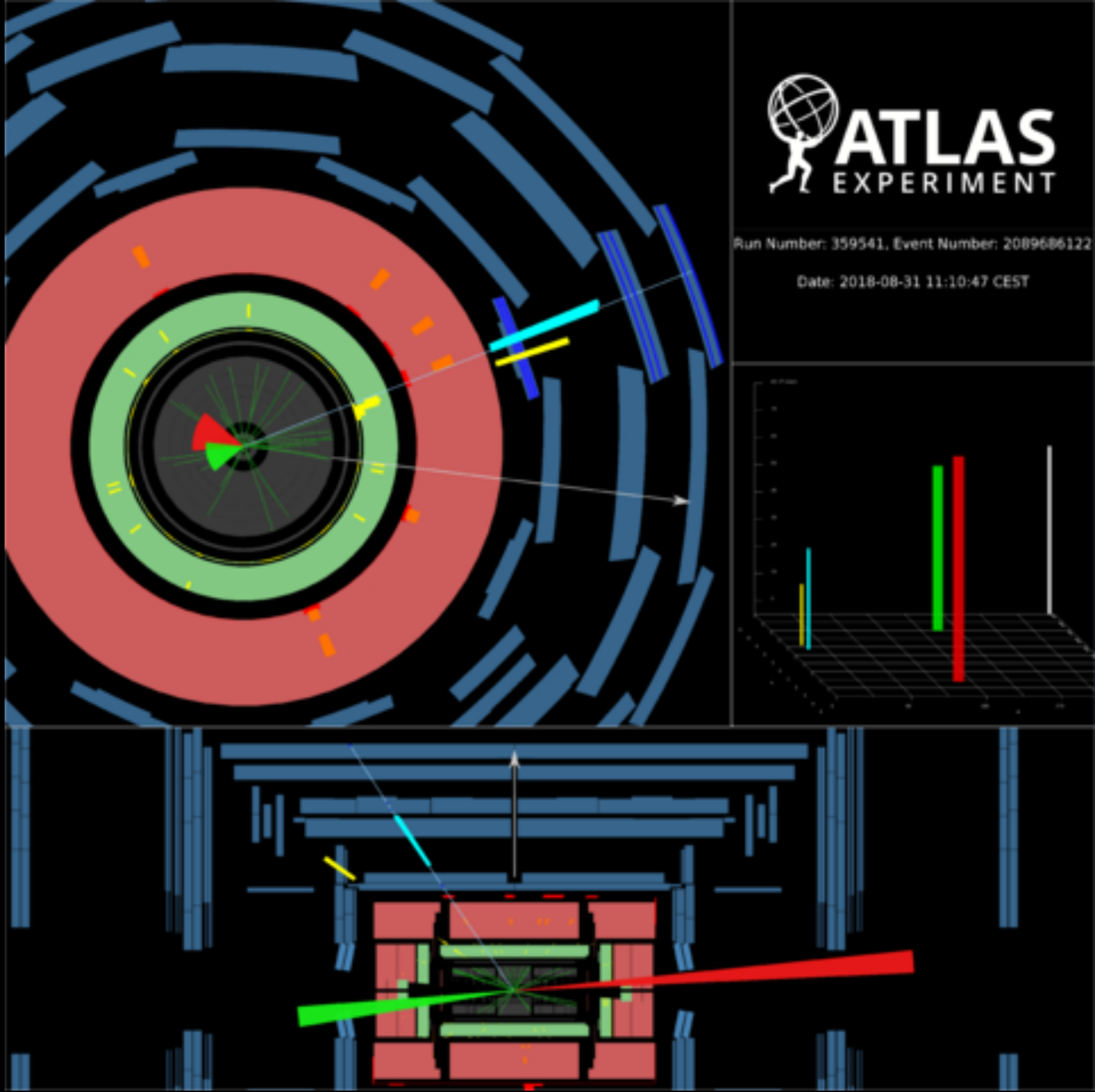
Characterizing the Higgs Boson at the Large Hadron Collider

Robin Hayes

CAP Congress 2021



ATLAS EXPERIMENT

UBC

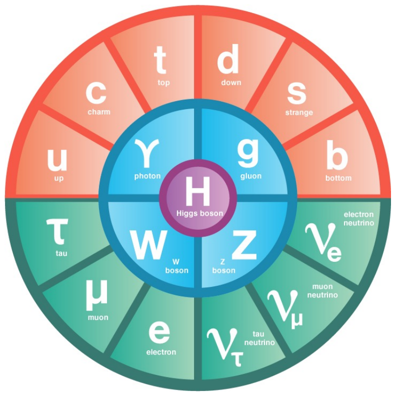
TRIUMF

Why the Higgs Boson?

The Higgs boson is the **most recently-discovered** particle of the Standard Model (SM).

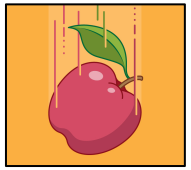
ATLAS-CONF-2012-091

It's completes the SM and is crucial to making it work as well as it does....

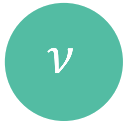


... which is very well, but not perfectly.

Dark matter?

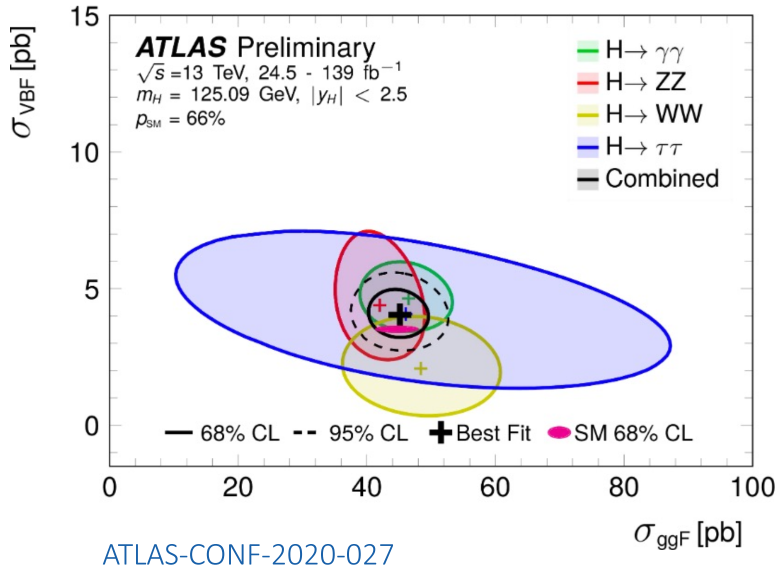


Gravity?



Neutrino masses?

Precision measurements of its properties **test the limits of the SM** and could reveal signs of **new physics**.



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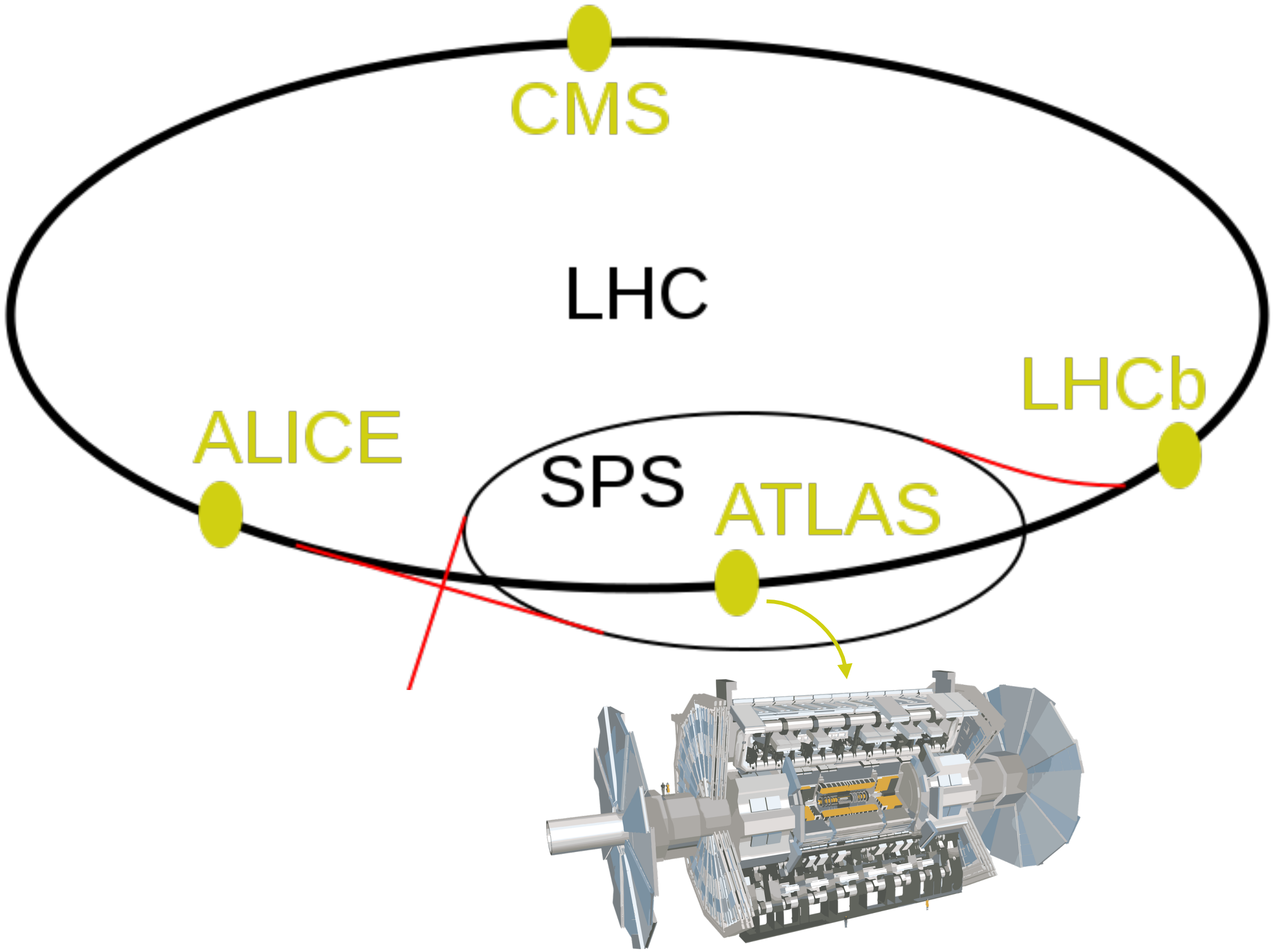
How Can We Study the Higgs Boson?

