Higgs boson couplings to b and c quarks

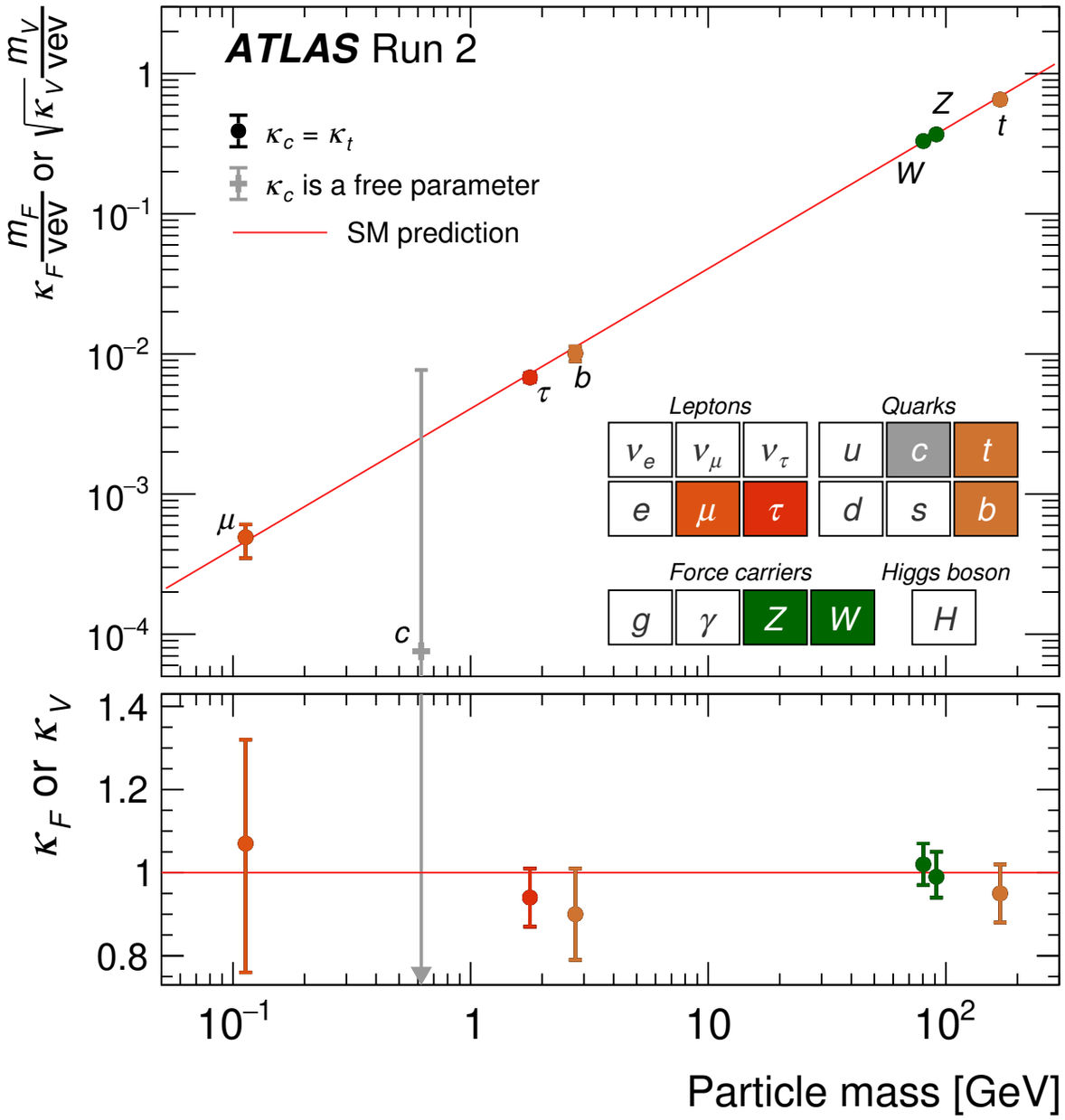
Alessandro Calandri - ETH Zürich
on behalf of the CMS and ATLAS Collaborations

Introduction and outline of the talk

Nature 607, 60-68 (2022)

➡ Higgs boson discovery opens up a new chapter for exploration

- detailed measurement of Higgs properties: couplings to 2nd and 3rd generation fermions and decay of Higgs to heavy-flavour quarks (b, c)
  - H→bb and H→cc couplings investigated in several Higgs production modes
- this talk will cover ATLAS and CMS results on Higgs couplings to heavy-flavours (b, c) using full Run 2 LHC dataset



➡ Several new results since Higgs 2021 on ATLAS/CMS Hbb/Hcc!

➡ Dedicated talk later in the session by J. Katzy on Higgs production in association with the top quark

ATLAS/CMS H→bb/H→cc with full Run 2 data

New since Higgs 2021

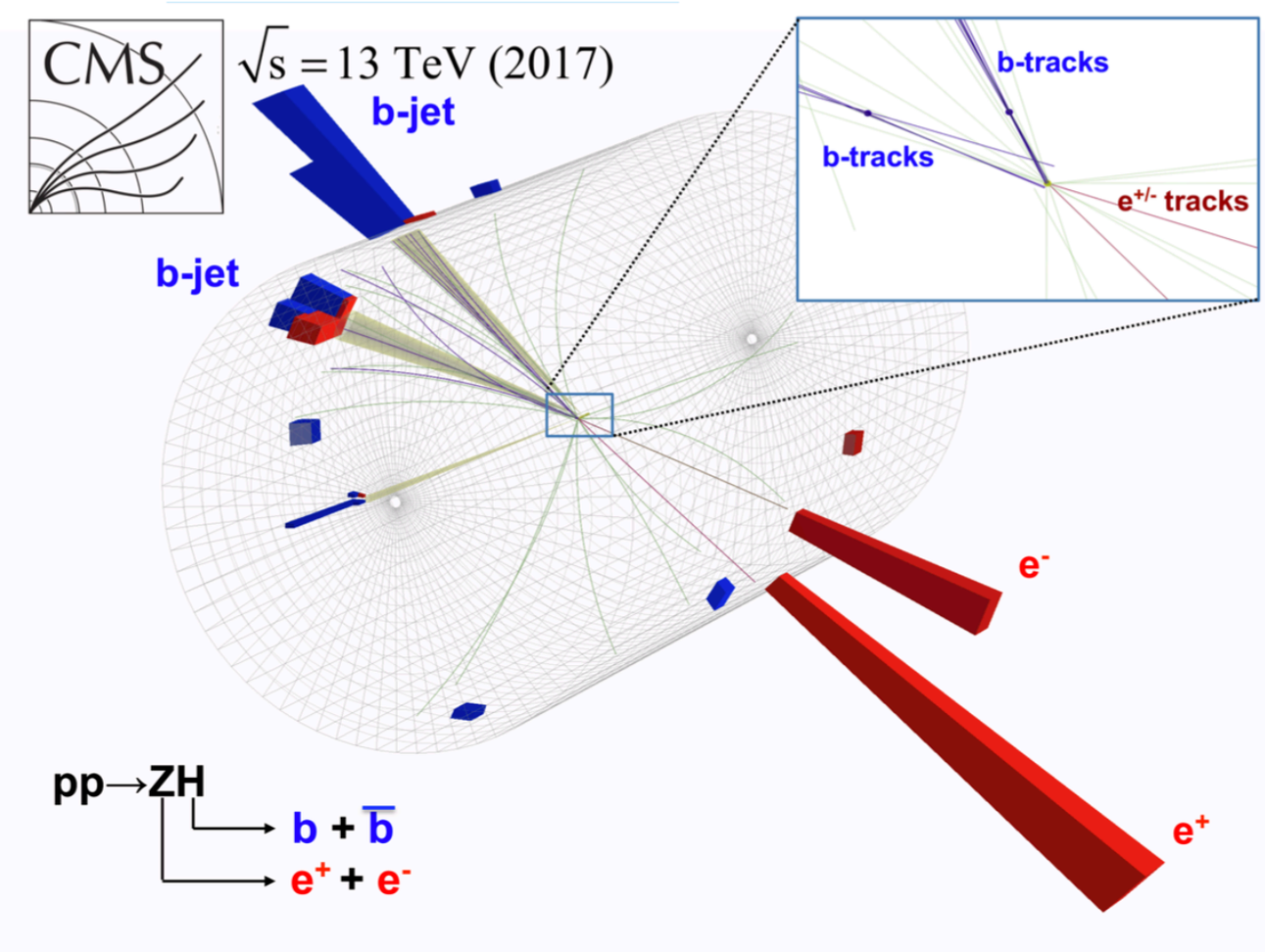
H→bb	ATLAS EXPERIMENT	CMS
VH(→bb) inclusive & STXS	ATLAS-CONF-2021-051	CMS-PAS-HIG-20-001
VH(→bb) differential/EFT	ATLAS-CONF-2021-051, ATLAS-CONF-2022-015	
VBF(→bb)	Eur. Phys. J. C 81, 537, JHEP 2021, 268	CMS-PAS-HIG-22-009 NEW New for Higgs 2022!
Boosted H→bb	Phys. Rev. D 105, 092003	JHEP 12(2020)085

H→cc	ATLAS EXPERIMENT	CMS
VH(→cc)	EPJC 82 (2022) 717	arXiv:2205.0550 (accepted PRL)
Boosted H→cc		CMS-PAS-HIG-21-012

Higgs couplings to bottom quarks

Largest branching ratio (~60%) - overwhelming jet production at LHC

- Several analysis challenges
  - flavour-tagging, modelling of copious QCD backgrounds, large uncertainties on V+jets
- Analysis features and measurement strategies
  - making use of several production modes, VH (golden channel), VBF, gluon fusion (dominant)
  - refined strategies and innovations on b-tagging (e.g. tackling boosted Hbb)
  - transitioning from inclusive μ to Simplified Template /Fiducial Cross-section
  - efforts to constraint on effective interactions using EFT-sensitive observables/measurements



VH(->bb) - analysis strategy

➡ Most sensitive production channel for Hbb couplings and large suppression of multi jet background

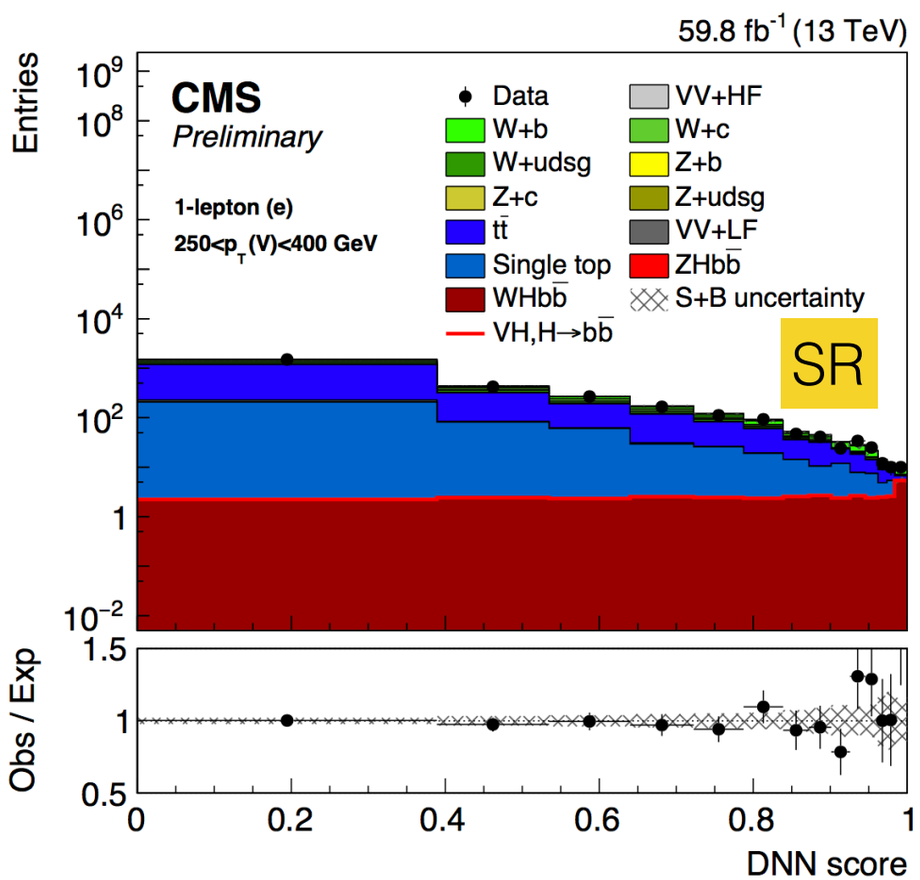
- 3 channels depending on the decay of the vector boson (0-lep: $Z\to\nu\nu$, 1lep: $W\to l\nu$, 2lep: $Z\to ll$)
- FSR recovery, 2-lep kinematic fit and application of b-jet energy regression to improve m(bb) invariant mass

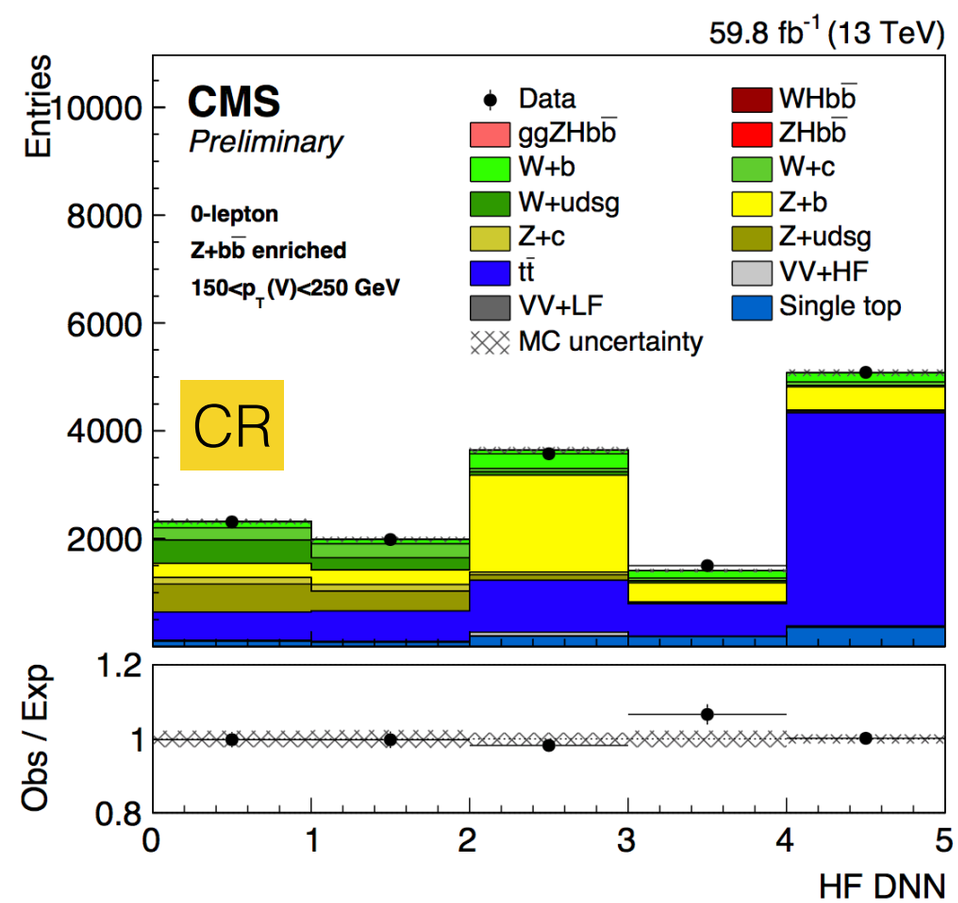
➡ Main backgrounds (V+ HF/LF jets and Top) constrained in 3 dedicated background-enriched CRs

- DNN multi-classifier in 0-lep and 1-lep channel to optimally constrain background processes

➡ DNN and BDT's in resolved and boosted signal regions for signal extraction

Several novelties for full Run 2 measurement: boosted analysis; STXS characterisation; updated V+jets modelling

