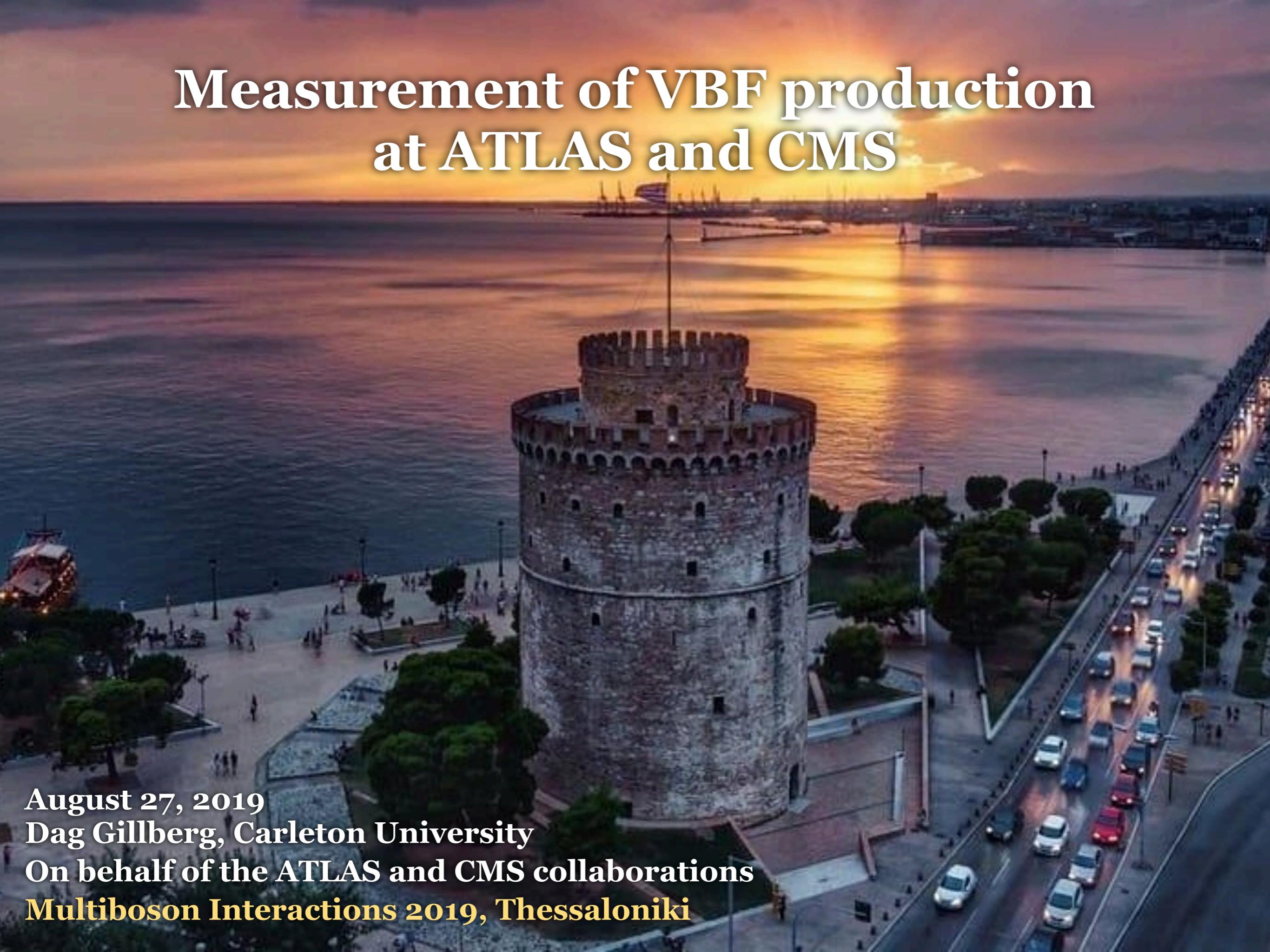


# Measurement of VBF production at ATLAS and CMS



August 27, 2019

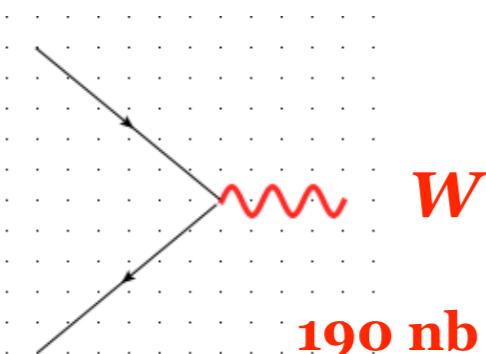
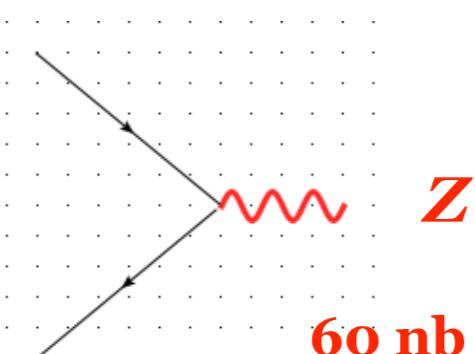
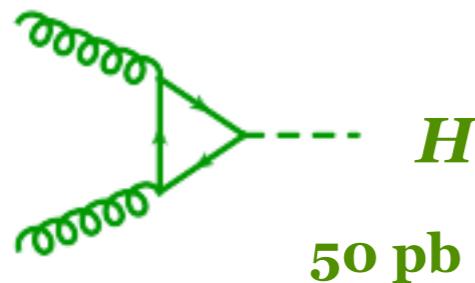
Dag Gillberg, Carleton University

On behalf of the ATLAS and CMS collaborations

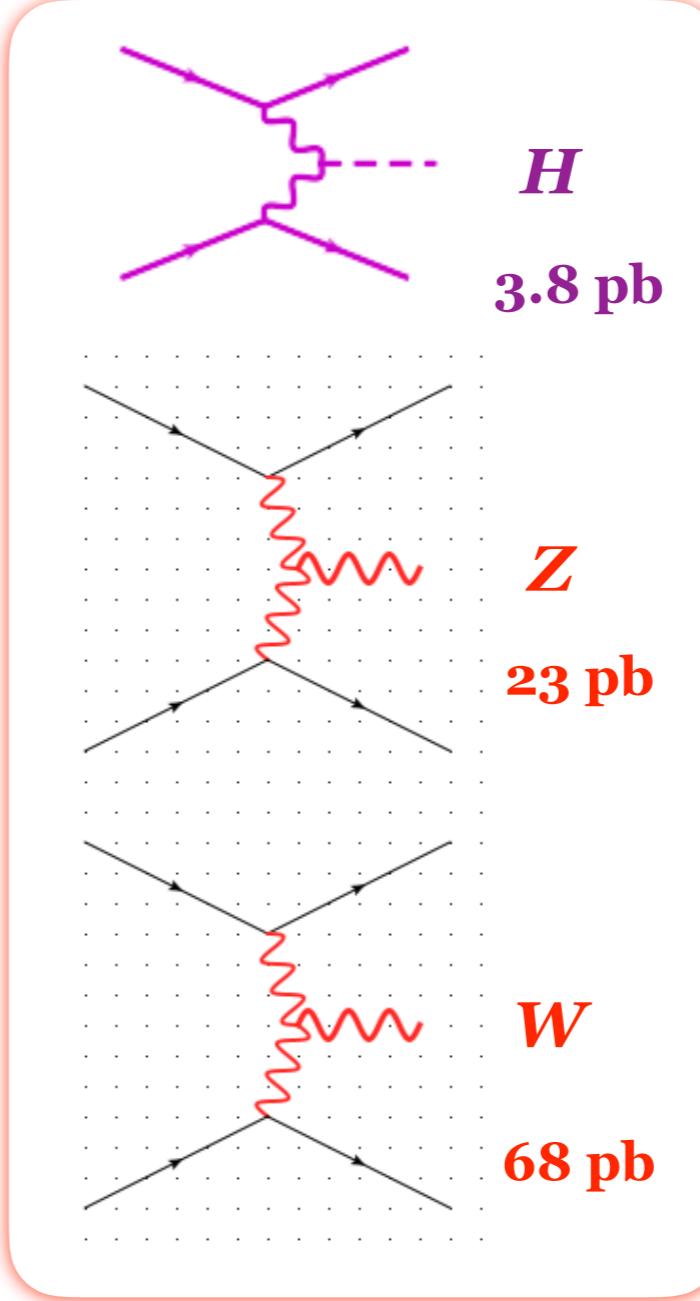
Multiboson Interactions 2019, Thessaloniki

# Single boson production at LHC

## Strong production



## Electroweak production (VBF)



@ 13 TeV

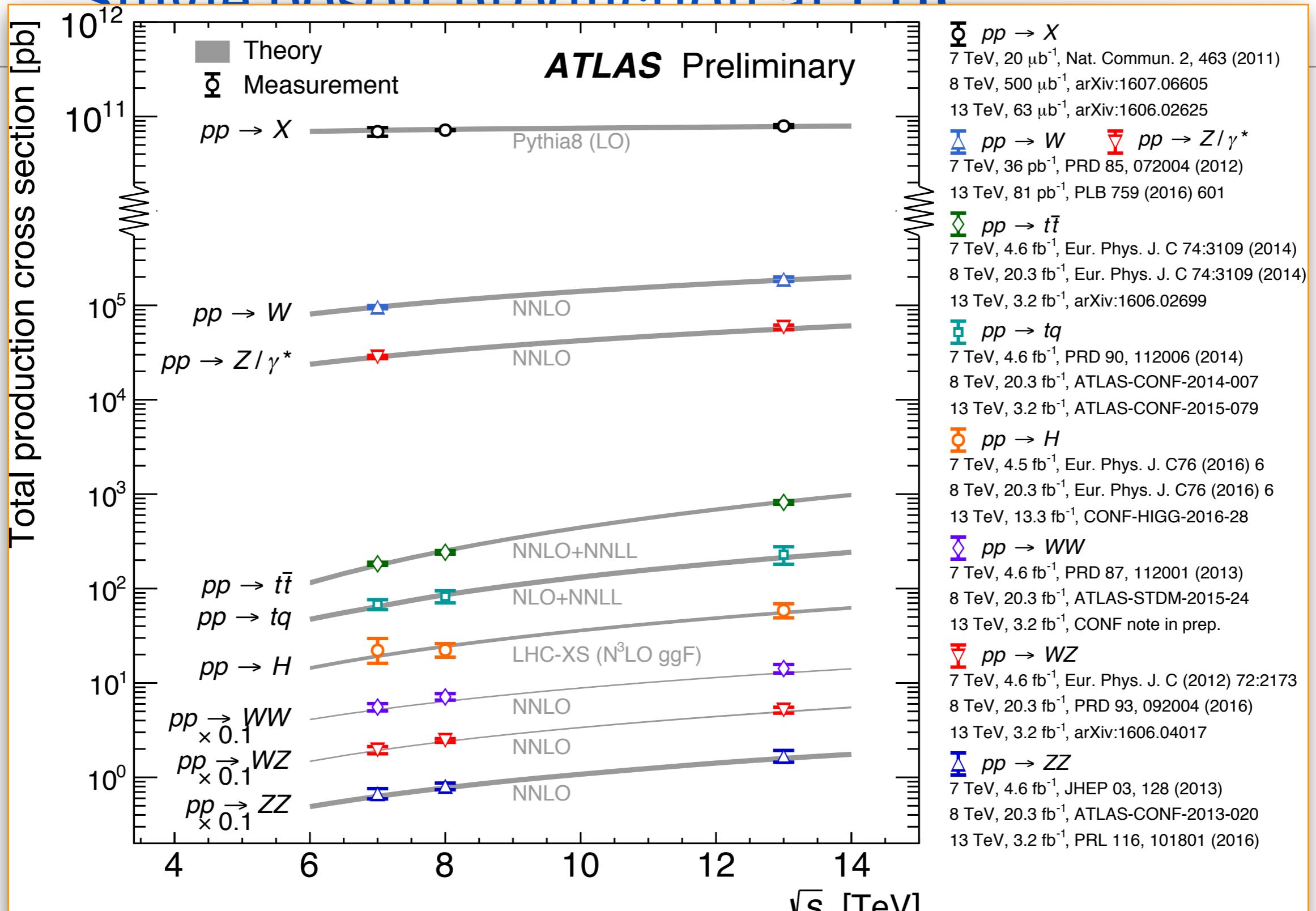
**Ratio**

**13 : 1**

**2700 : 1**

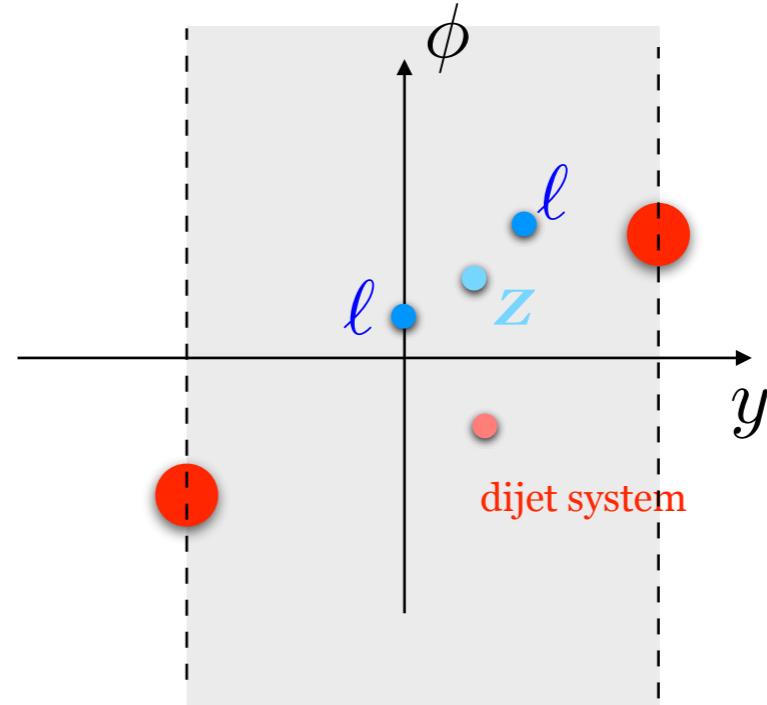
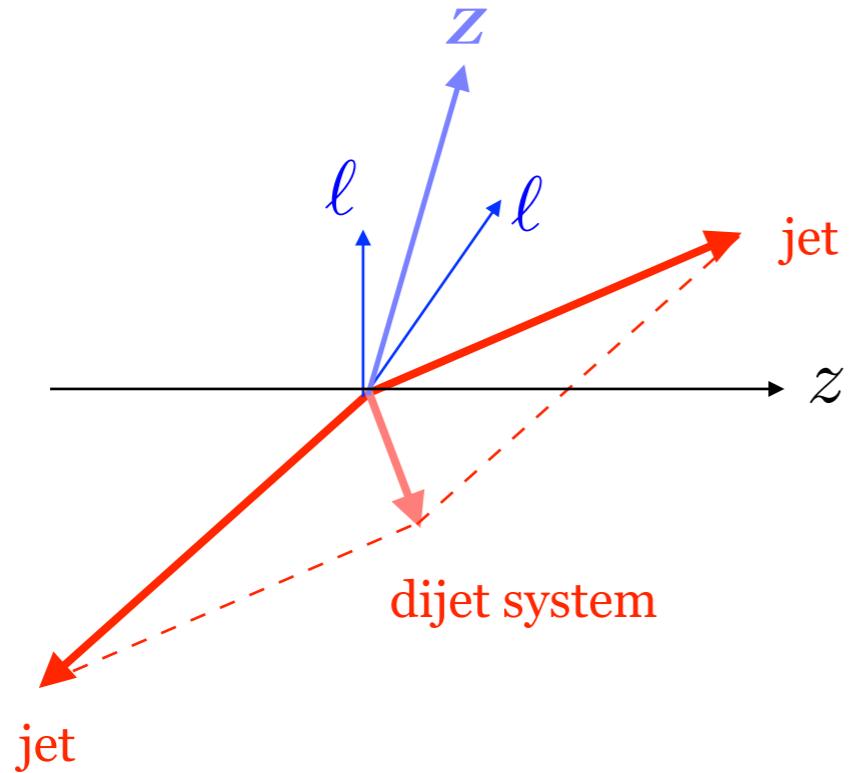
**2800 : 1**

# Single boson production at LHC



@ 13 TeV

# Typical VBF topology selection applied



$$\Delta y_{jj}$$

## VBF topology often exploited in analysis selection

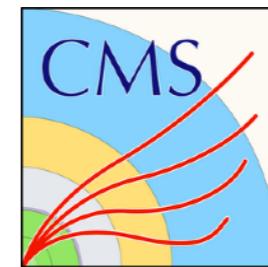
1. Large rapidity gap between jets  $\Delta y_{jj}$
2. Large dijet invariant mass  $m_{jj}$
3. Little hadronic activity in **rapidity gap** of two leading jets
4. Low  $p_T$  (or lack) of third jet / low  $p_T$  of “boson+jj” system
5. Boost (rapidity) of boson and dijet system similar
6.  $p_T$  of boson and dijet system similar + back-to-back in  $\phi$

Since  $\sigma_H \ll \sigma_V$  and EW/strong ratio better for Higgs, **Higgs analyses** typically use much **less stringent VBF topology selection**

$W/Z$ :  $p_T^{\text{jet}} \gtrsim 60 \text{ GeV}$ ,  $m_{jj} \gtrsim 1000 \text{ GeV}$

$H$ :  $p_T^{\text{jet}} \gtrsim 30 \text{ GeV}$ ,  $m_{jj} \gtrsim 400 \text{ GeV}$

# Results covered in this talk



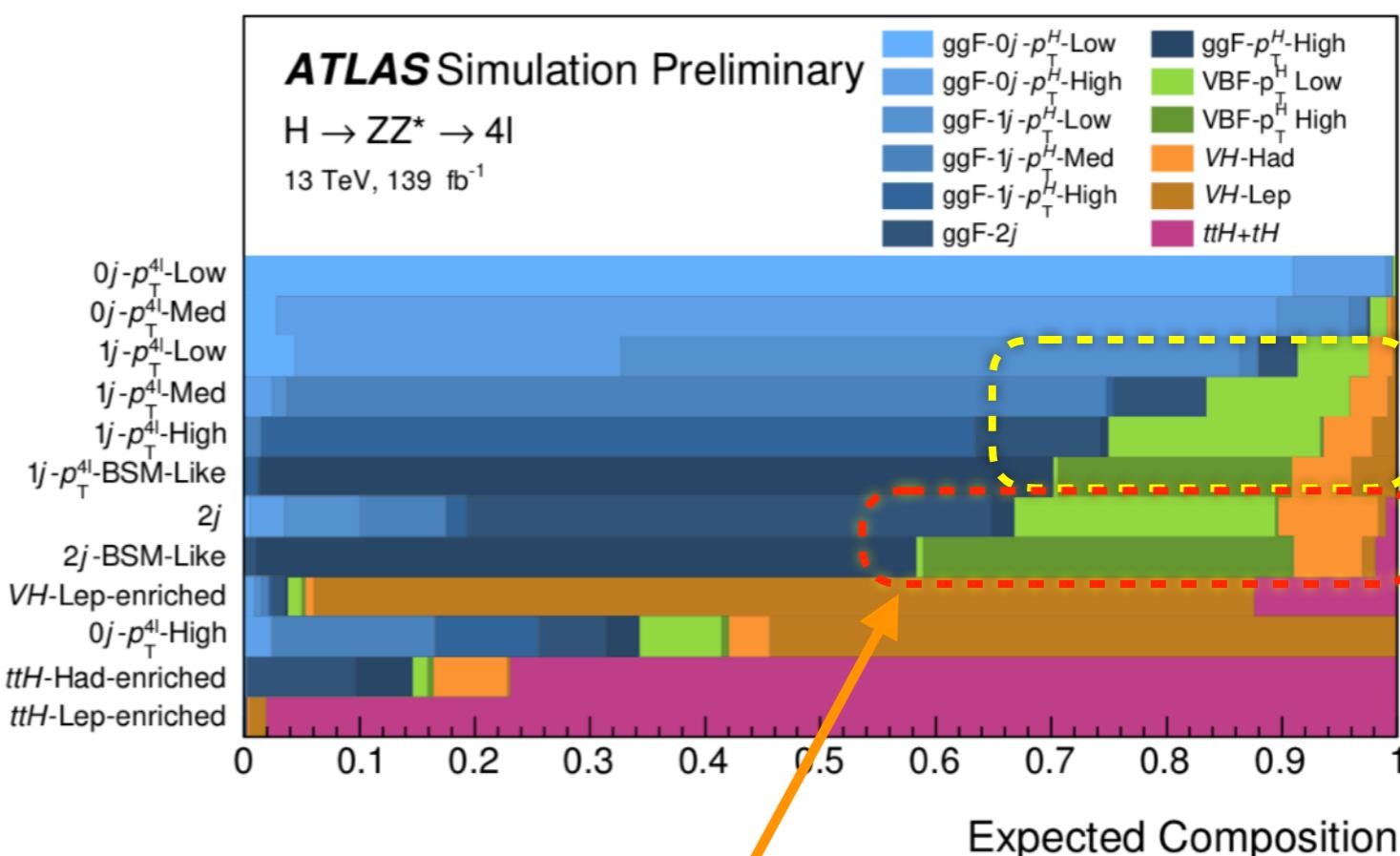
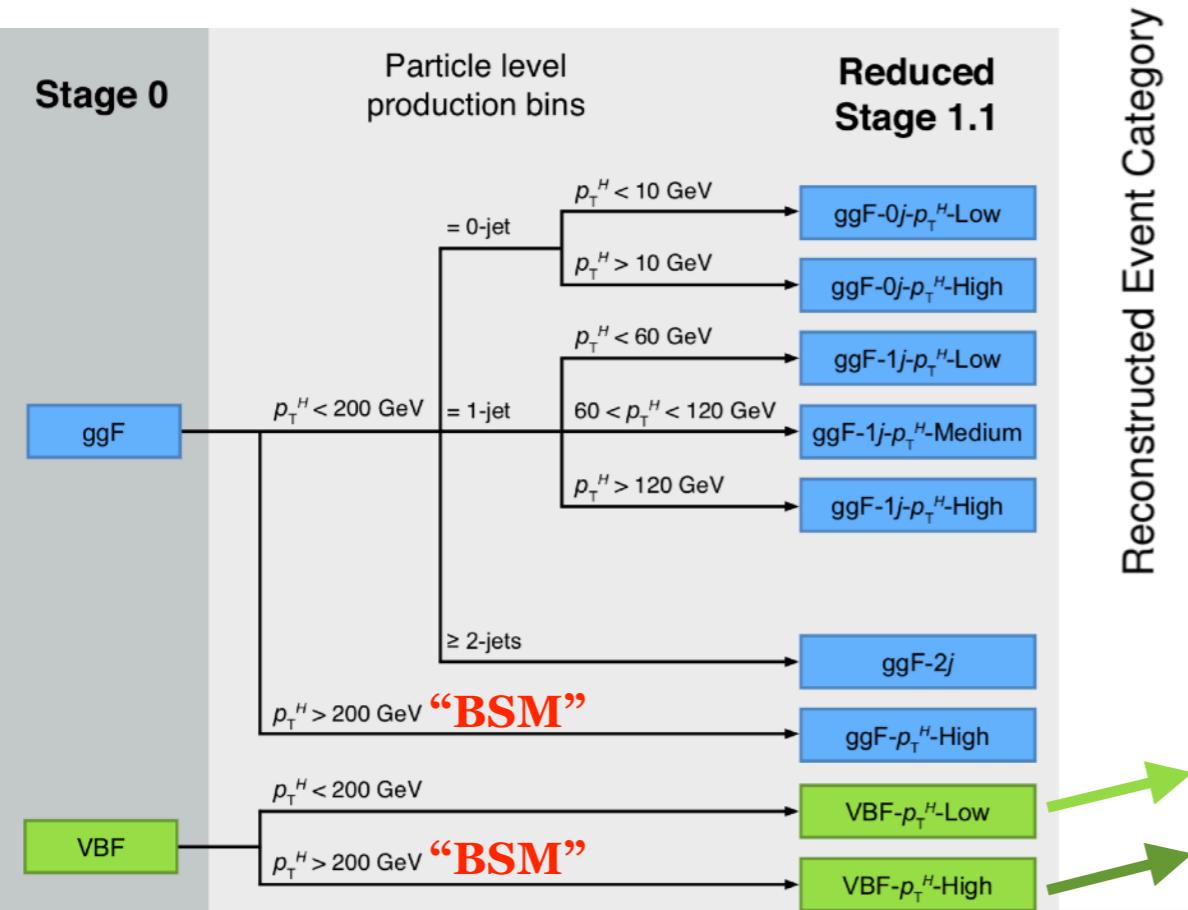
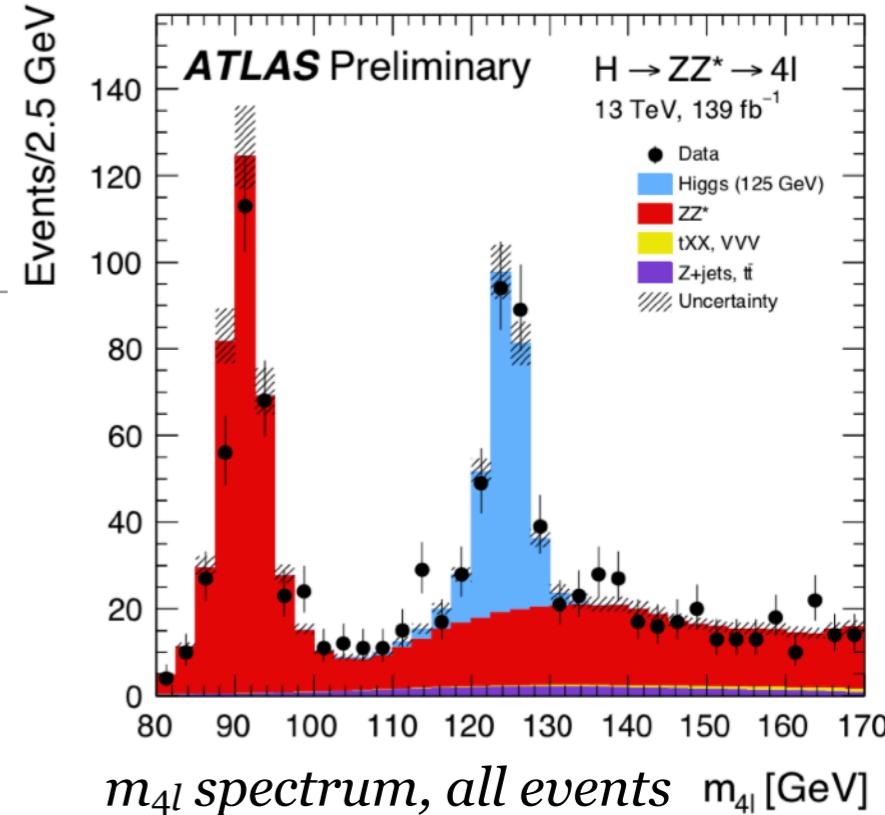
$H \rightarrow 4\ell$	<a href="#">ATLAS-CONF-2019-025, 139 fb<sup>-1</sup></a> <b>New</b>	<a href="#">HIG-19-001, 137 fb<sup>-1</sup></a> <b>New</b>
$H \rightarrow \gamma\gamma$	<a href="#">ATLAS-CONF-2018-028, 79.8 fb<sup>-1</sup></a>	<a href="#">HIG-18-029, 77.4 fb<sup>-1</sup></a> <b>New</b>
$H \rightarrow e\nu\mu\nu$	<a href="#">HIGG-2016-07, 36.1 fb<sup>-1</sup></a>	<a href="#">HIG-16-042, 35.9 fb<sup>-1</sup></a>
$H \rightarrow \tau\tau$	<a href="#">HIGG-2017-07, 36.1 fb<sup>-1</sup></a>	<a href="#">HIG-18-032, 77.4 fb<sup>-1</sup></a> <b>New</b>
$H$ combined	<a href="#">ATLAS-CONF-2019-005, 80 fb<sup>-1</sup></a> <b>New</b>	<a href="#">HIG-17-031, 35.9 fb<sup>-1</sup></a>
$Z \rightarrow \ell\ell$	<a href="#">STDM-2016-09, 3.2 fb<sup>-1</sup> @ 13 TeV (STDM-2013-02, 20 fb<sup>-1</sup> @ 8 TeV)</a>	<a href="#">SMP-16-018, 35.9 fb<sup>-1</sup> @ 13 TeV</a>
$W \rightarrow \ell\nu$	<a href="#">STDM-2014-11, 25 fb<sup>-1</sup> @ 7-8 TeV</a>	<a href="#">SMP-13-012, 19.3 fb<sup>-1</sup> @ 8 TeV</a>

**“New”** means that it was not shown at MBI2018  
(i.e. released in the last 12 months)

# I. Higgs boson results

# $H \rightarrow 4\ell$ (1/2)

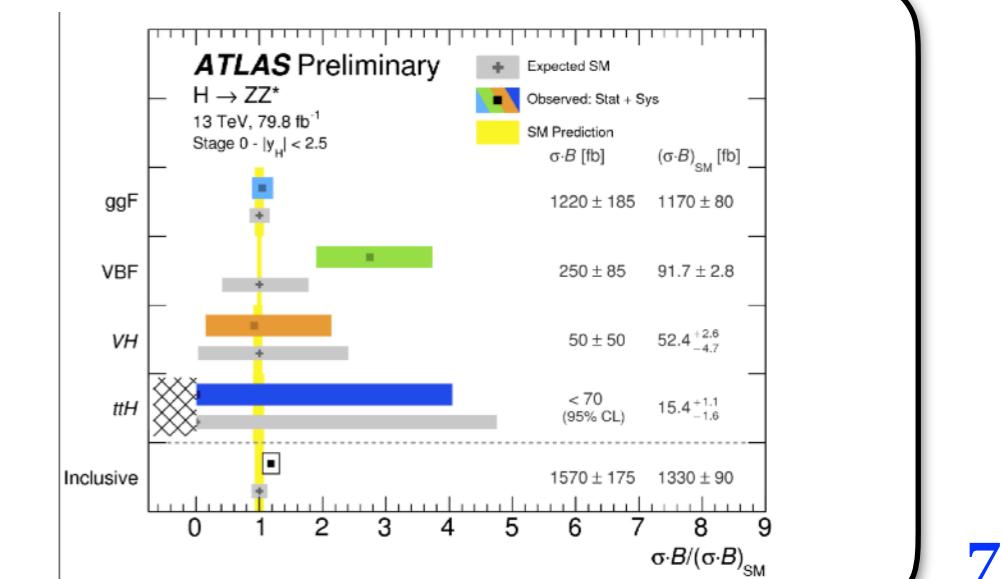
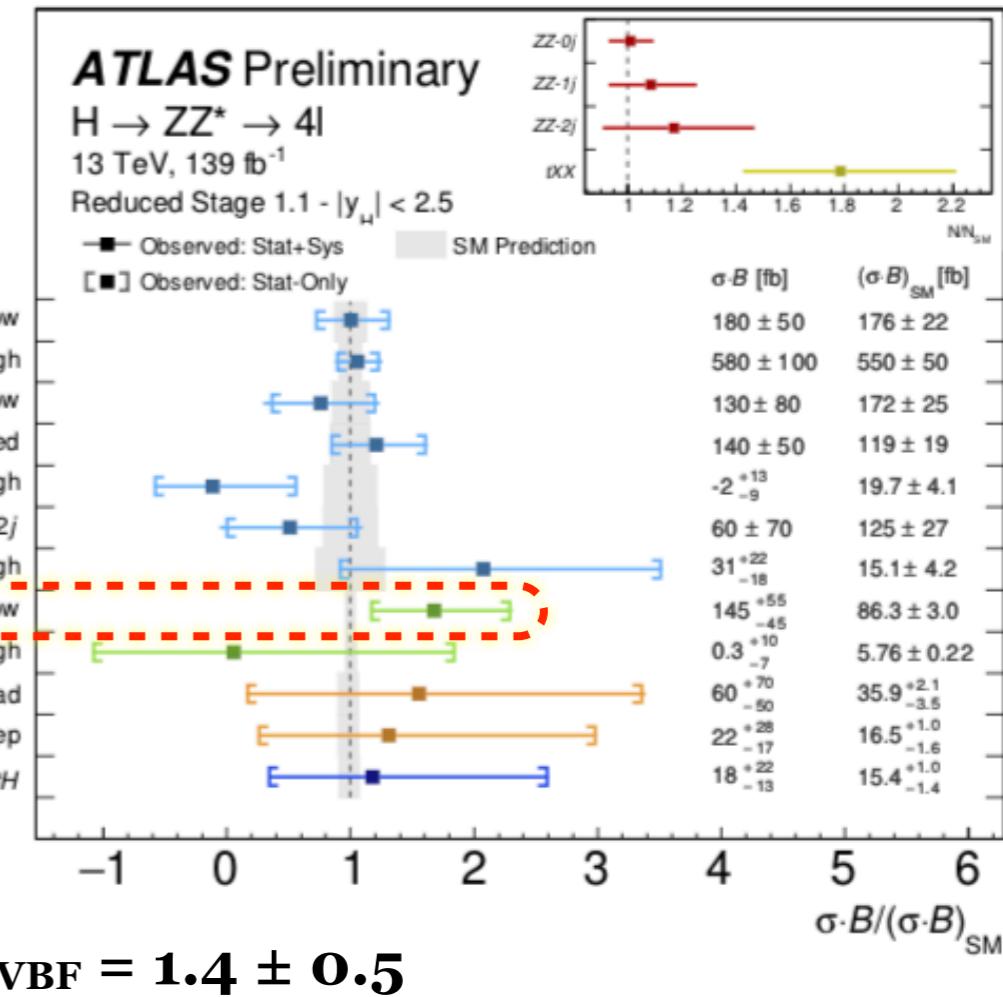
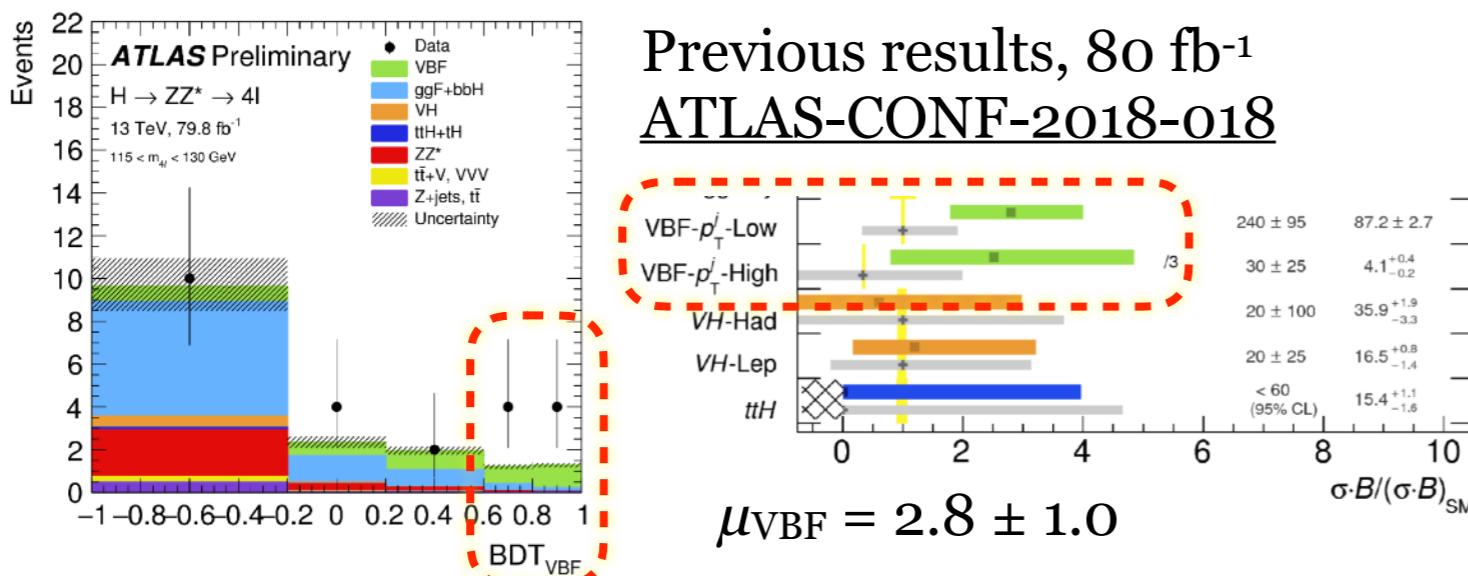
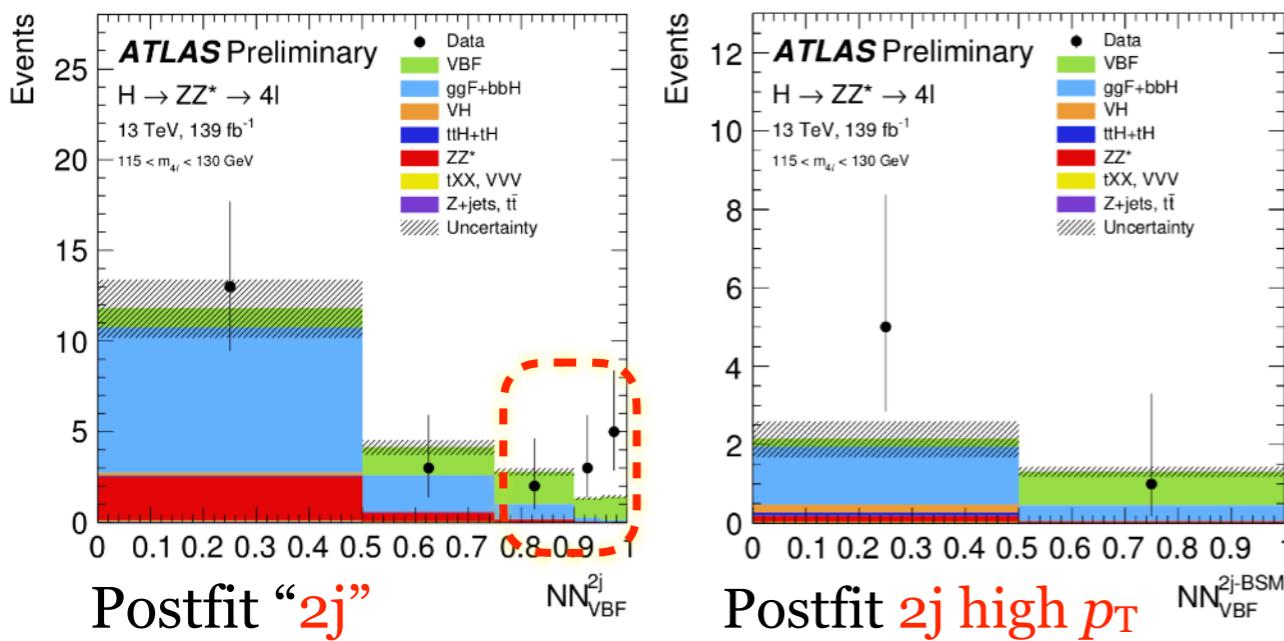
- Results based on full Run-2 dataset:  $139 \text{ fb}^{-1}$   
+75% data wrt previous result
- Measure VBF (and ggF) separately for  $p_{T,H} < 200 \text{ GeV}$  and  $p_{T,H} > 200 \text{ GeV}$  (sensitive to BSM models)
- STXS stage 1.1 observable defined at (truth) particle level

