VBF status report

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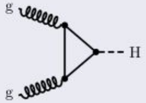
CERN, Geneva, Switzerland, Dec4 2024
LHC Higgs WG workshop 2024

VBF at the LHC

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

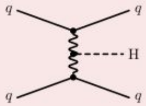
Numbers @ 13 TeV from
[de Florian et al.; 1610.07922]

Gluon fusion



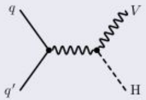
$\sigma_{\mathrm{ggF}} \approx 50\,\mathrm{pb}$

Vector-boson fusion



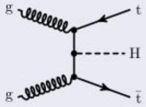
$\sigma_{\mathrm{vbf}} \approx 4\,\mathrm{pb}$

Higgs Strahlung



$\sigma_{\mathrm{HV}} \approx 2.5\,\mathrm{pb}$

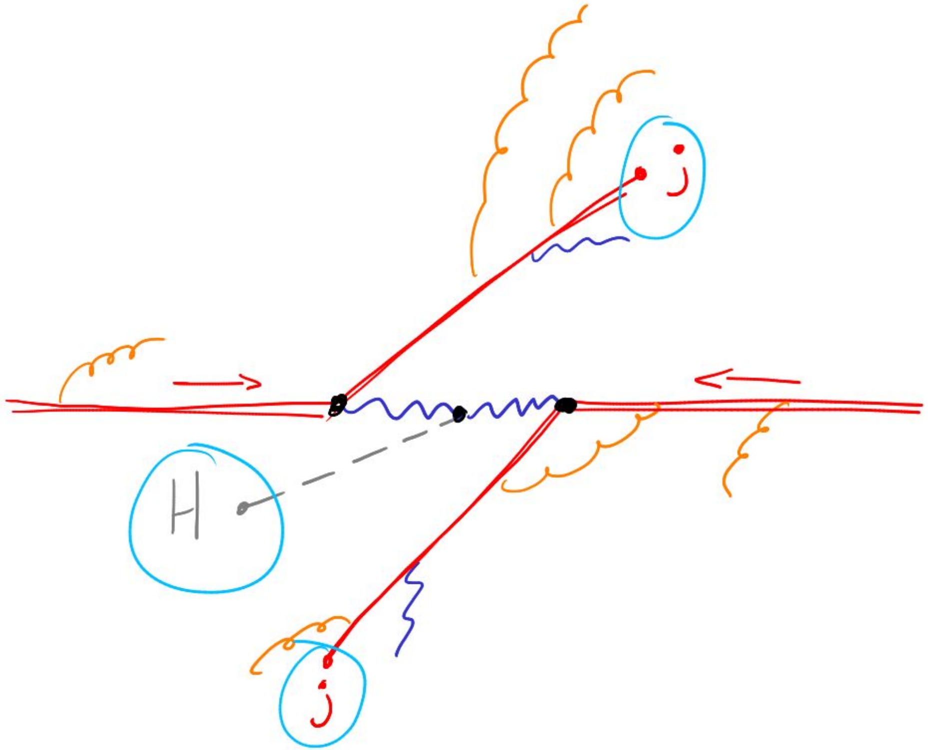
$t\bar{t}H$



$\sigma_{\mathrm{tth}} \approx 0.5\,\mathrm{pb}$

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!

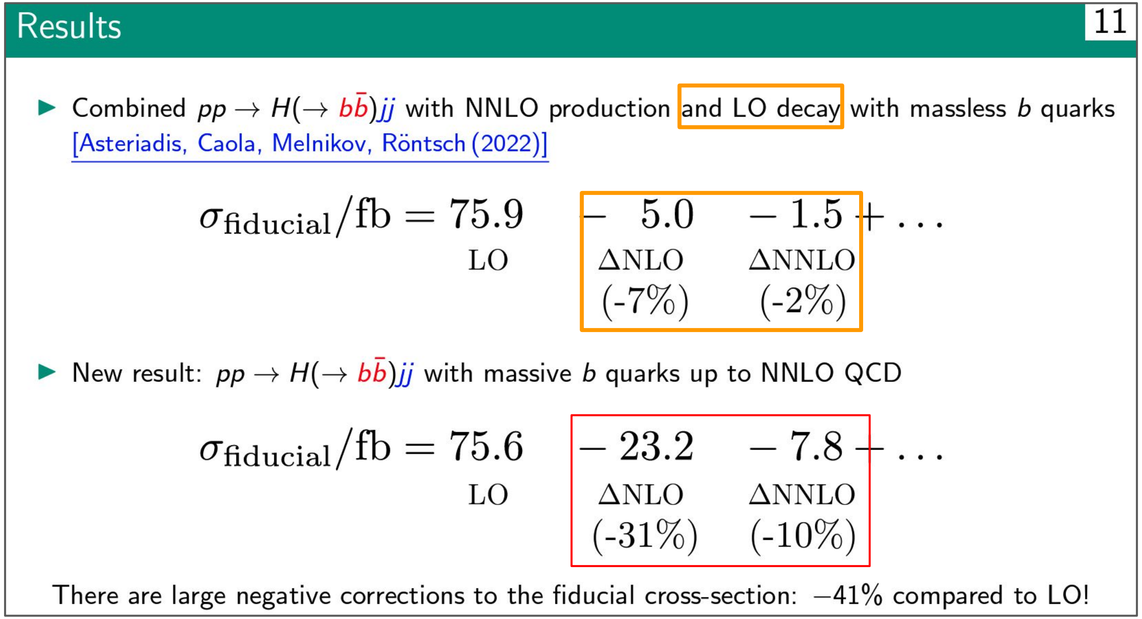
VBF working group and workshop

- VBF sub-group conveners (lhc-higgs-vbf-convener@cernNOSPAMPLEASE.ch)
  - ATLAS convener: Jiayi Chen
  - CMS convener: (outgoing) Gaetano Barone; (incoming) Soumya Mukherjee
    - *Thank you Gaetano for all your devotion to the VBF subgroup!*
  - Theory conveners: Mathieu Pellen, Silvia Ferrario Ravasio
- 2nd VBF workshop (VBF2024) was held at CERN this past October (https://indico.cern.ch/event/1442025/overview)
  - 60 participants (half in-person)
  - 1st VBF workshop: VBF2022 (https://indico.cern.ch/event/1186109/)
- The workshop aimed to
  - Review state-of-the-art of the theory and experiment communities
  - Discuss current theoretical and experimental bottleneck
  - Outlook for future advances and proposed/on-going new ideas
- **We will keep the workshop coming every 1.5yr-2yr**
  - **Subscribe to get notification:** lhc-higgs-vbf@cernNOSPAMPLEASE.ch

(Biased) selection VBF workshop contributions

Talk by Ivan Novikov, based on Phys.Rev.D 110 (2024) 5, 054017

- first NNLO-QCD full differential pp->Hjj->bbjj finds large negative correction to *fiducial* cross section comparing to LO decay results
- Difference in QCD correction is not covered by the scale variation



