Measurements of Higgs Vector Boson Fusion (VBF) production

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on behalf of the ATLAS and CMS collaborations

Higgs 2020 Conference
Oct 26-30, 2020

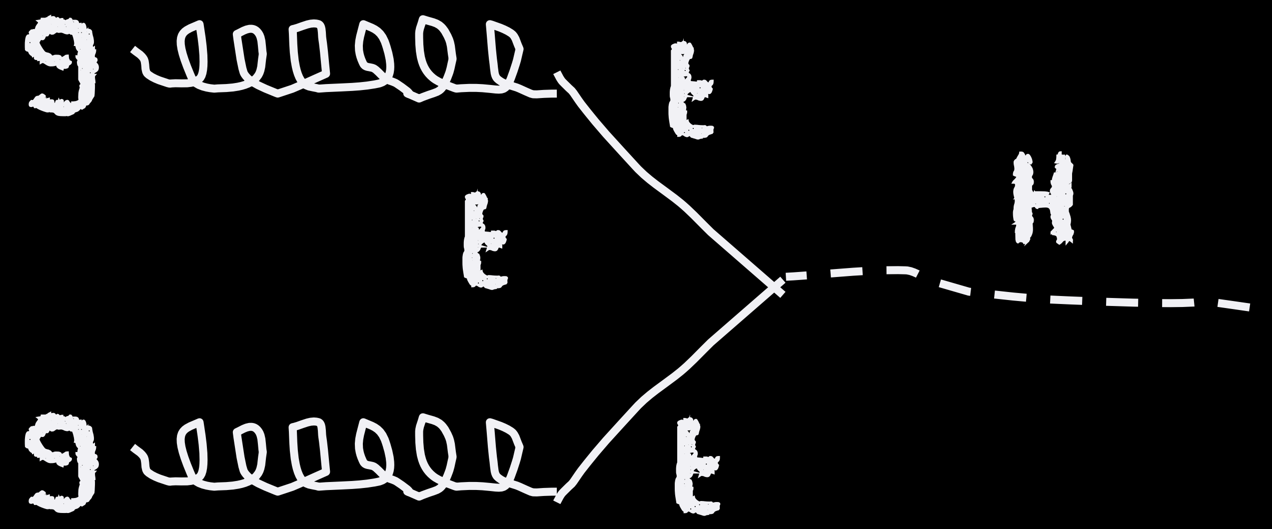
Outline

- **Higgs production mode at LHC**
- **Overview of Measurements of Higgs VBF production**
- **VBF H→bb**
- **VBF H→ττ**
- **VBF H → WW***
- **VBF H → ZZ***
- **VBF H →γ γ**
- **VBF H → invisible**
- **Summary**

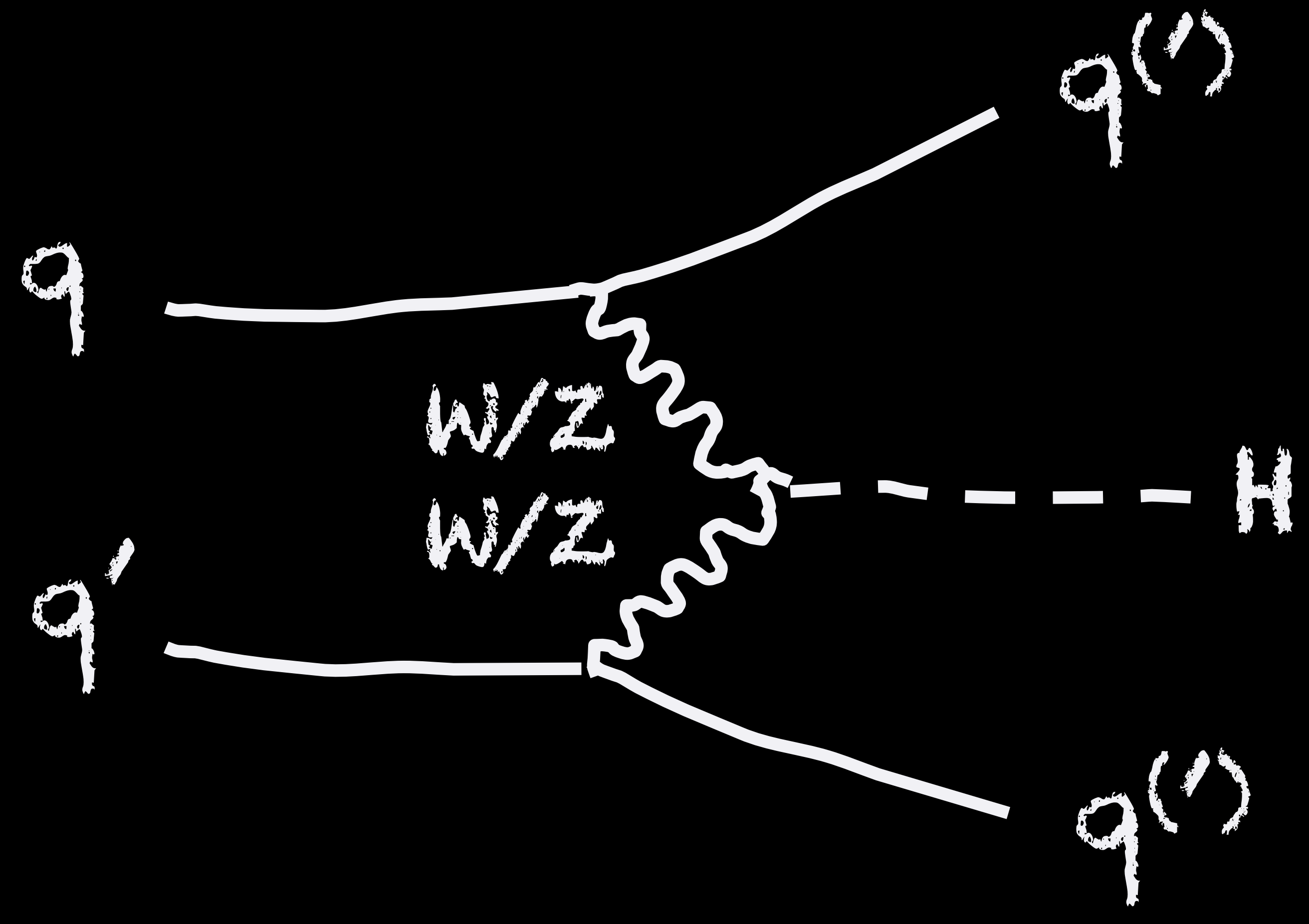
Higgs production at LHC

- At the LHC, the Higgs boson production is $\sigma_{H,total}$ = 56 pb at $\sqrt{s}$ = 13 TeV
- Dominantly by gluon fusion process
- VBF process is the second-largest Higgs production mode

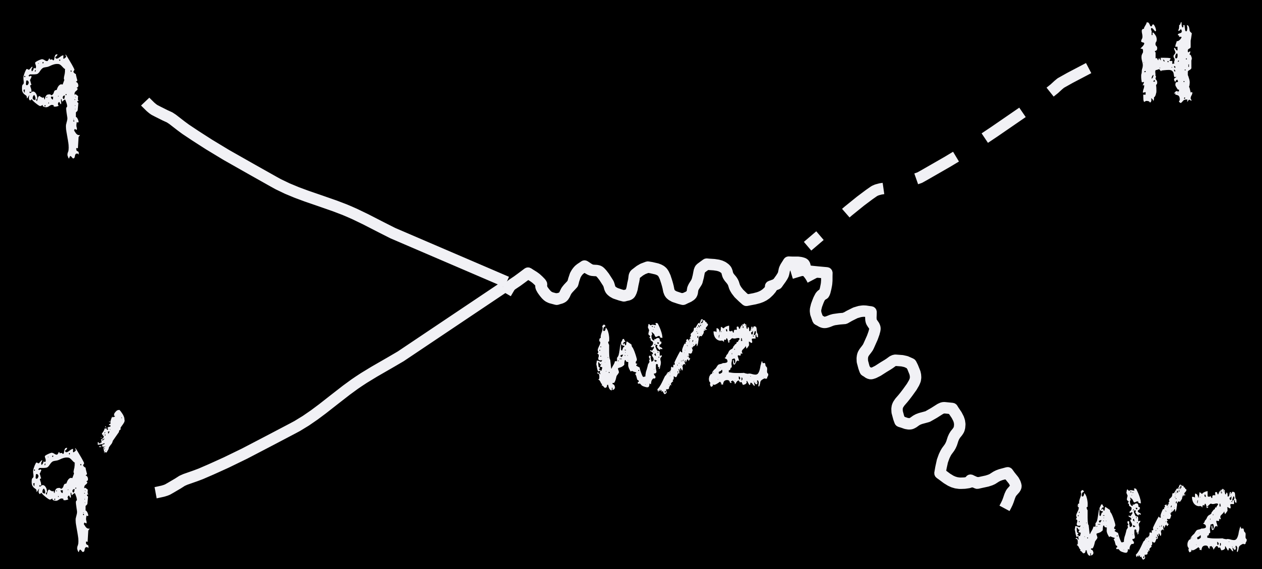
Gluon fusion $\sigma_{H,ggF} \sim$ 49 pb



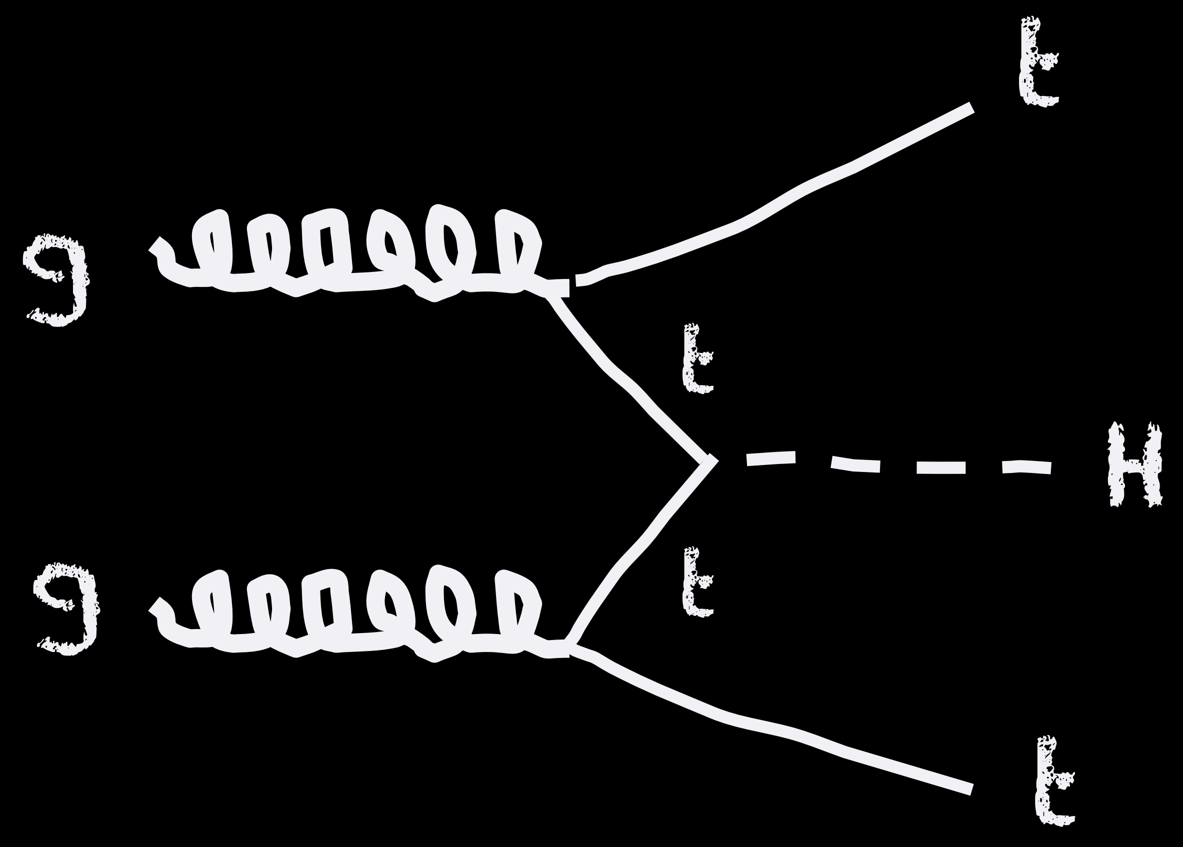
Vector Boson Fusion : VBF
($\sigma_{VBF} \sim$ 3.8 pb)



Higgs-strahlung
($\sigma_{W/Z+H} \sim$ 1.4/0.9 pb):



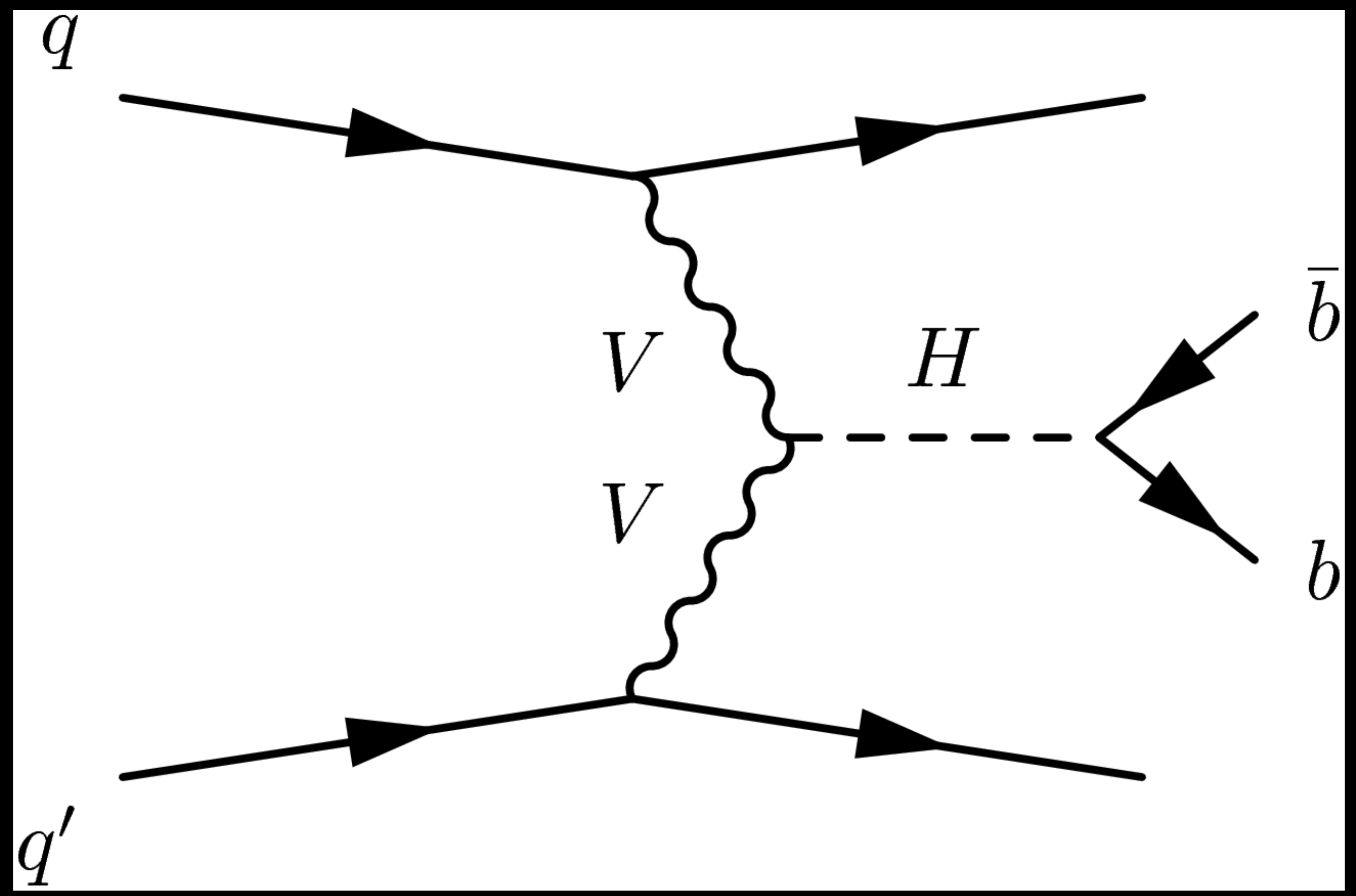
"ttH" production
($\sigma_{ttH} \sim \sigma_{bbH} \sim$ 0.5 pb)



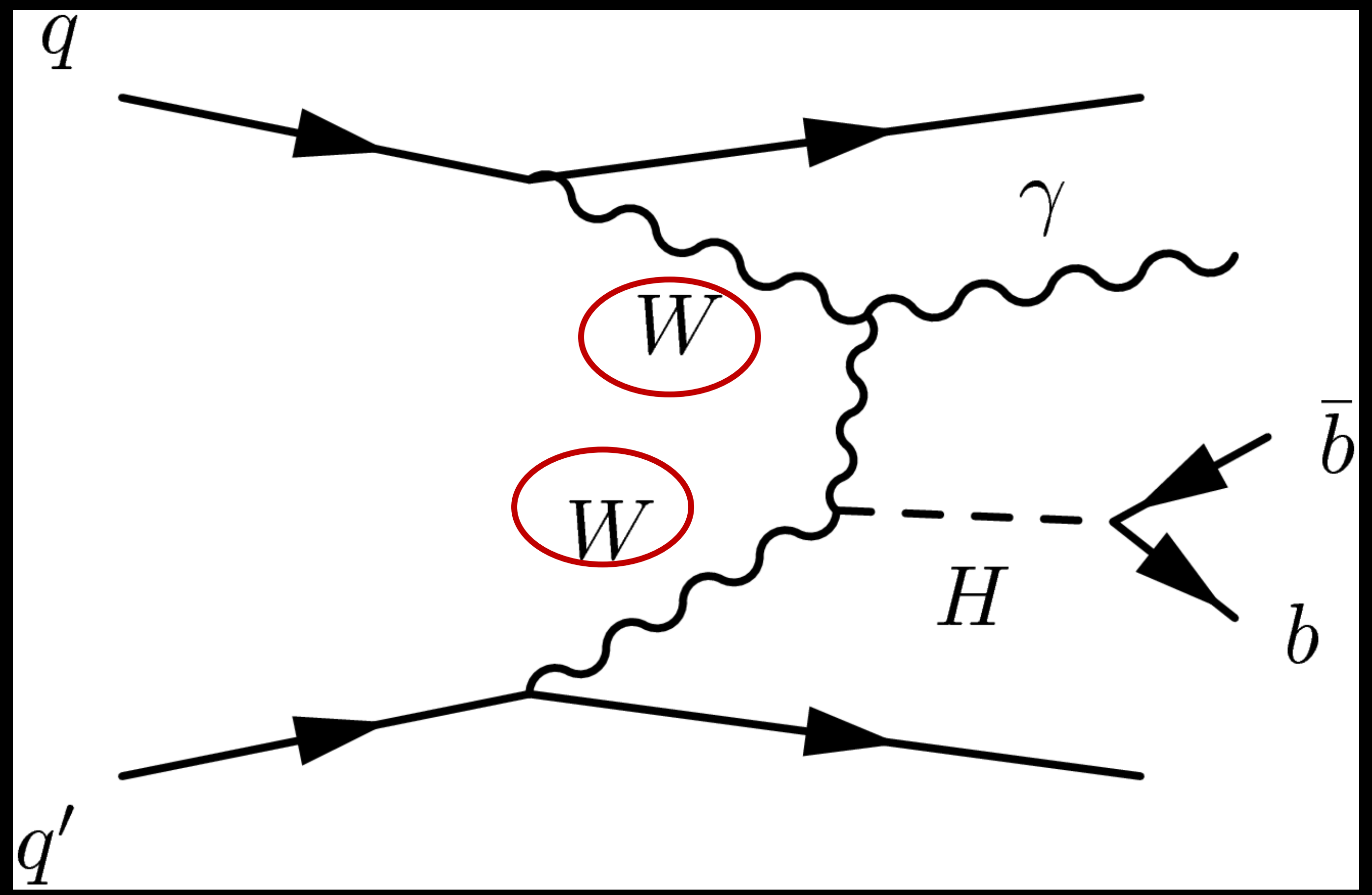
VBF H(→bb)

