Jets, Jets, Higgs & Jets

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Mostly HEJ = with Andersen, Hapola, Medley

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Outline

- Introduction
- Analysis of an Amplitude
- High Energy Jets
- Recent Jet Results
- Higgs Plus Jets
Why Study Jets?

- Complex Standard Model Process
  Therefore complex test of tools

- Test models of jet vetoes etc. here before Higgs

- IF new physics is hiding, need precision to find it

- Many tools available... with different strengths
Higher Orders

- Already seen \((n+1)\)-jet rates are not small
  - e.g. ATLAS \(Z+\)jets
  \[
  \frac{(n+1)\text{-jet rate}}{n\text{-jet rate}} \approx 0.2, \ n=1,\ldots,6 \ (!)
  \]
  - Rises to 0.3 after VBF cuts!

- NLO is only one more emission
  Consistently need to combine orders
to describe data

\[\text{arXiv:1304.7098} \]

\[\text{ATLAS W+jets} \quad \text{arXiv:1201.1276} \]
Merging Orders

- Number of approaches available to merge NLO
  Lönnblad & Prestel, Plätzer, ...

- Alternatively: calculate all-orders in the first place!

- High Energy Jets provides systematic description of hard, wide-angle emissions at all orders

- Price: have to approximate the matrix element
Amplitude Analyses
Start: qQ → qQ

\[ \frac{8g_s^4 |j^\mu(p_a, p_1) \cdot j_\mu(p_b, p_2)|^2}{9 \hat{t}^2} = \frac{4g_s^4 \hat{s}^2 + \hat{u}^2}{9 \hat{t}^2} \]

- Note “factorised” form: \( p_a, p_1 \) split from \( p_b, p_2 \)
- Current-current will be recurrent feature
**Exact result:**

\[
\frac{g_s^4 C_{CAM}}{6} \left| j^\mu(p_a, p_1) \cdot j_\mu(p_b, p_2) \right|^2 \hat{t}^2
\]

with

\[
C_{CAM} = \frac{1}{2} \left( C_A - \frac{1}{C_A} \right) \left( \frac{p_b^-}{p_2^-} + \frac{p_2^-}{p_b^-} \right) + \frac{1}{C_A}
\]

- Only t-pole remains explicitly
- In HE limit, matches \( qQ \rightarrow qQ \)
High Energy Limit

- The High Energy (Multi-Regge) limit is:
  
  \[ s_{ij} \rightarrow \infty, \quad |p_{\perp i}| \sim |p_{\perp j}|, \quad i, j = 1, ..., n \]

Universal behaviour before exact limit

Limiting value not relevant for phenomenology

Increasing rapidity spans \((y_f - y_b)\)
Dominant Momentum Configurations in HE limit correspond to those which would allow maximum t-channel exchanges:

- These are FKL configurations
- Other orderings are logarithmically suppressed.
Now: $qQ \rightarrow qgQ$

$$\mathcal{A} = (ig_s)^3 T_{1i}^g T_{ia}^d T_{3b}^d \varepsilon_{1\nu} \frac{\langle 1|\nu|g\rangle \langle g|\mu|a \rangle + 2p_1^\nu \langle 1|\mu|a \rangle}{s_{1g}t_{b3}} \langle 3|\mu|b \rangle$$

$$+ (ig_s)^3 T_{1i}^d T_{ia}^g T_{3b}^d \varepsilon_{1\nu} \frac{2p_a^\nu \langle 1|\mu|a \rangle - \langle 1|\mu|g\rangle \langle g|\nu|a \rangle}{t_{ag}t_{b3}} \langle 3|\mu|b \rangle$$

$$+ (ig_s)^3 T_{3i}^g T_{ib}^d T_{1a}^d \varepsilon_{1\nu} \frac{\langle 3|\nu|g\rangle \langle g|\mu|b \rangle + 2p_3^\nu \langle 3|\mu|b \rangle}{s_{3g}t_{a1}} \langle 1|\mu|a \rangle$$

