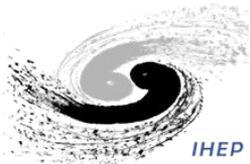# WG1 VBF report

*C. Bertella, P. Govoni, Y. Haddad, A. Karlberg, B. Jäger*
LHC Higgs XS workshop: 14-July-2017

# Introduction

- New organization of the WG1 XS subgroups: focus group on VBF
- New CMS convener: Yacine Haddad
- New egroup: lhc-higgs-vbf: please subscribe!
- A twiki page is under construction:
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGVBF
- Had our first meeting on 15th of June (https://indico.cern.ch/event/643726/)
- Define the roadmap for the VBF group
    - Theory inputs needed by the LHC analysis
    - Focus on major studies to be released in short/middle/long term scale (up to 1 year)
    - We tried to gather a list of topics of interest, to collect interest of people
    - Additional suggestions are welcome!

# LHC analyses status
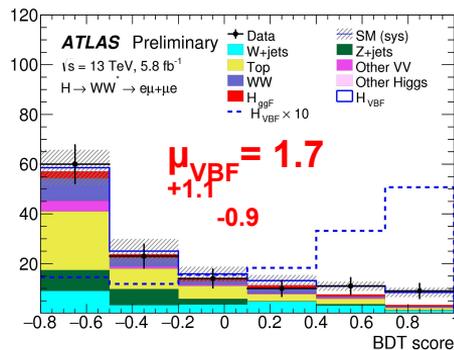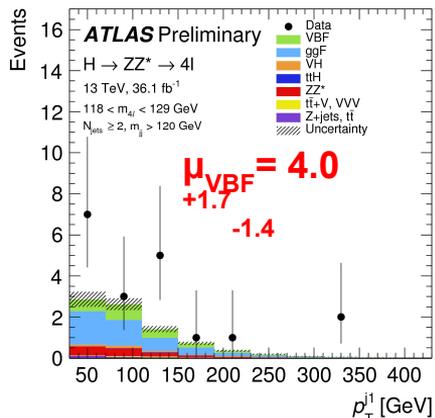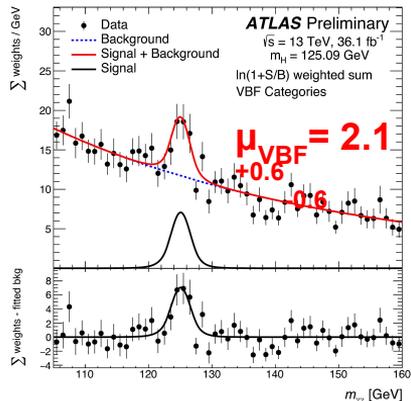


- Many new results @ 13 TeV
- More analyses ongoing with the full luminosity
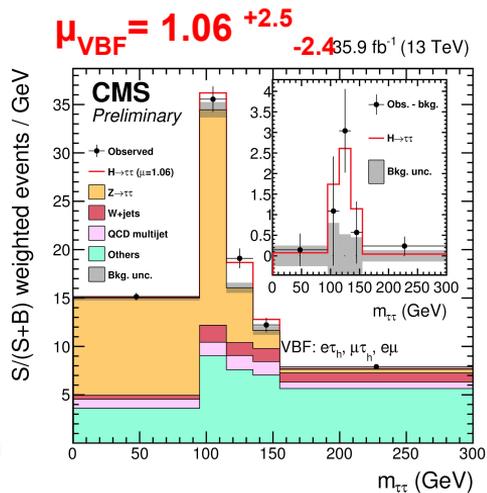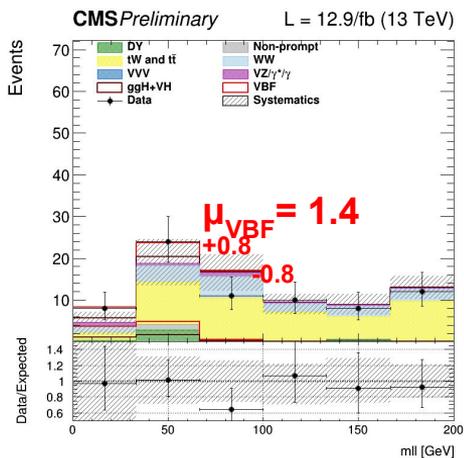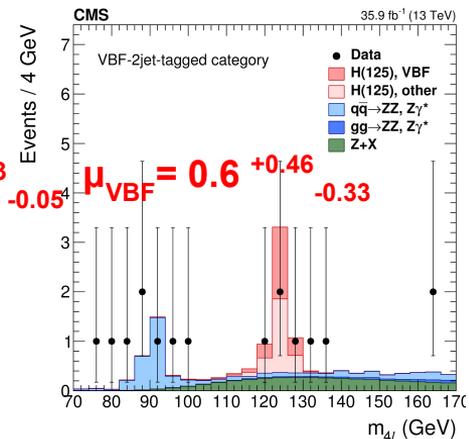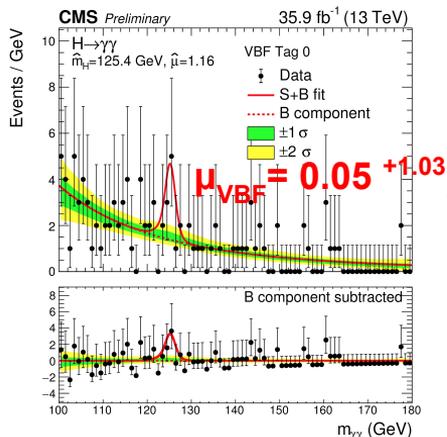
# LHC analyses status



