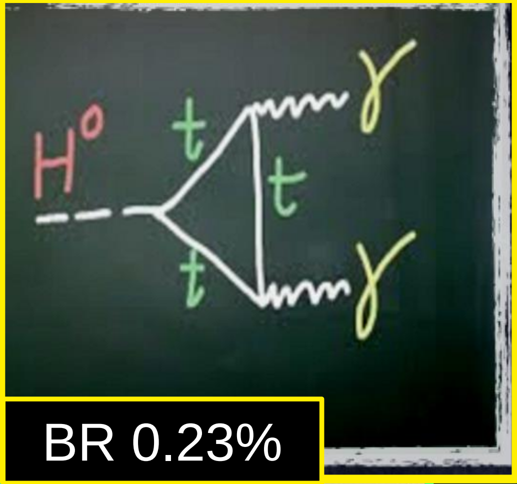
Many Modes Contribute near 125 GeV

ZZ, $\gamma\gamma$, WW, $\tau\tau$, bb [the big 5*]

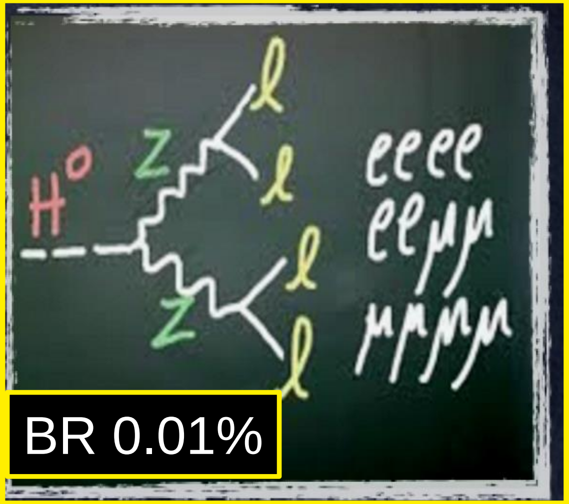
Rare High Mass Resolution Channels Have a Special Role:
$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow$ 4 Leptons



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*

CMS Higgs Mass Measurements

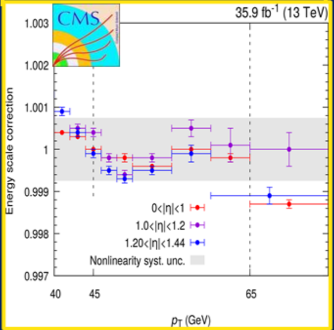
- **$H \to ZZ \to 4l$:** CMS-HIG-16-041 *JHEP 11 (2017) 047*

  m_H =125.26 ±0.21 (total) GeV
- ***$H \to \gamma\gamma$ using an improved ECAL calibration***

