Recent Developments with High Energy Jets (HEJ)

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Outline of presentation

- Overview of the High Energy Jets framework
  - Construction of high energy $2 \to n$ scattering amplitudes with leading log accuracy in $\frac{s}{t}$
- Recent developments in the HEJ2 framework
  - Added support for new processes of interest
  - Improvements to already supported processes at subleading logarithm
- Upcoming code release

arXiv:1902.08430 - Andersen, Hapola, Heil, Maier, Smillie

Overview of the HEJ formalism - I

$$\sigma_{inc} = \int \mathrm{d}\Phi_2 |\mathcal{M}|^2$$

For QCD inclusive $2 \to 2$ scattering, the cross section is given by the integral of the squared matrix element which is usually calculated to some order in α_s.

$$\sigma_{inc} = \alpha_s^2(\mathcal{K}_0) \quad \text{LO}$$
$$+\alpha_s^3 \left(\log\left(\frac{s}{t}\right) \mathcal{K}_{1;1} + \mathcal{K}_{1;0} \right) \quad \text{NLO}$$
$$+\alpha_s^4 \left(\log\left(\frac{s}{t}\right)^2 \mathcal{K}_{2;2} + \log\left(\frac{s}{t}\right) \mathcal{K}_{2;1} + \mathcal{K}_{2;0} \right) \quad \text{NNLO}$$
$$+\mathcal{O}(\alpha_s^5)$$

But each fixed order contains logs in s/t which will hurt the convergence of the perturbative expansion when $s \gg t$

Overview of the HEJ formalism - II

$$\sigma_{inc} = \alpha_s^2(\mathcal{K}_0) \quad \leftarrow \text{LO}$$
$$+\alpha_s^3\left(\log\left(\frac{s}{t}\right)\mathcal{K}_{1;1} + \mathcal{K}_{1;0}\right) \quad \leftarrow \text{NLO}$$
$$+\alpha_s^4\left(\log\left(\frac{s}{t}\right)^2\mathcal{K}_{2;2} + \log\left(\frac{s}{t}\right)\mathcal{K}_{2;1} + \mathcal{K}_{2;0}\right) \quad \leftarrow \text{NNLO}$$
$$+\mathcal{O}(\alpha_s^5)$$

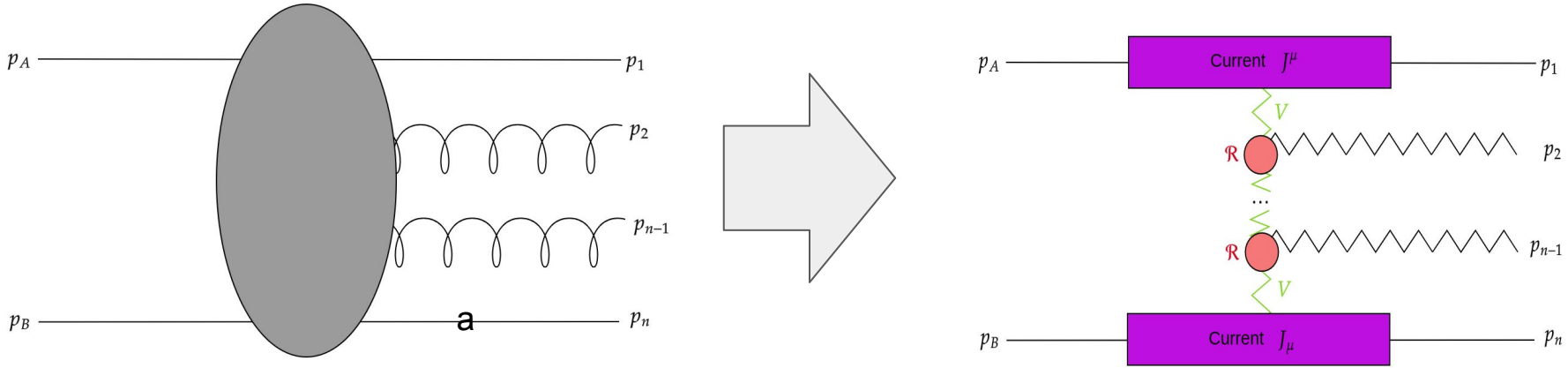
HEJ framework is designed to include all-order contributions at leading log accuracy:

