Higgs + 3 jets with GoSam + Sherpa

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$\Delta p \cdot \Delta q \geq \frac{1}{2} \hbar$
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Introduction

H + jets in gluon-gluon fusion (GGF)

- Dominant channel of Higgs production
- Large background, hard channel to directly study Higgs boson

Good understanding of GGF-channel is important

- Uncertainty of jet-veto efficiency
- Irreducible background for VBF-production

Note

In this talk $H + n$ jets is denoting inclusive result with jets $\geq n$

Recent Higgs + jets efforts with GoSam

pp → H + 2 jets with GoSam + Sherpa (Amegic)

[van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano]

- Cuts: 8 TeV, anti-kt $R = 0.5$ jets with $p_T > 20$ GeV, $|\eta| < 4$
- PDF: cteq6L1 for LO, cteq6mE for NLO
- Scale: $\mu_F = \mu_R = \hat{H}_T$, $\alpha_s(m_H)^2 \alpha_s(\mu_R)^{2+1}$ ← split scale scheme

pp → H + 3 jets with GoSam + Sherpa + MadGraph4

[Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano]

- Cuts: 8 TeV, anti-kt $R = 0.5$ jets with $p_T > 20$ GeV, $|\eta| < 4$
- PDF: cteq6L1 for LO, cteq6mE for NLO
- Scale: $\mu_F = \mu_R = \hat{H}_T/2$, $\alpha_s(m_H)^2 \alpha_s(\mu_R)^{3+1}$ ← split scale scheme

New results in this talk

pp → H + 2,3 jets with GoSam + Sherpa (Comix)

- Cuts: 8 TeV, anti-kt $R = 0.4$ jets with $p_T > 30$ GeV, $|\eta| < 4.4$
- PDF: CT10nlo for LO, CT10nlo for NLO

Unless stated otherwise results in this talk use **ATLAS GGF cuts** above.

Scale choices

$\mu_F = \mu_R = xQ$ scale variations $x \in (1, 0.5, 2)$

Scale A/B: $\mu_F = \mu_R = \hat{H}_T/2, \quad \alpha_s(m_H)^2\alpha_s(\mu_R)^{n+1}$

Scale C: $\mu_F = \mu_R = \hat{H}_T/2, \quad \alpha_s(\mu_R)^{2+n+1}$

Scale D: $\mu_F = \mu_R = m_H, \quad \alpha_s(\mu_R)^{2+n+1}$

$$\hat{H}_T = \sqrt{m_H^2 + p_{T,H}^2} + \sum_i^{partons} p_{T,i}$$

Unless stated otherwise results in this talk use **default scale C**.

NLO setup

Hard process ingredients

$$\sigma^{\mathrm{NLO}} = \int_n \left(\boxed{d\sigma_n^{\mathrm{B}}} + \underset{\substack{\uparrow\\ \text{bottleneck}}}{\boxed{d\sigma_n^{\mathrm{V}}}} + \int_1 \boxed{d\sigma_{n+1}^{\mathrm{S}}} \right) + \int_{n+1} \left(\underset{\substack{\uparrow\\ \text{bottleneck}}}{\boxed{d\sigma_{n+1}^{\mathrm{R}} - d\sigma_{n+1}^{\mathrm{S}}}} \right)$$

Complicated pieces

1. Virtual matrix elements [GoSam, Samurai, Ninja, Golem95C]
    - Integration over loop momentum
    - Higher rank loop integrals due to effective coupling
2. Real + subtraction [Sherpa, Comix]
    - Tree-like
    - Difficult phase-space integration
3. Linked with BLHA interface

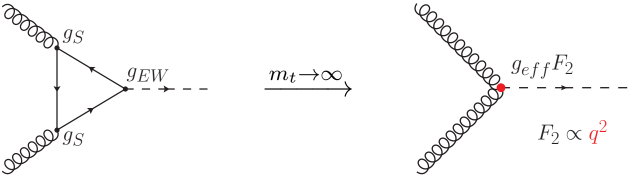
Higher rank loop integrals

Tensor rank of n-leg one-loop amplitude

$$\mathcal{A}_n = \int d^d q \frac{\mathcal{N}(q,\epsilon)}{D_0 D_1 \cdots D_{n-1}}$$

Rank $r_{\mathcal{N}} \leq n$ (in renormalizable theory, e.g. SM)

