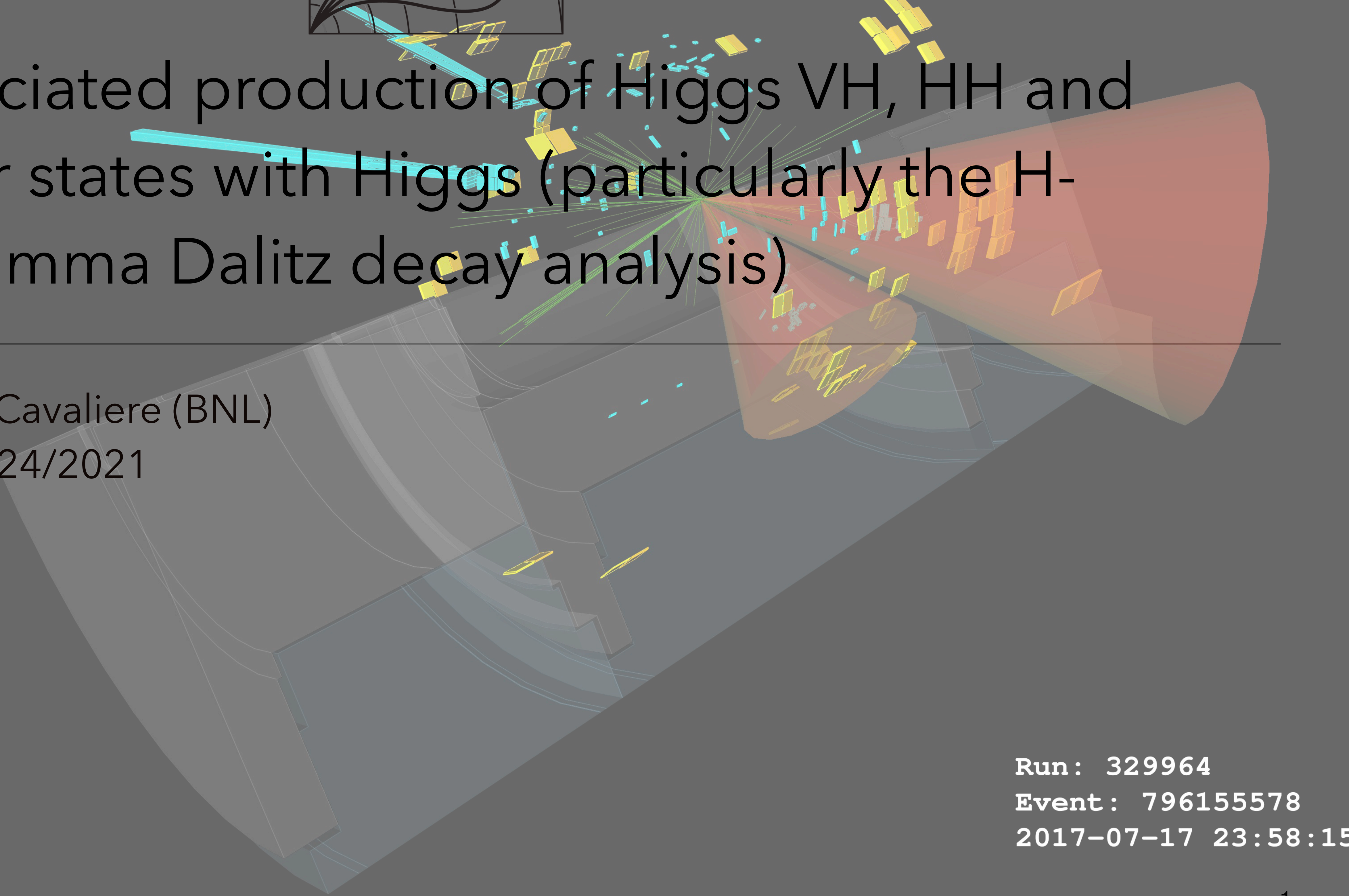
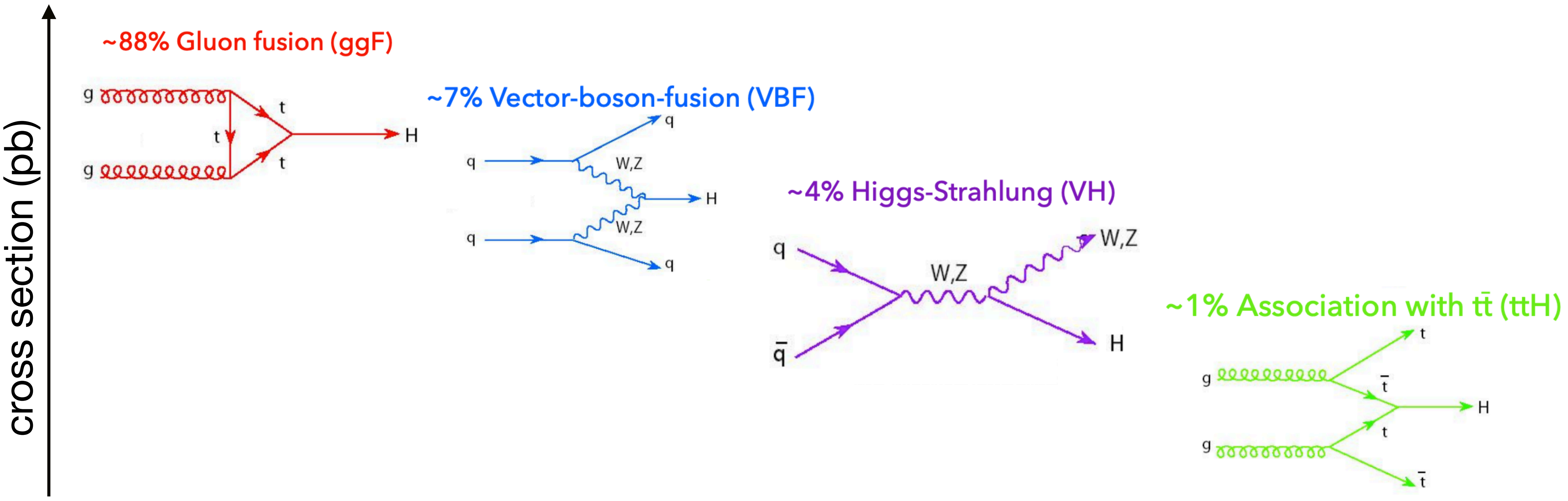
Associated production of Higgs VH, HH and other states with Higgs (particularly the H->llgamma Dalitz decay analysis)

Viviana Cavaliere (BNL)
MBI 08/24/2021



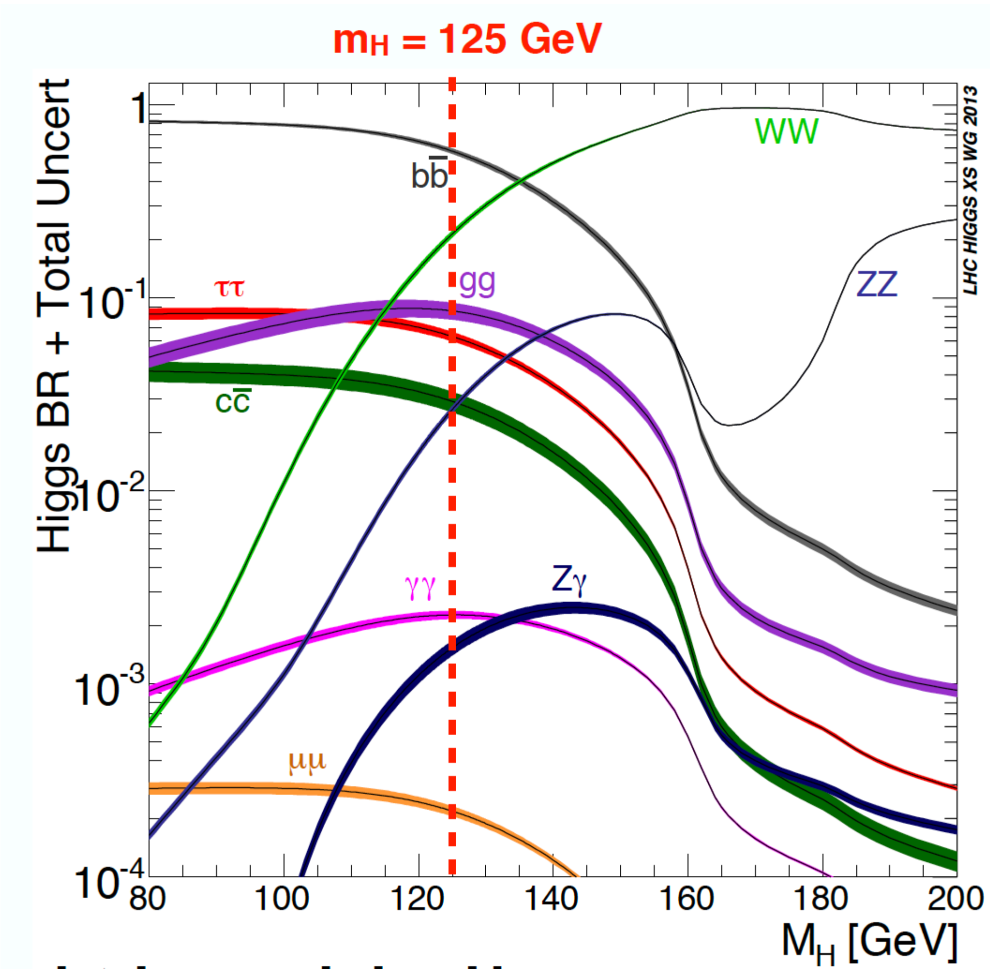
Introduction

- The discovery of the Higgs boson has opened the door to a wealth of phenomenology available for study
  - Higgs couples directly to all massive particles
  - Variety of production / decay modes within reach at the LHC
- All leading Higgs production modes have by now been observed



ggH & ttH give access to top-quark Yukawa coupling while VH & VBF to weak boson couplings

Higgs boson decays

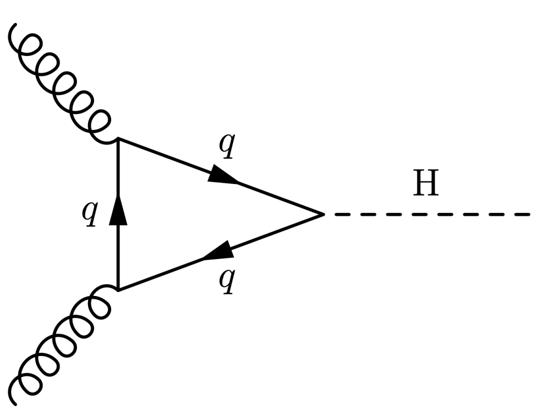


- Decay modes already established at the LHC:
  - $\mathcal{B}$(H → bb) ≈ 58 %
  - $\mathcal{B}$(H → WW*) ≈ 21 %
  - $\mathcal{B}$(H → ττ) ≈ 6.3 %
  - $\mathcal{B}$(H → ZZ) ≈ 2.6 %
  - $\mathcal{B}$(H → γγ) ≈ 0.23 %

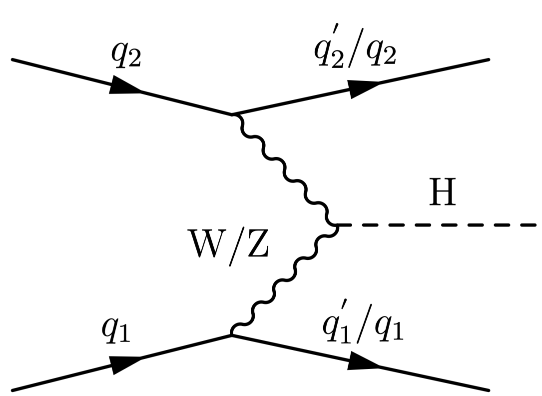
- Decay modes which just recently showed evidence:
  - $\mathcal{B}$(H → μμ) ≈ **2.2*10-4** provides access to Higgs coupling to 2nd generation of fermions
  - $\mathcal{B}$(H → Zγ) ≈ **1.5*10-4**

Simplified Template Cross Section (STXS)

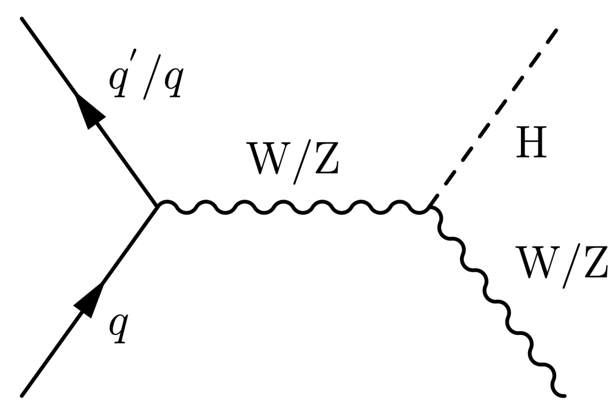
- One pathway to further study the Higgs is to perform cross section measurements within multiple phase space regions
- Two complementary approaches are being explored
  - Simplified template cross sections
  - Differential cross sections
- ATLAS, CMS and the theory community have been working together in the LHC Higgs Working Group to setup a common framework for Higgs boson measurements in Run 2.
  - STXS targets phase space regions within production modes, using Standard Model kinematics as a template.
    - Categorize each production mode in bins of key (truth) quantities
    - Reduce theory systematics, but more model-dependent.
    - No decay information available in STXS (for the moment).



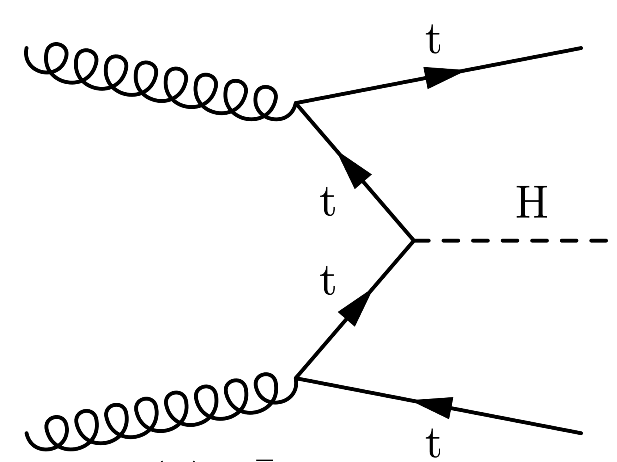
(a) Gluon Fusion



(b) Vector Boson Fusion



(c) Higgsstrahlung



(d) $t\bar{t}$ Production

$p_T(H)$
N_{jet}
M_{jj}, $p_T(H+jj)$

$p_T(H)$
N_{jet}
M_{jj}, $p_T(H+jj)$ (if Njets>1)

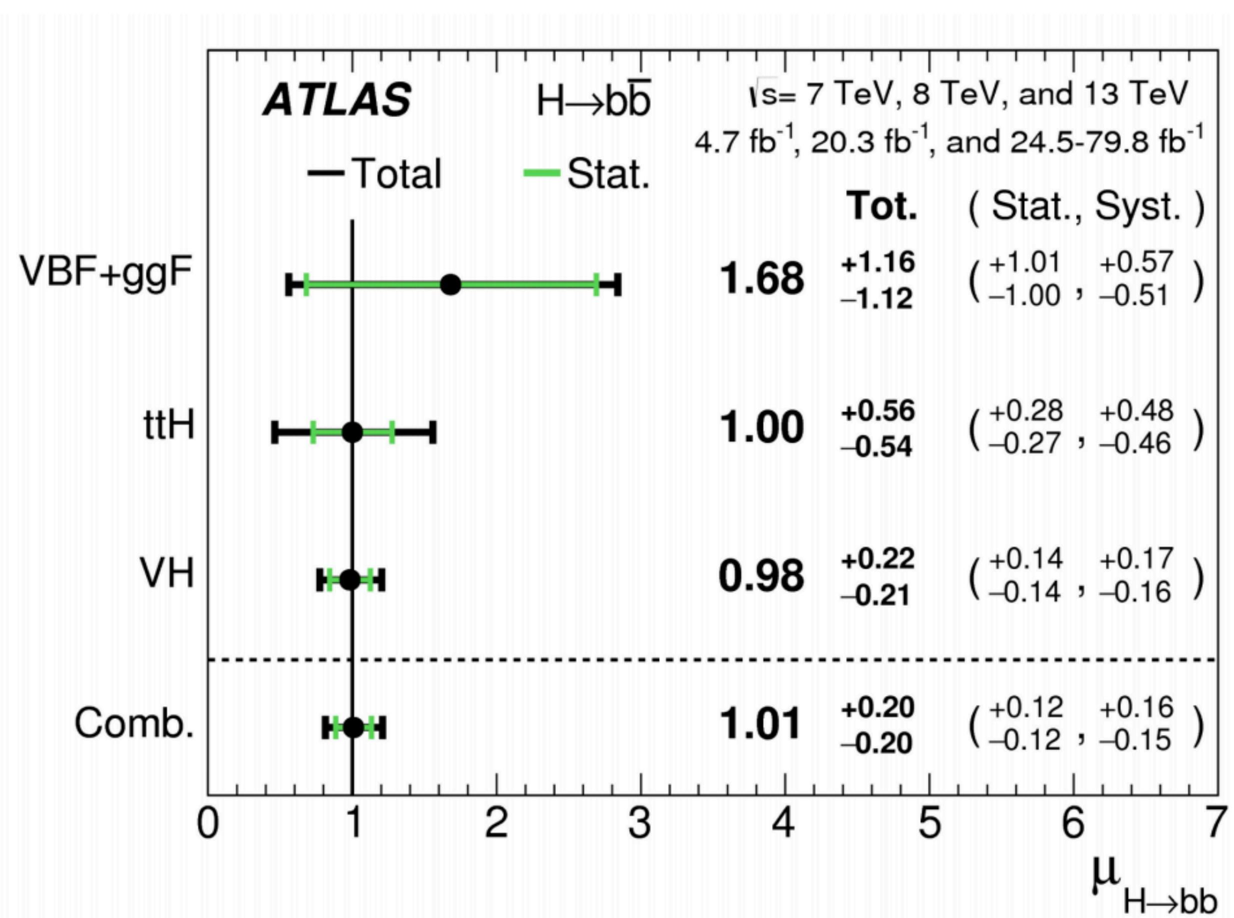
$p_T(V)$

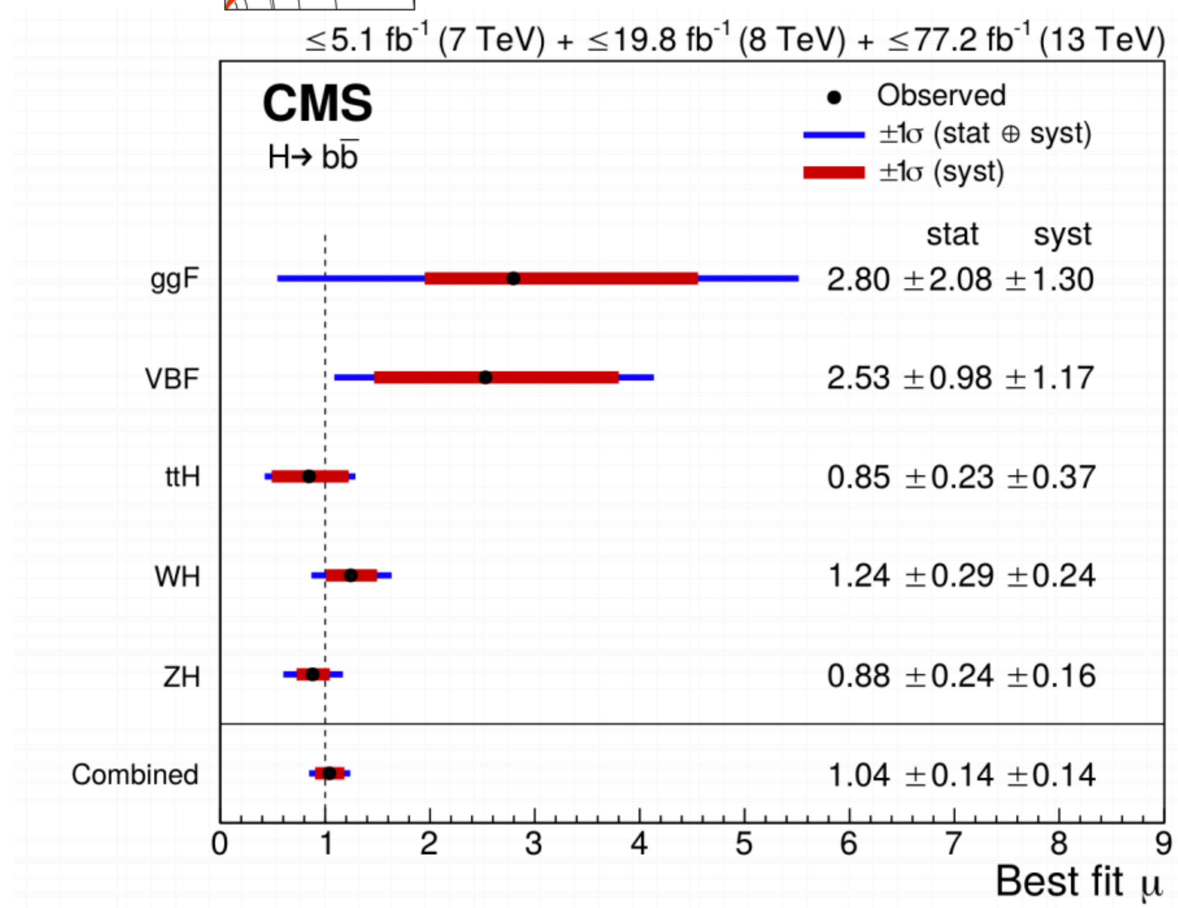
$p_T(H)$

Higgs boson production using decays to two b-quarks

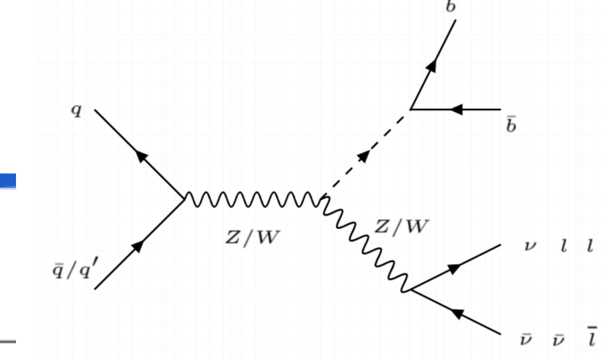
Observation of H->bb

- Observation of H→bb with Run I and partial Run II datasets independently by the ATLAS and CMS collaborations in 2018
  - most sensitive Higgs production channel: VH →suppression of multi-jet background due to leptonically decaying vector boson
  - all measurements so far consistent with the SM





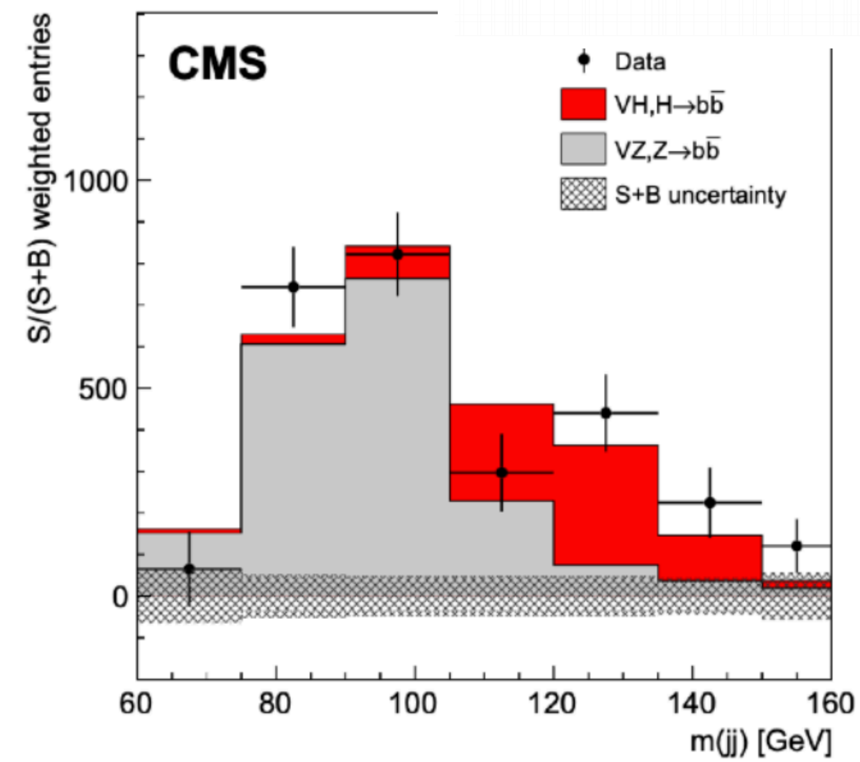
Resolved VH->bb (ATLAS and CMS)

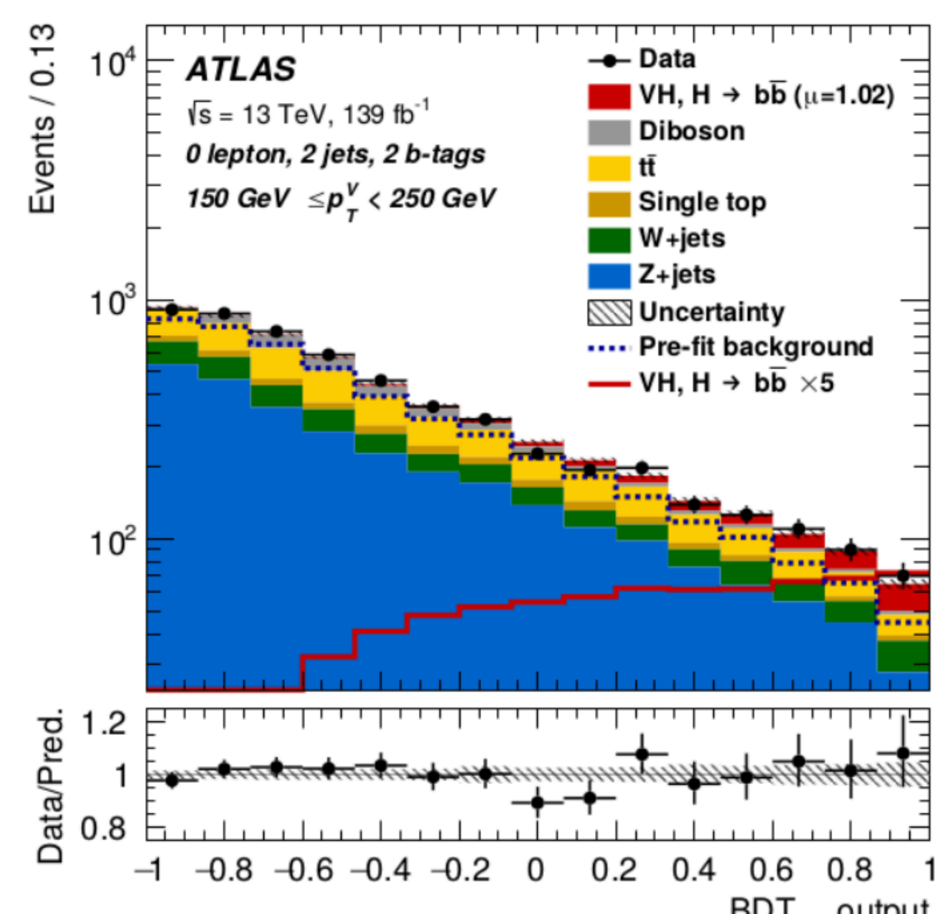


- Higgs production in association with W/Z boson decaying into leptons (event selection: 0,1 or 2 charged leptons with two b-jets)
- ATLAS: fit to the BDT output; CMS: fit to the DNN
- dominant backgrounds: V+jets, tt, single-top quark and diboson
- dominant uncertainties: b-tagging, jet & ET,miss, background modelling and signal systematic uncertainties
- CMS:

	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.22

- ATLAS: observed (expected) significance: VH→bb: 6.7 (6.7) σ in combination: ZH: 5.0 (5.4) σ, WH: 6.3 (5.2) σ