- **All hadronic channels (VBF H(→bb))**
  - **High statistics**
  - **Signal is characterised by 2 b-jets + 2 light-quark jets with large rapidity gap (VBF jets)**
- **Photon channel (VBF H(→bb)+γ)**
  - **Low statistics, suppresses the gluon-rich dominant non-resonant bbjj bkg.**
  - **probes WWH VBF production specifically, with little contribution from ZZH production**

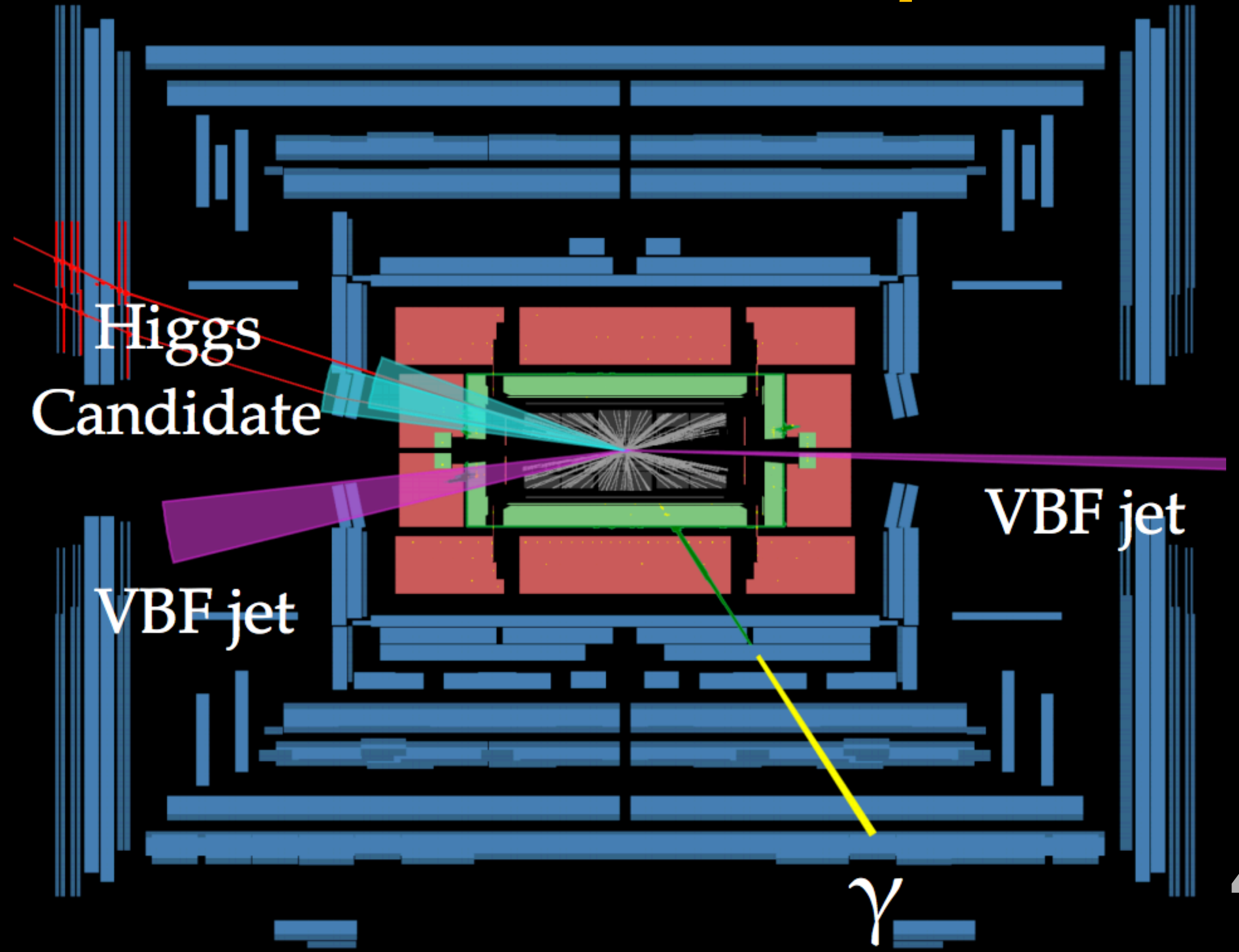
All hadronic analysis
VBF H(→bb)
ATLAS Full run II data
CERN-EP-2020-195



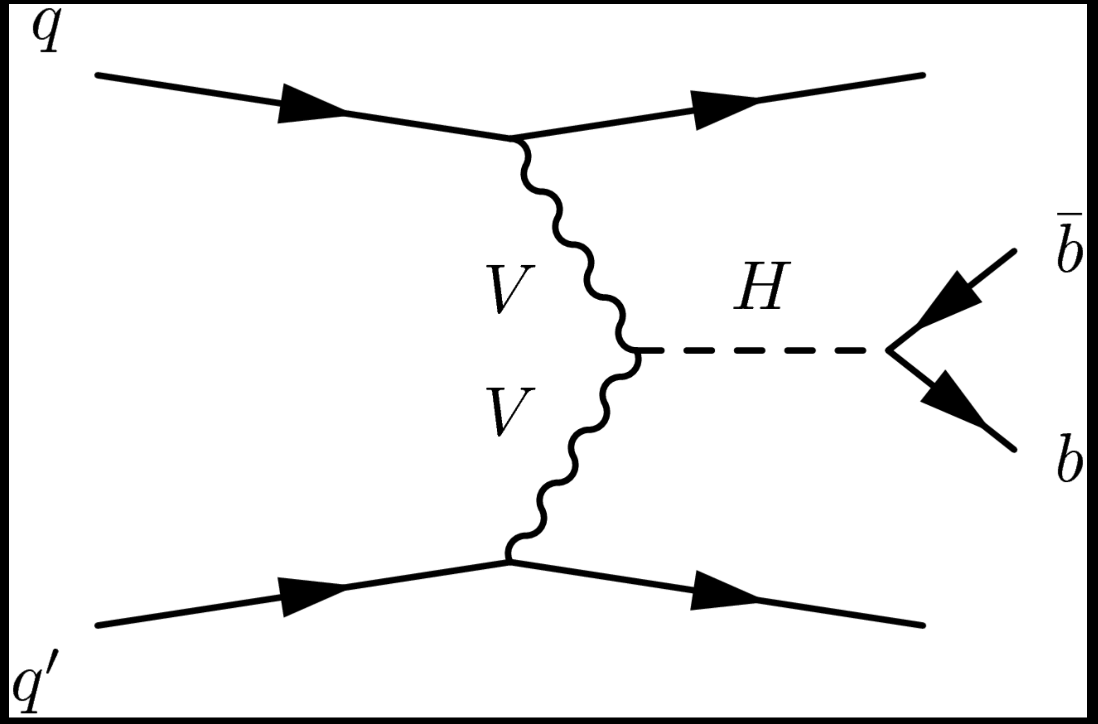
Photon tagged analysis
VBF H(→bb)+γ
ATLAS Full run II data
CERN-EP-2020-179



ATLAS Event display of VBF H(→bb)+γ



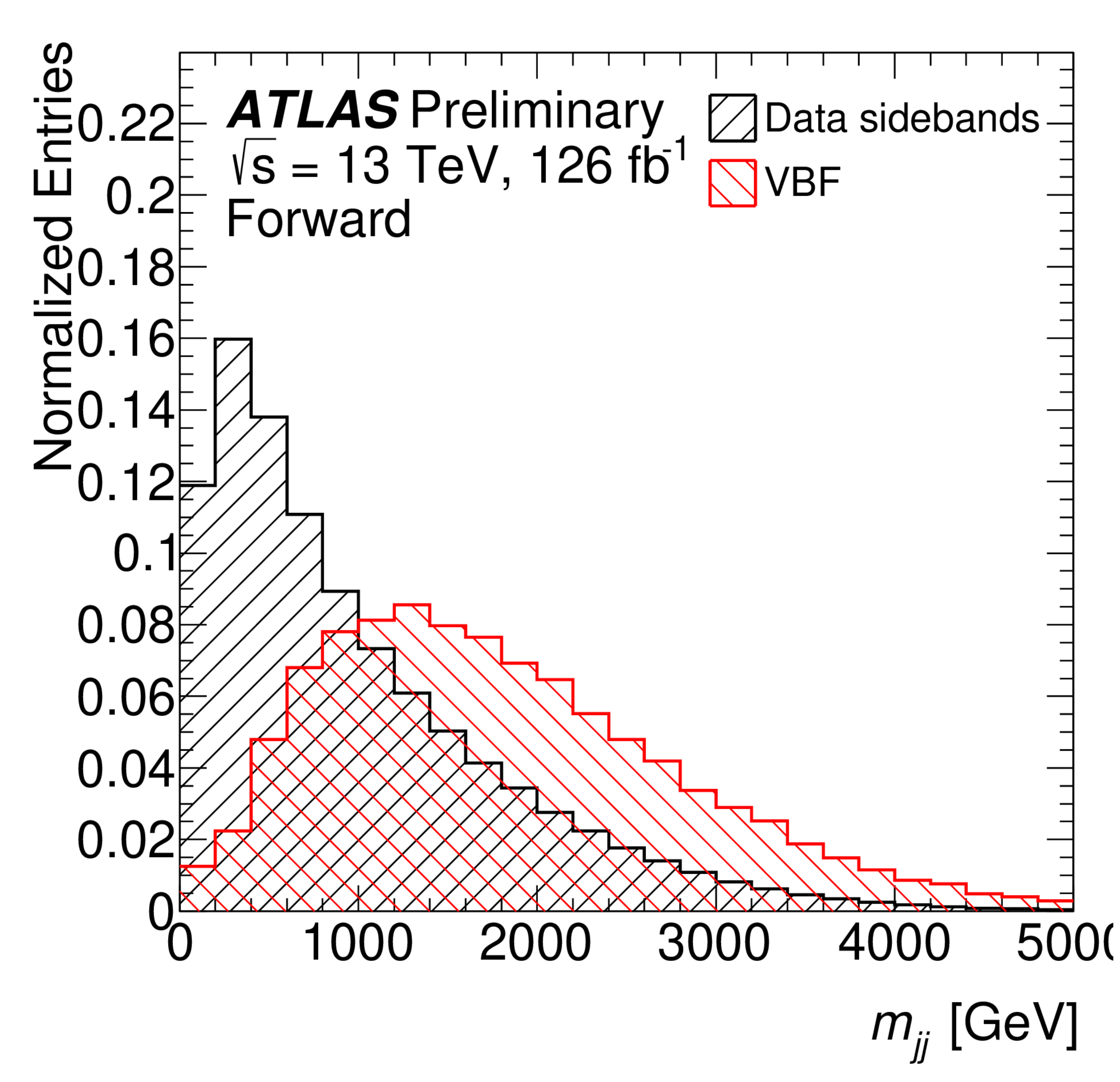
VBF H(→bb)



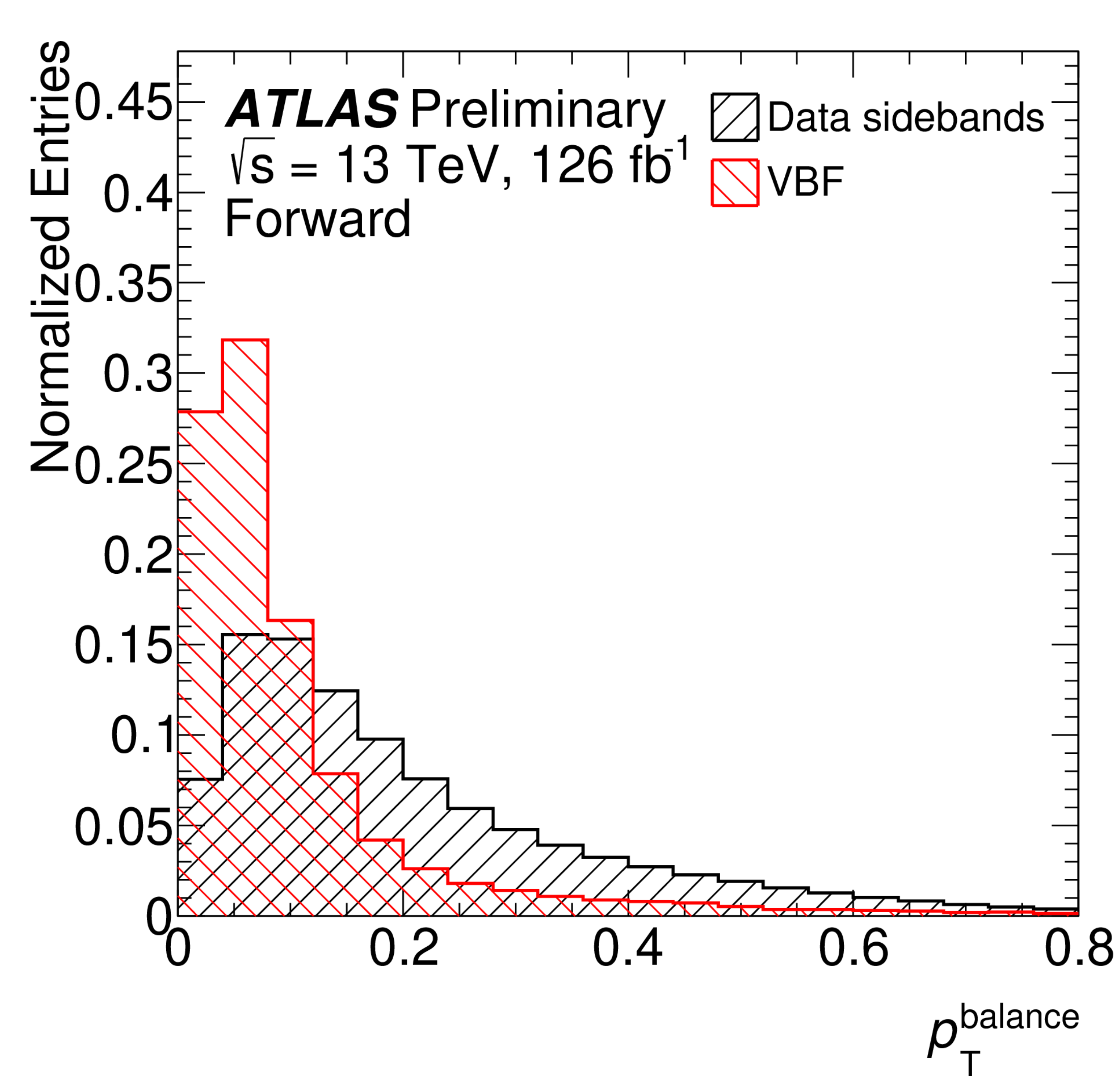
ATLAS Full run II paper
CERN-EP-2020-195

- ➢ **Adversarial neural network(ANN) is used**
- ☐ **Signal is modelled by signal MC simulations**
- ☐ **Background modelling from data sideband.**
- ☐ **12 input discriminant**
  - ✓ **VBF signature, eg: M_{jj}, pT_{jj} ...**
  - ✓ **Color connection between VBF jets and b jets: $p_T^{balance}$, Δη(bb, j j), Δϕ(bb, j j), n_{Jets} ..**
  - ✓ **Gluon/quark jets separation: eg:N_{track} j1(j2) :**