$$|\mathcal{M}_{\text{HEJ}}|^2 = LO + LL(+NLL)$$

No change in phase space $\mathrm{d}\Phi$

Work in progress

Overview of the HEJ formalism - III



In the Multi-Regge Kinematic (MRK) limit,

$$\forall i, j : |p_{i\perp}| \approx |p_{j\perp}|, s_{ij} \to \infty$$

Scattering amplitudes are known to

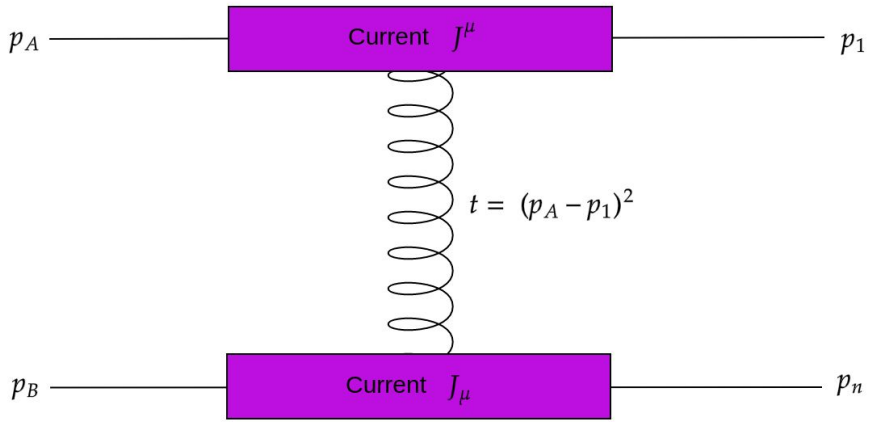
- be dominated by the t-channel singularity
- Factorise at the level of the square matrix element into distinct pieces

Overview of the HEJ formalism - IV

For $2 \to 2$ we can write the exact squared amplitude in a factorised form with

- A contraction over the currents
- An explicit t-channel pole

$$|\mathcal{M}|^2 \propto \frac{|J^\mu(p_A, p_1) J_\mu(p_B, p_n)|^2}{t^2}$$



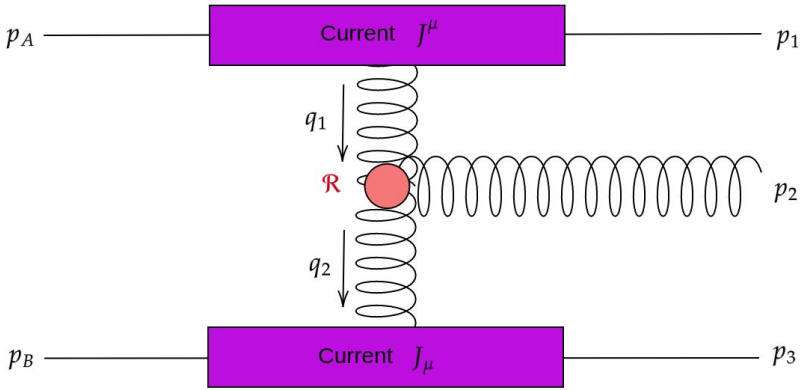
This holds for both quark and gluon processes.

Overview of the HEJ formalism - V

For each real emission we can make use of a modified effective Lipatov vertex.
Note that:

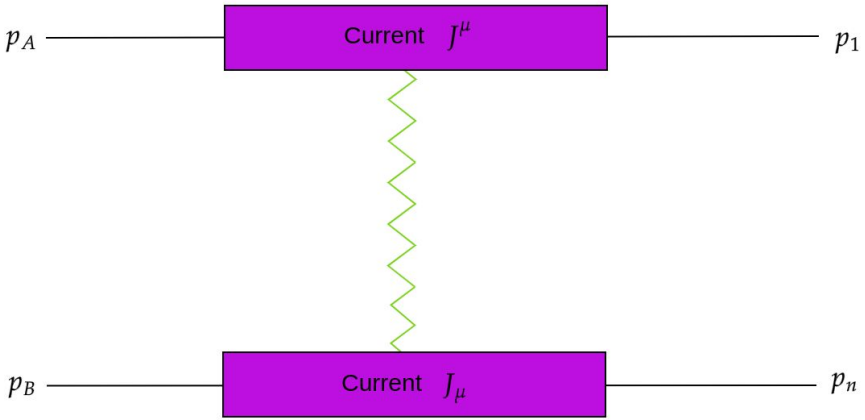
- The square amplitude is still factorised
- Each effective vertex is independently gauge invariant.

$$|\mathcal{M}|^2 \propto \frac{|J^\mu(p_A,p_1)J_\mu(p_B,p_n)|^2}{t^2} \times \left(\frac{-g^2}{t_1 t_2} V^\mu(q_1,q_2)V_\mu(q_1,q_2)\right)$$



$$\begin{aligned} V^\rho(q_1,q_2) = &-(q_1+q_2)^\rho \\ &+\frac{p_A^\rho}{2}\left(\frac{q_1^2}{p_2\cdot p_A}+\frac{p_2\cdot p_B}{p_A\cdot p_B}+\frac{p_2\cdot p_3}{p_A\cdot p_3}\right)+p_A\leftrightarrow p_1 \\ &-\frac{p_B^\rho}{2}\left(\frac{q_2^2}{p_2\cdot p_B}+\frac{p_2\cdot p_A}{p_B\cdot p_A}+\frac{p_2\cdot p_1}{p_B\cdot p_1}\right)-p_B\leftrightarrow p_3. \end{aligned}$$

Overview of the HEJ formalism - VI



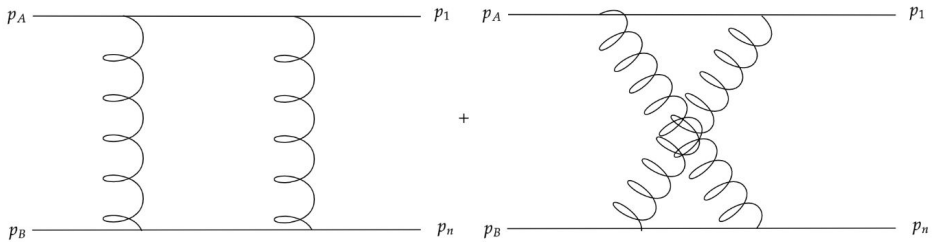
We include all order virtual corrections by "reggeising" the t-channel gluon momenta

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

$$\hat{\alpha}(q_i) = \alpha_s \, C_A \, t_i \int \frac{d^2 k_\perp}{(2\pi)^2} \frac{1}{k_\perp^2 (q_i - k)_\perp^2}$$

Motivation from virtual corrections to born level process:

$$\mathcal{M} \propto \hat{\alpha}(t) \frac{s}{t} \log\left(\frac{s}{t}\right)$$



Overview of the HEJ formalism - Master Equation

$$\overline{\left|\mathcal{M}^{\text{reg}}_{\text{HEJ}}(\{p_i\})\right|^2} = \frac{1}{4\,(N_C^2-1)}\,\|S_{f_1 f_2\to f_1 f_2}\|^2$$

Contraction of Born Level currents

$$\cdot\left(g^2\,K_{f_1}\,\frac{1}{t_1}\right)\cdot\left(g^2\,K_{f_2}\,\frac{1}{t_{n-1}}\right)$$

$$\cdot\prod_{i=1}^{n-2}\left(g^2 C_A\,\left(\frac{-1}{t_i t_{i+1}}V^{\mu}(q_i,q_{i+1})V_{\mu}(q_i,q_{i+1})-\frac{4}{\mathbf{p}_i^2}\,\theta\left(\mathbf{p}_i^2<\lambda^2\right)\right)\right)$$