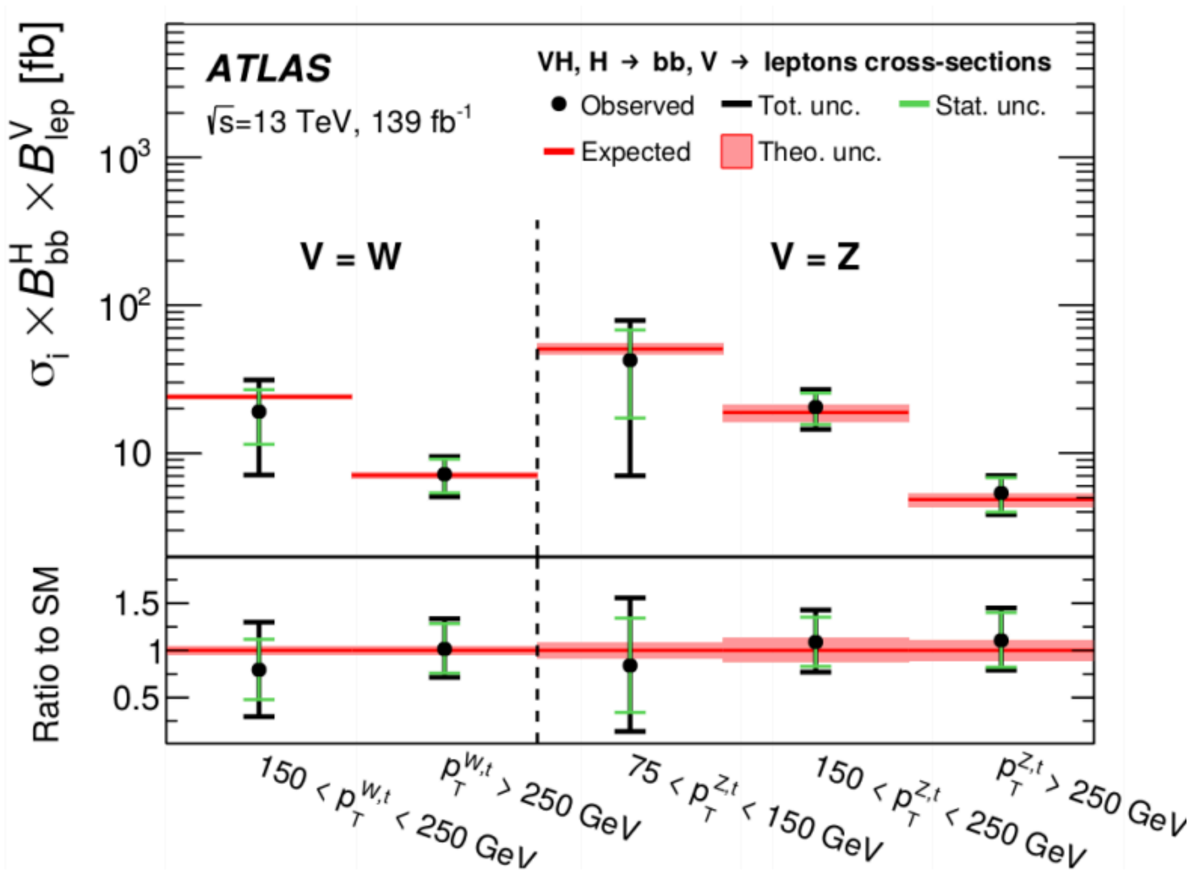
BSM constraints from VH

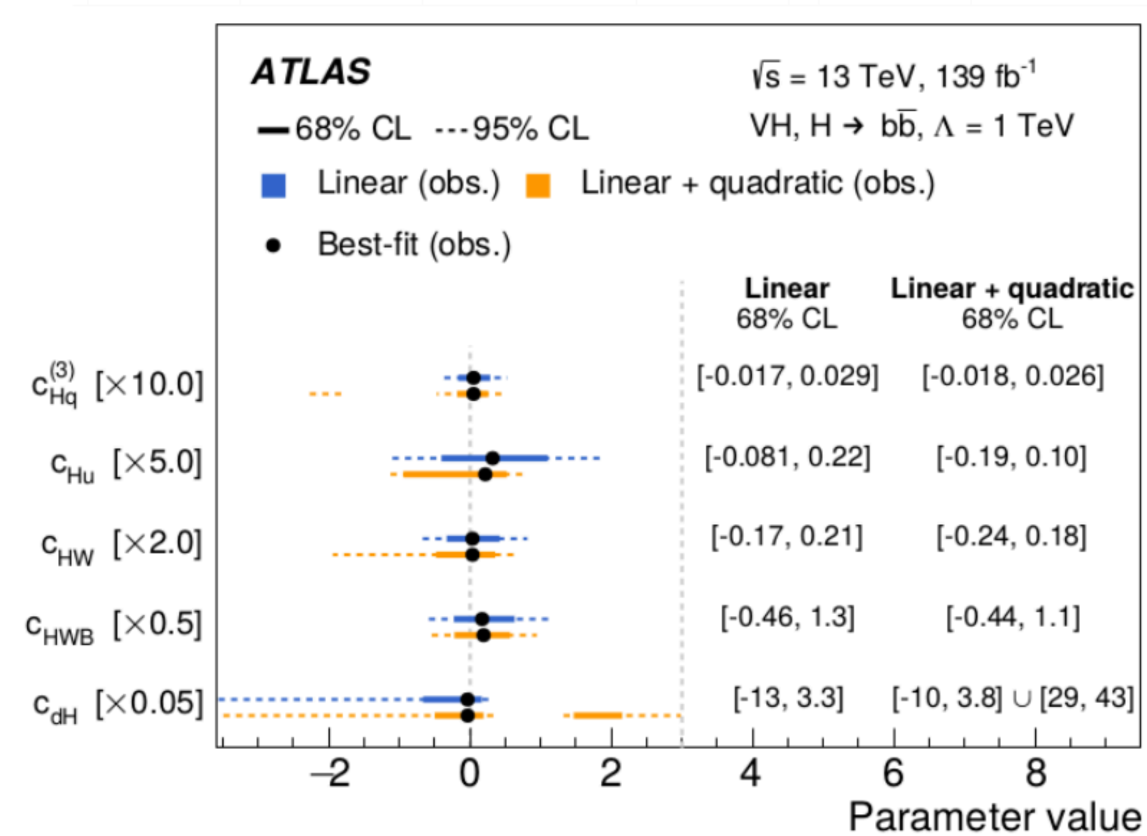
- Effective Lagrangian with dimension-six operators added to SM.
- Consider operators which modify H-W and/or H-Z interactions
- Access to VH production via H→b$\bar{b}$ allows direct constraints on these operators.

- $\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H)\, W^a_{\mu\nu}$,
- $\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H)\, B_{\mu\nu}$,
- $\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$,
- $\mathcal{O}_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$.

$$\bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2}, \quad \bar{c}_d = v^2\frac{c_d}{\Lambda^2},$$

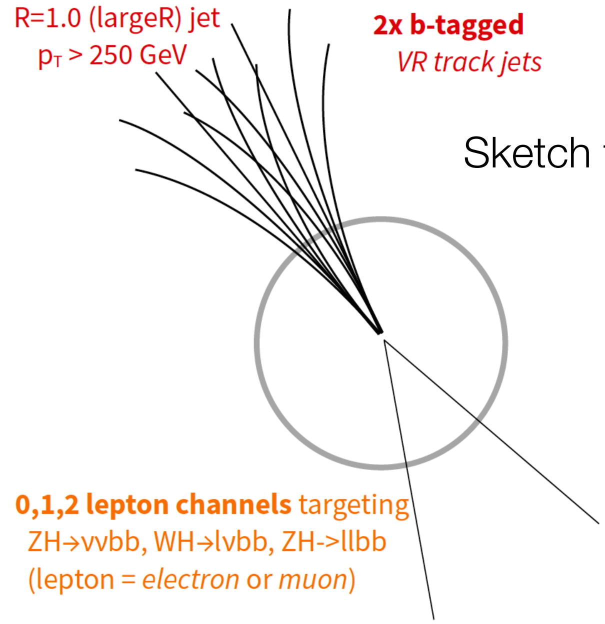
- Extracted cross section measurement in STXS bins (https://arxiv.org/pdf/1906.02754.pdf)
- used to set limits on dim-6 EFT operators





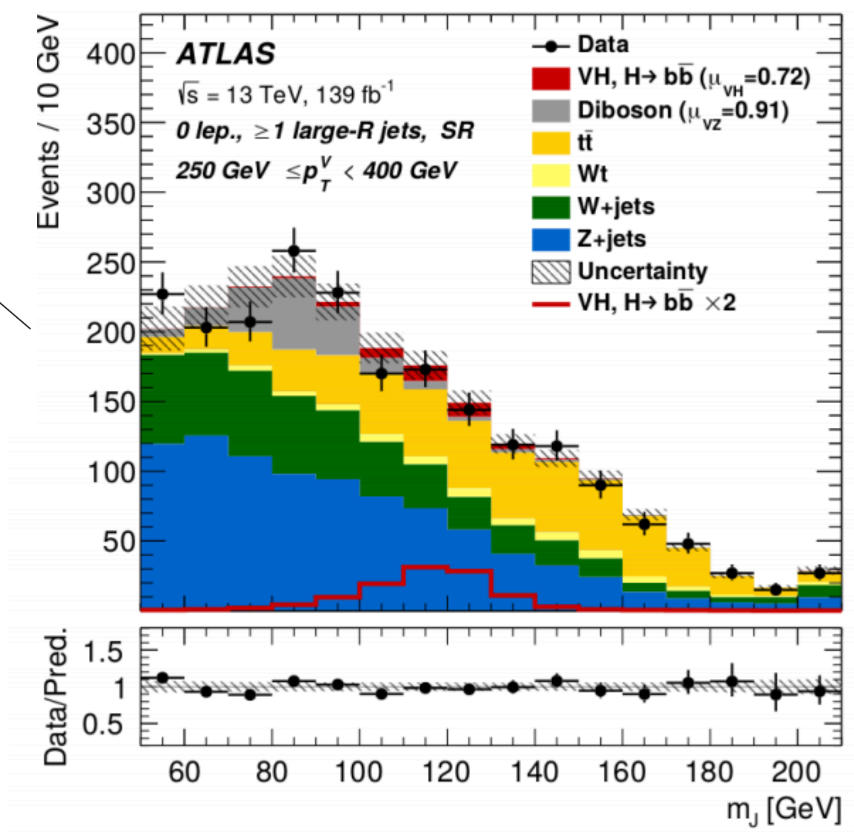
VH-> bb (boosted)

HIGG-2018-52

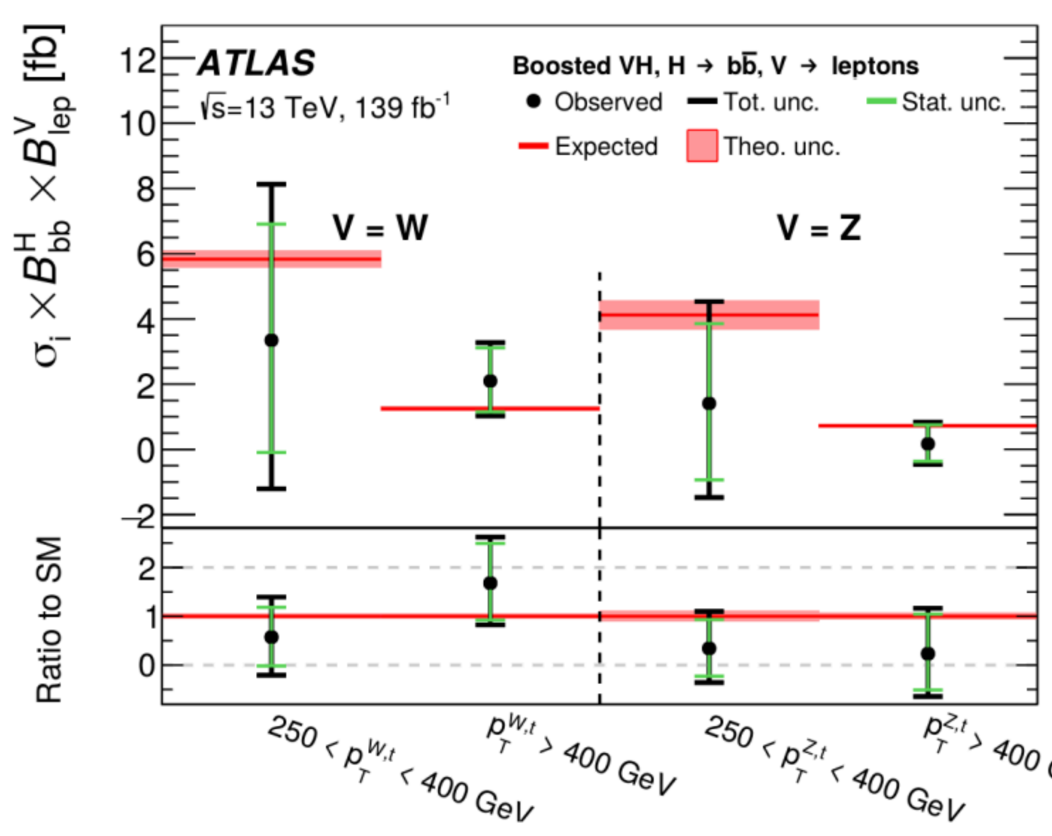


Sketch from K. Kritza

- new boosted analysis
- Higgs boson reconstruction as single large R-jet (R=1.0, pT > 250 GeV)
- track jets formed from charged-particle tracks for reconstruction of two-body decay within large R-jet
  - b tagging performed on track jets

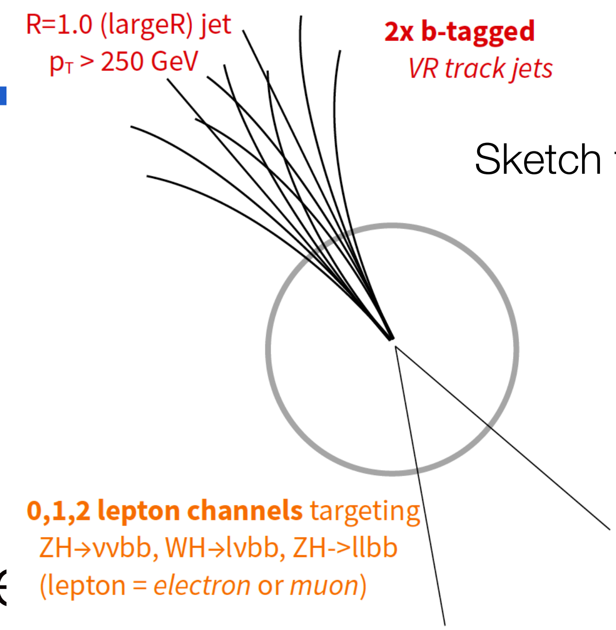


- signal extraction with profile likelihood fit to large R jet-mass
- dominant uncertainties: statistical including floating background normalization, large R-jet calibration, limited MC statistics
- Combination with resolved channel in progress
- Adds the pt bin> 400 GeV



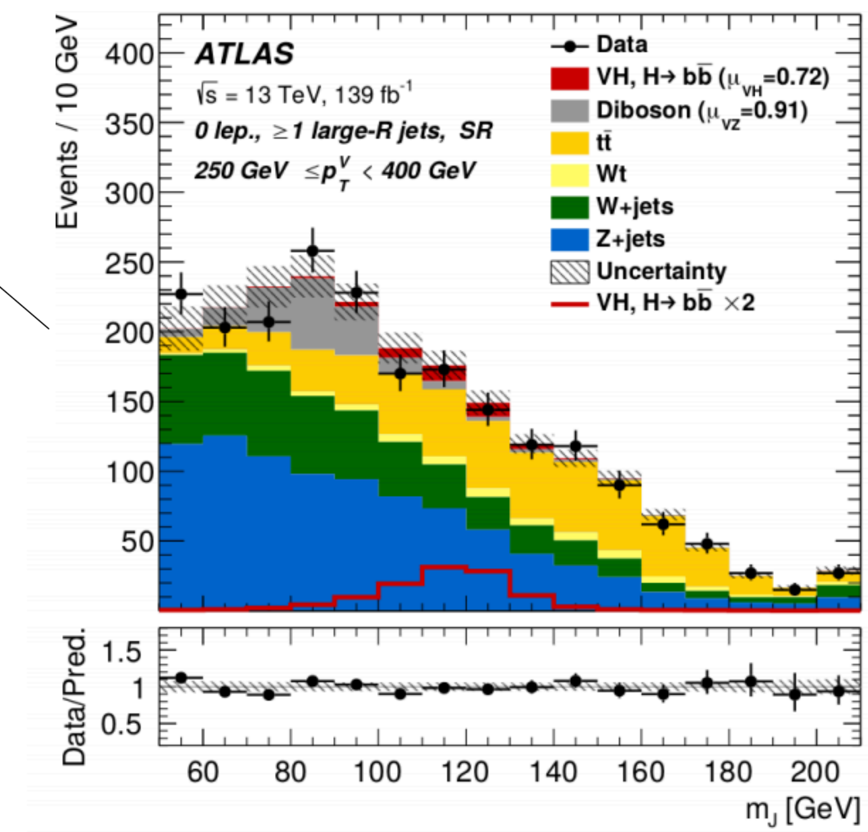
VH-> bb (boosted)

HIGG-2018-52

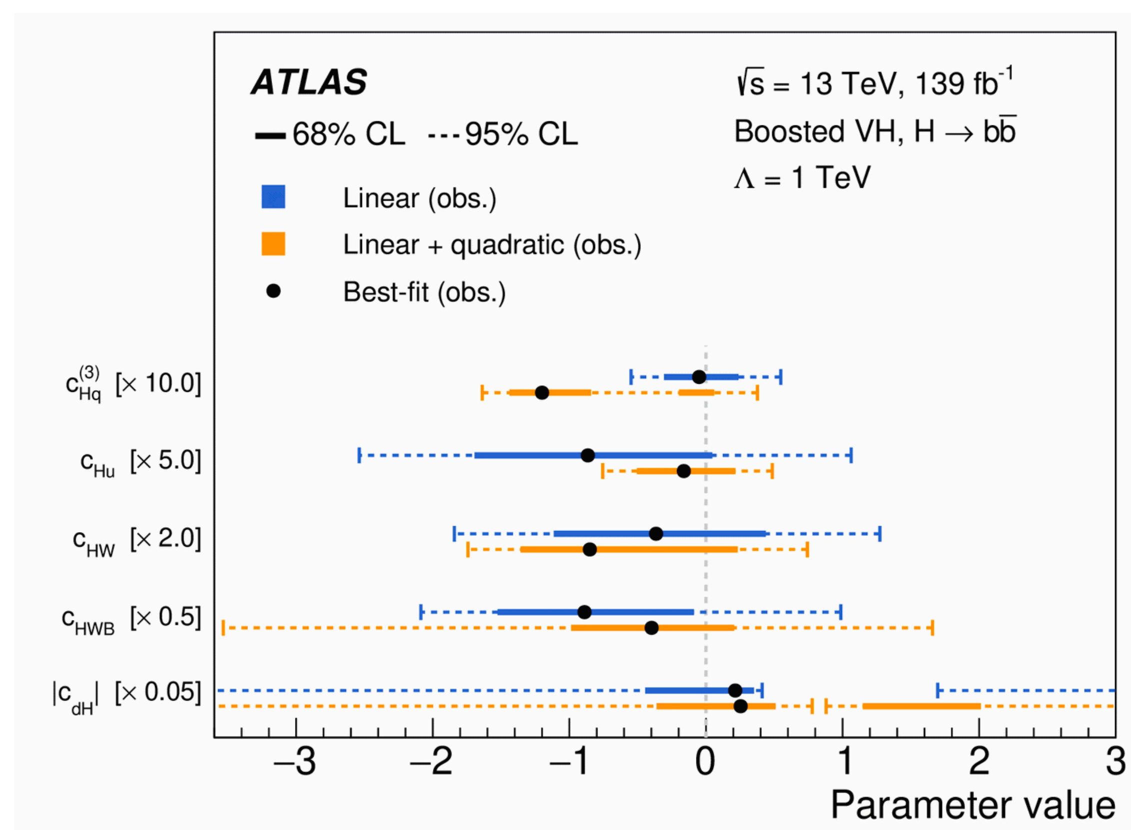


Sketch from K. Kritza

- new boosted analysis
- Higgs boson reconstruction as single large R-jet (R=1.0, pT > 250 GeV)
- track jets formed from charged-particle tracks for reconstruction of two-body decay within large R-jet
  - b tagging performed on track jets

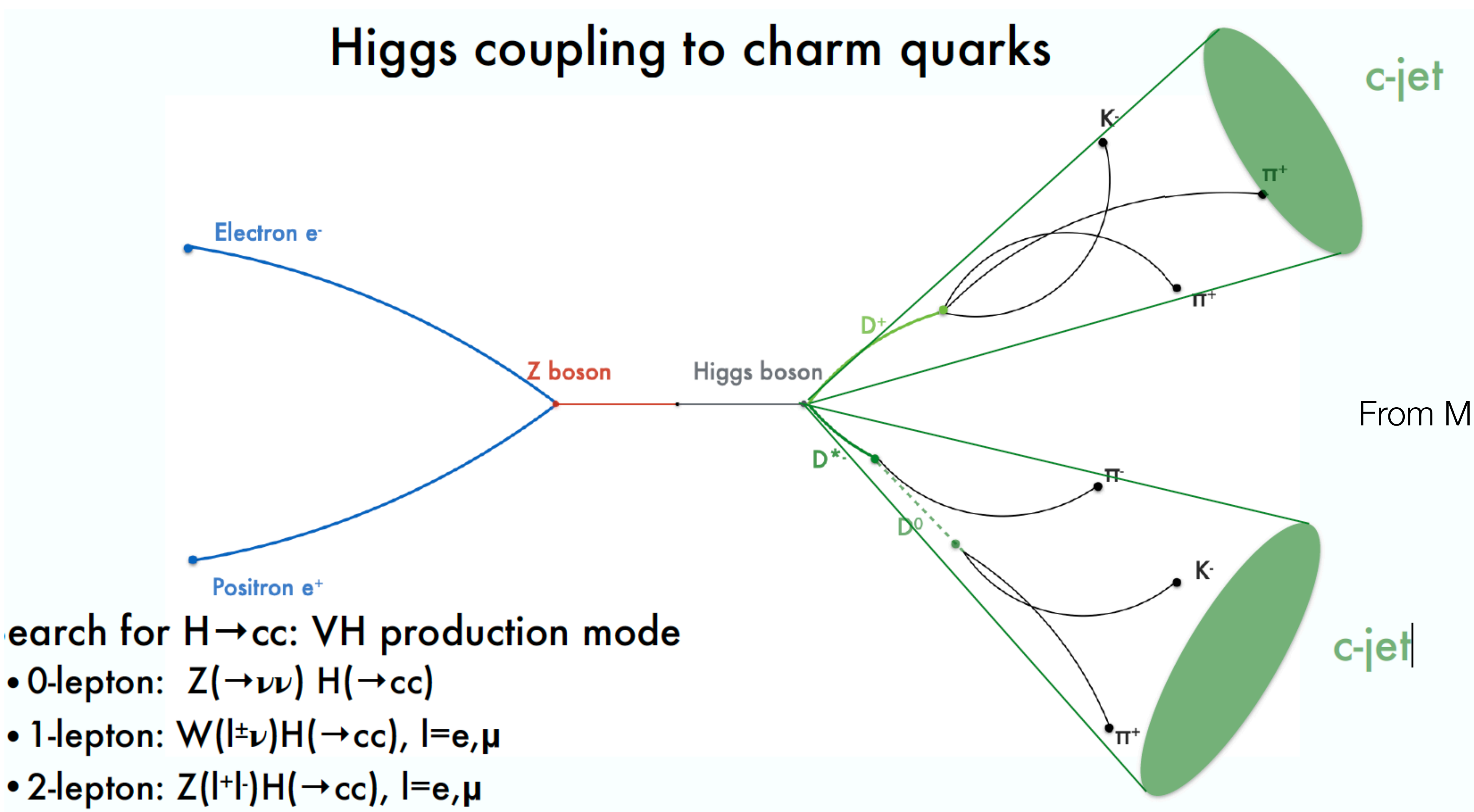


- signal extraction with profile likelihood fit to large R jet-mass
- dominant uncertainties: statistical including floating background normalization, large R-jet calibration, limited MC statistics
- Combination with resolved channel in progress
- Adds the pt bin> 400 GeV



Higgs couplings to 2nd gen quarks

- Test of Yukawa interactions w/ 2nd generation fermions: evidence for leptons only
- Search for H—> cc in associated production
- Dedicated charm tagging

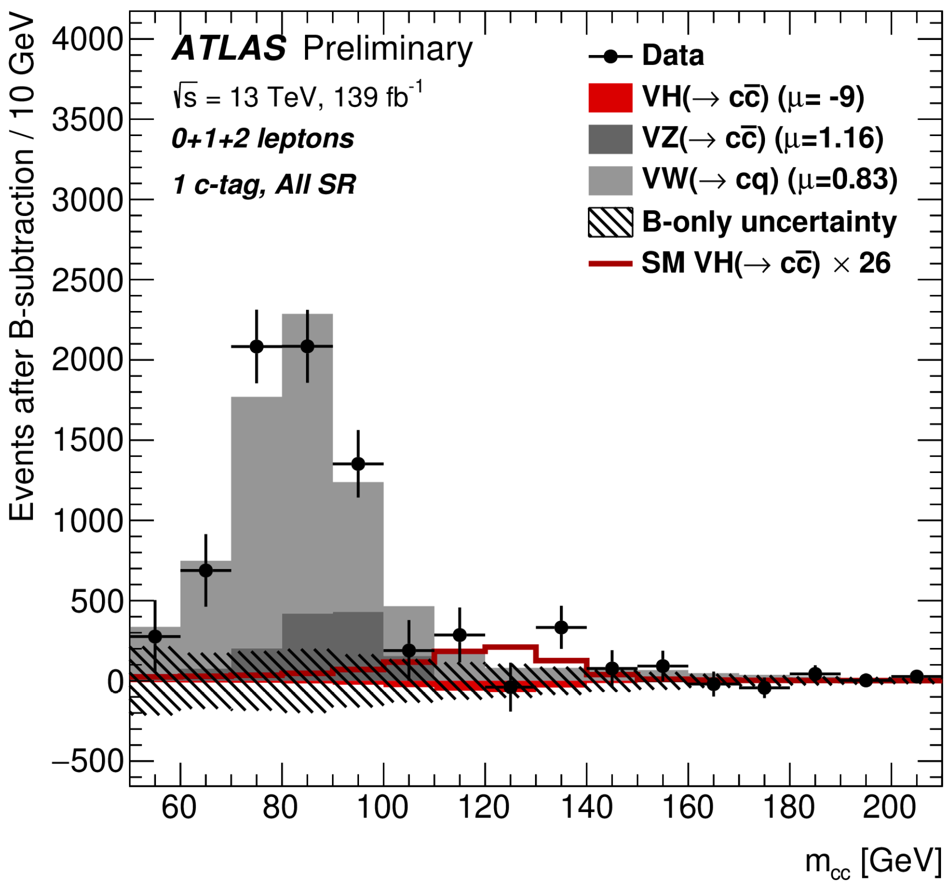


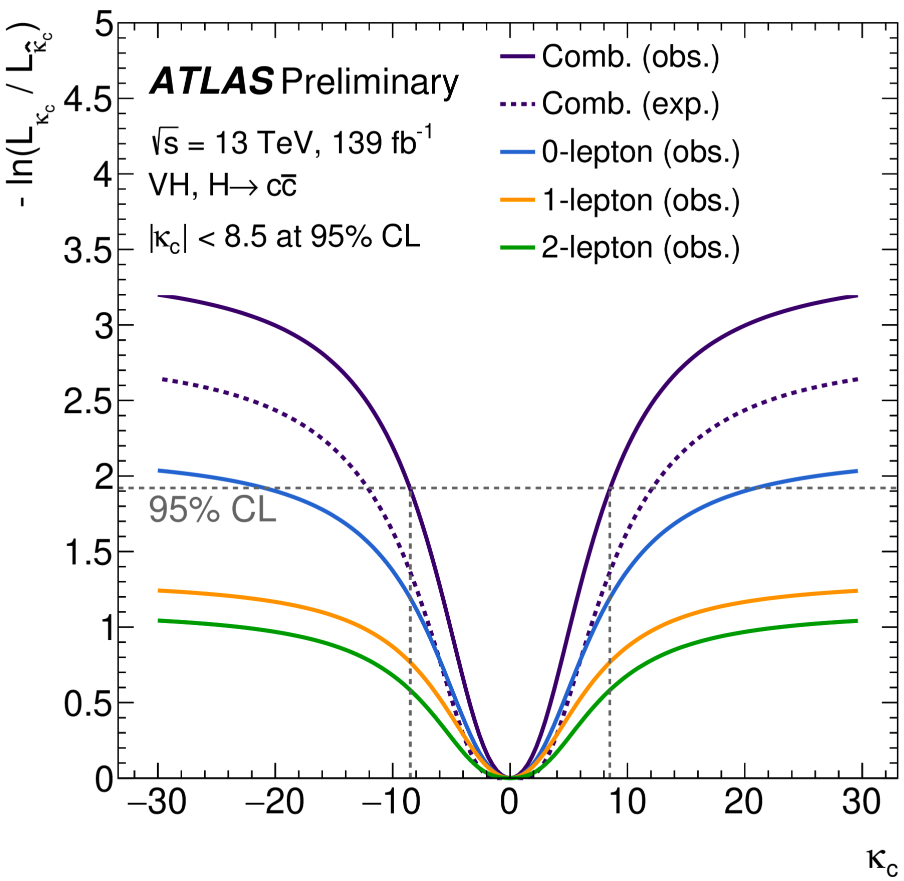
From M Stamenkovic (EPS talk)

Higgs couplings to 2nd gen quarks

ATLAS-CONF-2021-021

- Main backgrounds: Z+jets, W+jets and ttbar
- Discriminant: **m(cc)**
- Diboson fit results: validation of the analysis
  - VZ(cc): **2.6σ observed** (2.2 expected)
  - VW(cq): **3.8σ observed** (4.6 expected)
  - → First measurement of VZ(cc) and VW(cq) using c-tagging!



