Overview of High Energy Jets (HEJ)

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Outline

- HEJ
  - Motivation
  - Method
  - Experimental Analyses
- Extension - Next-to-Leading Log (NLL) in pure jet processes
- Conclusion/Outlook

Motivation

- HEJ is a framework which allows for an all-order resummation of high energy logs of the form $\ln(\frac{\hat{s}}{-\hat{t}})$. Such logs are important in the limit of large rapidity separations between final state particles at fixed momentum transfer, a regime that can be (and currently is being!) probed at the LHC
- Useful because these regions arise naturally in Higgs VBF analyses and BSM searches
- Formalism includes pure jets, Higgs plus jets, W plus jets [1,2] and now also Z plus jets [3]. It can be interfaced to a parton shower (ARIADNE [4]), allowing for a description of both shower and HE effects

[1] arXiv:0908.2786, [2] arXiv:1206.6763, [3] arXiv:1603.05460, [4] arXiv:1104.1316

Method - MRK Limit

- The goal - create a matrix element that can capture all-order behaviour in jet processes
- In the limit of infinite rapidity separation between all final state particles with a fixed momentum transfer $p_\perp$ between them (Multi-Regge Kinematic limit), QCD amplitudes are dominated by t-channel gluon exchange and emission, taking the factorised form;

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

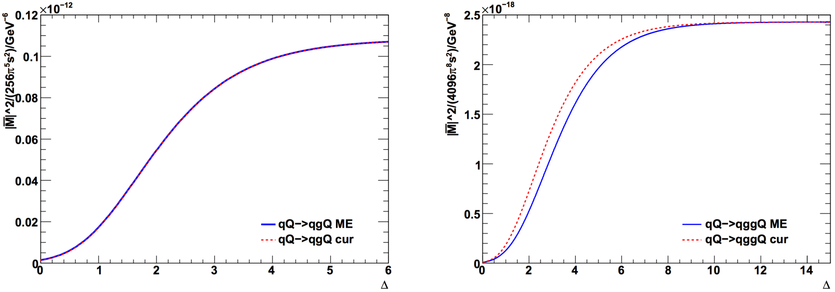
- HEJ uses this equation as a guide and keeps the factorisation structure whilst at the same time relaxing the assumptions that go into developing this limit. This will later give us a way of consistently including terms that appear at all orders in perturbation theory

Method - Currents and Effective Vertices

Building up from the simplest process $qQ \to qQ$ and considering extra gluon emissions, we arrive at the following expression for the amplitude squared;

$$|M^{HE}_{qQ\to q\ldots Q}|^2 = \frac{||S_{qQ\to qQ}||^2}{4(N_C^2-1)} \frac{g^2 C_F}{t_1} \left(\prod_{i=1}^{n-2} \frac{-g^2 C_A}{t_i t_{i+1}} V^\mu V_\mu \right) \frac{g^2 C_F}{t_{n-1}}$$

- *Currents* - $||S_{qQ\to qQ}||^2$ involves the contraction of quark currents $\bar{u}(p)\gamma^\mu u(q)$ which is exact - similar derivation for gluons shows the same structure
- Keeping the explicit t factors and the use of an *effective vertex* V^μ for gluon emission means we capture more of the full matrix element



$$p_i = k_\perp(\cosh(y_i), \cos(\phi_i), \sin(\phi_i), \sinh(y_i)), k_\perp = 40GeV$$

y_i related to Δ, such that increasing Δ means increasing rapidity separation between all final state particles

Method - Lipatov Ansatz

- Amplitude behaviour dictated by t-channel poles
- Can employ the *Lipatov Ansatz* for the virtual corrections to the process;

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

$$\hat{\alpha}(q_i) = \alpha_s C_A \frac{\Gamma(1-\varepsilon)}{(4\pi)^{2+\varepsilon}} \frac{2}{\varepsilon} \left(\frac{q_\perp^2}{\mu^2}\right)^{\varepsilon}$$

- This ansatz is accurate to *Leading Logarithmic* (LL) accuracy
- When combined with real corrections, the IR singularities from the real emissions are cancelled to all orders, and finite regularised matrix elements can be evaluated in 4D

