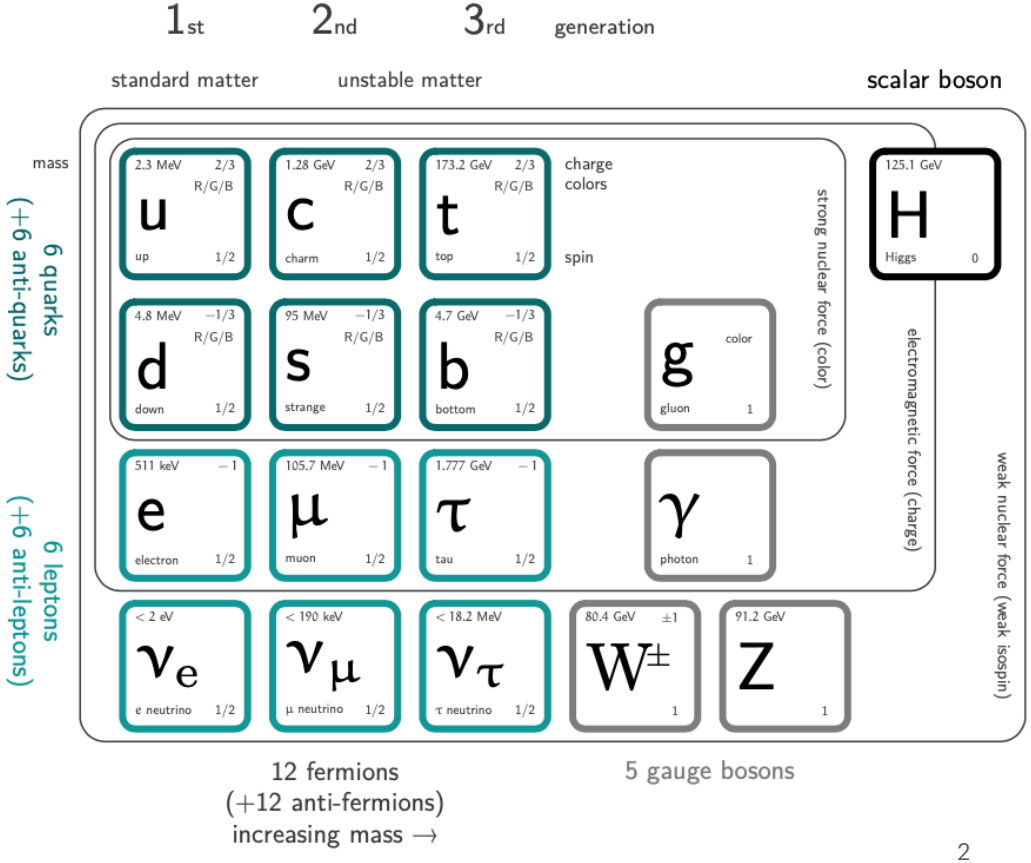
STXS AND COUPLING MEASUREMENTS IN HIGGS BOSON DECAYS TO 4 FINAL LEPTON STATES

Steffen Keßler 14.06.21

Standard Model of Particle Physics



- Best description of the subatomic world

So far so good

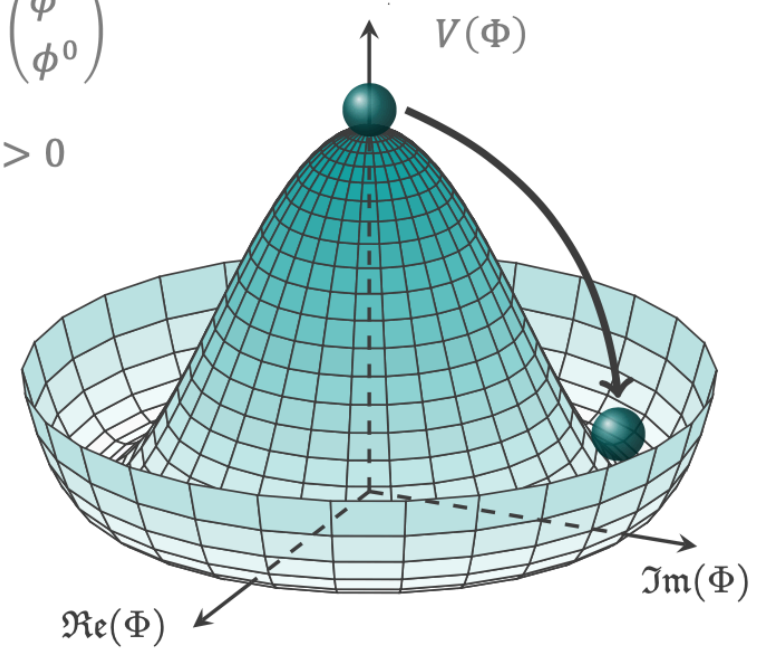
- What is dark matter?
- Matter/Antimatter asymmetry?
- Why are there 3 generations of quarks and leptons?
- ...

The Higgs Mechanism

$$\mathcal{L} = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}_\mu \Phi) - \underbrace{\left[\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2\right]}_{V(\Phi)}$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$-\mu^2 > 0$$



- Non vanishing vacuum expectation value $v = 246.22$ GeV
- Choosing a ground state spontaneously breaks $SU(2)_L \; x \; U(1)_Y$
- Invariance under $U(1)_Q$ still preserved

The Higgs Mechanism

- 3 out of 4 bosons become massive
- Resulting particle: Higgs Boson
- Fermions gain mass trough Yukawa interactions - proportional to $\langle \phi \rangle$
  - Mass of Higgs and self coupling free parameters in SM

→Ones measured:

  - All production & decay rates can be predicted by the SM

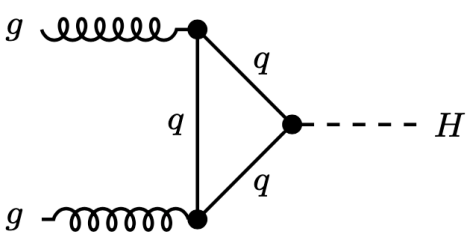
The Higgs Boson

- Massive scalar Boson ($m = 125.35 \pm 0.15$ GeV)
- Spin 0
- No color, no electric charge
- CP-even
- Narrow decay width ~4MeV

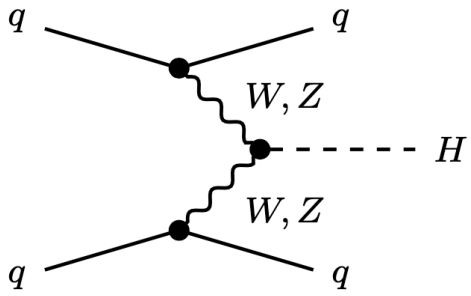
Higgs Boson Production & Decay

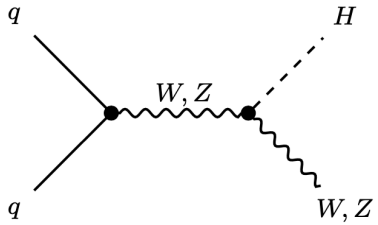
Production of the Higgs Boson with a mass of 125 GeV at $\sqrt{s} = 13$ TeV