Virtual corrections and unresolved real

$$\cdot\prod_{j=1}^{n-1}\exp\left[\omega^0(q_j,\lambda)(y_{j-1}-y_j)\right],$$

Resolved real emissions

$$\omega^0(q_j,\lambda) = -\frac{\alpha_s N_C}{\pi}\log\frac{\mathbf{q}_j^2}{\lambda^2}.$$

arXiv:1101:5394 - Andersen, Smillie

Performing high energy resummation with HEJ2

Fixed order input from MC event generator e.g. madgraph, sherpa, HEJfog

.lhe/.hepmc

HEJ2

- Resummation of fixed order FKL events
- Include resummation for subleading (NLL) configurations with an unordered gluon or qqbar vertex
- Include variations on a central scale choice

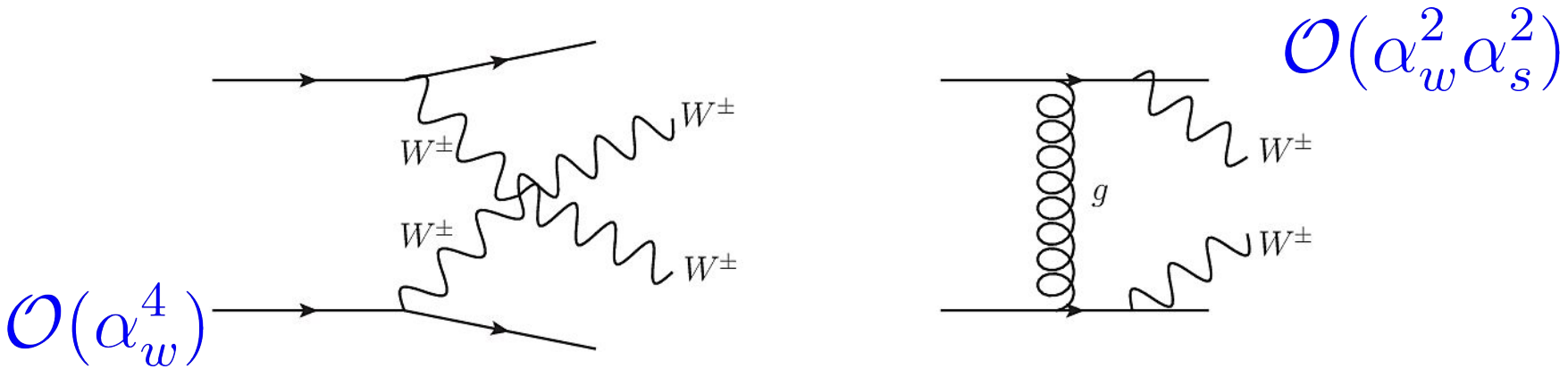
Pass resummation events to analysis framework e.g. root or rivet (natively supported).

.yoda/.root

- HEJ2 reads in events from a fixed order generator and returns resummation events to passed to an analysis framework.
- Supports a final state of qcd jets, W+jets, Z/photon + jets, Higgs + jets (where number of jets is at least 2. (At least as of release HEJ2.1)
- Can shower events with HEJ+pythia arXiv:2210.06898 - Andersen, Hassan, Jaskiewicz

Recent developments in the HEJ2 framework

Added support for new processes - same-sign WW bosons

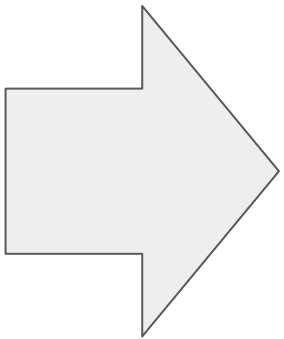


- Calculating the "QCD" $\mathcal{O}(\alpha_w^2\alpha_s^2)$ contribution to the process $pp \to W^\pm W^\pm + \geq 2j$
- This contribution is usually controlled by introducing VBS cuts in order to study the 4-W vertex, but it is important to be able to accurately describe the contribution which remains.