ATLAS-CONF-2015-044
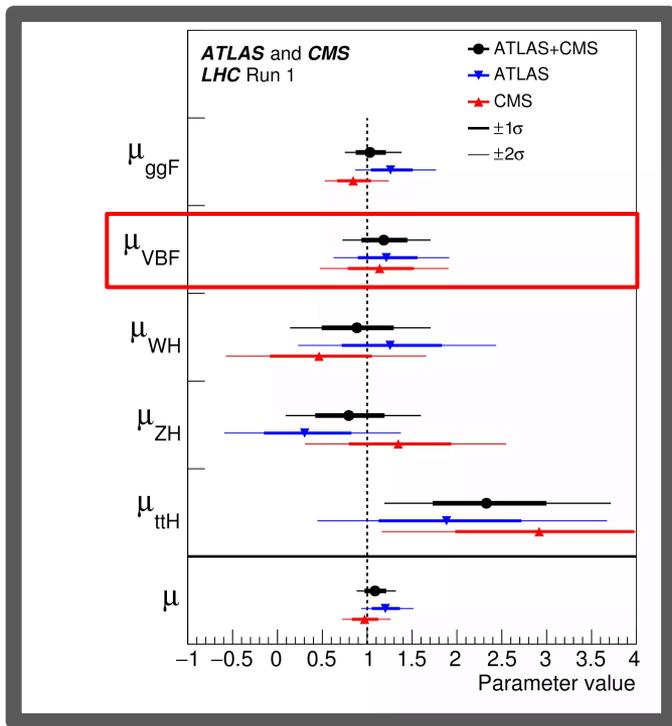
| Parameter | SM prediction | Best-fit value | Uncertainty Stat | Uncertainty Syst |
|---|---|---|---|---|
| $\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$ | $0.082 \pm 0.009$ | $0.11\,^{+0.03}_{-0.03}$ | $+0.03$ $-0.02$ | $+0.02$ $-0.01$ |

ATLAS-CONF-2017-047
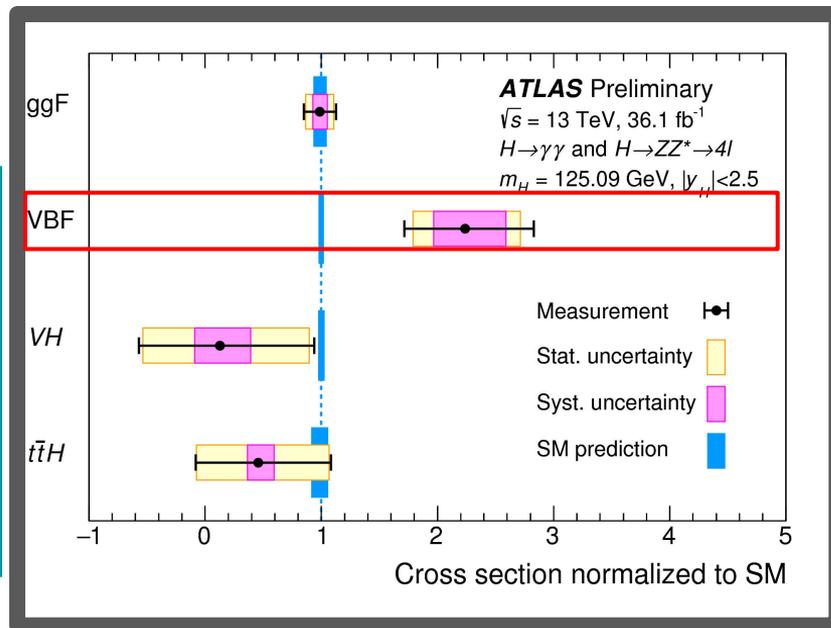
| Quantity | Result | Uncertainty Total | Stat. | Exp. | Th. | SM prediction |
|---|---|---|---|---|---|---|
| $\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$ $[10^{-2}]$ | $21.5$ | $^{+8.5}_{-6.3}$ | $\left(\begin{array}{c}+7.3\\-5.6\end{array}\right.$ | $+2.8$ $-1.7$ | $\left.\begin{array}{c}+3.6\\-2.2\end{array}\right)$ | $7.9\,^{+0.4}_{-0.6}$ |

