Predictions for GGF with VBF topology

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Higgs Cross section WG1 Meeting

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In collaboration with:

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

Outline

- **Computational setup**
- **Impact of VBF selection cuts**
- **Finite mass effects on Higgs pT and after VBF selection cuts**
- **Conclusions and outlook**

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://eospublic.cern.ch/eos/theory/project/GoSam

eos.web.cern.ch
Large Disk Storage at CERN

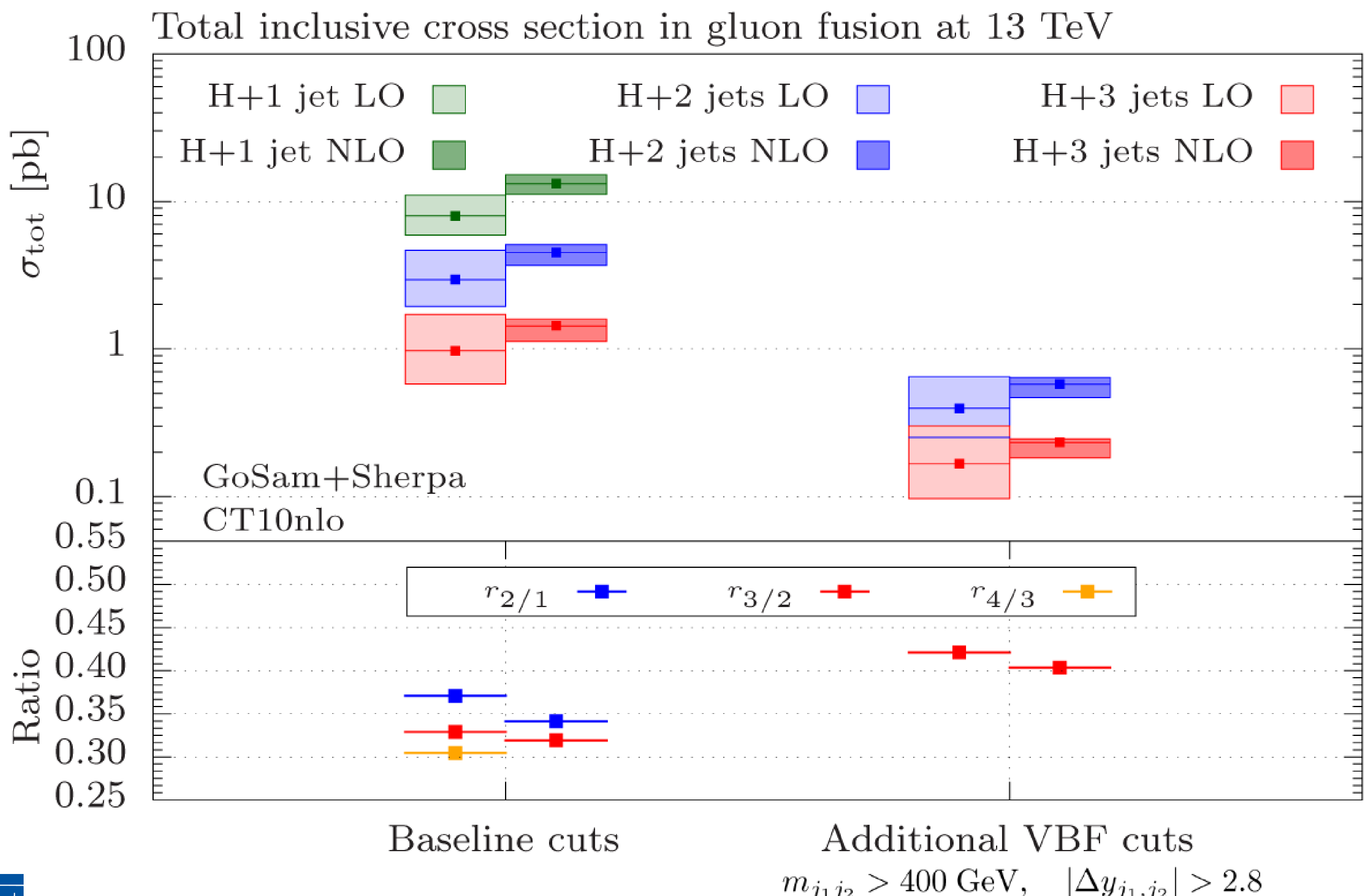
Physical setup

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

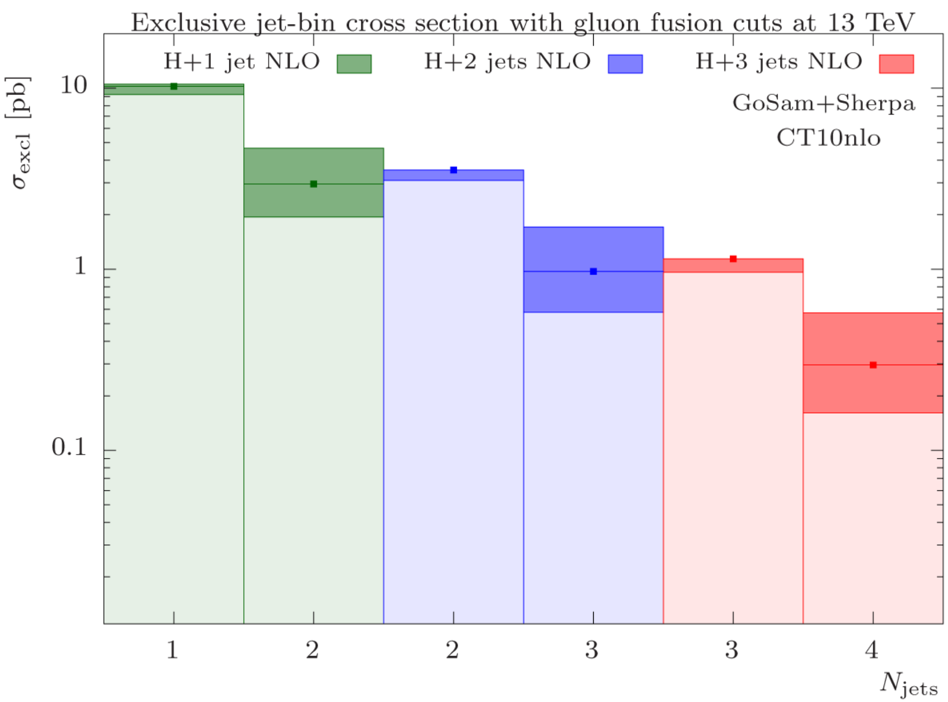
- scale choice: $\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\rm H}^2 + p_{T,\rm H}^2} + \sum_i |p_{T,i}|\right)$
- PDFs: CT10nlo or CT14nlo (see the single plots for details)
- masses: $m_H = 125.0 \text{ GeV}, \quad m_t = 172.3 \text{ GeV}, \quad m_b(m_H) = 3.38 \text{ GeV}$
- **Baseline cuts:** anti-kt with $p_T > 30 \text{ GeV}, \quad |\eta| < 4.4$
- **Additional VBF cuts**: $m_{j_1 j_2} > 400 \text{ GeV}, \quad |\Delta y_{j_1,j_2}| > 2.8$

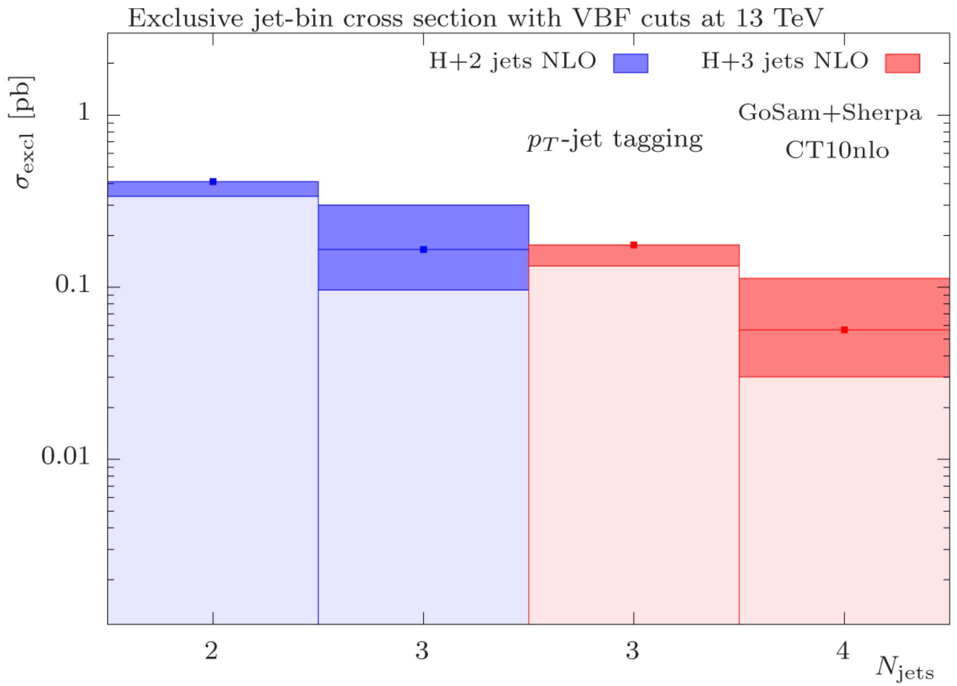
- Remark: basic Ntuples sets have events with $p_T > 25 \text{ GeV}, \; |\eta| < 4.5$ for the jets at the generation level