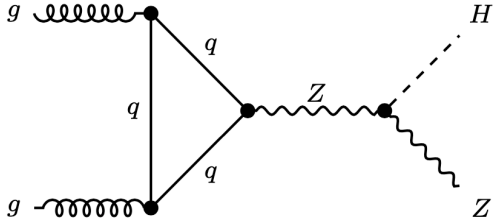
ggF



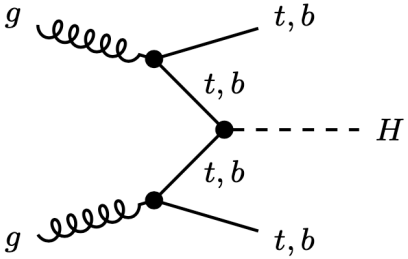
VBF

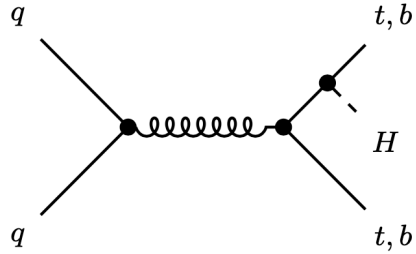






VH

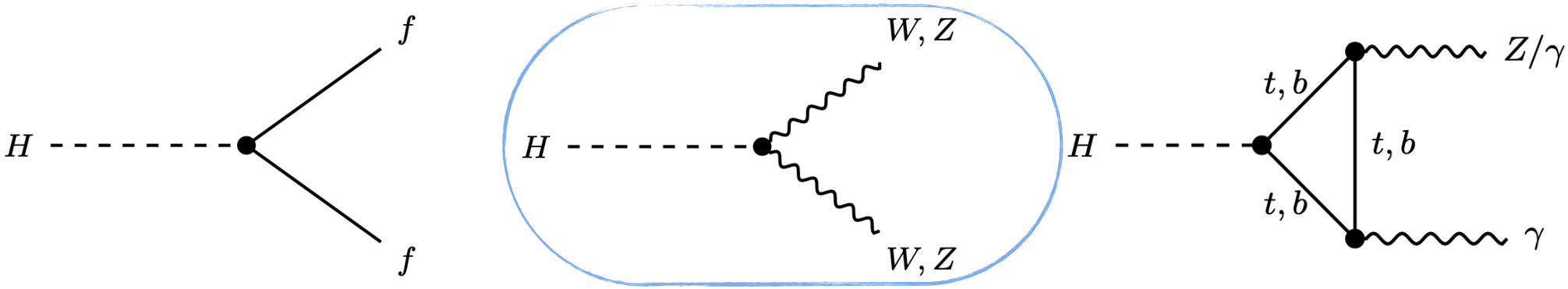




ttH

Higgs Boson Production & Decay

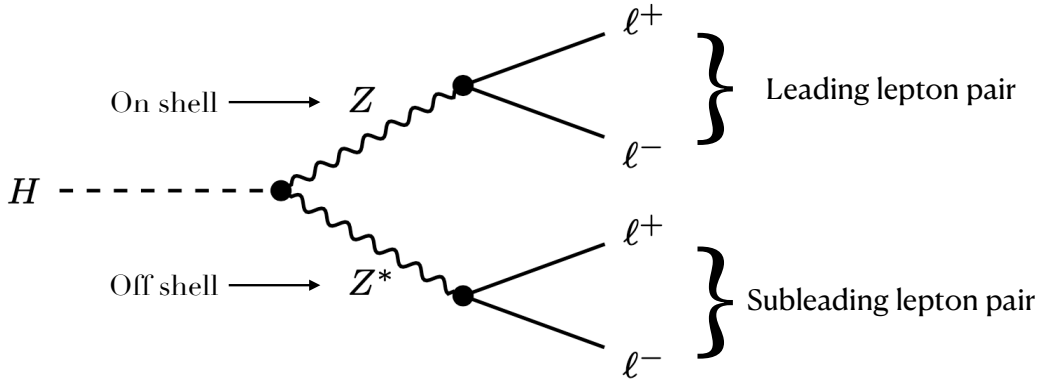
Decay of the Higgs Boson with a mass of 125 GeV at $\sqrt{s} = 13$ TeV



Motivation

- Many open questions
- Physics beyond the Standard Model (BSM)
  - Supersymmetry, string theory, M-theory and extra dimensions
- Experimental search for BSM physics
  - Direct search: search for new particles
  - Indirect search: precise measurements of the known particles and search for deviations from SM

WHY $H \rightarrow ZZ^* \rightarrow 4l$?



- Small branching ratio 0.00125 %
- Clear Higgs Boson signature
  - Full kinematic of the Higgs
  - Four leptons originate from the primary vertex.
  - Very good four-lepton invariant mass resolution of about 1 – 2 %
  - High signal-to-background ratio 2 : 1

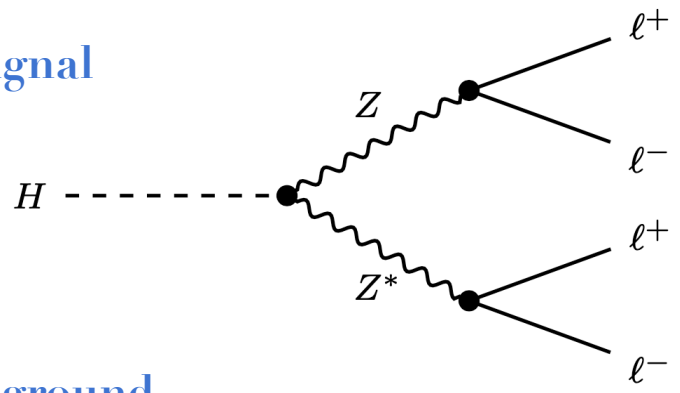
—> Precise measurement of the Higgs Boson properties

Background Processes

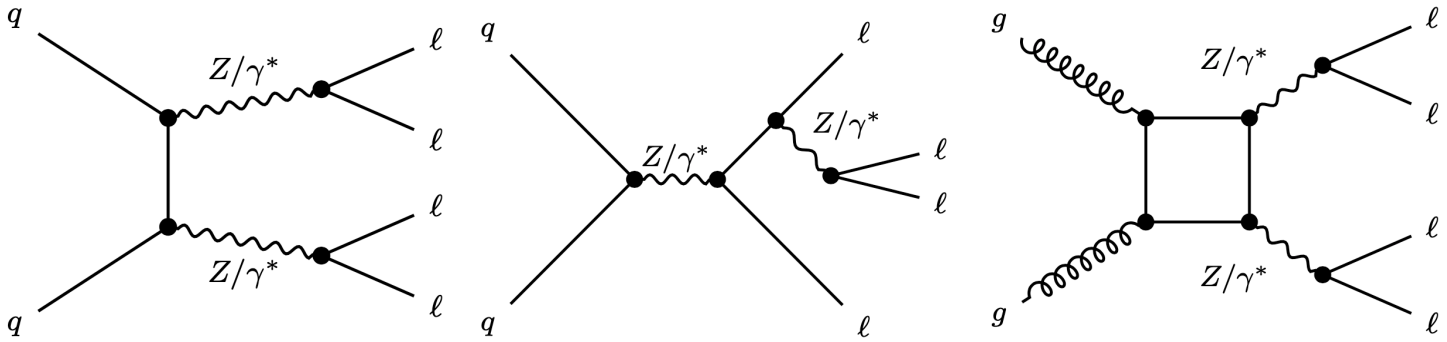
Irreducible Background: SM ZZ production

