

H+2j and H+3j predictions from GGF

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MAX-PLANCK-GESELLSCHAFT

Max Planck Institut für Physik

Higgs XS WG1: VBF Meeting

CERN

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In collaboration with:

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

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 $R=0.1, \dots, 1.0$
 - ✓ 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/>



Physical setup

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

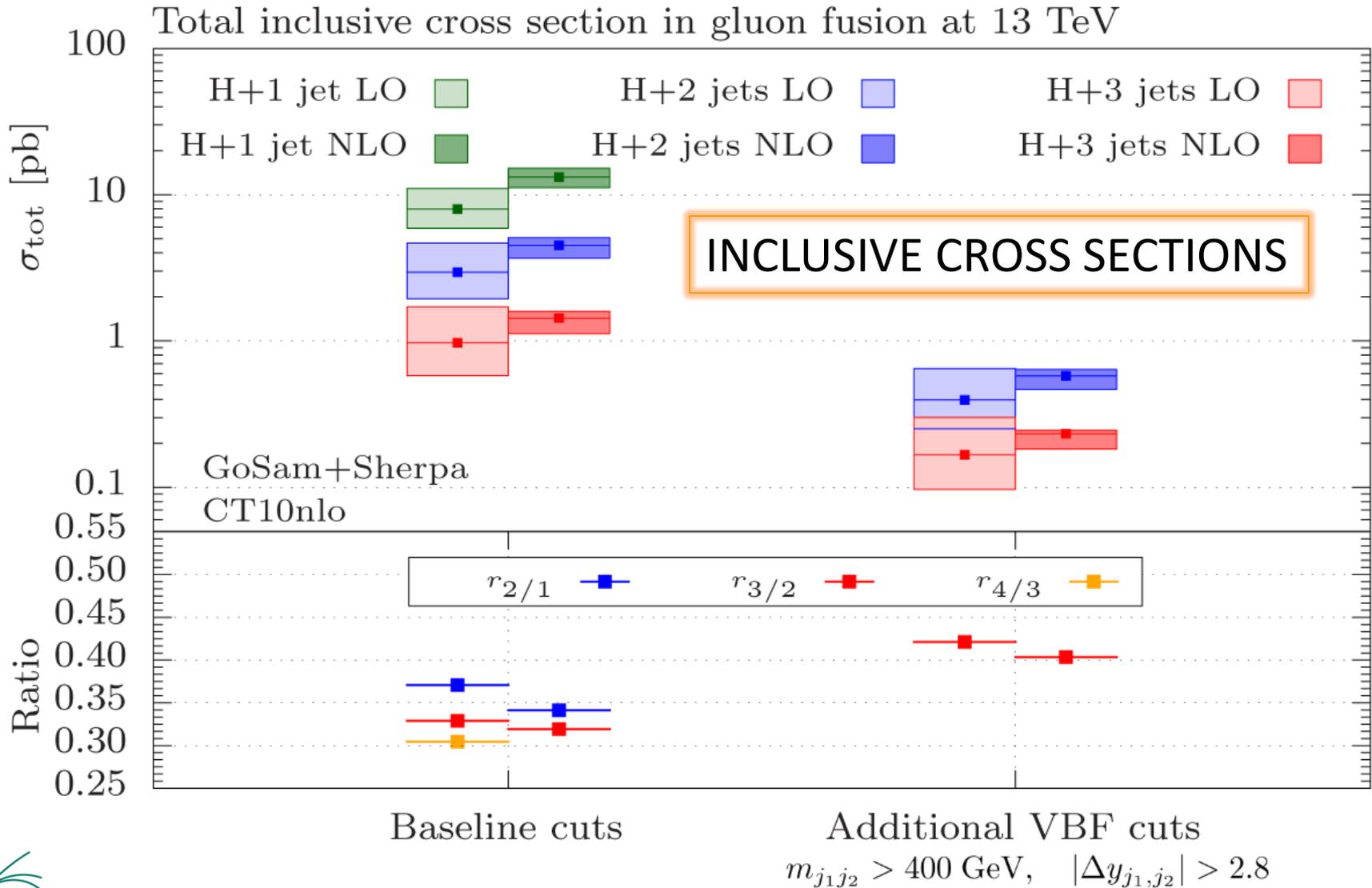
- scale choice: $\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2} \left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}| \right)$
- PDFs: CT10nlo or CT14nlo (see the single plots for details)
- masses: $m_H = 125.0$ GeV, $m_t = 172.3$ GeV, $m_b(m_H) = 3.38$ GeV

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

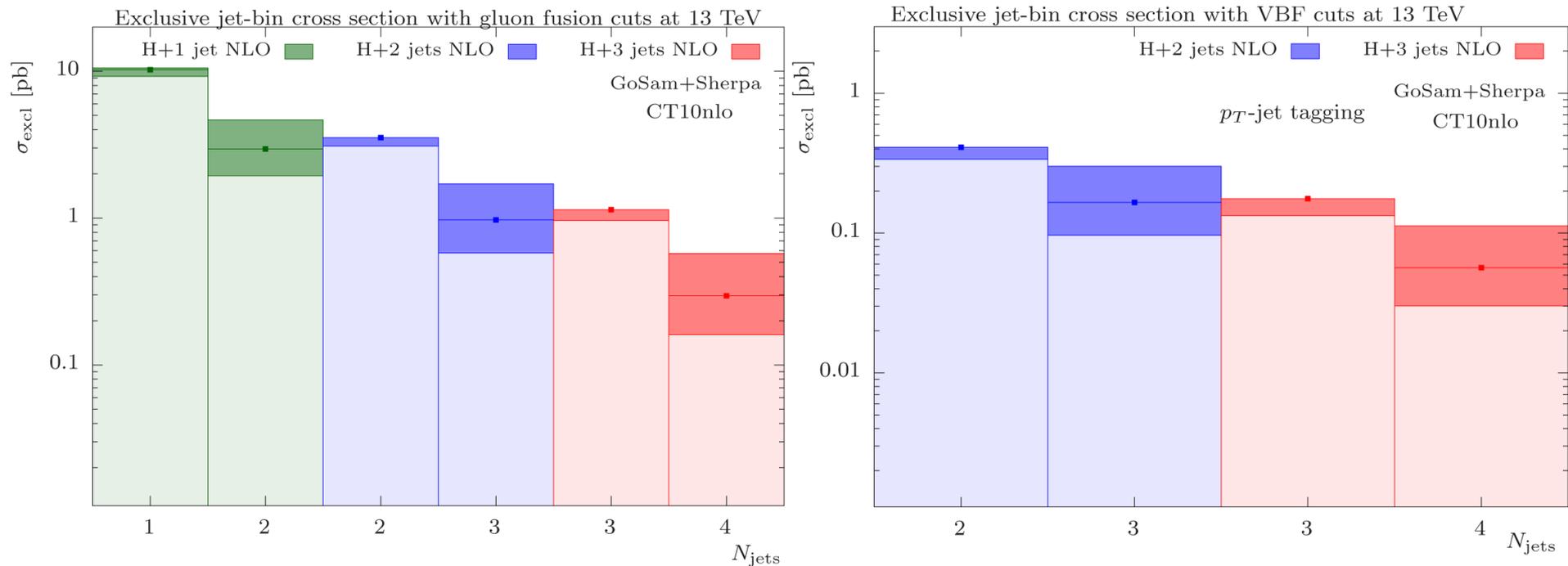
- Remark: basic Ntuples sets have events with $p_T > 25$ GeV, $|\eta| < 4.5$ for the jets at the generation level



Total cross section at 13 TeV



Total cross section at 13 TeV: exclusive jet bins

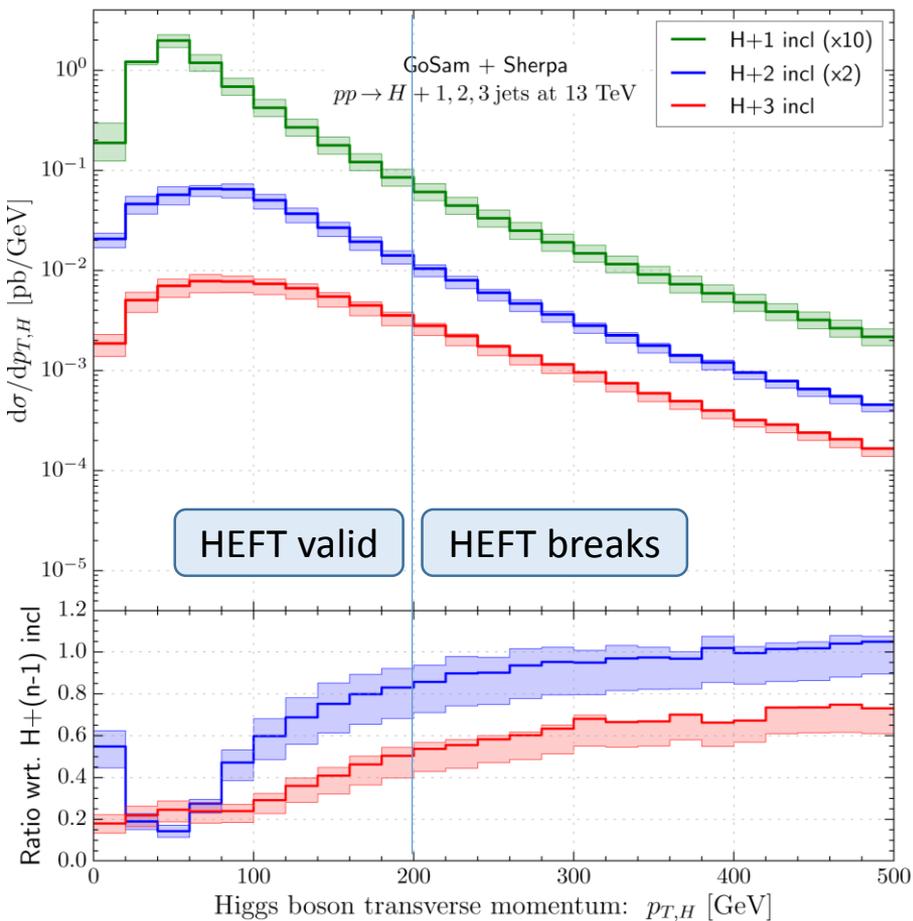


- Relative enhancement of the (n+1)-jet contribution in the VBF fiducial region
 - Larger portion of cross section described only at LO accuracy
 - i.e. **theoretical uncertainty increased** in the VBF fiducial region
- H+3j allows to determine the effects of the presence of a third jet with NLO accuracy
 - Particularly important for VBF studies
 - Fixed order approach limited. **Merged and matched** (e.g. MEPS@NLO) sample allows to consistently combine NLO predictions and also PS effects



Higgs p_T spectrum: H+2/3 jets contributions

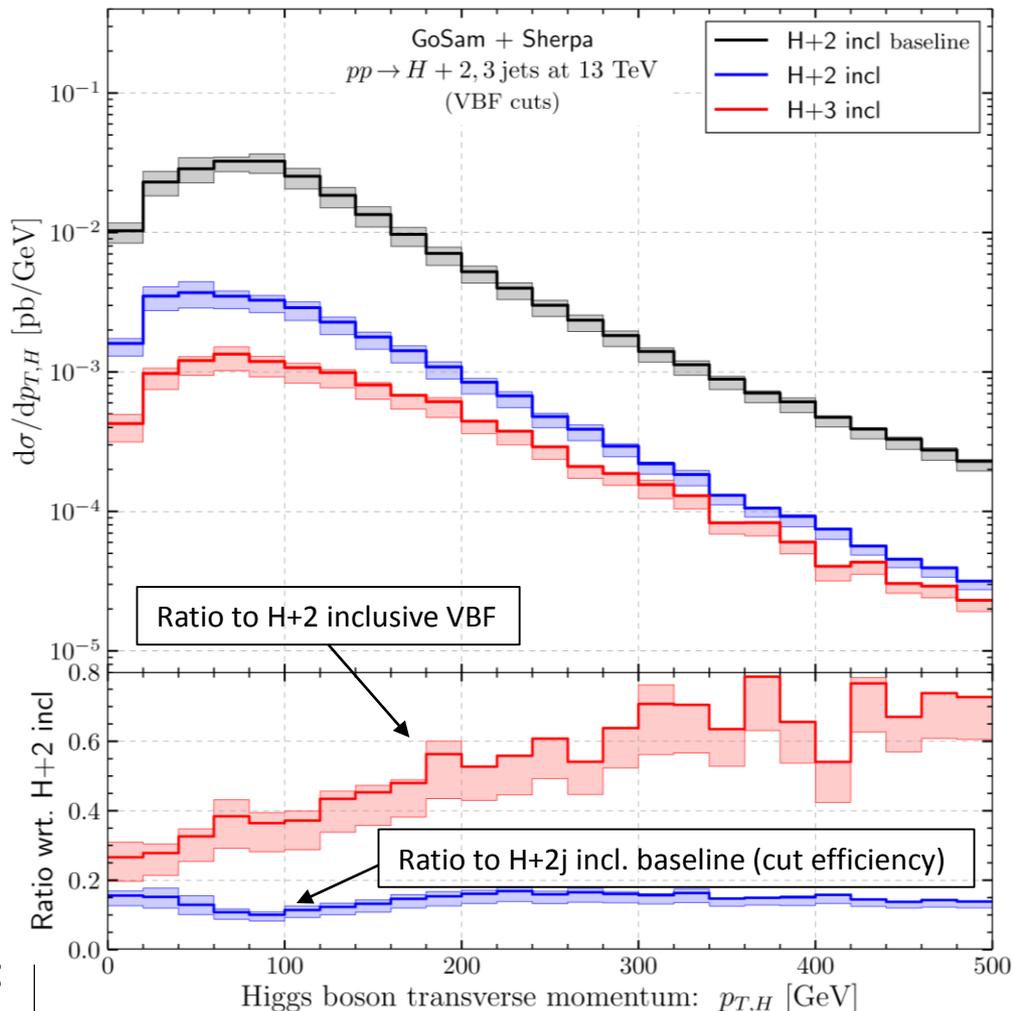
INCLUSIVE BASELINE



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.

