WG1:VH experimental view

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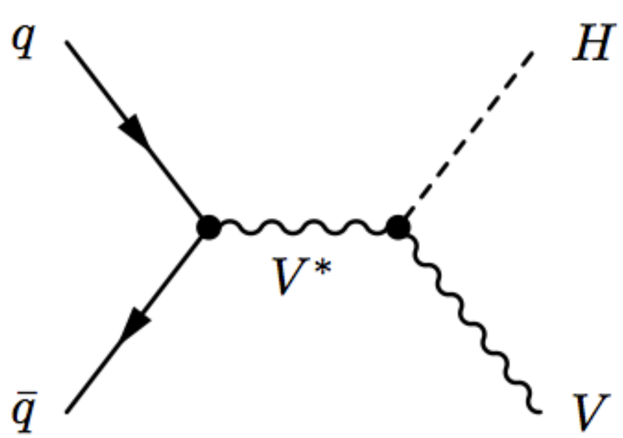
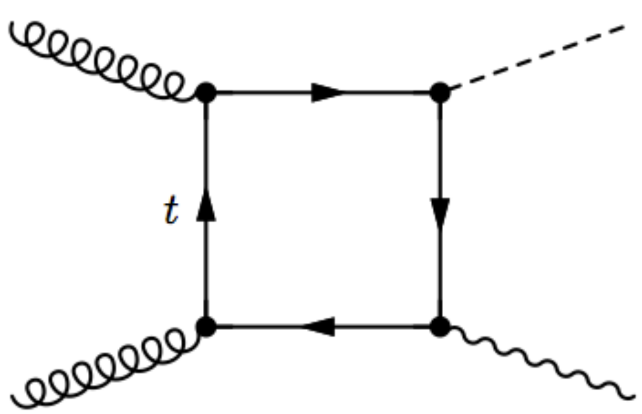
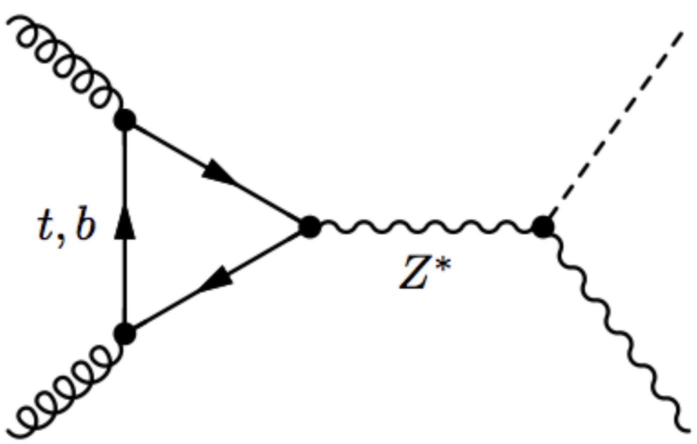
15th Workshop of the LHC Higgs Cross Section Working Group

Cern, 10-13 December 2018







Overview of recent VH activities

Activities ongoing in the VH WG1 subgroup

- state-of-the-art theory modeling of VH and H(bb) processes
- treatment of loop-induced gg→ZH
- modeling of V+heavy flavor processes (as background to VH(bb))
- contributions to HL/HE-LHC studies

- latest experimental VH results
  - → state of VH predictions / tools used by experimental collaborations
  - → main theory limitations & “whishlist”, possible improvements
  - → experimental treatment of SM backgrounds (V+heavy flavor)

- Simplified Template Cross Section STXS approach and EFT interpretations

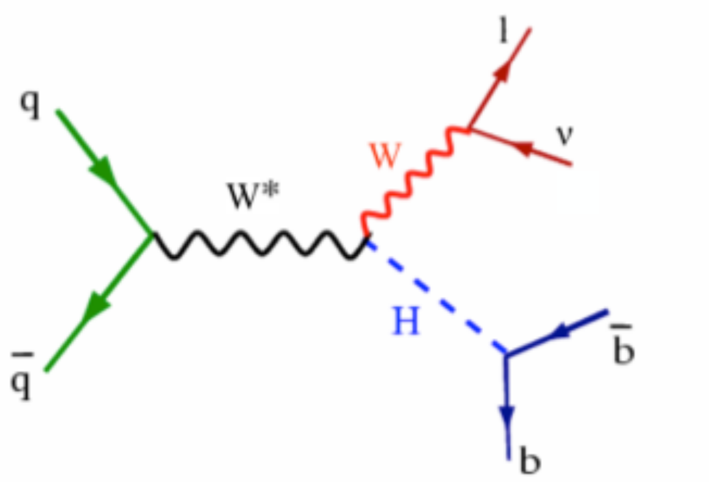
This talk: experimental take on VH matters, in light of recent results and towards the full Run-2 analyses

Emanuele's talk: overview from the theory side

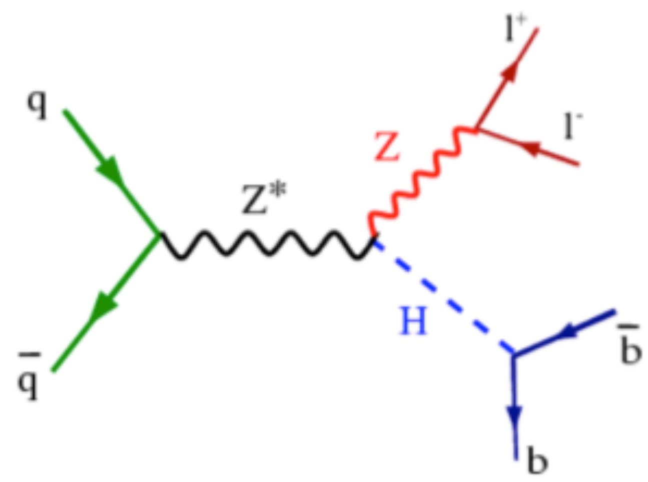
VH production @ LHC

focus on H(→bb)

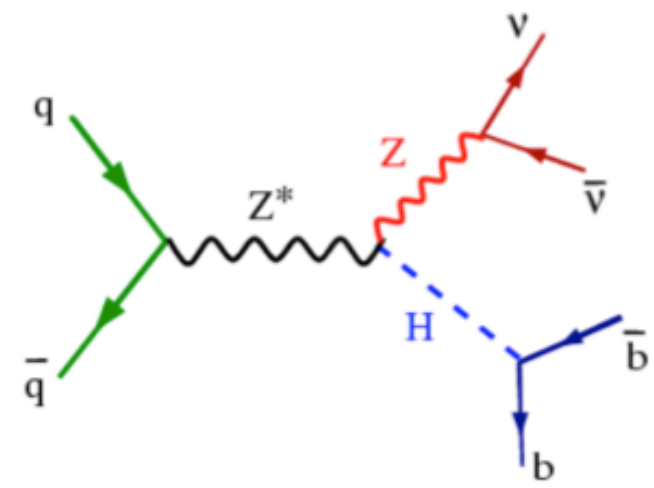
1-lepton



2-lepton

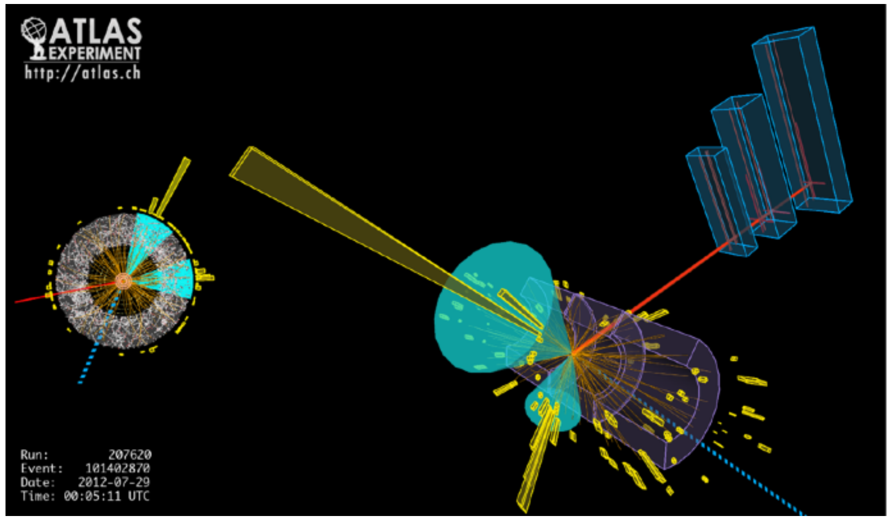


0-lepton

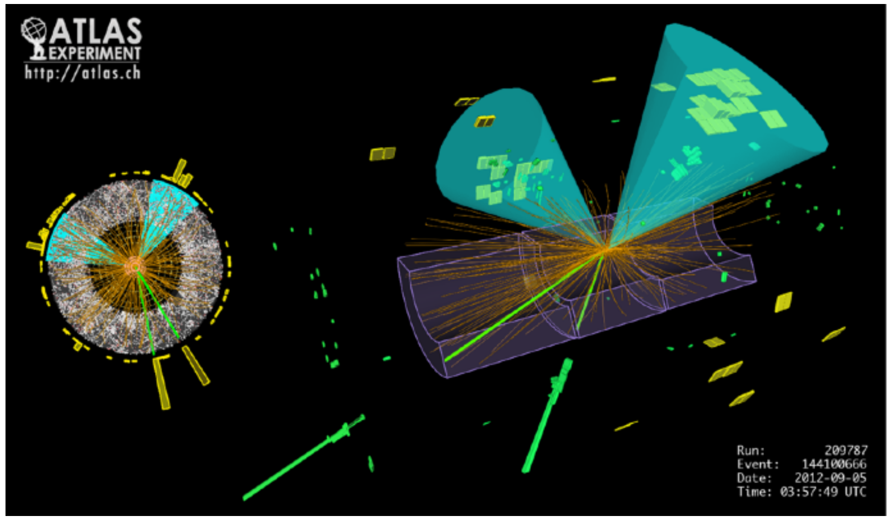


V→leptons signature

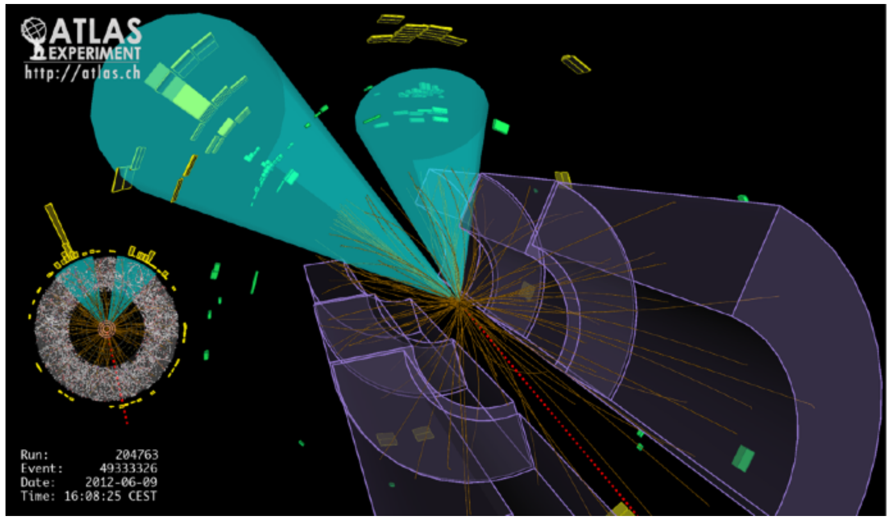
W(→lν)H(→bb)



Z(→ll)H(→bb)



Z(→νν)H(→bb)



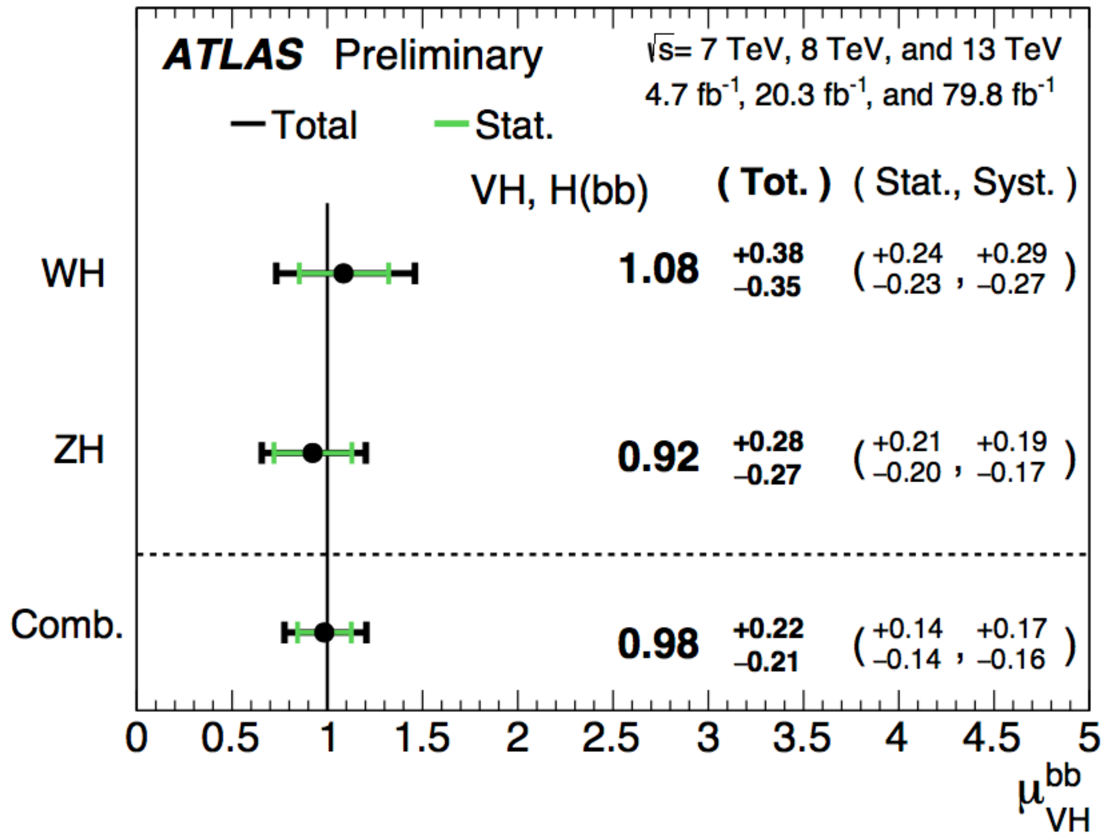
VH production @ LHC

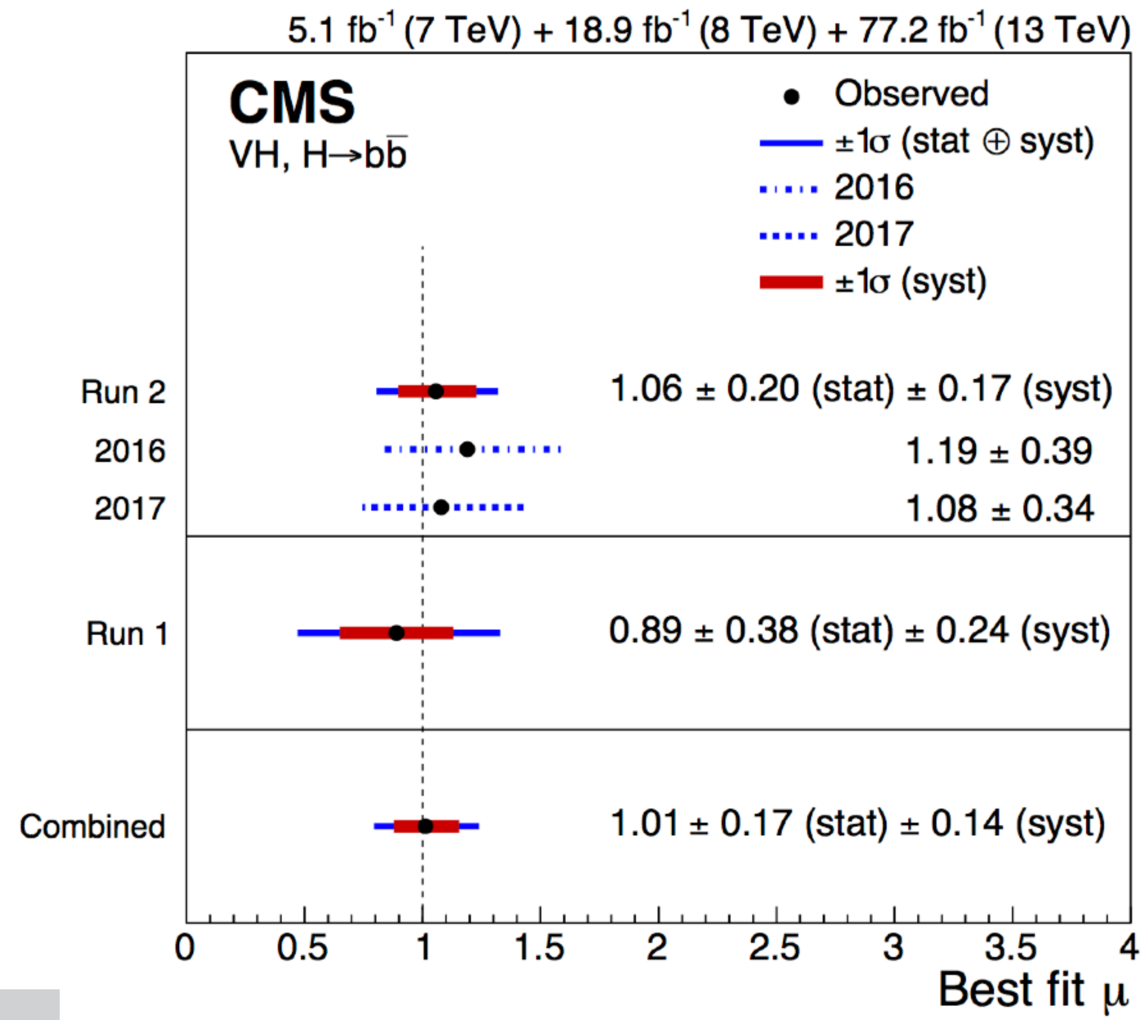
focus on H(→bb)

