

VBF status report

20th Workshop of the LHC Higgs Working Group

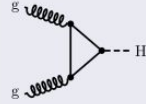
*J. Chen, S. Cooperstein, G. Barone
S. Ferrario Ravasio, M. Pellen*

CERN, Geneva, Switzerland, 14th November 2023

VBF at the LHC

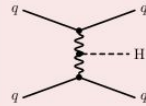
- Second largest production mechanism
- Coupling to weak boson (like Higgs Strahlung)
- Very special topology

Gluon fusion



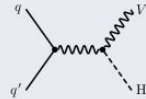
$$\sigma_{ggF} \approx 50 \text{ pb}$$

Vector-boson fusion



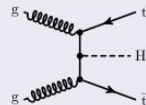
$$\sigma_{vbf} \approx 4 \text{ pb}$$

Higgs Strahlung



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

$t\bar{t}H$

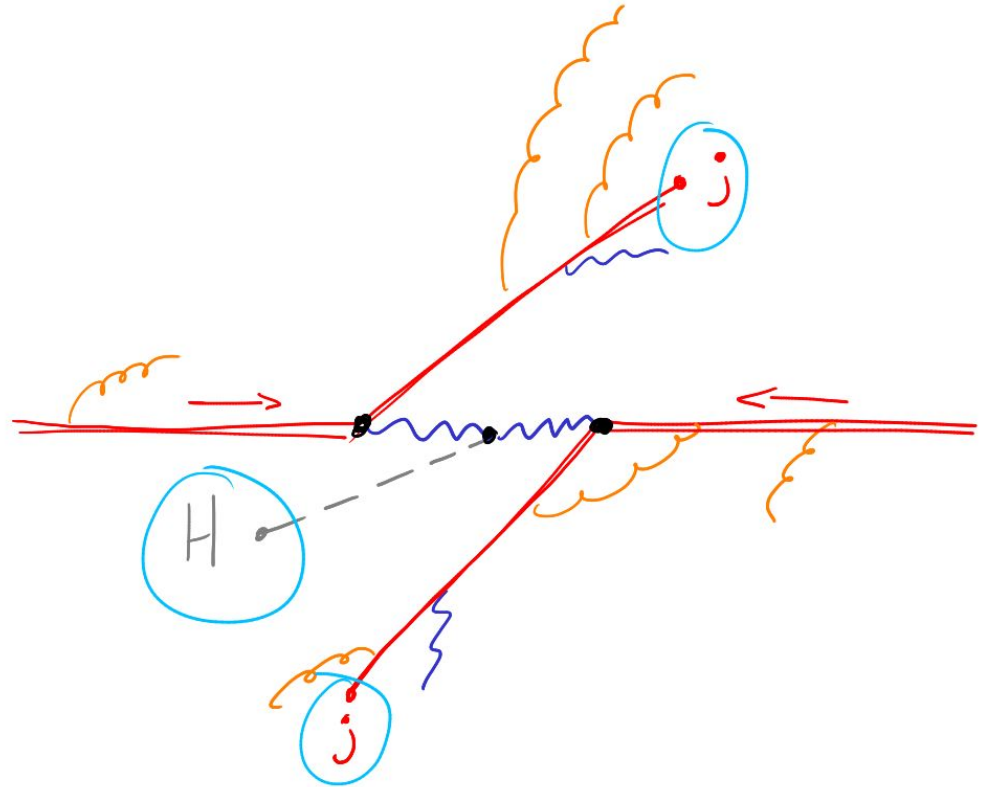


$$\sigma_{t\bar{t}H} \approx 0.5 \text{ pb}$$

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

VBF at the LHC

- 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



Only fiducial definition is physical!

