Electroweak Higgs Boson Production with Precision

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Parallel Talk

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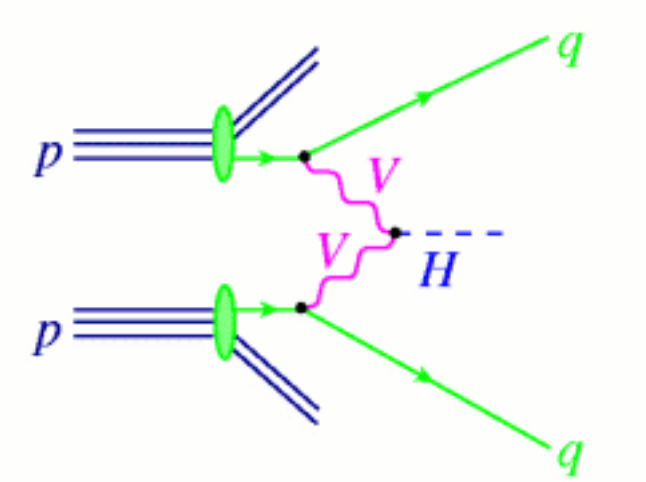
References and Thanks to Collaborators…

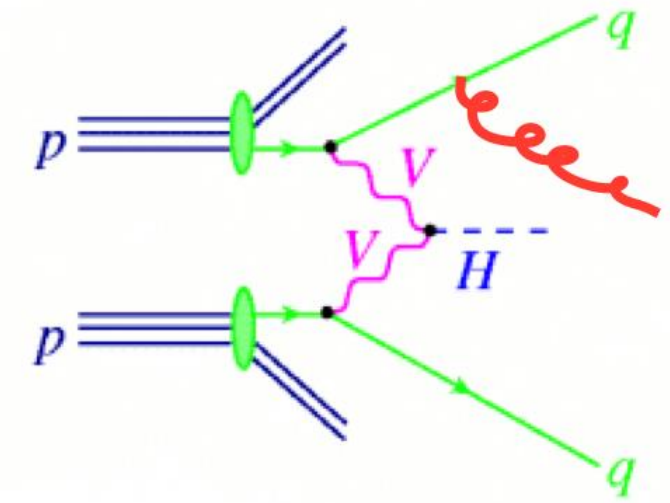
Collaborators: Simon Platzer, Peter Schichtel, Michael Rauch, Malin Sjodahl, Francisco Campanario, and Tinghua Chen.

- https://arxiv.org/abs/2109.03730 (NEW)
- https://arxiv.org/abs/1802.09955
- https://arxiv.org/abs/1308.2932
- https://arxiv.org/abs/0710.5621
- https://arxiv.org/abs/1610.07922

In a full talk I would discuss the history of calculations.

Vector Boson Fusion (+Jet)





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Simulation Tools and Matrix Elements

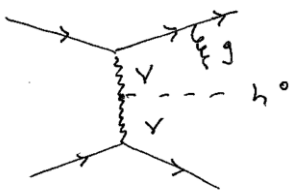
- Herwig 7 Event Generator (https://herwig.hepforge.org)
  - General purpose event generator,
  - parton showers, hadronization, MPI modeling
- HJETS++ (https://hjets.hepforge.org)
  - Add-on module to Herwig 7
- VBFNLO (https://www.itp.kit.edu/vbfnlo)
  - Interfaced to Herwig 7 via the Binoth One-Loop Accord

HJETS

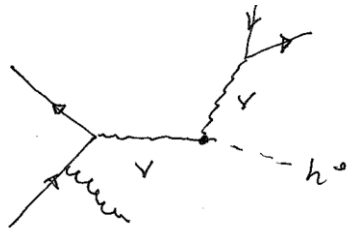
F. Campario, T. M. Figy, S. Platzer, and M. Sjodahl, PRL 111, 211802

- Matchbox [S. Platzer and S. Gieseke, arXiv:1109.6256]
  - Catani-Seymour Dipole subtraction [hep-ph/9605323]
  - Subtractive and POWHEG style matching to parton shower
  - ColorFull [M. Sjodahl, arXiv:1211.2099, http://colorfull.hepforge.org]
- Tensorial Reduction [F. Capanario, arXiv:1105.0920]
- Scalar Loop Integrals: OneLOop [A. van Hameren arXiv:1007.4716]

HJETS



(t - channels)



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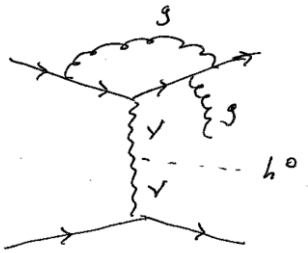
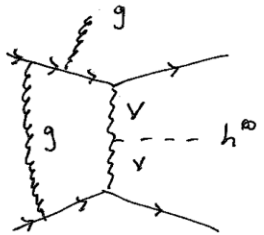
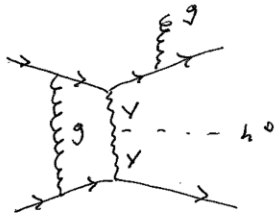