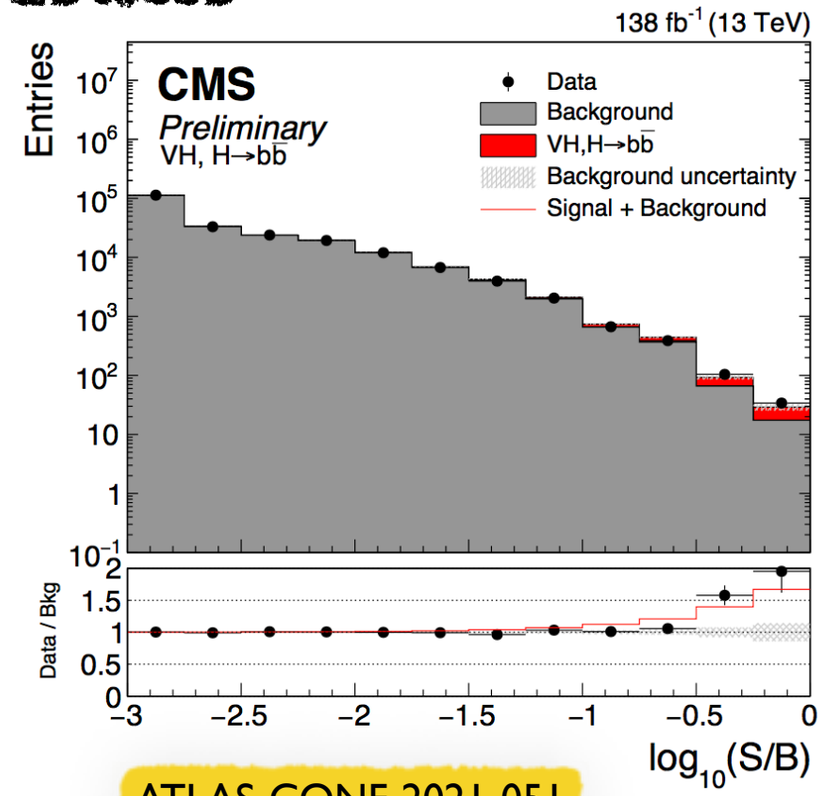


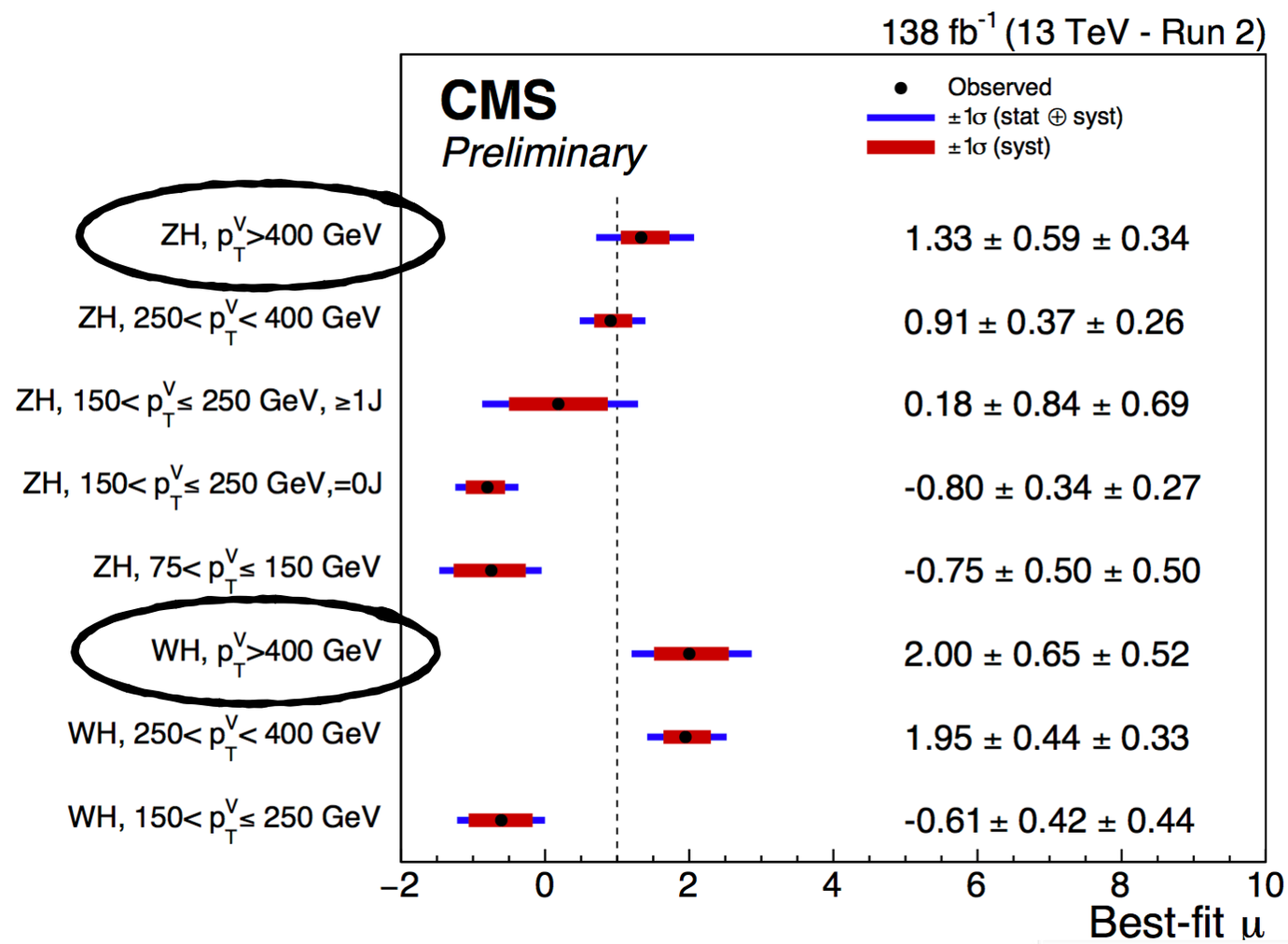


CMS-PAS_HIG-20-001

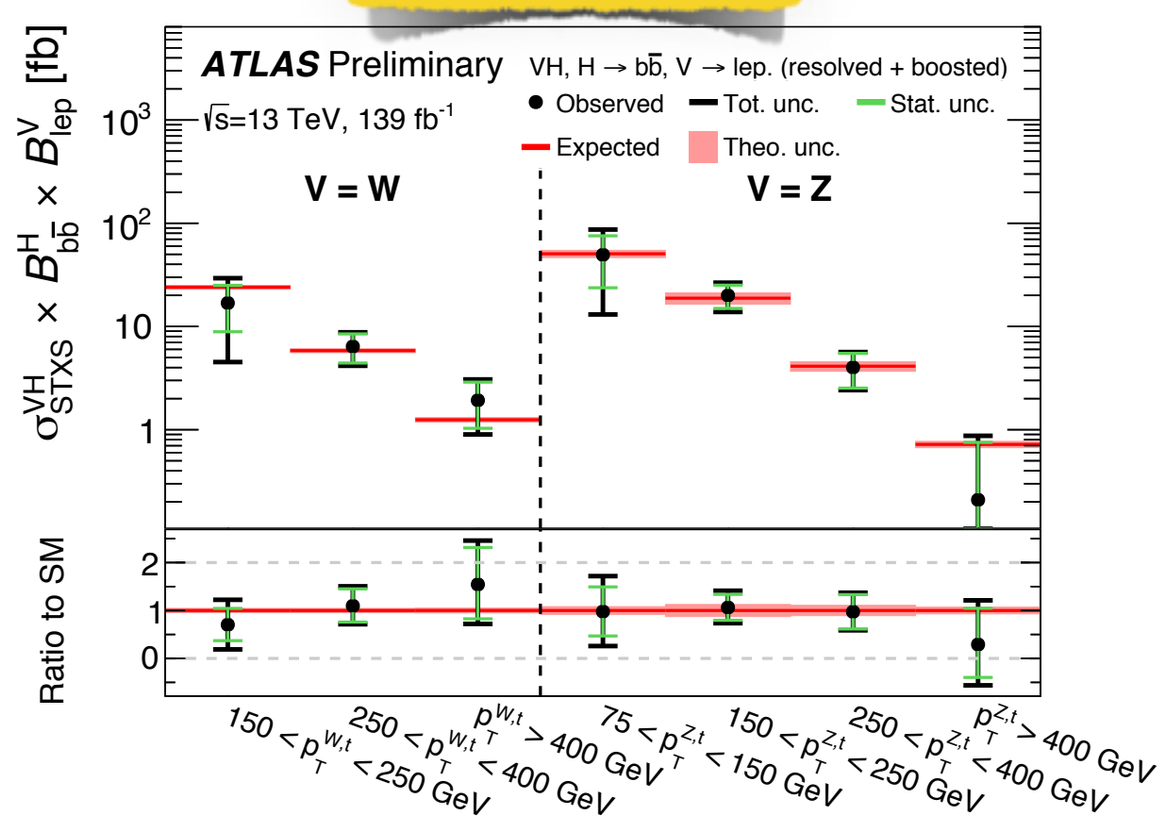
VH(->bb) - analysis results

- Mass-based and VZ→bb cross-check analysis: VZ, Z→bb: μ=1.16±0.13
- CMS Run 2 $\mu=0.58_{-0.18}^{+0.19}$ - observed (expected) significance: 3.3σ (5.2σ)
- Stage 1.2 VH STXS approach - inclusion of dedicated high momentum phase-space





ATLAS-CONF-2021-051



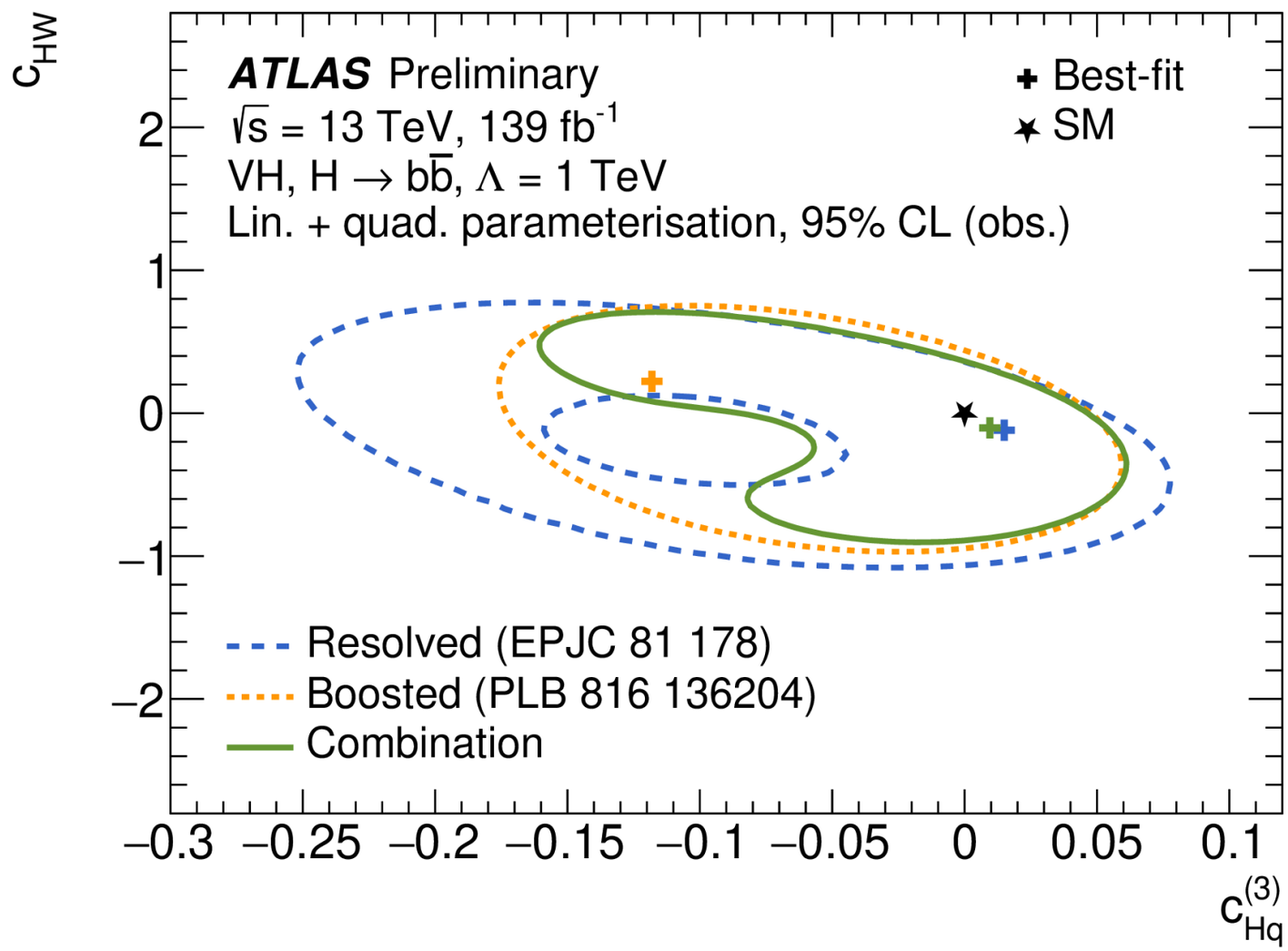
More details in N. Haubrich's and A. Nigamova's parallel session talks!

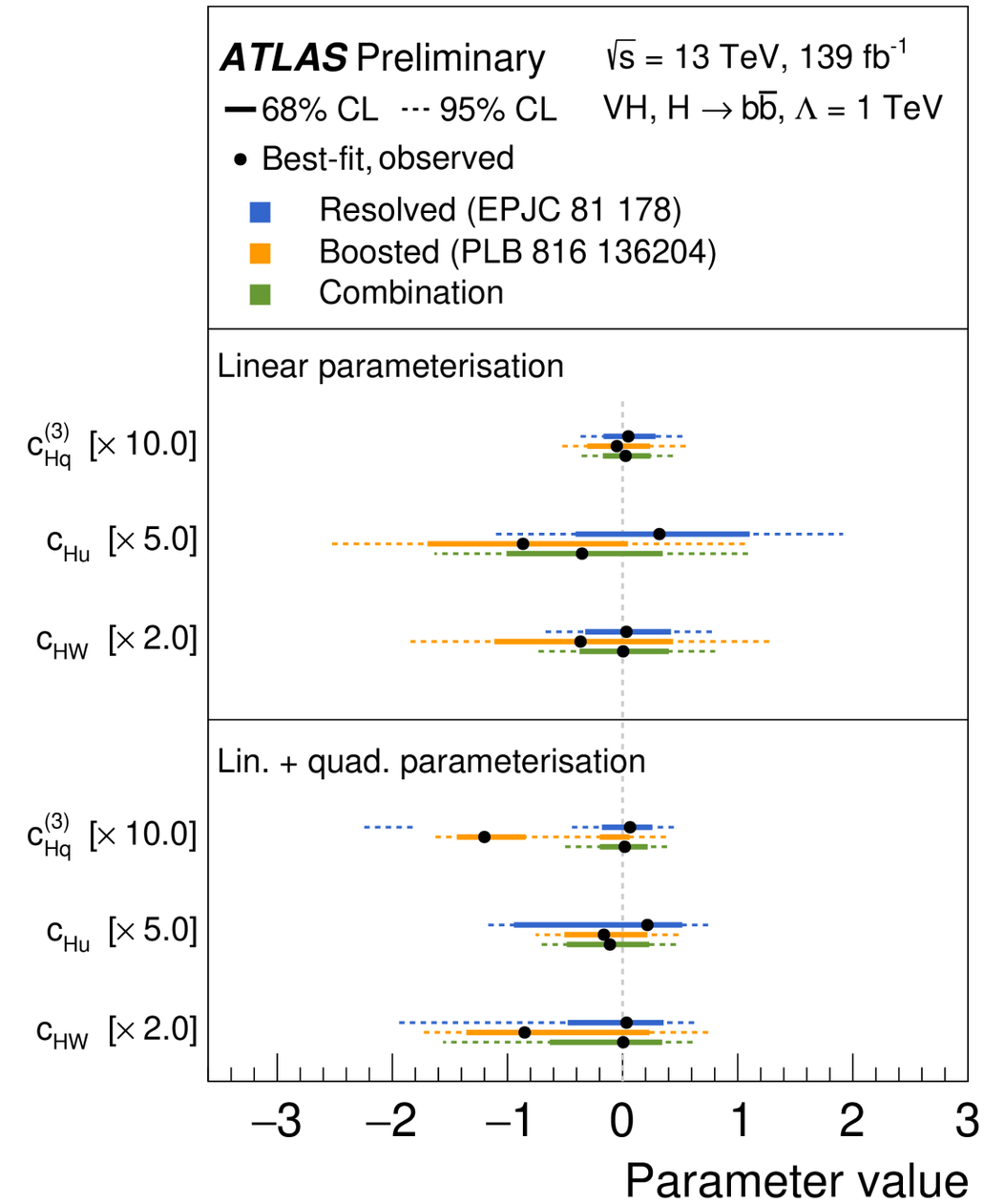
VH(->bb) - constraints on EFT operators

➡ Interpretation of STXS VH(bb) results to achieve constraints on effective interactions

- VH(bb) analysis has sensitivity to Wilson coefficients impacting production vertices
- both linear and quadratic terms included - impact of leading eigenvectors on STXS cross-section

ATLAS-CONF-2021-051

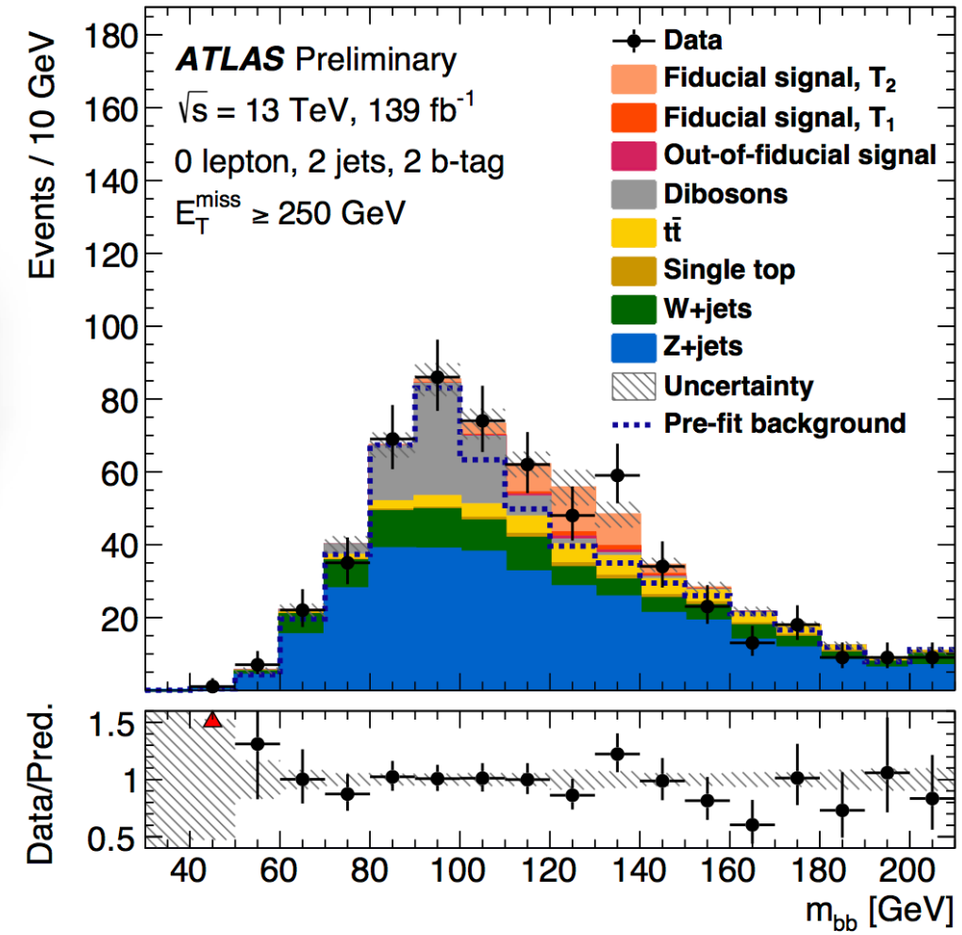


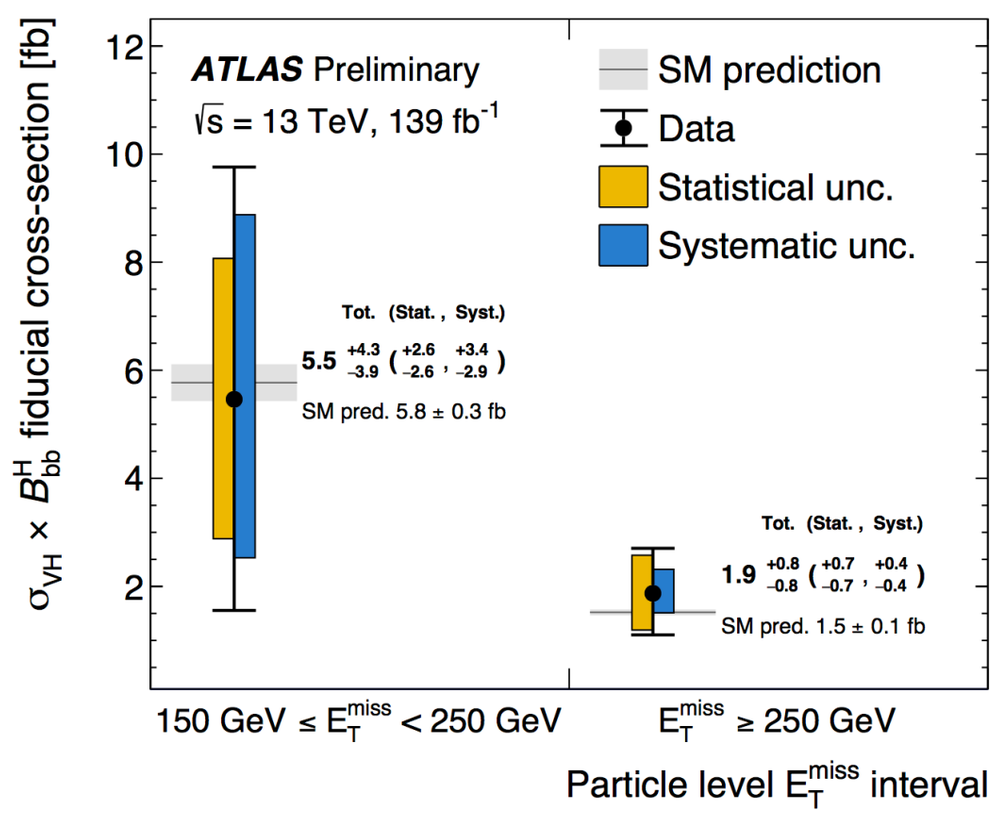


VH(->bb) - 0-lepton fiducial cross-section

ATLAS-CONF-2022-015

- Fiducial cross-section in VH(bb) 0lep channel in bins of MET (150-250 GeV, >250 GeV)
  - fiducial phase-space: particle-level selection close to detector-level: minimal model-dependency and mitigation of extrapolation uncertainties
- Cross-section using profile-likelihood unfolding
  - particle-level categories: reconstructed events passing particle-level selection and have particle-level MET in 150-250 or 250+ bins (T)
  - Off-fiducial categories (O): reco events in particle-level ET miss bin failing other particle level selection criteria
- Extract signal in detector level categories using m(bb) separately for fiducial and out-of-fiducial volumes





