Higgs + 3 jets production in NLO QCD

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References:

arXiv: 1506.01016

Outline

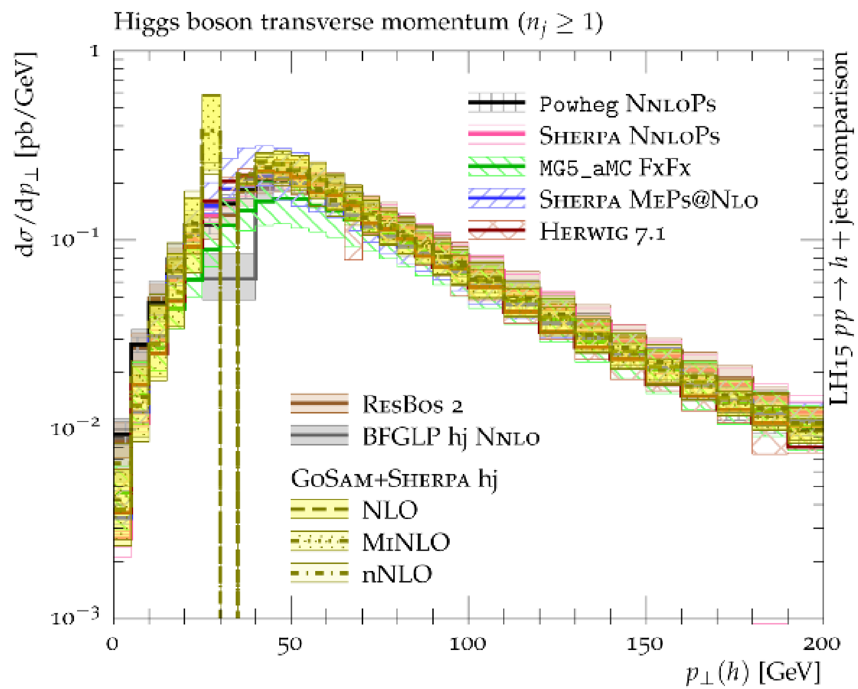
- **Introduction**

- **H+2 jets and H+3 jets in GGF at NLO**
  - Total cross section, scale dependence, PDFs, jet radius, jet tagging strategy
  - Effect of VBF selection cuts
  - Finite mass effects

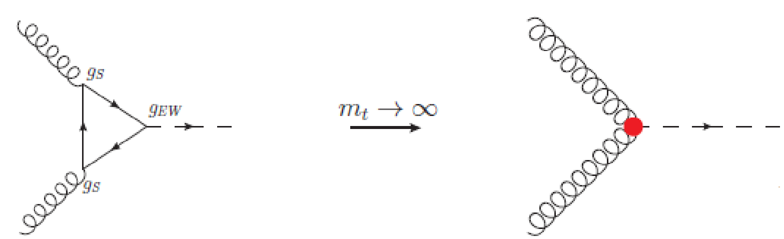
- **Conclusions & Outlook**

H+jets in gluon-gluon fusion at NLO

- LHC Run II will soon collect enough data to 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
- Furthermore:
    - How large are finite mass corrections?
    - When is it H+jets, when jets+H?

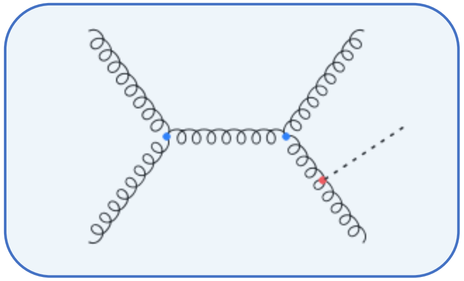


[Les Houches 2015 comparative study: 1605.04692]

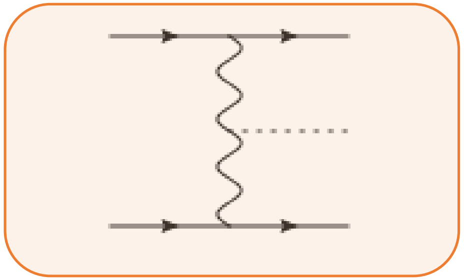


Higgs production in association with 2 and 3 jets

- 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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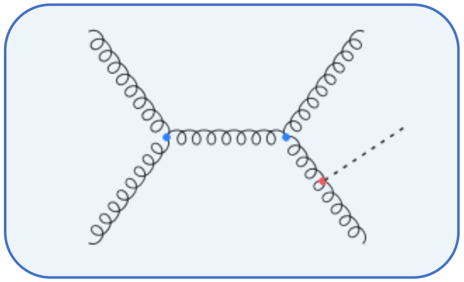

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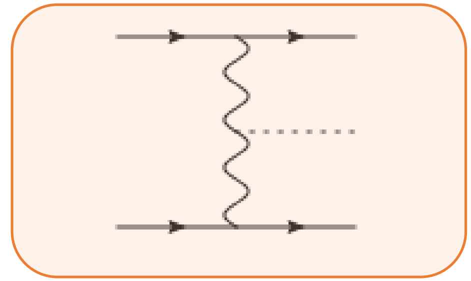


- The VBF-channel is very peculiar:

... 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,..)

- In this talk focus on GGF contribution

Computational setup

- Amplitudes computed with GoSam+Sherpa and 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, '08]

- 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 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)

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

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

- All results computed in the $m_{top} \longrightarrow \infty$ approximation
- 3 scale choices: $$\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\rm H}^2 + p_{T,{\rm H}}^2} + \sum_i |p_{T,i}|\right)$$

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

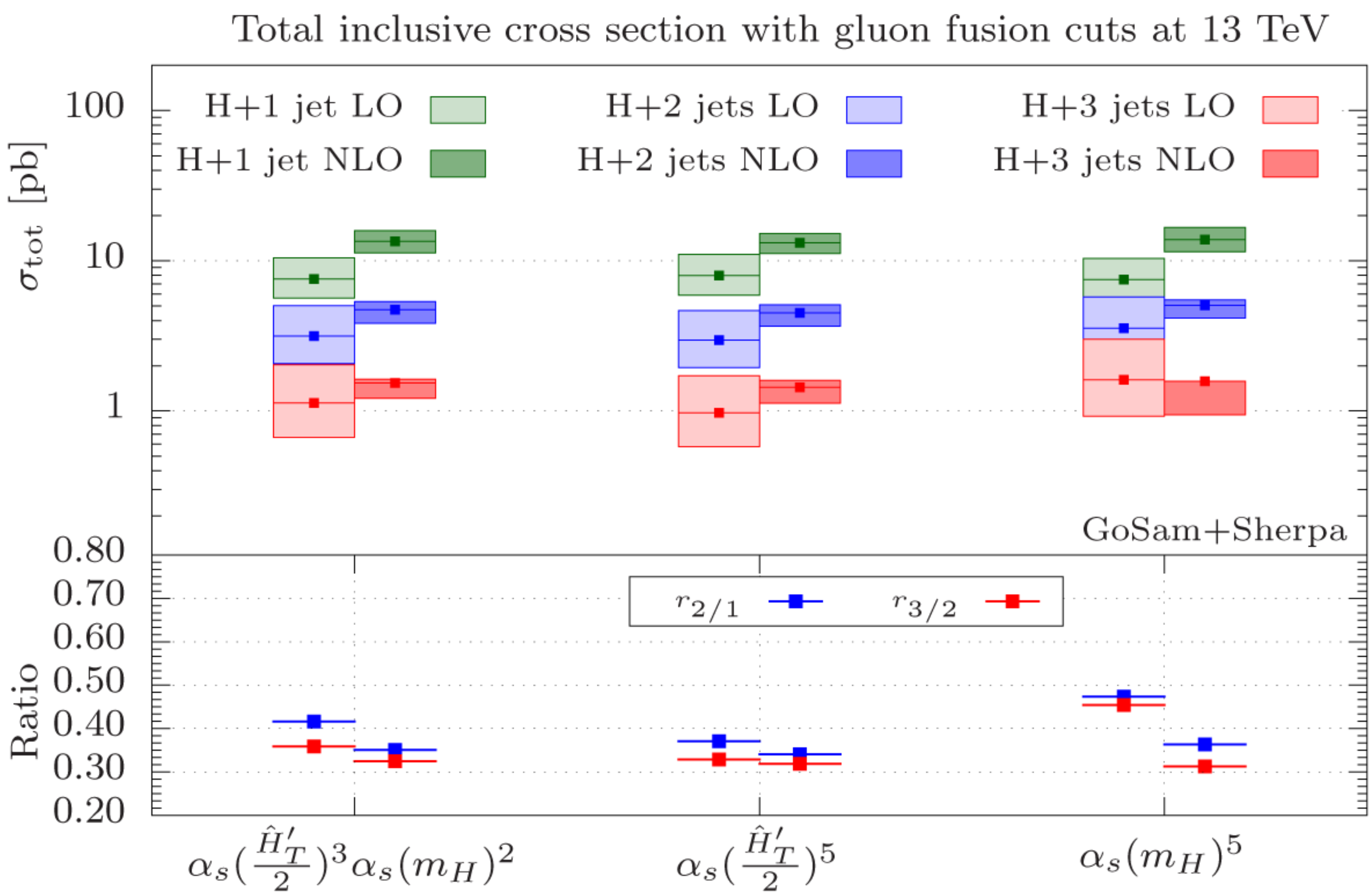
B: $\alpha_s\left(x \cdot \frac{\hat{H}'_T}{2}\right)^5$
Default

