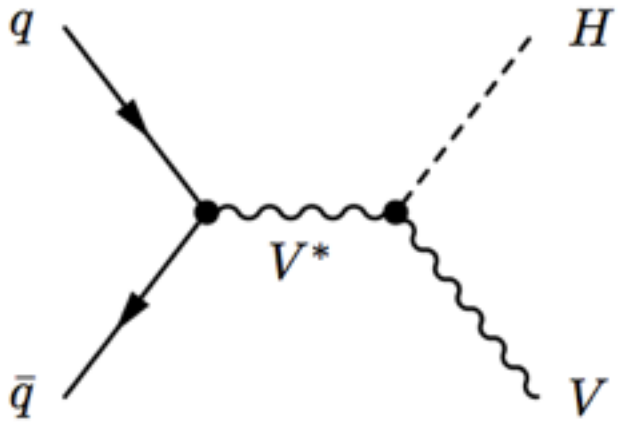
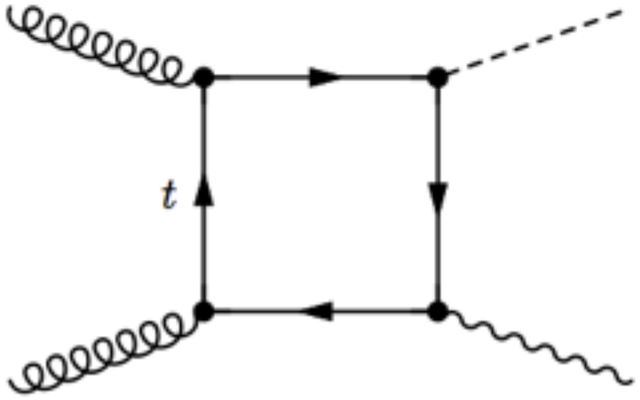
WG1:VH experimental view

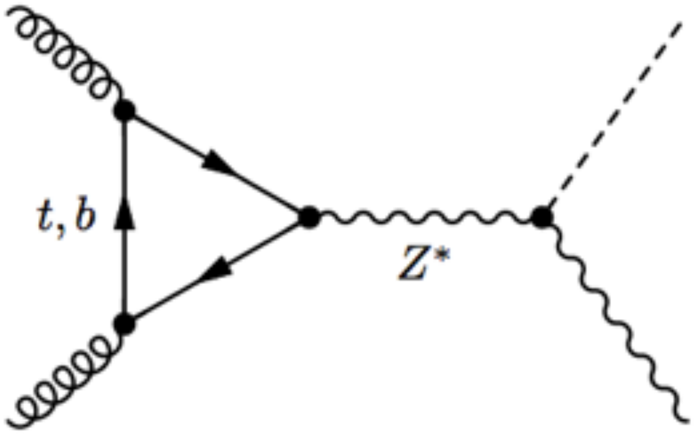
John Campbell, Francesco Tramontano, Luca Perrozzi, CP

13th Workshop of the LHC Higgs Cross Section Working Group

Cern, 13-14 July 2017







UNIVERSITÉ
DE GENÈVE

Organization of the VH subgroup

Re-organization post-YR4: VH and VBF WG1 subgroups are now splitted
(but still in strict collaboration on common issues and general topics…!)

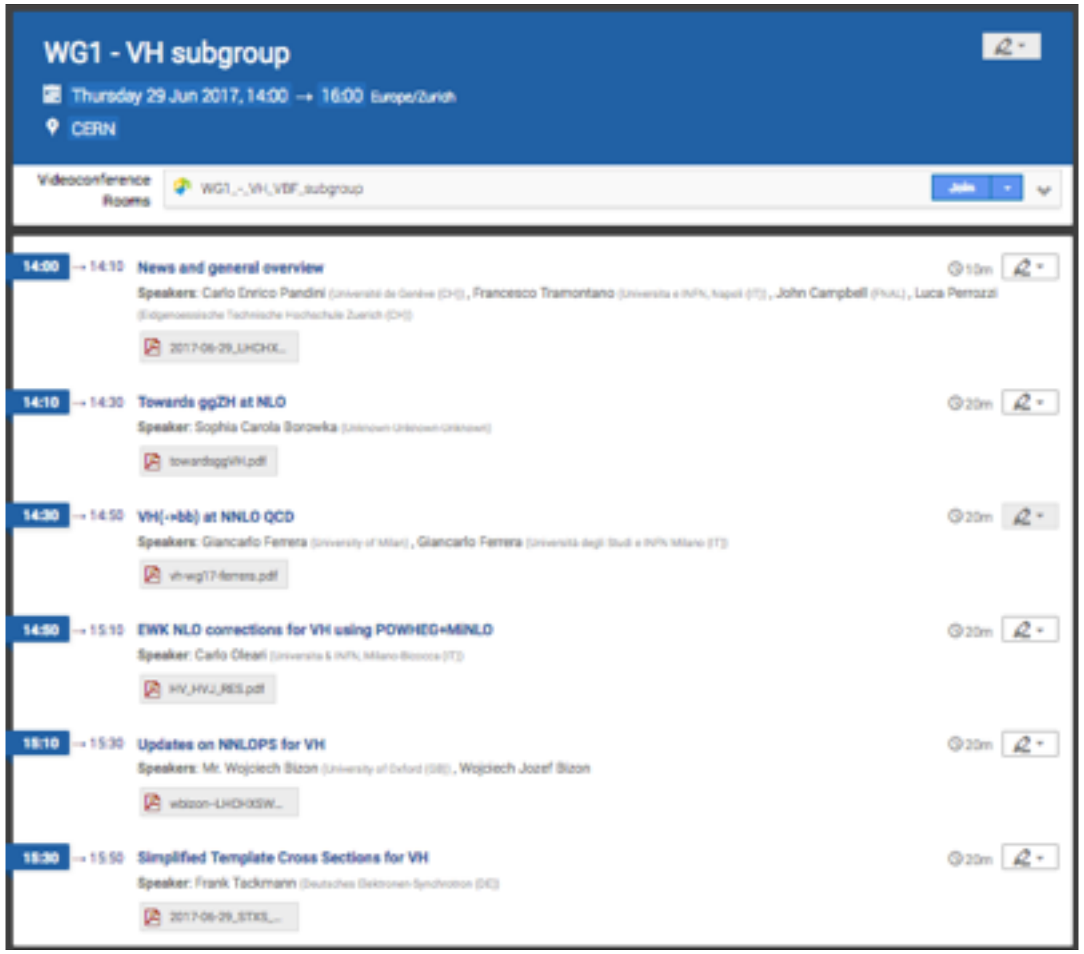
VH twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGVH (work in progress)

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/

First meeting on June 29, 2017:
several contributions and very fruitful discussions
(many of which covered in Francesco's talk)



WG1 - VH subgroup

Thursday 29 Jun 2017, 14:00 → 16:00 Europe/Zurich

CERN

Videoconference Rooms: WG1_-_VH_VBF_subgroup

14:00 → 14:10 News and general overview (10m)
Speakers: Carlo Enrico Pandini, Francesco Tramontano, John Campbell, Luca Perrozzi
2017-06-29_LHCHX...

14:10 → 14:30 Towards ggZH at NLO (20m)
Speaker: Sophia Carola Borowka
towardsggVH.pdf

14:30 → 14:50 VH(→bb) at NNLO QCD (20m)
Speakers: Giancarlo Ferrera, Giancarlo Ferrera
vh-wg17-ferrera.pdf

14:50 → 15:10 EWK NLO corrections for VH using POWHEG+MiNLO (20m)
Speaker: Carlo Oleari
HV_HVJ_RES.pdf

15:10 → 15:30 Updates on NNLOPS for VH (20m)
Speakers: Mr. Wojciech Bizon, Wojciech Jozef Bizon
wbizon-LHCHXSW...

15:30 → 15:50 Simplified Template Cross Sections for VH (20m)
Speaker: Frank Tackmann
2017-06-29_STXS_...

Outline and Introduction

Swift start of activities in the VH WG1 subgroup

first topics considered to design a roadmap for the future (short / medium / long term):

- precise modeling of VH processes @NNLO[QCD] and @NLO[EW]
- treatment of loop-induced gg→ZH
- latest experimental VH results
  - → state of VH predictions / tools used by experimental collaborations
  - → main theory limitations & “whishlist”, possible improvements
- Simplified Template Cross Section STXS approach
- open point: treatment of main SM backgrounds for VH measurements

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

Francesco’s talk: overview from the theory side - several contributions from the first VH subgroup meeting

VH signal model in ATLAS & CMS

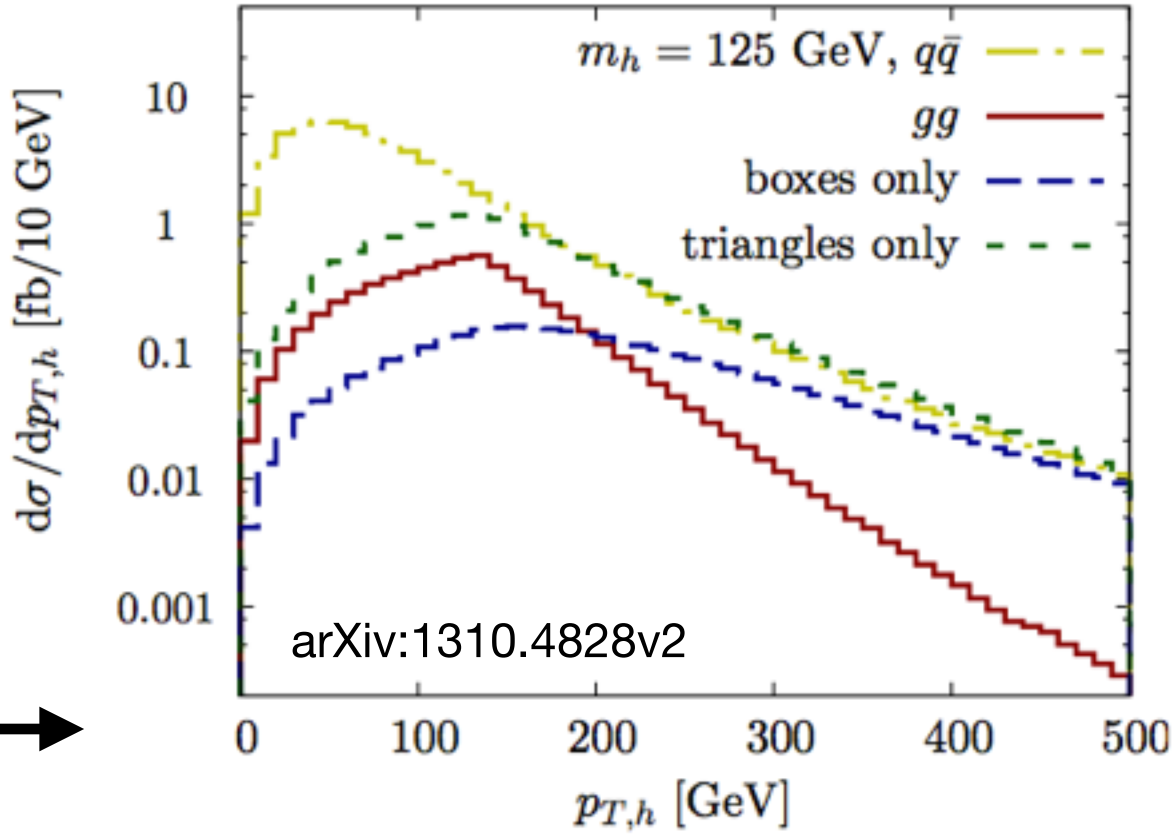
Monte Carlo events for VH processes

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

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

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



arXiv:1310.4828v2

EW Corrections from YR4:

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

XS(gg→ZH) O(14%) of total XS(pp→ZH) enhanced contribution at medium-high p_T^V

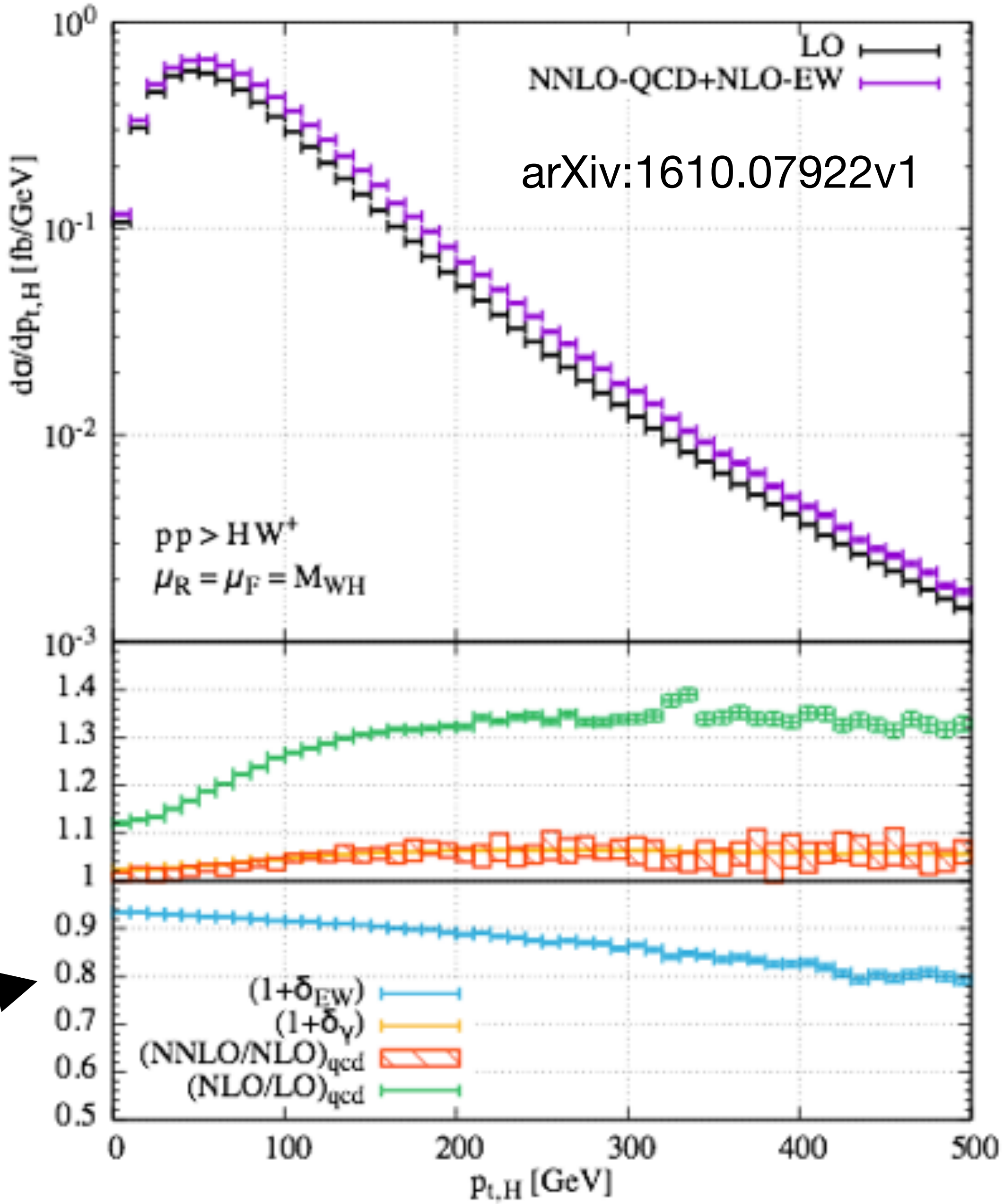
Future EW NLO accurate MC generators *(Francesco's talk)*

VH signal model in ATLAS & CMS

Monte Carlo events for VH processes

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

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



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

EW Corrections from YR4:

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

Future EW NLO accurate MC generators (Francesco's talk)

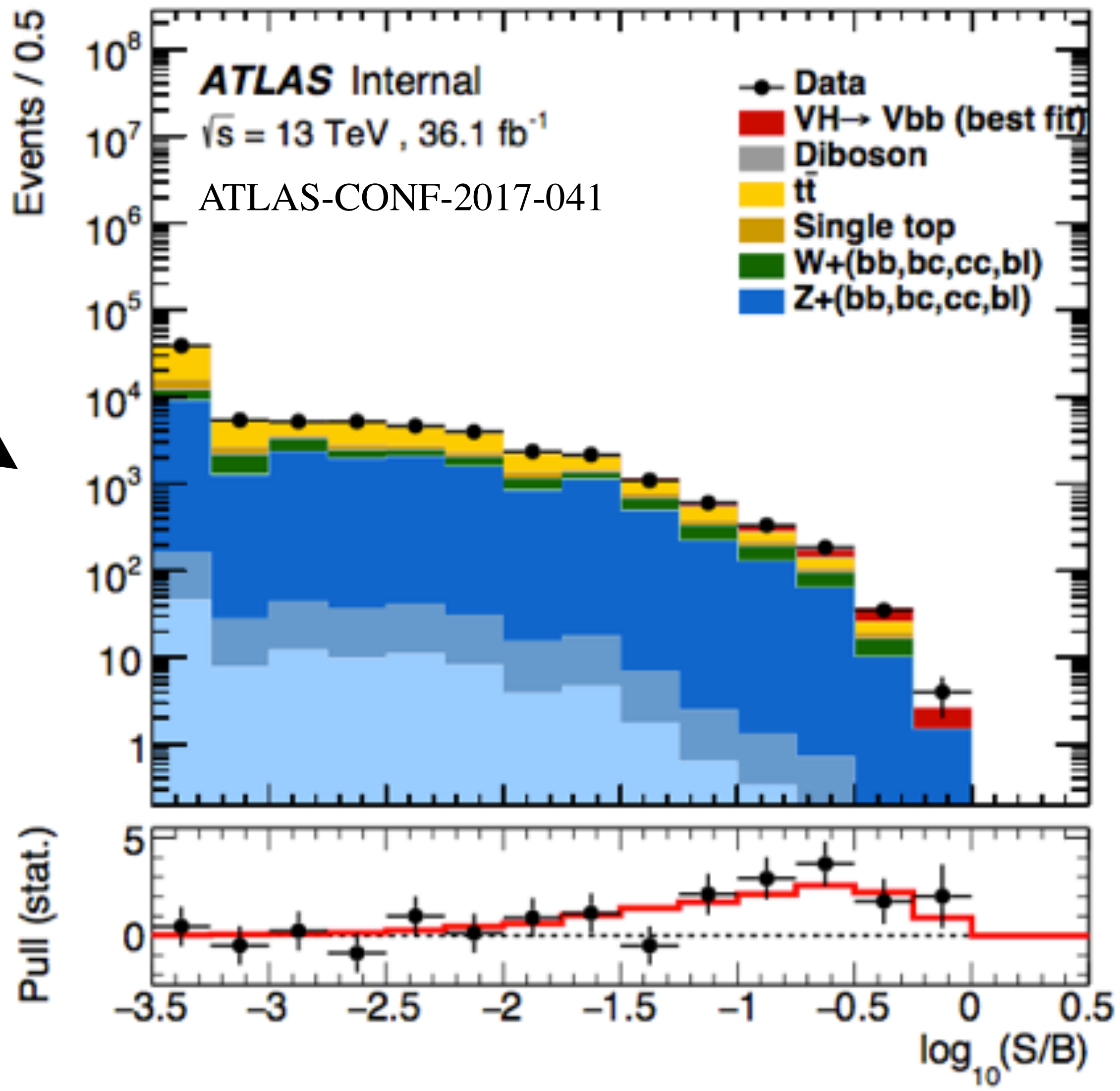
VH production @ LHC

Most relevant decay channel for VH production: H(→bb)
(other channels are sensitive to VH - H(→bb) relies on **V(lept.)H** production **almost** entirely)

From YR4: main selections and cuts coming from typical VH(→bb) requirement (+case study)

VH(bb)	significance obs(exp) [σ]	signal strength $\mu = \sigma/\sigma_{SM}$
ATLAS Run-1	1.4 (2.6)	0.5 ± 0.4 (±0.31 stat ±0.24 syst)
CMS Run-1	2.1 (2.5)	0.9 ± 0.4
ATLAS Run-2	3.5 (3.0)	1.2 ± 0.4

VH(bb) evidence @ 13 TeV



Main channels: V(→leptons: ll, lv, vv)+H(bb)
Standard selection cuts:

- 2 central jets (|η|<2.5) p_T > 20GeV reconstruct H(bb) candidate
- nJet ≤ 3 for Z(vv)H and W(lv)H channels
- p_T^V > 150GeV [+75-150GeV for Z(ll)H]
- multivariate approach MVA

Sensitive region relatively boosted: O(150-250)GeV

VH(bb) signal strength @ 13 TeV [L_{int} = 36/fb] = 1.2 ±0.24(stat) ±0.31(syst)

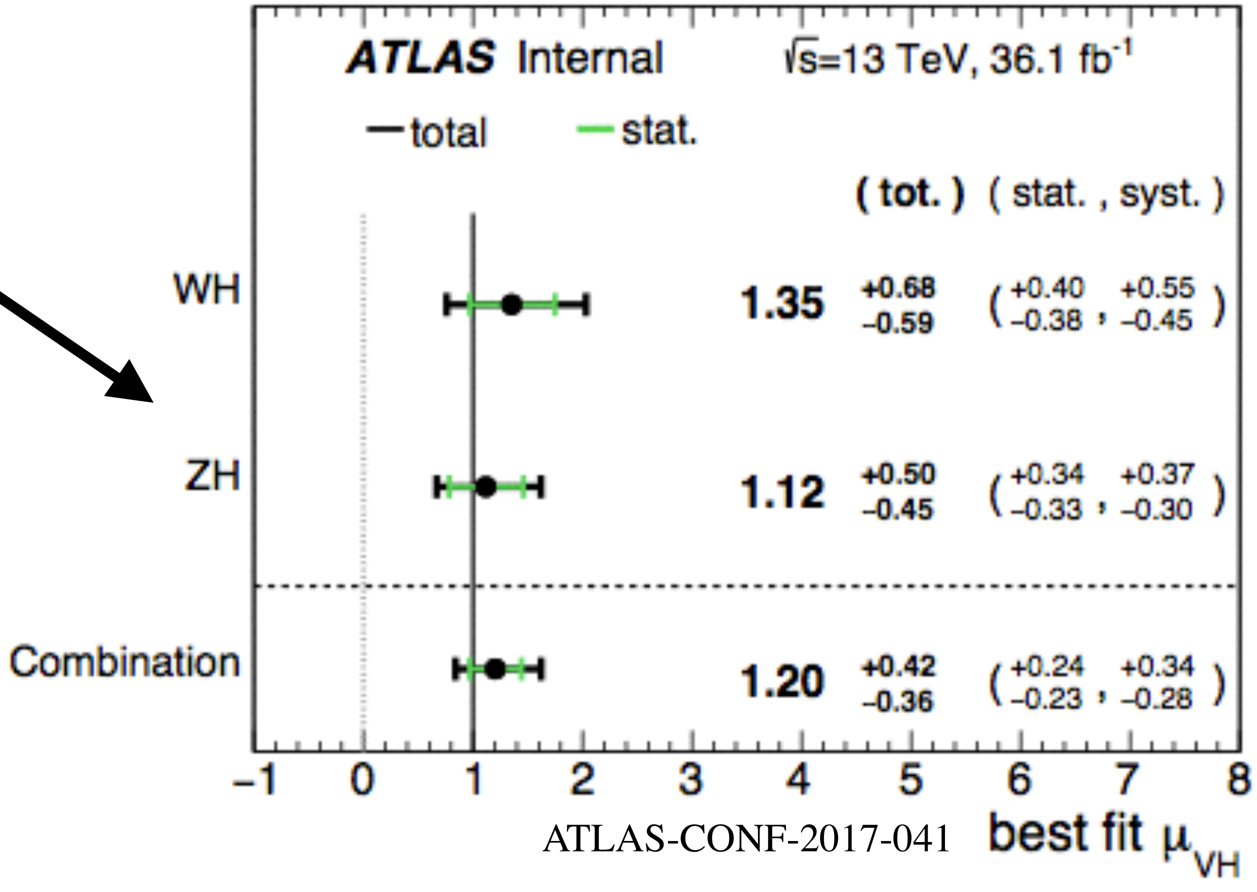
VH production @ LHC

Most relevant decay channel for VH production: H(→bb)
(other channels are sensitive to VH - H(→bb) relies on **V(lept.)H** production **almost** entirely)

From YR4: main selections and cuts coming from typical VH(→bb) requirement (+case study)

