High Energy Jets at the LHC

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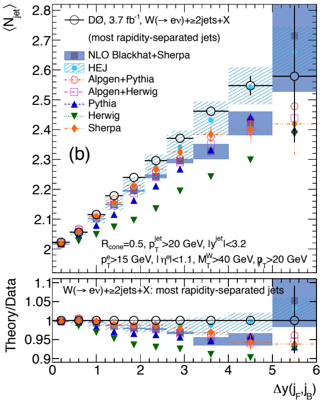
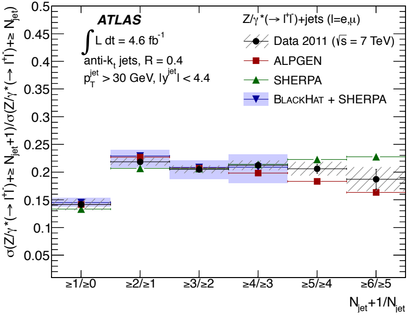
Outline

- Motivation - Why study high energy jets?
- The Problem At Hand
- Traditional Approaches
- The Need For Something New: `HEJ`
    - The MRK Limit
    - t-channel Dominance
    - Effective Vertices
- Extensions of the formalism
- Results

Motivation - Why study jets at the LHC?

- As we open up the available phasespace we observe an increase in jet activity (1302.6508, 1304.7098)





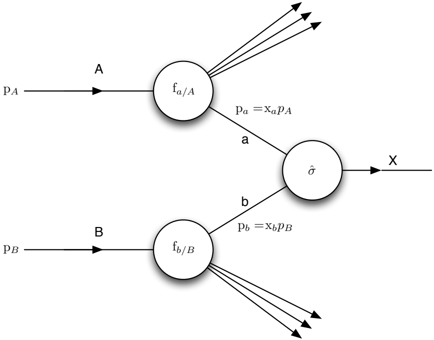
- and we have plenty of new phase space them at the LHC...

Motivation - Why High Energy Jets?

- Jets at the LHC provide an insight in to QCD processes at scales previously unseen.
- Useful for constraining PDF's
- Jets events are an important background to understand for the study of
  - Top Physics,
  - Higgs physics,
  - BSM Physics.

The Problem At Hand...

- QCD 'Factorisation' at the LHC



$$\sigma_{AB\to X} = \int dx_a dx_b f_{a/A}(x_a, \mu_F) f_{b/B}(x_b, \mu_F) \hat{\sigma}_{ab\to X}$$

- Here I will focus on the calculation of $\hat{\sigma}_{ab\to X}$

Problems with traditional approaches

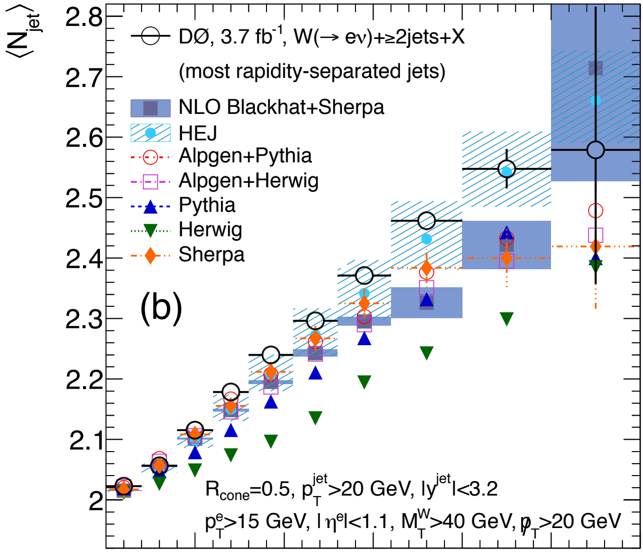
- 'Fixed Order' perturbation expansion:

$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \alpha_s^2(\mu_r^2)\hat{\sigma}^{(1)}_{ab\to X} + \dots$$

- The idea being that we may now truncate this series and calculate the terms in the series that remain.

- *Assumption*: $\hat{\sigma}^{(i)}$ are assume to be $\sim \mathcal{O}(1)$. But these higher order terms are logarithmically enhanced in some regions of phase space.

Traditional Approaches - Problems



A New Approach...

