Double Higgs Boson Production in Association of Jets in the Triplet Higgs Model at the LHC

Dr. Terrance Figy

Associate Professor

Department of Mathematics, Statistics, and Physics

Wichita State University

Extended Scalars form All Angles

CERN, Oct. 22, 2024

WSU WICHITA STATE UNIVERSITY

Single and Double Higgs Boson Production in Association of Jets using Herwig 7 in the SM and in BSM

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References and Thanks to Collaborators…

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

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

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Special Article - Tools for Experiment and Theory

NLO multijet merging for Higgs production beyond the VBF approximation

Tinghua Chen[1], Terrance M. Figy[1b] and Simon Plätzer[2,3,4]

[1] Department of Mathematics, Statistics and Physics, Wichita State University, 1845 Fairmount St, 67260, Wichita, KS, USA
[2] Institute of Physics, NAWI Graz, University of Graz, Universitätsplatz 5, 8010, Graz, Austria
[3] Particle Physics, Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090, Wien, Austria
[4] Erwin Schrödinger Institute for Mathematics and Physics, University of Vienna, Boltzmanngasse 9, 1090, Wien, Austria

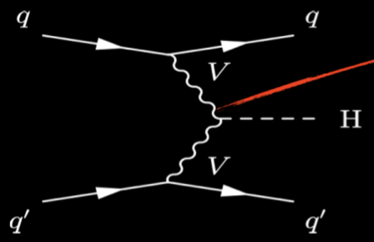
In a full talk I would discuss the history of calculations.

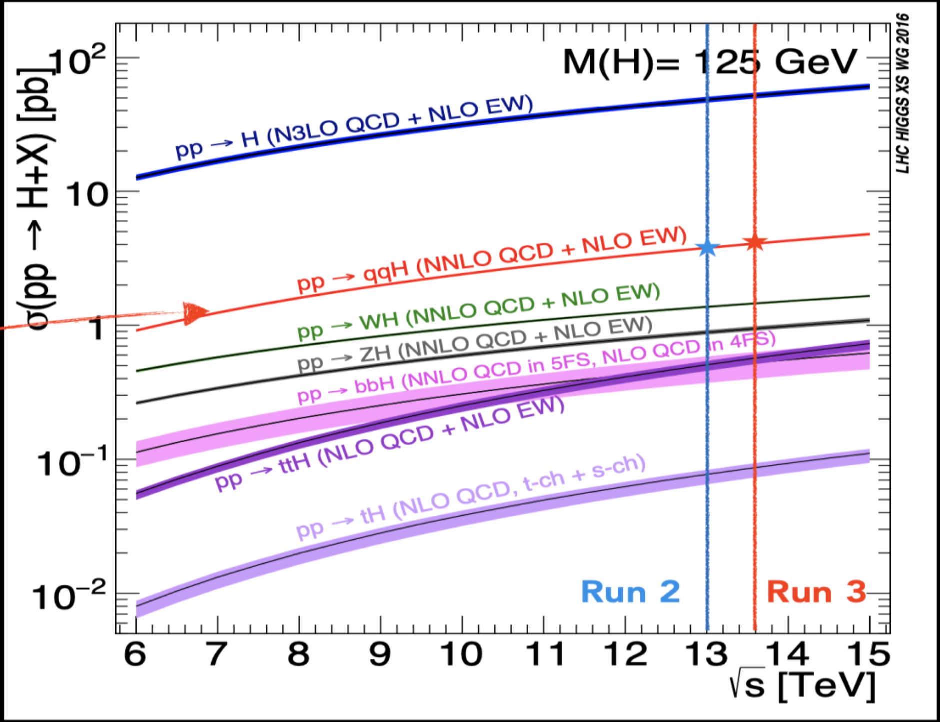
More References and Collaborators

- Anomalous Higgs boson couplings in vector boson fusion (Ph.D. Thesis 2023, Tinghua Chen). Related paper in progress.
- Azimuthal angle correlations for Higgs boson plus multi-jet events (J. Andersen, K. Arnold, D. Zeppenfeld)
- In Progress: Double Higgs via VBF in BSM scenarios.
- Collaborators: Tinghua Chen and Bathiya Samarakoon

WHAT IS VBF?

The **second most copious Higgs production mode** after gluon-gluon fusion





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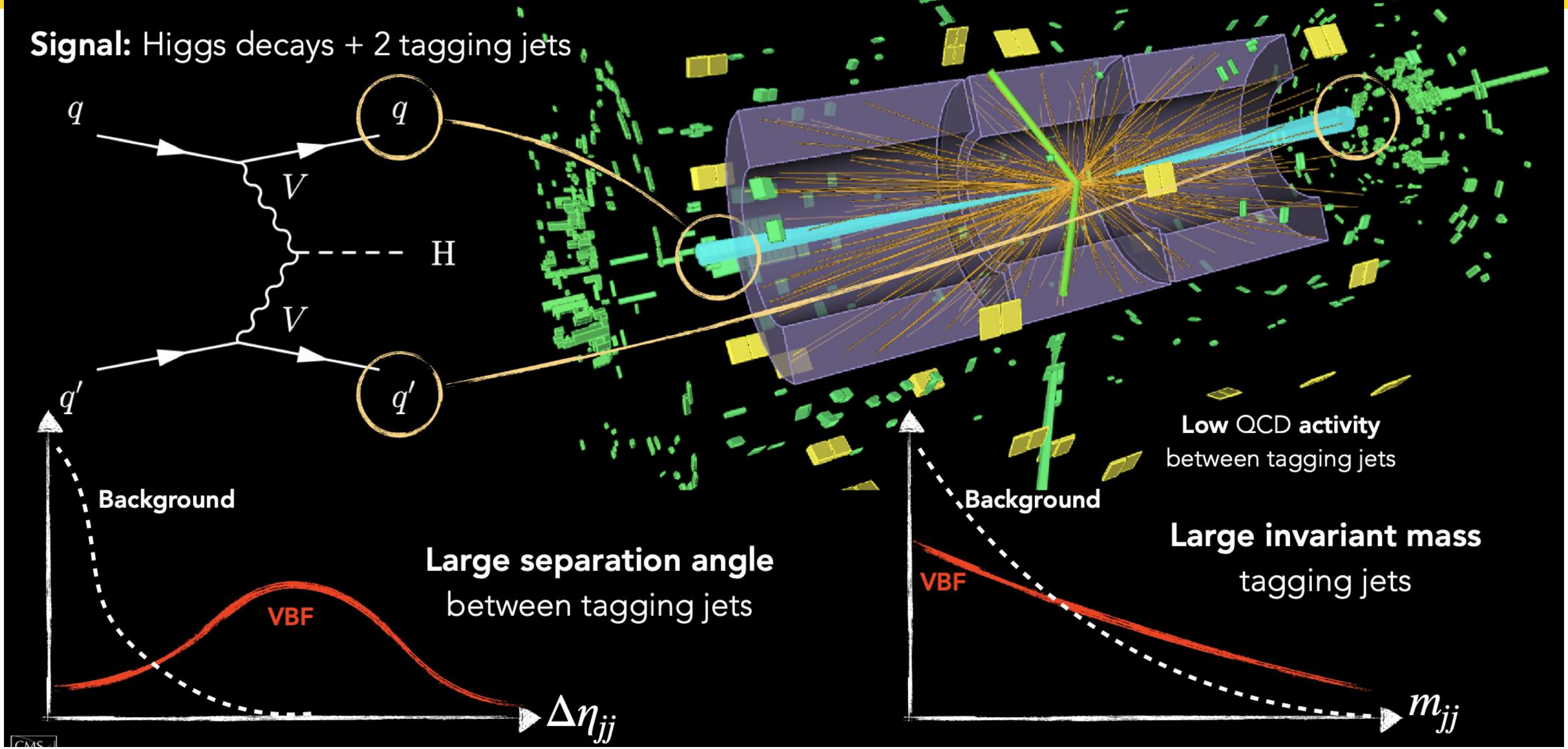
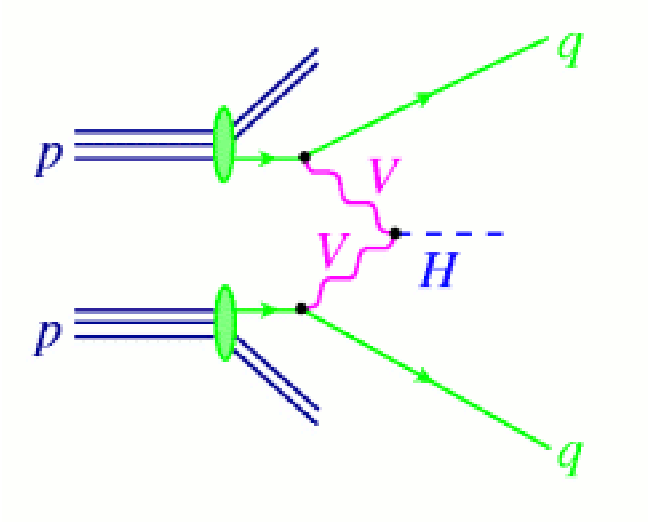
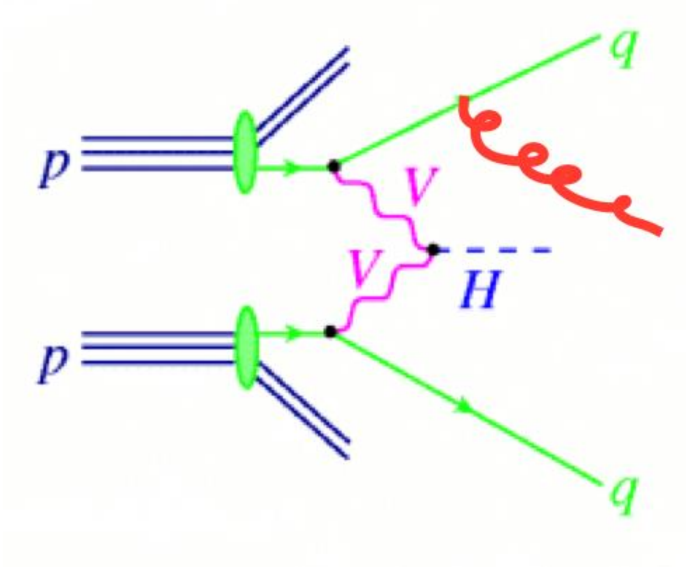
WHAT IS VBF?