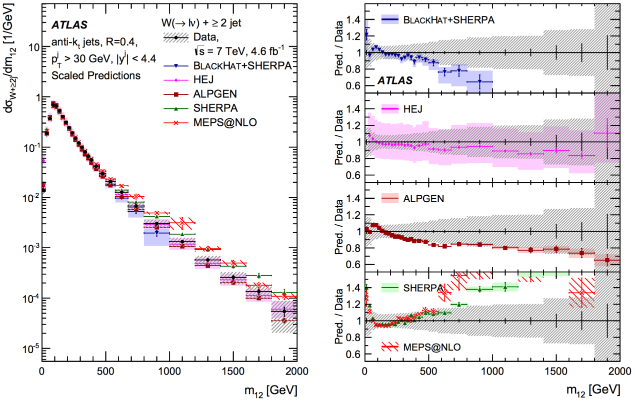
Method - Summary

- By exploiting properties of QCD matrix elements in the high energy limit, we are able to capture all-order behaviour
- By including matching to LO matrix elements (MadGraph), HEJ is able to describe the data well away from this limit as well
- We have a fully flexible Monte Carlo for all-order jet predictions that contains these large logarithms which threaten to spoil the convergence of the perturbation series

Web address - http://hej.web.cern.ch/HEJ

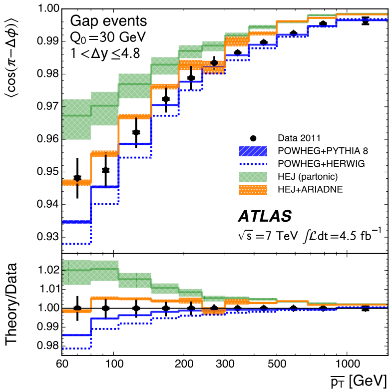
- Contributions from these large logs already seen in data

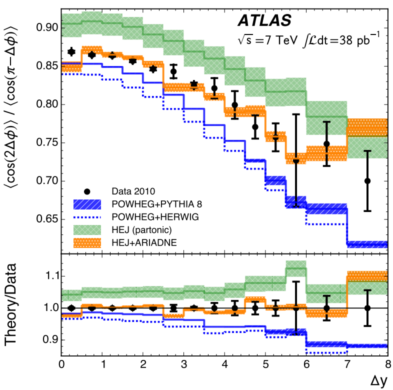
W + jets study, arXiv:1409.8639



Large m_{12} region is precisely where these logs become large and the breakdown of the fixed order approach is clear to see. Other more inclusive variables show agreement between all approaches

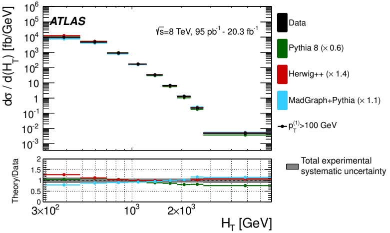
Jet veto and azimuthal decorrelation study, arXiv:1407.5756

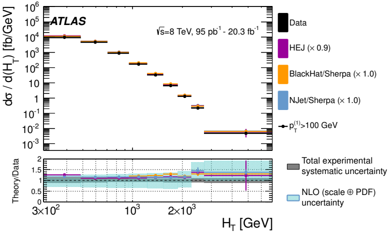




High Energy corrections needed - the all-order corrections in a parton shower are not enough here

Four jet study, arXiv:1509.07335





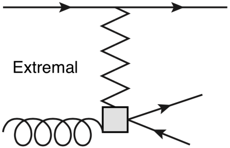
HEJ agrees well with data and other theory descriptions out to large values of Ht

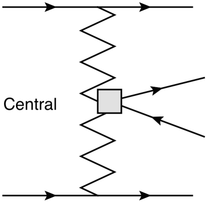
NLL Pure - Motivation

- The HEJ formalism is powerful enough to allow the inclusion of Next-to-Leading Log (NLL) effects. For full NLL accuracy in pure jet processes, we require knowledge of;
  - Loop corrections to one gluon emission
  - Two gluon emission without assumption of large rapidity gap
  - "Unordered" emissions (done)
  - Subleading partonic configurations (this talk)
- While these partonic configurations are formally NLL in the jet process, the description will be LL accurate in that particular subprocess
- Allows the resummation procedure applied to a wider range of processes

NLL Pure - Considerations

- Think about partonic processes not described with the pure gluonic emission approach. There are two cases to consider;





$$M_{qg\to qQQ} \sim \frac{\langle 1|\mu|a\rangle\, V^{\mu\nu}\varepsilon_\nu(p_b)}{t_1}$$

$$M_{qQ\to qq'\bar{q}'Q} \sim \frac{\langle 1|\mu|a\rangle\, V^{\mu\nu}\, \langle 4|\nu|b\rangle}{t_1 t_3}$$

- Where the Vs are again *effective vertices* which will capture the effect of the pair emission in the two cases