We need to produce it → Only possible at one place in the world: the **Large Hadron Collider (LHC)**.

Large Hadron Collider (LHC):

27 km circumference ring
4 main detectors

Two beams of protons are accelerated in opposite directions to COM energy of $\sqrt{s}$ = 13 TeV.



ATLAS Detector:

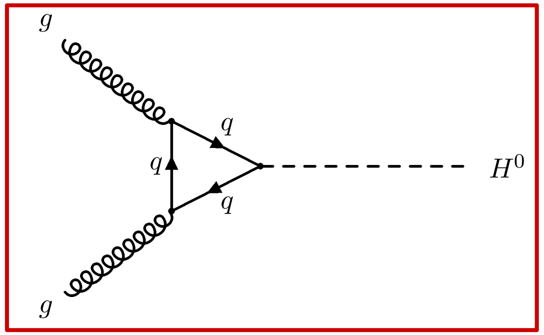
7,000-tonne detector

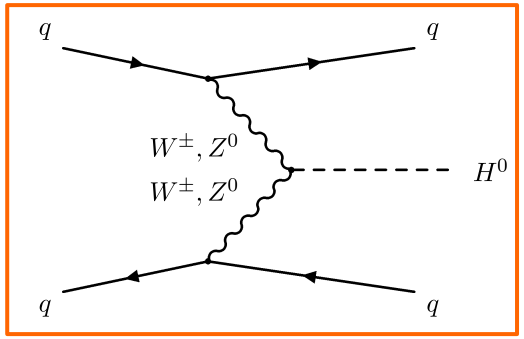
40M proton-proton collisions per second at its centre

Data collected by the ATLAS detector from 2015 to 2018 is analyzed for signs of the Higgs boson.

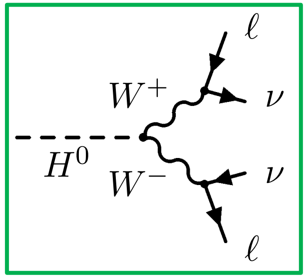
Higgs Production and Decay

Investigate **Higgs production** by two modes: gluon-gluon fusion (ggF) and vector boson fusion (VBF).

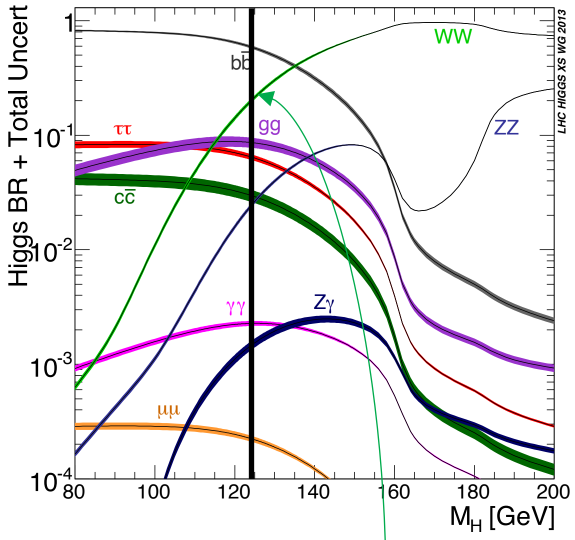




The Higgs boson decays before it reaches the detector, so we look for its **decay to two W bosons**.



arXiv:1307.1347

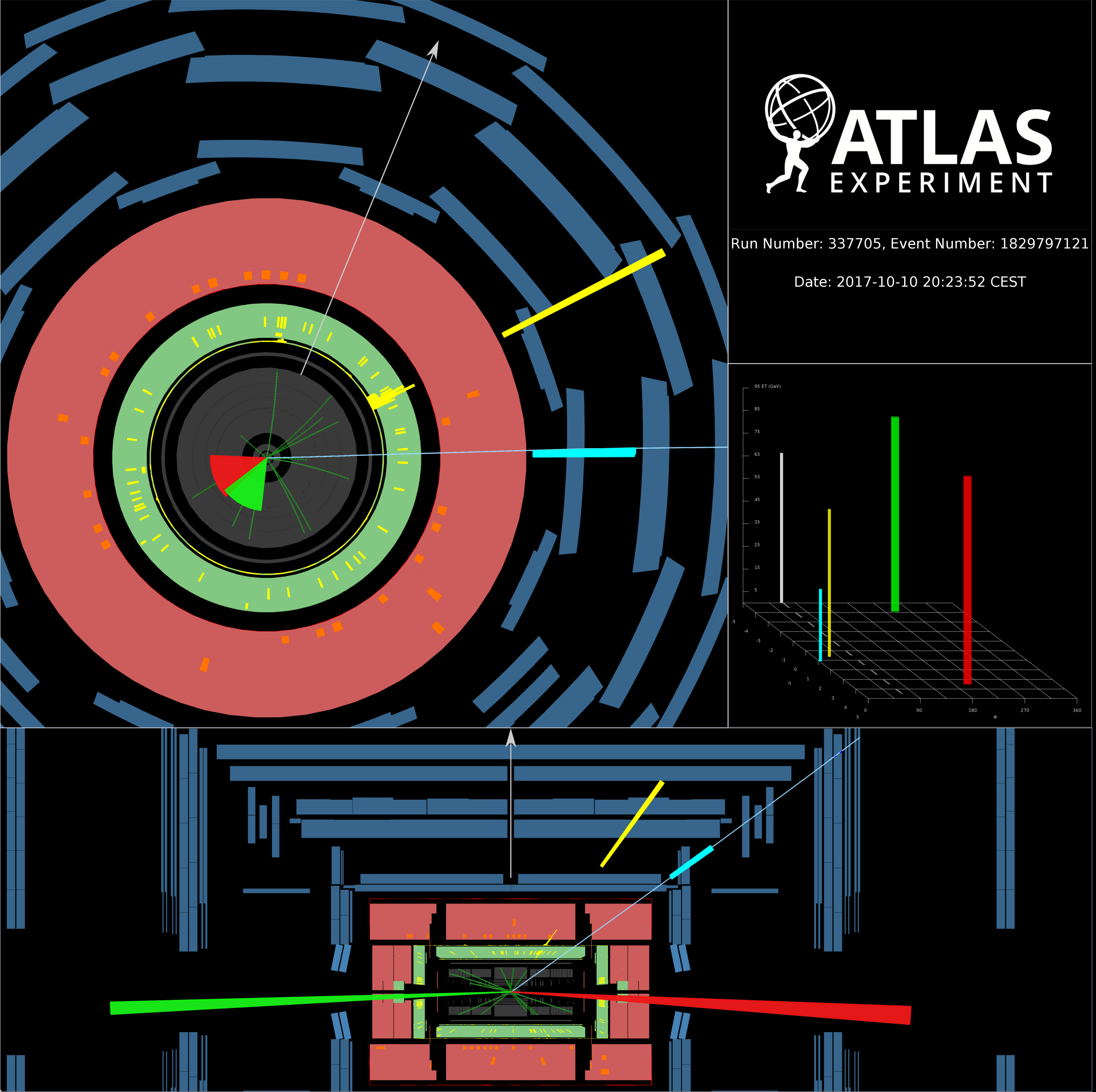


The branching ratio (probability of decay) for $H \to WW^*$ is the second-largest for m_H=125 GeV.

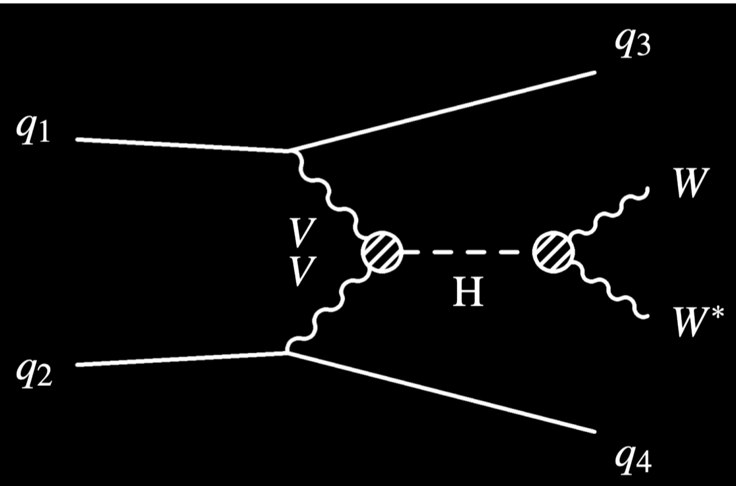
This talk:

Focus on VBF production followed by $H \to WW^*$ decay.

- Never previously observed by ATLAS.
- Theoretical importance:
  - Diagrams needed to prevent unitarity violation in W^+W^- scattering.
  - Sensitive to Higgs–vector boson coupling, a parameter predicted by the SM.
- Ultimately we measure Higgs production in both the ggF and VBF channels.



Identifying VBF $H \rightarrow WW^*$

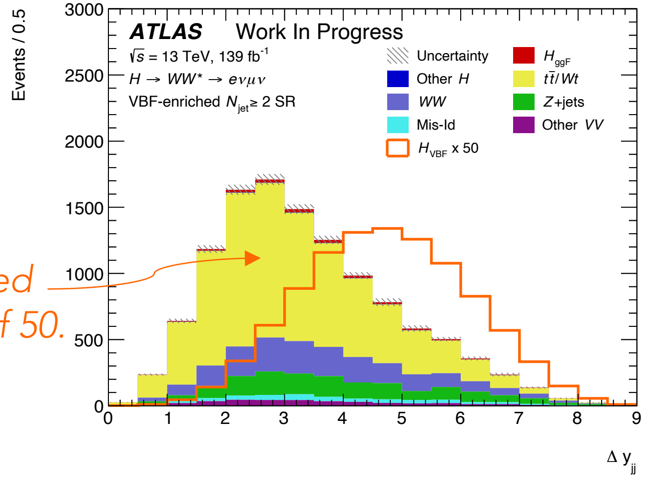


- 2 leptons, different flavour, opposite charge.
- $\geq$ 2 jets, p_T>30 GeV, m_{jj}>120 GeV
- Background rejection: No b-jets, and $m_{\tau\tau} < m_Z - 25$ GeV
- Central jet veto: no jets with p_T>30 GeV between the two leading jets.
- Outside lepton veto: no leptons outside the two leading jets.

