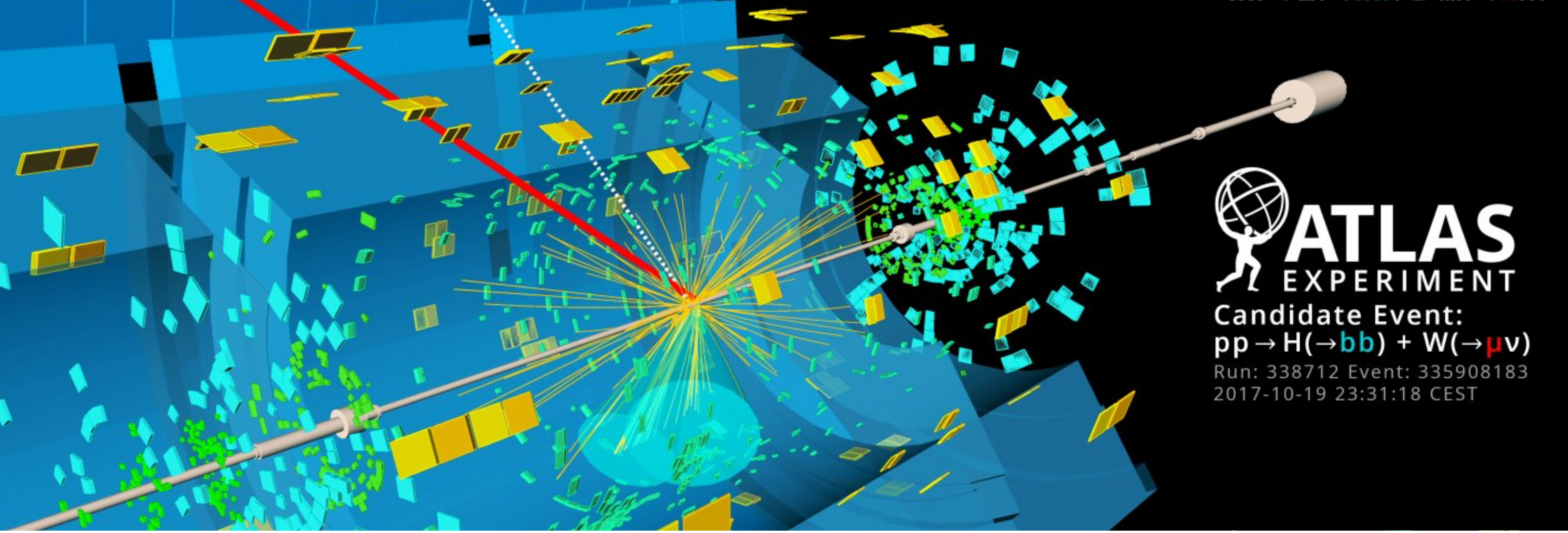

Measurements of the Higgs boson properties and their interpretations with the ATLAS experiment

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Lake Louise Winter Institute 2022

20th February 2022

Stony Brook University

ATLAS EXPERIMENT

CERN

What's next in the Higgs sector ?

We entered a new era for the Higgs sector:

After the discovery, the focus shifted towards the **measurement of its properties**

Is this "the Higgs"?

"precise" Higgs measurements → search for deviations from the SM in **differential cross-section** measurements.

More direct test of the SM

Less assumptions

Couplings: μ_{ggF}, μ_{VBF}, … κ_g, κ_V, …

STXS: $\sigma_{ggF} \times BR(H \rightarrow \gamma\gamma)$ — *Inclusive in the Higgs decay mode*

- Defined for specific **production modes**
- Maximise the experimental sensitivity

Fiducial xs: $\sigma_{Fid}(pp \rightarrow H \rightarrow \gamma\gamma)$ — *Inclusive in the production mode*

- Cross-section in the ***fiducial volume.***
- ***Minimise extrapolation*** *into experimentally invisible phase space*

Re-interpretation

Effective Field Theories (EFT)
and coupling modifiers

Parameterize each process based on specific kinematic observables:
eg. pT(H), N(jets), mjj, pT(H+2jets), pT(V)..

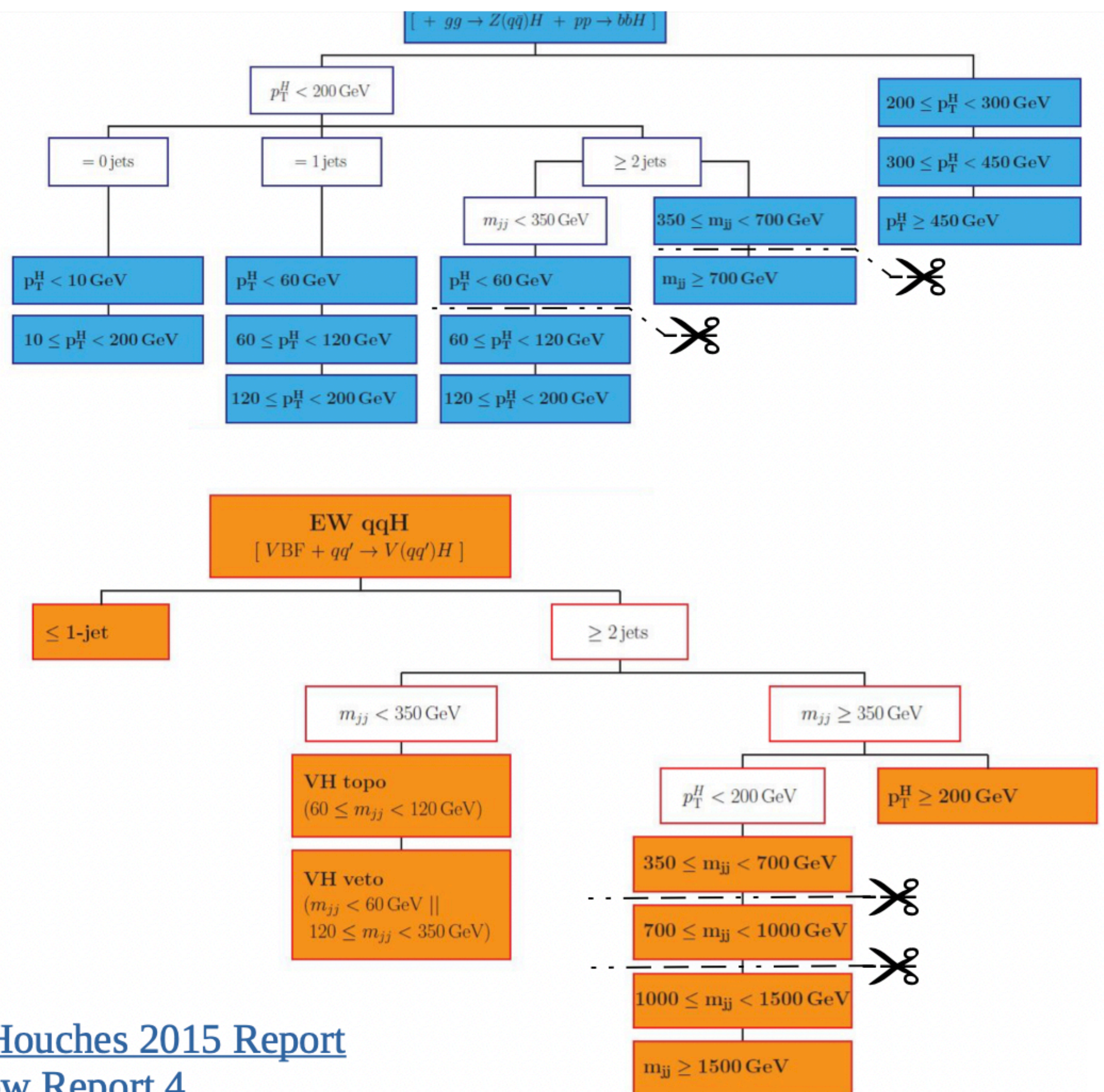
Probing the Higgs boson phase space:

Increased "resolution" to BSM effects:

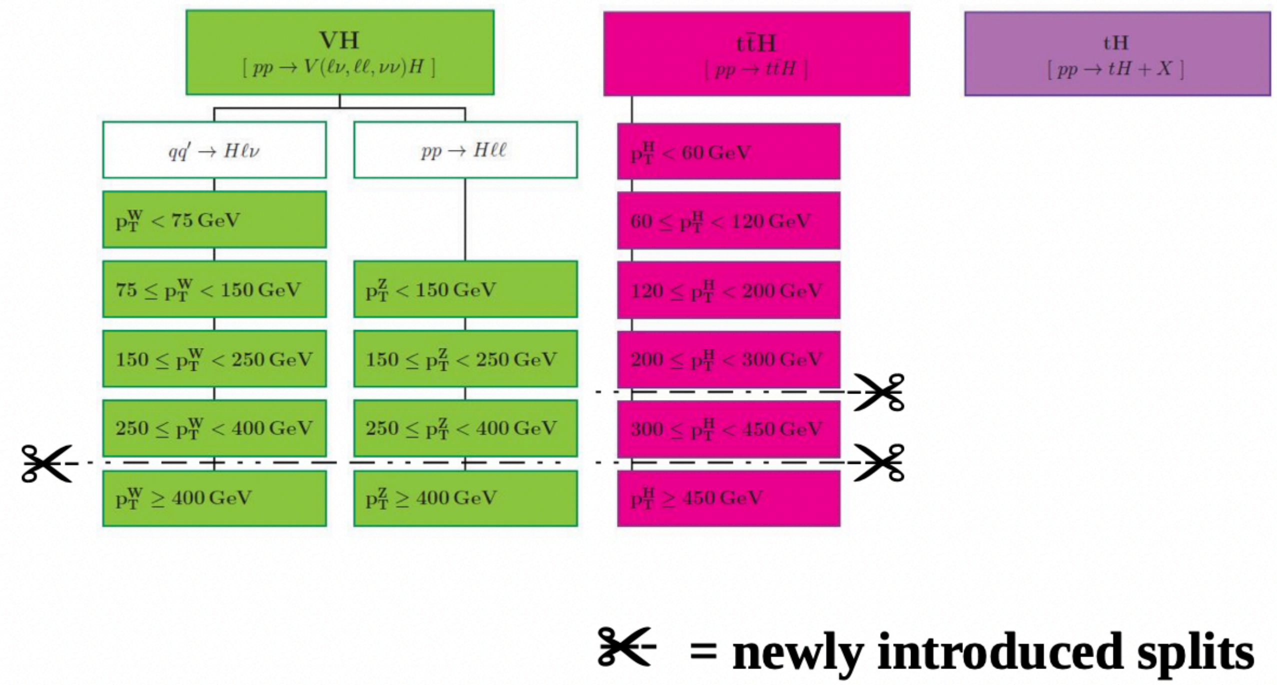
41 STXS bins in total

⇩

From H. Arnold @ Higgs2021 [Link]

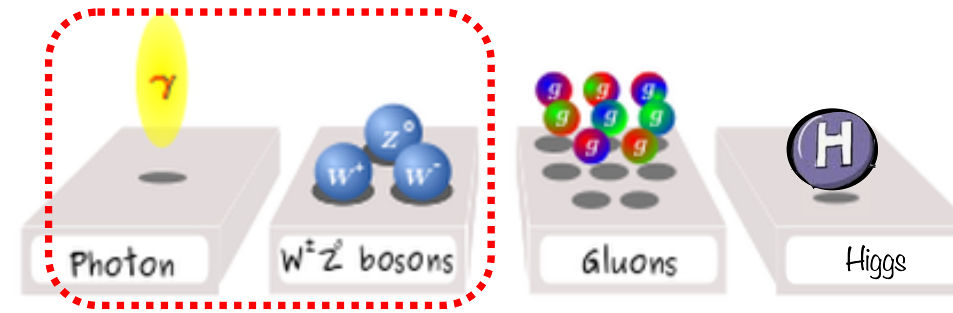


Les Houches 2015 Report
Yellow Report 4



Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
	$t\bar{t}H$	36.1
$H \to WW^*$	ggF, VBF	139
	$t\bar{t}H$	36.1
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{had}\tau_{had})$	139
	$t\bar{t}H$	36.1
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139
$H \to \mu\mu$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to Z\gamma$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to inv$	VBF	139

Global Higgs coupling fits → get constraints from all Higgs analyses in a single fit



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	VBF	126
	$t\bar{t}H$	139
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$H \to Z\gamma$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to inv$	VBF	139

Boson Decays

Higgs decays into photons and vector bosons

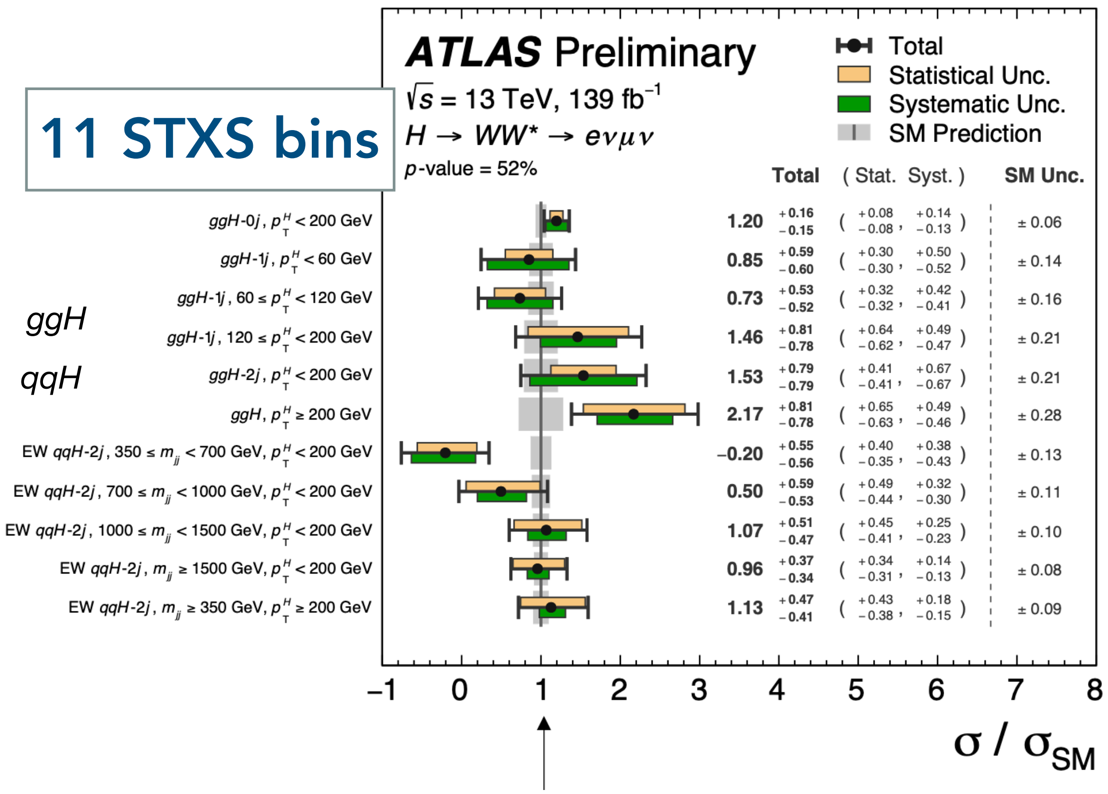
STXS measurements:

Channels with cleanest S/B ratio.
Lot of data: categorise the events in a fine way

- **H→WW→ℓνℓν:** Larger BR but worst resolution due to neutrinos.

BR

H→WW*→ℓνℓν: ATLAS-CONF-2021-014



STXS measurements:

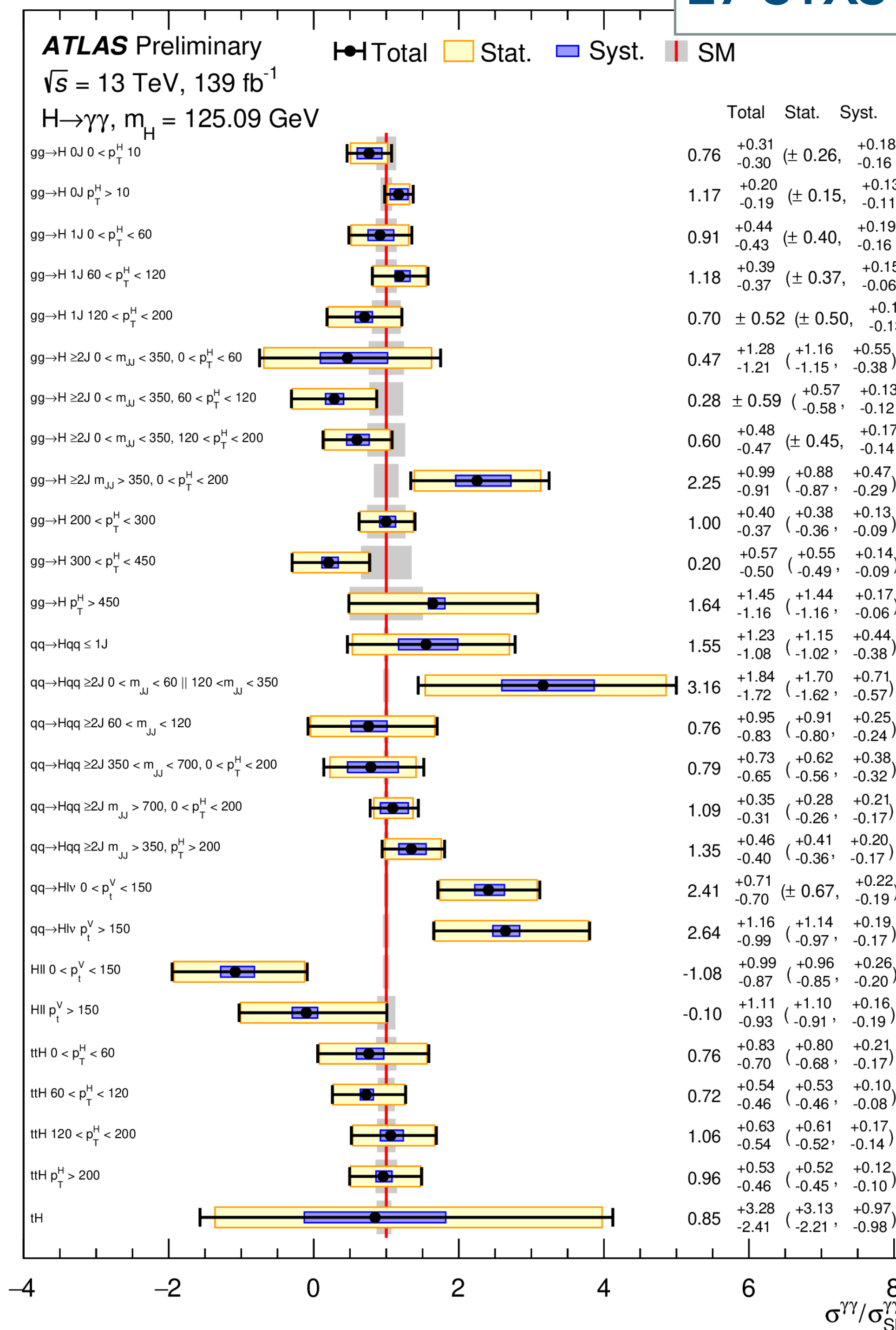
Channels with cleanest S/B ratio.
Lot of data: categorise the events in a fine way

BR

- **H→WW→$\ell\nu\ell\nu$:** Larger BR but worst resolution due to neutrinos.
- **H→$\gamma\gamma$:** Small BR but high control on the background in sidebands. decay through loop probes coupling to both fermions and vectors.

