Predictions for GGF with VBF topology

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CERN

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CERN

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In collaboration with:

Nicolas Greiner, Stefan Höche, Marek Schönherr, Jan-Christopher Winter

Special thanks to Jan for last minute plot preparation!

Computational setup

- Amplitudes in HEFT computed with GoSam+Sherpa via BLHA
  [Cullen, v. Deurzen, Greiner, Heinrich, Mastrolia, Mirabella, Ossola, Peraro, Schlenk, v. Soden-Fraunhofer, Tramontano, GL, '14]
  [Gleisberg, Höche, Krauss, Schönherr, Schumann]
  - Virtual amplitudes: GoSam with Ninja [v. Deurzen, Mastrolia, Mirabella, Ossola, Peraro, GL, '14]
    -> scalar loop integrals evaluated using OneLoop [v. Hameren, '11]
  - Tree amplitudes and integration: Sherpa with Comix [Gleisberg, Höche]
- Phenomenological analysis via generation of ROOT Ntuples:
  - Events for: H+1 / 2 / 3 jets; available for 8, 13, 14 and 100 TeV

  ✓For kt/anti-kt algorithm and R=0.1, … , 1.0

  ✓Allow for fast analysis, change of **scale, pdf, cuts, jet-tagging**
- Full theory result generated by reweighting the Born HEFT Ntuples with the amplitude carrying the full quark mass dependence.
- Publicly available on:

https://eospublichttp01.cern.ch/eos/theory/project/GoSam/

eos.web.cern.ch

Large Disk Storage at CERN

Physical setup

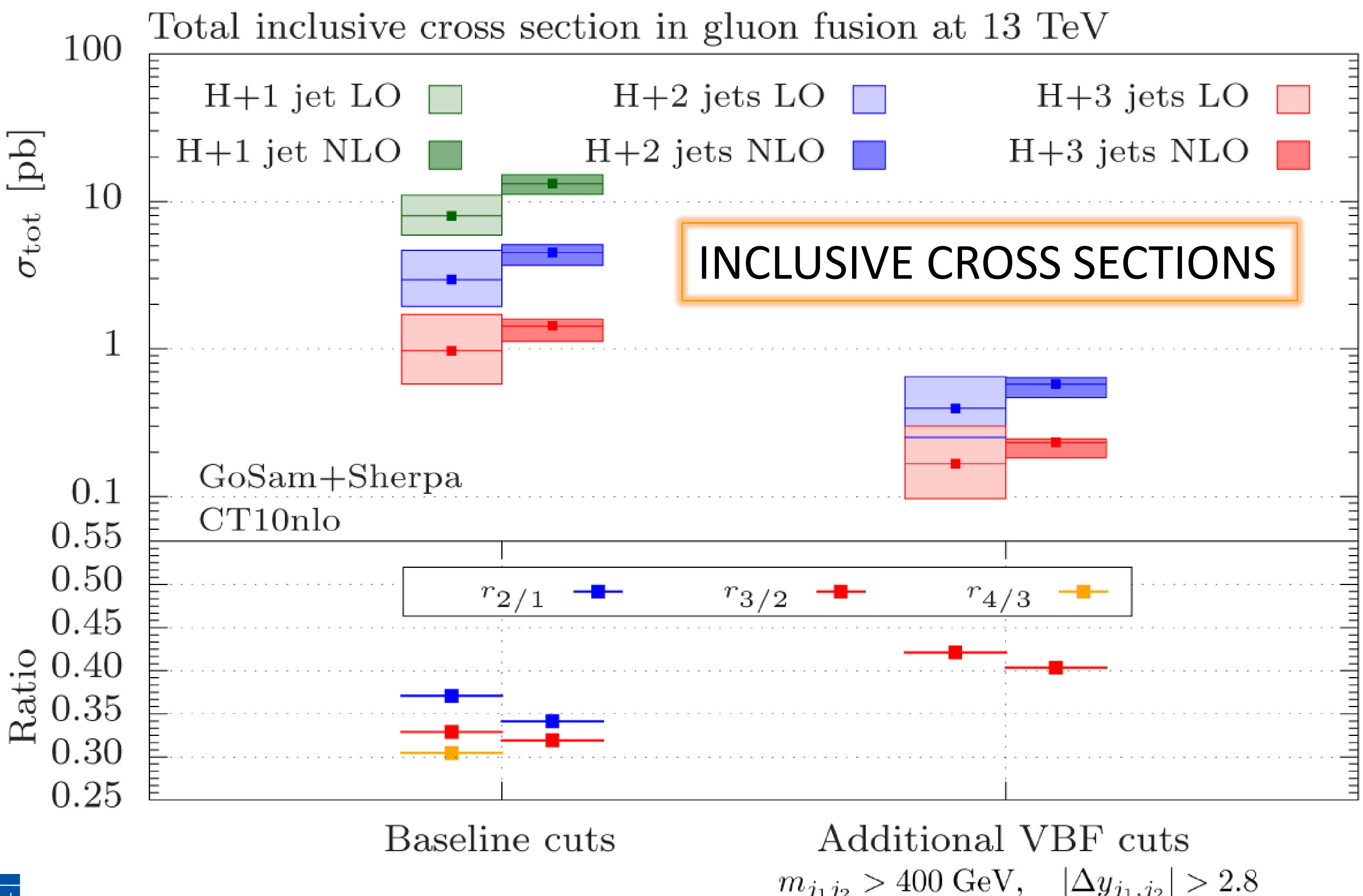
For both Higgs effective field theory (HEFT) and full SM:

- scale choice: $\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\rm H}^2 + p_{T,{\rm H}}^2} + \sum_i |p_{T,i}|\right)$
- PDFs: CT10nlo or CT14nlo (see the single plots for details)
- masses: $m_H = 125.0 \text{ GeV}, \quad m_t = 172.3 \text{ GeV}, \quad m_b(m_H) = 3.38 \text{ GeV}$

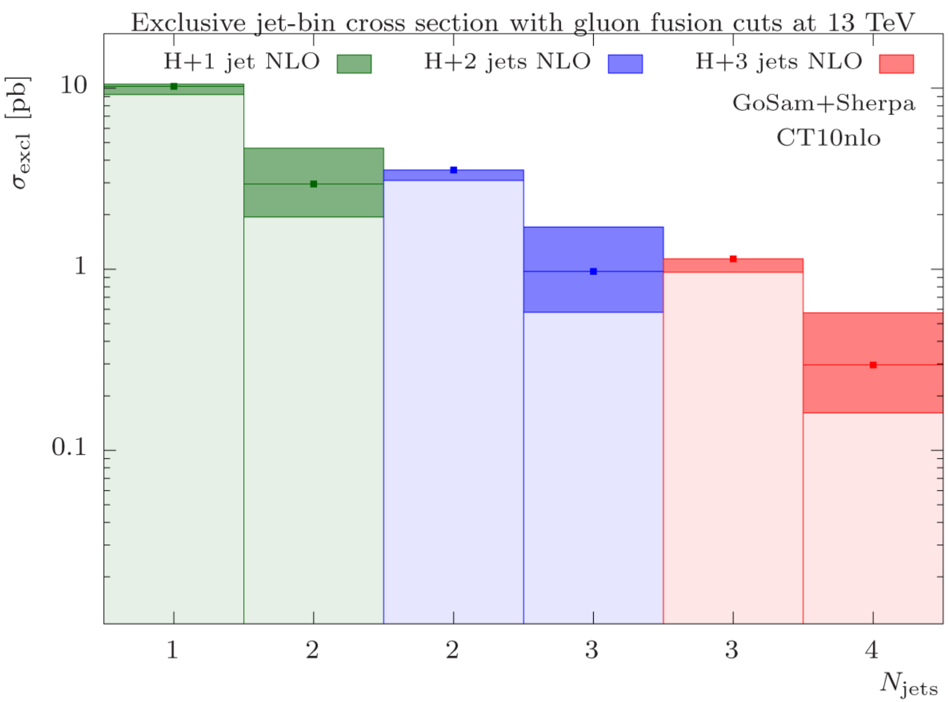
- **Baseline cuts:** anti-kt with $p_T > 30 \text{ GeV}, \quad |\eta| < 4.4$
- **Additional VBF cuts**: $m_{j_1 j_2} > 400 \text{ GeV}, \quad |\Delta y_{j_1,j_2}| > 2.8$

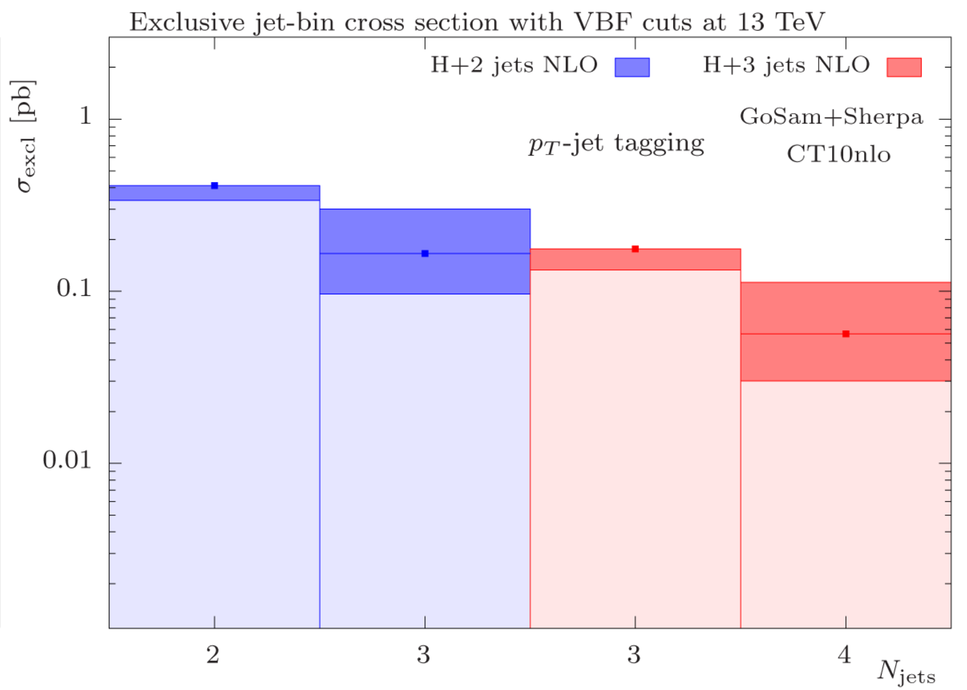
- Remark: basic Ntuples sets have events with $p_T > 25 \text{ GeV}, \ |\eta| < 4.5$ for the jets at the generation level

Total cross section at 13 TeV



Total cross section at 13 TeV: exclusive jet bins





- Relative enhancement of the (n+1)-jet contribution in the VBF fiducial region
  - Larger portion of cross section described only at LO accuracy
  - i.e. theoretical uncertainty increased in the VBF fiducial region

- H+3j allows to determine radiation of a third jet with NLO accuracy
  - Particularly important for VBF studies
  - Fixed order approach limited. Merged and matched (e.g. MEPS@NLO) sample allows to combine better NLO predictions and takes also PS effects into account