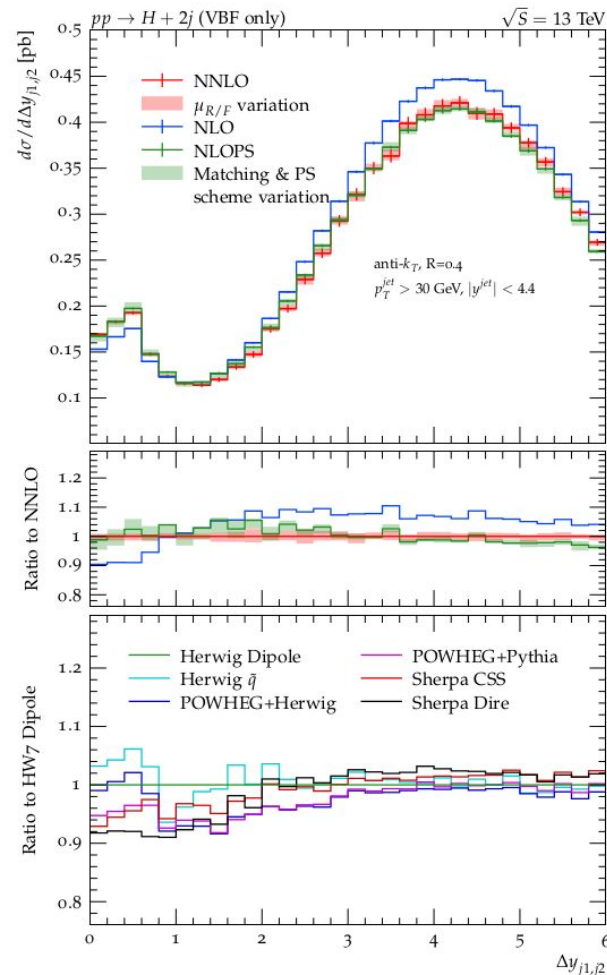
Recent theory developments

Recent theory work (1)

A comparative study of Higgs boson production from vector-boson fusion

[Buckley et al.; 2105.11399]

- Study of signal and background on wide range of Higgs-boson transverse momentum
- Study of jet radius dependence
- Comparison between the NNLO QCD predictions and several NLO QCD+PS ones for VBF signal
 - **Consistent picture!**

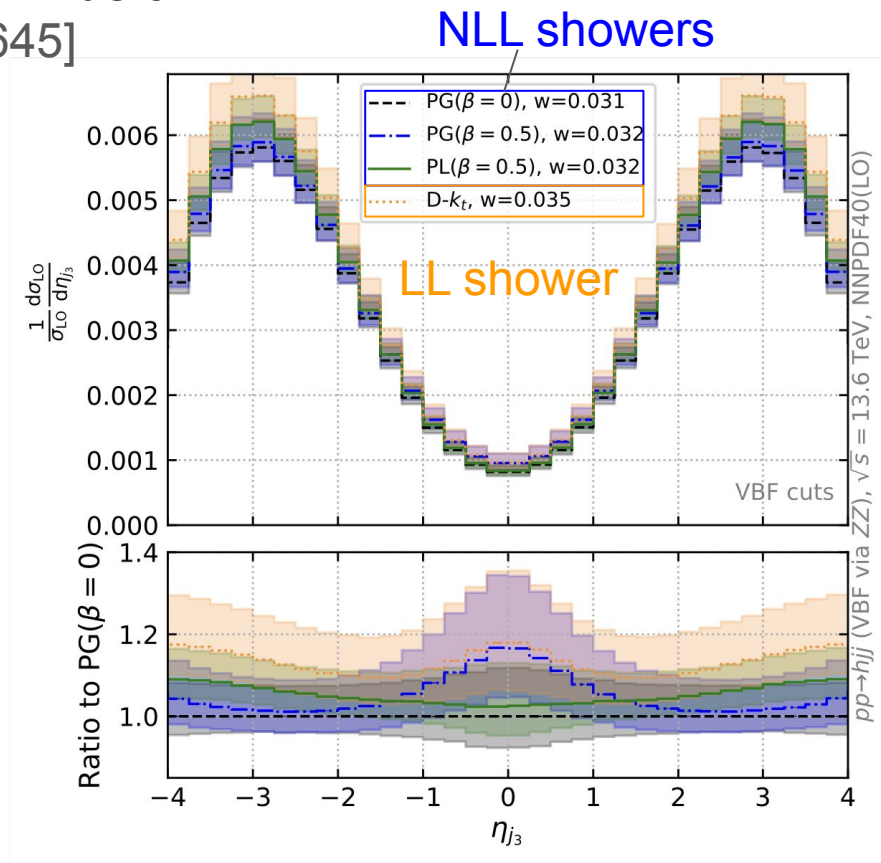


Recent theory work (2)

Next-to-leading-logarithmic PanScales showers for Deep Inelastic Scattering and Vector Boson Fusion

[van Beekveld, Ferrario Ravasio; 2305.08645]

