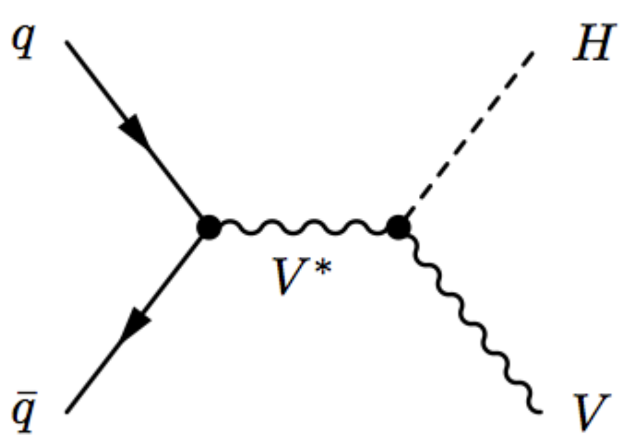
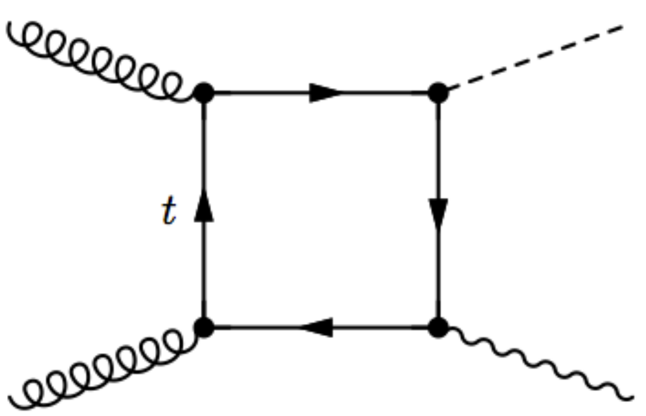
WG1:VH overview

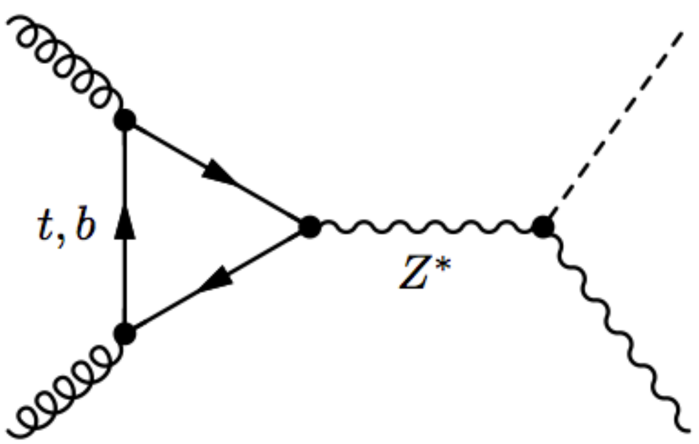
Thomas Calvet, Giancarlo Ferrera, Chris Palmer, Emanuele Re, Ciaran Williams, Carlo Pandini

16th Workshop of the LHC Higgs Cross Section Working Group

Cern, 16-18 October 2019







Overview

"Theory uncertainties" for VH

State-of-the-art VH modeling

Latest theory results

General overview of HXSWG-VH activities,
open points for discussions,
news from the VH-world,
experimental "wishes", ...

Overview

"Theory uncertainties" for VH

State-of-the-art VH modeling

Latest theory results

"Recently" topic of many discussions,
theory community interested in supporting experimental analyses limited by TH

- what are TH uncertainties in an ATLAS/CMS analysis?
- which TH uncertainties are typically critical for VH analyses?
- what would we need to improve?
- (parton-shower)

Overview

"Theory uncertainties" for VH

State-of-the-art VH modeling

Latest theory results

State-of-the-art for VH Monte Carlo modeling

- latest improvement vs current signal model in use from ATLAS and CMS
- the usual suspect: $gg \to ZH$
- where do we need improvement?
  how to combine different new tools?

Overview

"Theory uncertainties" for VH

State-of-the-art VH modeling

Latest theory results

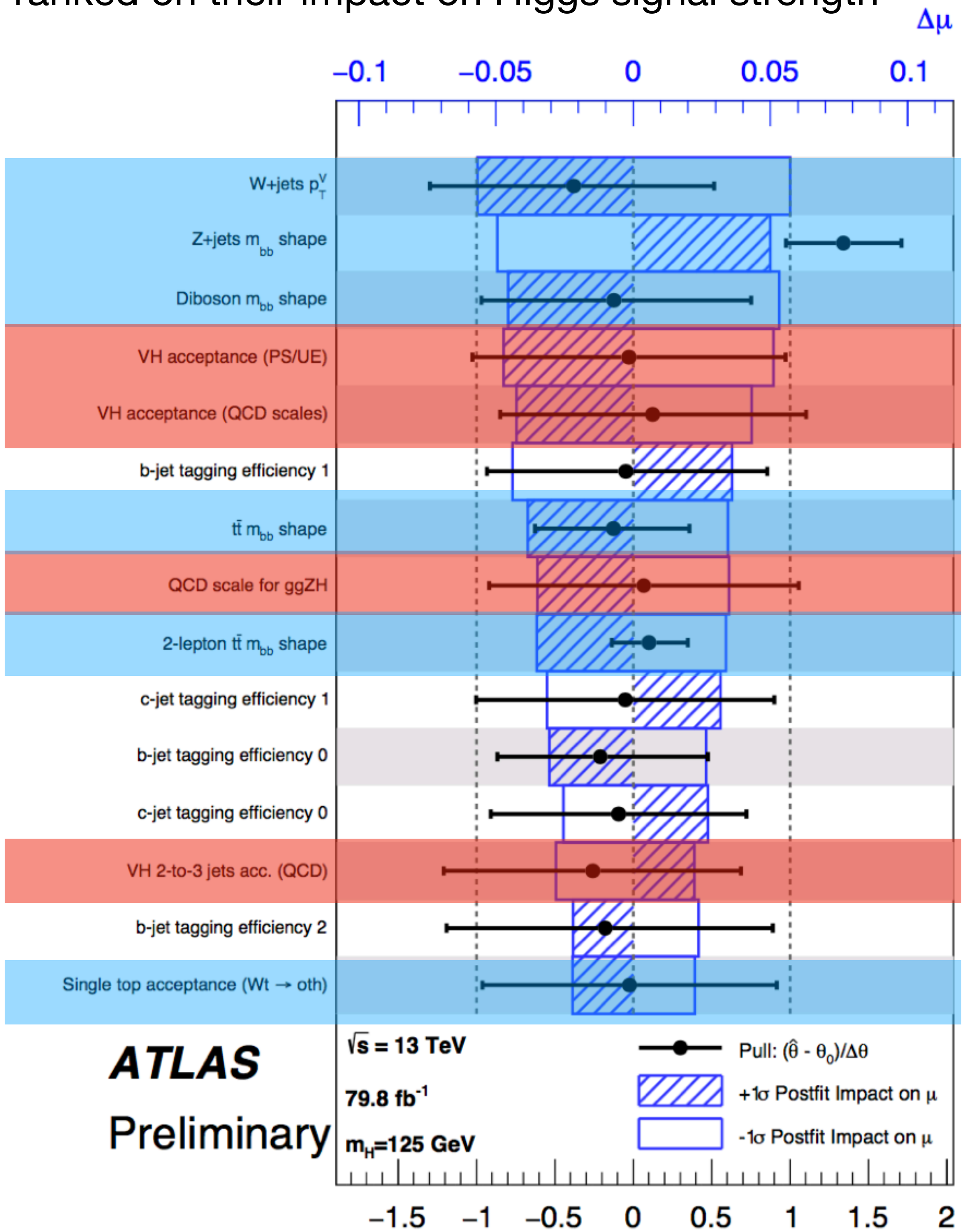
New prospects and interesting VH topics

- CP observables from VH production

Theory uncertainties in VH analysis

As usual, VH(bb) is the main candidate to consider VH production in exp. analyses ...

ATLAS uncertainties
ranked on their impact on Higgs signal strength



The usual message is: theory uncertainties are <u>very</u> important for VH(bb) analyses

Starting from the VH backgrounds ...

Answering the question**: how do we improve?** is far from being trivial

Background processes: Z/W+heavy flavor

Theory uncertainty on (large) backgrounds can be **<u>pulled</u>** from their original values, or **<u>constrained</u>** to smaller uncertainties

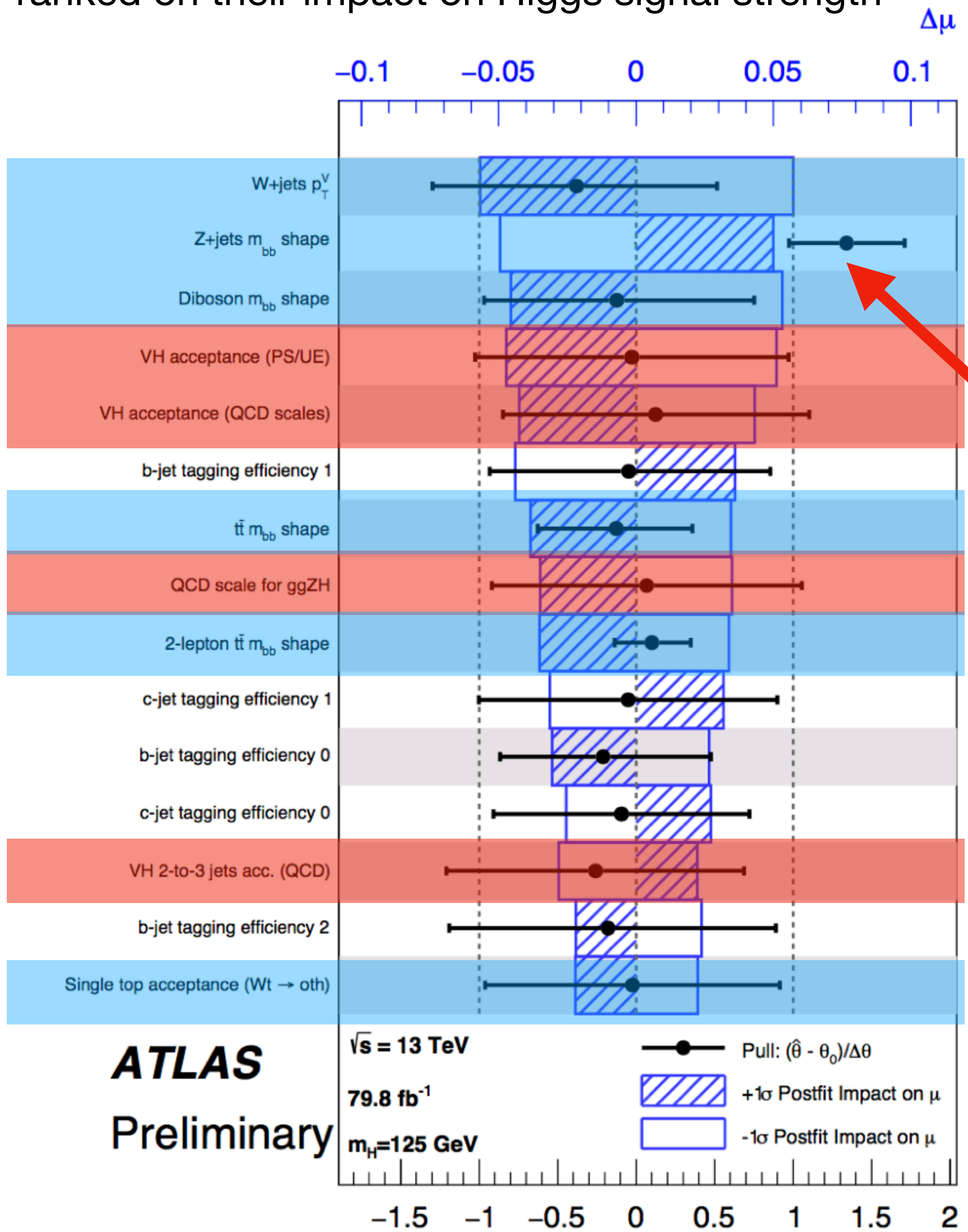
Important to remember: we are profiling these uncertainties in a fit to data !

Reducing the magnitude of the uncertainty is not guaranteed to improve the final results

Theory uncertainties in VH analysis

As usual, VH(bb) is the main candidate to consider VH production in exp. analyses ...

ATLAS uncertainties
ranked on their impact on Higgs signal strength



The usual message is: theory uncertainties are <u>very</u> important for VH(bb) analyses

Starting from the VH backgrounds ...

Answering the question**: how do we improve?**
is far from being trivial

Background processes: Z/W+heavy flavor

Theory uncertainty on (large) backgrounds can be **<u>pulled</u>** from their original values, or **<u>constrained</u>** to smaller uncertainties

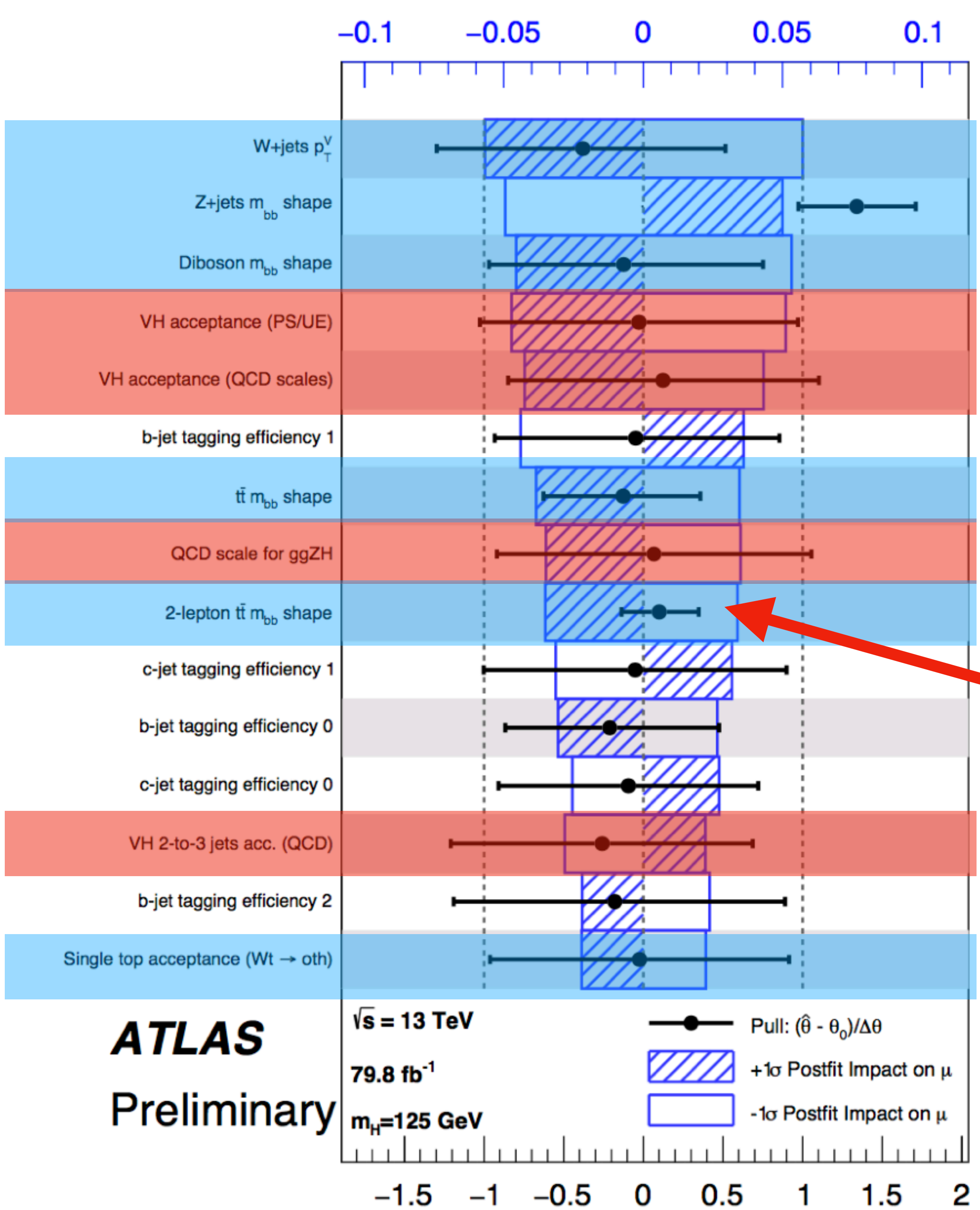
Important to remember: we are profiling these uncertainties in a fit to data !

Reducing the magnitude of the uncertainty is not guaranteed to improve the final results

Theory uncertainties in VH analysis

As usual, VH(bb) is the main candidate to consider VH production in exp. analyses ...

ATLAS uncertainties
ranked on their impact on Higgs signal strength



The usual message is: theory uncertainties are <u>very</u> important for VH(bb) analyses

Starting from the VH backgrounds ...

Answering the question: **how do we improve?** is far from being trivial

Background processes: Z/W+heavy flavor

Theory uncertainty on (large) backgrounds can be **<u>pulled</u>** from their original values, or **<u>constrained</u>** to smaller uncertainties

Important to remember: we are profiling these uncertainties in a fit to data !

Reducing the magnitude of the uncertainty is not guaranteed to improve the final results

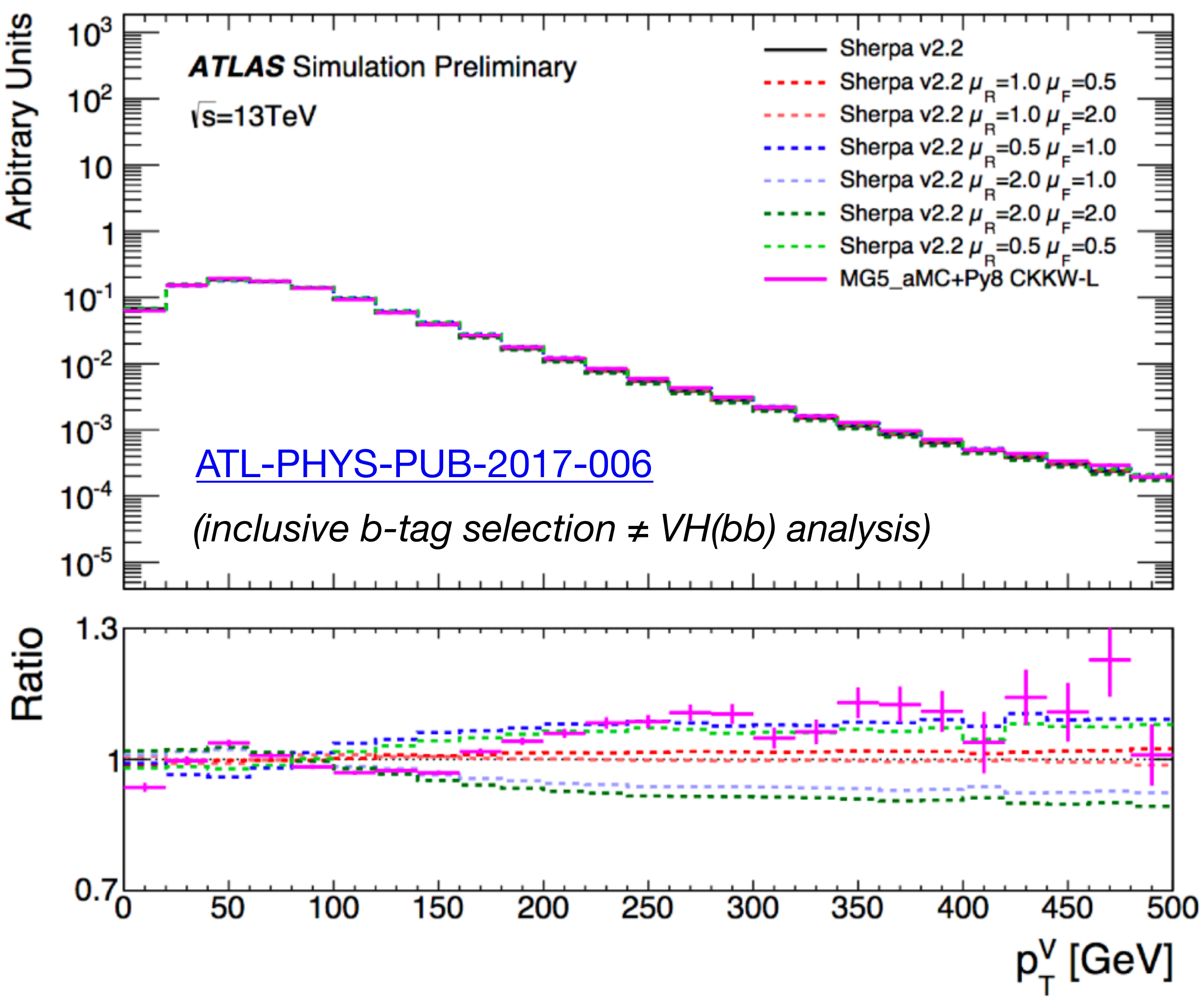
What are theory uncertainties for us?

All Higgs analyses rely on **Profile Likelihood Ratio fit to data** to extract the signal:
theory uncertainties encoded as Nuisance Parameters in the Likelihood

$$L(\mu, \vec{\beta}_{samp}, \vec{\theta}_s, \vec{\theta}_b, \vec{\theta}_{global}) = Pois(n|\mu_T) \cdot Pois(n_{samp}|\beta_{samp}) \cdot (\vec{\theta}_s, \vec{\theta}_b, \vec{\theta}_{global}),$$

- normalization effect: relative acceptance across different categories (and total XS)
- shape effect on discriminating variables / MVA input variables

We are not 'just' adding an uncertainty on the signal or background estimate
We are not 'just' adding an uncertainty on the final results (XS, signal strength, STXS, ...)



Example: **pT(V) theory uncertainty from Sherpa/Madgraph**

- shape-effect across the full pT(V) spectrum
- bin-by-bin correlated
- pull / constraint in the high-stat low-pT(V) region correlated to high-pT(V) shape
- same happens for CR-to-SR extrapolations

We use these theory unc. to implement a correlation model across our phase-space

What are theory uncertainties for us?

All Higgs analyses rely on **Profile Likelihood Ratio fit to data** to extract the signal:
theory uncertainties encoded as Nuisance Parameters in the Likelihood

$$L(\mu, \vec{\beta}_{samp}, \vec{\theta}_s, \vec{\theta}_b, \vec{\theta}_{global}) = Pois(n|\mu_T) \cdot Pois(n_{samp}|\beta_{samp}) \cdot (\vec{\theta}_s, \vec{\theta}_b, \vec{\theta}_{global}),$$

- normalization effect: relative acceptance across different categories
- shape effect on discriminating variables / MVA input variables

We are not 'just' adding an uncertainty on the signal or background estimate
We are not 'just' adding an uncertainty on the final results (XS, signal strength, STXS, ...)

*Lots of data available: we can likely reduce the magnitude of modeling uncertainties by **constraining them with data measurements***

*We are still going to build a **~theory-based extrapolation model** to correlate the analysis phase space: properly built theory uncertainties on our background model to control migrations / correlations / extrapolations (motivated by physics arguments)*

(often now relying on very naive TH uncertainties estimate: e.g. Sherpa/Madgraph)

ATLAS and CMS background model

Project started from ATLAS and CMS Higgs WG, hosted by HXSWG.

Goal: compare background predictions Z/W+heavy flavor in VH(bb) "*pre-fit*"

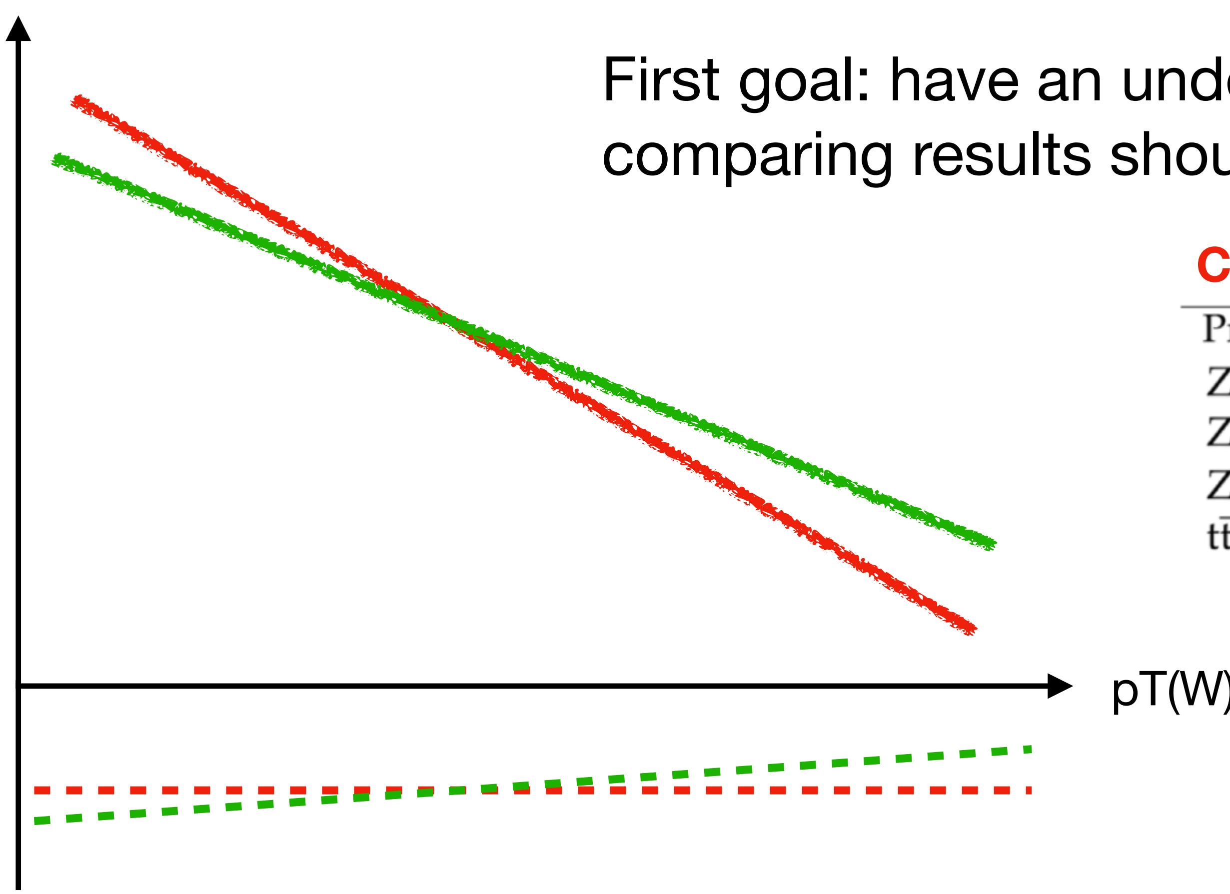
CMS (Madgraph V+0,1,2,3,4j@LO)

Background reweighting corrections for V+jets:

- $f(p_T^V)$ inclusive EW corrections
- $f(p_T^V)$ 1-lepton correction: W+light, W+b(b), ttbar, single-t
- deltaEta(jj) correction from LO/NLO
- CRs defined by inverting M(jj)-window

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

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



First goal: have an understanding of the "starting points"
comparing results should become much easier ...

CMS

Process	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T	$Z(\ell\ell)H$ high-p_T
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
$Z + b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
$t\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

ATLAS

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

Example! Adding the effect of each correction separately, systematic uncertainties, ...

ATLAS and CMS background model

Project started from ATLAS and CMS Higgs WG, hosted by HXSWG.

