Multi-Jet Production From HEJ

Jenni Smillie
Edinburgh University

Soft gluons and New Physics
Manchester

Jets at the LHC with High Energy Jets (HEJ)

Outline

- Why High Energy Resummation? $\leftarrow$ Jeppe's Talk
- Outline HEJ framework
  - Construction
  - Corrections
- W + jets
- Applications to new physics.

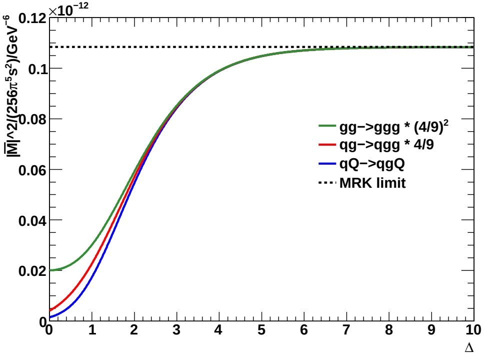
in collaboration with Jeppe Andersen

High Energy Behaviour

Universal behaviour in all channels

before exact limit reached.

We extract the parts of the amplitude which dominate at large s_{ij}



Increasing rapidity spans $(y_f - y_b)$

High Energy Limit

The Multi-Regge Kinematic (MRK) (or high energy) limit is:

$$\forall i, j \qquad s_{ij} \to \infty, \qquad |p_{\perp_i}| \sim |p_{\perp_j}|$$

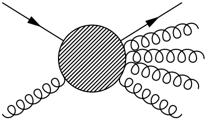
equivalently:

$$\forall i \in \{2, \ldots, n-1\} \; y_{i-1} \gg y_i \gg y_{i+1}, \qquad |p_{\perp_i}| \sim |p_{\perp_j}|$$

Throughout:

- Use longitudinal components: $p_i^{\pm} = E_i \pm p_{z_i}$.
- Number labels correspond to rapidity order.
  $p_{a,b}$ are forward/backward parton. E.g. $p_1^+ \to p_a^+$ in MRK.

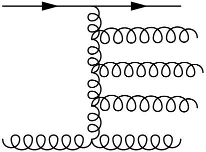
High Energy Limit



$\hat{s} \longrightarrow \infty$

$\longrightarrow$

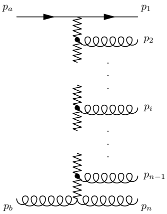
$|\hat{t}|$ fixed



- t-channel exchange of highest spin particle dominates.

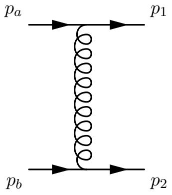
FKL configurations:

p_a & p_1 same type, p_b & p_n same type, $p_2, \ldots, p_{n-1}$ gluons.



Example 1: $qQ \to qQ$

The simplest case is $qQ \to qQ$.



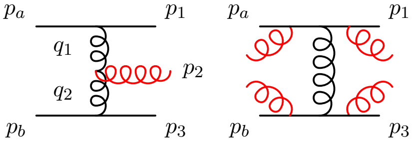
$$\frac{8g_s^4}{9}\frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{\hat{t}^2}$$

$$= \frac{4g_s^4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

- "Factorised" form – p_a and p_1 can be split from p_b and p_2.
- In High Energy limit, $\to\propto \hat{s}^2/\hat{t}^2$ as in plot.
- We will model all processes as current-current scattering.

Example 2: $qQ \to qgQ$

Can emit a gluon from 5 different points.



MRK limit of first diagram (e.g. $s_{2b} \gg s_{3b}$):

$$\mathcal{A}_g^{\mathrm{MRK}} = \frac{-2g_s^3 \hat{s}}{t_1 t_2} \, \mathcal{C}_g \varepsilon_\rho^* \left(-2p_a^\rho \frac{s_{2b}}{\hat{s}} + 2p_b^\rho \frac{s_{2a}}{\hat{s}} + (q_1 + q_2)^\rho \right)$$

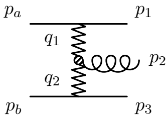
Eikonal approx for other diagrams gives, e.g.:

$$\mathcal{A}_{q1} = \mathcal{A}_{qQ \to qQ} \times (ig_s) \; \varepsilon_\rho^* \; \times \mathcal{C}_1 \frac{p_1^\rho}{p_1 \cdot p_2}$$

Notice $\mathcal{C}_1 - \mathcal{C}_a = \mathcal{C}_g$ from commutator or Jacobi identity.