- NLL PS for DIS-like processes (w/o non factorisable corr): VBF, VBS...
- Discrepancies between standard LL PS and NLL of the order of 15% for third jet observables, but similar to scale variations
- NLO+PS will be required (expected timeline: ~1 year)



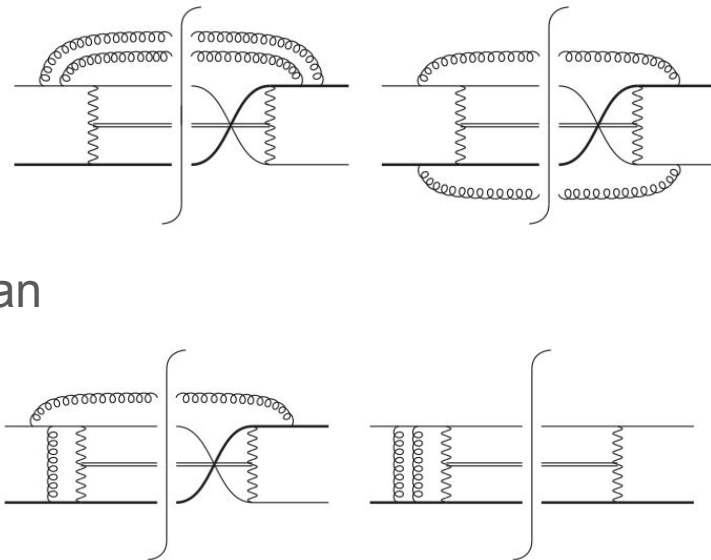
Recent theory work (3)

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



More in talk by Ming-Ming Long tomorrow ([link to indico](#))

Recent theory work (4)

Electroweak corrections and shower effects to Higgs production in association with two jets at the LHC

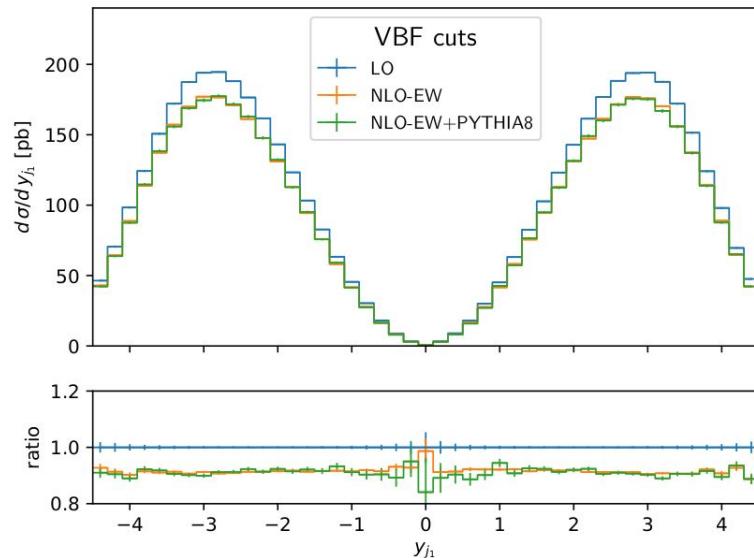
[Jäger, Scheller; 2208.00013]

- 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)

For more recent theory development:

Three-day workshop at CERN Oct. 19-21 2022

([link to indico](#))



Recent experimental developments

Most recent VBF results by ATLAS and CMS

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} , ...)