Higgs effective field theory



Rank $r_{\mathcal{N}} \leq n+1$

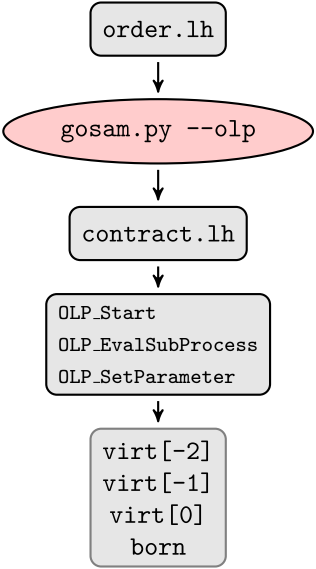
NEW: Higgs effective theory support in Comix [Höche]

Samurai, Ninja and Golem95C extended for higher rank integrals

[Mastrolia, Mirabella, Peraro; van Deurzen, Mastrolia]

[Guillet, Heinrich, von Soden-Fraunhofen]

Binoth Les Houches Accord interface to One Loop matrix elements



`order.lh`

`gosam.py --olp`

`contract.lh`

`OLP_Start`
`OLP_EvalSubProcess`
`OLP_SetParameter`

`virt[-2]`
`virt[-1]`
`virt[0]`
`born`

BLHA

- Simple uniform interface between Monte-Carlo (MC) and One Loop Providers (OLP) [arXiv:1001.1307, arXiv:1308.3462]

BLHA in GoSam 2.0

- Support BLHA1 and BLHA2
- Provide colour/spin-correlated trees
- UFO model import

BLHA extensions

- `OLP_Option` function for BLHA1

Efficient use of results is crucial

Higgs + 2 jets: (to 1 ‰ accuracy)

Total **1800 CPU-hours** (or ~ 1 day on 100 cores)

Part	Time [%]	Events[1]	Events/hour
B	4.5	$255 \cdot 10^6$	$3.2 \cdot 10^6$
I	7.1	$255 \cdot 10^6$	$2.0 \cdot 10^6$
RS	40.2	$505 \cdot 10^6$	$0.7 \cdot 10^6$
V	48.2	$20 \cdot 10^6$	$\mathbf{23500}$

Higgs + 3 jets: ($\times 18$ more expensive)

Total **33000 CPU-hours** (or ~ 14 days on 100 cores)

Part	Time [%]	Events[1]	Events/hour
B	0.3	$255 \cdot 10^6$	$2.7 \cdot 10^6$
I	1.8	$255 \cdot 10^6$	$0.4 \cdot 10^6$
RS	40.6	$2500 \cdot 10^6$	$0.2 \cdot 10^6$
V	57.4	$7.5 \cdot 10^6$	$\mathbf{400}$

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[1] Weighted events

Efficient use of results is crucial

What we might want to change in NLO calculation

- Scale variations. Different scale choices.
- Several jet definitions. Different cuts (e.g. p_T).
- New observables. New binning for observables.
- Different PDFs. Uncertainties in PDFs.

Running from the scratch every time Bad idea!

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

~ 4 million of CPU-hours (or 4.6 years on 100 cores)

Layered computation set-up Much better!

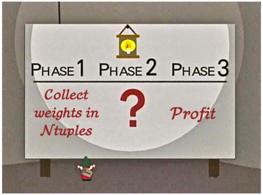
- Save generated events in ROOT NTuples. [arXiv:1003.1241]
- Analyze later (~ 50 CPU-hours per analysis).
- Interpolation grids with **APPLgrid** for fast PDF convolution and scale variations. [arXiv:1312.4460]

Saving events for further analysis

Sherpa ROOT NTuples output

[arXiv:1003.1241]

- Save weights, PDFs, scheme dependence
- Compact compressed storage
- Several jet algorithms at low cost
- Can change scales/PDFs during analysis



MiNLO with NTuples (work-in-progress)

- NTuples can be reweighted according to MiNLO procedure
- No possibility to have jet $p_T \to 0$, e.g. no H+2 from H+3
  (we start with fixed-order NLO, which needs p_T-cut for generation)

Available ROOT NTuples for Higgs + jets

Higgs + 2 jets: ~ 300 GB, 12 CPU-hours per analysis
Higgs + 3 jets: ~ 1000 GB, 50 CPU-hours per analysis

