Higgs boson production in association with jets: NLO corrections vs mass effects.

Gionata Luisoni

gionata.luisoni@cern.ch

CERN

Future challenges for precision QCD

IPPP, Durham

25.10.2016

In collaboration with:

Nicolas Greiner, Stefan Höche, Marek Schönherr, Jan-Christopher Winter and Valery Yundin

Outline

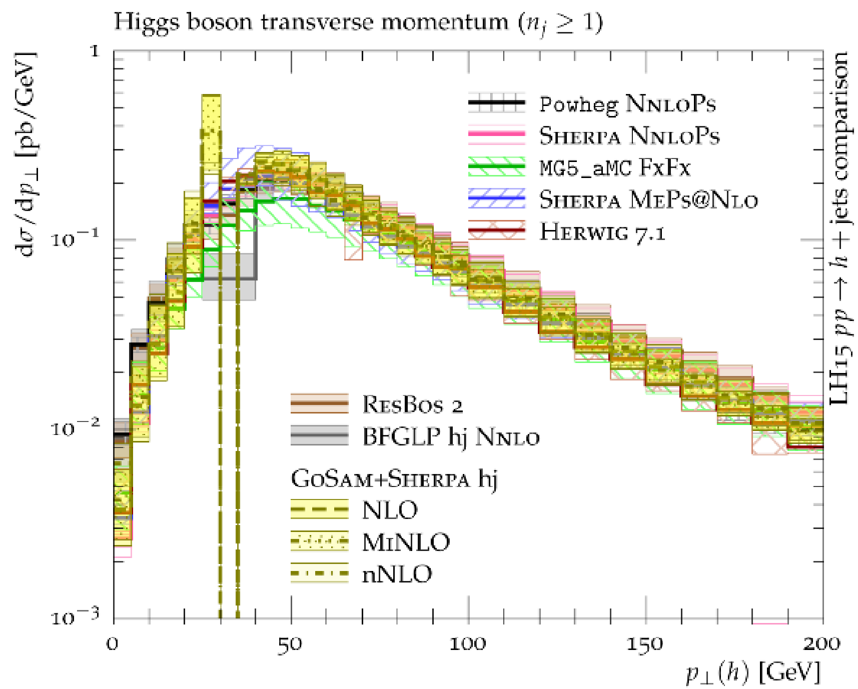
- **Introduction**
- **H+1,2 and 3 jets at LHC:**
  - NLO effective theory predictions compared to LO in the full SM at 13 TeV
  - The case of massless bottom quarks
- **Impact of VBF selection cuts**
- **Excursus: what changes at a 100 TeV collider?**
- **Conclusions and outlook**

H+jets in gluon-gluon fusion at NLO

- LHC Run II is collecting data very fast. This will soon allow for precise Higgs boson studies at 13 TeV

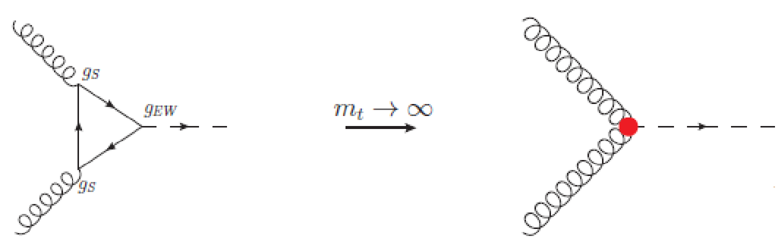
- Higher order corrections are particularly sizable in Higgs boson production in gluon-gluon fusion

- For a precise determination of the most important observables (e.g. the Higgs transverse momentum spectrum) a good control over higher multiplicities is relevant



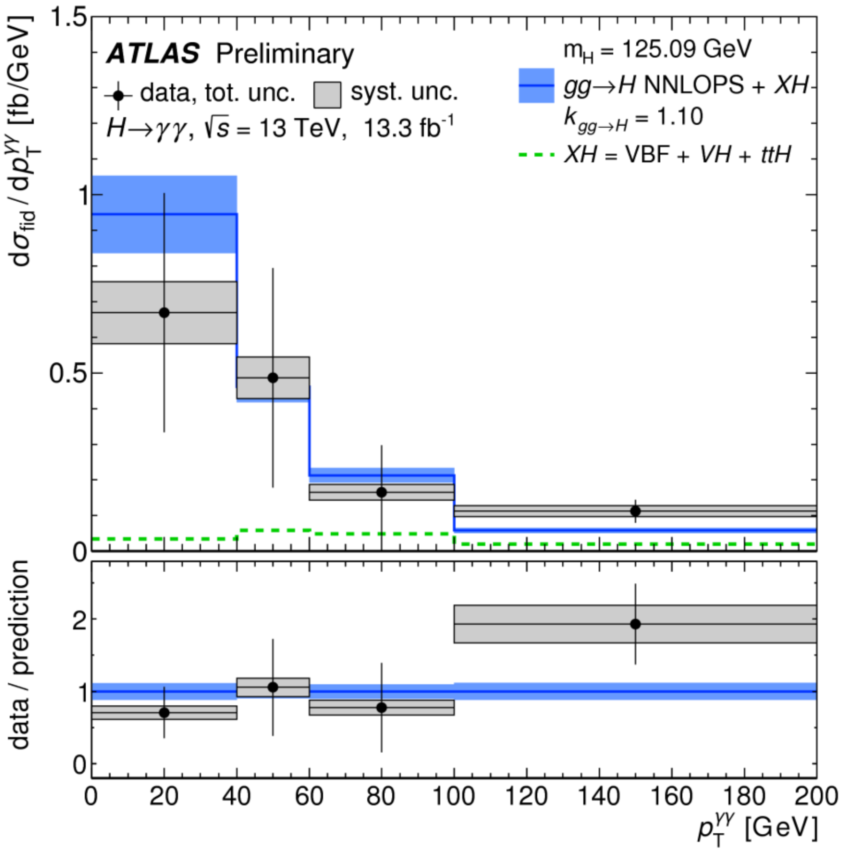
[Les Houches 2015 comparative study: 1605.04692]

- Furthermore:
  - How large are finite mass corrections?
  - Which observables are most affected?

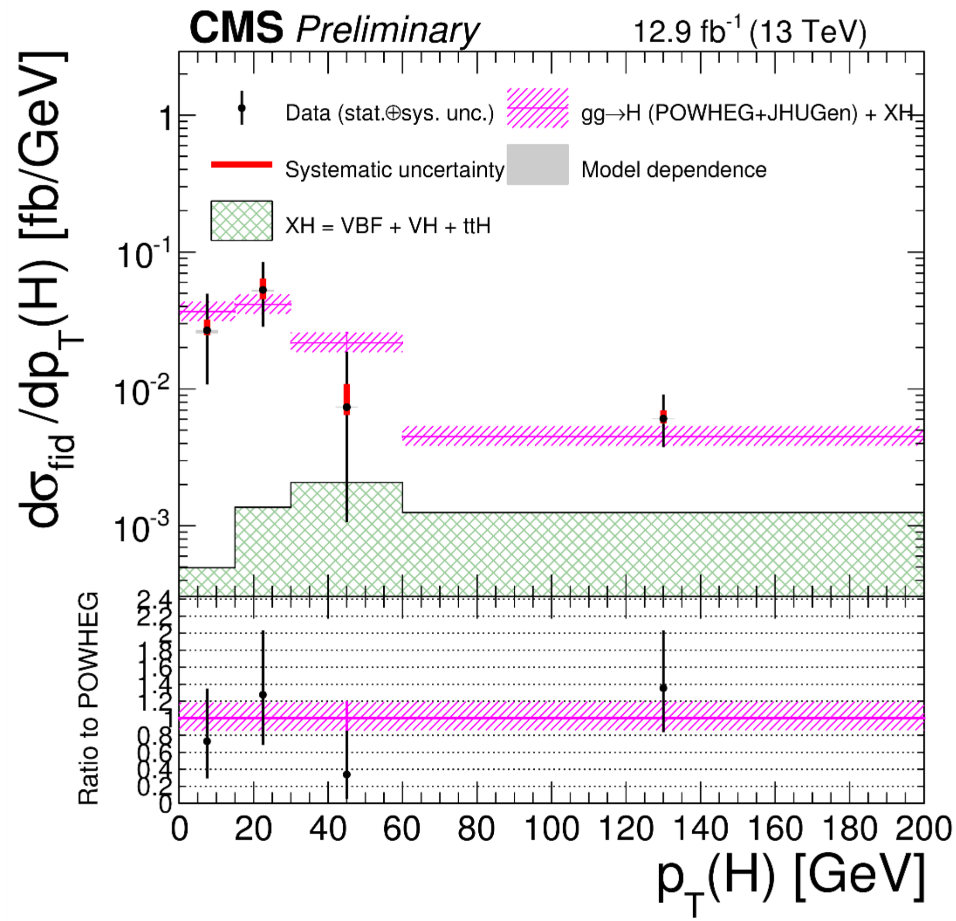


New results at 13 TeV

- Statistics for distributions still limited, but growing fast …



[ATLAS-CONF-2016-067]

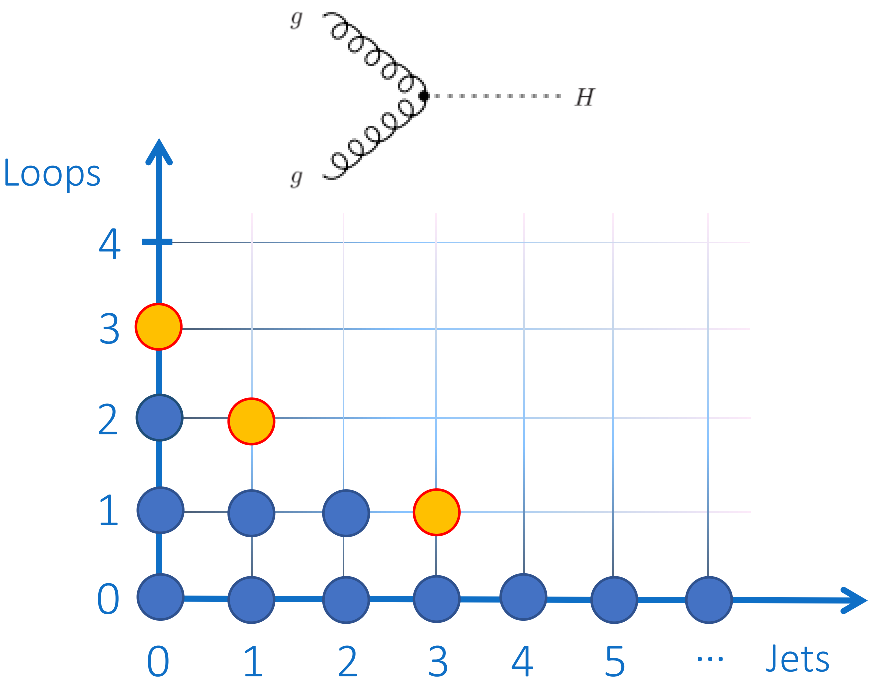


[CMS-PAS-HIG-16-033]

State of the art of the theoretical predictions

- Gluon fusion calculations in effective and full theory:

ME level   Shower/Hadron level   Approximate   New result (2015-2016)