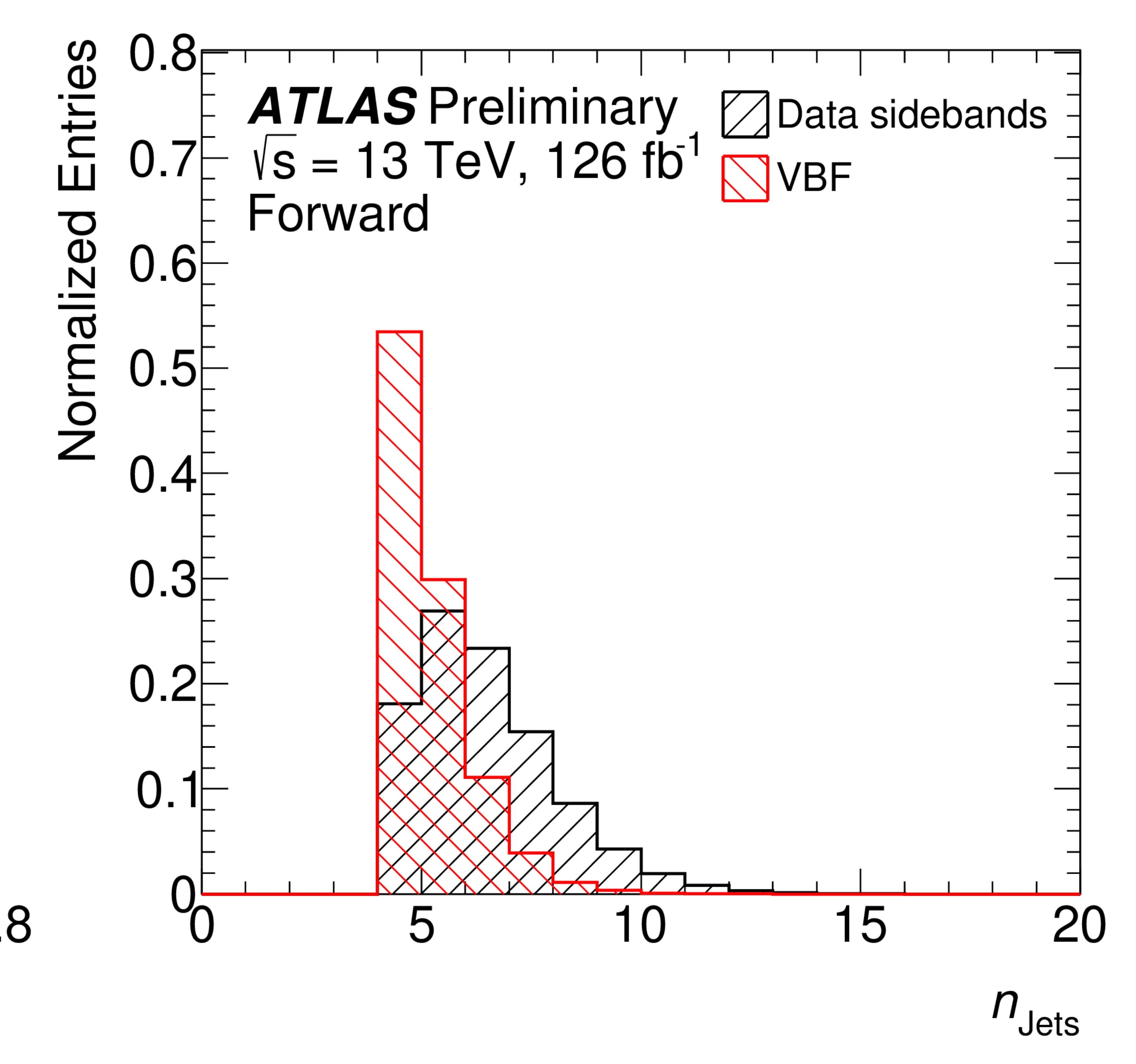
VBF dijet mass M_{jj}



$p_T^{balance}$



Number of jets: N_{jets}



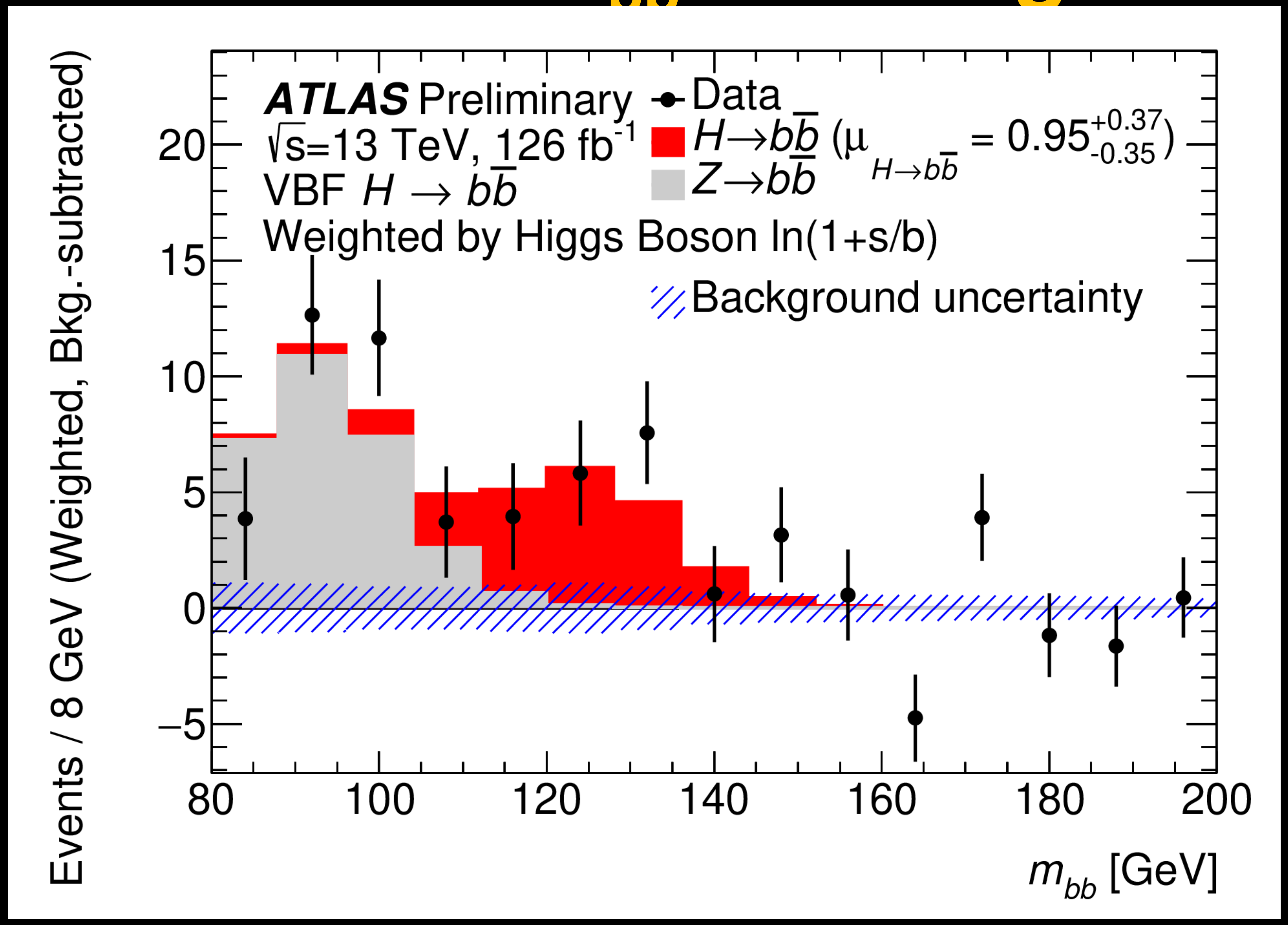
VBF H(→bb)

➢ Two channels, dedicated signal trigger for each

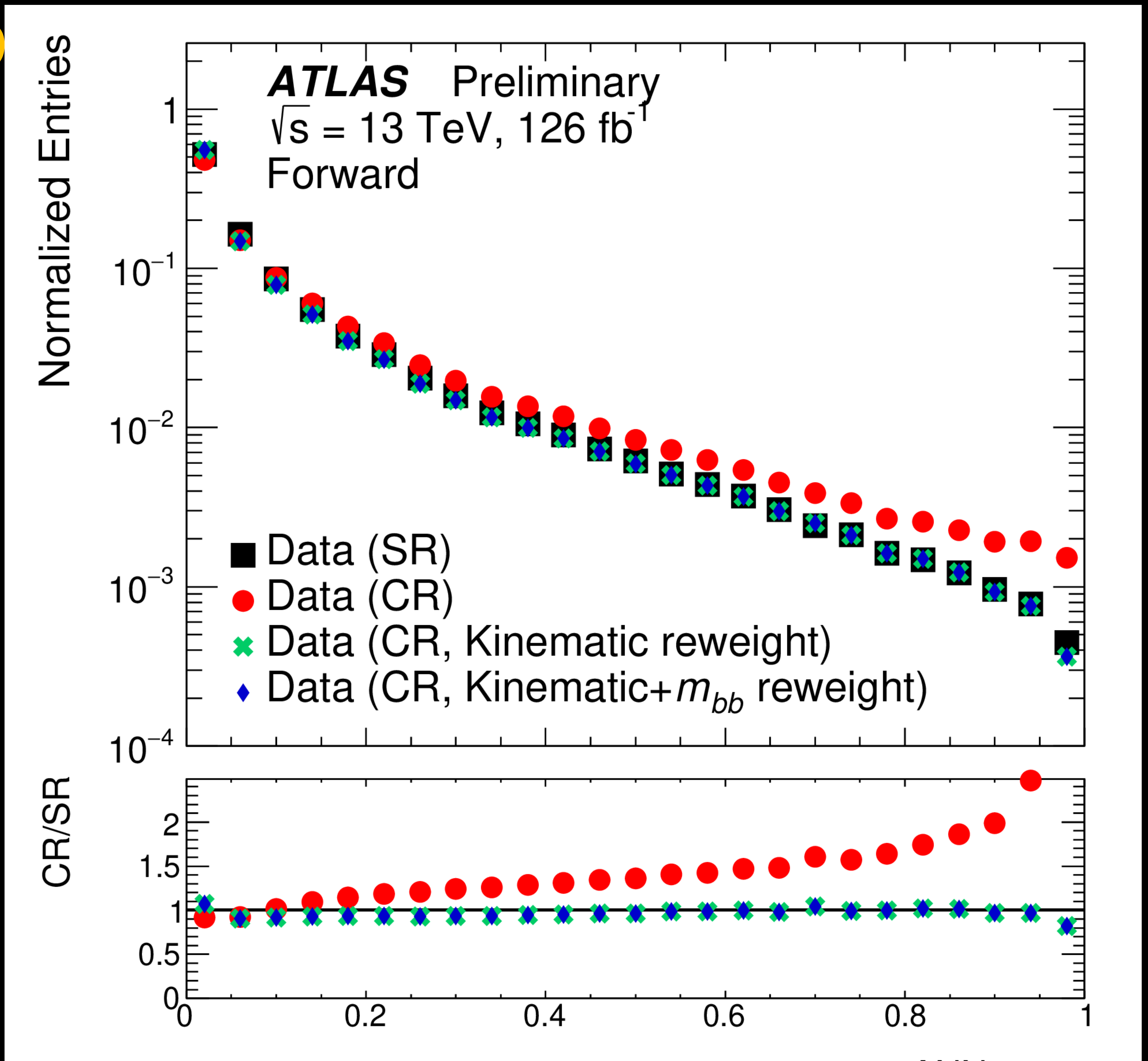
- ➢ Forward channel : 2 central bjets + 1 forward jet
- ➢ Central channel: 4 central jets with 2 bjets
- ☐ Events are categorized by ANN score and channels
- ☐ Simultaneous fit to m_{bb} in multiple event categories;

ATLAS Full run II paper
CERN-EP-2020-195

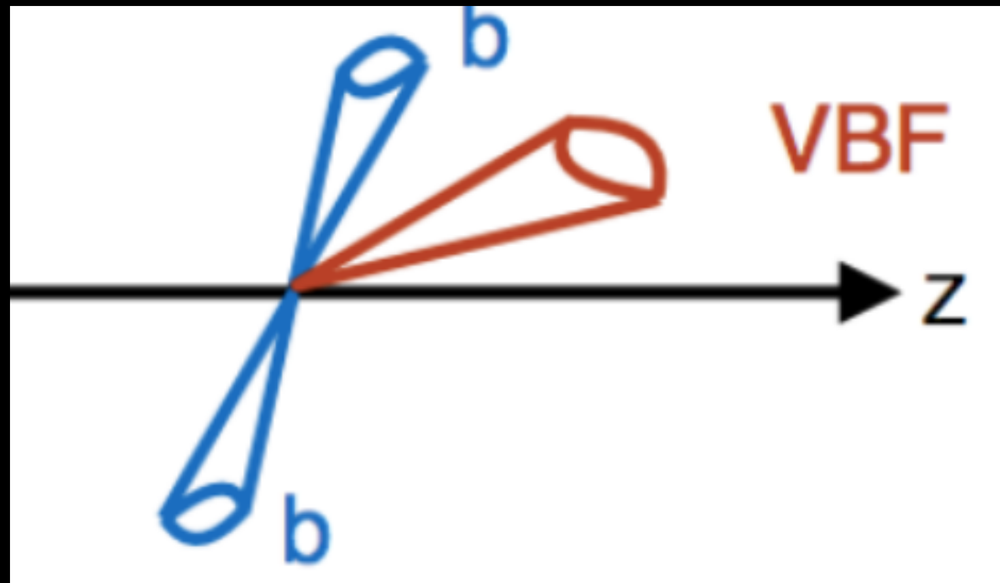
Combined m_{bb} in all regions



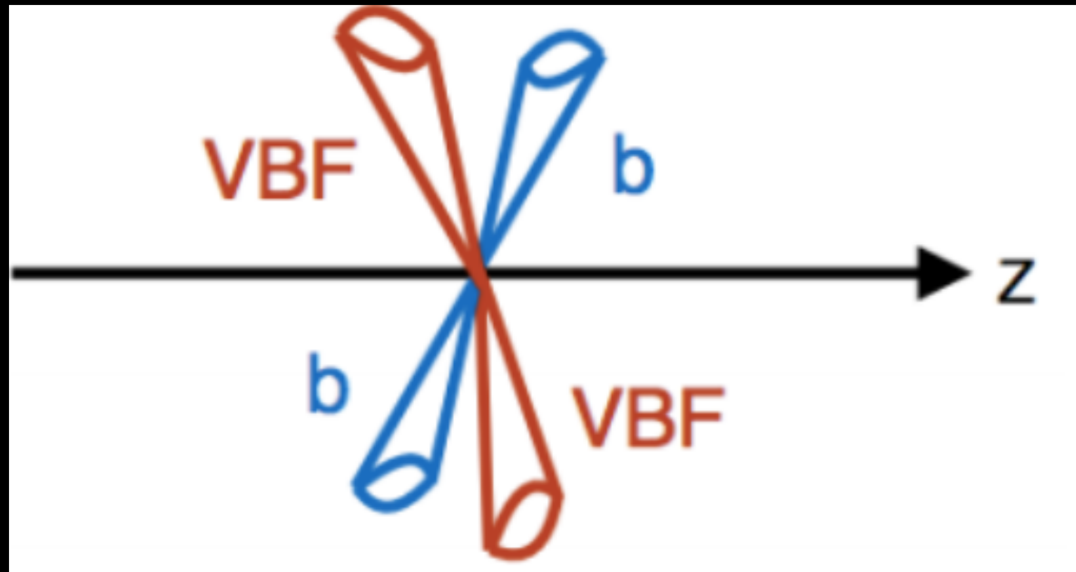
ANN score



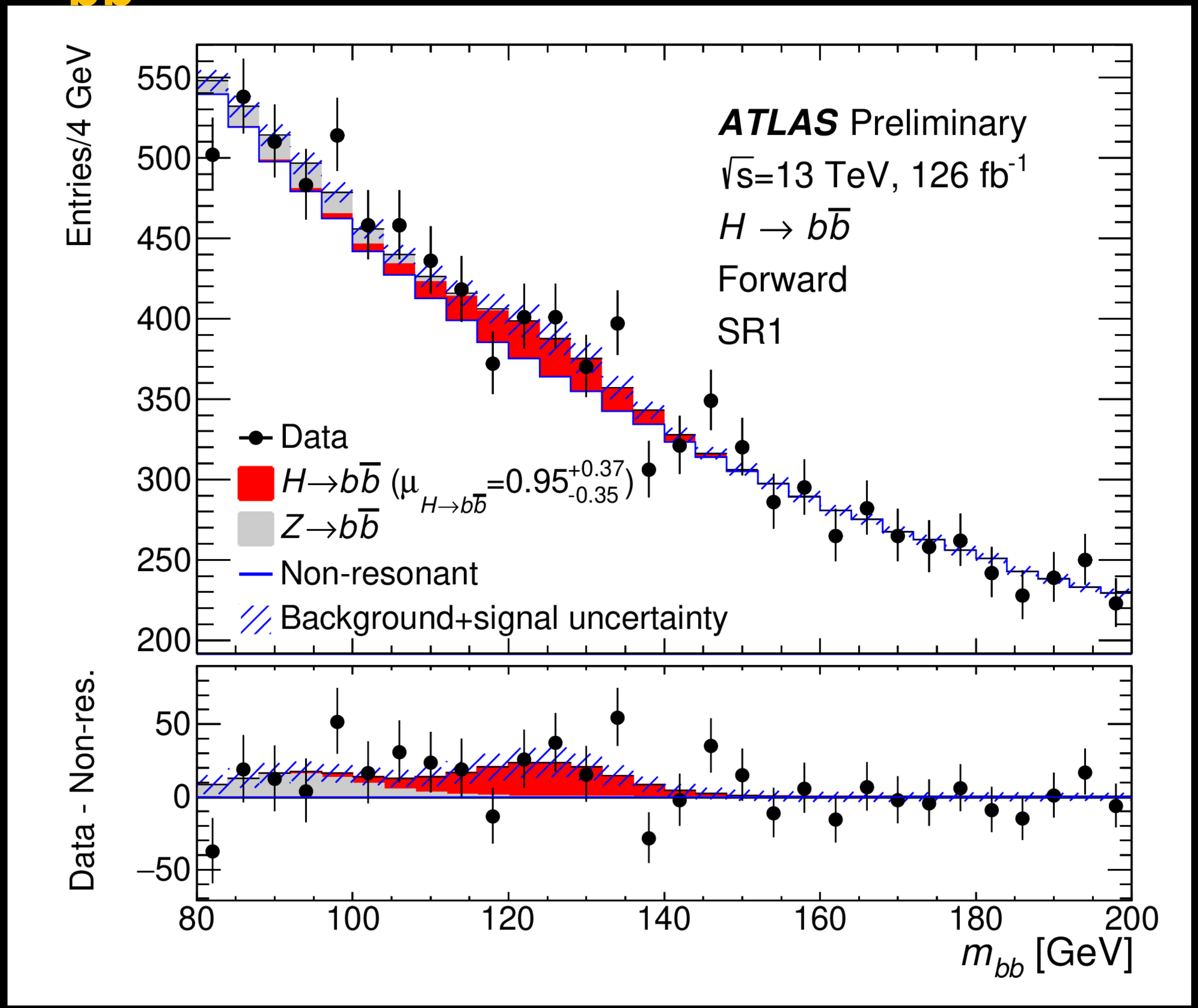
Forward channel (1fj+2b



Central channel (2b+2j)



m_{bb} in forward channel SR1 region



VBF H(→bb) +γ

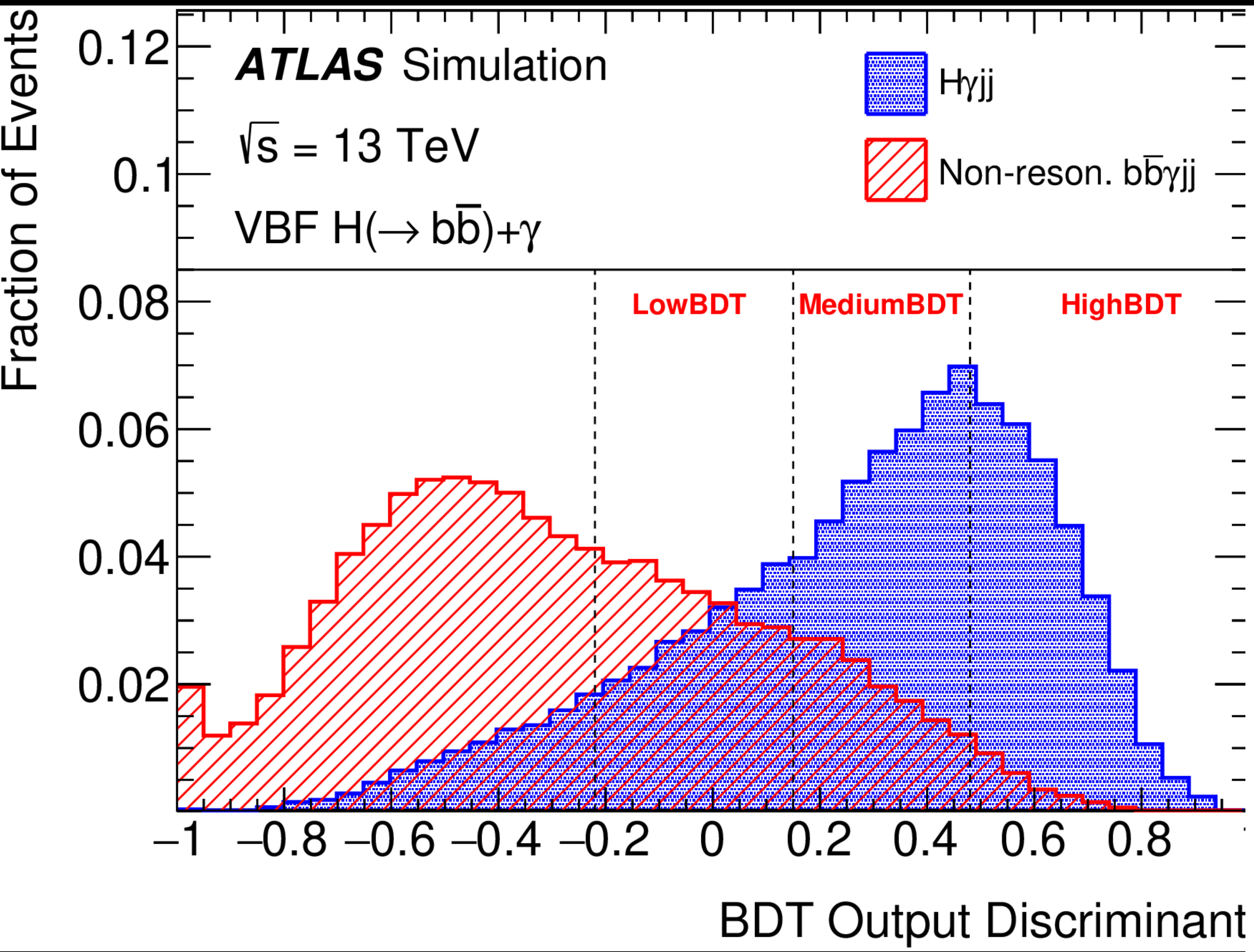
- **Dedicated trigger →low γ/jet pT threshold→ high efficiency**
  - **Level-1 trigger: single e/ γ trigger**
  - **High level trigger: high pT γ+ dijet m_{jj}>700GeV + 1 bjet**
- **Boosted decision tree (BDT) classifies events into categories**
  - **Optimized for both signal to background discrimination**
  - **Decorrelation of the BDT output score with m_{bb}**
- **Signal extracted from simultaneous fit to b-tagged jet pair invariant mass m_{bb} in multiple event categories;**

Run 2 132 fb^{-1} result
μ_{VBF}=1.3 ± 1.0.