Separating Signal from Background

After applying selections that target VBF $H \rightarrow WW^*$, background events still dominate by a factor of 60!

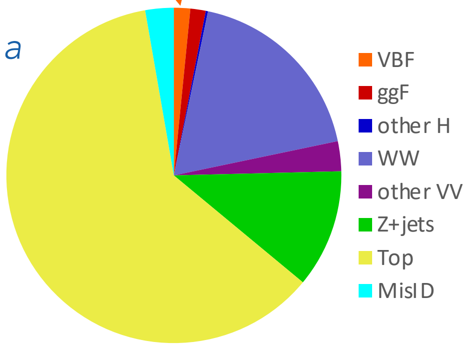
Other physics processes



Simulated signal scaled by factor of 50.

This sliver of orange is our signal!

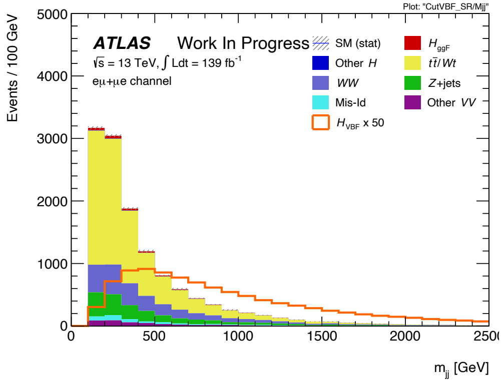
Everything else is a background.



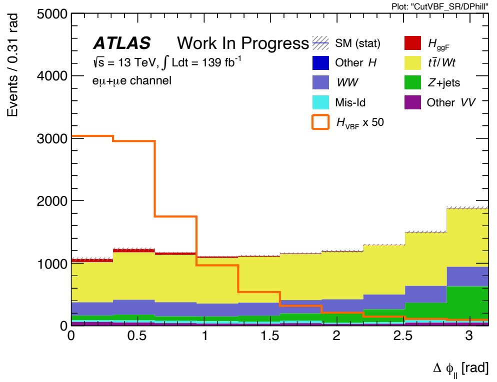
So we use a **deep neural network** (DNN) to distinguish signal from background.

- Trained on simulated events.
- Sorts events based on degree of resemblance to signal.
- Discrimination based on 15 input variables that target different features of our expected signal and background events.

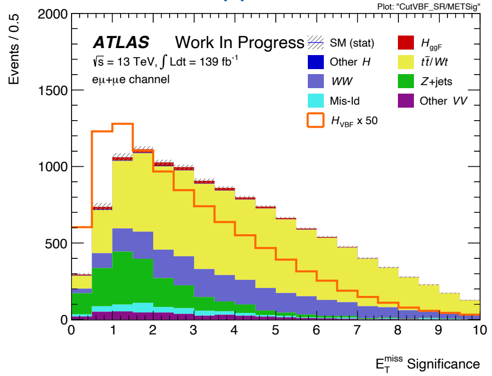
VBF topology



HWW decay



Top background suppression



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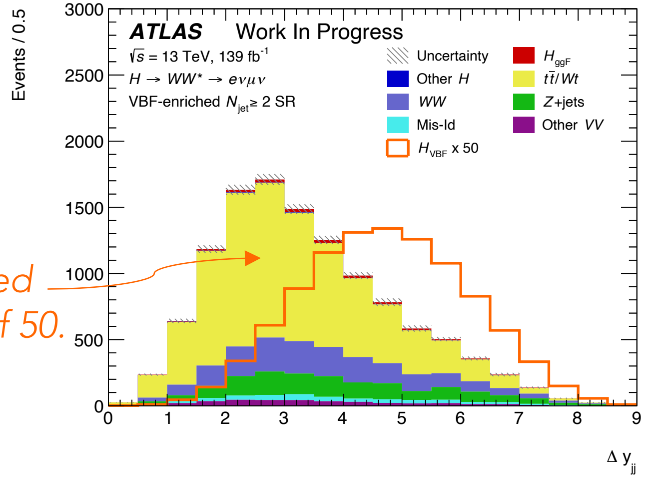
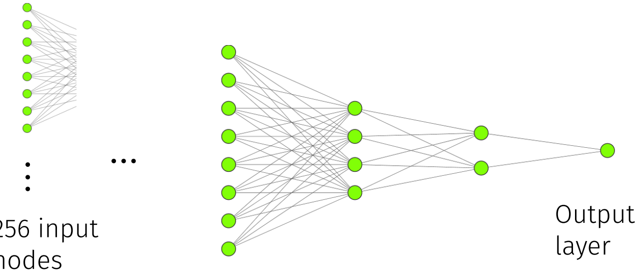
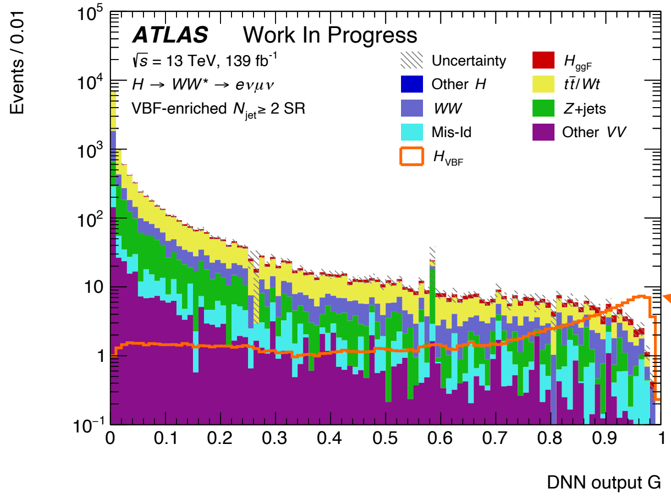


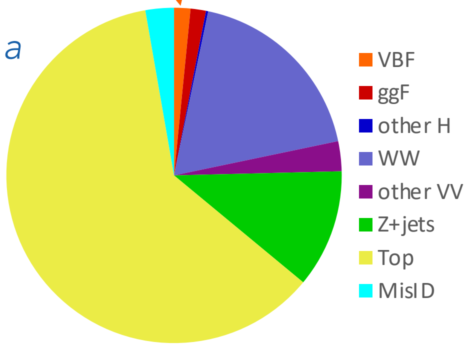
Sort events by DNN score



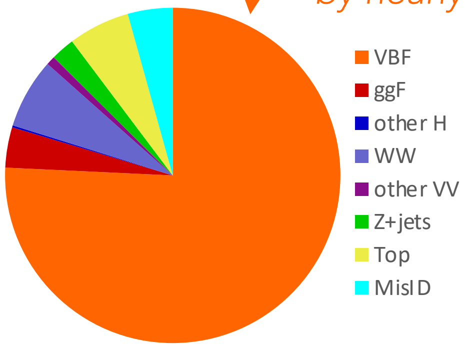


This sliver of orange is our signal!

Everything else is a background.



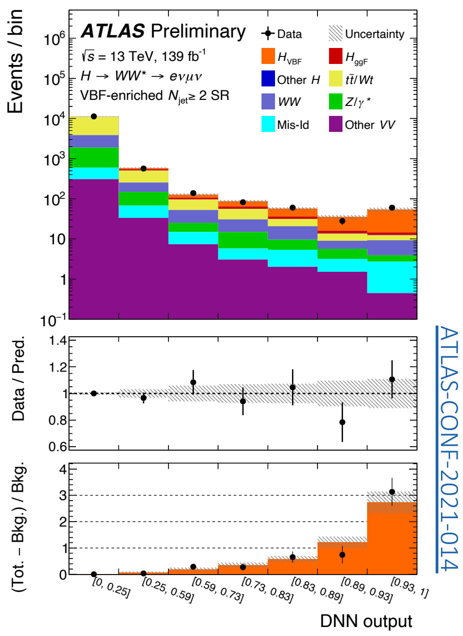
DNN score > 0.94: signal dominates by nearly 3:1.