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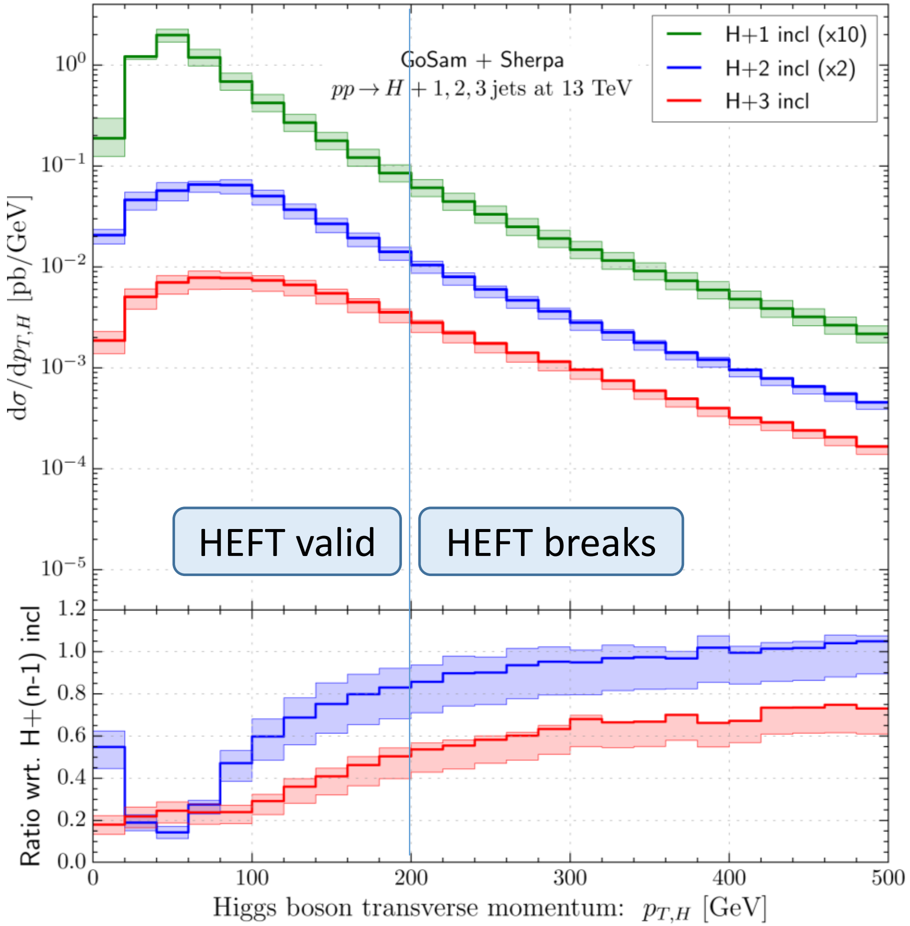
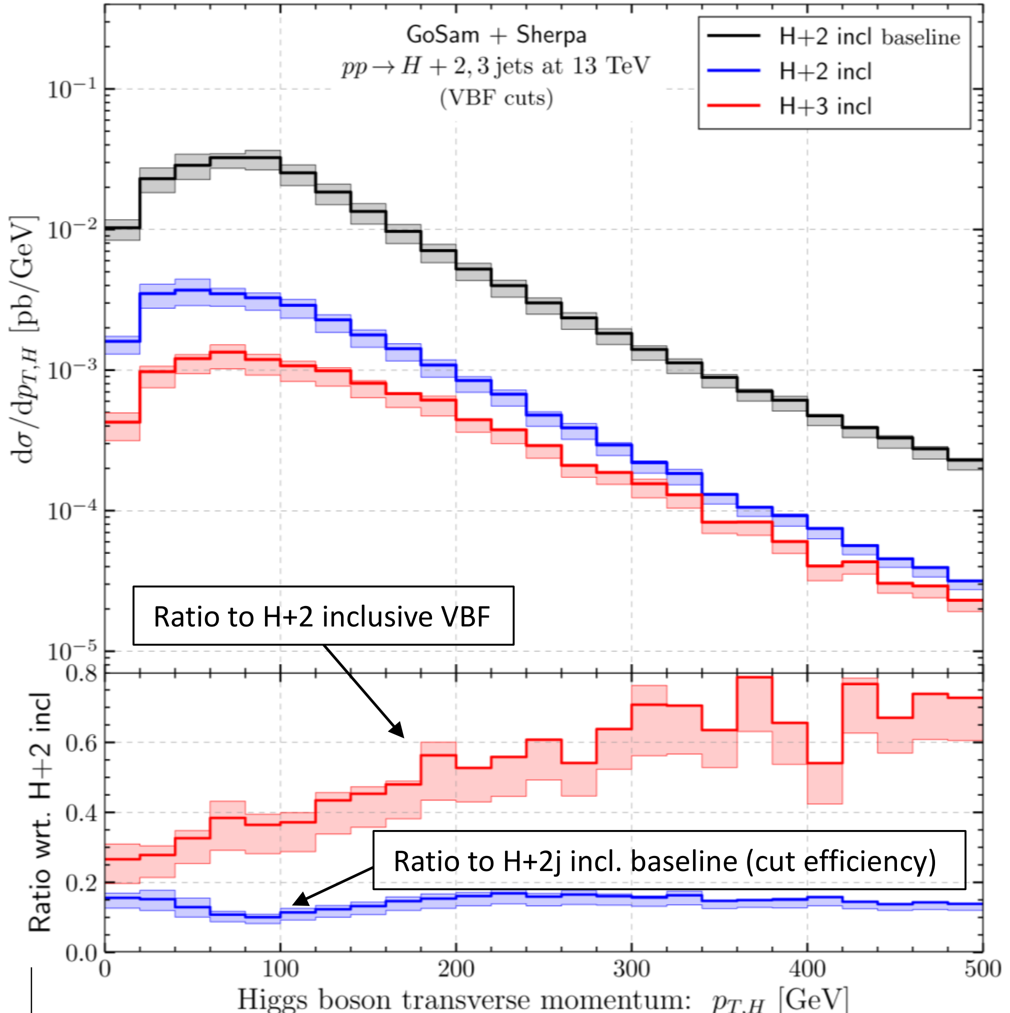
Higgs p_T spectrum: H+2/3 jets contributions

INCLUSIVE BASELINE



INCLUSIVE VBF



Around 200 GeV (where HEFT is still reliable):

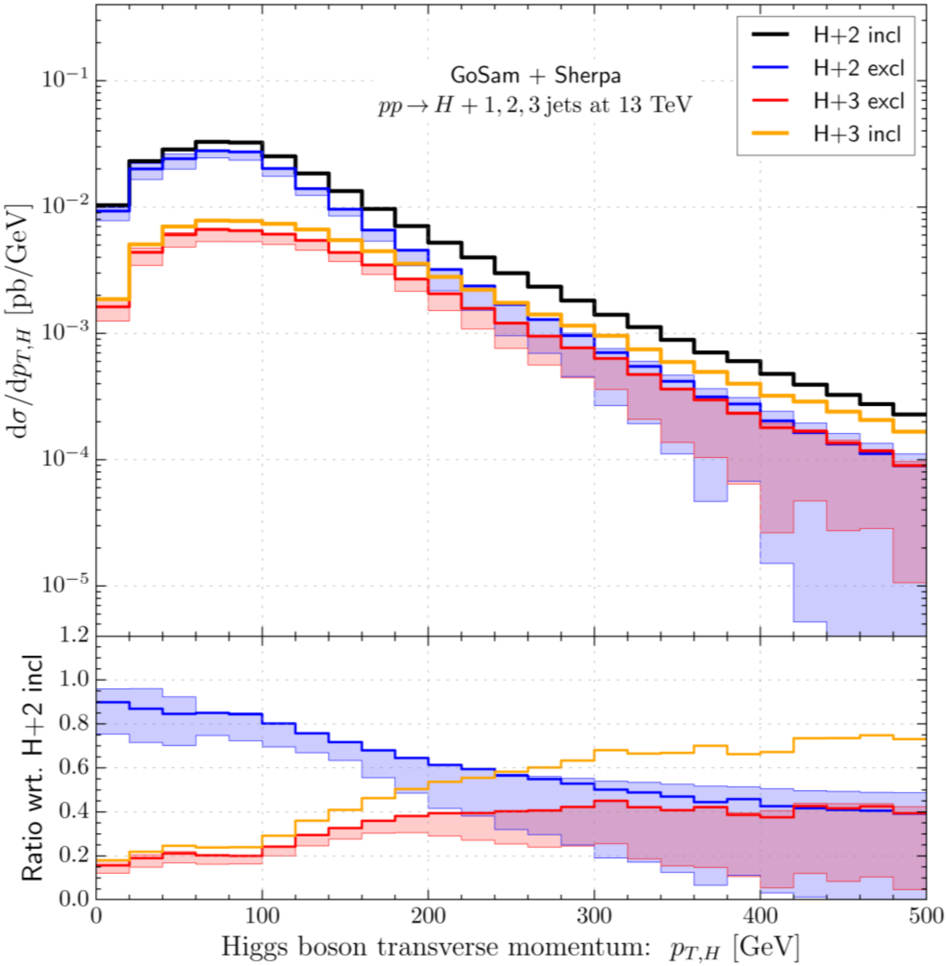
- NLO H+2j incl. is O(80%) of NLO H+1j incl.
- NLO H+3j incl. is O(50%) of NLO H+2j incl.

Relative importance of NLO H+3j grows faster:

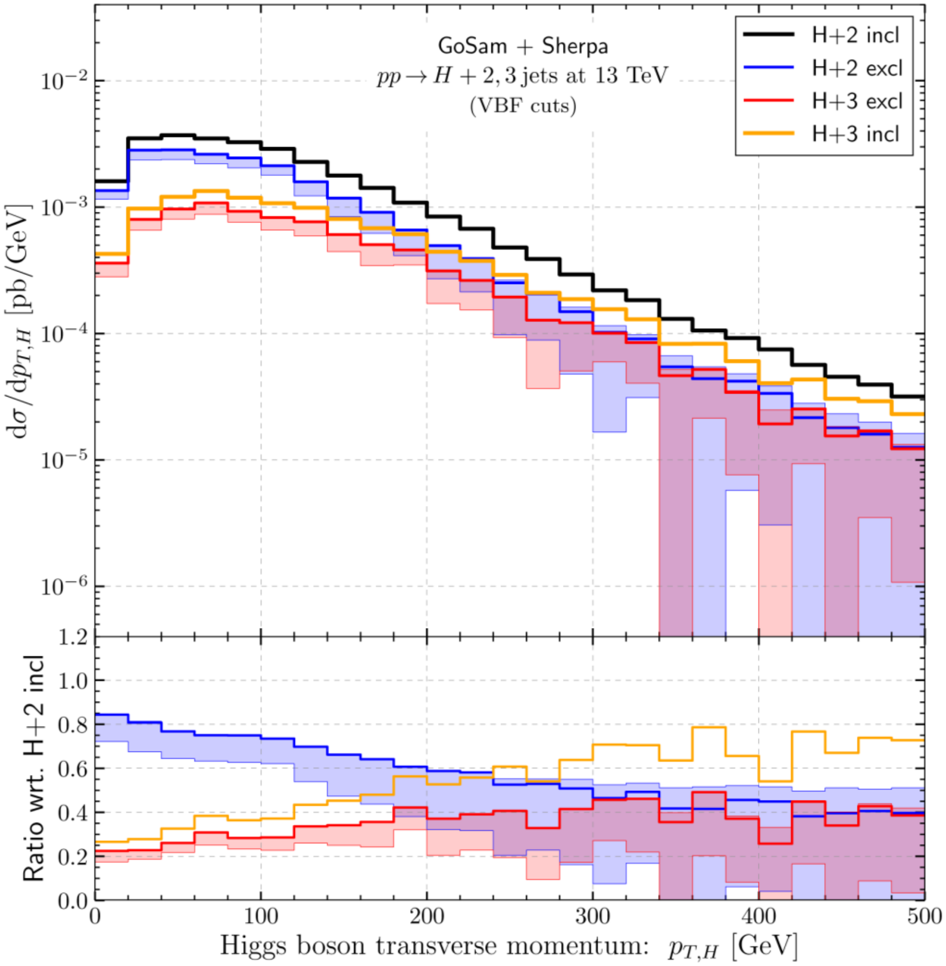
- at 100 GeV it is O(40%) of NLO H+2j incl.