# Signal model status

- Signal model by Powheg+Pythia8 and MadGraph5_aMC@NLO
- VBF modeling uncertainty rather important for H→WW systematic model
  ➔ Mainly coming from matching uncertainty - estimated from generator
  - Run-2 H→WW: impact of signal strength +14/-5% ([ATLAS-CONF-2016-112](#))
    - Comparison between Powheg and MadGraph5_aMC@NLO
- Parton Shower and Underlying Event systematics play an important role in VBF selections
  - Run-2 ATLAS H→ZZ  order of 5% ([ATLAS-CONF-2017-043](#))
    - Comparison of Pythia8 and Herwig7
  - Run-2 CMS H→γγ order of 7% ([HIG-16-040](#))
    - Comparison of Pythia8 and Herwig++ tunes
    - CMS is providing now eigenvalue envelopes from the experiment's Pythia tune fit

# Main theory limitation: ggH contamination

- Predictions for higher jet multiplicities extremely important for measurement of VBF production where ggH is an irreducible background
- NNLOPS will be used for Run-2 results
- ggH QCD scale estimated using Stewart-Tackmann method
  - Run-2 ATLAS H→ZZ  order of 11% (ATLAS-CONF-2017-043)
  - Run-2 CMS H→γγ order of 29(10)% yields(migration) (HIG-16-040)
  - Run-2 ATLAS H→WW: impact of signal strength 8%(6%) for 3(2)-jets inclusive (ATLAS-CONF-2016-112)                                         D. Gillberg' slides

```
Cross sections and fractional uncertainties
    STXS     sig      stat        mu      res     mig01    mig12      pTH      qm_b    qm_top      Tot
    VBF1   0.27 +/-  0.00     +7.9%    +7.9%    +3.9%   +16.2%    -2.5%    -2.4%    +0.1%   +20.3%
    VBF2   0.36 +/-  0.00     +7.9%    +7.9%    +3.9%   +16.2%    -0.9%    -1.1%    +0.2%   +20.1%
```

- Run-1 approach documented in YR3: uncertainties from MCFM parametrized as a function of $\Delta\phi(H,jj)$ — which is correlated to the third jet pT
  - NB: these uncertainties are from 8 TeV
- Alternative option: uncertainties from G. Luisoni (slides)

# Request from the collaborations

- LHC analyses will provide results using categories defined by the Simplified Template Cross Sections method
  - Stage 0: Closest correspondence to Run 1
  - Stage 1: "Minimal" hoped-for splitting for Run 2
- Provide theory uncertainties for the "stage 1" binning of the STXS
- QCD uncertainties: How are the uncertainties correlated in mjj regions ?
  - Option 1: single overall yield Δµ plus mjj shape/migration Δmjj
  - Option 2: uncorrelated sources Δlow and Δhigh for low and high mjj
- Discussion is ongoing with WG2
  - F. Tackmann' slides
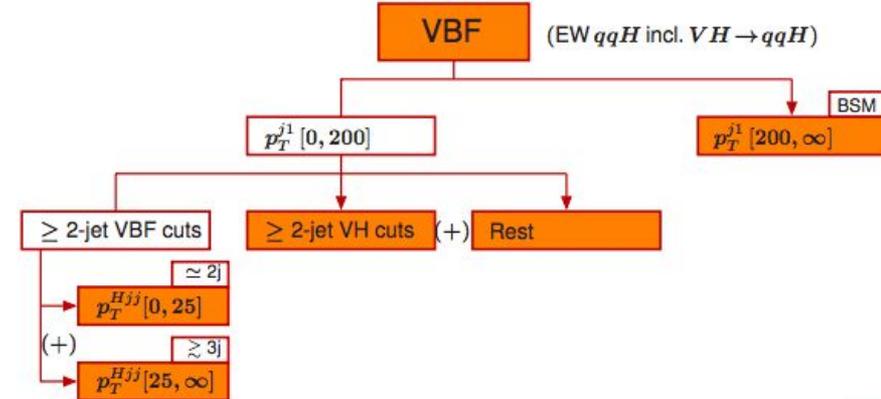
# Request from the collaborations