- The High Energy Jets (HEJ) package provides a systematic all-order description of QCD emissions.
- Motivated by behaviour of MEs in Multi-Regge Kinematic region of phase space
- Key ingredients:
  - Large invariant mass: $s_{ij} = 2p_i \cdot p_j \to \infty$
  - Effective vertices for extra emission,
  - The Lipatov ansatz to describe extra real emissions.

The Multi-Regge Kinematic (MRK) Limit

- Infinite invariant mass: $s_{ij} = 2p_i \cdot p_j \to \infty$

$$p_i = p_\perp \cdot (\cosh y, \cos\phi, \sin\phi, \sinh y)$$

$$\Rightarrow s_{ij} = 2p_{\perp i}p_{\perp j}(\cosh\Delta y - \underbrace{\cos\Delta\phi}_{\sim\mathcal{O}(1)})$$

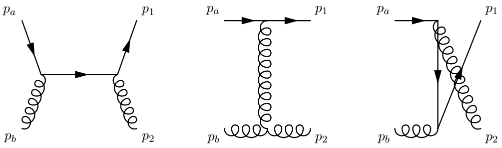
$$\Rightarrow s_{ij} \sim 2p_{\perp i}p_{\perp j}\cosh\Delta y$$

- So we can get large invariant mass having either:
  - Large perpendicular momentum or,
  - Large rapidity differences in final state jets.

The HEJ Package

- We start from the naturally ‘factorised’ form for the $2 \to 2$ scattering amplitude.

Naturally written as a contraction of a term depending only on $p_a \sim p_1$ and a term depending on $p_b \sim p_2$.

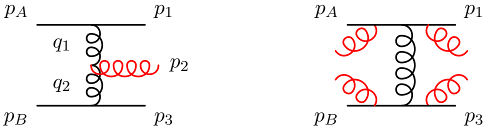


$$\mathcal{A}_{qg\to qg} \propto \frac{\langle a|\mu|1\rangle \cdot \langle b|\mu|2\rangle}{t}$$

- In the MRK limit the t-channel pole dominates

Adding extra emissions

- We then include further hard emissions by looking at the possible ways in which we can emit an extra gluon:



- These emission sites can be combined and, in the relavant limit, expressed as an effective vertex:

$$V^\mu(q_1,q_2) = -(q_1+q_2)^\mu \; + \; \frac{p_a^\mu}{2}\cdot\left(\frac{q_1^2}{p_a\cdot p_2}+\frac{p_b\cdot p_2}{p_a\cdot p_b}+\frac{p_2\cdot p_3}{p_a\cdot p_3}\right) + (p_a \leftrightarrow p_1)$$
$$\qquad - \; \frac{p_b^\mu}{2}\cdot\left(\frac{q_2^2}{p_b\cdot p_2}+\frac{p_a\cdot p_2}{p_a\cdot p_b}+\frac{p_1\cdot p_2}{p_1\cdot p_b}\right) - (p_b \leftrightarrow p_3).$$

- Gauge invariant in all of phase-space!

Recent Developments

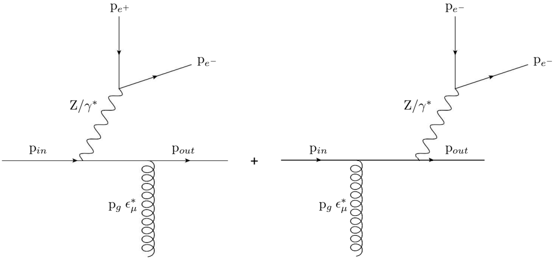
- Because of the simple structure of these amplitudes it is easy to extend the description to final states with EW bosons in.
- This has been done succesfully for W+j's and H+j's (1206.6763, H's paper pending) (Z+j's and in progress).
- E.g. The inclusion of a Z^0 in our final state can be included by modifying one of our contracted currents:

$$\mathcal{M}^{qg\to(Z^+\to)e^+e^-qg} = \frac{j_\mu^Z(p_a, p_1, p_e^+, p_e^-)\cdot\langle b|\mu|2\rangle}{t} \qquad (1)$$

- Where j_μ^Z is the 'current' which encodes all possible emission sites of the Z^0.

