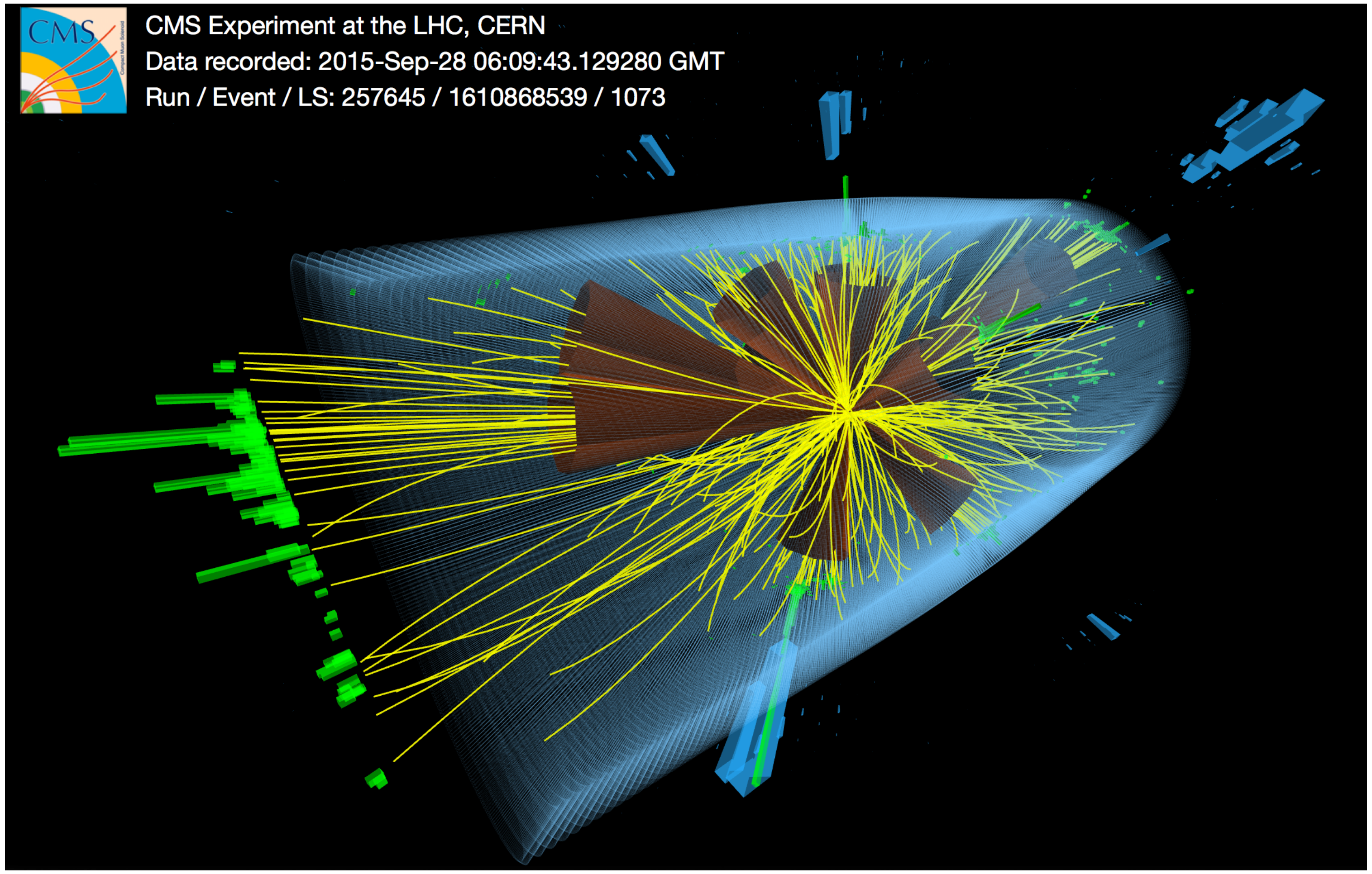
(Hard) Jet Production at High Energy Colliders



Jenni Smillie

PSR, Cambridge 24 Mar 2017

Introduction

- Previous picture = **12 jets** with p_T > **50 GeV** at CMS (13 TeV)

Many **Hard**

- Not just many jets, but also many scales: very difficult for theoretical descriptions.

- Phase space probed in Higgs boson analyses and searches for new physics put us right into the most difficult regions:

  Large rapidity separations or large invariant mass enhance (multi-)jet production (e.g. VBF)

  see ATLAS 1107.1641, D0 1302.6508, …

QCD at High Energy

- Extra power of α_s compensated by large phase space and large logarithms - **even more at 13 TeV, 100 TeV…**

- Already at LHC Run I, (n+1)-jet rates are not small compared to n-jet rates [0.2 rising to 0.3 after VBF cuts]

- Stability associated with NLO fails in difficult regions of phase space — demands a new approach

- **H**igh **E**nergy **J**ets sums leading logs in s/t at all orders in α_s

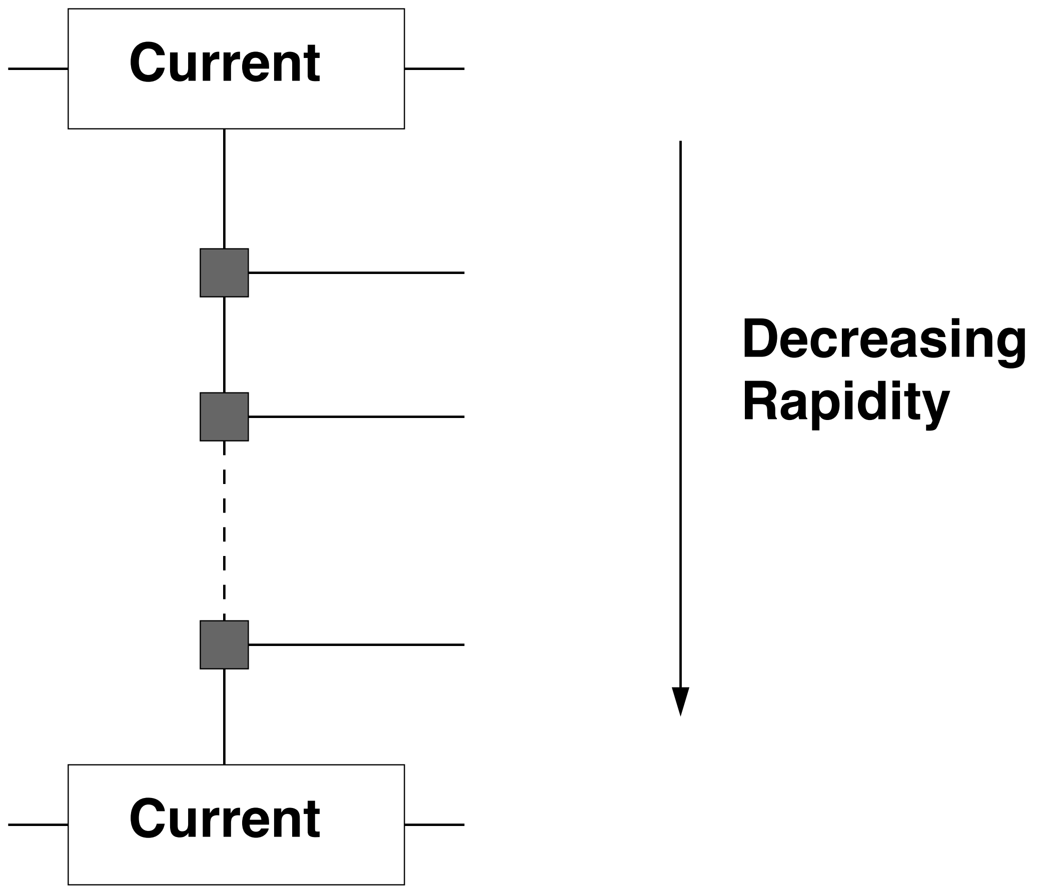
High Energy Jets (HEJ)

Amplitudes themselves become simpler in the “high energy” limit

$\Delta y_{ij} \rightarrow \infty$, $|p_{Ti}|$ finite

Can use this simpler structure to make an efficient event generator for arbitrary numbers of quarks/gluons.