ATLAS VBF $H \to \tau_{had}\tau_{had}$ candidate event
Signal: Higgs decays + 2 tagging jets
q
q
V
H
V
q′
q′
Background
VBF
$\Delta\eta_{jj}$
Large separation angle
between tagging jets
Low QCD activity
between tagging jets
Background
VBF
Large invariant mass
tagging jets
m_{jj}

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

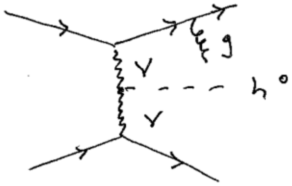
- VBFNLO (https://www.itp.kit.edu/vbfnlo)
  - Interfaced to Herwig 7 via the Binoth One-Loop Accord

HJETS

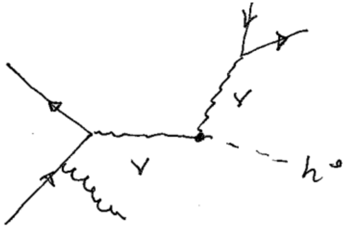
F. Campario, T. M. Figy, S. Platzer, and M. Sjodahl, PRL 111, 211802

- 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]

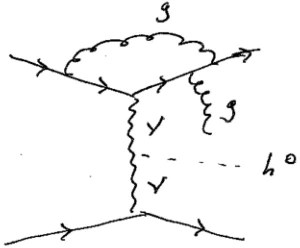
HJETS



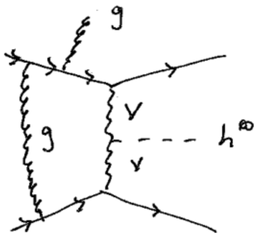
(t - channels)



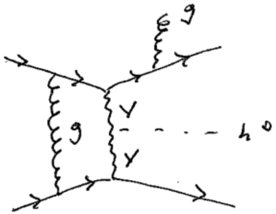
(s - channels)



box lines

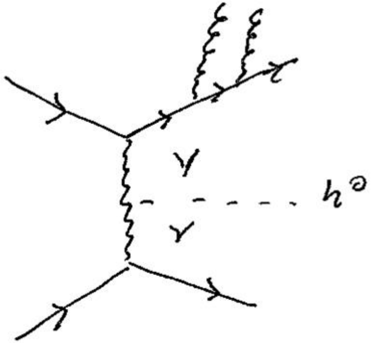


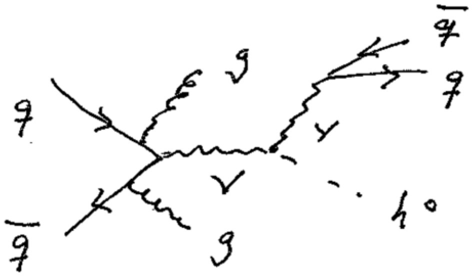
hexagons

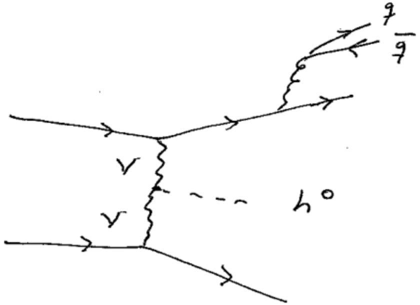


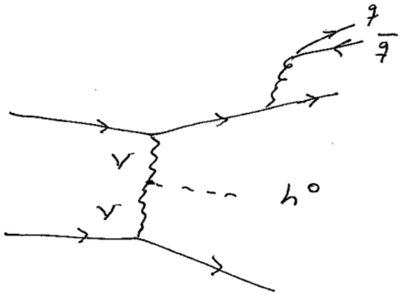
pentagons

HJETS



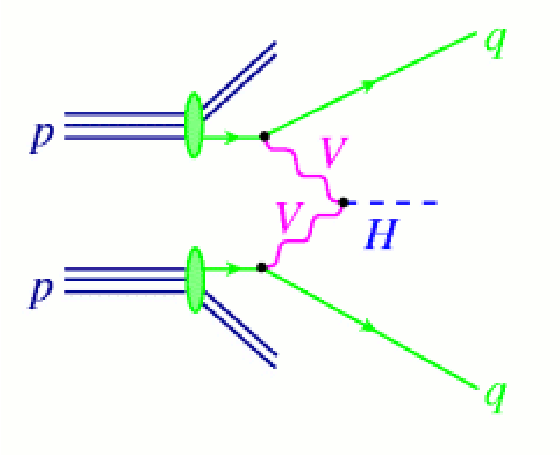






Real Corrections

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.

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`

H7

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

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

```
# 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

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

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

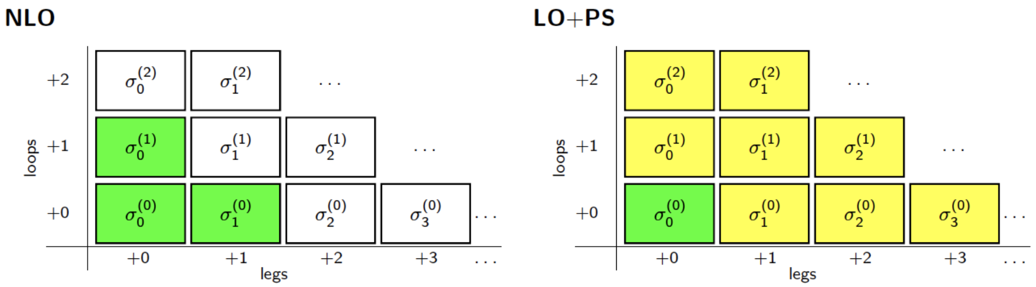
```
## PDF choice
##################################################
read Matchbox/FiveFlavourNoBMassScheme.in
read Matchbox/MMHT2014.in
##################################################
## Analyses
##################################################

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

Parton showers vs fixed-order calculations



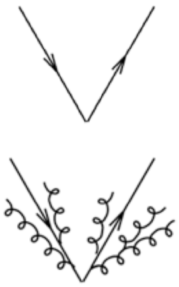
Fixed-order calculations → hard jets

- reliable at **high scales** if **no large scale hierarchies** are present
- **accurate** predictions for **limited number** of legs (+ loops)
- determines **perturbative accuracy** (LO, NLO, NNLO, . . .)

Showers → jet substructure

- reliable in **soft/collinear** regions if **large scale hierarchies** are present
- **approximate** predictions for **many** particles
- determines **logarithmic accuracy** (LL, NLL, NNLL, . . .)

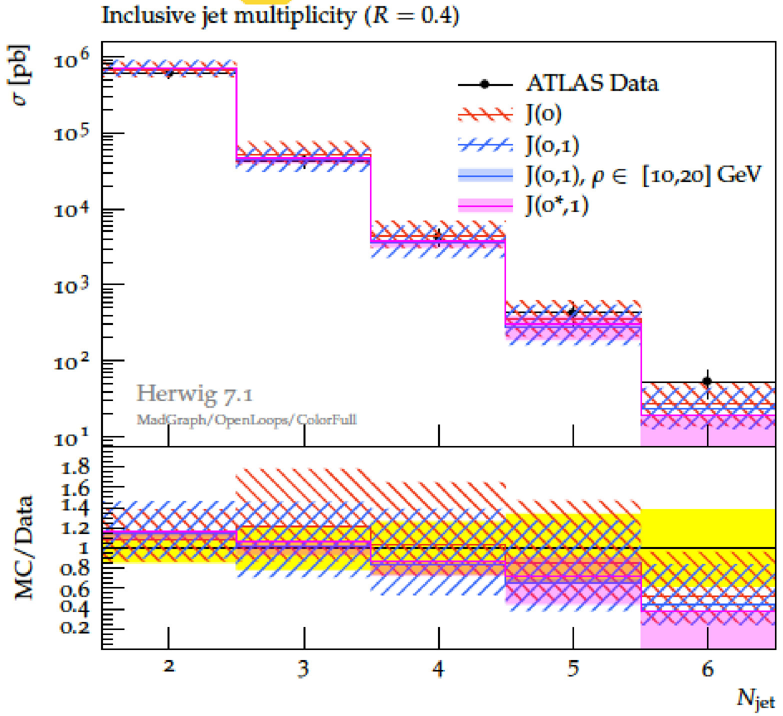
⇒ largely **complementary**, so ideally **combine them**!