INCLUSIVE VBF

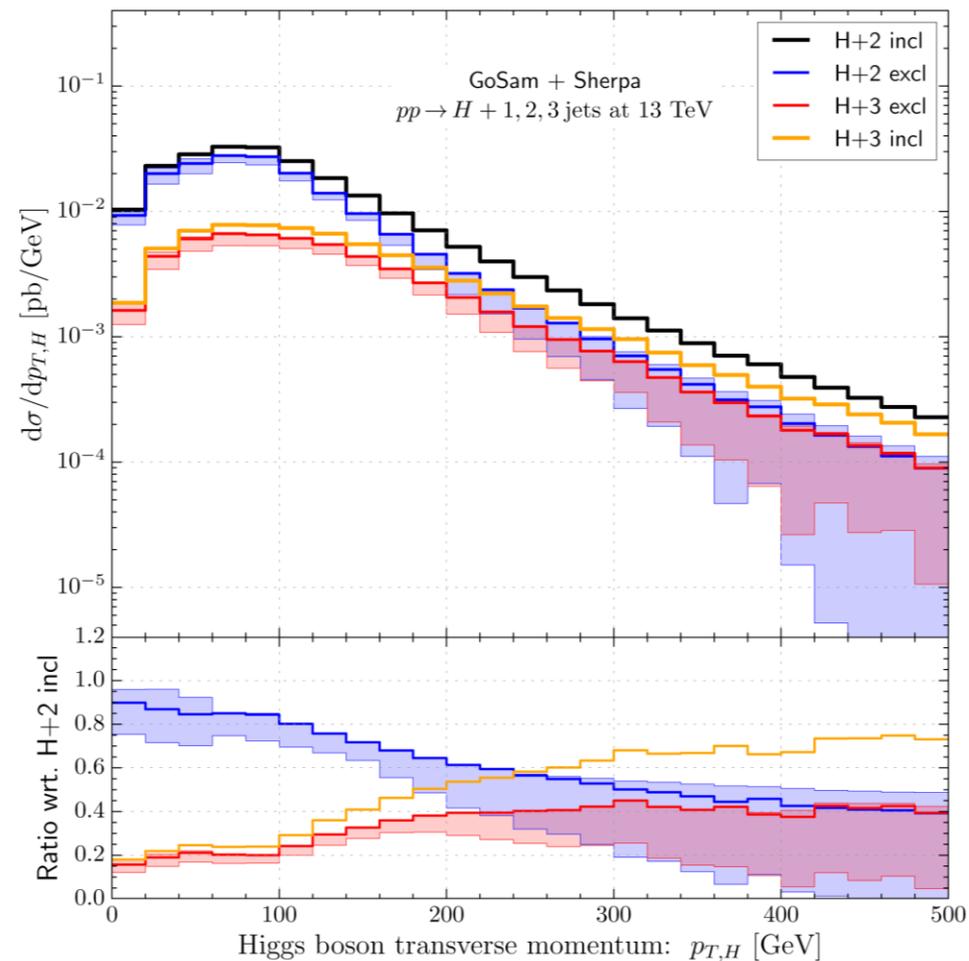


Relative importance of NLO H+3j grows faster:

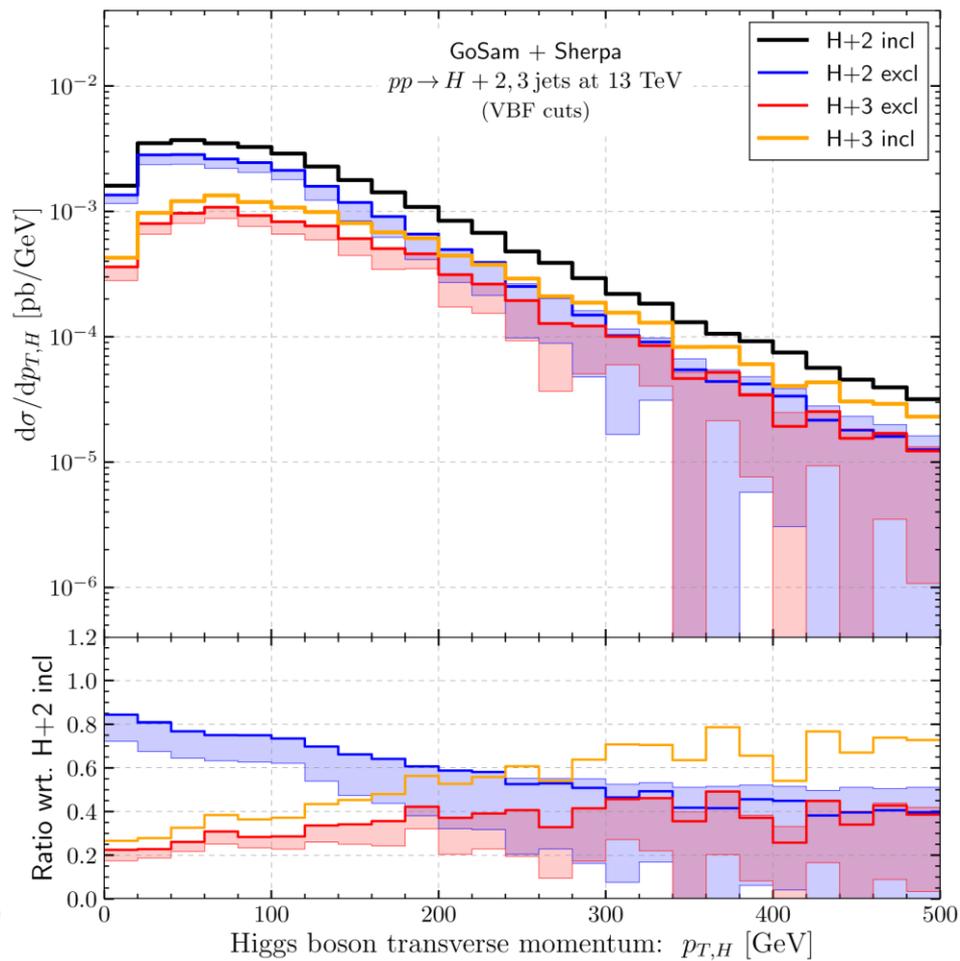
- at 100 GeV it is **O(40%)** of NLO H+2j incl.