box lines



hexagons



pentagons

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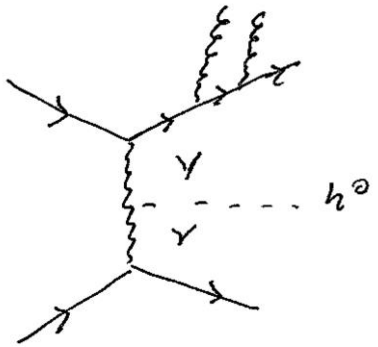
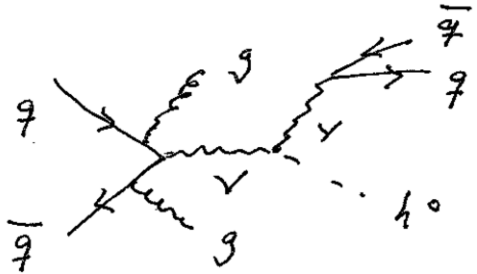
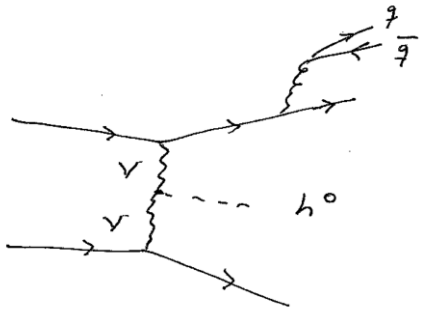
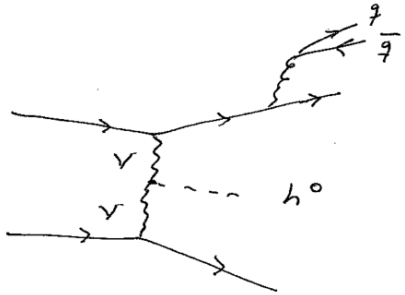
HJETS









Real Corrections

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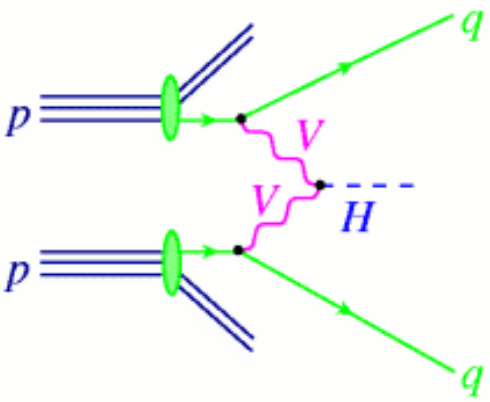
VBFNLO



Project Description

VBFNLO is a fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production in hadronic collisions at next to leading order in the strong coupling constant. VBFNLO includes Higgs and vector boson decays with full spin correlations and all off-shell effects. In addition, VBFNLO implements CP-even and CP-odd Higgs boson via gluon fusion, associated with two jets, at the leading order one loop level with the full top-quark and bottom-quark mass dependence in a generic two Higgs doublet model.

A variety of effects arising from beyond the Standard Model physics are implemented for selected processes. This includes anomalous couplings of Higgs and vector bosons and a Warped Higgsless extra dimension model. The program offers the possibility to generate Les Houches Accord event files for all processes available at leading order.

All implemented processes can be found here.

The list of people involved in VBFNLO is here.

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Herwig 7

Bootstrap script pulling in all dependencies. Tested on a large number of platforms.

→ `./herwig-bootstrap /where/to/install`

Documentation re-written from scratch: "living" sphinx sites replacing old wiki pages.

→ **Check out** `herwig.hepforge.org`

Update of detailed physics & manual will follow in due course.

Usage can be done as before, though **lots of parallelization added:**

- Separate building, grid adaption, and event generation
  → Cheaper parameter variations.
- Grid adaption parallelized in separate jobs (no IPC required)
  → `Herwig build --maxjobs=6 LHC-Matchbox.in`
  → `Herwig integrate --jobid=3 LHC-Matchbox.run ...`
- Multicore capabilities
  → `Herwig run --jobs=24 LHC-Matchbox.run`

terrancefigy — tmfigy@selene:~/HJets-Matching — ssh tmfigy@headnode.beocat.ksu.edu — Homebrew — 123×45

```
##################################################
## Herwig/Matchbox example input file
##################################################

##################################################
## Collider type
##################################################
read snippets/Matchbox.in
read snippets/PPCollider.in
#read snippets/MonacoSampler.in
##################################################
## Beam energy sqrt(s)
##################################################

cd /Herwig/EventHandlers
set EventHandler:LuminosityFunction:Energy 13000*GeV
set EventHandler:Weighted On

##################################################
## Process selection
##################################################

## Note that event generation may fail if no matching matrix element has
## been found.  Coupling orders are with respect to the Born process,
## i.e. NLO QCD does not require an additional power of alphas.

## Model assumptions
read Matchbox/StandardModelLike.in
read Matchbox/DiagonalCKM.in

## Set the order of the couplings
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 1
set Factory:OrderInAlphaEW 3
#set Factory:AlphaParameter 1.0
## Select the process
## You may use identifiers such as p, pbar, j, l, mu+, h0 etc.
do Factory:Process p p -> h0 j j j

# The next line can switch of hadronization
# # and MPI modelling. Use with care!!
read Matchbox/PQCDLevel.in

## Special settings required for on-shell production of unstable particles
## enable for on-shell top production
```

h + 3 jets

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```
# The next line can switch of hadronization
# # and MPI modelling. Use with care!!
read Matchbox/PQCDLevel.in