Total cross section at 13 TeV



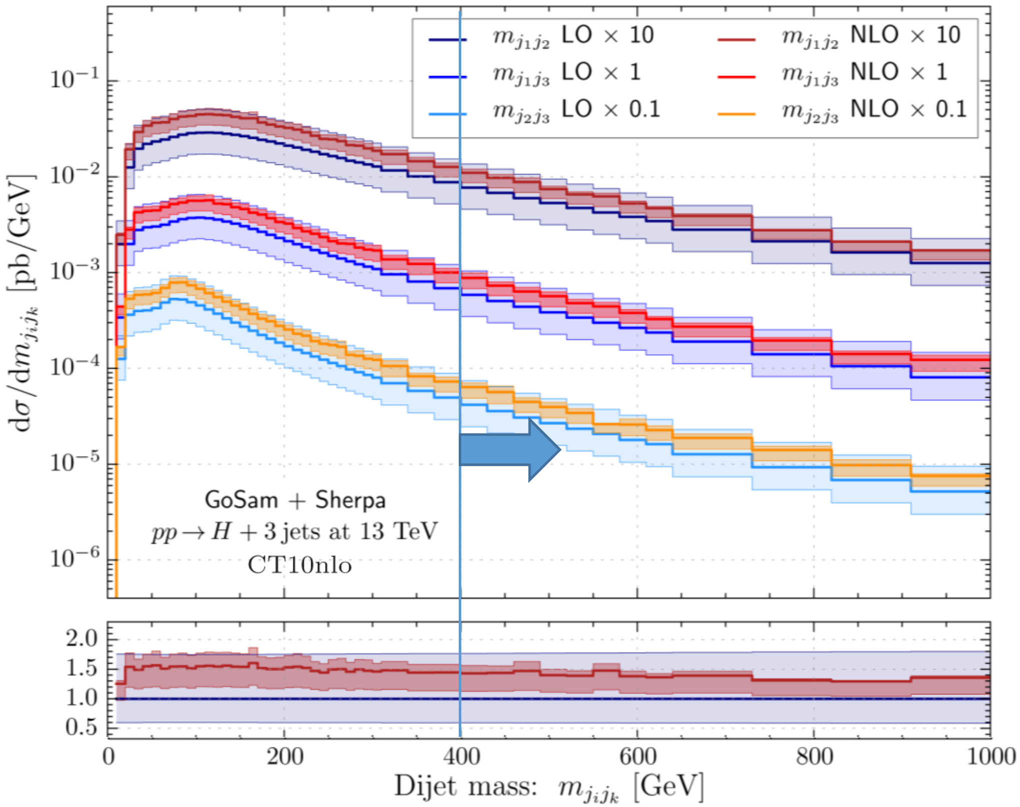
Total cross section at 13 TeV: exclusive jet bins

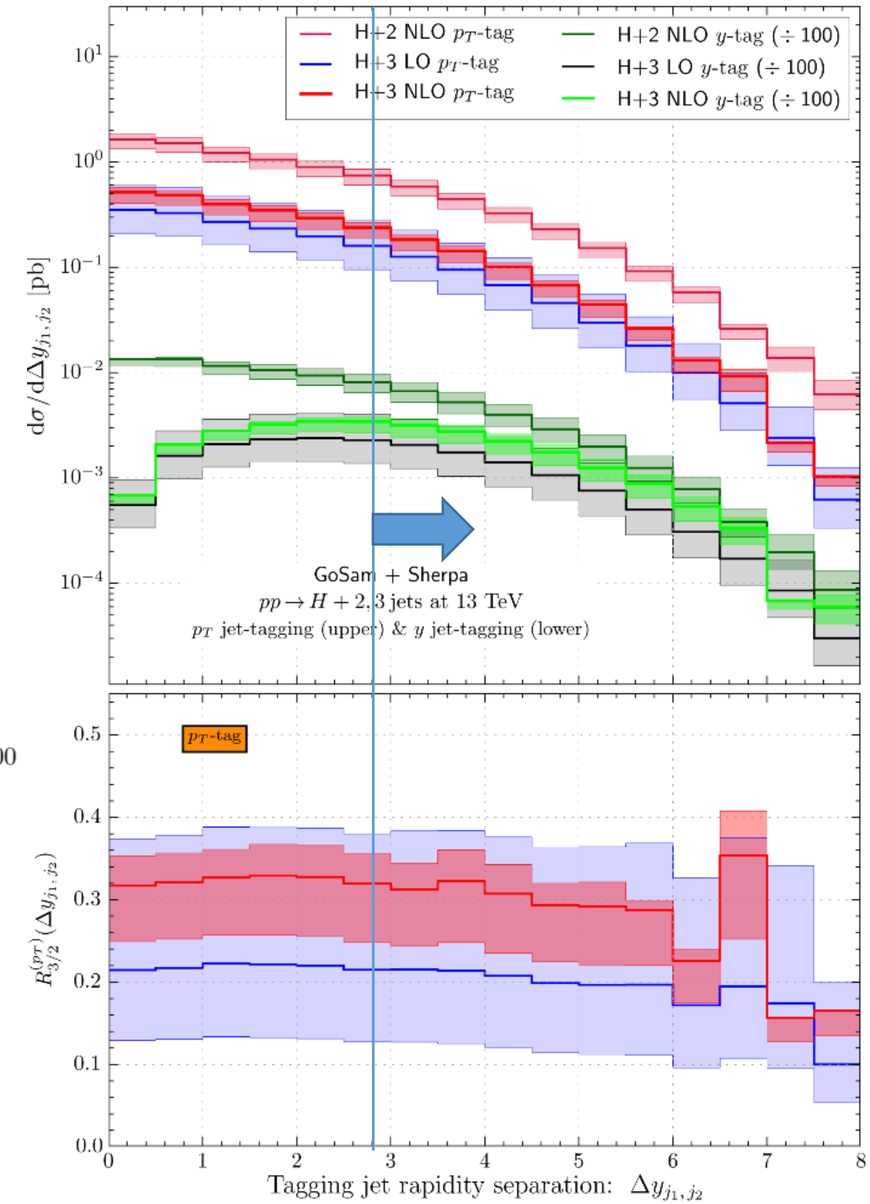




- Relative enhancement of the (n+1)-jet contribution in the VBF fiducial region
  - Larger portion of cross section described only at LO accuracy
  - i.e. theoretical uncertainty increased in the VBF fiducial region
- H+3j allows to determine radiation of a third jet with NLO accuracy
  - Fixed order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

VBF selection observables at fixed order



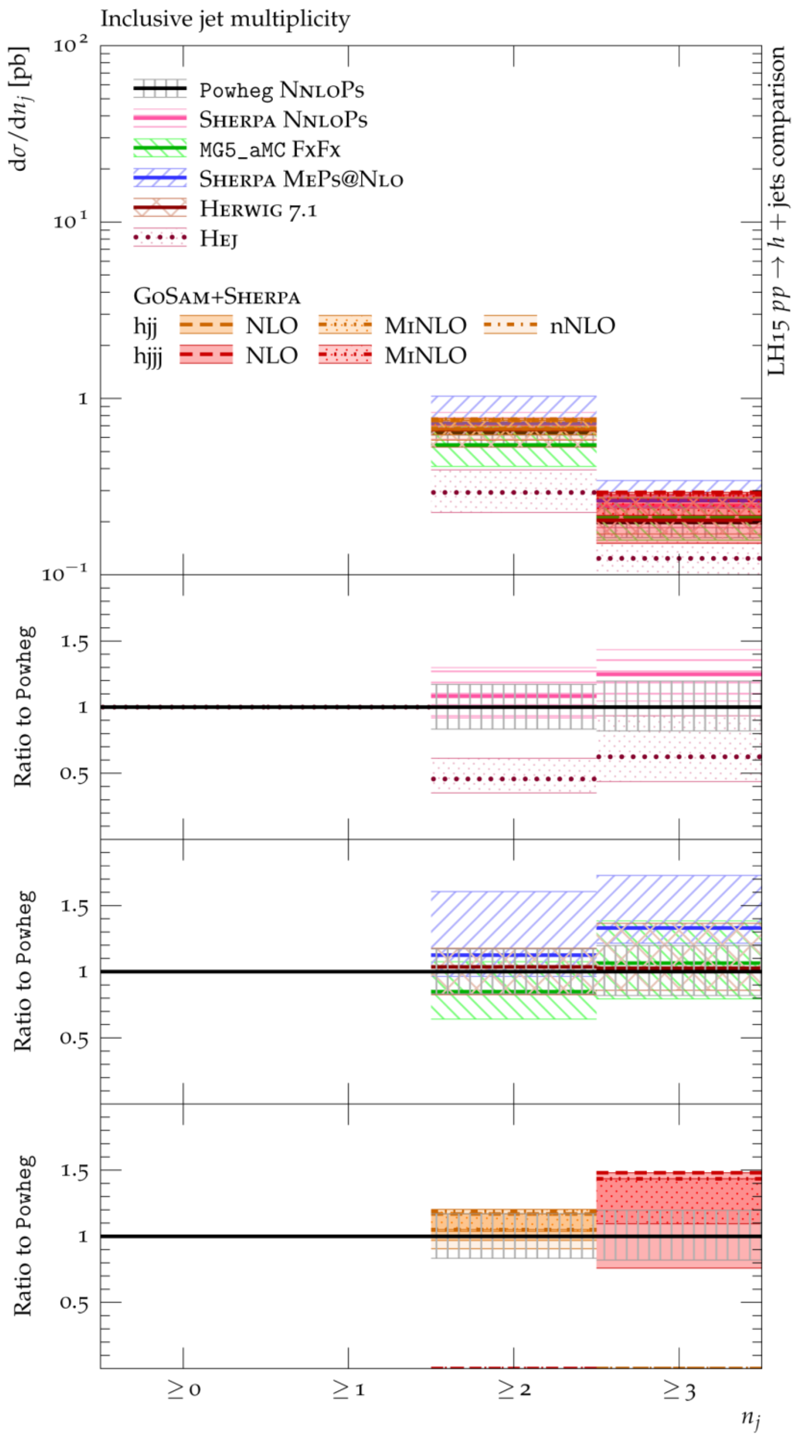


Question from WG conveners:
How do predictions with baseline cuts relate to VBF selection predictions?

- Can only be inferred from m_{jj} and Δy_{jj} distributions (if available)

Results from the LH2015 comparison

[arXiv:1605.04692]



Question from WG conveners:
How do one assign theory uncertainties if one use a MVA discriminant?

