

VBF roadmap for YR5

WG1 YR5 kick-off

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Update on inclusive numbers for 13.6 TeV

Motivation: provide reference numbers

References:

- N3LO QCD from proVBF [Dreyer, Karlberg; 1811.07918]
- NLO EW from Hawk [Denner, Dittmaier, Kallweit, Mück; 1112.5142, 1412.5390]
- NNLO non-fact. corrections [Asteriadis, Brønnum-Hansen, Long, Melnikov, Quarroz; 2305.08016, 2305.12937]

VBF (N3LO QCD + NLO EW) + sub-eikonal non-factorisable NNLO-QCD							
MH [GeV]	Cross Section [pb]	Uncertainty					
		Scale		TU	PDF+ α_s	PDF	α_s
		pos [%]	neg [%]	[%]	[%]	[%]	[%]
120.00	4.267E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
122.00	4.201E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
124.00	4.136E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
124.60	4.117E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
124.80	4.110E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
125.00	4.104E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
125.09	4.101E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
125.20	4.097E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
125.30	4.094E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
125.38	4.092E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
125.60	4.084E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
126.00	4.072E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
128.00	4.010E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4
130.00	3.949E+00	+0.1	-0.1	± 0.6	± 2.2	± 2.1	± 0.4

Big thanks to **Asteriadis, Brønnum-Hansen, Karlberg, Mück** who provided numbers!
Updated on twiki page ([link](#))

Recent theory developments (I)

Find more information to theory development in the [LHC WG workshop talk 2023](#)

- **On the non-factorizable corrections to Higgs boson production in weak boson fusion** [Asteriadis, Brønnum-Hansen, Melnikov; 2305.08016]
See also [Asteriadis, Brønnum-Hansen, Long, Melnikov, Quarroz; 2305.06292, 2309.06292]
 - Non-factorisable (NF) corrections at NNLO QCD smaller than factorisable ones but same order than N3LO QCD ones
 - Non-factorizable corrections dominated by two-loop virtual
 - Further understanding of fixed-order corrections
- **Electroweak corrections and shower effects to Higgs production in association with two jets at the LHC** [Jäger, Scheller; 2208.00013]
 - Implementation in Powheg
 - Both VH with hadronic decay and VBF
 - NLO QCD or NLO EW implemented ...
 - ... and matched to QCD or QED PS
(not both together)

Recent theory developments (II)

- **CENTRAL Jet Veto Studies for Electroweak Higgs Boson production**
 [Tinghua Chen, Terrance M. Figy, Simon Plätzer [Eur. Phys. J. C, 82 8 \(2022\) 704](#)]

- Using HT(jets) for the scale.
- central jet veto necessary to remove VH background
- Beyond 2 jets you need NLO 3 jet.

