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Higgs + jets in GGF/VBF

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In collaboration with
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SWISS NATIONAL SCIENCE FOUNDATION

Computational setup

- Amplitudes for **HEFT-GGF** and **VBF** computed with **GoSam** + **Sherpa** via BLHA
  [Cullen, v.Deurzen, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Schlenk, v.Soden-Fraunhofen, Tramontano, NG ‘14]
  [Gleisberg, Hoeche, Krauss, Schoenherr, Schuhmann]
  - Virtual amplitudes: **GoSam** with **Ninja** [v.Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro ‘14]
    Scalar integrals with **OneLoop** [v.Hameren ‘11]
  - Tree amplitudes and integration with **Sherpa** and **Comix** [Gleisberg, Hoeche ‘08]
- Phenomenological analysis via generation of **ROOT NTUPLES**
  - **GGF Events: H + 1 / 2 / 3** jets for 8, 13, 14 and 100 TeV
    VBF Events: H + 2 / 3 jets for 13 TeV
  - For kt / anti-kt with R = 0.1 (or larger)
  - Allows for fast analysis, change of **scale, pdf, cuts, jet-tagging**
- Full theory (GGF): **Reweighting** of **HEFT ntuples** with amplitude carrying full quark mass dependence

Physical Setup / Cuts

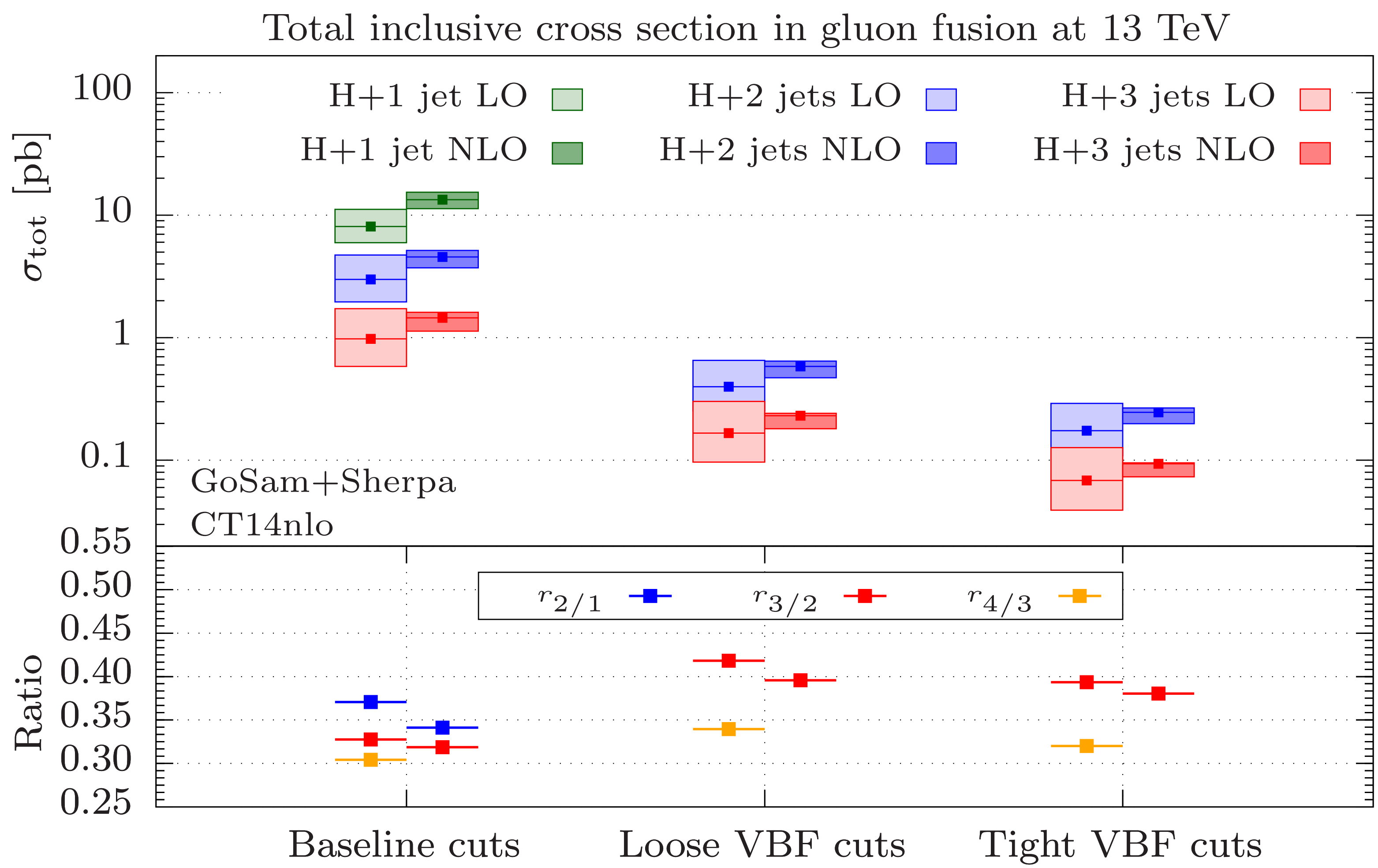
General settings (GGF HEFT, GGF Full, VBF)

- Scale choice: $\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_{\mathrm{H}}^2 + p_{T,\mathrm{H}}^2} + \sum_i |p_{T,i}|\right)$
- PDF: CT10nlo or CT14nlo (see single plots for details)
- Masses: $m_H = 125.0$ GeV, $m_t = 172.3$ GeV, $m_b(m_H) = 3.38$ GeV

Cuts

- **Baseline cuts:** anti-kt with $R = 0.4, \quad p_T > 30 \text{ GeV}, \quad |\eta| < 4.4$
- **VBF cuts loose:** $m_{j1,j2} > 400 \text{ GeV}, \quad |\Delta y_{j1,j2}| > 2.8$
- **VBF cuts tight:** $m_{j1,j2} > 600\ GeV \quad |\Delta_{j1,j2}| > 4.0$

Total cross sections GGF at 13 TeV



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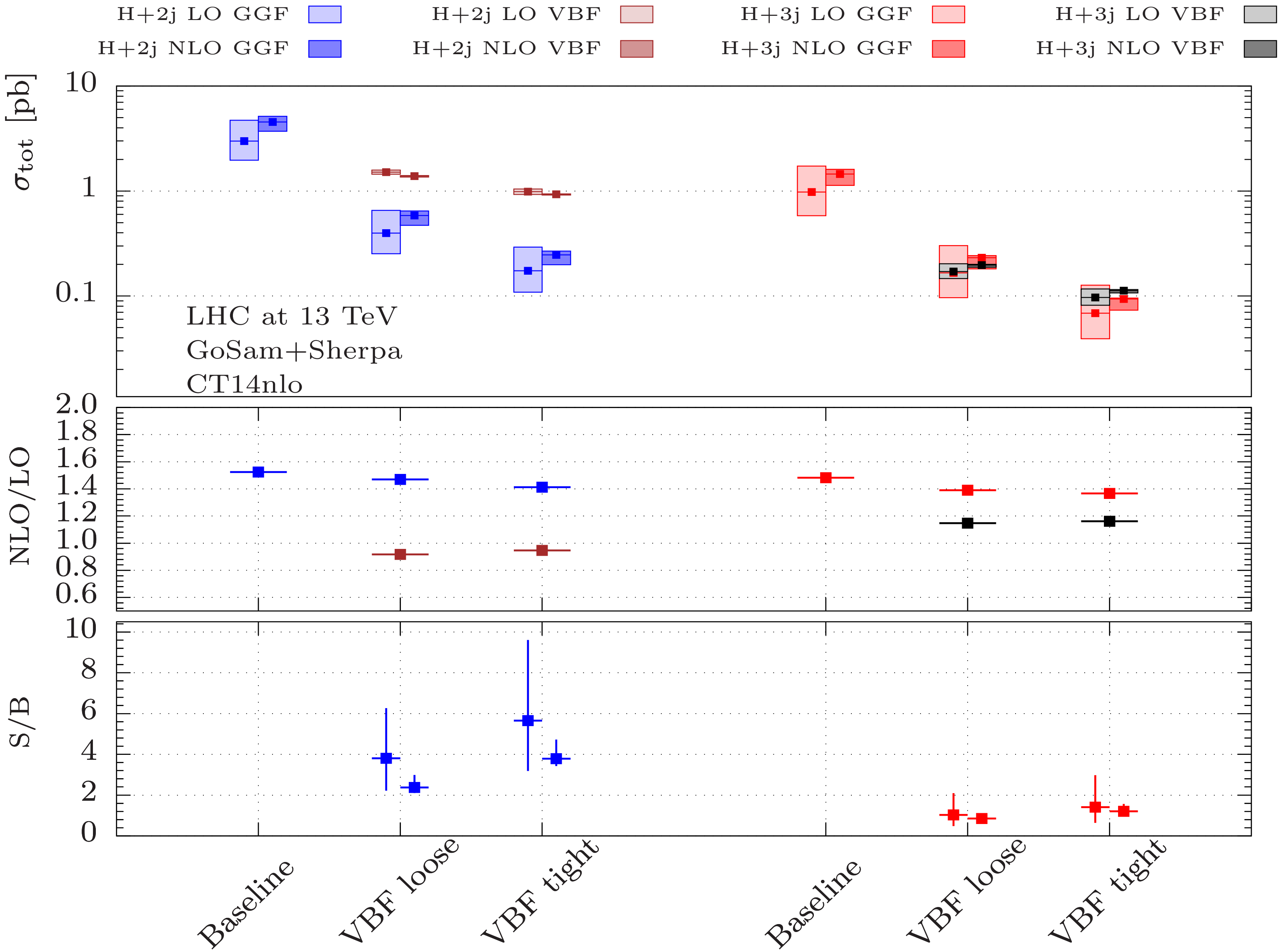
Total cross sections GGF and VBF at 13 TeV