## Special settings required for on-shell production of unstable particles
## enable for on-shell top production
# read Matchbox/OnShellTopProduction.in
## enable for on-shell W, Z or h production
# read Matchbox/OnShellWProduction.in
# read Matchbox/OnShellZProduction.in
read Matchbox/OnShellHProduction.in
# Special settings for the VBF approximation
#read Matchbox/VBFDiagramsOnly.in

##################################################
## Matrix element library selection
##################################################

## Select a generic tree/loop combination or a
## specialized NLO package

# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-MadGraph.in
# read Matchbox/MadGraph-NJet.in
# read Matchbox/MadGraph-OpenLoops.in
read HJets.in
#read Matchbox/VBFNLO.in

## Uncomment this to use ggh effective couplings
## currently only supported by MadGraph-GoSam

# read Matchbox/HiggsEffective.in

##################################################
## Cut selection
## See the documentation for more options
##################################################
cd /Herwig/Cuts
#set /Herwig/Cuts/ChargedLeptonPairMassCut:MinMass 60*GeV
#set /Herwig/Cuts/ChargedLeptonPairMassCut:MaxMass 120*GeV

#cd /Herwig/MatrixElements/Matchbox/Utility
#insert DiagramGenerator:ExcludeInternal 0 /Herwig/Particles/gamma
## cuts on additional jets -- details are set in the HJets-settings.in
## according to what we've fixed in the draft
```

HJets

VBFNLO

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terrancefigy — tmfigy@selene:~/HJets-Matching — ssh tmfigy@headnode.beocat.ksu.edu — Homebrew — 123×45

```
insert JetCuts:JetRegions 0 FirstJet
insert JetCuts:JetRegions 1 SecondJet
insert JetCuts:JetRegions 2 ThirdJet

##################################################
## Matching and shower selection
## Please also see flavour scheme settings
## towards the end of the input file.
##################################################

#read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
## use for strict LO/NLO comparisons
# read Matchbox/MCatLO-DefaultShower.in
## use for improved LO showering
# read Matchbox/LO-DefaultShower.in

read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
## use for strict LO/NLO comparisons
# read Matchbox/MCatLO-DipoleShower.in
## use for improved LO showering
#read Matchbox/LO-DipoleShower.in

#read Matchbox/NLO-NoShower.in
#read Matchbox/LO-NoShower.in

##################################################
## Scale uncertainties
##################################################

# read Matchbox/MuDown.in
# read Matchbox/MuUp.in

##################################################
## Shower scale uncertainties
##################################################

# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in
##################################################
## PDF choice
##################################################
--More--(78%)
```

Various setup:

1. Fixed Order
2. NLO/LO matching
    1. Subtractive
    2. Powheg

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terrancefigy — tmfigy@selene:~/HJets-Matching — ssh tmfigy@headnode.beocat.ksu.edu — Homebrew — 123×45

```
## PDF choice
################################################
read Matchbox/FiveFlavourNoBMassScheme.in
read Matchbox/MMHT2014.in
################################################
## Analyses
################################################

cd /Herwig/Analysis
#read snippets/Rivet.in
insert Rivet:Analyses 0 MC_H2JETS_04_0
insert Rivet:Analyses 1 MC_H2JETS_04_1
insert Rivet:Analyses 2 MC_H2JETS_04_2
insert Rivet:Analyses 3 MC_H_KTSPLITTINGS

insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
################################################
#
#  HJets settings aqccording to the paper draft
#  _NO_ reason to touch any cuts etc in here.
#
################################################

read HJets-settings.in

#cd /Herwig/Cuts
#set FirstJet:PtMin 20*GeV
#set SecondJet:PtMin 20*GeV
#set ThirdJet:PtMin 20*GeV

#do FirstJet:YRange -5.0 5.0
#do SecondJet:YRange -5.0 5.0
#do ThirdJet:YRange -5.0 5.0

################################################
## Save the generator
################################################