Results

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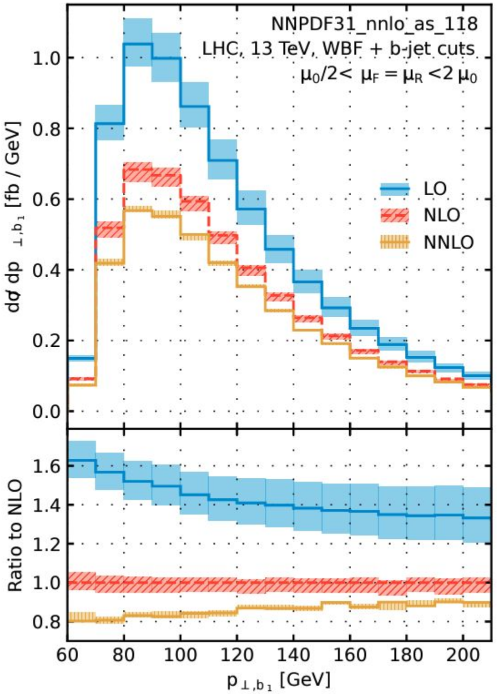
- Combined $pp \to H(\to b\bar{b})jj$ with NNLO production and LO decay with massless b quarks [Asteriadis, Caola, Melnikov, Röntsch (2022)]

$$\sigma_{\text{fiducial}}/\text{fb} = \underset{\text{LO}}{75.9} \; \underset{\substack{\Delta\text{NLO} \\ (-7\%)}}{-\,5.0} \; \underset{\substack{\Delta\text{NNLO} \\ (-2\%)}}{-\,1.5} + \ldots$$

- New result: $pp \to H(\to b\bar{b})jj$ with massive b quarks up to NNLO QCD

$$\sigma_{\text{fiducial}}/\text{fb} = \underset{\text{LO}}{75.6} \; \underset{\substack{\Delta\text{NLO} \\ (-31\%)}}{-\,23.2} \; \underset{\substack{\Delta\text{NNLO} \\ (-10\%)}}{-\,7.8} + \ldots$$

There are large negative corrections to the fiducial cross-section: -41% compared to LO!

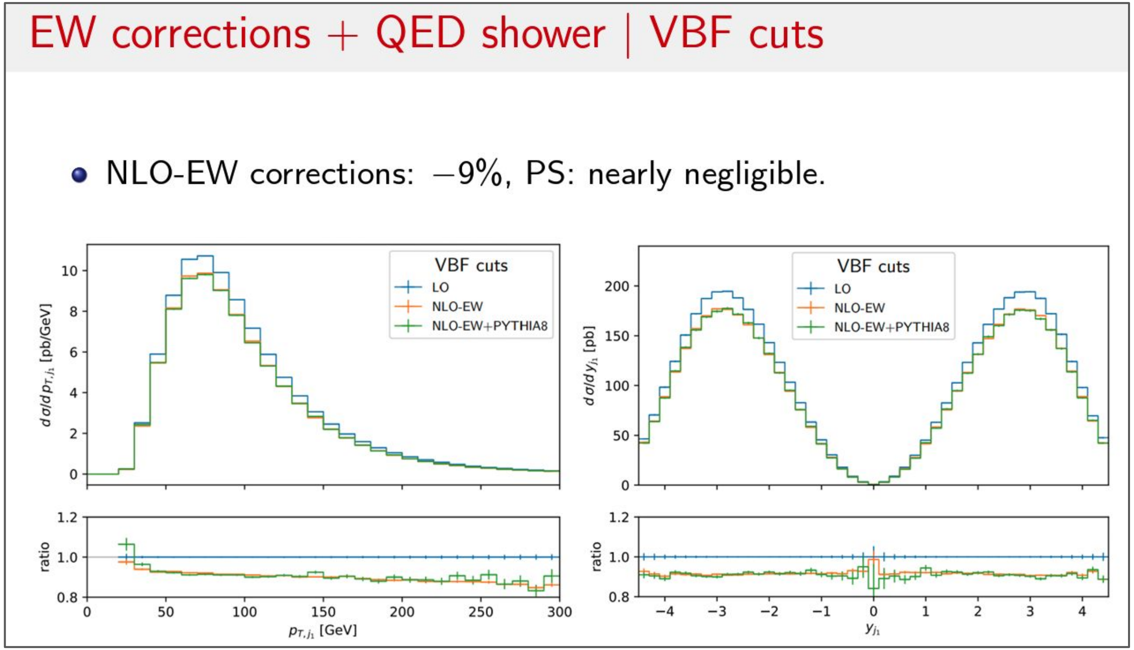


(Biased) selection VBF workshop contributions

Talk by Simon Reinhardt, based on J. High Energ. Phys. 2022, 191 (2022)

- Paper discussed implementation of full EW H+2jets production in Powheg box and matched to QED showers

- EW correction more pronounced in high energy phase space; QED shower nearly has no effect
- Work in progress: *combining EW and QCD* correction within Powheg box

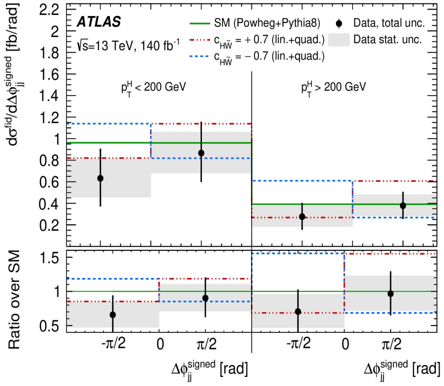


Recent experimental developments

Most recent VBF results by ATLAS and CMS

- Rich variety of decay channels, with differing phase spaces ($p_T(H)$, m_{jj}, …)

HIGG-2022-07



Inclusive VBF Overview

Slide credit: Jan Steggemann, Nicolas Berger
Experimental overview talk VBF workshop 2024

	CMS	ATLAS	
H→γγ	μ = 1.04 ±0.30(stat) ±0.06(theo) ±0.10(exp) HIG-19-015	σ/σ_{SM} = 1.20 ±0.18(stat) ±0.19(syst) HIGG-2020-16	#3
H→4l	μ = 0.48 ±0.41(stat) ±0.12(syst) HIG-19-001	σ/σ_{SM} = 1.21 ±0.44(stat) ±0.06(theo) ±0.10(exp) HIGG-2018-28	
H→WW*	**μ = 0.71 ±0.26** **HIG-20-013**	**σ/σ_{SM} = 0.93 ±0.13(stat) ±0.16(syst)** **HIGG-2021-20**	#2
H→bb	μ = 1.01 ±0.50 HIG-22-009	μ = 0.99 ±0.35 HIGG-2019-04	
H→ττ	**μ = 0.86 ±0.13(stat) ±0.05(theo) ±0.08(exp)** **HIG-19-010**	**σ/σ_{SM} = 0.93 ±0.12(stat) ±0.11(syst)** **HIGG-2022-07**	New #1

