Update of the Les Houches Higgs+jets study using NLO multi-leg approaches and fixed order

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FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
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Aim & focus

- study description of QCD activity in $pp \to h +$ jets
- use state-of-the-art fixed-order and/or resummed calculations, modern precision parton shower matched & multijet merged calcs
- inclusive wrt. to Higgs kinematics and decay channels to accommodate as many calculations as possible
- purely perturbative calculation, no non-perturbative physics $\rightarrow$ no MPI, hadronisation, intrisic $k_\perp$, etc.
- study (idealised) observables of theoretical interest/importance
- assess difference in description of these observables between MCs and fixed-order and/or resummed calculations
- provide RIVET analysis for common analysis with $O(100)$ observables $\rightarrow$ used by MCs and NLO calculations

Setup

- $pp \to h +$ jets in gluon fusion @ LHC 13 TeV
- HEFT in $m_t \to \infty$ limit, $m_b = 0$
- $m_h = 125\,\text{GeV}$, $\Gamma_h = 4.07\,\text{MeV}$
- PDF: `MMHT2014nlo68clas118` (LHAPDF id: 25200)
  `MMHT2014nnlo68cl` (LHAPDF id: 25300)
  $\to$ modern PDF set, $\alpha_S(m_Z) = 0.118$, 5 flavour running
- scales: preferably $\frac{1}{2}\,H_T'$ with $H_T' = m_\perp(h) + \sum_{i\in\{g,q\}} p_{\perp,i}$
  if not possible use scale that reduces to $\frac{1}{2}\,m_h$ in zero jet limit
- uncertainties: renormalisation and factorisation scale
  resummation scale, shower starting scale, etc.
  merging scale

`https://phystev.cnrs.fr/wiki/2015:groups:tools:hjets#contributions`

Contributions

Analytic resummations

- M. Grazzini et.al. HQT for $p_\perp(h)$ in $\boldsymbol{pp \to h}$ ✓
- F. Tackmann et.al. jet veto resummation in $\boldsymbol{pp \to h}$, $\boldsymbol{pp \to hj}$ ✗

Fixed-order calculations

- F. Petriello et.al. $\boldsymbol{pp \to hj}$ @ NNLO ✗
- G. Luisoni et.al. $\boldsymbol{pp \to h + 1, 2, 3j}$ @ NLO
  GoSam+Sherpa ✓
- S. Badger $\boldsymbol{pp \to h + (1, 2)j}$, $\boldsymbol{pp \to h + (2, 3)j}$ @ nNLO LoopSim
  GoSam+Sherpa ✓

Contributions

Parton-shower matched & multijet merged

- K. Becker (ATLAS) $pp \to h$ NNLOPS
  POWHEG-BOX+PYTHIA8 ✓
- S. Höche $pp \to h$ UN^{2}LOPS
  SHERPA ✗
- R. Frederix, E. Vryonidou $pp \to h + 0, 1, 2j$@NLO
  MG5_aMC+PYTHIA8 ✓
- J. Bellm, S. Plätzer, P. Schichtel $pp \to h + 0, 1, 2j$@NLO
  HERWIG7+MADGRAPH5+OPENLOOPS ✗
- S. Höche, M. Schönherr $pp \to h + 0, 1, 2, 3j$@NLO, $4, 5j$@LO
  SHERPA+GOSAM (✓)

BFKL resummation

- J. Andersen $pp \to h + \text{jets}$
  HEJ (✓)

Details on settings

HqT

- central value: $\mu_R = \mu_F = Q = \frac{1}{2}\, m_h$
- uncertainties: usual factor two variation with constraints $\frac{1}{2} < \mu_R/\mu_F < 2$ and $\frac{1}{2} < \mu_R/Q < 2$

GoSam+Sherpa NLO & LoopSim

- central value: $\mu_R = \mu_F = \frac{1}{2} \left[m_h + \sum_{\text{partons}} p_\perp \right]$
- uncertainties: 7-pt variation by factor two

Details on settings

POWHEG+PYTHIA8 NNLOPS

- central value: $\frac{1}{2}\,m_h$ for core, $k_\perp$ for emissions (CKKW/MiNLO)
- uncertainties: 7-pt in POWHEG, 3-pt in HNNLO for μ_R, μ_F

MADGRAPH+PYTHIA8

- central value: $\mu_R = \mu_F = m_\perp(h)$ on hj clustered config
- uncertainties: 7-pt for μ_R, μ_F, merging scale $\{25, 35, 50\}$