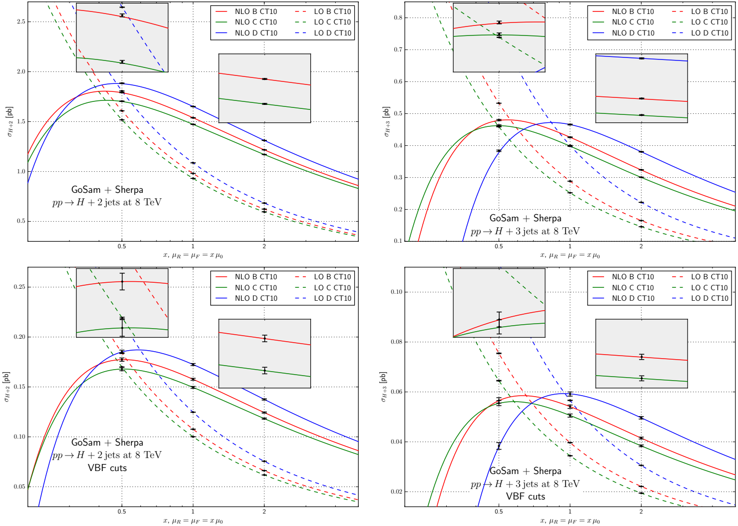
Anti-kt and kt jets with R $= 0.1, 0.2, \ldots, 1.0$, $p_T > 25$ GeV, $|\eta| < 4.5$

Interpolation grids to speed-up PDF convolution

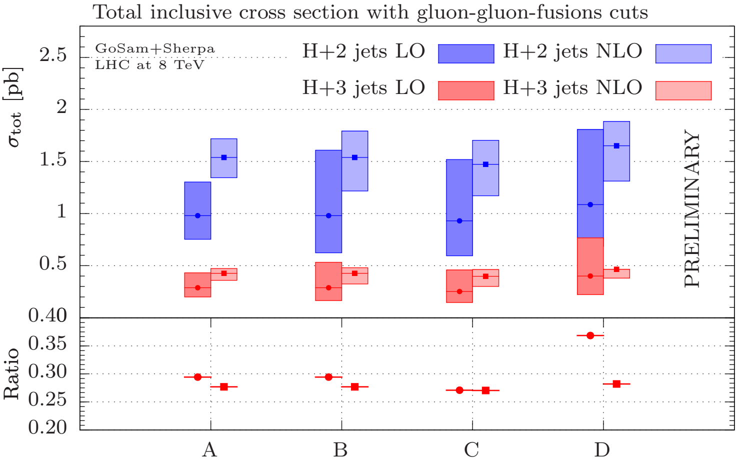
APPLgrid – interpolation grids in Q, x_1, x_2 for each bin in histogram.

NTuples: ~ 1000 GB space, ~ 50 hours to analyze, completely generic

APPLgrid: ~ 1 GB space, ~ 0.1 hour to analyze, specific observable/binning



$H+2,3$ total XS scale dependence



Total inclusive cross section with gluon-gluon-fusions cuts

A: $\alpha_s(x\,\frac{H_T}{2})^3\alpha_s(m_H)^2$

B: $\alpha_s(x\,\frac{H_T}{2})^3\alpha_s(x\,m_H)^2$

C: $\alpha_s(x\,\frac{H_T}{2})^5$

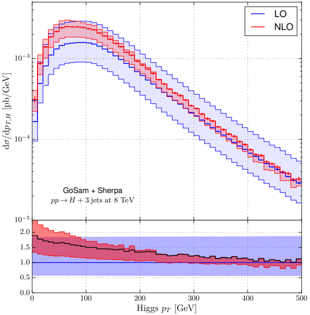
D: $\alpha_s(x\,m_H)^5$

A/B – split-scale (same central value, different scale variations)

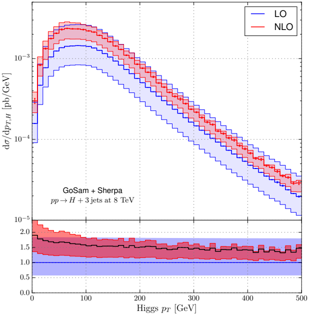
C – dynamic, D – fixed

Higgs p_T distribution with different scale choices in $H + 3$ jets

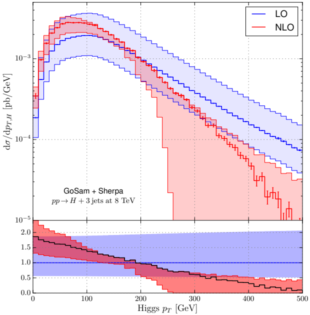
B:

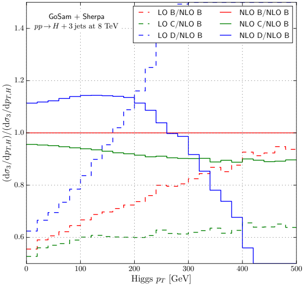


C:



D:





$H + 2, 3$ total XS for scale C

pp → H + 2,3 jets with GoSam + Sherpa (Comix)

- Cuts: 8 TeV, anti-kt $R = 0.4$ jets with $p_T > 30$ GeV, $|\eta| < 4.4$
- PDF: CT10nlo for LO, CT10nlo for NLO

pp → H + 2 jets

$$\sigma^{LO}_{H+2j}(\hat{H}_T/2) = 0.931(0.000)^{+0.588}_{-0.336}\,\mathrm{pb}$$

$$\sigma^{NLO}_{H+2j}(\hat{H}_T/2) = 1.473(0.002)^{+0.232}_{-0.302}\,\mathrm{pb}$$

NLO scale variations are about 28% of the LO scale uncertainty

pp → H + 3 jets

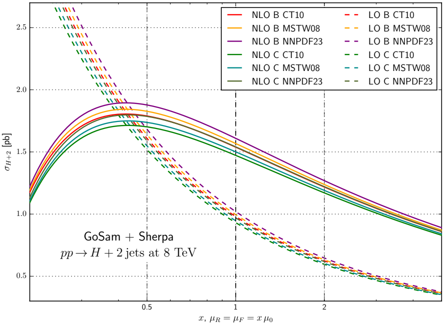
$$\sigma^{LO}_{H+3j}(\hat{H}_T/2) = 0.252(0.000)^{+0.207}_{-0.106}\,\mathrm{pb}$$

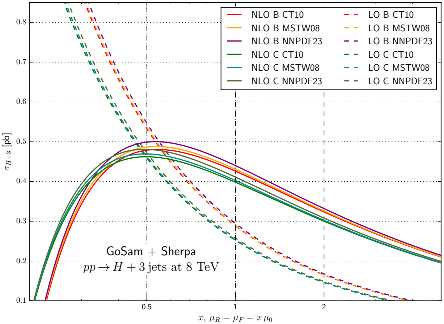
$$\sigma^{NLO}_{H+3j}(\hat{H}_T/2) = 0.398(0.001)^{+0.065}_{-0.098}\,\mathrm{pb}$$

NLO scale variations are about 33% of the LO scale uncertainty

$H + 2, 3$ total XS PDF dependence for scales B and C

All PDF sets use the same value of $\alpha_s(M_Z) = 0.118$





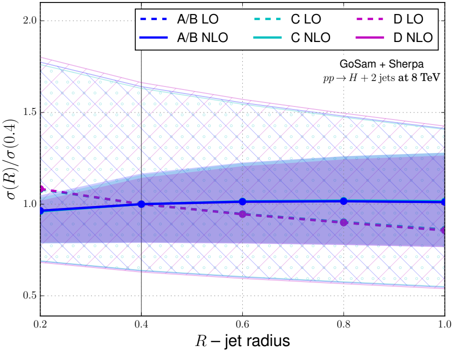
At NLO variations from different PDF sets are comparable with variations from scale choices.

