Higgs Boson with Multiple Jets

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Moriond QCD, La Thuile, 23.03.2014
Objective

- To use High Energy Jets (HEJ) to describe the Higgs production with 2 or more jets
  - Gluon fusion component
Why

- **Higgs + at least 2jets**
  - The azimuthal angle between the jets sensitive to the spin and CP eigenvalue of the Higgs boson
  - The pt of the Higgs dijet system is used to discriminate between WBF against the ggH production

- **Problem: Theoretical uncertainties**
  - Large hierarchy between the invariant mass of the dijets and the pt of the Higgs

- **Interference between WBF and gluon fusion is negligible**
Motivation for High Energy Jets

QCD matrix elements factorise at large $\Delta y_{fb}$ if $y_{i-1} \ll y_i \ll y_{i+1}$ and $p_{\perp i} \sim p_{\perp j}$

$$|\mathcal{M}_{gg \to g...g}\rangle^2 = \frac{4s^2}{N_C - 1} \frac{g^2 C_A}{|p_{\perp i}|^2} \left( \prod_{i=2}^{n-1} \frac{4g^2 C_A}{|p_{\perp i}|^2} \right) \frac{g^2 C_A}{|p_{\perp i}|^2},$$

$$|\mathcal{M}_{qg \to qg...g}\rangle^2 = \frac{4s^2}{N_C - 1} \frac{g^2 C_F}{|p_{\perp i}|^2} \left( \prod_{i=2}^{n-1} \frac{4g^2 C_A}{|p_{\perp i}|^2} \right) \frac{g^2 C_A}{|p_{\perp i}|^2},$$

$$|\mathcal{M}_{qQ \to qg...Q}\rangle^2 = \frac{4s^2}{N_C - 1} \frac{g^2 C_F}{|p_{\perp i}|^2} \left( \prod_{i=2}^{n-1} \frac{4g^2 C_A}{|p_{\perp i}|^2} \right) \frac{g^2 C_F}{|p_{\perp i}|^2}.$$

Partons rapidity ordered. We call these FKL configurations.
Motivation for High Energy Jets

- QCD matrix elements factorise at large $\Delta y_{fb}$ if $y_{i-1} \ll y_i \ll y_{i+1}$ and $p_{\perp i} \sim p_{\perp j}$

- Partons rapidity ordered. We call these FKL configurations.
Motivation for High Energy Jets

- The exact limit is not a good approximation where the most of the cross section comes from

\[
\frac{M^2}{256 \sigma_s^2 \pi^3} = 1.0 \times 10^{-22}
\]

\[qQ \rightarrow qhgQ\]
Motivation for High Energy Jets

- Not even for the processes which factorise de facto
  - $qQ \rightarrow qQ$ and $qg \rightarrow qg$

\[
||S||^2 = \sum_{\text{helicity}} |\langle 1, h_1 | \mu | a, h_a \rangle \langle 2, h_2 | \mu | b, h_b \rangle|^2
\]

\[
|\mathcal{M}_{(q/g)Q \rightarrow (q/g)Q}|^2 = \frac{1}{4(N_C^2 - 1)} ||S||^2 \cdot \left( g^2 K \frac{1}{t_1} \right) \cdot \left( g^2 K \frac{1}{t_2} \right)
\]

where

\[
K = \begin{cases} 
C_F, & \text{for quark} \\
\frac{1}{2} \frac{1+z^2}{z} \left( C_A - \frac{1}{C_A} \right) + \frac{1}{C_A}, & \text{for gluon} \quad (z = p_2^- / p_b^-)
\end{cases}
\]
Requirements for HEJ design

1. t-channel factorisation
   ▶ Makes effective phase space integration possible for high multiplicities

2. exact description of helicity configurations which factorise by default
   ▶ Exact limit is not good approximation within the detector acceptances

3. gauge invariant (not only at the limit)
   ▶ Obviously

4. access to 4-momenta of all the final state partons
   ▶ Exclusive variables
Tree level matrix element

- Contraction of two currents multiplied with effective vertices

\[
\begin{align*}
|\mathcal{M}_{f_1 f_2 \rightarrow f_1 g \ldots g f_n}|^2 &= \frac{1}{4(N_C^2 - 1)} \| S \|^2 \\
&= \left( g^2 K \frac{1}{t_1} \right) \cdot \left( g^2 K \frac{1}{t_n} \right) \\
&\cdot \left( \prod_{i=1}^{n-1} \left( -\frac{g^2 C_A}{t_i t_{i+1}} V^\mu(q_i, q_{i+1}) V_\mu(q_i, q_{i+1}) \right) \right)
\end{align*}
\]
Take into account the leading contribution from emissions off both the t-channel exchange and the two incoming and the most forward/backward patrons.

\[
V^\rho(q_i, q_{i+1}) = -(q_i + q_{i+1})^\rho
\]

\[
+ \frac{p_a^\rho}{2} \left( \frac{q_i^2}{p_i+1p_a} + \frac{p_i+1p_b}{p_ap_b} + \frac{p_i+1p_n}{p_ap_n} \right) + p_a \leftrightarrow p_1
\]

\[
- \frac{p_b^\rho}{2} \left( \frac{q_{i+1}^2}{p_i+1p_b} + \frac{p_i+1p_a}{p_ap_b} + \frac{p_i+1p_1}{p_bp_1} \right) - p_b \leftrightarrow p_n
\]
Does it work?