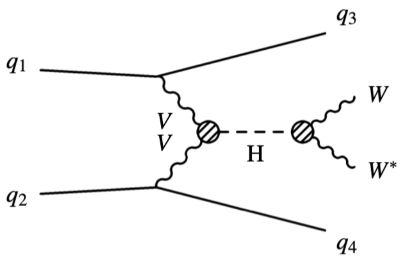


ggF and VBF Cross-Section Measurement

- Categorize events into 7 DNN bins, increasingly enriched in VBF $H \rightarrow WW^*$:

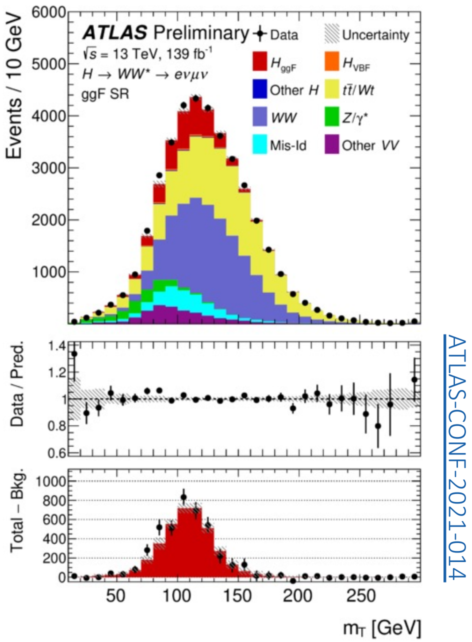
VBF

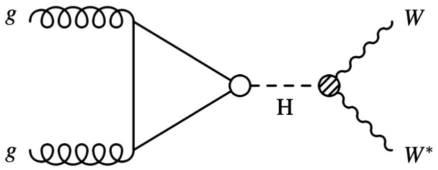




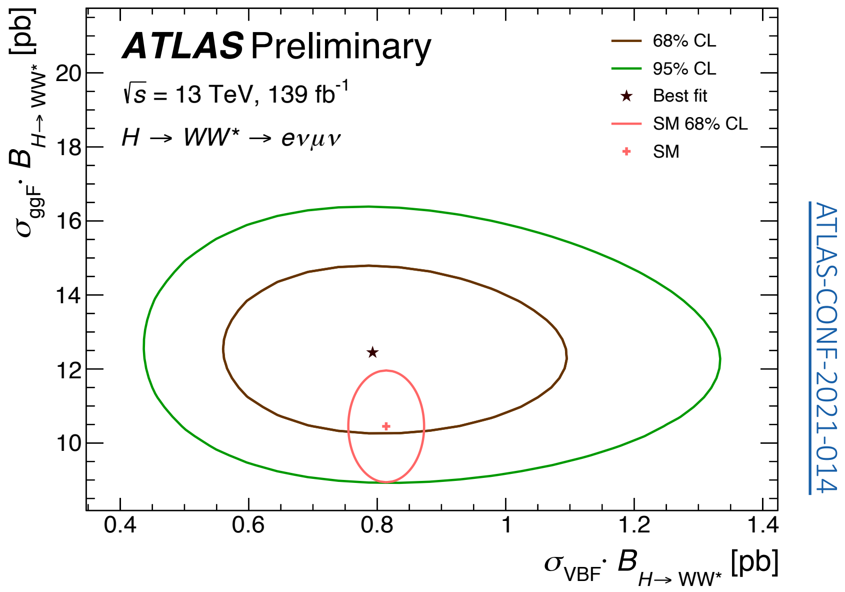
- Separately apply cuts that target ggF $H \rightarrow WW^*$:

ggF





- Apply a profile likelihood fit to measure the cross-sections for both production modes simultaneously.



Best-fit values of σ_{VBF} and σ_{ggF} agree with the SM.

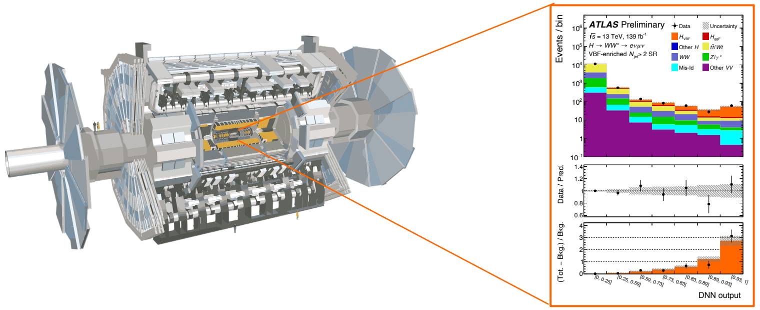
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*} = 0.79^{+0.19}_{-0.16} \text{ pb}$$

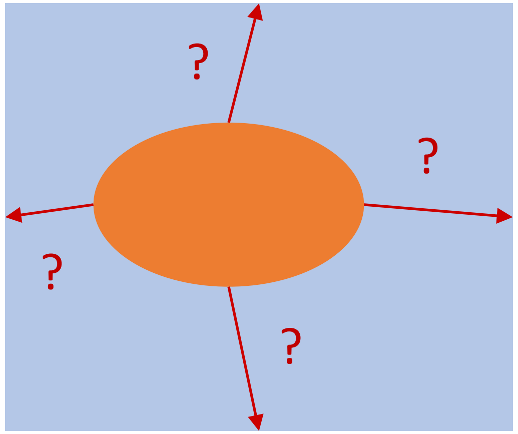
$$\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\rightarrow WW^*} = 12.4 \pm 1.5 \text{ pb}$$

Also the first observation of VBF $H \rightarrow WW^*$!

Beyond Inclusive Cross-Sections

We observe a process in a signal region defined by our detector's geometric coverage and our kinematic cuts...





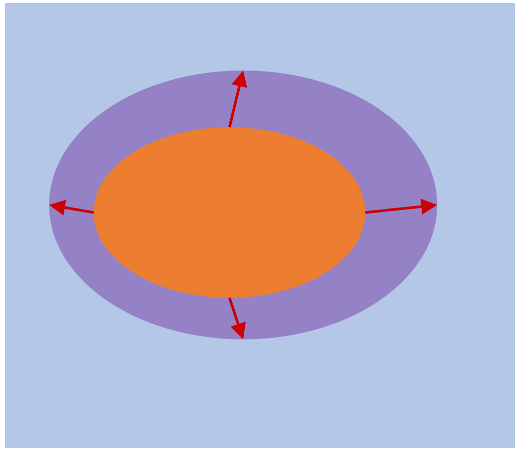
... But we aim to measure a cross-section for the total phase space.

What's in-between?

- ➢ Extrapolation introduces uncertainty.

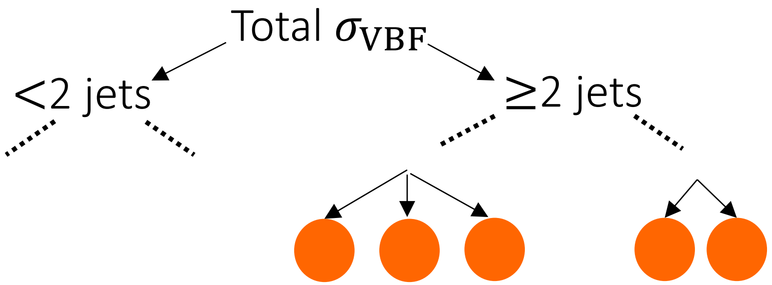
We **reduce uncertainty** and **increase sensitivity** by minimizing extrapolation.

- ➢ Measure cross-sections in (close to) the regions we can actually see.
- ➢ Also enhances sensitivity to Beyond the SM (BSM) effects that might show up only in one part of phase space.



How does this look for VBF and ggF?

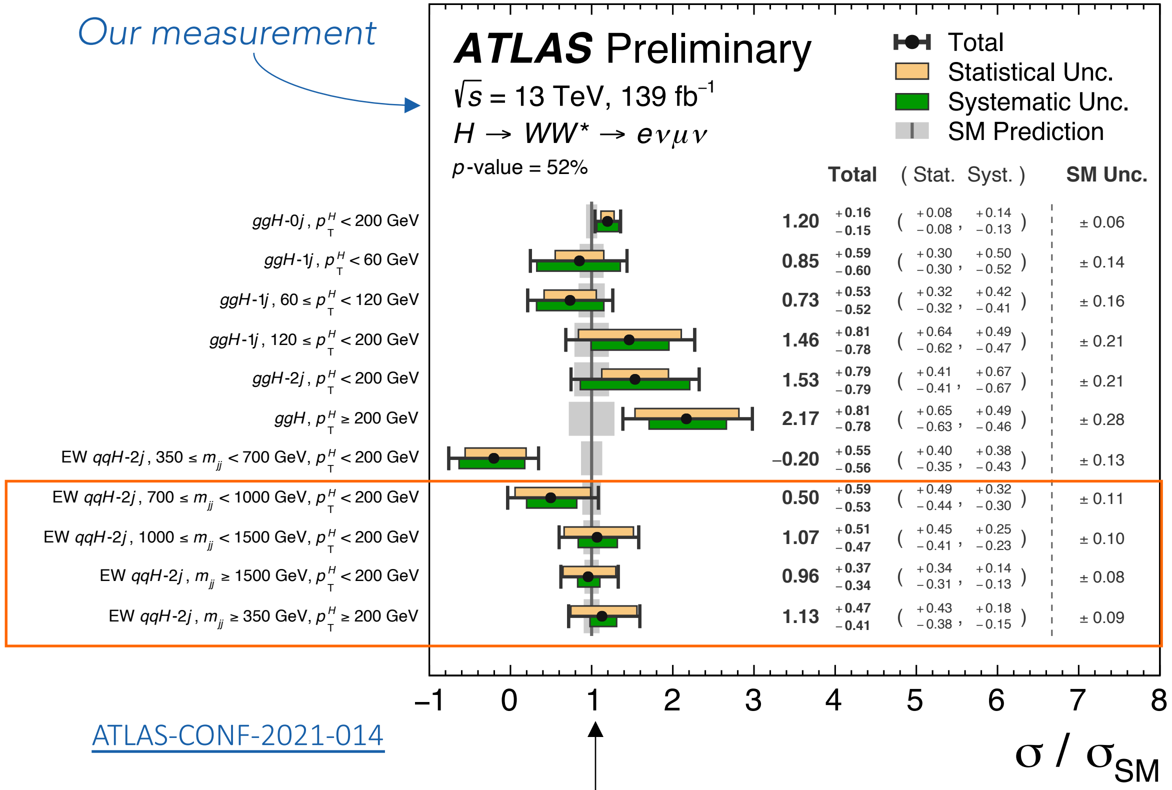
- ➢ Define subsets of phase space, measure a cross-section for each one.



Beyond Inclusive Cross-Sections

We measure cross-sections for ggF and VBF Higgs boson production in 11 kinematic regions.

