Higgs Boson production in association with jets in gluon-gluon fusion

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In collaboration with:

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References:

arXiv:1307.4737 and arXiv: 1506.01016

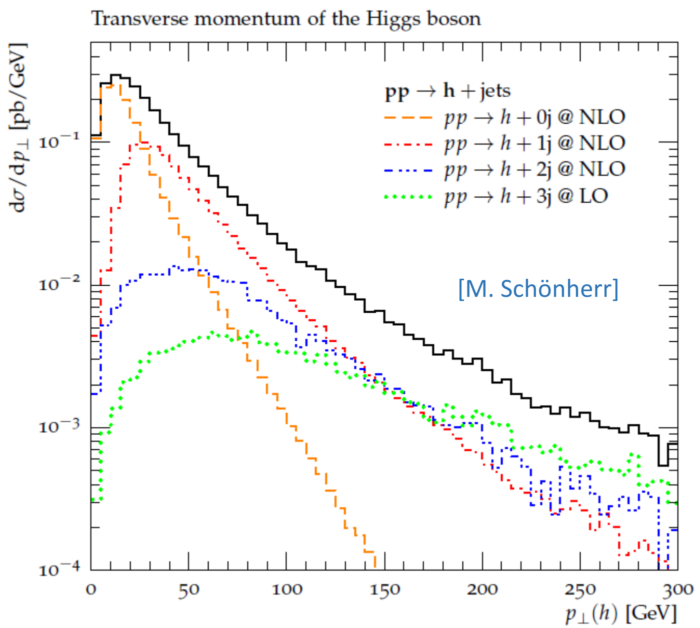
Outline

- **Introduction**
- **H+2 jets and H+3 jets in GGF**
  - Computational setup
  - Root Ntuples
  - Total cross section, scale dependence, PDFs, jet radius, jet tagging strategy
  - Effect of VBF selection cuts
- **Outlook**
  - Finite mass effects
  - Beyond pure FO: merging and matching - the LH2015 study
- **Conclusions**

H+jets in gluon-gluon fusion at NLO

- So far: very accurate predictions for inclusive Higgs production

- For higher jet multiplicities beyond LO accuracy we need to «give up some loops» in favor of more legs at lower accuracy
  - Different multiplicities can be merged at NLO and/or LO accuracy

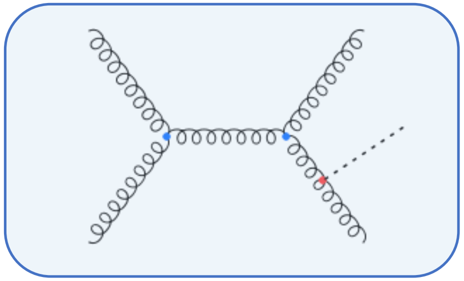


- Furthermore: for processes in which the Higgs boson is unavoidably accompagnied by jets, we can explicitly request the presence of further jets (this is the case in VBF production)

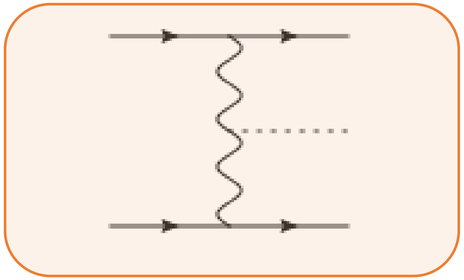
- Important to keep in mind that we are working in an effective theory with limited predictive power!

Higgs production in association with 2 and 3 jets

- When **two** (light) accompanying jets are tagged, the Higgs boson can be produced via GGF or VBF.



vs.



- The VBF-channel is very peculiar:
  - Largest cross section that involves tree-level production of the Higgs
  - Probes coupling of Higgs to electroweak bosons
  - Very distinctive signature:
    - ➢ 2 forward jets with large invariant mass, little central jet activity
    - ➢ easier to tag decays that normally have large background (e.g. $\tau\tau$)
  - Particularly sensitive to CP properties and non-standard interactions

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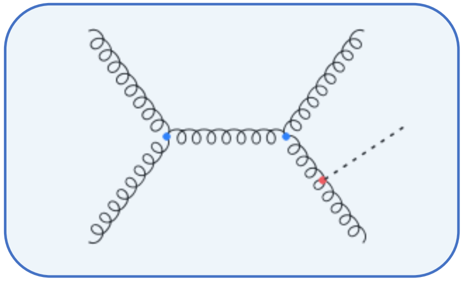

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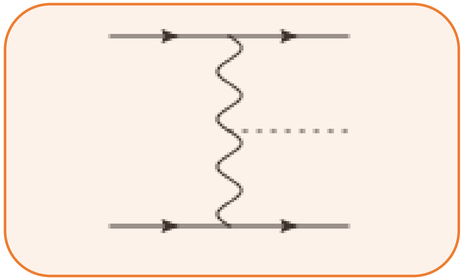


- The VBF-channel is very peculiar:

… but:

➢ In order to be able to fully exploit all these features, it is important to know how to discriminate it from the large GGF background, and to keep uncertainties under control, by choosing the best selection strategies.

➢ For this reason a precise knowledge of the **H+2 jets** and **H+3 jets** processes both in GGF and in VBF is important (effects of veto, exclusive jet bins,..)

- <u>In this talk</u> focus on the computation of the GGF contribution

NLO Results

- For a full NLO calculation other ingredients are needed:

$$\sigma_{\mathrm{NLO}} = \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{Born}} + \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{NLO}} - \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NLO}}\right) + \int_{\mathrm{d}\Phi_m} \left[\int_{\mathrm{d}\Phi_1} \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NLO}} + \mathrm{d}\sigma^{V}_{\mathrm{NLO}}\right]$$

- Virtual corrections

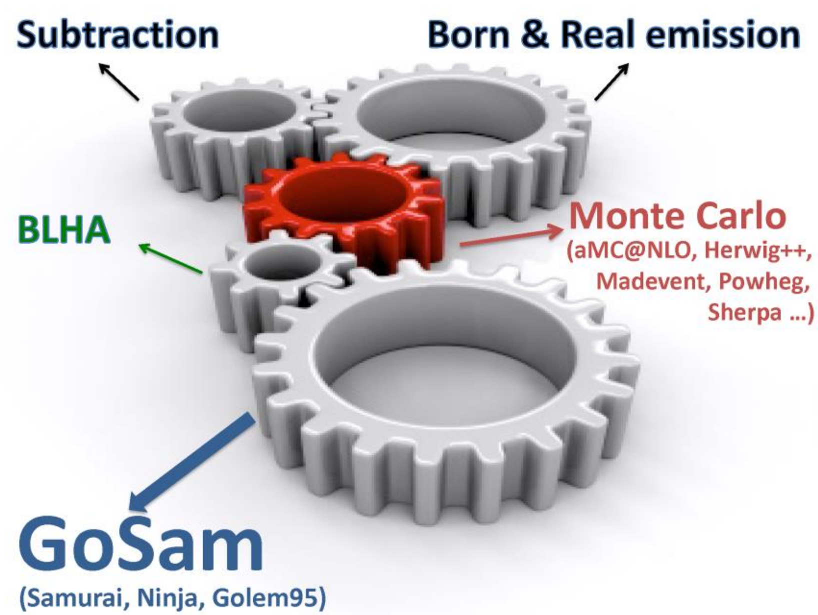
One Loop Program: GoSam

BLHA

Monte Carlo: Sherpa

- Tree amplitude
- Subtraction scheme
- Phase space integral

NTuples



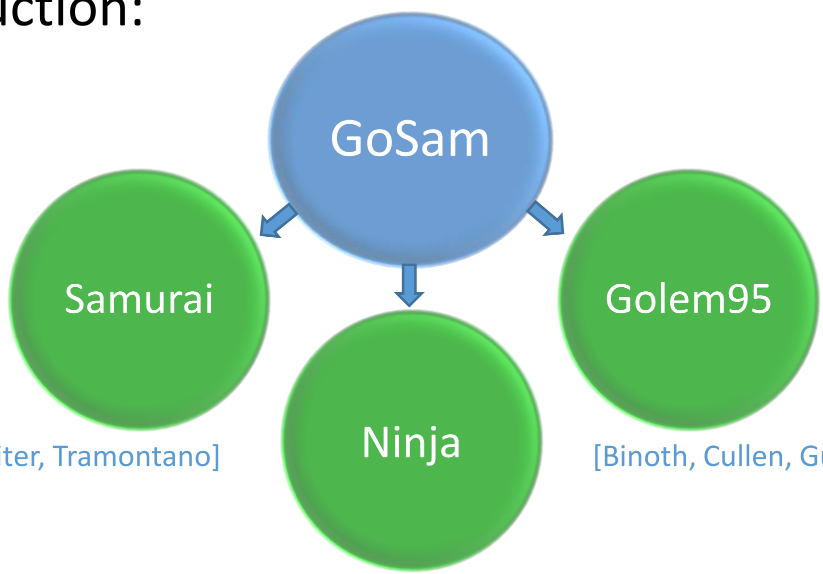
[**GoSam**: Binoth, Cullen, v. Deurzen, Greiner, Heinrich, Jahn, Mastrolia, Mirabella, Ossola, Peraro, Reiter, Reichel, Schlenk, v. Soden-Fraunhofer, Tramontano, GL]

[**Sherpa**: Gleisberg, Höche, Krauss, Schönherr, Schumann, Winter, Zapp]