  m_H = 125.78 ± 0.26 (total) GeV

  CMS-HIG-19-004 *PLB 805 (2020) 135425*

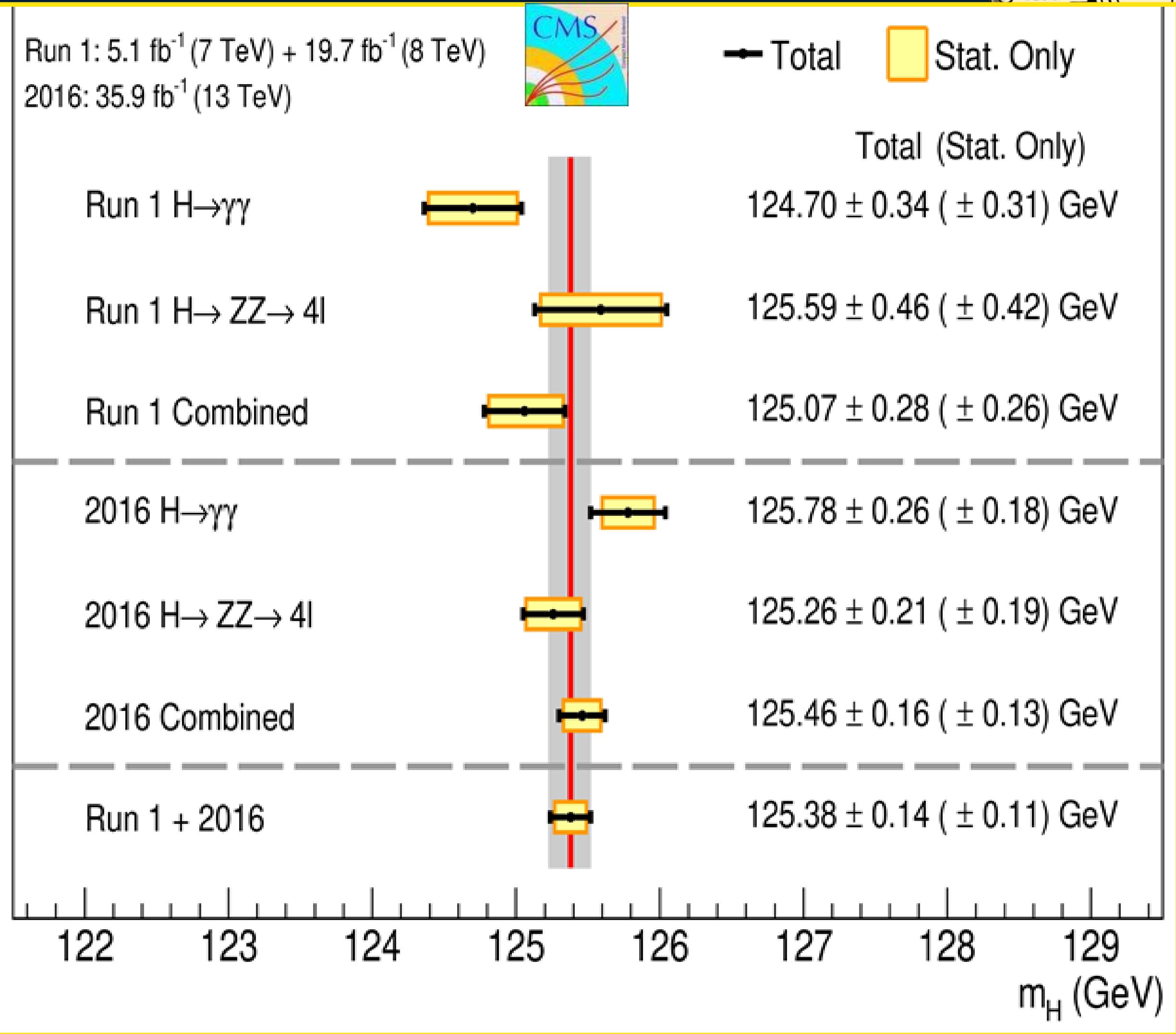
Photon Energy Scale correction vs p_T

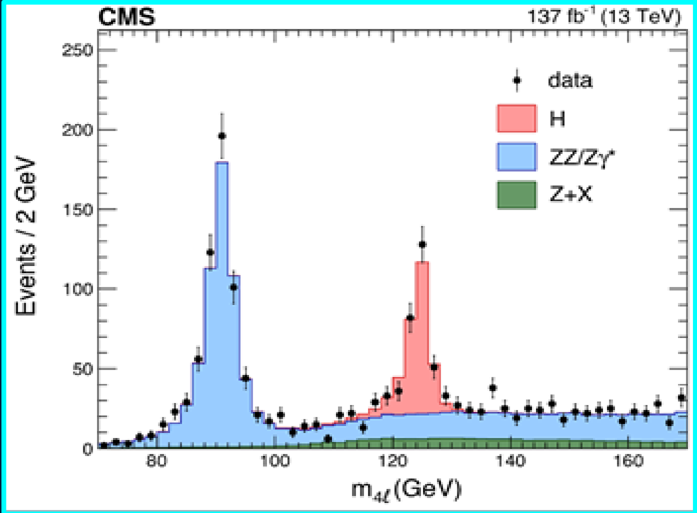


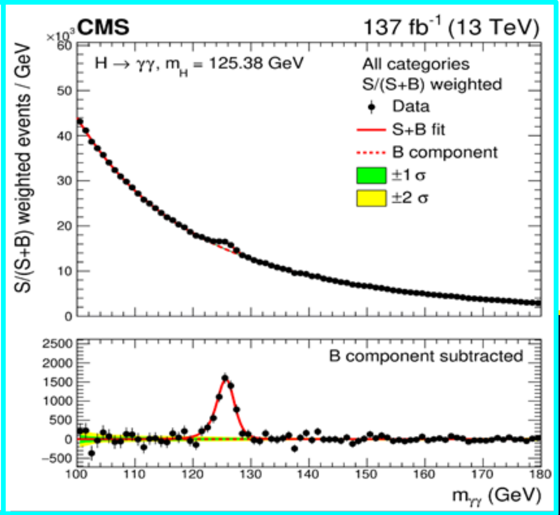
- **Run-2 / 2016 Combination**

  m_H = 125.46 ±0.21 (total) GeV
- **Combination with Run1 Result**

  m_H = 125.38 ±0.14 (total) GeV
  - **The most precise measurement to date (0.11%)**
  - **Central value consistently used in CMS analyses**