Applies to loop diagrams too: gives leading log terms at all orders in α_s



Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394, +Hapola 1201.6763, +Medley 1603.05460, +Brooks, Cockburn, Maier

Main Equations

Squared Matrix Element

$$\overline{\left|\mathcal{M}^{\rm reg}_{\rm HEJ}(\{p_i\})\right|}^2 = \frac{1}{4\,(N_C^2-1)}\;\|S_{f_1f_2\to f_1f_2}\|^2$$
$$\cdot\left(g^2\,K_{f_1}\,\frac{1}{t_1}\right)\cdot\left(g^2\,K_{f_2}\,\frac{1}{t_{n-1}}\right)$$
$$\cdot\prod_{i=1}^{n-2}\left(g^2 C_A\,\left(\frac{-1}{t_it_{i+1}}V^\mu(q_i,q_{i+1})V_\mu(q_i,q_{i+1})-\frac{4}{\mathbf{p}_i^2}\,\theta\left(\mathbf{p}_i^2<\lambda^2\right)\right)\right)$$
$$\cdot\prod_{j=1}^{n-1}\exp\left[\omega^0(q_j,\lambda)(y_j-y_{j+1})\right],$$

Cross Section

$$\sigma_{2j}^{\rm resum,match}=\sum_{f_1,f_2}\sum_{n=2}^{\infty}\prod_{i=1}^{n}\left(\int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty}\frac{{\rm d}^2\mathbf{p}_{i\perp}}{(2\pi)^3}\int\frac{{\rm d}y_i}{2}\right)\frac{\overline{\left|\mathcal{M}_{\rm HEJ}^{f_1f_2\to f_1g\cdots gf_2}(\{p_i\})\right|}^2}{\hat{s}^2}$$
$$\times\sum_m\mathcal{O}^e_{mj}(\{p_i\})\;w_{m-{\rm jet}}$$
$$\times\quad x_af_{A,f_1}(x_a,Q_a)\;x_2f_{B,f_2}(x_b,Q_b)\;(2\pi)^4\;\delta^2\!\left(\sum_{i=1}^{n}\mathbf{p}_{i\perp}\right)\;\mathcal{O}_{2j}(\{p_i\})$$

$$\sigma_{2j}=\sigma_{2j}^{\rm resum,match}+\sum_n\sigma_{nj}^{\rm non-FKL}$$

Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394

Main Equations

Skeleton/Born Process

$$\overline{\left|\mathcal{M}_{\text{HEJ}}^{\text{reg}}(\{p_i\})\right|}^2 = \frac{1}{4\,(N_C^2-1)}\,\|S_{f_1 f_2\to f_1 f_2}\|^2$$
$$\cdot\left(g^2\,K_{f_1}\,\frac{1}{t_1}\right)\cdot\left(g^2\,K_{f_2}\,\frac{1}{t_{n-1}}\right)$$
$$\cdot\prod_{i=1}^{n-2}\left(g^2 C_A\left(\frac{-1}{t_i t_{i+1}}V^\mu(q_i,q_{i+1})V_\mu(q_i,q_{i+1})-\frac{4}{\mathbf{p}_i^2}\,\theta\left(\mathbf{p}_i^2<\lambda^2\right)\right)\right)$$
$$\cdot\prod_{j=1}^{n-1}\exp\left[\omega^0(q_j,\lambda)(y_j-y_{j+1})\right],$$

Resolved Real Emissions

Virtual + Unresolved Real (finite)

$$\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2}\sum_{n=2}^{\infty}\prod_{i=1}^{n}\left(\int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty}\frac{d^2\mathbf{p}_{i\perp}}{(2\pi)^3}\int\frac{dy_i}{2}\right)\frac{\overline{\left|\mathcal{M}_{\text{HEJ}}^{f_1 f_2\to f_1 g\cdots g f_2}(\{p_i\})\right|}^2}{\hat{s}^2}$$
$$\times\sum_m \mathcal{O}_{mj}^e(\{p_i\})\;w_{m-\text{jet}}$$
$$\times\quad x_a f_{A,f_1}(x_a,Q_a)\;x_2 f_{B,f_2}(x_b,Q_b)\;(2\pi)^4\;\delta^2\left(\sum_{i=1}^{n}\mathbf{p}_{i\perp}\right)\;\mathcal{O}_{2j}(\{p_i\})$$

Merging

$$\sigma_{2j} = \sigma_{2j}^{\text{resum,match}} + \sum_n \sigma_{nj}^{\text{non-FKL}}$$

Matching

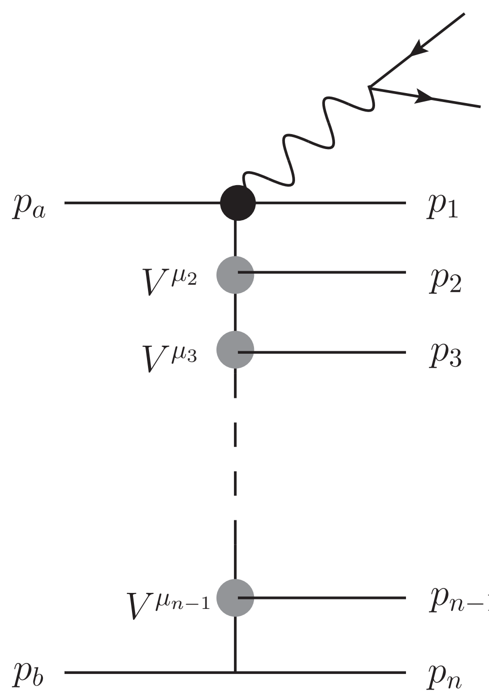
Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394

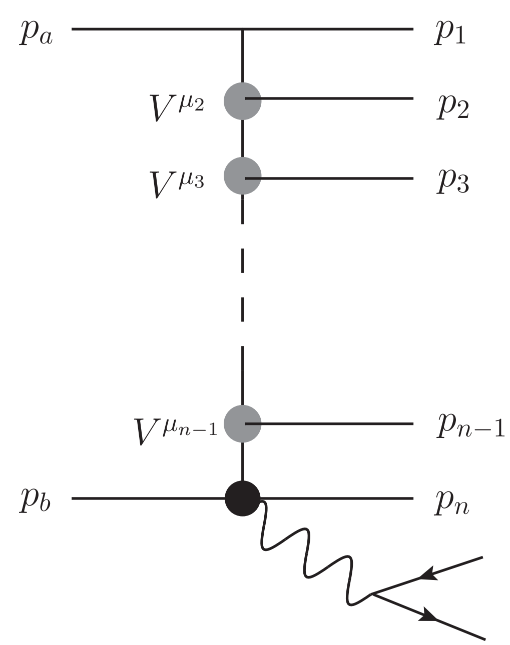
Z/γ^*+Jets

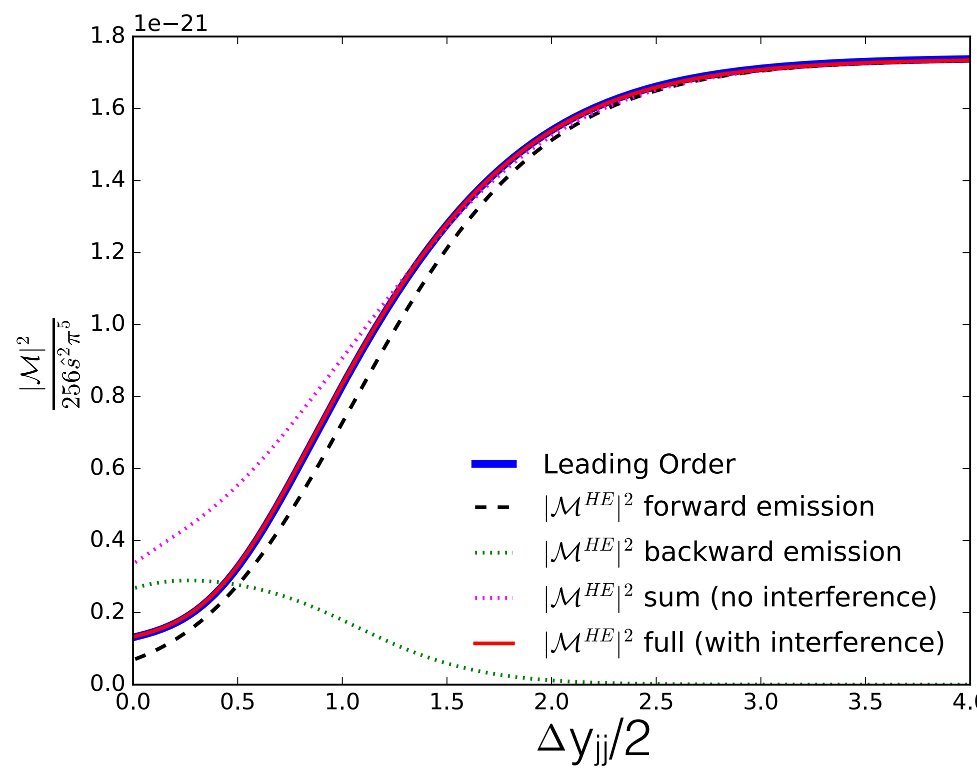
Latest addition extends HEJ method to Z plus jets