GoSam

http://gosam.hepforge.org

- An automated tool to compute virtual 1-loop amplitudes:
  - Generation of numerators based on Feynman diagrams
    ➔ QGRAF [Nogueira]
  - Algebraic manipulation in D-dimensions before reduction
    ➔ FORM-4 [Kuipers, Ueda, Vermaseren]
  - Optimization: caching/grouping/summing
  - Reduction:



[Mastrolia, Ossola, Reiter, Tramontano]

[Binoth, Cullen, Guillet, Heinrich, Pilon, Reiter]

[Mastrolia, Mirabella, Peraro]
[Van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro; Peraro]

All reduction programs support higher rank integrals

Towards GoSam@2loop: see talk by G. Heinrich

Computational setup

- Virtual amplitudes: GoSam with Ninja

[Mastrolia, Mirabella, Ossola, Peraro; v. Deurzen, Mastrolia, Ossola, Peraro, GL; Peraro]

-> scalar loop integrals evaluated using OneLoop [v. Hameren]

- 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 and 13 TeV and now for 14 and 100 TeV too

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

✓Allow for fast analysis, change of **scale, pdf, cuts, jet-tagging**

Root Ntuples format

- Root Ntuple are compressed event files with all ingredients needed to compute differential distributions for a specific process

'id'	Event ID to identify correlated real sub-events.
'nparticle'	Number of outgoing partons.
'E/px/py/pz'	Momentum components of the partons.
'kf'	Parton PDG code.
'weight'	Event weight, if sub-event is treated independently.
'weight2'	Event weight, if correlated sub-events are treated as single event.
'me_wgt'	ME weight (w/o PDF), corresponds to 'weight'.
'me_wgt2'	ME weight (w/o PDF), corresponds to 'weight2'.
'id1'	PDG code of incoming parton 1.
'id2'	PDG code of incoming parton 2.
'fac_scale'	Factorisation scale.
'ren_scale'	Renormalisation scale.
'x1'	Bjorken-x of incoming parton 1.
'x2'	Bjorken-x of incoming parton 2.
'x1p'	x' for I-piece of incoming parton 1.
'x2p'	x' for I-piece of incoming parton 2.
'nuwgt'	Number of additional ME weights for loops and integrated subtraction terms.
'usr_wgt[nuwgt]'	Additional ME weights for loops and integrated subtraction terms.

Produced sets of 'B', 'V', 'I' and 'RS' Ntuples which can be analyzed and processed separately

The new EDNtuples (Exact Double Ntuples)

- In order to allow for more flexibility Ntuples format was extended for most recent the Higgs+jets studies:

- Event kinematics stored in double precision instead of float
- Flavor of initial particles

MiNLO scale choice

[Hamilton, Nason, Zanderighi; Höche]

- Store exact number of trials between two events at generation

Exact statistical treatment

- Phase space weight

A posteriori change of event weight related to ME

Used e.g. for finite top mass corrections..

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 year on 100 cores)

Physical setup

[Greiner, Höche, Schönherr, Yundin, Winter, GL, ‘15]

- All results computed in the $m_{top} \longrightarrow \infty$ approximation

- 3 scale choices: $$\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\mathrm{H}}^2 + p_{T,\mathrm{H}}^2} + \sum_i |p_{T,i}|\right)$$

A: $\alpha_s\left(x \cdot \frac{\hat{H}'_T}{2}\right)^3 \alpha_s\left(x \cdot m_{\mathrm{H}}\right)^2$

B: $\alpha_s\left(x \cdot \frac{\hat{H}'_T}{2}\right)^5$
Default

C: $\alpha_s\left(x \cdot m_{\mathrm{H}}\right)^5$

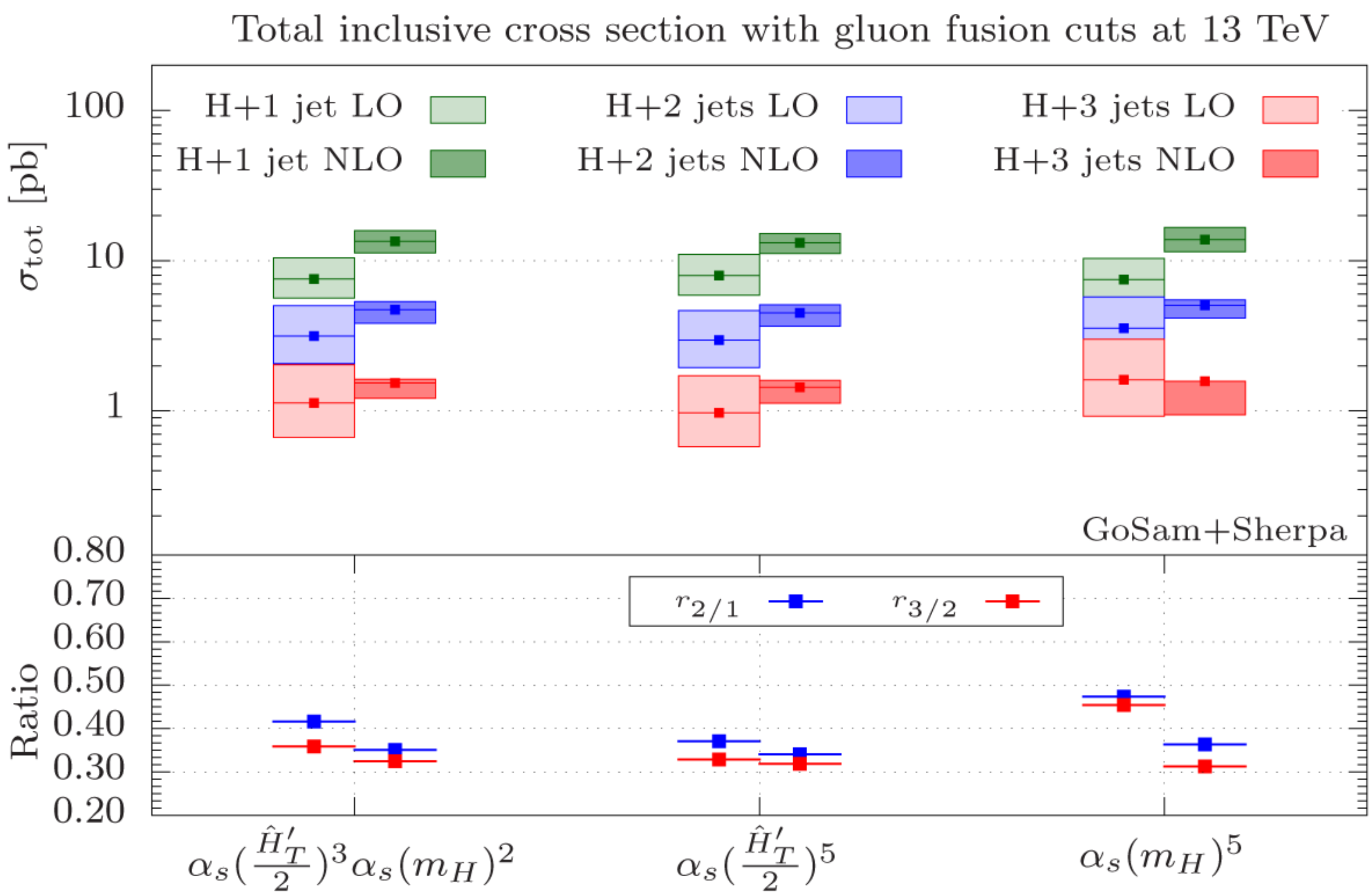
- PDFs: CT10nlo

- **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 set has events with $p_T > 25\ \mathrm{GeV}$, $|\eta| < 4.5$ for the jets at the generation level