Higgs p_T spectrum: H+2/3 jets contributions

EXCLUSIVE BASELINE

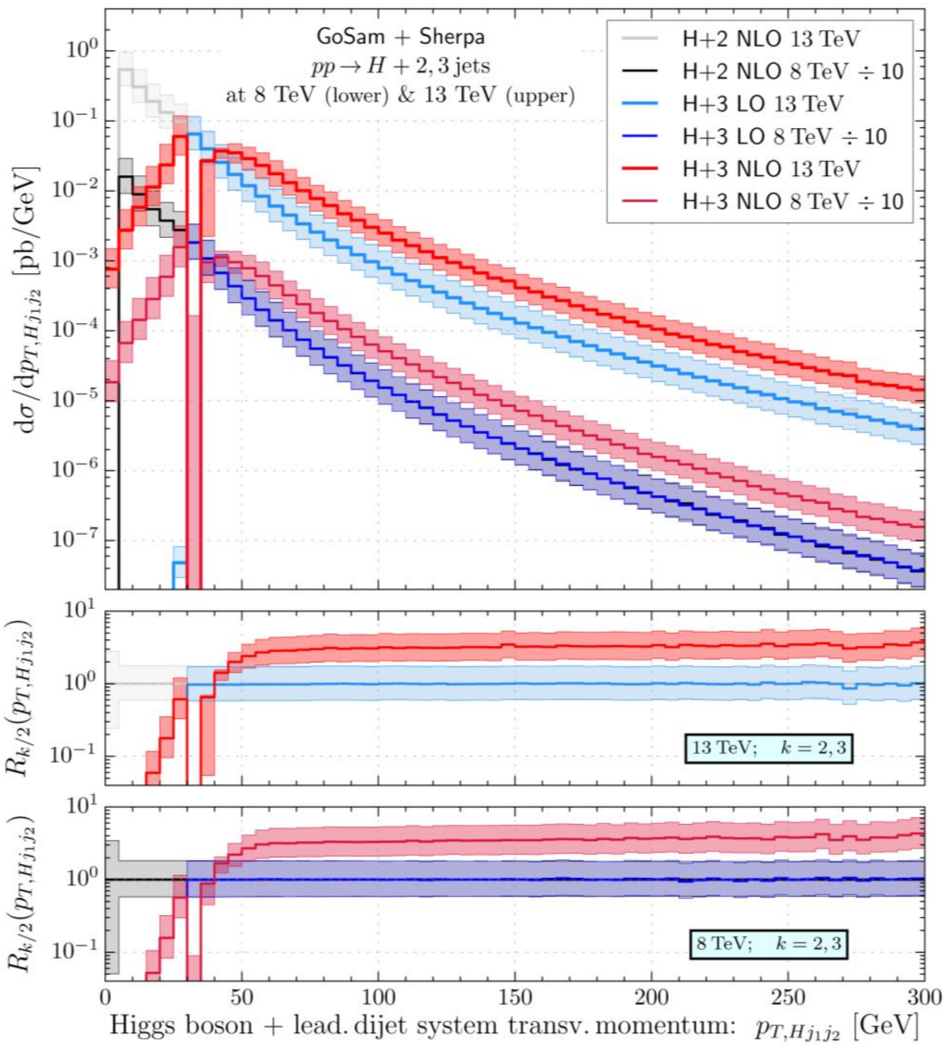


EXCLUSIVE VBF

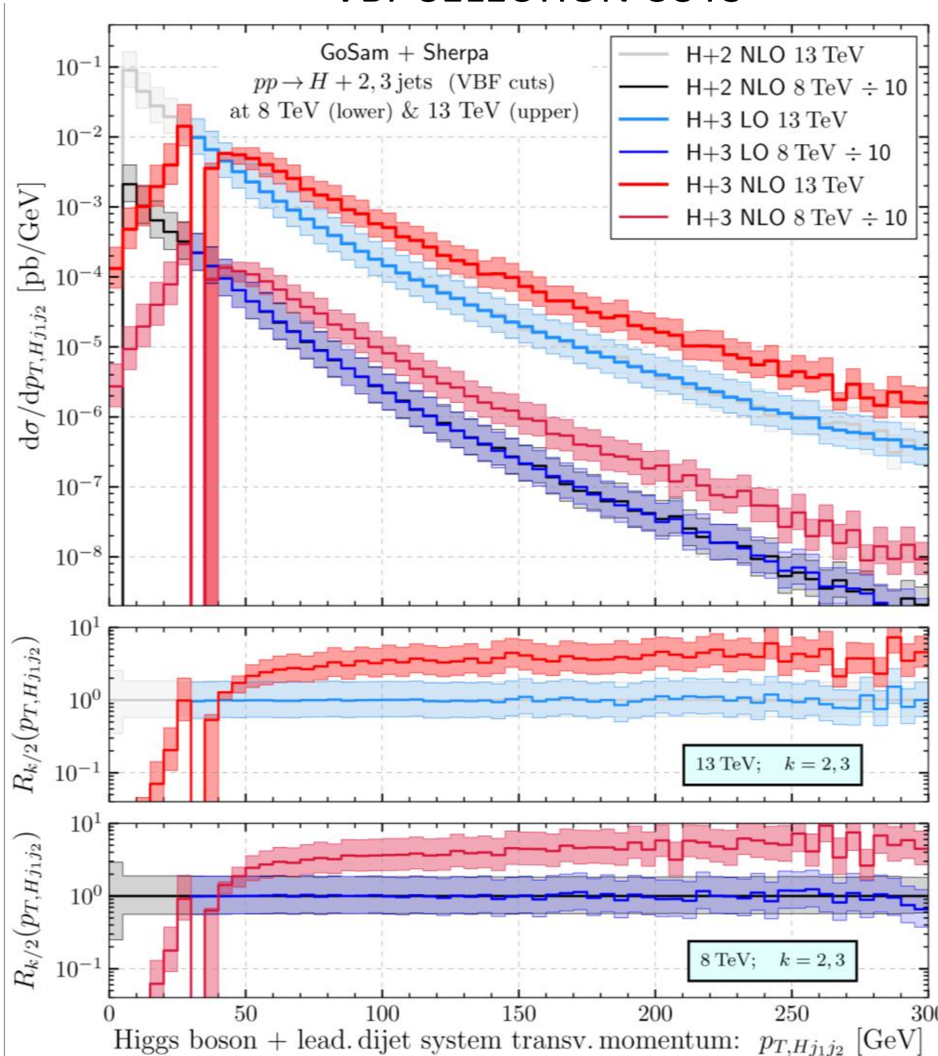


Higgs-j1-j2 system p_T spectrum

BASELINE CUTS



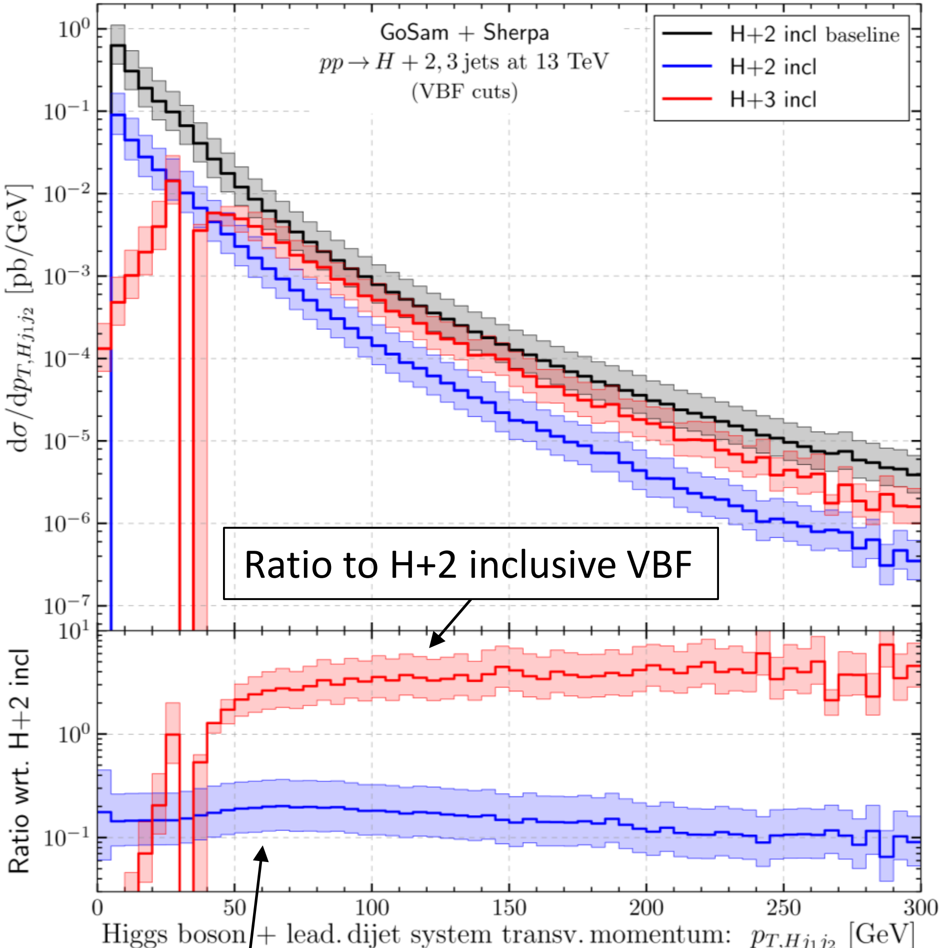
VBF SELECTION CUTS



- Observable very sensitive to real radiation: NLO/LO K-factor ≈ 4
- VBF selection cuts do not lead to big changes