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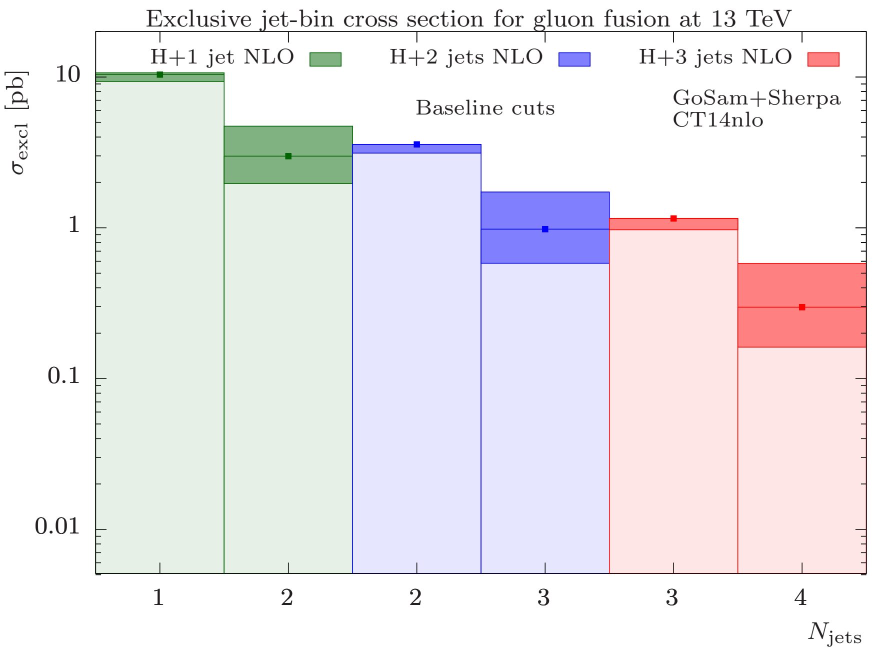
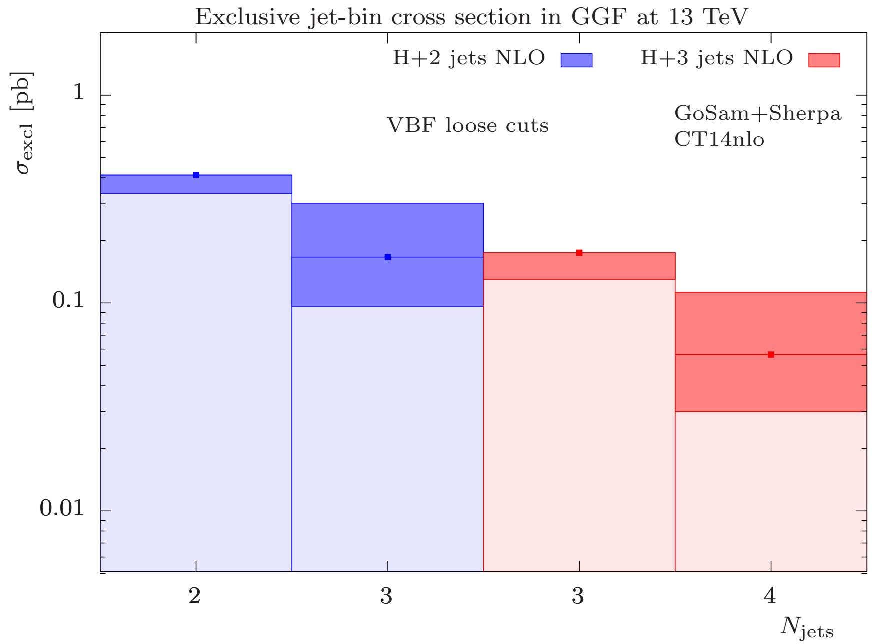
Exclusive jet bin cross sections

GGF baseline cuts



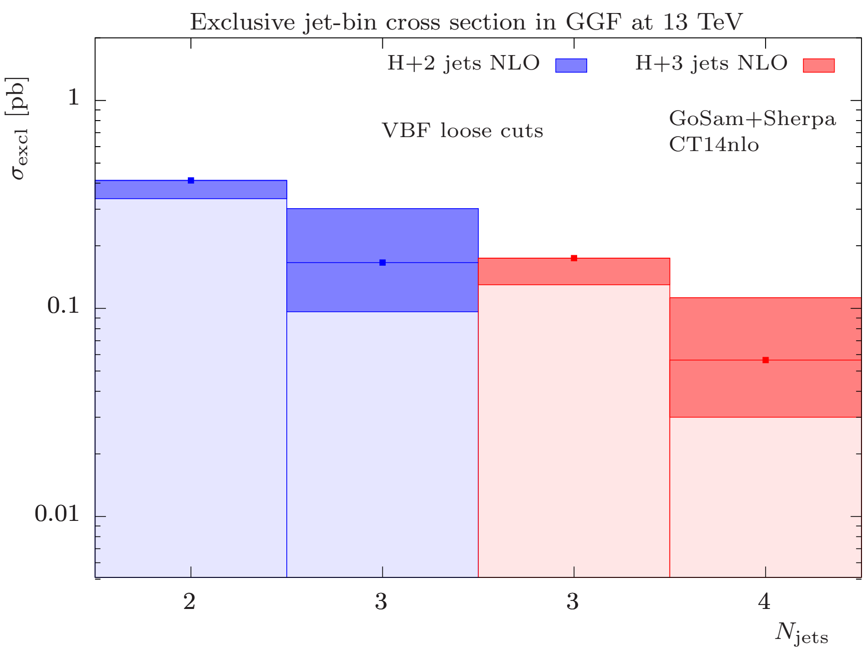
GGF with VBF cuts



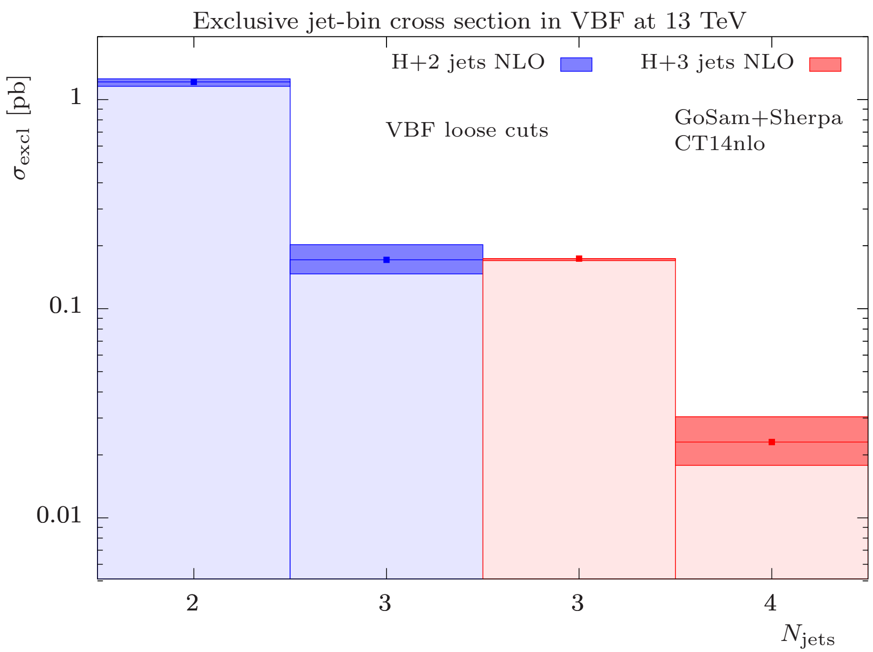
- Large fraction of cross section only described with LO accuracy
- Application of VBF cuts enhances contribution of additional jet

