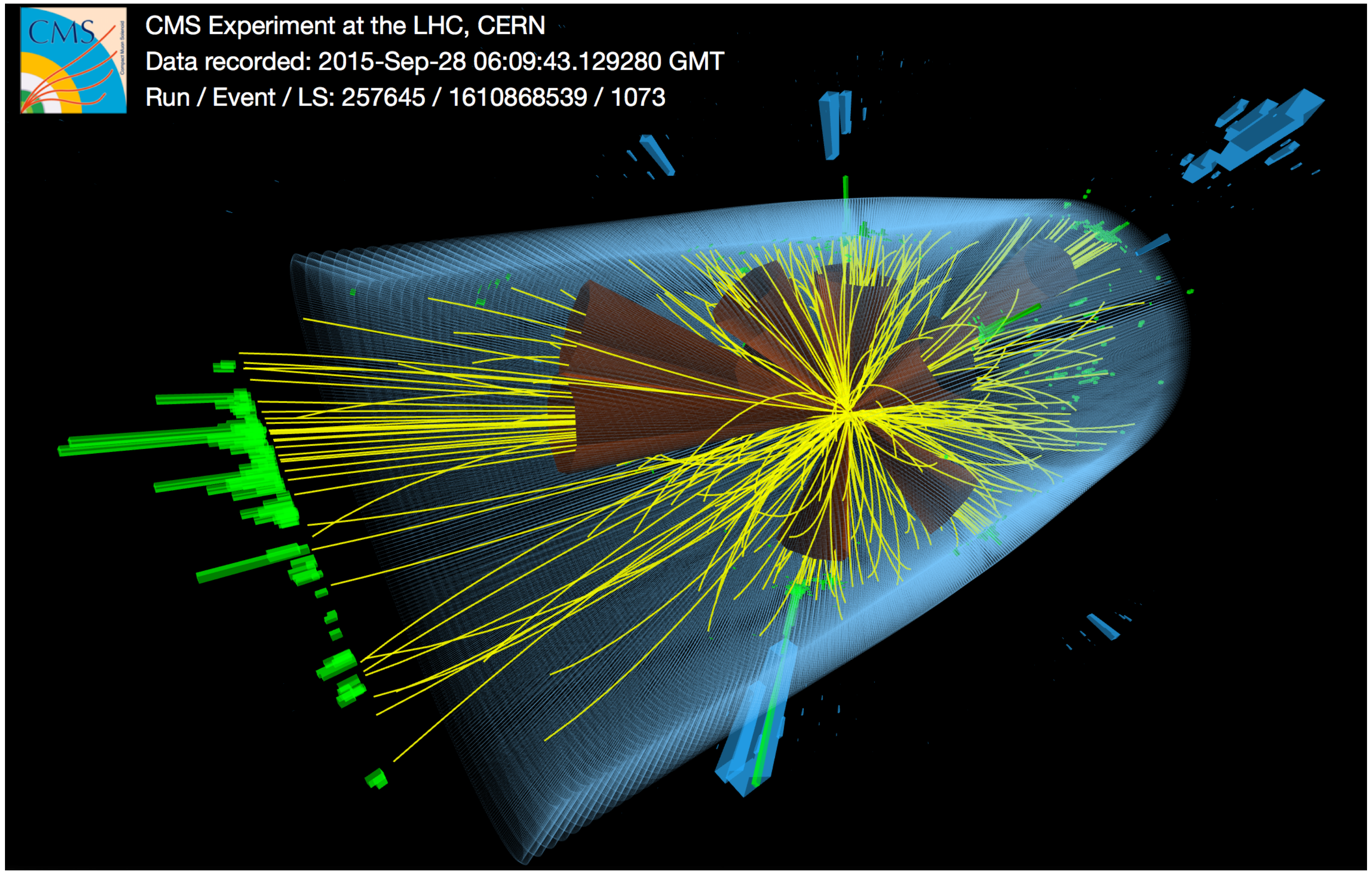
High Energy Jets (HEJ)
MCnet Overview Talk



Jenni Smillie

wishing Jeppe Andersen a speedy recovery

The University of Edinburgh
Higgs Centre for Theoretical Physics

HEJ People

Part of the MCNet “Durham team”:

James Black

Helen Brooks

James Cockburn

Jack Medley

Tuomas Hapola

Andreas Maier

Jeppe Andersen

Jenni Smillie

The High Energy Problem

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

↑ **Many** ↑ **Hard**

The High Energy Problem

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↑ **Many** ↑ **Hard**

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

- 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, …

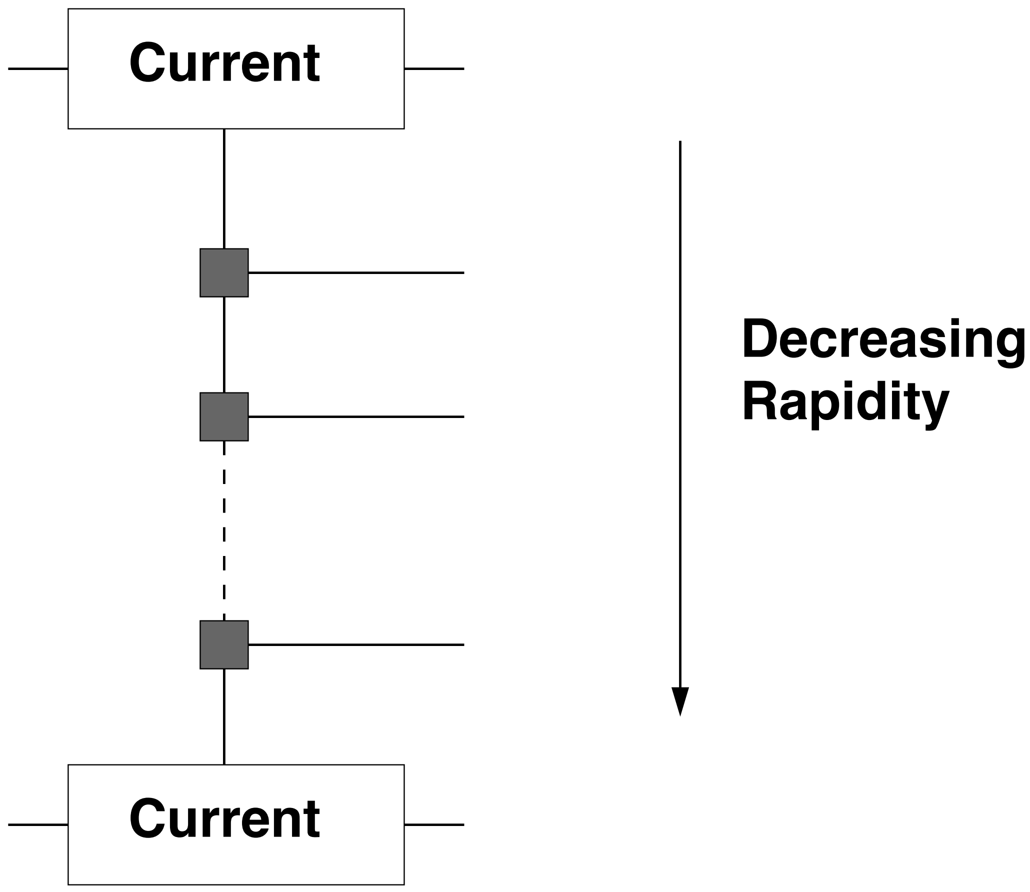
High Energy Jets (HEJ)