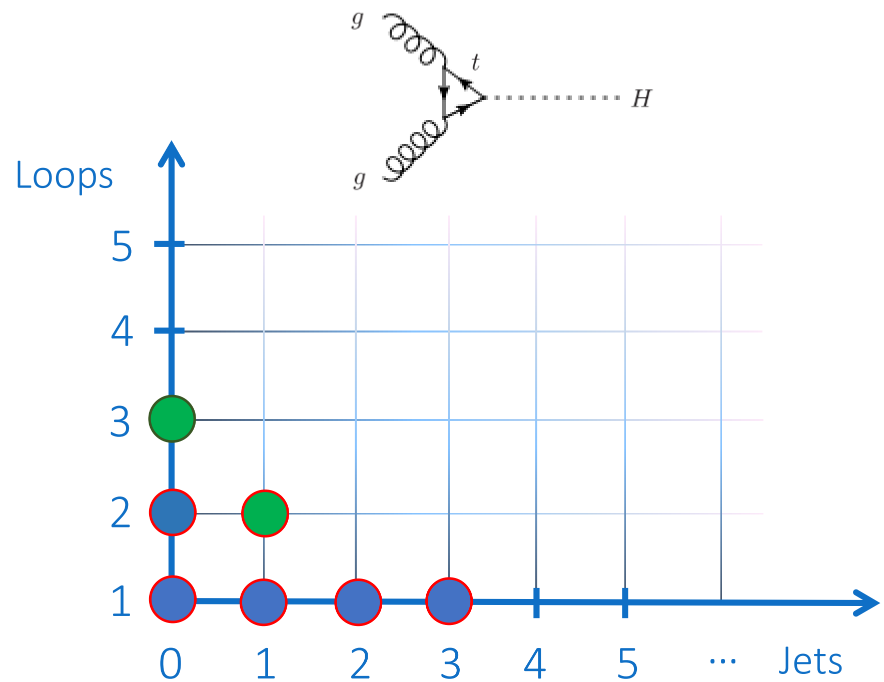


Latest results:

[H: 1503.06056, 1602.00695]

[H+1j: 1504.07922, 1505.03893,1508.02684, 1607.08817]

[H+3j: 1506.01016]



Latest results:

[H+0,1,2j NLO merged + PS: 1410.5806]

[H+0,1,2j approx. NLO merged + PS: 1604.03017]

[H+1,2,3j LO: 1608.01195]

[H+1j approx. NLO: 1609.00367]

[H+1j approx. NNLO for p_T: 1607.08817]

-- > Furthermore: planar 2-loop MI [1609.06685]

NLO effective theory vs mass effects

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 Ntuple files:
  - Events for: H+1 / 2 / 3 jets → ~ **2 TB** per CM energy set

  ✓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.

Root Ntuples and timing

- Ntuples allow for fast analysis, change of **scale, pdf, cuts, jet radius**
    - ➢ on average 50 CPU hours per analysis for H+3 jets

Investigating different scale choices, performing the scale variation, varying the radii and changing selection cuts takes time:

- ➢ If we would run from scratch every time:

(3 scale variations) x (4 scales) x (5 jet radii) x (2 cuts) = 120

- ➢ which means approx. 4 million CPU hours (4.6 years on 100 cores)

NOW: Publicly available on:

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

https://eospublic.cern.ch/eos/theory/project/GoSam (only within CERN)

Physical setup

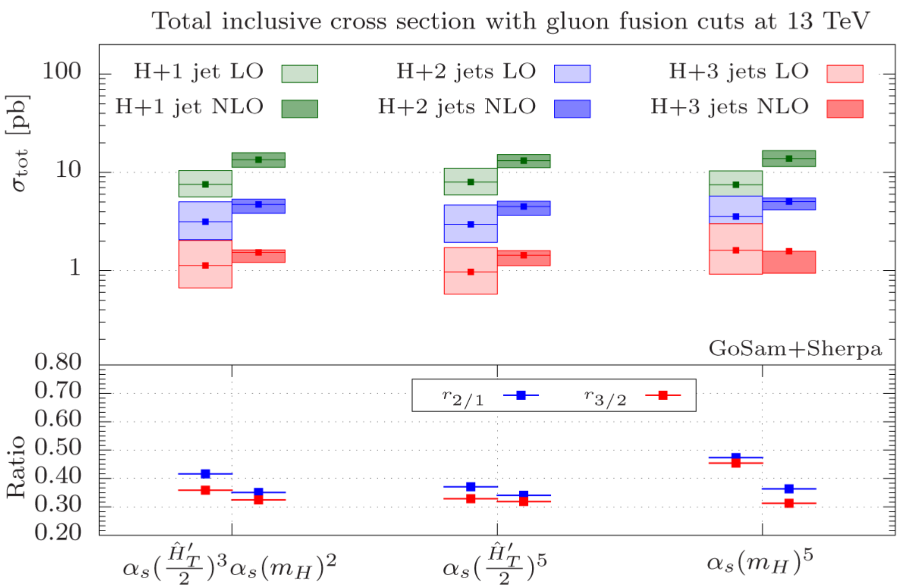
For both 13 and 100 TeV:

- scale choice: $\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\mathrm{H}}^2 + p_{T,\mathrm{H}}^2} + \sum_i |p_{T,i}|\right)$
- PDFs: CT14nlo
- masses: $m_H = 125.0\ \mathrm{GeV}, \quad m_t = 172.3\ \mathrm{GeV}, \quad m_b(m_H) = 3.38\ \mathrm{GeV}$

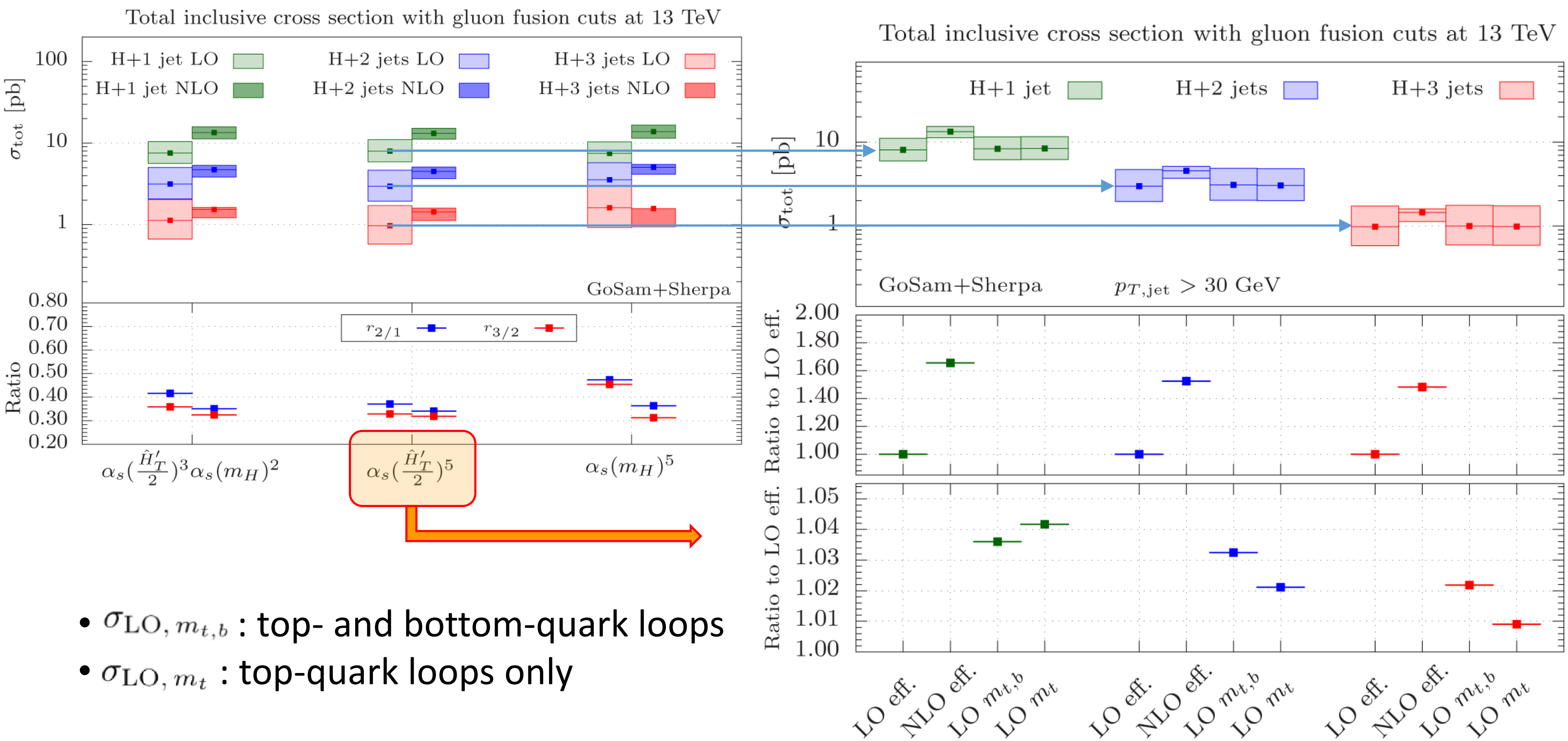
- **Baseline cuts:** anti-kt with $p_T > 30\ \mathrm{GeV}, \quad |\eta| < 4.4$
- **Additional VBF cuts**: $m_{j_1 j_2} > 400\ \mathrm{GeV}, \quad |\Delta y_{j_1, j_2}| > 2.8$

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

Total cross section: 13 TeV



Total cross section: 13 TeV

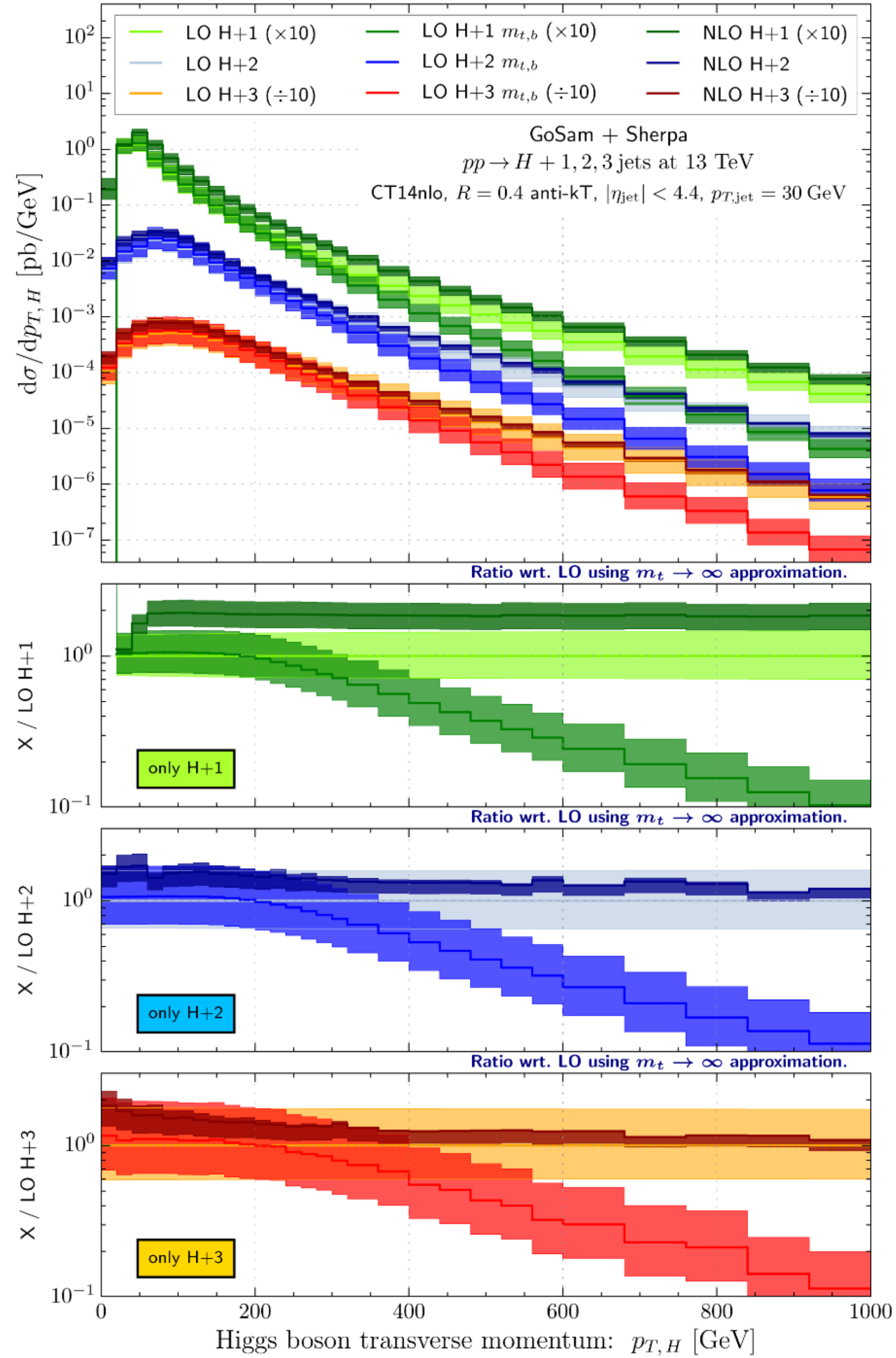


- $\sigma_{\mathrm{LO},\,m_{t,b}}$: top- and bottom-quark loops
- $\sigma_{\mathrm{LO},\,m_t}$: top-quark loops only