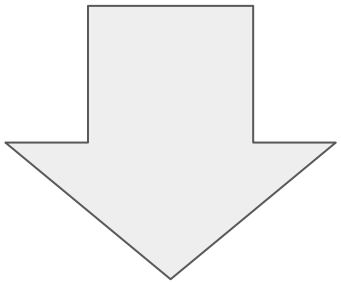
arXiv:2107.06818 - Andersen, Ducloué, CE, Maier, Nail, Smillie

Added support for new processes - same-sign WW bosons

VBS Cuts
- Large dijet invariant mass m_{jj}
- Large dijet rapidity separation Δy_{jj}



A large difference in scales $s \gg t$
leading to a breakdown of
the perturbative expansion in α_s



The VBS (VBF) cuts designed to restrict the contribution from QCD diagrams directly lead to a breakdown of the perturbative description of these diagrams!

The need for HEJ resummation with a logarithmically accurate description

arXiv:2107.06818 - Andersen, Ducloué, CE, Maier, Nail, Smillie

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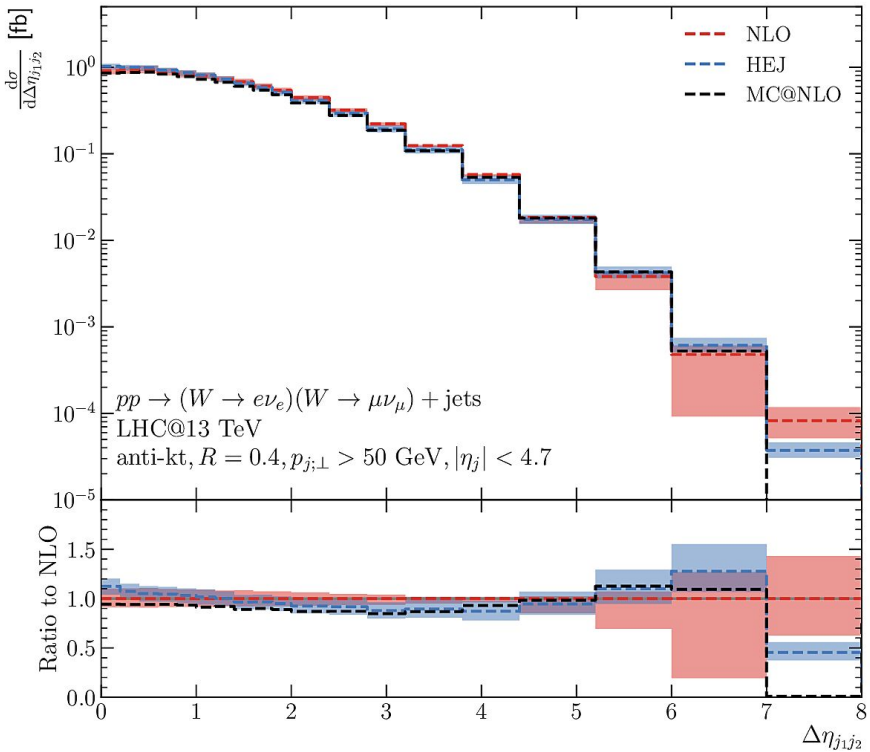


- Comparison of HEJ at leading log versus NLO for same-sign WW production alongside at least 2 jets for VBS studies
- Following the setup of a recent CMS study: arXiv:2005.01173 - CMS Collaboration
- Comparisons of the two with and without additional VBS cuts on the dijet mass and rapidity separation.
- Differences in the tails of distributions (not accounted for by the parton shower)

arXiv:2107.06818 - Andersen, Ducloué, CE, Maier, Nail, Smillie

Added support for new processes - inclusive Higgs + 1 jet

arXiv:2210.10671 - Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, Smillie

- Added resummation for inclusive Higgs plus one jet production:

$$pp \to H+ \geq 1j$$

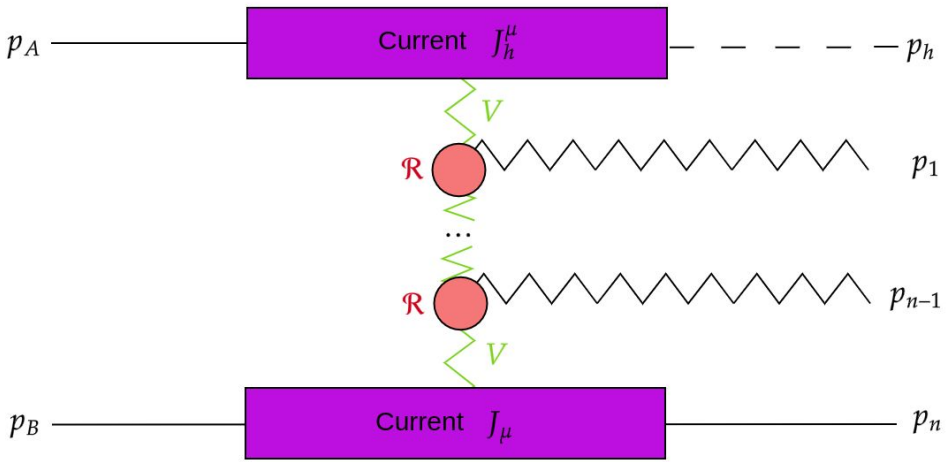
- Use the same building blocks as for pure QCD jets with factorised matrix element approach.

$$|\mathcal{M}_H|^2 = \mathcal{B} \times \prod \mathcal{R} \times \prod \mathcal{V}$$

Born-level square amplitude with Higgs current

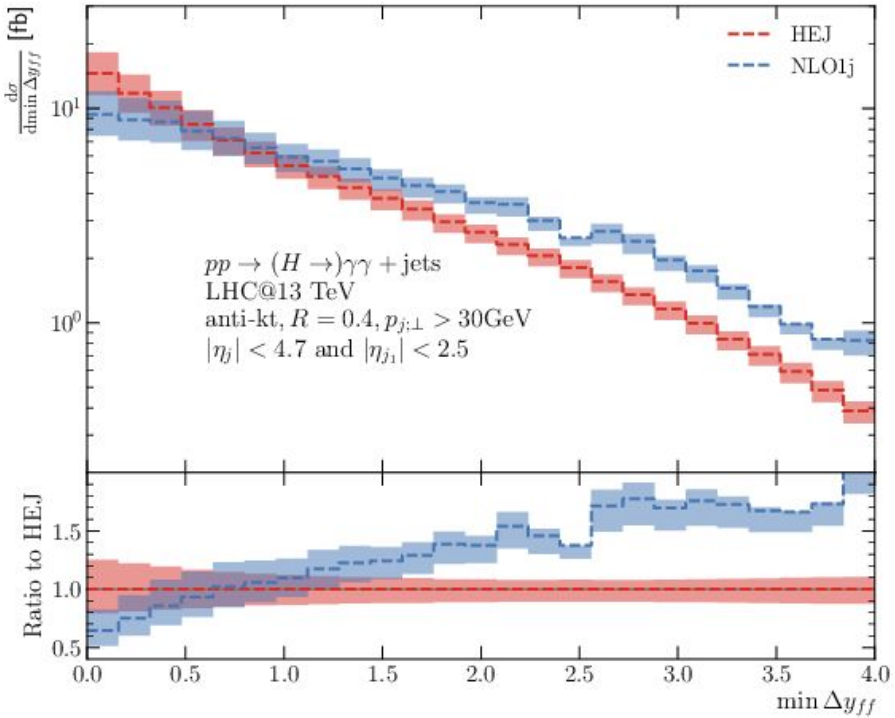
Real corrections via Lipatov Vertex

Virtual corrections via Lipatov Ansatz



Added support for new processes - inclusive Higgs + 1 jet

arXiv:2210.10671 - Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, Smillie



- Comparison of HEJ vs NLO 1j for both
  - 13TeV CMS Analysis

  arXiv:2208.12279. - CMS Collaboration
  - 8TeV ATLAS Analysis

  arXiv:1407.4222 - ATLAS Collaboration
- Includes contributions with Higgs current (like on previous slide) and Higgs emission on quark current
- Again we see differences in the tails of distributions from the higher order corrections