Goal: compare background predictions Z/W+heavy flavor in VH(bb) "*pre-fit*"

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

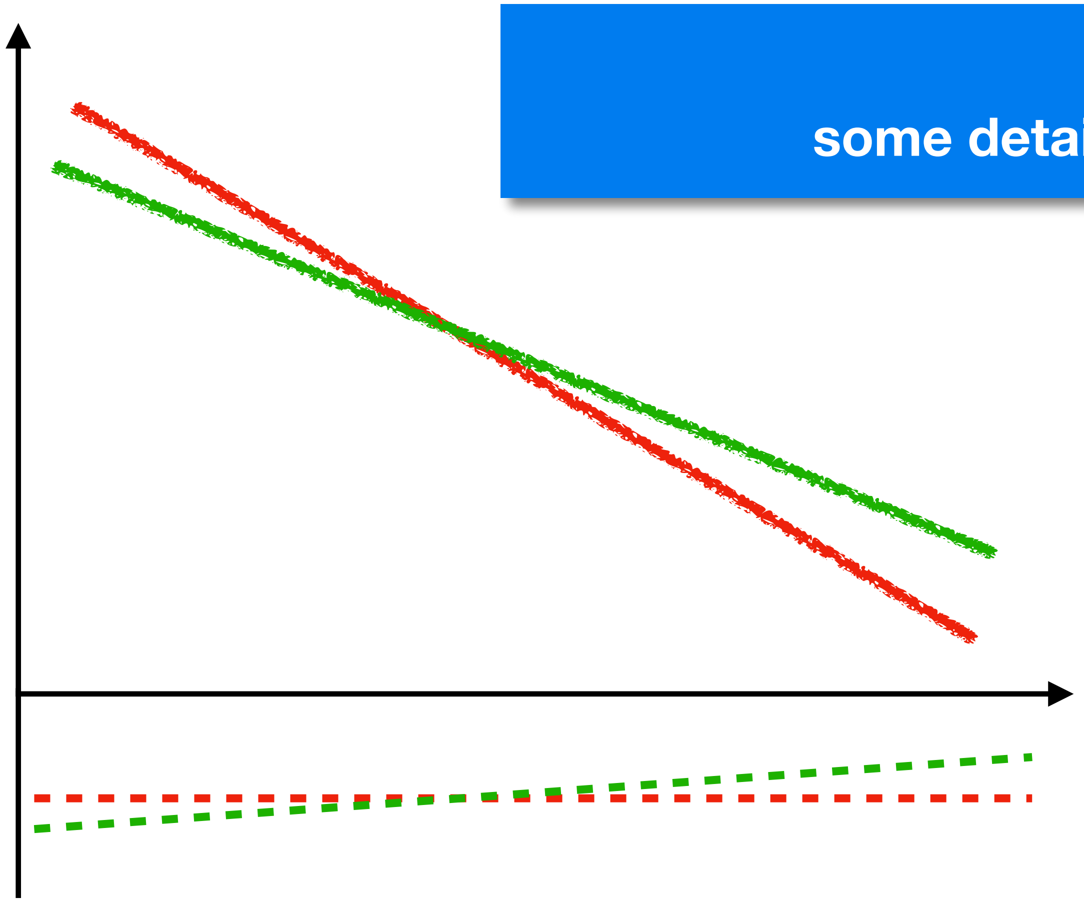
Background reweighting corrections for V+jets:

- $f(p_T^V)$ inclusive EW corrections
- $f(p_T^V)$ 1-lepton correction:
  W+light, W+b(b), ttbar, single-t
- deltaEta(jj) correction from LO/NLO
- CRs defined by inverting M(jj)-window

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

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

First plots and results ready!
some details to digest, so they are not shown today



CMS

Process	Z(νν)H	W(ℓν)H	Z(ℓℓ)H low-p_T	Z(ℓℓ)H high-p_T
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$\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
t$\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

ATLAS

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

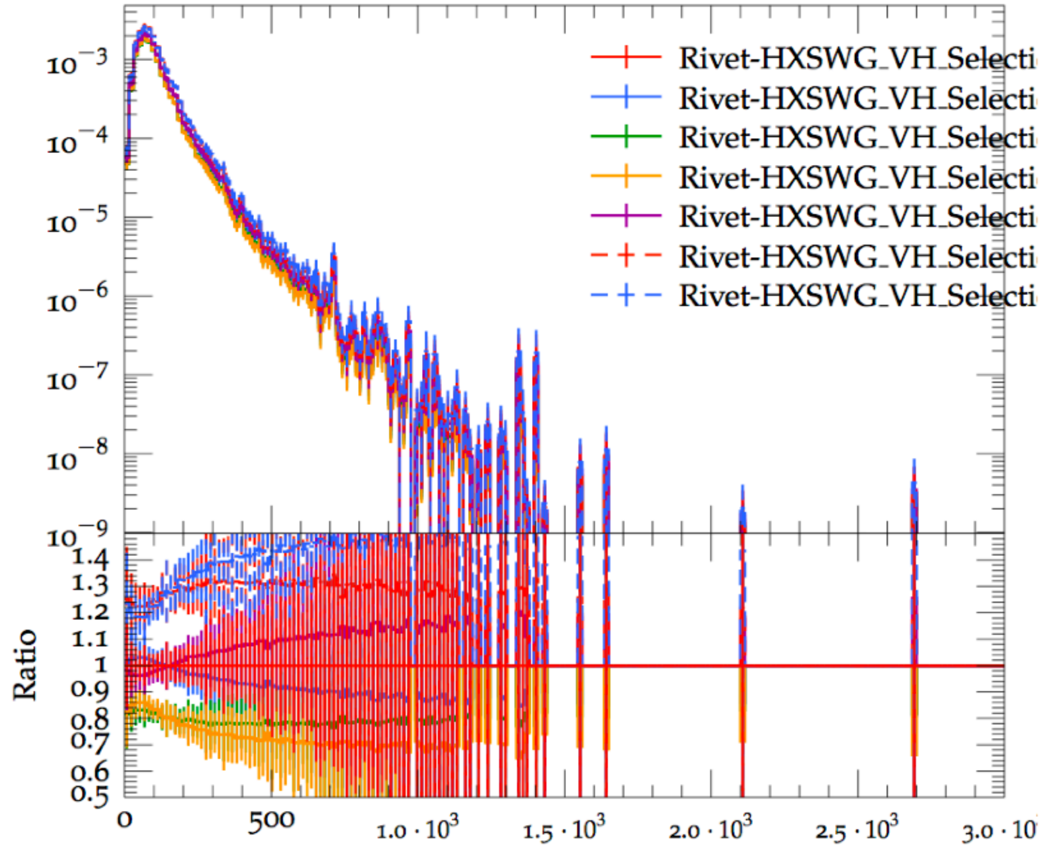
Example! Adding the effect of each correction separately, systematic uncertainties, ...

V+heavy flavor background model

HXSWG-VH: use ATLAS/CMS study to boost a detailed work on V+heavy flavor modeling for VH(bb)?
Already discussed and proposed/started in the past: this is a good starting point to pick it up

(Interest from several MC groups and authors)

- **POWHEG+MiNLO** for Wbbar [Oleari et al., arXiv:1502.01213]
- **Sherpa V+HF** @ NLO+PS (multi-jet merging) [Krauss et al., arXiv:1612.04640]
- **Herwig7** (NLO standalone)
- high-jet multiplicity **f.o. prediction from BlackHat+Sherpa** (Wbb+3jets) [Anger et al., arXiv:1712.05721]
- (possibly) **4+5FS** implementation from Bagnaschi et al., arXiv:1803.04336



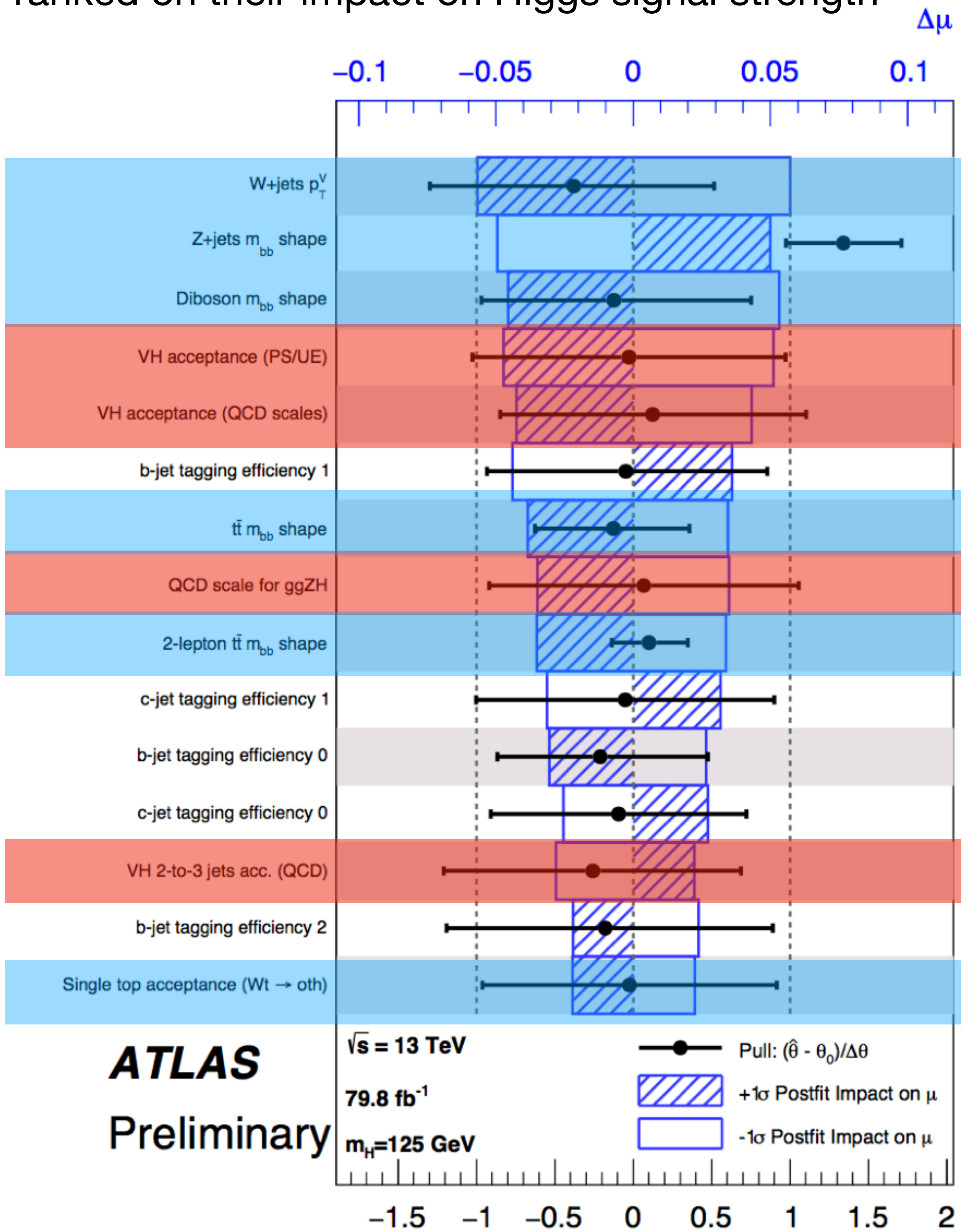
Very preliminary results shown by Emanuele at the 15th General Assembly (no further progress)

[Wbb NLO+PS, thanks to L. Buonocore, C. Oleari, F. Tramontano]

Theory uncertainties in VH analysis

As usual, VH(bb) is the main candidate to consider VH production in exp. analyses ...

ATLAS uncertainties
ranked on their impact on Higgs signal strength



The usual message is: theory uncertainties are <u>very</u> important for VH(bb) analyses

Moving to the VH signal processes ...

Answering the question**: how do we improve?**
is far from being trivial

Note: <u>cannot rely on data to constrain signal TH unc.!</u>

VH signal processes (in red on the left)

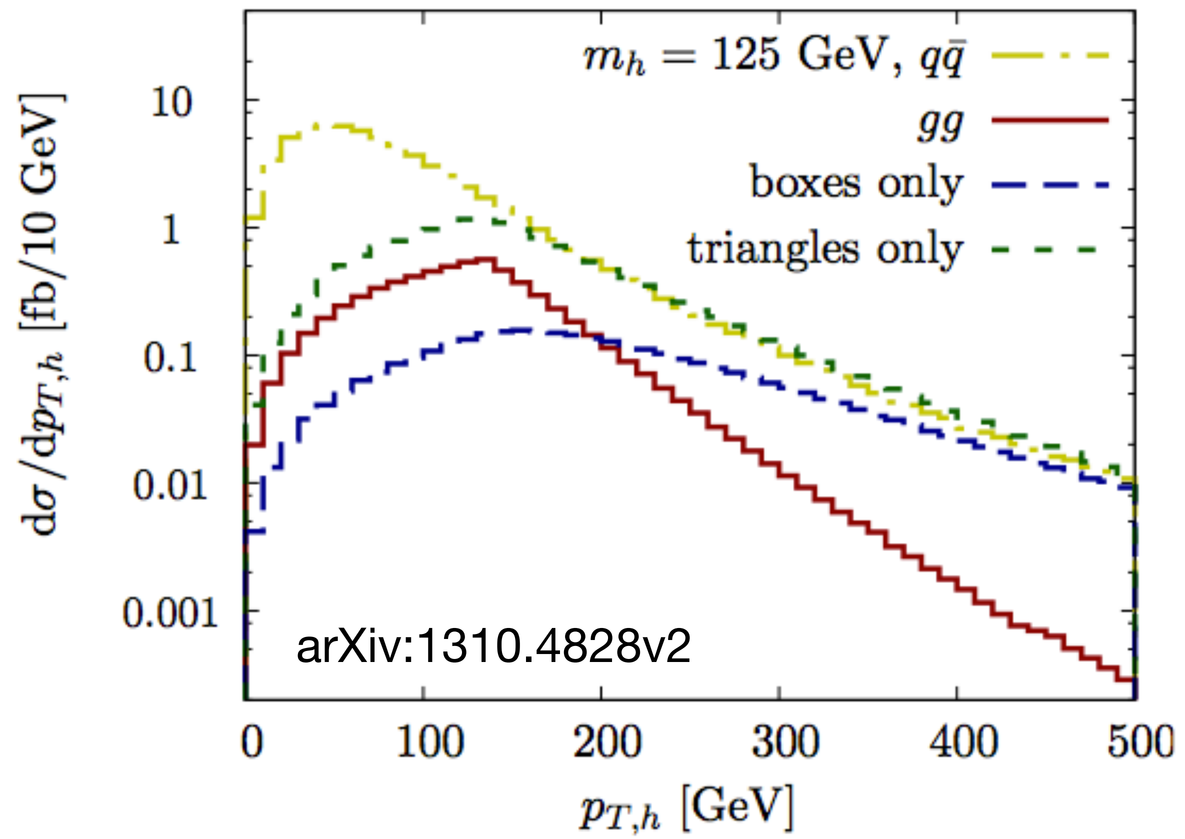
- **QCD perturbative uncertainties: partly addressed by STXS approach**
  - see talk by Chris this afternoon
- **Parton-shower "uncertainties"**
  - parallel session on Thursday
- **gg→ZH loop-induced production**

Towards ggZH@NLO

Loop-induced ggZH production provided at LO@QCD by POWHEG

- **loop-induced gg→ZH**: **NLO**(approx)+**NLL[QCD]** kNLO~2 from (mtop→∞) calculation
- **large theory uncertainty** (scale unc. ~25%)

XS(gg→ZH) O(15%) of total XS(pp→ZH)
enhanced contribution at medium-high p_T^V



Relying on the mtop→∞ approximation
(in the regime where the loop-induced contribution becomes interesting) is quite limiting

(bulk of the ggZH cross-section lives around 2mtop with production threshold around 216 GeV)

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

Cancellations exploited in HH may not be valid for ggZH

Number of mass scales is the main limiting factors, “numerics” might help in reducing the complexity [already exploited for single-top NNLO calculations]

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

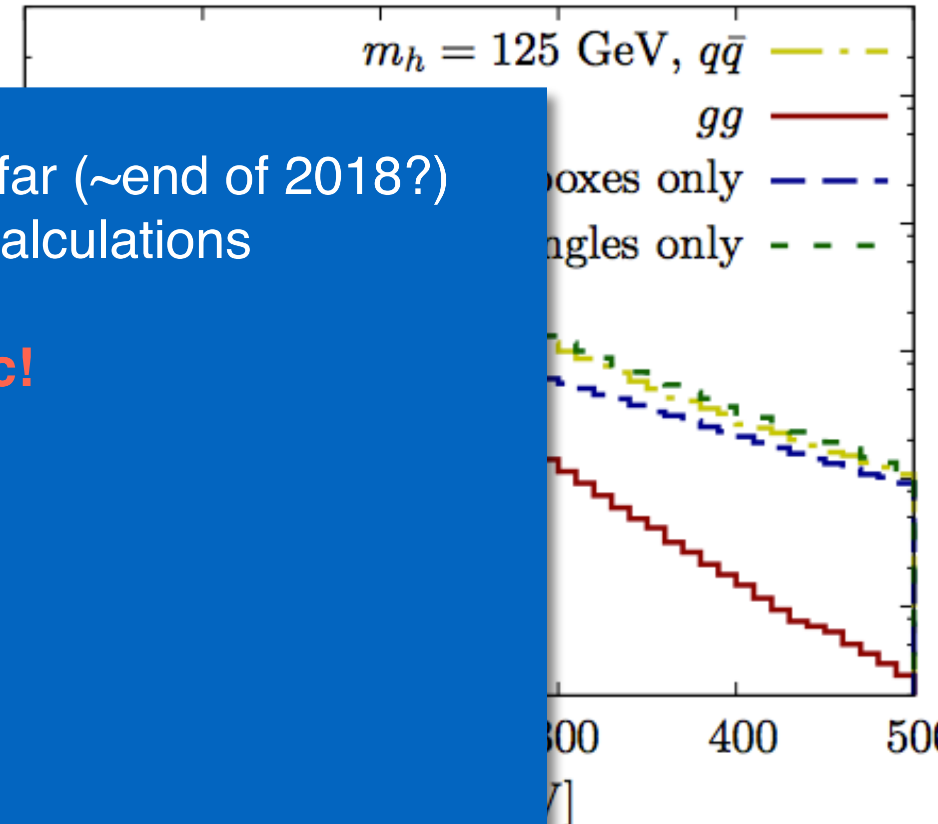
Double Higgs may lead the way - but lots of work needed for ggZH!

Towards ggZH@NLO

Loop-induced ggZH production provided at LO@QCD by POWHEG

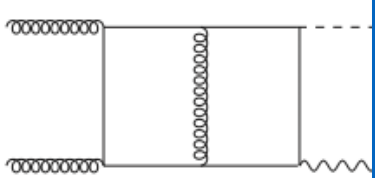
- **loop-induced gg→ZH**: **NLO**(approx)+**NLL[QCD]**
  kNLO~2 from (mtop→∞) calculation
- **large theory uncertainty** (scale unc. ~25%)

XS(gg→ZH) O(15%) of total XS(pp→ZH)
enhanced contribution at medium-high p_T^V



Relying on the mt
(in the regime wh
becomes interest

(bulk of the ggZH
with production th



Exact NLO ggZH calculation should not be too far (~end of 2018?)
given the recent improvements in HH calculations

Apparently overly optimistic!

Fiducial cross section	MCFM-8.0
no $gg \to HZ$	$7.14^{+0.5\%}_{-0.9\%}$ fb
with $gg \to HZ$	$7.92^{+2.0\%}_{-1.5\%}$ fb
no $gg \to HZ$, high-$p_{t,Z}$	$1.21^{+0.1\%}_{-0.2\%}$ fb
with $gg \to HZ$, high-$p_{t,Z}$	$1.49^{+5.3\%}_{-4.1\%}$ fb

Astill, Bizoń, Re, Zanderighi

pT(H)>150GeV
From sub-percent level
to O(5%) TH uncertainty

Numerical appro

1. generation of
2. reduction of a
3. computation o

ations exploited in HH may
valid for ggZH

Number o complexity

[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!

gg→ZH modeling

process	p_T^V boundaries [GeV]	Cross Section [fb]	QCD unc [%]
WH	[0, 75[	216.4	3.0
WH	[75, 150[	135.0	3.4
WH	[150, 250[	41.24	3.6
WH	[250, ∞[	12.16	3.9
ZH	[0, 75[	112.4	6.7
ZH	[75, 150[	87.0	7.8
ZH	[150, 250[	32.3	12
ZH	[250, ∞[	8.33	10
$gg \to ZH$	[0, 75[	6.7	100
$gg \to ZH$	[75, 150[	17.0	37
$gg \to ZH$	[150, 250[	10.2	38
$gg \to ZH$	[250, ∞[	1.94	41

QCD uncertainty in STXS

Drell-Yan VH: QCD uncertainties from POWHEG MiNLO+PS scale variations

O(3-10%)

gg→ZH: QCD uncertainties from POWHEG LO+PS scale variations

O(100%)

Improvement from the MC side

From <u>mg5_aMC</u>@NLO, <u>Sherpa</u>:

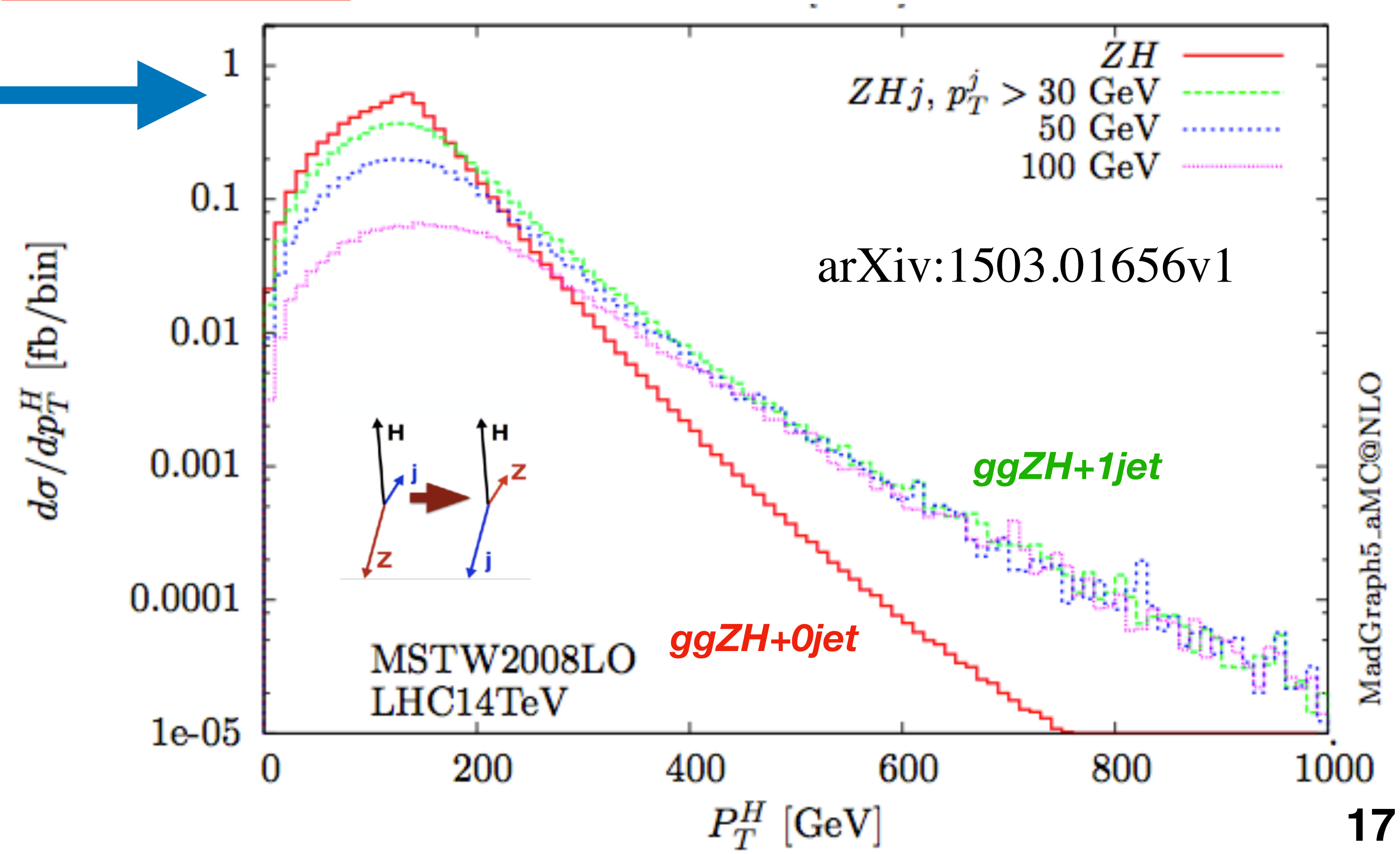
gg→ZH 0+1jet@LO multileg prediction

Improved modeling:

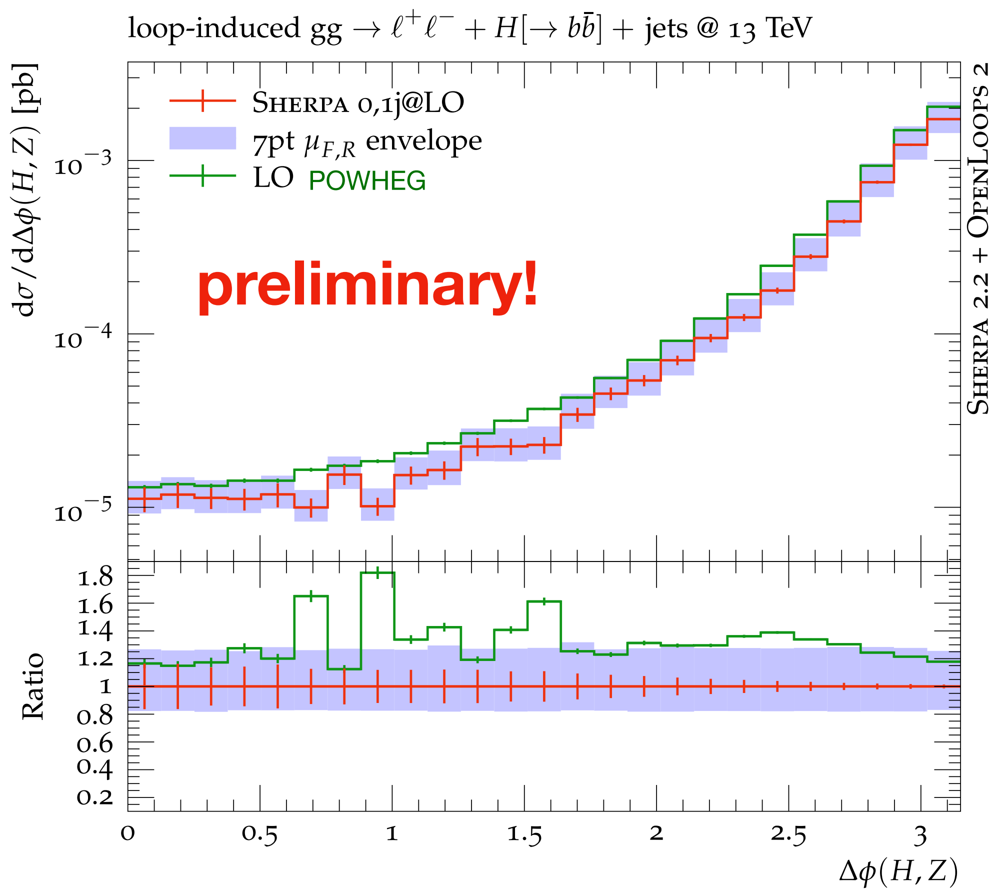
(ZH) recoiling against hard jet topologies

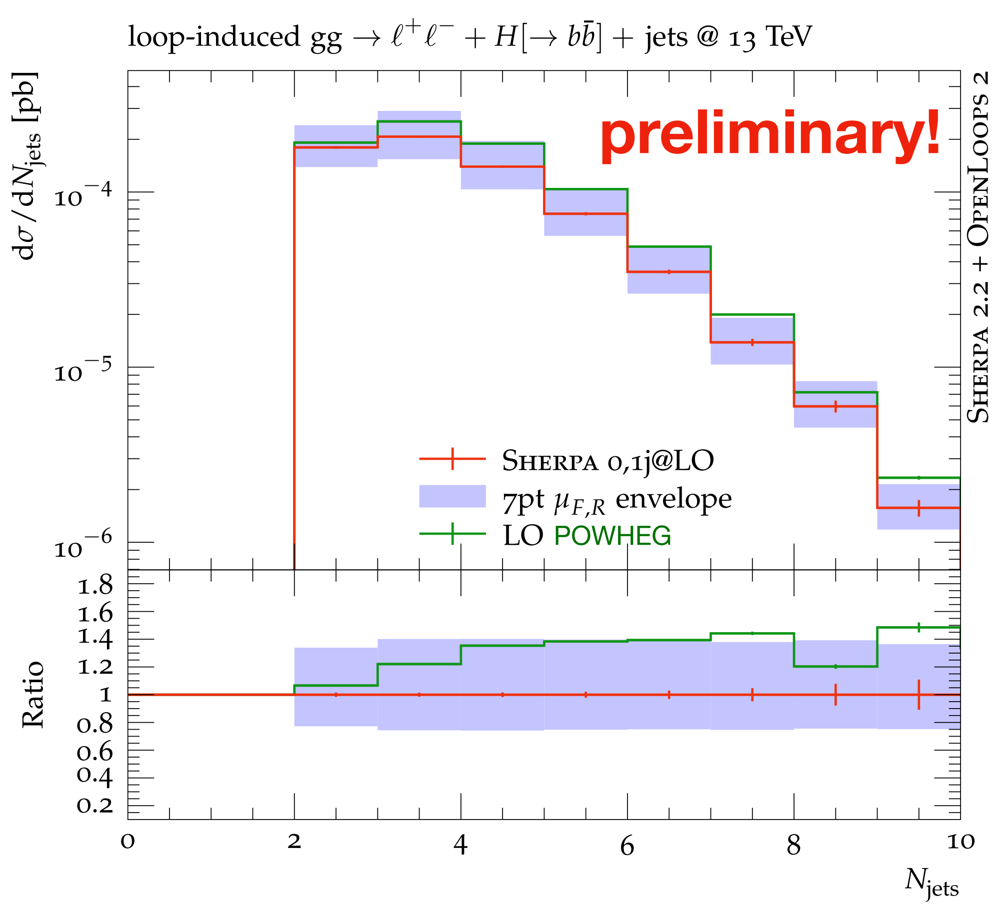
Les Houches Study:

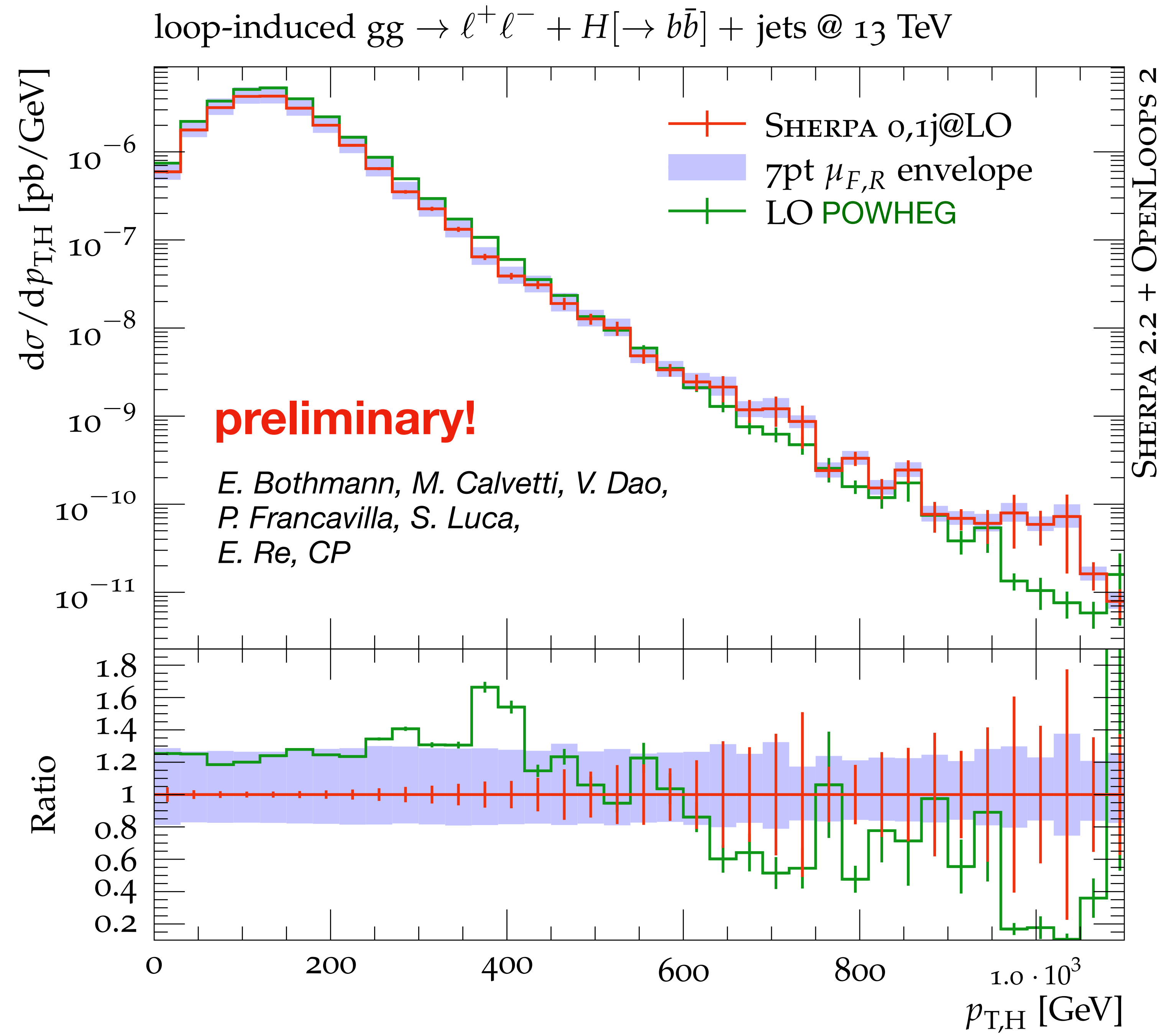
- multileg 0+1jet@LO setup vs inclusive LO (and ATLAS/CMS MC)
- QCD uncertainties across STXS bin categorization



gg→ZH modeling







First plots from **Sherpa** and **POWHEG,**
mg5_aMC@NLO+Pythia8 setup almost ready
(thanks to Eleni for the mg5 feedback)

Modeling of VH processes: state-of-the-art

Many new improvements on VH modeling, not yet used by experimental collaborations

Current MC model from ATLAS and CMS:

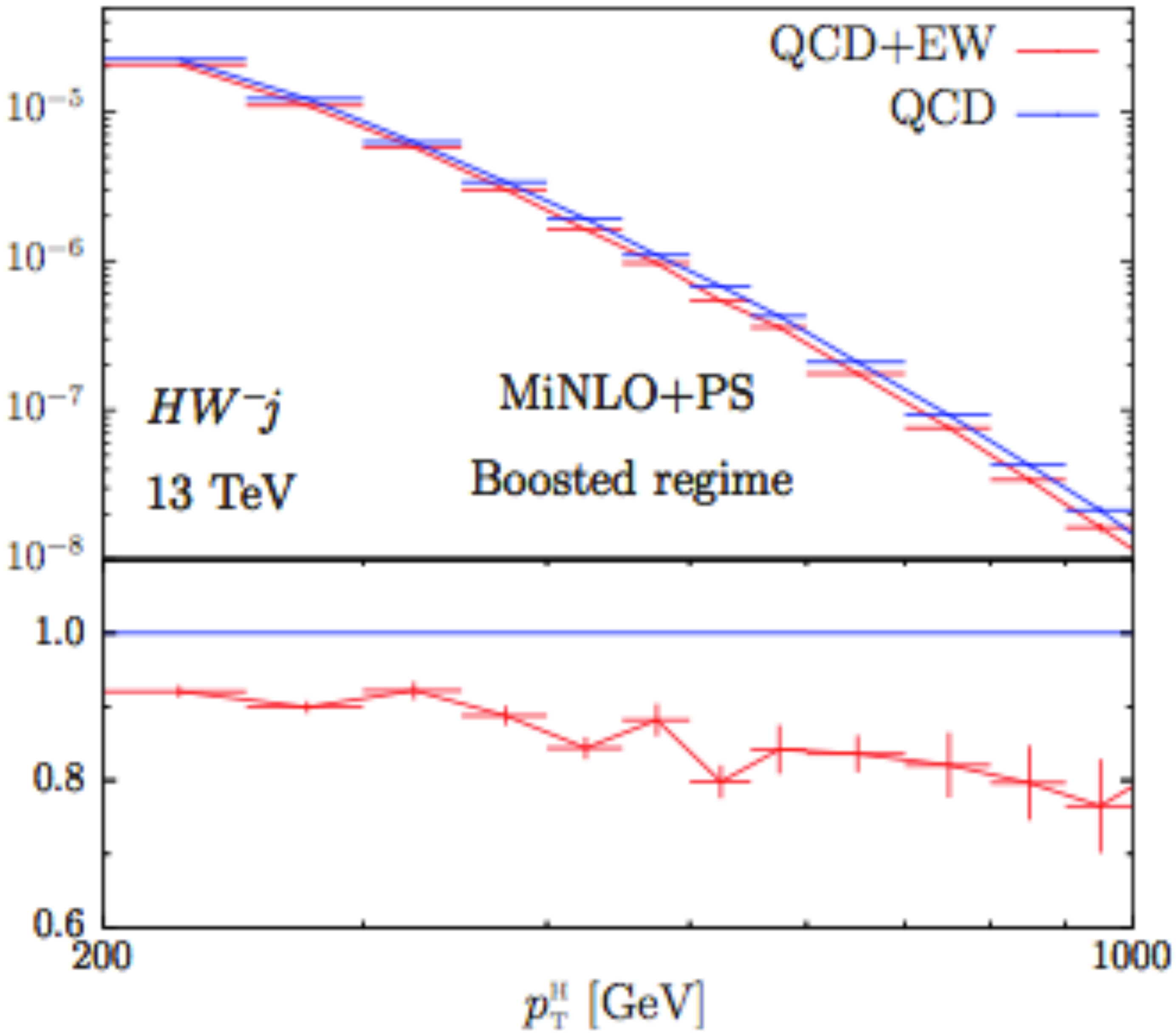
- Drell-Yan VH: POWHEG MiNLO (HZJ, HWJ) + Pythia8; HAWK EW reweighting in pT(V)
- gg→ZH: POWHEG LO + Pythia8

H(→bb) decay modeled by Pythia8 parton-shower

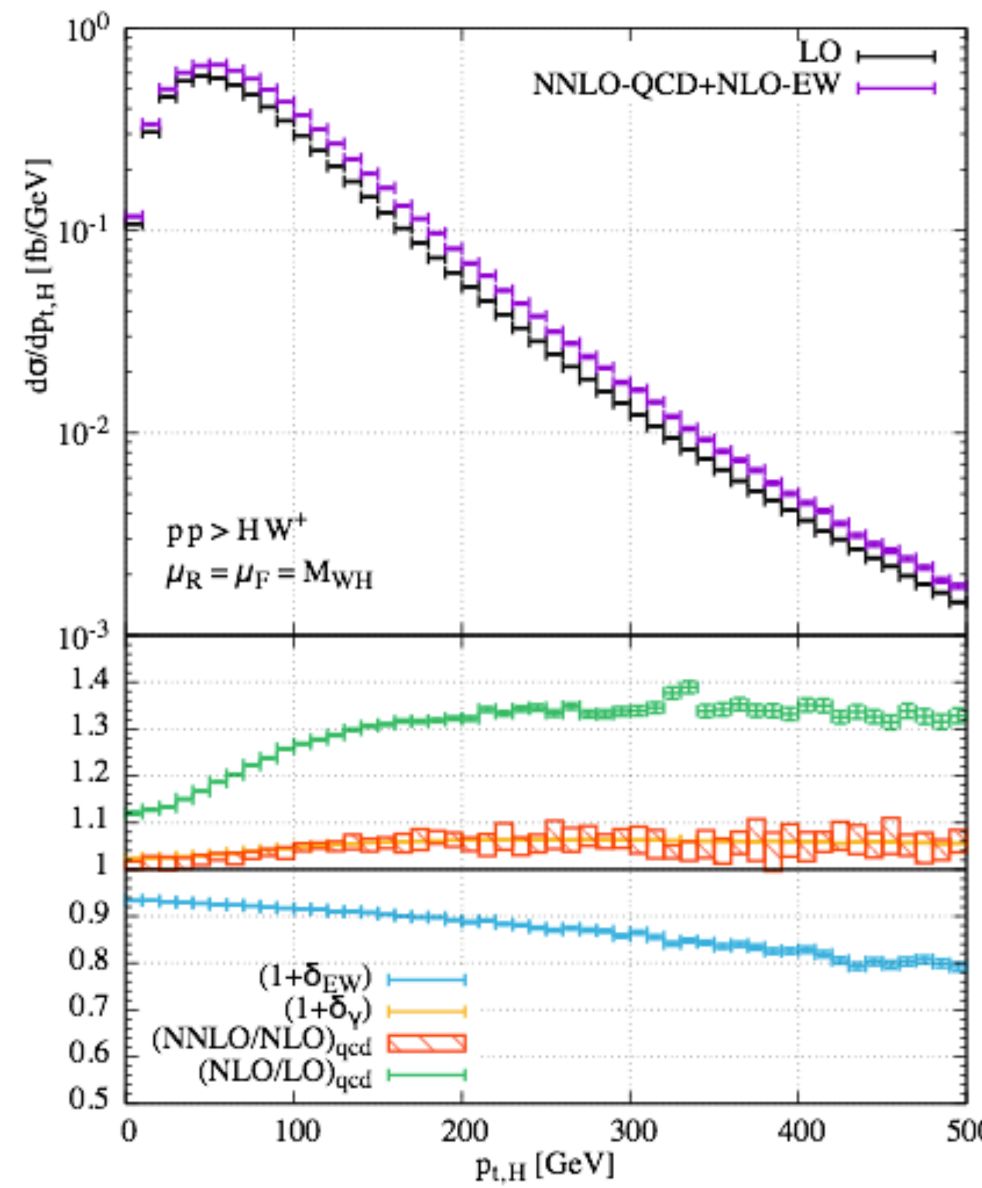
NLO Electroweak corrections: now available from MC codes

Granata, Lindert, Oleari, Pozzorini

MiNLO-accurate in QCD & EW



Consistent with YR4 corrections



Modeling of VH processes: state-of-the-art

Many new improvements on VH modeling, not yet used by experimental collaborations

Current MC model from ATLAS and CMS:

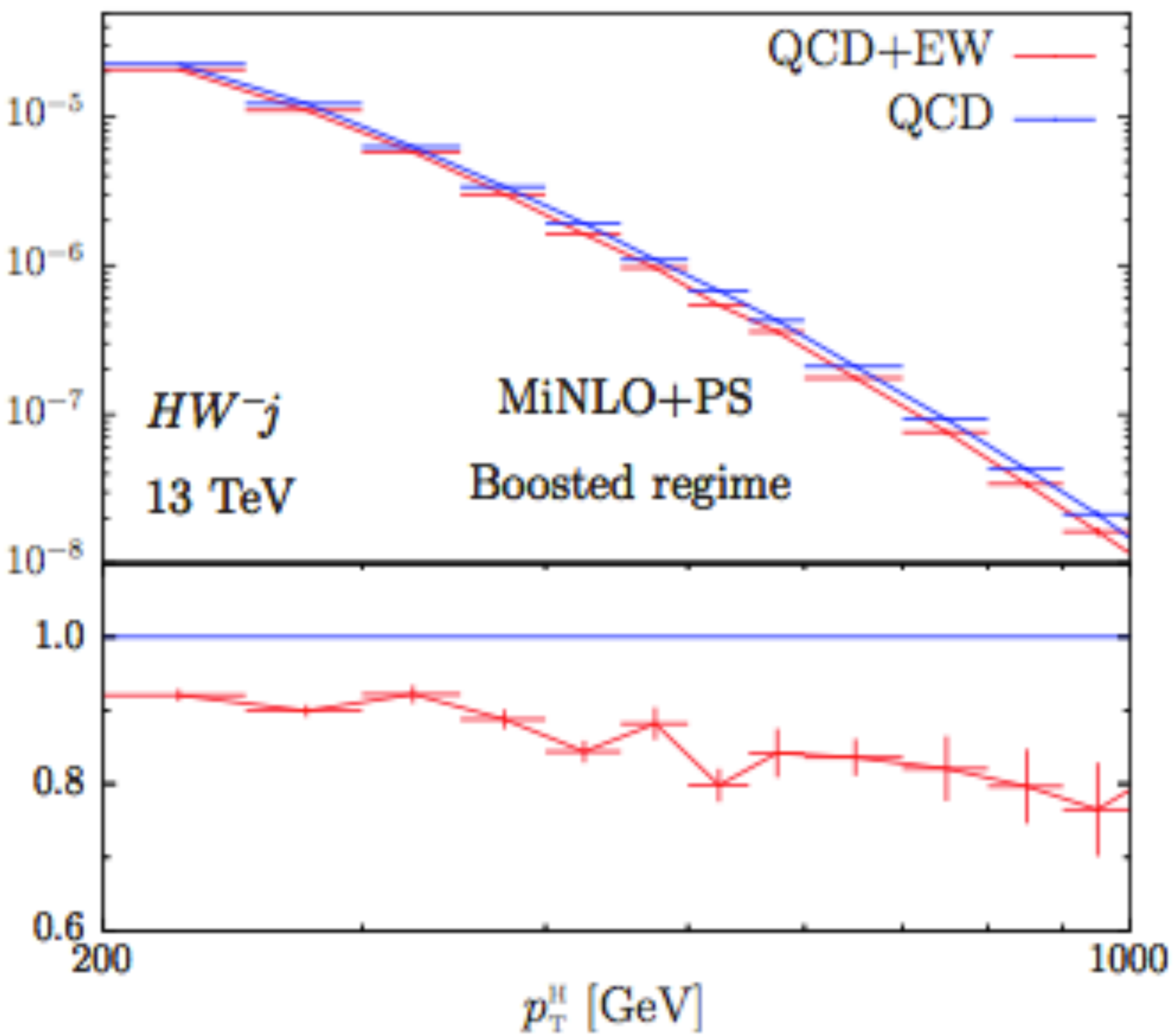
- Drell-Yan VH: POWHEG MiNLO (HZJ, HWJ) + Pythia8; HAWK EW reweighting in pT(V)
- gg→ZH: POWHEG LO + Pythia8

H(→bb) decay modeled by Pythia8 parton-shower

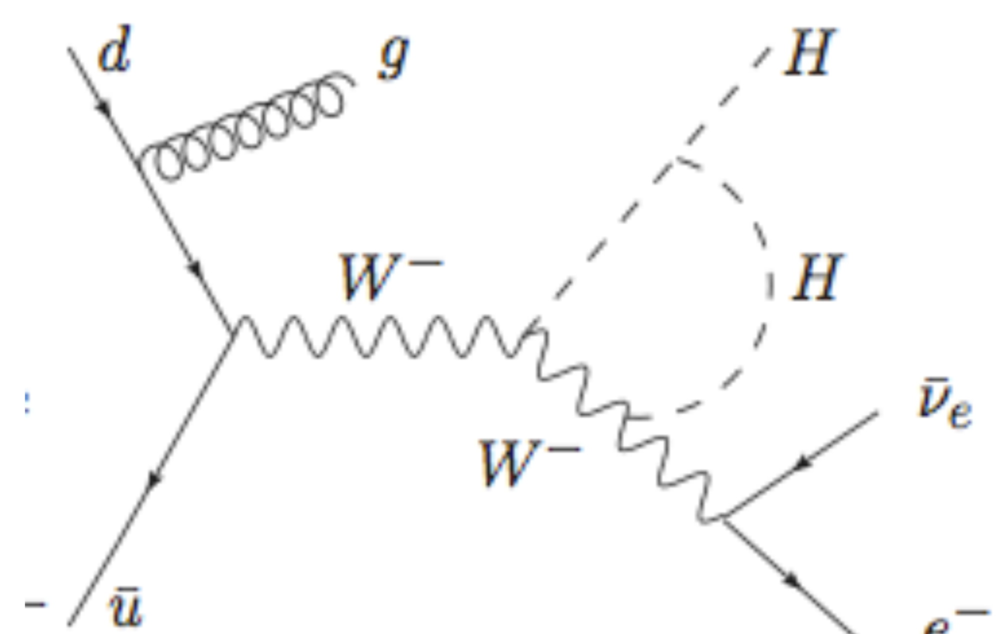
NLO Electroweak corrections: now available from MC codes

Granata, Lindert, Oleari, Pozzorini

MiNLO-accurate in QCD & EW



NLO EW corrections introduce dependence on Higgs trilinear coupling:



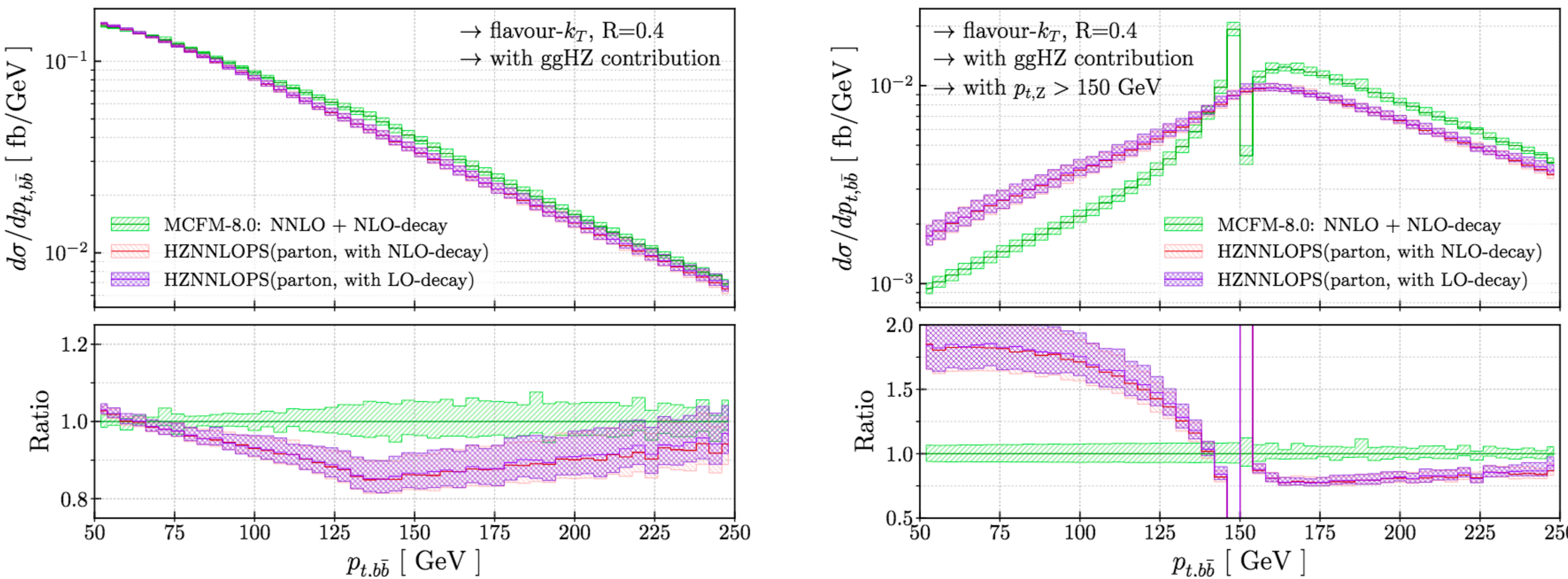
Recently used to extract k_lambda from single-Higgs production measurements: VH sensitive at low-pT(H) ATL-PHYS-PUB-2019-009

Modeling of VH processes: state-of-the-art

Astill, Bizoń, Re, Zanderighi

NNLOPS + NLO H(→bb) decay

- MCFM(HVNNLO) input for NNLO calculation, POWHEG-BOX-RES (MiNLO) for NLO corrections in production and in decay
- gg→ZH included (with mtop dependence) just at LO, no extra partons at fixed order



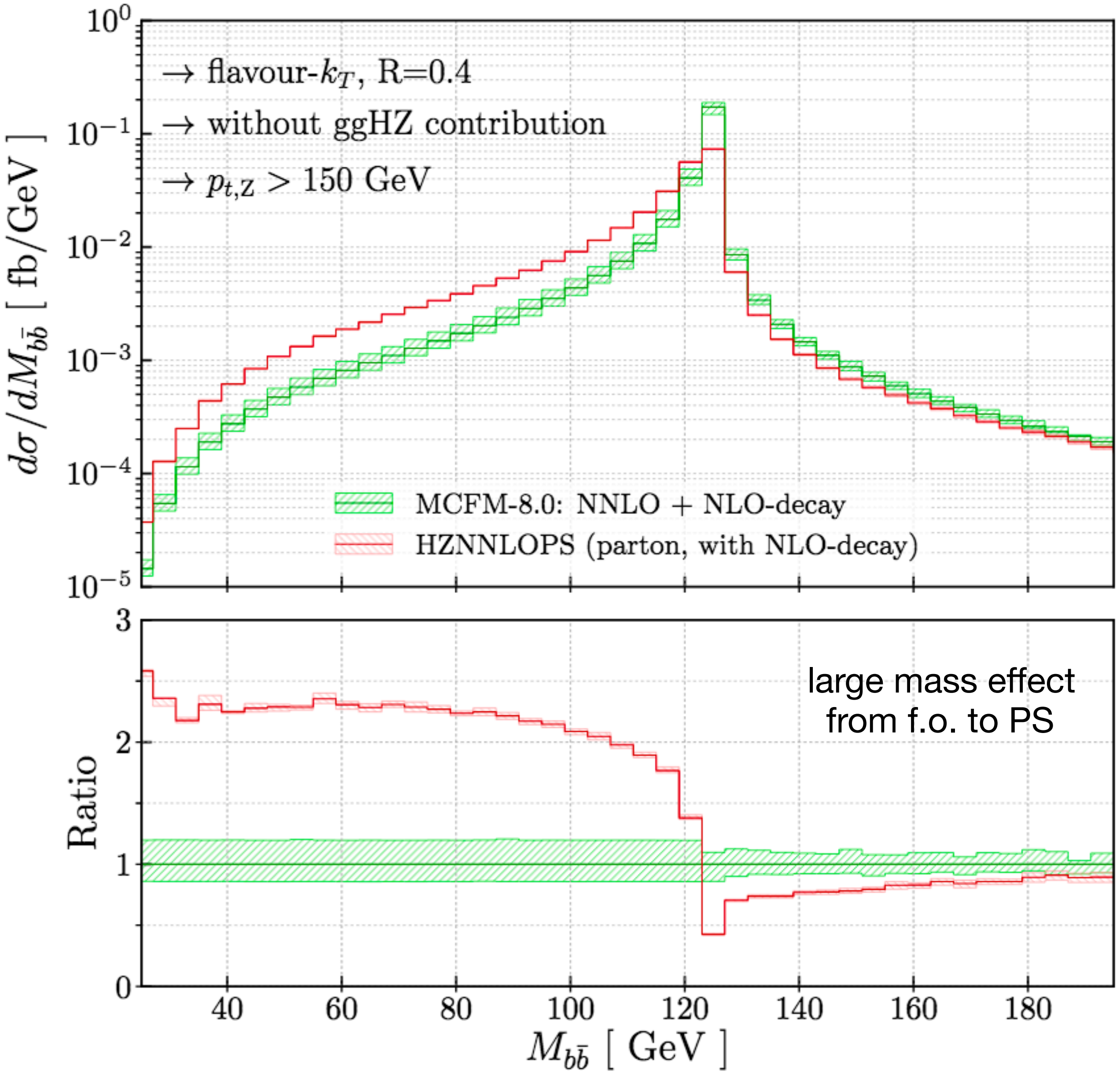
- green vs (red/purple): large effect from ggZH contribution (not accounted for in MCFM)

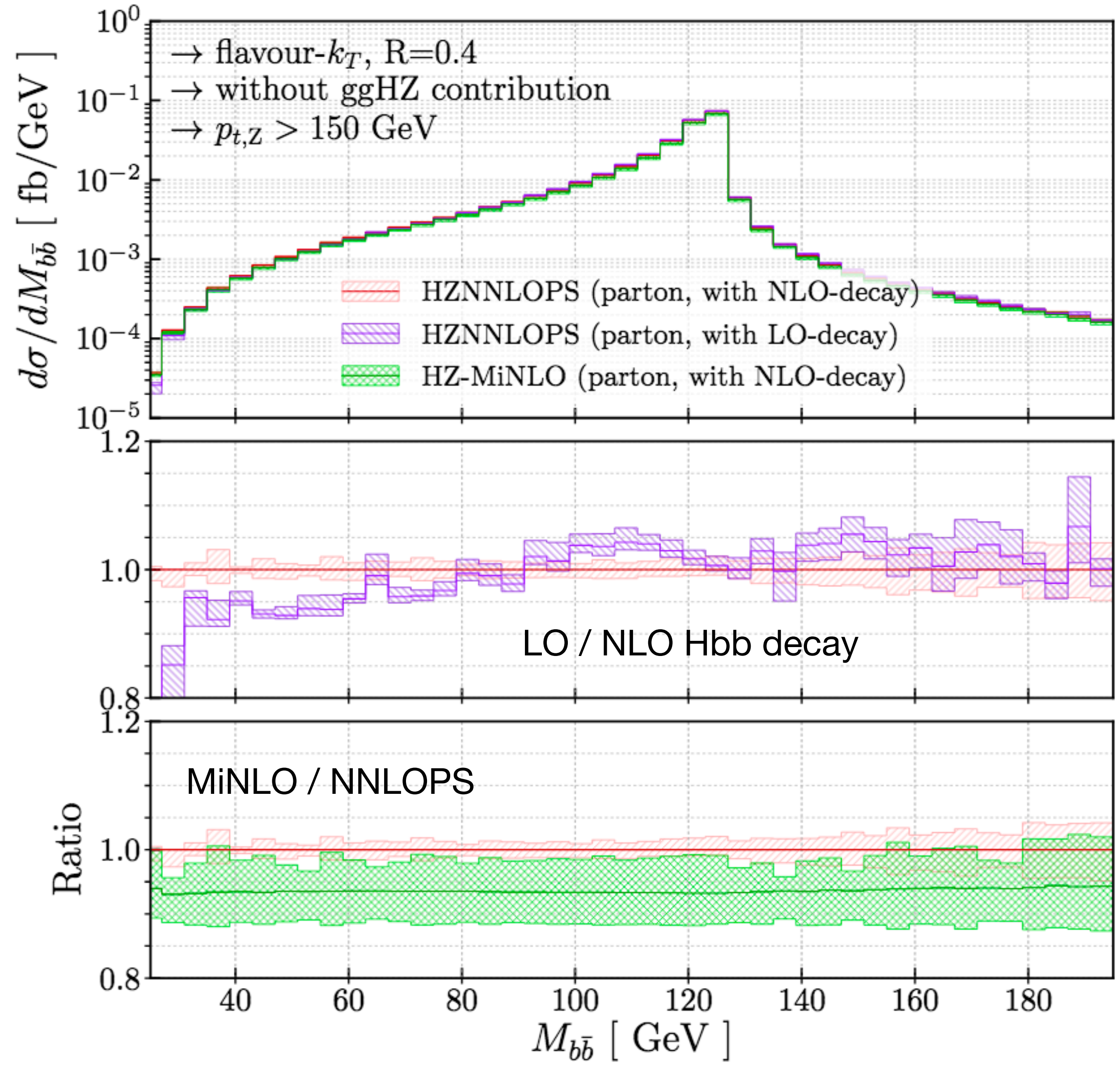
Modeling of VH processes: state-of-the-art