Higgs p_T spectrum: H+2/3 jets contributions

EXCLUSIVE BASELINE

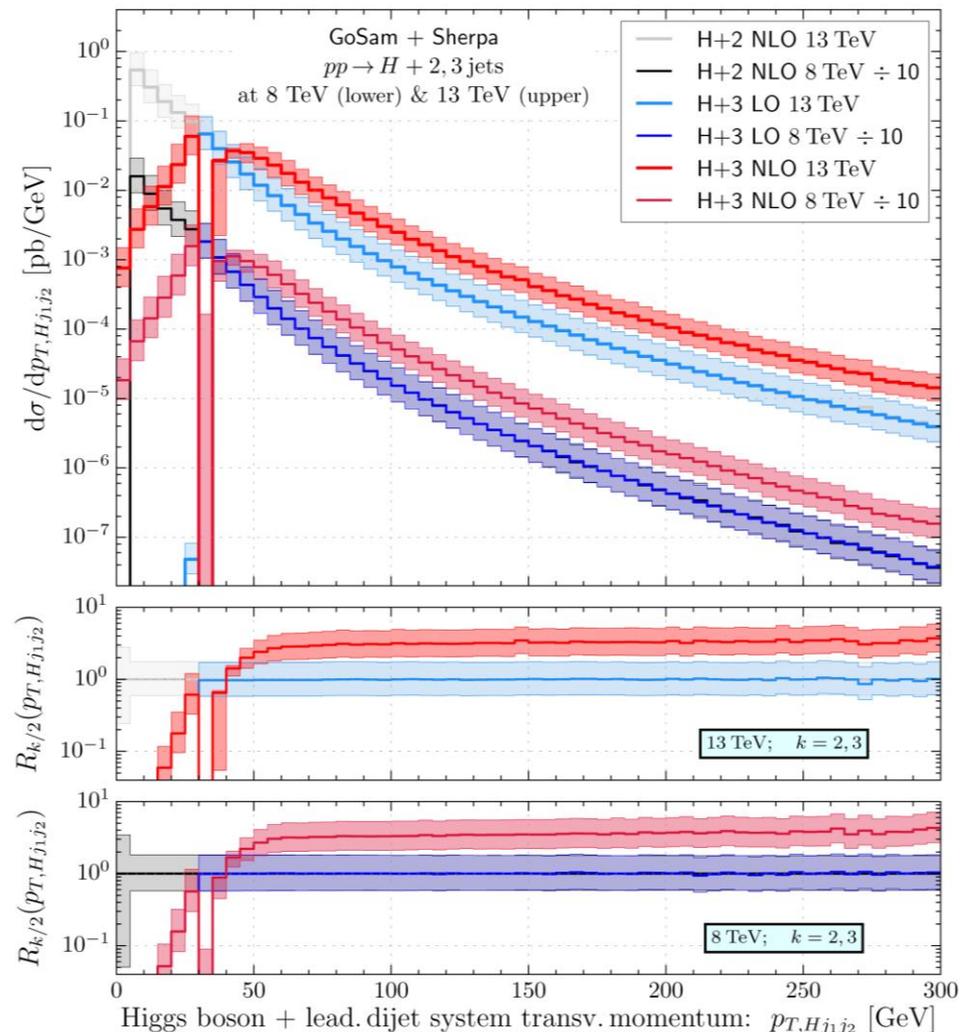


EXCLUSIVE VBF

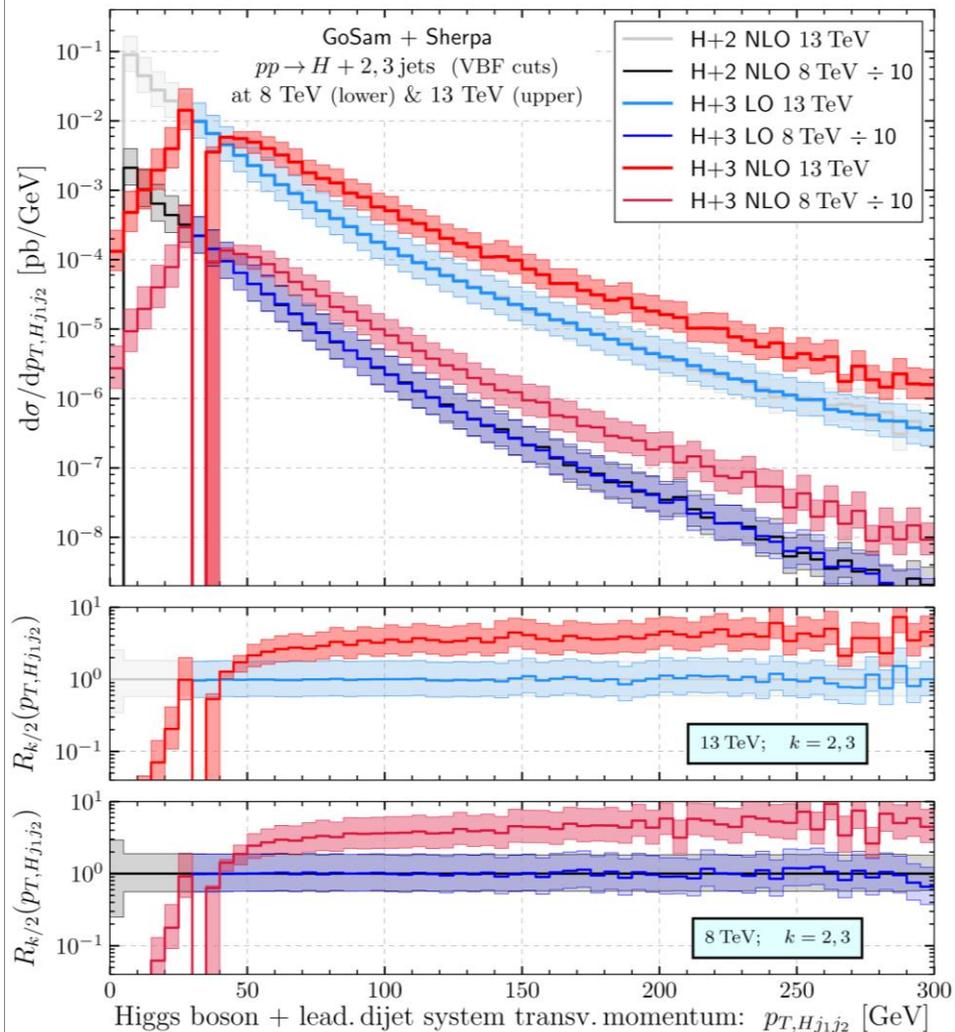


Higgs-j1-j2 system p_T spectrum

BASELINE CUTS



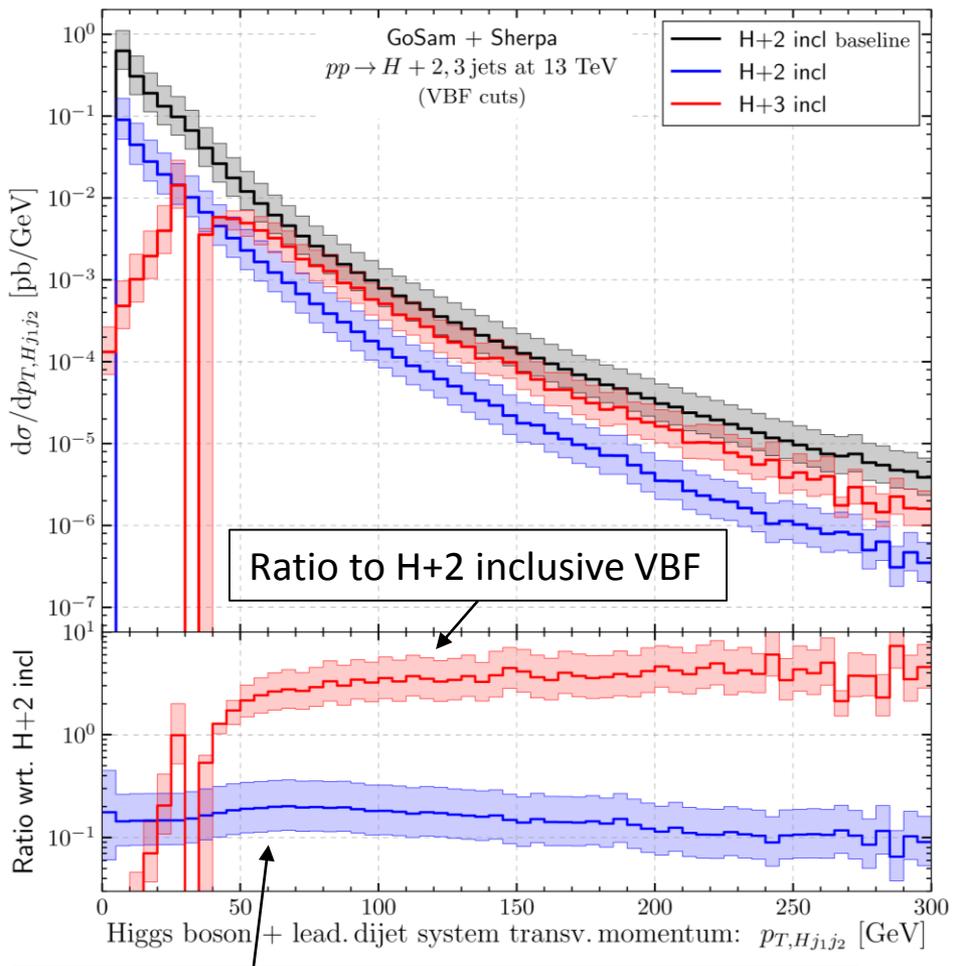
VBF SELECTION CUTS



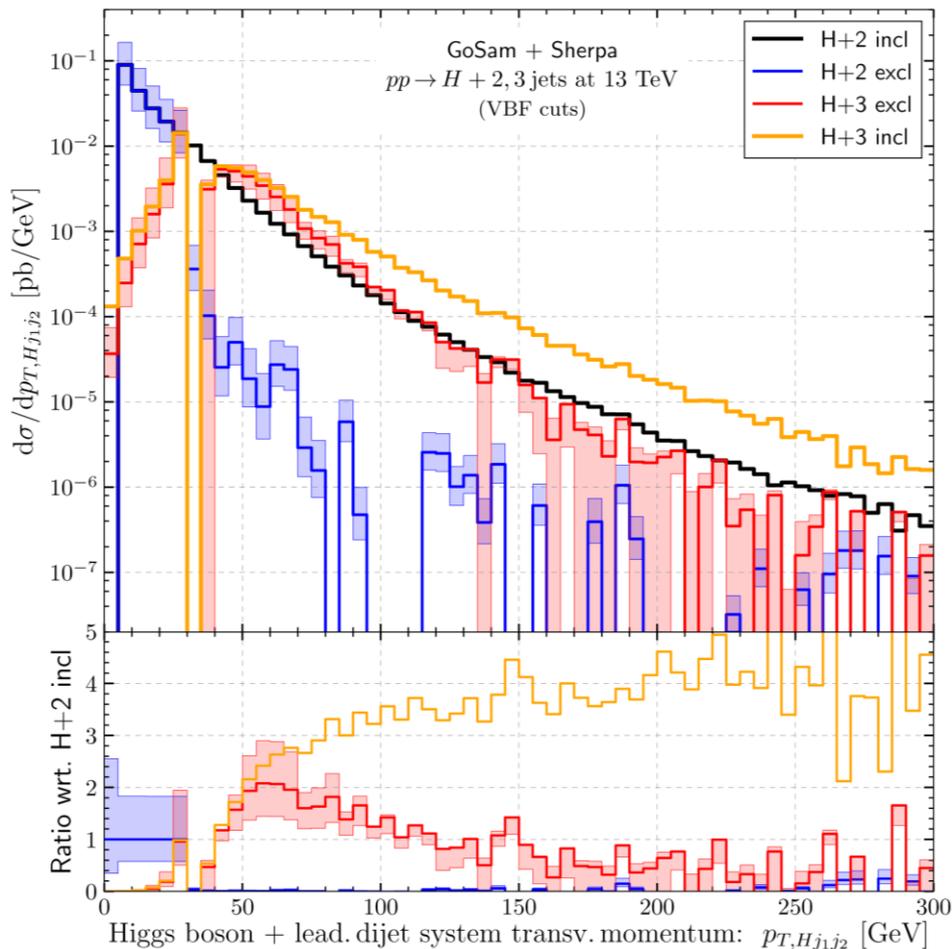
- Observable very sensitive to real radiation: NLO/LO K-factor ≈ 4
- VBF selection cuts do not have a large impact

Higgs-j1-j2 system p_T spectrum: ratios

INCLUSIVE



EXCLUSIVE



➤ Gap between red and orange curves: effect of real radiation

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

Merging & Matching

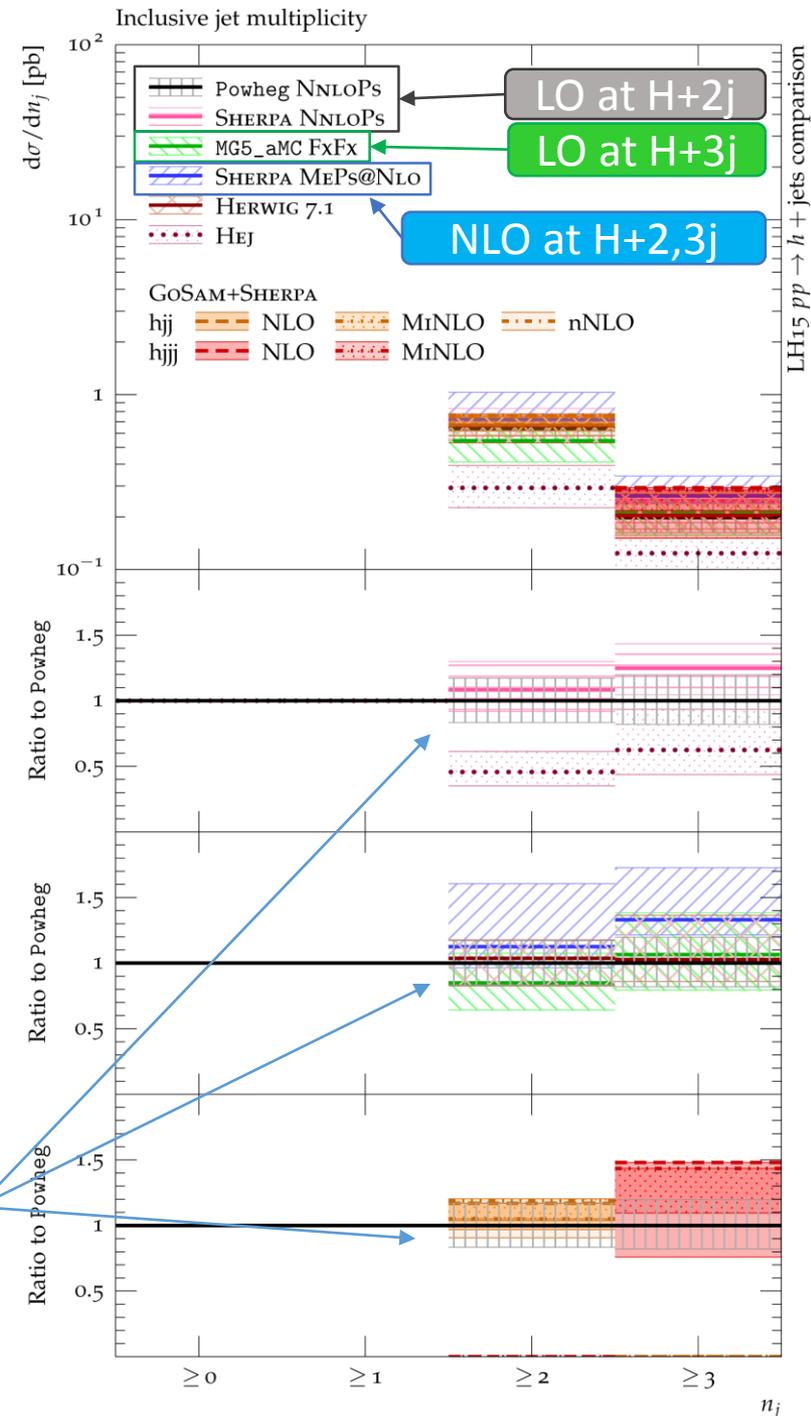
- Results from the LH2015 comparison
- Inclusive jet bins with VBF selection cuts

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

HOWEVER

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

Underestimation of the uncertainties in NNLOPS predictions!



Alternative jet tagging strategy: y instead of p_T

Usually:

- jets ordered by decreasing transverse momentum

p_T -tagging

What if we use rapidity?

- define two leading jets by the most forward/backward jets:
(subleading jets are the remaining ones ordered in p_T)

y -tagging

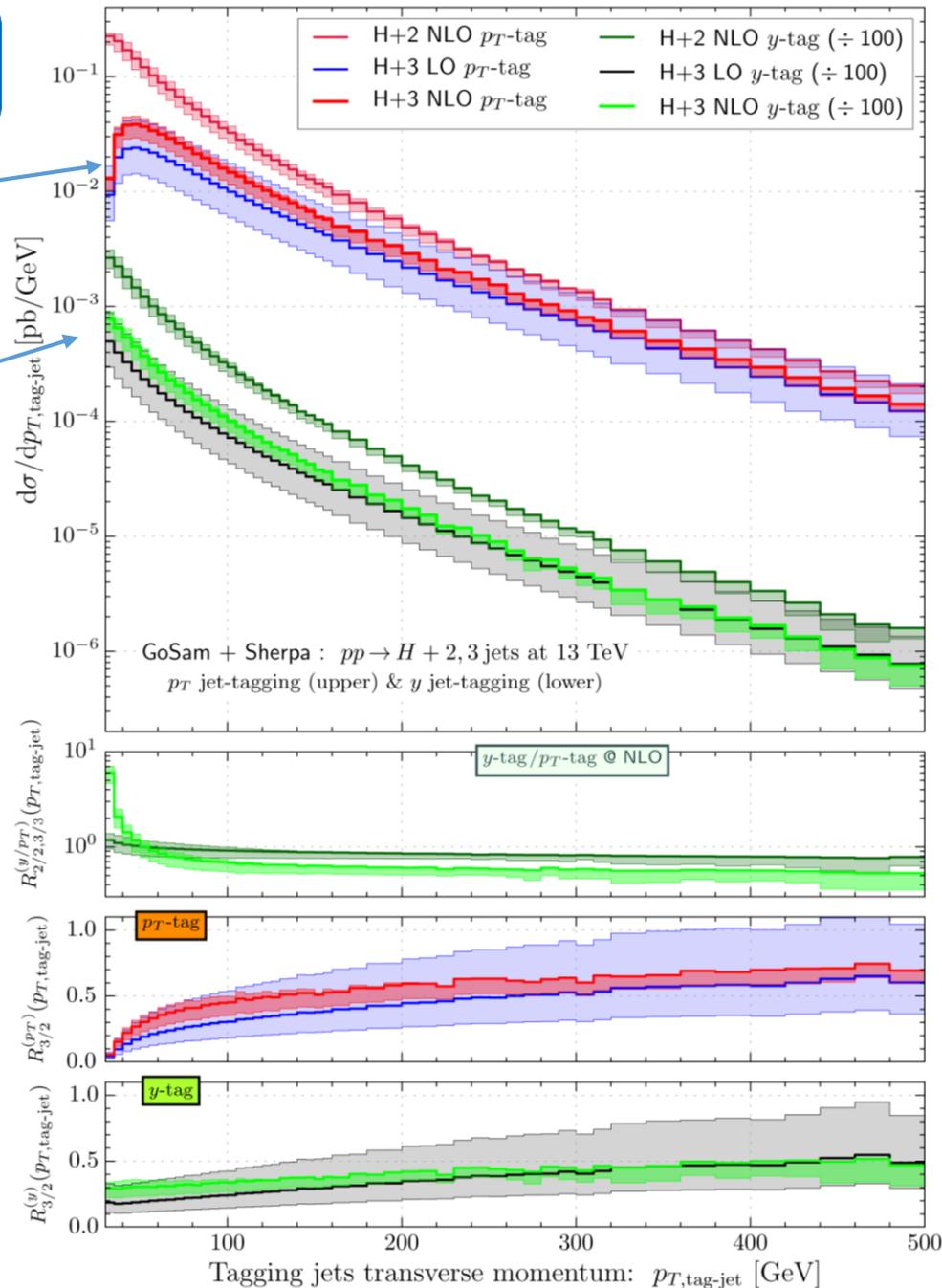


Alternative jet tagging

p_t -tagging

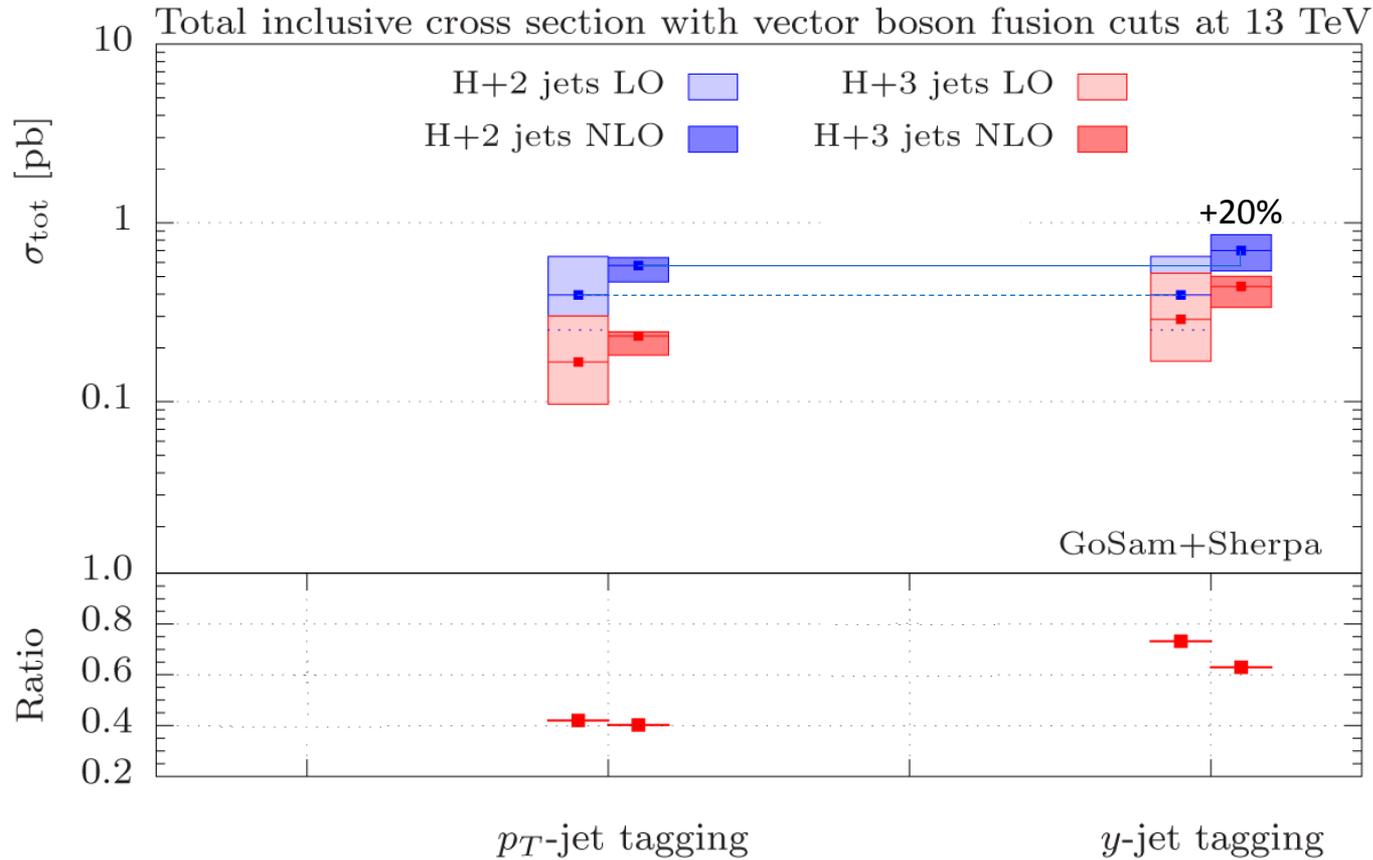
y -tagging

- Look at the **inclusive tagging jets transverse momentum**
- With increasing number of jets, two tagging schemes differ more
- Different behavior especially at low p_t



