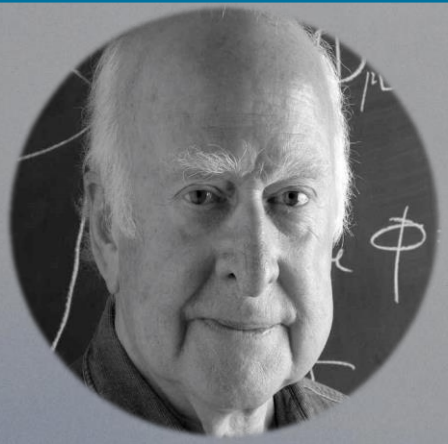
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

von Humboldt Stiftung/Found

# Higgs + 3 jets in ggf at NLO

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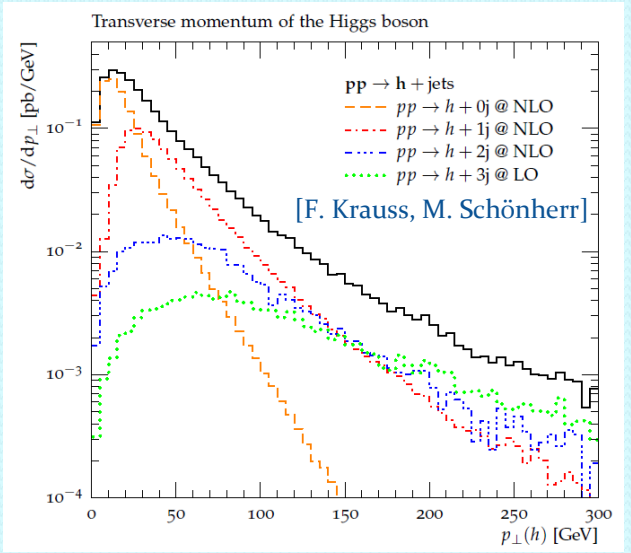
In collaboration with:

N. Greiner, S. Höche, M. Schönherr, V. Yundin and J. Winter

# H+jets in gluon-gluon fusion

- Dominant channel of Higgs production
- Large background makes it a prohibitive channel to directly study the Higgs boson
- Nonetheless precise knowledge of GGF-channel is crucial:
  - When applying vetoes to jets

➔ H+jets cross section needed to estimate untertainties in efficiencies



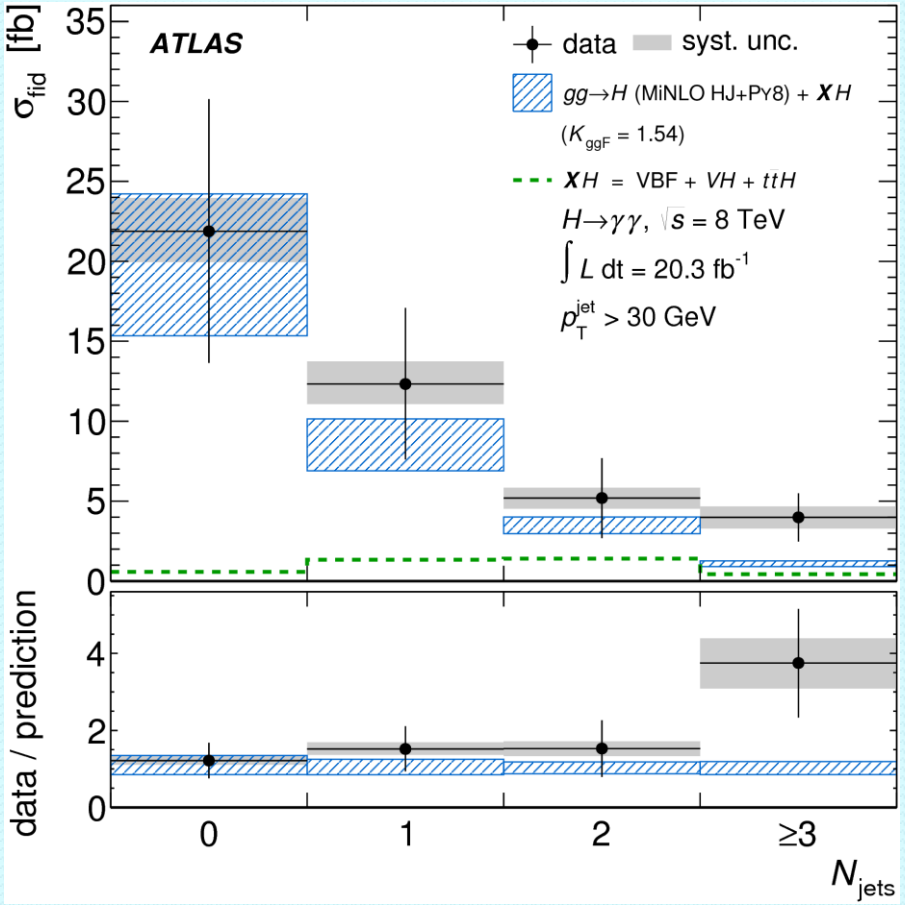

  - When studying VBF production channel

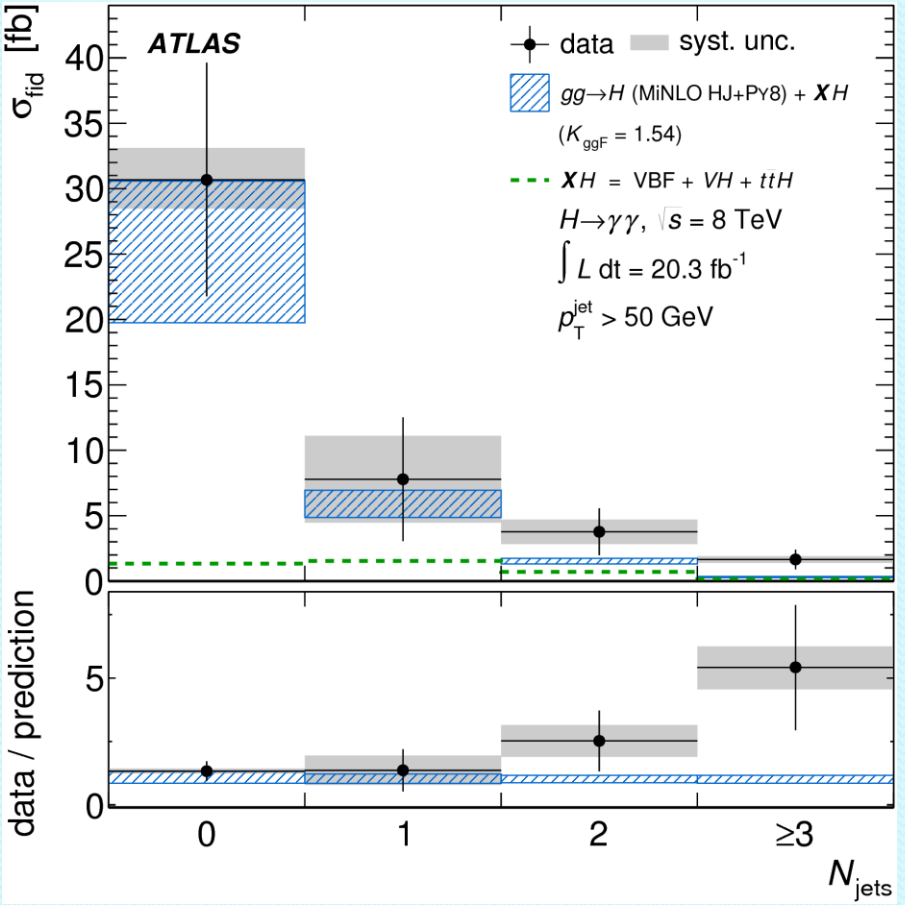
➔ Estimate contamination in VBF sample of events coming from gluon-gluon fusion channel

➔ H+2j sample can describe further radiation only at LO

# H+jets in gluon-gluon fusion

- Recent ATLAS measurement:



# NLO Results

- Ingredients for a full NLO calculation:

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

- Virtual corrections

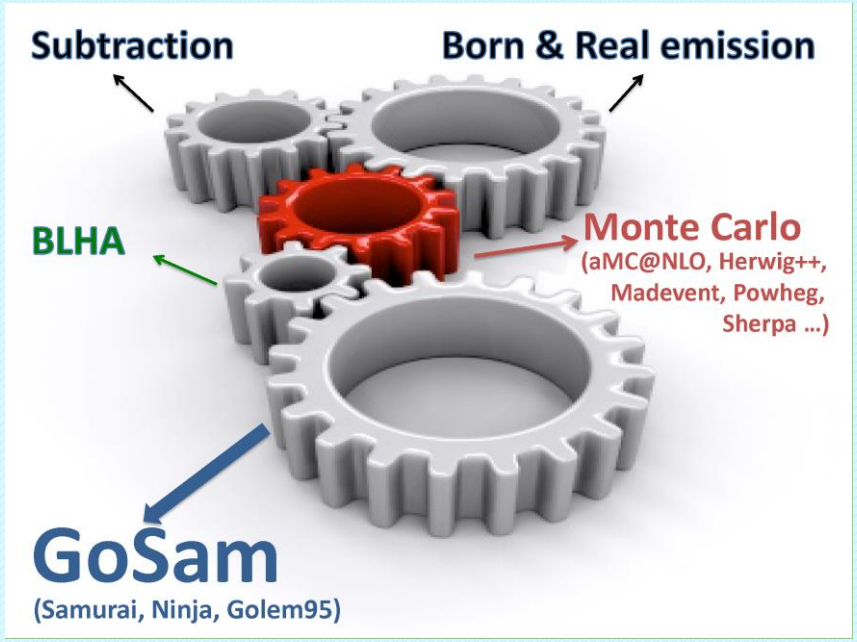
**One Loop Program**

BLHA-1

**Monte Carlo**

Tree amplitude

- Subtraction scheme
- Phase space integral

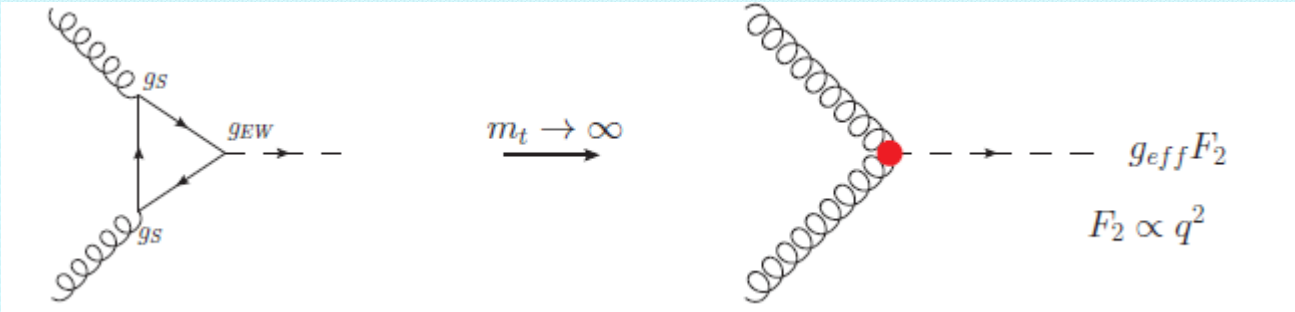


# Higher rank loop integrals

- For any 1-loop amplitude $\mathcal{A}_n = \int d^d\bar{q} \frac{\mathcal{N}(\bar{q},\epsilon)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{n-1}}$