Our measurement



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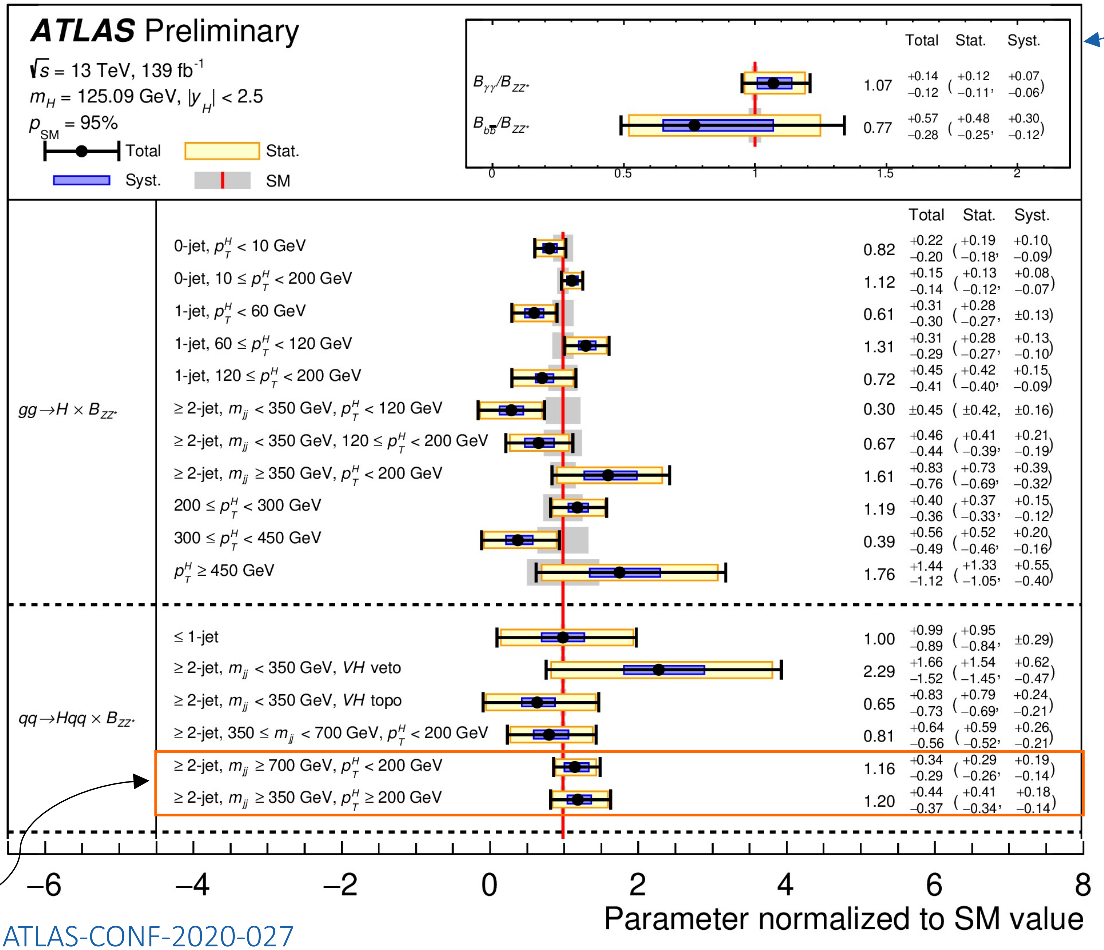
Combination of all other Higgs results from ATLAS so far.



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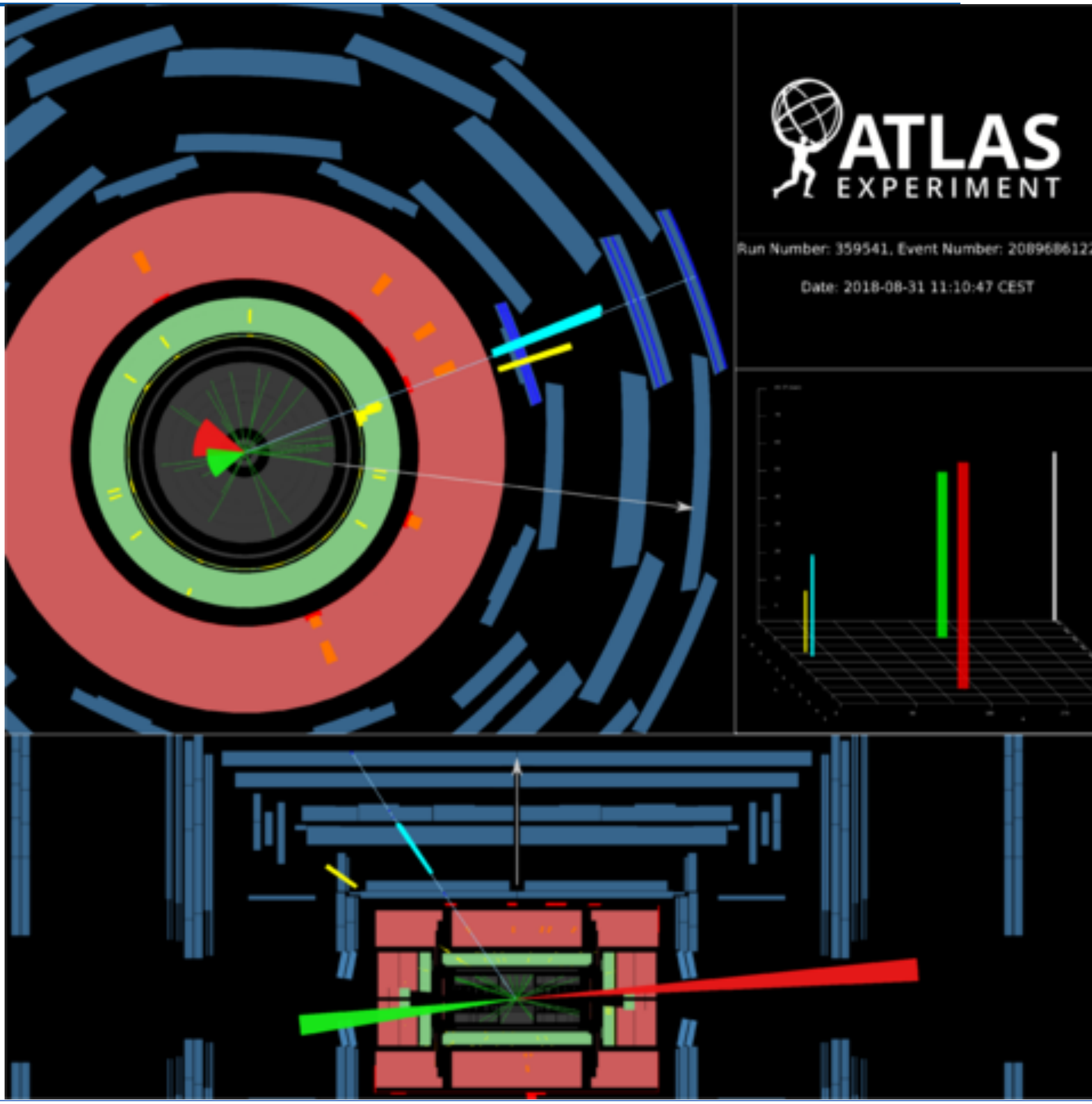
Results are **compatible with the SM** and (for VBF) **competitive with the latest combination** of all Higgs results measured with the ATLAS detector.

Conclusions

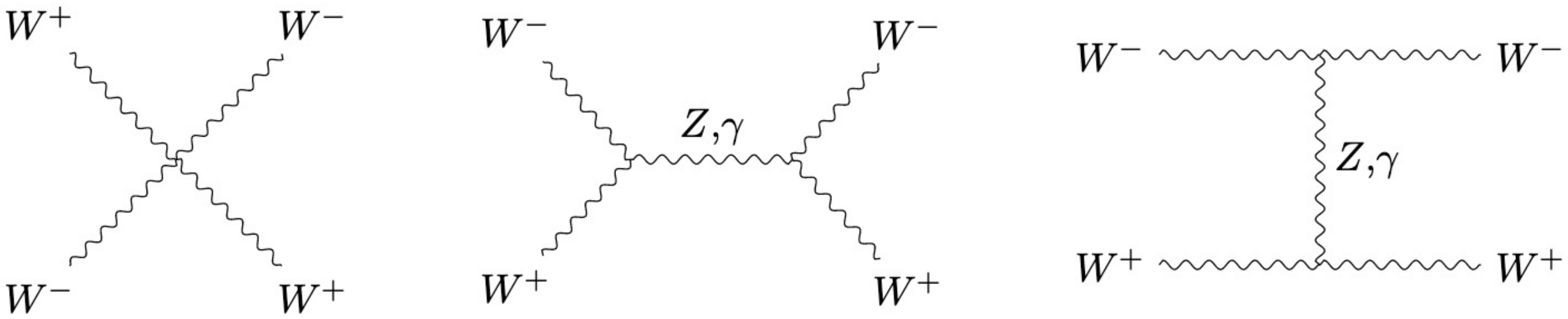
- Studying the Higgs boson with the ATLAS detector allows us to probe the type of fundamental interactions that are possible in the universe, and perform precision tests of the Standard Model.
- This measurement of the VBF and ggF $H \rightarrow WW^*$ cross-sections is the most precise to-date, and so far shows consistency with the SM.
- Future measurements will benefit from a larger dataset and improving understanding of measurement uncertainties to further test the limits of the SM.



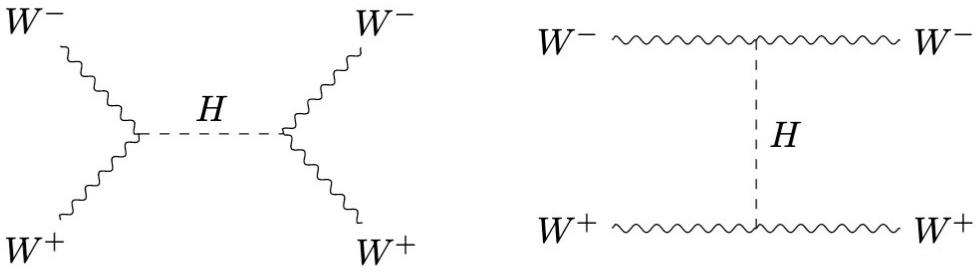
Backup

Unitarity Violation in W^+W^- Scattering

$s \gg m_W$: cross-section of W^+W^- scattering grows proportionally to s, and unitarity is violated.