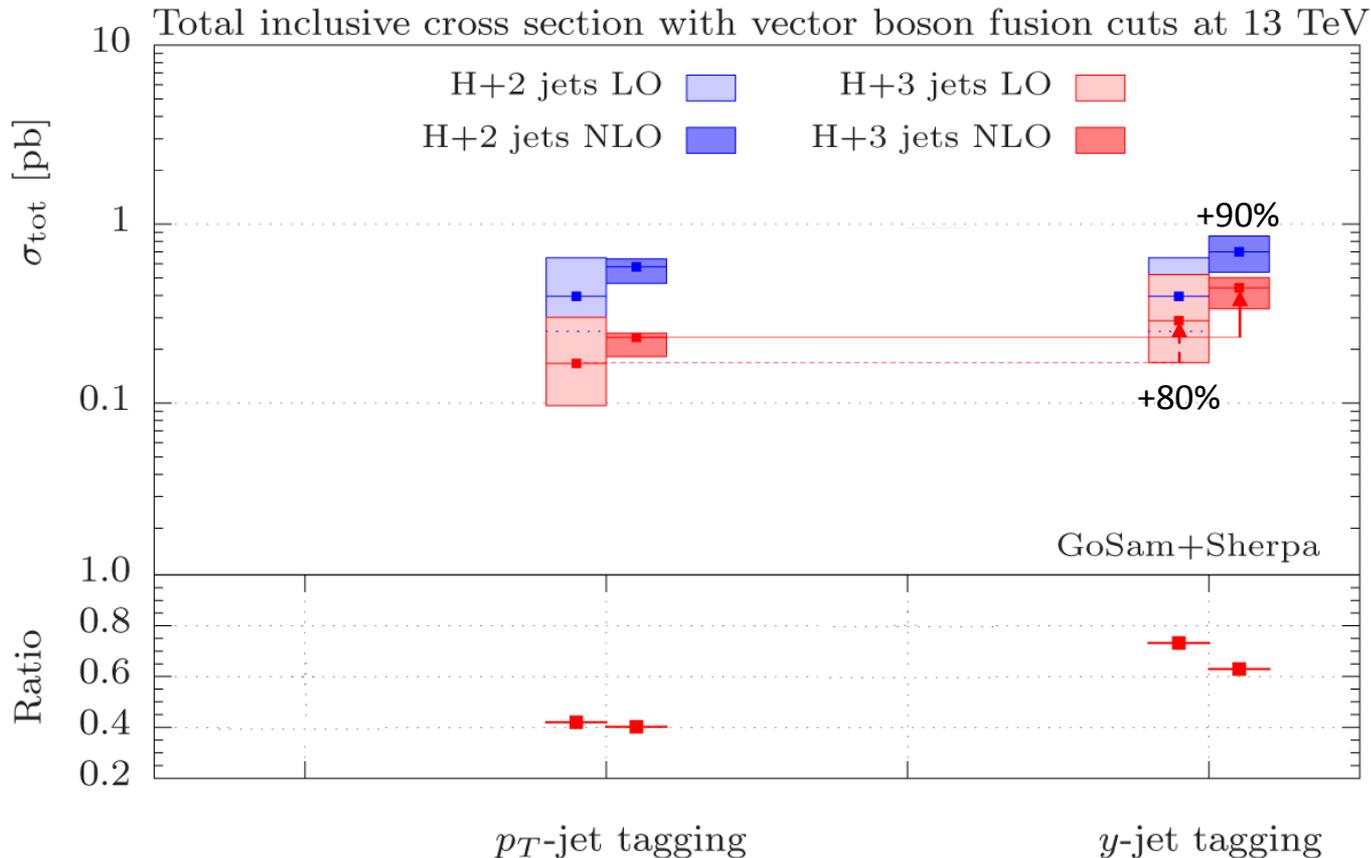
Alternative jet tagging: Total XS

- Total cross section:



Alternative jet tagging: Total XS

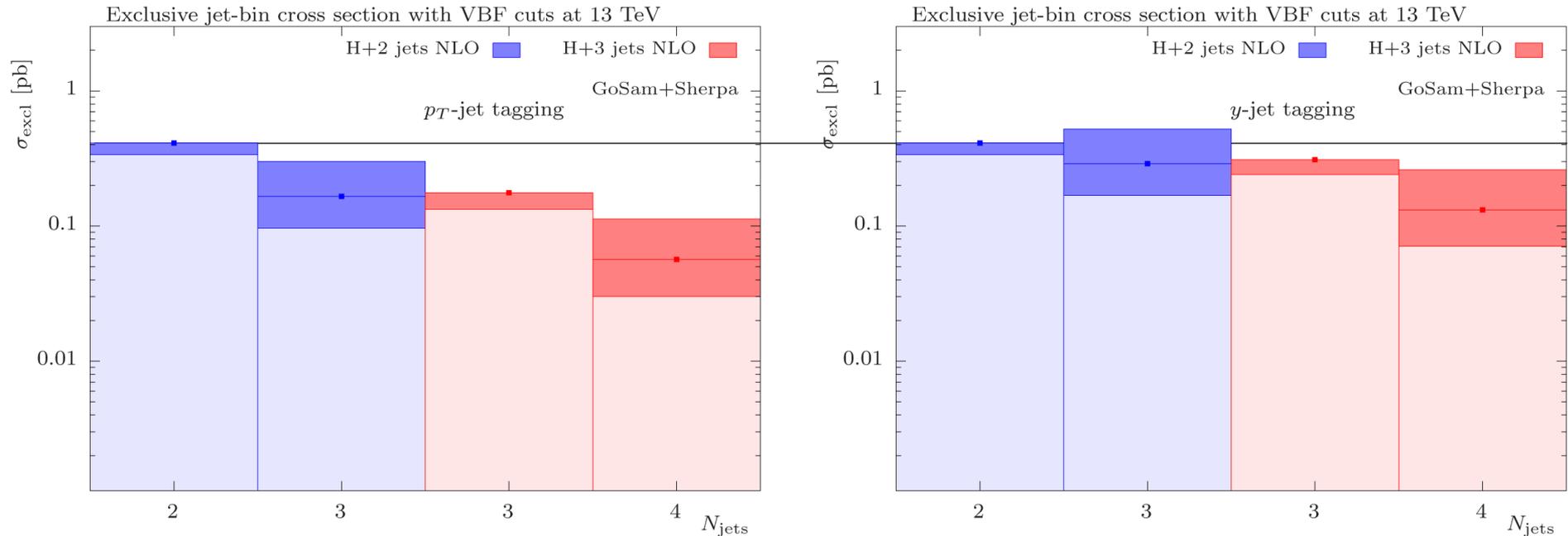
- Total cross section:



y -tagging **more sensitive to additional radiation:**
 - increase in XS | larger K-factors | larger $r_{3/2}$ ratio



Alternative jet tagging: exclusive jet bins

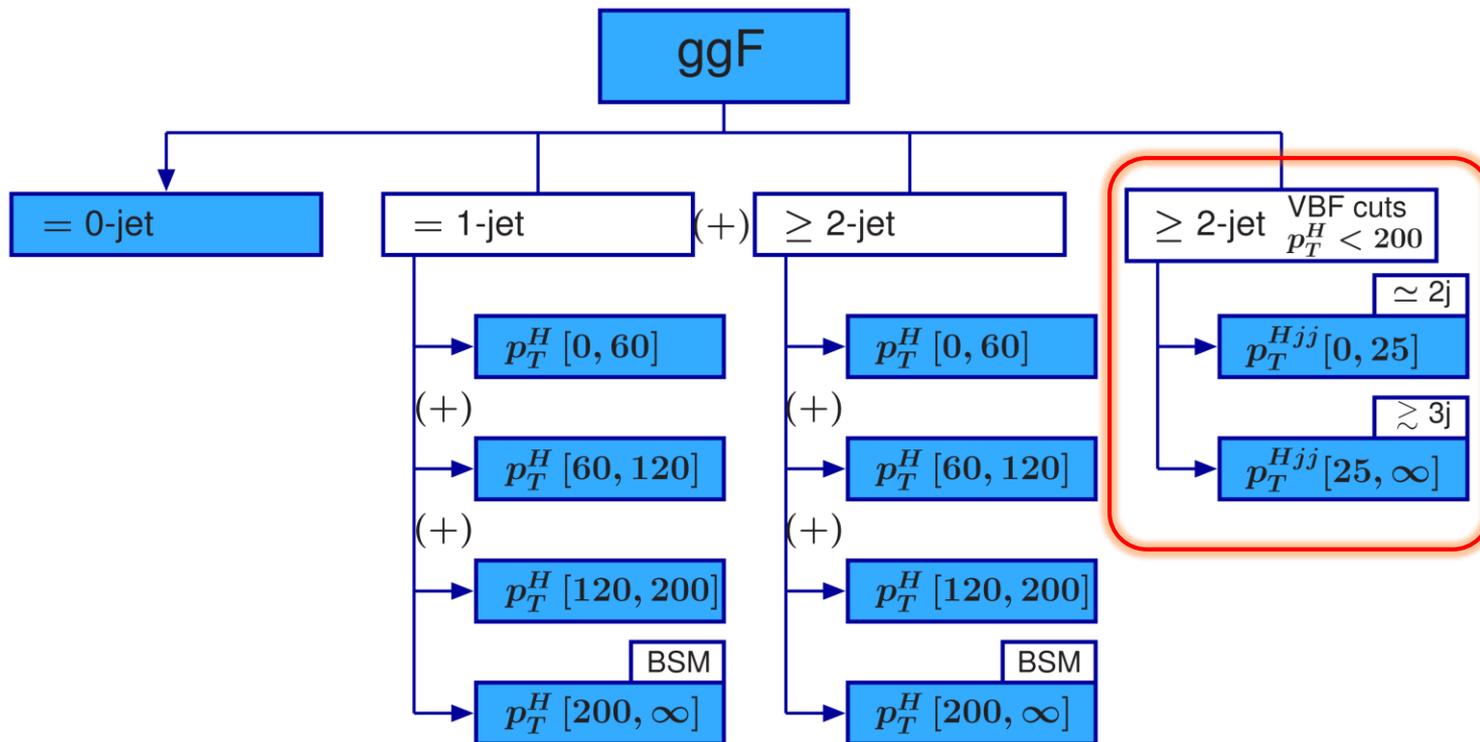


- VBF cuts enhance real radiation contribution (y -tagging even more)
 - larger portion of total XS described with LO accuracy if using H+2j @ NLO only
 - H+3j NLO needed for accurate 3 jet prediction and exclusive H+2j XS



Alternative jet tagging: can this help

- Despite larger scale uncertainties **y-tagging might reduce GGF contribution** to H+2 jets vbf bin, being more sensitive to additional radiation
 - How big are scale uncertainties? How does this depend on the scale choice?
 - Further investigation could be worth!



Conclusions

- Higher order QCD corrections to Higgs boson production in association with jets in ggF are **large** and also the effect of larger multiplicities (>2 jets) on rather inclusive observables needs **to be considered** in order to reach a good theoretical accuracy
- VBF fiducial cuts **increase sensitivity** to additional 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!
- Alternative **y-tagging strategy**: can this help reducing the GGF contamination in the VBF signal?
- Not touched:
 - Depending on the kinematical cuts (especially p_T requirements), **mass effects** may (will) play a **major role** in differential distributions
 - VBF selection cuts do not particularly enhance mass effects