Andersen, Medley, JMS arXiv:1603.05460

Interference effects from quark lines mean more complicated than W+Jets





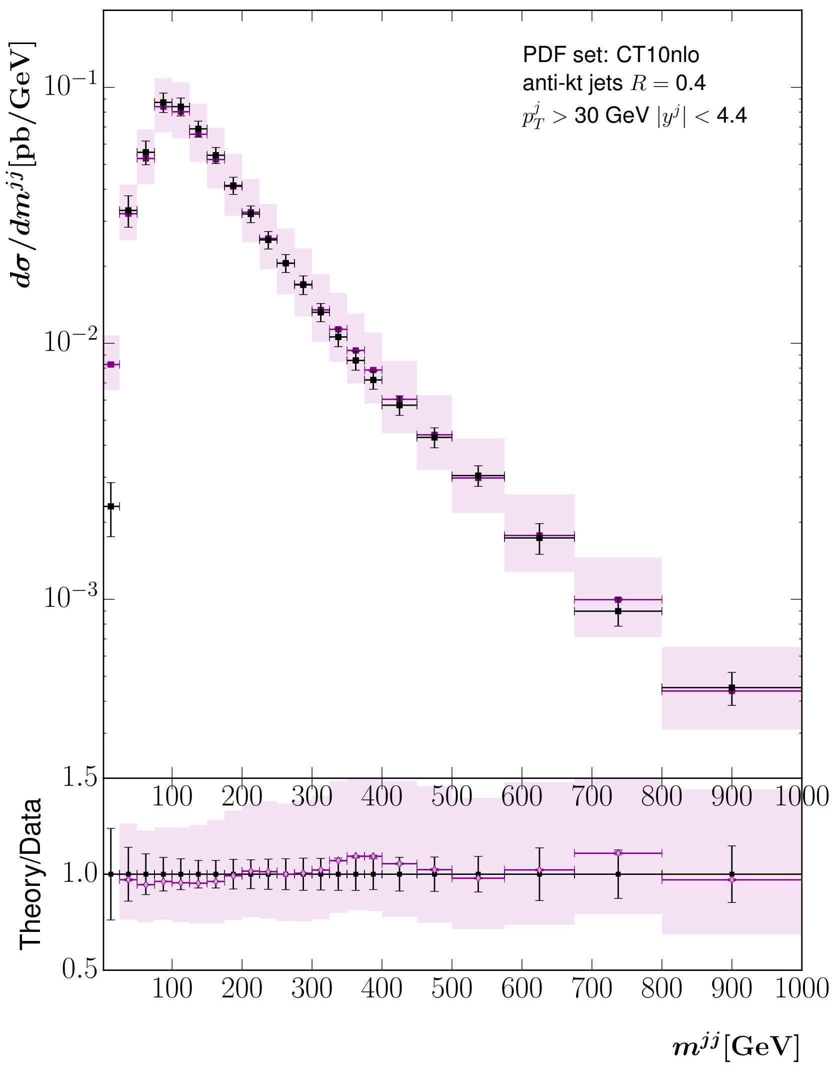


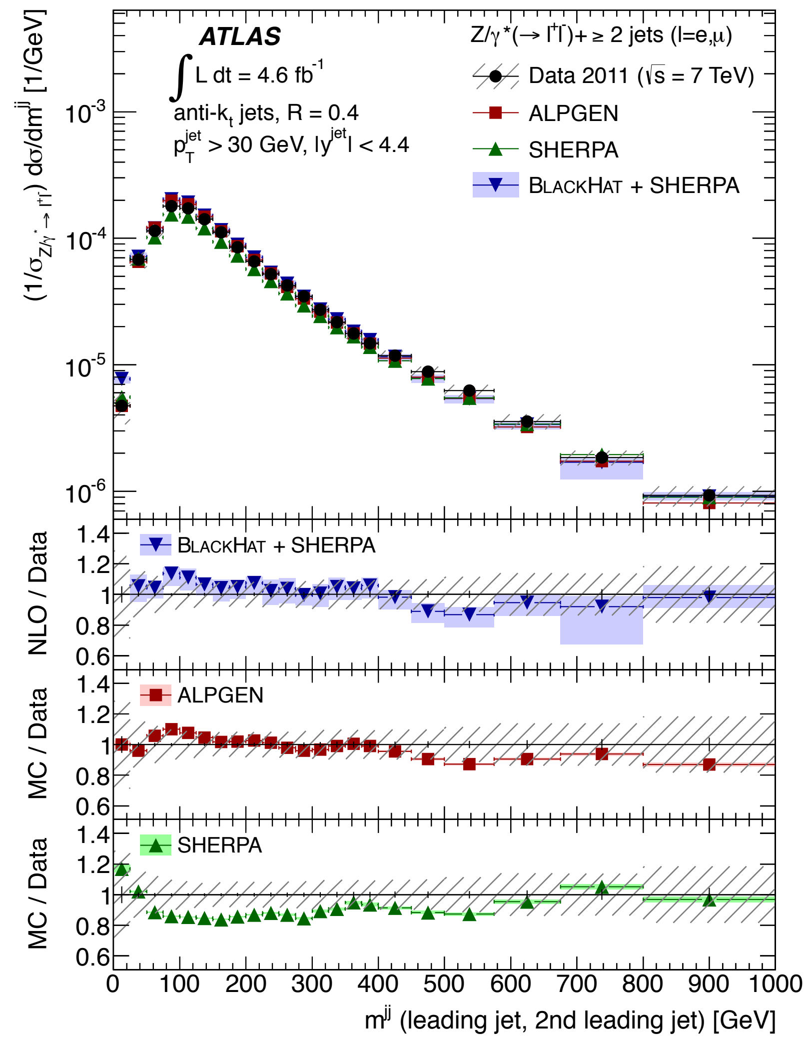
Only able to do this because we operate on the amplitudes and not amp-squared