Higgs-j1-j2 system p_T spectrum: ratios

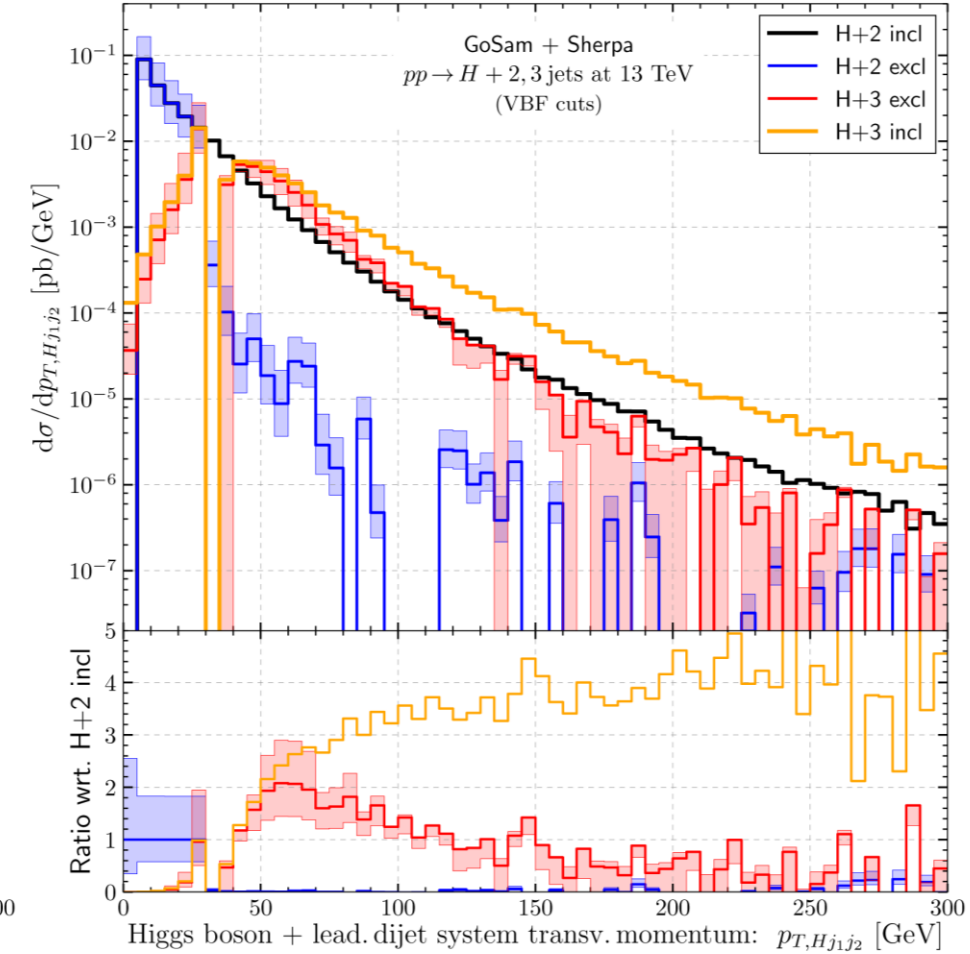
INCLUSIVE



Ratio to H+2 inclusive VBF

Ratio to H+2 inclusive baseline (cut efficiency)

EXCLUSIVE



[Blue curve do not completely vanishes above p_T cut due to very forward/backward hard jets]

Merging & Matching

- Results form the LH2015 comparison

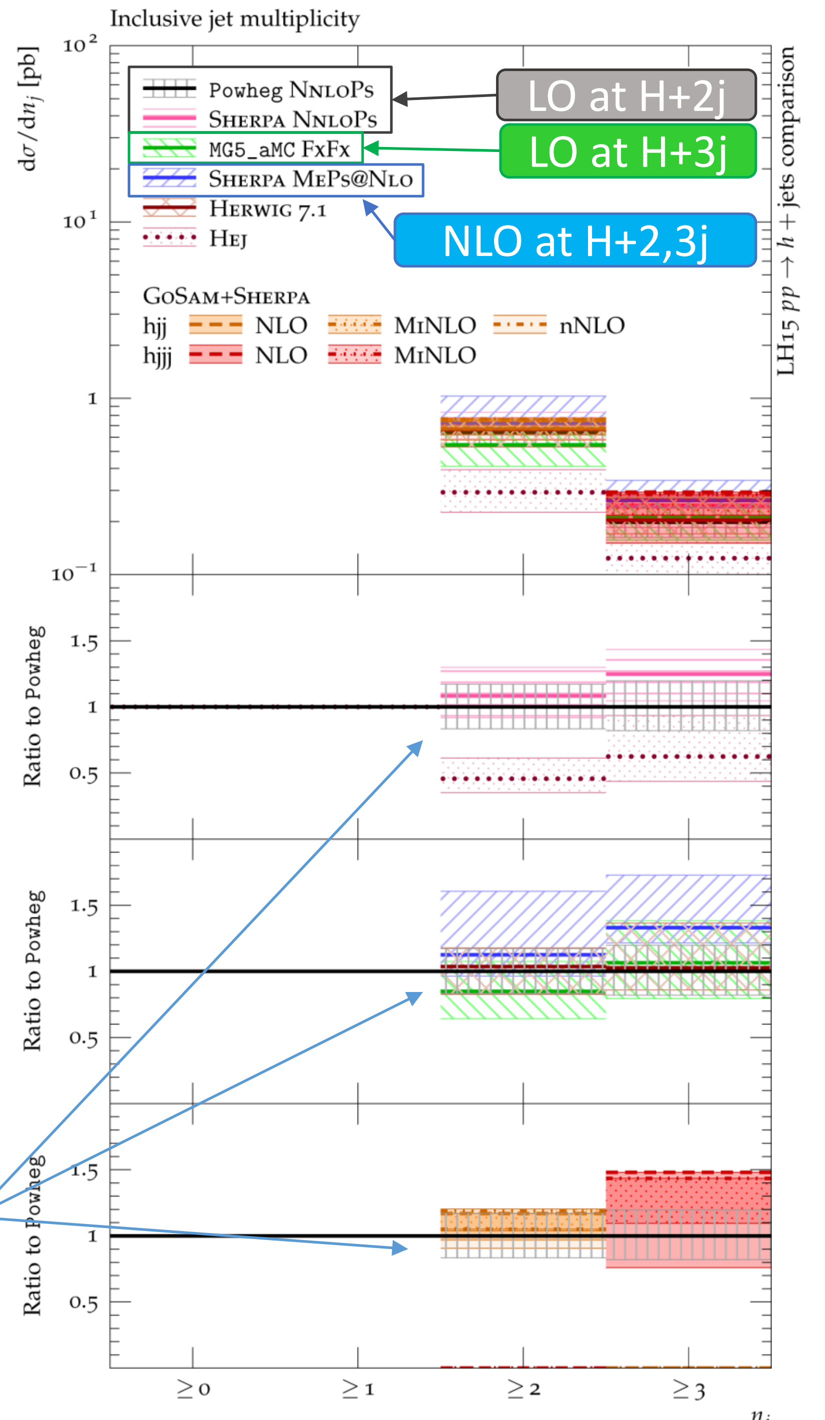
➢ Inclusive jet bins with VBF selection cuts

Merged samples allow to describe several multiplicities with better accuracy taking and also PS effects into account..

HOWEVER

the resulting uncertainty has to be taken with grain of salt, depending on the observable under consideration, and the known accuracy of the merged prediction!!

Unterestimation of the uncertainties in NNLOPS predictions!



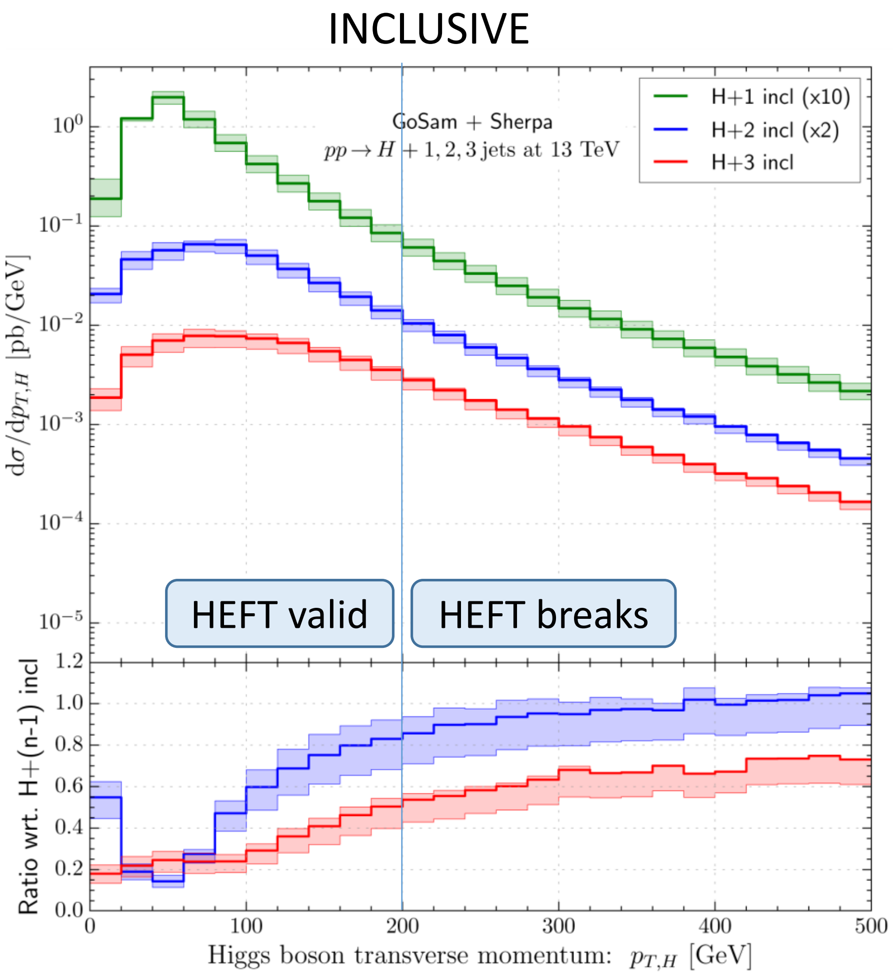
Conclusions

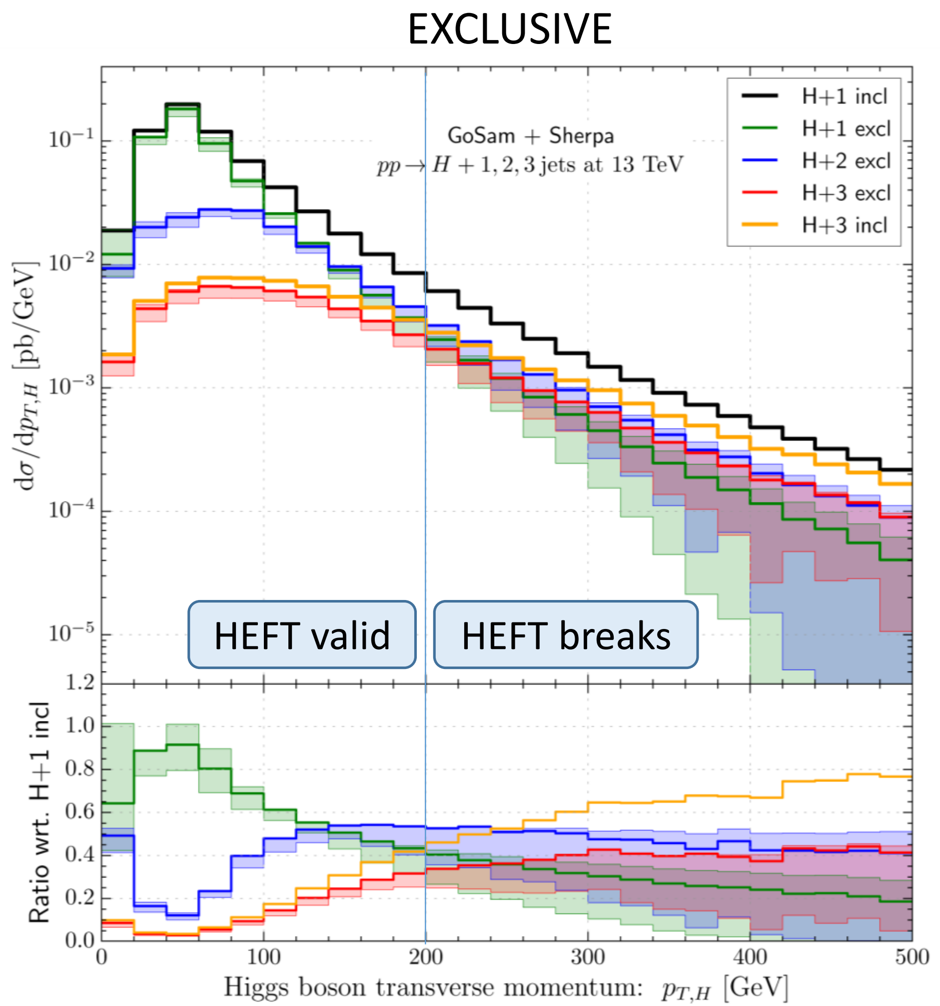
- Higher order QCD corrections to Higgs boson production in association with jets in ggf are large and also larger multiplicities (>2 jets) need to be considered in order to reach a reasonable theoretical accuracy
- VBF fiducial cuts increase sensitivity to radiation: larger uncertainty
- p_T of Higgs-j1-j2 system very sensitive to additional radiation
- Matched and merged predictions allow to describe several multiplicities with potentially higher accuracy **BUT** their reliability depends on the observable under consideration!