Example 2: $qQ \to qgQ$

Add these together to get effective vertex:



$$\mathcal{A}_{qQ\to qgQ} = g_s^3\ \mathcal{C}_g\ \varepsilon_\rho^*\ \frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{q_1^2 q_2^2}\ V^\rho(q_1,q_2)$$

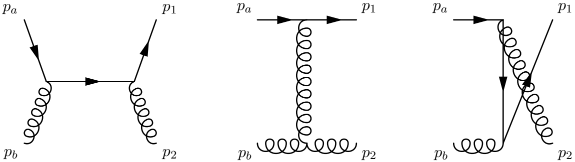
$$\begin{aligned} V^\rho(q_1,q_2) = & -(q_1+q_2)^\rho \\ & +\frac{p_a^\rho}{2}\left(\frac{q_1^2}{p_2\cdot p_a}+\frac{p_2\cdot p_b}{p_a\cdot p_b}+\frac{p_2\cdot p_3}{p_a\cdot p_3}\right)+p_a\leftrightarrow p_1 \\ & -\frac{p_b^\rho}{2}\left(\frac{q_2^2}{p_2\cdot p_b}+\frac{p_2\cdot p_a}{p_b\cdot p_a}+\frac{p_2\cdot p_1}{p_b\cdot p_1}\right)-p_b\leftrightarrow p_3. \end{aligned}$$

Gauge invariant and in HE limit, agrees with the Lipatov vertex.

Andersen&JS [arXiv:0908.2786]

Example 3: $qg \to qg$

3 channels for $qg \to qg$:



For helicity conserving configs, EXACT result is (still):

$$\frac{g_s^4 C_{CAM}}{6} \; \frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{\hat{t}^2}.$$

The poles in s and u cancel.

Colour acceleration modifier (CAM) replaces C_F by

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

Andersen&JS arXiv:0910.5113

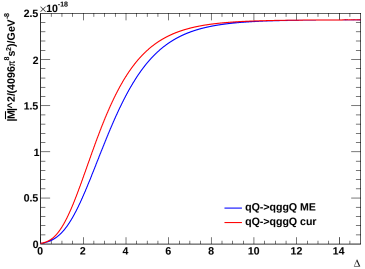
Example 3: $qg \to qg$

- The helicity conserving amplitudes are dominant in the High Energy limit.
- Two of the suppressed cases still have no pole in s or u. They are sums of terms like before.
- Only two have remaining poles which are suppressed in HE limit which we neglect.

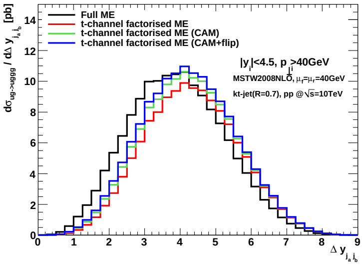
We therefore treat an incoming gluon as an incoming quark multiplied by C_{CAM}.

Andersen&JS arXiv:0910.5113

Does It Work?



$qQ \to qggQ$

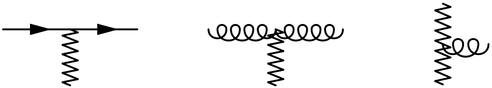


$qg \to qggg$

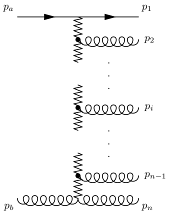
Full matrix elements taken from `Standalone MadGraph`.

Resummation

We have:



They are assembled like this:



- The number of emissions is a variable in our integration.
- These give us the leading log terms ($\alpha_s^i \log^i s/t$) for *all i*.

Regulation

- Must still regulate the divergences from soft emissions.

HE limit of virtual corrections given by the Lipatov ansatz:

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

$$\hat{\alpha}(q_i) = \alpha_s \; C_A \; t_i \int \frac{d^{2+2\epsilon} k_\perp}{(2\pi)^{2+2\epsilon}} \frac{1}{k_\perp^2 (q_i - k)_\perp^2} \rightarrow -g_s^2 C_A \; \frac{\Gamma(1-\varepsilon)}{(4\pi)^{2+\varepsilon}} \frac{2}{\varepsilon} \left(\mathbf{q}^2/\mu^2\right)^\varepsilon$$

Proved to NLL: Fadin, Fiore, Kozlov, Reznichenko: hep-ph/0602006

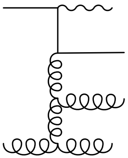
Add to real corrections to leave finite sum.