Exclusive jet bins: GGF vs VBF

GGF with VBF cuts

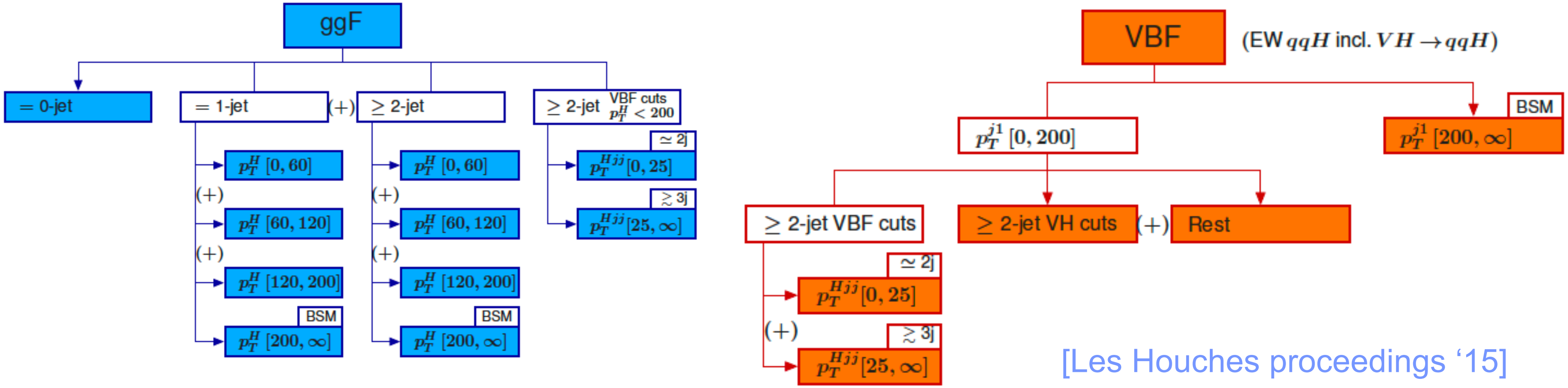


VBF with VBF cuts



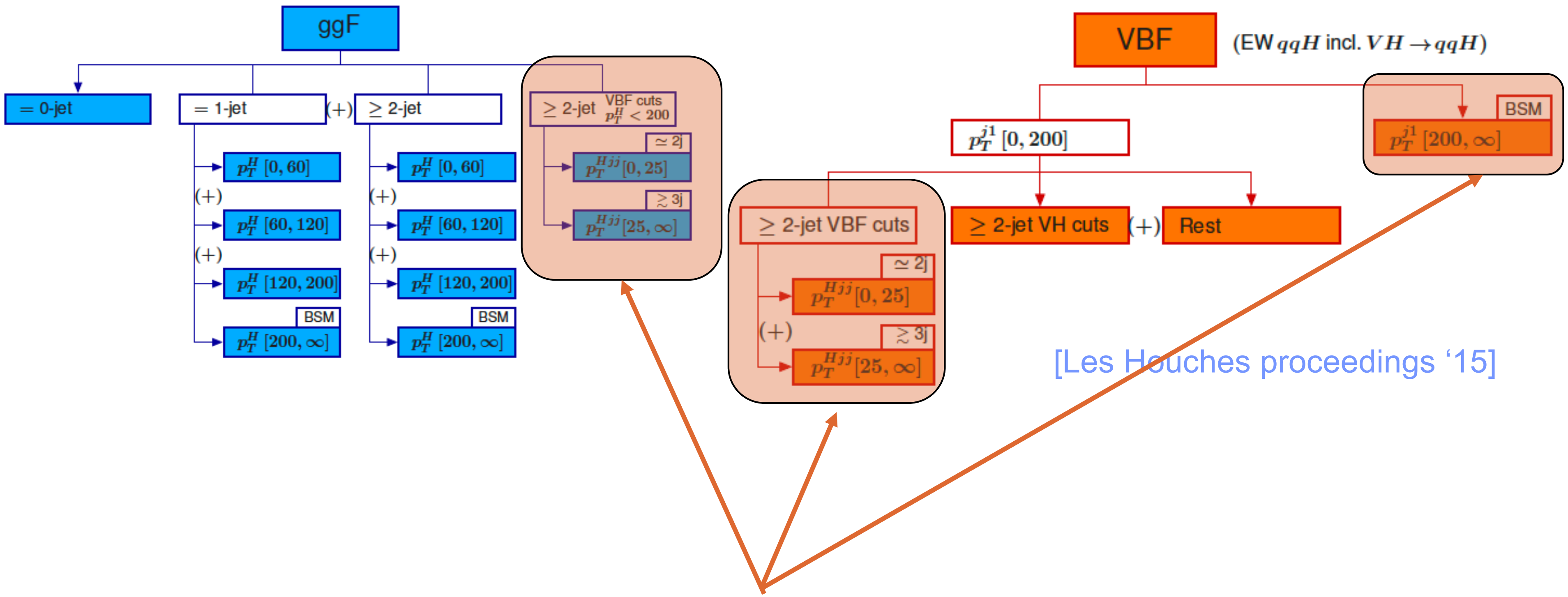
- 3 – jet contribution are of very similar size in GGF and VBF
- Contribution of additional jet considerably smaller in VBF compared to GGF

Simplified Template Cross Sections (STXS)



[Les Houches proceedings ‘15]

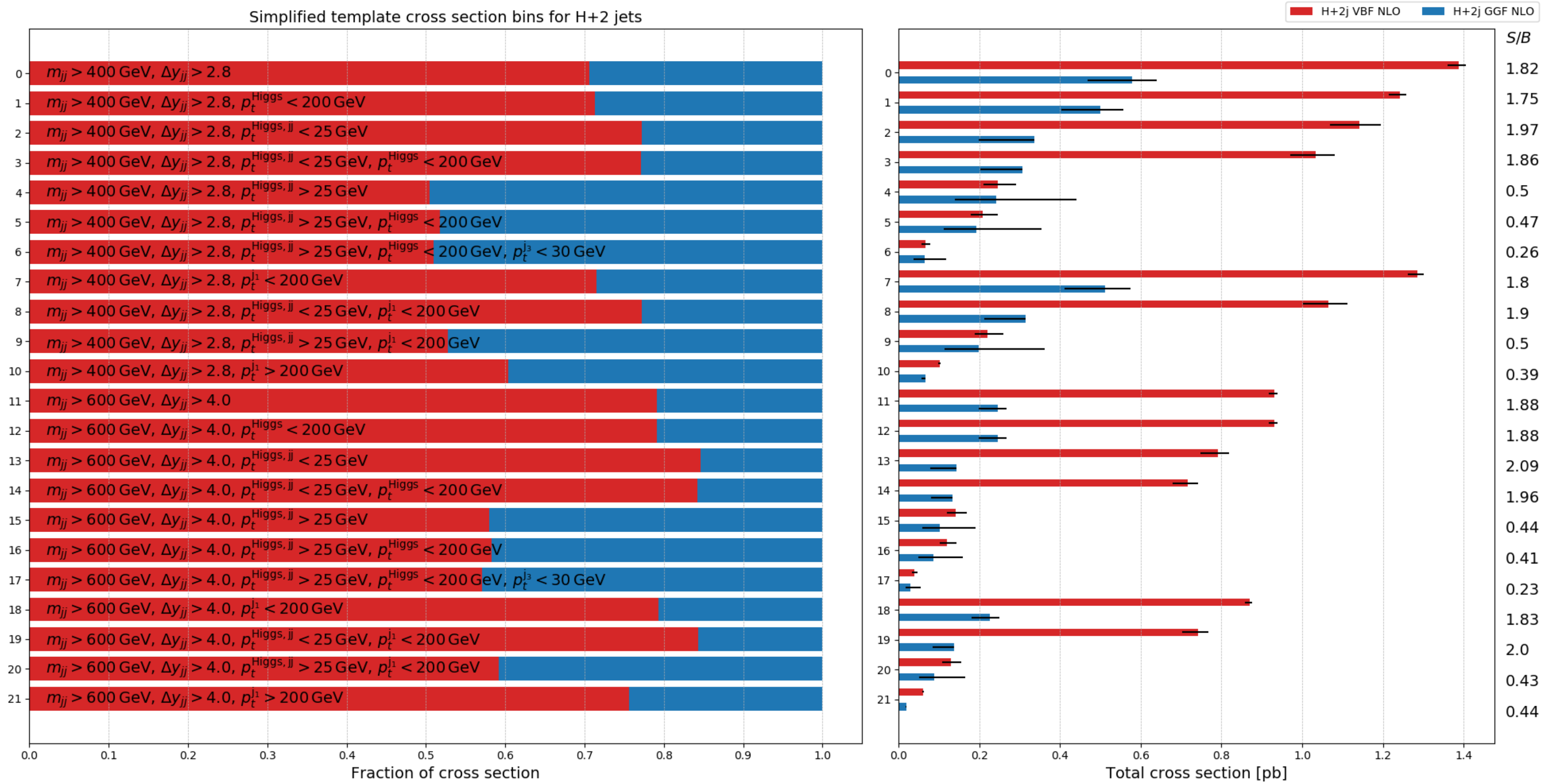
Simplified Template Cross Sections (STXS)



[Les Houches proceedings '15]

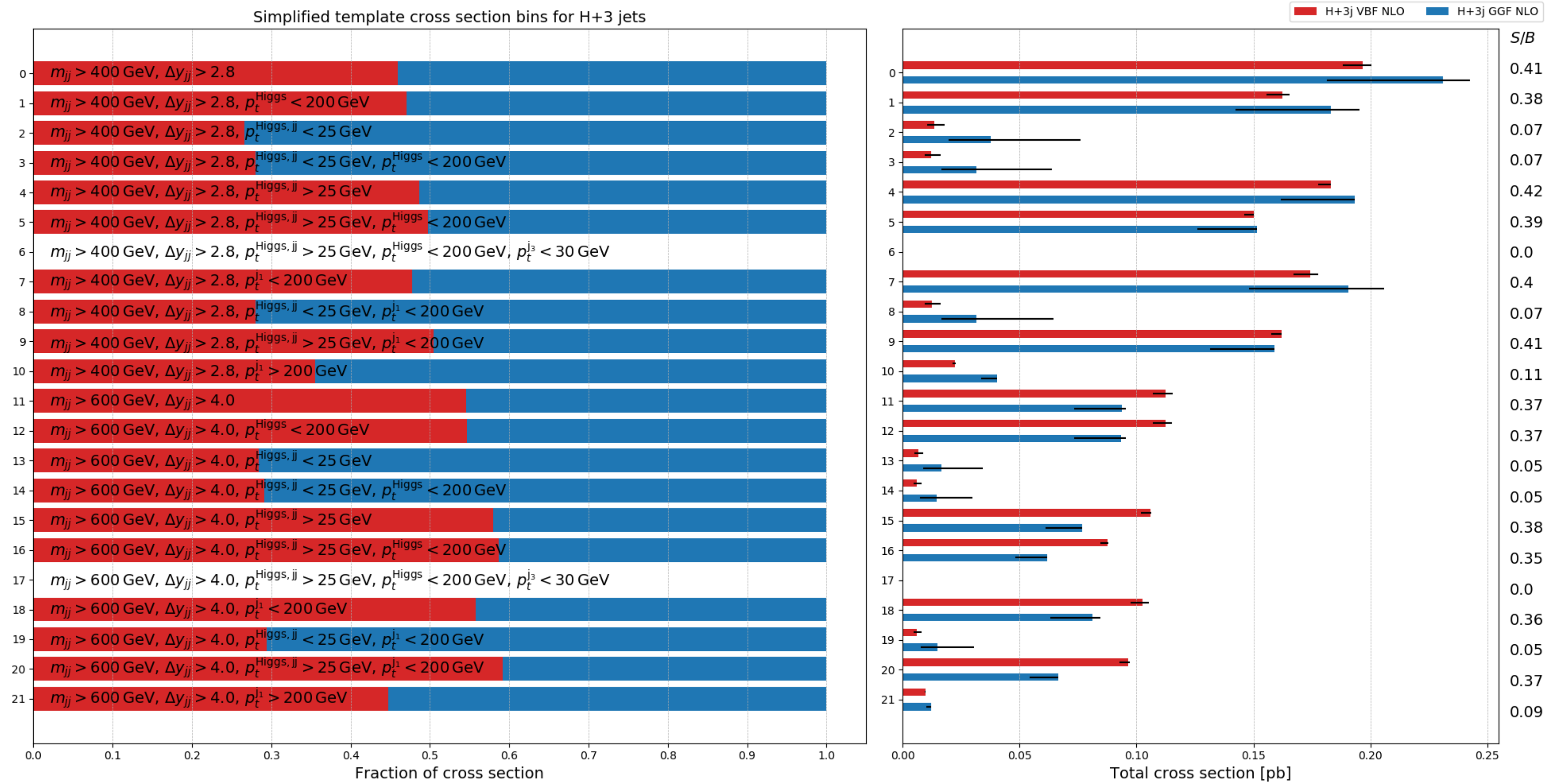
- Analyse both GGF and VBF signal for STXS bins
  -> Determine composition for each bin