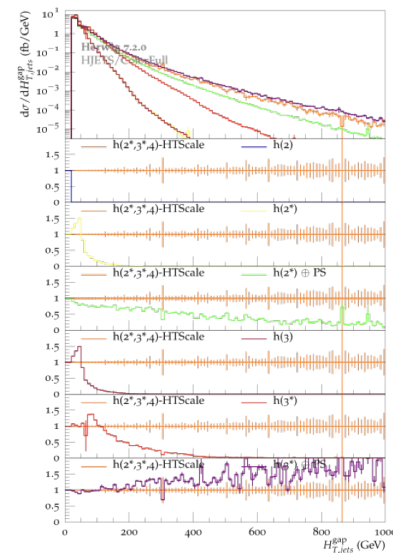
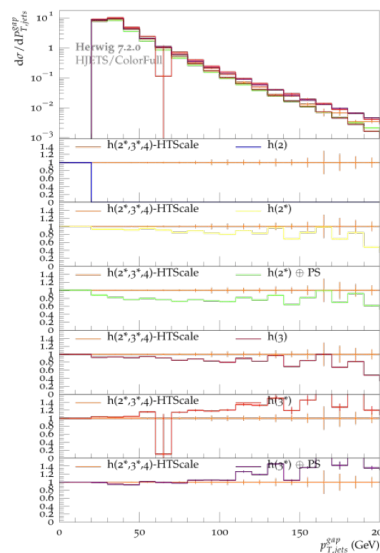
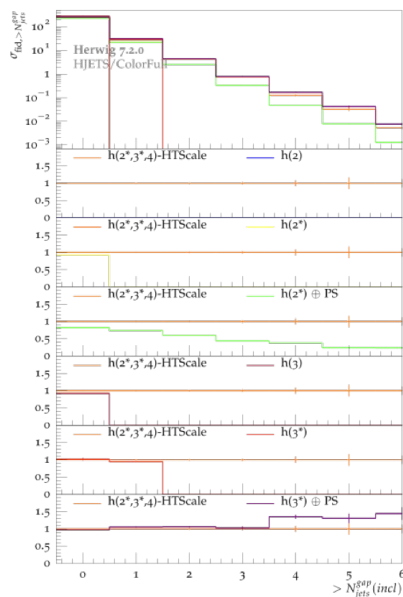
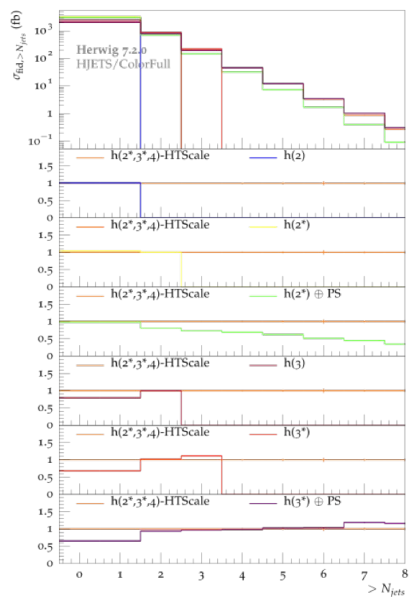
References and Thanks to Collaborators...

Collaborators: Simon Platzer, Peter Schichtel, Michael Rauch, Malin Sjödal, Francisco Campanario, and Tinghua Chen.

- <https://arxiv.org/abs/2109.03730> (Published in 2022!)
- <https://arxiv.org/abs/1802.09955>
- <https://arxiv.org/abs/1610.07922>
- <https://arxiv.org/abs/1308.2932>
- <https://arxiv.org/abs/0710.5621>



- Gap Jets are quite soft.
- Again, you need NLO for more than 2 jets



Recent theory developments (III)

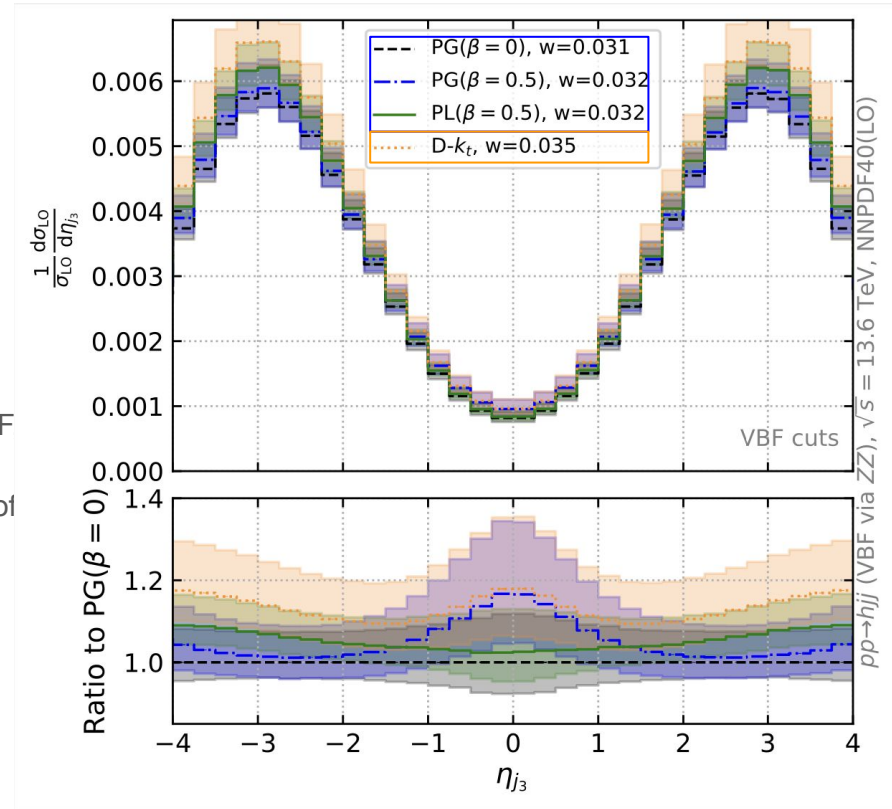
- **Electroweak corrections and shower effects to Higgs production in association with two jets at the LHC** [Jäger, Scheller; 2208.00013]