do /Herwig/MatrixElements/Matchbox/Factory:ProductionMode

#set /Herwig/Generators/EventGenerator:IntermediateOutput Yes

cd /Herwig/Generators
saverun LHC-Matchbox EventGenerator
[tmfigy@selene HJets-Matching]$
```

Rivet analysis for implementing selection cuts and histogram.

Custom run setting can be read in.

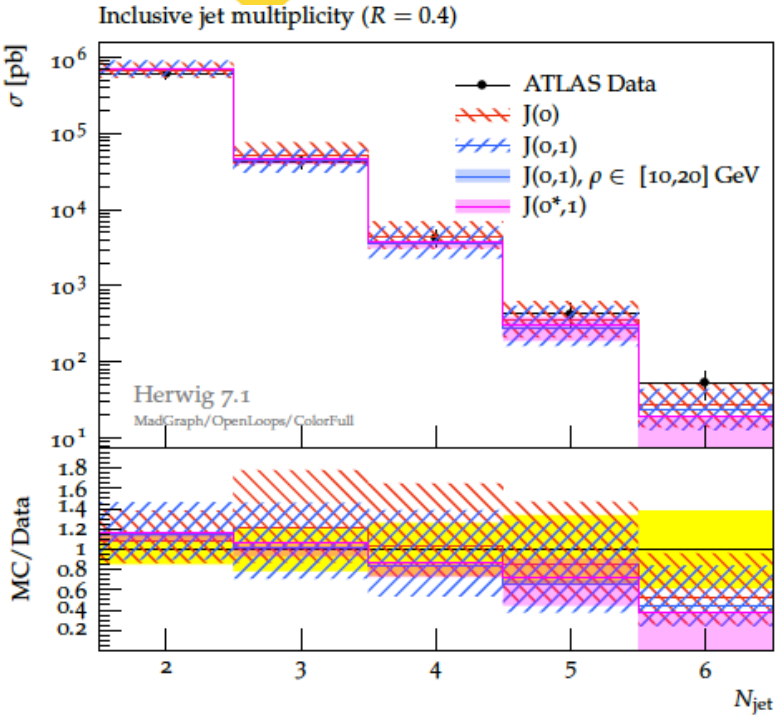
NLO Matching in Herwig 7

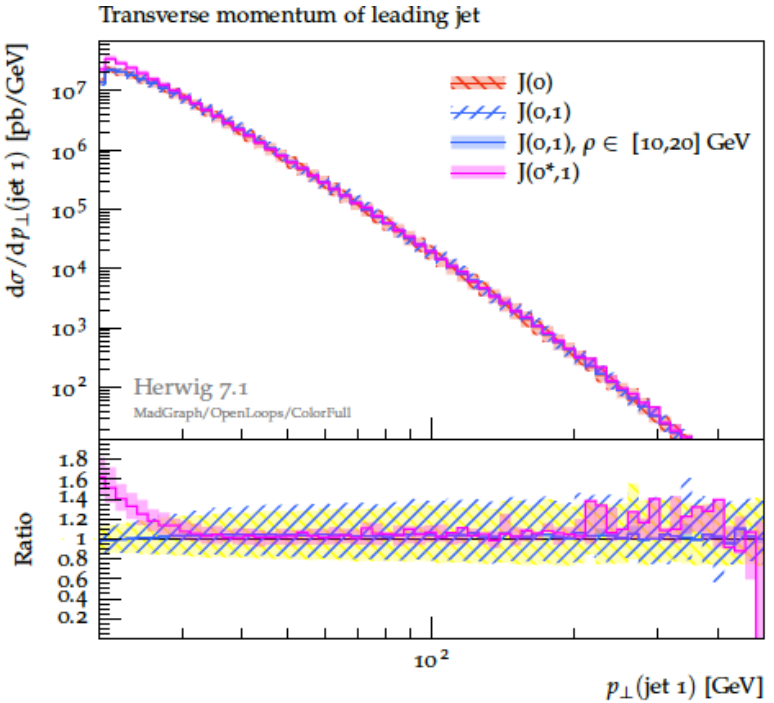
$$\sigma_{\mathrm{NLO}}^{\mathrm{matched}} = \int_n (\mathrm{d}\sigma_{\mathrm{LO}} + \mathrm{d}\sigma_{\mathrm{virt}}) + \int_n \int_1 (\mathrm{d}\sigma_{\mathrm{PS}} - \mathrm{d}\sigma_{\mathrm{sub}}) + \int_{n+1} (\mathrm{d}\sigma_{\mathrm{R}} - \mathrm{d}\sigma_{\mathrm{PS}}) \ ,$$