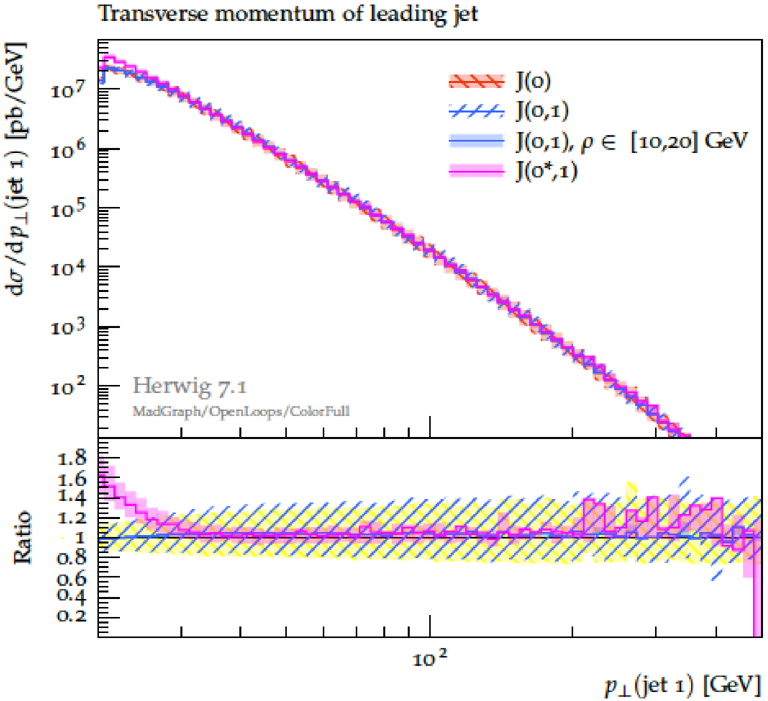


See
https://arxiv.org/pdf/1605.07851.pdf
https://arxiv.org/pdf/1912.06509.pdf
https://arxiv.org/pdf/1109.6256.pdf

NLO Merging in Herwig 7

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





Dijet Production at the LHC

Definitions

- The rapidity y is defined as

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right),$$

- The separation of rapidity between two jets is

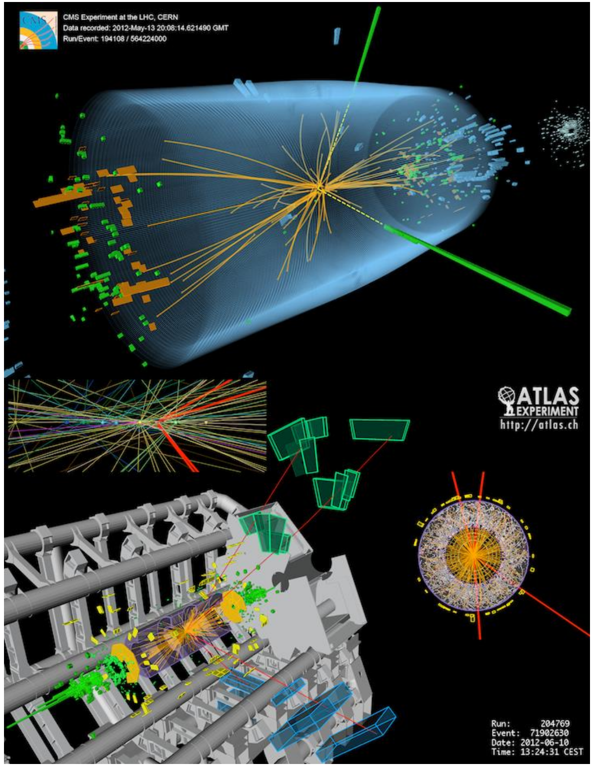
$$\Delta y_{j_1 j_2} = |y_{j_1} - y_{j_2}|,$$

- The transverse momentum, p_T is defined by

$$p_T = \sqrt{p_x^2 + p_y^2},$$

- invariant mass for two jets, defined as

$$m_{j_1 j_2} = \sqrt{(p_{j_1} + p_{j_2})^2},$$



Input Parameters and Event Selection

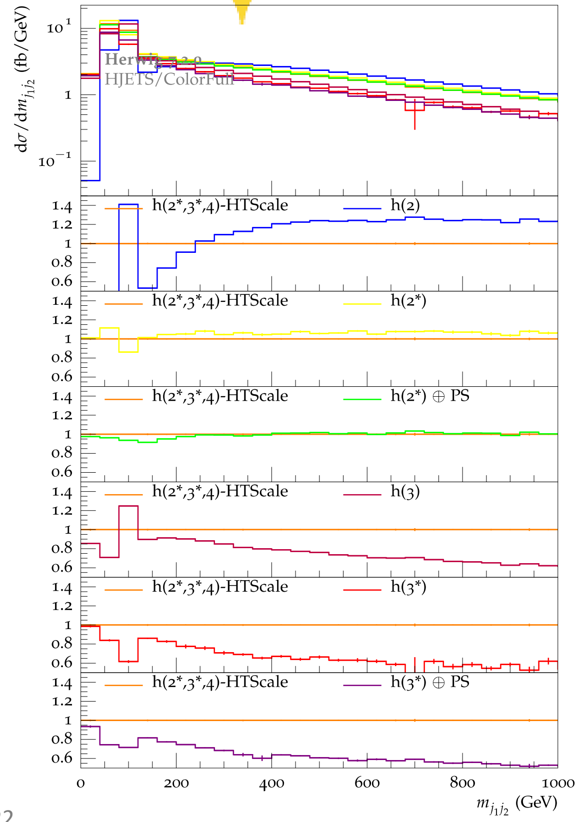
- CMS Energy of Collider and Beam Type: pp LHC (13 TeV).
- PDF set (LHAPDF): PDF4LHC15_nnlo_100_pdfas.
- Factorization and renormalization scales set to HT(jets) scale.
- Anti-k_T Jet clustering (R=0.4) using FastJet, at least two jets with $p_{T,jets} > 25$ GeV.
- Matched results use a MC@NLO type matching. No hadronization or MPI have been included in the simulations.
- The LOOSE selection cuts is defined as

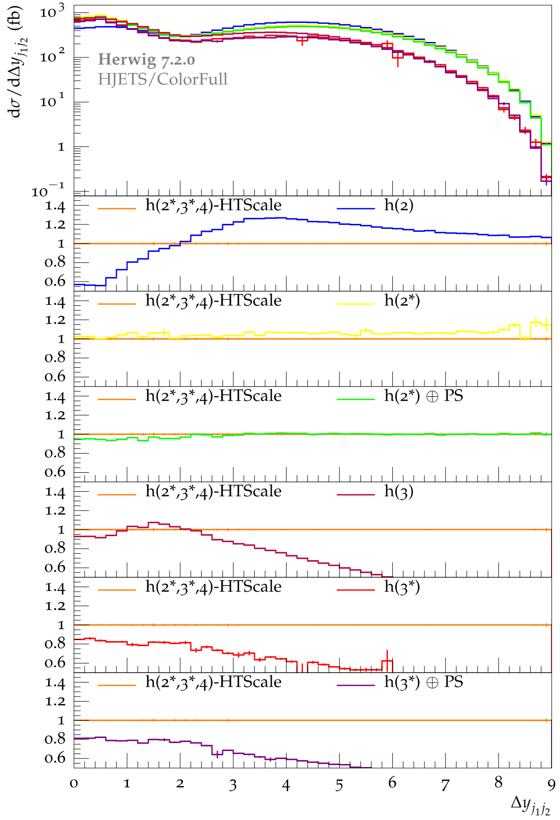
$$m_{j_1 j_2} > 200 \text{ GeV}, \quad \Delta y_{j_1 j_2} > 1. \tag{34}$$

- The TIGHT selection cuts is defined as

$$m_{j_1 j_2} > 600 \text{ GeV}, \quad \Delta y_{j_1 j_2} > 4.5, \quad y_{j_1} \cdot y_{j_2} < 0. \tag{35}$$

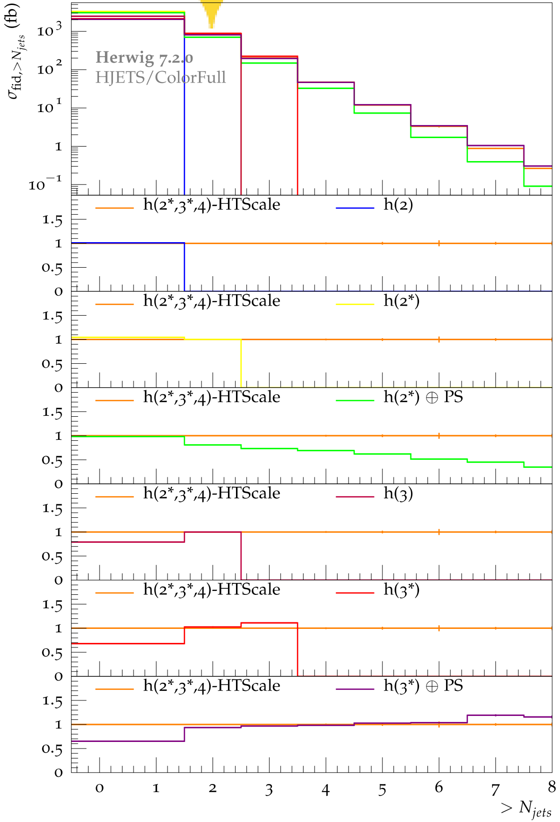
Rapidity Gap and Invariant Mass

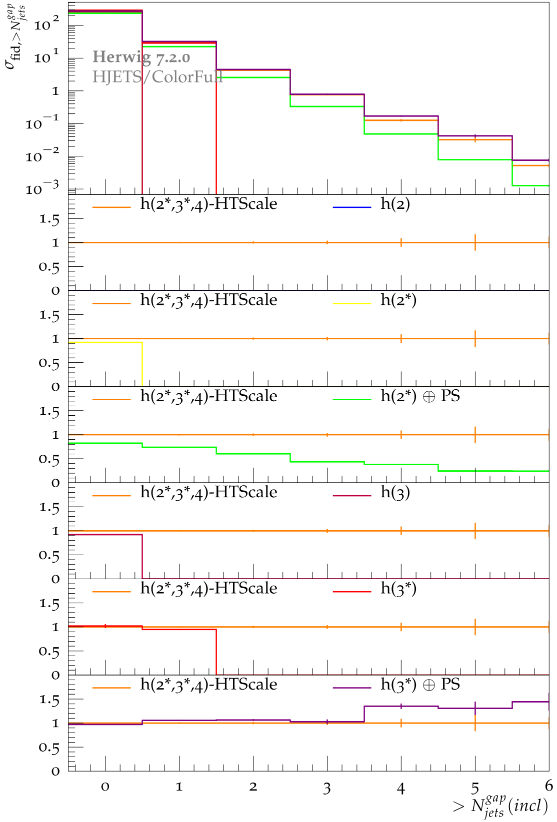




NLO+PS does a good job overall for 2 jet observables.