However, amplitudes themselves become simpler in the "high energy" limit

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

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

Main Equations

Squared Matrix Element

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

Cross Section

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

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

Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394

Main Equations

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

Skeleton/Born Process

Resolved Real Emissions

Virtual + Unresolved Real (finite)

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

Merging

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

Matching

Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394

HEJ Principles

The HEJ description is:

- exact for simple processes (2 to 2 (+X))
- gauge invariant in all phase space
- sufficiently fast for numerical integration (up to 30 gluons)
- accurate to leading logarithm in s/t
- merged with LO samples for 2j, 3j and 4j

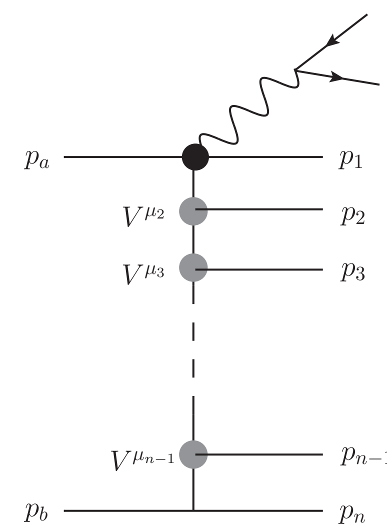
Result: fully flexible (exclusive) MC event generator for
jets, W+dijets, H+dijets, Z+dijets
compatible with LHAPDF, Rivet, fastjet, …

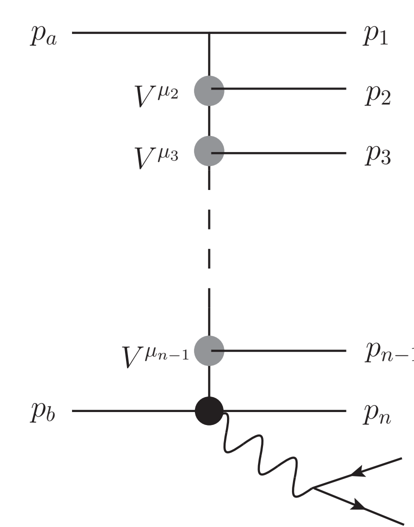
http://cern.ch/hej

Four Years in a Slide

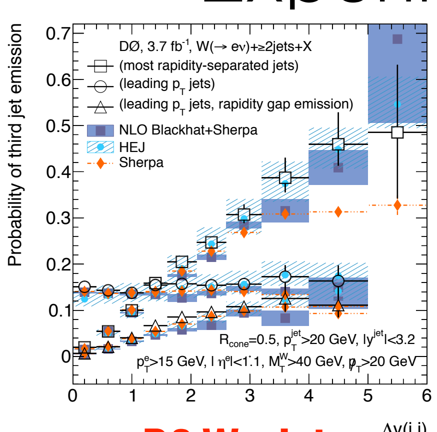
Theory developments:

- Unordered emissions
- Z plus dijets
- HEJ + Parton Shower

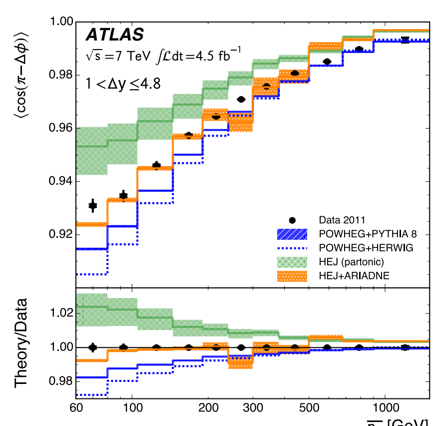




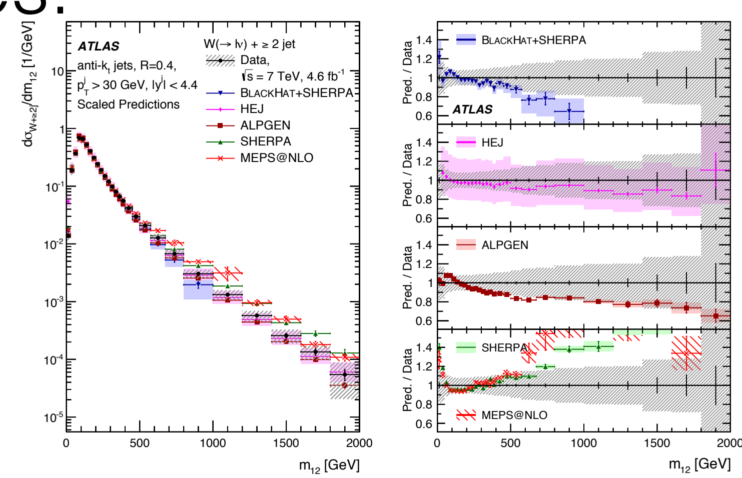
Experimental Analyses:



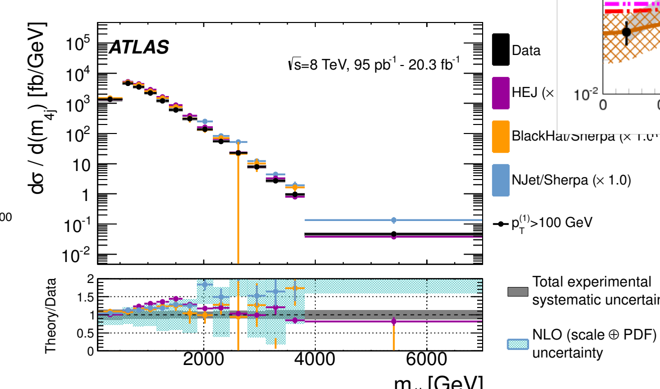
D0 W+Jets
arXiv:1302.6508



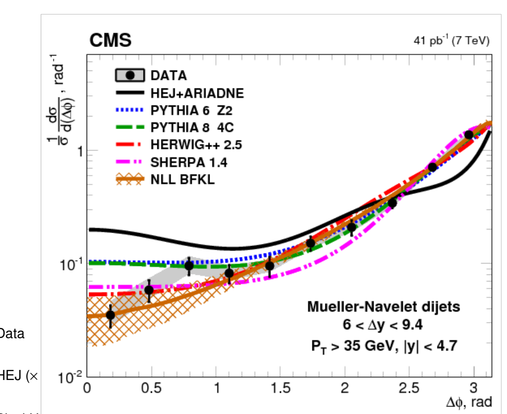
ATLAS Jet Vetos 2
arXiv:1407.5756



ATLAS W+Jets
arXiv:1409.8639



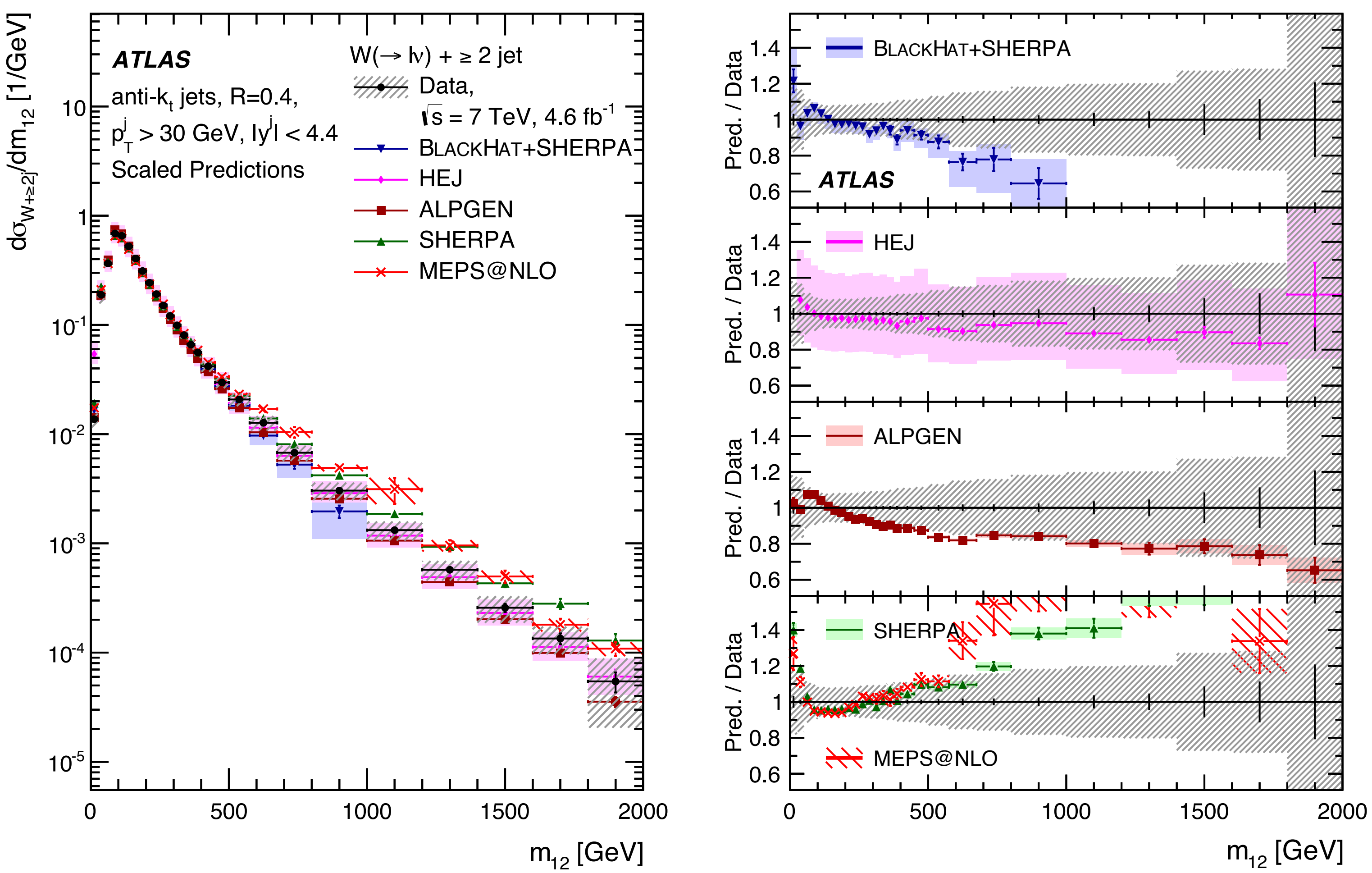
ATLAS 4-Jets
arXiv:1509.07335



CMS Dijets
arXiv:1601.06713

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.