CMS Search for Higgs Pair Production HH

Run2 2016 35.9/fb

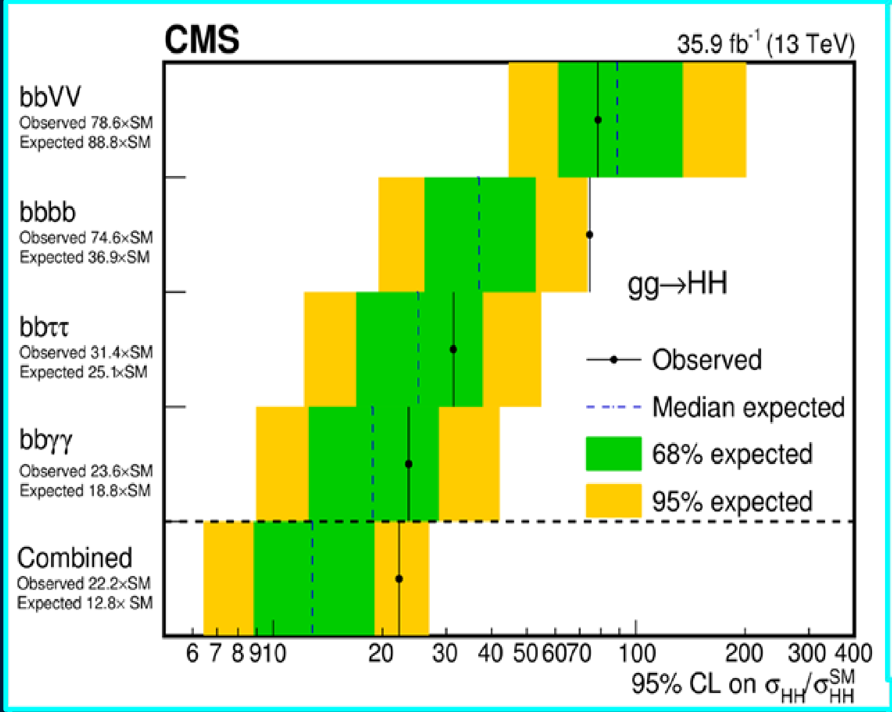
CMS-HIG-17-030

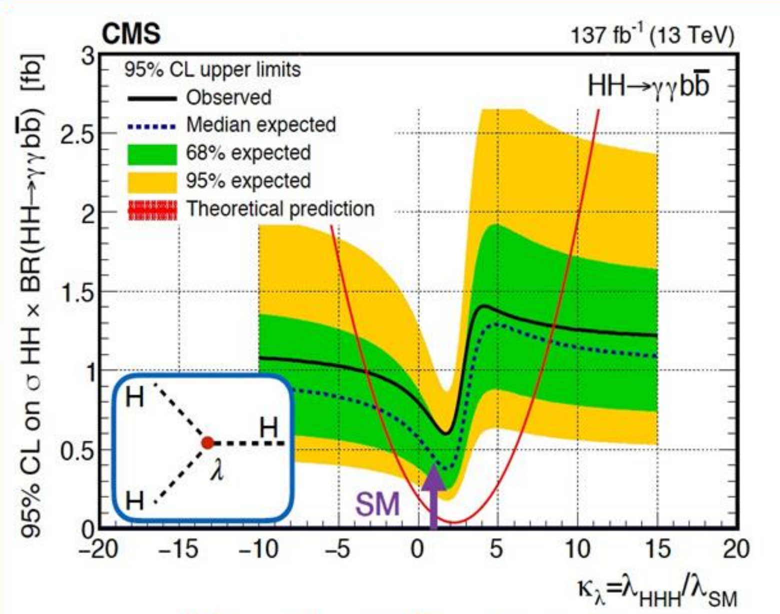
PRL 122 (2019) 121803

Full Run2 137/fb

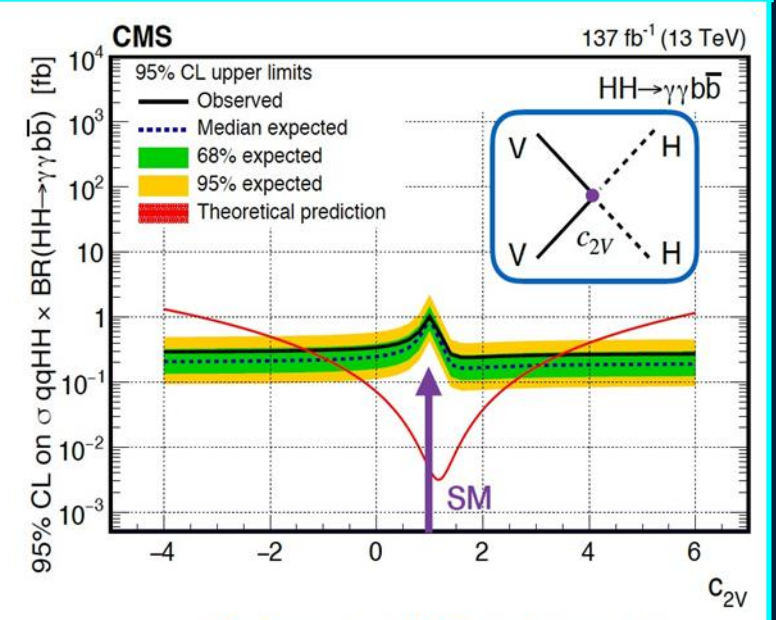
CMS-HIG-19-018

JHEP 03 (2021) 257





Driven by ggF categories



Driven by VBF categories

Combination of HH searches

σ/σ_{SM} < 22 (13) at 95% CL

Inclusive HH →γγbb

σ/σ_{SM} < 7.7 (5.2) at 95% CL

VBF HH → γγ bb

σ/σ_{SM} < 225 (208) at 95% CL

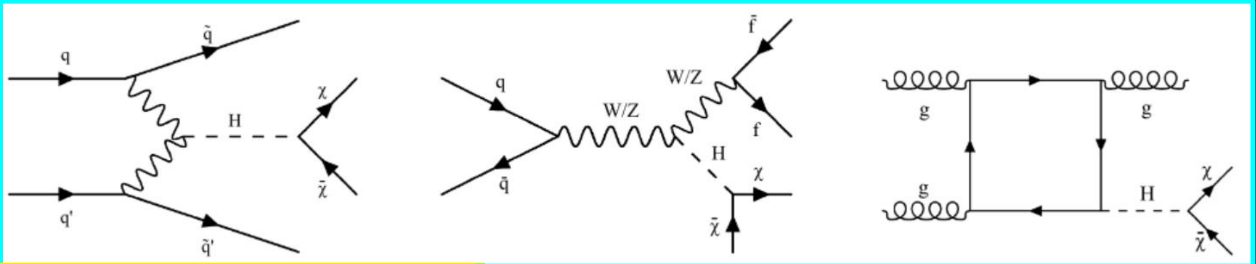
Constraints on anomalous HHH (κ_λ) and VVHH (C_{2V}) couplings