Includes interference terms missing in e.g. electroweak shower

Z/γ*+Jets vs Data

Andersen, Medley, JMS arXiv:1603.05460 | **ATLAS arXiv:1304.7098**



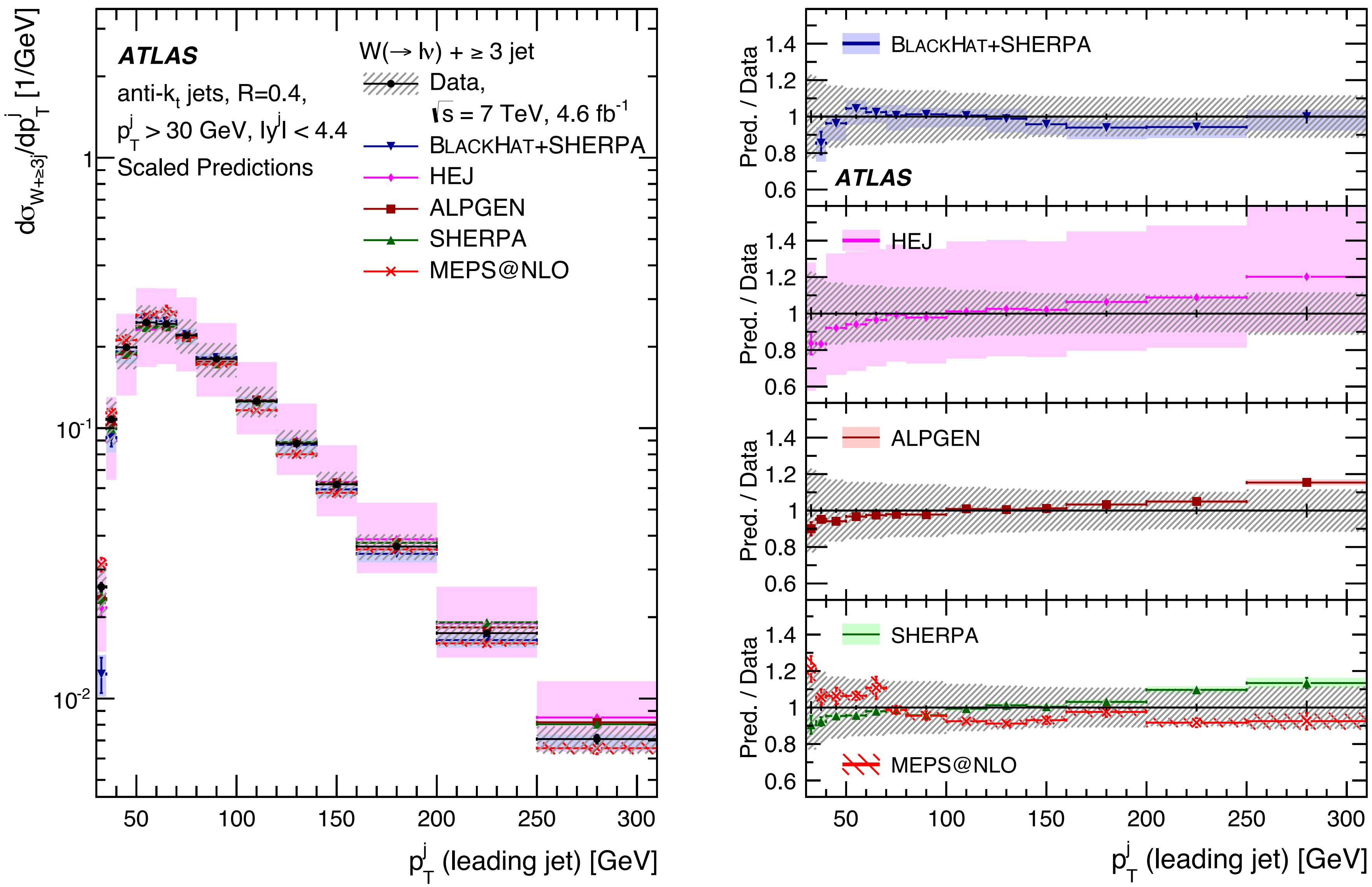


HEJ predictions gives good description across range

Uncertainty only shown for Blackhat+Sherpa on right

HEJ uncertainty is basically LO, but almost pure normalisation

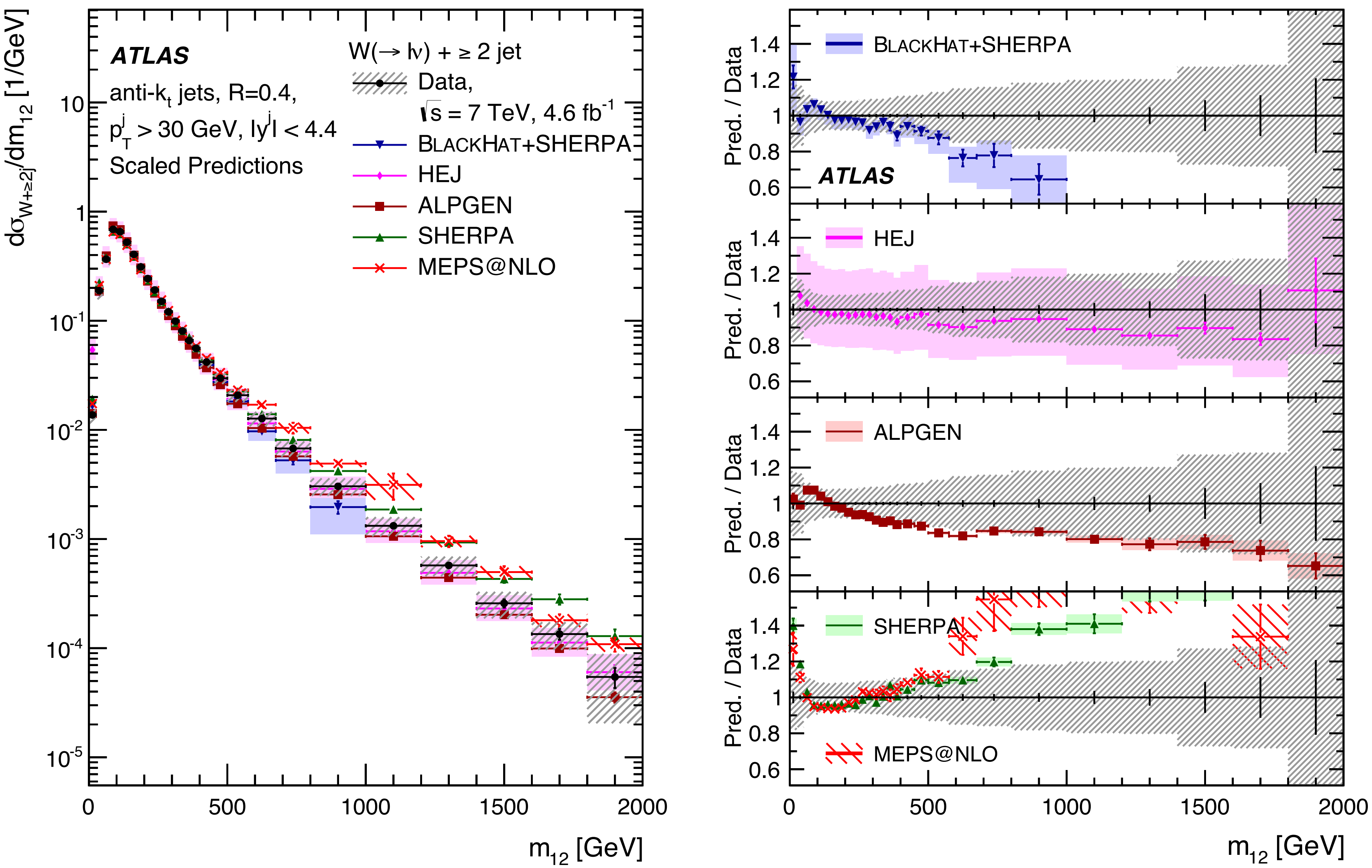
ATLAS W+Jets arXiv:1409.8639



In this distribution (pT of the leading jet in inclusive 3j events), the theory predictions show similar levels of agreement. BlackHat+Sherpa is best.

Only top two have scale variations included. HEJ is basically LO scale var.