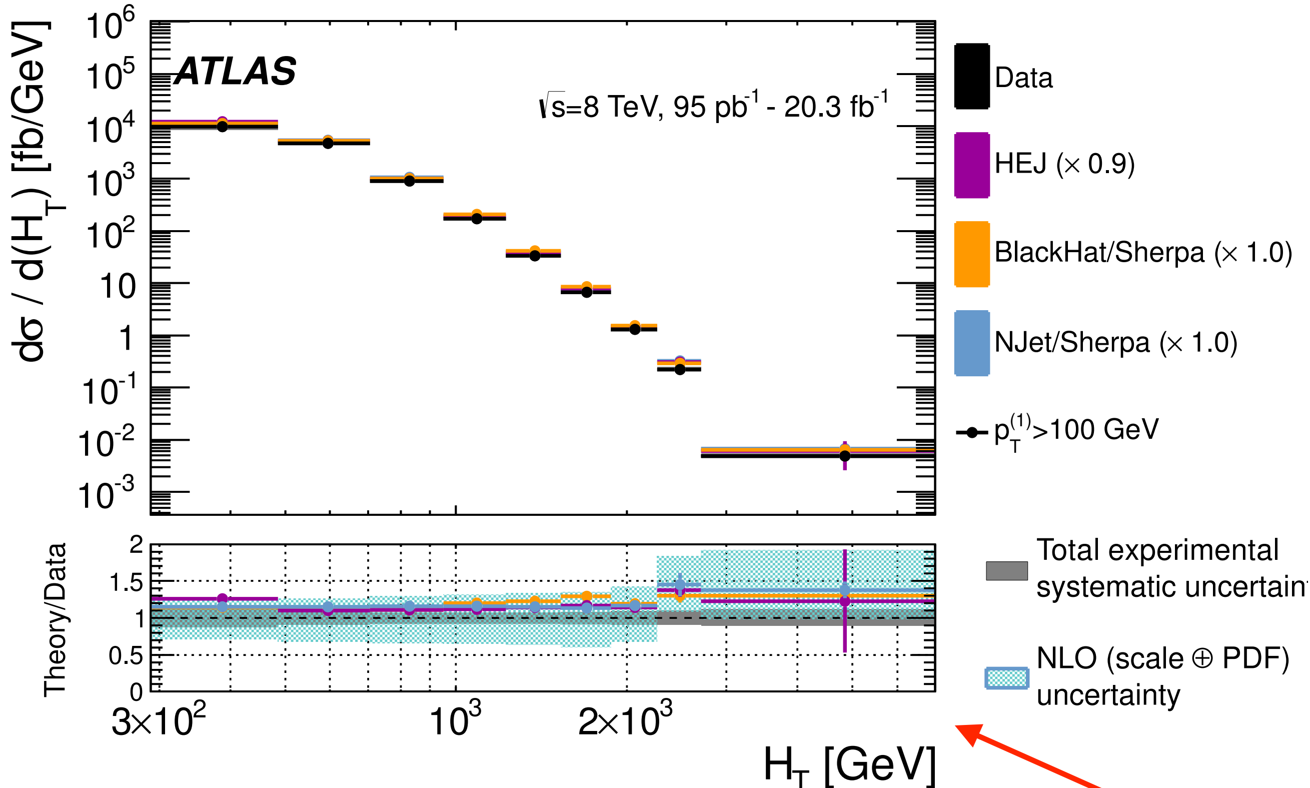


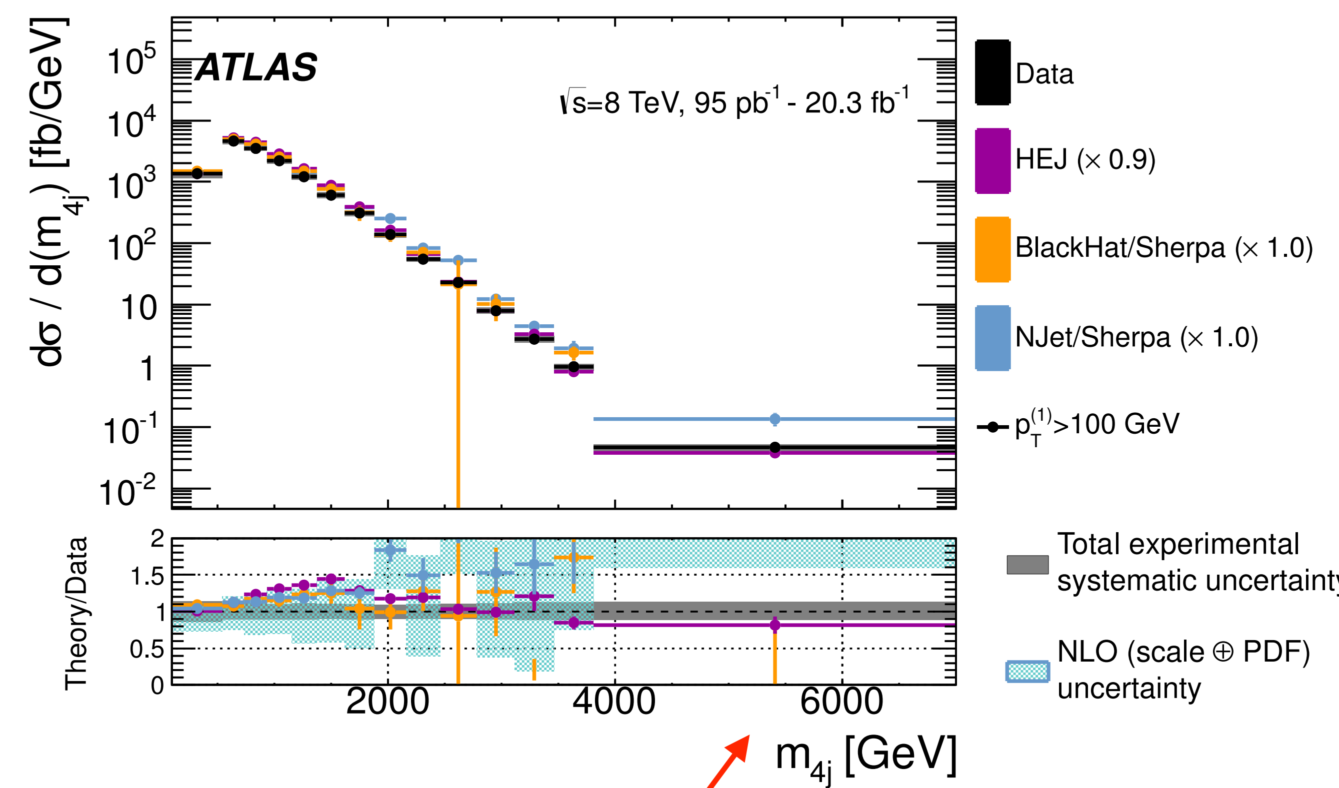
Some distributions show similar levels of agreement across descriptions.

Others show worse agreement with HEJ: improved by including sub-leading corrections (ongoing work).

ATLAS 4-Jets arXiv:1509.07335

The first exp. analysis where HEJ predictions include subleading corrections:
Reduces dependence on matching component





Large momentum usually difficult region for HEJ: good description now

Very high energies measured (already at Run I)

ATLAS 4-Jets arXiv:1509.07335

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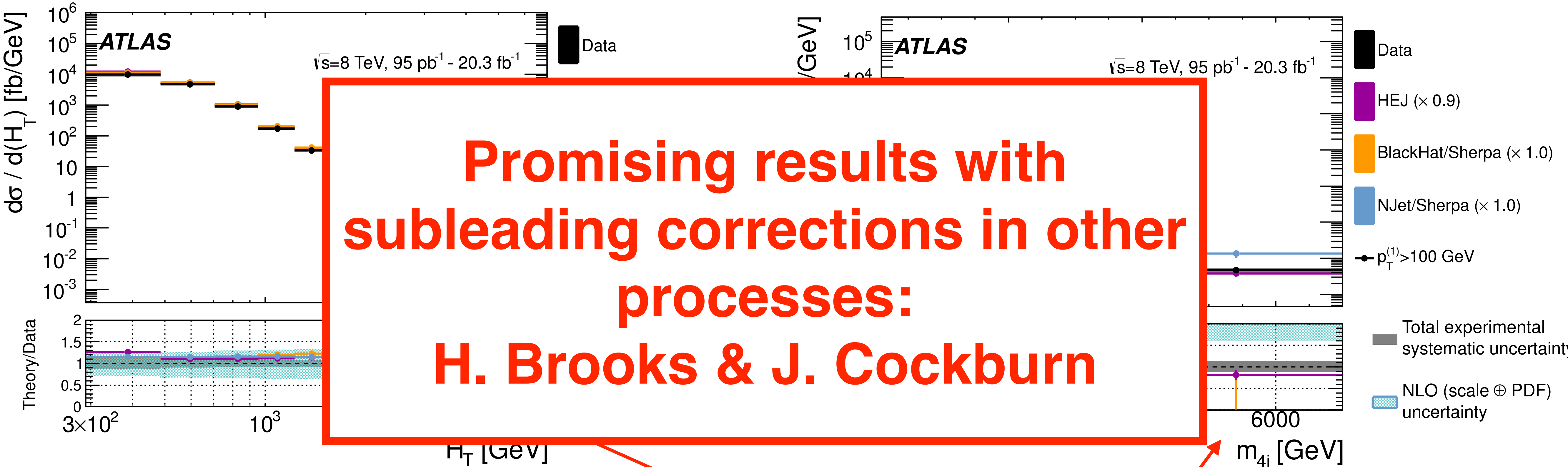


Promising results with subleading corrections in other processes: H. Brooks & J. Cockburn

Large momentum usually difficult region for HEJ: good description now

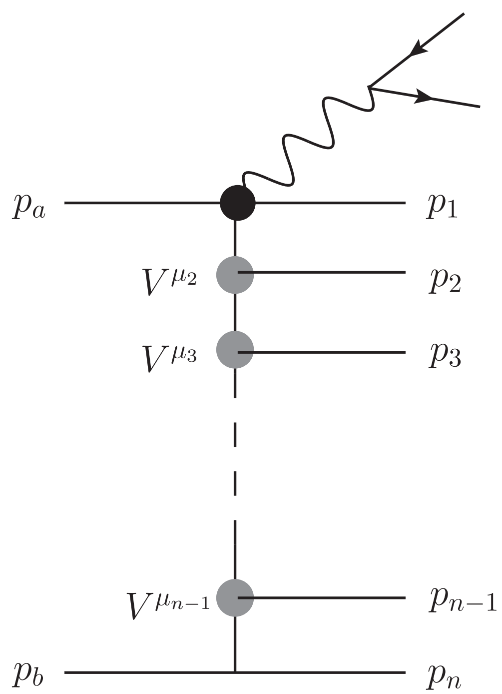
Very high energies measured (already at Run I)