$$+ (ig_s)^3 T_{3i}^d T_{ib}^g T_{1a}^d \varepsilon_{1\nu} \frac{2p_b^\nu \langle 3|\mu|b \rangle - \langle 2|\mu|g\rangle \langle g|\nu|b \rangle}{t_{bg}t_{a1}} \langle 1|\mu|a \rangle$$

$$- g_s^3 f_{\alpha\beta\gamma} T_{1a}^\alpha T_{2b}^\beta \varepsilon_{1\nu} \frac{\langle 1|\rho|a\rangle \langle 3|\mu|b \rangle}{t_{a1}t_{b3}} \left(2p_g^\mu g_{\nu\rho} - 2p_g^\rho g^{\mu\nu} - (q_1 + q_2)^\nu g^{\mu\rho}\right).$$
Now: \( qQ \to qgQ \)

\[
\mathcal{A} = (i g_s)^3 \left( T_{1i}^g T_{ia}^d T_{3b}^d \right) \varepsilon_{1\nu} \frac{\langle 1|\nu|g\rangle \langle g|\mu|a\rangle + 2p_1^\nu \langle 1|\mu|a\rangle}{s_1 t_{b3}} \langle 3|\mu|b\rangle
\]

\[
+ (i g_s)^3 \left( T_{1i}^d T_{ia}^g T_{3b}^d \right) \varepsilon_{1\nu} \frac{2p_1^\nu \langle 1|\mu|a\rangle - \langle 1|\mu|g\rangle \langle g|\nu|a\rangle}{t_{a1} t_{b3}} \langle 3|\mu|b\rangle
\]

\[
+ (i g_s)^3 \left( T_{3i}^g T_{ib}^d T_{1a}^d \right) \varepsilon_{1\nu} \frac{\langle 3|\nu|g\rangle \langle g|\mu|b\rangle + 2p_3^\nu \langle 3|\mu|b\rangle}{s_3 t_{a1}} \langle 1|\mu|a\rangle
\]

\[
+ (i g_s)^3 \left( T_{3i}^d T_{ib}^g T_{1a}^d \right) \varepsilon_{1\nu} \frac{2p_3^\nu \langle 3|\mu|b\rangle - \langle 3|\mu|g\rangle \langle g|\nu|b\rangle}{t_{a1} t_{b3}} \langle 1|\mu|a\rangle
\]

\[-g_s^3 f^{\alpha\beta\gamma} T_{1a}^\alpha T_{3b}^\beta \varepsilon_{1\nu} \frac{\langle 1|\rho|a\rangle \langle 3|\mu|b\rangle}{t_{a1} t_{b3}} \left( 2p_1^\mu g^{\nu\rho} - 2p_3^\mu g^{\rho\nu} - (q_1 + q_2)^\nu g^{\mu\rho} \right).\]
Now: $qQ \to qgQ$

Combine these to get effective vertex:

$$A_{qQ \to qgQ} = g_s^3 \, C_g \, \varepsilon^* \, \frac{j^\mu(p_a, p_1) \cdot j^\mu(p_b, p_3)}{q_1^2 q_2^2} \, V^\rho(q_1, q_2)$$

$$V^\rho(q_1, q_2) = - (q_1 + q_2)^\rho$$

$$+ \frac{p_a^\rho}{2} \left( \frac{q_1^2}{p_2 \cdot p_a} + \frac{p_2 \cdot p_b}{p_a \cdot p_b} + \frac{p_2 \cdot p_3}{p_a \cdot p_3} \right) + p_a \leftrightarrow p_1$$

$$- \frac{p_b^\rho}{2} \left( \frac{q_2^2}{p_2 \cdot p_b} + \frac{p_2 \cdot p_a}{p_b \cdot p_a} + \frac{p_2 \cdot p_1}{p_b \cdot p_1} \right) - p_b \leftrightarrow p_3.$$
$qQ \rightarrow qg \ldots gQ$

Continue to higher orders

$y_1 > y_2 > \ldots > y_n$

Each momentum configuration has one diagram.