ATLAS W+Jets arXiv:1409.8639

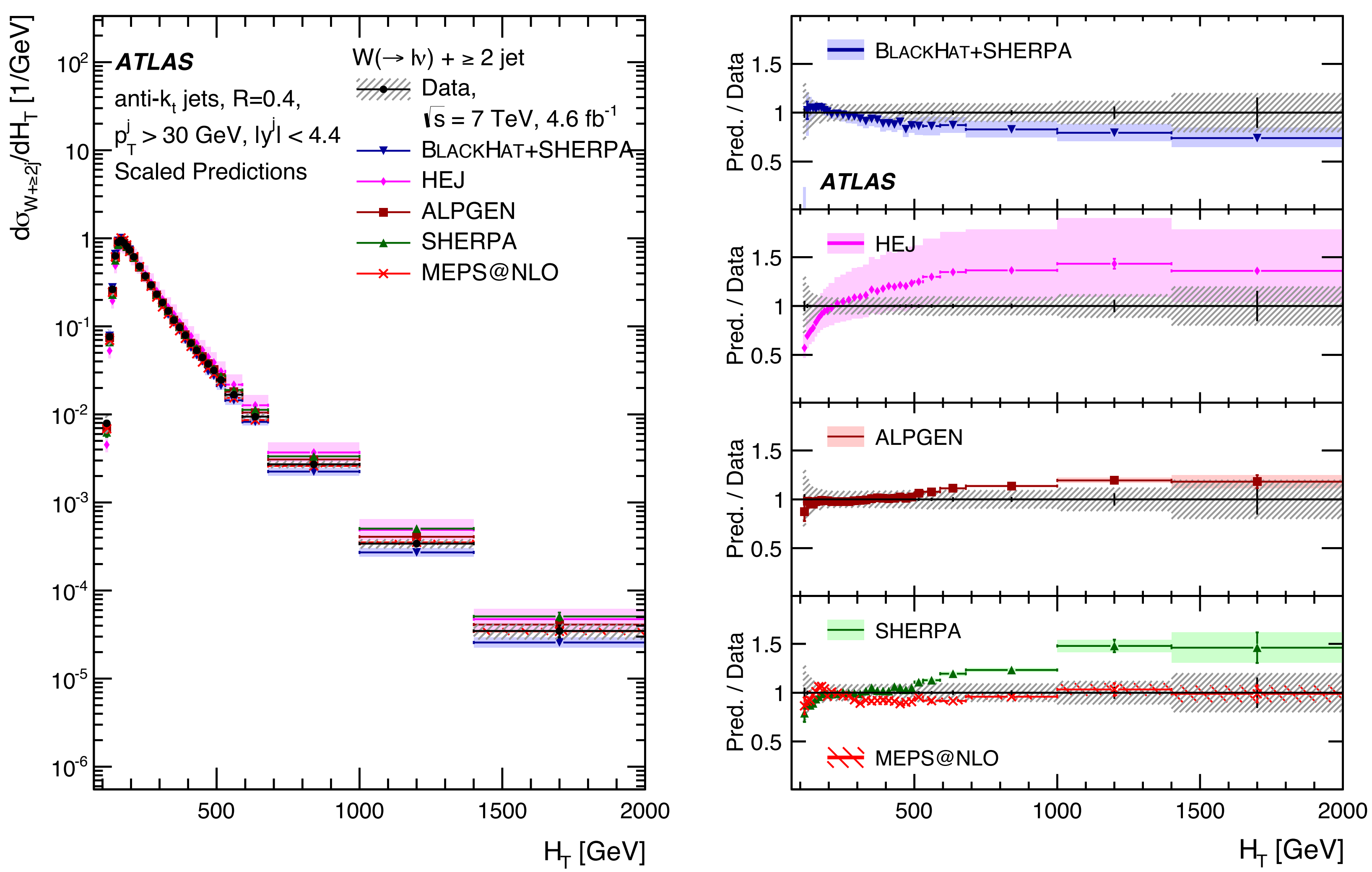


The logs uniquely described in HEJ become increasingly important as m_{12} increases. Seen here where the HEJ prediction remains flat while others deviate.

ATLAS W+Jets arXiv:1409.8639

However, other variables require evolution in p_T
E.g. Large H_T = sum of transverse momentum of visible particles

arXiv:1409.8639



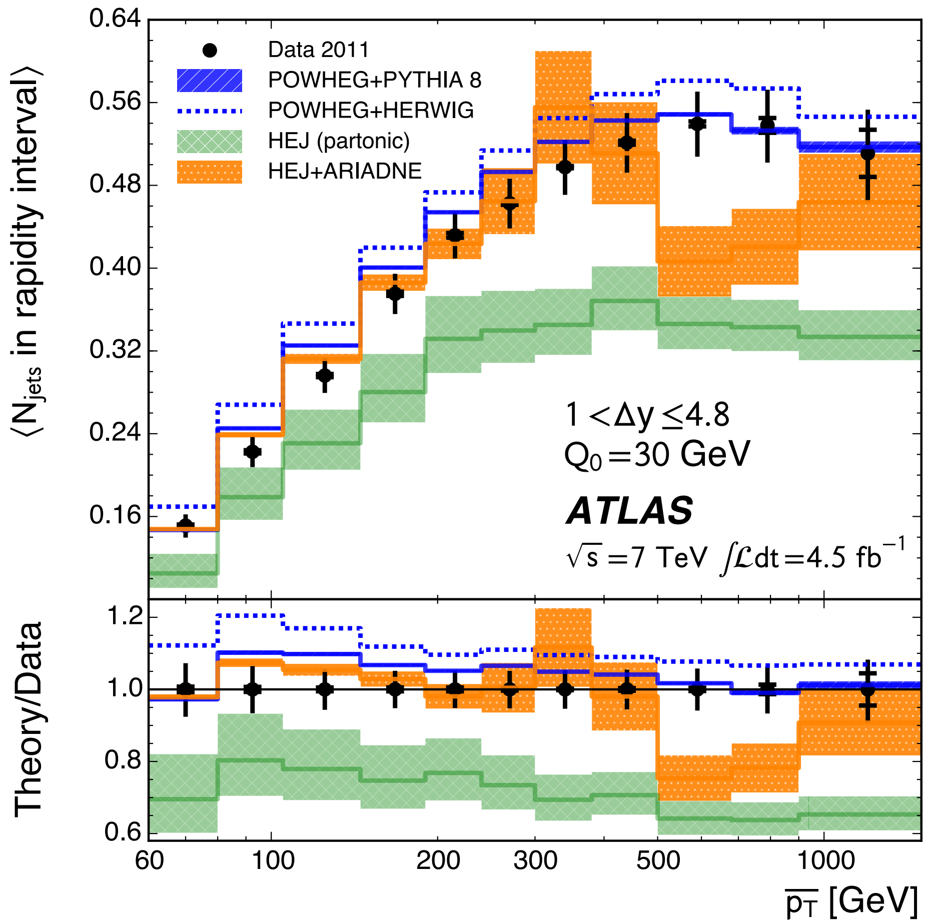
No single tool gives good description of all variables for this simple SM process

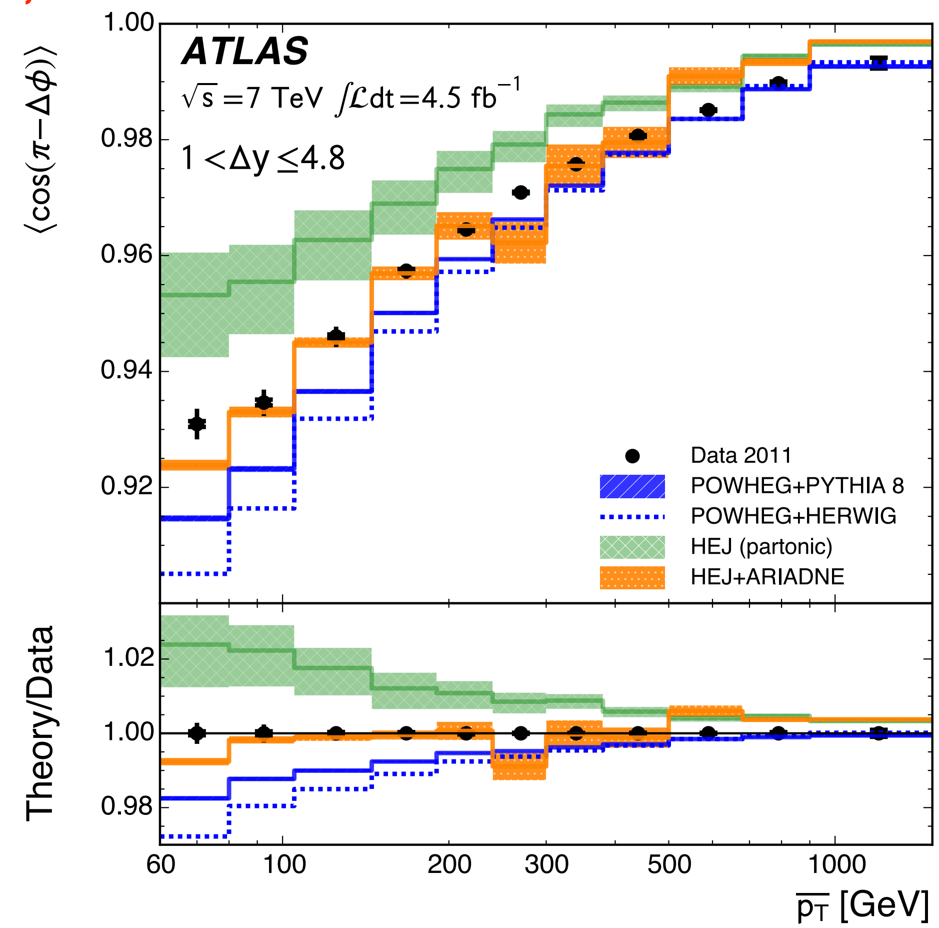
clear need for a combination of all effects