VH(bb)	**significance obs(exp) [σ]**	**signal strength $\mu = \sigma/\sigma_{SM}$**
ATLAS Run-1	1.4 (2.6)	0.5 ± 0.4 (±0.31 stat ±0.24 syst)
CMS Run-1	2.1 (2.5)	0.9 ± 0.4
ATLAS Run-2	3.5 (3.0)	1.2 ± 0.4

VH(bb) evidence @ 13 TeV



ATLAS-CONF-2017-041

Main channels: V(→leptons: ll, lv, vv)+H(bb)
Standard selection cuts:

- 2 central jets (|η|<2.5) $p_T > 20$GeV reconstruct H(bb) candidate
- nJet ≤ 3 for Z(vv)H and W(lv)H channels
- $p_T^V > 150$GeV [+75-150GeV for Z(ll)H]
- multivariate approach MVA

Sensitive region relatively boosted: O(150-250)GeV

VH(bb) signal strength @ 13 TeV [L_{int} = 36/fb] = 1.2 ±0.24(stat) ±0.31(syst)

VH production @ 13TeV - signal modeling

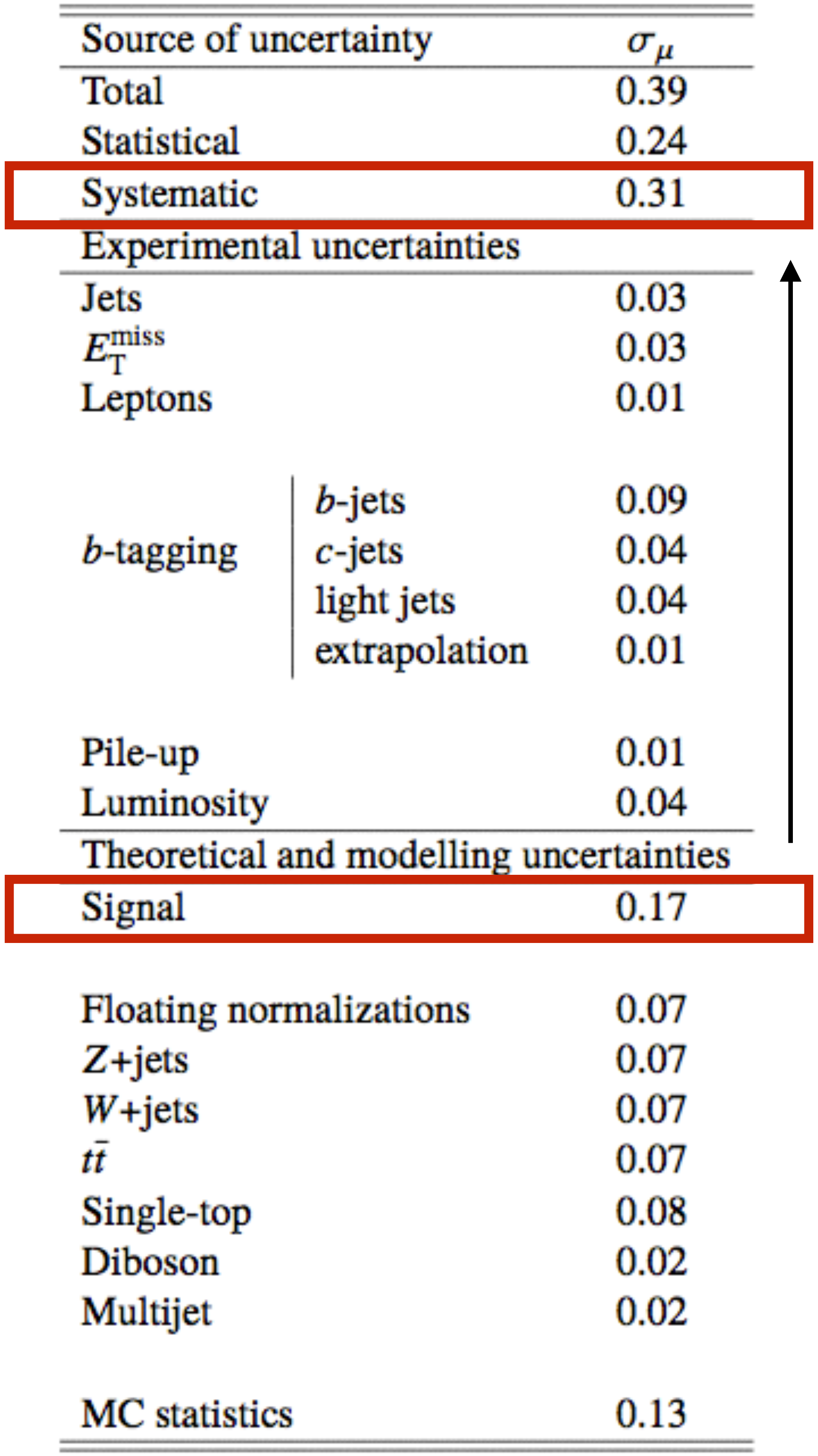
VH(bb) signal strength @ 13 TeV [Lint = 36/fb] = ***1.2 ±0.24(stat) ±0.31(syst)***

Important role of VH signal systematic uncertainties in VH(bb) analyses:

1. UEPS acceptance uncertainties
   “experimental recipe”:
   Pythia8 vs Herwig7 +
   PS eigentune variations
2. QCD scale variations
   (total XS from YR4, acceptance from
   Powheg-MiNLO variations)

Good understanding of the VH signal model becomes even more critical with additional data:

L_{int}	**stat.** error on $\mu = \sigma/\sigma_{SM}$	**syst.** error on $\mu = \sigma/\sigma_{SM}$
36/fb	0.24	0.31
150/fb	0.12	?



Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalizations		0.07
Z+jets		0.07
W+jets		0.07
$t\bar{t}$		0.07
Single-top		0.08
Diboson		0.02
Multijet		0.02
MC statistics		0.13

VH production @ 13TeV - signal modeling

VH(bb) signal strength @ 13 TeV [Lint = 36/fb] = ***1.2 ±0.24(stat) ±0.31(syst)***

Important role of VH signal systematic uncertainties in VH(bb) analyses:

1. UEPS acceptance uncertainties
   "experimental recipe":
   Pythia8 vs Herwig7 +
   PS eigentune variations

2. QCD scale variations
   (total XS from YR4, acceptance from Powheg-MiNLO variations)

"PS uncertainties"
Long-standing topic
Possible improvements in the treatment of UE/PS/MPI/had. uncertianties?

QCD scale variations
possible improvements from NNLOPS applied to Powheg-MiNLO
& improved prediction for gg→ZH

(Francesco's talk)

Good understanding of the VH signal model becomes even more critical with additional data:

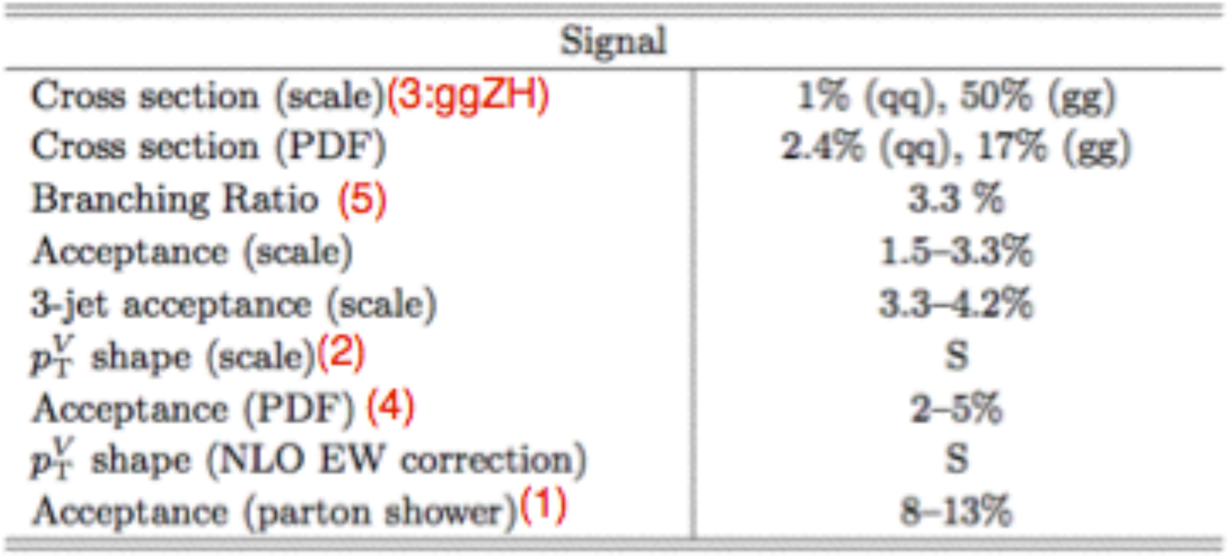
L_{int}	**stat.** error on $\mu = \sigma/\sigma_{SM}$	**syst.** error on $\mu = \sigma/\sigma_{SM}$
36/fb	0.24	0.31
150/fb	0.12	?

VH production @ Run-1 - signal modeling

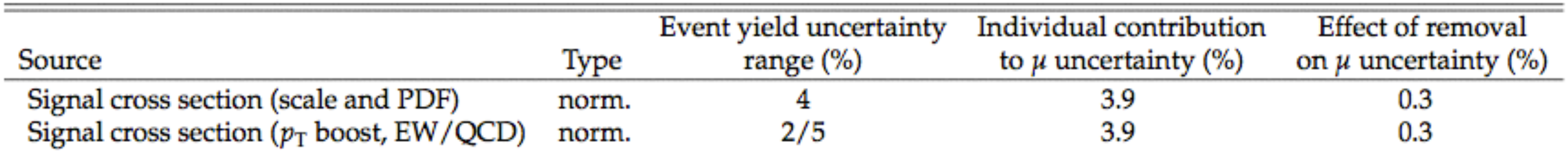
Snapshot from Run-1 - main VH theory limitations for VH searches

- VH signal modeling: O(5%) on $\mu = \sigma/\sigma_{SM}$ - not limiting but still relevant
- dominated by UEPS uncertainties and QCD scale variations

VH(bb)	**significance obs(exp) [σ]**	**signal strength $\mu = \sigma/\sigma_{SM}$**
ATLAS Run-1	1.4 (2.6)	0.5 ± 0.4 (±0.31 stat ±0.24 syst)
CMS Run-1	2.1 (2.5)	0.9 ± 0.4



Signal	
Cross section (scale)(3:ggZH)	1% (qq), 50% (gg)
Cross section (PDF)	2.4% (qq), 17% (gg)
Branching Ratio (5)	3.3 %
Acceptance (scale)	1.5–3.3%
3-jet acceptance (scale)	3.3–4.2%
p_T^V shape (scale)(2)	S
Acceptance (PDF) (4)	2–5%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)(1)	8–13%



Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3

Total uncertainty on VH(bb) XS of O(3-5%)

- significant effect when considering acceptance variations across **nJet** or p_T^V regions: feedback on current techniques (e.g. Stewart-Tackmann), possible improvements
- parton-shower effects can be large and difficult to assess properly