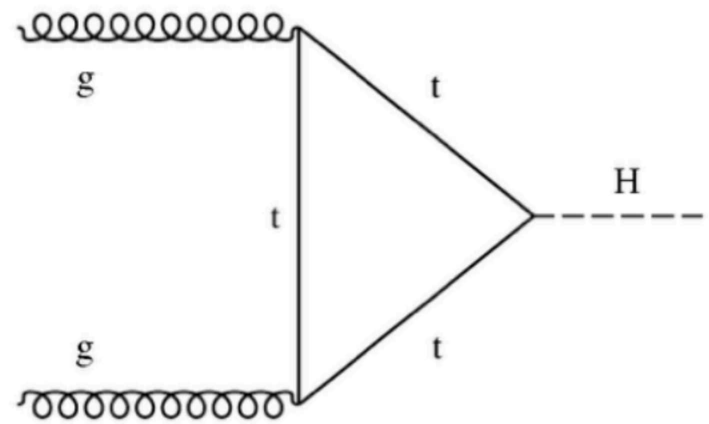


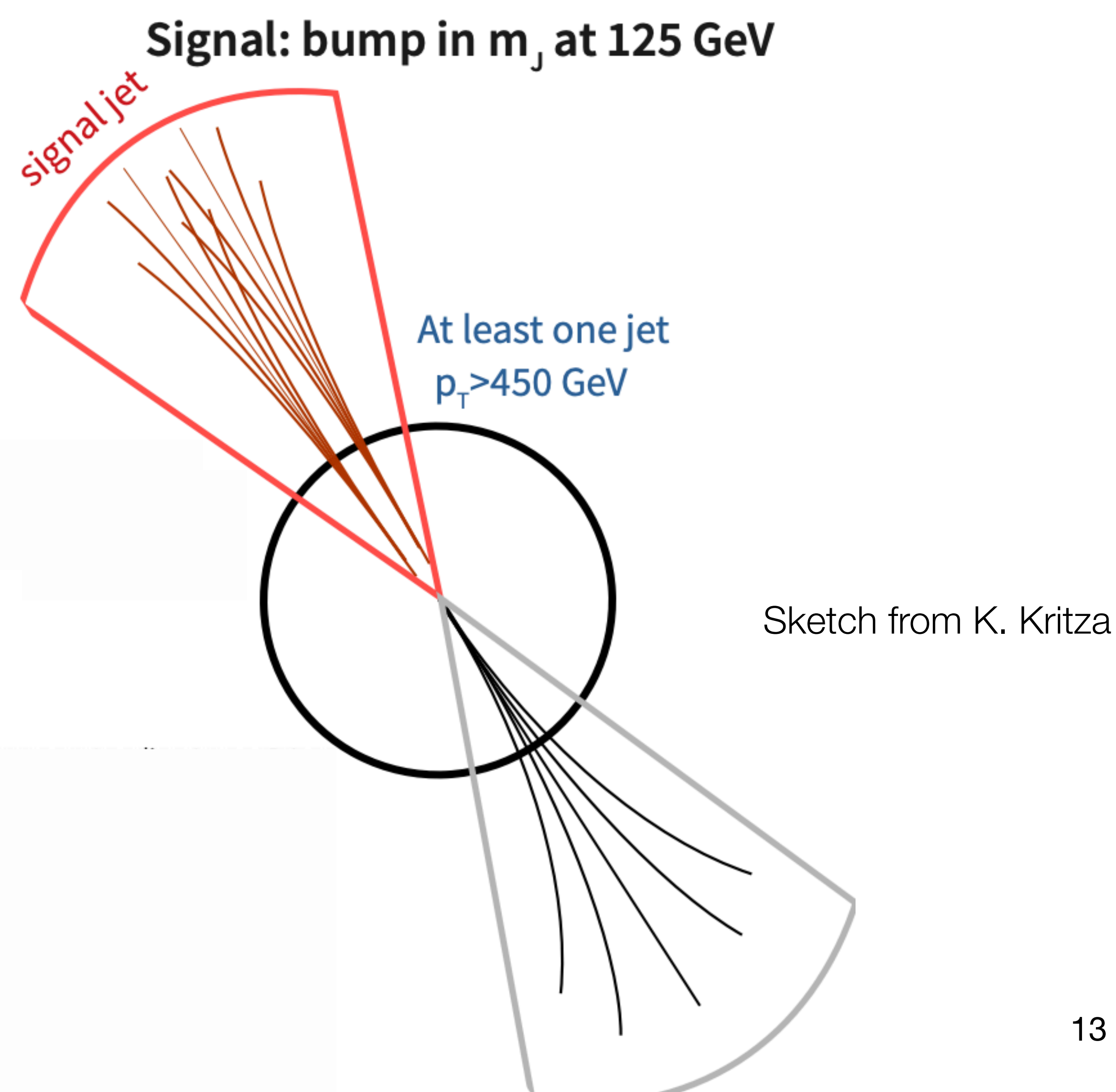
- κ_C interpretation: quantify possible deviations from the SM
  - Assume κ_i = 1 for other fermions and bosons and no BSM contributions to Higgs width
  - Only sensitive to κ_C if μ < 35 due to Higgs width in parametrisation
  - Direct constraint: | κc | < 8.5 @ 95% CL (<12.4 @ 95%CL expected)
  - Similar sensitivities to κ_C between direct and indirect constraints → Complementary approaches

Limit on signal strength: **$\mu_{H\to cc}$< 26 x SM** @95% CL (< 31x SM expected) → Best limit on VH(cc) up to this day!

ggH (H->bb)

- ggH (H->bb) production is the dominant production mode but overwhelmed by the background
  - Look at boosted selection
- Can probe y_t
- Analysis targeting inclusive in production mode high Higgs
  - sensitivity to BSM
- Inclusive
- pT differential measurement (STXS)
- fiducial measurement (pT,truth>450 GeV)



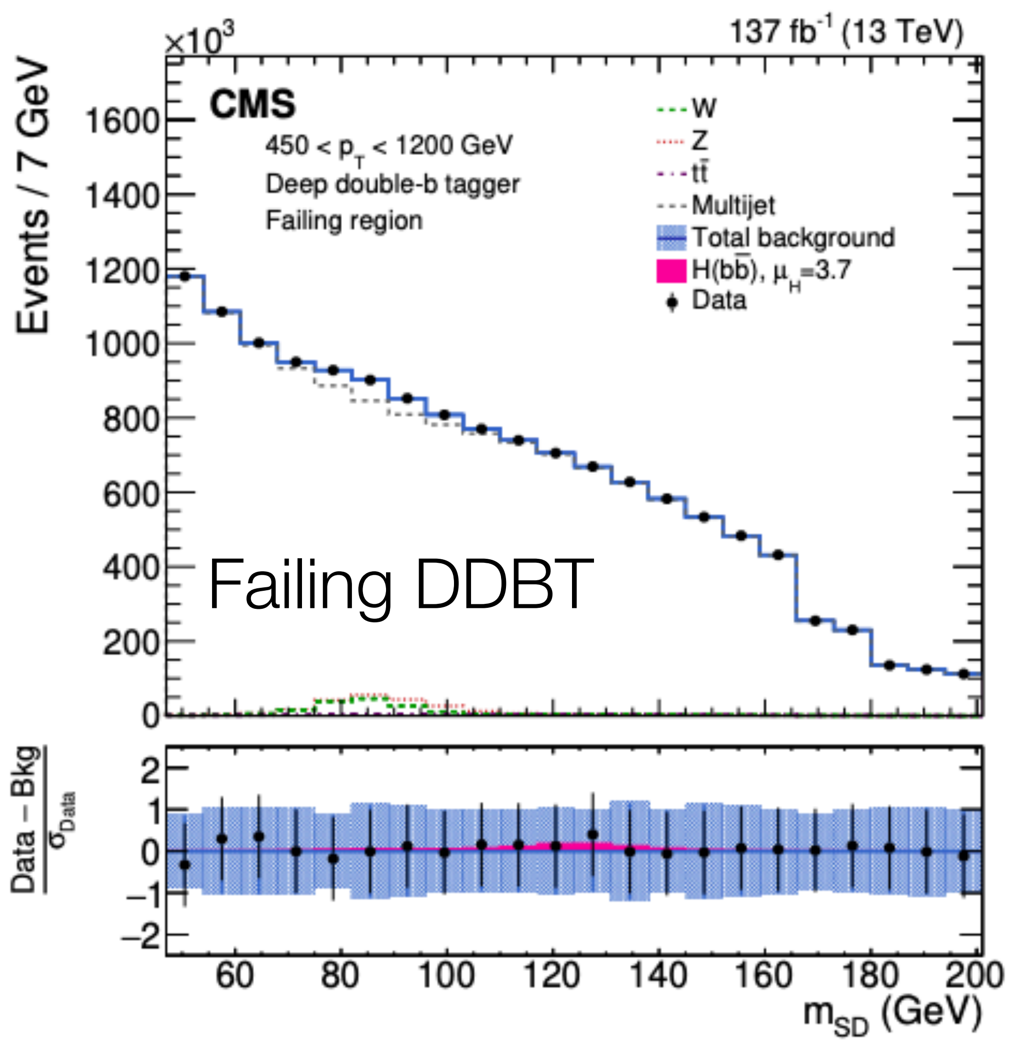


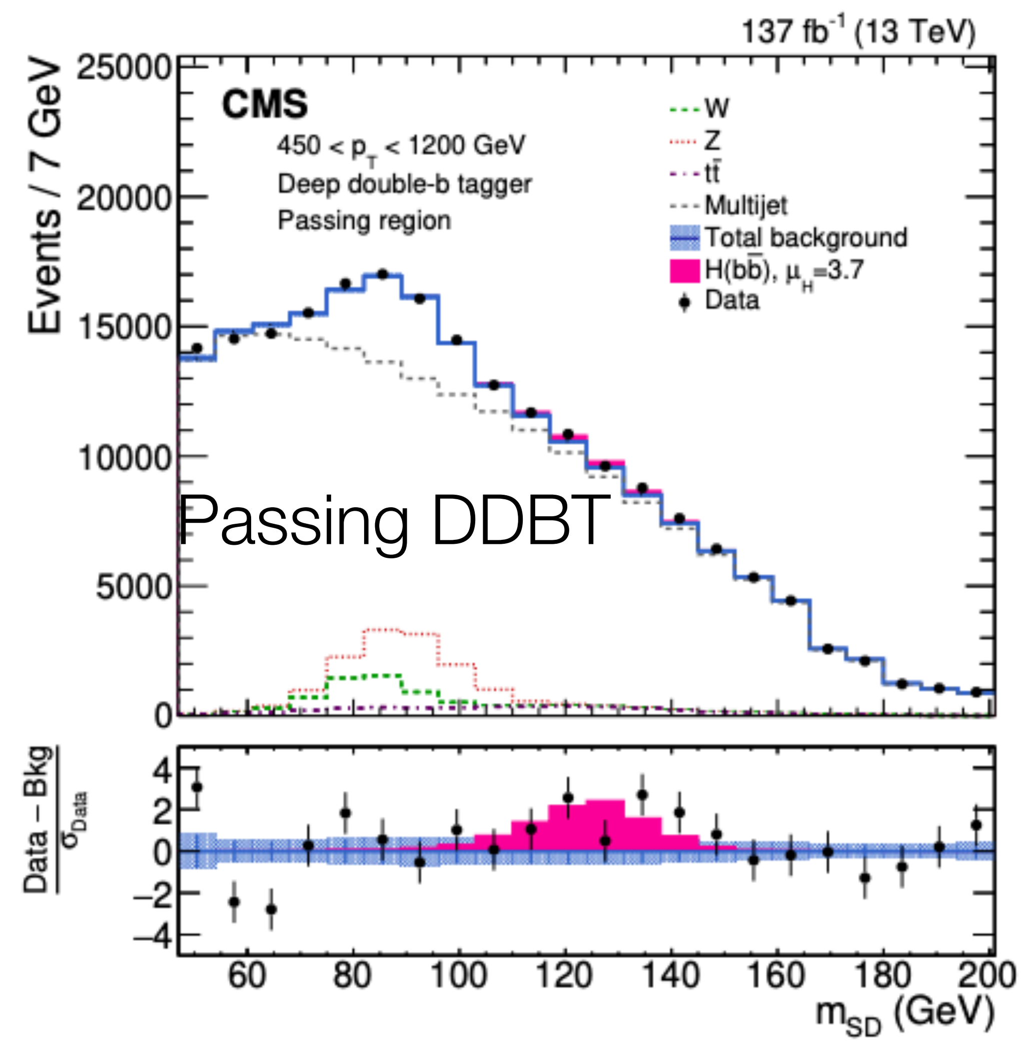
Sketch from K. Kritza

ggH (H->bb) (CMS)

JHEP12(2020)085

- Higgs reconstructed in boosted topology
    - new DeepDoubleBTag (DDBT) algorithm (1.6x signal efficiency)
- QCD bkg. estimated using CR, populated with events failing DDBT selection.
    - Transferred to SR
- Higgs candidate mass is fitted for signal extraction

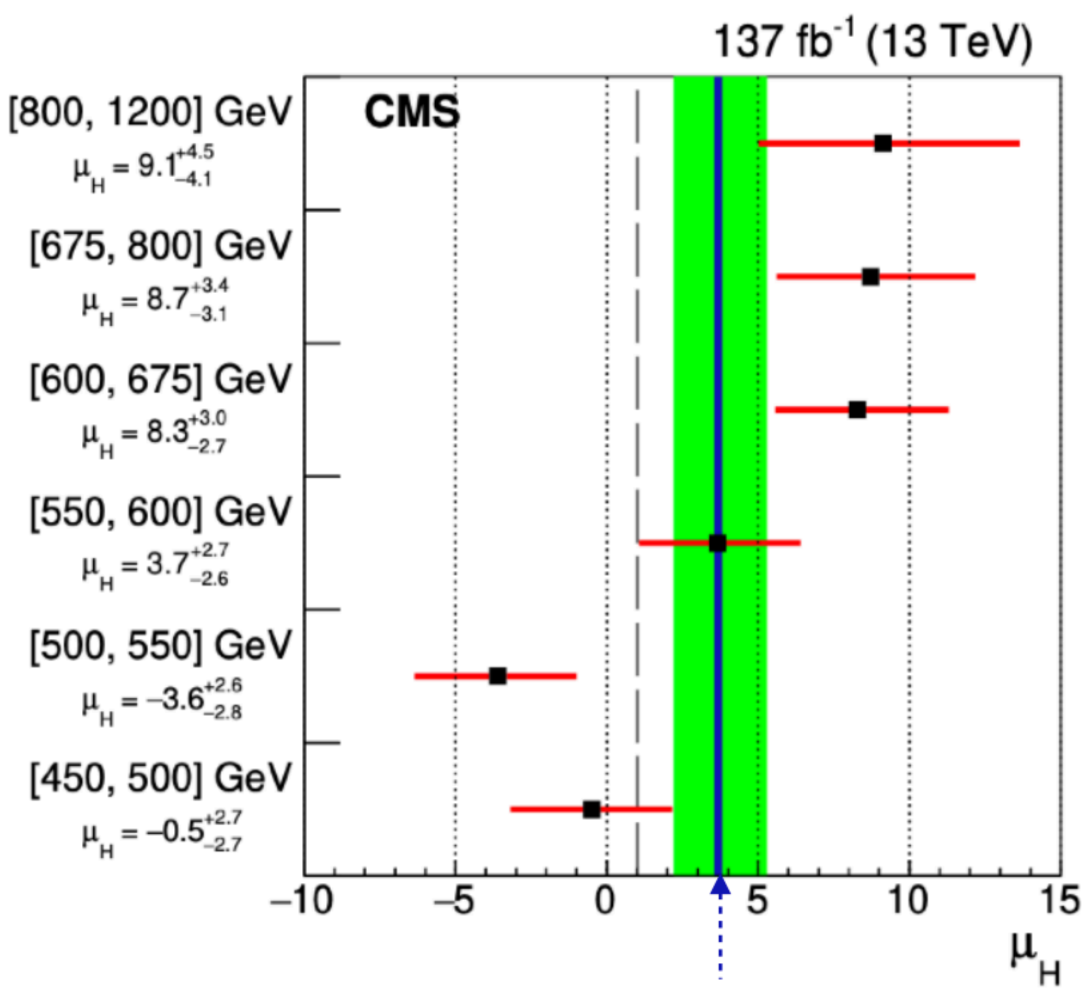


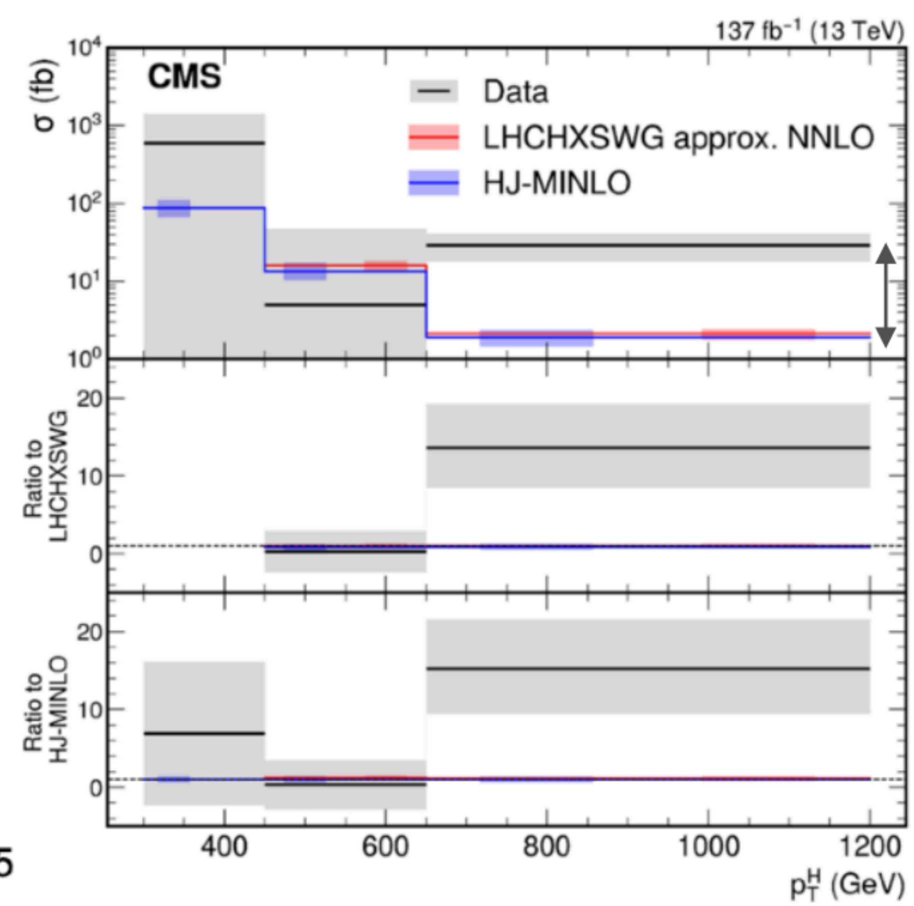


ggH (H->bb) (CMS)

JHEP12(2020)085

- Other processes are fixed to SM prediction:
    - 2.5 wrt. bkg only, 1.9 wrt. SM
- For differential measurement STXS bins are used; 2.6 local significance $P_T(H) > 650$ GeV





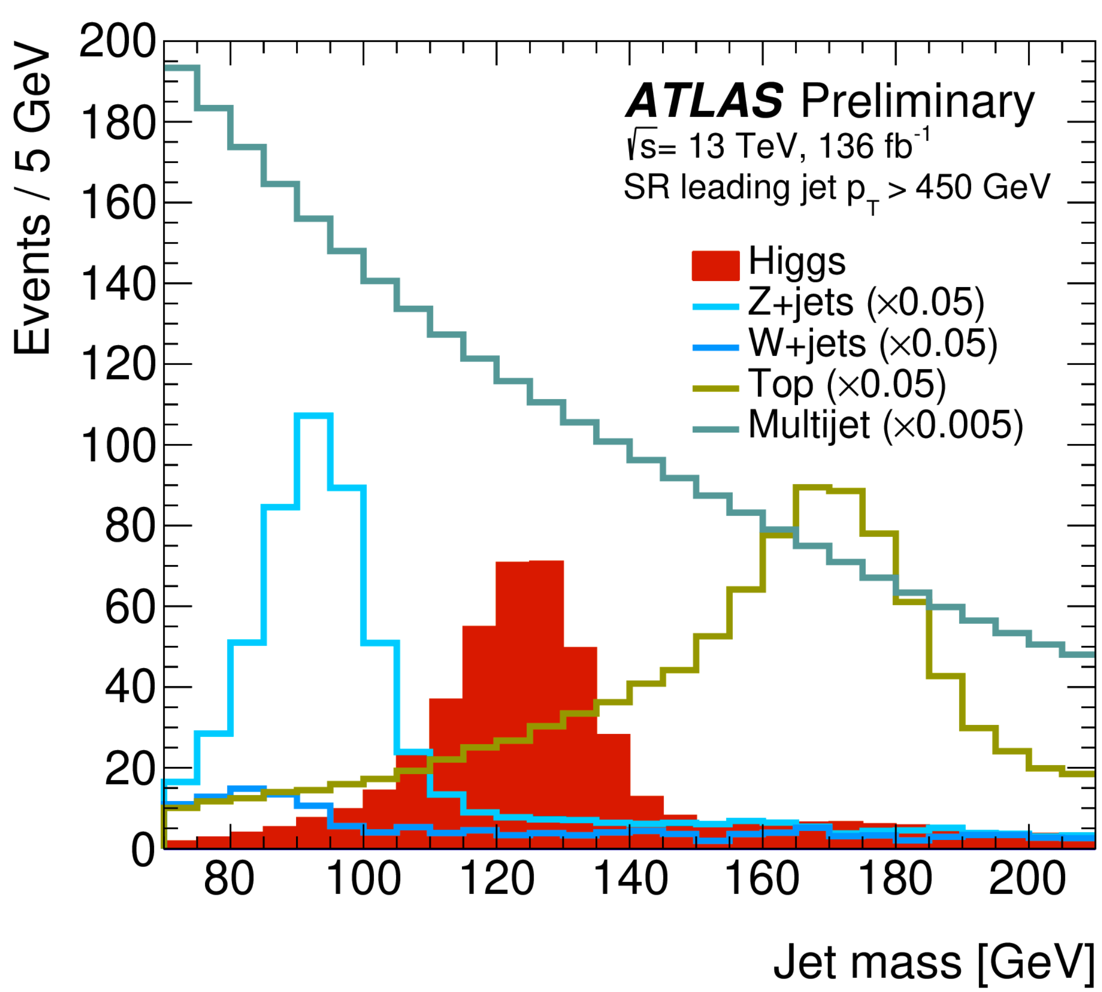
$$\mu_{\mathrm{H}} = 3.7 \pm 1.2\,(\mathrm{stat})^{+0.8}_{-0.7}\,(\mathrm{syst})^{+0.8}_{-0.5}\,(\mathrm{theo}) = 3.7^{+1.6}_{-1.5}$$

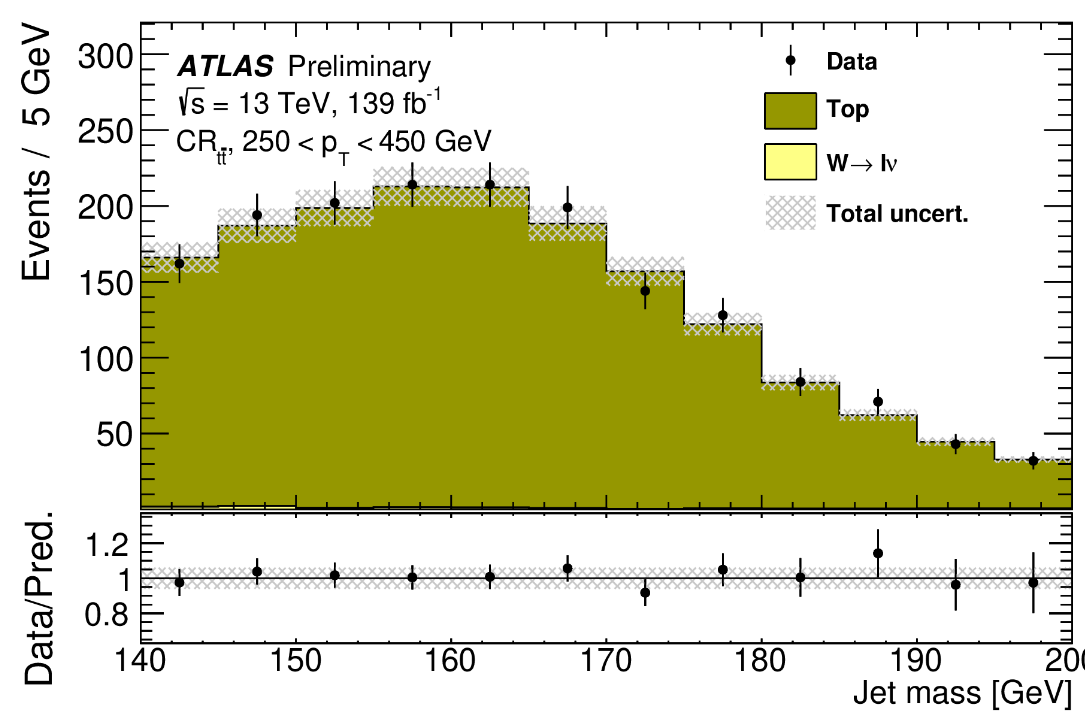
ggH (H->bb) (ATLAS)

ATLAS-CONF-2021-010

- Fit QCD with smooth function
  - extensively validated in 0-btag region
- W/Z + jets
  - Shape from simulation
  - Fully floating during fit (standard candle)
  - Mostly Z+jets after b-tagging

- ttbar
  - Shape from simulation
  - CRttbar for normalization



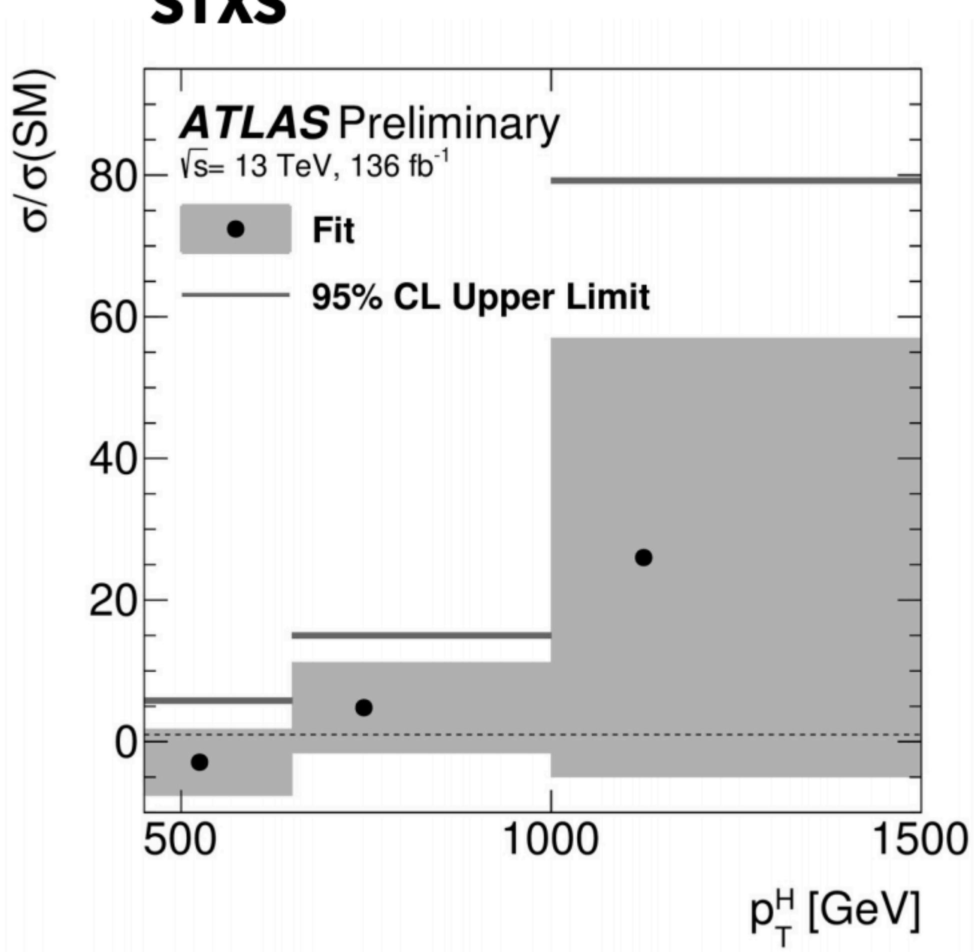


ggH (H->bb) (ATLAS)