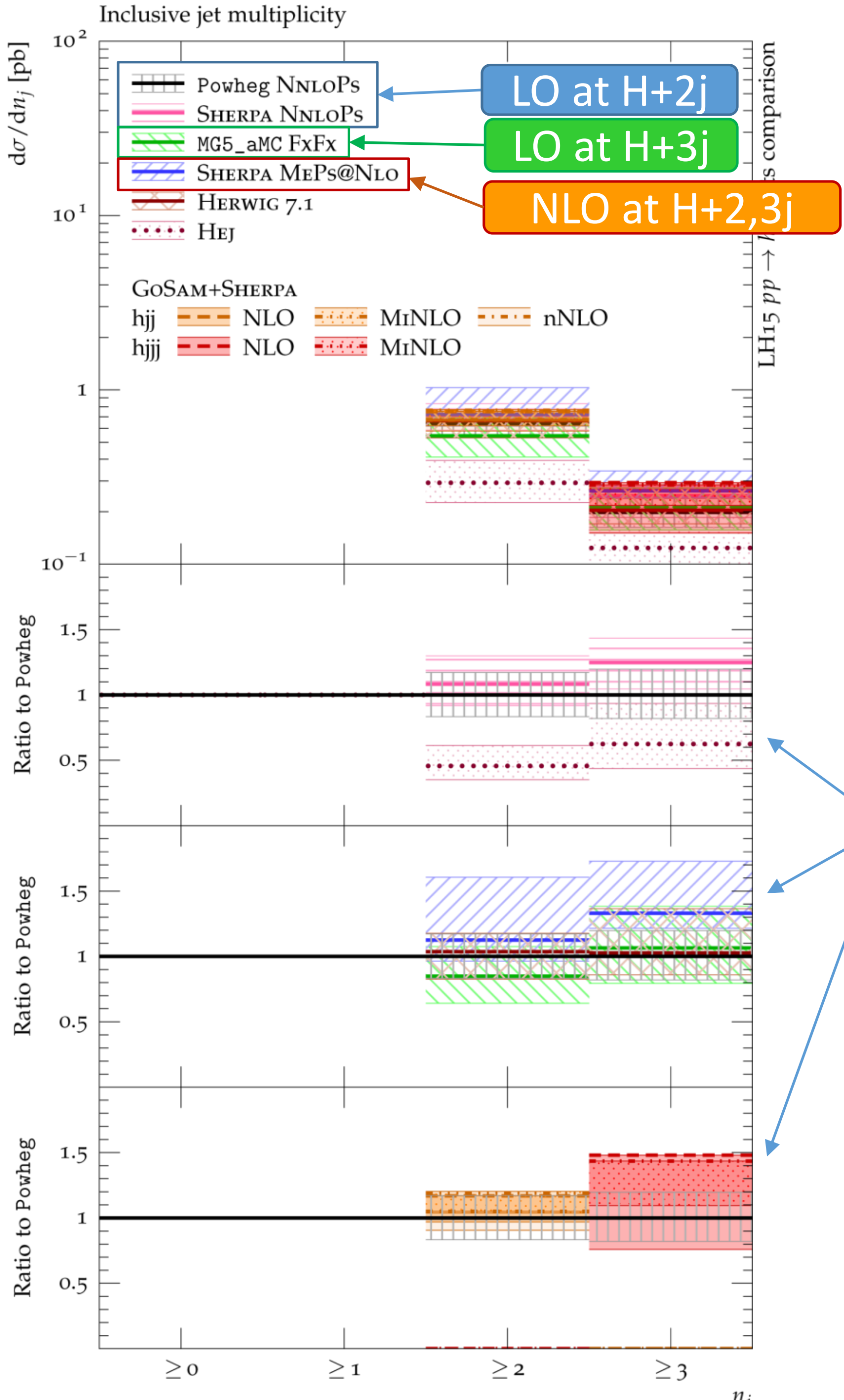
Very hard to tell from a theoretical perspective.

Merged sample, e.g. MEPS@NLO, probably best mean to check MVA uncertainties

- NLO accuracy over several multiplicities and also PS effects considered..

HOWEVER

Matched and merged samples can account for theoretical scale uncertainties of different multiplicities and also parton shower effects **BUT** one has always to take the resulting uncertainty with grain of salt, depending on the observable under consideration!!



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Very similar uncertainties!

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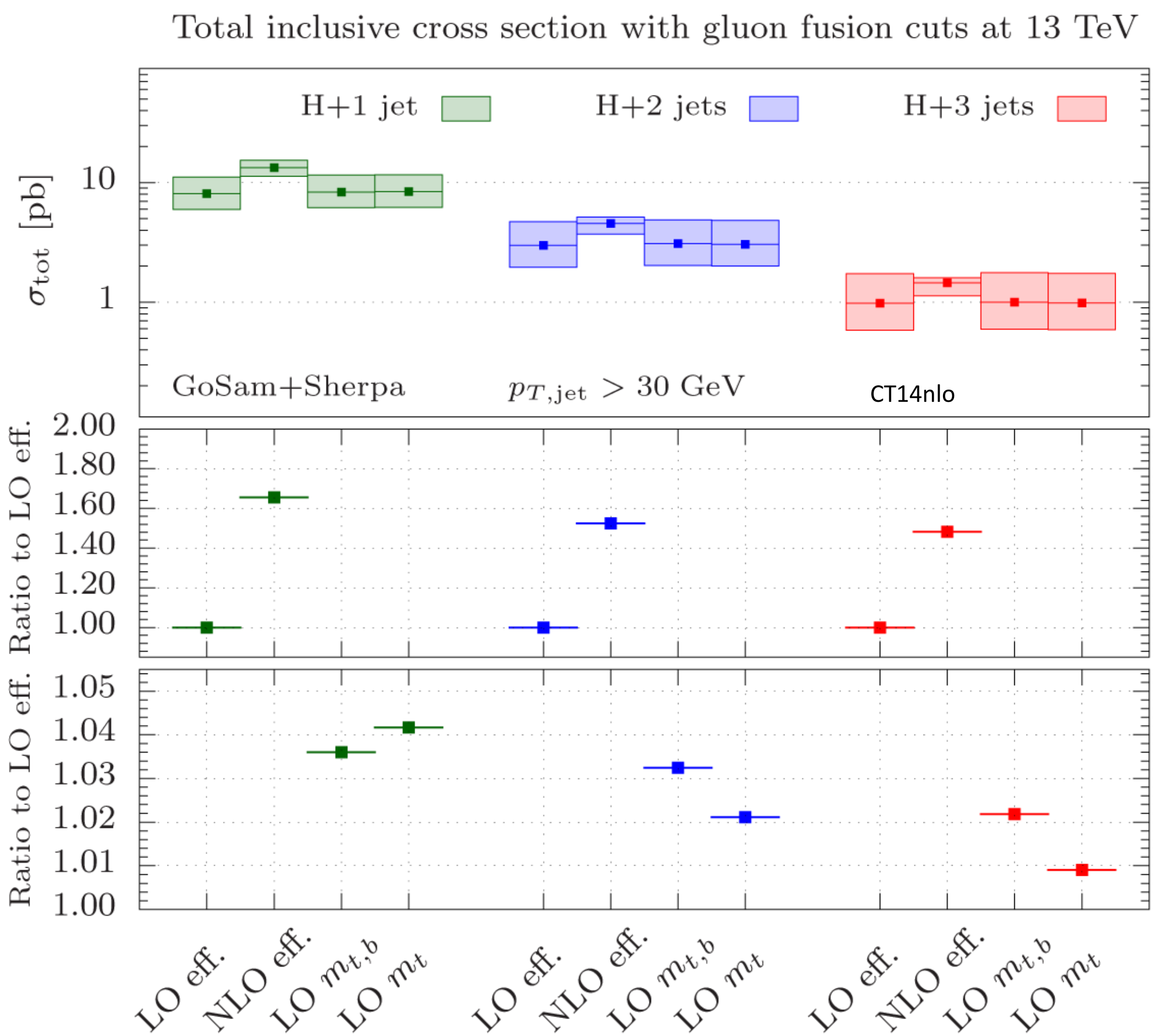
What about finite mass effects?

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

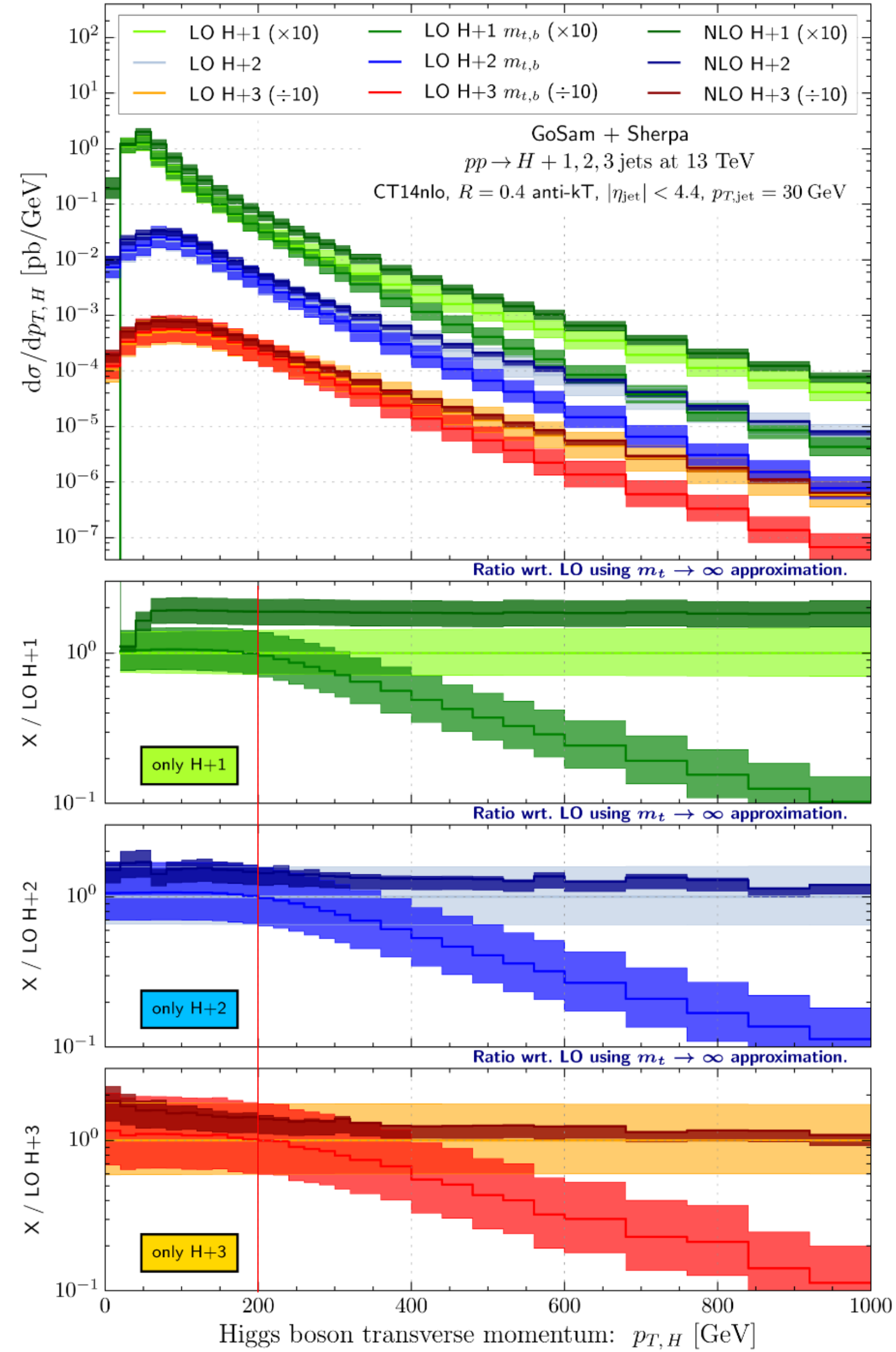
- $\sigma_{\mathrm{LO},\, m_{t,b}}$: top- and bottom-quark loops
- $\sigma_{\mathrm{LO},\, m_t}$: top-quark loops only

