Jets at the LHC

New Possibilities

Jeppe R. Andersen
in collaboration with Jennifer M. Smillie

Blois workshop, Dec 17 2011

Jets at the LHC

The age old hunt…

Effects beyond NLO DGLAP?
…apart from the obvious soft and collinear regions (shower profile)
Do we need more than NLO DGLAP to describe the hard jet events at the LHC?

The News

The data collected in 2010 already show effects beyond **NLO** DGLAP…

1. for some observables based on hard jets
2. in certain regions of phase space

Scope of this talk

Will not discuss several interesting effects:

- jet broadening (shower profiles)
- impact of underlying event on the jet energy

⋮

These are (well?) described by a tunable shower MC.

Will instead focus on the description of the **hard event**, and in particular on observables not well described by **NLO** DGLAP.

Outline

Idea/Motivation

Investigate the radiation pattern in DiJets for two reasons:

1. Because it is an interesting QCD laboratory
2. DiJets act as a test bed for studies of h+DiJets

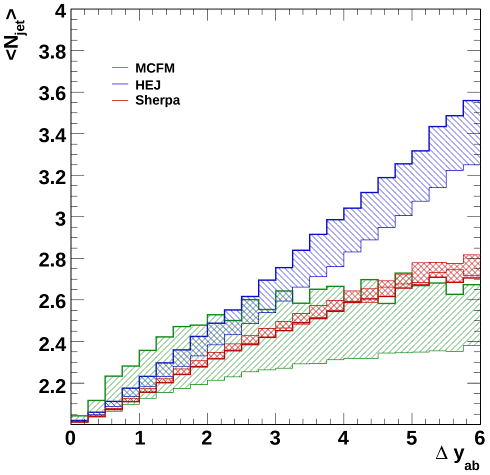
Which regions of phase space receive large corrections from hard perturbative corrections (= additional jet activity)

Compare the description of hard jet activity from NLO, NLO+shower, High Energy Jets.
Dijets, W+Dijets, H+Dijets; Similarities in Jet Activity

Drivers of Emission

1. Collinear (jet profile)
2. Soft (p_t-hierarchies)
3. Opening of phase space (semi-hard emissions - not related to a divergence of $|M|^2$).
   Think (e.g.) multiple jets of fixed p_t, with increasing rapidity span (span=max difference in rapidity of two hard jets=Δy).
   All calculations will agree that number of additional jets increases - but the amount of radiation will differ (wildly) - e.g. due to **limitations** on the **number** (NLO) or **hardness** (shower) of allowed additional radiation.

Increasing Rapidity Span → Increasing Number of Jets



J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.1241

h+dijets (at least 40GeV). Δy_{ab}: Rapidity difference between most forward and backward hard jet

Compare NLO (green), CKKW matched shower (red), and High Energy Jets (blue).

All models show a clear increase in the number of hard jets as the rapidity span Δy_{ab} increases.

Please recall this plot when I discuss the results of the ATLAS study of $\langle N_{\text{jets}} \rangle$

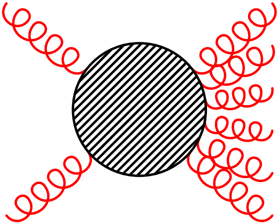
HEJ (High Energy Jets)

Goal (inspired by the great Fadin & Lipatov)

Sufficiently **simple** model for hard radiative corrections that the all-order sum can be evaluated explicitly (completely exclusive)

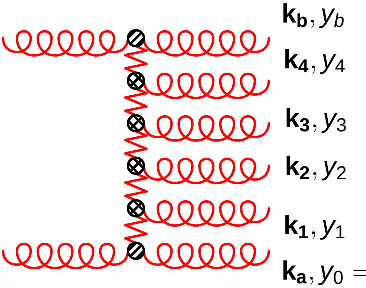
but. . .