→ **Possible to provide guidelines to address these points?**

Background studies for VH analyses

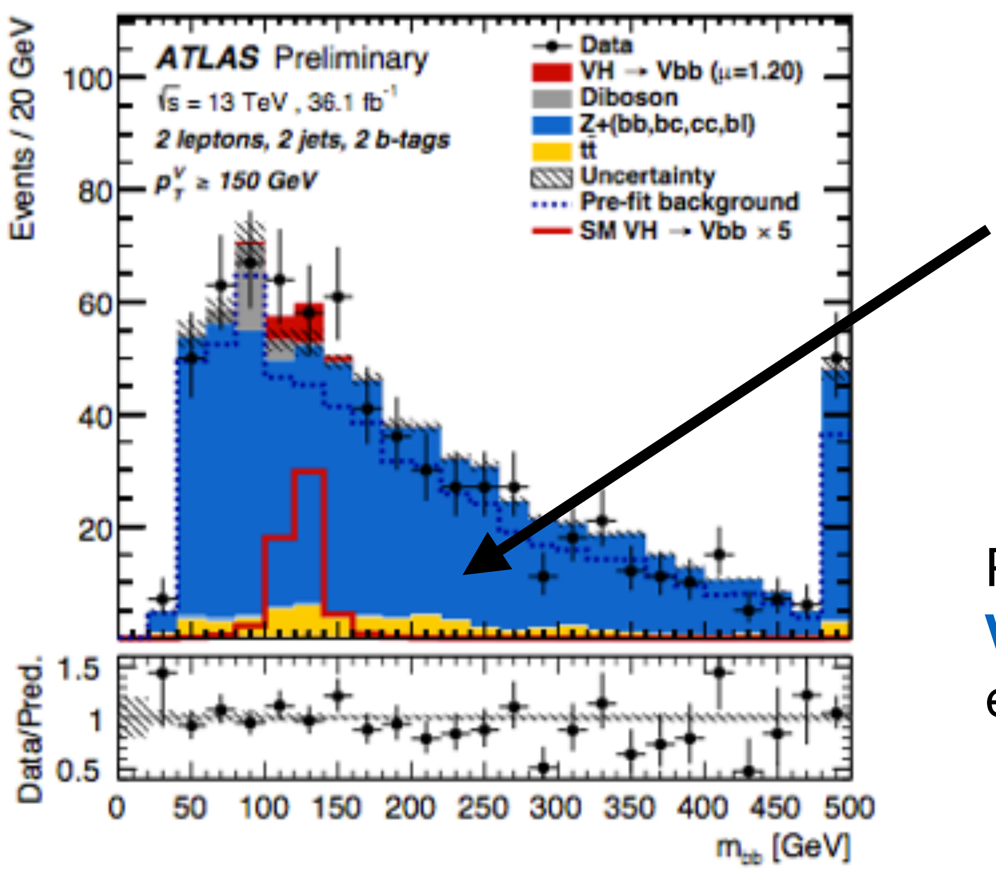
Systematic bkg studies, for all VH searches are **beyond the scope of the LHC HXSWG**

However: main VH *user/contributor* [**VH(bb**)] can be quite sensitive to background modeling

V+heavy-flavor background:

The WG1:VH subgroup can be the forum to gather discussions on modeling issues for this major background, specifically in the VH(bb) phase-space

- guidlines on the impact of MC generator choices on experimental analyses: LO vs NLO, 4F vs 5F, matching options, alternative MC generators, …
- impact of higher-order prediction in the specific phase-space
- estimate of theoretical uncertainties related to VH(bb) selections



Large Z(ll)+heavy-flavor contribution m(bb) background prediction is improved by fitting to data

However, accurate MC modeling is beneficial when training complex MVA analyses

Possible to extend to a future discussion on **VZ(bb) diboson background** modeling: standard candle used by experimental analysis to validate VH(bb) searches / measurements

Simplified Template Cross Sections - VH

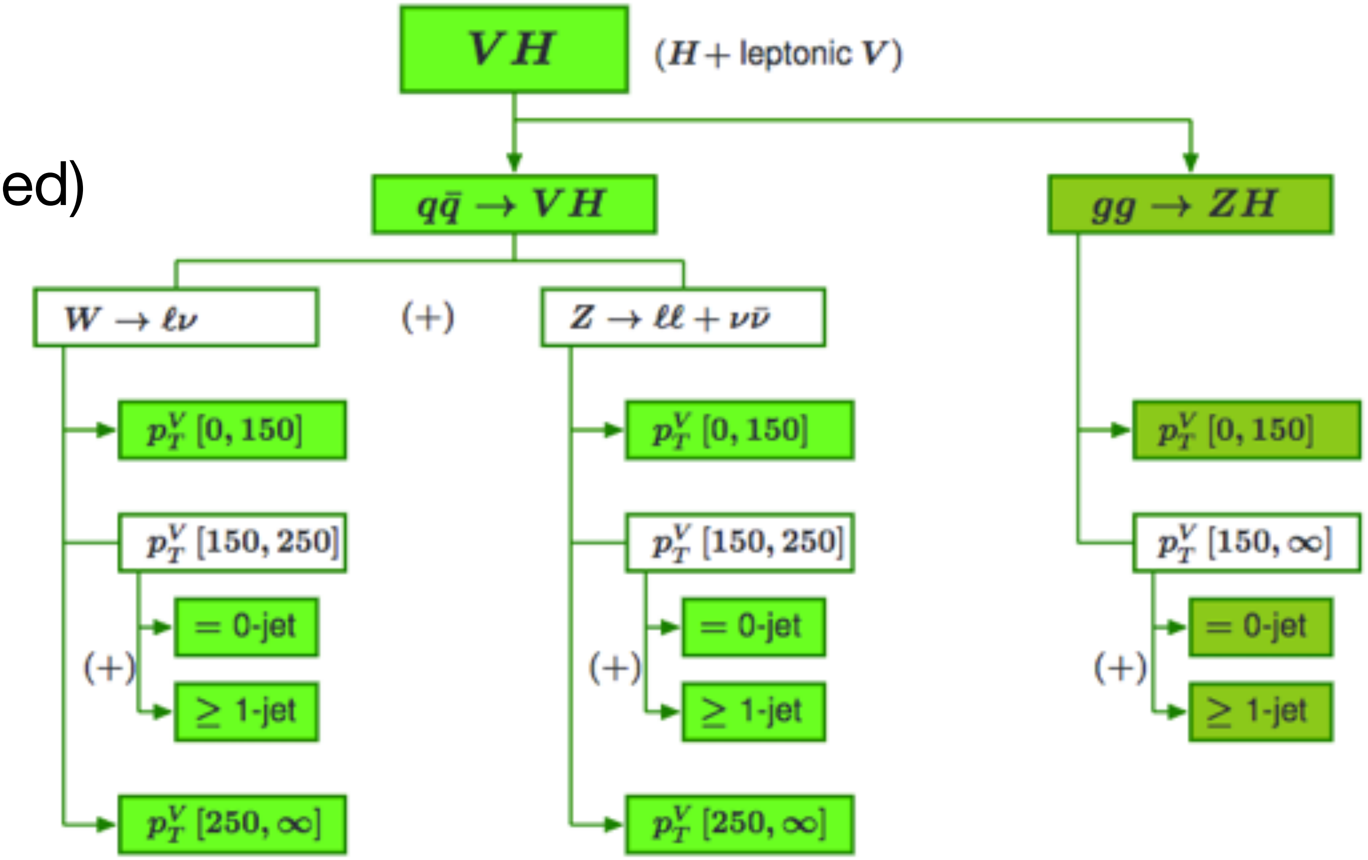
Moving towards STXS approach for VH measurements:

Strong theory-experiment collaboration!

➝ experiments will provide results in STXS bins (stage0 ➝ stage1)
➝ theorists will provide estimates of theory uncertainties in STXS bins
(and afterwards, of course, interpretations!)

VH:STXS categorization

- “VH” bins include leptonic VH (H undecayed)
- qq ➝ V(qq)H as part of “VBF” bins
- gg ➝ Z(qq)H as part of “ggF”



VH:STXS uncertainties sources

- **QCD**: nJet and p_T^V migration effects correlating WH and ZH prod. modes
- **EW**: Sudakow effects (corr. WH and ZH)
  non-Sudakow uncertainties (uncorr. WH and ZH)
- **note**: separate/uncorrelated uncertainties for Drell-Yan-like ZH, and loop-induced gg➝ZH
  correlation with other STXS bins to be studied

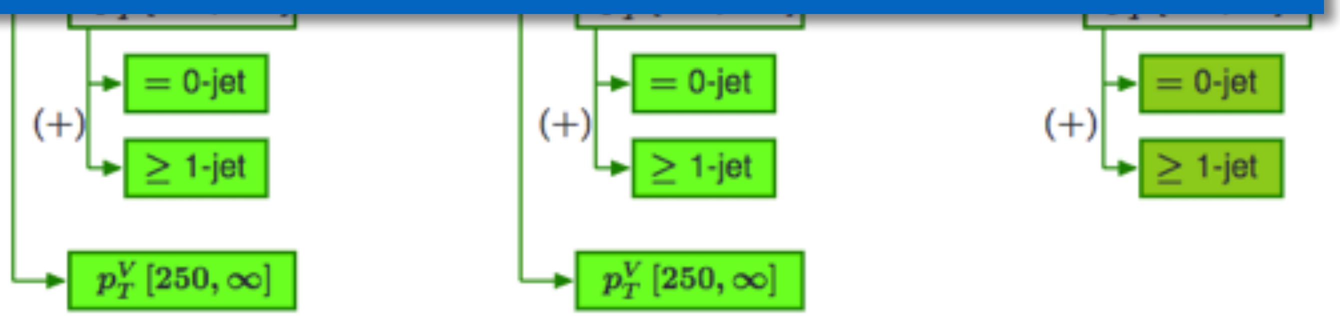
Simplified Template Cross Sections - VH

WG2:STXS

- main guidelines / recommendations on the STXS approach (e.g. baseline STXS bin split, 1st uncertainty scheme, …)
- contact point among Higgs “production modes” for STXS matters (e.g. VH contributions to VBF and ggF bins, consistent unc. treatment)

WG1:VH

- discussion on finer details of STXS bin split / uncertainty scheme: gather feedback from VH theory experts
- **estimate** of theory uncertainty for the STXS framework
- focused experimental point of view on feasibility/practicality



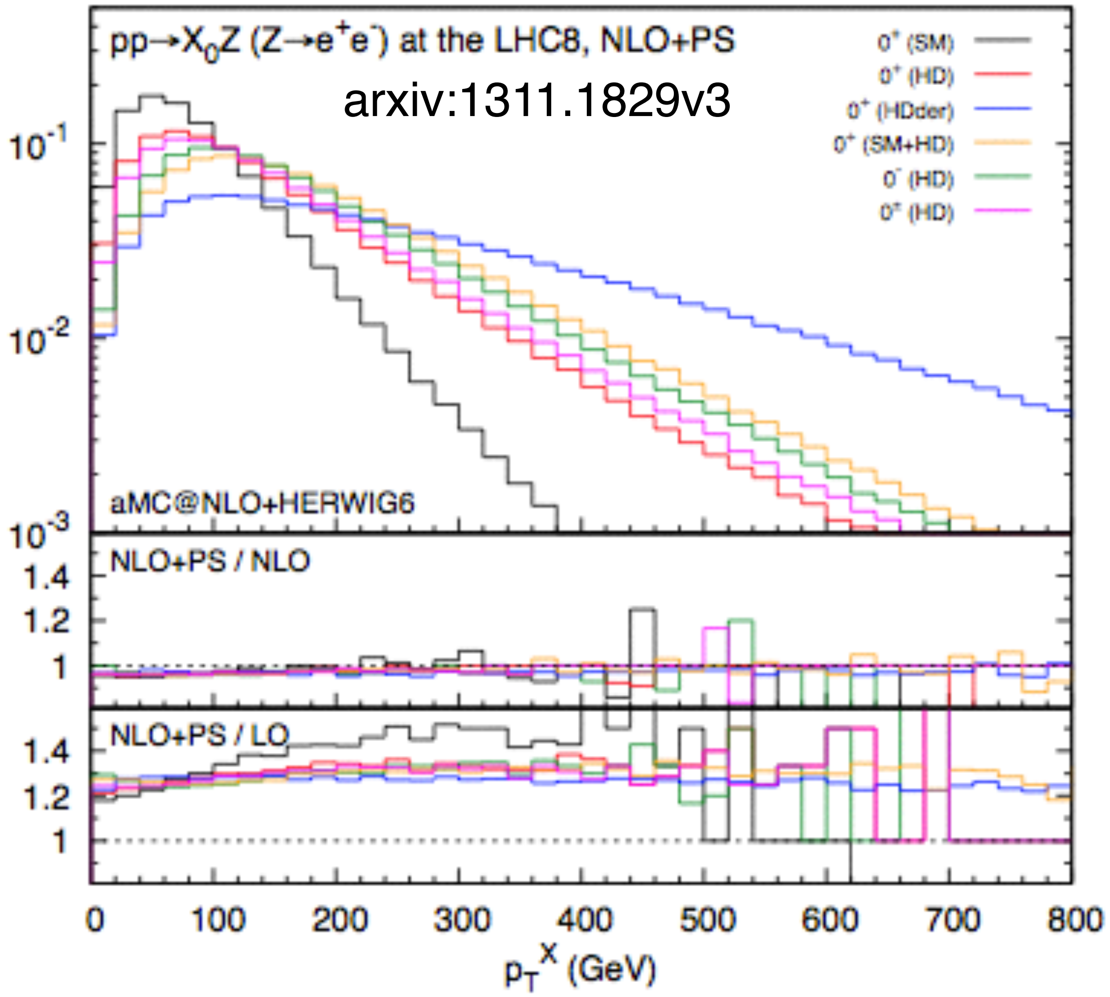
VH:STXS uncertainties sources

- **QCD**: nJet and p_T^V migration effects correlating WH and ZH prod. modes
- **EW**: Sudakow effects (corr. WH and ZH)
  non-Sudakow uncertainties (uncorr. WH and ZH)
- **note**: separate/uncorrelated uncertainties for Drell-Yan-like ZH, and loop-induced gg→ZH
  correlation with other STXS bins to be studied