Higgs boson p_T

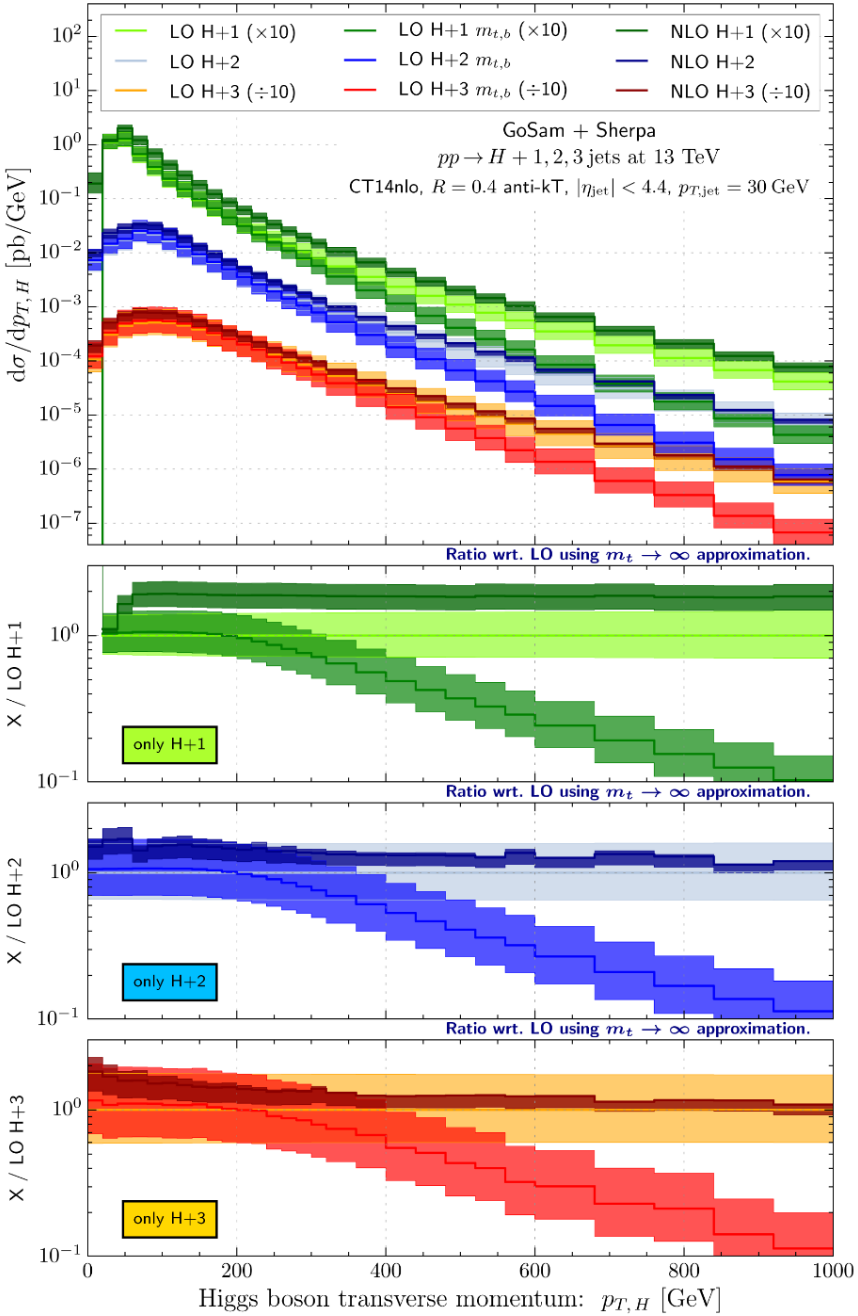
- Transverse momentum related observables known to receive significant corrections

- Effective theory starts to break down at $p_{T,\,H} \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.

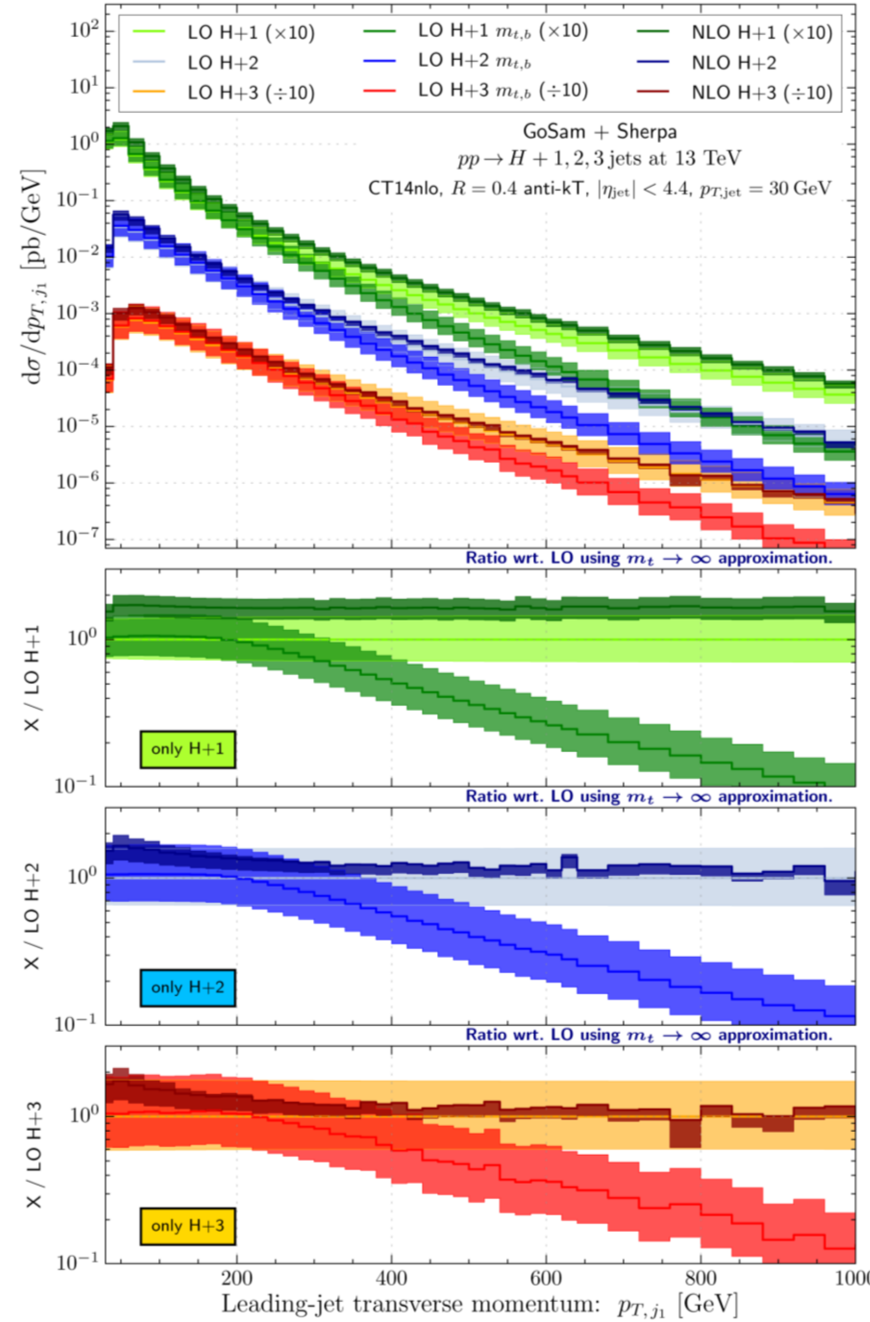
- Very similar behavior for the three different multiplicities



Higgs pT:



Leading jet pT:

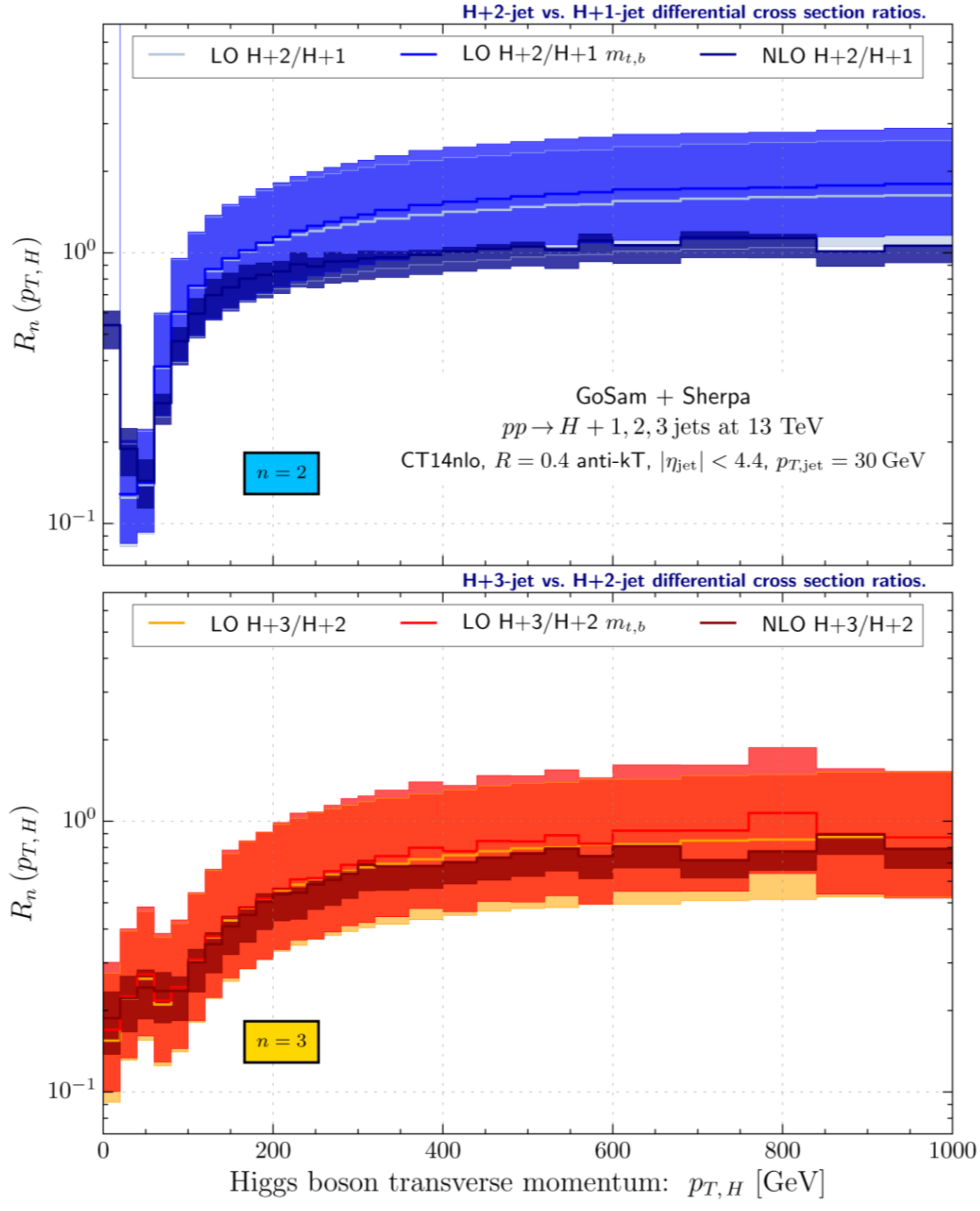


Higgs boson p_T

- Ratios of successive differential cross sections:

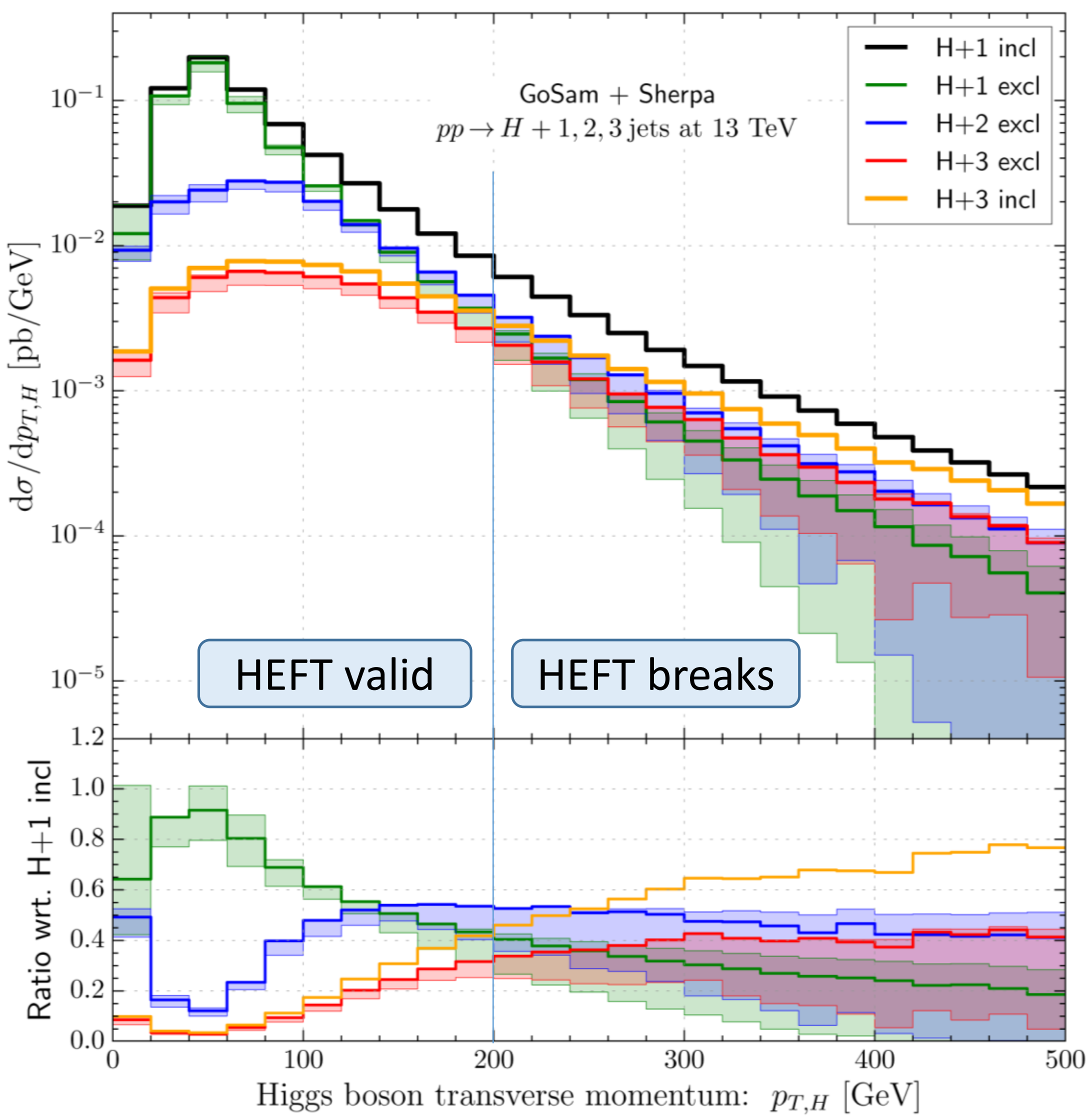
$$R_n(O) = \frac{\frac{d\sigma}{dO}(\mathrm{H}+n\,\mathrm{jets})}{\frac{d\sigma}{dO}(\mathrm{H}+(n-1)\,\mathrm{jets})}$$

➢ relative importance of higher multiplicities remains stable under mass corrections



Higgs transverse momentum spectrum at 13 TeV

- Importance of exclusive H+2/3 jets contribution in Higgs p_T spectrum:



Around 200 GeV
(where HEFT is still reliable):