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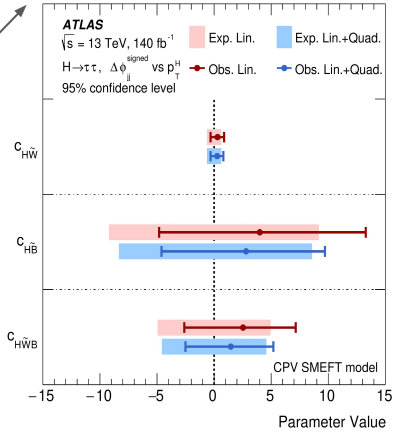


2D differential measurement yielded the most stringent constraint on CP odd EFT operators (Warsaw basis) to-date

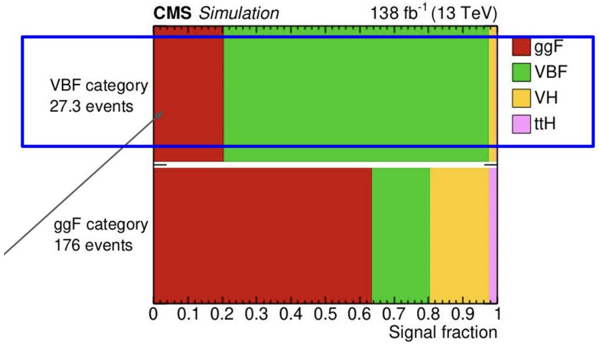
Experimental bottlenecks

- Small signal/background and **large ggF contamination**
- Analysis strategy generally follows (find Atul's talk on ggF contamination treatment in CMS):
  - apply VBF topology selection (ggF/VBF ratio >1 in low energy phase space);
  - Multivariate Techniques (reduce ggF/VBF to <<0.5) and measure ggF and VBF simultaneously

Boosted Hbb

CMS-HIG-21-020

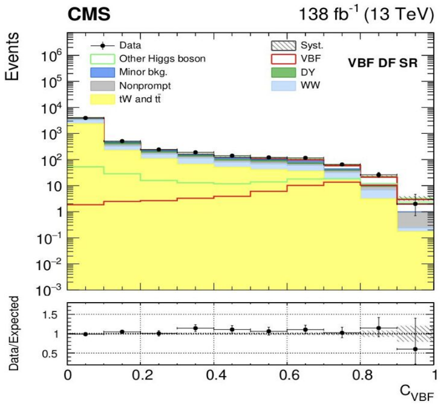
20% ggF contamination from MC simul



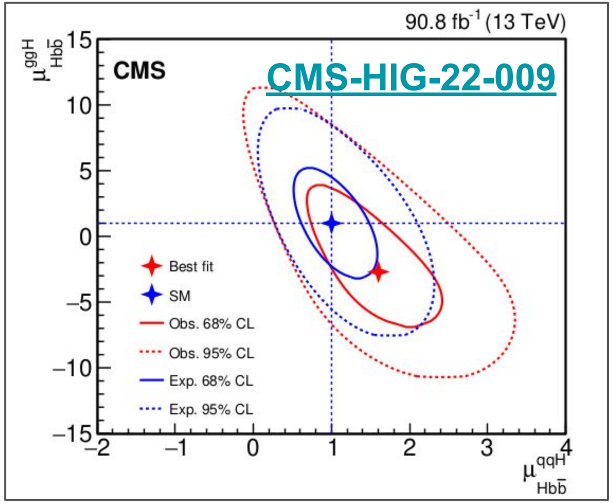
HWW CMS-HIG-21-020

DNN extensively increase the VBF sensitivity

Process	VBF DF	VBF SF
ggH	114 ± 8 (115)	21 ± 2 (21)
VBF	62 ± 11 (91)	39 ± 5 (57)



Simultaneous measurement of VBF and ggF in VBF topology of resolved H→ bb



- Dedicated ggF analysis categories to constraint ggF contamination, based on multiclass MVA techniques.

Experimental bottlenecks

Signal modeling uncertainty (shower and matching) remains the leading systematic source:

- Nominal: Powheg Box at NLO QCD + Pythia 8 (dipole recoil) for UE/PS/hadronization, normalized to NNLO QCD + *NLO EW*
- Shower and matching uncertainty:
    - ATLAS: Pythia8 vs Herwig7 = shower uncertainty; MG vs Powheg (+Herwig7) = matching uncertainty
    - CMS: varied Pythia scales or 2-point comparison with Herwig7 → analysis-dependent

Uncertainties

ATLAS H→ττ

Production mode	ggF	ttH	VBF	VH
Best-fit value	0.94	0.77	0.93	0.91
Total uncertainty	±0.30	±0.97	±0.16	±0.62
Statistical uncertainty	±0.15	±0.82	±0.12	±0.52
Total systematic uncertainty	±0.26	±0.51	±0.11	±0.34
Samples size	±0.09	±0.32	±0.03	±0.25
Theoretical uncertainty in signal	±0.19	±0.14	±0.10	±0.13
Jet and E_T^{miss}	±0.12	±0.14	±0.03	±0.11
Hadronic τ-lepton decays	±0.05	±0.09	±0.01	±0.04
Misidentified τ-lepton background	±0.05	±0.05	±0.02	±0.11
Luminosity	±0.01	±0.01	±0.01	±0.02
Theoretical uncertainty in top-quark processes	±0.01	±0.30	–	±0.02
Theoretical uncertainty in Z + jets processes	±0.03	±0.07	–	±0.02
Flavour tagging	±0.02	±0.05	±0.01	±0.01
Electrons and muons	±0.02	±0.01	±0.01	±0.02

Mainly UE/PS (Pythia8 vs. Herwig7), both for VBF, and ggF in VBF phase space

+ QCD μ_R/μ_F
+ gg→H jet-bin migrations
+ VBF ME (Powheg vs. MG)

CMS H→WW

Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{ggH}/\mu_{ggH}$	$\Delta\mu_{VBF}/\mu_{VBF}$	$\Delta\mu_{WH}/\mu_{WH}$	$\Delta\mu_{ZH}/\mu_{ZH}$
Theory (signal)	4%	5%	13%	2%	<1%
Theory (background)	3%	3%	2%	4%	5%
Lepton misidentification	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b tagging	2%	2%	3%	<1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	<1%	2%	<1%	3%
Jet energy resolution	<1%	1%	<1%	<1%	3%
p_T^{miss} scale	<1%	1%	<1%	2%	2%
PDF	1%	2%	<1%	<1%	2%
Parton shower	<1%	2%	<1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

Main differences w.r.t. ATLAS:

- PS uncertainties from varying Pythia PS weights (also dominant)
- Some of the analyses don't use the recommended dipole shower yet, to be improved for future measurements

Raffaele's talk has a nice discussion of the CMS uncertainty model

Outlook for Run3

- new matching&PS systematics recommendation
- Within experiment, should investigate signal modeling dependency, e.g. parton shower uncertainty ←→ third jet selection (e.g. central jet veto)
    - See slide22