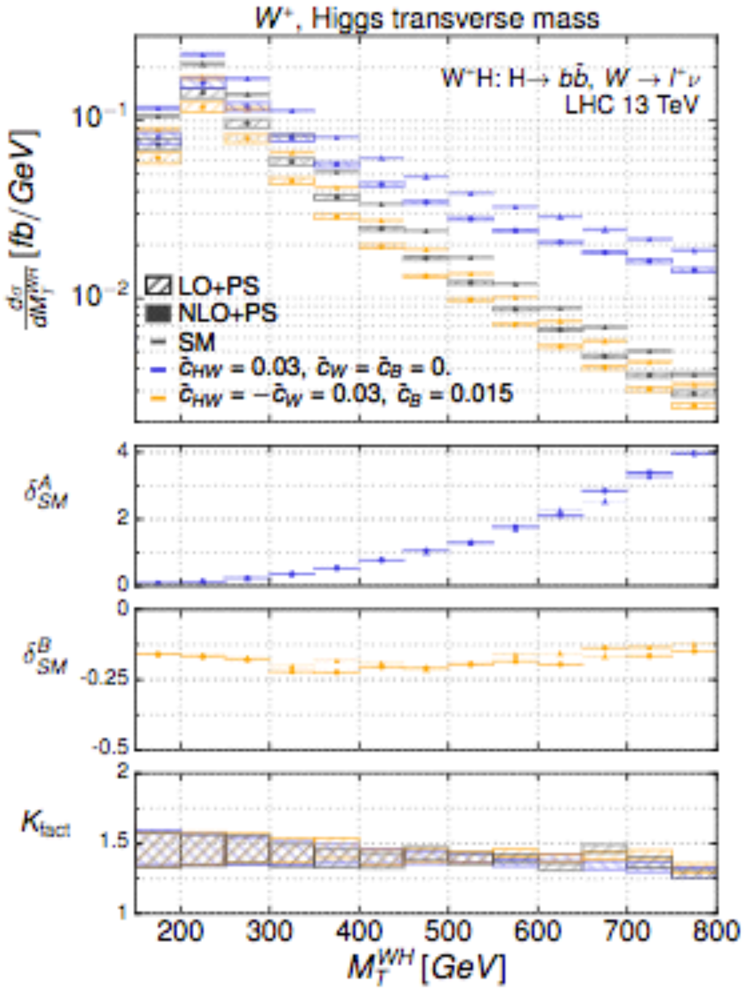
Interaction with other WGs: BSM VH

VH production can play a relevant role both in specific BSM models and in EFTs

- possible sinergy with WG(2,3) on EFT anomalous coupling studies and model-specific BSM VH production ?
- SM VH predictions at high precision: can we benefit from same/similar level of precision for BSM VH production? could shared experience & tool help?



arxiv:1311.1829v3



Some examples already from Francesco Riva's talk this morning

- EFT / PO tools at NLO QCD already available for VH
- common issues (e.g. higher-order QCD, EW corrections - treatment of ggZH, treatment of uncertainties) may benefit from WG2-WG1 interaction

Conclusions and Outlook

- **WG1:VH activities ongoing** - many different contributions already discussed in the first meeting → lots of material to define an interesting roadmap for the future

- **VH experimental results**:
  main channel VH(bb) can reach level of evidence with current dataset

  → **very** important to have a clear plan of improvements already for the short/medium-term (full LHC Run-2 dataset)

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

  STXS approach could become very interesting with full Run-2 dataset [potentially 5σ - O(20%) precision on μ]

- Potential opening to background studies related specifically to VH(bb) phase-space

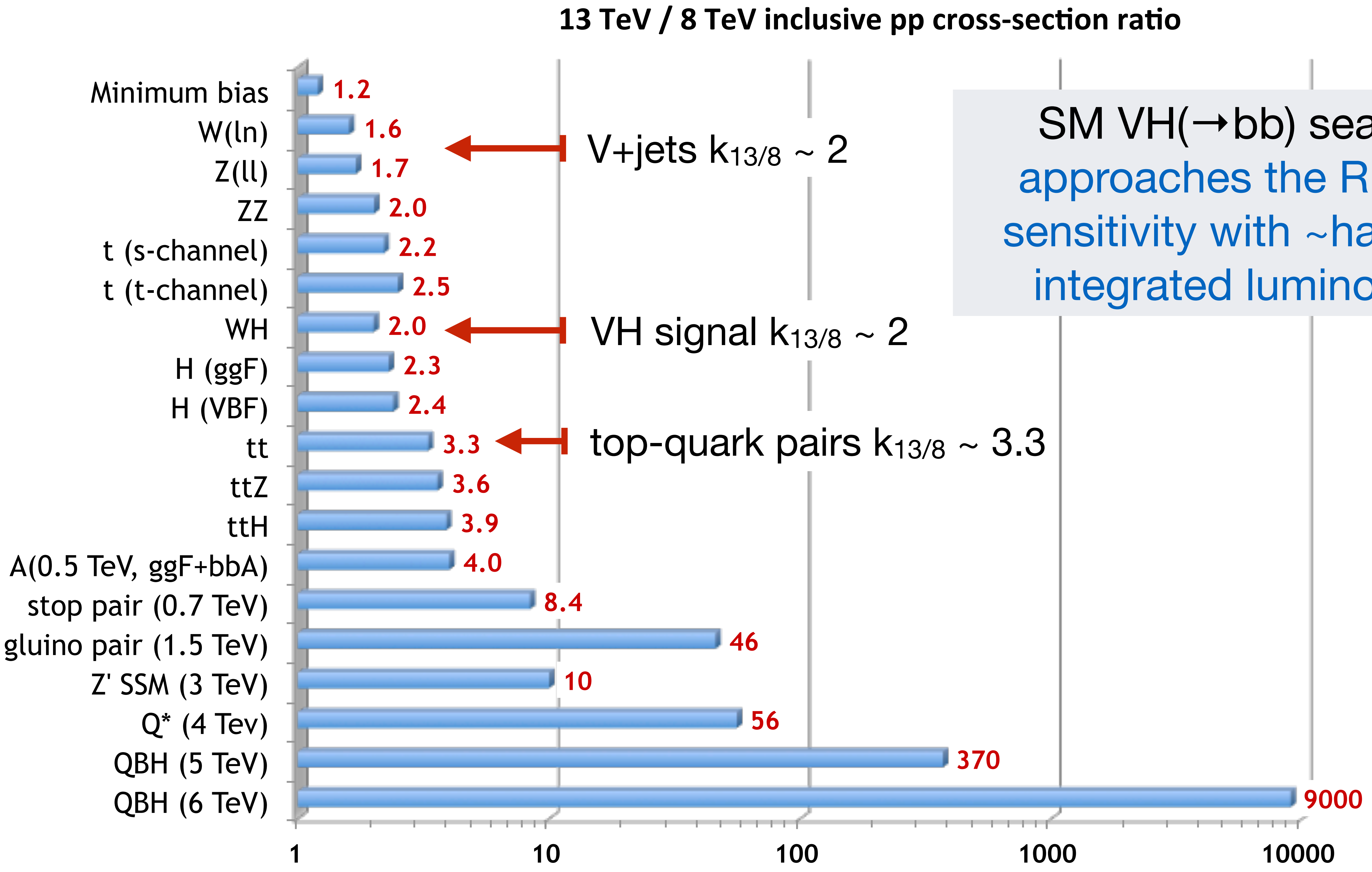
- Several theory developments on a medium-long timescale (see *Francesco's talk*): feedback on the "experimental sensitivity" to these improvements

- BSM VH - possible interaction with other WG* ?

Back-up

VH(bb) searches @ 13TeV

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



V+jets $k_{13/8}$ ~ 2

VH signal $k_{13/8}$ ~ 2

top-quark pairs $k_{13/8}$ ~ 3.3

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

Simplified Template Cross Sections - VH

STXS: separating measurements from interpretations

- maximize measurements sensitivity
- minimize theory dependence (models&systematics)

- combine **all decay channels**
- measure **XS instead of signal strengths**
- measure XS separately for **production modes**
- measure XS in **simplified fiducial volumes**
- allow for advanced analysis techniques (**MVAs**)

Exclusive phase space regions ("bins") defined to

- maximize experimental sensitivity
- minimize dependence on theory uncertainties directly folded into the measurements
- provide sensitivity to BSM scenarios

$$\sigma^{meas} = A^{ggH} \times \mu_{ggH} \times \sigma_{ggH}^{SM} + A^{VBF} \times \mu_{VBF} \times \sigma_{VBF}^{SM}$$

$$= A^{ggH} \times \sigma_{ggH} + A^{VBF} \times \sigma_{VBF}$$

A^{ggH}, A^{VBF} Signal acceptance theory dependent

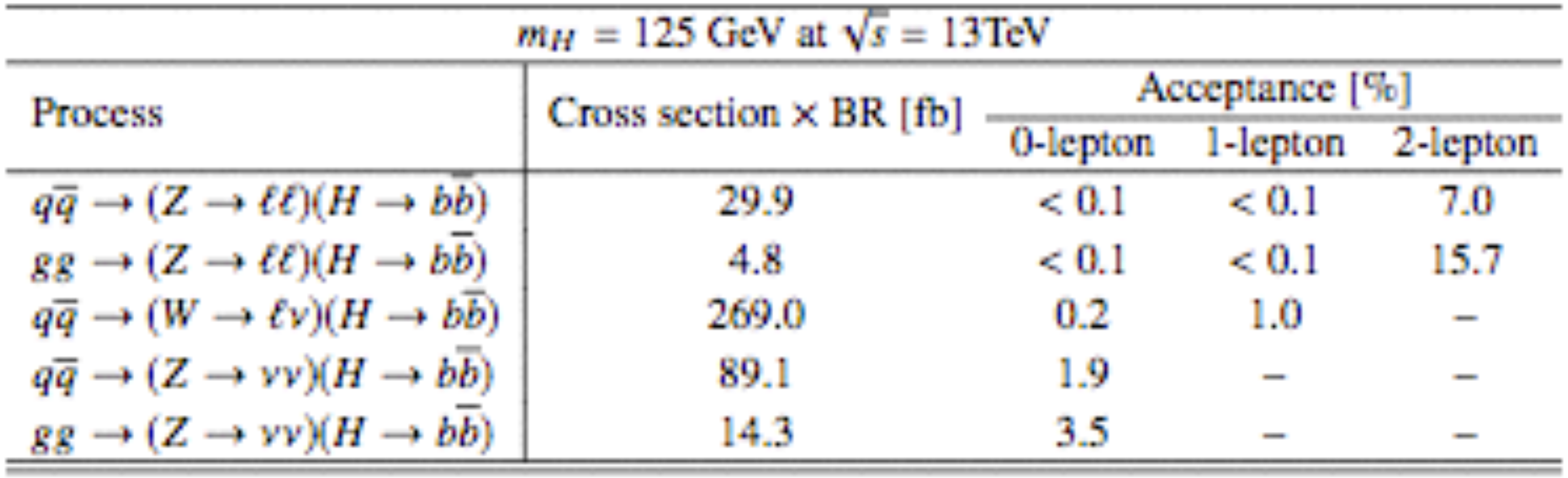
$$\Big\downarrow$$

$$\sigma^{meas} = A_a^{ggH} \times \sigma^{a}{}_{ggH}{}^{SM} + A_b^{ggH} \times \sigma^{b}{}_{ggH}{}^{SM} + A_c^{VBF} \times \sigma^{c}{}_{VBF}{}^{SM}$$

a,b,c = "bins" of STXS

A_i^{ggH}, A_i^{VBF} Signal acceptance dependent on SM signal kinematic only within the given bin "i" [reduce theory dependence]