- 4 leptons in final state
- Indistinguishable from signal

Signal

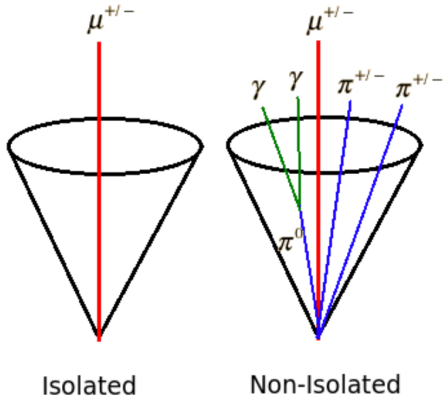


Background

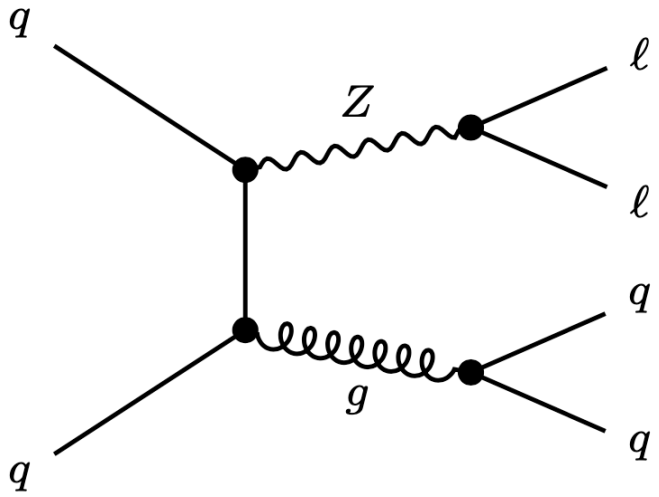


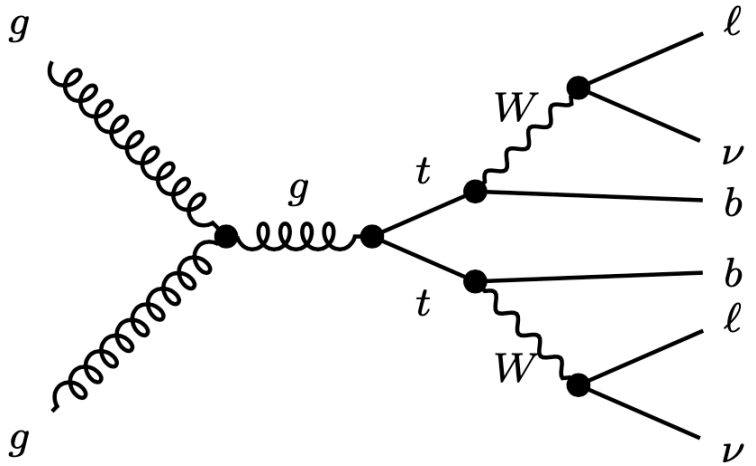
Background Processes

Reducible Background: Z+jets, tt, …



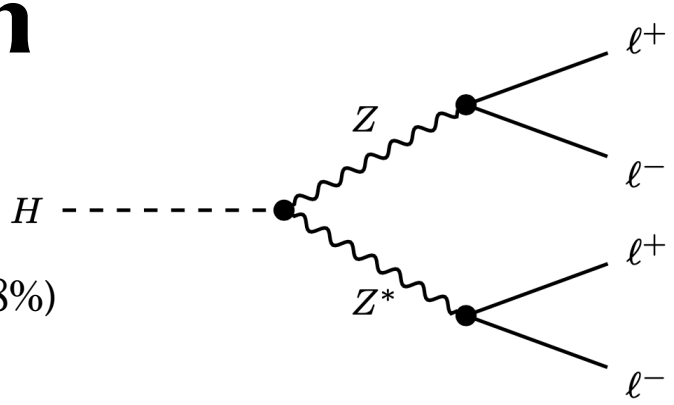
- Less than four prompt leptons in final state
- At least one lepton originates from a jet



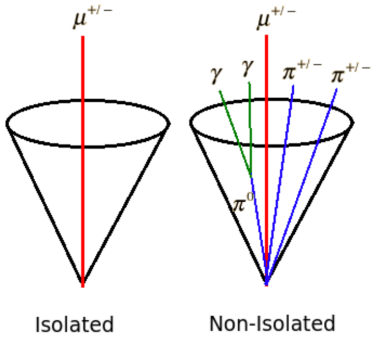


Event Selection

Of Lepton Quadruplets



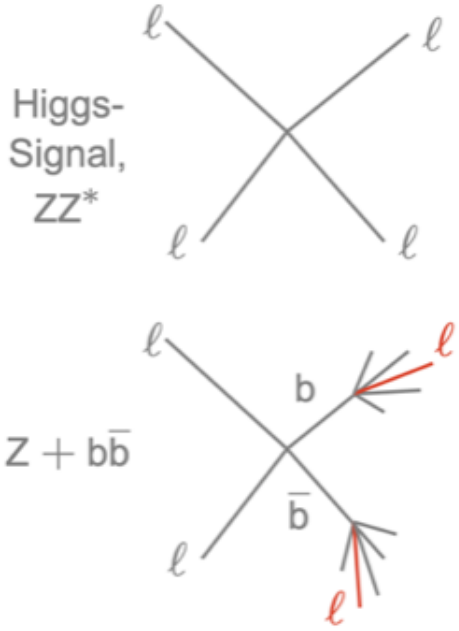
- 2 pairs opposite electric charge, same flavor
  - Single-lepton, di-lepton & tri-lepton triggers with high efficiency (98%)
  - Lepton identification & p_T−threshold criteria have to be satisfied
  - All leptons originate from the same vertex
  - Well separated
- Cut on invariant masses
  - Leading lepton pair:
    $50\ \text{GeV} < m_{12} < 106\ \text{GeV}$
  - Subleading lepton pair:
    $m_{\text{threshold}} < m_{34} < 115\ \text{GeV}$

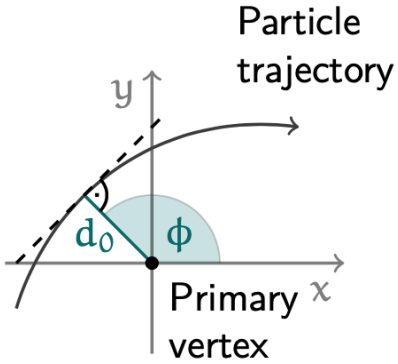


Event Selection

Background suppression

- Muon (electron) isolation
  - $I^{\text{track}}_{\mu(e)} = < 0.15(0.15)$
  - $I^{\text{calo}}_{\mu(e)} = < 0.30(0.20)$
- d_0-significance
  - Muons: $|d_0/\sigma(d_0)| < 3.0$
  - Electrons: $|d_0/\sigma(d_0)| < 5.0$