C: $\alpha_s\,(x \cdot m_{\rm H})^5$

- 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

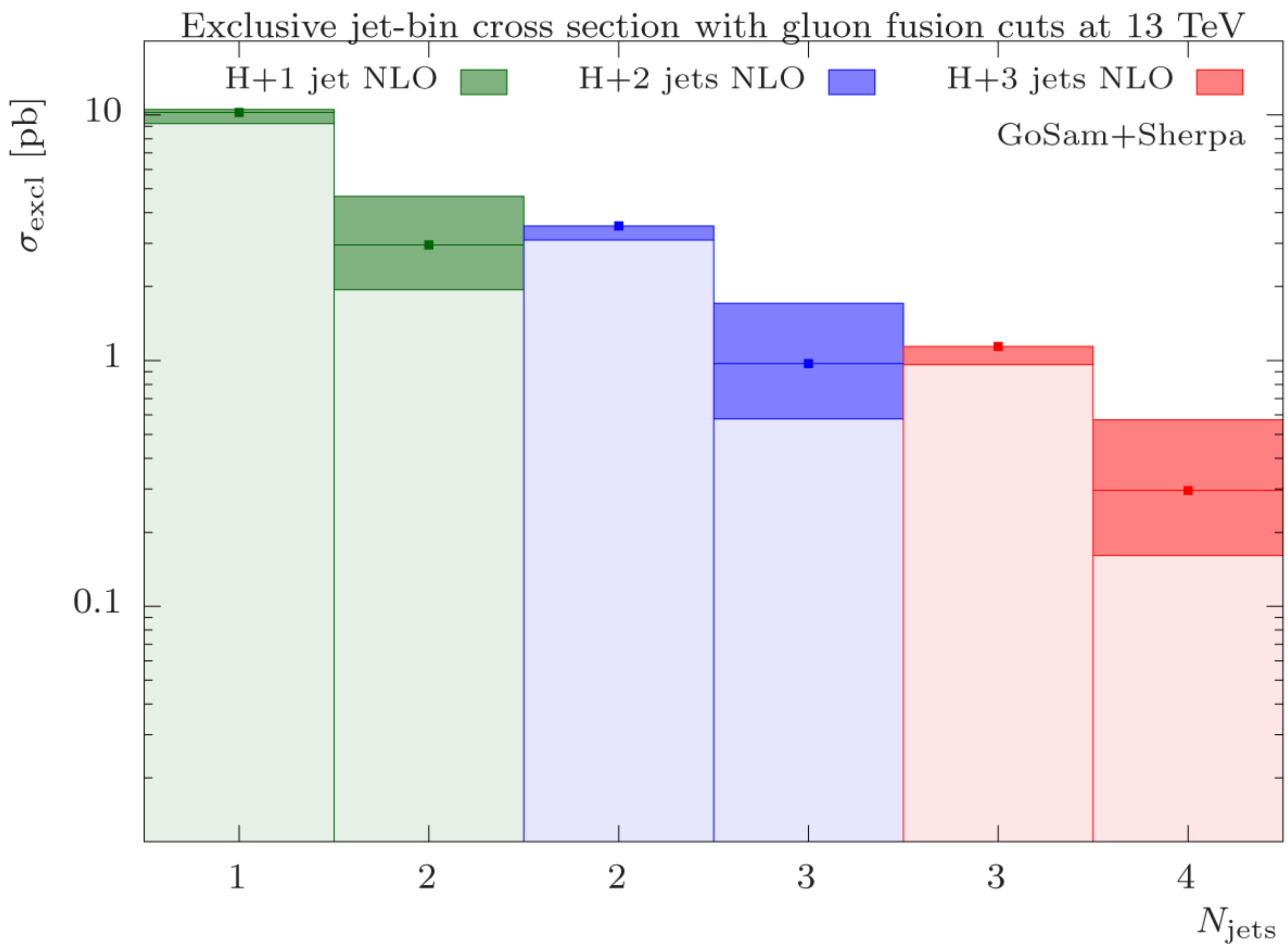
Total cross section: 13 TeV



- $r_{3/2}$ 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



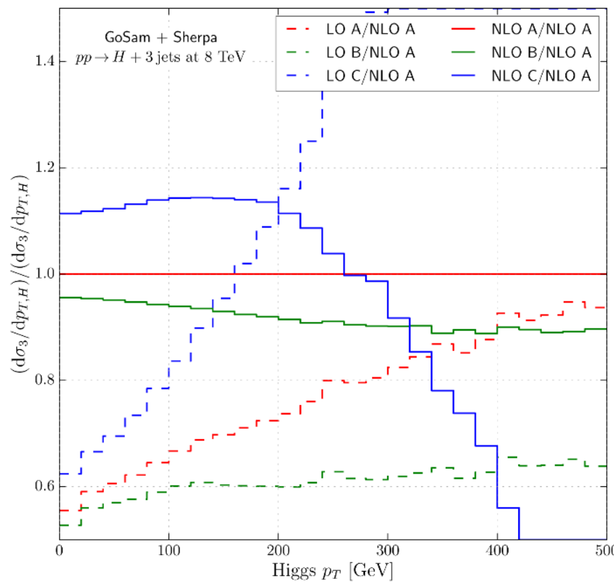
- For each of the final state multiplicities the respective (n+1)-jet contribution is sizeable

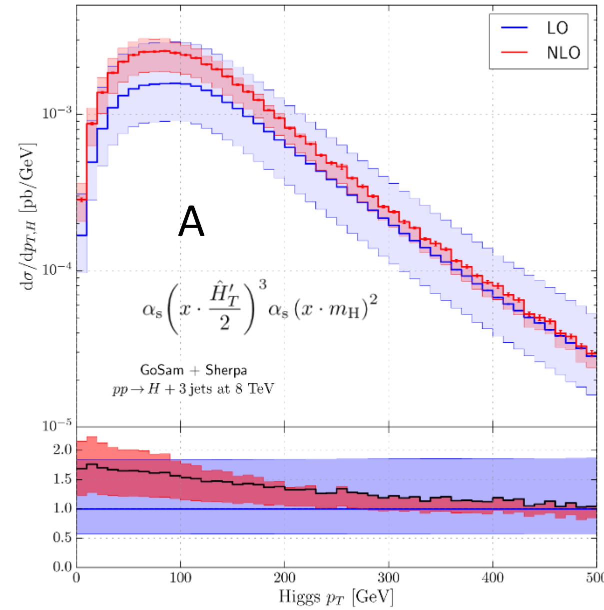
Scales and scale dependence: H+3 jets

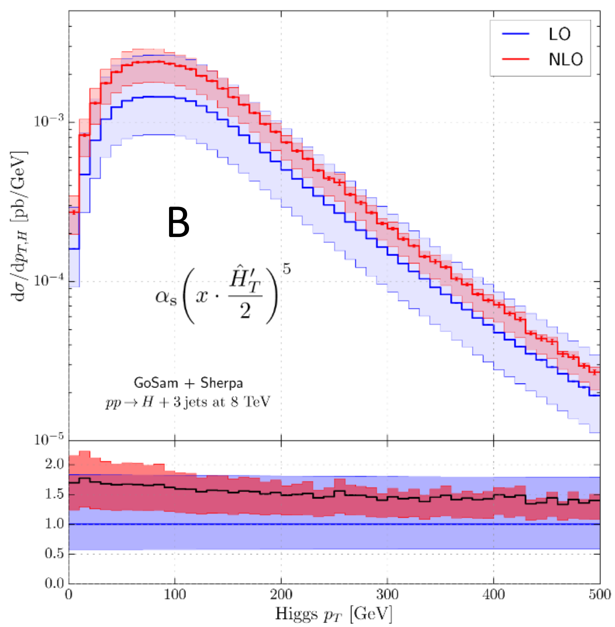
Transverse momentum Distribution for scale choices A, B and C