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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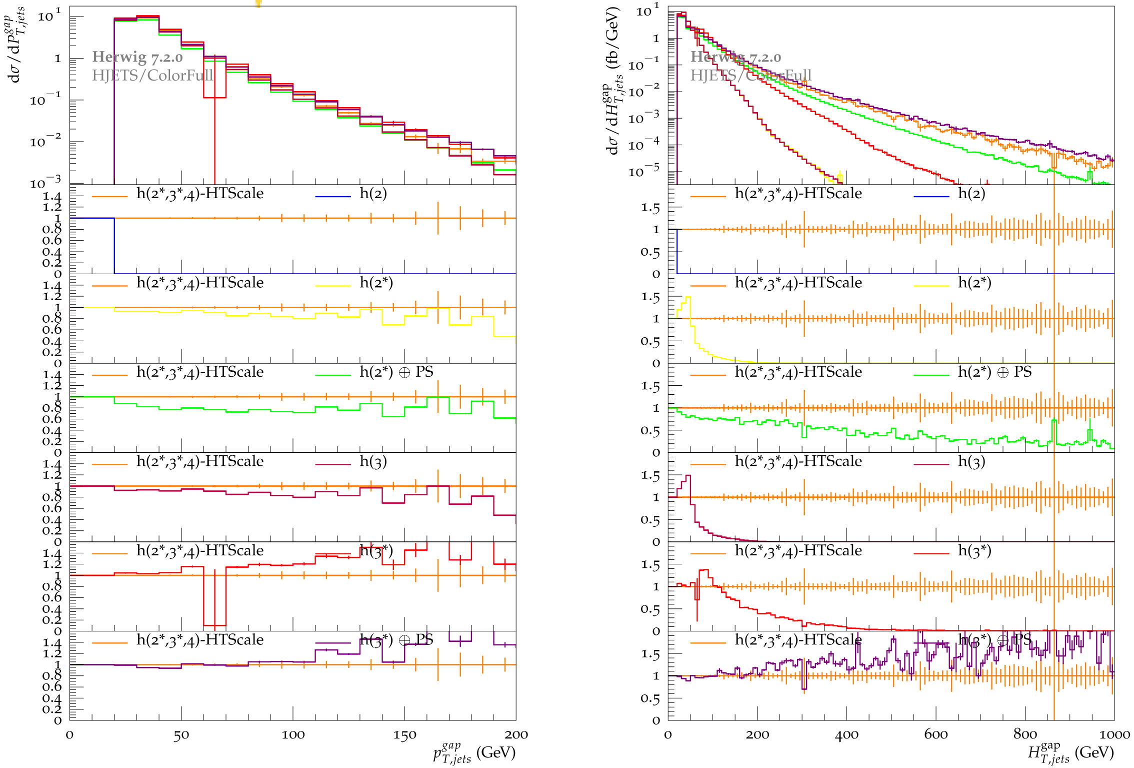
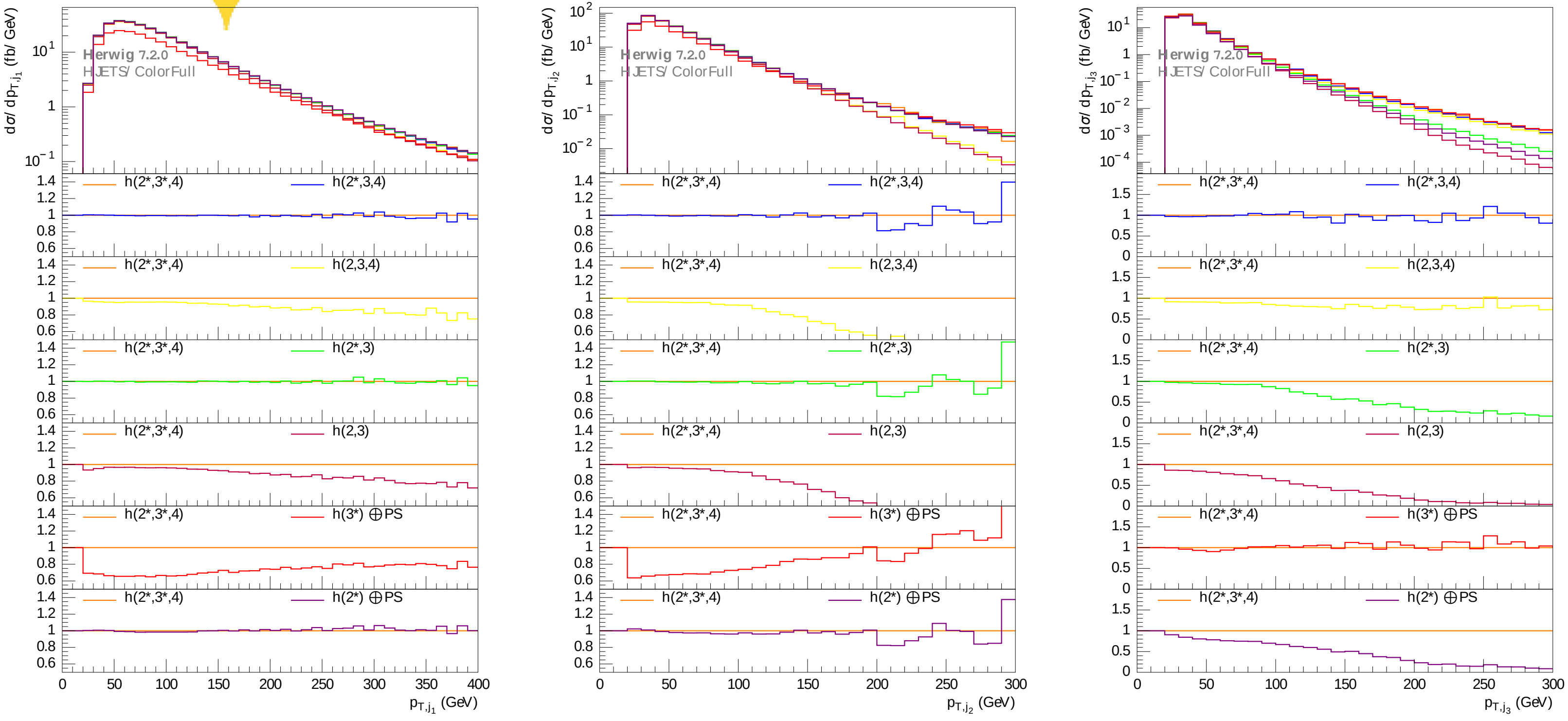
Gap Jet Activity



Gap Jets are quite soft.

Again, you need NLO for more than 2 jets

Transverse Momentum Spectrum (fixed scale: mh)



VBFNLO vs HJETS – Tight Selection Cuts

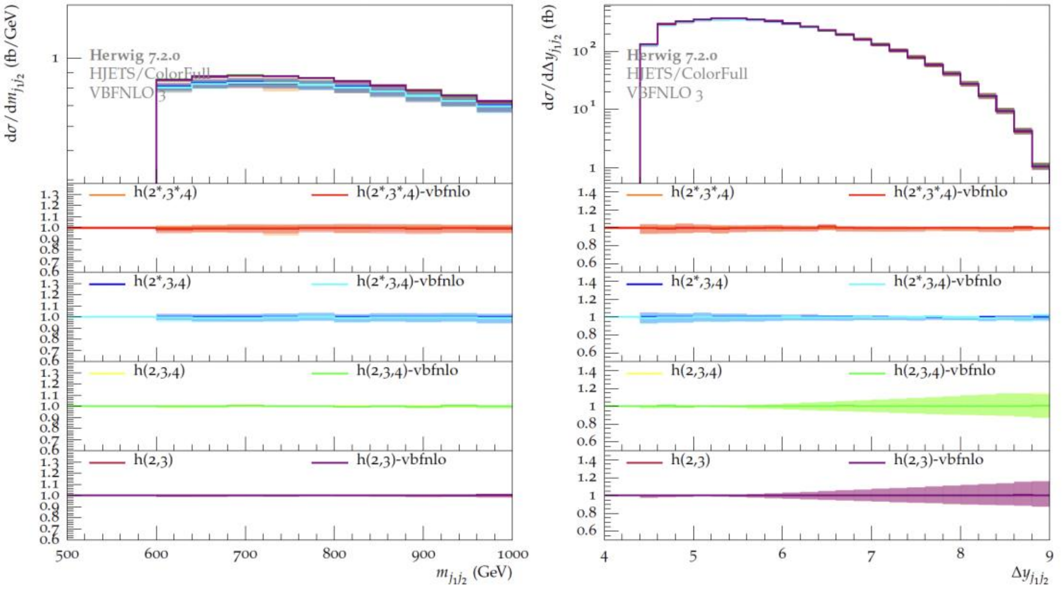


Figure: The distribution of invariant mass (left) and rapidity gap (right) of the two tagging jets with TIGHT cuts.