Sufficiently **accurate** that the description is relevant



High Energy Limit $\longrightarrow$

$|\hat{t}|$ fixed, $\hat{s} \to \infty$



$$\mathcal{A}^R_{2\to 2+n} = \frac{\Gamma_{A'A}}{q_0^2}\left(\prod_{i=1}^{n} e^{\omega(q_i)(y_{i-1}-y_i)}\frac{V^{J_i}(q_i,q_{i+1})}{q_i^2 q_{i+1}^2}\right) e^{\omega(q_{n+1})(y_n-y_{n+1})}\frac{\Gamma_{B'B}}{q_{n+1}^2}$$

$q_i = \mathbf{k}_a + \sum_{l=1}^{i-1}\mathbf{k}_l$

LL: Fadin, Kuraev, Lipatov; NLL: Fadin, Fiore, Kozlov, Reznichenko

Maintain (at LL) terms of the form

$$\left(\alpha_s \ln \frac{\hat{s}_{ij}}{|\hat{t}_i|}\right)$$

to all orders in α_s.

At LL only gluon production; at NLL also quark–anti-quark pairs produced. Approximation of any-jet rate possible.

Comparison of 3-jet scattering amplitudes

Universal behaviour of scattering amplitudes in the HE limit:

$$\forall i \in \{2,\ldots,n-1\} : y_{i-1} \gg y_i \gg y_{i+1}$$
$$\forall i,j : |p_{i\perp}| \approx |p_{j\perp}|$$

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

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

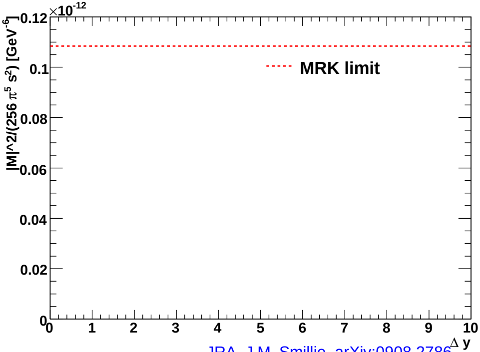
$$\left|\overline{\mathcal{M}}^{MRK}_{qQ\to qg\cdots Q}\right|^2 = \frac{4\,s^2}{N_C^2-1}\,\frac{g^2\,C_F}{|p_{1\perp}|^2}\left(\prod_{i=2}^{n-1}\frac{4\,g^2 C_A}{|p_{i\perp}|^2}\right)\frac{g^2\,C_F}{|p_{n\perp}|^2},$$

Allow for analytic resummation (BFKL equation).
However, how well does this actually approximate the amplitude?

Comparison of 3-jet scattering amplitudes

Study just a slice in phase space:

40GeV jets in Mercedes star (transverse) configuration. Rapidities at $-\Delta y, 0, \Delta y$.



JRA, J.M. Smillie, arXiv:0908.2786

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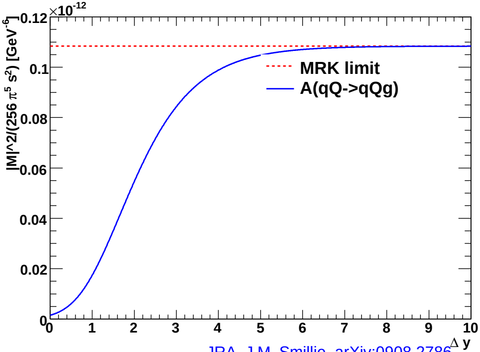

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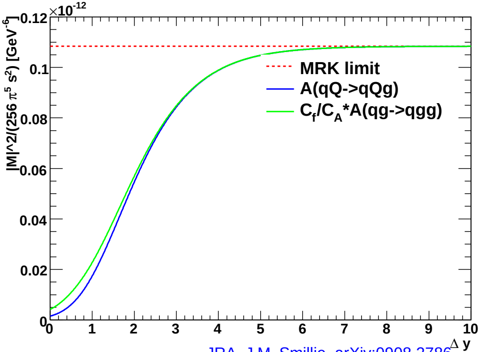

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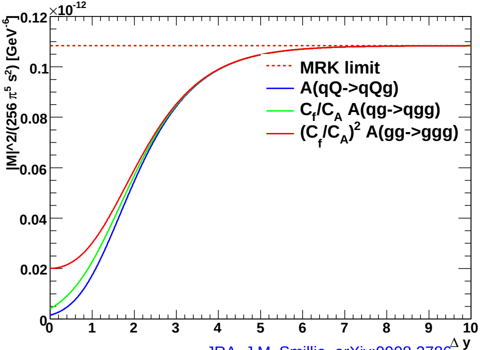