See https://arxiv.org/pdf/1605.07851.pdf
https://arxiv.org/pdf/1912.06509.pdf
https://arxiv.org/pdf/1109.6256.pdf

NLO Merging in Herwig 7

See https://arxiv.org/pdf/1705.06700.pdf





Dijet Production at the LHC

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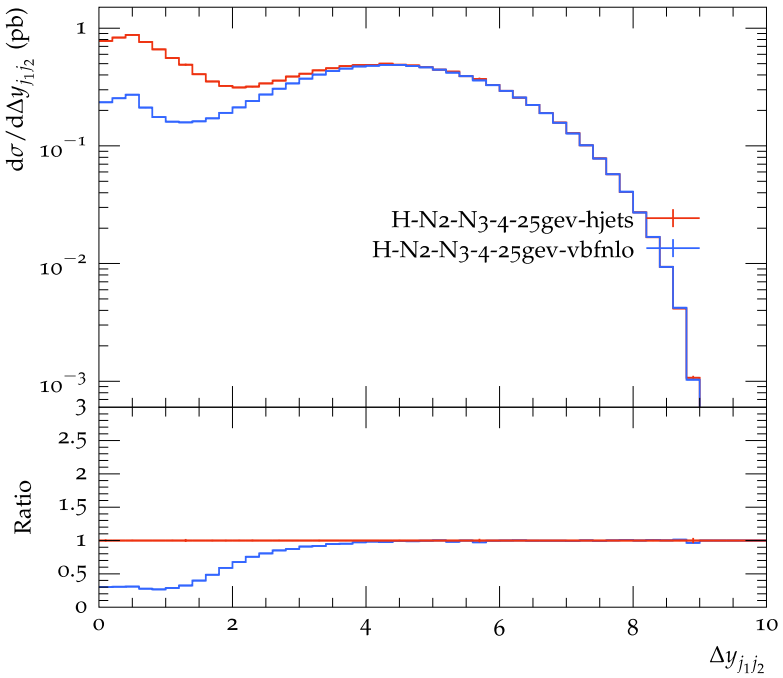
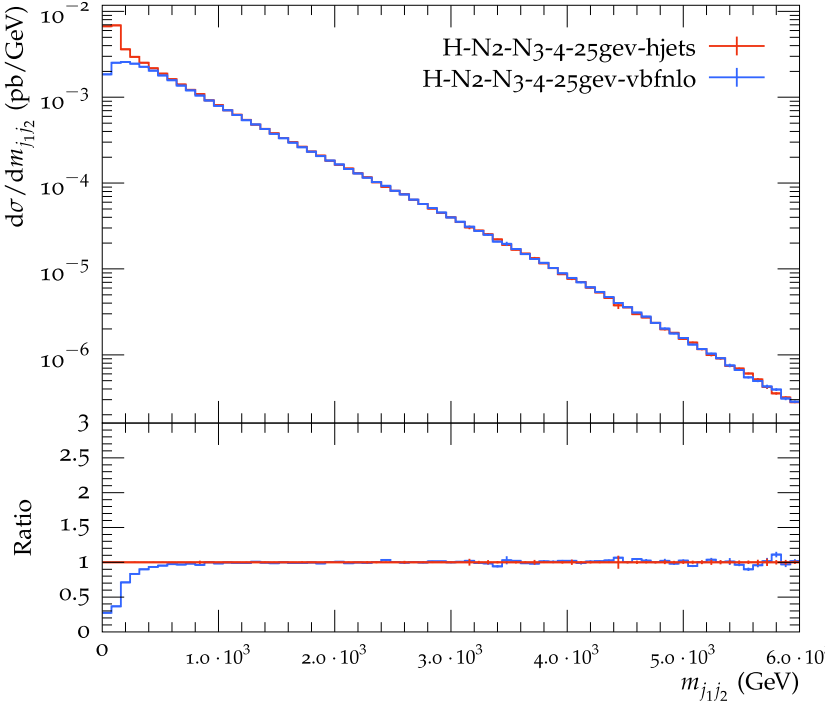
Input Parameters and Event Selection Cuts

- CMS Energy of Collider and Beam Type: pp LHC (13 TeV)
- PDF set (LHAPDF): PDF4LHC15_nnlo_100_pdfas
- Factorization and renormalization scales: HT(jets)