Anomalous Higgs Couplings

The effective Lagrangian can be written as the following equation:

$$\mathcal{L} = \frac{g_{5e}^{HWW}}{\Lambda_{5e}} H W_{\mu\nu}^{+} W^{-\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_{5o}} H \tilde{W}_{\mu\nu}^{+} W^{-\mu\nu} + \frac{g_{5e}^{HZZ}}{2\Lambda_{5e}} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_{5o}} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} . \quad (36)$$

The general tensor structure of the HVV vertex in the massless quark limit is

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho}, q_{2\sigma} \quad (37)$$

if $a_2 = a_3 = 0$, then a_1 represents the SM case.

Anomalous Higgs Couplings

The form factors a_2 and a_3 can be derived from the effective Lagrangian of Eq. (36),

$$a_2(q_1, q_2) = -\frac{2}{\Lambda_{5e}} g_{5e}^{HWW} , \qquad a_3(q_1, q_2) = \frac{2}{\Lambda_{5o}} g_{5o}^{HWW} \qquad (38)$$

for the HWW vertex, and

$$a_2(q_1, q_2) = -\frac{2}{\Lambda_{5e}} g_{5e}^{HZZ} , \qquad a_3(q_1, q_2) = \frac{2}{\Lambda_{5o}} g_{5o}^{HZZ} \qquad (39)$$

Anomalous Higgs Couplings

- pure CP-even: $g_{5e}^{HZZ} = g_{5o}^{HZZ} = 0.5$,
- pure CP-odd: $g_{5o}^{HWW} = g_{5o}^{HWW} = 0.5$,
- CP-mixed: $g_{5e}^{HWW} = g_{5o}^{HWW} = g_{5e}^{HZZ} = g_{5o}^{HZZ} = 0.5$.

CP Sensitive Observables

$|\Delta\phi_{j_1j_2}|$ is defined as

$$|\Delta\phi_{j_1j_2}| = |\phi_{j_1} - \phi_{j_2}|$$

$\Delta\phi_{j_fj_b}$ is define as

$$\Delta\phi_{j_fj_b} = \begin{cases} \phi_{j_1} - \phi_{j_2}, & y_{j_1} > y_{j_2} \\ \phi_{j_2} - \phi_{j_1}, & y_{j_1} < y_{j_2} \end{cases}$$

$\Delta\phi_{j_fj_b}$ also satisfies

$$\Delta\phi_{j_fj_b} = \begin{cases} \Delta\phi_{j_fj_b} + 2\pi, & \Delta\phi_{j_fj_b} < -\pi \\ \Delta\phi_{j_fj_b} - 2\pi, & \Delta\phi_{j_fj_b} > \pi \end{cases}$$

ϕ_2 is defined as

$$\phi_2 = \angle(\mathbf{q}_{a\perp}, \mathbf{q}_{b\perp}),$$

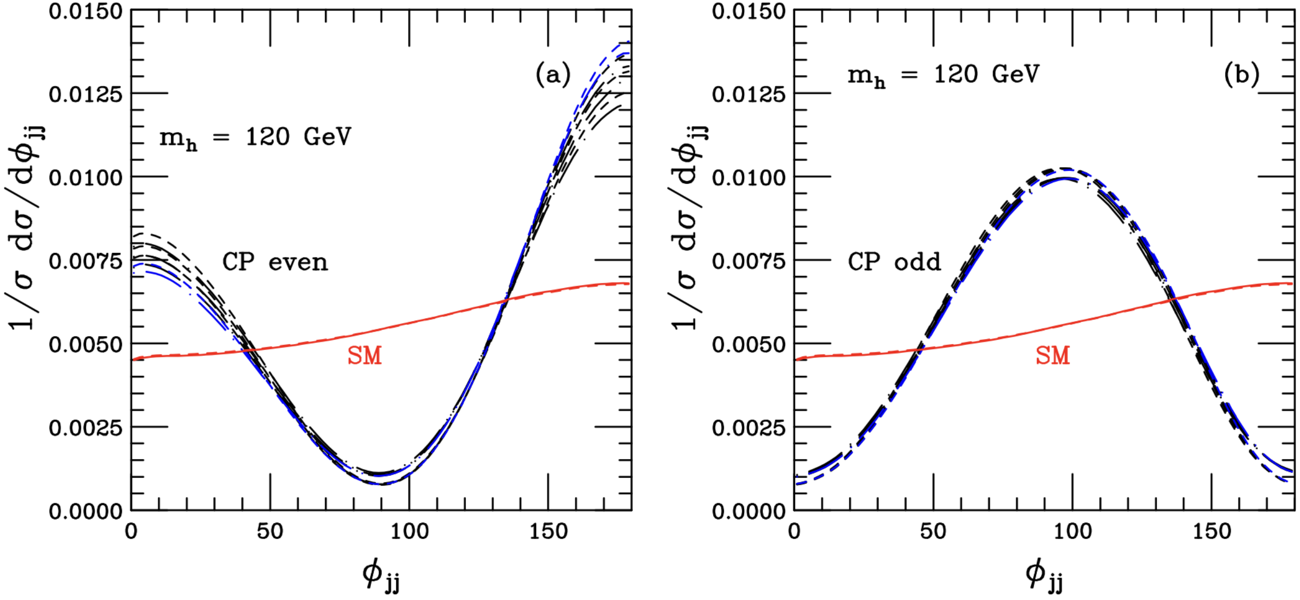
where

$$q_a = \sum_{j\in\{\text{jets}:y_j<y_h\}} p_j, \quad q_b = \sum_{j\in\{\text{jets}:y_j>y_h\}} p_j,$$

Anomalous Higgs in VBFNLO

- Anomalous Higgs Couplings were implemented into VBFNLO since 2004 for Higgs + 2 jets via VBF.
- In 2012 there was an interest in using the PowHEG implementation of Higgs + 2 jets via VBF and a reweighting technique to generate predictions include parton shower and hadronization effects.
- Today you can use VBFNLO with Herwig 7 to simulate Higgs Production with Anom Couplings (See Release Note—VBFNLO 3.0 for details, https://arxiv.org/abs/2405.06990)

H+2 jets at Fixed Order (2004, arXiv: 0403297v1)



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Results using VBFNLO interfaced to Herwig 7

H+3 jets now allows anom couplings

You can now merge H+2 and H+3 NLO calculations using Herwig 7.

Also, H+2 and H+3 jet NLO matched calcuations can be performed using Herwig 7

Azimuthal Angle Correlations

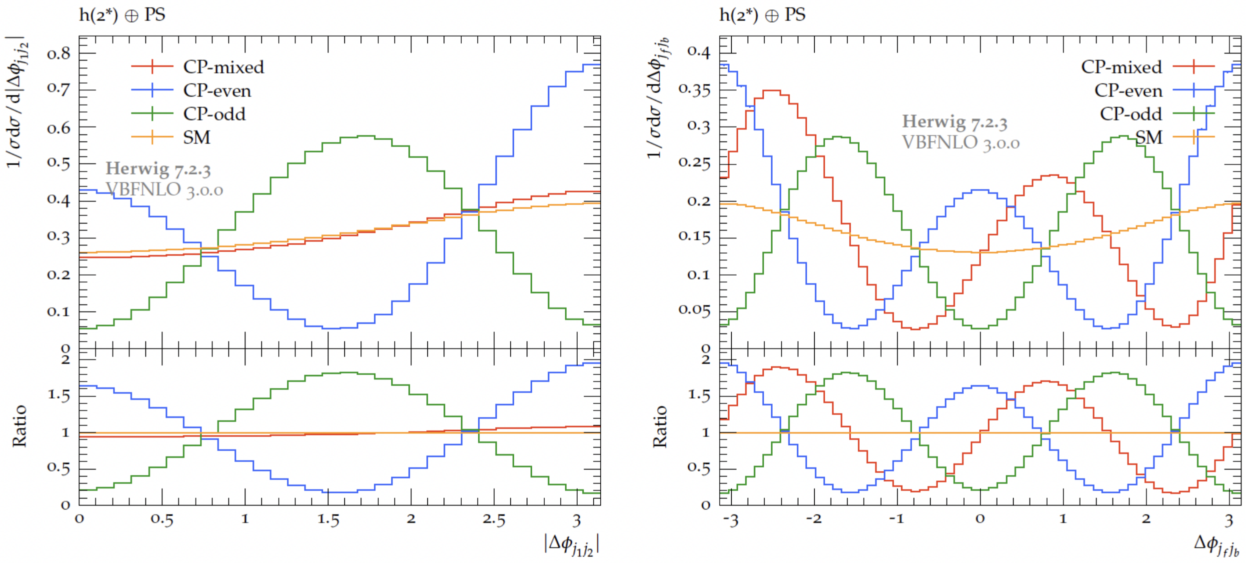

Figure: The distribution for of $|\Delta\phi_{j_1 j_2}|$ (left) and $\Delta\phi_{j_f j_b}$ (right) for matched setup $h(2^\star) \bigoplus \mathrm{PS}$ using TIGHT selection cuts.