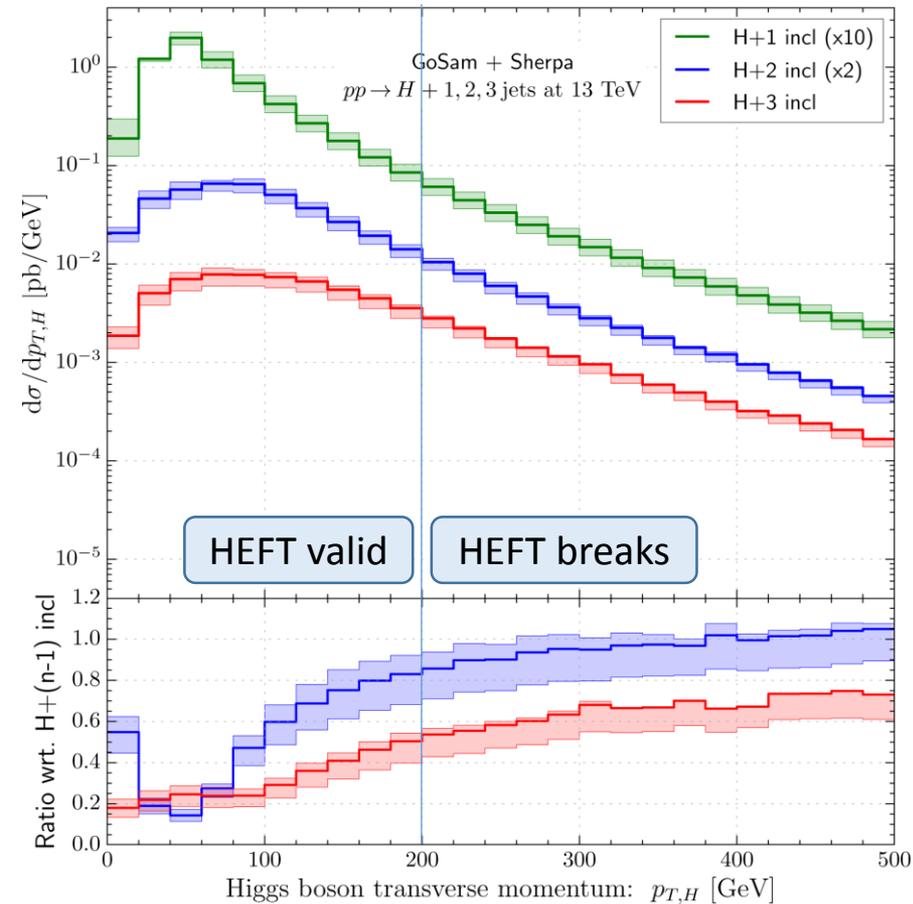


Backup

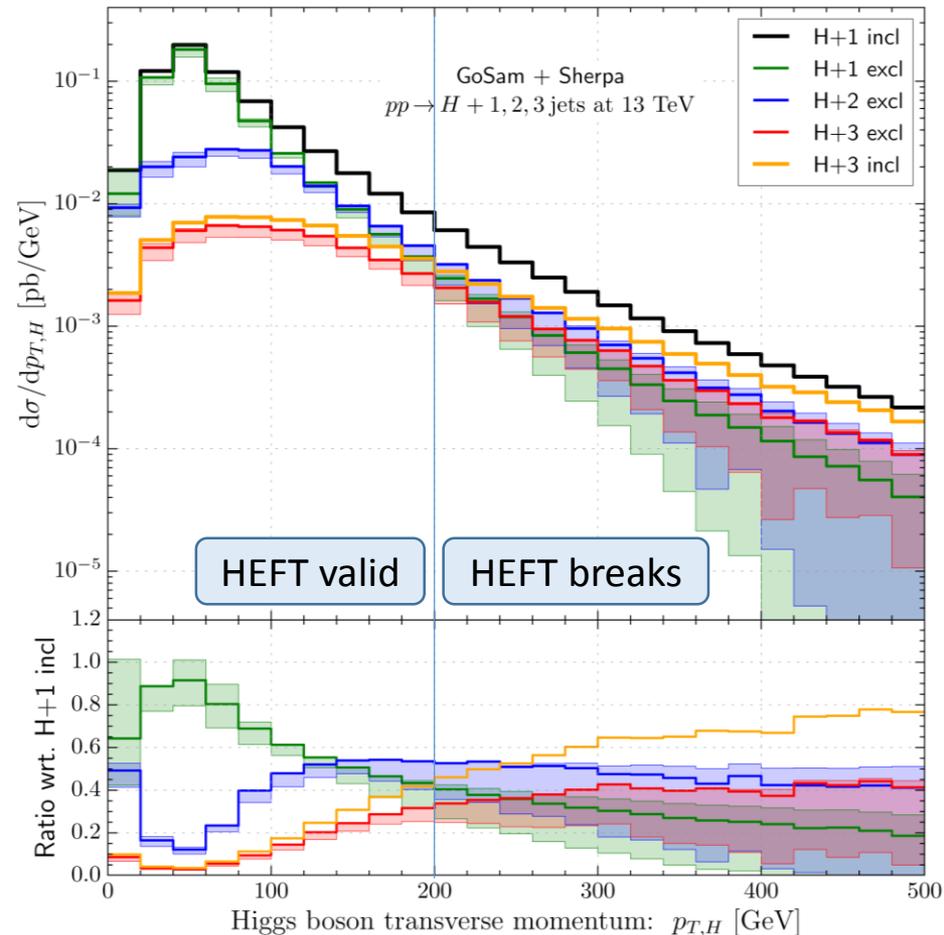


Higgs p_T spectrum: H+2/3 jets contributions

INCLUSIVE



EXCLUSIVE

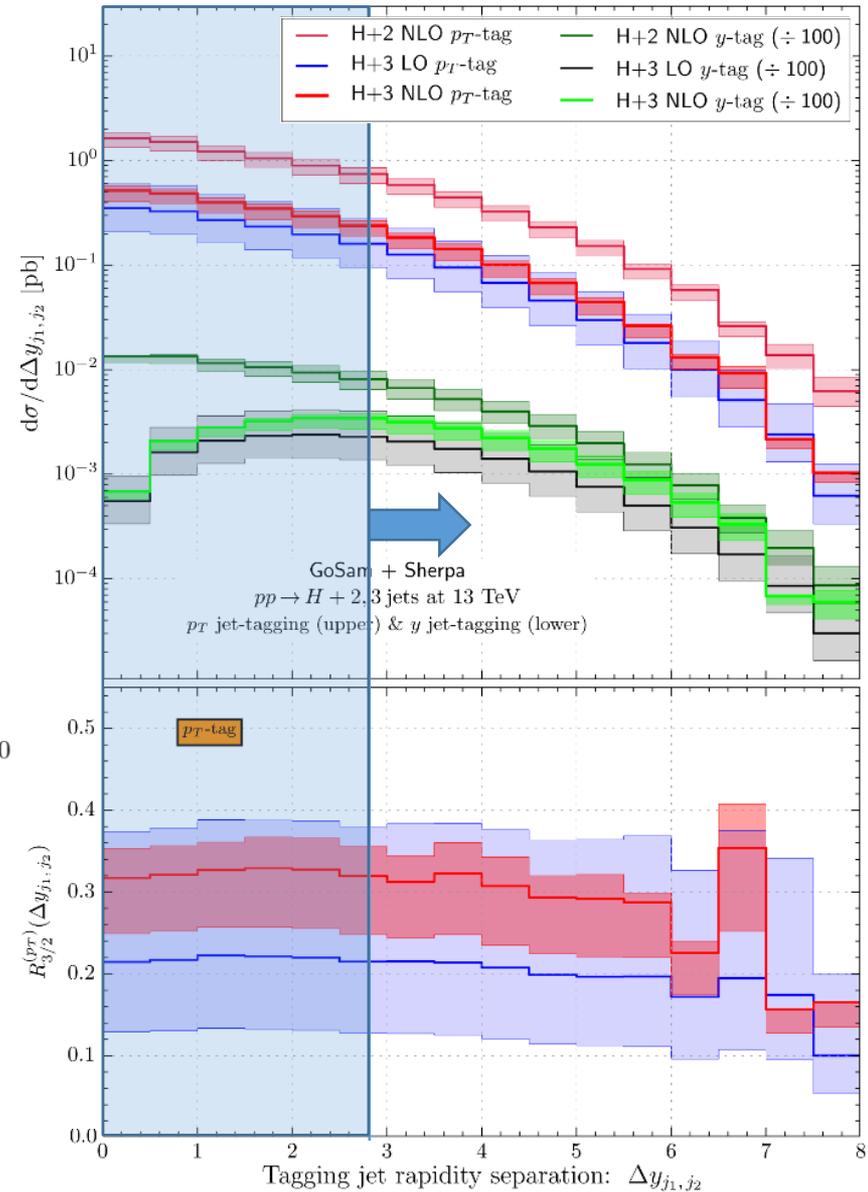
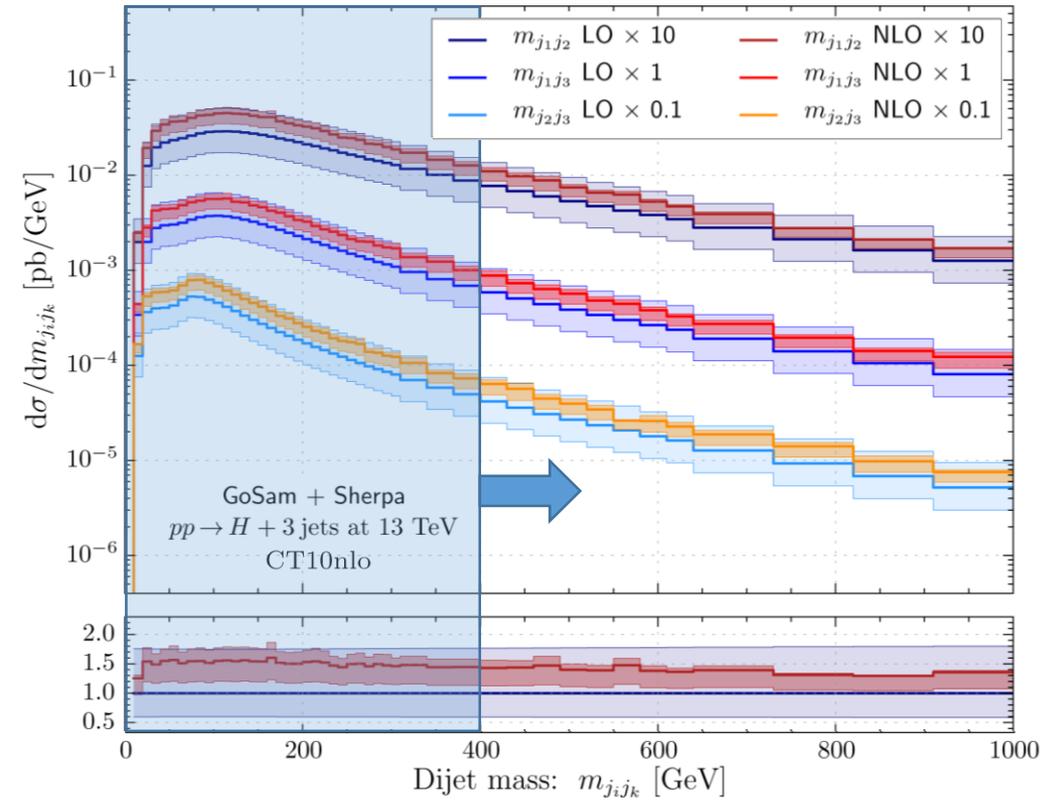


Around 200 GeV (where HEFT is still reliable):

- 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



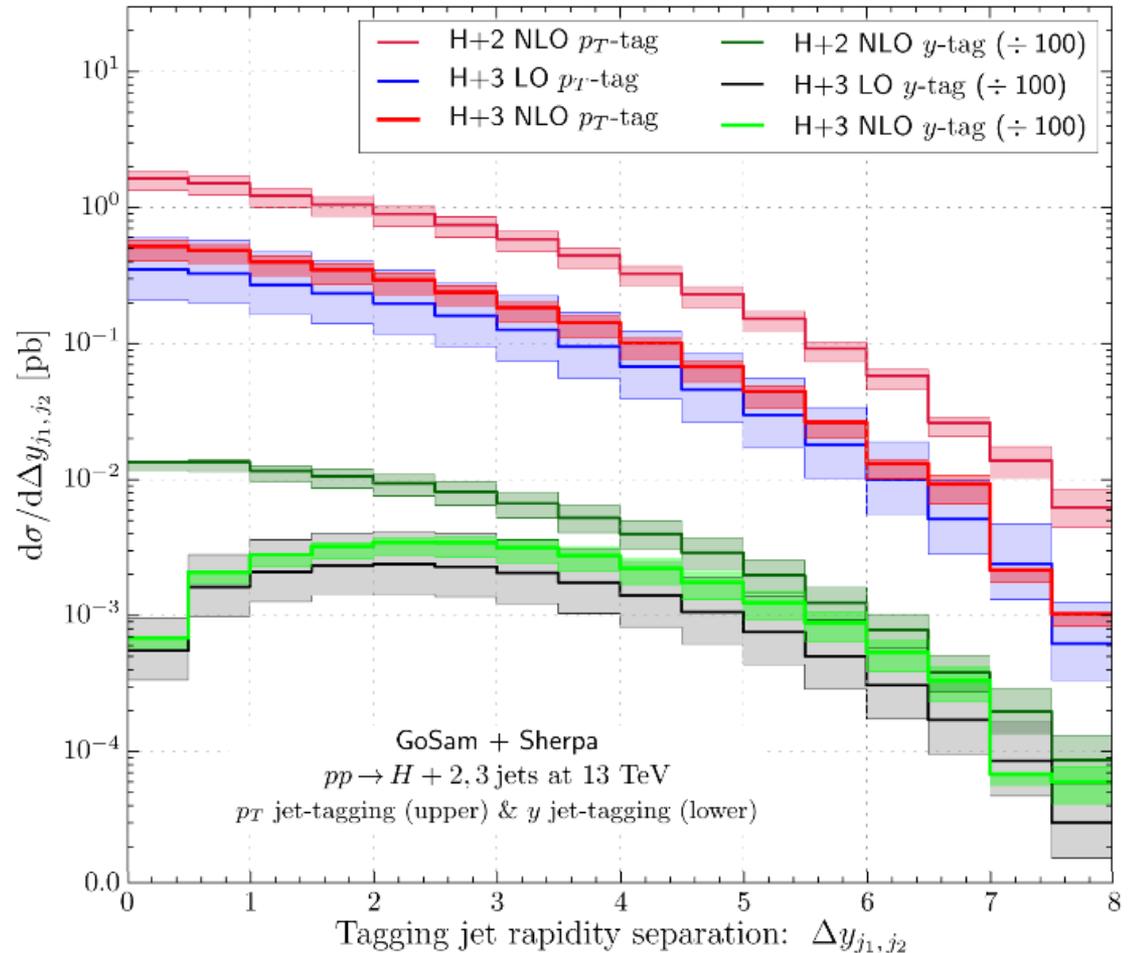
Relation between baseline and VBF selection cuts can be inferred from $m_{j_1 j_2}$ and $\Delta y_{j_1 j_2}$ distributions



High energy limit

- Using a **y-tagging** strategy allows us to investigate universal QCD properties in high-energy limit

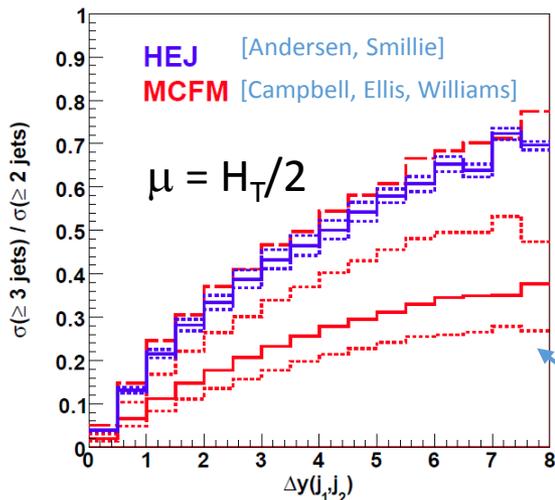
- Again: different tagging has larger impact on high multiplicity
- y-tagging leads to a shift towards larger rapidity differences



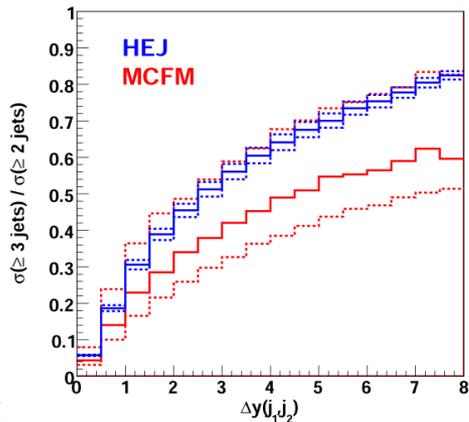
- To which extend can NLO computation describe high-energy effects?
- How does this look like at 100 TeV?