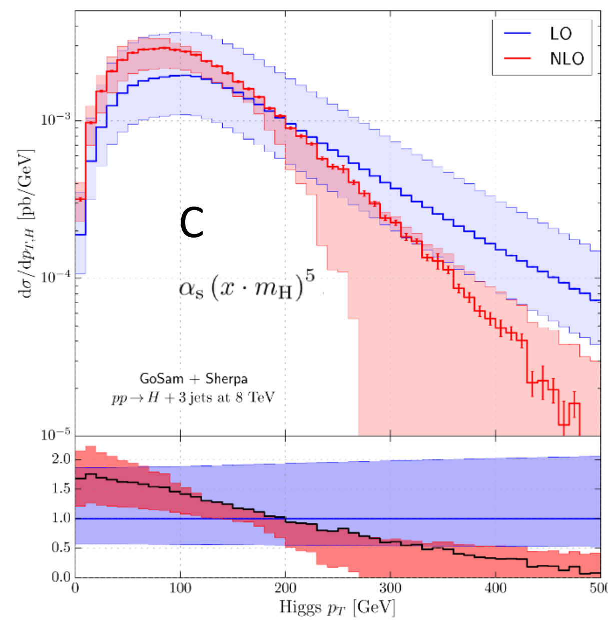
- Fixed scale (C) not a good choice

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









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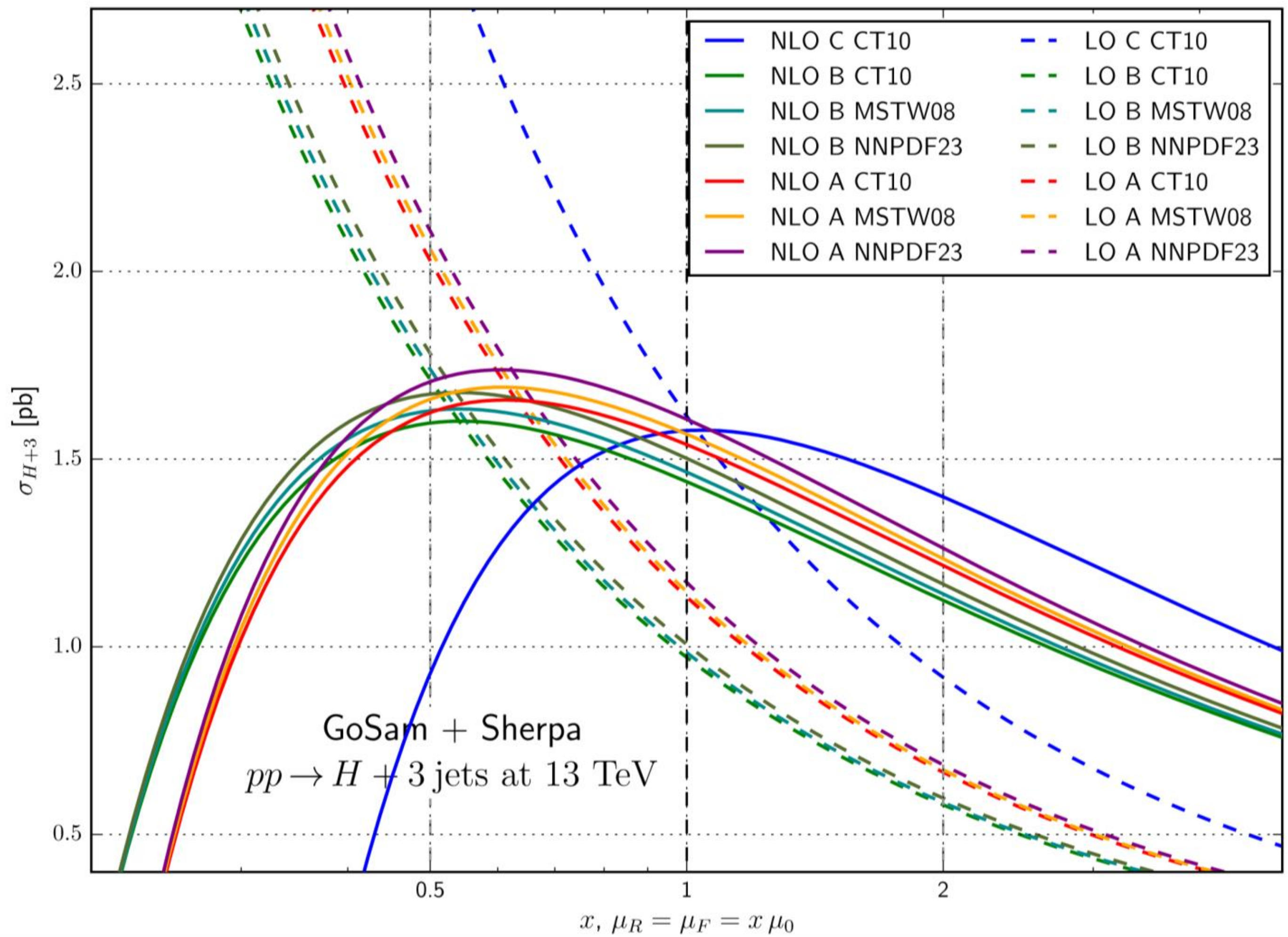
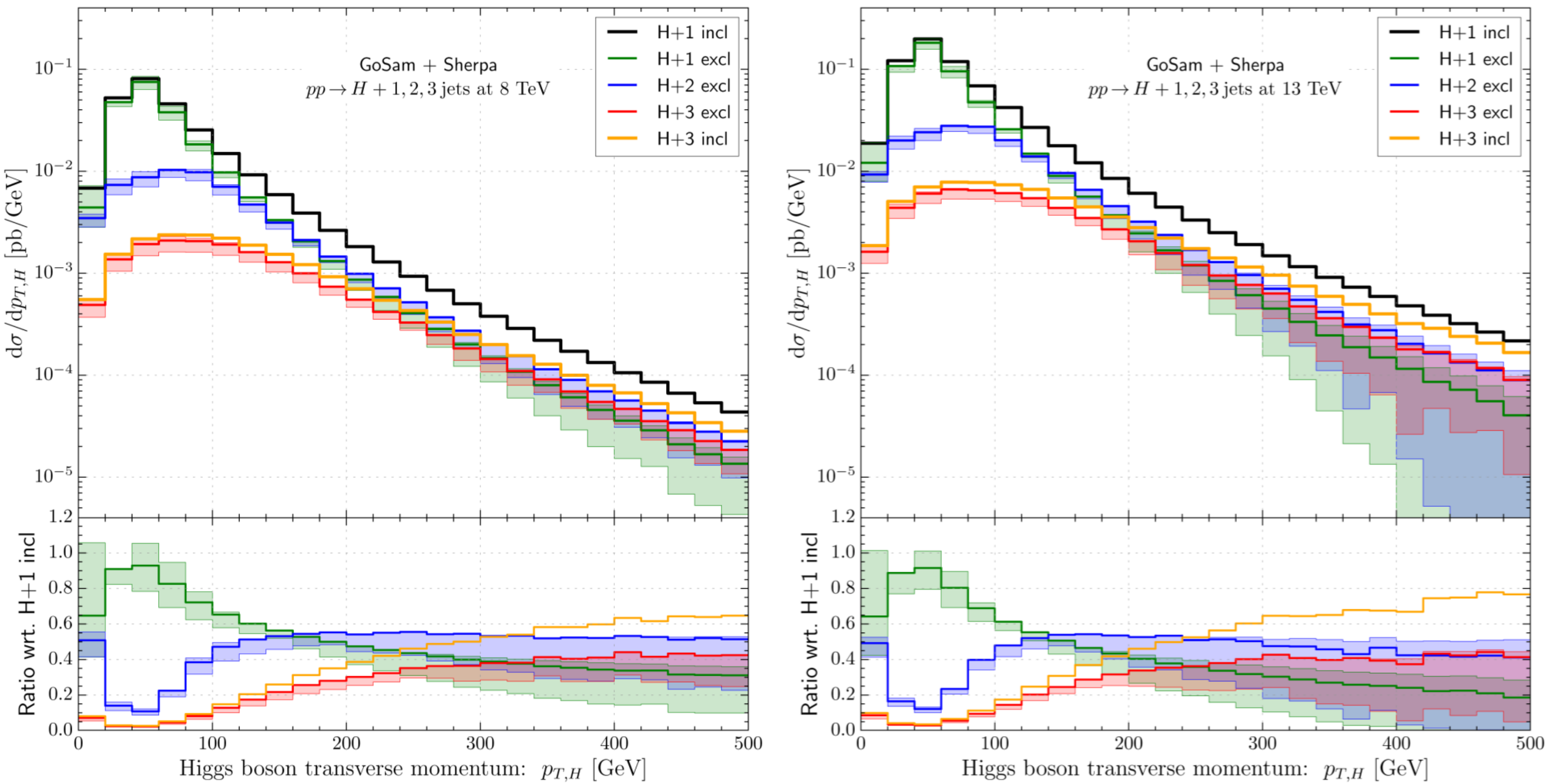