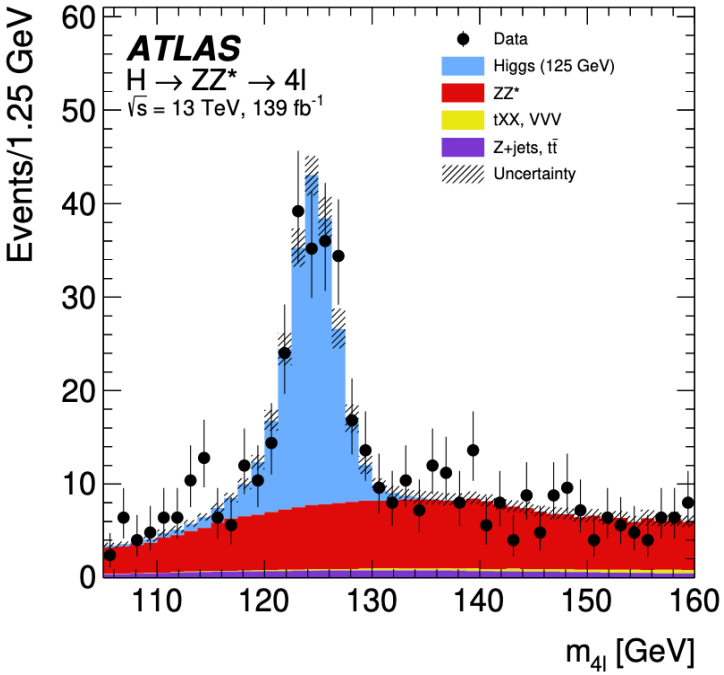


Results

Expected and observed number of events for the four lepton decay after the event selection

$$115 \text{ GeV} < m_{4l} < 130 \text{ GeV}$$

Final state	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
4μ	78 ± 5	38.0 ± 2.1	2.85 ± 0.18	119 ± 5	115
$2e2\mu$	53.0 ± 3.1	26.1 ± 1.4	2.98 ± 0.19	82.0 ± 3.4	96
$2\mu2e$	40.1 ± 2.9	17.3 ± 1.3	3.6 ± 0.5	61.0 ± 3.2	57
$4e$	35.3 ± 2.6	15.0 ± 1.5	2.91 ± 0.33	53.2 ± 3.1	42
Total	206 ± 13	96 ± 6	12.2 ± 1.0	315 ± 14	310



Data and simulation in good agreement

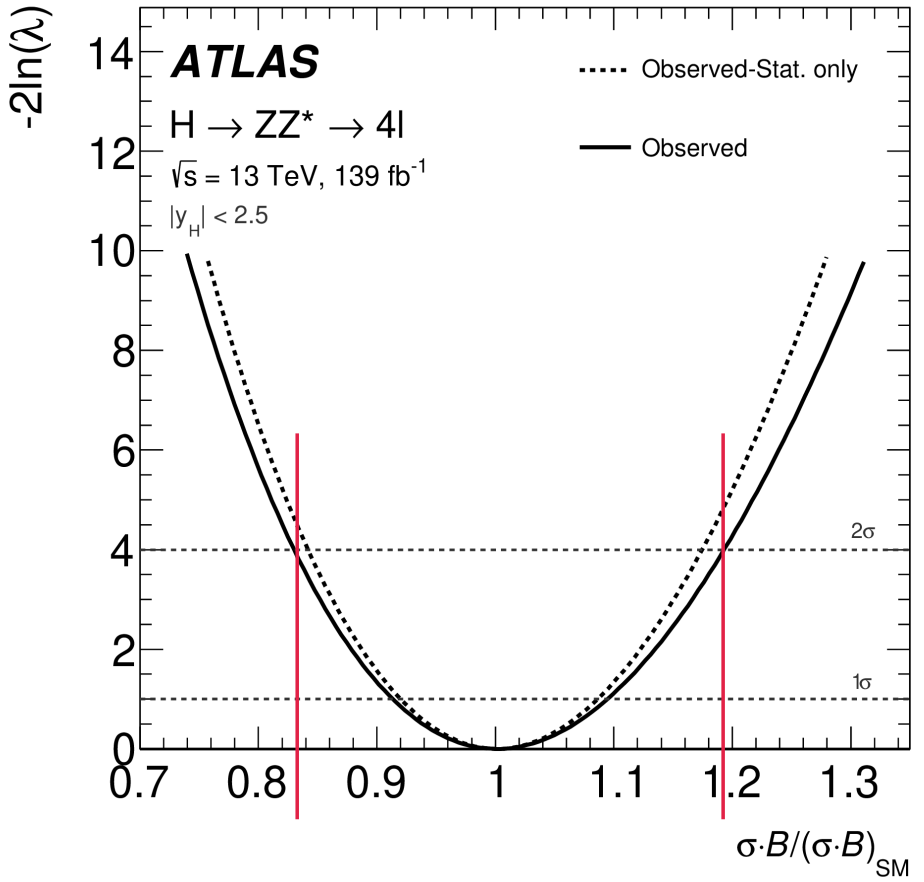
Results

Inclusive $H \to ZZ^*$ production cross-section

$$\sigma \cdot \mathscr{B} \equiv \sigma \cdot \mathscr{B}\,(H \to ZZ^*) = 1.34 \pm 0.12 \text{ pb}$$

$$\left(\sigma \cdot \mathscr{B}\right)_{\text{SM}} \equiv \left(\sigma \cdot \mathscr{B}\,(H \to ZZ^*)\right)_{\text{SM}} = 1.33 \pm 0.08 \text{ pb}$$

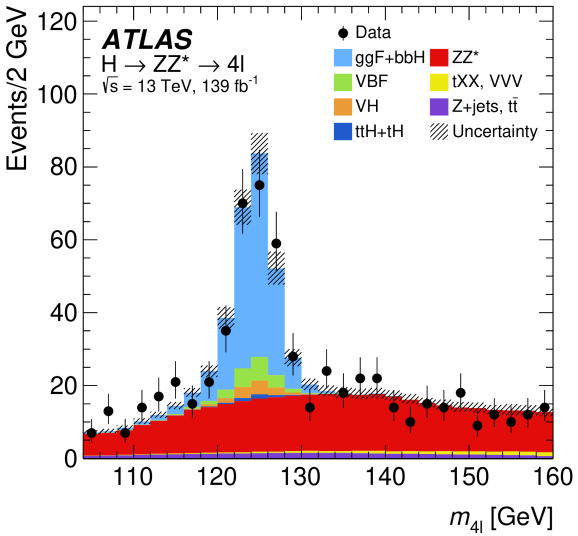
In very good agreement with the SM prediction

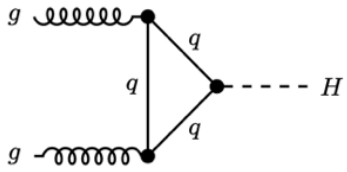


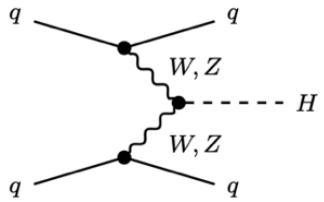
Measuring the Coupling Properties

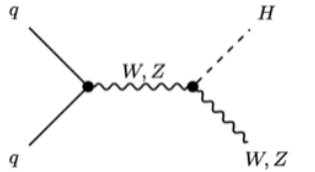
Simplified Template Cross Sections (STXS)

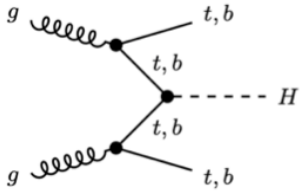
- Exclusive measurement of $(\sigma \cdot \mathscr{B})$ with STXS
- Production mode stage:
  - Measurement of $(\sigma \cdot \mathscr{B})$ for the main production modes