- 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 (more later)
- Possibility to estimate NLO cross section with full mass dependence from K-factors

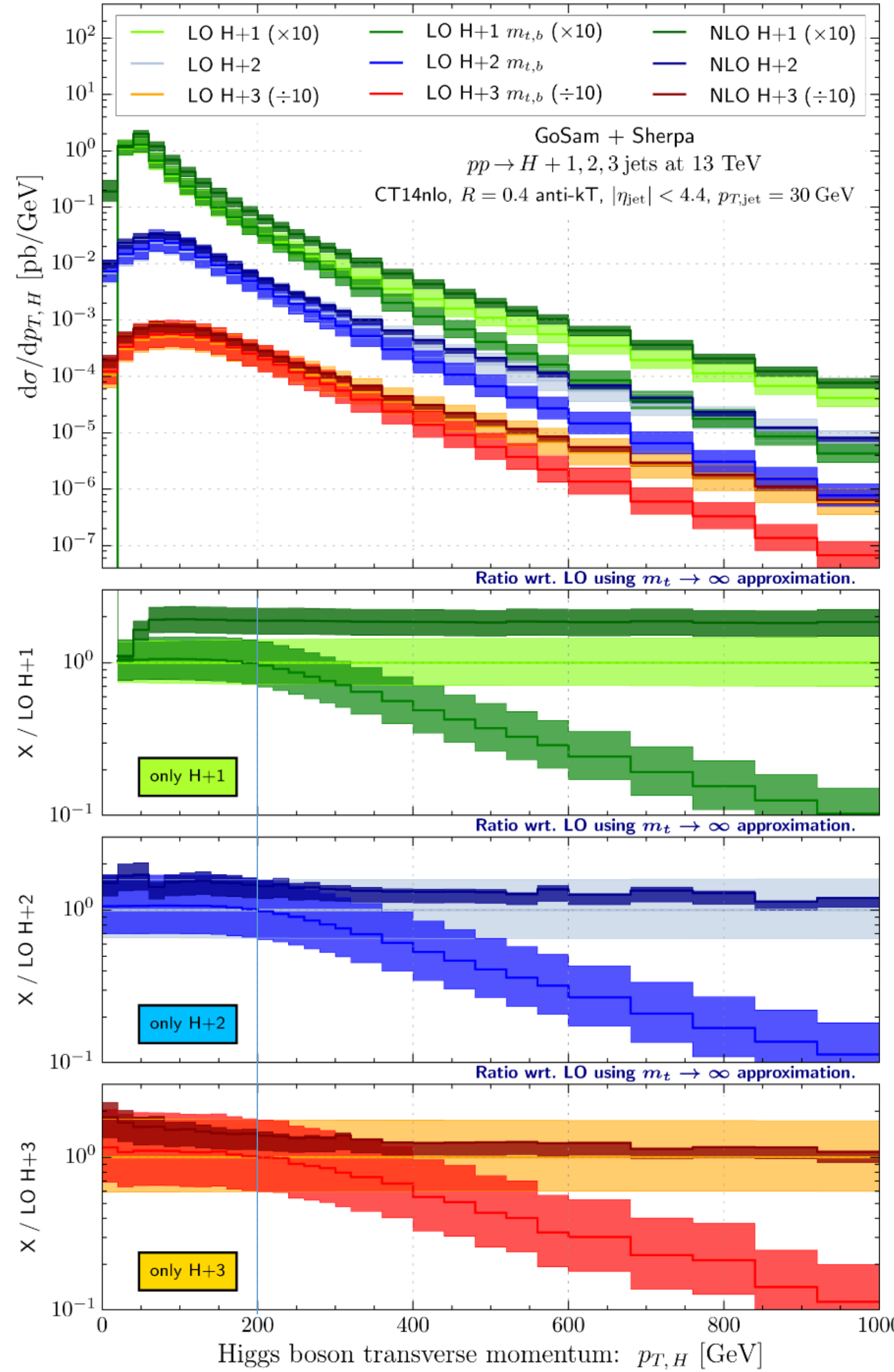
Higgs boson p_T

- Transverse momentum related observables known to receive significant corrections



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.

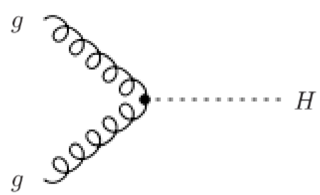


Interludio: Effective vs. Full theory scaling

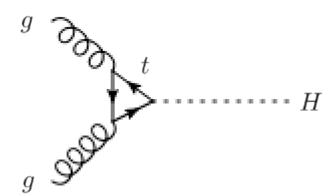
- Breakdown of effective theory can be understood comparing the high energy limit of a pointlike ggH interaction with that of a loop-mediated one:

  - Consider the transverse momentum behaviour of the gg --> H amplitude when gluons are off shell

[Catani, Ciafaloni, Hautmann, '91] [Hautmann, '02] [Pasechnik, Teryaev, Szczurek, '06] [Marzani, Ball, Del Duca, Forte, Vicini, '08]



Transverse momenta can reach kinematic limit given by CM energy



Contribution from large transverse momenta suppressed by massive quark loop

$$\hat{\sigma} \underset{\hat{s}\to\infty}{\sim} \begin{cases} \sum_{k=1}^{\infty} \alpha_s^k \ln^{2k-1}\left(\frac{\hat{s}}{m_H^2}\right) & \text{pointlike: } m_t \to \infty \\ \sum_{k=1}^{\infty} \alpha_s^k \ln^{k-1}\left(\frac{\hat{s}}{m_H^2}\right) & \text{resolved: finite } m_t \end{cases}$$

Corresponding scaling in Higgs pT computed recently:

[Forte Muselli, '15] [Caola, Forte, Marzani, Muselli, Vita, '16]

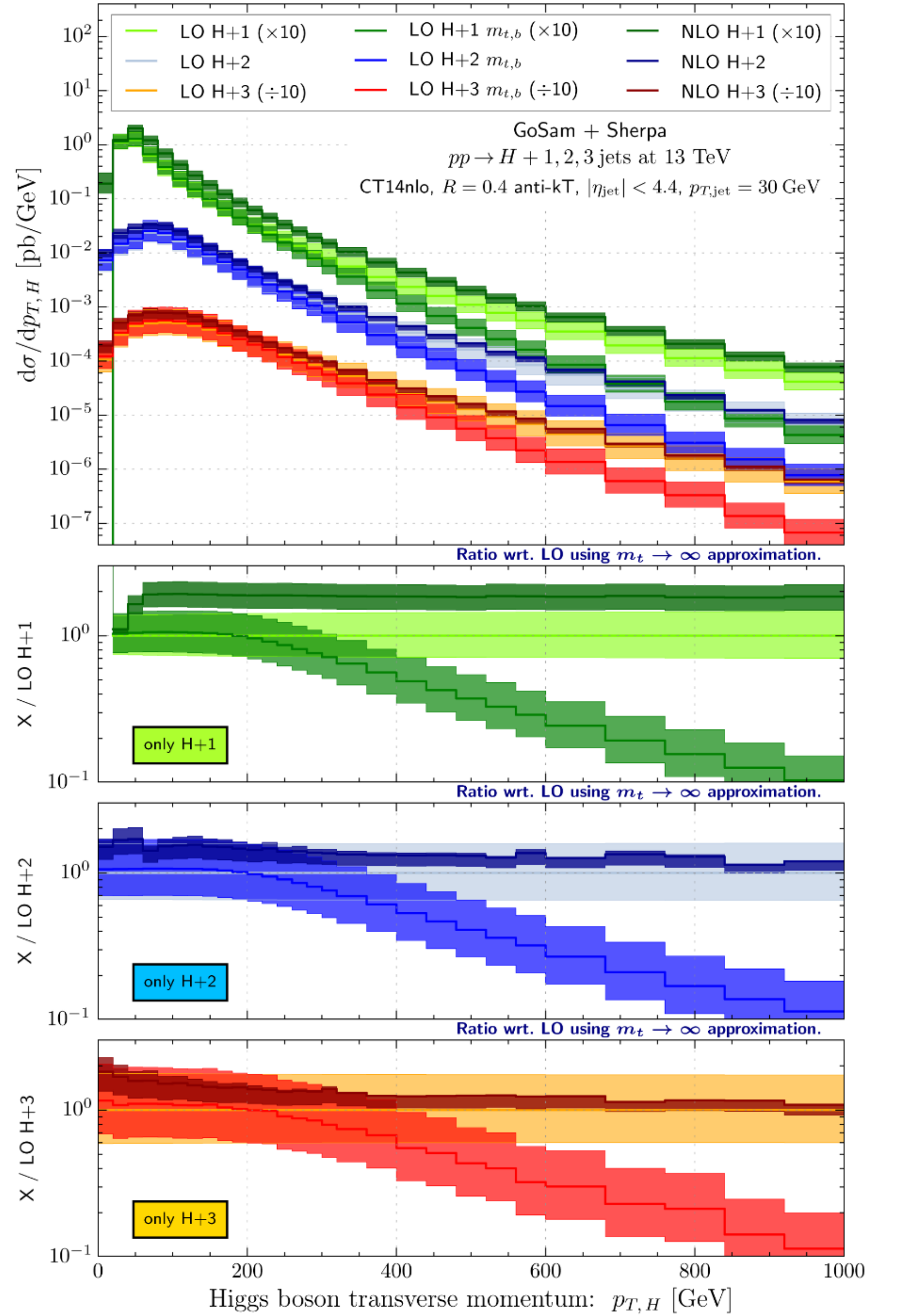
- as $p_{T,\,H} \to \infty$ differential cross section (in p_T^2):

drops like $(p_{T,\,H}^2)^{-1}$

drops like $(p_{T,\,H}^2)^{-2}$

Higgs boson p_T

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



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.