SHERPA+GOSAM

- central value: $\frac{1}{2}\,m_h$ for core config, t for reconstructed emissions
- uncertainties: not included yet

HEJ

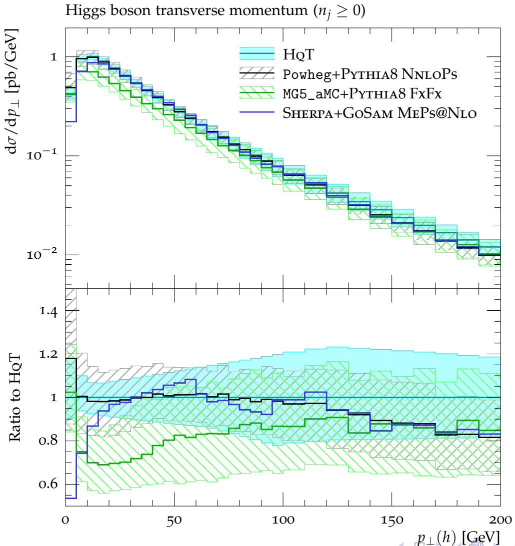
- central value: $\mu_R = \mu_F = \frac{1}{2}\,H_T'$
- uncertainties: not included yet

Results

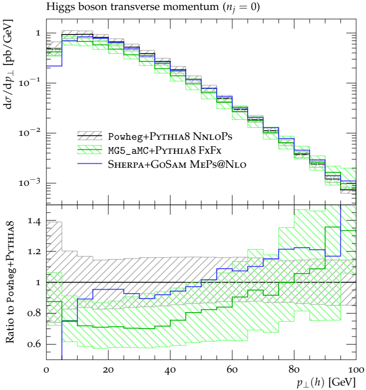
Basic properties of the analysis

- Higgs either stable in generation or built from constituents ($\gamma\gamma$), require $m(\text{constituents}) \in [124, 126]$ GeV
- jets defined using anti-$k_\perp$, $R = 0.4$, $p_\perp > 30$ GeV, $|\eta| < 4.4$, built from everything but the Higgs constituents
- build observables from thus defined Higgs and jet momenta
  - observables in various incl. and excl. jet bins
  - two types of VBF selections ($\Delta y(j_1, j_2) > 2.8$, $m(j_1, j_2) > 400$ GeV)
    a) leading jet pair satisfies criteria
    b) any jet pair satisfies criteria
  - $\mathcal{O}(100)$ observables

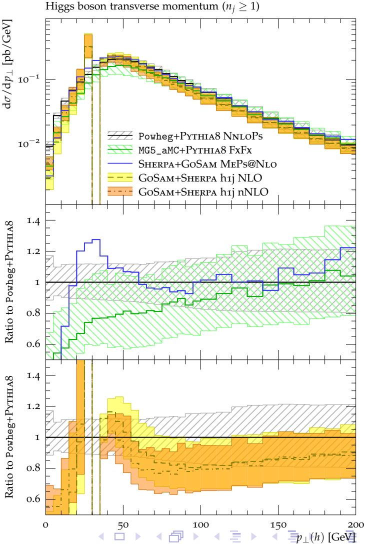
Results


Higgs boson transverse momentum ($n_j \geq 0$)
HqT
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
$d\sigma/dp_\perp$ [pb/GeV]
1
10^{-1}
10^{-2}
Ratio to HqT
1.4
1.2
1
0.8
0.6
0
50
100
150
200
$p_\perp(h)$ [GeV]

Results

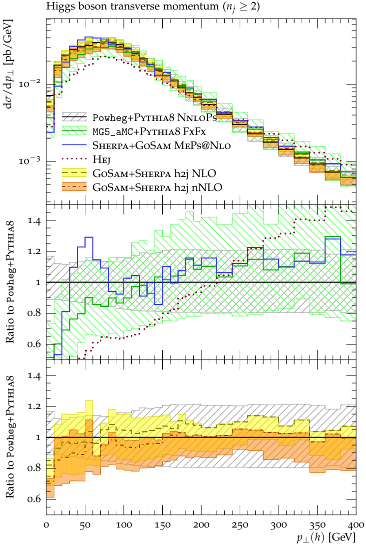


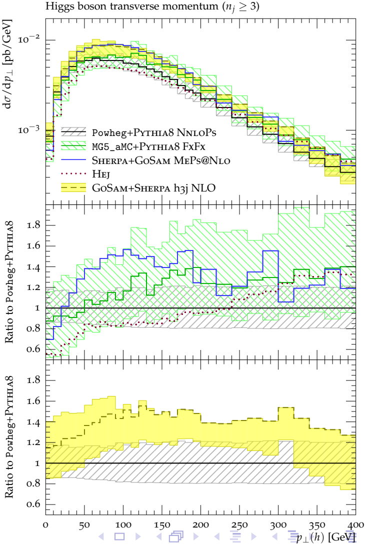
Higgs boson transverse momentum ($n_j = 0$)
dσ/dp⊥ [pb/GeV]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Ratio to Powheg+Pythia8
$p_\perp(h)$ [GeV]