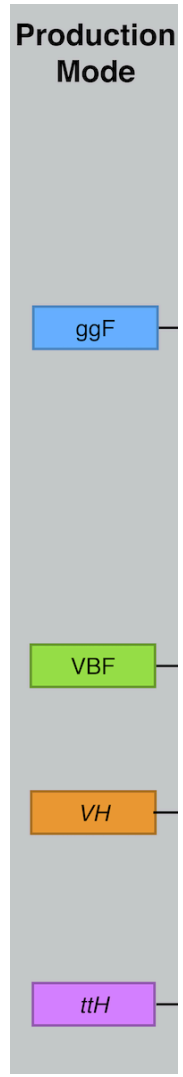








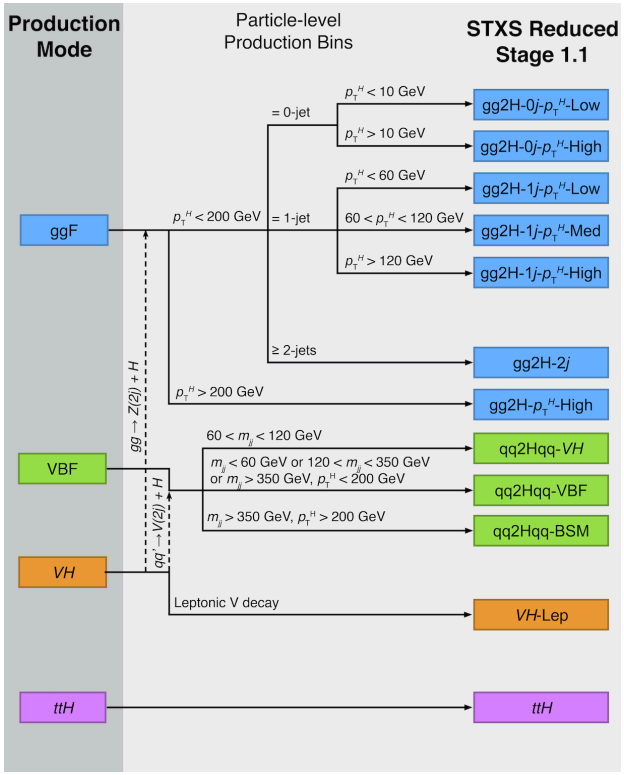




Measuring the Coupling Properties

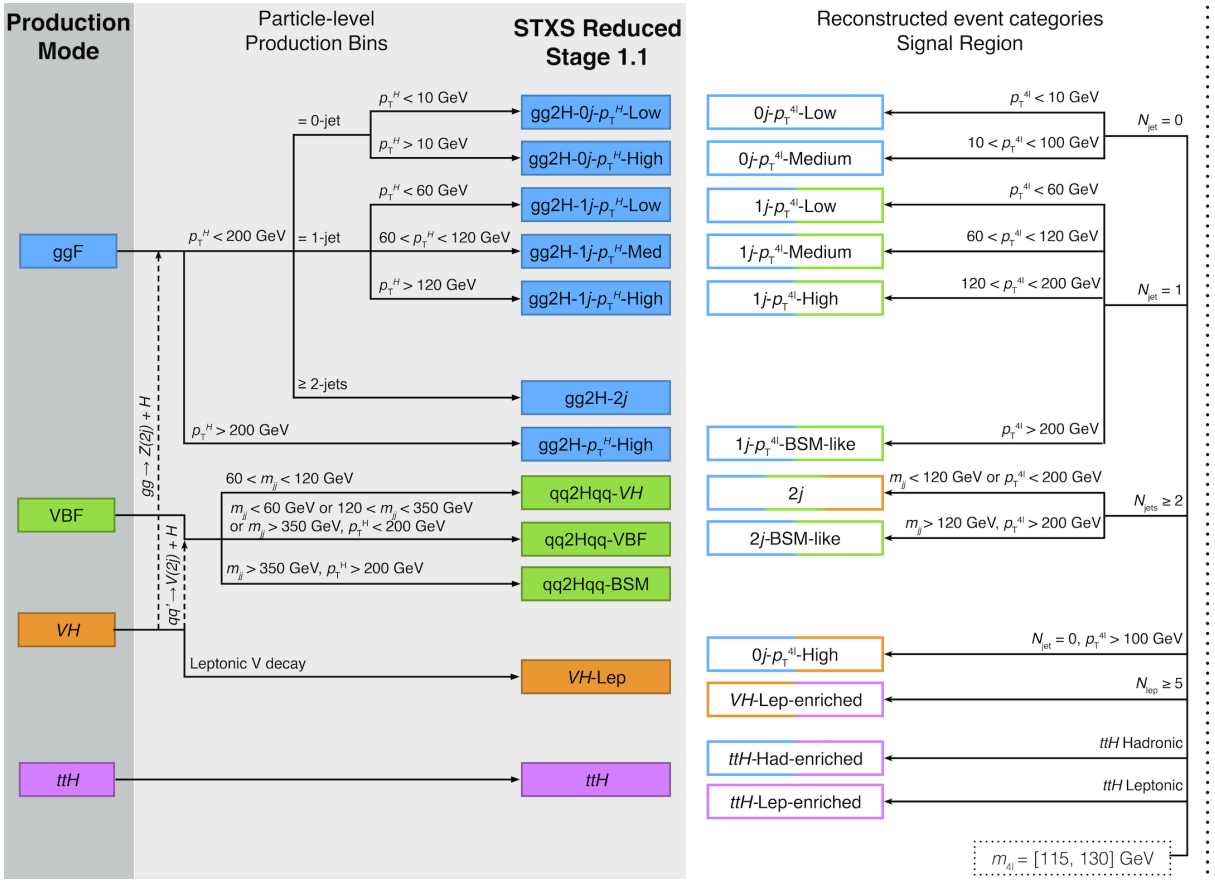
STXS Reduced Stage 1.1

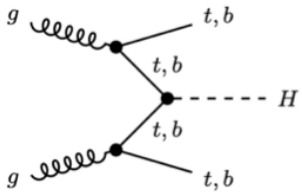
- Several exclusive phase-space bins in dedicated fiducial regions
  - $N_{\text{jet}}, p_T^H, m_{jj}$
- Particle-level production bins
- Minimize theoretical uncertainties
- Isolate BSM physics
- Allows combination with other channels



Measuring the Coupling Properties

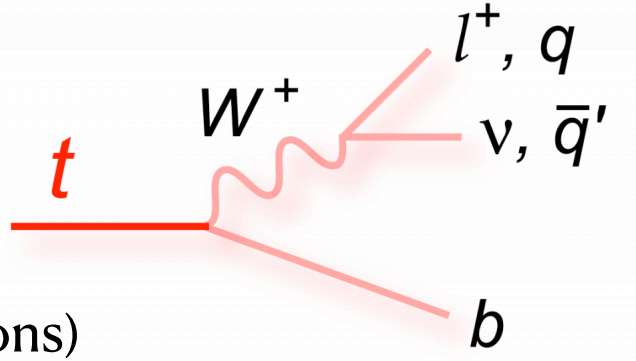
Match With Reconstructed Event Categories





