Status and progress of HEJ

Sebastian Jaskiewicz

Parton Showers and Resummation 2023

University of Milano-Bicocca, Milan, Italy

June 7th, 2023

On behalf of HEJ collaboration

Introduction

- Large high-energy logarithms are important to understand at the LHC: *High Energy Jets* (**HEJ**) framework → overview of **HEJ**
- Transverse momentum hierarchies, collinear splittings, MPI, and hadronization described by parton showers: **Pythia**.
- This talk: Merging High-Energy resummation of **HEJ** with **Pythia** parton shower → **HEJ+Pythia**: showered events from **HEJ** input.

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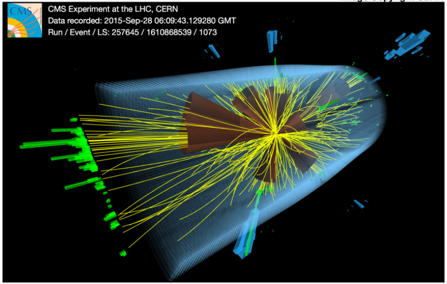
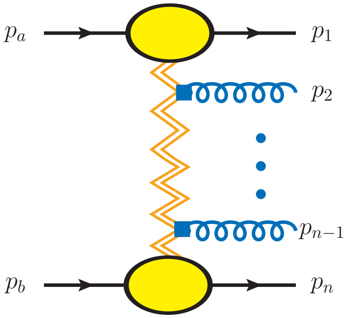


High Energy Jets (HEJ) framework

High Energy Jets resums large logarithms in s/t, same as the BFKL equation.
[J. Andersen, J. Smillie, 0908.2786] [J. Andersen, J. Smillie, 0910.5113] [J. Andersen, J. Smillie, 1101.5394] [J. Andersen, J. Black, H. Brooks, B. Ducloué, M. Heil, A. Maier, J. Smillie, 2110.15692] [J. Andersen, B. Ducloué, H. Hassan, C. Elrick, A. Maier, G. Nail, J. Paltrinieri, A. Papaefstathiou, J. Smillie, 2303.15778].



High Energy limit for $2 \to n$ scattering

$$\hat{s} \gg \hat{s}_{ij} \gg k_\perp \quad \hat{s}_{ij} = (p_i + p_j)^2$$

$$y_1 \ll y_2 \ll \ldots \ll y_{n-1} \ll y_n \quad p_{i\perp} \approx k_\perp$$

HEJ is built to describe effects from hard, wide angle emissions. Large $\ln(s/t)$ logs.

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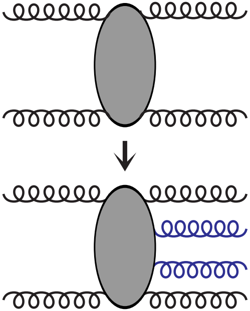

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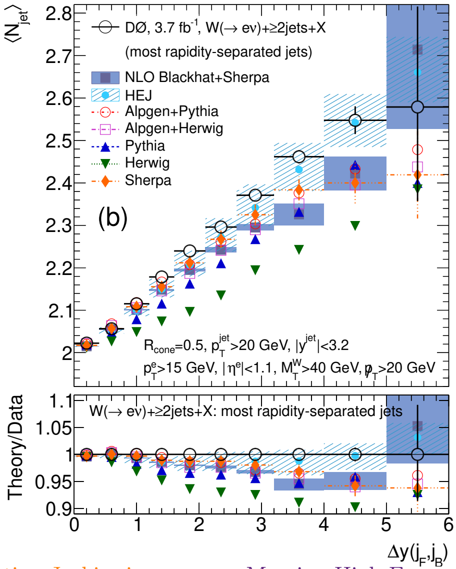
HEJ is built to describe effects from hard, wide angle emissions. Large $\ln(s/t)$ logs.

$\geq$LL + LO accurate

HEJ Motivations



HEJ describes data well in the High Energy region. Parton showers do not resum these logarithms.

Measurement of $W+\geq$ 2jets.

Average number of jets as rapidity between most forward (j_F) and backward (j_B) increases.

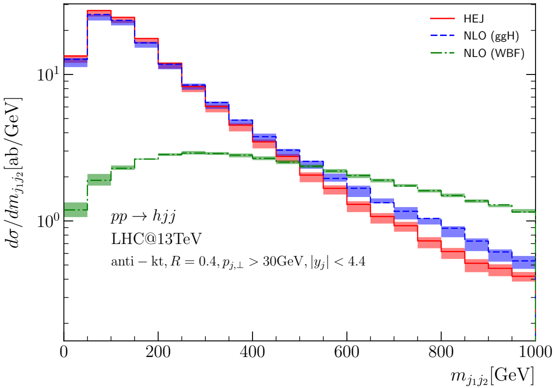
[D0 Collaboration, 1302.6508]

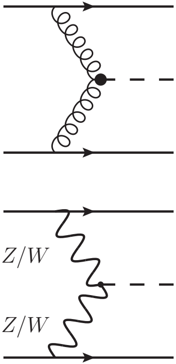
Corrections proportional to $\Delta y_{j_F,j_B}$