ATLAS-CONF-2021-010

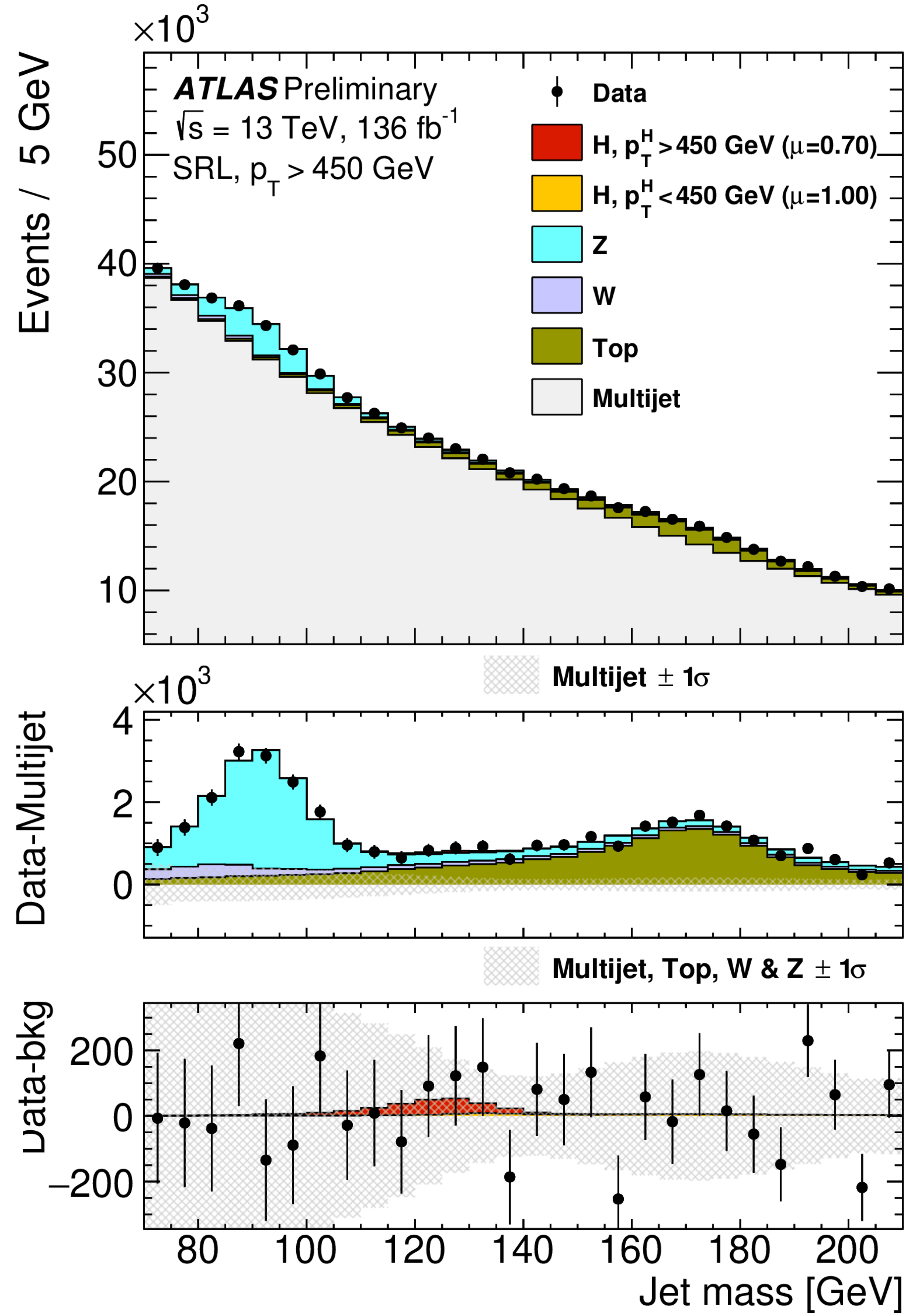
- **Z→bb peak**
  - **Good validation of background estimation**
- Inclusive:
  - $\mu_H = 1.1 \pm 3.6$
  - $\mu Z = 1.25 \pm 0.22$

STXS



Fiducial

p_T^H/Jet p_T	μ_H Exp.	μ_H Obs.	μ_Z Exp.	μ_Z Obs.	$\mu_{t\bar{t}}$ Exp.	$\mu_{t\bar{t}}$ Obs.
> 450 GeV	1.0 ± 3.3	0.7 ± 3.3	1.00 ± 0.18	1.27 ± 0.22	1.00 ± 0.07	0.81 ± 0.06
> 1 TeV	1.0 ± 29.0	26 ± 31	1.0 ± 1.6	2.4 ± 1.7	1.0 ± 0.3	0.51 ± 0.19

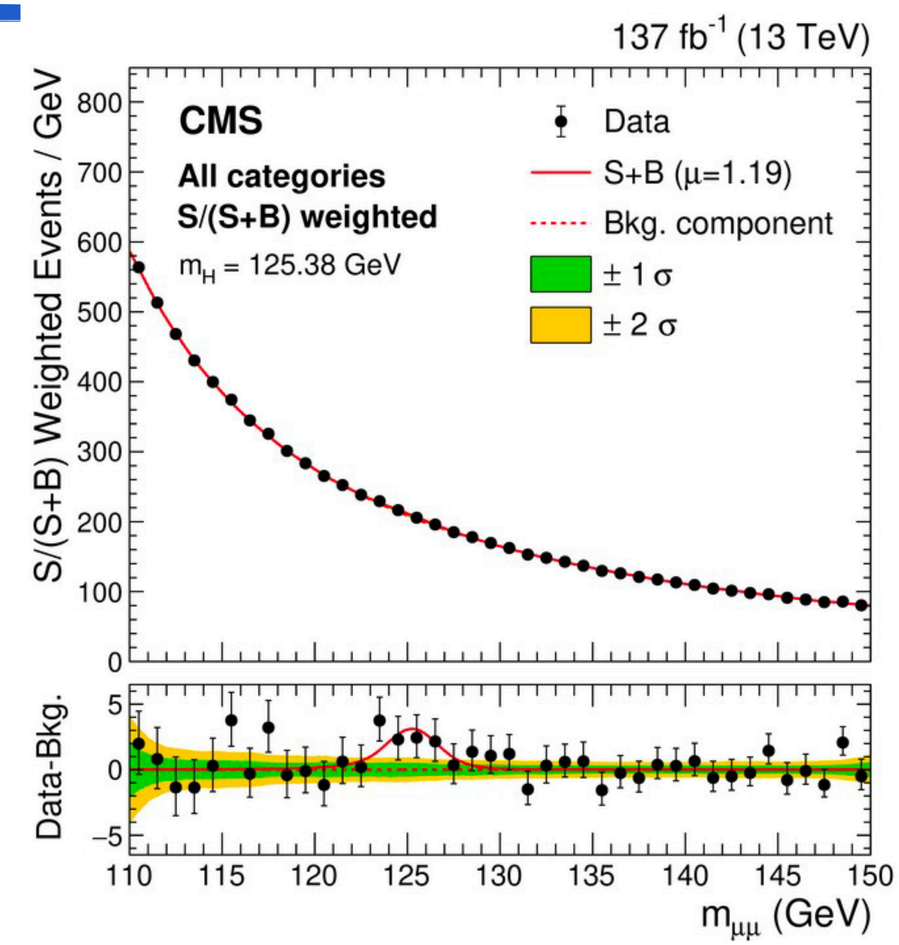


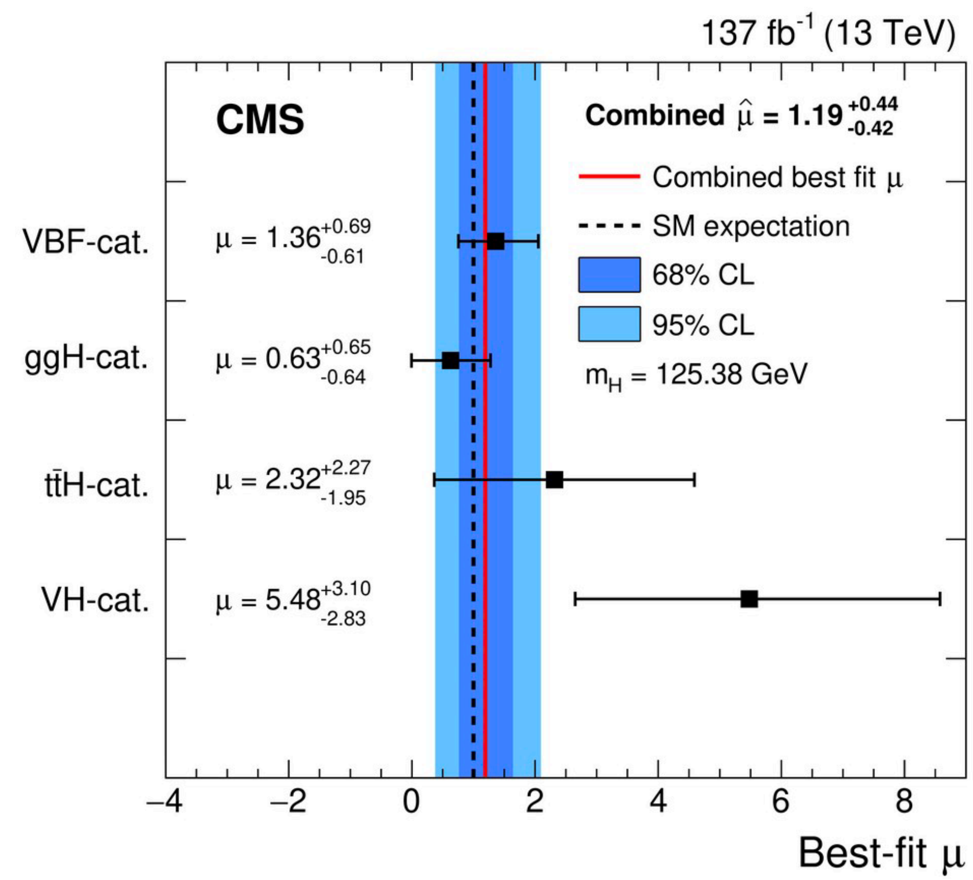
Rare higgs boson decays

Higgs->μμ (CMS)

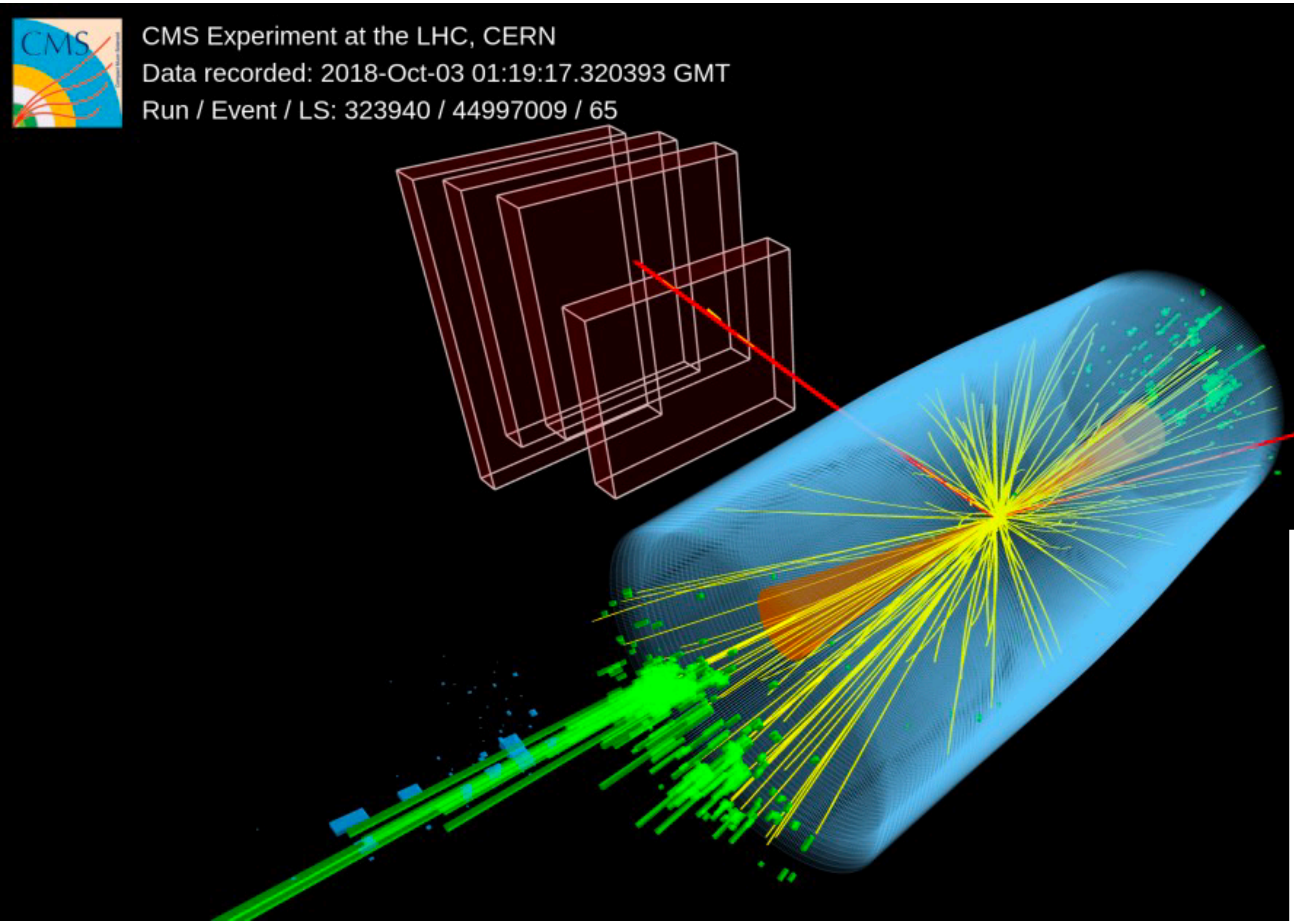
JHEP 01 (2021) 148

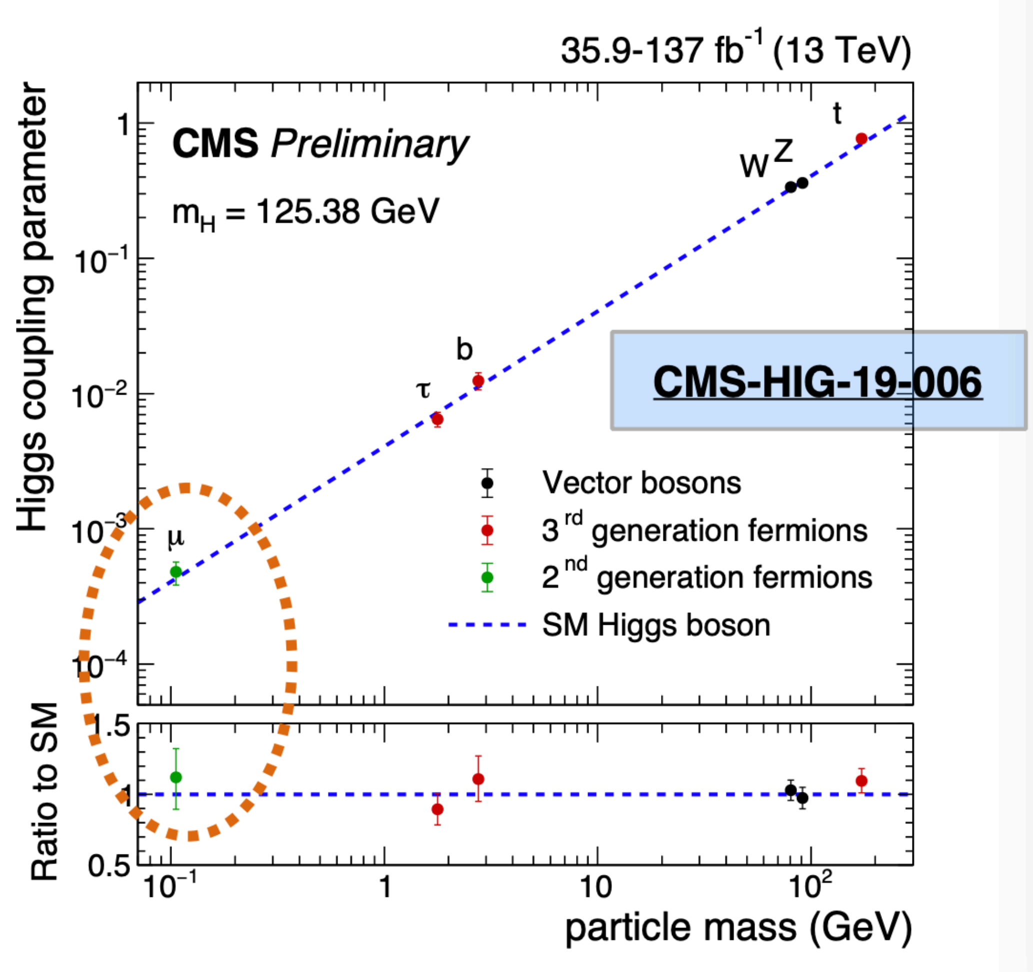
- Search divided by the production modes:
  - VBF (no b jets, no additional leptons, VBF selection), expected sensitivity: +20%.
  - ggH (no b jets, no additional leptons, VBF veto),
  - VH (no b jets, 1 or 2 additional leptons),
  - ttH leptonic or hadronic (≥1 b jets, 1 add. or 2 add. leptons),
- A multivariate discriminator is trained in each region
  - categories with different signal purity,
  - fit the Higgs boson peak dimuon mass.
- Improvements in new analysis:
  - Muon track fitted using primary vertex, ==> p_T resolution improvement (3 – 10 %).
  - Final state radiation (FSR) energy recovery: p_T resolution improvement (3%), signal efficiency increase (2%).
  - Change to the background function to fit==> Reduced number of free parameters → improved sensitivity ~10%





Higgs->μμ



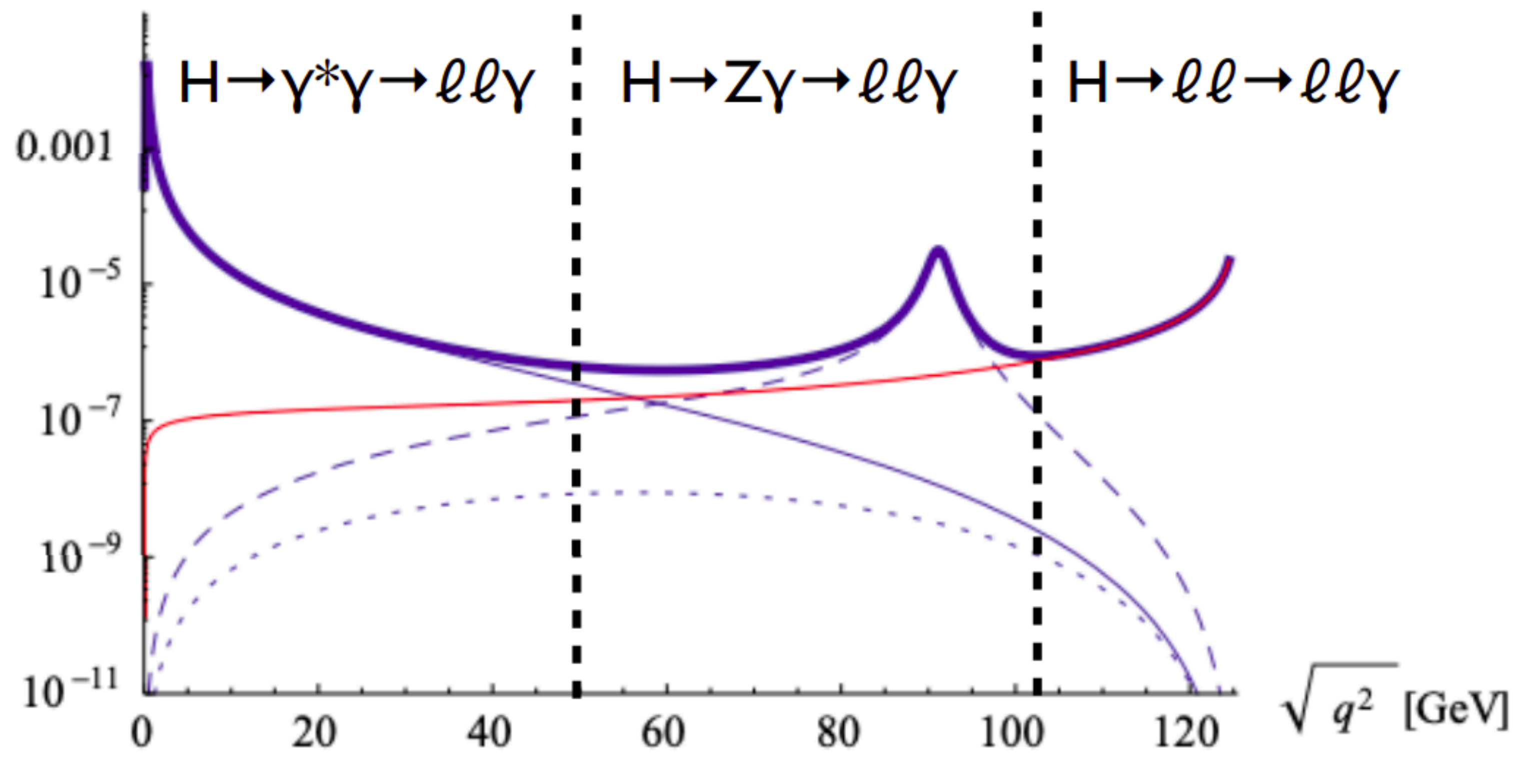


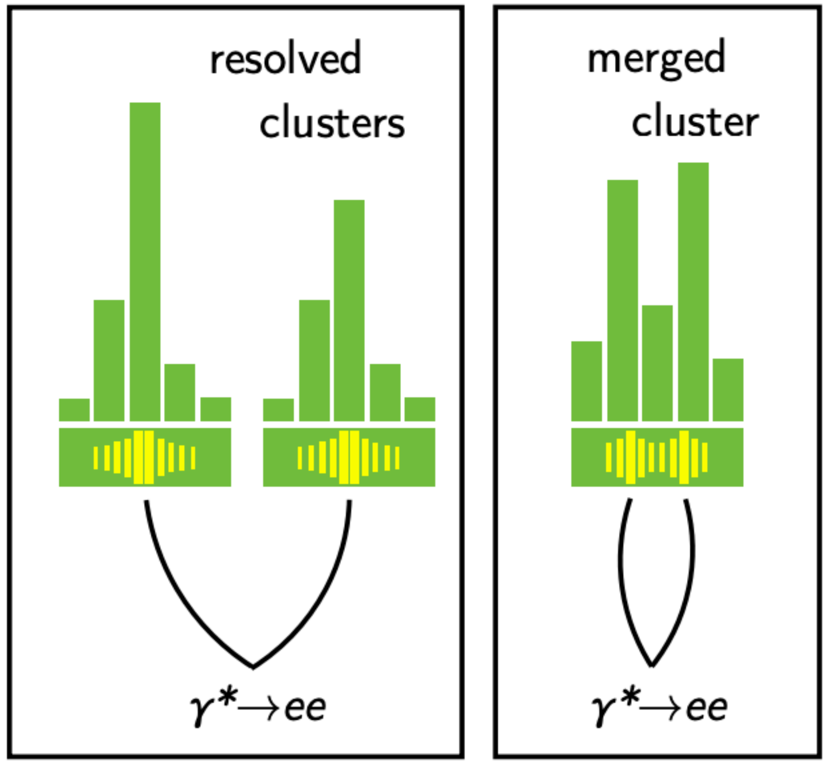
p-value: 3.0σ (2.5σ exp.), – μ = 1.19 ± 0.40 (stat) ± 0.15 (syst) → statistically limited.

H-> γ* (->ll) γ decay

ATLAS: 10.1016/j.physletb.2021.1364

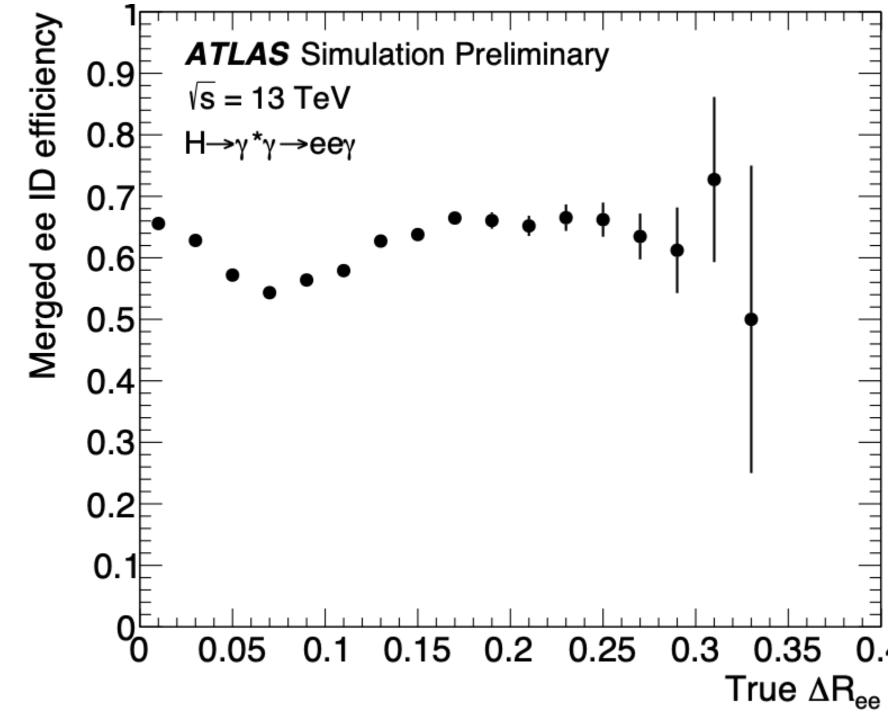
- The Higgs boson can decay to a lepton pair and a photon in three main ways:
  - the leptons can be produced via an intermediate Z boson (H→Zγ→ℓℓγ)
  - or a virtual photon (H→γ*γ→ℓℓγ),
  - or two leptons (H→ℓℓ) with one lepton radiating a final-state photon.
- Target the decay mediated by the virtual photon.
  - focus on events where the dilepton mass ($m_{\ell\ell}$) is less than 30 GeV,
  - Due to the low mass of the dilepton pair they are often very collimated
- Limited spacial resolutoon of the detector
  - Merged electron + Photon / 2 electrons + Photon
  - Not an issue for muons