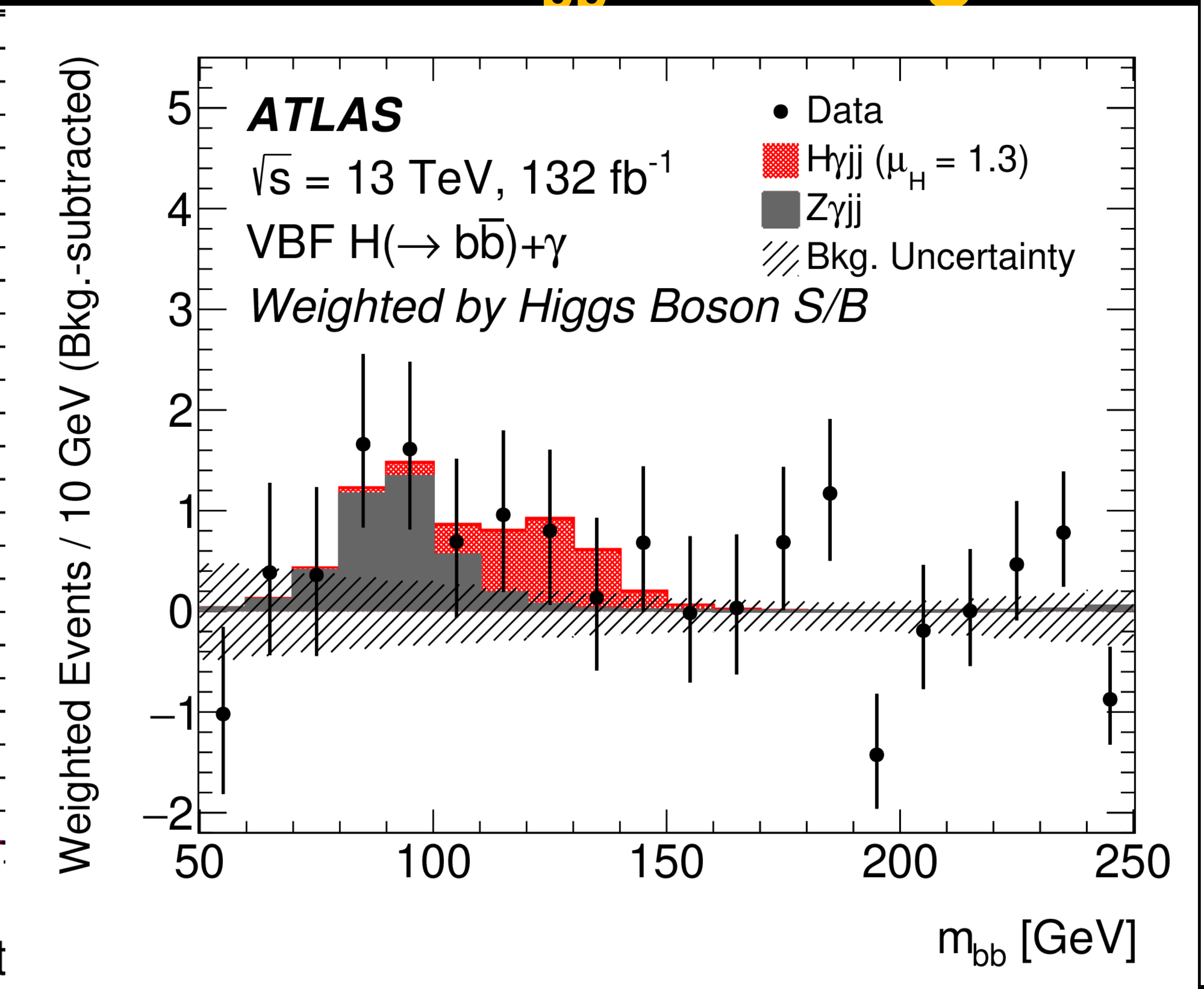
1.3 σ (1.0 σ) obs. (exp) significance

CERN-EP-2020-179

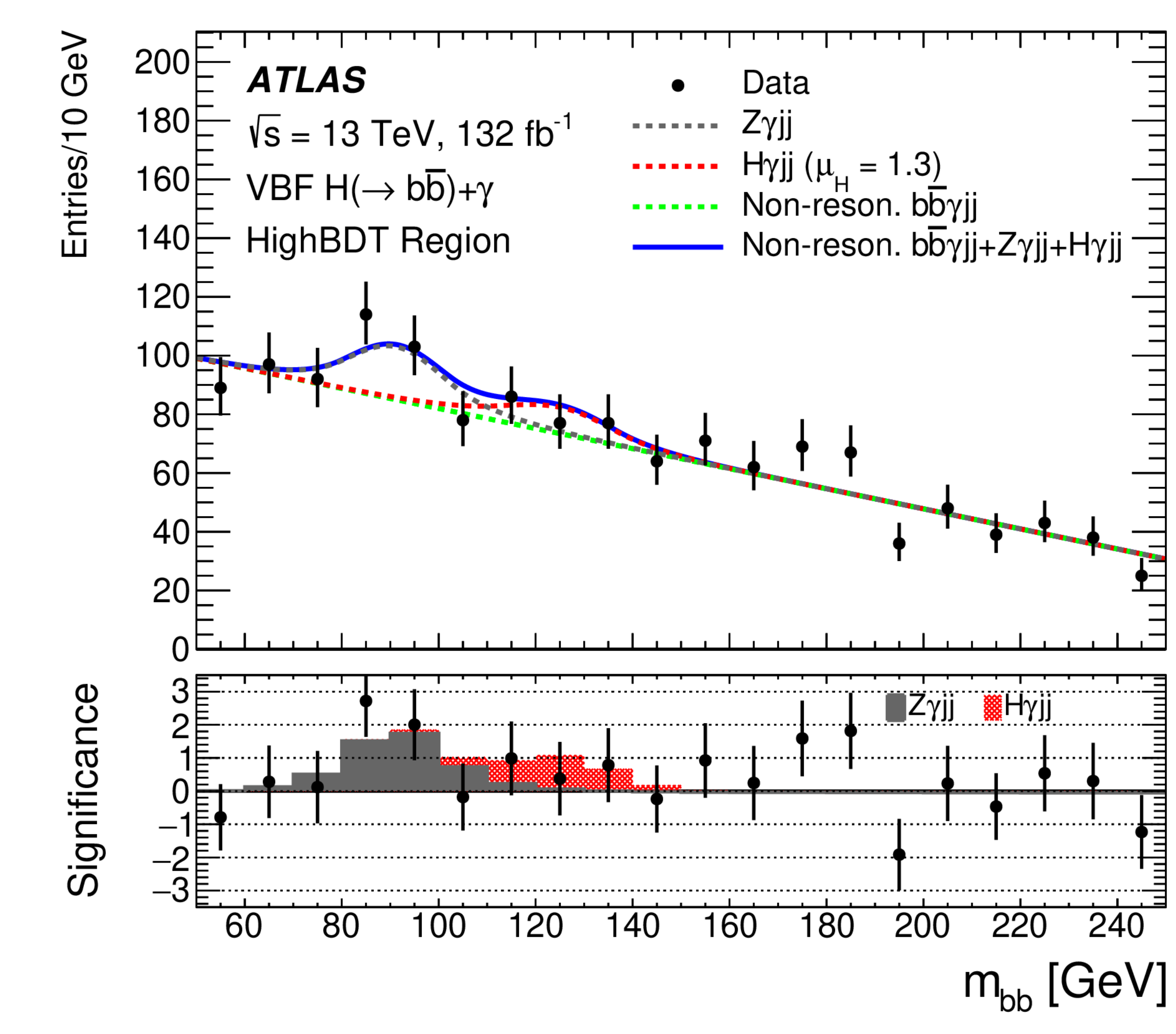
BDT score distribution



Combined m_{bb} in all regions



m_{bb} fit in high BDT region



VBF H(→bb)

VBF H→bb	Dataset	obs. (exp.) Significance	Paper Reference
ATLAS	Full Run 2	2.9σ(2.9σ)	CERN-EP-2020-195, CERN-EP-2020-179
CMS	Run 1	2.2σ(0.8σ)	Phys. Rev. D 92 (2015) 032008

➢ **Analysis stat. limited, dominant exp. systematic contributions**

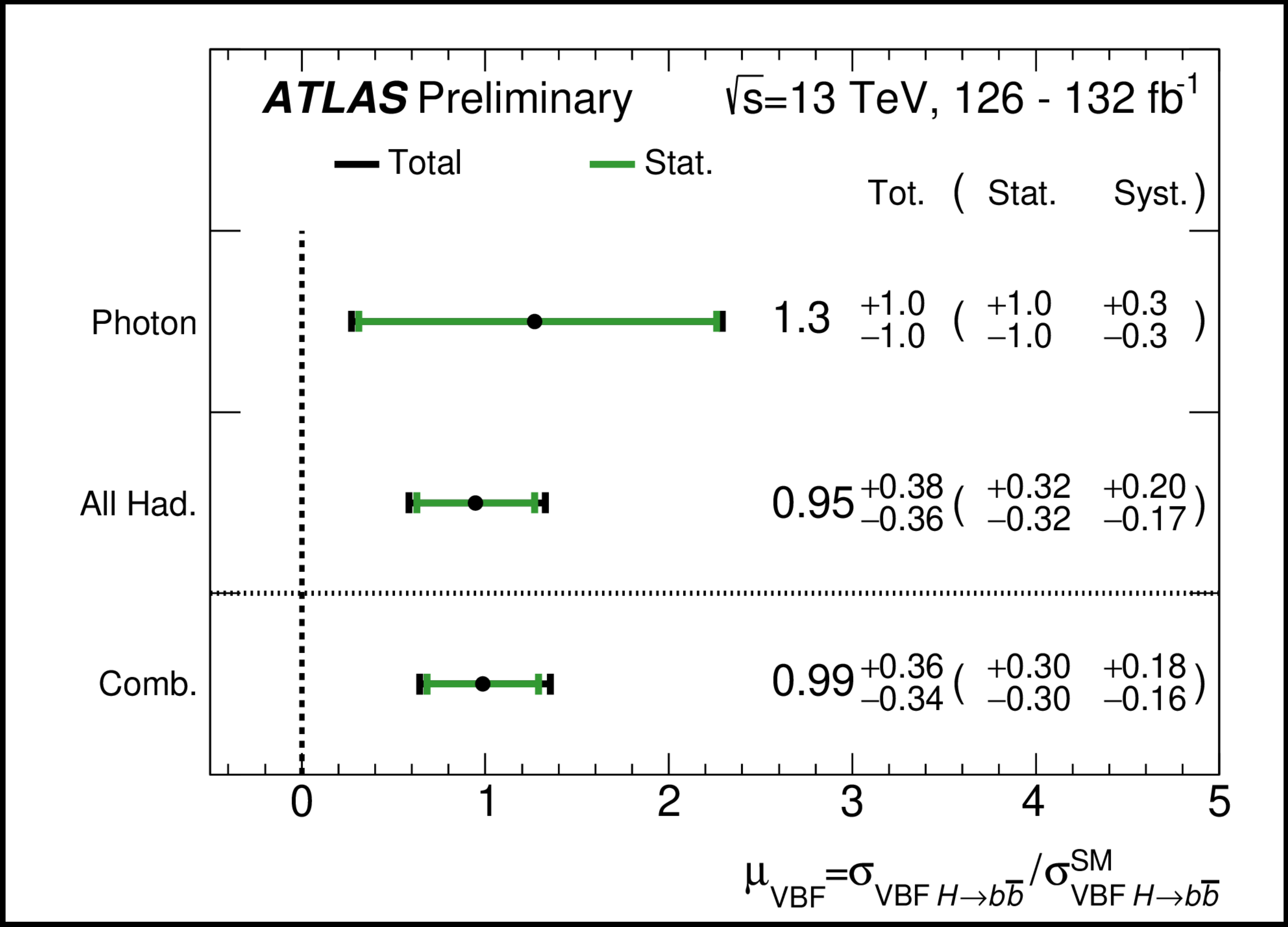
- ☐ **Jet energy scale and flavour tagging uncertainties;**
- ☐ **Non-resonant bkg parameters**

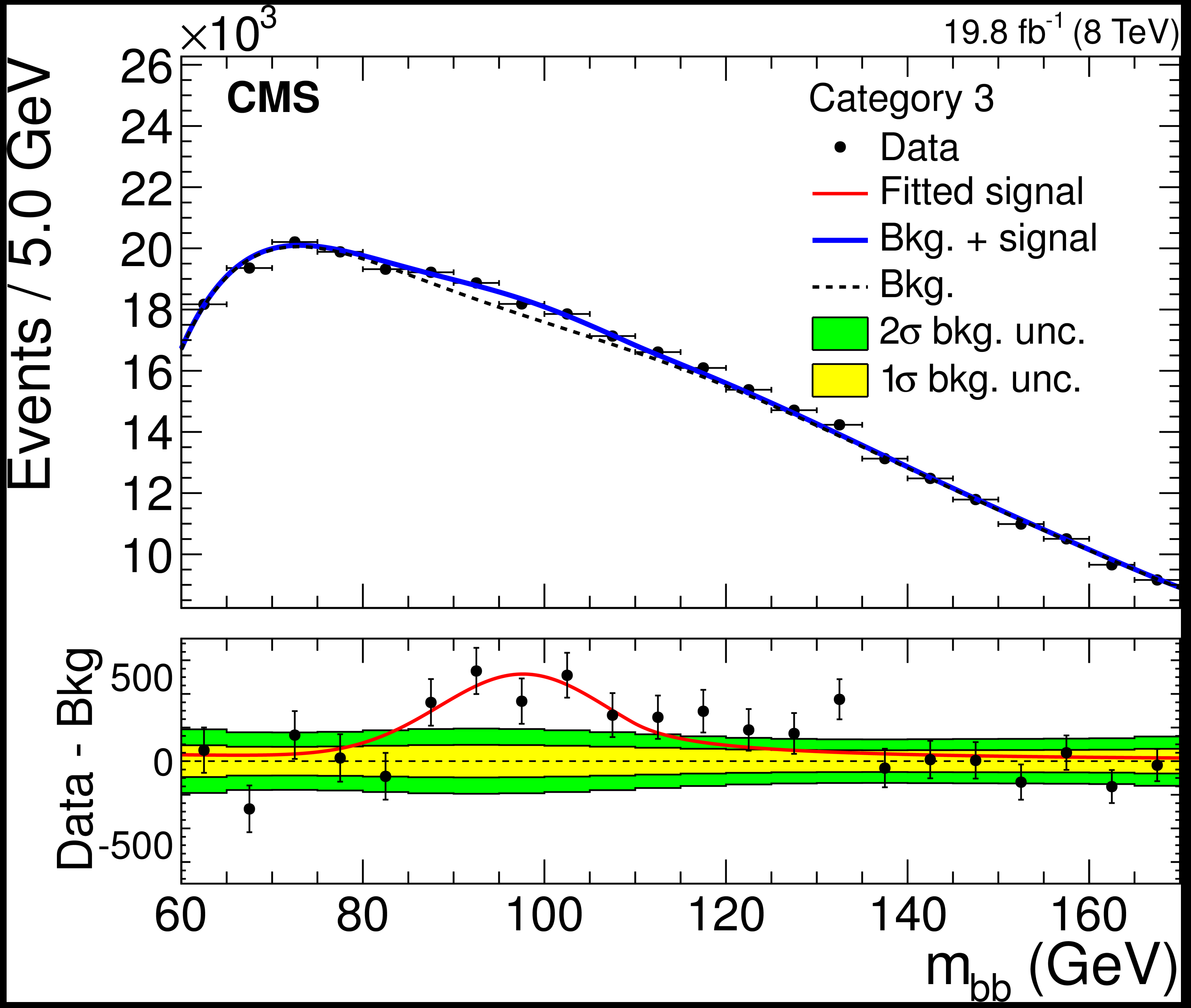
more info in Reina's talk In Yukawa Session today

VBF H(→bb)+γ

VBF H(→bb)