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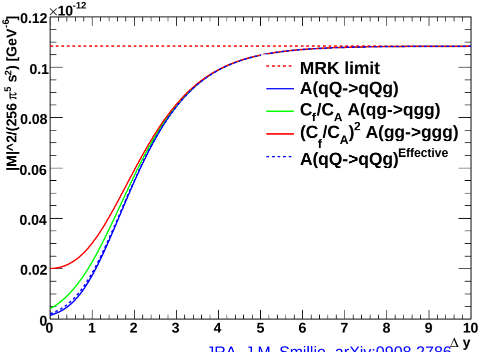

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High Energy Jets (HEJ):

1) Inspiration from Fadin&Lipatov: dominance by t-channel
2) No kinematic approximations in invariants (denominator)
3) Accurate definition of currents (coupling through t-channel exchange)
4) Gauge invariance. Not just asymptotically.

All-Orders, Regularisation, etc.

- Have prescription for $2 \to n$ matrix element, including virtual corrections: Lipatov Ansatz $1/t \to 1/t \exp(-\omega(t)\Delta y_{ij})$
- Organisation of cancellation of IR (soft) divergences is easy
- Can calculate the sum over the n-particle phase space explicitly ($n \sim 30$) to get the all-order corrections (just as if one had provided all the $N^{30}LO$ matrix elements and a regularisation procedure)
- **Match** to n-jet tree-level where this can be evaluated in reasonable time
- Resummation of HEJ recently merged with a **parton shower** - lots of ongoing work

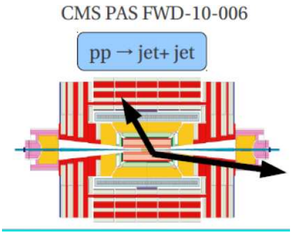
Comparison to data

Two drivers for multi-jet production:

- large ratio of transverse scales (shower resummation)
- Colour exchange over a range in rapidity

The LHC has the energy to explore the second mechanism.
Several interesting studies already with the first (2010) year of data!