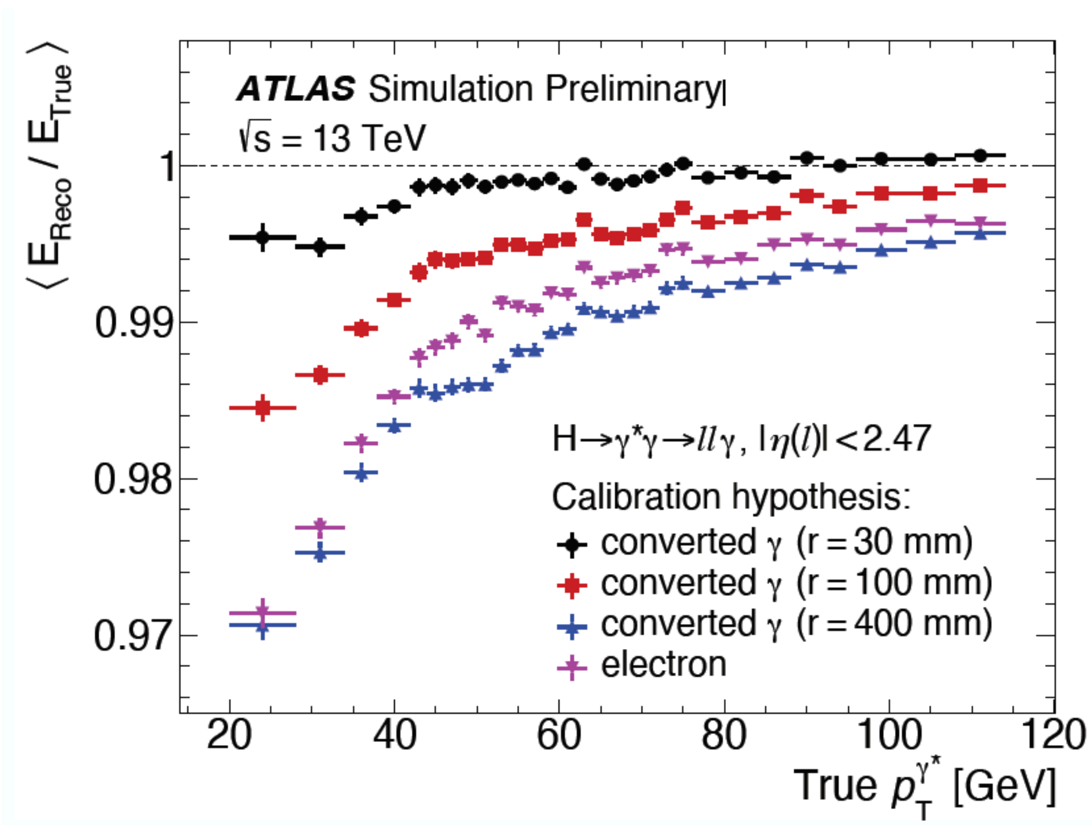


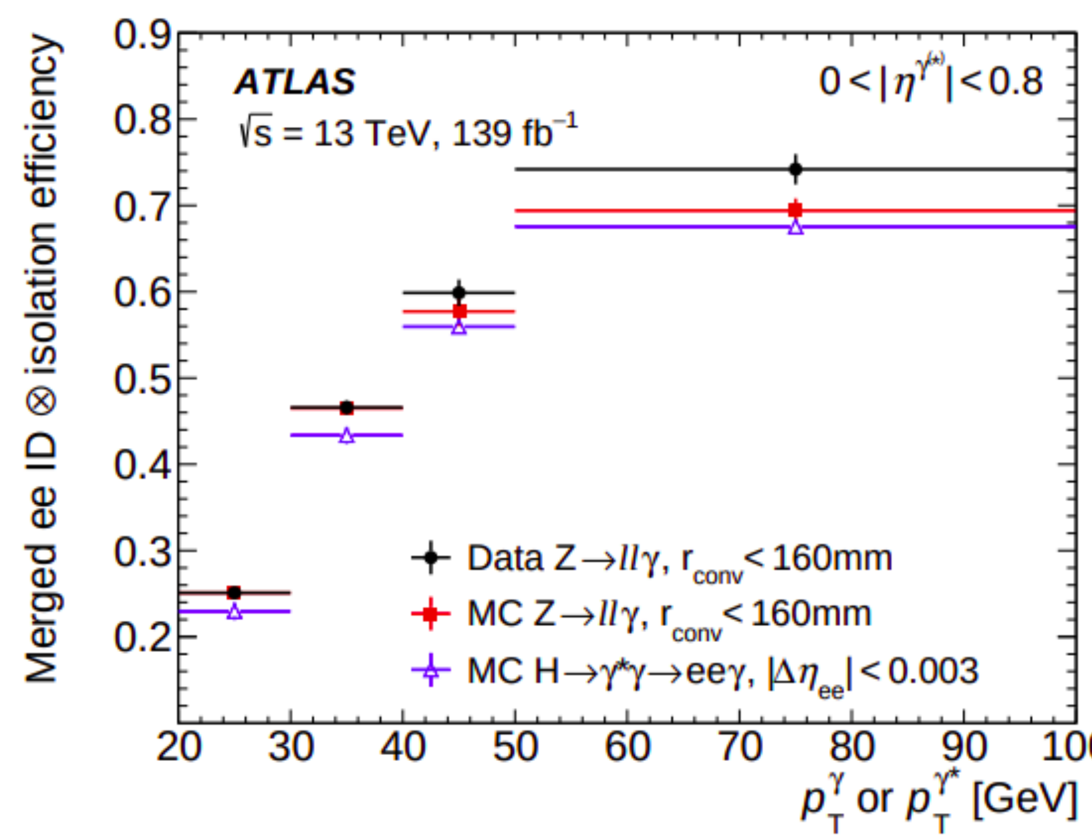
H-> γ* (->ll) γ decay

ATLAS: 10.1016/j.physletb.2021.136412



- Merged electron identification: Largely look like converted to ee pairs early expect ⟹broader cluster
- Cut based PID inputs: Variables constructed from the tracks and EM shower shapes
- Use Z→llγ events to perform efficiency measurements ==> converted photons as a proxy
- Calibration: A merged electron (γ*) looks like photon conversions treat them as such
  - Calibrate γ* as an early converted photon with radius 30mm
- The small differences taken as additional systematic uncertainty

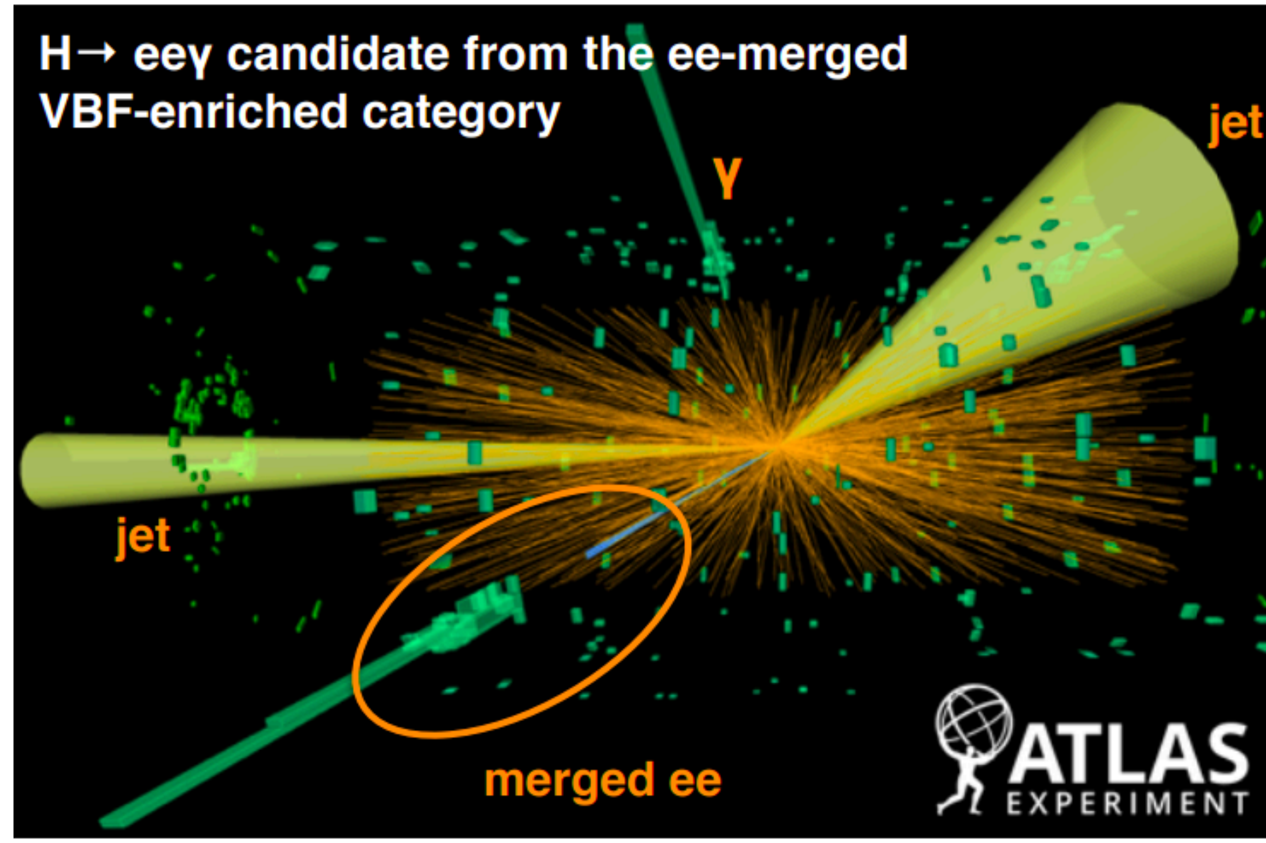




H-> γ* (->ll) γ decay

ATLAS: 10.1016/j.physletb.2021.136412

- Event Selection:
  - Require event to have with 2 leptons and photon
  - $m_{\ell\ell} < 30$ GeV
  - Veto J/ψ and Y(nS) mass range
  - 105 GeV < $m_{\ell\ell\gamma}$ < 160 GeV
  - Relative pT : $p_T(\ell\ell)/m_{\ell\ell} > 0.3$, $p_T(\gamma)/m_{\ell\ell\gamma} > 0.3$
  - Signal Efficiency: μμγ ~28%, eeγ ~14%



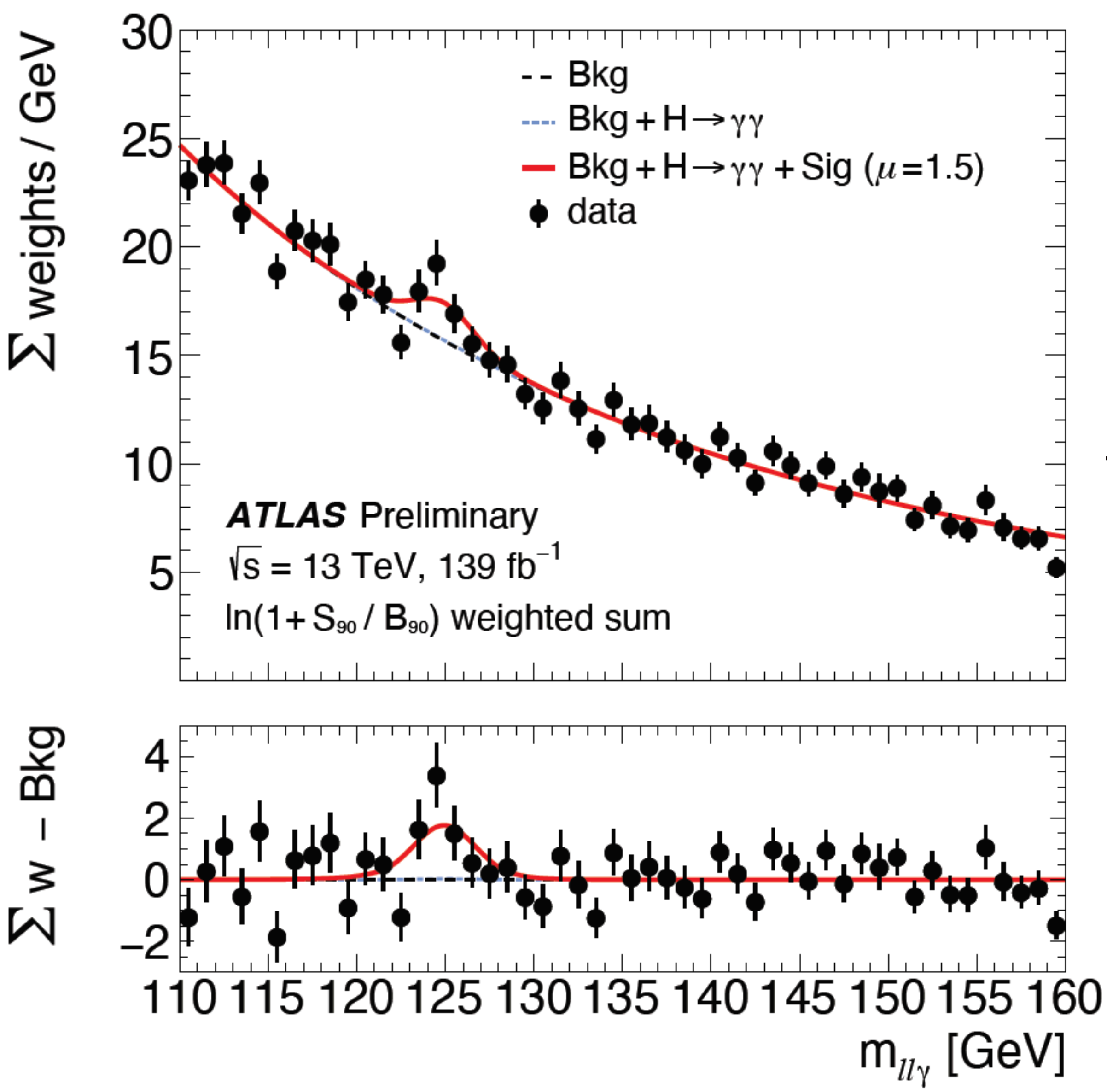
- ***Production categories:***

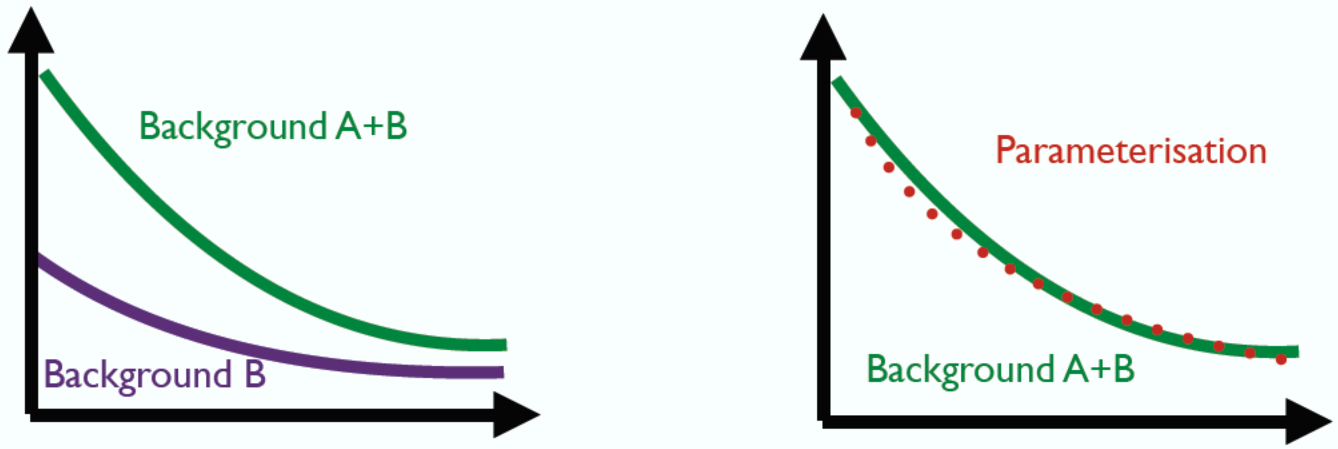
VBF enriched	ggH high p_T(H)	ggH low p_T (H)

- ***Decay categories:***

$\mu\mu\gamma$	$ee\gamma$ resolved	$ee\gamma$ merged

H-> gamma* (->ll) gamma decay





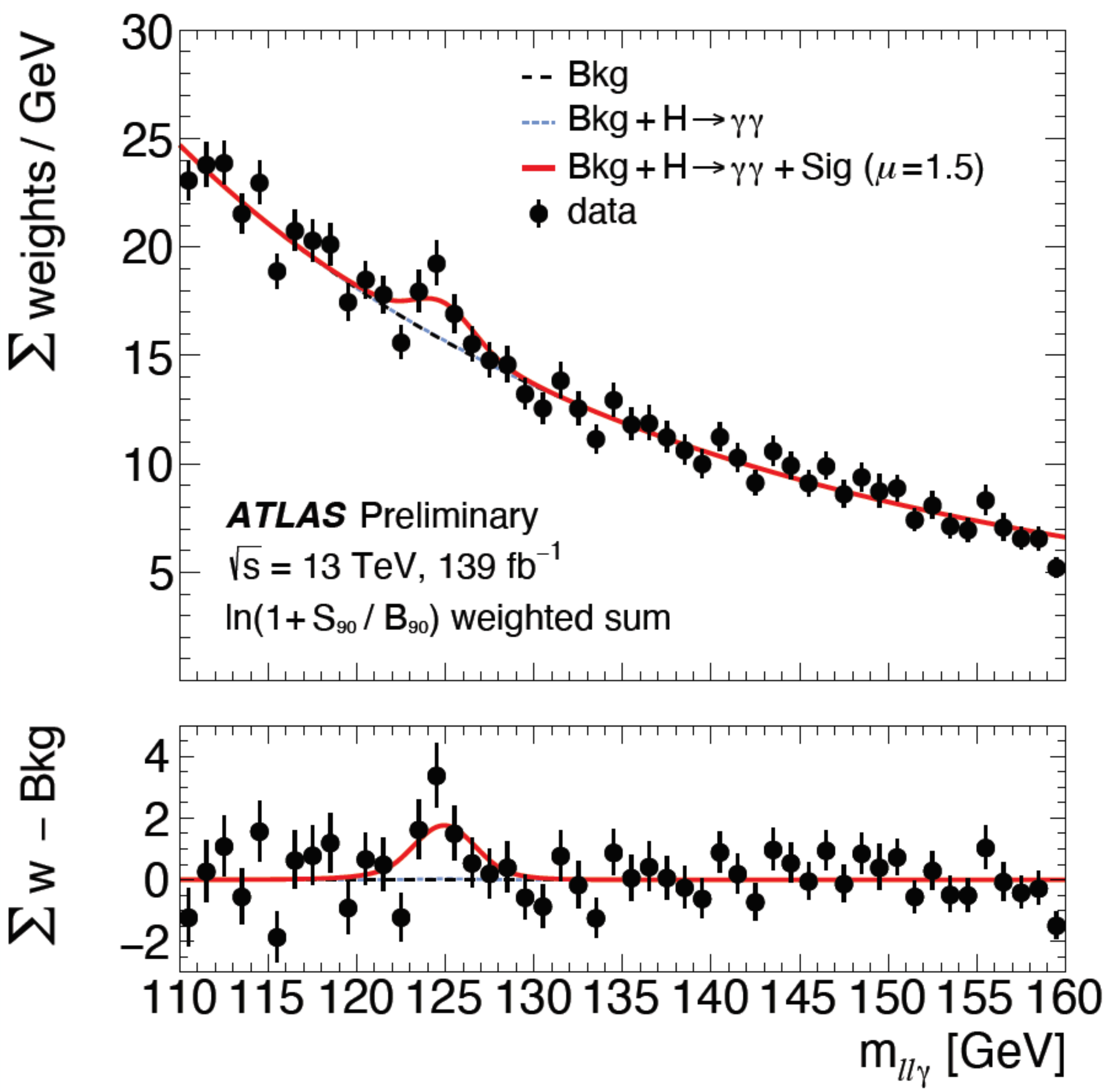
- Create template for each contributing process:
  - Composition: Using isolation templates, derived in a region with inverted ID, and then normalised in the high-isolation tail
  - Use MC (LO Sherpa 2.2) ℓℓγ to model the irreducible ℓℓγ background
    - Reweight this generator-level sample to account for reconstruction-level effects
    - Obtain shapes for fake backgrounds in data control regions
    - Components added together with measured compositions
- Fit using a background function

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

$\sigma \times BR(\ell\ell\gamma)|_{m_{\ell\ell}<30\ \text{GeV}}$: $8.7\ ^{+2.8}_{-2.7}\ \text{fb} = 8.7\ ^{+2.7}_{-2.7}\ \text{(stat.)}\ ^{+0.7}_{-0.6}\ \text{(syst.) fb}$

Significance above background-only hypothesis: 3.2σ (expected 2.1σ)

H-> gamma* (->ll) gamma decay



Source	μ	$\sigma \times \mathcal{B}$
Spurious Signal	6.1	
$\mathcal{B}(H \to \ell\ell\gamma)$	5.8	–
QCD	4.7	1.1
ℓ, γ, jets	4.0	
PDF	2.3	0.9
Luminosity	1.7	
Pile-up	1.7	
Minor prod. modes	0.8	
$H \to \gamma\gamma$ bkg	0.7	
Parton Shower	0.3	
Total systematic	11	7.9
Statistical	31	
Total	33	32

- Analysis is statistically limited
- Leading experimental systematics
  - background modelling uncertainty
  - lepton efficiency/resolutions

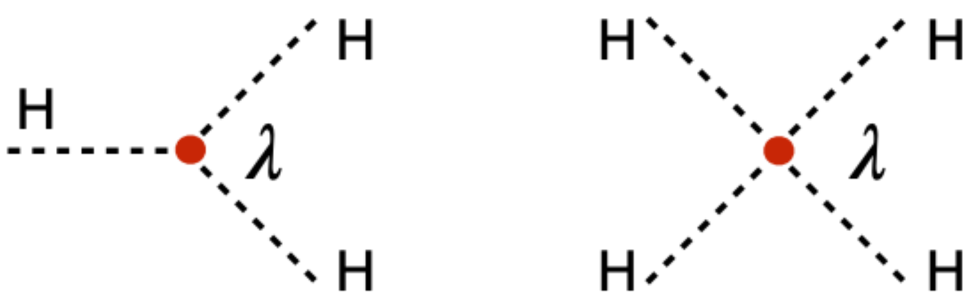
- Observed: $\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$

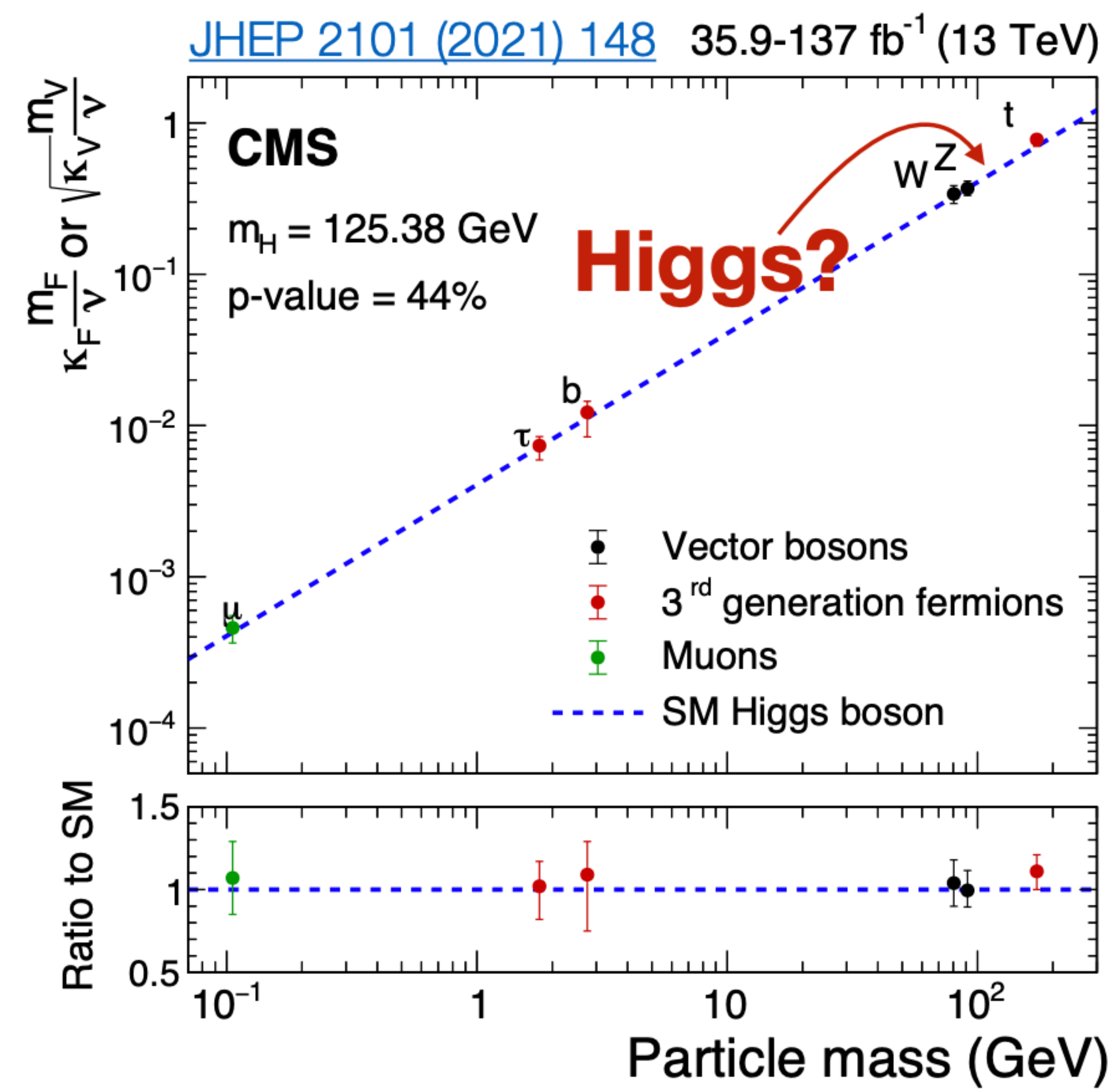
  $\sigma \times \text{BR}(\ell\ell\gamma)|_{m_{\ell\ell}<30\text{ GeV}}$: $8.7\ ^{+2.8}_{-2.7}\ \text{fb} = 8.7\ ^{+2.7}_{-2.7}\ (\text{stat.})\ ^{+0.7}_{-0.6}\ (\text{syst.})\ \text{fb}$

Double Higgs production

The Higgs boson and its self-coupling

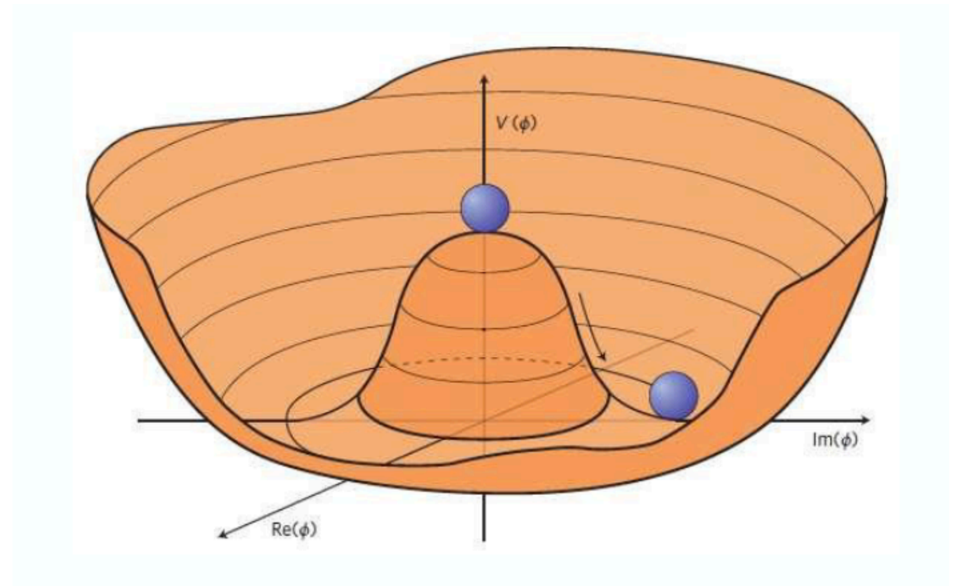
- Higgs boson mass measurements getting very precise…
- Interactions with fermions and vector boson well established by now..
- But the Higgs boson self-interaction is not yet measured experimentally!



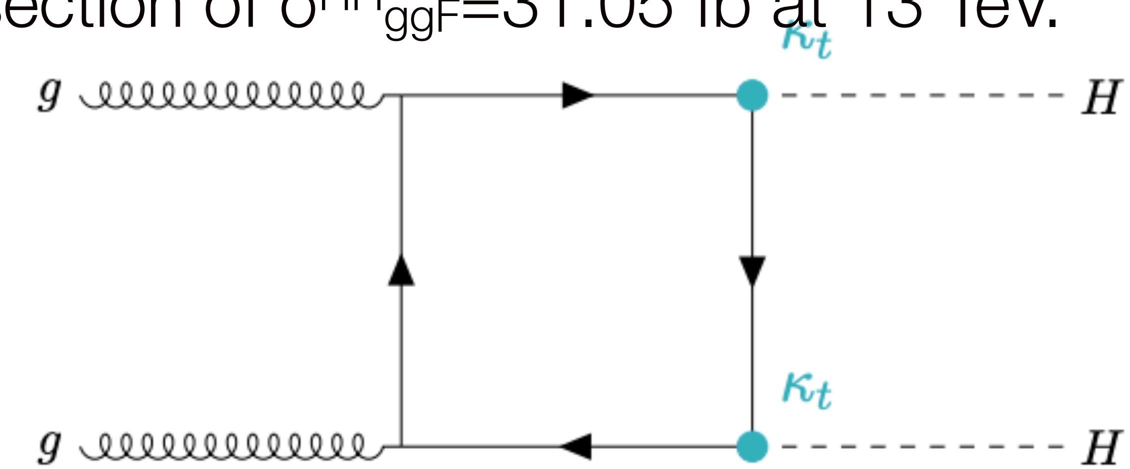


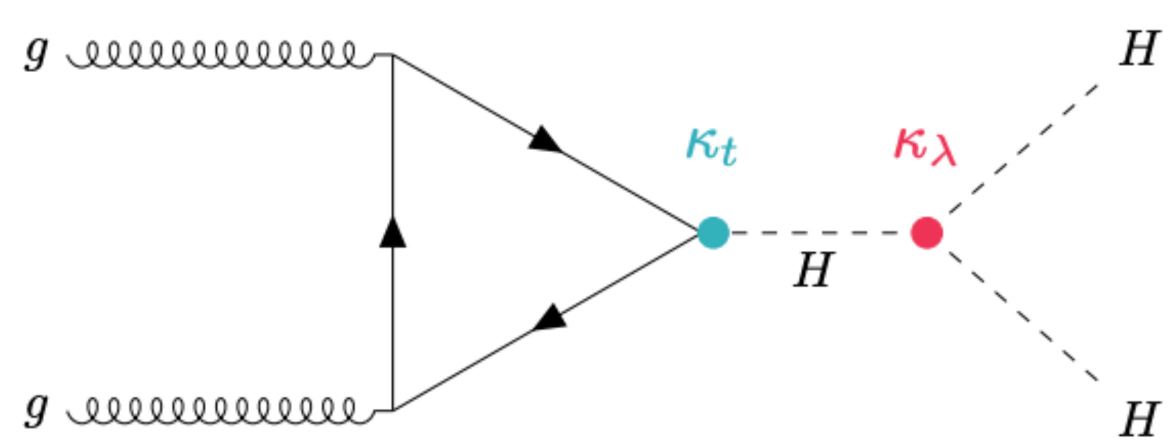
Searches for diHiggs production

- Measuring HH production will gives us access to the triple Higgs coupling (self coupling) λ_3, which gives information of the shape of the Higgs potential:
  - $V(H) = 1/2\ m^2_H H^2 + \lambda_3 v H^3 + 1/4\ \lambda_4 v H^4 + O(H5\ )$
  - linked to a wide range of open questions in particle physics ==> characterizing it is a major goal of HL-LHC



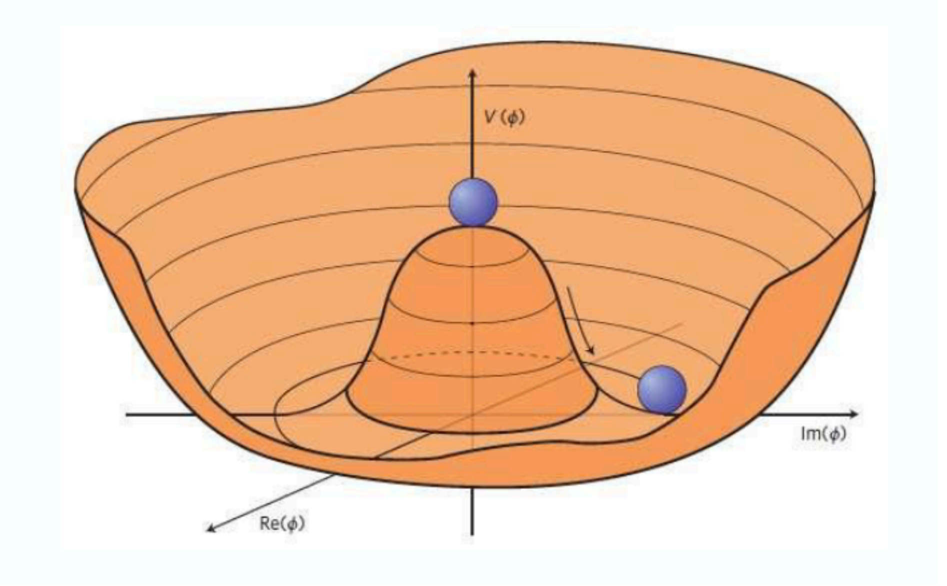
- The HH leading production mode is gluon gluon fusion (ggF):
- The coupling modifier κ_λ controls the strength of the Higgs self coupling with respect to SM: $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$
- Destructive interference between the two diagrams results in a very small SM cross section of σ^{HH}_{ggF}=31.05 fb at 13 TeV.