Rank: $r_{\mathcal{N}}$ = # powers of loop momentum in numerator $\mathcal{N}(\bar{q})$

- in SM with renormalizable gauges: $r_{\mathcal{N}} \leq n$
- in SM with effective Hgg vertex or ADD models: $r_{\mathcal{N}} \leq n+1$




Adapt reduction programs Samurai, Ninja and Golem95C to deal with higher rank loop integrals

NEW

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

[Guillet, Heinrich, von Soden-Fraunhofen]

# H+jets: virtual corrections

| | Processes | # Diagrams | # Helicities | # Groups | Timing (col.+hel. summed) |
|---|---|---|---|---|---|
| H+0 jets | $g+g \longrightarrow H$ | 1 | 1 | 1 | < 1 ms |
| H+1 jets | $q+\bar{q} \longrightarrow H+g$ | 14 | 4 | 3 | ~ 3 ms |
| | $g+g \longrightarrow H+g$ | 48 | 8 | 3 | ~ 7 ms |
| | | **62** | | | |
| H+2 jets | $q+\bar{q} \longrightarrow H+q'+\bar{q}'$ | 32 | 4 | 6 | ~ 9 ms |
| | $q+\bar{q} \longrightarrow H+q+\bar{q}$ | 64 | 6 | 8 | ~ 15 ms |
| | $q+\bar{q} \longrightarrow H+g+g$ | 179 | 8 | 12 | ~ 56 ms |
| | $g+g \longrightarrow H+g+g$ | 651 | 16 | 12 | ~ 309 ms |
| | | **926** | | | |
| H+3 jets | $q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$ | 467 | 8 | 32 | ~ 68 ms |
| | $q+\bar{q} \longrightarrow H+q+\bar{q}+g$ | 868 | 12 | 44 | ~ 157 ms |
| | $q+\bar{q} \longrightarrow H+g+g+g$ | 2519 | 16 | 60 | ~ 999 ms |
| | $g+g \longrightarrow H+g+g+g$ | 9325 | 32 | 60 | ~ 8'960 ms |
| | | **13179** | | | |

# H+jets in gluon-gluon fusion

## H+3 jets

- Calculation setup so far:
  - B amplitudes: Sherpa (Amegic)
  - V amplitudes: GoSam

  } PS integration: Sherpa (BLHA)

  - IRS amplitudes: MG4/MadDipole

  } PS integration: MadEvent

  ↳ Full NLO

- Checks:
  - ✓ Gauge invariance of virtual amplitudes
  - ✓ α-independence of IRS contribution
  - ✓ H+2j comparison and B comparison for combination

# H+2 jets

[van Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano]

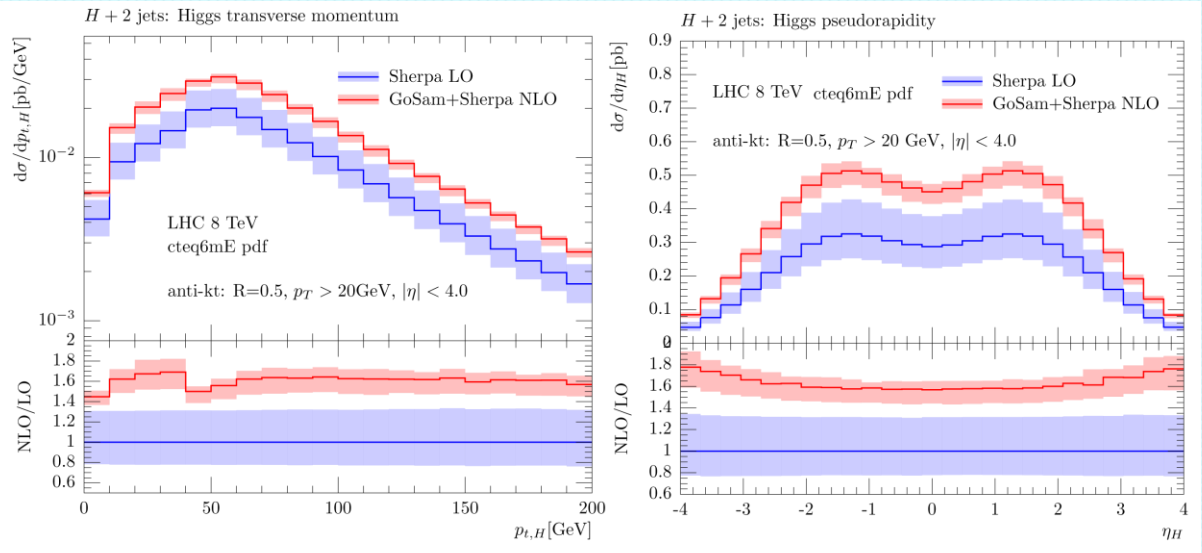
- Computed using GoSam + Sherpa
- Possibility to test the framework by comparing to existing results/codes
  --> agreement with MCFM (v6.4) [Campbell, Ellis, Williams]

- Calculation setup: LHC 8 TeV

anti-kt: R=0.5 $p_T$>20 GeV $|\eta| < 4.0$

PDFs: cteq6L1 @ LO cteq6mE @ NLO

scales: $\mu_F = \mu_R = \hat{H}_T = \left( \sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}| \right)$



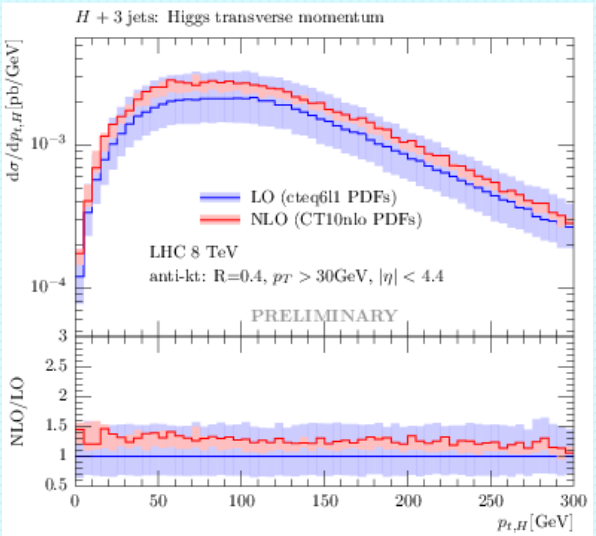
# First H+3 jets results

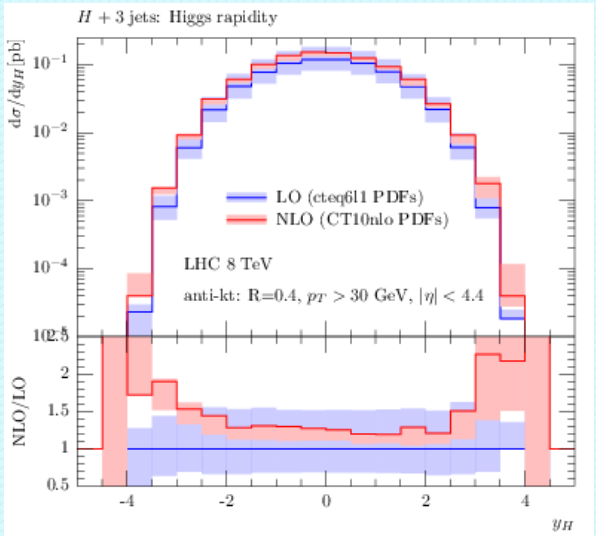
- Computed using GoSam + Sherpa + MadGraph4/MadDipole/MadEvent
  - Calculation setup: LHC 8 TeV with ATLAS cuts

anti-kt: R=0.4 $p_T$>30 GeV $|\eta| < 4.4$

PDFs: cteq6L1 @ LO CT10nlo @ NLO

scales: $\mu_F = \mu_R = \frac{\hat{H}_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$




[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter; 1307.4737, LH2013]

# H+jets in gluon-gluon fusion

## H+3 jets

- Calculation setup so far:
  - B amplitudes: Sherpa (Amegic)
  - V amplitudes: GoSam

  } PS integration: Sherpa (BLHA)

  - IRS amplitudes: MG4/MadDipole

  } PS integration: MadEvent

  → Full NLO

- New ongoing calculation:
  - B amplitudes: Sherpa (Comix)
  - V amplitudes: GoSam
  - IRS amplitudes: Sherpa (Comix)

  } PS integration: Sherpa (BLHA)

  → Full NLO + merging + shower

  → NLO Events as NTuples

# Ntuples for H+2jets and H+3jets

[LH2010; 1310.7439]

- At present ~ 1.3T of Ntuples files:
  - H+2 jets:
    - 50 B and I files of 5 Milion events each
    - 200 V files of 100000 events each
    - 100 RS files of 5 Milion events each

    } Storage Space: ~ 317 G
  - H+3 jets:
    - 50 B and I files of 5 Milion events each
    - 300 V files of 25000 events each
    - 500 RS files of 5 Milion events each

    } Storage Space: ~ 1 T
- Advantages:
  - Flexibility / portability / moderately fast to reanalyse