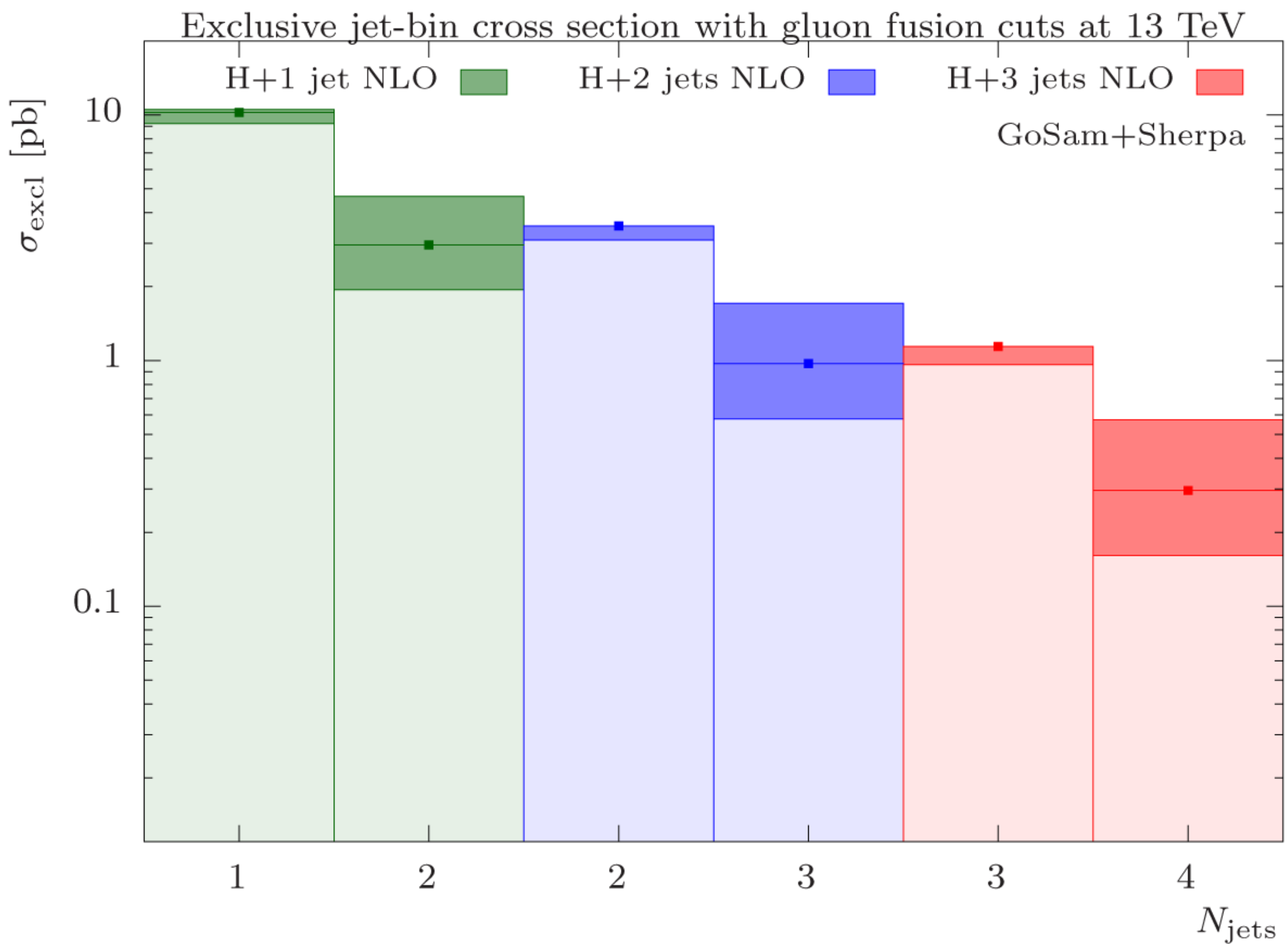
Total cross section: 13 TeV



- $r_{3/2}$ ratio very stable --> extrapolate?
- possibility to compare ratios between different hard processes

$$r_{n/n-1} = \frac{\sigma_{\mathrm{tot}}(\mathrm{H}+n\,\mathrm{jets})}{\sigma_{\mathrm{tot}}(\mathrm{H}+(n-1)\,\mathrm{jets})}$$

Exclusive jet-bin cross sections



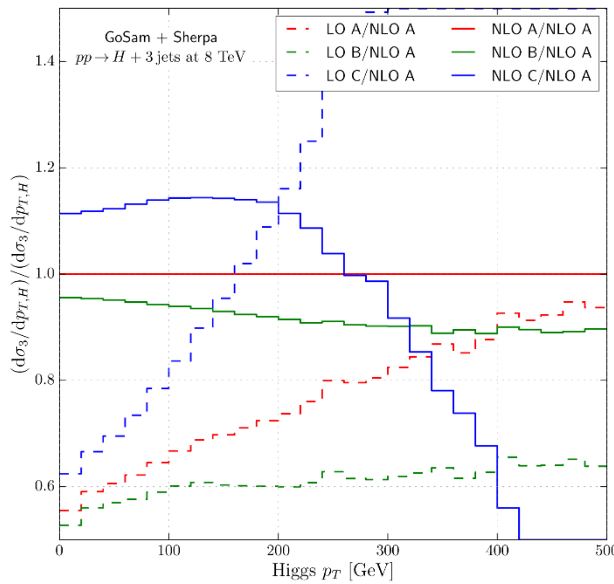
- For each of the final state multiplicities the respective (n+1)-jet contribution is sizeable

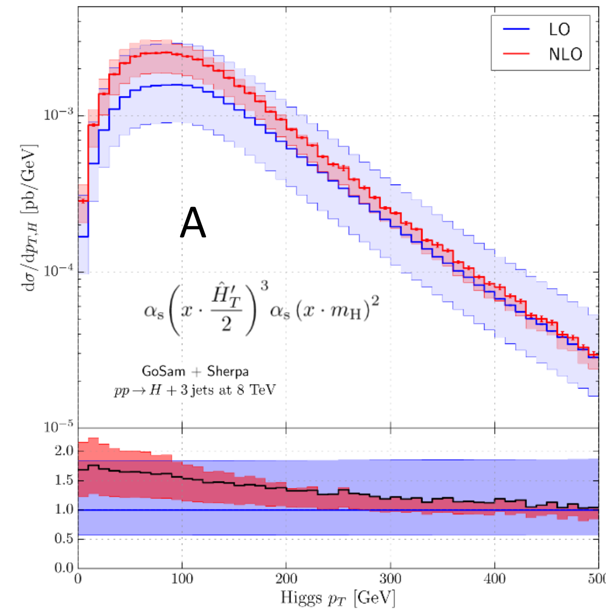
Scales and scale dependence: H+3 jets

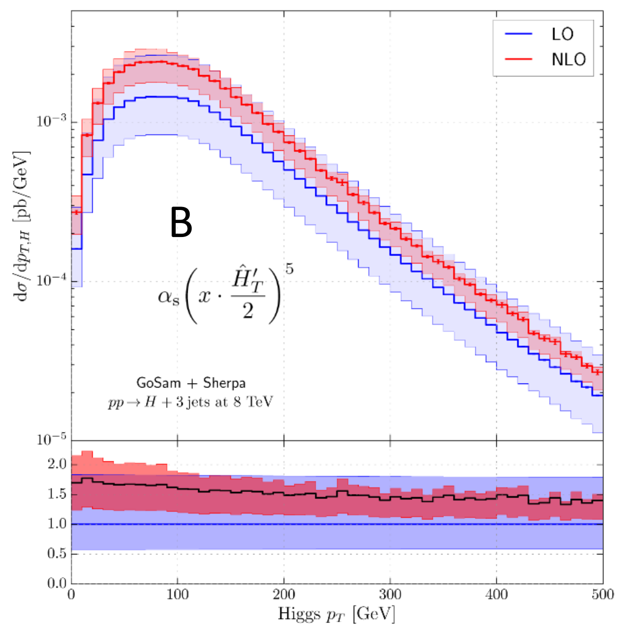
Transverse momentum Distribution for scale choices A, B and C

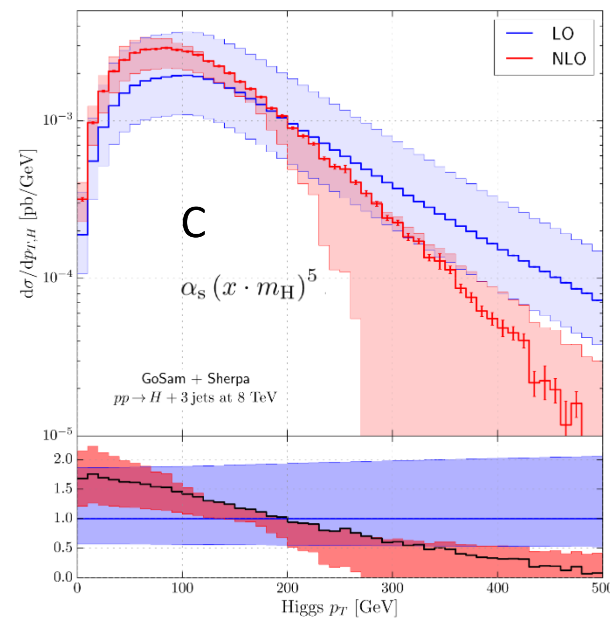
- Fixed scale (C) not a good choice

- Scale choice (B) gives the best combination of moderate radiative corrections and constant K-factor (NLO/LO ratio).