Astill, Bizoń, Re, Zanderighi

NNLOPS + NLO H(→bb) decay

- MCFM(HVNNLO) input for NNLO calculation, POWHEG-BOX-RES (MiNLO) fro NLO corrections in production and in decay
- gg→ZH included (with mtop dependence) just at LO, no extra partons at fixed order



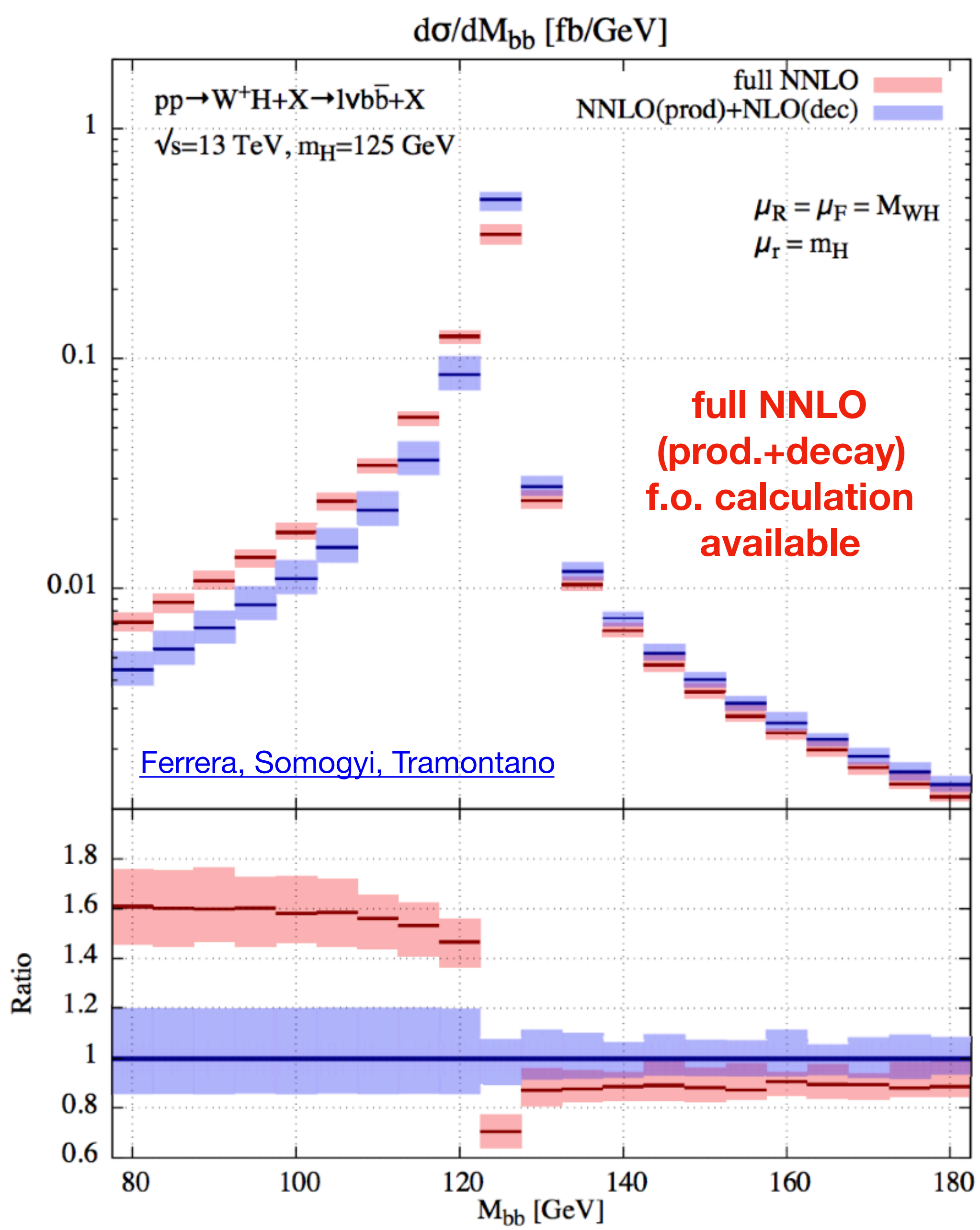


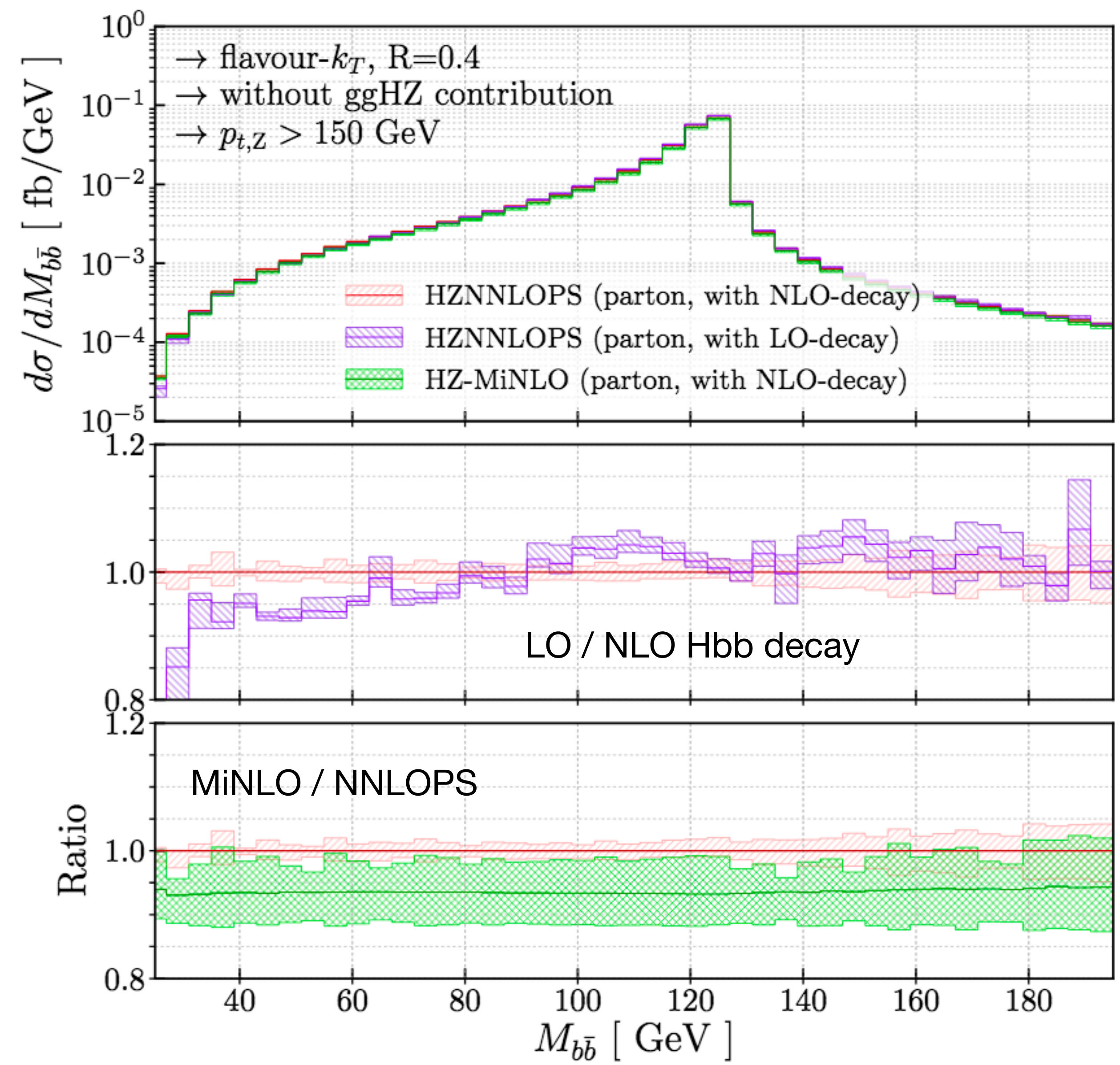
Modeling of VH processes: state-of-the-art

Astill, Bizoń, Re, Zanderighi

NNLOPS + NLO H(→bb) decay

- MCFM(HVNNLO) input for NNLO calculation, POWHEG-BOX-RES (MiNLO) fro NLO corrections in production and in decay
- gg→ZH included (with mtop dependence) just at LO, no extra partons at fixed order





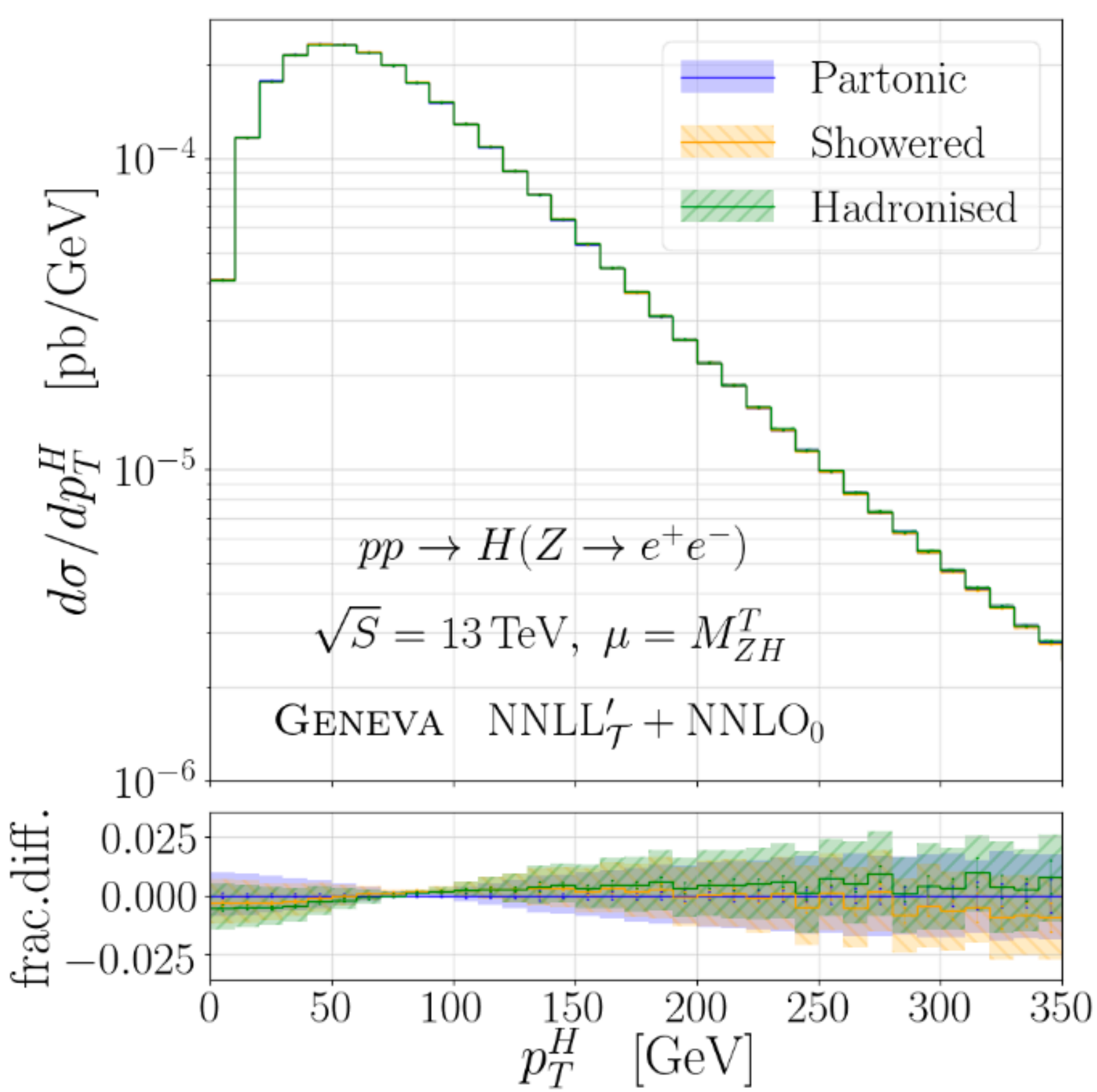
Caola, Luisoni, Melnikov, Röntsch   Gauld, Gehrmann-De Ridder, Glover, Huss, Majer

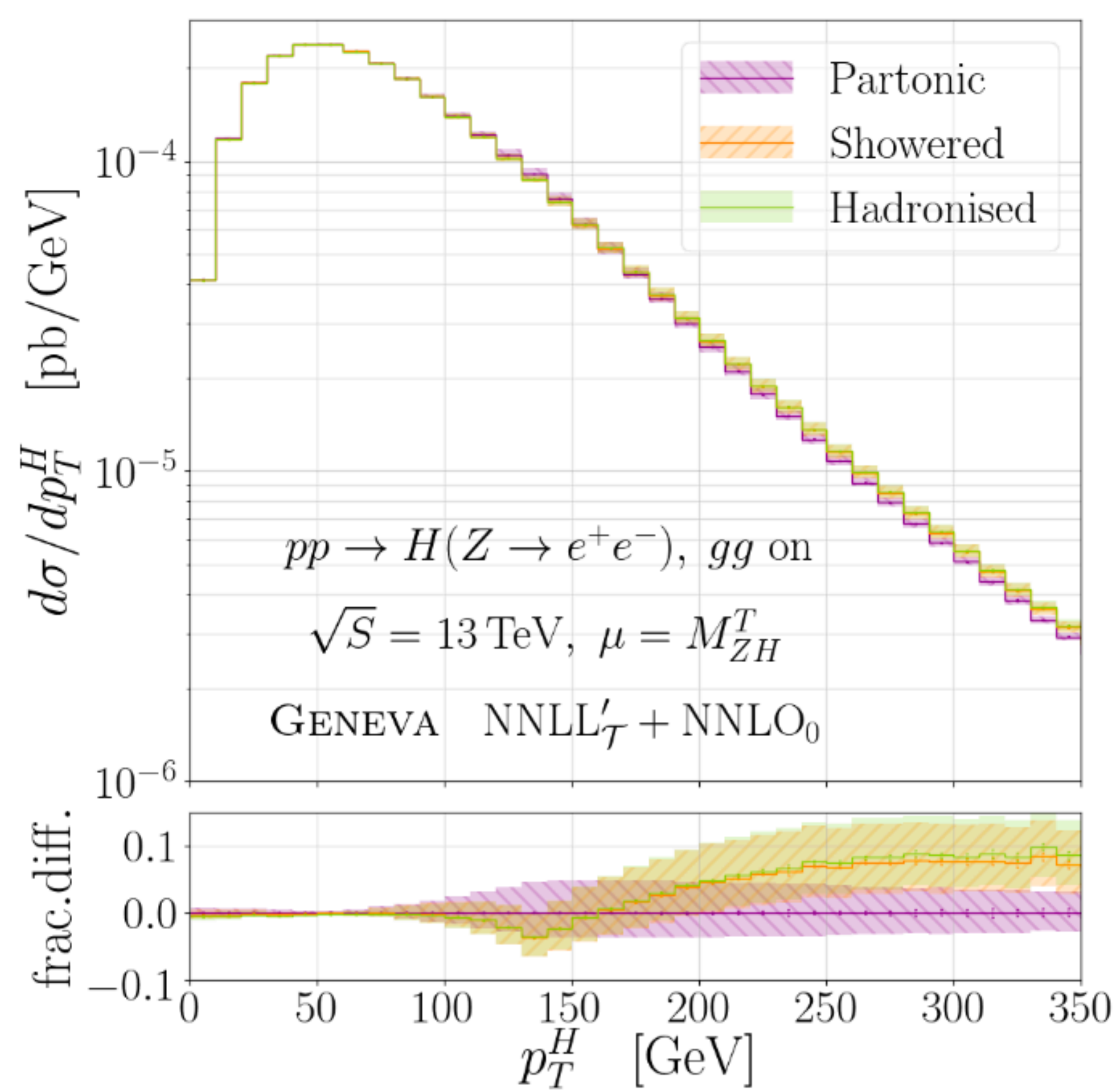
Modeling of VH processes: state-of-the-art

Alioli, Broggio, Kallweit, Lim, Rottoli

Geneva approach (NNLO for inclusive observables)

- NNLO matched to SCET resummed NNLL’ beam thrust matched to PS
- Sub-percent level agreement with NNLO calculations for inclusive observables
- PS has negligible effects on inclusive quantities
- Including sizeable loop induced gg →ZH leads to enhanced PS sensitivity



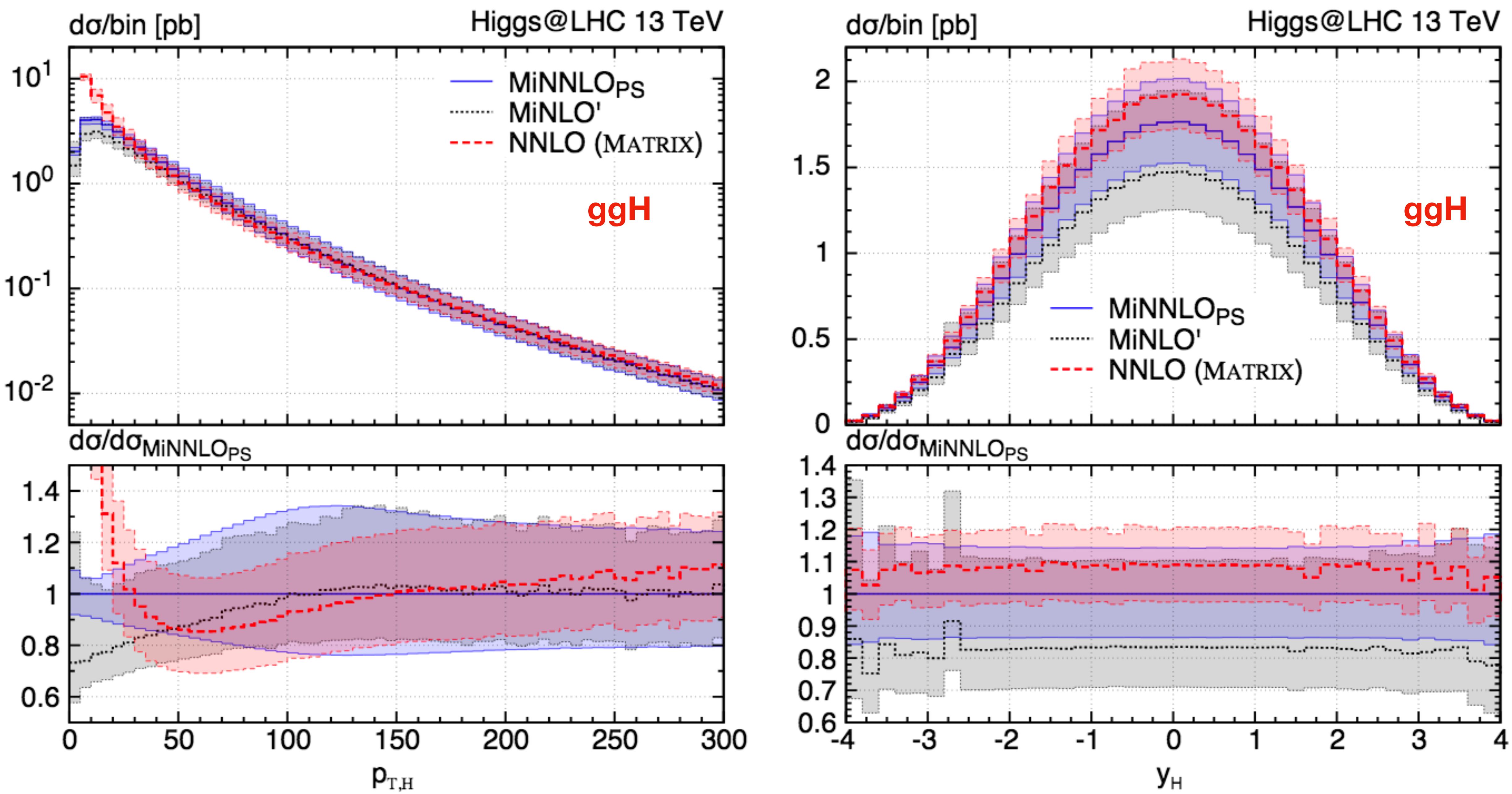


Modeling of VH processes: state-of-the-art

Monni, Nason, Re, Wiesemann, Zanderighi

Towards the future... MiNNLOPS approach: A new method to match NNLO QCD to parton showers

- reaching NNLOPS, without typical NNLOPS reweighting
- currently available for Drell-Yan and ggH production, to be extended to VH production in the future

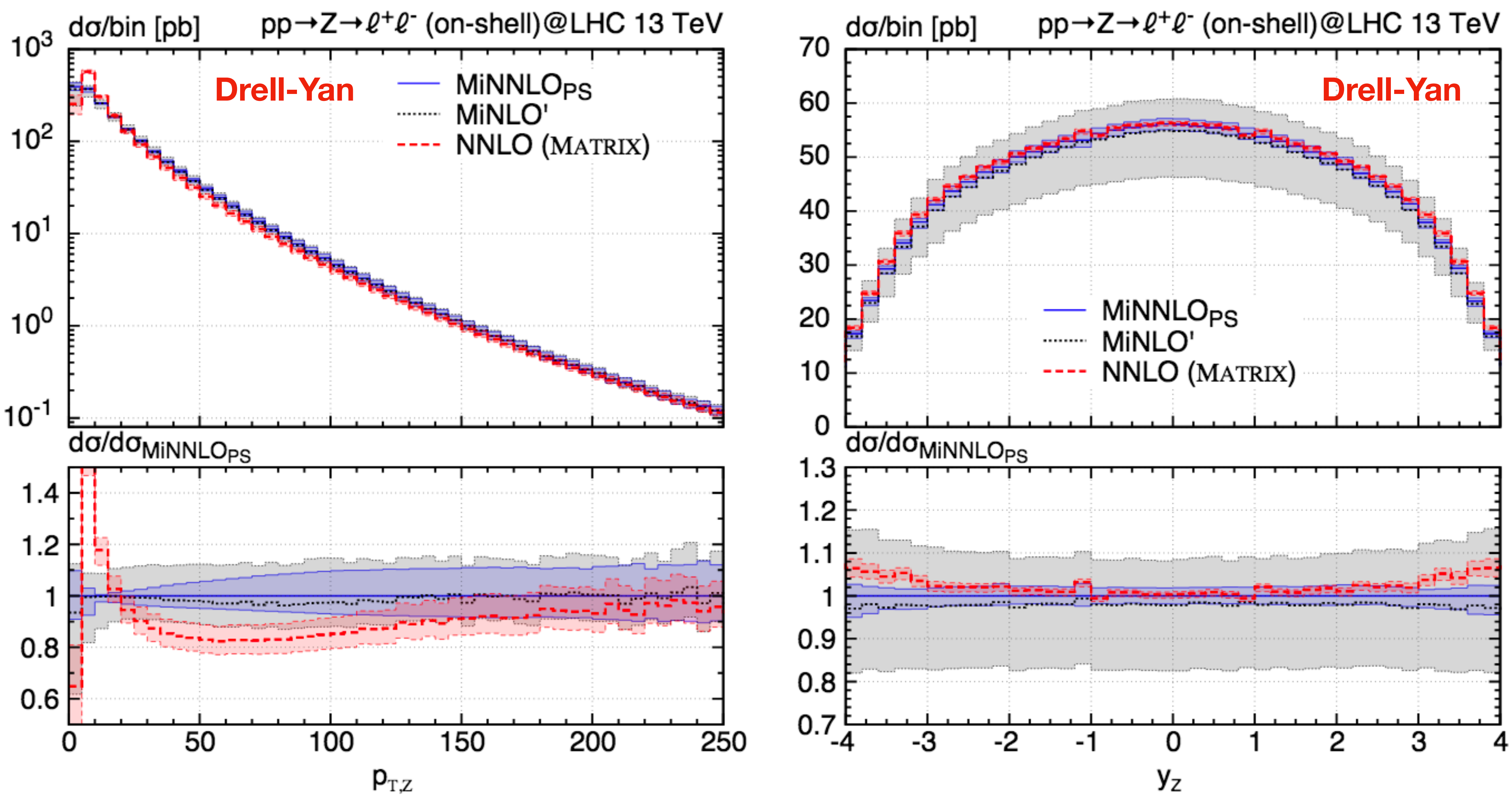


Modeling of VH processes: state-of-the-art

Monni, Nason, Re, Wiesemann, Zanderighi

Towards the future... MiNNLOPS approach: A new method to match NNLO QCD to parton showers

- reaching NNLOPS, without typical NNLOPS reweighting
- currently available for Drell-Yan and ggH production, to be extended to VH production in the future



Modeling of VH processes: state-of-the-art

Questions to address in the HXSWG-VH:

- which of these tools are critical for experimental analyses ?
  (thus high-priority to include in ATLAS / CMS software)

  → which effects are dominant in the VH / VH(bb) phase space ?

- how do we combine different effects?

  → e.g. EW NLO + QCD NNLOPS?
  simple EW rescaling based on (MiNLO+EW@NLO) / (MiNLO)

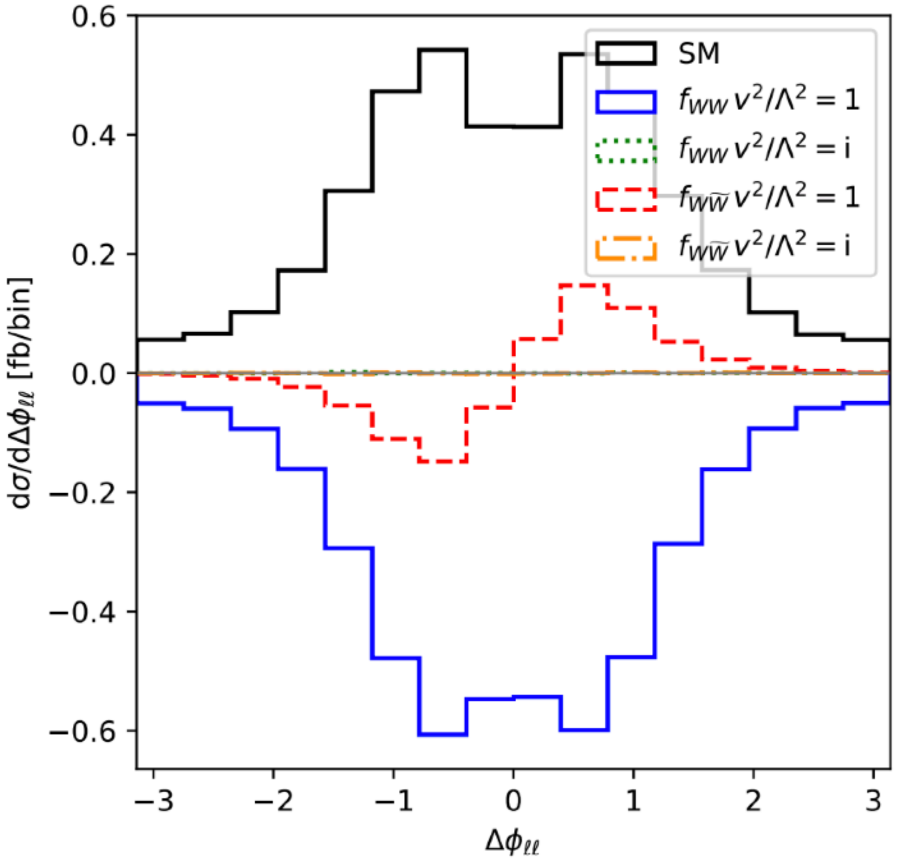
  → Hbb decay at NLO - improvement over current parton-shower model?