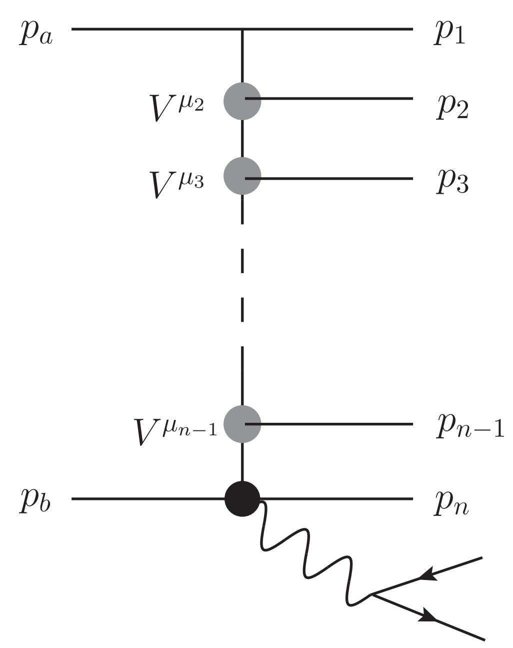
Z/γ^*+Jets

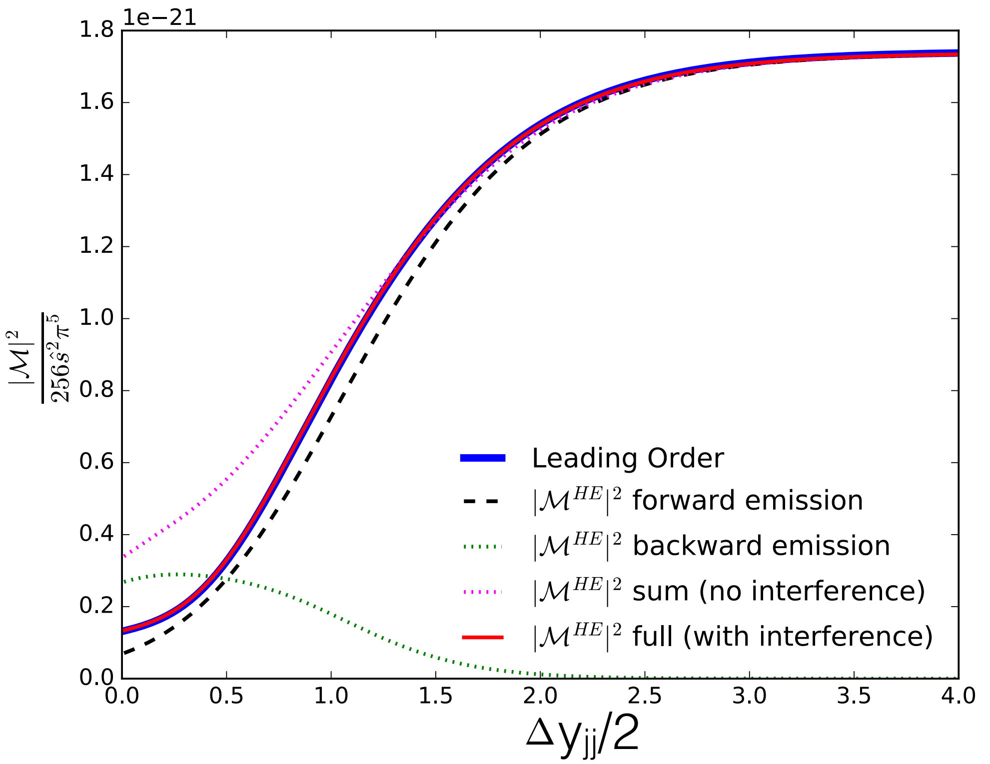
Interference effects from quark lines mean more complicated than W+Jets