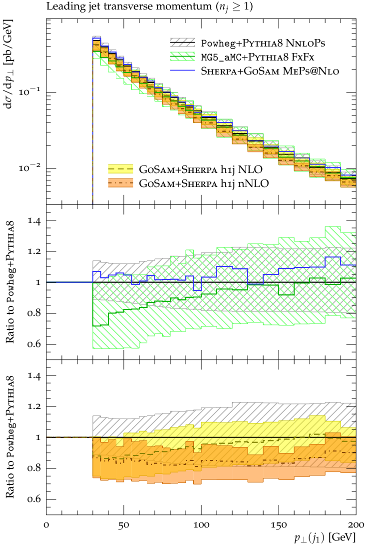
Higgs boson transverse momentum ($n_j \geq 1$)
dσ/dp⊥ [pb/GeV]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
GoSam+Sherpa h1j NLO
GoSam+Sherpa h1j nNLO
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
$p_\perp(h)$ [GeV]

Results

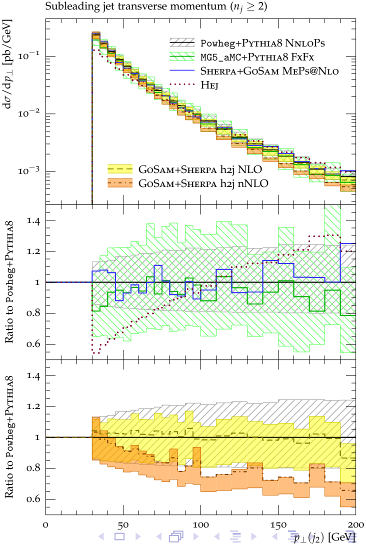

Higgs boson transverse momentum ($n_j \geq 2$)
$d\sigma/dp_\perp$ [pb/GeV]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Hej
GoSam+Sherpa h2j NLO
GoSam+Sherpa h2j nNLO
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
$p_\perp(h)$ [GeV]


Higgs boson transverse momentum ($n_j \geq 3$)
$d\sigma/dp_\perp$ [pb/GeV]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Hej
GoSam+Sherpa h3j NLO
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
$p_\perp(h)$ [GeV]

Results

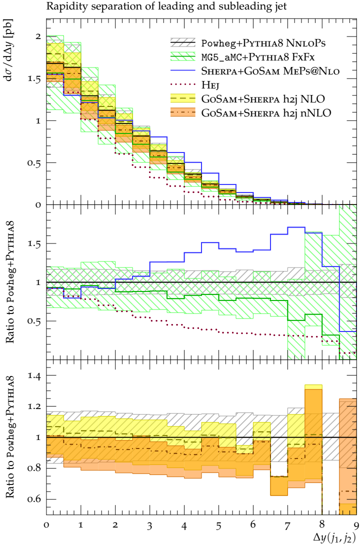


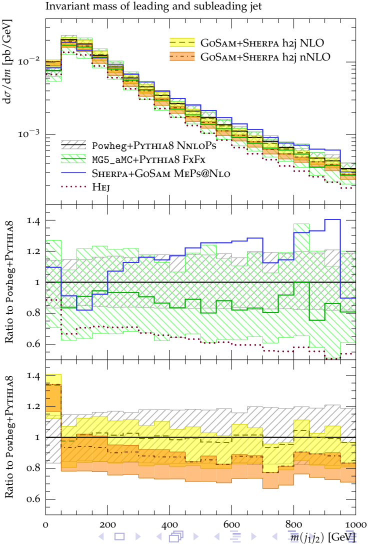
Leading jet transverse momentum ($n_j \geq 1$)
$d\sigma/dp_\perp$ [pb/GeV]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
GoSam+Sherpa h1j NLO
GoSam+Sherpa h1j nNLO
Ratio to Powheg+Pythia8
$p_\perp(j_1)$ [GeV]