Simplified Template Cross Sections (STXS)



Based on **H+2 NLO** for both GGF and VBF

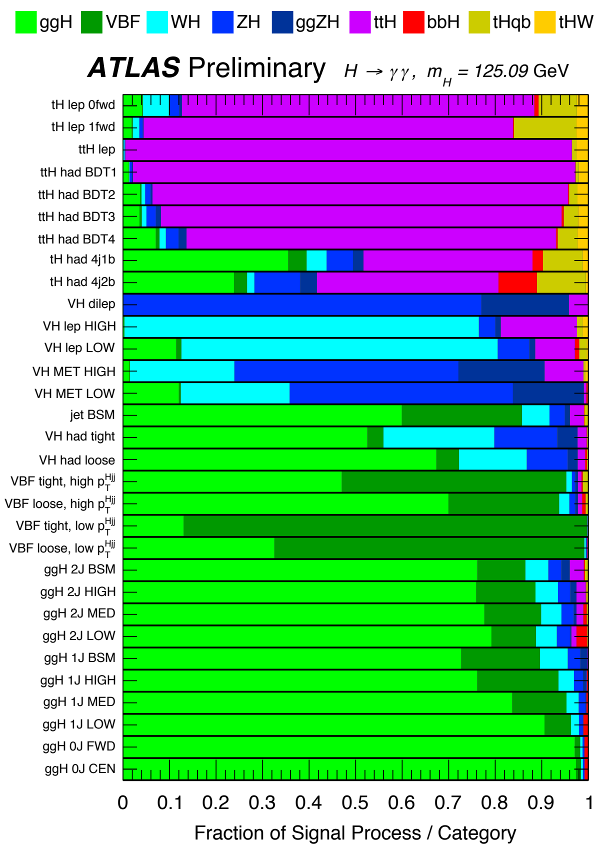
Simplified Template Cross Sections (STXS)

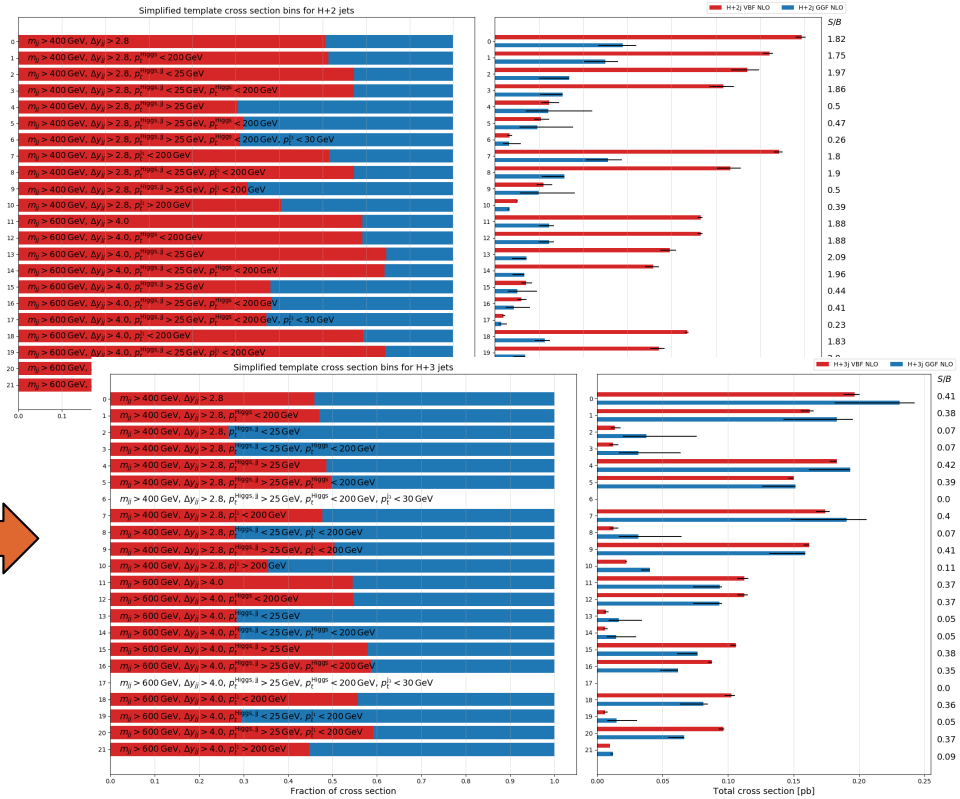


Based on **H+3 NLO** for both GGF and VBF

Simplified Template Cross Sections (STXS)

Plan: Compare this to the expected composition from experimentalists for fiducial cross sections





[ATLAS-CONF-2017-45]

Fiducial cross sections

- Adding decays $H \to \gamma\gamma,\ H- > ZZ \to 4l$ to analysis ✔
- Rivet analysis for both decay channels for ATLAS and CMS (4 analyses) ✔
- Setup checked against YR4 results ✔
- TODO
  - Extend analyses to incorporate alternative tagging schemes (y-tagging)
  - Run analyses and produce fiducial cross sections (total cross sections and differential distributions)

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H + n jets in GGF

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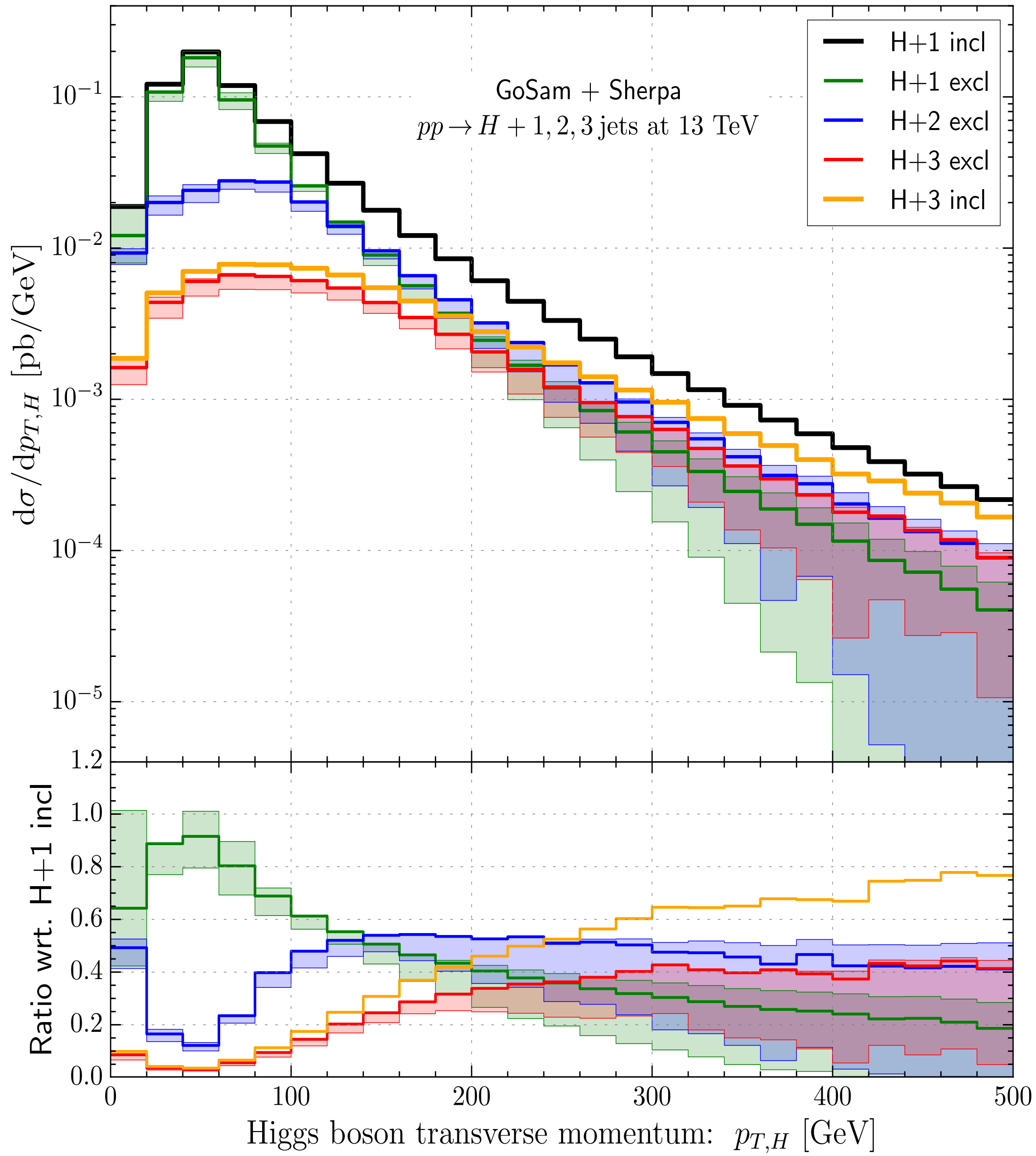

Transverse Momentum of Higgs

- Ratio plots normalized to inclusive H+1
- Jet multiplicity has considerable impact on distribution:
  - ~120 GeV: 2nd jet contribution more important than 1st
  - ~250 GeV: 3rd jet more important than 1st
  - ~300 GeV: 4th jet dominant contribution

-> Requires multi-jet merging (Meps@NLO in progress)

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VBF cuts on GGF contribution