The HXSWG-VH might be the right place to study some of these questions and provide some guidelines on ***how to integrate these new tools in experimental analyses***

VH CP sensitive observables

Brehmer, Kling, Plehn, Tait

Recent project in VBF: CP sensitive observable through dPhi(jj)
Can something similar be explored for VH production and decay?



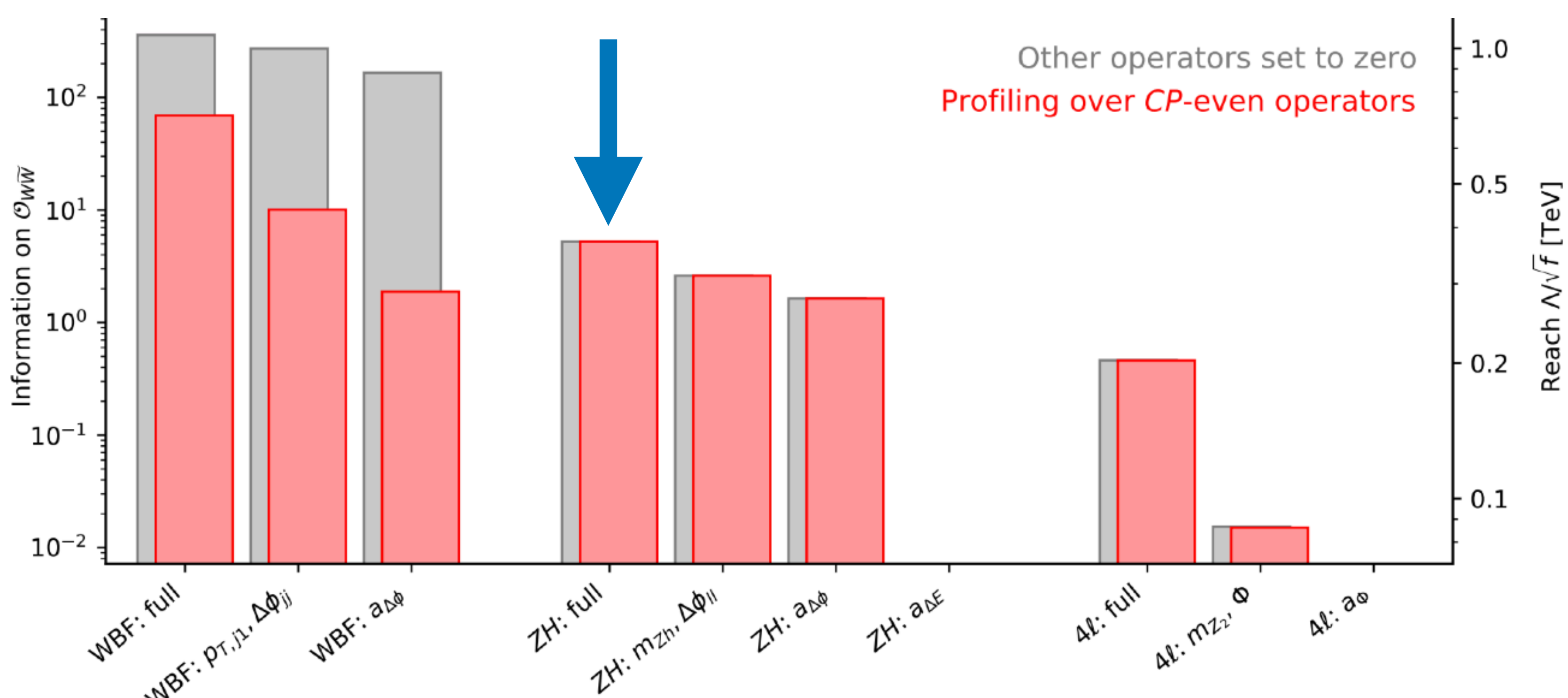
dPhi(ll) CP-sensitive observable for Z(ll)H

$$O_1 = \epsilon_{\mu\nu\rho\sigma}\, k_1^\mu k_2^\nu q_{\ell+}^\rho q_{\ell-}^\sigma\ \mathrm{sign}((k_1 - k_2)\cdot(q_1 - q_2))\ ,$$

$$O_1 \to \Delta\phi_{\ell\ell} \equiv (\phi_{\ell+} - \phi_{\ell-})\ \mathrm{sign}(q_{z,\ell+} - q_{z,\ell-})_{\mathrm{cm}}\ .$$

k = initial parton
q = outgoing leptons

Genuine CP-odd observable can be constructed
reflecting CP-symmetry properties w/o additional assumptions
(momentum flow through H vertex can be enhanced via kinematic cuts)

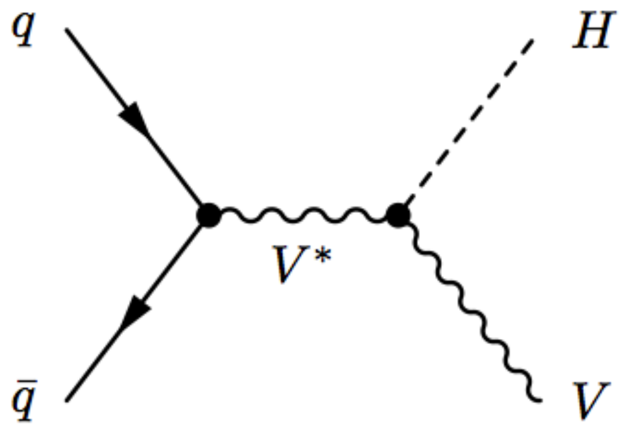


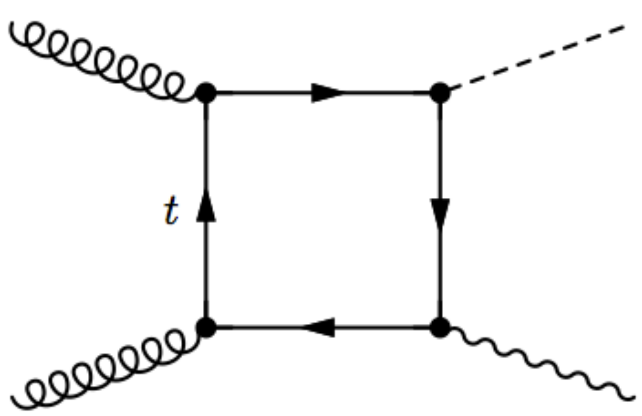
ZH: smaller reach than VBF, but unaffected by other operators

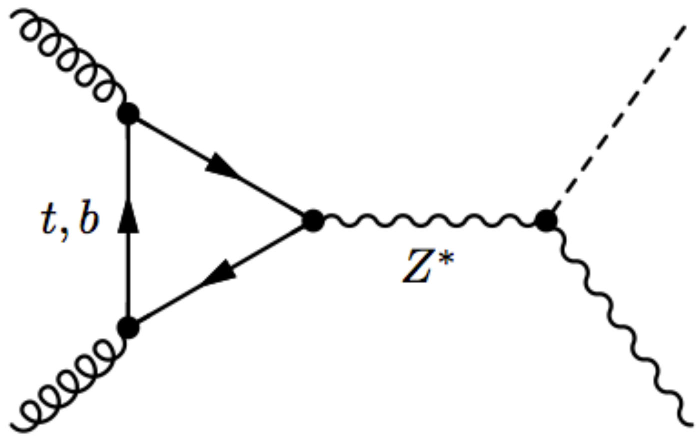
Interesting idea to use VH to probe Higgs CP-properties:
possible STXS categorization?

Thanks!

to all past VH sub-conveners ... Elisabetta Pianori, Francesco Tramontano, Jason Nielsen, Emanuele Perrozzi, John Campbell, Emanuele Re, Thomas Calvet, Chris Palmer, Giancarlo Ferrera, Ciaran Williams, ...







BACK-UP

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

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]

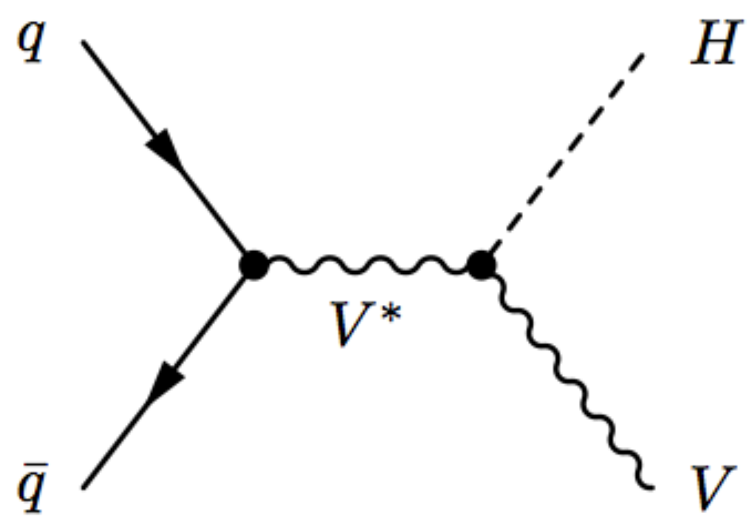
Indico page for VH WG1 meetings:

https://indico.cern.ch/category/5847/

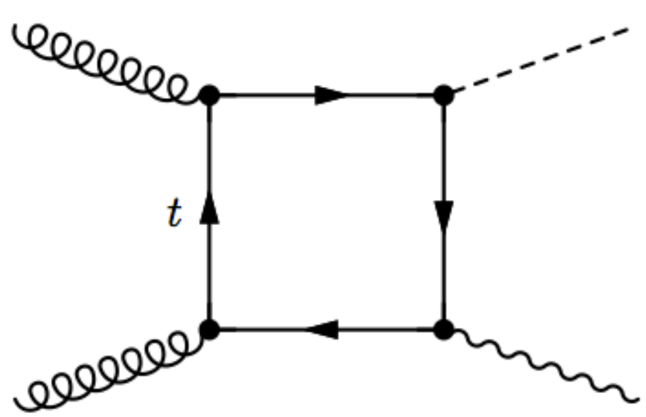
VH - associated Higgs production

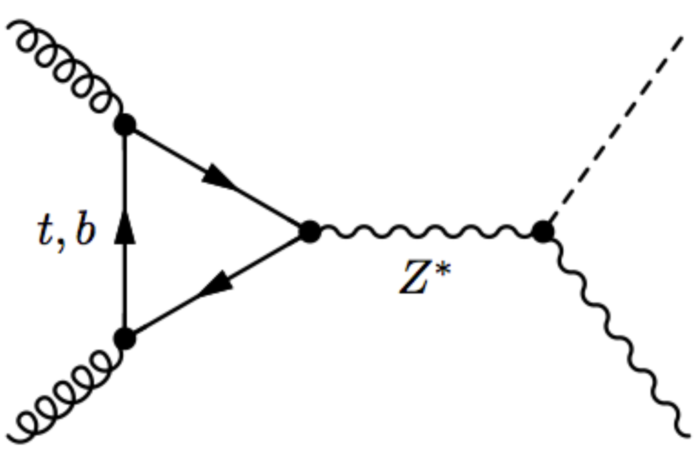
Quick reminder: what is included under "VH" Higgs processes?

- **Drell-Yan production of WH and ZH pairs**
  known up to NNLO QCD and NLO EW



- **loop-induced gluon-fusion ZH pair production**
  known up to LO QCD (same aS order as NNLO Drell-Yan ZH)

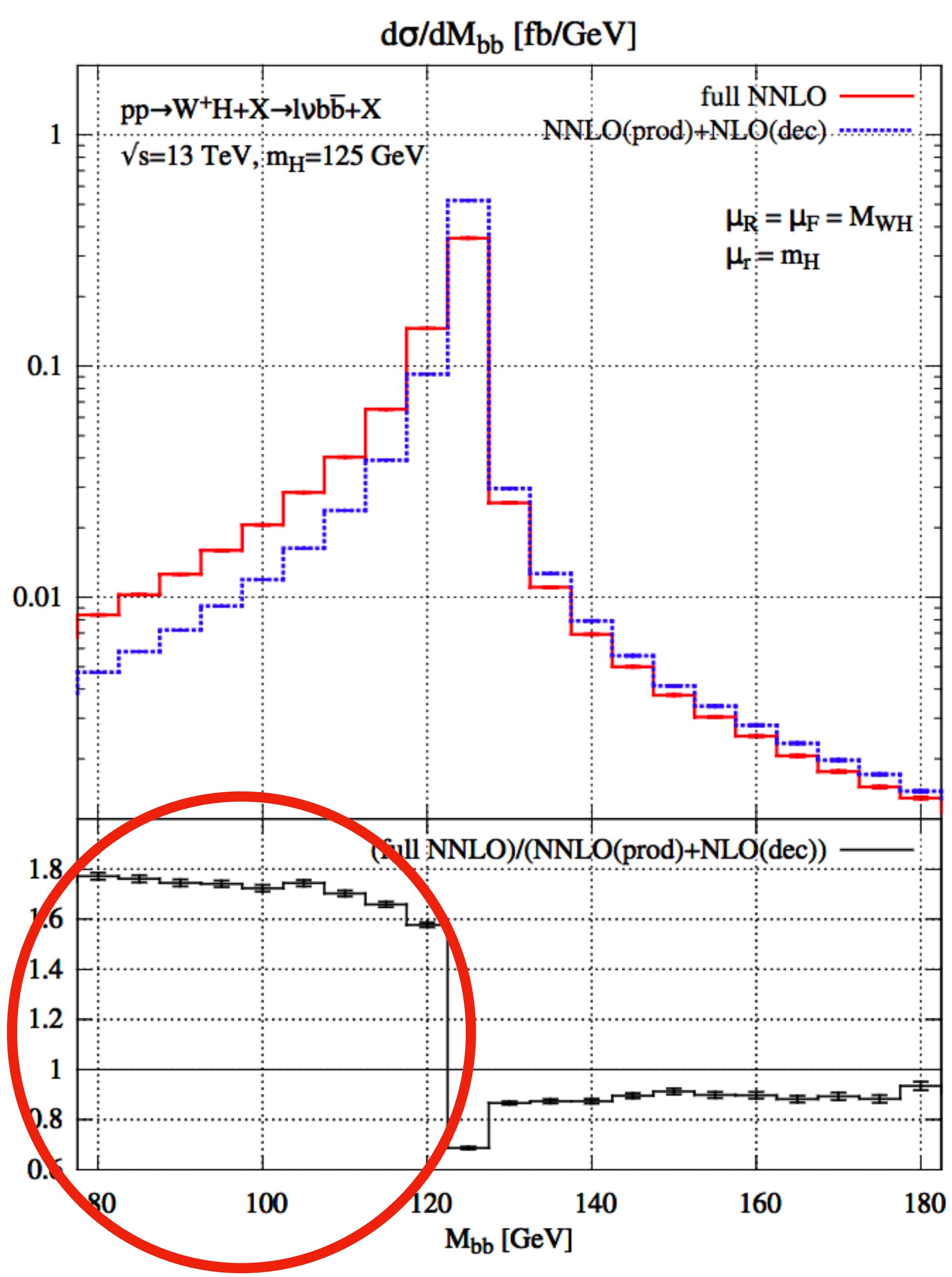




State of the art VH(bb) QCD tools

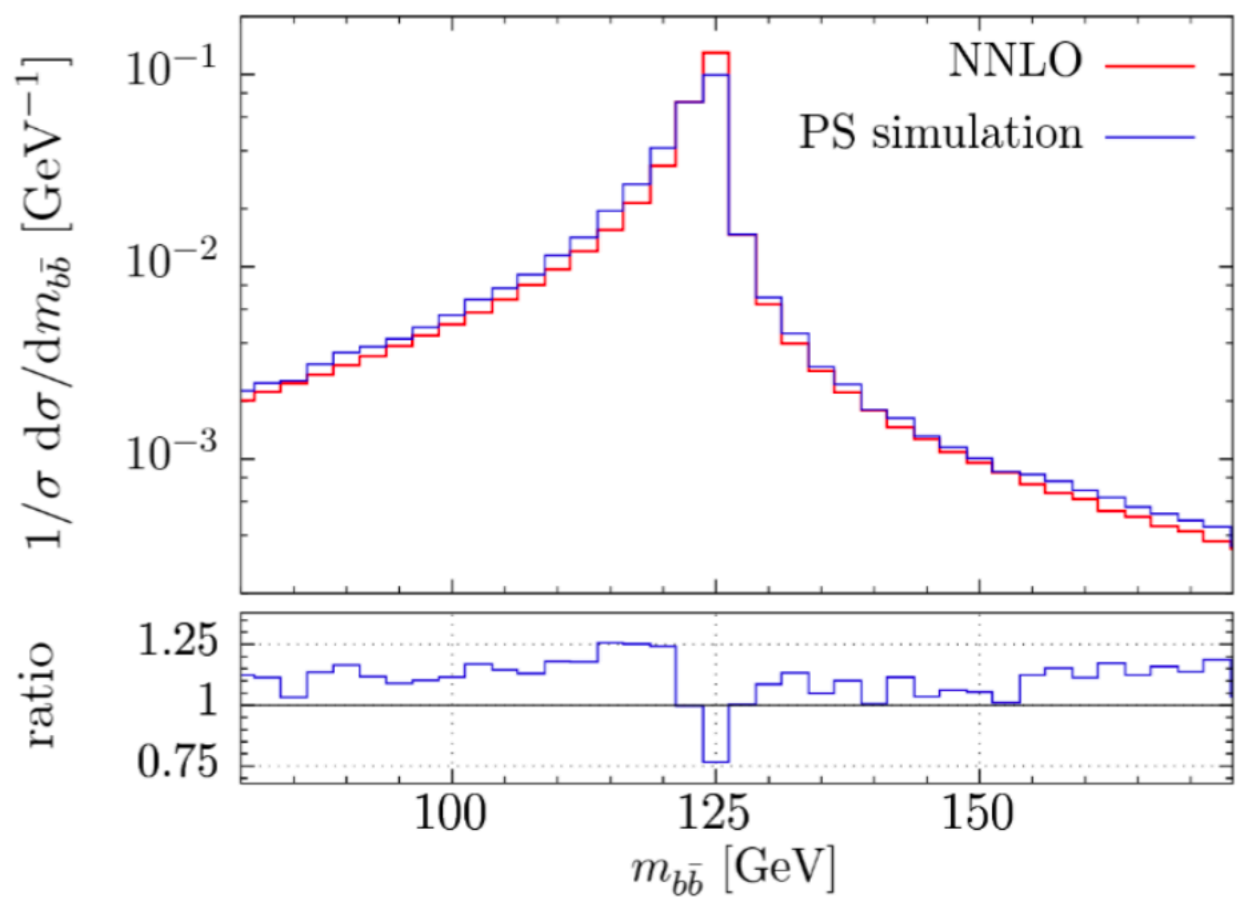
What are the best available calculations / MC tools for VH modeling?

- fixed order: **NNLO(VH production) + NNLO(Hbb decay)**
  available in massless-b limit, ongoing work for massive b (decay)
  very large corrections in regions not populated by lower-order
  largely covered by parton-showering in ME+PS generation



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

comparison to parton-showered MC prediction



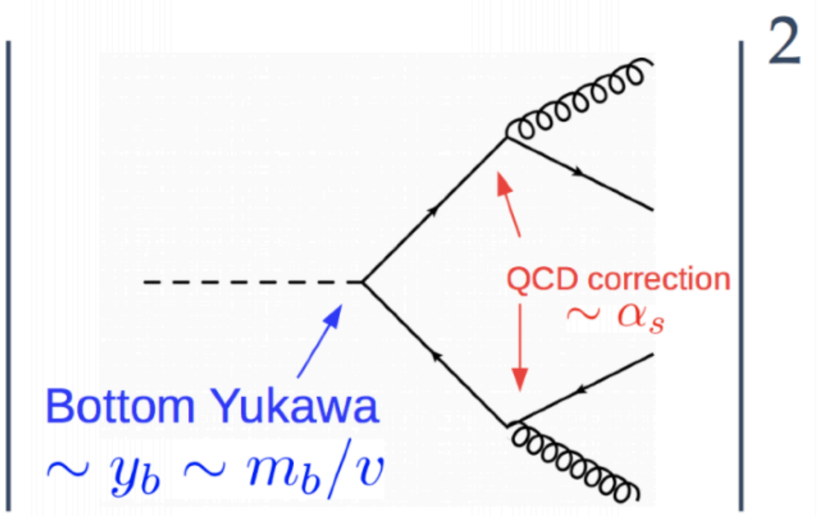
Caola et al 1712.06954

Decay in the massless approximation: extract Yukawa and then set $m_b = 0$

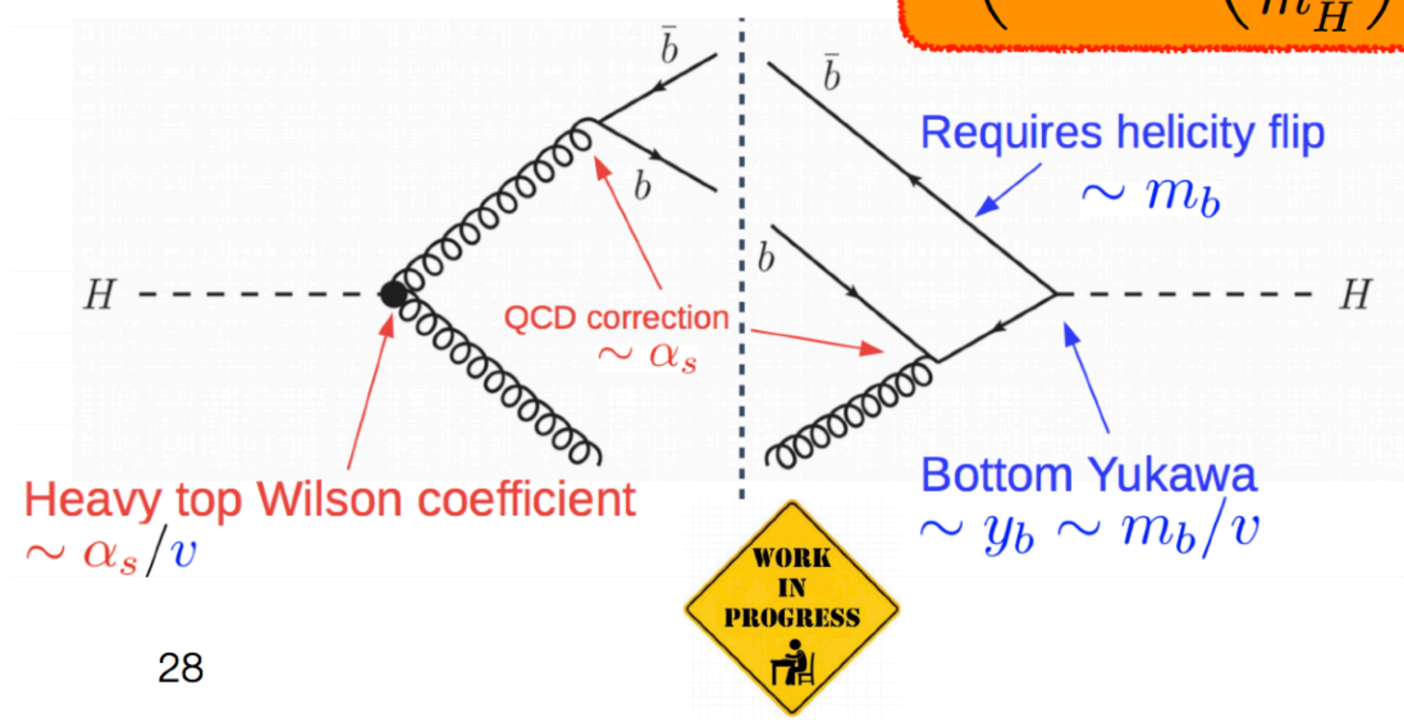
$$\boxed{\Gamma_{H\to bb} = y_b^2 \left(\Gamma_{m_b=0} + \mathcal{O}\left(\frac{m_b^2}{m_H^2}\right)\right)}$$

Above works at LO and NLO, but fails at NNLO as it neglects contributions that are of the same order, i.e. $y_b^2\alpha_s^2$, that arise in diagrams with a helicity flip (and hence a mass insertion)

Standard NNLO correction: $\boxed{\mathcal{O}(y_b^2\alpha_s^2)}$



New NNLO contribution: $\boxed{\mathcal{O}\left(y_b^2\alpha_s^2 \ln\left(\frac{m_b^2}{m_H^2}\right)\right)}$



28

slide from G. Zanderighi talk at Higgs Couplings 2018

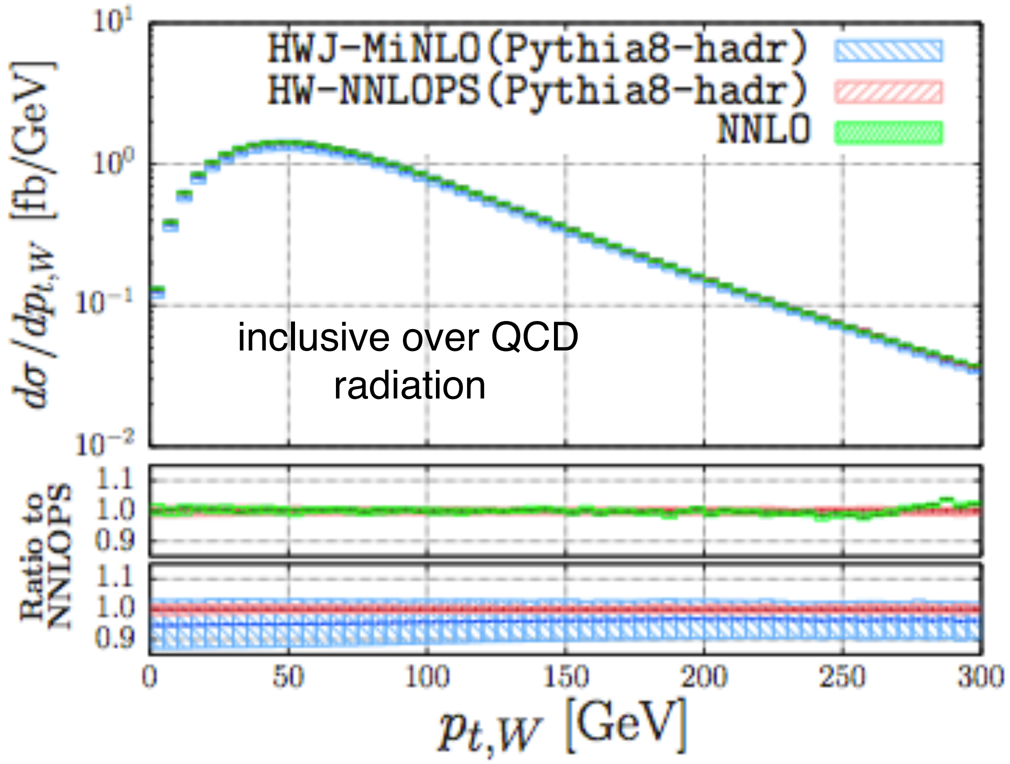
Recent progress on higher-order corrections for H->bb also include the N3LO fully-differential calculation: https://arxiv.org/abs/1904.08960