Slide credit: Jan Steggemann, Nicolas Berger
Experimental overview talk
VBF workshop 2024

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]

M_H[GeV]	σ^{VBF}[fb]	Δ_{scale}[%]	$\Delta_{PDF/\alpha_s/PDF\oplus\alpha_s}$[%]	Δ_{TU}[%]	σ^{DIS}_{N3LO}[fb]	δ_{EW}[%]	σ_γ[fb]	σ_{nf}[fb]	$\sigma_{s/t/u}$[fb]
120.00	3967	$^{+0.13}_{-0.091}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	4148	-5.2	36.1	-8.9	-11.5
122.00	3905	$^{+0.13}_{-0.092}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	4082	-5.2	35.8	-8.5	-10.6
124.00	3844	$^{+0.13}_{-0.092}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	4017	-5.2	35.4	-8.2	-10.2
124.60	3825	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3998	-5.2	35.3	-8.1	-10.0
124.80	3819	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3992	-5.2	35.3	-8.1	-10.0
125.00	3813	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3985	-5.2	35.2	-8.0	-10.0
125.09	3811	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3982	-5.2	35.2	-8.0	-10.0
125.20	3807	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3979	-5.2	35.2	-8.0	-10.0
125.30	3804	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3976	-5.2	35.2	-8.0	-9.9
125.38	3802	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3973	-5.2	35.2	-8.0	-9.8
125.60	3795	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3966	-5.2	35.1	-8.0	-9.7
126.00	3784	$^{+0.13}_{-0.093}$	$\pm2.1/\pm0.4/\pm2.2$	±1.0	3954	-5.2	35.1	-7.9	-9.6
128.00	3725	$^{+0.13}_{-0.093}$	$\pm2.2/\pm0.4/\pm2.2$	±1.0	3892	-5.2	34.7	-7.7	-9.2
130.00	3667	$^{+0.13}_{-0.094}$	$\pm2.2/\pm0.3/\pm2.2$	±0.9	3831	-5.2	34.3	-7.5	-8.6

Combination according to:

$$\sigma^{VBF} = \sigma^{DIS}_{N3LO}(1+\delta_{EW}) + \sigma_\gamma$$

Big thanks to **Asteriadis, Brønnum-Hansen, Karlberg, Mück** who provided numbers!
Numbers built in document already (thanks to Karlberg)

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

Differential study in fiducial volume at 13.6 TeV

- Event selections: mixture of ATLAS and CMS
- Rivet routine + run cards + Events available in a repository
- Beyond 1D distributions (2D, 3D) and also in STXS bins

1. State-of-the-art numbers for fixed order
    - Inclusion of everything available (typically in different places and/or in different set-ups)
2. State-of-the-art number for NLO+PS
    - Only perturbative part (no Underlying Event or hadronisation)
    - Make recommendations for uncertainties

Summarise state-of-the-art on th. and exp. and their latest references

- Th. findings are not always well propagated to exp.
  Important for theorists to get credits through proper citations

Article to be published this winter (this time for real!)
in **Physics Community Reports** form **SciPost**

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:

Gaetano Barone[1], Jiayi Chen[2], Stephane Cooperstein[3], Nikita Dolganov[2], Silvia Ferrario Ravasio[4], Yacine Haddad[5], Stefan Höche[6], Barbara Jäger[7], Alexander Karlberg[4], Alexander Mück[8], Mathieu Pellen[9], Christian T. Preuss[10], Daniel Reichelt[4,11], Simon Reinhardt[7], Marco Zaro[12]

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

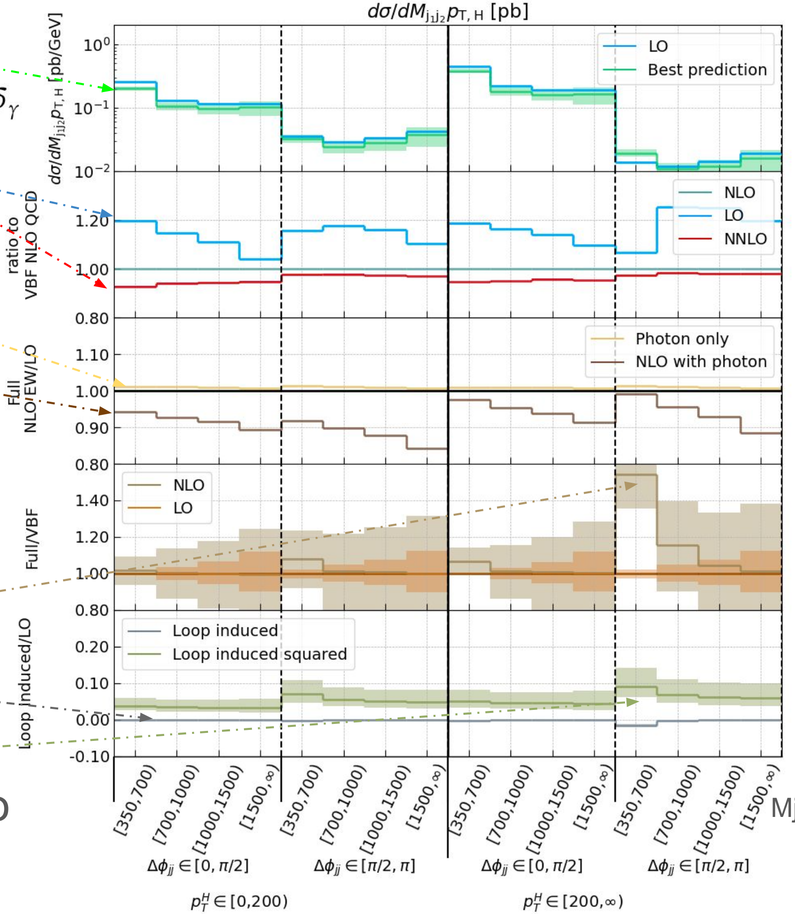
Systematic study at differential level (Fixed order)

- Combination for best predicction:

$$\sigma_{\text{best}} = \sigma^{\text{Full}}_{\text{NLO QCD}} \times (1 + \delta^{\text{VBF}}_{\text{NNLO QCD}} + \delta^{\text{NF VBF}}_{\text{NNLO QCD}}) \times (1 + \delta^{\text{Full}}_{\text{NLO EW}}) + \delta_{\gamma}$$

- Moderate QCD corrections for VBF approximation
- Small photon-induced corrections
- EW correction negatively large in high-energy limit (Sudakov logarithms)
- VBF approximation good at LO but not at NLO QCD (effect of VH)
- Interference with loop-induced=0
- Loop-induced squared (quark channels only i.e. part of ggF with two jets) not negligible

Example of distribution, preliminary



3D STXS bins

more *inclusive* phase space definition:

anti-kT R=0.4 jets

$p_{\text{T,j}} > 30\,\text{GeV}$

$|\eta_{\text{H}}| < 2.5.$

Systematic study at differential level (NLO+PS)

List of predictions:

- **Powheg**+**Pythia** (Dipole)
- **Powheg**+**Pythia** (Vincia)
- **Powheg**+**Herwig** (Angular Ordered)
- **Madgraph**+**Herwig** (Angular Ordered)
- **Herwig**, **MC@NLO** internal (AO)
- **Herwig**, **MC@NLO** internal (Dipole)
- **Sherpa**, **MC@NLO** internal (Default PS)
- **Sherpa**, **MC@NLO** internal (Dire)

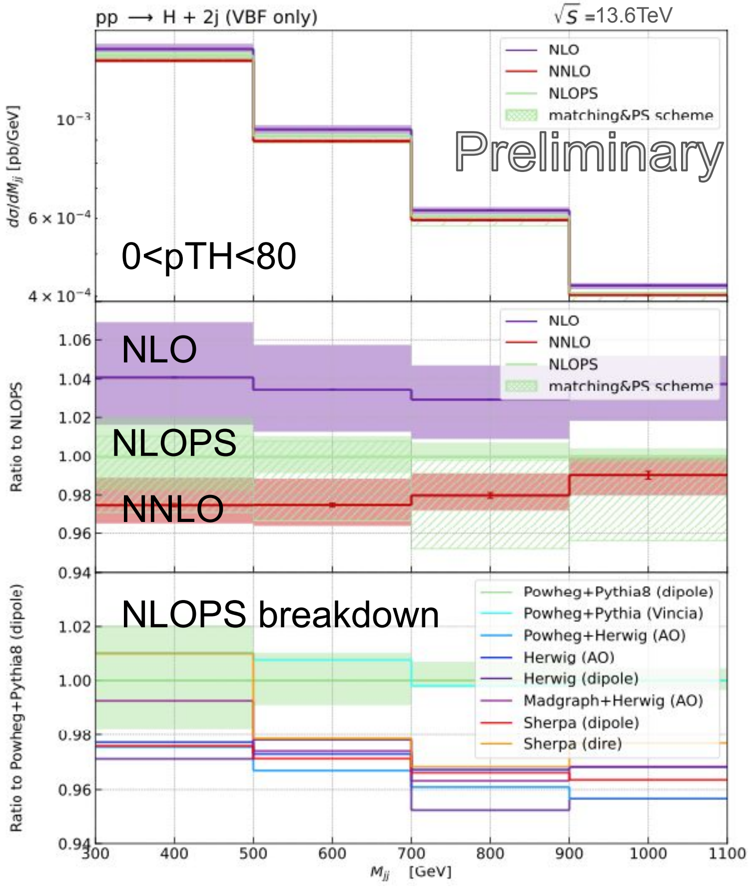
2 different **matching methods**: **multiplicative** and **additive**

6 different **parton showers**, 2 for every GPMC (**Pythia**, **Herwig** and **Sherpa**)

Phase-space:

$$p_{\mathrm{T,j}} > 20\,\mathrm{GeV} \quad \text{and} \quad |\eta_{\mathrm{j}}| < 4.7.$$
$$m_{\mathrm{jj}} > 300\,\mathrm{GeV} \quad \text{and} \quad |\Delta y_{\mathrm{jj}}| > 2.$$

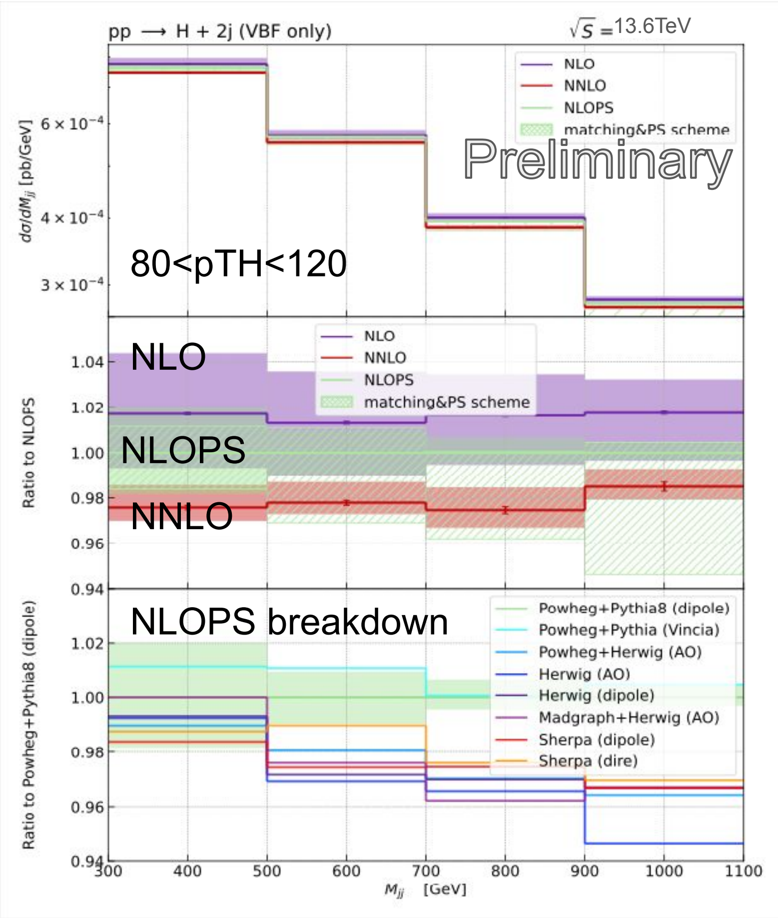
Dijet invariant mass vs pT Higgs



Mjj is an exemplificative **inclusive distribution**. Properties:

- Scale uncertainties of reference NLOPS smaller than NLO
- NLOPS predictions tends to be closer to NNLO then NLO
- The span of NLOPS predictions comprises also NNLO
- Span of NLOPS is **few percent**

Dijet invariant mass vs pT Higgs



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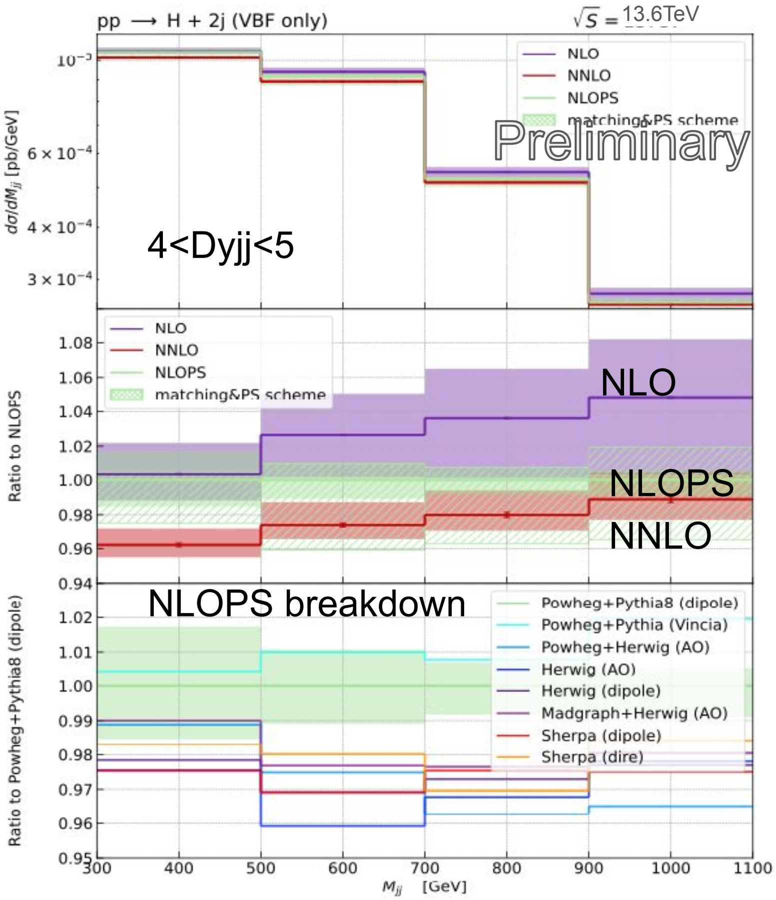
..changing the pT cut does not change