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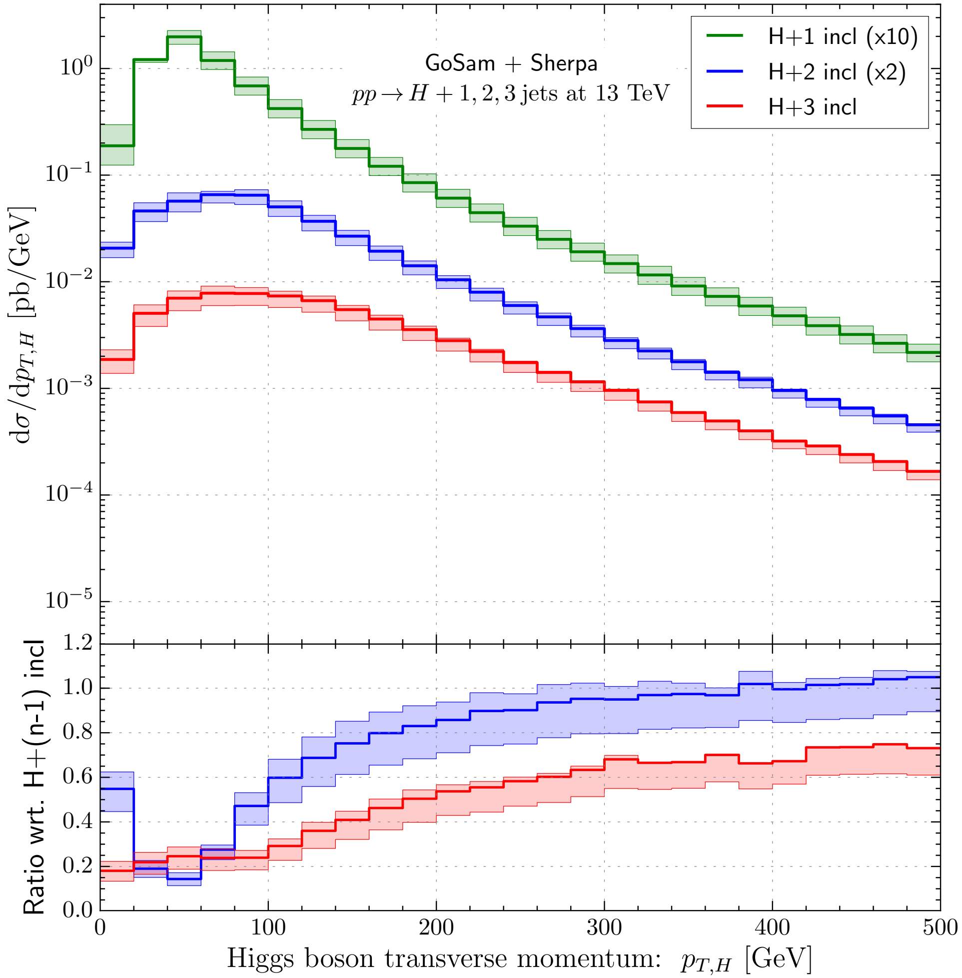
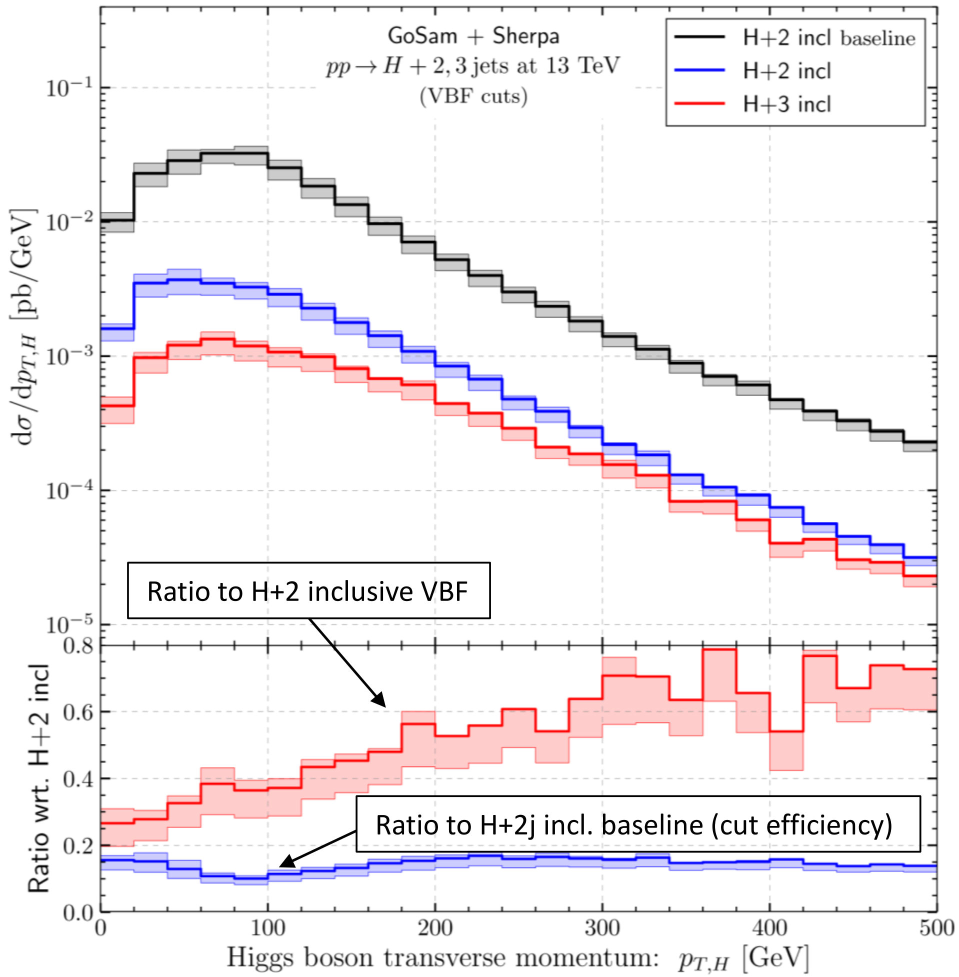
Inclusive baseline