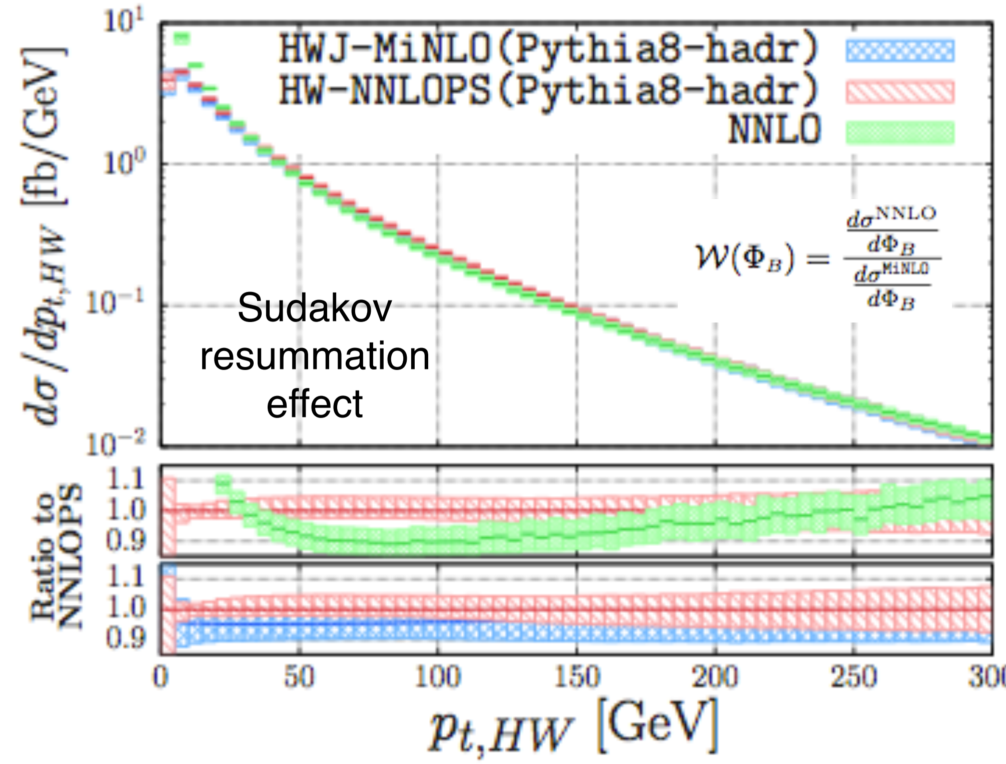
QCD → NNLOPS VH

NNLOPS (WH)
arXiv:1603.01620v1

Reweight Powheg (MiNLO) NLO prediction to the NNLO fixed order calculation from *hv@nnlo*

Already done in ATLAS for ggF, not trivial for VH (6-dim reweighting)

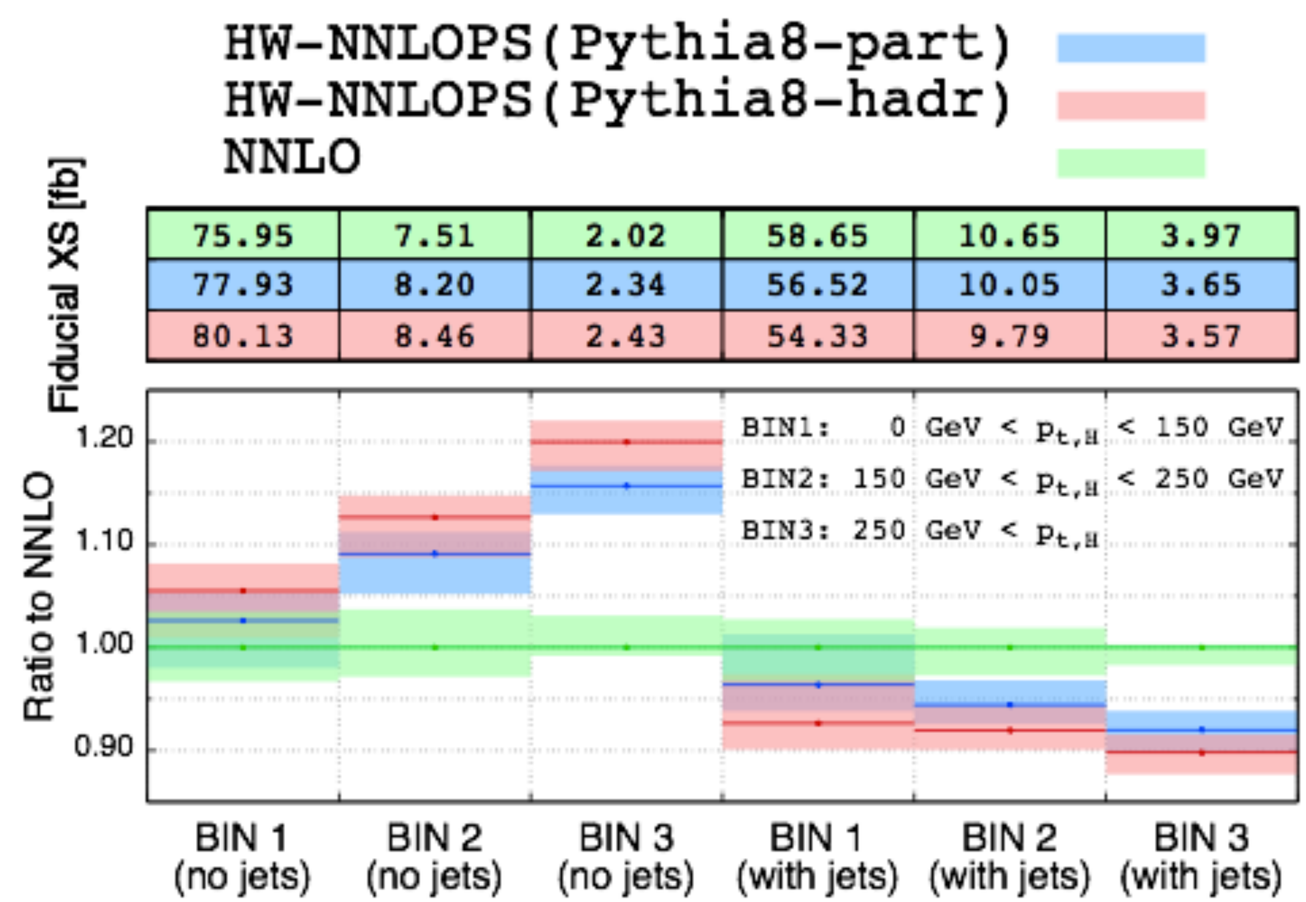




A. with very inclusive cuts kNNLO fairly flat
B. strong reduction of scale uncertainties (8% → 1.3%)
C. impact of parton-shower on NNLO prediction (jet-veto / jet-binning)

Results available for WH and ZH Including H(→bb) decay @ NLO, at LHE level (on top of NNLO)

(to be combined with EW@NLO)



jets counted if pT > 20 GeV and |η| < 4.5

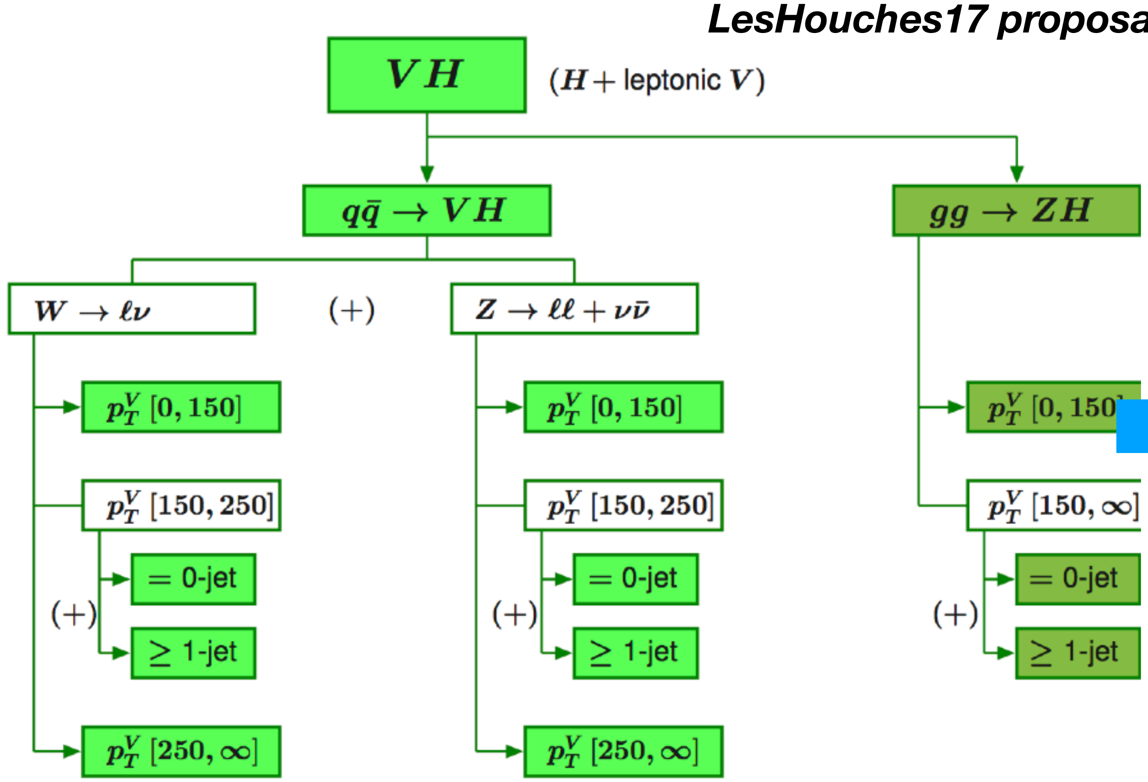
VH Simplified Template Cross Sections

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

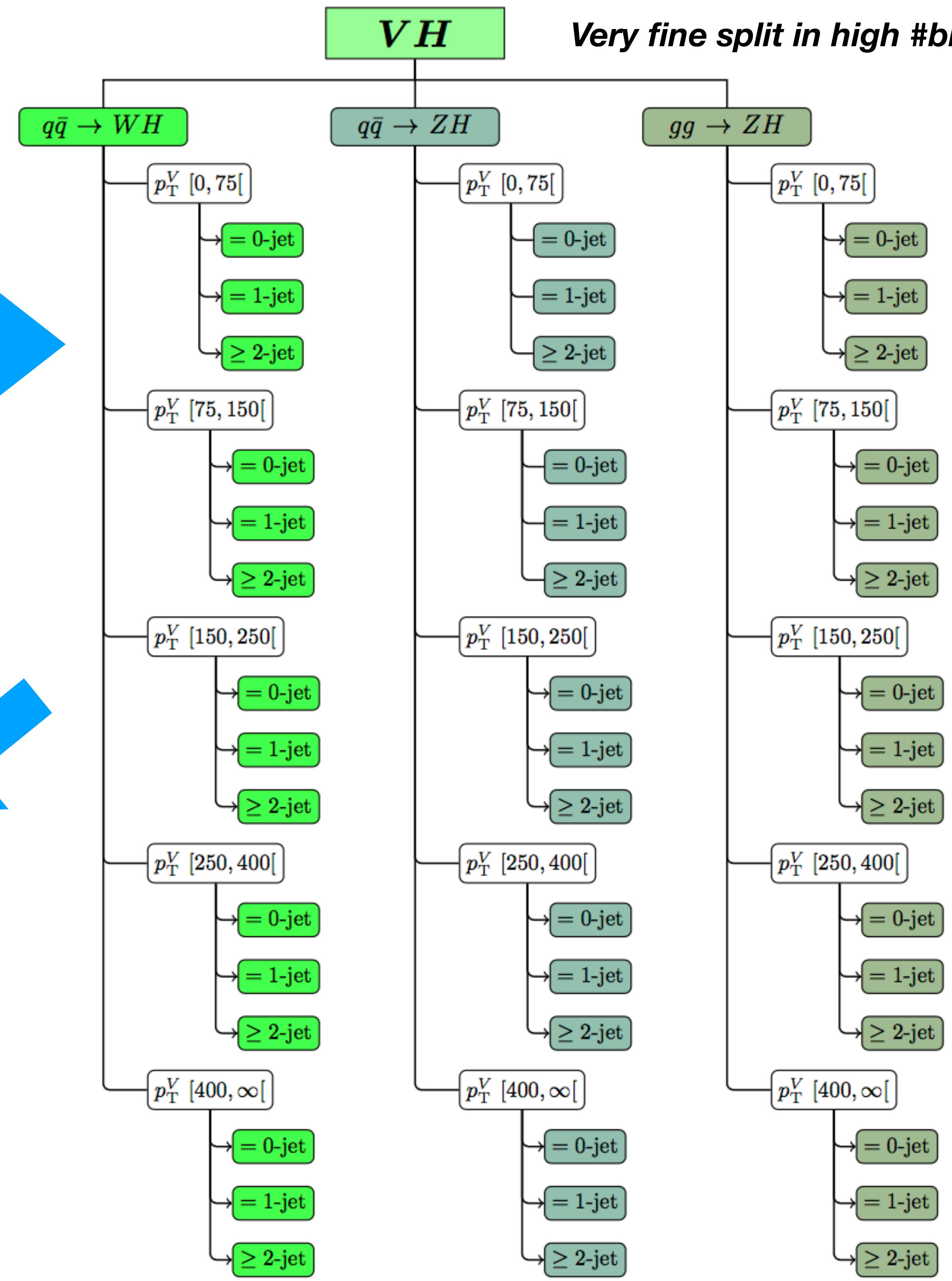
- **revisit the STXS bin definition for VH**

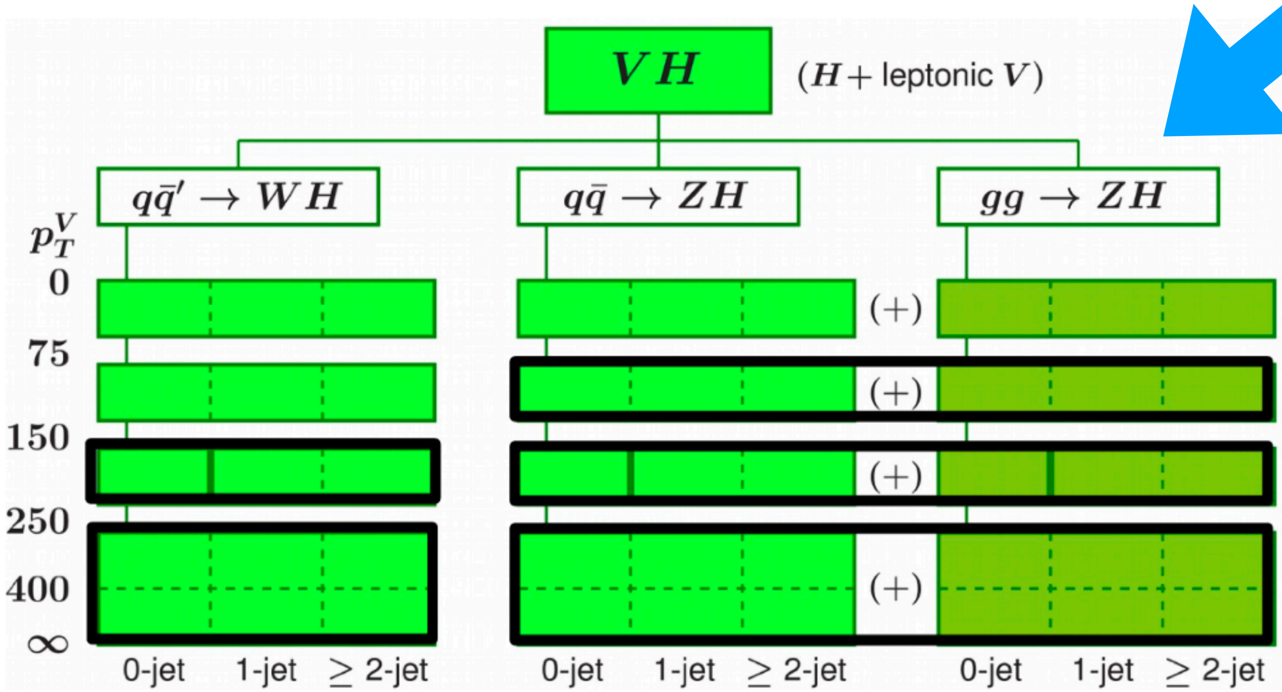
Higgs Couplings 2018:
ATLAS-CONF-2018-053
ATL-PHYS-PUB-2018-035

LesHouches17 proposal



Very fine split in high #bins

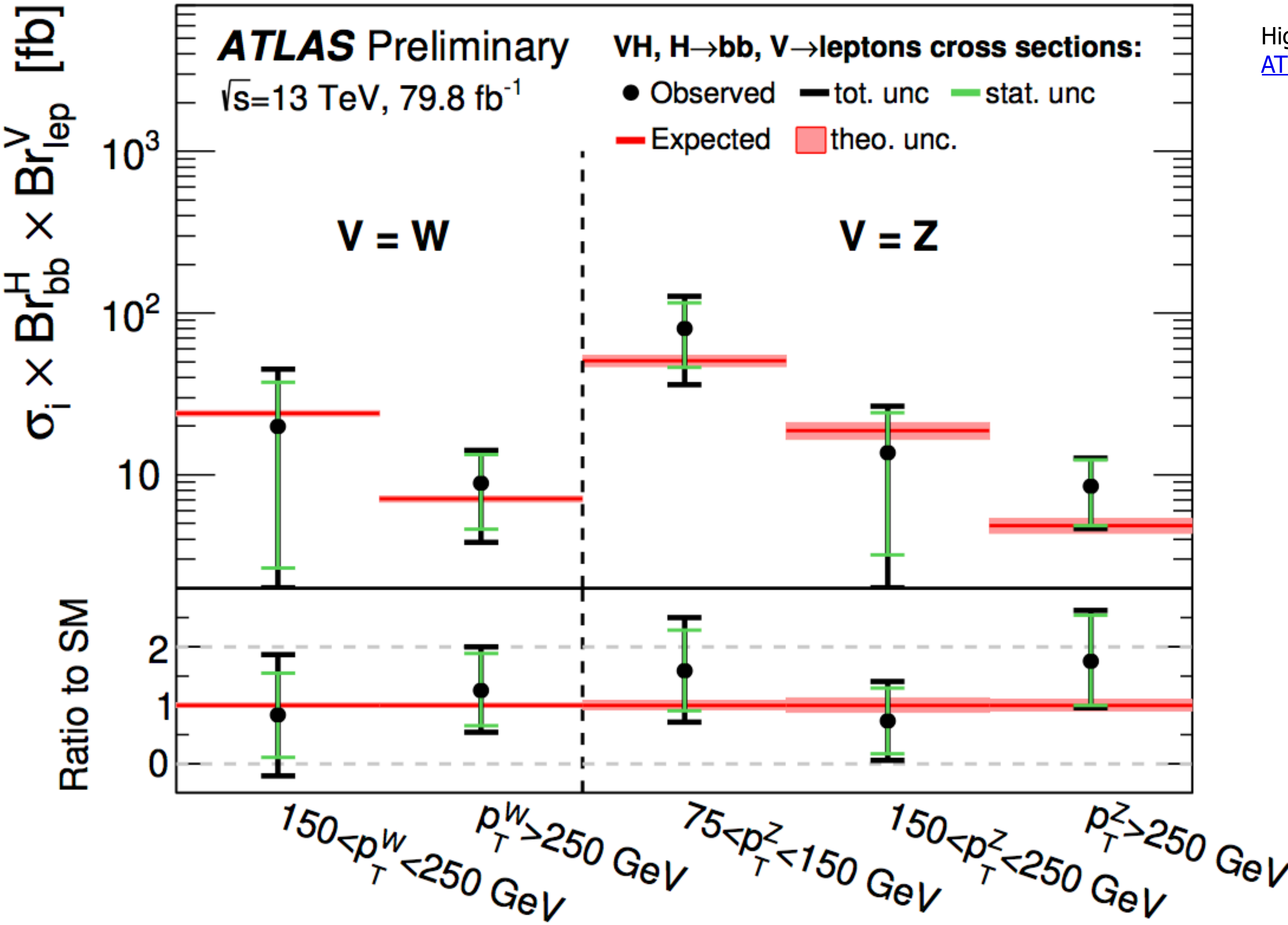




Measured regions: towards a pT(V) differential measurement

Simplified Template Cross Sections

ATLAS measurement in the 5 STXS bin split:



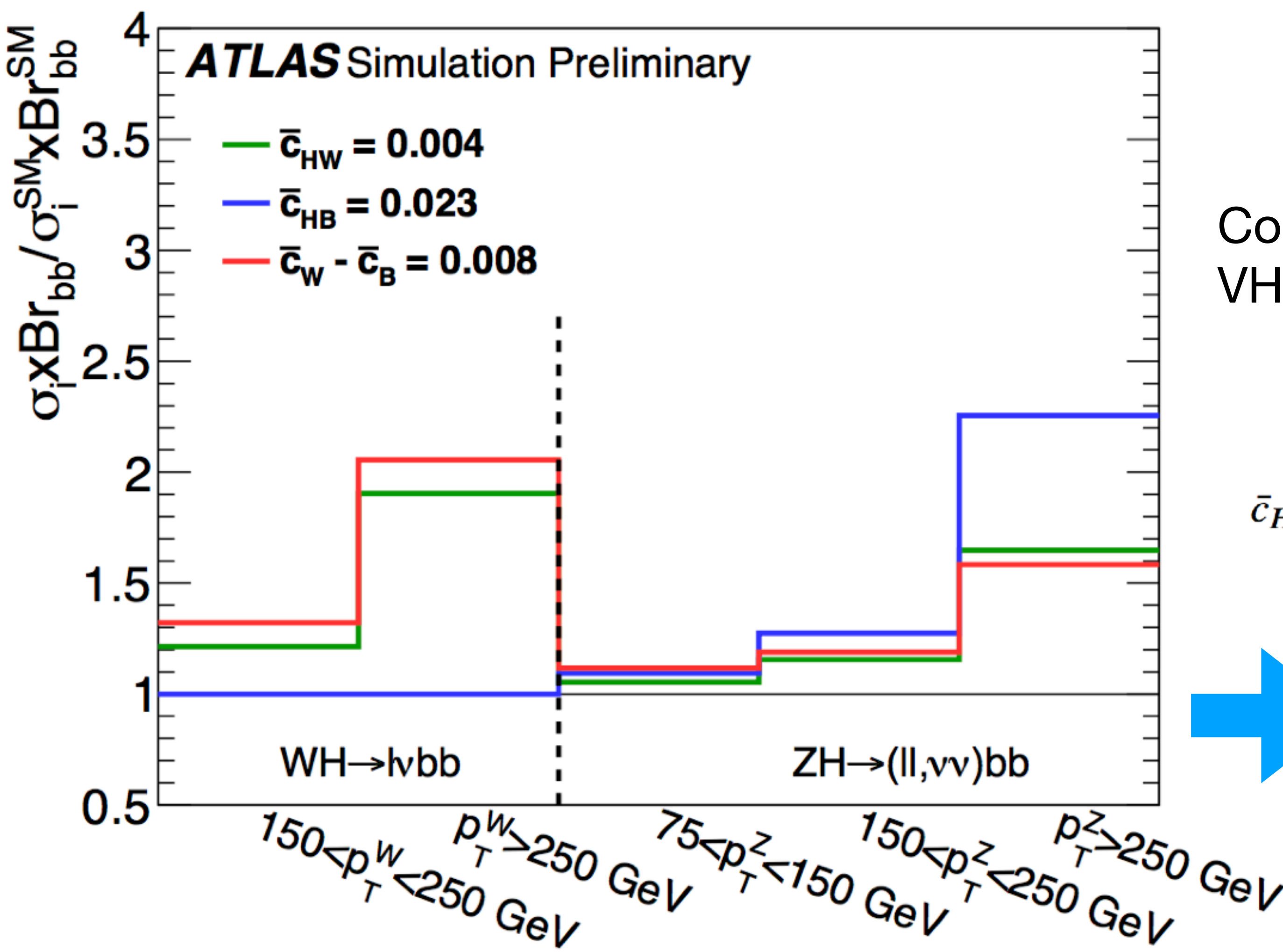
Higgs Couplings 2018: [ATLAS-CONF-2018-053]

ATLAS definition the VH STXS uncertainty scheme: only the first step ...
starting from here to improve 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



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

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]

ggZH@NLO: experimental sensitivity?

Harlander, Klappert, Papaefstathiou, CP

Very basic idea (from discussions at Les Houches) to limit systematics via ratio measurement ...

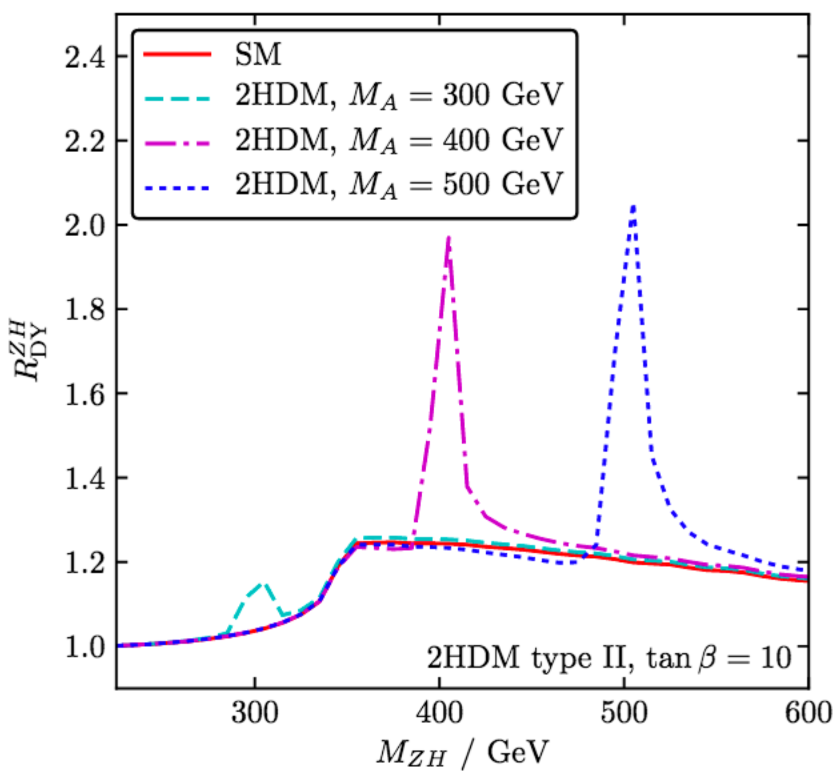
$$R_{\mathrm{DY}}^{ZH} \equiv \frac{\sigma_{\mathrm{exp}}^{ZH}}{\sigma_{\mathrm{DY}}^{ZH}}$$

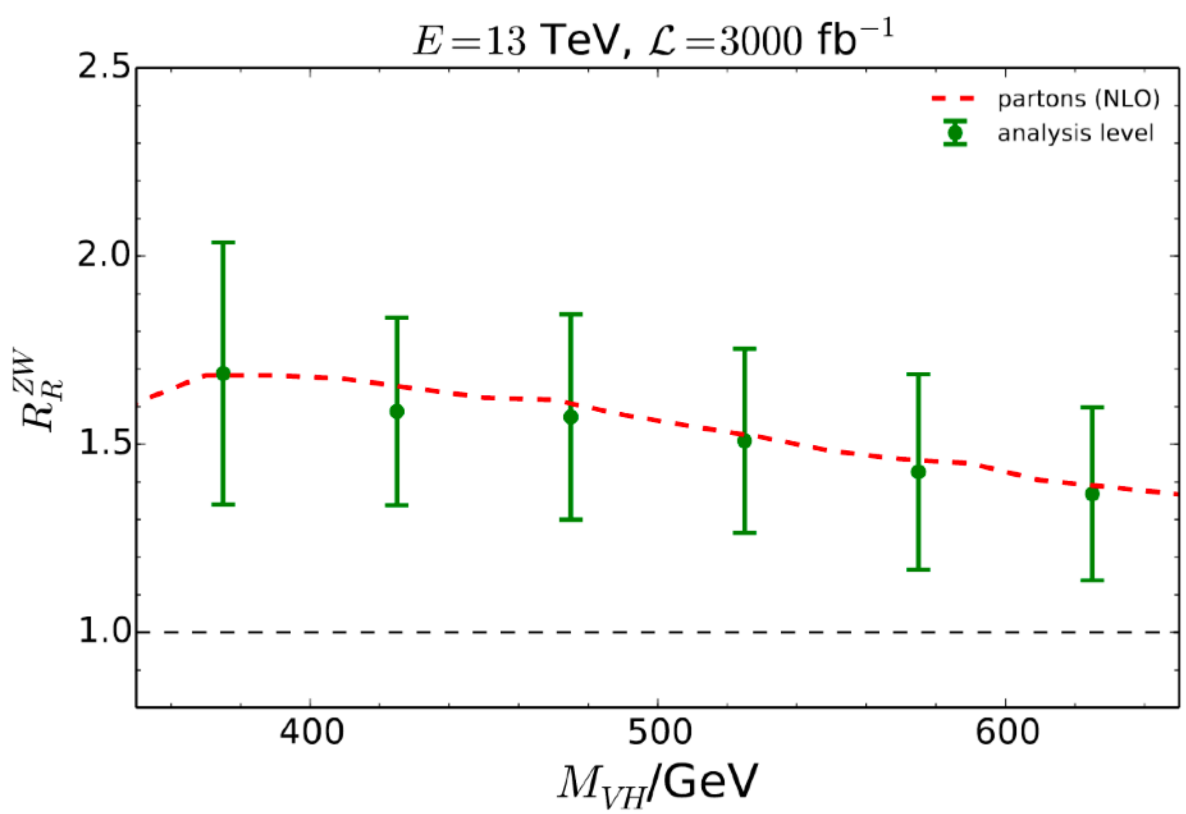
Sensitive to ggZH (and potential deviations from SM, likely to manifest through loop contribution)

$$R_R^{ZW} = \frac{\sigma^{ZH}/\sigma^{WH}_{\mathrm{exp}}}{\sigma_{\mathrm{DY}}^{ZH}/\sigma^{WH}} \equiv \frac{R^{ZW}}{R_{\mathrm{DY}}^{ZW}} \qquad R_R^{ZW} = 1 + \frac{\mathrm{d}N_{gg}^{ZH}}{\mathrm{d}N_{\mathrm{DY}}^{ZH}}$$

Exploit (ZH, WH) similarity to reduce impact of systematic uncertainties (both TH and EXP): double-ratio sensitive to ggZH contribution (and deviations)

Pheno truth-level analysis of 1-lepton and 2-lepton channels, looking at m(VH) distribution:





- TH uncertainties fully re-evaluated
- EXP uncertainties extrapolated from 36/fb VH(bb) ATLAS results

$$\mu_{Zh} = 1.12^{+0.34}_{-0.33}(\mathrm{stat.})^{+0.37}_{-0.30}(\mathrm{syst.})$$

$$\mu_{Wh} = 1.35^{+0.40}_{-0.38}(\mathrm{stat.})^{+0.55}_{-0.45}(\mathrm{syst.})$$

ggZH@NLO: experimental sensitivity?