- Anti-Kt Jet clustering (R=0.4) using FastJet:
  - At least two jets with pTjet > 25 GeV
- Results include a dipole parton shower as implemented in Herwig 7. Matched results use a MC@NLO type matching. No hadronization or MPI have been included in the simulations.

For more details contact me via email.

VBFNLO vs. HJETS for h(2*,3*,4)





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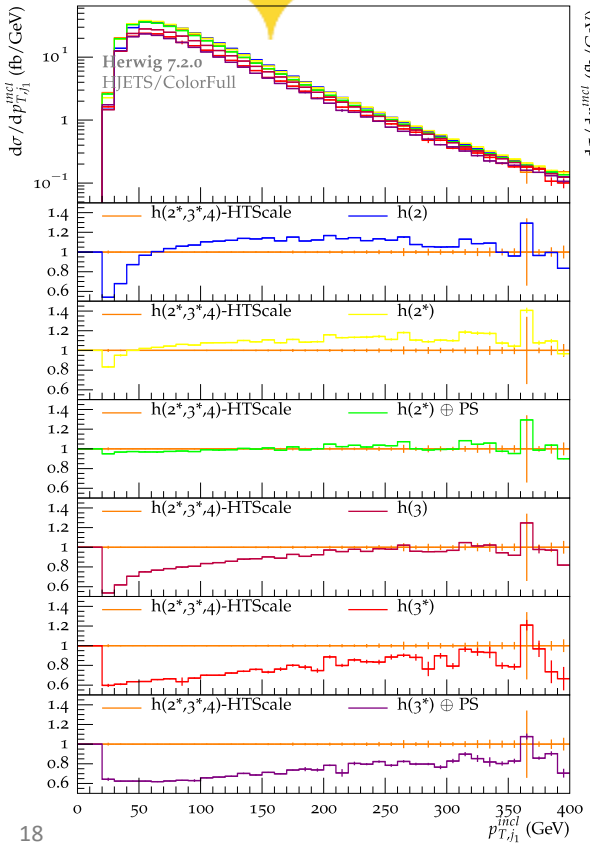
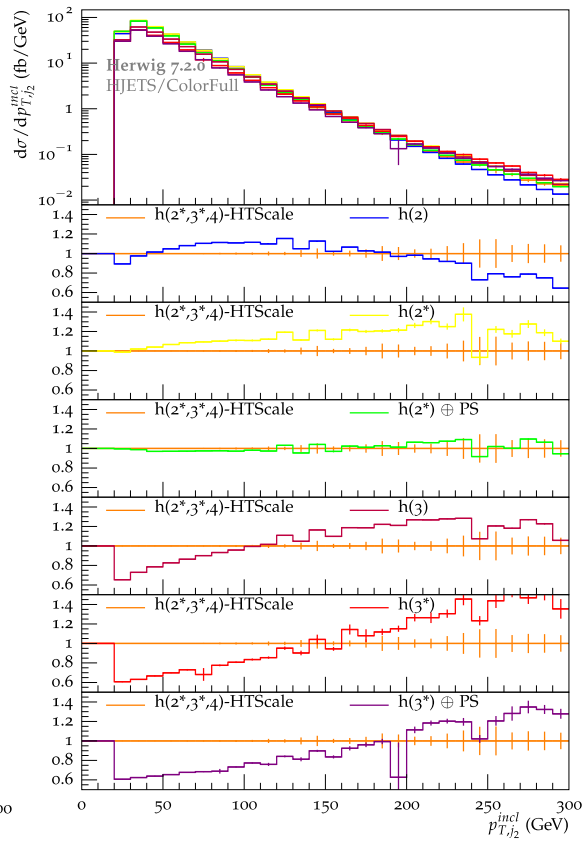
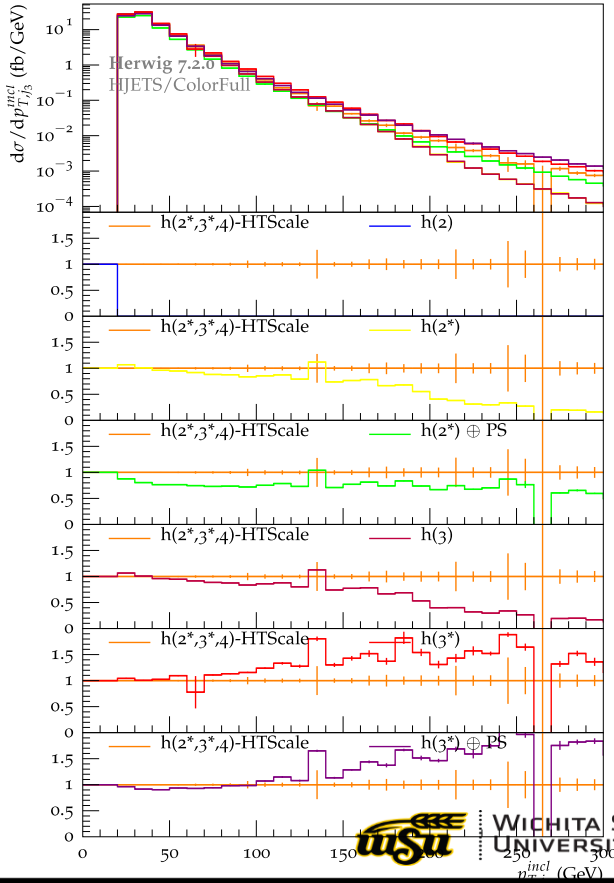
Transverse Momentum Spectrum







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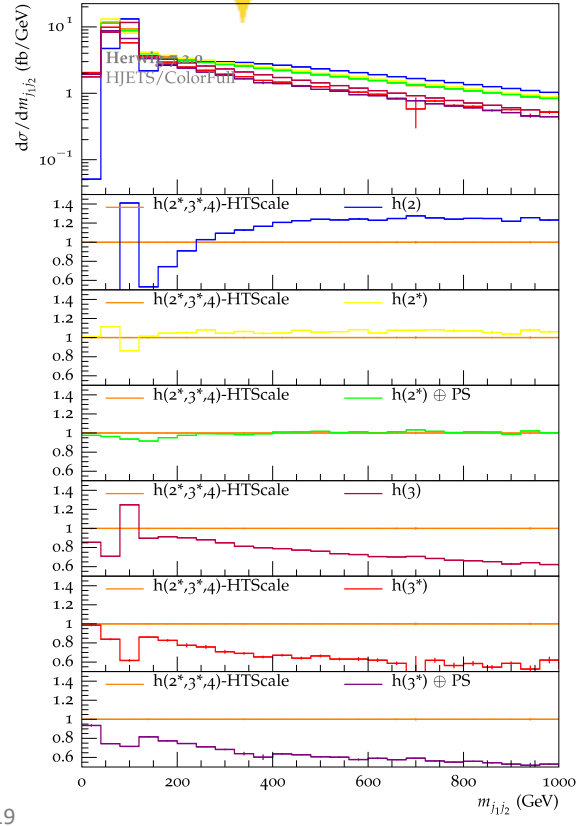