Combined





VBF H→ττ

☐Systematics uncertainty donated

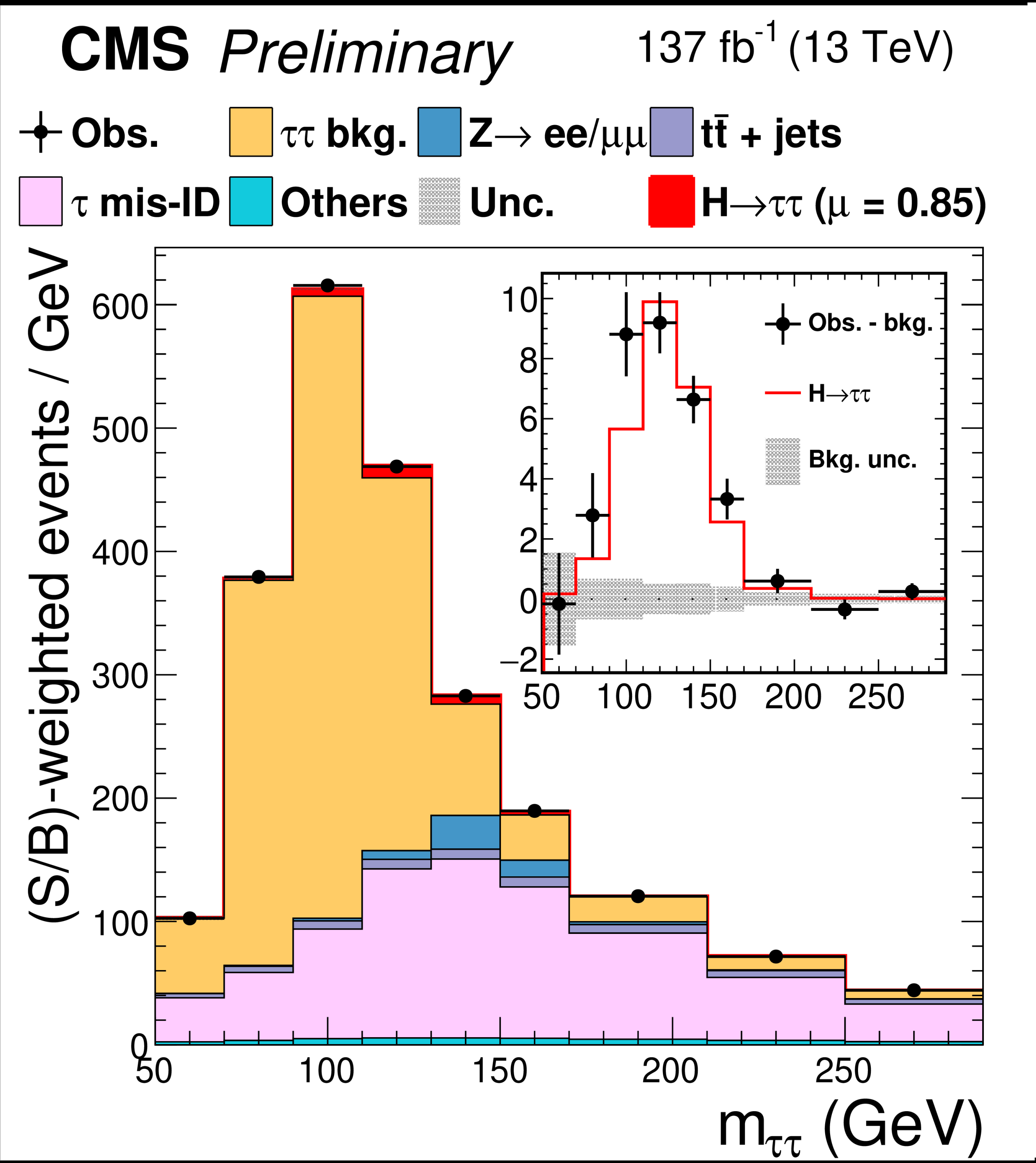
- ➢ Signal theory uncertainty. is leading syst. in ATLAS
- ✓ Parton shower syst. → Pythia7 Vs Herwig
- ✓ Acceptance of ggF Higgs in the VBF phase space

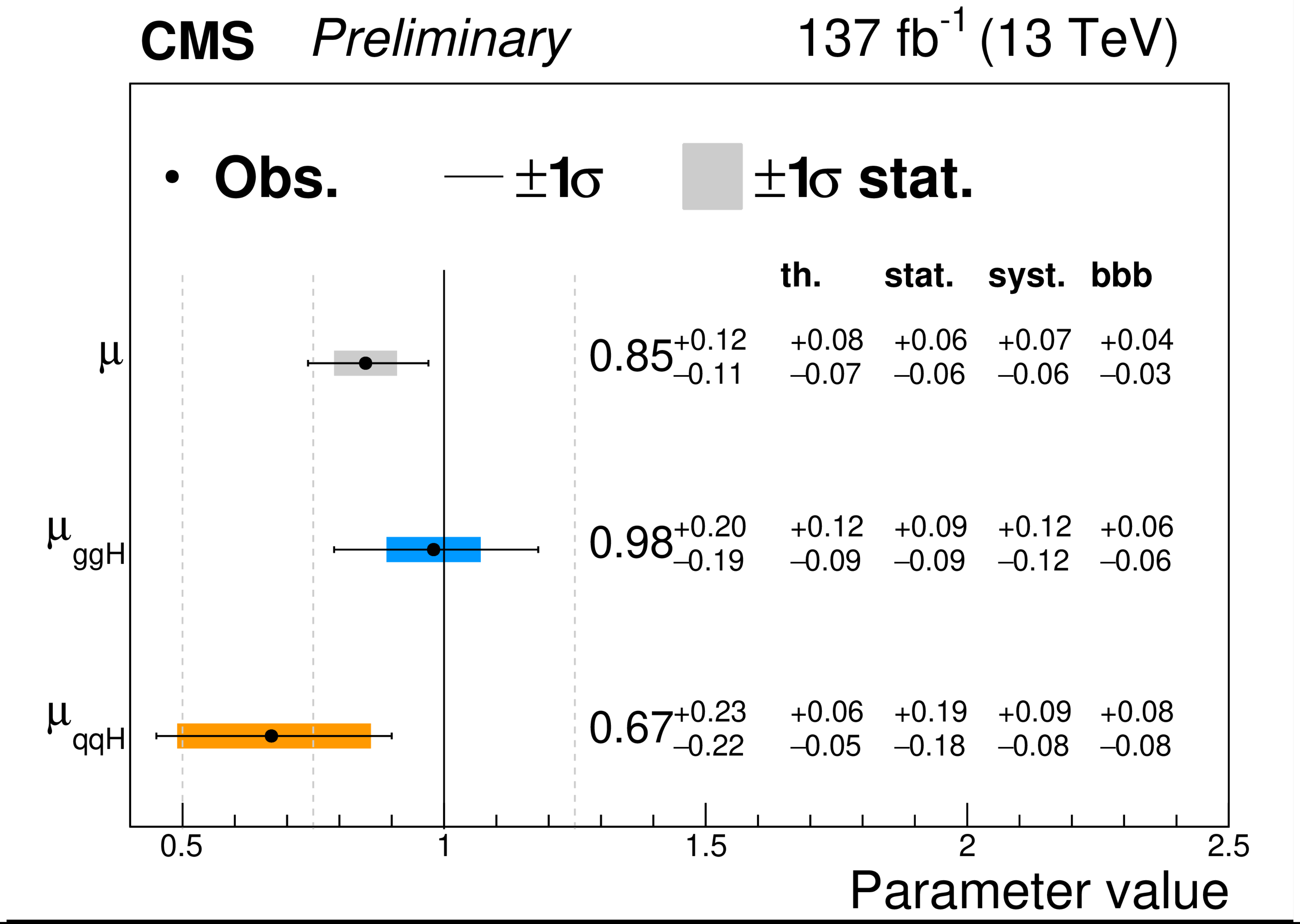
More info in Andrea Carlo Marini's plenary talk yesterday
More details in Mohammadhassan 's YST talk on Thursday

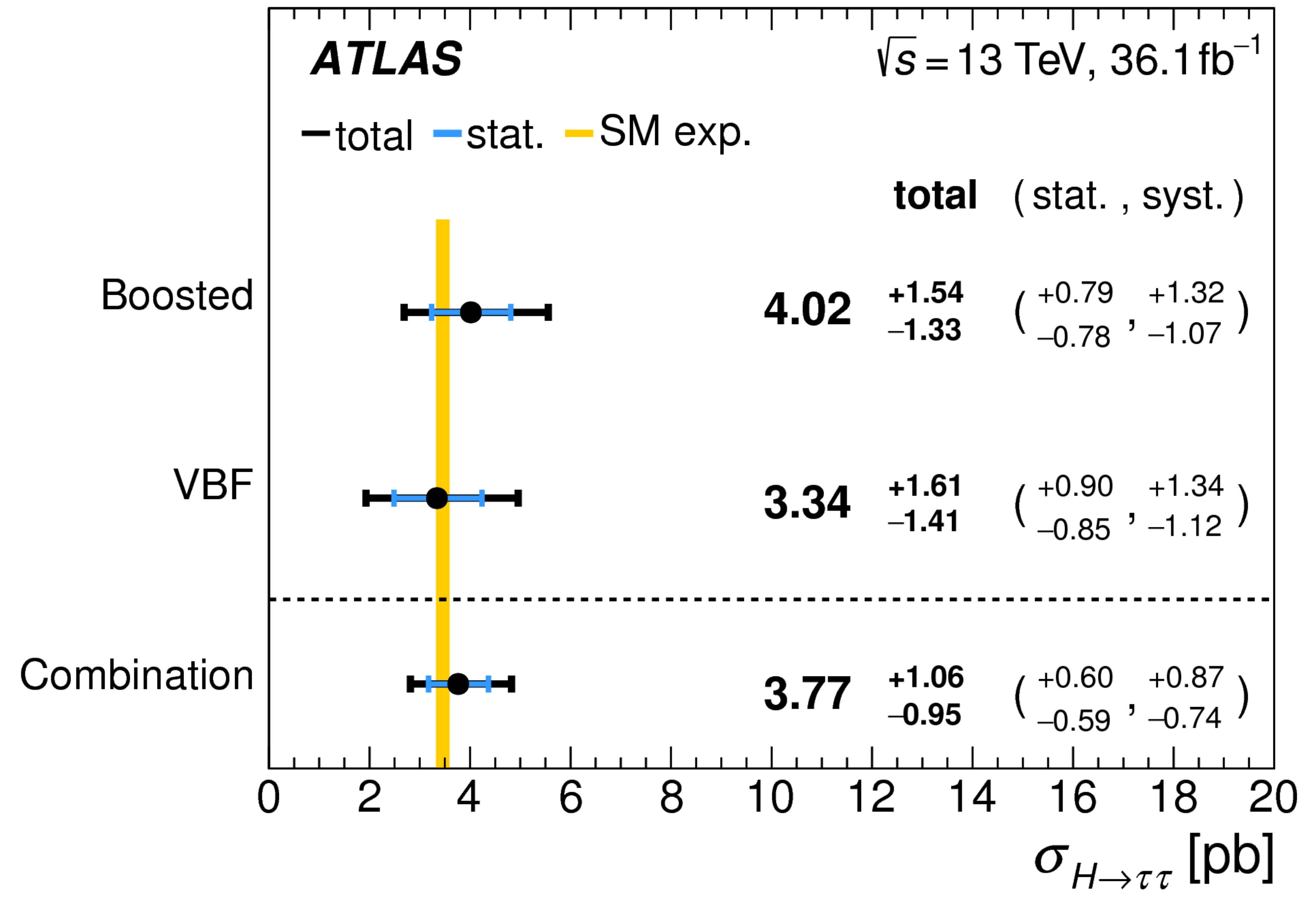
CMS full run II analysis (137/fb)
CMS-PAS-HIG-19-010

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ [%] Observed	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ [%] Expected
Theoretical uncert. in signal	+13.4 / −8.7	+12.0 / −7.8
Background statistics	+10.8 / −9.9	+10.1 / −9.7
Jets and E_T^{miss}	+11.2 / −9.1	+10.4 / −8.4
Background normalization	+6.3 / −4.4	+6.3 / −4.4
Misidentified τ	+4.5 / −4.2	+3.4 / −3.2
Theoretical uncert. in background	+4.6 / −3.6	+5.0 / −4.0
Hadronic τ decays	+4.4 / −2.9	+5.5 / −4.0
Flavor tagging	+3.4 / −3.4	+3.0 / −2.3
Luminosity	+3.3 / −2.4	+3.1 / −2.2
Electrons and muons	+1.2 / −0.9	+1.1 / −0.8
Total systematic uncert.	+23 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −25	+27 / −24

ATLAS:Phys. Rev. D 99, 072001







ATLAS VBF $H \to WW^* \to e\nu\mu\nu$

- ATLAS new result with full run II data(139 fb^{-1})： ATLAS-CONF-2020-045
- Higher sensitivity compared to 36fb^{-1} paper
- **Highlight of event pre-selection :**
- **Lepton selection:** 2 different-flavour leptons with opposite charge

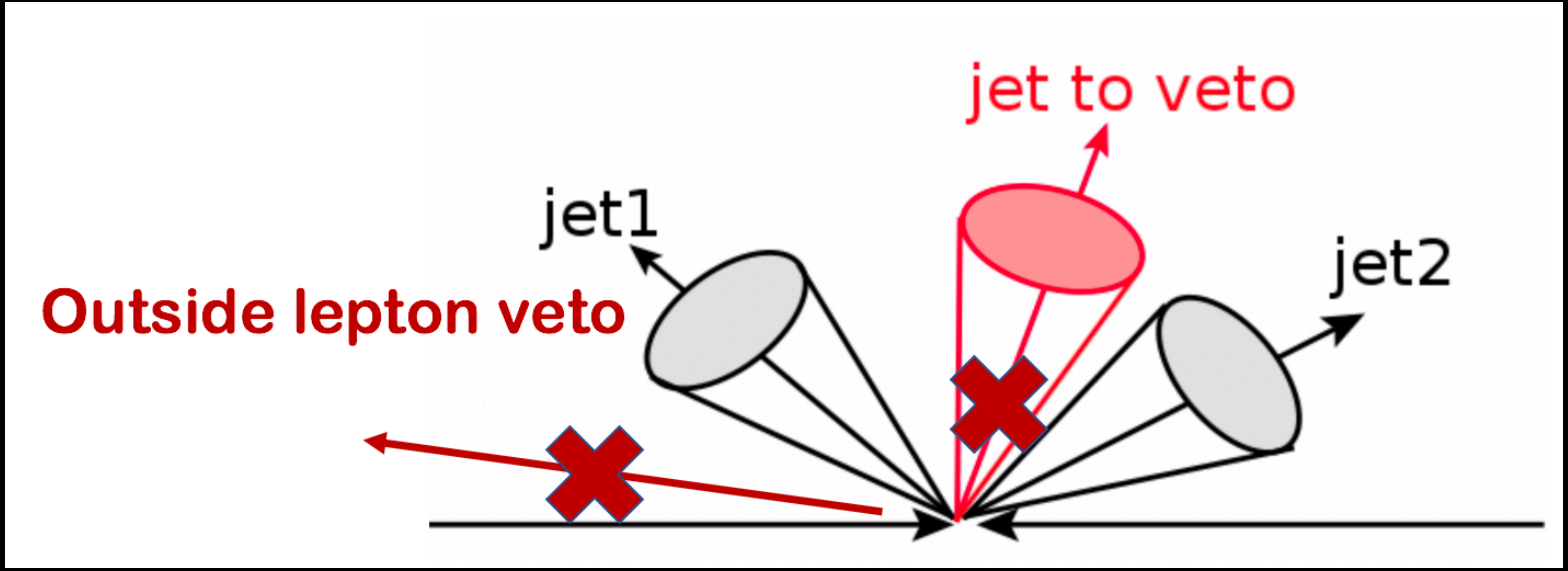
VBF signature:

- **VBF jets cut**： 2jet with p_T>30GeV, M_{jj}> 120GeV
- **Optimisation of central jet veto:** p_T>20 GeV → p_T>30 GeV
- **Outside-lepton veto** ： veto Lepton outside the jet rapidity gap

Background rejection:

- **Top suppression** : Veto b jets → **reverse to build Top control region**
- **Z+jet suppression:** $m_{\tau\tau} < m_Z - 25$GeV