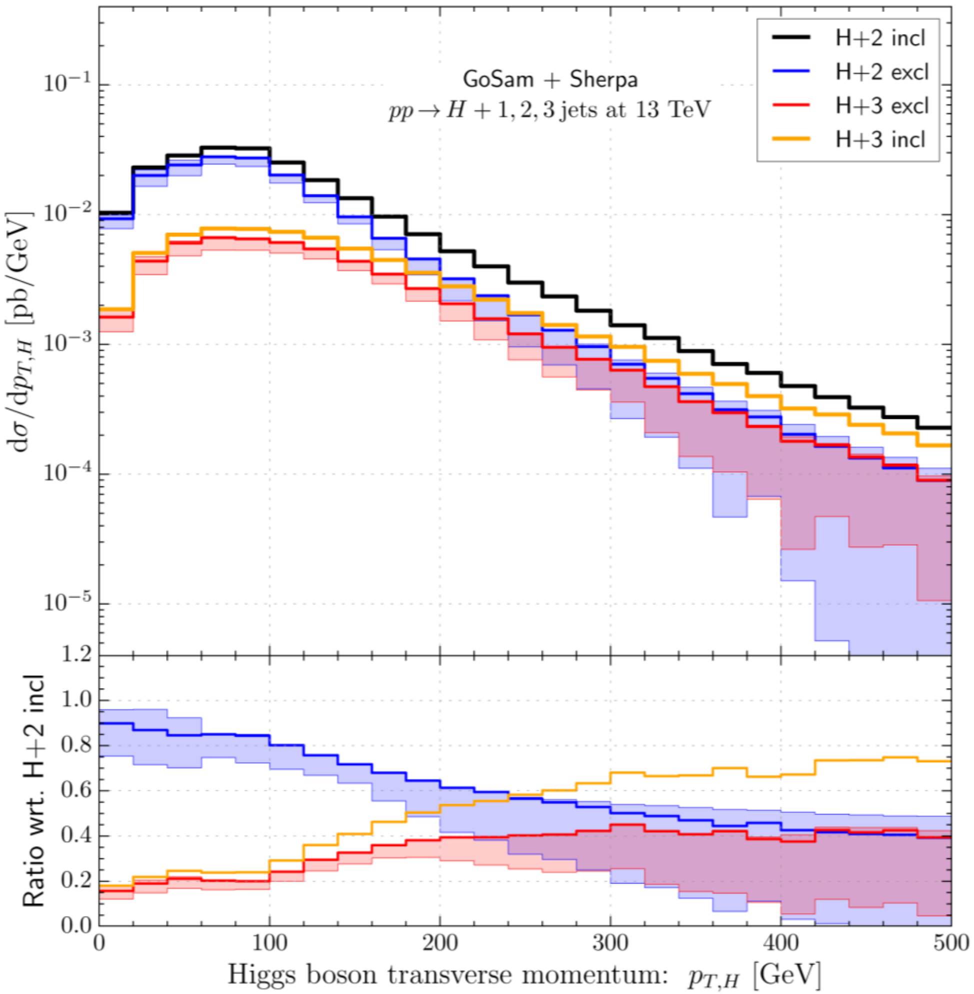


Inclusive VBF

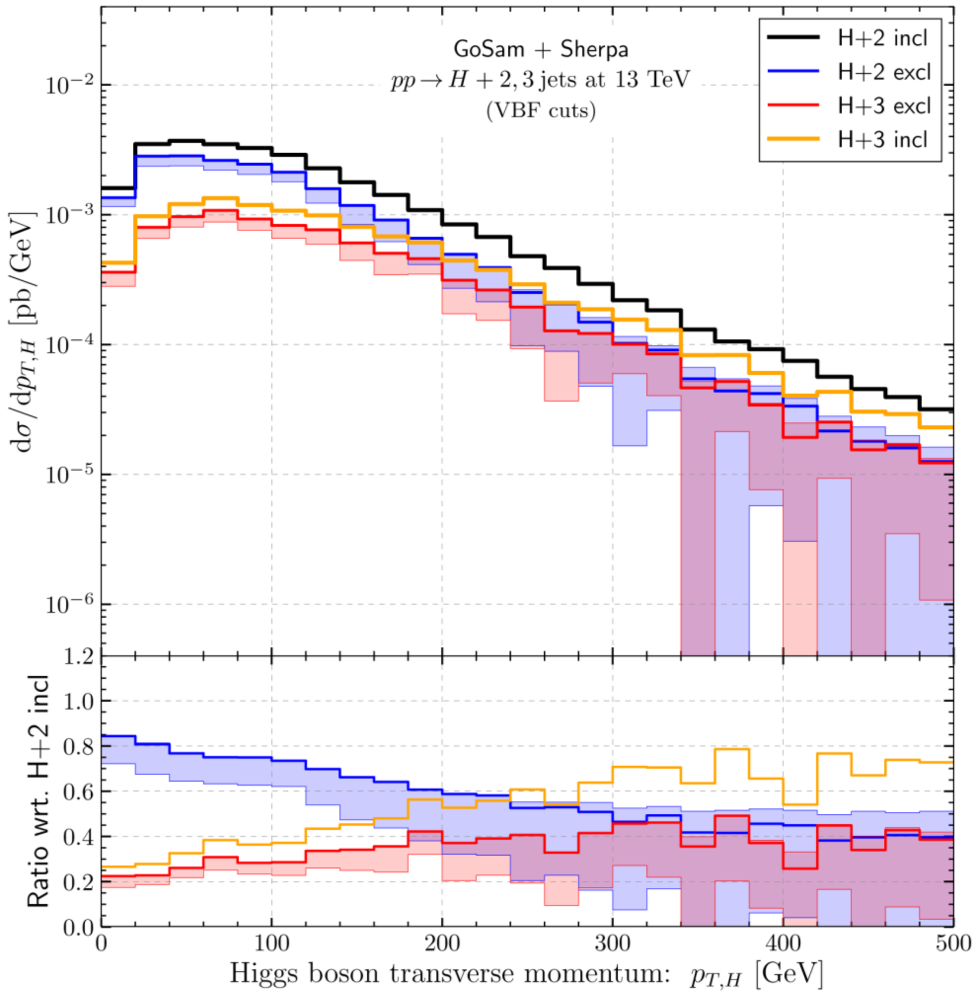


VBF cuts on GGF contribution

Exclusive baseline

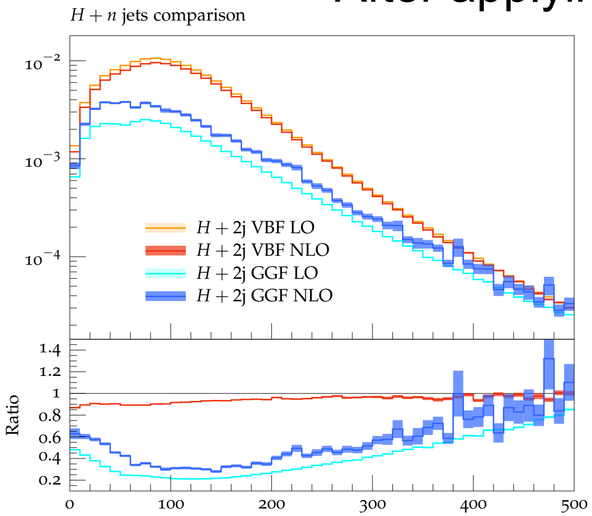


Exclusive VBF

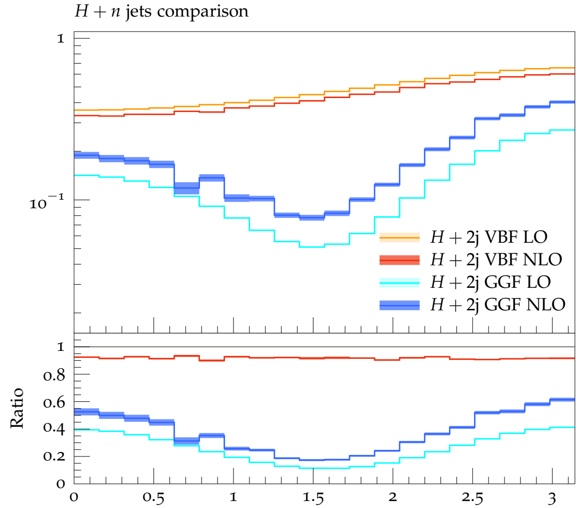


Differential distributions for GGF and VBF

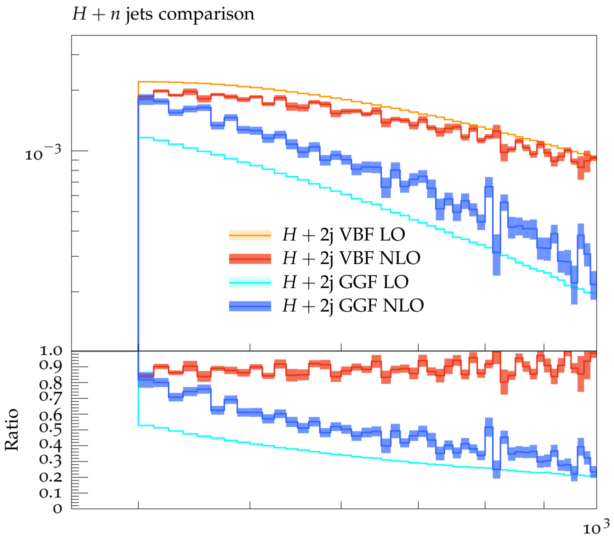
After applying VBF cuts on GGF (**preliminary plots**)



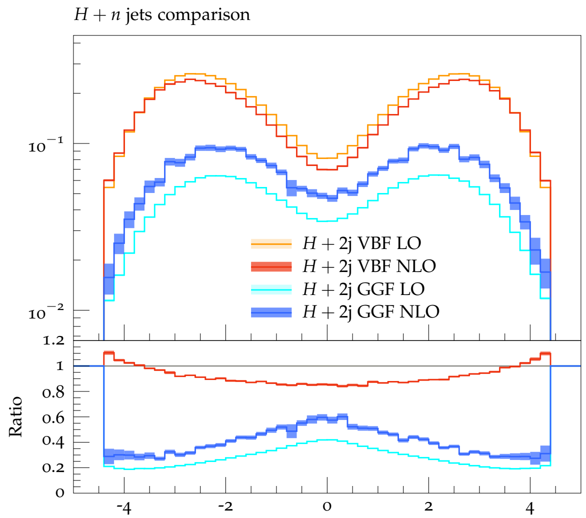
$p_{T,H}$



$\Delta\Phi_{jj}$



m_{jj}



y_{j1}

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Differential distributions for GGF and VBF

After applying VBF cuts on GGF (**preliminary plots**)

How can we separate GGF from VBF ??

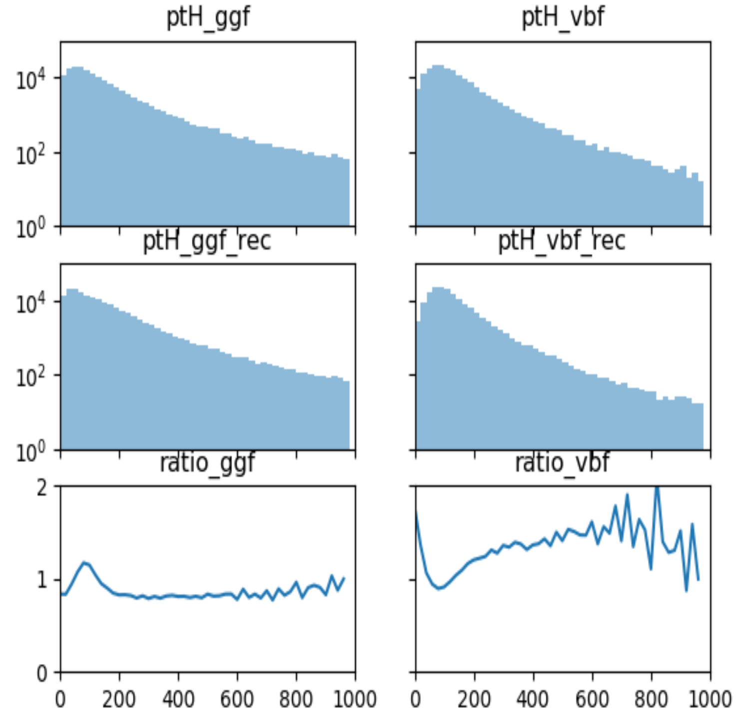
Tensorflow

- Apply **Google's Tensorflow** machine learning algorithms to distinguish between GGF and VBF
- Use ntuples for GGF and VBF as training/ evaluation sets
- Input variables:

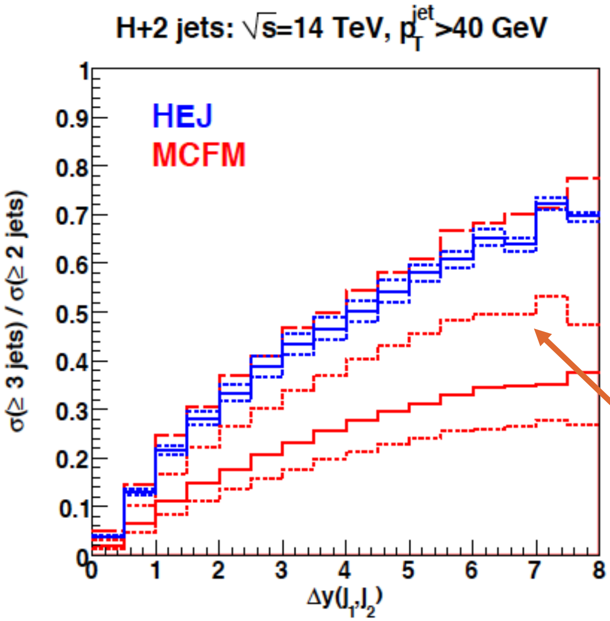
$$p_{T,H}\,, p_{T,j1,j2}, m_{jj}, \Delta\Phi_{jj}, y_{j1,j2}, \Delta y_{jj}$$

$$z^* = \frac{y_H - \left(\frac{y_{j1}+y_{j2}}{2}\right)}{\Delta y_{jj}} \qquad R_{p_{T,j}} = \frac{p_{T,j1j2}}{p_{T,j1}+p_{T,j2}}$$