HEJ Motivations: Higgs + DiJets

These logarithms are crucial in describing regions selected by VBF cuts

$$\Delta y_{jj} > 2.8 \qquad m_{jj} > 400\text{GeV}$$





[J. Andersen, M. Heil, A. Maier, J. Smillie, in 1803.07977]

High Energy Jets

Most recent release: **HEJ 2.2**

`https://hej.hepforge.org/`

arXiv:2303.15778

J. Andersen, B. Ducloué, H. Hassan, C. Elrick, A. Maier, G. Nail, J. Paltrinieri, A. Papaefstathiou, J. Smillie

Processes:

- ≥ 2 jets
- H and ≥ 1 jets
- $W(\to \ell\, \nu)$ and ≥ 2 jets
- Z/γ^* and ≥ 2 jets
- $W^{\pm}W^{\pm}$ and ≥ 2 jets

On-going work

- NLO matching
- NLL resummation

High-Energy and Soft-Collinear Resummation for Jet Production at the LHC: HEJ+Pythia

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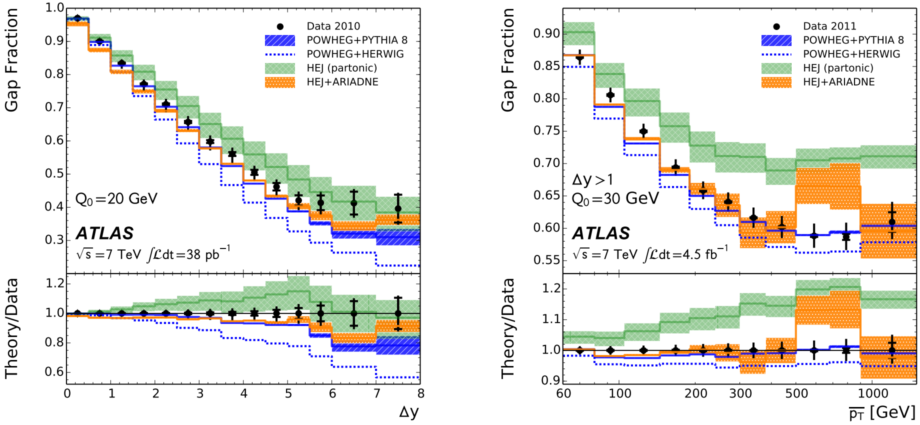
In collaboration with Jeppe Andersen, Hitham Hassan, and Leif Lönnblad

Beyond the High-Energy limit

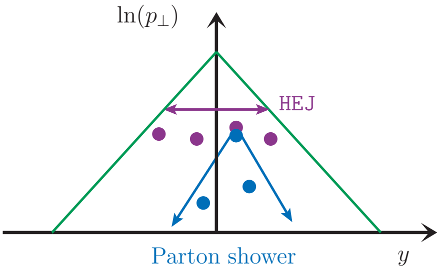
- HEJ describes high-energy logarithms well
- Transverse momentum hierarchies are not captured → Parton Showers



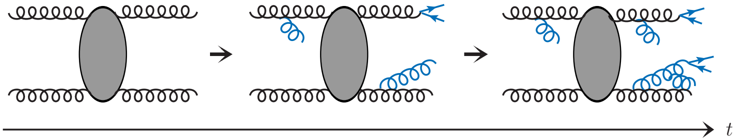
[ATLAS collaboration, 1407.5756]

Parton Showers

Soft and collinear splittings described by parton showers.
Our method uses `Pythia`.
[T. Sjöstrand, S. Mrenna, P. Skands, hep-ph/0603175][T. Sjöstrand, S. Ask, J. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. Rasmussen, P. Skands, 1410.3012] → see C. Preuss talk

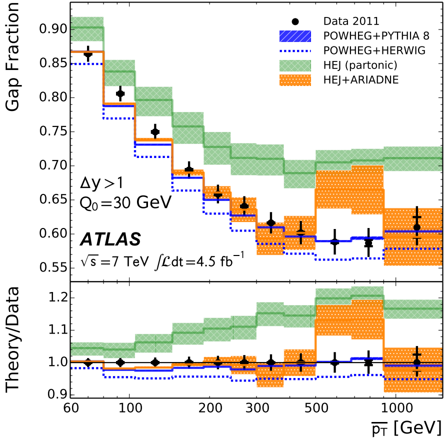


$$\Delta_{ab}(t_n, t_m) = \exp\left[-\int_{t_m}^{t_n} \frac{dt}{t} \left(\frac{\alpha_s(t)}{2\pi} \int dz P_{ab}(z) \right) \right]$$



HEJ+Ariadne

The **HEJ+Ariadne** method uses subtracted Sudakov factors to generate parton shower emissions.
[J. Andersen, L. Lönnblad, J. Smillie, 1104.1316][ATLAS collaboration, 1407.5756]



The splitting function in HEJ is

$$P^{\texttt{HEJ}} = \frac{|\mathcal{M}^{\texttt{HEJ}}_{n+1}|^2}{|\mathcal{M}^{\texttt{HEJ}}_{n}|^2}$$

Procedure starts with **HEJ**.