→ $|m_{\tau\tau} - m_Z| < 25$GeV **to build Z+jet control region**

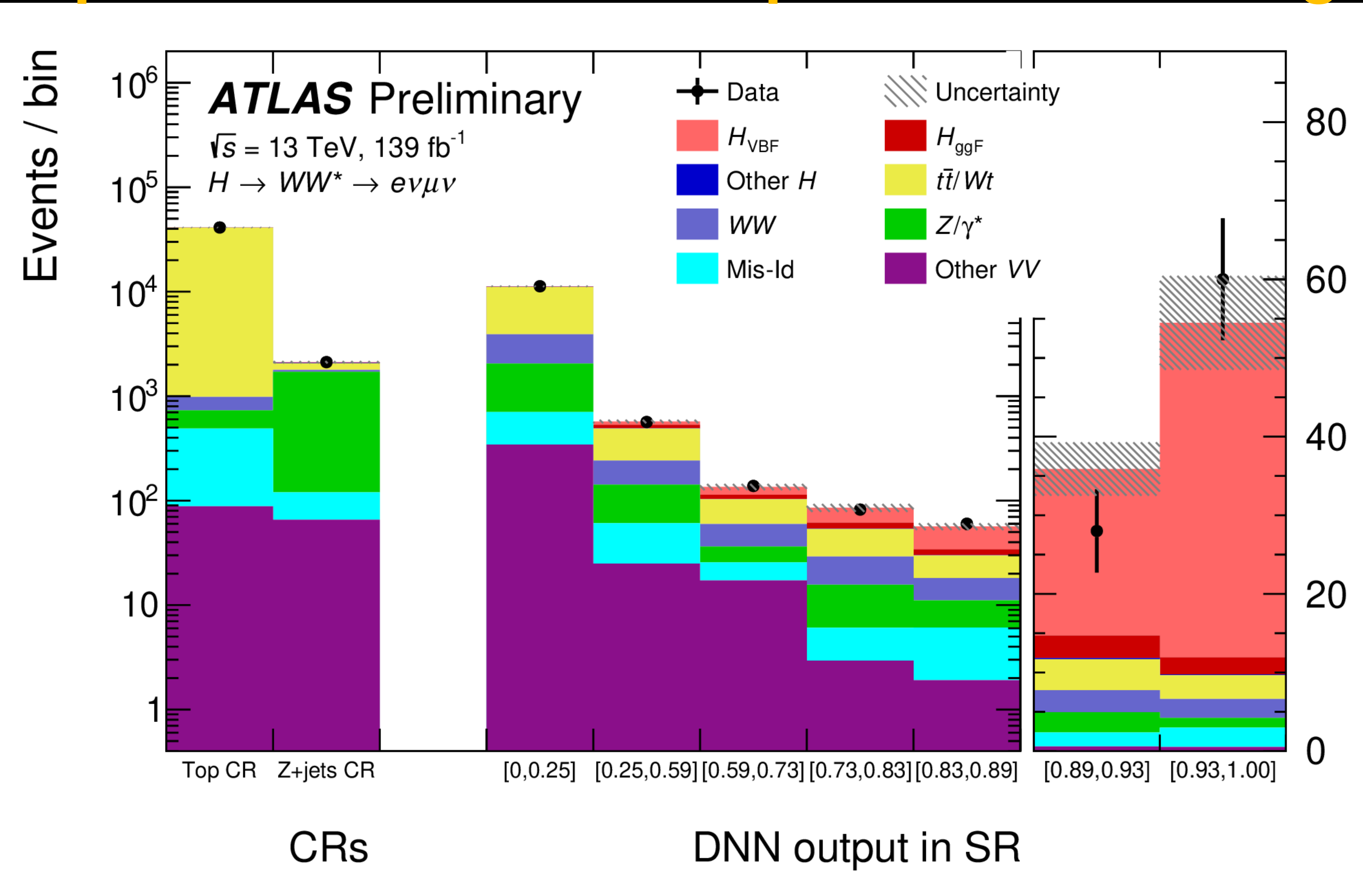


ATLAS VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

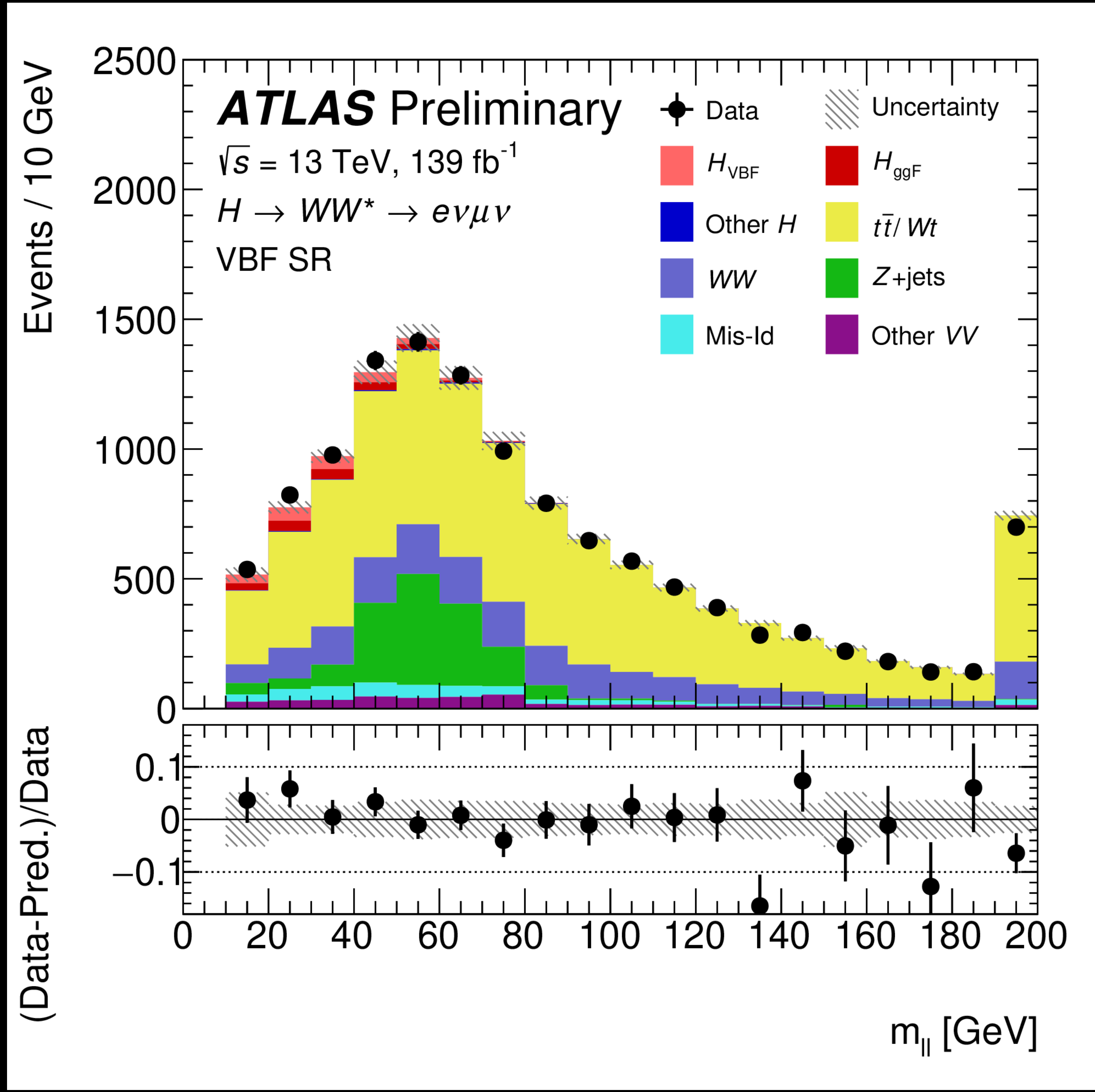
- **Highlight:**
- **Deep Neural Networks (DNN) is used to replace BDT in previous analysis**
- **Feedforward network, 8 dense layers.**
- **Discrimination based on 15 variables:**
- **VBF topology:** $\Delta y_{jj}, m_{jj}, \eta_{\ell}^{\text{centrality}}, m_{\ell1j1}, m_{\ell1j2}, m_{\ell2j1}, m_{\ell2j2}\, p_{\mathrm{T}}^{\text{jet}_1}, p_{\mathrm{T}}^{\text{jet}_2}, p_{\mathrm{T}}^{\text{jet}_3}$
- $H \rightarrow WW$ **decay:** $\Delta\phi_{\ell\ell}, m_{\ell\ell}, m_{\mathrm{T}}$
- **Top suppression:** $p_{\mathrm{T}}^{\text{tot}}$, MET significance

ATLAS Full run II analysis
ATLAS-CONF-2020-045

Deep Neural Networks output in different regions



Postfit Di-lepton mass distribution



VBF H → WW*

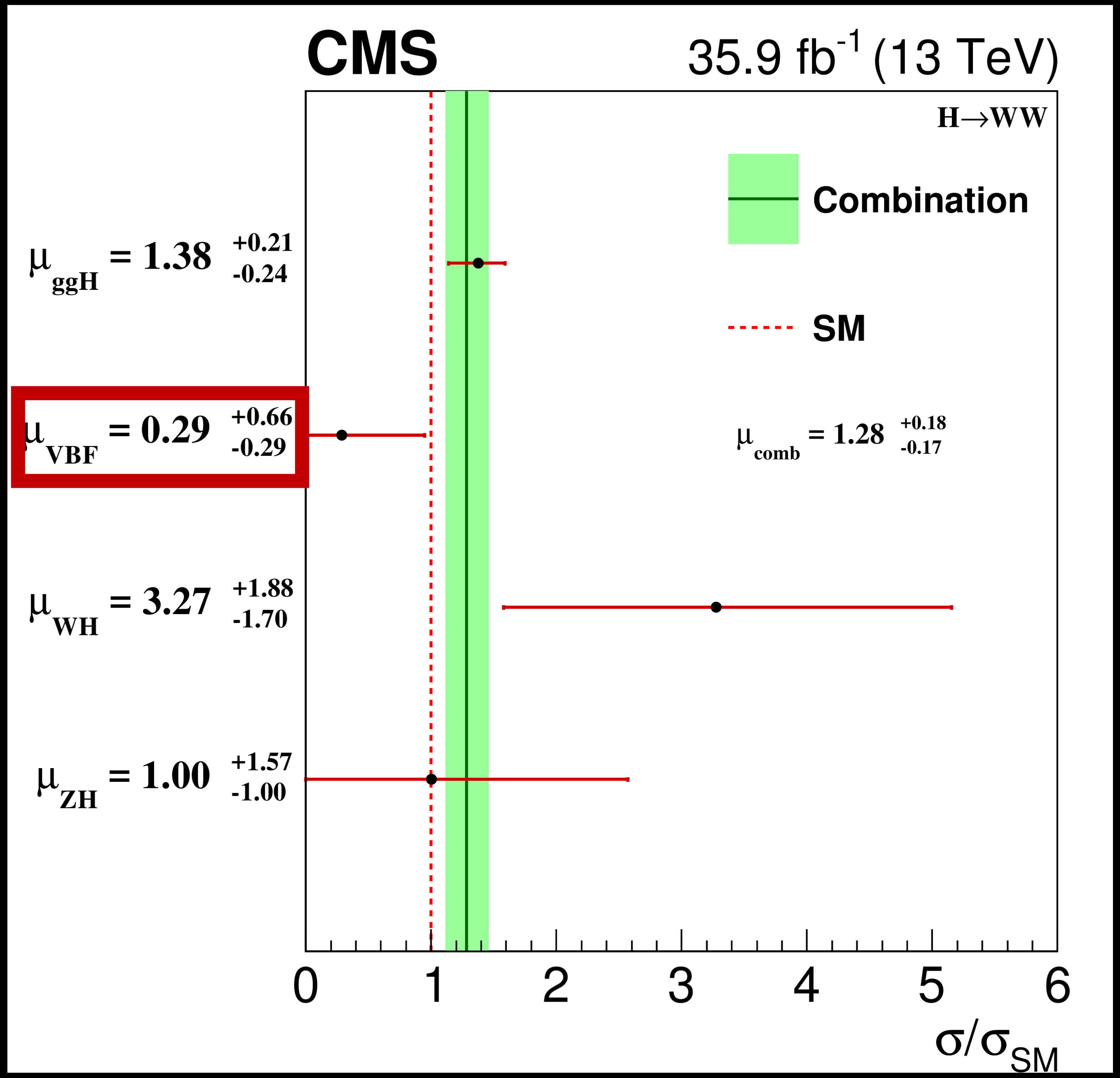
Full run II ATLAS VBF H → WW* analysis , 7.0σ(6.2σ) obs.(Exp.) Significance

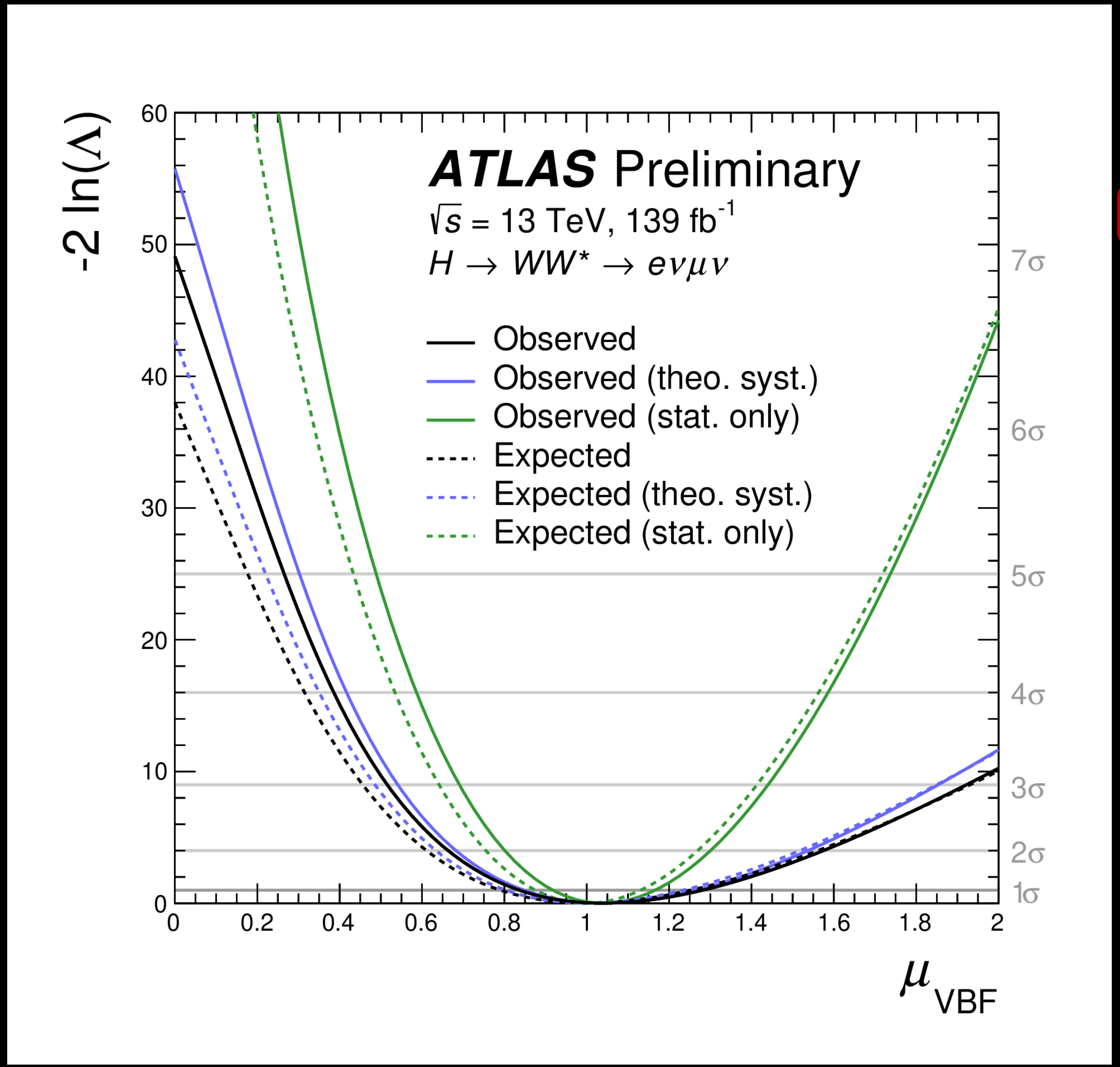
- **ggH and ttH Higgs production are considered background (20% of total Bkg)**
- **Theory systematics dominated: VBF parton shower uncertainty**

	Production mode	Data luminosity	obs. (exp.)Significance
ATLAS	VBF H → WW*	Run 2 (139 fb^{-1})	7.0σ(6.2σ)
CMS	All modes H → WW	Run 2 (35.9 fb^{-1})	9.1σ(7.1σ)

Phys. Lett. B 791 (2019) 96

$$\mu_{VBF} = 1.04^{+0.13}_{-0.12}\ \text{stat.}\ ^{+0.09}_{-0.08}\ \text{exp.}\ ^{+0.17}_{-0.12}\ \text{sig. theo.}\ ^{+0.08}_{-0.07}\ \text{bkg. theo.}$$





Source	$\Delta\mu_{\text{VBF}}/\mu_{\text{VBF}}$ [%]
Data statistics	12.5
Total systematics	17.8
Experimental uncertainties	8.8
Missing ET	4.7
MC statistics	3.1
Jet energy scale	2.2
Luminosity	1.9
Modelling of pile-up	1.7
b-tagging	1.6
Jet energy resolution	1.4
Misidentified leptons	0.9
VBF signal theory uncertainties	14.4
Background theory uncertainties	7.7
ggF Higgs	5.2
Top-quark	3.3
WW	2.5
Z+jets	1.9
Total	22

VBF H → ZZ*

- ATLAS: Final fits use Neural Networks inside categories
- CMS: Multi-dimensional fit with m_{4l} and the discriminant (D_{2jet} is sensitive to VBF)

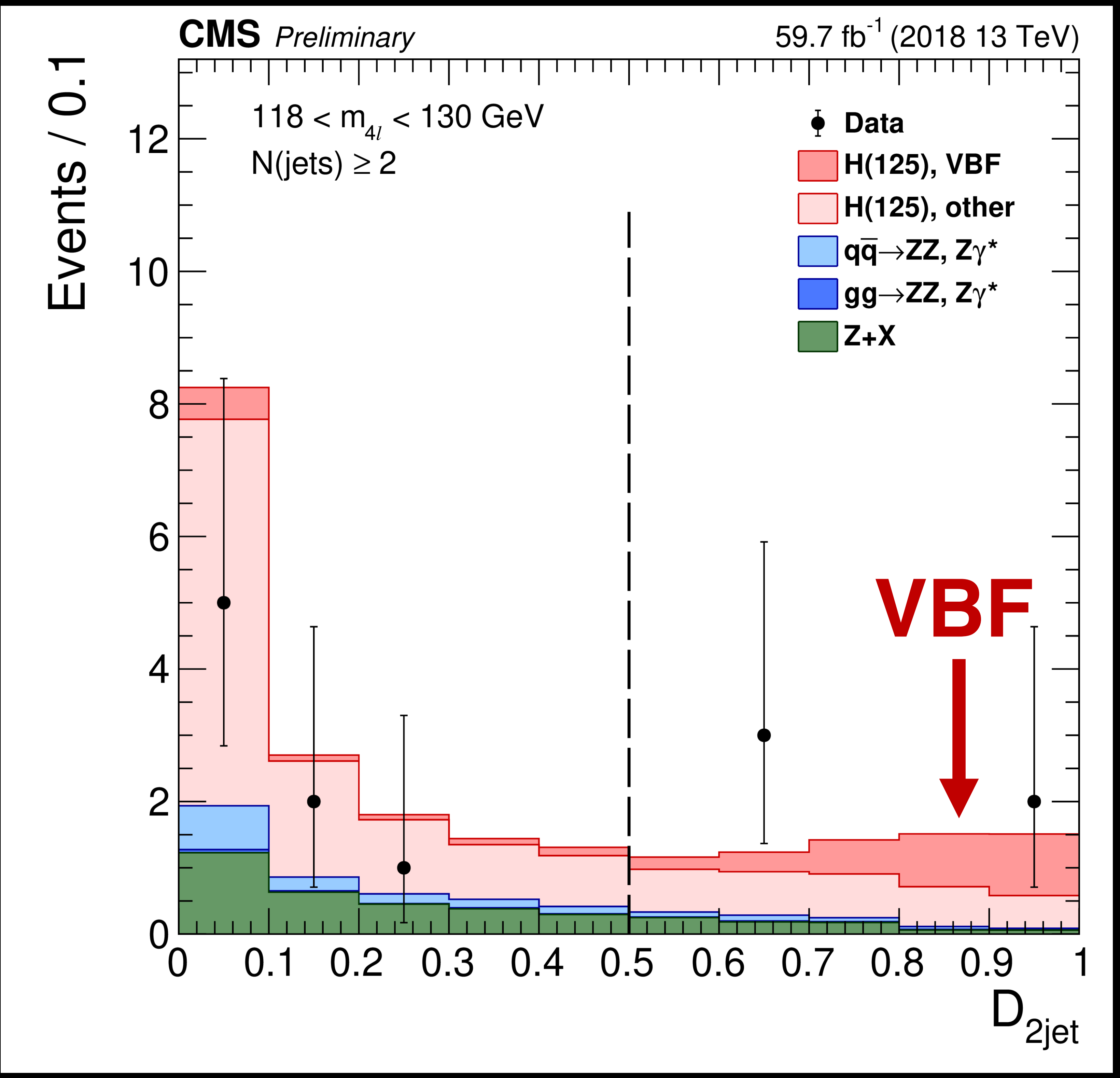
$$\mathcal{D}_{2\text{jet}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{VBF}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