- Implementation in Powheg
- Both VH with hadronic decay and VBF
- NLO QCD **or** NLO EW implemented ...
- ... and matched to QCD or QED PS

- **Next-to-leading-logarithmic PanScales showers for Deep Inelastic Scattering and Vector Boson Fusion** [van Beekveld, Ferrario Ravasio; 2305.08645]

- NNL PS for DIS-like processes (w/o non factorisable corr): VBF VBS...
- Discrepancies between standard **LL PS** and **NLL** of the order of for third jet observables, but similar to scale variations
- NLO+PS will be required

NLL showers



Recent experimental developments

Dedicated measurements of VBF H entering the “precision” era.

Possible in rich variety of decay channels, with differing phase spaces ($p_T(H)$, m_{jj} , ...)

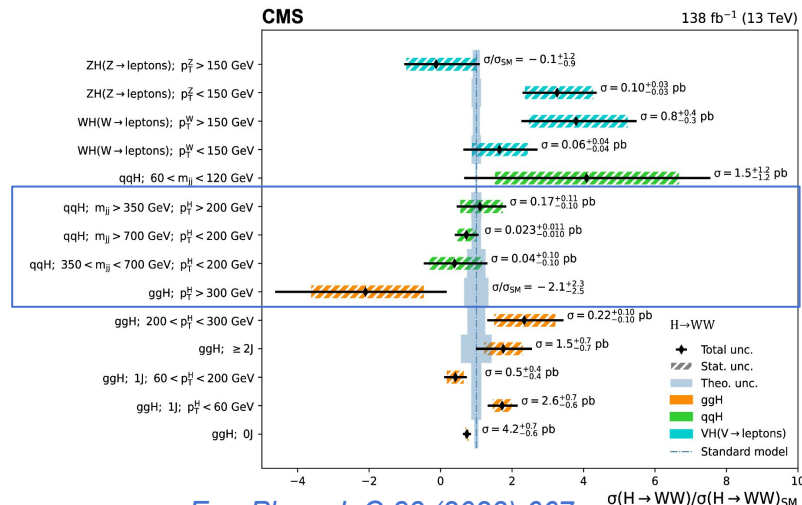
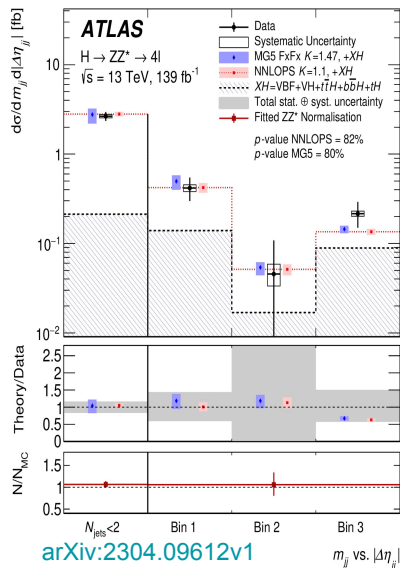
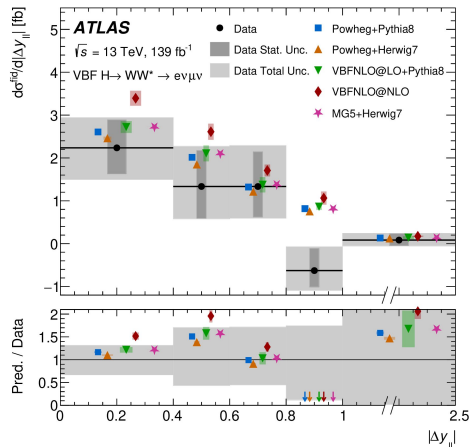
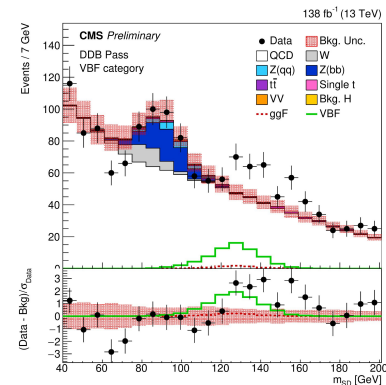
Most recent results in:

Fiducial measurements in: $H \rightarrow WW$, $H \rightarrow ZZ$ [ATLAS], STXS $H \rightarrow WW$ [CMS]

Boosted $H \rightarrow bb$ [CMS]

Small signal/background \rightarrow extensive use of Multivariate Techniques

Modelling uncertainties in extrapolations between kinematic regions become ever more relevant



Typical VBF uncertainties in exp. measurements

Theory uncertainty relative sizes in
typical VBF measurements

Primary theory uncertainties impacting
experimental measurements

- PS (leading)
- ggH contribution in VBF-enriched regions

	VBF H	ggH (in VBF-enriched region)
PDF	<1%	<3%
QCD scale	<1%	2-20%
UE	<1.5%	<2-3%
Parton shower	5-15%	4-10%

Systematic study at differential level

Method: differential study in fiducial volume at 13.6 TeV

Event selections: mixture of ATLAS and CMS

Rivet routine + run cards (for reproducibility)

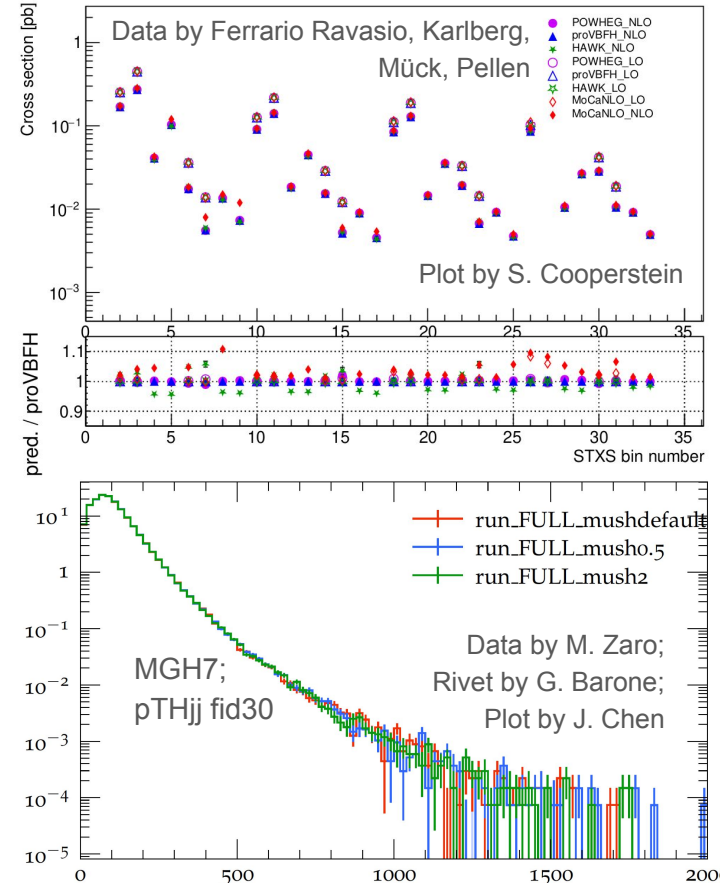
Beyond 1D distributions (2D, 3D) and also in STXS bins

State-of-the-art numbers for fixed order

State-of-the-art number for NLO+PS

1. Provide state-of-the-art predictions at the differential level at fixed order
 - NNLO QCD + NLO EW
 - Evaluation of various approximations (full vs. vbf approx.)
 - Non-factorizable corrections
 - Irreducible background and interferences
 - Tuned comparison of various fixed-order codes
 - **with different approximations**
 - Data produced at LO and NLO QCD
2. PS predictions and uncertainties in VBF
 - Alline with set-up of fixed-order study
 - Agreement on what combinations to run
 - Comparison of different parton shower (different physics)
 - Provide recommendations for PS uncertainty
3. Interpretation of physical result
 - Provide refined estimate of uncertainties
 - EW corrections, VBF approximation, ...
 - Understand differences and make recommendations