$n$ becomes integration variable

N.B. This is not a Feynman diagram!
Does It Work?

$qQ \rightarrow qggQ$

$qg \rightarrow qggg$
Even when it’s not supposed to!

Gluon now pulled forward of both quarks:

\[ \text{us} \rightarrow \text{usg} \]
Last part is to regulate divergences when $p_i \to 0$

$\text{HE limit of virtual corrections is given by}$

the Lipatov Ansatz

$$\bar{\alpha}(q_i) = \alpha_s \ C_A \ t_i \ \int \ \frac{d^{2+2\epsilon} k_\perp}{(2\pi)^{2+2\epsilon}} \ \frac{1}{k_\perp^2 (q_i - k)^2_\perp}$$

$$\rightarrow -g_s^2 C_A \ \frac{\Gamma(1 - \epsilon)}{(4\pi)^{2+\epsilon}} \ \frac{2}{\epsilon} \ (q^2 / \mu^2)^\epsilon$$

Proved to next-to-leading log

Fadin, Fiore, Kozlov & Reznichenko: hep-ph/0602006
Assembly

Build fully-flexible Monte Carlo from these

Match to exact LO if cluster into 2, 3 or 4 jets

Publicly available at

http://cern.ch/hej

Jets, W+jets, Higgs+jets, HEJ+ARIADNE
In a Nutshell:

- High Energy Jets describes QCD emissions at large $s_{ij}$
  - Captures hard jet production

$$s_{ij} = 2p_{T_i}p_{T_j} (\cosh(y_i - y_j) - \cos(\phi_i - \phi_j))$$

- Opposite limit to a parton shower, which sums large contributions at small $s_{ij}$
  - Good at jet substructure, underestimates rate/hardness

- Can combine both (but not straight-forward).
Early Jet Results
ATLAS: gap fraction

Gap Fraction = \frac{\text{no jets in gap}}{2j \text{ inclusive}}

\bar{p}_T = \text{average } p_T \text{ of tagging jets}

Here, tagging is most forward & most backward

Good agreement with POWHEG + PYTHIA & HEJ

arXiv:1107.1641
ATLAS: gap fraction

Now, tagging jets are leading \( p_T \)

Hierarchy in \( p_T \) (up to factor 10!)
\( p_T \) evolution not in HEJ

Evolution in rapidity
HEJ description good, POWHEG undershoots

arXiv:1107.1641
ATLAS: jet veto analysis

Lastly, average number of additional jets.

More than one extra jet on average for $\Delta y > 3$

Clearly beyond NLO!
DiJet Comparison

POWHEG+PYTHIA and HEJ gave very similar predictions
Can they be distinguished?

\[ p_{T,j} > 35 \text{ GeV}, \quad p_{T,j1} > 45 \text{ GeV}, \quad |y_j| < 4.7 \]

Choose cuts which do not induce \( p_T \) hierarchy

Alioli, Andersen, Oleari, Re & JMS  arXiv:1202.1475
DiJet Comparison

Other variables show little difference, e.g. $\cos(\phi_{fb})$

$\phi_{fb}$ = azimuthal angle between forward and backward jet

Azimuthal decorrelation gives measure of extra radiation

Alioli, Andersen, Oleari, Re & JMS  arXiv:1202.1475
Recent W+jets Results
Extension to Ws

qg-channel dominant for $W+nj$ at LHC

Treated in HE limit before, with constraint on decays

In HEJ:

No constraints on decay products of $W$ (or $Z/\gamma^*$)
ATLAS W+dijets

HEJ again gives good description:

Note large impact of higher orders!