# Calculation Setup

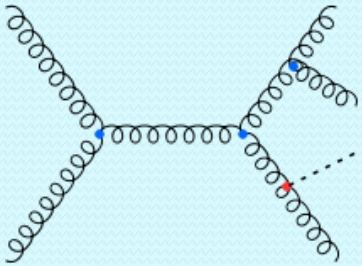
[Greiner, Höche, G.L., Schönherr, Yundin, Winter]

- So far results for LHC at 8 TeV:

anti-kt: R=0.4 $p_T$>30 GeV $|\eta| < 4.4$

PDFs: CT10nlo

- Scales:
  - Default: (A)



$$\mu_F = \mu_R = \frac{\hat{H}_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$$

$$\alpha_s^5 \longrightarrow \alpha_s^2(m_H)\alpha_s^3(x\,\hat{H}_T/2) \qquad x = 0.5,\ 2$$

  - Variation:
    - (B): $\alpha_s^5 \longrightarrow \alpha_s^2(x\,m_H)\alpha_s^3(x\,\hat{H}_T/2) \qquad x = 0.5,\ 2$
    - (C): $\alpha_s^5 \longrightarrow \alpha_s^5(x\,\hat{H}_T/2) \qquad x = 0.5,\ 2$
    - (D): $\alpha_s^5 \longrightarrow \alpha_s^5(x\,m_H) \qquad x = 0.5,\ 2$

# Inclusive cross section

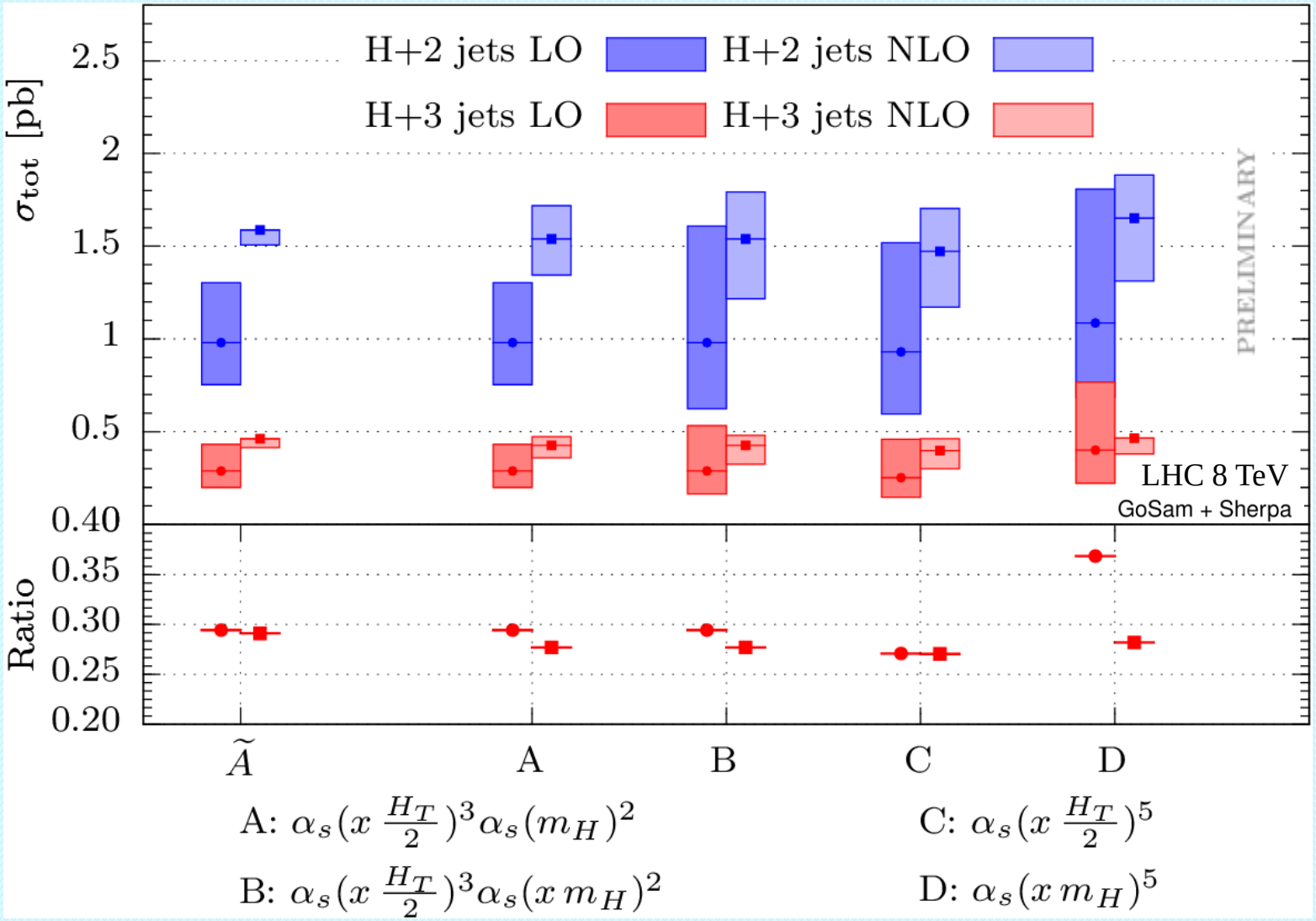
$\sigma_n$ : inclusive cross section
$f_n$ : inclusive $n$-jet fraction
$r_{(n+1)/n} = \sigma_{n+1}/\sigma_n$

Results are in pb:

| Sample | Cross sections for Higgs boson plus | | | | | |
|---|---|---|---|---|---|---|
| $K$-factor | $\geq 2$ jets | $f_3$ | $\geq 3$ jets | $f_4$ | $\geq 4$ jets | $r_{3/2}$ |
| LO | | | | | | |
| $H+2$-jets (NLO PDFs) | $0.980\ ^{+0.323}_{-0.226}$ | | | | | |
| $H+3$-jets (NLO PDFs) | (0.289) | 1.0 | $0.289^{+0.143}_{-0.089}$ | | | 0.295 |
| NLO | | | | | | |
| $H+2$-jets | $1.539^{+0.180}_{-0.194}$ | 0.188 | 0.289 | | | |
| $H+3$-jets | (0.426) | 1.0 | $0.426^{+0.046}_{-0.067}$ | 0.181 | 0.077 | 0.277 |
| $K_2$, $K_3$ (NLO PDFs for LO) | 1.57 | | 1.47 | | | |