H→$\gamma\gamma$: ATLAS-CONF-2020-026

27 STXS bins

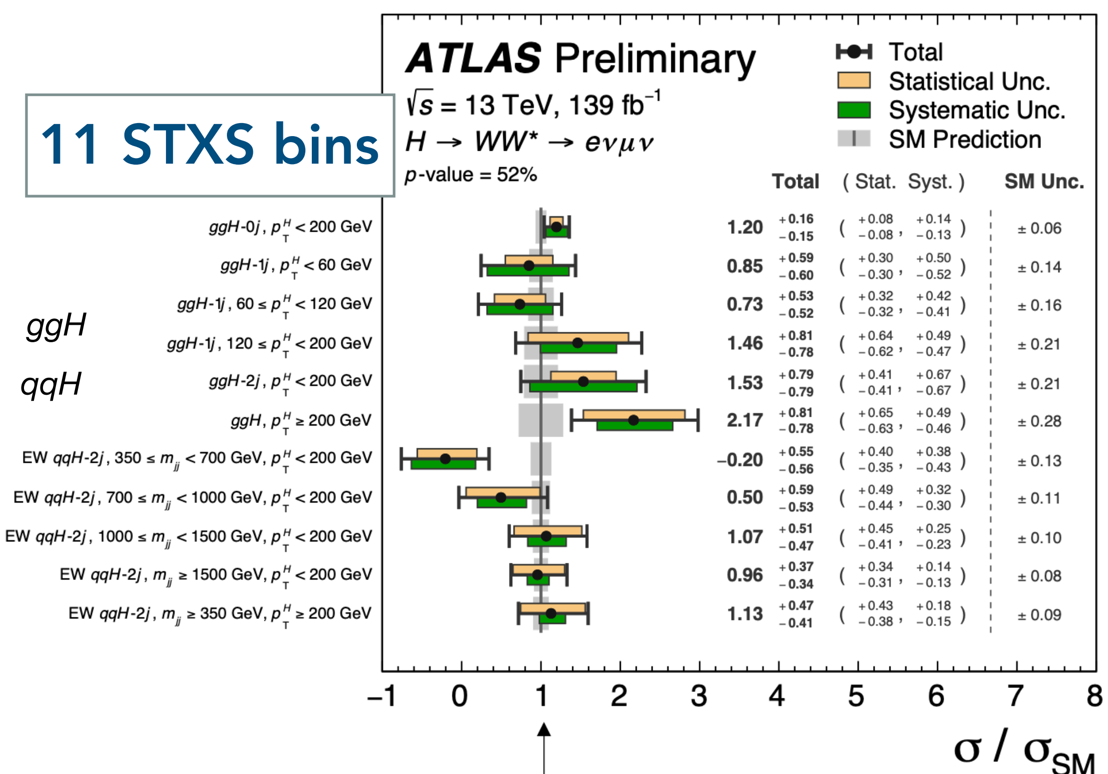


H→WW*→$\ell\nu\ell\nu$: ATLAS-CONF-2021-014

11 STXS bins

ggH

qqH



STXS measurements:

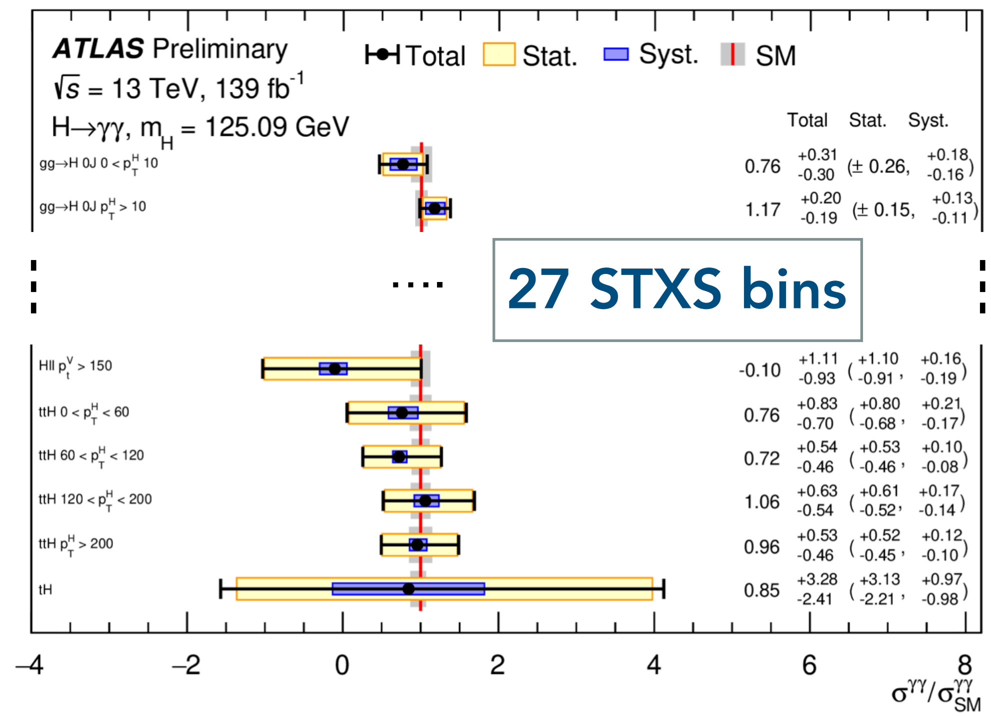
Channels with cleanest S/B ratio.

Lot of data: categorise the events in a fine way

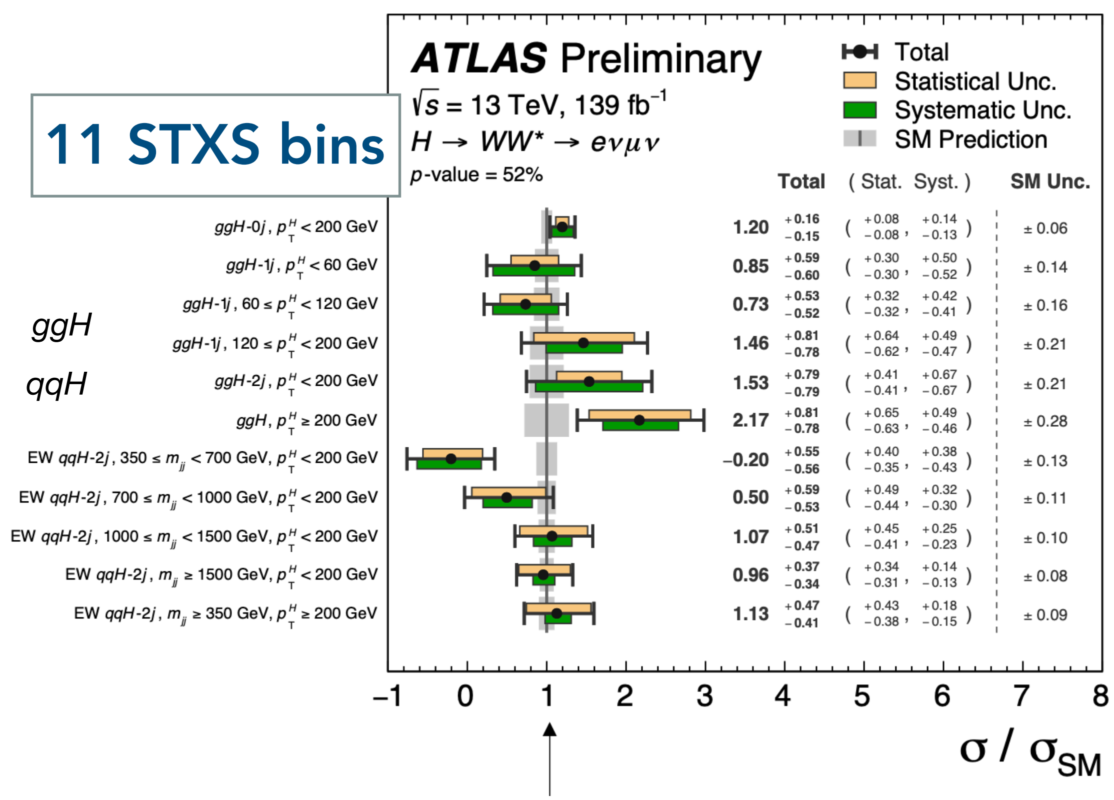
BR

- **H→WW→ℓνℓν:** Larger BR but worst resolution due to neutrinos.
- **H→γγ:** Small BR but high control on the background in sidebands. decay through loop probes coupling to both fermions and vectors.
- **H→ZZ→4ℓ:** Lowest BR but very clean final state.
  - Main bkg: ZZ*, from data+simulation

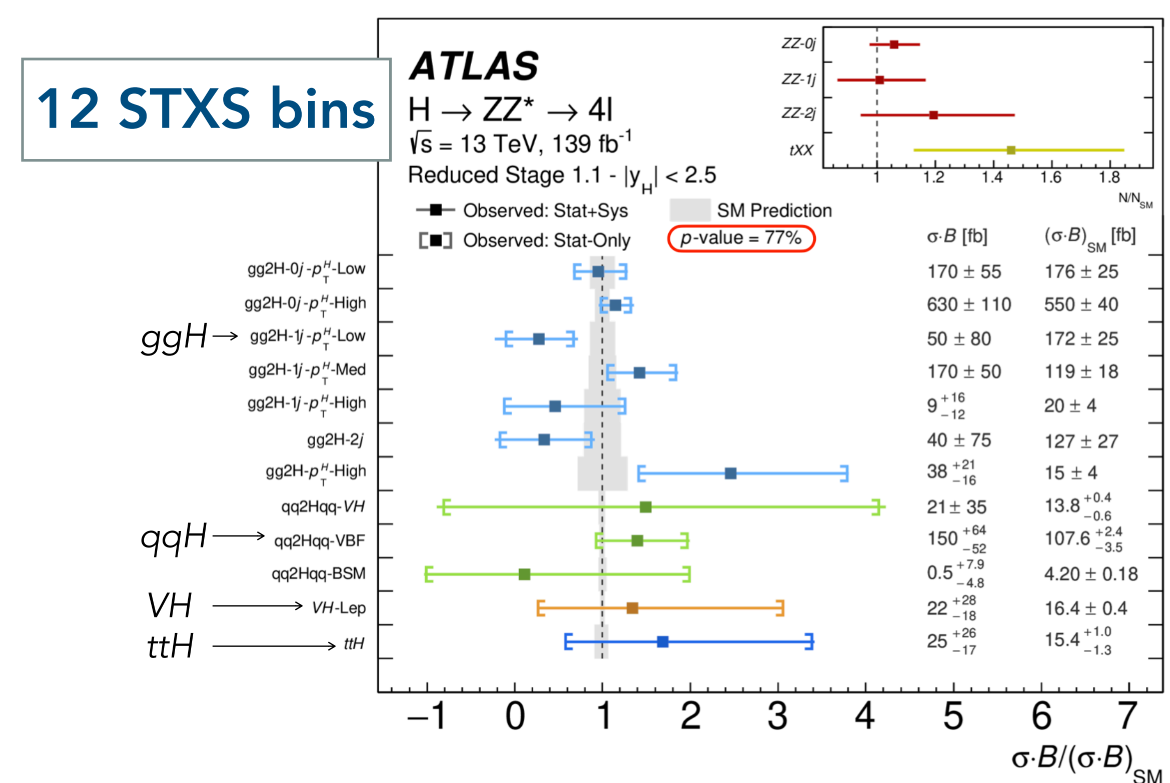
H→γγ: ATLAS-CONF-2020-026



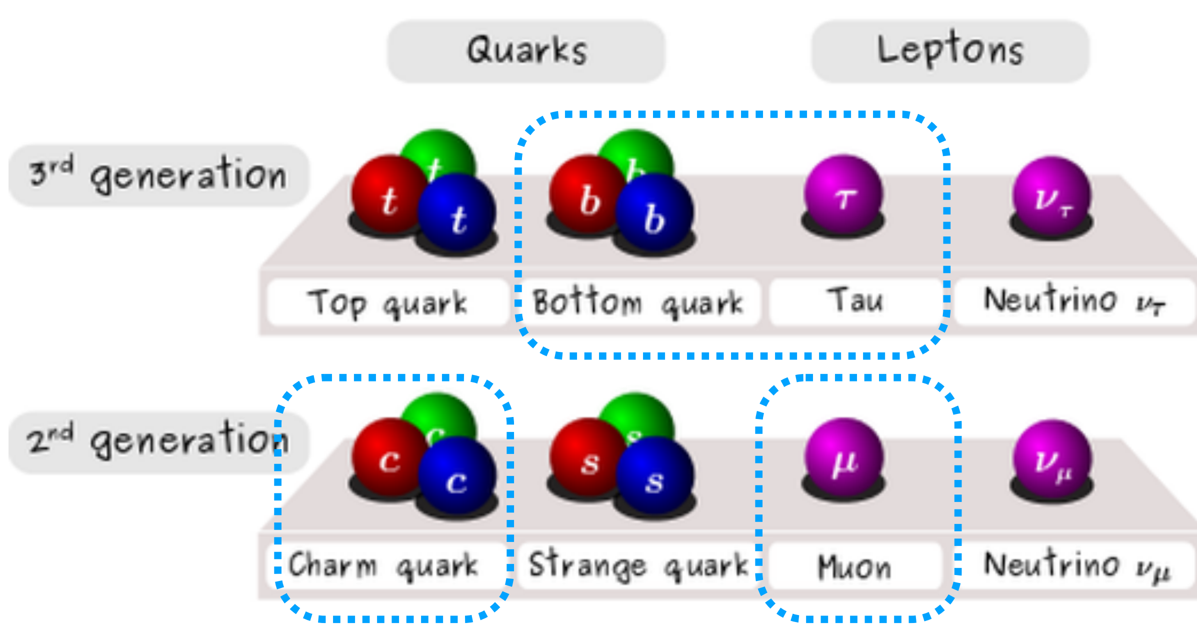
H→WW*→ℓνℓν: ATLAS-CONF-2021-014



H→ZZ*→4ℓ: Eur. Phys. J. C 80 (2020) 957



Coupling to Fermions



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$H \to Z\gamma$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to inv$	VBF	139

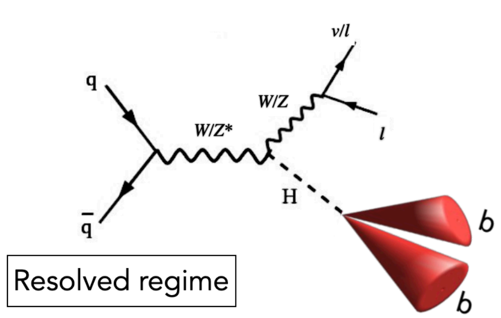
(+H→cc not included in global combination yet)

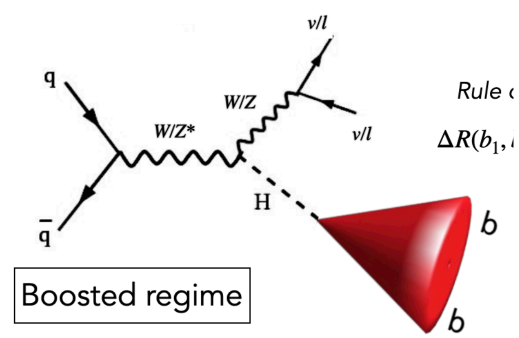
VH,H→bb results:

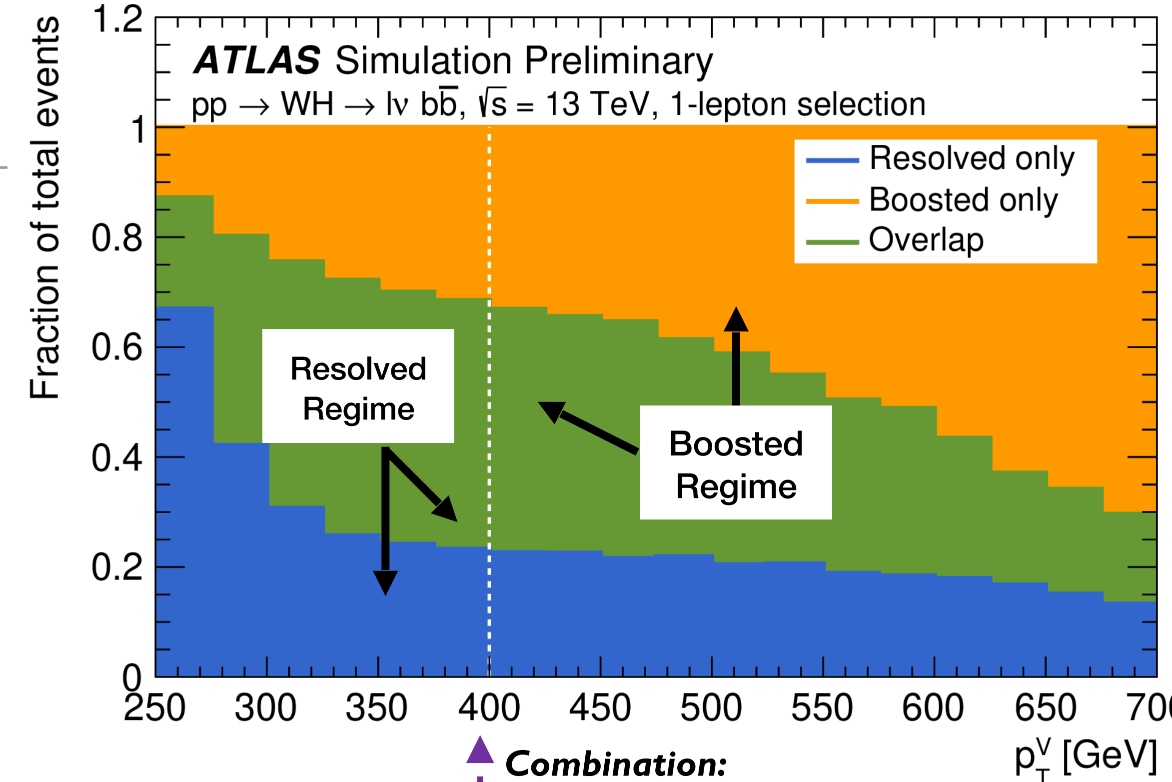
VH production mode: exploit additional leptonic signatures in the final state.