H

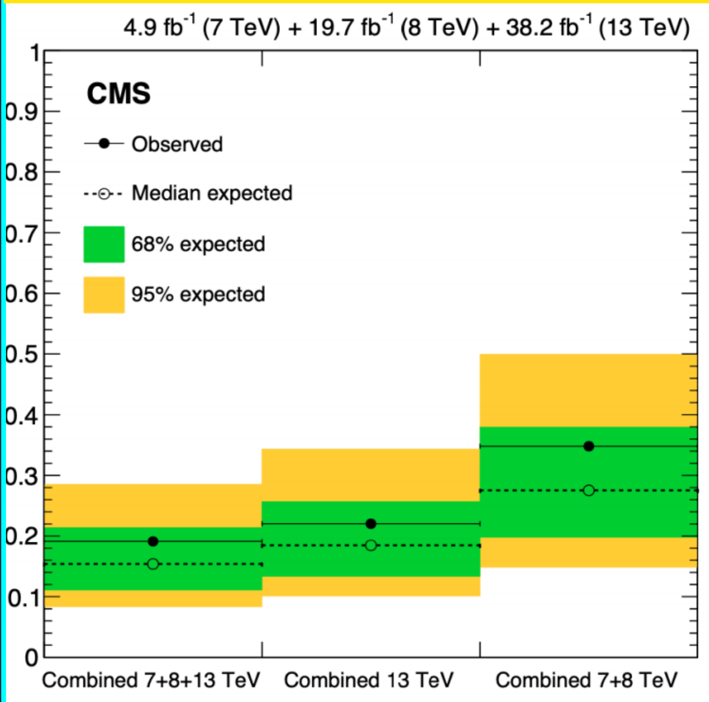
Phys. Lett. B 793 (2019) 520

Search for Higgs → Invisible Decays

In the SM BR(H → ZZ → νννν) ≈ 10^{-3}
Invisible decays are a portal to Dark Matter and other BSM Physics