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Azimuthal Angle Correlations

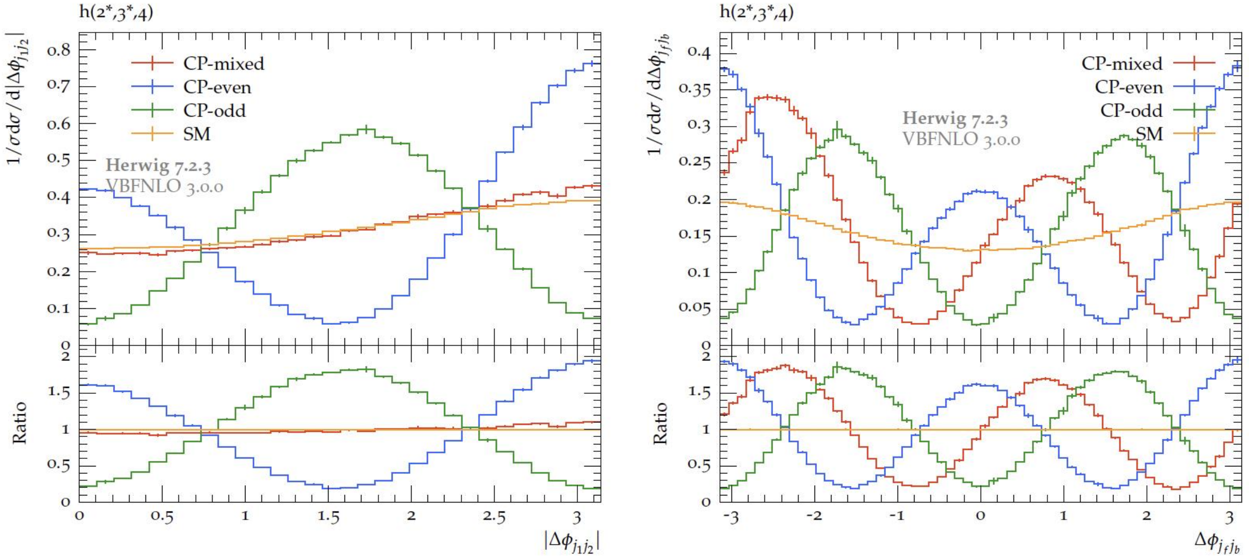

Figure: The distribution for of $|\Delta\phi_{j_1 j_2}|$ (left) and $\Delta\phi_{j_f j_b}$ (right) for merged setup $h(2^*, 3^*, 4)$ using TIGHT selection cuts.

Azimuthal Angle Correlations

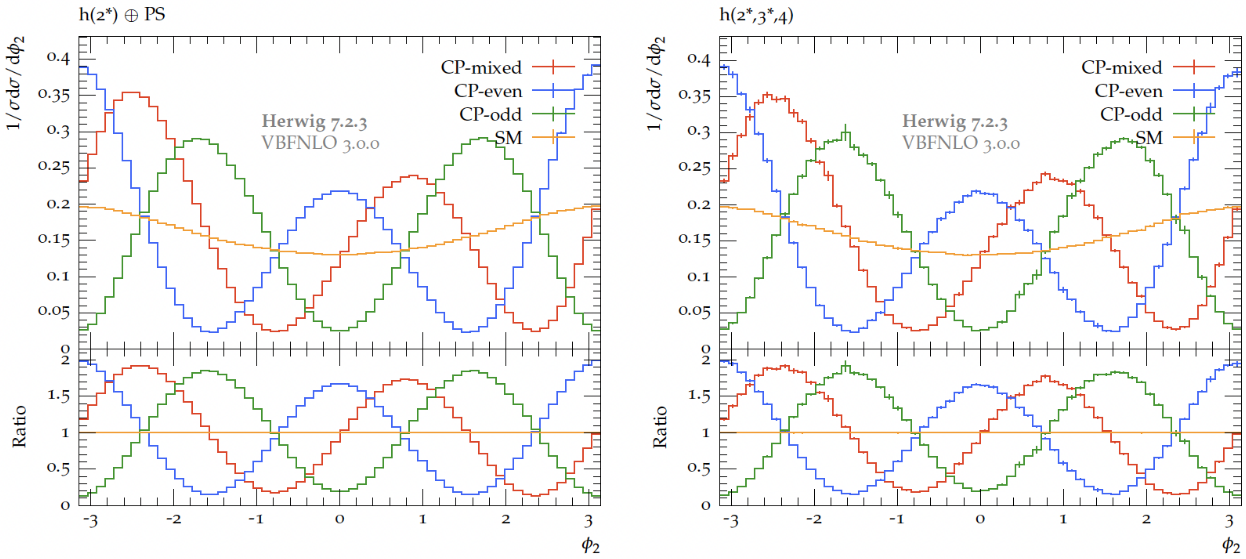

Figure: Distributions of ϕ_2 *for* $h(2^\star)\bigoplus \mathrm{PS}$ *(left) and* $h(2^*, 3^*, 4)$ *(right) using TIGHT cuts.*

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Invariant Mass of Di-Tag System

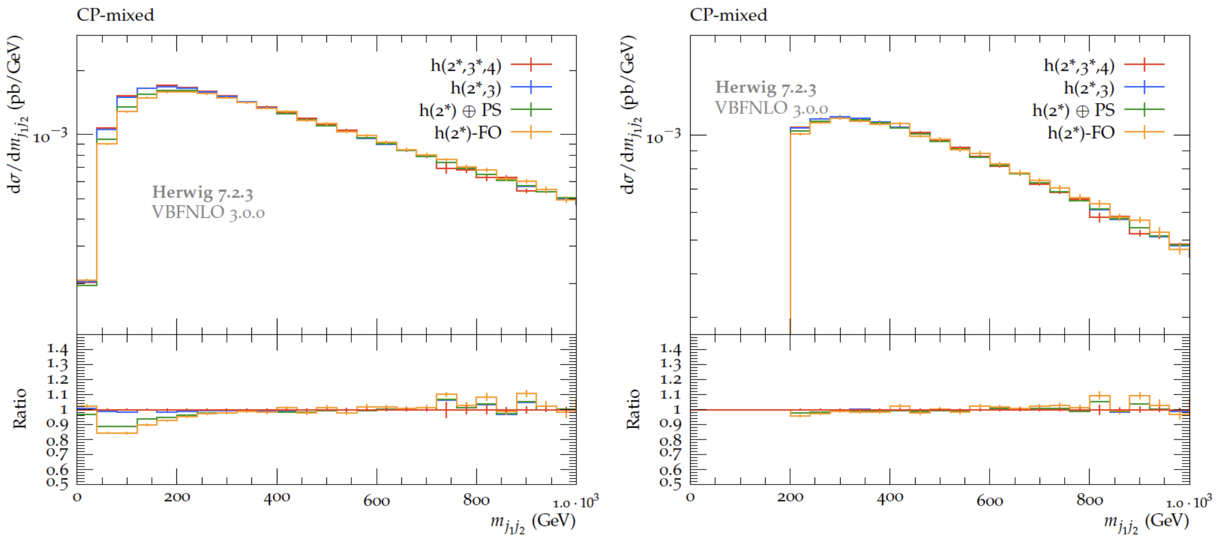


Figure: The distribution of $m_{j_1 j_2}$ with INCL cuts (left) and LOOSE cuts (right) for CP-mixed anomalous couplings. The ratio plot compared $h(2^\star, 3^\star, 4)$, $h(2^\star, 3)$, $h(2^\star) \bigoplus \mathrm{PS}$, and $h(2^\star)$ fixed order, with the merged setup $h(2^\star, 3^\star, 4)$ as the reference.

Rapidity Gap

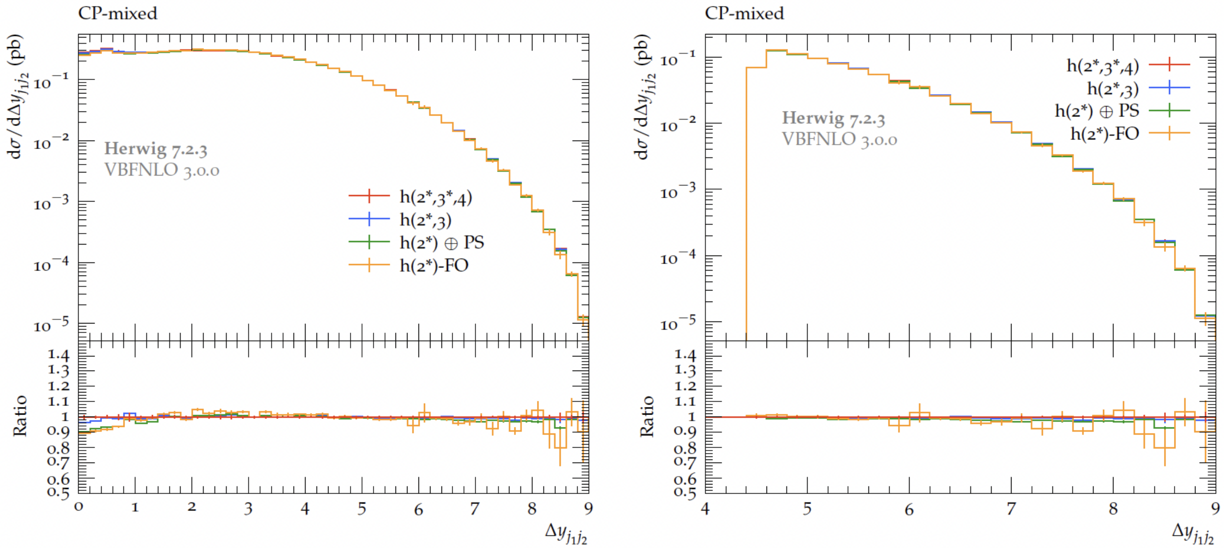


Figure: The distribution of $\Delta y_{j_1 j_2}$ with INCL cuts (left) and TIGHT cuts (right) for CP-mixed anomalous couplings. The ratio plot compared $h(2^\star, 3^\star, 4)$, $h(2^\star, 3)$, $h(2^\star) \bigoplus \mathrm{PS}$, and $h(2^\star)$ fixed order, with the merged setup $h(2^\star, 3^\star, 4)$ as the reference.