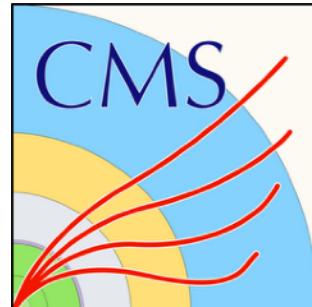


Analysis categories relevant for VBF:  
“2j” with  $m_{jj} > 120 \text{ GeV}$ , “1j”: one VBF jet falls below  $p_T = 30 \text{ GeV}$

$H \rightarrow 4\ell$  (2/2)

- Main changes relevant to VBF wrt previous analysis:
  - +75% more data, VBF extraction based on neural nets instead of BDT

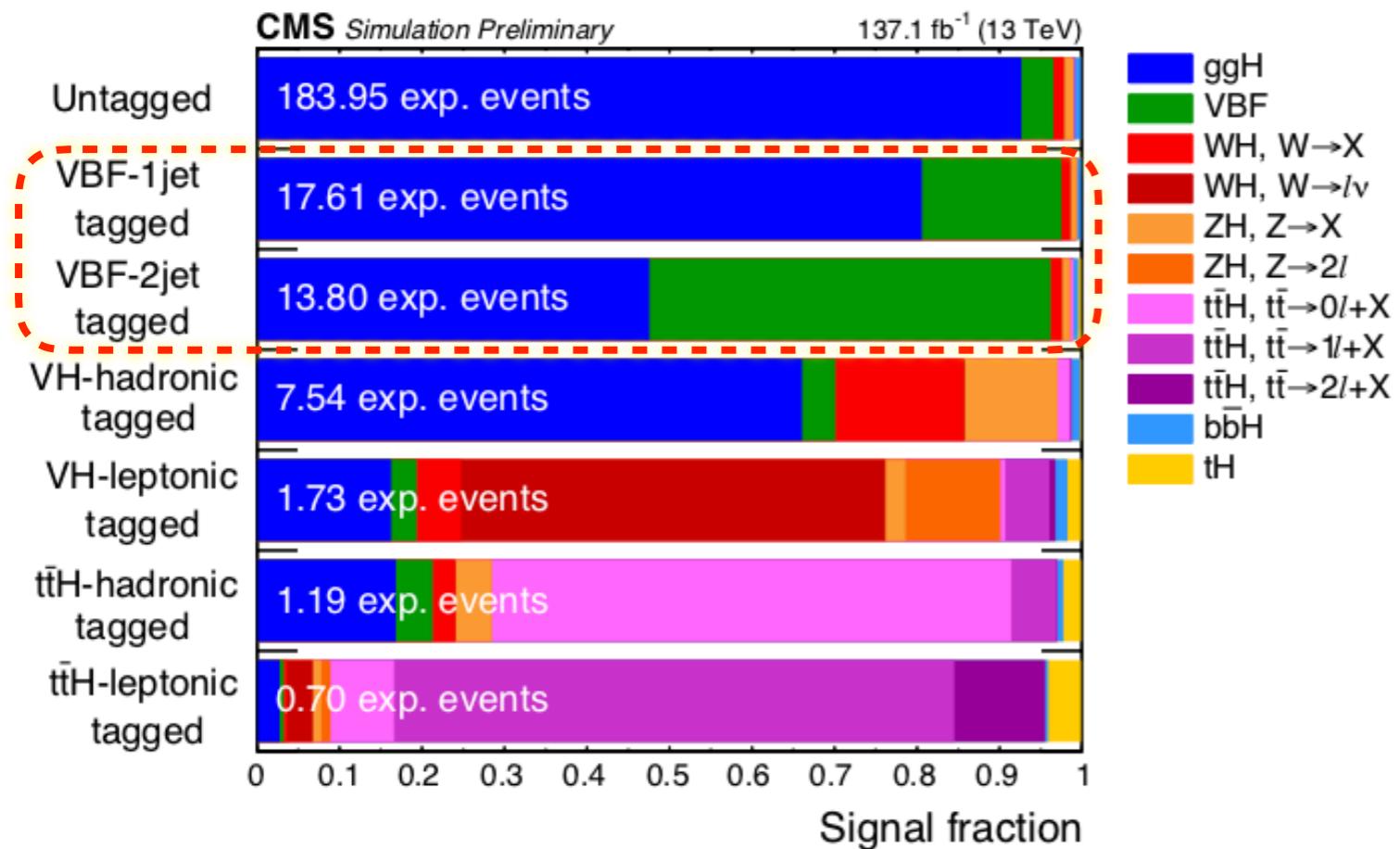




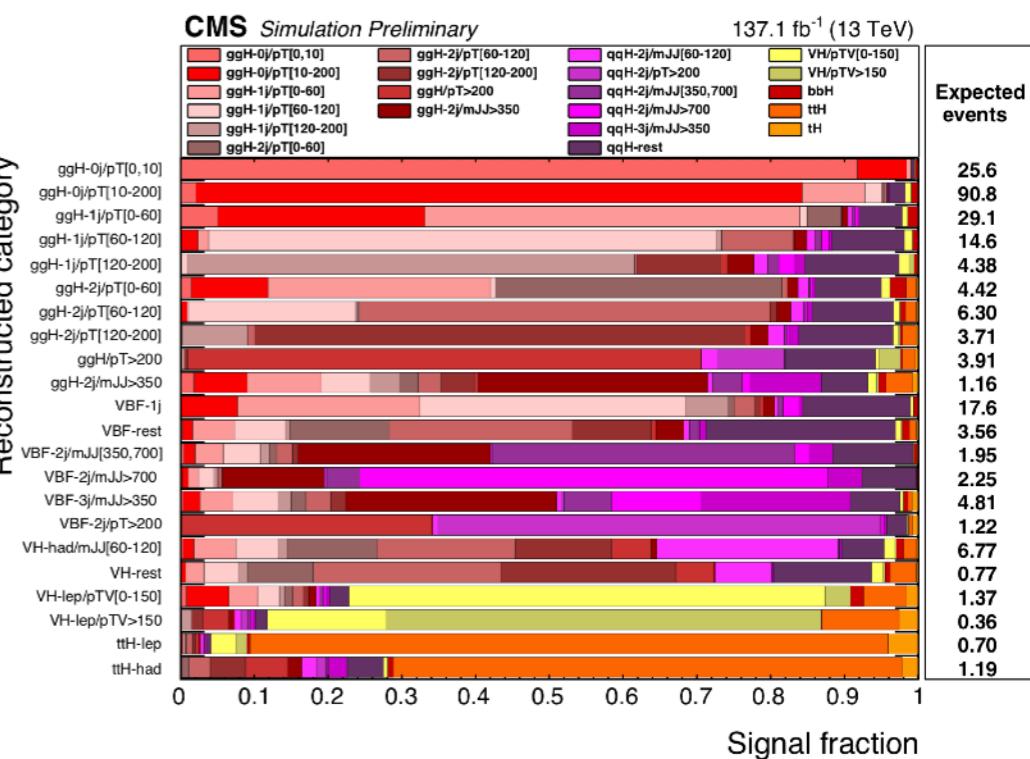
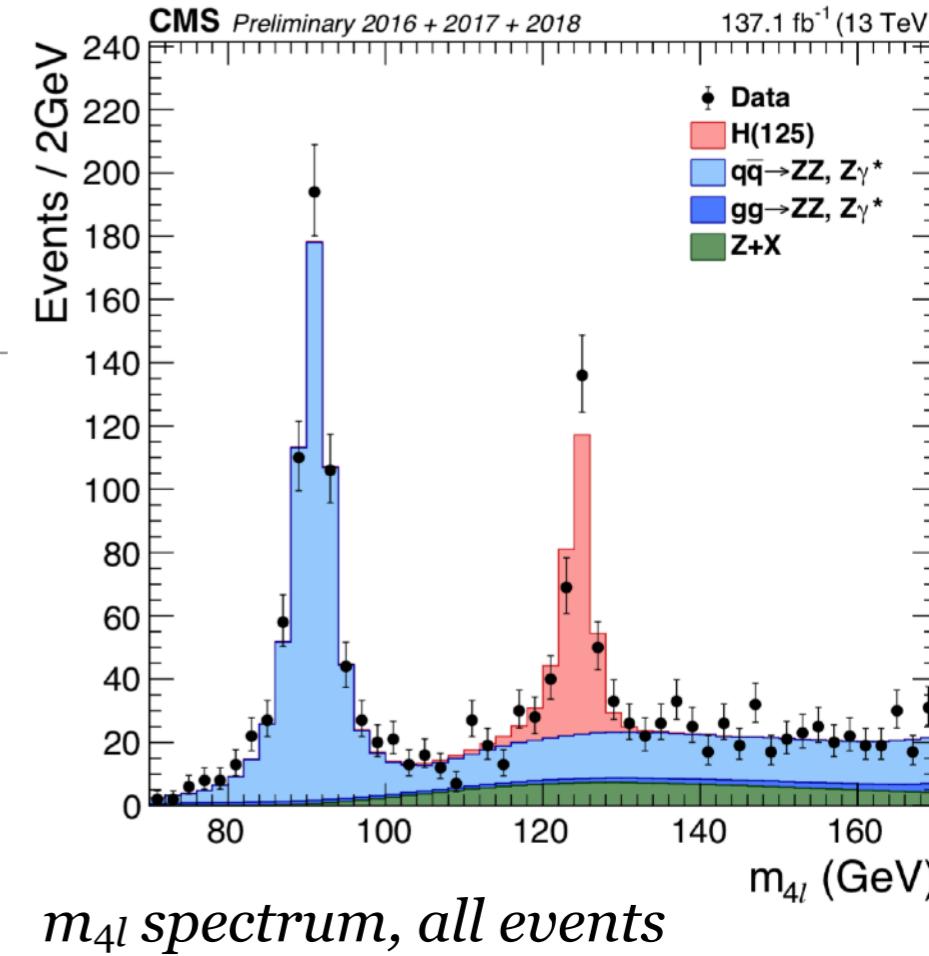
[HIG-19-001](#)

# $H \rightarrow 4\ell$ (1/2)

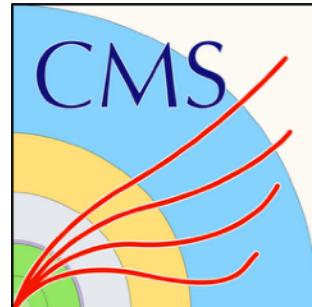
- Results based on full Run-2 dataset:  $137 \text{ fb}^{-1}$
- Event first split into 7 analysis categories
  - Then split finer into 22 subcategories based on several matrix element discriminators



7 main analysis categories



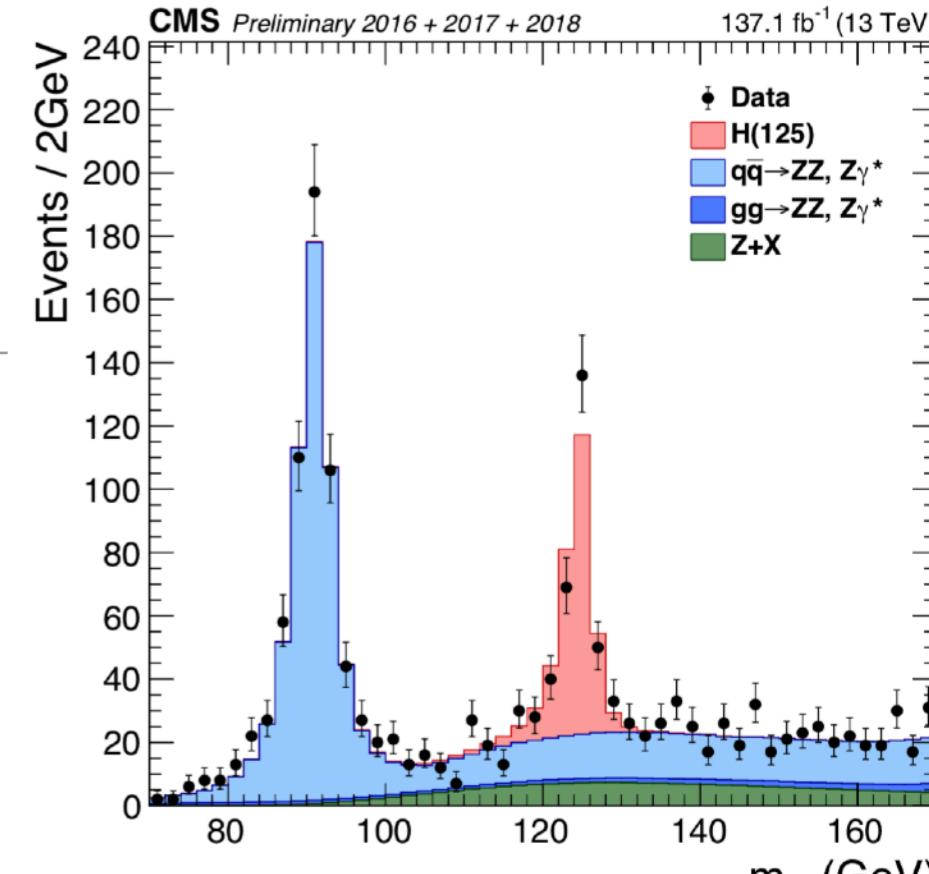
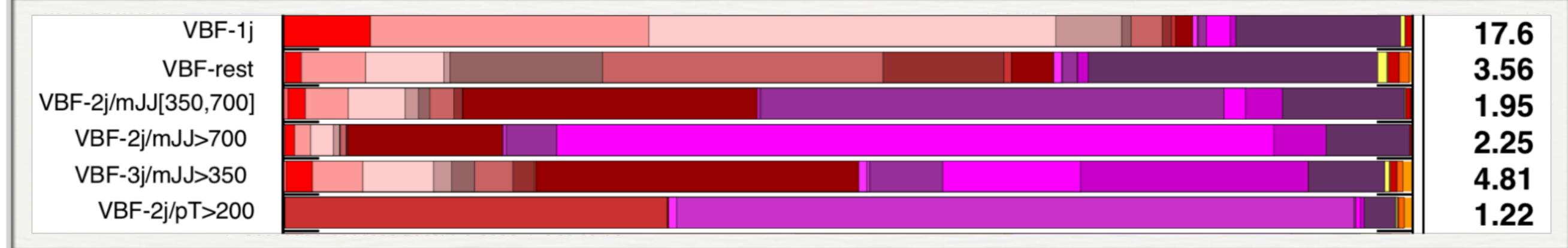
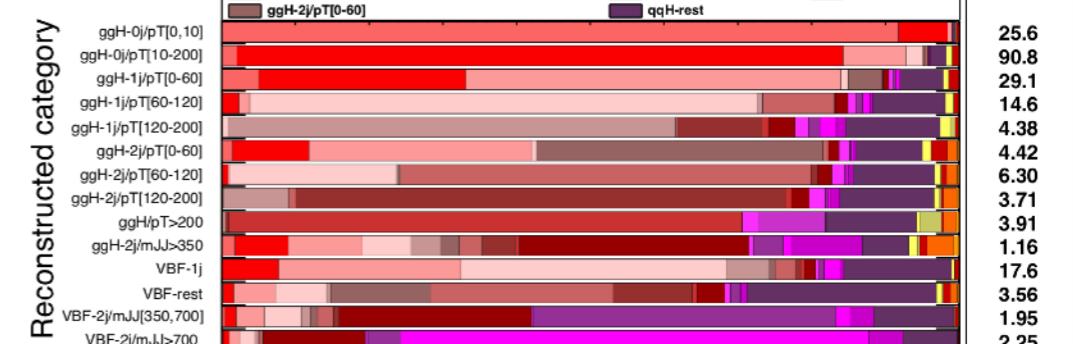
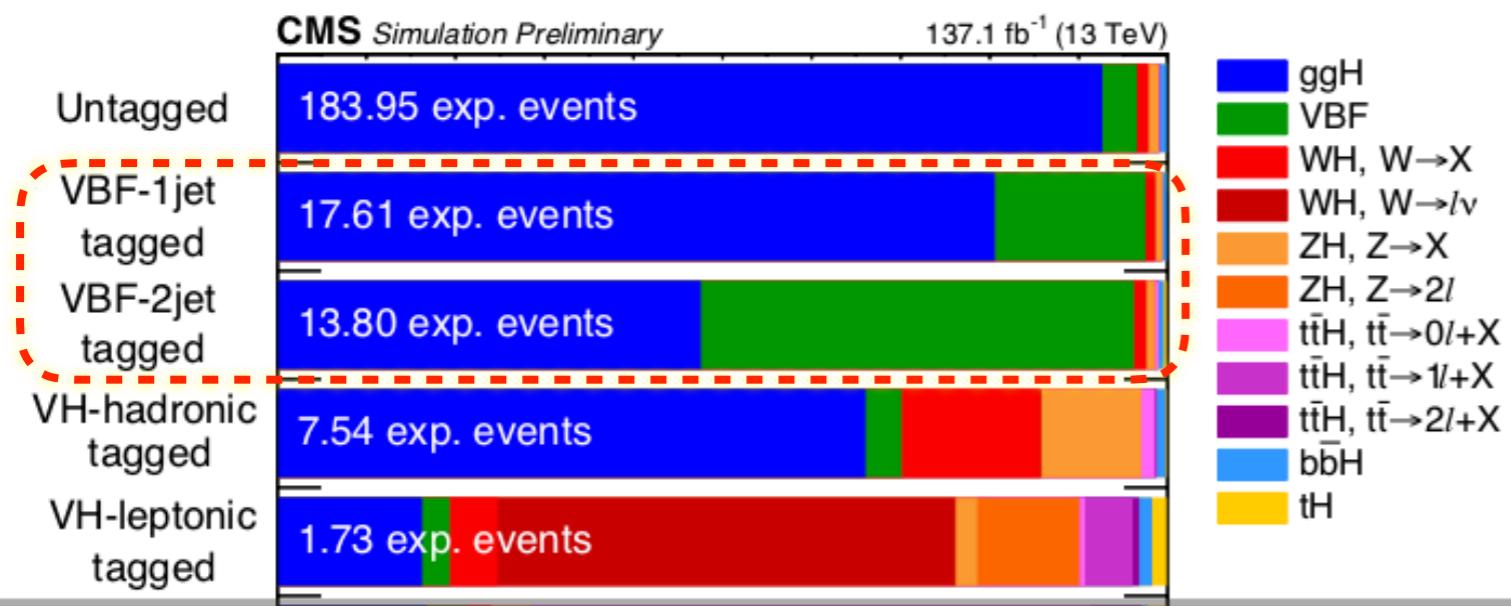
22 sub categories



[HIG-19-001](#)

# $H \rightarrow 4\ell$ (1/2)

- Results based on full Run-2 dataset:  $137 \text{ fb}^{-1}$
- Event first split into 7 analysis categories
  - Then split finer into 22 subcategories based on several matrix element discriminators



$m_{4l}$  spectrum, all events

“VBF 2 jet  $m_{jj} > 700$ ” analysis expects 2.25 events with  $\sim 80\%$  VBF purity.

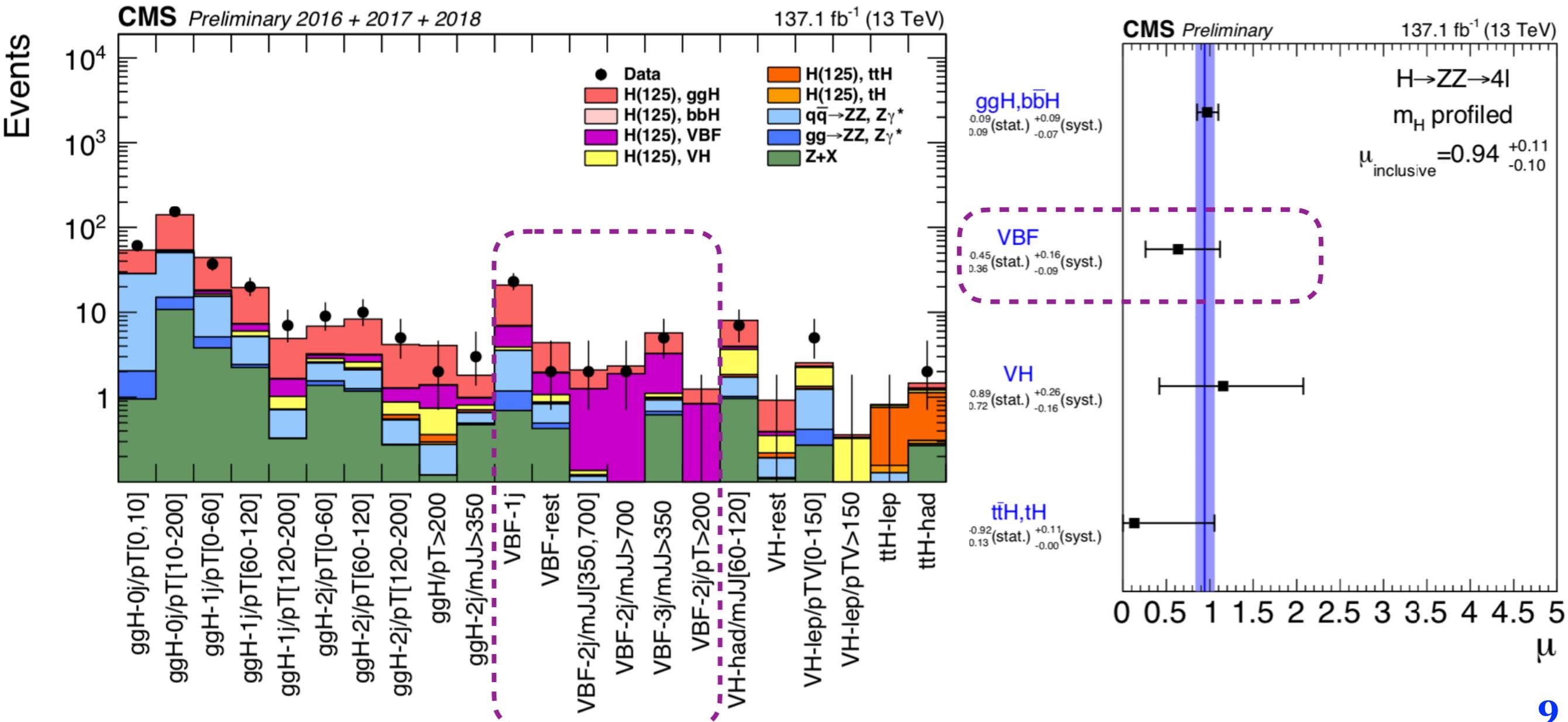


[HIG-19-001](#)

$H \rightarrow 4\ell$  (2/2)

	Expected	Observed
$\mu_{\text{inclusive}}$	$1.00^{+0.08}_{-0.08}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$
$\mu_{\text{ggH}}$	$1.00^{+0.10}_{-0.10}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.97^{+0.09}_{-0.09}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$
$\mu_{\text{VBF}}$	$1.00^{+0.54}_{-0.45}(\text{stat.})^{+0.27}_{-0.14}(\text{syst.})$	$0.64^{+0.45}_{-0.36}(\text{stat.})^{+0.16}_{-0.09}(\text{syst.})$
$\mu_{\text{VH}}$	$1.00^{+0.91}_{-0.72}(\text{stat.})^{+0.29}_{-0.16}(\text{syst.})$	$1.15^{+0.89}_{-0.72}(\text{stat.})^{+0.26}_{-0.16}(\text{syst.})$
$\mu_{\text{t}\bar{\text{t}}\text{H},\text{tH}}$	$1.00^{+1.16}_{-0.73}(\text{stat.})^{+0.19}_{-0.04}(\text{syst.})$	$0.13^{+0.92}_{-0.13}(\text{stat.})^{+0.11}_{-0.00}(\text{syst.})$

*Expected and observed event counts in each of the 22 analysis categories.  
Predicted counts are split into Higgs production mode and backgrounds.*



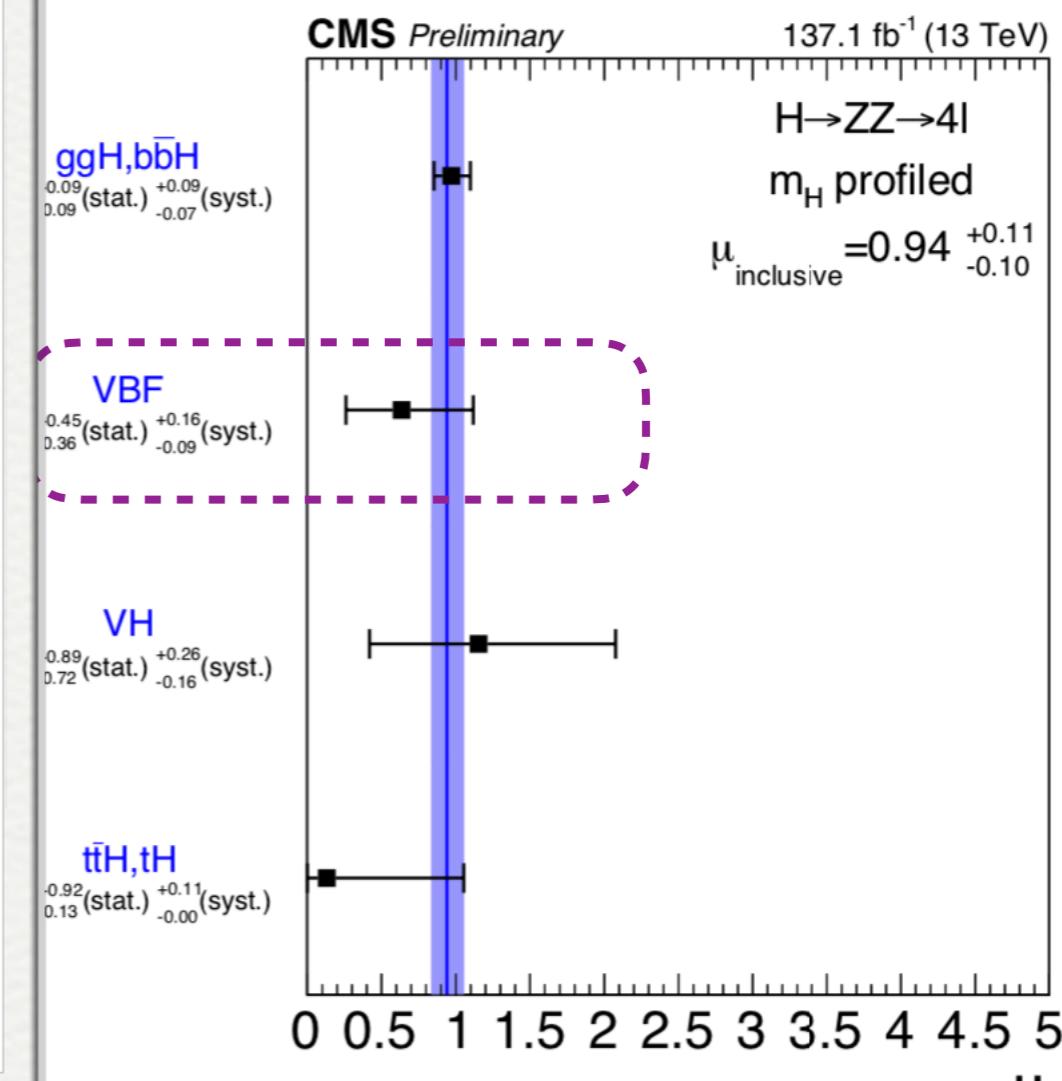
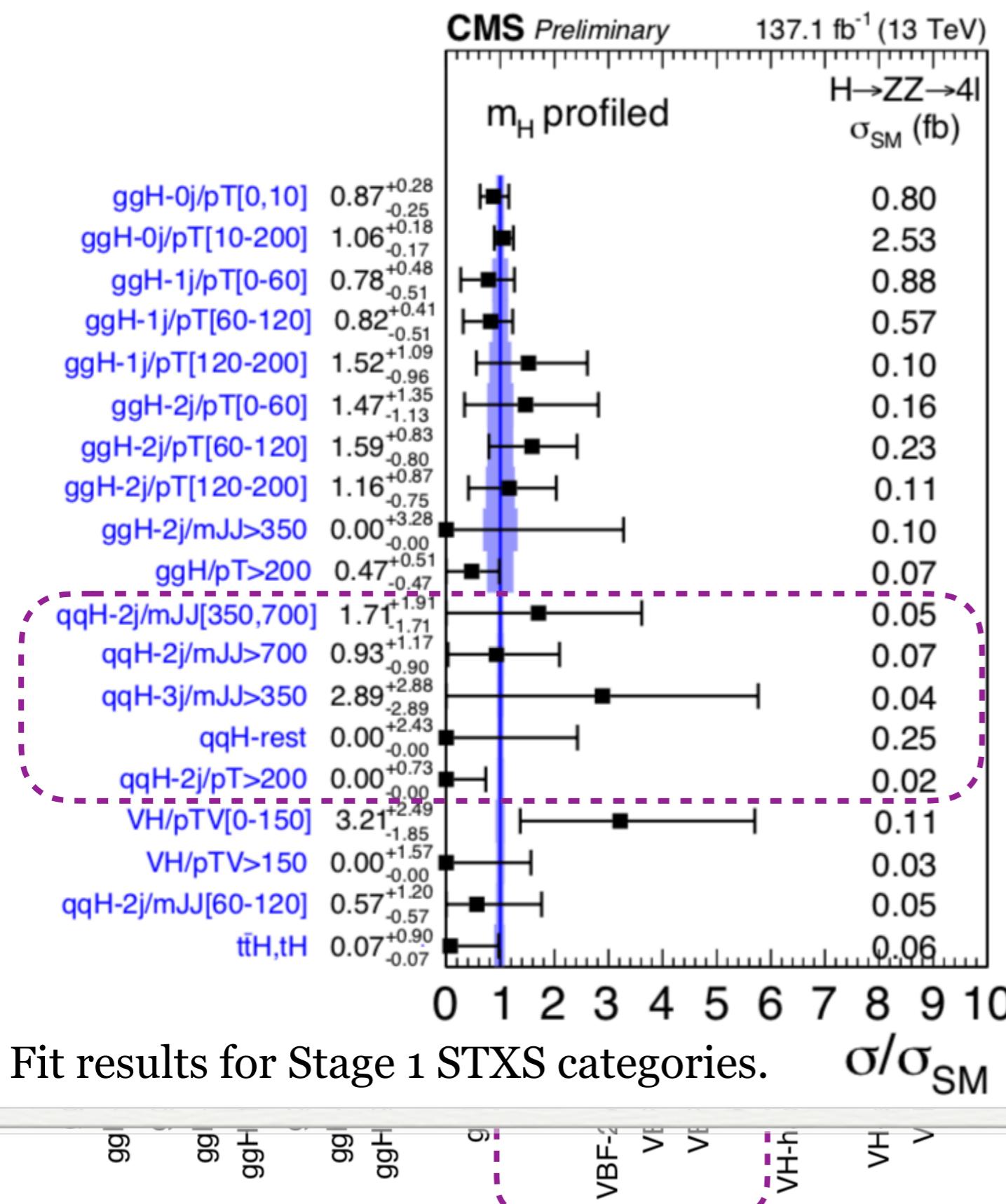
$\mu_{\text{inclusive}}$ 

Expected

Observed

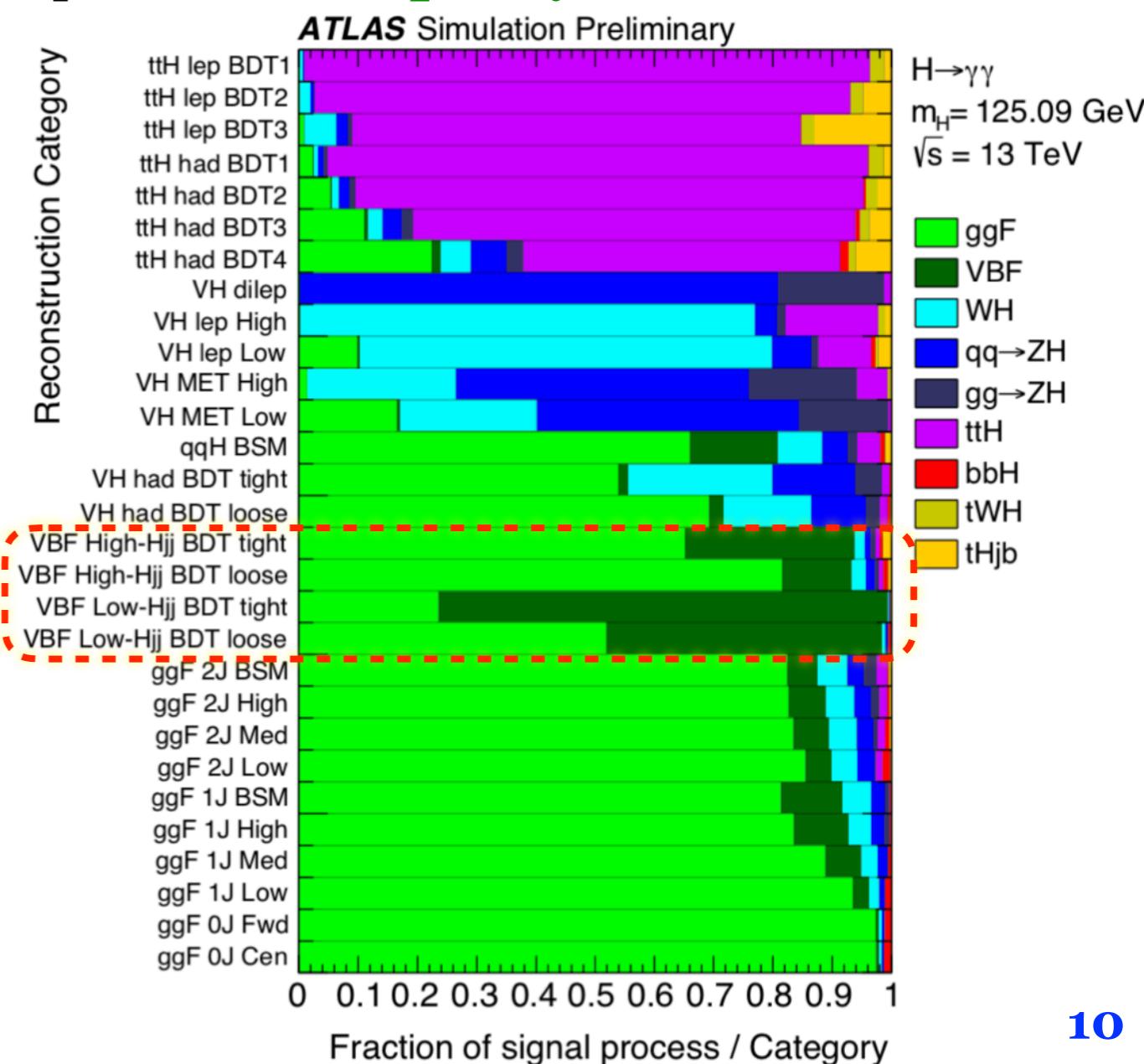
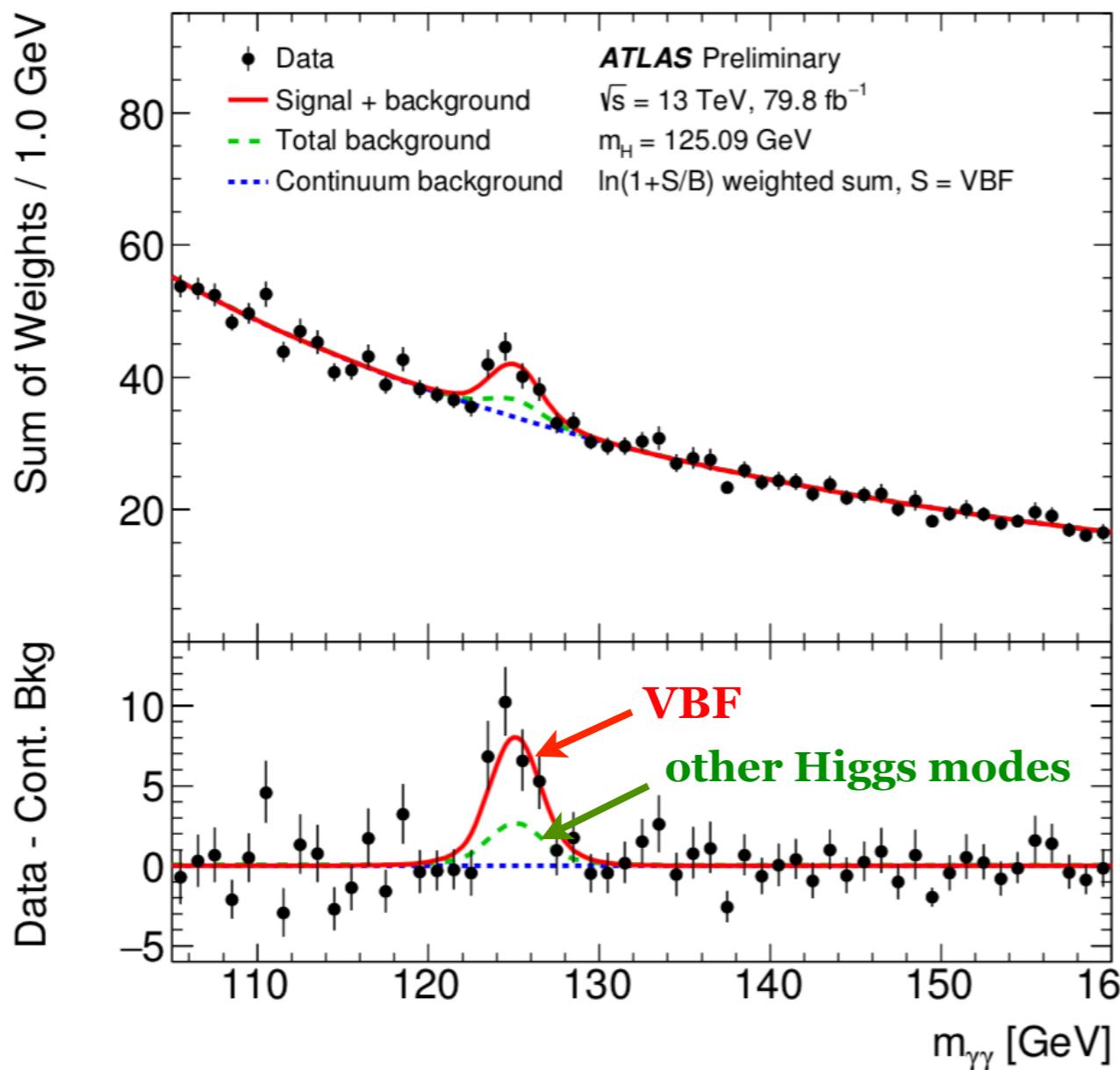
$1.00^{+0.08}_{-0.08}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$
$1.00^{+0.10}_{-0.10}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.97^{+0.09}_{-0.09}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$
$1.00^{+0.54}_{-0.45}(\text{stat.})^{+0.27}_{-0.14}(\text{syst.})$	$0.64^{+0.45}_{-0.36}(\text{stat.})^{+0.16}_{-0.09}(\text{syst.})$
$1.00^{+0.91}_{-0.72}(\text{stat.})^{+0.29}_{-0.16}(\text{syst.})$	$1.15^{+0.89}_{-0.72}(\text{stat.})^{+0.26}_{-0.16}(\text{syst.})$
$1.00^{+1.16}_{-0.73}(\text{stat.})^{+0.19}_{-0.04}(\text{syst.})$	$0.13^{+0.92}_{-0.13}(\text{stat.})^{+0.11}_{-0.00}(\text{syst.})$