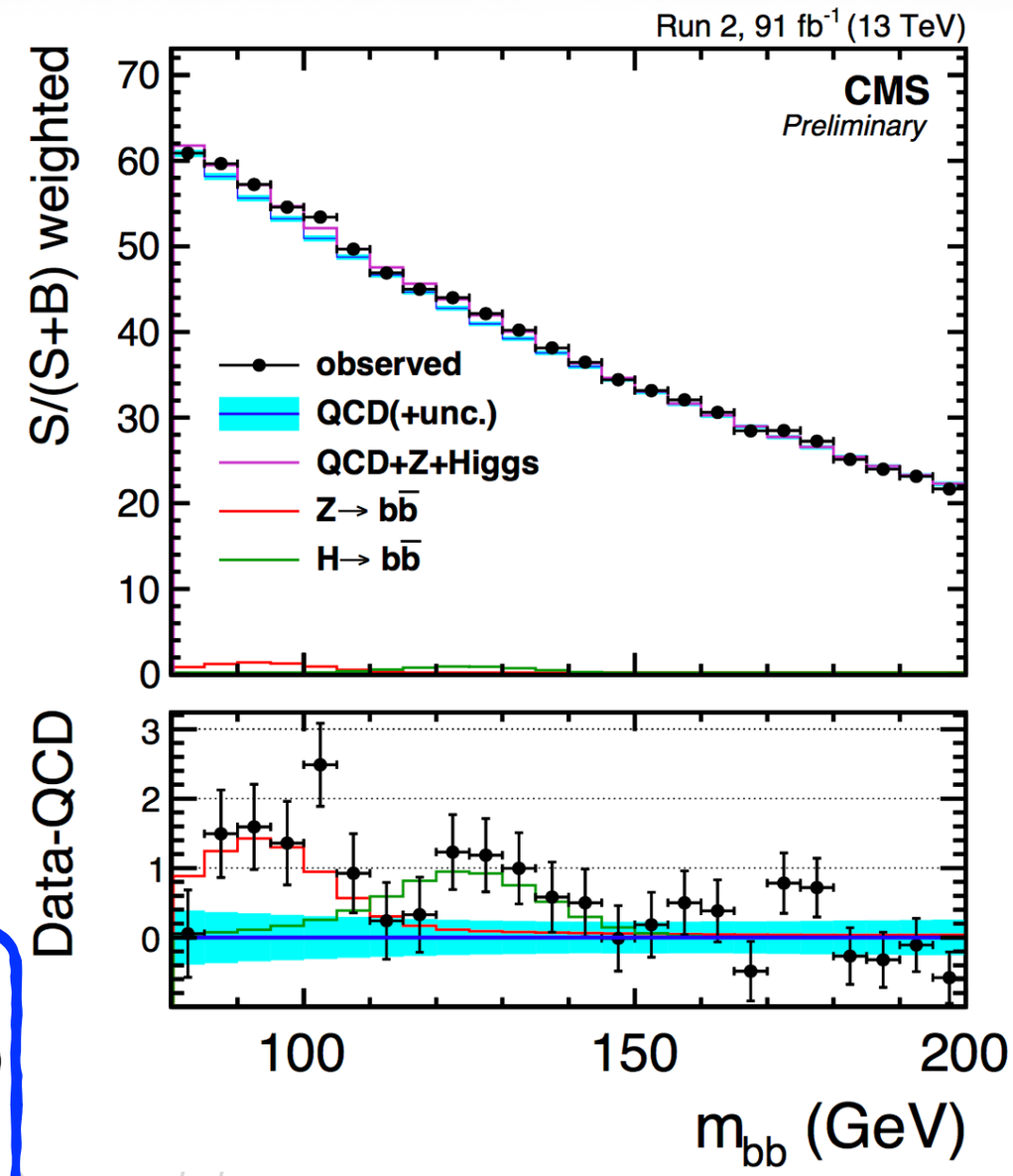
New for Higgs 2022!

VBF H->bb

➡ VBF - second most dominant Higgs production at the LHC - VBF jets with large η gap and little activity in the central region

➡ CMS analysis strategy: MVA used to slice SR and m(bb) employed as observable for signal extraction

- analysis categories: VBF, GGF and Z+jets production
- gluon-fusion treated as part of the signal
- two freely-floating parameters for signal and normalisation of Z+jets background
- uncertainty dominated by VBF PS+hadronisation model achieved as 2-point systematics



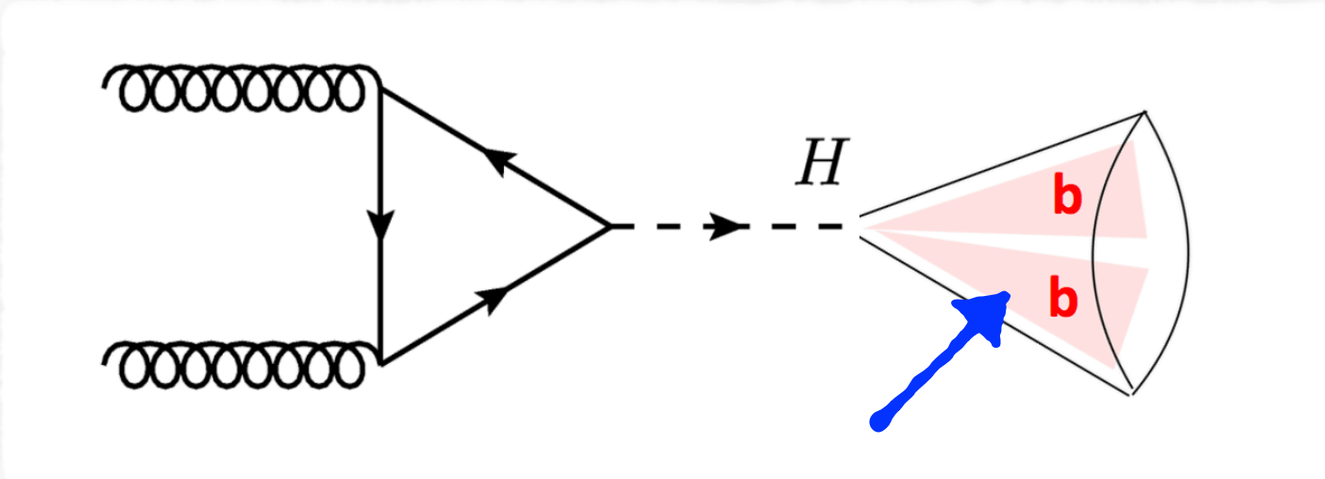
➡ Exclusive VBF production (gluon-fusion to SM predictions): μ=0.97±0.48, significance: 2.4σ (observed), 2.7σ (expected)

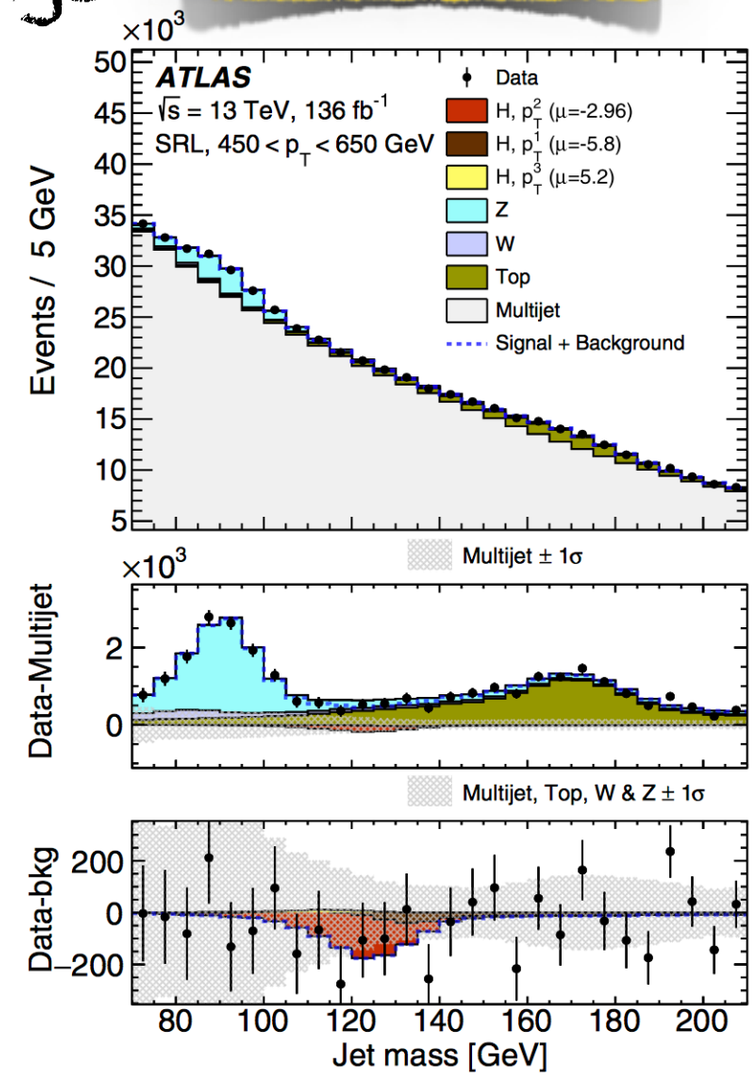
➡ Inclusive measurement of Higgs production in association with two jets (gluon-fusion included): μ=0.92±0.44, significance: 2.5σ (observed), 2.9σ (expected)

More details in S. Mukherjee's parallel session talk!

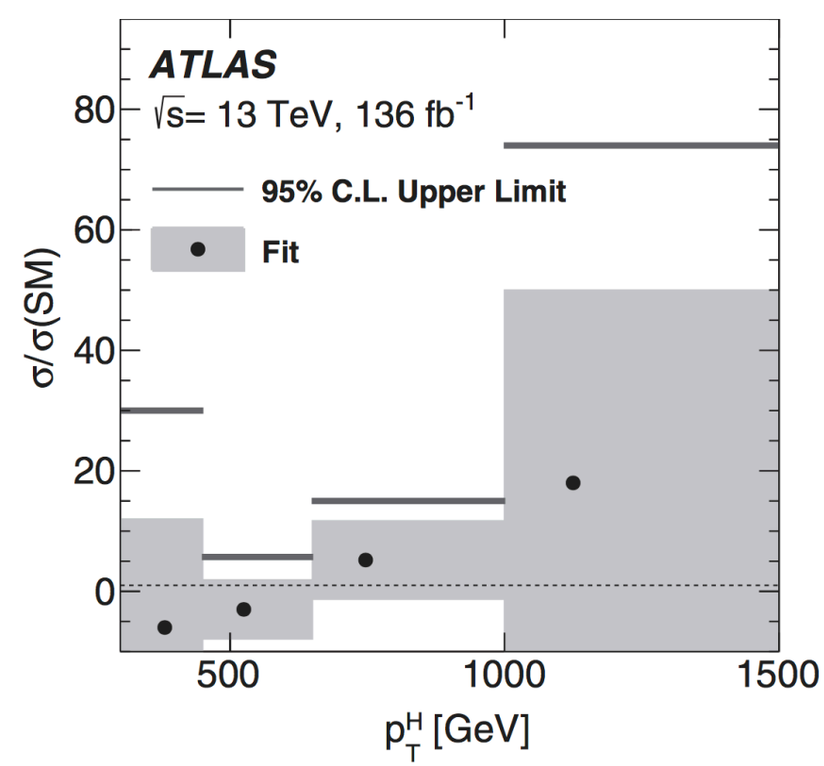
Boosted H->bb couplings

Phys. Rev. D 105, 092003





- Highly-boosted Higgs (ptH>450 GeV) recoiling against a jet in overwhelming QCD background
  - selection based on large-R jets containing b-tagged track-jets
  - SR (double b-tagged jets) for signal extraction; validation and control regions to model backgrounds (V+jets, QCD and Top)
- Z(→bb) + jets used to validate analysis (μ=1.29±0.22)
- Several measurements of ATLAS H→bb boosted results
  - inclusive signal strength - μ=0.8±3.2 (still stat. limited)
  - gluon-fusion STXS-like bins, fiducial/differential cross-section using pt(H)

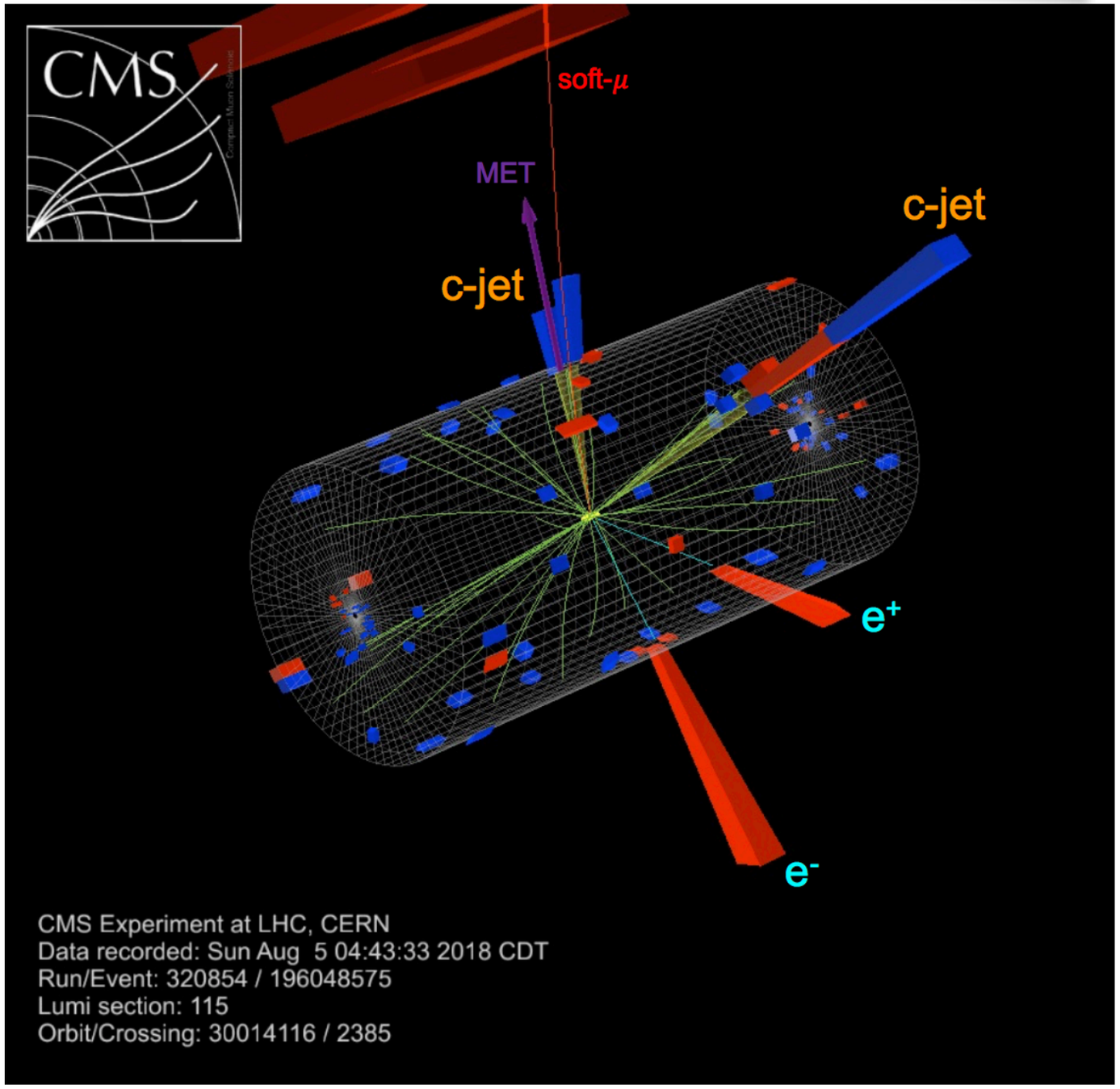


CMS full Run 2: JHEP12(2020)085

Higgs couplings to charm quarks

Higgs couplings to 2nd generation quarks (H→cc) at the LHC extremely challenging

- H→cc branching ratio significantly smaller than H→bb
- c-tagging is more difficult than b-tagging
  - dedicated ML-based taggers and precise methods to calibrate charm tagging in data
  - charm-jet energy regression to improve m(cc) resolution using ML techniques (CMS)



Novel analysis/flavour tagging techniques have paid off - reaching sensitivity expected with larger dataset!