Then, parton shower emissions are generated according to $P^{\texttt{Ariadne}}$ - parton shower splitting function.

If these could not have been produced by **HEJ** they are accepted. Otherwise veto with probability $\mathcal{P}^{\text{veto}} = P^{\texttt{HEJ}}/P^{\texttt{Ariadne}}$.

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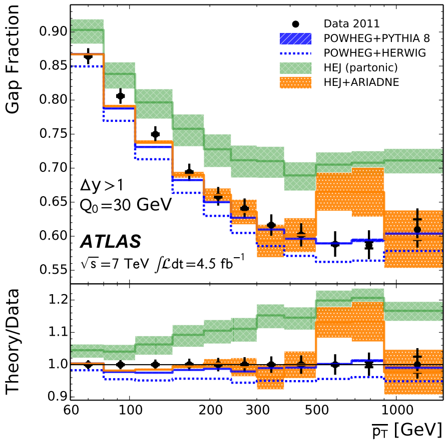

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No parton shower emissions at earlier stages

CKKW-L method

CKKW-L are method for merging Fixed-Order matrix elements with Parton Showers.

[S. Catani, F. Krauss, R. Kuhn, B. Webber, hep-ph/0109231] [L. Lönnblad, hep-ph/0112284]

Aims:

- generate N hardest emissions using matrix elements
- add Parton Shower

Phase space is divided at some *merging scale* t_{ms} if:

- $t > t_{ms}$ – matrix element region
- $t < t_{ms}$ – parton shower region

[A. Buckley et al, 1101.2599]

$$d\sigma^{\text{CKKWL}} = d\Phi_0\, B(\Phi_0) + \sum_{n=1}^{N_{\max}} d\Phi_n\; R(t_n)\theta(t_n - t_{ms})\,\Delta(t_n, t_{ms}) \times \prod_{m=1}^{n} P(t_m, z_m)\,\theta(t_{ms} - t_m)\,\Delta(t_{m-1}, t_m)$$

Previous method: HEJ+Pythia (2017)

The first **HEJ+Pythia** merging was based on the CKKW-L.

[J. Andersen, H. Brooks, L. Lönnblad, 1712.00178]

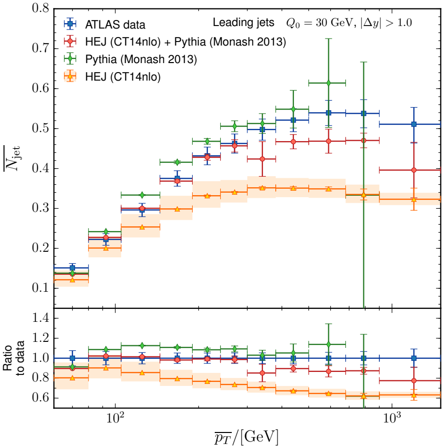
This method uses **HEJ** as a matrix element generator.

History of states is generated by **Pythia**, which then preforms trial emissions.

If trial emission is a **HEJ** like emission, veto with probability $P^{\texttt{HEJ}}/P^{\texttt{Pythia}}$ and move on.

If trial emission is not a **HEJ** state, accept it and shower freely from here.

First collinear (PS) emission is accepted.



Data from: [ATLAS Collaboration, 1407.5756]

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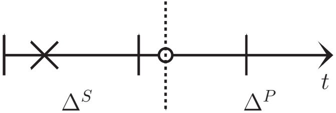

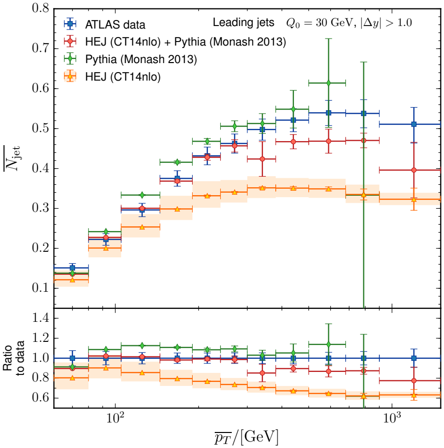

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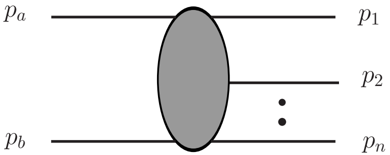
HEJ States Classification

In the Regge limit the amplitudes have the following scaling

[R. Brower, C. DeTar, J. Weis, 1974]



$$\mathcal{M} \propto s_{12}^{\alpha_{12}} s_{23}^{\alpha_{23}} \cdots s_{n-1,n}^{\alpha_{n-1,n}} f(\{p_{Ti}\})$$

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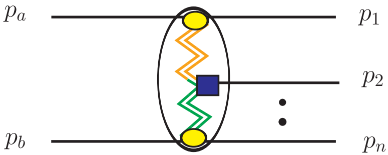

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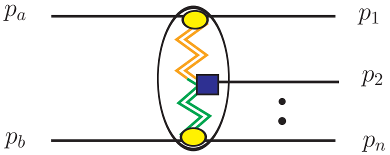