Dijet invariant mass vs Dijet rapidity



Mjj is an exemplificative **inclusive distribution**. Properties:

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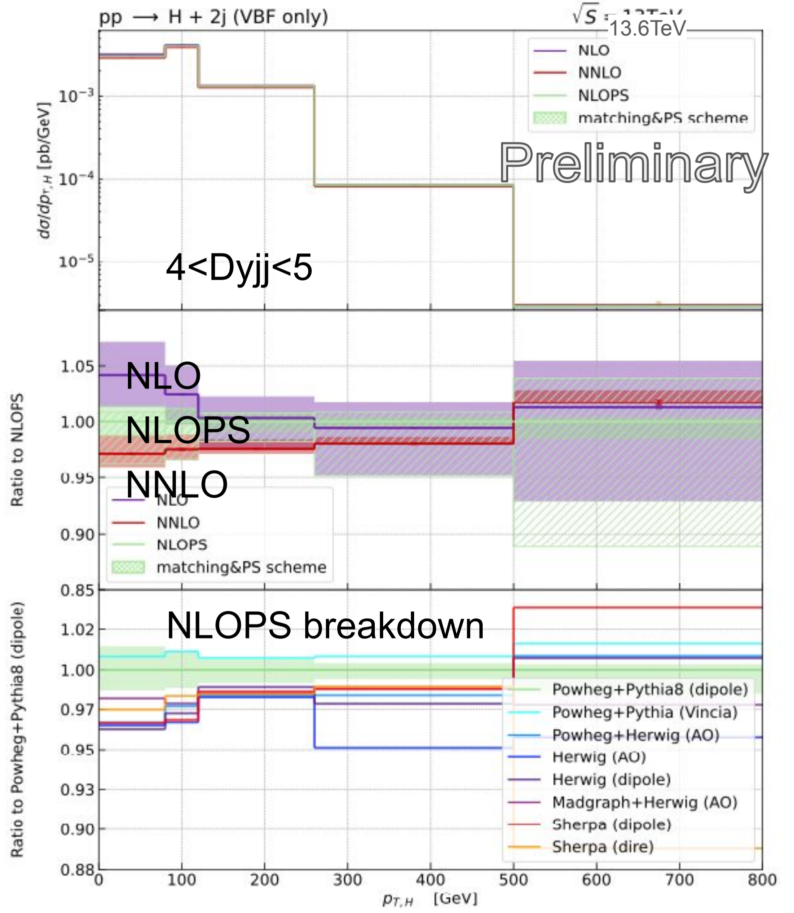
- The span of NLOPS predictions comprises also NNLO
- Span of NLOPS is **few percent**

…cutting in Dyjj does not change

Higgs transverse momentum vs Dijet rapidity

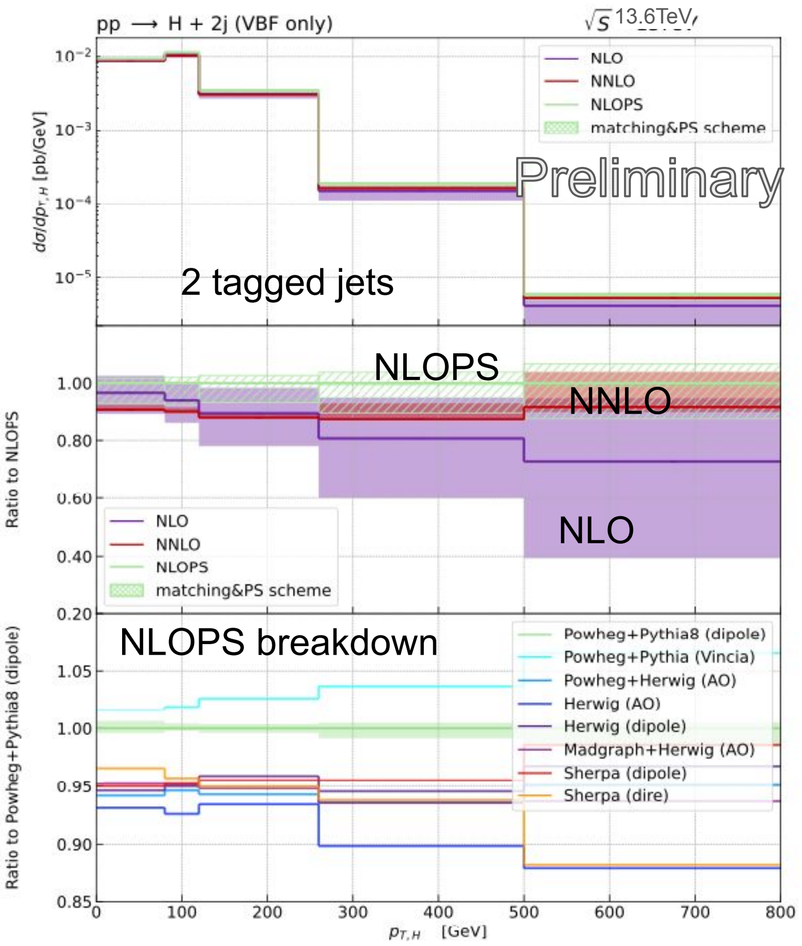


The Higgs pT is an exemplificative **inclusive distribution**. Properties:

- Scale uncertainties of reference NLOPS smaller than NLO
- NLOPS predictions tends to be closer to NNLO then NLO
- The span of NLOPS predictions comprises also NNLO
- Span of NLOPS is **few percent** (10% in the tail)

Pattern identical to Mjj (with **large uncertainties at large ptH**)