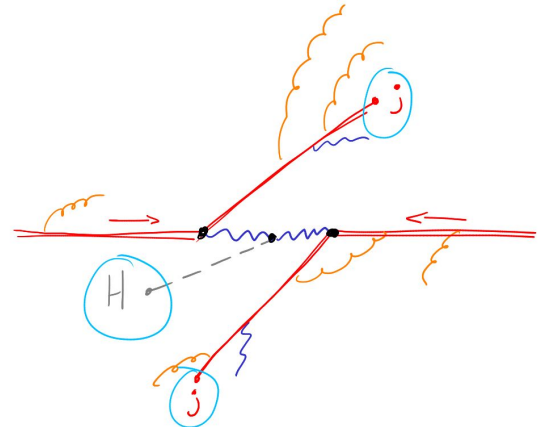
Well on track for a first **Physics Community Reports** form **SciPost** that can be part of the YR5.



Beyond the these studies: A Roadmap for more YR5 studies (time ordered)

1. State-of-the-art predictions (multi differential)
 - For fixed order and *with parton-shower* corrections for 13.6 TeV (on-going)
 - To be submitted to SciPost community report
2. Harmonising fiducial definitions:
 - of cross sections across experiments and theory for VBF/VBS/multi boson predictions.
 - [\[2406.00708\]](#) for first proposal, work within EWWG/Les Houches workshop (on-going)
3. ggF contribution in VBF phase-space, and impact of hadronisation/MPI
(on-going LHE study)
4. VBF Interference with $V(H \rightarrow jj)$ (at the very least dedicated $V(H \rightarrow jj)$ (N)NLOPS generator)
5. Best predictions and recommendations for VBF+photon
6. **Your ideas.**

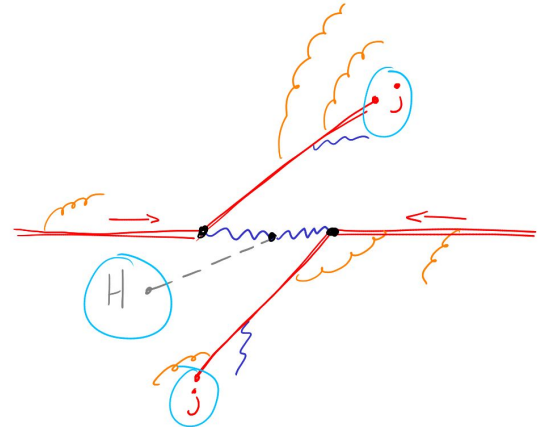
NB: All ideas are not feasible at once.



Conclusions

- If you want to contribute/have ideas, please contact us!
- e-group: lhc-higgs-vbf, just subscribe!
- A twiki page is available summarising the main activities ([link](#))
- **Planning for a second iteration of the VBF workshop in Fall.**
 - Good occasion for harmonizing the strategies for YR5.
- Email us at lhc-higgs-vbf-convener@cernNOSPAMPLEASE.ch

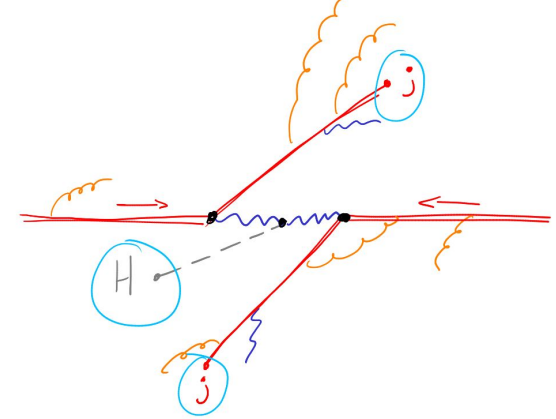
THANK YOU.



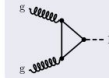
BACK UP

VBF at the LHC

- Second largest production mechanism
- Coupling to weak boson (like Higgs Strahlung)
- Very special topology
 - Signature: 2 jets + H
 - Jets intrinsically separated due to special topology
 - Exclusive cuts to access the process
 - Typically: large invariant mass of the two jets and large rapidity separation

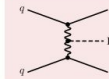


Gluon fusion



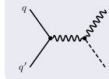
$$\sigma_{ggF} \approx 50 \text{ pb}$$

Vector-boson fusion



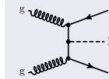
$$\sigma_{vbf} \approx 4 \text{ pb}$$

Higgs Strahlung



$$\sigma_{HV} \approx 2.5 \text{ pb}$$

t \bar{t} H



$$\sigma_{t\bar{t}H} \approx 0.5 \text{ pb}$$

Only fiducial definition is physical!