Recent observation of VH and H(→bb) from ATLAS and CMS, dedicated HXSWG meeting

CMS: Phys. Rev. Lett. 121 (2018) 121801
ATLAS: Phys. Lett. B 786 (2018) 59

[From Run-1 + O(80/fb)Run-2 dataset]





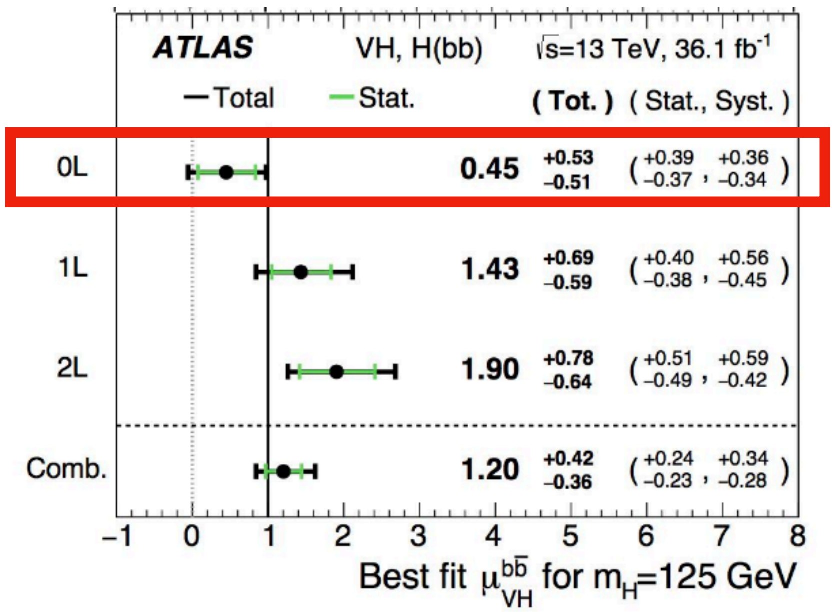
VH(bb)	significance obs(exp) [σ]	signal strength $\mu = \sigma/\sigma_{SM}$
ATLAS	4.9 (5.1)	0.98 ± 0.2 (±0.14 stat ±0.17 syst)
CMS	4.8 (4.9)	1.01 ± 0.23 (±0.17 stat ±0.14 syst)

(5-sigma observation of VH and (separately) of H(bb) is obtained by combining with other production modes and decay channel)

VH production @ LHC

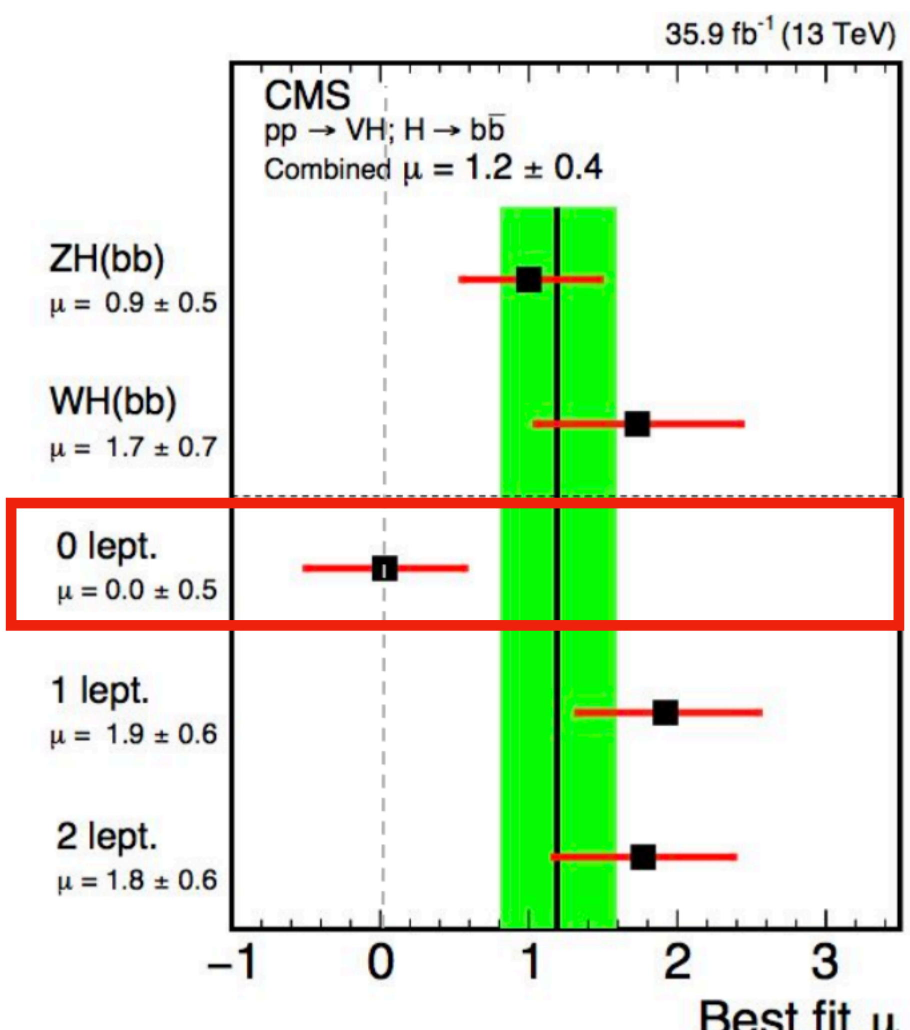
focus on H(→bb)

Results very much consistent with SM expectations: **no** 0-lepton "discrepancy"



Signal strength parameter	Signal strength
0-lepton	$1.04^{+0.34}_{-0.32}$
1-lepton	$1.09^{+0.46}_{-0.42}$
2-lepton	$1.38^{+0.46}_{-0.42}$
$VH, H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$

80/fb [2016+2017]



36/fb [2016]

41/fb [2017]

	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34

VH production @ LHC

focus on H(→bb)

WG1:VH contribution towards VH(bb) experimental analysis, focused on two sides:

VH Higgs associated production

modeling of main backgrounds
V+heavy flavor production

ATLAS - 80/fb [2016+2017]

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multijet		0.005
MC statistical		0.070

CMS - 41/fb [2017]

Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33

Modeling of VH signal process

Feedback to experimental collaboration on best options on the market to model VH processes [more detail in Emanuele's talk]:

- NNLOPS prediction
- loop-induced gg→ZH production
- inclusion of EW@NLO corrections
- impact of NNLO H(→bb) decay
- etc.

Important
Implementing the publicly available tools in the experimental analysis not always trivial
(large SW infrastructure for MC generation)

Current VH signal model in ATLAS and CMS (consistent!)

qqZH, WH	Powheg-MiNLO + Pythia8	MiNLO[QCD]
loop-induced gg→ZH	Powheg + Pythia8	LO[QCD]

Cross-section predictions from YR4:

- qqZH and WH: **NNLO[QCD]+NLO[EW]** including photon-induced (3% in WH, 1% ZH) and top-loop induced (1%) contributions
- loop-induced gg→ZH: **NLO**(approx)**+NLL[QCD]** kNLO~2 from (mtop→∞) calculation

- PDF4LHC15 set for matrix-element
- dedicated ATLAS / CMS PS tunes

EW Corrections from YR4:

- NLO EW differential reweighting (generally applied as $f(p_T^V)$) from HAWK

TH Uncertainties for VH signal process

Treatment of theory uncertainties on VH processes

- [total XS uncertainties from YR4] + [acceptance uncertainties]
  from usual combination of QCD scale variations, PDF+alpha_S, parton-shower, EW corrections

- moving toward Simplified Template Cross Section approach
  treatment of signal TH systematics treated under the STXS framework
  [*much more detail in Thomas' talk this afternoon*]

- TH uncertainties not included in the STXS 'interpretation stage'
  parton-shower, underlying event, hadronization treatment
  Very different approach between ATLAS and CMS
  (in ATLAS up to 10% effect in signal acceptance from PS variations, leading TH syst on VH)

Table 6: Summary of the systematic uncertainties in the signal modelling. "PS/UE" indicates parton shower / underlying event. An "S" symbol is used when only a shape uncertainty is assessed. Where the size of an acceptance systematic uncertainty varies between regions, a range is displayed.

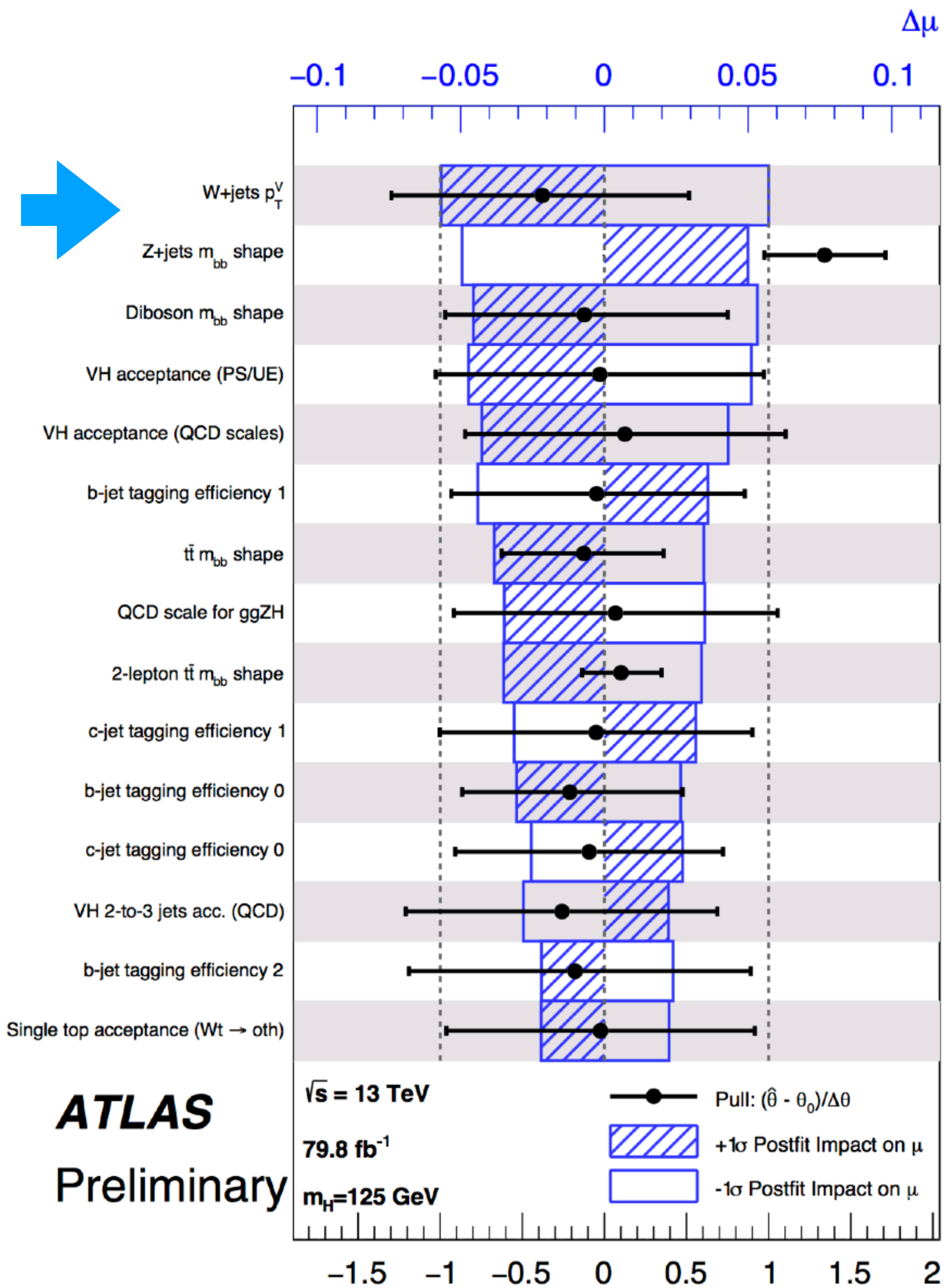
ATLAS - 80/fb [2016+2017]

Signal	
Cross section (scale)	0.7% (qq), 27% (gg)
Cross section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching ratio	1.7 %
Acceptance from scale variations (var.)	2.5 – 8.8%
Acceptance from PS/UE var. for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance from PS/UE var. for 3 jets	1.8 – 11%
Acceptance from PDF+α_S var.	0.5 – 1.3%
m_{bb}, p_T^V, from scale var.	S
m_{bb}, p_T^V, from PS/UE var.	S
m_{bb}, p_T^V, from PDF+α_S var.	S
p_T^V from NLO EW correction	S

Dedicated discussion session on parton-shower treatment on Tuesday morning

Modeling of background processes

Theory/MC predictions for V+heavy flavor processes can be rather important for VH(bb): while with increasing amount of data we will pin down these processes more precisely, our prior prediction and the implementation of systematic variations can impact the analysis significantly



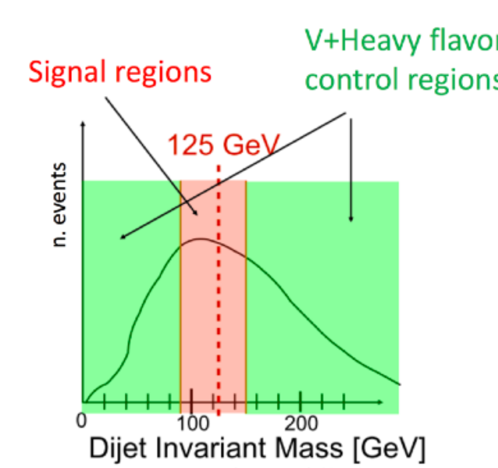
ATLAS/CMS adopt different strategies

ATLAS:

- **Sherpa V+0,1,2j@NLO + 3,4j@LO**
- **dedicated W+hf CR**
  at low m(top), high m(bb)
  no Z+hf CR, full m(bb) spectrum to MVA

CMS:

- **Madgraph V+0,1,2,3,4j@LO**
  $f(p_T^V)$ + deltaEta(jj) corrections
  (LO vs NLO, EW corrections, data/MC)
- **sideband approach:**
  SR around m(bb) peak
  CR from high/low-m(bb)



Comparing is not trivial ...

Modeling of background processes

The **normalization** of these background processes is fully determined from data, pointing to some sizable discrepancy from the MC prediction:

ATLAS - 80/fb [2016+2017]

W + HF 2-jet	1.19 ± 0.12
W + HF 3-jet	1.05 ± 0.12
Z + HF 2-jet	1.37 ± 0.11
Z + HF 3-jet	1.09 ± 0.09

CMS - 41/fb [2017]

Process	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T	$Z(\ell\ell)H$ high-p_T
W + udscg	1.04 ± 0.07	1.04 ± 0.07	–	–
W + b	2.09 ± 0.16	2.09 ± 0.16	–	–
W + b$\bar{\text{b}}$	1.74 ± 0.21	1.74 ± 0.21	–	–
Z + udscg	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
Z + b	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
Z + b$\bar{\text{b}}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08

2017

- can we (reasonably) harmonize some aspects of the background treatment, to facilitate the ATLAS/CMS comparison? what can we learn from these numbers?
- MC prediction not always reliable: what about systematic on pT(V), m(bb), etc.? (these can bias the signal measurement, by correlating different phase spaces)

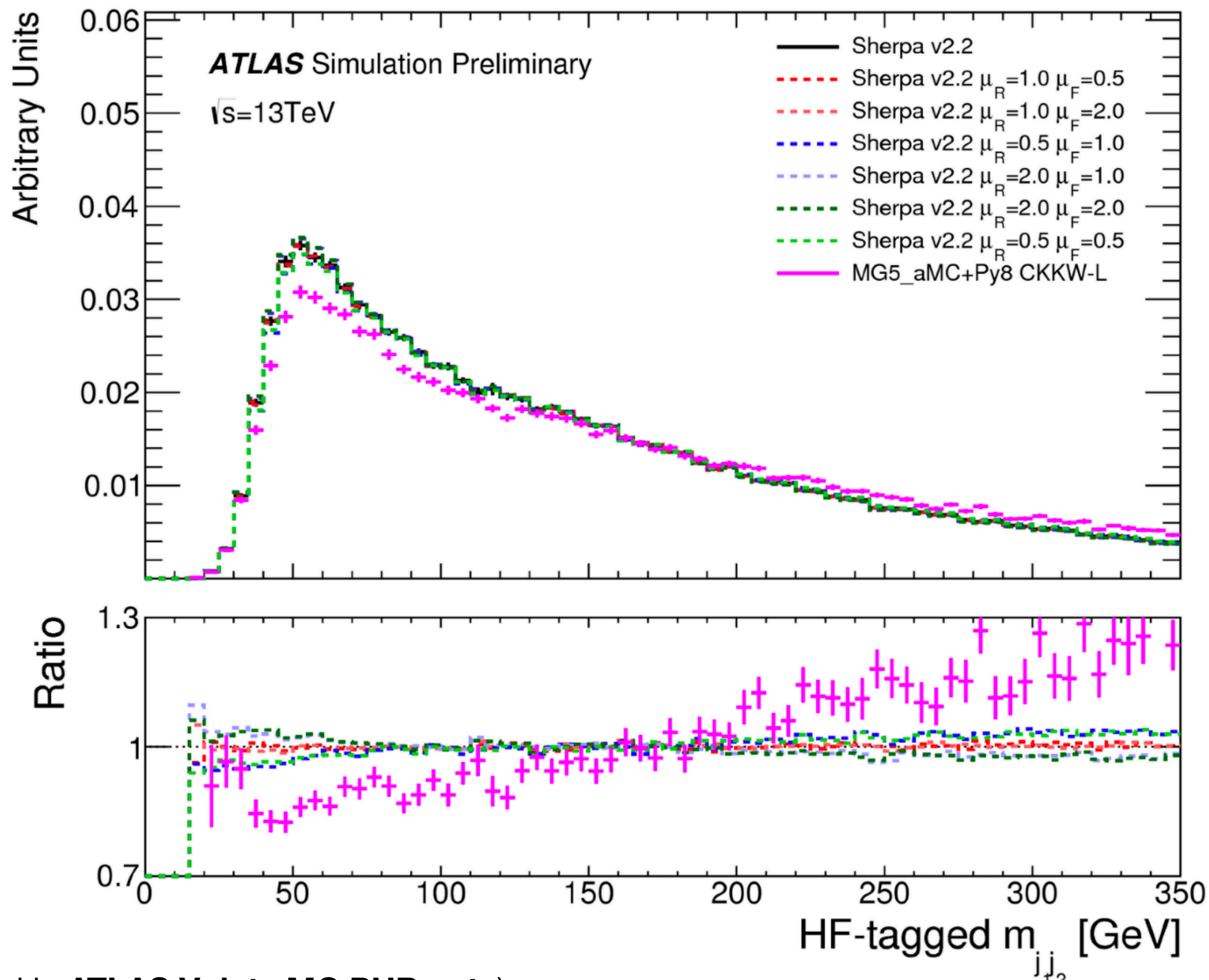
Modeling study starting in the VH sub-group with 2 goals:

1. support choice of MC generator for experimental analyses
2. provide guidelines for the estimate of proper TH uncertainties on V+hf

[more details in Emanuele's talk -- contributors are very welcome to join!]