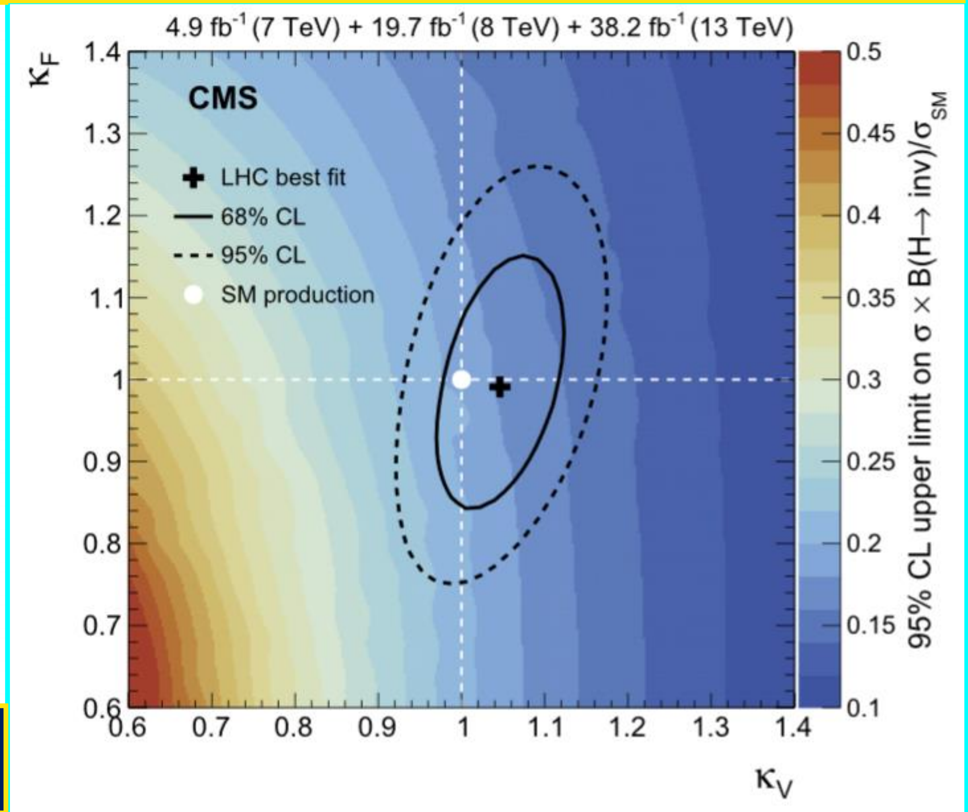


95% CL Upper Limit on σ X BR (H → Inv)/ σ_{SM}

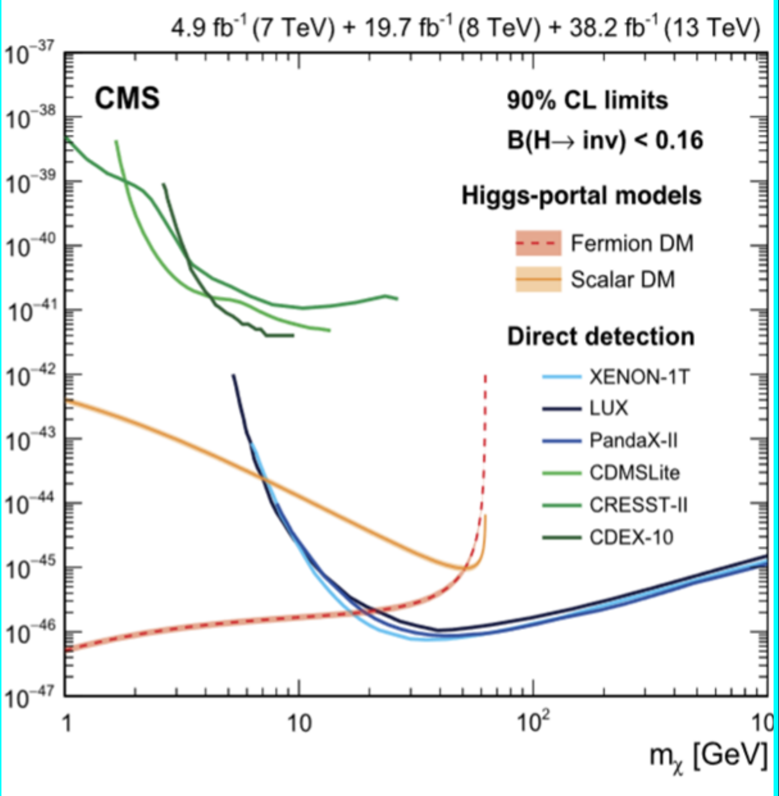


Combined = 0.19 observed (0.15 expected)

95% CL Upper Limit on σ X BR (H → Inv)/ σ_{SM} in the κ_F κ_V plane



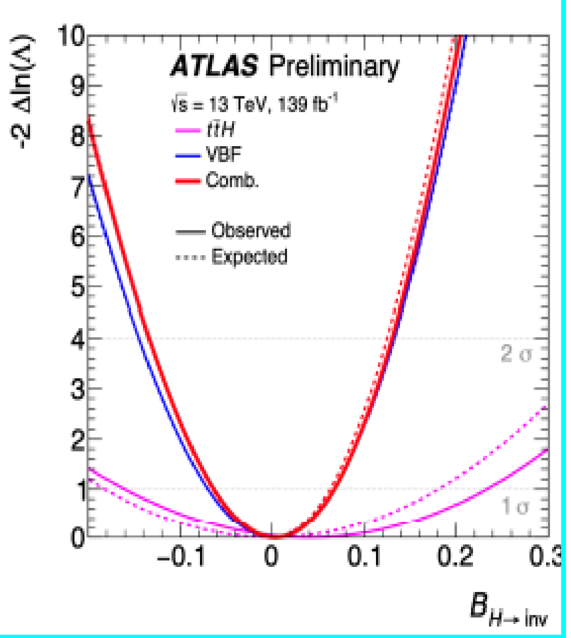
σ^{SI} (DM-nucleon) vs Mχ 90% CL UL in Higgs portal DM Models