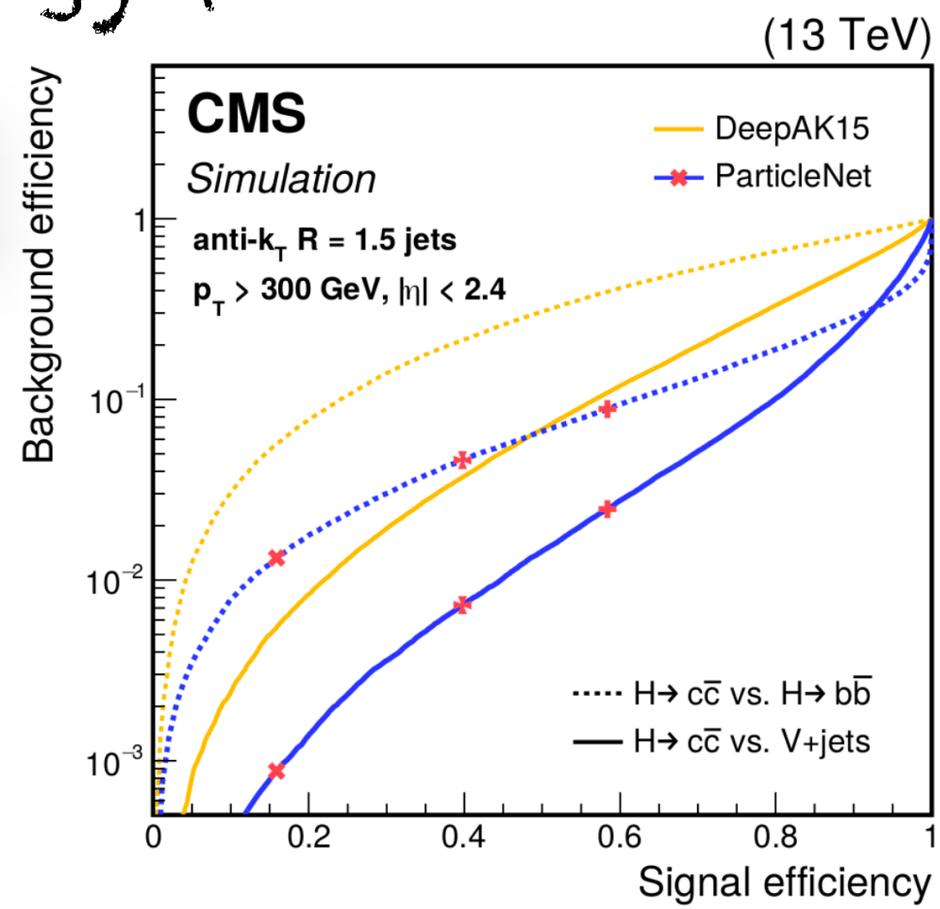
VH (->cc) analysis strategy & results

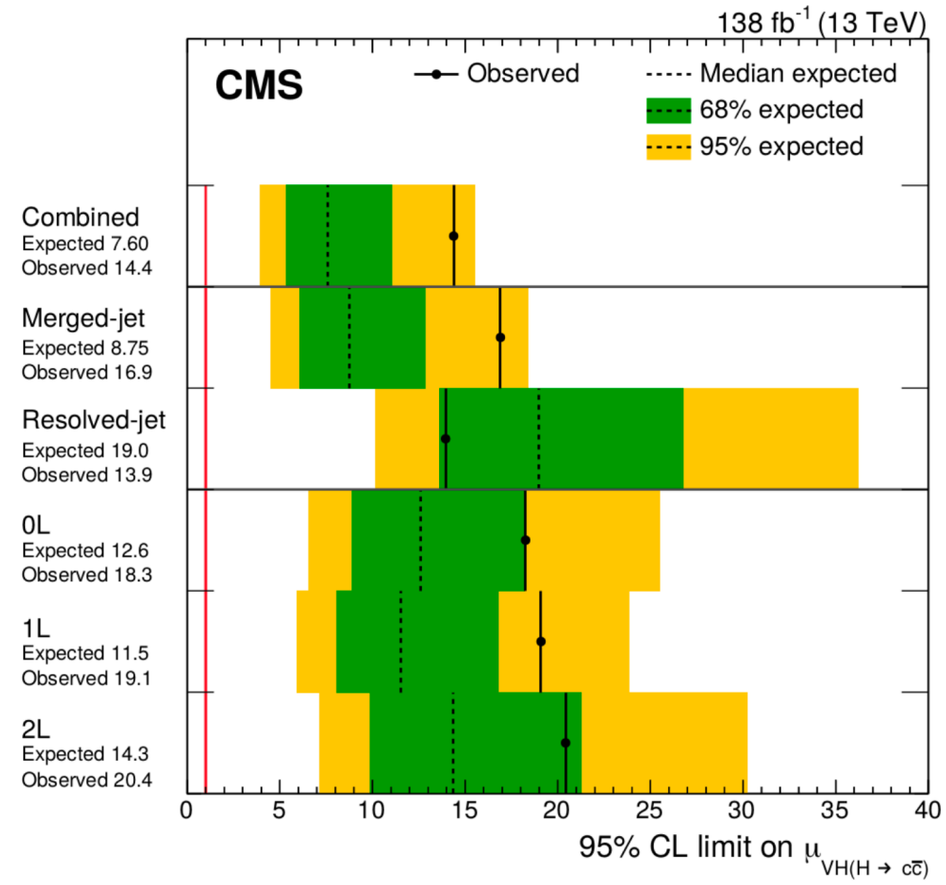
arXiv: 2205.05550 (accepted in PRL)

- Most stringent constraints on Higgs-charm Yukawa coupling at the LHC

- Charm-jet identification algorithm (ParticleNet) largely enhances signal efficiency
- Resolved (AK4) and merged jet (AK15) topologies
- CRs used to constrain main processes (V+c, V+b, TT)
- Cross-check VZ, Z→cc analysis: μ=1.01±0.22 → first observation of VZ, Z→cc at hadron collider
- Kinematic BDT (resolved-jet topology) or mass of H candidate (merged-jet topology) as discriminants → observed limit: 14 X SM (7.6 X SM expected)
- Analysis is statistically-dominated
  - dominant systematics uncertainties: finite simulation statistics and c-jet identification/calibrations

More details in M. Stamenkovic parallel session talk

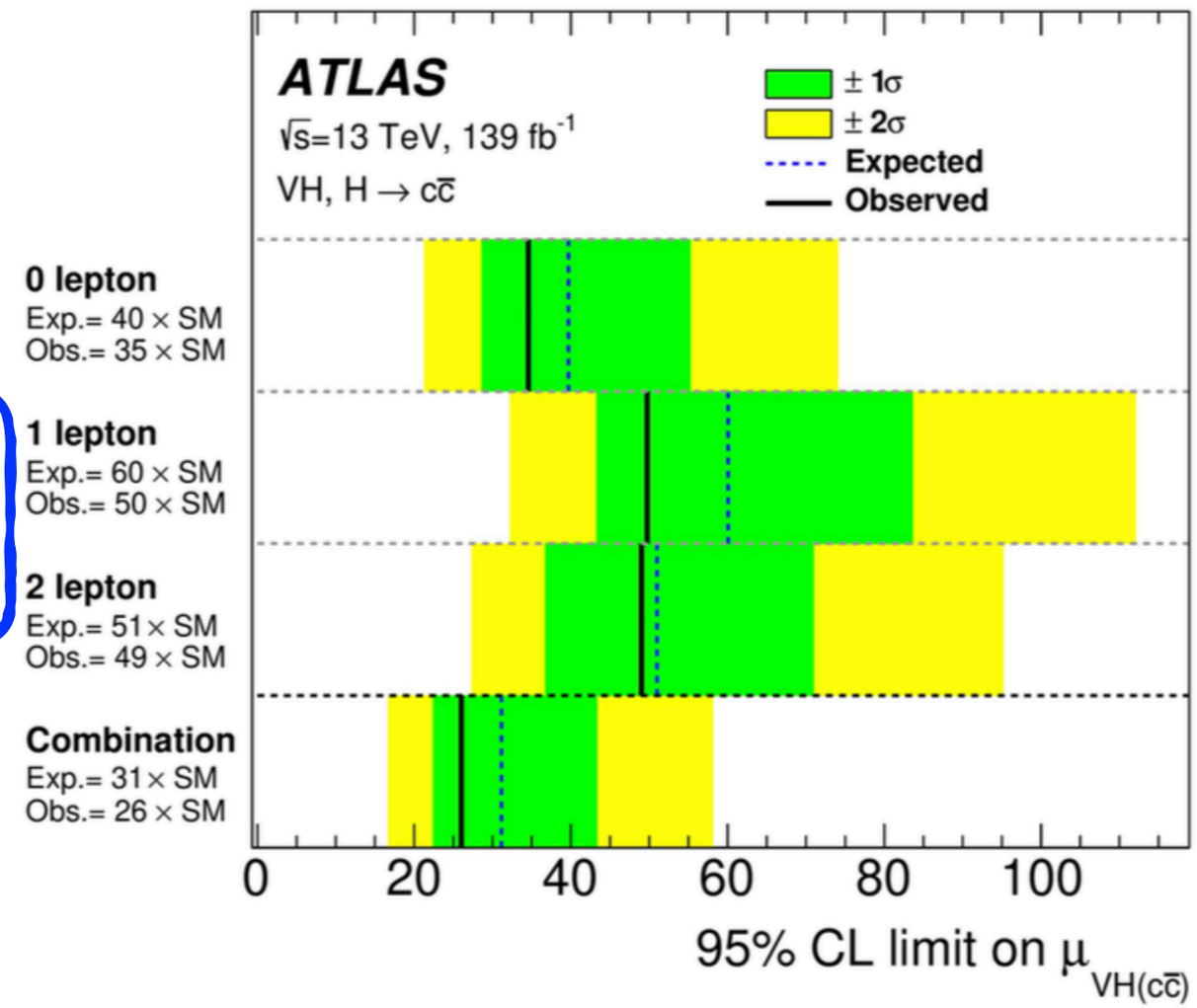




VH(->cc) - analysis strategy & results

Eur. Phys. J. C 82 (2022) 717

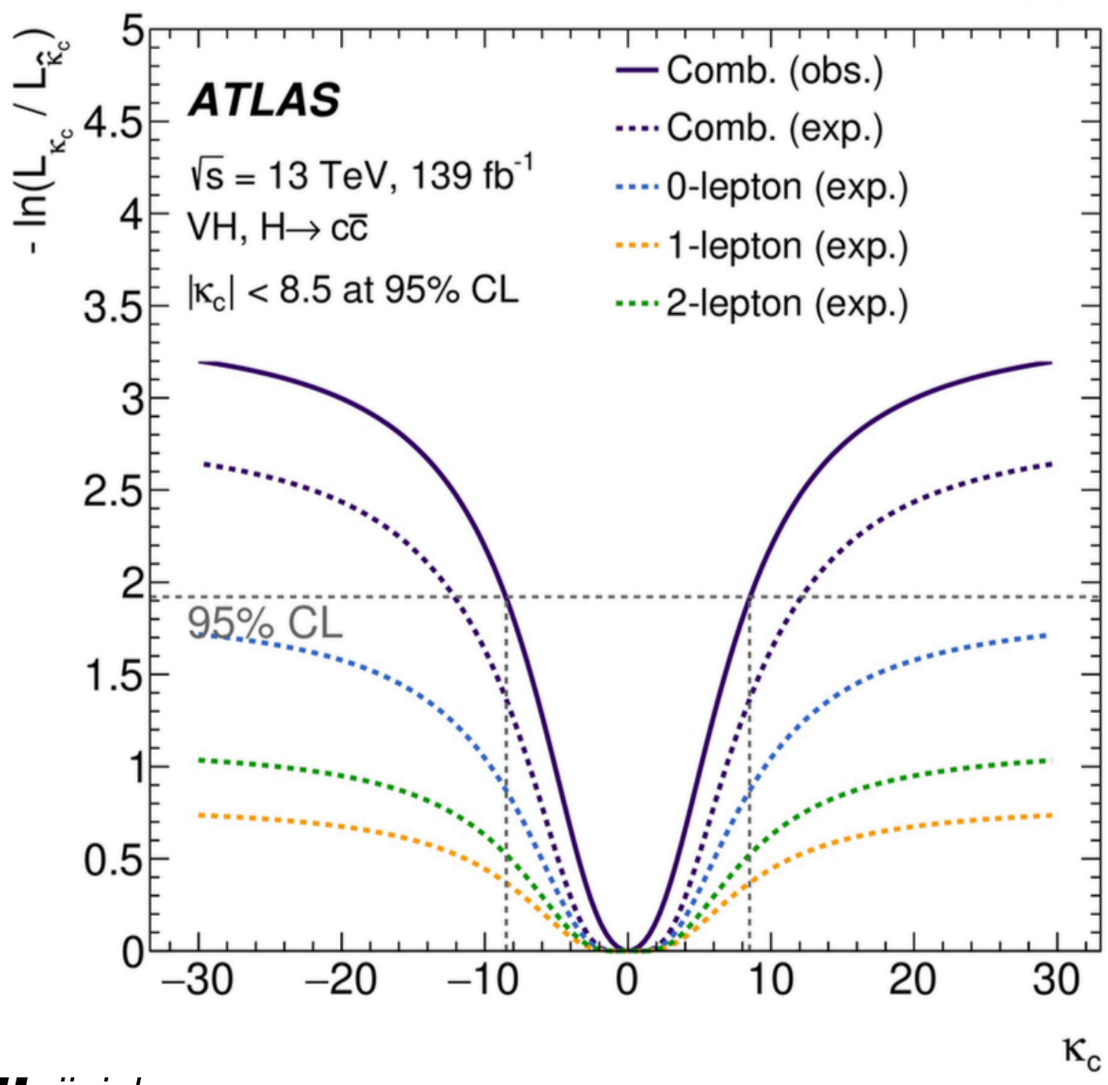
- Flavour tagging - identification of c-jets and orthogonality with VH(bb)
  - c-tagging + b-veto w/ efficiency WP's (MV2c10/DL1)
- Dedicated studies on V+jets uncertainty modelling
- Simultaneous fit of SRs+CRs using m(cc) for signal extraction + diboson analysis as cross-check → observed limit: 26 X SM (31 X SM expected)
- Uncertainty dominated by 2-point systematics on V+jets modelling and data statistics

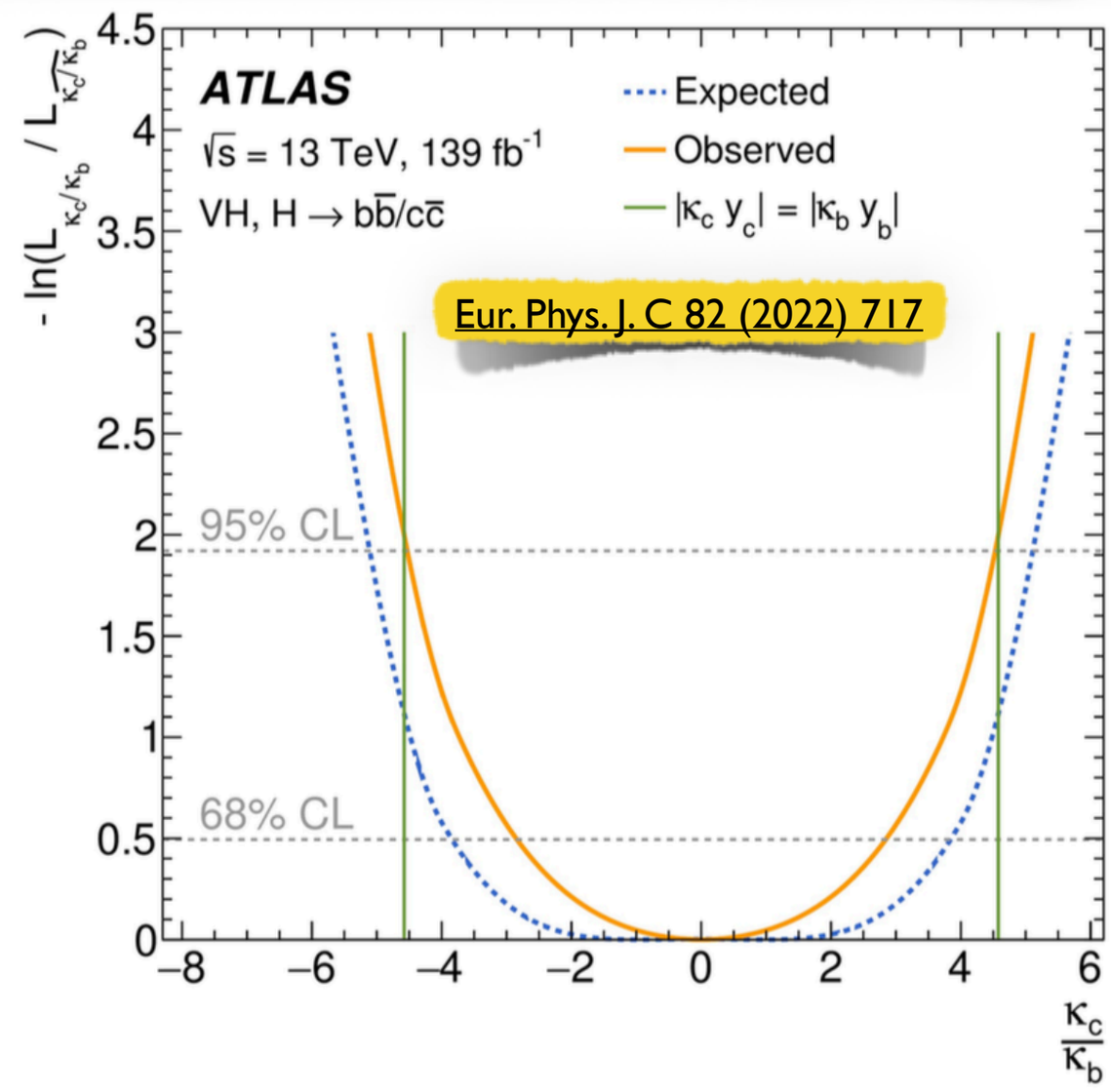


Interpretation of ATLAS/CMS Hcc results → direct constraints on charm-coupling modifiers
- ATLAS VHbb+VHcc combination probes b/c coupling universality

VH (->cc) - constraints on H→cc couplings

- Direct coupling modifiers: observed |k(c)|<8.5 X SM @ 95% CL (expected 12.4) assuming all other coupling are SM-like
- Higgs-charm couplings also extracted indirectly (e.g. differential ptH measurements from other decay modes) or with exclusive decays (H→J/Ψγ) [more in G. Umoret's talk later in this session!]
- Probing b/c universality: observed |k(c)/k(b)|<4.5 - experimentally show for the first time that the Hcc is weaker than Hbb coupling





Eur. Phys. J. C 82 (2022) 717

Inclusive H->cc in boosted topology

CMS-PAS-HIG-21-012

➡ Targeting inclusive Higgs boson production in the boosted phase-space pt(H)>450 GeV and Hcc decay