Three VH(bb) results with full Run II data:

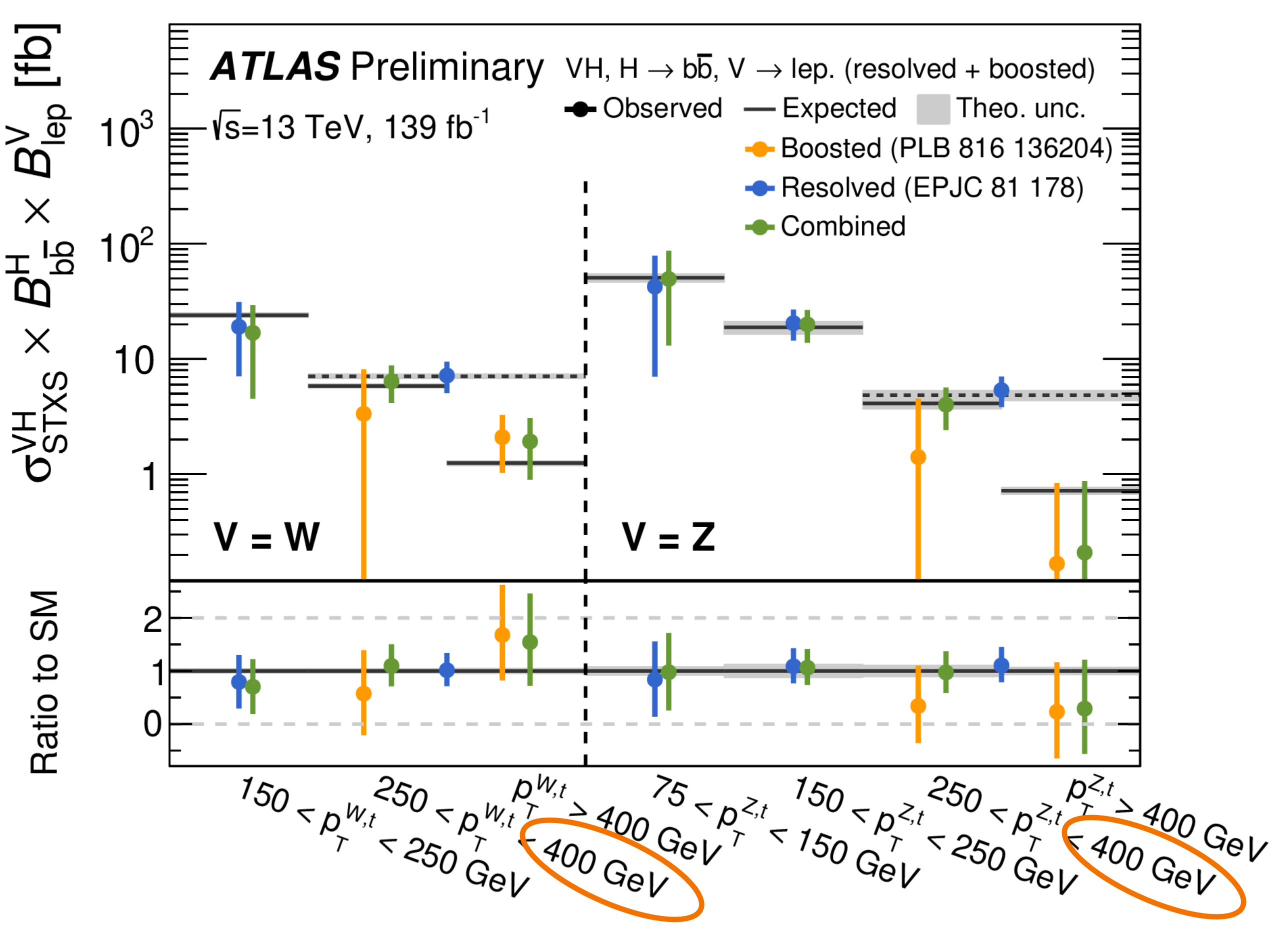
- VH(bb) in **resolved regime:** Eur. Phys. J. C 81 (2021) 178
- VH(bb) in **boosted regime**: Phys. Lett. B 816 (2021) 136204
- VH(bb) **resolved+boosted combination**: ATLAS-CONF-2021-051



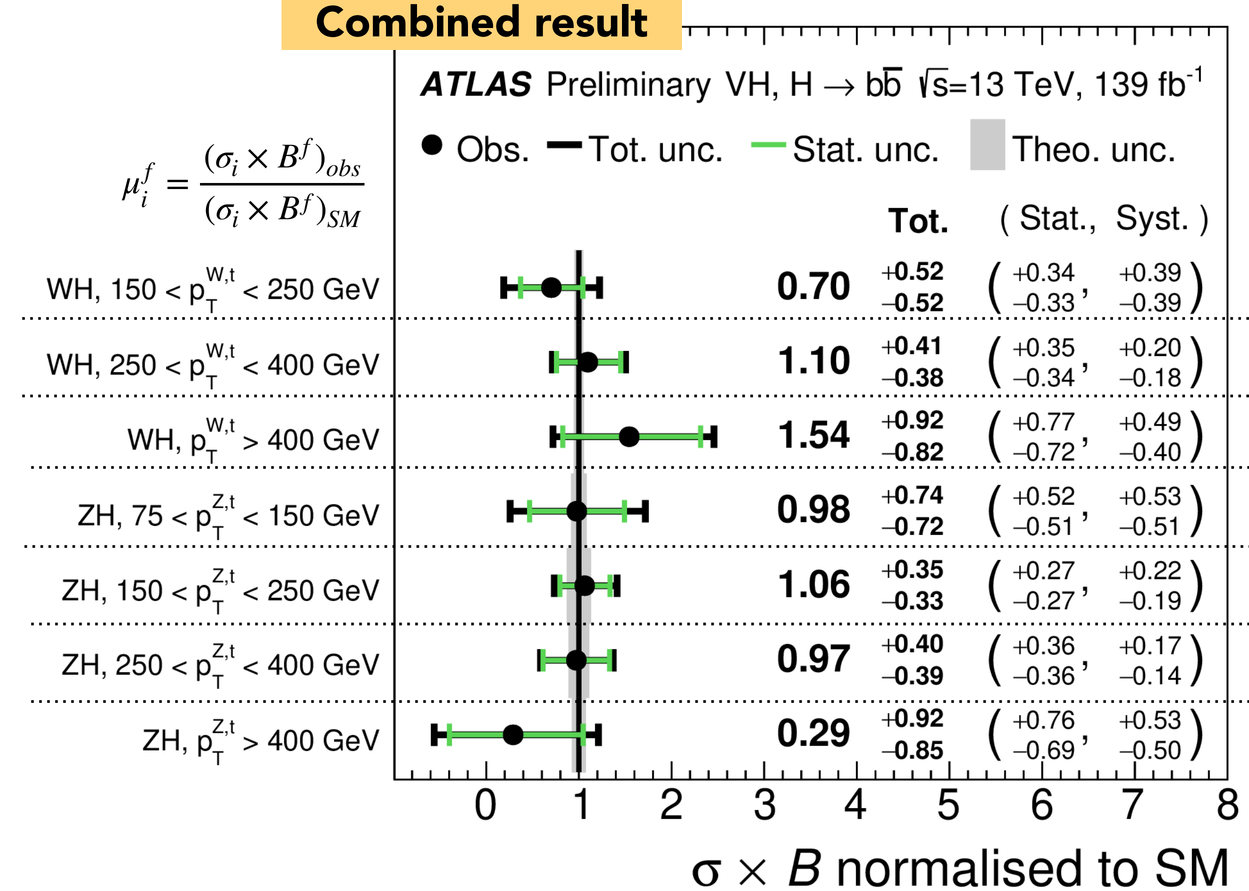




▲ ***Combination:*** *Orthogonality ensured adding a cut on the transverse momentum of the vector boson at 400 GeV*

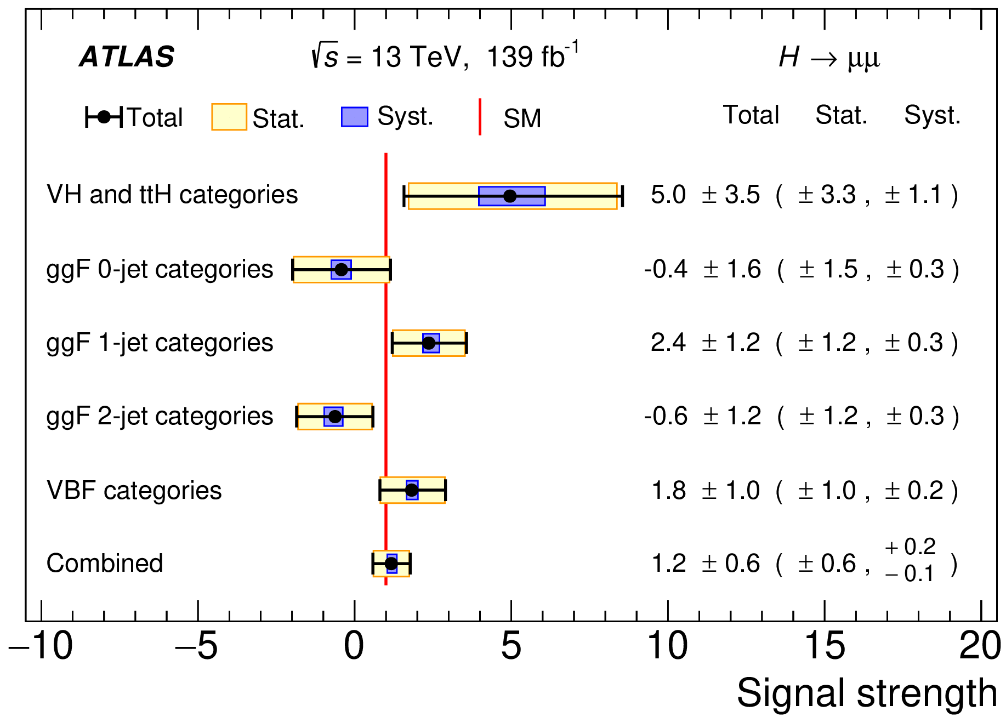


Combined result



Slide on H→bb in other production modes in backup

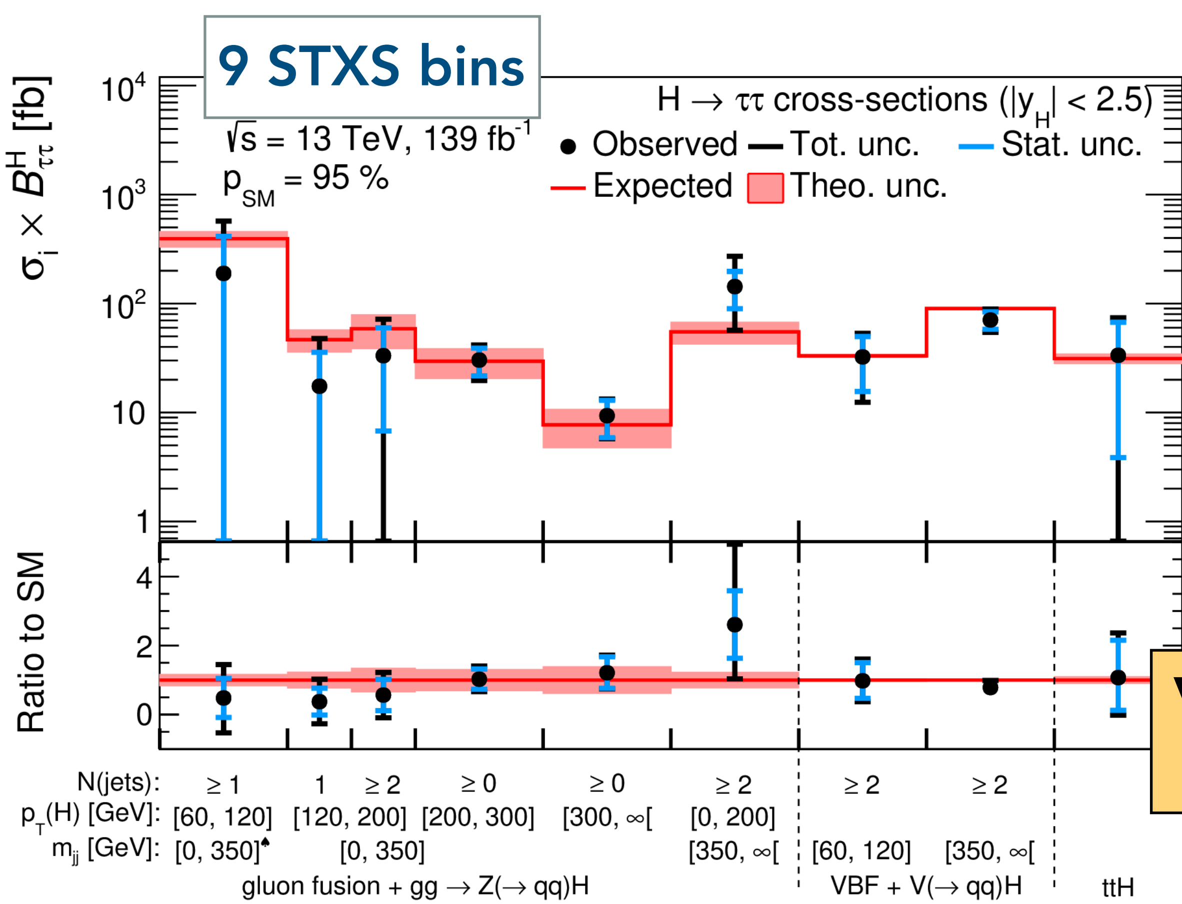
Coupling to leptons:



H→μμ: Phys. Lett. B 812 (2021)

- Fully reconstructed final states with low hadronic activity.
- **Very rare process:**
  - B(H→μμ) ~ (2.17 ± 0.04)×10^{-4}
  - Large backgrounds from **Drell-Yann**
  - **Significance: 2.0σ (1.7σ) obs. (exp.), μ = 1.2 ± 0.6**.

σ(H→μμ) /σSM(H→μμ) < 2.2 at 95%CL.



H→ττ couplings/STXS: CERN-EP-2021-217

- **Largest direct decay to Leptons.**
- Complicated by experimental challenges associated with τ lepton decay
- Three decay channels considered: $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{e,\mu}$ and $\tau_e\tau_\mu$
- VBF, VH and ttH enriched regions + boosted categories targeting at ggH

VBF, H→ττ observation and ggH, H→ττ evidence standalone
at 5.3 (6.2) σ and 3.9 (4.6) σ, respectively!

Inclusive measurements:

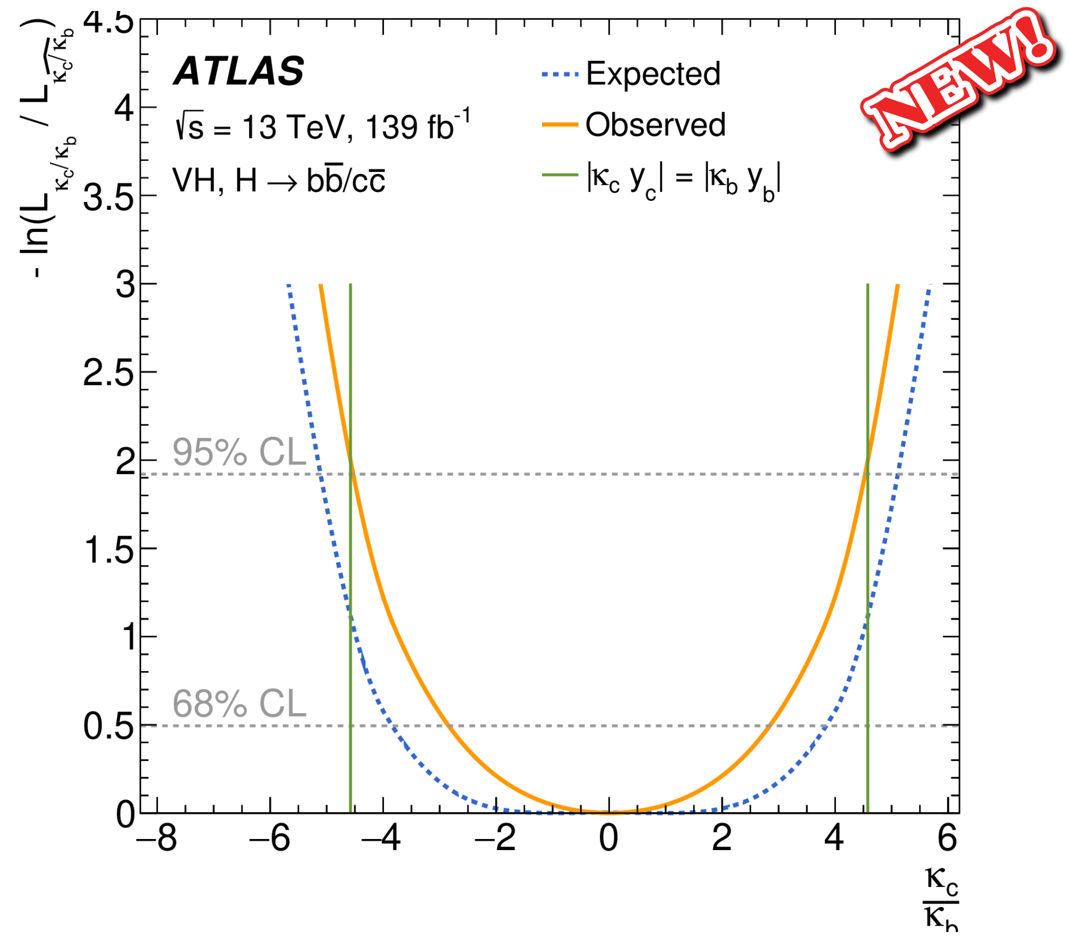
VH, H→cc: CERN-EP-2021-251

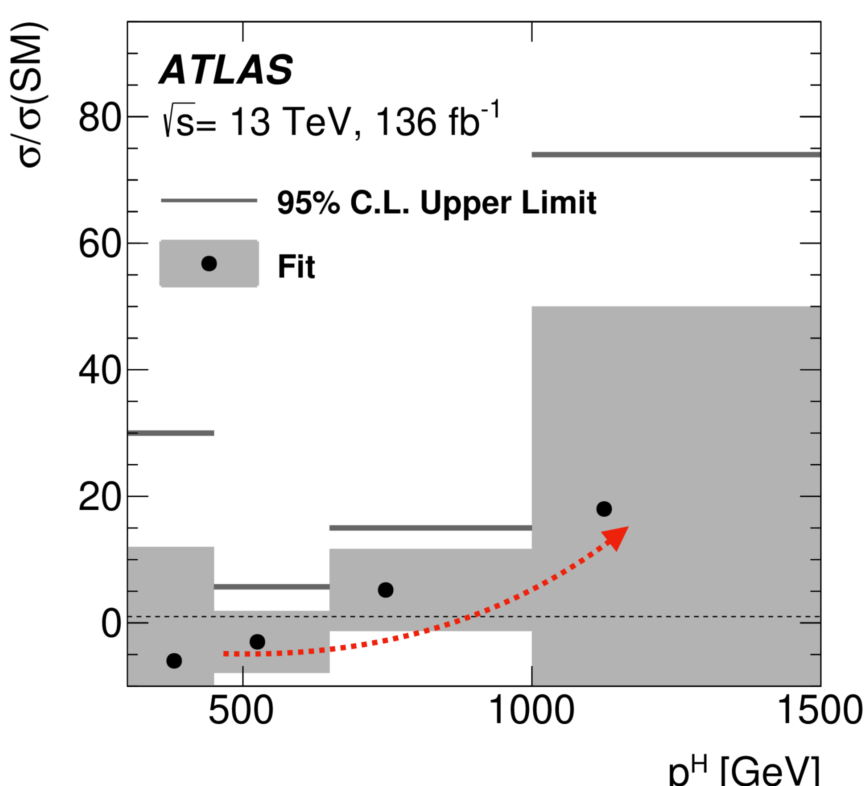
- **Direct constraints using H→cc decays**
- Use charm-tagging with dedicated c-tag + b-veto WP
- **First direct limit on κ_c @ 95%CL with $|\kappa_c| < 8.5$**
- VH(cc) + VH(bb) combination:
  - **Exclude $|\kappa_c y_c| = |\kappa_b y_b|$ at 95% CL**

$$\mu_{VH(c\bar{c})}(\kappa_c) = \frac{\kappa_c^2}{1 + B^{\mathrm{SM}}_{H\to c\bar{c}}(\kappa_c^2 - 1)},$$