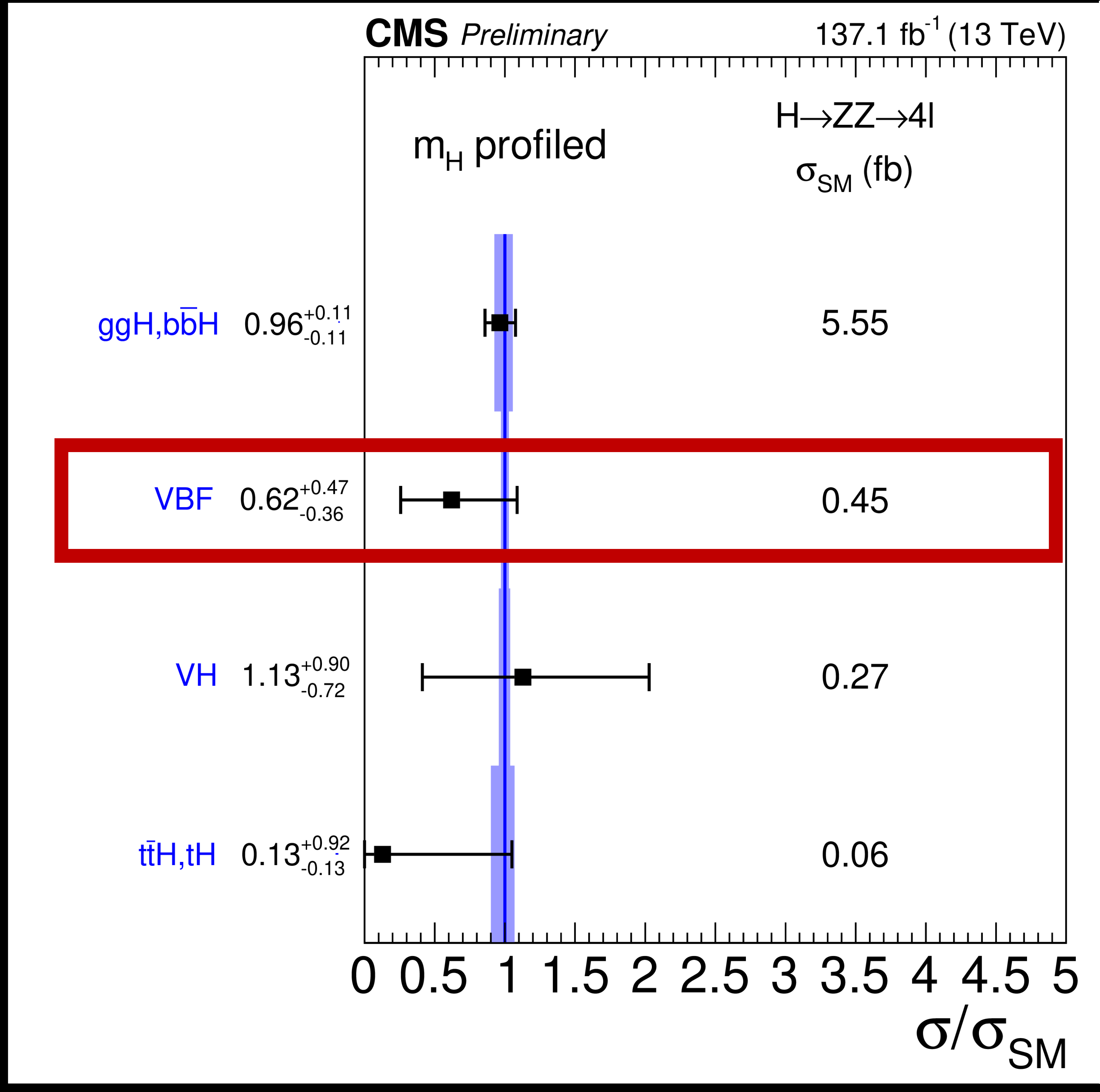
$$\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}) = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell})$$

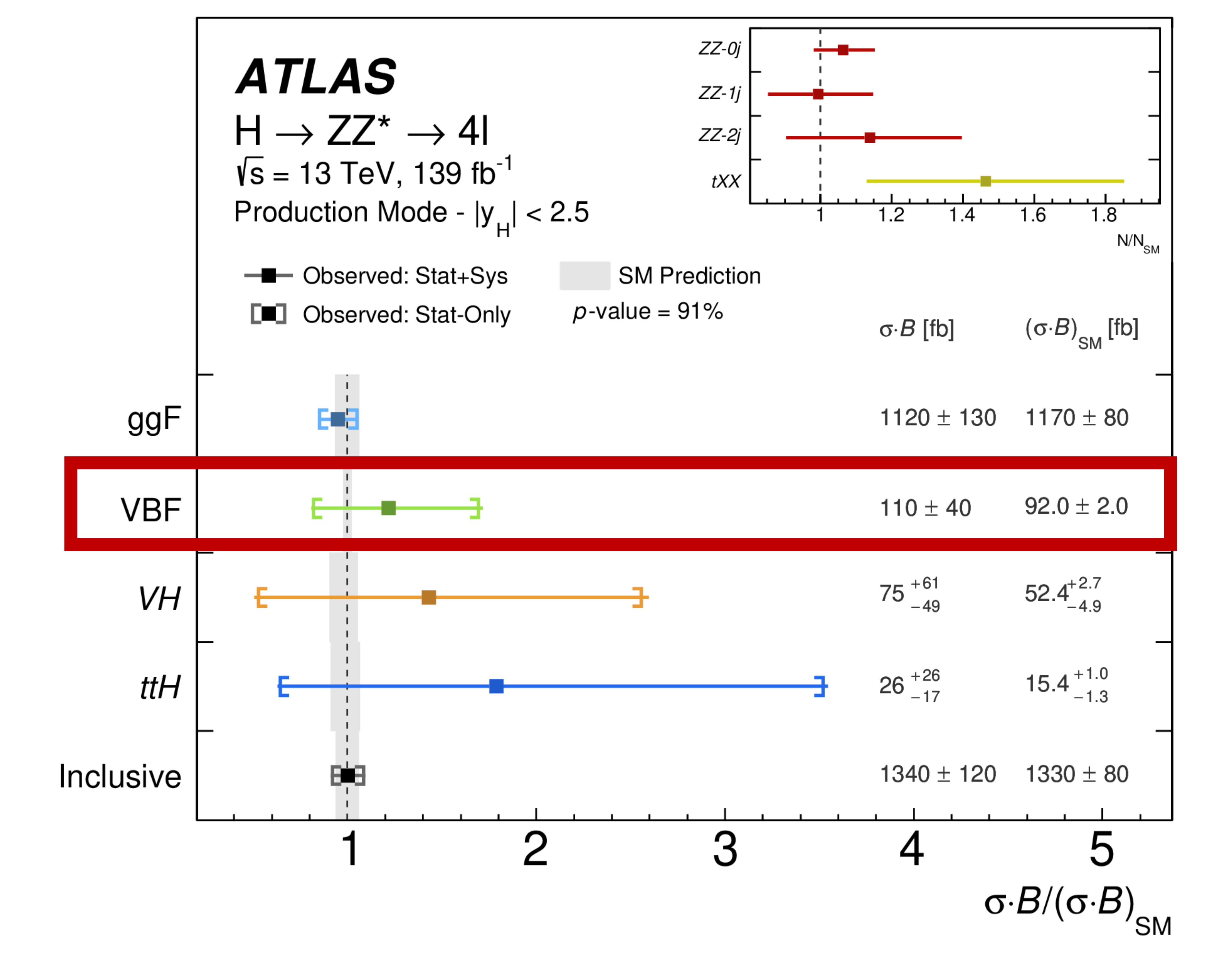
ρ_{VBF}, ρ_{HJJ} are probabilities obtained from the JHUGEN matrix elements

CMS full run II analysis
CMS PAS HIG-19-001

ATLAS full run II analysis
arXiv:2004.03447





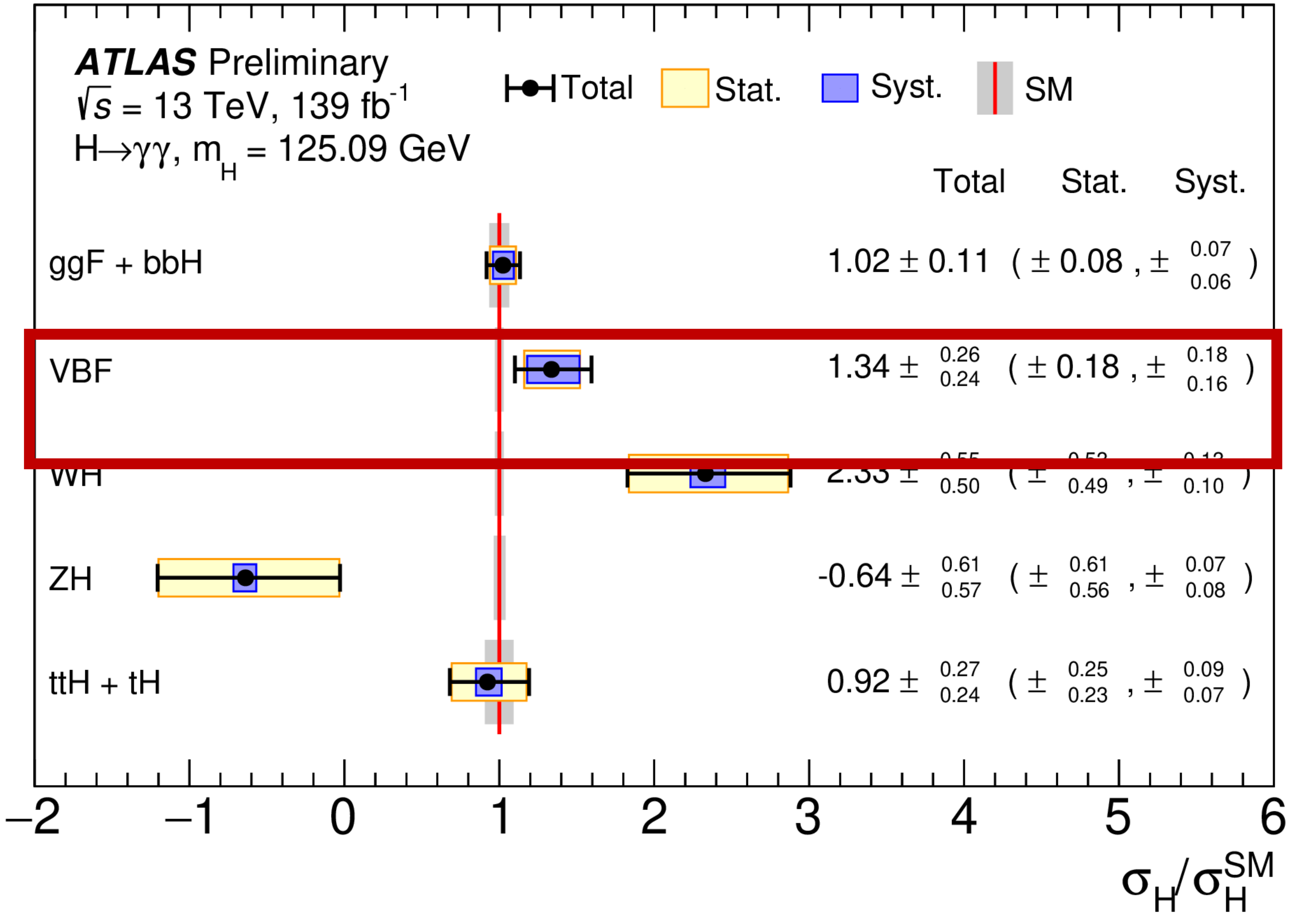


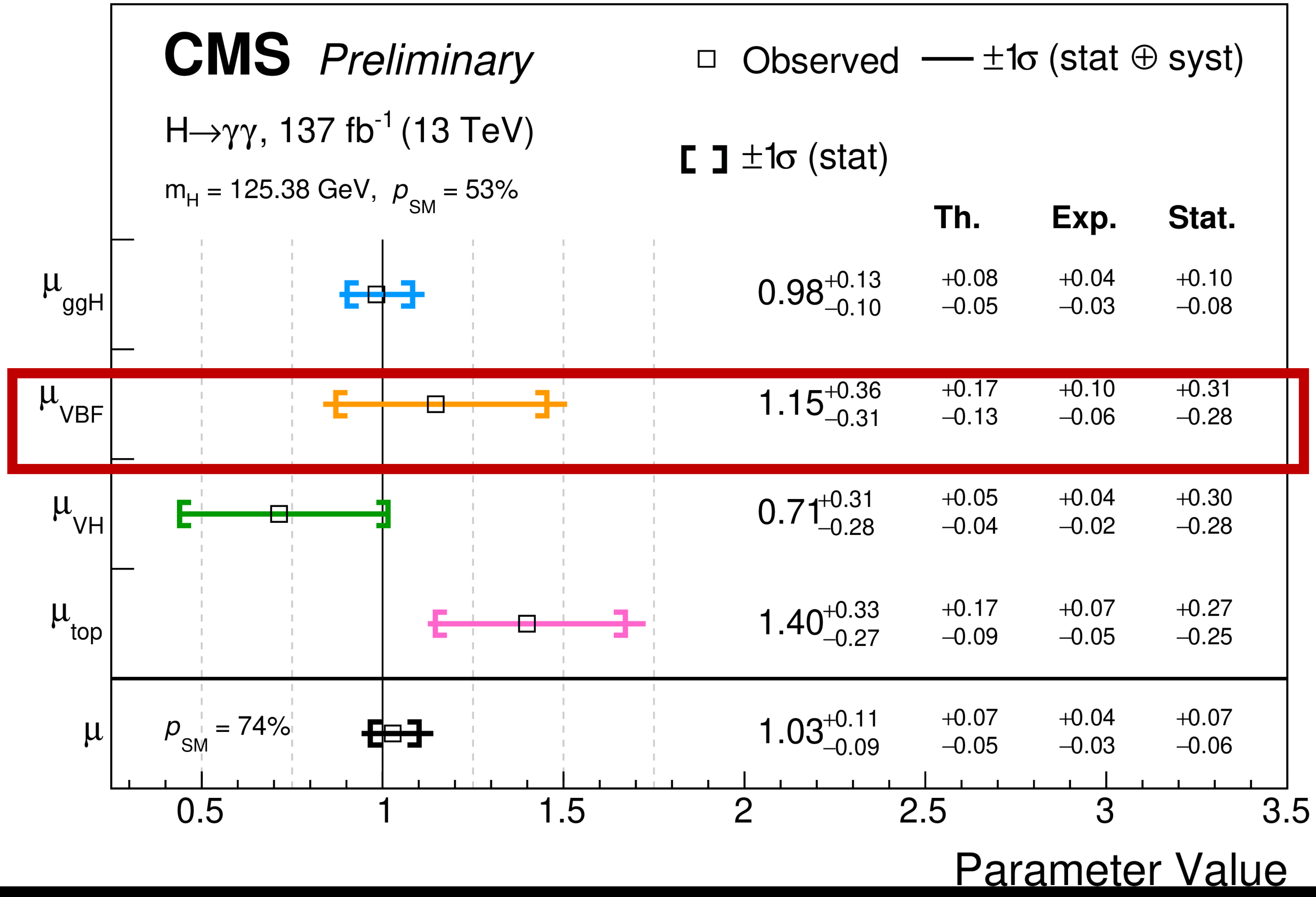
VBF H →γ γ

- H →γ γ channel provides one of the most precise measurements on VBF Higgs production
- The signal strength of VBF Higgs production is consistent with SM prediction.

ATLAS full run II H →γ γ analysis: ATLAS-CONF-2019-029

CMS full run II H →γ γ analysis: CMS-PAS-HIG-19-015





VBF H →γ γ

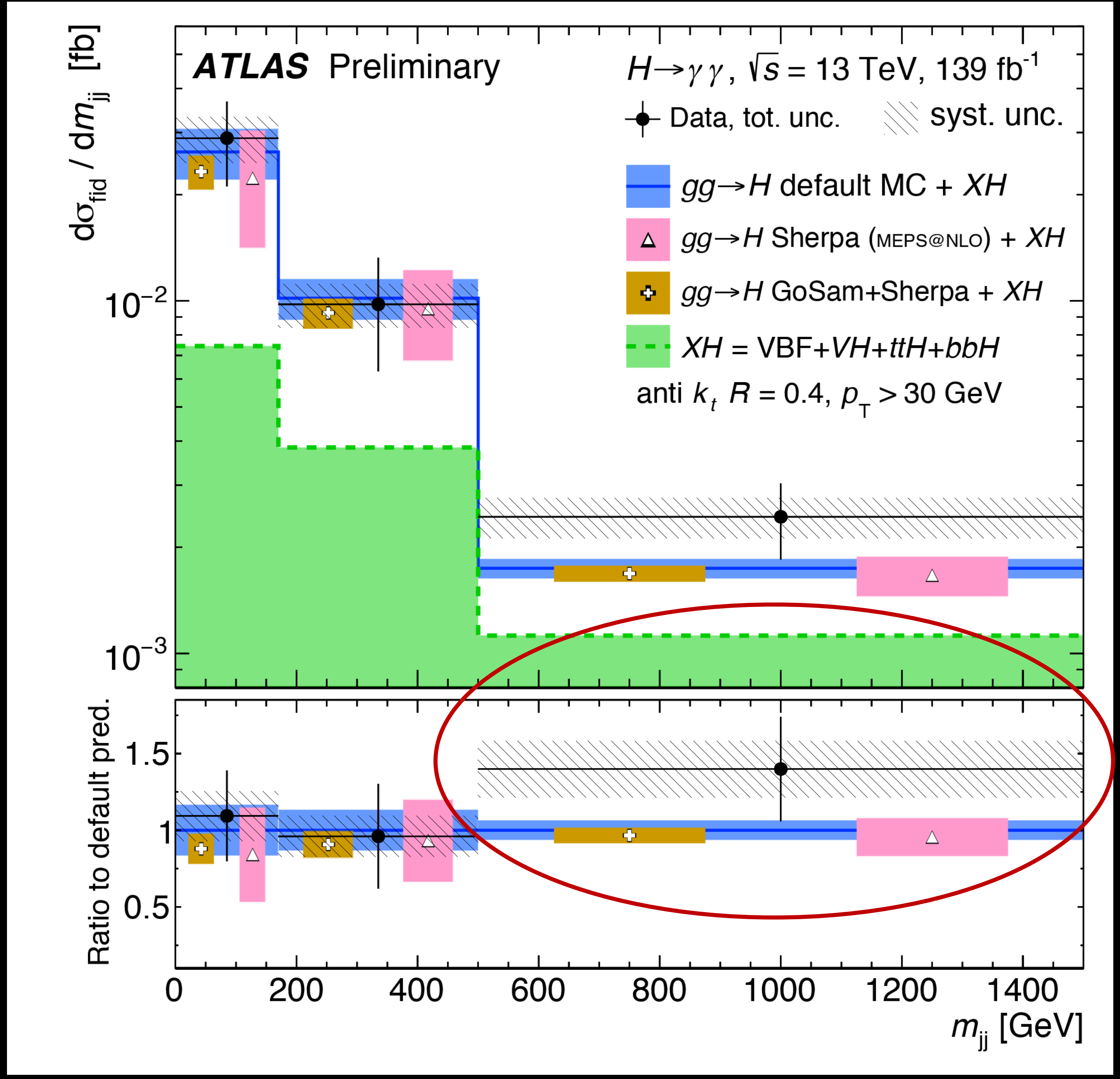
- ➢ **More Differential measurements are needed to understand MC modelling of VBF jets**