Assembly

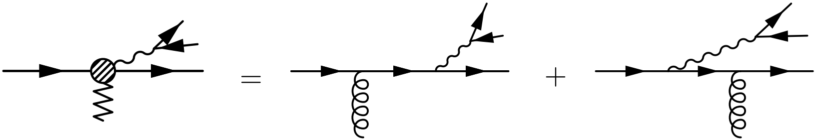
- These pieces are implemented in a fully flexible Monte Carlo.
  $\longrightarrow$ Allows arbitrary cuts and analyses.
- Matching included for jets and W+jets, up to 4 jets.
  Matrix elements taken from Standalone `MadGraph`.
- Linking to a parton shower almost complete.
  Andersen & Lönnblad
- Les Houches Accord output for W+jets.
  with Warshawski

Jet code available at www.cern.ch/HEJ and in GENSER library.

Remaining Parts – Weak Bosons

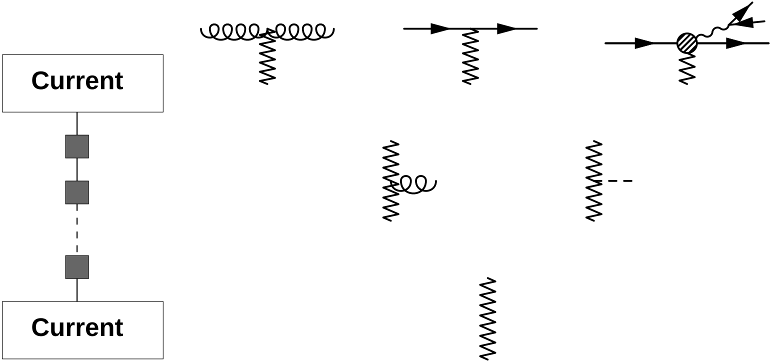


- W+jets at the LHC:
- Treated in full HE limit before, with constraint on decay products. Andersen, Del Duca, Maltoni, Stirling: hep-ph/0105146
- In HEJ:

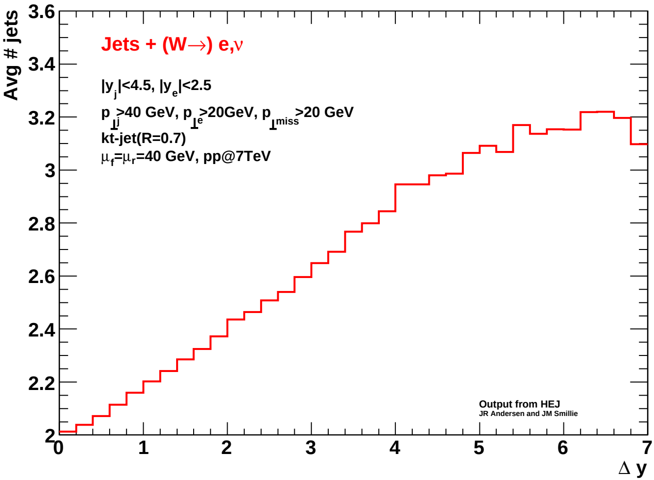


No constraints on the decay products of the W/Z.

Components

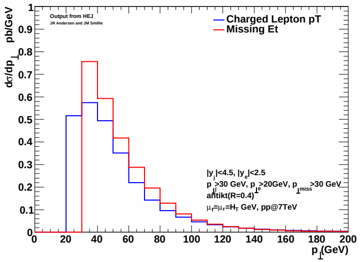


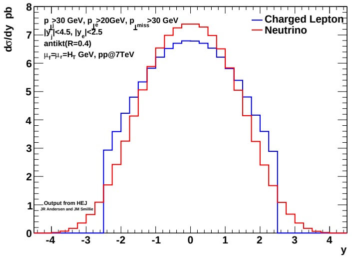
W+jets


Avg # jets
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
Jets + (W→) e,ν
|y_j|<4.5, |y_e|<2.5
p_⊥j>40 GeV, p_⊥e>20GeV, p_⊥miss>20 GeV
kt-jet(R=0.7)
μ_f=μ_r=40 GeV, pp@7TeV
Output from HEJ
JR Andersen and JM Smillie
0
1
2
3
4
5
6
7
Δ y

W+jets

Can also analyse decay products of the W:





W+jets and New Physics – W^+/W^- Ratio

- W+jets is an important background to many new physics signals
  - Single lepton plus n jets very common (SUSY, UED, ...)