- From backup slides:
  - Depending on the kinematical cuts (especially p_T requirements), mass effects will play a major role in differential distributions
    - VBF selection cuts do not particularly enhance mass effects

Backup

Higgs p_T spectrum: H+2/3 jets contributions

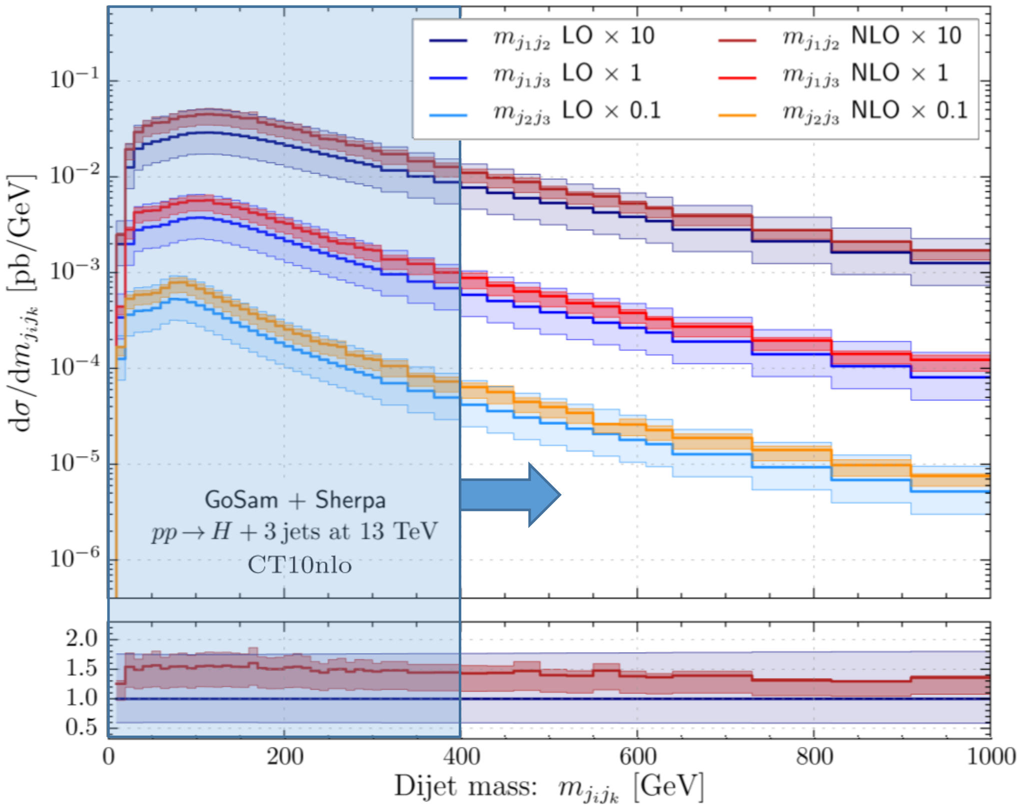


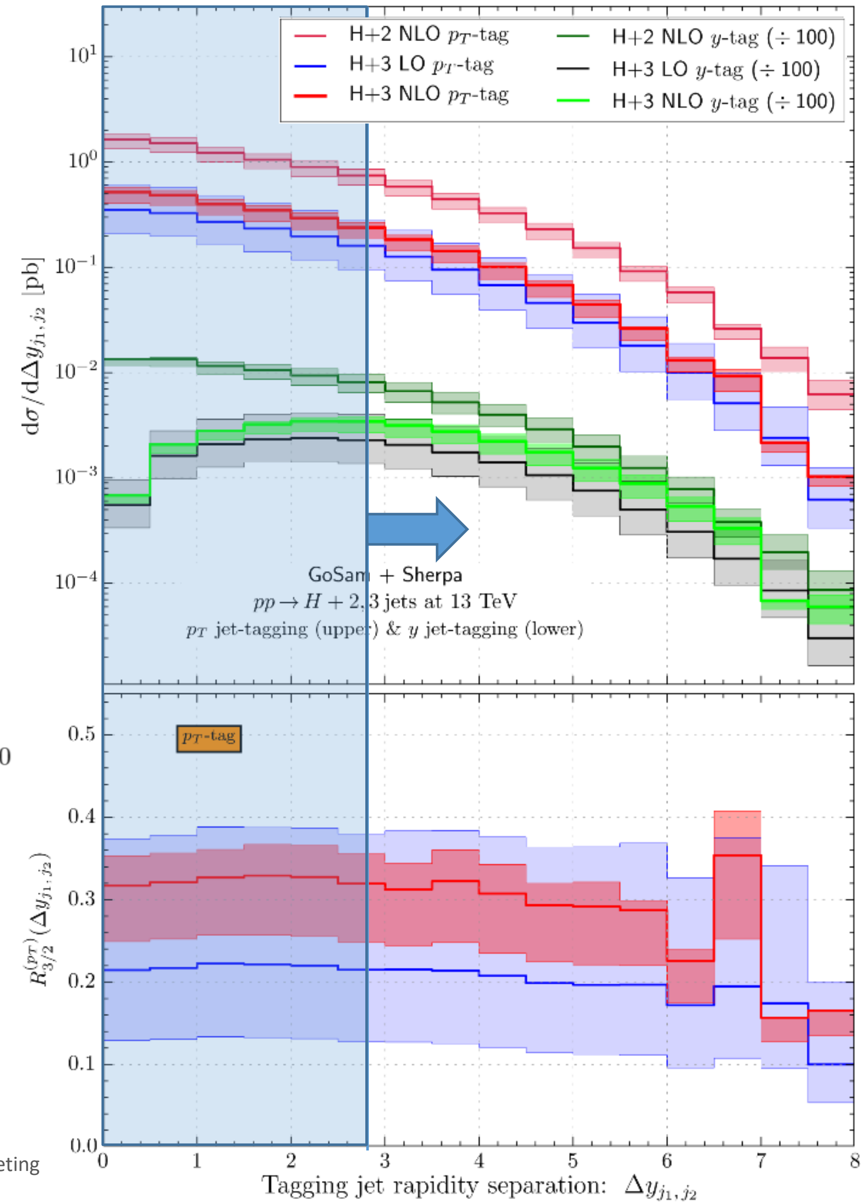


Around 200 GeV (where HEFT is still reliable):

- NLO H+2j incl. is O(80%) of NLO H+1j incl.
- NLO H+3j incl. is O(50%) of NLO H+2j incl.
- NLO H+2j excl. is O(50%) of NLO H+1j incl.
- NLO H+3j excl. is O(30%) of NLO H+1j incl.

VBF selection observables at fixed order

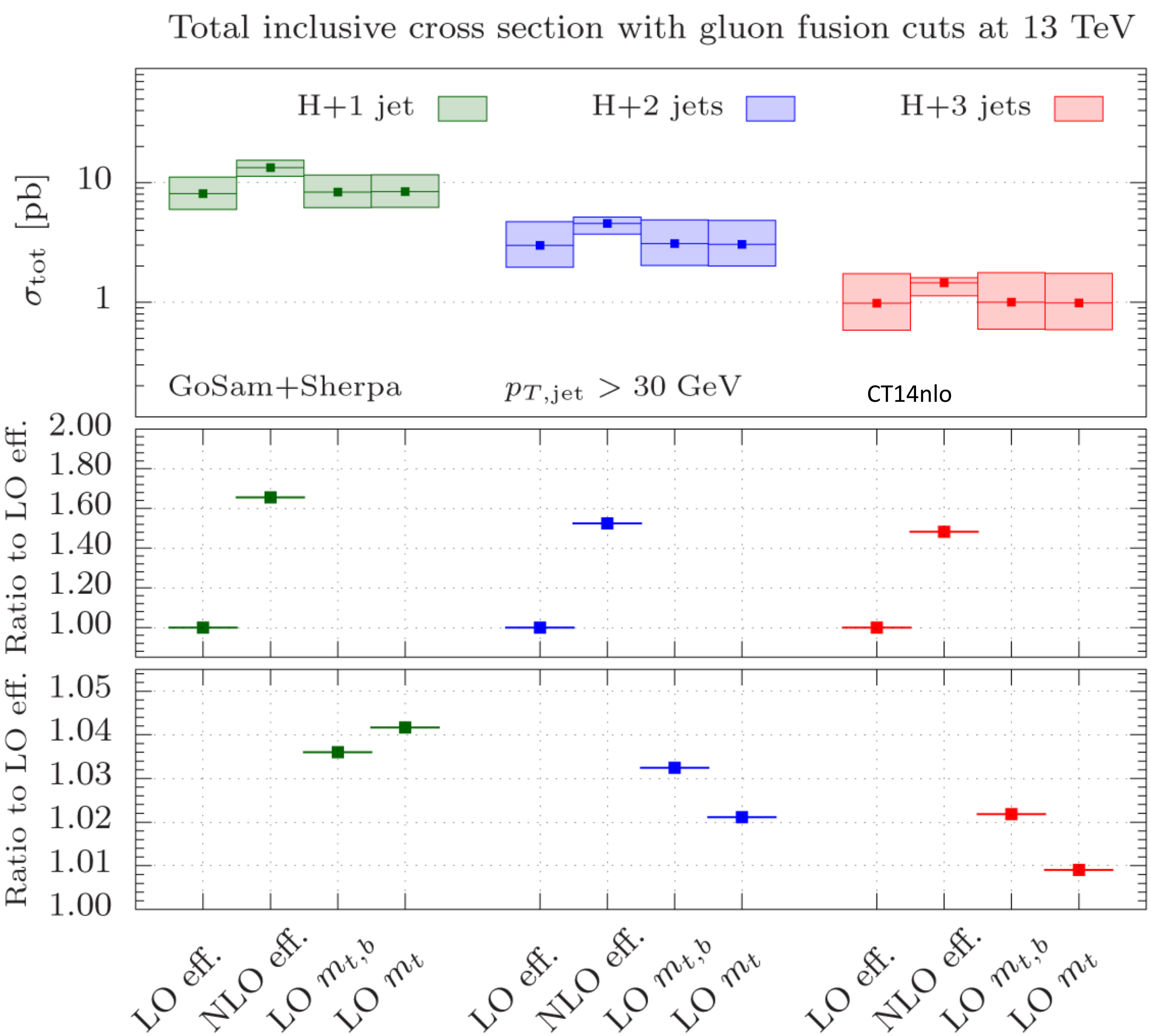




Relation between baseline and VBF selection cuts can be inferred from m_{j1j2} and Δy_{j1j2} distributions