- PDF convolution and scale variation performed with ApplGrid

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

Higgs transverse momentum spectrum: 8, 13 TeV

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

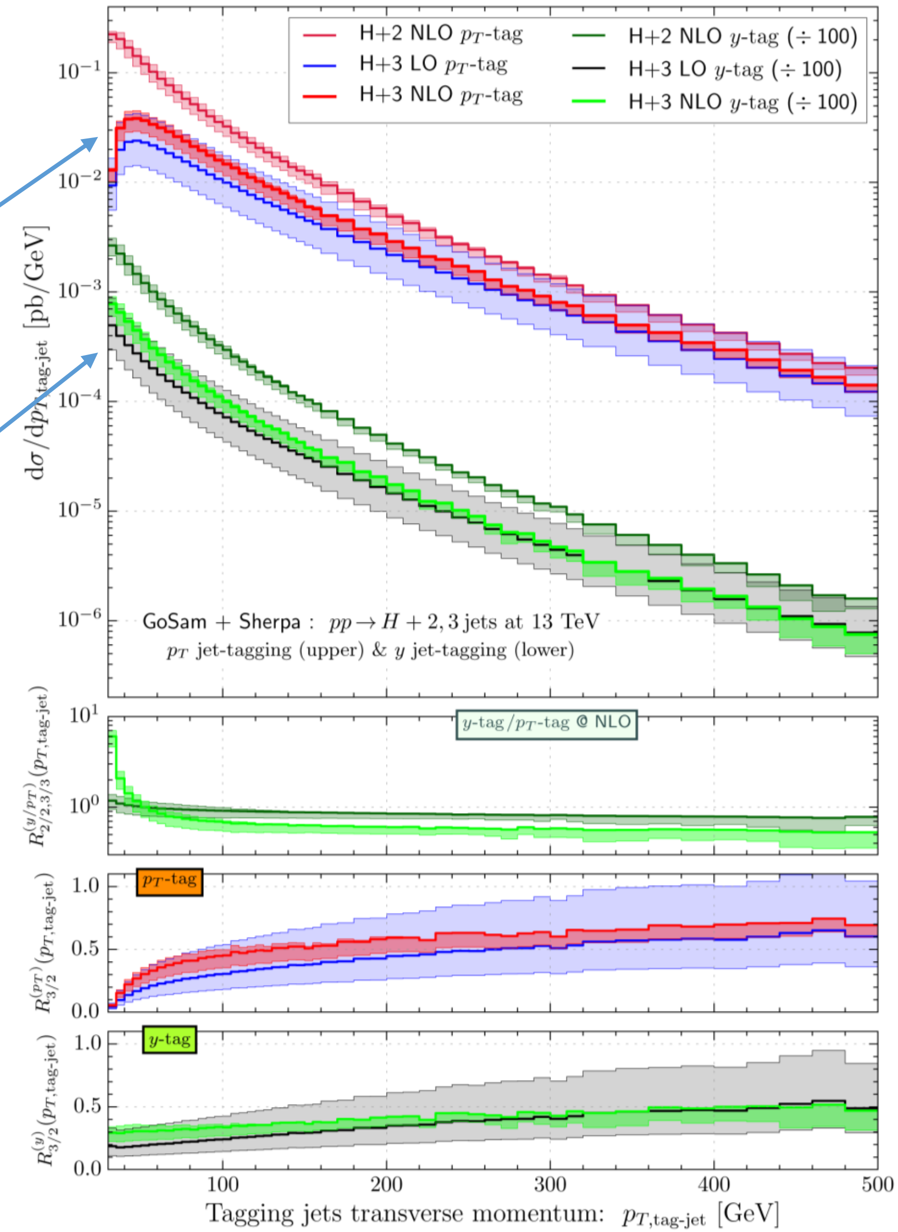


Alternative jet tagging strategy

- 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



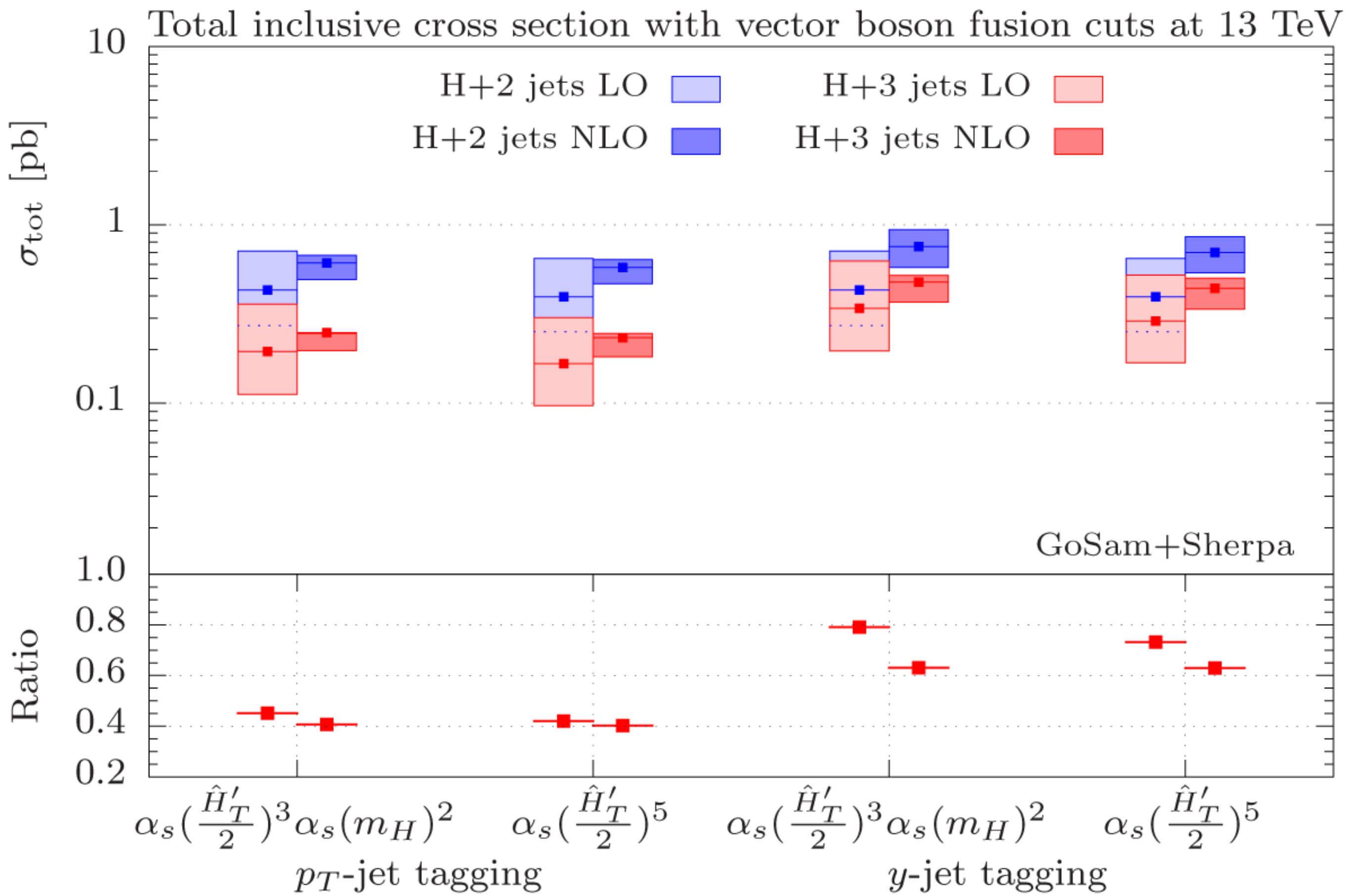
- Inclusive tagging jets transverse momentum
  - With increasing number of jets, two tagging schemes differ more
  - Different behavior especially at low p_t

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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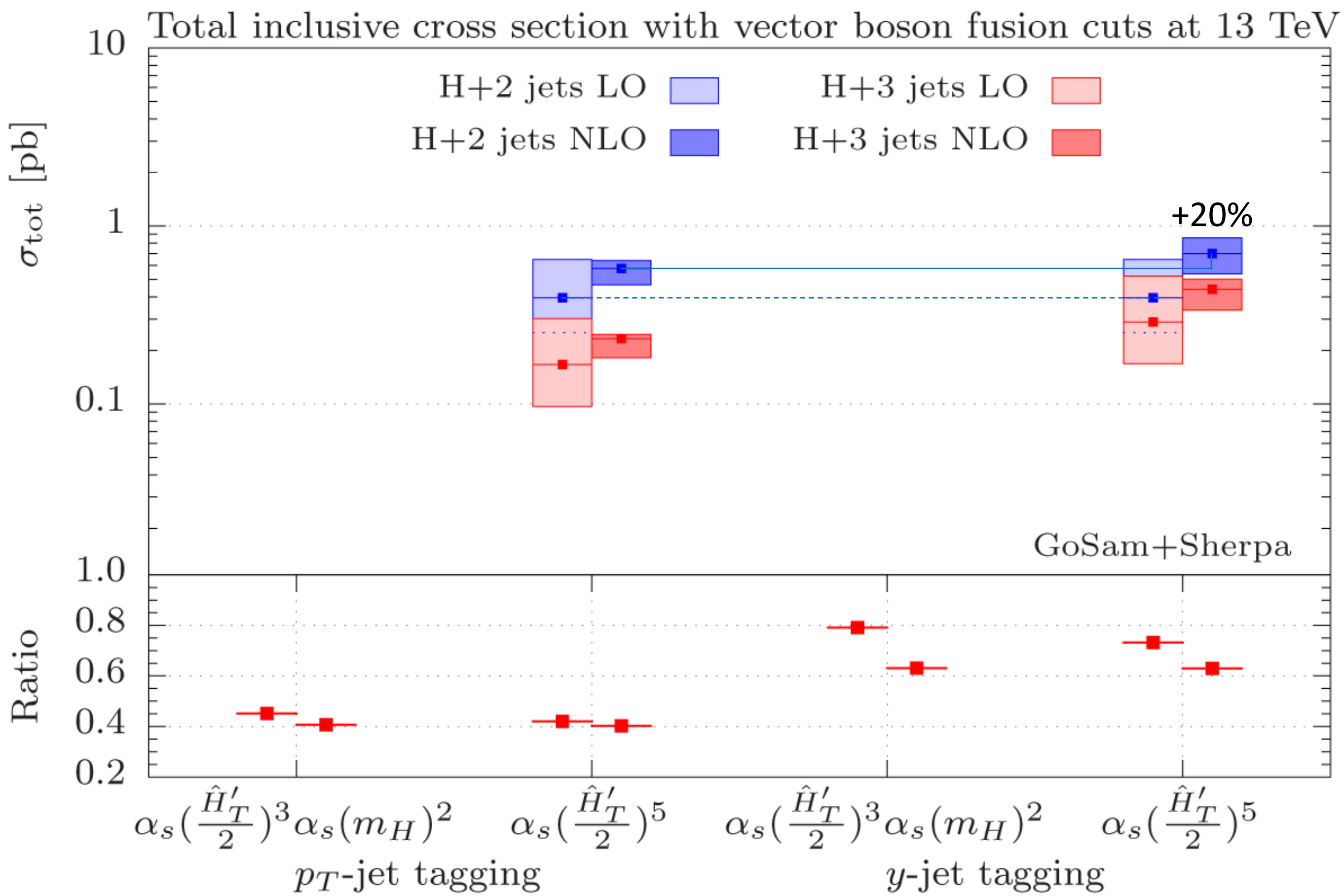