New results extend HEJ method to Z plus jets

Andersen, Medley, JMS arXiv:1603.05460





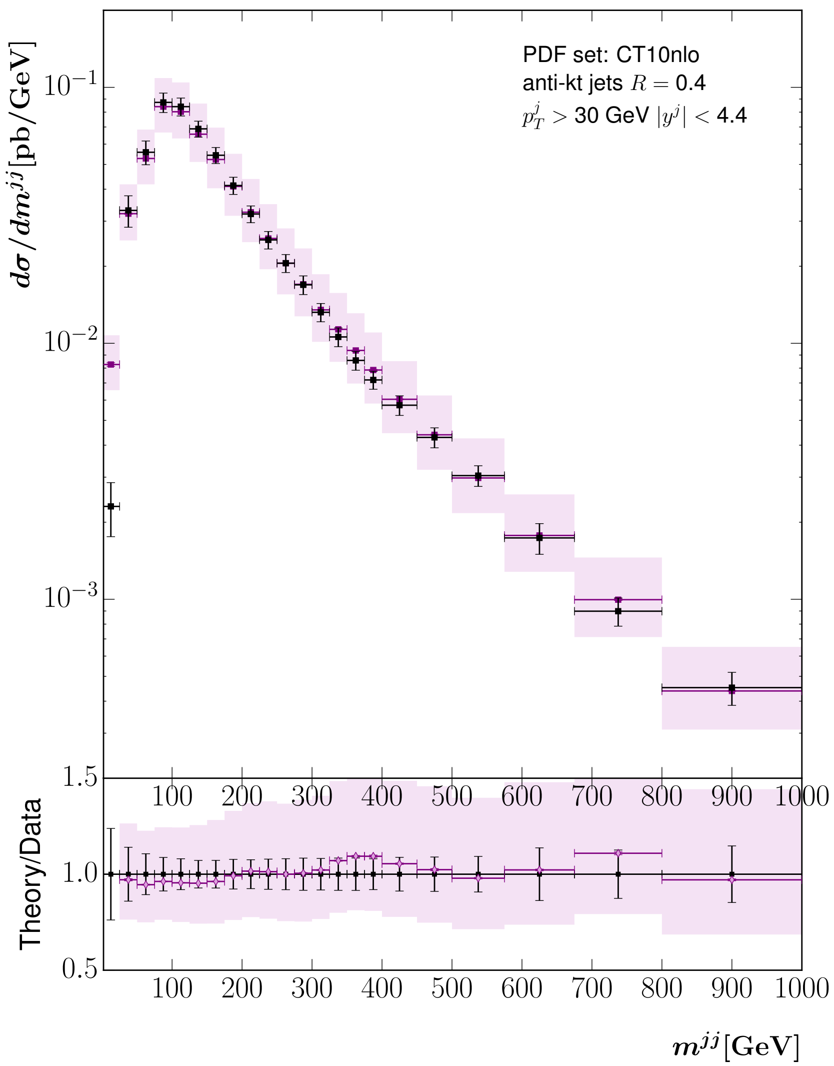


Only able to do this because we operate on the amplitudes and not amp-squared

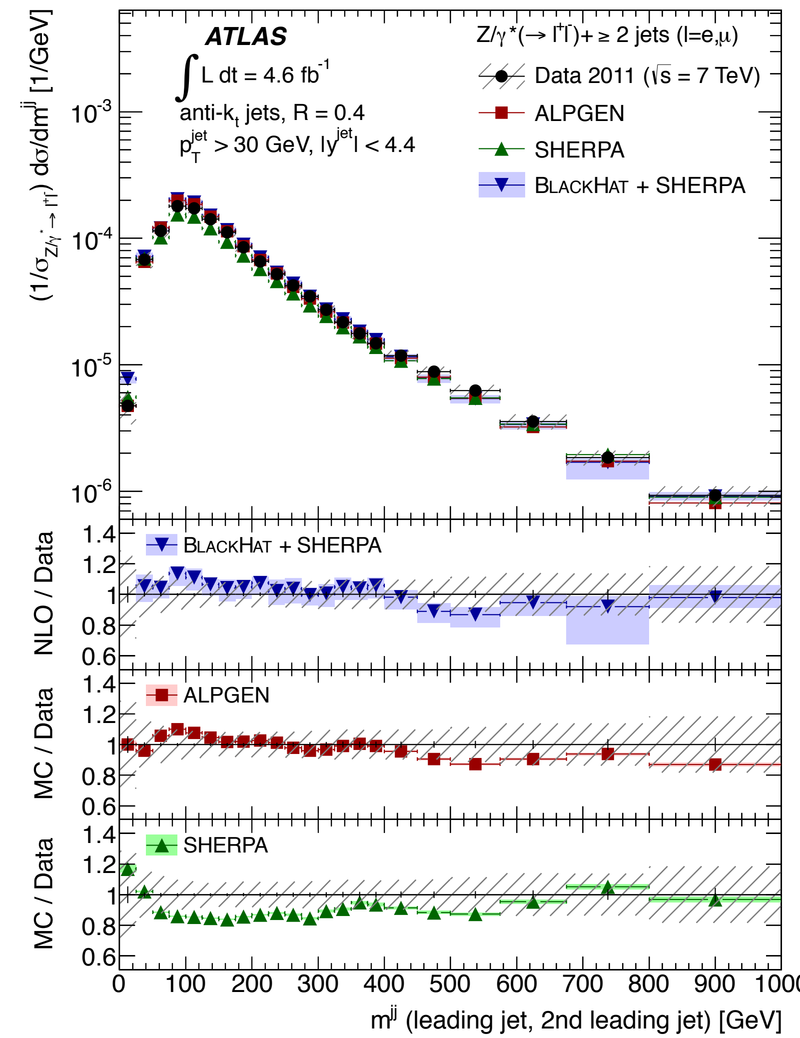
Includes interference terms missing in e.g. electroweak shower

Z+Jets vs Data

Andersen, Medley, JMS arXiv:1603.05460



ATLAS arXiv:1304.7098



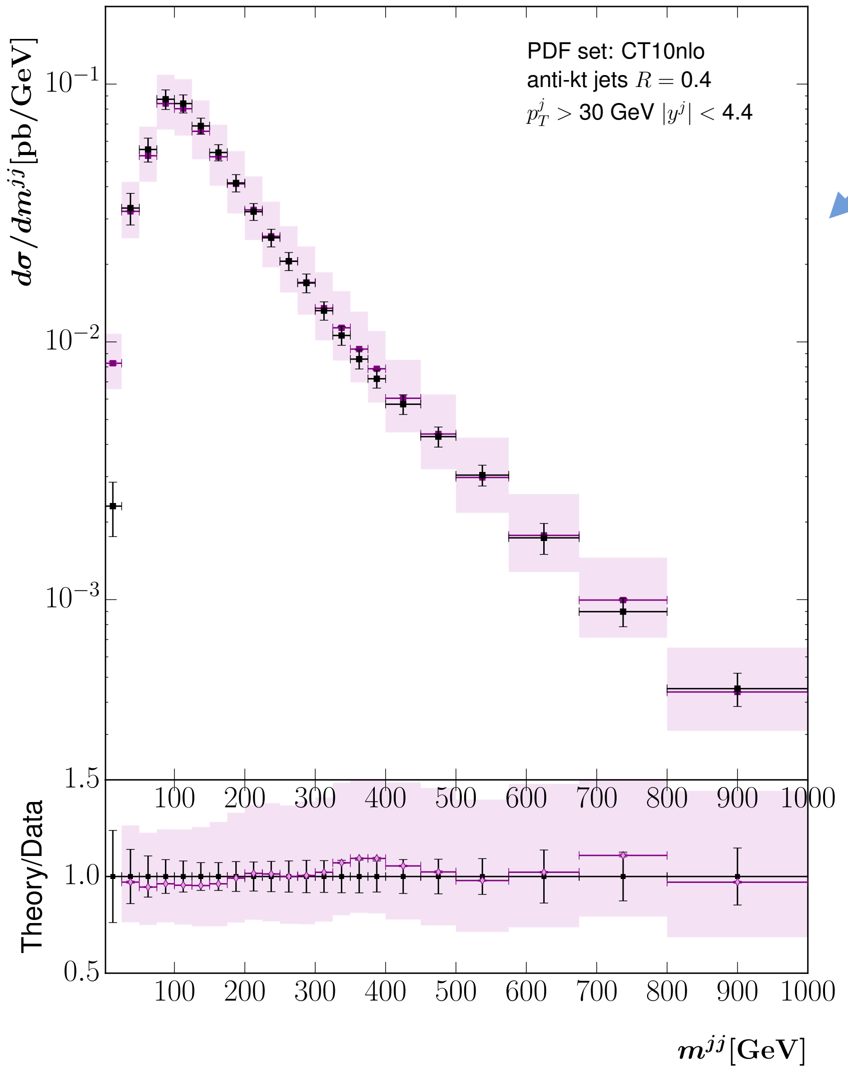
HEJ gives good description in this process too