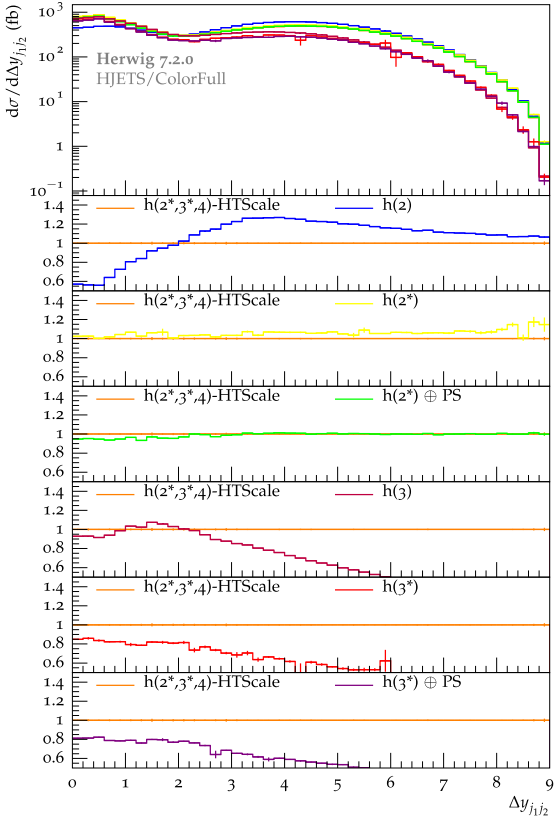
Rapidity Gap and Invariant Mass





NLO+PS does a good job overall for 2 jet observables.

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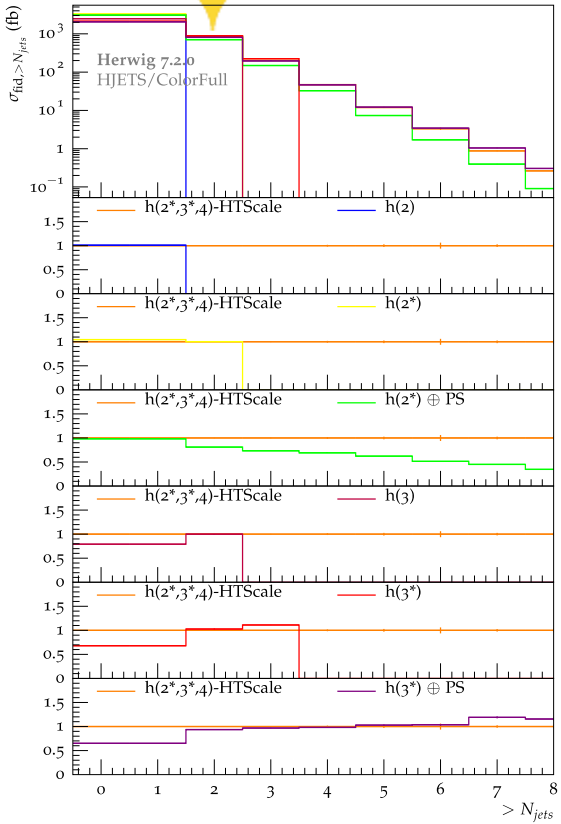
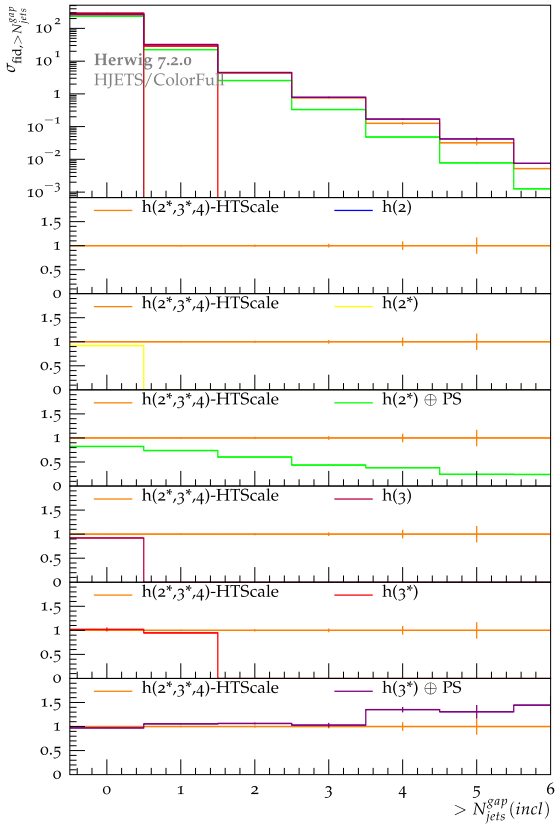
Inclusive Jet and Gap Jet Cross Section





Using HT(jets) for the scale.

Gap jets reside between yj1 and yj2.

Beyond 2 jets you need NLO 3 jet.

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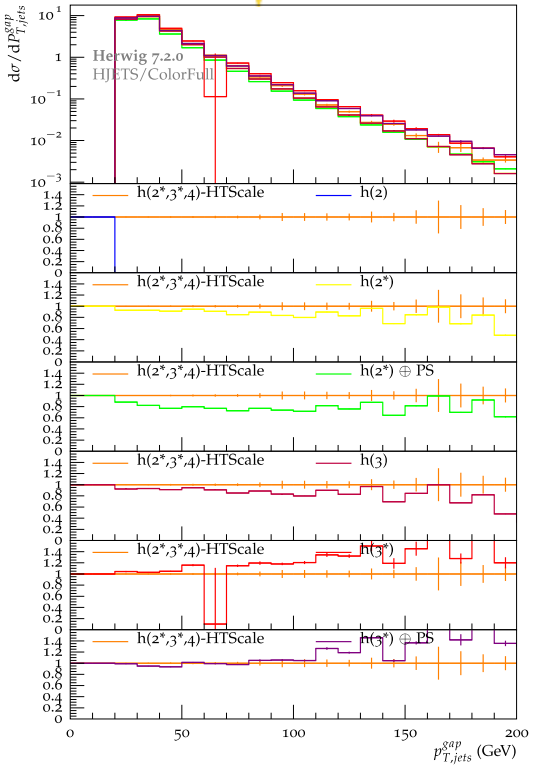
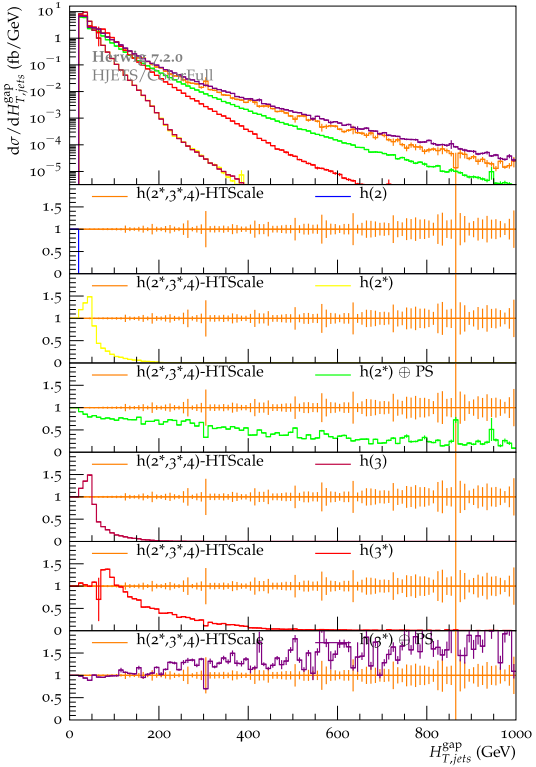
Gap Jet Activity





Gap Jets are quite soft.

Again, you need NLO for more than 2 jets