Recent Developments

- Diagramatically:



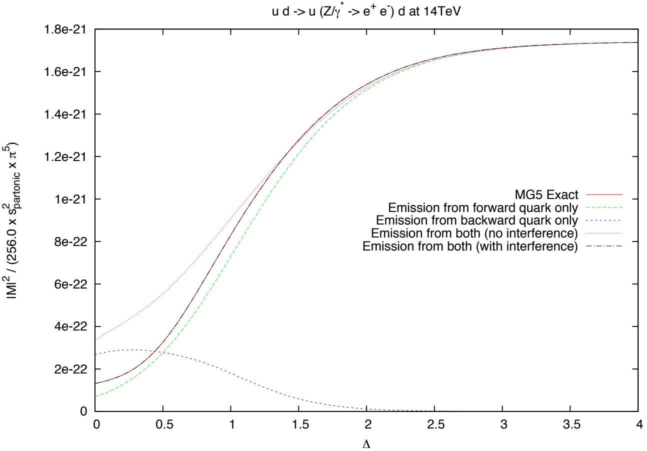
- The *only* change to our matrix element is that we must replace the $\langle 1|\mu|a\rangle$ current with a more complicated form:

$$j^Z_\mu(h_q,h_l) = \left(\frac{2p_1^\sigma \langle 1^{h_q}|\gamma^\mu|a^{h_q}\rangle + \langle 1^{h_q}|\gamma^\sigma|e^+_{h_q}\rangle\langle e^+_{h_q}|\gamma^\mu|a^{h_q}\rangle + \langle 1^{h_q}|\gamma^\sigma|e^-_{h_q}\rangle\langle e^-_{h_q}|\gamma^\mu|a^{h_q}\rangle}{t_a} + \ldots \right.$$

$$\left. \ldots + \frac{2p_a^\sigma \langle 1^{h_q}|\gamma^\mu|a^{h_q}\rangle - \langle 1^{h_q}|\gamma^\mu|e^+_{h_q}\rangle\langle e^+_{h_q}|\gamma^\sigma|a^{h_q}\rangle - \langle 1^{h_q}|\gamma^\mu|e^-_{h_q}\rangle\langle e^-_{h_q}|\gamma^\sigma|a^{h_q}\rangle}{t_b} \right) \langle e^+_{h_l}|\gamma_\sigma|e^-_{h_l}\rangle$$

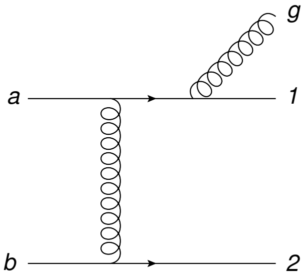
Recent Developments - Z+jets

- Other complexities arise due to the possibility of the γ^* channel interference
- Need an improved regularisation to include all possible emission sites for the boson.



Recent Developments - H+jets and 'unordered' emissions

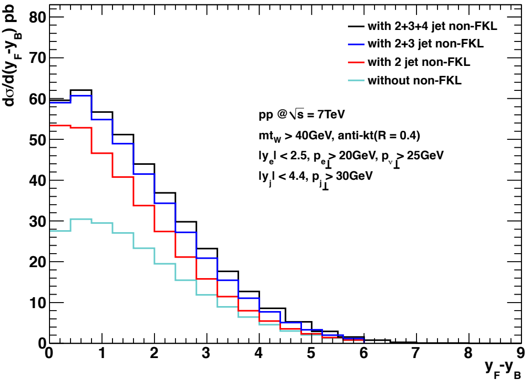
- HEJ requires a strong rapidity ordering of all final state partons.
- We have recently widened the region of applicability of our resummation to include diagrams which have one 'unordered emission' e.g.



- This has been succesfully implemented in the H+j's code.