Higgs plus jets in GGF with VBF selection cuts

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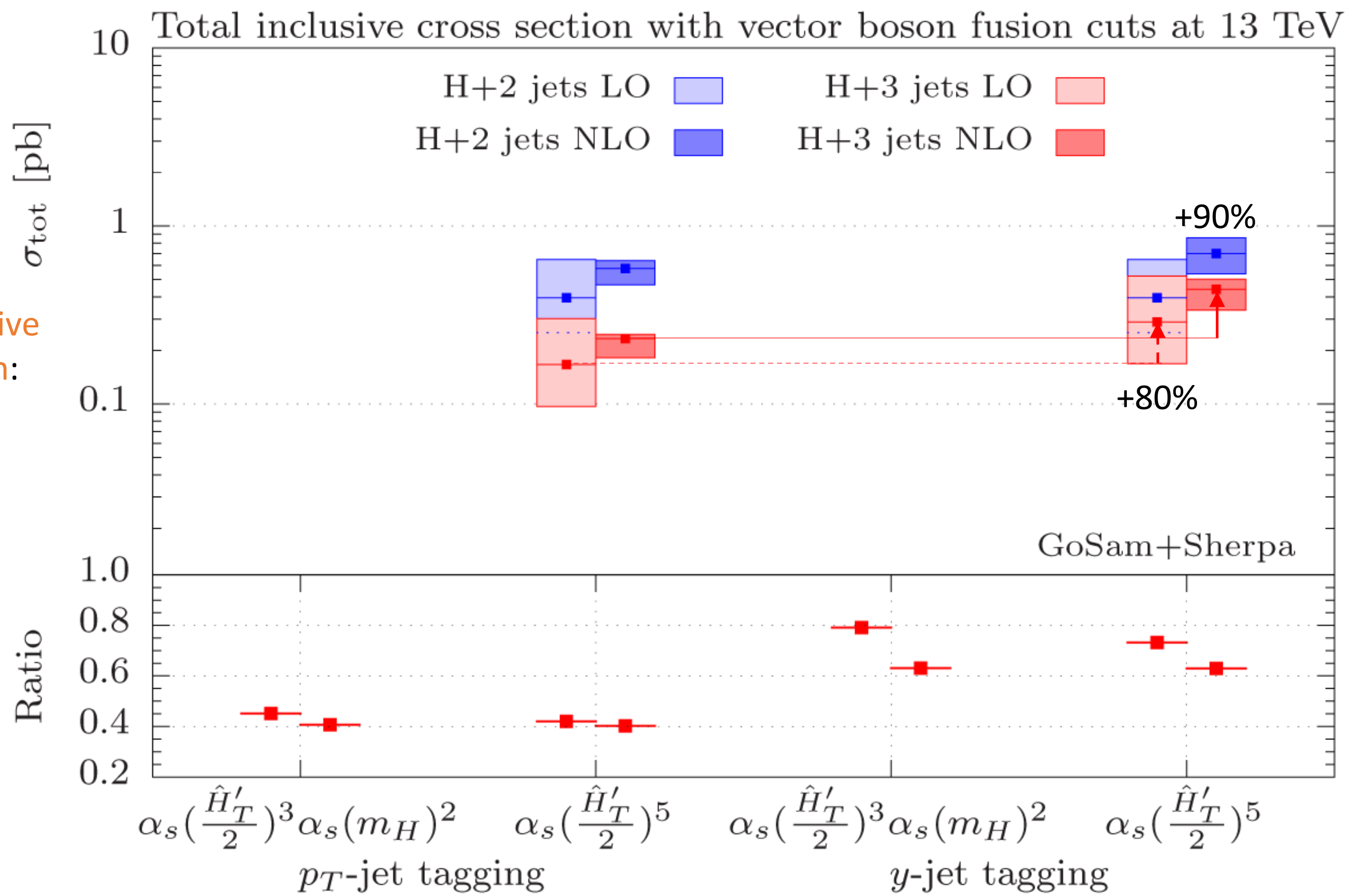
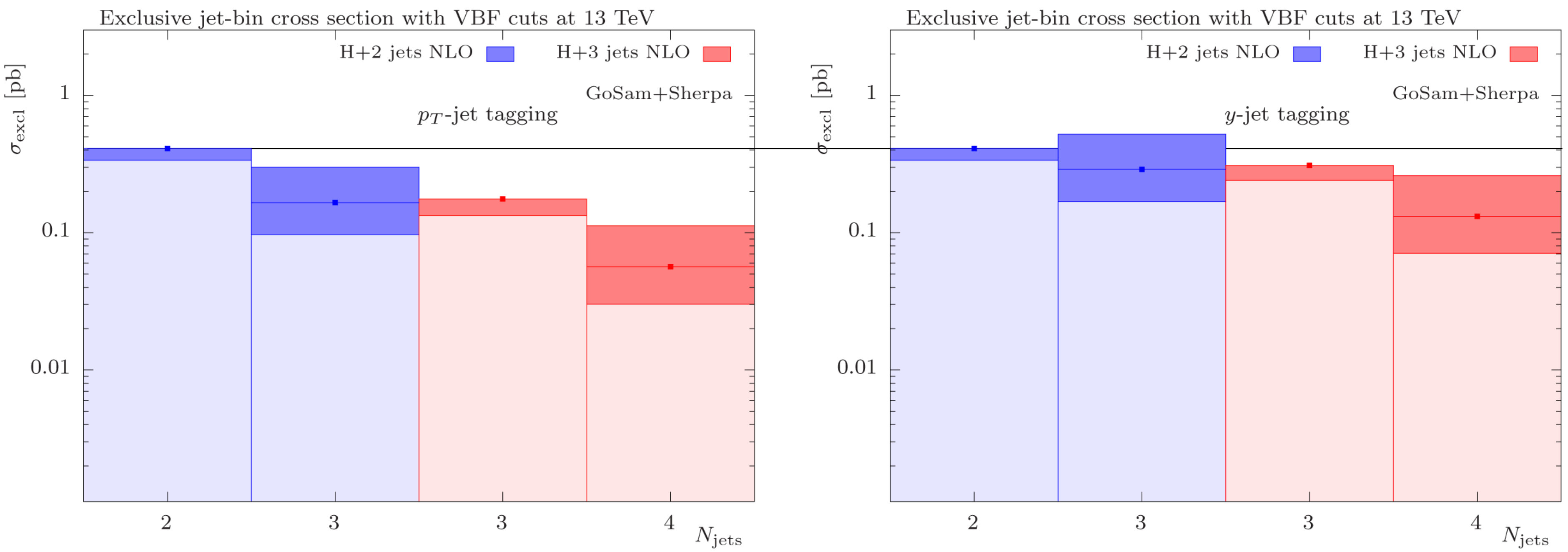
- Total cross section:

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

Finite Mass Effects

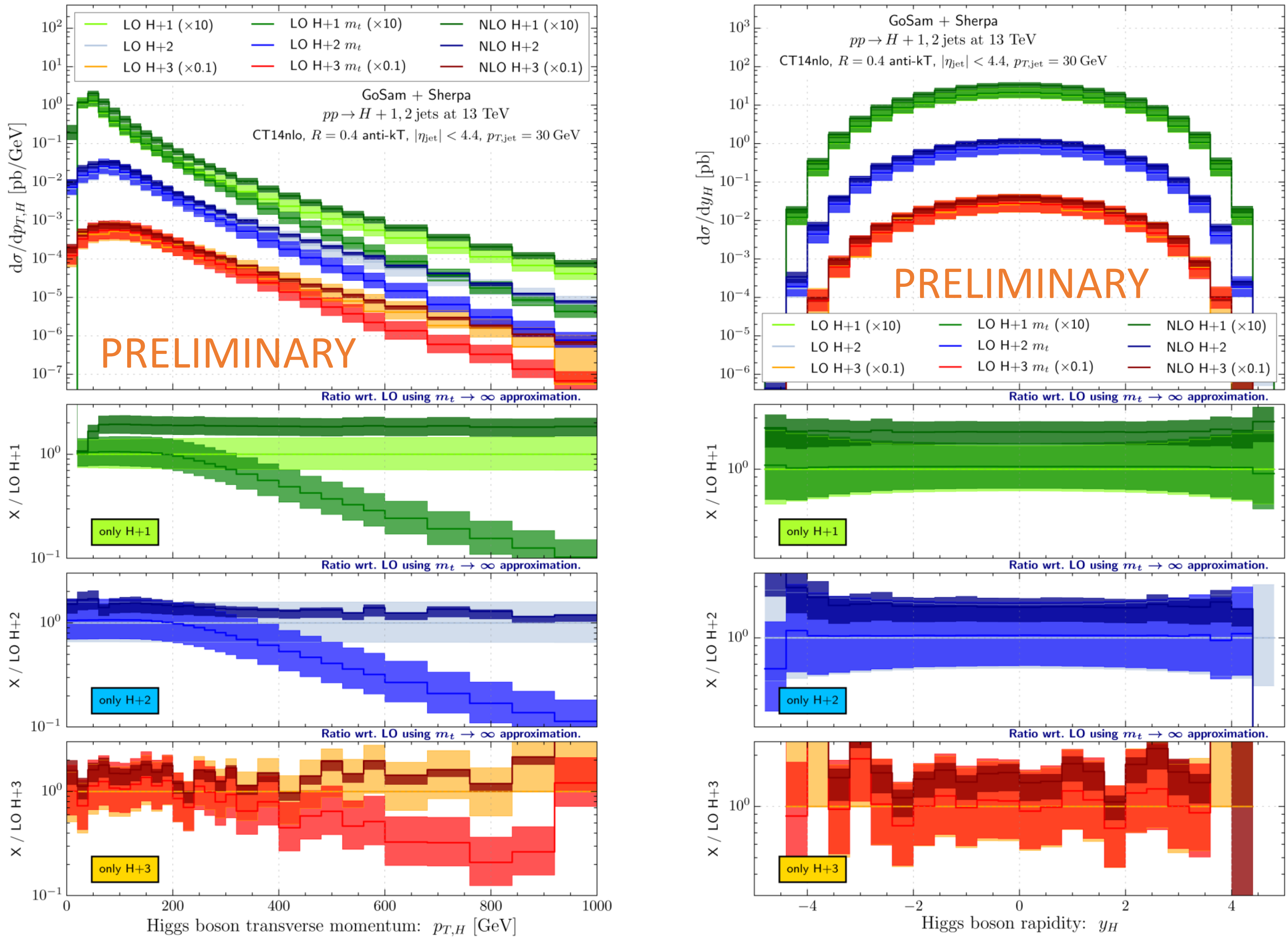
Finite quark mass effects

[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?
  - Recently studied also in the context of multijet merging up to H+2 jets

[Frederix, Frixione, Vryonidou, Wiesemann, '16]

- **Setup:** $\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\rm H}^2 + p_{T,{\rm H}}^2} + \sum_i |p_{T,i}|\right)$
  - $m_{\rm H} = 125\ GeV$; $m_{\rm top} = 172.3\ GeV$
  - PDFs: CT14nlo
  - Baseline cuts: anti-kt with $p_T > 30$ GeV, $|\eta| < 4.4$


LO H+1 (×10)
LO H+2
LO H+3 (×0.1)
LO H+1 m_t (×10)
LO H+2 m_t
LO H+3 m_t (×0.1)
NLO H+1 (×10)
NLO H+2
NLO H+3 (×0.1)
GoSam + Sherpa
$pp \to H + 1, 2$ jets at 13 TeV
CT14nlo, $R = 0.4$ anti-kT, $|\eta_{\rm jet}| < 4.4$, $p_{T,\rm jet} = 30$ GeV
PRELIMINARY
$d\sigma/dp_{T,H}$ [pb/GeV]
$d\sigma/dy_H$ [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
Higgs boson transverse momentum: $p_{T,H}$ [GeV]
Higgs boson rapidity: y_H