[Report of the Snowmass 2013 energy frontier QCD working group, 1310.5189]

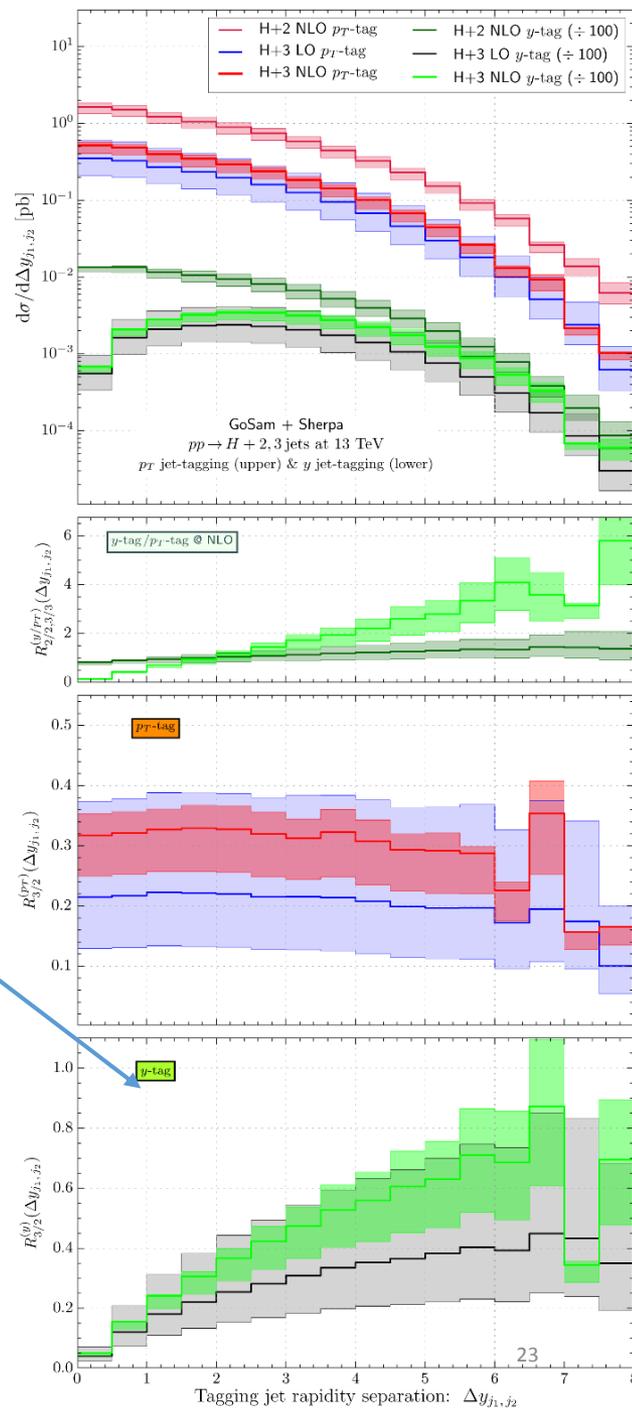
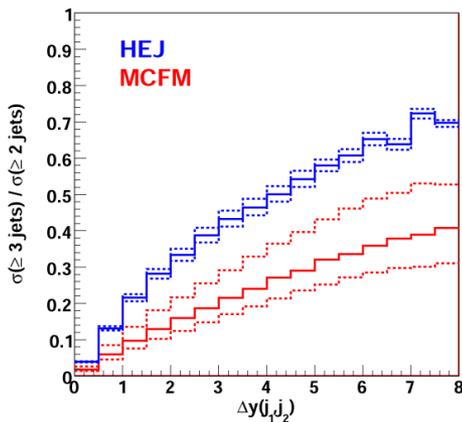
H+2 jets: $\sqrt{s}=14$ TeV, $p_T^{\text{jet}} > 40$ GeV



H+2 jets: $\sqrt{s}=100$ TeV, $p_T^{\text{jet}} > 40$ GeV



H+2 jets: $\sqrt{s}=100$ TeV, $p_T^{\text{jet}} > 160$ GeV

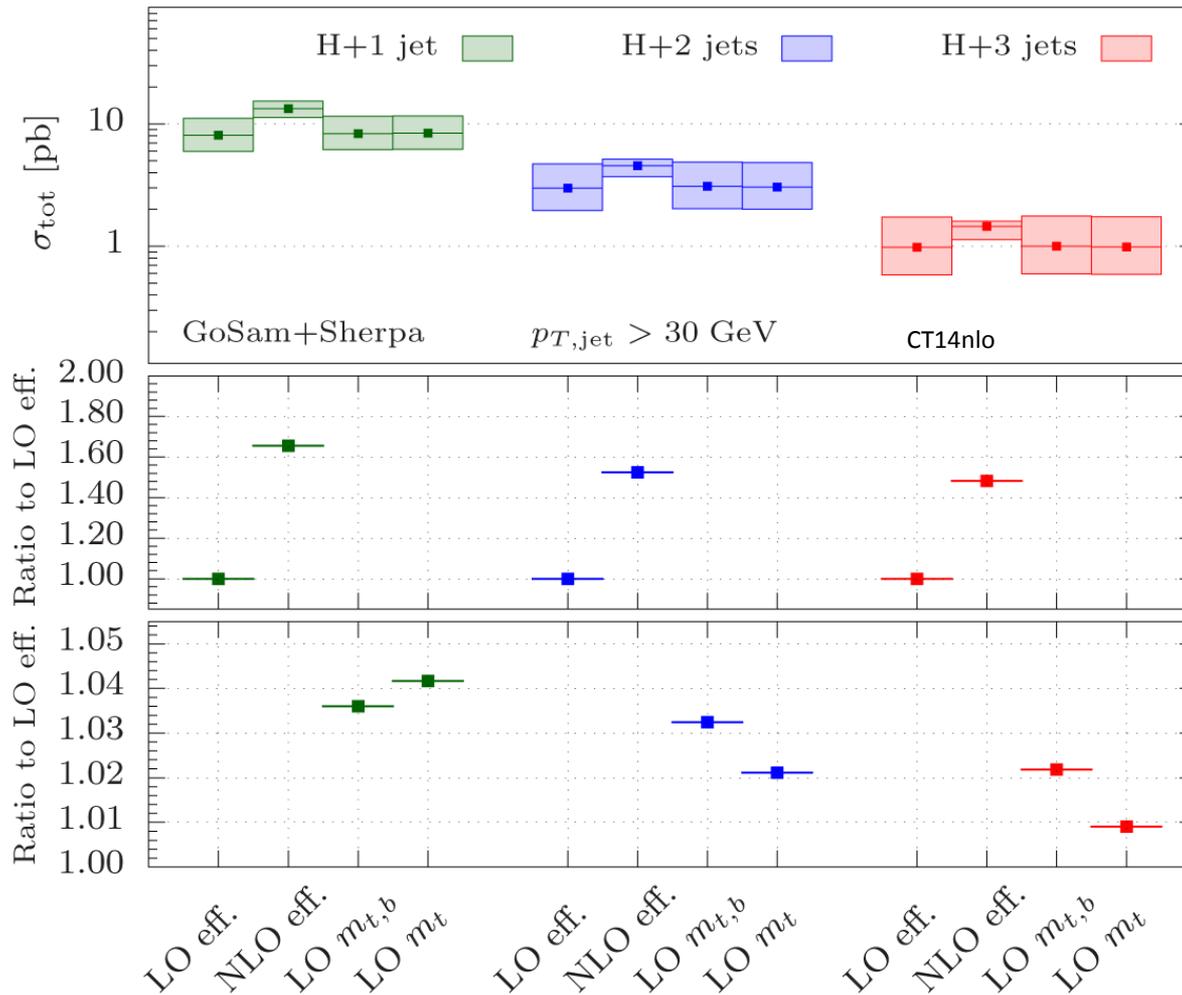


Finite mass effects



Total cross section: 13 TeV

Total inclusive cross section with gluon fusion cuts at 13 TeV



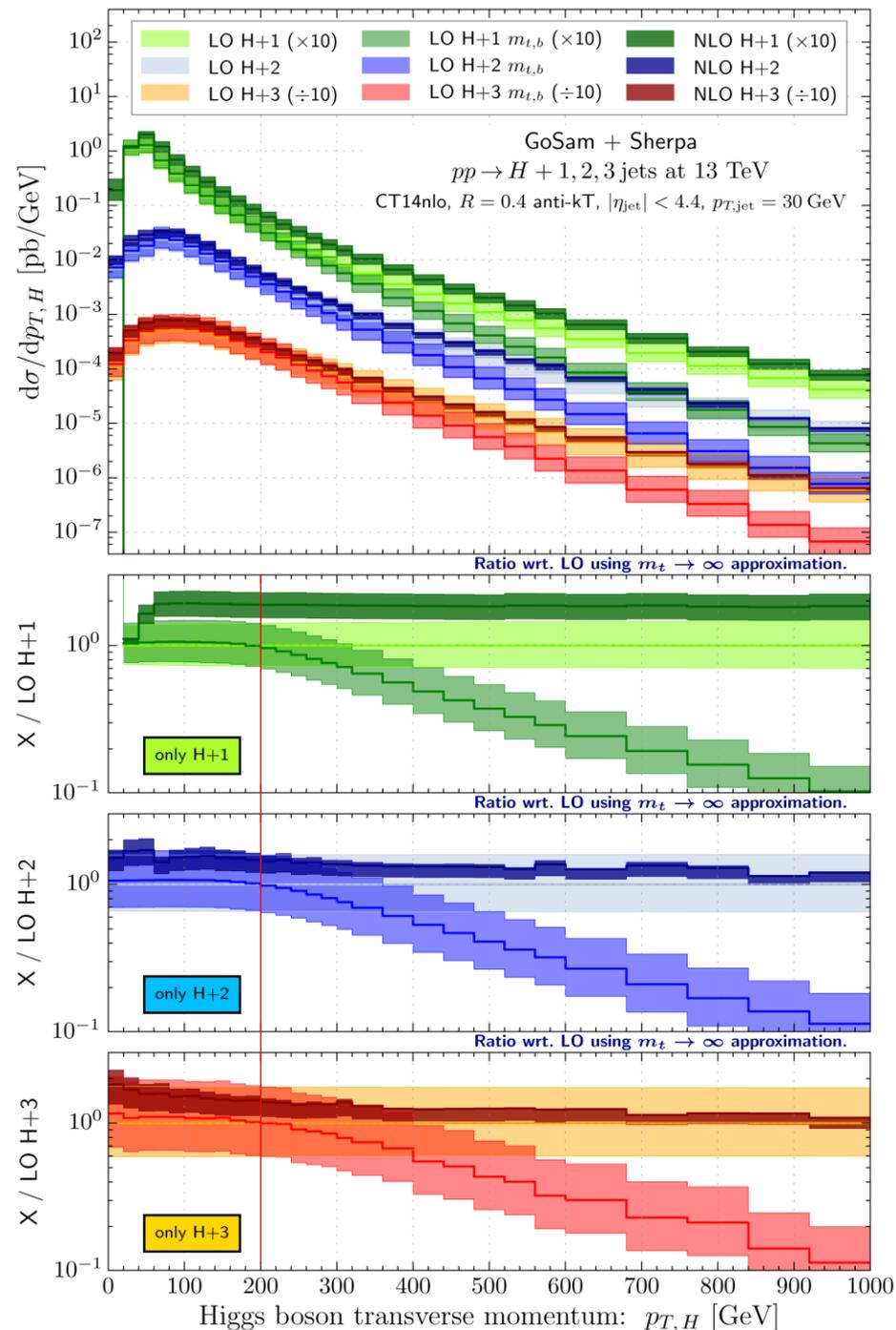
- Reduction of the size of NLO corrections for higher multiplicity
- Relative difference due to bottom-quark O(1%)
- Sign flip in corrections due to bottom-top quark interference
- Possibility to estimate NLO cross section with full mass dependence from K-factors



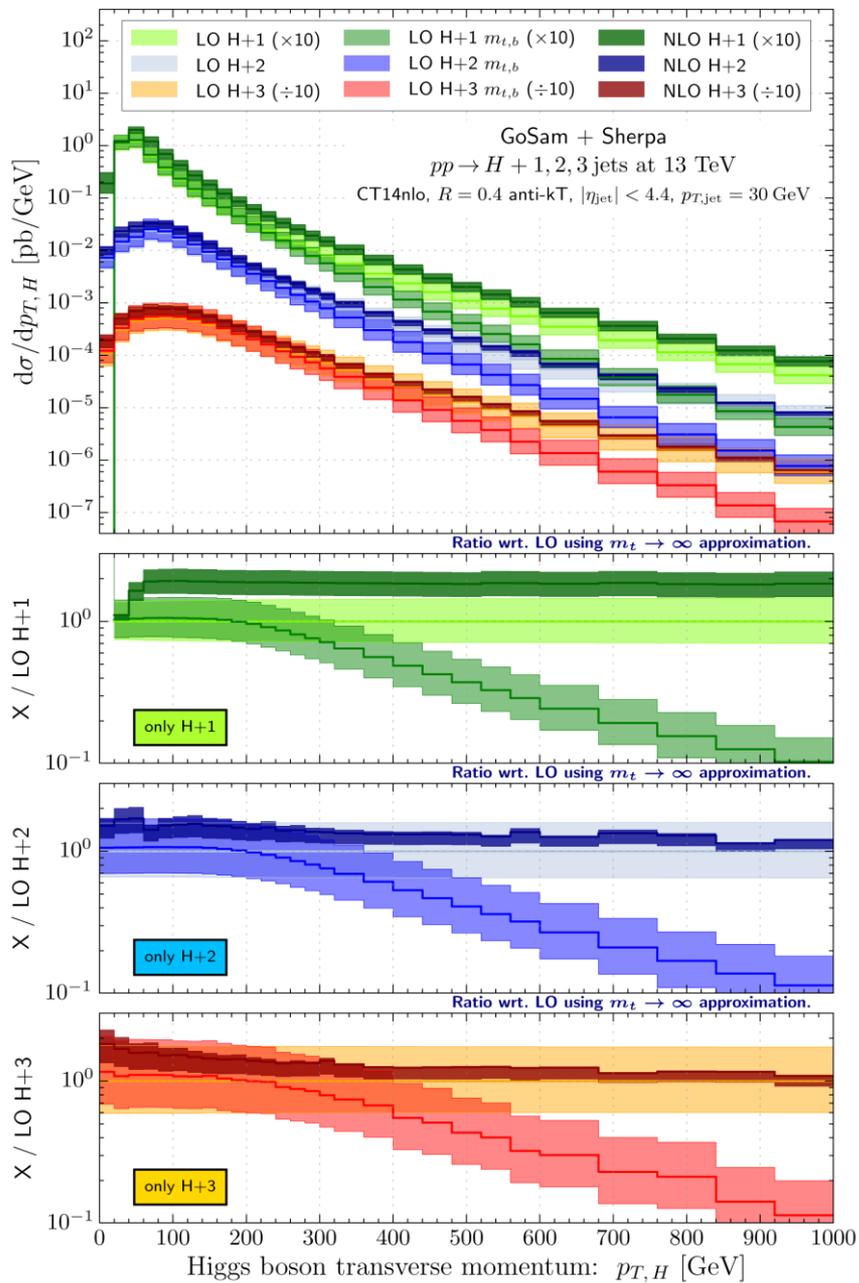
- $\sigma_{LO, m_{t,b}}$: top- and bottom-quark loops
- σ_{LO, m_t} : top-quark loops only