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Conclusions

- We find that NLO H+2 jets matched a shower does not describe the radiation pattern between the tagging jets.
- So, you really do need to include H+3 jets at NLO in order to understand the radiation activity between the tagging jets.

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Auxiliary Slides

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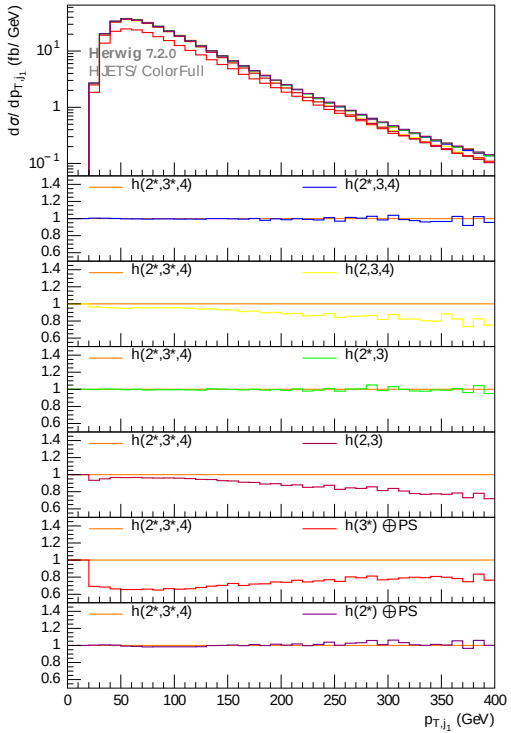
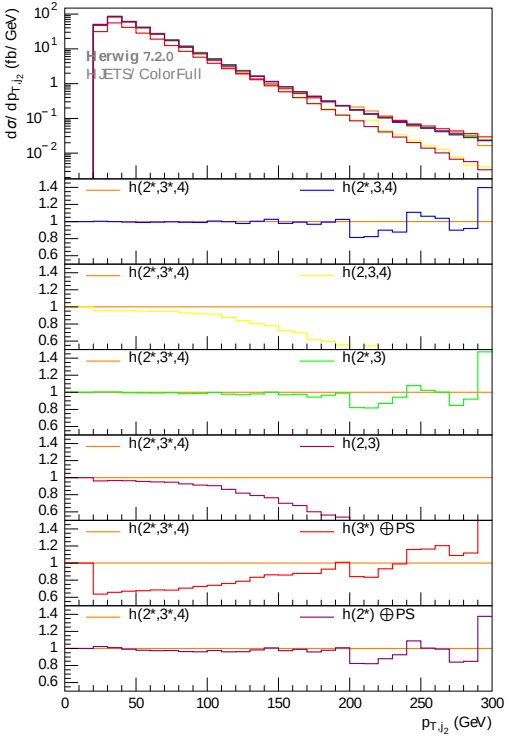
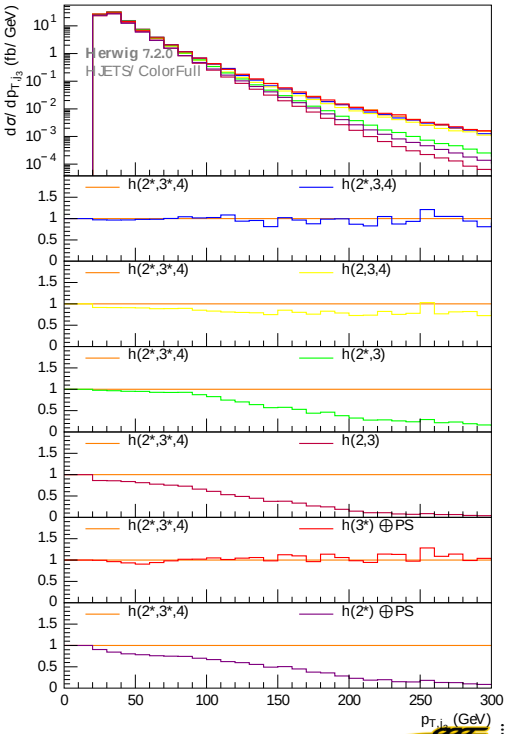
Transverse Momentum Spectrum (fixed scale: mh)







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