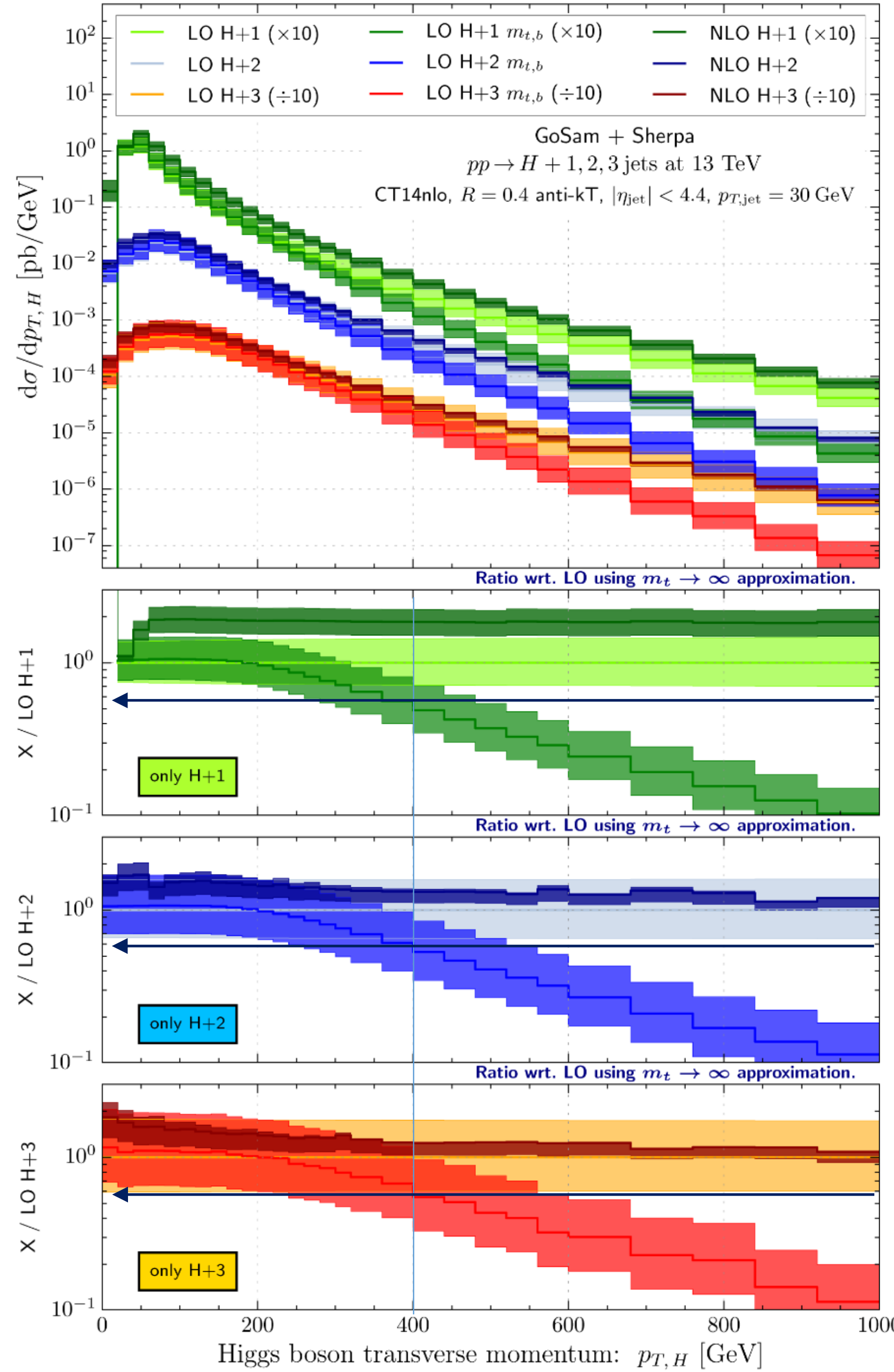
- Rough scaling behaviour from plots:

$$\frac{\frac{\mathrm{d}\sigma}{\mathrm{d}p_{T,\,H}}(p_{T,\,H} = 1.0\ \mathrm{TeV})}{\frac{\mathrm{d}\sigma}{\mathrm{d}p_{T,\,H}}(p_{T,\,H} = 0.4\ \mathrm{TeV})} \approx \frac{10\%}{60\%} = \frac{1}{6}$$

  high-energy limit prediction:

$$\left(\frac{400\ \mathrm{GeV}}{1000\ \mathrm{GeV}}\right)^2 = \frac{4}{25}$$

- Very similar behaviour for the three different multiplicities



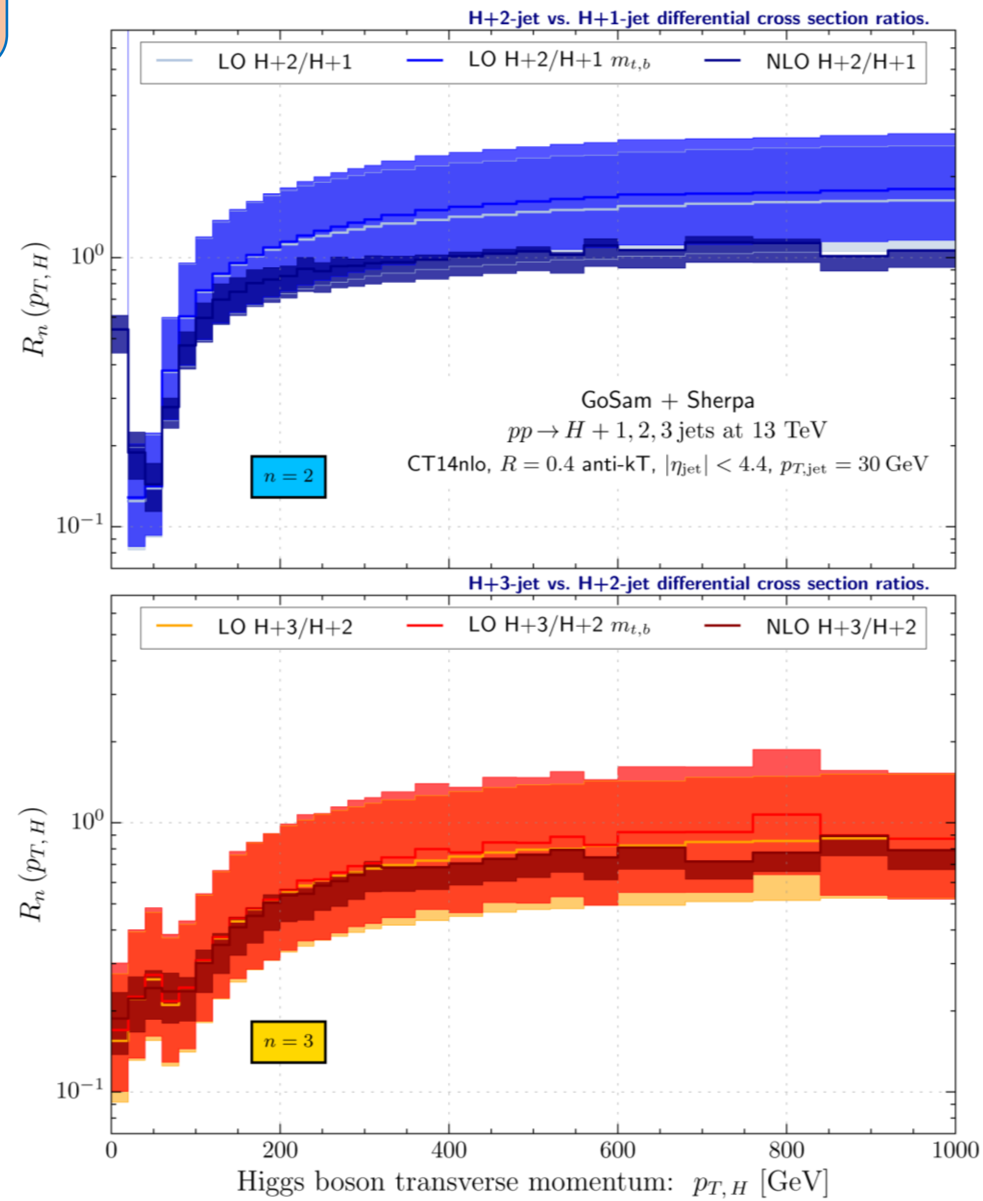
Higgs boson p_T

- 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

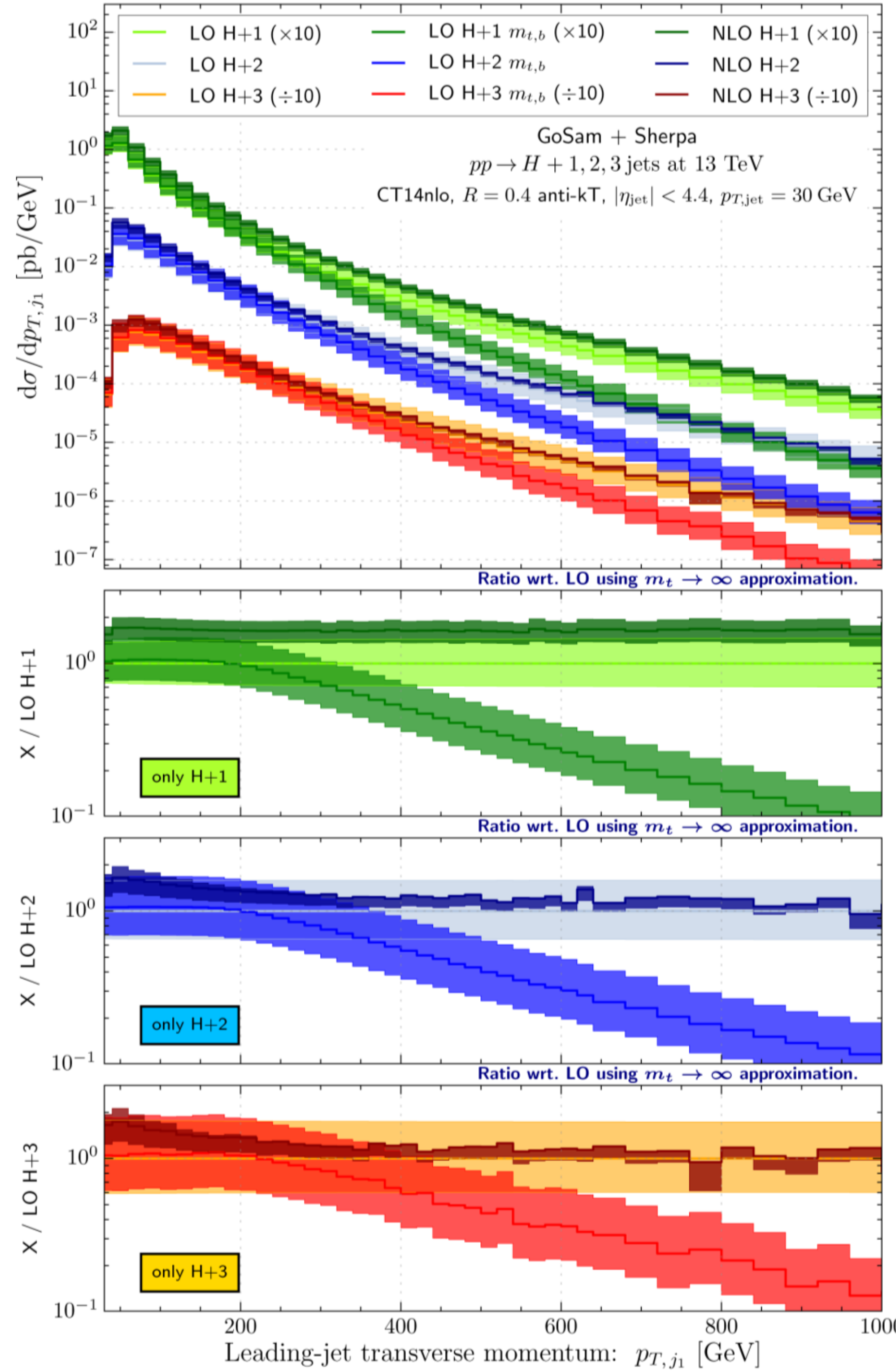
➢ suggests that the different scaling of effective and full theory also holds for higher multiplicities