Higgs boson p_T

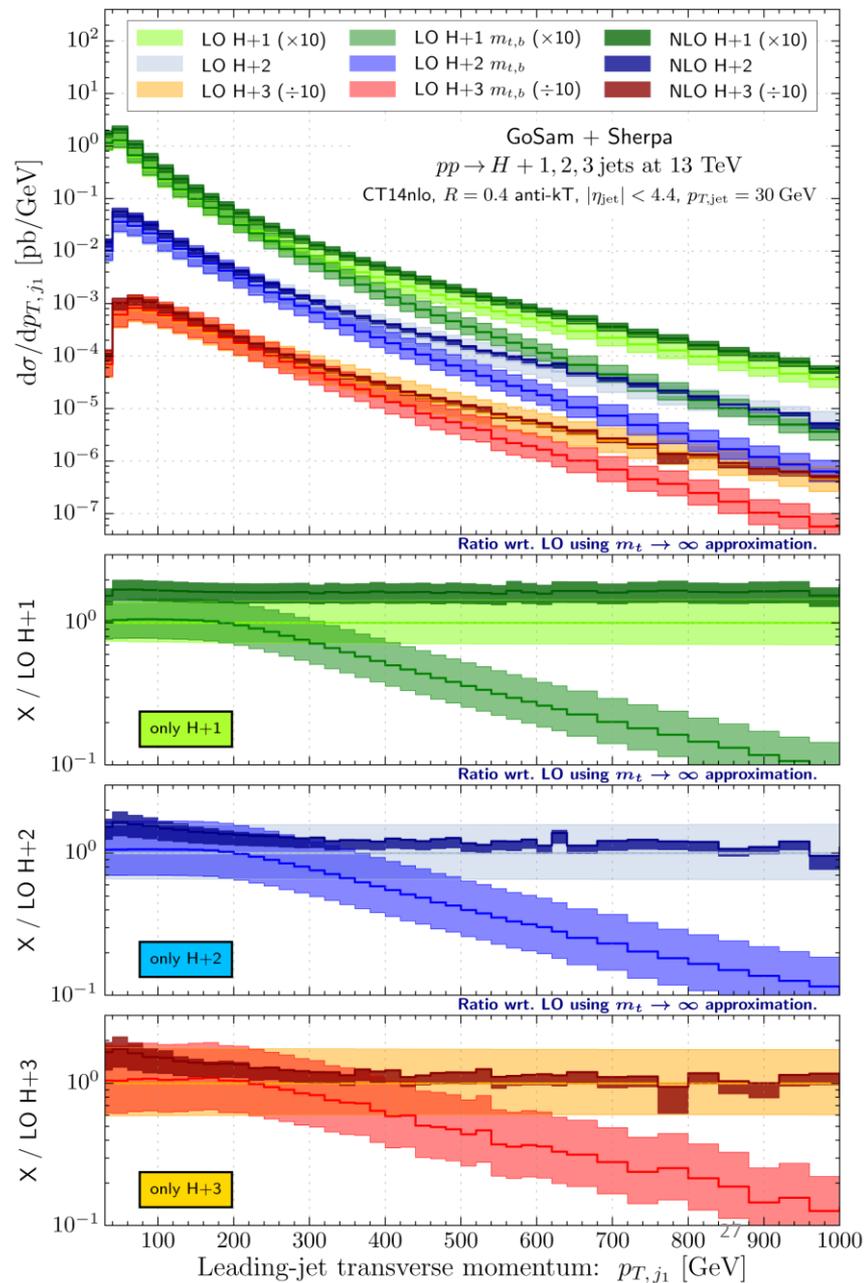
- Transverse momentum related observables known to receive significant corrections
- Effective theory starts to break down at $p_{T,H} \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.
- Very **similar** behavior for the three different multiplicities



Higgs pT:



Leading jet pT:

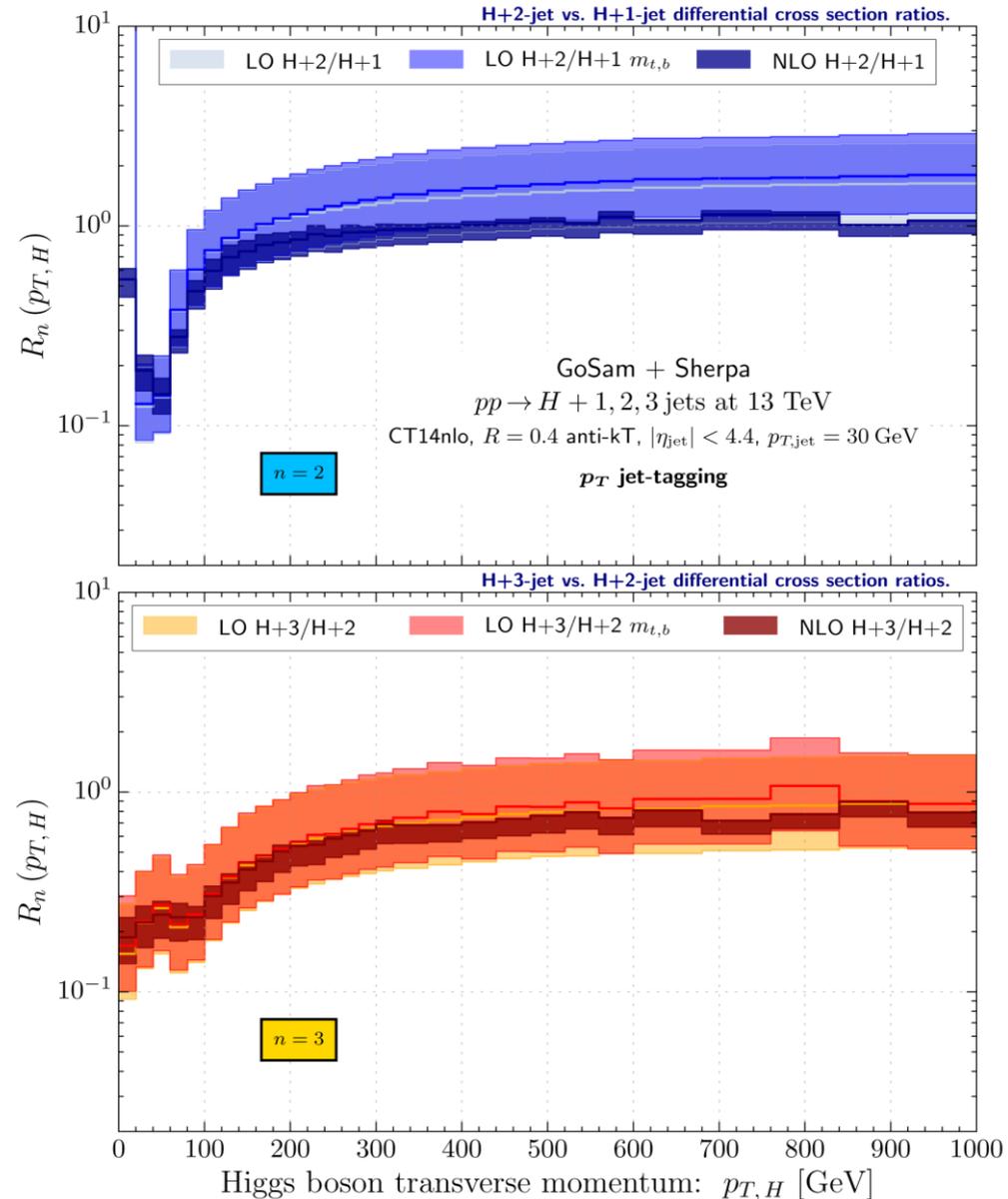


Higgs boson p_T

- Ratios of successive differential cross sections:

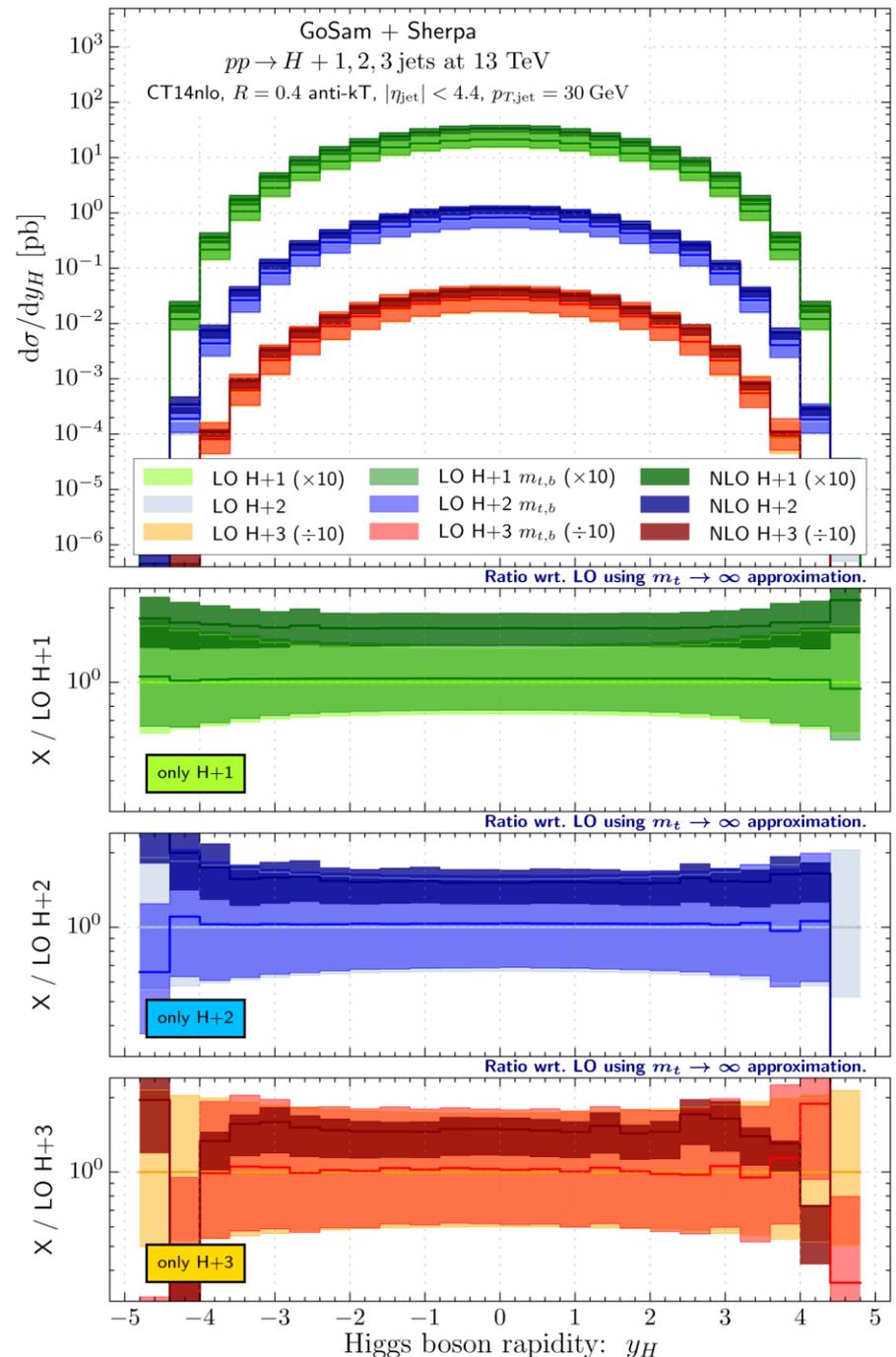
$$R_n(O) = \frac{\frac{d\sigma}{dO}(\text{H}+n \text{ jets})}{\frac{d\sigma}{dO}(\text{H}+(n-1) \text{ jets})}$$

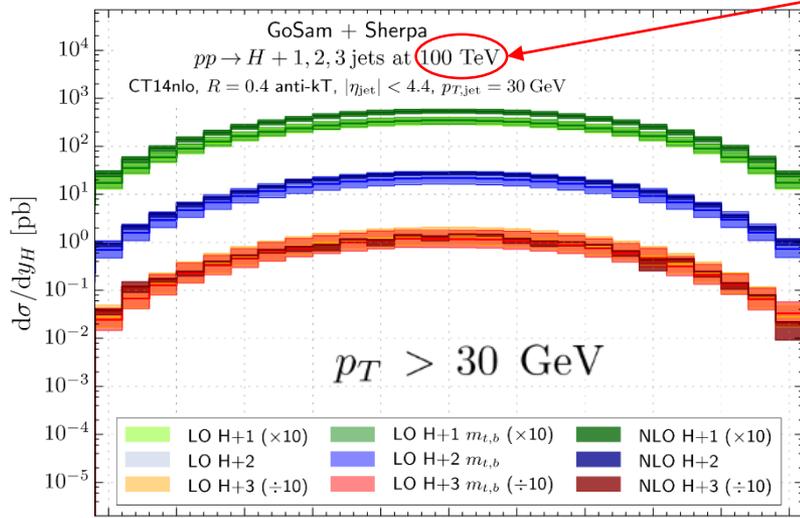
- relative importance of higher multiplicities remains stable under mass corrections



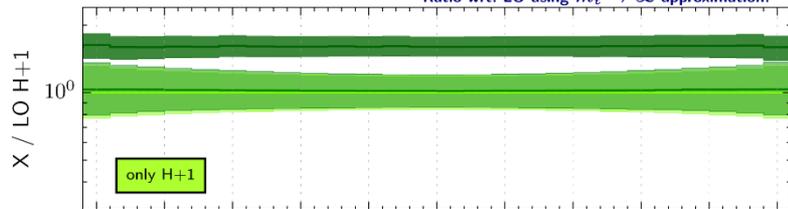
Higgs boson rapidity

- 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!