Numbers @ 13 TeV from
[de Florian et al.; 1610.07922]

The elephant in the room...

- PS agree on the perturbative side... [Buckley et al.; 2105.11399] **(theory finding)**
- Larger disagreement observed on **experimental side** ...

Potential solutions:

- Related to uncertainty prescription?
- Related to extrapolation procedure?
- Related to inclusion of non-perturbative effects (UE, hadronisation) in PS?
- Could there be a problem with the tuning of exp. samples with wrong PS recoil scheme?
(one line summary of idea discussed at Les Houches)

[Ballestrero et al.;1803.07943], [Jäger, Karlberg, Plätzer, Scheller, Zaro; 2003.12435], [Bittrich, Kirchgaeßer, Papaefstathiou, Plätzer, Todt; 2110.01623], [Höche, Mrenna, Payne, Preuss, Skands; 2106.10987]

- Worth to be investigated!



[Source: Bing image creator]

Given the status what is relevant to do within the WG ...

- Summarise state of the art on th. and exp.
 - Th. findings are not always well propagated to exp.
Important for theorists to get credits through proper citations
- **Differential** study in fiducial volume at 13.6 TeV
 - Event selections: mixture of ATLAS and CMS
 - Rivet routine + run cards (for reproducibility)
 - Beyond 1D distributions (2D, 3D) and also in STXS bins
- State-of-the-art numbers for fixed order
 - Inclusion of everything available (typically in different places and/or in different set-ups)
- State-of-the-art number for NLO+PS
 - Only perturbative part (no UE and hadronisation)
 - Make recommendations for uncertainties

The leading culprit: PS uncertainties

Leading uncertainties, ATLAS

VBF $H \rightarrow \gamma\gamma$ [JHEP 07 \(2023\) 088](#)

Leading uncertainties, CMS VBF $H \rightarrow bb$ [arXiv:2308.01253](#),

See J. Dickinson [talk](#)

Source of systematic uncertainty	Impact on signal strength [%]
VBF parton shower	13.0
Jet energy scale	7.7
Trigger efficiency	6.7
Parton shower (final-state radiation)	5.6
b jet regression smearing	3.3
b tagging efficiency	3.0
Pileup modeling	2.3
b jet regression scale	2.0
Jet energy resolution	1.5

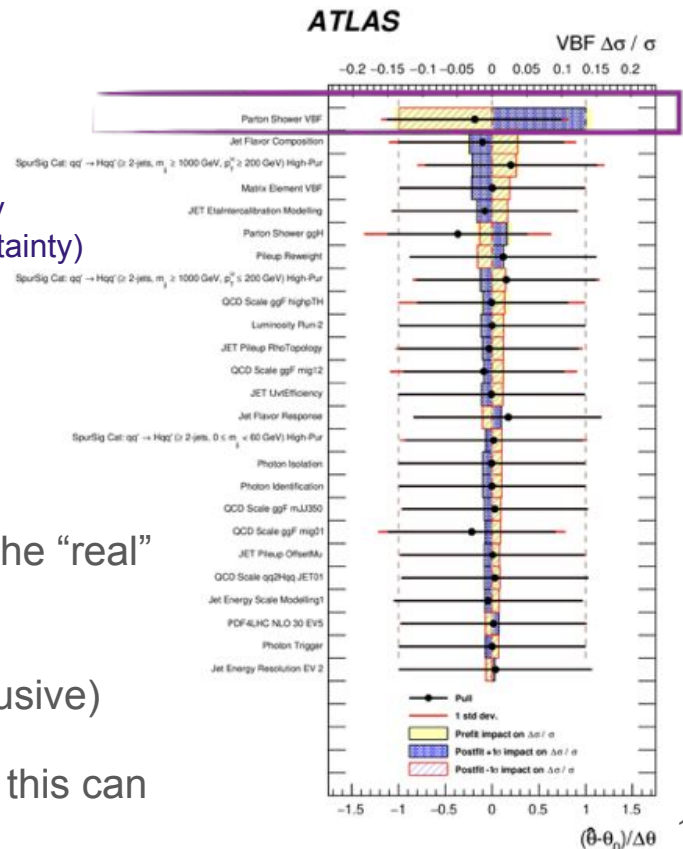
Parton shower uncertainty
(leading systematic uncertainty)