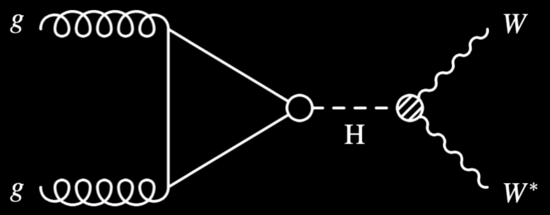


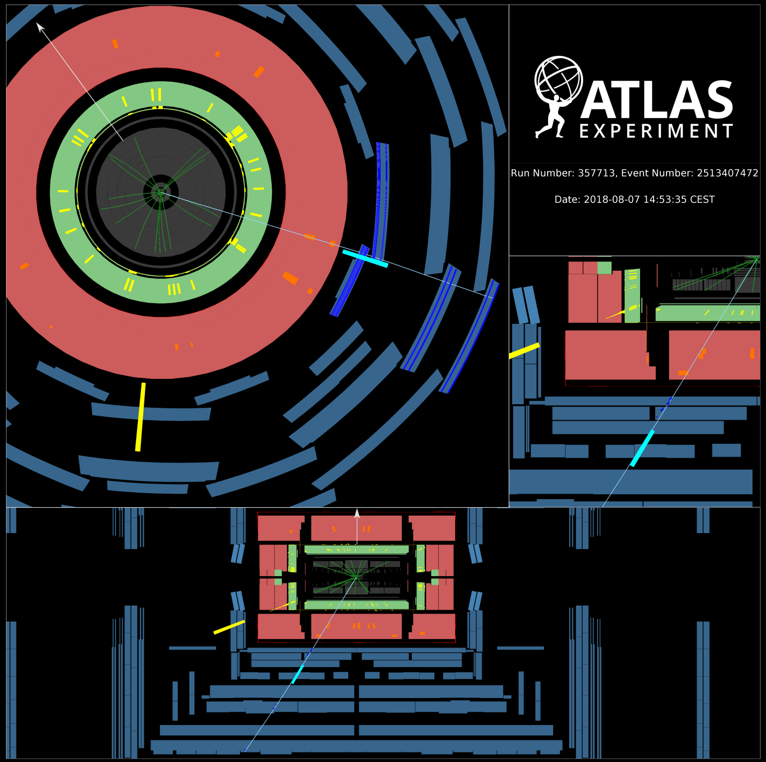
Restore unitarity by including new diagrams that modify the W^+W^- scattering vertices and introduce some cancellation:



If the H-W coupling isn't as predicted by the SM, this could again violate unitarity → Higgs-W coupling is a sensitive observable to new physics.

ggF


g
g
H
W
W*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EXPERIMENT
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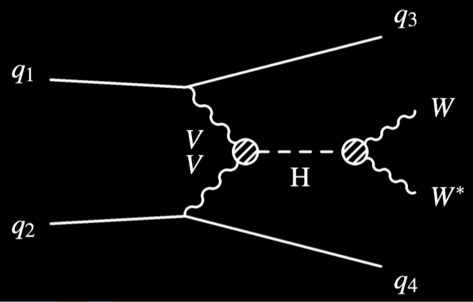
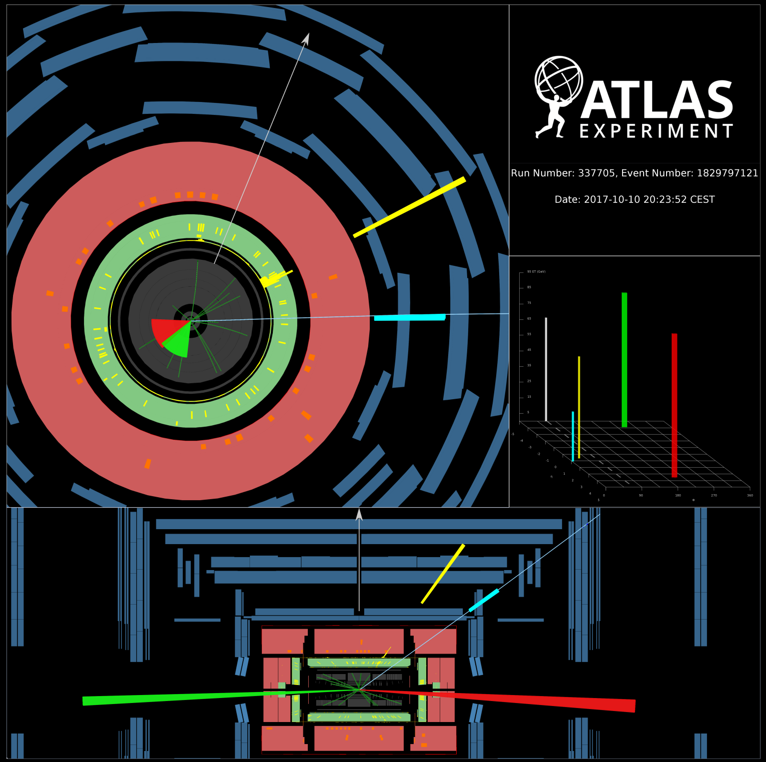
Date: 2018-08-07 14:53:35 CEST

VBF


q1
q2
q3
q4
V
V
H
W
W*


ATLAS
EXPERIMENT
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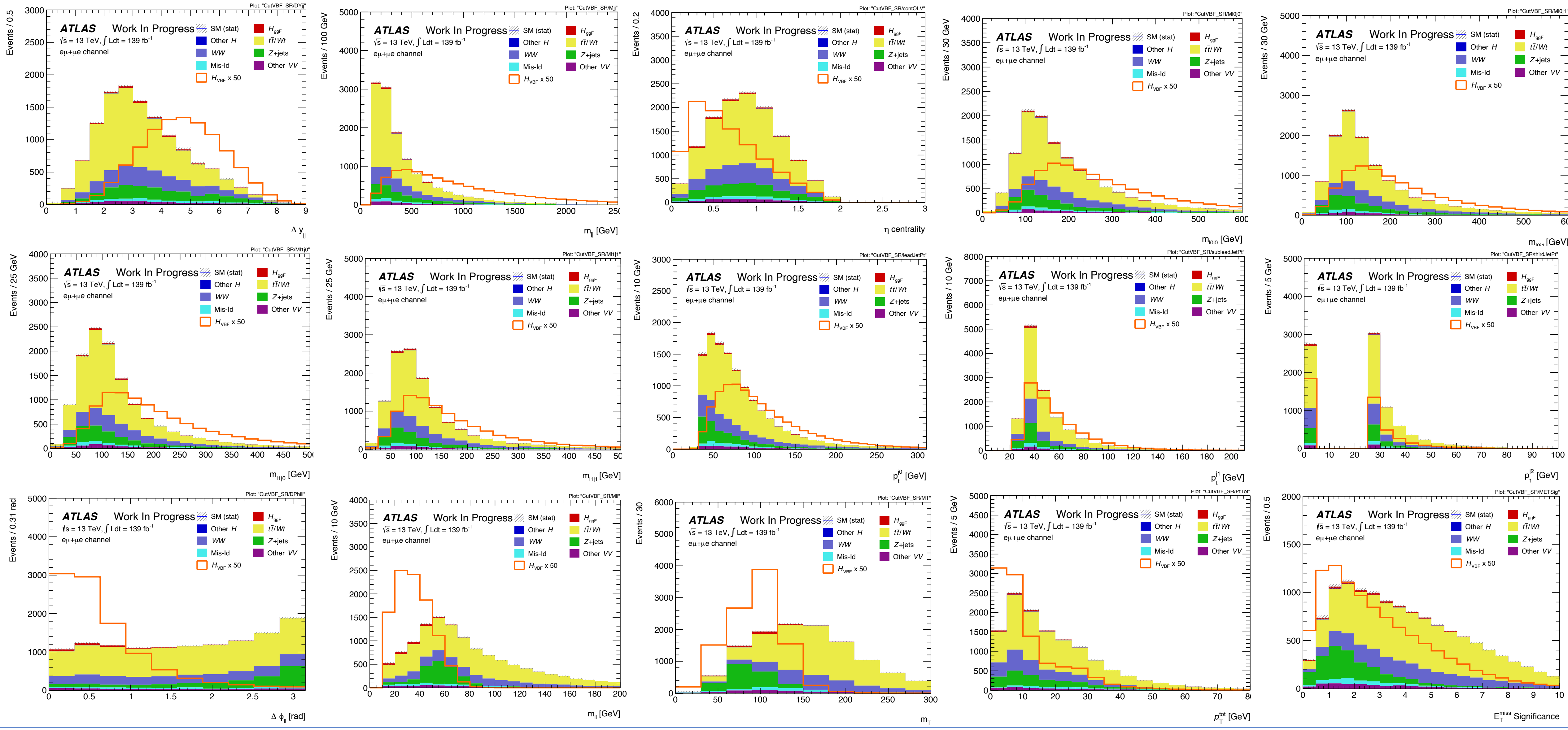
Date: 2017-10-10 20:23:52 CEST

DNN Input Variables



Further DNN Details (1)

Technical Details

- Feedforward network, 8 dense layers
- Infrastructure: keras + TensorFlow
- Inputs written out at b-veto stage, weighted according to their fraction of total background at b-veto stage (except VBF, **weighted to contribute to 4%, and ggF, assigned weight*10**)

Binning optimization algorithm

Combine bins until Signal $\geq$ 10 events, Bkg $\geq$ 10 events, BkgUnc < 20%. Then set bin boundary once Signal>20 events.