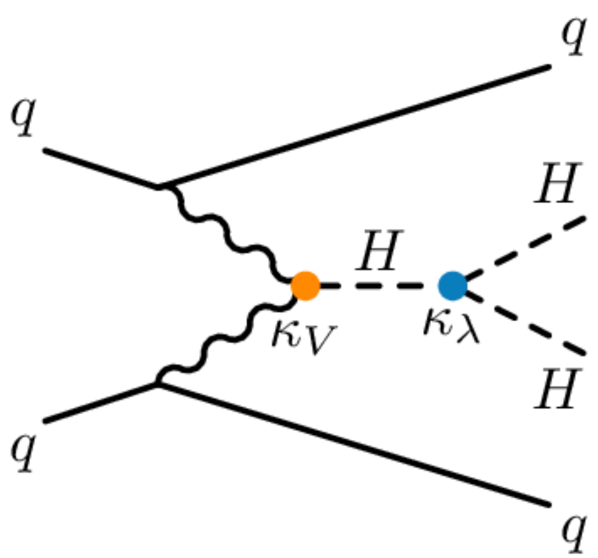


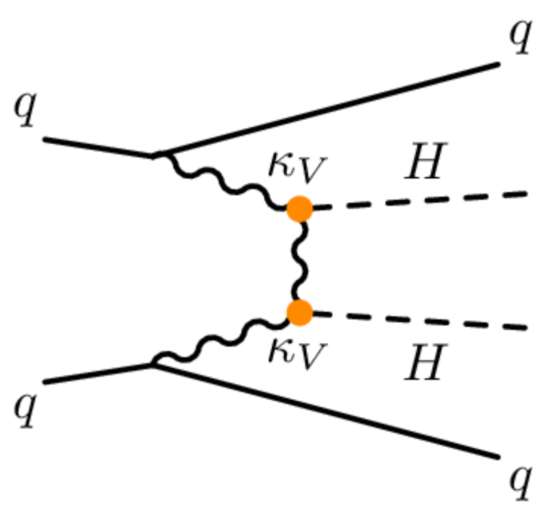
Searches for diHiggs production

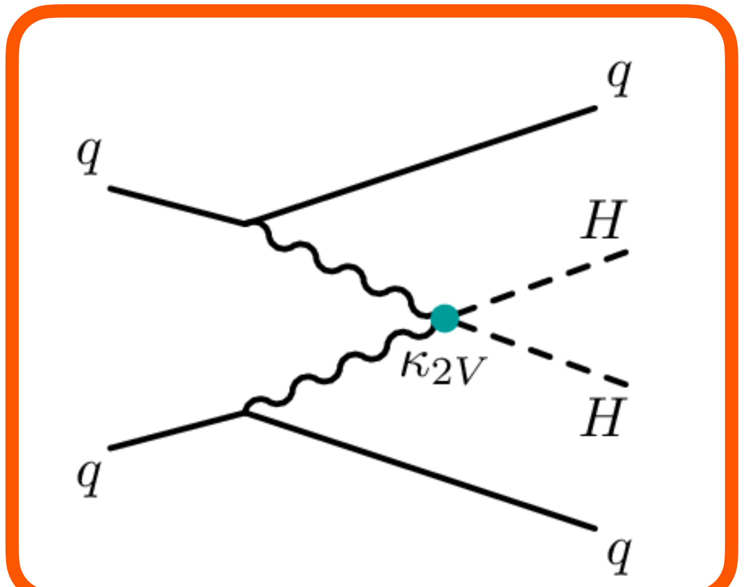
- Measuring HH production will gives us access to the triple Higgs coupling (self coupling) λ_3, which gives information of the shape of the Higgs potential:
  - $V(H) = 1/2\ m^2_H H^2 + \lambda_3 v H^3 + 1/4\ \lambda_4 v H^4 + O(H5\ )$
  - linked to a wide range of open questions in particle physics ==> characterizing it is a major goal of HL-LHC



- VBF production mode also very important
- Gives unique access to k_{2V}

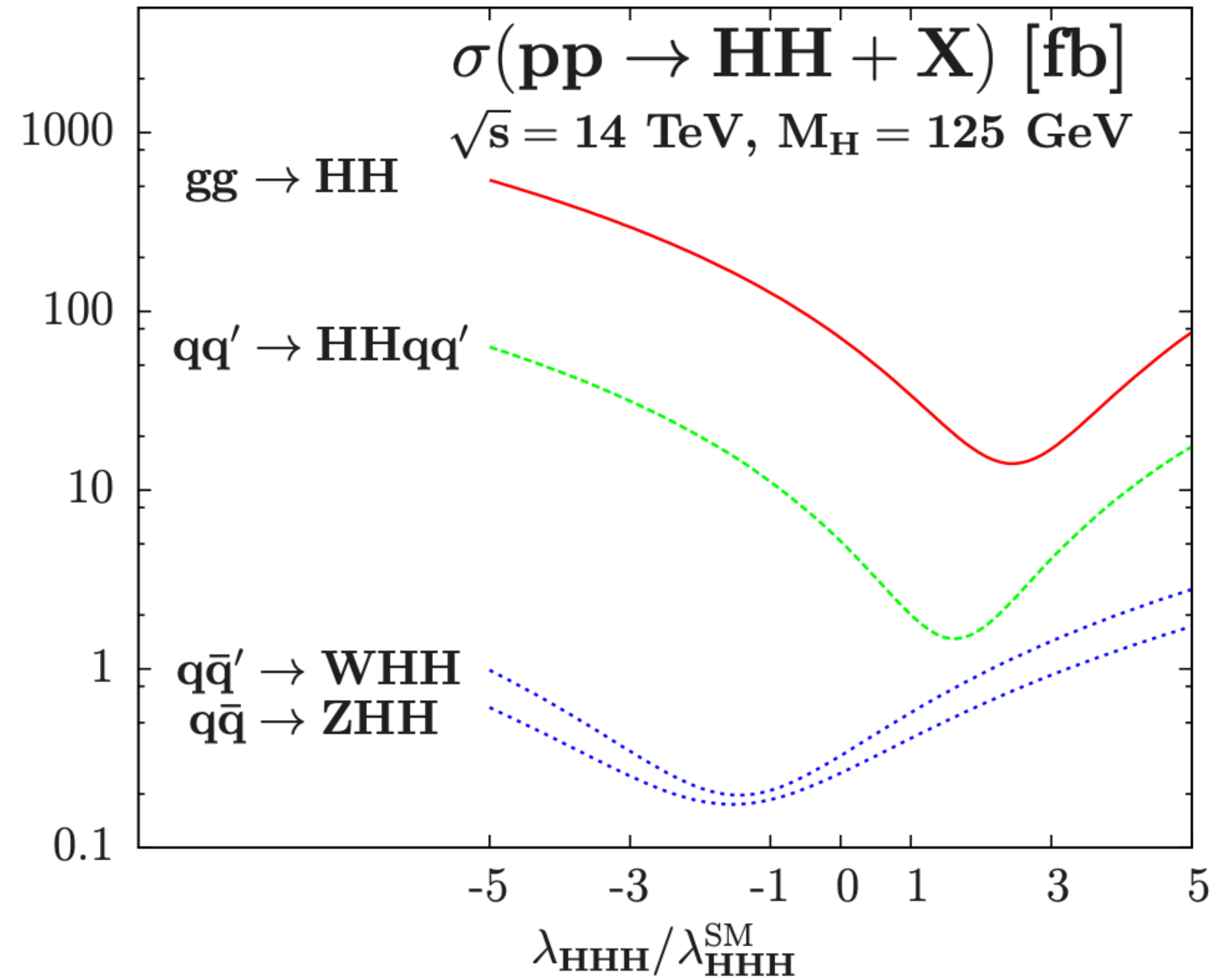


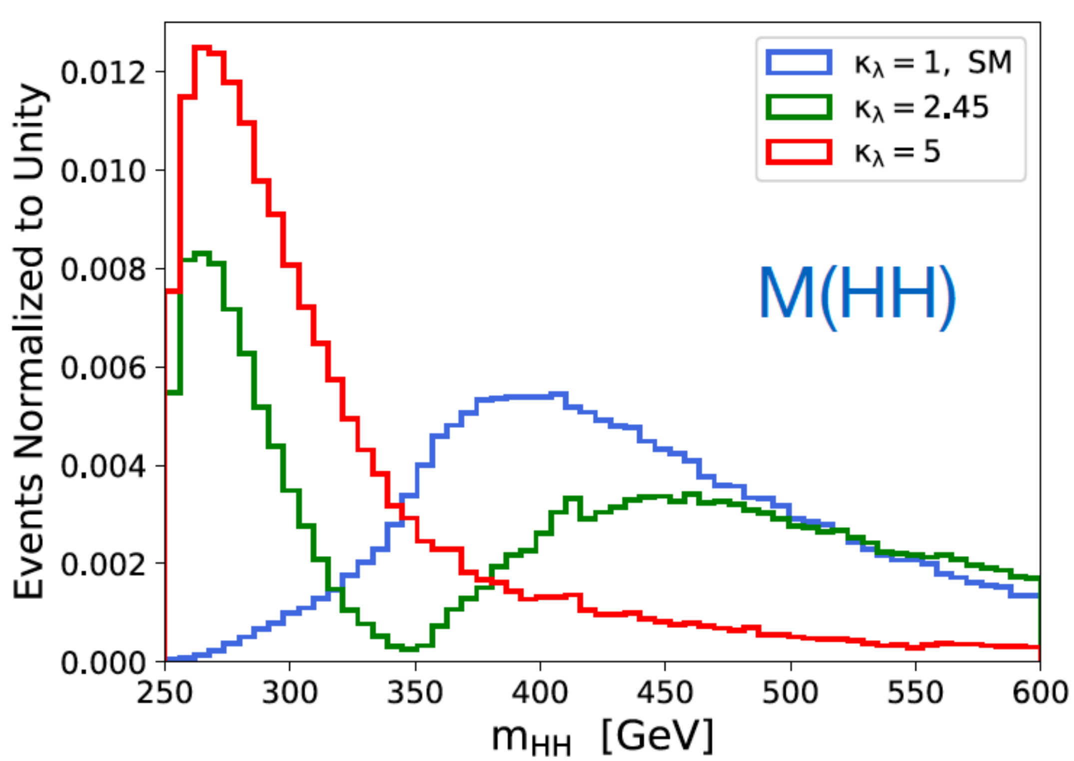




Searches for diHiggs production

- Modifications of couplings → significant enhancements in xsec. and changes in kinematics
- Constraints on anomalous couplings
- Sensitive already with Run2 Data!





HH decay modes

- Due to the large branching ratio (BR), most searches require at least one H->bb. Different decay modes of the second Higgs are considered.
- σ^{HH} @ 13 TeV ~ 30 fb (1000 x smaller than single H)
- Run 2 $\int L$~140 fb^{-1} ~4k HH events
- Scales up to about 10^5 in HL-LHC
- Combination (and complementarity) of various final states fundamental for observation!

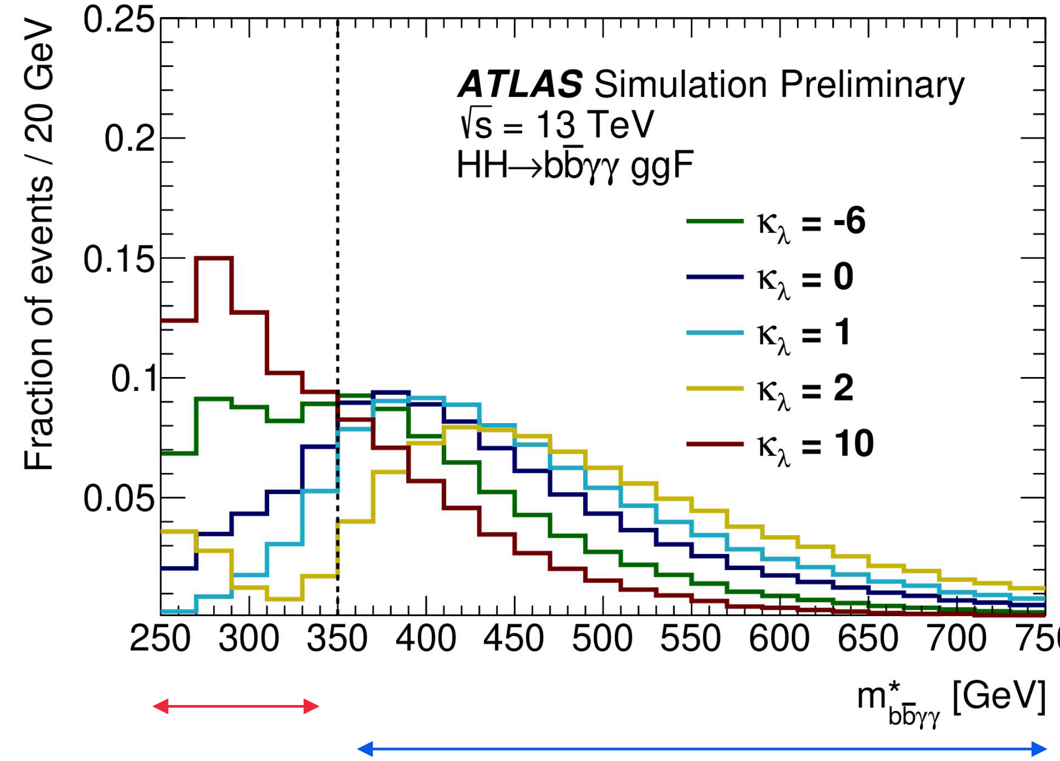
Targeted *HH* decays shown today

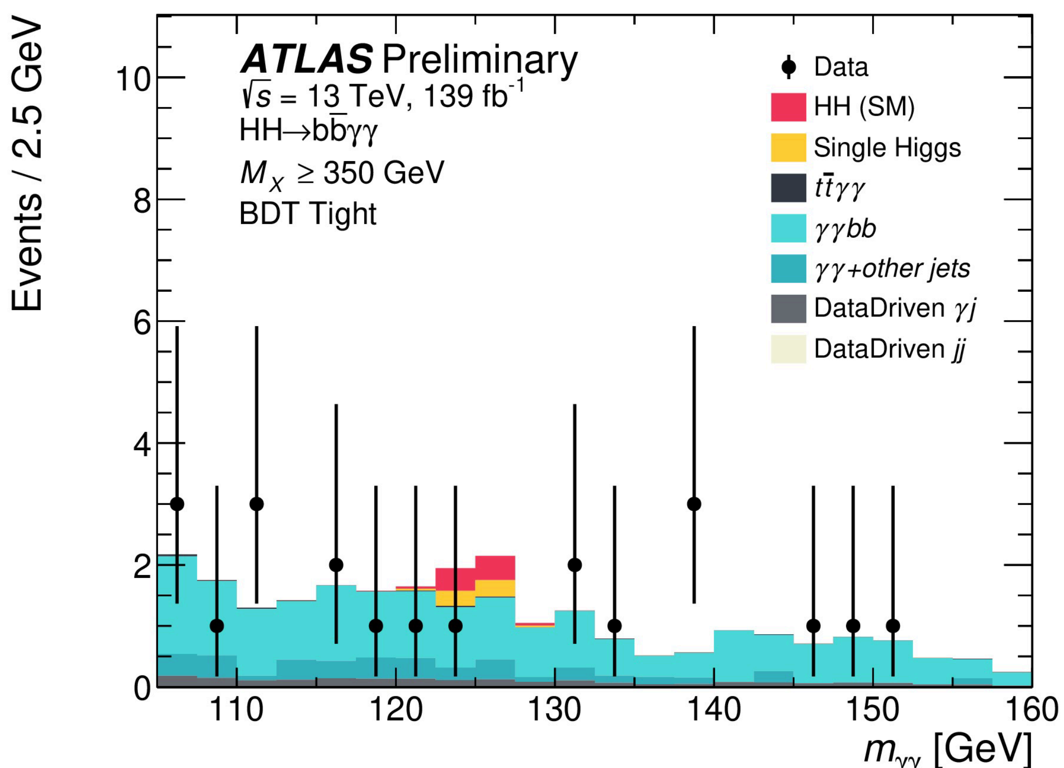
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

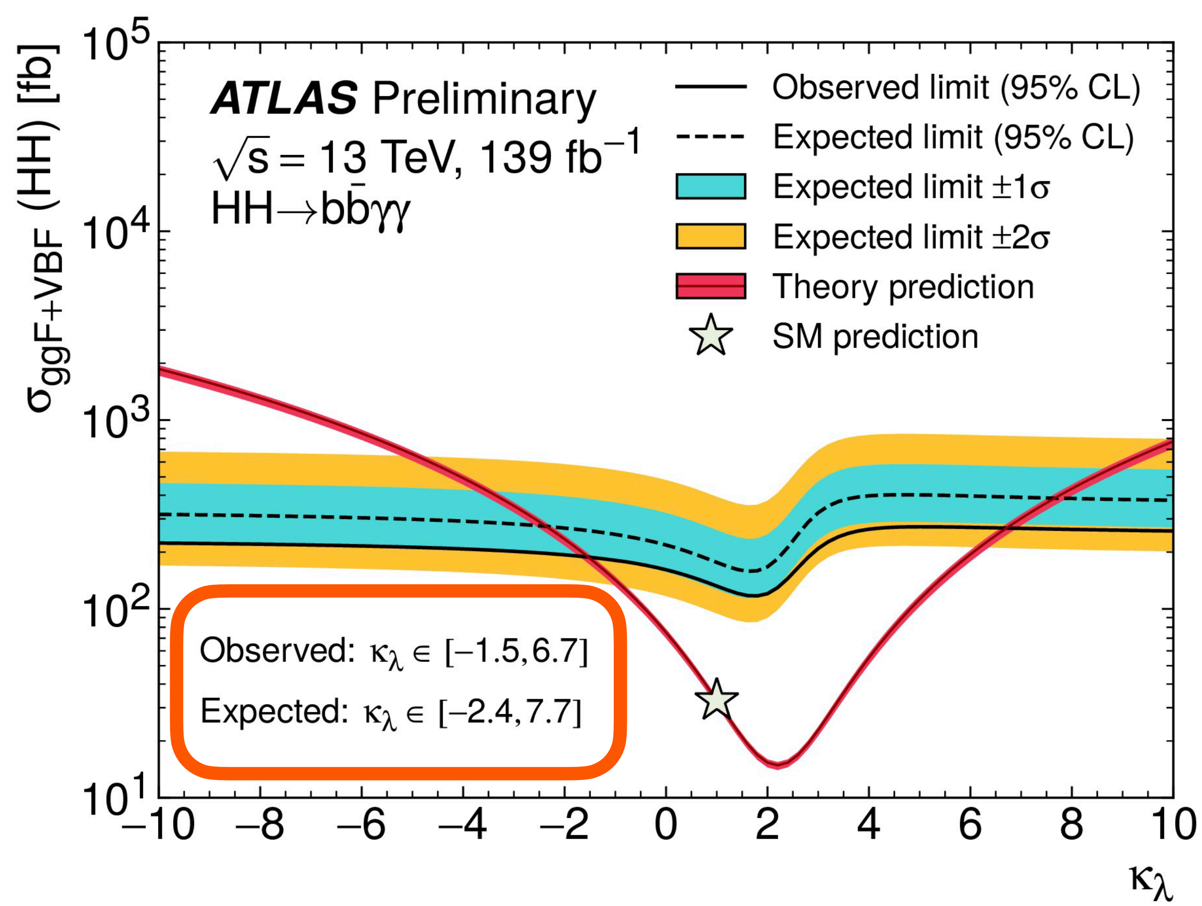
ATL-COM-PHYS-2021-052

ATLAS HH → bbγγ (139 fb^{-1})

- Two different BDTs are used for events with high/low Mx masses to discriminate $\kappa_\lambda = 1$ or $\kappa_\lambda = 10$ against background. A total of 4 regions are defined from cuts on the score of the BDTs.
- The sidebands are fit to estimate the non-resonant background with data.
- Final fit on the $m_{\gamma\gamma}$ in the 4 categories







σ_{HH} (ggF+VBF)/σ_{HH} SM (ggF+VBF) < 4.1 (5.5) at 95% CL

World's best constraints to date on Higgs boson's self coupling!

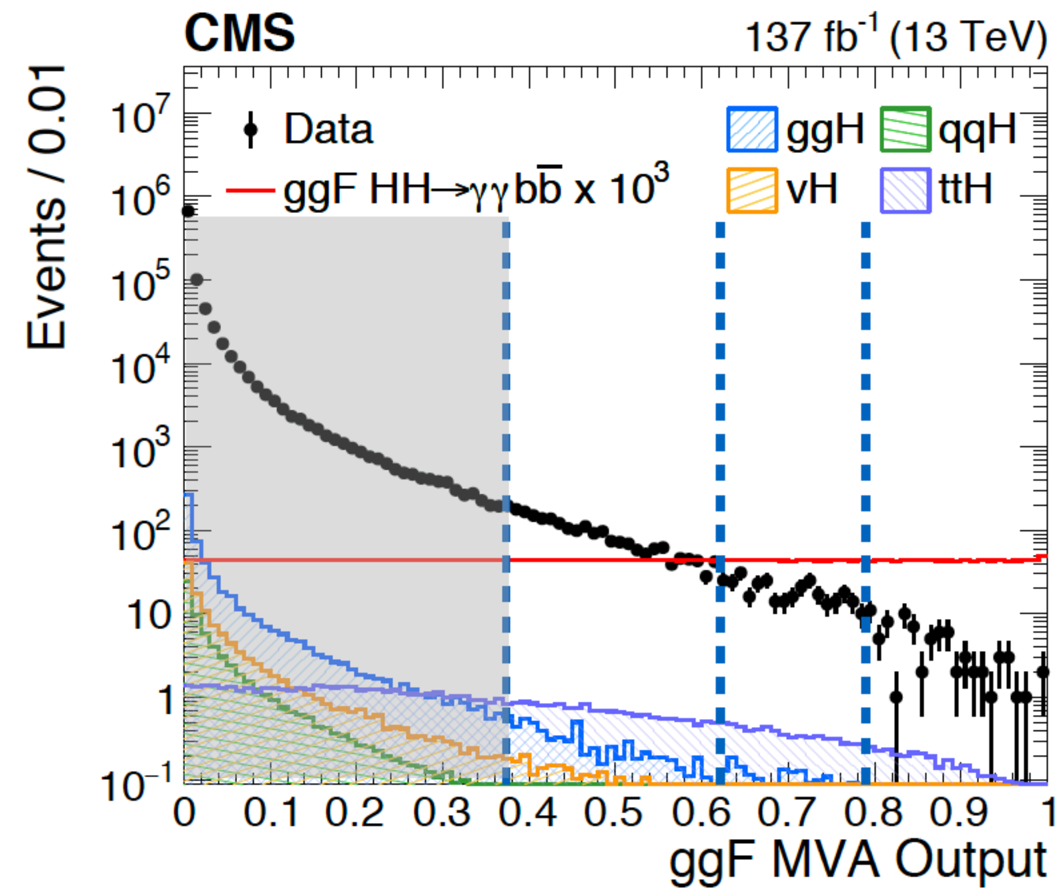
5x improvement wrt previous result, ~3x due to analysis techniques driven by mHH categorization & MVA as well as b-jet corrections

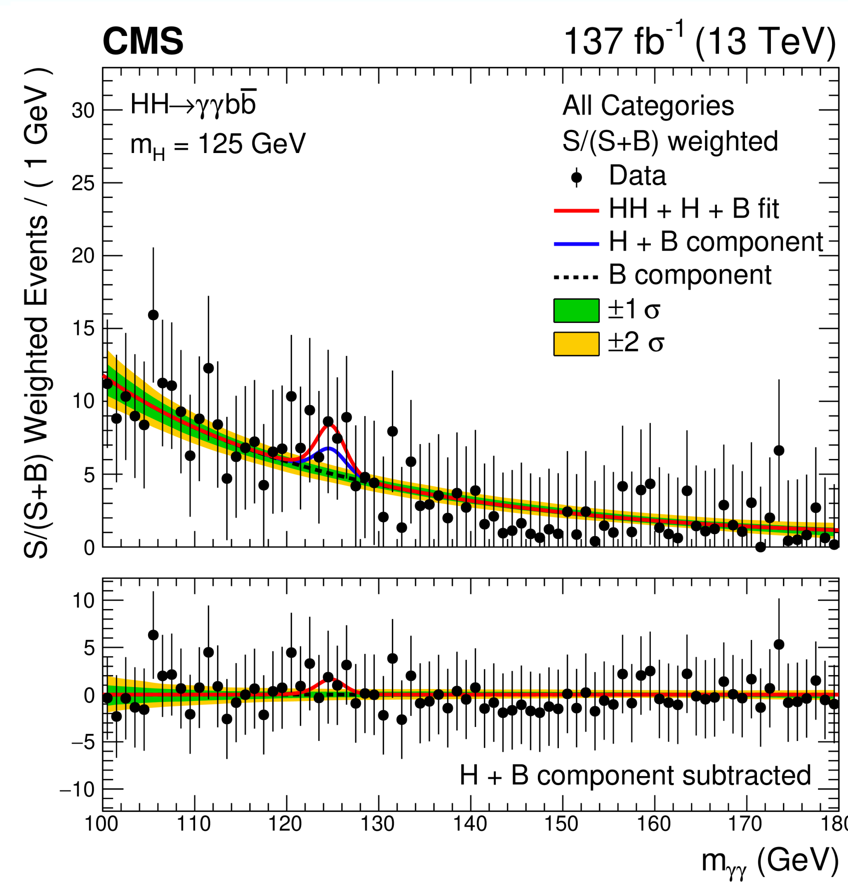
Statistically dominated, few % impact from systematics

CMS (HH → bbγγ) 137 fb-1

JHEP 03 (2021) 257

- A ggF and VBF BDT are used to discriminate the HH signals against background + a DNN is also used to further discriminate against ttH.
  - M(bb) energy resolution improved by 25% with DNN-based b jet energy regression
- A 2D fit to $m_{\gamma\gamma}$ and m_{jj} side bands is performed in all regions to estimate the non-resonant backgrounds with data.