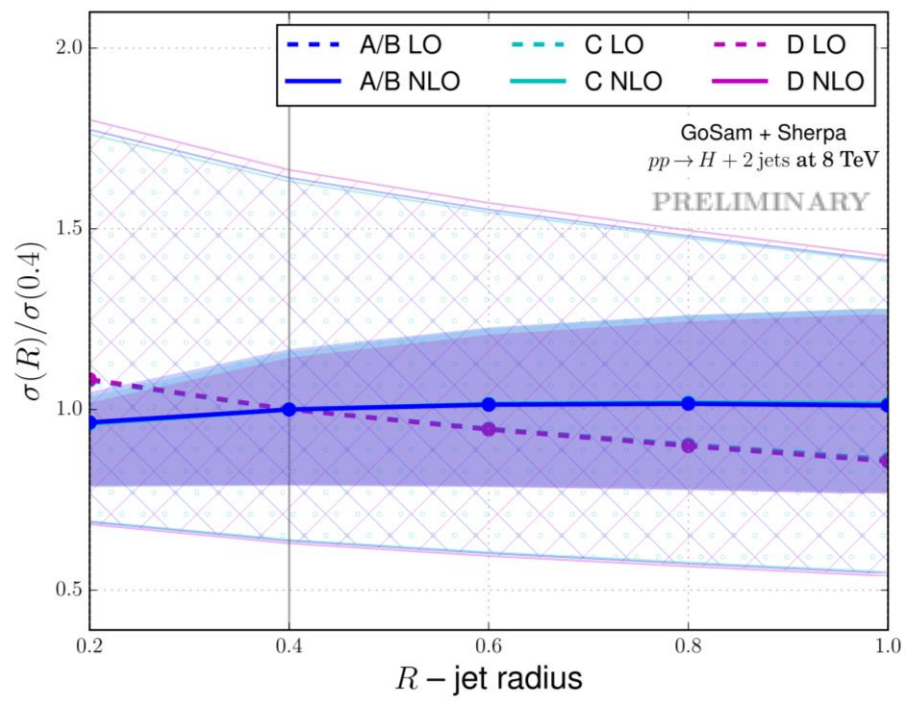
PRELIMINARY

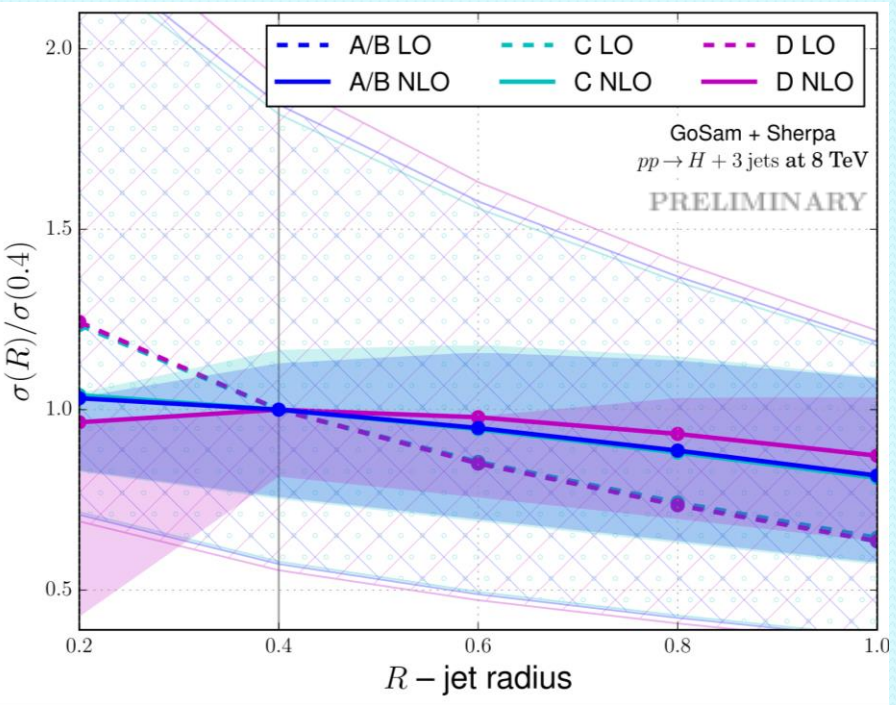
# Dependence on scale choice




PRELIMINARY

# Jet radius dependence



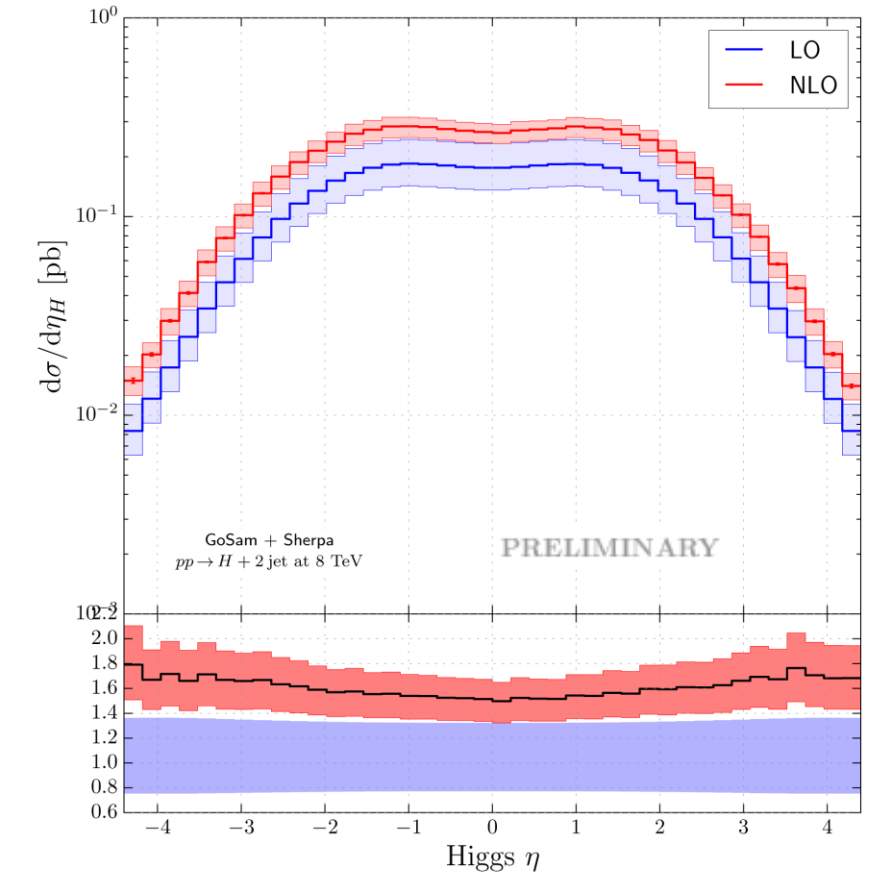



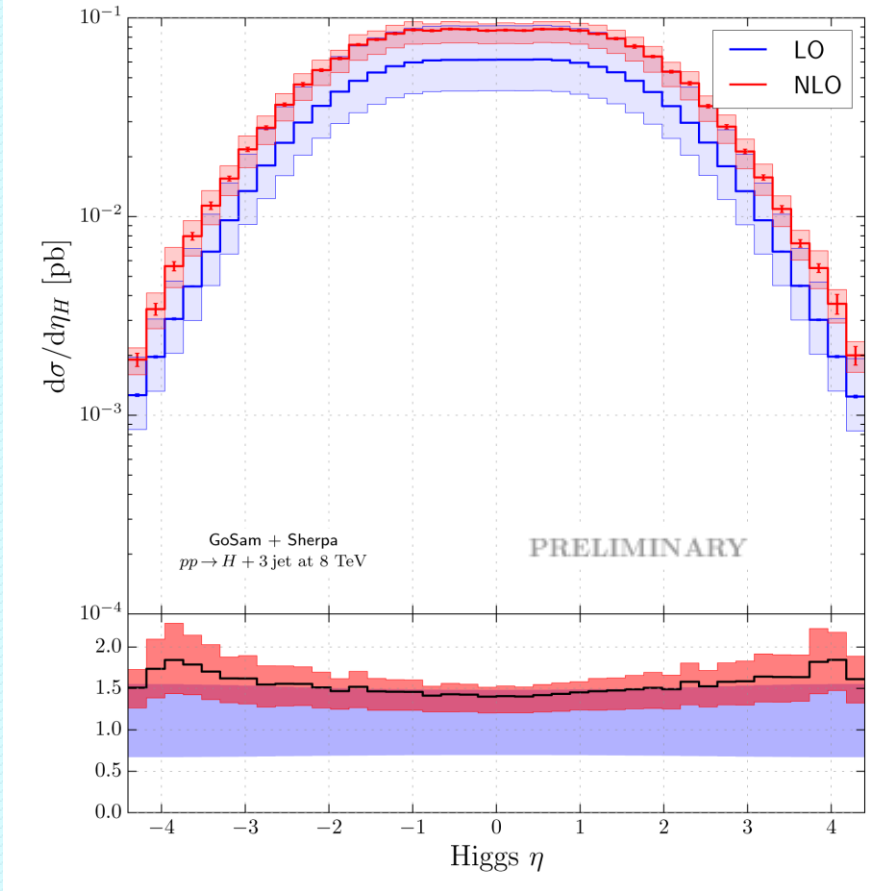

PRELIMINARY

- Ntuples for R=0.1, … , 1.0
- At NLO dependence on jet radius stabilizes

# Higgs pseudorapidity

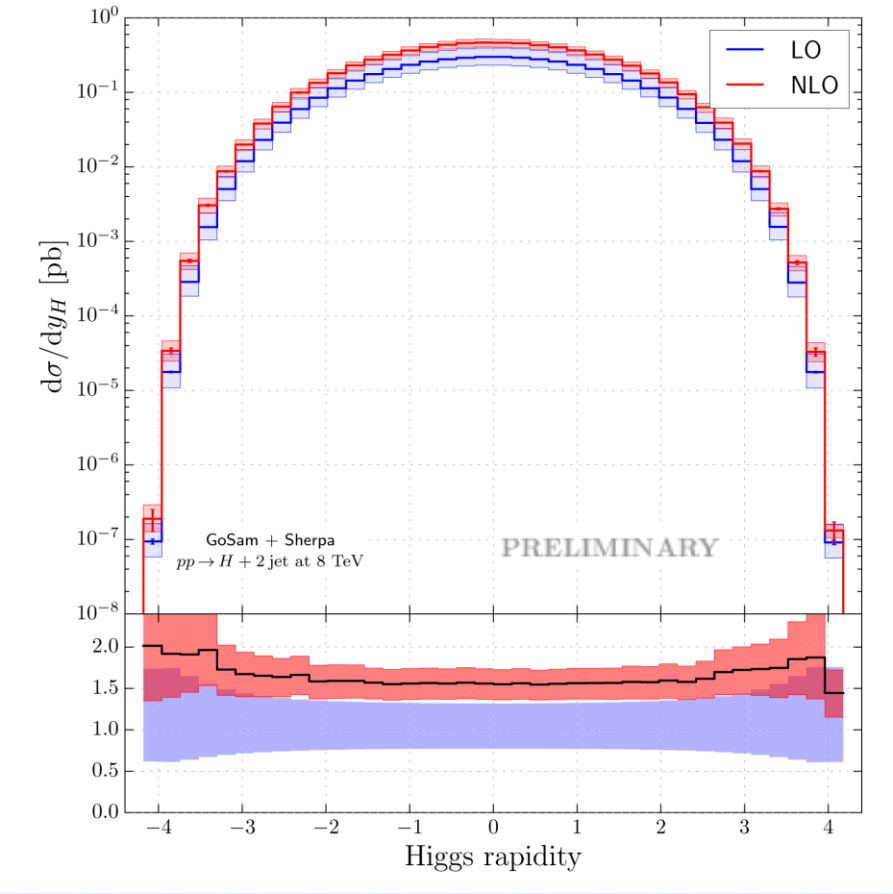
PRELIMINARY

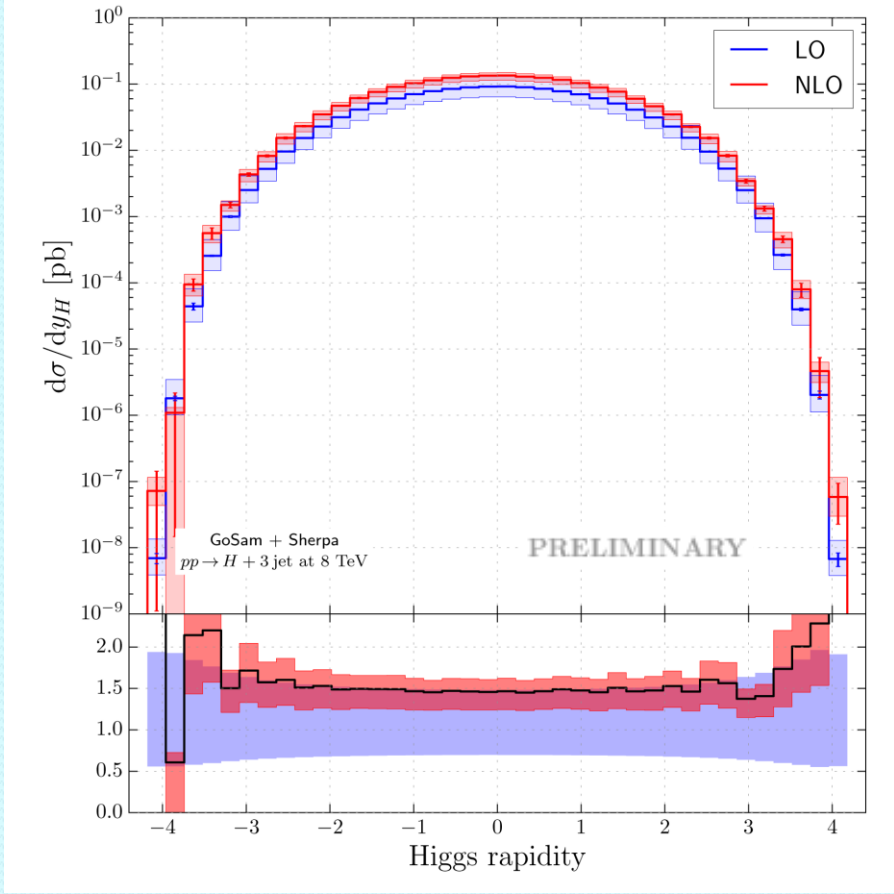