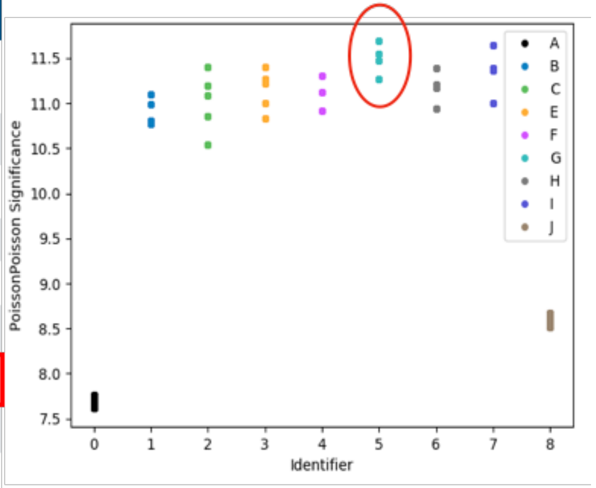
Bins chosen:

[0.0, .25, .59, .73, .83, .89, 0.93, 1.00]

Variable configuration

- Performance estimated with quadrature sum of bin-by-bin significance

Training ID	Variables
DNN A	combOfMasses, DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL (8)
DNN J	combOfMasses, DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, **mL*J* (4)** (12)
DNN B	DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, **mL*J* (4), ptJ1/2/3** (14)
DNN C	DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, mL*J* (4), ptJ1/2/3, **HTSoft** (15)
DNN E	DPhill, DYjj, mjj, mll, mT, ptTot, **centraliyL1, centralityL2**, mL*J* (4), ptJ1/2/3 (15)
DNN F	DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, mL*J* (4), ptJ1/2/3, **ptL1/2** (16)
DNN G	DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, mL*J* (4), ptJ1/2/3, **METSig** (15)
DNN H	DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, mL*J* (4), ptJ1/2/3, **MET** (15)
DNN I	DPhill, DYjj, mjj, mll, mT, ptTot, sumOfCentralitiesL, mL*J* (4), ptJ1/2/3, **centralJetpT** (15)

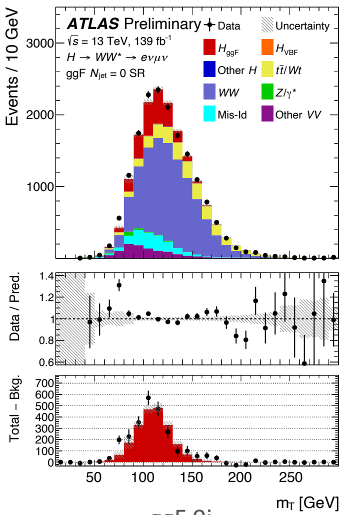


Significance, Z, of observing n events given b background events with uncertainty σ on the background.

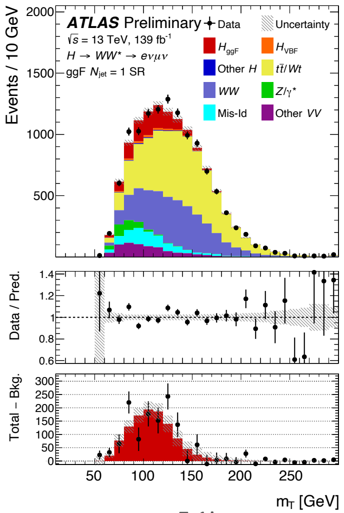
$$Z = \begin{cases} +\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n \geqslant b \\ -\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n < b. \end{cases}$$

Background Processes in Couplings Signal Regions

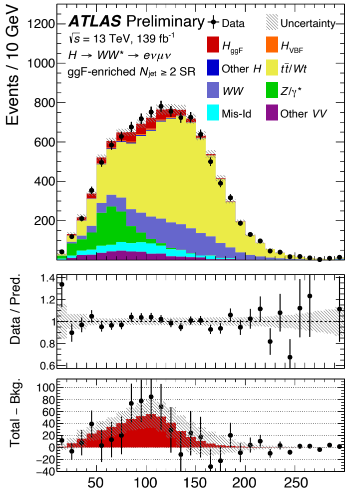
ggF 0j



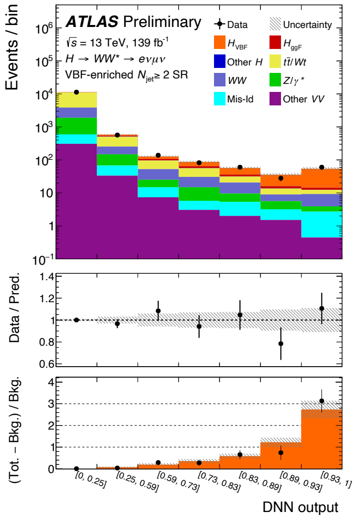
ggF 1j



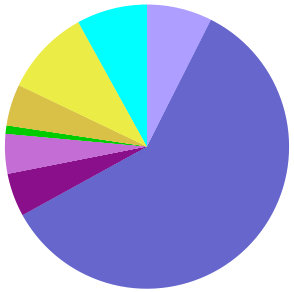
ggF 2j



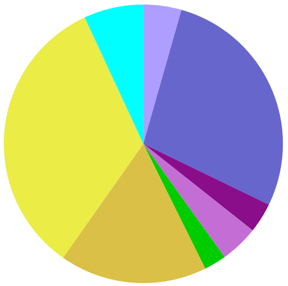
VBF



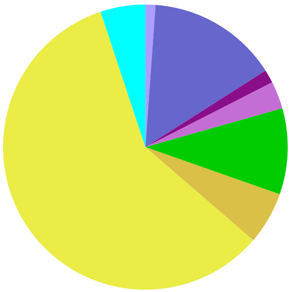
ggF 0j



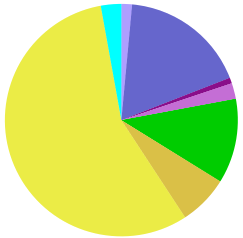
ggF 1j



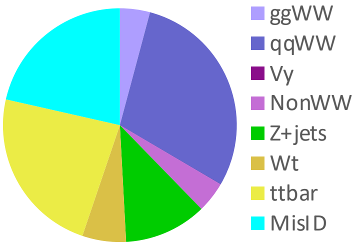
ggF 2j



VBF

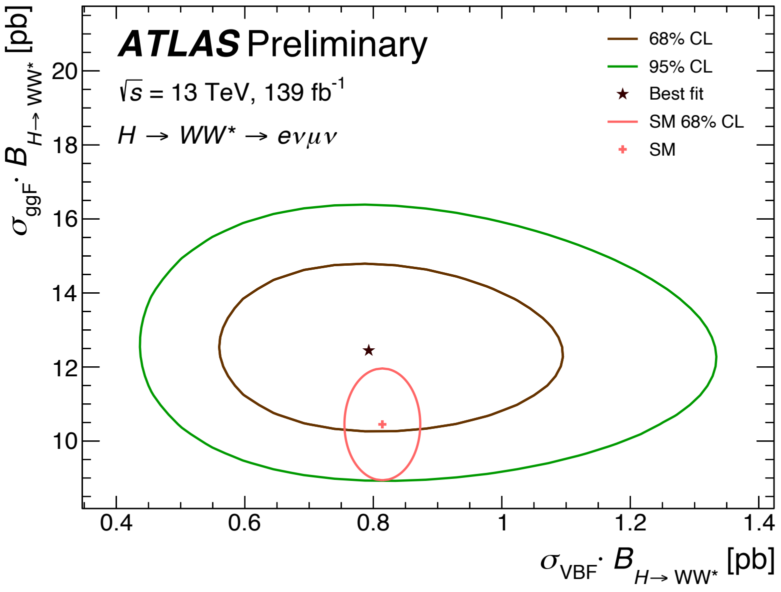


VBF, last DNN bin



Results: Total

$$\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 12.4 \pm 1.5 \text{ pb}$$
$$= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp syst.)} {}^{+0.7}_{-0.6} \text{ (sig theo.)} \pm 1.0 \text{ (bkg theo.) pb}$$
$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.79 {}^{+0.19}_{-0.16} \text{ pb}$$
$$= 0.79 {}^{+0.11}_{-0.10} \text{ (stat.)} {}^{+0.06}_{-0.05} \text{ (exp syst.)} {}^{+0.13}_{-0.09} \text{ (sig theo.)} {}^{+0.08}_{-0.06} \text{ (bkg theo.) pb,}$$