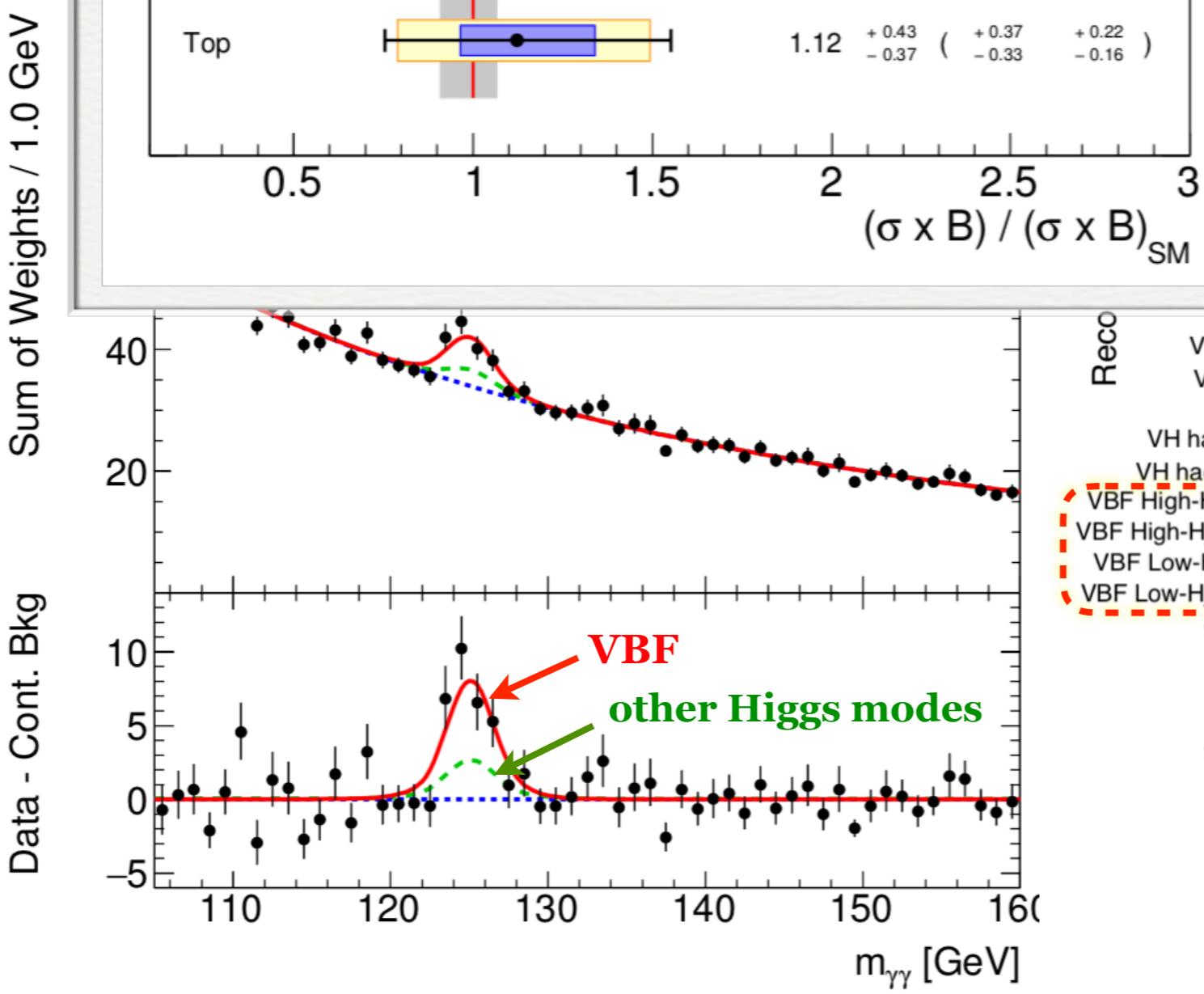
analysis categories.  
and backgrounds.



$H \rightarrow \gamma\gamma$ 

- Based on 2015-2017 dataset (full Run-2 analysis in progress)
- Measure 9 STXS stage 1 categories and signal strengths
- Four VBF optimized analysis categories, up to **75% VBF purity**

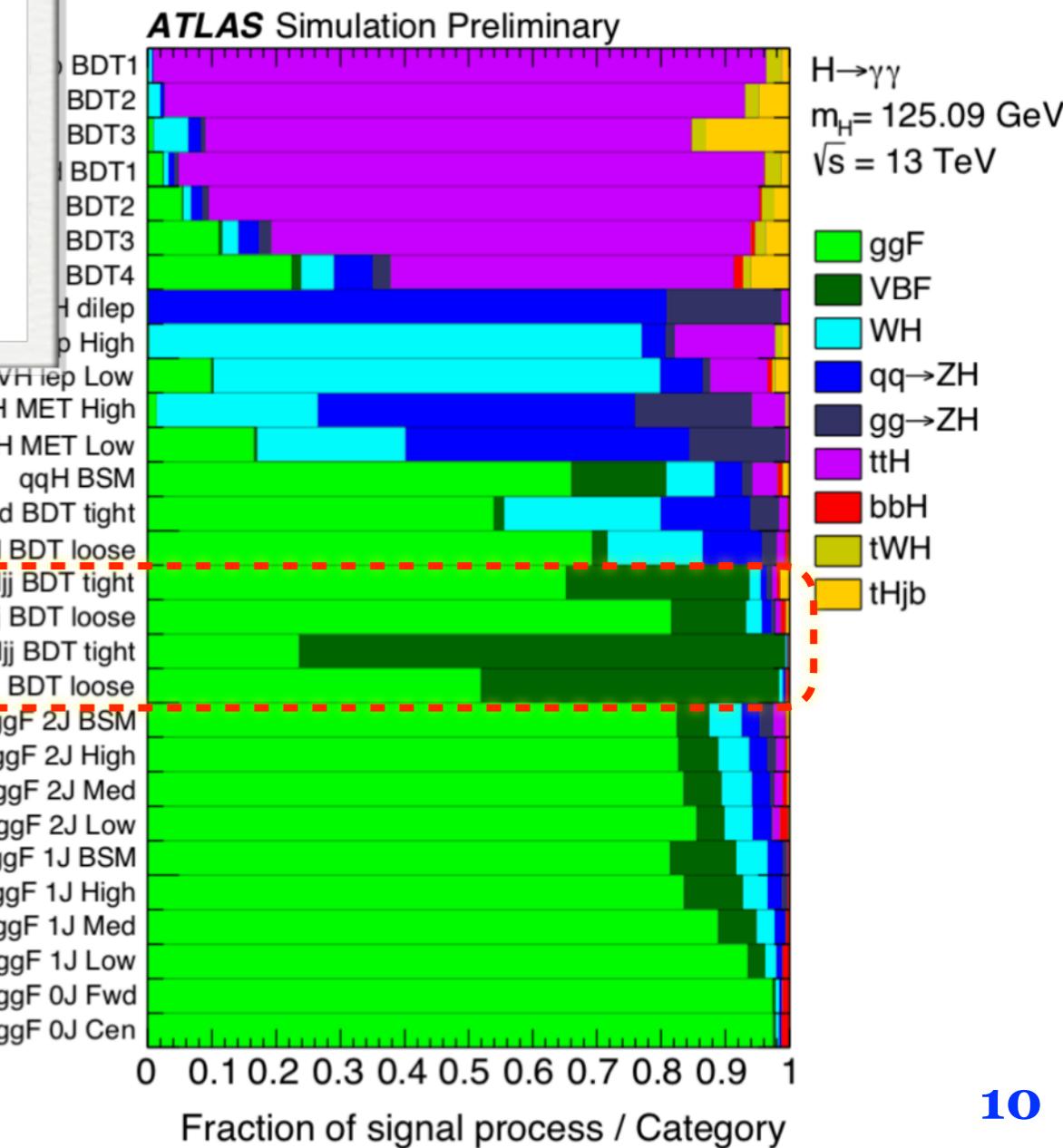




in progress)

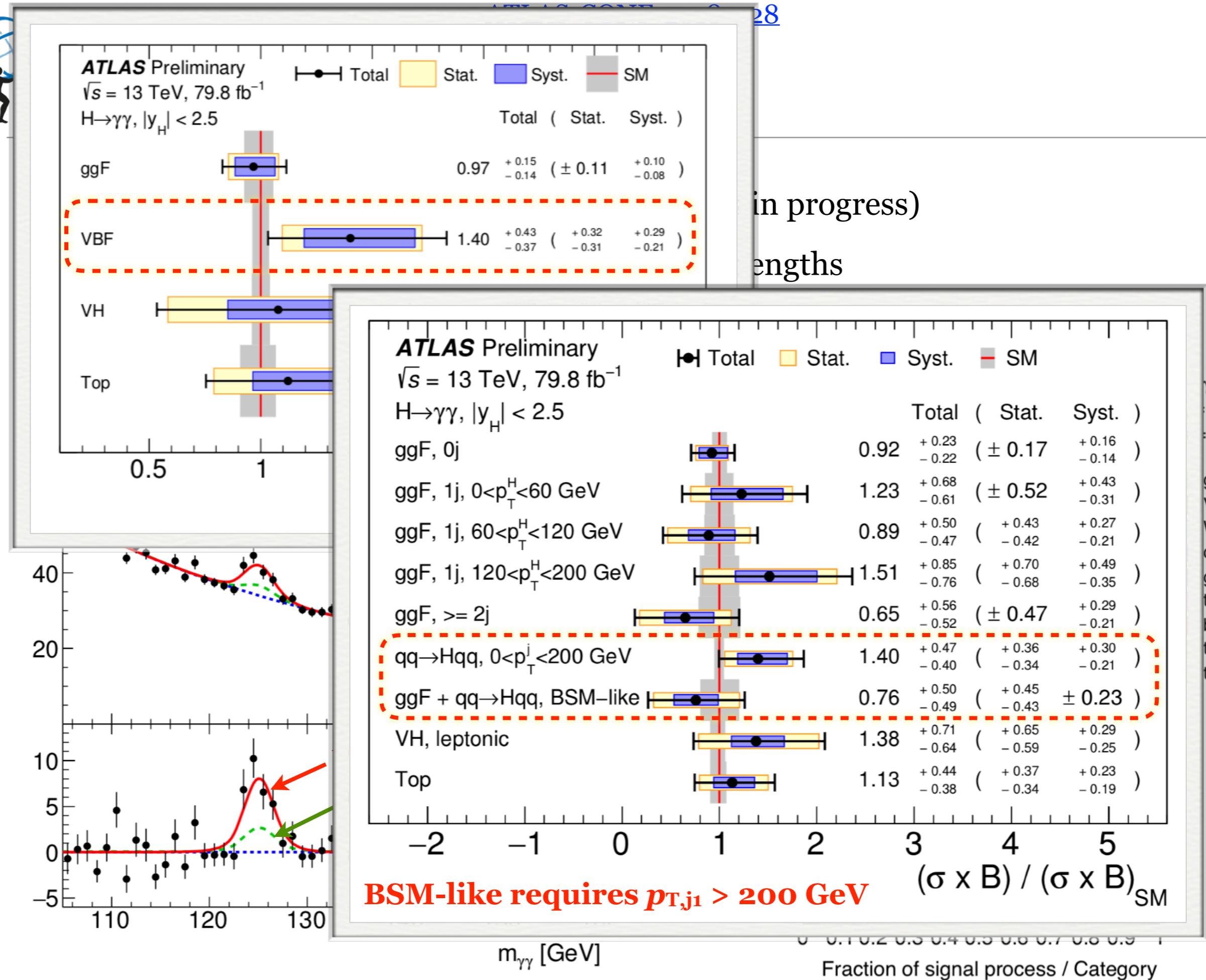
lengths

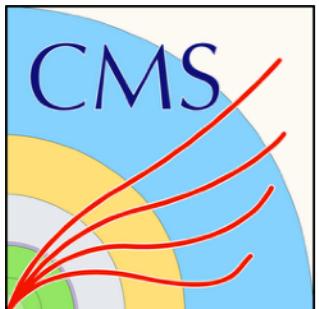
## % VBF purity





Sum of Weights / 1.0 GeV



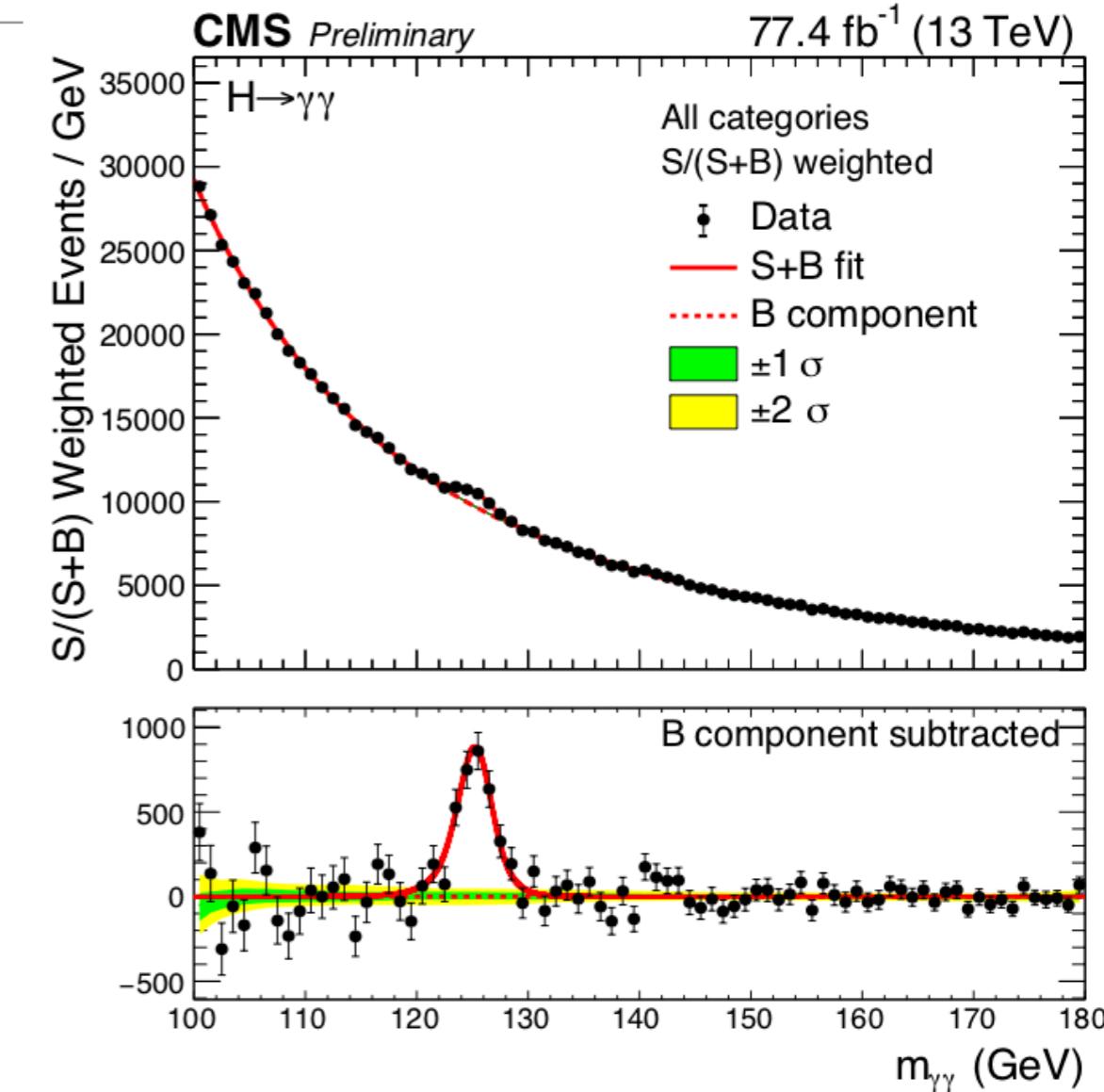
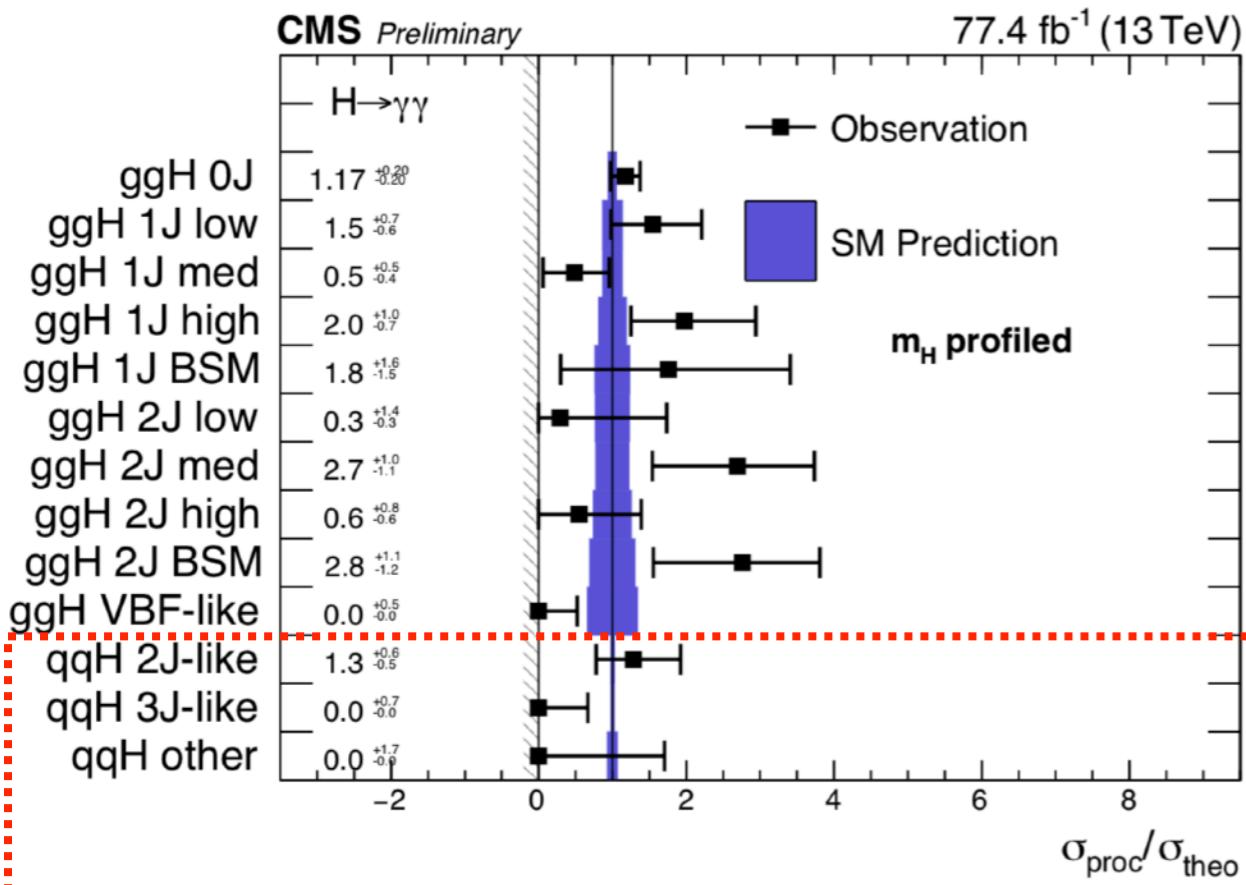


[HIG-18-029](#)

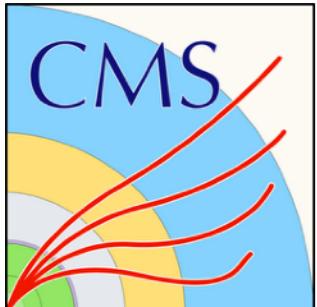
## $H \rightarrow \gamma\gamma$

- Based on 2016+2017 dataset,  $77.4 \text{ fb}^{-1}$
- Dataset split into 24 analysis categories
  - Six of them dedicated to VBF using BDTs
- The fitted VBF signal strength is extracted as part of a seven parameter fit to be:

$$\sigma_{q q H} / \sigma_{q q H}^{\text{SM}} = 0.8^{+0.4}_{-0.3}$$



- A 13 parameter fit measures 3 VBF STXS categories, and one "VBF-like ggF" category



# VBF in $H \rightarrow W^*W \rightarrow e\nu\mu\nu$

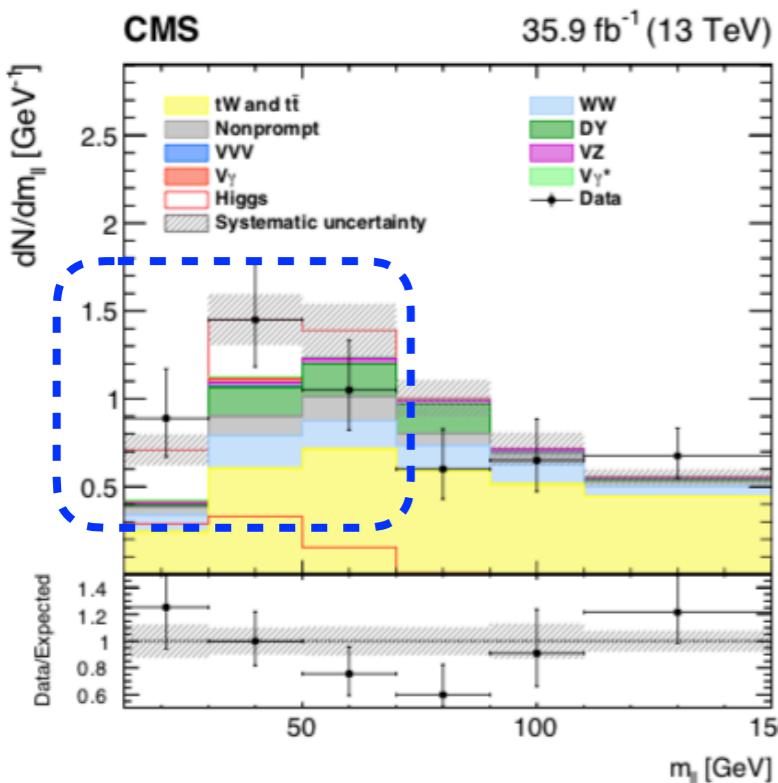
Physics Letters B  
Volume 791, 10 April 2019, Pages 96-129

- Based on 2016 13 TeV dataset ( $35.9 \text{ fb}^{-1}$ )
- Signal strength measured in event categories
- VBF-tagged selection (reco. level) in  $e\nu\mu\nu$  events

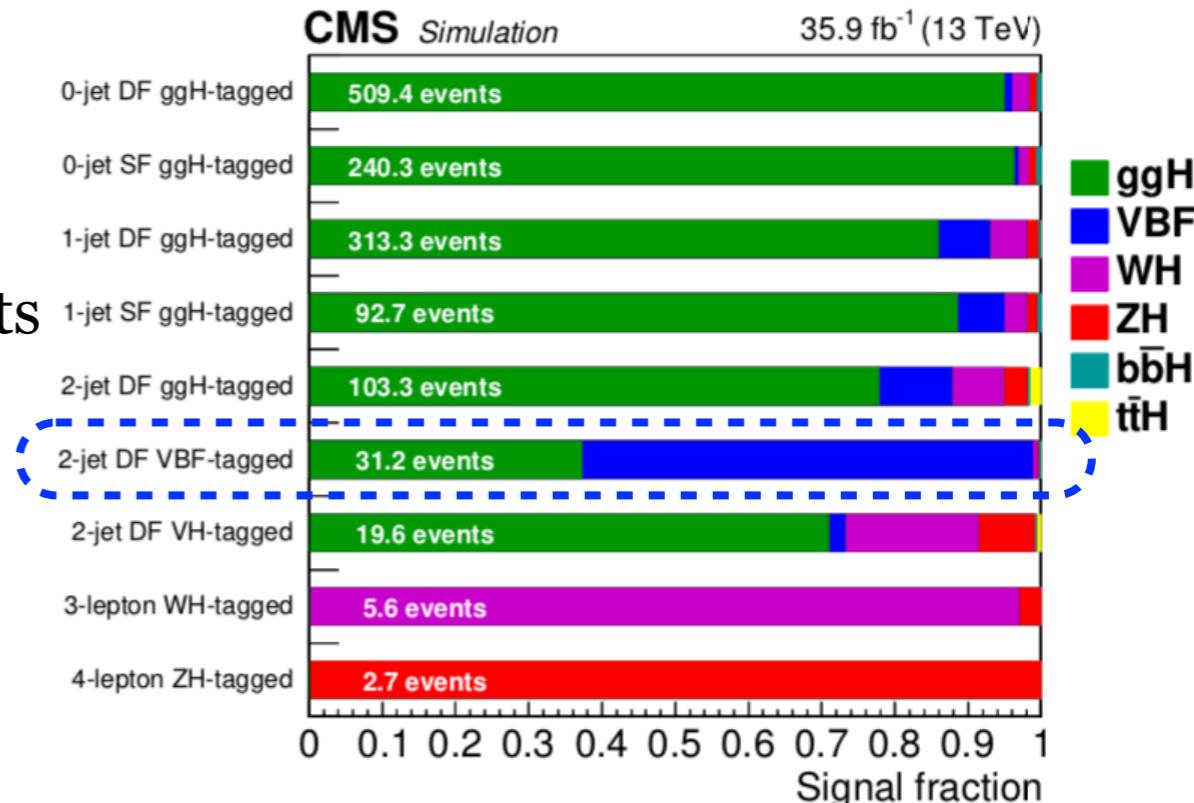
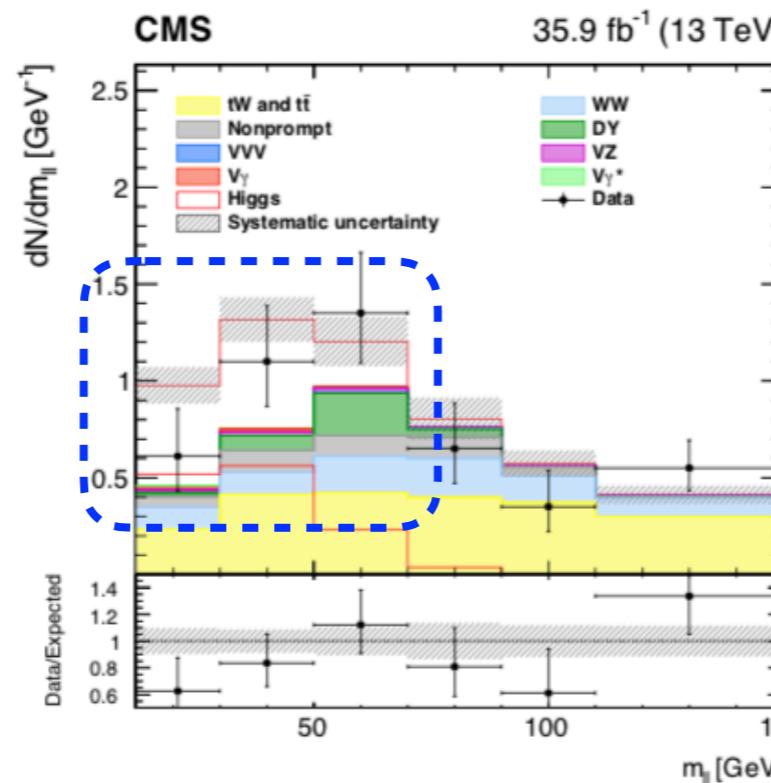
$$N_{\text{jets}}^{30 \text{ GeV}} = 2, \Delta\eta > 3.5$$

- 31.2 expected events with **high VBF purity**
- Measured  $m_{e\mu}$  spectrum for such events with

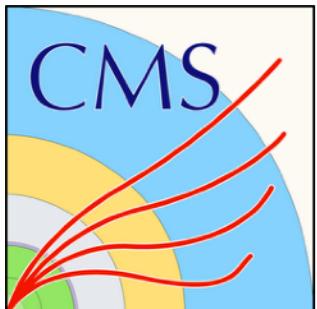
$$m_{jj} \in (400, 700) \text{ GeV}$$



$$m_{jj} > 700 \text{ GeV}$$



Slight deficit in  
Higgs  $m_{ll}$  region for  
VBF-tagged events  
 $\mu = 0.72^{+0.44}_{-0.41}$



# VBF in $H \rightarrow W^*W \rightarrow e\nu\mu\nu$

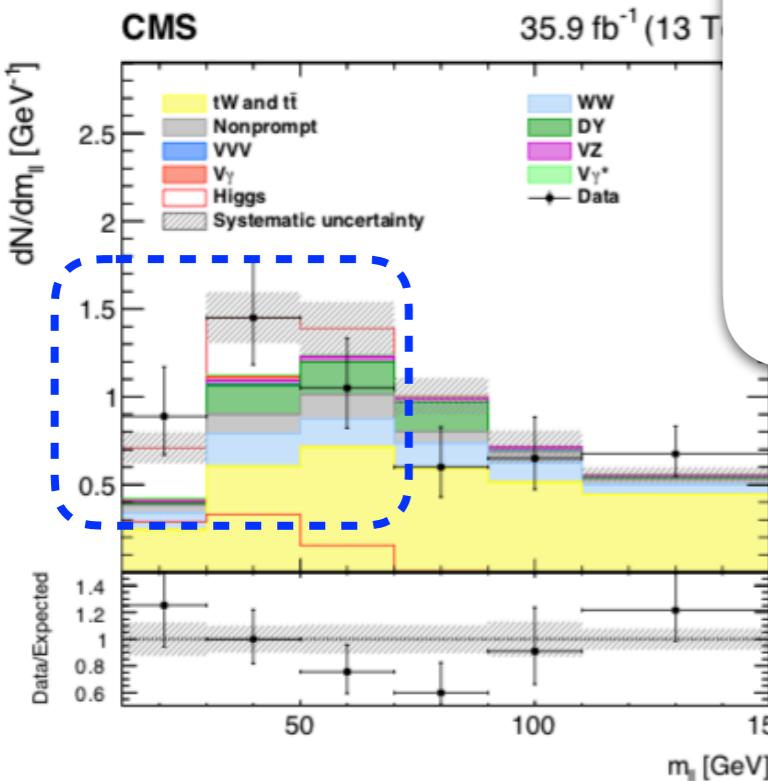
Physics Letters B  
Volume 791, 10 April 2019, Pages 96-129

- Based on 2016 13 TeV data
- Signal strength measurement
- VBF-tagged selection

$$N_{\text{jets}}^{30 \text{ GeV}}$$

- 31.2 expected events
- Measured  $m_{e\mu}$  spectrum

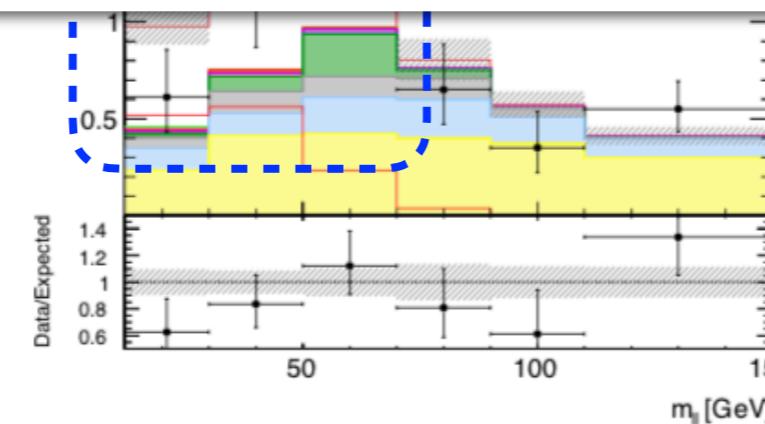
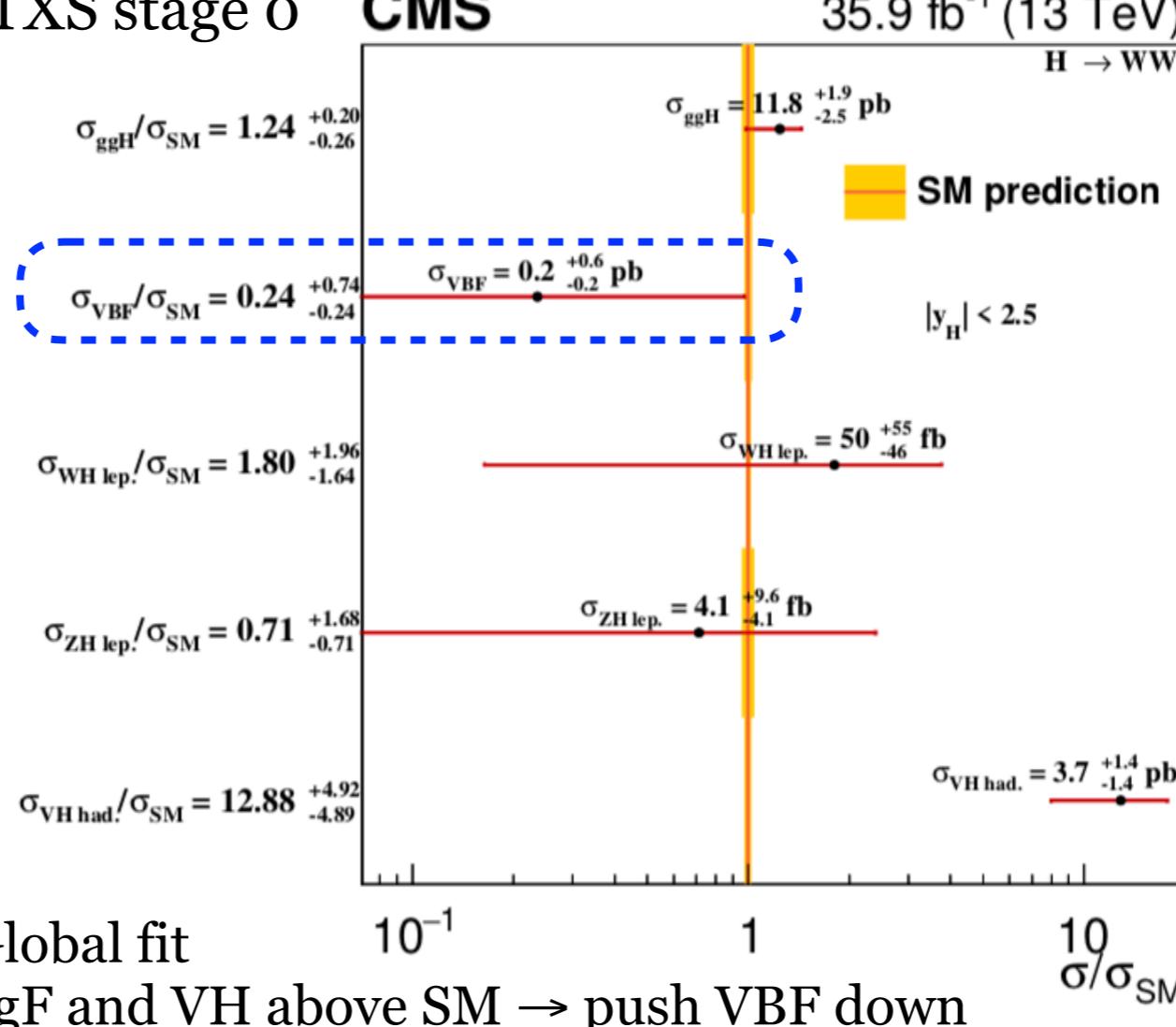
$$m_{jj} \in (400, 700) \text{ GeV}$$