Current experimental prescription: symmetrized two-point
Pythia dipole recoil vs. Herwig7

- Rather ad-hoc, not clear whether this properly captures the “real” uncertainty

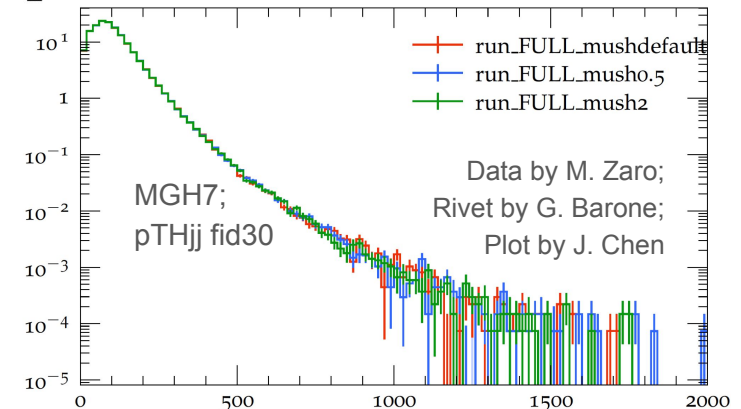
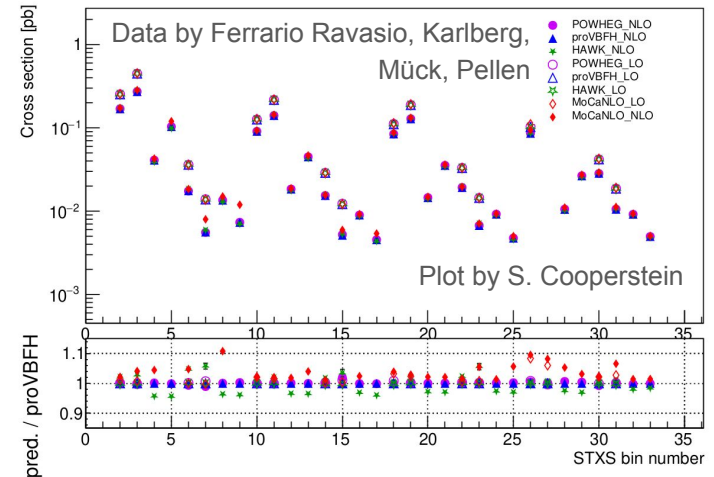
Uncertainty can approach ~15% of measured signal rate (inclusive)

- With Run-2 measurements already at 20-30% precision, this can become a limitation already at Run-3



Follow up, systematic study at differential level (Fixed order)

1. Provide state-of-the-art predictions at the differential level at fixed order
 - NNLO QCD + NLO EW
 - Evaluation of various approximations (full vs. vbf approx.)
 - Non-factorisable corrections
 - Irreducible background and interferences
2. Tuned comparison of various fixed-order codes (**with different approximations**)
 - Data produced at LO and NLO QCD
3. Interpretation of physical result
 - provided refined estimate of uncertainties (EW corrections, VBF approximation, ...)
 - understand differences and make recommendations



Follow up, systematic study at differential level (PS)

PS predictions and uncertainties in VBF

- Same set-up as for fixed order
- Use Powheg/Sherpa/MG_aMC@NLO with different parton showers
- Alline with set-up of fixed-order study
- Agreement on what combinations to run
- Comparison of different parton shower (different physics)
- Provide recommendations for PS uncertainty

List of predictions:

- POWHEG BOX + Pythia8 (dipole and Vincia) and Herwig7 (AO and dipole)
- Madgraph5_MC@NLO + Herwgi7 AO
- Herwig7 standalone, dipole shower with MC@NLO, for VBF and full EW Hjj
- Sherpa standalone, dipole shower with MC@NLO, for VBF and full EW Hjj