- NLO H+2j excl. is O(50%) of NLO H+1j inclusive

- NLO H+3j excl. is O(30%) of NLO H+1j inclusive

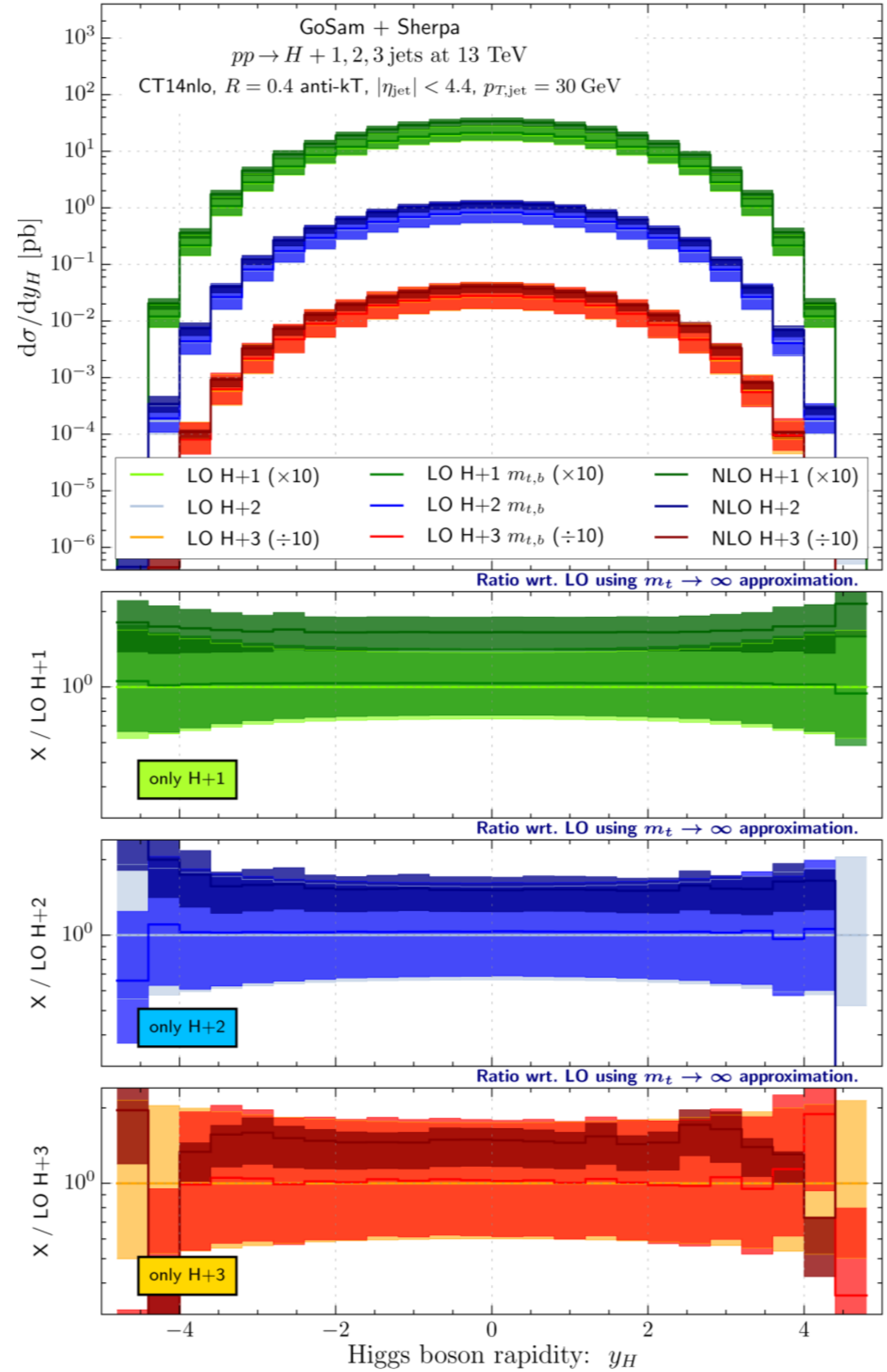
Higgs boson rapidity

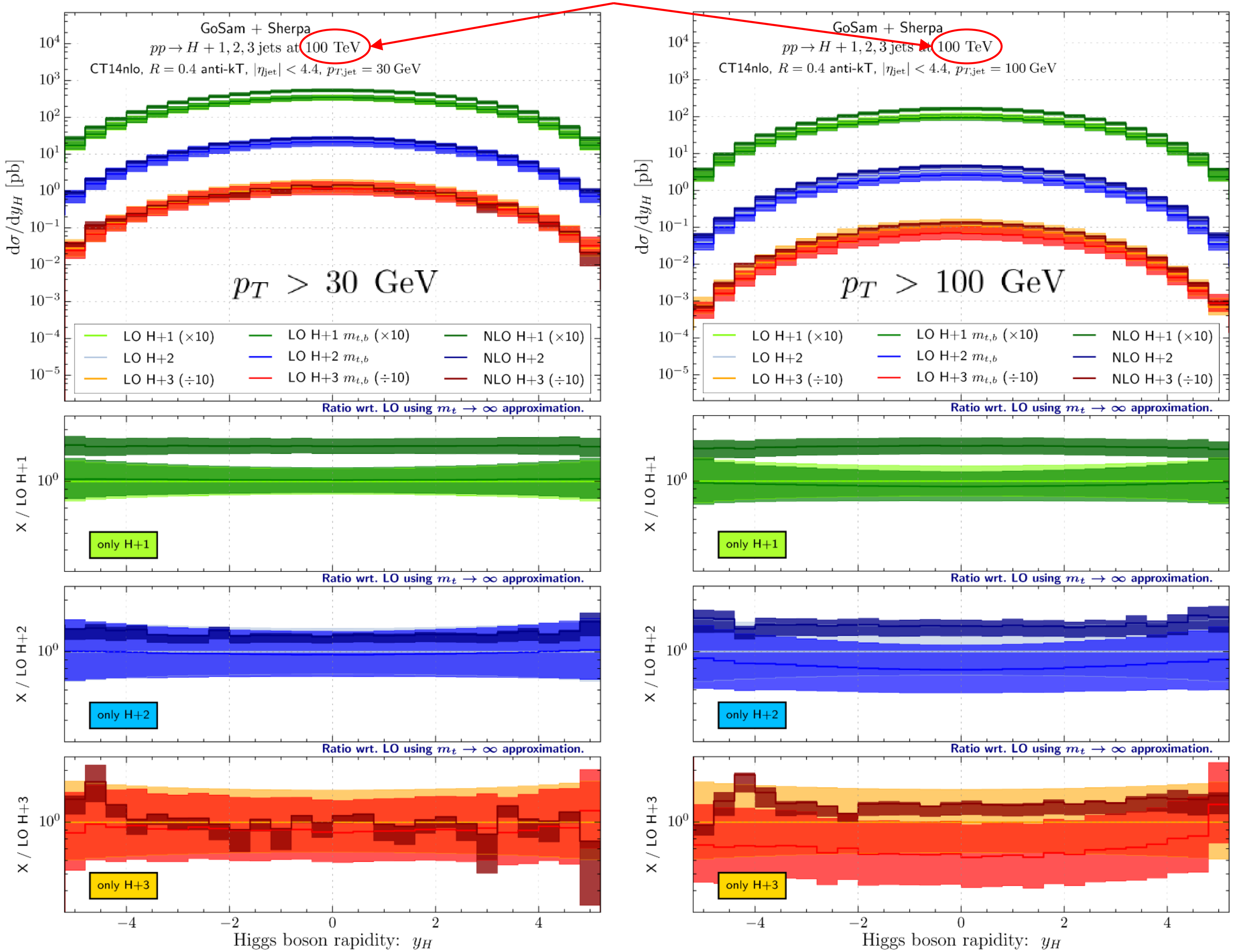
- Mass corrections small over full kinematical range:

➢ 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!





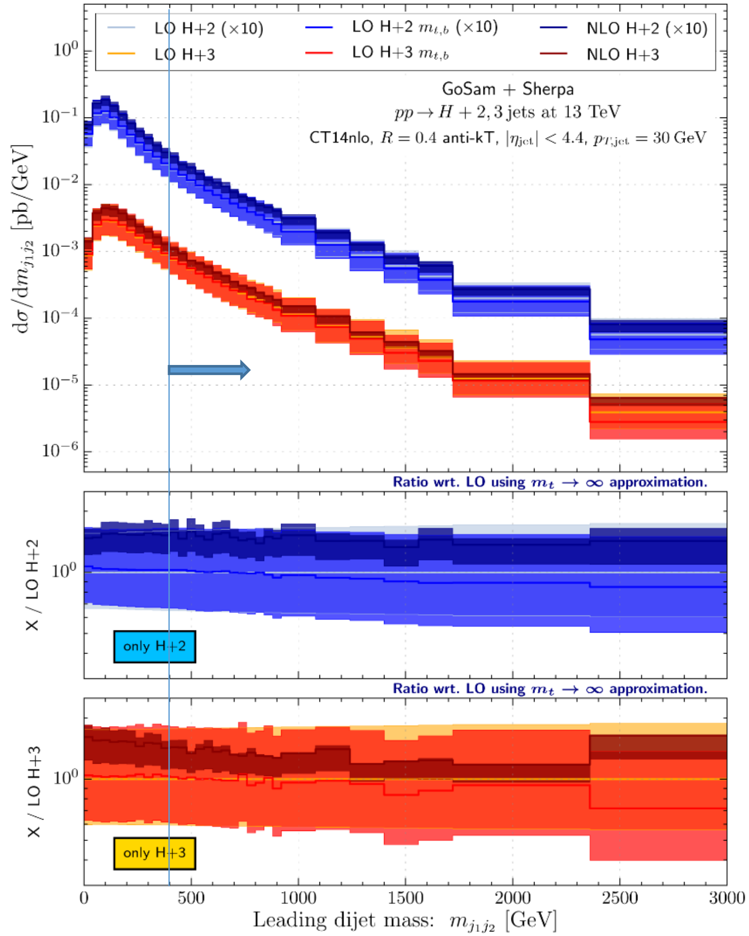
Regime in which HEFT breaks down is reached more easily when a harder pT cut is imposed. Mass effects therefore become much more important!

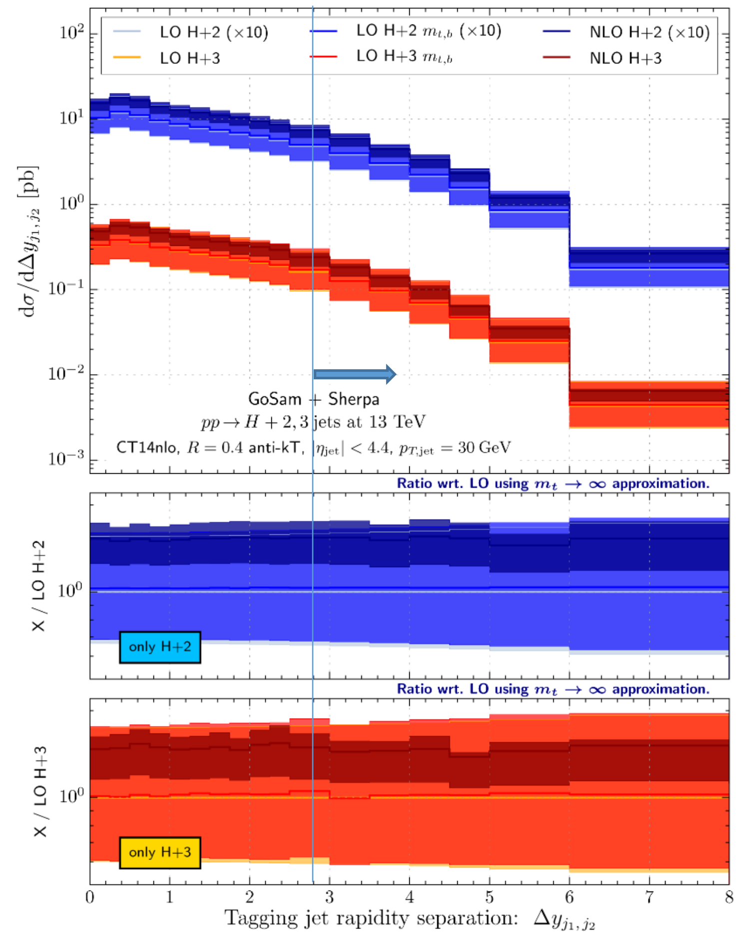
Higgs plus jets in GGF with VBF selection cuts

- 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:





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

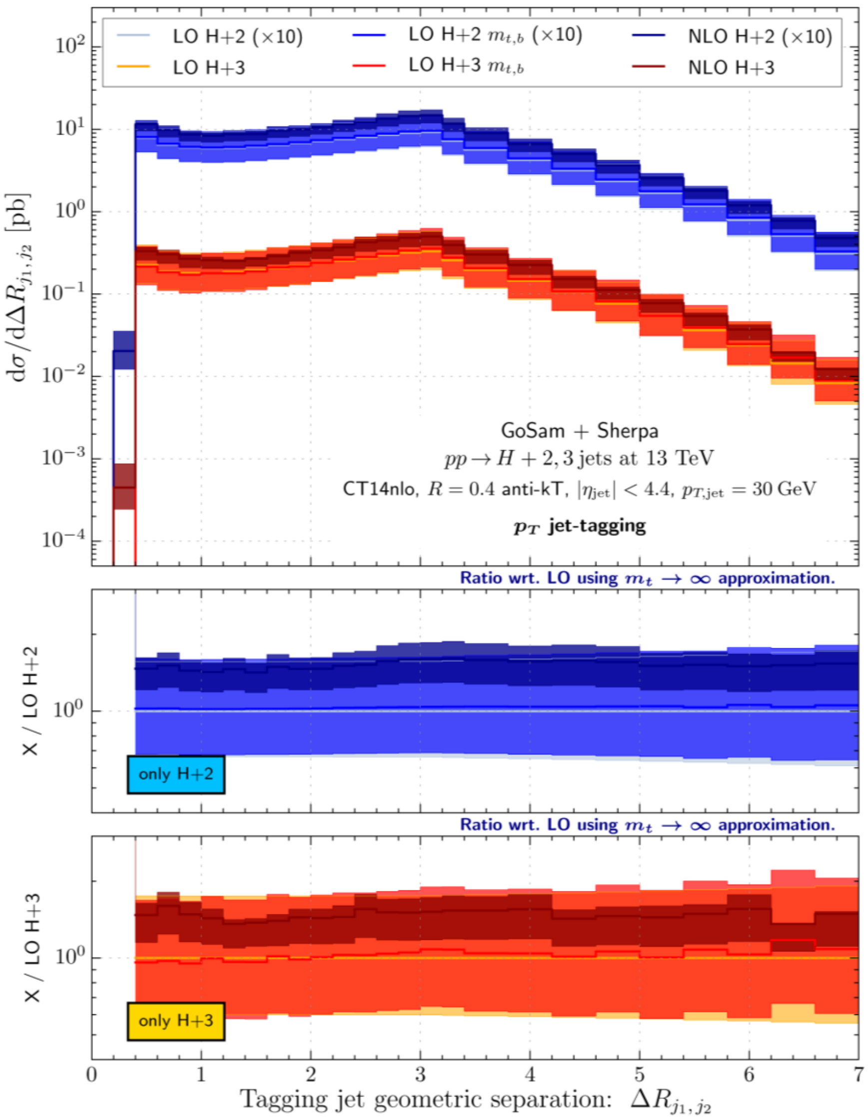
- Total cross section:

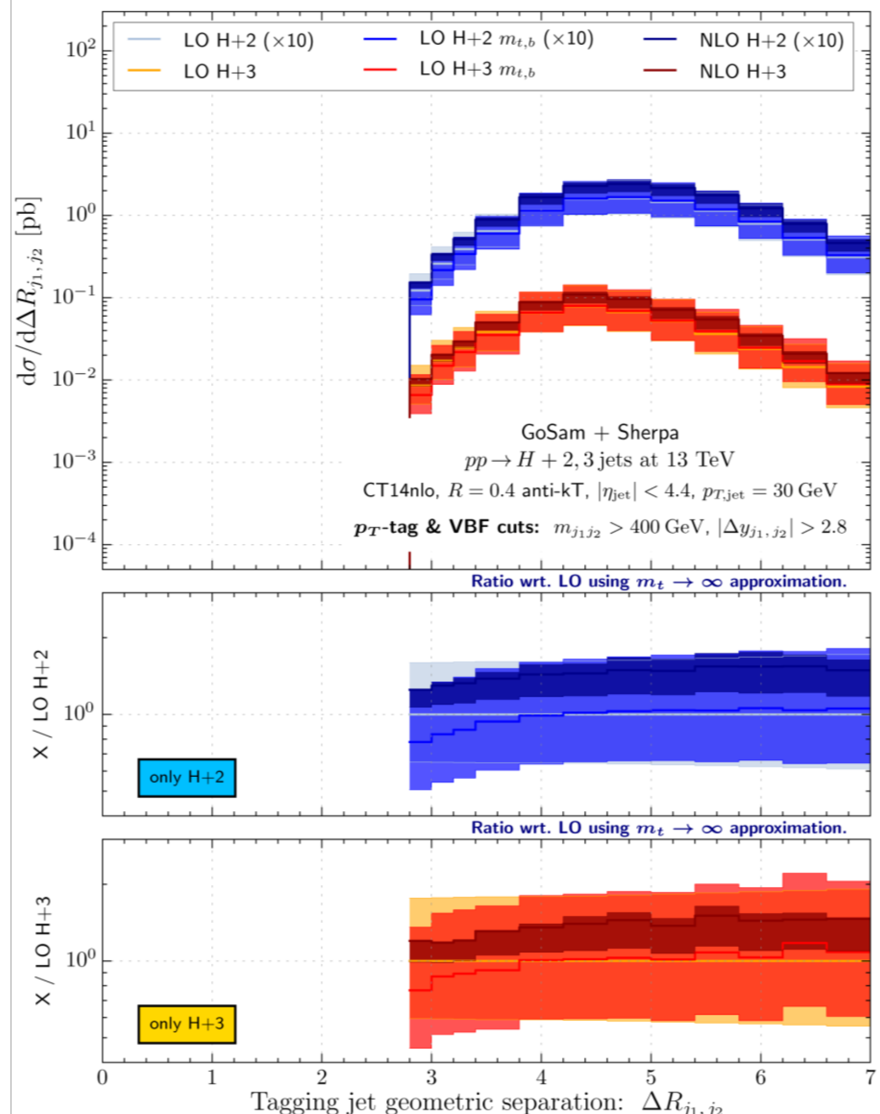
Numbers in [pb]	H+2 jets	H+3 jets
$\sigma_{\text{LO, eff.}}$	$0.397^{+64\%}_{-36\%}$	$0.166^{+82\%}_{-42\%}$
$\sigma_{\text{NLO, eff.}}$	$0.584^{+10\%}_{-19\%}$	$0.231^{+5\%}_{-22\%}$
$\sigma_{\text{LO},\, m_{t,b}}$	$0.404^{+65\%}_{-37\%}$	$0.167^{+82\%}_{-42\%}$
$\sigma_{\text{LO},\, m_t}$	$0.398^{+65\%}_{-37\%}$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

- 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:





Conclusions and Outlook

- VBF fiducial cuts increase sensitivity to radiation: larger uncertainty
- Matched and merged predictions can help estimating uncertainties **BUT** their reliability depends on the observable under consideration!
- 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
- Depending on the kinematical cuts (especially p_T requirements), mass effects will play a major role in differential distributions
  - Even if this may not be highly relevant for LHC Run II, boosted analyses and future runs will be very sensitive to this
  - VBF selection cuts do not particularly enhance mass effects

Backup

Total cross sections in number

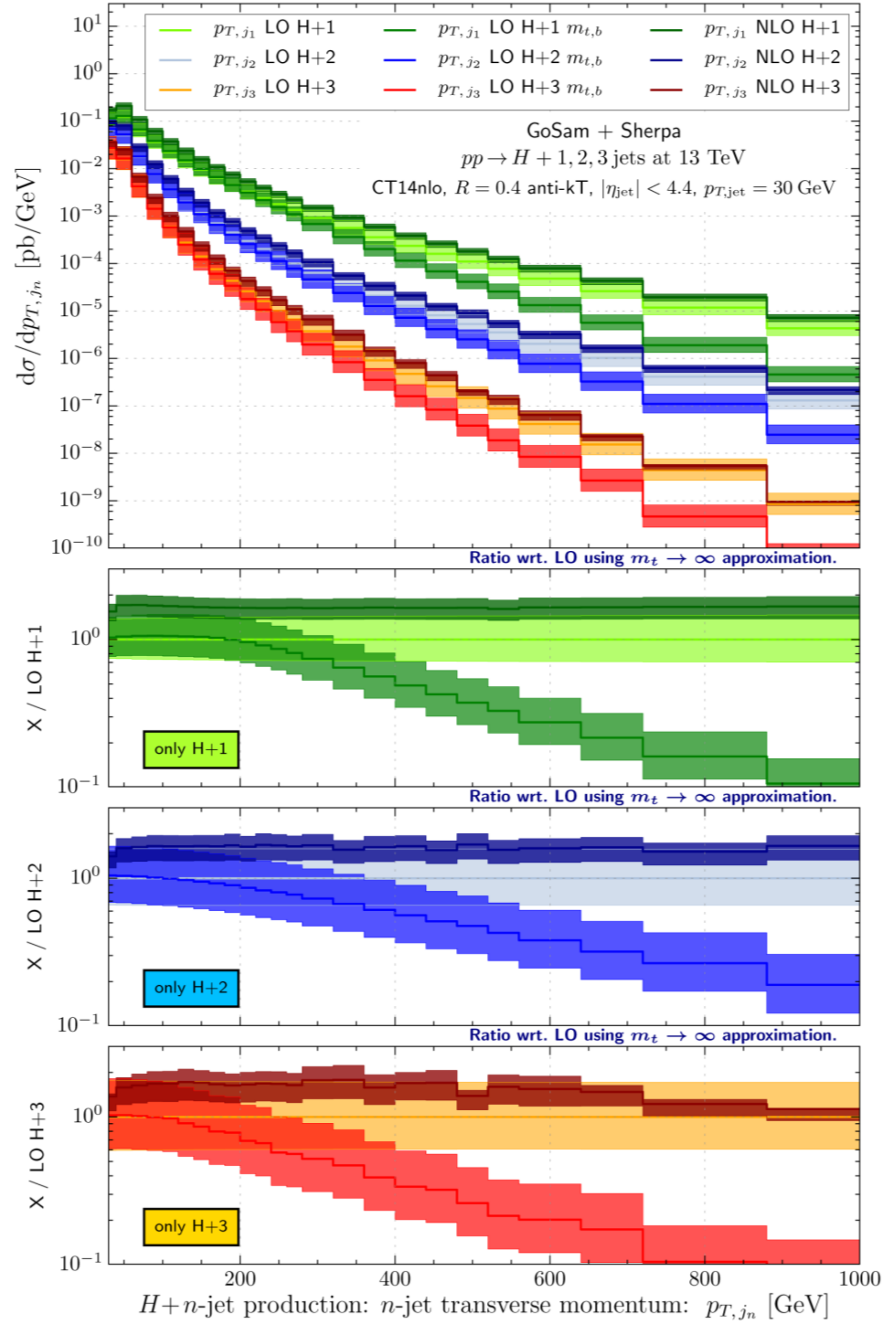
Numbers in [pb]	$p_{T,\text{jet}} > 30$ GeV		$p_{T,\text{jet}} > 100$ GeV
$\sqrt{s}$	13 TeV	100 TeV	100 TeV
H+1 jet			
$\sigma_{\text{LO, eff.}}$	$8.06^{+38\%}_{-26\%}$	$196^{+21\%}_{-17\%}$	$55.7^{+24\%}_{-19\%}$
$\sigma_{\text{NLO, eff.}}$	$13.3^{+15\%}_{-15\%}$	$315^{+11\%}_{-10\%}$	$88.8^{+11\%}_{-11\%}$
$\sigma_{\text{LO}, m_{t,b}}$	$8.35^{+38\%}_{-26\%}$	$200^{+20\%}_{-17\%}$	$52.3^{+24\%}_{-19\%}$
σ_{LO, m_t}	$8.40^{+38\%}_{-26\%}$	$201^{+20\%}_{-17\%}$	$51.3^{+24\%}_{-18\%}$
H+2 jets			
$\sigma_{\text{LO, eff.}}$	$2.99^{+58\%}_{-34\%}$	$124^{+39\%}_{-27\%}$	$16.5^{+41\%}_{-28\%}$
$\sigma_{\text{NLO, eff.}}$	$4.55^{+13\%}_{-18\%}$	$156^{+3\%}_{-10\%}$	$23.3^{+9\%}_{-13\%}$
$\sigma_{\text{LO}, m_{t,b}}$	$3.08^{+58\%}_{-34\%}$	$121^{+39\%}_{-26\%}$	$13.2^{+41\%}_{-27\%}$
σ_{LO, m_t}	$3.05^{+58\%}_{-34\%}$	$120^{+39\%}_{-26\%}$	$13.0^{+41\%}_{-27\%}$
H+3 jets			
$\sigma_{\text{LO, eff.}}$	$0.98^{+76\%}_{-41\%}$	$70.4^{+56\%}_{-34\%}$	$5.13^{+56\%}_{-34\%}$
$\sigma_{\text{NLO, eff.}}$	$1.45^{+11\%}_{-22\%}$	$72.0^{-16\%}_{-7\%}$	$6.52^{+2\%}_{-14\%}$
$\sigma_{\text{LO}, m_{t,b}}$	$1.00^{+77\%}_{-41\%}$	$63.3^{+56\%}_{-34\%}$	$3.38^{+57\%}_{-34\%}$
σ_{LO, m_t}	$0.99^{+77\%}_{-41\%}$	$62.7^{+56\%}_{-34\%}$	$3.32^{+56\%}_{-34\%}$