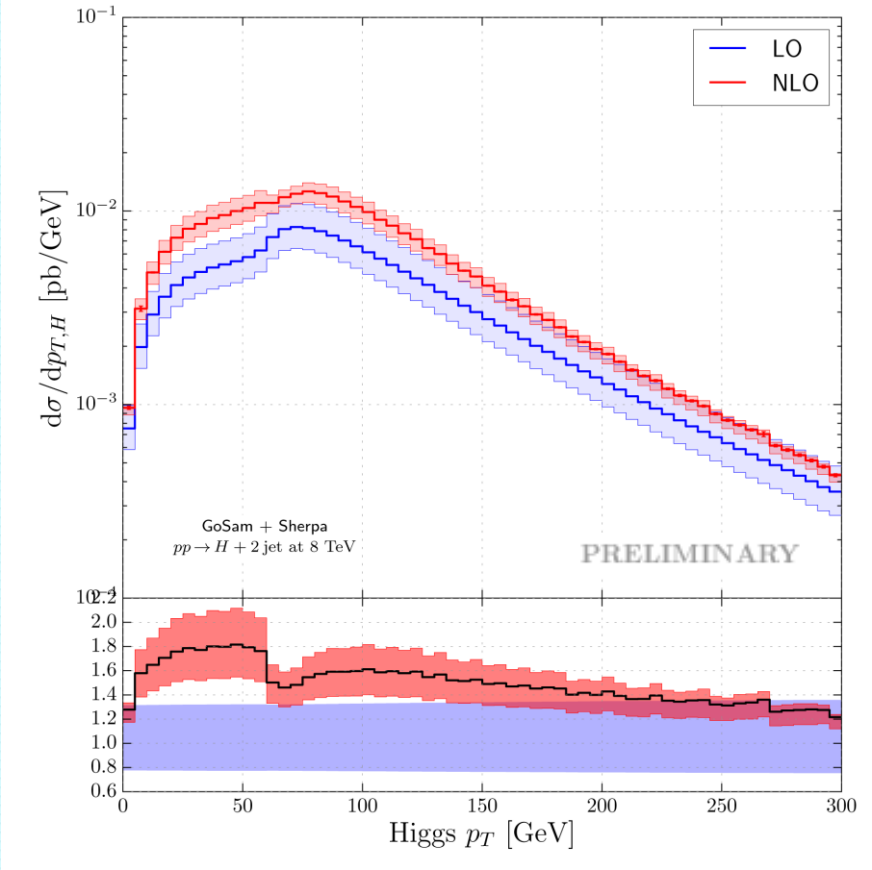
# Higgs rapidity

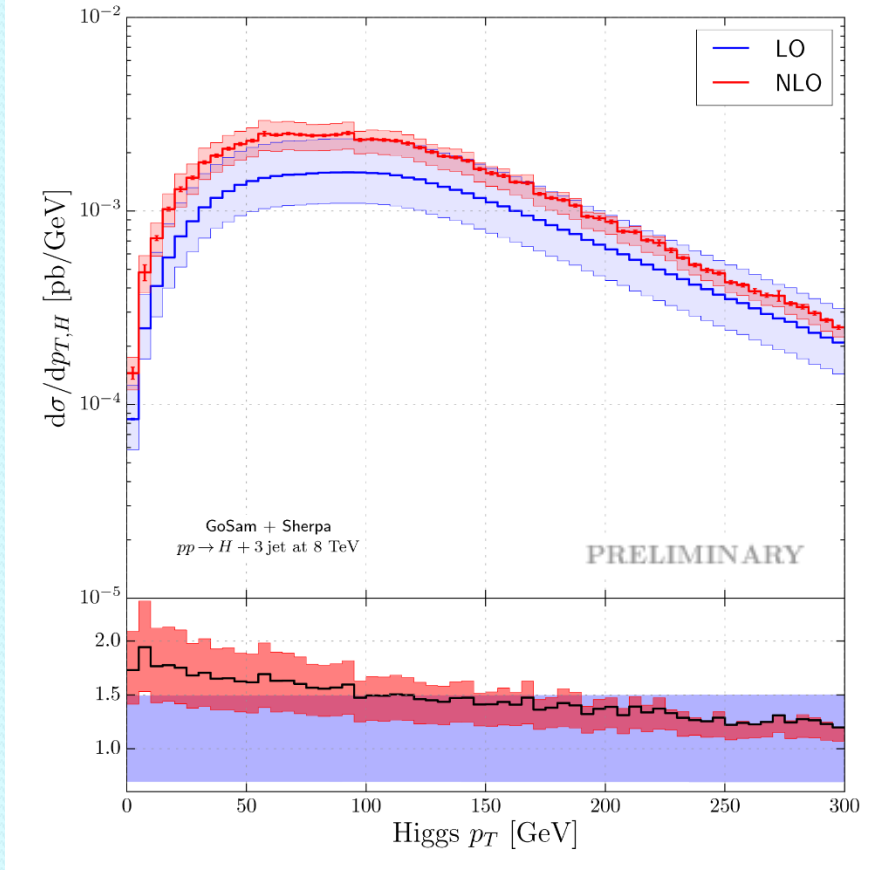
PRELIMINARY



# Higgs transverse momentum

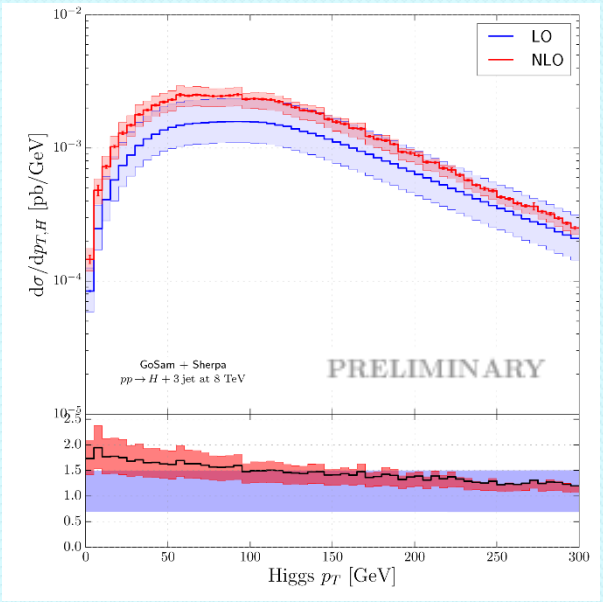


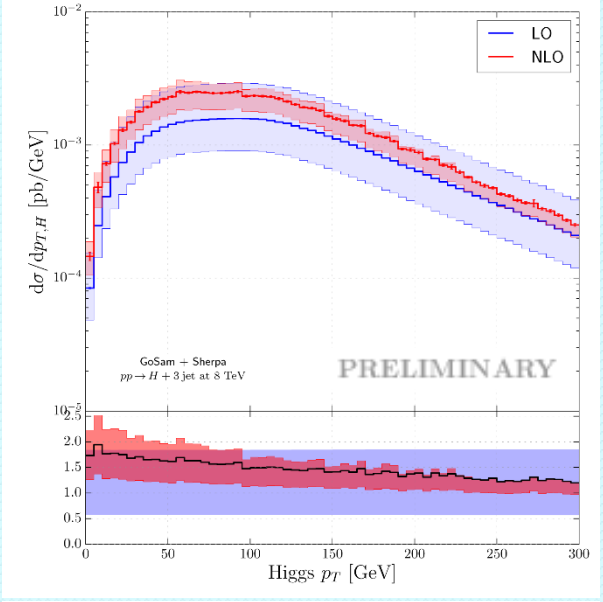

PRELIMINARY

# Dependence on scale choice

(A)




(B)

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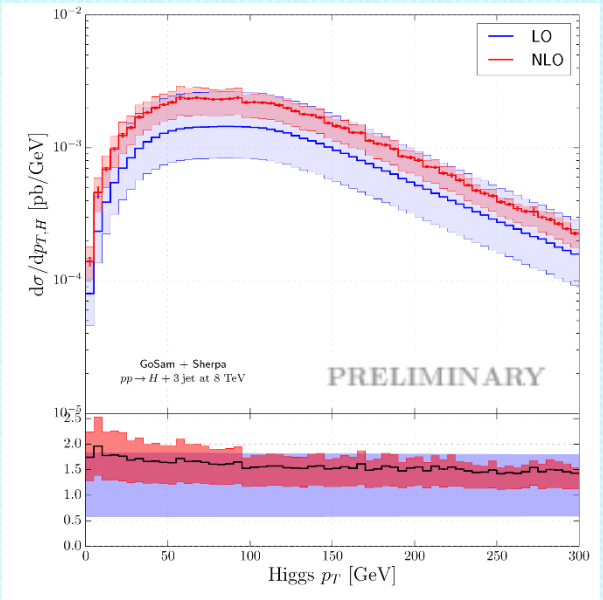
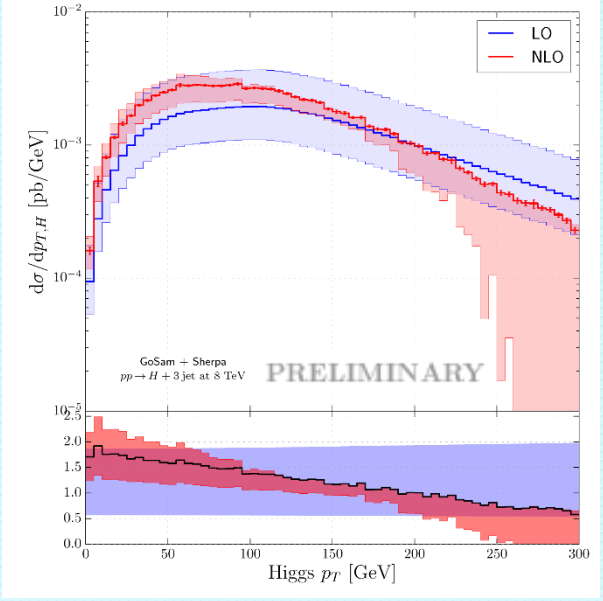
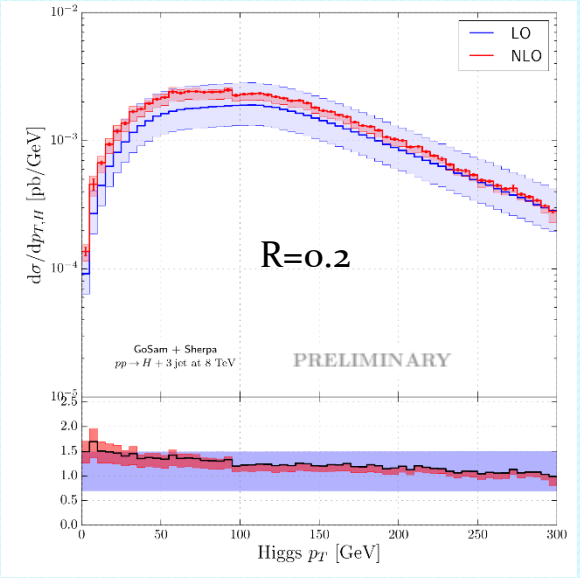