\[ |M|^2 \frac{1e^{-22}}{256^{\frac{3}{2}} \pi^3} \]

\[ qQ \rightarrow qhgQ \]

- Red: MadGraph
- Cyan: HE limit
- Blue: HEJ
Virtual corrections

To all orders in leading log accuracy using the Lipatov ansatz
  Resums the logarithms which will break the perturbative expansion in $\alpha_s$

$$\frac{1}{t_i} \rightarrow \frac{1}{t_i} \exp \left[ \hat{\alpha}(q_i)(y_{i-1} - y_i) \right]$$

$$\hat{\alpha}(q_i) = -g^2 C_A \frac{\Gamma(1 - \epsilon) 2}{(4\pi)^{2+\epsilon}} \frac{2}{\epsilon} \left( \frac{q^2}{\mu^2} \right)^\epsilon$$
Comparison $W+\text{Jets}$ data

- Similar to $H+\text{Jets}$

- Things to keep in mind
  1. Low multiplicities are matched to LO accuracy
  2. no free parameters to vary (except scale choices)
  3. resummation in $\log(s_{ij}/t_i)$
  4. large $\Delta y \rightarrow$ large $x$
  5. large $\Delta y_{fb} \rightarrow$ more hard radiation $\rightarrow$ larger $x$
  6. Does not include collinear singularities
    - This is a job for shower

J. R. Andersen, T.H., J. M. Smillie, JHEP 1209 (2012) 047
W+Jets at D0

Phys.Rev. D88 (2013) 092001
Study of jets produced in association with a W boson in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector
Unordered emissions

► All the gluon emission between current partons
► Relaxing rapidity ordering between the two outermost partons allows to resum more of the cross section
  ► \( y_1 \gg y_g \gg y_2 \) \( \Rightarrow \) \( y_g \sim y_1 \gg y_2 \)
► This is accounted with the replacement

\[
j^\mu \rightarrow j^{\text{uno}}_\mu \left( p_1, p_g, p_a \right) = \\
i \varepsilon_{g\nu} \left( T_{1i}^\beta T_{ia}^\gamma \left( U_{1}^{\mu\nu} - L^{\mu\nu} \right) + T_{1i}^\gamma T_{ia}^\beta \left( U_{2}^{\mu\nu} + L^{\mu\nu} \right) \right)
\]

\[
U_1^{\mu\nu} = \frac{1}{s_{1g}} \left( j_1^\nu j_1^\mu + 2 p_1^\nu j_1^\mu \right), \quad U_2^{\mu\nu} = \frac{1}{t_{ag}} \left( 2 j_1^\mu p_a^\nu - j_g^\mu j_g^\nu \right)
\]

\[
L^{\mu\nu} = \frac{1}{t_{a1}} \left( -2 p_g^\mu j_1^\nu + 2 p_g \cdot j_1 a \epsilon^{\mu\nu} + \left( q_1 + q_2 \right)^\nu j_1^\mu + \frac{t_{b2}}{2} j_1^\mu \left( \frac{p_2^\nu}{p_g \cdot p_2} + \frac{p_b^\nu}{p_g \cdot p_b} \right) \right)
\]
Matrix element with the Higgs

- Only the contraction of currents changes

\[ ||S||^2 = \sum_{\text{helicity}} \left| \langle 1, h_1| \mu |a, h_a \rangle V^{H}_{\mu \nu} \langle 2, h_2| \nu |b, h_b \rangle \right|^2 \]

\[ V^{H}_{\mu \nu} = \frac{\alpha_S}{3\pi V} (q_{i-1} \cdot q_i \ g_{\mu \nu} - q_{i-1} \mu q_{i\nu}) \]

J. R. Andersen, T.H., J. M. Smillie, in preparation
Pt of H-dijet system

Higgs + DiJets

anti-$k_T$, $R = 0.4$

$s = 8$ TeV, $m_H = 125$ GeV

$\Delta y_{jj} > 2.8$

$|y_j| < 4.4$, $|y_\gamma| < 2.37$

$|p_{\gamma j}| > 0.35 m_{\gamma\gamma}$, $p_{T\gamma_2} > 0.25 m_{\gamma\gamma}$

ATLAS-CONF-072 cuts + WBF cut
Conclusions

- HEJ describes hard wide-angle emissions to all orders
- These effects have been seen to be important already in Tevatron data
- The jet min pt cut should be large to clearly see these effects
  - MPI and UE suppressed
  - Testing really the perturbation theory
- Describes well $W+\text{jets}$ data
  - Thus expected to perform well with the Higgs + jets
The azimuthal angle between 2 jets is sensitive to the CP structure of the Higgs coupling to top quarks.

The effective Higgs gluon coupling

\[ V^H \sim \begin{cases} q_1 q_2 \ g^{\mu\nu} - q_1^\nu q_2^\mu & \text{CP-even} \\ \epsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma & \text{CP-odd} \end{cases} \]

Different dependence on the angle between the jets

\[ |\mathcal{M}|^2 \sim \begin{cases} \cos^2 \phi & \text{CP-even} \\ \sin^2 \phi & \text{CP-odd} \end{cases} \]
How to generalise to multi jets

- $\phi_2$: Azimuthal angle between the $k_1$ and $k_2$
  - $k_1 = \sum p_i$, $p_i$ rapidity less than the rapidity of the Higgs
  - $k_2 = \sum p_i$, $p_i$ rapidity larger than the rapidity of the Higgs