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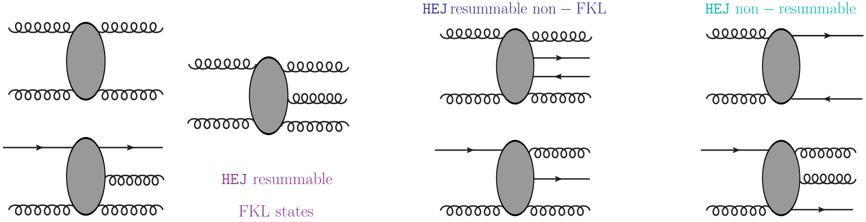
The leading order input into **HEJ** is classified as either “resummable” or “non-resummable”



HEJ+Pythia: Merging procedure

We express **HEJ** in the parton shower language and feed in **HEJ** events.

The phase-space is covered twice, once with **HEJ** and then with **Pythia**, the subtraction is done point-by-point in phase space ensuring logarithms of both **HEJ** and **Pythia** are kept.

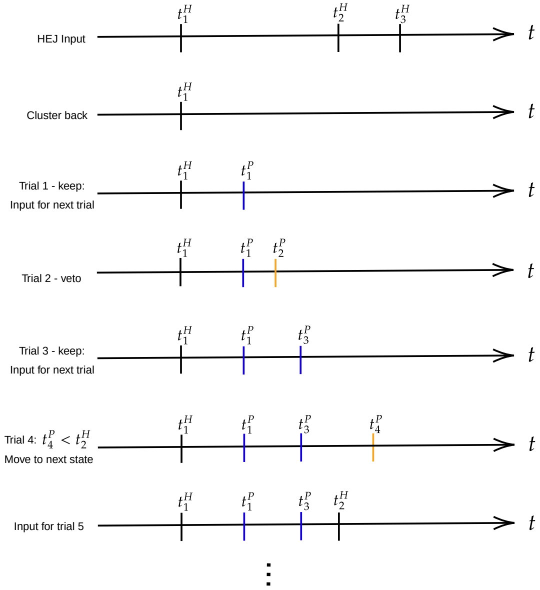
The **HEJ+Pythia** method constructs **histories** for resummable **HEJ** events. → this is to ensure that the full phase space of **HEJ** is explored by the shower.

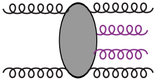
Then, we let parton shower add subtracted shower emissions in between the states of the history, and continue the Pythia shower with a subtracted splitting kernel until hadronisation

$$d\sigma_{m,n}^{\texttt{HEJ+Pythia}} = d\sigma_2^* \prod_{i=1}^{m-2} P_i^H \Delta_{i-1,i}^H \left[\prod_{\lambda=1}^{\lambda_i} P_{i_\lambda}^S \Delta_{i_{\lambda-1},i_\lambda}^S \right] \prod_{j=m-2+\mathcal{N}}^{n} P_j^S \Delta_{j-1,j}^S$$

$$\Delta^S(t_{i-1}, t_i) = \exp\left\{ -\int_{t_i}^{t_{i-1}} dt \int dz \, \underbrace{\Theta(P^P(t,z) - P^H(t,z)) \left[P^P(t,z) - P^H(t,z) \right]}_{\text{Subtracted splitting probability: } P^S(t,z)} \right\}$$

HEJ+Pythia: Merging





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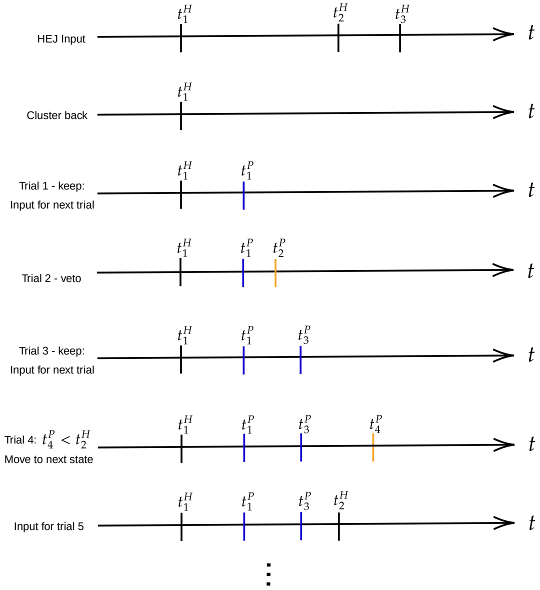

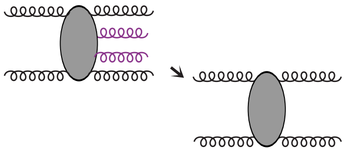

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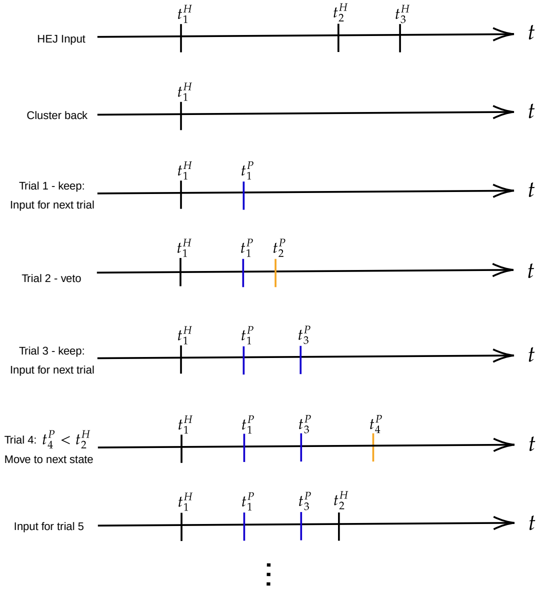