For H + 2 scales B and C are almost the same

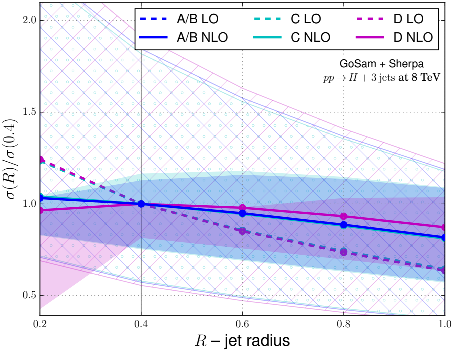
Anti-kt jet radius dependence

$\sigma(R)$ normalized on $\sigma(0.4)$

Higgs + 2 jets



Higgs + 3 jets



NTuples for $R = 0.1, 0.2, \ldots, 1.0$

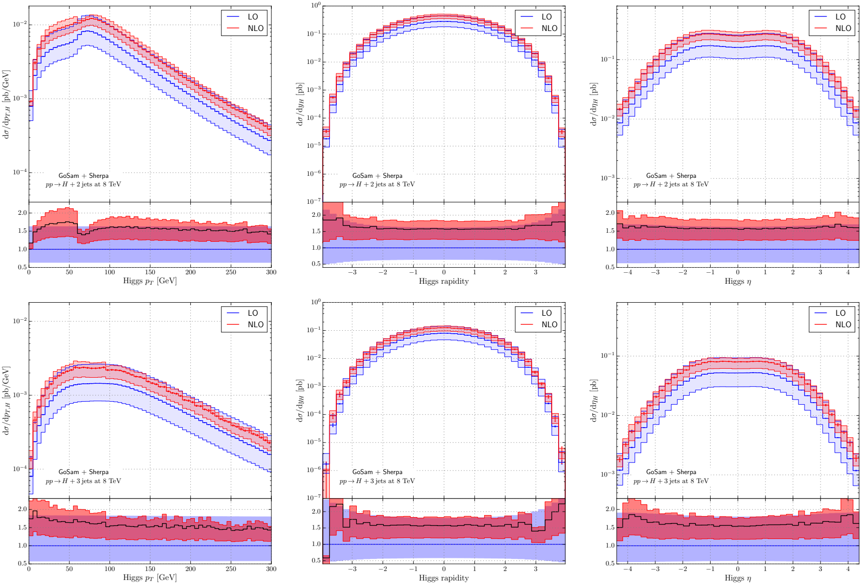
At NLO dependence on jet radius is more stable