Coupling modifier

μ(VH, H→cc) < 26 at 95% CL (31 expected)



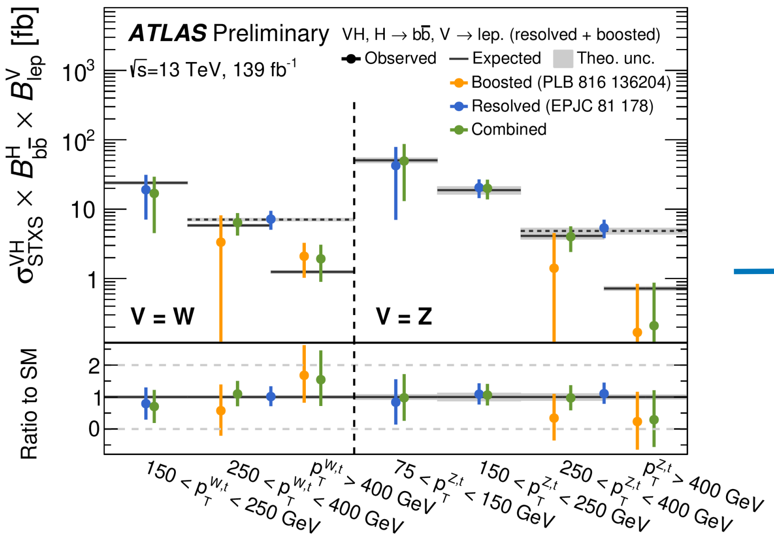


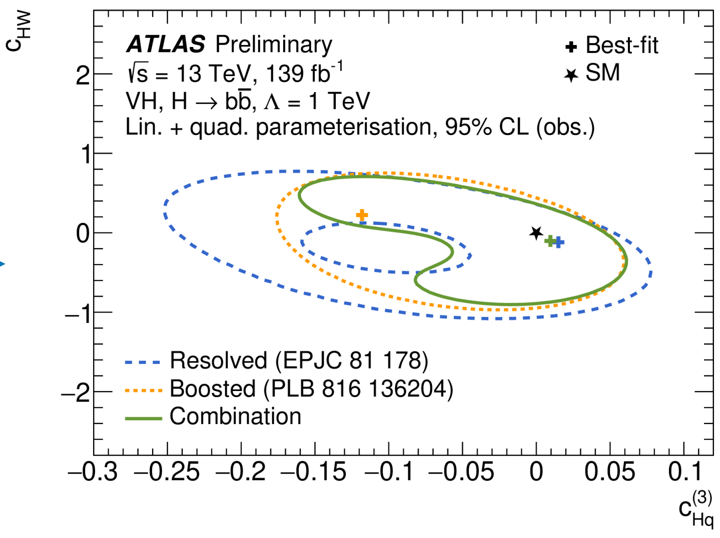
Boosted all-hadronic H→bb: CERN-EP-2021-185

- **Constraints on Higgs boson inclusive production with transverse momentum above 1 TeV.**
- Events categorised according to p_T of H→bb candidate jet. H → bb jet mass used as fit discriminant.
- biggest challenge: modelling of the multi-jet background through a smooth continuous function.

p_T^H	μ_H	σ_H [fb]	
		Best fit	95% CL upper limit
> 450 GeV	0.7 ± 3.3	13 ± 52 (stat.) ± 32 (syst.) ± 3 (theory)	144
> 1 TeV	26 ± 31	3.4 ± 3.9 (stat.) ± 1.0 (syst.) ± 0.8 (theory)	10.3

How can we profit from these results?

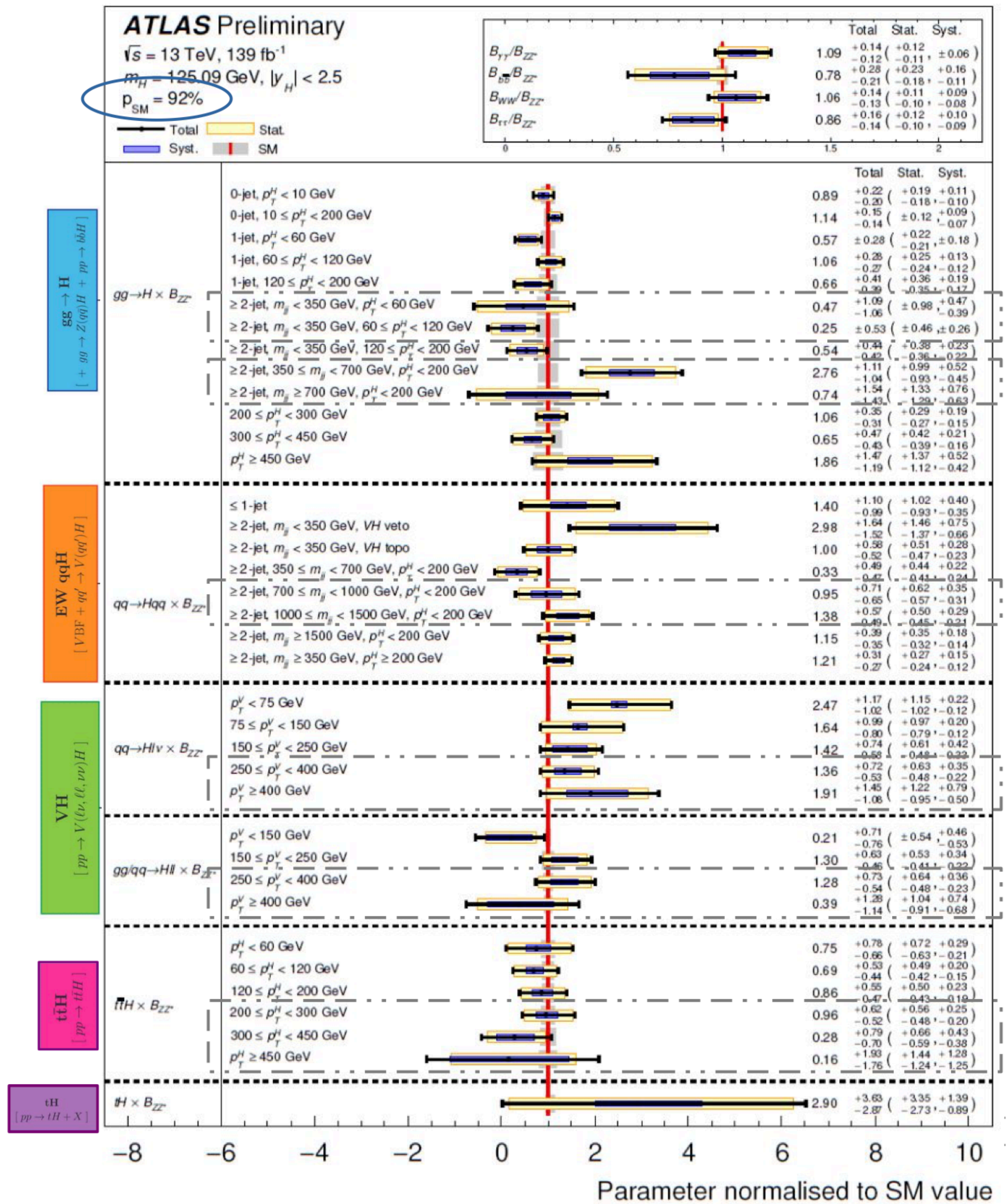




The Higgs coupling combination:

Latest Result Presented @ Higgs2021 ATLAS-CONF-2021-053

41 STXS bins in total



20%

Statistically dominated in most bins

300%

SMEFT interpretation: Brief Introduction

SMEFT = Standard Model Effective Field Theory Interpretation

Motivation:

- **Test presence of BSM physics assuming that new physics decouples at the current scale Λ >> v,E**
- Parameterise BSM effects using Effective Lagrangian operators

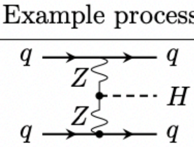
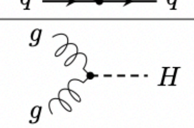
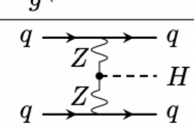
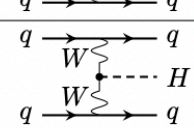
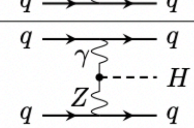
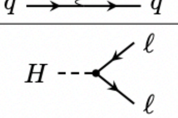
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \ldots,$$

Wilson coefficients

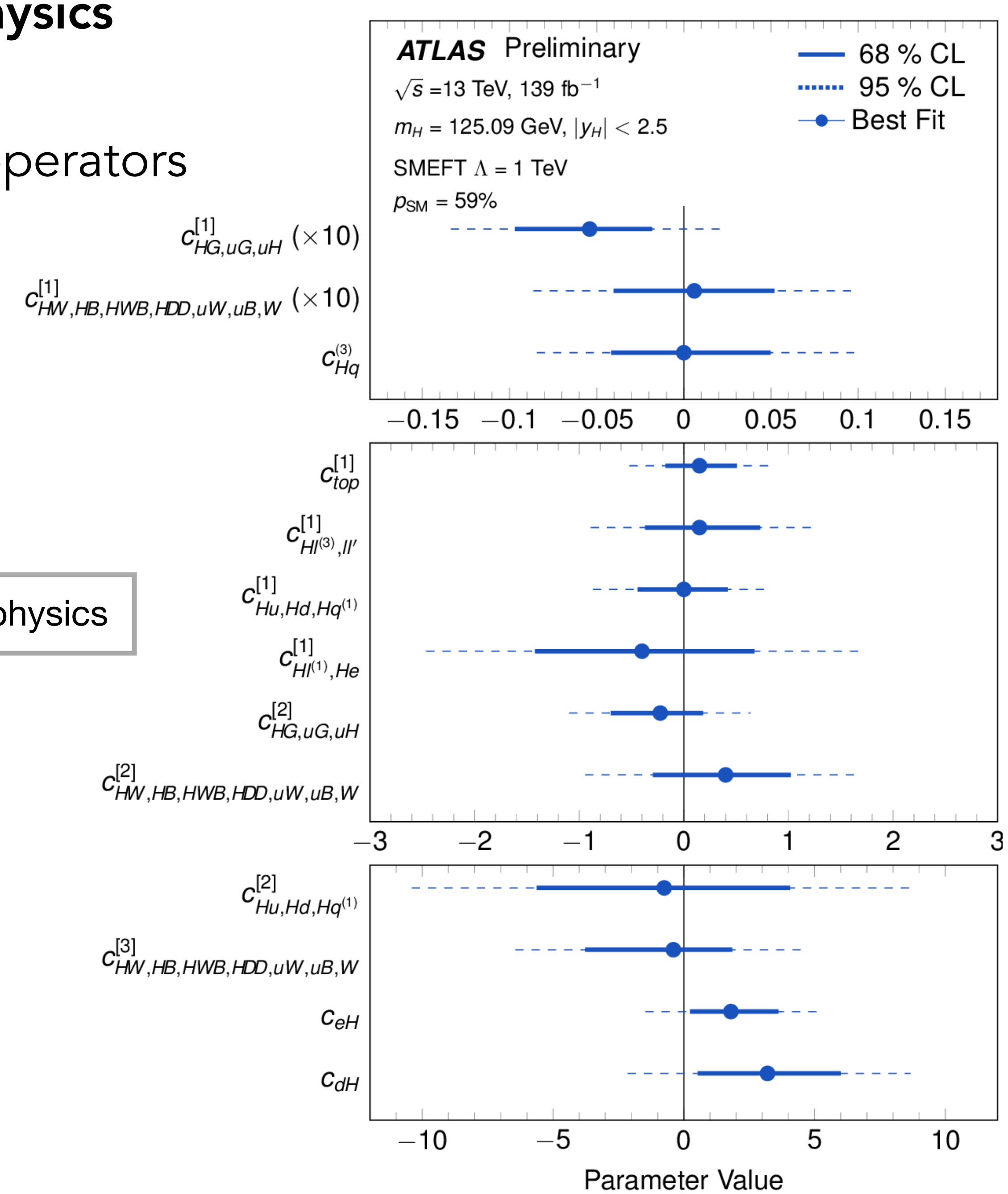
Scale of new physics (1 TeV)

Dimension-6 operators describing new physics

Some examples →

Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	

EFT Constraints:



In Total around 30 c_i: Group them to fit only 13 param.
→ Eigenvector decomposition of STXS covariance matrix (keep only Eigenvalues> 0.1)

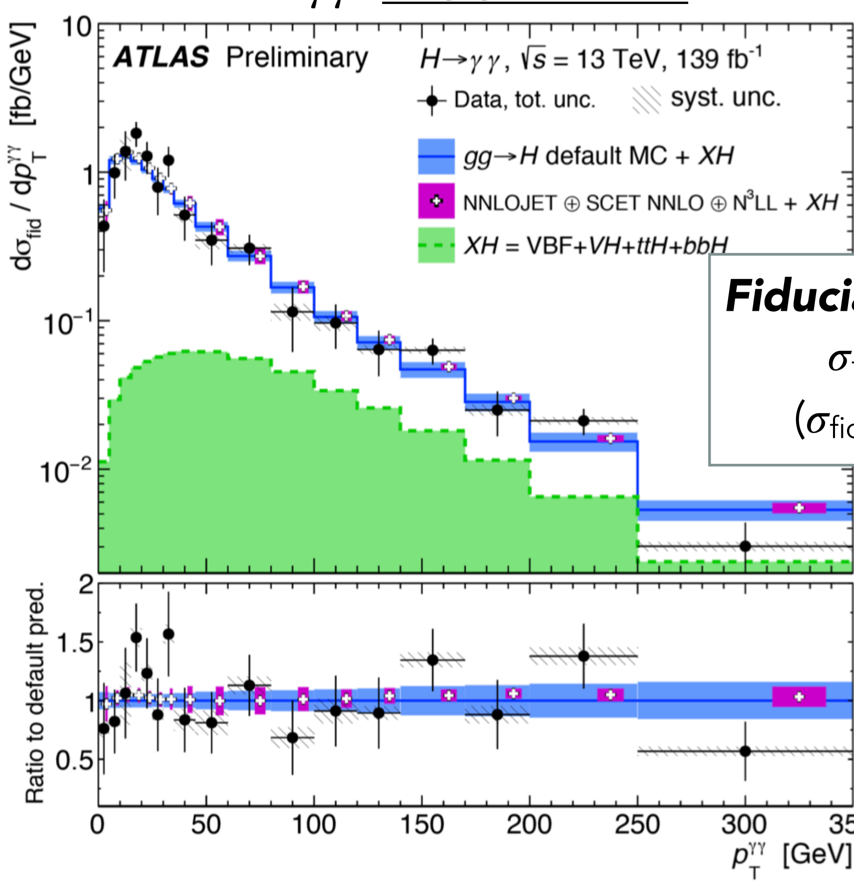
$H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$ fiducial cross-sections:

Unfolding to particle-level σ*BR using response matrix method, implemented directly in likelihood function.

$$\sigma_{i,\text{fid}} = \sigma_i \times A_i \times \mathcal{B} = \frac{N_{i,\text{fit}}}{\mathcal{L} \times C_i}$$

- A_i: detector acceptance
- $\mathcal{B}$: branching
- C_i: detector efficiency

$H\rightarrow\gamma\gamma$: HIGG-2019-13

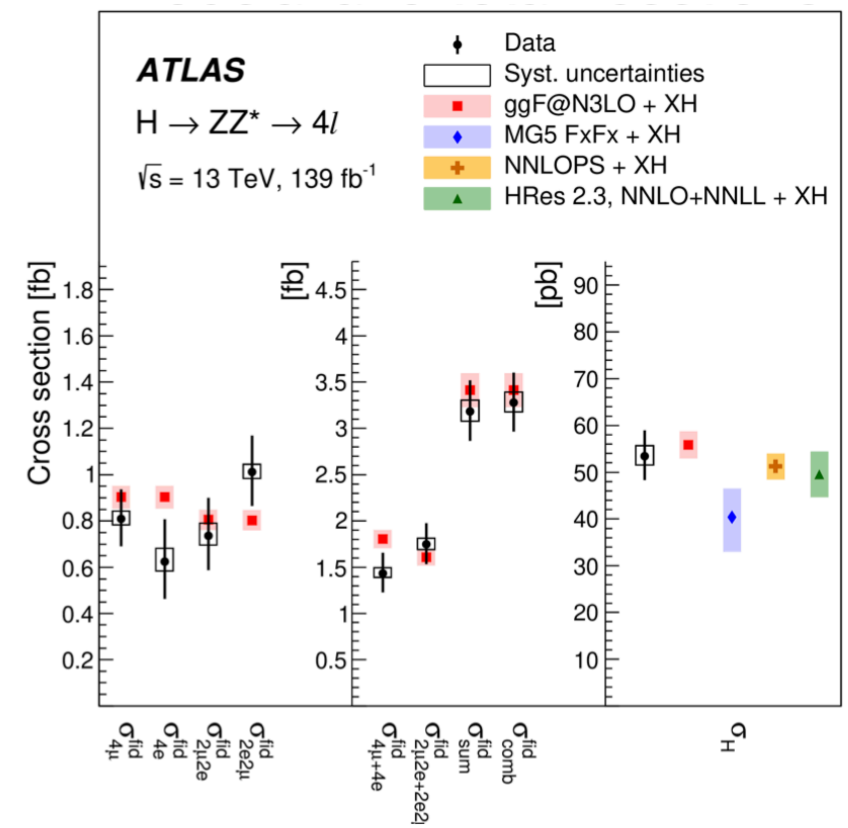


Fiducial x-section pp→H→γγ:

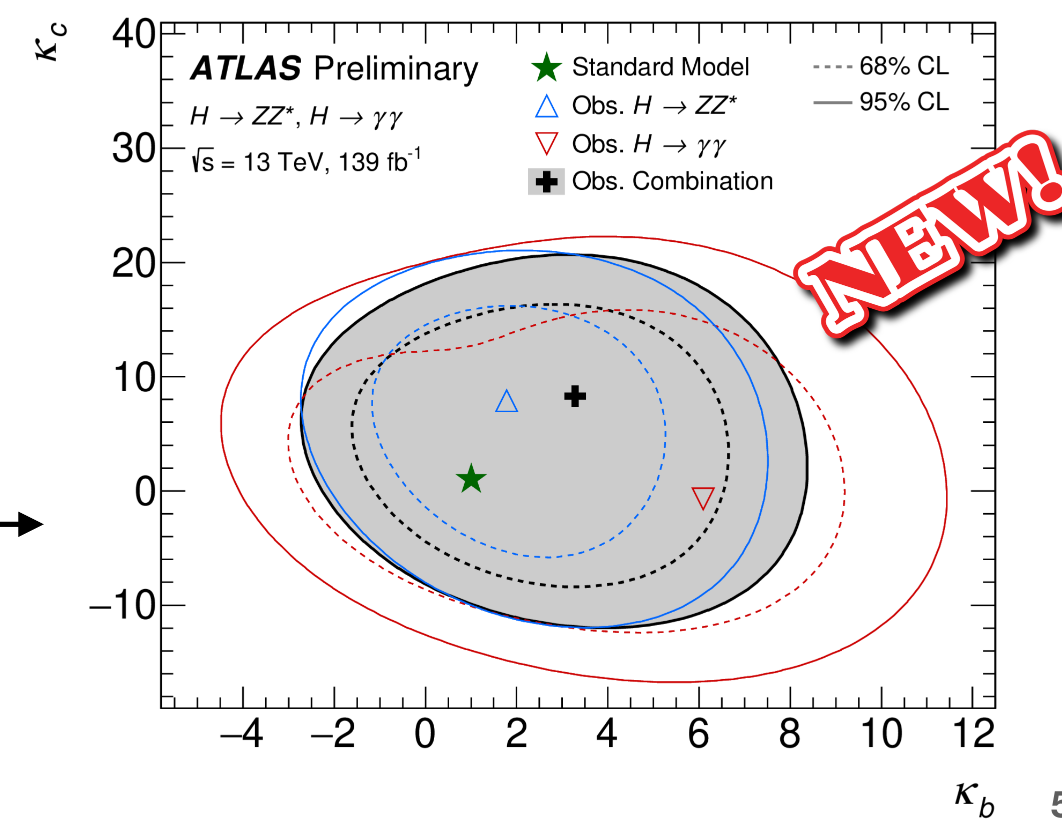
$\sigma_{\text{fid}}\cdot B$ = 65.2 ± 7.1 fb

$(\sigma_{\text{fid}}\cdot B)_{SM}$ = 63.6 ± 3.3 fb

$H\rightarrow ZZ^*$: HIGG-2018-29



$H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$ differential x-section combination: ATLAS-CONF-2022-002 →



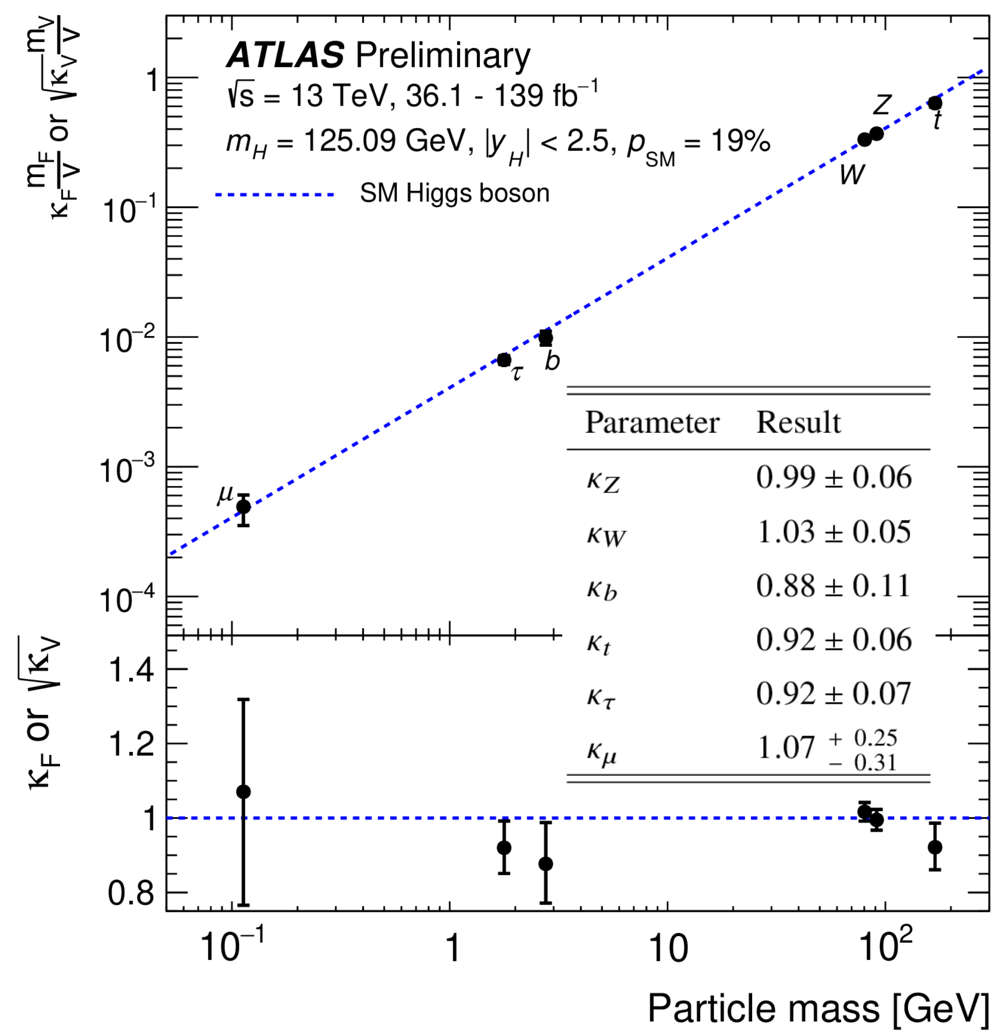
indirectly probe the Yukawa coupling of the Higgs boson to bottom and charm quarks from Higgs p_T shape!

Conclusions

All analyses show an overall good agreement the with the Standard Model predictions

- **"Precision era":** Moved from inclusive searches to differential x-section measurements
- Full-Run2 results provide **high sensitivity to the *main* Higgs boson production and decay modes**
  - **STXS** uncertainties varying between 20% and 300%.
  - First **fiducial x-sections** in boson decay channels (uncertainties below 30%).
- *Not covered - backup:*
  - *H→invisible combination (ATLAS-CONF-2020-052)*
  - *Higgs as dark matter portal (ZH→ℓℓ+MET CERN-EP-2021-204)*

ATLAS-CONF-2021-053.



Combinations and interpretations:

- ATLAS most granular simultaneous measurement to date: **41 STXS bins in total.**
- Reinterpretations in terms of EFT or coupling modifiers set **constraints on BSM scenarios.**

More data ⇒ more measurements, more differential, more complicated interpretations

Backup

The Higgs boson in the Standard Model:

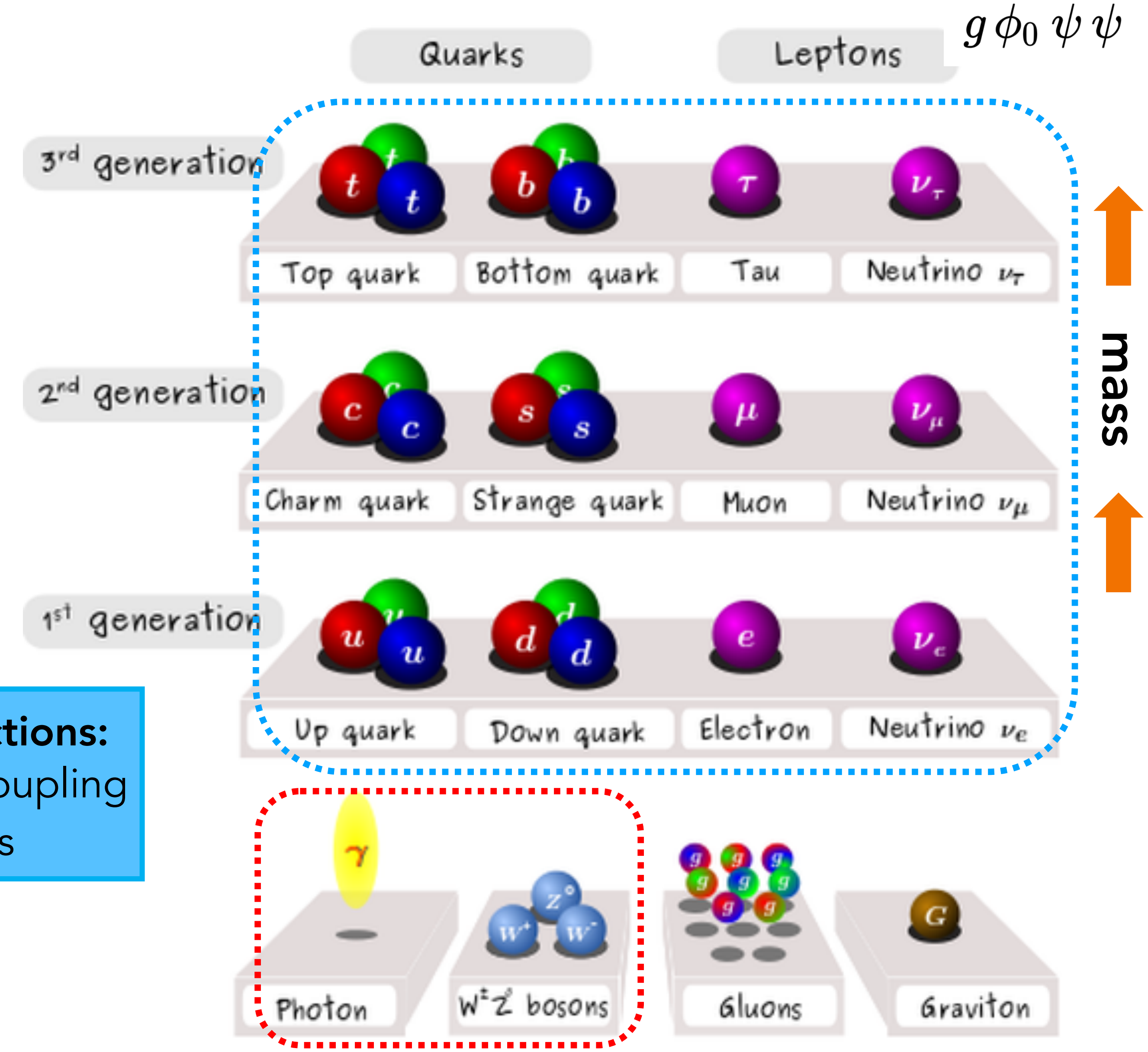
- In the Standard Model (SM):
  - The Higgs boson is the *mediator* of the Higgs field.
  - The Higgs mechanism provides masses to bosons and fermions
- The Higgs boson discovery in 2012 opened the way to the study of new sectors of the SM Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Yukawa Interactions: Explaining the coupling to fermions

Higgs Mechanism: Explaining the coupling to bosons

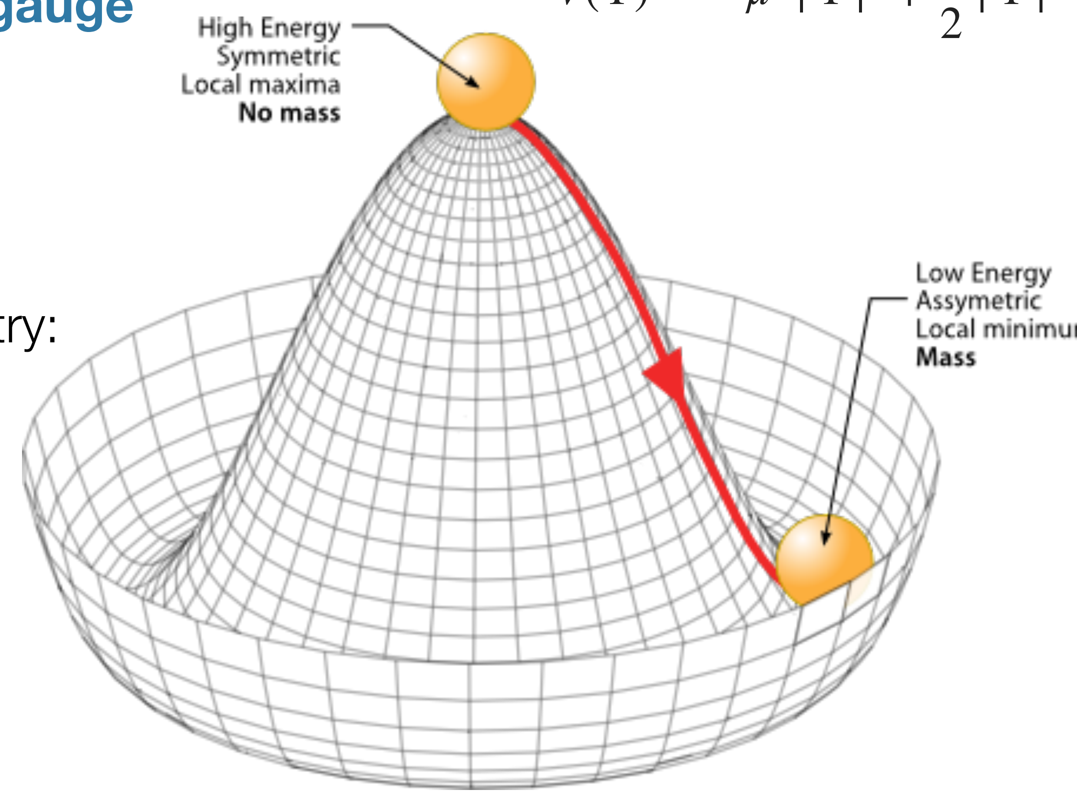
$g\, \phi_0\, \bar{\psi}\, \psi$



Theory: Higgs sector in the Standard Model

Introducing mass terms for fermions and bosons would **destroy** the **gauge invariance of the Lagrangian** (*non-renormalizable theory*)

$$V(\Phi) = -\mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$$



The Higgs Mechanism:

Add a **scalar field to the SM lagrangian**, invariant for gauge symmetry:

$$\mathcal{L}_{Higgs} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

Minimize the potential and **let the vacuum acquire a specific value:**

$$\frac{\partial V(\Phi)}{\partial \Phi} = 0 \quad \Rightarrow \quad |\Phi_0| = v = \sqrt{\frac{\mu^2}{\lambda}}$$

This **spontaneously breaks the SU(2)xU(1) symmetry.**

$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$

High energy → **Low energy**

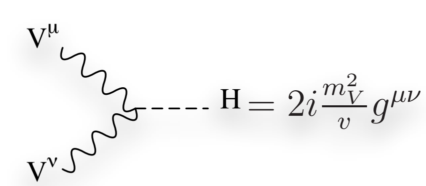
no mass for γ

EW Bosons:

$$\mathscr{L} \supset \boxed{\frac{g^2v^2}{4}} W_\mu^+ W^{-\mu} + \frac{1}{2}\boxed{\frac{(g^2+g'^2)\,v^2}{4}} Z_\mu Z^\mu$$

$$+ \frac{g^2 v}{2} W_\mu^+ W^{-\mu} H + \frac{1}{2}\frac{(g^2+g'^2)\,v}{2} Z_\mu Z^\mu H$$

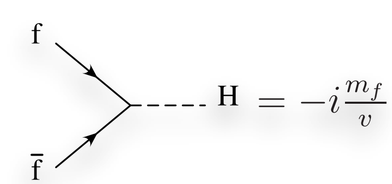
mass terms for Weak bosons ← $W_\mu^\pm \quad Z_\mu \quad A_\mu$



Interaction vertices

Fermions:

$$\mathscr{L} \supset -\left(\boxed{\frac{y_{yukawa} v}{\sqrt{2}}} \bar{f}f\right) - \frac{y_{yukawa}}{\sqrt{2}} H\bar{f}f$$



mass term for fermions

Phenomenology of the Higgs boson @ the LHC:

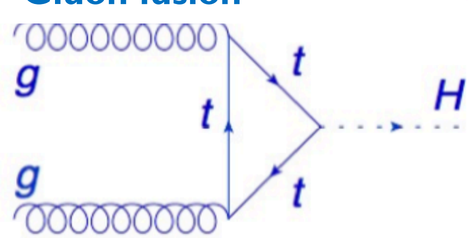
In the Standard Model (SM) the Higgs boson is the mediator of the Higgs field.