Rapidity Gap and Rapidity

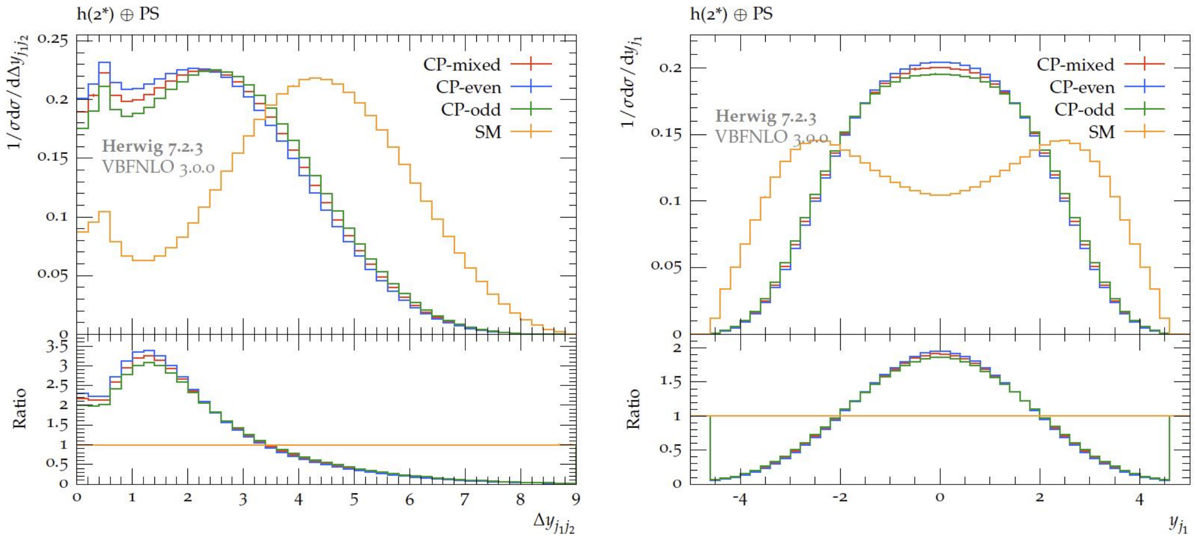


Figure: The distribution of $\Delta y_{j_1 j_2}$ (left) and y_{j_1} (right) for $h(2^\star) \bigoplus \mathrm{PS}$ with INCL cuts.

Rapidity Gap and Rapidity

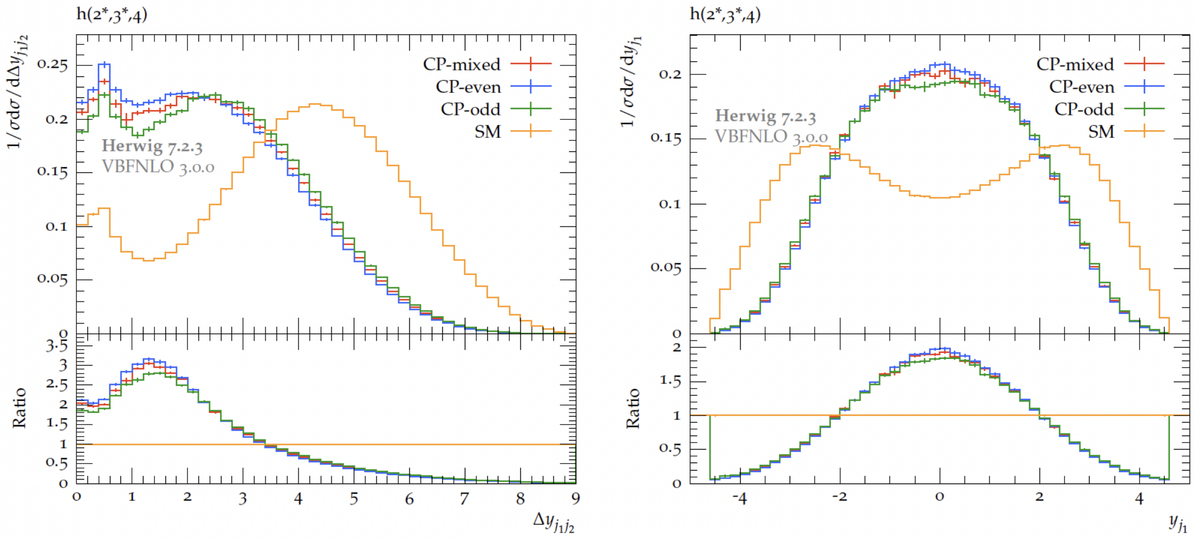


Figure: The distribution of $\Delta y_{j_1 j_2}$ (left) and y_{j_1} (right) for $h(2^\star, 3^\star, 4)$ with INCL cuts.

Transverse Momentum

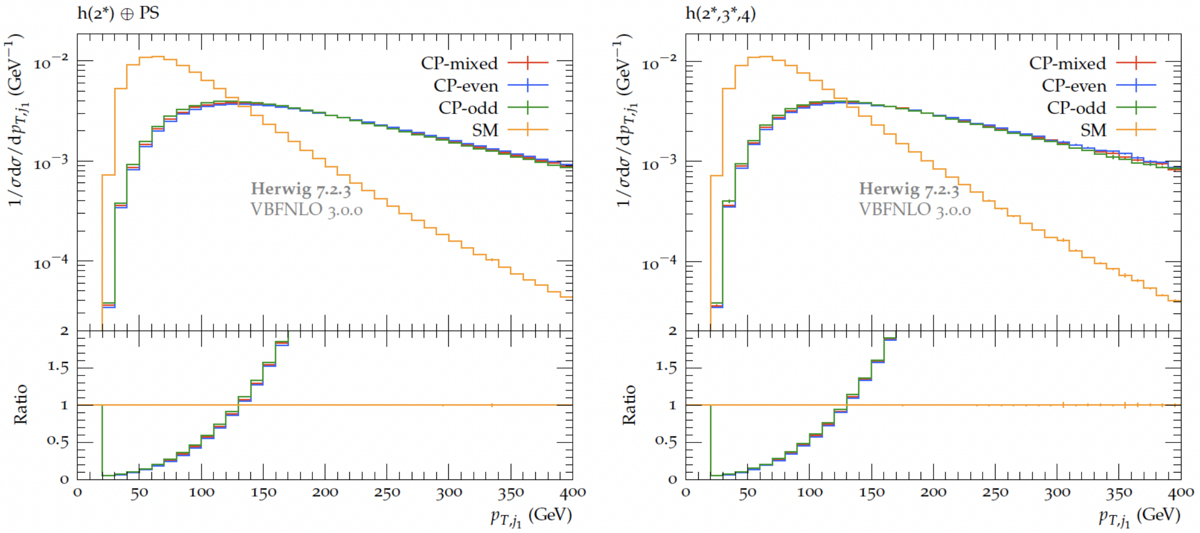


Figure: The distribution of P_{T,j_1} for $h(2^\star) \bigoplus \mathrm{PS}$ (left) and $h(2^\star, 3^\star, 4)$ (right) with INCL cuts.

Higgs Triplet Model (Type II Seesaw Model)

arXiv:1105.1925

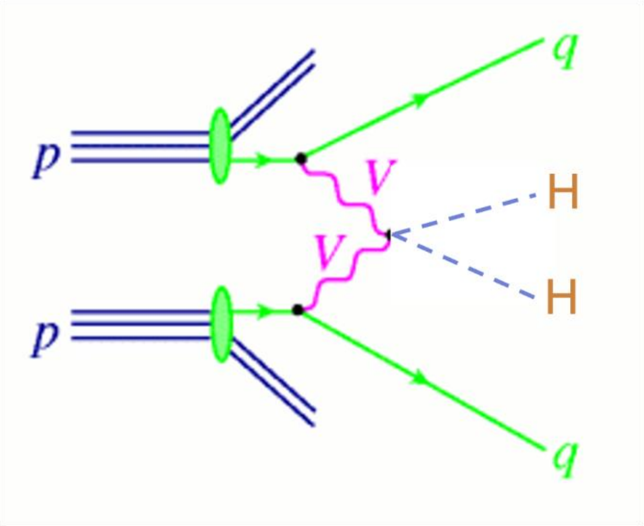
- The motivation for the Higgs Triplet Model stems from the observation that two doublets can be decomposed into a triplet and a singlet representation $(2 \otimes 2 = 3 \oplus 1)$.