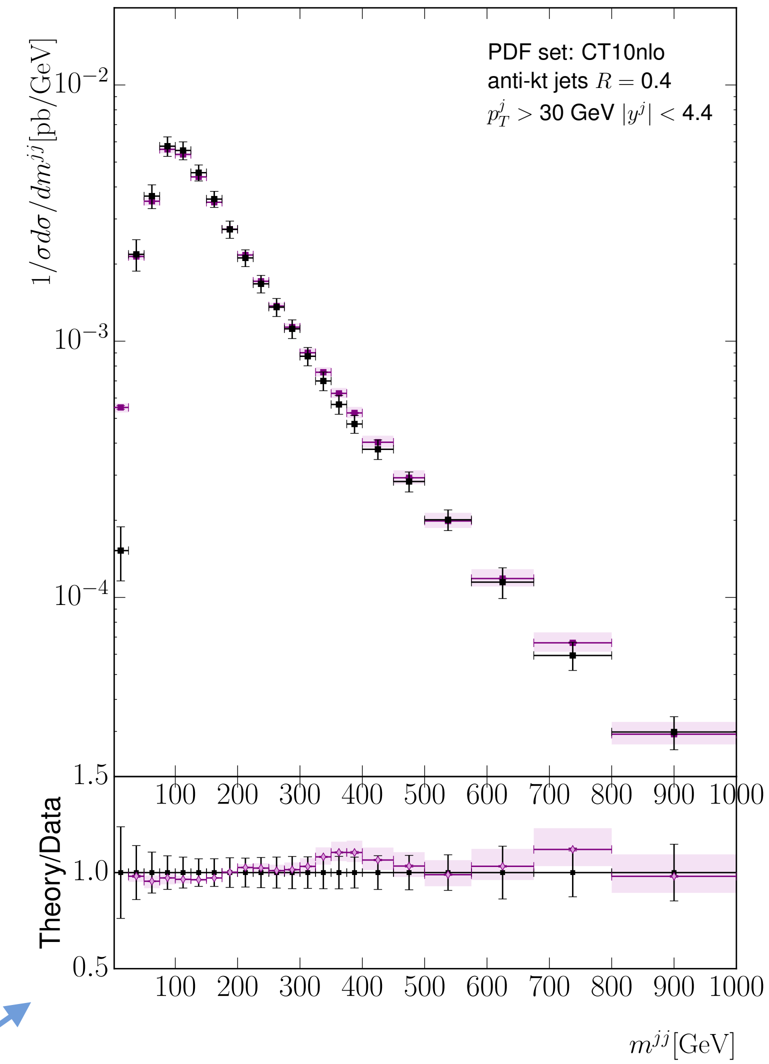
Note range is only half of earlier W + dijets

Z+Jets

We don't need to normalise to give good agreement

Andersen, Medley, JMS arXiv:1603.05460



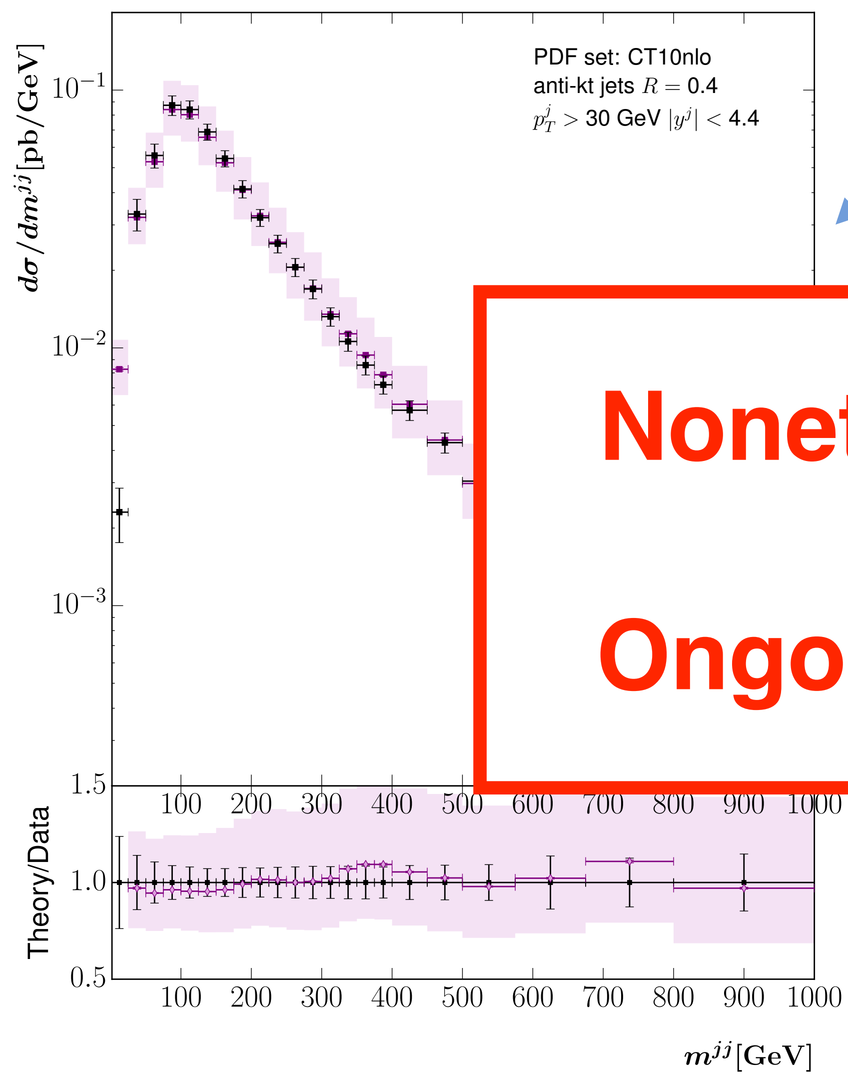


When normalise, theory uncertainty massively reduced; agreement still as good.
Agreement of central line is significant despite large band

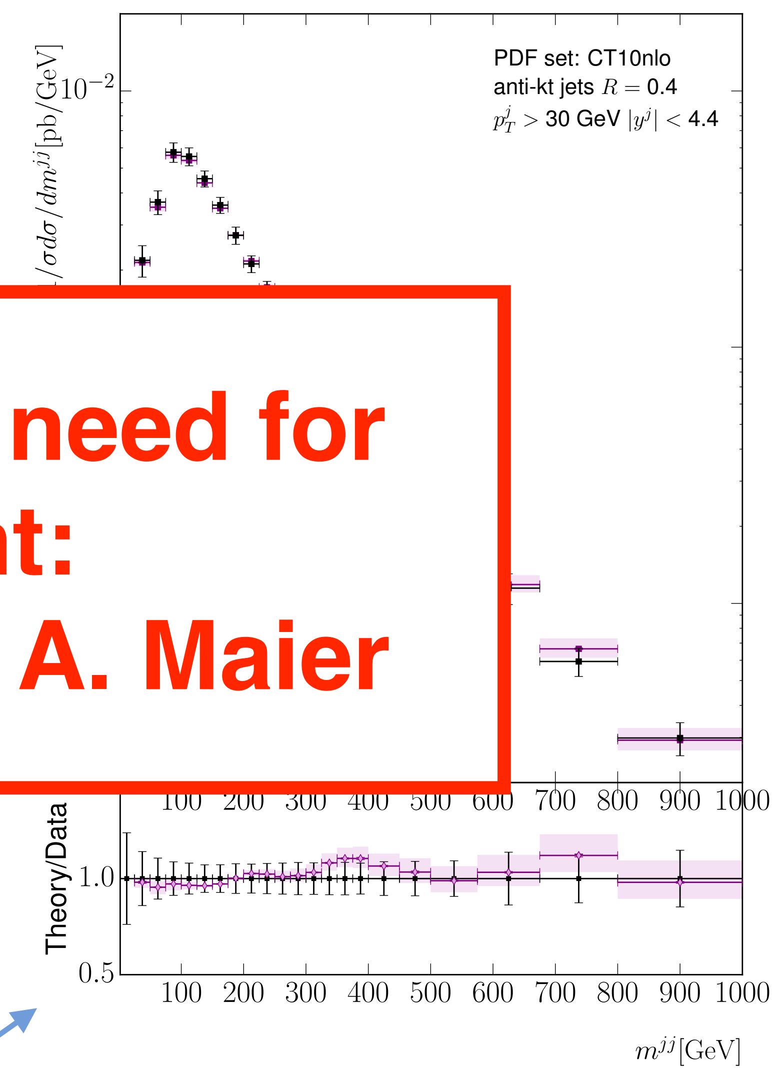
Z+Jets

We don't need to normalise to give good agreement

Andersen, Medley, JMS arXiv:1603.05460



Nonetheless, clear need for improvement:
Ongoing work with A. Maier



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Combining with Parton Shower