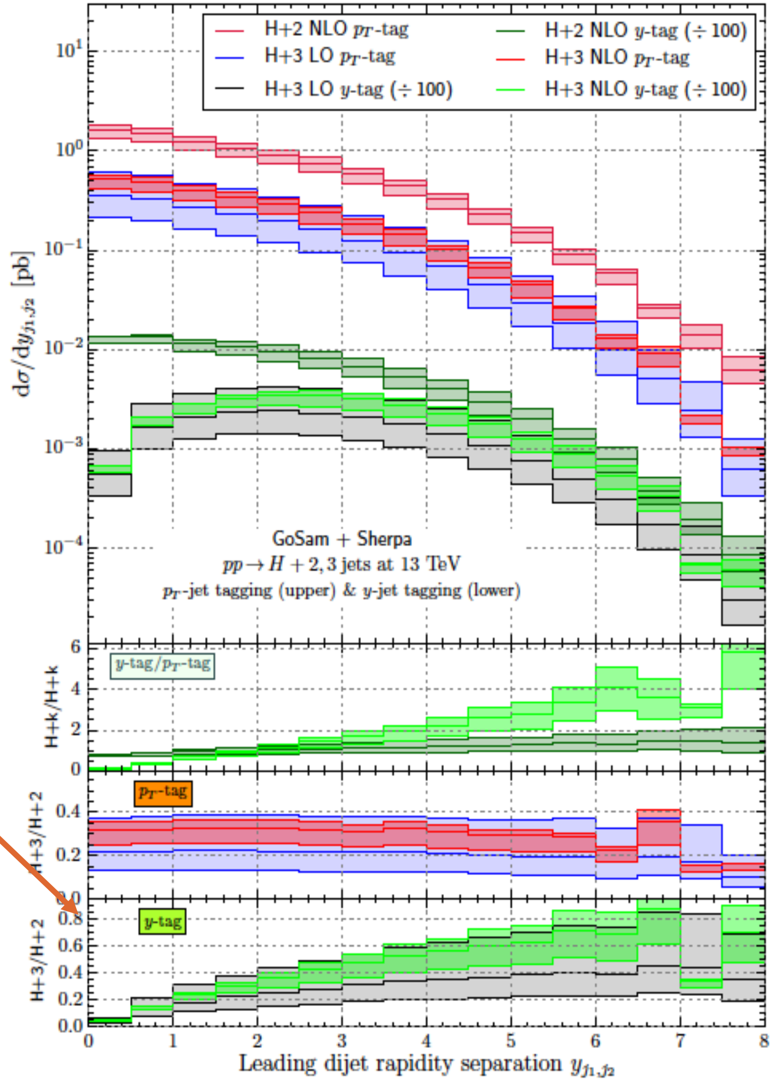
- Accuracy for H+2: ~70%, H+3: ~65% (highly dependent on composition of set)
- WORK IN PROGRESS (PRELIMINARY)



High energy limit



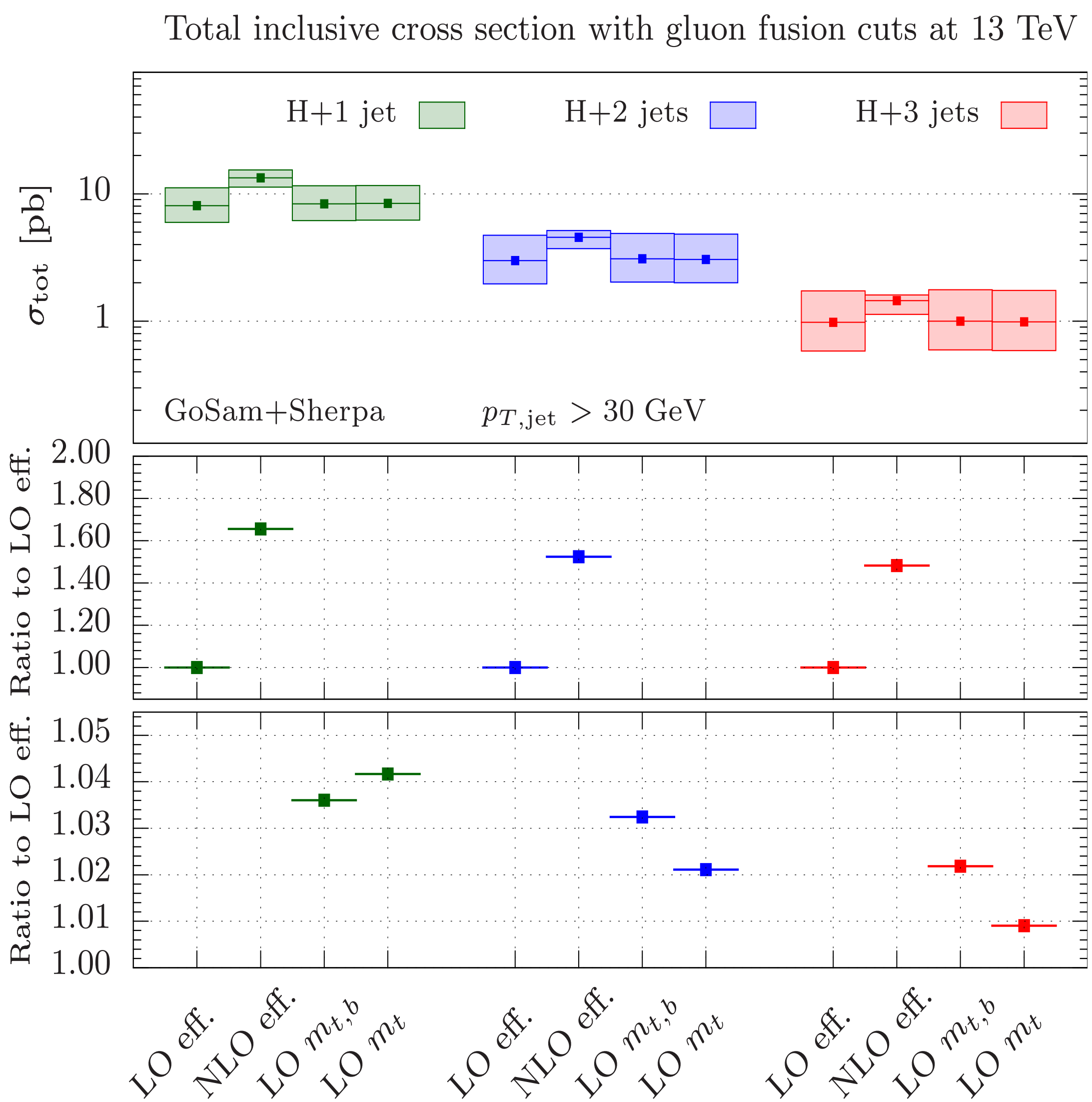
[Snowmass Working group report QCD: 1310.5189]



- **y-tagging** leads to non-flat K-factors for certain observables, i.e. rapidity difference between tagging jets
- Discrepancy between **HEJ** [Andersen,Smillie '09, '11] and **MCFM** [Campbell,Ellis,Williams '10] can largely be resolved by adding NLO corrections

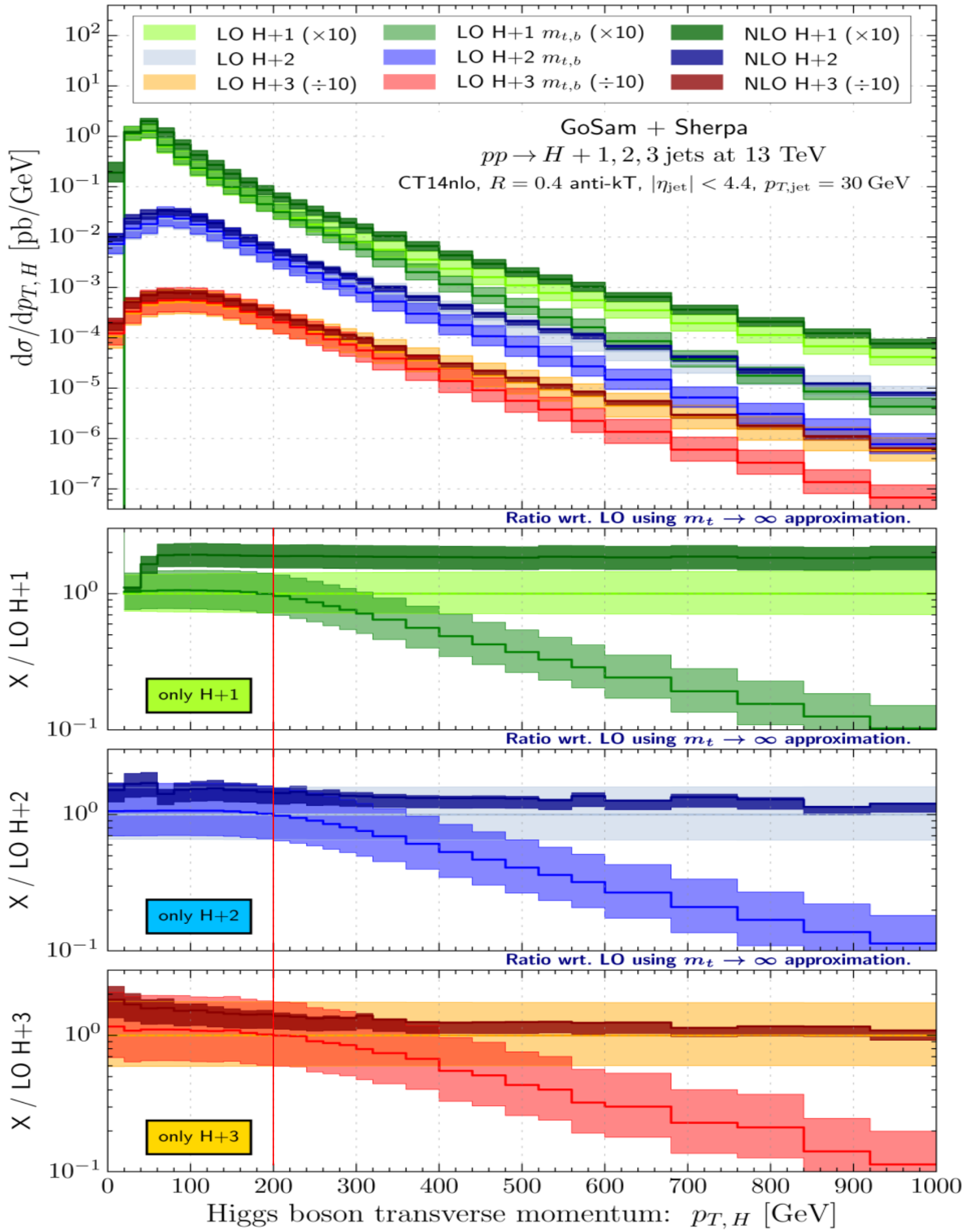
Finite mass effects

Total cross sections 13 TeV



- Slight reduction of NLO corrections at higher multiplicities
- Relative difference due to bottom quark contribution O(1%)
- Sign flip in corrections due to top-bottom interference
- Possibility to estimate NLO cross section in full theory from K-factors of effective theory ?