STXS stage 0

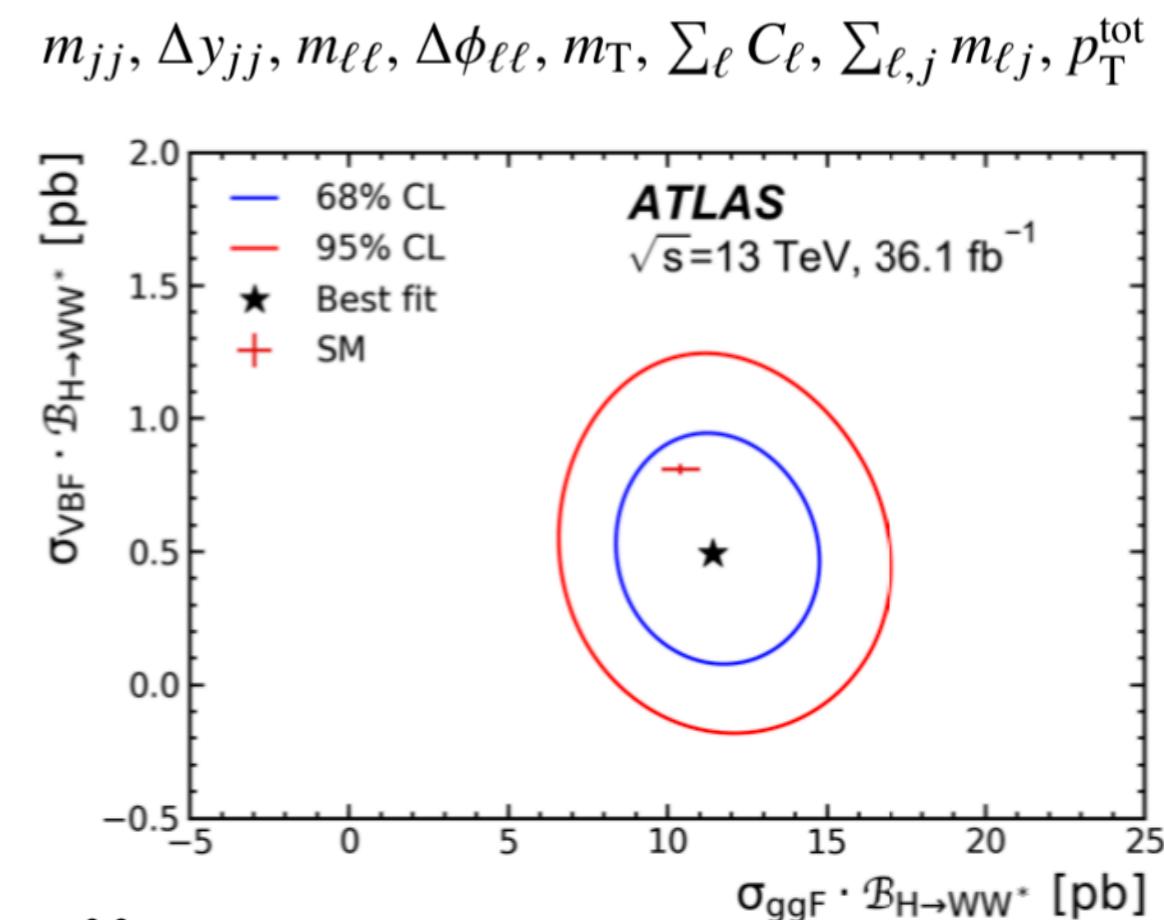
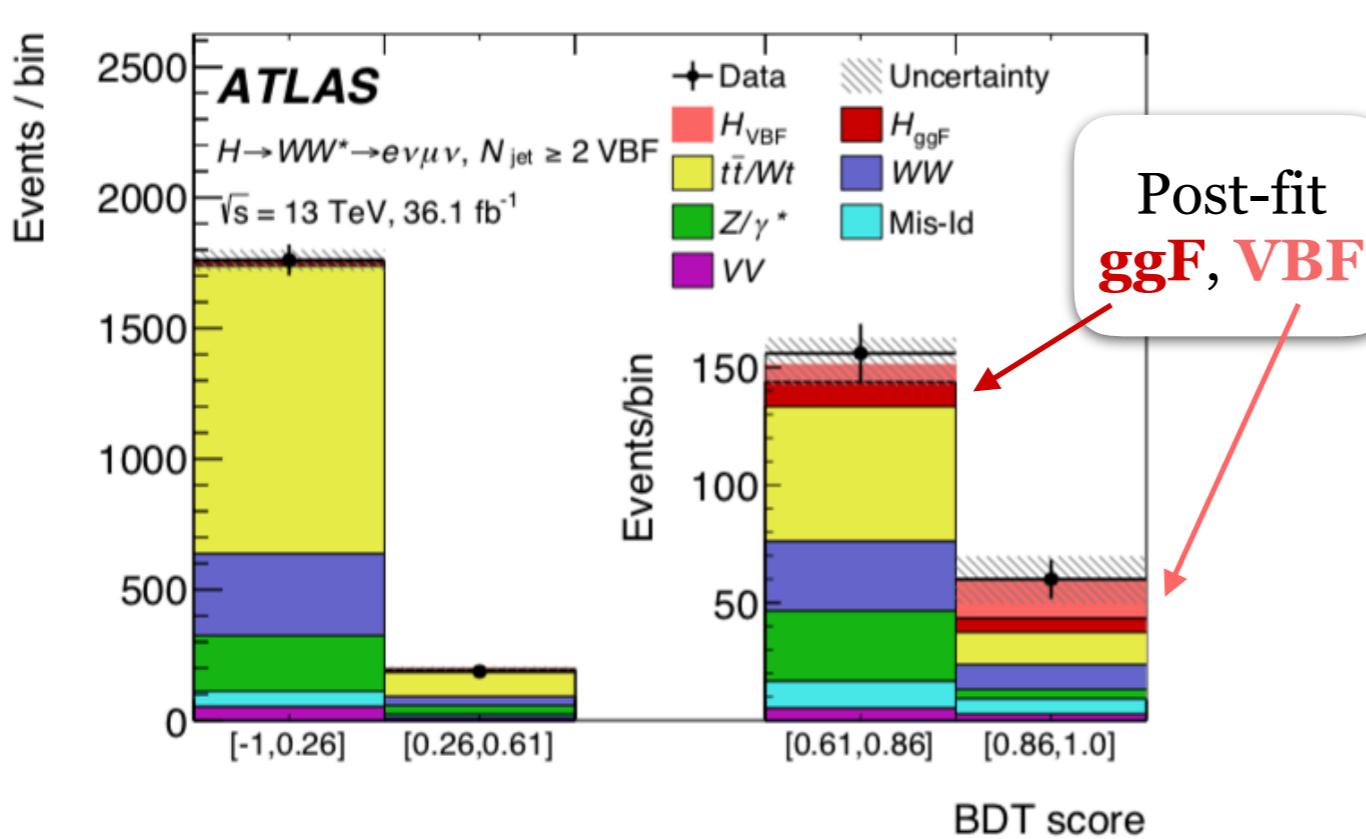
CMS

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$



Slight deficit in  
Higgs  $m_{ll}$  region for  
VBF-tagged events  
 $\mu = 0.72^{+0.44}_{-0.41}$

- Based on 2015+2016 13 TeV dataset ( $36.1 \text{ fb}^{-1}$ )
- VBF measurement based on events with:  
 $N_{\text{jets}} \geq 2$ , no  $p_T > 20 \text{ GeV}$  jet and none of the leptons in  $jj$ -rapidity gap
- These events further split based on 4-BDT bins to enhance VBF. Variables used:



$$\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.2}_{-1.1}(\text{theo syst.})^{+1.4}_{-1.3}(\text{exp syst.}) \text{ pb} = 11.4^{+2.2}_{-2.1} \text{ pb}$$

$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.10(\text{theo syst.})^{+0.12}_{-0.13}(\text{exp syst.}) \text{ pb} = 0.50^{+0.29}_{-0.28} \text{ pb}$$

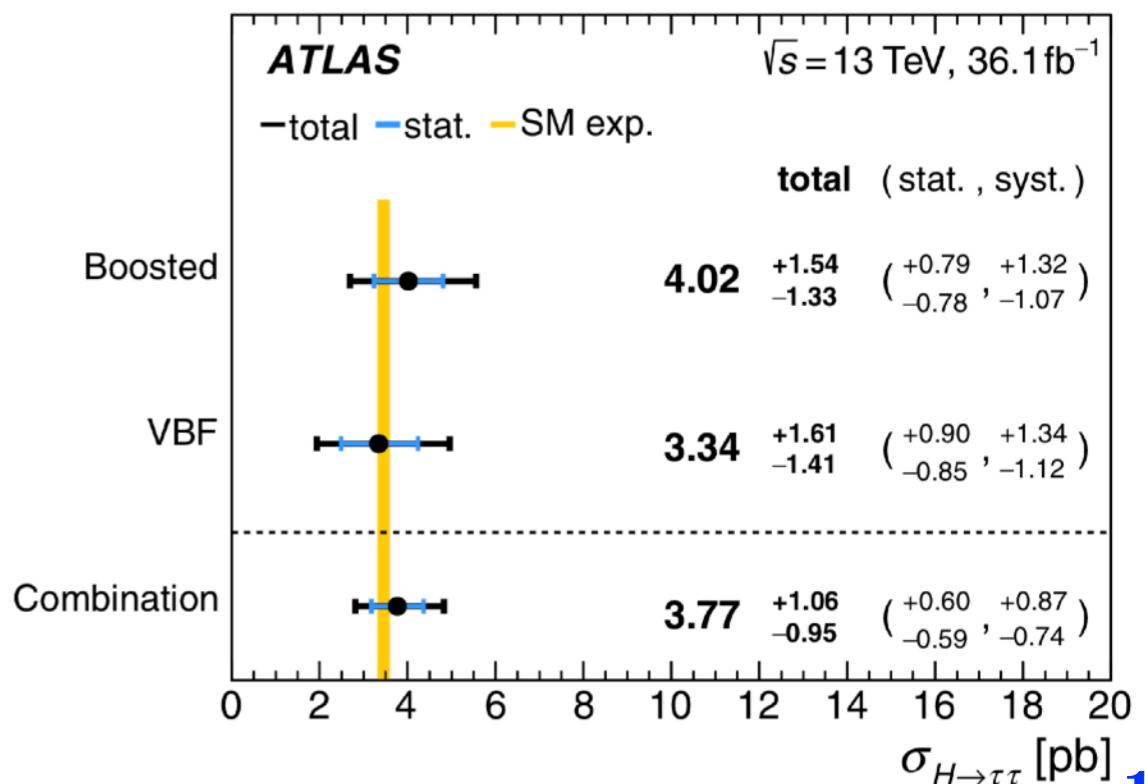
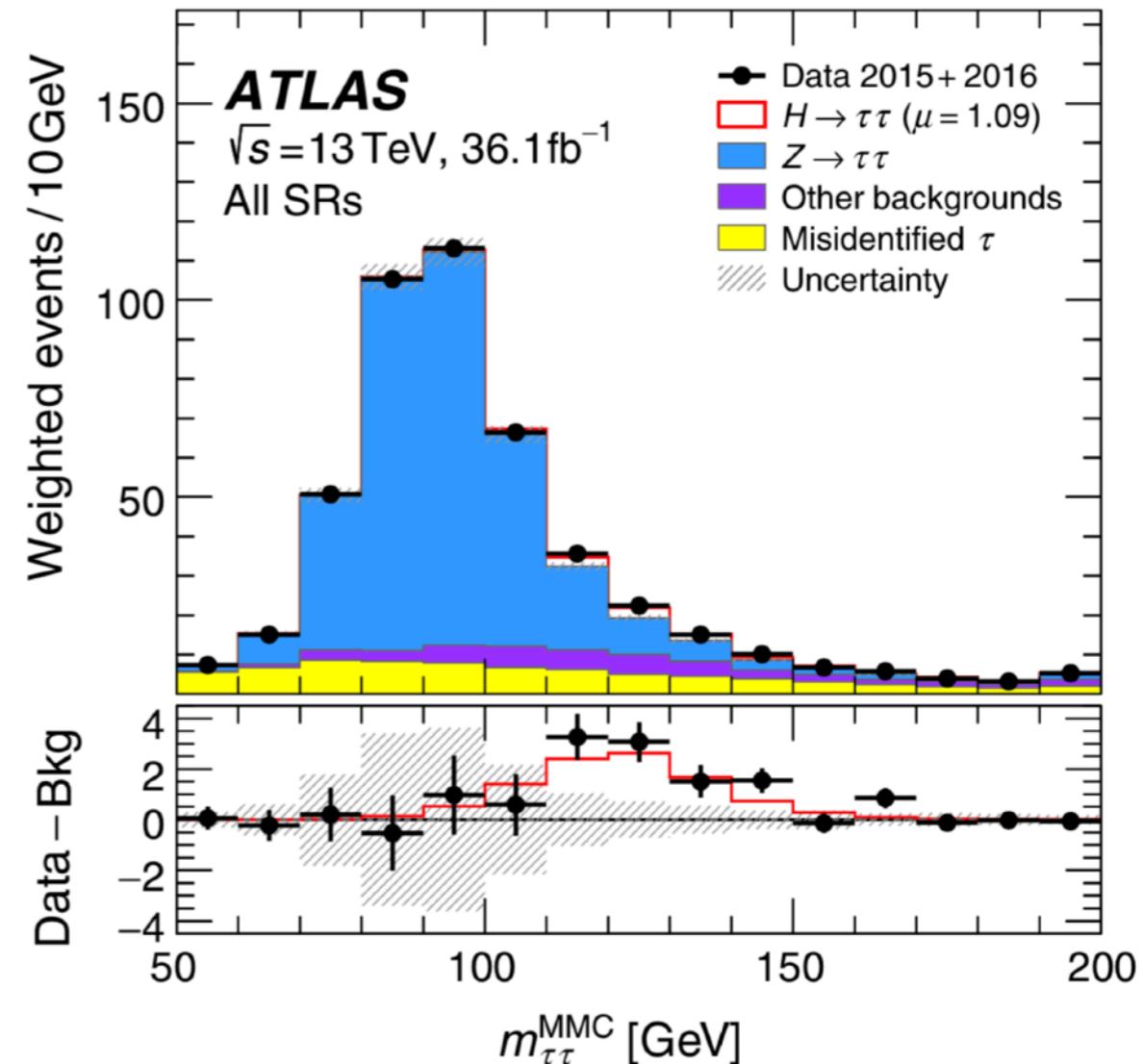
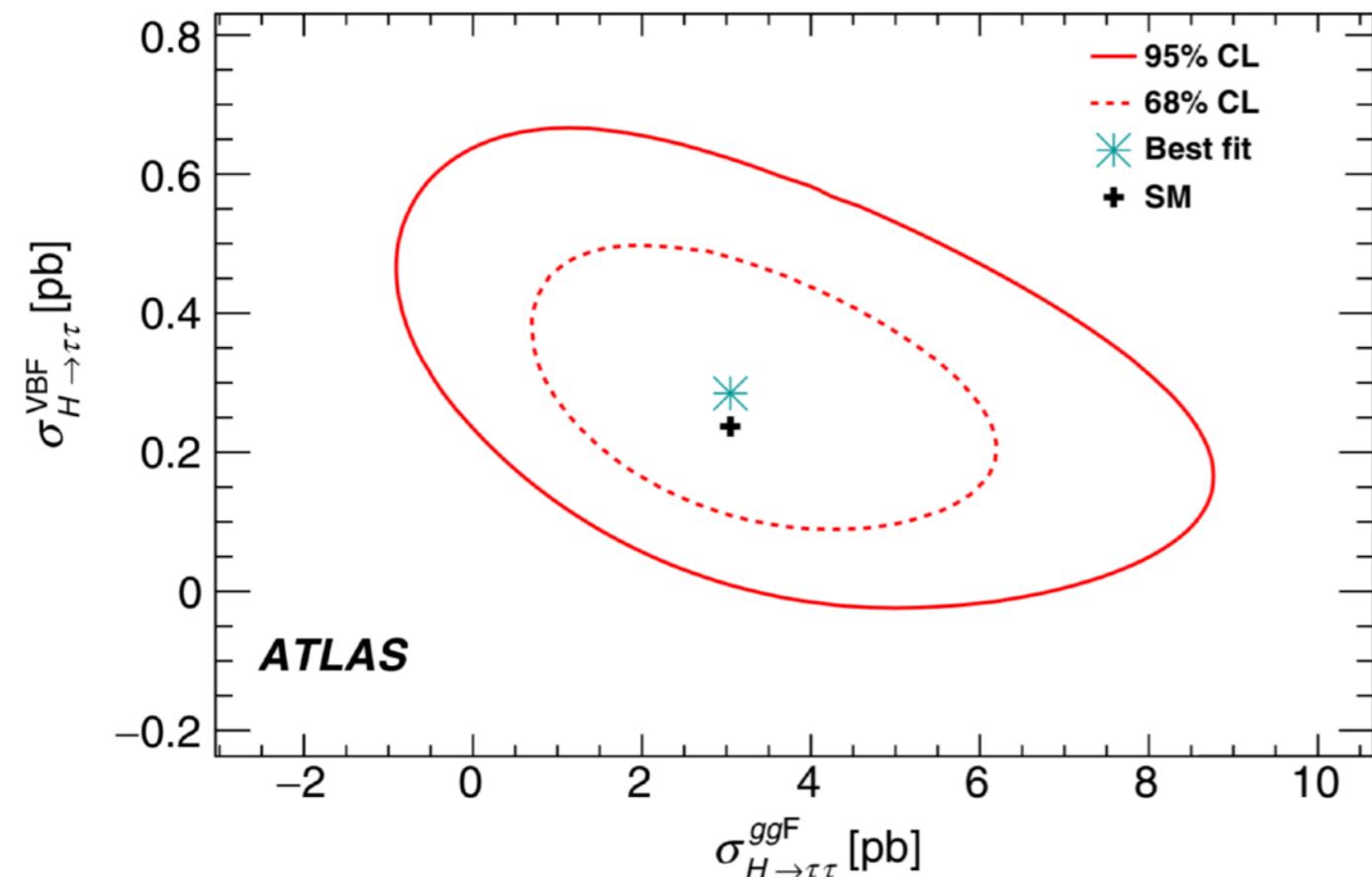
VBF expected:  $0.81 \pm 0.02 \text{ pb}$

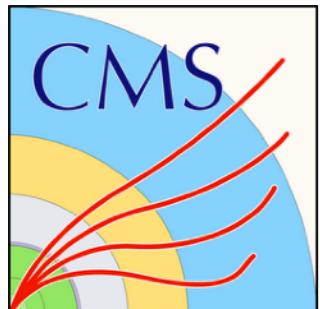
$\mu_{\text{ggF}}$	$= 1.10^{+0.21}_{-0.20}$
$\mu_{\text{VBF}}$	$= 0.62^{+0.36}_{-0.35}$



$H \rightarrow \tau\tau$

- Based on 2015-2016 dataset
- Targets boosted (high  $p_{T,H}$ ) ggF and VBF
- Complex event categorization with 13 SRs, seven of which target VBF
- Dominant systematic uncertainties from QCD calculations (assumed shape of  $p_{TH}$ ,  $p_{Tj}$  etc) and jet energy resolution and scale



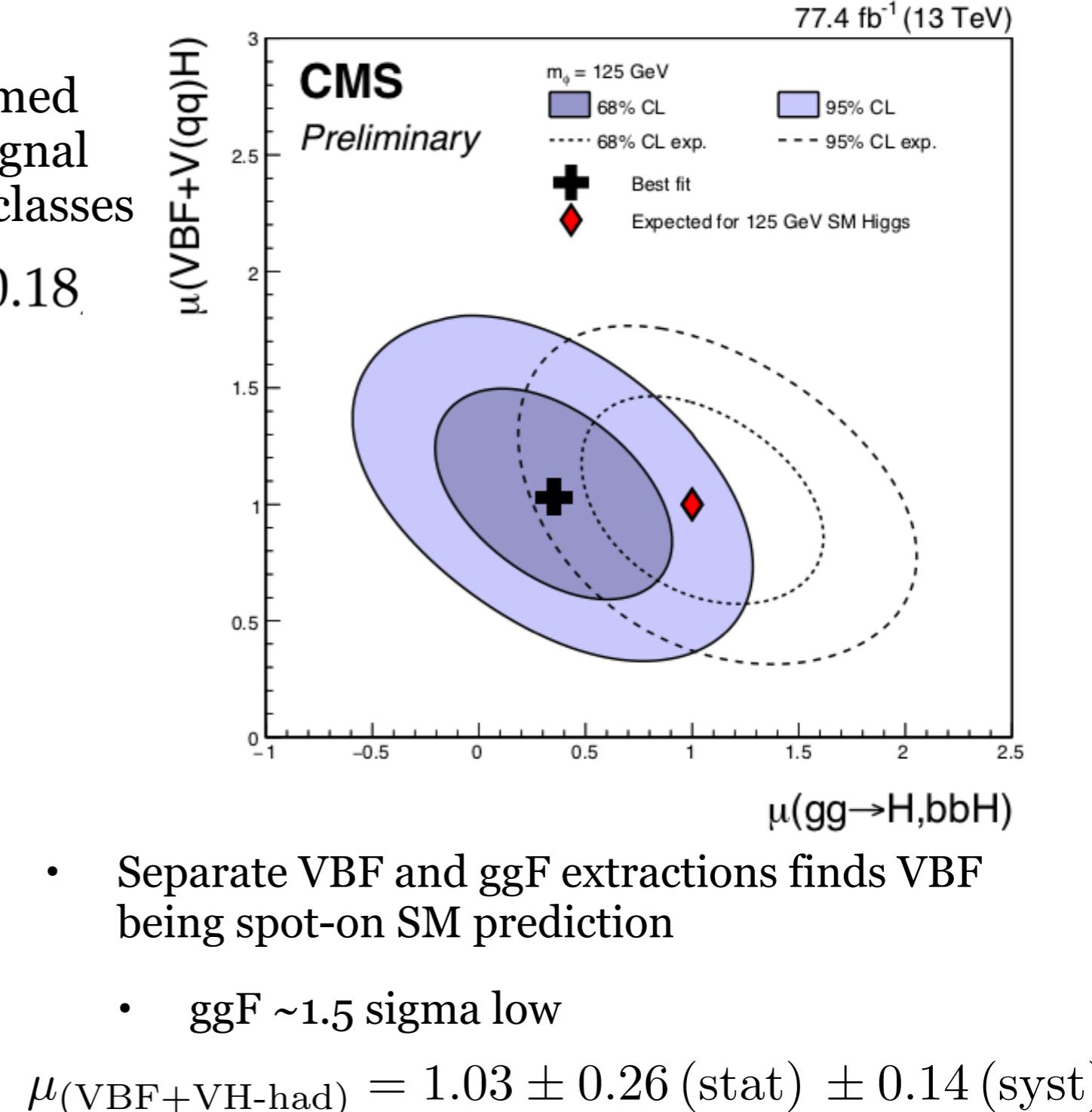
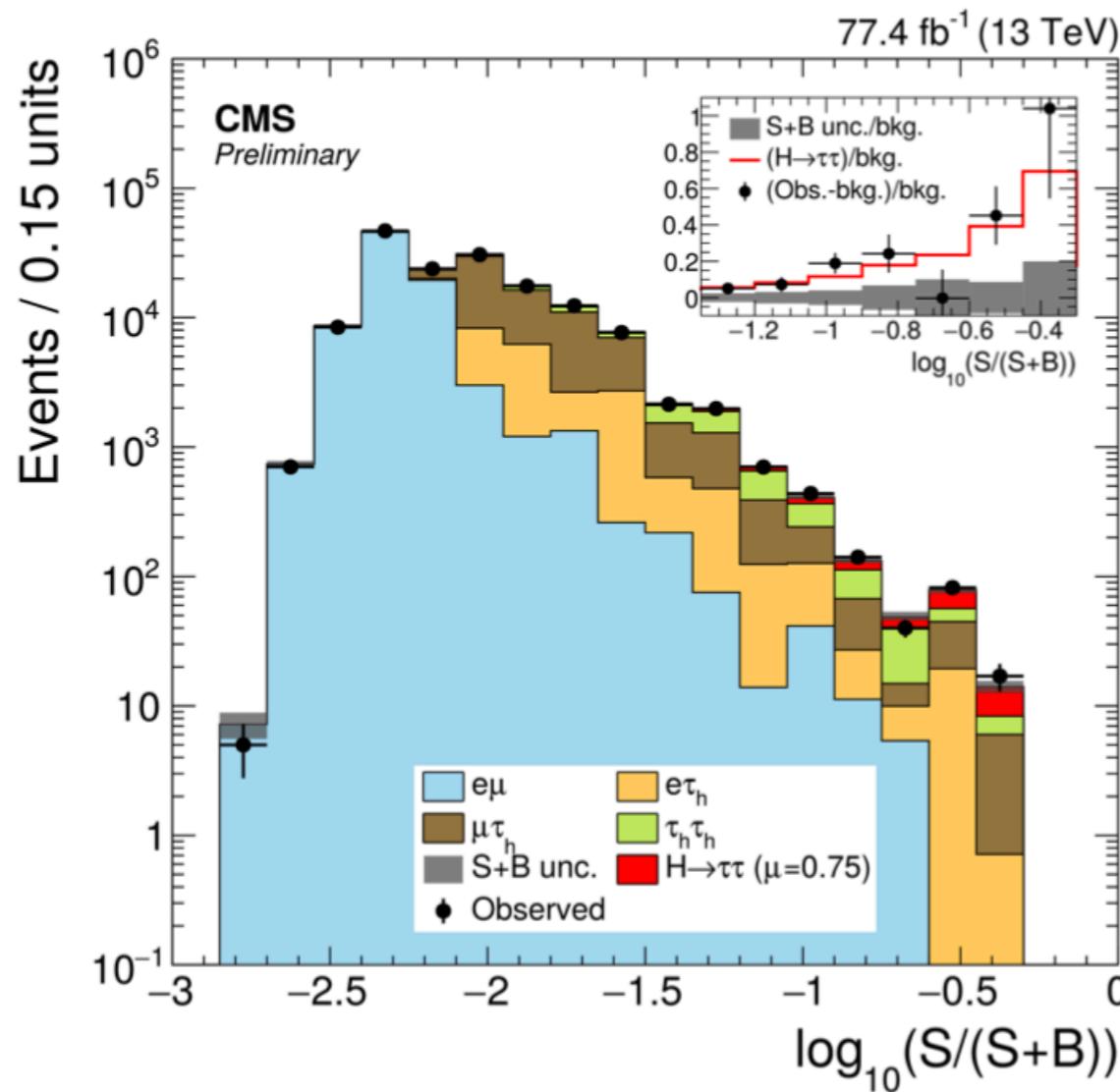


[HIG-18-032](#)

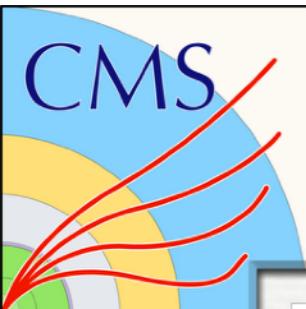
$H \rightarrow \tau\tau$

Physics Letters B  
Volume 779, 10 April 2018, Pages 283-316

- Based on 2016-2017 dataset
- Complex event classification is performed using a NN splitting events into two signal (ggF and qqH) and eight background classes
- 1-POI likelihood fit:  $\mu_{\text{incl}} = 0.75 \pm 0.18$



- Separate VBF and ggF extractions finds VBF being spot-on SM prediction
    - ggF  $\sim 1.5$  sigma low
- $\mu_{\text{VBF+VH-had}} = 1.03 \pm 0.26 \text{ (stat)} \pm 0.14 \text{ (syst)}$



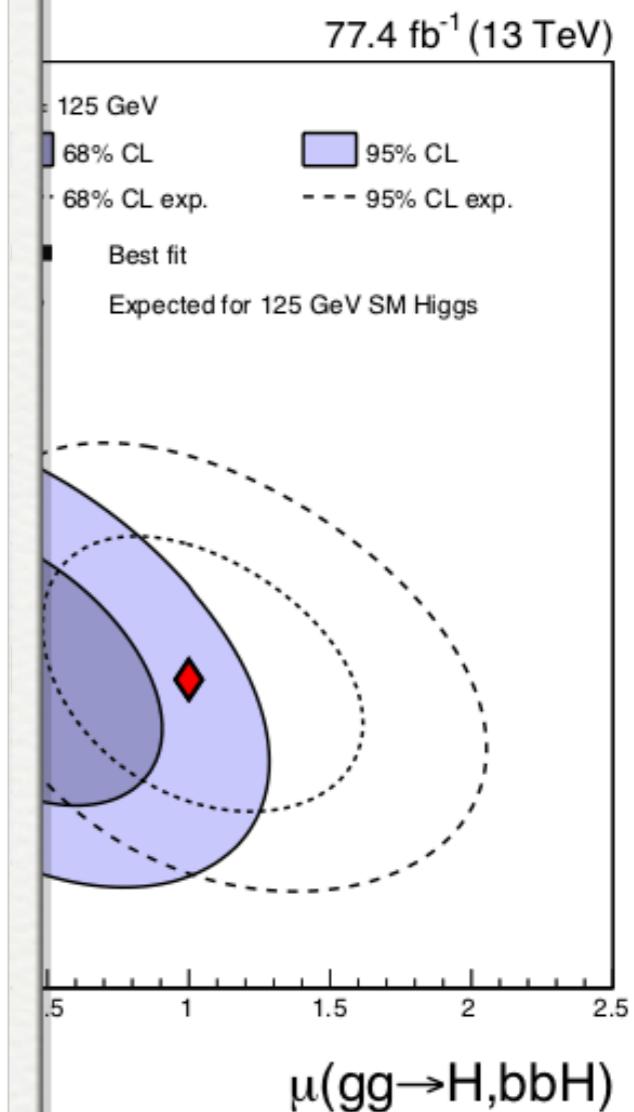
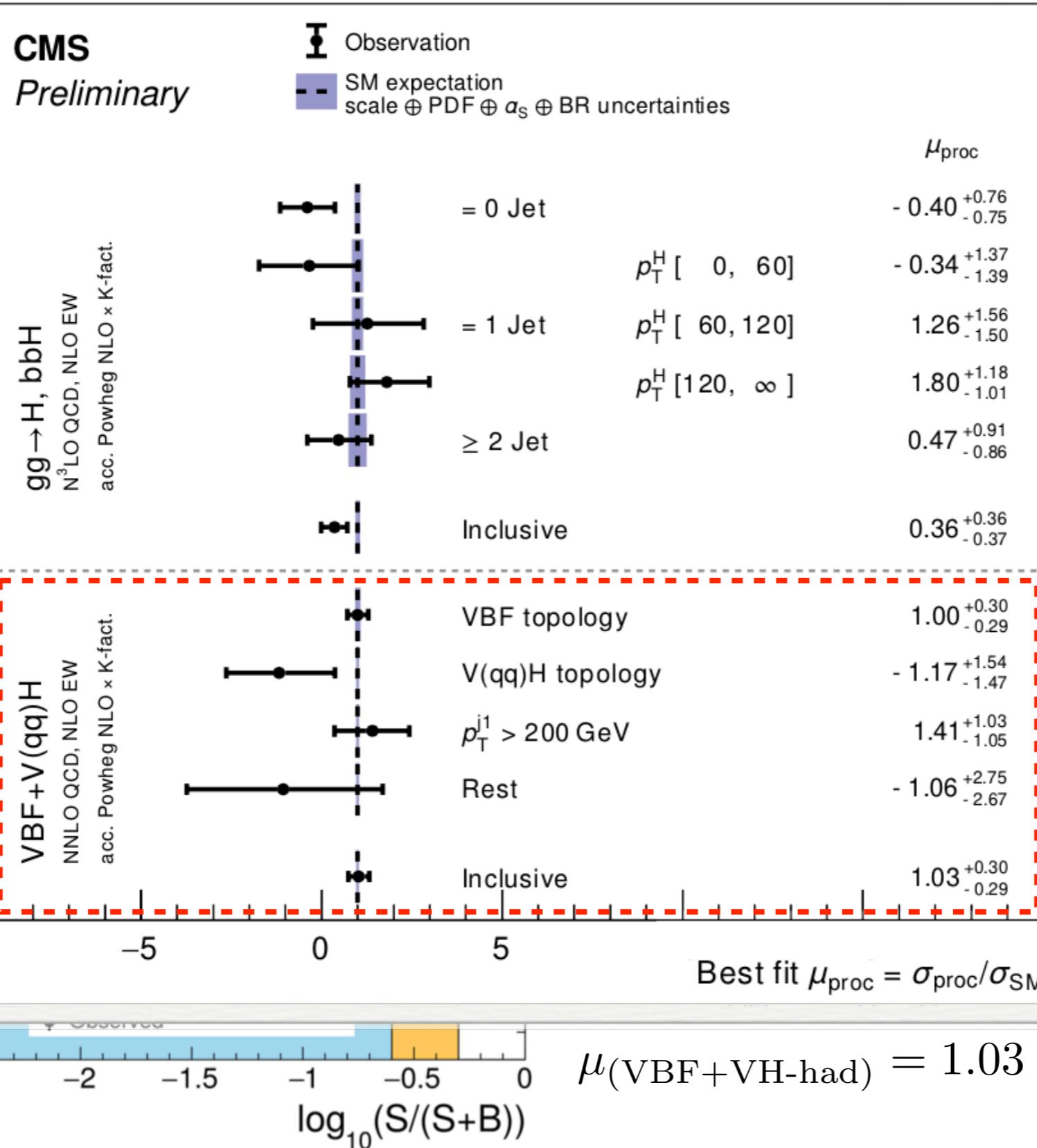
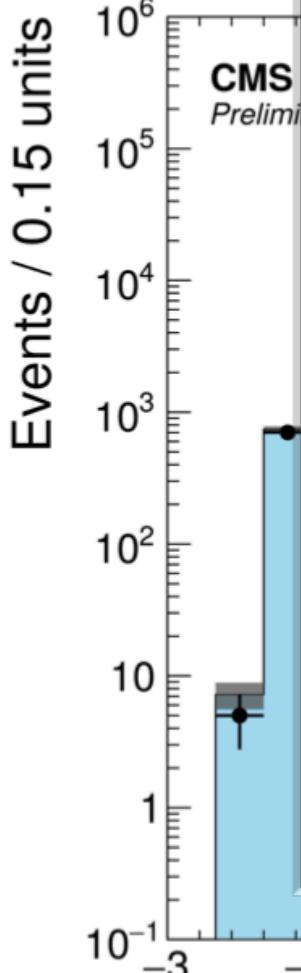
[HIG-18-032](#)

$H \rightarrow \tau\tau$

Physics Letters B  
Volume 779, 10 April 2018, Pages 283-316

- Based on 77.4  $\text{fb}^{-1}$  at 13 TeV
- Complete analysis using a combined fit (ggF and VBF)