Modeling of background processes

Just one example of **areas of improvement**: ATLAS V+hf uncertainties largely dominated by Sherpa (NLO) / Madgraph (LO) comparison [clearly not fully motivated from TH]



(Described in **ATLAS V+jets MC PUB note**)

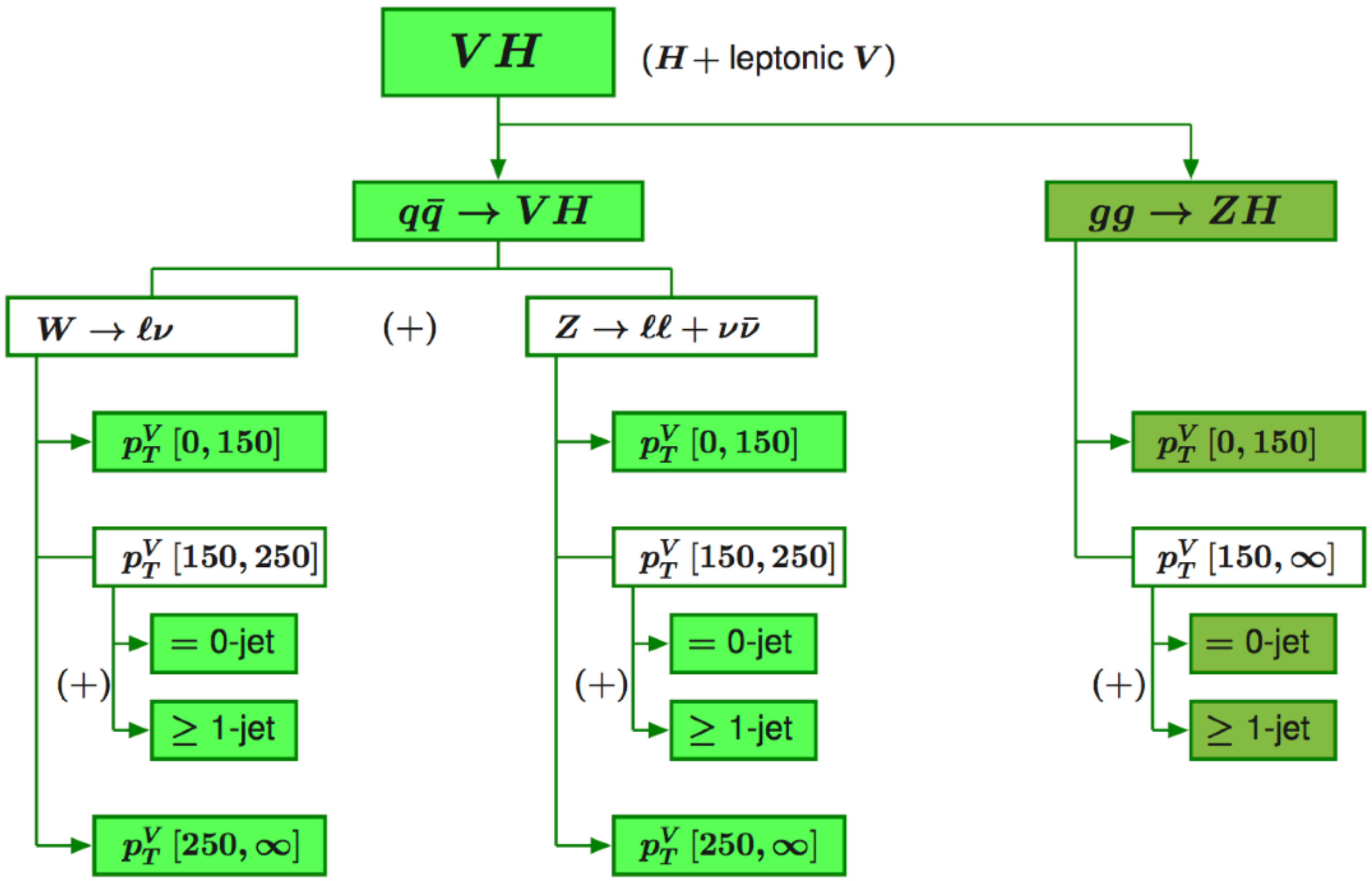
Simplified Template Cross Sections

ATLAS re-interpreting the Run-2 data analysis in STXS measurement and EFT fits

Super-short intro on VH STXS (dedicated session this afternoon):

Higgs Couplings 2018:
ATLAS-CONF-2018-053

LesHouches17 Stage-1 bin split



- "VH" bins include leptonic VH (H undecayed)
- qq → V(qq)H as part of "VBF" bins
- gg → Z(qq)H as part of "ggF"

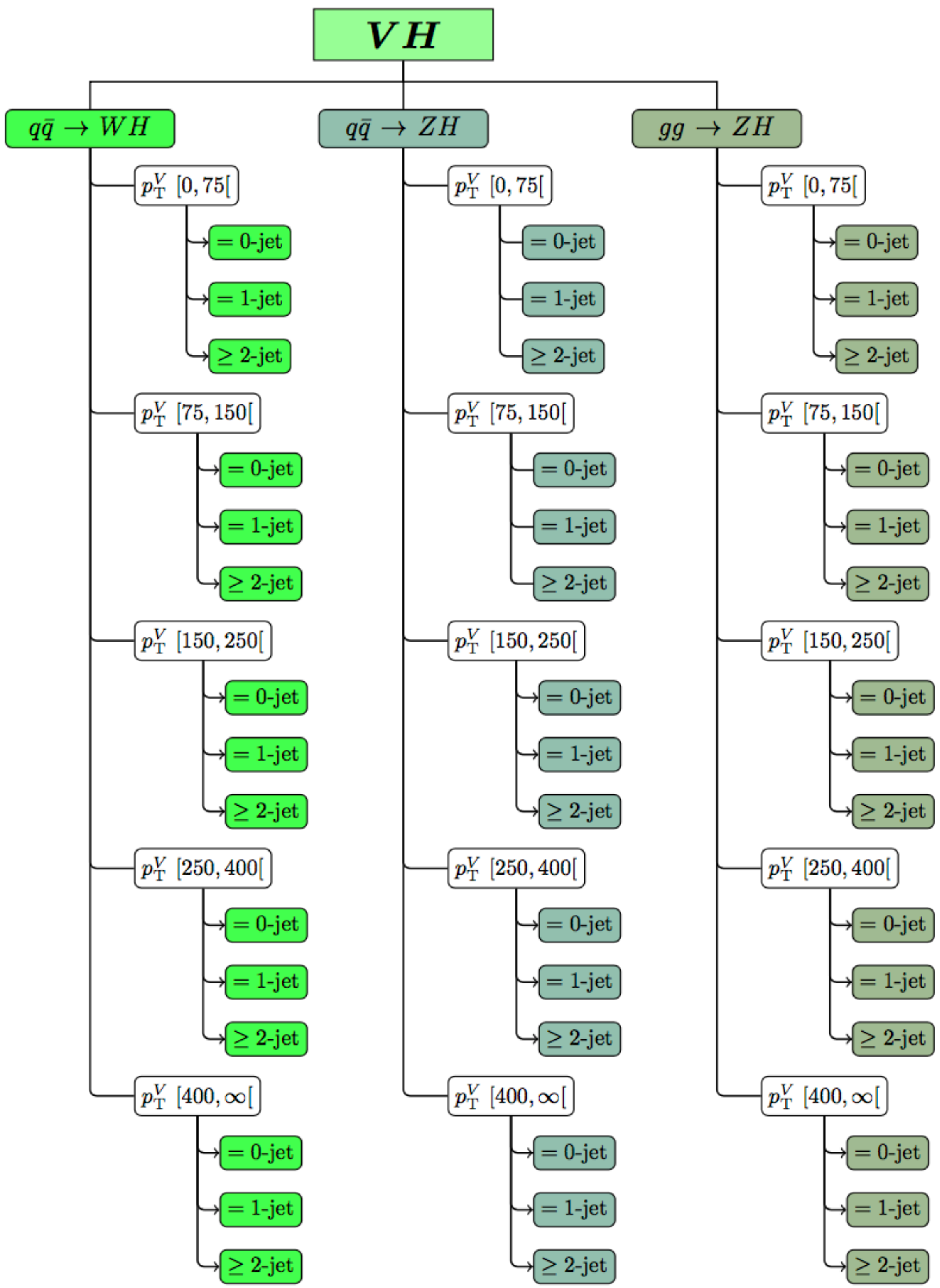
STXS ≠ fiducial XS (and complementary)
[fid/diff XS minimize theory dependence and acceptance corrections, decayed Higgs, ...]

(reference from LesHouches2017)

- **optimized for analysis sensitivity** (e.g. in this case driven by VH(bb) categorization)
- **reducing dominant theory dependence in the measurement** (by moving it to the interpretation stage)
- **reduced residual theory uncertainties** within the measurement of each bin (if residual th. uncertainties become large in the exp. acceptance for a bin, the bin the be further split in sub-categories)

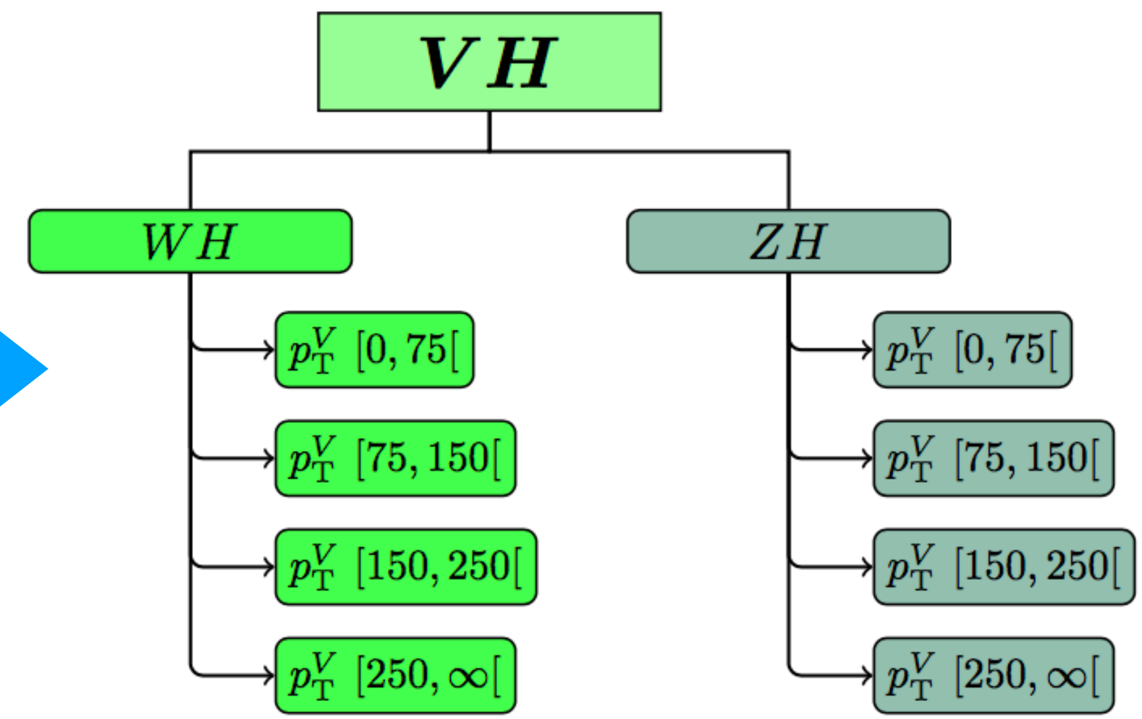
Simplified Template Cross Sections

Started from a **very fine** split in STXS bins to estimate uncertainties in each category, and moved to the measurement of coarser regions, divided in W/ZH and pT(V):



Higgs Couplings 2018:
ATLAS-CONF-2018-053

Towards a pT(V) measurement:
(potentially merging the pT(V)>150GeV region)

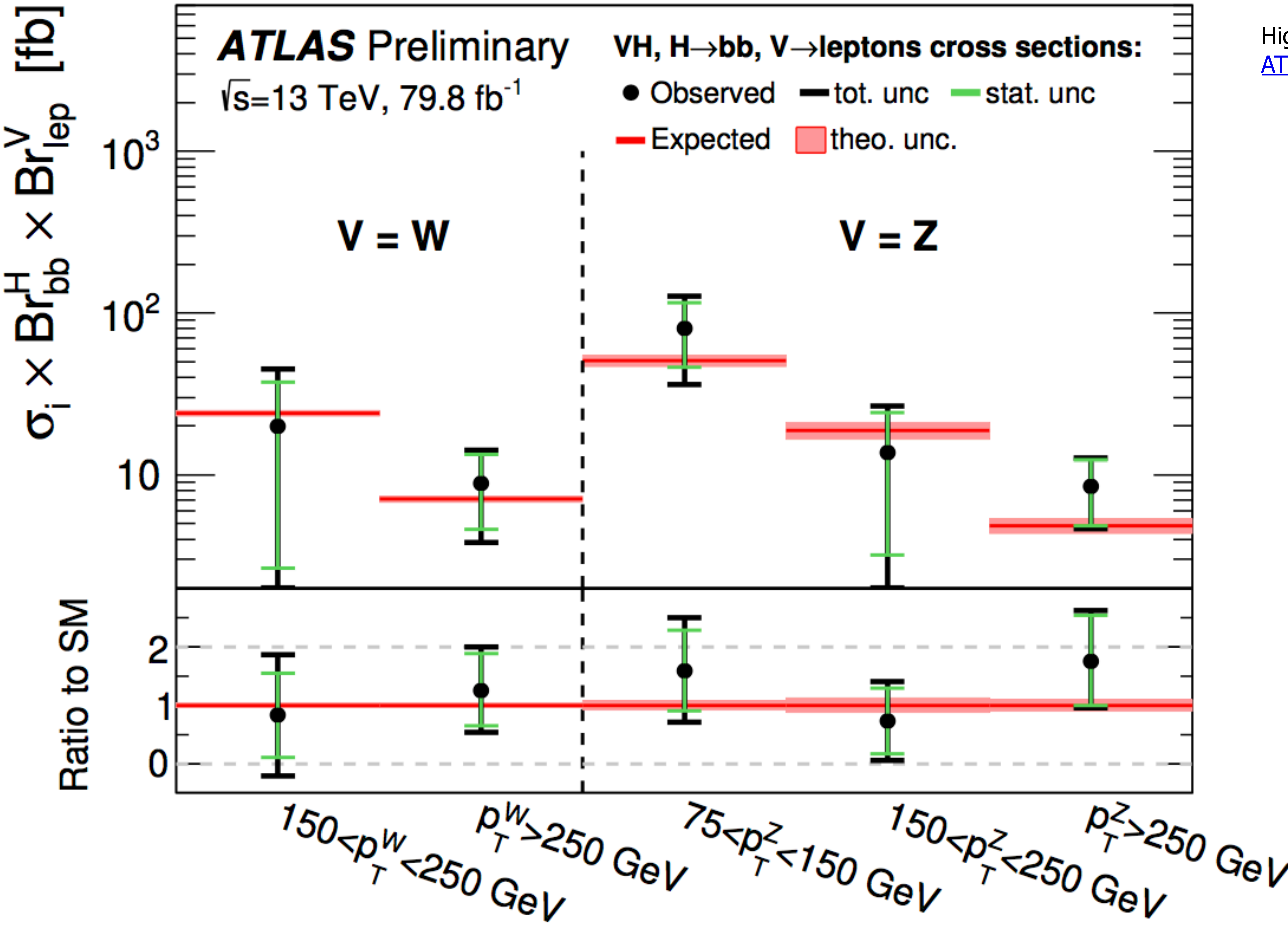


Full details on the implementation of this uncertainty scheme in Thomas' talk this afternoon!