- ggF uncertainties in VBF-like regions  are becoming more relevant, could there be recommendations with the latest updates?
    - Topic in between ggF and VBF WGs
- Several analyses use MVA discriminants to separate VBF from ggF, starting from all events with (at least) 2 jets. → need to assess uncertainty on both normalization and shape of such MVA discriminants
    - YR3 addresses the problem but needs to be revisited.

# Central jet veto

- Jet activity in between the two tagging jets is strongly suppressed in VBF, which is not the case in QCD induced Hjj background.
- Hence, requiring no central jet activity can help significantly reduce the Hjj background without losing too much of the VBF signal.
- When matching NLO VBF to a parton shower, various showers give significantly different central jet activity and disagree widely on the Njets distribution (Nason, Oleari: 0911.5299).
- The third jet distributions stabilise when NLO VBF Hjjj is matched with a parton shower (Jäger, Schissler, Zeppenfeld: 1405.6950).

# Central Jet Veto (preliminary study)

- Third jet in VBF described at LO in MC sample currently used by experimental collaborations
- NNLO calculation might shed some light on parton shower models
- Preliminary studies (with F. Dreyer) suggest pt-ordered showers agree well with NNLO calculation



pt ordered, $\min(y_1, y_2) < y_3 < \max(y_1, y_2)$

$$\min(y_{j1}, y_{j2}) < y_{j3} < \max(y_{j1}, y_{j2})$$

$$p_{t,\text{tag}} > 25 \text{ GeV}, \quad M_{jj} > 600 \text{ GeV}, \quad \Delta y_{jj} > 4.5, \quad y_{j1}y_{j2} < 0, \quad y_j < 4.5$$
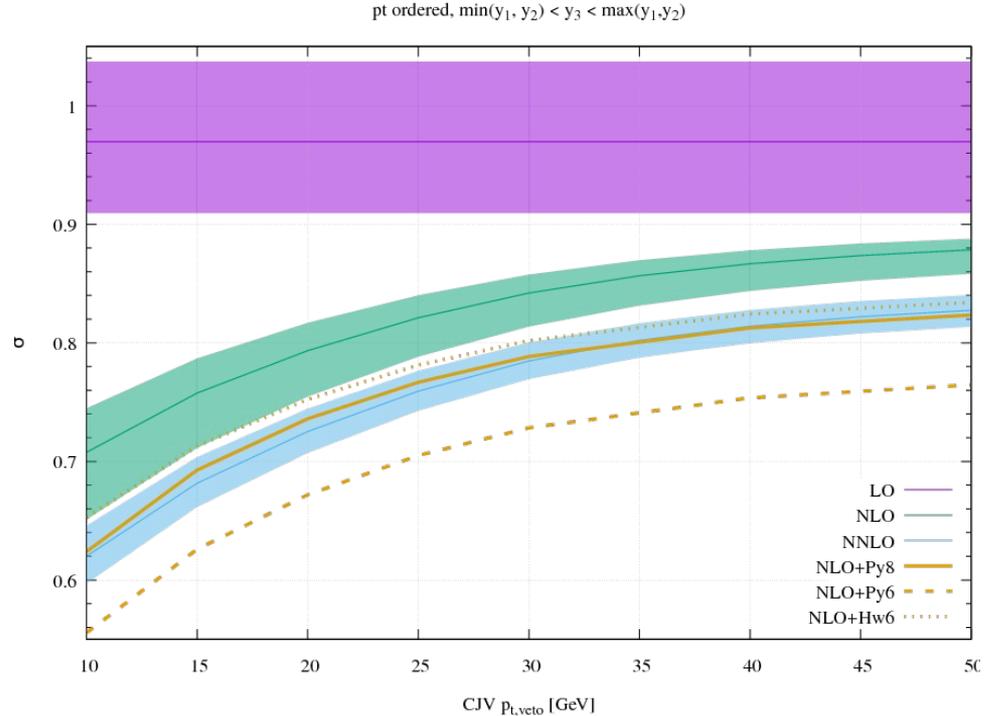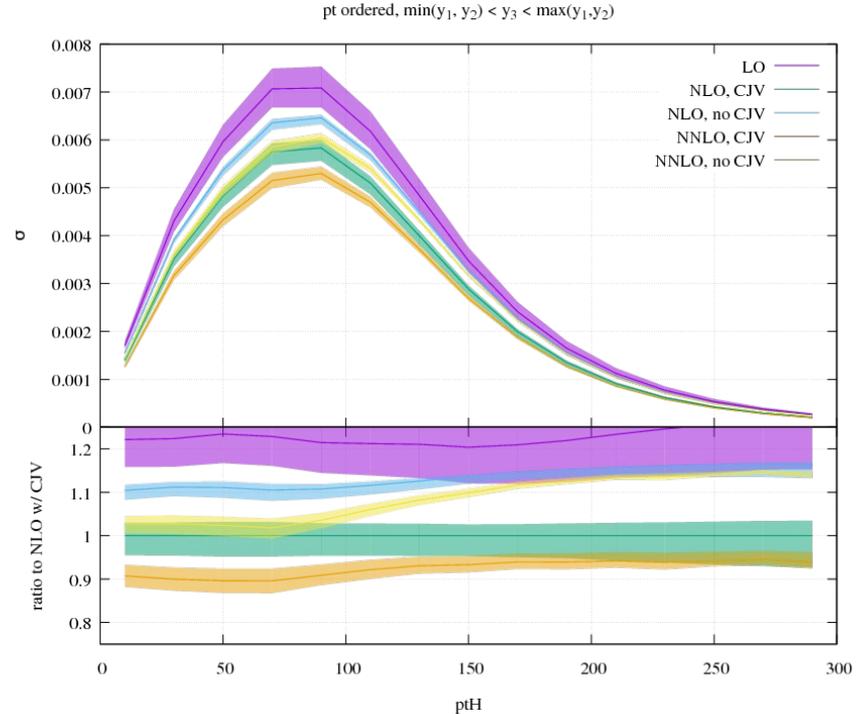
# Central Jet Veto (preliminary study)