Parton shower sums large contributions at small s_{ij}

HEJ sums large contributions at large s_{ij}

HEJ + Ariadne

Andersen, Lönnblad, JMS arXiv:1104.1316

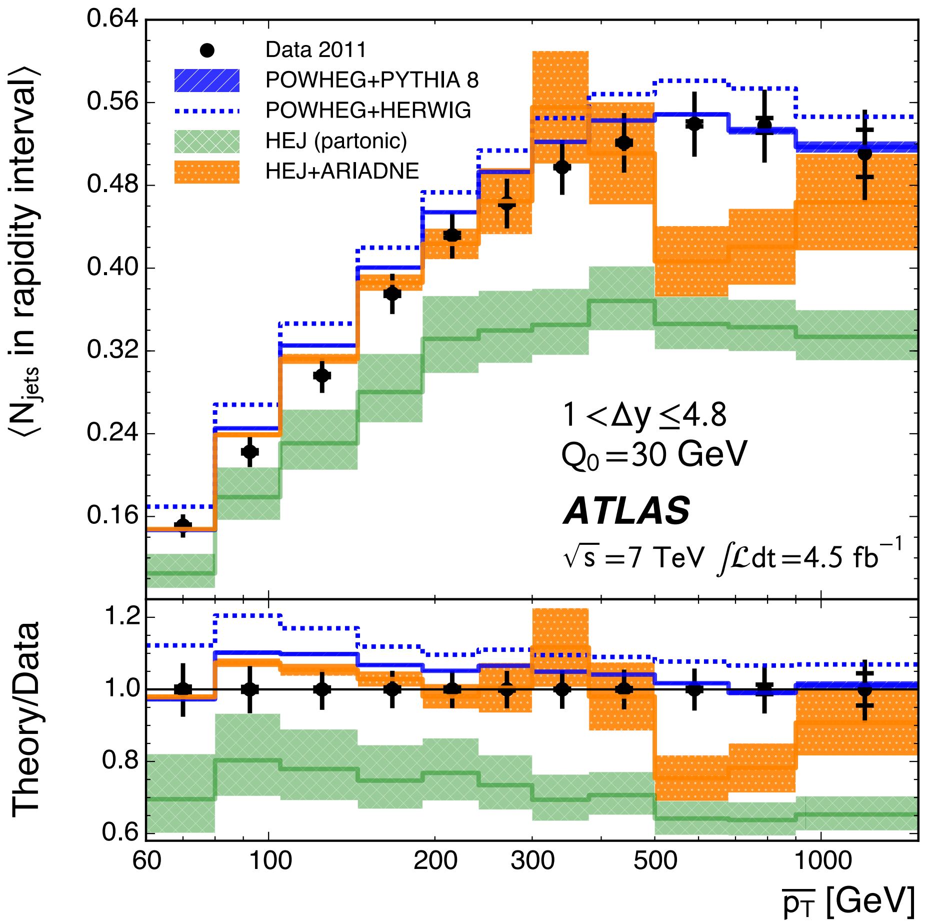
- Systematically removes overlap region (mostly soft)
- But number of HEJ emissions restricts PS phase space

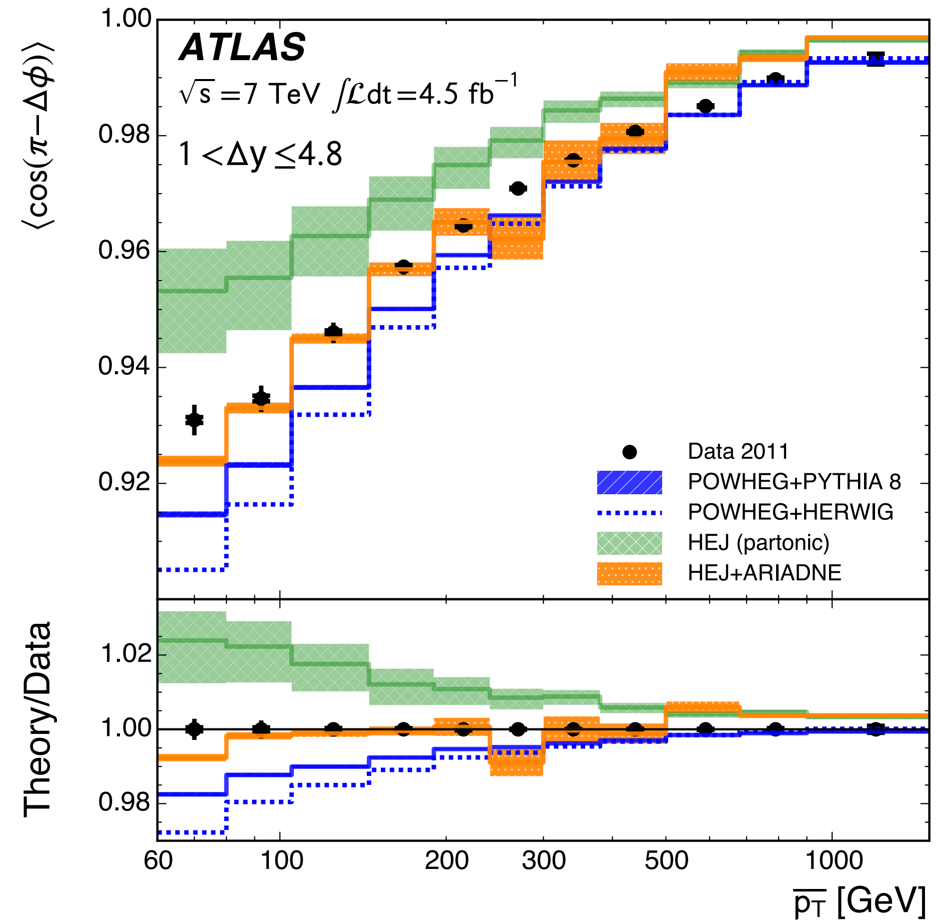
Andersen, Brooks, Lönnblad: New merging algorithm to address this (MCNet studentship)

Combining with Parton Shower

Green = “pure” HEJ, orange = HEJ + Ariadne, blue = POWHEG

ATLAS arXiv:1405.5756





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

See also ATLAS 1107.1641, CMS 1202.0704, 1204.0696, 1601.06713, D0 1302.6508

Conclusions

- Huge phase space for extra hard jets, and for enhancements of higher-order coefficients which damage convergence of fixed-order expansion

- The effect is already seen in 7 TeV LHC data!
  Will be more important at 13 TeV and FCC

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

Immediate Priorities:

- Subleading corrections in wider applications
- HEJ + Parton Shower
- NLO accuracy