- Will look at two aspects in this talk: W^+/W^- ratio and H_T.

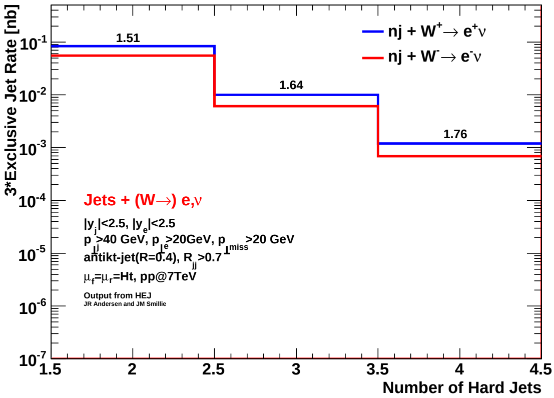
At LHC, $\sigma(W^+) \neq \sigma(W^-)$ because of proton-proton initial state.

Fixed order standard model: 2j = 1.35, 3j = 1.45, 4j = 1.55

W' models: $R_\pm = 2$–3.

Kom & Stirling, arXiv:1004.3404,1010.2988

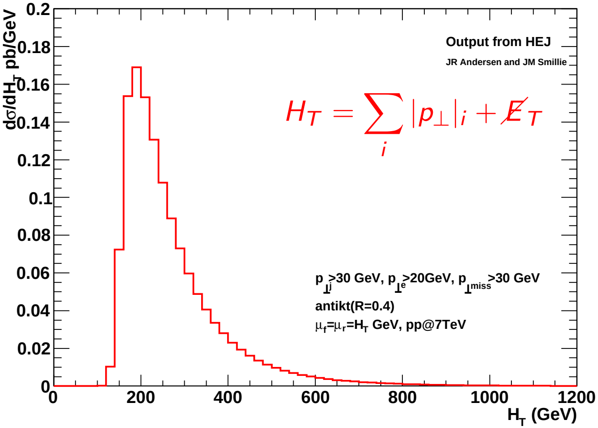
W+/W- Ratio



Ratios slightly higher than seen (and used) at fixed order.

H_T Distribution

The H_T distribution is used to gauge the scale of new physics.



H_T Distribution

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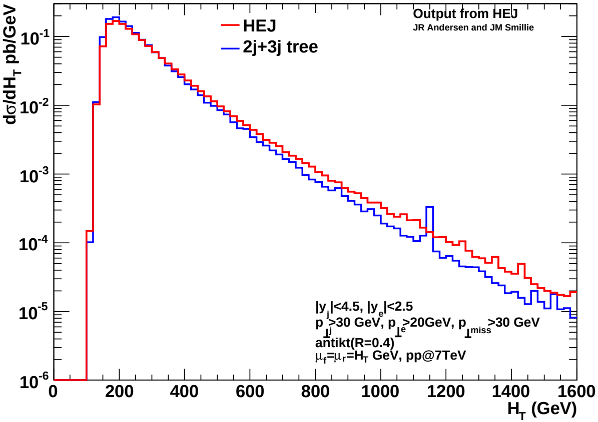
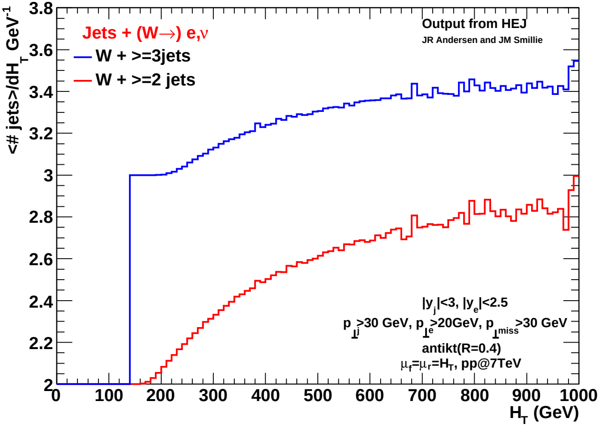


H_T Distribution

In $\geq 2j$ and $\geq 3j$ samples, averages show effect of extra emissions.



Conclusions

- The HEJ framework approximates production of multiple jets.
- Applied to jets, W+jets, Z+jets, H+jets in a flexible way.
- Available at `www.cern.ch/HEJ` and in the GENSER library.
- Additional emissions affect new physics searches.
- An important tool to make the most of LHC data.