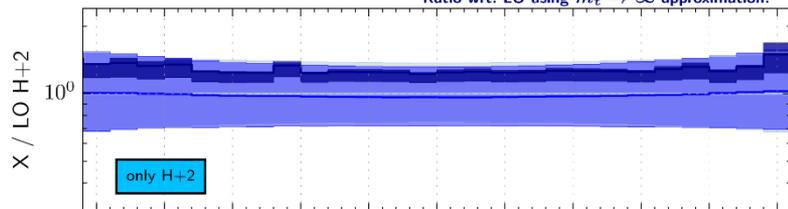




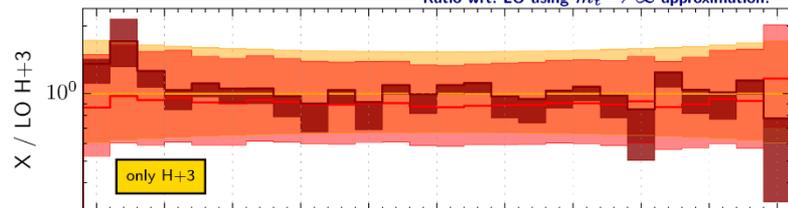
Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



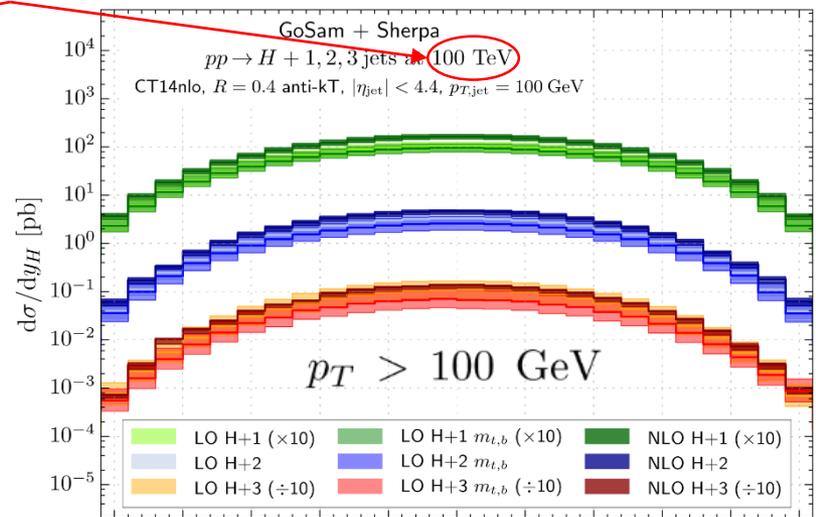
Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



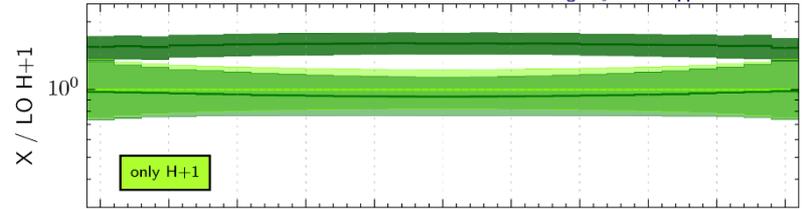
Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



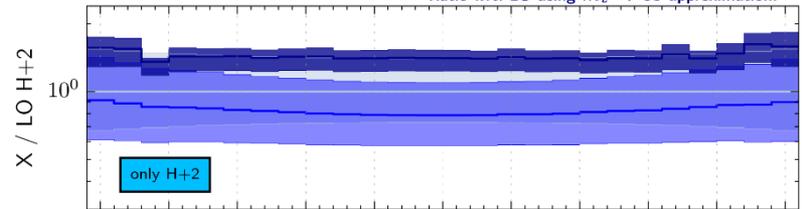
Higgs boson rapidity: y_H



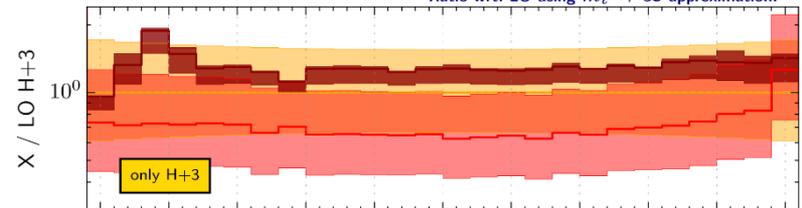
Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



Higgs boson rapidity: y_H

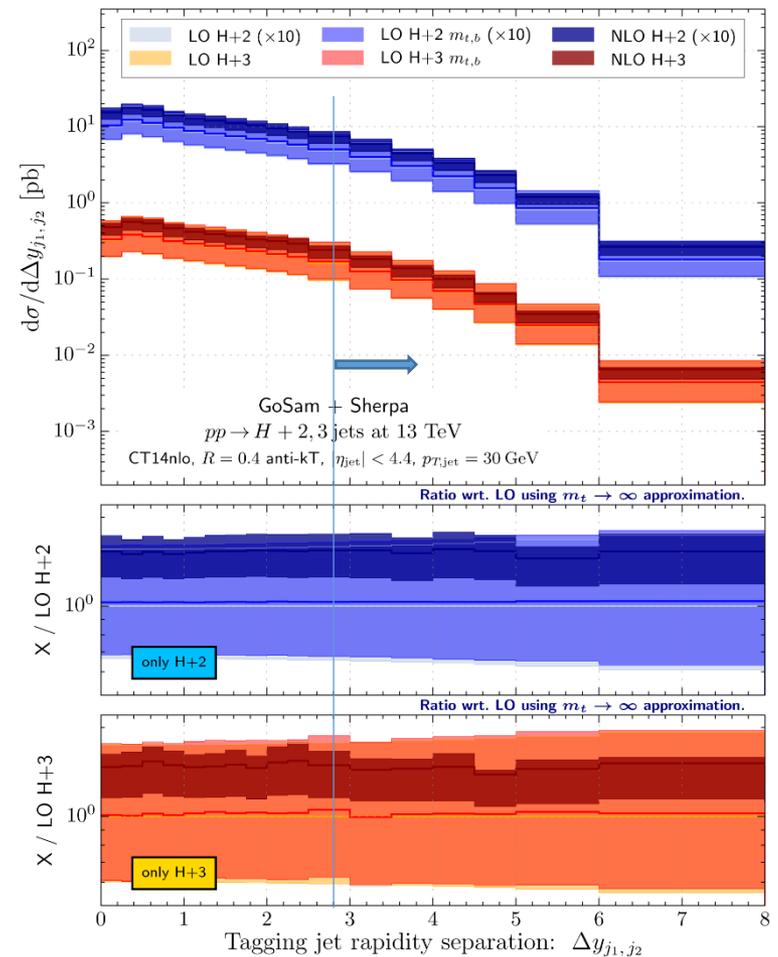
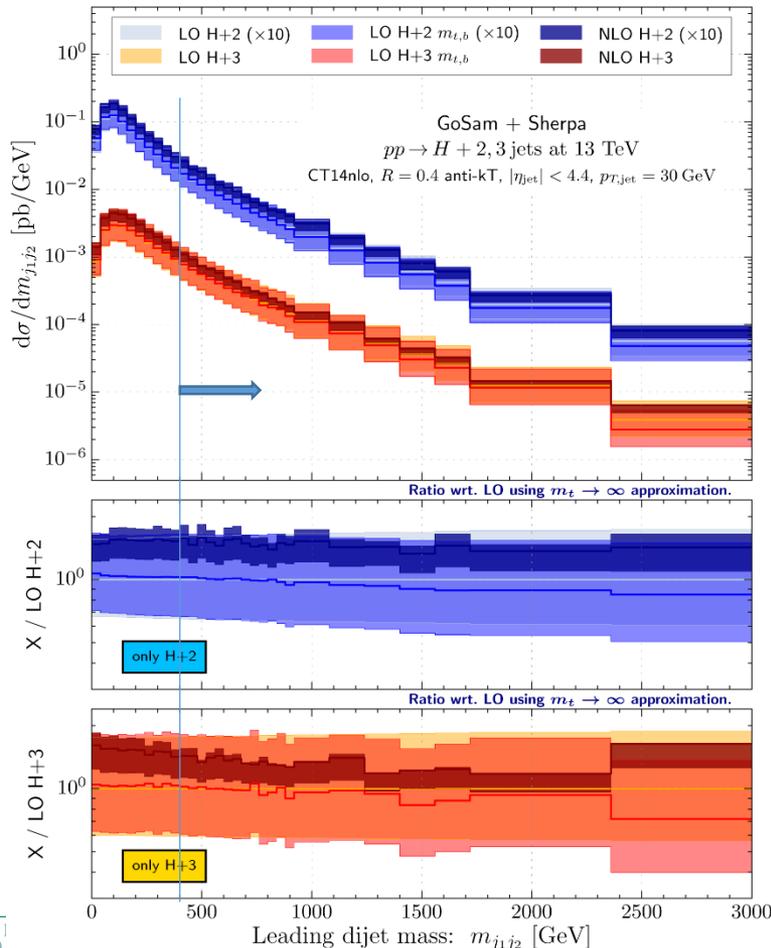
Regime in which HEFT breaks down is reached more easily when a harder p_T cut is imposed.
 Mass effects therefore become much more important!

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:

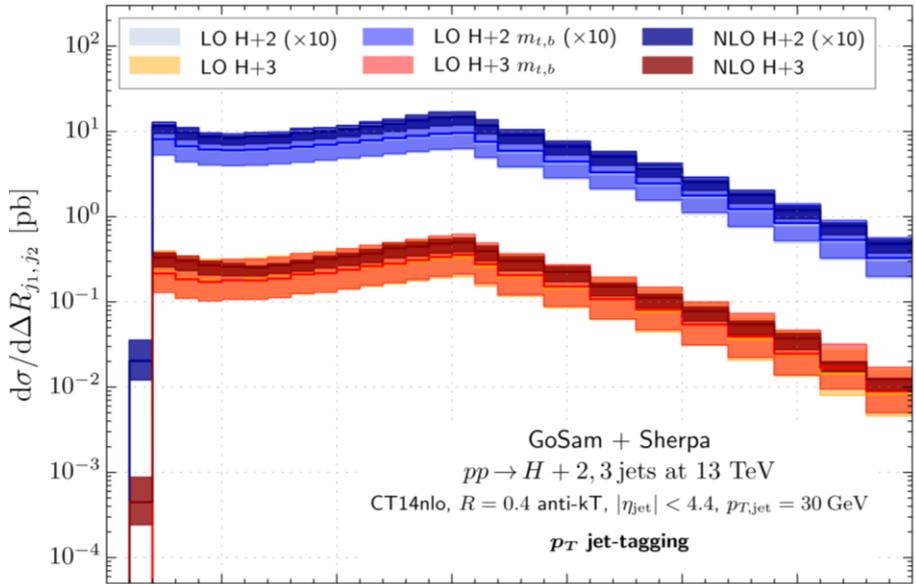
Numbers in [pb]	H+2 jets	H+3 jets
$\sigma_{\text{LO, eff.}}$	$0.397^{+64\%}_{-36\%}$	$0.166^{+82\%}_{-42\%}$
$\sigma_{\text{NLO, eff.}}$	$0.584^{+10\%}_{-19\%}$	$0.231^{+5\%}_{-22\%}$
$\sigma_{\text{LO, } m_{t,b}}$	$0.404^{+65\%}_{-37\%}$	$0.167^{+82\%}_{-42\%}$
$\sigma_{\text{LO, } m_t}$	$0.398^{+65\%}_{-37\%}$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

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

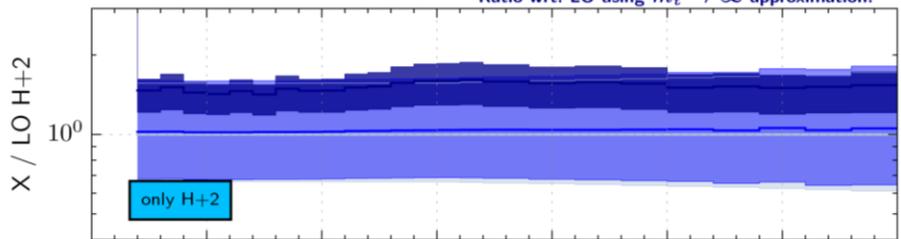


Radial distance between tagging jets

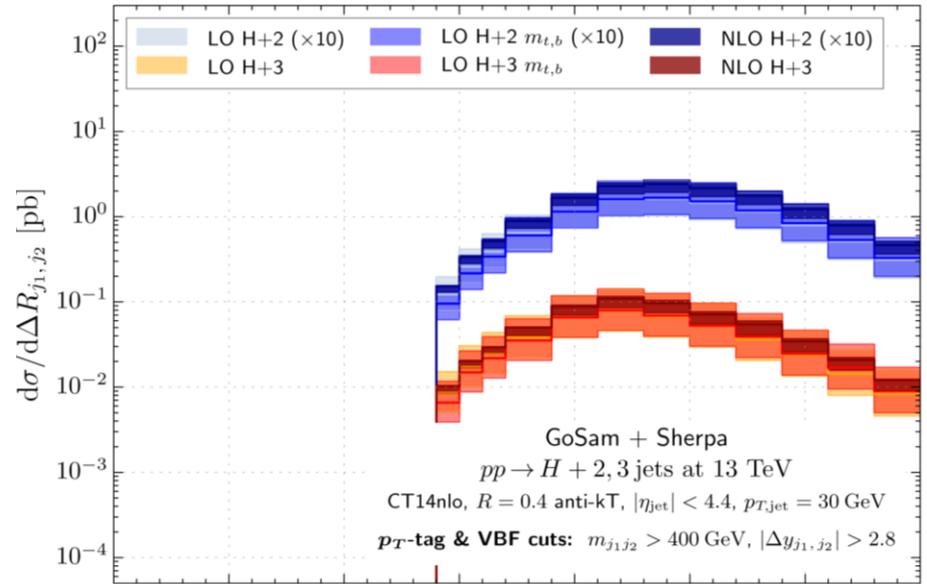
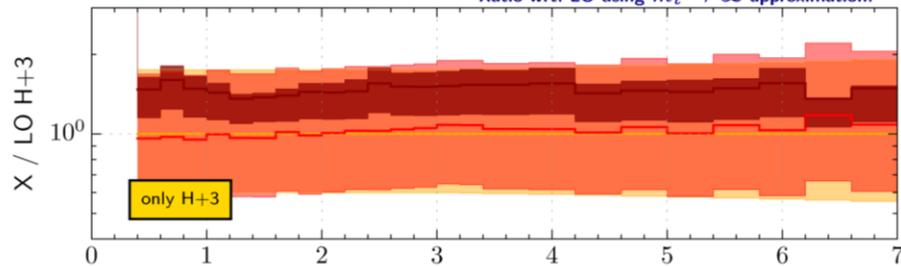
- Effects of VBF selection cuts wrt. baseline cuts:



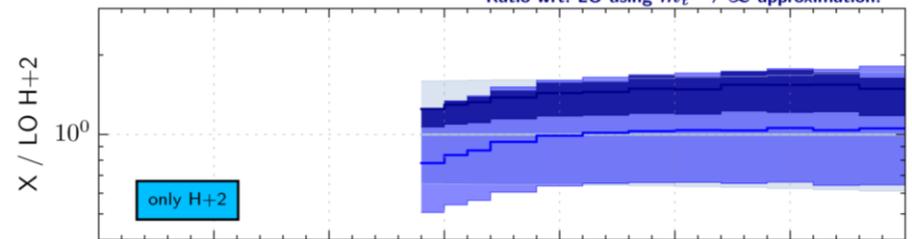
Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



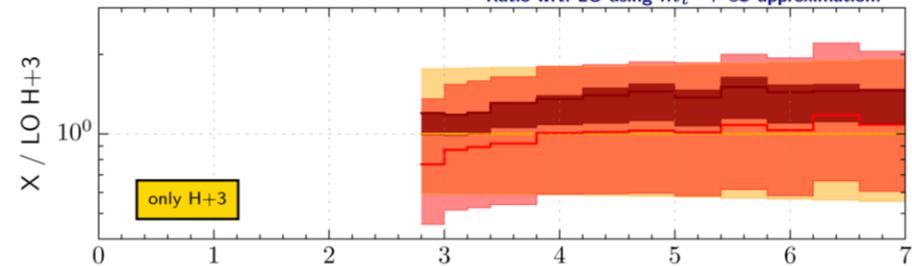
Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



Ratio wrt. LO using $m_t \rightarrow \infty$ approximation.



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%
 - primarily 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