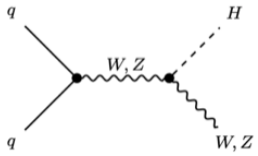
Reconstructed Production Modes

ttH

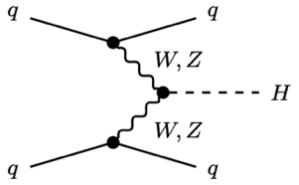


- Top quark decays into W boson and bottom quark
  - At least one b-tagged jet in final state
- *ttH-Had-enriched* (Fully hadronic decay of both W bosons)
  - At least four additional jets
- *ttH-Lep-enriched* (At least one leptonic decay of a W boson)
  - At least one additional lepton with $p_T > 12$ GeV & at least two jets in the final state

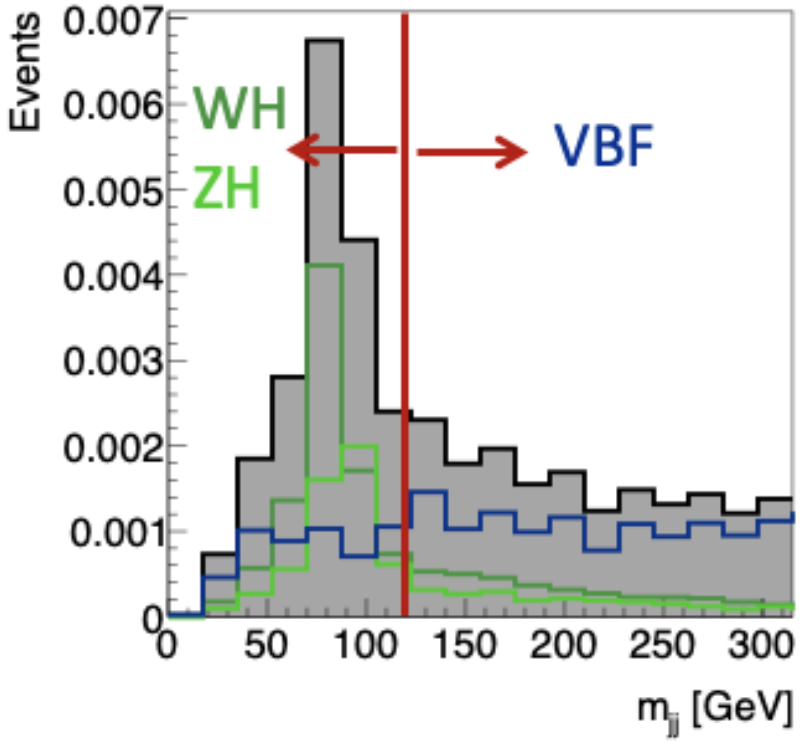
Reconstructed Production Modes



VH & VBF

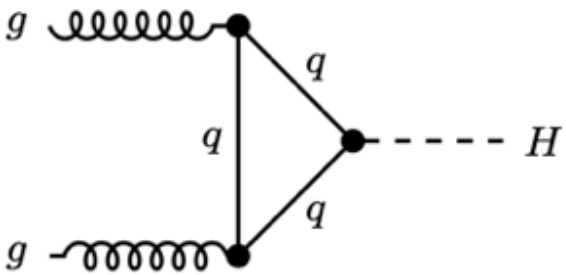


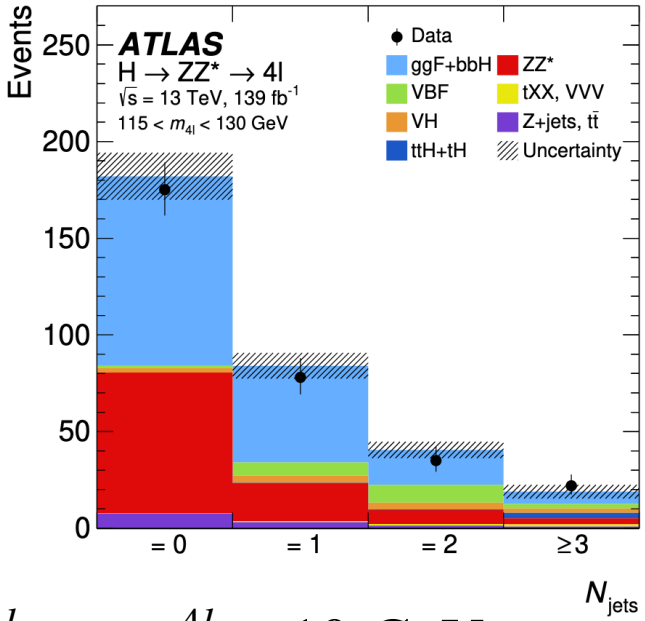
- *VH-Lep-enriched* (leptonically decaying vector boson)
  - Events with additional leptons which do not fulfill the *ttH* requirements
- *2j-BSM-like*
  - At least 2 jets with $m_{jj} > 120$ GeV & $p_T^{4l} > 200$ GeV
- *2j*
  - Remaining events with at least 2 jets



Reconstructed Production Modes

ggF





1 jets:

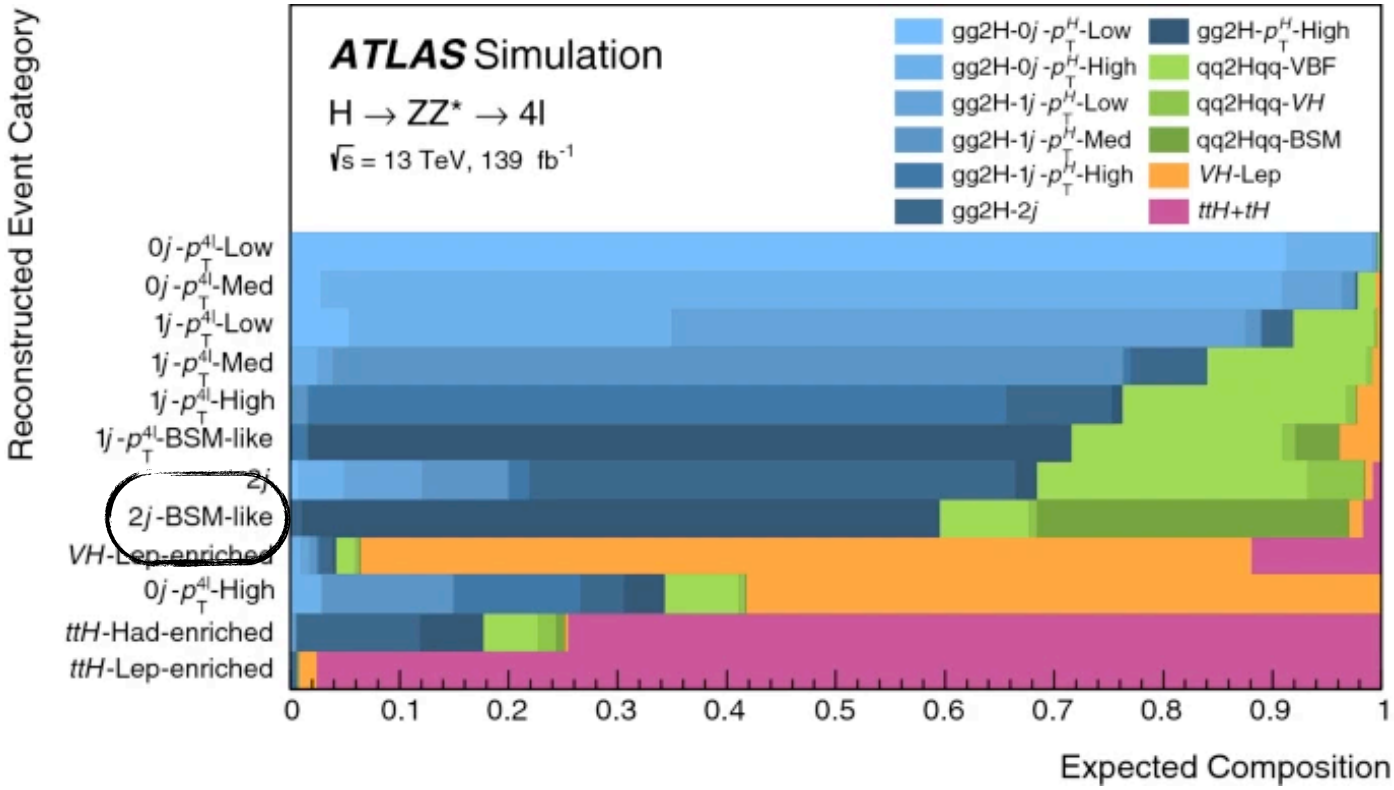
- $\underline{1j\text{-}p_T^{4l}\text{-}Low}$: $p_T^{4l} < 60$ GeV
- $\underline{1j\text{-}p_T^{4l}\text{-}Med}$: 60 GeV $< p_T^{4l} <$ 120 GeV
- $\underline{1j\text{-}p_T^{4l}\text{-}High}$: 120 GeV $< p_T^{4l} <$ 200 GeV
- $\underline{1j\text{-}p_T^{4l}\text{-}BSM\text{-}like}$: $p_T^{4l} > 200$ GeV