Detailed in dedicated ATLAS PUB note
ATL-PHYS-PUB-2018-035

Simplified Template Cross Sections

ATLAS measurement in the 5 STXS bin split:



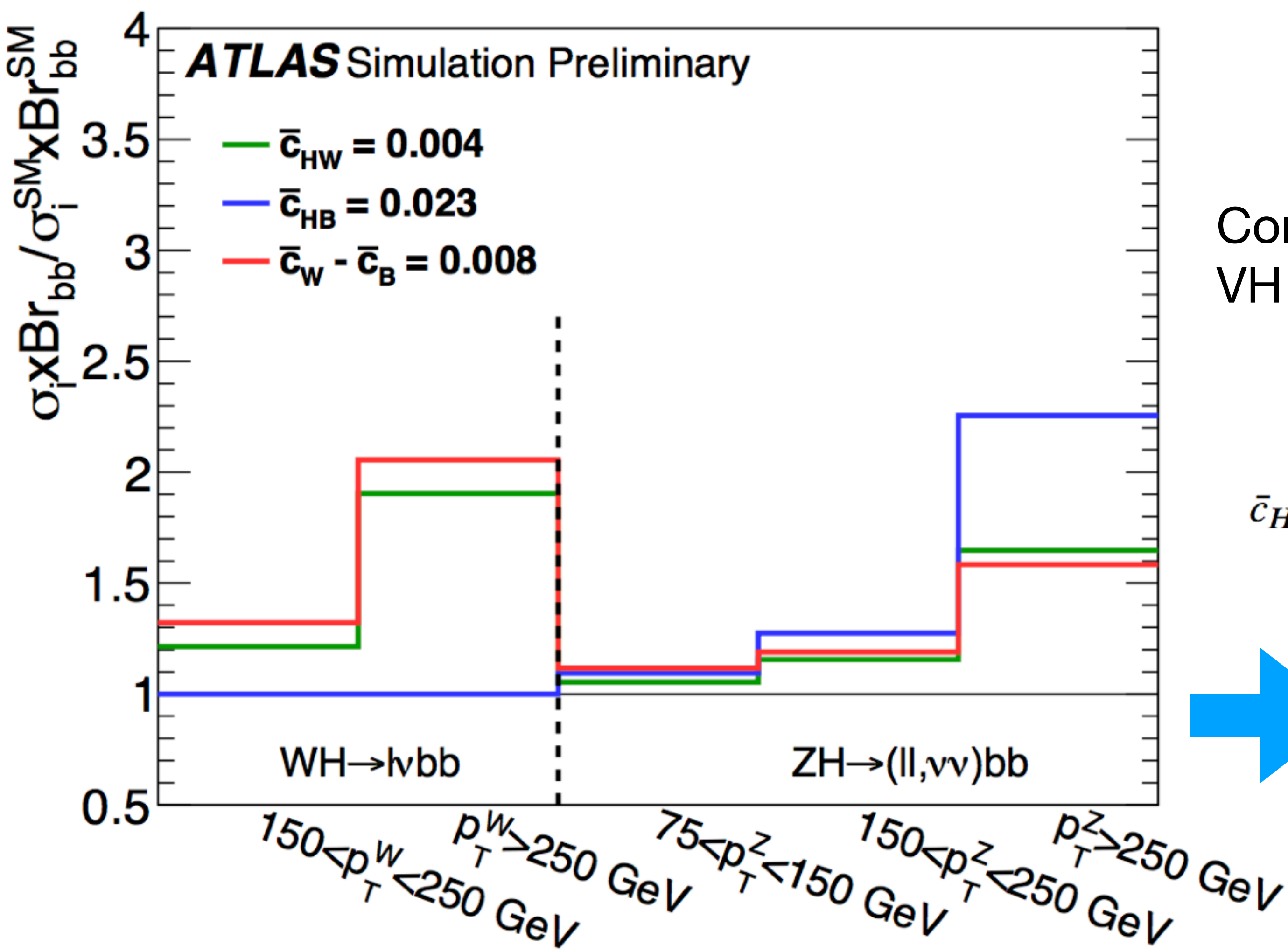
Higgs Couplings 2018:
ATLAS-CONF-2018-053

Some effort (also within HXSWG-VH) to define the VH STXS uncertainty scheme: planning to start from here to improve it with state-of-the-art TH tools / predictions, harmonization with CMS → **towards an HXSWG-VH Official Report public document**

EFT VH interpretation

Fitting the STXS pT(V) measurement we can constrain EFT Lagrangian coefficients, in the Strongly Interacting Light Higgs extension:

Higgs Couplings 2018: ATLAS-CONF-2018-053



$$\mathscr{L} = \mathscr{L}_{SM} + \sum c_i \mathscr{O}_{6i}/\Lambda_{NP}^2$$

Constrain on coefficients for operators modifying the VH interaction

$$\bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2},$$

Sensitivity coming from high-pT(V) regions (differential information quite powerful)

Table 7: The expected and observed 95% confidence level intervals for the effective Lagrangian coefficients $\bar{c}_{HW}$, $\bar{c}_{HB}$, $\bar{c}_W - \bar{c}_B$ when the other coefficients are assumed to vanish.

Parameter	Expected 95% CL intervals	Observed 95% CL intervals
$\bar{c}_{HW}$	[−0.018, 0.004]	[−0.019,−0.010] ∪ [−0.005, 0.006]
$\bar{c}_{HB}$	[−0.082, 0.023]	[−0.092,0.029]
$\bar{c}_W - \bar{c}_B$	[−0.034, 0.080]	[−0.036,−0.024] ∪ [−0.009, 0.010]

Conclusions and Outlook

- **VH experimental results**:
  main channel VH(bb) reached observation level from both ATLAS and CMS

  → first STXS measurement and EFT interpretations,
  more to come with the full Run-2 dataset

  → **feedback** from experimental collaborations crucial to provide **practical** guidelines to address the most sensitive issues

- HXSWG VH active on several sides to with the goal of supporting experimental analyses for VH

- useful interaction point between ATLAS and CMS for VH(bb): planning to strengthen this interaction (e.g. towards consistent STXS treatment)

Some VH references

HXSWG(1) VH sub-group

VH twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGVH (work in progress)

Mailing lists

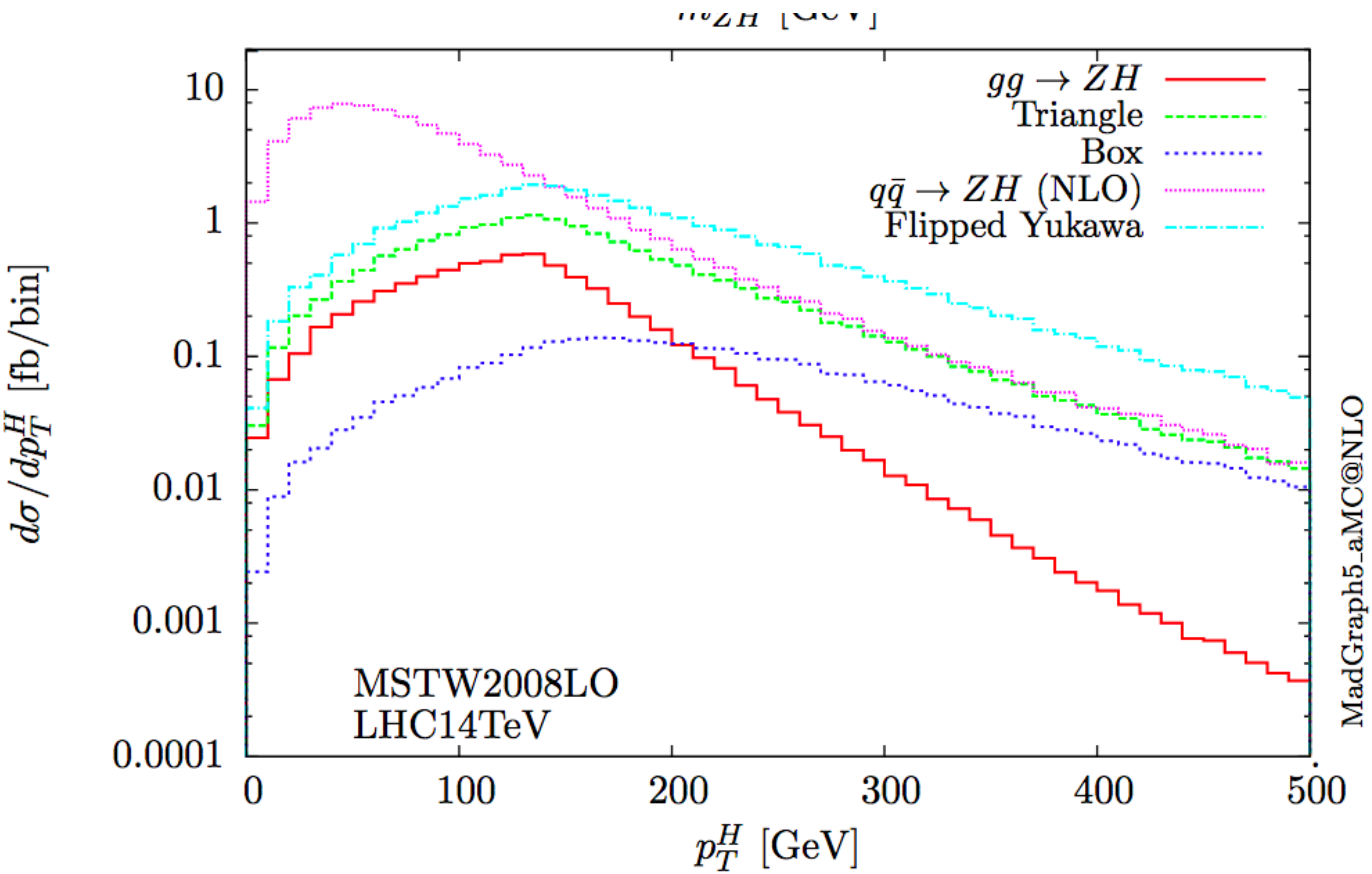
- lhc-higgs-xsbr@cern.ch
  [general WG1 thread - for discussions / meeting advertisement]
- lhc-higgs-vh-convener@cern.ch
  [conveners mailing list - for direct communication]

Indico page for VH WG1 meetings:
https://indico.cern.ch/category/5847/

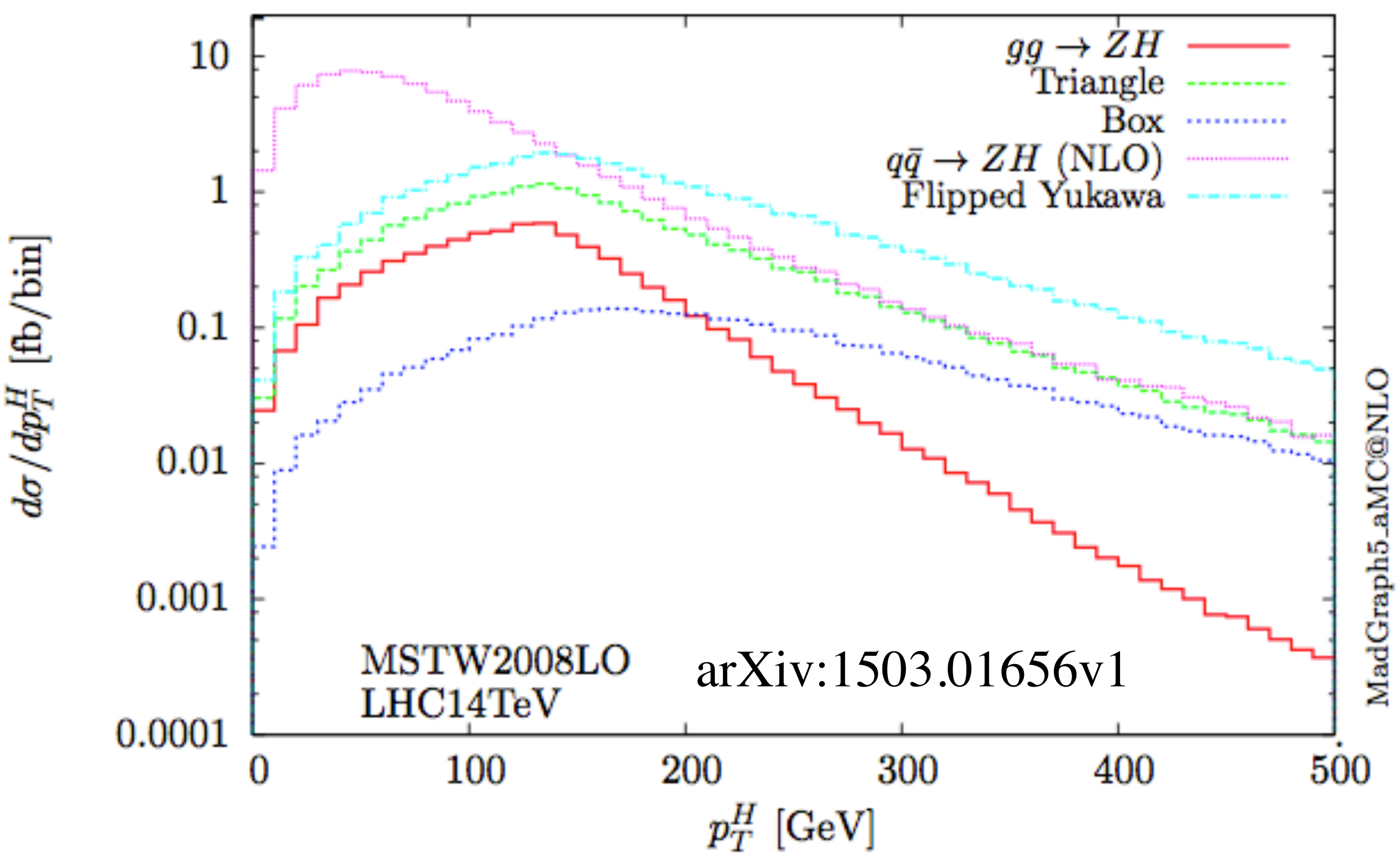
VH	VH XS prediction and uncertainties in STXS framework	Software tool providing central value and uncertainties + recommendations
VH	HL/HE-LHC 27TeV VH cross-section	VH cross-section and uncertainties calculation at 27TeV
VH	V+hf modeling for VH(bb)	[public note] MC comparison across several V+hf MC tools targeting VH(bb) phase space, guidelines for theory uncertainties on V+hf predictions
VH	ggZH merged predictions	[potentially public note] Comparison between showered ggZH 0+1jet merged LO MC prediction, and ggZH LO prediction

