High-energy resummation for the background to weak boson fusion

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Andersen, Hapola, AM, Smillie; JHEP 1709 (2017) 065; arXiv:1706.01002
Andersen, Hapola, Heil, AM, Smillie; JHEP 1808 (2018) 090; arXiv:1805.04446
Andersen, Cockburn, Heil, AM, Smillie; arXiv:18???.??????
Higgs production in weak-boson fusion

- Second largest channel for Higgs production
- Direct probe of couplings to weak bosons
- Widely separated jets
  \[ \leftrightarrow \text{WBF cuts: } y_{j_1j_2} > 2.8, m_{j_1j_2} > 400 \text{ GeV} \]
- Known at NNLO: \( \sim 5\% \) correction
  
  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015; Cruz-Martinez, Gehrmann, Glover, Huss 2018]
- Gluon-fusion background with major uncertainty
Gluon fusion background

• LO with full mass dependence for $H + 2, 3$ jets:
  $\sim 2\%$ correction to $m \to \infty$  
  [Greiner, Höche, Luisoni, Schönherr, Winter 2016]

• $H + 2, 3$ jets with $m \to \infty$ known at NLO:
  large contribution from higher multiplicities  
  [Cullen et al. 2013]

plot from [Greiner, Höche, Luisoni, Schönherr, Winter, Yundin 2015]
Multi-Regge kinematics for $H+\text{jets}$

High energy limit:

- Outgoing invariant masses $\gg t$-channel momenta
- Large rapidity separations
- Dominated by FKL configurations

[$\text{Fadin, Kuraev, Lipatov 1975–1977}$]

Single $t$-channel gluon exchange possible
Multi-Regge kinematics for $H+\text{jets}$

High energy limit:
- Outgoing invariant masses $\gg t$-channel momenta
- Large rapidity separations
- Non-FKL configurations suppressed

$\text{No single } t\text{-channel gluon exchange possible}$
High Energy Jets (HEJ) resummation
Matrix element [Andersen, Del Duca, Smillie, White 2008–2010]

\[ j^\mu \]

\[ \exp \left( \omega^0(q_i) \Delta y_i / t_i \right) \]

"Reggeised gluon"

\[ V^{\nu_i}(q_i, q_{i+1}) \]

Lipatov vertex

Increasing rapidity
High Energy Jets (HEJ) resummation

Matching to leading order

Fixed-order FKL event
MadGraph, Sherpa, ...
\( \sim |M_{LO}|^2 \)

Resummation events
Keep Higgs + jet rapidities, shift jet \( p_\perp \)
\( \sim |M_{HEJ}|^2 \)

Final resummation event weight
\( \sim \frac{|M_{LO}|^2 |M_{HEJ}|^2}{|M_{HEJ, LO}|^2} \)
High Energy Jets (HEJ) resummation

Improvments

- High-multiplicity (> 4 jets) input events in HEJ approximation
  \[ |M_{\text{HEJ, LO}}|^2 |M_{\text{HEJ}}|^2 = |M_{\text{HEJ}}|^2 \]

- Subleading corrections beyond FKL
  e.g. unordered emissions \( j_{\text{uno}} \)

- Finite quark-mass effects
Results
Invariant mass distribution

$\mu = H_T / 2$

$\mu = \max(m_{j_1j_2}, m_h)$

$\sigma_{\text{HEJ}}$ rescaled to $\sigma_{\text{NLO}}$
Jet multiplicity

$pp \rightarrow h(\rightarrow \gamma\gamma)jj$

LHC@13 TeV

anti-$k_t$, $R = 0.4$, $p_{T,j} > 30$ GeV, $|y_j| < 4.4$

Avg. number of jets excluding jets outside the two hardest

$pp \rightarrow h(\rightarrow \gamma\gamma)jj$

LHC@13 TeV

anti-$k_t$, $R = 0.4$, $p_{T,j} > 30$ GeV, $|y_j| < 4.4$

Avg. number of jets excluding jets outside the two hardest
Higgs transverse momentum distribution

$$pp \rightarrow h(\rightarrow \gamma\gamma)jj$$
LHC@13 TeV
anti − kt, $R = 0.4$, $p_{j,\perp} > 30$ GeV, $|y_j| < 4.4$

inclusive

WBF cuts
Higgs transverse momentum distribution

Quark mass effects
Angular separation

\[ \frac{d\sigma}{d\phi_{j_1j_2}} \text{[fb/rad]} \]

**pp → h(→ \gamma\gamma)jj**

LHC@13 TeV

anti - kt, \( R = 0.4 \), \( p_{j,\perp} > 30 \text{ GeV} \), \( |y_j| < 4.4 \)

| \( y_{j_1} - y_{j_2} \) | > 2.8, \( m_{j_1j_2} > 400 \text{ GeV} \)

**inclusive**

**WBF cuts**

\[ \Delta y = |y_{j_1} - y_{j_2}| > 2.8 \]

\[ m_{j_1j_2} > 400 \text{ GeV} \]
Jet veto efficiency

[Rainwater, Szalapski, Zeppenfeld 1996]
Conclusion

- Need good prediction for $H+\text{ jets}$ in WBF region \textit{now}
- High-energy resummation has significant effects
- Work in progress:
  - NLO matching at event level
  - Combination with parton shower \cite{Andersen, Brooks, L"onnblad 2017}
- Benchmark HEJ processes: $W, Z/\gamma +\text{ jets}$
Backup
Comparison for $W + jets$

[arXiv:1703.04362]

**ATLAS**

Wjj signal region ($M_{jj} > 0.5$ TeV)

Theory/Data

$1/\sigma_W^W \cdot df/\Delta y/\text{bin width}$

$\Delta y_{i_1 i_2}$

Dijet mass $[\text{GeV}]$

$3 	imes 10^2$ $3 	imes 10^3$

$5 	imes 10^2$ $1.0$ $1.5$

$0.5$ $1.0$ $1.5$ $2.0$ $4.0$ $6.0$ $8.0$

Data $\sqrt{s} = 8$ TeV, 20.2 fb$^{-1}$
POWHEG+PYTHIA8 (QCD+EW)
POWHEG+PYTHIA8 (QCD)
SHERPA (QCD+EW)
SHERPA (QCD)
HEJ (QCD) + POW+PY (EW)

Data $\sqrt{s} = 8$ TeV, 20.2 fb$^{-1}$
POWHEG+PYTHIA8 (QCD+EW)
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SHERPA (QCD)
HEJ (QCD) + POW+PY (EW)
Comparison to leading-order matrix element

\[ |M|^2 / \left( \frac{256 s^2 \pi^5}{\tau} \right) \]

\( u d \rightarrow g u H d \)

Madgraph

HEJ (Born level only)
Scaling of matrix element

\[ \Delta = \Delta y_{fb}/2 \]

\[ |M_i|^2/\sigma^2 \]

\[ |M_1|^2/\sigma^2 \]

\[ |M_2|^2/\sigma^2 \]

\[ |M_3|^2/\sigma^2 \]