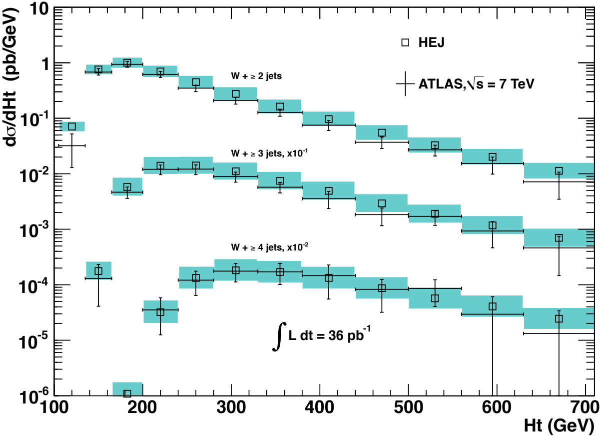
Results - Non-FKL Matching

- We include the extra configurations which arent resummed, up to 4 jets:

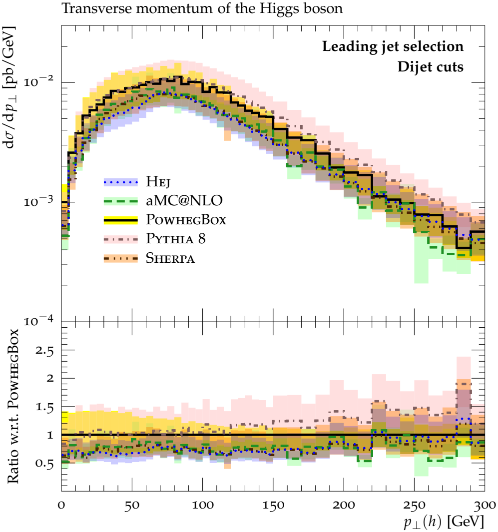


Results - W+jets

- An ATLAS study showing various results differential cross-section of $W + j$'s at different H_T. Even at quite low H_t we have a good description.

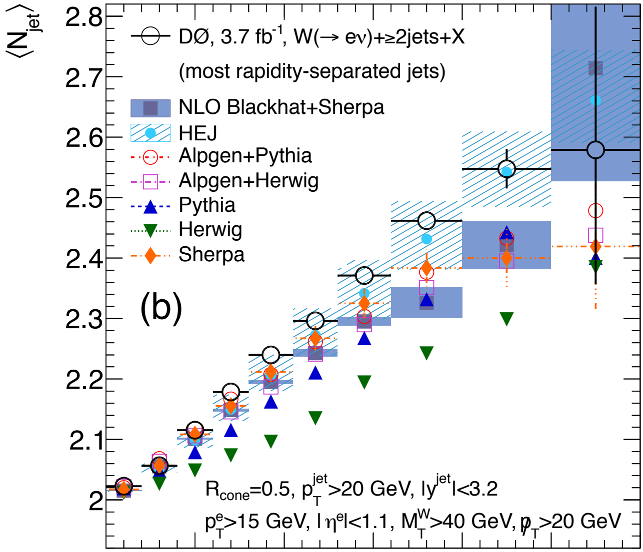


Results - H+jets



- Les Houches paper coming soon!

Results - W+jets



In Summary

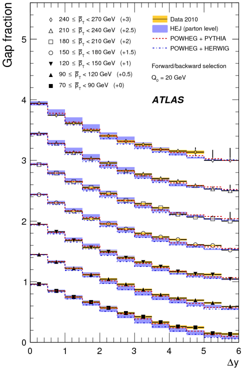
- The LHC has given us access to new regions of phase space where we need to rethink our approach to QCD calculations,
- Jets at the LHC provide us with a good check of SM processes as well as a look at what is coming next,
- The HEJ approach provides an elegant way to describe physics which was traditionally tricky to calculate,
- Recent extensions of our formalism mean we can describe a wide range of important LHC processes,
- Good description of data seen so far.

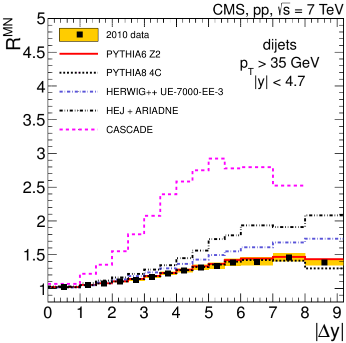
www.cern.ch/HEJ/

Thanks for listening!

Backup - Mueller-Navalet Jets at the LHC

- Both CMS and ATLAS have published studies.
- CMS shows NLO matches with the data and HEJ overestimates jet activity.





- Why do NLO undershoot in ATLAS? Are we really probing the hard scatter here or testing MPI, UE tuning?