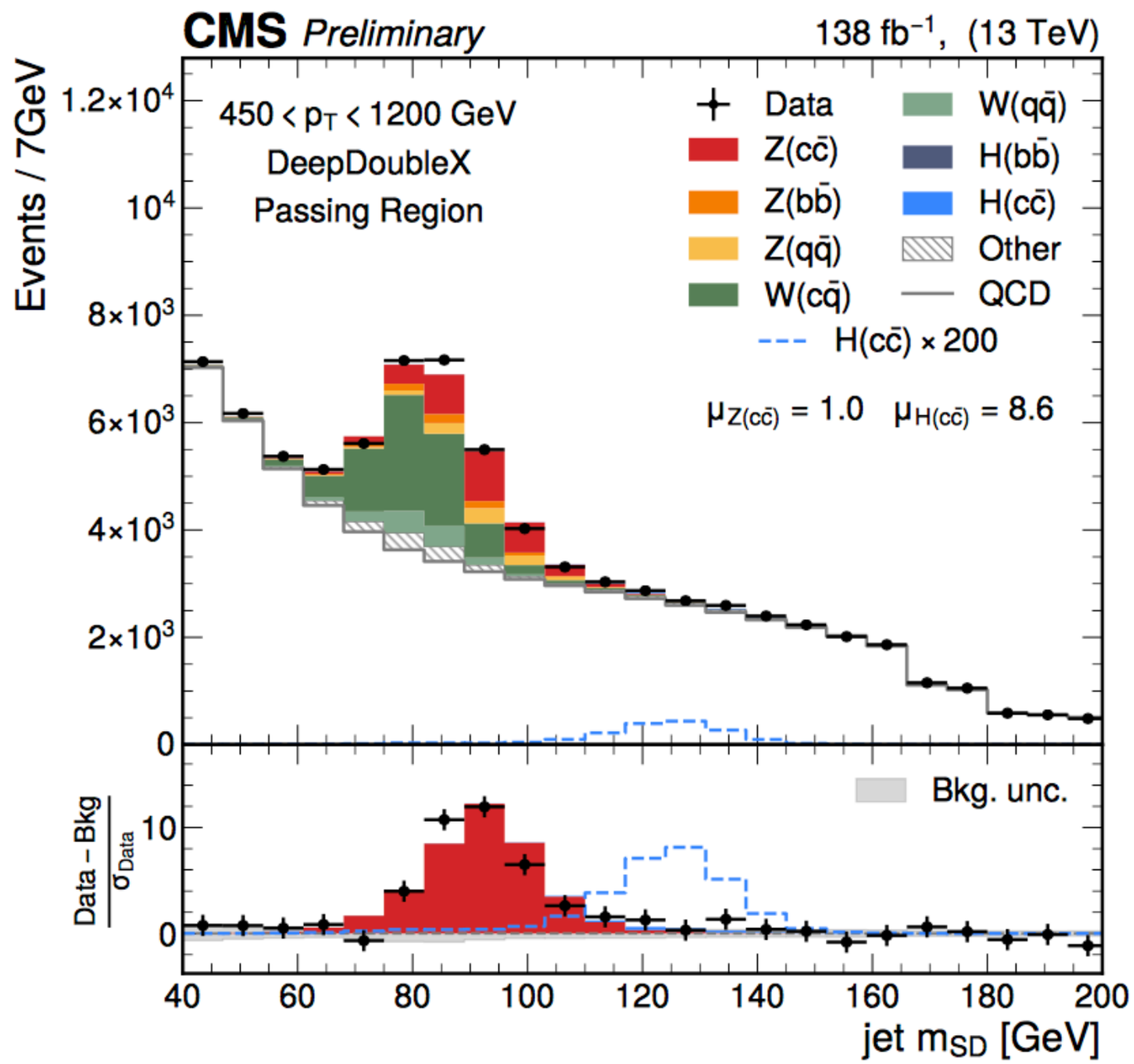
➡ AK8 double b-tagging algorithm (DeepDoubleX) for selection and SR/CR definition

- soft-drop mass used as template fit

➡ QCD modeling using data-driven in CR and propagated to SR

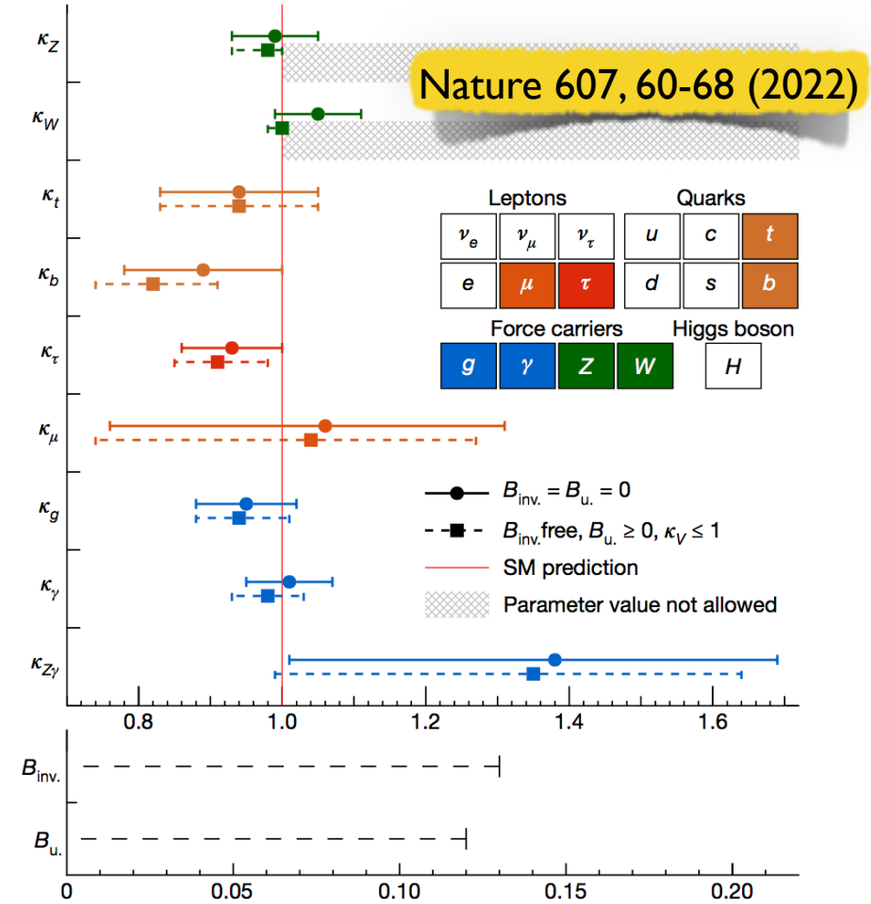
➡ Cross check Z→cc to validate the method → first observation of Z→cc (boosted) at hadron collider

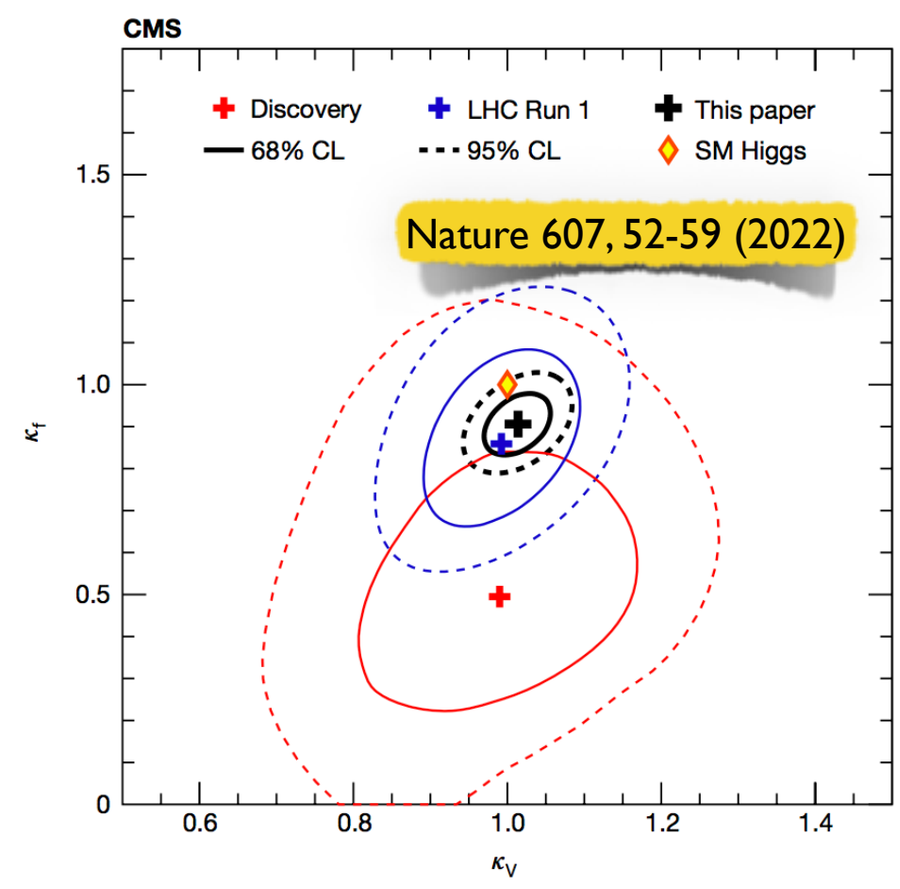
➡ Observed (expected) upper limit: 45(38)X SM (still stat. limited, large additional uncertainties on QCD modeling)



Wrapping-up and outlook

- Impressive suite of results by ATLAS and CMS on characterisation of Higgs boson couplings to b/c quarks
- Several production modes and decays explored by CMS and ATLAS to characterise Yukawa sector
  - explored all production modes and H→bb decays using inclusive, STXS, fiducial, differential analyses - approaching precision measurement era
  - exciting results on H→cc in ATLAS and CMS
- Improvements on all fronts from the experimental community in the Higgs heavy-flavour sector
- Additional outstanding Run 2 results still in the pipeline - Hbb/Hcc community also actively engaged to preparing results and further extend the Yukawa sector characterisation with Run 3 LHC data!



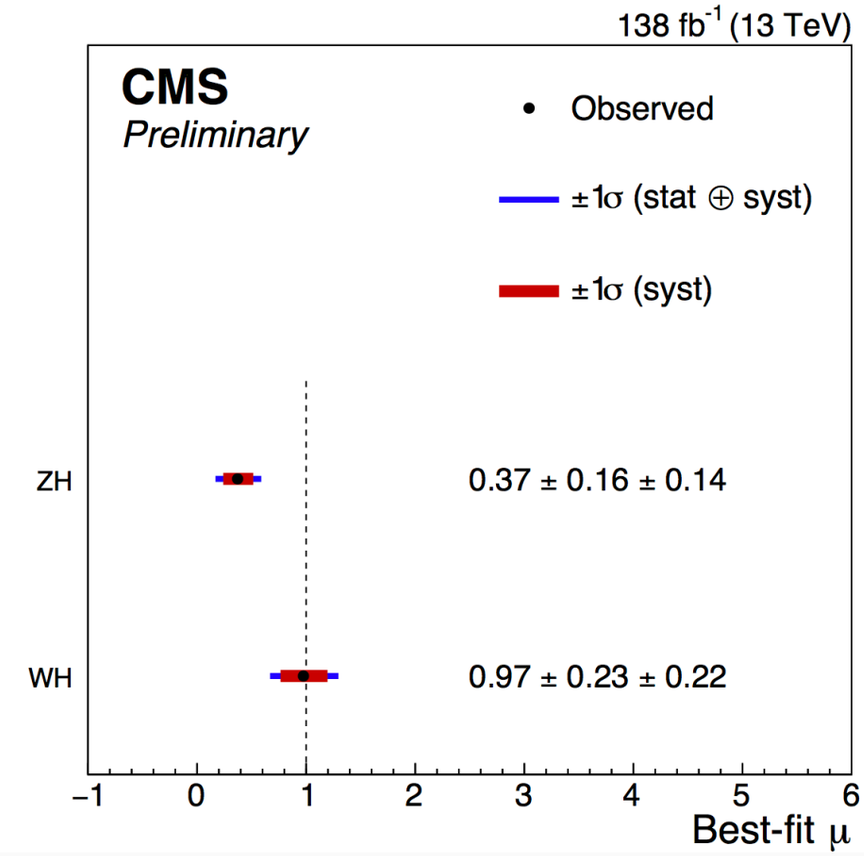


Backup slides

VH(->bb) - inclusive results & cross-checks

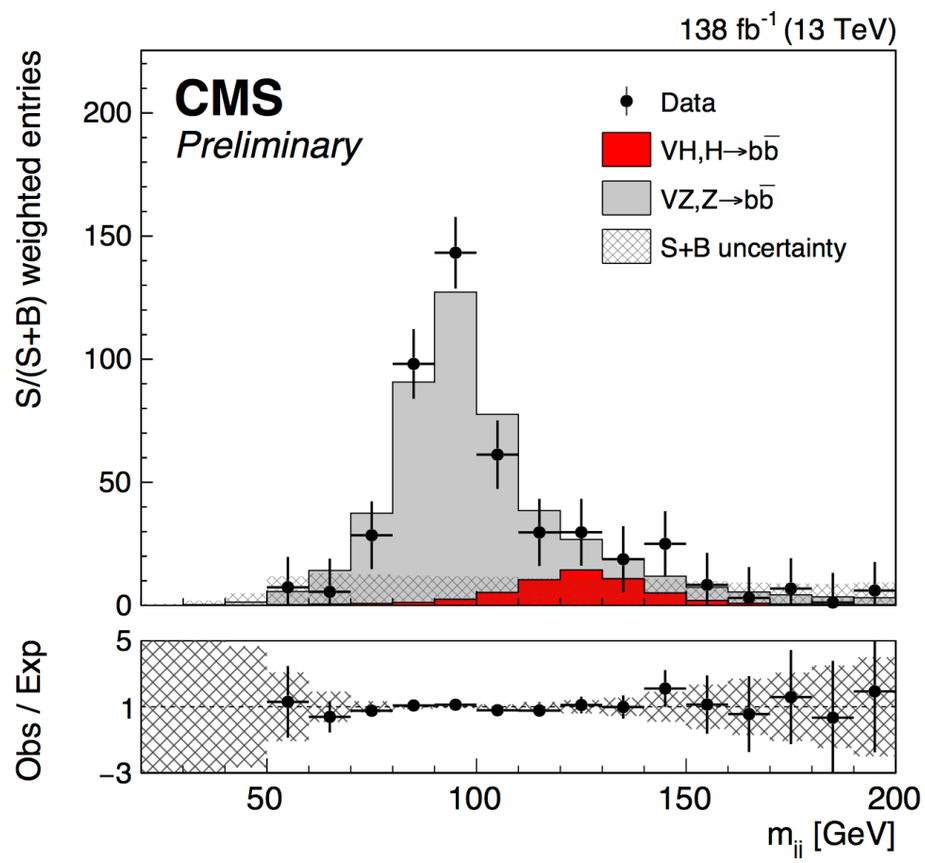
CMS-PAS_HIG-20-001

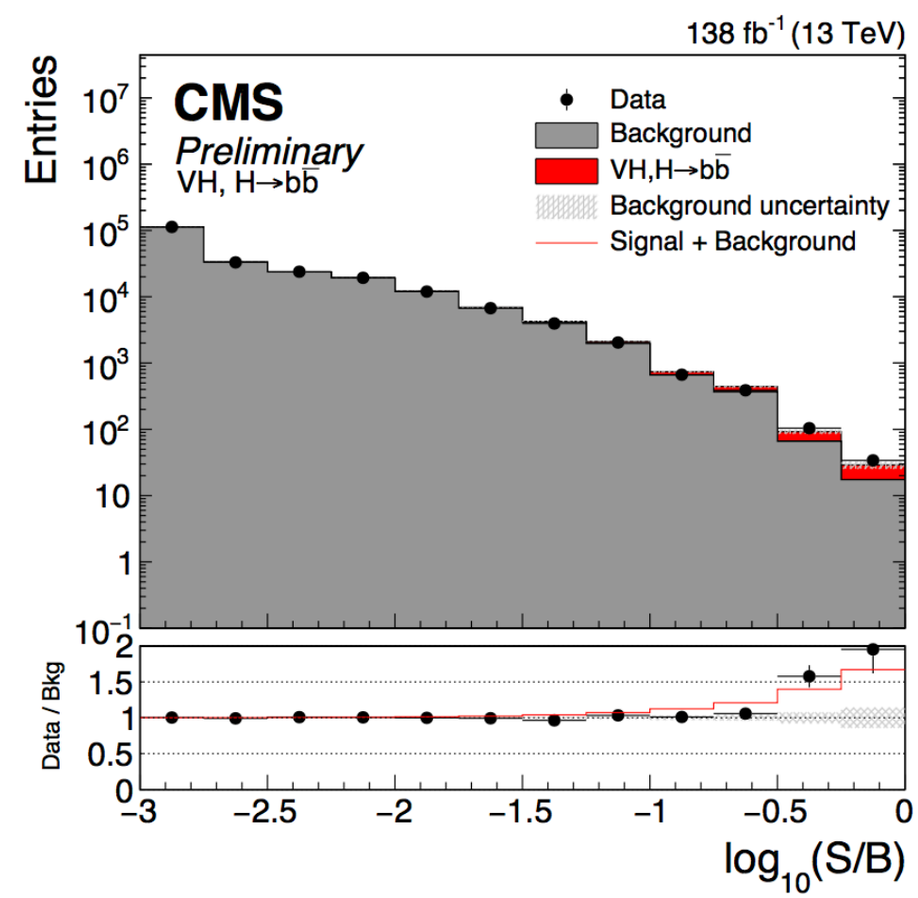
- Inclusive Run 2 signal strength: $\mu=0.58_{-0.18}^{+0.19}$ - observed (expected) significance: 3.3σ (5.2σ)
  - uncertainty dominated by V+jets modelling and simulation statistics; background scale-factors extracted in-situ