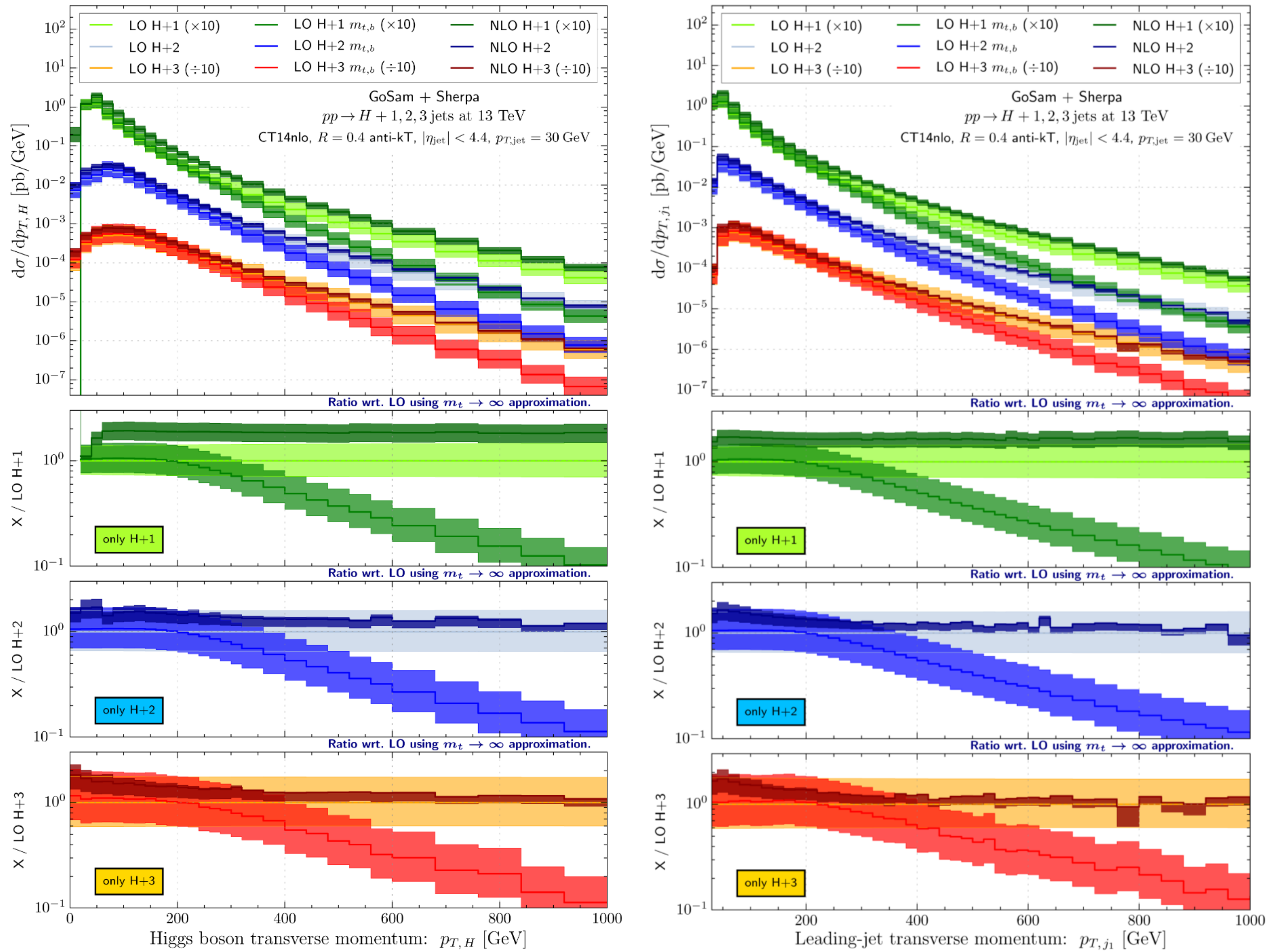


Leading jet p_T

- For H+1j: $p_{T,\,H} = p_{T,\,j_1}$
- However a very similar behaviour is observed also for the higher multiplicities

➢ We can compare them directly ...



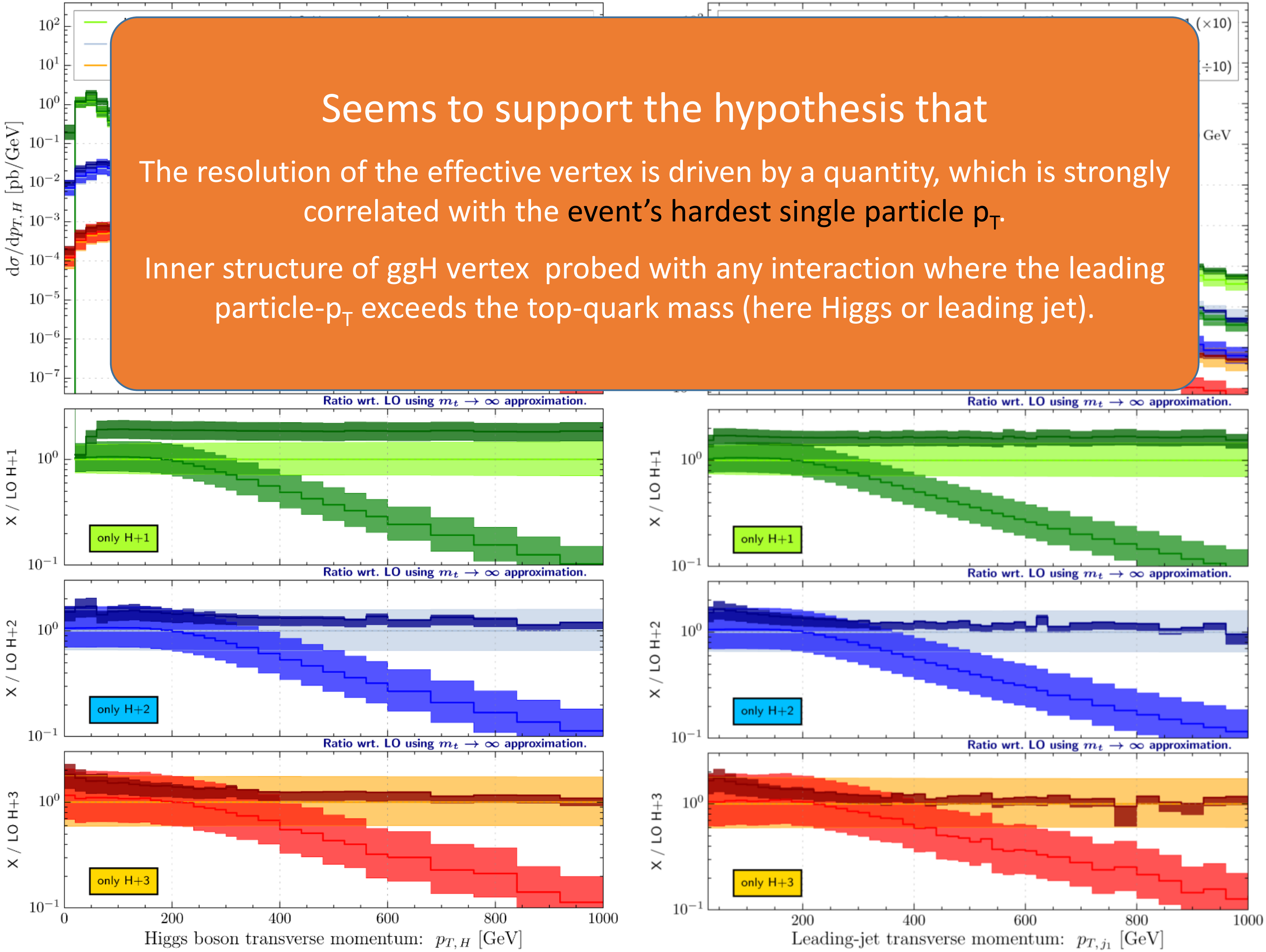


LO H+1 (×10)
LO H+2
LO H+3 (÷10)
LO H+1 $m_{t,b}$ (×10)
LO H+2 $m_{t,b}$
LO H+3 $m_{t,b}$ (÷10)
NLO H+1 (×10)
NLO H+2
NLO H+3 (÷10)
GoSam + Sherpa
$pp \to H + 1, 2, 3$ jets at 13 TeV
CT14nlo, $R = 0.4$ anti-kT, $|\eta_{\rm jet}| < 4.4$, $p_{T,\rm jet} = 30$ GeV
$d\sigma/dp_{T,H}$ [pb/GeV]
$d\sigma/dp_{T,j_1}$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

Seems to support the hypothesis that

The resolution of the effective vertex is driven by a quantity, which is strongly correlated with the event's hardest single particle p_T.

Inner structure of ggH vertex probed with any interaction where the leading particle-p_T exceeds the top-quark mass (here Higgs or leading jet).

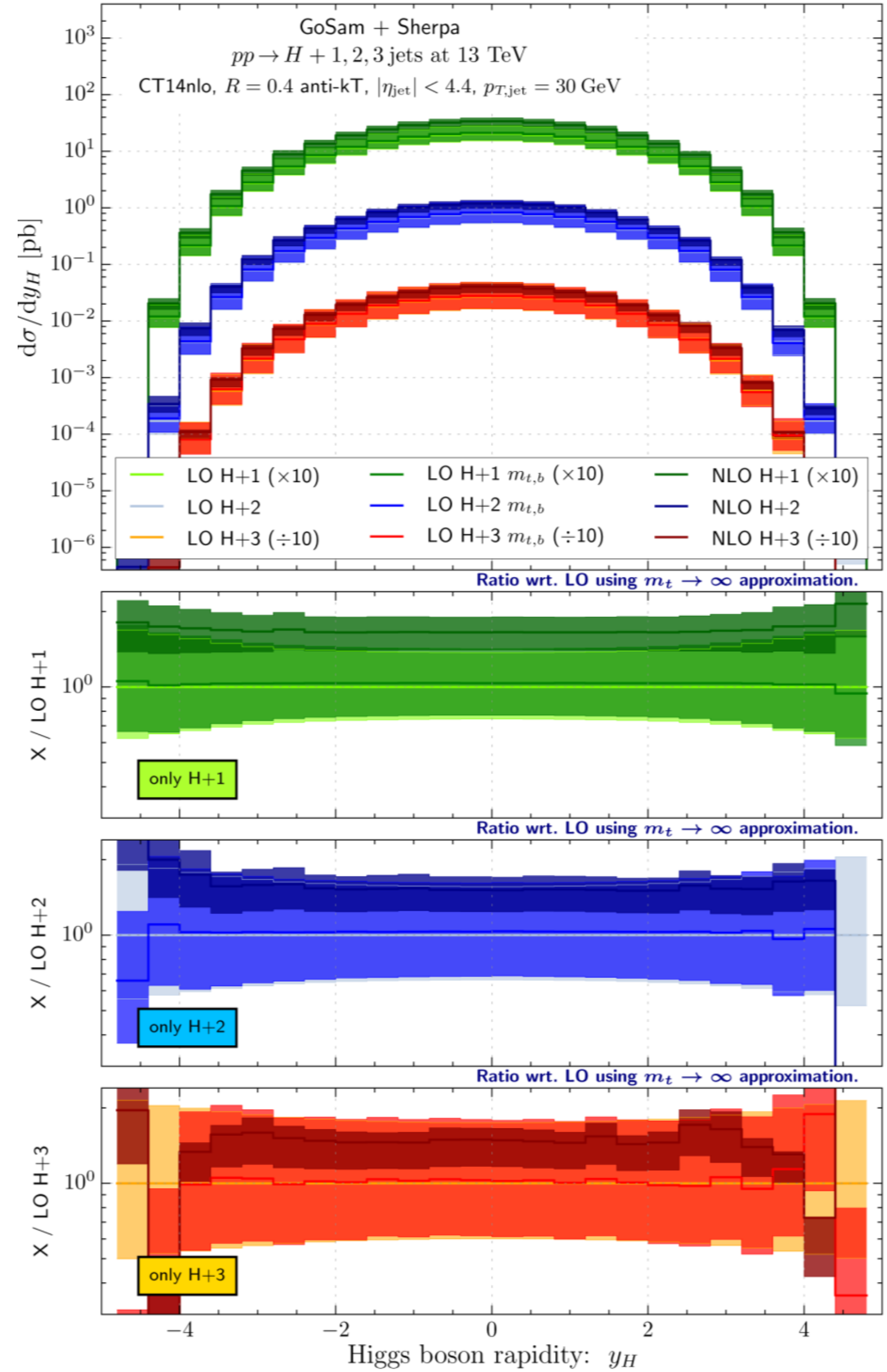


Higgs boson rapidity

- Mass corrections small over full kinematical range:

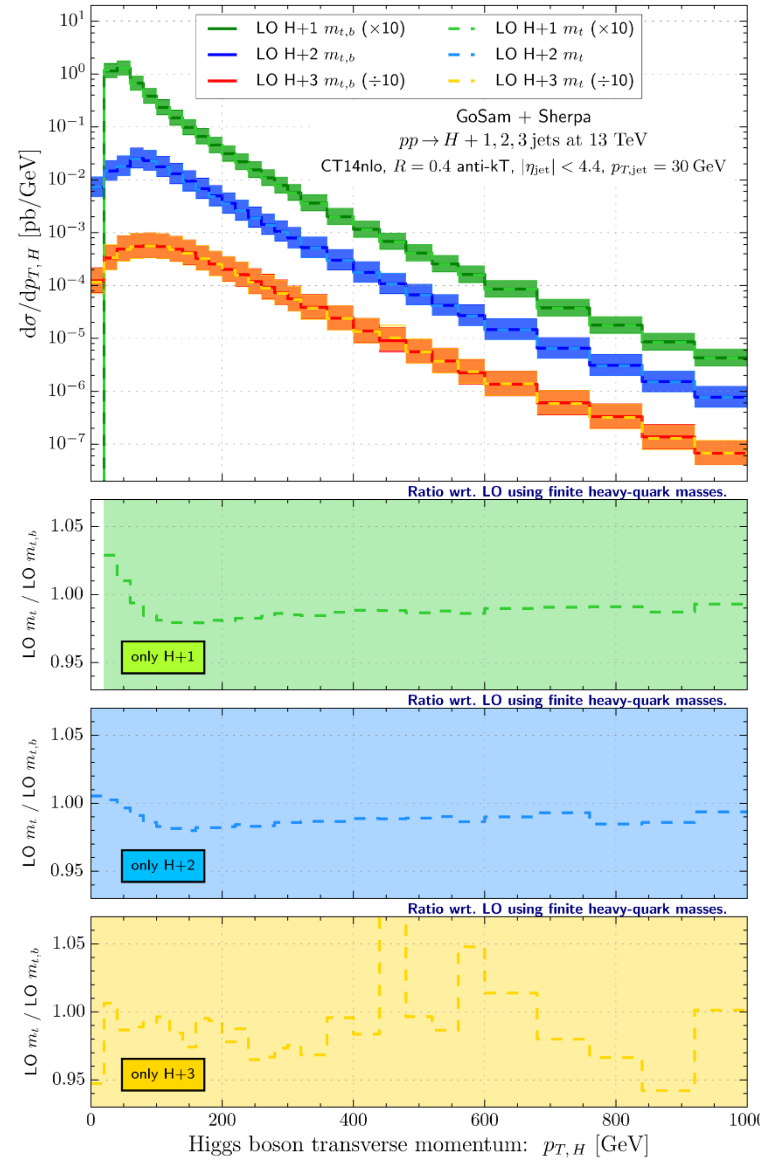
➢ Regions of phase space where quark-loop is resolved are smeared over the entire range

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



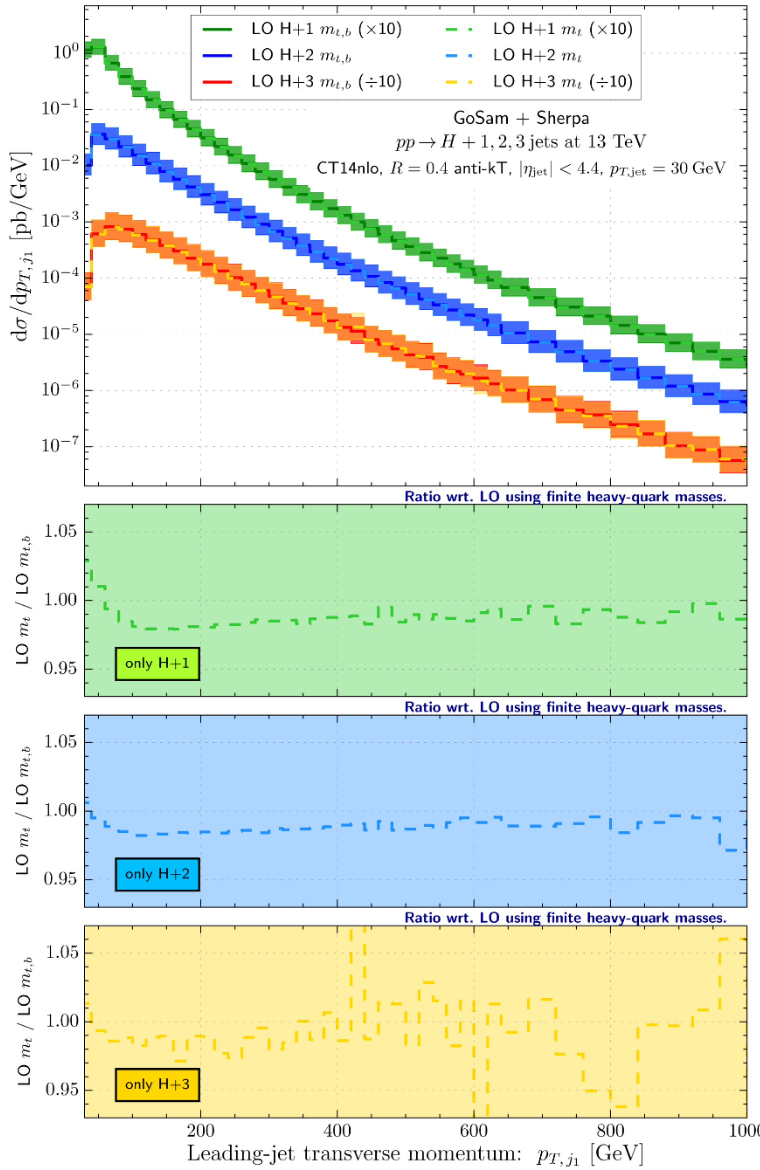
Massless bottom quarks

- 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



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.
  - ➢ Leading jet p_T

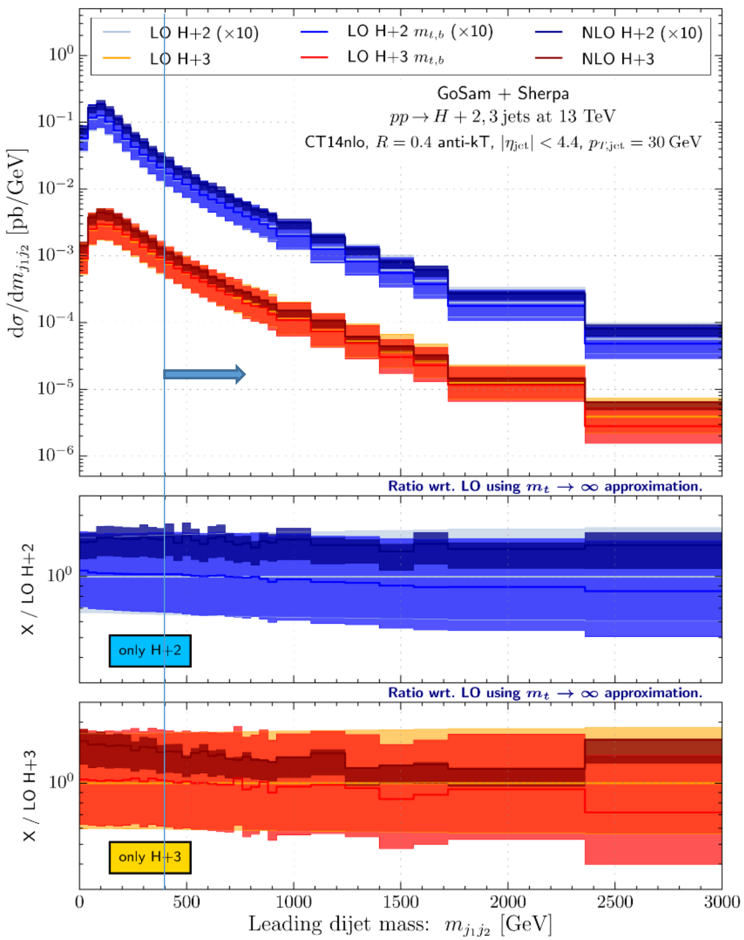


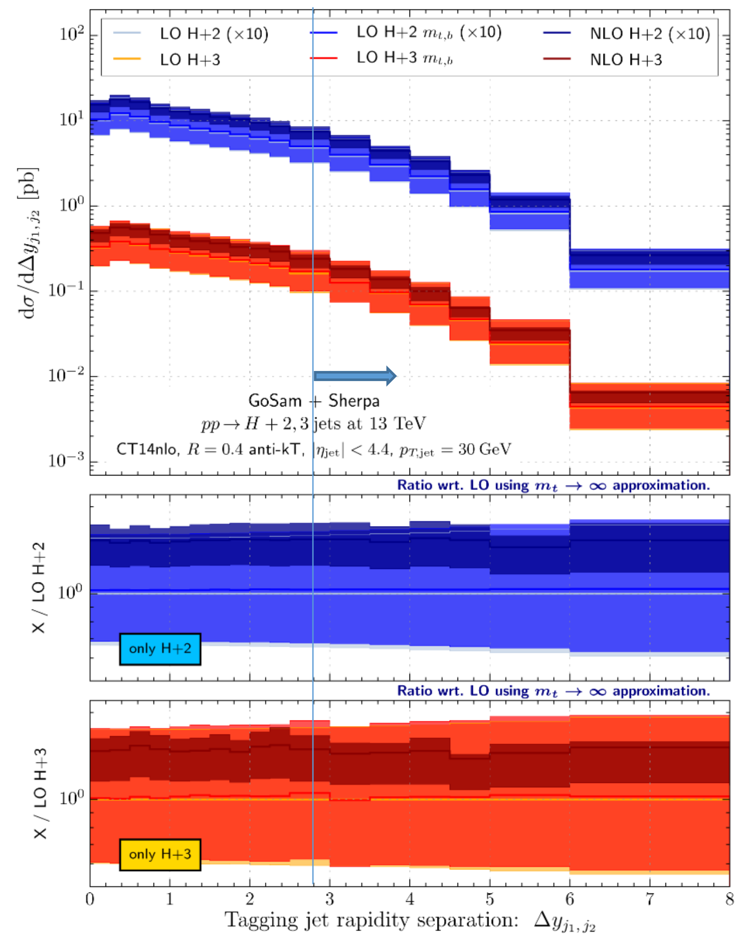
Higgs plus jets in GGF with VBF selection cuts

- 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:

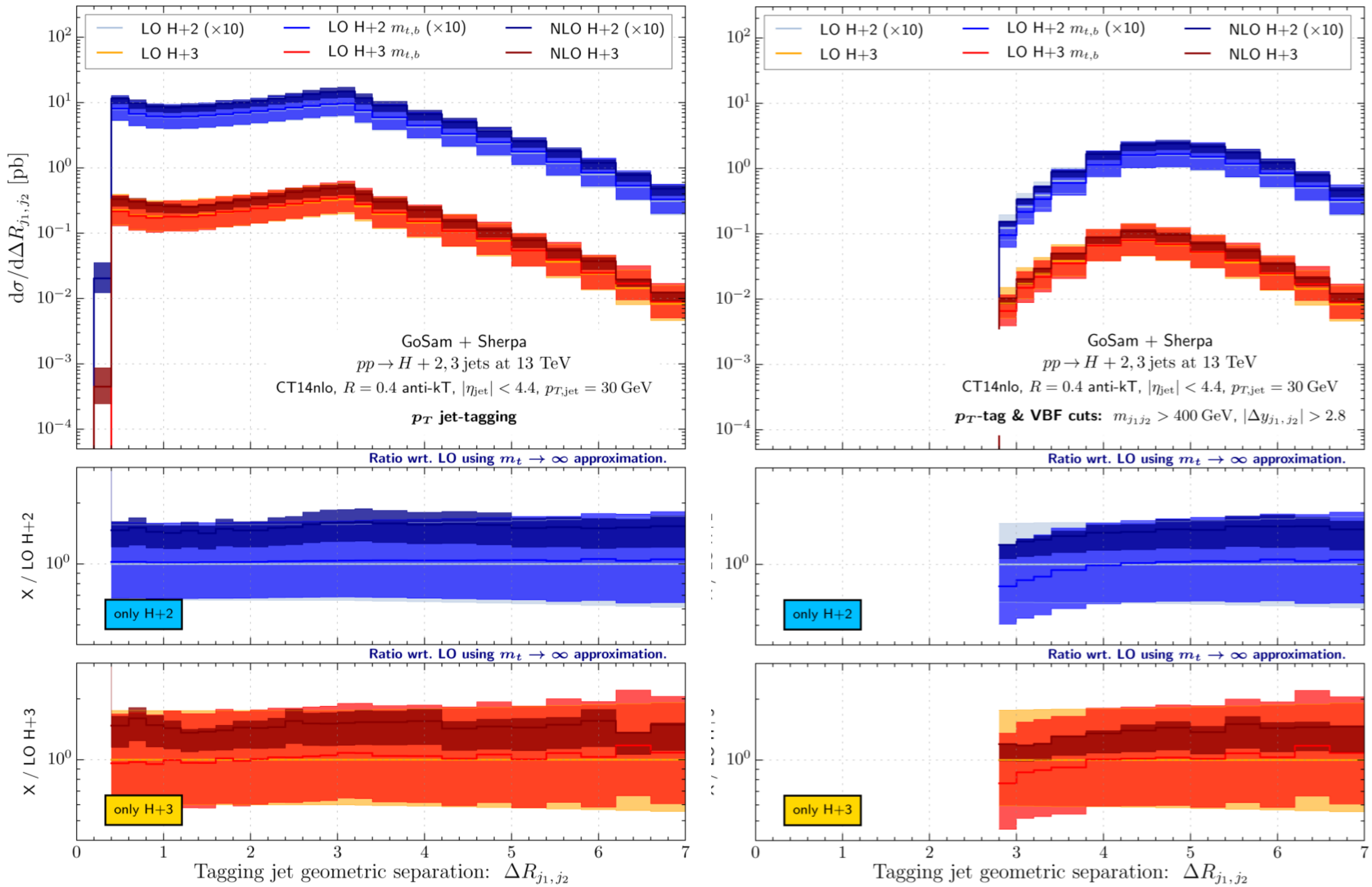
Numbers in [pb]	H+2 jets	H+3 jets
$\sigma_{\mathrm{LO,\,eff.}}$	$0.397^{+64\%}_{-36\%}$	$0.166^{+82\%}_{-42\%}$
$\sigma_{\mathrm{NLO,\,eff.}}$	$0.584^{+10\%}_{-19\%}$	$0.231^{+5\%}_{-22\%}$
$\sigma_{\mathrm{LO},\,m_{t,b}}$	$0.404^{+65\%}_{-37\%}$	$0.167^{+82\%}_{-42\%}$
$\sigma_{\mathrm{LO},\,m_t}$	$0.398^{+65\%}_{-37\%}$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

- 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

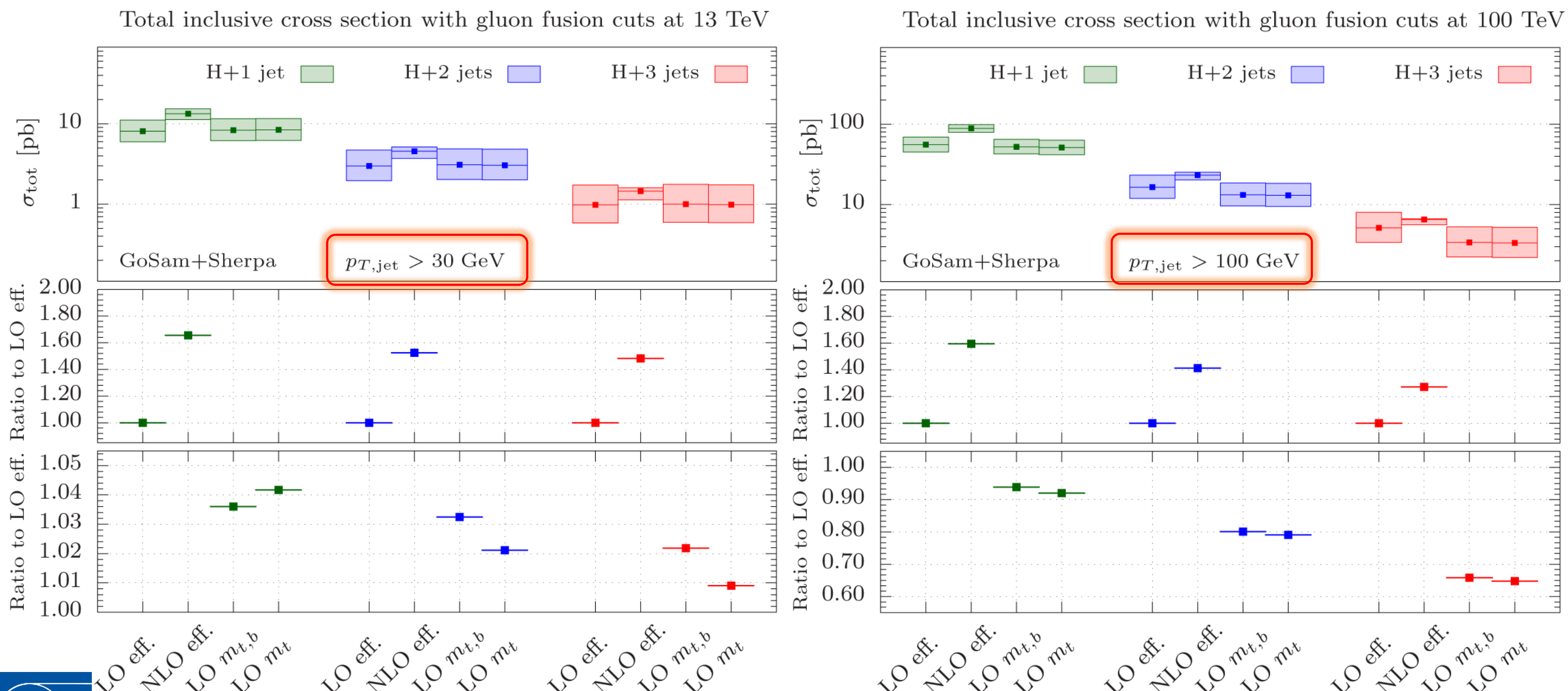
- Effects of VBF selection cuts wrt. baseline cuts:



What changes at a 100 TeV collider?

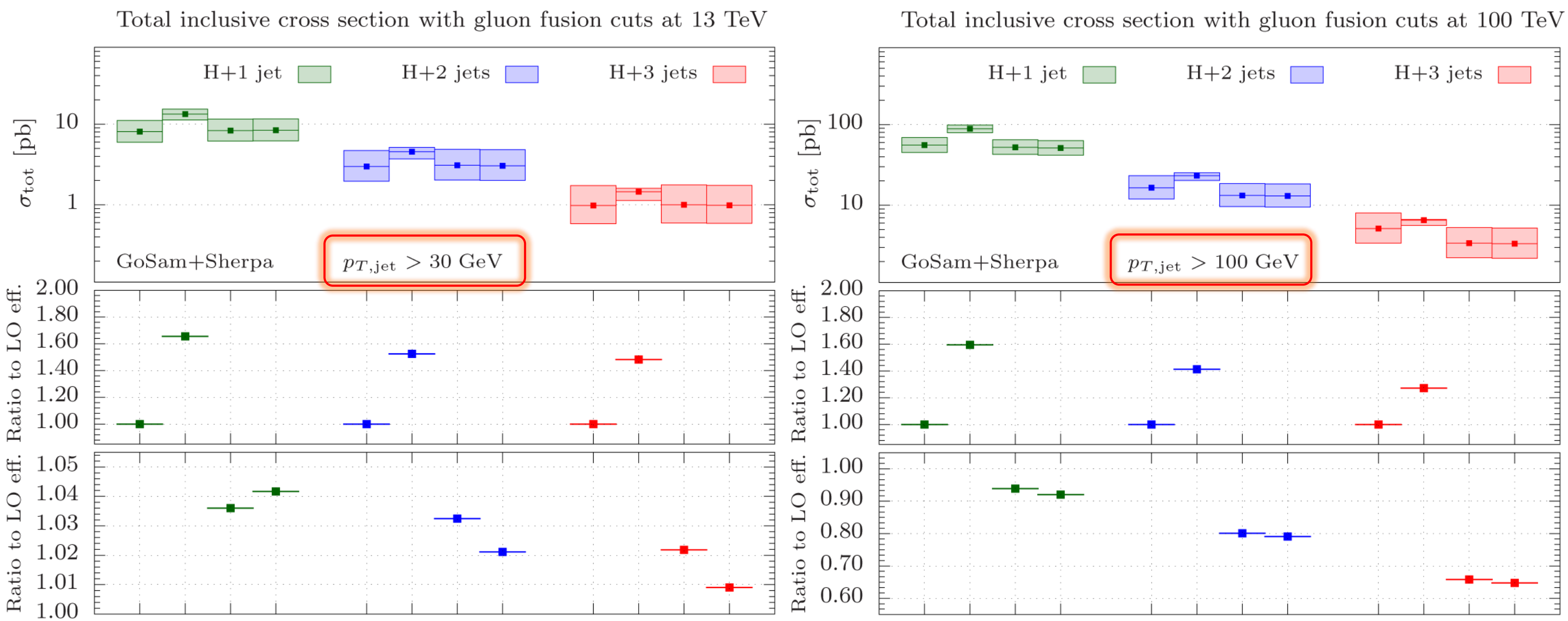
Total cross section: 13 vs 100 TeV

- At 100 TeV run with two different minimal transverse momenta:
  - Anti-kt with $p_T > 30$ GeV and $p_T > 100$ GeV
- Comparison with 13 TeV:



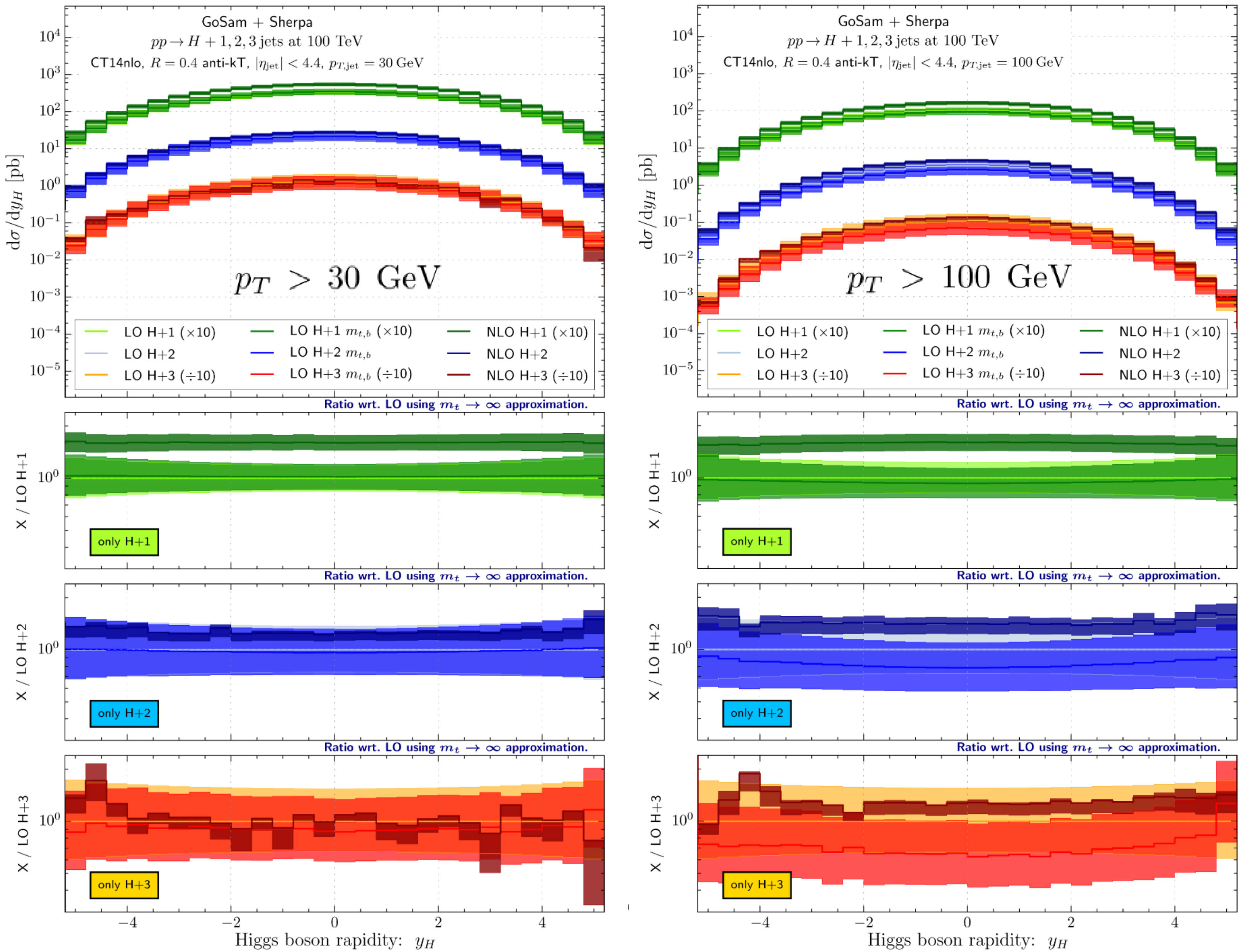
Total cross section: 13 vs 100 TeV

- At 100 TeV run with two different minimal transverse momenta:
  - Anti-kt with $p_T > 30\ \mathrm{GeV}$ and $p_T > 100\ \mathrm{GeV}$
- Comparison with 13 TeV:



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

Higgs boson rapidity at 100 TeV



Conclusions and Outlook

- Higher order QCD corrections to Higgs boson production in association with jets in ggf are large and therefore need to be considered in order to reach a reasonable theoretical accuracy
  - A lot of work was put and is still put in improving these predictions

- 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, future runs and future colliders will be very sensitive to this (FCC is the extreme case)
  - Main driver for the break down of the effective theory seems to be the transverse momentum of the hardest particle in the event
  - Lots of effort lately are put into improving the accuracy of finite mass corrections (NLO will be needed in future)

Backup

Total cross sections in number

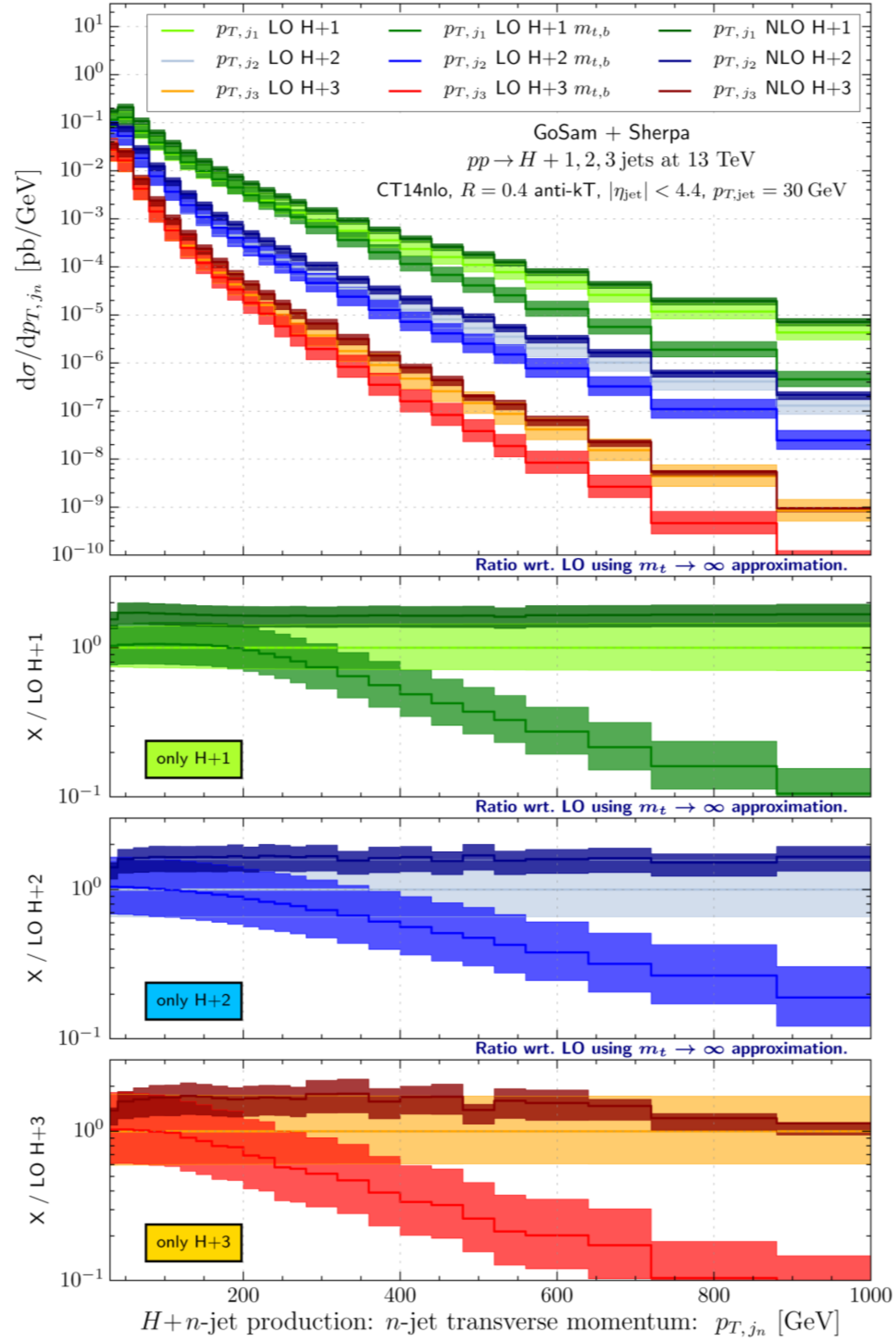
Numbers in [pb]	$p_{T,\text{jet}} > 30$ GeV		$p_{T,\text{jet}} > 100$ GeV
$\sqrt{s}$	13 TeV	100 TeV	100 TeV
H+1 jet			
$\sigma_{\text{LO, eff.}}$	$8.06^{+38\%}_{-26\%}$	$196^{+21\%}_{-17\%}$	$55.7^{+24\%}_{-19\%}$
$\sigma_{\text{NLO, eff.}}$	$13.3^{+15\%}_{-15\%}$	$315^{+11\%}_{-10\%}$	$88.8^{+11\%}_{-11\%}$
$\sigma_{\text{LO}, m_{t,b}}$	$8.35^{+38\%}_{-26\%}$	$200^{+20\%}_{-17\%}$	$52.3^{+24\%}_{-19\%}$
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}	$0.99^{+77\%}_{-41\%}$	$62.7^{+56\%}_{-34\%}$	$3.32^{+56\%}_{-34\%}$

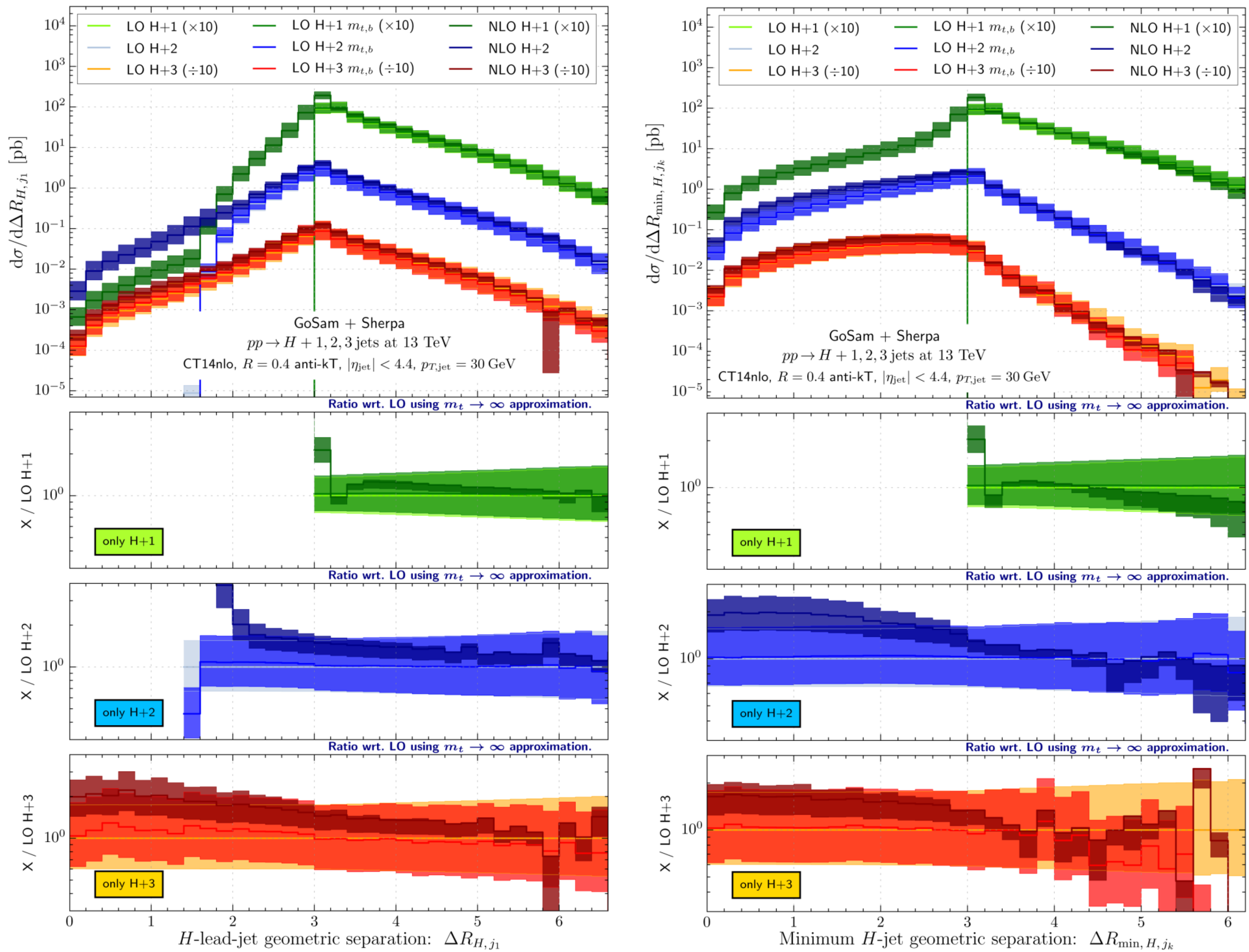
Wimpiest jet p_T

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

Higgs transverse momentum spectrum: 8, 13 TeV

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