Events / 0.15 units

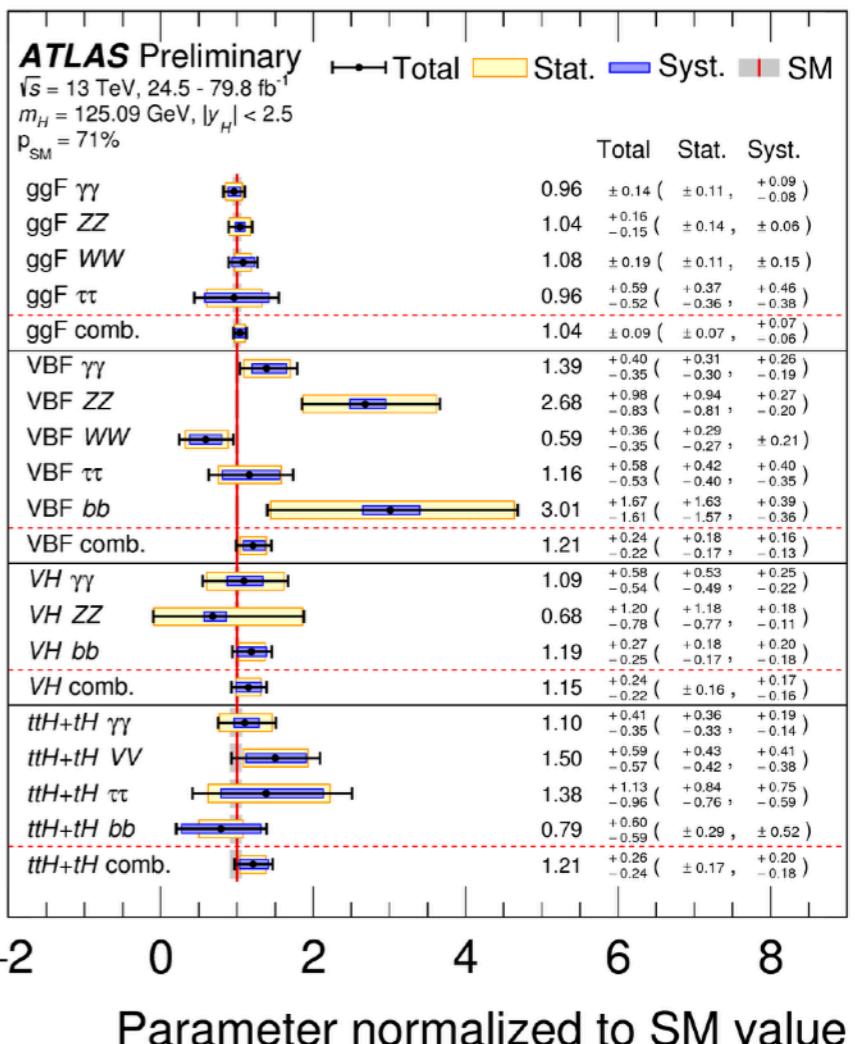
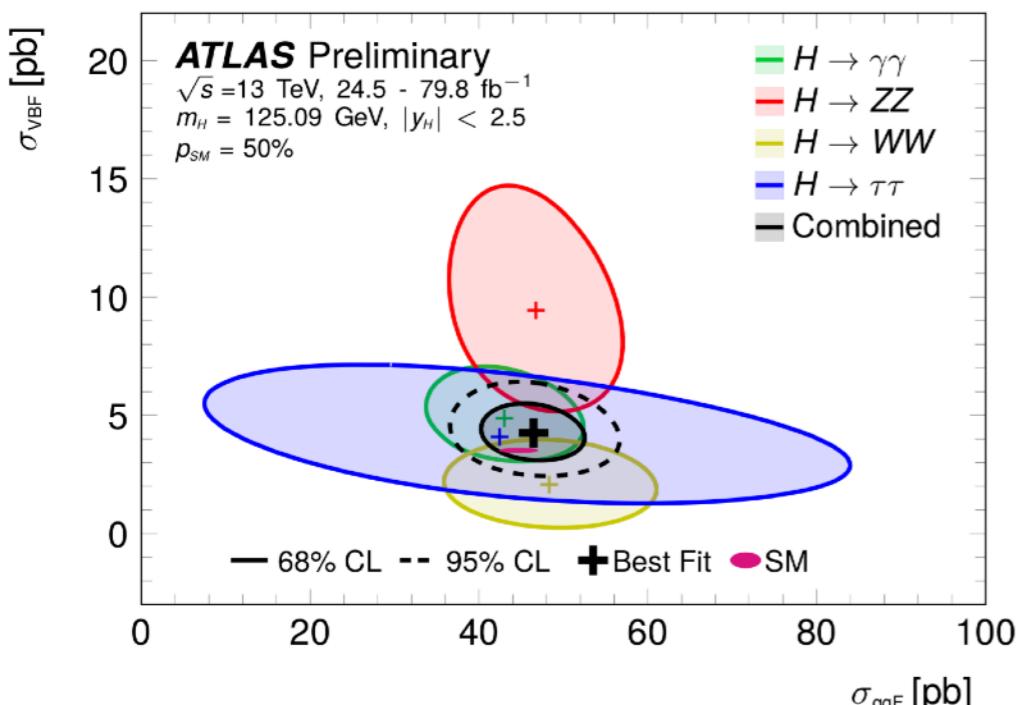


xtractions finds VBF  
action

# Combined Higgs result

- Based on 2015-2017  $\gamma\gamma$ ,  $ZZ$ ,  $WW$ ,  $\tau\tau$ ,  $bb$  data (up to  $80 \text{ fb}^{-1}$ )
  - Note: hence based on previous HZZ result
- 5 parameter production mode gives VBF 1.21 times SM
  - Statistical uncertainty dominates

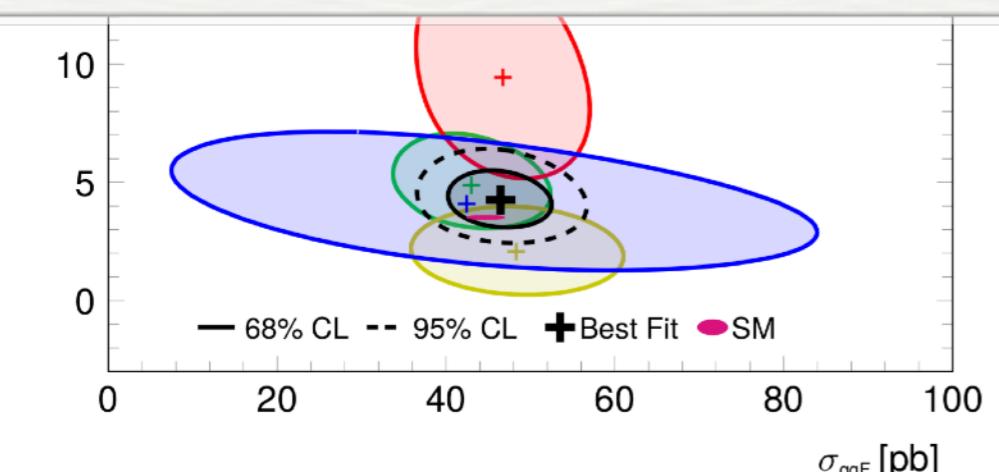
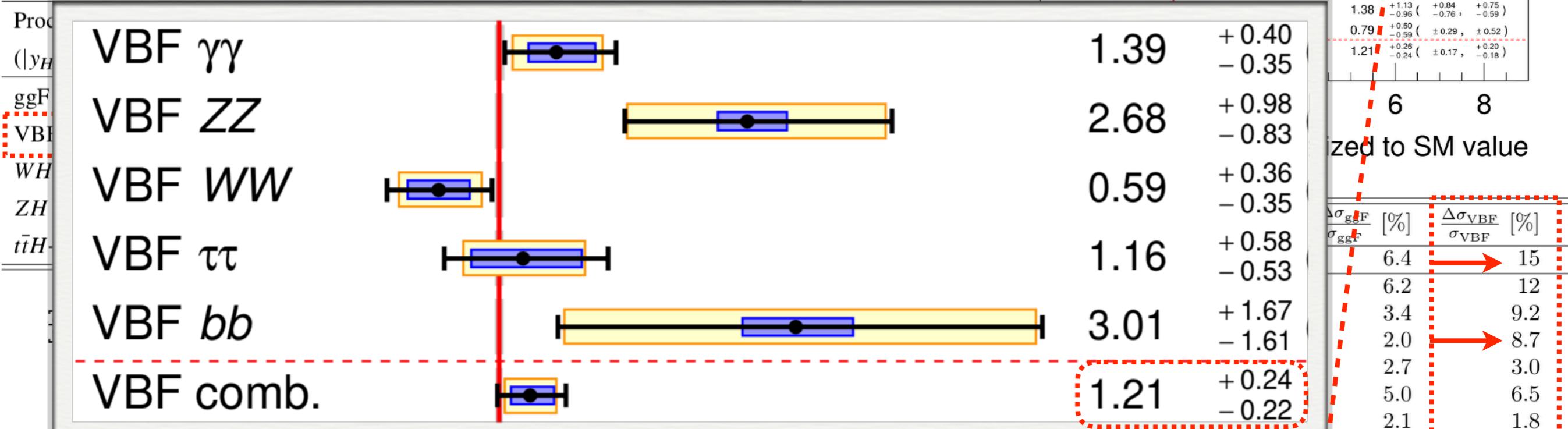
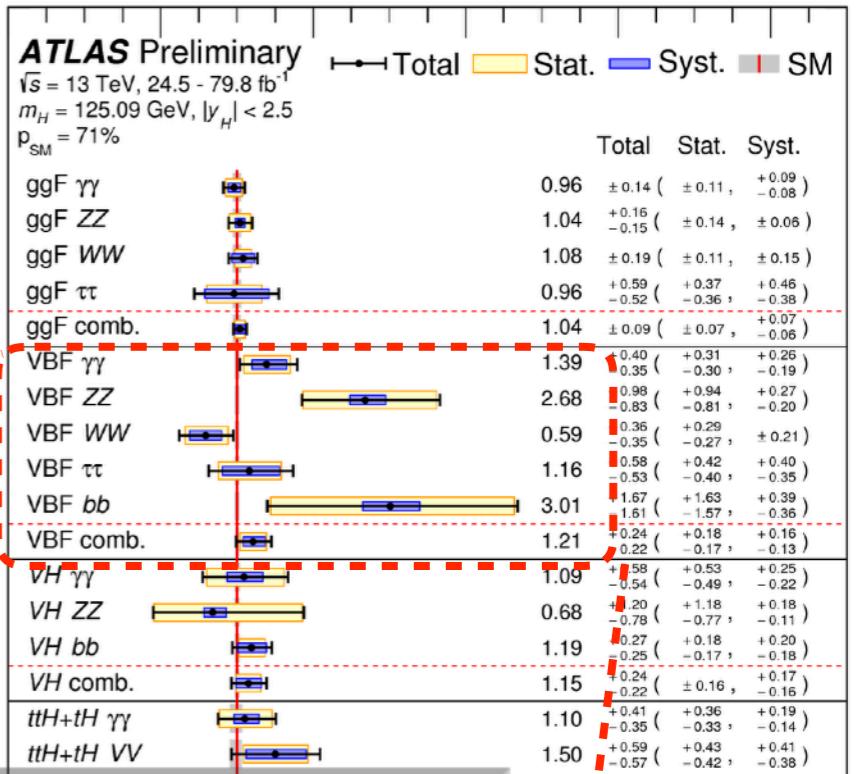
Process ( $ y_H  < 2.5$ )	Value [pb]	Uncertainty [pb]					SM pred. [pb]
		Total	Stat.	Exp.	Sig. th.	Bkg. th.	
ggF	46.5	$\pm 4.0$	$\pm 3.1$	$\pm 2.2$	$\pm 0.9$	$\pm 1.3$	$44.7 \pm 2.2$
VBF	4.25	$+0.84$	$+0.63$	$+0.35$	$+0.42$	$+0.14$	$3.515 \pm 0.075$
WH	1.57	$+0.48$	$+0.34$	$+0.25$	$+0.11$	$\pm 0.20$	$1.204 \pm 0.024$
ZH	0.84	$+0.25$	$\pm 0.19$	$\pm 0.09$	$+0.07$	$-0.04$	$0.797^{+0.033}_{-0.026}$
$t\bar{t}H+tH$	0.71	$+0.15$	$\pm 0.10$	$\pm 0.07$	$+0.05$	$+0.08$	$0.586^{+0.034}_{-0.049}$



Uncertainty source	$\frac{\Delta\sigma_{\text{ggF}}}{\sigma_{\text{ggF}}} [\%]$	$\frac{\Delta\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}} [\%]$
Statistical uncertainties	6.4	15
Systematic uncertainties	6.2	12
Theory uncertainties	3.4	9.2
Signal	2.0	8.7
Background	2.7	3.0
Experimental uncertainties (excl. MC stat.)	5.0	6.5
Luminosity	2.1	1.8
Background modeling	2.5	2.2
Jets, $E_T^{\text{miss}}$	0.9	5.4
Flavour tagging	0.9	1.3
Electrons, photons	2.5	1.7
Muons	0.4	0.3
$\tau$ -lepton	0.2	1.3
Other	2.5	1.2
MC statistical uncertainties	1.6	4.8
Total uncertainties	8.9	19

# Combined Higgs result

- Based on 2015-2017  $\gamma\gamma$ ,  $ZZ$ ,  $WW$ ,  $\tau\tau$ ,  $bb$  data (up to  $80 \text{ fb}^{-1}$ )
  - Note: hence based on previous  $HZZ$  result
- 5 parameter production mode gives VBF 1.21 times SM
  - Statistical uncertainty dominates



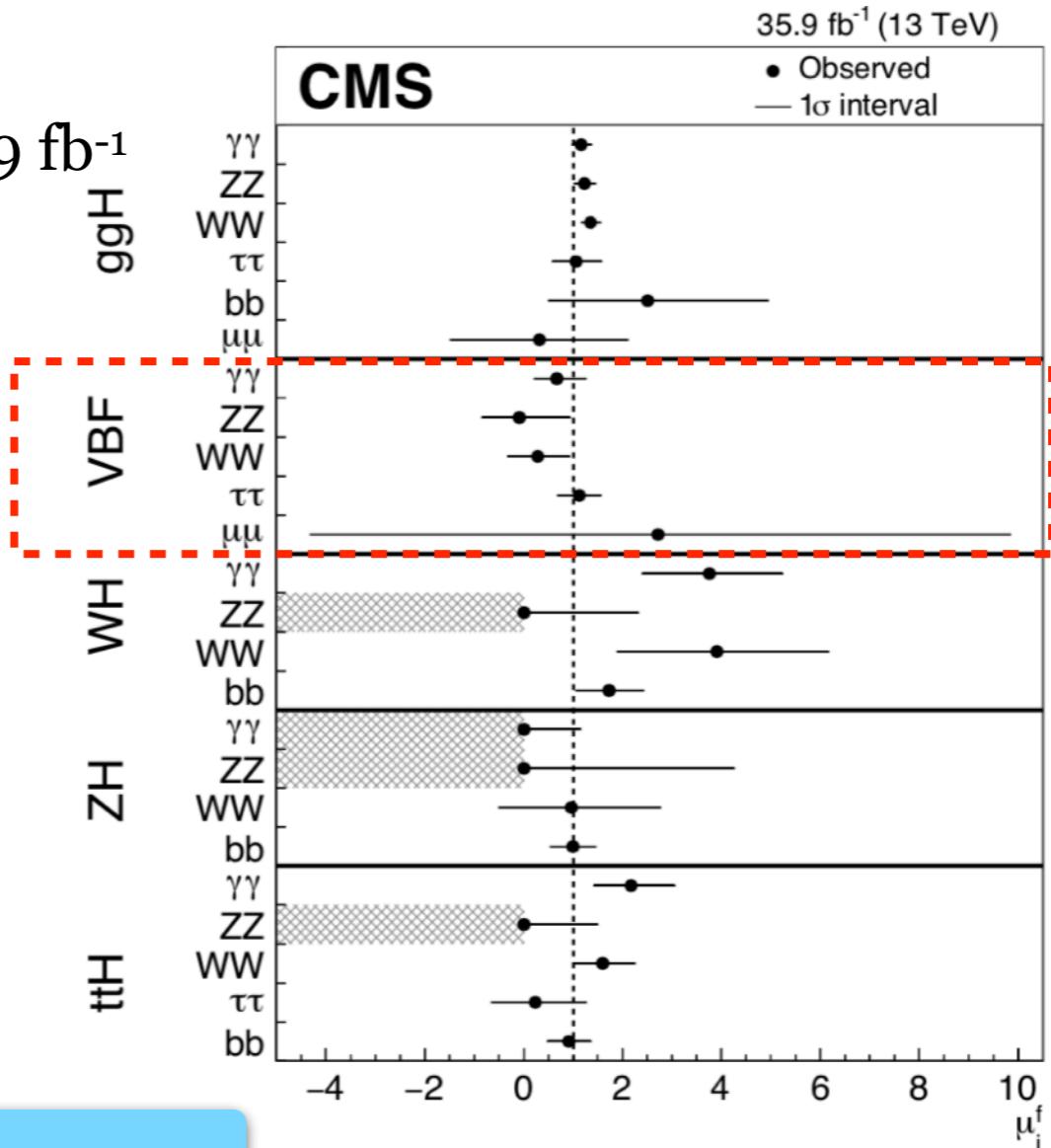
**<20% uncertainty!**



# Combined Higgs results

- Based on **2016** dataset  $\gamma\gamma, ZZ, WW, \tau\tau, bb, \mu\mu$   $35.9 \text{ fb}^{-1}$ 
  - Note: only 25% of full Run-2 dataset
- Combined measurement still quite precise:
  - 23% stat error, 17% sys error
$$\mu_{\text{VBF}} = 0.73^{+0.30}_{-0.27}$$
- As for ATLAS  
 Several channels important:  $\gamma\gamma, WW, \tau\tau$

	ggH			VBF		
	Best fit value	Uncertainty stat	Uncertainty syst	Best fit value	Uncertainty stat	Uncertainty syst
H $\rightarrow \tau\tau$	1.05 (+0.45) (-0.41)	+0.25 (+0.23) (-0.23)	+0.46 (+0.38) (-0.34)	1.12 (+0.45) (-0.43)	+0.45 (+0.37) (-0.35)	+0.37 (+0.25) (-0.24)
H $\rightarrow WW$	1.35 (+0.17) (-0.16)	+0.12 (+0.10) (-0.10)	+0.17 (+0.13) (-0.12)	0.28 (+0.62) (-0.58)	+0.64 (+0.57) (-0.53)	+0.58 (+0.26) (-0.25)
H $\rightarrow ZZ$	1.22 (+0.22) (-0.20)	+0.20 (+0.20) (-0.19)	+0.12 (+0.10) (-0.07)	-0.09 (+1.27) (-0.99)	+1.02 (+1.25) (-0.97)	+1.00 (+0.23) (-0.21)
H $\rightarrow \gamma\gamma$	1.16 (+0.17) (-0.16)	+0.17 (+0.14) (-0.14)	+0.13 (+0.11) (-0.08)	0.67 (+0.59) (-0.48)	+0.59 (+0.48) (-0.43)	+0.49 (+0.34) (-0.21)



New:  $1.03 \pm 0.30$   
(VBF+VH-had)

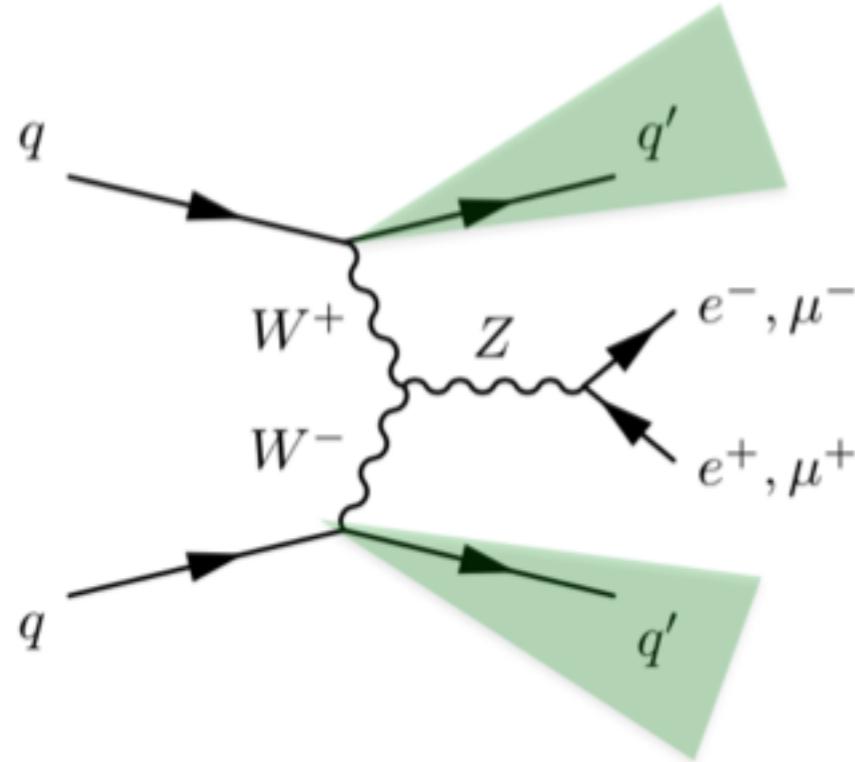
New:  $0.64 \pm 0.45$

New:  $0.8 \pm 0.4$

## II. EW $Zjj$ VBF results

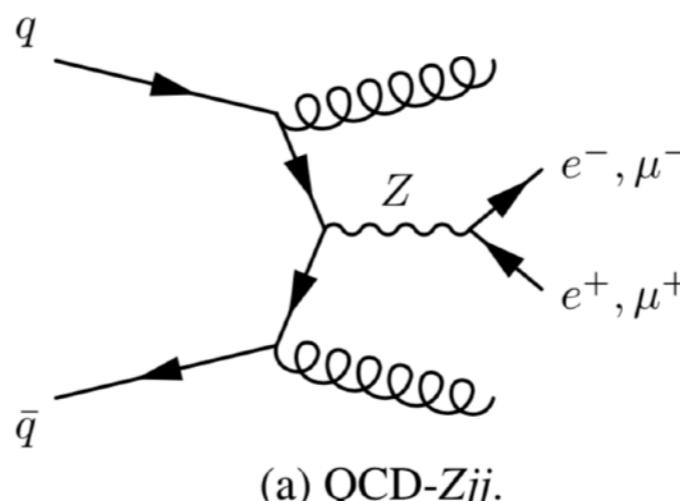
ATLAS	CMS
<u>STDM-2016-09, 3.2 fb<sup>-1</sup></u>	<u>SMP-16-018, 35.9 fb<sup>-1</sup></u>

# Electroweak $Zjj$ production



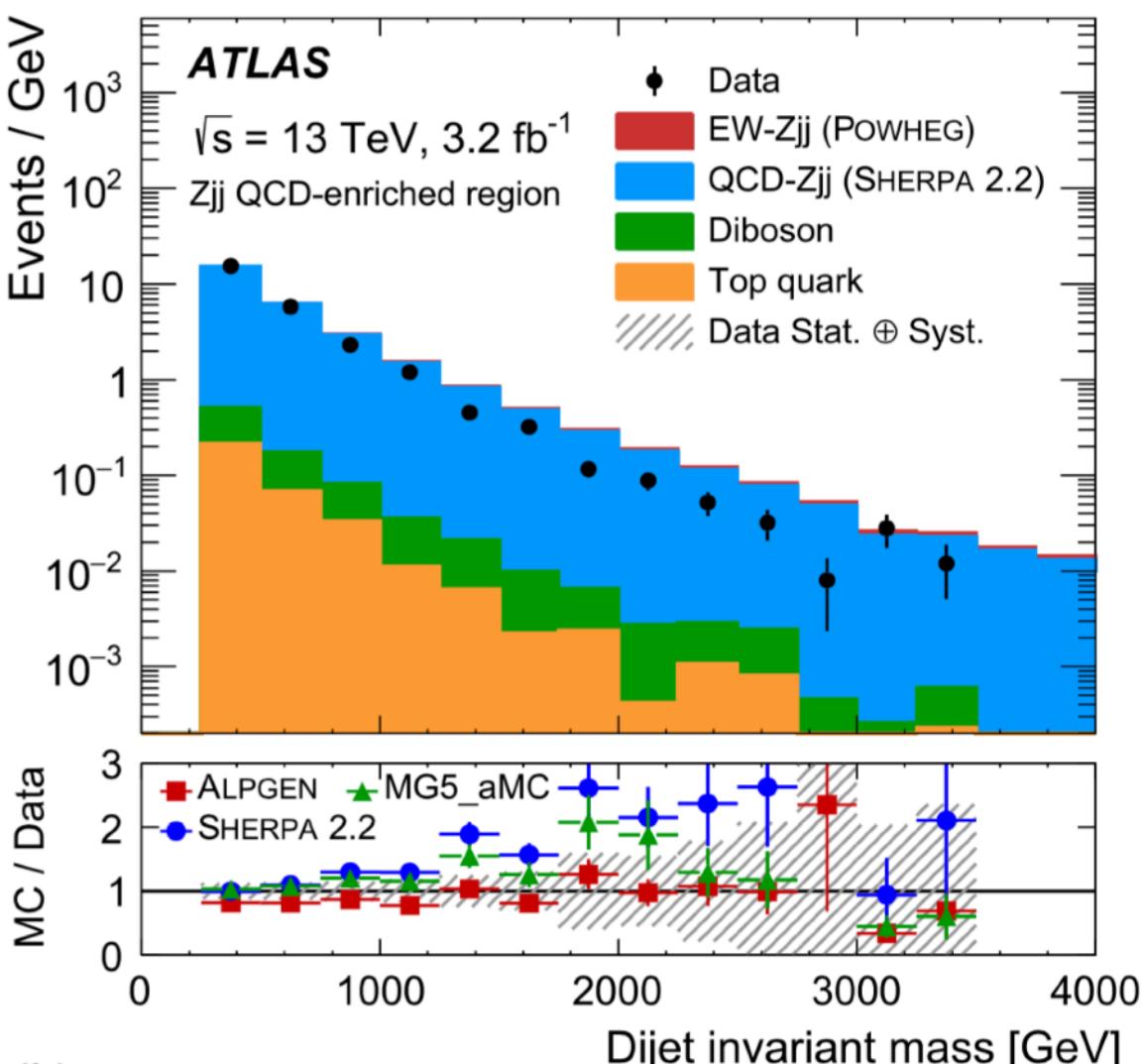
- First studies at 7 TeV by CMS, observation by ATLAS at 8 TeV, confirmed by CMS
- Remeasured by both experiments at 13 TeV
- Measurements
  - ATLAS: fiducial cross sections
  - CMS: signal strength and inclusive cross sections (BDT based)
- Different phase-space targeted by ATLAS and CMS: comparison of results not straight forward

- Dominant background: Strong  $Zjj$  production (standard  $Z$  production + 2 jets)
  - Referred to as QCD- $Zjj$  or just “QCD” on ATLAS plots
  - Drell-Yan by CMS

(a) QCD- $Zjj$ .

# VBF Z result (1/2)

- Results based on first 13 TeV data (2015) 3.2 fb<sup>-1</sup>
- Six fiducial regions defined to measure inclusive Zjj (strong and EW combined)
- EW Zjj signal extracted from template fit vs  $m_{jj}$  in EW enhanced region
- Main issue: Modelling of strong Zjj contribution



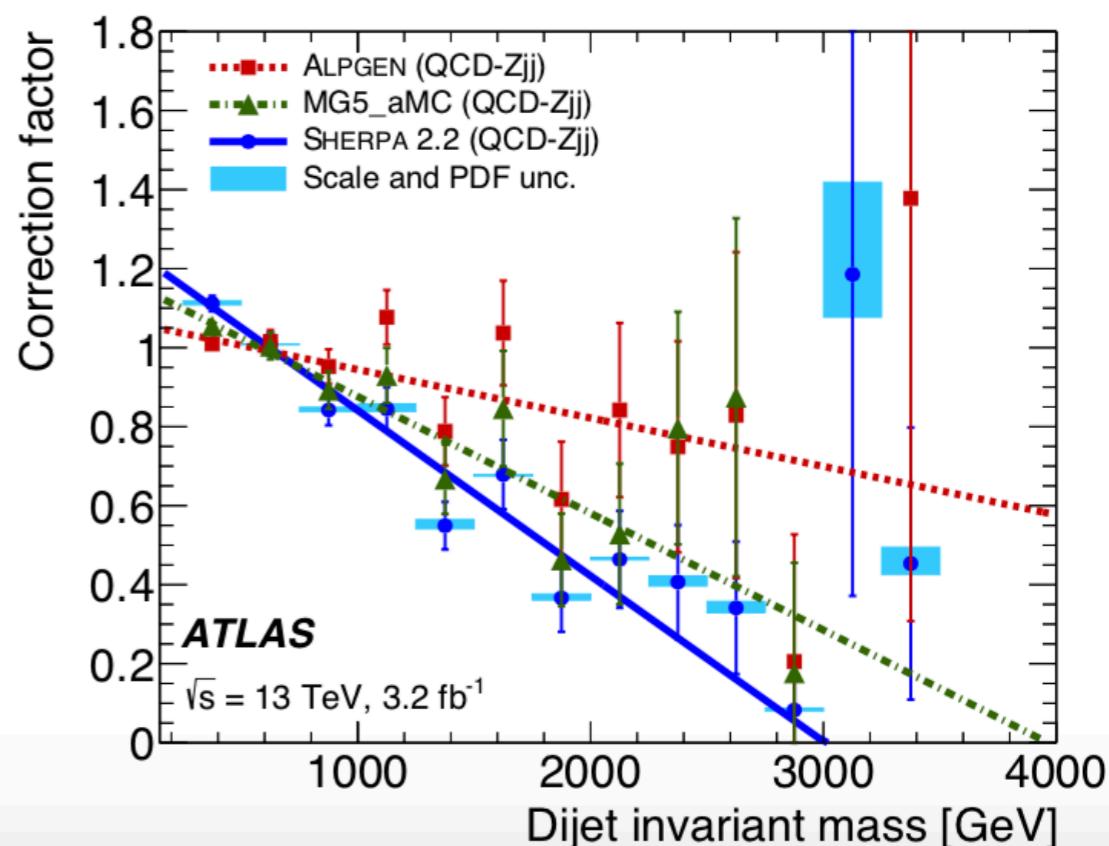
Summary of the particle-level selection criteria defining the six fiducial regions (see text for details).

Object	Fiducial region					
	Baseline	High-mass	High- $p_T$	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$ \eta  < 2.47$ , $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
Jets	$ y  < 4.4$					
	$p_T^{j_1} > 55$ GeV	$p_T^{j_1} > 85$ GeV	$p_T^{j_1} > 55$ GeV			
	$p_T^{j_2} > 45$ GeV	$p_T^{j_2} > 75$ GeV	$p_T^{j_2} > 45$ GeV			
	-	$m_{jj} > 1$ TeV	-	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Dijet system	-	$m_{jj} > 1$ TeV	-	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	-			$N_{\text{jet } (p_T > 25 \text{ GeV})}^{\text{interval}} = 0$	$N_{\text{jet } (p_T > 25 \text{ GeV})}^{\text{interval}} \geq 1$	
Zjj system	-			$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance},3} < 0.15$	

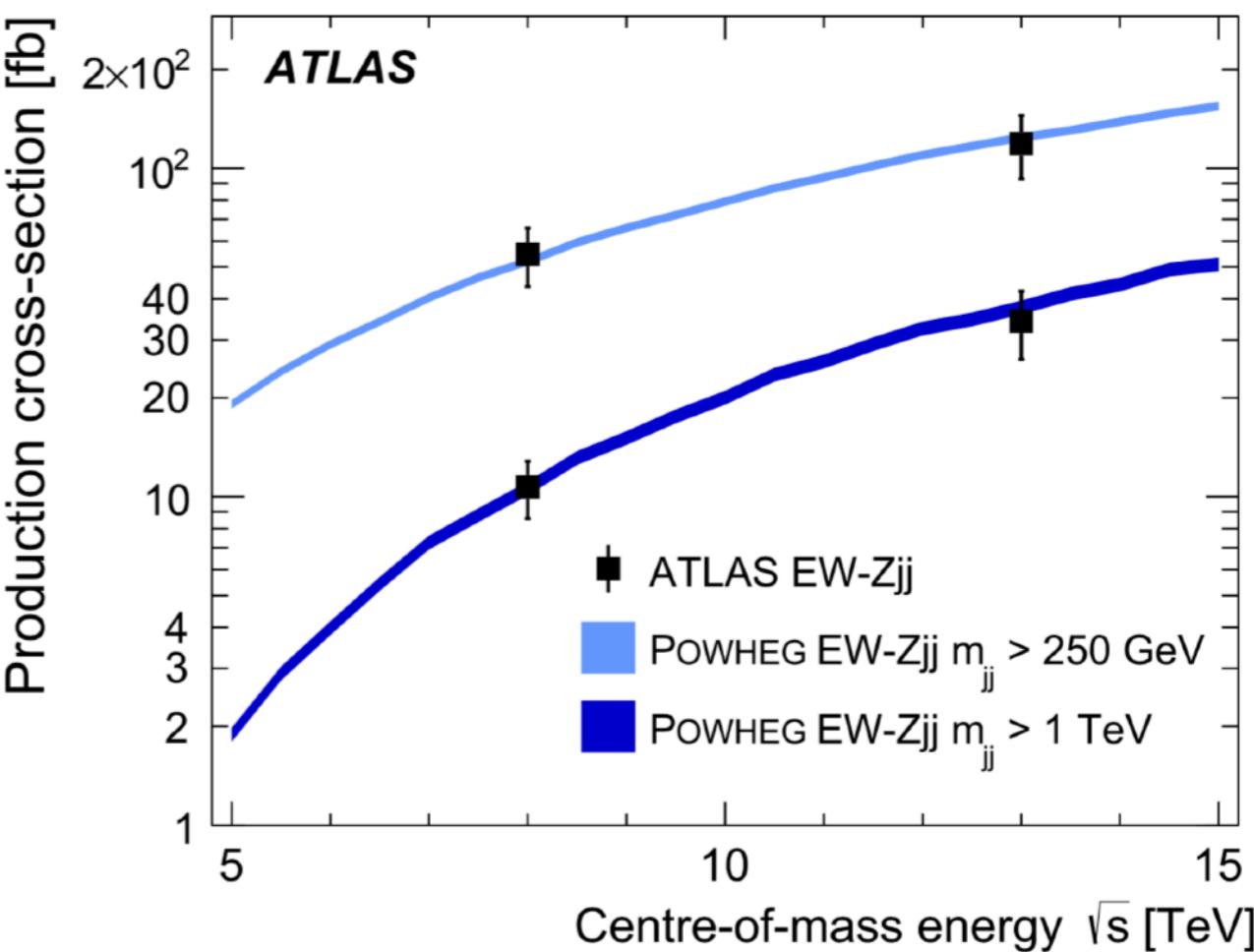
MC samples tend to overestimate strong Zjj at high  $m_{jj}$ . In particular Sherpa.

# VBF Z result (2/2)

- A data-based correction factor is derived in the strong- $Z_{jj}$  enhanced region and is applied also to the strong  $Z_{jj}$  prediction in the VBF region
  - Scales down strong  $Z_{jj}$  template at high  $m_{jj}$
  - Crucial to get sensible EW  $Z_{jj}$  measurements
- After this data-driven correction to the dominant background, measured  $\sigma_{VBF}$  is very close to SM prediction
  - Dominant uncertainty bkg modelling
- Analysis based on full Run-2 dataset that includes differential cross section measurements is in progress

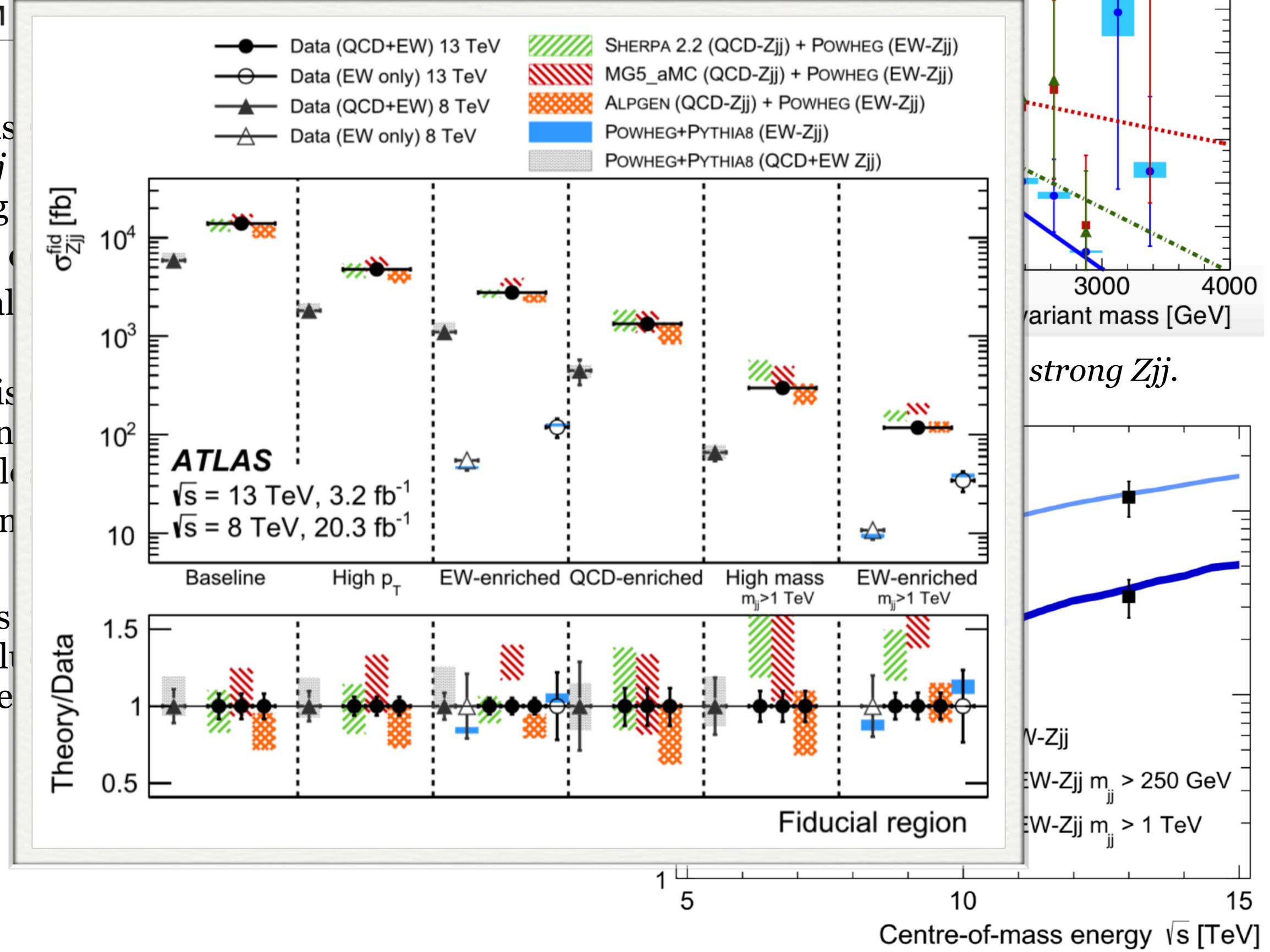


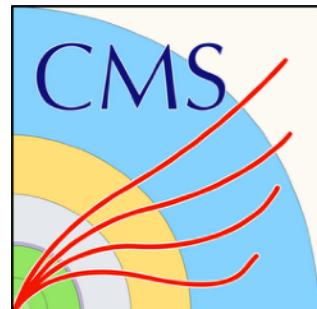
*Correction applied to strong  $Z_{jj}$ .*



## VBF $Z$ result (2/2)

- A data-based strong- $Z_{jj}$  fit to the strong  $Z$  signal.
- Scales & PDFs are crucial.
- After this analysis, the dominant source of uncertainty is very clear.
- Dominant uncertainty is statistical.
- Analysis based on data that includes the  $Z$  signal measurement.