Higgs transverse momentum vs number of jets

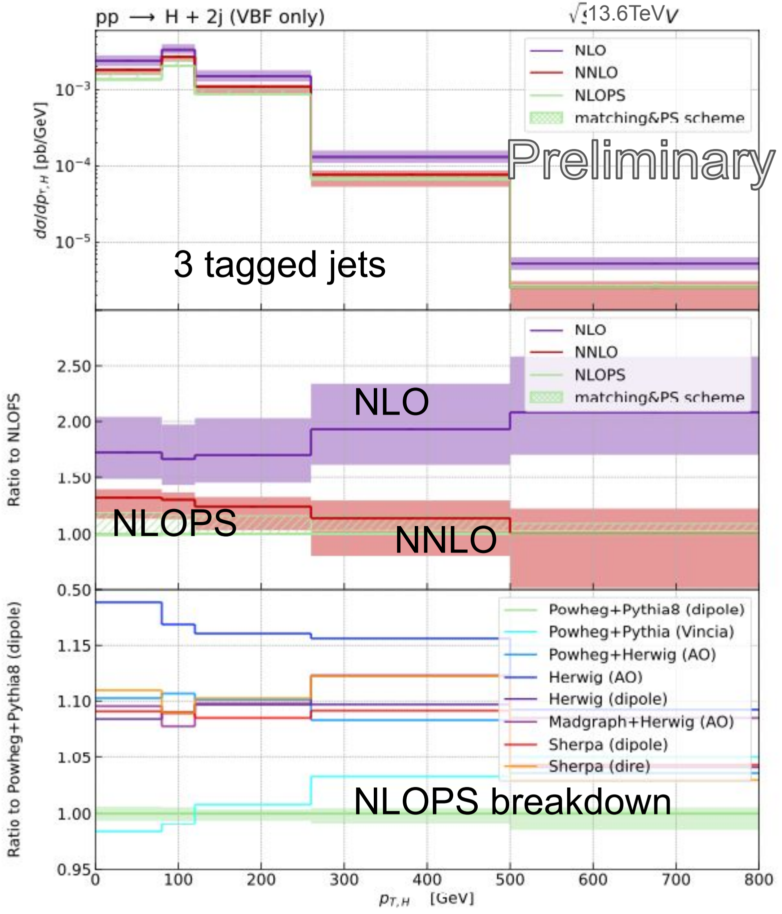


The Higgs pT is an exemplificative **inclusive distribution**.

The **number of tagged jets** is an **exclusive distribution**, i.e. directly sensitive to the amount of radiation generated.

Requiring **exactly 2 jets** however leads to a pattern similar to the one for inclusive distributions, with some small variations on how the several NLOPS are ordered respect to each others

Higgs transverse momentum vs number of jets



The Higgs pT is an exemplificative **inclusive distribution**.

The **number of tagged jets** is an **exclusive distribution**, i.e. directly sensitive to the amount of radiation generated.

Requiring **exactly 3 jets** inflates the uncertainties, and NLOPS predictions are nominally only LO accurate: ordering between several NLOPS completely inverted

[Source: Bing image creator]

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 explanations:

- Related to uncertainty prescription?
  - revisited in current WG study; more preliminary study in lightning talk this Friday
- Related to extrapolation procedure?
  - Crucial to study 3rd jet selection in experiment
- Related to inclusion of non-perturbative effects (UE, hadronisation) in PS?
- Could there be a problem with the tunning of exp. samples with wrong PS recoil scheme?
  (one line summary of idea discussed at Les Houches 2023)

  [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!

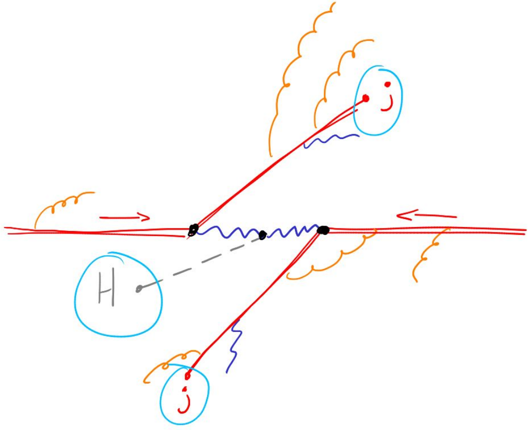
Summary

- Updated number for inclusive cross section
- Study for differential predictions public very soon
  - With detailed study of PS shower&matching schemes

Outlook

- ggF contamination in VBF signal region & hadronisation/underyling event effects
  [Chen, Haddad, Höche, Huss, Huston, Jezo, Lindert, Plaetzer, Preuss, Ferrario Ravasio, Tarek, Winter, …]
- **YOUR IDEA** …

THANK YOU.



BACK UP

Inclusive numbers

The results are combined according to

$$\sigma^{\mathrm{VBF}} = \sigma^{\mathrm{DIS}}_{\mathrm{N3LO}}(1 + \delta_{\mathrm{EW}}) + \sigma_{\gamma} \tag{6}$$

and the theory uncertainties are computed as

$$\Delta_{\mathrm{TU}} = \max\left\{0.5\%, \delta^2_{\mathrm{EW}}\right\} + \frac{|\sigma_{\mathrm{nf}}| + |\sigma_{\mathrm{s/t/u}}|}{\sigma^{\mathrm{VBF}}}\% \tag{7}$$

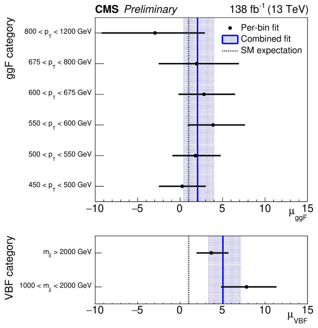
for $\sqrt{s} = \{13, 13.6, 14\}$ TeV. For the legacy numbers correspsonding to $\sqrt{s} = \{7, 8\}$ TeV the non-factorisable contribution, σ_{nf}, was not computed, and we instead set

$$\Delta_{\mathrm{TU}} = \max\left[\max\left\{0.5\%, \delta^2_{\mathrm{EW}}\right\} + \frac{|\sigma_{\mathrm{s/t/u}}|}{\sigma^{\mathrm{VBF}}}\%, 1.0\%\right]. \tag{8}$$

In fact, in this case it always corresponds to 1%.