Finite mass effects

Total cross section: 13 TeV

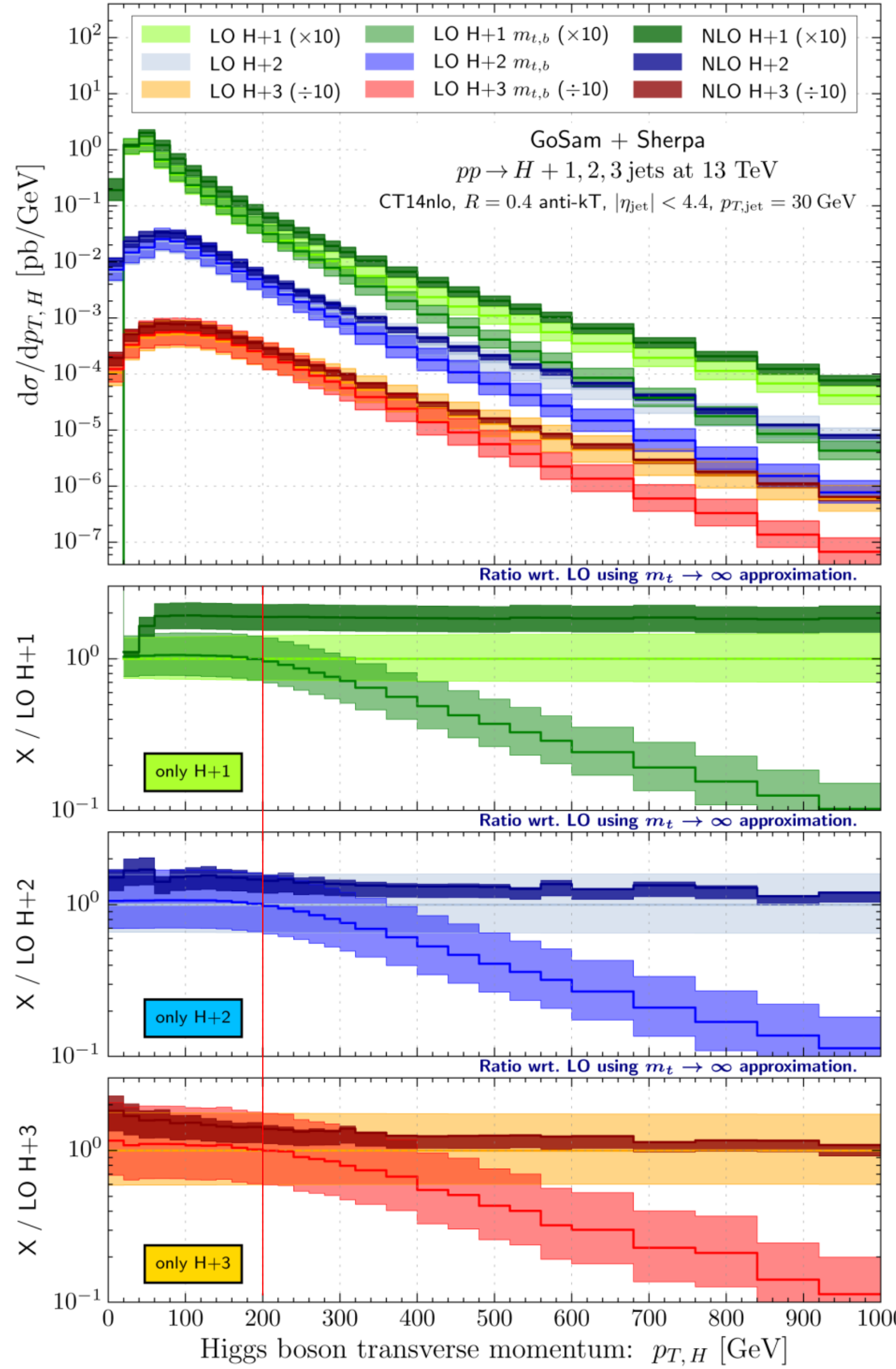


- Reduction of the size of NLO corrections for higher multiplicity
- Relative difference due to bottom-quark O(1%)
- Sign flip in corrections due to bottom-top quark interference
- Possibility to estimate NLO cross section with full mass dependence from K-factors

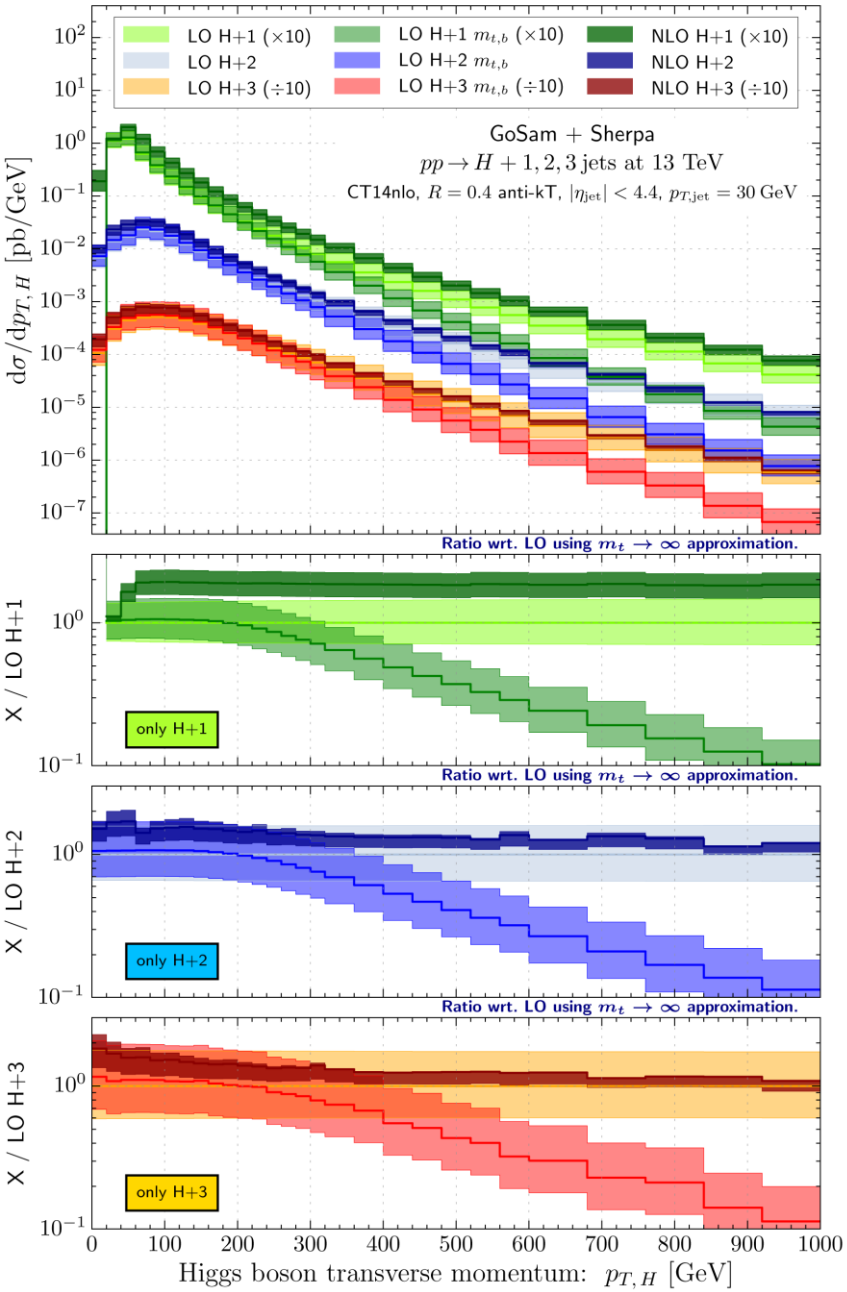
- $\sigma_{\text{LO}, m_{t,b}}$: top- and bottom-quark loops
- σ_{LO, m_t} : top-quark loops only

Higgs boson p_T

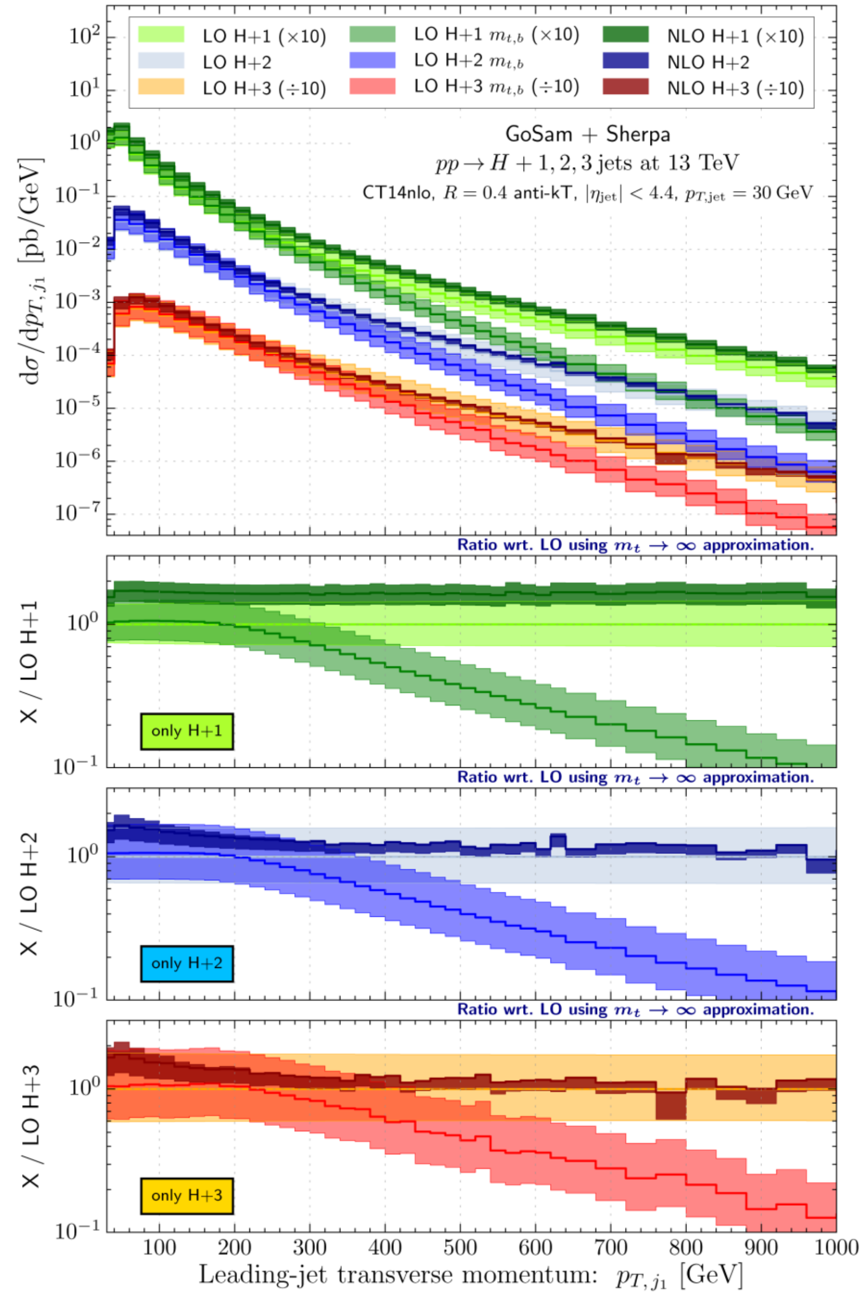
- Transverse momentum related observables known to receive significant corrections
- Effective theory starts to break down at $p_{T,H} \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.
- Very similar behavior for the three different multiplicities