0 jets:

- $\underline{0j\text{-}p_T^{4l}\text{-}Low}$: $p_T^{4l} < 10$ GeV
- $\underline{0j\text{-}p_T^{4l}\text{-}Med}$: 10 GeV $< p_T^{4l} <$ 100 GeV
- $\underline{0j\text{-}p_T^{4l}\text{-}High}$: $p_T^{4l} > 100$ GeV

Reconstructed Production Modes

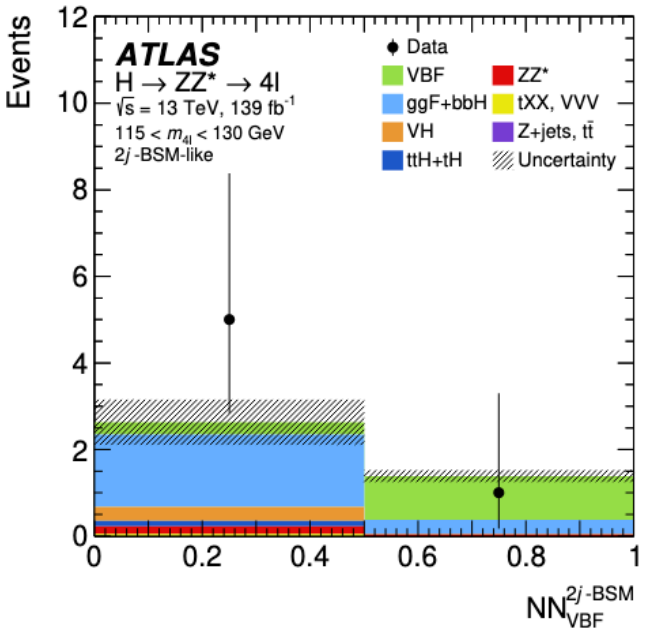
Signal composition in terms of the Reduced Stage 1.1 production bins in each reconstructed event category

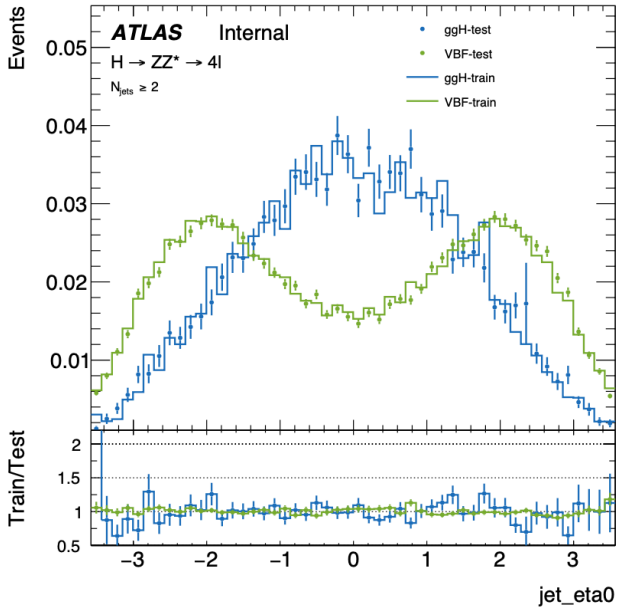


Reconstructed Production Modes

NN Discriminants

- Probability for the event to originate from the given process





Results

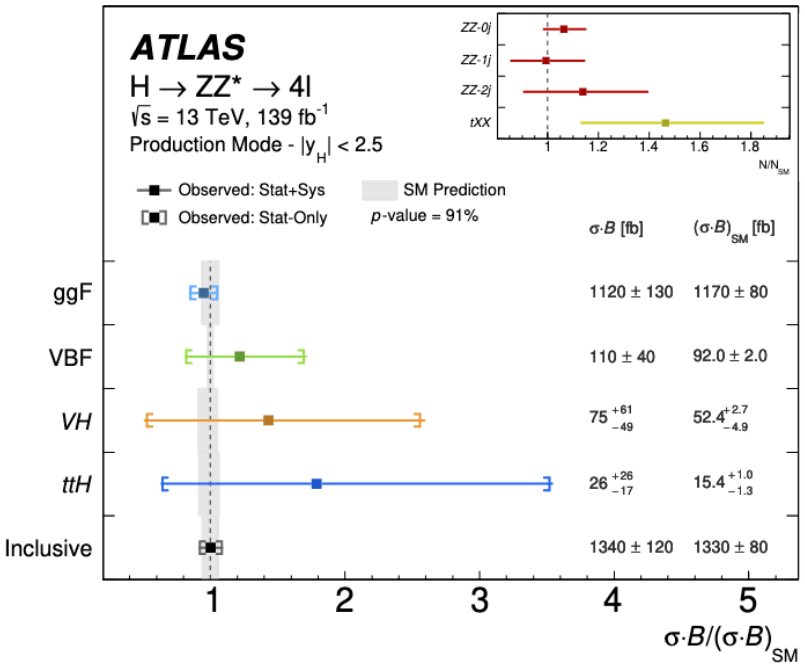
Expected and observed number of events for the four lepton decay for the reconstructed event categories