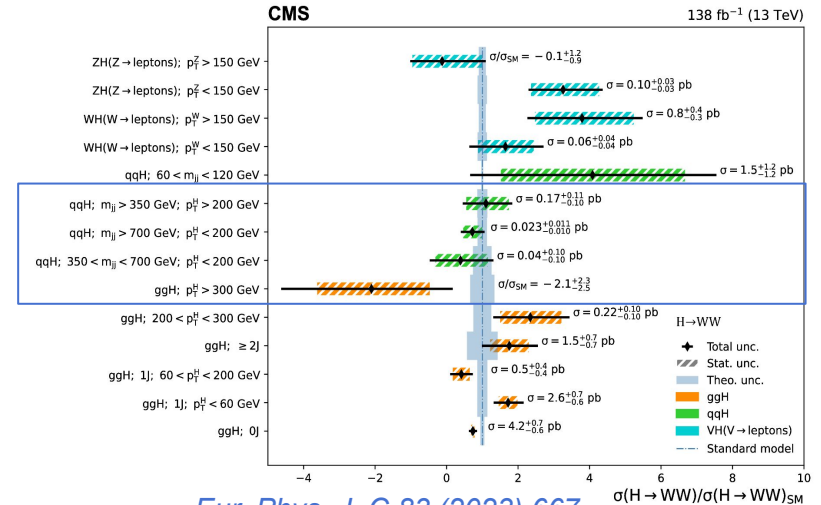
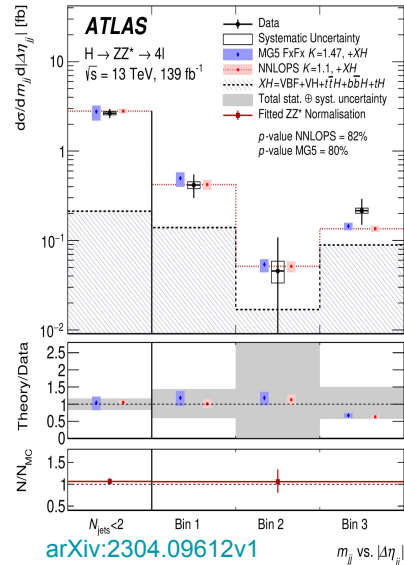
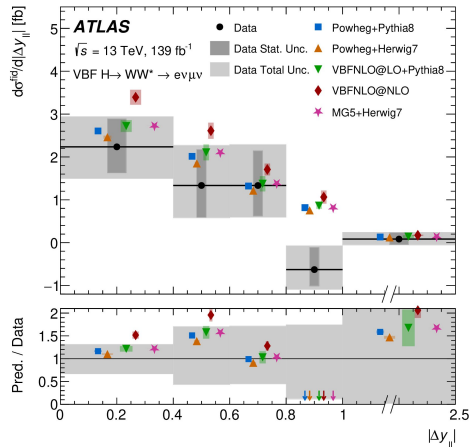
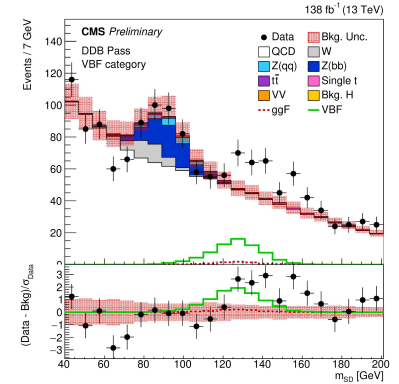
Most recent results in:

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%

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

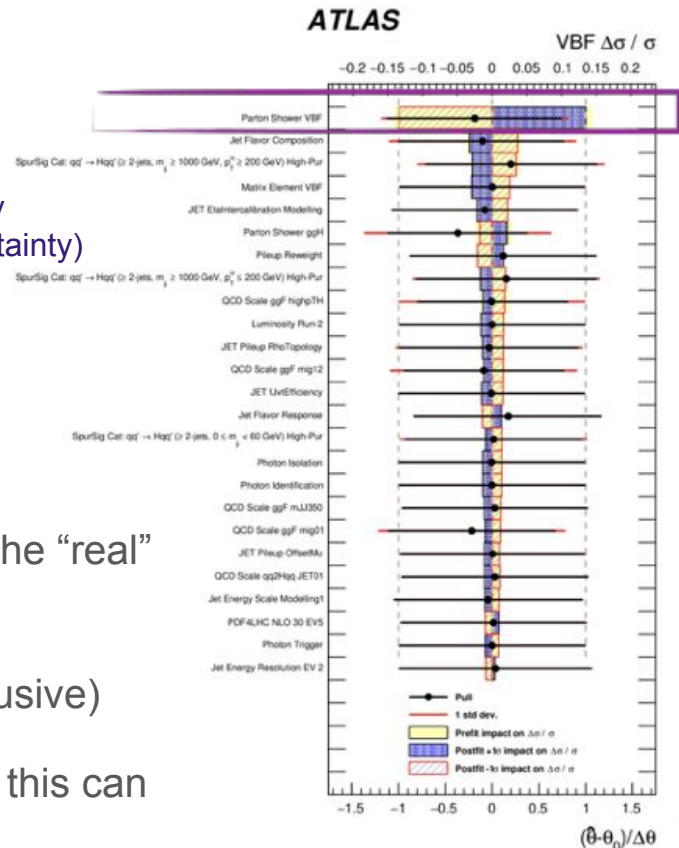
Parton shower uncertainty
 (leading systematic uncertainty)

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



Recent and ongoing WG activities

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 soon on twiki page ([link](#))

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

All this will end up in an article/note to be published this winter
(most likely in **Physics Community Reports** from **SciPost**; can we be first?)