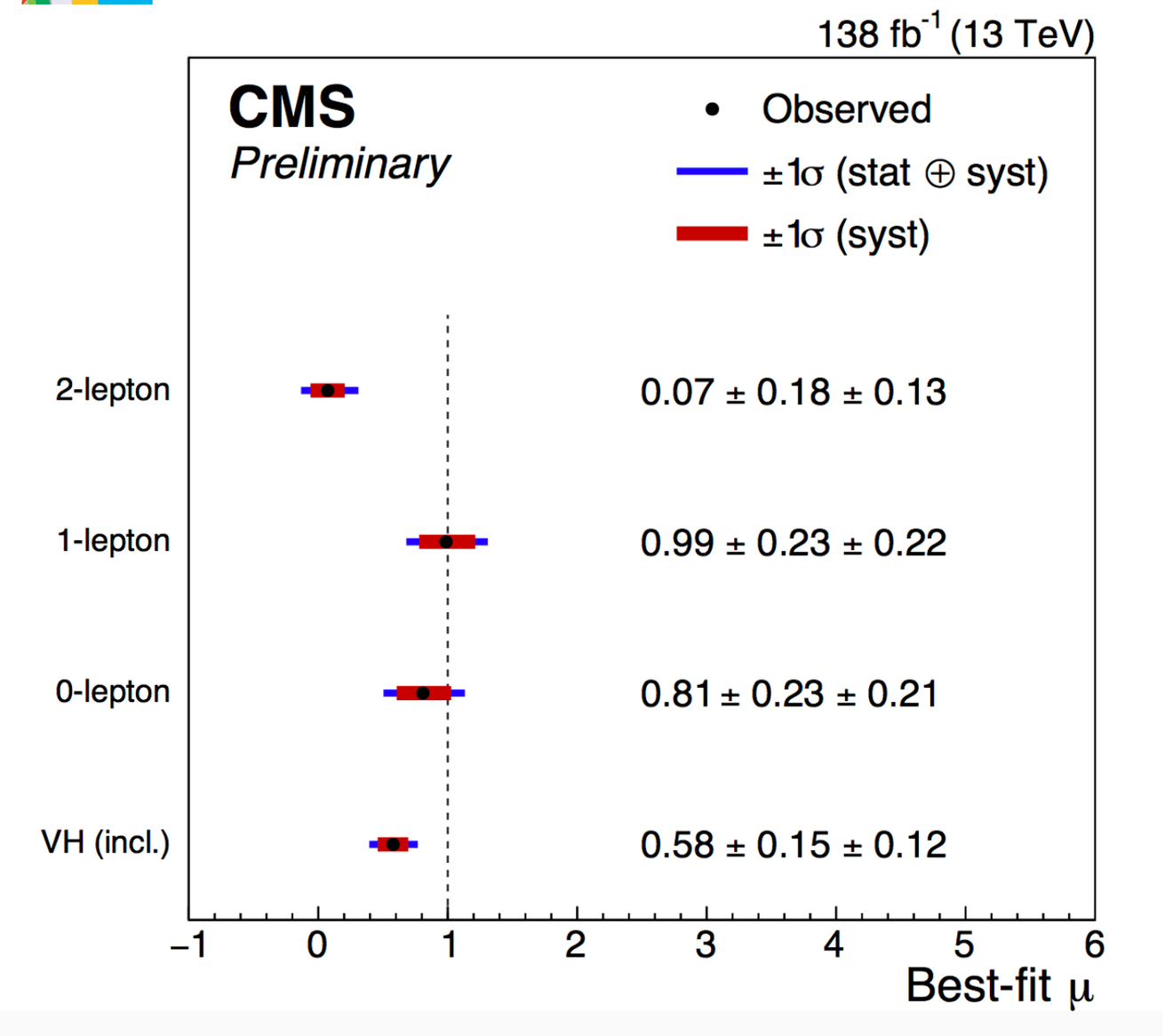
- Several cross-checks of DNN-based analysis results:
  - VZ, Z→bb: μ=1.16±0.13
  - direct visualisation of VH/VZ signal peaks with dijet invariant mass (mass-decorrelated DNN) - μ=0.34±0.34

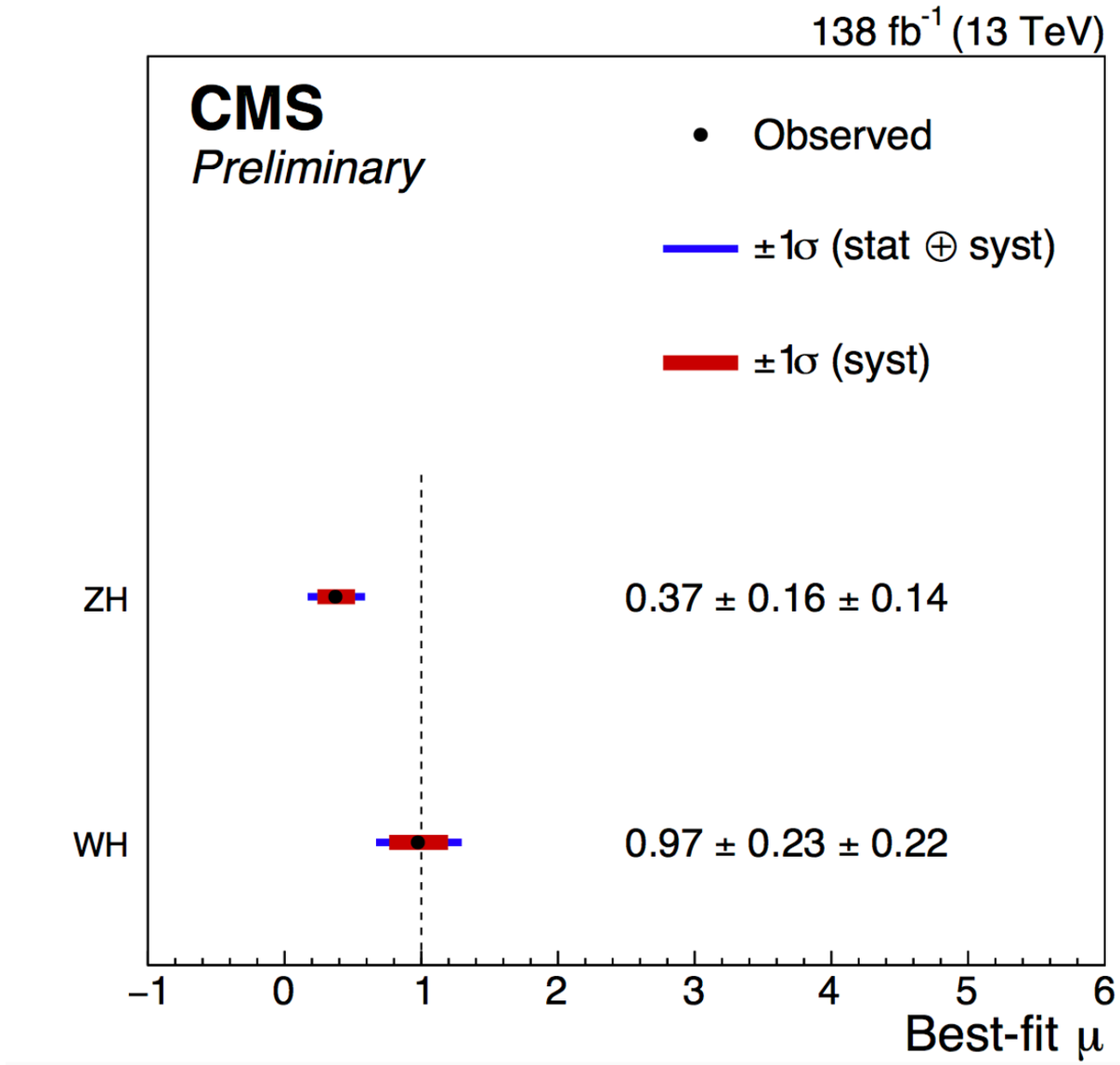
Jackknife compatibility test on 2017 results against previously published analysis: 2σ compatibility, ~50% analysis correlation





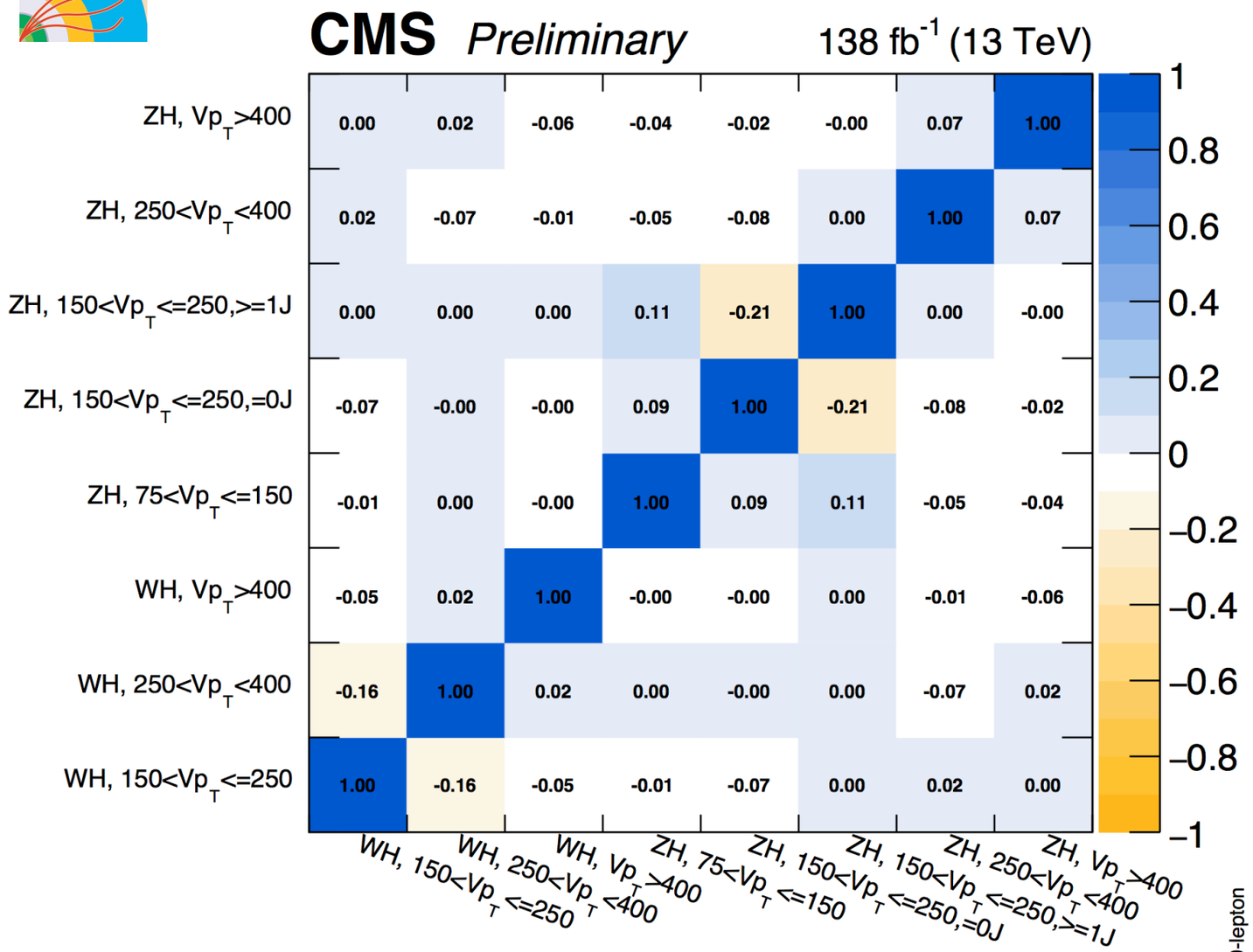
CMS VH(->bb)



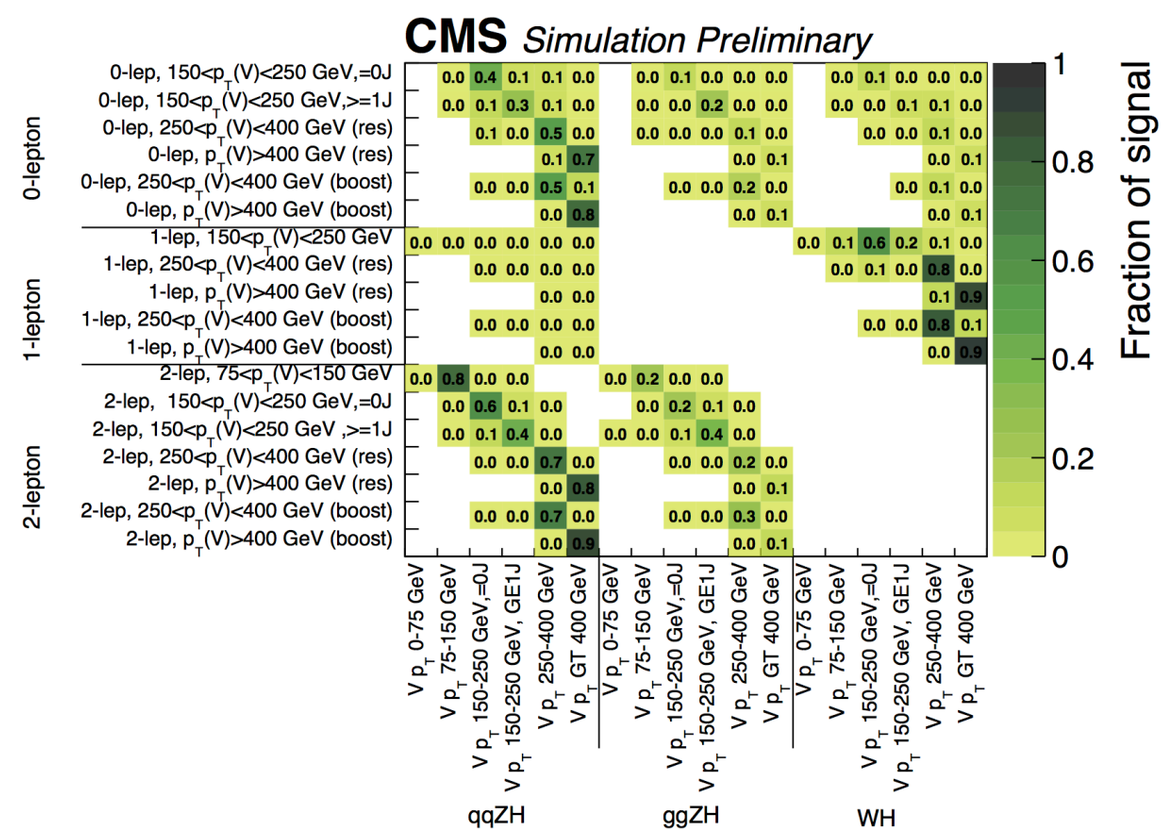


- per-channel p-value vs inclusive signal strength: 1.9σ; vs SM: 2.9σ (entirely dominated by 2lep)
- ZH vs 0lep/2lep compatiblity p-value: 20%

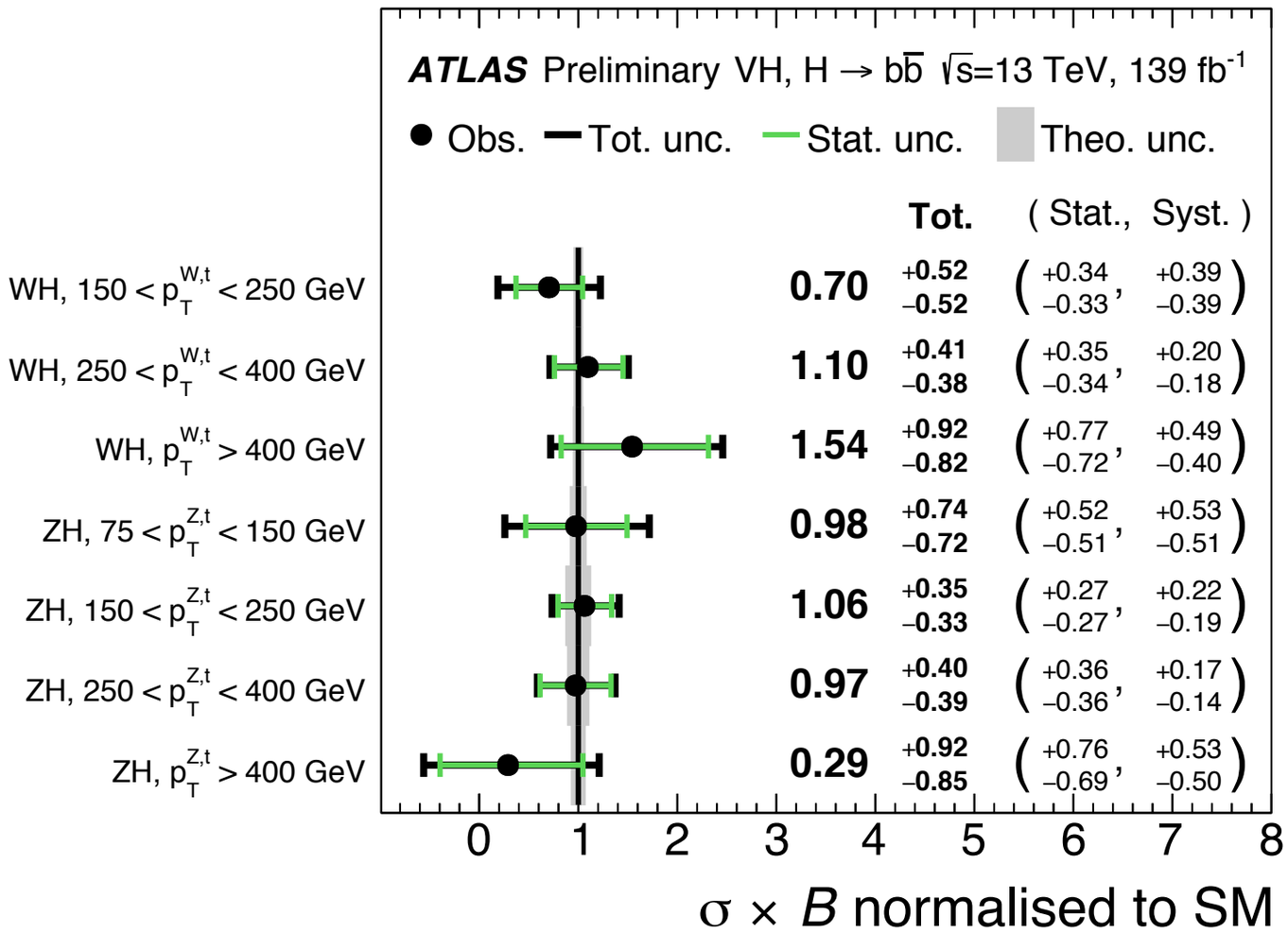
CMS VH(->bb)