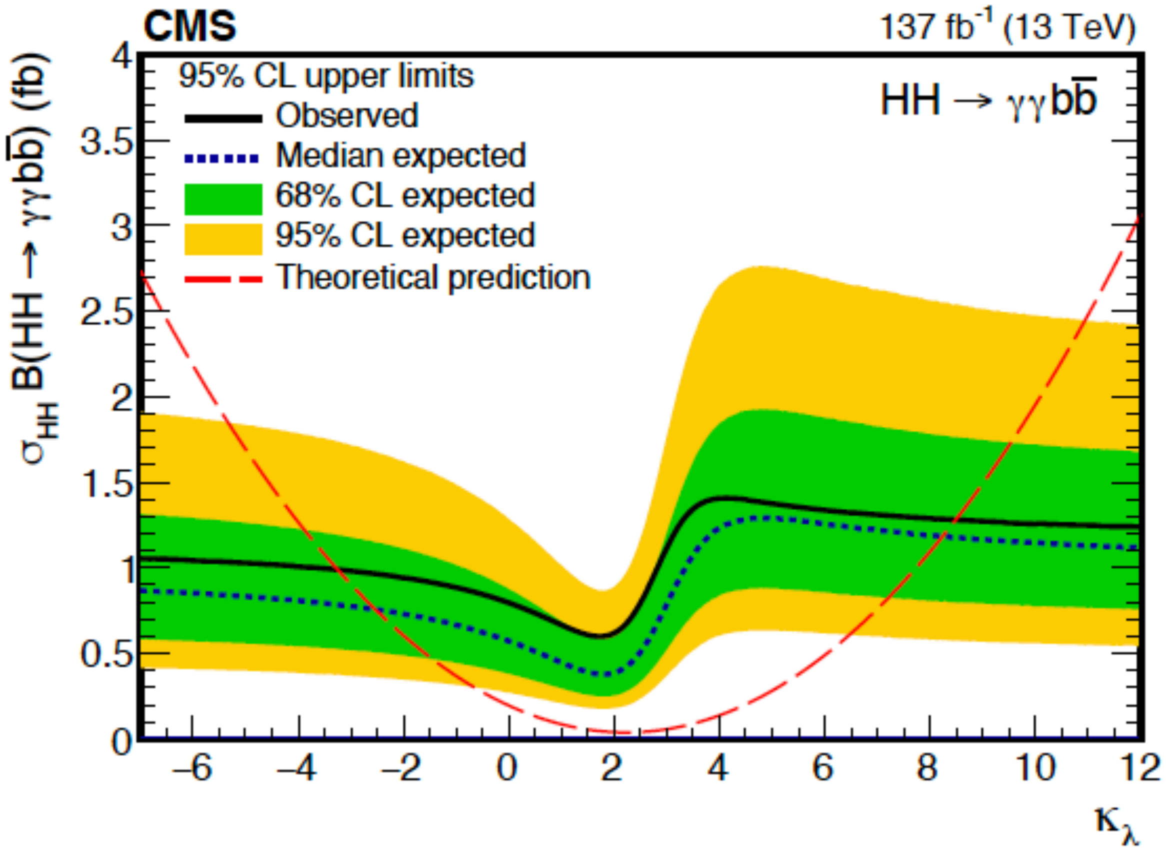


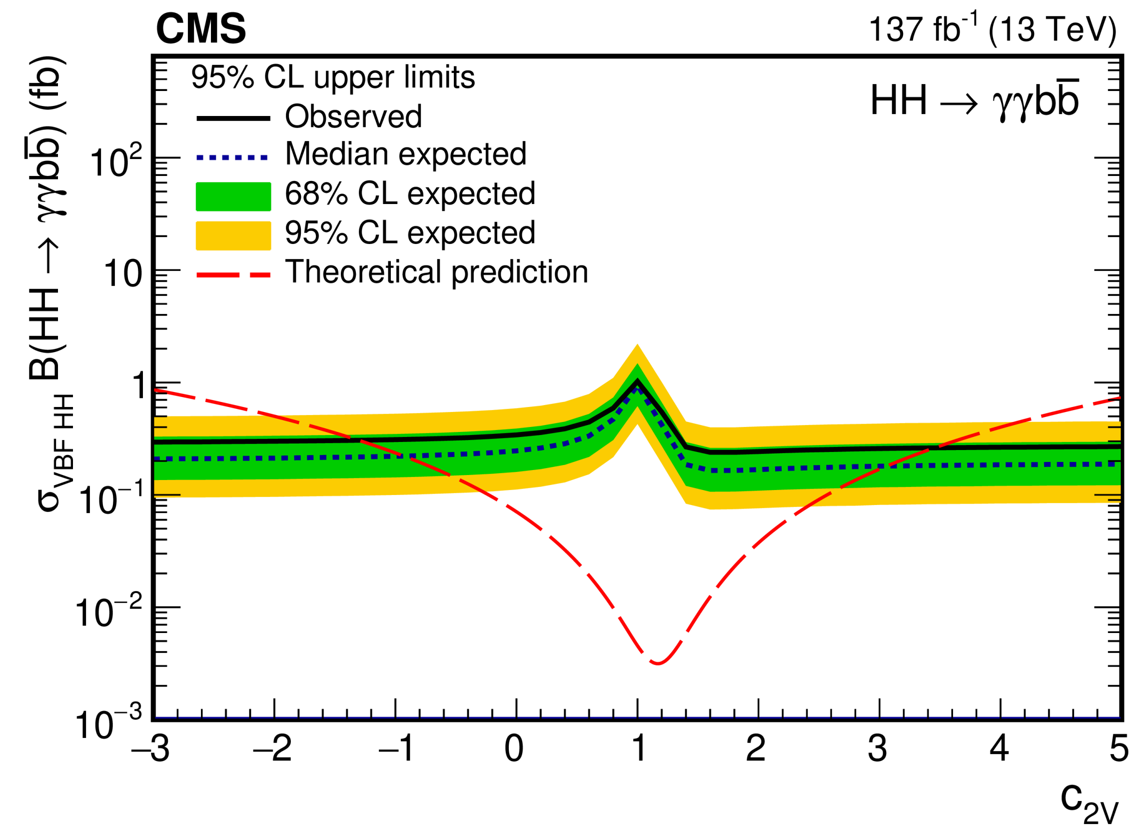


CMS (HH → bbγγ) 137 fb-1

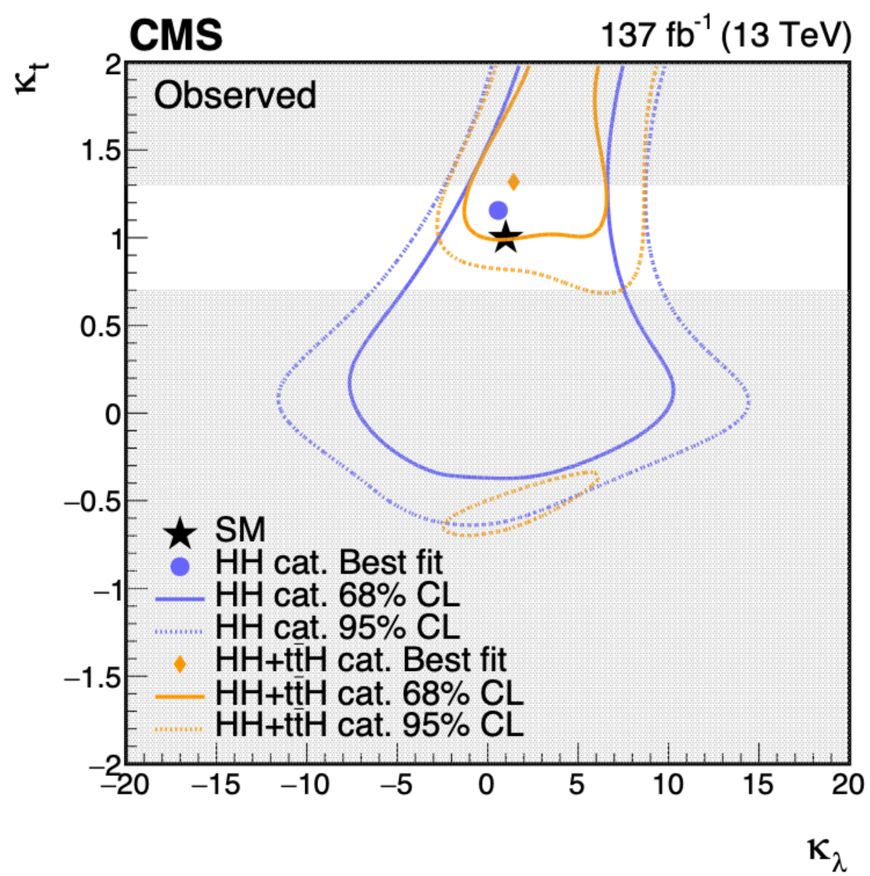
JHEP 03 (2021) 257

Search limited by statistics



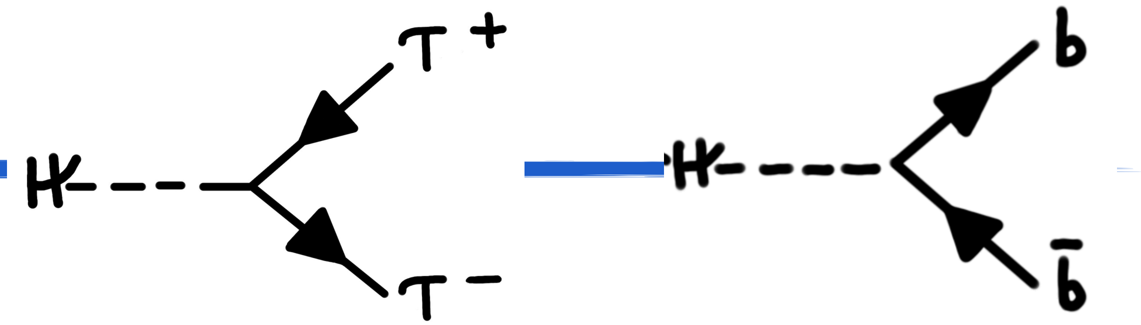


- σ_{HH} (ggF+VBF)/σ_{HH} SM (ggF+VBF) < 7.7 (5.2) at 95% CL
- -3.3(–2.5) < κ_λ < 8.5 (8.2)



- σ_{HH} (VBF)/σ_{HH} SM (VBF) < 225 (208) at 95% CL
- -1.3(–0.9) < c_{2V} < 3.5 (3.0)

ATLAS HH->bbtautau

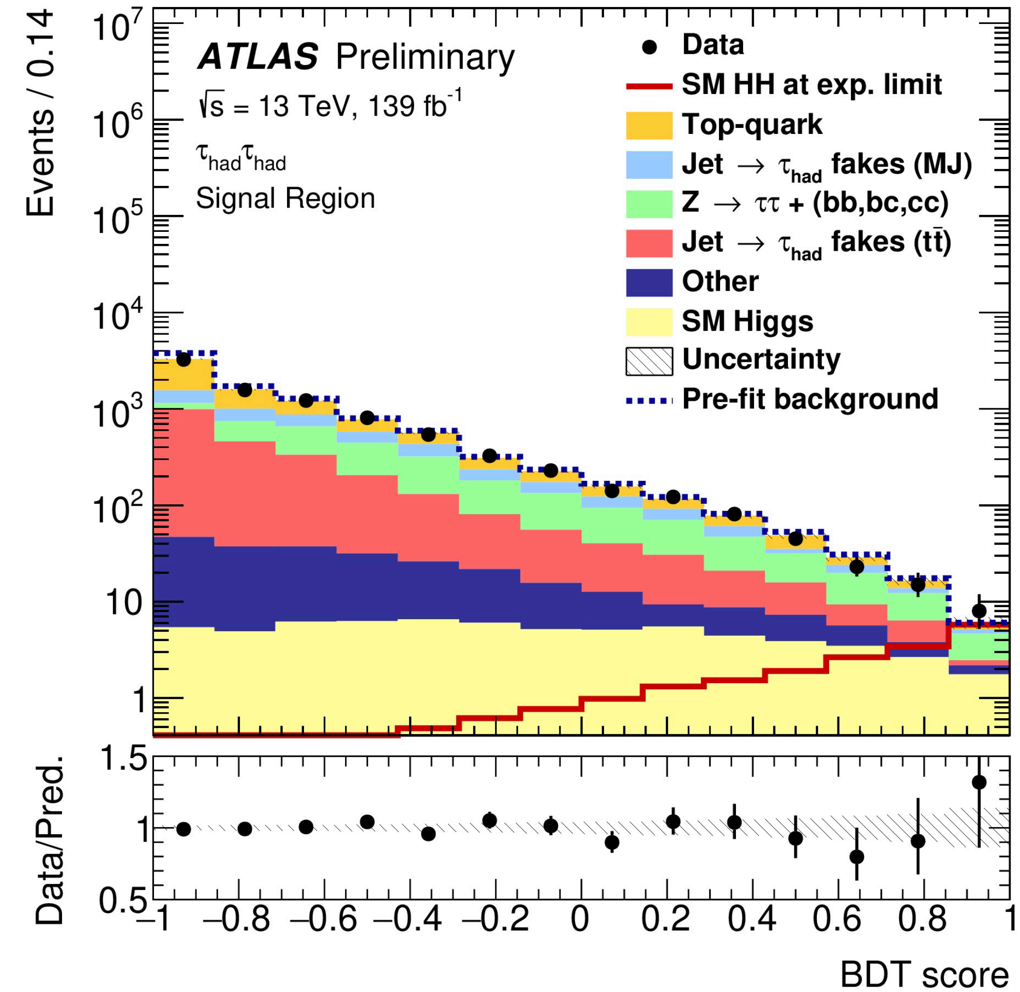


- Relatively large BR and relatively clean final state
- Optimized for ggF but includes also VBF signal
- Fit performed on the MVA in 3 categories:
  - $\tau_{had}\tau_{had}$
  - $\tau_{lep}\tau_{had}$ (e/μ & opp. charged τ)
    - Single Lepton Trigger (SLT) and Lepton+Tau Trigger (LTT)
- Backgrounds from: true τ in $t\bar{t}$ and Z+HF (from MC, normalization from data)
  - Control region for Z+HF (m_{ll})
- fake τ in $t\bar{t}$ and multi-jet (data-driven)

4x improvement wrt to previous results!

- 2x due to the τ and b-jet reconstruction and identification improvements and to analysis techniques=> MVA and fake tau estimates
- Statistically dominated, largest systematics from background modeling

ATLAS-CONF-2021-030

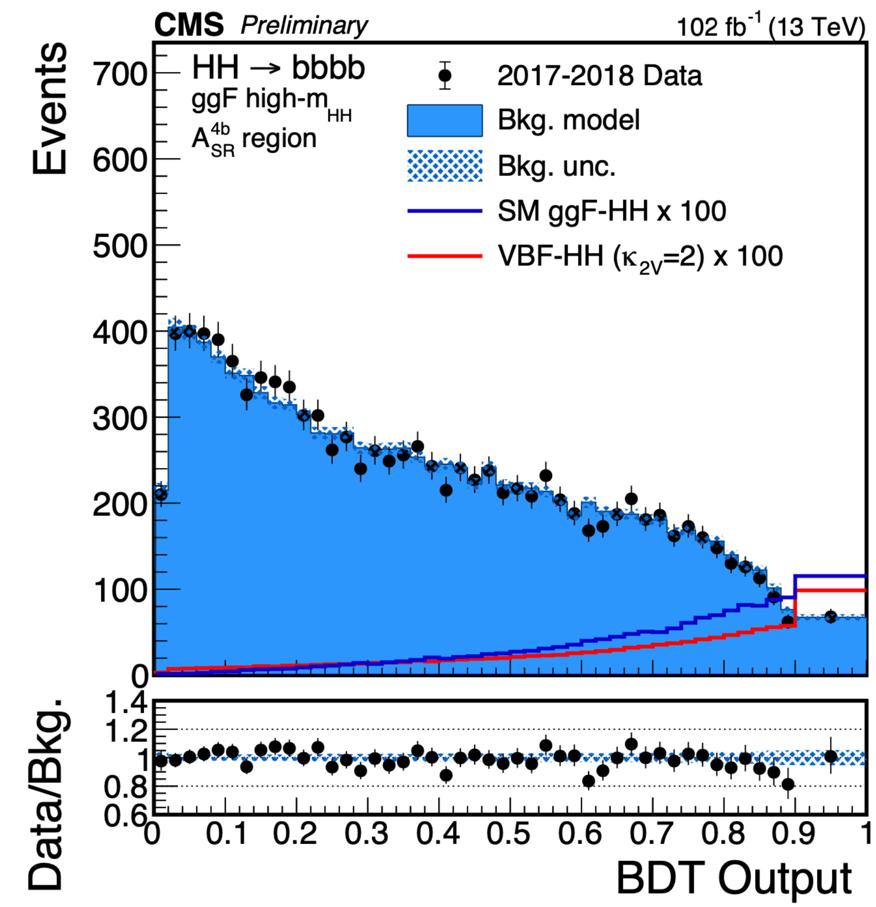


		Observed	−2 σ	−1 σ	Expected	+1 σ	+2 σ
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	265	124	167	231	322	432
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.65	2.08	2.79	3.87	5.39	7.22

CMS HH->4b (138fb^{-1})

CMS-PAS-HIG-20-005

- HH candidates reconstructed from 4 jets and $\chi = (m_{H1} - 125)^2 + (m_{H2} - 120)^2$ is used to divide events in SR and CR
- VBF candidates are selected by requiring 2 additional non b-jets and a VBF-vs-ggF BDT is used to reduce mis-classification of ggF events.
- VBF-vs-ggF BDT or a dedicated ggF BDT are used to enhance sensitivity to both SM and BSM scenarios, resulting in a total of 4 SRs.
- The large multijet background is estimated from data and a maximum likelihood binned fit is simultaneously performed in all SRs.

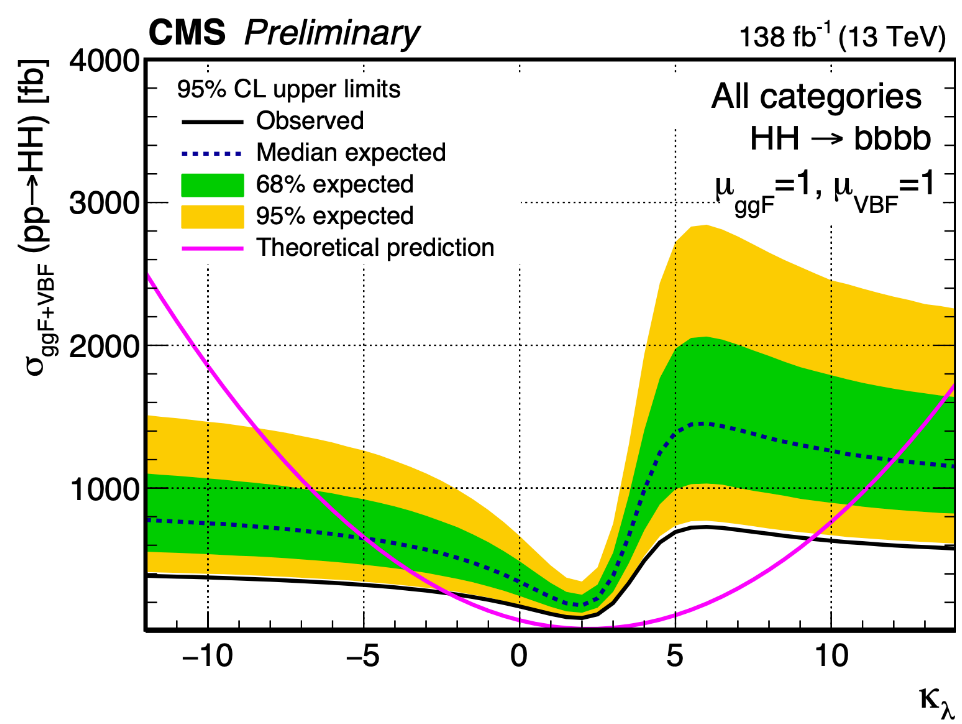


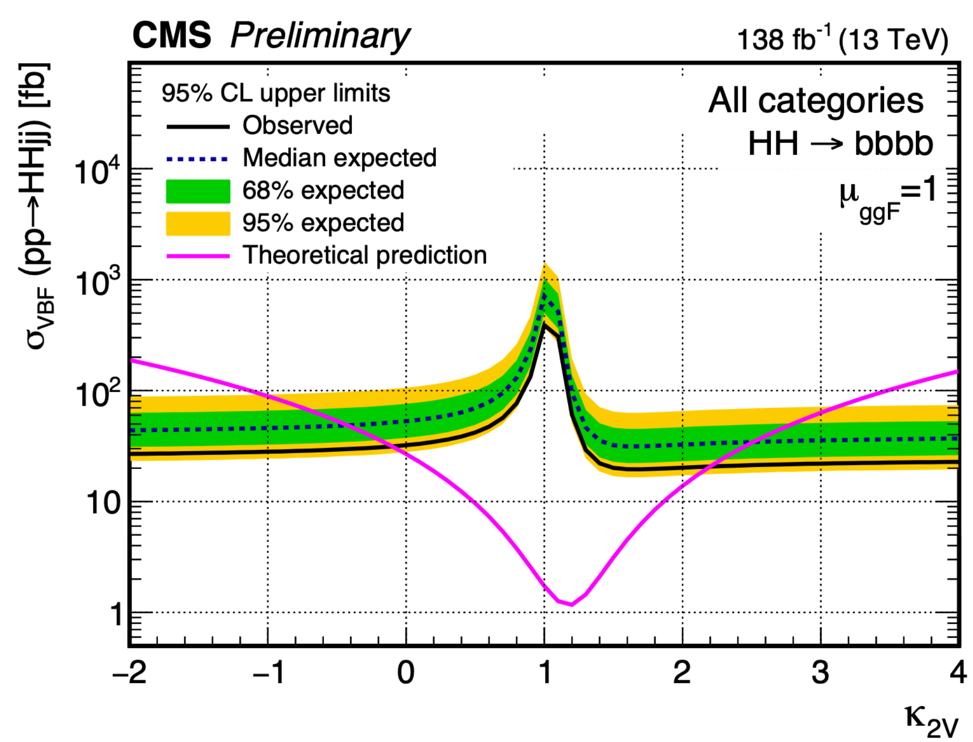
$$\sigma^{HH}_{ggF+VBF} < 3.6\ (7.3) \times \sigma^{HH\ SM}_{ggF+VBF}$$

$$-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$$

$$-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$$

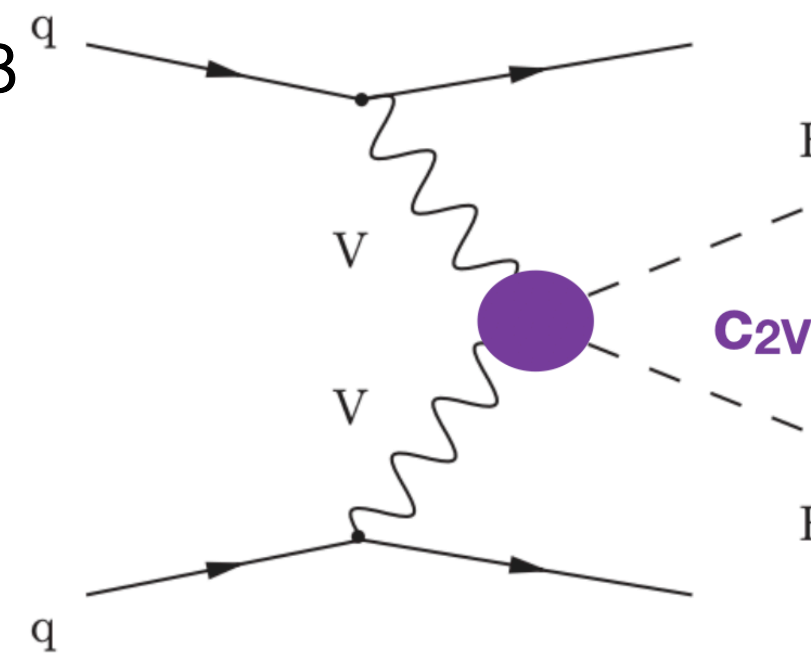
observed (expe

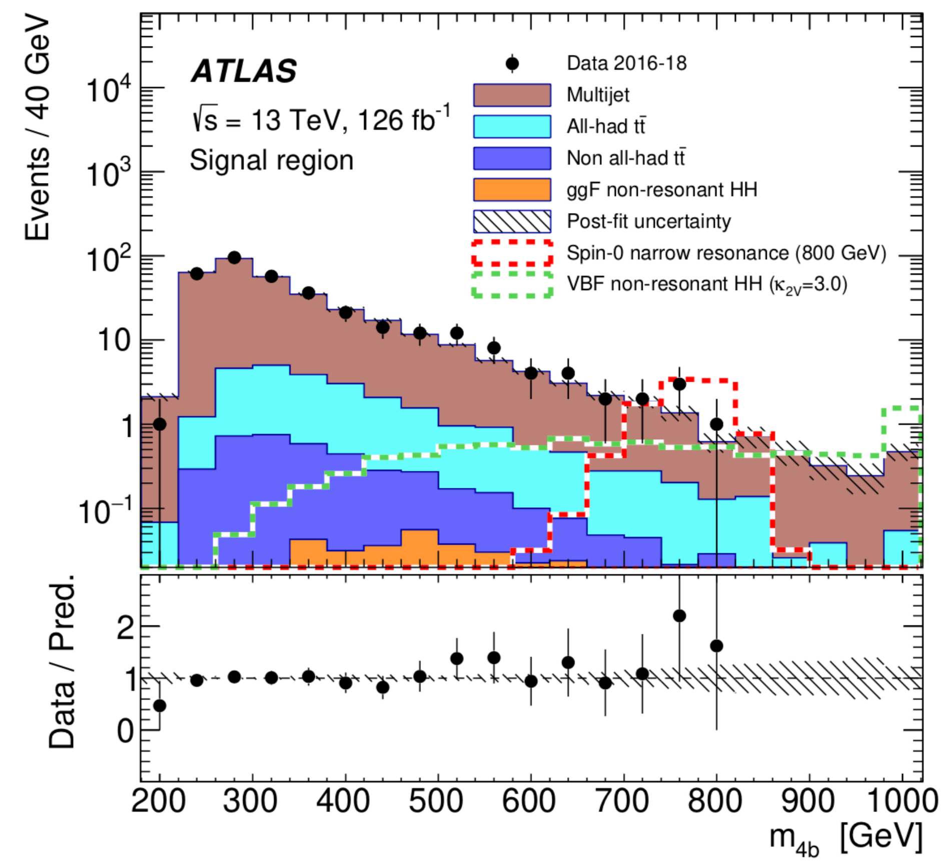


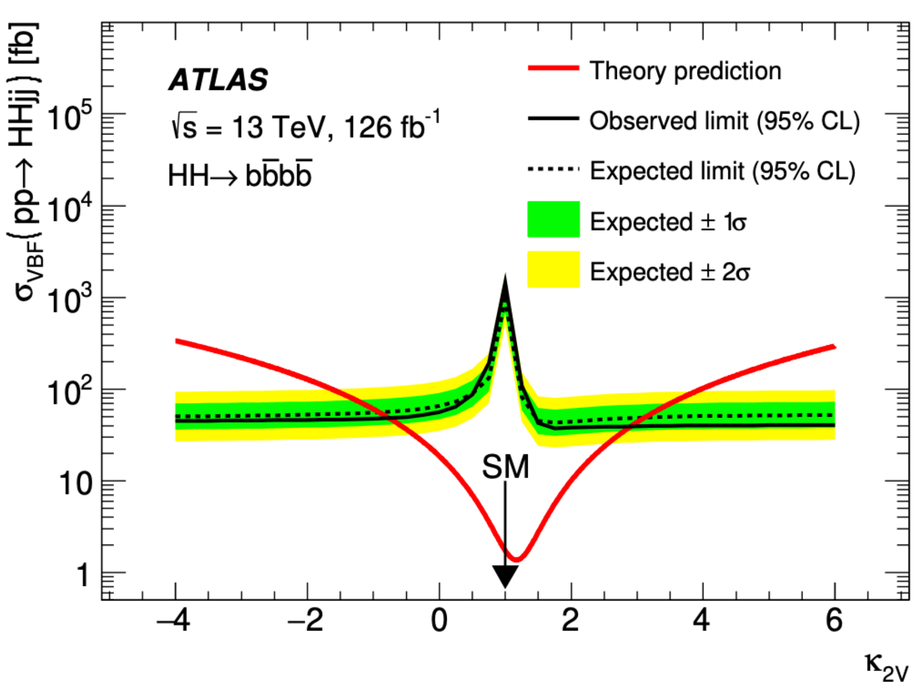


ATLAS VBF HH->4b JHEP 07 (2020) 108

- Targeting specifically VBF HH
- Distinct VBF signature: two high p_T jets with large rapidity gap and invariant mass
- 4 b jets final state : M(bb) energy resolution improved by 25% with BDT energy regression
- Main challenge - multijet background, estimated from data events with lower b-jet multiplicity
- Fit m_{4b} to extract presence of signal







Observed (expected) :