VH Signal Model @ 13TeV



$m_H = 125$ GeV at $\sqrt{s} = 13$TeV				
Process	Cross section × BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$q\bar{q} \to (Z \to \ell\ell)(H \to b\bar{b})$	29.9	< 0.1	< 0.1	7.0
$gg \to (Z \to \ell\ell)(H \to b\bar{b})$	4.8	< 0.1	< 0.1	15.7
$q\bar{q} \to (W \to \ell\nu)(H \to b\bar{b})$	269.0	0.2	1.0	–
$q\bar{q} \to (Z \to \nu\nu)(H \to b\bar{b})$	89.1	1.9	–	–
$gg \to (Z \to \nu\nu)(H \to b\bar{b})$	14.3	3.5	–	–

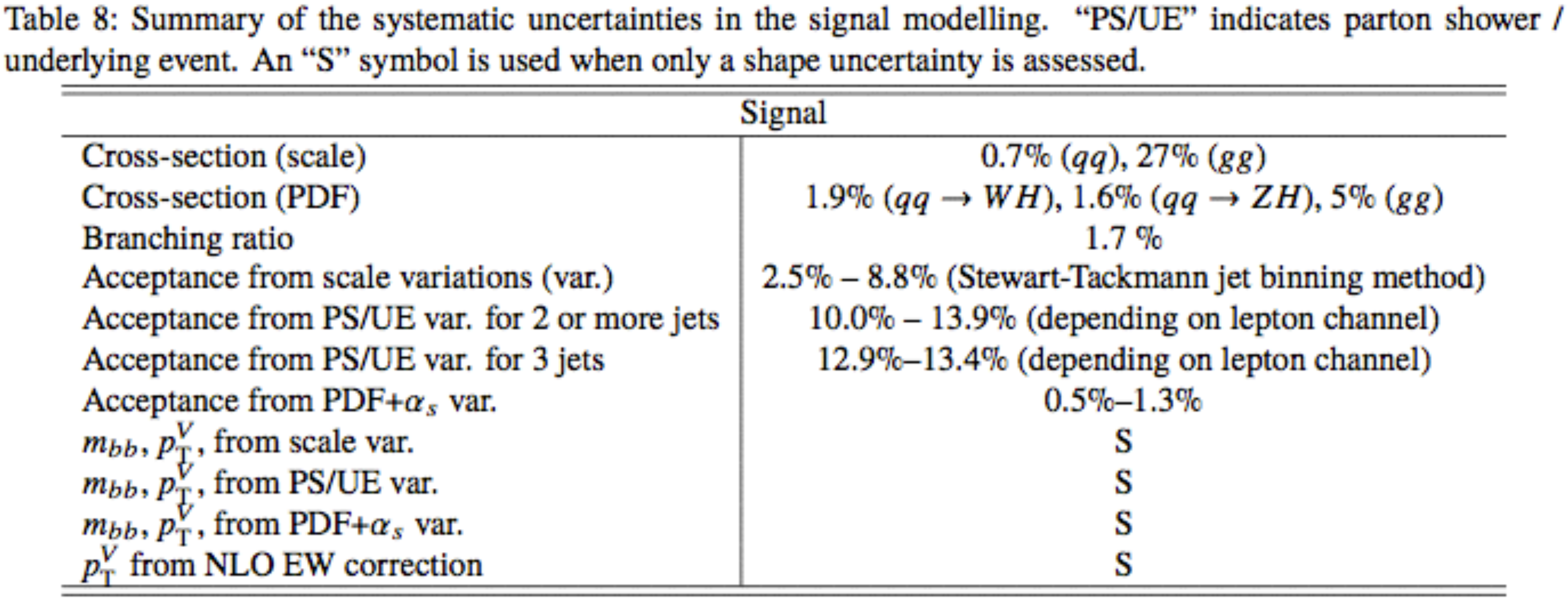
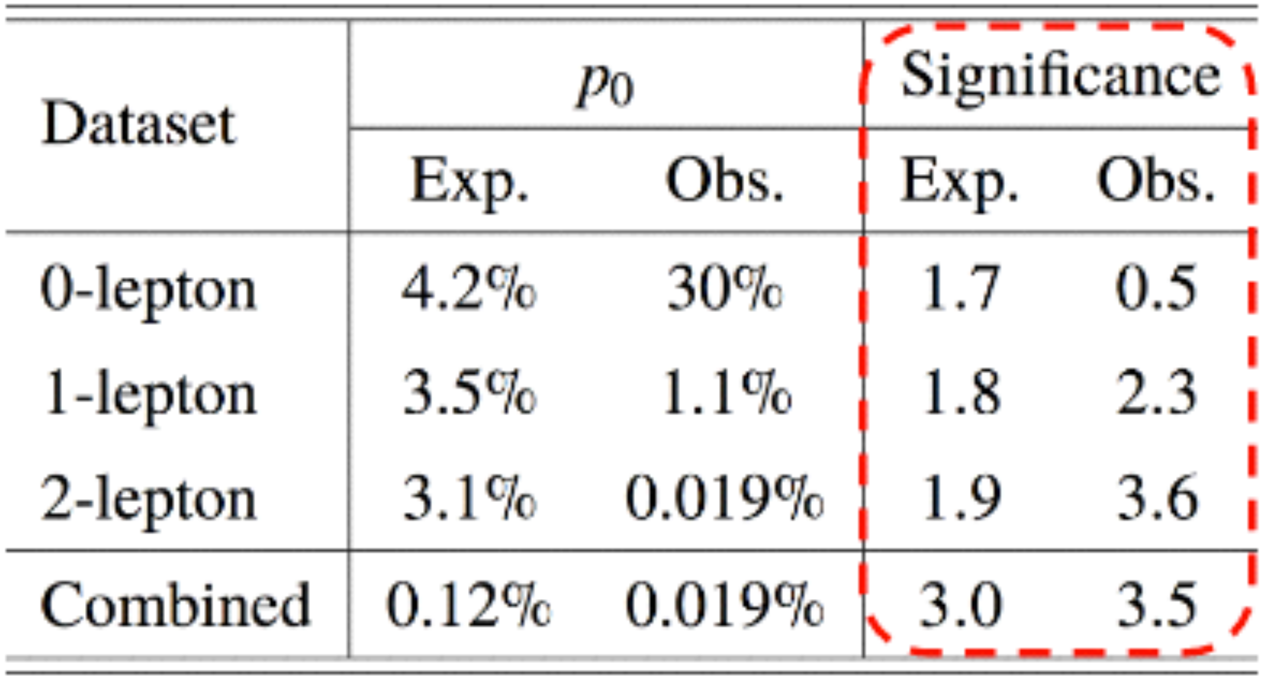


Table 8: Summary of the systematic uncertainties in the signal modelling. “PS/UE” indicates parton shower / underlying event. An “S” symbol is used when only a shape uncertainty is assessed.

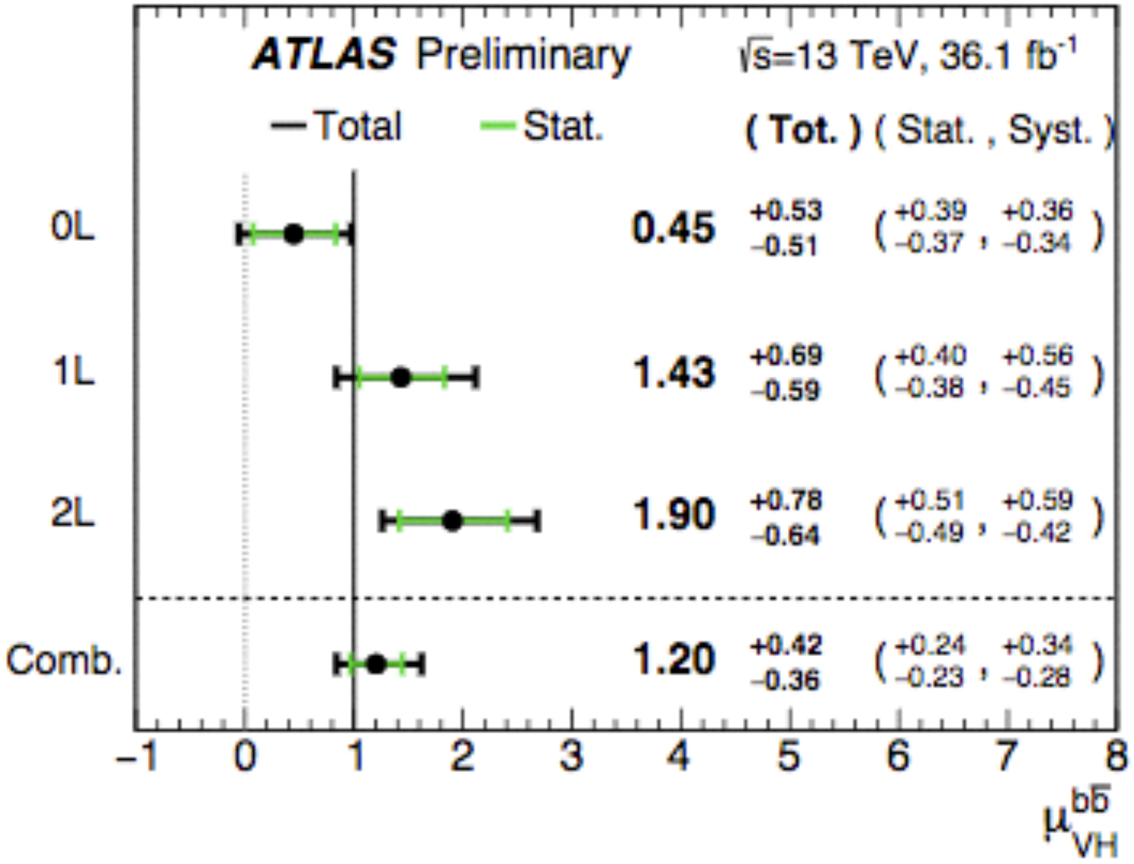
Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance from scale variations (var.)	2.5% – 8.8% (Stewart-Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	10.0% – 13.9% (depending on lepton channel)
Acceptance from PS/UE var. for 3 jets	12.9%–13.4% (depending on lepton channel)
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

VH(bb) @ 13TeV [ATLAS]

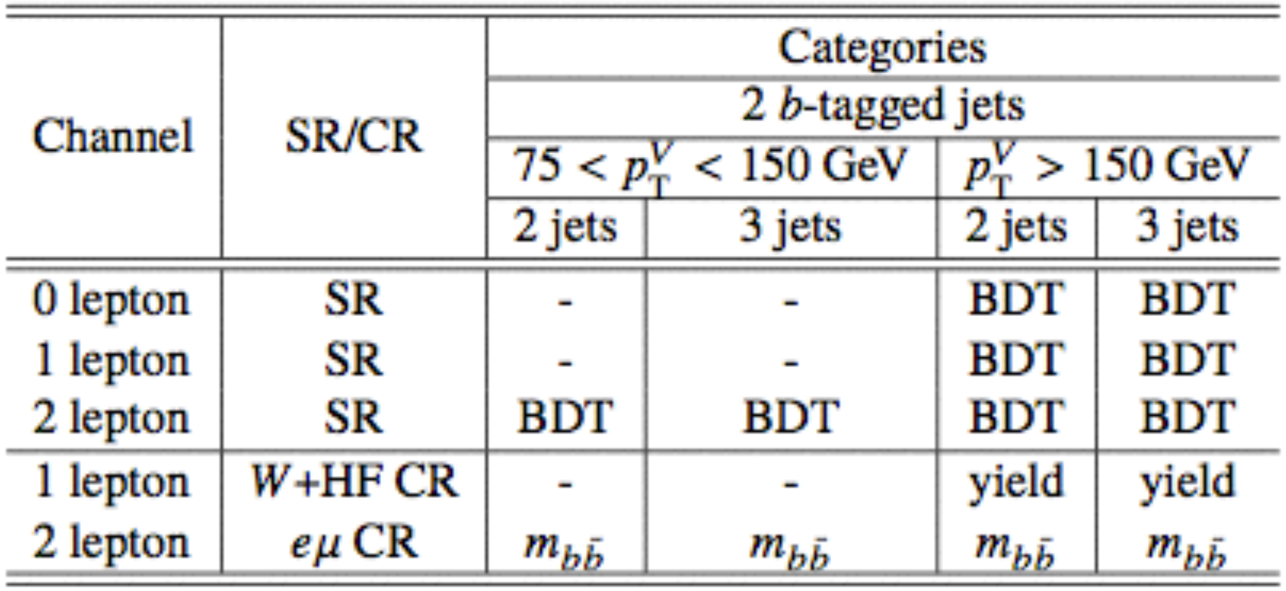
Evidence of VH(bb) at 3.5 obs. sigma (3.5 exp.)



Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5



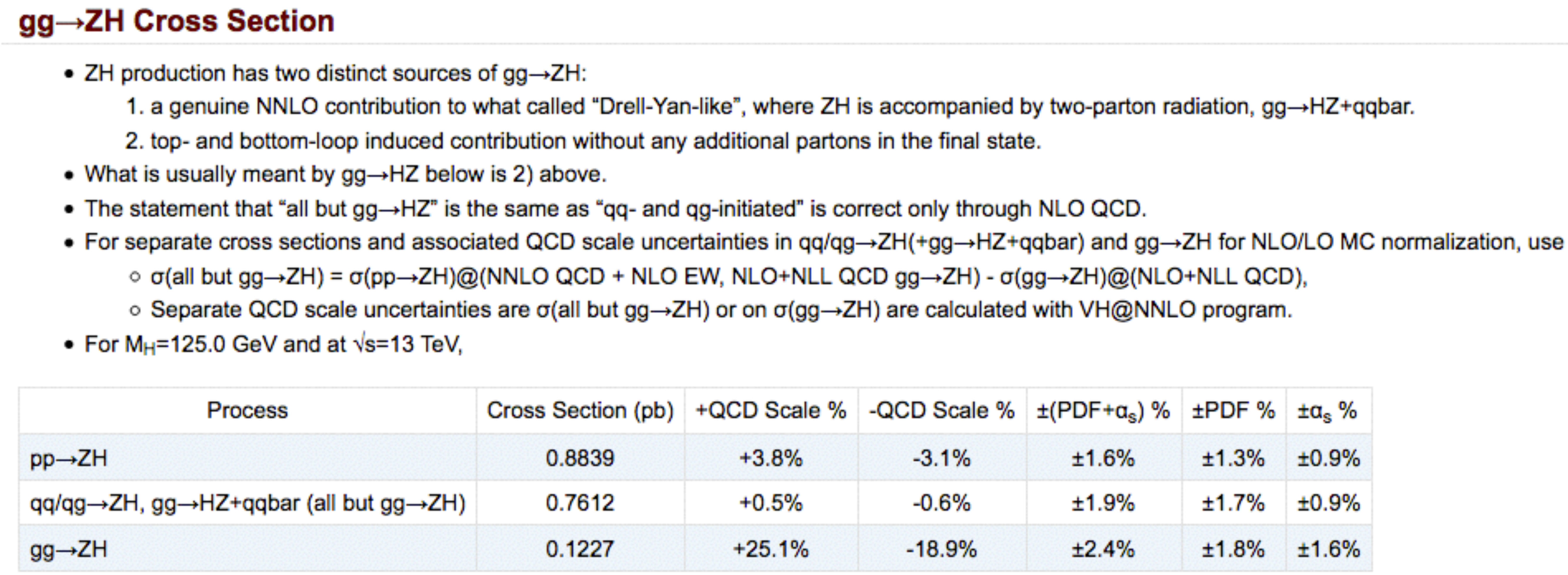
- 3-lepton channels compatible at ~10%
- XS(VH->Vbb) = 1.57 ($^{+0.54}$, $_{-0.47}$) pb [from a simple signal strength scaling]
- XS$_{\text{expSM}}$(VH->Vbb) = 1.31 pb
- provide sensitivity to BSM scenarios



Channel	SR/CR	Categories			
		2 b-tagged jets			
		$75 < p_T^V < 150$ GeV		$p_T^V > 150$ GeV	
		2 jets	3 jets	2 jets	3 jets
0 lepton	SR	-	-	BDT	BDT
1 lepton	SR	-	-	BDT	BDT
2 lepton	SR	BDT	BDT	BDT	BDT
1 lepton	W+HF CR	-	-	yield	yield
2 lepton	$e\mu$ CR	$m_{b\bar{b}}$	$m_{b\bar{b}}$	$m_{b\bar{b}}$	$m_{b\bar{b}}$

ZH XS update

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

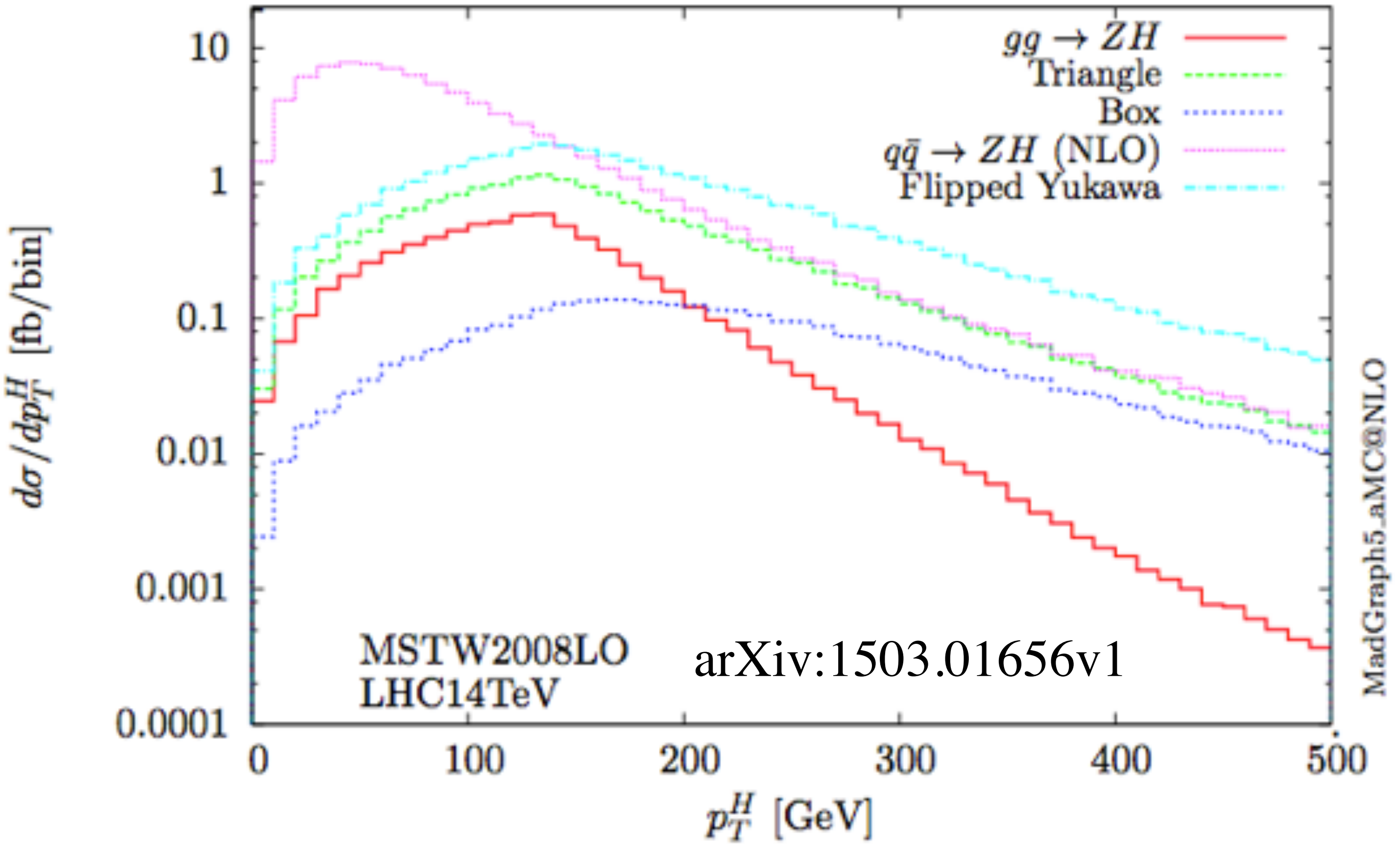


gg→ZH Cross Section

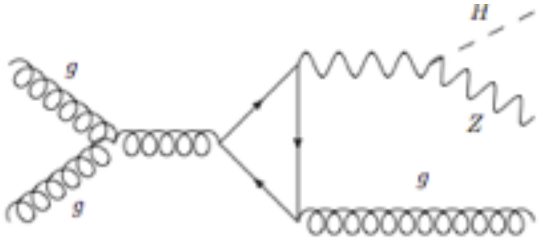
- ZH production has two distinct sources of gg→ZH:
  1. a genuine NNLO contribution to what called “Drell-Yan-like”, where ZH is accompanied by two-parton radiation, gg→HZ+qqbar.
  2. top- and bottom-loop induced contribution without any additional partons in the final state.
- What is usually meant 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 √s=13 TeV,

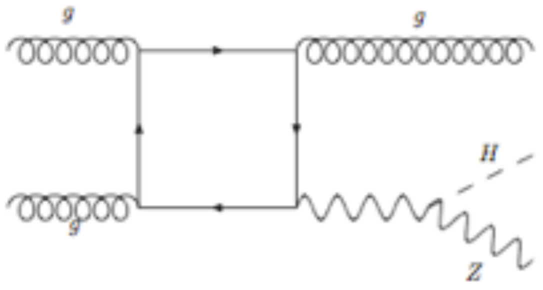
Process	Cross Section (pb)	+QCD Scale %	-QCD Scale %	±(PDF+α_s) %	±PDF %	±α_s %
pp→ZH	0.8839	+3.8%	-3.1%	±1.6%	±1.3%	±0.9%
qq/qg→ZH, gg→HZ+qqbar (all but gg→ZH)	0.7612	+0.5%	-0.6%	±1.9%	±1.7%	±0.9%
gg→ZH	0.1227	+25.1%	-18.9%	±2.4%	±1.8%	±1.6%