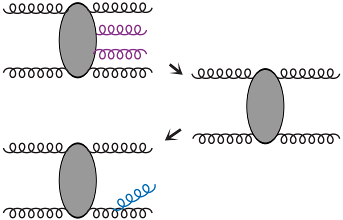

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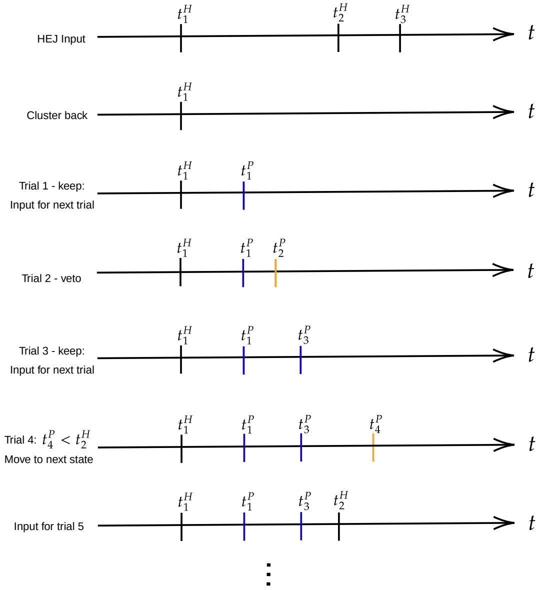

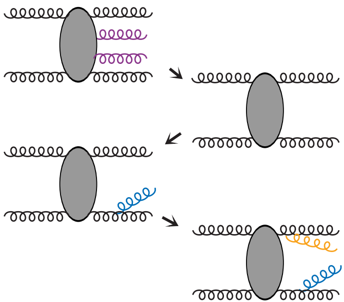

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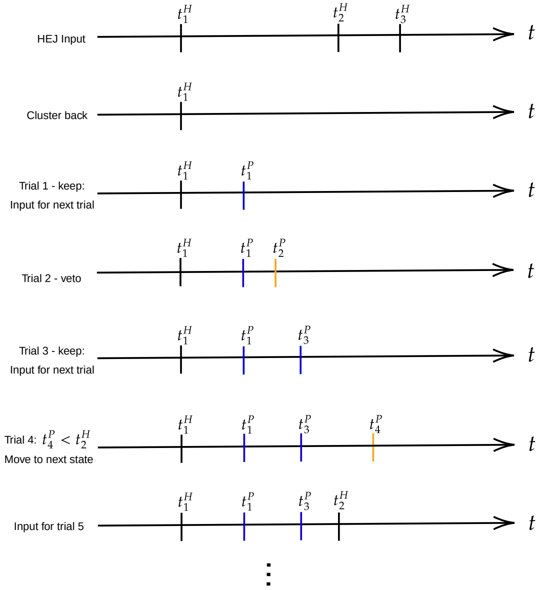

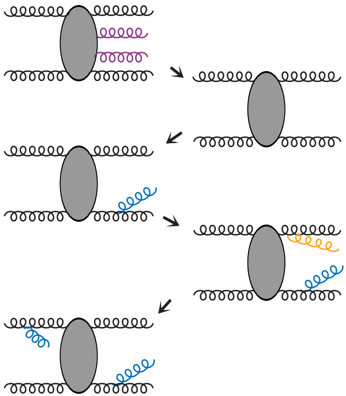

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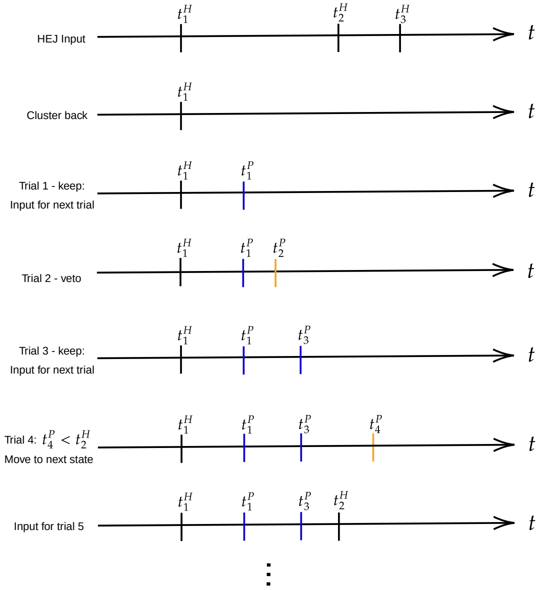