- The NNLO corrections tend to follow the same pattern as without the CJV - lower fiducial cross sections due to softer tagging jets.

- Corrections are in general of the same size as without the CJV (5-6% for fiducial xsec and up to 10-15% in certain kinematic regions)
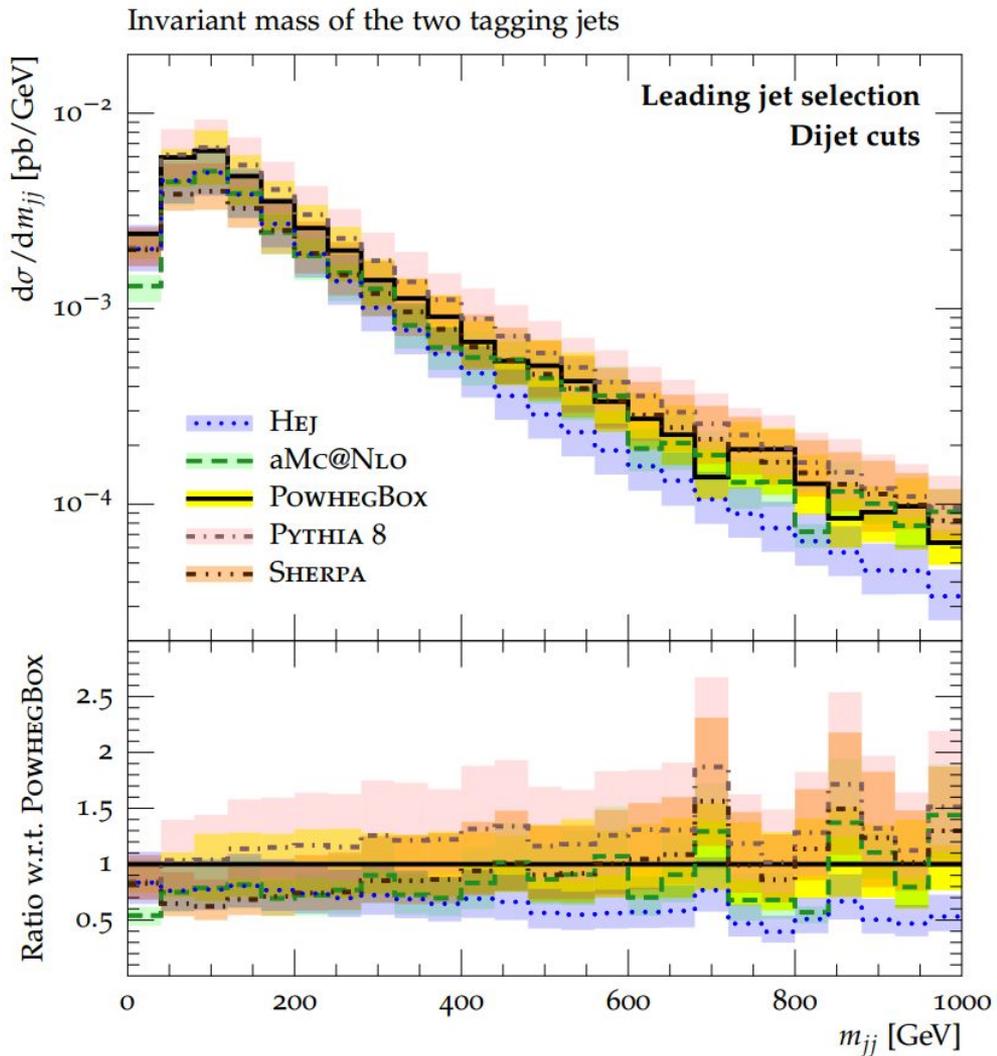