Combining with Parton Shower

Green = “pure” HEJ, orange = HEJ + Ariadne (parton shower), blue = POWHEG

Andersen, Lönnblad, JMS arXiv:1104.1316 **ATLAS arXiv:1405.5756**



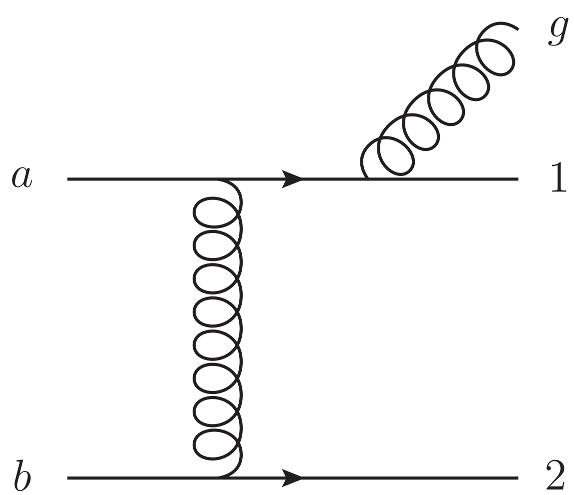


Analysis clearly testing shower effects as effects are large.
But **also** clear still need HEJ corrections to describe some distributions.

Improved HEJ+PS models important direction of ongoing work **Andersen, Brooks, Lönnblad; Bothmann, Höche**

In HEJ itself…

- Have seen HEJ description worsens in regions where matching component is more significant, e.g. large momentum
- Description already leading-log in inclusive dijets, but is <u>not</u> leading-log for all subprocesses
- Adding these will move more of the cross section into part subject to resummation

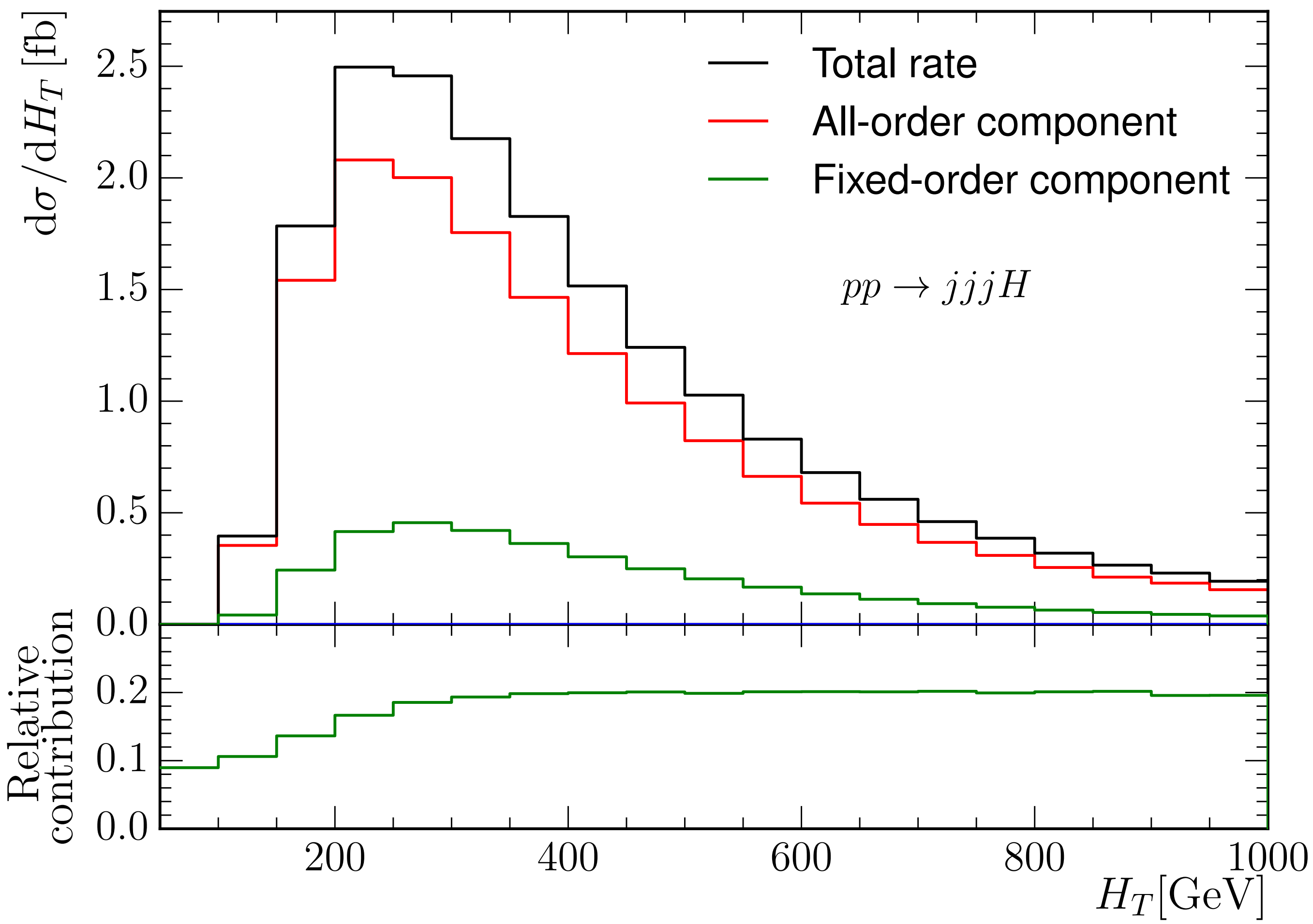


$+ \ldots$

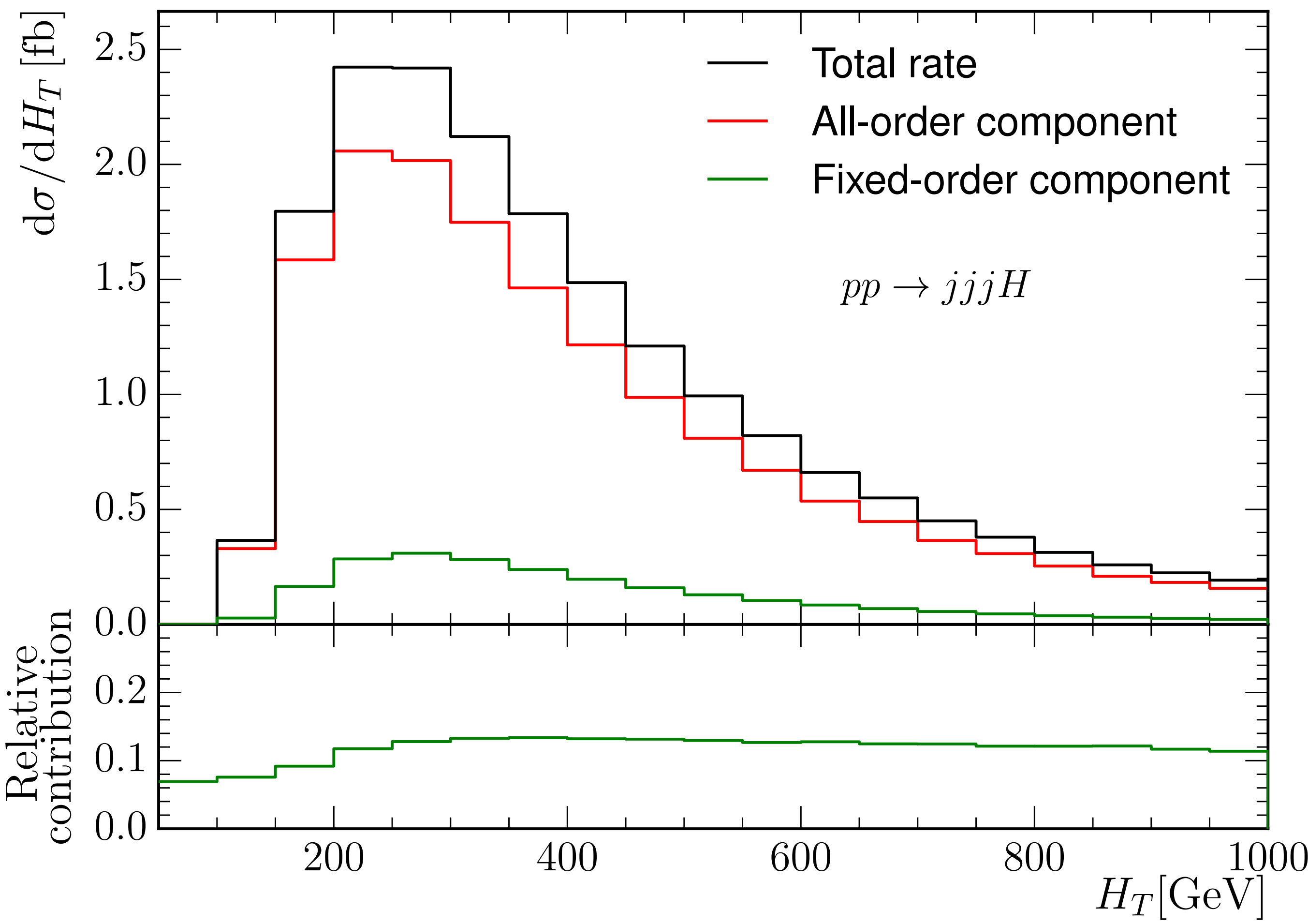
Example 1: allow a gluon emission outside in rapidity of a quark