Conclusions

- Presented NLO QCD results at 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 on EOS (copying procedure in progress)
  - allow for fast change in the analysis (within generation limits)

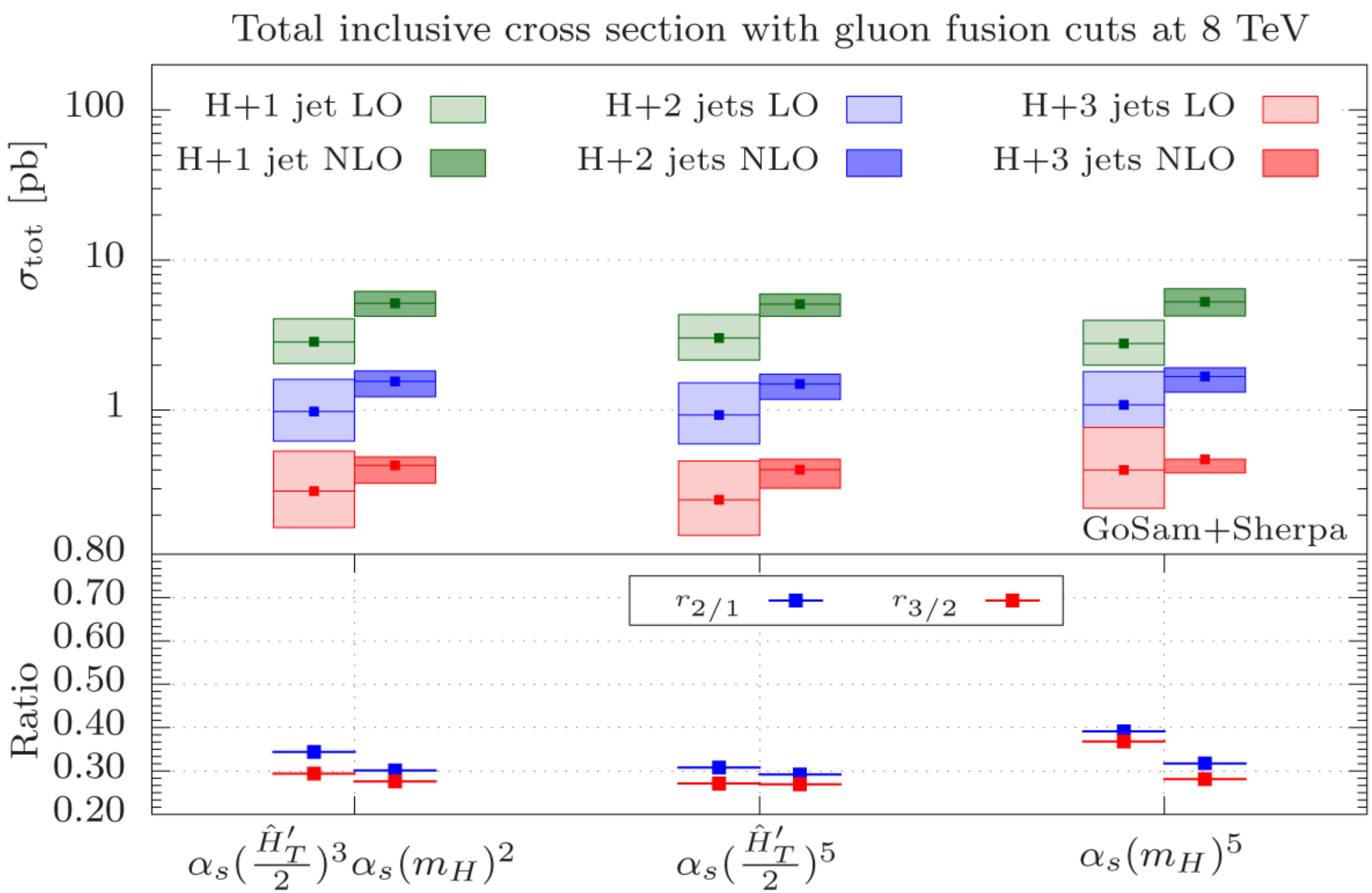
- Shown results 13 TeV
  - Scale and radius dependence
  - Different tagging strategy and impacts of VBF cuts
  - Impact of finite mass effects

OUTLOOK:

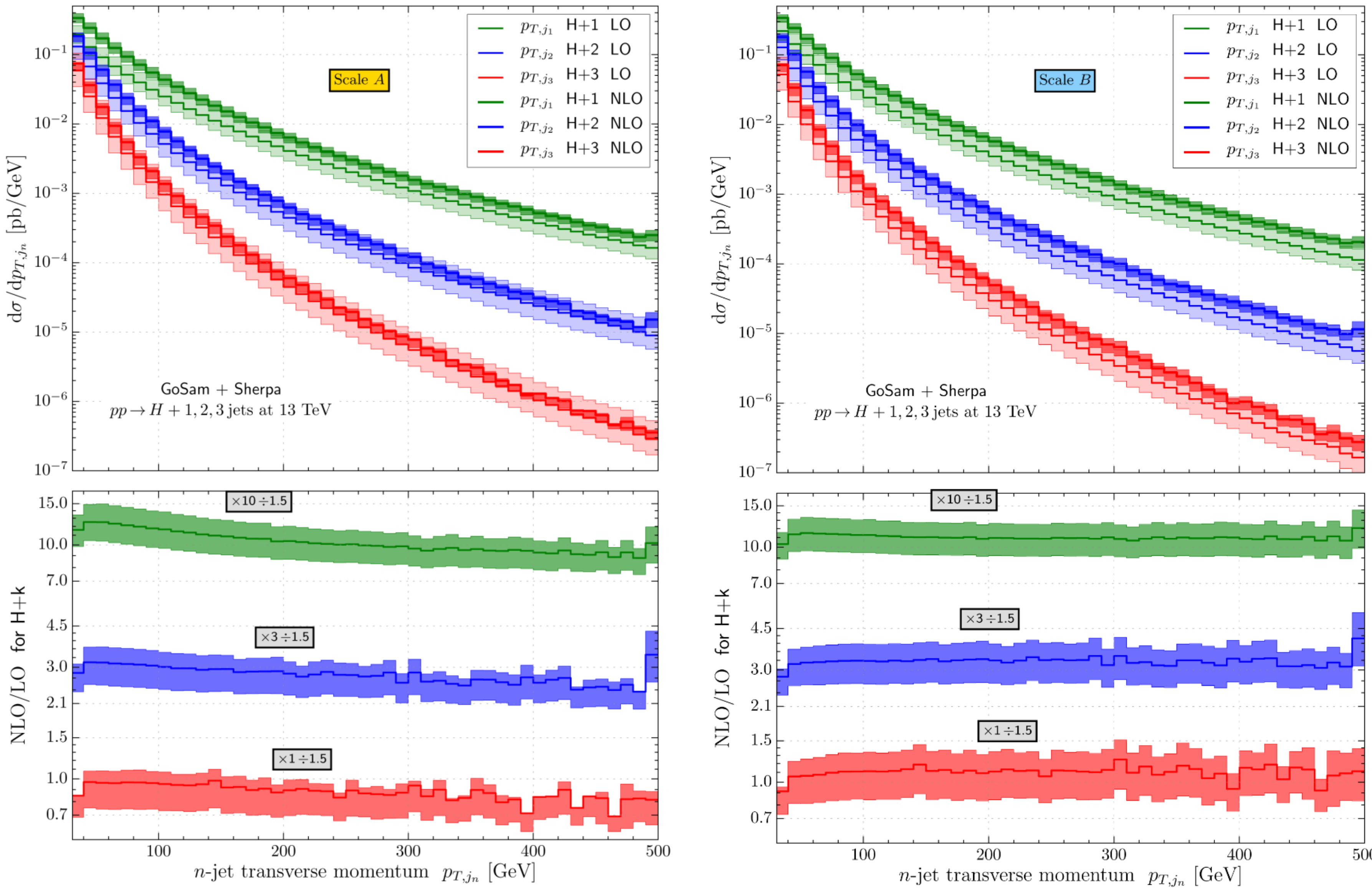
- Validity range of infinite top-mass approximation
- More realistic fiducial cuts to allow direct comparison to data
- Impact of merging and matching to parton shower