$$\min(y_{j1}, y_{j2}) < y_{j3} < \max(y_{j1}, y_{j2})$$

$$p_{t,\text{tag}} > 25 \text{ GeV}, \quad M_{jj} > 600 \text{ GeV}, \quad \Delta y_{jj} > 4.5, \quad y_{j1}y_{j2} < 0, \quad y_j < 4.5$$

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# Background modelling

- ggH background estimated using NNLOPS (2nd jet LO)
- Recent work suggests the xsec is overestimated under VBF cuts
  [J. Andersen, T. Hapola, A. Maier, J. Smillie]
- Main uncertainty comes from background modelling
- A dedicated study of backgrounds and optimisation of VBF cuts could be valuable (cross over with ggH sub-group)



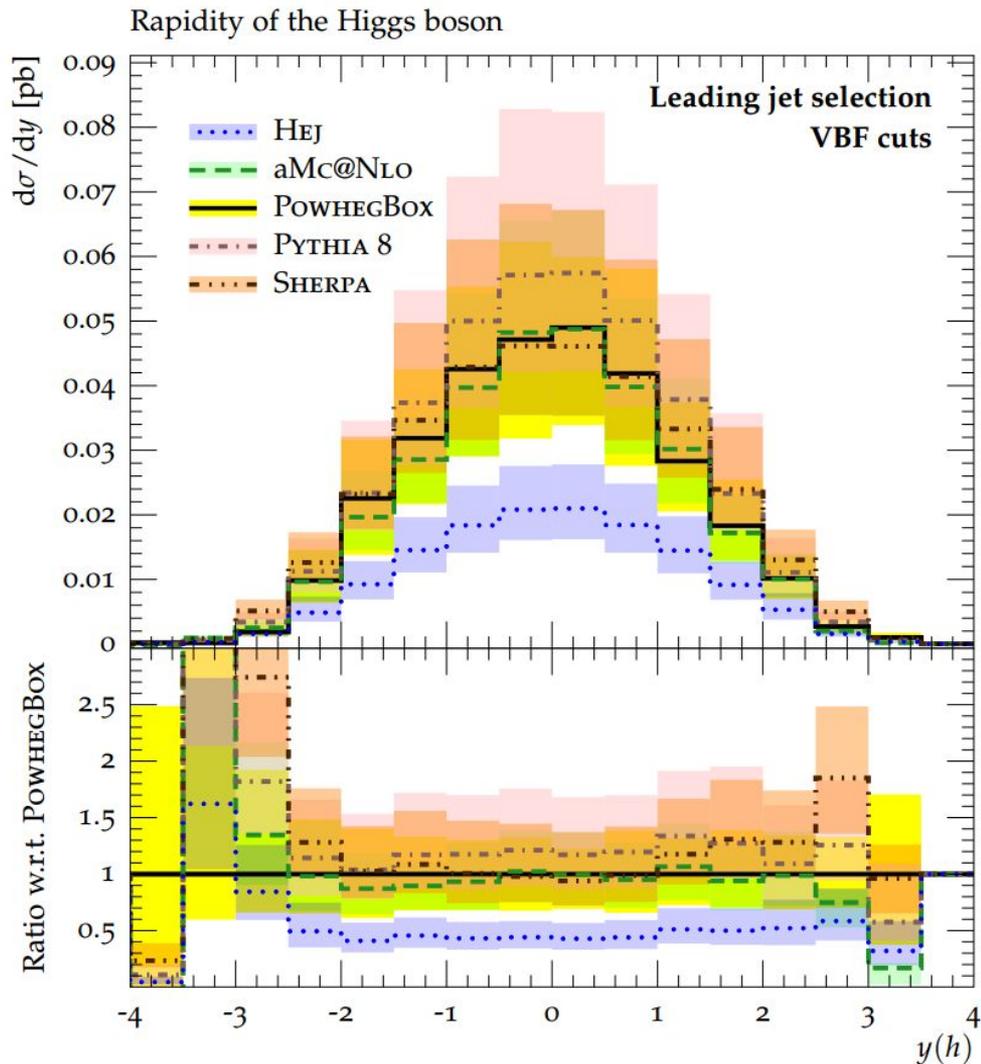Invariant mass of the two tagging jets

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Rapidity of the Higgs boson

# Higher order corrections

- Currently no way of including NNLO-QCD and NLO-EW corrections at event generation