Impact in Higgs+jets

Without unordered resummation



With unordered resummation

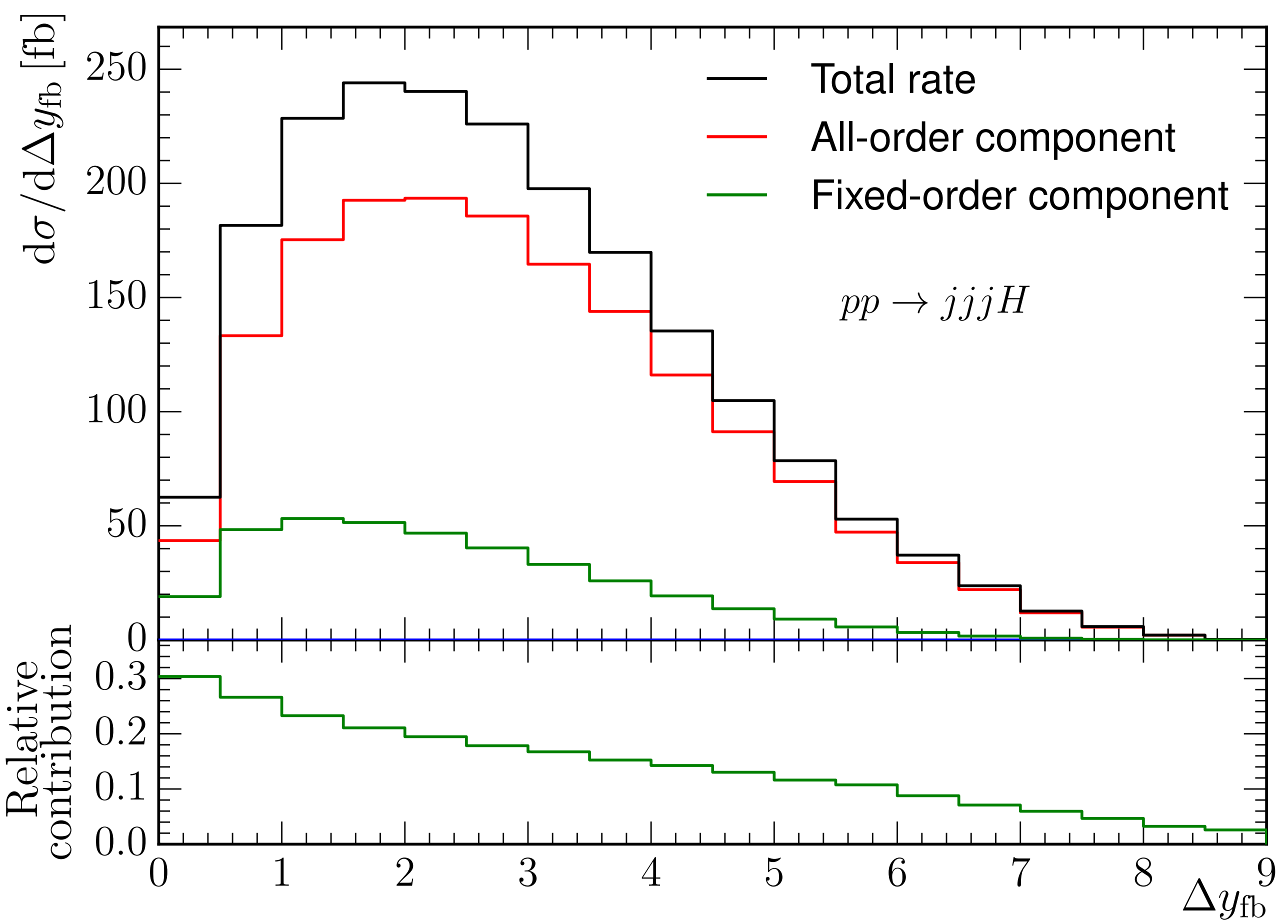


Fixed order component reduced from ~20% to ~12%

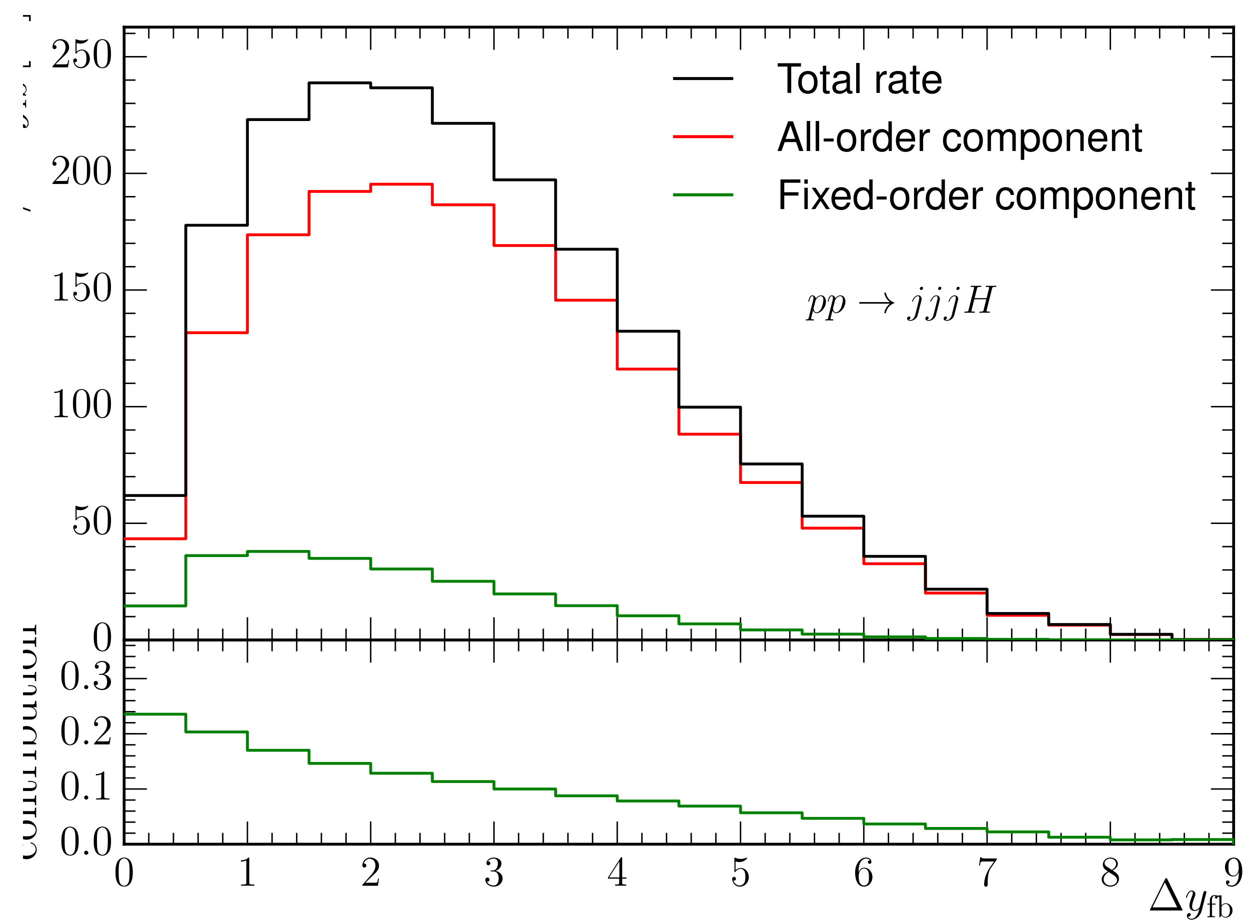
Andersen, Maier, JS: to appear

Impact in Higgs+jets

Without unordered resummation



With unordered resummation



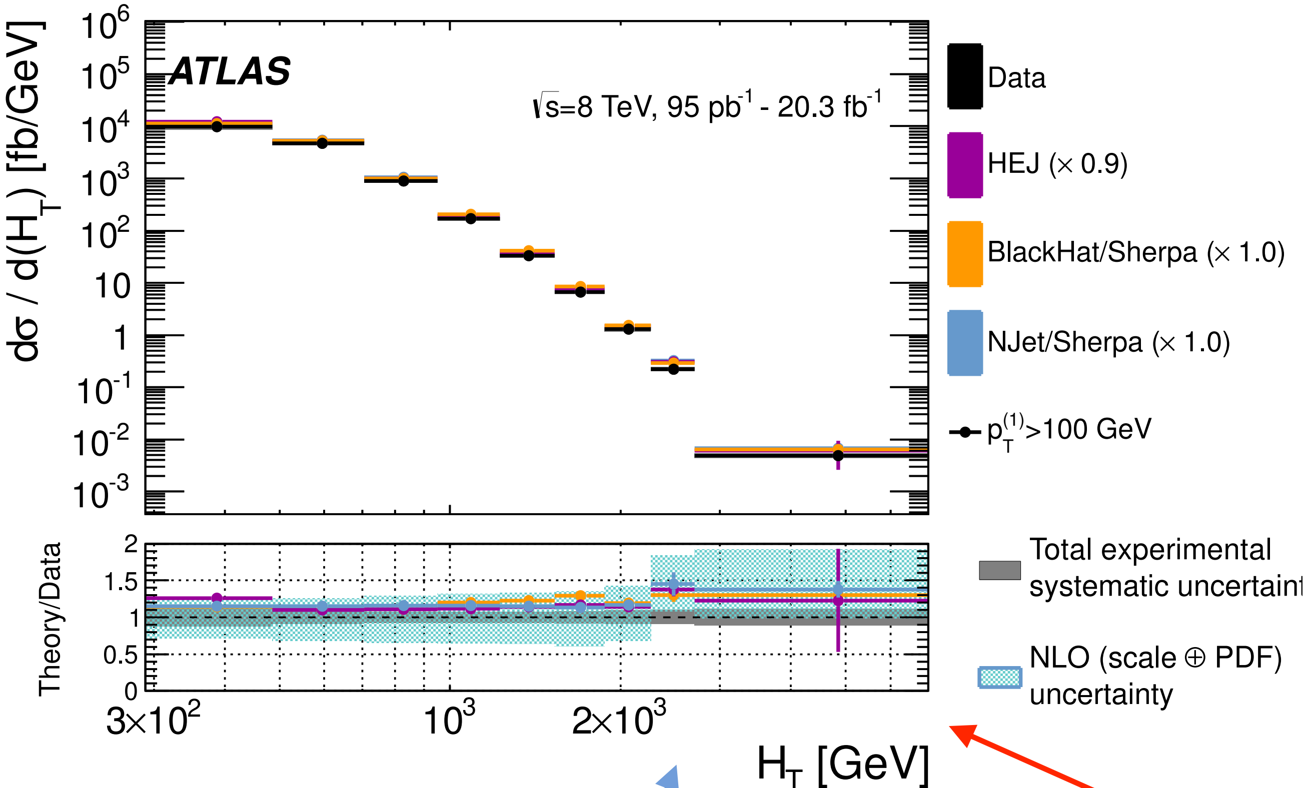
Drop with Δyfb illustrates dominant LL in HE limit in all-order part

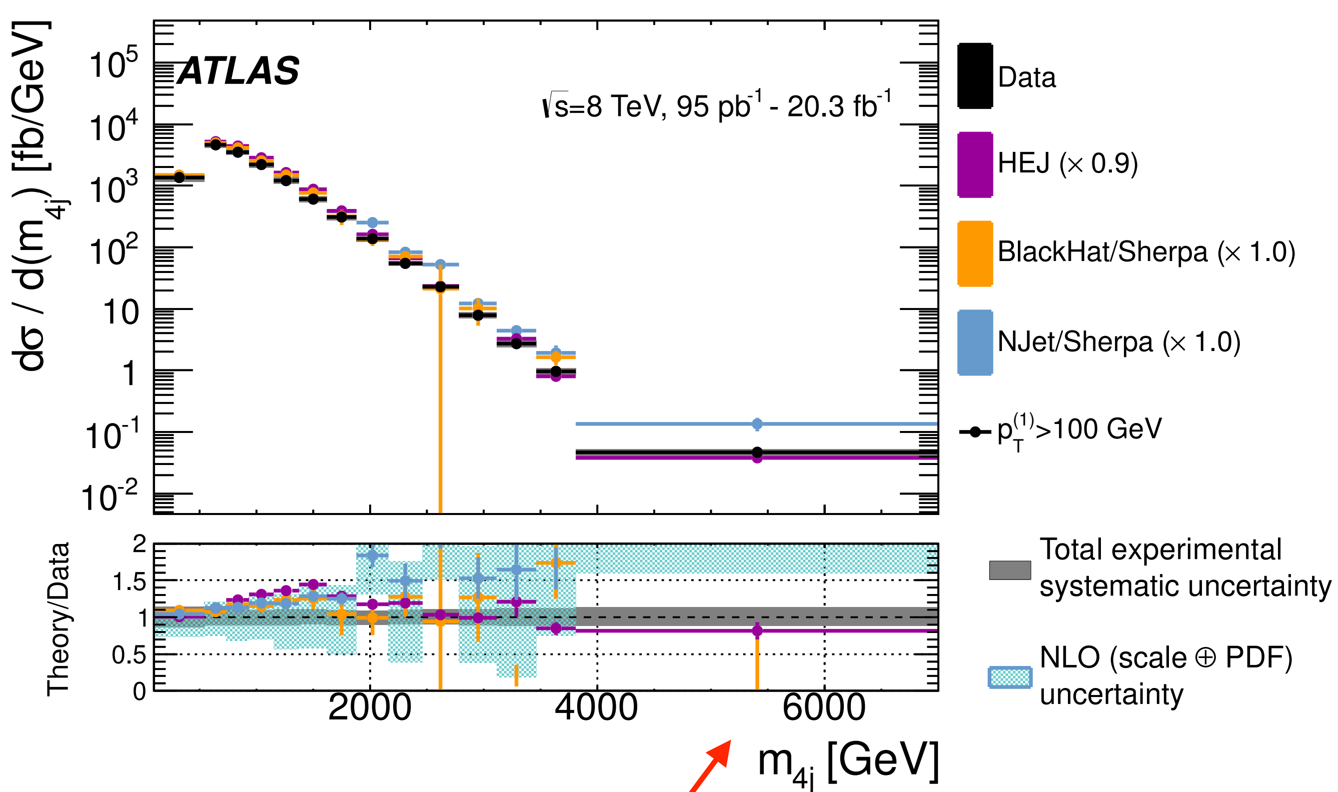
With un-ordered correction, fixed-order starts lower and drops faster

Andersen, Maier, JS: to appear

ATLAS 4-Jets arXiv:1509.07335

The first exp. analysis where HEJ predictions include this correction





Large momentum usually difficult region for HEJ: good description now

Very high energies measured (already at Run I)

Conclusions

CMS Experiment at the LHC, CERN
Data recorded: 2015-Sep-28 06:09:43.129280 GMT
Run / Event / LS: 257645 / 1610868539 / 1073

- Huge phase space for extra hard jets & enhancements of higher-order coefficients damage convergence of pert. exp.

- The effect is already seen in Run I LHC data!
  Will be more important at Run II and beyond

- We **must** allow for this in our theoretical predictions — High Energy Jets offers a solution (in flexible MC)

- First sub-leading corrections and new HEJ+Pythia improving HEJ approach further still, with more to come

- This is a theory challenge, but interesting physics!