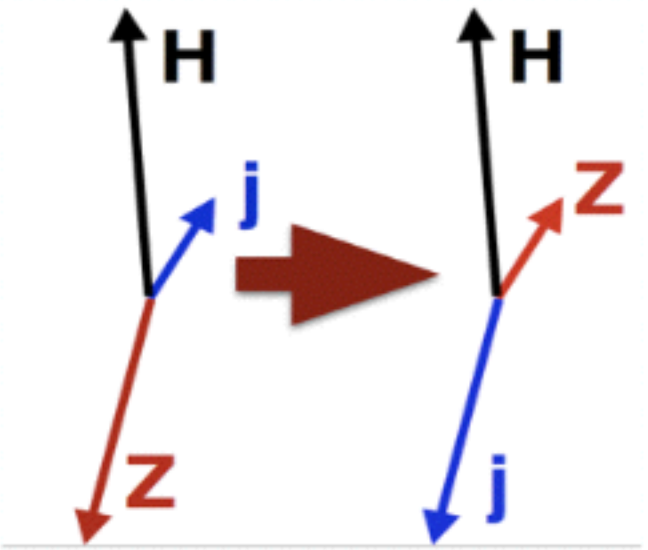
ggZH (loop-induced) diagrams

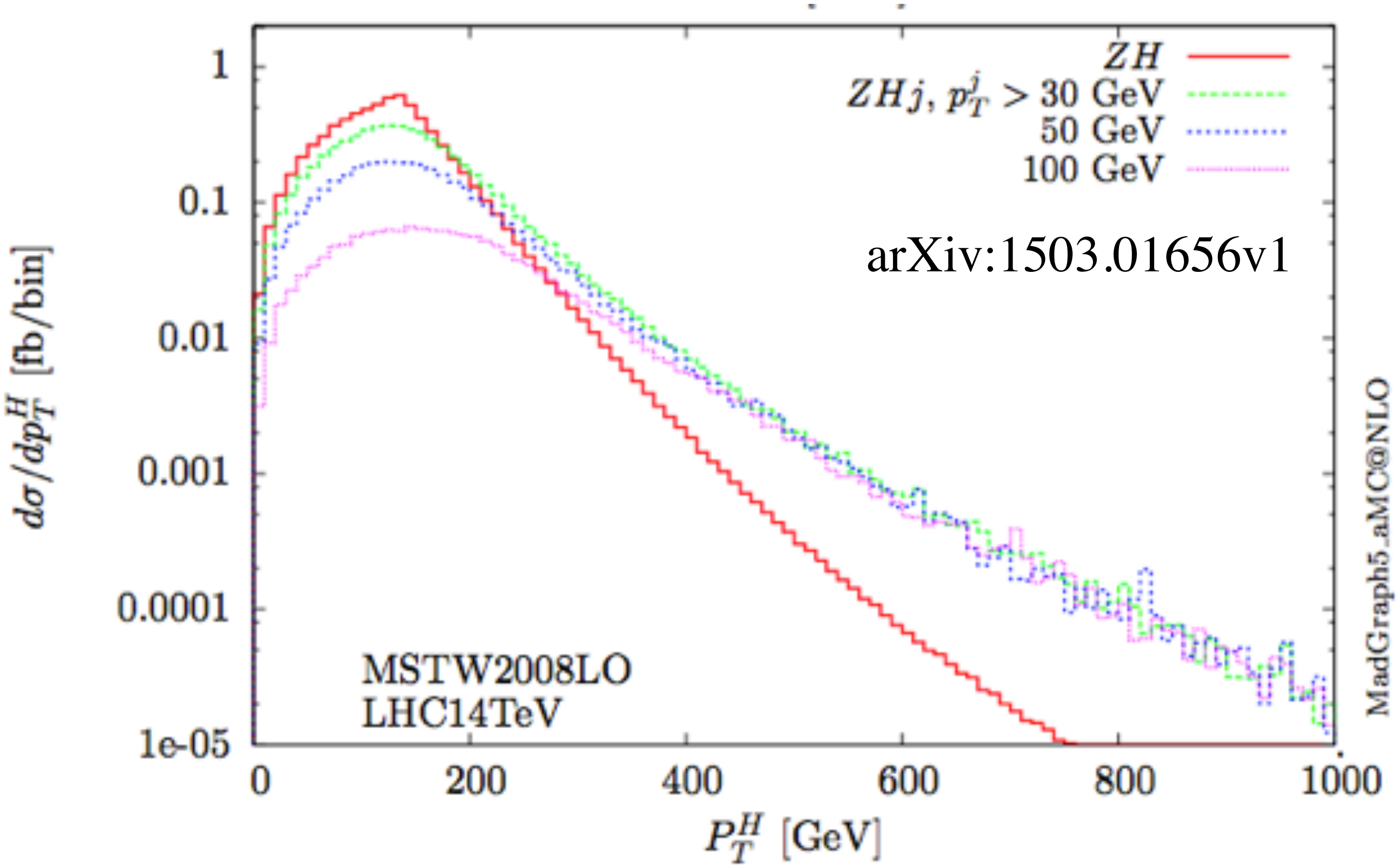


arXiv:1503.01656v1









arXiv:1503.01656v1

Latest PO development: NLO in QCD

HiggsPO code can be found at http://www.physik.uzh.ch/data/HiggsPO/

Allows to simulate EW Higgs production (VH, VBF) in the PO formalism @ NLO in QCD.

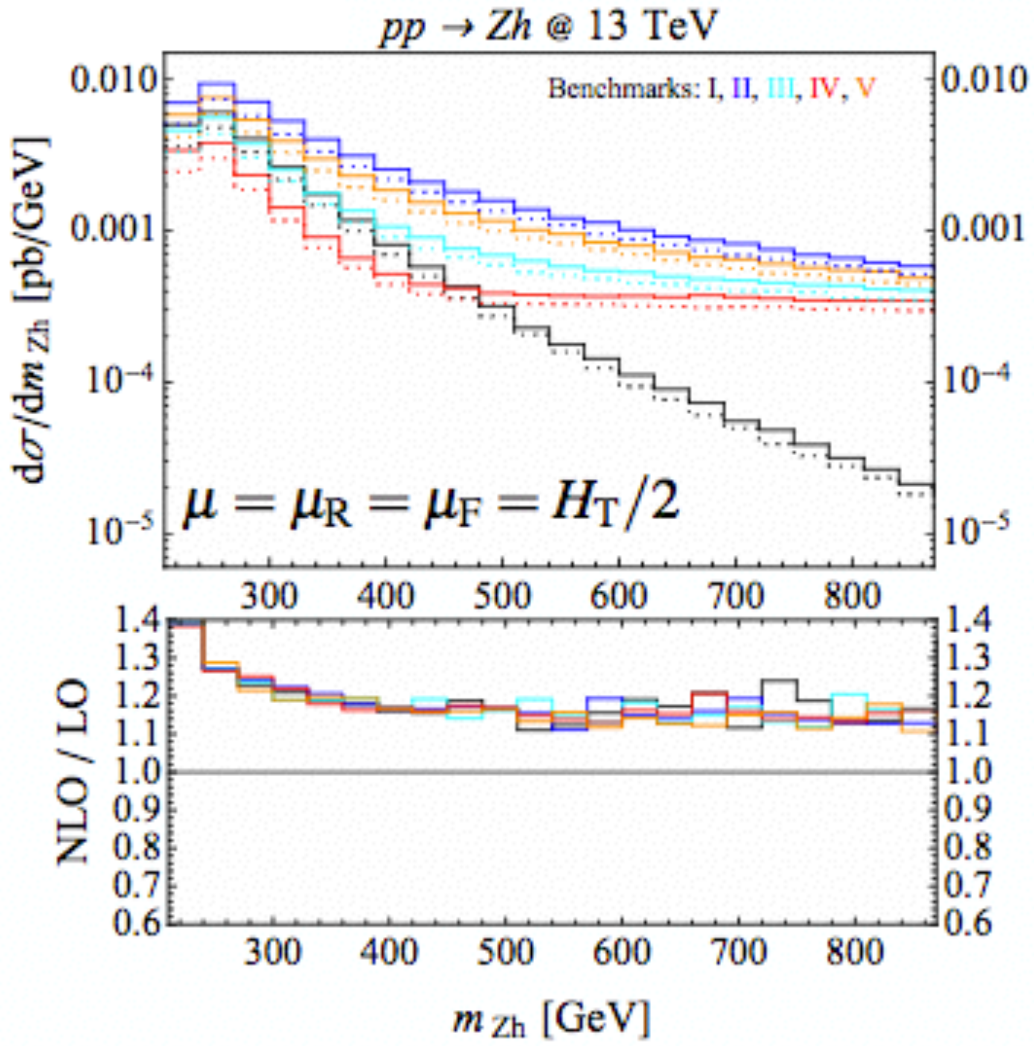
Download the model

Version 1.2 - NEW

HiggsPO UFO model for electroweak Higgs production at NLO in QCD.

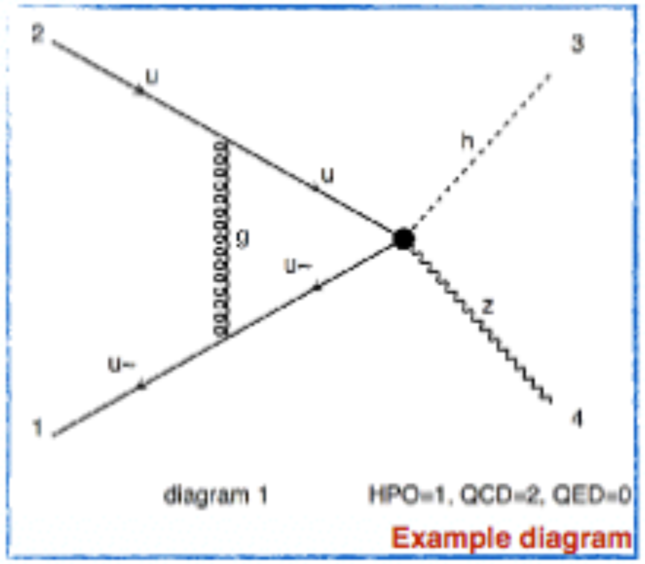
- UFO model: HPO_ewk_prod_NLO (zip)
- Presentation and examples (slides from the LHC HXSWG meeting of May 8th, 2017): link

Example: Zh at NLO



For info and examples see A. Greljo talk at WG2 kickoff meeting.

Paper coming soon.



Example diagram

Parton Shower Models and Variations

AZNLO: *designed for the Powheg+Pythia8 NLO+PS generator, and provide a very good description of ISR in the low and medium p_T region*

Measurements of the Z/γ_* boson transverse momentum distribution (and ϕ^*_η angular correlation) in pp collisions at $\sqrt{s}$ = 7 TeV

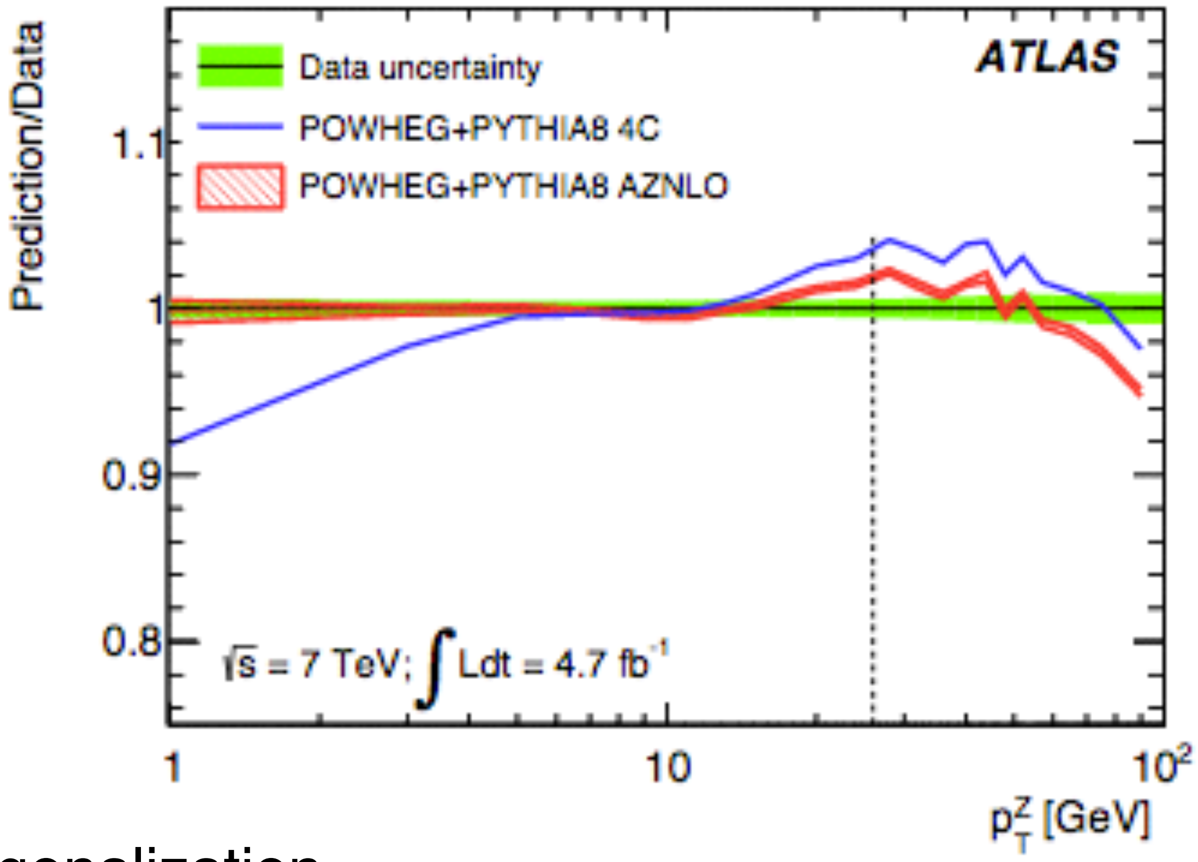
JHEP, 09:145, 2014

1211.6899

Strategy for the Powheg+Pythia8 tune → tunes performed for $p_T(Z)<26$GeV and $\phi^*_\eta<0.29$ (best description of the tuning parameters)

The tuning only varies the ISR shower cut-off and the primordial k_T in Pythia8: essentially constrained by data $p_T(Z)<12$GeV - not affected by tuning upper bound (plus MPI parameters)

Tuned predictions agree with the measured XS within 2% for $p_T(Z)<50$GeV



“Eigentune variations”:

only covering ISR/primordial-k_T variations scale variations for FSR and MPI cut-off paramaters are recommended to cover the full range of UE/PS/MPI uncertainties

- VAR1,VAR2: eigentune diagonalization
- MPIUp, MPIDown
- FSRUp, FSRDown

(CTEQ6L1) LO PDF
Main31 ME+PS matching