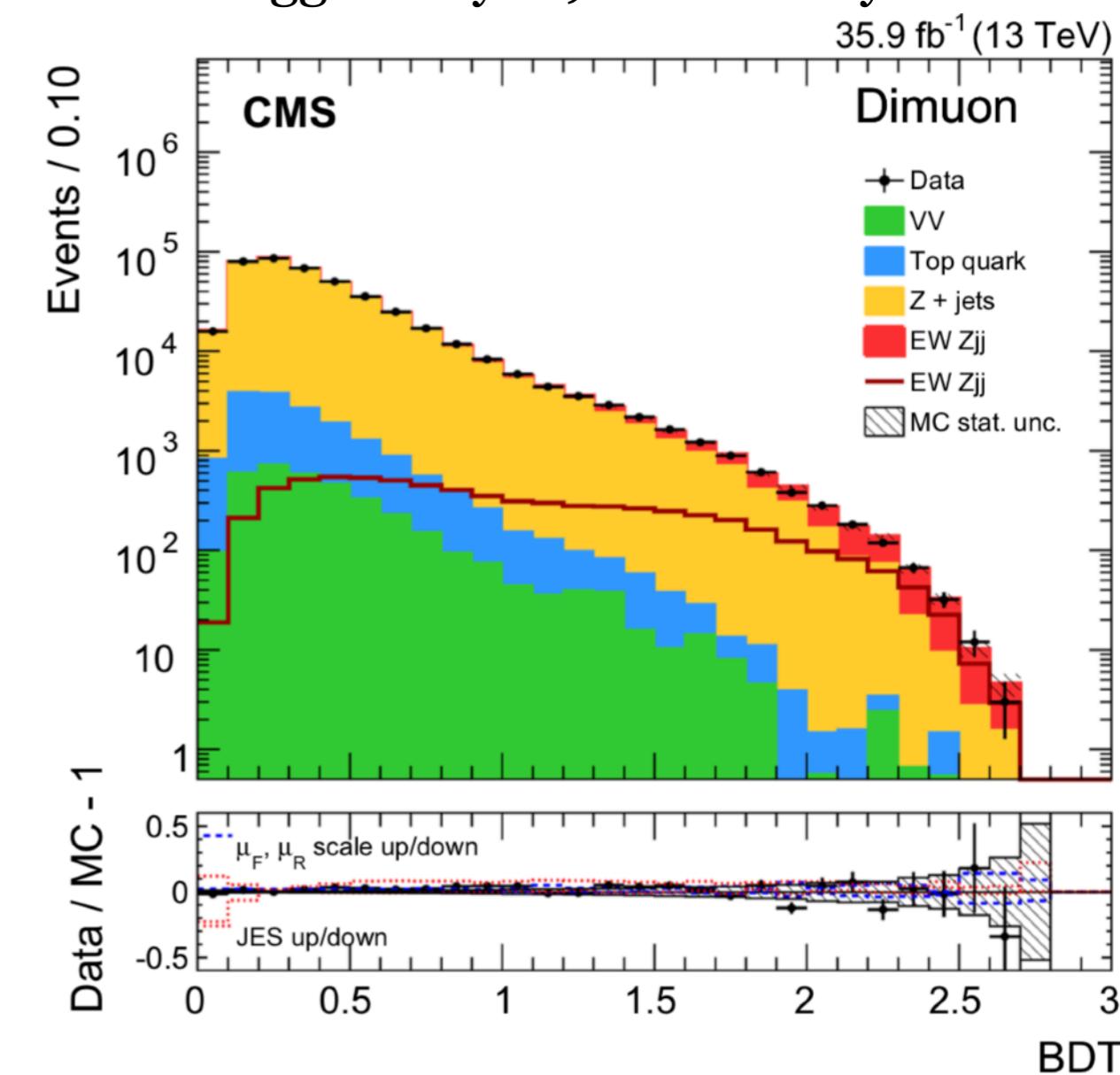
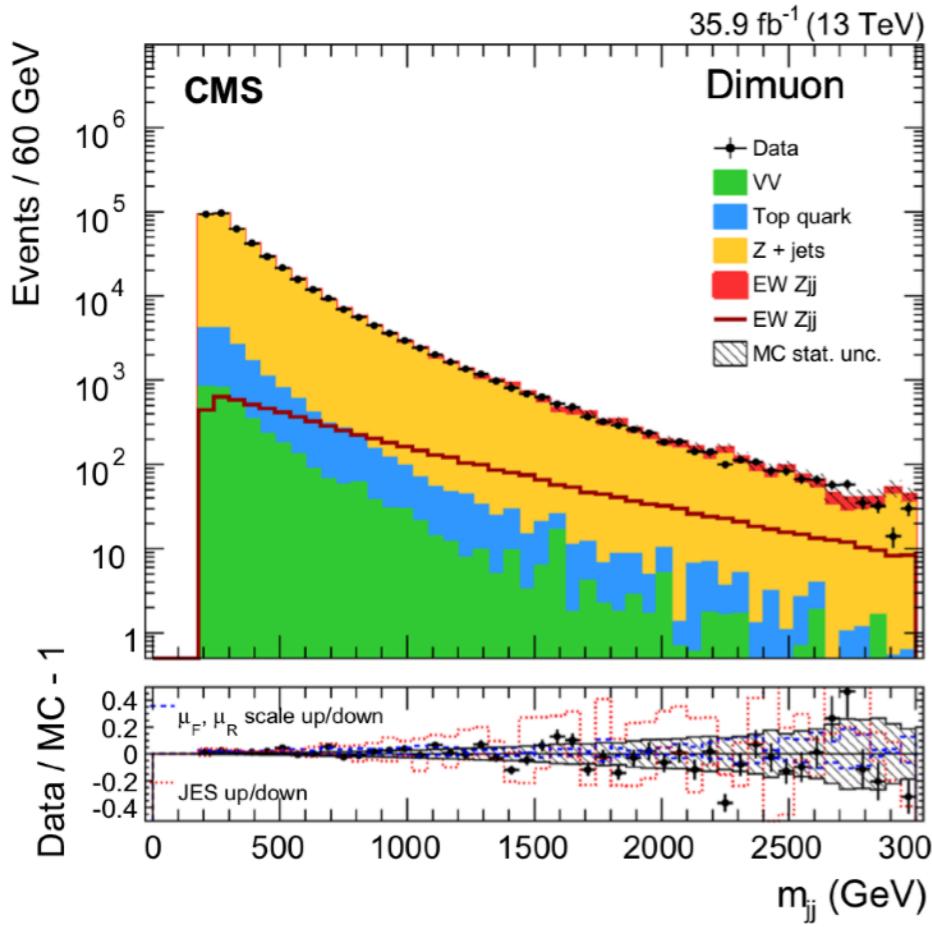
# VBF Z result (1/2)

CMS Collaboration

28 December 2017

[Eur. Phys. J. C 78 \(2018\) 589](https://doi.org/10.1140/epjc/s10050-018-6089-1)

- Results based on 2016 13 TeV data  $35.9 \text{ fb}^{-1}$
- Important difference wrt to ATLAS: strong  $Zjj$  modelled by aMC@NLO accurate to **NLO** for the first **three jets** using the FxFx merging prescription
- Different strategy: very loose preselection (similar to Higgs analysis) followed by BDT analysis using 5 input variables:  
 $m_{jj}$ ,  $\Delta\eta_{jj}$ ,  $p_{T,jj}$ ,  $j_1$  and  $j_2$  quark-gluon tagging score,  $p_{T,Zjj} / H_{T,Zjj}$



# VBF Z result (2/2)

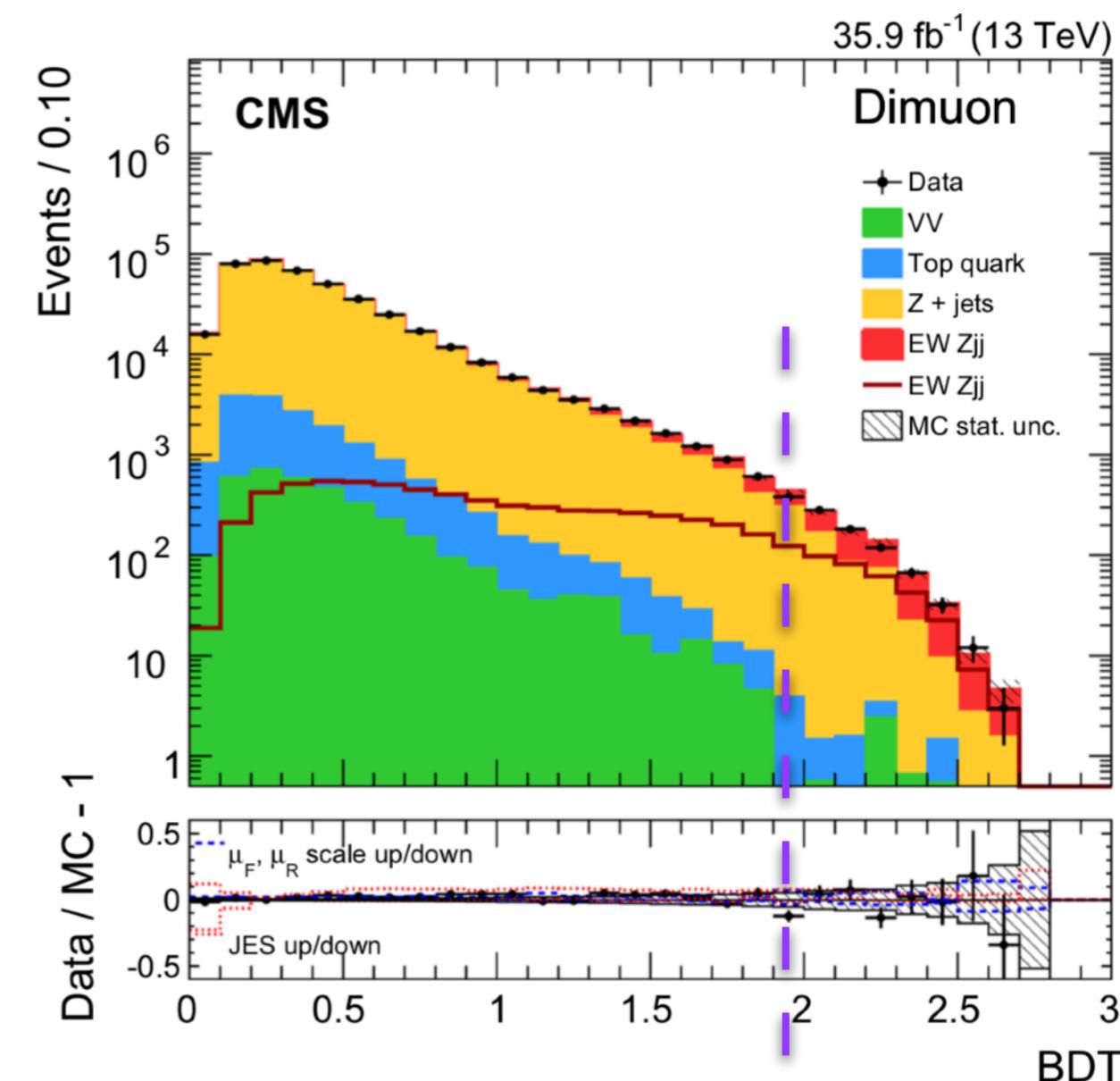
CMS Collaboration

28 December 2017

[Eur. Phys. J. C 78 \(2018\) 589](https://doi.org/10.1140/epjc/s10050-018-6009-0)

- Measured EW  $Zjj$  cross section found consistent with SM
  - Several systematics significant @ 3-6%  
Uncertainties on strong  $Z+jets$  ( $\mu_r/\mu_f$ , parton-shower, interference with EW  $Zjj$ )  
JES/JER, pileup, MC statistics
- $p_{TZ}$  spectrum also studied for aTGC providing 1D constraints on  $c_{WWW}$ ,  $c_W$ .
  - In particular sensitive to  $c_{WWW}$

Coupling constant	Observed 95% CL interval ( $\text{TeV}^{-2}$ )
$c_{WWW}/\Lambda^2$	$[-2.6, 2.6]$
$c_W/\Lambda^2$	$[-8.4, 10.1]$
- Also study hadronic jet kinematics in EW  $Zjj$  enhanced region
  - Jet vetoes,  $pTj3$ ,  $H_T$  of tracks
  - Indication MC overestimate such jet, in particular when Pythia used for PS



### III. VBF $W$ results

ATLAS

CMS

STDM-2014-11, 25 fb<sup>-1</sup> @ 7-8 TeV    SMP-13-012, 19.3 fb<sup>-1</sup> @ 8 TeV

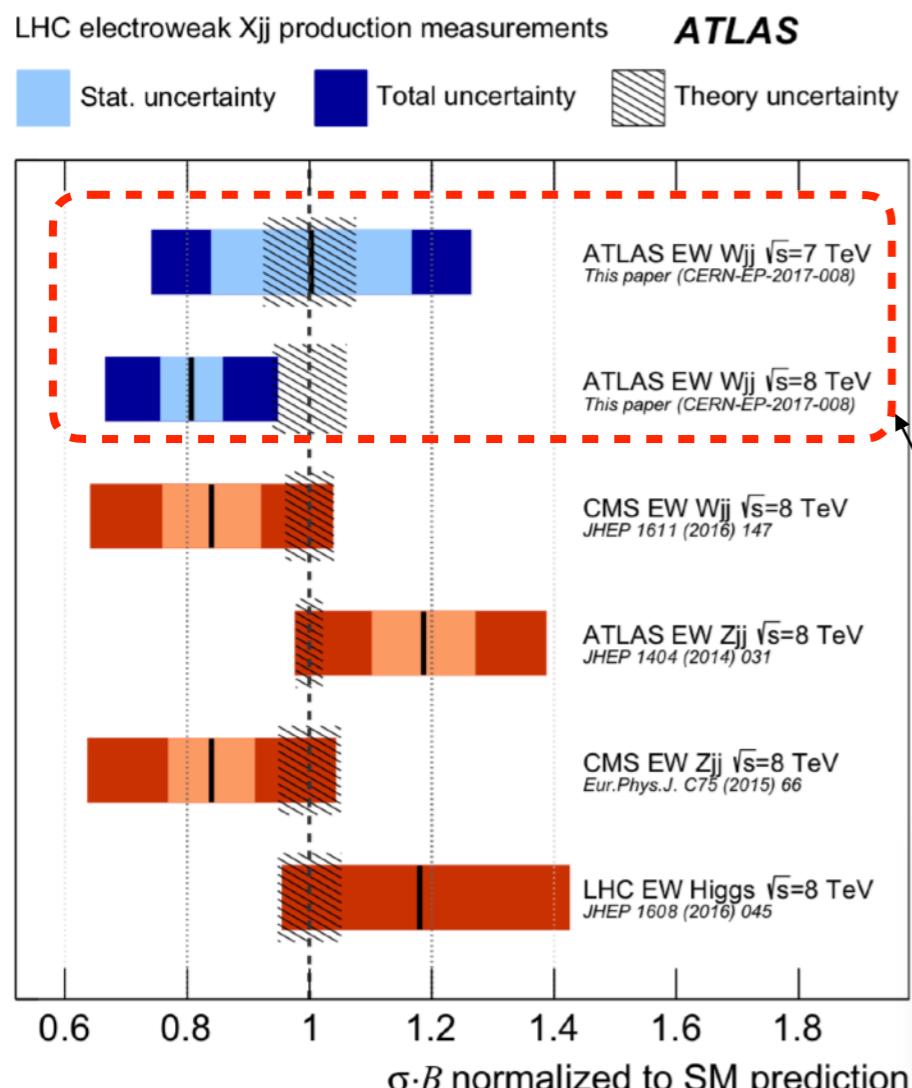
# EW $Wjj$ result

13 March 2017

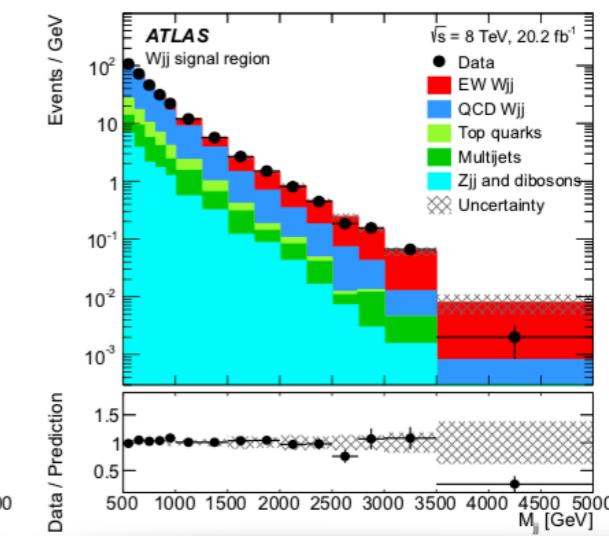
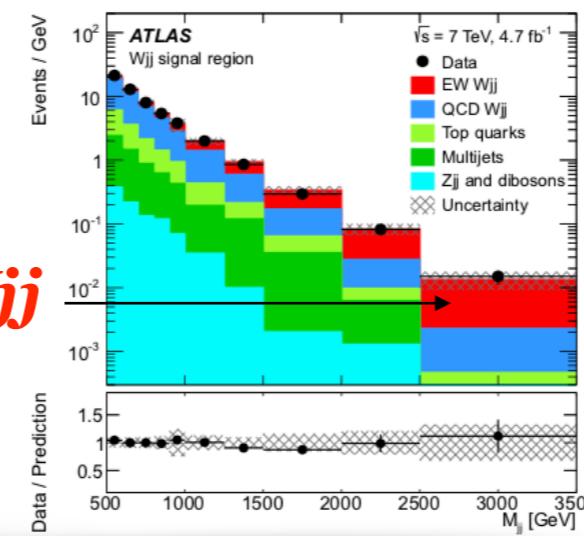
- 2011+2012 dataset (7+8 TeV)
- Measurement in several fiducial region, separately EW and strong  $Wjj$
- Selection: Standard  $W \rightarrow \ell\nu$  selection and

$$\begin{aligned} p_T^{j_1} &> 80 \text{ GeV} \\ p_T^{j_2} &> 60 \text{ GeV} \\ \text{Jet } |y| &< 4.4 \\ M_{jj} &> 500 \text{ GeV} \\ \Delta y(j_1, j_2) &> 2 \\ \Delta R(j, \ell) &> 0.3 \end{aligned}$$

Fiducial and differential measurements
Signal region
Forward-lepton control region
Central-jet validation region
Differential measurements only
Inclusive regions
Forward-lepton/central-jet region
High-mass signal region
Anomalous coupling measurements only
High- $q^2$ region



- Control regions used to constrain **strong  $Wjj$**
- Cross section (of SR) extracted from  $m_{jj}$  template fit

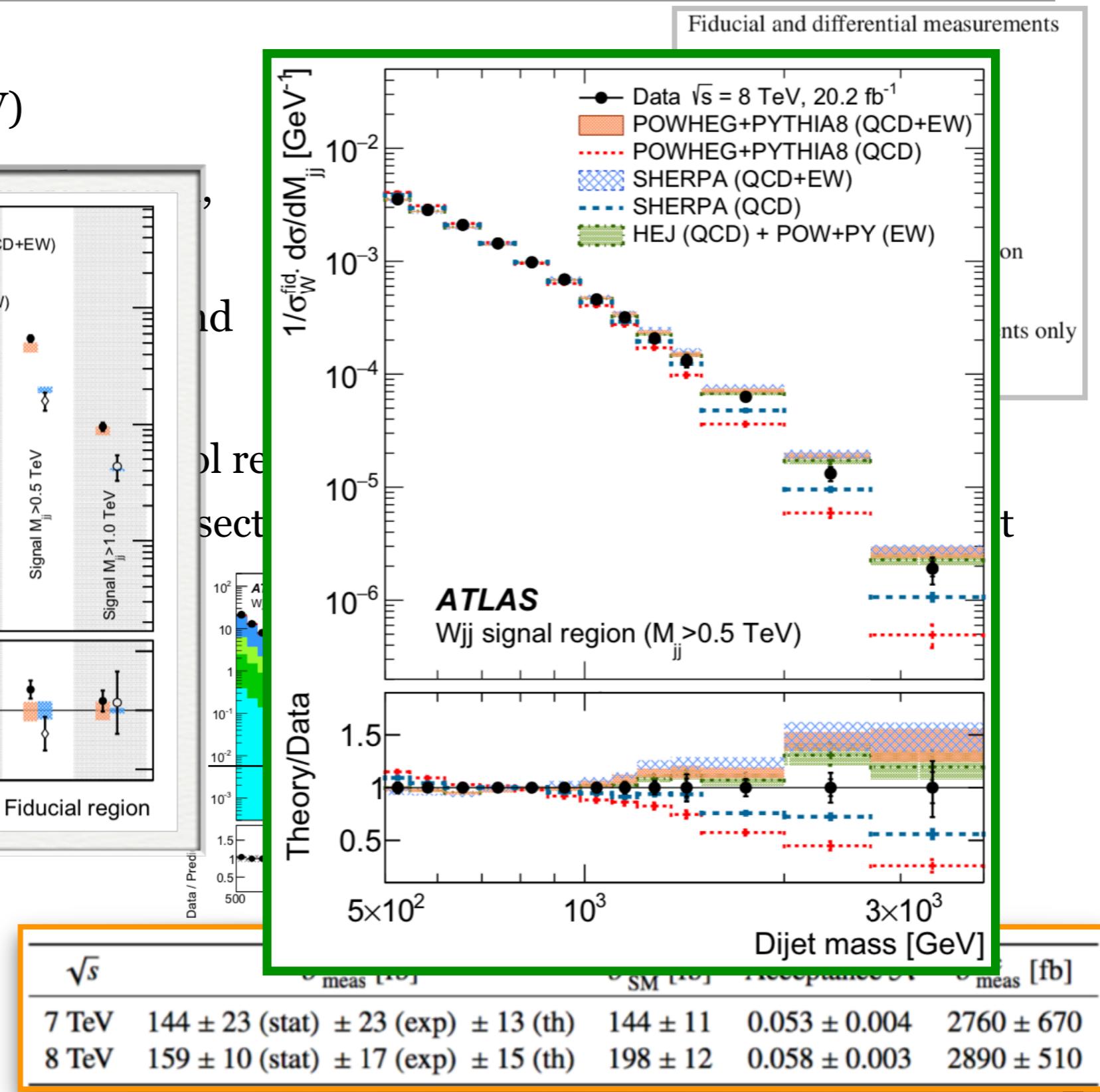
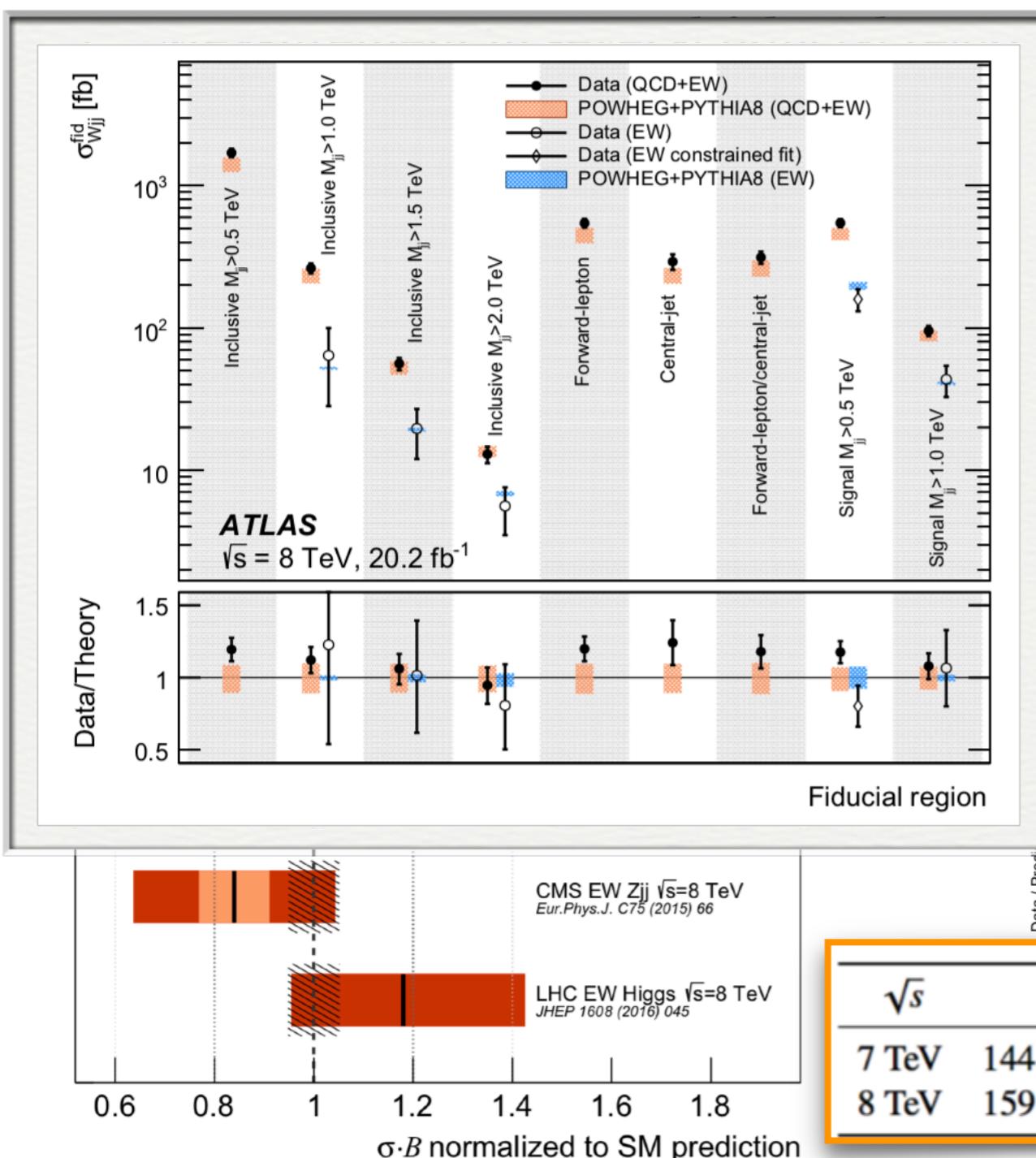

**EW  $Wjj$** 

$\sqrt{s}$	$\sigma_{\text{meas}}^{\text{fid}}$ [fb]	$\sigma_{\text{SM}}^{\text{fid}}$ [fb]	Acceptance $\mathcal{A}$	$\sigma_{\text{meas}}^{\text{inc}}$ [fb]
7 TeV	$144 \pm 23 \text{ (stat)} \pm 23 \text{ (exp)} \pm 13 \text{ (th)}$	$144 \pm 11$	$0.053 \pm 0.004$	$2760 \pm 670$
8 TeV	$159 \pm 10 \text{ (stat)} \pm 17 \text{ (exp)} \pm 15 \text{ (th)}$	$198 \pm 12$	$0.058 \pm 0.003$	$2890 \pm 510$

# EW $Wjj$ result

13 March 2017

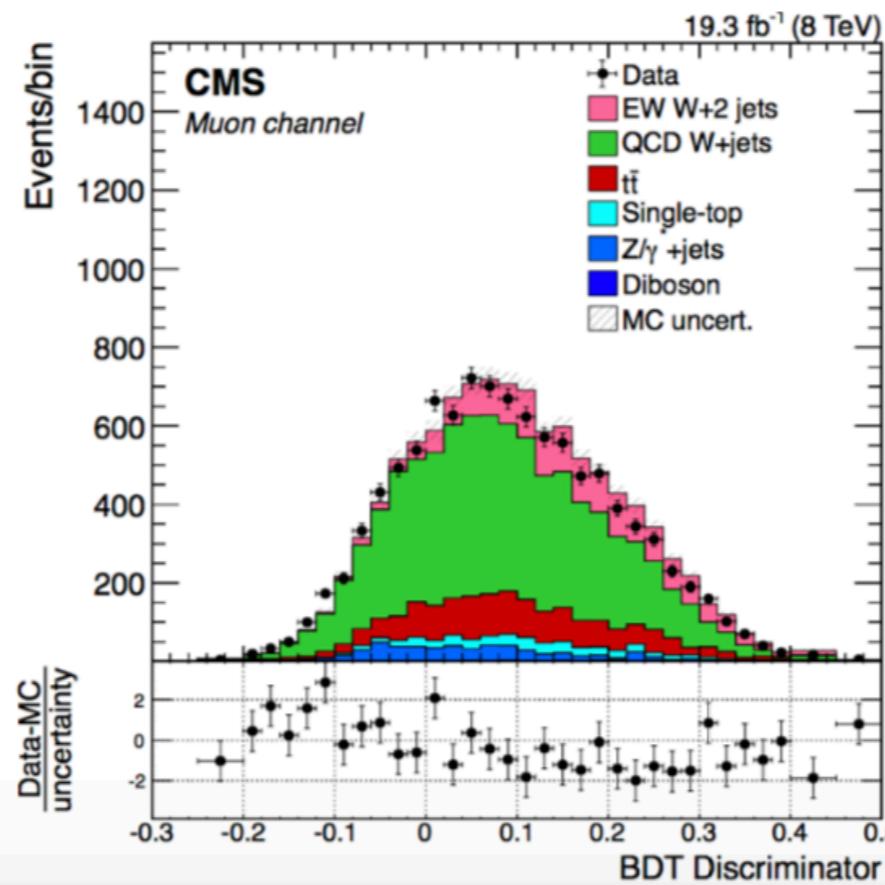
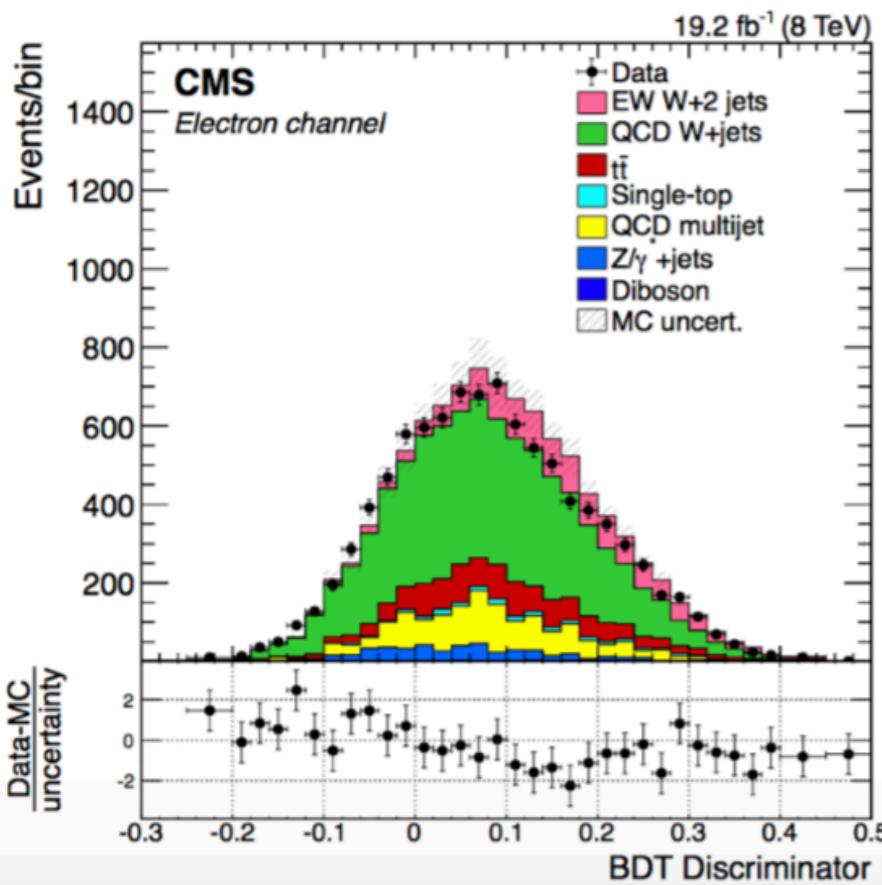
- 2011+2012 dataset (7+8 TeV)



# VBF W

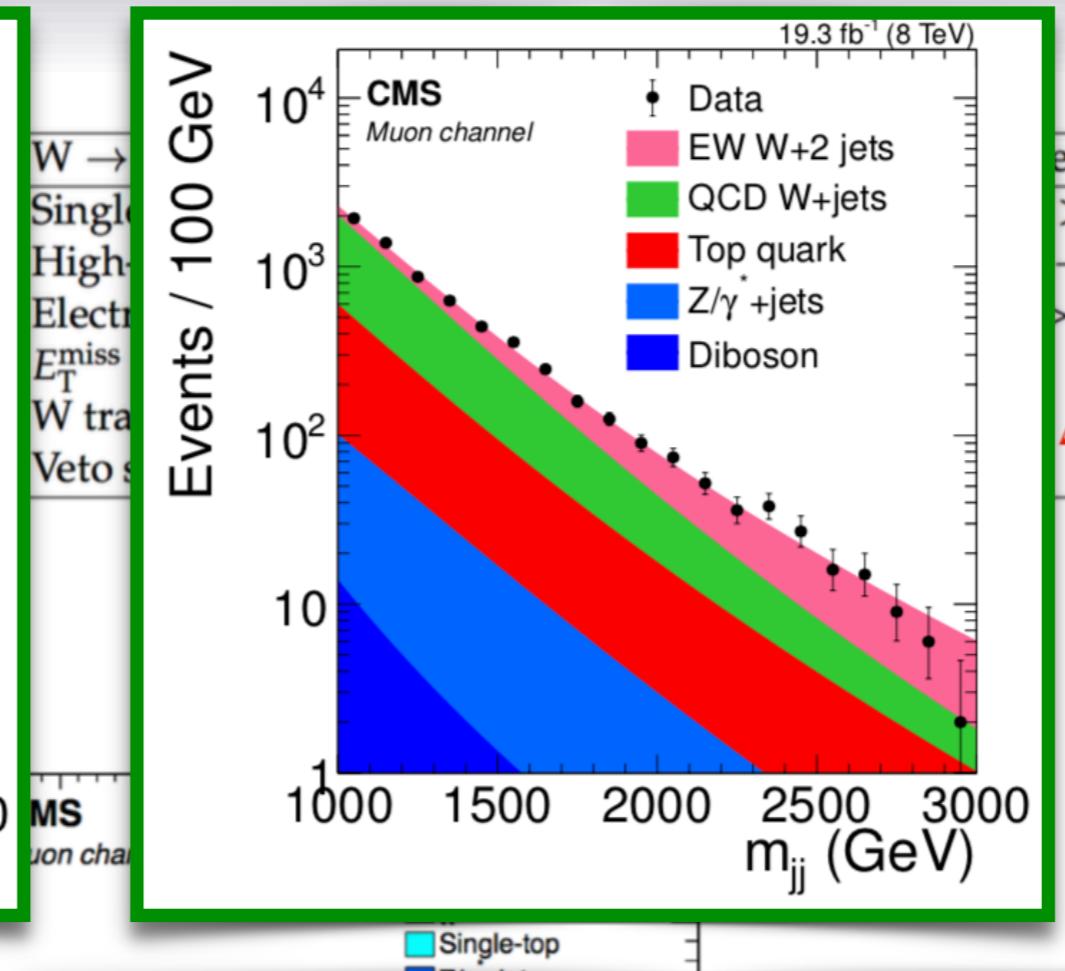
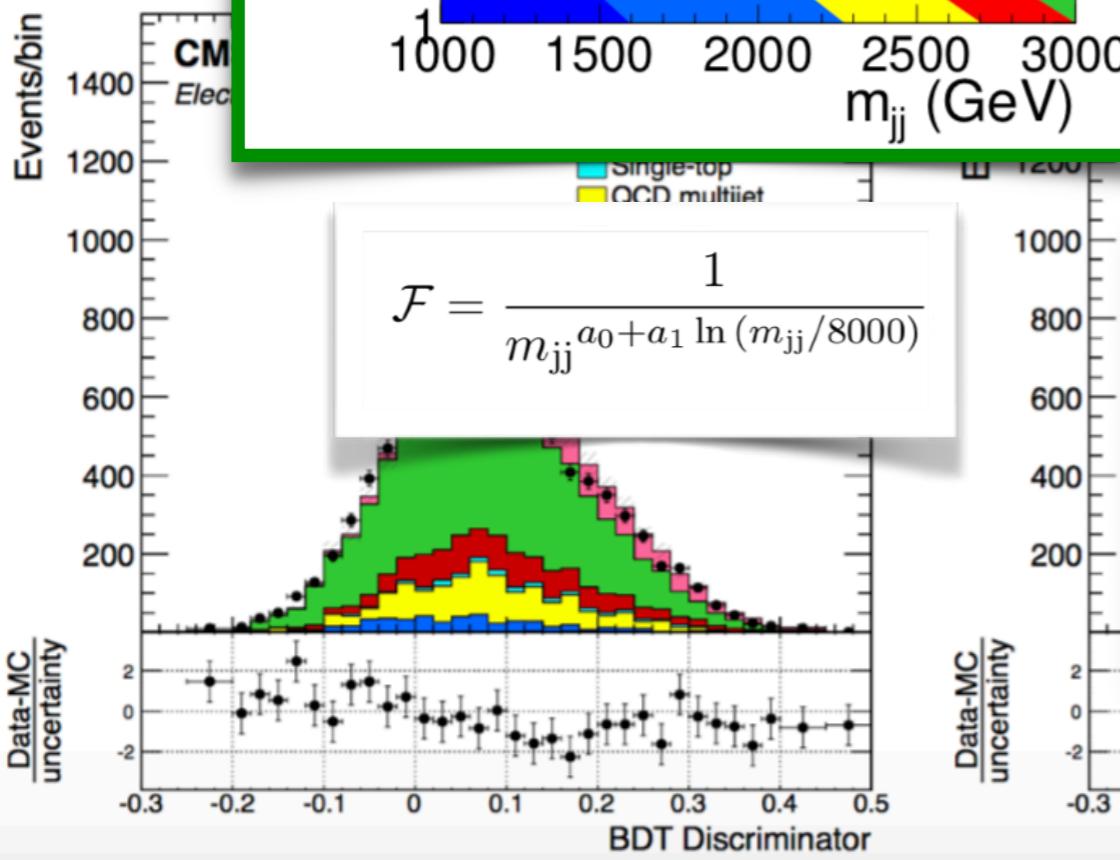
Fiducial xsec extracted  
from fit to BDT  
discriminant at high dijet  
mass (8 TeV)

$W \rightarrow \ell\nu$ Lepton requirements	Jet requirements
Single lepton trigger	$p_T^{j1} > 60 \text{ GeV}, p_T^{j2} > 50 \text{ GeV}$
High-quality lepton ID and isolation	$ y_W - (y_{j1} + y_{j2})/2  < 1.2$
Electron (muon) $p_T > 30$ (25) GeV	$m_{jj} > 1000 \text{ GeV}$
$E_T^{\text{miss}} > 30$ (25) GeV for electron (muon) channels	
W transverse mass $> 30 \text{ GeV}$	
Veto second lepton	no $ \Delta\eta $ requirement (?)