Simultaneous production of central and forward jet

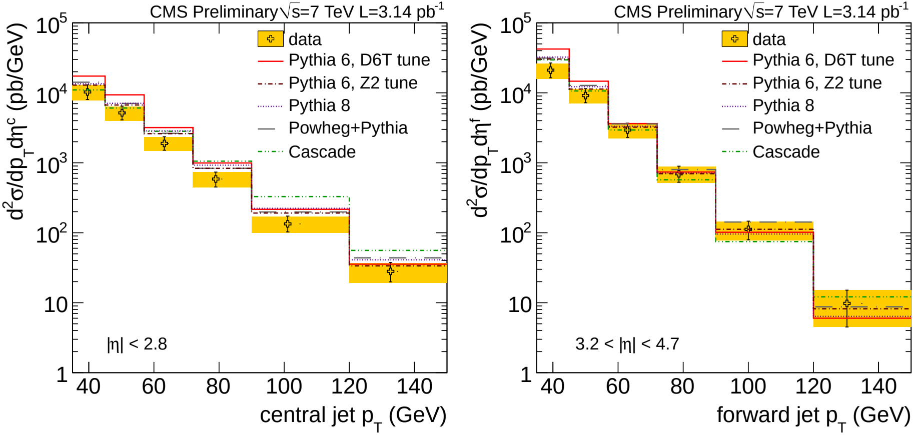


Jets: anti-kt, R=.5, $p_t > 35$GeV

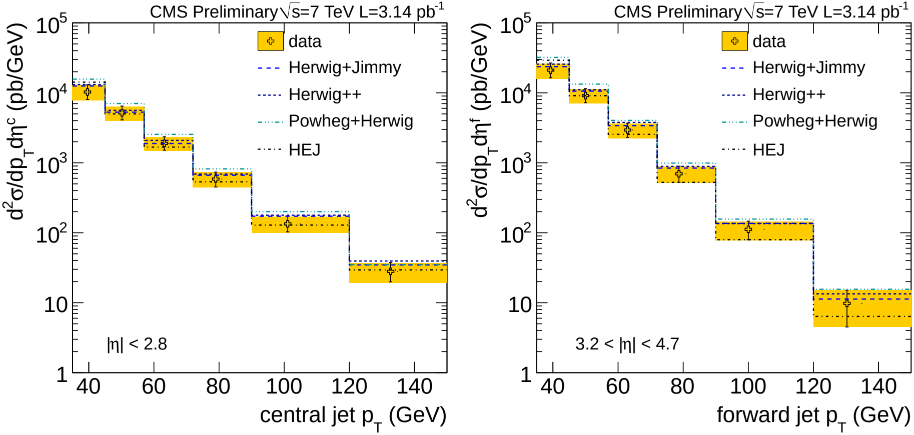
$$\text{central} : |\eta| < 2.8$$
$$\text{forward} : 3.2 < |\eta| < 4.7$$

(not particularly large rapidity spans, typically 1 unit).
Measure the p_t-spectrum of the central and the forward jet. Any difference is obviously due to additional radiation.

Comparison to Theory, I

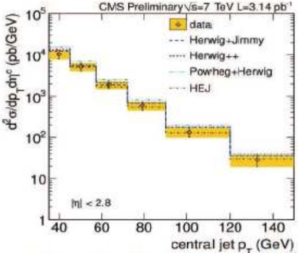


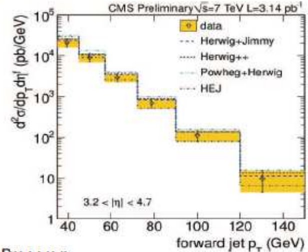
Comparison to Theory, II



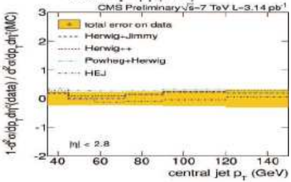
Forward-central jets (pp, LHC)

- Constrains multi-jets production & DGLAP vs BFKL dynamics



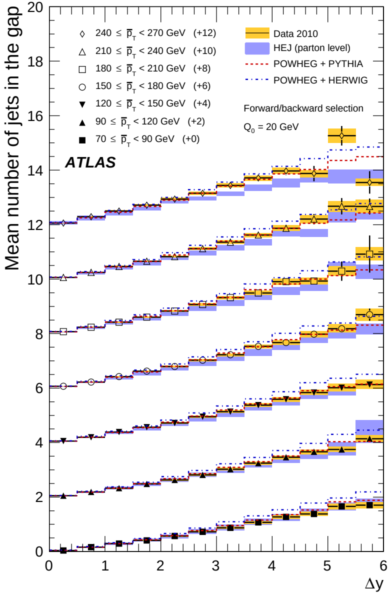


- HERWIG somehow better than PYTHIA.
- POWHEG (NLO) does not help.
- HEJ (BFKL-multijets) best agreement.



CMS (A. Massironi)

Atlas Study of Further Jet Activity in Dijet Events



The Atlas event selection does not cleanly separate the two "drivers" of jet production. (cut on $\bar{p}_t$ induces large p_t-hierarchy on forward/backward jet, besides the hierarchy between large $\bar{p}_t$ and Q_0, the general jet scale)

HEJ slightly undershoots the jet activity when large ratios of transverse scales are imposed (fully understood).

Very good agreement in the most important regions of phase space

Obviously *beyond* NLO (more than one extra jet on average at large Δy!)

Wish for new studies

Fruitful combination. . .

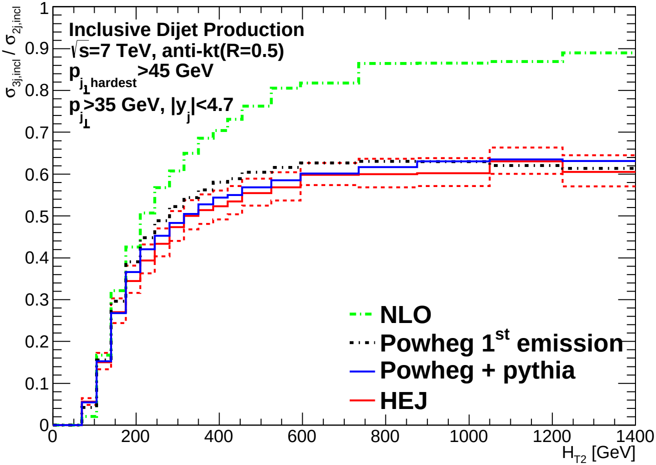
- Simple CMS cuts

  Additional: Requiring the hardest jet slightly harder than the general jet scale ensures a physical behaviour of the NLO calculation.