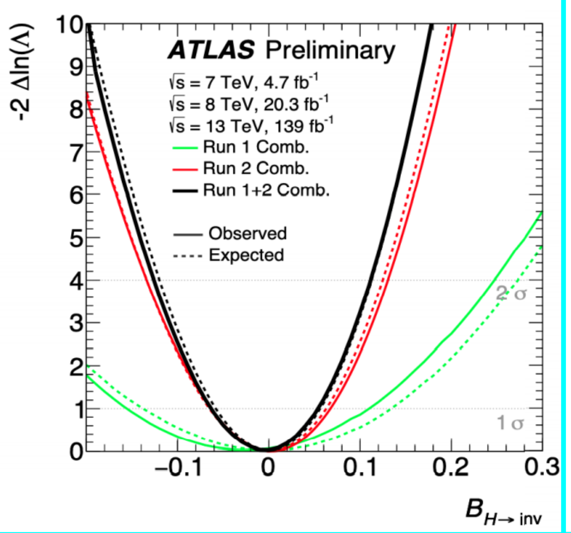


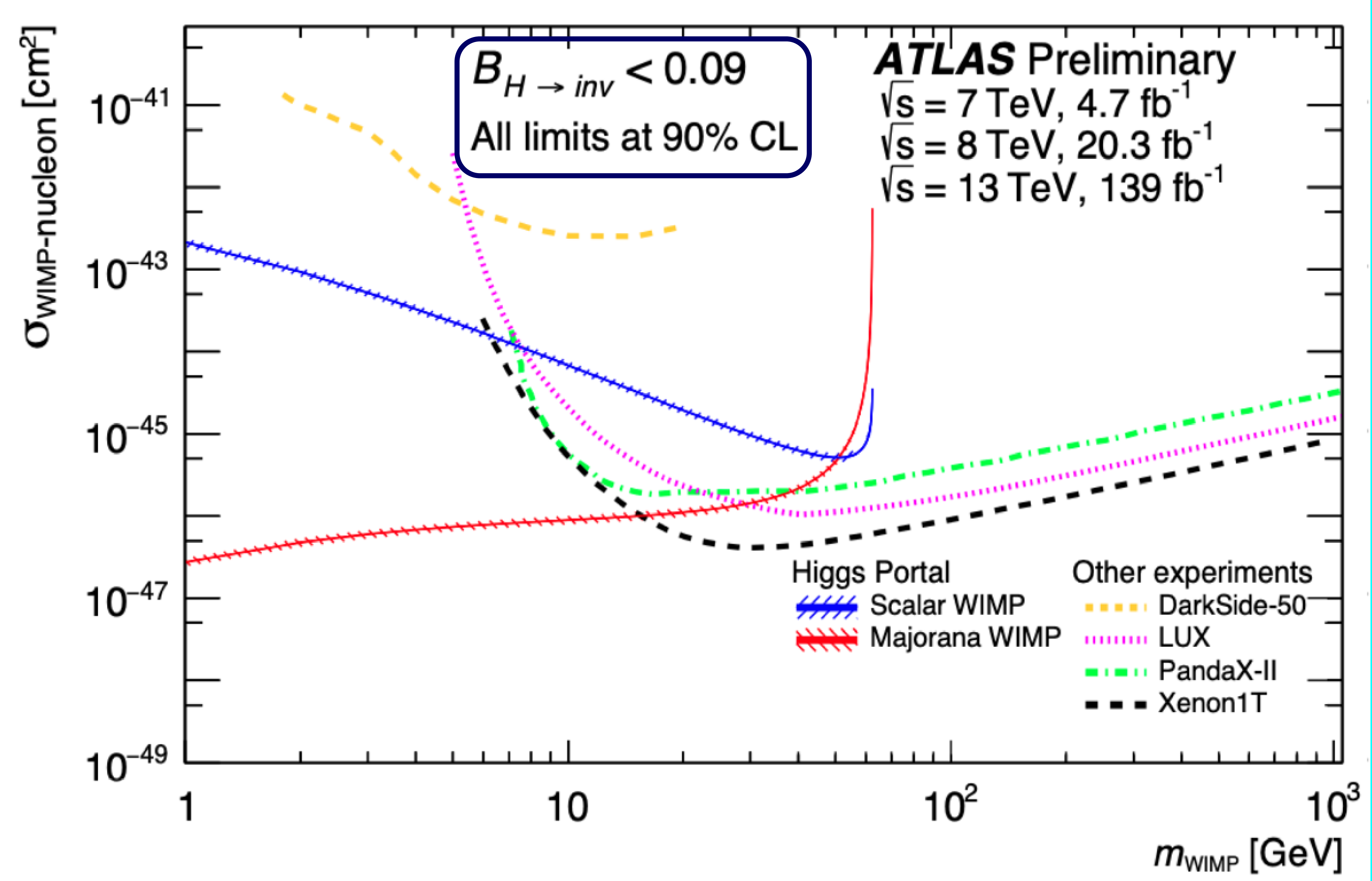
ATLAS CONF-2020-052

Higgs → Invisible Search Combination

Full Run1 + Run2



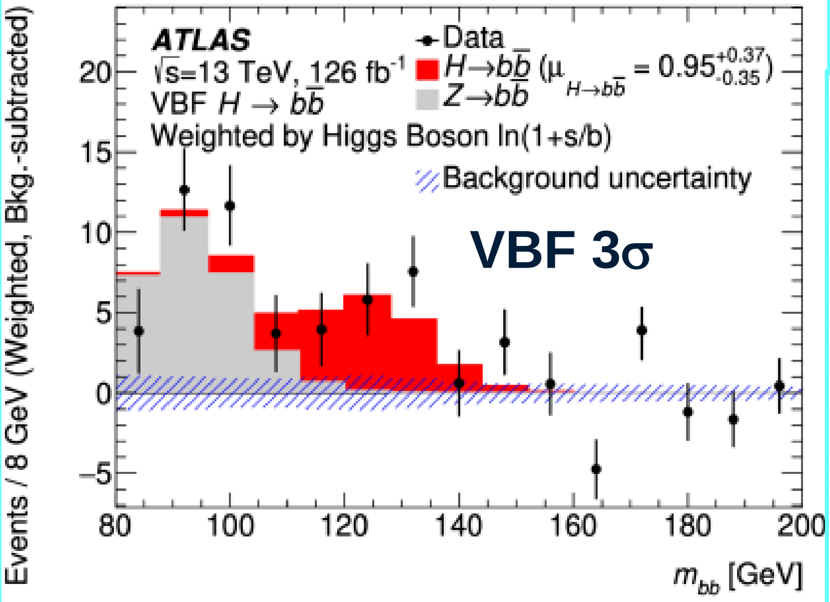


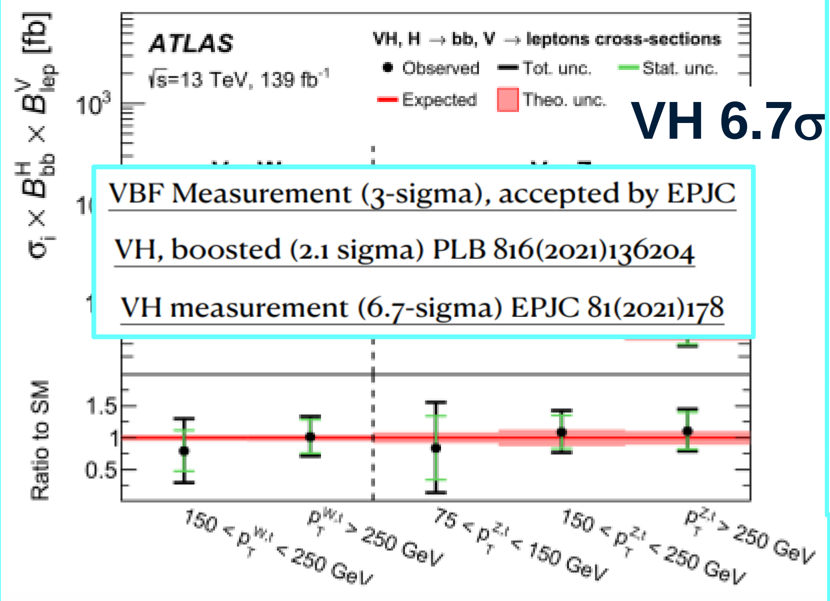


Higgs → bb: VBF, VH boosted

Full Run2 139/fb