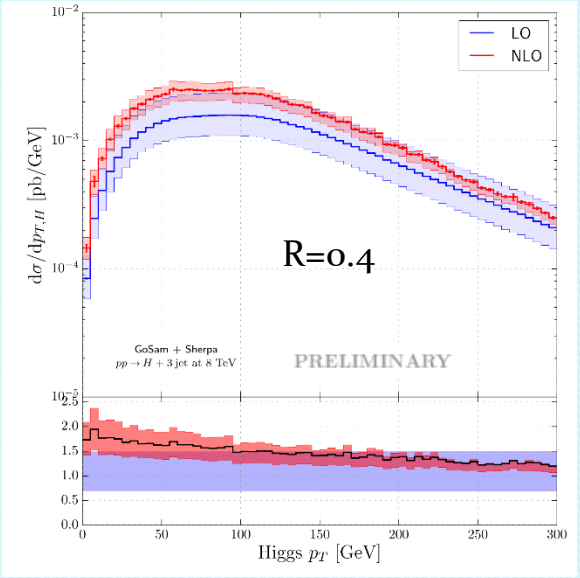

(D)

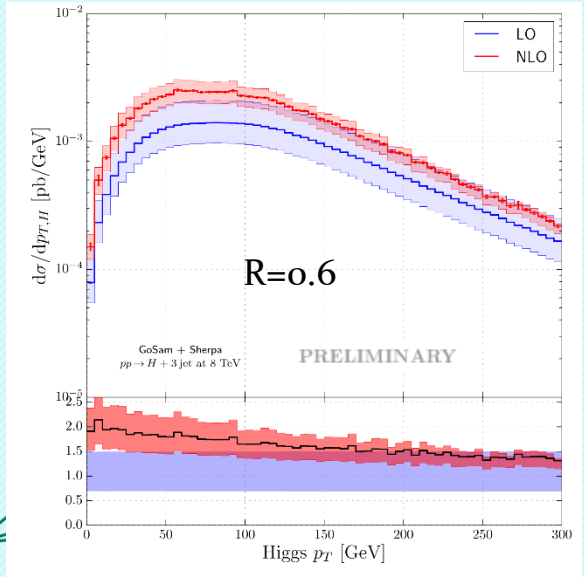


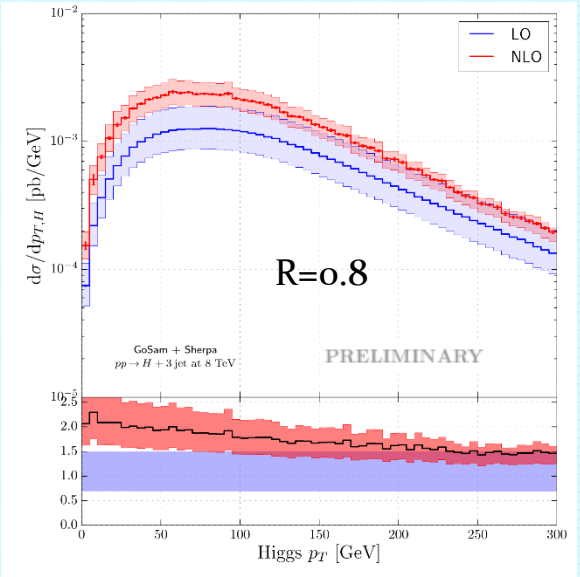

PRELIMINARY

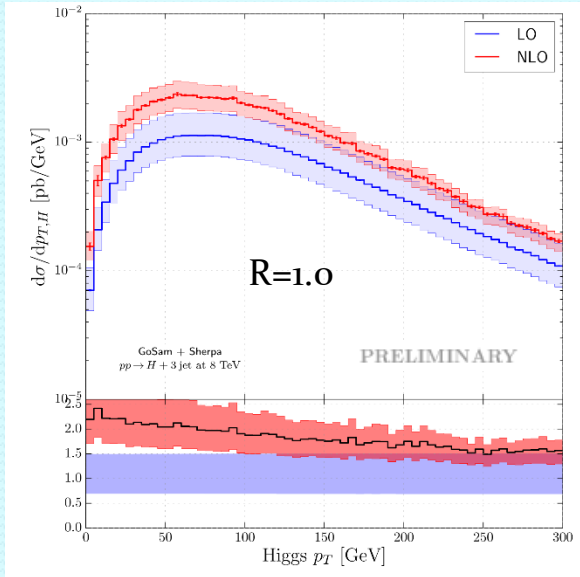
# Jet radius dependence



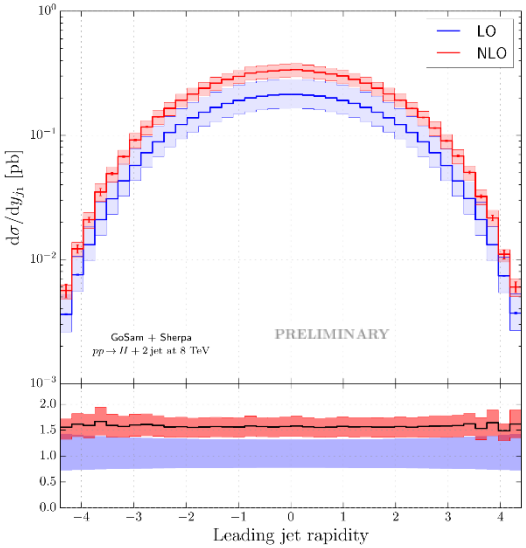

PRELIMINARY

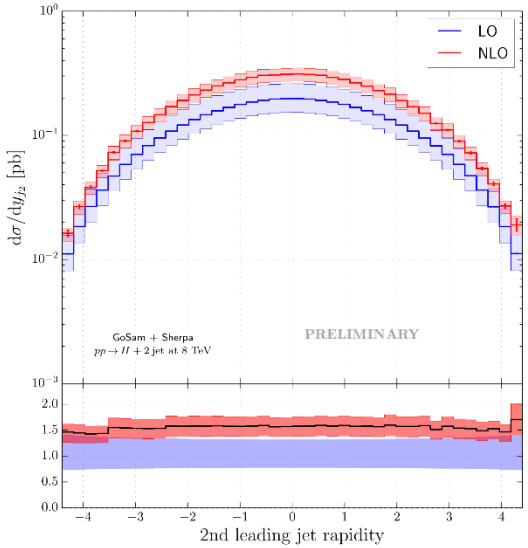
# Jets rapidities

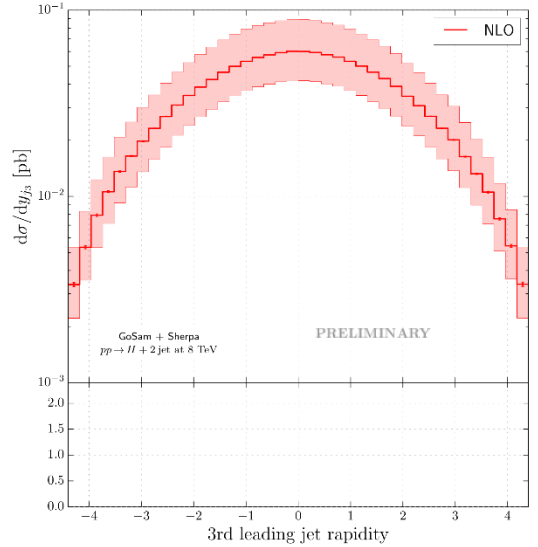
- 1st jet
- 2nd jet
- 3rd jet

PRELIMINARY

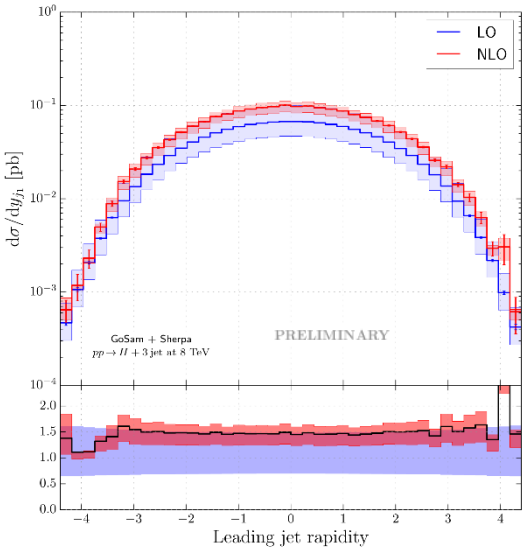
H+2 jets

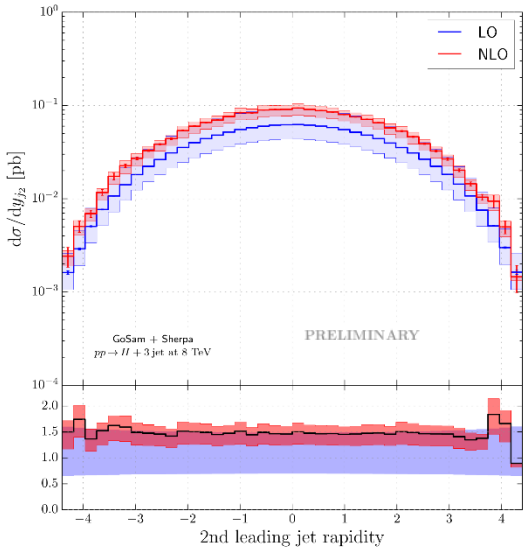


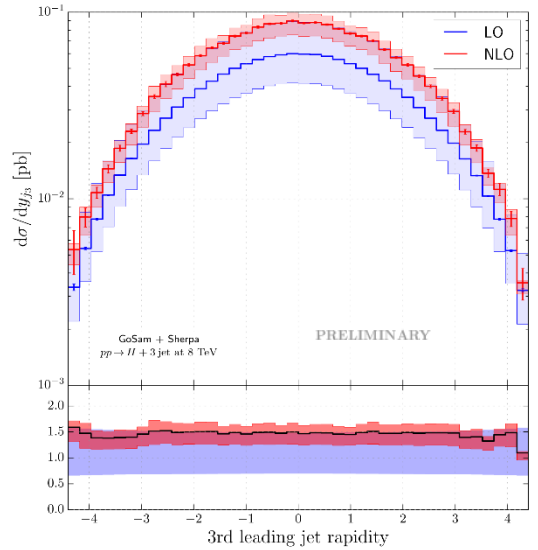




H+3 jets



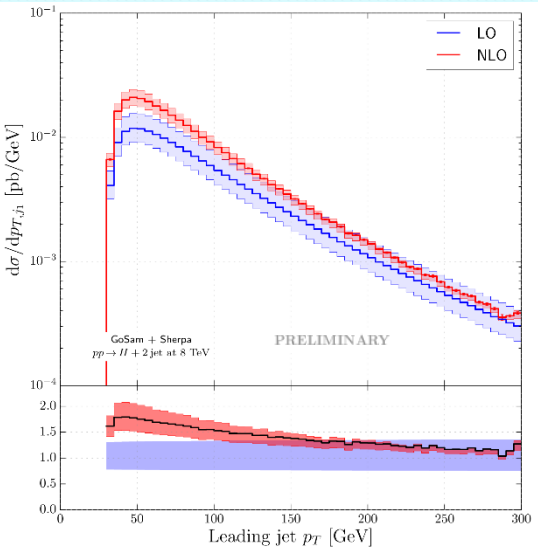



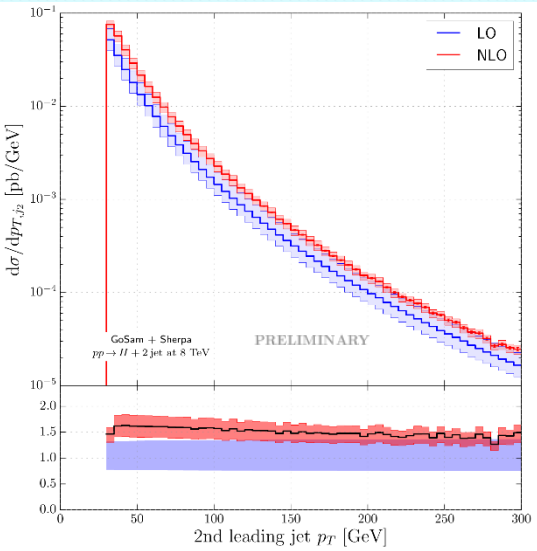
# Jets transverse momenta

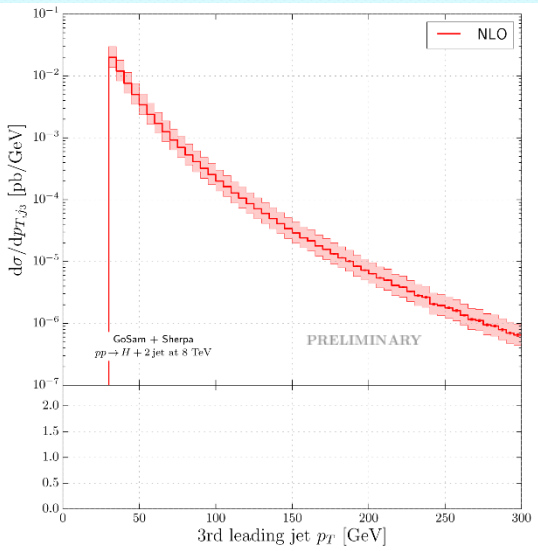