# VBF W

Fiducial  
from  
discussions



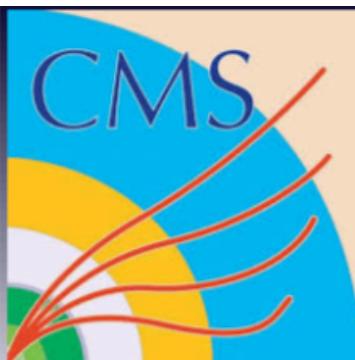
Channel	Measured cross section
Electron	$0.41 \pm 0.04 \text{ (stat)} \pm 0.09 \text{ (syst)} \pm 0.01 \text{ (lumi)} \text{ pb}$
Muon	$0.43 \pm 0.04 \text{ (stat)} \pm 0.10 \text{ (syst)} \pm 0.01 \text{ (lumi)} \text{ pb}$
Combined	$0.42 \pm 0.04 \text{ (stat)} \pm 0.09 \text{ (syst)} \pm 0.01 \text{ (lumi)} \text{ pb}$

**SM (@LO)**  $0.50 \pm 0.02 \text{ (scale)} \pm 0.02 \text{ (PDF)} \text{ pb}$

requirements

- > 60 GeV,  $p_T^{j2} > 50 \text{ GeV}$
- $(y_{j1} + y_{j2})/2 | < 1.2$
- > 1000 GeV

$\Delta\eta l$  requirement (?)



# VBF W - uncertainties

## CMS measurement uncertainties

Source of uncertainty	Electrons	Muons
Integrated luminosity	2.6%	
Jet energy scale	5.4%	7.3%
Jet energy resolution	2.2%	3.7%
QCD W+jets shape and normalization	13.0%	16.7%
Top quark background shape and normalization	5.5%	6.0%
Interference effect	14.4%	13.8%
Jets faking electrons fraction (electron channel)	4.4%	—
Lepton trigger efficiency	0.9%	1.0%
Lepton selection efficiency	1.8%	2.0%
Pileup	<1%	<1%
Fiducial acceptance	1.7%	1.7%
Total (without integrated luminosity)	21.6%	24.1%

Large interference uncertainty  
at CMS not seen in ATLAS.

JES/JER and QCD W+jets modeling  
uncertainties dominate.

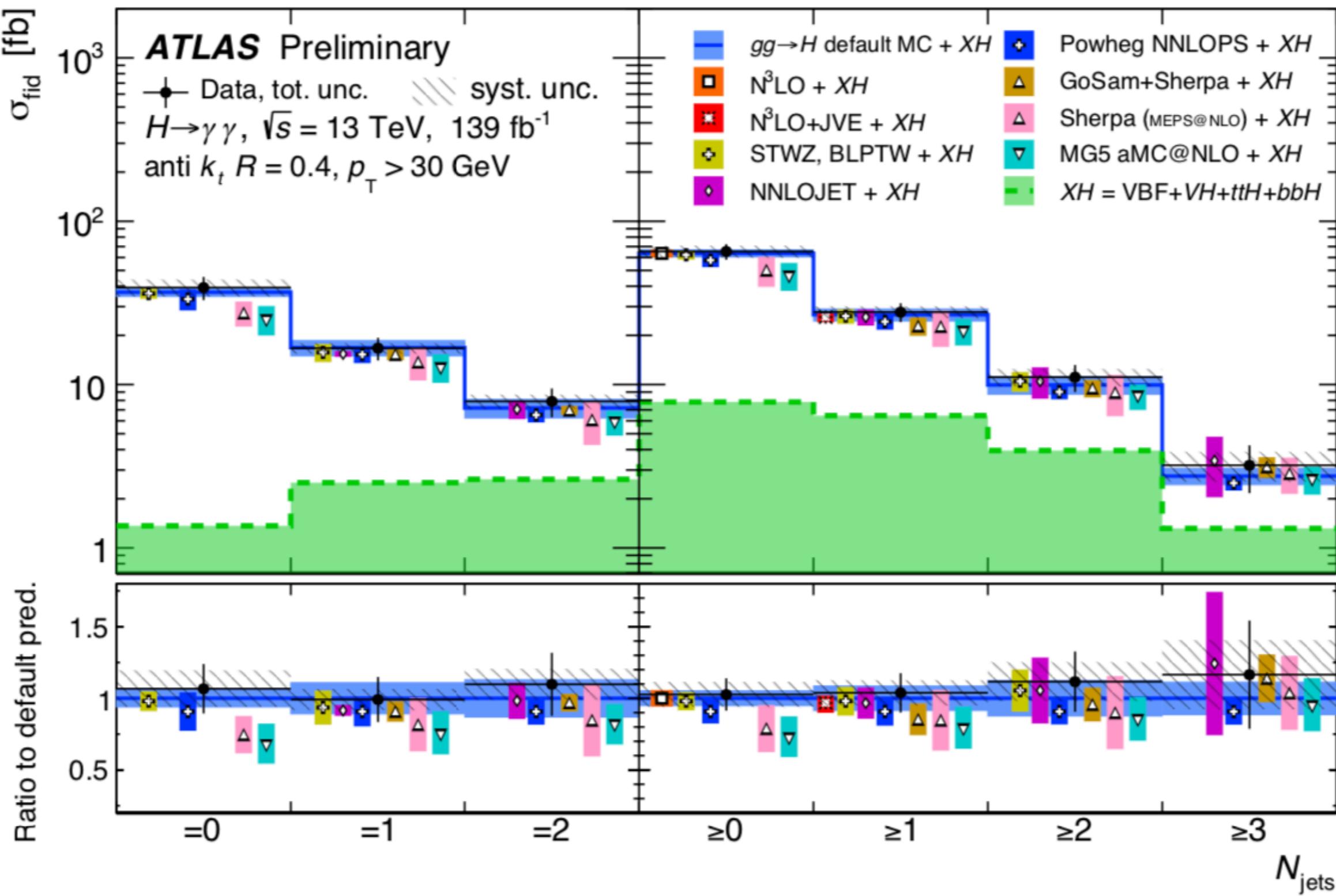
## ATLAS measurement uncertainties

Source	Uncertainty in $\mu_{EW}$	
	7 TeV	8 TeV
Statistical		
Signal region	0.094	0.028
Control region	0.127	0.044
Experimental		
Jet energy scale ( $\eta$ intercalibration)	0.124	0.053
Jet energy scale and resolution (other)	0.096	0.059
Luminosity	0.018	0.019
Lepton and $E_T^{\text{miss}}$ reconstruction	0.021	0.012
Multijet background	0.064	0.019
Theoretical		
MC statistics (signal region)	0.027	0.026
MC statistics (control region)	0.029	0.019
EW $Wjj$ (scale and parton shower)	0.012	0.031
QCD $Wjj$ (scale and parton shower)	0.043	0.018
Interference (EW and QCD $Wjj$ )	0.037	0.032
Parton distribution functions	0.053	0.052
Other background cross sections	0.002	0.002
EW $Wjj$ cross section	0.076	0.061
Total	0.26	0.14

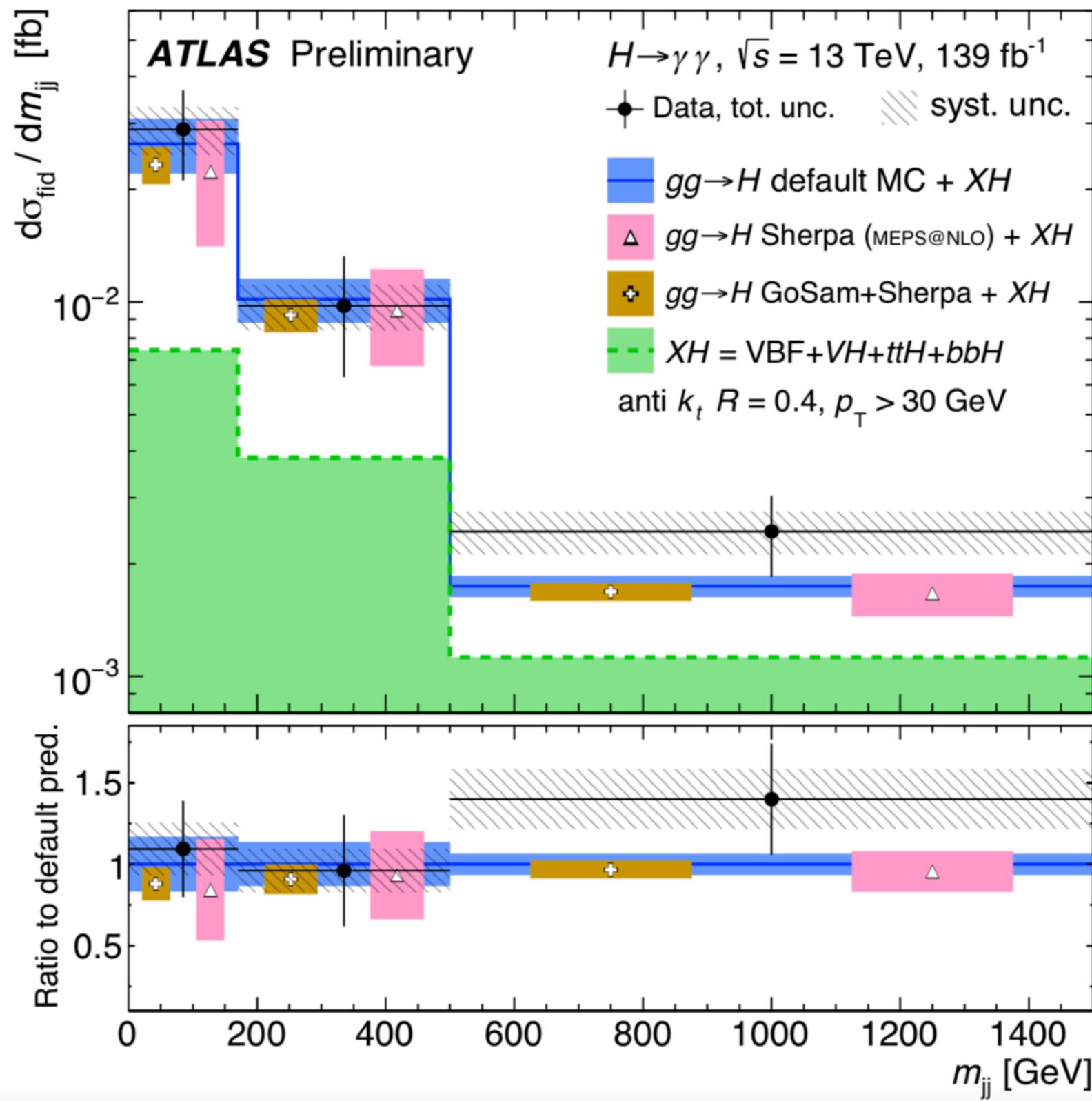
# Conclusion and outlook

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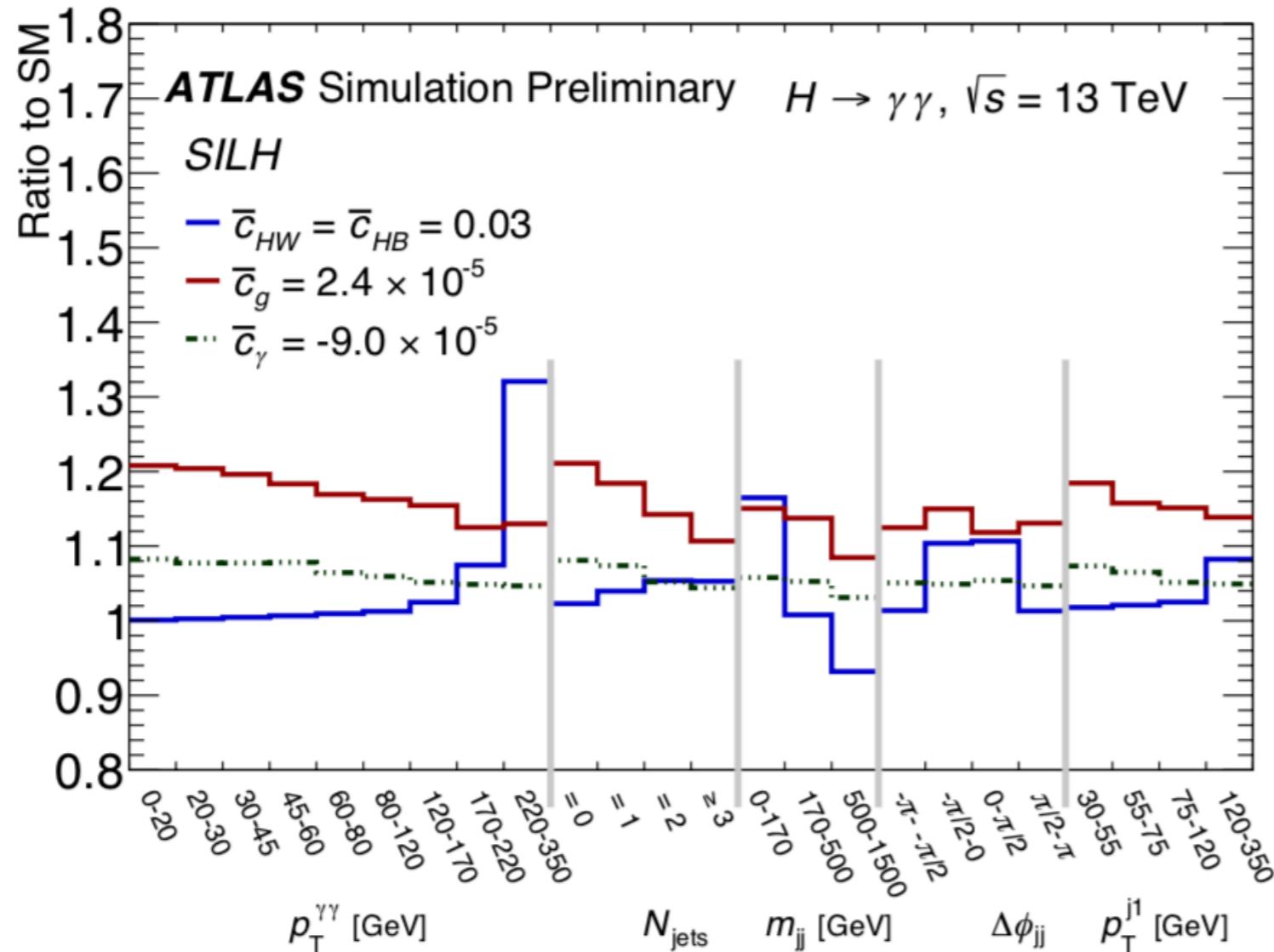
- Higgs VBF
  - Agreement with SM prediction
  - Statistical uncertainty still dominating
    - But expected to be very close to systematics for full Run2 combined results!
  - Differential measurements of inclusive Higgs boson production ( $ggF + VBF + VH + ttH \dots$ ) are being made but still have sizeable uncertainties in regions relevant to VBF
- $Z$  and  $W$  VBF
  - Systematics dominated
  - Background modelling often main systematics
  - New ideas to reduce systematics and/or use of new MC could help significantly

Full Run-2  $H \rightarrow \gamma\gamma$ 


# Full Run-2 $H \rightarrow \gamma\gamma$

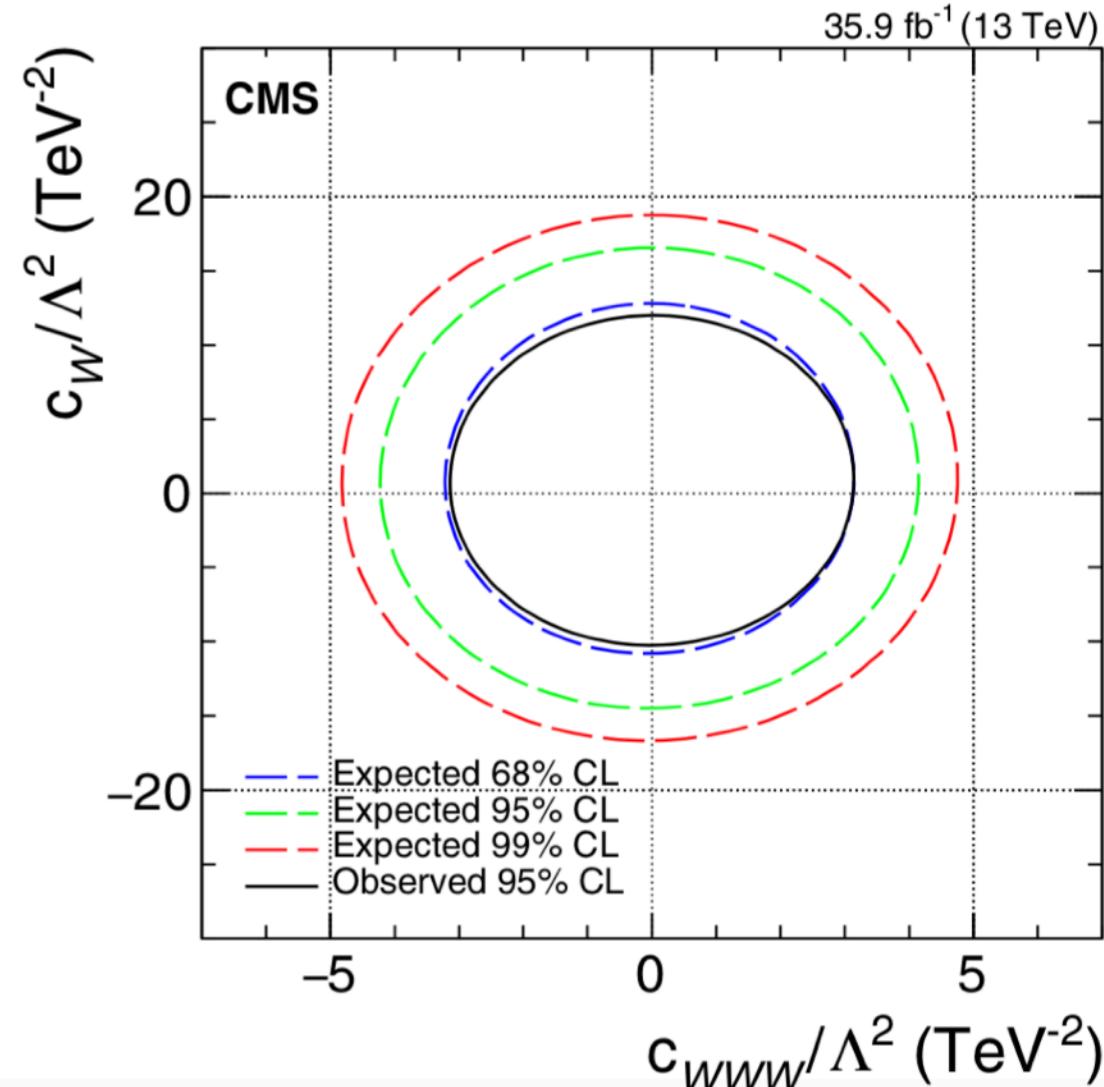
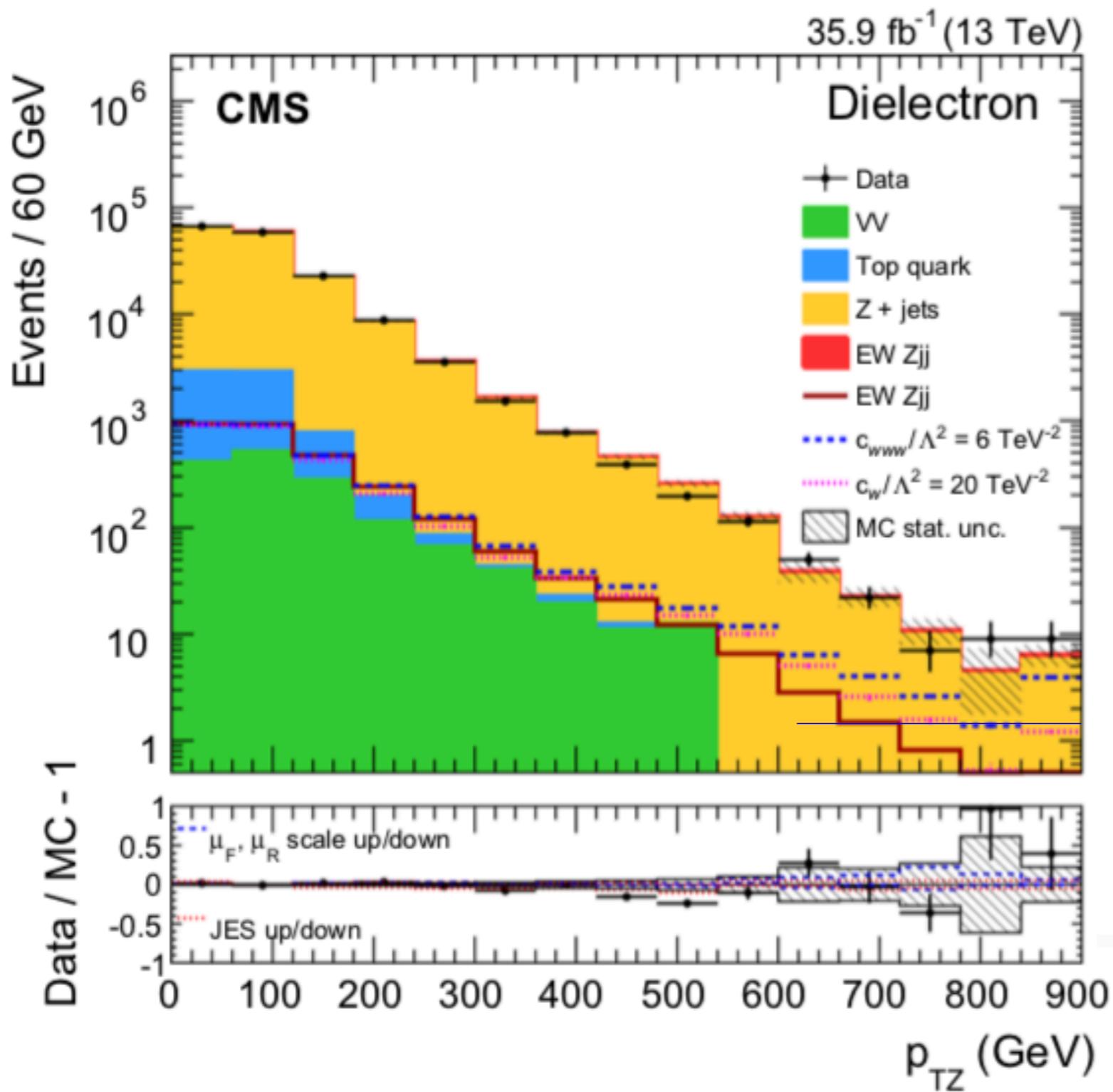


# EFT limits



$$\frac{\sigma_i^{\text{best}}}{\sigma_i^{\text{MG}}(c=0)} \sigma_i^{\text{MG}}(c)$$

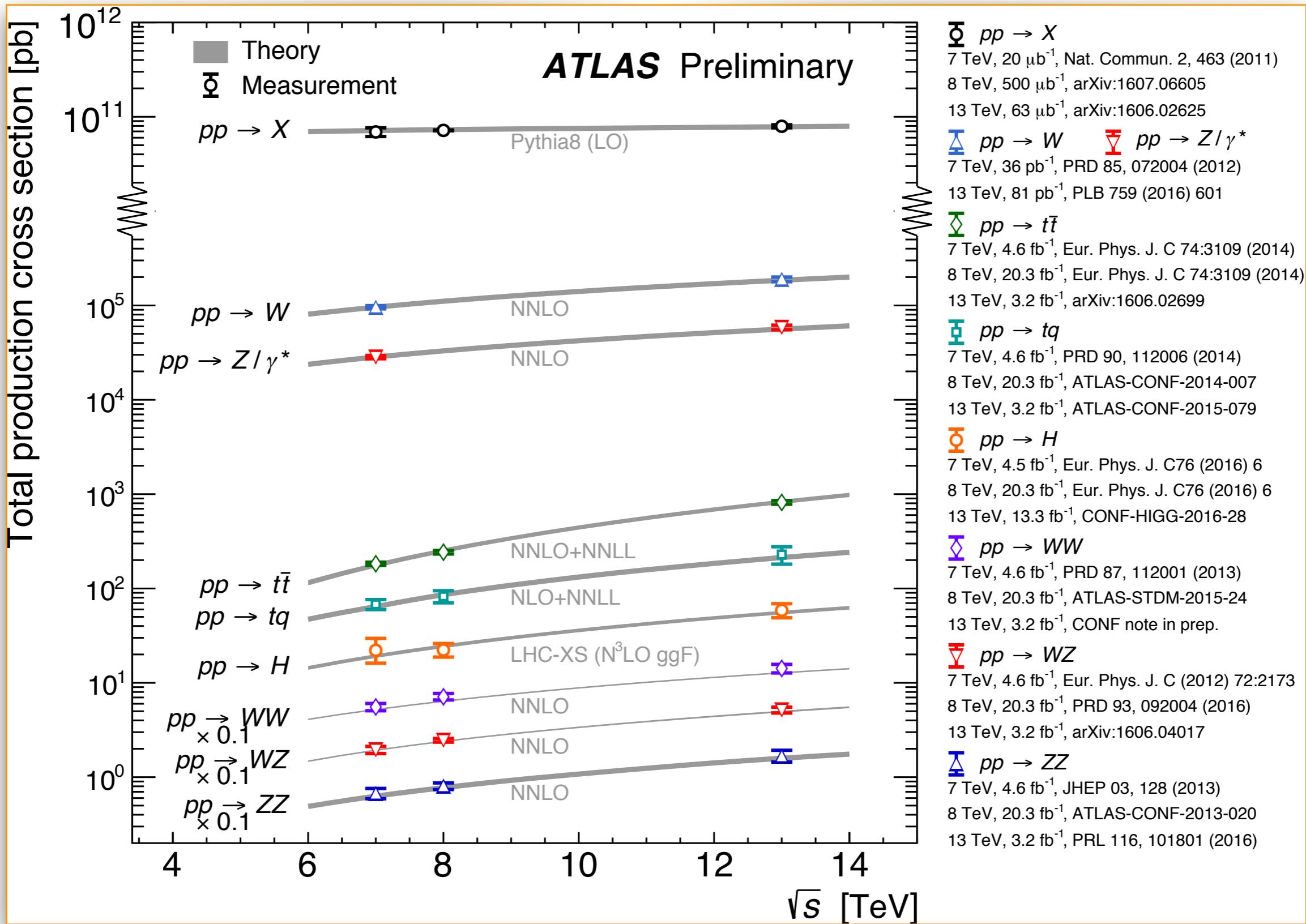
Bin-by-bin prediction from  
EFT model provided by  
MG5\_MC@NLO

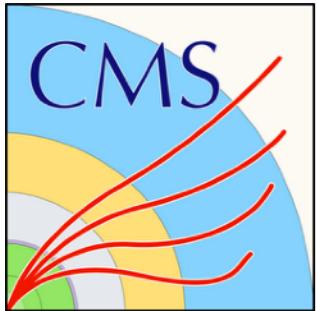


**Table 2** One-dimensional limits on the ATGC EFT parameters at 95% CL

[arXiv:1205.4231 \[hep-ph\]](https://arxiv.org/abs/1205.4231)

Coupling constant	Expected 95% CL interval (TeV <sup>-2</sup> )	Observed 95% CL interval (TeV <sup>-2</sup> )
$c_{www}/\Lambda^2$	[-3.7, 3.6]	[-2.6, 2.6]
$c_w/\Lambda^2$	[-12.6, 14.7]	[-8.4, 10.1]

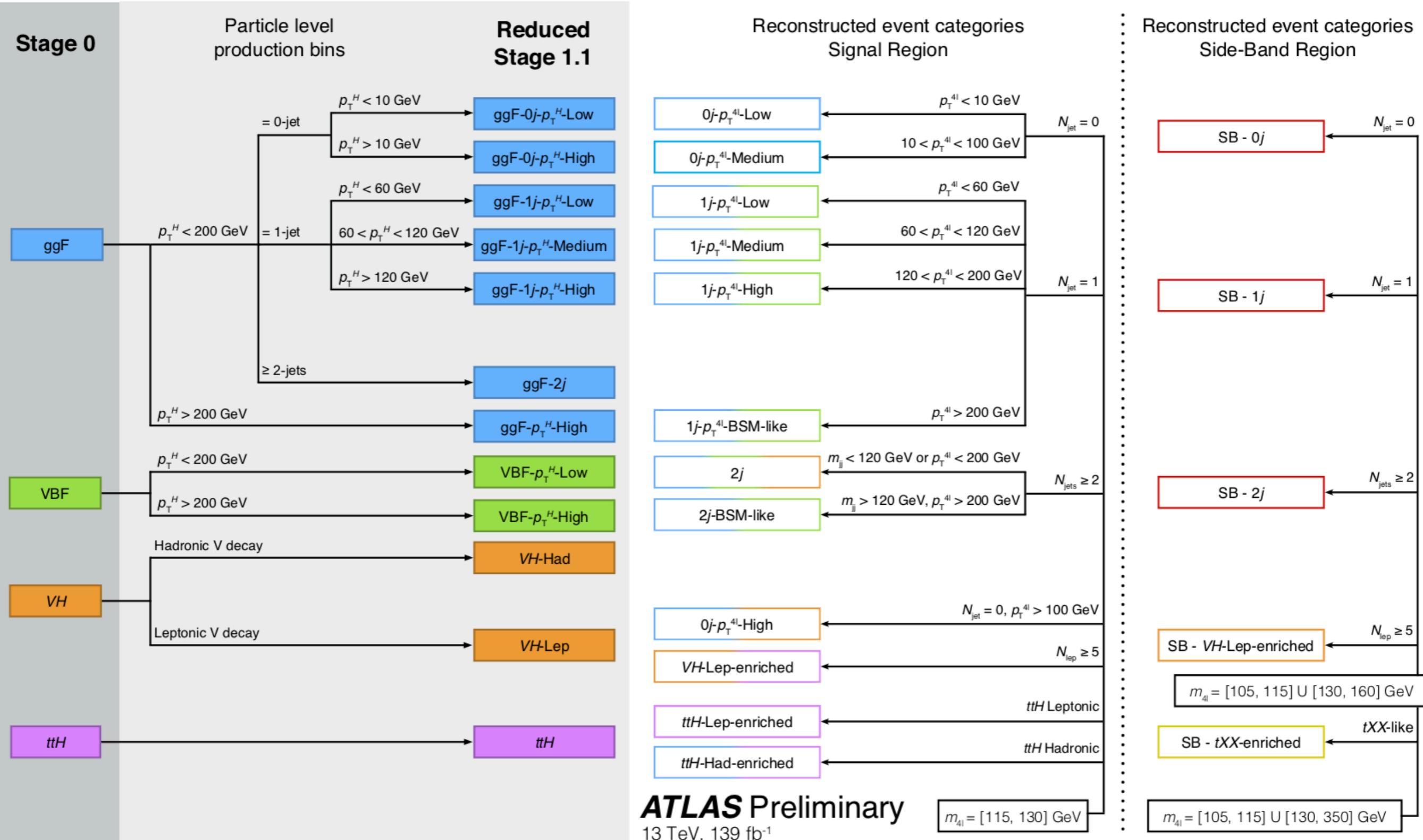




# CMS Higgs combination

Decay tags	Production tags	Number of categories	Expected signal fractions	Mass resolution
$H \rightarrow \gamma\gamma$ , Section 3.1	Untagged	4	74–91% ggH	
	VBF	3	51–80% VBF	
	VH hadronic	1	25% WH, 15% ZH	
	WH leptonic	2	64–83% WH	≈1–2%
	ZH leptonic	1	98% ZH	
	VH $p_T^{\text{miss}}$	1	59% VH	
	ttH	2	80–89% ttH, ≈8% tH	
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ , Section 3.2	Untagged	3	≈95% ggH	
	VBF 1, 2-jet	6	≈11–47% VBF	
	VH hadronic	3	≈13% WH, ≈10% ZH	
	VH leptonic	3	≈46% WH	≈1–2%
	VH $p_T^{\text{miss}}$	3	≈56% ZH	
	ttH	3	≈71% ttH	
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ , Section 3.3	ggH 0, 1, 2-jet	17	≈55–92% ggH, up to ≈15% $H \rightarrow \tau\tau$	
	VBF 2-jet	2	≈47% VBF, up to ≈25% $H \rightarrow \tau\tau$	
	ggH 0, 1-jet	6	≈84–94% ggH	
	VH 2-jet	1	22% VH, 21% $H \rightarrow \tau\tau$	≈20%
	3 $\ell$	2	≈80% WH, up to 19% $H \rightarrow \tau\tau$	
	ZH leptonic	2	85–90% ZH, up to 14% $H \rightarrow \tau\tau$	
$H \rightarrow \tau\tau$ , Section 3.4	0-jet	4	≈70–98% ggH, 29% $H \rightarrow WW$ in e $\mu$	
	VBF	4	≈35–60% VBF, 42% $H \rightarrow WW$ in e $\mu$	≈10–20%
	Boosted	4	≈48–83% ggH, 43% $H \rightarrow WW$ in e $\mu$	