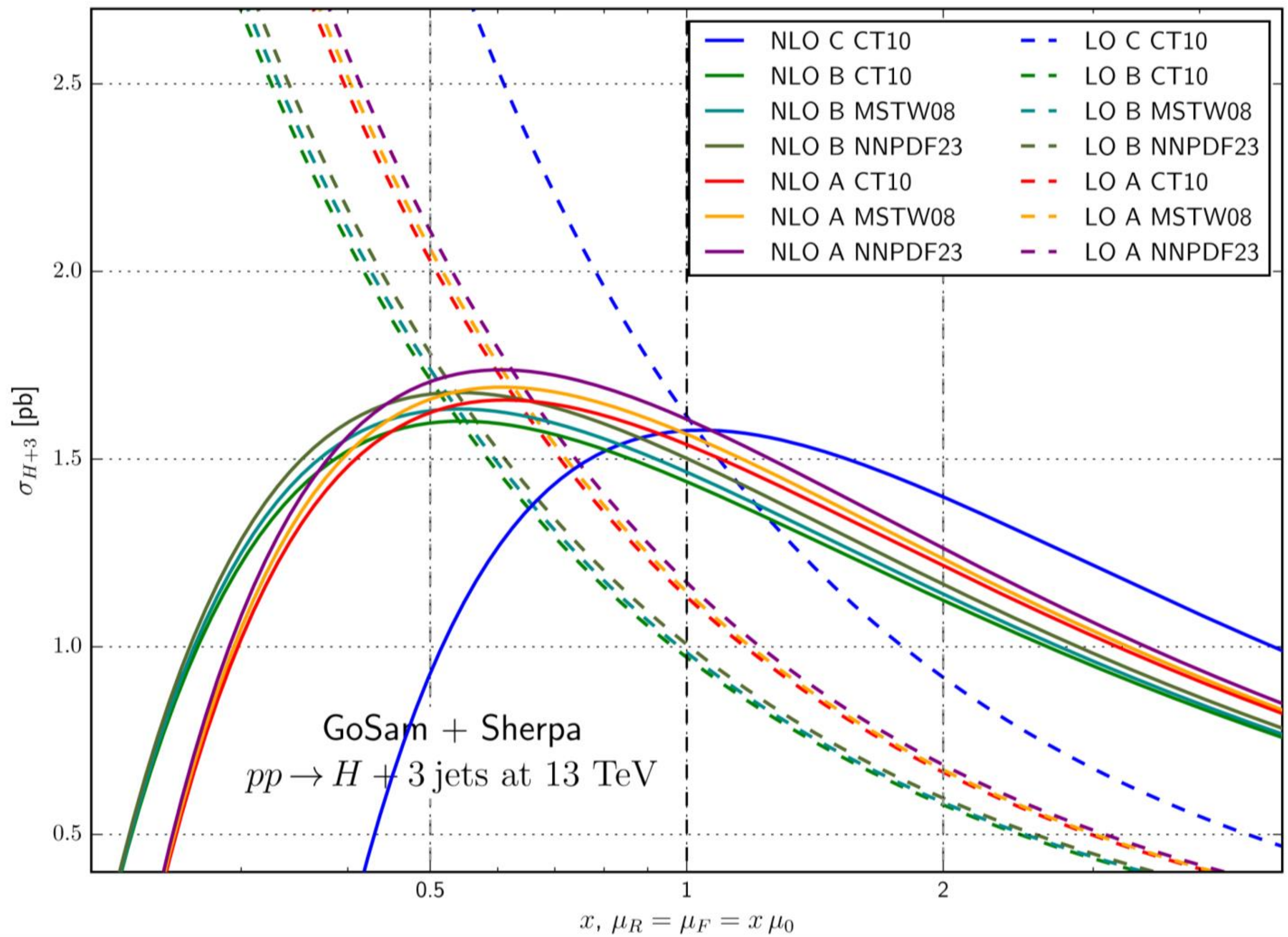






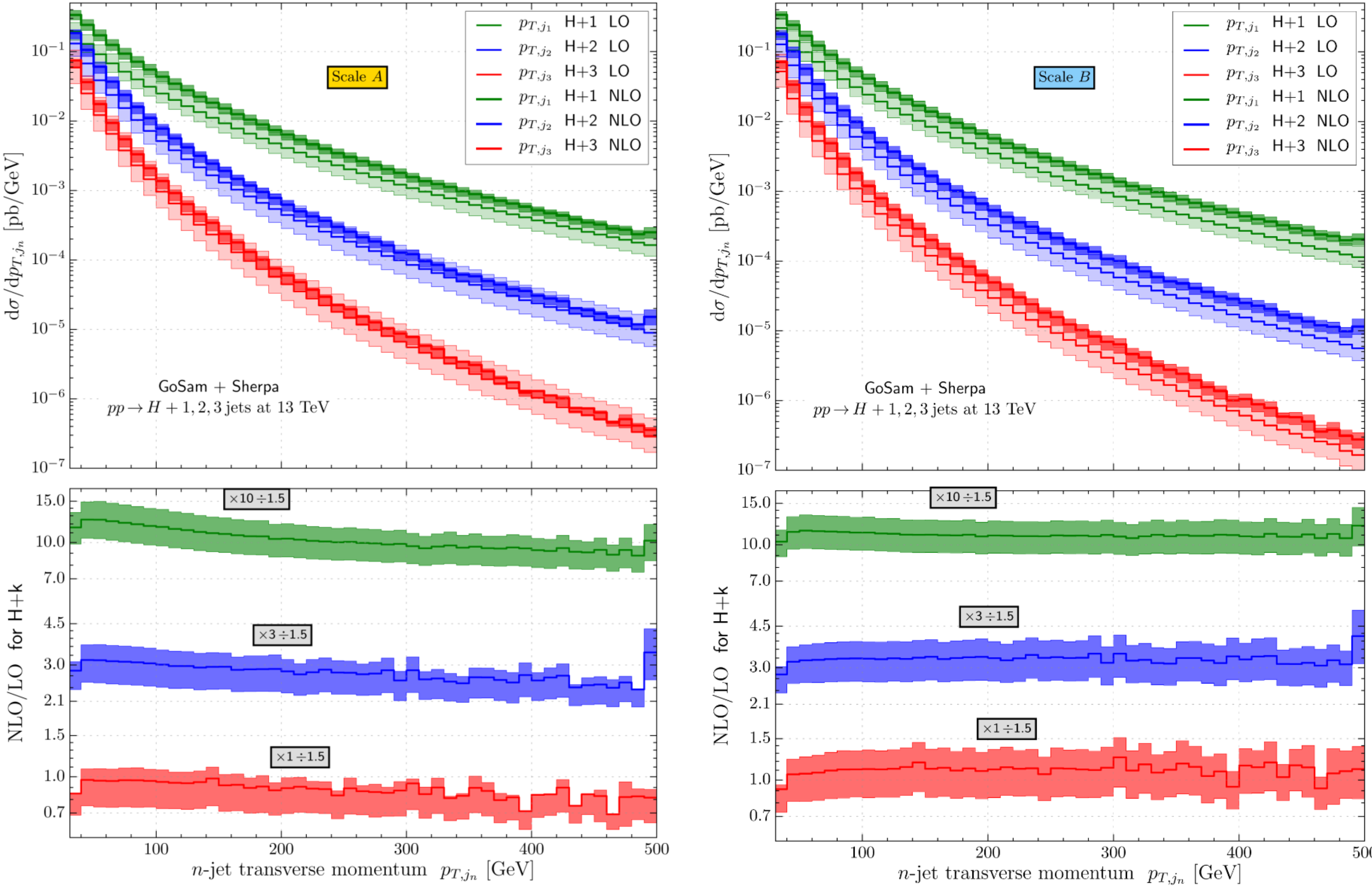


Scales and scale dependence: H+3 jets



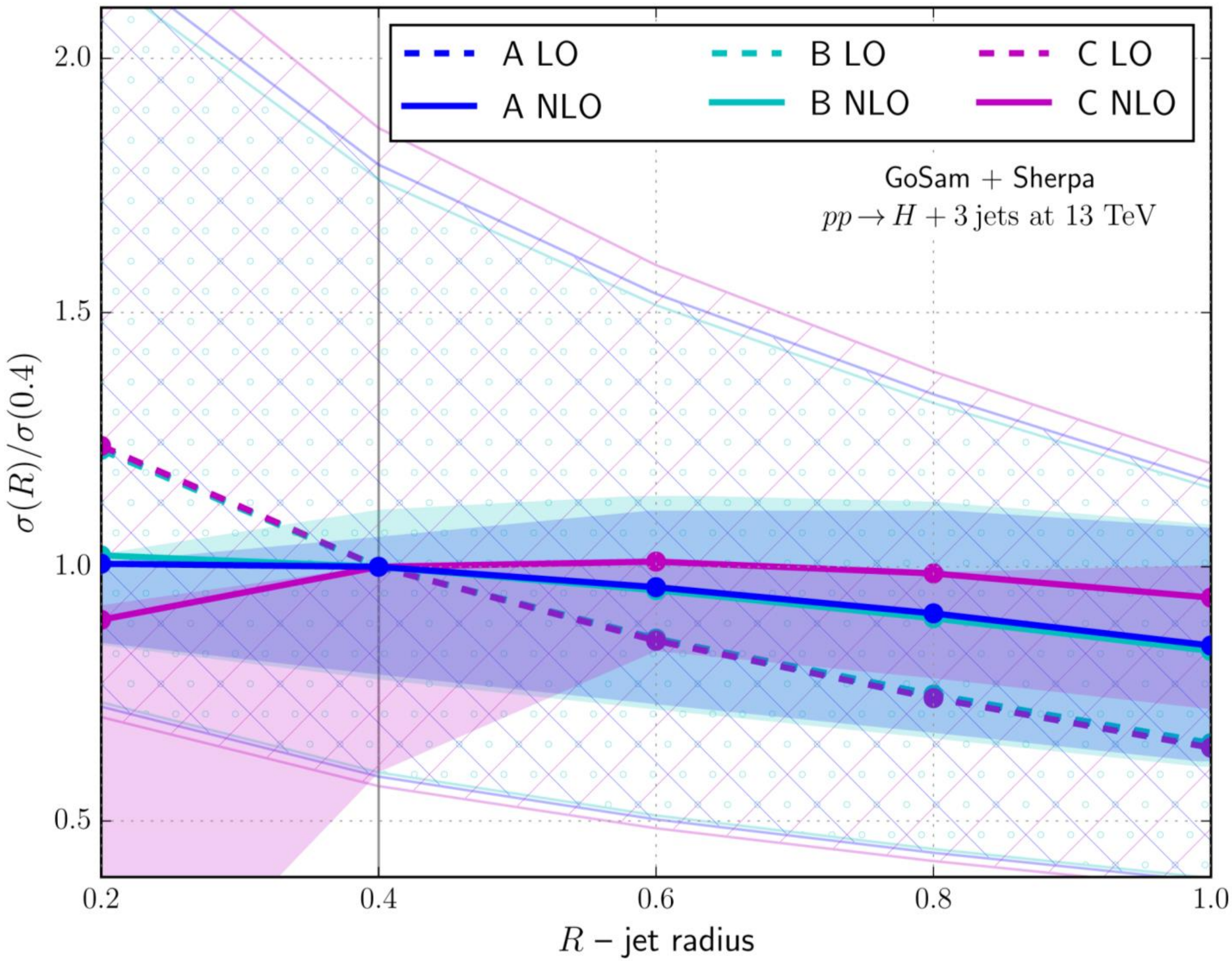
- PDF convolution and scale variation performed with ApplGrid

[Carli, Clements, Cooper-Sarkar, Gweland, Salam, Siegert, Starovoitov, Sutton, '10]



- The K-factor of the wimpiest jet is flat when using the scale choice B
  - This is consistent with similar observations made for V+jets (V = Z, W).