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}, …)

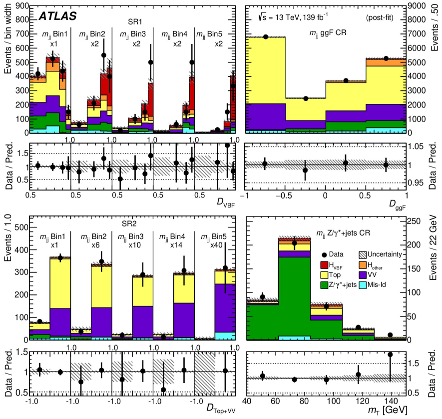
Most recent results in:

Fiducial measurements in: H→WW, H→ZZ [ATLAS], STXS H→WW [CMS]

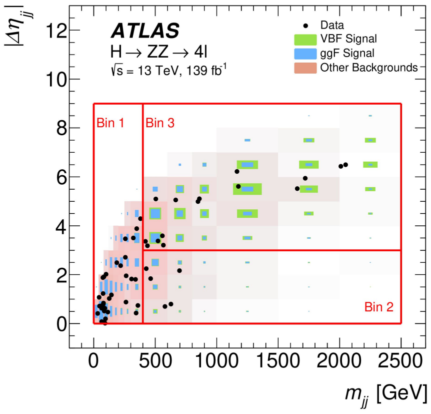
Boosted H→bb [CMS]

Small signal/background → extensive use of Multivariate Techniques

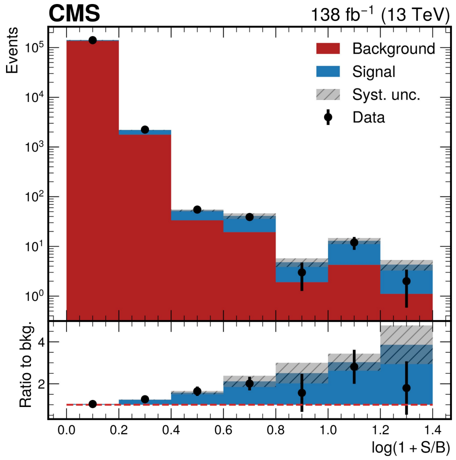
Modelling uncertainties in extrapolations between kinematic regions become evermore relevant



Phys. Rev. D 108, 072003



arXiv:2304.09612v1



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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)

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

Typical VBF uncertainties in exp. measurements

Primary theory uncertainties impacting experimental measurements

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

Theory uncertainty relative sizes in **typical** VBF measurements

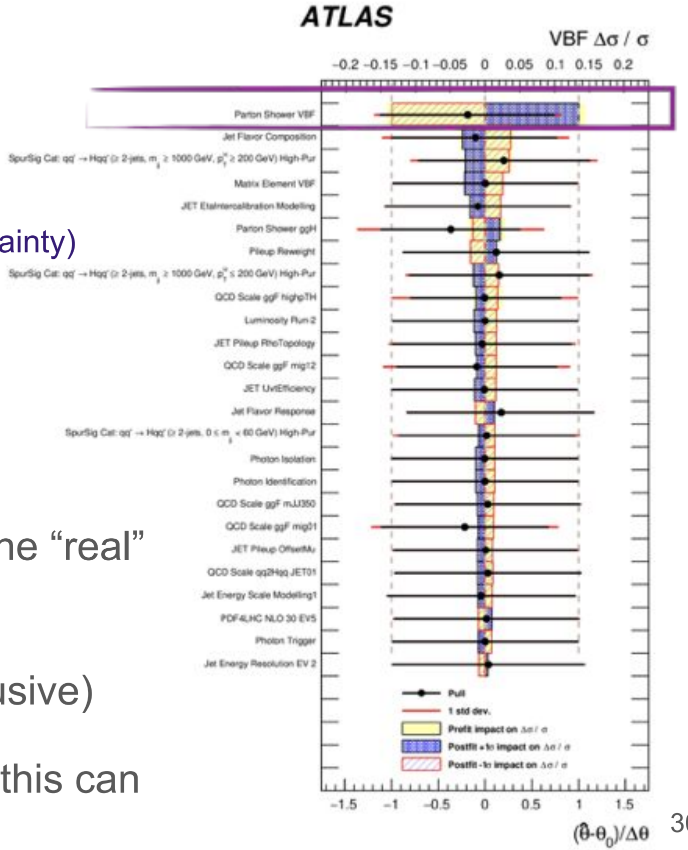
	VBF H	**ggH (in VBF-enriched region)**
PDF	<1%	<3%
QCD scale	<1%	**2-20%**
UE	<1.5%	<2-3%
Parton shower	**5-15%**	**4-10%**

The leading culprit: PS uncertainties

Leading uncertainties, CMS VBF H→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

Leading uncertainties, ATLAS VBF H→γγ ***JHEP 07 (2023) 088***



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

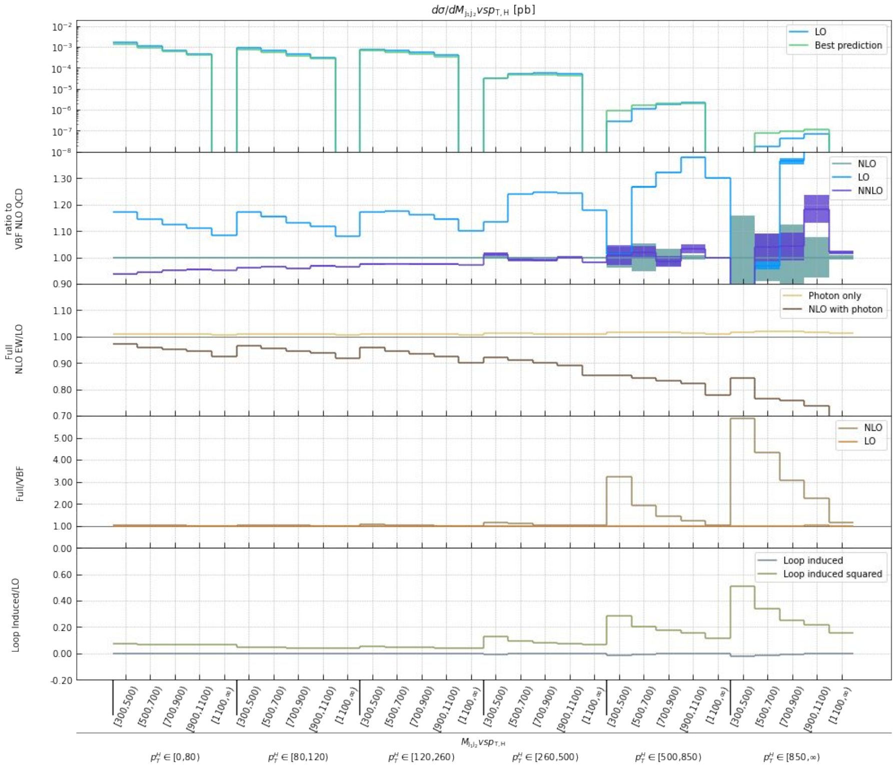
Systematic study at differential level (Fixed order)

- Combination:

$$\sigma_{\text{best}} = \sigma^{\text{Full}}_{\text{NLO QCD}} \times (1 + \delta^{\text{VBF}}_{\text{NNLO QCD}} + \delta^{\text{NF VBF}}_{\text{NNLO QCD}}) \times (1 + \delta^{\text{Full}}_{\text{NLO EW}}) + \delta_{\gamma}$$

- Largest QCD corrections for VBF approximation in exclusive region
- Small photon-induced corrections
- EW correction negatively large in high-energy limit (Sudakov logarithms)
- VBF approximation good at LO but not at NLO QCD (effect of VH)
- Interference with loop-induced=0
- Loop-induced squared (quark channels only i.e. part of ggF with two jets) not negligible

Example of distribution, preliminary



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 ways out:

- 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 tunning of exp. samples with wrong PS recoil scheme?
(one line summary of idea discussed at Les Houches 2023)

[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]