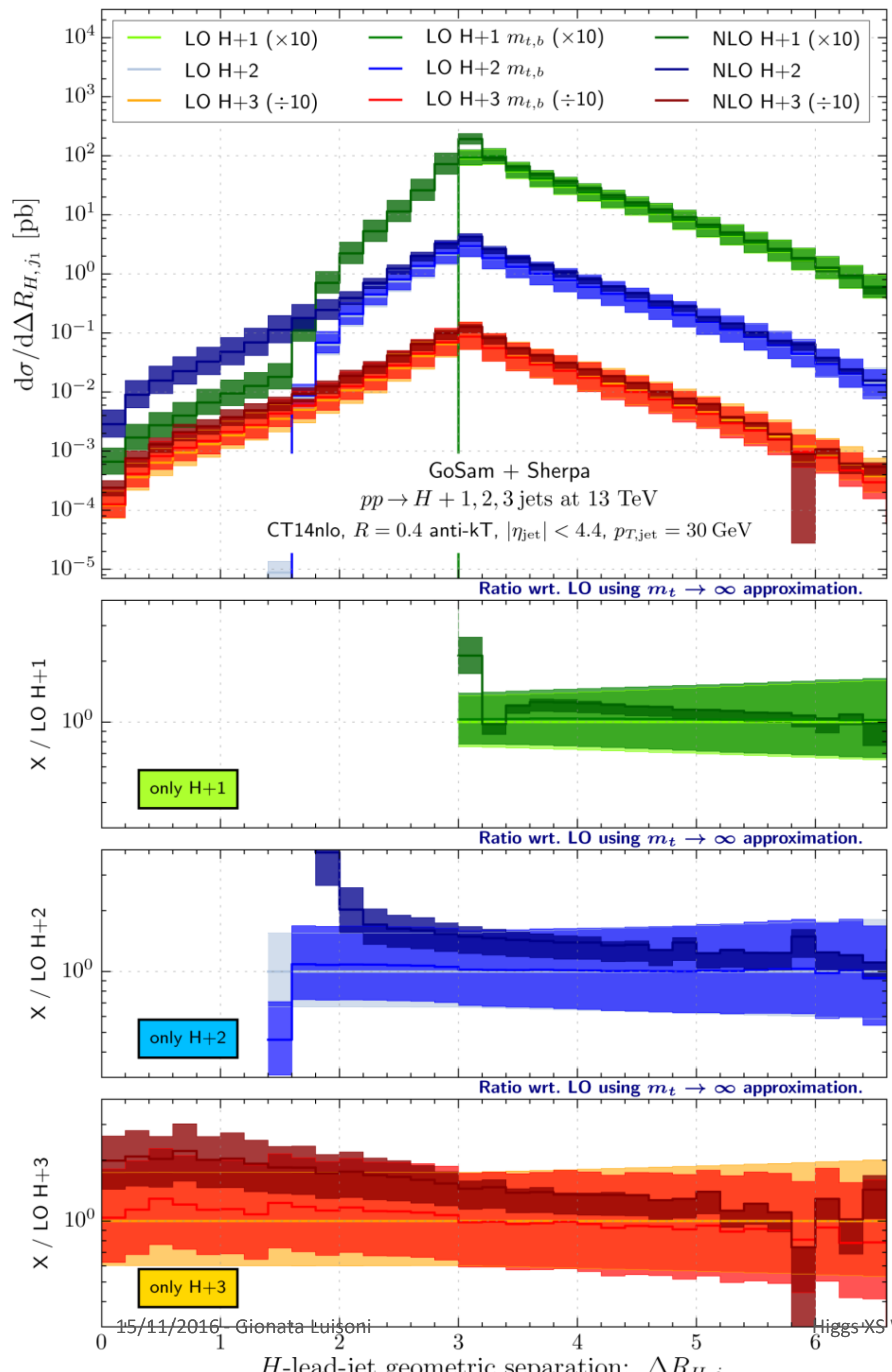
Wimpiest jet p_T

- Full theory predictions start to deviate from effective one even earlier for H+2j and H+3j

➢ consequence of the pT ordering of the jets:

  ➢ There hast to be 1 or 2 harder jets that drive the breakdown of the effective theory approach




LO H+1 (×10)
LO H+2
LO H+3 (÷10)
LO H+1 $m_{t,b}$ (×10)
LO H+2 $m_{t,b}$
LO H+3 $m_{t,b}$ (÷10)
NLO H+1 (×10)
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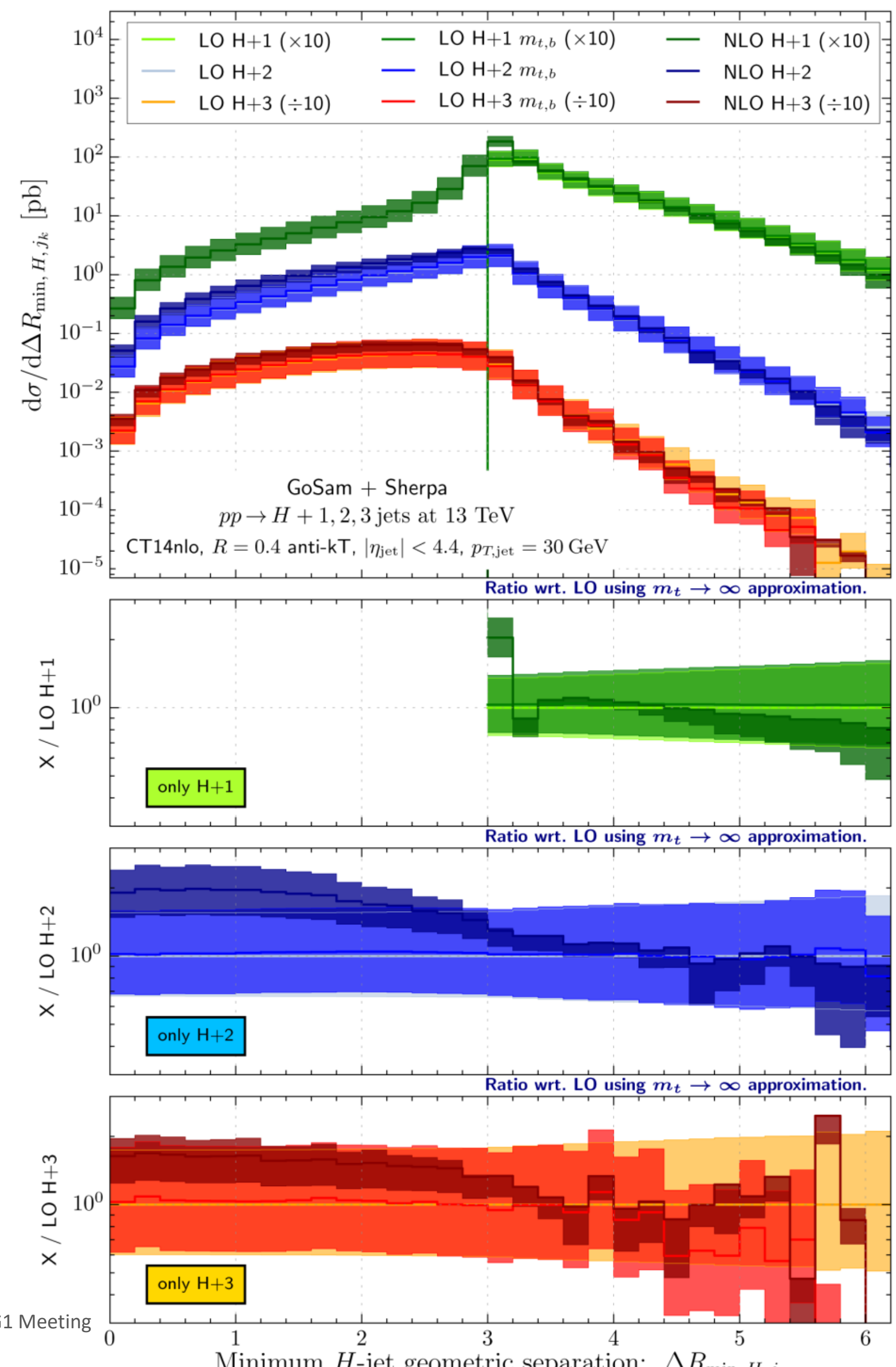
GoSam + Sherpa
$pp \to H + 1, 2, 3$ jets at 13 TeV
CT14nlo, $R = 0.4$ anti-kT, $|\eta_{\mathrm{jet}}| < 4.4$, $p_{T,\mathrm{jet}} = 30$ GeV
$\mathrm{d}\sigma/\mathrm{d}\Delta R_{H,j_1}$ [pb]
Ratio wrt. LO using $m_t \to \infty$ approximation.
X / LO H+1
only H+1
X / LO H+2
only H+2
X / LO H+3
only H+3
H-lead-jet geometric separation: $\Delta R_{H,j_1}$


LO H+1 (×10)
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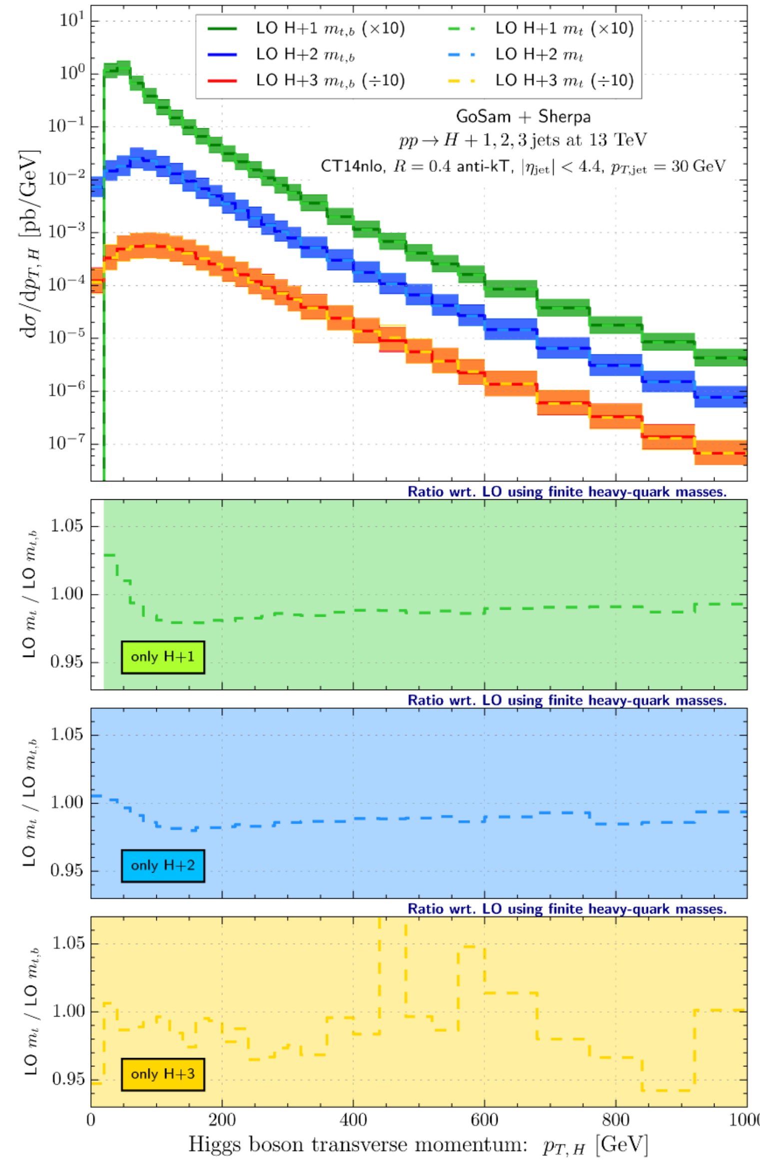
Minimum H-jet geometric separation: $\Delta R_{\mathrm{min},H,j_k}$

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



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  - ➢ 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.
  - ➢ Leading jet p_T