Follow up, systematic study at differential level

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. PS predictions and uncertainties in VBF
 - Same set-up as for fixed order
 - Use Powheg/Sherpa/MG_aMC@NLO with different parton showers

Team:

G. Barone, J. Chen, S. Cooperstein, S. Ferrario Ravasio, Y. Haddad, S. Höche, A. Karlberg, A. Mück, M. Pellen, C. Preuss, M. Zaro

Codes: Hawk, proVBFH, MoCaNLO, Powheg, Sherpa, Pythia, Herwig, MG_aMC@NLO

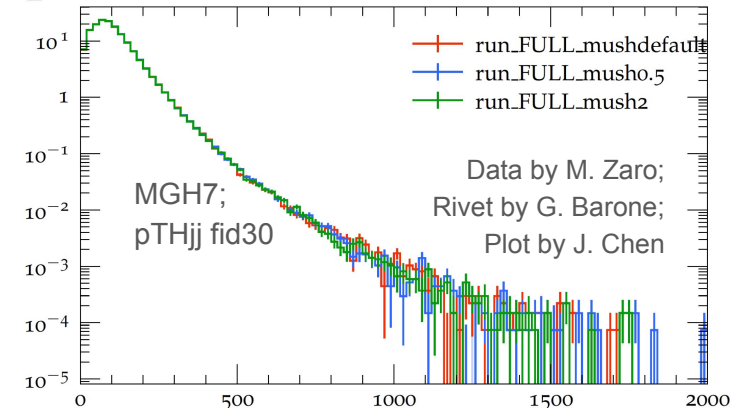
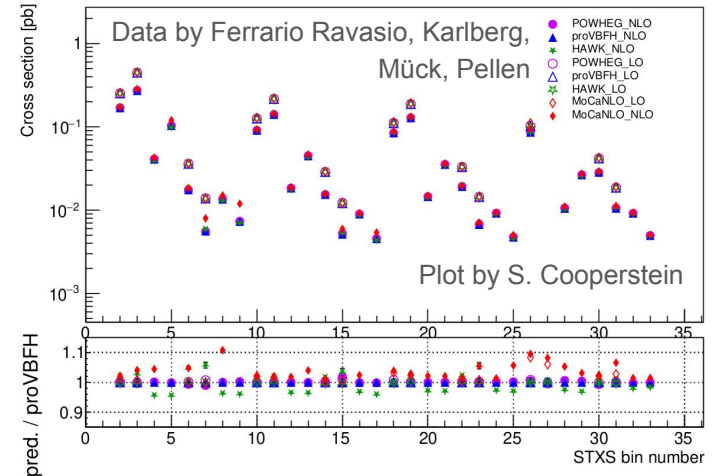
Follow up, systematic study at differential level (Fixed order)

1. Tuned comparison of various fixed-order codes (with different approximations)

- Data produced at LO and NLO QCD
- Fine for fiducial set-up -> Input OK.
- investigating for STXS set-up:
 - VBF approximate: OK
 - full computation: almost OK

2. 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)

Comparison of different parton shower

- 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 ...
... based on previous findings [Buckley et al.; 2105.11399]

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

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]

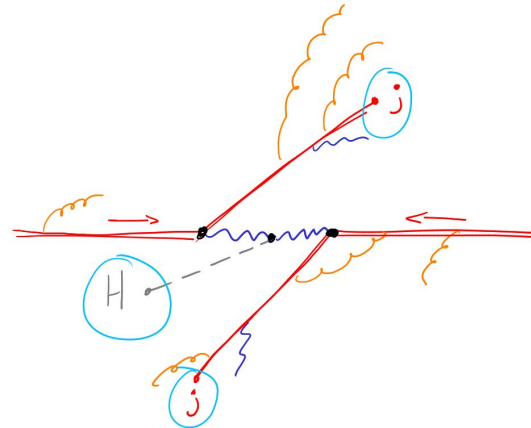
Propaganda slide

- 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](#))
- Email us at lhc-higgs-vbf-convener@cernNOSPAMPLEASE.ch
- Stay tune/give us feedback, we might organise a small workshop in March at CERN (if there is significant interest)

Outlook (in chronological order)

- Differential predictions @ 13.6 TeV:
 - Article with prediction and recommendations
 - Git repository with all analyses and run cards (reproducibility)
- ggF contamination in VBF signal region & hadronisation/underlying event effects
[Chen, Haddad, Höche, Huss, Huston, Jezo, Lindert, Plaetzer, Preuss, Ferrario Ravasio, Tarek, Winter, ...]
- **YOUR IDEA ...**

THANK YOU.