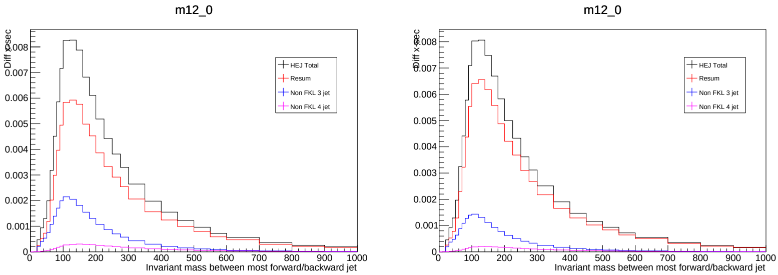
NLL Pure - Method

- Draw all Feynman diagrams at leading order for the two cases and get the full amplitude
- By making as few approximations as possible, create the desired structure
- Easily stated, can be tricky to do

$$V^{\mu\nu}_{extremal} = \frac{C_1}{s_{nb}}\left(\bar{u}_{n-1}\gamma^{\mu}(\not{p}_n - \not{p}_b)\gamma^{\nu} u_n\right) - \frac{C_2}{s_{n-1,b}}\left(\bar{u}_{n-1}\gamma^{\nu}(\not{p}_{n-1} - \not{p}_b)\gamma^{\mu} u_n\right) + i\frac{C_t}{s_{n,n-1}} V^{\mu\nu\rho}_{3g}\langle n-1|\rho|n\rangle$$

$$V^{\mu\nu}_{central} = \frac{C_1}{s_{q\bar{q}}}\left(\eta^{\mu\nu} V^{\sigma}_{eik,sym} + V^{\mu\nu\sigma}_{3g}\right)\langle p_q|\sigma|p_{\bar{q}}\rangle + \frac{iC_2}{(q_{in}-p_q)^2} V^{\mu\nu}_{qprop} - \frac{iC_3}{(q_{in}-p_{\bar{q}})^2} V^{\mu\nu}_{crossed}$$

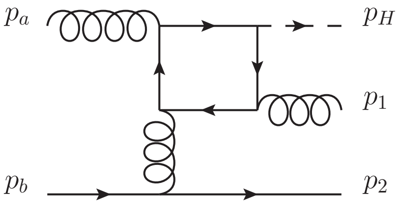
Inclusive 3 jet differential cross section,
$p_{T,min} = 30 GeV, |y_{max}| = 4.4, R = 0.6$



Fixed order parts (blue and yellow) are migrating to the resummation part (red), leading to a lesser dependence on fixed order matching in the full HEJ run (black)

Conclusions/Outlook

- By use of the Lipatov Ansatz, HEJ provides a formalism for capturing the LL part of multi-jet production amplitudes at hadronic colliders
- HEJ can now also capture some of the NLL terms and work continues into including more (unordered W)
- Work is also underway to incorporate finite mass effects in Higgs production



(Backup) NLL Pure - Results

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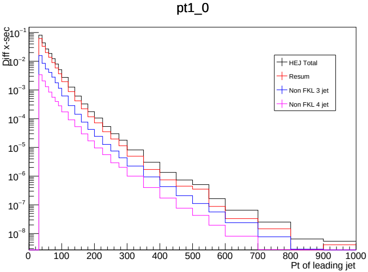
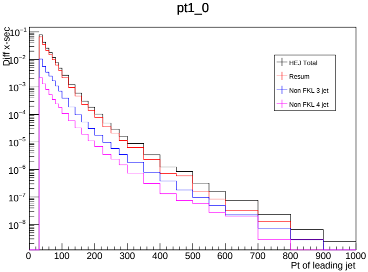
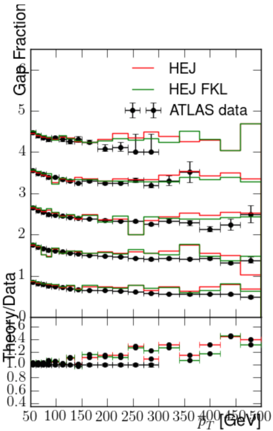
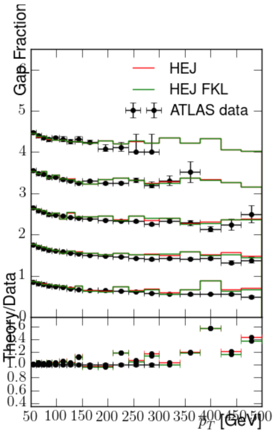




Dependence on LO part in high p_T region reduced by this migration

(Backup) NLL Pure - Results





This migration of events into the resummation formalism allows for better description of observables that are sensitive to it