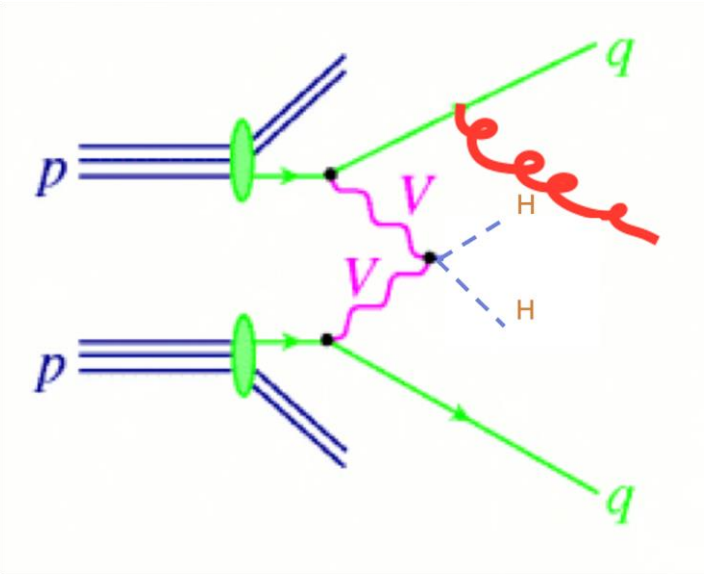
$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

$$V(\Phi,\Delta) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^T i\sigma \Delta^\dagger H) + h.c] + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 \left(Tr(\Delta^\dagger \Delta)\right)^2 + \lambda_3 \left(Tr(\Delta^\dagger \Delta)^2\right) + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

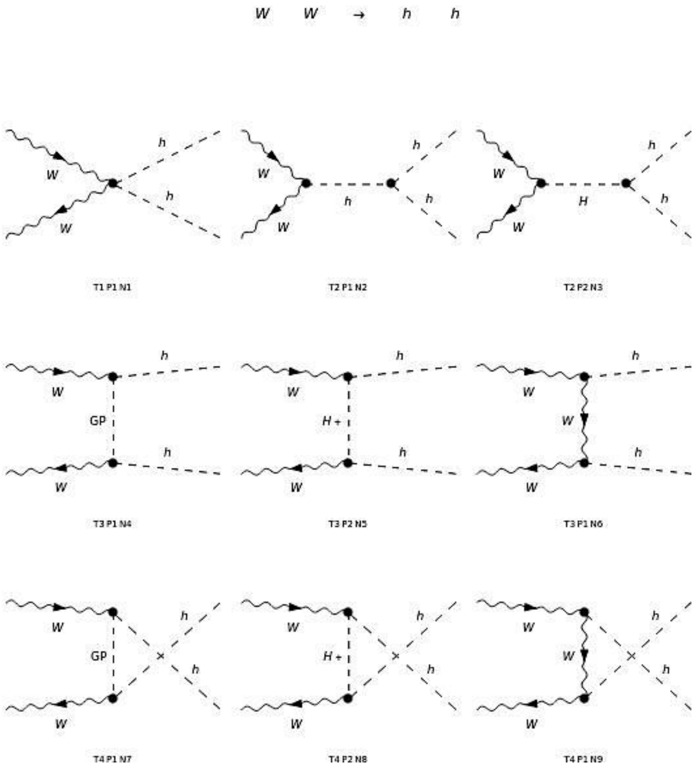
- There are 7 physical Higgs states: $h^0, H^0, A^0, H^\pm, H^{\pm\pm}\}$

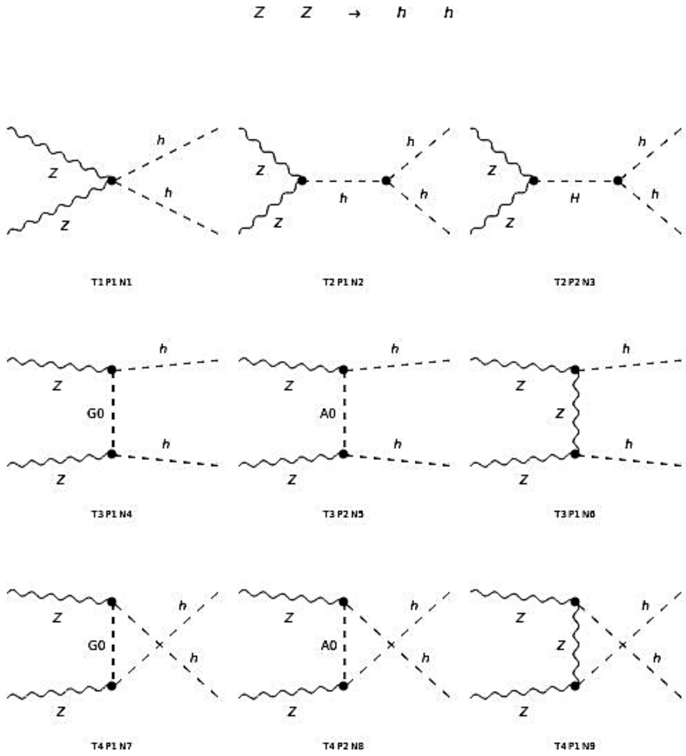
Double Higgs Production via VBF



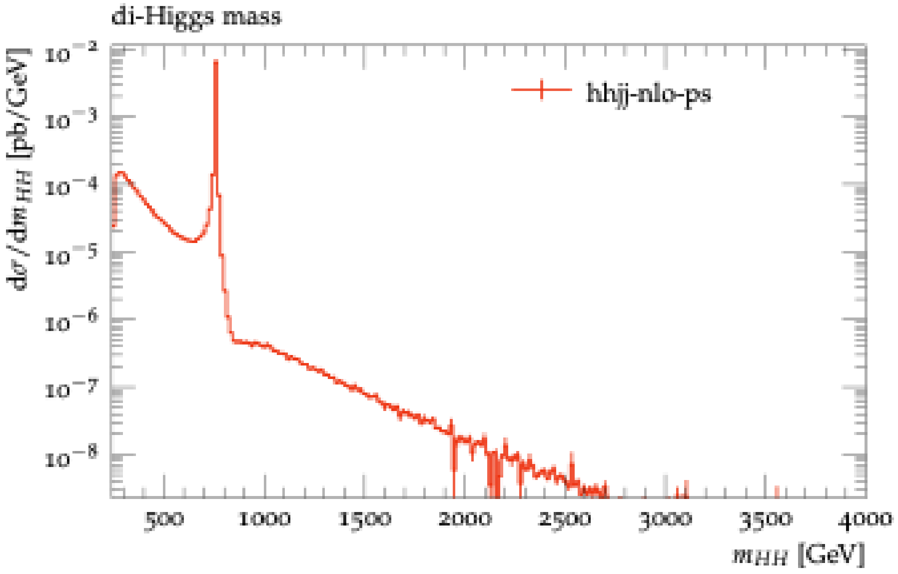


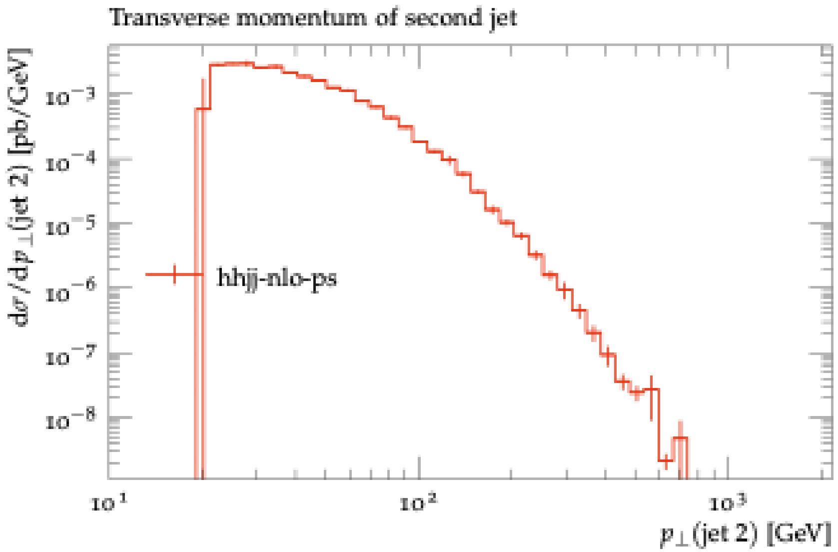
Double Higgs Production via VBF





Double Higgs via VBF Matched to Parton Showers (Type II Seesaw Model)





arXiv:0806.2200

Questions

Auxiliary Slides

Parameter Space

- We can establish a parameter space as follows:

$$P = \{M_{h^0} = 125\ GeV, M_{H^0}, M_{A^0}, M_{H^\pm}, M_{H^{\pm\pm}} v_\Delta, v, \cos(\alpha)\}$$

v	$246.2\ GeV$
v_Δ	$5.78\ GeV$
$\cos\alpha$	0.9
M_{h^0}	$125.000\ GeV$
M_{H^0}	$758.695\ GeV$
M_{A^0}	$758.695\ GeV$
$M_{H^\pm}$	$570.63\ GeV$
$M_{H^{\pm\pm}}$	$275.0\ GeV$

Work on Muon Colliders

Double Higgs boson production via photon fusion at muon colliders within the triplet Higgs model

Bathiya Samarakoon(Wichita State U.)
Terrance M. Figy(Wichita State U.)

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