BACK UP

Most recent VBF results by ATLAS and CMS

[CMS-PAS-HIG-21-020](#), See J. Dickinson [talk](#)

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} , ...)

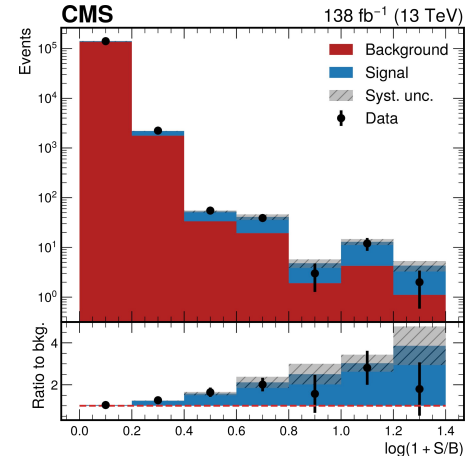
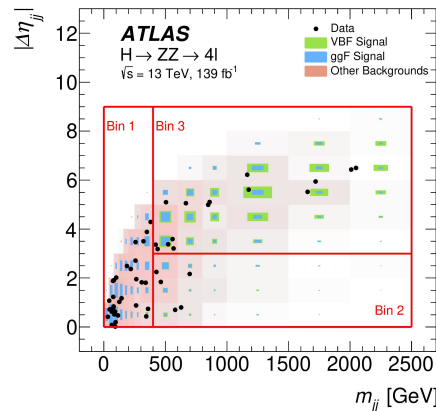
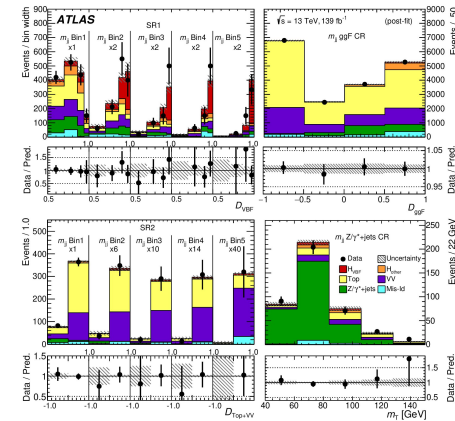
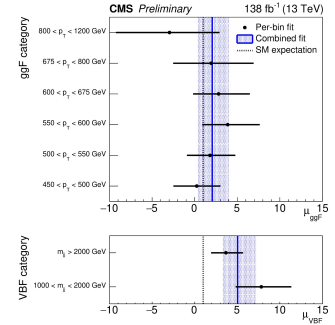
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Boosted $H \rightarrow bb$ [CMS]

Small signal/background \rightarrow extensive use of Multivariate Techniques

Modelling uncertainties in extrapolations between kinematic regions become evermore relevant



Brief overview of recent work on exp. side

Systematic uncertainties, of which theory is significant component, approaching statistical uncertainties

- If we do not further improve on this front it will limit many measurements soon enough...

Run-2 VBF H measurements by decay channel (CMS)

	$\mu_{\text{VBF}} = \sigma/\sigma_{\text{SM}}$	$\Delta\mu_{\text{STAT}}$	$\Delta\mu_{\text{SYST}}$
H$\rightarrow\tau\tau$	$0.81^{+0.17}_{-0.16}$	± 0.14	± 0.10
H$\rightarrow WW$	$0.71^{+0.28}_{-0.35}$	± 0.20	± 0.16
H$\rightarrow\gamma\gamma$	$1.04^{+0.34}_{-0.31}$	± 0.31	+0.16 / -0.09
H$\rightarrow ZZ$	$0.48^{+0.48}_{-0.38}$	+0.46 / -0.37	+0.14 / -0.10
H$\rightarrow bb$	$0.92^{+0.45}_{-0.39}$	± 0.32	+0.31 / -0.22
H$\rightarrow\mu\mu$	$1.36^{+0.69}_{-0.61}$	(dominant)	