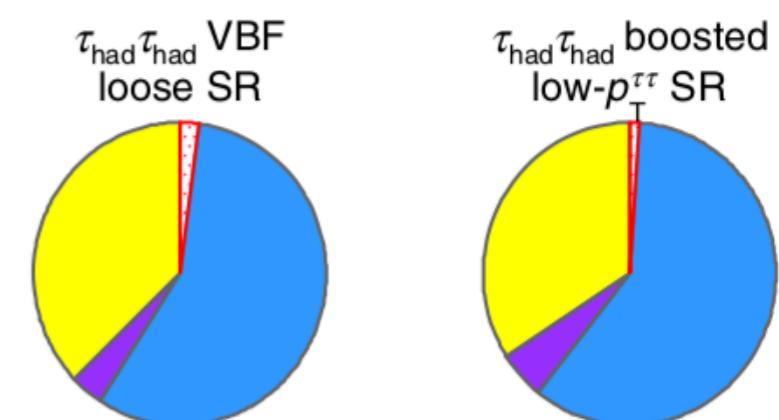
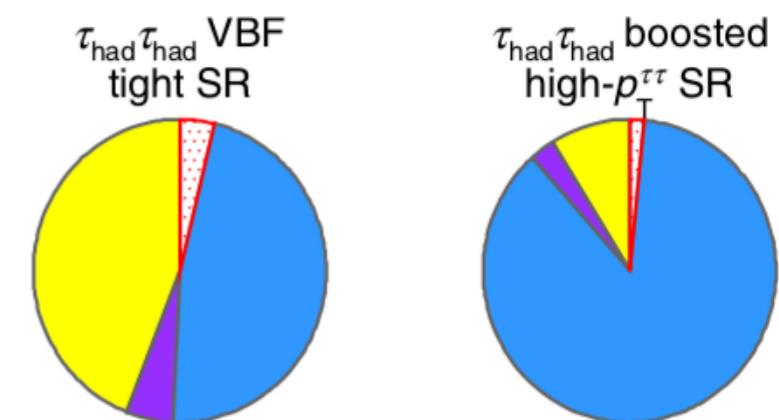
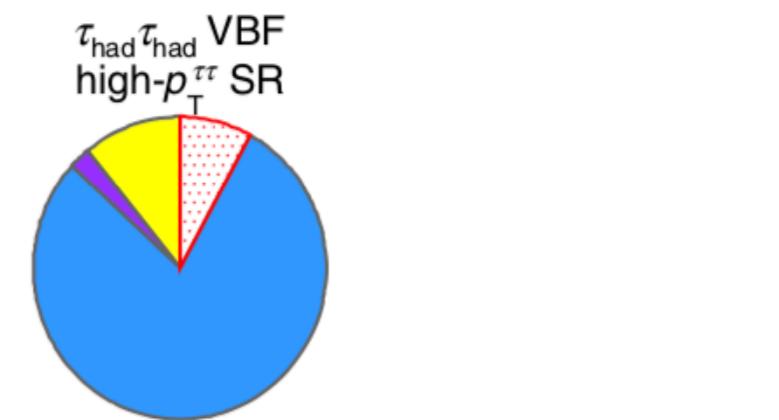
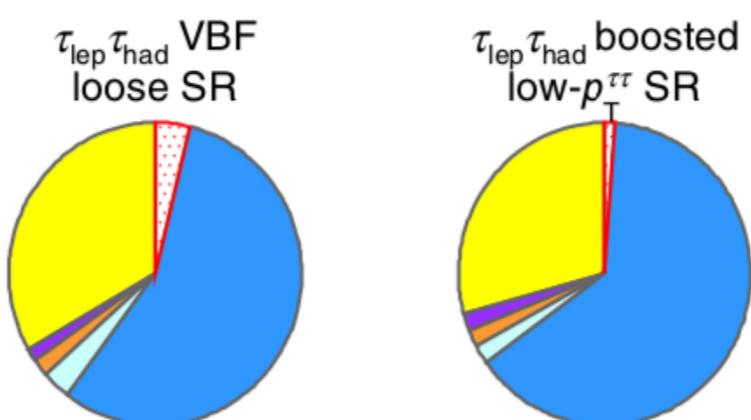
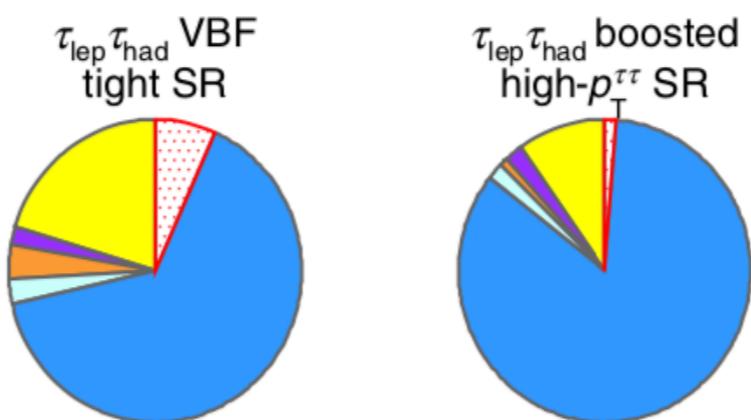
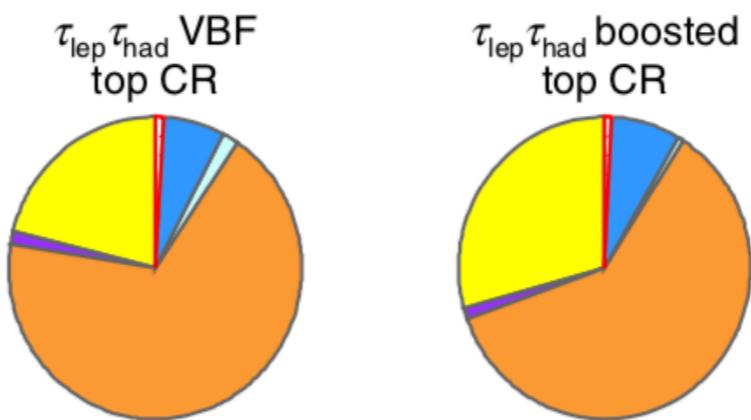
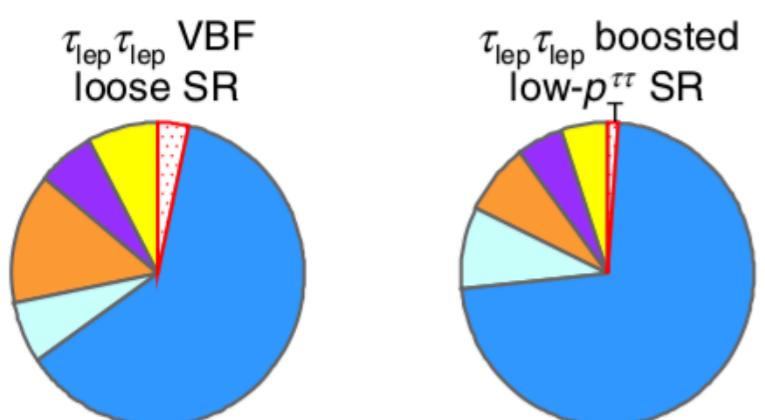
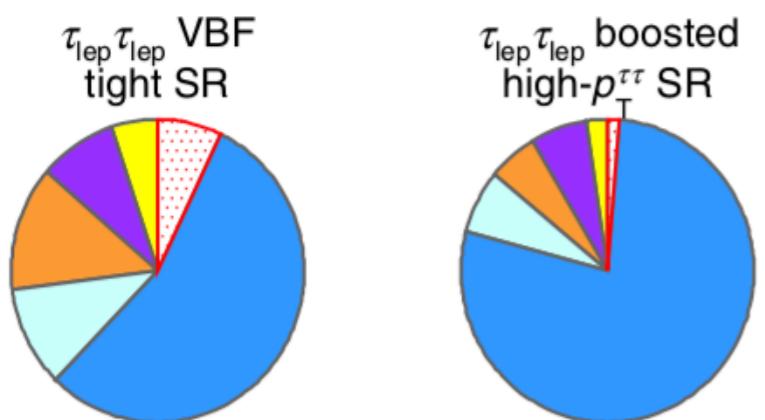
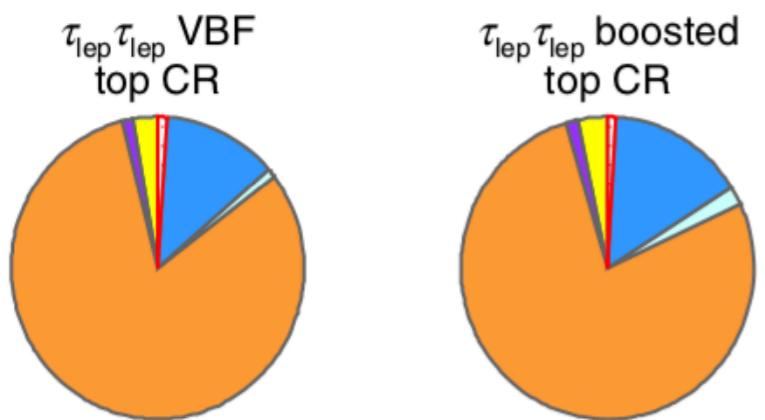
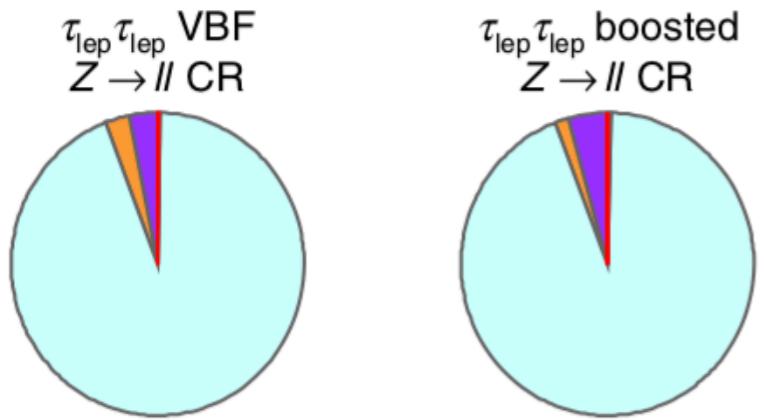
# H->4l ATLAS event and STXS categories



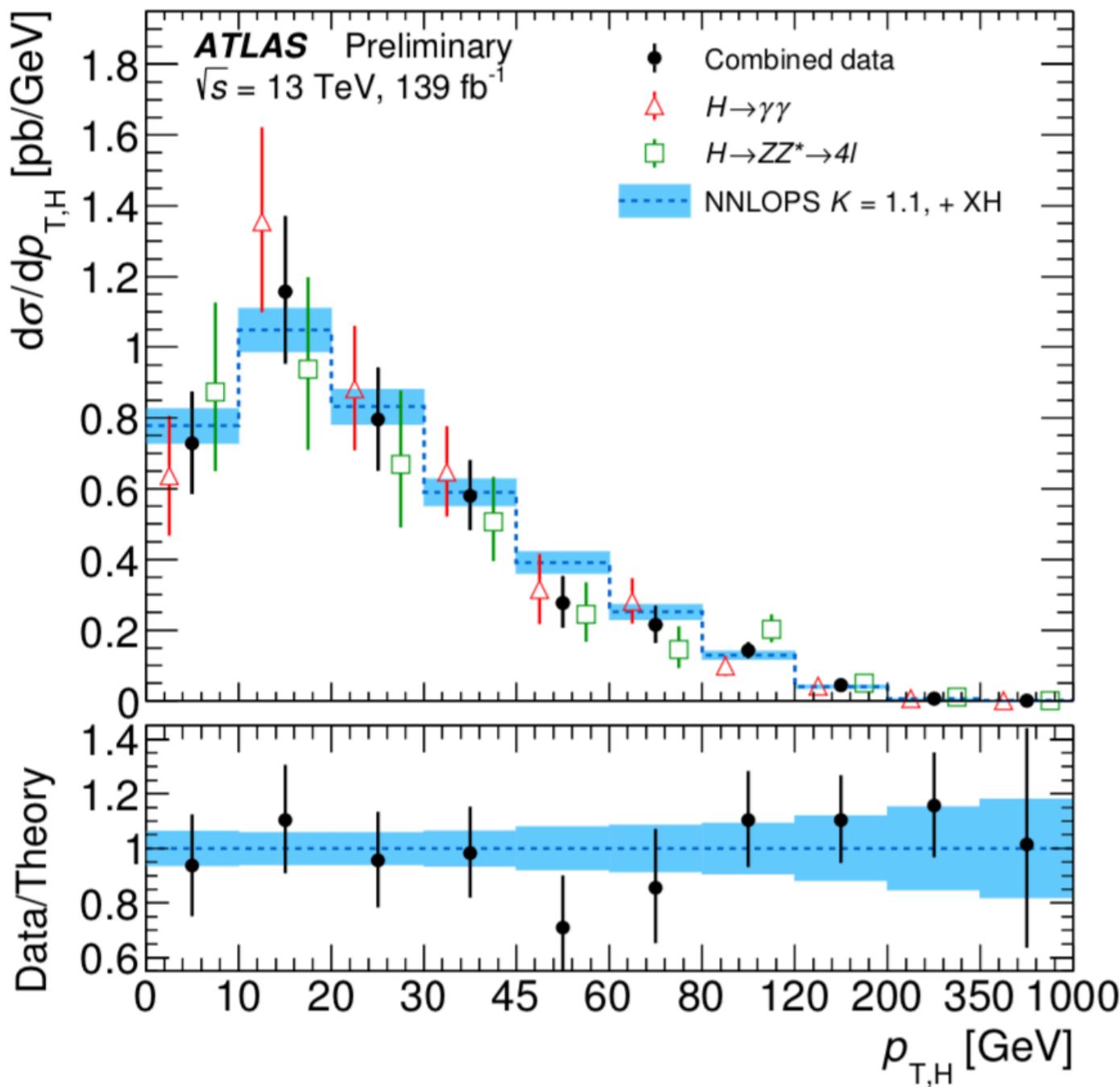
# ATLAS $H \rightarrow \tau\tau$ SRs and CRs

ATLAS

$\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$



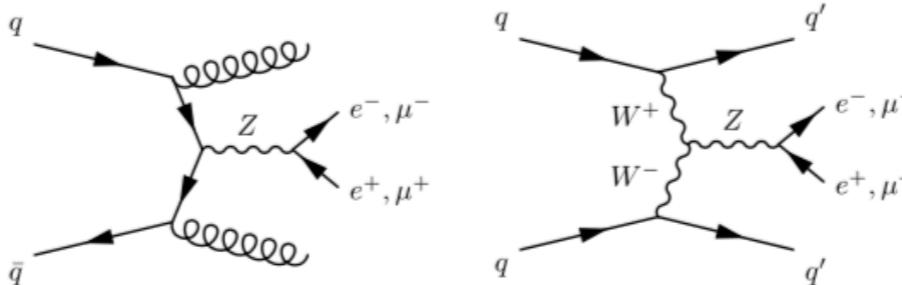
- 
- ATLAS public results  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>
  - ATLAS conference talk page:  
<https://glance.cern.ch/atlas/speakers/publicglance/talksbyconference>



# Z+di-jets

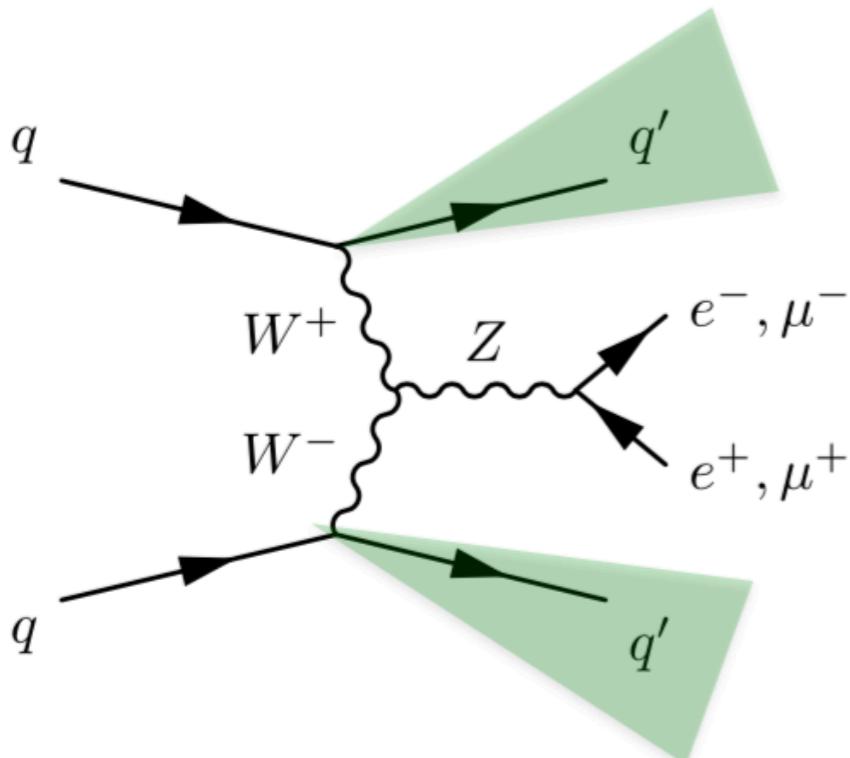
## via Vector Boson Fusion

**QCD-Zjj:**  
Abundant production process at the LHC



**EW-Zjj:**  
Rare production process at the LHC, Standard candle for other VBF processes (Higgs, BSM)

- First studies at 7 TeV by CMS, Observation by ATLAS at 8 TeV, confirmed by CMS
- Re-measured by both experiments at 13 TeV (ATLAS with  $3.2 \text{ fb}^{-1}$ , CMS with  $35.9 \text{ fb}^{-1}$ )
- No straightforward comparison between ATLAS and CMS because of different kinematics
- Main background is from QCD-Zjj production (about 10x larger than VBF production)



High energy jets, separated by large interval in rapidity with low additional hadronic activity because the t-channel exchange of the vector boson implies no color reconnection

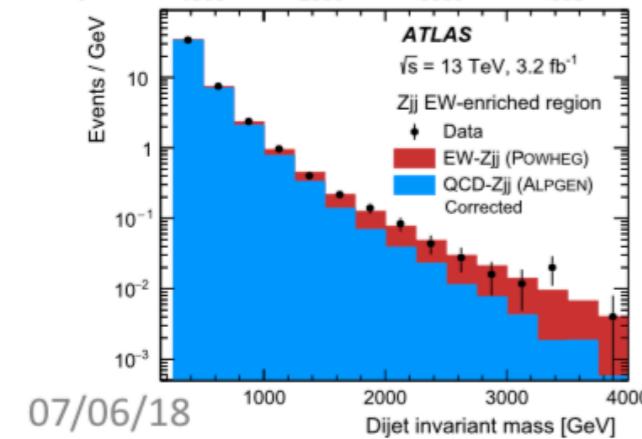
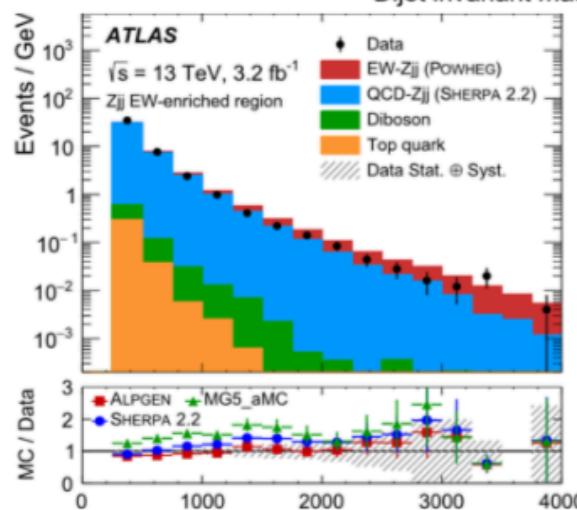
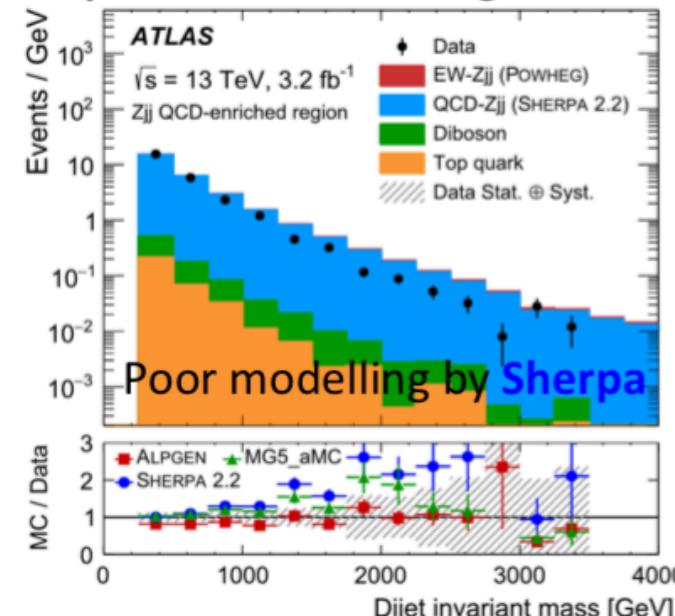


EW-Zjj are characterised by:

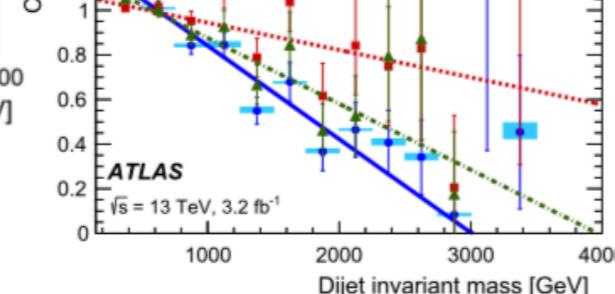
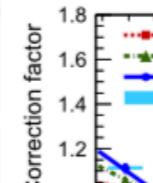
- large  $\Delta\eta_{jj}$ ,
- large  $m_{jj}$ ,
- large  $p_T$

# VBF Z+di-jets

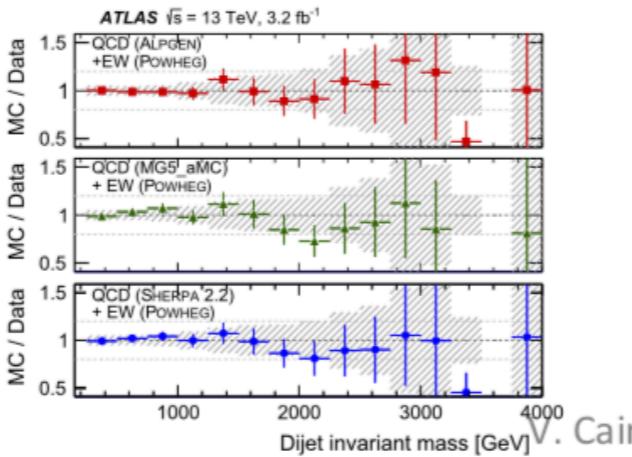
6 fid. regions, including **QCD** and **EW** enriched regions. **Fits to templates in the EW region to measure fiducial cross-section.**



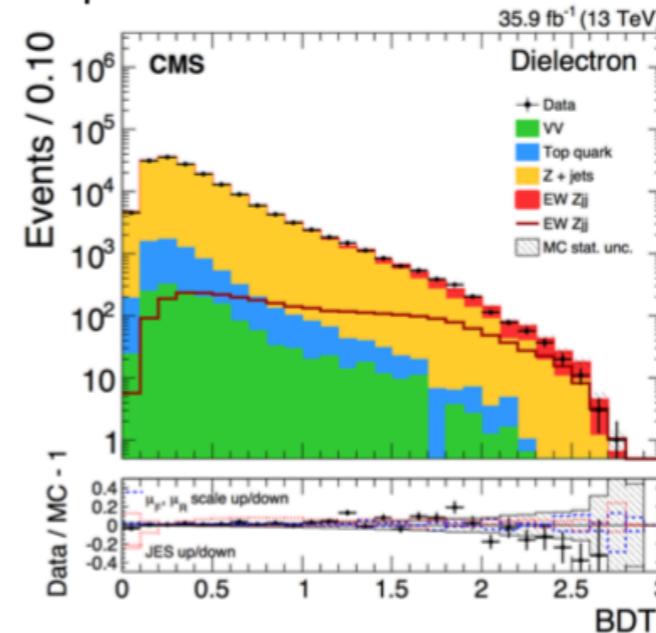
Data-driven correction factors to QCD Zjj templates before fitting QCD+EW Zjj in EW-enriched region.



EW-enriched region post-fit (QCD-Zjj reweighted and bkg subtracted)



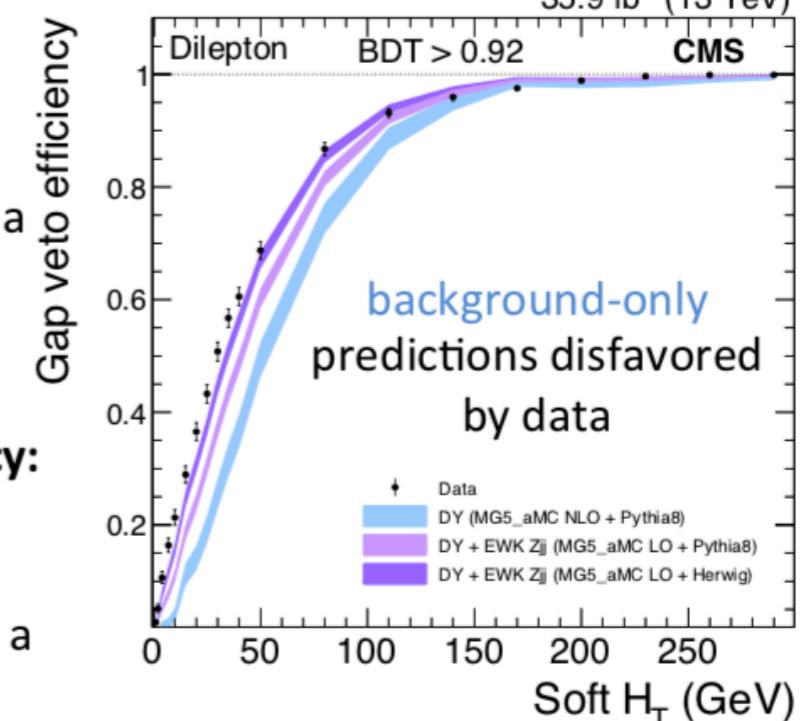
**MVA** with 7 discriminating variables (most important ones:  $m_{jj}$  and  $\Delta\eta_{jj}$ ) to achieve **EW** and **Drell-Yan** Zjj separation.



$$BDT' = \tanh^{-1}((BDT + 1)/2)$$

Presence of a signal is established → **properties of the hadronic activity** can be studied (in a region with  $BDT > 0.92$ , signal enriched).

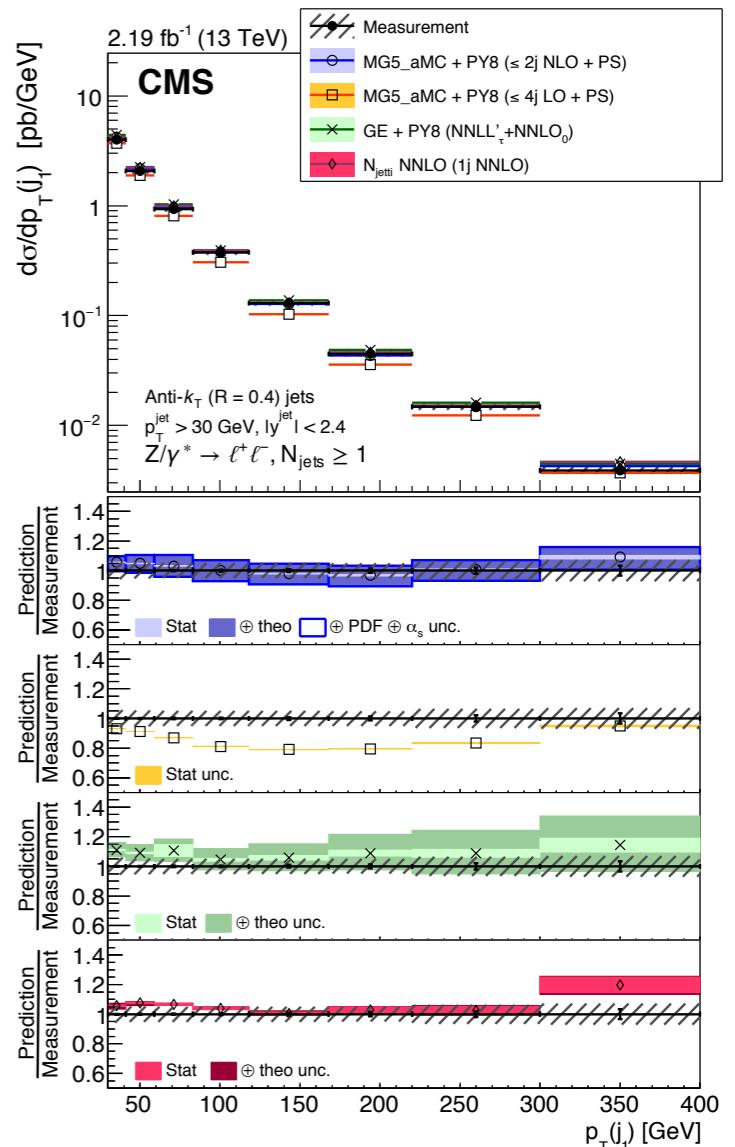
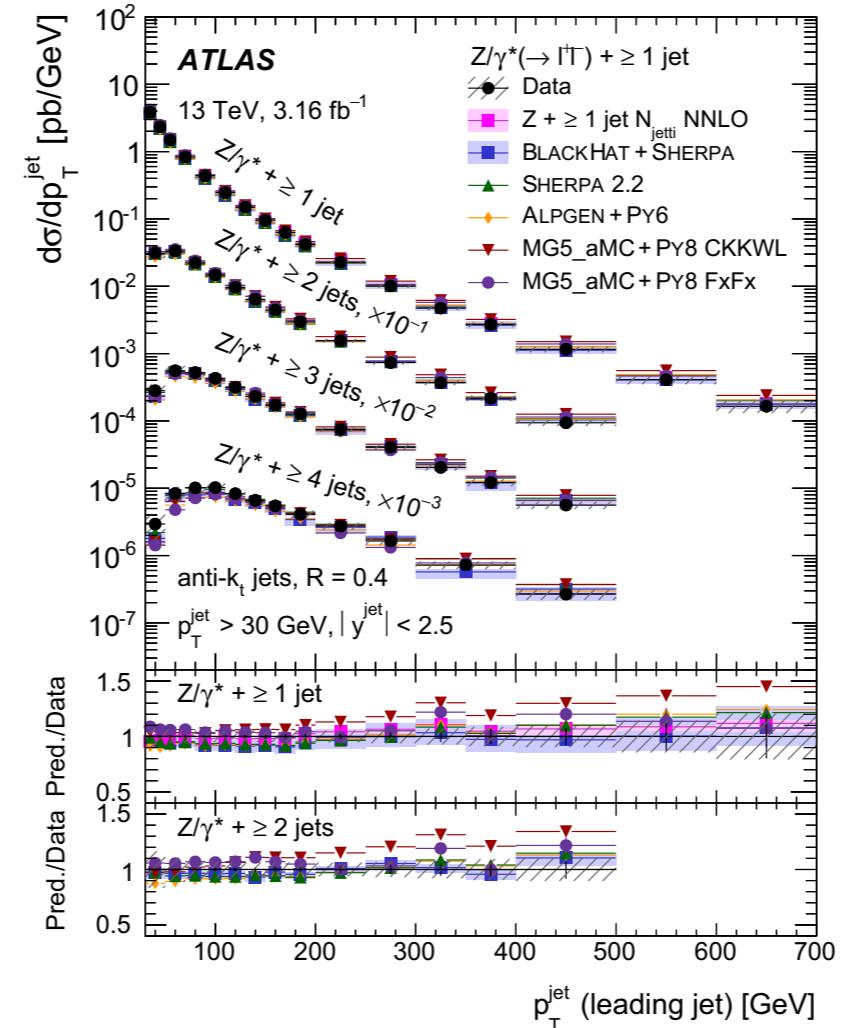
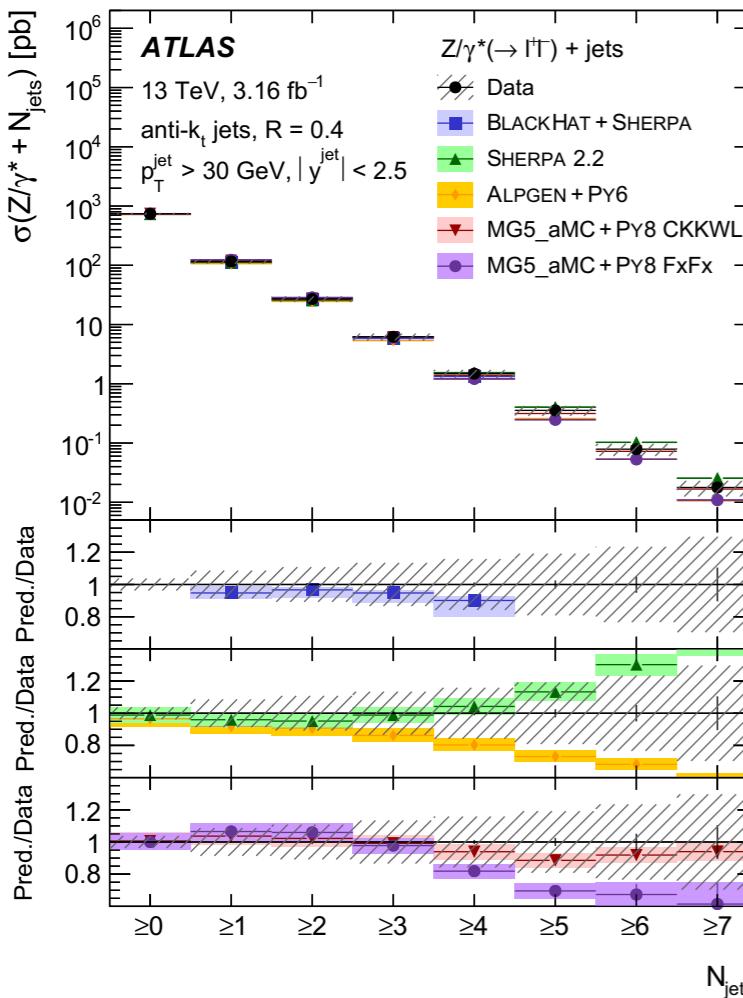
**Gap veto efficiency:** fraction of events with a measured gap activity below a given threshold



background-only predictions disfavored by data

# Z Boson + jets @ 13 TeV

- **Cross sections unfolded at particle level** for jet multiplicities up to 7 (ATLAS) and 6 (CMS) and differentially vs the transverse momentum of the Z boson and several jet kinematic variables.
- Dominant systematic uncertainty from **jet energy scale**



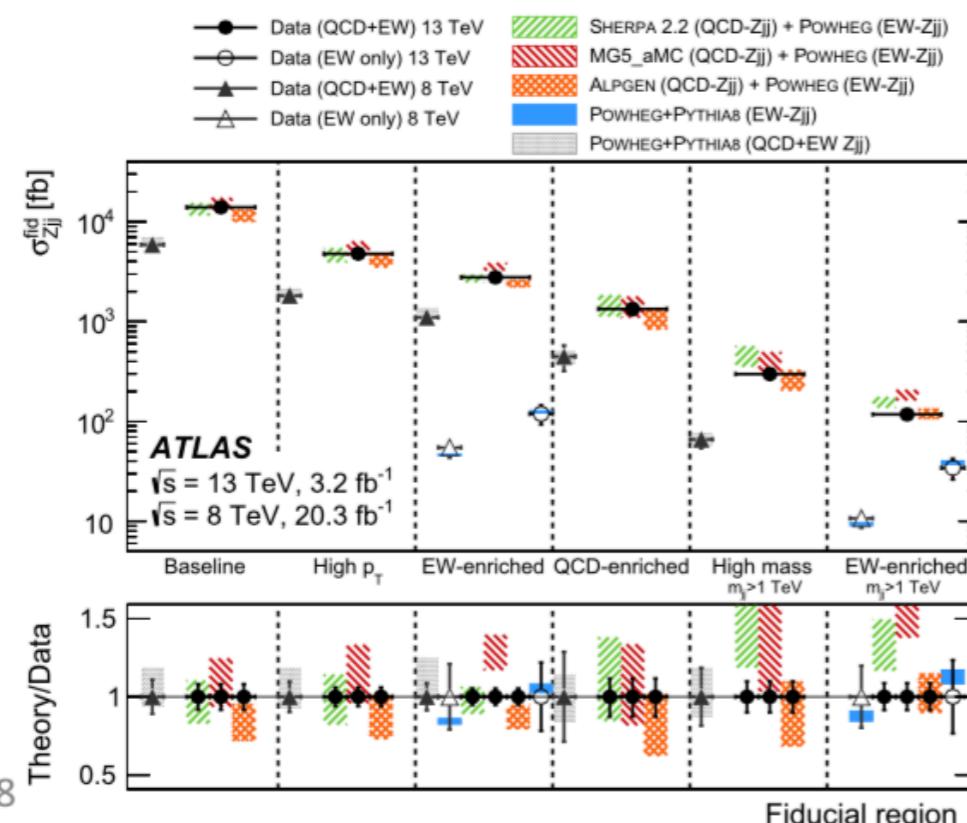
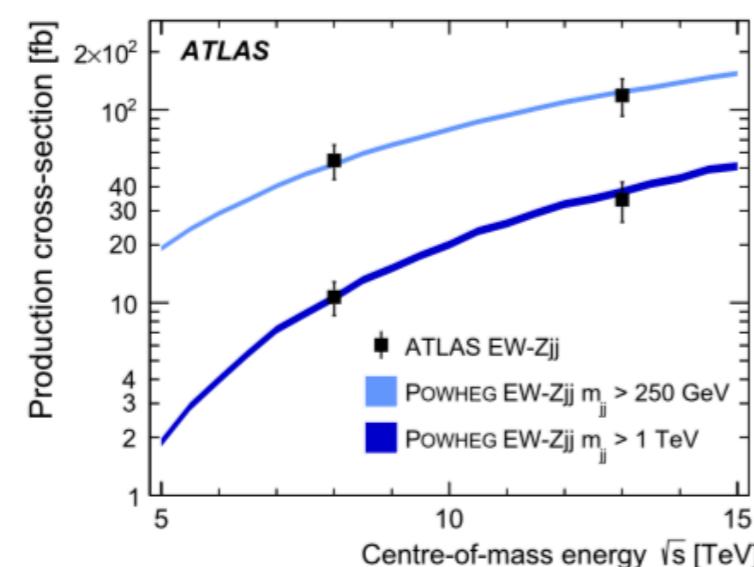
- **Sherpa 2.2, Alpgen+Py6, MG5\_aMC+Py8 FxFx** do not describe data precisely for high jet multiplicity (large fraction of jets produced by PS), but MG5\_aMC+Py8 FxFx does a good job for  $p_T^{\text{jet}}$
- Distributions dominated by a single jet multiplicity are modelled well by fixed-order NLO (**BlackHat +Sherpa**) or NNLO (**Njetty**) calculations
- Too-hard jet spectrum by **MG5\_aMC+Py8 CKKWL** (LO matrix elements)

# VBF Z+di-jets



Fiducial region

	EW-Zjj cross-sections [fb]			
	Measured	POWHEG+PYTHIA		
EW-enriched, $m_{jj} > 250$ GeV	119 $\pm 16$ $\pm 20$ $\pm 2$	125.2 $\pm 3.4$		
EW-enriched, $m_{jj} > 1$ TeV	34.2 $\pm 5.8$ $\pm 5.5$ $\pm 0.7$	38.5 $\pm 1.5$		



**Signal strength and cross-section for combined electron and muon channel compatible with SM:**

$$\mu = 1.02 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)} = 1.02 \pm 0.11 \text{ (total)},$$

$$\sigma(\text{EW } \ell\ell jj) = 552 \pm 19 \text{ (stat)} \pm 55 \text{ (syst)} \text{ fb} = 552 \pm 58 \text{ (total) fb}$$

$$\text{SM prediction } \sigma_{\text{LO}}(\text{EW } \ell\ell jj) = 543 \pm 24 \text{ fb}$$

Cross-sections cannot be directly compared between ATLAS and CMS because of the different phase spaces, but a very different size of the systematic uncertainty can be noticed: almost a factor of 2 smaller in CMS, driven by different treatment of the QCD background