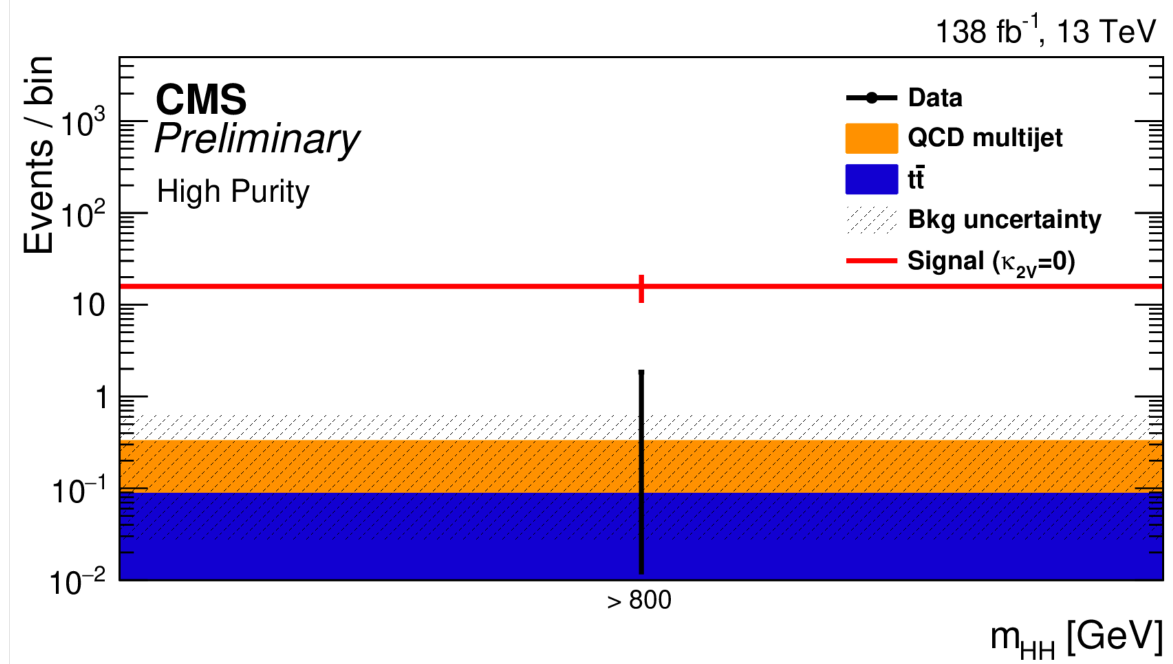
$\sigma^{VBF}/\sigma^{VBF}_{SM} < 840(550)$ at 95%CL

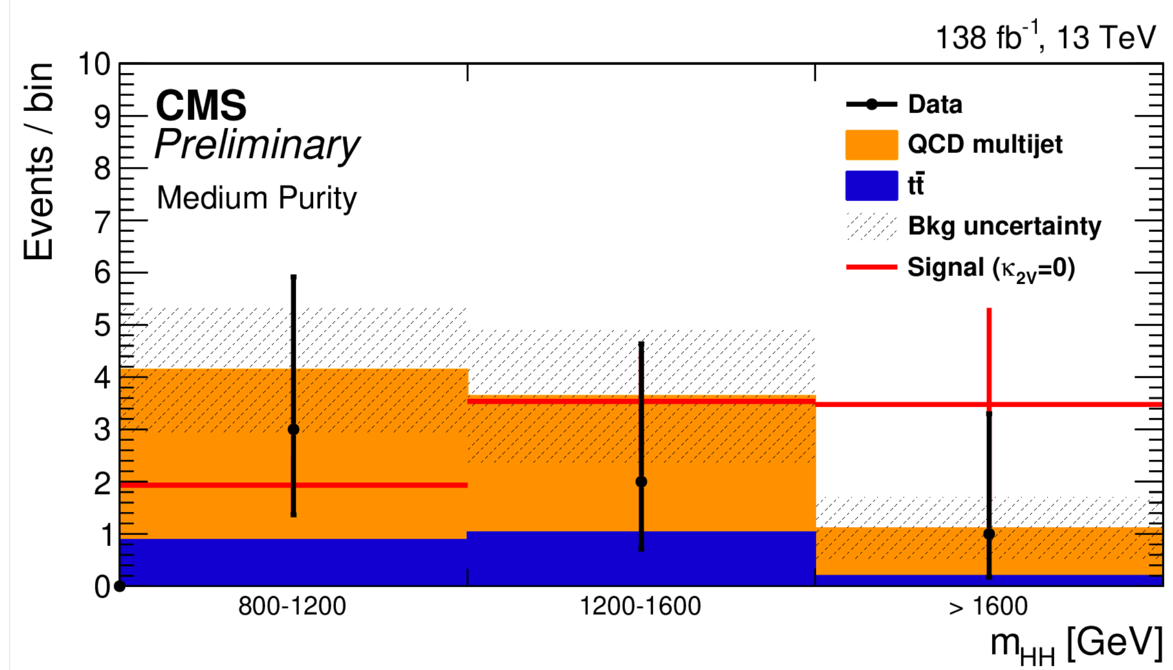
$-0.43\ (-0.55) < c_{2V} < 2.56\ (2.72)$

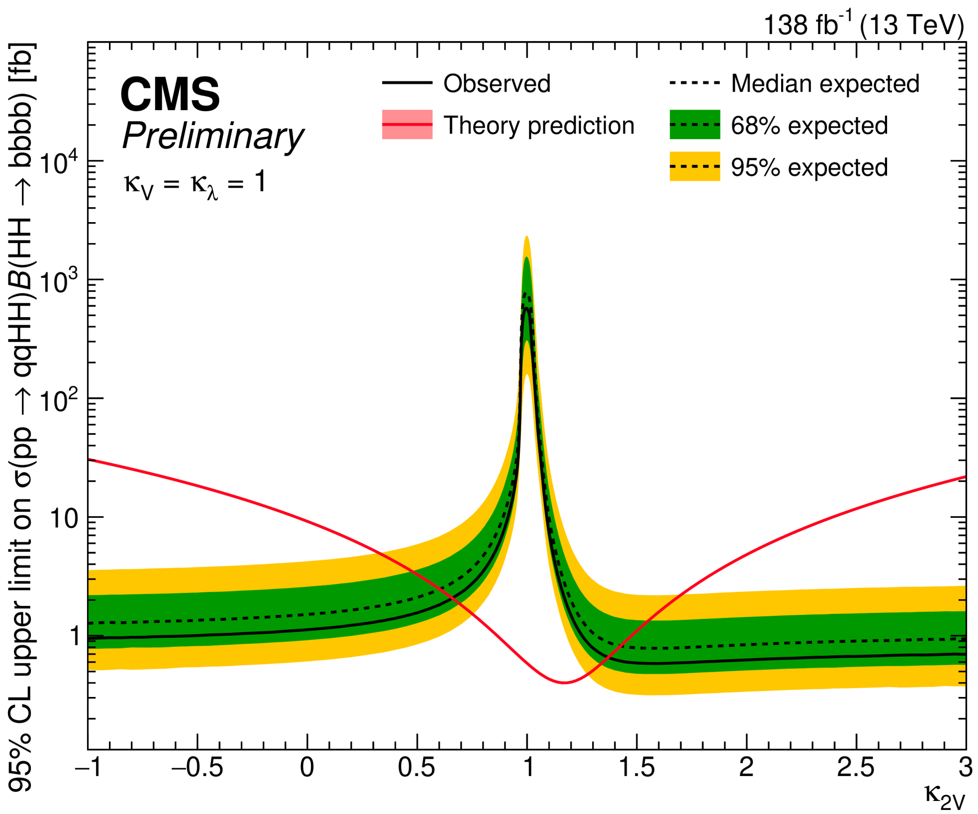
CMS HH->4b (boosted)

B2G-21-001

- Modified couplings can lead to boosted topologies!
- Less combinatorics than resolved search
  - 2 defined large R jets, 1 per Higgs decay.
- H->bb identified using novel neural network (NN) algorithm, ParticleNet
  - graph convolutional NNs, multi-classifier
  - 3 event categories according the ParticleNet score (high, medium and low purity)
- QCD multijet background estimated using sidebands in data
- Fit is performed on m_{HH}







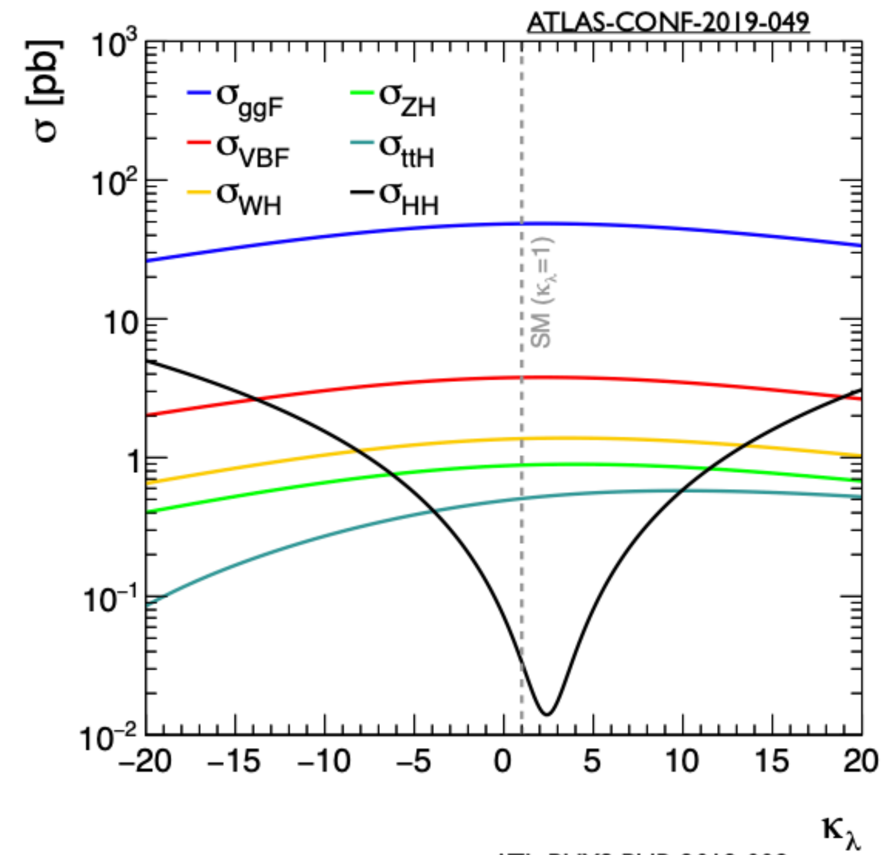
κ_{VV}=0 is shown in red
Very sensitive search!

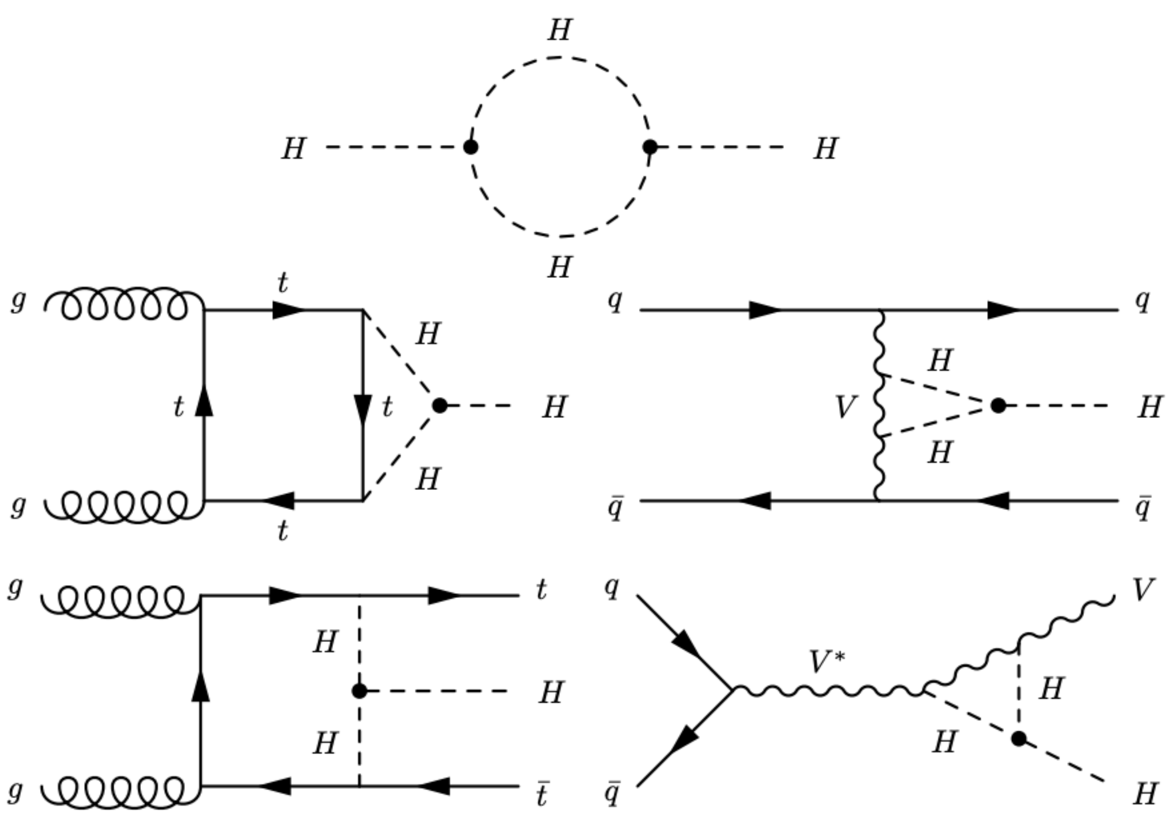
Observed: $0.6 < \kappa_{VV} < 1.4$
Expected: $0.6 < \kappa_{VV} < 1.4$

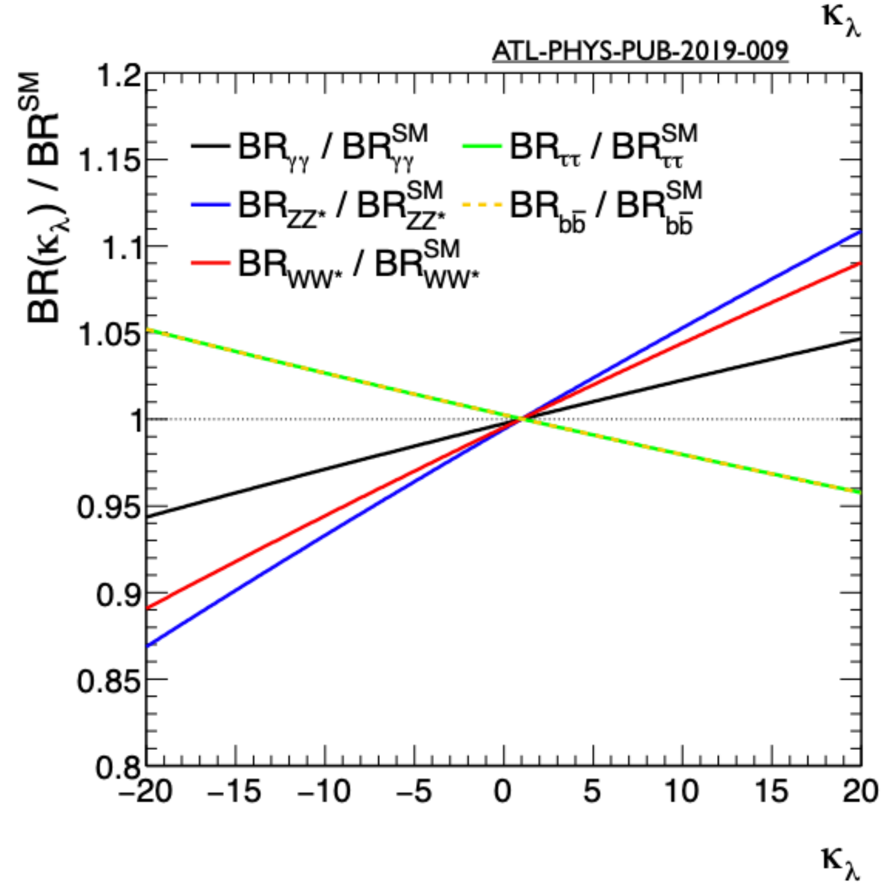
Best to date!
Assuming $\kappa_t=\kappa_V=1$, $\kappa_{VV}=0$ is excluded at a CL higher than 99.99%.

Single Higgs and Double Higgs self-coupling limit

- NLO EW corrections give Higgs cross-section, branching ratios, and kinematics dependence on κλ:
  - Can perform a combined analysis, using single and double Higgs!

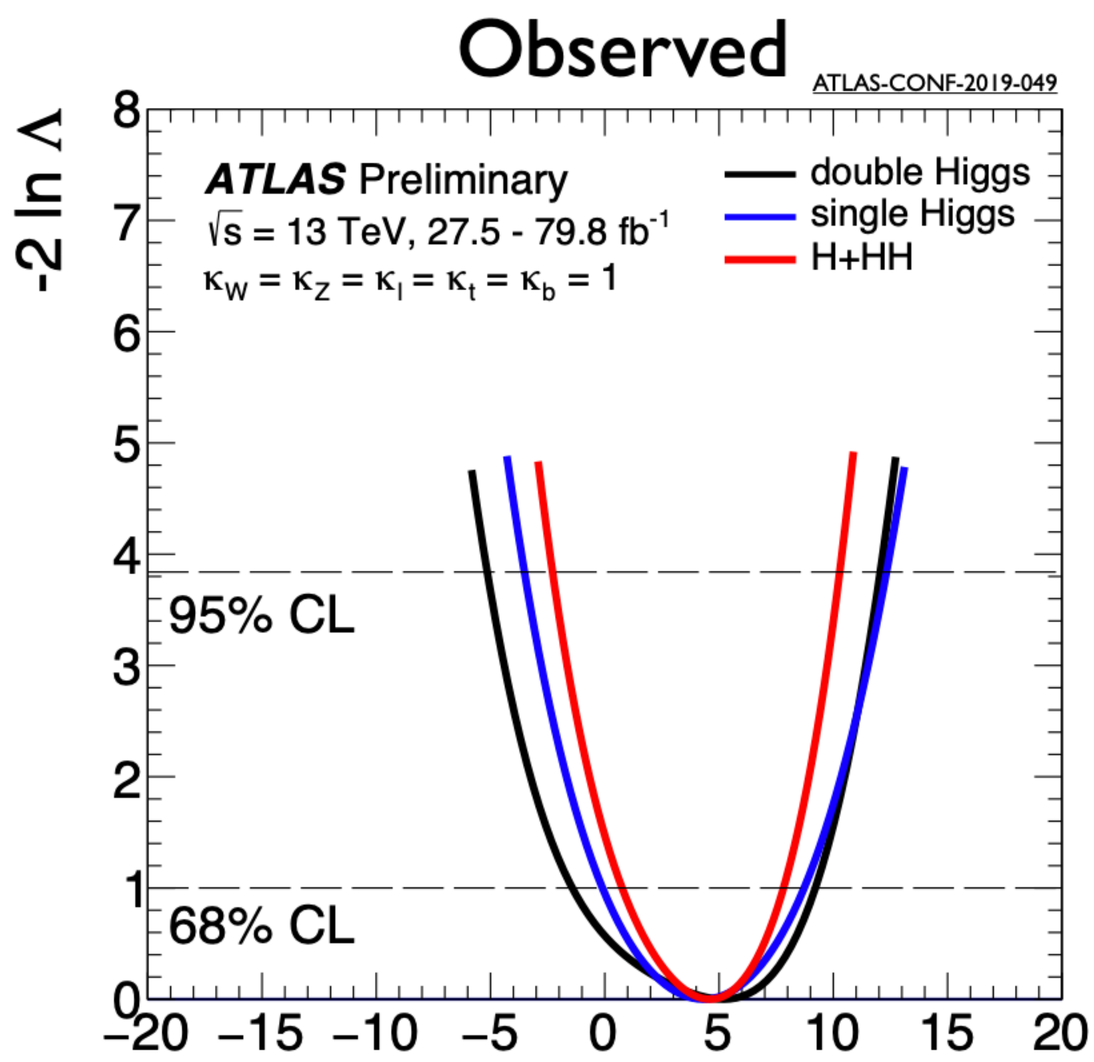




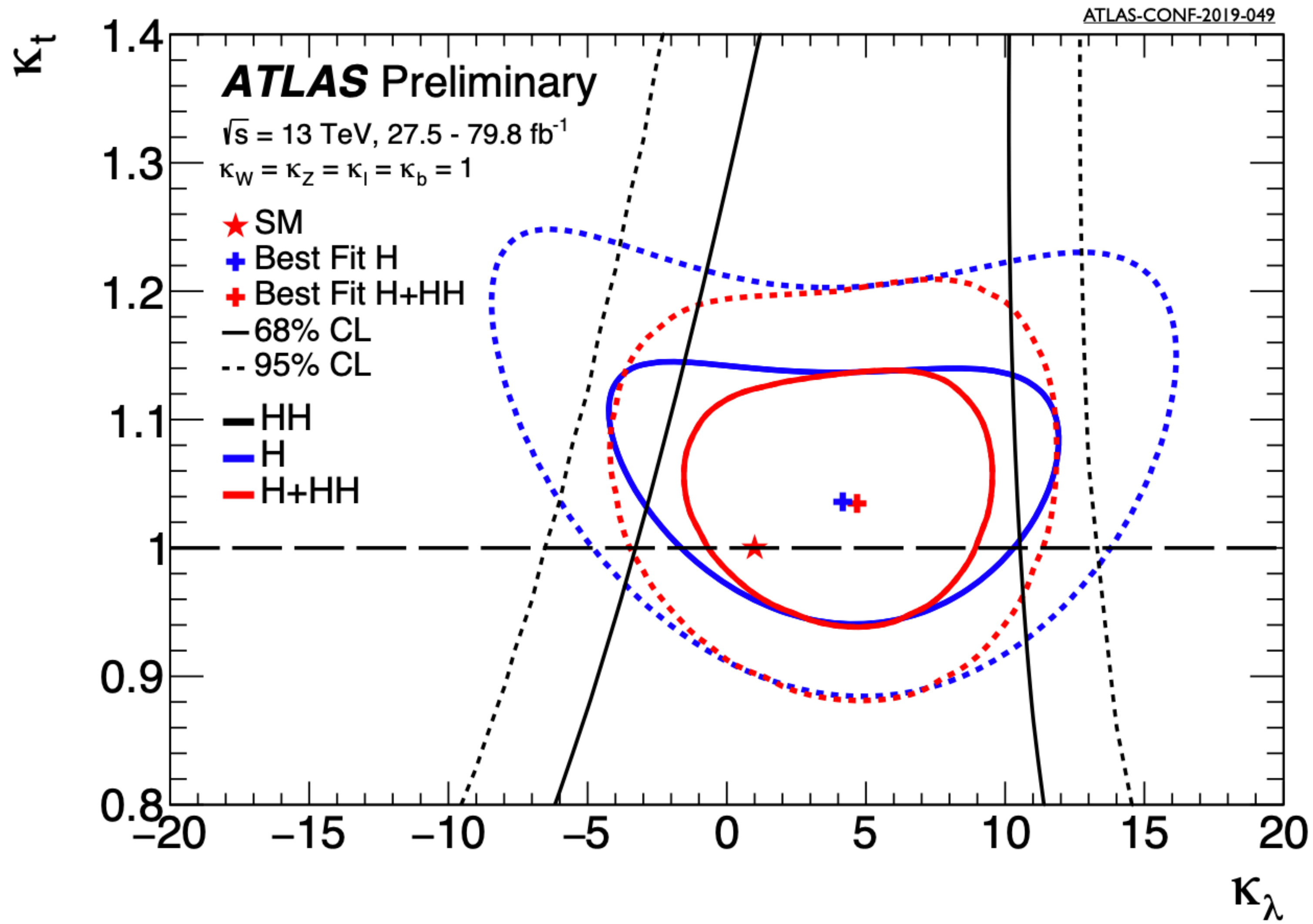


Single Higgs and Double Higgs self-coupling limit

Analysis	Integrated luminosity (fb^{-1})	Ref.
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8	[21,22]
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8	[23,24]
$H \to WW^* \to e\nu\mu\nu$	36.1	[25]
$H \to \tau^+\tau^-$	36.1	[26]
VH, $H \to b\bar{b}$	79.8	[27,28]
$t\bar{t}H$, $H \to b\bar{b}$	36.1	[29]
$t\bar{t}H$, $H \to$ multilepton	36.1	[30]
$HH \to b\bar{b}b\bar{b}$	27.5	[31]
$HH \to b\bar{b}\tau^+\tau^-$	36.1	[32]
$HH \to b\bar{b}\gamma\gamma$	36.1	[33]



New physics only in κ_λ



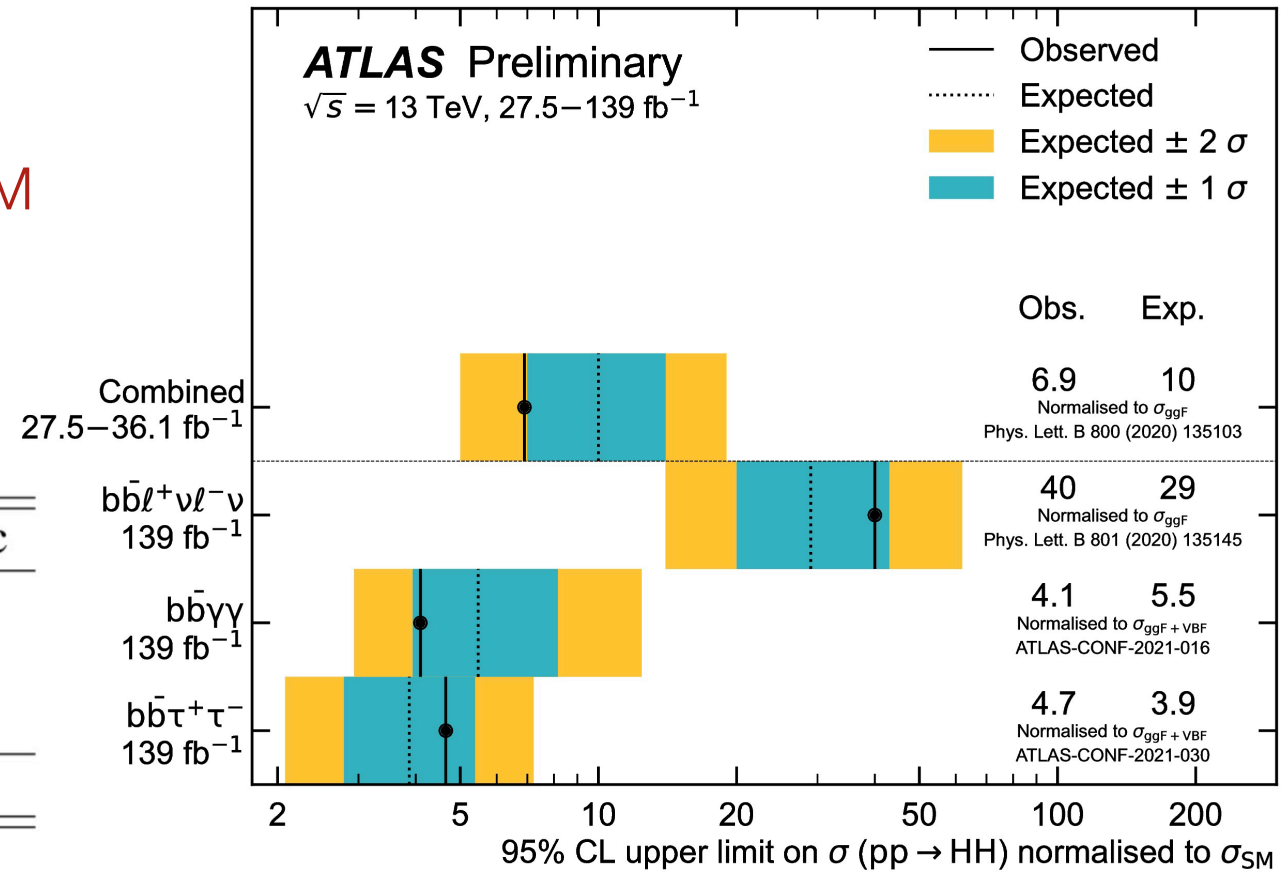
Di-Higgs measurements cannot simultaneously constrain κ_λ and κ_t
Need single Higgs!

Summary

- Entered the era of precision physics for the Higgs
- Evidence of rare Higgs decays: H->μμ and H->Zγ
- Current EFT constraints from VH and boosted ggH->bb are dominated by statistical uncertainties at high pT(V).
  - Can expect significant improvement from Run-3 datasets.
  - At HL-LHC, experimentally cleaner decay modes (H→ZZ, H→γγ) will also contribute significantly
- HH: channels are now even better than the 36 fb^{-1} HH combination!
  - Great analysis improvements in all final states compared to early Run 2
  - Run 3 could already be a game changer for a first statistically significant evidence of HH
- VBF new in the game:
  - Best constraint in κ_{VV} to date! Assuming SM values for all other couplings (κ_t, κ_V, κ_λ) we can exclude κ_{VV}=0!

(old) HL-LHC projections

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.2	0.5
$HH \to b\bar{b}\tau^+\tau^-$	2.3	2.0
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.3	2.9



Backup