Backup

Total cross section: 8 TeV

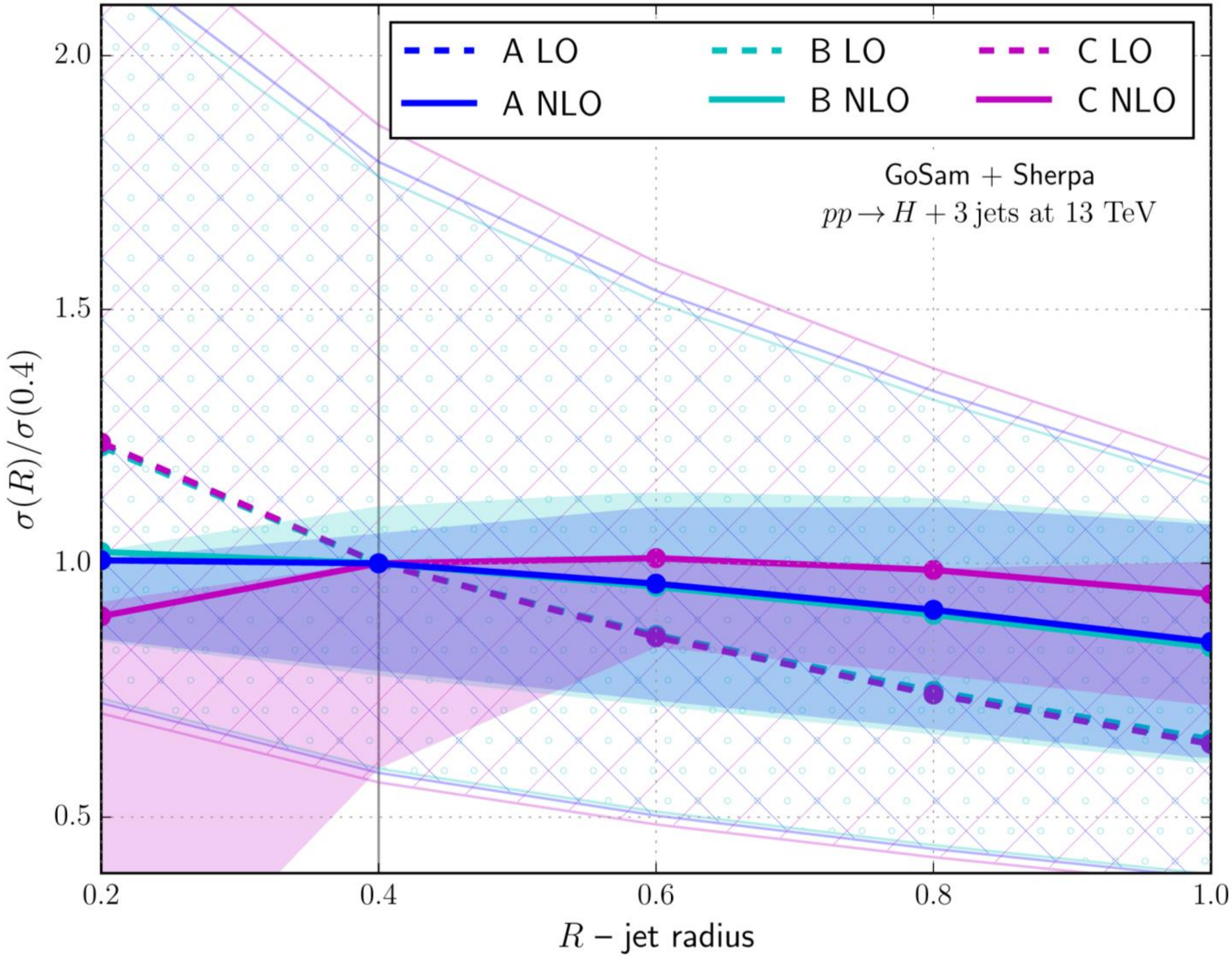


$$r_{n/n-1} = \frac{\sigma_{\text{tot}}(\text{H}+n\,\text{jets})}{\sigma_{\text{tot}}(\text{H}+(n-1)\,\text{jets})}$$



- 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:

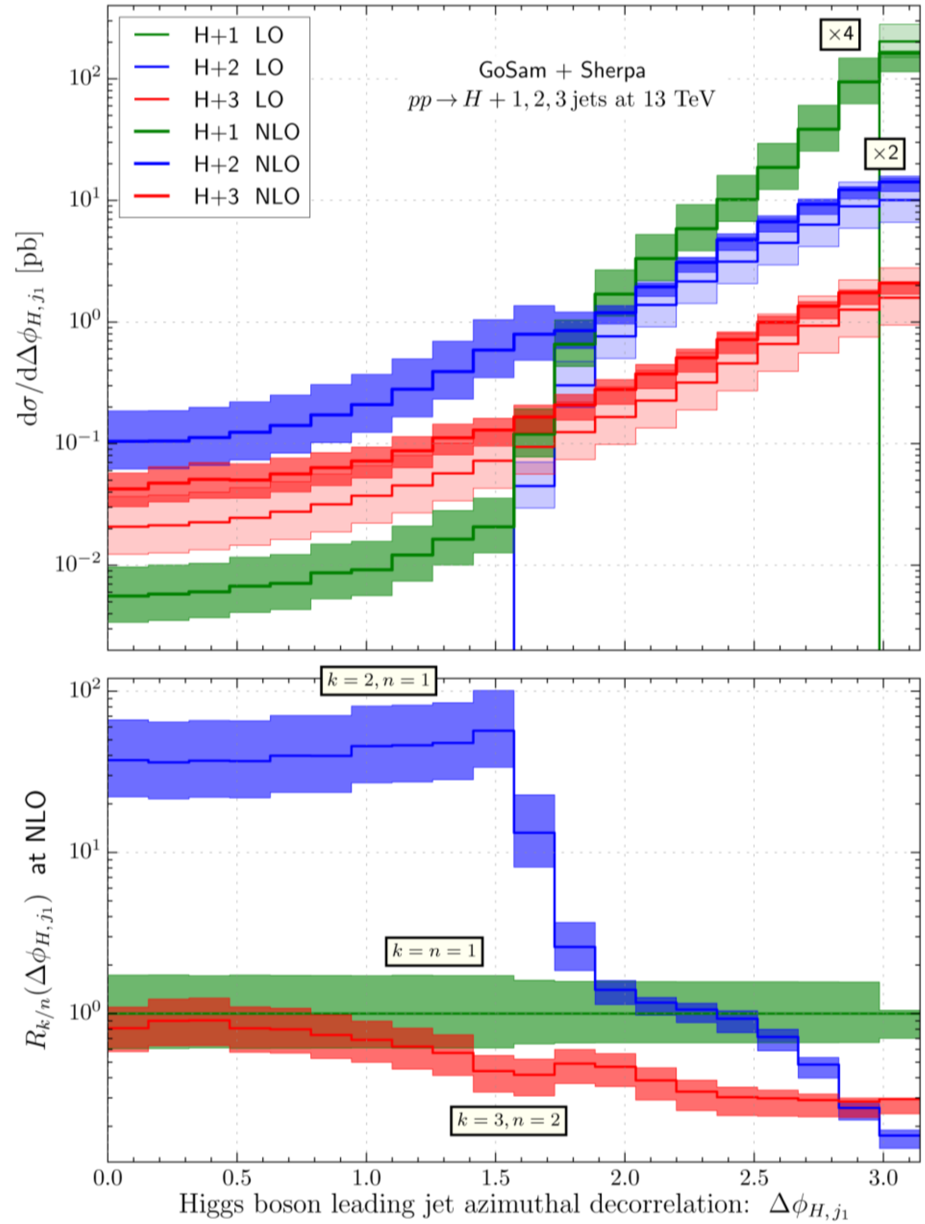
- be too soft, leading to a rejection of the event (especially for small R)
- be clustered together leading to an increase for average R.
- at large values of R same mechanism as LO dominates

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:

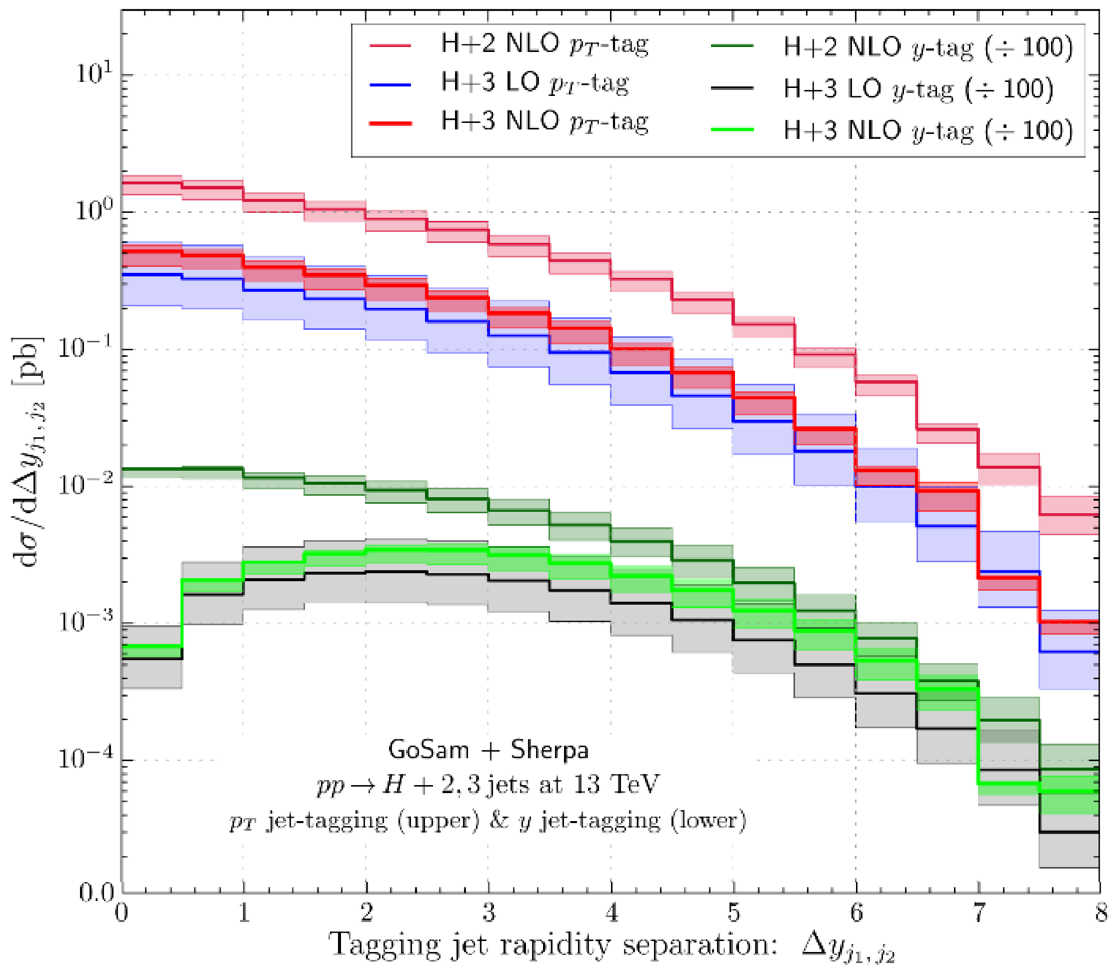
$$R_{k/n}(O) = \frac{\frac{d\sigma}{dO}(\mathrm{H}+k\,\mathrm{jets})}{\frac{d\sigma}{dO}(\mathrm{H}+n\,\mathrm{jets})}$$