- ATLAS study

Ratio of Inclusive Jet Rates vs. H_{T2}

In Collaboration with POWHEG

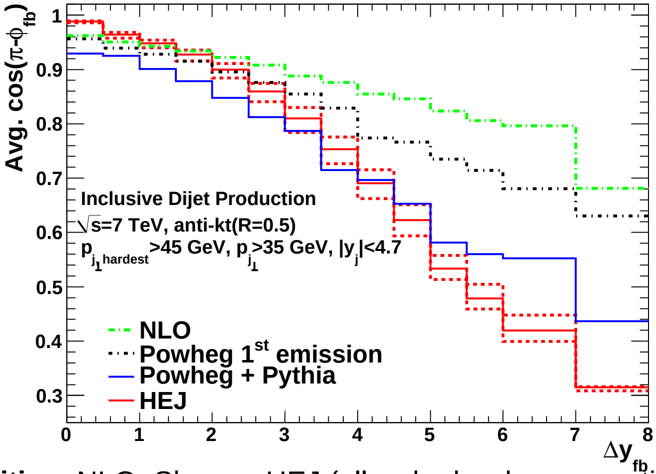


Similarities: NLO+Shower, HEJ (all-order hard resummation)

Difference: NLO

Azimuthal Decorellation vs. Rapidity

In Collaboration with POWHEG



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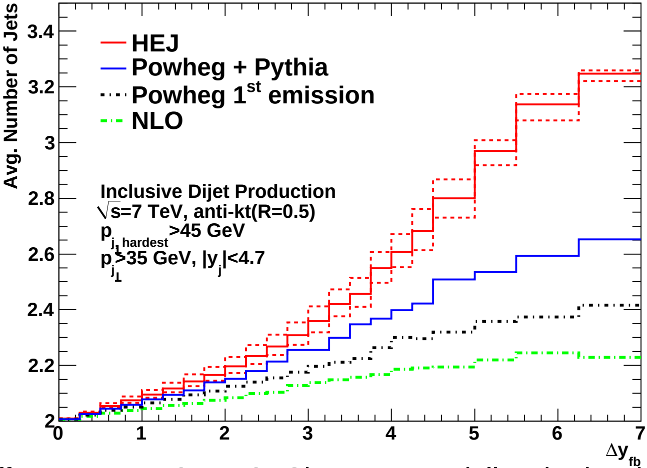
Average number of Hard Jets

In Collaboration with POWHEG



Clear differences: NLO, NLO+Shower, HEJ (all-order hard resummation)

Ratio of Inclusive Jet Rates vs. Rapidity

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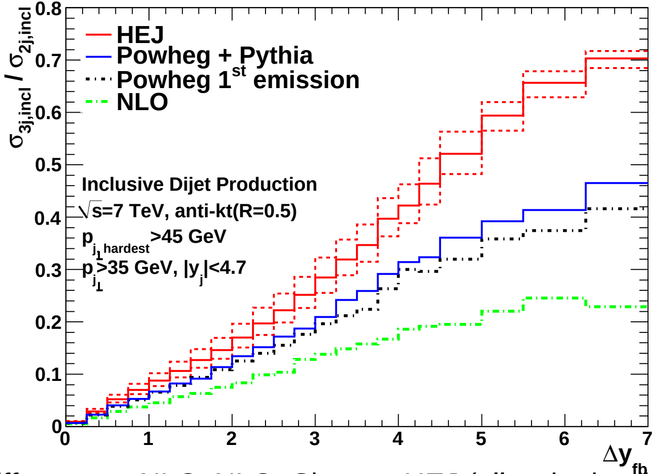

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Summary

- The LHC has the energy to probe the Multi-Regge-Kinematic region
- Effects of multiple hard emissions have already been observed
- ...but the analyses can be made much cleaner
- Please do so, since this will teach us much about QCD; and about jet veto effects in h+dijets.