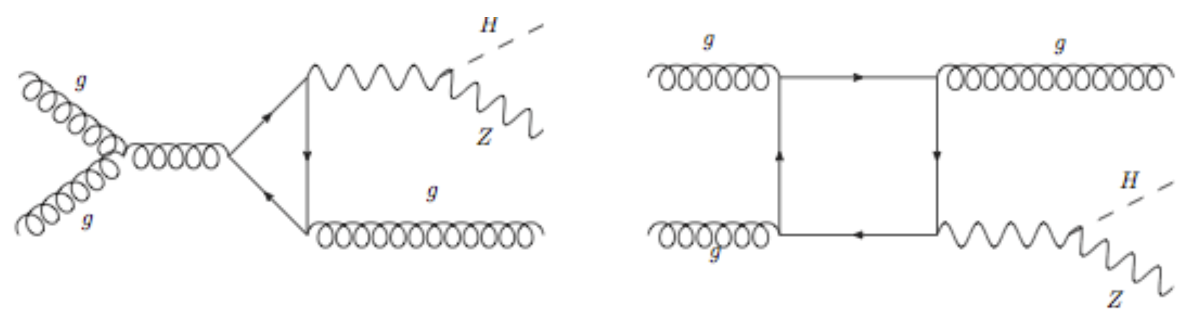
BACK-UP

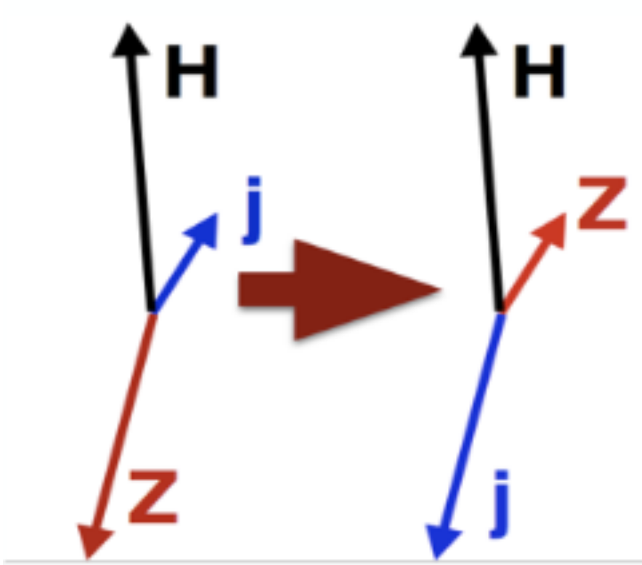
gg→ZH (loop-induced) MC modeling

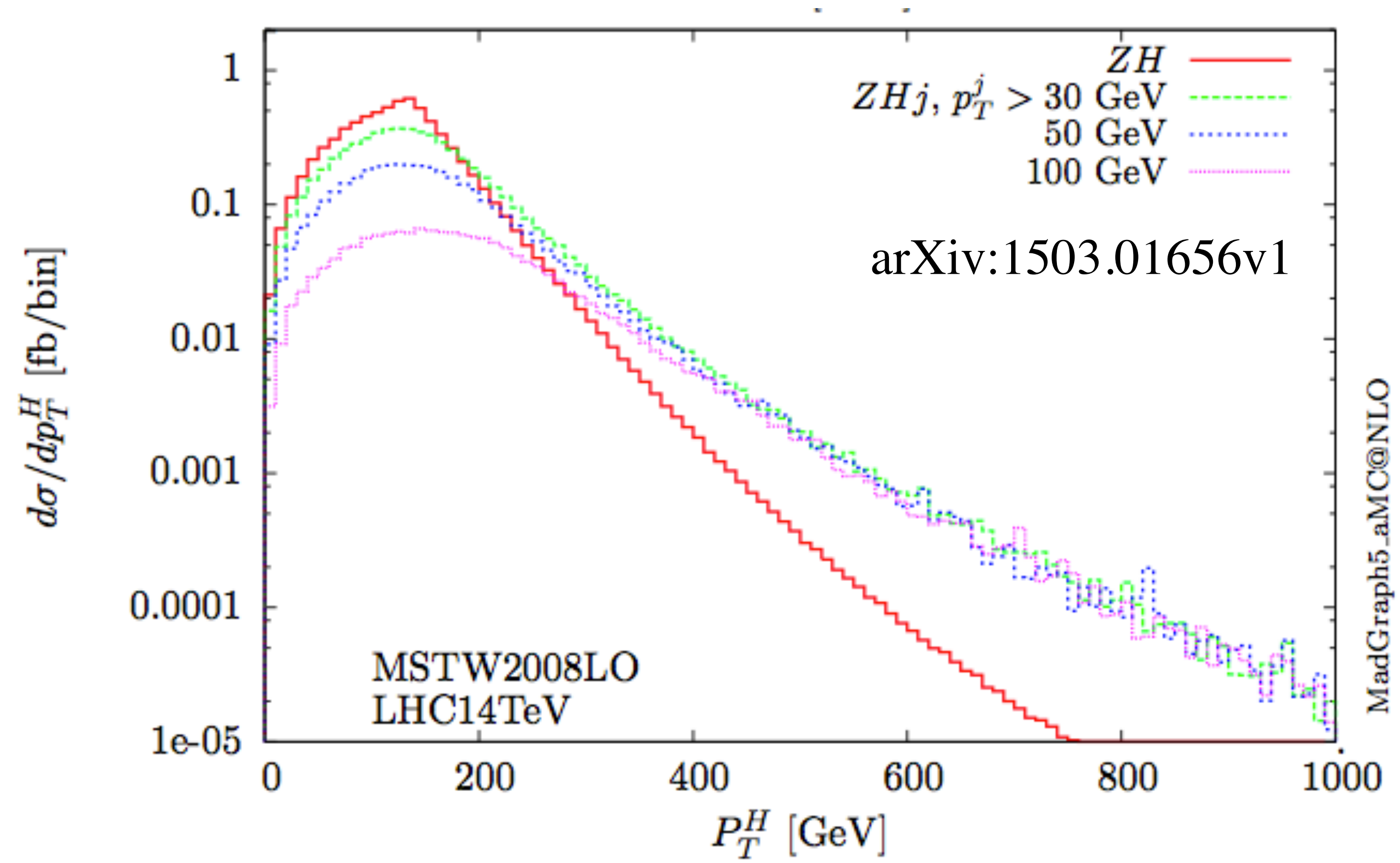


ggZH (loop-induced) diagrams









Towards ggZH@NLO

Double-Higgs (HH) production is now known (exactly) at NLO in QCD:
it may be a learning / starting point for ggZH NLO calculations

(Long term update!)

Numerical approach adopted for HH

1. generation of diagrams for amplitude
2. reduction of amplitude to a set of master integrals
3. computation of master integrals

Additional mass-scale makes this step much more complex

Non-finite double-box integrals may spoil convergence

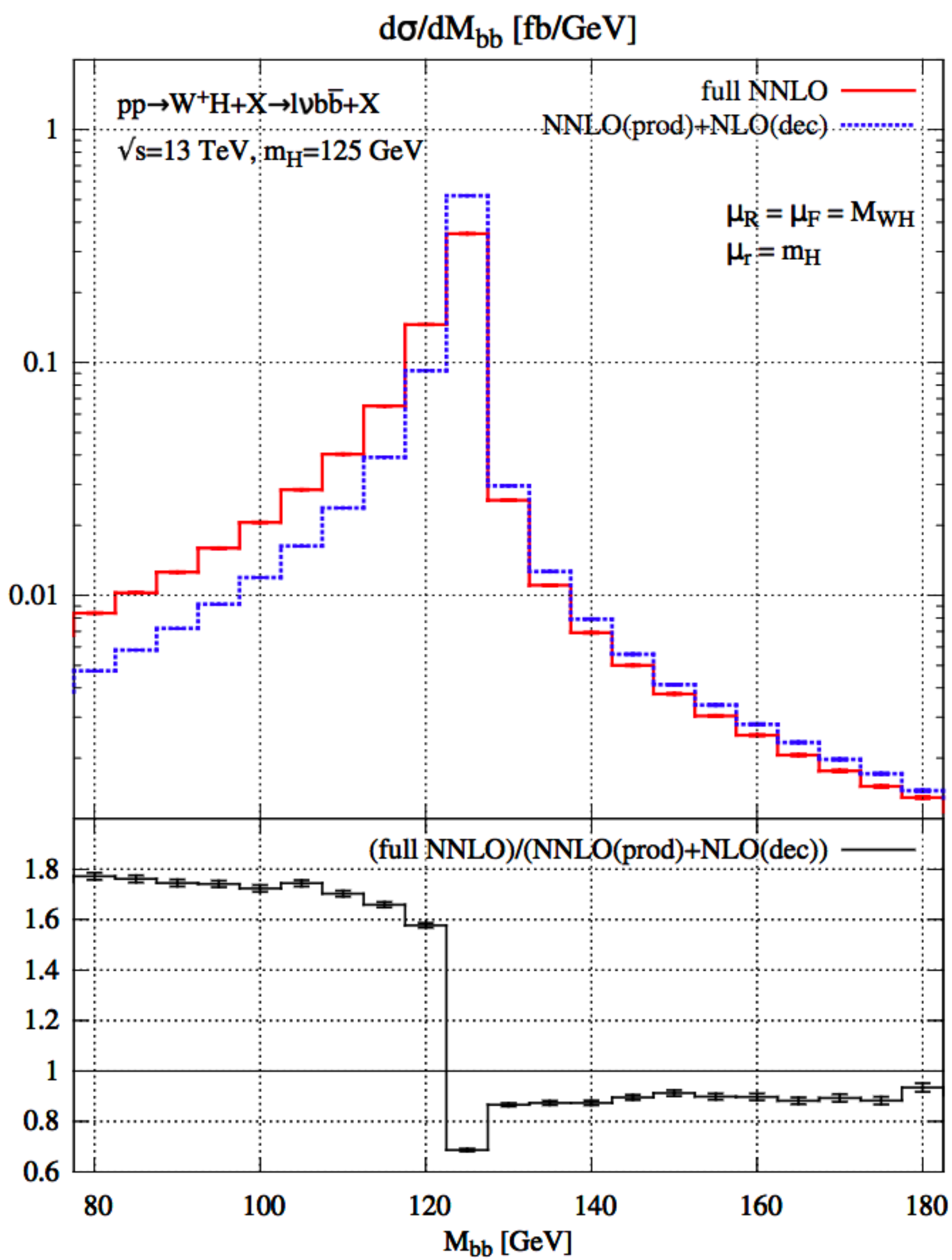
Cancellataions exploited in HH may not be valid for ggZH

Interesting note: since the number of scales is the main limiting factors, “numerics” might help in reducing the complexity — expressing different masses (mZ, mH, mtop) as function of a single one, by using the numeric ratio among them [already exploited for single-top NNLO calculations]

$$m_z : m_H : m_t \approx 8 : 11 : 15$$

Double Higgs may lead the way - but lots of work needed for ggZH!

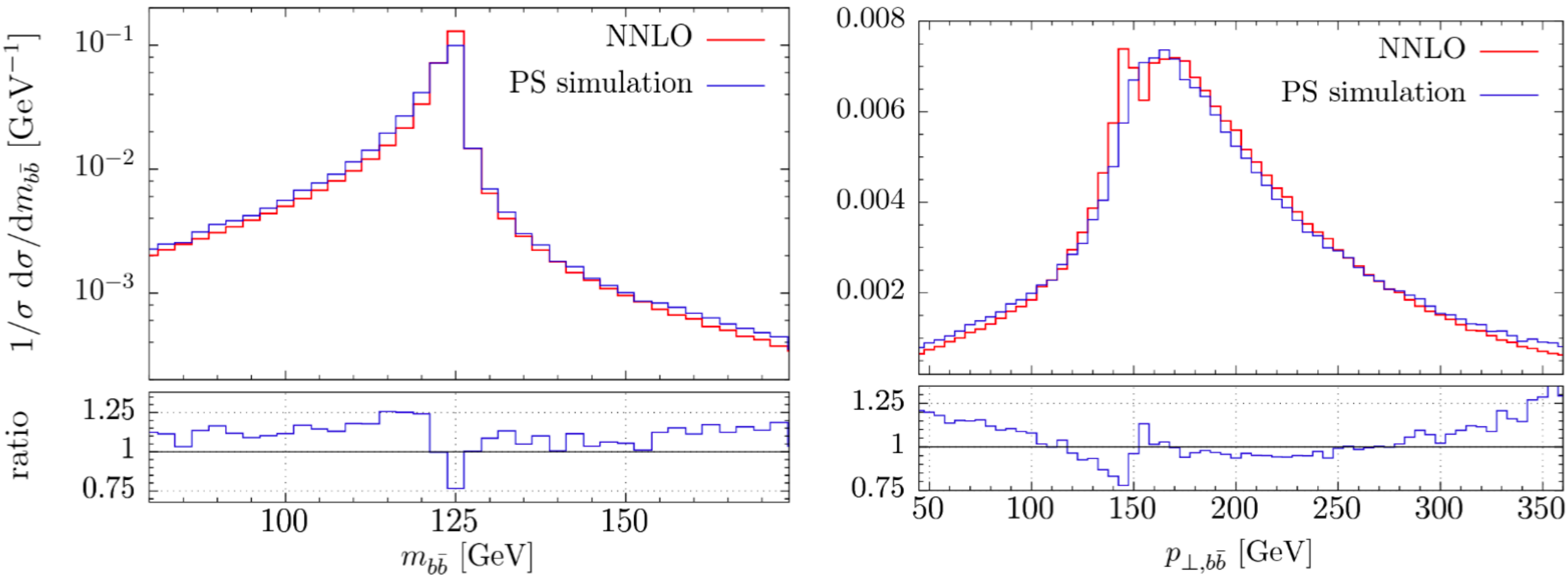
QCD → H(bb) @ NNLO decay



- small impact on total XS (~7%)
- impact is strongly phase space dependent
- up to 80% for m(bb)<120GeV (NNLO extra FSR)

New investigation of interference effects between ME and decay, and **comparison to parton-showered MC prediction**

QCD → H(bb) @ NNLO decay



New <u>investigation</u> of interference effects between ME and decay, and **comparison to parton-showered MC prediction** (PowhegMiNLO+Pythia8 as we are using)

PS provides a good description of the NNLO shape, with more events in the more events in the m(bb) and pT(bb) tails

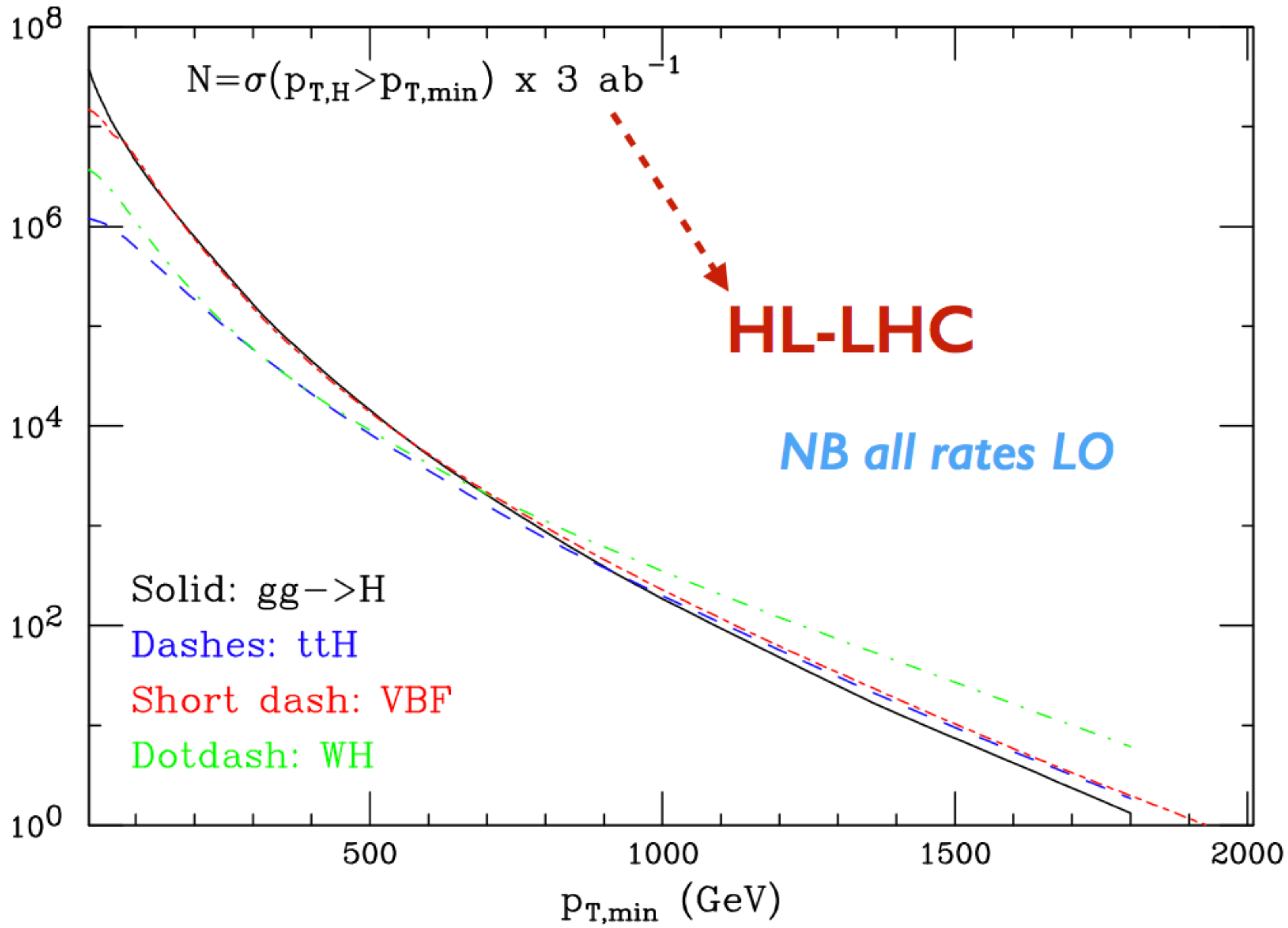
(Ongoing work to re-compute with massive b-quarks)

VH @ high-pT

H(bb) boosted results by CMS sparked interest on high-pT Higgs searches/measurements

p_T^{cut}	$\Sigma_{\mathrm{ggF}}(p_T^{\mathrm{cut}}) \times \mathrm{BR}$ [fb]	$\Sigma_{\mathrm{VBF}}(p_T^{\mathrm{cut}}) \times \mathrm{BR}$ [fb]	$\Sigma_{\mathrm{ggF+VBF}}(p_T^{\mathrm{cut}}) \times \mathrm{BR}$ [fb]
450 GeV	$11.1^{+4\%}_{-8.9\%}$	$4.71^{+1\%}_{-1\%}$	$15.3^{+2.8\%}_{-6.3\%}$

What is the impact of VH?