Dependence of the jet radius R



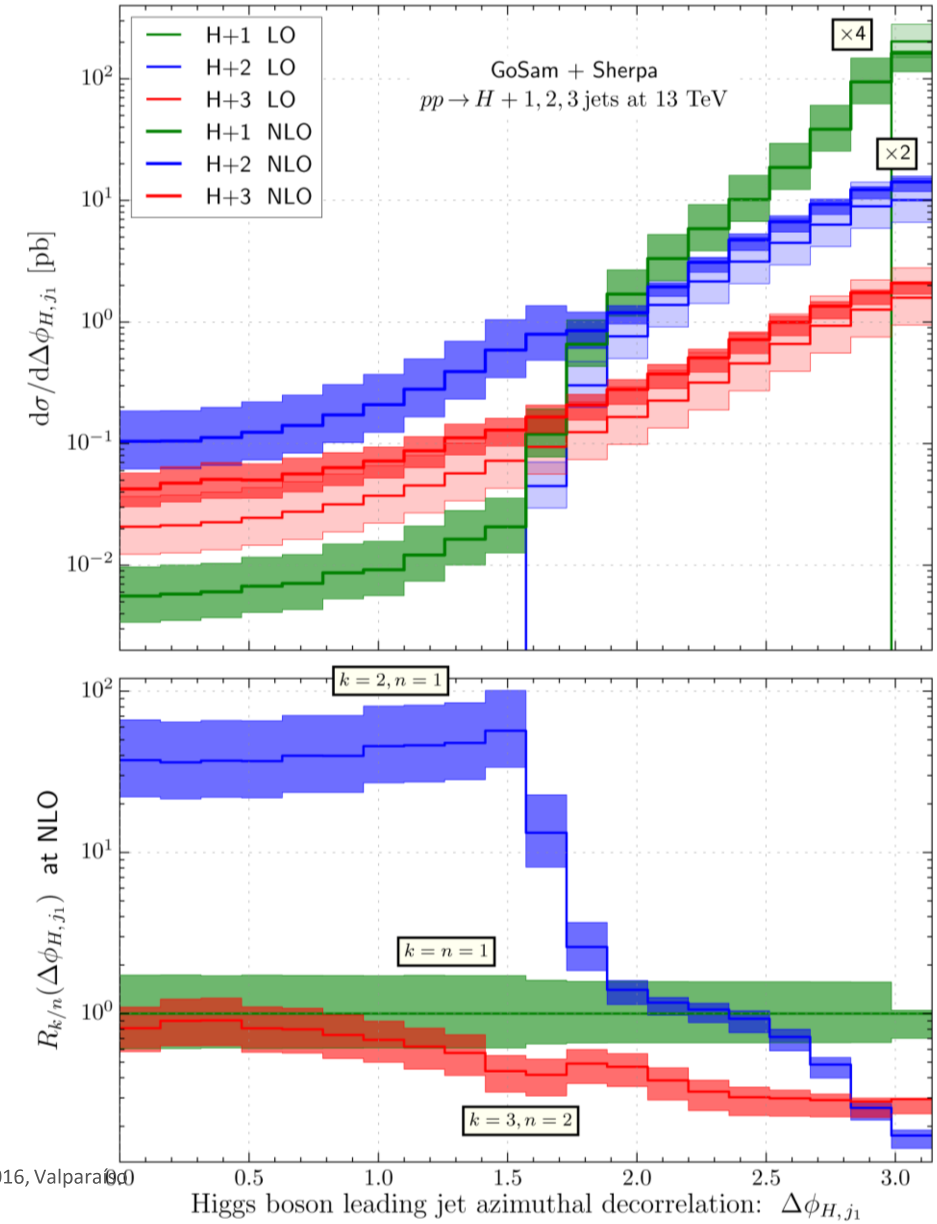
At LO:
With larger radius partons are clustered in the same jet leading to higher rejection rate

At NLO:
More partons which are on average softer. They can:

- be too soft, leading to a rejection of the event (especially for small R)
- be clustered together leading to an increase for average R.
- at large values of R same mechanism as LO dominates

Higgs-leading jet azimuthal separation

- Observable directly influenced by different orders and multiplicities:
  - H+1 jet is NLO accurate at $\Delta\phi = \pi$
  - H+2 jets is NLO accurate in $\pi/2 < \Delta\phi < \pi$
  - H+3 jets is NLO accurate in $0 < \Delta\phi < \pi$

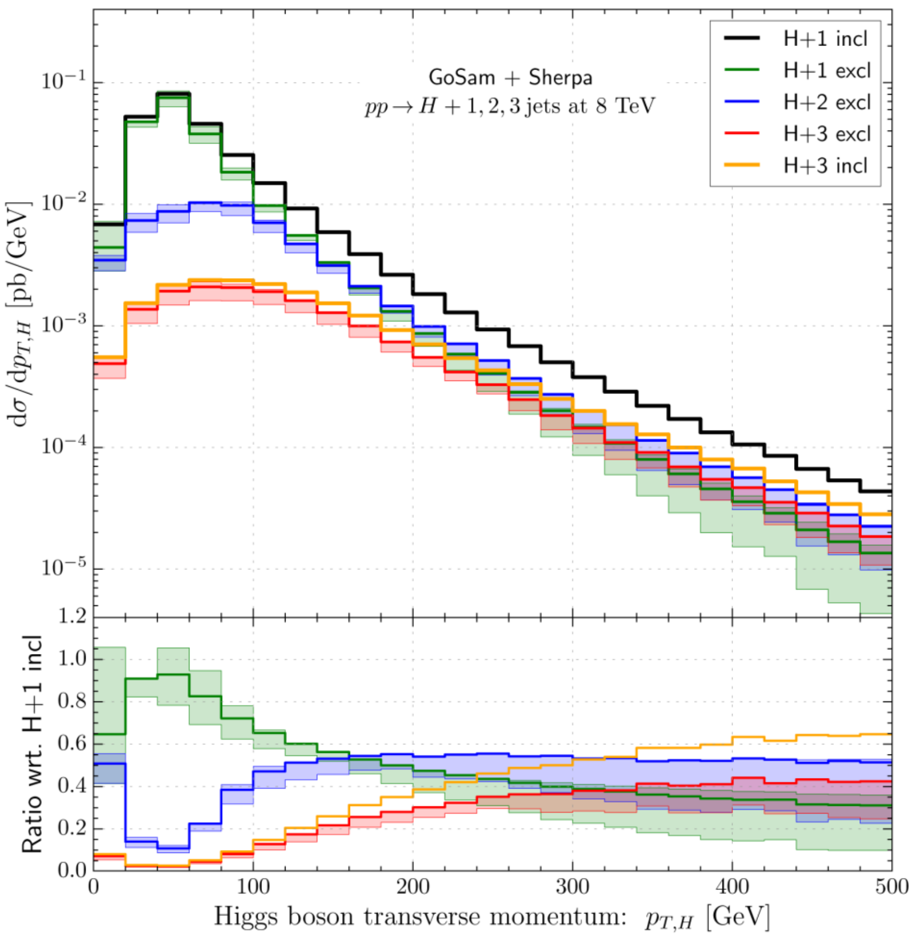


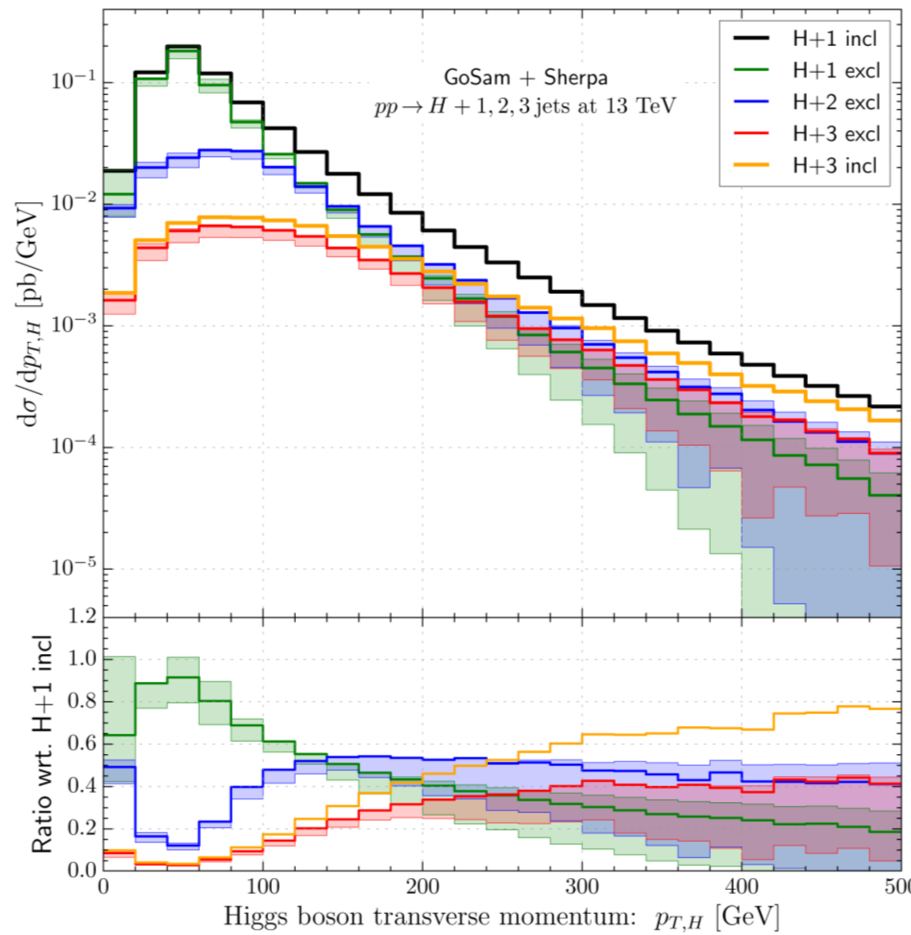
R-ration defined as:

$$R_{k/n}(O) = \frac{\frac{d\sigma}{dO}(\mathrm{H}+k\,\mathrm{jets})}{\frac{d\sigma}{dO}(\mathrm{H}+n\,\mathrm{jets})}$$