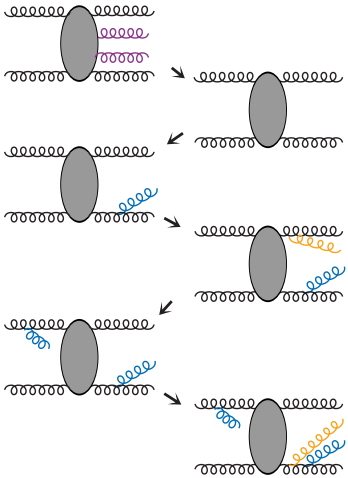

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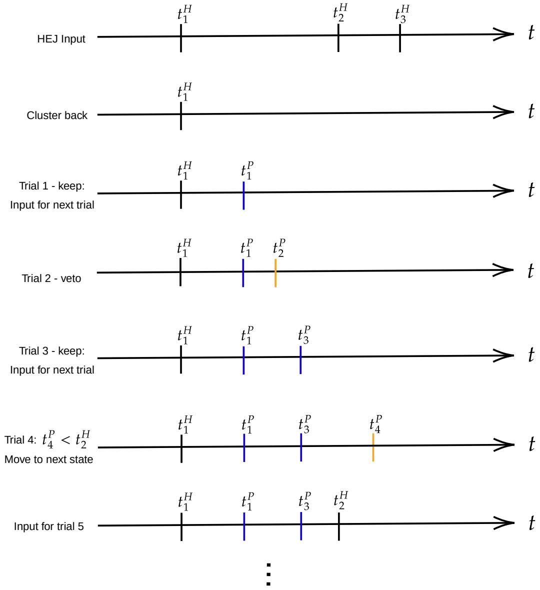

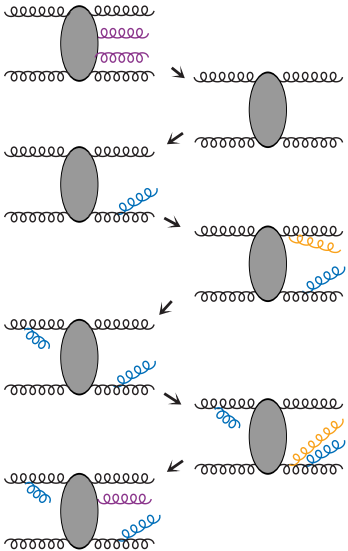

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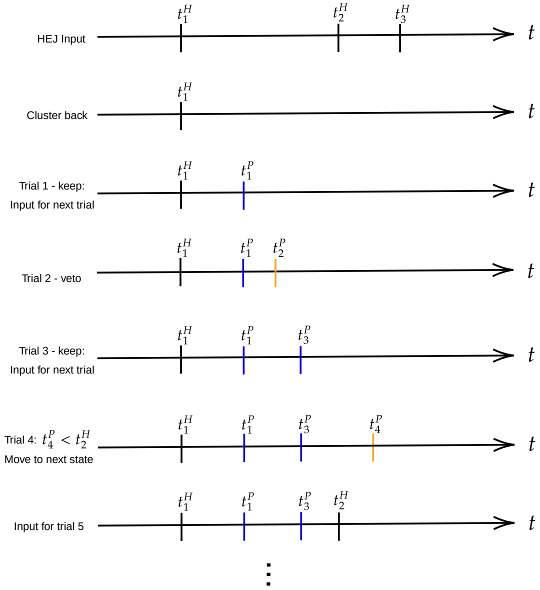
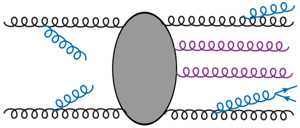
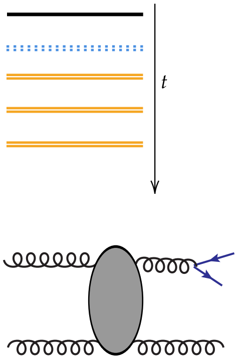
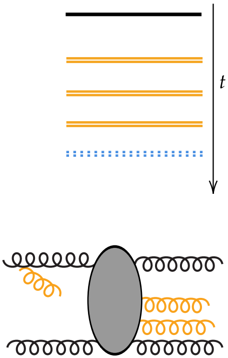




Classification of events

Consider the following evolution history:





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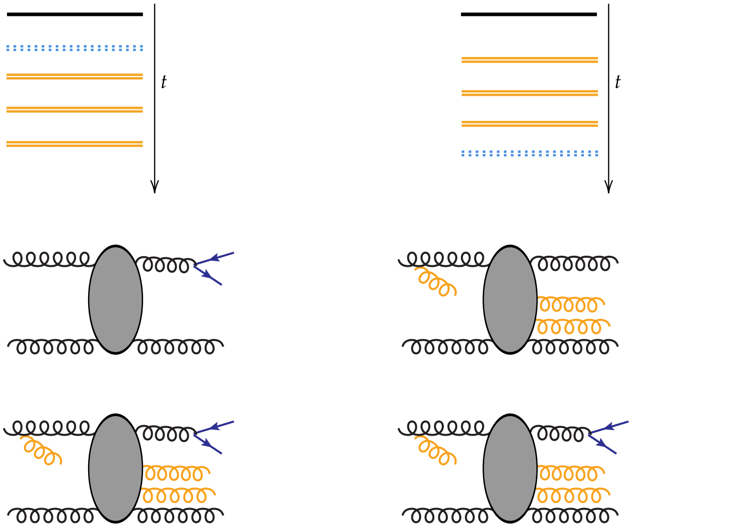
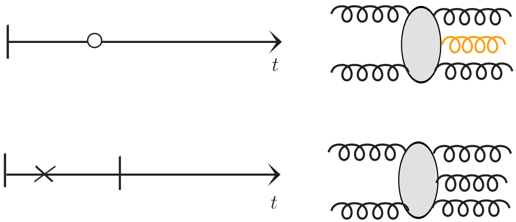