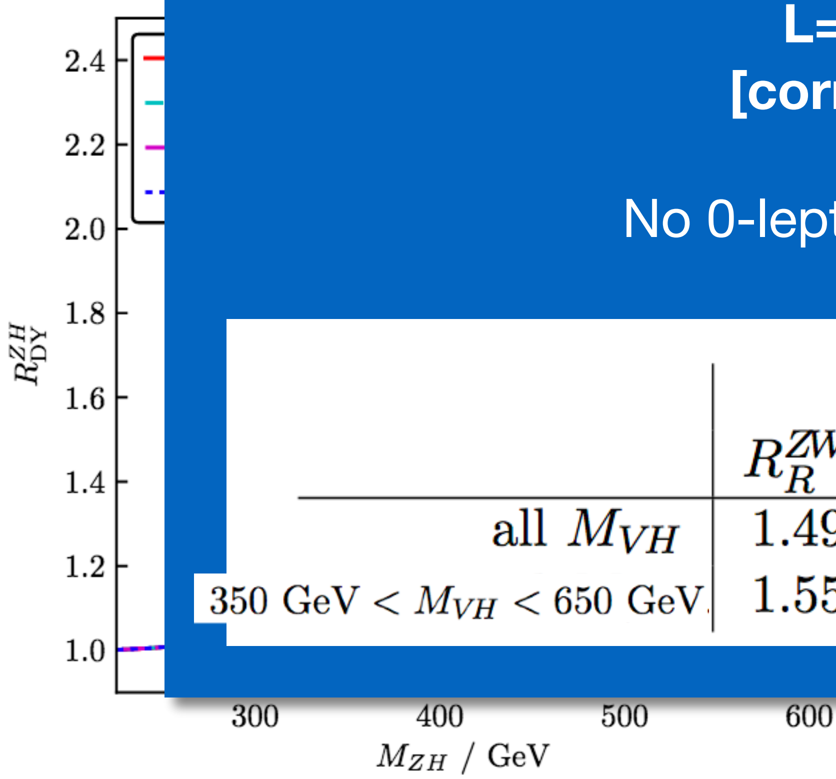
Harlander, Klappert, Papaefstathiou, CP

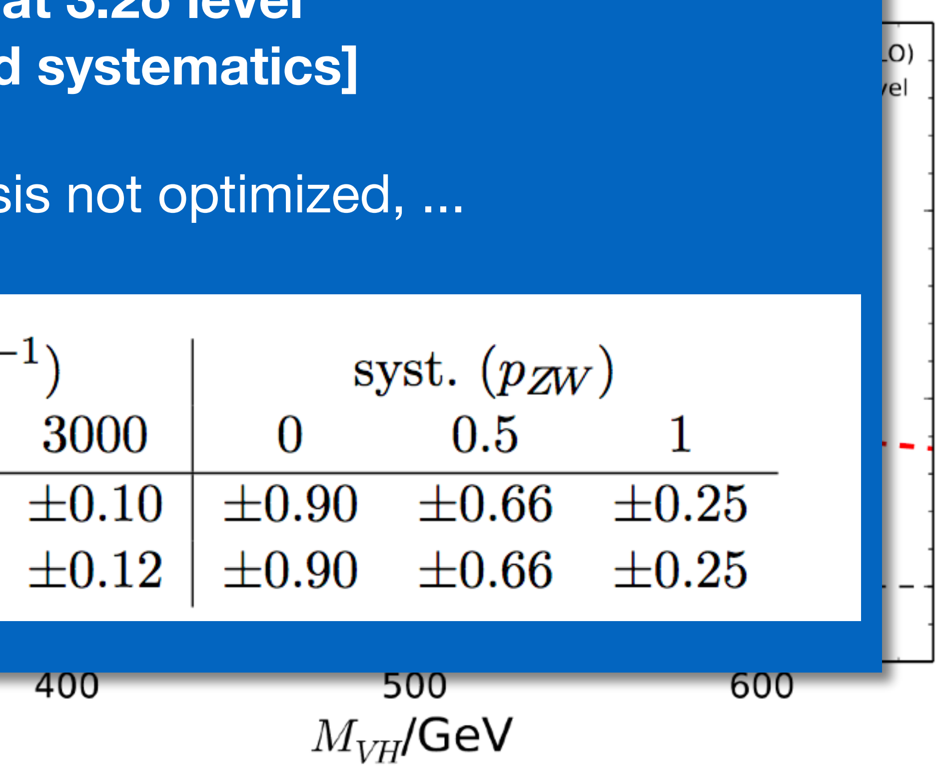
Very basic idea (from discussions at Les Houches) to limit systematics via ratio measurement ...

$$R_{\rm DY}^{ZH} \equiv \frac{\sigma^{ZH}_{\rm exp}}{ZH}\quad\quad R_R^{ZW} = \frac{\sigma^{ZH}/\sigma^{WH}_{\rm exp}}{ZH/\ WH} \equiv \frac{R^{ZW}}{R^{ZW}}\quad\quad R_R^{ZW} = 1 + \frac{\mathrm{d}N_{gg}^{ZH}}{\mathrm{d}N_{\rm DY}^{ZH}}$$

Sensitive t
deviatior
manifest thr

Pheno truth ... oution:





Standard Model ggZH experimental measurement:

L=3/ab - sensitivity at 2σ level
[correlated systematics]

L=3/ab - sensitivity at 3.2σ level
[correlated and halved systematics]

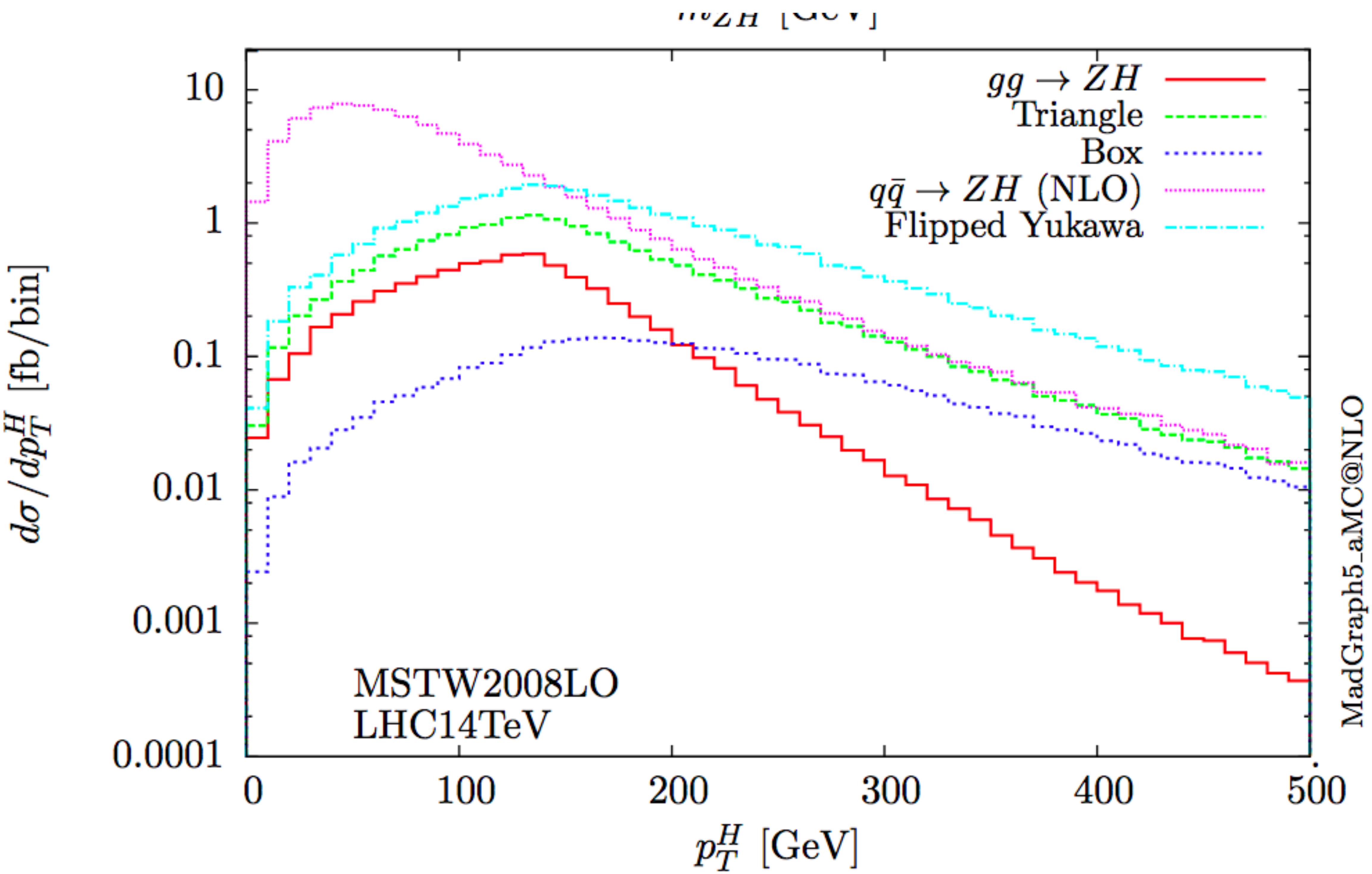
No 0-lepton channel, analysis not optimized, ...

	R_R^{ZW}	stat. $(\mathcal{L}/\mathrm{fb}^{-1})$ 36.1	300	3000	syst. (p_{ZW}) 0	0.5	1
all M_{VH}	1.49	±0.90	±0.31	±0.10	±0.90	±0.66	±0.25
350 GeV < M_{VH} < 650 GeV	1.55	±1.08	±0.38	±0.12	±0.90	±0.66	±0.25

- TH uncertainties fully re-evaluated
- EXP uncertainties extrapolated from 36/fb VH(bb) ATLAS results

$$\mu_{Zh} = 1.12^{+0.34}_{-0.33}(\text{stat.})^{+0.37}_{-0.30}(\text{syst.})$$
$$\mu_{Wh} = 1.35^{+0.40}_{-0.38}(\text{stat.})^{+0.55}_{-0.45}(\text{syst.})$$

gg→ZH (loop-induced) MC modeling



gg→ZH (loop-induced) MC modeling

Hasselhuhn, Luthe, Steinhauser 1611.05881

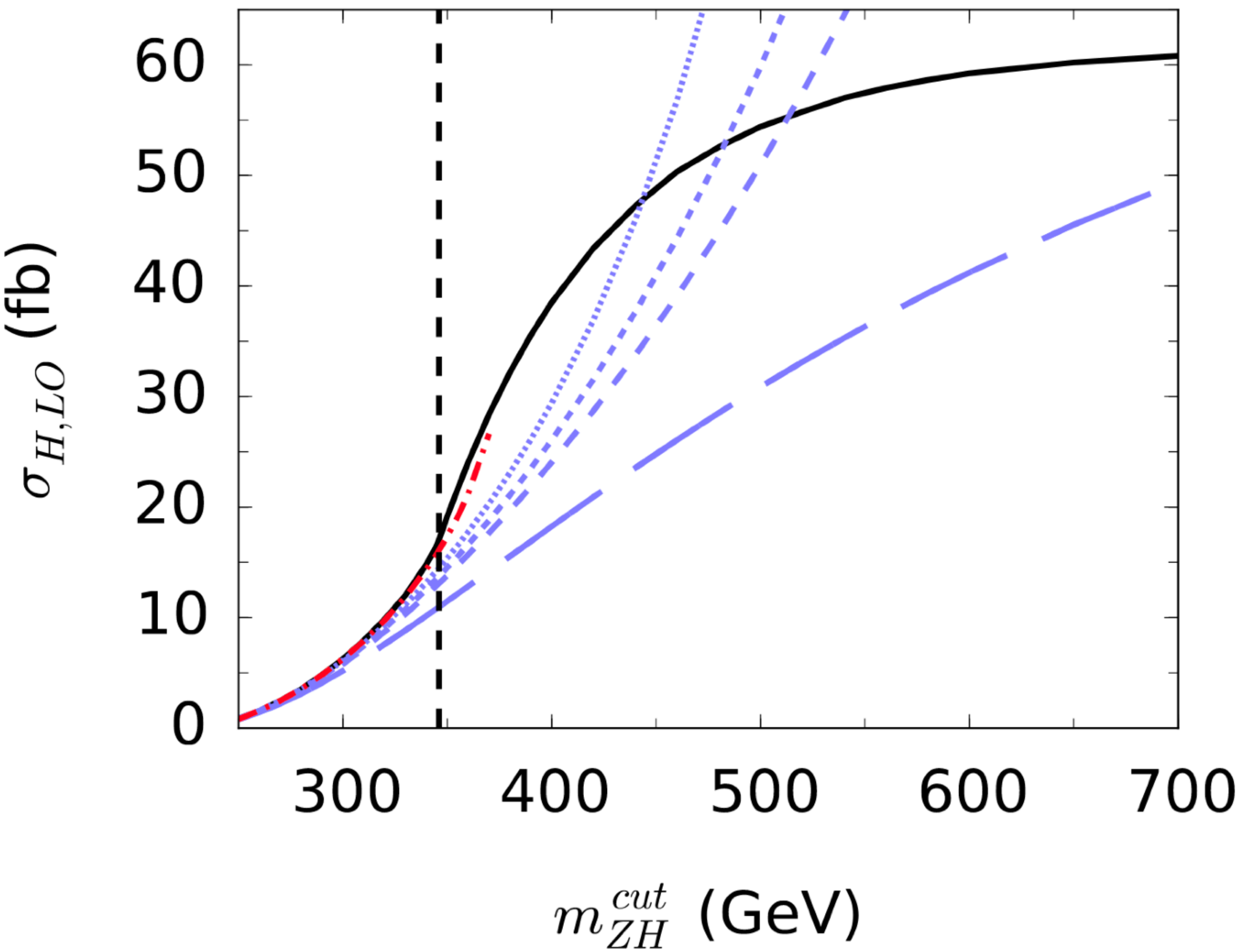


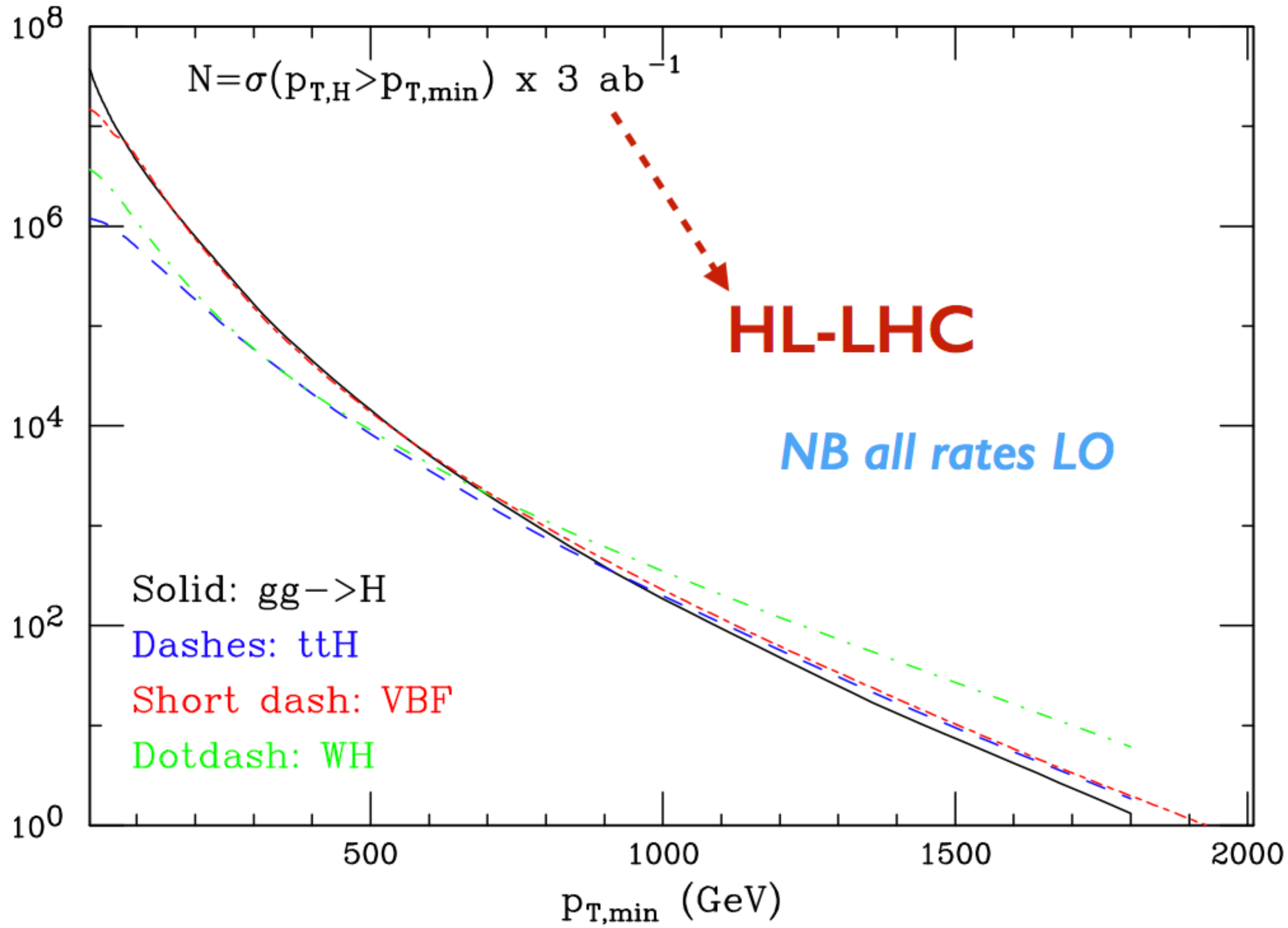
Figure 3: Hadronic LO $gg \to ZH$ cross section as a function of m_{ZH}^{cut}, the cut on the invariant mass of the Z-Higgs system. The exact result is shown in black. The dashed (blue) curves correspond to the expanded results (see caption of Fig. 2 for more details) and the [2/2] Padé approximation is shown as dash-dotted (red) curve.

VH @ high-pT - looking towards HL

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

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

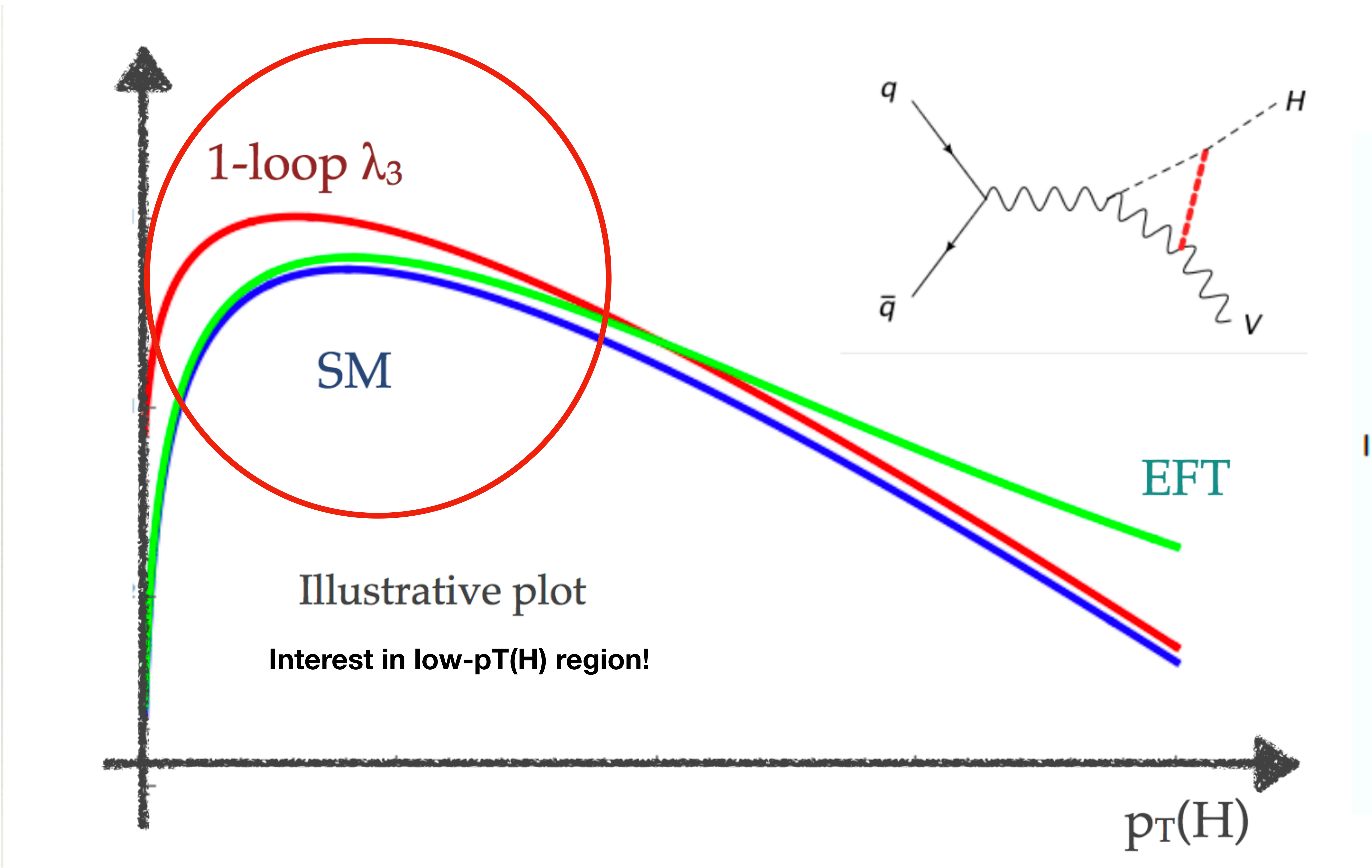
What is the impact of VH?



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

NLO VH electroweak corrections

From Fabio Maltoni's talk at HXSWG General Assembly in July 2017



NLO VH electroweak corrections

1607.04251

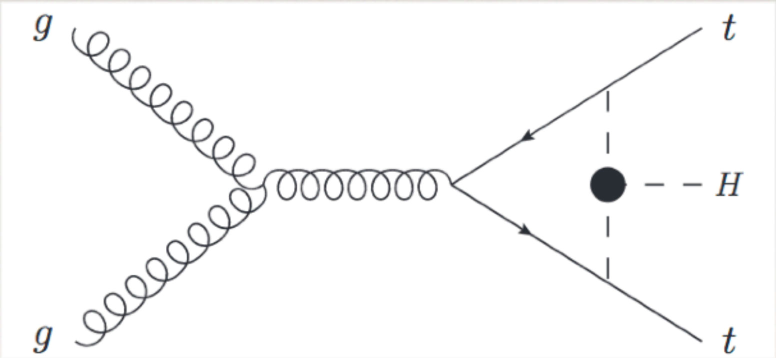
$$\delta\sigma \equiv \frac{\sigma_{\rm NLO} - \sigma_{\rm NLO}^{\rm SM}}{\sigma_{\rm LO}} = (\kappa_\lambda - 1)\boxed{C_1} + (\kappa_\lambda^2 - 1)\boxed{C_2}$$

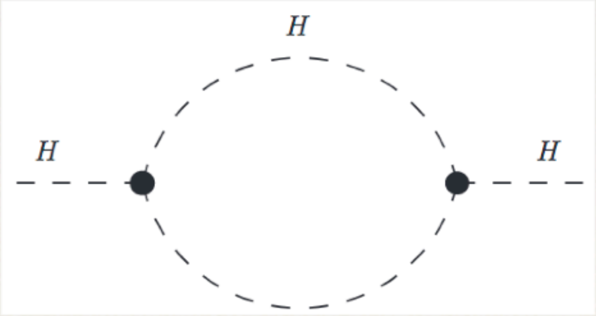
Process and kinematics dependent

$$C_1^\sigma = \frac{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, 2\Re\left(\mathcal{M}_{ij}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM},ij}\right) d\Phi}{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, |\mathcal{M}_{ij}^0|^2 d\Phi}$$

overall and universal

$$C_2 = \frac{\delta Z_H}{(1 - \kappa_\lambda^2 \delta Z_H)}$$





Similar (but simpler) formula for C_1 of decay widths.