ATLAS data arXiv:1201.1276
Andersen, Hapola & JMS arXiv:1206.6763
D0 W+Jets

Really thorough analysis: 40 observables!

This is the difference between:
Leading Jets
Most forward/backward Jets
D0 W+Jets

Probability of third jet emission versus $\Delta y$ of:

- Most forward/backward Jets
- Hardest Jets
- Hardest Jets, counting only jets between $y(j,j) > 20$ GeV, $|\eta_T^{jet}| < 3.2$

$R_{\text{cone}} = 0.5$, $p_T^{jet} > 20$ GeV, $|\eta^{jet}| < 3.2$
$p_T > 15$ GeV, $|\eta| < 1.1$, $M_T^W > 40$ GeV, $p_T > 20$ GeV

D0, 3.7 fb$^{-1}$, $W(\rightarrow e\nu) + \geq 2$jets + X

(most rapidity-separated jets)

(leading $p_T$ jets)

(leading $p_T$ jets, rapidity gap emission)

NLO Blackhat+Sherpa

HEJ

Sherpa

arXiv:1302.6508
Higgs Plus Jets
Higgs Plus Jets

• Vector Boson Fusion is 2nd largest production channel

• Key opportunity to study VVH vertex

• Use distinctive topology to select events

Here:

\[ p_{T,j} > 20 \text{ GeV}, \quad |\eta_j| \leq 5, \quad R_{jj} > 0.6 \]
Higgs Plus Jets

Typical “VBF” cuts:

\[ p_{T,j} > 25 \text{ GeV}, \quad |\eta_j| \leq 5, \quad |\Delta \eta_{jj}| > 2.8, \quad m_{jj} > 400 \text{ GeV} \]

Puts us right into the difficult region!

Want to use azimuthal angle between jets to study CP structure of the vertex:

HE limit tells you how to extend to n jets

Andersen, Arnold & Zeppenfeld  arXiv:1001.3822

Figy, Hankele, Klämke & Zeppenfeld  hep-ph/0609075
In heavy top-mass limit:

\[ V_{Hgg}(p^\mu, q^\nu) = \frac{i\alpha_s}{3\pi v} (p \cdot q g^{\mu\nu} - p^\nu q^\mu) \]

- Different CP structure so can contaminate study.
- Interesting to study in own right
- Gluons expected to radiate more
  \[ \therefore \text{use a "jet veto" between tagged jets to separate} \]
Multi-Jet Descriptions

To extract couplings cleanly, need to separate Weak Boson Fusion and Gluon-Gluon Fusion (ideally both!)

Here, will focus on Gluon-Gluon Fusion.

Jet radiation patterns universal across processes.

Use existing data to test descriptions.
Higgs in HEJ

\[ \frac{j_\mu j_\mu}{\hat{t}} \rightarrow \frac{j_\mu j_\nu}{q_1^2 q_2^2} (g_{\mu\nu} q_1 \cdot q_2 - q_{1\nu} q_{2\mu}) \]

Insert this anywhere in the gluon chain
Higgs XS WG Studies

Gavin Salam’s Dec Talk:

Distributions of \( ggF+2j \) BEFORE VBF topological cuts

MINLO, Sherpa & HEJ all agree at central jet rapidities; aMC@NLO 25-30% lower
factor 2 difference between aMC@NLO and Sherpa/MINLO, smaller differences between MINLO, Sherpa

recall Sherpa is H+2@LO, aMC@NLO & MINLO are H+2@NLO
Higgs XS WG YR3 2013

- Difference in shape expected

- Impact on cross section:
  About 10% for MCFM, POWHEG & SHERPA; 6% for HEJ

- More investigation required
Summary

- Hard QCD radiation feature of LHC collisions
- Data has clearly shown effects beyond pure NLO
- Flexible MC description from HEJ
  Built from HE properties of amplitudes
- Important applications to Higgs+Jets studies
  Ongoing work to probe differences

http://cern.ch/hej