ATLAS CONF-2021-010



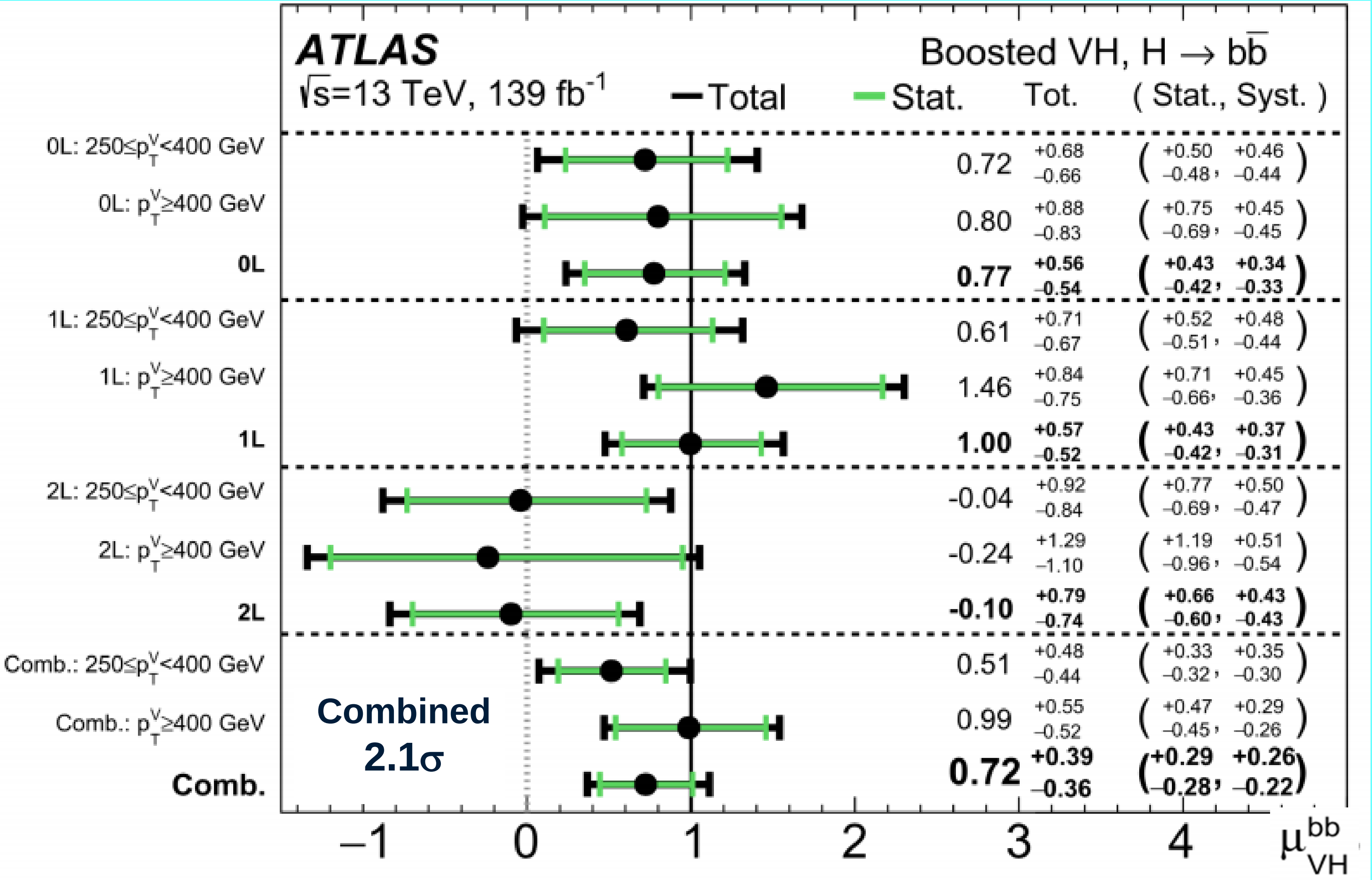


VBF Measurement (3-sigma), accepted by EPJC

VH, boosted (2.1 sigma) PLB 816(2021)136204

VH measurement (6.7-sigma) EPJC 81(2021)178

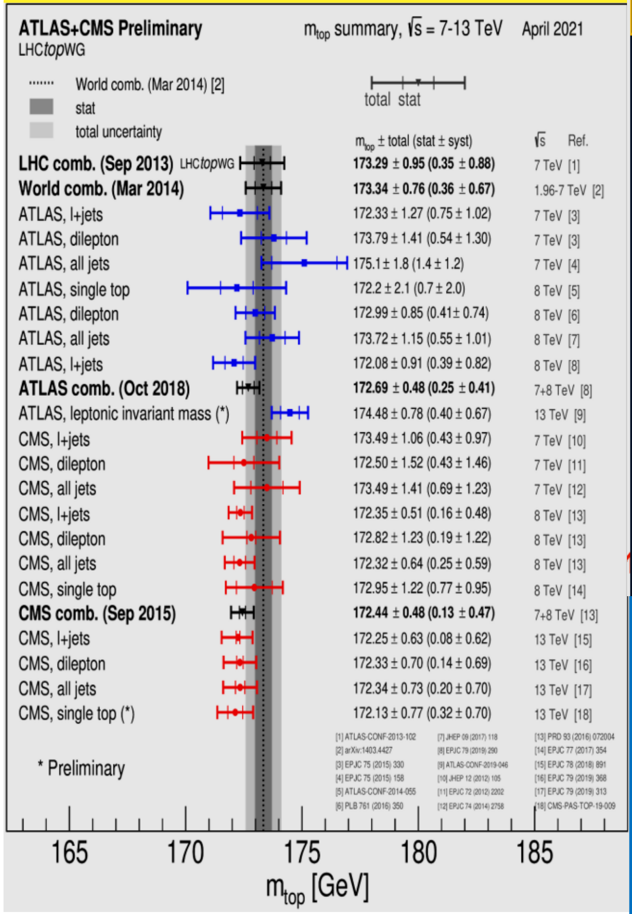
Boosted VH: 0,1,2 Leptons, Medium and High p_T + Combined