The Higgs mechanism provides masses to bosons and fermions

Production modes:

Gluon fusion

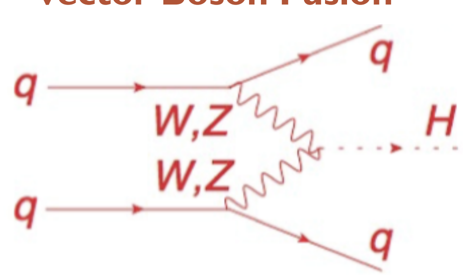
observed



88% of the total

Vector Boson Fusion

observed



7% of the total

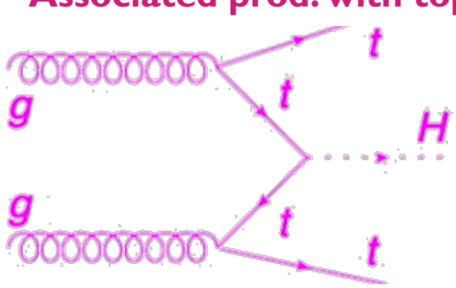
Associated prod. with Z/W

observed

3% of the total

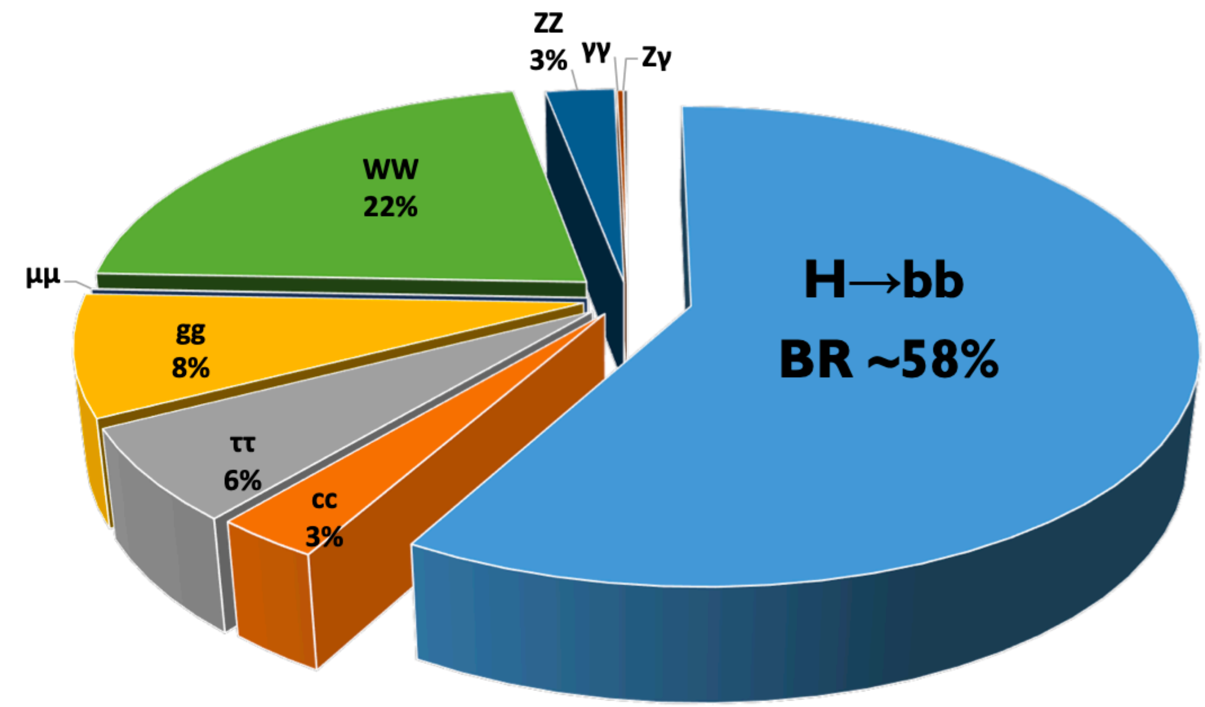
Associated prod. with top

observed



1% of the total

Decay modes:



Observed (5σ) production modes:

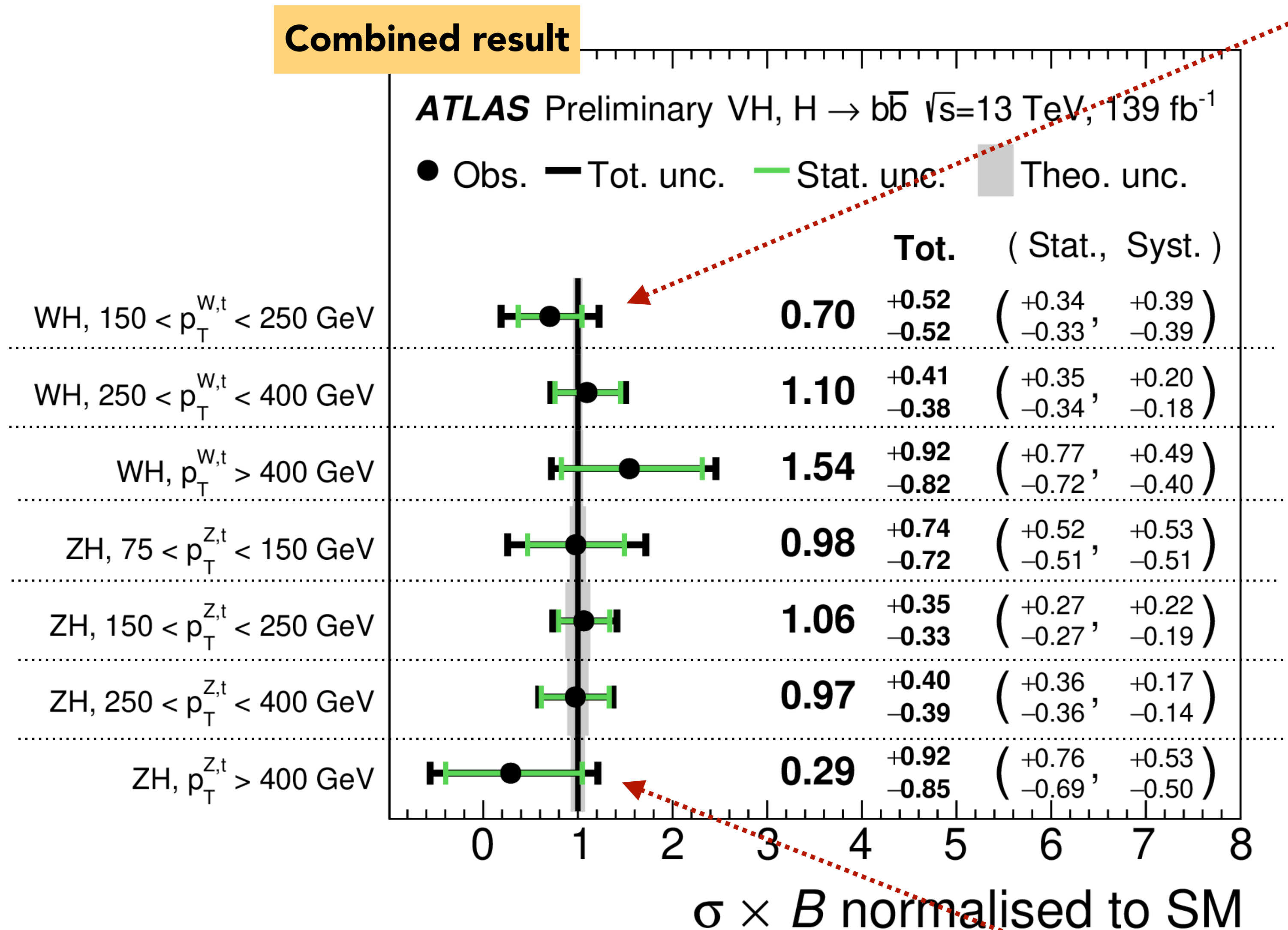
- Gluon gluon fusion, VBF (Run-1)
- ttH, VH (Run-2)

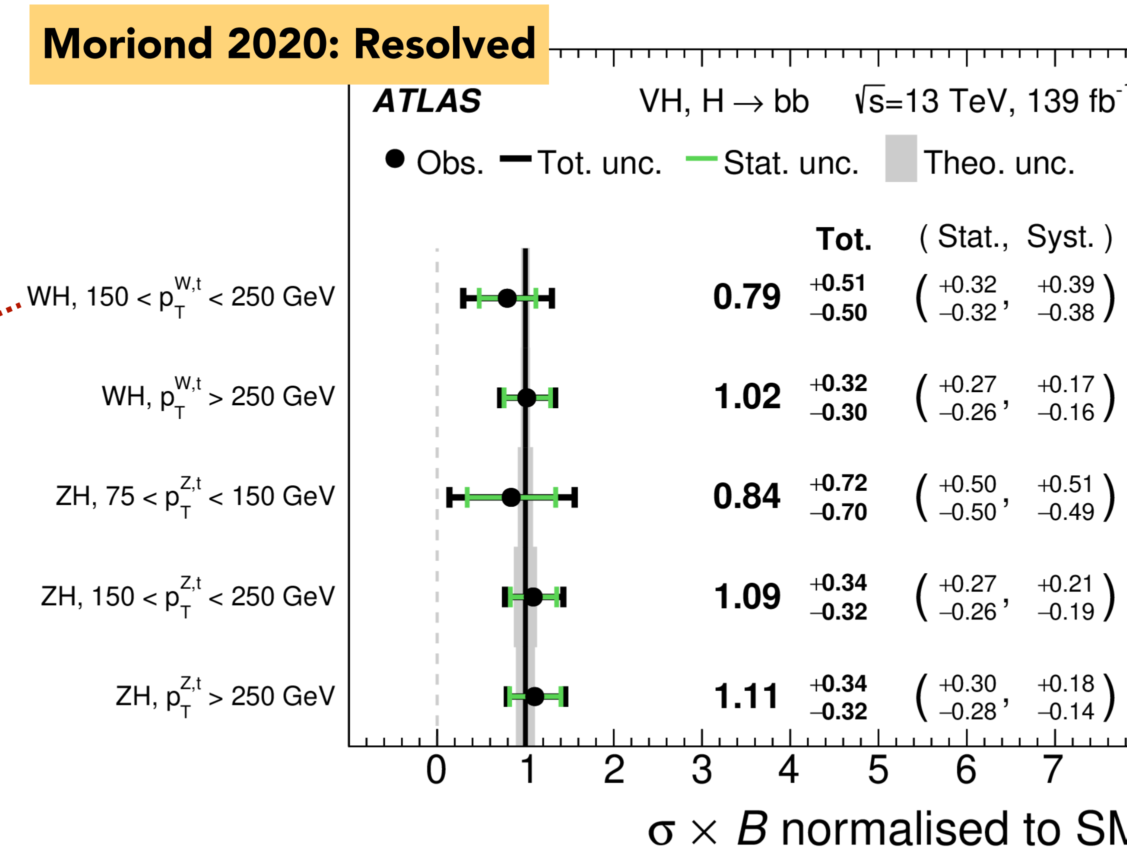
Observed (5σ) decay modes:

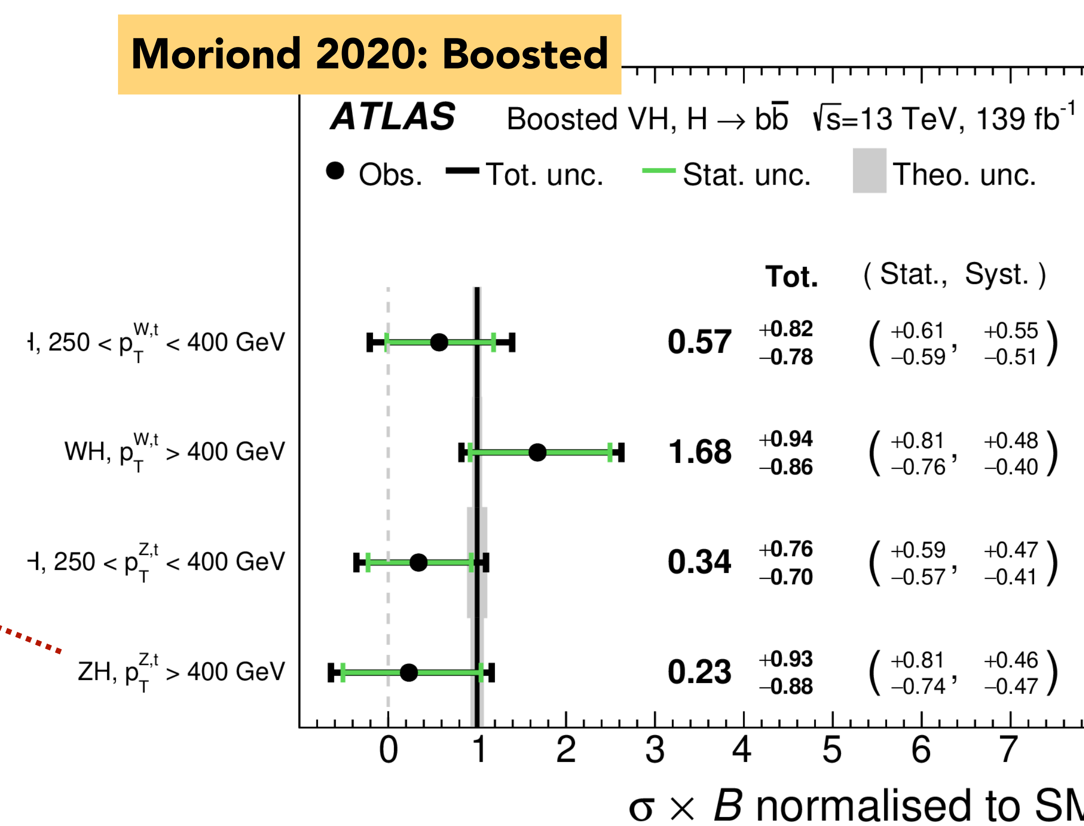
- To bosons: H→ZZ, H→WW, H→$\gamma\gamma$
- To fermions: H→$\tau\tau$, H→bb

VH, H→bb Combination: Results

ATLAS-CONF-2021-051 @ Higgs Hunting 2021







The changes in the central values with respect to the individual analyses remain within 0.3σ

SMEFT interpretation: Brief Introduction

SMEFT = Standard Model Effective Field Theory Interpretation

Motivation:

- **Test presence of BSM physics assuming that new physics decouples at the current scale Λ >> v,E**
- Parameterise BSM effects using Effective Lagrangian operators*

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \dots,$$

Wilson coefficients

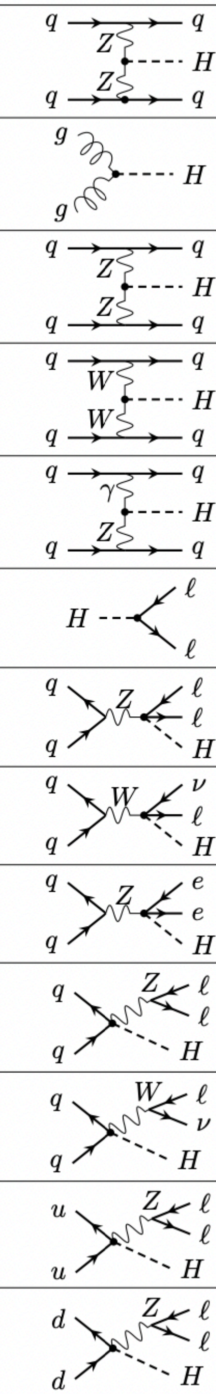
Scale of new physics (1 TeV)

Dimension-6 operators describing new physics

Technicalities:

- **Constrain <u>Dim. 6 operators</u> impacting the Higgs coupling to SM**
- Parametrise their impact on the **<u>signal yields</u>** in each STXS bin
- Parametrise **σ(qq→ZH)**, **σ(qq→WH)**, **BR(H→bb)** as polynomials in sensitivity to **c_i**

Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

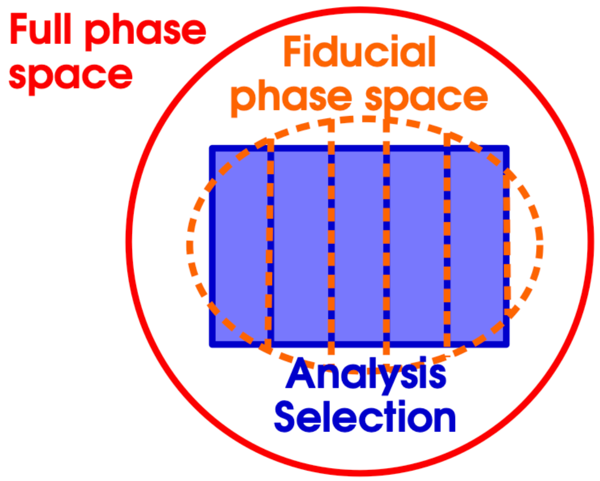


SMEFT Framework (Warsaw basis)

Fiducial cross-sections:

$$\sigma_{i,\mathrm{fid}} = \sigma_i \times A_i \times \mathcal{B} = \frac{N_{i,\mathrm{fit}}}{\mathcal{L} \times C_i}$$

detector acceptance (A_i), branching ($\mathcal{B}$), detector efficiency (C_i)



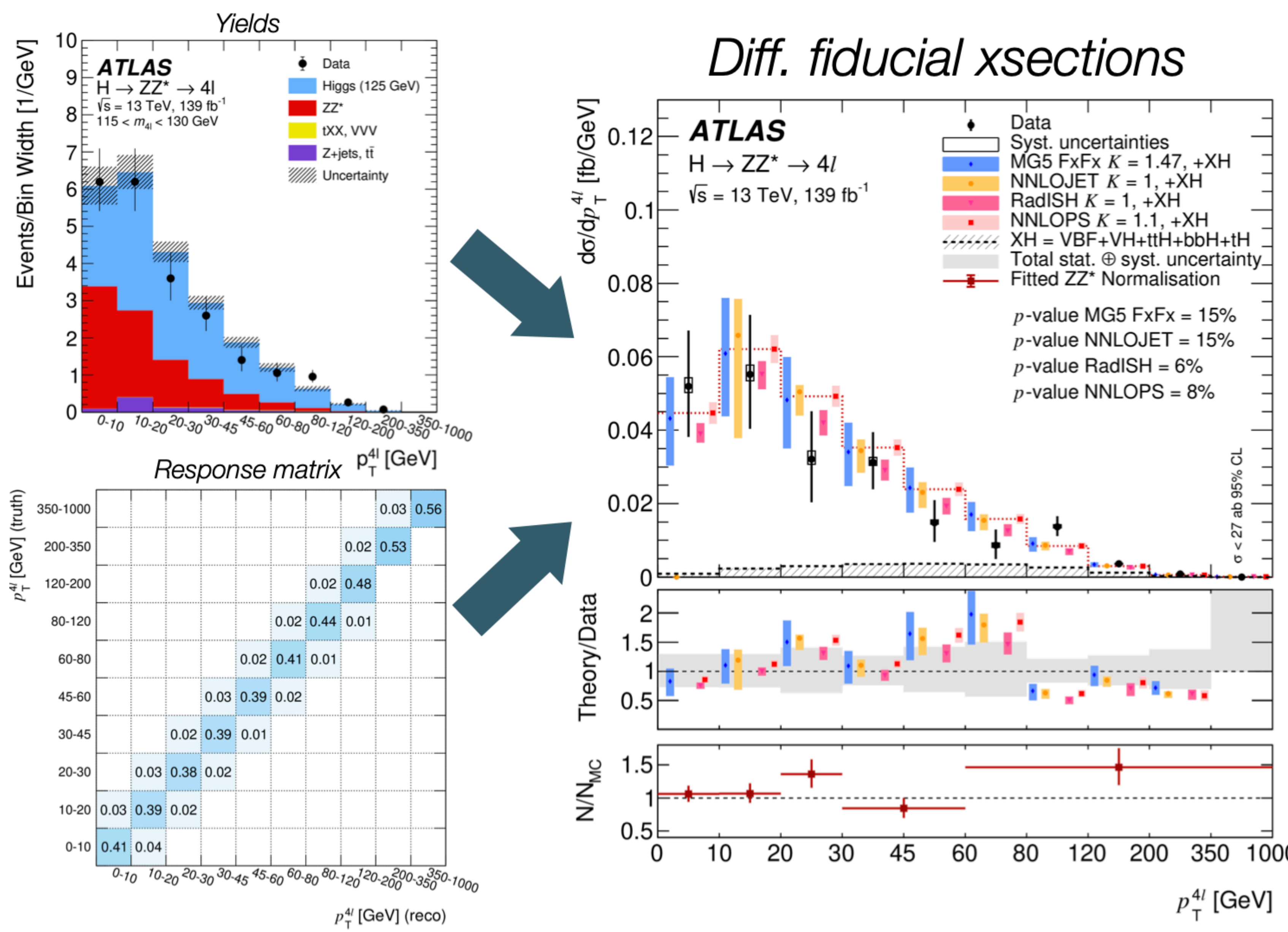
Examples:

pTH = sensitive to perturbative QCD calculations

Y_H = sensitive to the parton distribution functions (PDF)