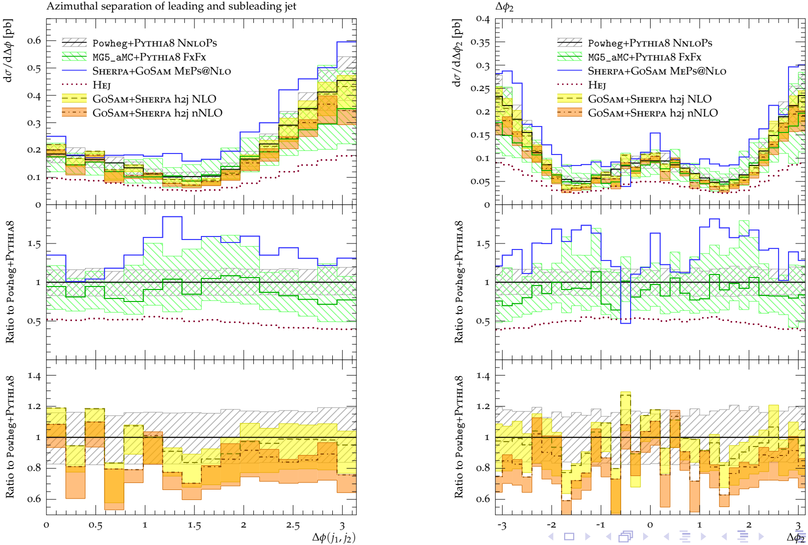
Subleading jet transverse momentum ($n_j \geq 2$)
$d\sigma/dp_\perp$ [pb/GeV]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
HEJ
GoSam+Sherpa h2j NLO
GoSam+Sherpa h2j nNLO
Ratio to Powheg+Pythia8
$p_\perp(j_2)$ [GeV]

Results


Rapidity separation of leading and subleading jet
dσ/dΔy [pb]
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Hej
GoSam+Sherpa h2j NLO
GoSam+Sherpa h2j nNLO
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
Δy(j1, j2)

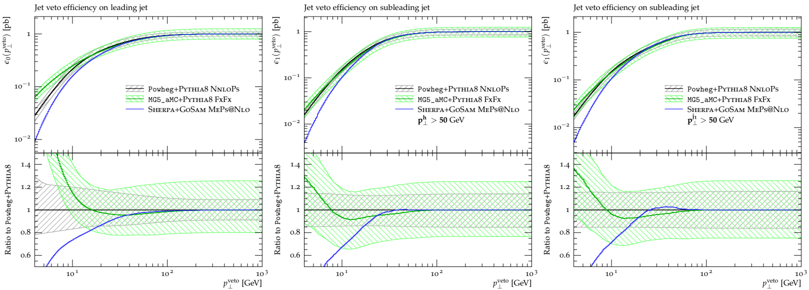

Invariant mass of leading and subleading jet
dσ/dm [pb/GeV]
GoSam+Sherpa h2j NLO
GoSam+Sherpa h2j nNLO
Powheg+Pythia8 NnloPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Hej
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
m(j1j2) [GeV]

Results



Azimuthal separation of leading and subleading jet
$d\sigma/d\Delta\phi$ [pb]
Powheg+Pythia8 NNLOPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Hej
GoSam+Sherpa h2j NLO
GoSam+Sherpa h2j nNLO
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
$\Delta\phi(j_1, j_2)$
$\Delta\phi_2$
$d\sigma/d\Delta\phi_2$ [pb]
Powheg+Pythia8 NNLOPs
MG5_aMC+Pythia8 FxFx
Sherpa+GoSam MePs@Nlo
Hej
GoSam+Sherpa h2j NLO
GoSam+Sherpa h2j nNLO
Ratio to Powheg+Pythia8
Ratio to Powheg+Pythia8
$\Delta\phi_2$

Results



$$\epsilon_i(p_\perp^{\rm veto}) = \frac{\sigma_i(p_\perp^{j_{i+1}} < p_\perp^{\rm veto})}{\sigma_{i,\rm incl}}$$

here: keep $\sigma_{i,\rm incl}$ fixed for uncertainty

Conclusions & outlook

Status & observations:

- good agreement between tools in many observables
  mostly within the respective uncertainties
- the more exclusive, the larger the differences
  not always covered by the uncertainties
- uncertainties in parton shower and POWHEG exponent not estimated
  leads to an underestimate of uncertainties dominated by these components

Remaining tasks:

- incorporate remaining contributions
- increase statistics on some contributions
- finalise note
- though late, identify synergies with similar YR4 effort

Thank you for your attention!