Important to keep high-pT modeling under control: EW@NLO, ggZH contribution

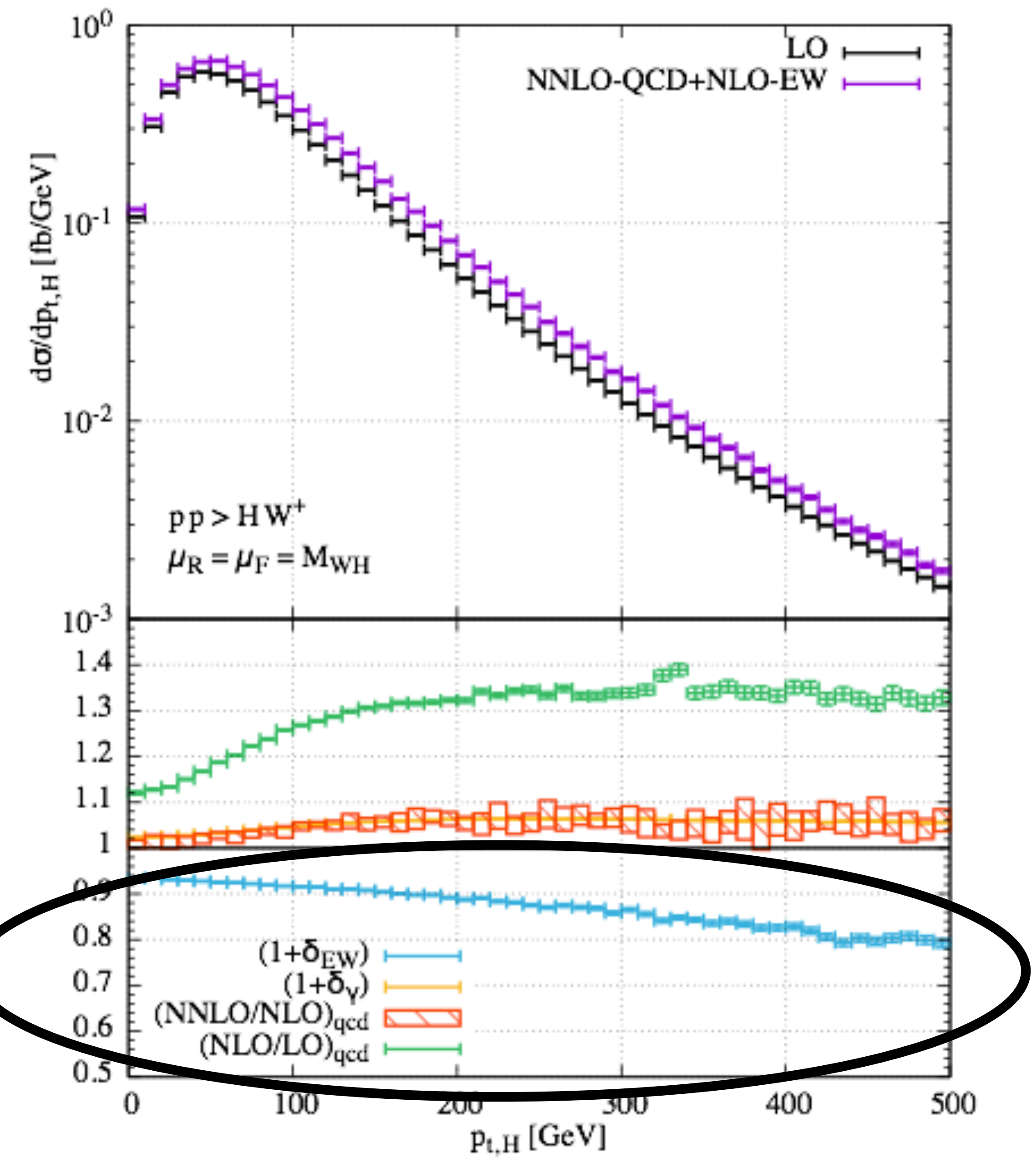
Extra slide: VH @ NLO (EW)

EW Corrections from YR4:

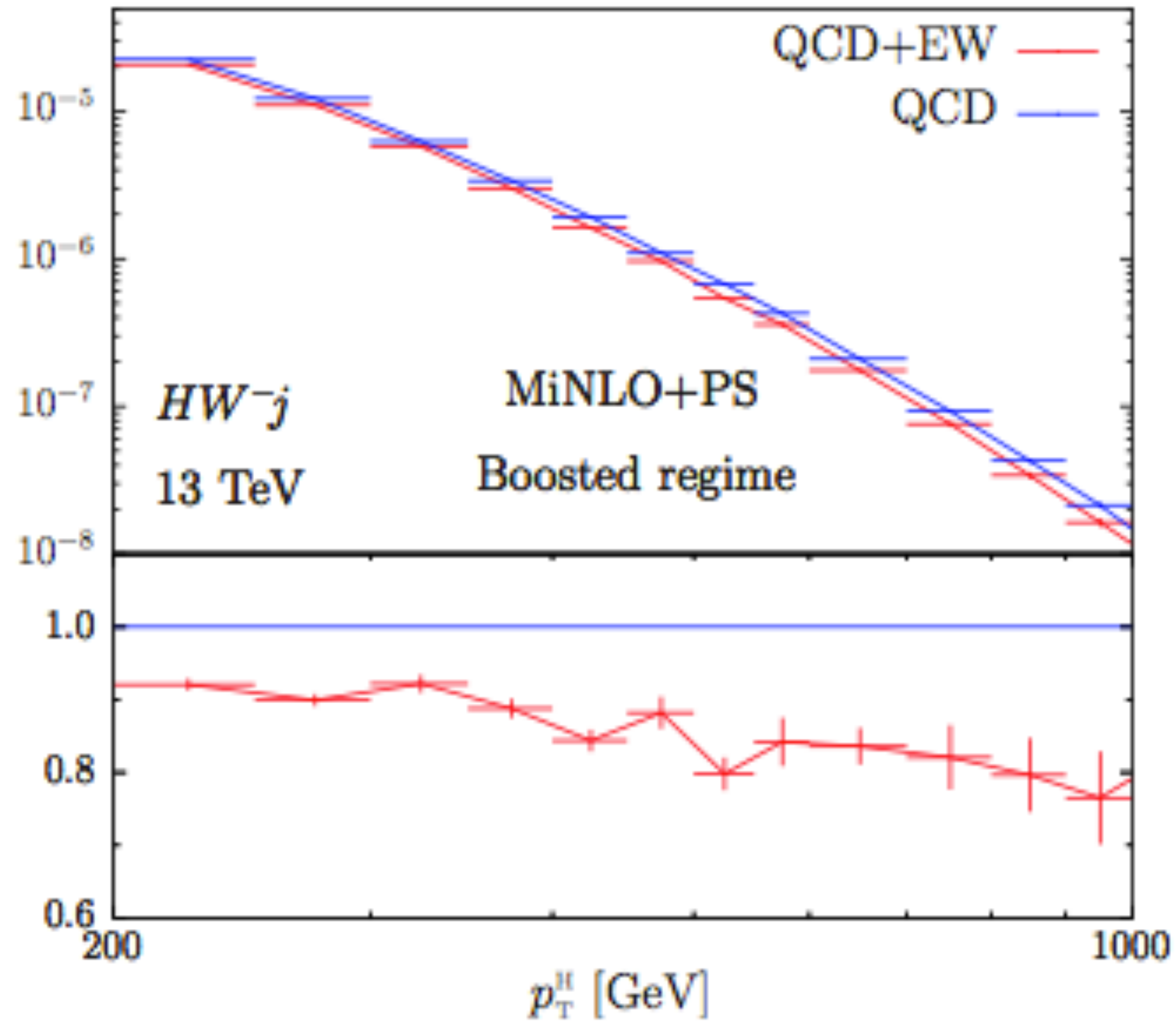
- NLO EW differential reweighting (applied as f(p_T^V)) from HAWK

Only available for V(leptons)H processes

Last updates at WG1:VH



Now available directly from POWHEGBOX-RES code, for HV and HVJ processes! (arXiv:1706.03522)



MiNLO achieves NLO accuracy for quantities inclusive (wrt the additional jet) e.g. pT(WH)

HVJ can be NLO accurate (for inclusive quantites) in QCD **and** EW

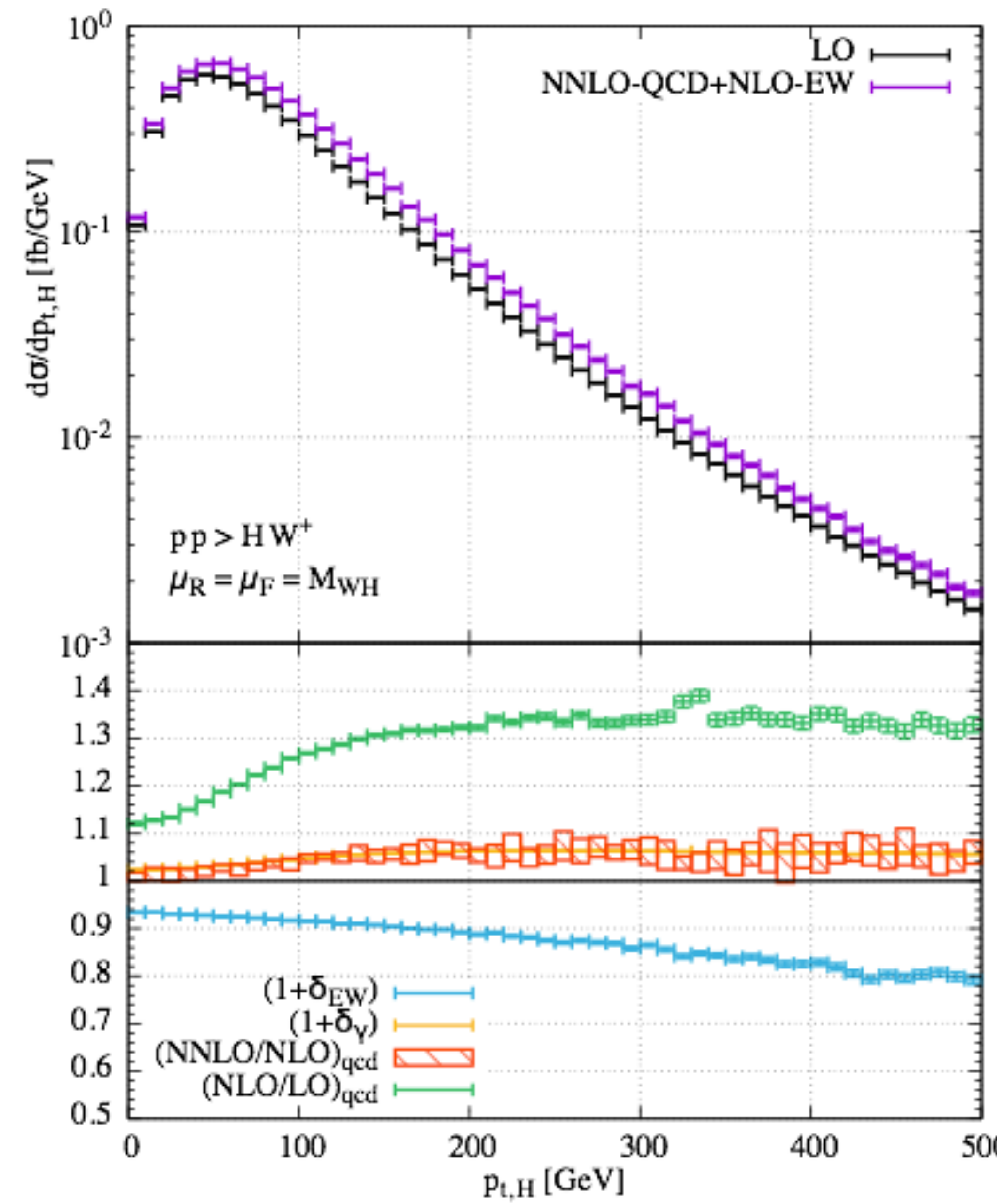
EW → NLO corrections

EW Corrections from YR4:

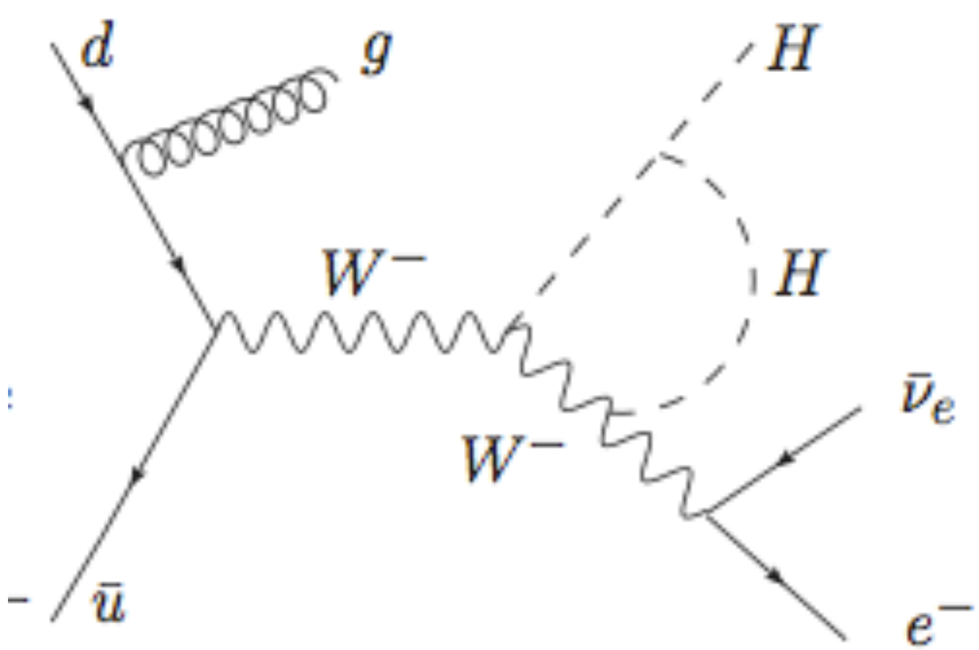
- NLO EW differential reweighting (applied as $f(p_T^V)$) from HAWK

Only available for V(leptons)H processes

Last updates at WG1:VH



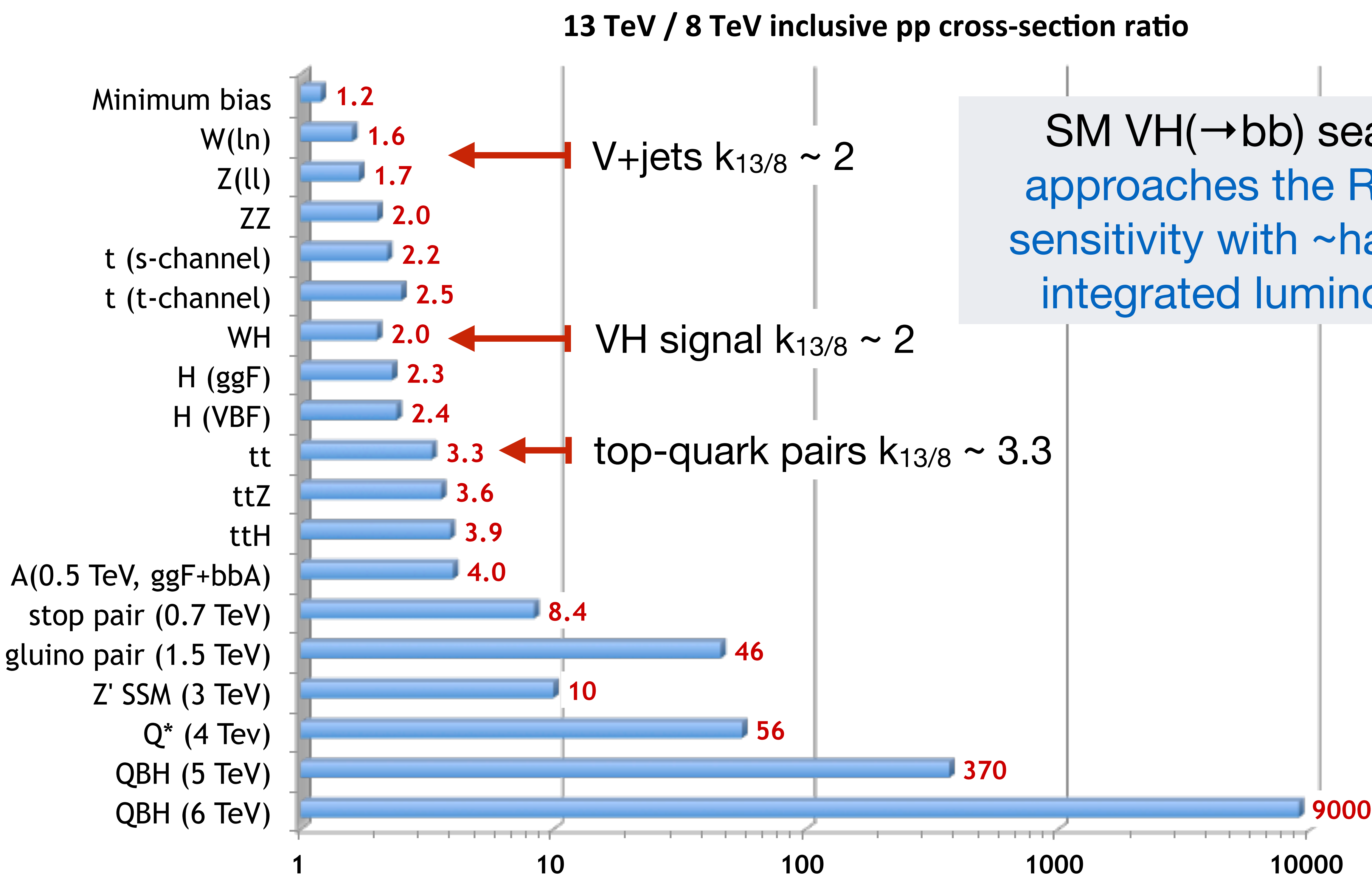
Now available directly from POWHEGBOX-RES code, for HV and HVJ processes! (arXiv:1706.03522)



Interesting note: full NLO EW included in POWHEGBOX corrections includes dependence on H trilinear couplings!