HEJ+Pythia: subtracted shower

Once the original HEJ input state is recovered and dressed, the subtracted shower continues until hadronization.

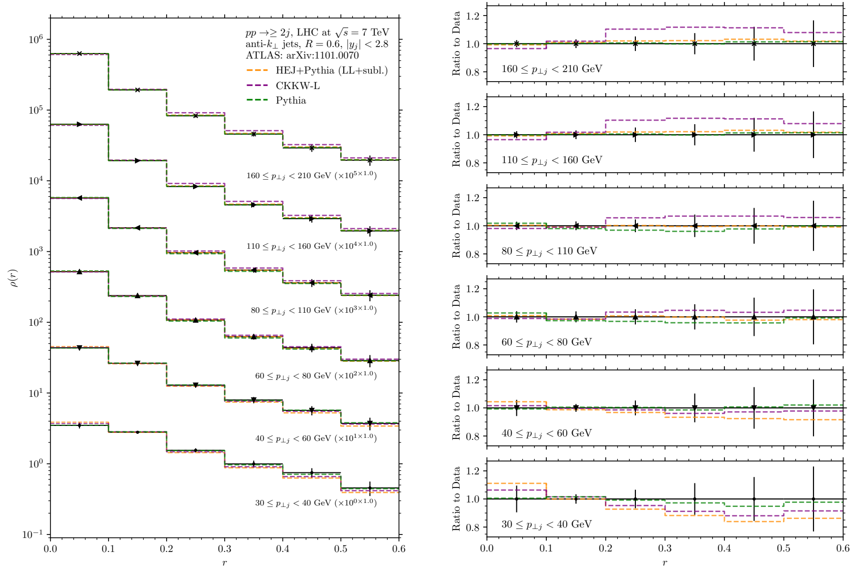
$$d\sigma_{m,n}^{\texttt{HEJ+Pythia}} = d\sigma_2^* \prod_{i=1}^{m-2} P_i^H \Delta_{i-1,i}^H \left[\prod_{\lambda=1}^{\lambda_i} P_{i_\lambda}^S \Delta_{i_{\lambda-1},i_\lambda}^S \right] \prod_{j=m-2+\mathcal{N}}^{n} P_j^S \Delta_{j-1,j}^S$$

Showered low multiplicity HEJ events can resemble higher multiplicity HEJ events → subtraction needed.



Results

Results: Jet Shapes



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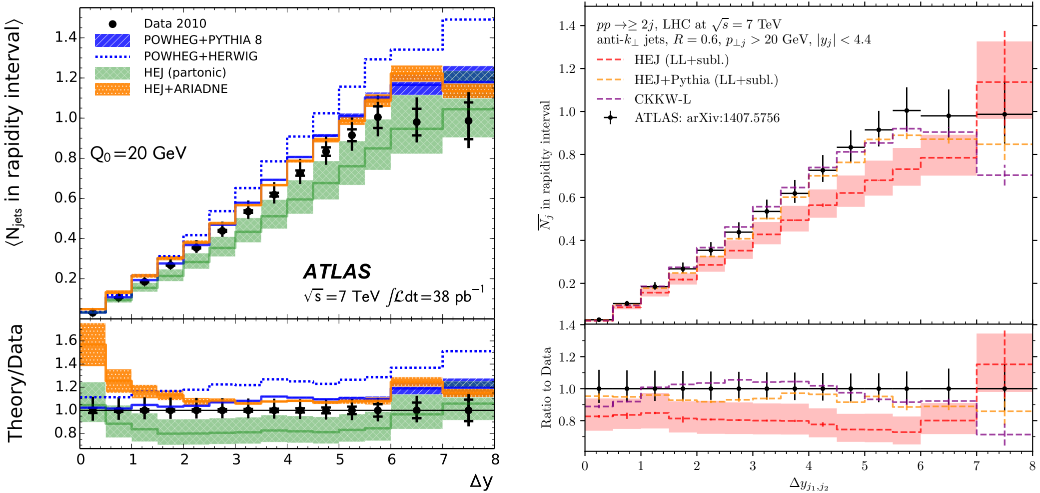
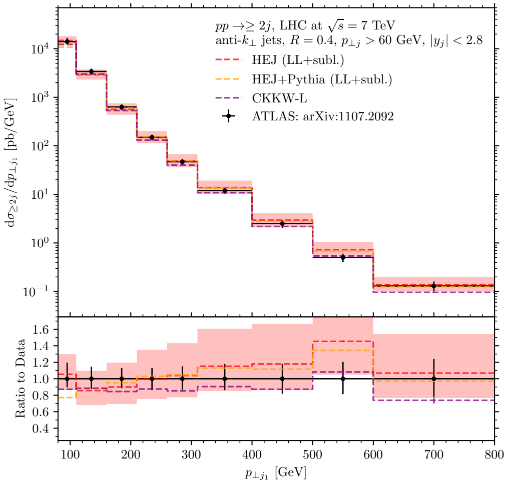
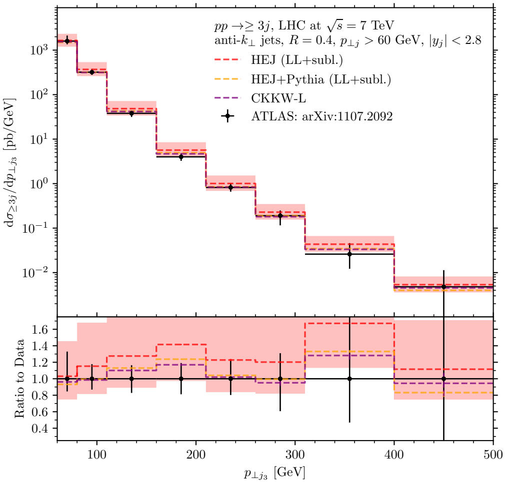