□ Found small discrepancy between data and MC

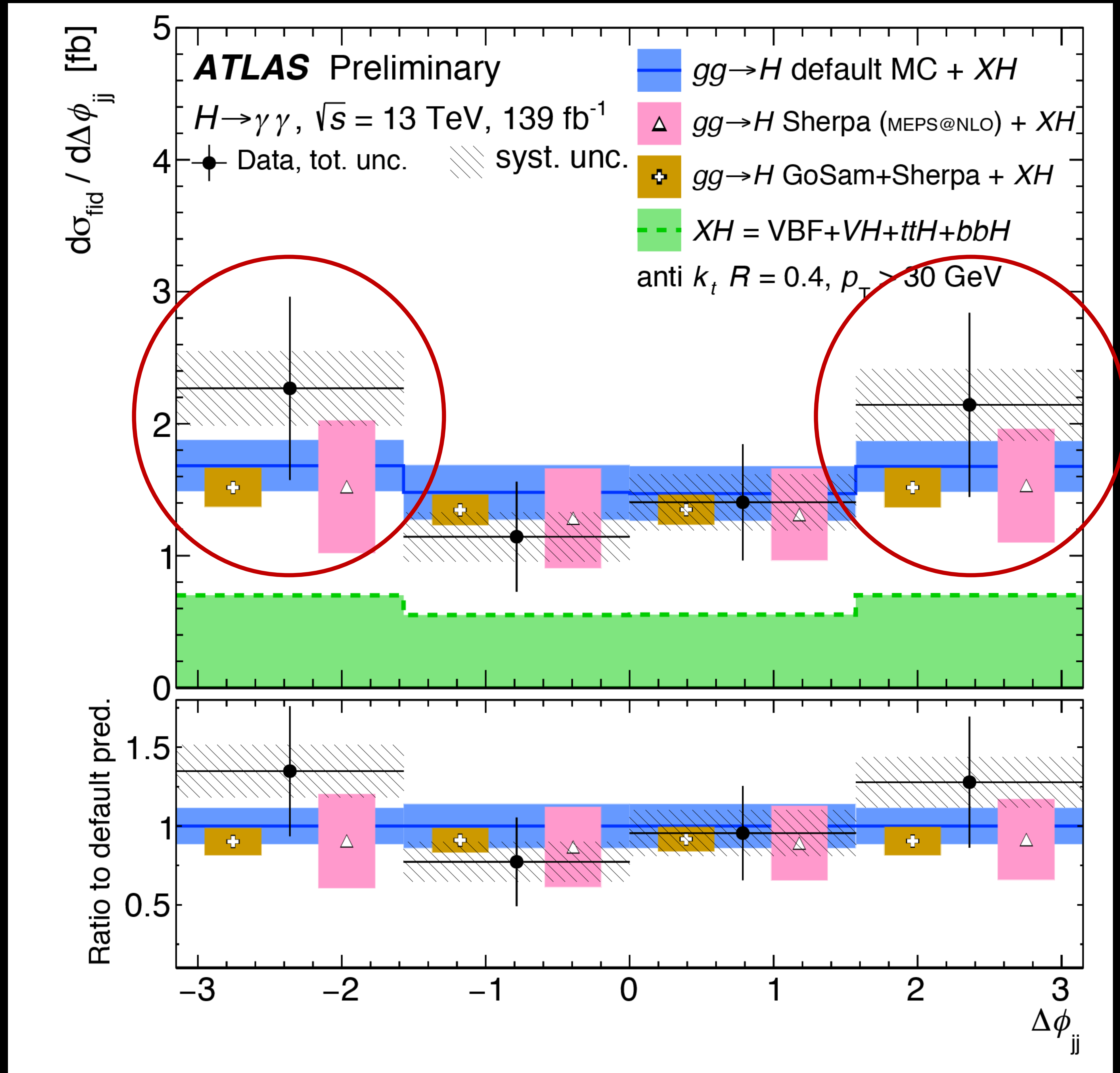
- ✓ **In high di-jet mass**
- ✓ **In large |$\Delta\phi_{jj}$| region**

ATLAS full run II analysis: ATLAS-CONF-2019-029

Di-jet mass



VBF jets $\Delta\phi_{jj}$

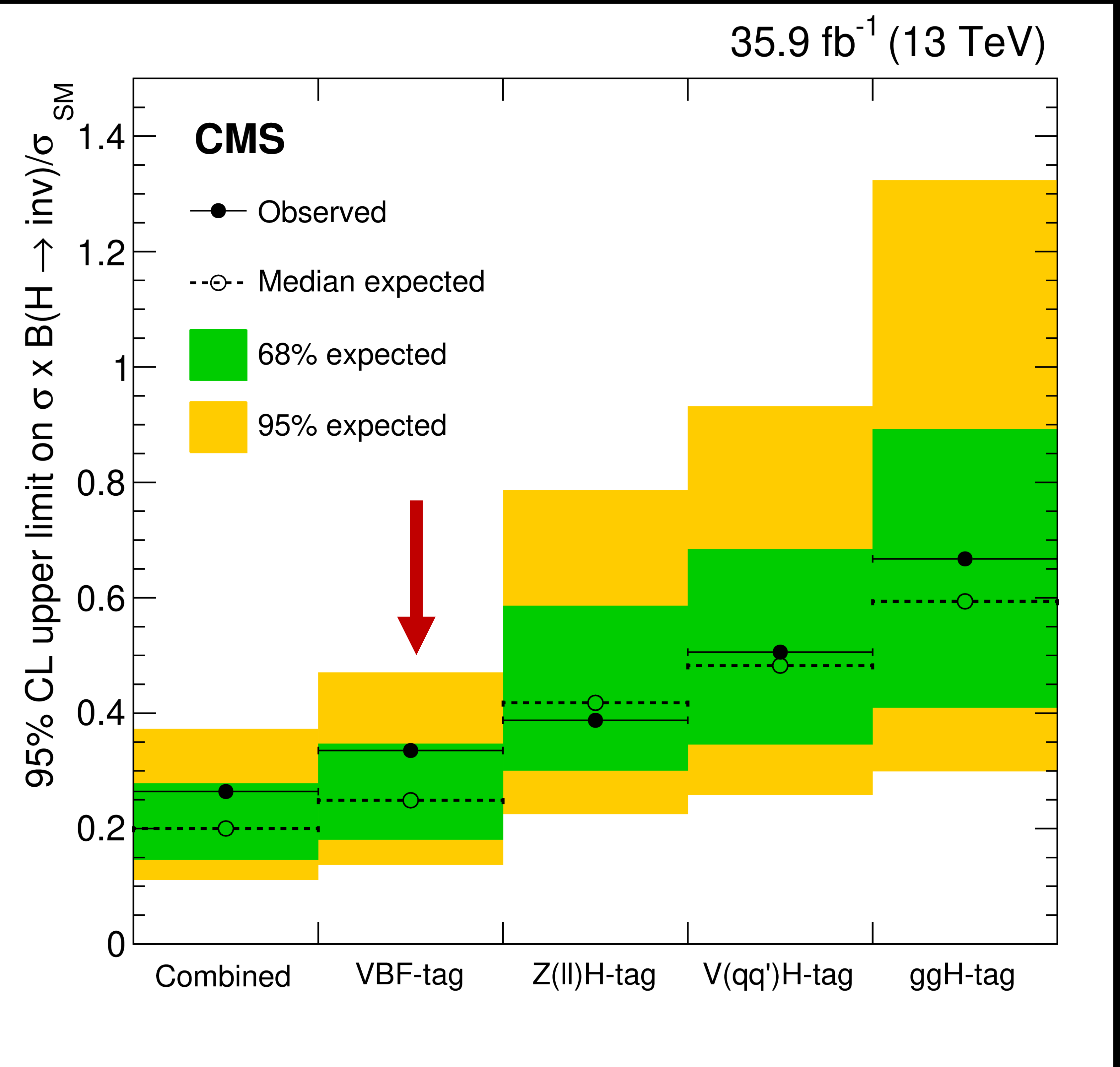


VBF H → invisible

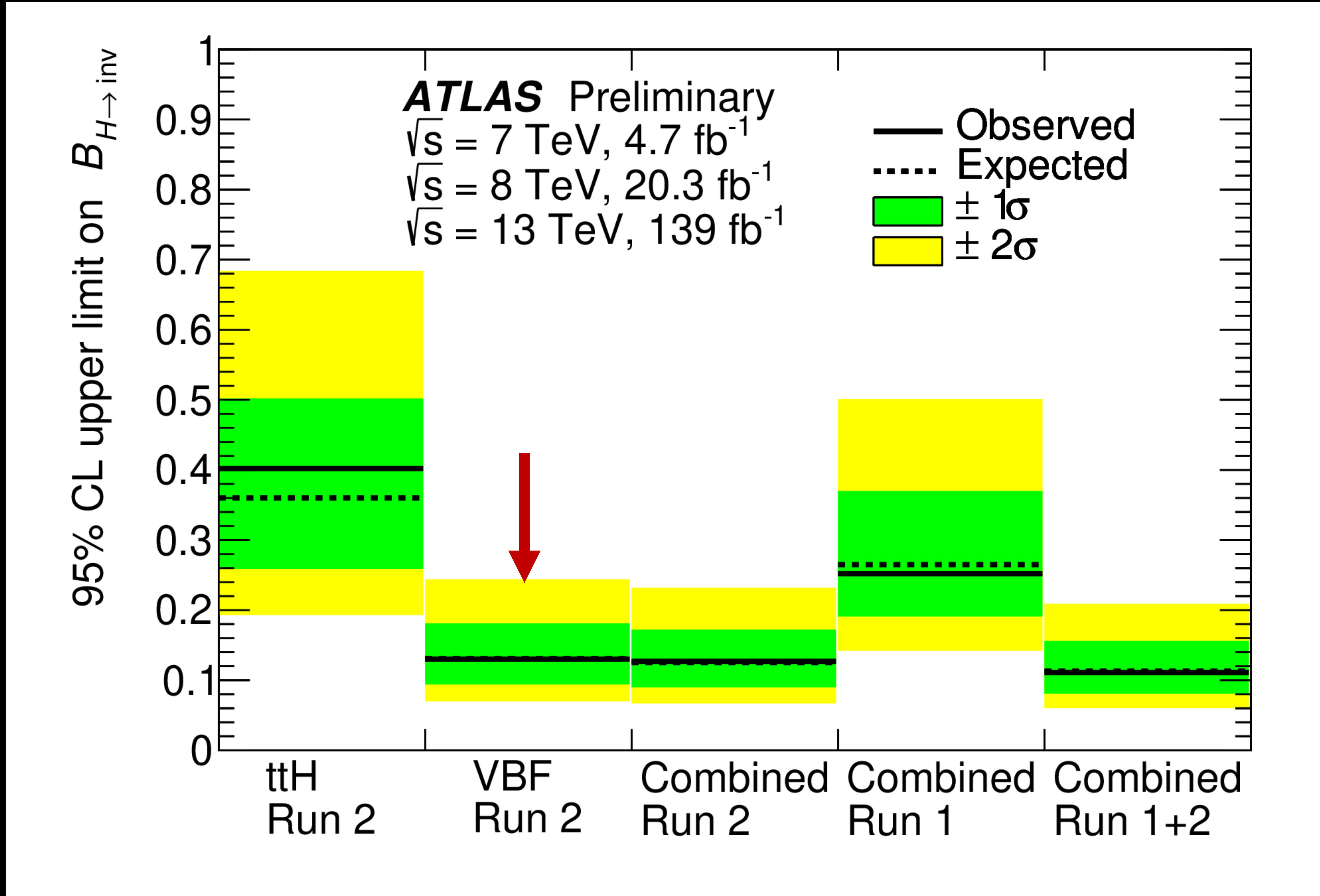
- Small fraction of the Higgs boson decays invisibly (H → invisible) in SM theory (~0.1%)
- Sensitive to new physics. Important to get upper limit of H → invisible
- ATLAS 95% CL upper limit of 13%(13%) observed (expected) , Run-1 and Run-2 (139/fb)
- CMS 95% CL upper limit of 19% (15%) observed (expected), Run-1 and Run-2 (36/fb)
- VBF channel has the best sensitivity to H → invisible decay

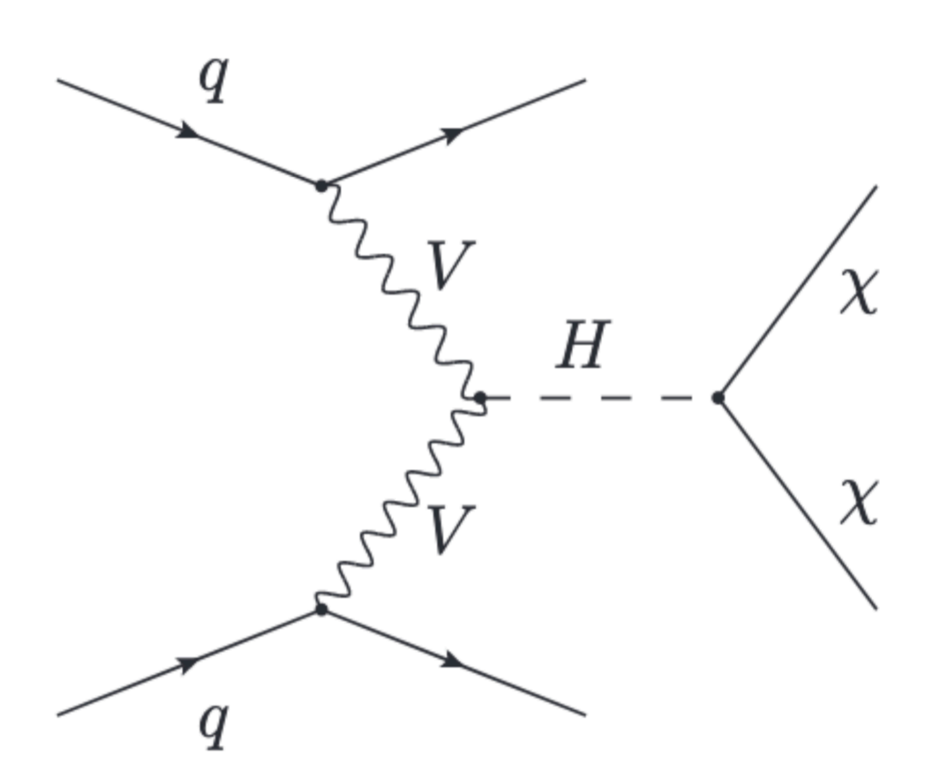
More info in Benedikt Maier's talk in plenary section tomorrow

CMS:Phys. Lett. B 793 (2019) 520



ATLAS: ATLAS-CONF-2020-069



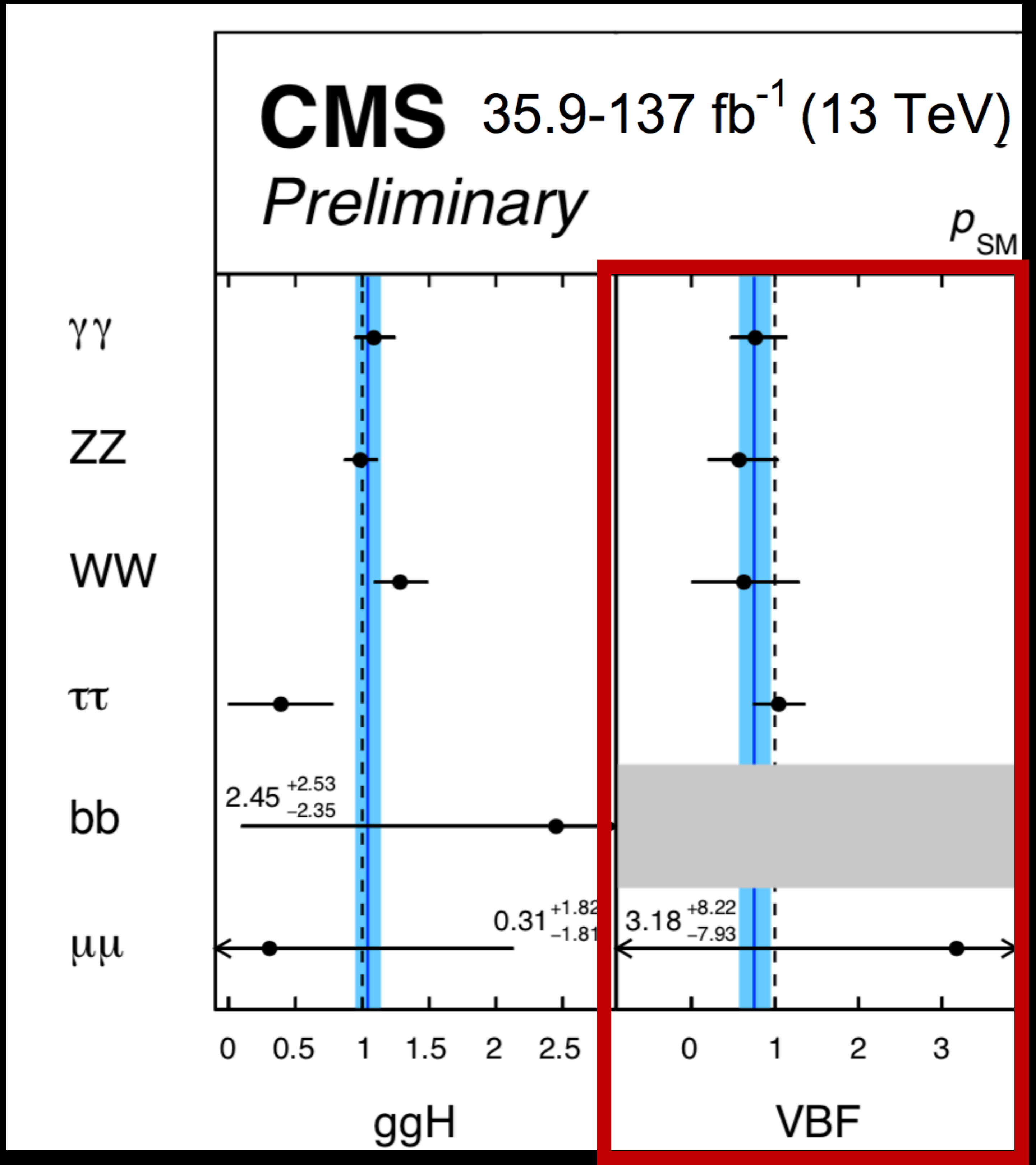


Summary

VBF process is the second-largest Higgs production mode

- **ATLAS/CMS measurements show no visible deviation from SM prediction**
- **VBF process is one of the most powerful channel in H→ττ, and H → invisible search**
- **Theory uncertainty on parton shower modelling became an important systematics**
- **More differential measurements to improve MC modelling of VBF observations**

CMS-PAS-HIG-19-005



ATLAS-CONF-2020-027