High energy limit

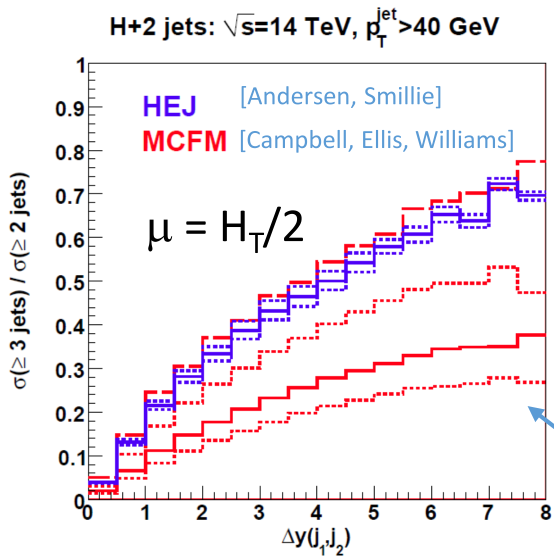
- Using a y-tagging strategy allows us to investigate universal QCD properties in high-energy limit

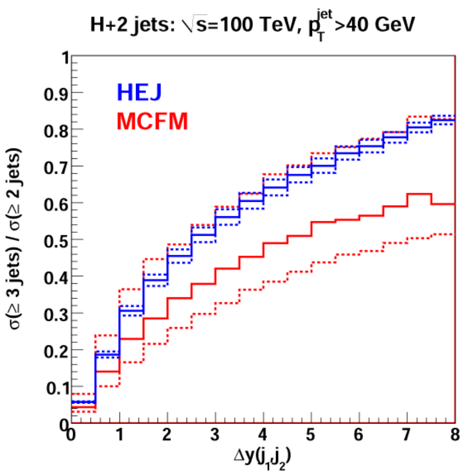
- Again: different tagging has larger impact on high multiplicity
- y-tagging leads to a shift towards larger rapidity differences

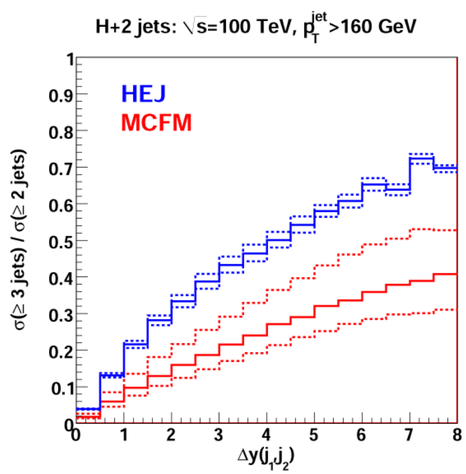


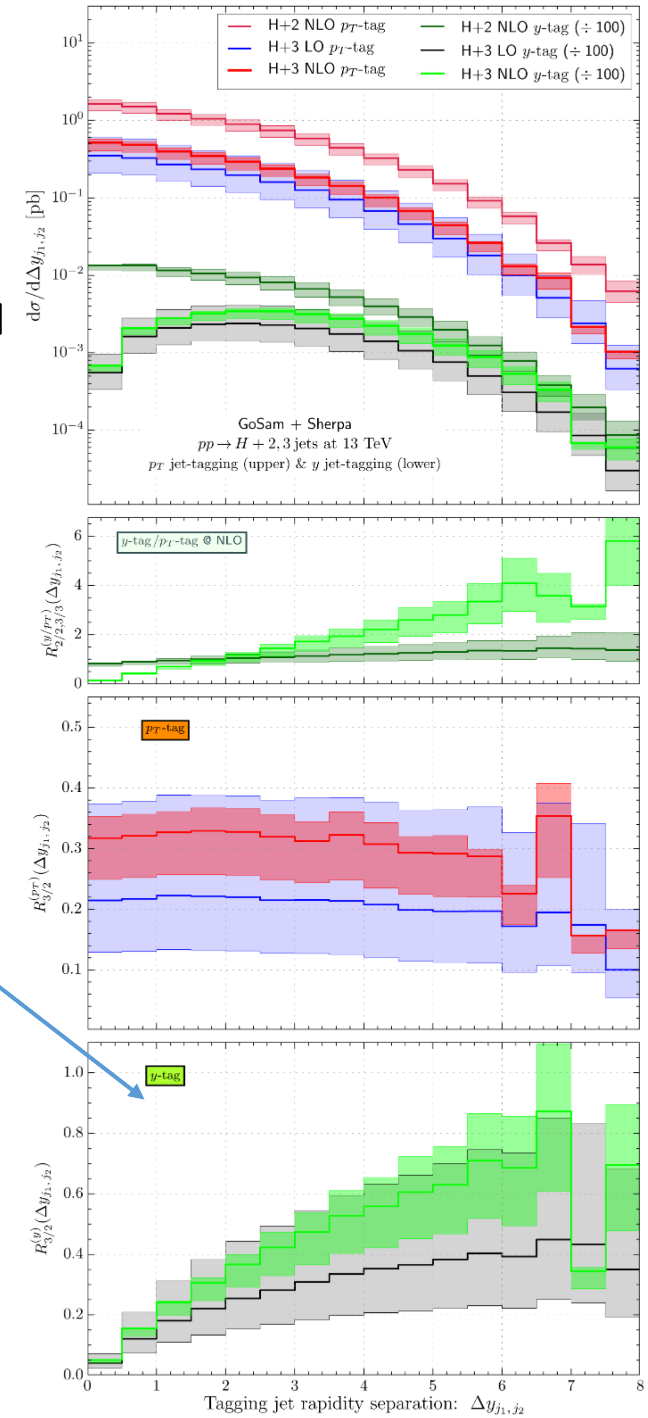
- To which extend can NLO computation describe high-energy effects?
- How does this look like at 100 TeV?

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

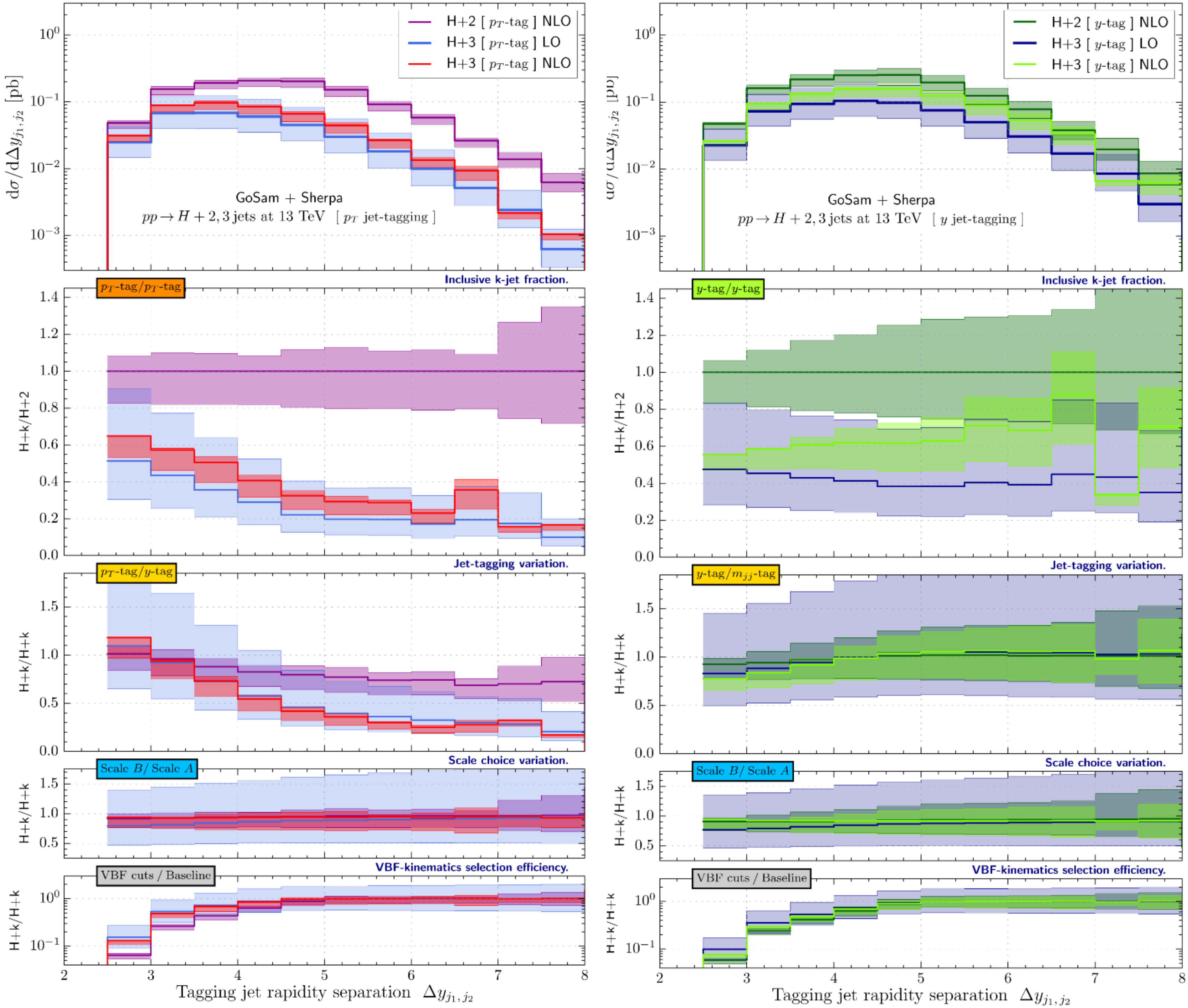








$\Delta y_{j_1,j_2}$



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