Higgs pT:



Leading jet pT:

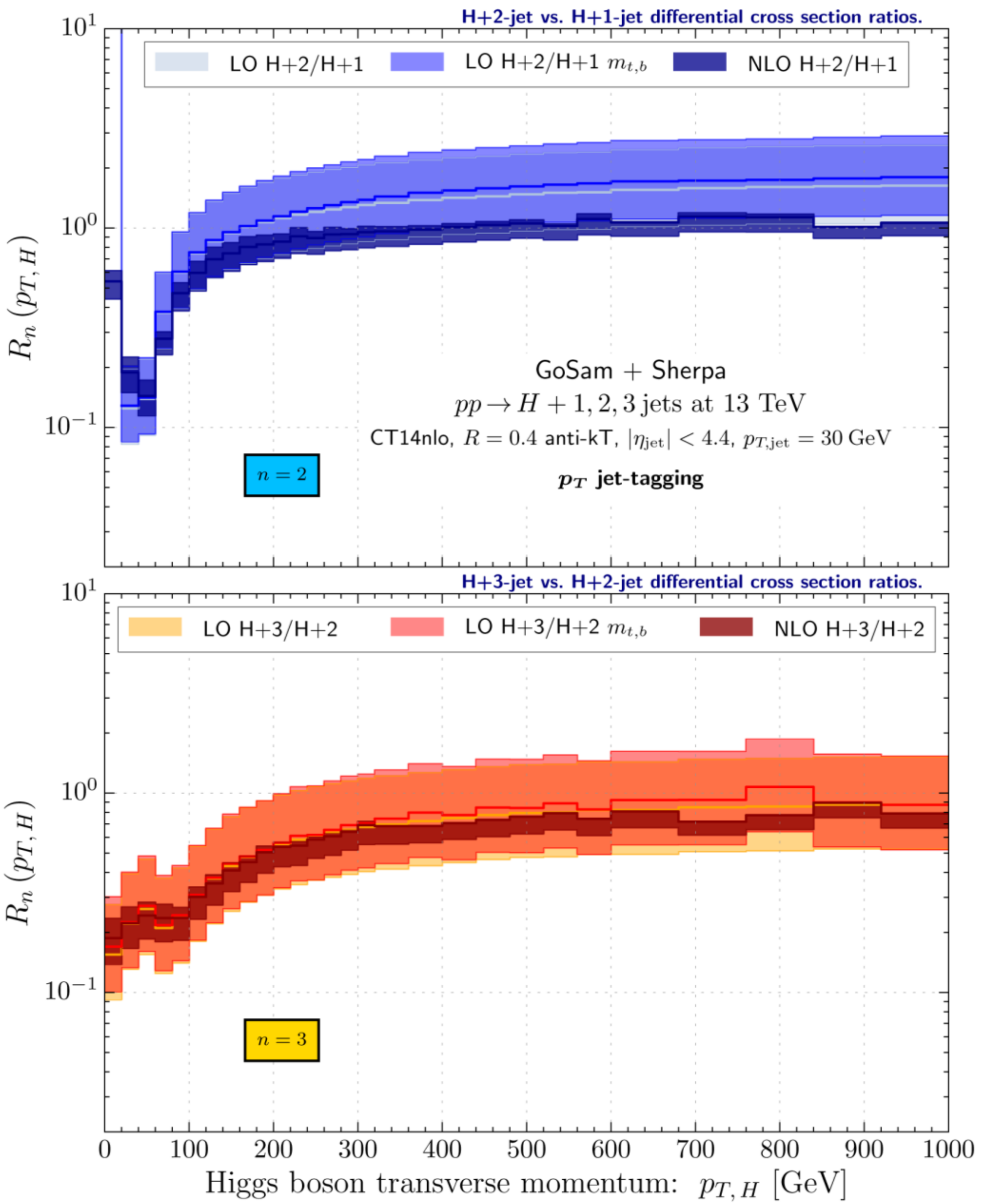


Higgs boson p_T

- Ratios of successive differential cross sections:

$$R_n(O) = \frac{\frac{d\sigma}{dO}(\mathrm{H}+n\,\mathrm{jets})}{\frac{d\sigma}{dO}(\mathrm{H}+(n-1)\,\mathrm{jets})}$$

➢ relative importance of higher multiplicities remains stable under mass corrections



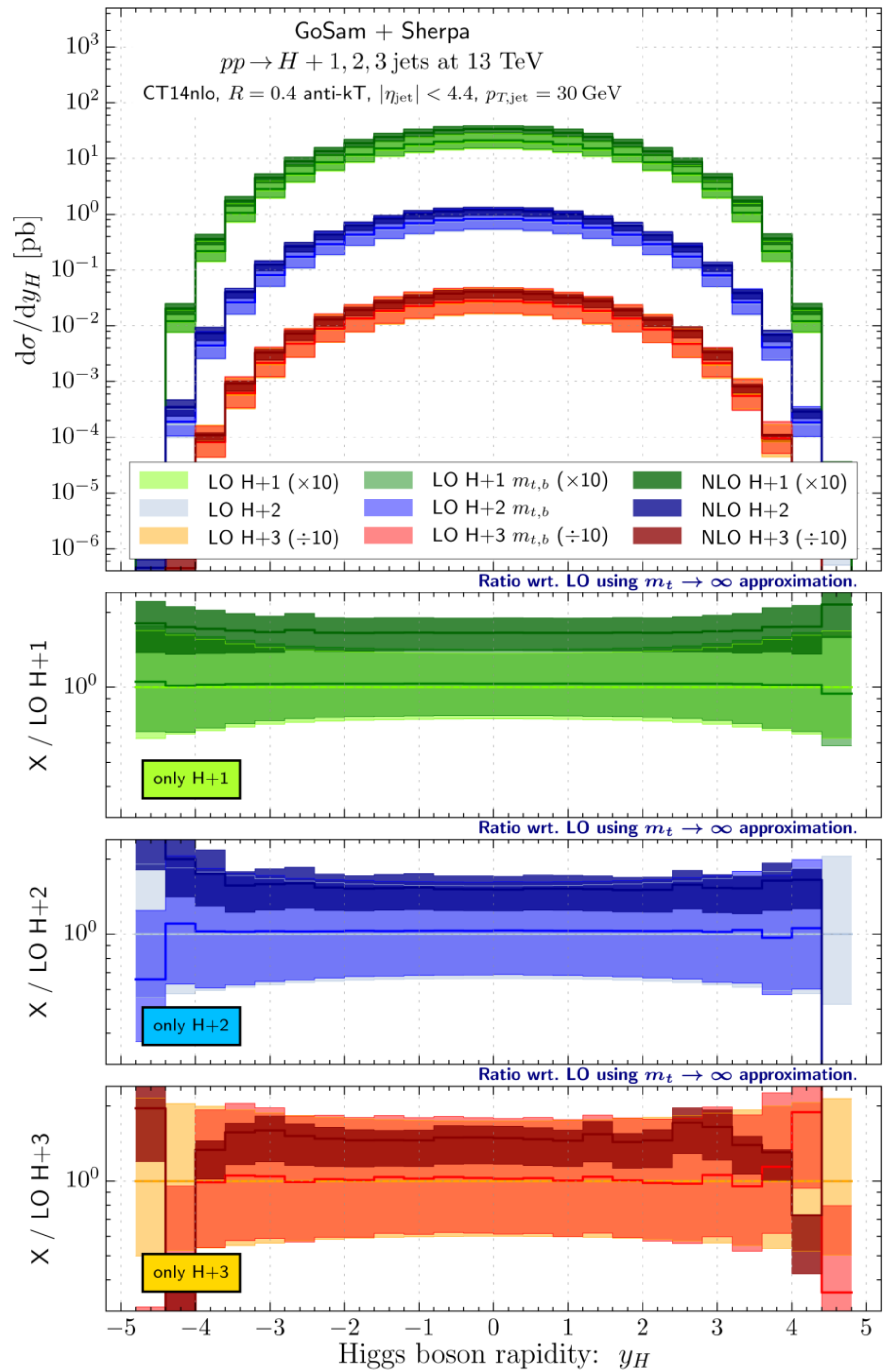
Higgs boson rapidity

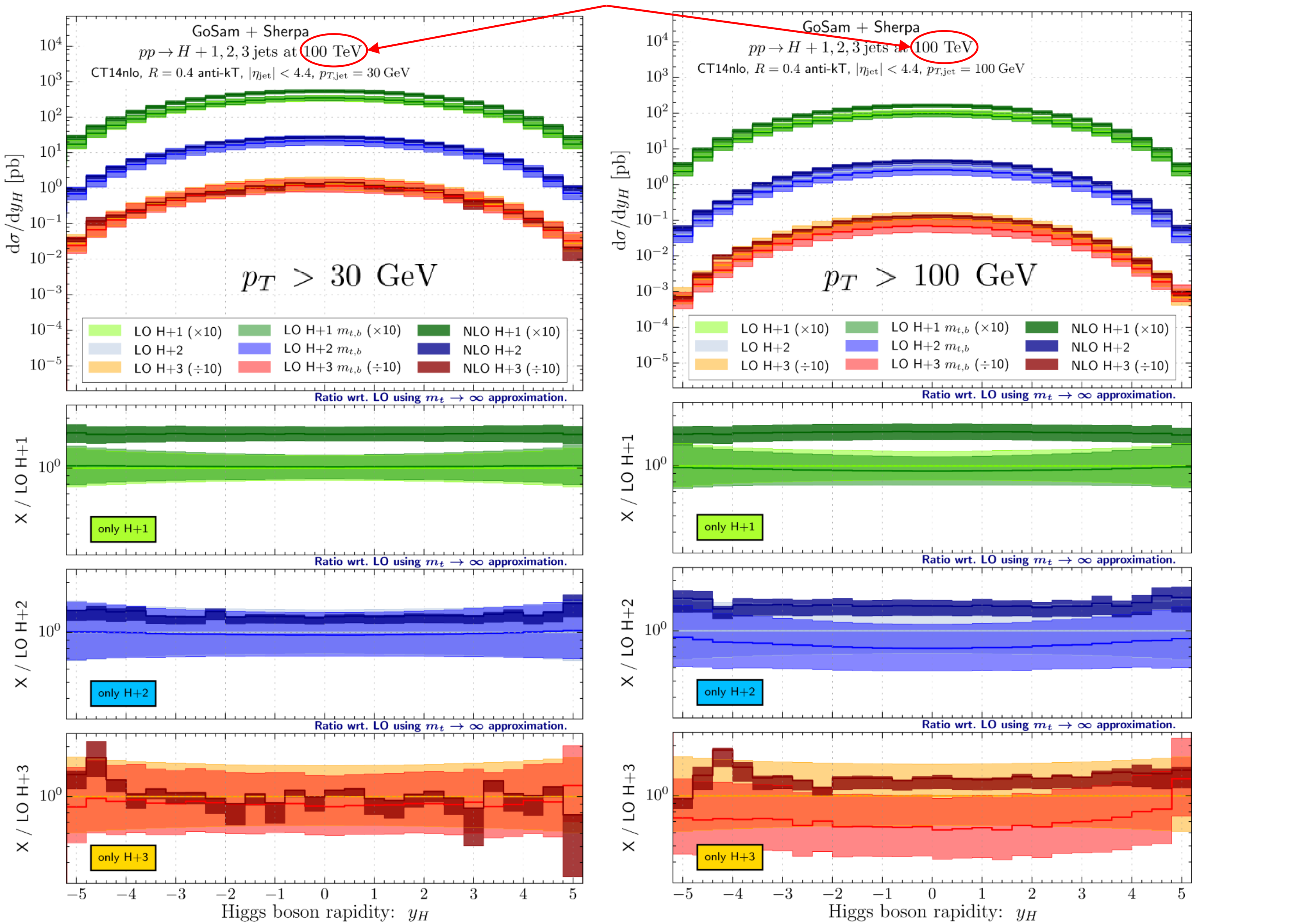
- Mass corrections small over full kinematical range:

➢ Regions of phase space where quark-loop is resolved are smeared over the entire range

➢ For the bulk of the cross sections mass effects are small

➢ This changes if one cuts harder on the jets!