Reconstructed event category	Signal	ZZ^* background	tXX background	Other backgrounds	Total expected	Observed
Signal			$115 < m_{4\ell} < 130$ GeV			
$0j$-$p_{\mathrm{T}}^{4\ell}$-Low	24.2 ± 3.5	30 ± 4	–	0.93 ± 0.13	55 ± 5	56
$0j$-$p_{\mathrm{T}}^{4\ell}$-Med	76 ± 8	37 ± 4	–	6.5 ± 0.6	120 ± 9	117
$0j$-$p_{\mathrm{T}}^{4\ell}$-High	0.355 ± 0.031	0.020 ± 0.012	0.0094 ± 0.0027	0.30 ± 0.05	0.69 ± 0.06	1
$1j$-$p_{\mathrm{T}}^{4\ell}$-Low	34 ± 4	15.5 ± 2.7	–	1.91 ± 0.29	52 ± 5	41
$1j$-$p_{\mathrm{T}}^{4\ell}$-Med	20.8 ± 2.8	4.0 ± 0.7	0.114 ± 0.013	1.02 ± 0.19	26.0 ± 2.9	31
$1j$-$p_{\mathrm{T}}^{4\ell}$-High	4.7 ± 0.8	0.48 ± 0.10	0.043 ± 0.008	0.27 ± 0.04	5.5 ± 0.8	4
$1j$-$p_{\mathrm{T}}^{4\ell}$-BSM-like	1.23 ± 0.23	0.069 ± 0.031	0.0067 ± 0.0031	0.062 ± 0.012	1.37 ± 0.23	2
$2j$	38 ± 5	9.1 ± 2.7	0.95 ± 0.08	2.13 ± 0.31	50 ± 6	48
$2j$-BSM-like	3.3 ± 0.6	0.18 ± 0.06	0.032 ± 0.005	0.091 ± 0.017	3.6 ± 0.6	6
VH-Lep-enriched	1.29 ± 0.07	0.156 ± 0.025	0.039 ± 0.009	0.0194 ± 0.0032	1.50 ± 0.08	1
ttH-Had-enriched	1.02 ± 0.18	0.058 ± 0.025	0.252 ± 0.032	0.119 ± 0.033	1.45 ± 0.18	2
ttH-Lep-enriched	0.42 ± 0.04	0.002 ± 0.005	0.0157 ± 0.0023	0.0028 ± 0.0029	0.44 ± 0.04	1

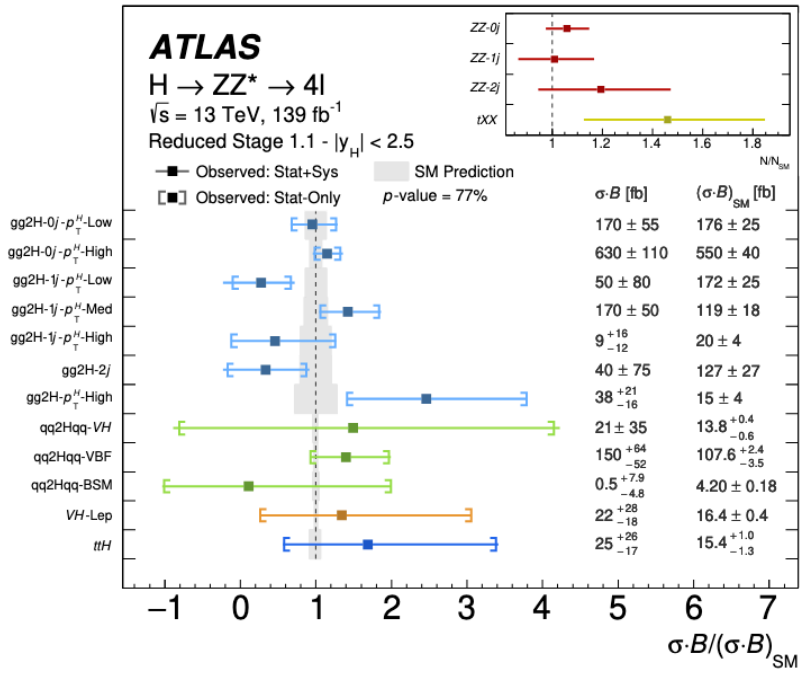
The expected event yields are in good agreement with the observed ones

Results

Production Mode Stage



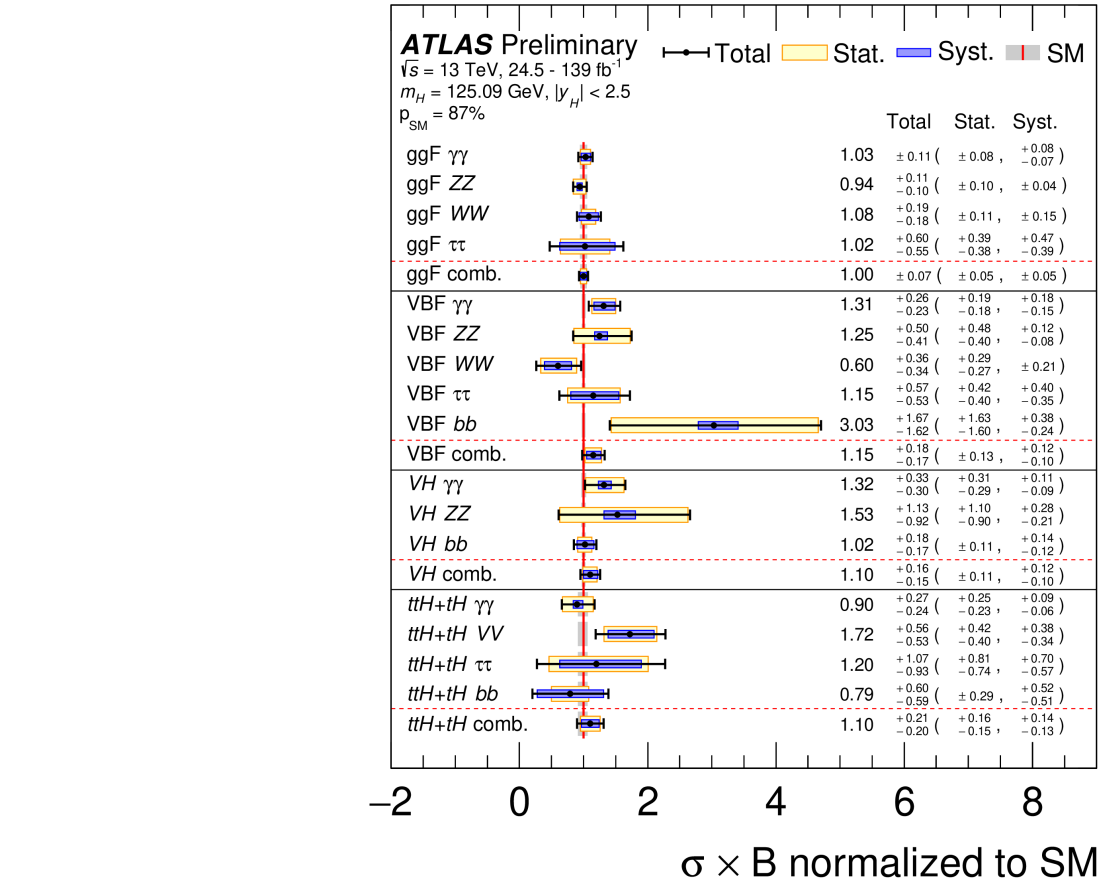
STXS Reduced Stage 1.1



Both stages agree good with the SM predictions

Results

Combined Measurements at Production Mode Stage



Outlook

- So far all measurements agree with the SM
- Uncertainties in some prod and decay modes quit large
- Effects from BSM physics are still not excluded
- One possibility to search for new physics in the Higgs sector:
  - Describe deviations from the SM prediction in context of an effective field theory (EFT)
  - Parametrize each production bin as a function of EFT parameters
  - Already done in some decay channels (also in H4l)
  - To increase the sensitivity: EFT interpretation of the combined measurements

Thank You

Verena Walbrecht

Prof Dr. Kroha

https://arxiv.org/pdf/2004.03447.pdf

https://arxiv.org/pdf/2004.03969.pdf