Higgs transverse momentum spectrum: 8, 13 TeV

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



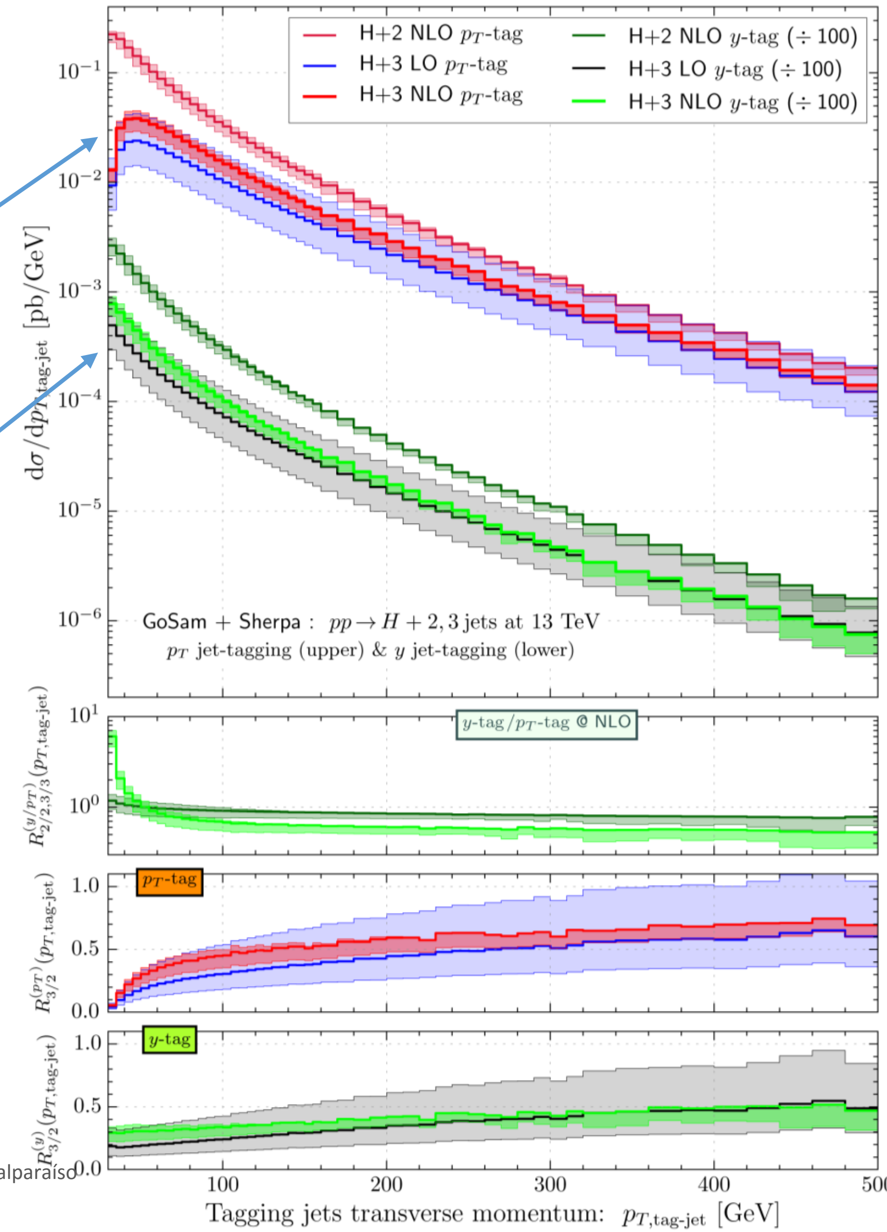


Alternative jet tagging strategy

- Instead of ordering jets by decreasing transverse momentum (p_t-tagging), define two leading jets by the most forward/backward jet (y-tagging)

p_t-tagging strategy:
two leading jets defined according to their transverse momentum

y-tagging strategy:
two leading jets define according to their rapidity by considering the most forward and most backward jet



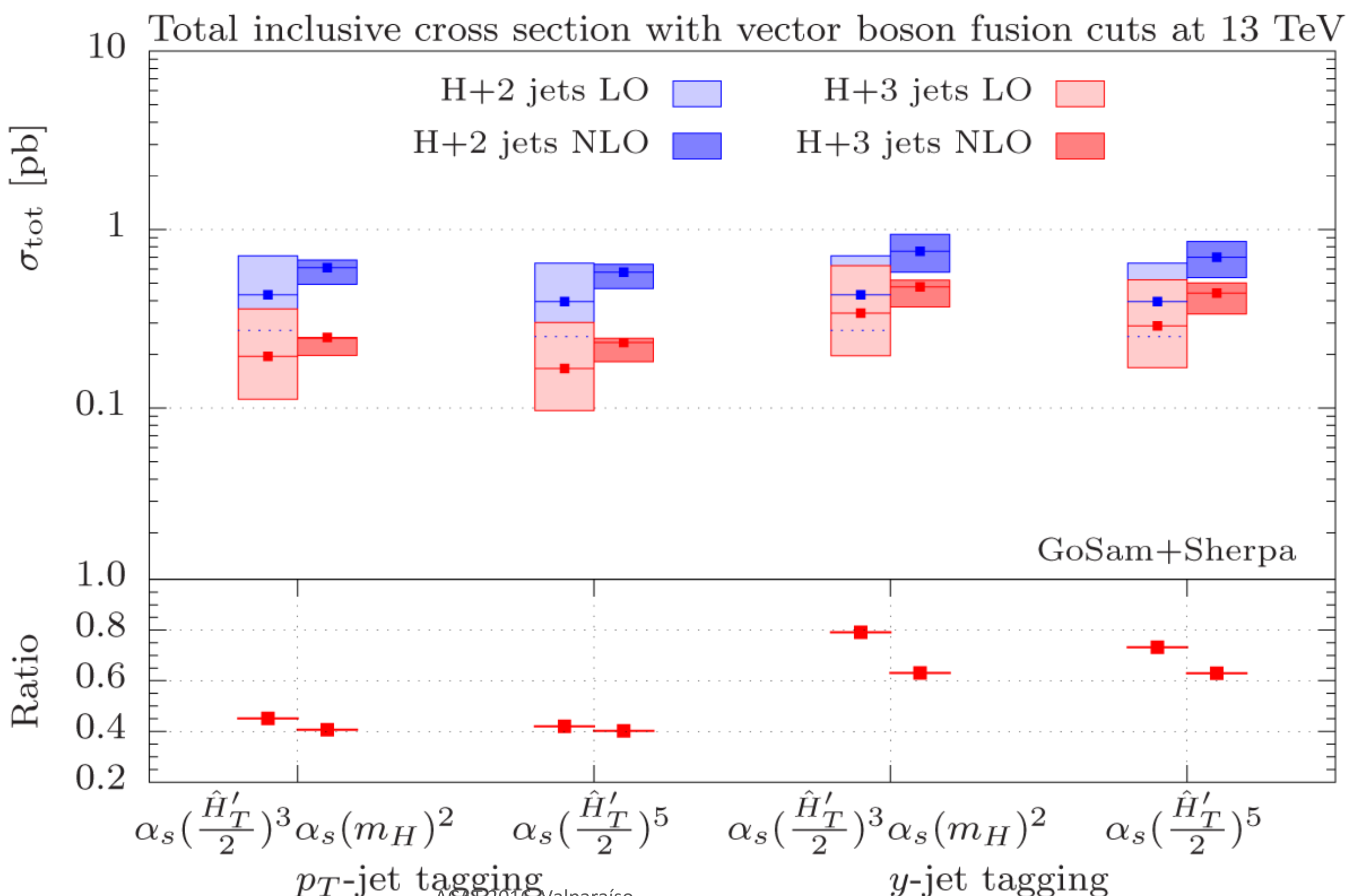
- Inclusive tagging jets transverse momentum
  - With increasing number of jets, two tagging schemes differ more
  - Different behavior especially at low p_t

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 cut to the baseline set:

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

- Total cross section:



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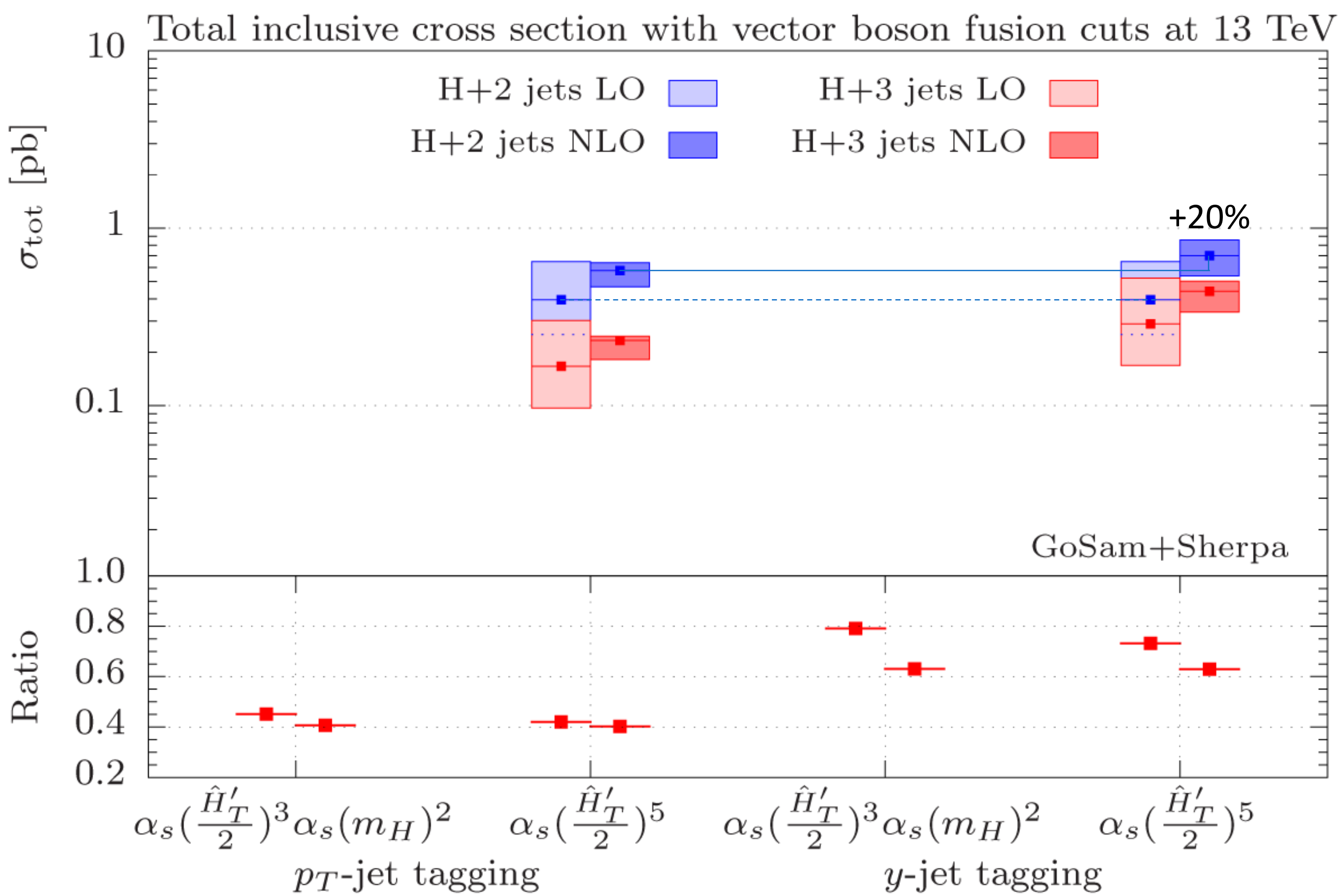

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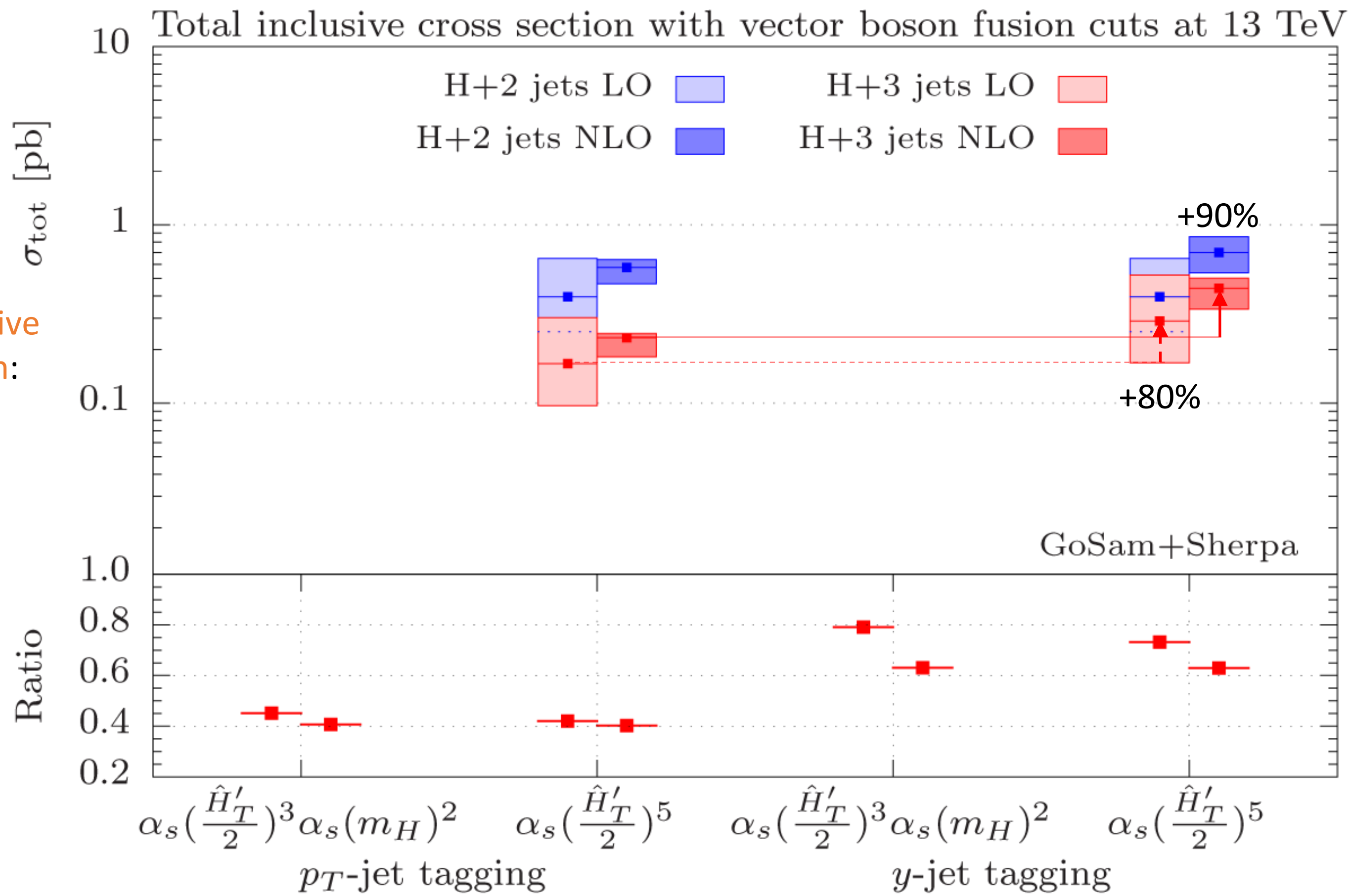
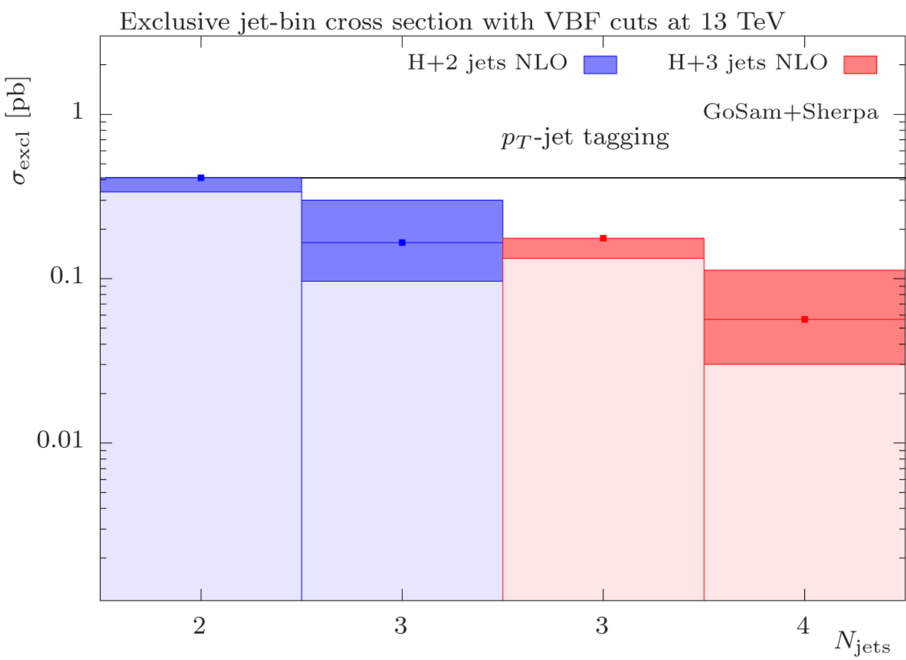
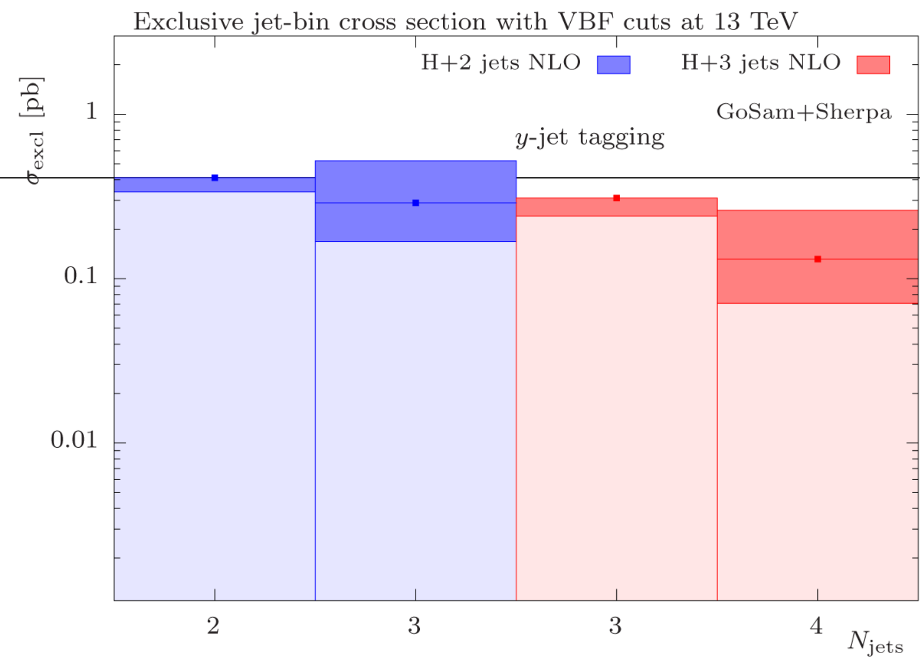
- Total cross section:

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



Exclusive jet bins





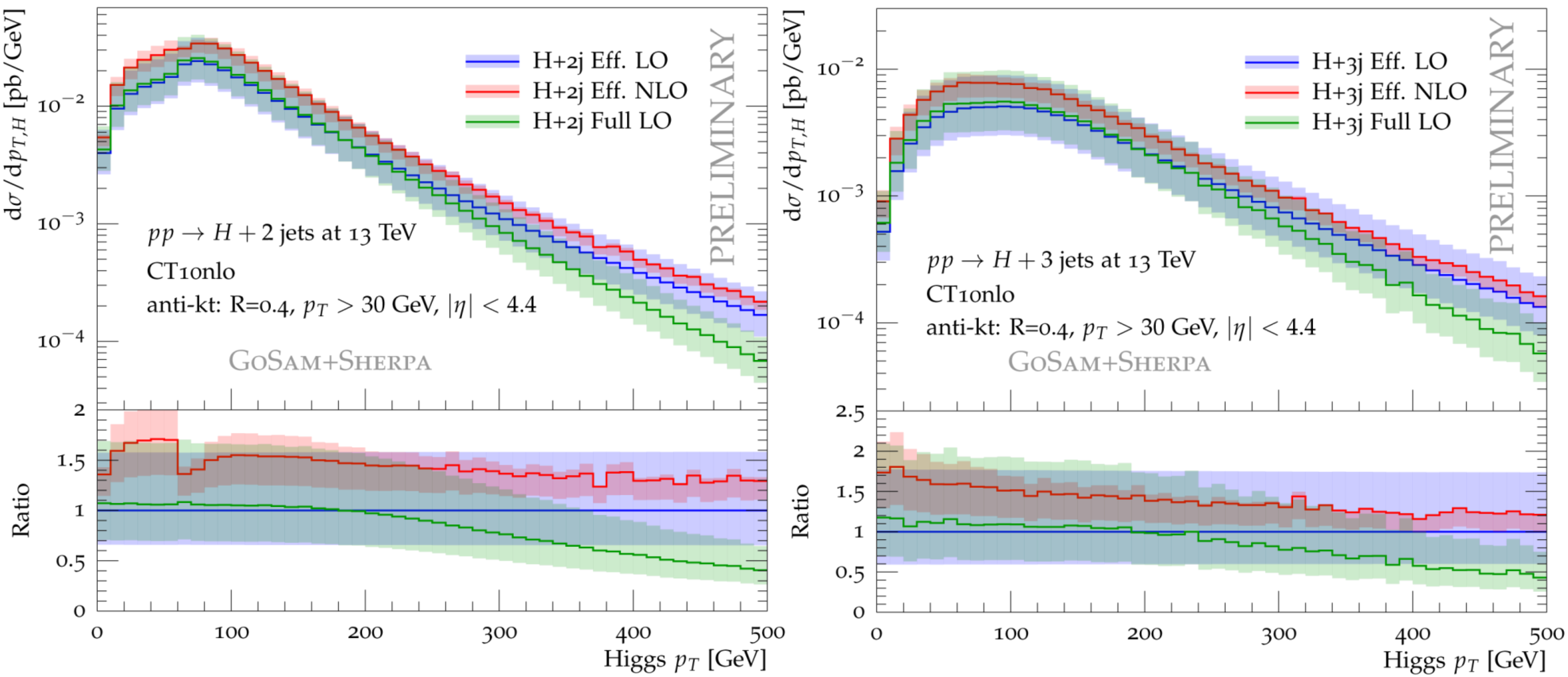
- VBF cuts enhance real radiation contribution (y-tagging even more)
  - larger portion of total XS described with LO accuracy if using H+2j @ NLO only
  - H+3j NLO needed for accurate 3 jet prediction and exclusive H+2j XS

Outlook

Finite quark mass effects

[Greiner, Höche, Schönherr, Winter, GL, in prep.]

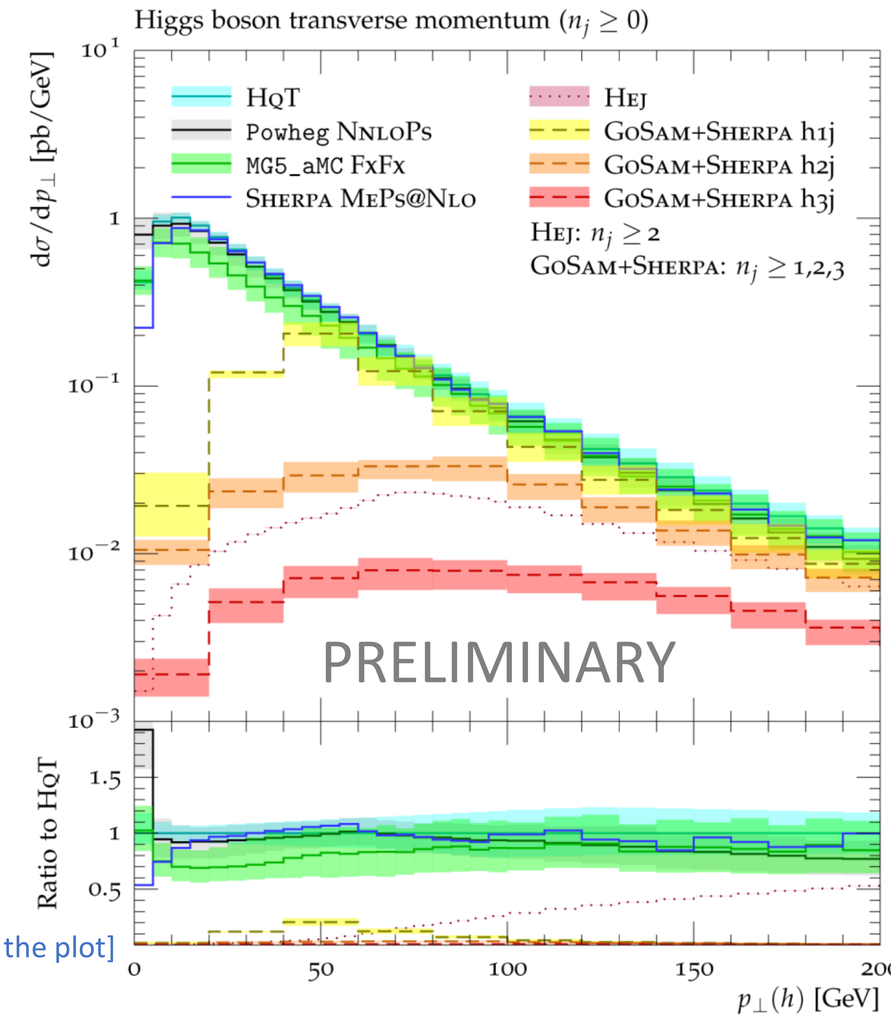
- How good is the effective theory description?
- Where does it break down and how big are the effects due to massive quarks running in the loop?



Comparison with other predictions

- In the context of the Les Houches 2015 proceedings, ongoing study to compare pure fixed order results for H+1,2 and 3 jets at the best possible available accuracy with predictions merged and matched to parton shower, to understand the effects and the differences among several schemes available:
  - HqT
  - Powheg Higgs NNLO+PS
  - MG5_aMC FxFx
  - Sherpa MEPS@NLO
  - HEJ
  - GoSam+Sherpa H+1,2,3 jets
  - nNLO LoopSim for H+1,2 jets
  - H+1 jet @ NNLO

➢ Preliminary results for next week's meetings at CERN, stay tuned!



[Thanks to M. Schönherr for providing the plot]

Conclusions

- Presented NLO QCD results at 8 and 13 TeV for H+1/2/3 jets computed SHERPA (COMIX) interfaced to GoSam and via generation of ROOT Ntuple files:
  - available for 8, 13, 14 and 100 TeV upon request
  - allow for fast change in the analysis (within generation limits)

- Shown results at 8 and 13 TeV
  - Scale and radius dependence
  - Different tagging strategy

OUTLOOK:

- Validity range of infinite top-mass approximation
- More realistic fiducial cuts to allow direct comparison to data
- Impact of merging and matching to parton shower