Higgs p_T, y and η distributions

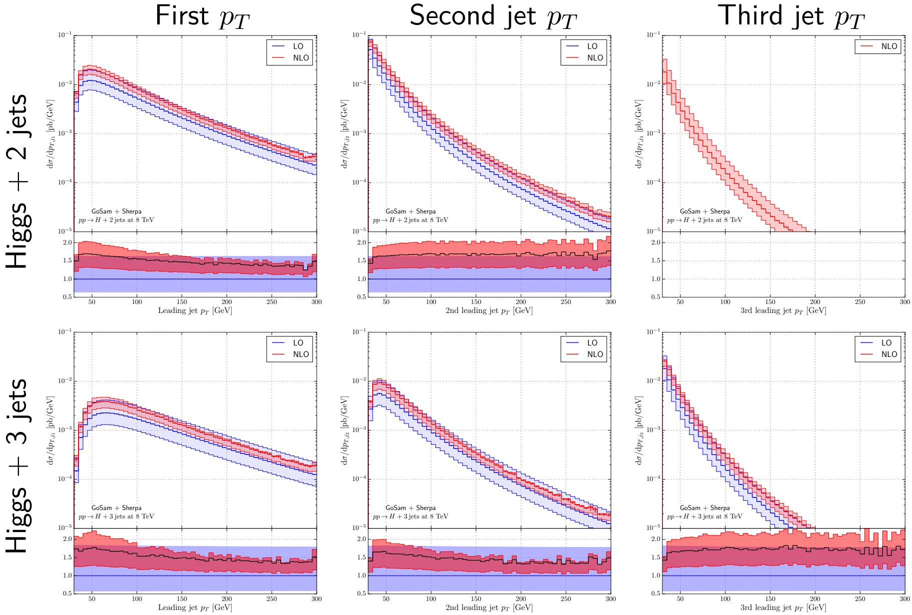
Higgs p_T Higgs y Higgs η

Higgs + 2 jets

Higgs + 3 jets

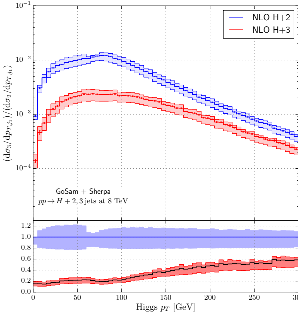


Jet p_T distributions

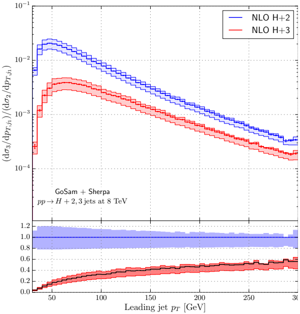


3/2 ratio higgs p_T and jet p_T distributions

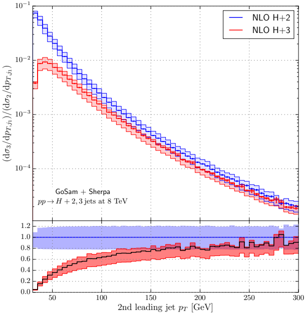
Higgs p_T



First jet p_T



Second jet p_T



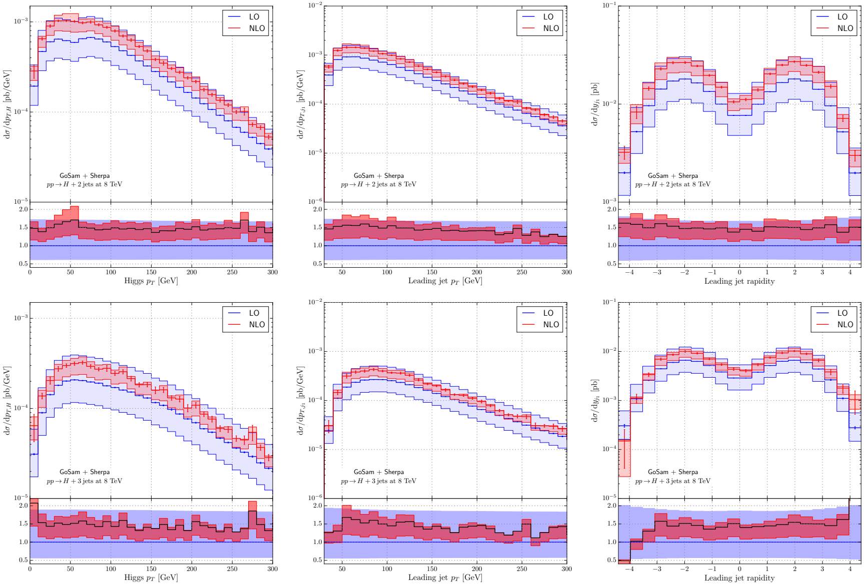
- $r_{3/2}$: varying p_T dependence
  (moderate for $p_{T,H}$ and $p_{T,1}$, strong for $p_{T,2}$)

Results with VBF-like cuts (7% of events)

Higgs p_T First jet p_T First jet y

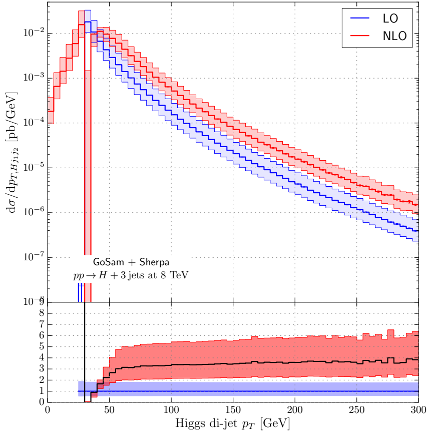
Higgs + 2 jets (VBF-cuts)

Higgs + 3 jets (VBF-cuts)

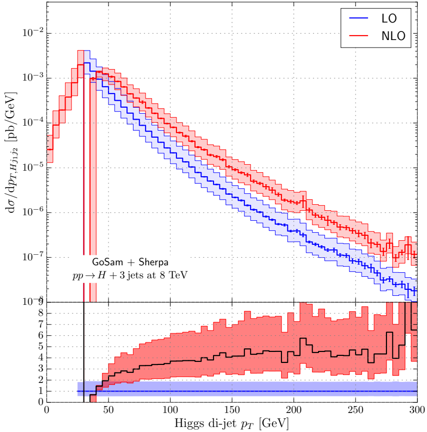


Hjj transverse momentum

Higgs + 3 jets (GGF cuts)



Higgs + 3 jets (VBF cuts)



Conclusions

Summary

- New calculation of $H + 3$ jets at NLO with GoSam+Sherpa
- NLO work-flow with NTuples and APPLgrid
- ~ 1.3 TB of NTuples available for $H + 2$ and $H + 3$

Work in progress

- Finish validation
- Verify MiNLO implementation for NTuples and compare to other scales
- More accurate study for VBF-like cuts

Outlook

- Matching to shower and merging of different multiplicities