N_jet T(lead jet) = probe theoretical modelling of High pT QCD radiation

N_jet also sensitive to different Higgs production modes

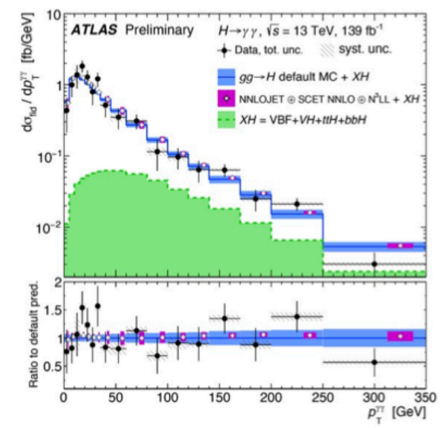


STXS vs Fiducial x-sections:

https://cds.cern.ch/record/2765932/files/ATL-PHYS-SLIDE-2021-144.pdf

Pros and Cons

dif/fid XS



- ⊕ **Minimizes model-dependence**
  - → Small extrapolations and SM assumptions (mainly through unfolding)
  - → Reinterpretable in models with similar A ⇒ Long measurement lifetime
- ⊖ **Simple experimental selection only (should match truth-level selection)**

- ⊕ **Can be performed for any measurement variable**
- ⊖ **Only 1 or 2 variables at a time (but can have fine binning)**
- o **Works best for "clean" modes** : good resolution, manageable backgrounds
- ⊖ **Fiducial region depends on final state** ⇒ cannot trivially combine different modes

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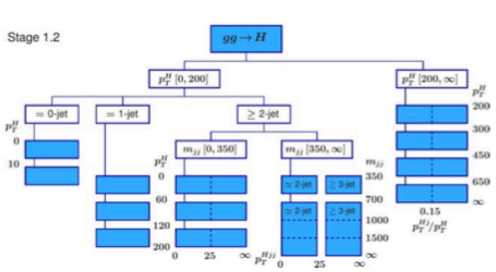
STXS

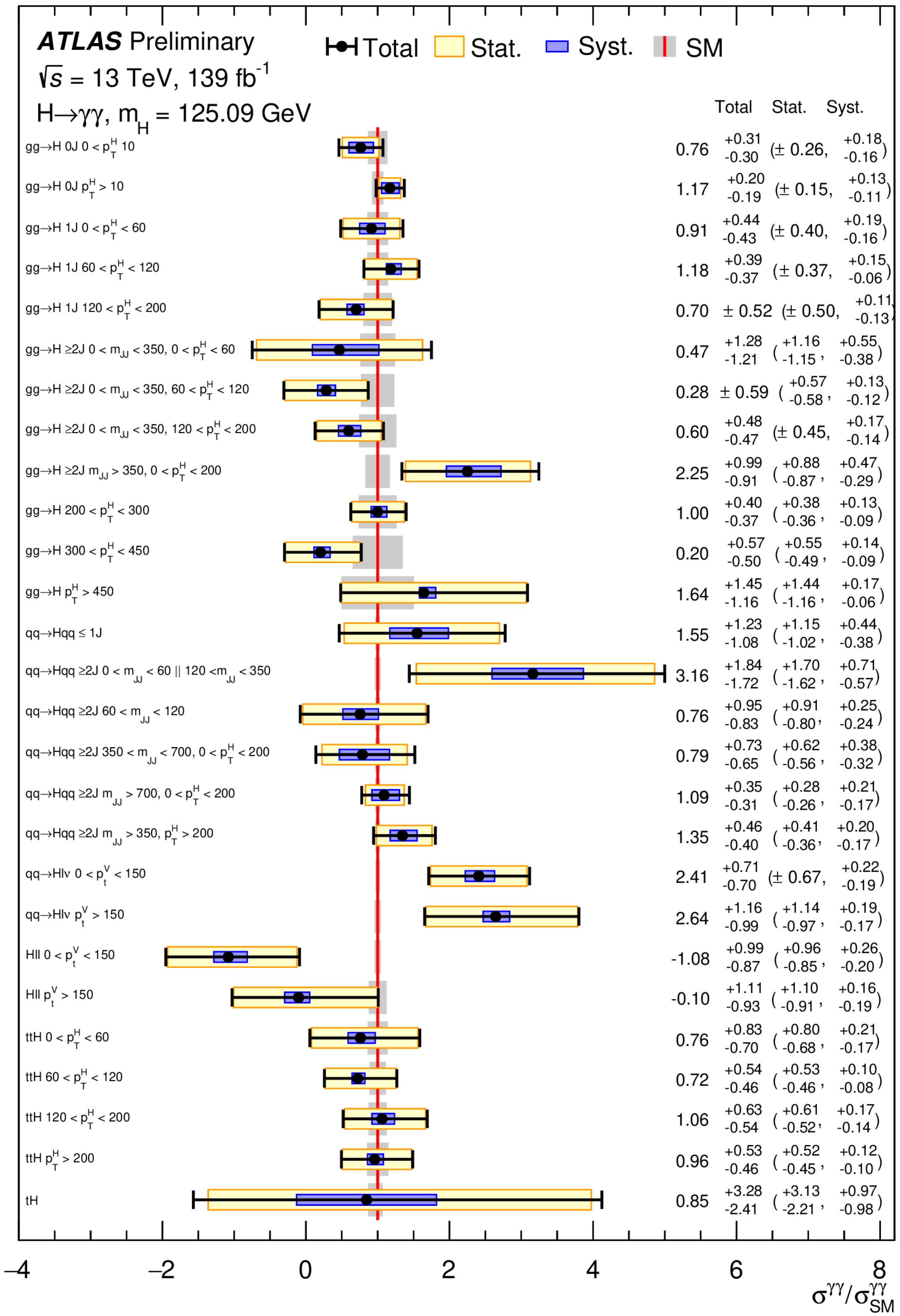


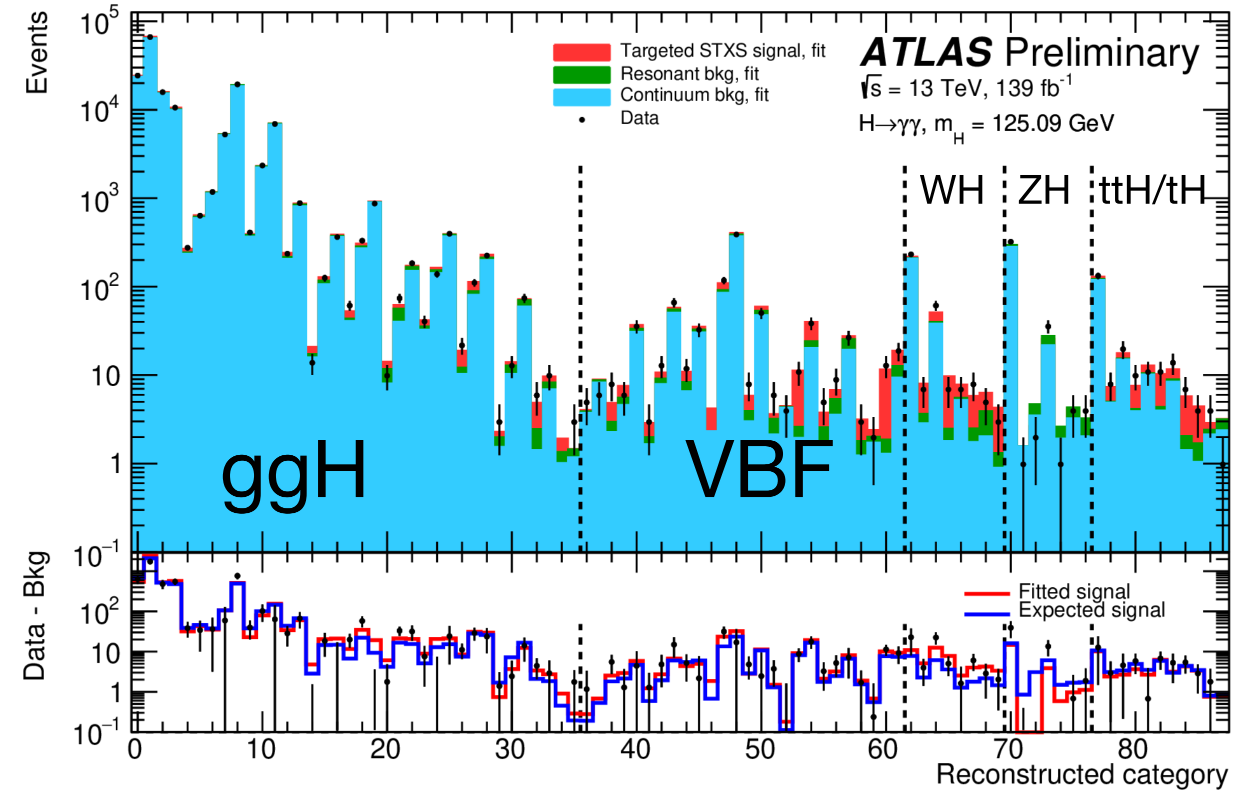
- ⊖ **SM description within each bin ⇒ Larger model-dependence**
- ⊕ **SM description within each bin ⇒ Can use MVAs/NNs/ML.**
- ⊕ **Well-suited to measure perturbations from SM (e.g. SMEFT)**

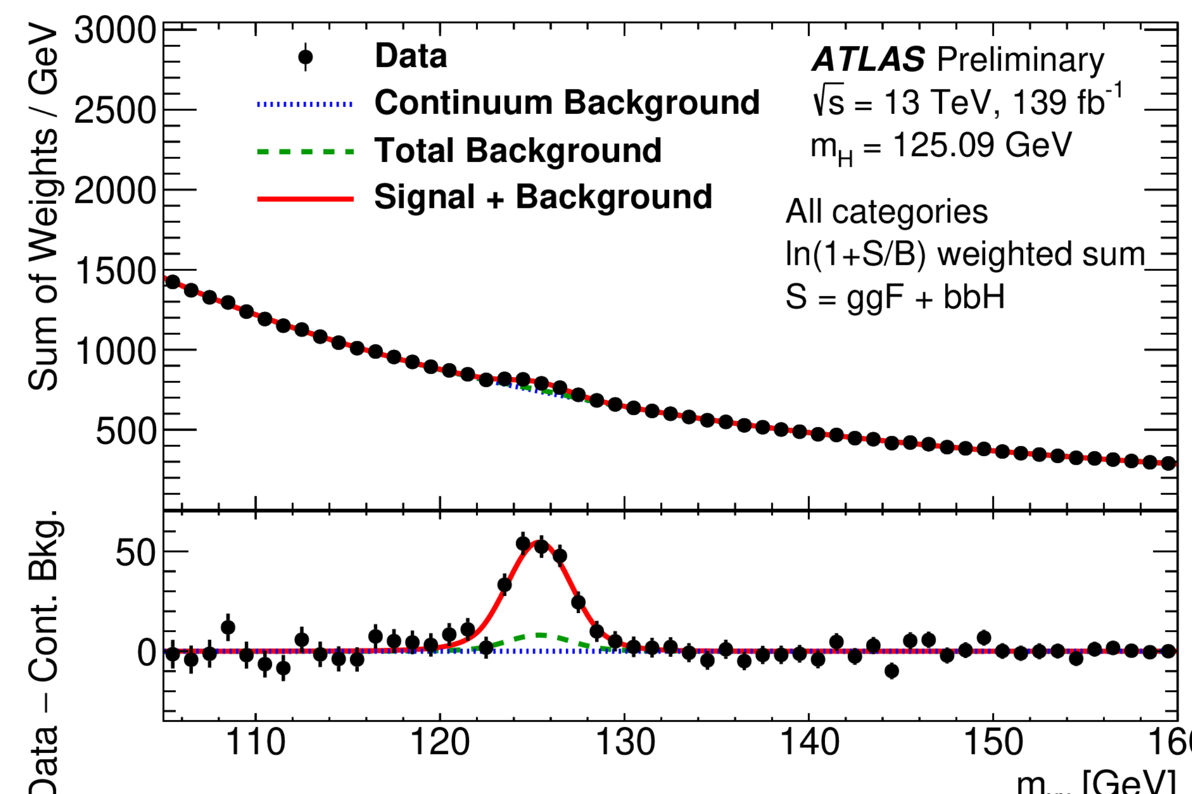
- ⊕ **Common binning includes information from multiple variables**
- ⊖ **Larger bins, only limited number of variables**
- ⊕ **Common binning for all decay modes ⇒ simplifies combination**

12

H→γγ STXS measurement:



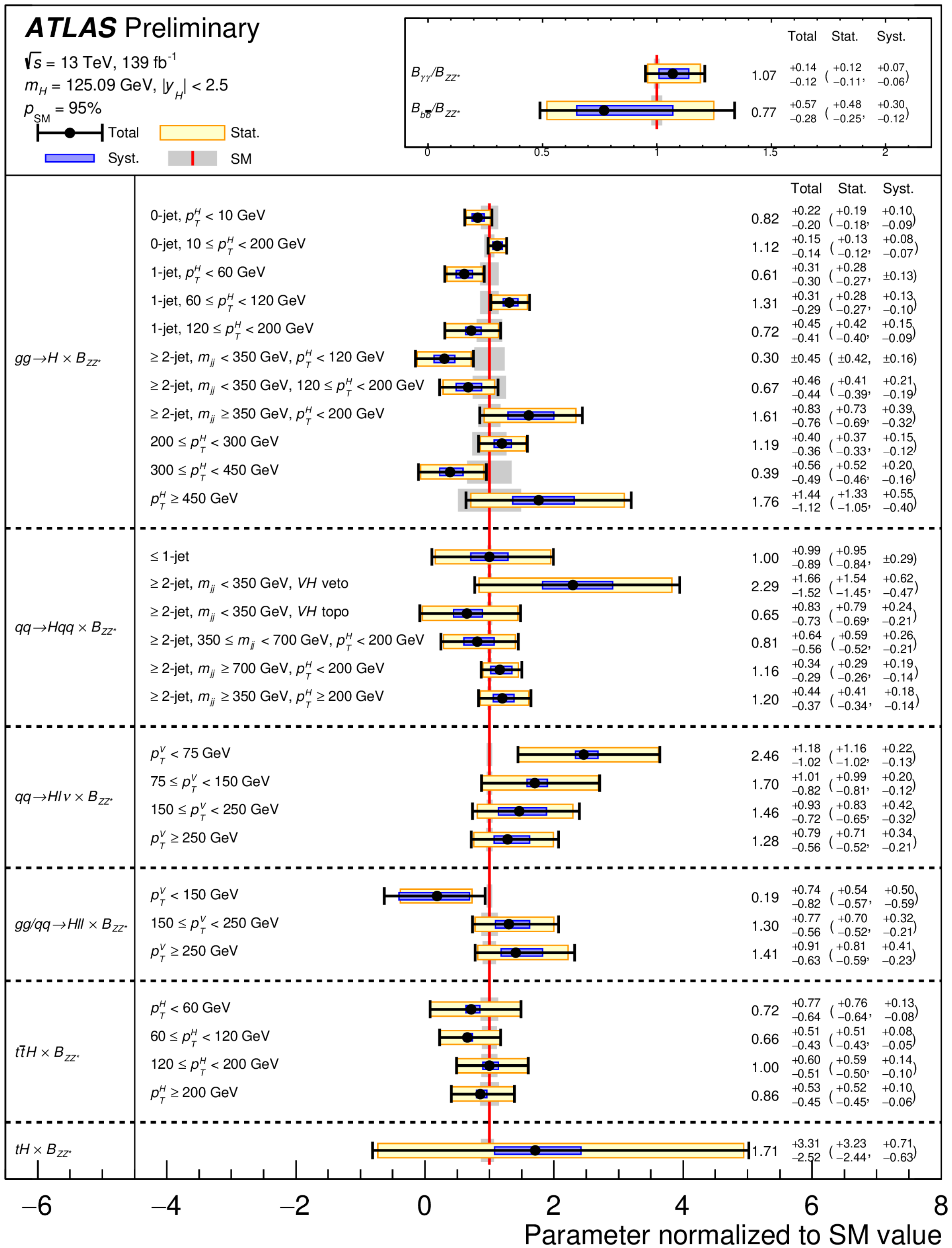




The Higgs coupling combination:

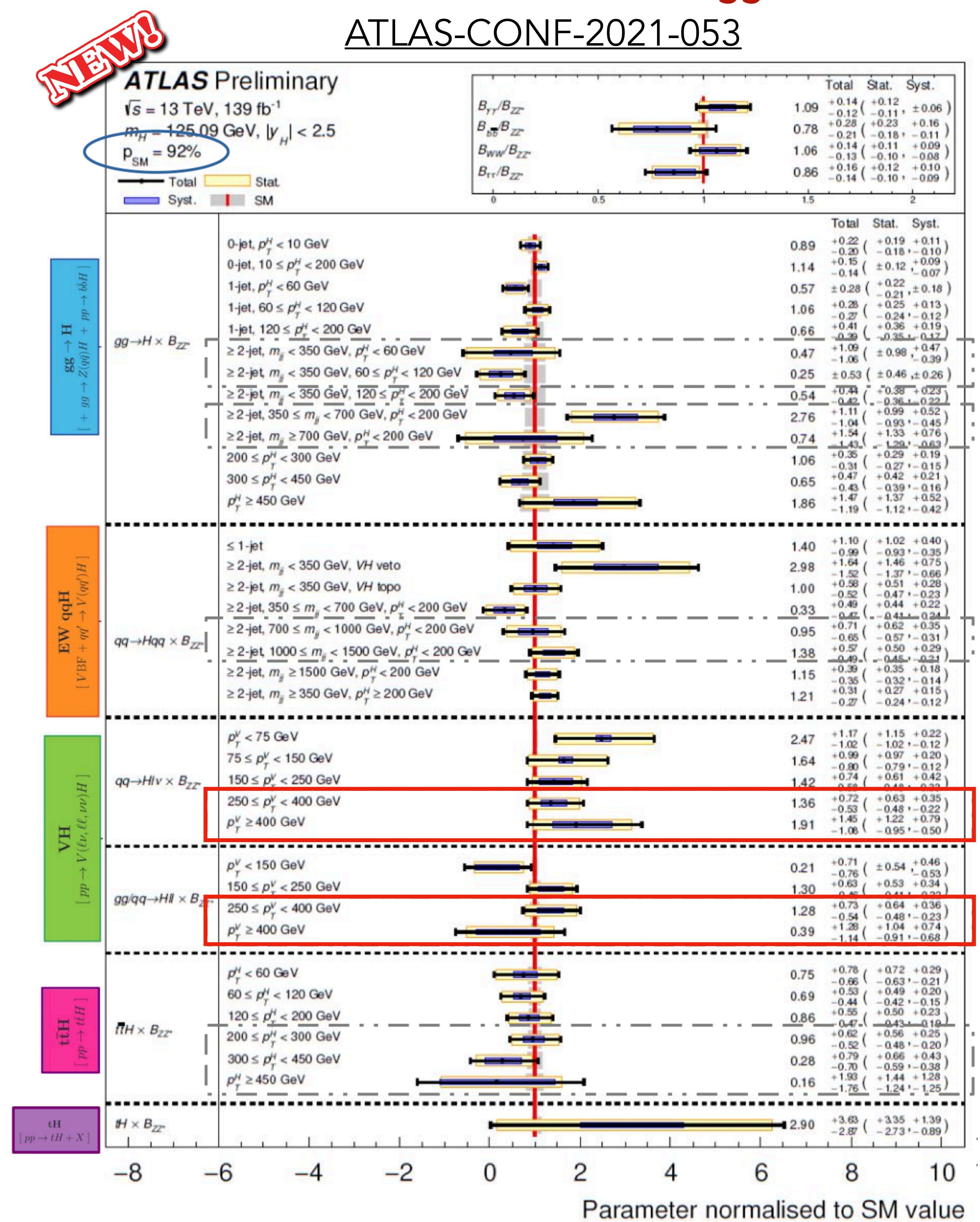
2020 Result Presented @ EPS2020

ATLAS-CONF-2020-027



Latest Result Presented @ Higgs2021

ATLAS-CONF-2021-053



Wilson coefficients & EV decomposition:

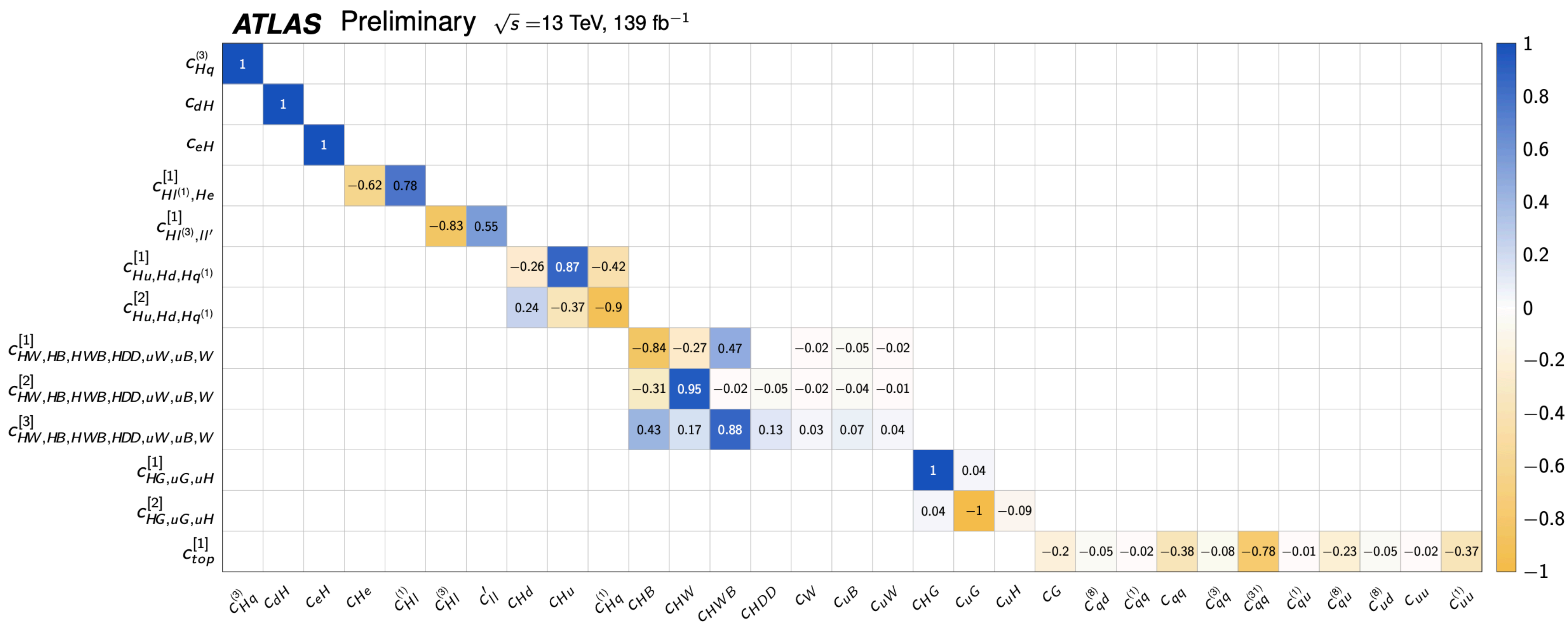
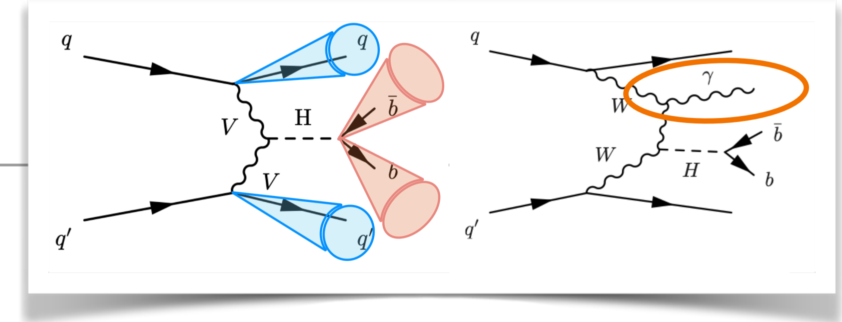
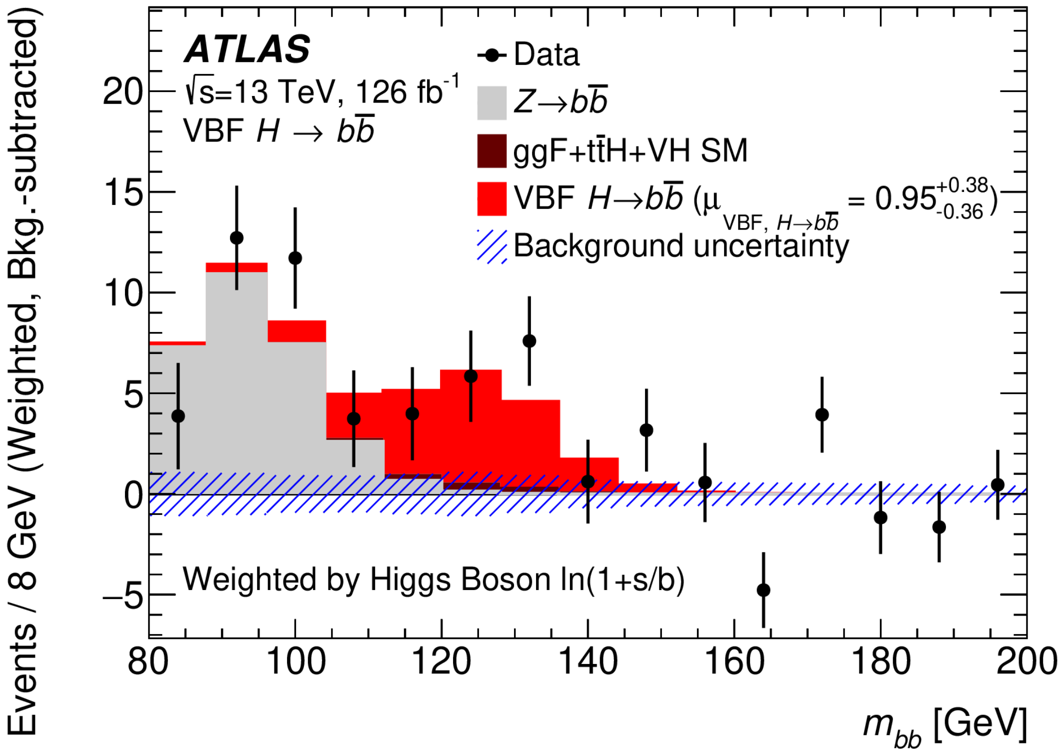


Figure 17: Visualisation of the projection matrix from the Warsaw basis c_i (x-axis) to the fit basis c'_i (y-axis).

H→bb in other production modes:

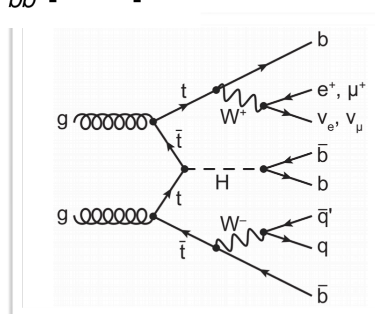




VBF, H→bb: HIGG-2019-04, HIGG-2020-14

- Categorisation into regions based on the output of an ANN
- Inclusive **VBF(H→bb) significance of 2.6σ (2.8σ) obs. (exp.)**
- Result **combined with VBF+γ analysis:**
  - **VBF significance at 2.9σ (2.9σ) obs. (exp.)**

$$\mu_{VBF,H\rightarrow b\bar{b},\mathrm{comb.}} = 0.99^{+0.30}_{-0.30}(\mathrm{stat.})^{+0.18}_{-0.16}(\mathrm{syst.})$$

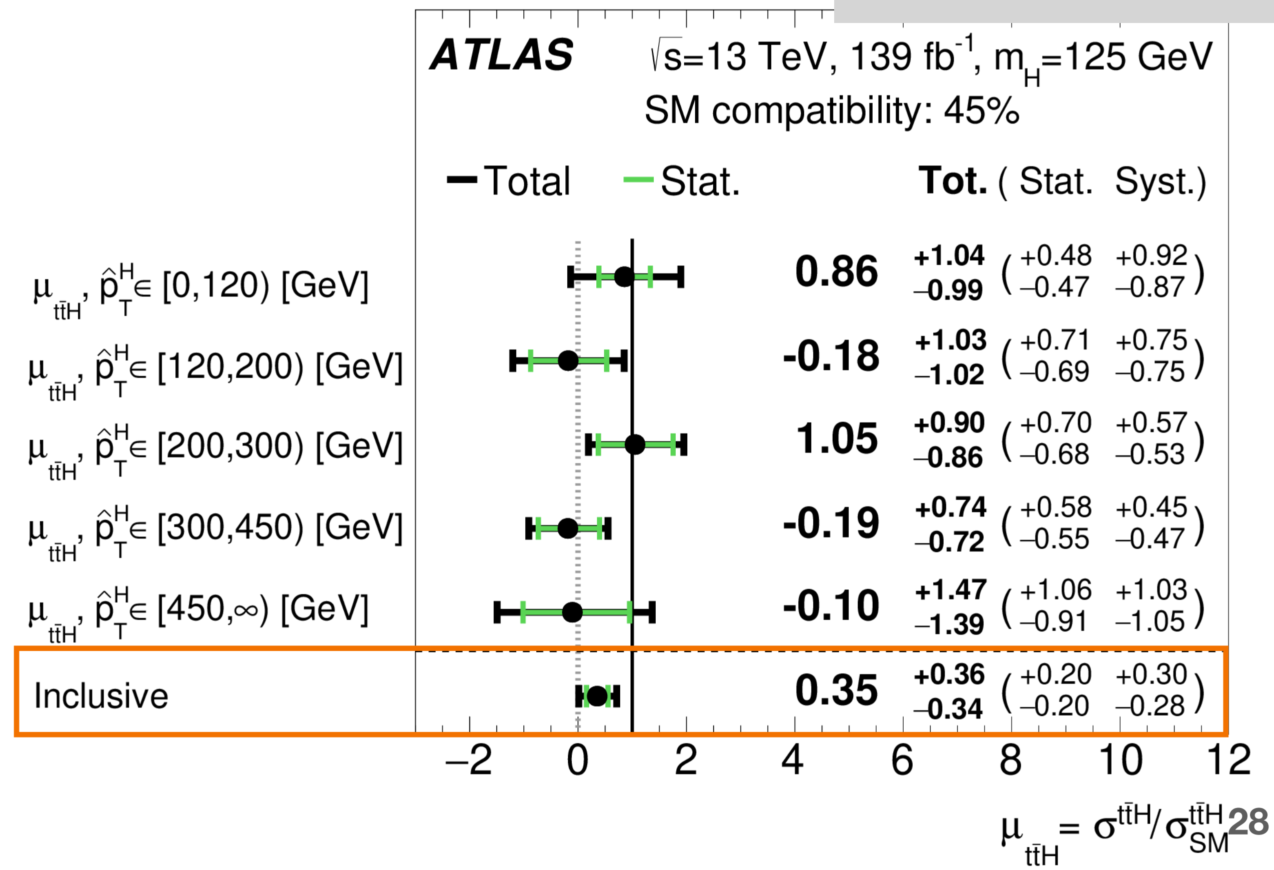


ttH, H→bb: HIGG-2020-23

- **Challenging final state:**
  - Combinatorics from many b-jets
  - **Large background from tt+HF jets.**
- Events categorised by *tt* decay mode (1lep, 2lep) and candidate Higgs boson p_T.
- **Probe boosted p_T regime as well.**

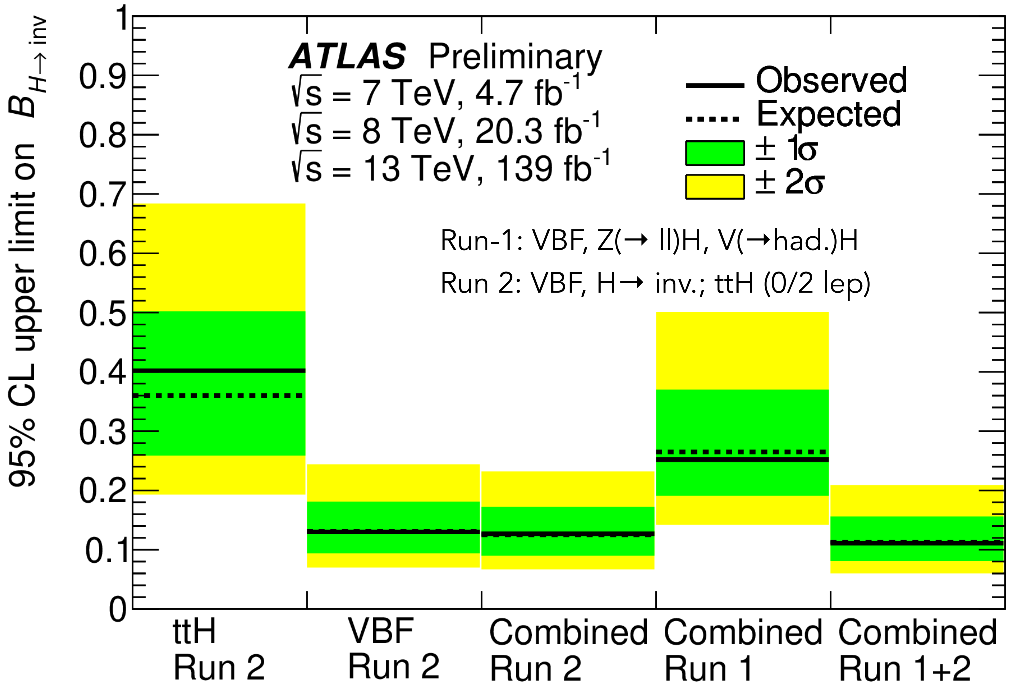
Inclusive significance of 1.3σ (obs.) 3.0σ (exp.).

STXS measurement



H→invisible and the dark matter portal:

"Invisible" = missing transverse momentum (MET)



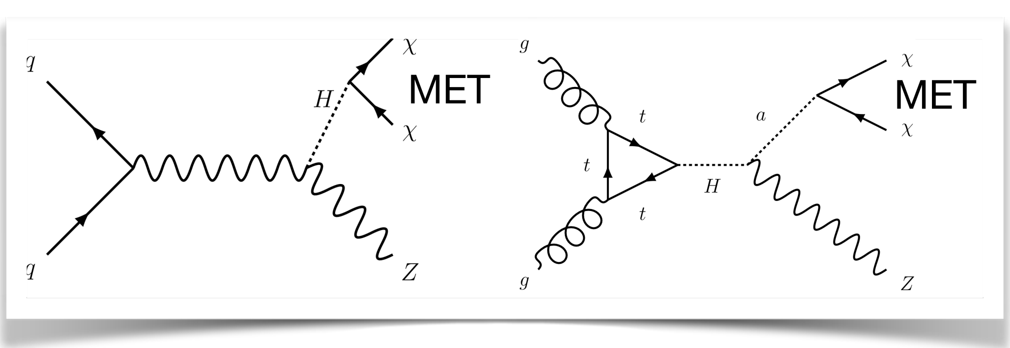
H→invisible combination: CONF-2020-052

- In the **SM, H → invisible is from H→ ZZ*→ 4ν – BR = 0.1%**
- In **Higgs portal models**, H→invisible contributions arise from H→ XX; X: dark matter (DM) particle, e.g. WIMPs

upper limits @ 95% CL on B(H→ inv.) obs. (exp.):
Run 2 combination: 0.13 (0.12+0.05-0.04)
Run 1+2 combination: 0.11 (0.11+0.04-0.03)

NEW!

ZH→ℓℓ+MET: CERN-EP-2021-204



upper limit @ 95% CL:
B(H→ inv.) < 0.18 (0.18) obs. (exp.)

Set exclusion limits for simplified dark matter models and 2HDM+*a* models