Mass effects in Higgs 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.
- Very similar behavior for the three different multiplicities

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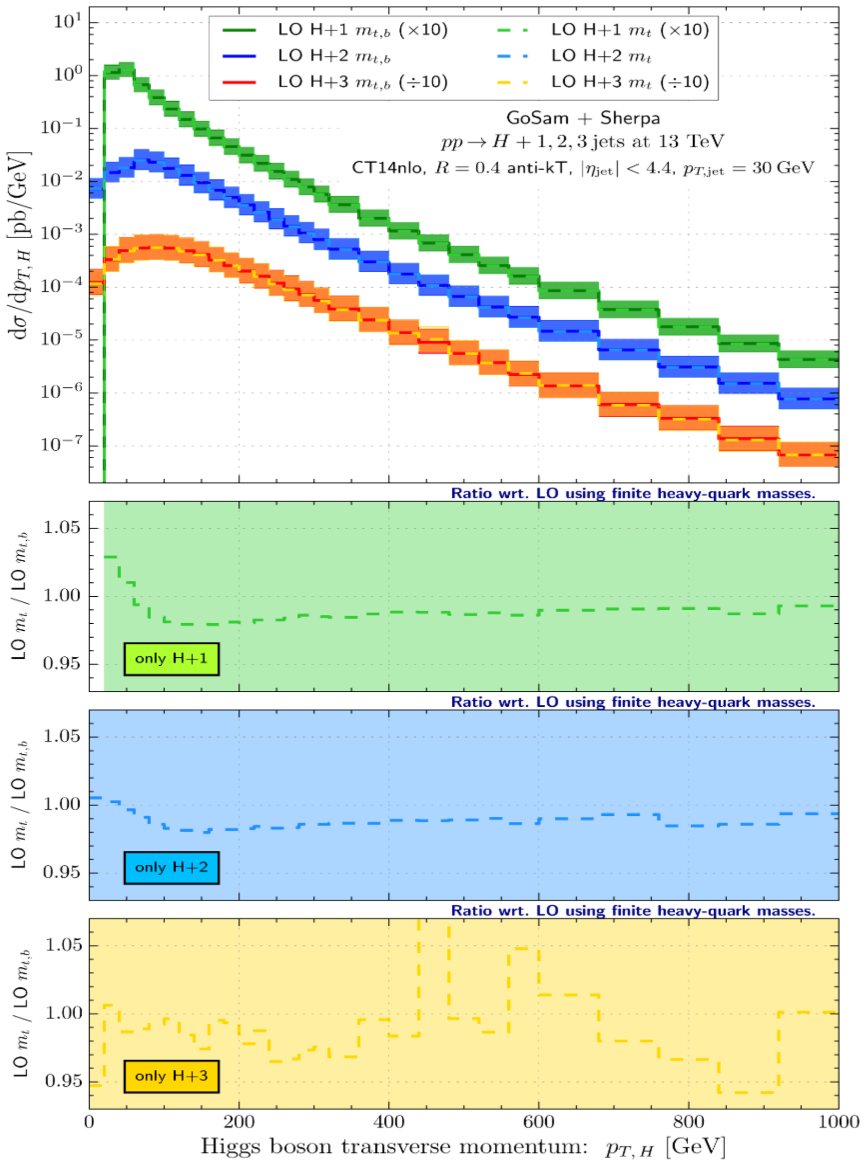
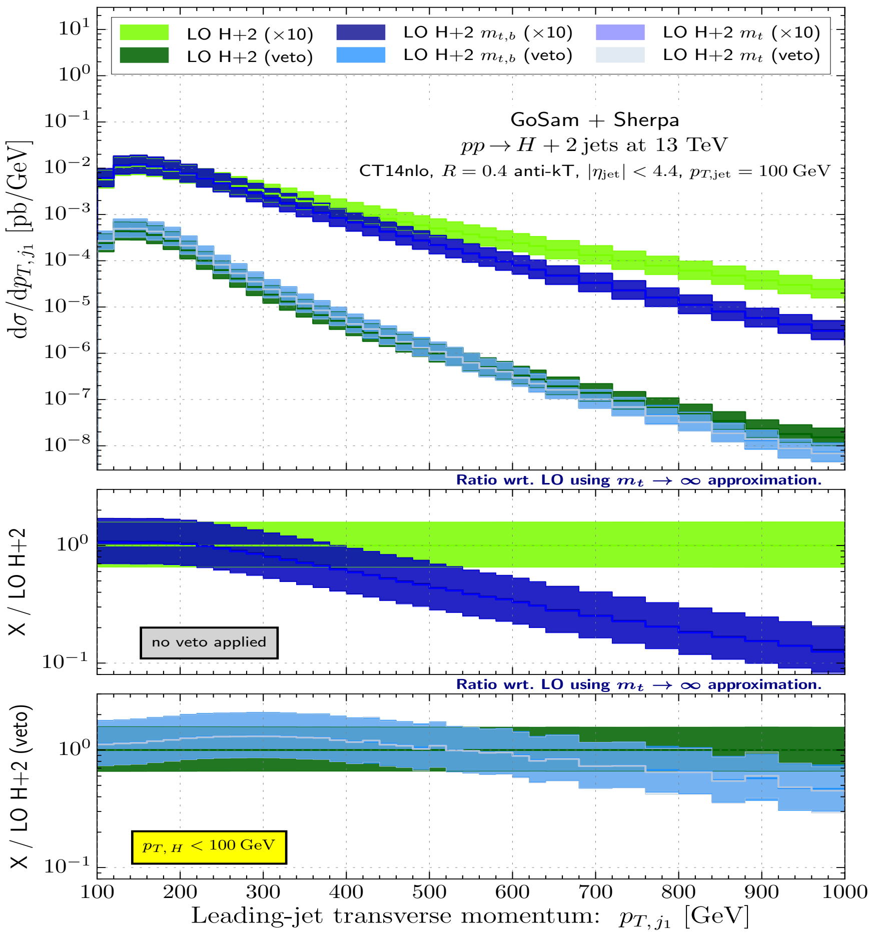
Effect of bottom quark mass

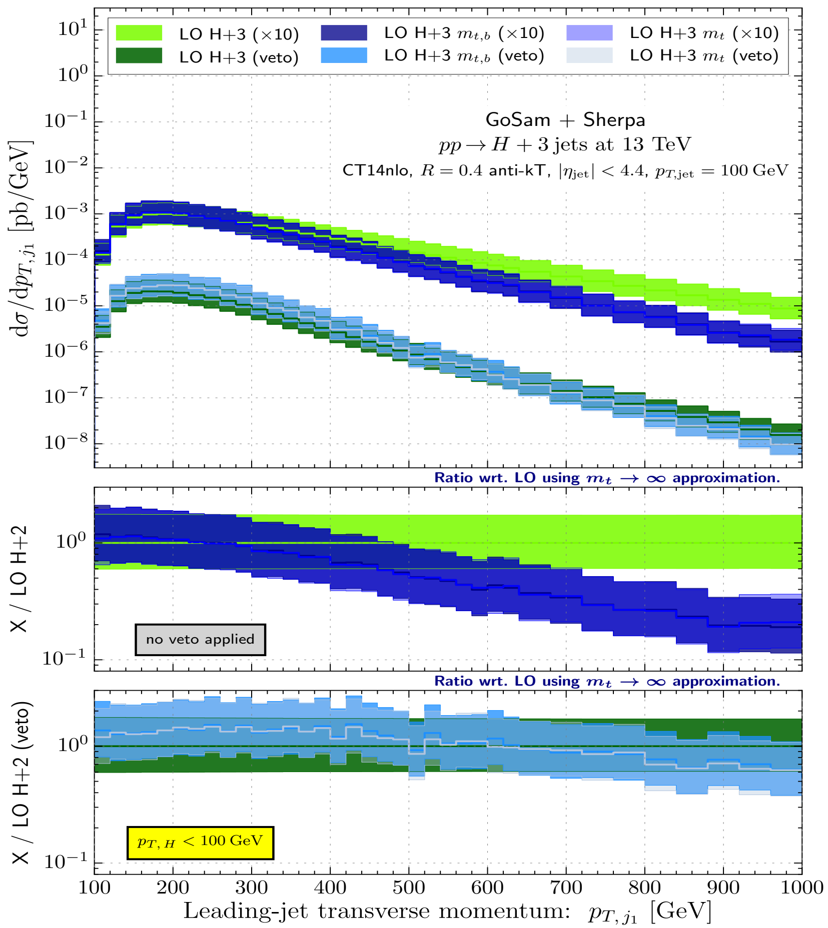


Comparison between top- plus bottom-quark and top-quark only results:

- Difference well below scale uncertainty and never exceeds 5%
- Primarily concerns soft region
- Depends on jet multiplicity
- Destructive interference in the total H+1j cross section stems from soft region, whereas contribution becomes positive in region where b-quark can be considered massless

Mass effects in GGF





- $p_{T,H} < 100\ \mathrm{GeV}$: Veto on Higgs p_T can effectively reduce mass effects

Conclusions and Outlook

- Gluon Fusion contribution strongly influenced by higher jet multiplicities
  -> Requires jet merging to improve accuracy of prediction

- Mass effects dominant in a region beyond ~200 GeV
  -> Breakdown of HEFT approach
  -> Effect of bottom quark mass negligible

- Work in progress:
  - MEPS@NLO for merged sample of H+1,2,3 in GGF
  - Results for fiducial cross sections for $H \to \gamma\gamma,\ H- > ZZ \to 4l$