Upcoming code release - HEJ2.2

Subleading NLL

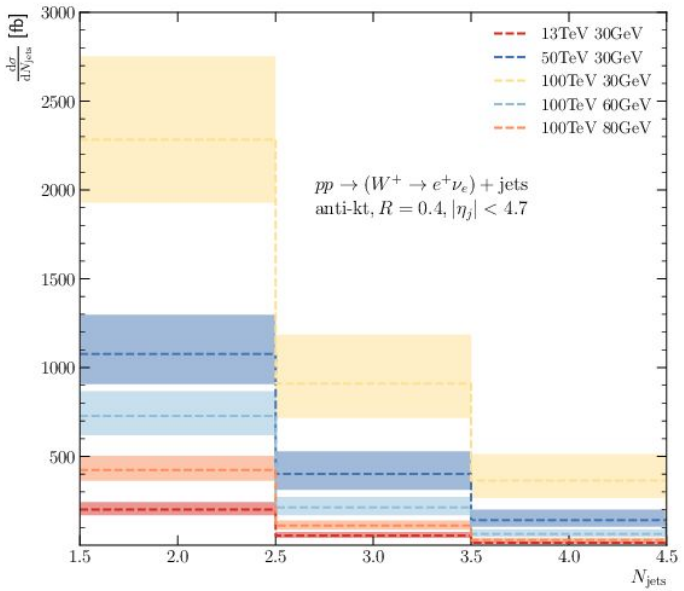
	FKL	unordered	extremal qqbar	central qqbar
pure jets	Yes	Yes	Yes	Yes
Higgs + jets	Yes	Yes	No	No
W + jets	Yes	Yes	Yes	Yes
Z/γ + jets	Yes	Yes	No	No
same-sign W + jets	Yes	No	No	No

- HEJ v2.1 out now, with v2.2 releasing soon
- HEJ2.2 includes:
  - Same-sign WW
  - H + 1j
  - Various sampling improvements for the fixed order generator

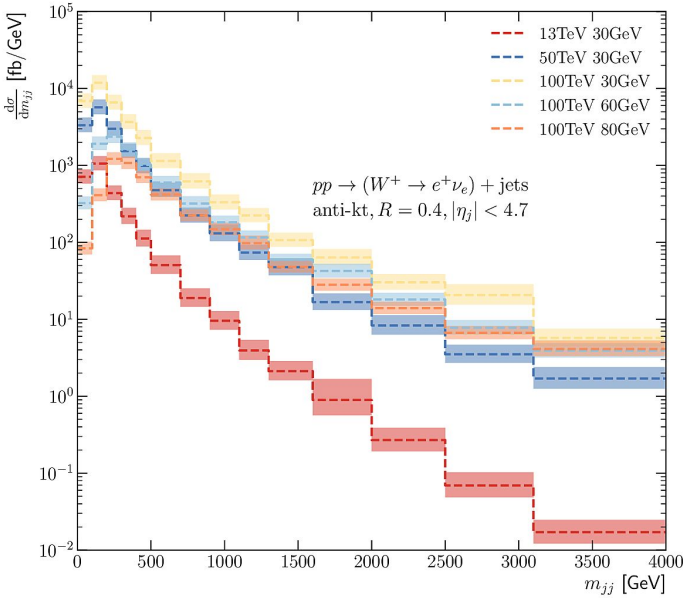
https://hub.docker.com/r/hejdock/hej

https://hej.hepforge.org/

Looking forward to higher energies - W + jets



Exclusive Jet Rates



Dijet mass

- Large jet rates can be controlled by using a higher minimum jet pT cut
- …but will see a large impact of these high energy logs in the shape of observable distributions.

Wrapping things up

- High Energy Jets is a framework for including all-order corrections for 2 to n scattering amplitudes
- HEJ2.2 (publicly releasing soon) includes support for resummation with Higgs plus one jet and for same-sign W production with at least 2 jets
- Going to higher center of mass energies is going to increase the contribution from these logarithms, making clear the need for resummation
- Work ongoing to achieve full next to leading log accuracy.

https://hej.hepforge.org/

https://hub.docker.com/r/hejdock/hej