Data 2010
POWHEG+PYTHIA 8
POWHEG+HERWIG
HEJ (partonic)
HEJ+ARIADNE
Q0 =20 GeV
ATLAS
√s =7 TeV ∫ℒdt=38 pb−1
⟨Njets in rapidity interval⟩
Theory/Data
Δy
pp →≥ 2j, LHC at √s = 7 TeV
anti-k⊥ jets, R = 0.6, p⊥j > 20 GeV, |yj| < 4.4
HEJ (LL+subl.)
HEJ+Pythia (LL+subl.)
CKKW-L
ATLAS: arXiv:1407.5756
N̄j in rapidity interval
Ratio to Data
Δyj1,j2

Results: Multi-jet Cross-sections





Summary

- Most recent release: `HEJ` **2.2** `https://hej.hepforge.org/`

Recent developments

- Introduced improved method to combine high-energy resummation implemented in `HEJ` with soft-collinear logarithms of `Pythia`
- Implemented in `HEJ+Pythia` software
- We cover the full phase space of both `HEJ` and `Pythia` and subtract overlapping contributions, keeping accuracy of both and retaining LO accuracy
- Demonstrated correct implementation using jet shapes and multi-jet observables

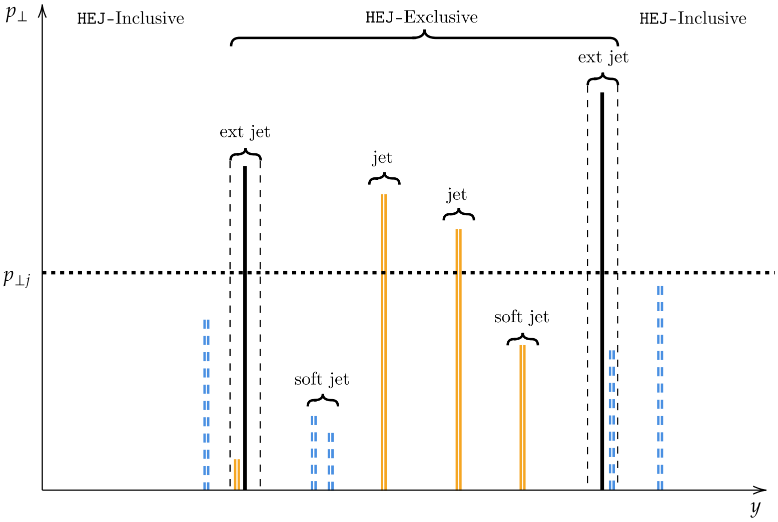
Outlook

- Implementation of this procedure to other processes, for example W + jets

Thank you!

Auxiliary slides

Phase space



$p_\perp$
HEJ-Inclusive
HEJ-Exclusive
HEJ-Inclusive
ext jet
ext jet
jet
jet
soft jet
soft jet
$p_{\perp j}$
y

Recoil Strategy

When we add back an emission from a trial event to an arbitrary later stage in the history, we recoil the additional momentum according to the following global strategy:

1. Reshuffle the excess transverse momentum across the final state partons, conserving the mass and rapidity of each.
2. Rescale all transverse momenta by a constant factor λ such that the invariant mass of the initial state $\sqrt{\hat{s}}$ is conserved and again reassign the E and p_z components of each final state particle such that the rapidities and masses of each are conserved.
3. Sum over positive and negative lightcone components of the final state momenta to find physical analogues for the momenta of the initial state partons.
4. Boost along the z-axis such that that the initial state momenta are the same as they were in the original state, using the momenta in step 3. to derive the rapidity ψ. This ensures that beam energies are not exceeded if many emissions are added.

Thank you