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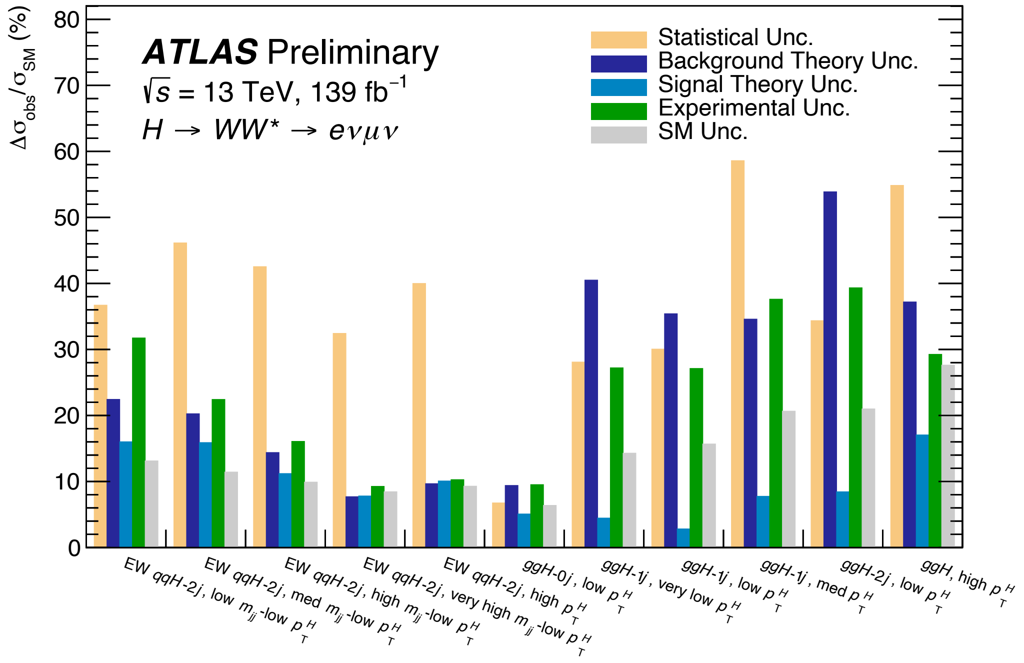
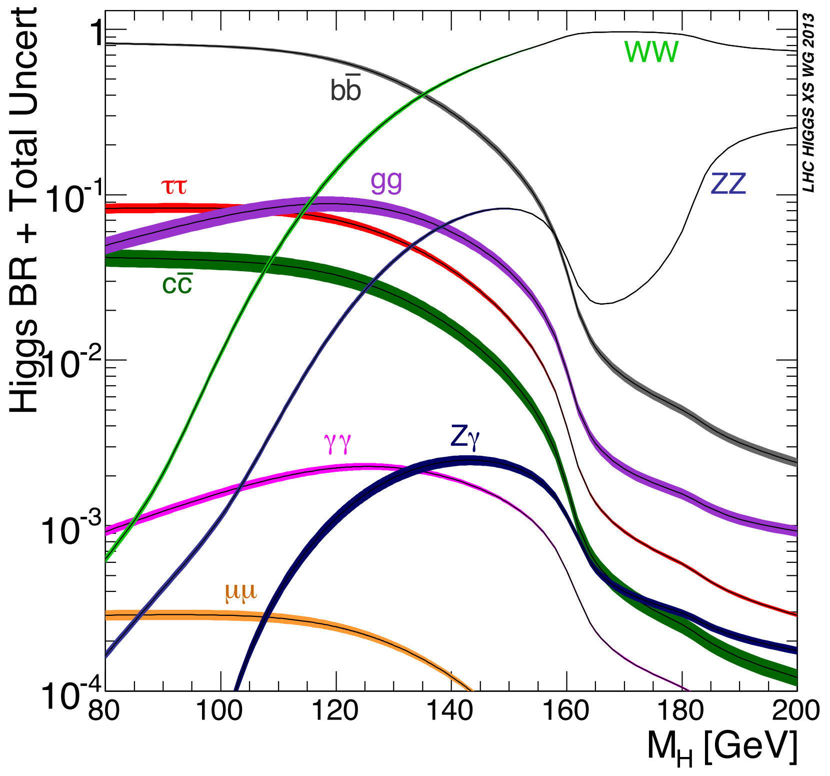
Source	$\frac{\Delta\sigma_{\text{ggF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{ggF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	5	13
Total systematic uncertainties	11	18
MC statistical uncertainties	4	3.2
Experimental uncertainties	6	7
Flavour Tagging	2.4	0.9
Jet energy scale	1.4	3.3
Jet energy resolution	2.3	1.9
$E_{\text{T}}^{\text{miss}}$	1.9	5
Muons	2.1	0.7
Electrons	1.5	0.3
Fake factors	2.4	1.0
Pile-up	2.4	1.3
Luminosity	2.0	2.1
Theoretical uncertainties	8	16
ggF	5	4
VBF	0.7	13
Top	4	5
$Z\tau\tau$	2.0	2.1
WW	4	5
Other VV	3	1.2
Background normalisations	5	5
WW	3.1	0.5
Top	2.4	2.2
$Z\tau\tau$	3.1	4
TOTAL	12	22

Results: STXS

STXS category ($\sigma_i \times B_{WW}$)	Value [fb]	Uncertainty [fb] Total	Stat.	Exp. Syst.	Sig. Theo.	Bkg. Theo.	SM prediction [fb]
ggH-0j, low p_T^H p_T^H < 200 GeV	7000	$^{+900}_{-900}$	$^{+400}_{-400}$	$^{+600}_{-500}$	$^{+300}_{-300}$	$^{+600}_{-500}$	5900 ± 400
ggH-1j, very low p_T^H p_T^H < 60 GeV	1190	$^{+820}_{-840}$	$^{+390}_{-390}$	$^{+380}_{-380}$	$^{+70}_{-60}$	$^{+550}_{-580}$	1400 ± 200
ggH-1j, low p_T^H 60 ≤ p_T^H < 120 GeV	710	$^{+510}_{-510}$	$^{+290}_{-290}$	$^{+270}_{-260}$	$^{+30}_{-30}$	$^{+340}_{-340}$	970 ± 150
ggH-1j, med p_T^H 120 ≤ p_T^H < 200 GeV	230	$^{+130}_{-120}$	$^{+90}_{-90}$	$^{+60}_{-60}$	$^{+10}_{-10}$	$^{+60}_{-50}$	160 ± 30
ggH-2j, low p_T^H p_T^H < 200 GeV	1560	$^{+800}_{-800}$	$^{+350}_{-350}$	$^{+400}_{-400}$	$^{+90}_{-80}$	$^{+550}_{-540}$	1010 ± 210
ggH, high p_T^H p_T^H ≥ 200 GeV	270	$^{+100}_{-100}$	$^{+70}_{-70}$	$^{+40}_{-40}$	$^{+30}_{-10}$	$^{+50}_{-40}$	122 ± 34
EW qqH-2j, low m_{jj}-low p_T^H 350 ≤ m_{jj} < 700 GeV, p_T^H < 200 GeV	−20	$^{+60}_{-60}$	$^{+40}_{-40}$	$^{+30}_{-40}$	$^{+10}_{-20}$	$^{+20}_{-30}$	109 ± 14
EW qqH-2j, med m_{jj}-low p_T^H 700 ≤ m_{jj} < 1000 GeV, p_T^H < 200 GeV	28	$^{+33}_{-30}$	$^{+27}_{-24}$	$^{+12}_{-13}$	$^{+10}_{-8}$	$^{+11}_{-11}$	56 ± 6
EW qqH-2j, high m_{jj}-low p_T^H 1000 ≤ m_{jj} < 1500 GeV, p_T^H < 200 GeV	54	$^{+26}_{-24}$	$^{+23}_{-20}$	$^{+8}_{-8}$	$^{+7}_{-5}$	$^{+7}_{-7}$	51 ± 5
EW qqH-2j, very high m_{jj}-low p_T^H m_{jj} ≥ 1500 GeV, p_T^H < 200 GeV	48	$^{+19}_{-17}$	$^{+17}_{-15}$	$^{+5}_{-5}$	$^{+5}_{-3}$	$^{+4}_{-4}$	50 ± 4
EW qqH-2j, high p_T^H m_{jj} ≥ 350 GeV, p_T^H ≥ 200 GeV	36	$^{+15}_{-13}$	$^{+13}_{-12}$	$^{+3}_{-3}$	$^{+4}_{-3}$	$^{+3}_{-3}$	32 ± 3



Branching Ratios



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

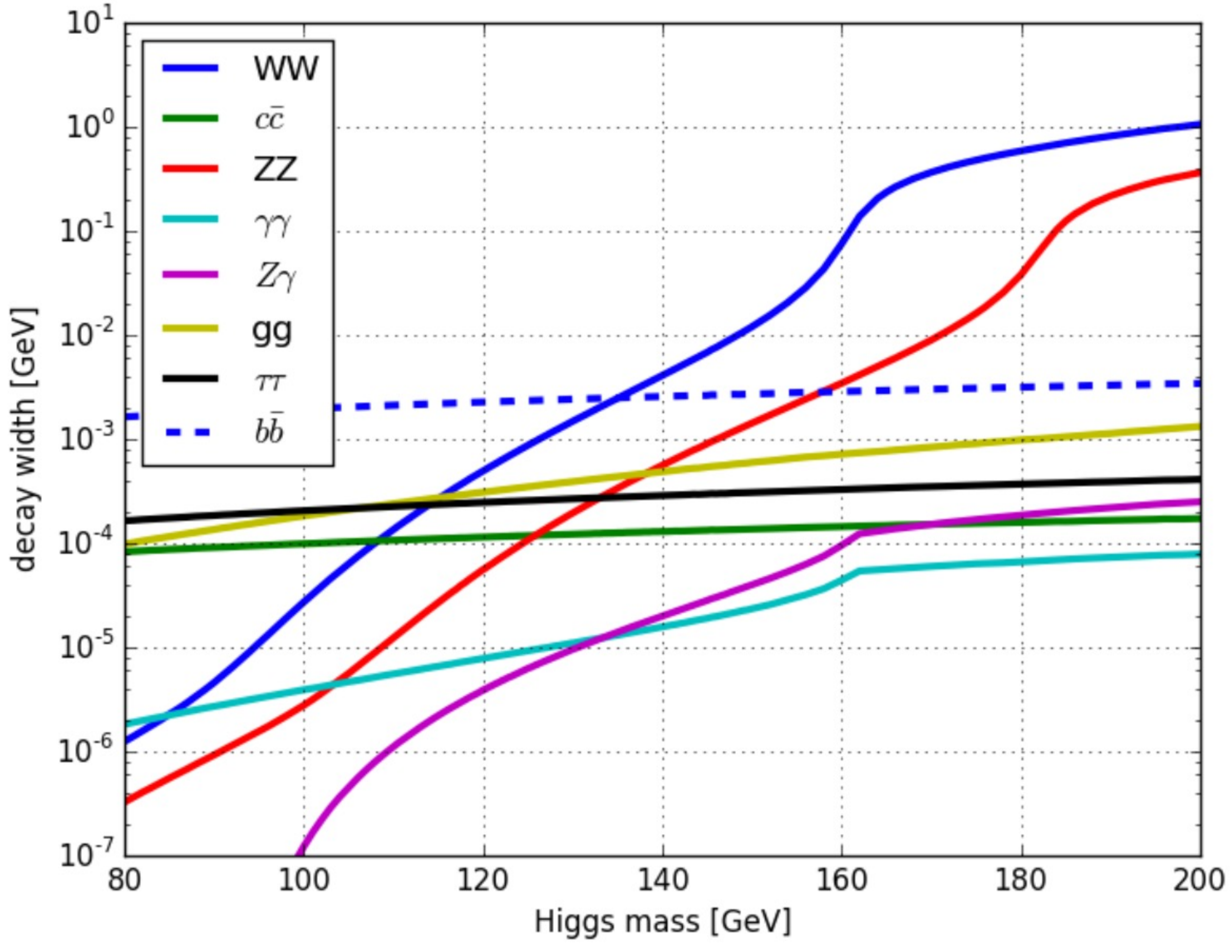


Table A1-14, https://arxiv.org/pdf/1307.1347.pdf