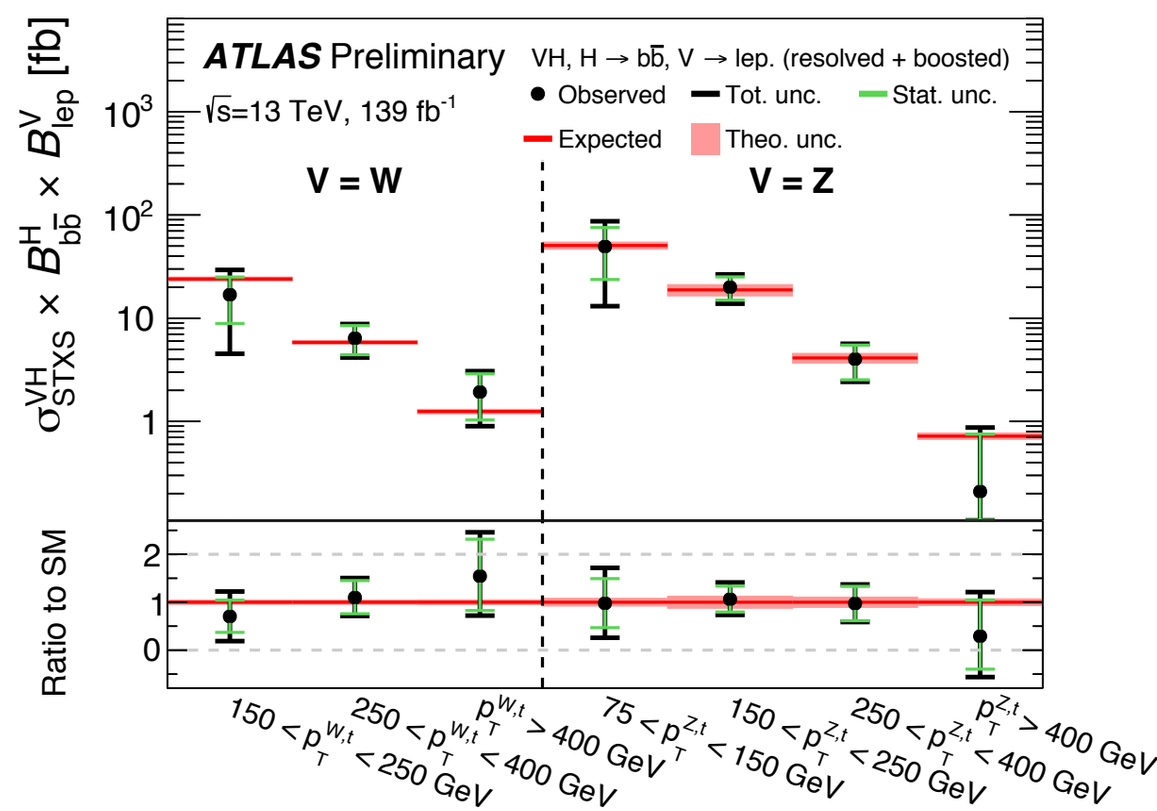


STXS POI correlations



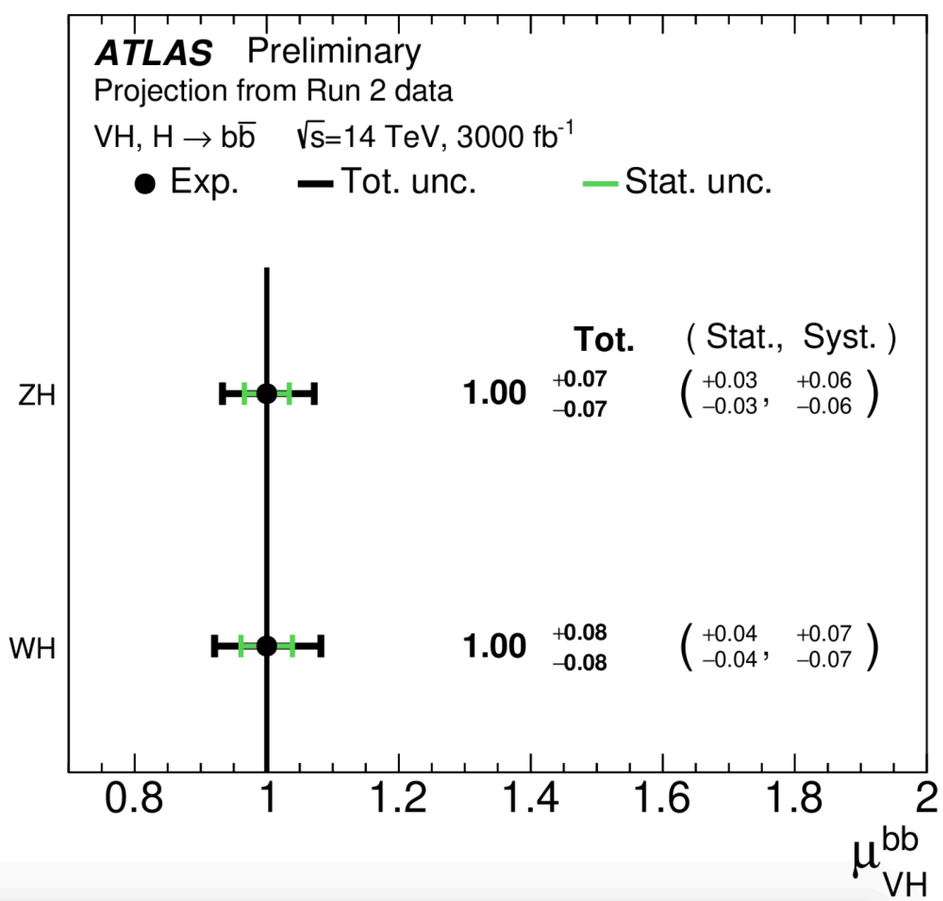
ATLAS VH(->bb)

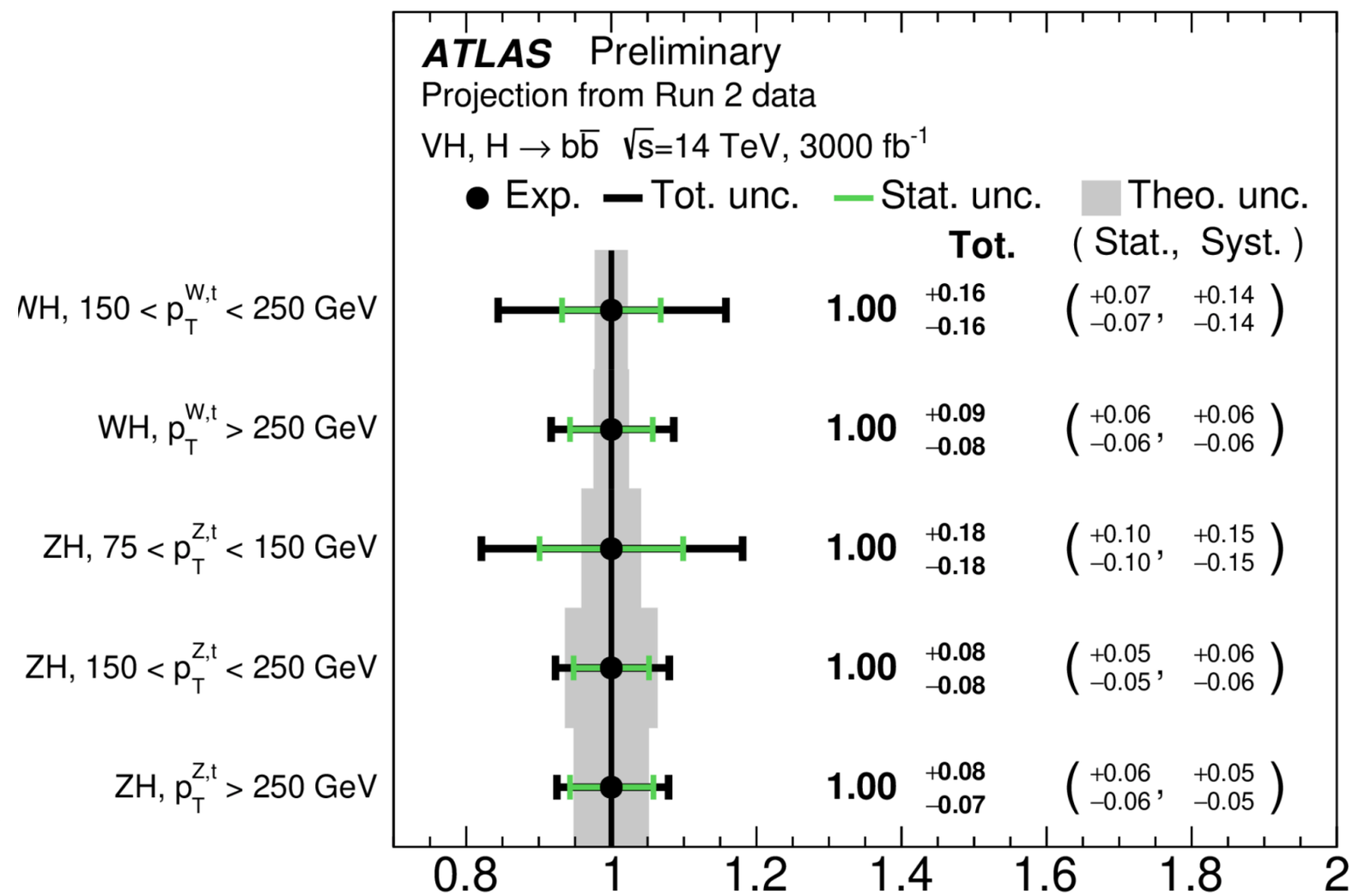

ATLAS Preliminary VH, H → bb̄ √s=13 TeV, 139 fb-1
Obs.
Tot. unc.
Stat. unc.
Theo. unc.
Tot.
(Stat., Syst.)
WH, 150 < p_T^W,t < 250 GeV 0.70 +0.52 −0.52 (+0.34 −0.33 , +0.39 −0.39)
WH, 250 < p_T^W,t < 400 GeV 1.10 +0.41 −0.38 (+0.35 −0.34 , +0.20 −0.18)
WH, p_T^W,t > 400 GeV 1.54 +0.92 −0.82 (+0.77 −0.72 , +0.49 −0.40)
ZH, 75 < p_T^Z,t < 150 GeV 0.98 +0.74 −0.72 (+0.52 −0.51 , +0.53 −0.51)
ZH, 150 < p_T^Z,t < 250 GeV 1.06 +0.35 −0.33 (+0.27 −0.27 , +0.22 −0.19)
ZH, 250 < p_T^Z,t < 400 GeV 0.97 +0.40 −0.39 (+0.36 −0.36 , +0.17 −0.14)
ZH, p_T^Z,t > 400 GeV 0.29 +0.92 −0.85 (+0.76 −0.69 , +0.53 −0.50)
0 1 2 3 4 5 6 7 8
σ × B normalised to SM


ATLAS Preliminary
√s=13 TeV, 139 fb-1
VH, H → bb̄, V → lep. (resolved + boosted)
Observed
Tot. unc.
Stat. unc.
Expected
Theo. unc.
V = W
V = Z
σ^VH_STXS × B^H_bb̄ × B^V_lep [fb]
Ratio to SM
150 < p_T^W,t < 250 GeV
250 < p_T^W,t < 400 GeV
p_T^W,t > 400 GeV
75 < p_T^Z,t < 150 GeV
150 < p_T^Z,t < 250 GeV
250 < p_T^Z,t < 400 GeV
p_T^Z,t > 400 GeV

Prospects on VH (->bb) ATLAS @ HL-LHC

- Studies available on VHbb extrapolations @ HL-LHC
  - ATLAS-PHYS-PUB-2021-039





VBF Hbb (inclusive & photon-tagged)

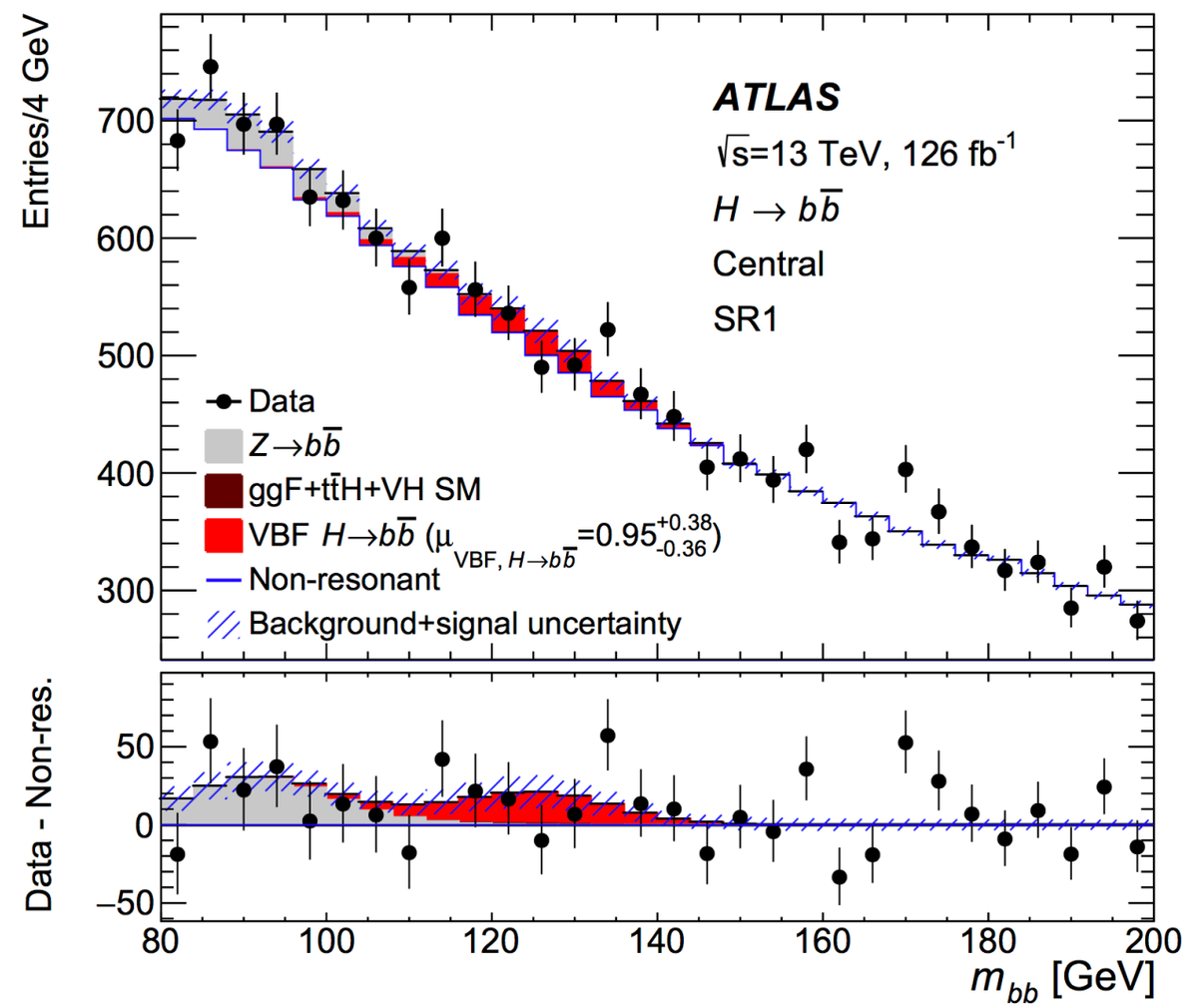
Eur. Phys. J. C 81, 537 (2021) J. High Energ. Phys. 2021, 268 (2021)

- VBF - second most dominant Hggs production at the LHC - distinctive features with VBF jets with large pseudorapidity gap and little activity in the central region

- Additional mode: associated production with a photon - ATLAS analysis targets both processes

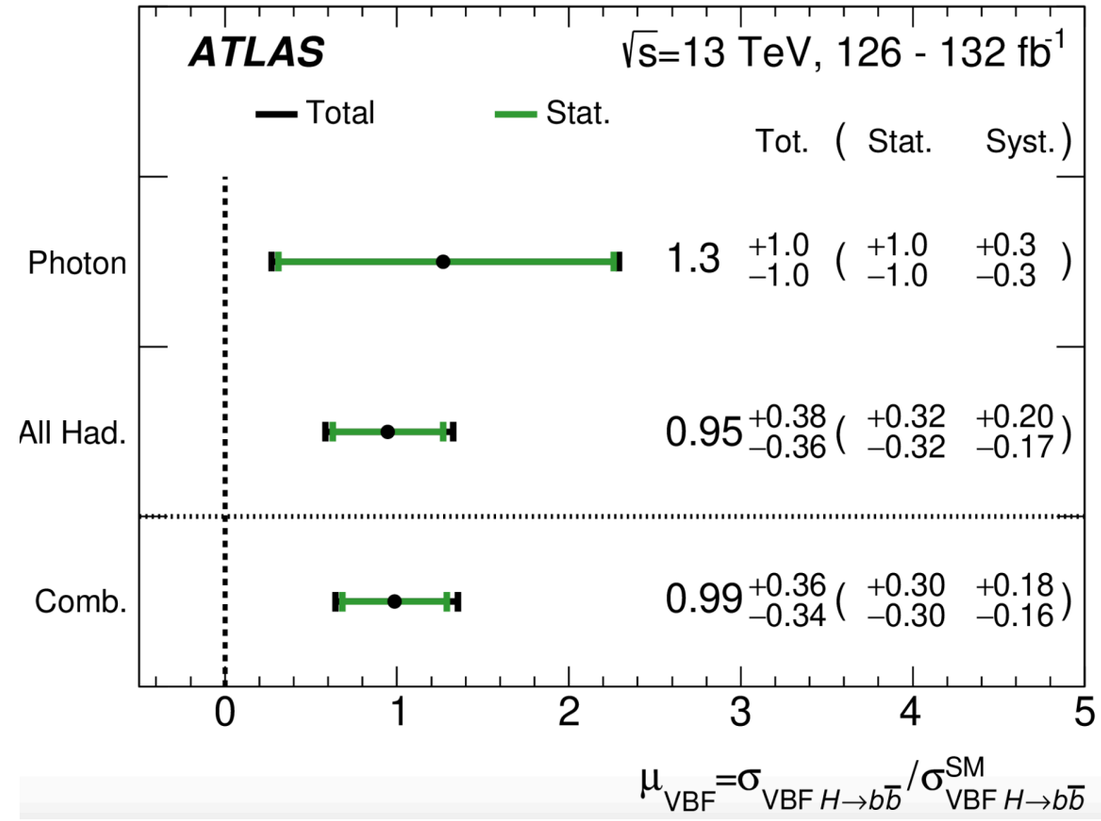
- All-hadronic final state using ANN (adversarial neural network) to categorise events and fit m(bb)

- Hadronic + photon final state using BDT to categorise events and fit m(bb) in each region