- A MiNLO type reweighting would be ideal but is not feasible at the moment
- Instead: use the fact that NNLO-QCD corrections are rather flat and well approximated by shower except for in the jet rapidity separation
- Feasibility studies under way



[ M. Cacciari, F. A. Dreyer, AK, G. P. Salam, G. Zanderighi]
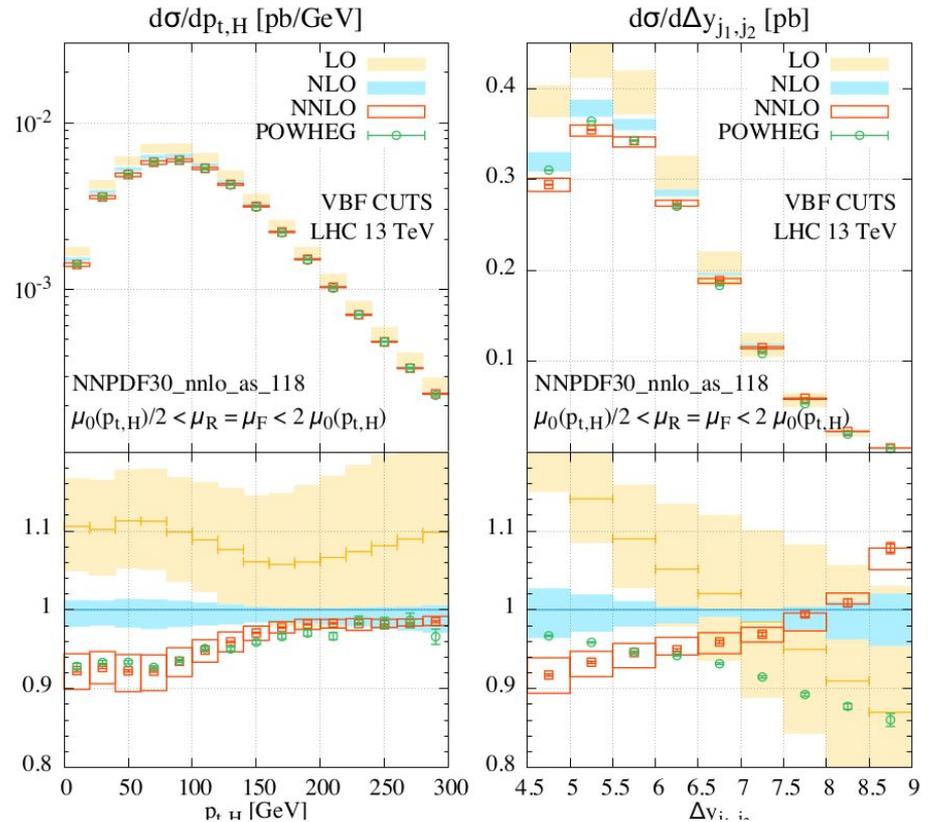
# VBF WG1 roadmap: short term

- Simplified Template Cross Sections uncertainty
- Parton shower accuracy:
  - Comparisons between different merged samples and between different showering options
  - Possible new recommendations on the central value and on the uncertainties to be adopted in the analyses
- CJV systematics:
  - CJV definition used by experimental collaboration may not be trivial (third jet information as input for MVA)
  - Third jet in VBF described at LO in MC sample currently used by experimental collaborations
  - Compare third jet kinematics of VBF Hjj NLO with VBF Hjjj NLO