VH(bb) searches @ 13TeV

First search for the SM VH(bb) search with 13 TeV data from the LHC Run-2



SM VH(→bb) search approaches the Run-1 sensitivity with ~half the integrated luminosity

VH Signal Model

Uncertainties on the total XS from HXSWG numbers (previous slide)

Acceptance uncertainties (not coming from HXSWG prescriptions):

CMS

- **QCD factorization / renormalization** scale variations by 0.5 and 2.0 independently
- **PDF uncertainties from** NNPDF replicas

→ uncertainties on the total rate of the signal, **and** on the shape of the BDT discriminating function

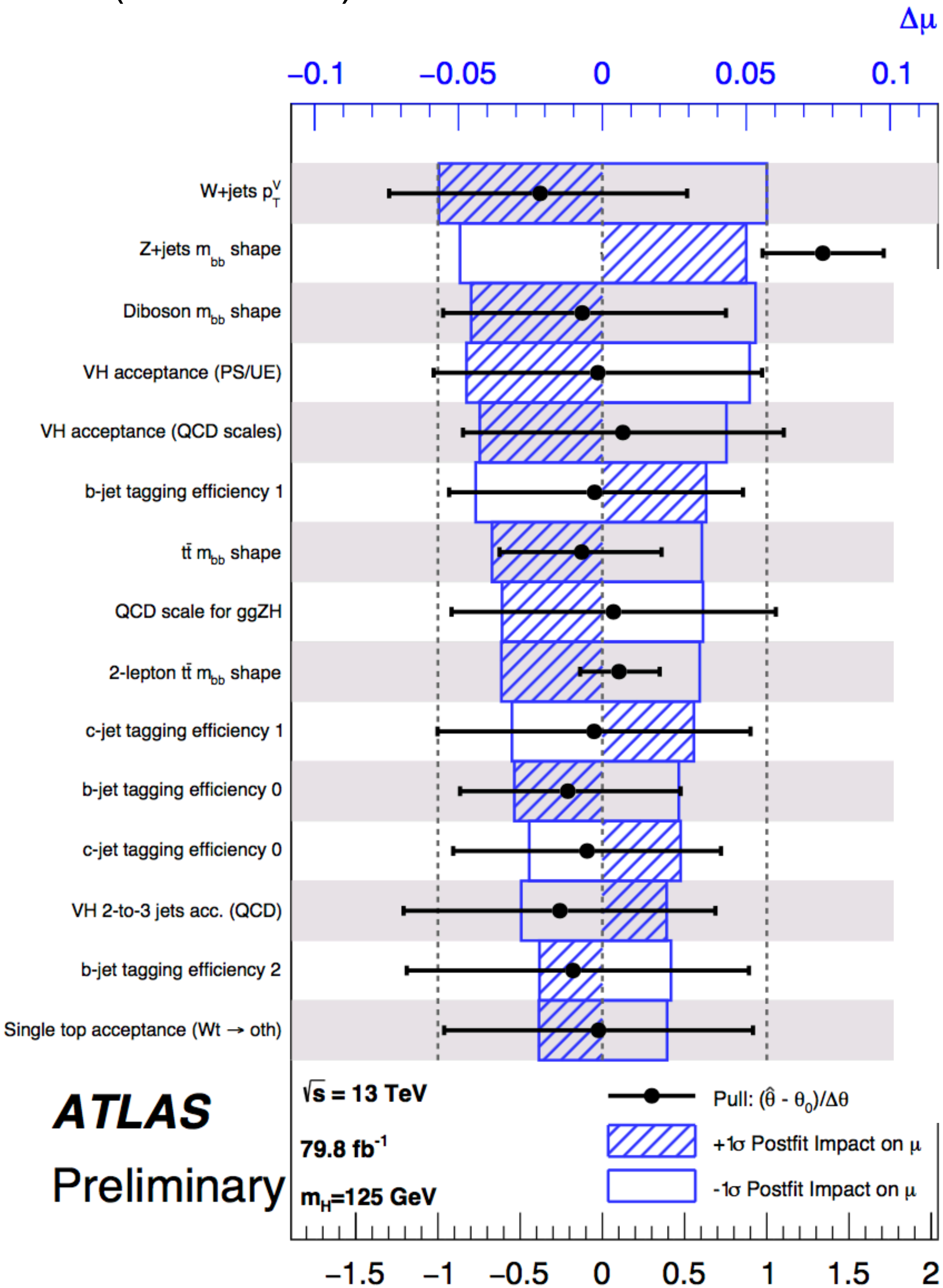
ATLAS

- **QCD factorization / renormalization** scale variations by 0.5 and 2.0 independently [avoiding (0.5,2.0) and (2.0,0.5) applied according to Stewart-Tackmann method for exclusive jet-bins
- **PDF uncertainties from:** PDF4LHC15_30 PDFs set at 68% CL interval
- **UE/PS/MPI uncertainties from:** AZNLO eigentune variations

  Powheg+Pythia8 / Powheg+Herwig comparison

→ uncertainties on the signal acceptance **and** on the shape of pTV and m(bb)

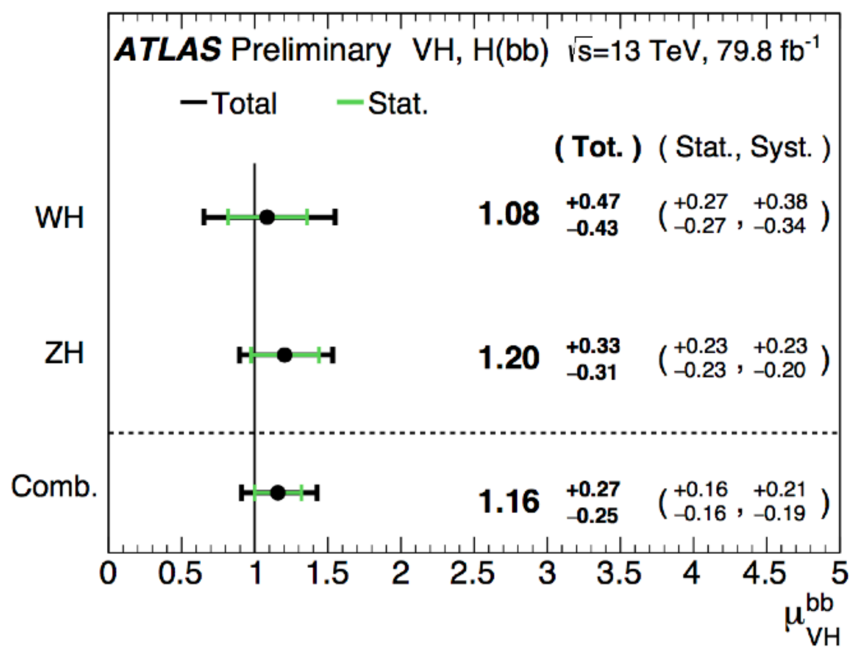
(13TeV data)

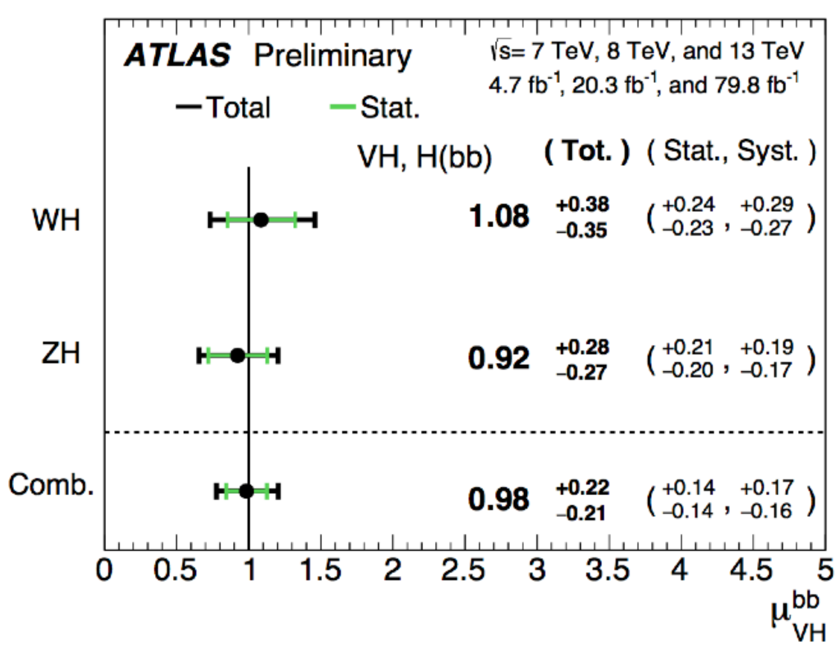


(2017 data)

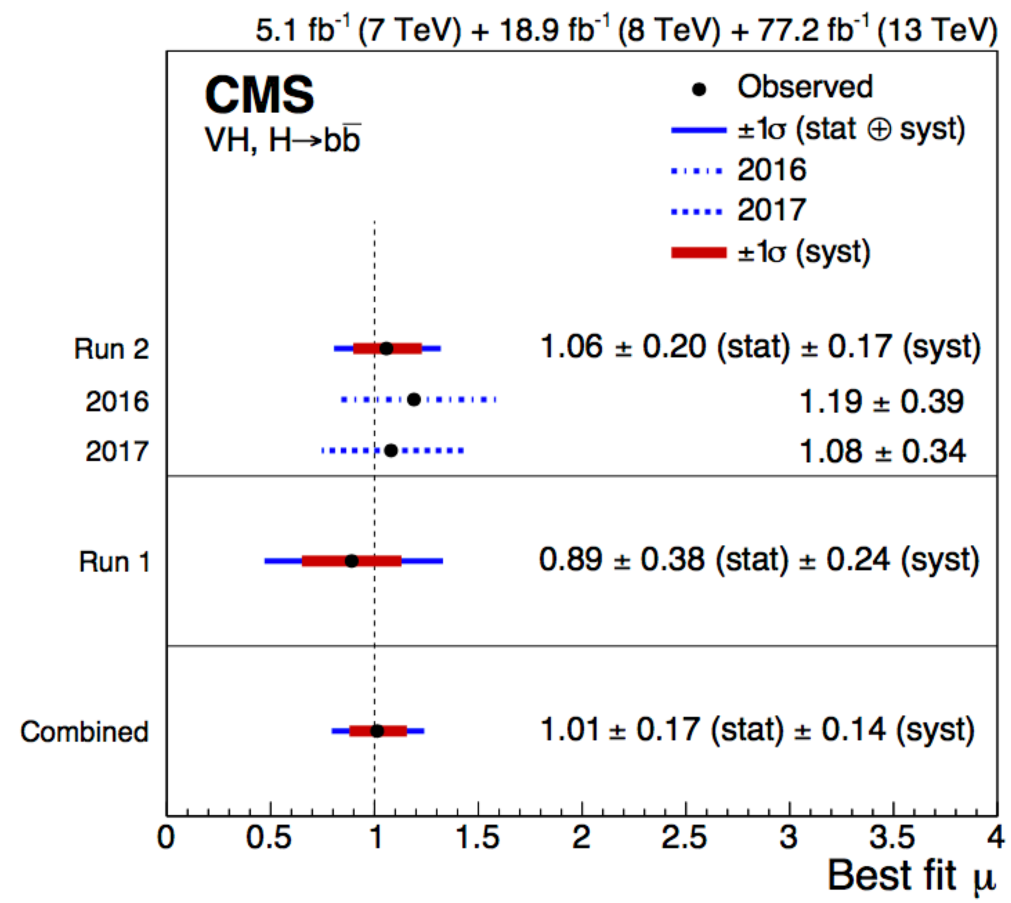
Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33

Signal strength parameter	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH, H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9





Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.22

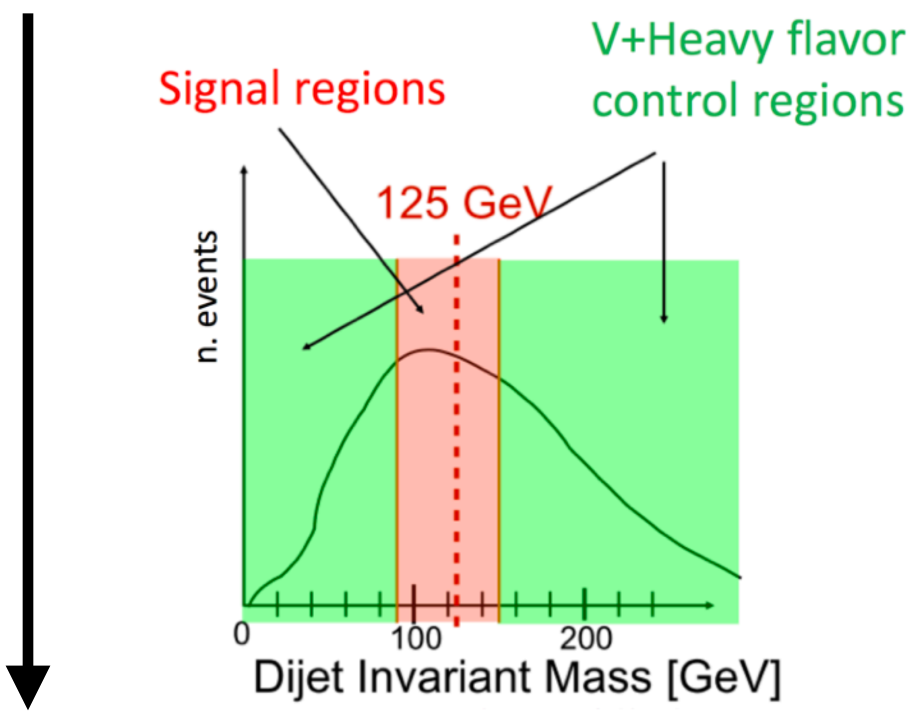


V+jets background modeling strategies

CMS (Madgraph V+0,1,2,3,4j@LO)

- **V+(heavy-flavor) modeling**
  CRs defined by inverting M(jj)-window

  (DCSV2 or DNN fit in CR)

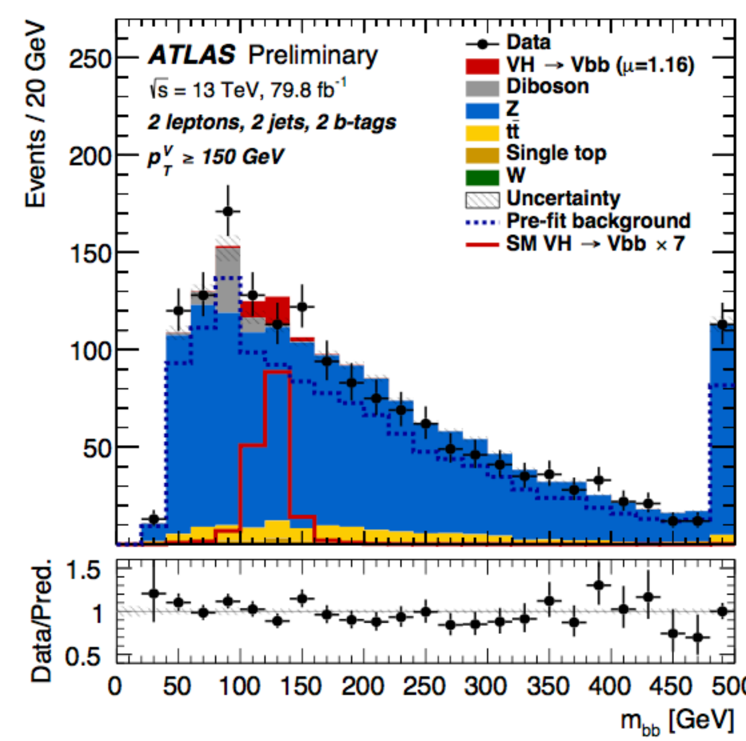


ATLAS (Sherpa V+0,1,2j@NLO + 3,4j@LO)

- **V+(heavy-flavor) modeling**
  W: dedicated CR (large m-top, low m-bb)
  - yield only, no shape
  Z: no *dedicated* CR -
  full m-bb spectrum included in the SRs

V+hf = V+(bb, bc, bl, cc)

ATLAS



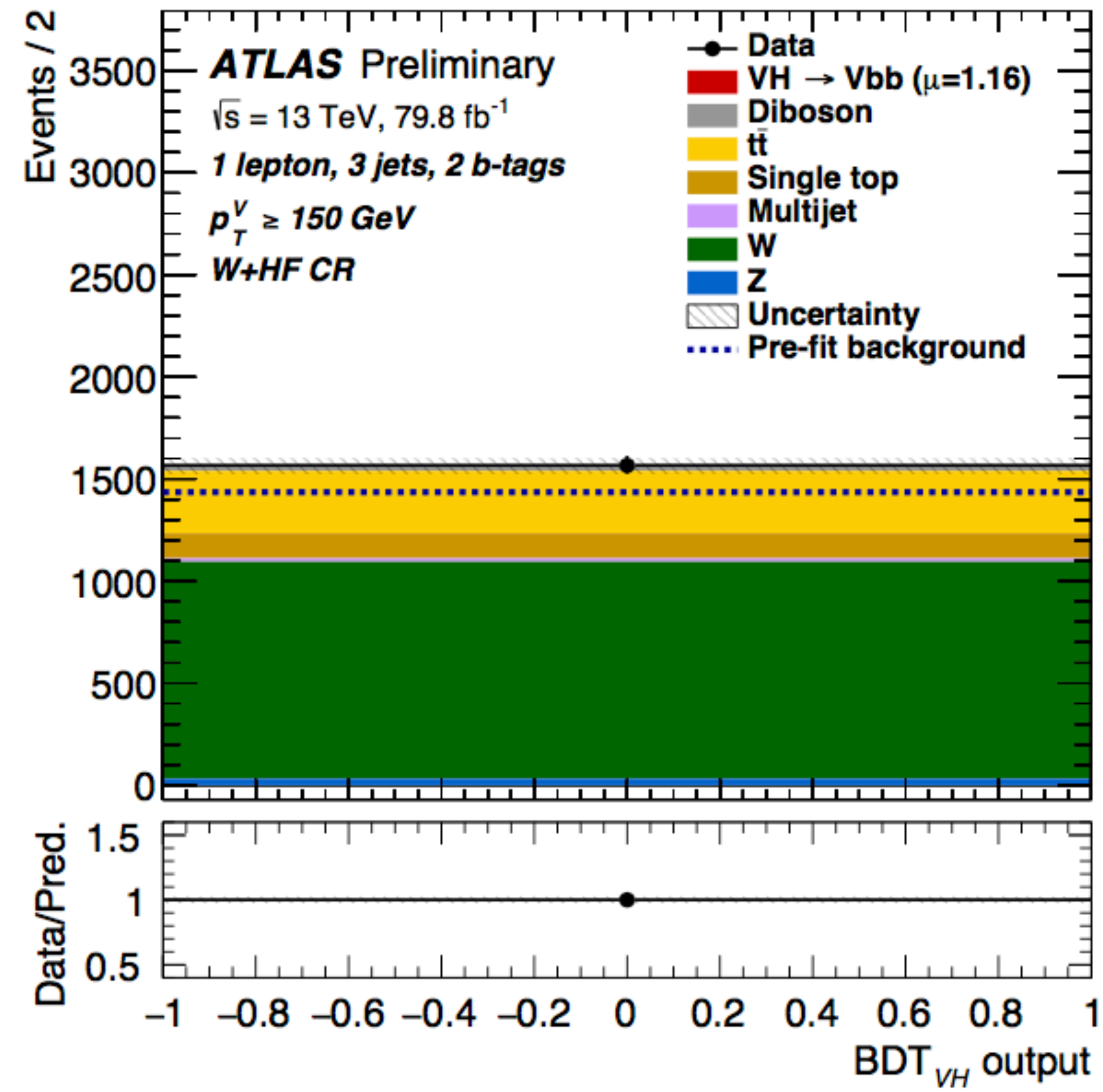
Background reweighting corrections for V+jets:

- $f(p_T^V)$ inclusive correction (up to 10% at 400GeV) accounting for EW corrections
- $f(p_T^V)$ dedicated 1-lepton correction on W+light, W+b(b), ttbar, single-t
- deltaEta(jj) correction from LO/NLO comparison (depending on #b-labeled jets)

W+heavy flavors - dominated by 1-lepton channel

ATLAS

- **standard 1-lepton selection + m(bb) < 75GeV m(top) > 225GeV**
- extrapolation uncertainties from CR to SR obtained from
  - Sherpa 2.2.1 muR, muF, ckkw, qsf scale variations
  - Sherpa 2.2.1 comparison with Madgraph_aMC@NLO 2.2.2 (merging up to four extra parton CKKW-L @ LO, Qcut = 30GeV)



W + jets	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
W + HF normalisation	Floating (2-jet, 3-jet)
$W + bl$-to-$W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc$-to-$W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc$-to-$W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)
m_{bb}, p_T^V	S

Z+heavy flavors - dominated by (0)2-lepton channel

ATLAS

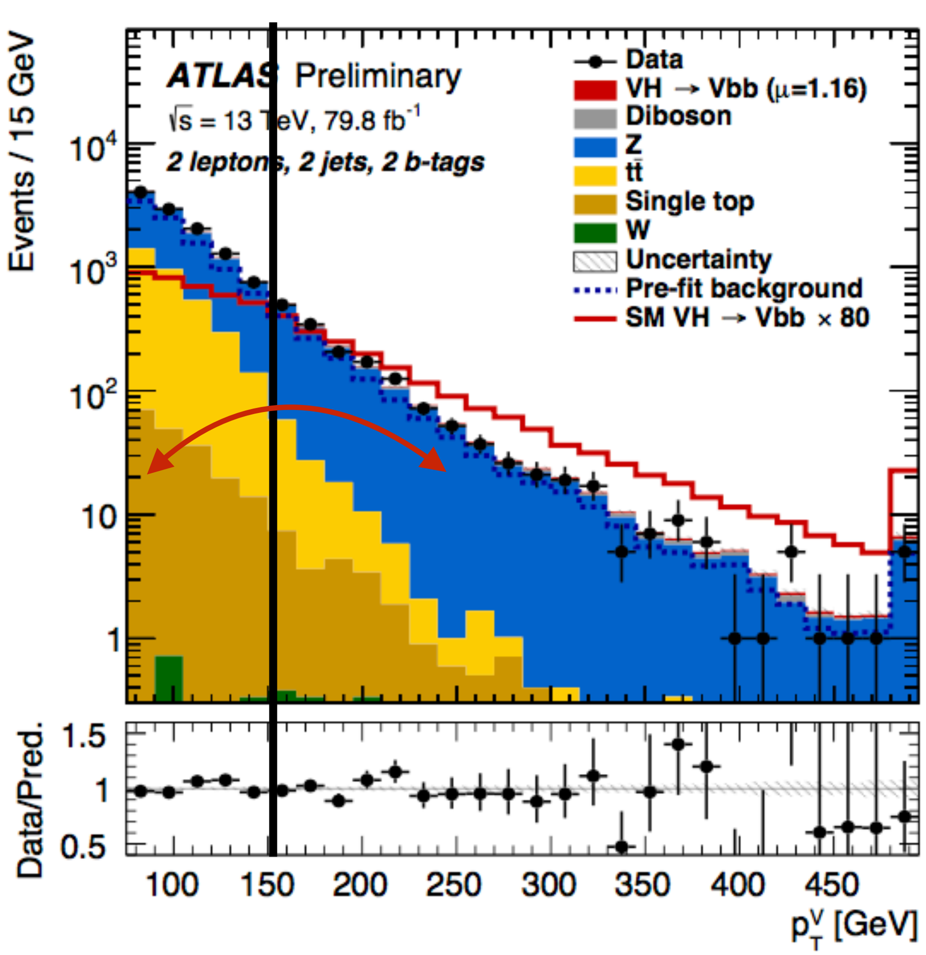
- **no dedicated control region for Z+hf**
- no m(bb) window selection applied in the nominal analysis selection

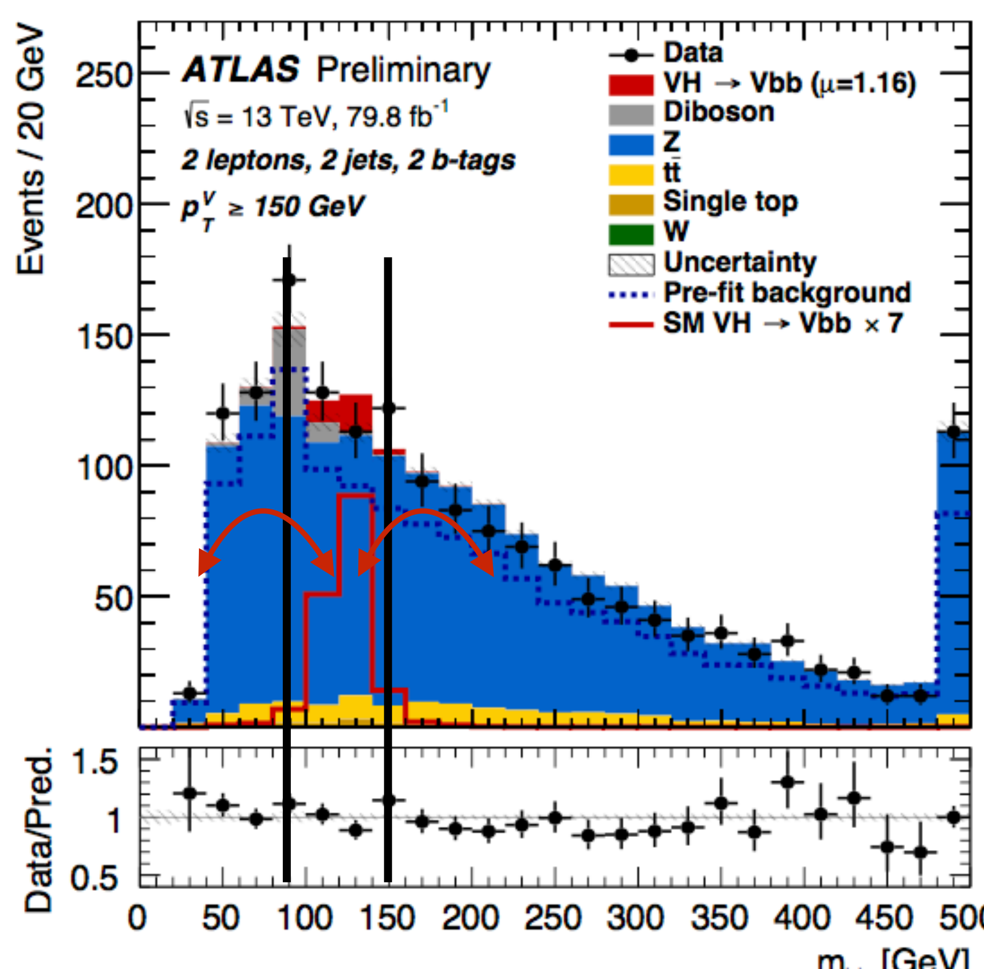
	Z + jets
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
Z + HF normalisation	Floating (2-jet, 3-jet)
$Z + bc$-to-$Z + bb$ ratio	30 – 40%
$Z + cc$-to-$Z + bb$ ratio	13 – 15%
$Z + bl$-to-$Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S

- **m(bb) and pTV** shape systematic derived from data/MC in Z+hf enriched-region
  (2-lepton) x (1-btag)
  (2-lepton) x (2-btag) x (remove events with m(jj) around mH)

(+ MET-significance cut
to suppress ttbar contamination)

control over (high/low-VpT) or (sidebands/central m(bb)) normalization



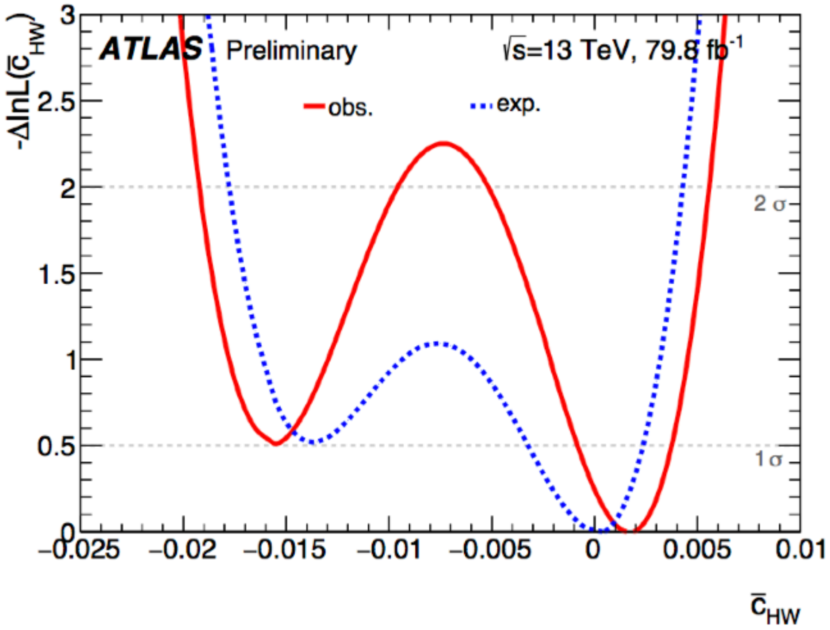


EFT VH fits

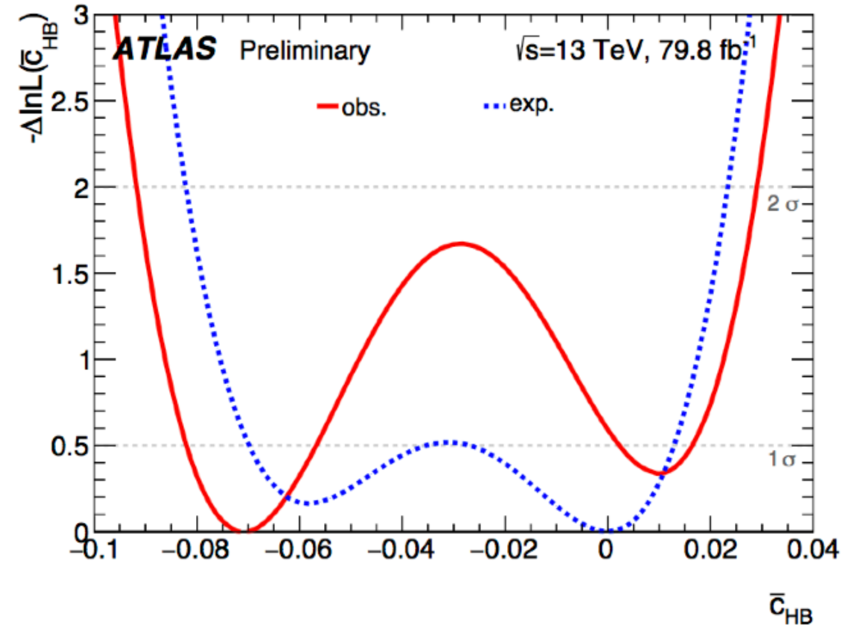
Operator	Expression	HEL coefficient	Vertices
$\mathcal{O}_g$	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\mathtt{cG} = \frac{m_W^2}{g_s^2} \bar{c}_g$	Hgg
$\mathcal{O}_\gamma$	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\mathtt{cA} = \frac{m_W^2}{g'^2} \bar{c}_\gamma$	$H\gamma\gamma, HZZ$
$\mathcal{O}_u$	$y_u \|H\|^2 \bar{u}_l H u_R + \text{h.c.}$	$\mathtt{cu} = v^2 \bar{c}_u$	$Ht\bar{t}$
$\mathcal{O}_{HW}$	$i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu}$	$\mathtt{cHW} = \frac{m_W^2}{g} \bar{c}_{HW}$	HWW, HZZ
$\mathcal{O}_{HB}$	$i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu}$	$\mathtt{cHB} = \frac{m_W^2}{g'} \bar{c}_{HB}$	HZZ
$\mathcal{O}_W$	$i\,\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$\mathtt{cWW} = \frac{m_W^2}{g} \bar{c}_W$	HWW, HZZ
$\mathcal{O}_B$	$i\,\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$	$\mathtt{cB} = \frac{m_W^2}{g'} \bar{c}_B$	HZZ

- $\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu}$,
- $\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu}$,
- $\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$, $\quad \bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2}$,
- $\mathcal{O}_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$,

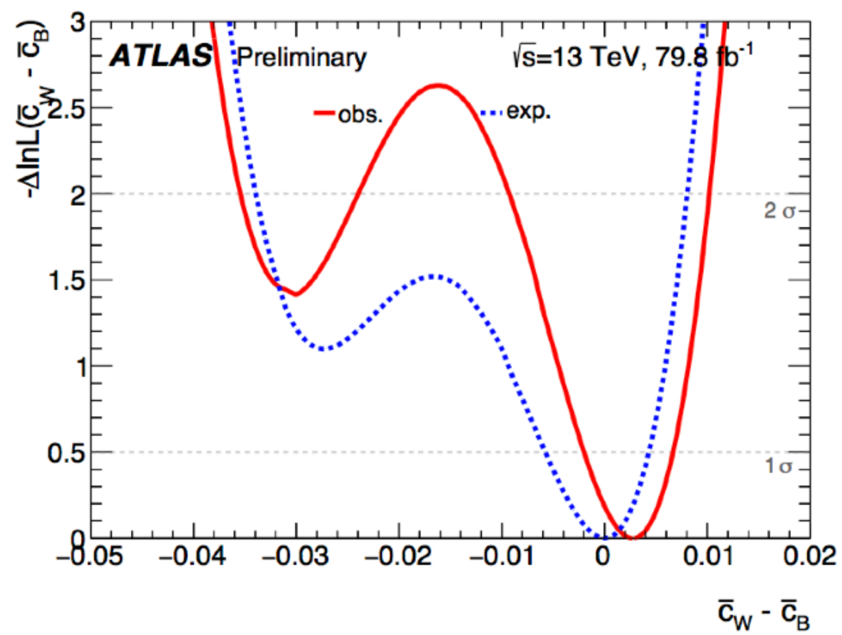
EFT VH fits



(a) $\bar{c}_{HW}$



(b) $\bar{c}_{HB}$



(c) $\bar{c}_W - \bar{c}_B$

Table 6: The expected and observed 68% confidence level intervals for the effective Lagrangian coefficients $\bar{c}_{HW}$, $\bar{c}_{HB}$, $\bar{c}_W - \bar{c}_B$ when the other coefficients are assumed to vanish.

Coefficient	Expected 68% CL intervals	Observed 68% CL intervals
$\bar{c}_{HW}$	[−0.0032, 0.0024]	[−0.0008, 0.0037]
$\bar{c}_{HB}$	[−0.069, −0.036]⋃[−0.026, 0.013]	[−0.082, −0.057] ⋃ [0.002, 0.017]
$\bar{c}_W - \bar{c}_B$	[−0.0060, 0.0045]	[−0.0020, 0.0065]

ZH XS update

post-YR4 update: separate uncertainties for qqZH and ggZH (many thanks to Robert!)

gg→ZH Cross Section

- ZH production has two distinct sources of gg→ZH:
  1. a genuine NNLO contribution to what called "Drell-Yan-like", where ZH is accompanied by two-parton radiation, gg→HZ+qqbar.
  2. top- and bottom-loop induced contribution without any additional partons in the final state.
- What is usually meant by gg→HZ below is 2) above.
- The statement that "all but gg→HZ" is the same as "qq- and qg-initiated" is correct only through NLO QCD.
- For separate cross sections and associated QCD scale uncertainties in qq/qg→ZH(+gg→HZ+qqbar) and gg→ZH for NLO/LO MC normalization, use
  - σ(all but gg→ZH) = σ(pp→ZH)@(NNLO QCD + NLO EW, NLO+NLL QCD gg→ZH) - σ(gg→ZH)@(NLO+NLL QCD),
  - Separate QCD scale uncertainties are σ(all but gg→ZH) or on σ(gg→ZH) are calculated with VH@NNLO program.
- For M_H=125.0 GeV and at $\sqrt{s}$=13 TeV,

Process	Cross Section (pb)	+QCD Scale %	-QCD Scale %	±(PDF+α_s) %	±PDF %	±α_s %
pp→ZH	0.8839	+3.8%	-3.1%	±1.6%	±1.3%	±0.9%
qq/qg→ZH, gg→HZ+qqbar (all but gg→ZH)	0.7612	+0.5%	-0.6%	±1.9%	±1.7%	±0.9%
gg→ZH	0.1227	+25.1%	-18.9%	±2.4%	±1.8%	±1.6%