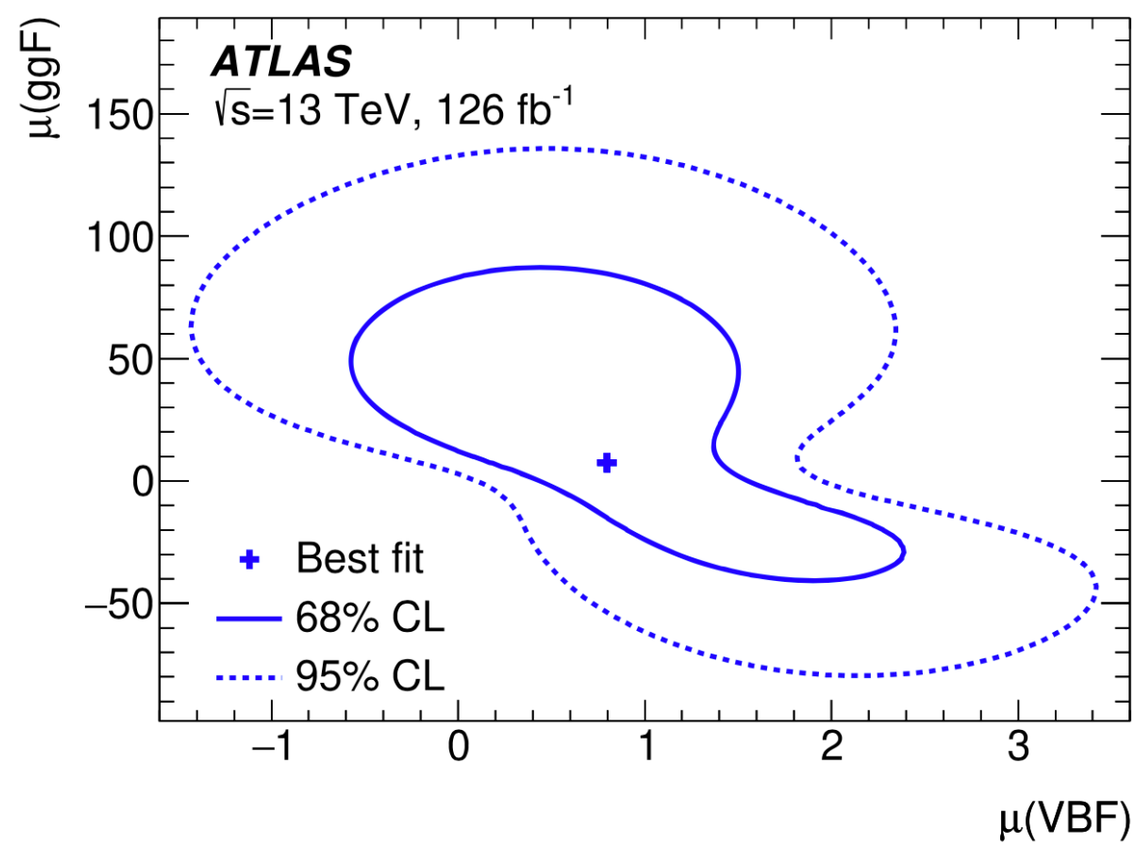


- Expected (observed) combination: 2.9σ (2.9σ), two-dimensional scan of gluon-fusion and vector-boson fusion signal strengths also provided

VBF Hbb (inclusive & photon-tagged) - results



- Expected (observed) combination: 2.9σ (2.9σ), dominated by all-hadronic channel
- 2-dimensional scan of gluon-fusion and vector-boson fusion also provided

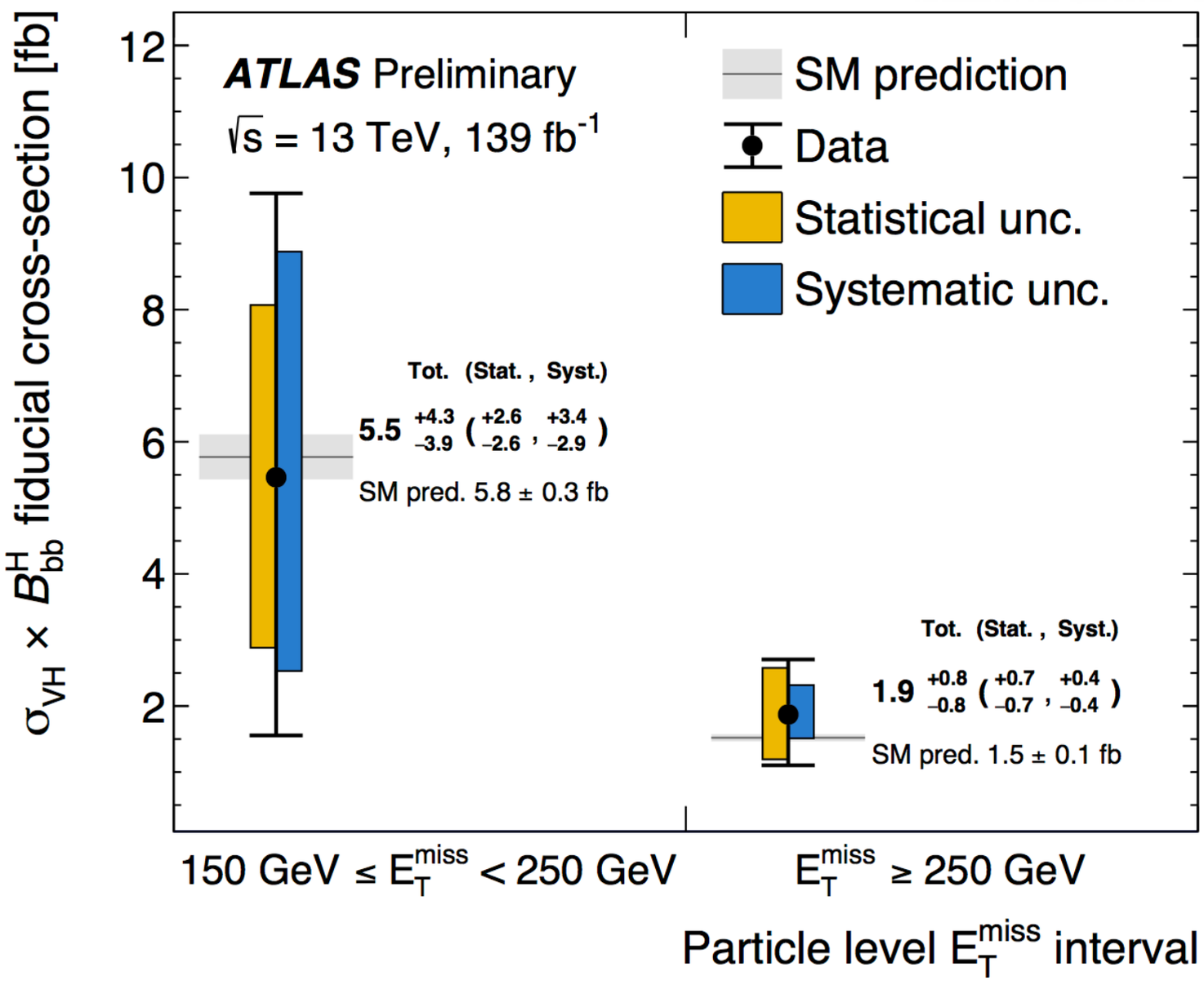


VH(->bb) - 0-lepton fiducial cross-section (2)

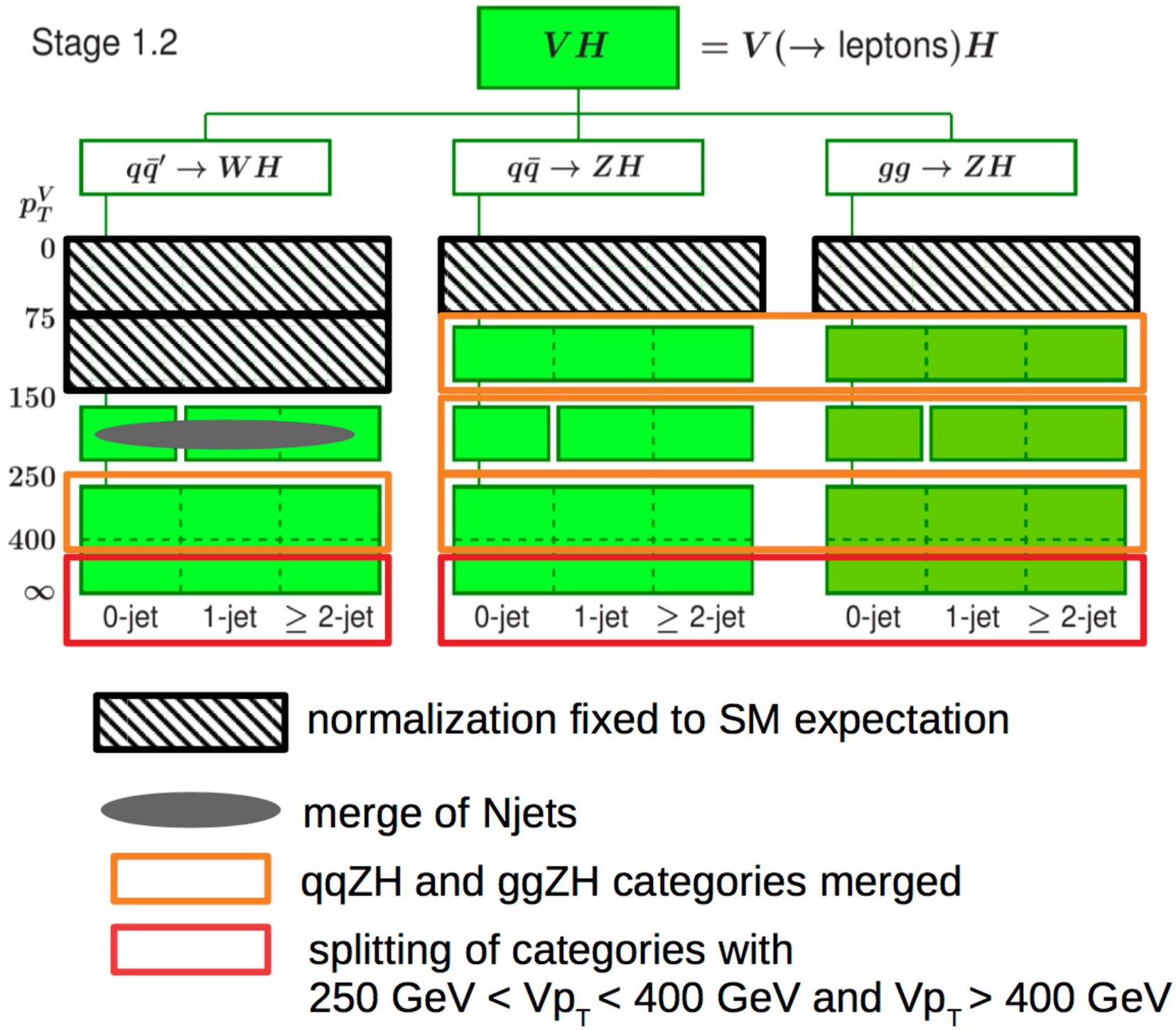
➡ Dominant unfolding uncertainties → presence of out-of fiducial events and contamination of events from different particle-level categories in detector-level categories

Source of uncertainty		σ_μ T_1	T_2
Total		0.71	0.53
Statistical		0.45	0.46
Systematic		0.55	0.26
Experimental		0.21	0.14
Jets		0.16	0.11
Missing transverse momentum		0.06	0.05
Flavour-tagging	b-jets	0.06	0.06
	c-jets	0.06	0.04
	light-flavour jets	0.03	0.01
Leptons		0.01	0.04
Pile-up		0.02	0.02
Luminosity		0.02	0.02
Background modelling		0.29	0.14
$t\bar{t}$		0.18	0.06
Dibosons		0.14	0.06
Z + jets		0.13	0.08
W + jets		0.10	0.03
Single top quark		0.07	0.04
Fiducial templates modelling		0.18	0.11
Unfolding uncertainty, T_1		0.17	< 0.01
PS model acceptance		0.01	0.09
Unfolding uncertainty, T_2		< 0.01	0.05
WH/ZH		0.01	0.03
NLO EW		0.01	0.02
QCD scale acceptance, $ggZH$		0.02	0.01
2/3 jets ratio		0.01	0.01
PS model m_{bb} shape		0.01	< 0.01
QCD scale acceptance		0.01	< 0.01
PDF acceptance		< 0.01	< 0.01
MC statistics		0.17	0.11
Floating normalizations		0.14	0.06

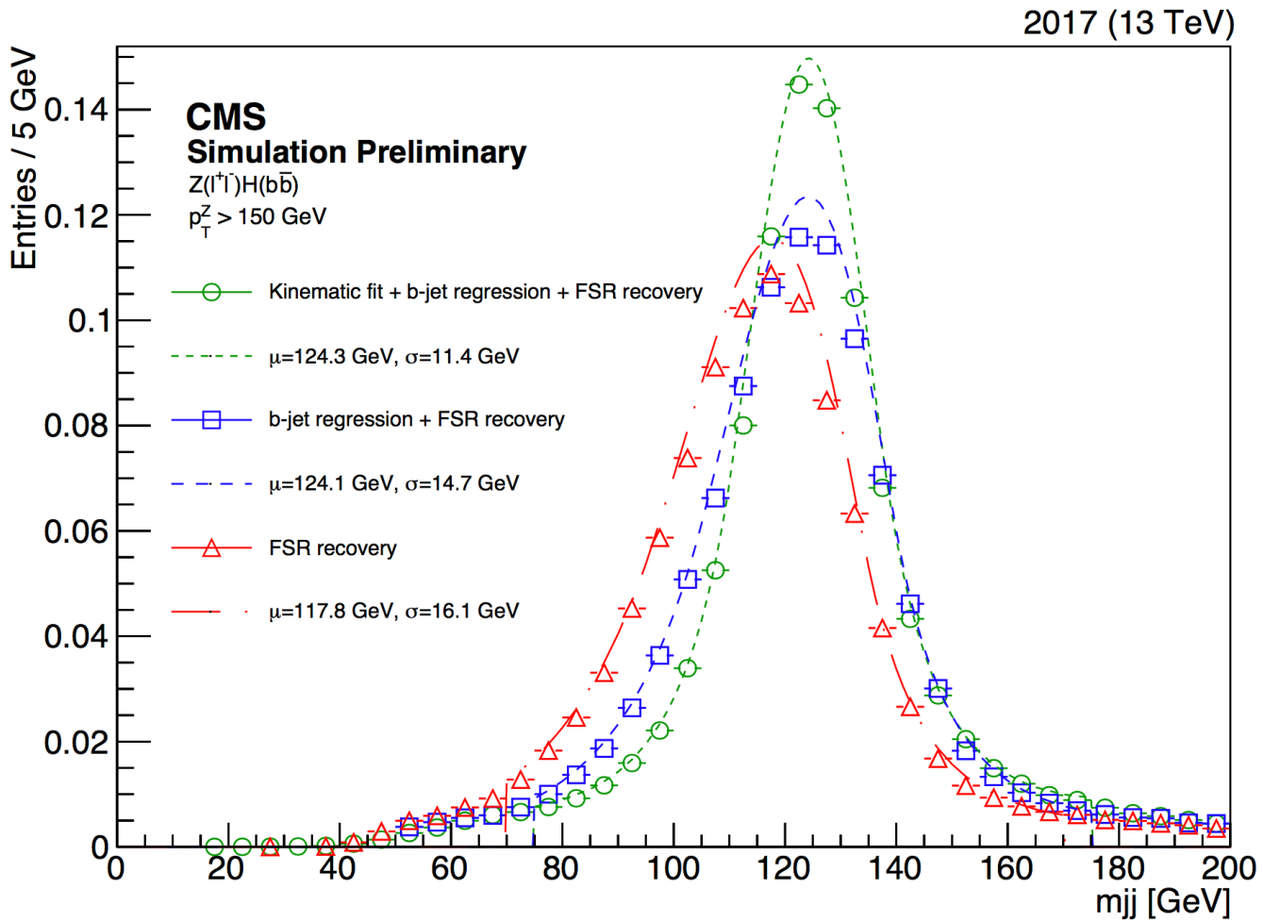
ATLAS-CONF-2022-015

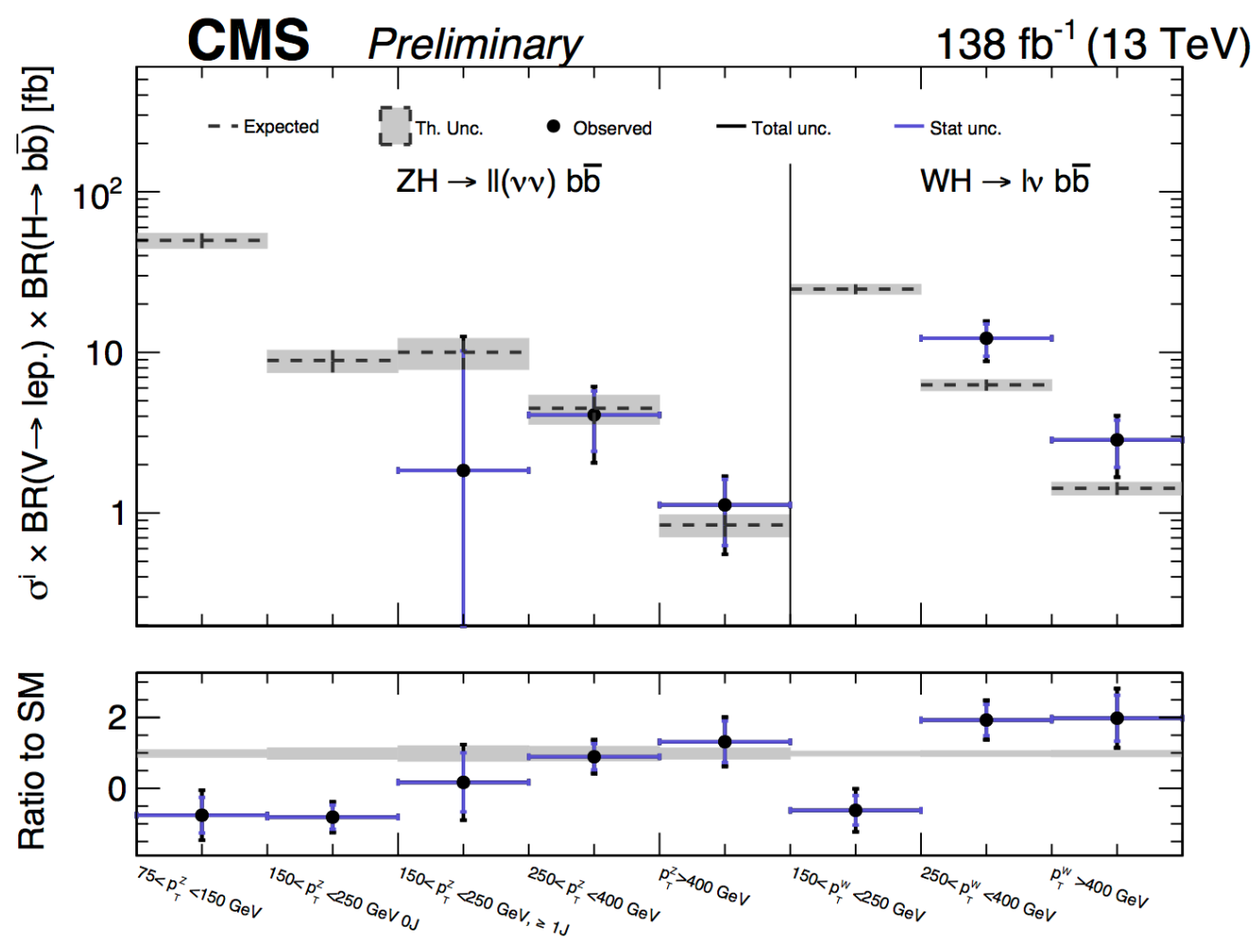


VH(->bb) - STXS Stage 1.2



VH(->bb) - CMS analysis strategy





Prospects on VH (->cc) CMS @ HL-LHC

- Simultaneous extraction of Hbb and Hcc signal strengths
  - expected sensitivity is approaching the SM value for Hcc couplings