# VBF WG1 roadmap: medium/long term

- Higher-order corrections (NNLOPS)
- Merging of VBF +2jet NLO and VBF + 3jets NLO
- ggH background uncertainties:
  - Large contamination of theory uncertainties from ggHjj in signal
  - ggHjj signal overestimated by current generators
- High Higgs pT:
  - First measurements of the high pT Higgs spectrum (above 0.5 TeV) are being published (CMS HIG-17-010)
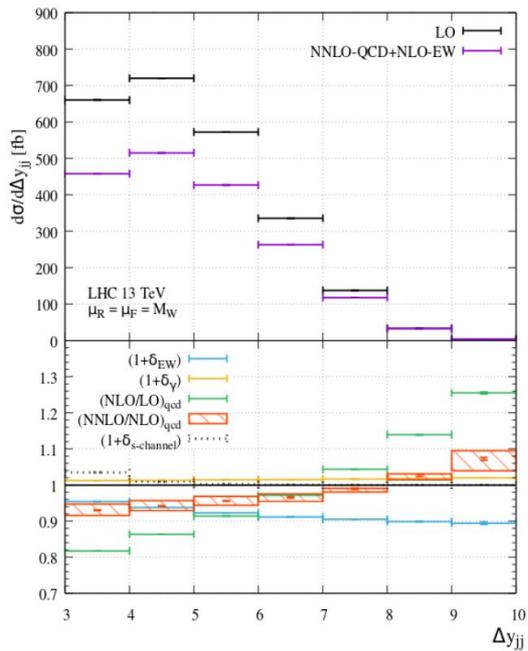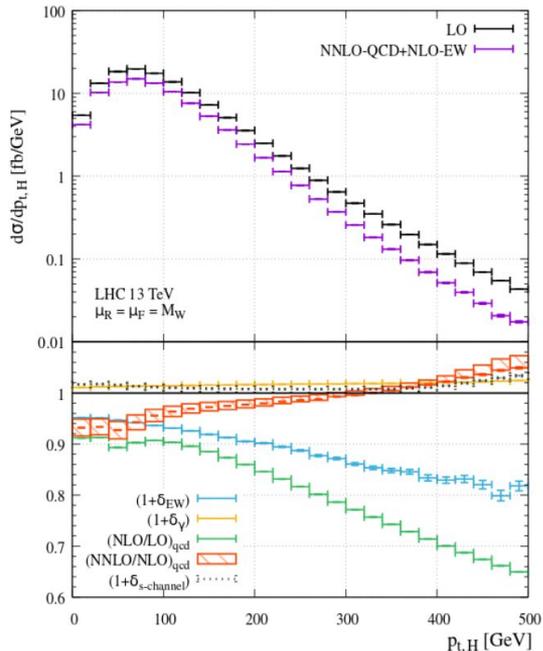  - Dedicated study at higher orders in QCD and EW and with additional jets are needed to be compared to data

# Backup

# Parametrization of VBF uncertainties

| Bin | QCD uncertainties (Option 2) | | | | | EW uncertainties | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | $\Delta_{\text{low}}$ | $\Delta_{\text{high}}$ | $\Delta_\mu^{\text{VH}}$ | $\Delta_{200}$ | $\Delta_{25}$ | $\Delta_{\text{Sud}}$ | $\Delta_{\text{hard}}$ | $\Delta_{W,Z,\gamma}^{\text{VH}}$ |
| $p_T^j\ [0,200]$ | $\approx 1$ | $\approx 1$ | $\approx 1$ | $-1$ | | $y_1$ | $*$ | |
| VBF cuts | $\approx 0$ | $\approx 1$ | $\approx 0$ | $-x_1$ | $0$ | $y_2$ | $*$ | |
| $p_T^{Hjj}\ [0, 25]$ | | $z$ | | $-x_1 z$ | $+1$ | $\cdots$ | $*$ | |
| $p_T^{Hjj}\ [25, \infty]$ | | $1 - z$ | | $-x_1(1-z)$ | $-1$ | $\cdots$ | $*$ | |
| VH cuts | $?$ | $?$ | $\approx 1$ | $-x_2$ | | $y_3$ | $*$ | $1$ |
| Rest | $\approx 1$ | $\approx 0$ | $?$ | $-x_3$ | | $y_4$ | $*$ | |
| $p_T^j\ [200,\infty]$ | $?$ | $?$ | $?$ | $+1$ | | $1 - y_i$ | $*$ | |

# VBF NNLO Corrections

- Experiments would like to profit from computations of fully differential NNLO QCD + NLO EWK cross sections, likely via 1D reweighting of NLO samples
- Discussions ongoing to determine the appropriate variable and phase space



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