- 1st jet
- 2nd jet
- 3rd jet

PRELIMINARY

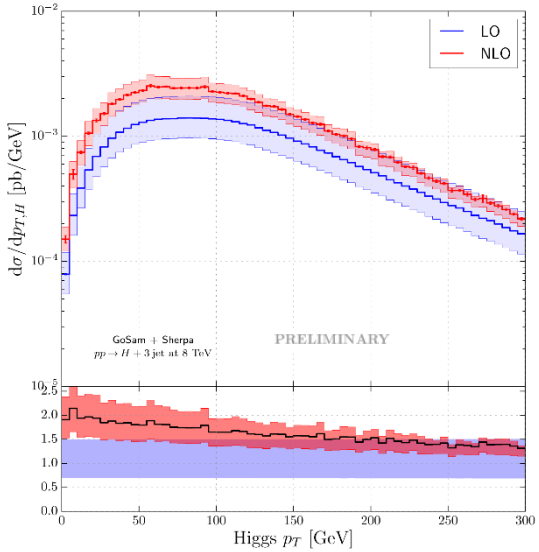
H+2 jets

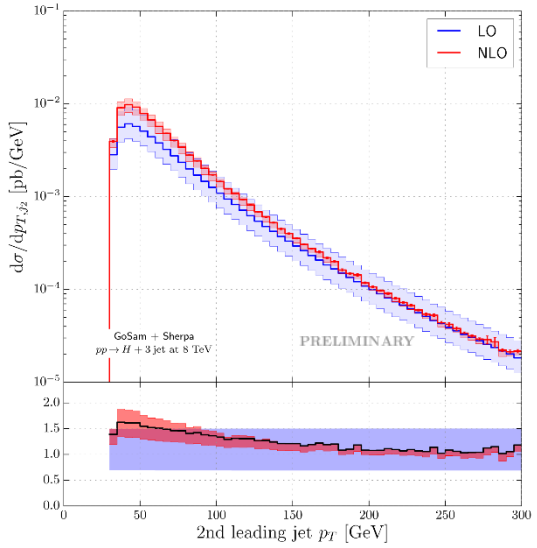


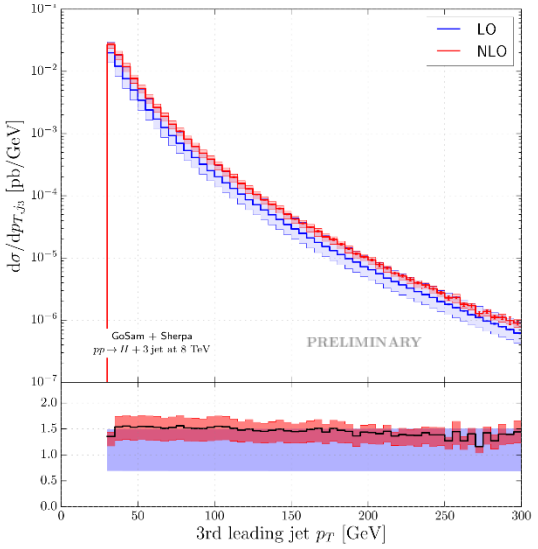




H+3 jets

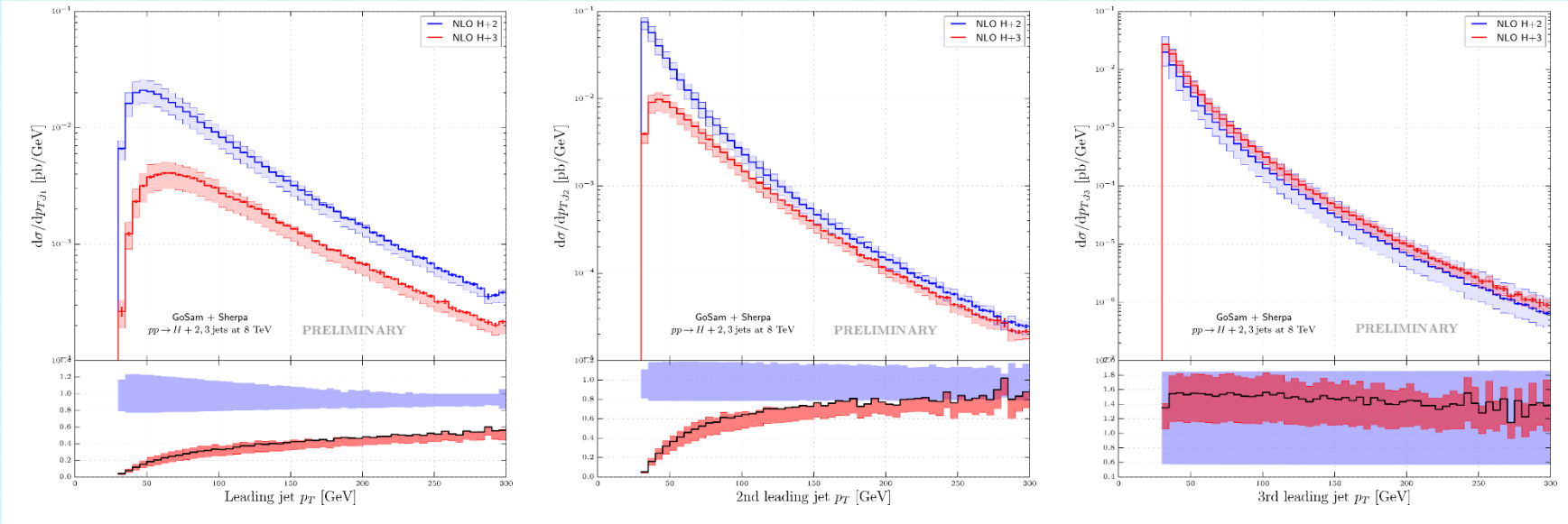


# Jets transverse momenta

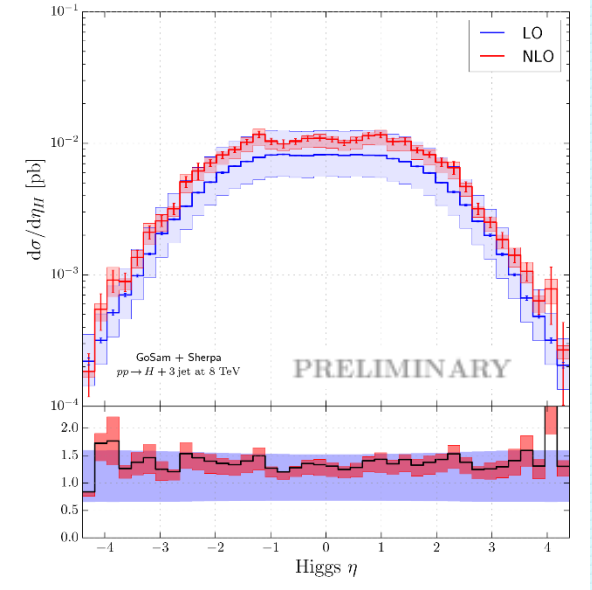
- 1st jet
- 2nd jet
- 3rd jet

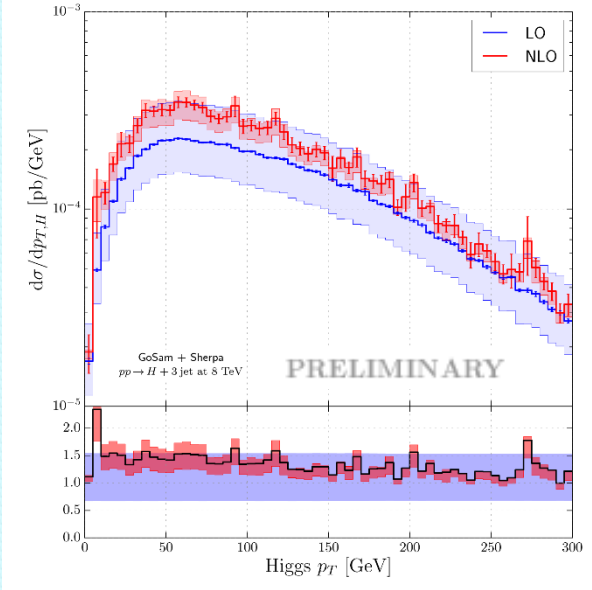


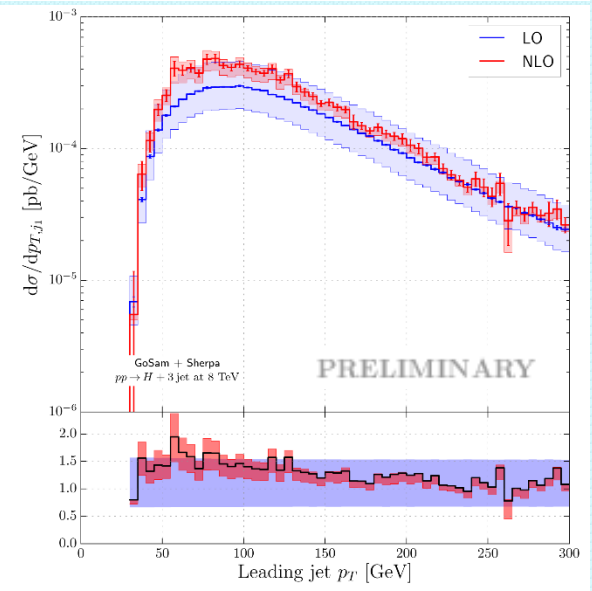

PRELIMINARY

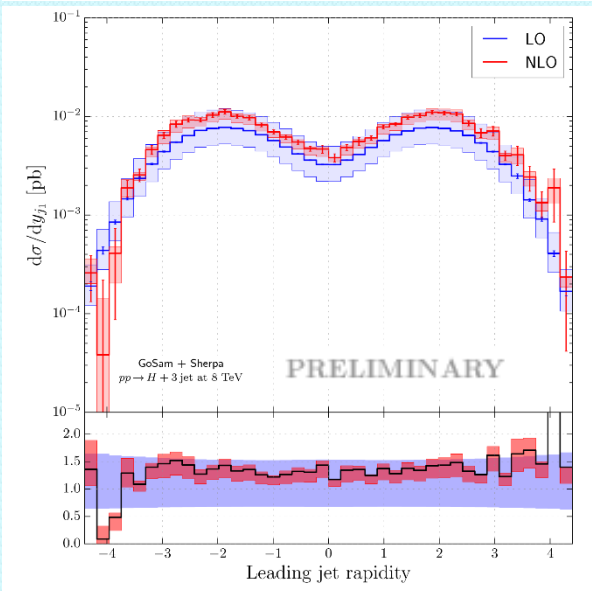
- $r_{3/2}$: strong dependence in $Pt_j$ distributions (50% at 100 GeV)
- $r_{3/2}$: different behaviour for hardest and 2nd hardest jet than for 3rd hardest one

# Results with VBF-type cuts



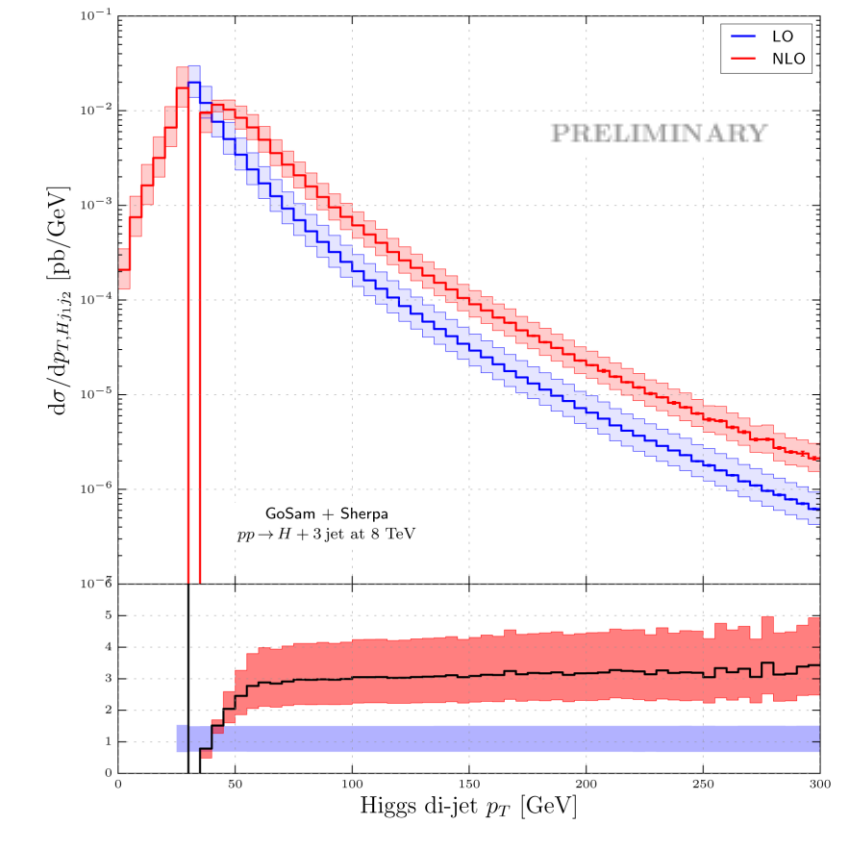