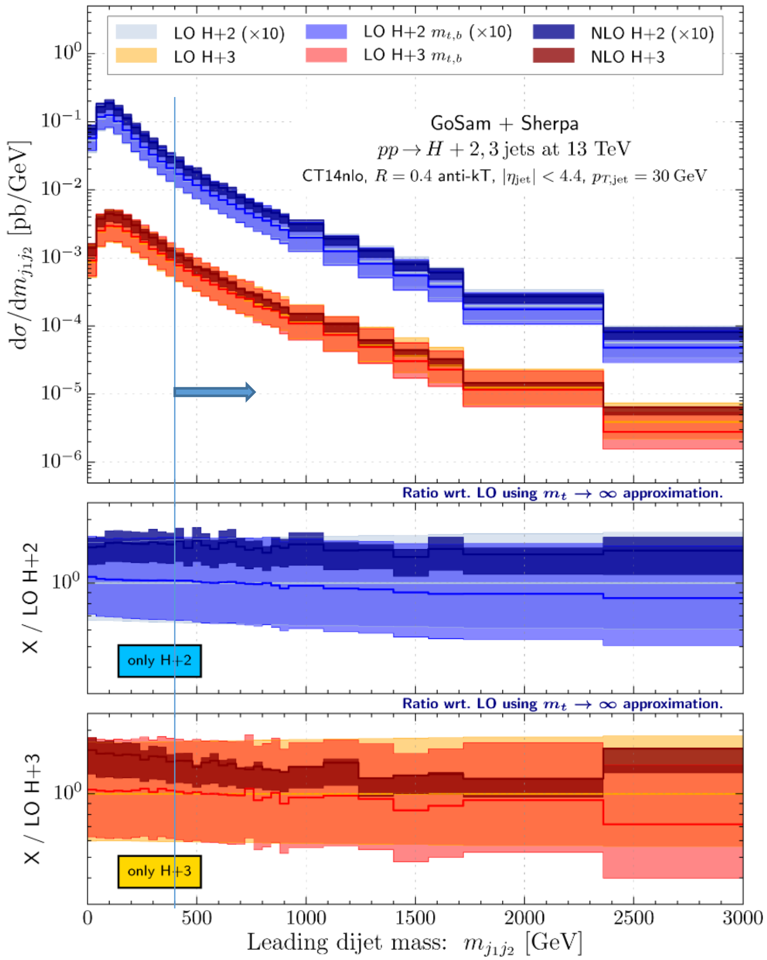
Regime in which HEFT breaks down is reached more easily when a harder pT cut is imposed. Mass effects therefore become much more important!

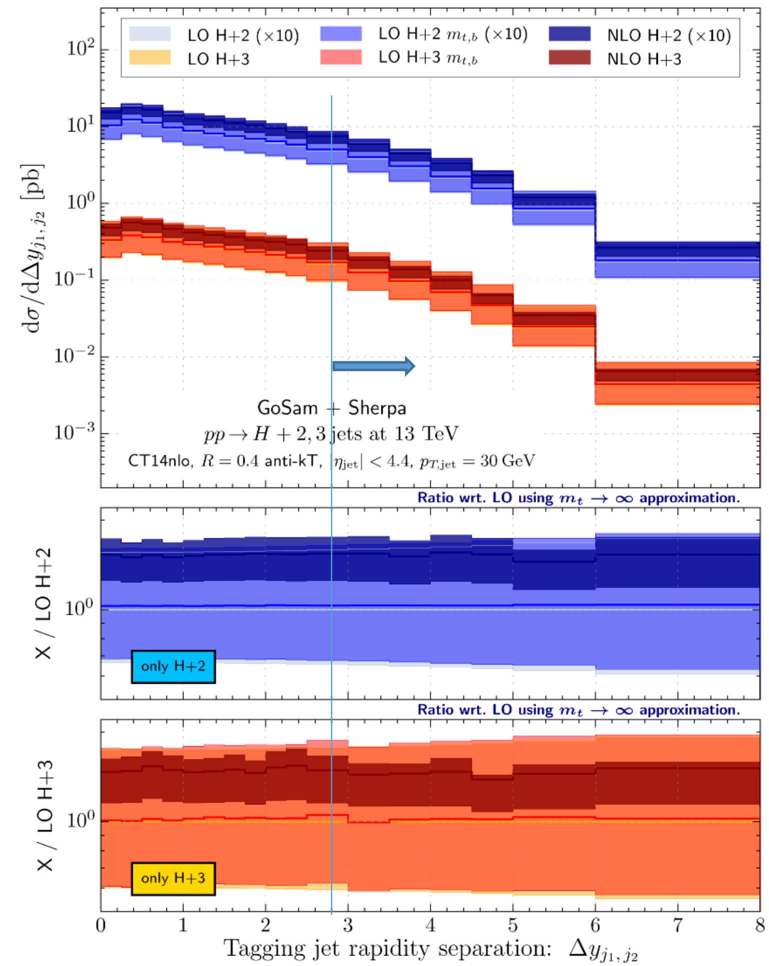
Higgs plus jets in GGF with VBF selection cuts

- In order to estimate the size of the GGF contribution in the presence of VBF selection cuts, add the following requirements to the baseline set:

$$m_{j_1 j_2} > 400\ \text{GeV}, \quad |\Delta y_{j_1,j_2}| > 2.8$$

- Effects of these cuts on phase space:





Higgs plus jets in GGF with VBF selection cuts

- In order to estimate the size of the GGF contribution in the presence of VBF selection cuts, add the following requirements to the baseline set:

$$m_{j_1 j_2} > 400 \text{ GeV}, \quad |\Delta y_{j_1,j_2}| > 2.8$$

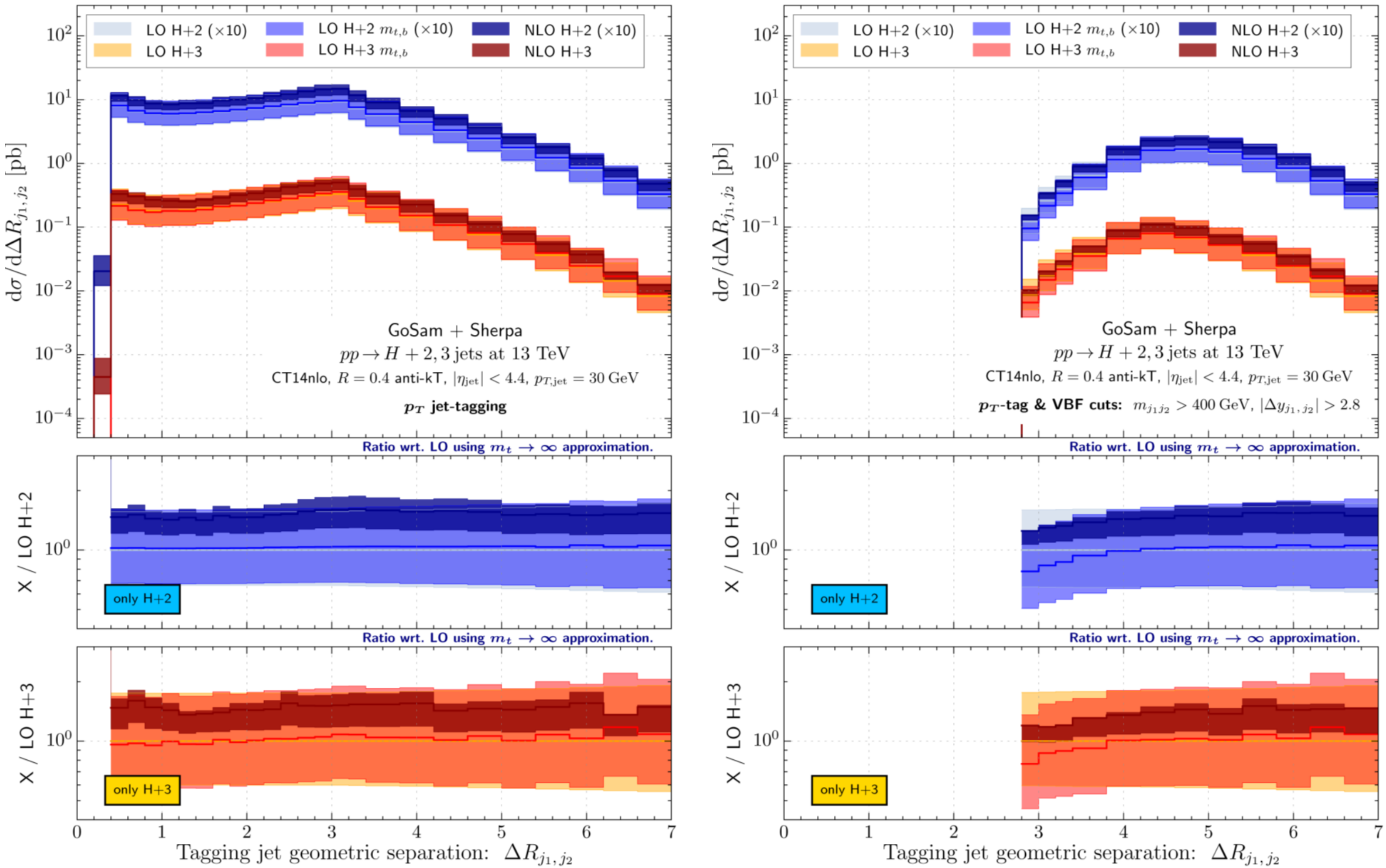
- Total cross section:

Numbers in [pb]	H+2 jets	H+3 jets
$\sigma_{\text{LO, eff.}}$	$0.397^{+64\%}_{-36\%}$	$0.166^{+82\%}_{-42\%}$
$\sigma_{\text{NLO, eff.}}$	$0.584^{+10\%}_{-19\%}$	$0.231^{+5\%}_{-22\%}$
$\sigma_{\text{LO}, m_{t,b}}$	$0.404^{+65\%}_{-37\%}$	$0.167^{+82\%}_{-42\%}$
σ_{LO, m_t}	$0.398^{+65\%}_{-37\%}$	$0.165^{+82\%}_{-42\%}$

- Similar pattern as without VBF-type cuts
- Same conclusions hold also for many differential observables like for example $\Delta\phi_{j_1,j_2}$

Radial distance between tagging jets

- Effects of VBF selection cuts wrt. baseline cuts:



Massless bottom quarks

- Comparison between top- and bottom-quark predictions and top-quark only results:
  - ➢ difference is well below scale uncertainty and never exceeds 5%
  - ➢ primarely concerns soft region
  - ➢ is multiplicity dependent
  - ➢ destructive interference observed in the total H+1j cross section stems from the soft region, whereas net contribution becomes positive in regions where the bottom quark can be considered as massless.
  - ➢ Higgs p_T