Note that branching ratios do not depend on C_2

Main meetings from the past

Date	Indico link	Meeting
29/06/2017	https://indico.cern.ch/event/648099/	HXSWG VH meeting (TH updates)
13-14/07/2017	https://indico.cern.ch/event/595100/	13th general assembly
17/10/2017	https://indico.cern.ch/event/666958/	**ATLAS/CMS HXSWG VH(bb) meeting**
29/01/2018	https://indico.cern.ch/event/698454/	HXSWG VH meeting (TH updates)
26-27/03/2018	https://indico.cern.ch/event/665524/	14th general assembly
09/04/2018	https://indico.cern.ch/event/718756/	HXSWG VH meeting (STXS)
08/05/2018	https://indico.cern.ch/event/728282/	HXSWG VH restricted discussion on STXS (#1)
17/05/2018	https://indico.cern.ch/event/729312/	WG2 Fid/dif/STXS (VH STXS discussion)
25/10/2018	https://indico.cern.ch/event/767903/	HXSWG VH restricted discussion on STXS (#2)
15/11/2018	https://indico.cern.ch/event/770424/	**ATLAS/CMS HXSWG VH(bb) meeting**
19/11/2018	https://indico.cern.ch/event/772776/	HXSWG VH meeting: PS and modeling studies
23/11/2018	https://indico.cern.ch/event/773249/	WG2 Fid/dif/STXS (VH STXS discussion)
10-12/12/2018	https://indico.cern.ch/event/740110/	15th general assembly

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

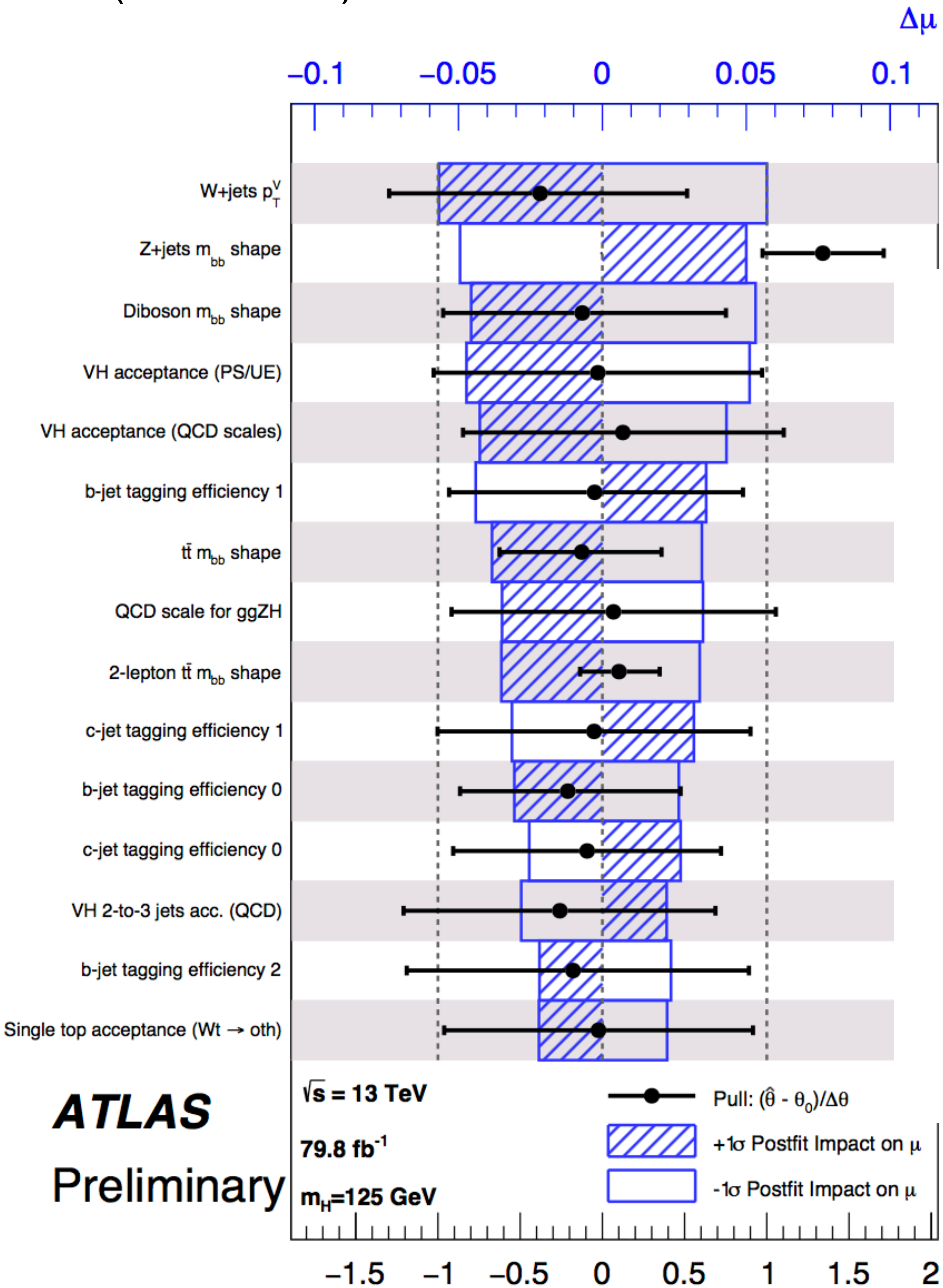
→ uncertainties on the total rate of the signal, **and** on the shape of the BDT discriminating function

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)

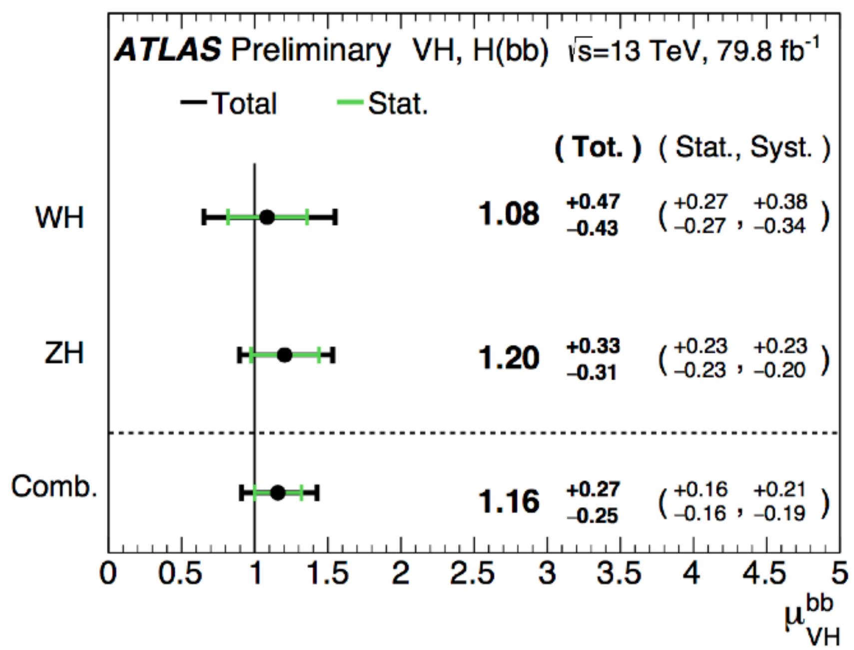


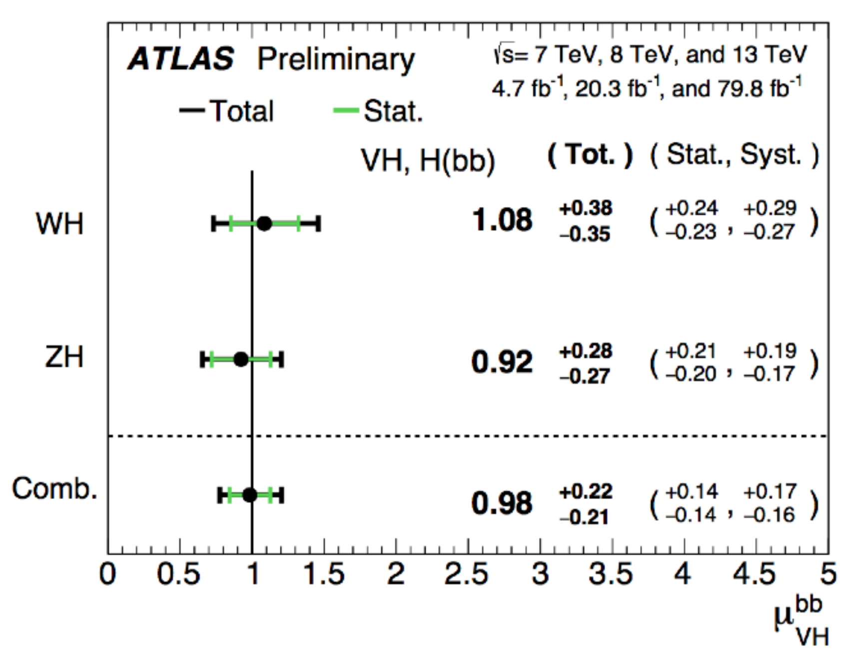
(2017 data)

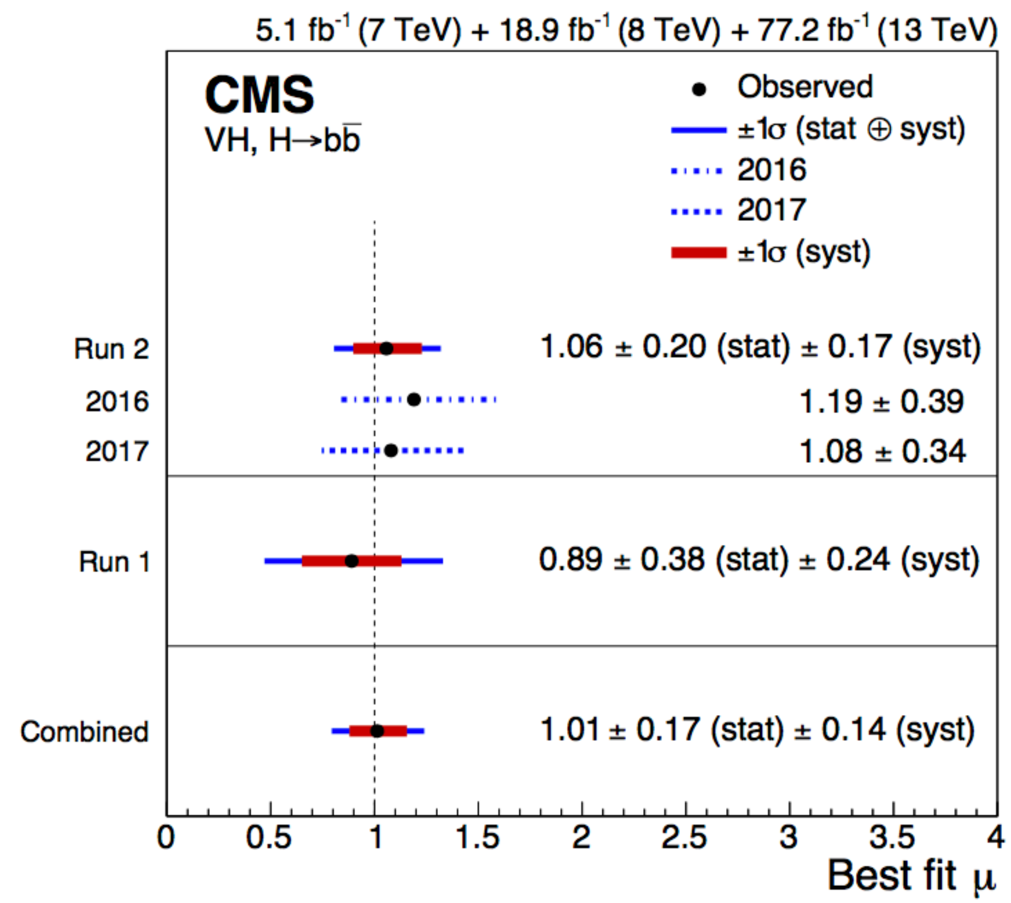
Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental 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	Significance (σ) 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





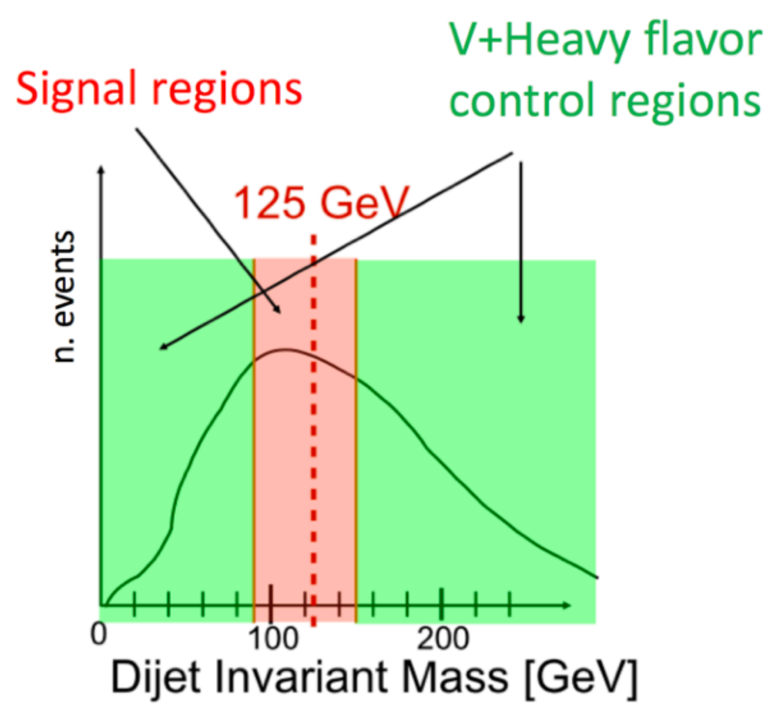


V+jets background modeling strategies

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)

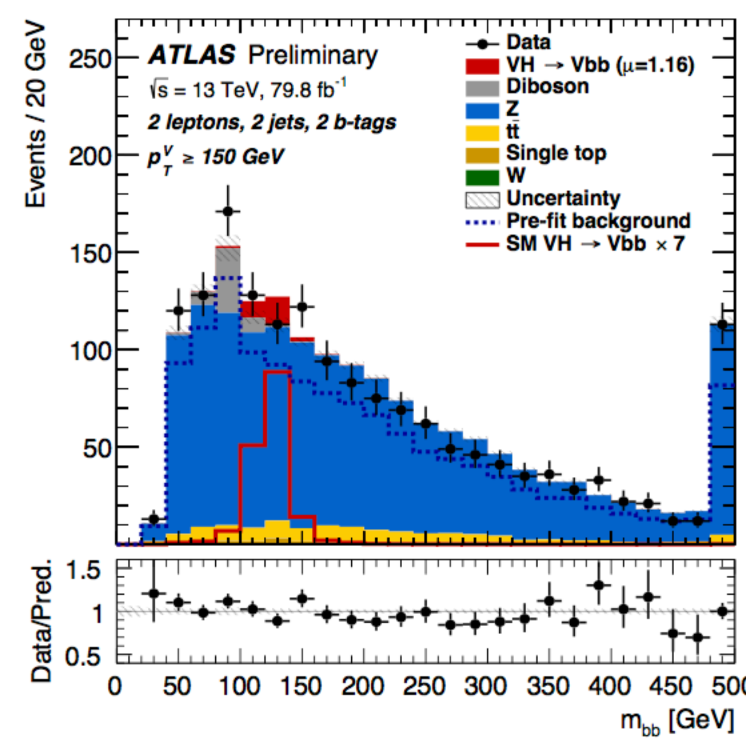


ATLAS (Sherpa V+0,1,2j@NLO + 3,4j@LO)

- **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)

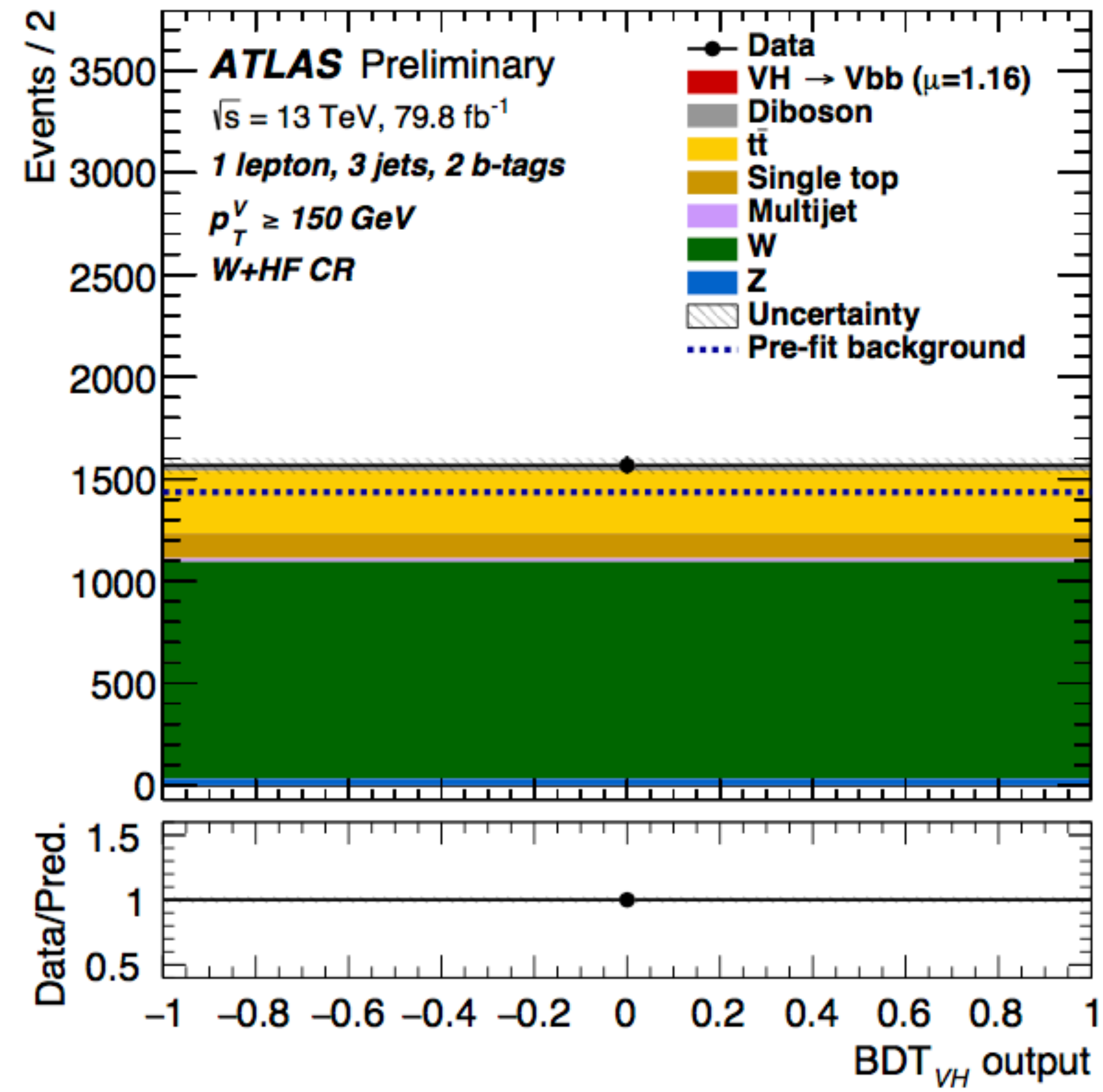
W+heavy flavors - dominated by 1-lepton channel

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%
$\boxed{W + \text{HF CR to SR ratio}}$	$\boxed{10\% \text{ (1-lepton)}}$
$m_{bb}, p_{\mathrm{T}}^{V}$	S

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

ATLAS

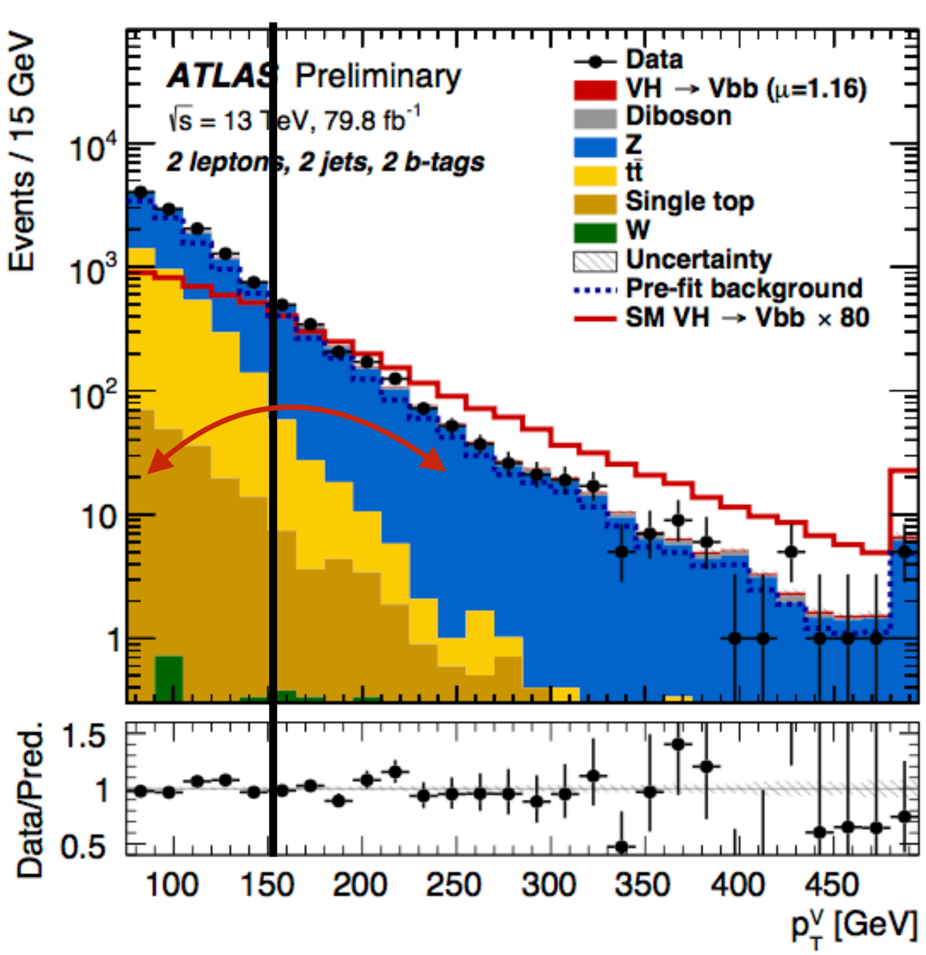
- **no dedicated control region for Z+hf**
- no m(bb) window selection applied in the nominal analysis selection

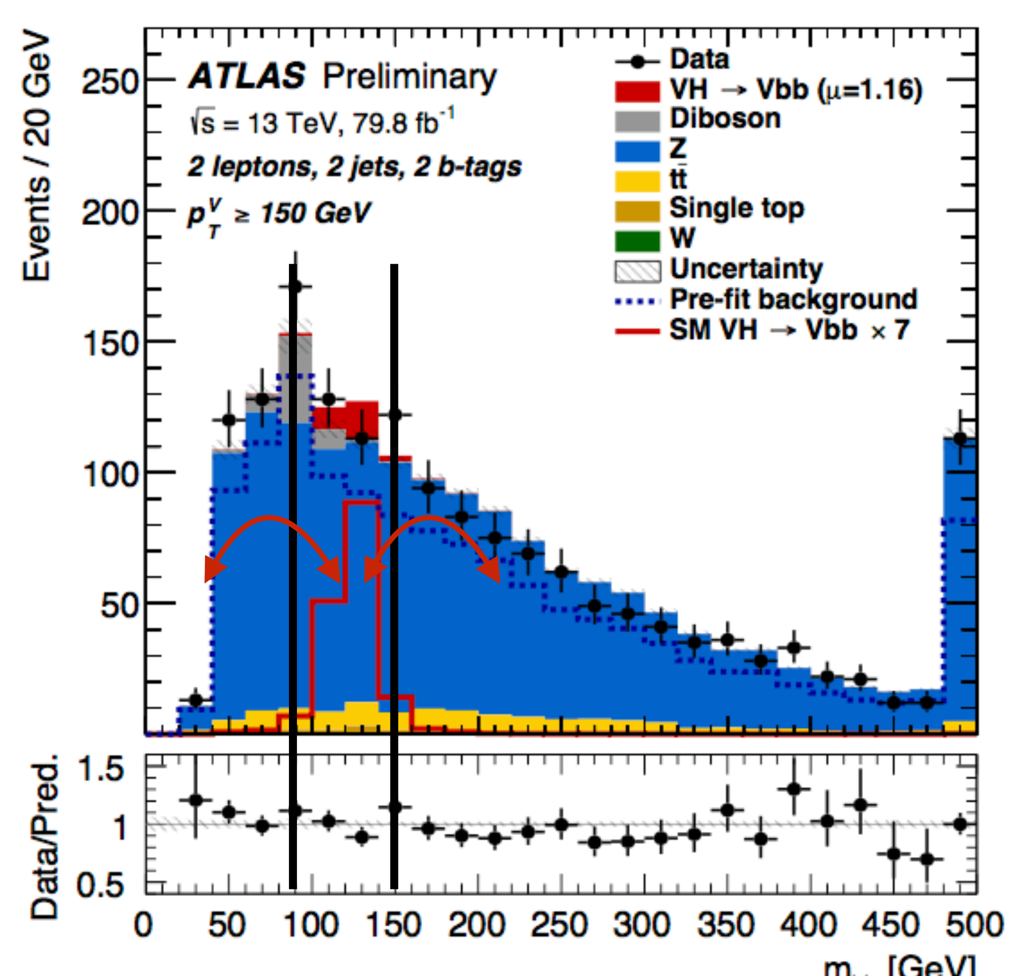
	Z + jets
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
Z + HF normalisation	Floating (2-jet, 3-jet)
$Z + bc$-to-$Z + bb$ ratio	30 – 40%
$Z + cc$-to-$Z + bb$ ratio	13 – 15%
$Z + bl$-to-$Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S

- **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



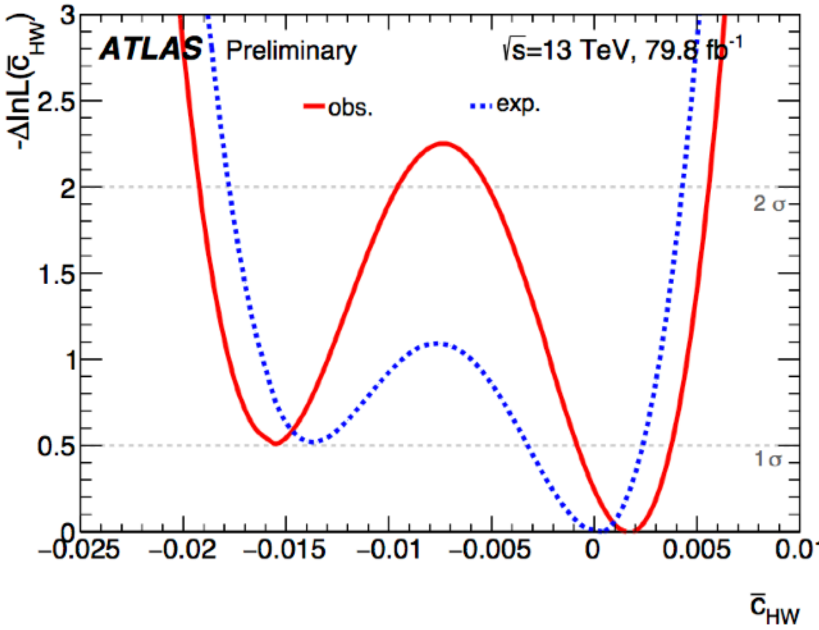


EFT VH fits

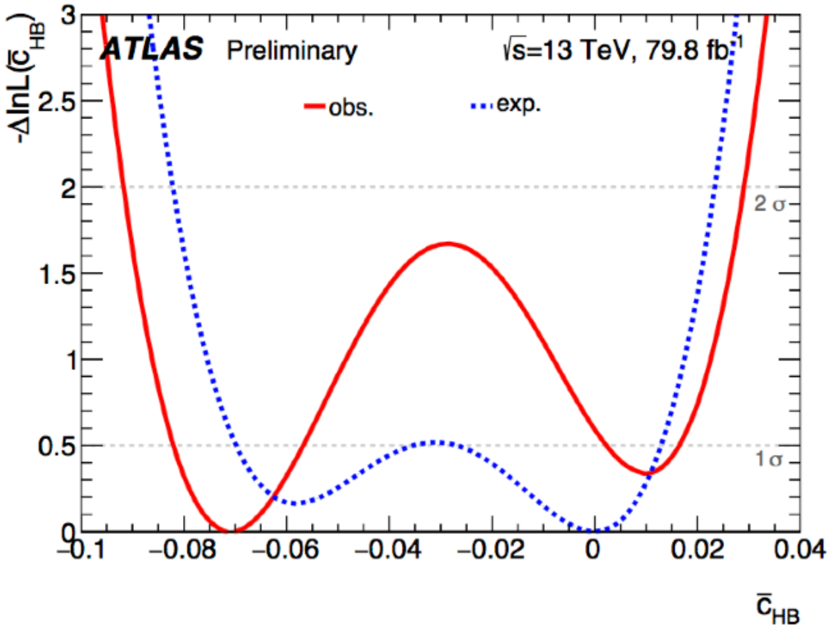
Operator	Expression	HEL coefficient	Vertices
O_g	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\mathtt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$	Hgg
O_γ	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathtt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$	$H\gamma\gamma, HZZ$
O_u	$y_u \lvert H\rvert^2 \bar{u}_l H u_R + \text{h.c.}$	$\mathtt{cu} = v^2 \bar{c}_u$	$Ht\bar{t}$
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
O_{HB}	$i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu}$	$\mathtt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$	HZZ
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
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

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

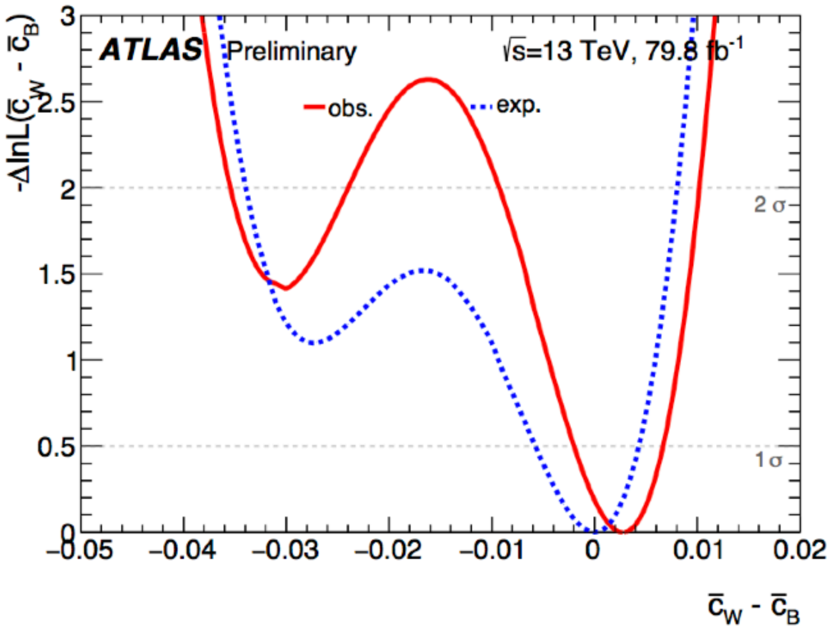
EFT VH fits



(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
$\bar{c}_{HW}$	$[-0.0032, 0.0024]$	$[-0.0008, 0.0037]$
$\bar{c}_{HB}$	$[-0.069, -0.036] \cup [-0.026, 0.013]$	$[-0.082, -0.057] \cup [0.002, 0.017]$
$\bar{c}_W - \bar{c}_B$	$[-0.0060, 0.0045]$	$[-0.0020, 0.0065]$

ZH XS update

<u>post-YR4 update</u>: 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%