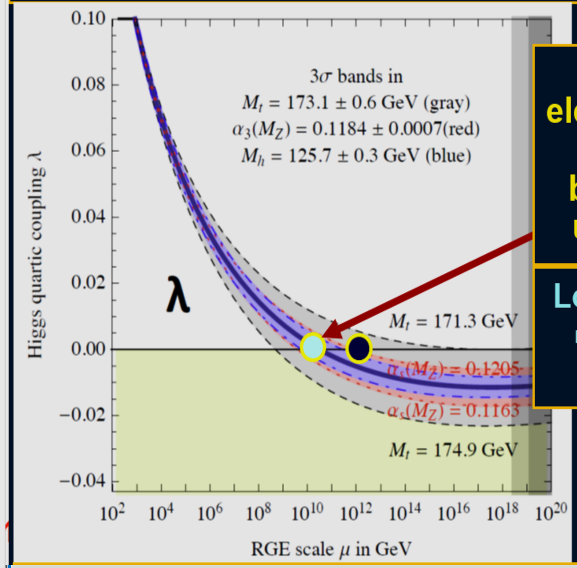
VBF: *Eur. Phys. J. C. 81 (2021) 537* Boosted VH: *Phys. Lett.B 816 (2021) 136204*

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



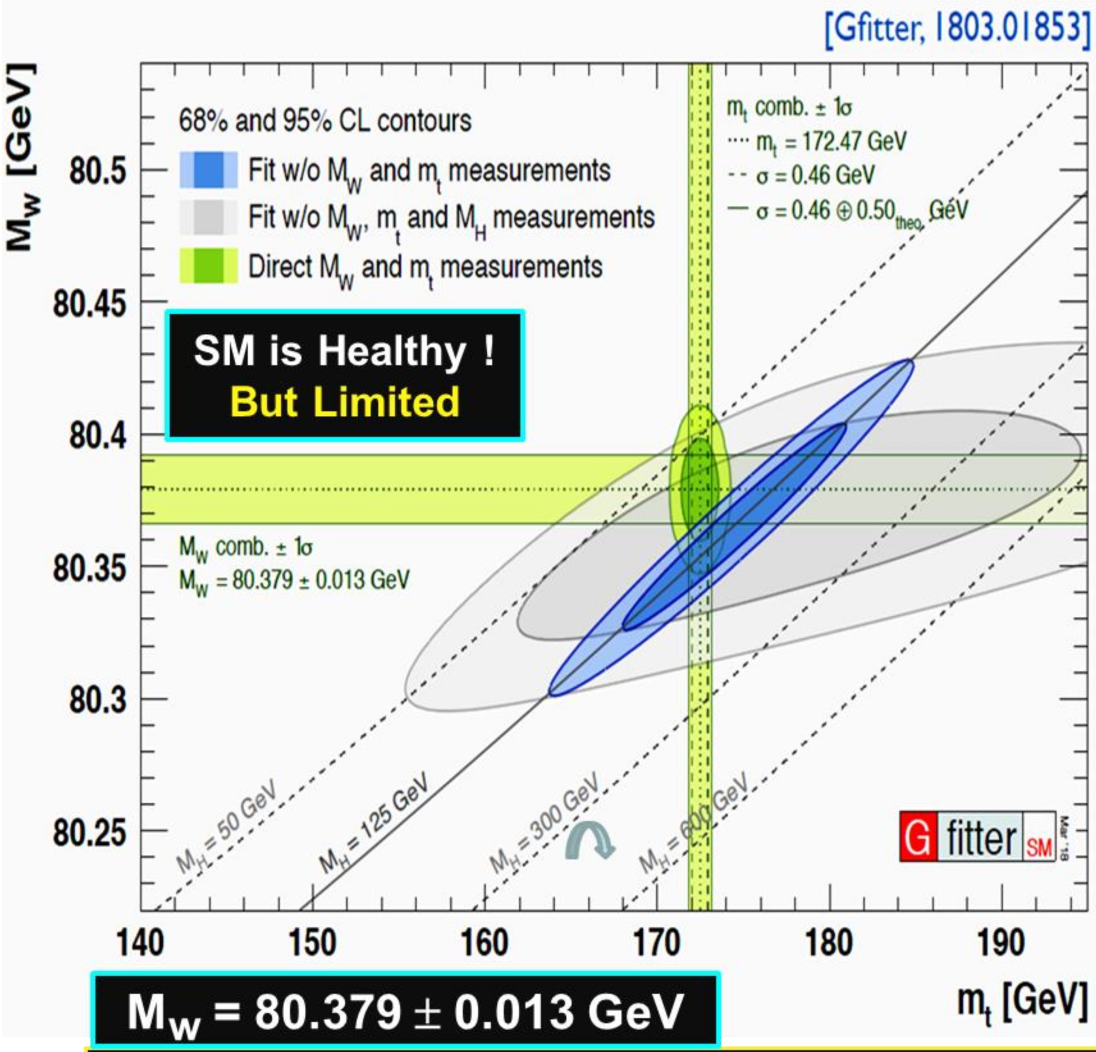
λ < 0 ➔ electroweak vacuum becomes unstable

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