- Only about 7% of events from Ntuples pass VBF cuts
- R-dependence has only small effect on efficiency, whereas pt-cut has a much larger one

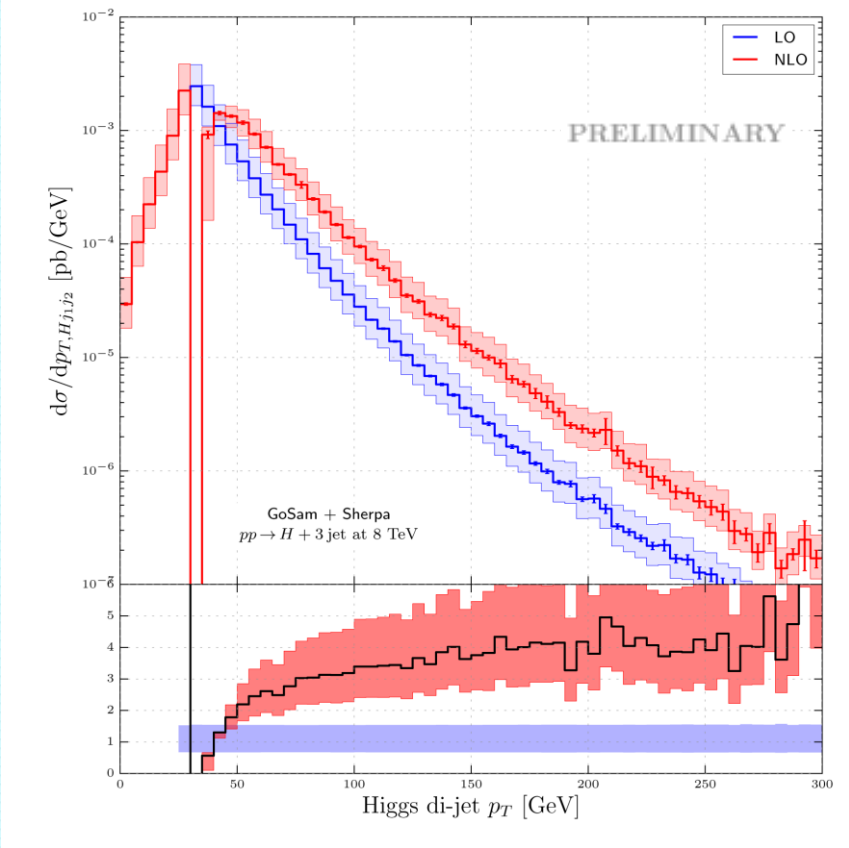
PRELIMINARY

# Hjj transverse momentum

PRELIMINARY




GGF-type cuts




VBF-type cuts

# Conclusions & Outlook

- Preliminary new H+3 jets at NLO in ggf
  - Computed using GoSam+Sherpa
  - ~1.3 Tb of Ntuples availables
  - Scale / radius dependence
  - Momenta and rapidities of Higgs and jets

- Work in progress
  - Finish validation
  - More accurate study of impact of VBF-type cuts
  - Correlation observables / scale choices / PDFs
  - Matching to shower and merging of different multiplicities